Studying The Nuclear (And Neutron) Matter Equation Of State With The CBM Experiment At FAIR

Kshitij Agarwal

Eberhard Karls Universität Tübingen (DE)

Hirschegg 2020 – Nuclear Equation Of State and Neutron Stars

International Workshop XLVIII on Gross Properties of Nuclei and Nuclear Excitations

Hirschegg, Kleinwalsertal, Austria, January 12 - 18, 2020

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

MATHEMATISCH-NATURWISSENSCHAFTLICHE FAKULTÄT
Physikalisches Institut

GSI

CBM

FAIR

Topics Addressed In This Talk

- Heavy Ion Collisions ↔ Astrophysical Events & Objects
- High Density EoS Observables for CBM@FAIR
  - Nuclear Symmetric Matter EOS
  - Neutron Matter EOS
    - Symmetry Energy
    - Hyperons in Dense Matter: ΛN, ΛNN, and ΛΛN interactions
- Experimental Challenges
- Summary and Outlook

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- **High Density EoS Observables for CBM@FAIR**
  - **Nuclear Symmetric Matter EOS**
  - **Neutron Matter EOS**
    - **Symmetry Energy**
    - **Hyperons in Dense Matter: ΛN, ΛNN, and ΛΛN interactions**
- **Experimental Challenges**
- **Summary and Outlook**

Other relevant 'experiment' talks in this workshop:

- **Mo. 17:00** — **William Lynch (MSU) – Experimental Constraints on the EoS of Dense Matter**
- **Mo. 17:40** — **Peter Senger (GSI) – Nuclear Equation of State from Reactions**
- **Wed. 17:00** — **Arnaud Le Fevre (GSI) – Asymmetry energy and nuclear matter EoS: What have we learnt from experiments at SIS18?**

Heavy Ion Collisions

↕

Astrophysical Events And Objects

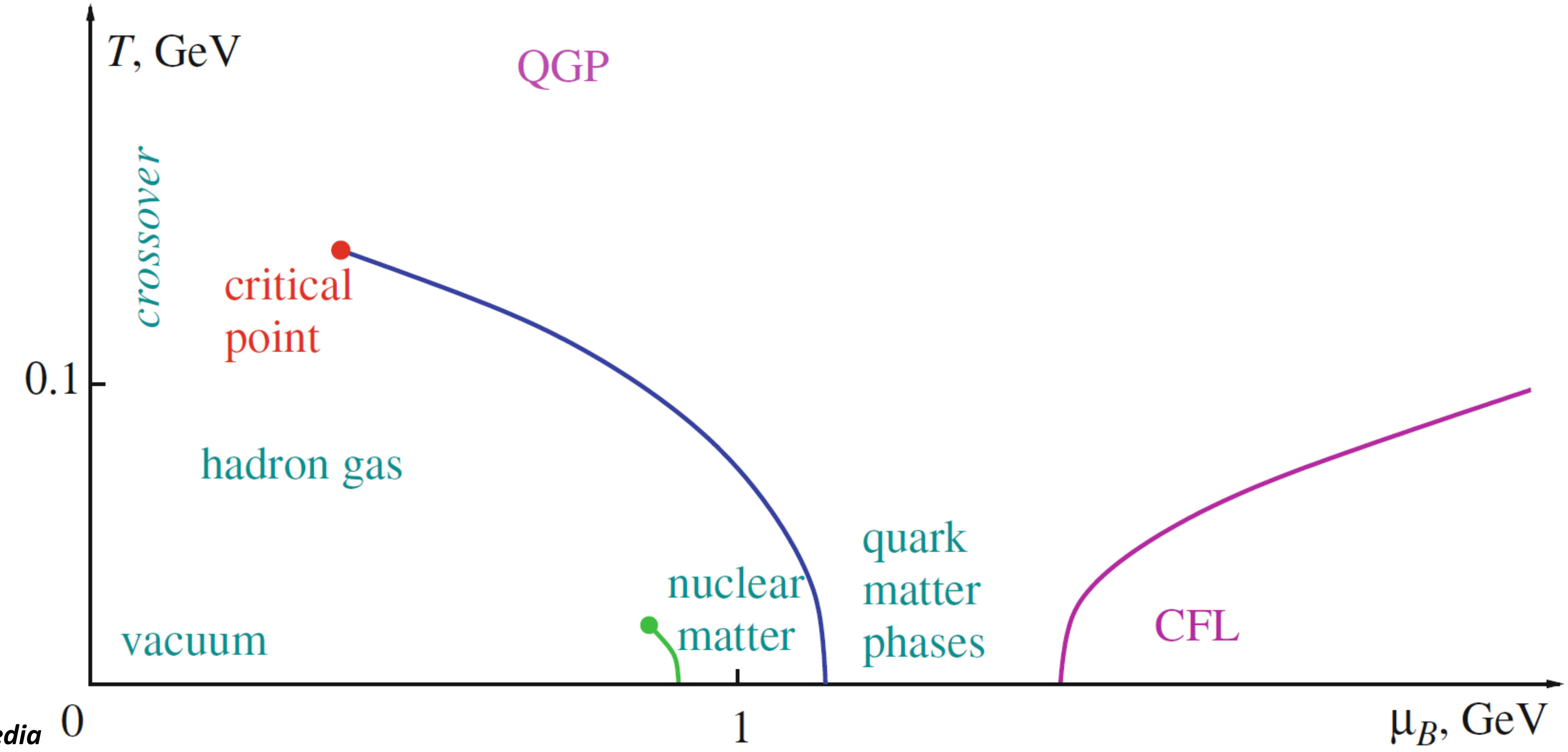
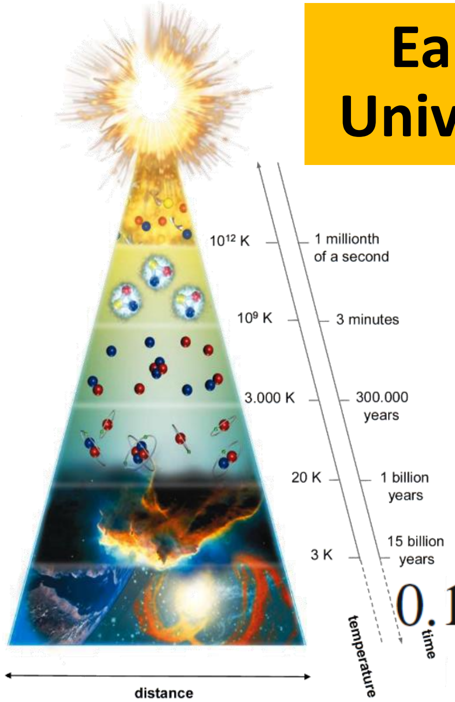
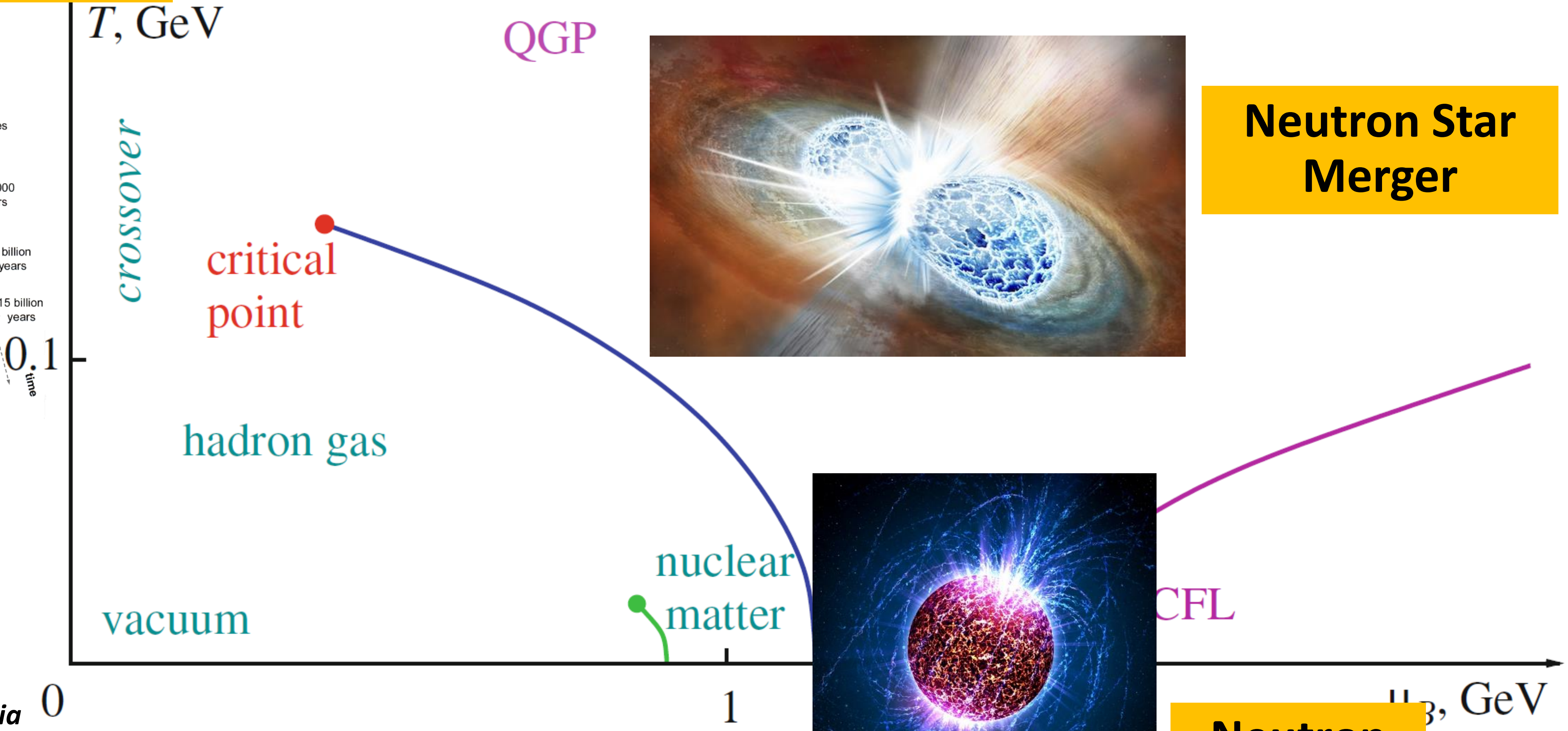


Image credits: Wikimedia
Robin Dienel, Carnegie Institution for Science
Friman et al., The CBM Physics Book, Springer (2010)
GSI-DOC-2004-Mar-196-2



Early Universe



Neutron Star Merger

Neutron Stars

Image credits: Wikimedia
Robin Dienel, Carnegie Institution for Science
Friman et al., The CBM Physics Book, Springer (2010)
GSI-DOC-2004-Mar-196-2

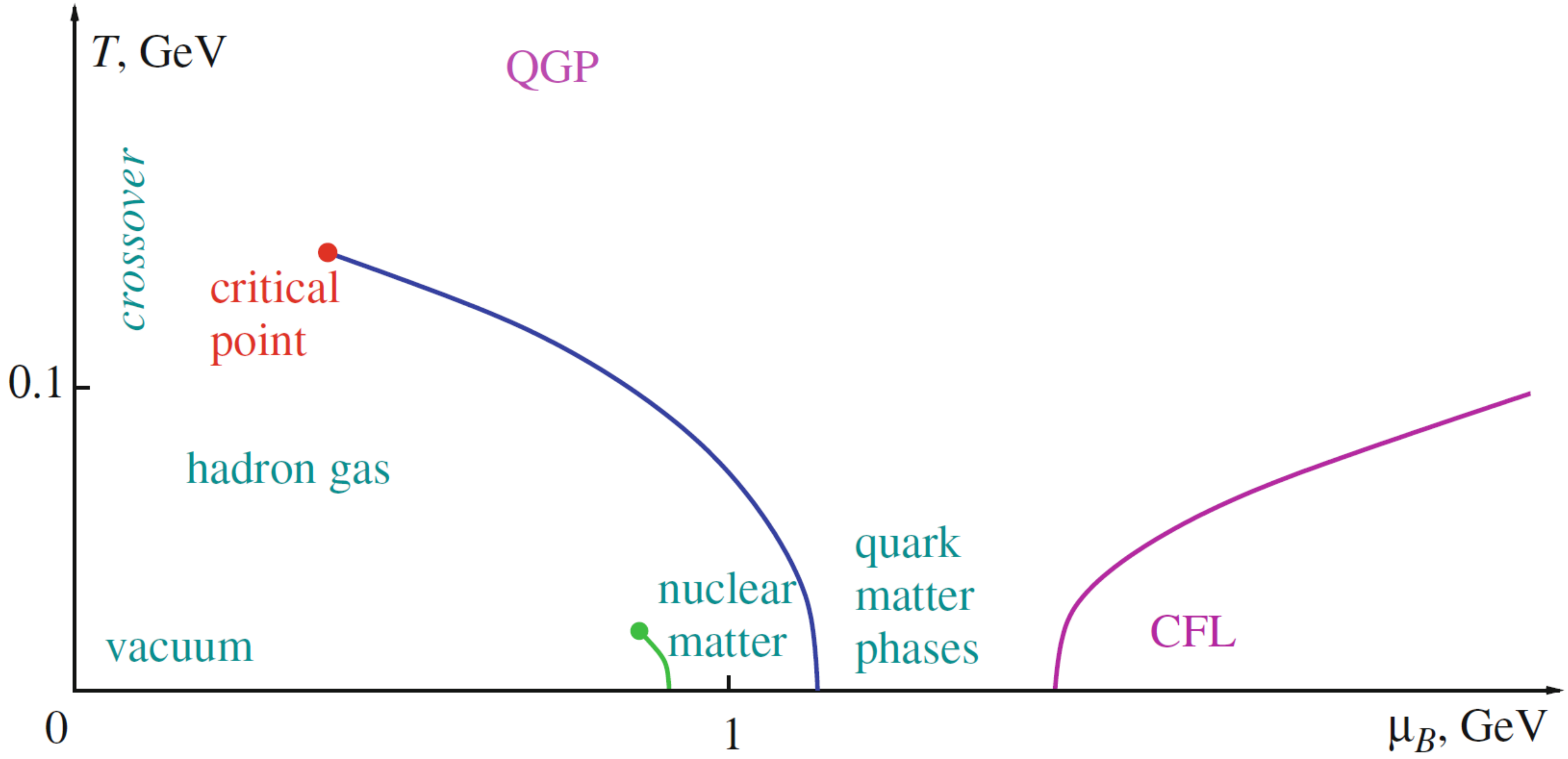
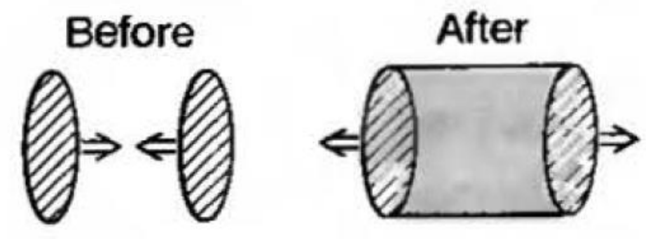
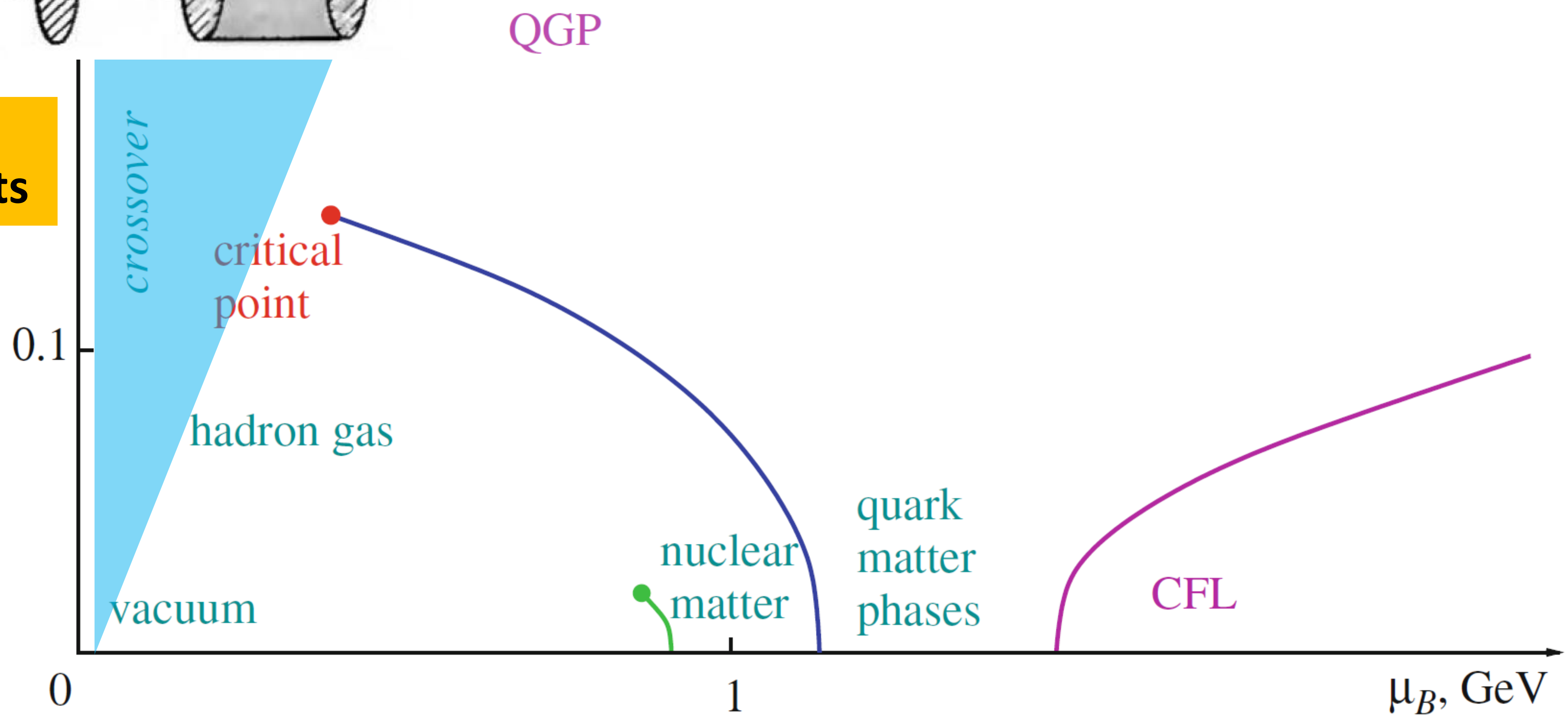


Image credits: Friman et al., The CBM Physics Book, Springer (2010)
T. Galatyuk, WE-Heraeus Physics School – 2017

Heavy Ion Collisions ⟷ Astrophysical Events & Objects



Collider Experiments



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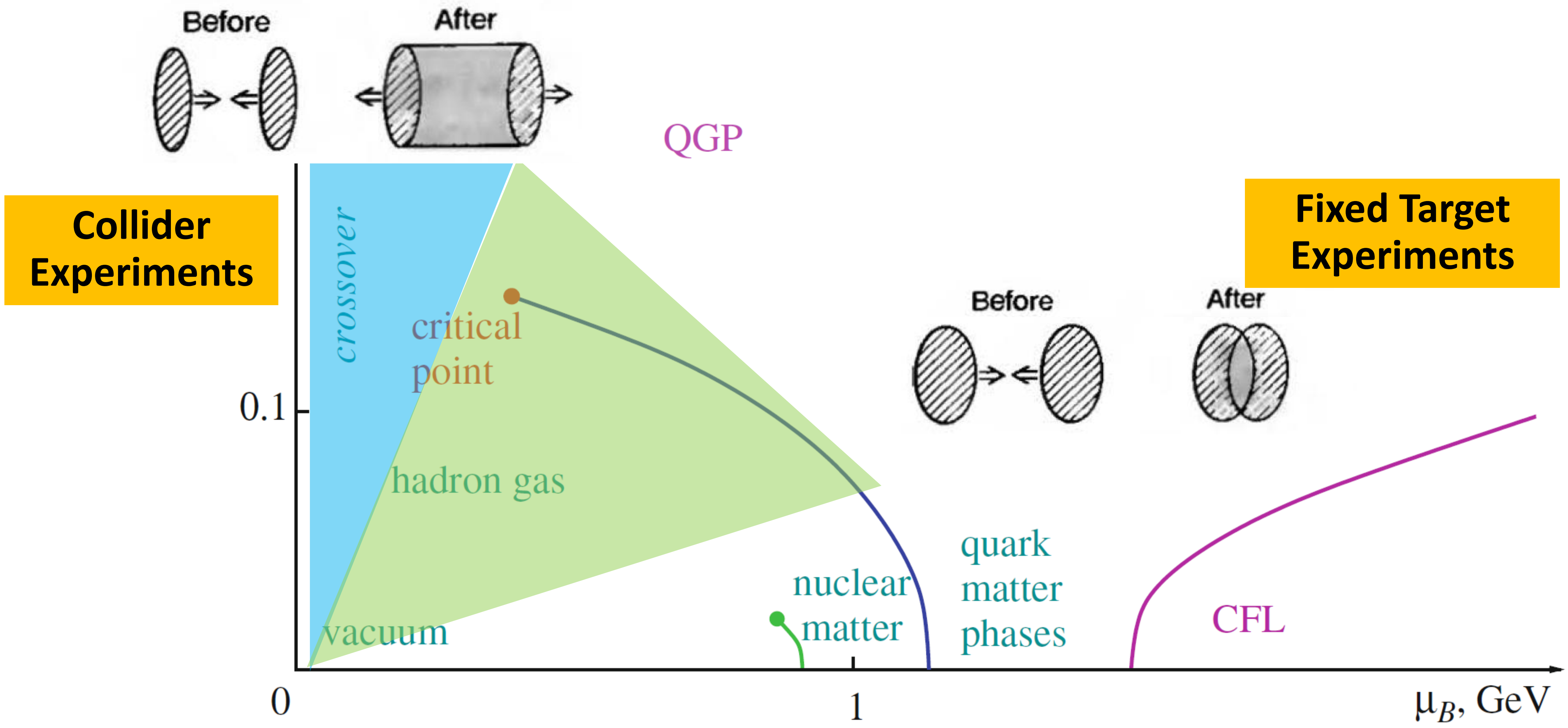

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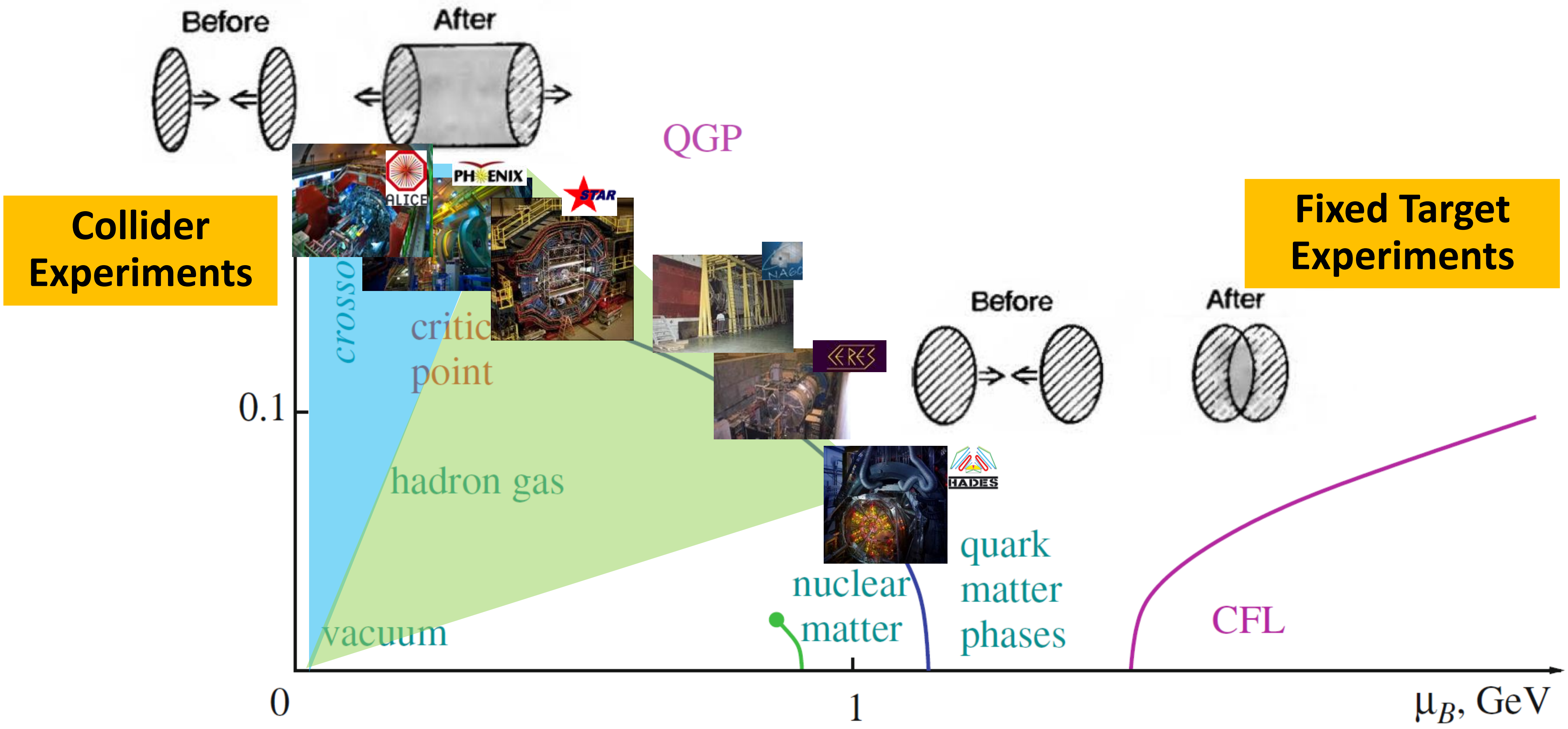
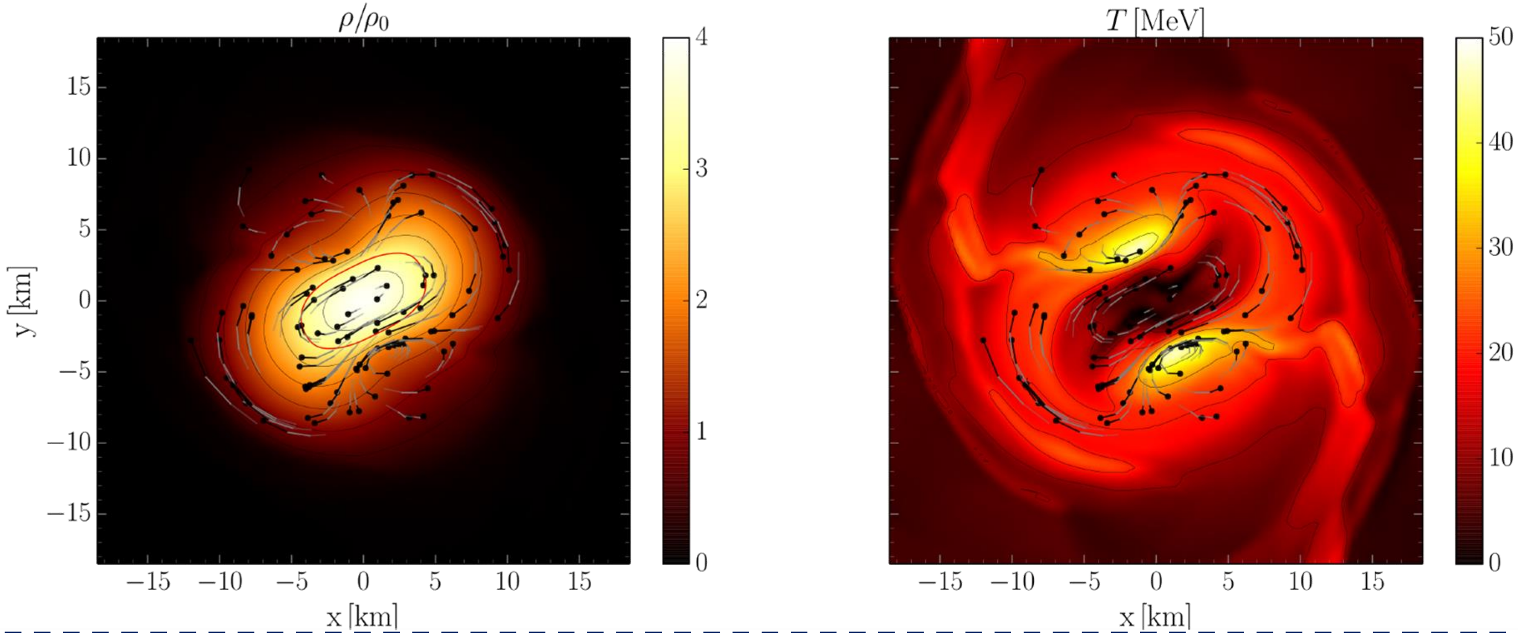
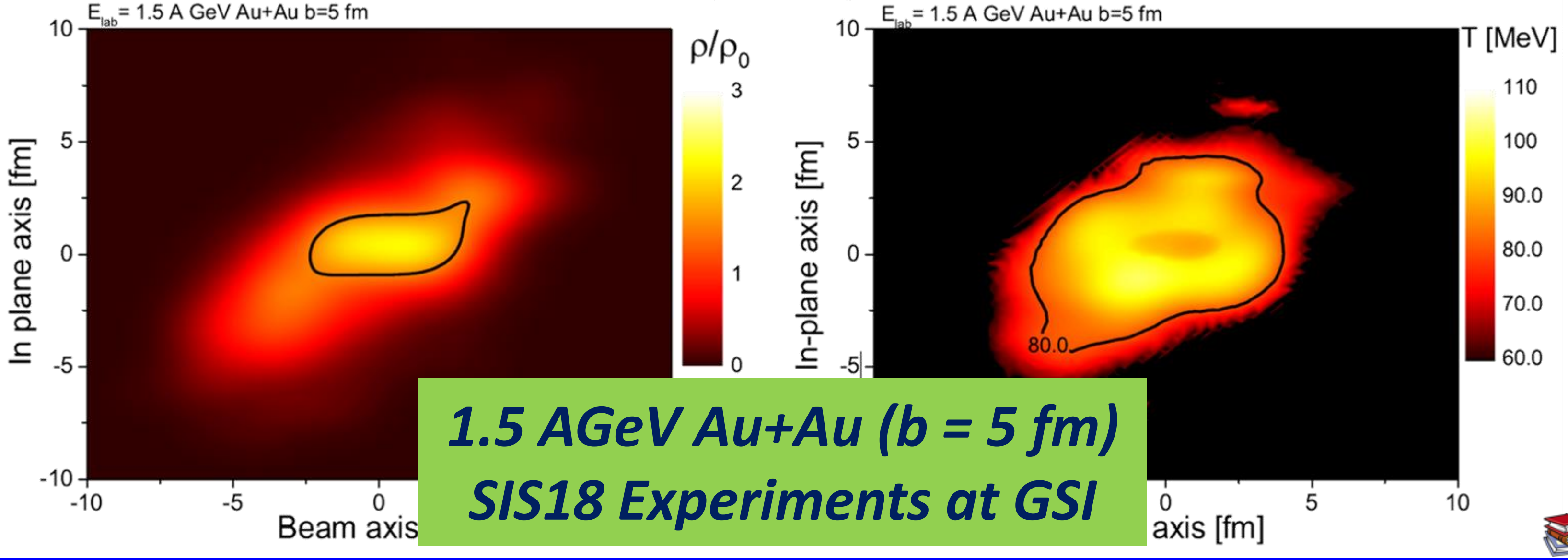


Image credits: Friman et al., The CBM Physics Book, Springer (2010)
T. Galatyuk, WE-Heraeus Physics School – 2017

CREATING HIGH-DENSITY (AND HIGH-TEMPERATURE) MEDIUM





1.5 AGeV Au+Au (b = 5 fm)
SIS18 Experiments at GSI

Neutron Star Mergers

Equation of State (EOS)

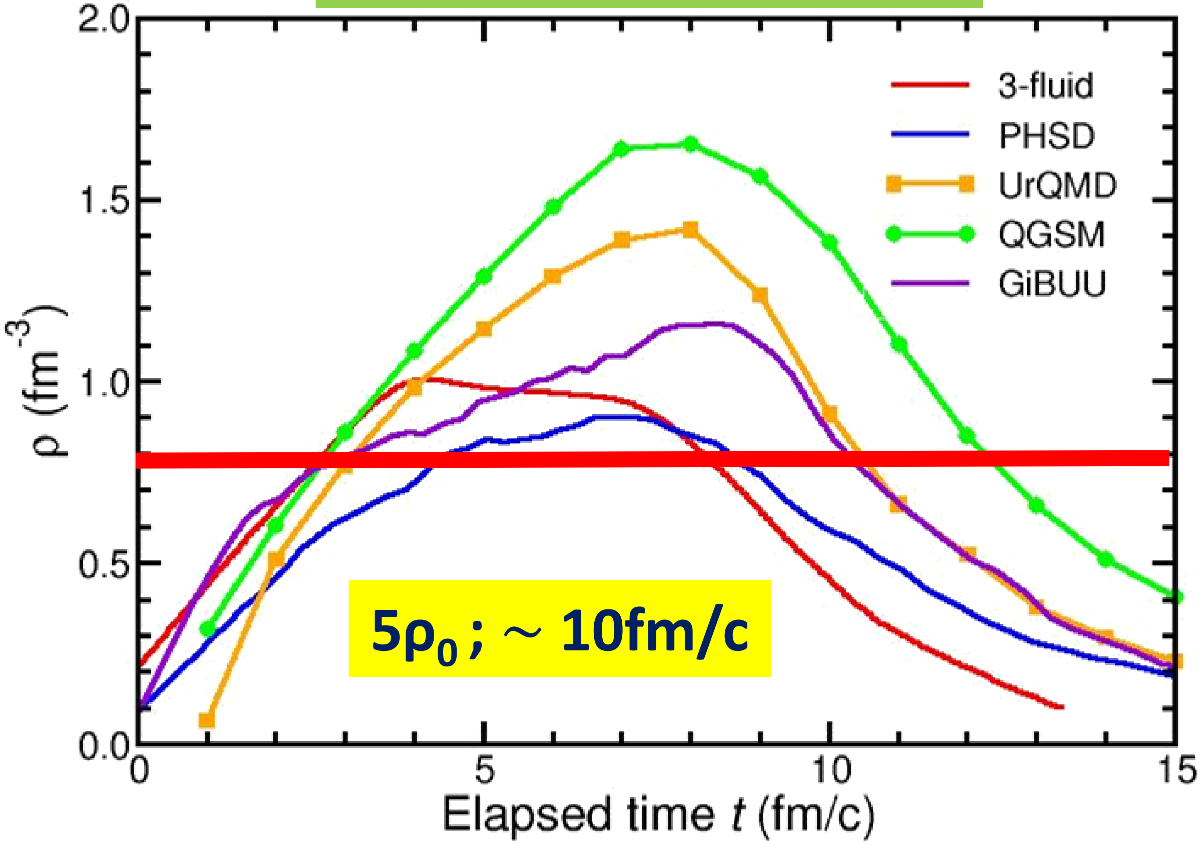
$\rho > \rho_0$

Heavy Ion Collisions

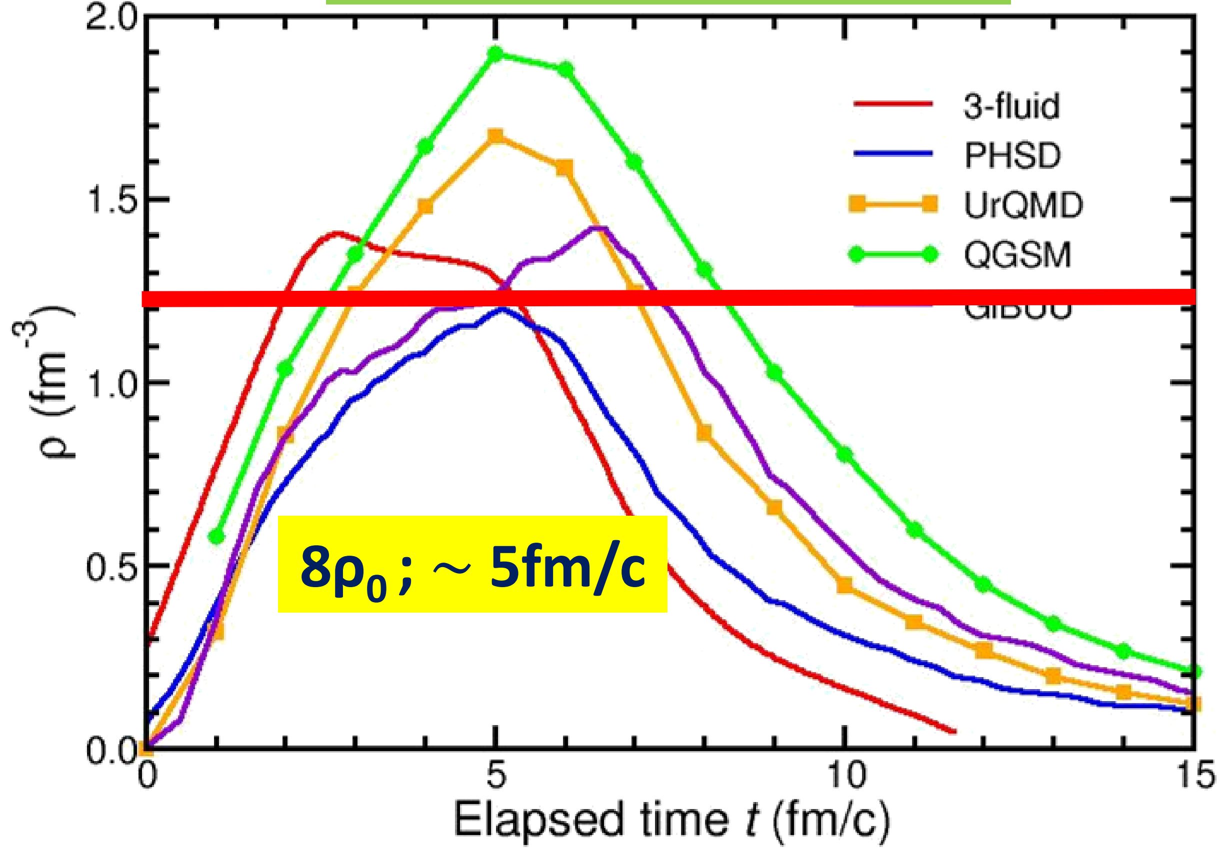
M. Hanauske et al., 2017 J. Phys.: Conf. Ser. 878 012031

Even Higher Achievable Densities In Au-Au Collisions

5 A GeV Au+Au (b = 0)



10 A GeV Au+Au (b = 0)



J. Randrup & J. Cleymans, PRC 74 (2006) 047901
I.C. Arsene et al., PRC 75 (2007) 034902
Friman et al., The CBM Physics Book, Springer (2010)

Compressed Baryonic Matter (CBM) Experiment

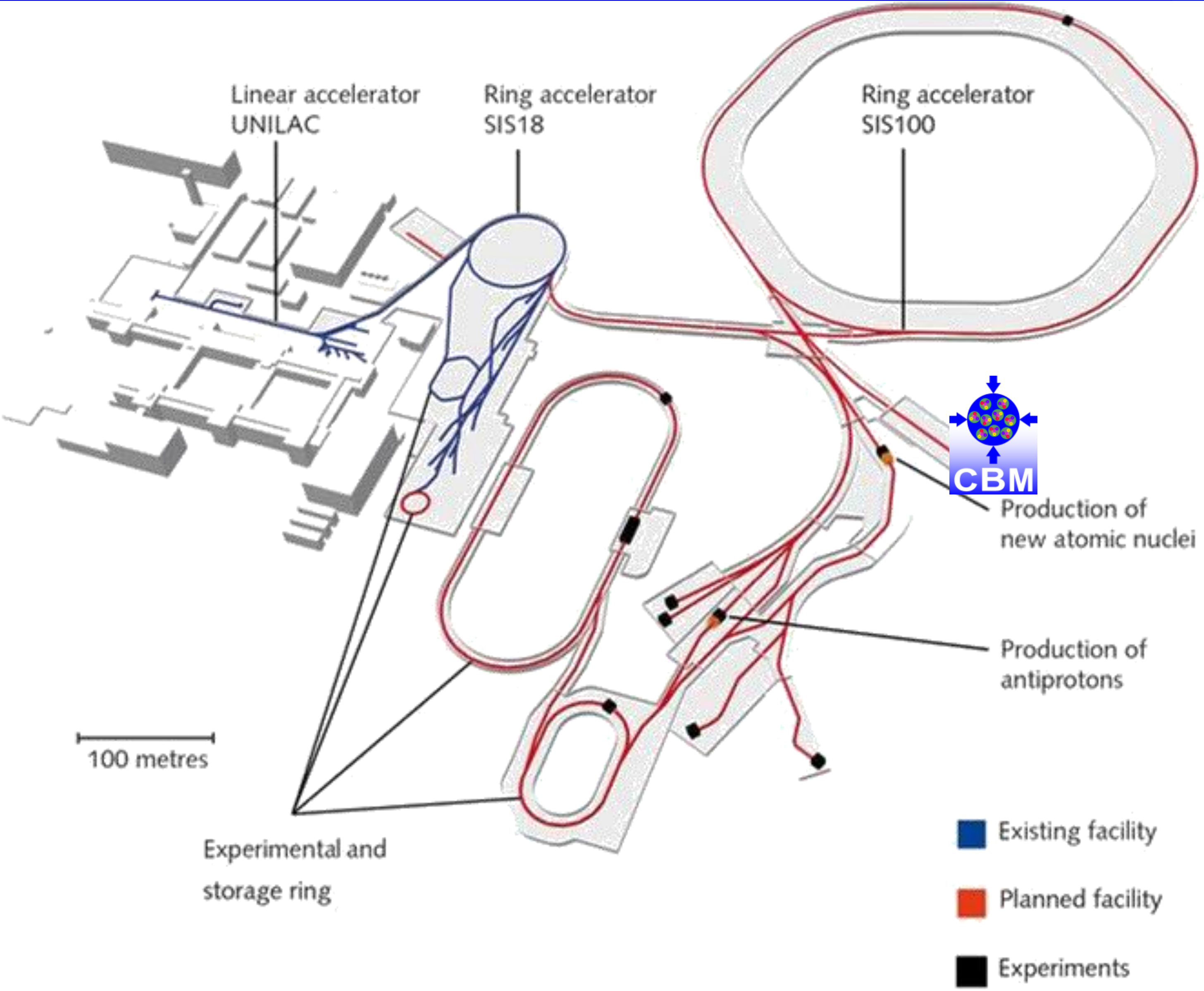
GSI-FAIR SIS100 accelerator – 11 AGeV (Au), $8\rho_0$

Collision Energies and Systems available at SIS100

Beam	Z	A	E (AGeV)
p	1	1	29
d	1	2	14
Ca	20	40	14
Ni	28	58	13.6
In	49	115	11.9
Au	79	197	11
U	92	238	10.7

CBM Collision Energies:

$$\sqrt{s_{NN}} = 2.5 \ \ldots 4.9 \text{ GeV}$$



High Density EoS Observables For CBM@FAIR

Nuclear Matter Equation Of State (EoS)

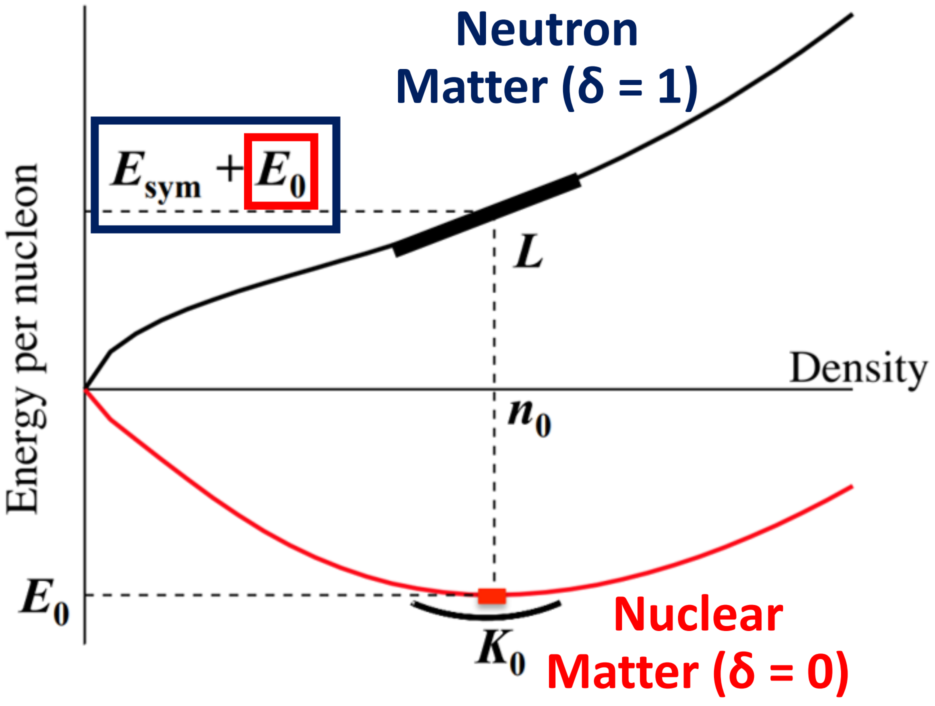
EOS – **Equation relating the state variables, such as pressure, temperature, density, energy and isospin asymmetry, under a given set of physical conditions**

Binding Energy per nucleon:
(semi-empirical mass formula)

$$\frac{E}{A}(\delta) = \left[-a_{vol} + \frac{a_{surf}}{A^{1/3}} + a_c\frac{Z^2}{A^{4/3}} + \frac{E_{pair}}{A}\right] + \left[a_{sym}\left(\frac{N-Z}{A}\right)^2\right]$$

Symmetry Term
 # protons = # neutrons

Asymmetry Term
 # protons ≠ # neutrons



$$\frac{E}{A}(\rho,\delta) = \left[\frac{E}{A}(\rho,0)\right] + \left[E_{sym}(\rho)\times\delta^2\right]$$

Neutron Matter EOS	Nuclear/Symmetric Matter EOS	Symmetry Energy

where, $\delta = \frac{\rho_N - \rho_P}{\rho_N + \rho_P}$

Hajime Togashi, New perspectives on Neutron Star Interiors - ECT (2017)*

EoS w/ CBM Case #1

Symmetric Matter Equation Of State

$$E_A(\rho, \delta) = E_A(\rho, 0) + E_{SYM}(\rho) \cdot \delta^2$$

Experimental Observables [I] – Collective Flow

Collective flow of nucleons driven by the pressure gradient –
Sensitive to nuclear incompressibility, κ → Equation of State

Two observables of the high pressures results in matter to be ejected in specific directions:

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Collective flow of nucleons driven by the pressure gradient –
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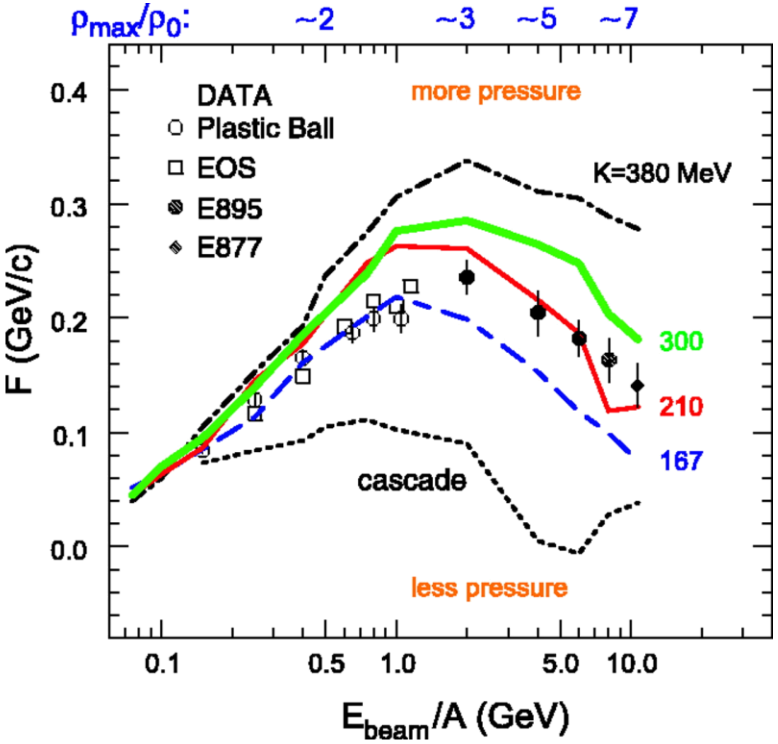
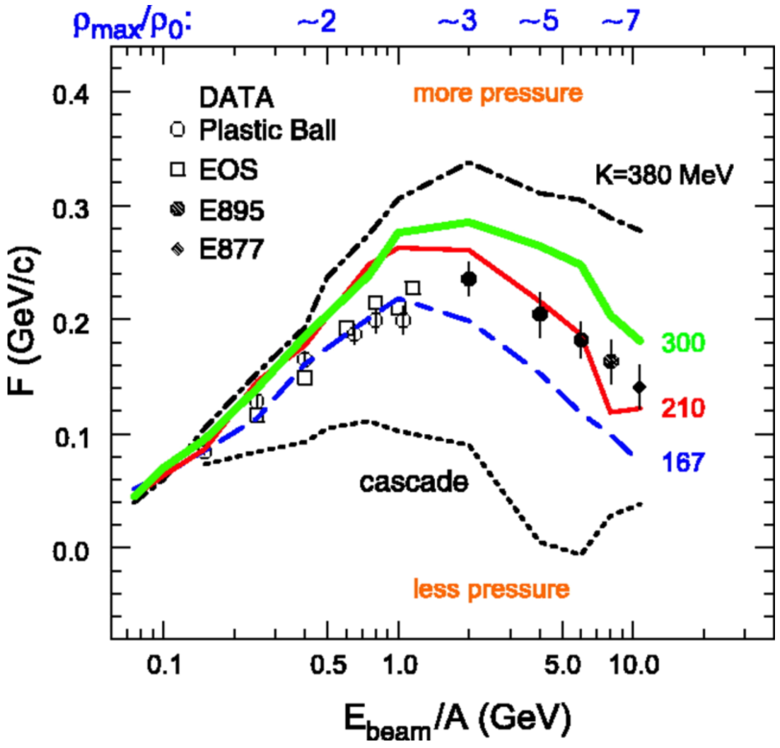


F ≡ Magnitude of sideward deflection
↓
$$\kappa = 170 - 210 \text{ MeV}$$

Two observables of the high pressures results in matter to be ejected in specific directions:

- **Directed Flow v_1 Nucleons deflected sideways in the reaction plane**

Collective flow of nucleons driven by the pressure gradient – Sensitive to nuclear incompressibility, κ → Equation of State



F ≡ Magnitude of sideward deflection

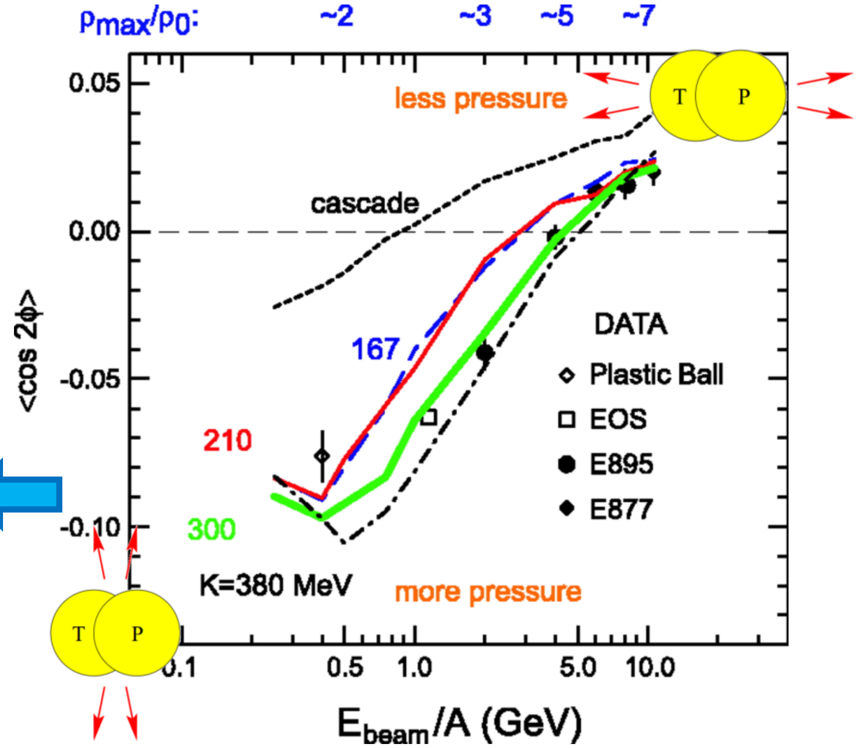
↓

$\kappa = 170 - 210$ MeV

<cos(2φ)> ≡ Direction of particle ejection

↓

$\kappa = 170 - 370$ MeV



Two observables of the high pressures results in matter to be ejected in specific directions:

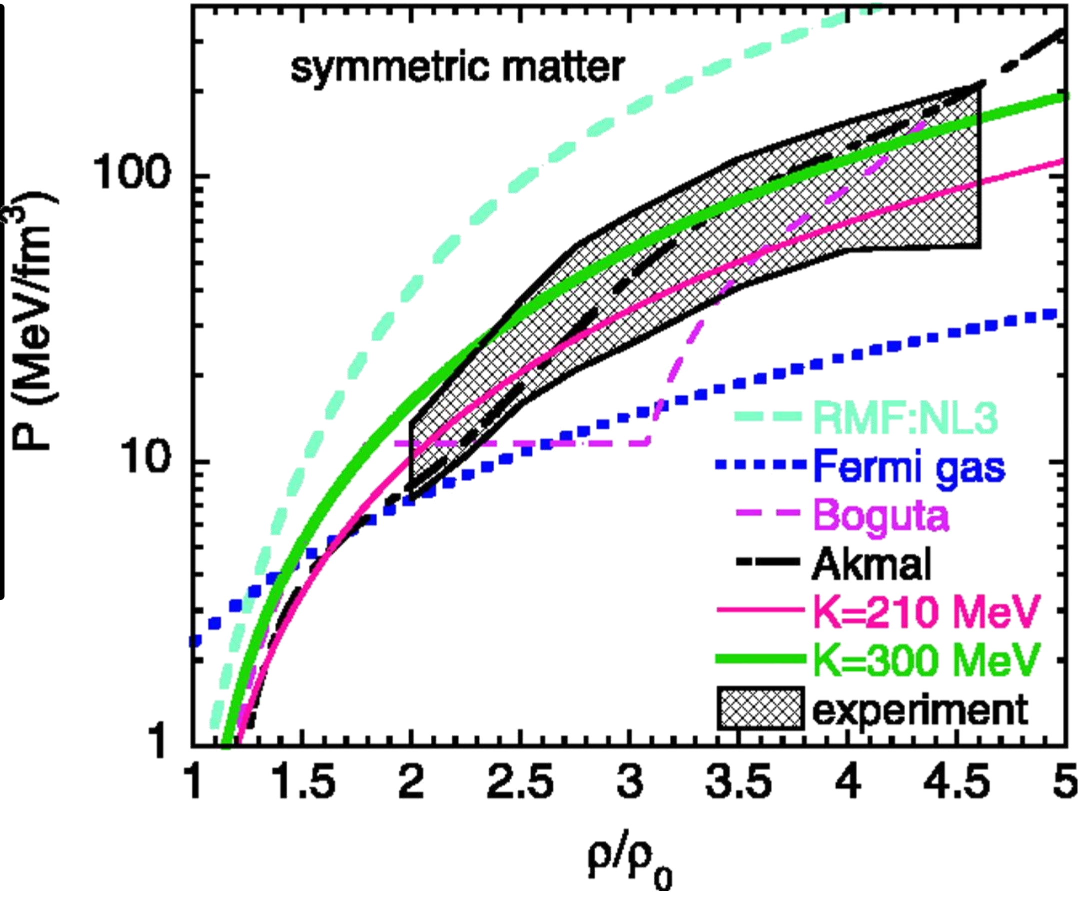
- **Directed Flow v_1** Nucleons deflected sideways in the reaction plane
- **Elliptic Flow v_2** Nucleons are "squeezed out" above and below or "expanded in" the reaction plane

Collective flow of nucleons driven by the pressure gradient – Sensitive to nuclear incompressibility, κ → Equation of State

Nuclear Incompressibility, $\kappa \sim 200 - 300$ MeV

Reflects that the interpretation of proton flow data using transport models is not straight forward as it depends on:

- **Equation of state**
- **In-medium nucleon-nucleon cross section**
- **In-medium momentum-dependent interactions**
- **Nucleonic clusters**



P. Danielewicz et al., Science 298 (2002) 1592

Collective flow of nucleons driven by the pressure gradient – Sensitive to nuclear incompressibility, κ → Equation of State

Nuclear Incompressibility, $\kappa \sim 200-300$ MeV

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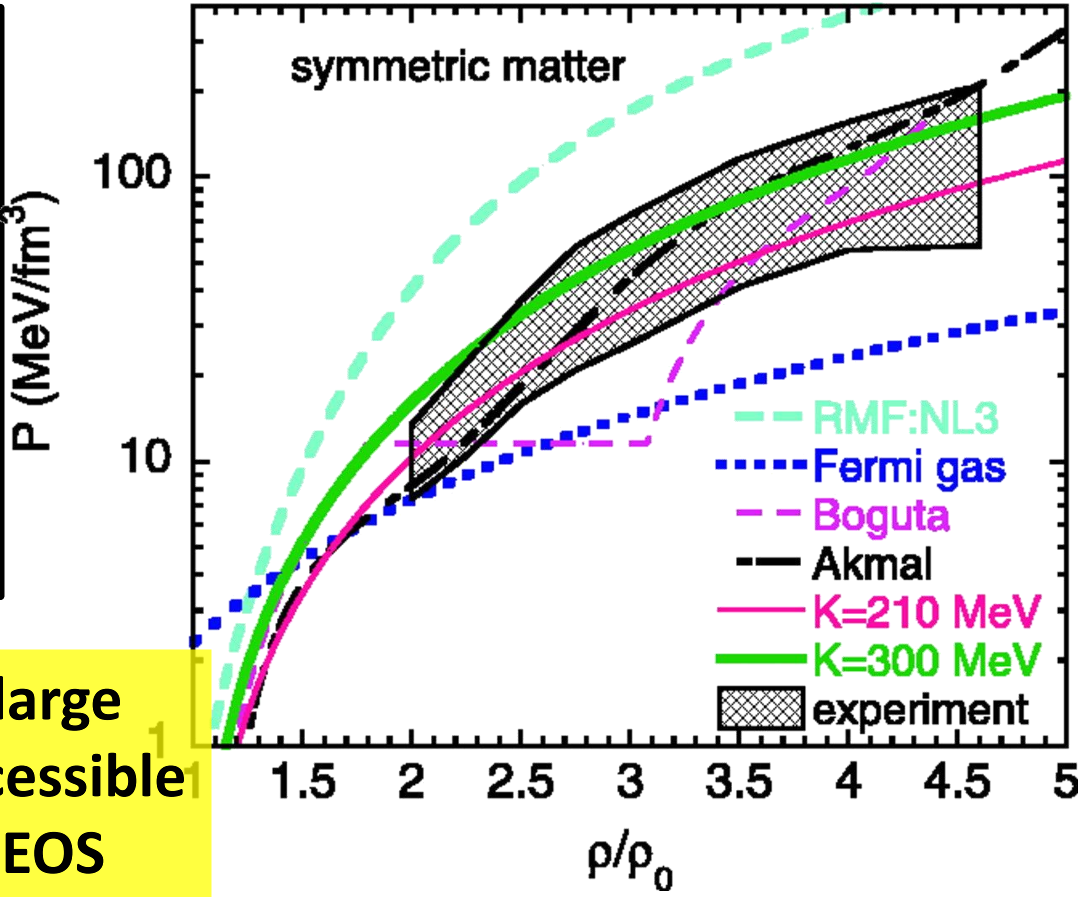
Precise multi-differential flow measurements for a large variety of hadron species over a range of densities accessible with CBM can narrow down the symmetric matter EOS



P. Danielewicz et al., Science 298 (2002) 1592

Idea: Strangeness Yield ∝ Baryonic Density ∝ Compressibility ∝ EOS

NN → NΔ

NΔ → N$K^+\Lambda^0$

πN → $K^+\Lambda^0$

$E_{threshold}$ = 1.58 GeV

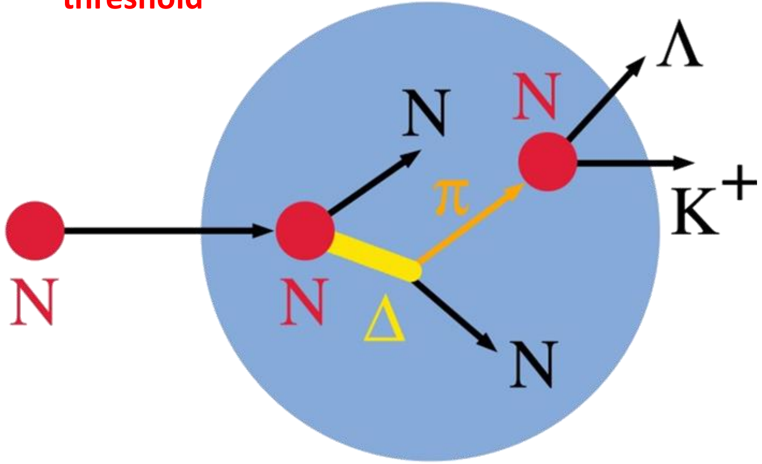


Image credit: P. Senger, GSI-Darmstadt

Idea: Strangeness Yield ∝ Baryonic Density ∝ Compressibility ∝ EOS

Experimentally at SIS18: Measuring K^+ yields in a system where compression is expected (Au-Au) w.r.t. system where no compression is expected (C-C)

$NN \rightarrow N\Delta$

$N\Delta \rightarrow NK^+\Lambda^0$

$\pi N \rightarrow K^+\Lambda^0$

$E_{threshold} = 1.58$ GeV

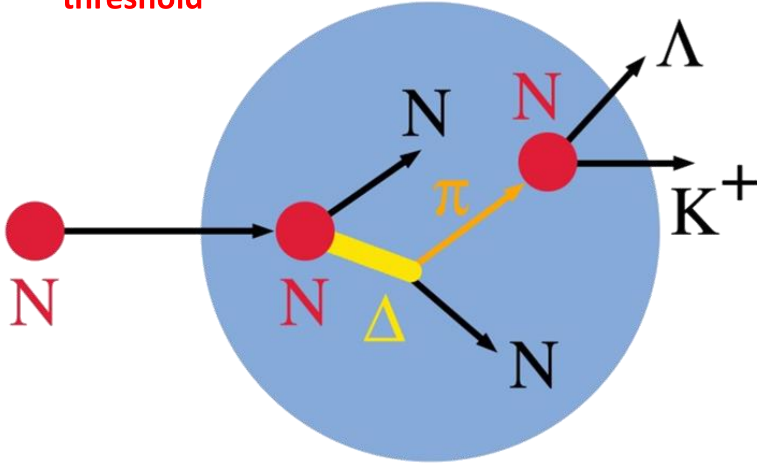
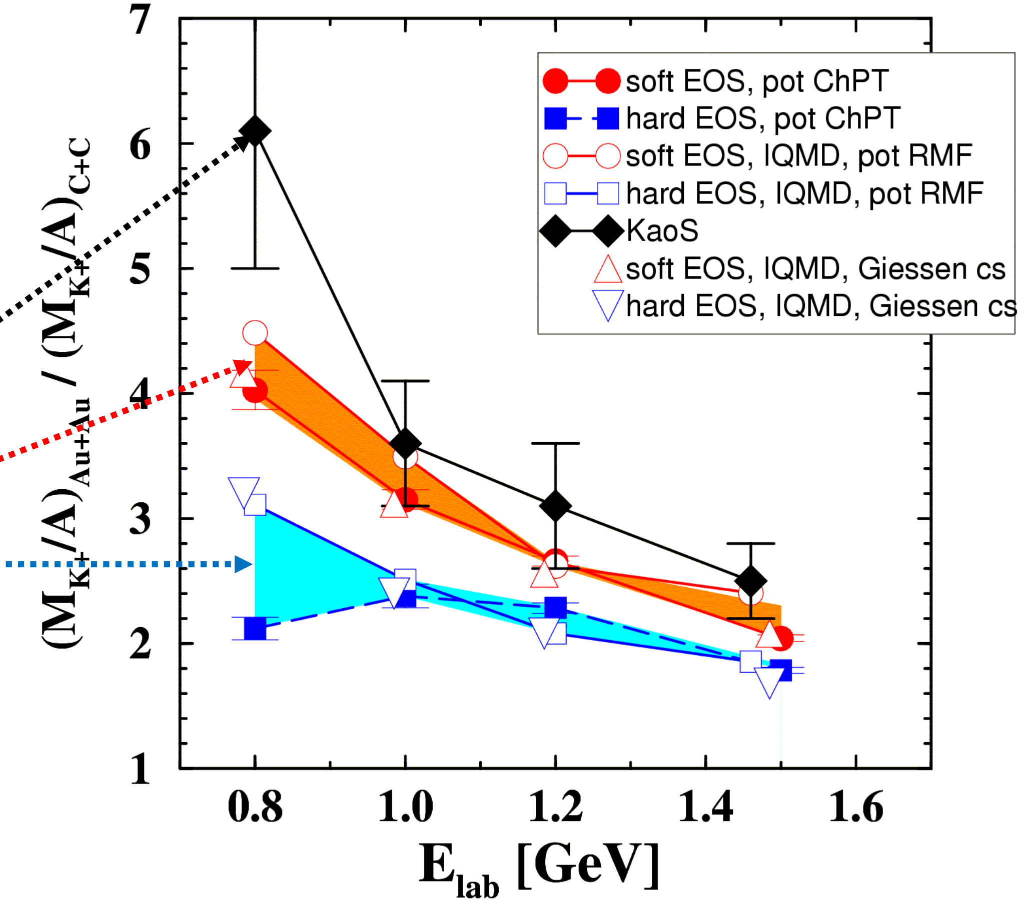


Image credit: P. Senger, GSI-Darmstadt

KaoS (Exp.)

