The $\bar{\text{P}}$ANDA Experiment at FAIR

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Hadrons from Quarks and Gluons
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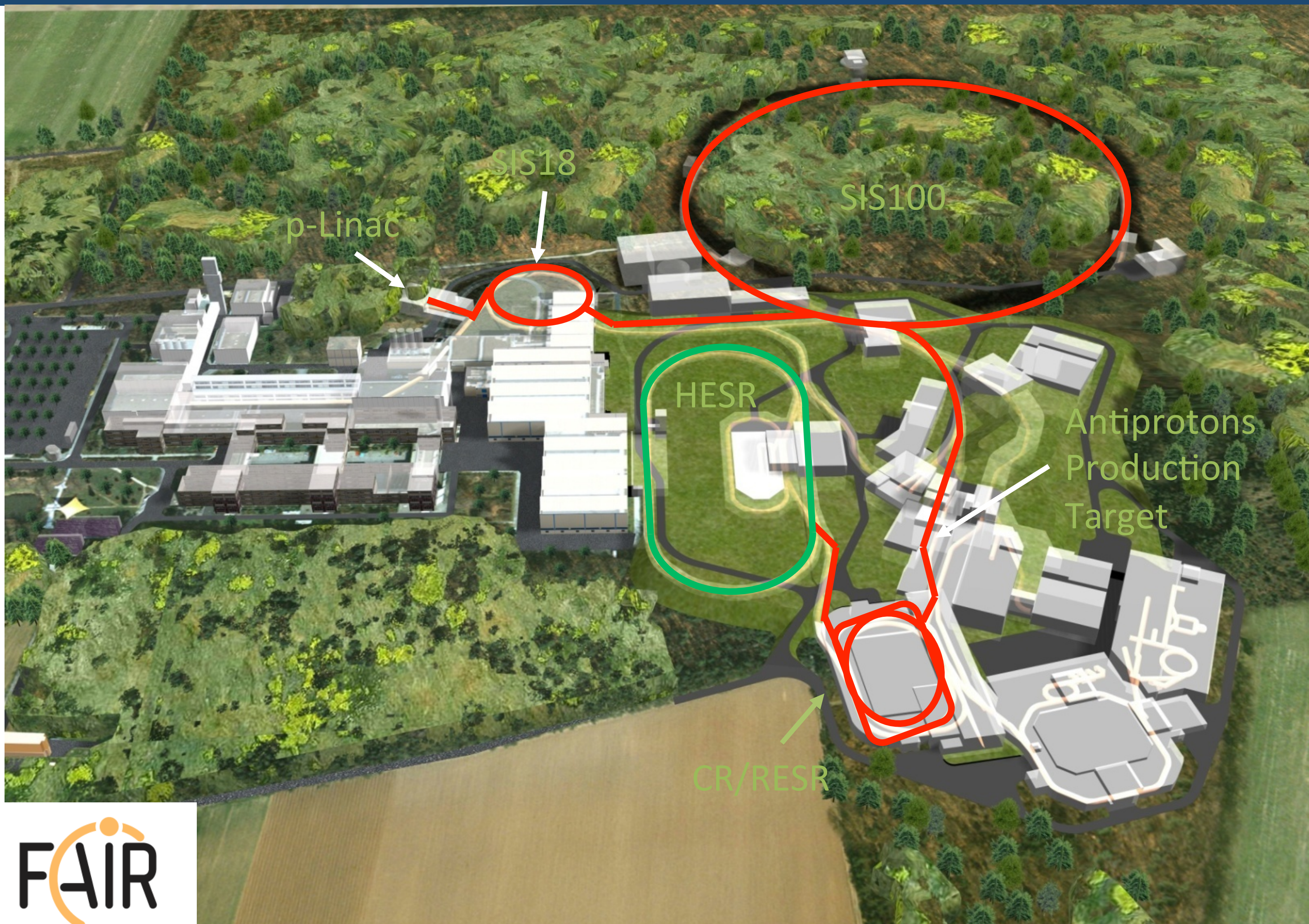
Outline

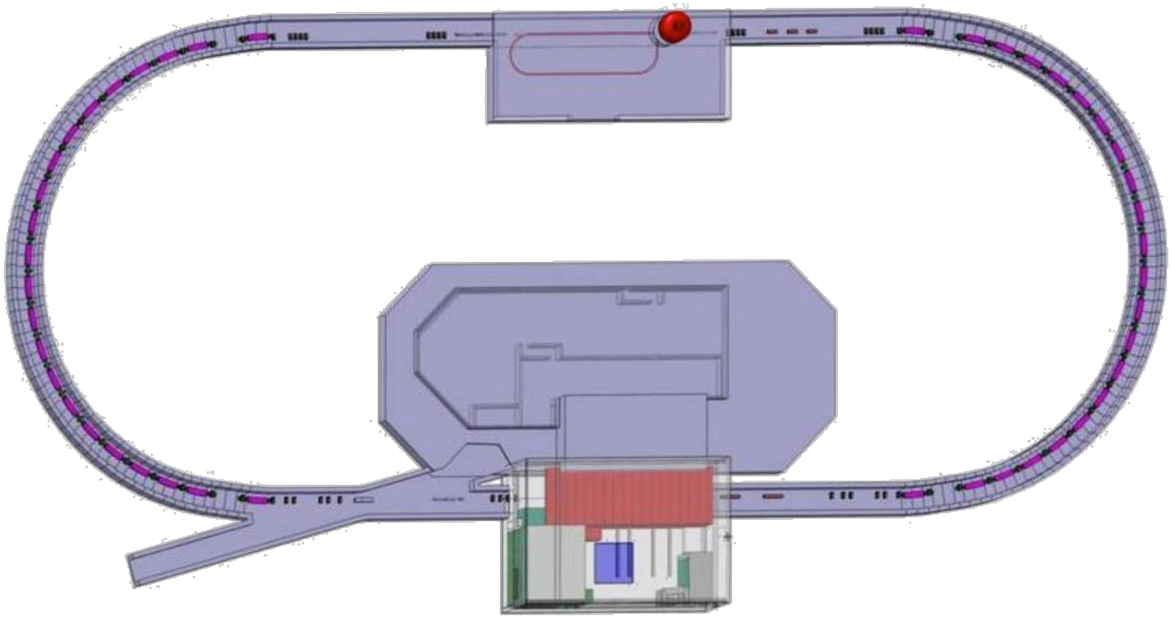
- Introduction
  - The FAIR facility
  - Experimental Method
- The $\bar{\text{P}}$ANDA experiment
  - The $\bar{\text{P}}$ANDA Physics Program
  - The $\bar{\text{P}}$ANDA Detector
- Summary and Outlook

GSI Helmholtz Center and FAIR



Facility for Antiproton and Ion Research

High-Energy Storage Ring



Production rate 2×10^{7}/sec

P_{beam} = 1.5 - 15 GeV/c

Internal Target 4×10^{15} cm^{-2}

High resolution mode