Soft EOS (Th.)

Hard EOS (Th.)



Experiment: C. Sturm et al., (KaoS Collaboration) Phys. Rev. Lett. 86 (2001) 39

Theory: QMD Ch. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974

IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649

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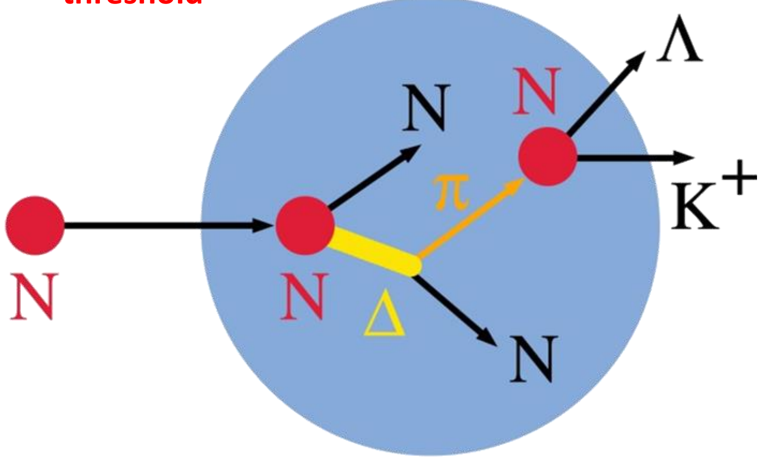
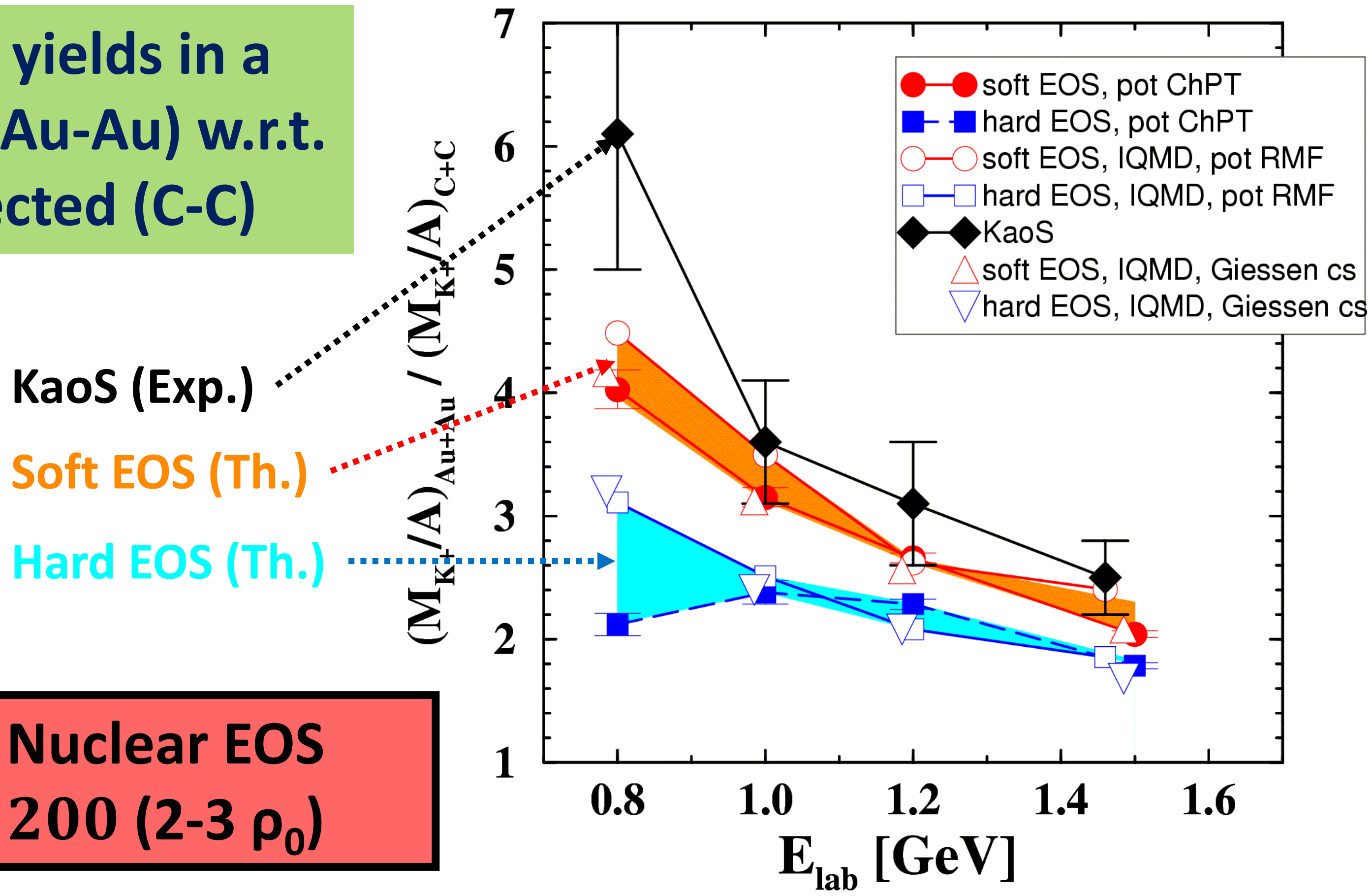


Image credit: P. Senger, GSI-Darmstadt

Soft Nuclear EOS

$\kappa \approx 200$ (2-3 ρ_0)



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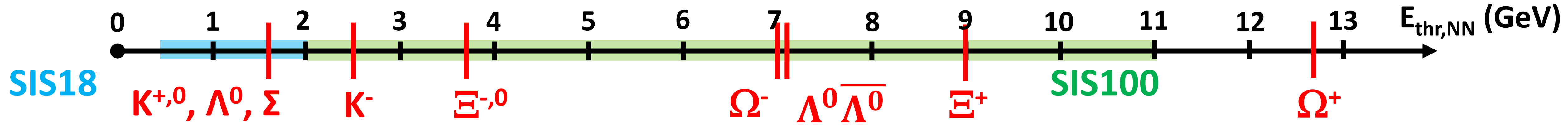
Theory: QMD Ch. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974

IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649

EXPERIMENTAL OBSERVABLES [II] – (SUB)THRESHOLD PRODUCTION

Idea: Strangeness Yield ∝ Baryonic Density ∝ Compressibility ∝ EOS



<u>Direct Kaon & Hyperon Production:</u>

$pp \rightarrow K^+\Lambda^0 p$ $(E_{thr} = 1.6\text{ GeV})$

$pp \rightarrow K^-K^+ p$ $(E_{thr} = 2.5\text{ GeV})$

<u>Direct Multi-Strange Hyperon Production:</u>

$pp \rightarrow \Xi^- K^+K^+ p$ $(E_{thr} = 3.7\text{ GeV})$

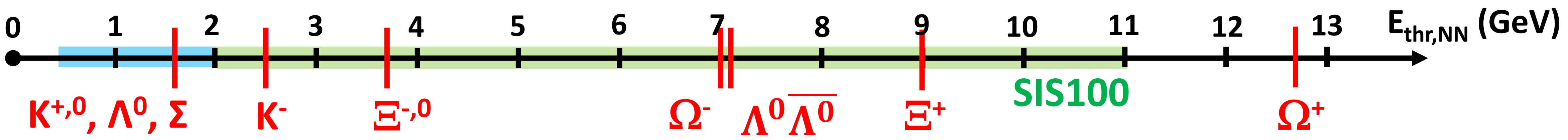
$pp \rightarrow \Omega^- K^+K^+K^0 p$ $(E_{thr} = 7.0\text{ GeV})$

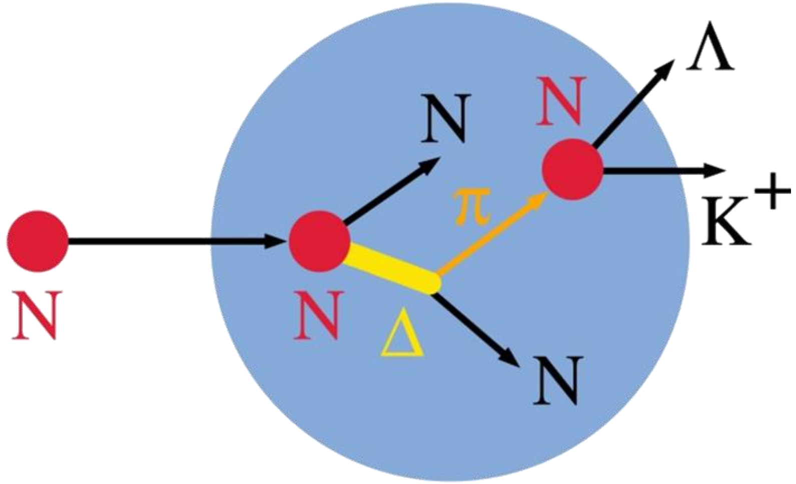
$pp \rightarrow \Lambda^0\bar{\Lambda}^0 pp$ $(E_{thr} = 7.1\text{ GeV})$

$pp \rightarrow \Xi^+ \Xi^- pp$ $(E_{thr} = 9.0\text{ GeV})$

$pp \rightarrow \Omega^+ \Omega^- pp$ $(E_{thr} = 12.7\text{ GeV})$

Idea: Strangeness Yield ∝ Baryonic Density ∝ Compressibility ∝ EOS





Direct Kaon & Hyperon Production:

$pp \rightarrow K^+\Lambda^0 p$ (E_{thr} = 1.6 GeV)

$pp \rightarrow K^-K^+p$ (E_{thr} = 2.5 GeV)

Direct Multi-Strange Hyperon Production:

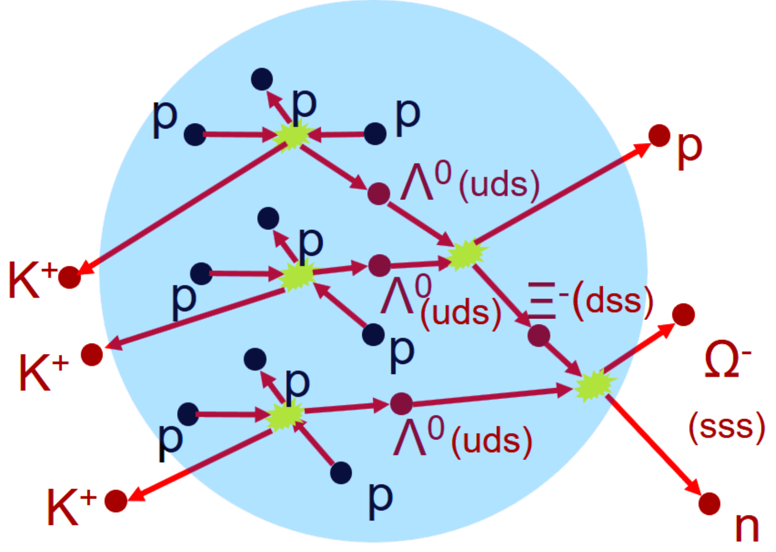
$pp \rightarrow \Xi^- K^+K^+p$ (E_{thr} = 3.7 GeV)

$pp \rightarrow \Omega^- K^+K^+K^0p$ (E_{thr} = 7.0 GeV)

$pp \rightarrow \Lambda^0\overline{\Lambda}^0 pp$ (E_{thr} = 7.1 GeV)

$pp \rightarrow \Xi^+ \Xi^- pp$ (E_{thr} = 9.0 GeV)

$pp \rightarrow \Omega^+ \Omega^- pp$ (E_{thr} = 12.7 GeV)



$NN \rightarrow N\Delta$

$N\Delta \rightarrow NK^+\Lambda^0$

$\pi N \rightarrow K^+Y$ ($Y = \Lambda,\Sigma$)

$pp \rightarrow K^+p\Lambda^0$

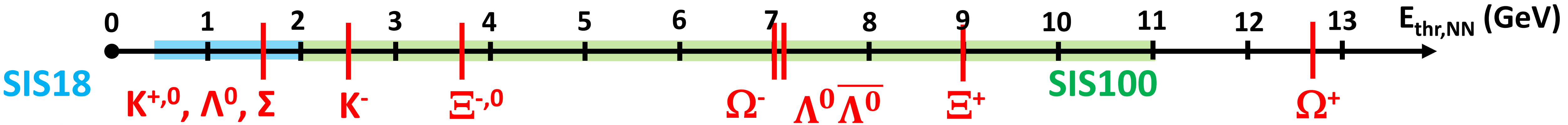
$pp \rightarrow K^+p\Lambda^0$ → $\Lambda^0\Lambda^0 \rightarrow \Xi^- p$

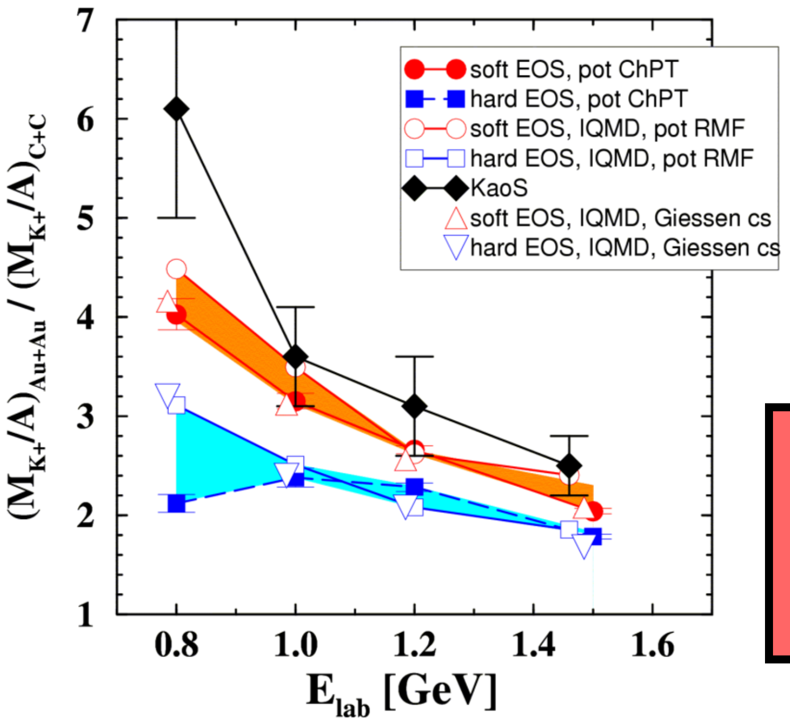
$pp \rightarrow K^+p\Lambda^0$ → $\Lambda^0\Xi^- \rightarrow \Omega^- n$

Image credit: P. Senger, GSI-Darmstadt

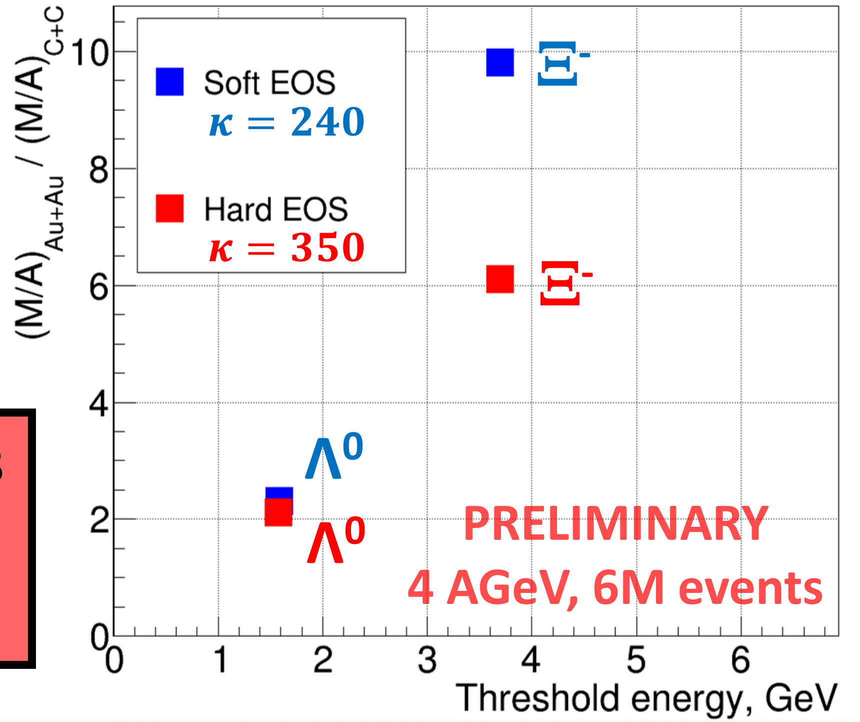
Experimental Observables [II] – (Sub)Threshold Production

Idea: Strangeness Yield ∝ Baryonic Density ∝ Compressibility ∝ EOS





Multi-Strange Hyperons promising for EOS at $\rho \geq$ 2-3 ρ_0



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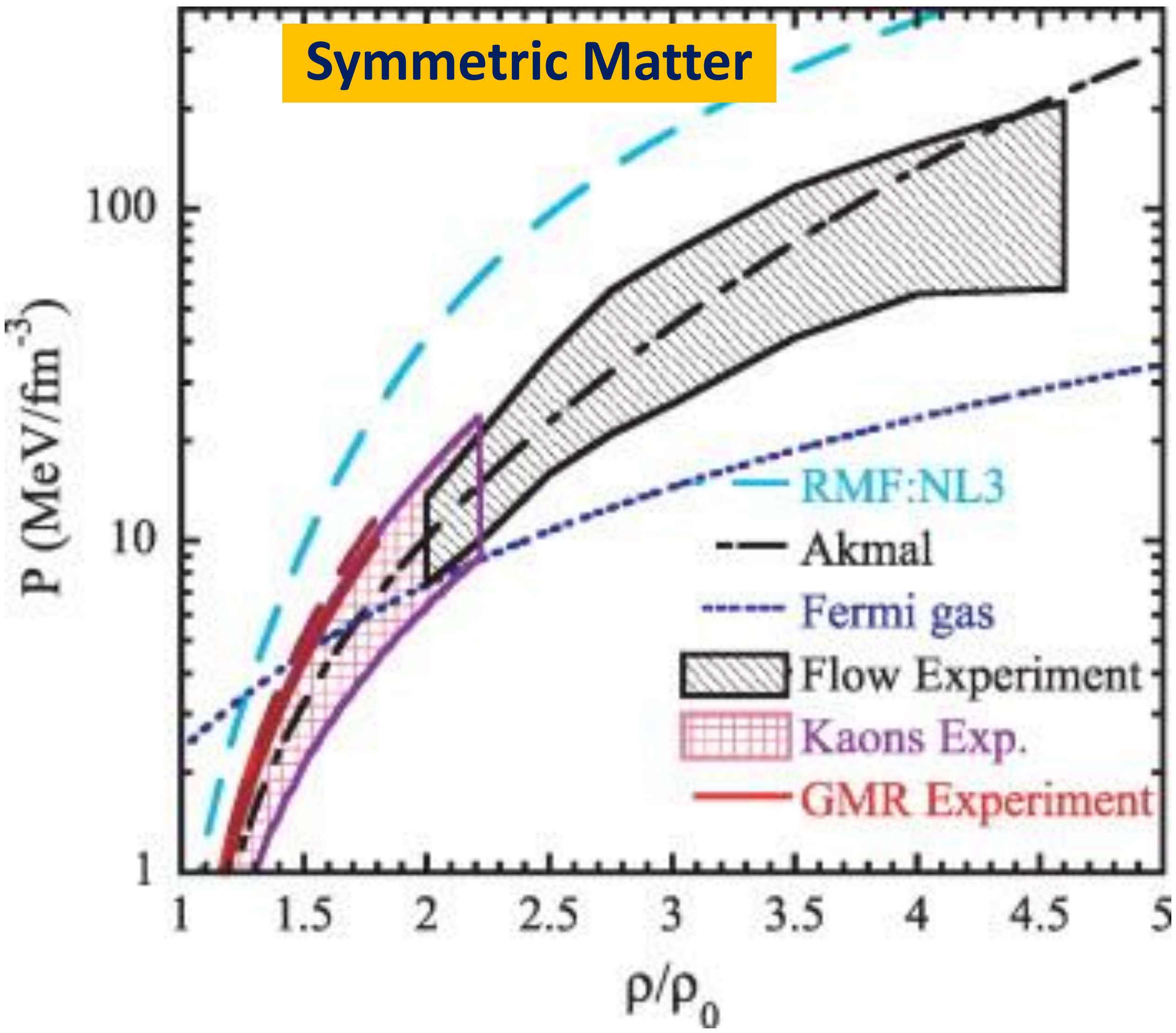
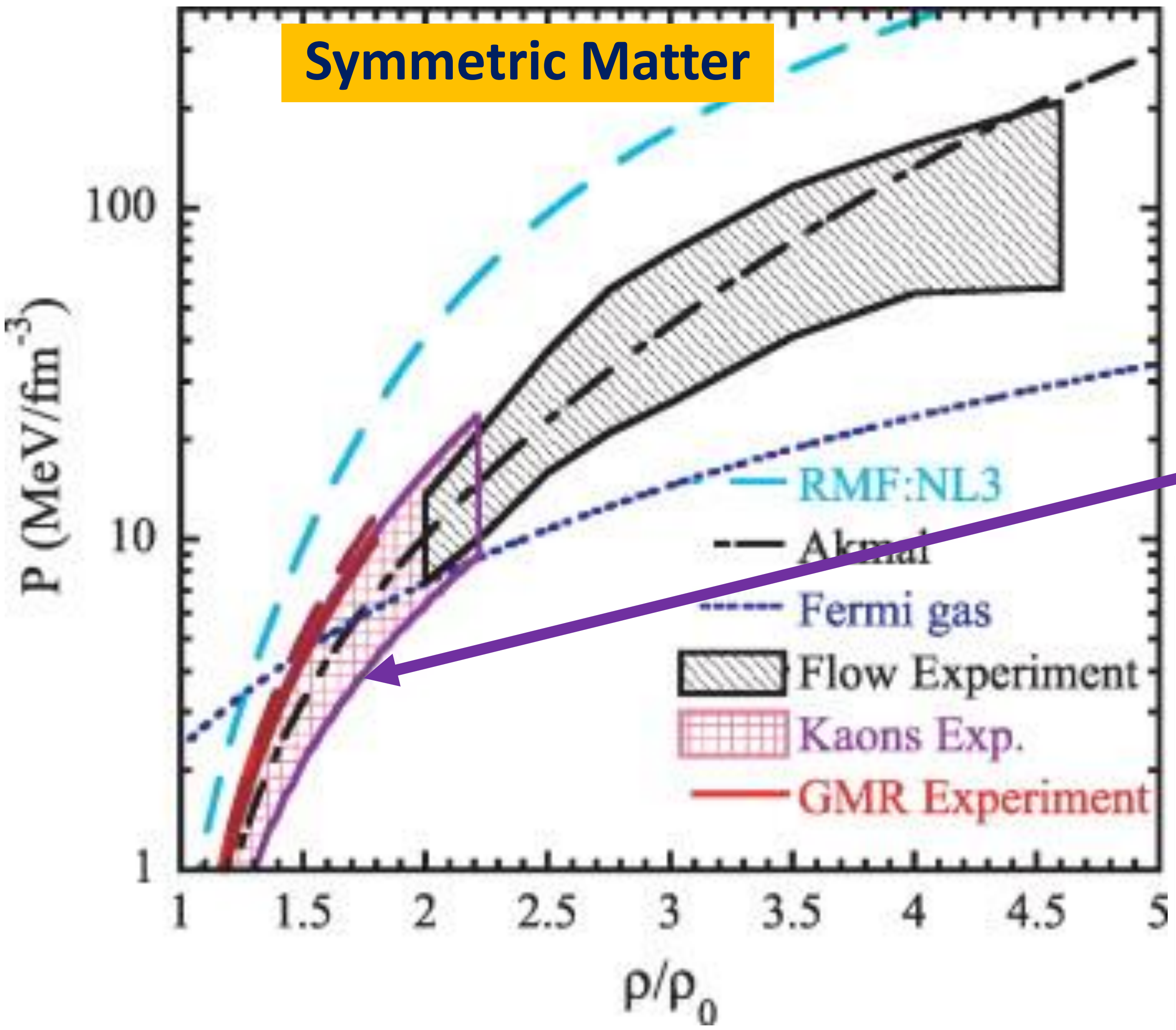
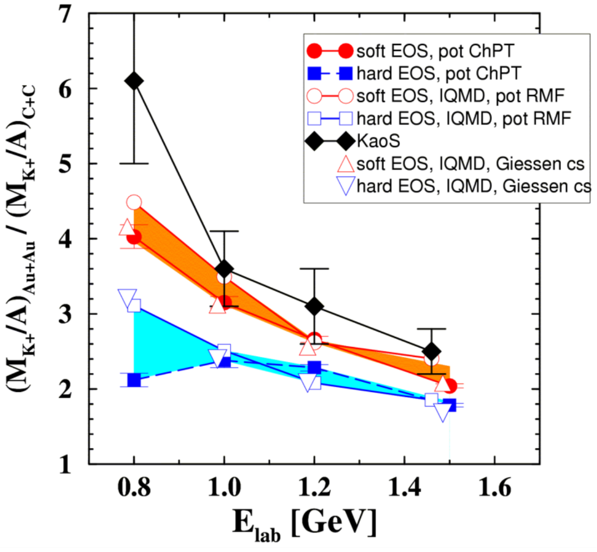
PHQMD: J. Aichelin, E. Bratkovskaya, V. Kireyeu et al.
P. Senger, 4th CBM China Workshop (2019)



W.G. Lynch et al., PrPNP, 62, 427 (2009); arXiv:0901.0412 [nucl-ex]

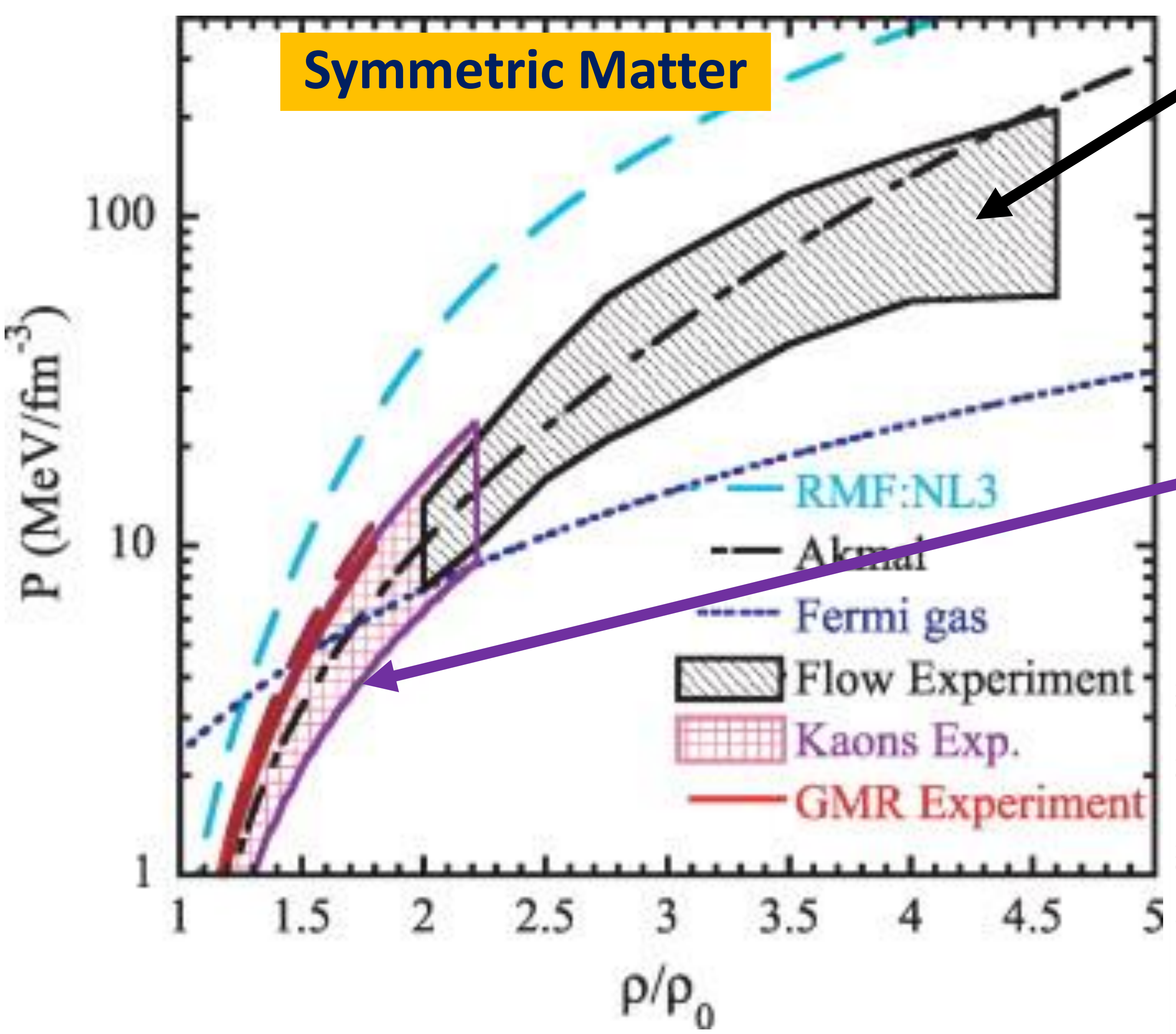


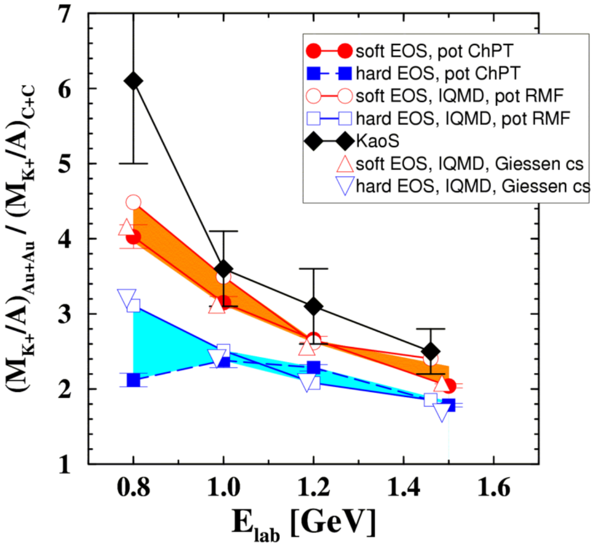
Kaon Experiments
(ρ/ρ_0 = 1.2 – 2.2)

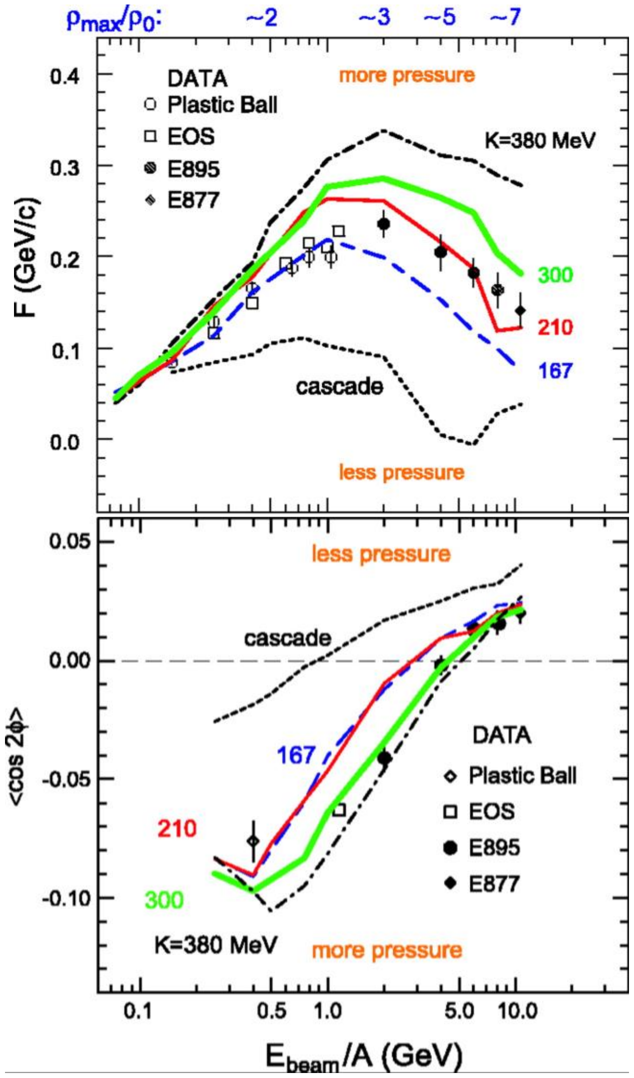


W.G. Lynch et al., PrPNP, 62, 427 (2009); arXiv:0901.0412 [nucl-ex]

Symmetric Matter Equation Of State (EOS) – Current Status

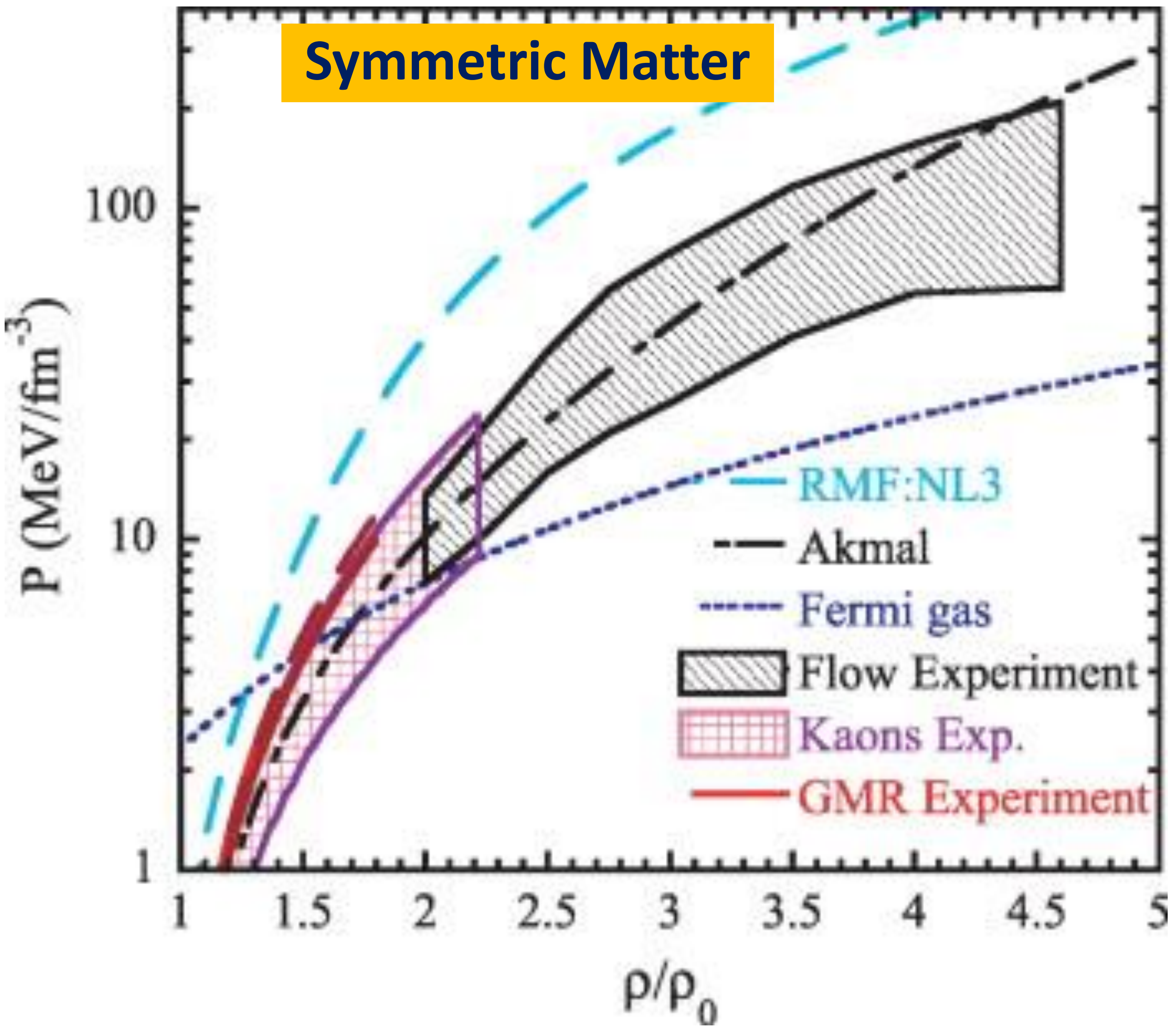


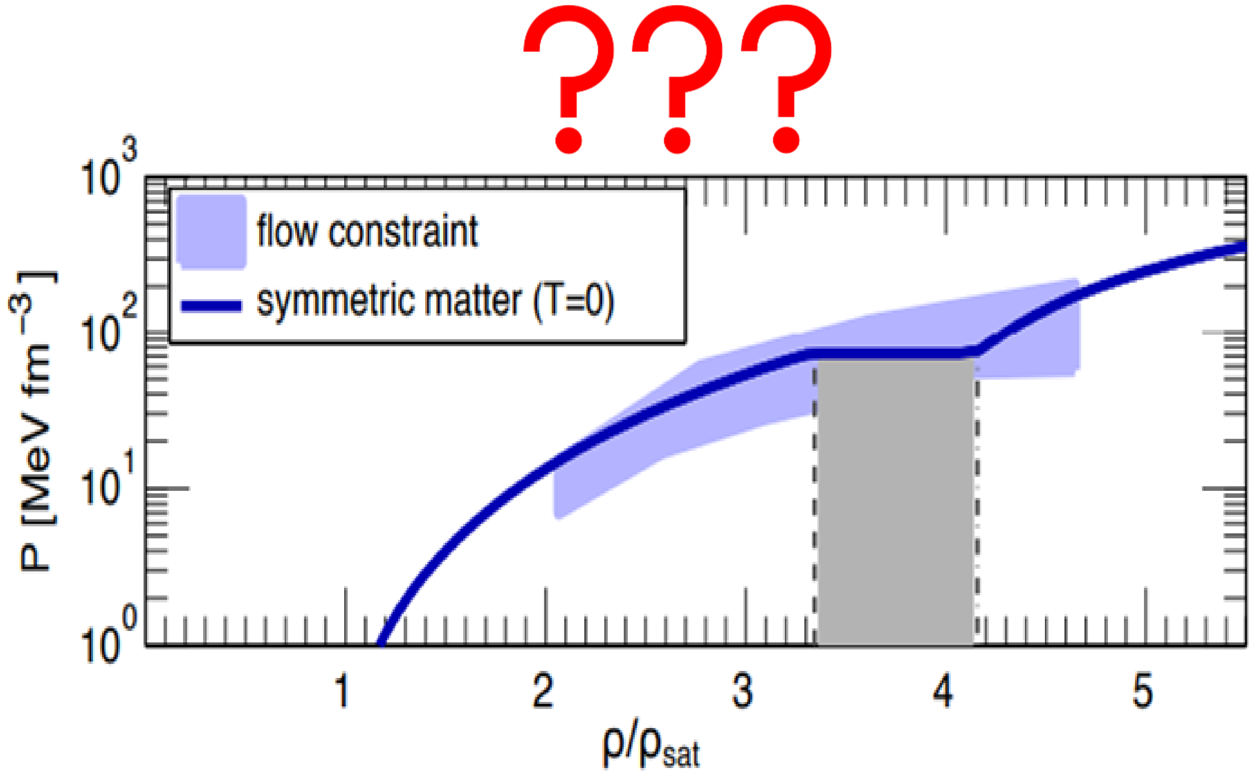




W.G. Lynch et al., PrPNP, 62, 427 (2009); arXiv:0901.0412 [nucl-ex]

Symmetric Matter Equation Of State (EOS) – Future ?





Precision measurement of EOS can enable CBM to detect phase transition in symmetric nuclear matter at high ρ

W.G. Lynch et al., PrPNP, 62, 427 (2009); arXiv:0901.0412 [nucl-ex]

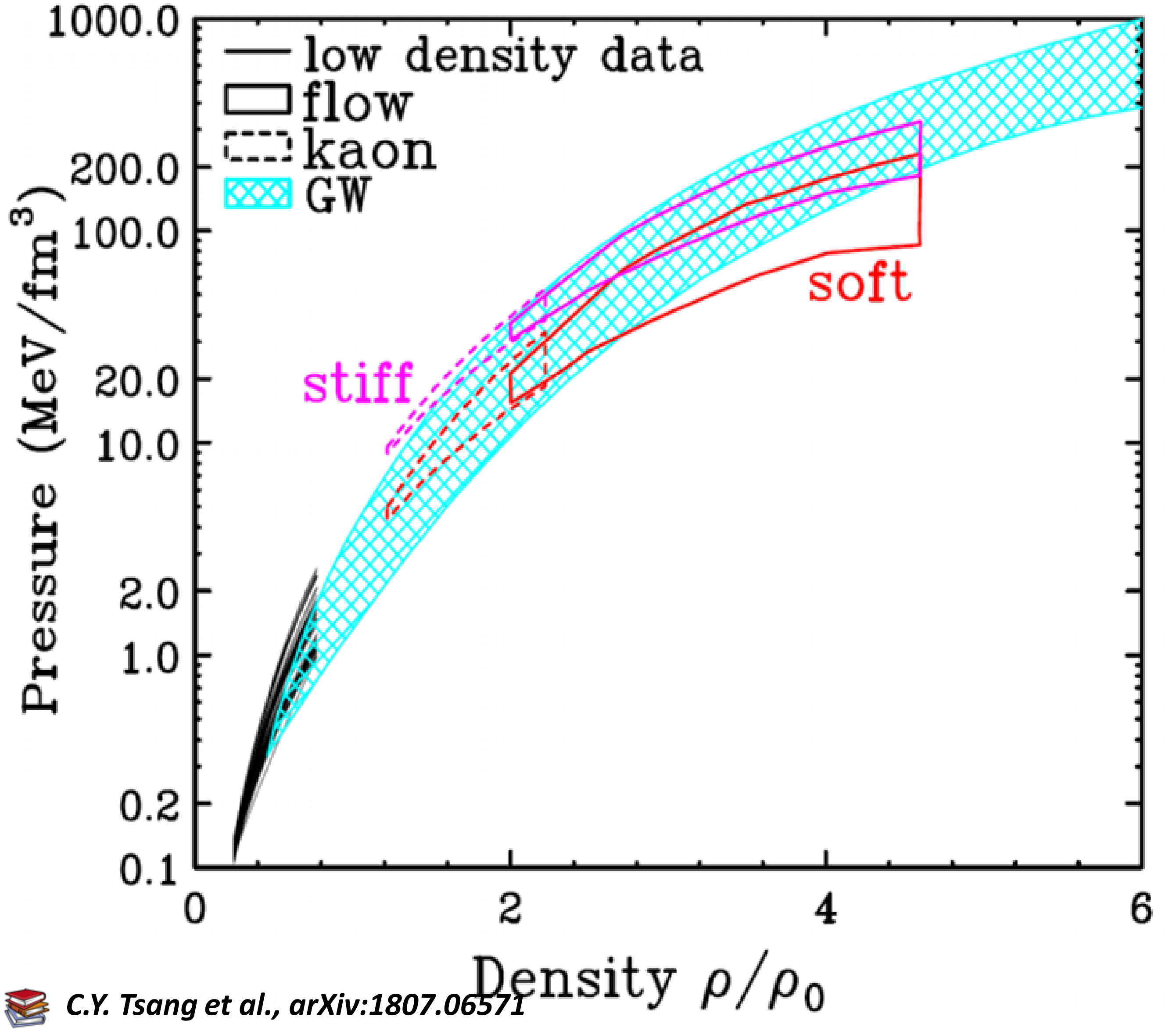
T. Fischer et al., Nat Astron 2, 980-986 (2018); arXiv:1712.08788 [astro-ph.HE]

EoS W/ CBM Case #2

Nuclear Symmetry Energy

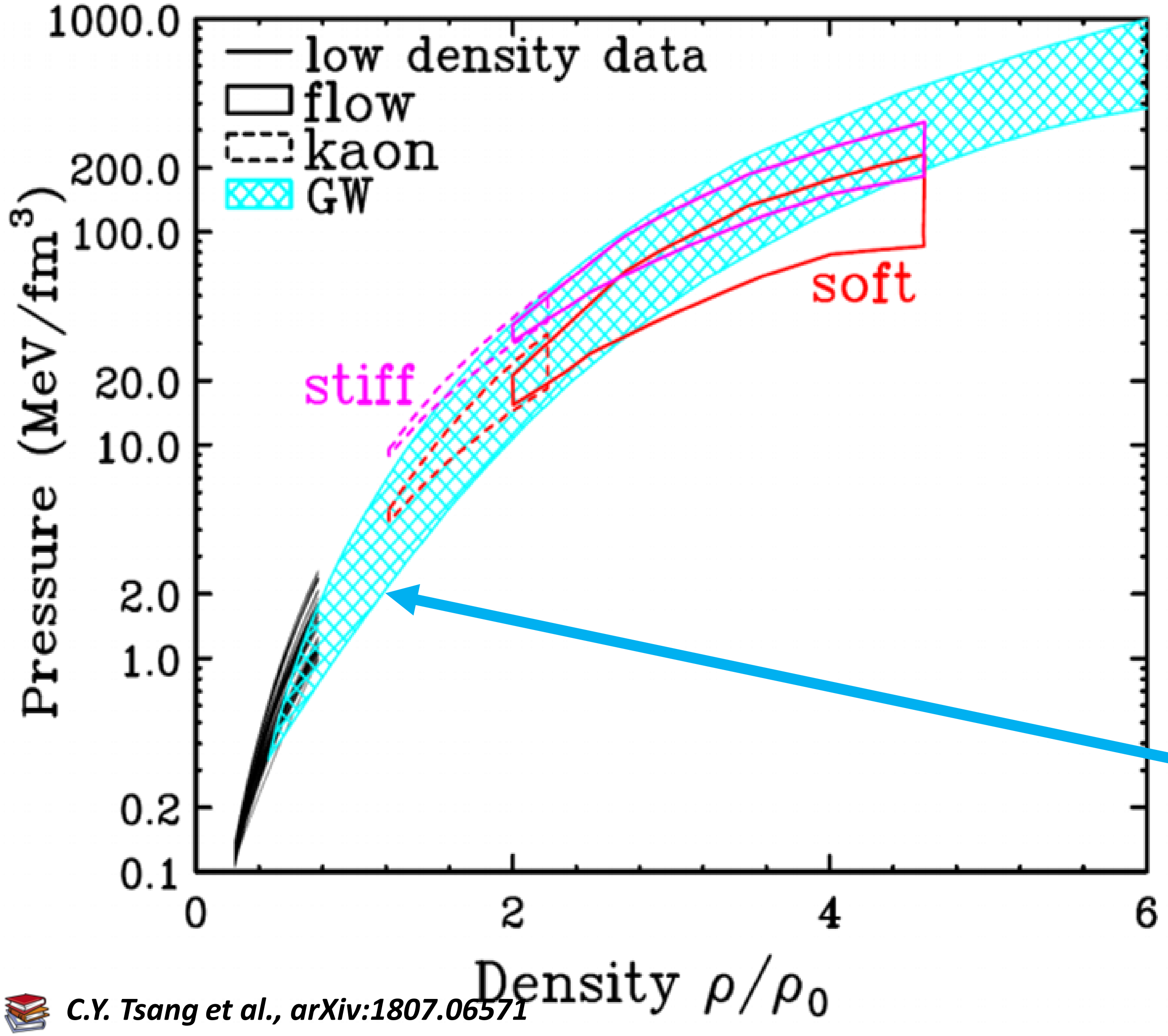
$$E_A(\rho,\delta) = E_A(\rho,0) + E_{SYM}(\rho)\cdot\delta^2$$

Neutron Matter Equation Of State (EOS) – Current Status

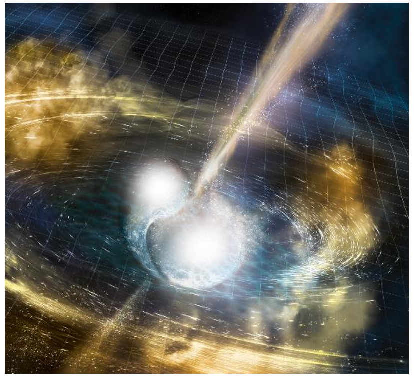


C.Y. Tsang et al., arXiv:1807.06571
LIGO-VIRGO: B. P. Abbott, et al., arXiv:1805.11581 (2018)

NEUTRON MATTER EQUATION OF STATE (EOS) – CURRENT STATUS



Graviational Waves
GW170817



C.Y. Tsang et al., arXiv:1807.06571
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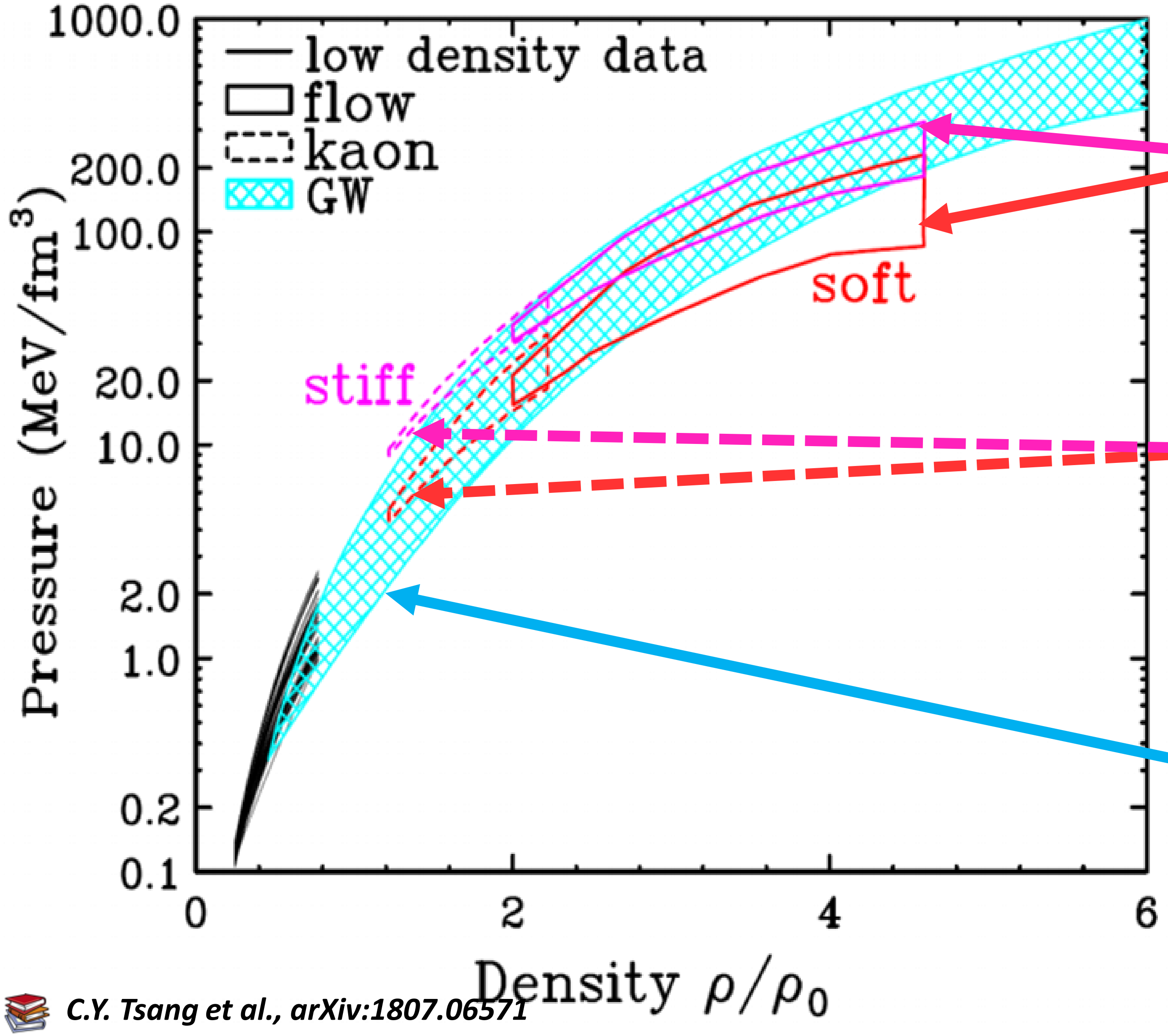
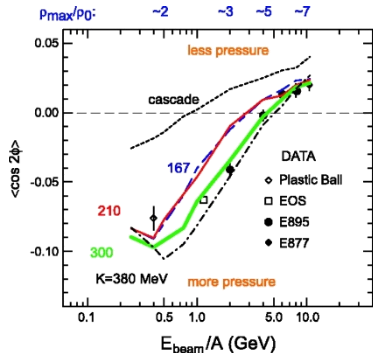
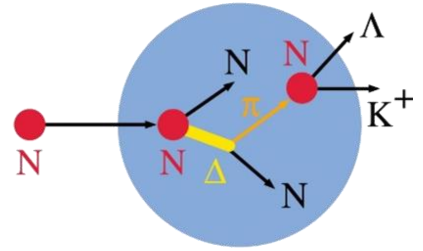


Flow Experiments
(ρ/ρ_0 = 2 – 4.5)
Soft-Stiff EOS



Kaon Experiments
(ρ/ρ_0 = 1.2 – 2.2)
Soft EOS



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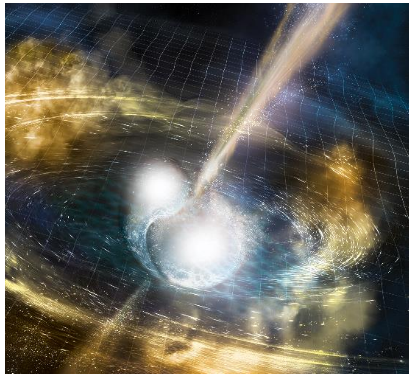

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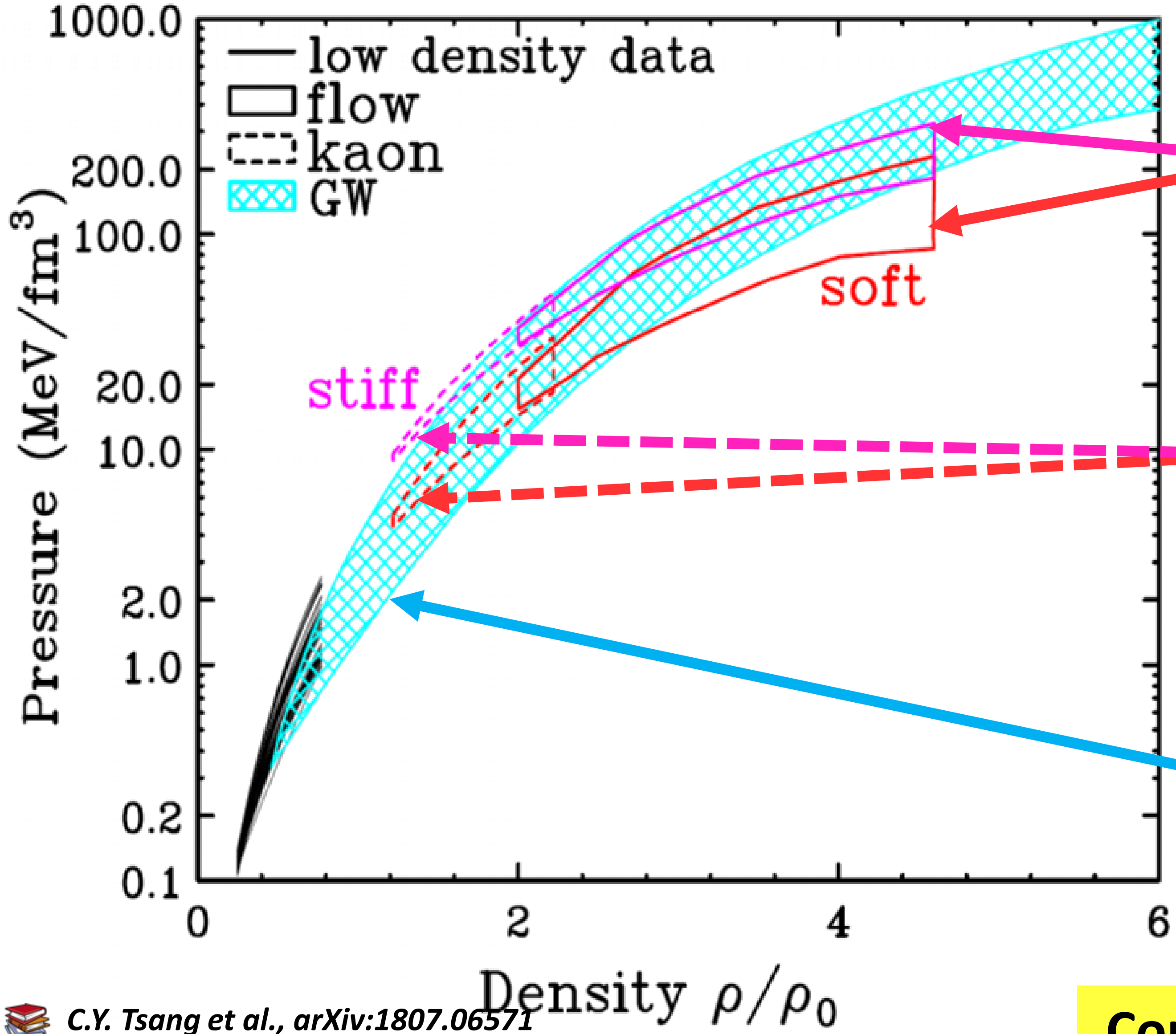

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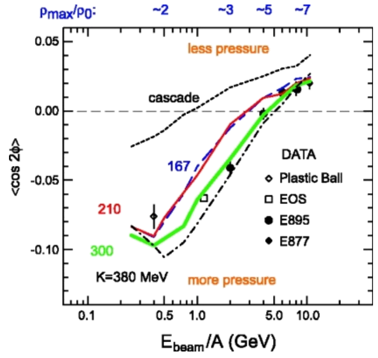

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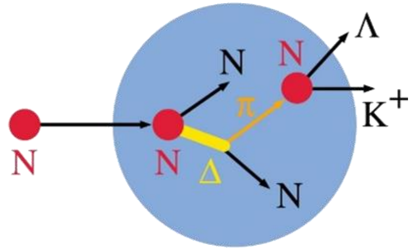

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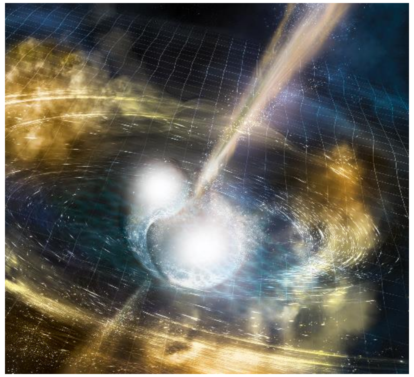


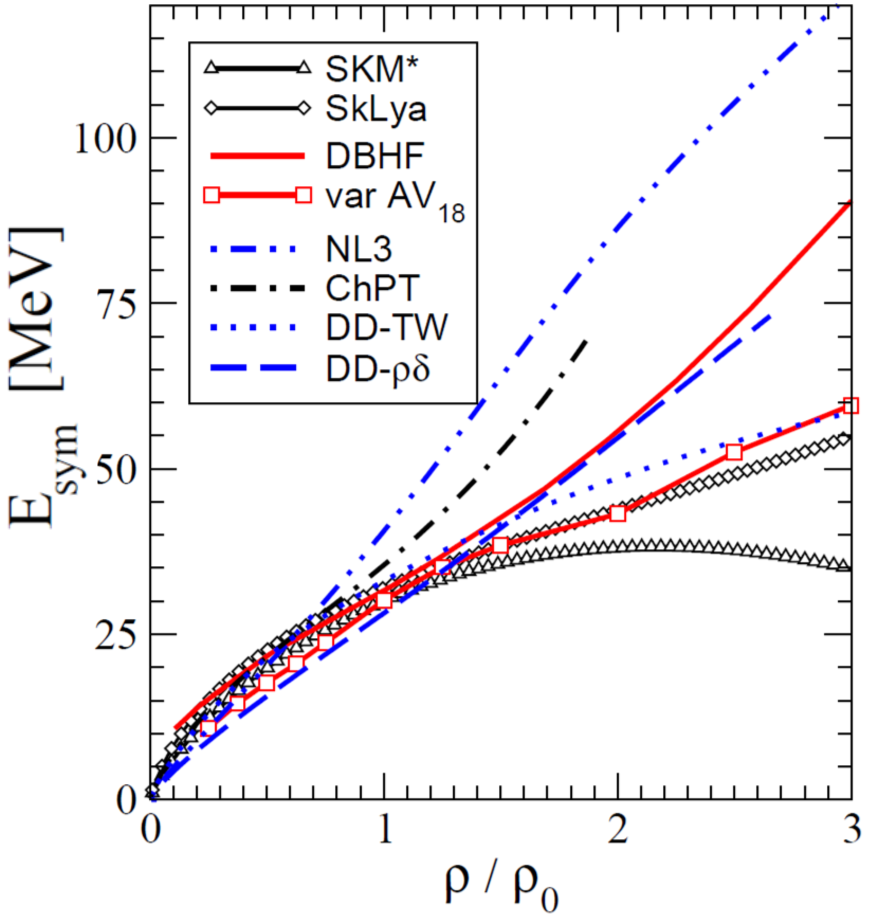
C.Y. Tsang et al., arXiv:1807.06571
LIGO-VIRGO: B. P. Abbott, et al., arXiv:1805.11581 (2018)

Constraints on Asymmetric Matter EOS → CBM

NUCLEAR SYMMETRY ENERGY: $E_A(\rho,\delta) = E_A(\rho,0) + E_{SYM}(\rho)\cdot\delta^2$

$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \ldots$$

Slope **Curvature**



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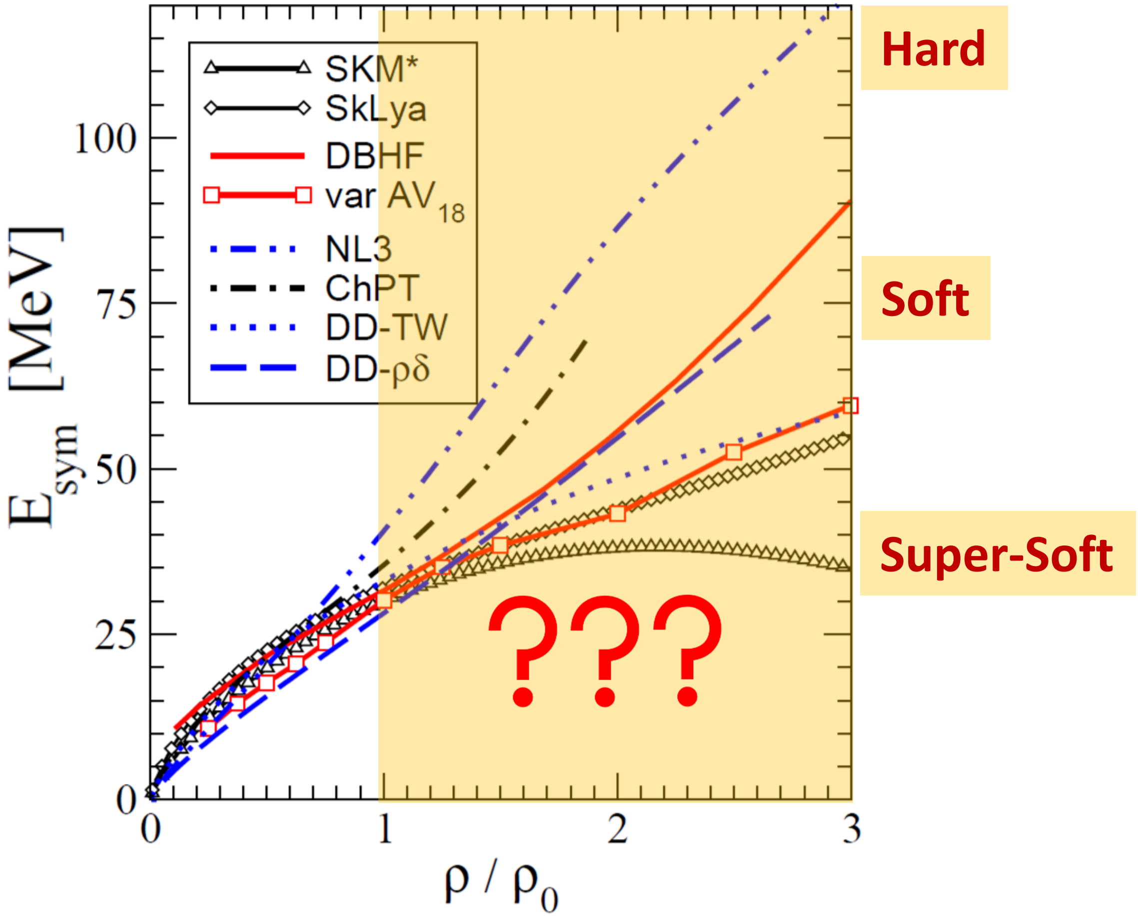

Largely unconstrained at densities $\rho > \rho_0$

Related to uncertainty of three-body and tensor forces at high density

C. Fuchs, H.H. Wolter, EPJA 30 (2006) 5
B-A Li, À. Ramos, G. Verde et al., Eur. Phys. J. A (2014) 50: 9

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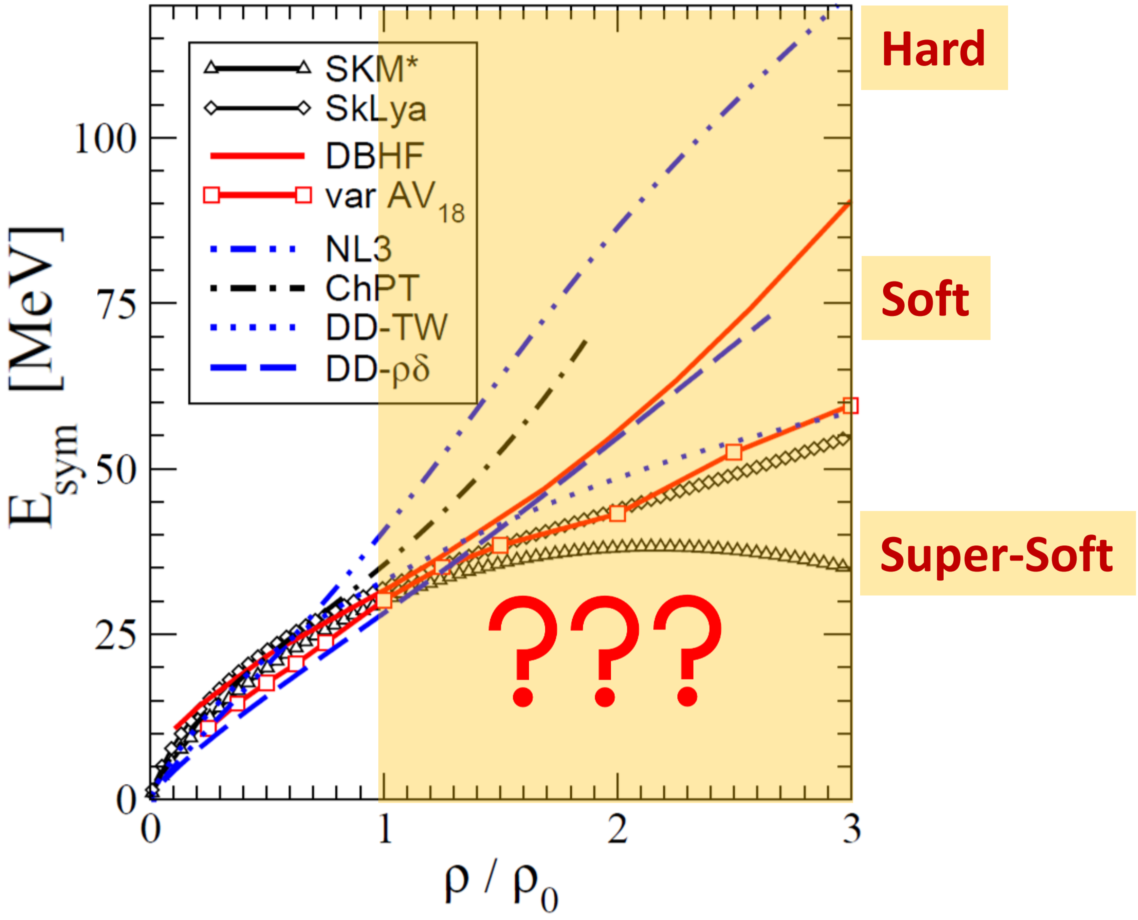


Largely unconstrained at densities $\rho > \rho_0$

Related to uncertainty of three-body and tensor forces at high density

Identification of differential observables (e.g. differences or ratios of observables) to enhance the response to asymmetry as the iso-scalar dynamics largely cancels

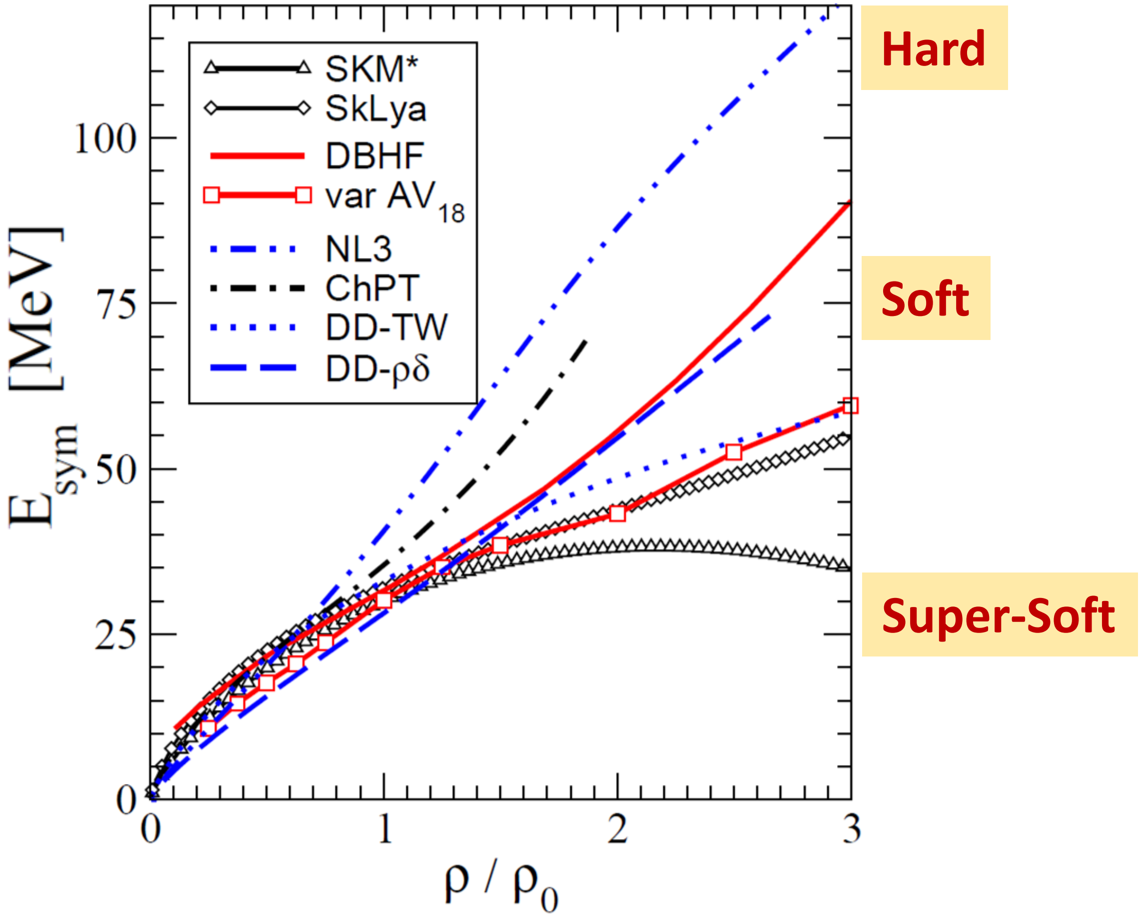
C. Fuchs, H.H. Wolter, EPJA 30 (2006) 5
B-A Li, À. Ramos, G. Verde et al., Eur. Phys. J. A (2014) 50: 9

NUCLEAR SYMMETRY ENERGY: $E_A(\rho,\delta) = E_A(\rho,0) + E_{SYM}(\rho)\cdot\delta^2$

Parameterization in transport (UrQMD, IQMD)

$$E_{sym}(\rho) = 22\ \text{MeV}\left(\frac{\rho}{\rho_0}\right)^{\gamma} + 12\ \text{MeV}\left(\frac{\rho}{\rho_0}\right)^{2/3}$$

γ	0.5	1.0	1.5
L [MeV]	57	90	123



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CBM

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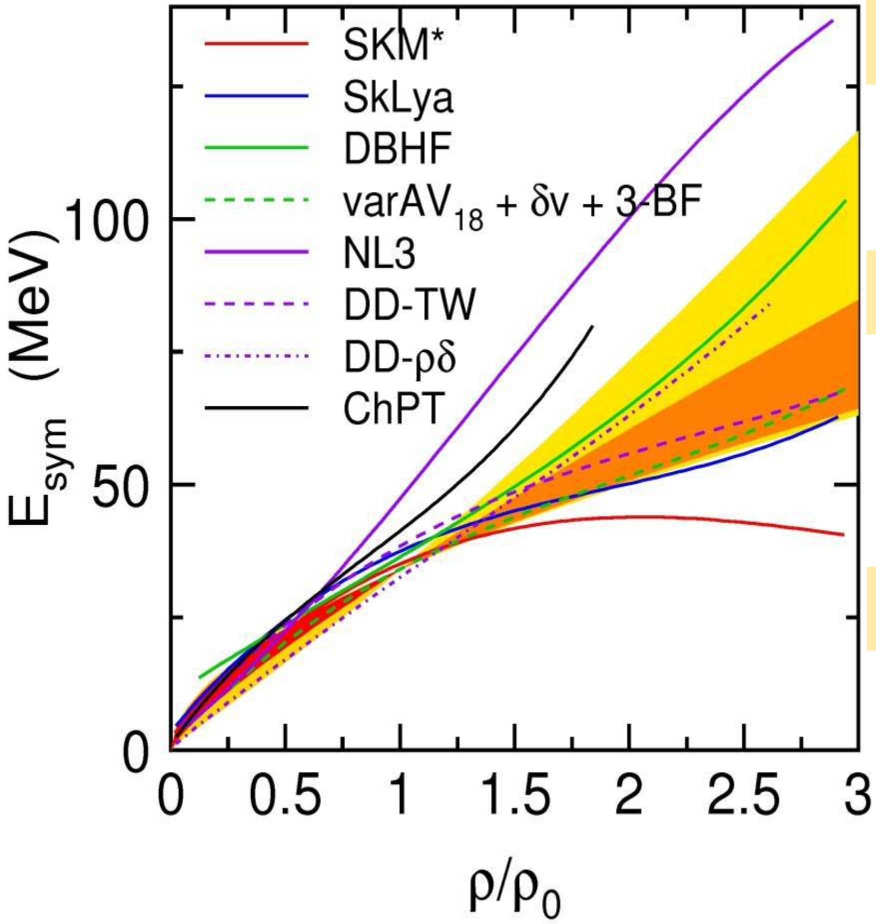

Hard

Soft

Super-Soft

Idea: Measurement of differential collective flow of neutrons w.r.t. protons or overall charged particles

FOPI-LAND: $\gamma = 0.90 \pm 0.40$

ASY-EOS: $\gamma = 0.72 \pm 0.19$

Au-Au 0.4 AGeV
FOPI-LAND and ASY-EOS @ SIS18

L = 72 ± 13 MeV
K_{sym} = -70 … -40 MeV

P. Russotto et al., Phys.Lett. B697 (2011) 471-476
P. Russotto et al., Phys.Rev. C94 (2016) no.3, 034608

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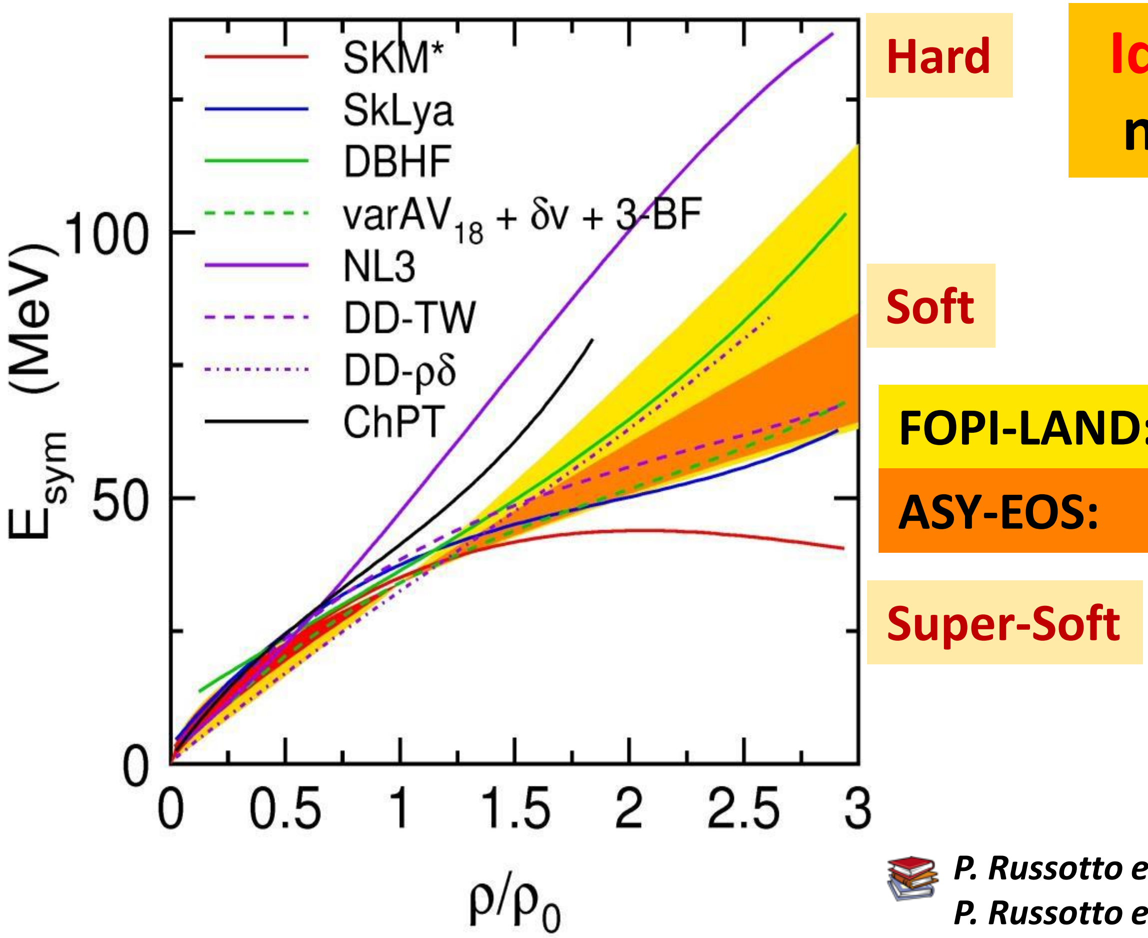

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Moderately soft asy-EOS ≤ $2\rho_0$
Possible at higher densities (≥ $2\rho_0$) with CBM

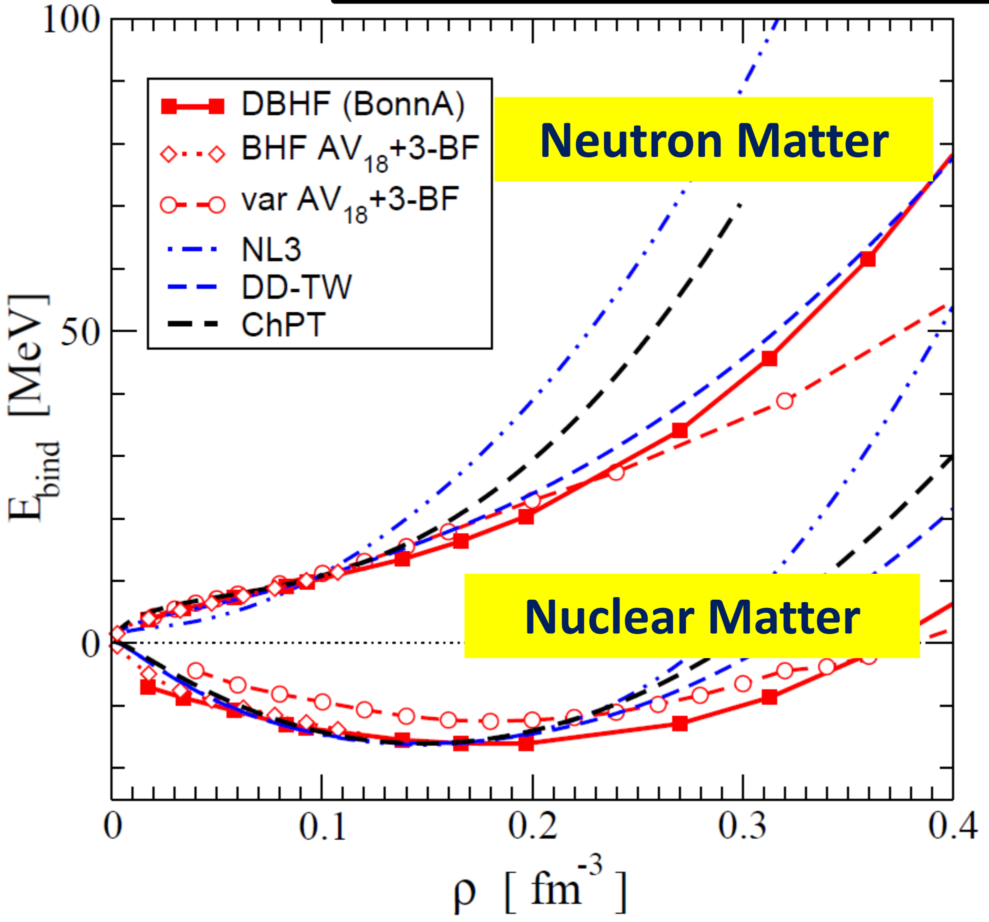
P. Russotto et al., Phys.Lett. B697 (2011) 471-476
P. Russotto et al., Phys.Rev. C94 (2016) no.3, 034608

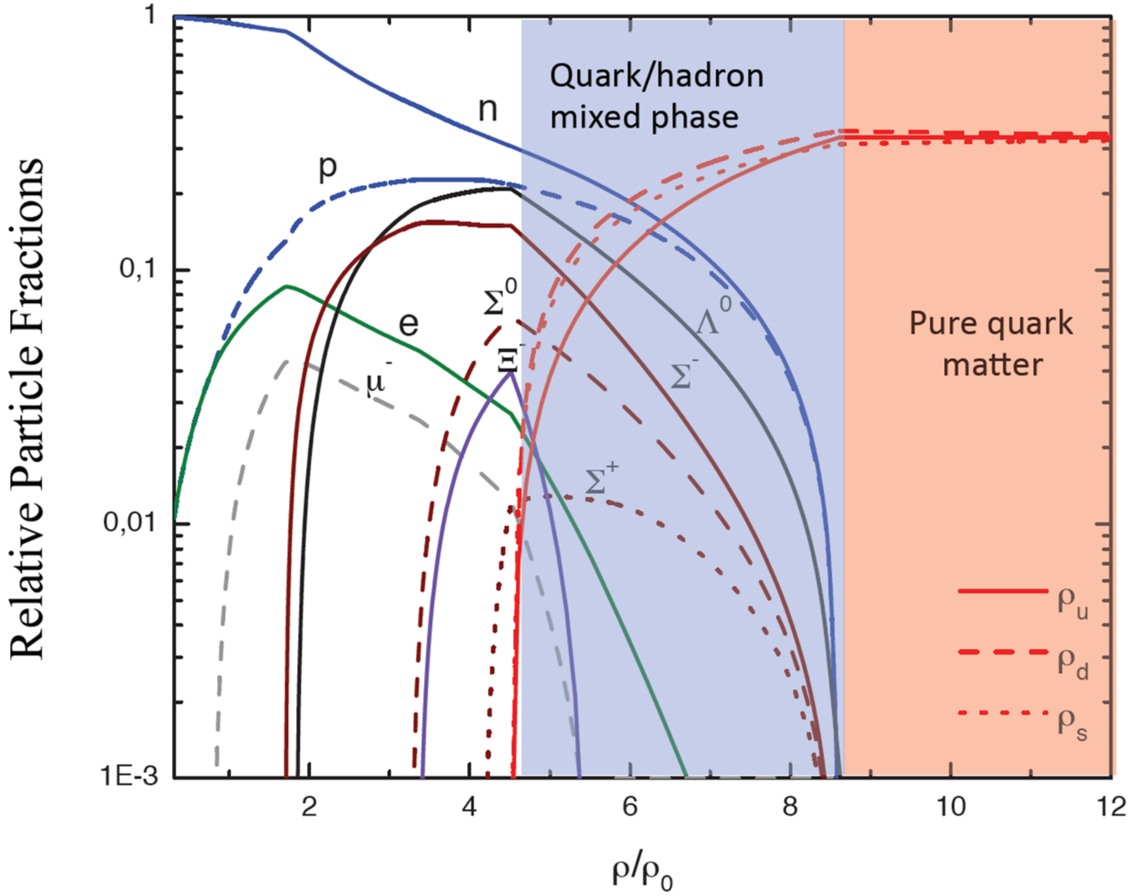
EoS W/ CBM Case #3

2,3-Body Hyperon-Nucleon (Λ-N) And Hyperon-Hyperon (Λ-Λ) Interactions

'Strange Matter' – Hyperons In Massive Neutron Stars

At higher densities (> $4\rho_0$), inclusion and interactions of hyperons become an important ingredient to microscopically connect neuclear and neutron matter





C. Fuchs, H.H. Wolter, EPJA 30 (2006) 5
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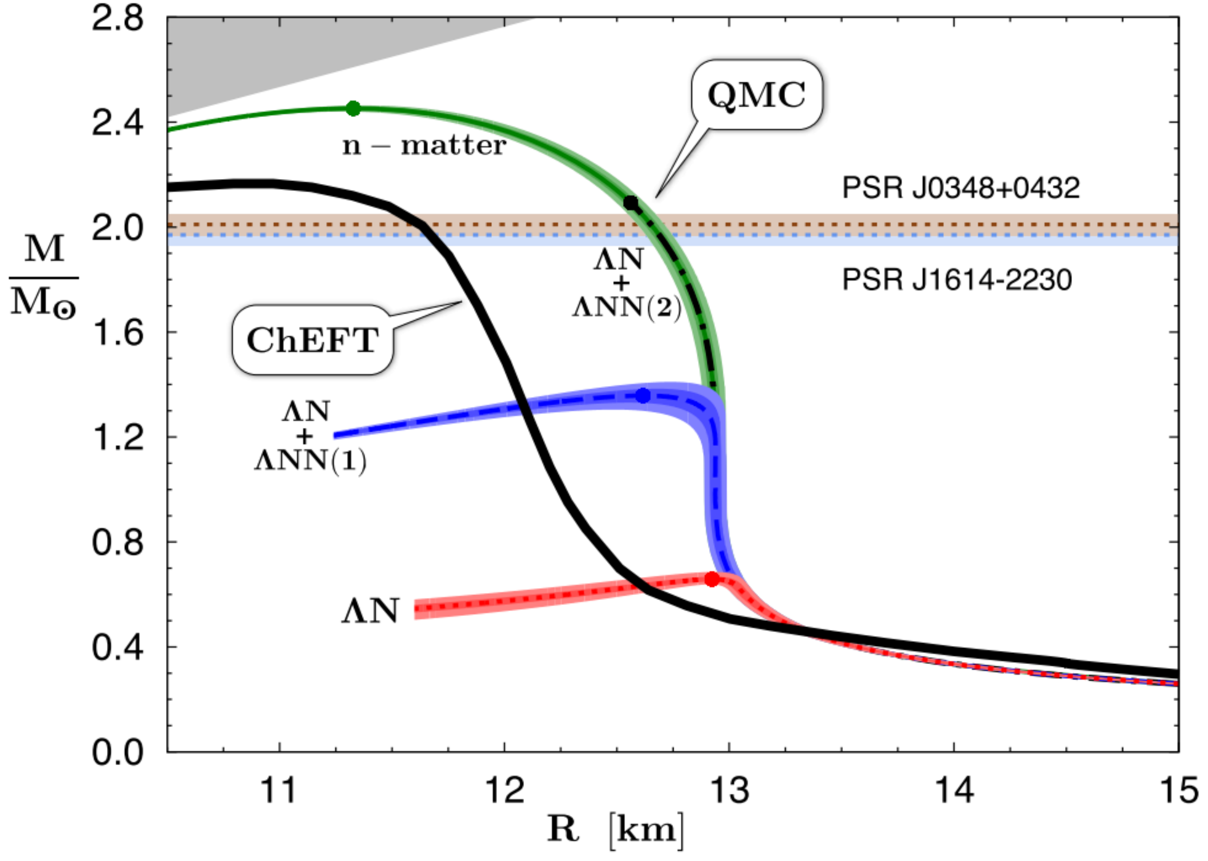
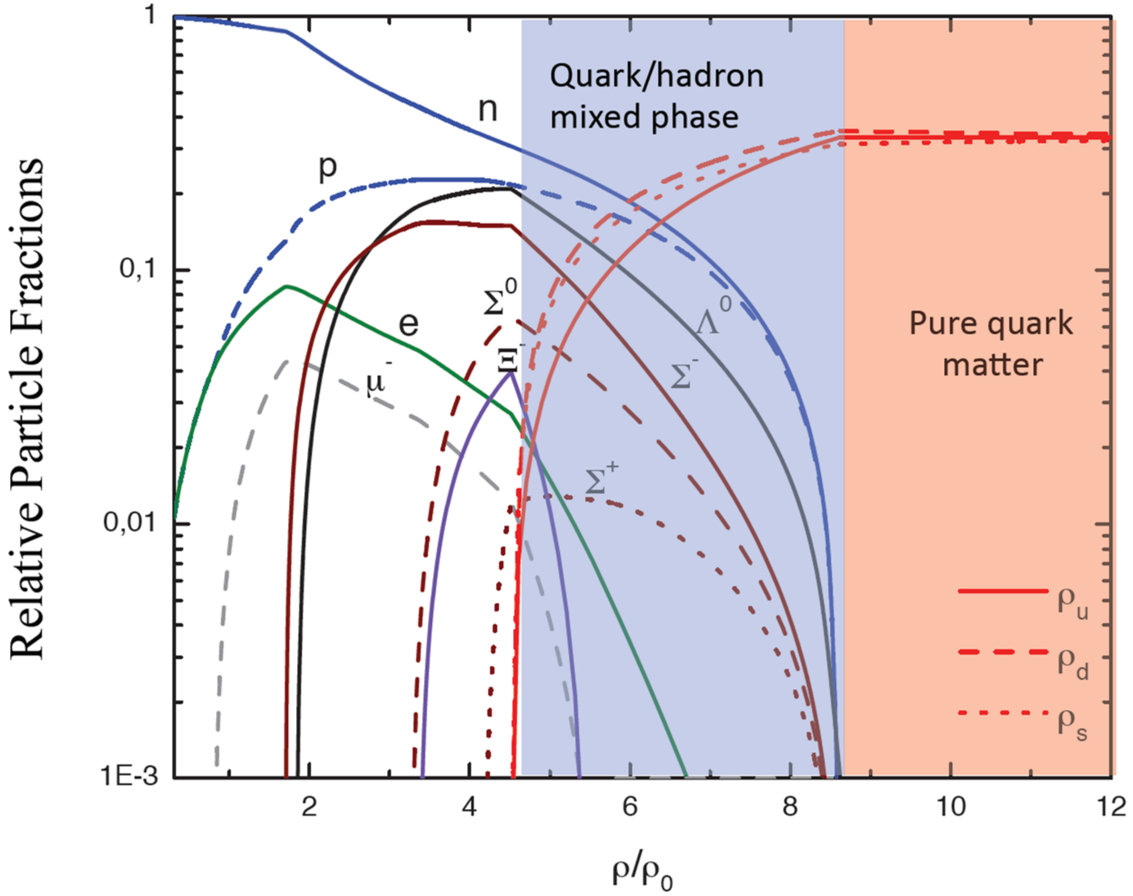
M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657
Phys. Rev. C 89, 015806, 2014

'Strange Matter' – Hyperons In Massive Neutron Stars

But: Inclusion of hyperons results in EoS too soft to support 2-solar-mass n-stars
Unless: Strong repulsion in YN and YNN … interactions





W. Weise, EMMI Workshop - Probing Dense Baryonic Matter with Hadrons (2019)

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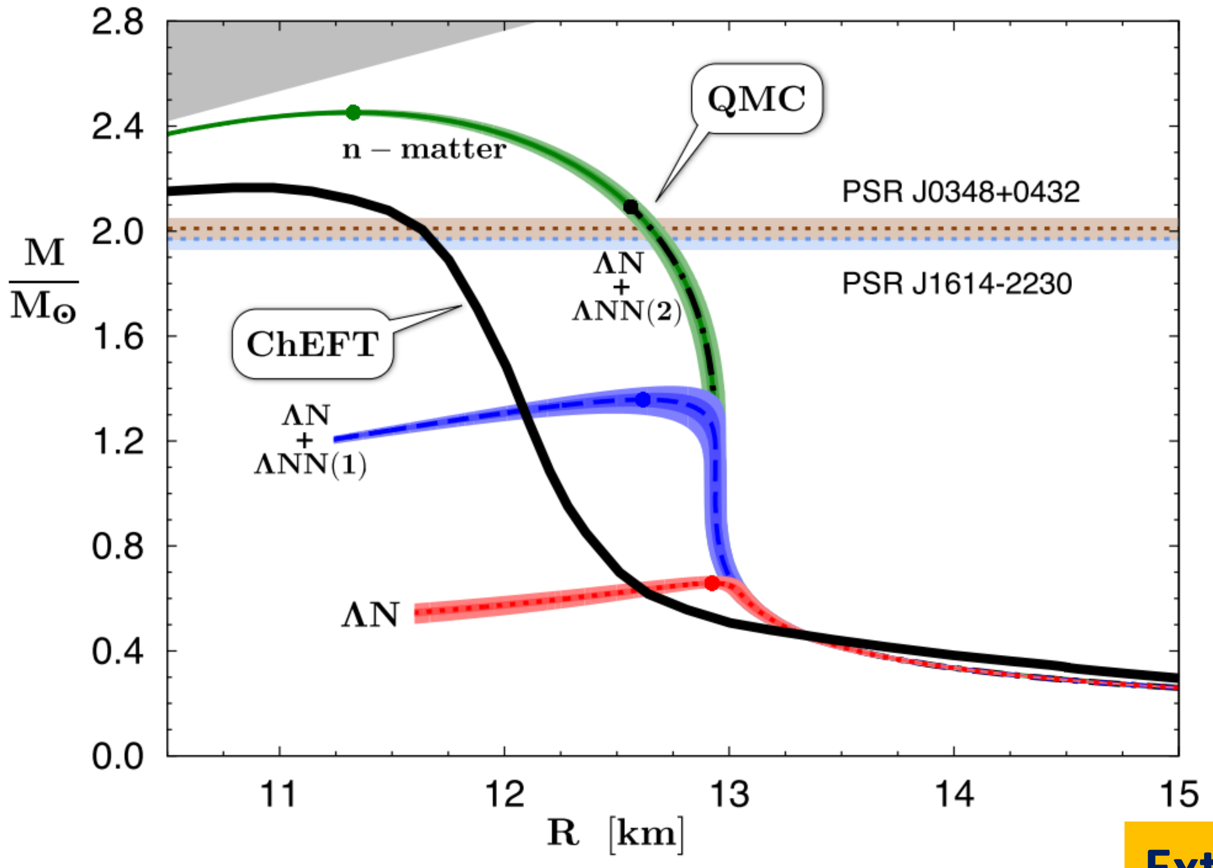
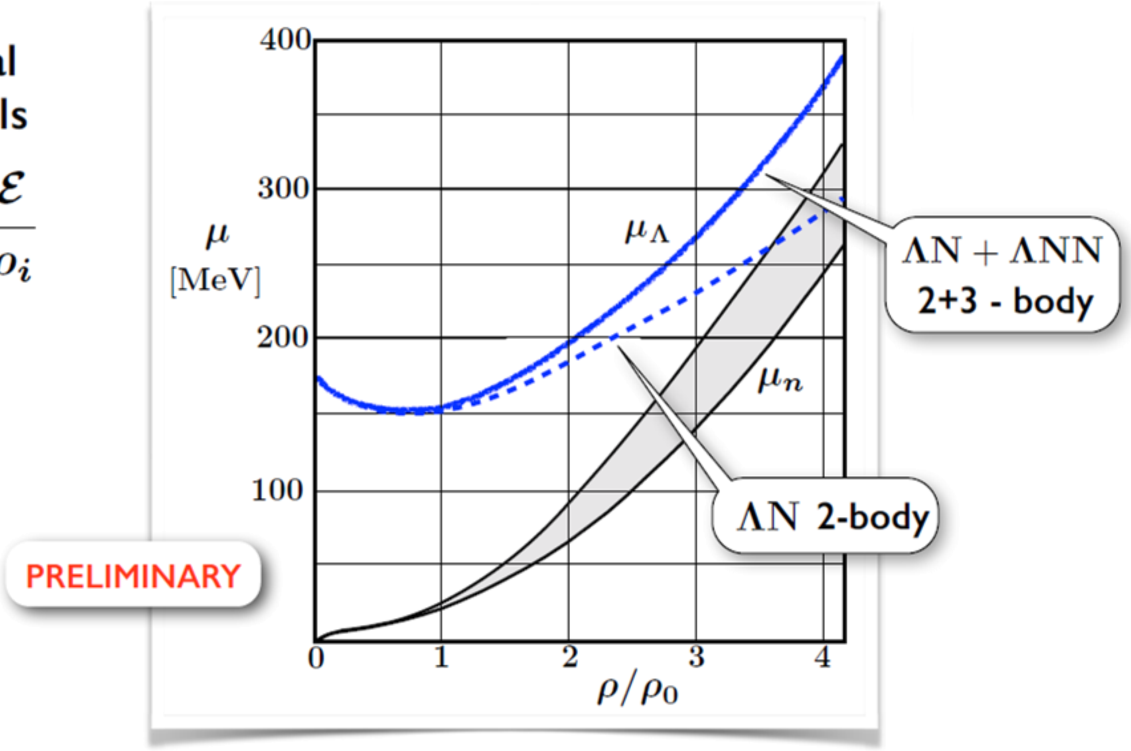


chemical potentials

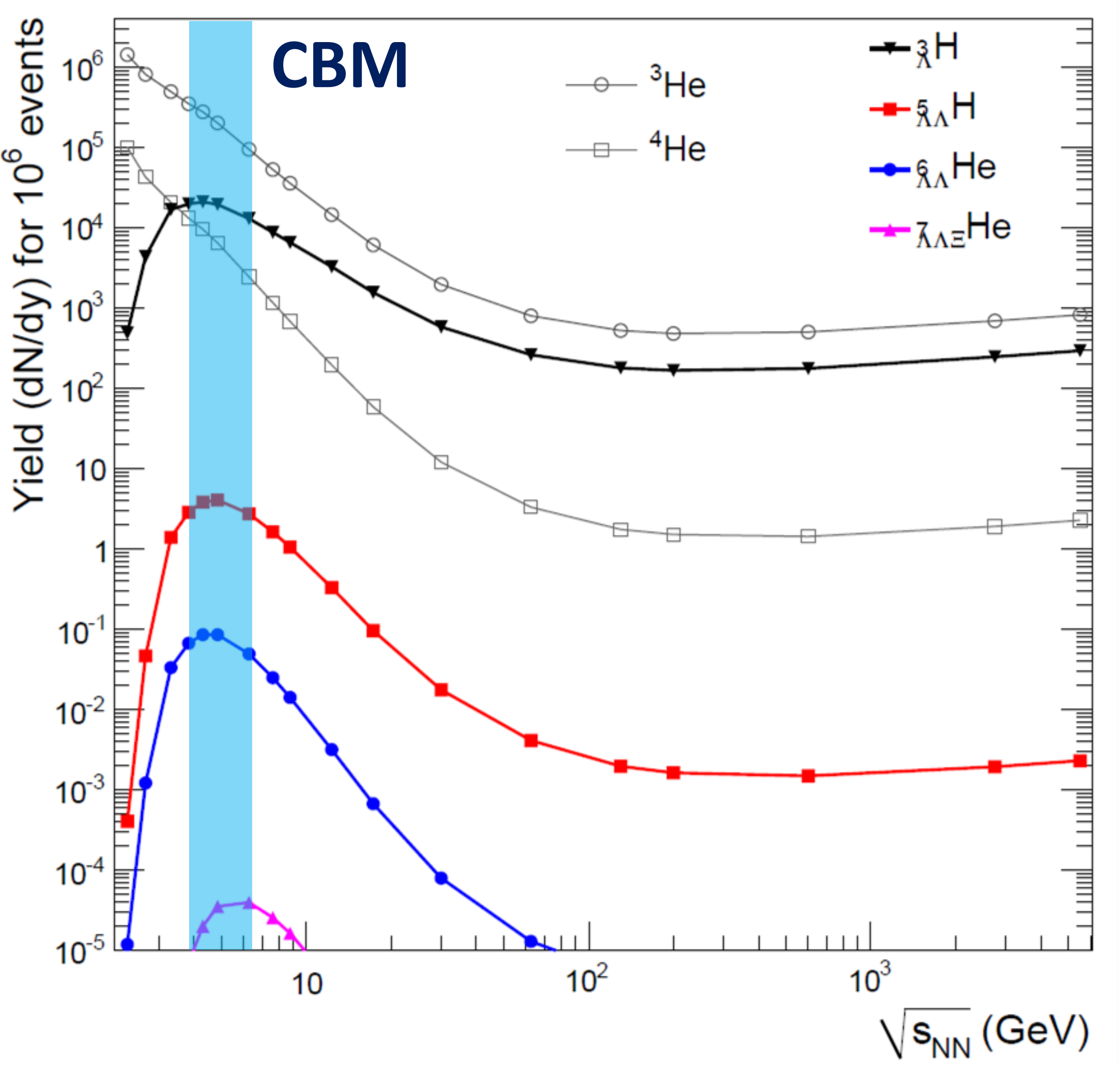
$$\mu_i = \frac{\partial \mathcal{E}}{\partial \rho_i}$$



W. Weise, EMMI Workshop - Probing Dense Baryonic Matter with Hadrons (2019)

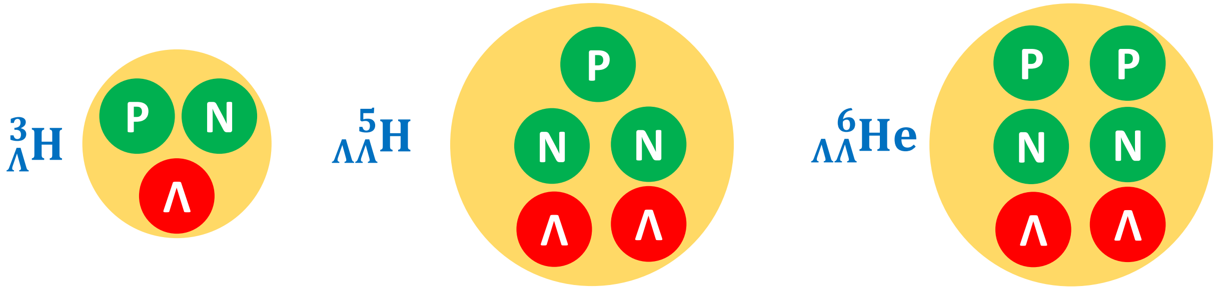
Extrapolations using Λ single particle potential in neutron (star) matter from Chiral SU(3) EFT interactions

Understanding Λ-N, Λ-Λ Interactions With CBM



Thermal Model: A. Andronic et al., Phys. Lett. B697 (2011) 203

Hypernuclei produced in dense matter are excellent particles to study Λ-N, Λ-Λ interactions!



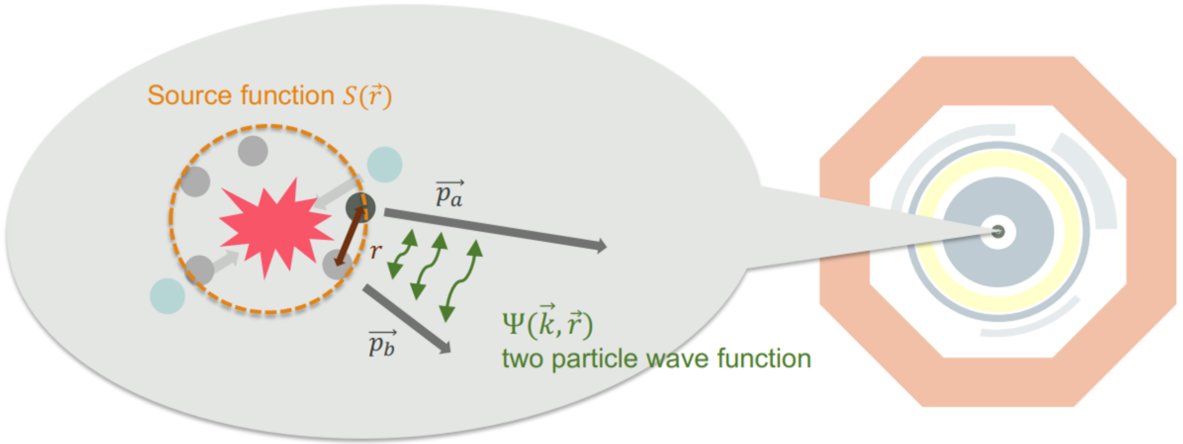
Experimental Observables

- Particle Yields (also shown in the image)
- Lifetimes
- Collective Flow

No experimental data in CBM energy range
Huge discovery potential !!!

Understanding Λ-N, Λ-Λ Interactions With CBM

Idea: Femtoscopy to study the correlation functions (cross-sections) w.r.t. momentum



Statistical definition ***Experimental definition*** ***Theoretical definition***

$$C(k) = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \mathcal{N}\frac{N_{\text{Same}}(k)}{N_{\text{Mixed}}(k)} = \int S(\vec{r})\left|\Psi(\vec{k},\vec{r})\right|^2 \mathrm{d}^3\vec{r} \xrightarrow{k\to\infty} 1$$

Single-particle momenta

Relative distance / reduced momentum in the rest frame of the pair

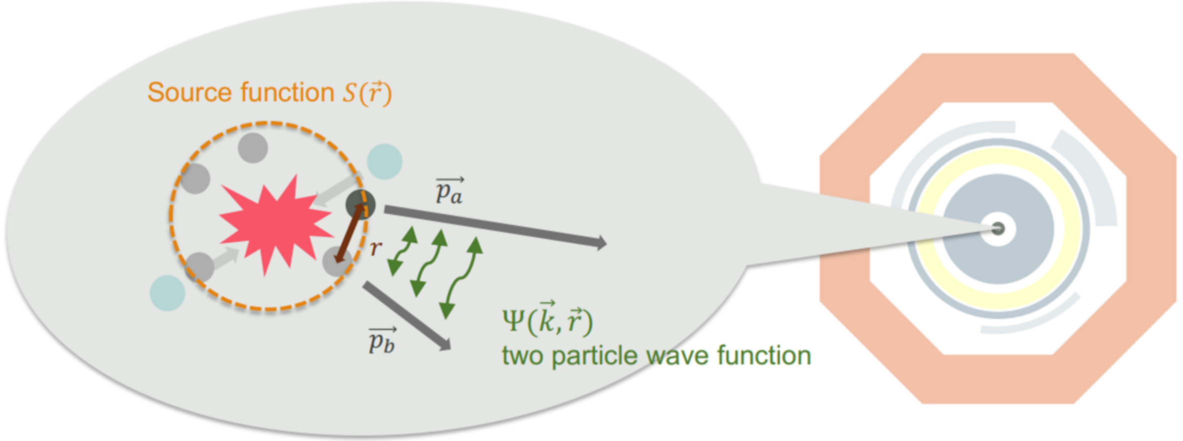
Lisa, Pratt, Wiedemann, Solz, Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

$k^* = |\, p_a^* - p_b^* \,|$ and $\overrightarrow{p_a^*} + \overrightarrow{p_b^*} = 0$

UNDERSTANDING Λ-N, Λ-Λ INTERACTIONS WITH CBM

Idea: Femtoscopy to study the correlation functions (cross-sections) w.r.t. momentum

CATS – Correlation Analysis Tool Using the Schrödinger Equation (TUM - Fabbietti et al.)
Numerical sol. of the Schrödinger Solution to obtain 'exact' solutions to obtain the correlation functions



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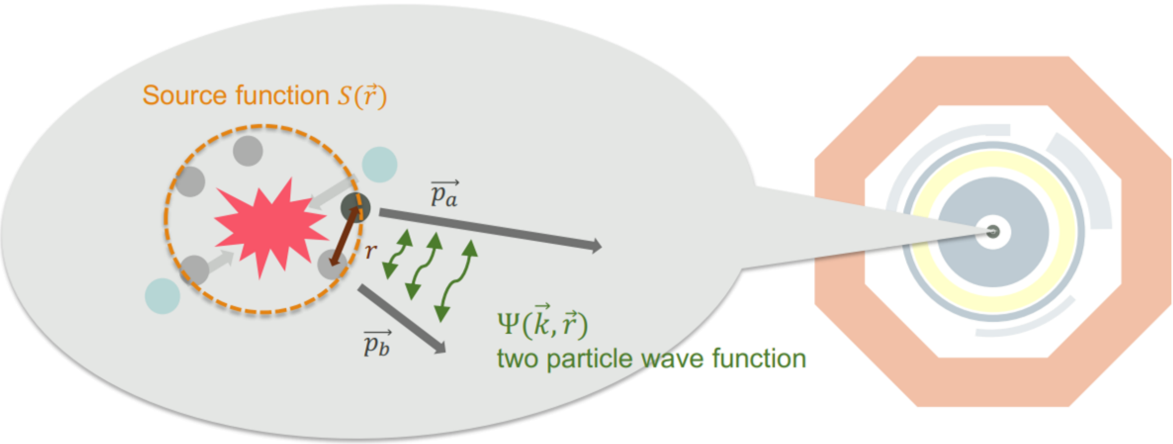

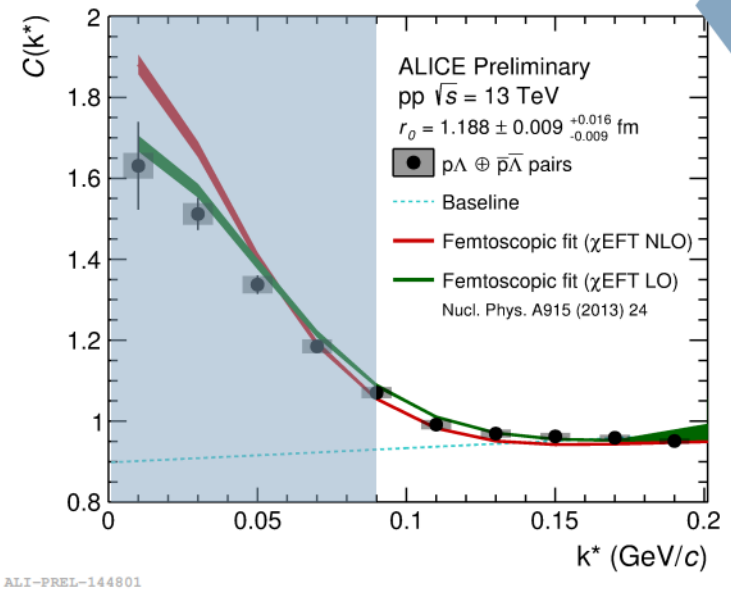

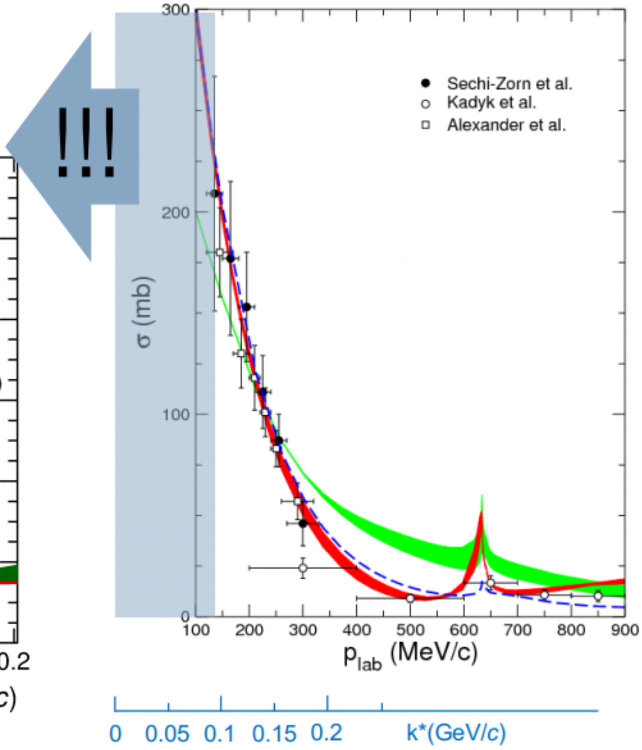

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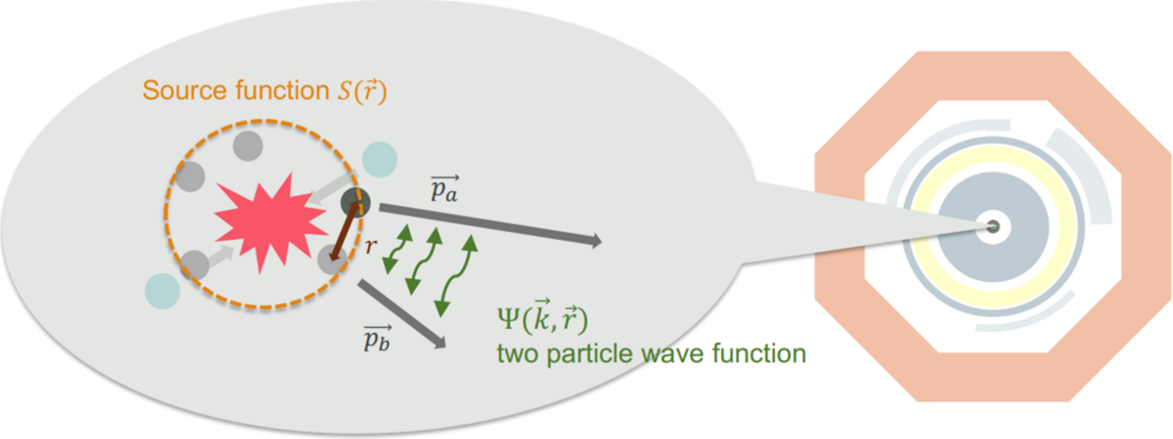

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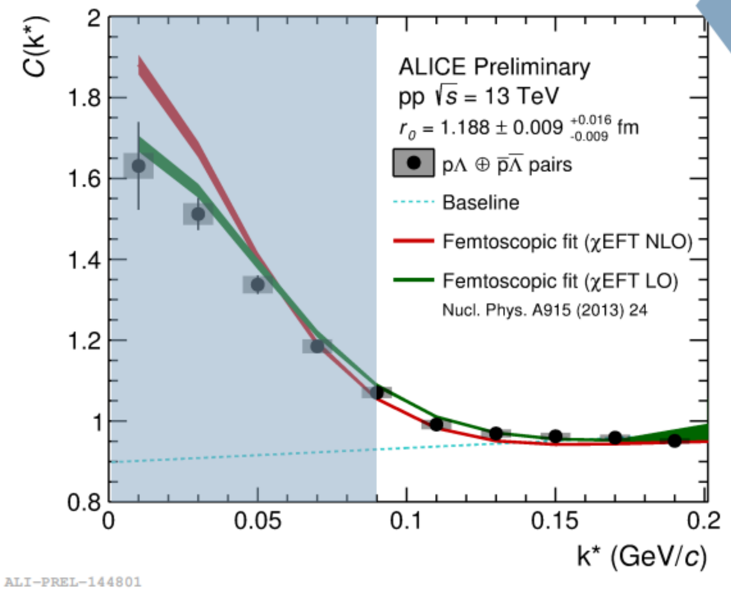
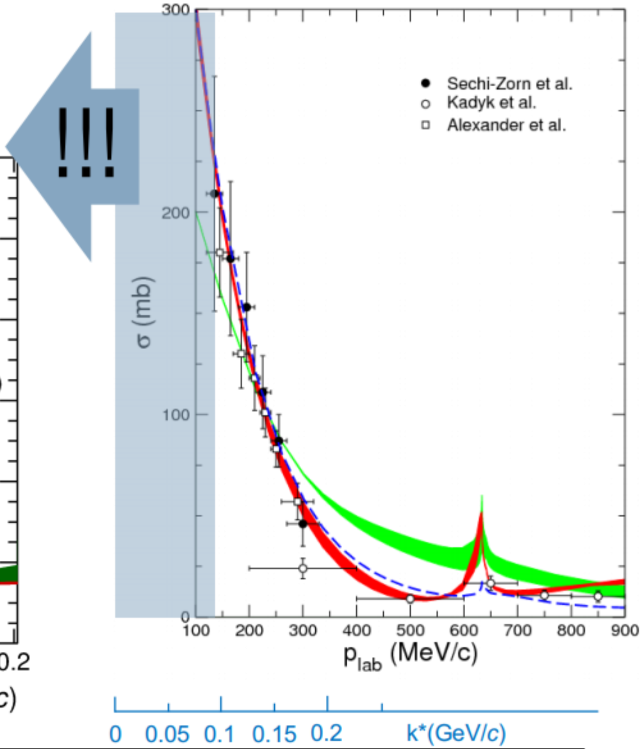




Experimentally shown for ALICE@LHC ($\mu_B = 0$)
Possible at CBM@FAIR ($\mu_B > 0$)?

Summary Of The EoS Experimental Probes With CBM@FAIR

Nuclear Symmetric Matter EOS:

- Collective flow of Baryons (π, K, p, Λ, Ξ, Ω,...) driven by the fireball's pressure gradient
- Sub-Threshold Particle Production of Multi-Strange Hyperons via multi-step processes

Neutron Matter EOS:

Symmetry Energy:

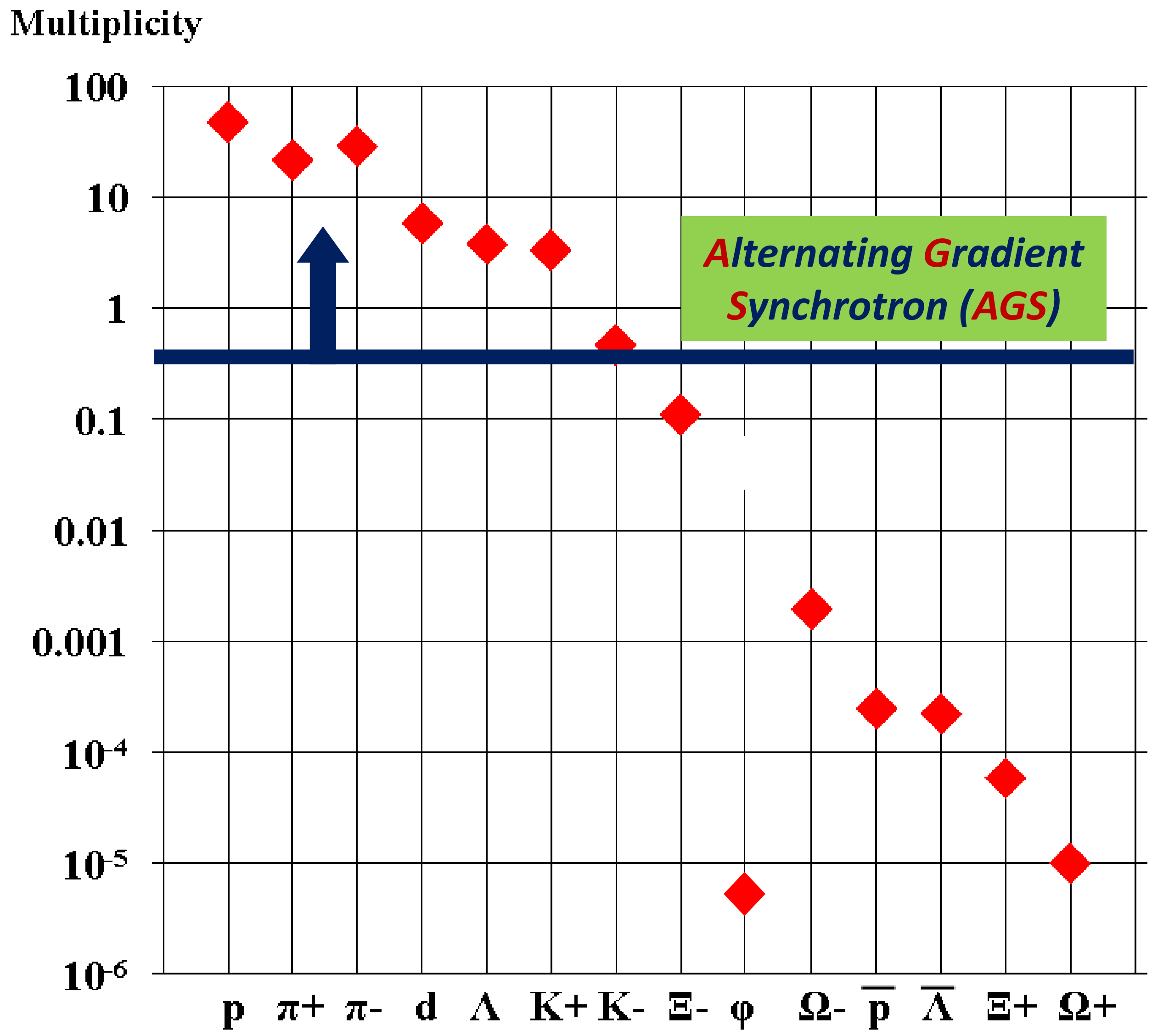
- Neutron/Proton Elliptic Flow
- Sub-Threshold Particle Production of isospin-opposite particles ($I_3 = \pm 1$) ?

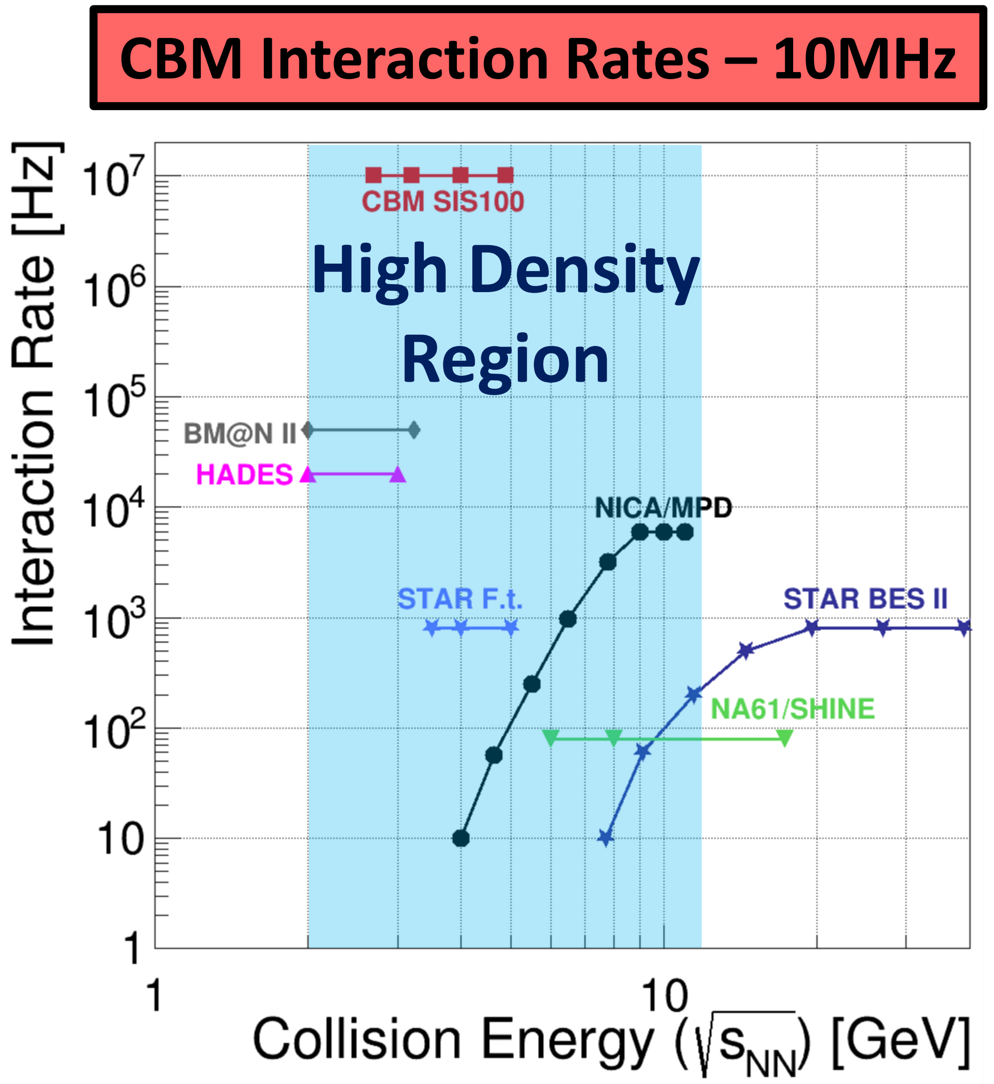
Hyperon Puzzle (ΛN, ΛNN, and ΛΛN interactions)

- Hypernuclei production and yields
- Hypernuclei lifetime
- Hypernuclei Collective Flow
- Correlation functions to study interaction cross-sections by using CATS

Experimental Challenges

(Too) Rare Probes





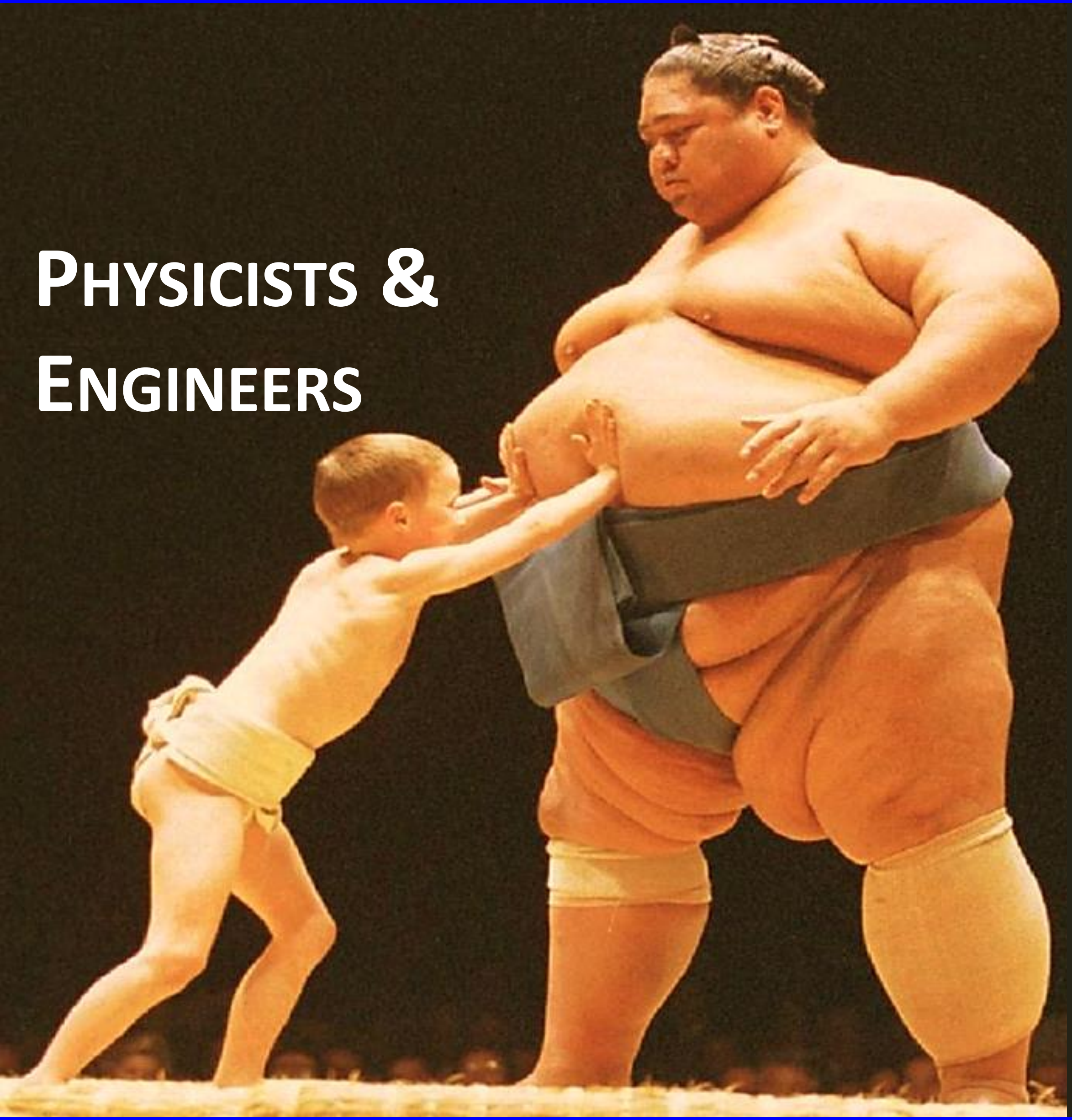
Statistical model, A. Andronic, priv. comm. to P. Senger

T. Ablyazimov et al. [CBM Collaboration] Eur. Phys. J. A (2017)

DAY-1: EXPECTED PARTICLE YIELDS AU+AU @ 6, 10 AGEV

Particle (mass MeV/c²)	Multiplicity central ev. 6 AGeV	Multiplicity central ev. 10 AGeV	decay mode	BR	ε (%)	yield in 90 days 6AGeV	yield in 90 days 10 AGeV	IR MHz
$\bar{\Lambda}$ (1115)	$5.1\cdot10^{-3}$	0.041	$\bar{p}\pi^+$	0.64	19.7	$1.2\cdot10^{8}$	$1.0\cdot10^{9}$	**0.1**
Ξ^- (1321)	0.11	0.36	$\Lambda\pi^-$	1	9.9	$2.0\cdot10^{9}$	$7.0\cdot10^{9}$	**0.1**
Ξ^+ (1321)	$1.8\cdot10^{-3}$	$1.5\cdot10^{-2}$	$\bar{\Lambda}\pi^+$	1	8.7	$3.0\cdot10^{7}$	$2.5\cdot10^{8}$	**0.1**
Ω^- (1672)	$6.8\cdot10^{-4}$	$4.4\cdot10^{-3}$	ΛK^-	0.68	4.4	$4.0\cdot10^{6}$	$2.6\cdot10^{7}$	**0.1**
Ω^+ (1672)	$1.4\cdot10^{-5}$	$2.6\cdot10^{-3}$	$\bar{\Lambda}K^+$	0.68	3.9	$7.0\cdot10^{4}$	$1.4\cdot10^{7}$	**0.1**
$^{3}_{\Lambda}$H (2993)	$4.2\cdot10^{-2}$	$3.8\cdot10^{-2}$	$^{3}He\pi^-$	0.25	12.7	$2.7\cdot10^{8}$	$2.5\cdot10^{8}$	**0.1**
$^{4}_{\Lambda}$He (3930)	$2.4\cdot10^{-3}$	$1.9\cdot10^{-3}$	$^{3}Hep\pi^-$	0.32	11.4	$1.7\cdot10^{7}$	$1.4\cdot10^{7}$	**0.1**
$^{5}_{\Lambda\Lambda}$He(5047)		$5.0\cdot10^{-6}$	$^{3}He2p2\pi$	0.01	3	15	250	**0.1**
$^{6}_{\Lambda\Lambda}$He(5986)		$1.0\cdot10^{-7}$	$^{4}He2p2\pi$	0.01	1.2			**0.1**

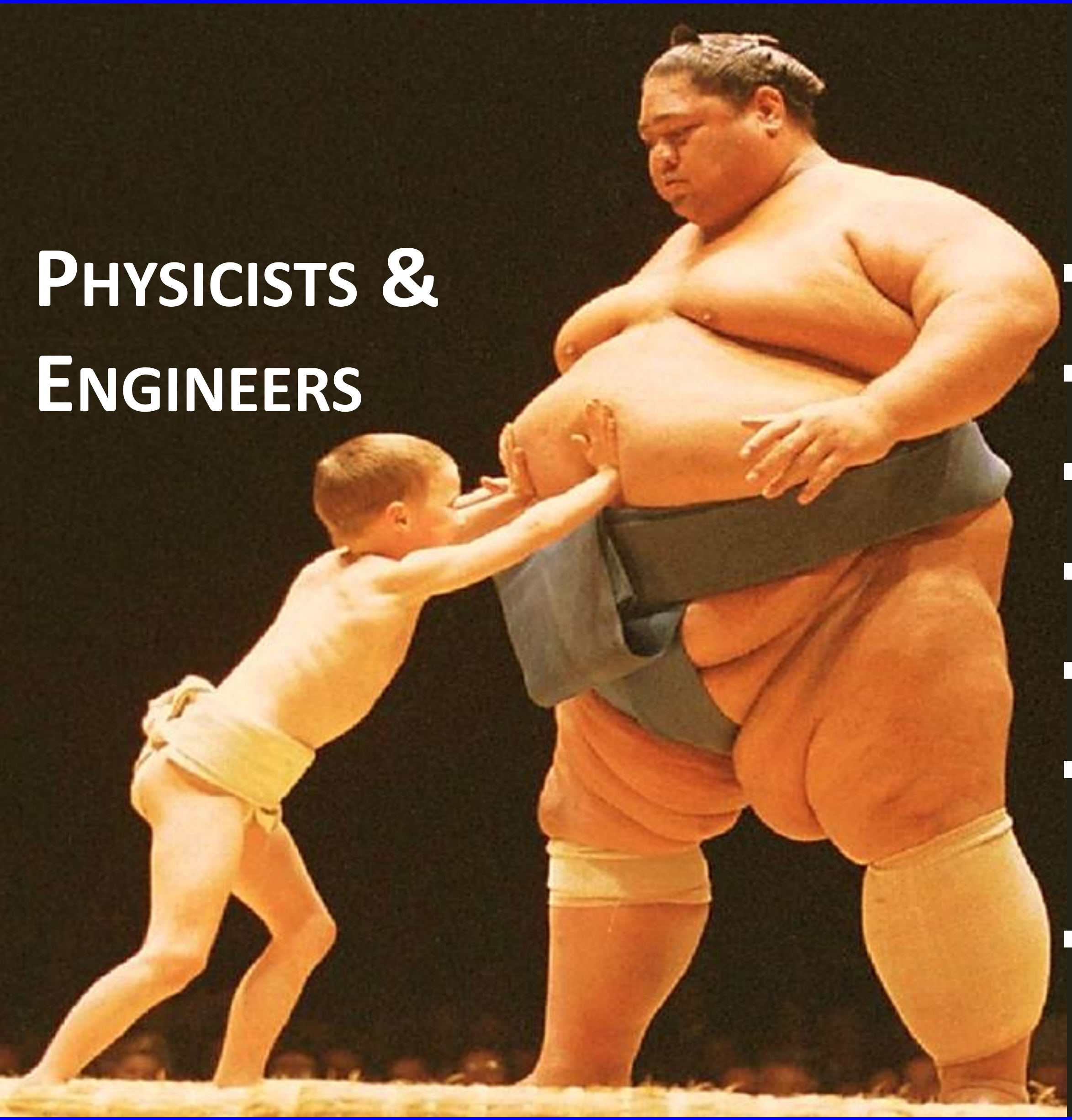
I. Vassiliev, 34th CBM Collaboration Meeting (2019)



Experimental Challenges

Image Credits: https://imgflip.com/memetemplate/166876537/kid-vs-sumo-wrestler

IT'S TOUGH



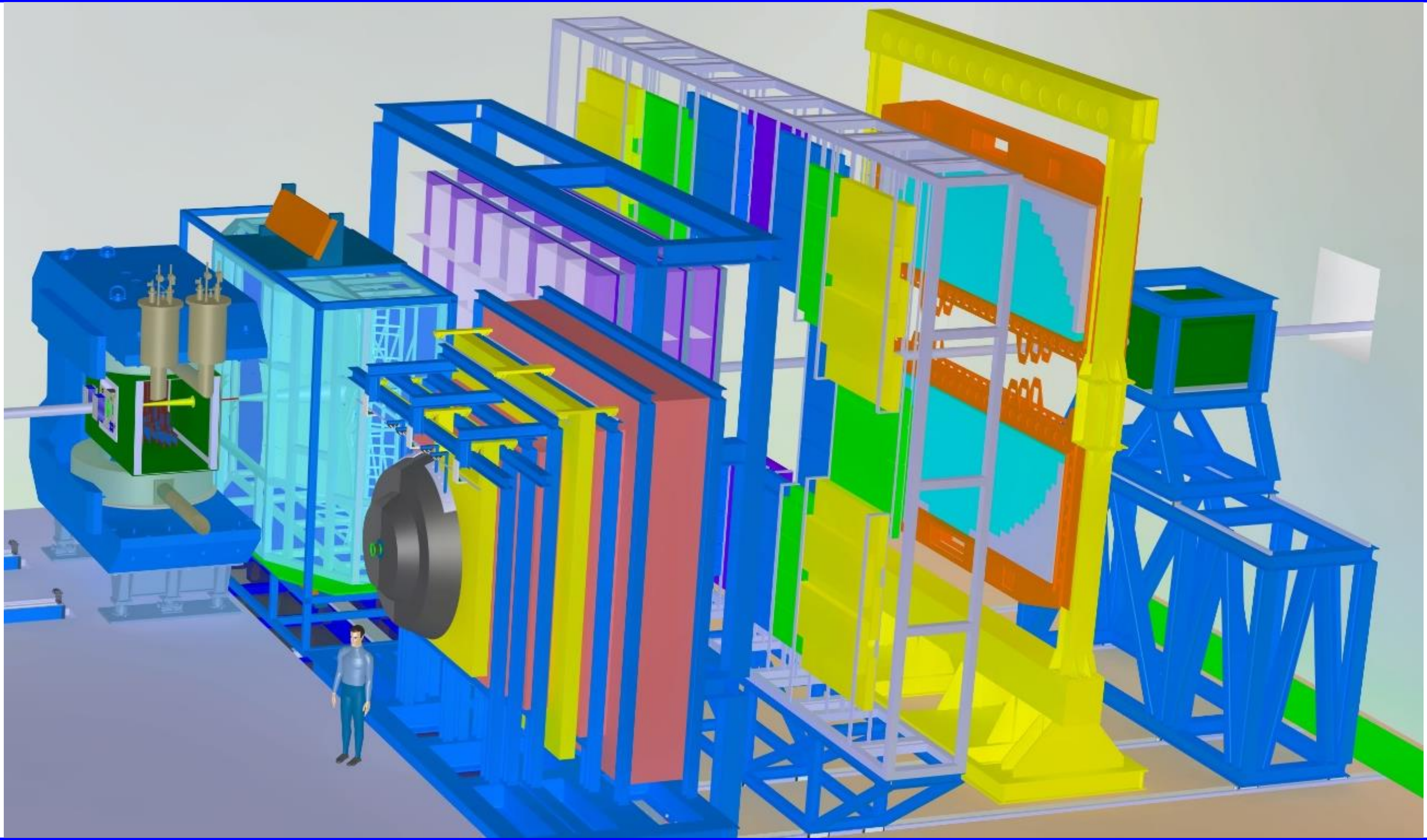
PHYSICISTS & ENGINEERS

EXPERIMENTAL CHALLENGES

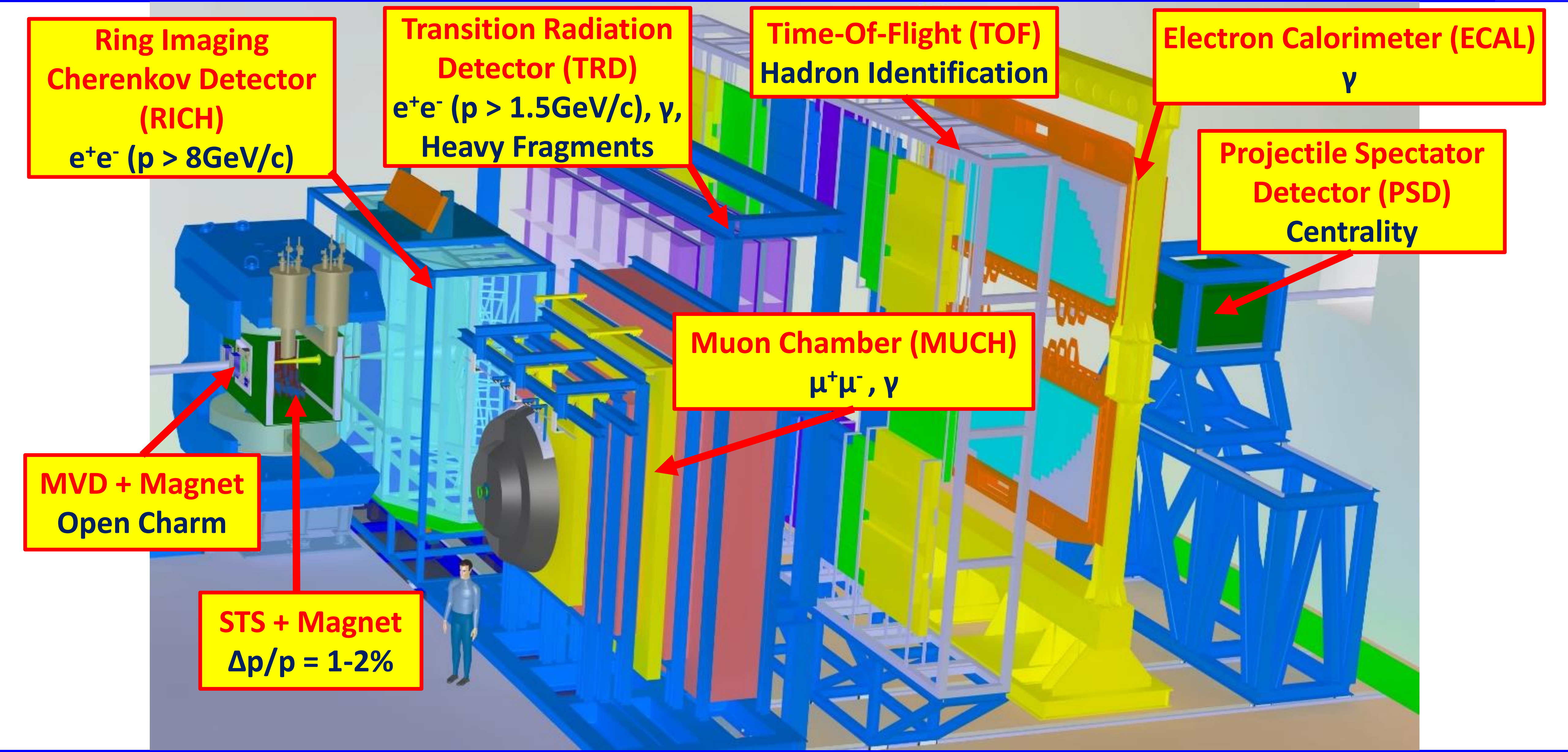
- 10^5 - 10^7 Au + Au reactions/sec
- Determination of (displaced) vertices ($\sigma \approx 50$ μm)
- Identification of leptons and hadrons
- Fast and radiation hard detectors
- Trigger-less Free-streaming readout electronics
- High speed data acquisition and high performance computer farm for online event selection
- 4-D event reconstruction

Image Credits: https://imgflip.com/memetemplate/166876537/kid-vs-sumo-wrestler

CBM Experimental Setup

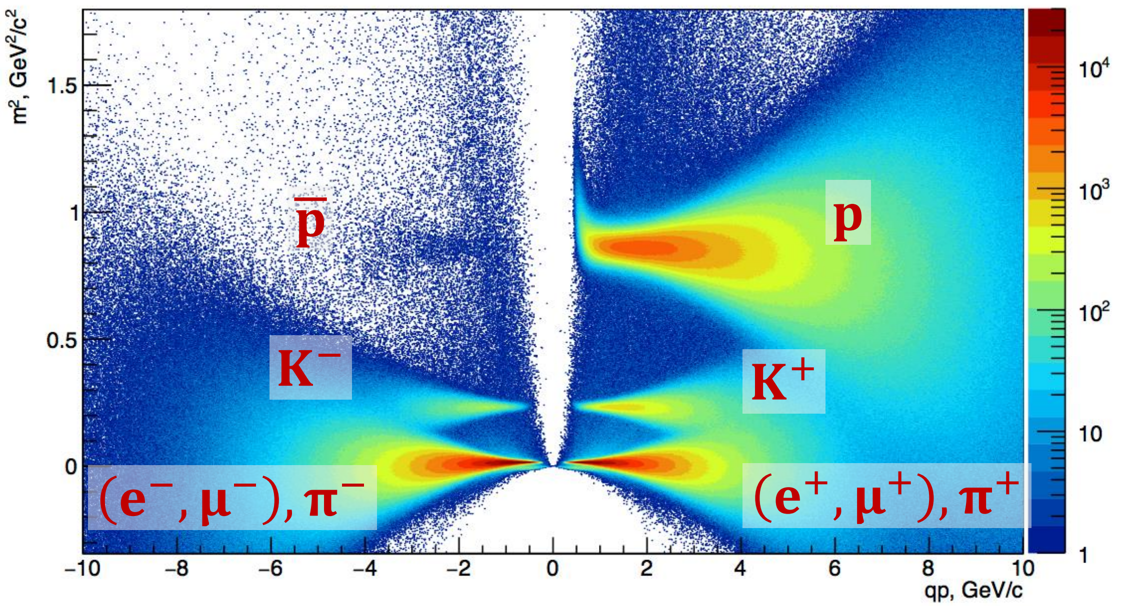


CBM Experimental Setup

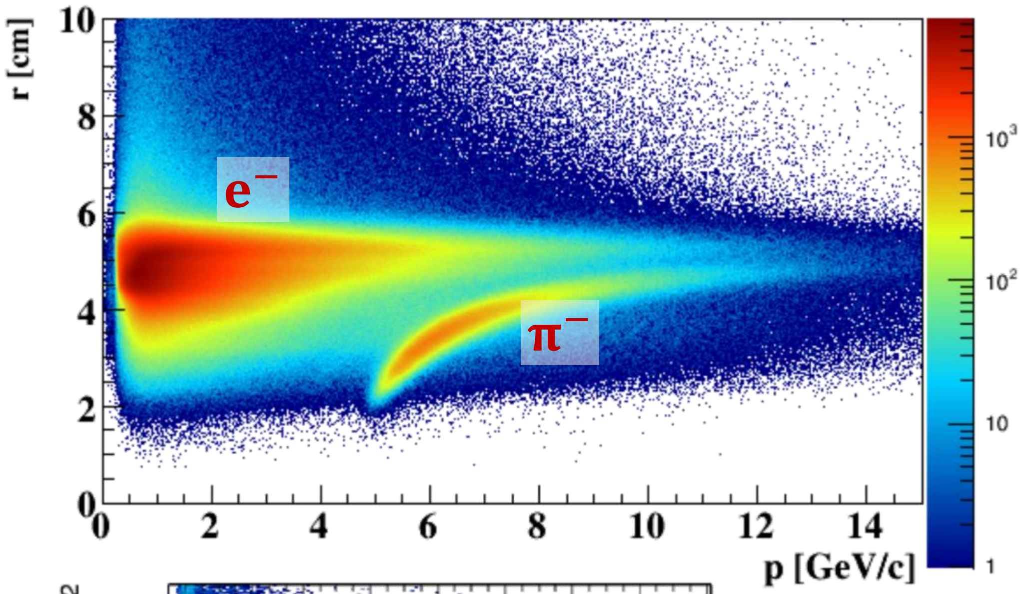


Particle Identification (PID) With CBM

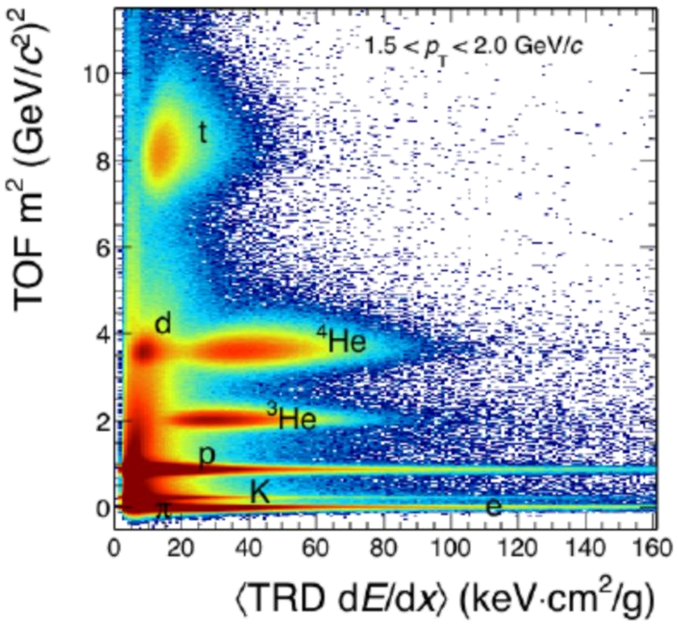
ToF
Hadron Identification



High purity identification of charged protons, pions, electrons and light nuclei

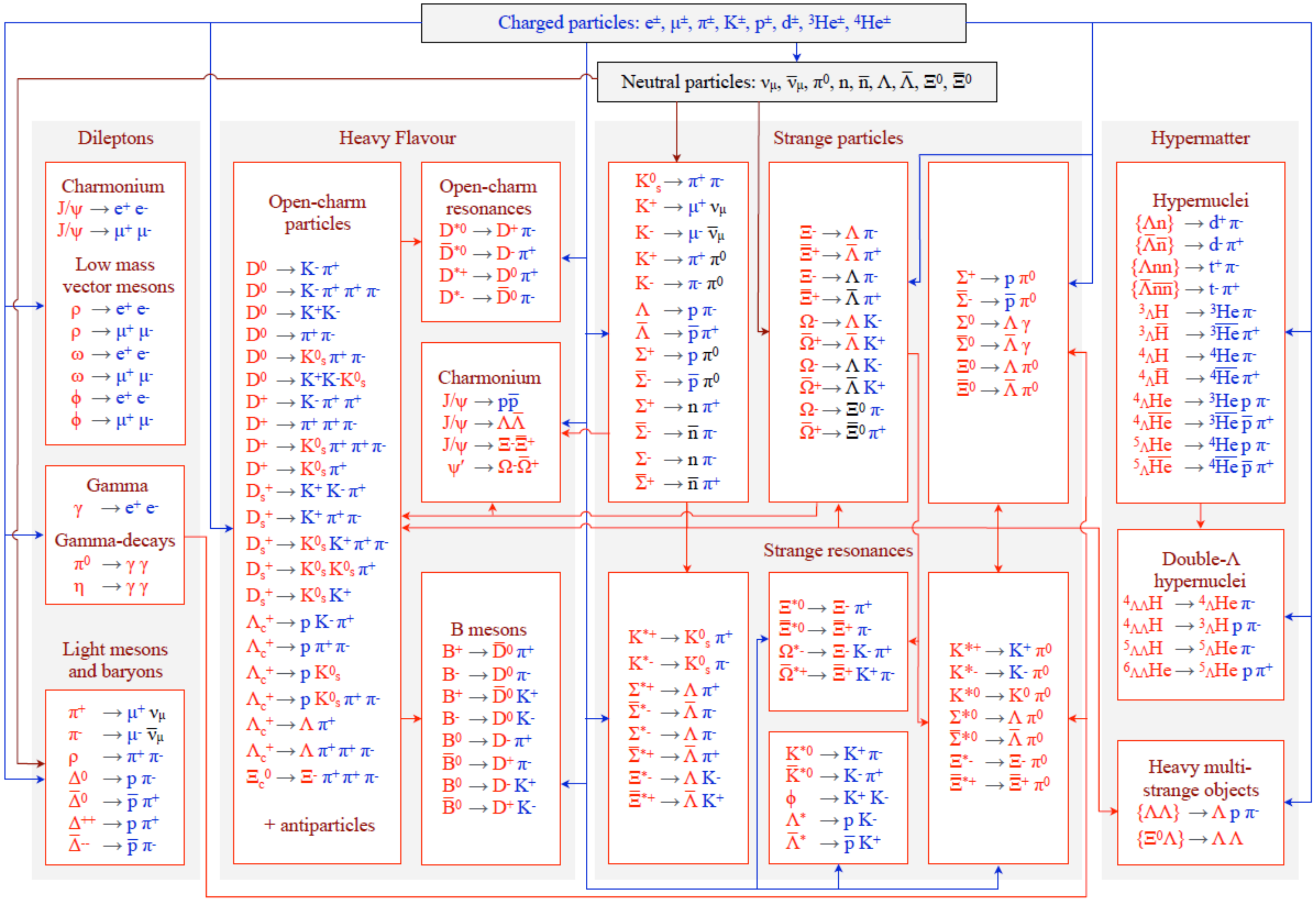


RICH
Electron Identification



TRD + ToF
Electron, Light Nuclei, Heavy Fragments

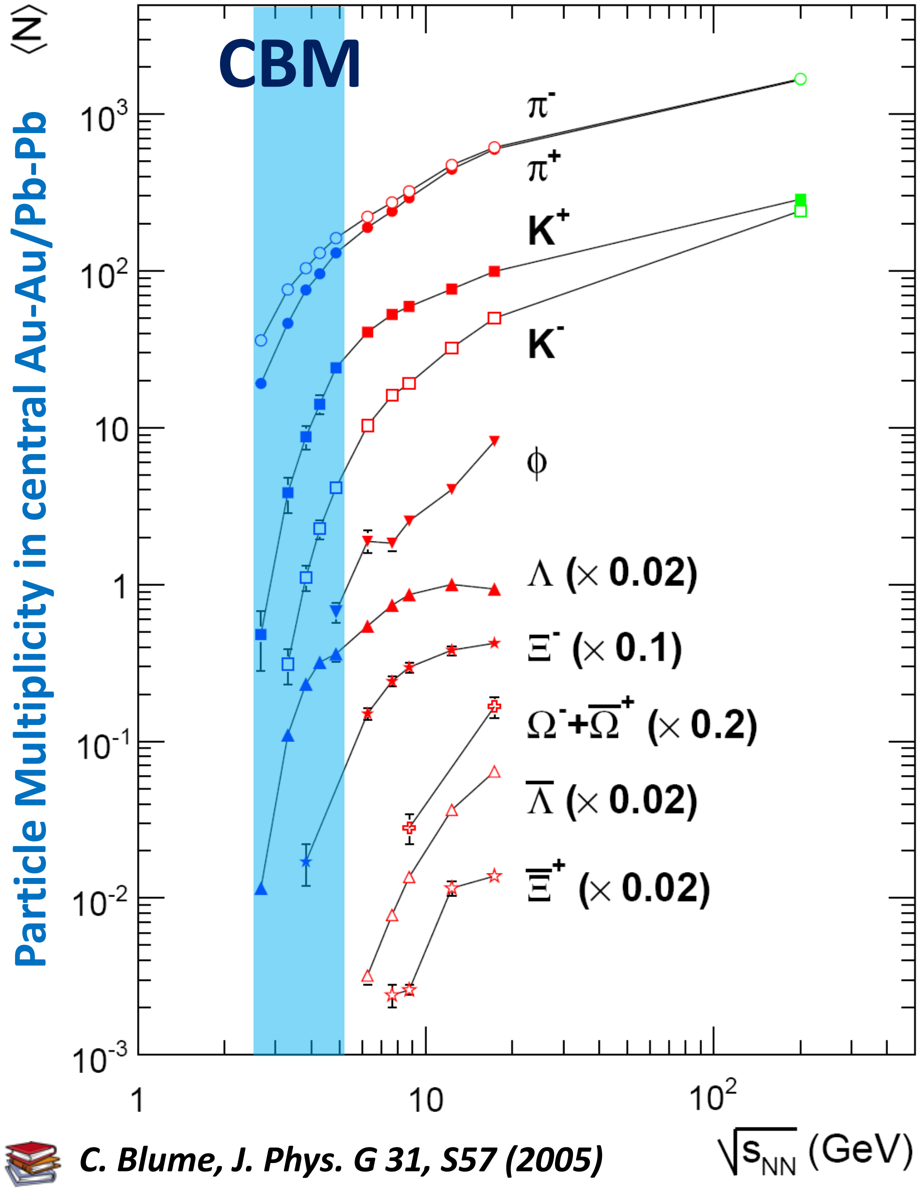
KALMAN FILTER PARTICLE FINDER (KFPF)



- **Almost 150 decays**
- **All decays are reconstructed in one go – online!**
- **Based on the Kalman filter method – mathematically correct parameters and their errors**
- **Available in and approbated within STAR, ALICE, PANDA**

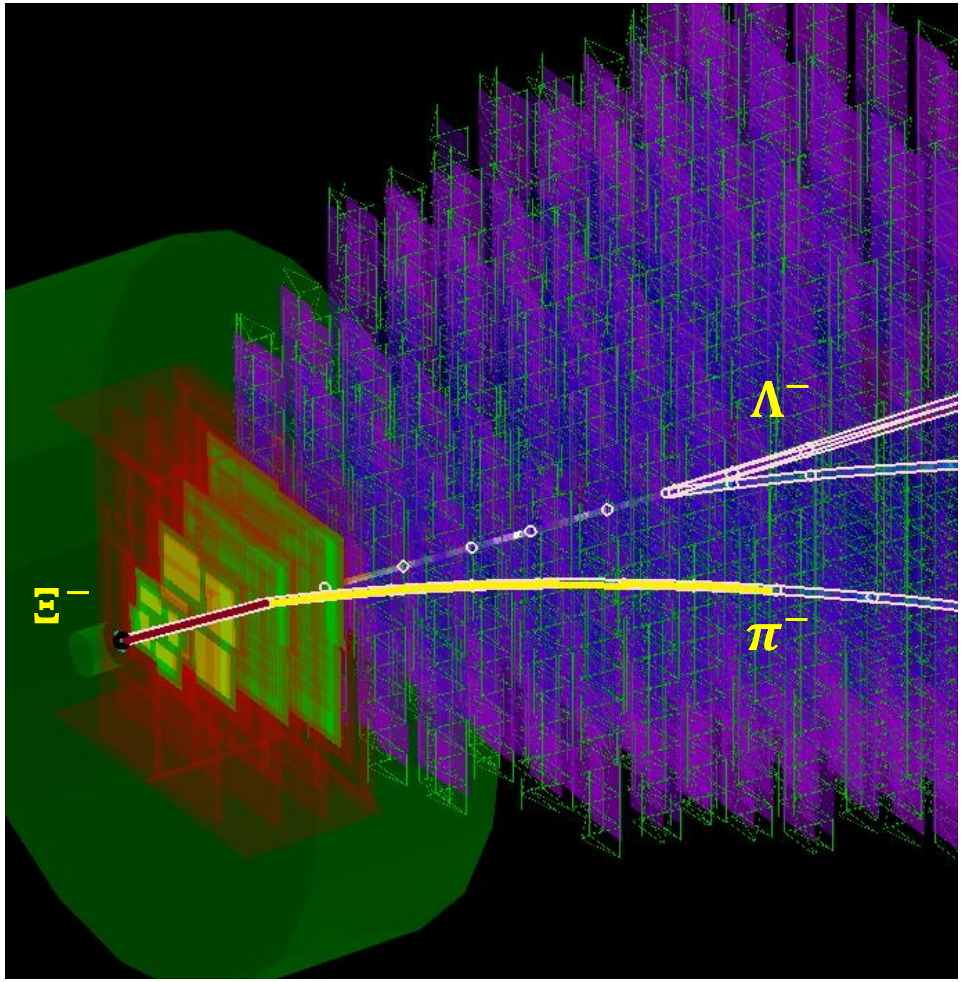
M. Zyzak, I. Vassiliev et al. – GSI Darmstadt

CBM'S CAPABILITES IN HYPERON DETECTION & RECONSTRUCTION



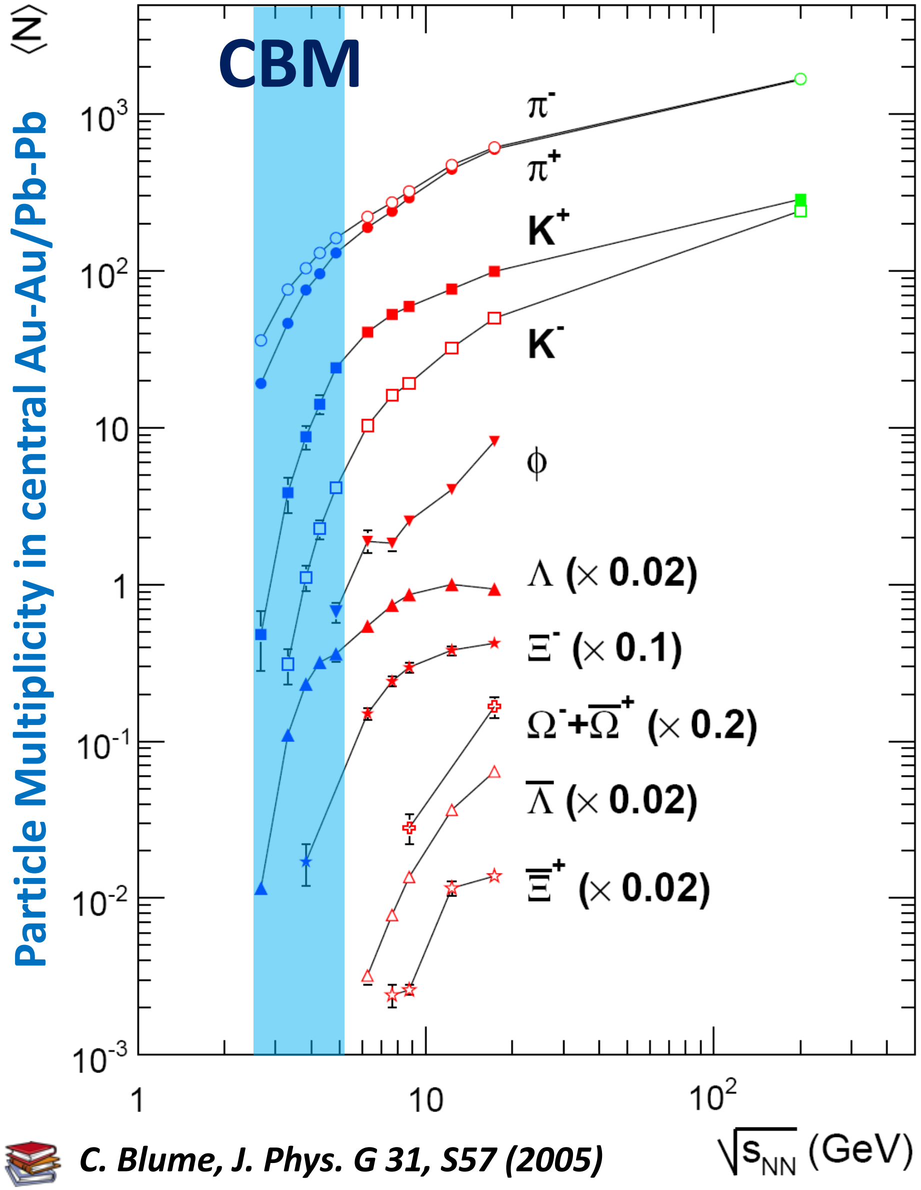
C. Blume, J. Phys. G 31, S57 (2005)

Ξ^- Decay Topology reconstructed in CBM



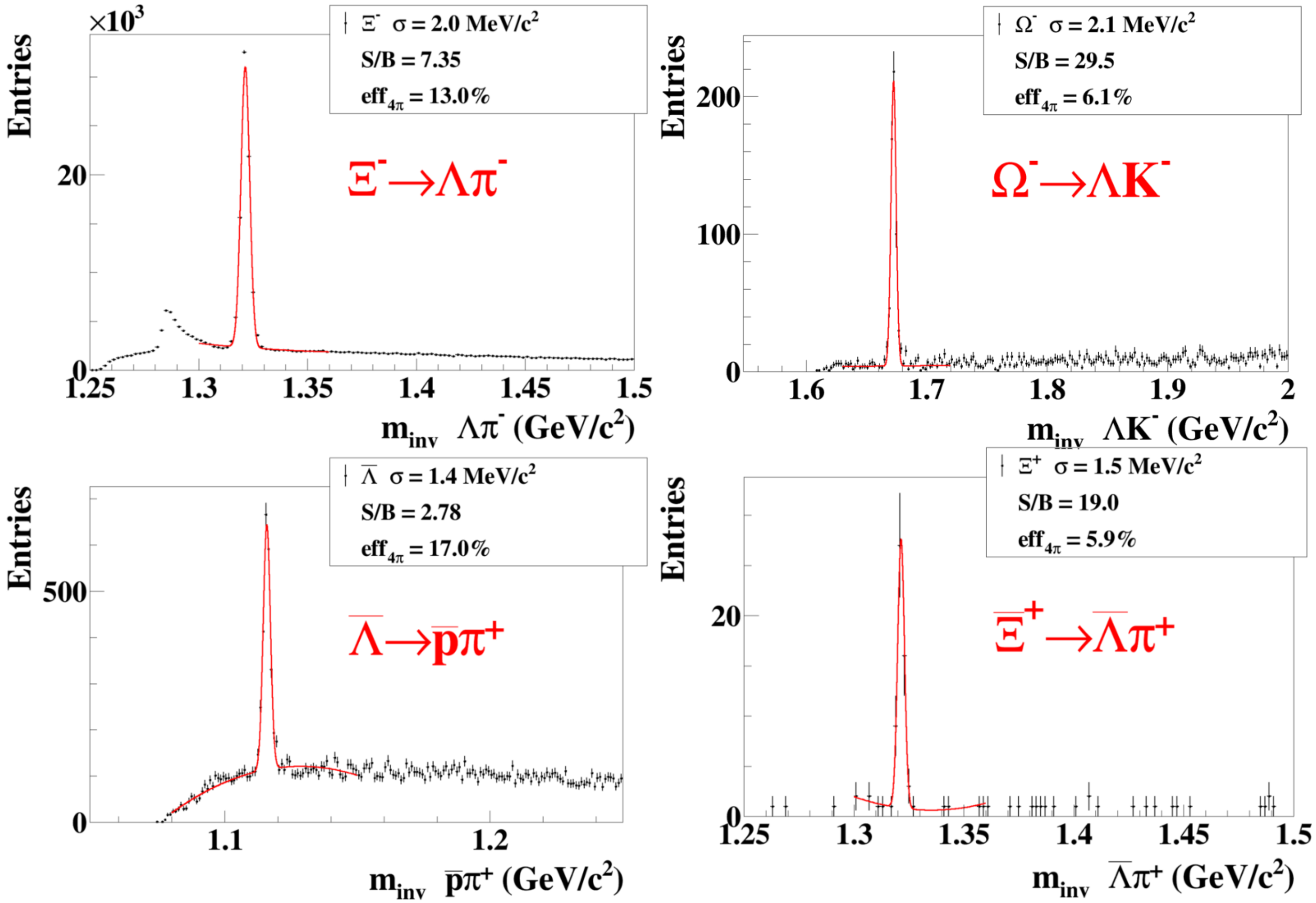
I. Vassiliev, Quark Matter (2018)

CBM'S CAPABILITES IN HYPERON DETECTION & RECONSTRUCTION



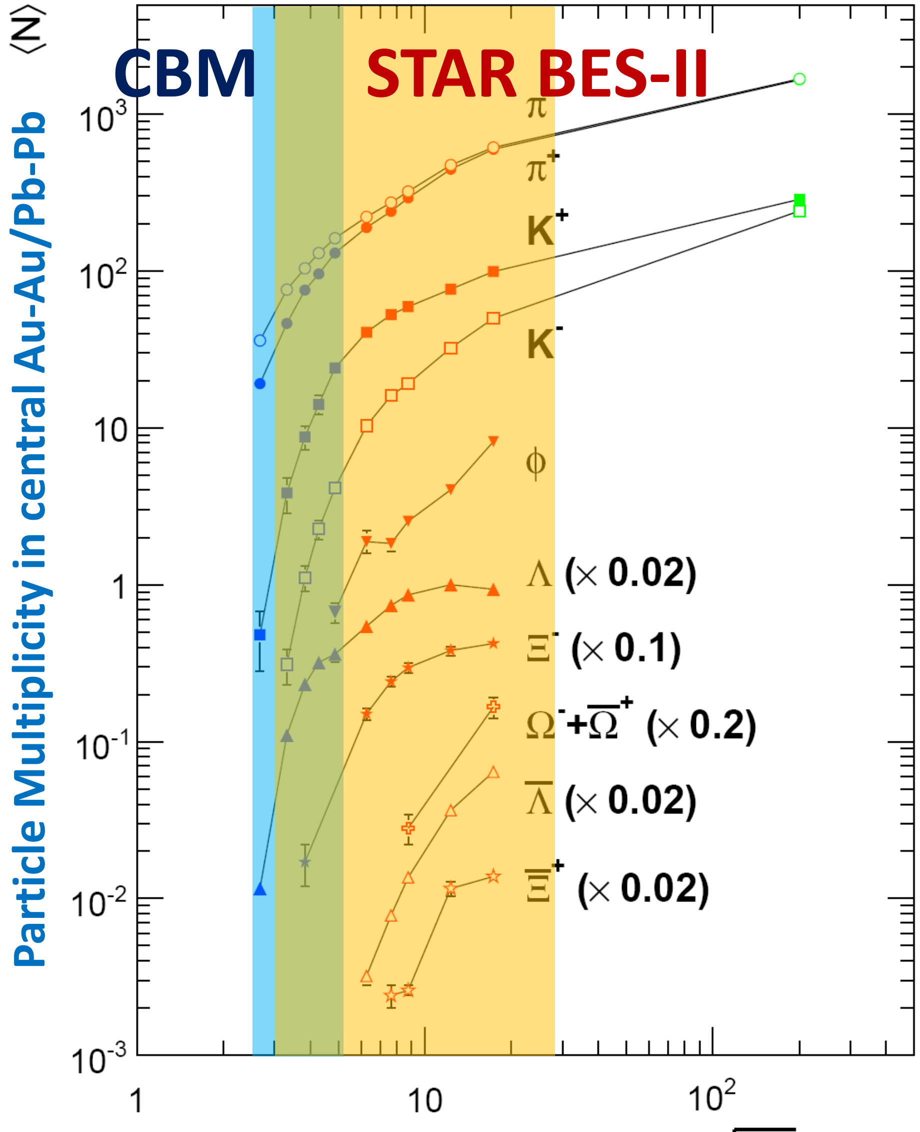
C. Blume, J. Phys. G 31, S57 (2005)

CBM Performance using UrQMD Au+Au collisions 10 AGeV (b=0)



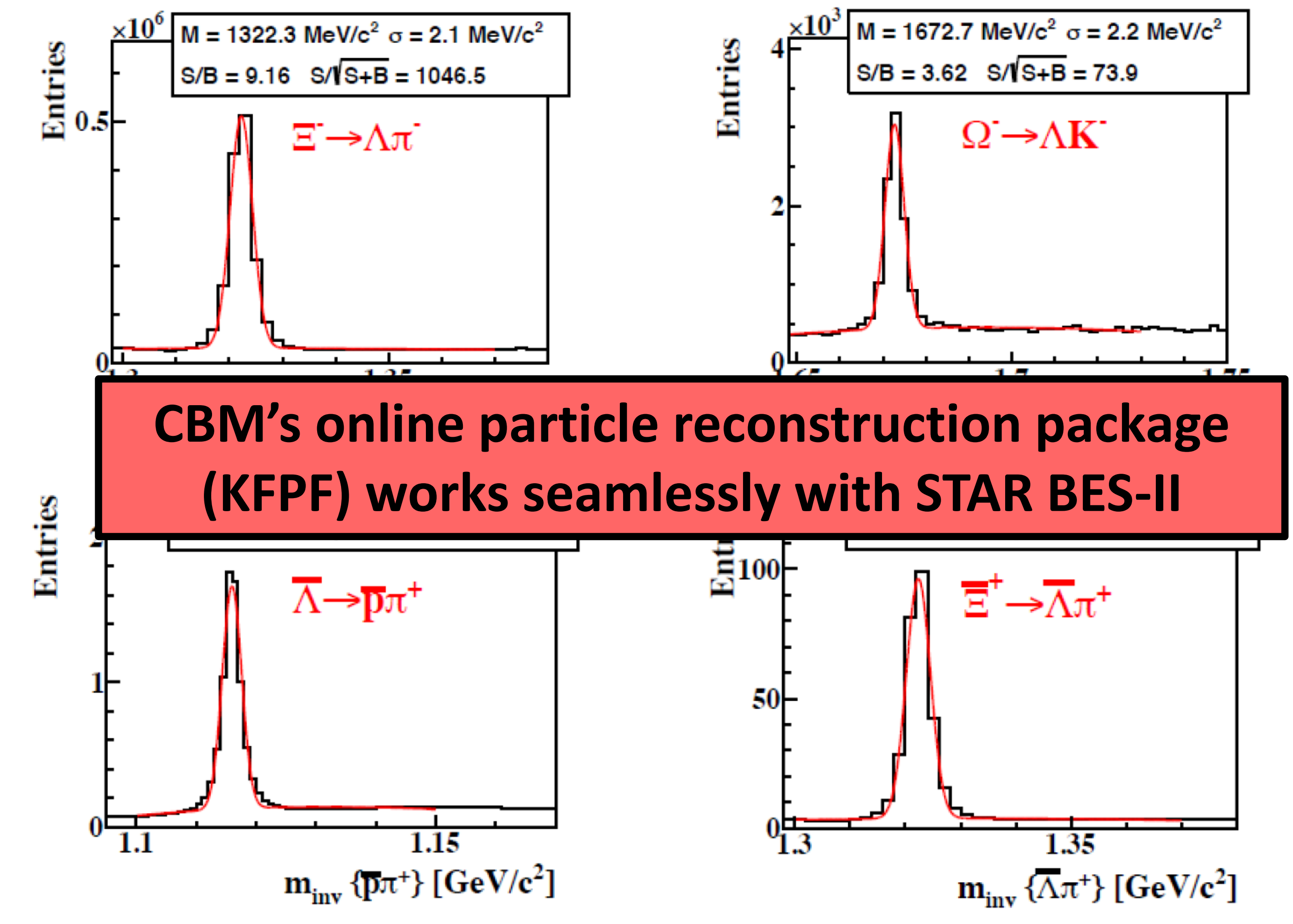
I. Vassiliev, 34th CBM Collaboration Meeting (2019)

CBM'S CAPABILITES IN HYPERON DETECTION & RECONSTRUCTION



C. Blume, J. Phys. G 31, S57 (2005)

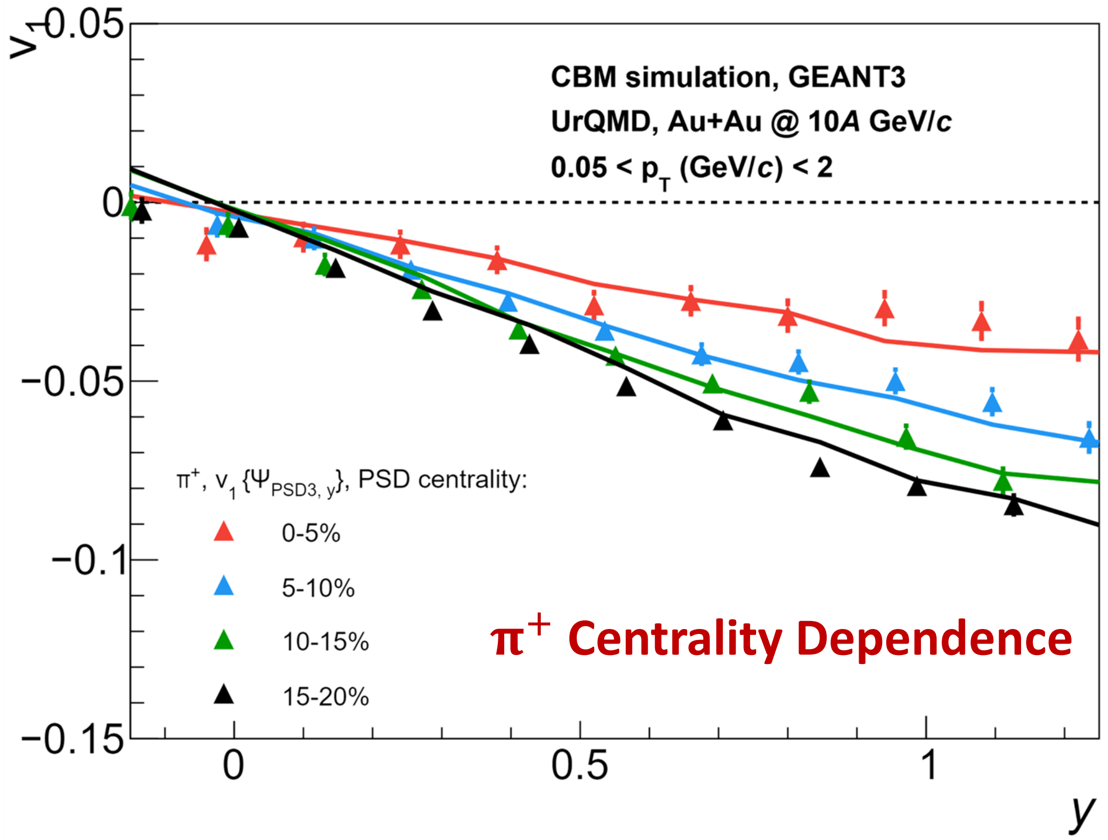
STAR BES-II Performance at Au+Au collisions 14.5 GeV (200M events)

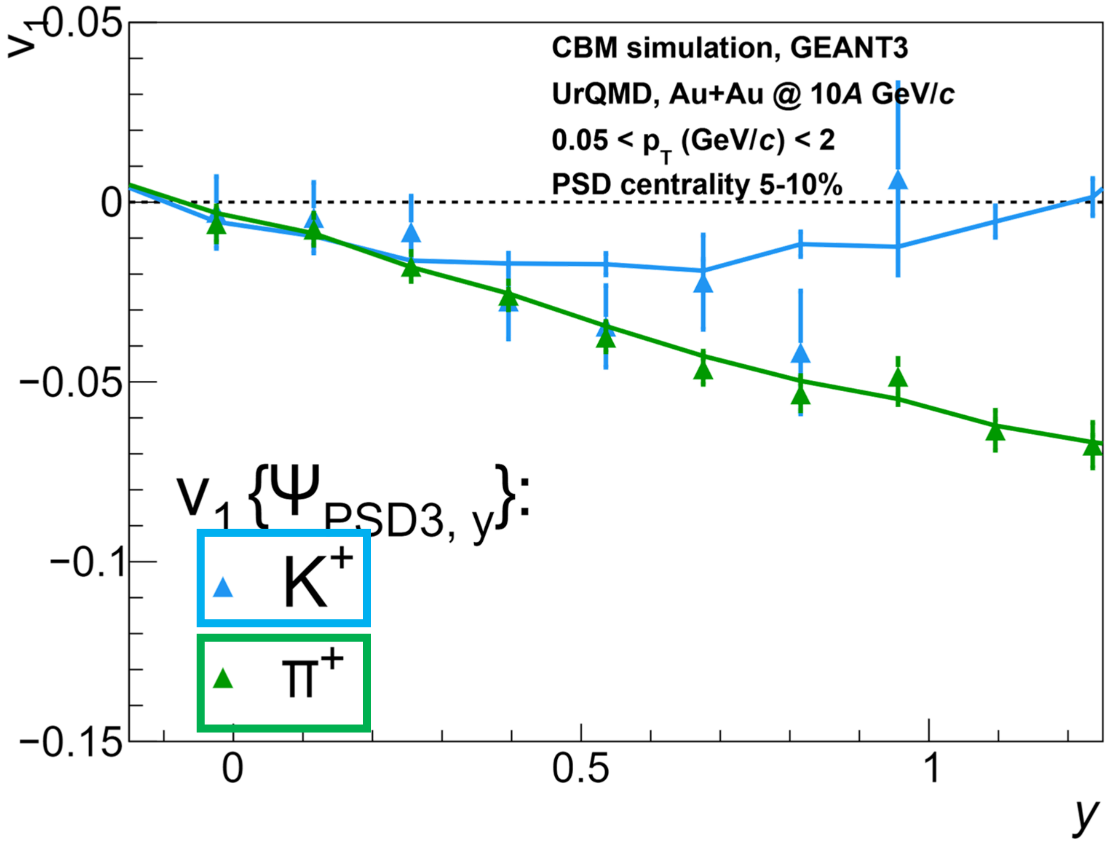


CBM's online particle reconstruction package (KFPF) works seamlessly with STAR BES-II

I. Vassiliev, 3rd EMMI Workshop on Anti-Matter, Hyper-Matter and Exotica Production at the LHC (2019)

CBM Performance using UrQMD Au+Au collisions 10 AGeV

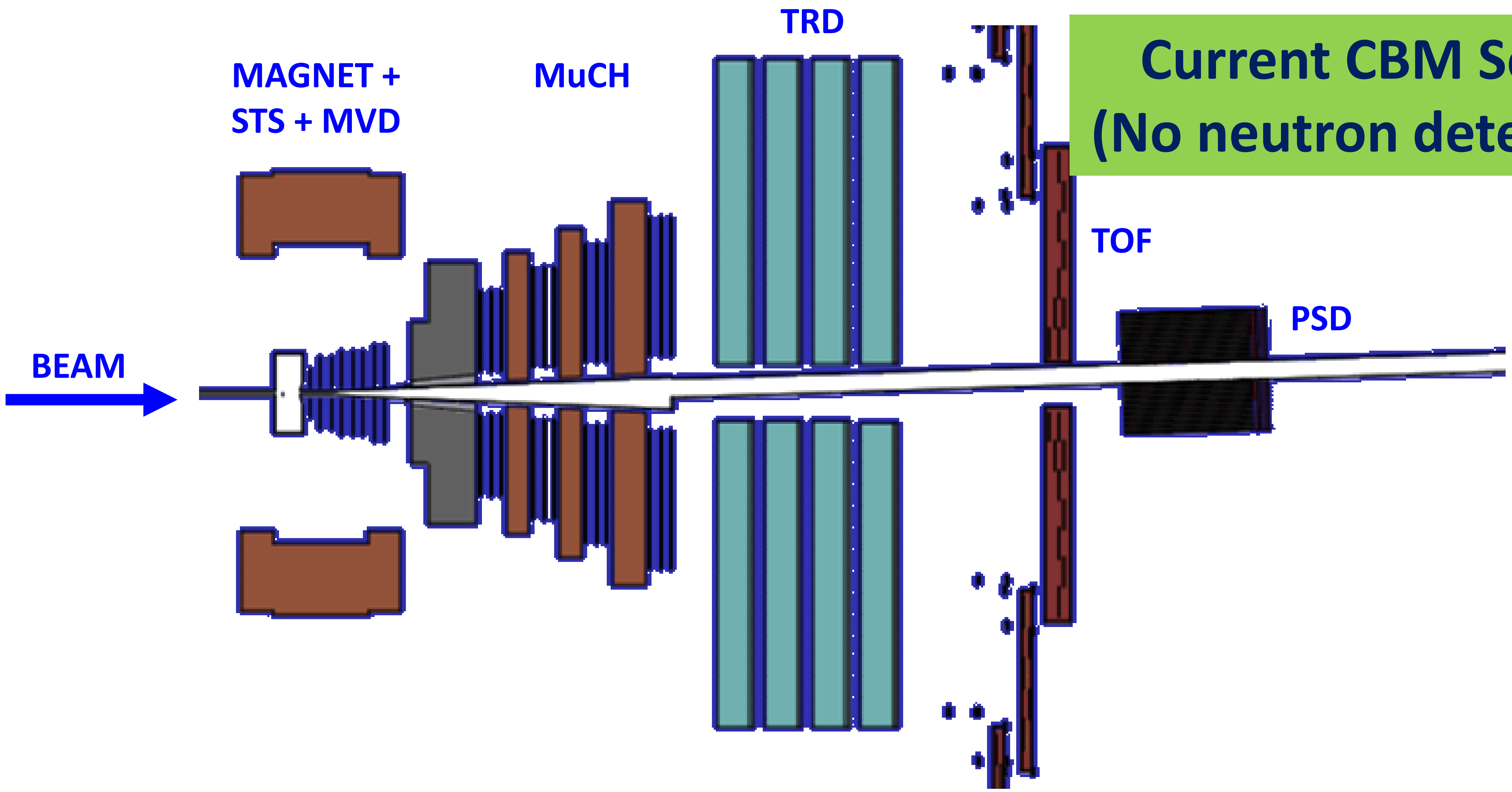




"Input" model v_1 is recovered using "data-driven" methods with projectile spectators

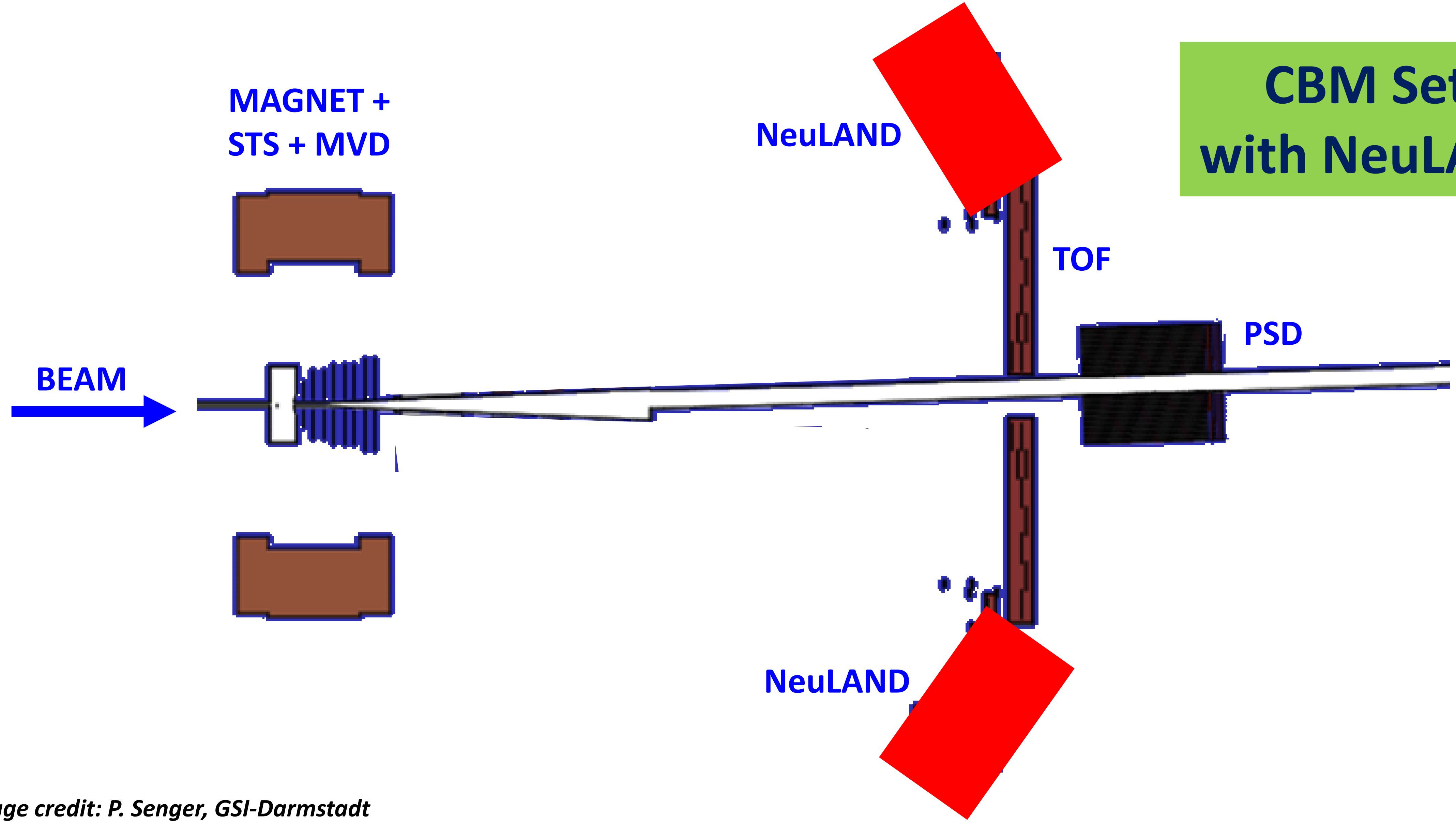
V. Klochkov, PhD Thesis – Uni. Frankfurt (2019)
O. Golosov et al., Quark Matter (2019)
O. Golosov et al., 34th CBM Collaboration Meeting (2019)

NUCLEAR SYMMETRY ENERGY AT HIGHER DENSITIES ($\rho \geq 2\rho_0$)



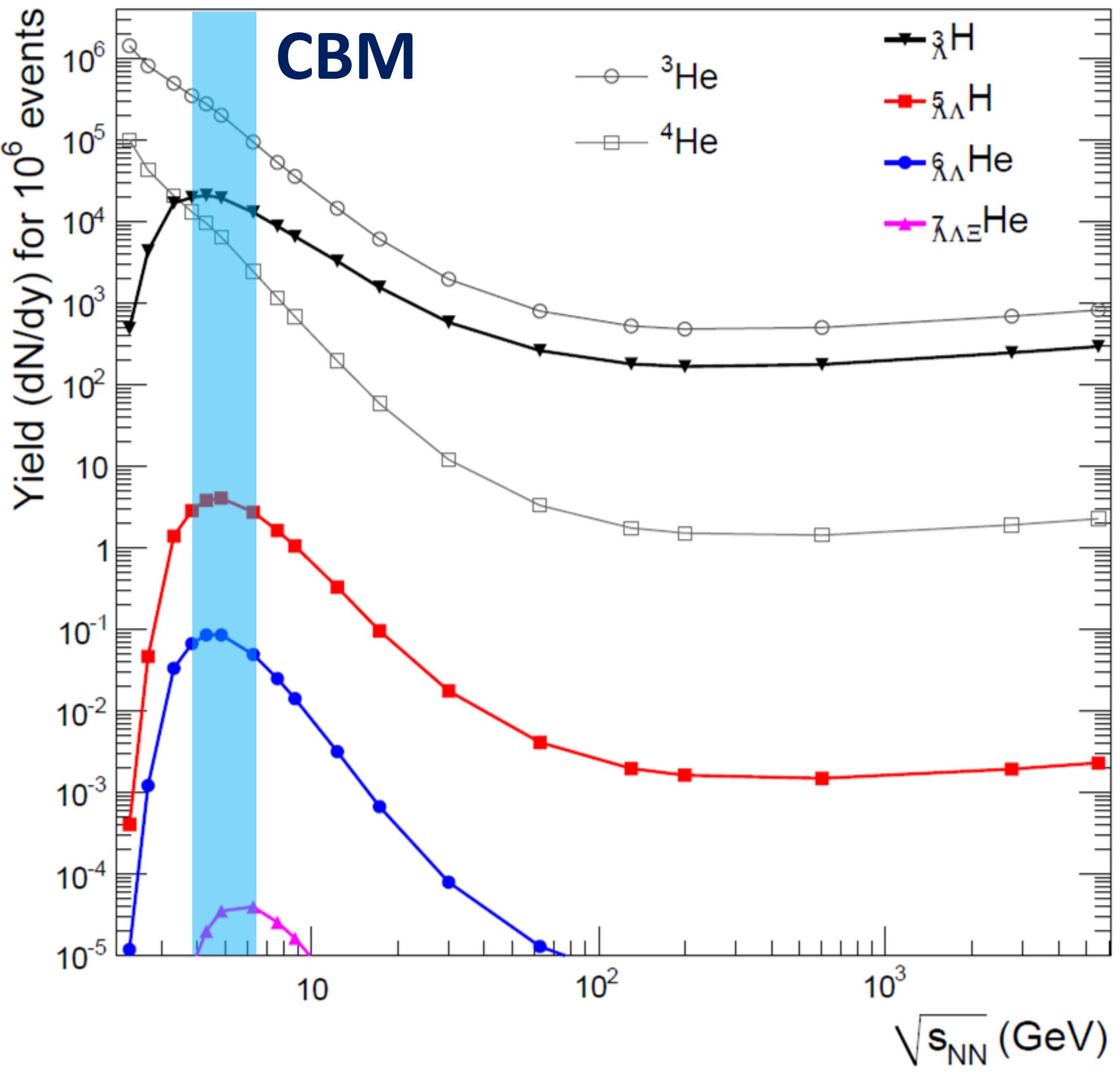
Current CBM Setup
(No neutron detection)

NUCLEAR SYMMETRY ENERGY AT HIGHER DENSITIES ($\rho \geq 2\rho_0$)



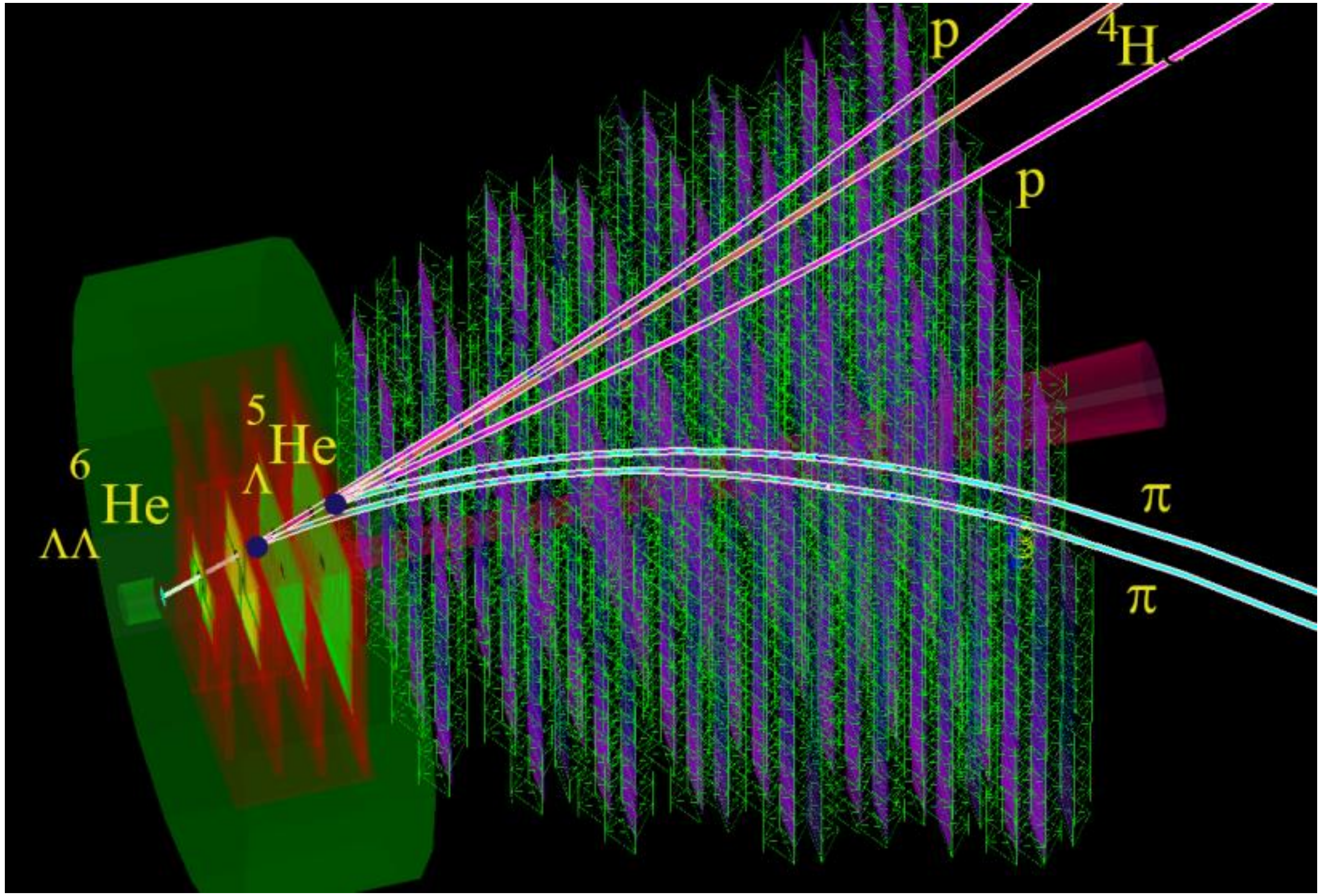
CBM Setup with NeuLAND ?

Image credit: P. Senger, GSI-Darmstadt



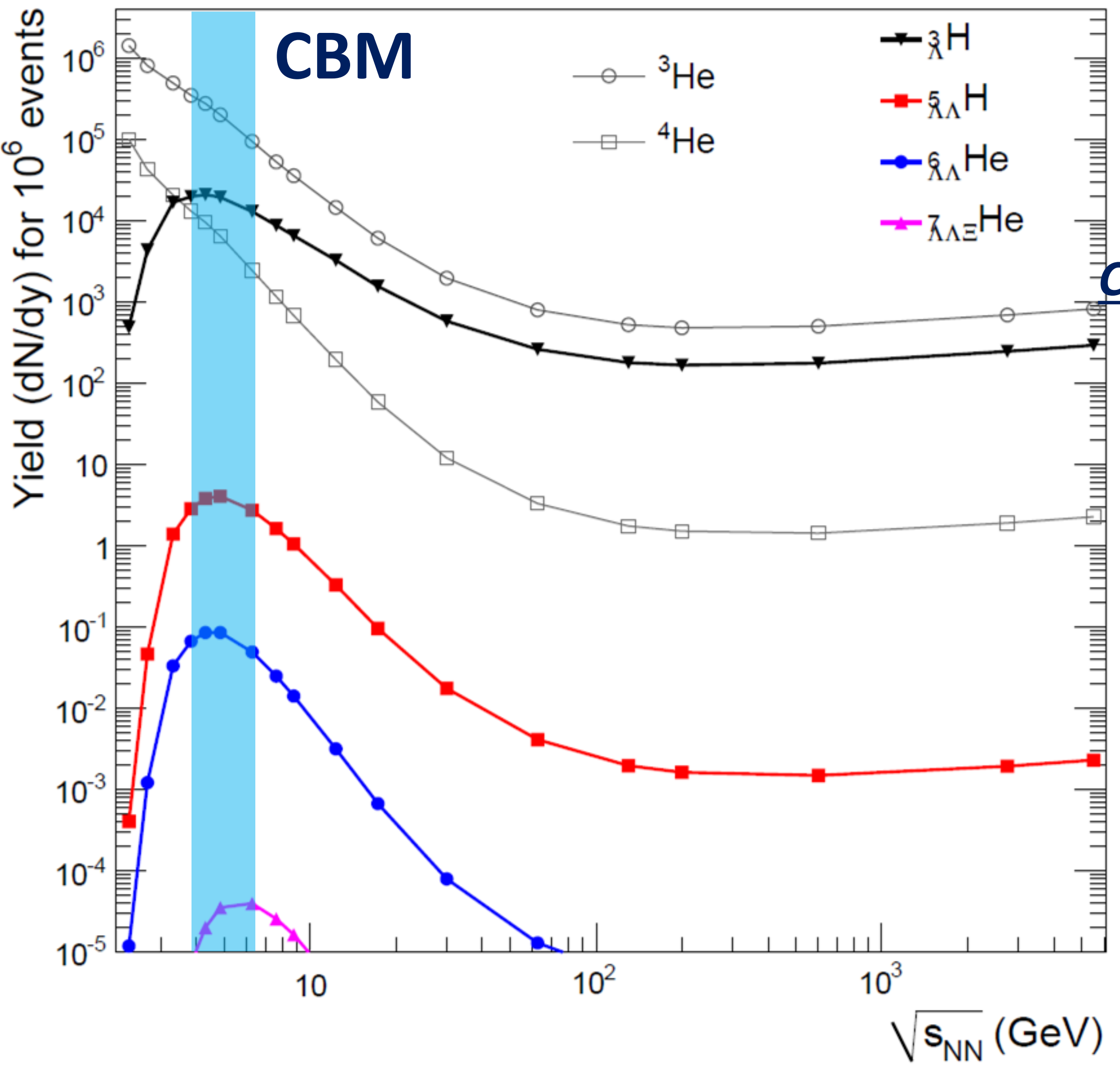
Thermal Model: A. Andronic et al., Phys. Lett. B697 (2011) 203

$^{6}_{\Lambda\Lambda}$He Decay Topology reconstructed in CBM



I. Vassiliev, Quark Matter (2018)

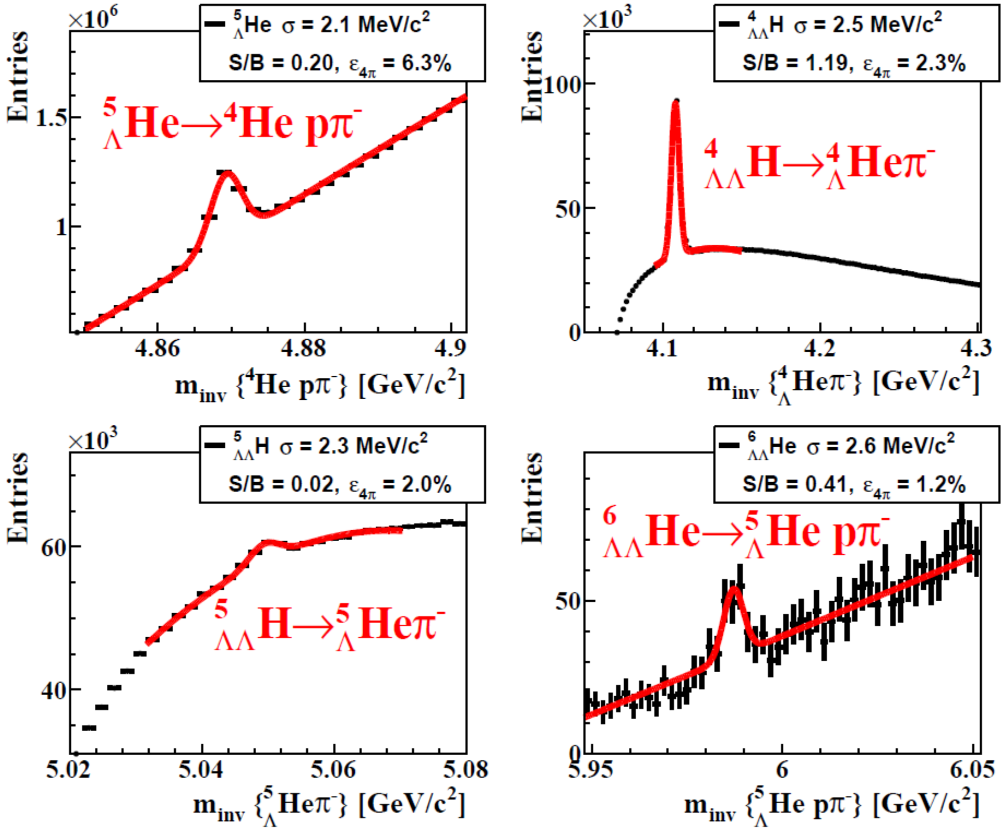
Understanding Λ-N, Λ-Λ Interactions With CBM



Thermal Model: A. Andronic et al., Phys. Lett. B697 (2011) 203

	Multiplicity	Yield 1 week	Int. Rate	Branching Ratio, Efficiency
$_{\Lambda\Lambda}{}^5$H	$5 \cdot 10^{-6}$	3000	1 MHz	10%, 1%
$_{\Lambda\Lambda}{}^6$He	$1 \cdot 10^{-7}$	60	1 MHz	10%, 1%

CBM Performance using UrQMD Au+Au collisions 10 AGeV (b=0)



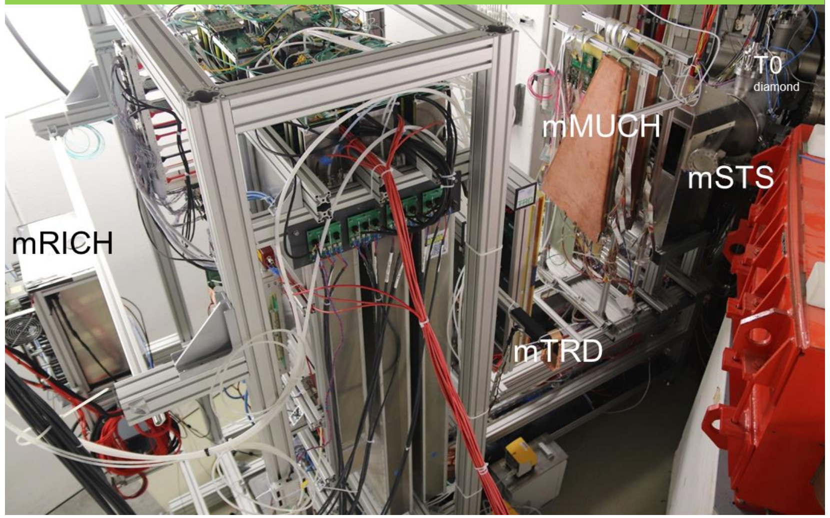
FAIR Phase 0 – Avoiding Risks And Spectacular Failures...

"However, we can save 3% and 3 months of work by skipping soil tests!"

FAIR Phase 0 Research Program

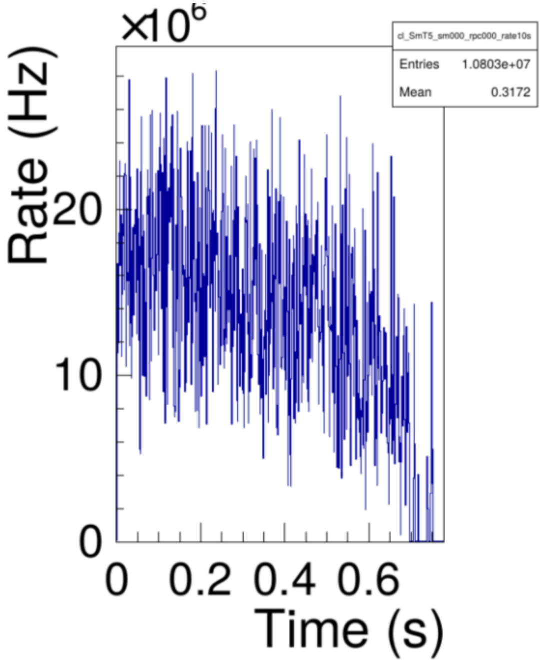
mCBM @ SIS18

mCBM @SIS18

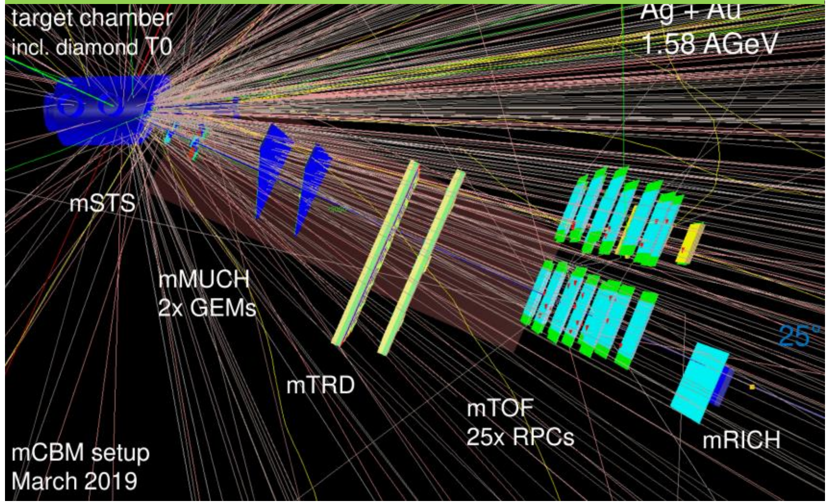


mCBM – Test-setup at SIS18 at 10 MHz

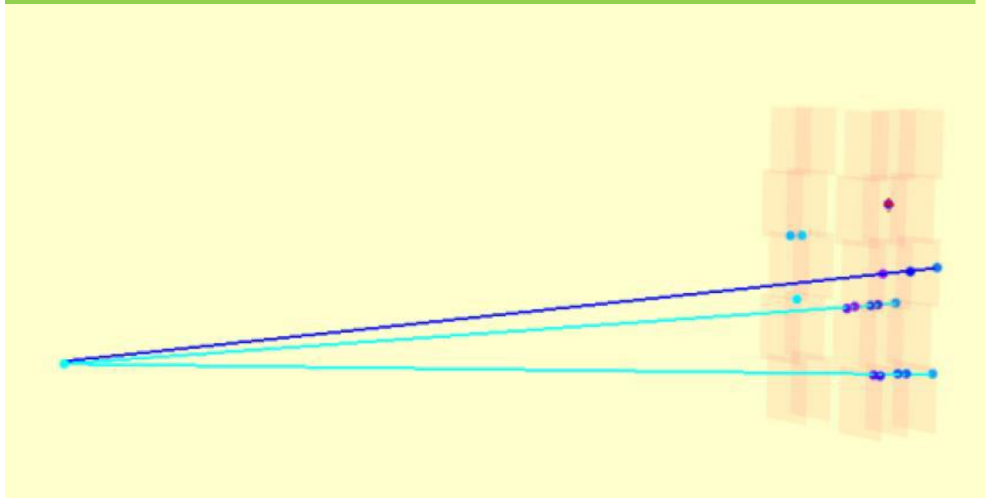
- Free streaming read-out and data transport to the mFLES
- Online reconstruction
- Offline data analysis
- Controls
- Detector tests of final detector prototypes



UrQMD sim. – Ag+Au 1.58 AGeV



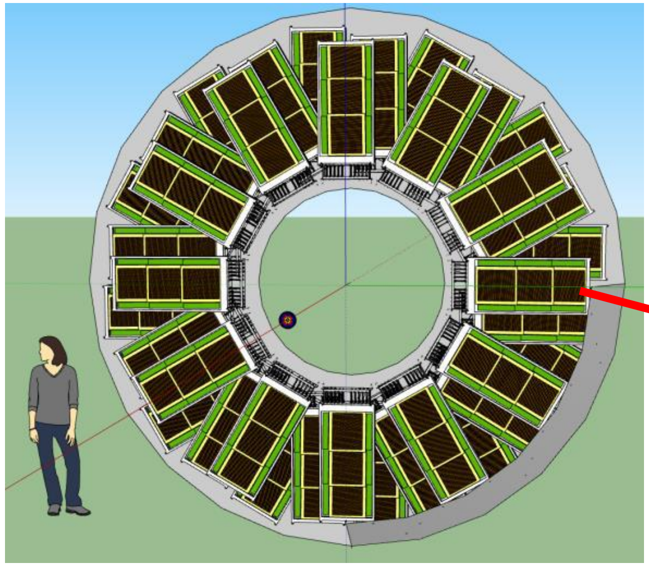
mToF Event Display

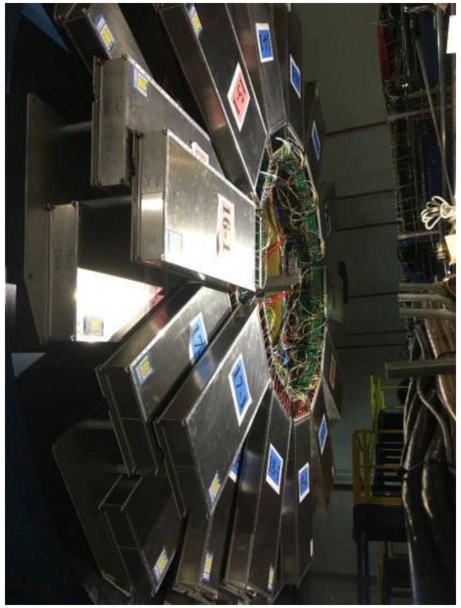


Beam Rate - $R(T_0)$ 2 x 10^7Hz
With Target Thickness P_{int} = 10 %
So, Interaction Rate R_{int} = 2 x 10^6Hz

High rate capability of mCBM demonstrated at 2 MHz!

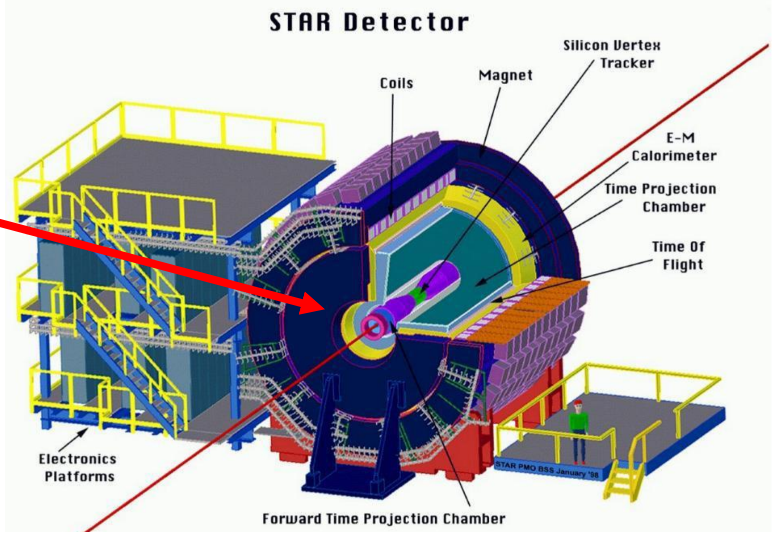
eTOF @ STAR-BNL

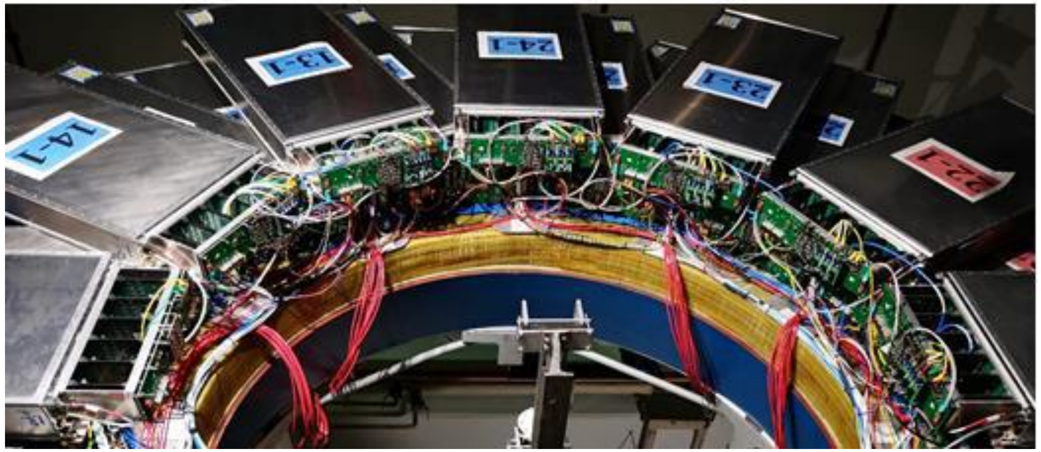




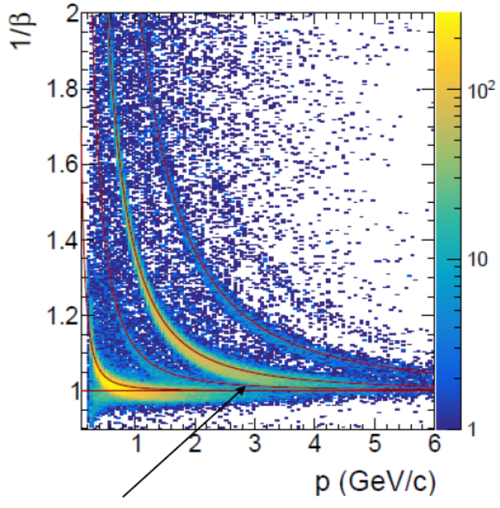
Successfully Installed and Operational

36 modules, 108 MRPCs, ~7000 channels



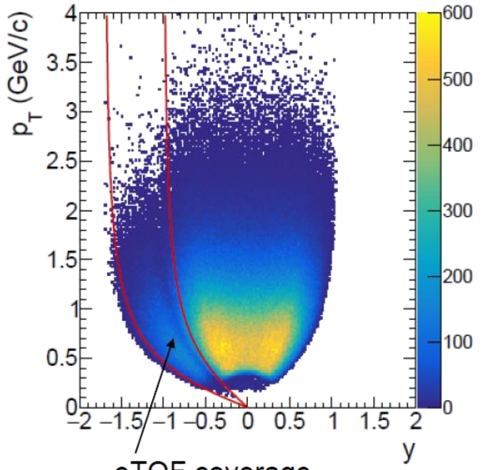


PID capability



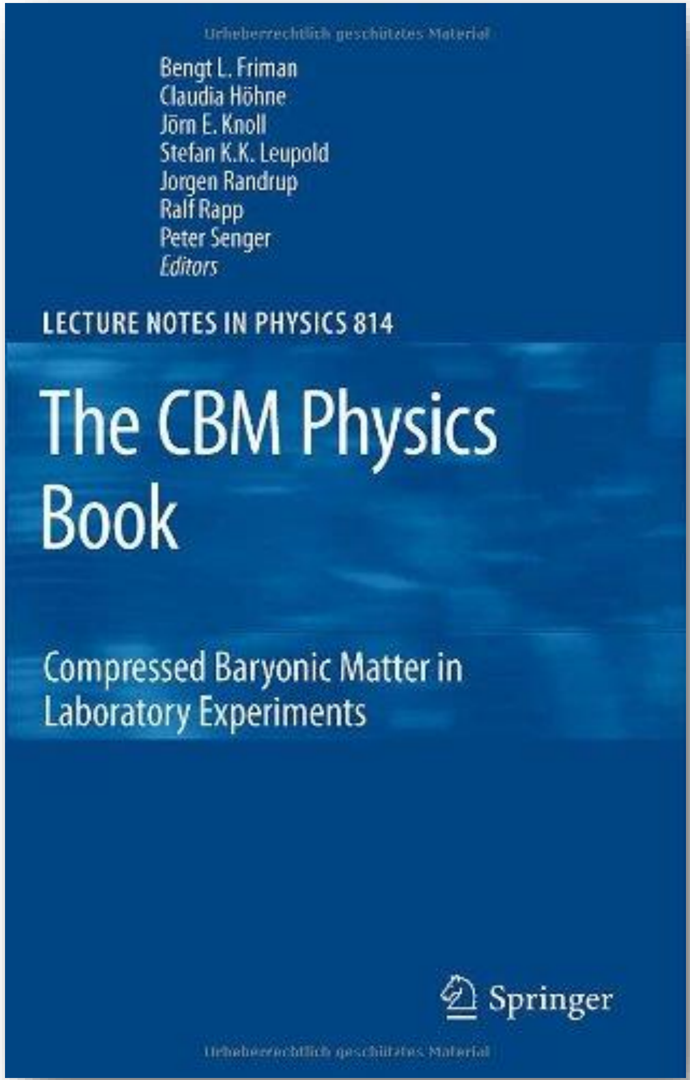
p/π separation up to 3 GeV/c

Phase space distribution



eTOF coverage - extension in p_T and y

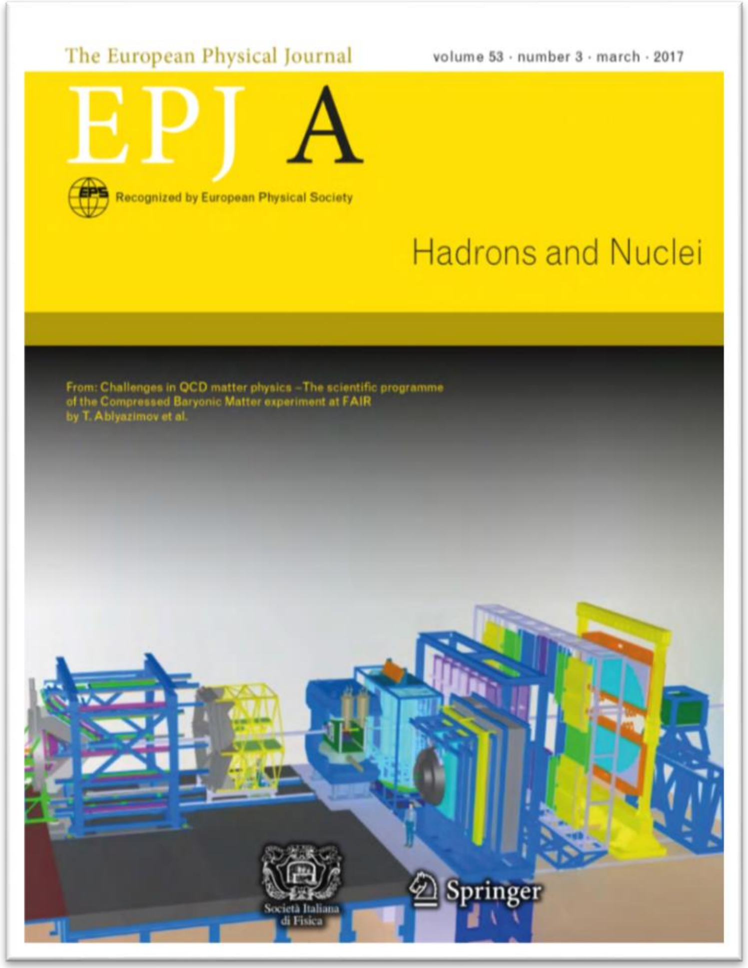
More Literature ???



The CBM Physics Book

Foreword by Frank Wilczek

Springer Series:
Lecture Notes in Physics, Vol. 814
1st Edition., 2011, 960 p., Hardcover
ISBN: 978-3-642-13292-6



Electronic Authors version:
http://www.gsi.de/documents/DOC-2009-Sep-120-1.pdf

“Challenges in QCD Matter Physics – the scientific programme of the Compressed Baryonic Matter Experiment at FAIR”

T. Ablyazimov et al. [CBM Collaboration] Eur. Phys. J. A (2017)

Summary

CBM@FAIR (2 – 11 AGeV Au-Au) provides unique conditions in lab to probe QCD matter properties at neutron star core densities, including the high density EOS, and the search for new phases expected for densities above $5\rho_0$

Nuclear Symmetric Matter EOS:

- Collective flow of Baryons (π, K, p, Λ, Ξ, Ω,...) driven by the fireball's pressure gradient
- Sub-Threshold Particle Production of Multi-Strange Hyperons via multi-step processes

Neutron Matter EOS:

Symmetry Energy:

- Neutron/Proton Elliptic Flow → Possible to upgrade with NewLAND
- Sub-Threshold Particle Production of isospin-opposite particles ($I_3 = \pm 1$) ?

Hyperon Puzzle (ΛN, ΛNN, and ΛΛN interactions)

- Hypernuclei production, yields, lifetime, collective flow
- Correlation functions to study interaction cross-sections by using CATS

Summary

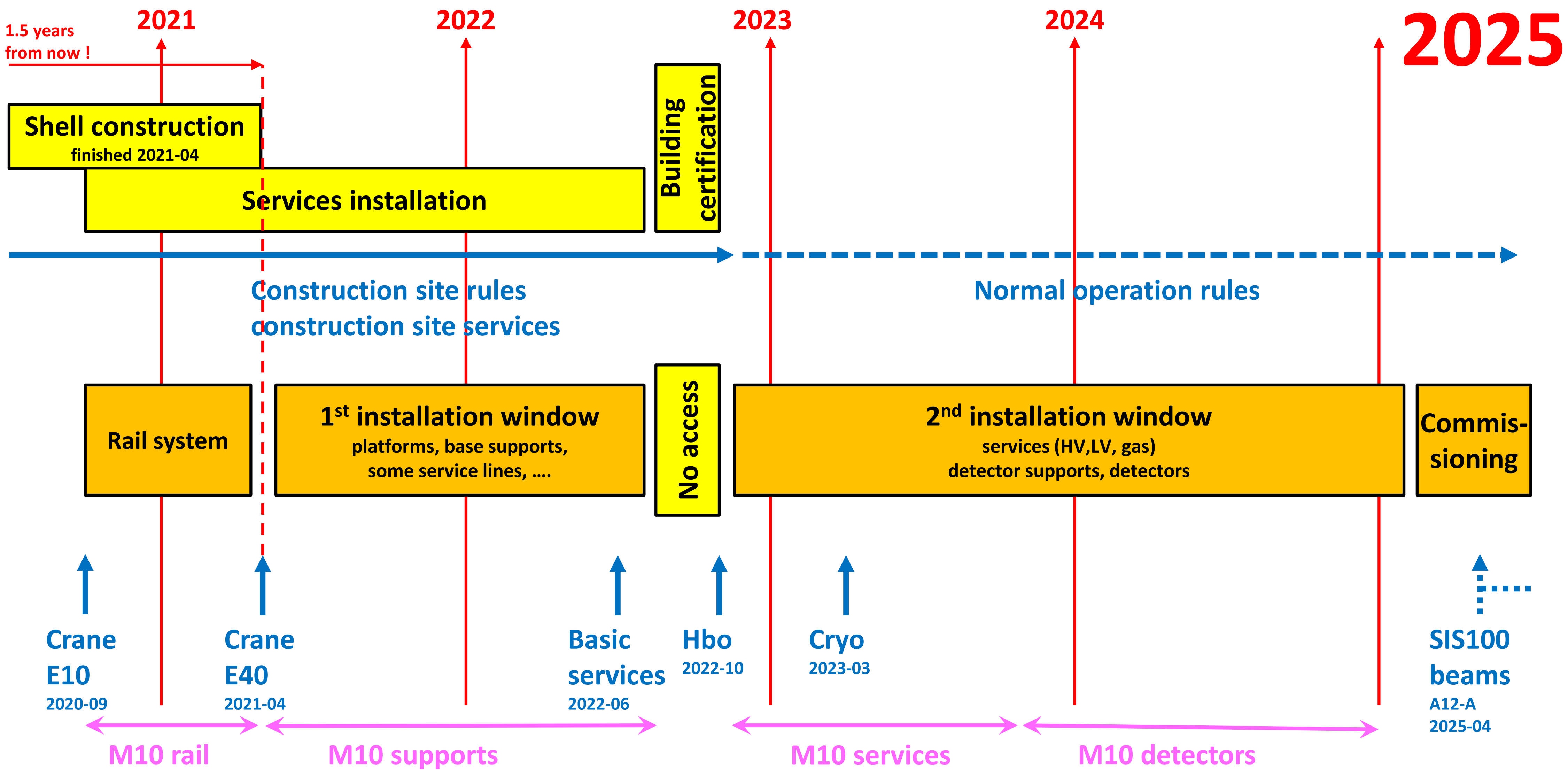
Experimental Requirements

- Unique measurements of bulk & rare probes with CBM
- High-rate capability of detectors and triggerless DAQ
- Online event reconstruction and selection

Testing CBM components and analysis methods within FAIR Phase-0

- mCBM campaign ongoing → great learning experience and proof-of-principle for DAQ
- eTOF @ BES-II sucessfully installed
- KF Particle Finder successfully used in BES-II particle reconstruction

OUTLOOK – HOPEFULLY THE TIMELINES REMAIN 'STIFF'



W.F.J. Müller, Joint FAIR ECE 11 and ECSG 02 meeting (2019)

Almost There…

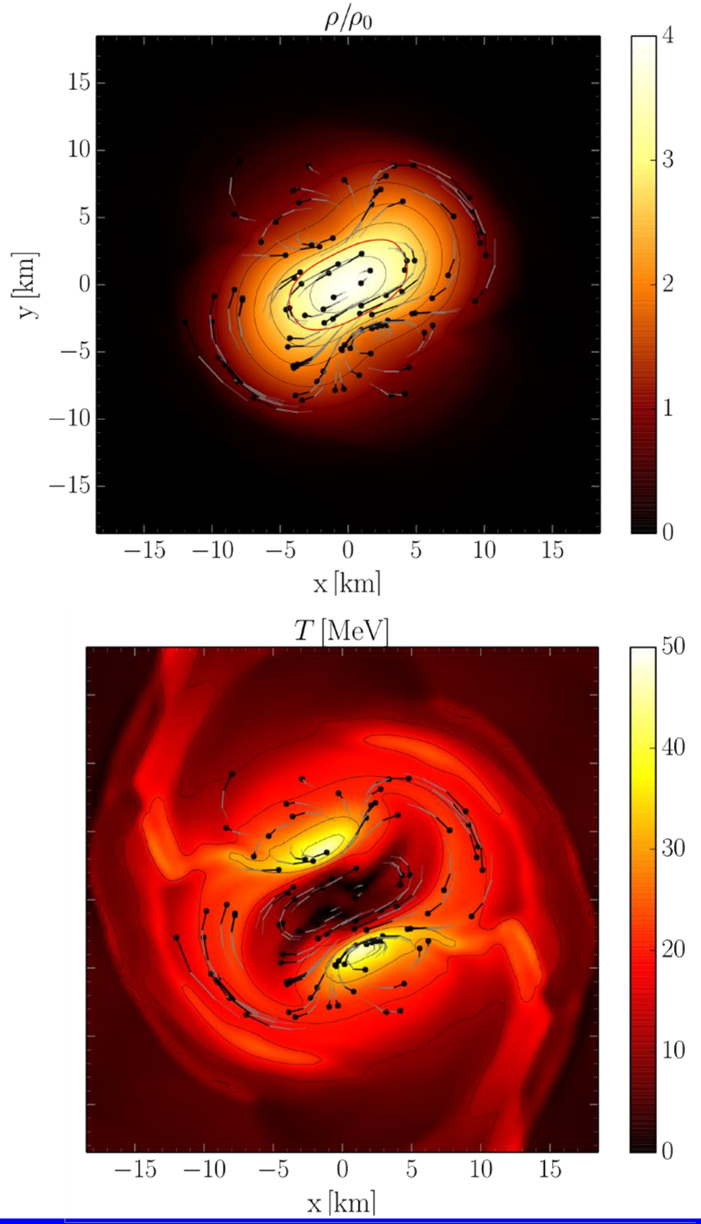
ALMOST THERE…

Almost There…

ALMOST THERE…

Thanks A Lot For Your Attention ☺

Back-Up
Additional Slides



Based on numerical-relativity simulations of merging neutron star binaries, the emitted GW and the interior structure of the generated hyper-massive neutron stars (HMNS) have been analyzed in detail.

Distributions of the rest-mass density ρ in units of ρ0 (top panel) and the temperature (bottom panel) on the equatorial plane at a post-merger time of t = 6.34 ms for the LS220-M132 binary.

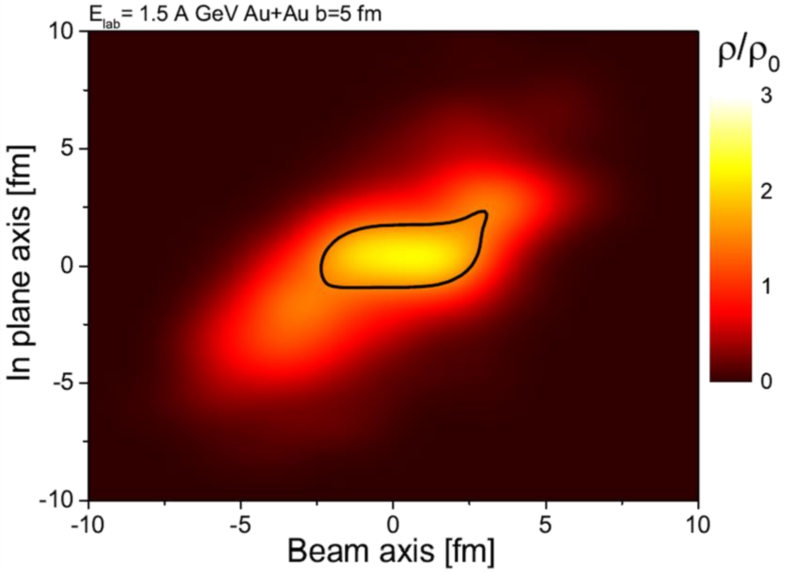
Also shown are portions of the flowlines of several tracer particles that remain close to the (x, y)-plane and for which we show only the final part of the flowlines.

In the top picture, the black iso-contours have been drawn at ρ/ρ0 = 0.5n (n ∈ N), while the red iso-contour indicates ρ = 3 ρ0. The temperature iso-contours (right picture) have been drawn at T = 10n MeV

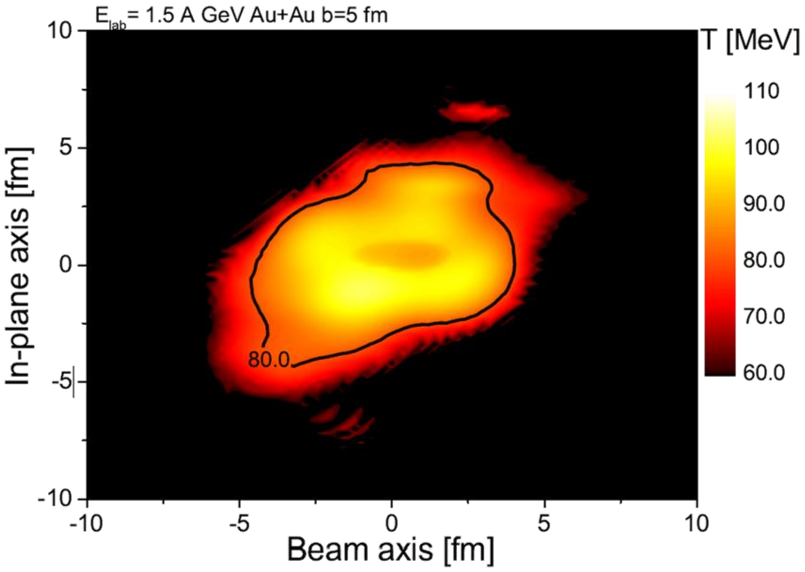
M. Hanauske et al., 2017 J. Phys.: Conf. Ser. 878 012031

Heavy Ion Collisions ↔ Astrophysical Events & Objects

1.5 AGeV Au+Au (b = 5 fm, non-central), SIS18 Experiments at GSI (Snap-shot of the densities at t = 15fm/c → partially in local equilibrium)

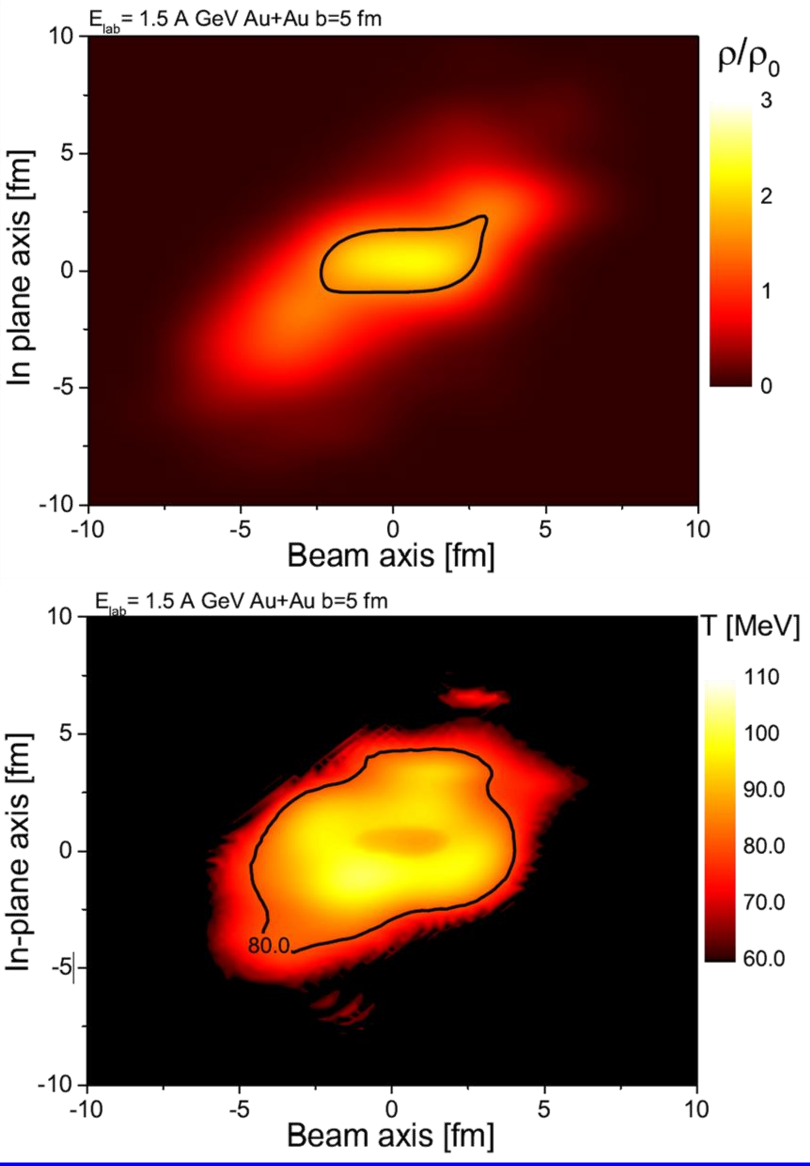


- **The contour where the density exceeds two times nuclear ground state density is highlighted (black dashed line).**
- **The densities where calculated using the UrQMD transport model.**



- **The contour where the density exceeds 80 MeV is highlighted (black dashed line).**
- **The temperature has been calculated from the density and energy density using the QχP model (Quark-Hadron Chiral Parity Doublet Model) for the equation of state**

M. Hanauske et al., 2017 J. Phys.: Conf. Ser. 878 012031



1.5 AGeV Au+Au (b = 5 fm, non-central), SIS18 Experiments at GSI (Snap-shot of the densities at t = 15fm/c → partially in local equilibrium)

QχP model: ***In this approach, an explicit mass term for baryons in the Lagrangian is possible, which preserves chiral symmetry. In this model, the signature for chiral symmetry restoration is the degeneracy of the usual baryons and their respective negative-parity partner states***

Taking into account the scalar and vector condensates in mean-field approximation, the resulting Lagrangian $\mathcal{L}_\mathcal{B}$ includes [27]

$$\mathcal{L}_\mathcal{B} = \sum_i (\bar{B}_i i \partial\!\!\!/ B_i) + \sum_i \left(\bar{B}_i m_i^* B_i\right) + \sum_i \left(\bar{B}_i \gamma_\mu (g_{\omega i}\omega^\mu + g_{\rho i}\rho^\mu + g_{\phi i}\phi^\mu) B_i\right) , \quad (6)$$

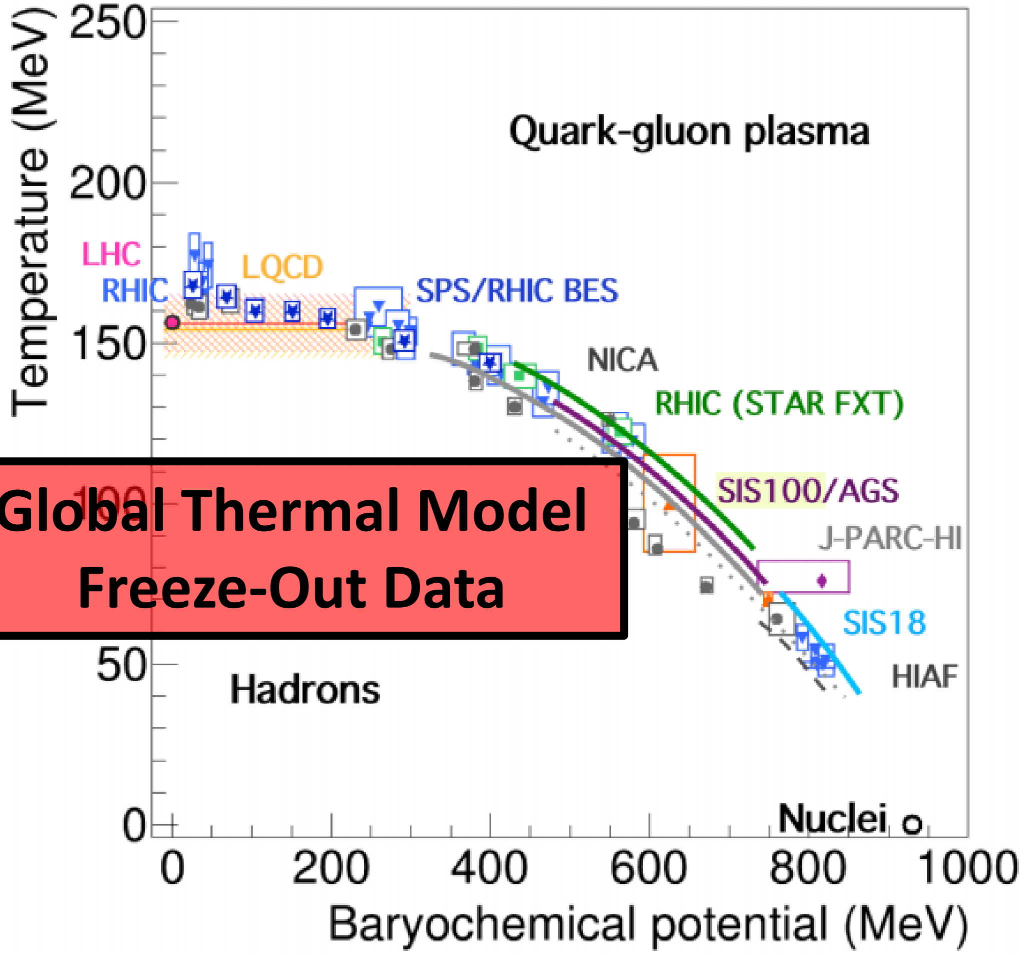
summing over the states of the baryon octet. Furthermore the scalar meson interaction, driving the spontaneous breaking of the chiral symmetry, is expressed in terms of SU(3) invariants $I_2 = (\sigma^2 + \zeta^2)$, $I_4 = -(\sigma^4/2 + \zeta^4)$ and $I_6 = (\sigma^6 + 4\zeta^6)$ as:

$$V = V_0 + \frac{1}{2} k_0 I_2 - k_1 I_2^2 - k_2 I_4 + k_6 I_6 , \quad (7)$$

where V_0 is fixed by demanding a vanishing potential in the vacuum. The quark and gluonic degrees of freedom are introduced as done in the PNJL approach [30, 31]. This model uses the Polyakov loop

M. Hanauske et al., 2017 J. Phys.: Conf. Ser. 878 012031

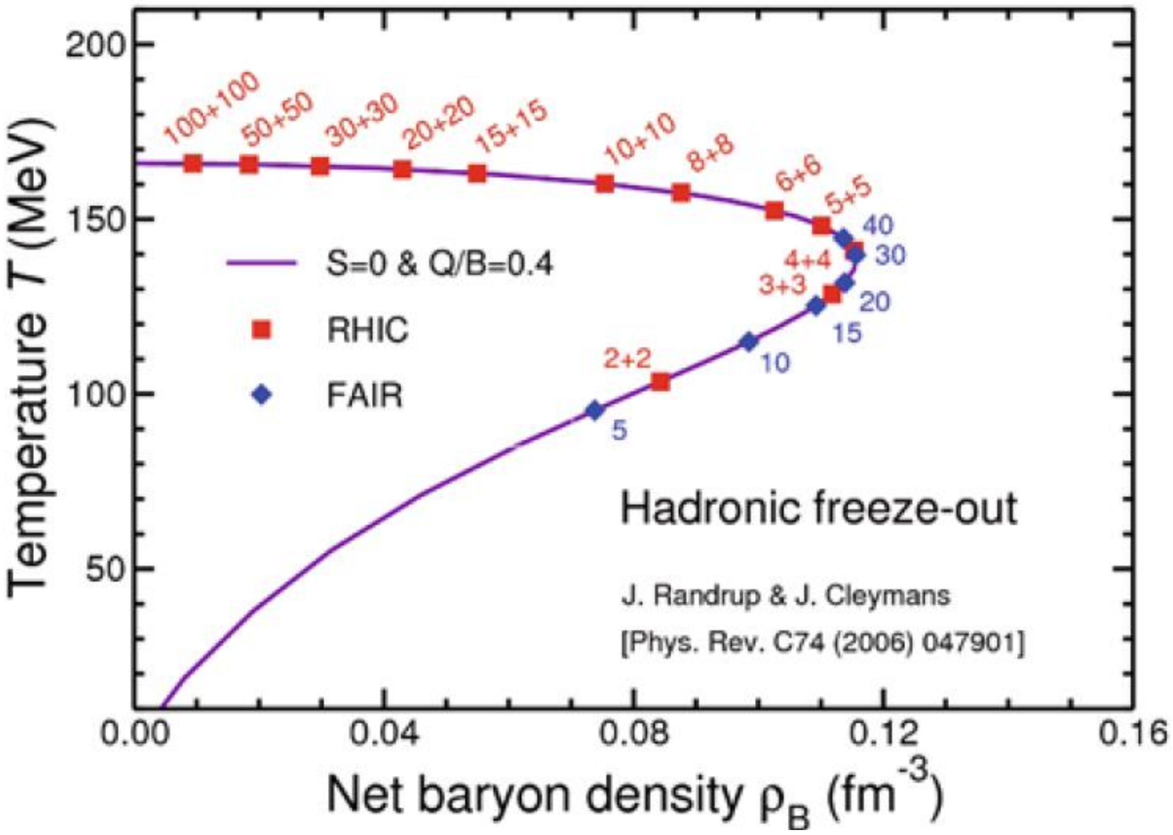
Heavy Ion Collisions ⟷ Astrophysical Events & Objects



Global Thermal Model Freeze-Out Data

Plot: T. Galatyuk

Becattini et al., Phys. Lett. B ***764*** *(2017) 241*
STAR, Phys. Review C ***96*** *(2017) 044904*
Andronic et al., arXiv:1710.09425 and refs. therein



Hadronic Freeze-Out Line comparison RHIC v/s FAIR (Au-Au in AGeV)

Collision Energies and Systems available at SIS100

Beam	Z	A	E (AGeV)
p	1	1	29
d	1	2	14
Ca	20	40	14
Ni	28	58	13.6
In	49	115	11.9
Au	79	197	11
U	92	238	10.7

$$\frac{E}{A} = \sqrt{\left(0.3 \cdot B \cdot r \cdot \frac{Z}{A}\right)^2 + m^2} - m$$

$B \cdot r$ = Beam Rigidity [T.m]
= 100 T.m for SIS100

m = Mass of nucleon

Essentially the energy available is determined by the bending power of the magnets, quantified as Beam Rigidity (B.r)

$$E_{CM} = \sqrt{s} = \sqrt{{m_1}^2 + {m_2}^2 + 2 \cdot m_2 \cdot E_{proj}}$$

For fixed target experiments,

$$E_{CM} = \sqrt{s} \cong \sqrt{2 \cdot m_2 \cdot E_{proj}}$$

$$\sqrt{s_{NN}} = \frac{\sqrt{s}}{A}$$

Collective flow of nucleons driven by the pressure gradient – Sensitive to nuclear compressibility: EOS

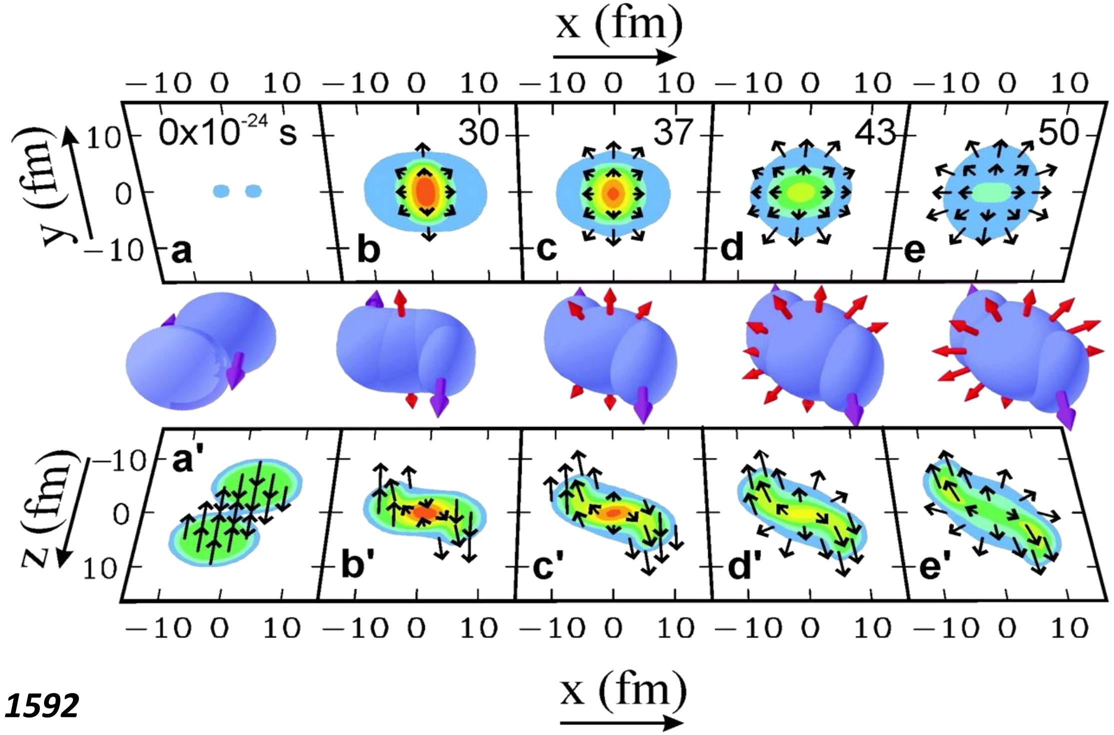
Au-Au 1AGeV

Front Plane

Pressure Contours

Top Plane

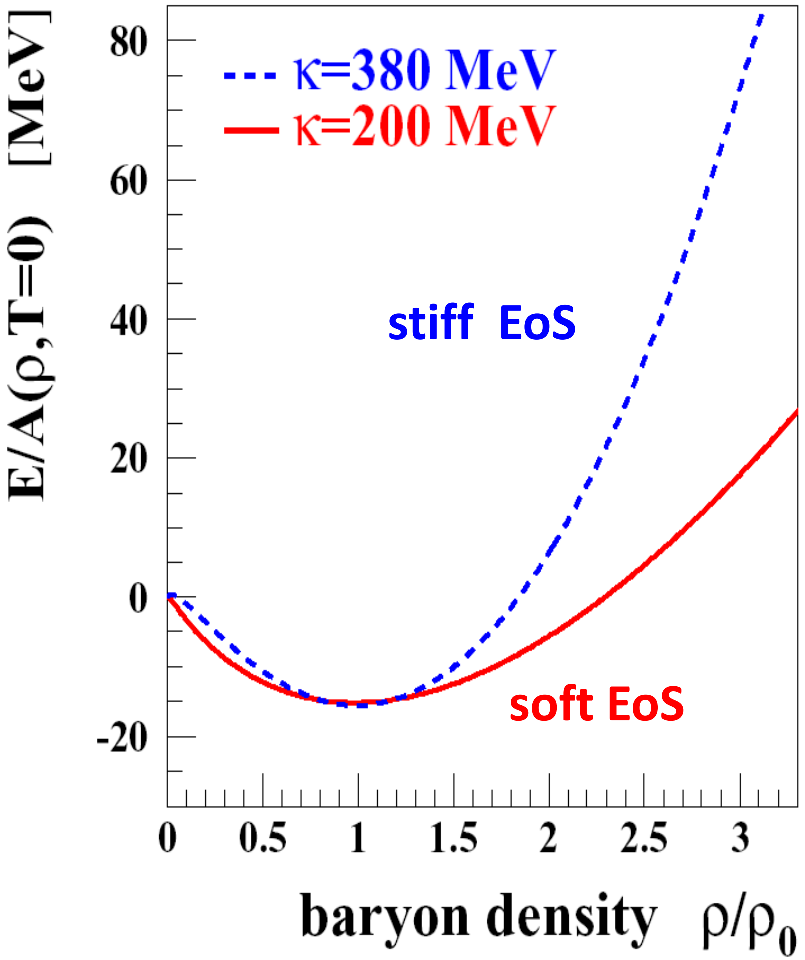
Density Contours



P. Danielewicz et al., Science 298 (2002) 1592

Two observables of the high pressures results in matter to be ejected in specific directions:

- **Directed Flow v_1 Nucleons deflected sideways in the reaction plane**
- **Elliptic Flow v_2 Nucleons are "squeezed out" above and below or "expanded in" the reaction plane**



Nuclear equation-of-state at T = 0 : "compressional" energy

$$E/A\,(\rho, T=0) \;=\; \frac{1}{\rho}\int U\,(\rho)\, d\rho$$

Effective NN-Potential (Skyrme)

$$U\,(\rho) \;=\; \alpha\left(\frac{\rho}{\rho_0}\right) \;+\; \beta\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

	α [MeV]	β [MeV]	γ
κ = 380 MeV	-124	70.5	2
κ = 200 MeV	-356	303	7/6

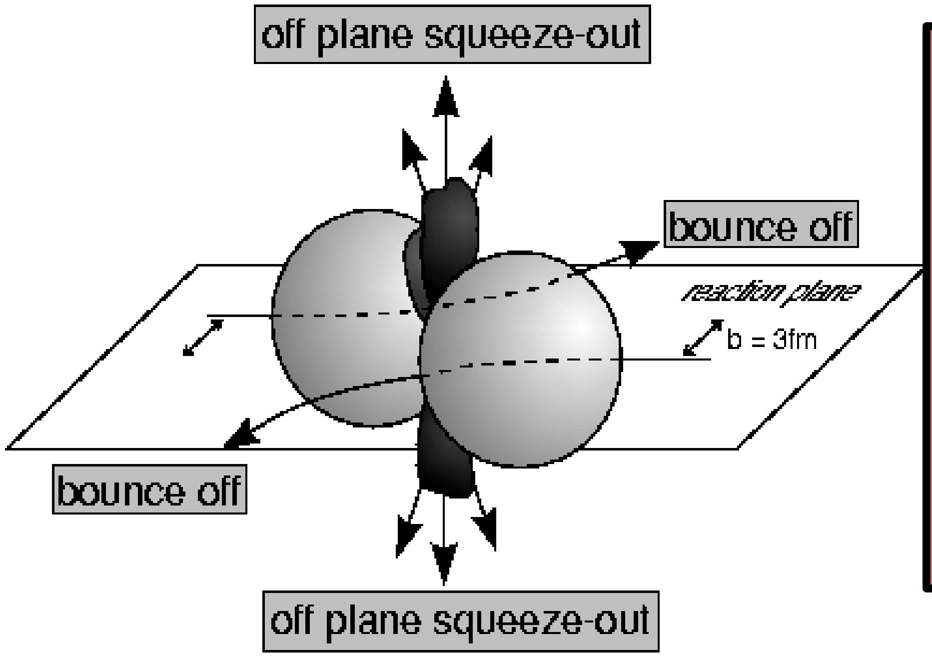
Compression Modulus :

$$\kappa \;=\; \left(9\rho^2\,\frac{\partial^2 E/A(\rho, T=0)}{\partial\rho^2}\right)_{\rho=\rho_0}$$

Image and slide credits: C. Sturm, GSI-Darmstadt

EXPERIMENTAL OBSERVABLES [I] – COLLECTIVE FLOW

**Collective flow of nucleons driven by the pressure gradient –
Sensitive to nuclear compressibility: EOS**

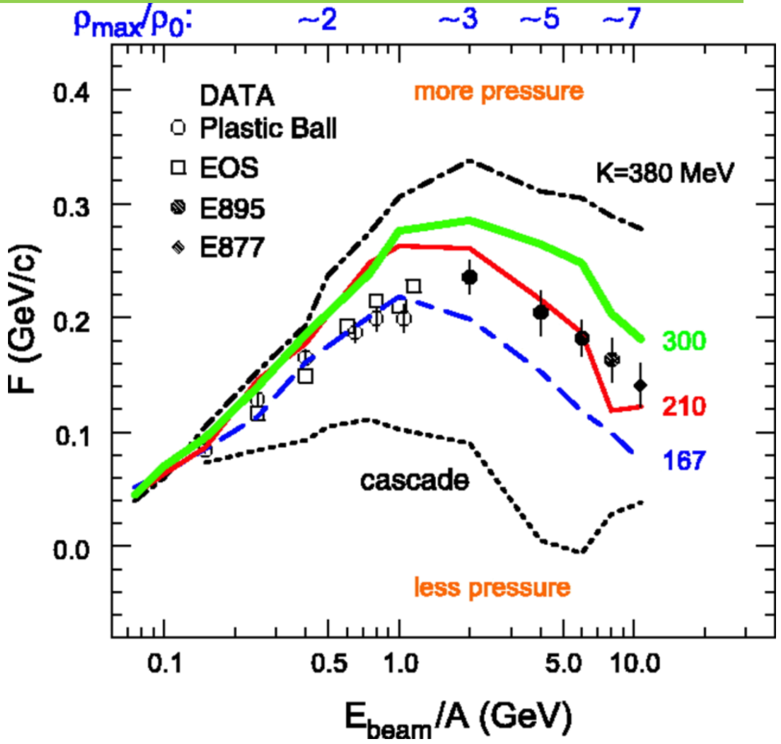


F ≡ Magnitude of sideward deflection

↓

F ∝ Fireball Pressure

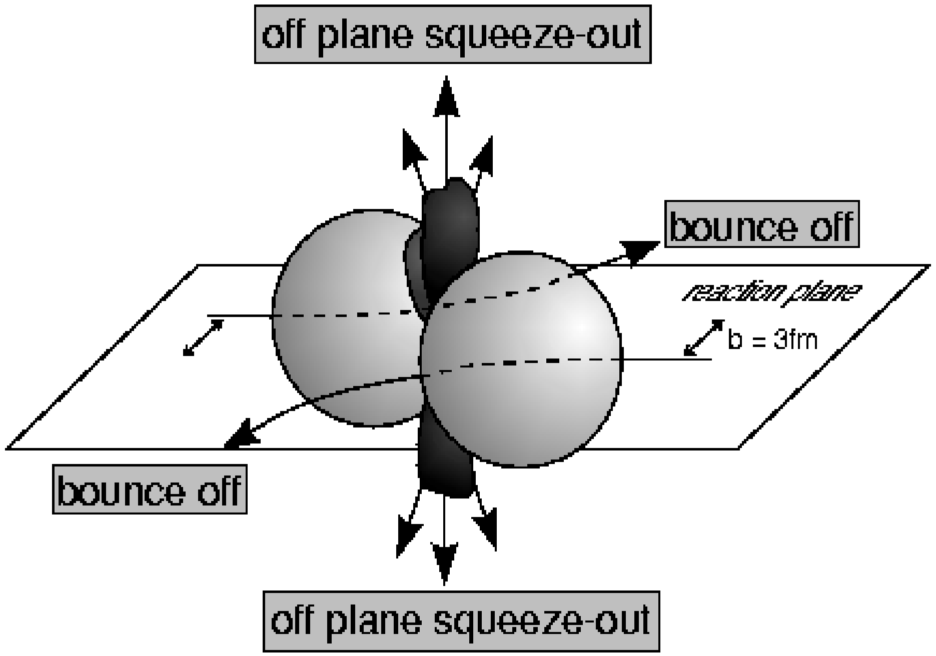
Nuclear Incompressibility,
$\kappa = 170 - 210$ MeV



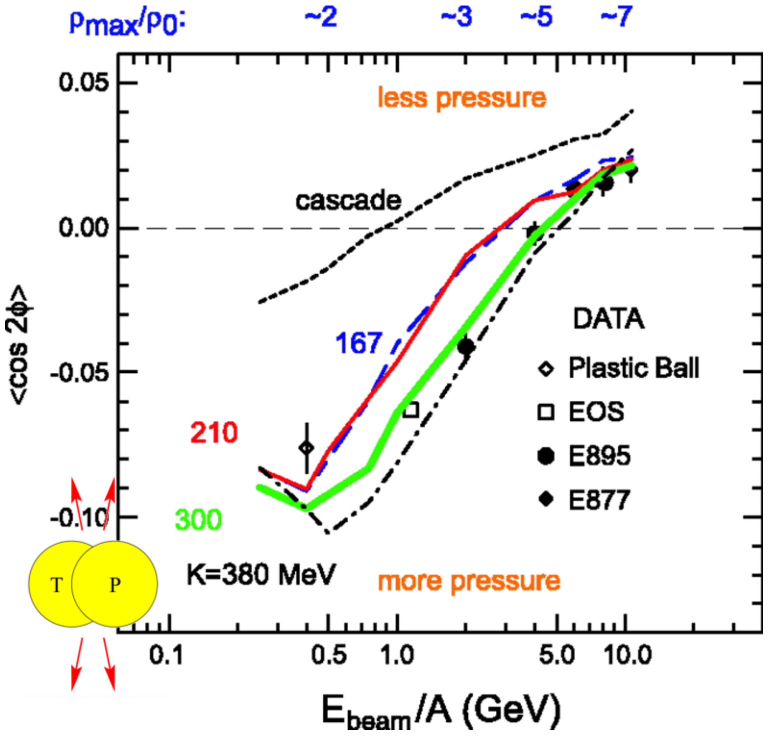
Two observables of the high pressures results in matter to be ejected in specific directions:

- **Directed Flow v_1 Nucleons deflected sideways in the reaction plane**
- **Elliptic Flow v_2 Nucleons are "squeezed out" above and below or "expanded in" the reaction plane**

Collective flow of nucleons driven by the pressure gradient – Sensitive to nuclear compressibility: EOS



Reflects higher pressure of the fireball
↓
[φ = 90°, 270°]
[cos(2φ) = -1]



Two observables of the high pressures results in matter to be ejected in specific directions:

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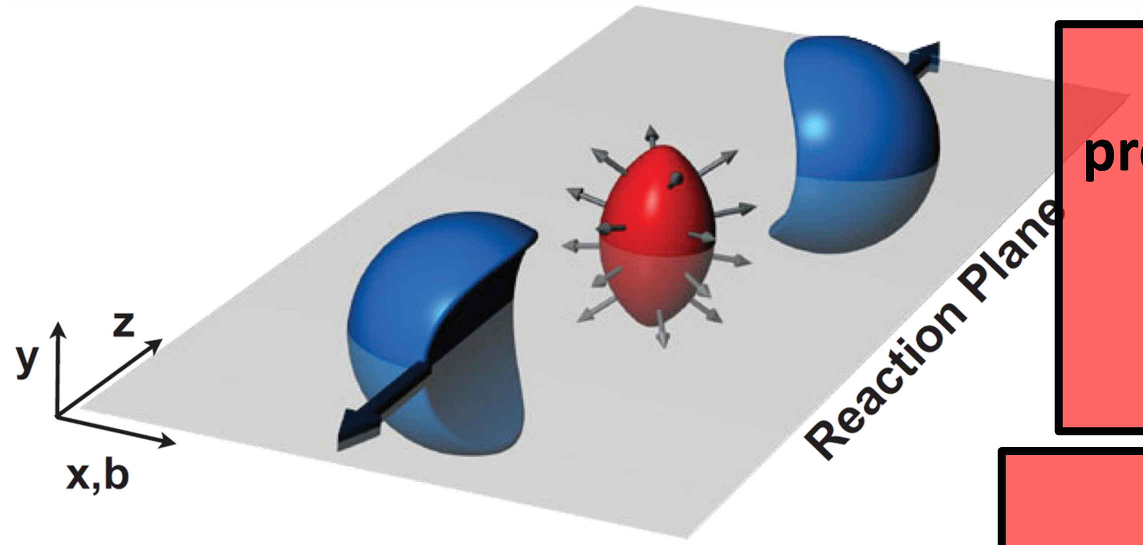
Collective flow of nucleons driven by the pressure gradient – Sensitive to nuclear compressibility: EOS



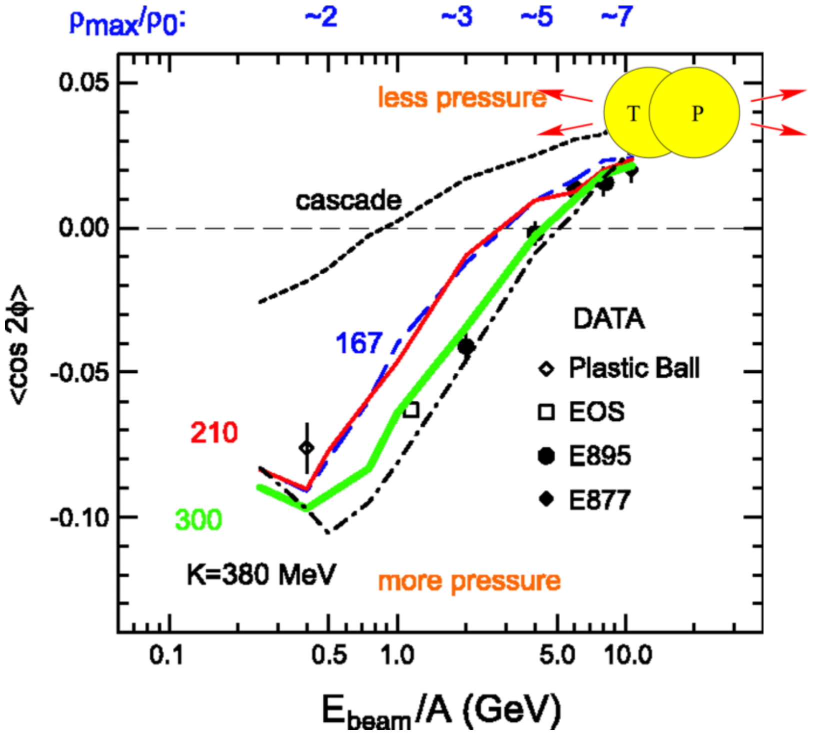
Reflects lower pressure of the fireball

↓

[φ = 0°, 180°]

[cos(2φ) = +1]

Nuclear Incompressibility, $\kappa = 170 - 370$ MeV



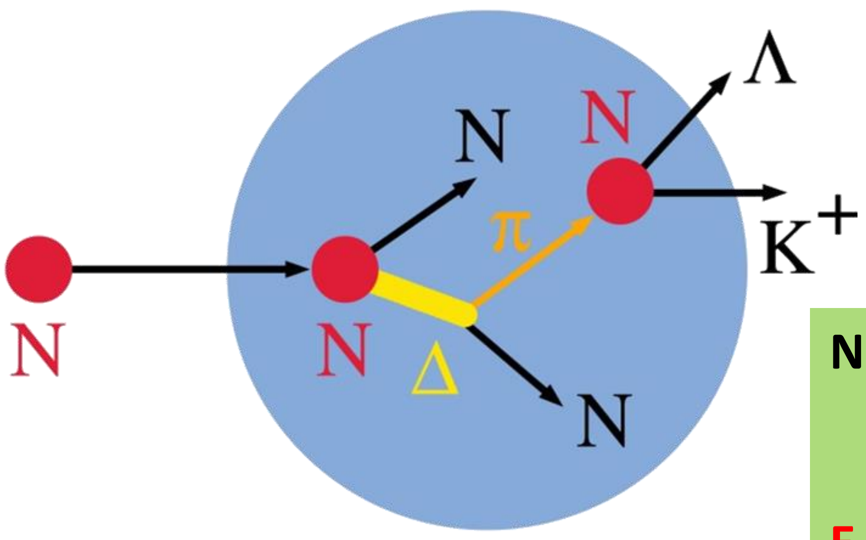
Two observables of the high pressures results in matter to be ejected in specific directions:

- **Directed Flow v_1** **Nucleons deflected sideways in the reaction plane**
- **Elliptic Flow v_2** **Nucleons are "squeezed out" above and below or "expanded in" the reaction plane**

(Sub)Threshold Particle Production – Particles NOT produced in initial head-on collisions, but in multiple low energy collisions → Collisions are enhanced in high-density medium

Strangeness – Kaon yields ($K^+(u\bar{s})$) are particularly sensitive to the medium density [proven at KAOS-GSI]
Long mean-free path length of K^+ (only elastic scattering) & no absorption → Penetrating probe

Idea: Strangeness Yield (K^+) ∝ Baryonic Density ∝ Compressibility ∝ EOS

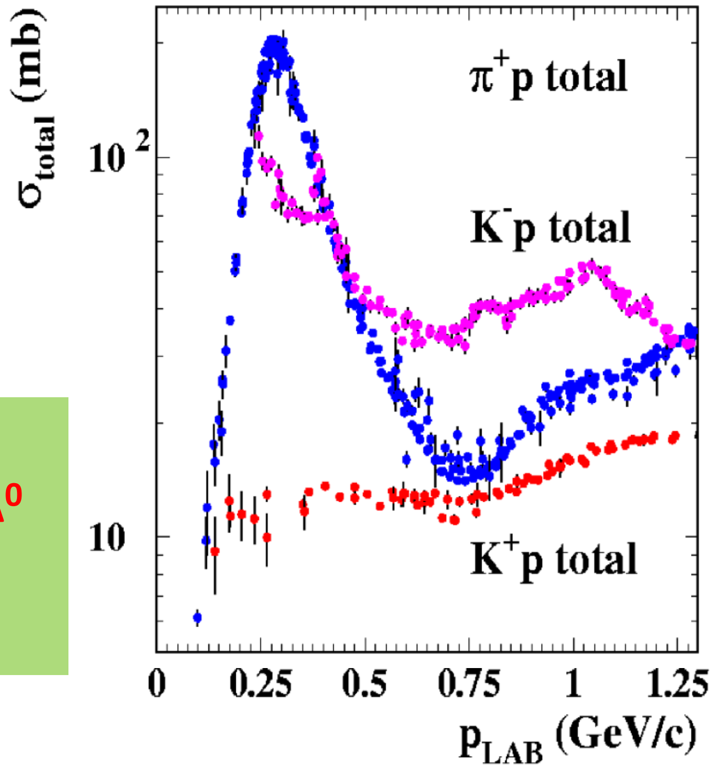


$NN \rightarrow N\Delta$

$N\Delta \rightarrow NK^+\Lambda^0$

$\pi N \rightarrow K^+\Lambda^0$

$E_{threshold} = 1.58$ GeV



Mean Free Path at ρ_0

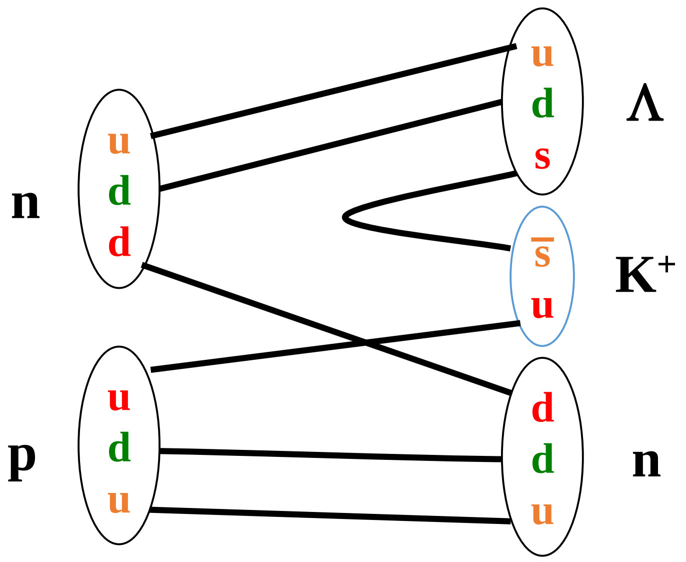
$\lambda_{\pi^+} \cong 0.3\,fm$

$\lambda_{K^+} \cong 5\,fm$

$\lambda_{K^-} \cong 0.8\,fm$

Image credit: (Left) P. Senger, GSI-Darmstadt
(Right) PDG, Phys.Rev D 54, 1 (1996)

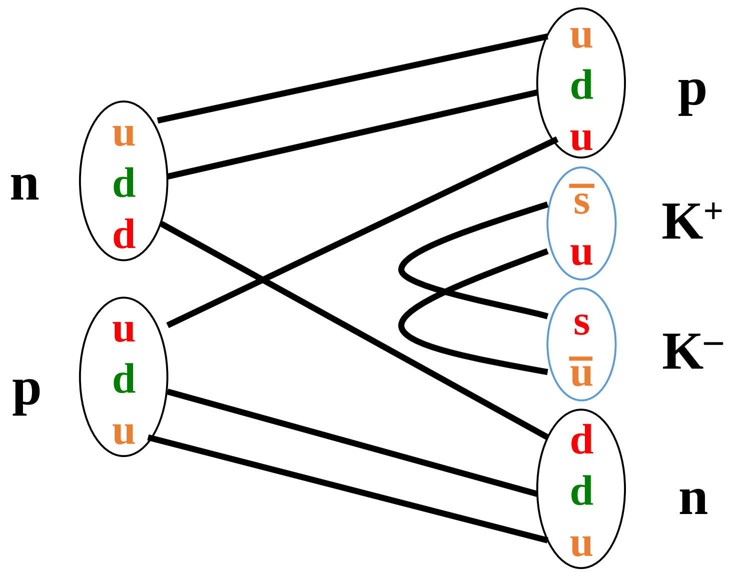
Kaons



production threshold
in NN collisions :

$E_{lab} = 1.58\ GeV$

Antikaons



production threshold
in NN collisions :

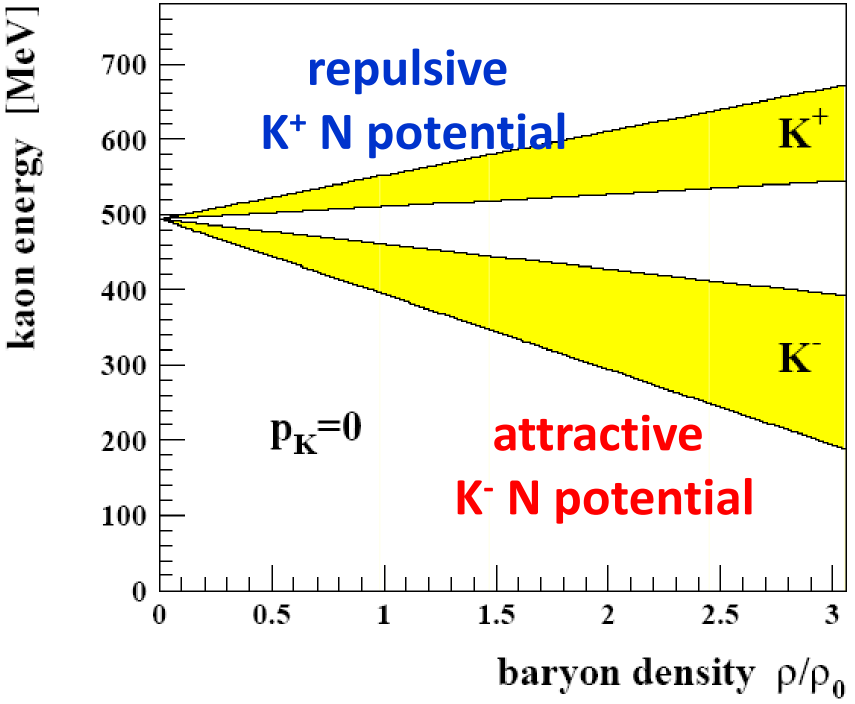
$E_{lab} = 2.5\ GeV$

Associate K^+ production with K^-

Image and slide credits: C. Sturm, GSI-Darmstadt

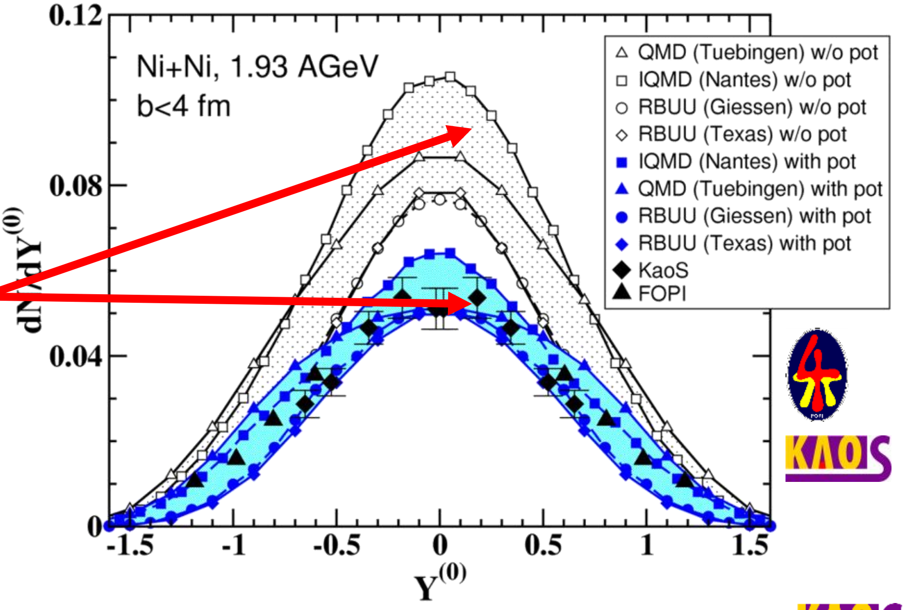
$V_{K+N} = +25 \pm 5\ \rho/\rho_0$ MeV

Envelope of several microscopic calculations: all predict the same trend!



1. Effect on Production → Yield
Reduced K+ yield due to increased in-medium K+ mass

2. Effect on Propagation → Angular Dist.
Preferential out-of-plane flow (squeeze out) for K+ suggests repulsive potentials



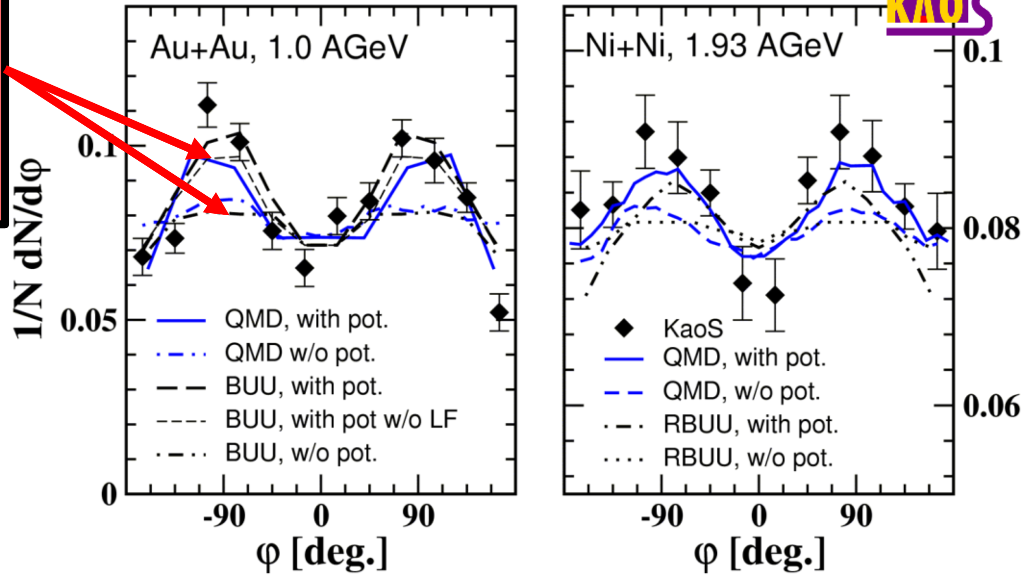


Image and slide credits: C. Sturm, GSI-Darmstadt

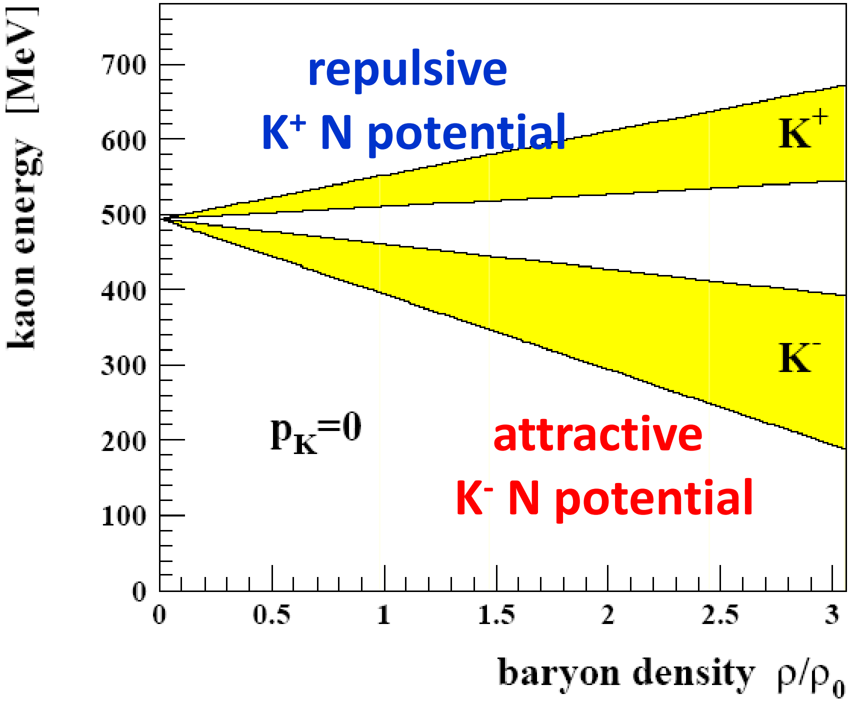
Image credit (Right-Top):
Data: M. Menzel et al., (KaoS Collab.), Phys. Lett. B 495 (2000) 26
K. Wisniewski et al., (FOPI Collab.), Eur. Phys. J A 9 (2000) 515

Image credit (Right-Bottom):
Data: Y. Shin et al., (KaoS Collaboration), Phys. Rev. Lett. 81 (1998) 1576
F. Uhlig et al., (KaoS Collaboration), Phys. Rev. Lett. 95 (2005) 012301
Calculations: A. Larionov, U. Mosel, nucl-th/0504023

Attractive Anti-Kaon (K^-N) Potential

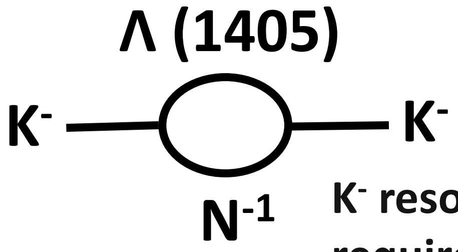
$V_{K\text{-}N} = -80 \pm 20\ \rho/\rho_0$ MeV

Envelope of several microscopic calculations: all predict the same trend!



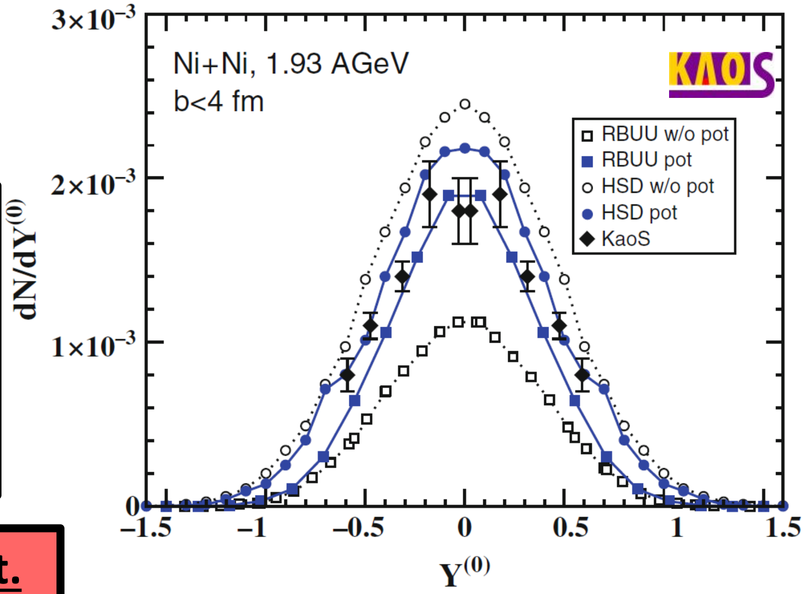
<u>1. Effect on Production → Yield</u>
The results of the calculations depend on the density dependence of the cross section for strangeness exchange which is still a matter of investigations

<u>2. Effect on Propagation → Angular Dist.</u>
Preferential in-plane flow for K- suggests attractive potentials



K^- resonant around threshold and requires non-perturbative approaches

Density dependency and off-shell behavior of the hyperon resonances?



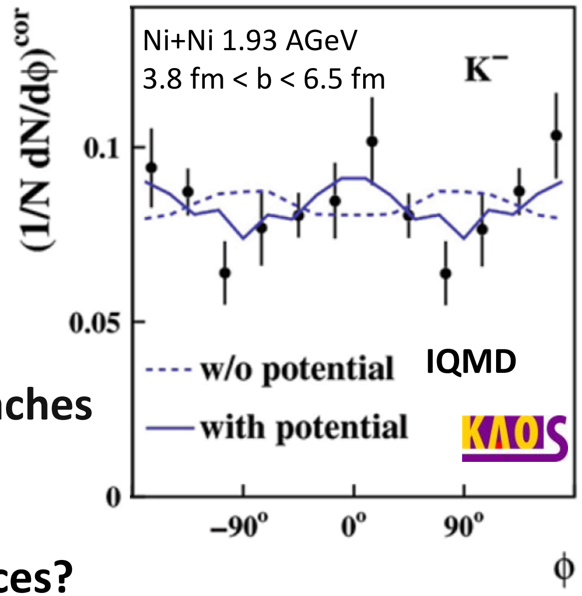
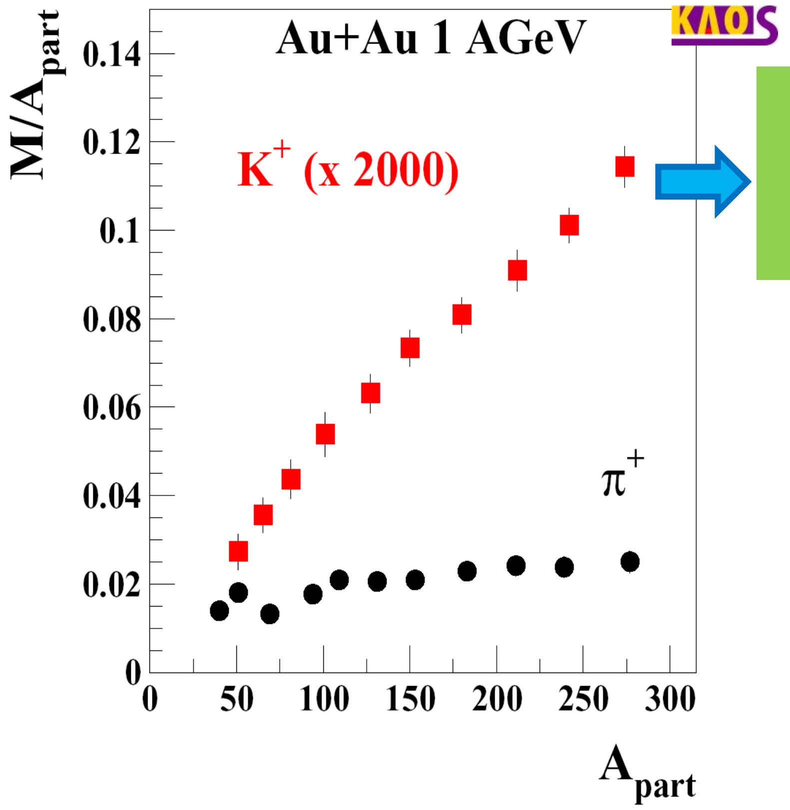


Image and slide credits: C. Sturm, GSI-Darmstadt

Image credit (Right-Top):
Data: M. Menzel et al., (KaoS Collab.), Phys. Lett. B 495 (2000) 26

Image credit (Right-Bottom):
Data: F. Uhlig et al., (KaoS Collaboration), Phys. Rev. Lett. 95 (2005) 012301
Calculations: C. Hartnack, J. Aichelin, J. Phys. G 28, 1649 (2002)

"Subthreshold" K^+ production

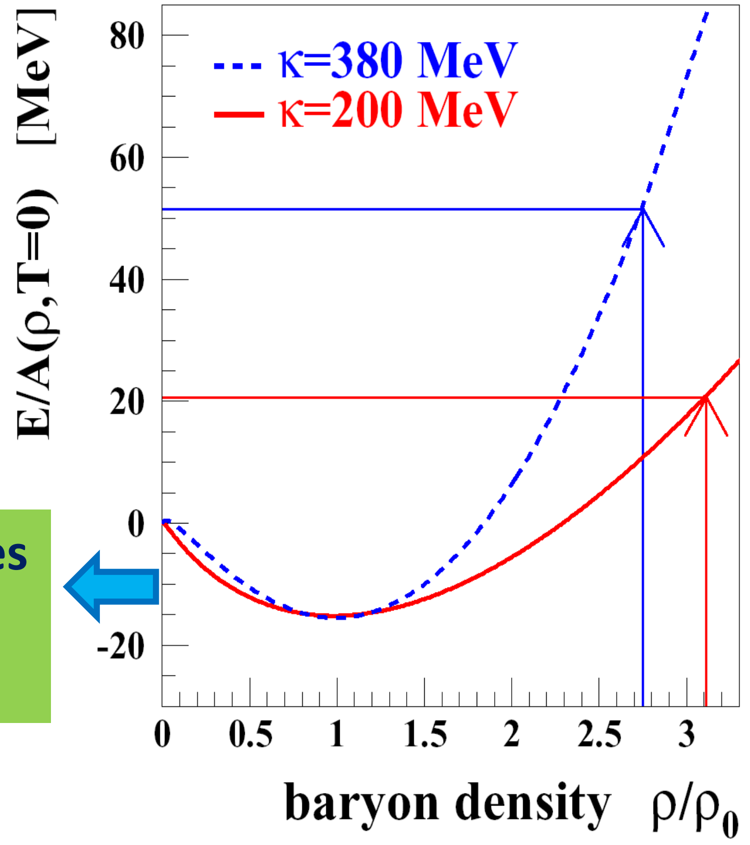


Peripheral Collisions

Central Collisions

"Subthreshold" K^+ mesons predominantly produced by collective effects → multi step processes

Probability of multi step processes increases nonlinearly with the baryon density



M: multiplicity = number / per collision

A_{part} : number of participating nucleons

<u>IQMD:</u> Au+Au 1AGeV

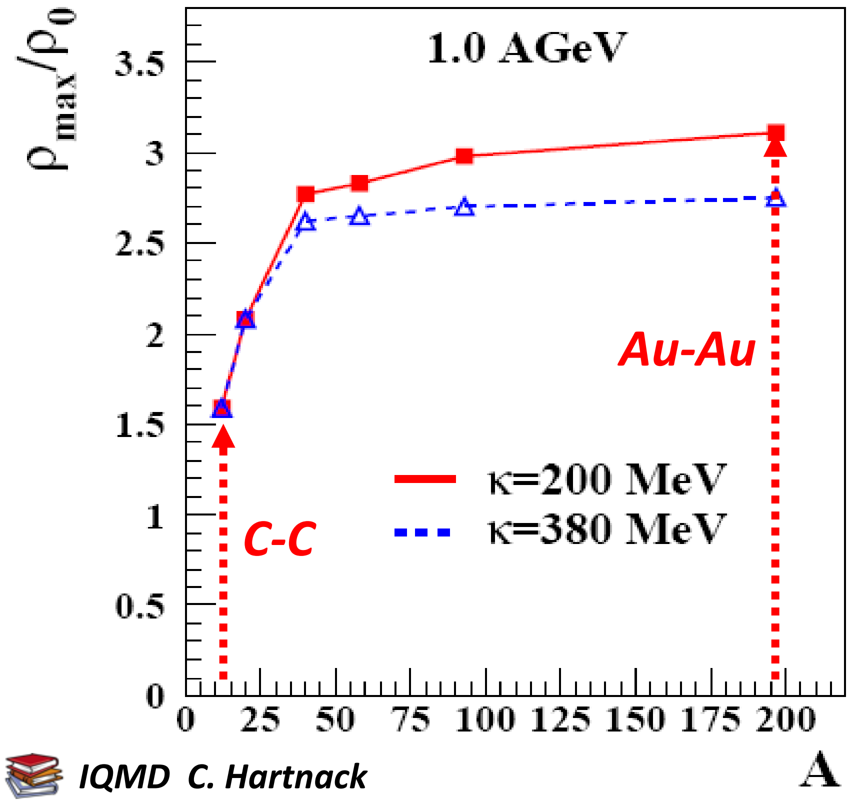
stiff EoS $\rho_{max} / \rho_0 \cong 2.7$

soft EoS $\rho_{max} / \rho_0 \cong 3.1$

Image and slide credits: C. Sturm, GSI-Darmstadt

Idea: Strangeness Yield (K^+) ∝ Baryonic Density ∝ Compressibility ∝ EOS

Experimentally: Measuring K^+ yields in a system where compression is expected (Au-Au) w.r.t. system where no compression is expected (C-C)

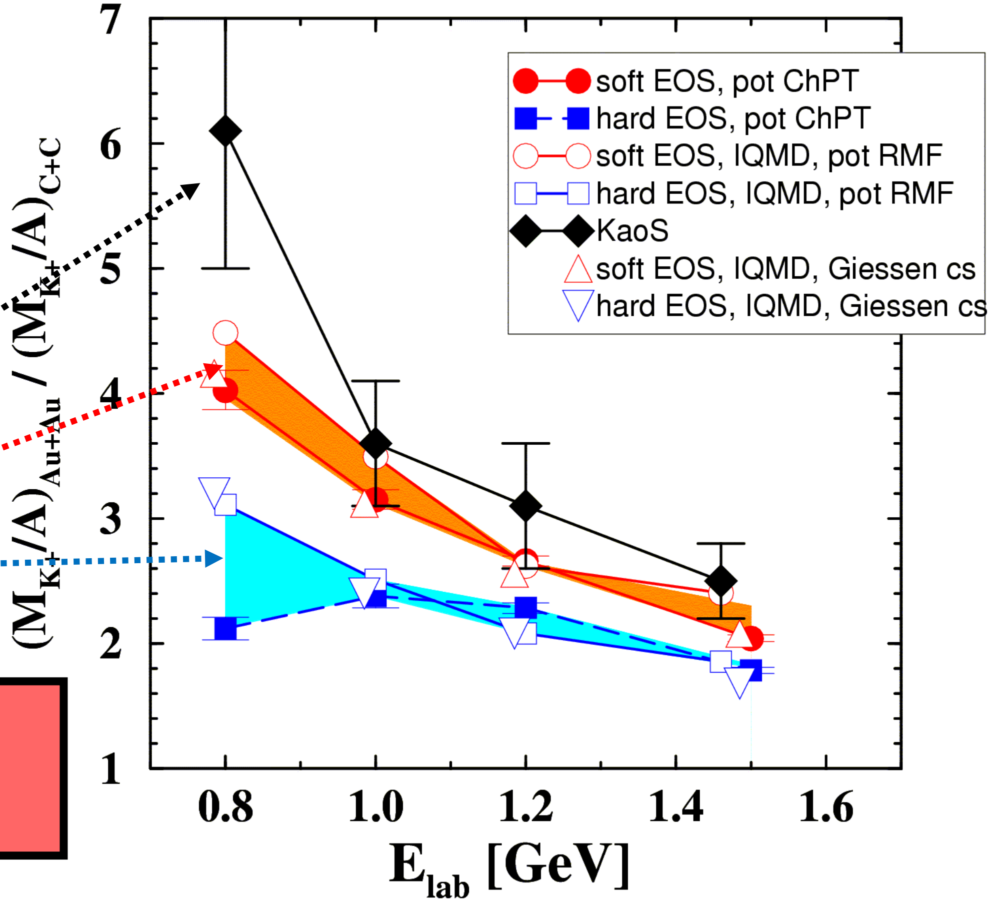


IQMD C. Hartnack

KaoS (Exp.)

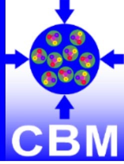
Soft EOS (Th.)

Hard EOS (Th.)

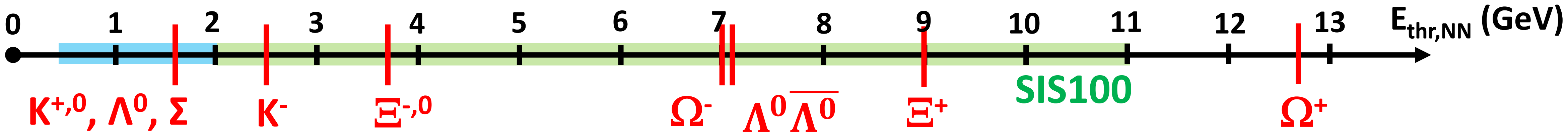


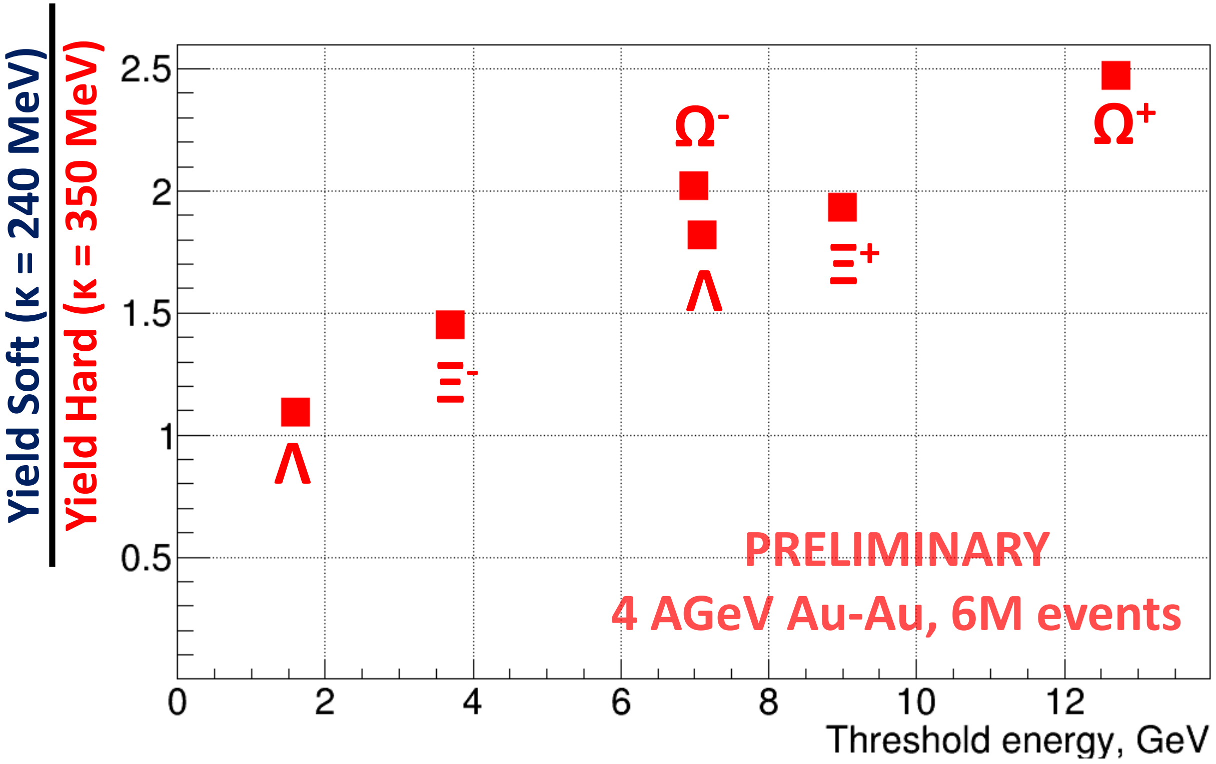
Soft Nuclear EOS
$\kappa \approx 200$ (2-3 ρ_0)

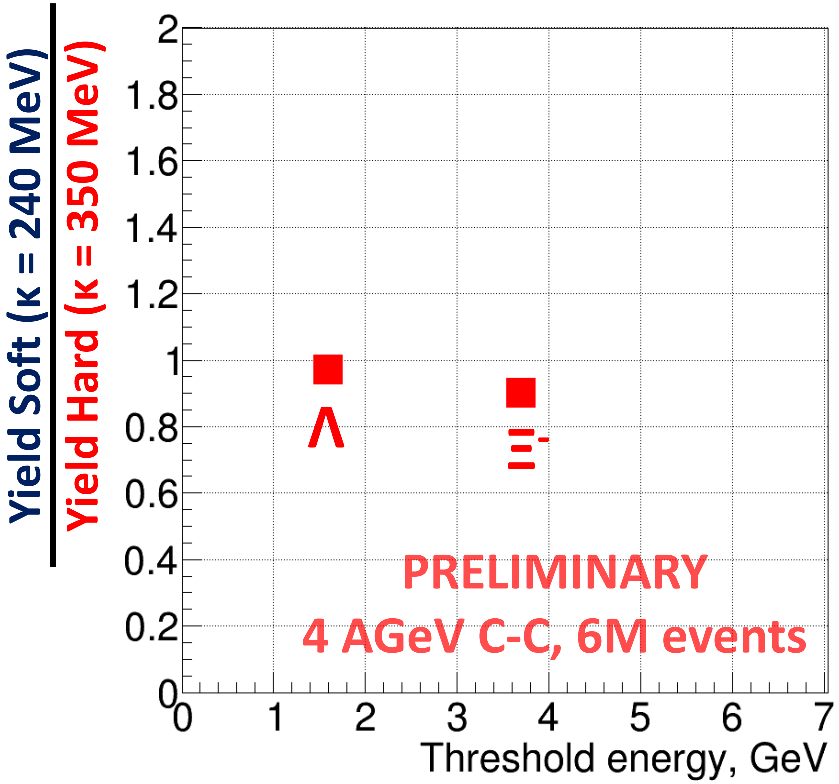
Experiment: C. Sturm et al., (KaoS Collaboration) Phys. Rev. Lett. 86 (2001) 39
Theory: QMD Ch. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649



Idea: Strangeness Yield ∝ Baryonic Density ∝ Compressibility ∝ EOS







PHQMD: J. Aichelin, E. Bratkovskaya, V. Kireyeu et al.
P. Senger, 4th CBM China Workshop (2019)

PARTON-HADRON-QUANTUM-MOLECULAR DYNAMICS (PHQMD)

The goal: to develop a **unified n-body microscopic transport approach** for the description of heavy-ion dynamics and dynamical cluster formation from low to ultra-relativistic energies

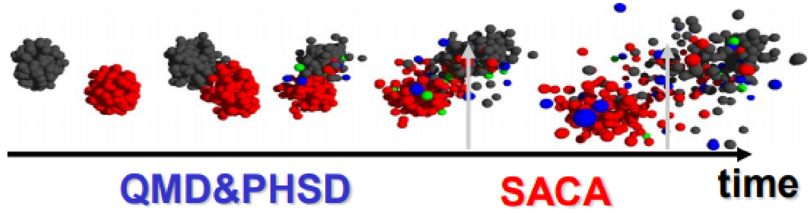
Realization: combined model **PHQMD = (PHSD & QMD) & SACA**

Parton-Hadron-Quantum-Molecular Dynamics

Initialization → propagation of baryons:
QMD (Quantum-Molecular Dynamics)

Propagation of partons (quarks, gluons) and mesons
+ collision integral = interactions of hadrons and partons (QGP)
from PHSD (Parton-Hadron-String Dynamics)

Clusters recognition:
SACA (Simulated Annealing Clusterization Algorithm)
vs. MST (Minimum Spanning Tree)



PHQMD: E. Bratkovskaya, Strange Quark Matter SQM (2019)

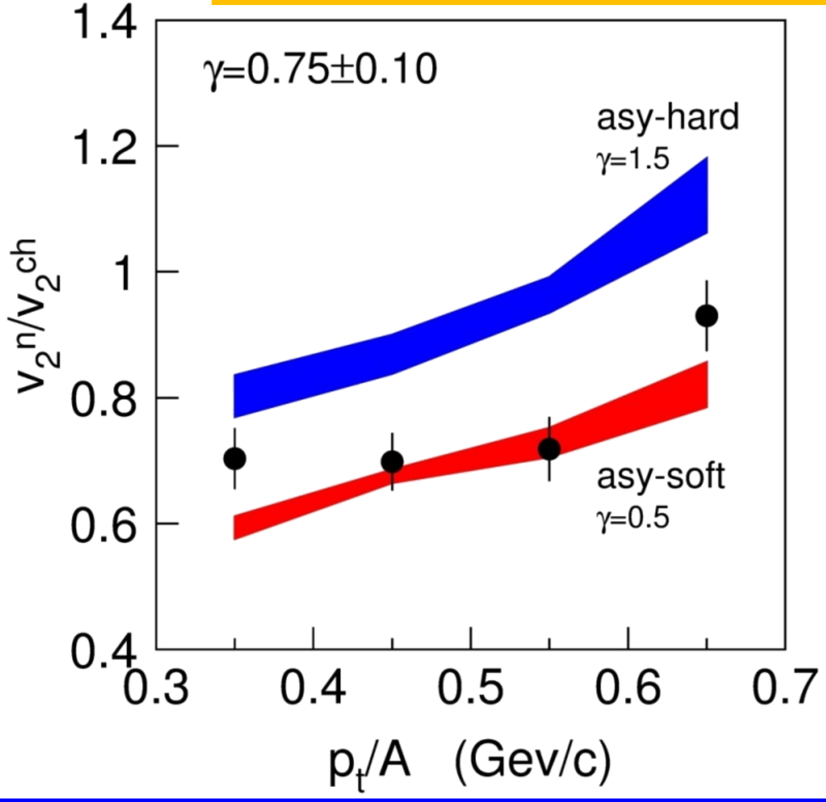
NUCLEAR SYMMETRY ENERGY: $E_A(\rho,\delta) = E_A(\rho,0) + E_{SYM}(\rho).\delta^2$

Parameterization in transport

$$E_{sym}(\rho) = 22\ \text{MeV}\left(\frac{\rho}{\rho_0}\right)^{\gamma} + 12\ \text{MeV}\left(\frac{\rho}{\rho_0}\right)^{2/3}$$

γ	0.5	1.0	1.5
L [MeV]	57	90	123

Idea: Measurement of differential collective flow of isospin opposite particles (neutrons w.r.t. protons or overall charged particles)

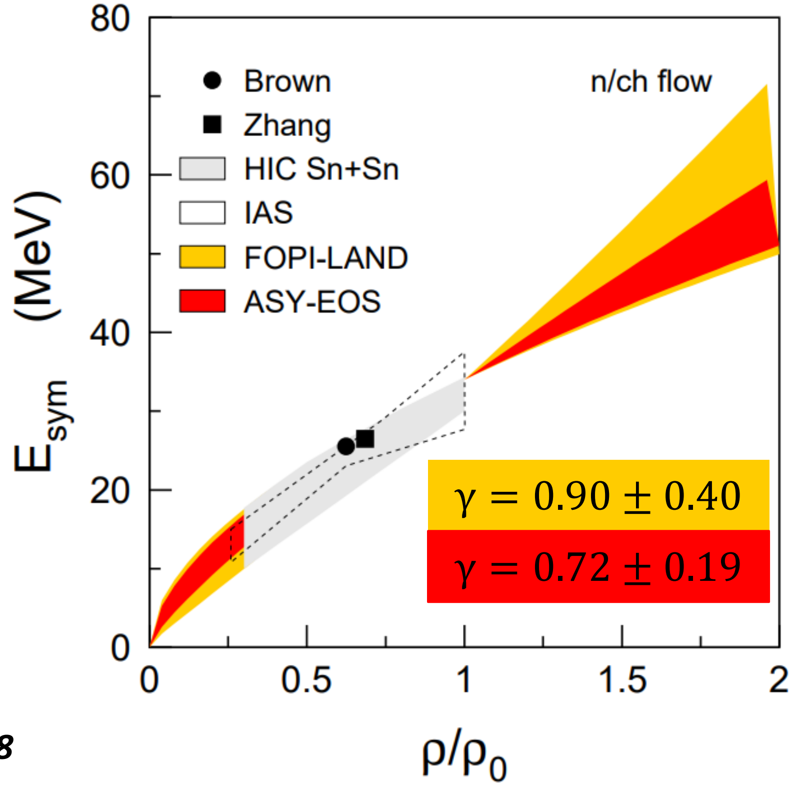


Au-Au 0.4 AGeV
FOPI-LAND and ASY-EOS

L = 72 ± 13 MeV
K_{sym} = -70 … -40 MeV

Moderately soft asy-EOS ≤ $2\rho_0$
Higher densities???

P. Russotto et al., Phys.Lett. B697 (2011) 471-476
P. Russotto et al., Phys.Rev. C94 (2016) no.3, 034608

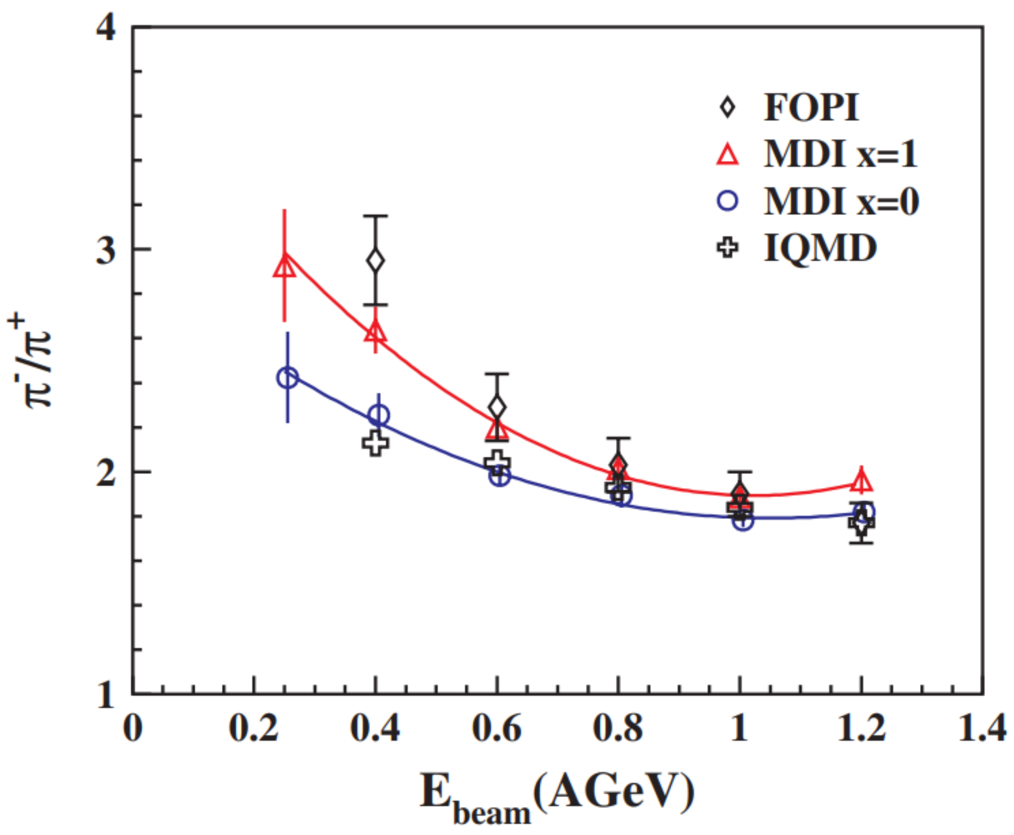


Nuclear Symmetry Energy: $E_A(\rho,\delta) = E_A(\rho,0) + E_{SYM}(\rho).\delta^2$

The isospin and momentum-dependent mean-field potential

$$U(\rho,\beta,p,\tau,x) = A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^\sigma (1 - x\beta^2) - 8\tau x \frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\beta\rho_{\tau'} + \frac{2C_{\tau\tau}}{\rho_0}\int d^3\vec{p}\,'\frac{f_\tau(\vec{r},\vec{p}\,')}{1+(\vec{p}-\vec{p}\,')^2/\Lambda^2} + \frac{2C_{\tau\tau'}}{\rho_0}\int d^3\vec{p}\,'\frac{f_{\tau'}(\vec{r},\vec{p}\,')}{1+(\vec{p}-\vec{p}\,')^2/\Lambda^2}, \quad (2)$$

x	L (MeV)	K_{sym} (MeV)
−2	152	418
−1	106	127
0	61	−163
1	15	−454
2	−31	−745



Xiao et al., Phys. Rev. Lett. 102, 062502 (2009)
M. D. Cozma, Phys. Rev. C 95, 014601 (2017)

Idea: Measurement of particle yields of isospin opposite particles (pions) for lower energies

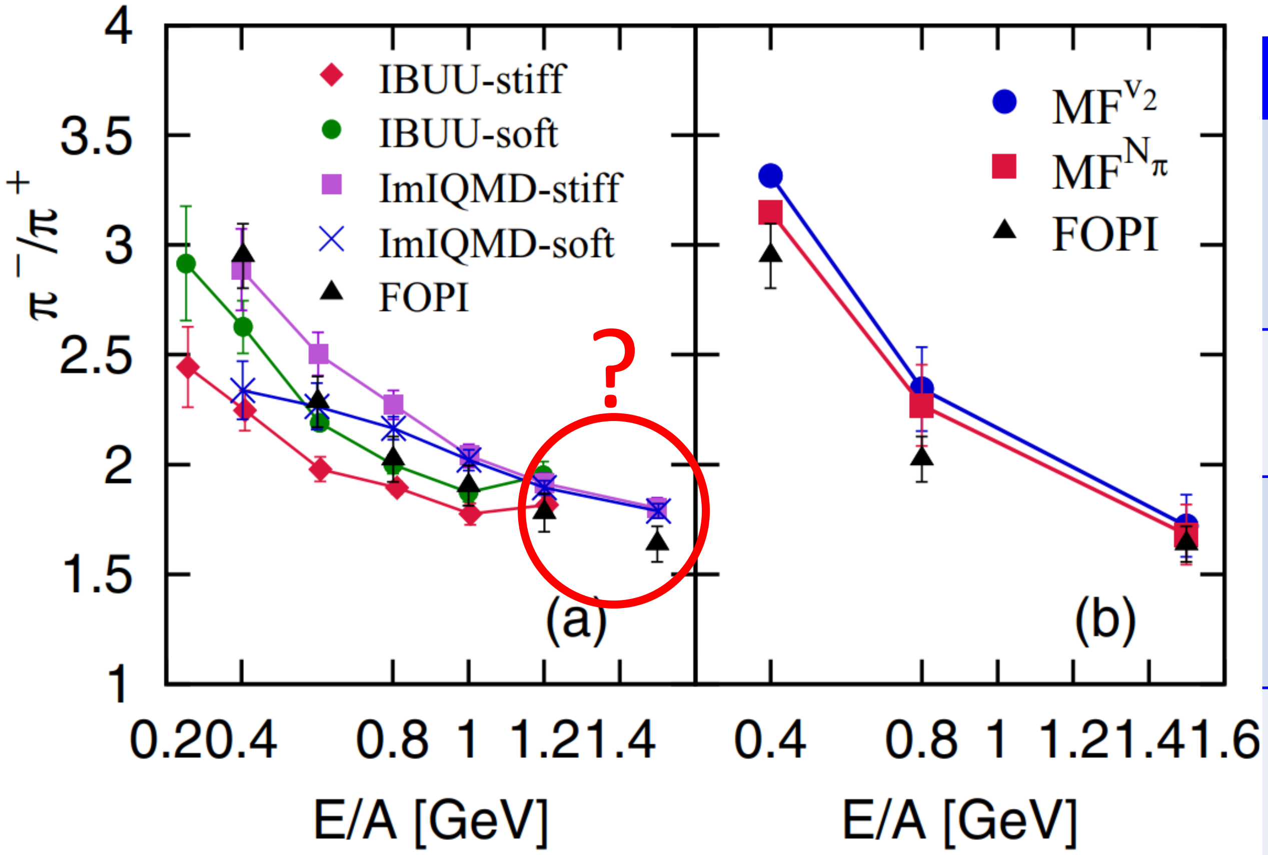
Described by very soft asy-EOS ≤ $2\rho_0$
Inconsistent with the n/p flow data
Still true for higher densities???

- **pion optical potential**
- **self energies different for π- and π+**
- **potentials and characteristics of Δ**

WORK IN PROGRESS

Nuclear Symmetry Energy At Higher Densities ($\rho \geq 2\rho_0$)

Idea: Measurement of yield ratios of isospin opposite particles at sub-threshold energies is suitable for higher energies where pion ration could loose sensitivity



I_3	Particle	Production	E_{thr}	Decay
+1	Σ^+(uus)	$pp \to \Sigma^+ K^+ n$ $pp \to \Sigma^+ K^0 p$ $pn \to \Sigma^+ K^0 n$	1.8 GeV	$\Sigma^+ \to p\pi^0$ $\Sigma^+ \to n\pi^+$
-1	Σ^-(dds)	$pn \to \Sigma^- K^+ p$ $nn \to \Sigma^- K^+ n$	1.8 GeV	$\Sigma^- \to n\pi^-$
+½	Ξ^0 (uss)	$pp \to \Xi^0 K^+ K^0 p$ $pn \to \Xi^0 K^0 K^0 p$ $nn \to \Xi^0 K^0 K^0 n$	3.7 GeV	$\Xi^0 \to \Lambda\pi^0$
-½	Ξ^- (dss)	$pp \to \Xi^- K^+ K^+ p$ $pn \to \Xi^- K^+ K^+ n$ $nn \to \Xi^- K^0 K^+ n$	3.7 GeV	$\Xi^- \to \Lambda\pi^-$

Jun Hong and P. Danielewicz, Phys. Rev. C90, 024605 (2014)
P. Senger, 3rd and 4th CBM China Meeting (2018-2019)

MODELLING THE CORRELATION FUNCTION

$$C(k^*) = C_{baseline}(k^*) \cdot \left(1 + \lambda_{genuine} \cdot \left(C_{genuine}(k^*) - 1\right) + \sum \lambda_{ij} \cdot \left(C_{ij}(k^*) - 1\right)\right)$$

Baseline *Genuine correlation* *Residuals*

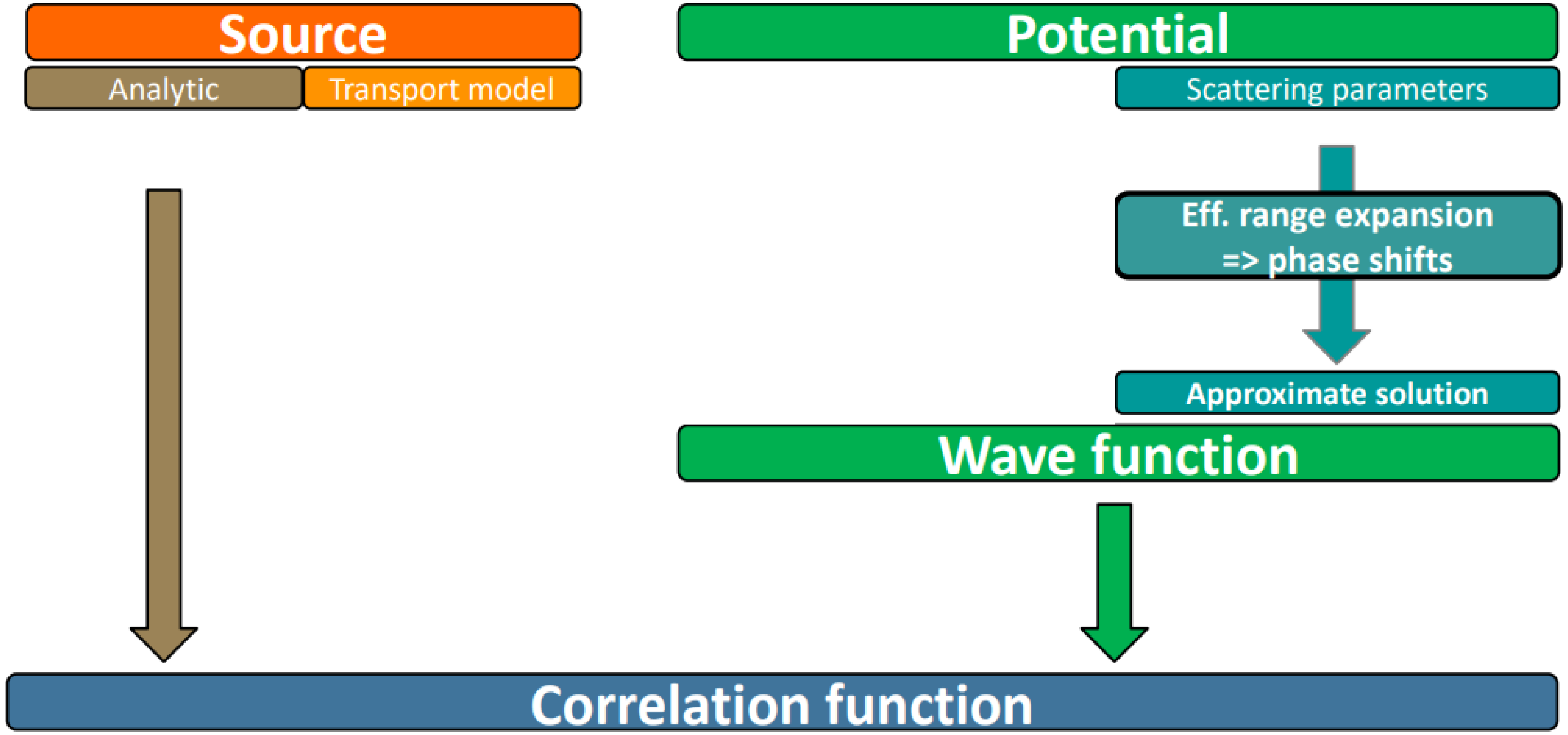
CATS Correlation Analysis Tool Using the Schrödinger Equation		Lednický
Numerical Solver		Analytical Model
Analytical source distribution Distributions from transport models	**Source**	Gaussian source distribution
Solution of the two particle Schrödinger Equation ➢ Can incorporate any strong interaction potential, Coulomb interaction and effects of quantum statistics	**Wave function**	Based on the effective range expansion ➢ The interaction is modelled using the scattering length (f_0) and the effective range (d_0)
p-p, p-Ξ and p-Λ (NLO) Correlation function	**Used to fit**	p-Λ (LO) and Λ-Λ Correlation function

Eur. Phys. J. C (2018) 78:394.

R. Lednicky and V. L. Lyuboshits, Sov. J. Nucl. Phys. **35**, 770 (1982), [Yad. Fiz.35,1316(1981)].

Andi Mathis, ALICE Collaboration, Exploring the perfect liquid, München (2018)

LEDNICKY MODEL



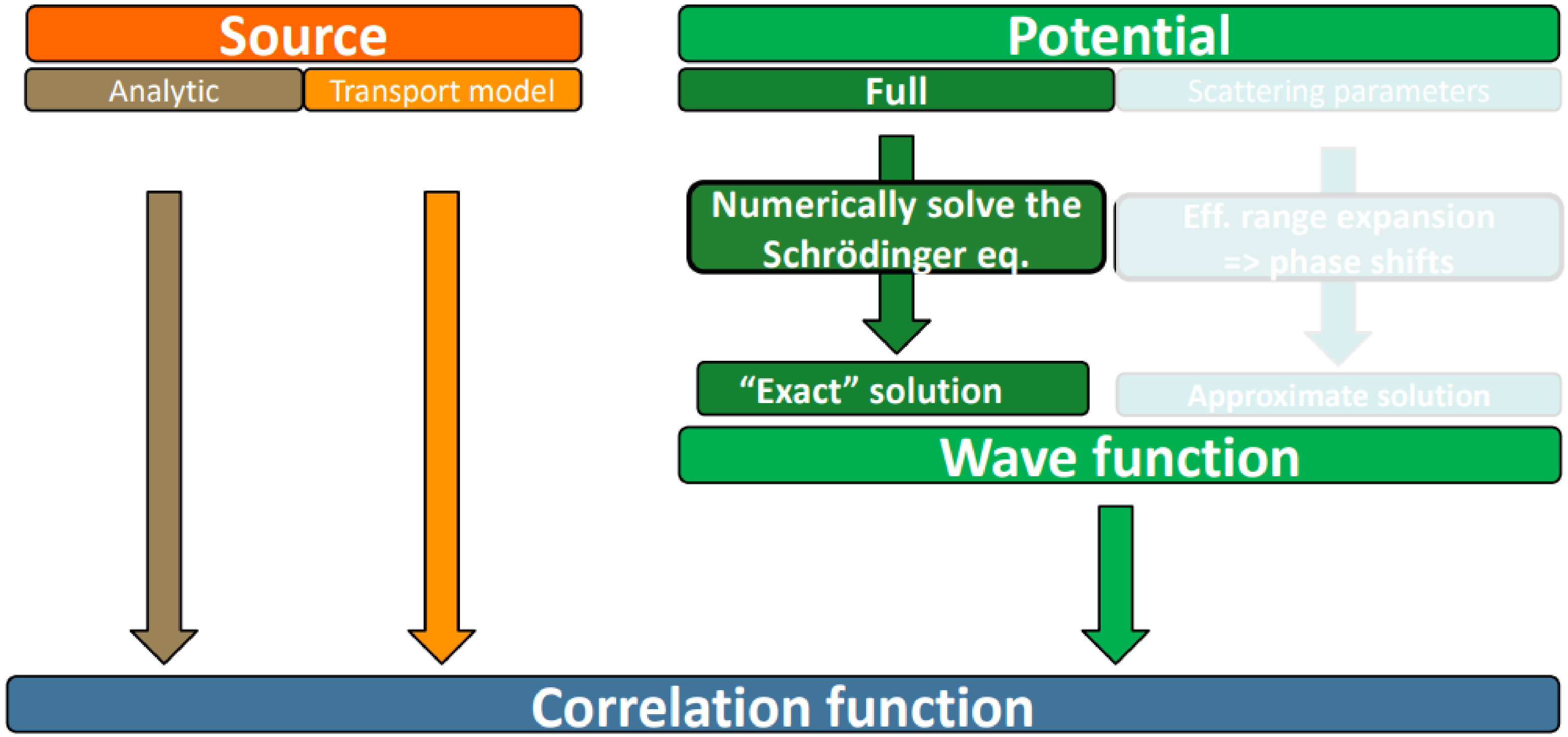
$$C(k) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k)}{R_G^{\Lambda p}} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} R_G^{\Lambda p}} \right) + 2 \frac{\mathcal{R} f^S(k)}{\sqrt{\pi} R_G^{\Lambda p}} F_1(Q R_G^{\Lambda p}) - \frac{\mathcal{I} f^S(k)}{R_G^{\Lambda p}} F_2(Q R_G^{\Lambda p}) \right]$$

Depends on scattering parameters, might locally break down for small sources

Valentina Mantovani Sarti, ALICE Collaboration, – QNP18 Satellite Workshop (2018)

R. Lednicky and V. L. Lyuboshits, Sov. J. Nucl. Phys. **35**, 770 (1982), [Yad. Fiz.35,1316(1981)].

CATS

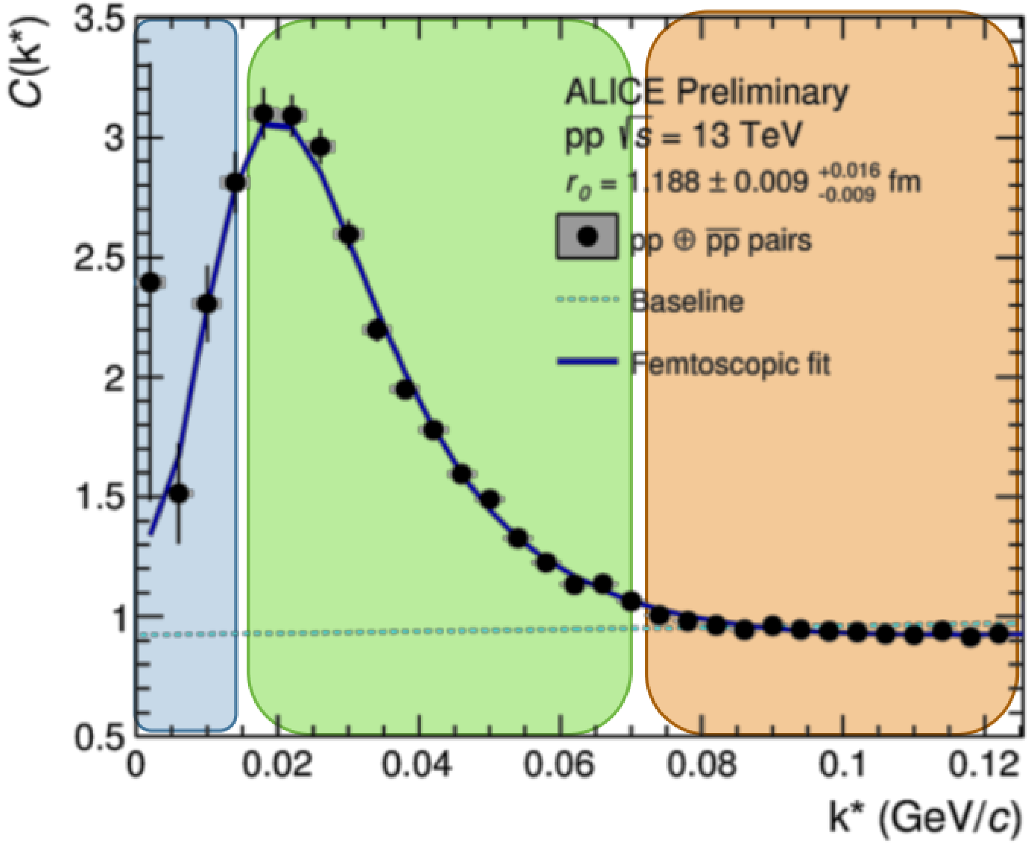


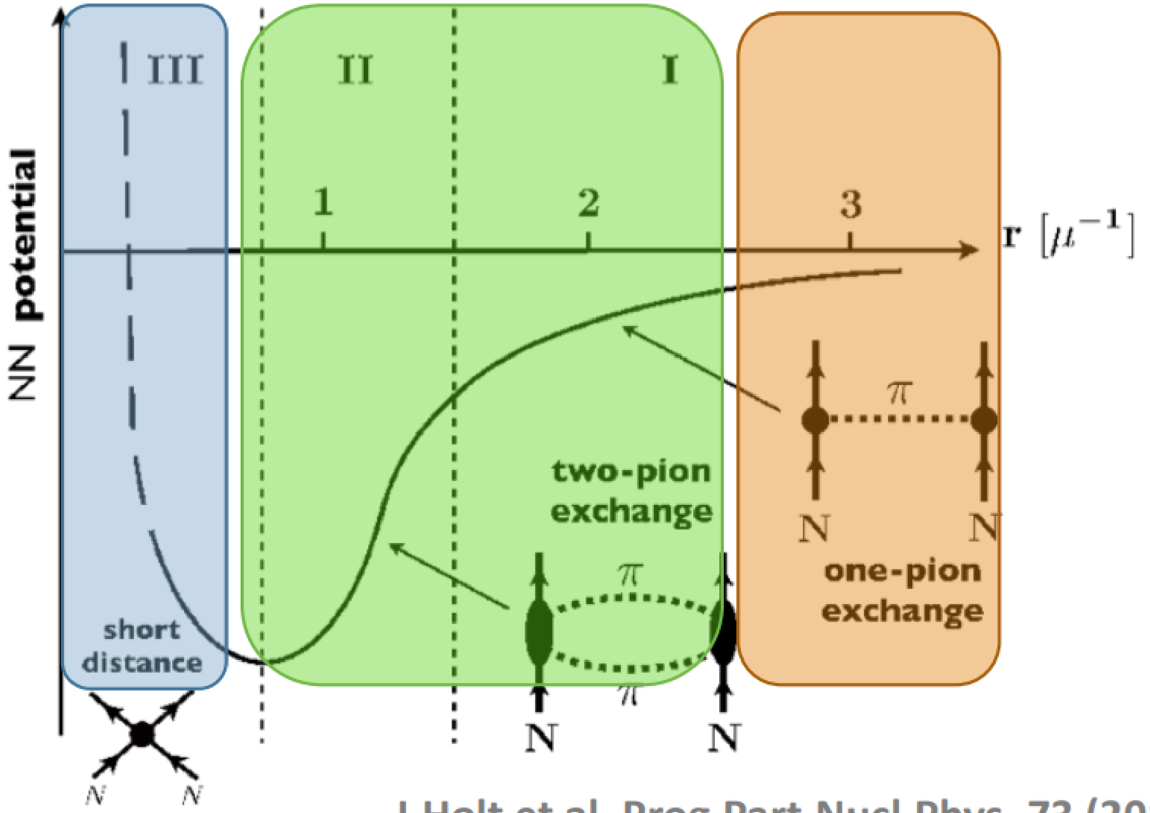
$$C(k) = \int S(\vec{r},k)|\psi(\vec{r},k)|^2 \, d\vec{r} \xrightarrow{k\to\infty} 1$$

(D.L.Mihaylov et al. Eur.Phys.J. C78 (2018) no.5,394)

Valentina Mantovani Sarti, ALICE Collaboration, – QNP18 Satellite Workshop (2018)

$$C(k^*) \longrightarrow \begin{cases} > 1 \text{ attraction} \\ = 1 \text{ no interaction} \\ < 1 \text{ repulsion} \end{cases}$$





J.Holt et al, Prog.Part.Nucl.Phys. 73 (2013)

26

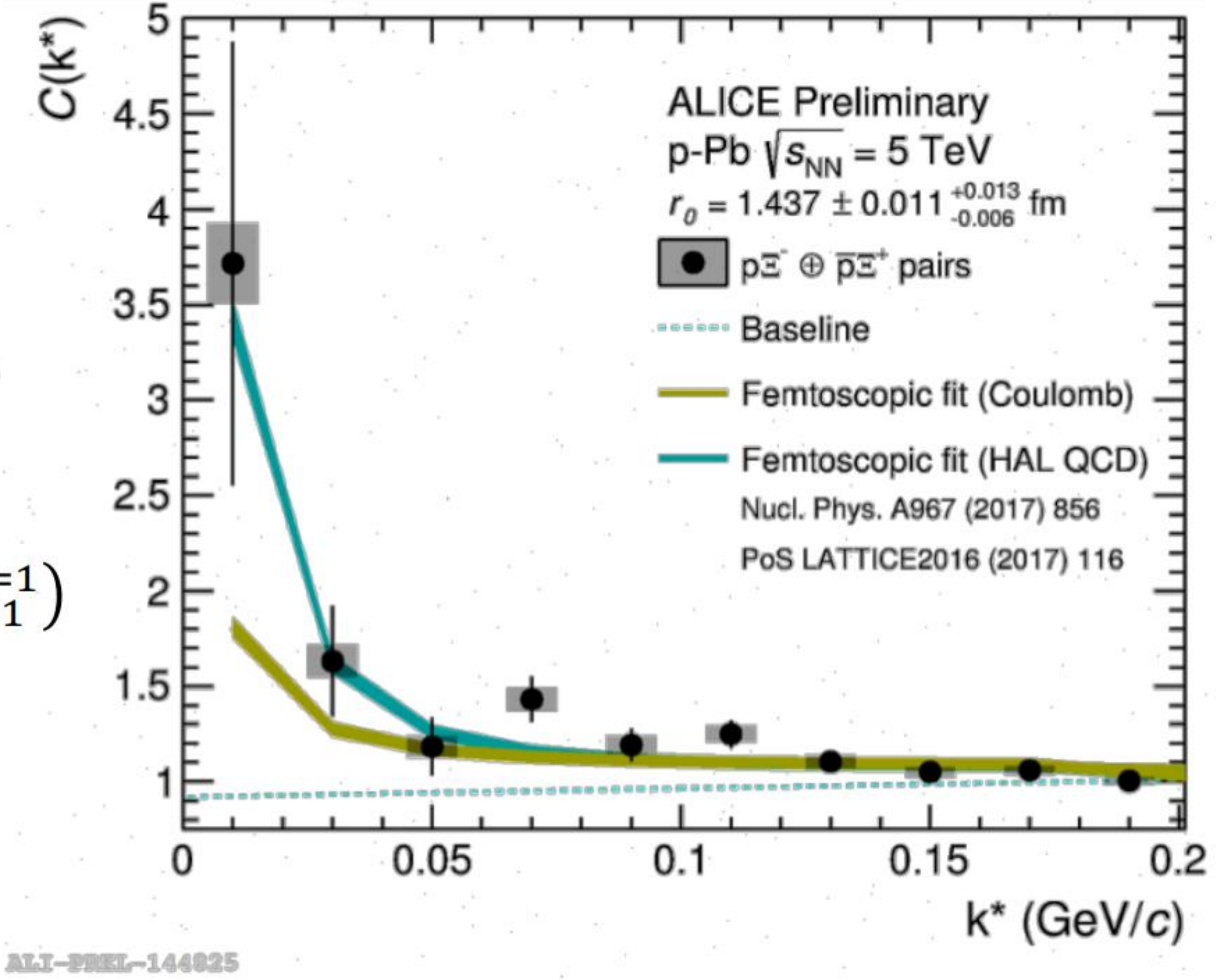
Valentina Mantovani Sarti, ALICE Collaboration, – QNP18 Satellite Workshop (2018)

P-XI- CORRELATION FUNCTION IN P-PB 5.02 TEV

- **<u>First observation of strong attractive interaction in p-Ξ^-</u>**
- modeled with preliminary QCD strong potential by the HAL QCD collaboration
  Potential from Hatsuda et al., NPA967 (2017) 856, PoS Lattice2016 (2017) 116

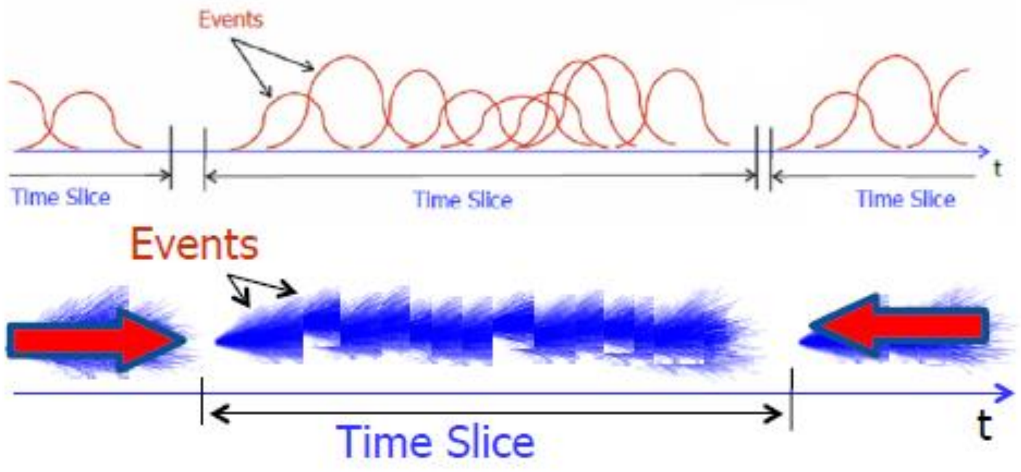
$$C(k^*) = \frac{1}{8}\left(C_{I=0}^{S=0} + C_{I=1}^{S=0}\right) + \frac{3}{8}\left(C_{I=0}^{S=1} + C_{I=1}^{S=1}\right)$$

COULOMB-ONLY HYPHOTESIS EXCLUDED AROUND 3σ



Valentina Mantovani Sarti, ALICE Collaboration, – QNP18 Satellite Workshop (2018)

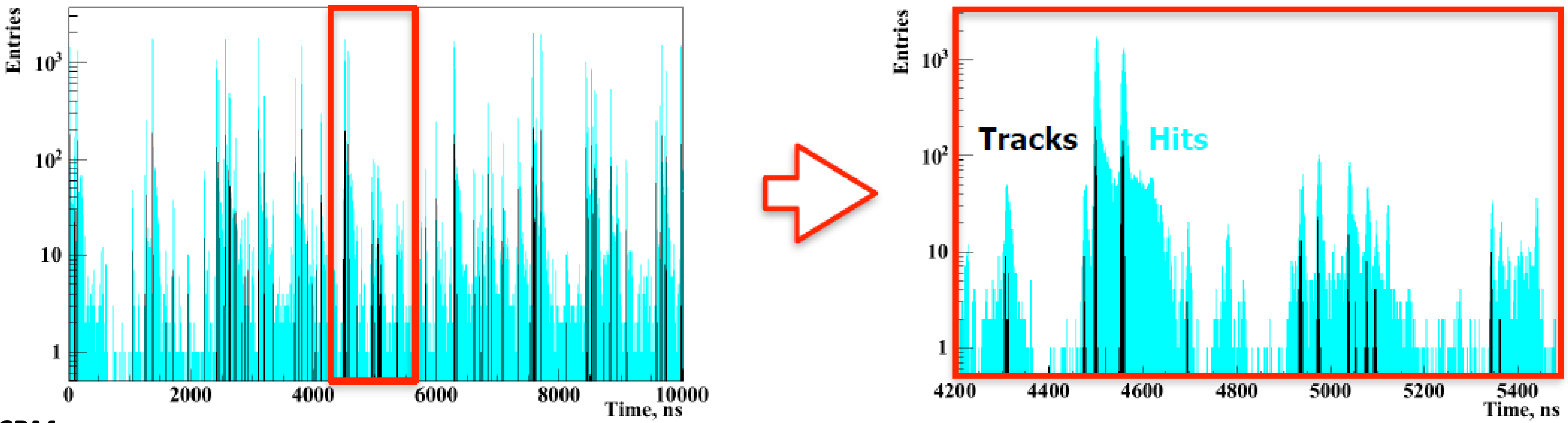
4D RECONSTRUCTION



- The beam will be continuous (no bunch structure).
- Detector hits will be marked with a time stamp.
- Events in the selected time window (time slice) will overlap in time.
- Reconstruction will be in 4D (x,y,z,t).
- Reconstruction of time slices rather than events will be needed.
- Events will be defined based on the reconstructed tracks.

100 AuAu mbias events at 10 AGeV at 10^7 Hz

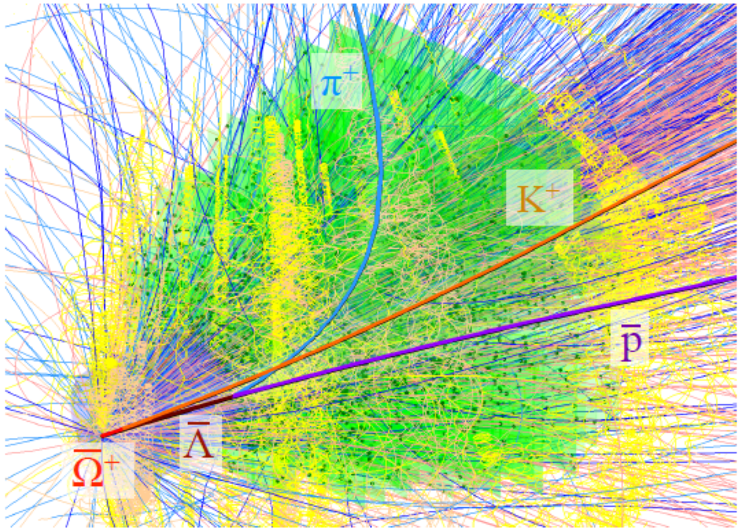
Reconstructed tracks - zoom



Maksym Zyzak, CBM Collaboration, EUNPC 2018,

Reconstructed tracks clearly represent groups, which correspond to the original events

Concept of KF Particle



$$\bar{\Omega}^+ \leftarrow \bar{\Lambda}\, K^+$$
$$\bar{\Lambda} \leftarrow \bar{p}\, \pi^+$$

```
KFParticle Lambda(P, Pi);                    // construct anti Lambda
Lambda.SetMassConstraint(1.1157);            // improve momentum and mass
KFParticle Omega(K, Lambda);                 // construct anti Omega
PV -= (P; Pi; K);                            // clean the primary vertex
PV += Omega;                                 // add Omega to the primary vertex
Omega.SetProductionVertex(PV);               // Omega is fully fitted
(K; Lambda).SetProductionVertex(Omega);      // K, Lambda are fully fitted
(P; Pi).SetProductionVertex(Lambda);         // p, pi are fully fitted
```

1. KFParticle class describes particles by:

$$\mathbf{r} = \{\, x, y, z, p_x, p_y, p_z, E \,\}$$

State vector

$$C = \langle \mathbf{r}\mathbf{r}^T \rangle = \begin{bmatrix} \sigma_x^2 & C_{xy} & C_{xz} & C_{xp_x} & C_{xp_y} & C_{xp_z} & C_{xE} \\ C_{xy} & \sigma_y^2 & C_{yz} & C_{yp_x} & C_{yp_y} & C_{yp_z} & C_{yE} \\ C_{xz} & C_{yz} & \sigma_z^2 & C_{zp_x} & C_{zp_y} & C_{zp_z} & C_{zE} \\ C_{xp_x} & C_{yp_x} & C_{zp_x} & \sigma_{p_x}^2 & C_{p_xp_y} & C_{p_xp_z} & C_{p_xE} \\ C_{xp_y} & C_{yp_y} & C_{zp_y} & C_{p_xp_y} & \sigma_{p_y}^2 & C_{p_yp_z} & C_{p_yE} \\ C_{xp_z} & C_{yp_z} & C_{zp_z} & C_{p_xp_z} & C_{p_yp_z} & \sigma_{p_z}^2 & C_{p_zE} \\ C_{xE} & C_{yE} & C_{zE} & C_{p_xE} & C_{p_yE} & C_{p_zE} & \sigma_E^2 \end{bmatrix}$$

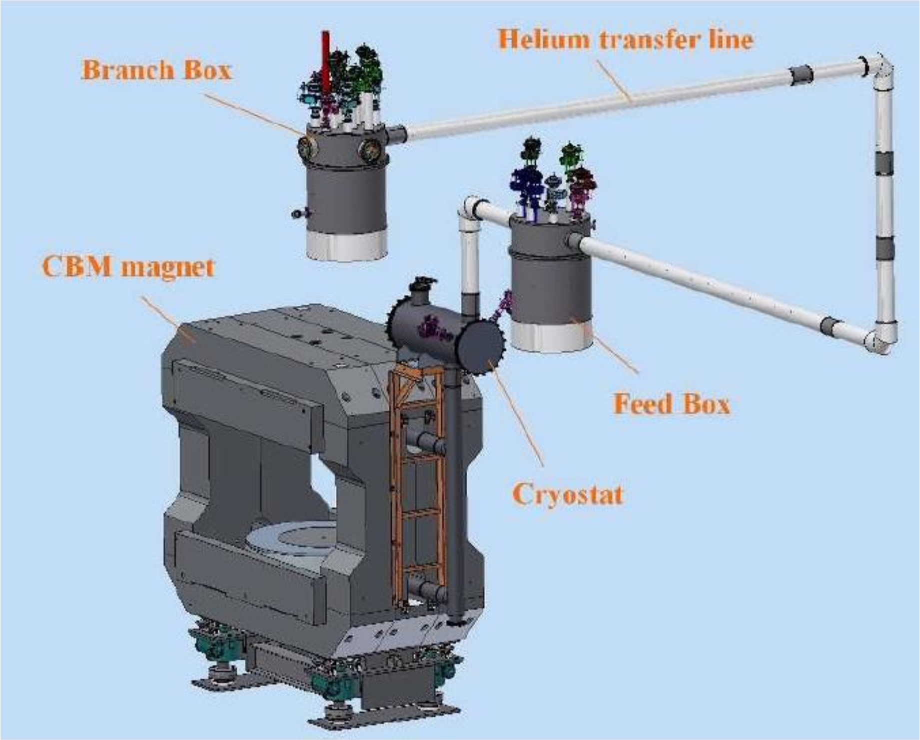
Covariance matrix

2. Covariance matrix contains essential information about tracking and detector performance.
3. The method for mathematically correct usage of covariance matrices is provided by the KF Particle package based on the Kalman filter (KF) developed by FIAS group[1,2] primarily for CBM and ALICE.
4. Heavy mathematics requires fast and vectorised algorithms.
5. Mother and daughter particles are KFParticle and are treated in the same way.
6. The natural and simple interface allows to reconstruct easily rather complicated decay chains.
7. The package is geometry independent and can be easily adapted to different experiments.

1. KF Particle — S. Gorbunov, "On-line reconstruction algorithms for the CBM and ALICE experiments," Dissertation thesis, Goethe University of Frankfurt, 2012, http://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/docId/29538
2. KF Particle Finder — M. Zyzak, "Online selection of short-lived particles on many-core computer architectures in the CBM experiment at FAIR," Dissertation thesis, Goethe University of Frankfurt, 2016, http://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/docId/41428

CBM SC magnet

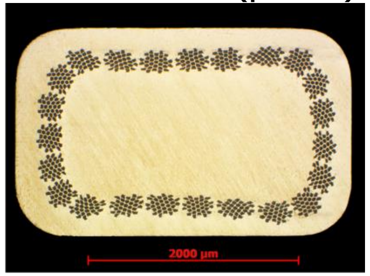
In-kind contribution by Russia, built by BINP Novosibirsk



Production status:

- The bare SC cable is manufactured

Cross section (photo)



- Contract for SC cable insulation signed with VNIIKP
- Machining of the magnet yoke will start in October 2019

Next steps:

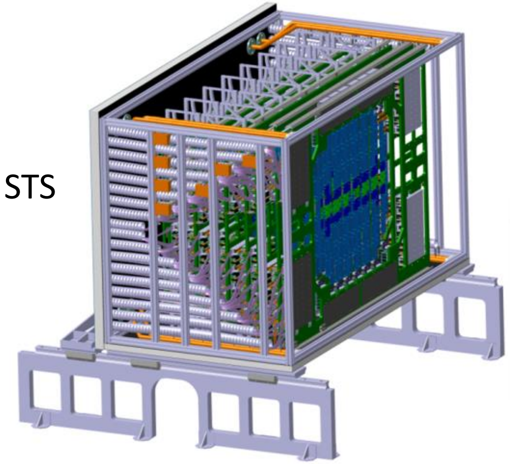
- Preliminary Design Review in Nov. 2019
  Agreement on the cooling circuit, cryostat, coil support struts, control system
- Final Design Review in May 2020
  All technical drawings finished
- Construction in 2020 - 2021

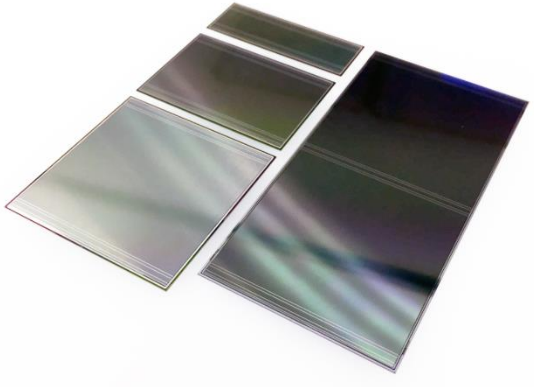
Silicon Tracking System

➢ Charged particle track reconstruction, momentum determination

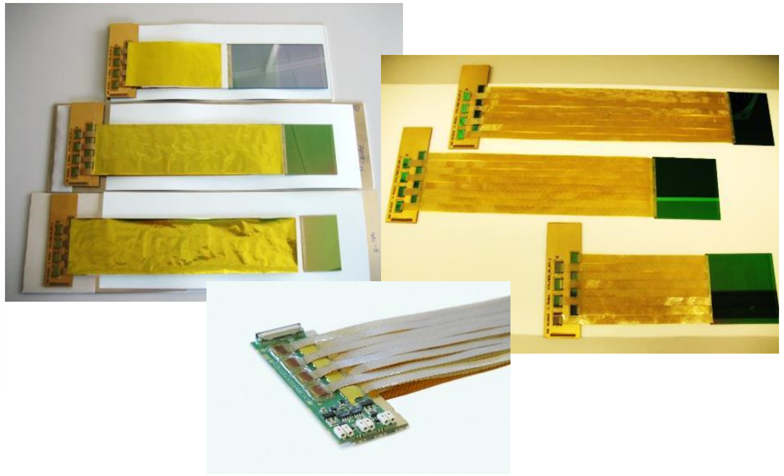
In-kind contributions by Germany, Russia, Poland:
GSI, JINR, KIT Karlsruhe, JU + AGH Krakow, KINR Kiev, Univ. Tübingen, Warsaw UT

STS





Silicon microstrip sensors



Module assembly at GSI and JINR

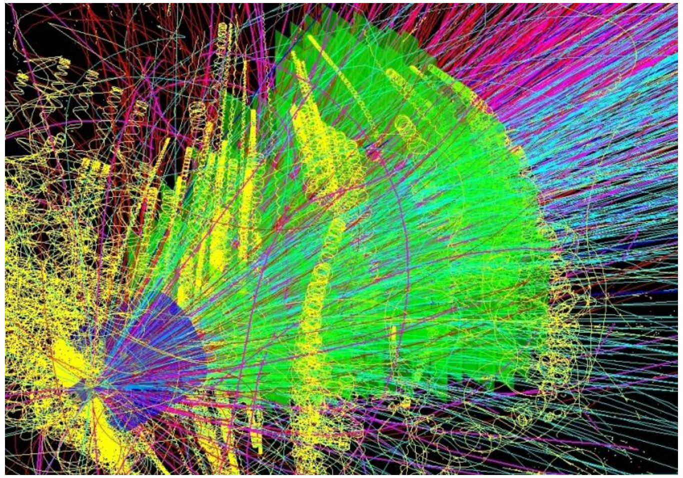
Status:

TDR approved by FAIR in July, 2013

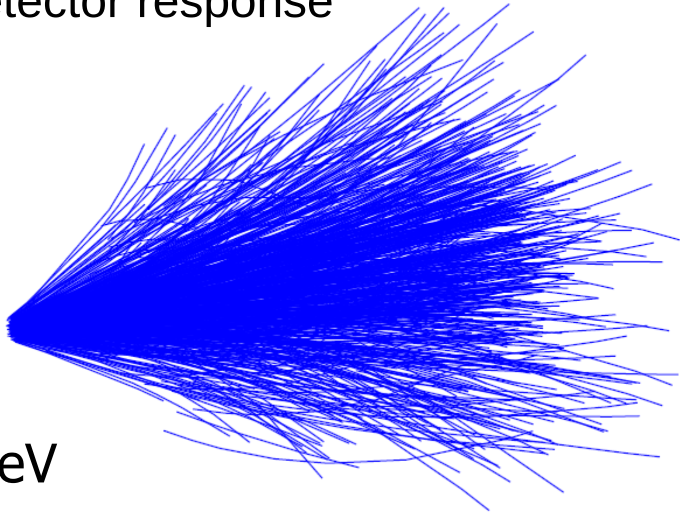
- Radiation tolerance of silicon sensors tested up to n_{eq} (1 MeV) = 2×10^{14} /cm^2.
- 1100 silicon microstrip sensors ordered from vendor Hamamatsu Photonics, delivery scheduled in batches from 11/2019 to 10/2020.
- Second design iteration of the STS-XYTER ASIC made, applied to prototype modules.
- Carbon fiber ladders ordered in company, delivery until 10/2019.
- Module and ladder assembly procedures established, working towards declaring production readiness. Start of series production in 2020.
- System engineering and system integration progressing.
- Demonstrator detector mSTS operated in mCBM experiment.

Charged particle track reconstruction

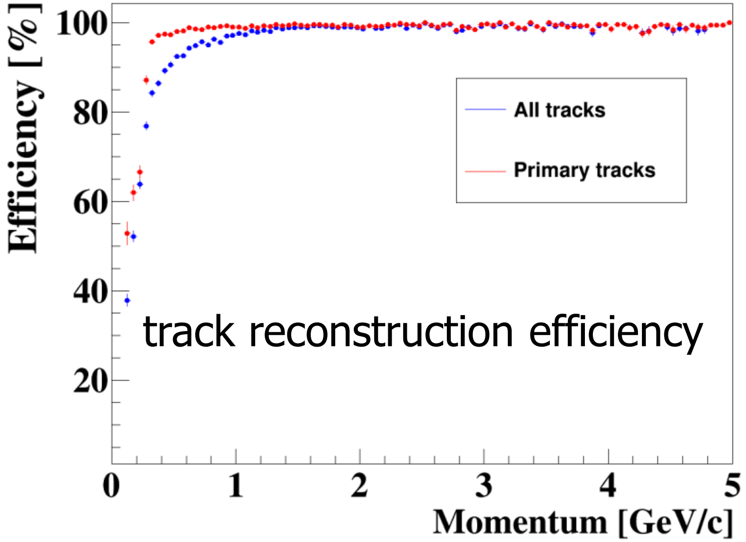
Event generators UrQMD 3.3, PHSD
Transport code GEANT3, FLUKA
Realistic detector geometries, material budget and detector response

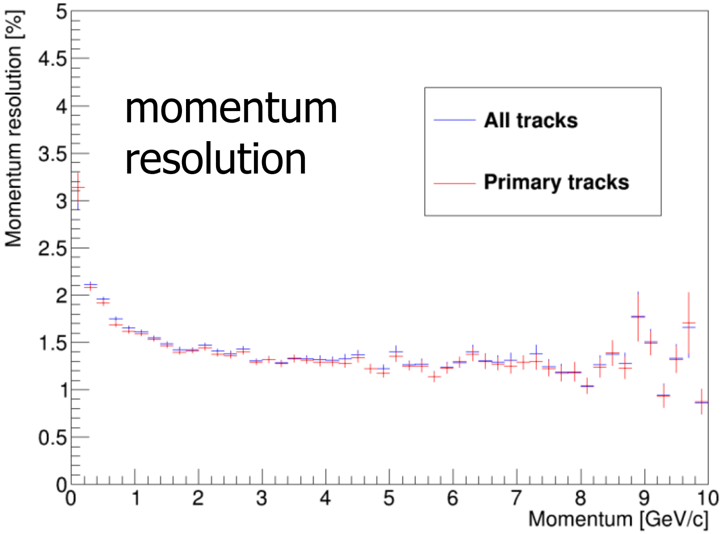


reconstruction



Au+Au 10 A GeV



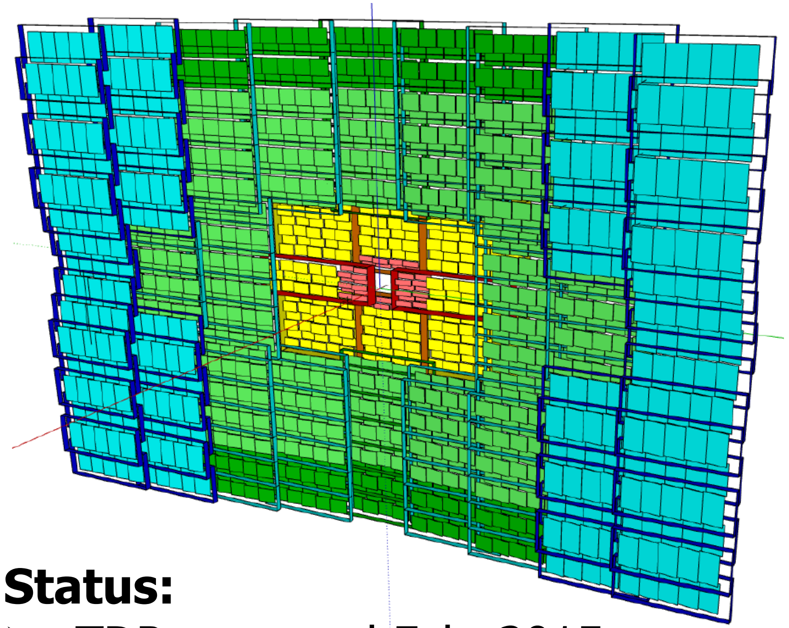


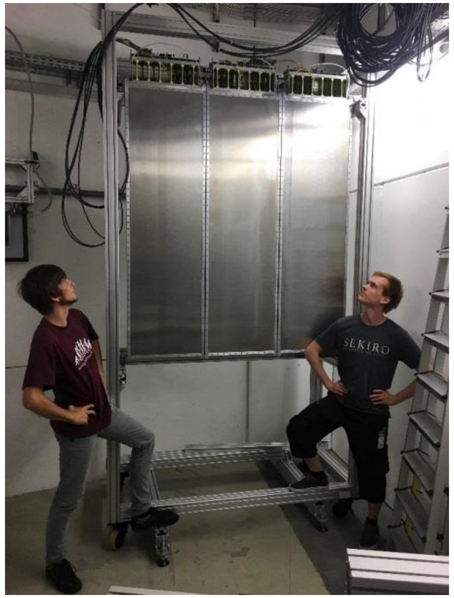
The high-rate MRPC TOF wall

- Particle identification

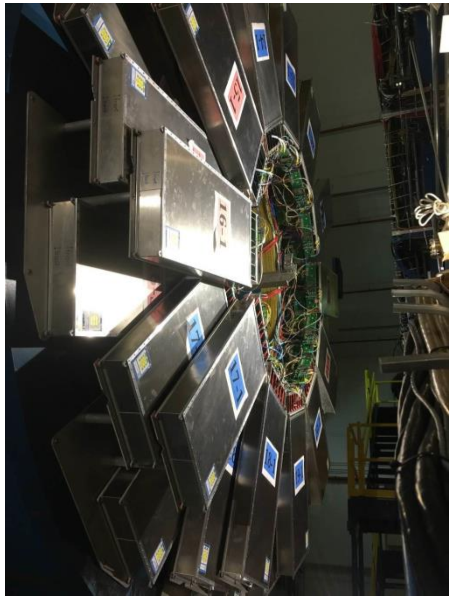
Challenge: Time resolution 50 ps up to 25 kHz/cm^2. Total area 100 m^2

In-kind contributions by Germany, China, Romania:
THU Beijing, NIPNE Bucharest, GSI Darmstadt, TU Darmstadt, IfI Frankfurt, USTC Hefei, Univ. Heidelberg, ITEP Moscow, HZDR Rossendorf, CCNU Wuhan.

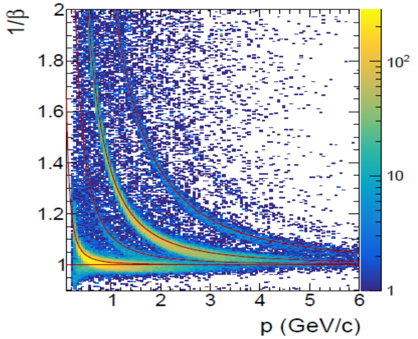




TOF at mCBM



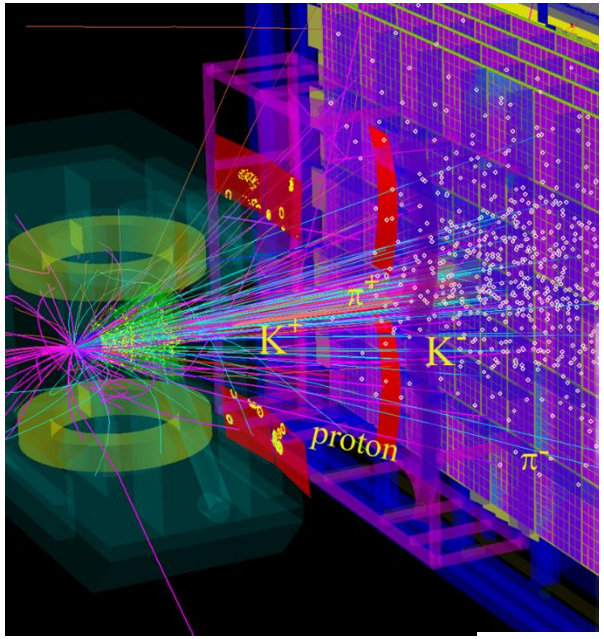
TOF at STAR

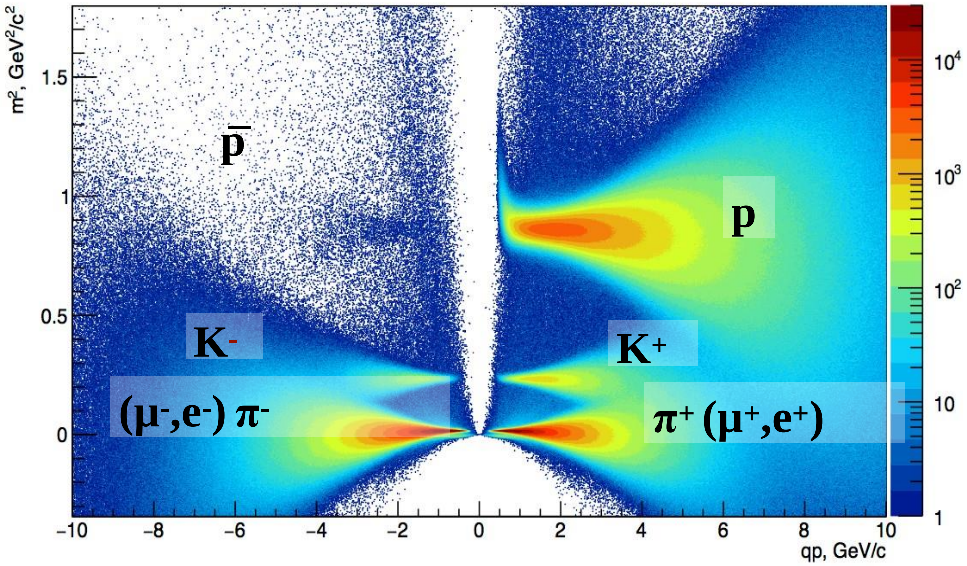


Status:

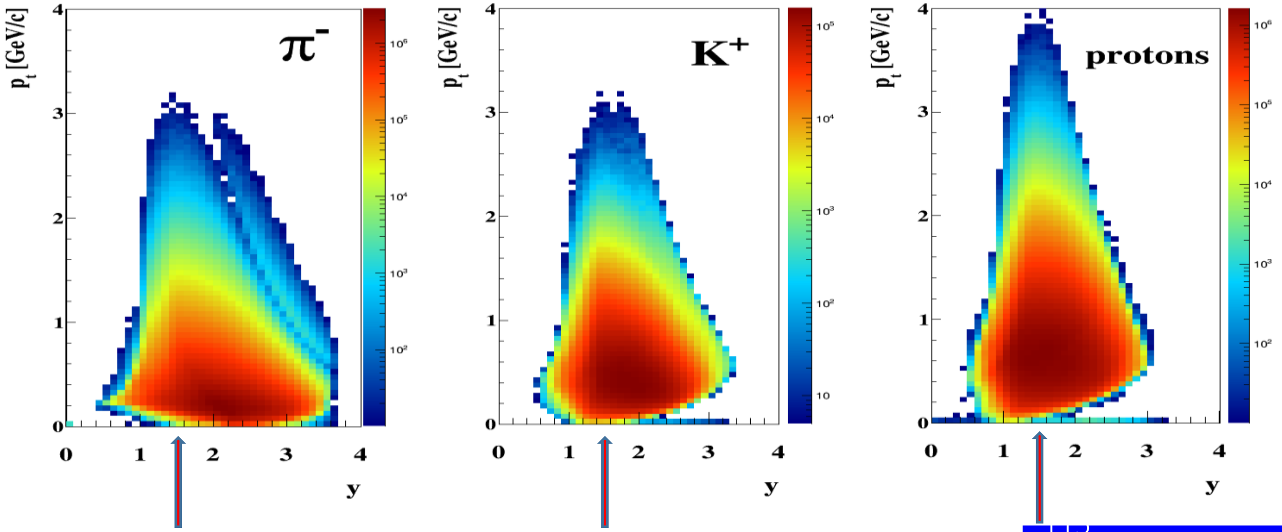
- TDR approved Feb. 2015
- Full size prototype TOF MRPC detectors installed and operated at mCBM (GSI) and STAR (RHIC)
- PID capability at STAR demonstrated

Hadron identification by STS + TOF



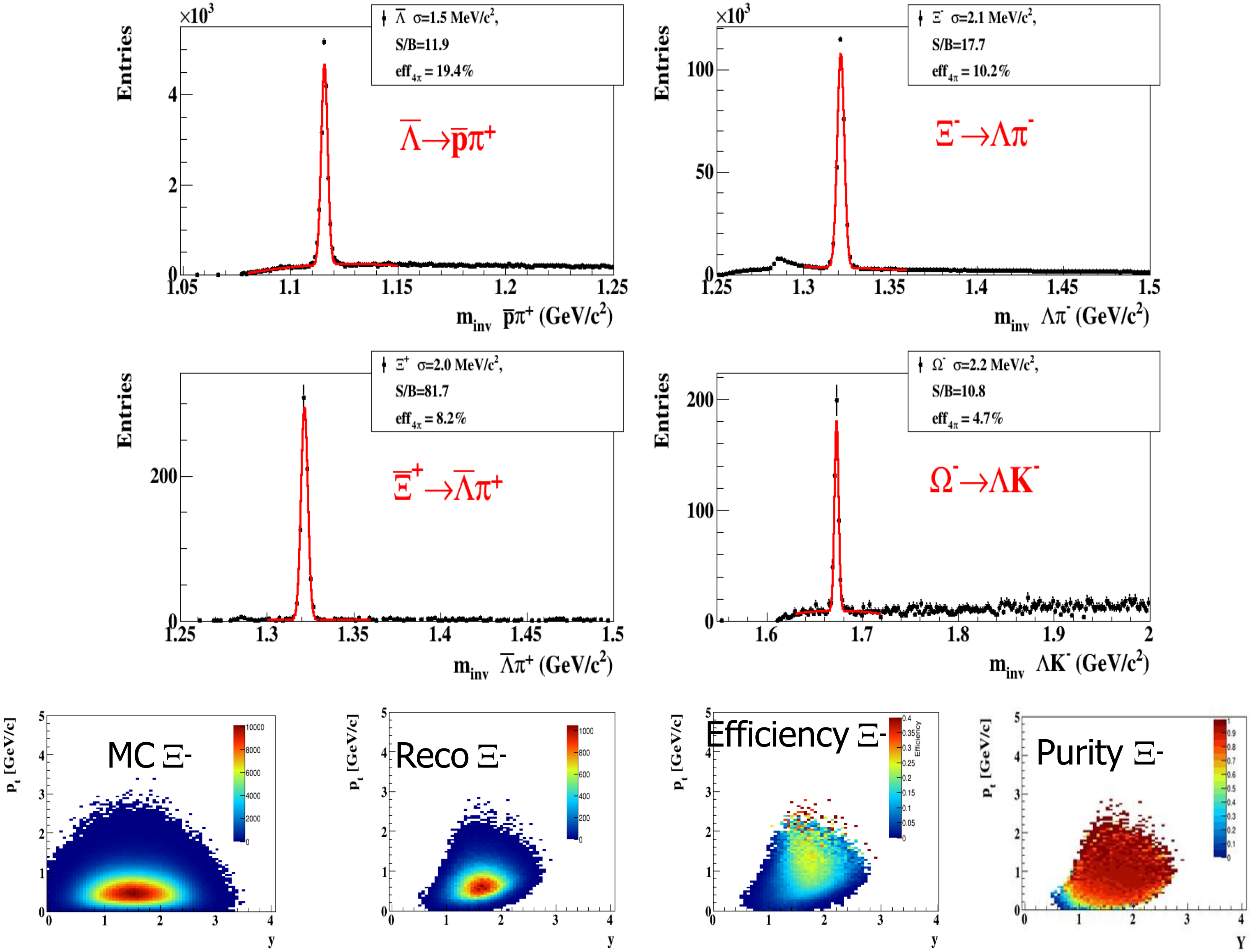


Au+Au collisions
10 A GeV



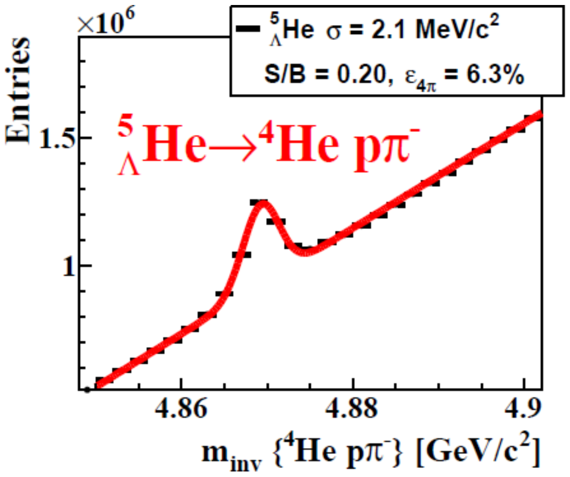
Hyperon reconstruction (STS+TOF)

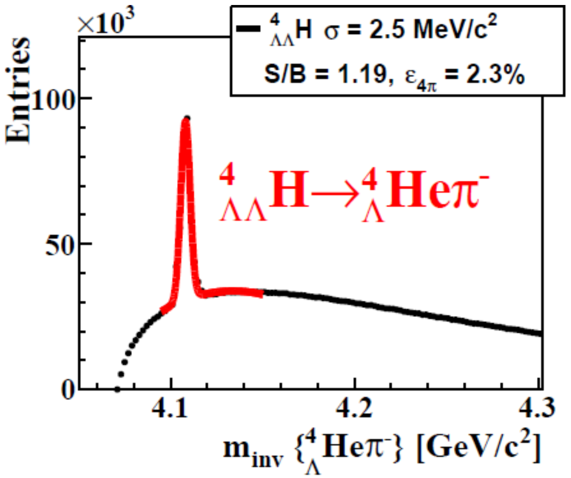
5 M central Au+Au collisions 10A GeV/c

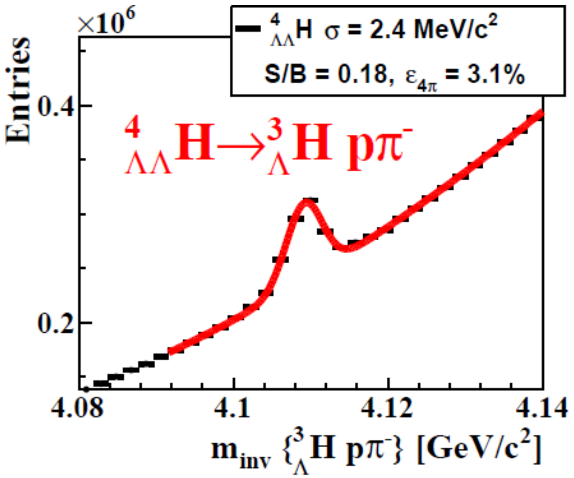


Hypernuclei reconstruction (STS+TOF)

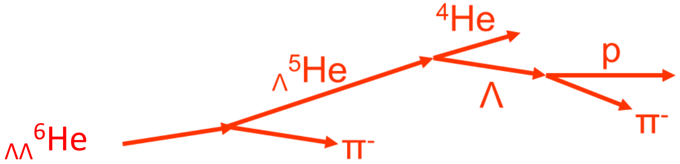
5 M min. bias Au+Au collisions 10A GeV/c



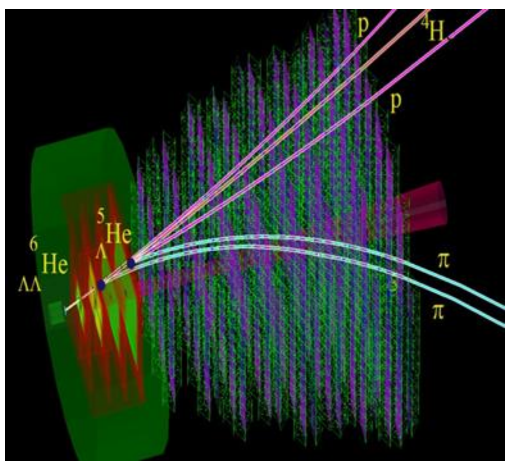


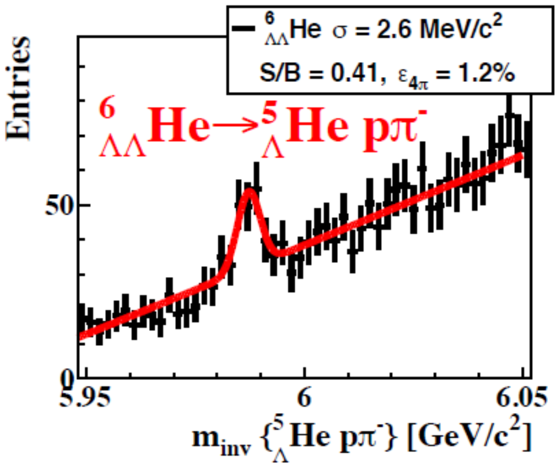


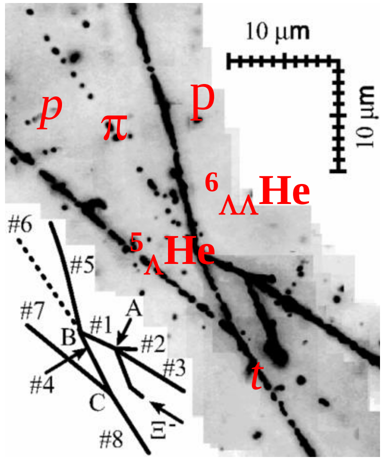
Example:



$_{\Lambda\Lambda}{}^{6}$He yield 60/week
(reaction rate 1 MHz, BR 10%, efficiency 1%)





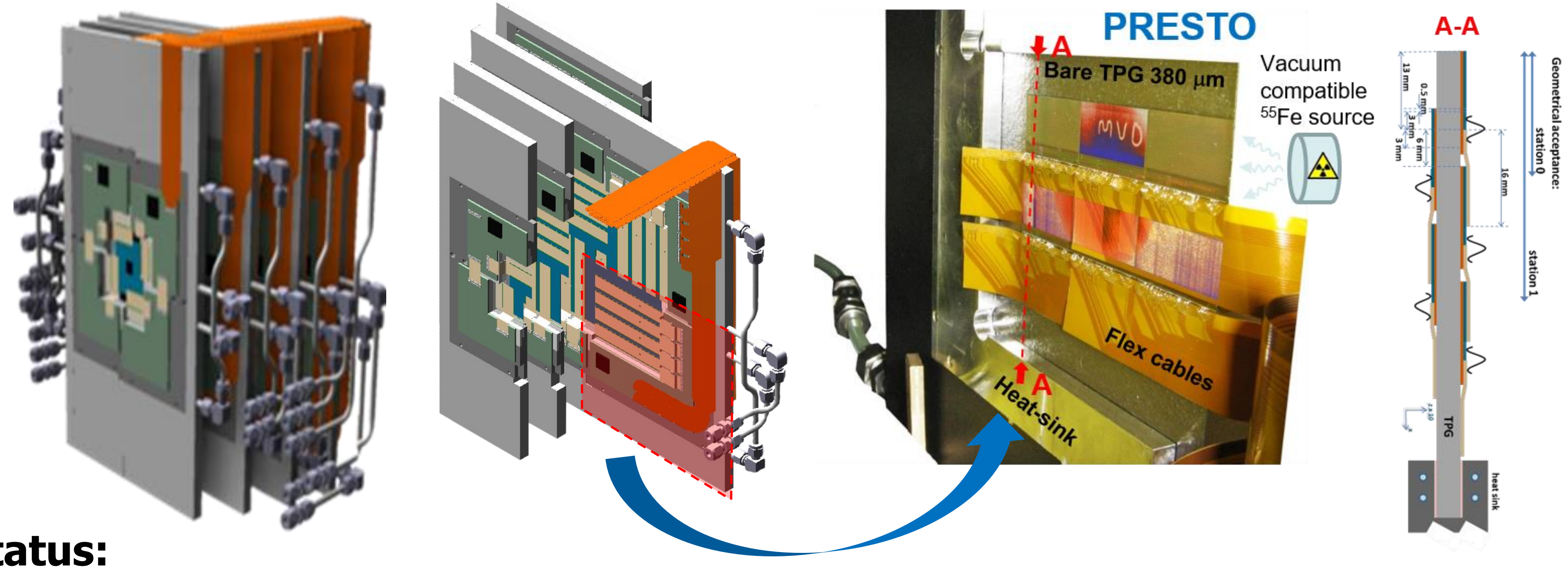


Nagara event

Micro Vertex Detector (MVD)

In-kind contributions by Germany, France: Univ. Frankfurt, IPHC Strasbourg

- Background suppression for di-electron measurements
- Determination of secondary vertices of open charm decays (τ = 10^{-12}-10^{-13} s)
- Improved tracking for hyperon-ID

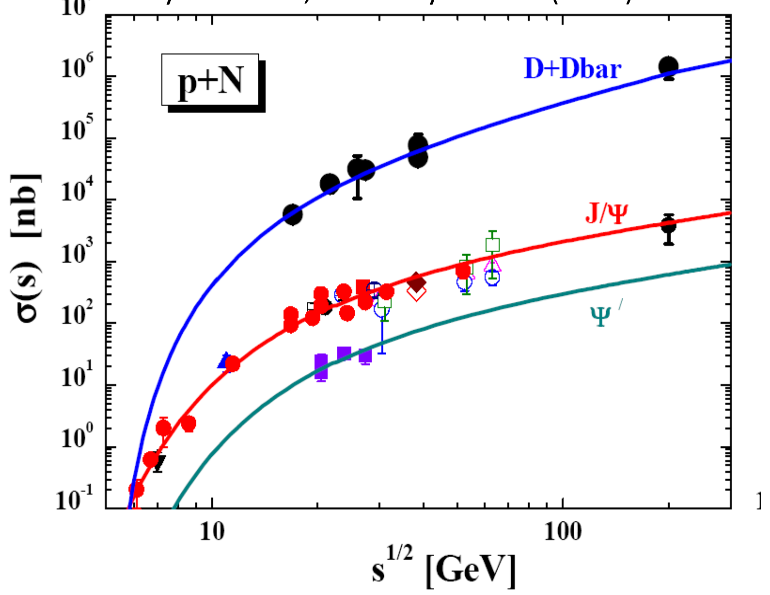


Status:

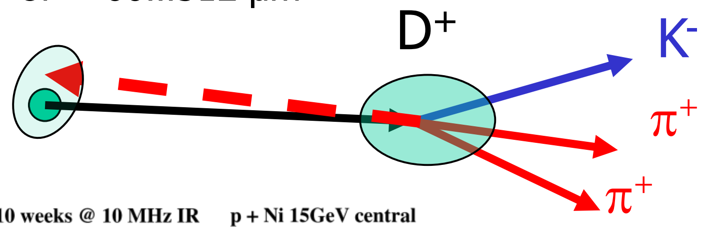
- Prototyping well advanced with PRESTO module: integration concept (vacuum operation / material budget) demonstrated
- Dedicated CBM sensor in synergy with ALICE-ITS upgrade: improved in-pixel logic and data throughput, R/O time ~ 5 µs.
- Dedicated CBM MVD pixels sensor prototype MIMOSIS-0 in house and being characterized.
- First full size sensor MIMOSIS-1 design reviewed, submission in Sept. 19.

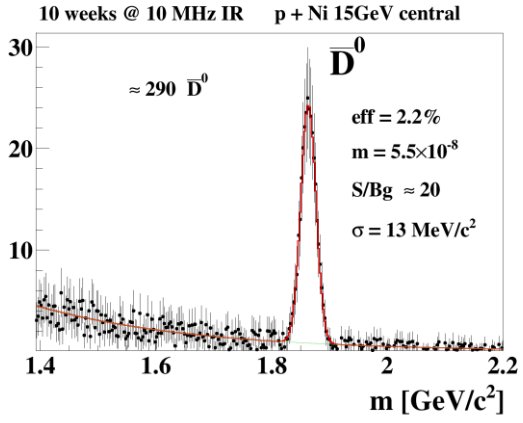
Open charm (MVD + STS + TOF)

O. Lynnik et al., Nucl. Phys. A 786 (2007) 183



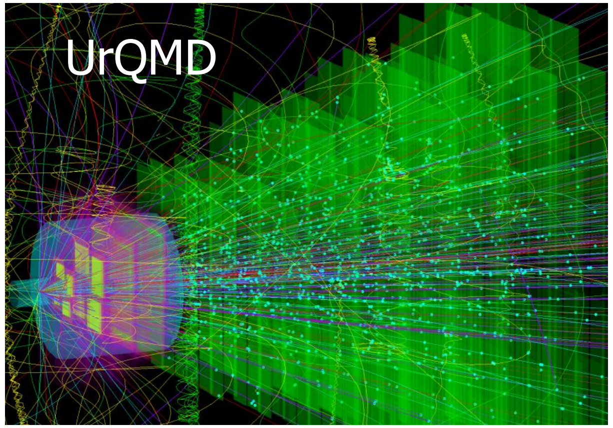
cτ = 60…312 μm

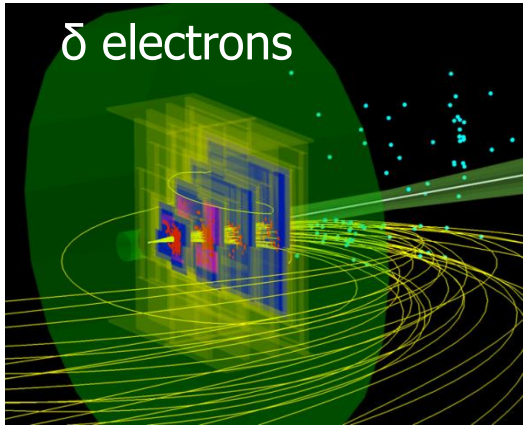




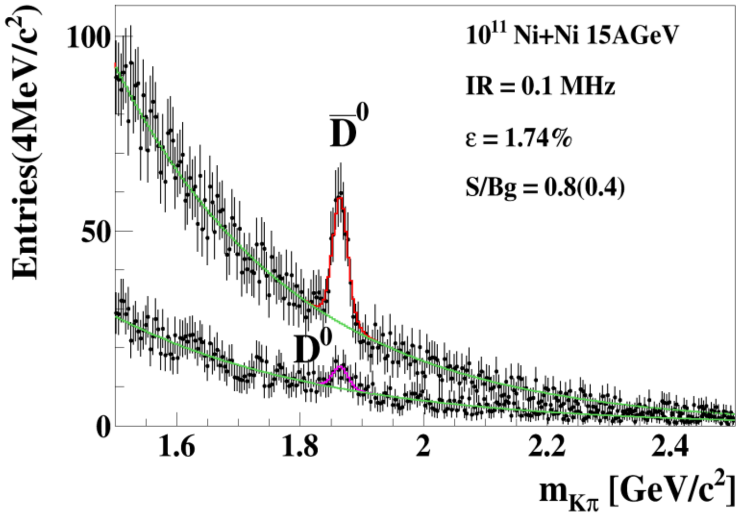
Simulation p + N 15 GeV

Ni + Ni central collisions at 15 A GeV





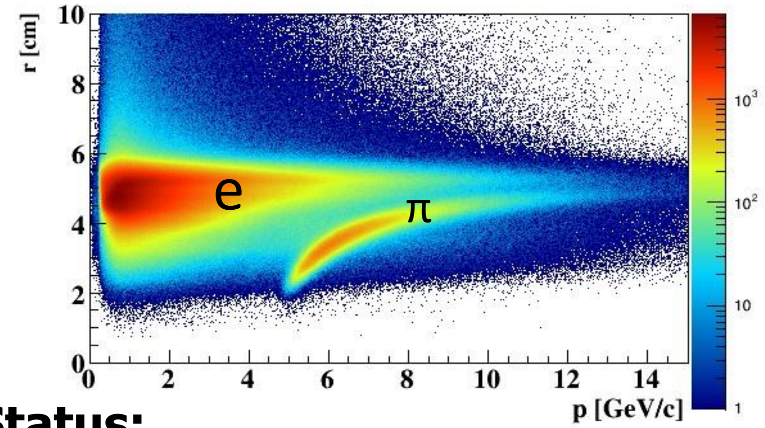
260 $\overline{D^0}$ and 45 D^0 in 2 weeks at IR = 0.1 MHz

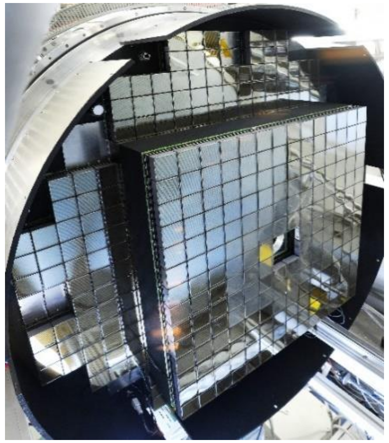


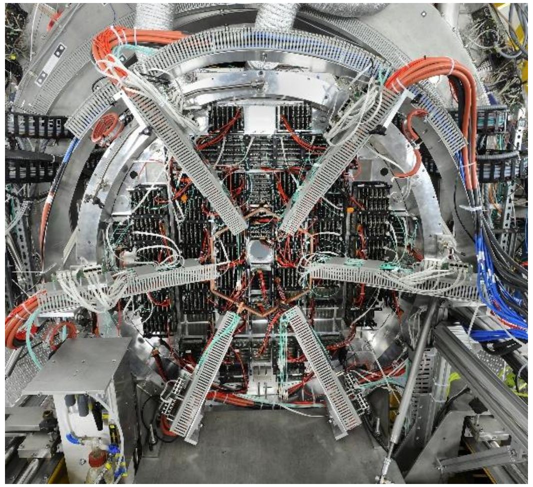
Ring-Imaging Cherenkov (RICH) Detector

➢ Electron identification

In-kind contributions by Germany, Russia:
Univ. Gießen, Univ. Wuppertal, PNPI Gatchina, GSI

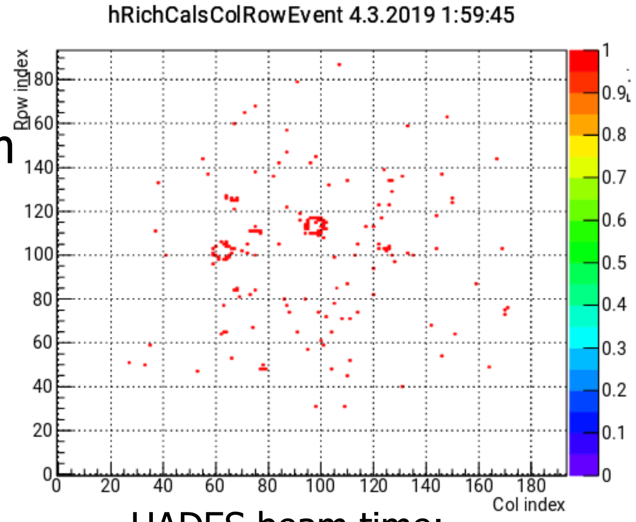






Status:

- All 1100 H12700 MAPMTs delivered and tested, 428 MAPMTs including readout chain integrated in HADES RICH detector; successful participation in HADES beam time 2019
- Concept for new structure of mirror wall with substantially reduced material budget, first prototype under stress test
- First hardware/ software implementation for the measurement of mirror misalignments and software correction cycle ready



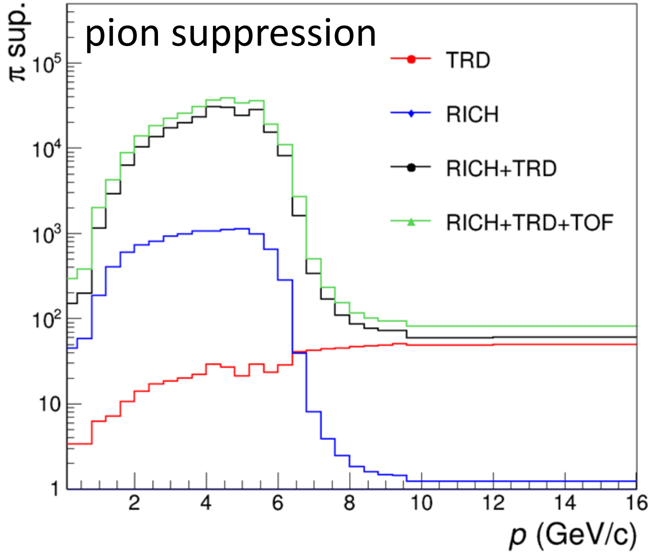
HADES beam time:
ω-meson candidate

Transition Radiation Detector (TRD)

- Electron identification, energy-loss measurements

In-kind contributions by Germany, Romania:
NIPNE Bucharest, Univ. Frankfurt, Univ. Heidelberg, Univ. Münster

Challenge:
$\varepsilon(e^{\pm}) = 90\%$
$\varepsilon(\pi) = 5\%$
at 100 kHz/cm^2



Status:

<u>Beam and laboratory tests</u>

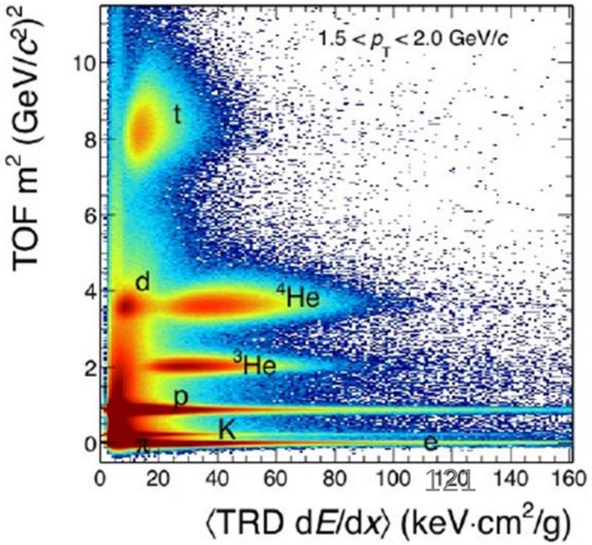
- First results from GIF++: Stable chamber and readout operation at high γ-irradiation
- X-ray test setup in Bucharest: 2-D position reconstruction of irradiated area

<u>Infrastructure</u>

- First design suggestions for support structure (Münster)
- Integration of type-1 modules in progress (Bucharest)

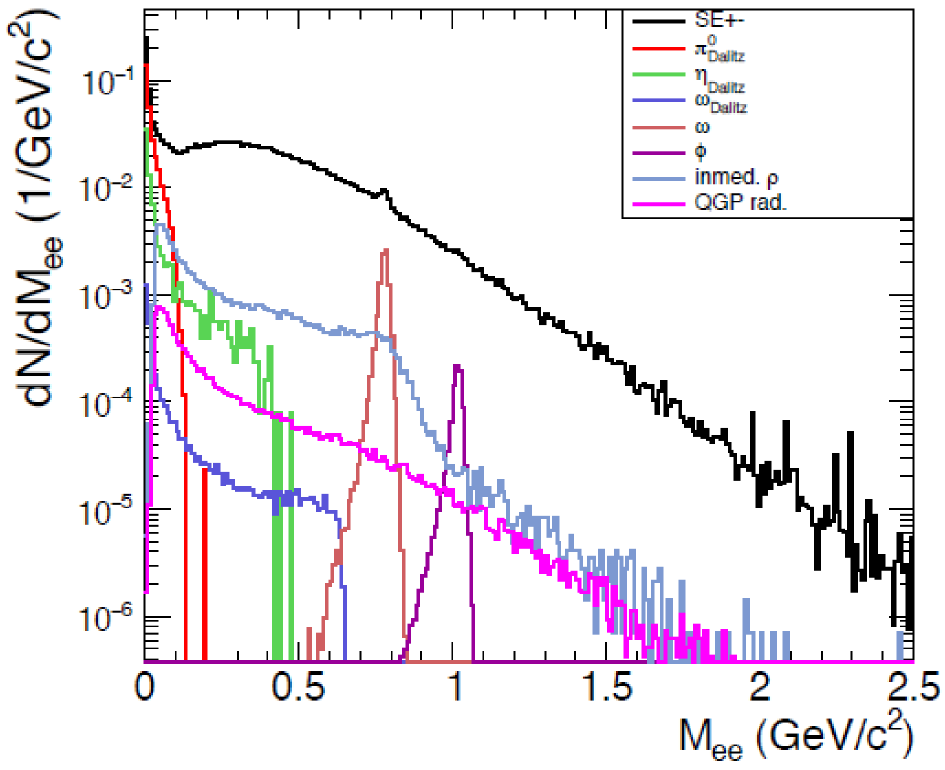
<u>Front-end electronics</u>

- 15000 SPADIC2.2 chips (final version) produced in engineering run
- Chips are packaged (BGA) and being mounted on FEBs



Dilepton invariant mass spectra
for central Au+Au collisions at 8A GeV

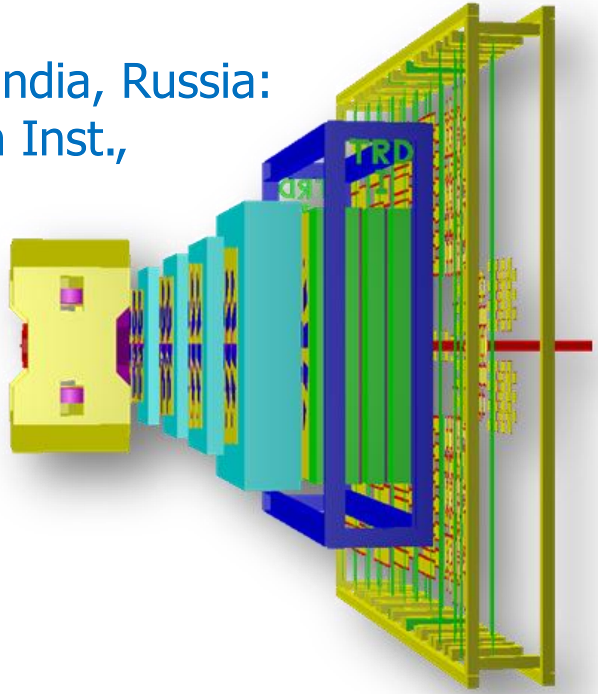
Di-electrons: MVD+STS+RICH+TRD+TOF



Muon Chamber (MuCh) System

- ➢ Muon identification

In-kind contributions by india, Russia:
VECC Kolkata +12 Indian Inst.,
PNPI Gatchina,

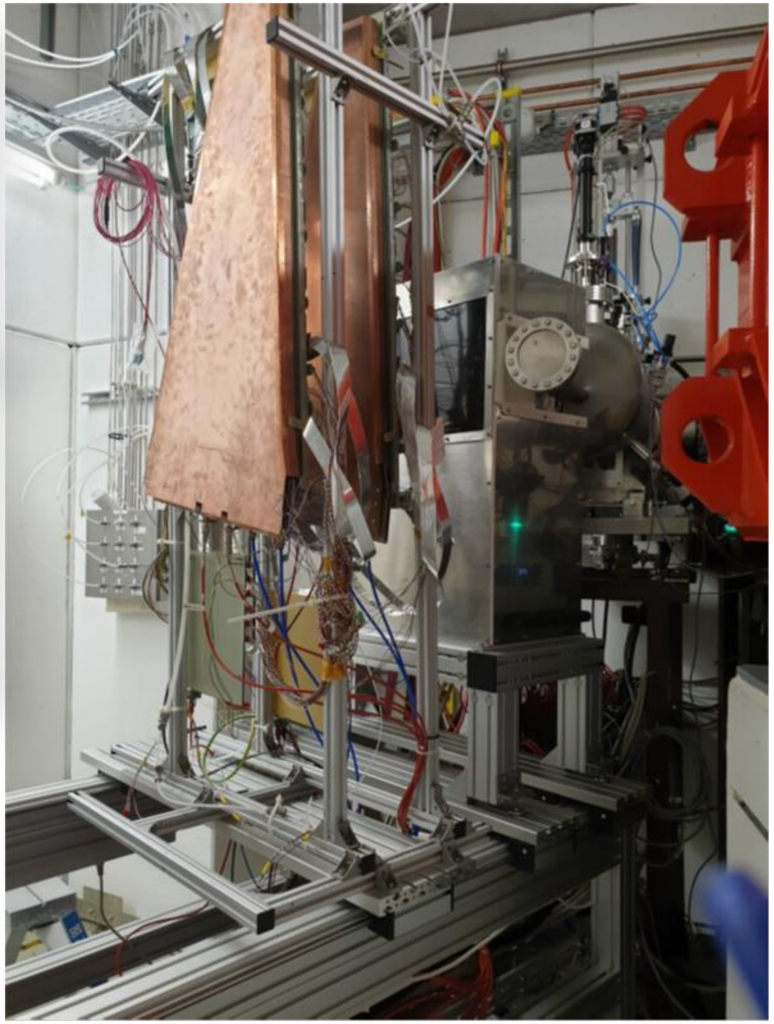


<u>MuCh at SIS100:</u>

- ➢ 2 GEM triplets, 2 tracking detector tripletts,TRD
- ➢ Bakelite RPCs under investigation for stations 3 and 4.
- ➢ High rate (kHz) operationrequires low resistivity Bakelite

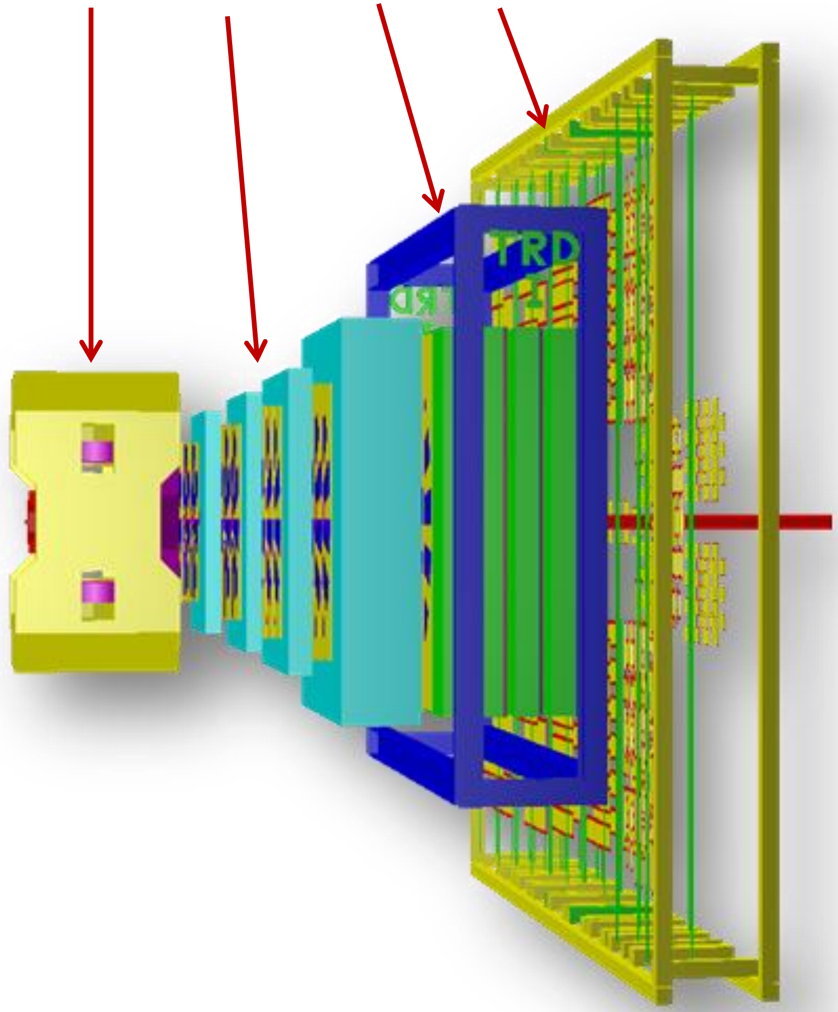
Status:

- ➢ TDR approved in Feb. 2015
- ➢ Full size prototype GEM detectors build at VECC and under test in mCBM
- ➢ The GBTx emulator was implemented and tested.
- ➢ mainframe and absorbers and under construction at PNPI

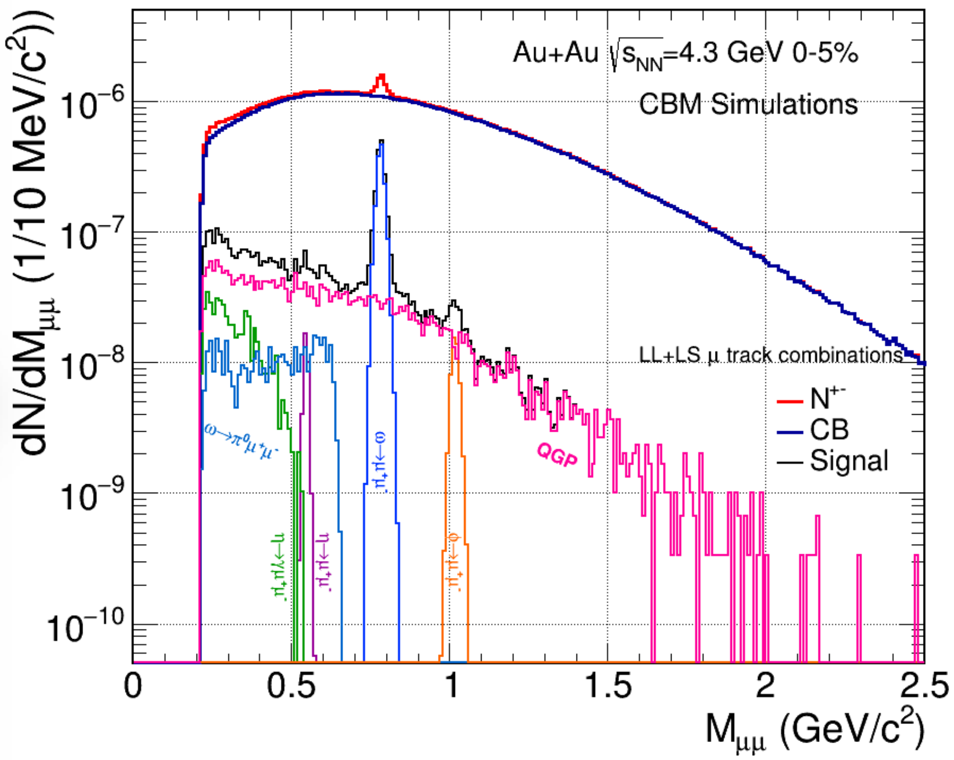


Full size GEM detectors tested with free-streaming read-out electronics in the mCBM setup at GSI 2019

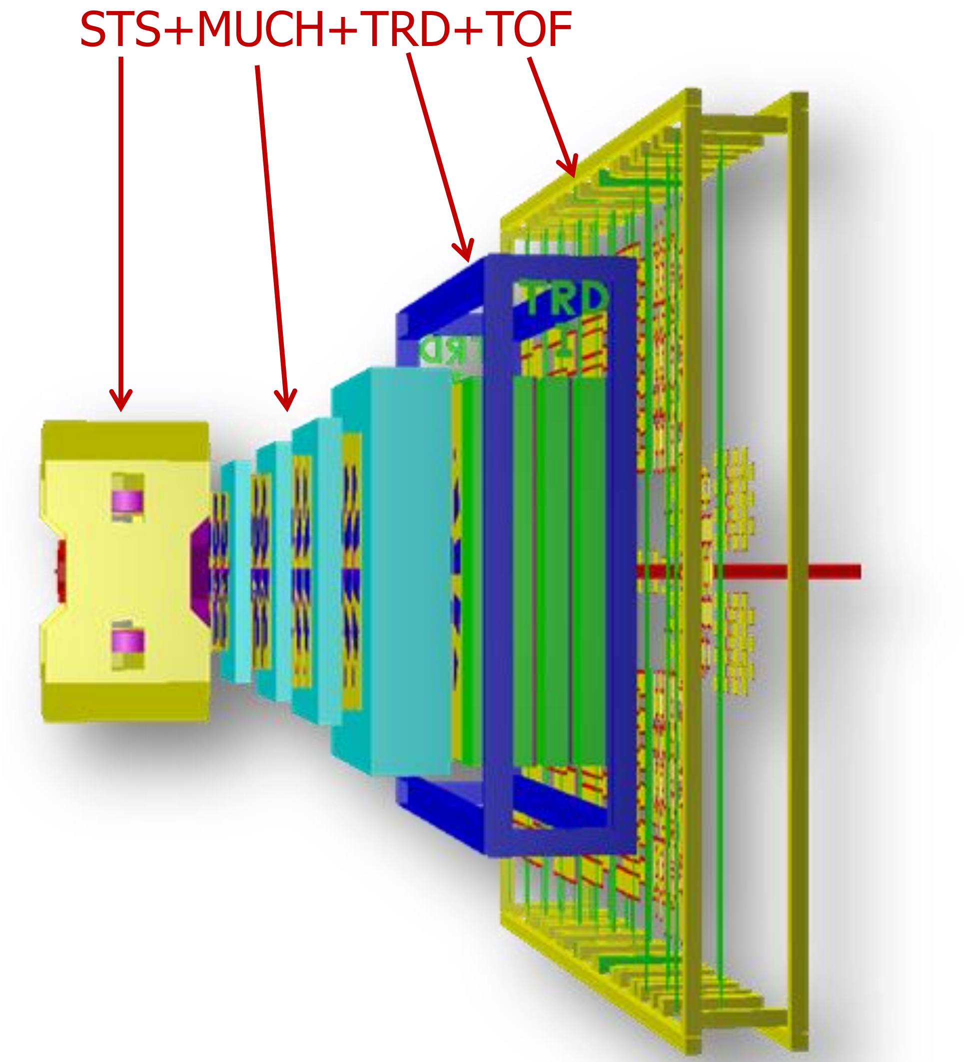
Dilepton invariant mass spectra for central Au+Au collisions at 8A GeV



Di-muons

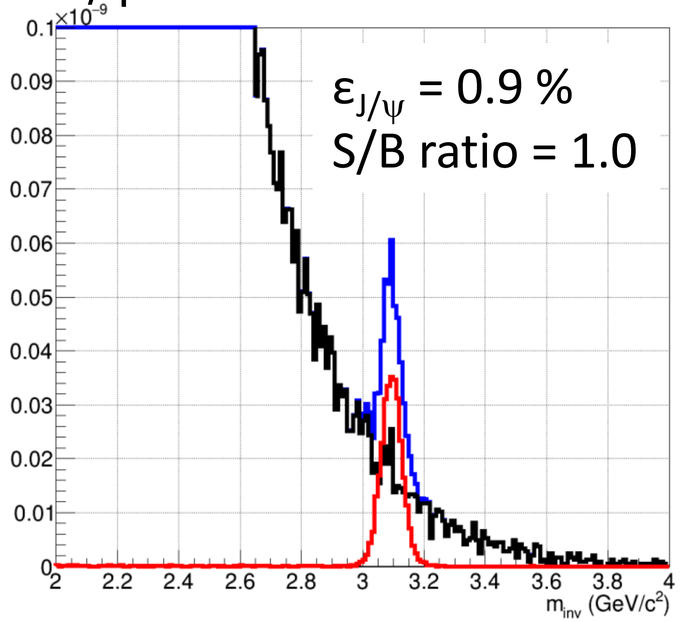


Charmonium
for central Au+Au collisions at 10A GeV



Sub-threshold charm production in nuclear collisions J. Steinheimer, A. Botvina, M. Bleicher arXiv:1605.03439

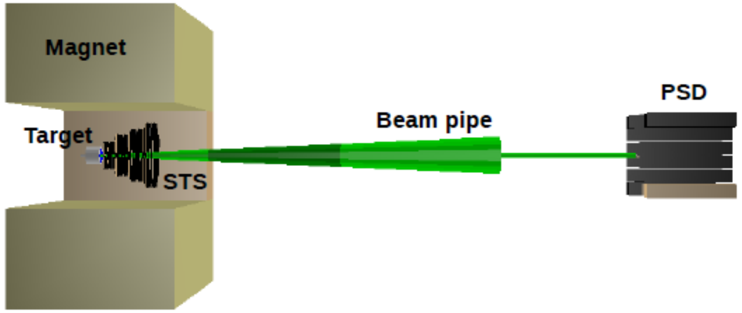
6480 J/ψ in 2 weeks at IR = 10 MHz

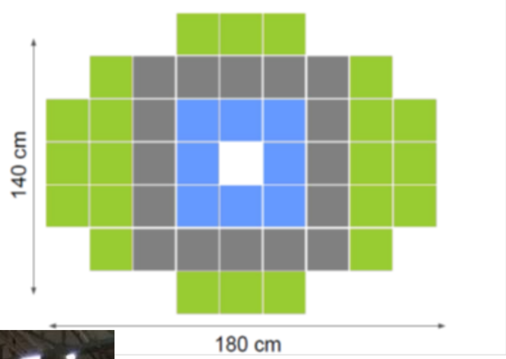


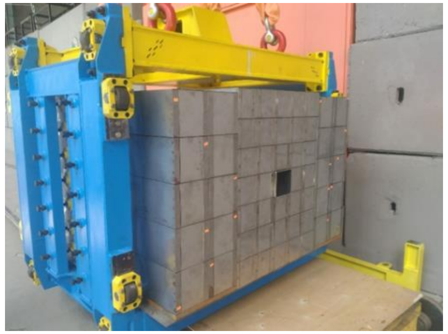
Projectile Spectator Detector

- determination of collision centrality and orientation of the reaction plane

In-kind contributions by Russia, Czech Rep.: INR Moscow, TU Darmstadt, Rez Prague







PSD at
BM@N JINR
20 modules.
June 2019

PSD at
NA61 CERN SPS.
13 modules.
April 2019

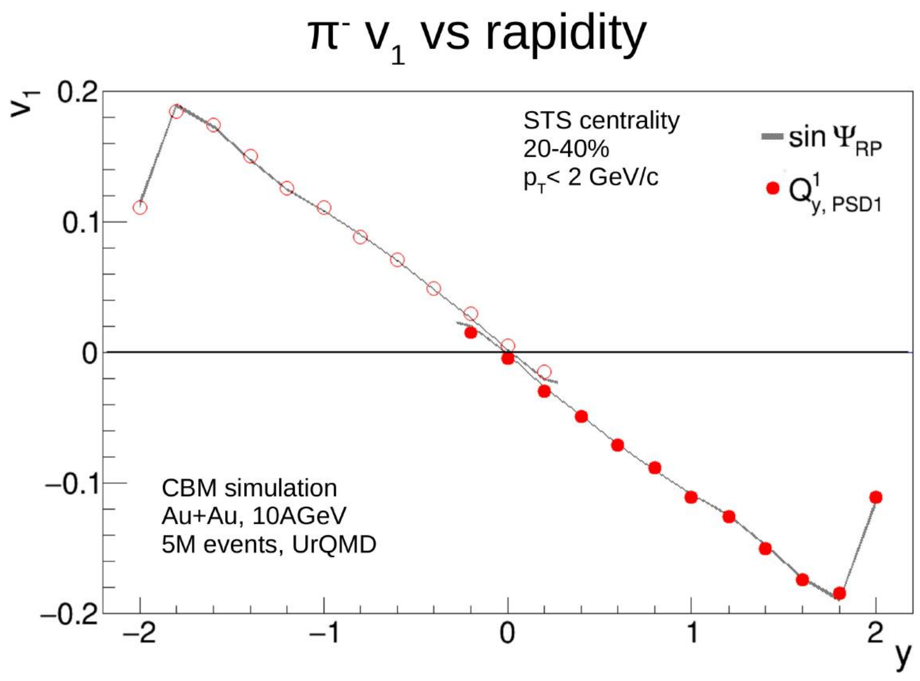
PSD at
mCBM GSI.
1 module.
April 2019

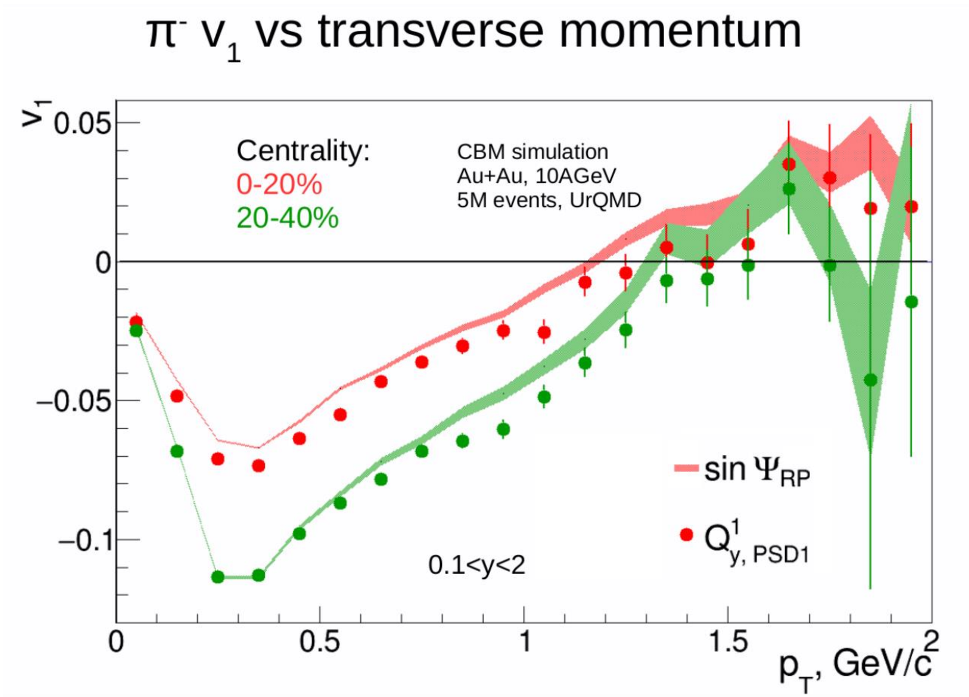
Status:

- TDR approved Feb. 2015;
- At present, all 44 PSD CBM modules have been fully assembled at INR, Moscow;
- Prototype of the PSD readout electronics based on PANDA ECAL sampling ADC is tested and integrated for mPSD readout at mCBM;
- PSD modules tested with cosmic rays at INR Moscow and withhadron beams at CERN
- Most of the PSD CBM modules have been already integrated in the BM@N, NA61 and mCBM experiments and will be used during FAIR-Phase-0;
- Reconstruction algorithms for the reaction plane and centrality determination were developed

Projectile Spectator Detector

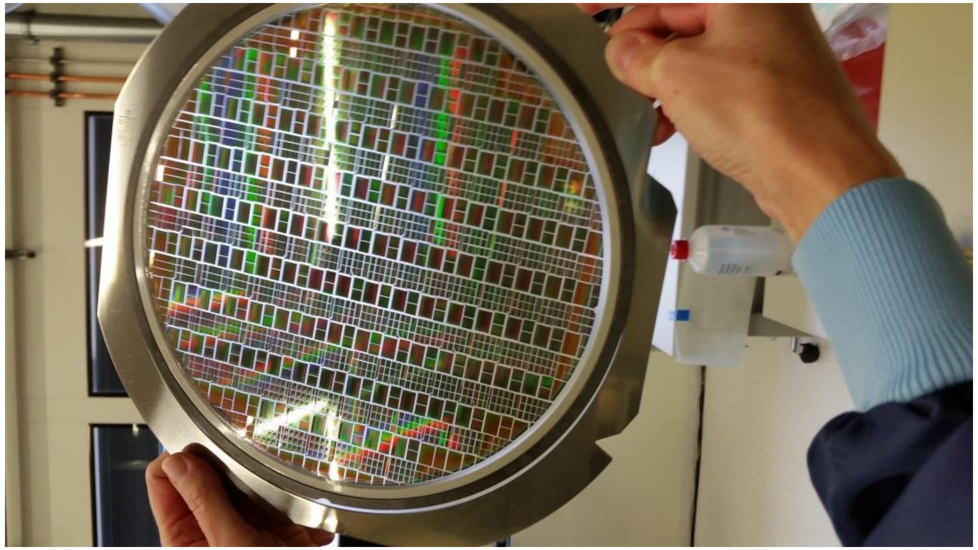
Reconstructed directed flow of π^- in Au+Au collisions at 10 A GeV





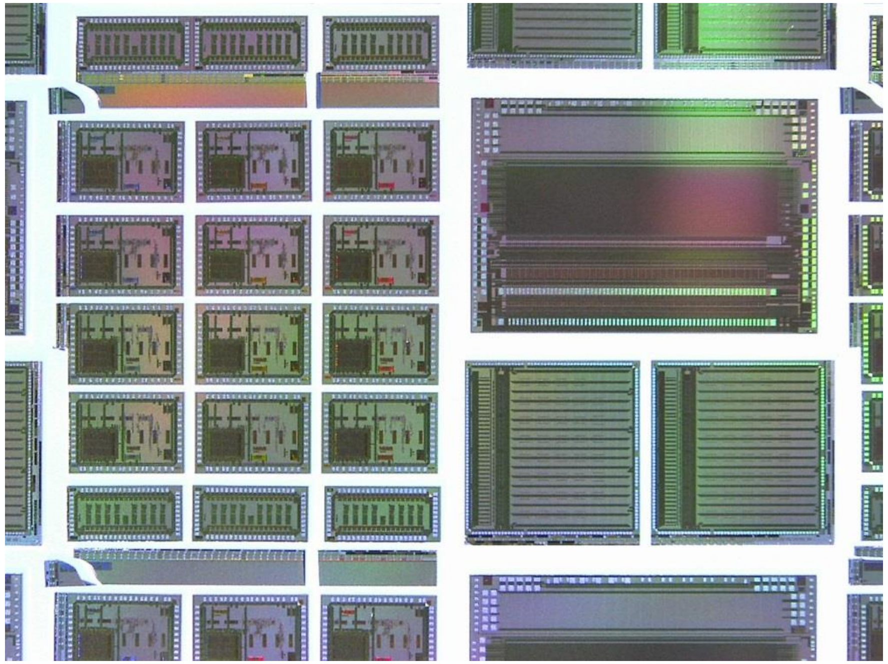
Successful Multi Project Chip Prototyping for CBM

In-kind contributions by Germany, Poland: GSI Darmstadt, Univ. Heidelberg, AGH Krakow



5 final prototype chips for CBM:

- STS-XYTER and Much-XYTER
- Get4 in two versions for TOF
- PADI production for CBM@STAR
- SPADIC for CBM-TRD

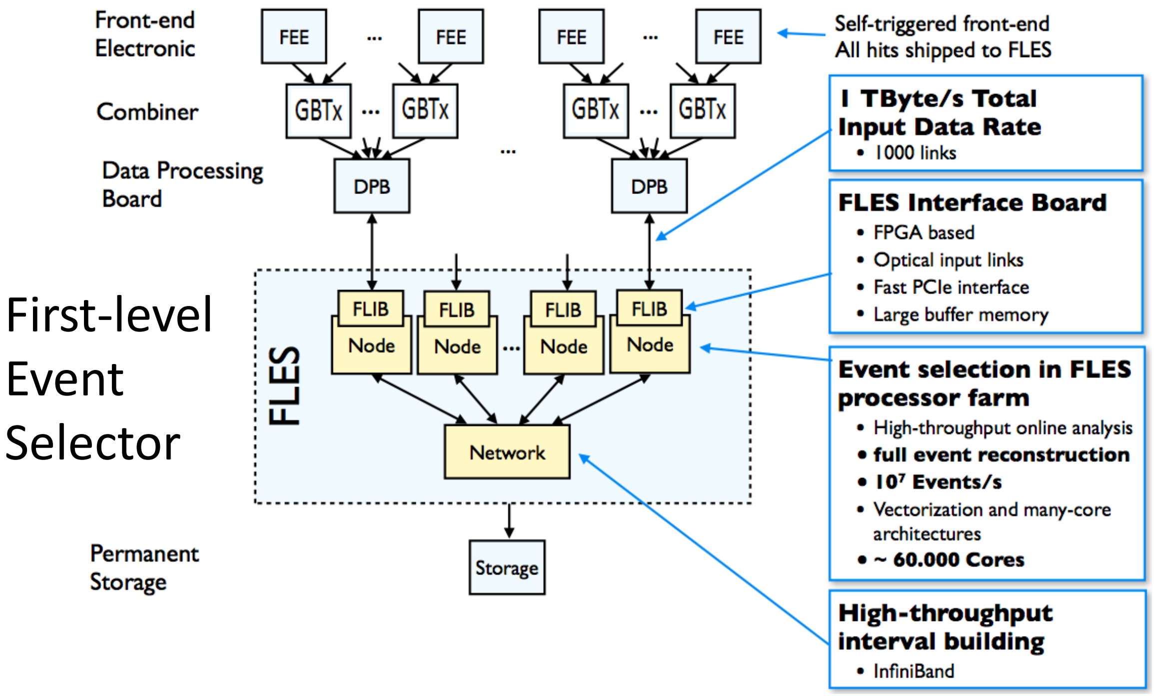


Produced Chips:

- Several thousand STS-XYTER and MUCH-XYTER Chips for detector prototyping
- Full number of PADI Chips needed for CBM-Tof at STAR
- Full number of Get4 TDC chips needed for CBM-Tof at STAR
- Full number of SPADIC Chips for CBM-TRD

CBM online systems

In-kind contributions by Germany, Poland, India:
Univ. Frankfurt, FIAS, GSI Darmstadt, KIT Karlsruhe, IIT Kharagpur, Warsaw UT

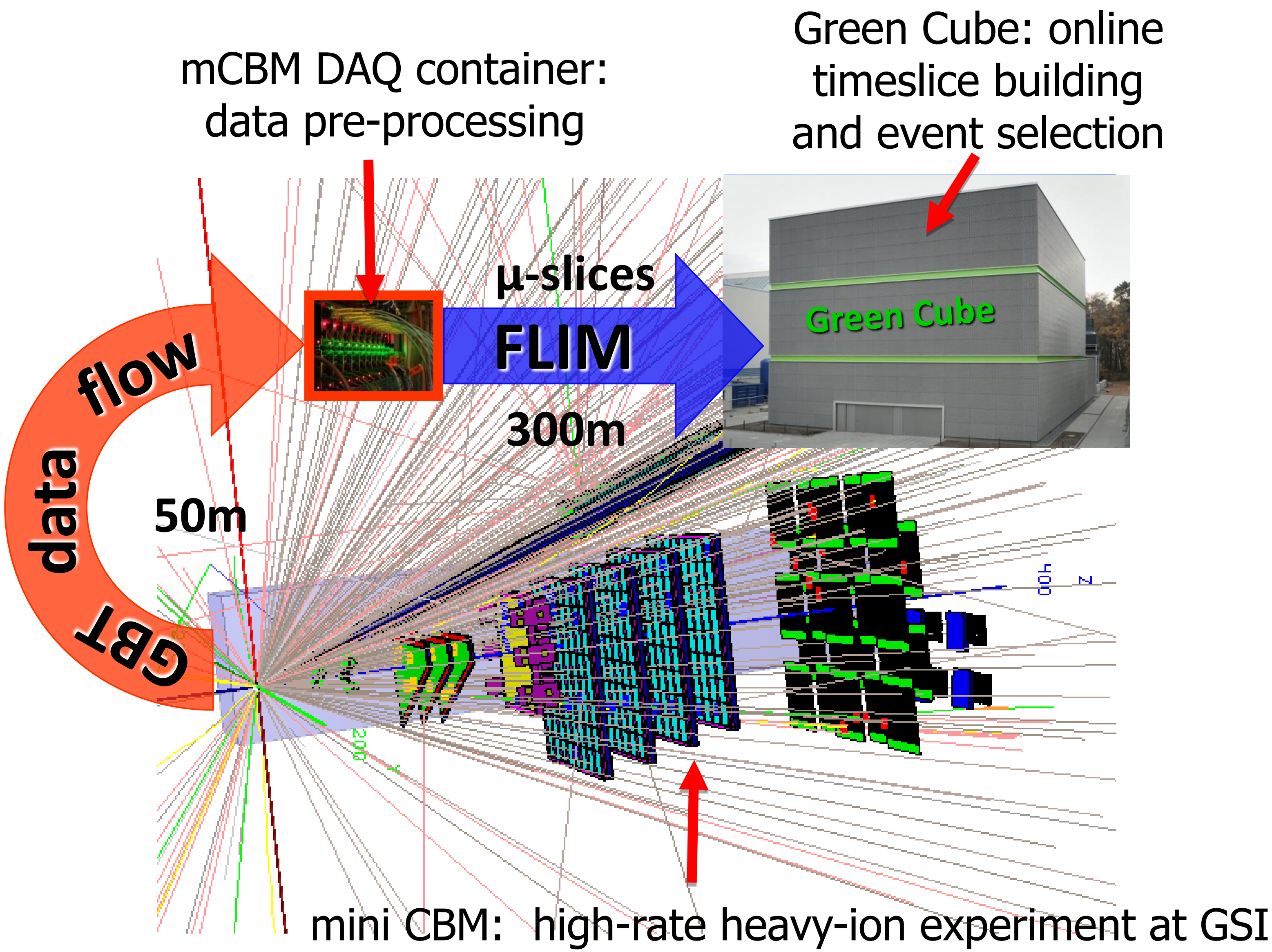


Novel readout system: no hardware trigger on events, detector hits with time stamps, full online 4-D track and event reconstruction.

Status:

- FLES input interface designed
- FLESnet software successfully applied in beam tests with detectors
- TDRs on DAQ, FLES

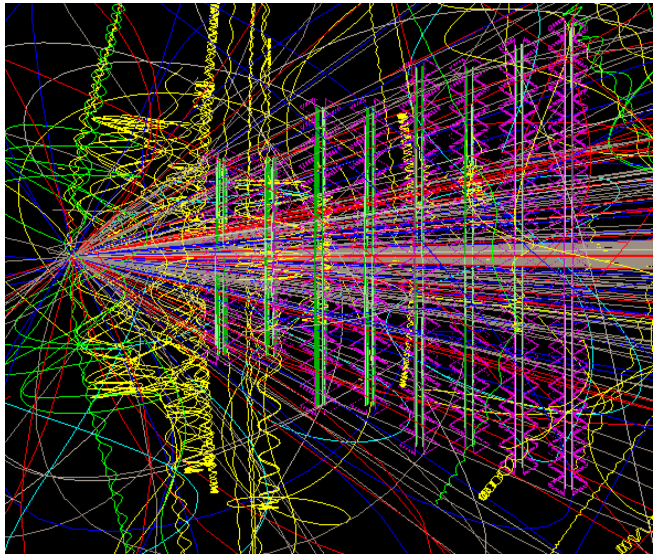
mCBM DAQ



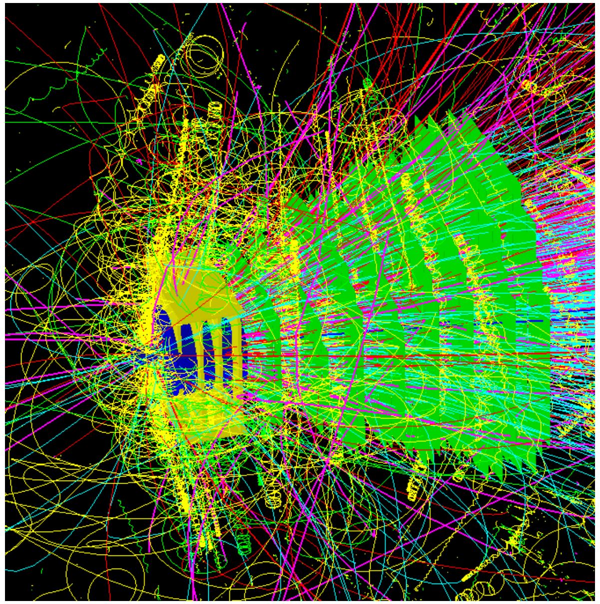
mCBM DAQ container:
data pre-processing
Green Cube: online
timeslice building
and event selection
µ-slices
FLIM
300m
Green Cube
data flow
GBT
50m
mini CBM: high-rate heavy-ion experiment at GSI

4D track and event reconstruction

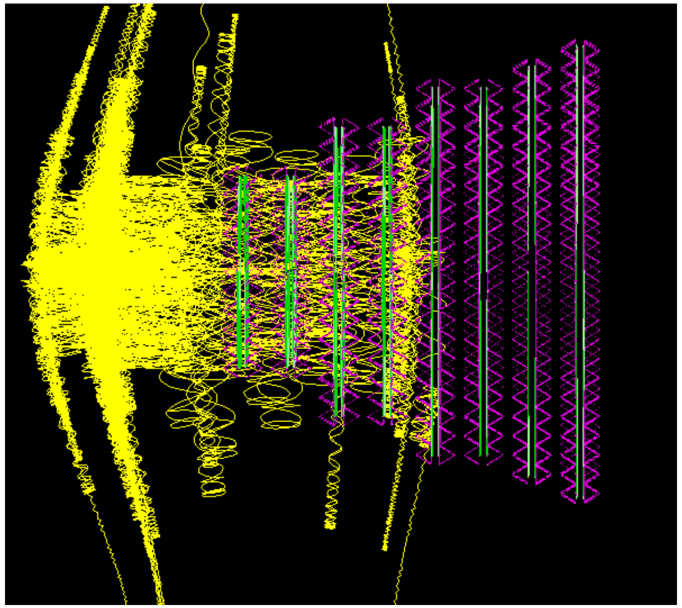
Au+Au 8 A GeV
peripheral collision
UrQMD + GEANT3



Au+Au 8 A GeV
central collision
UrQMD + GEANT3

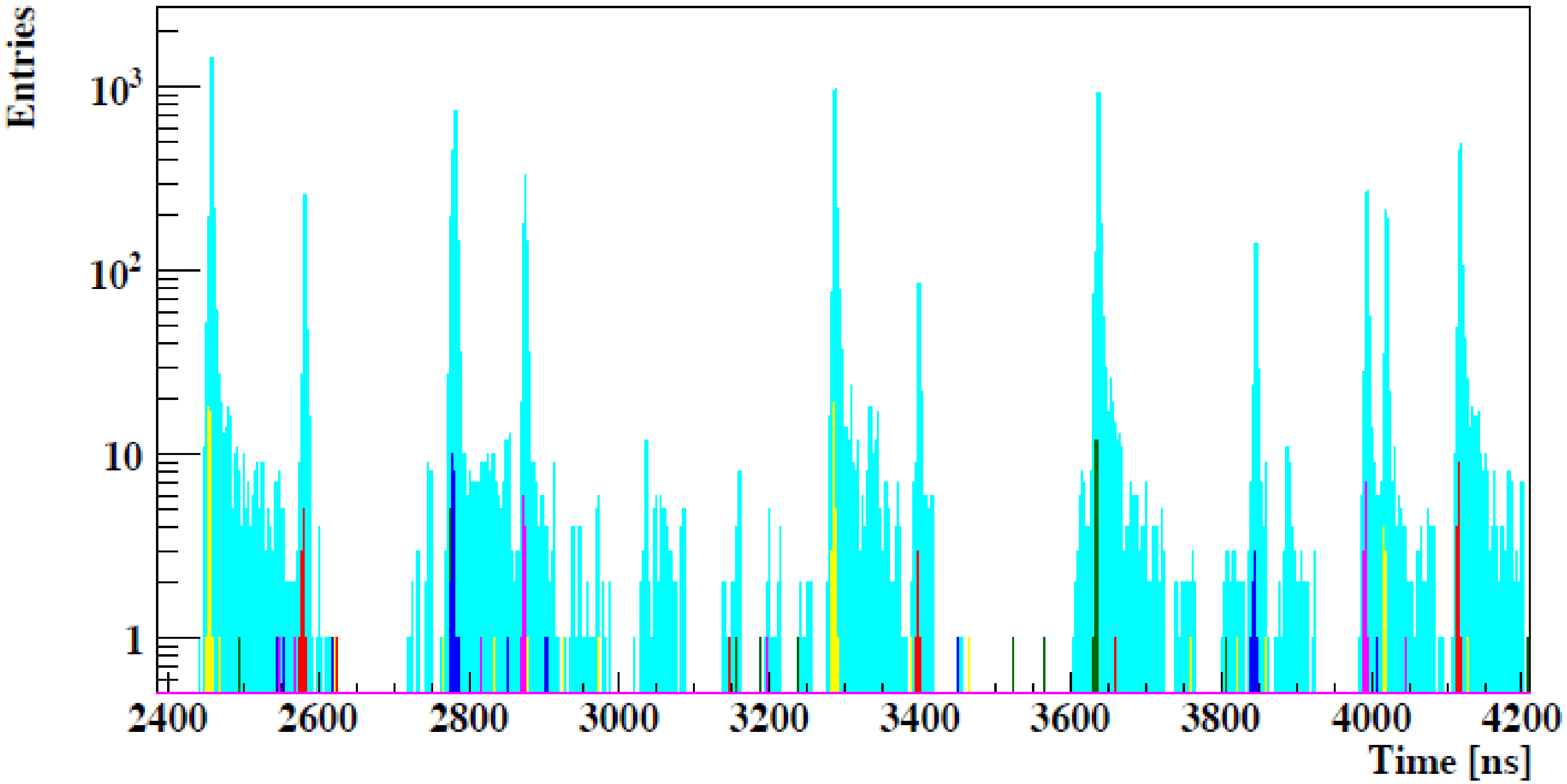


Au beam 8 A GeV
one single ion
passing the target
FairIon + GEANT3



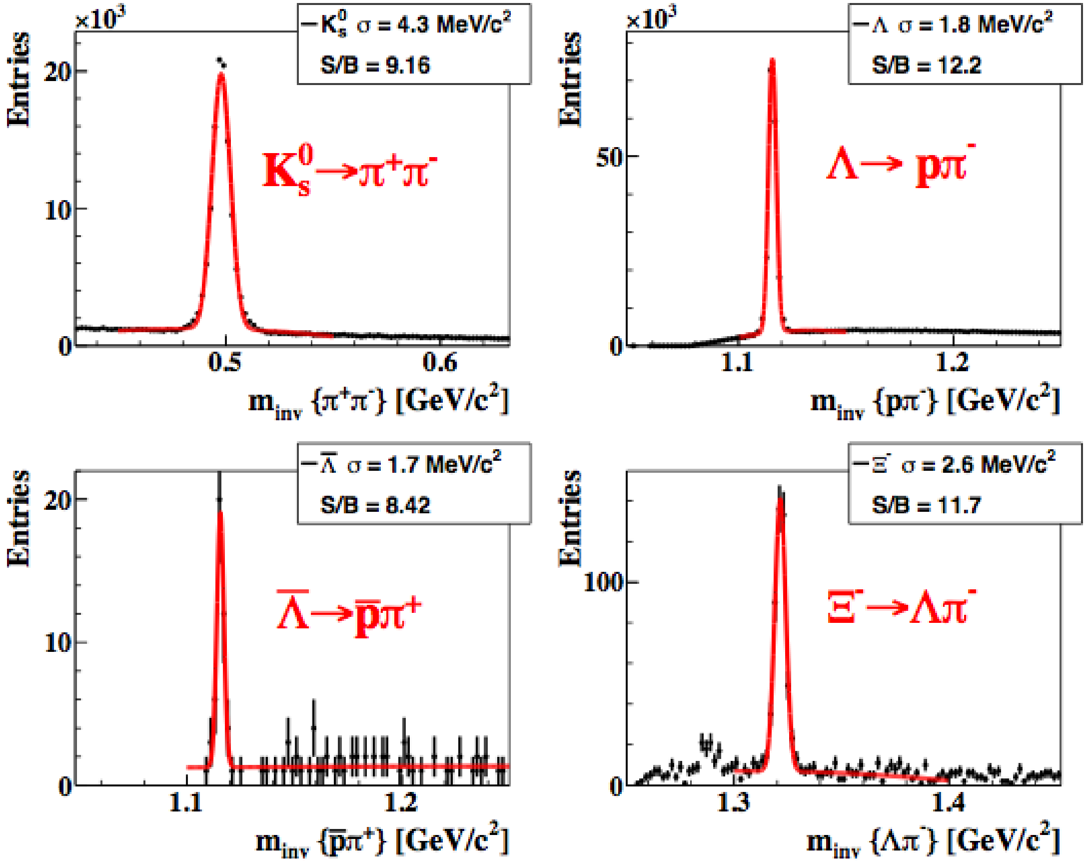
4D track and event reconstruction

Hit and track time distribution for
Au+Au 10 AGeV mbias events at 10 MHz (UrQMD)



4D reconstruction

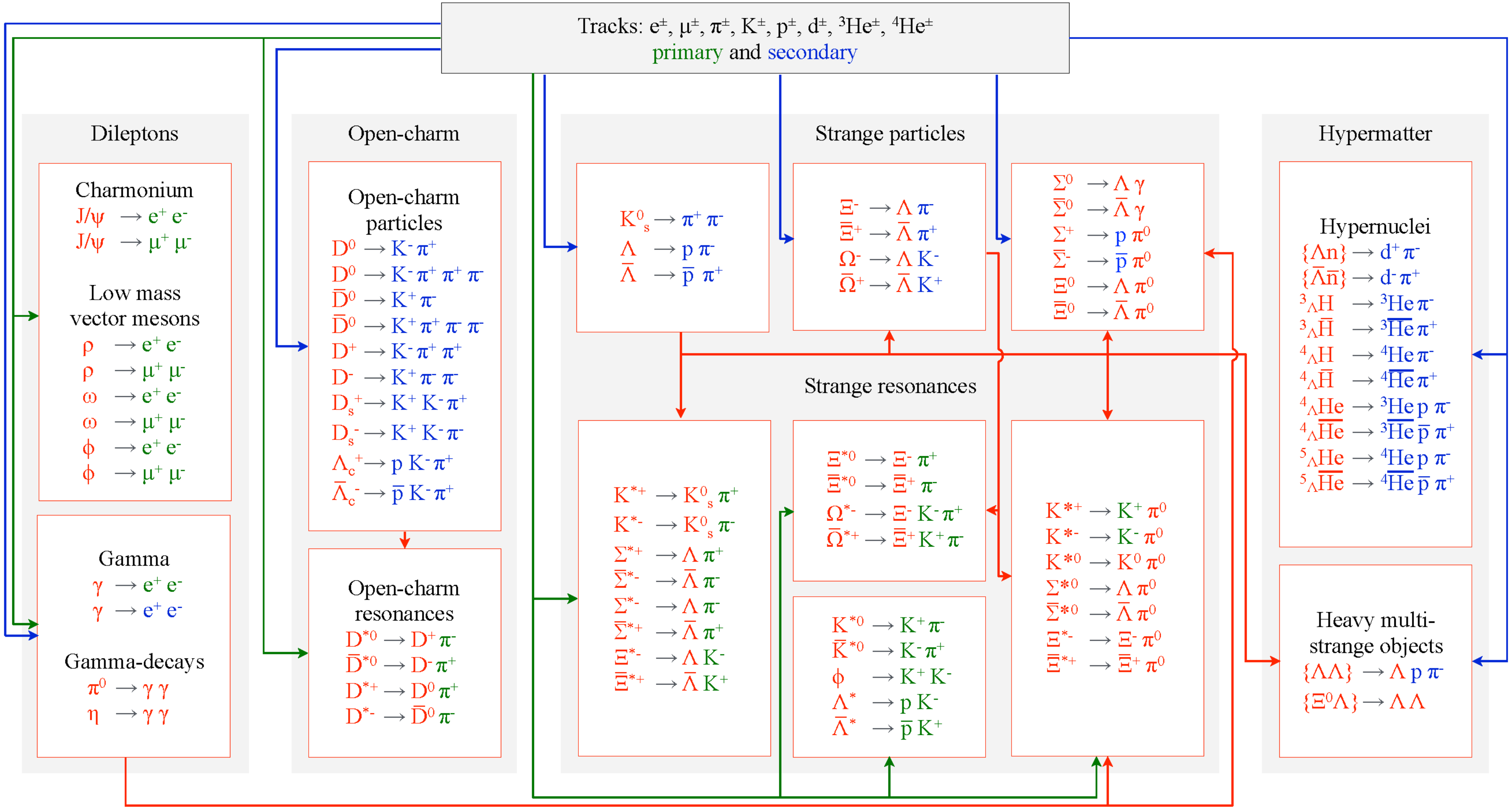
10 MHz Au+Au, 10 AGeV,
300k mbias UrQMD events, ideal PID



		K^0s	Λ	$\bar{\Lambda}$	Ξ^-
3 D	ε_{method}, %	68.6	61.2	67	46.7
	$\varepsilon_{4\pi}$, %	20.7	19.4	28	10.5
	S/B	10.6	23.7	12.7	21.8
0.1 MHz	ε_{method}, %	68.5	62.0	62	45.2
	$\varepsilon_{4\pi}$, %	21.1	20.6	32	11.7
	S/B	9.8	12.9	10	14.2
1 MHz	ε_{method}, %	67.5	60.9	59	46.0
	$\varepsilon_{4\pi}$, %	19.4	18.7	26	10.6
	S/B	9.3	12.5	10	12.3
10 MHz	ε_{method}, %	66.8	60.0	64	41.8
	$\varepsilon_{4\pi}$, %	17.6	16.7	28	8.2
	S/B	9.2	12.2	8	11.7

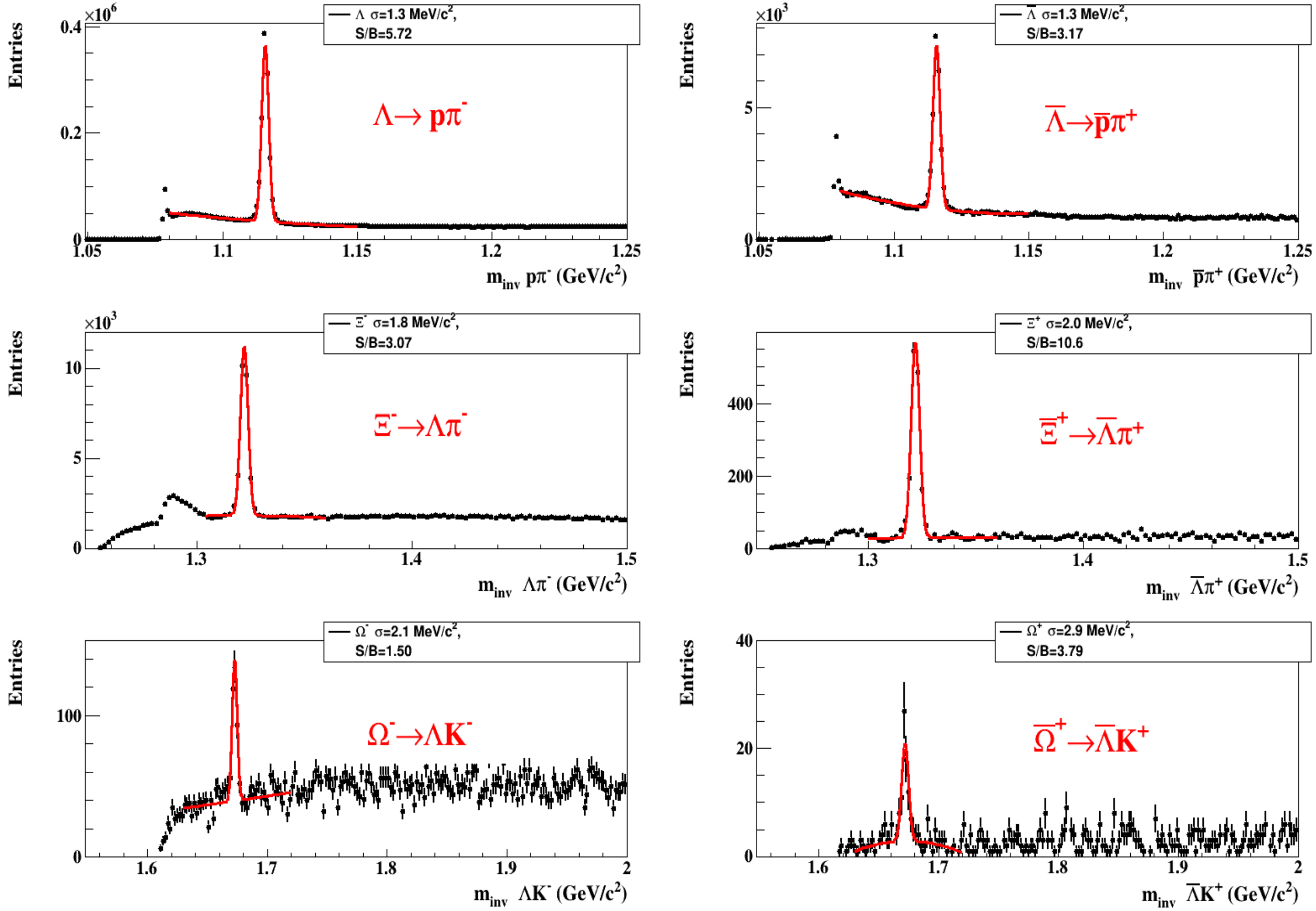
all mother particles emitted from one primary vertex

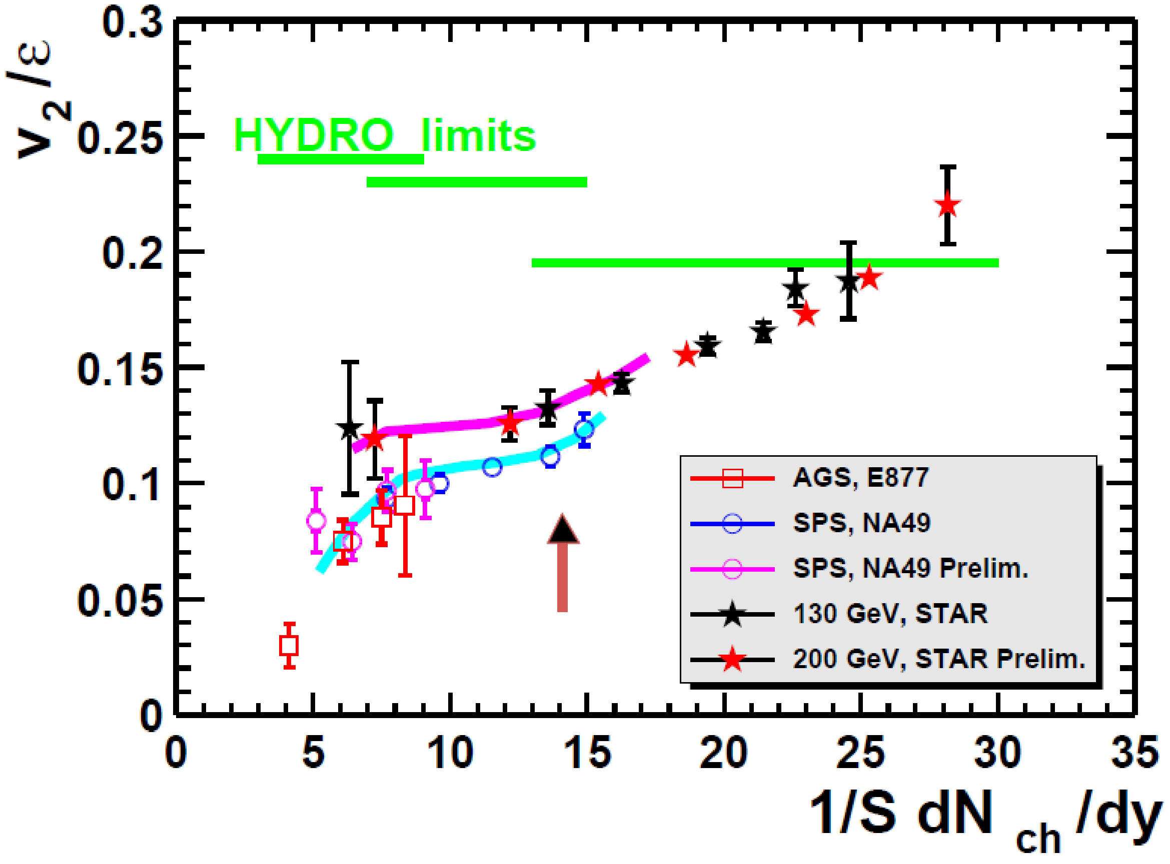
Titelmasterformat durch Klicken bearbeiten



successfully used online in the STAR experiment

Real data analyzed with CBM KF Particle Finder
STAR 4.4 M mbias AuAu collisions, $\sqrt{s_{NN}}$=7.7 GeV





What makes 3FD-Hydro so special to be used even at SIS energies, despite being below the HYDRO limits (perfect fluid)?

This indicates the transition from density-driven dynamics with non-vanishing viscosity to the geometry-driven dynamics of almost perfect hydrodynamics. It suggests that at RHIC energies particle densities are already large enough, respectively interaction lengths short enough, for the systems to reach the hydrodynamical limit.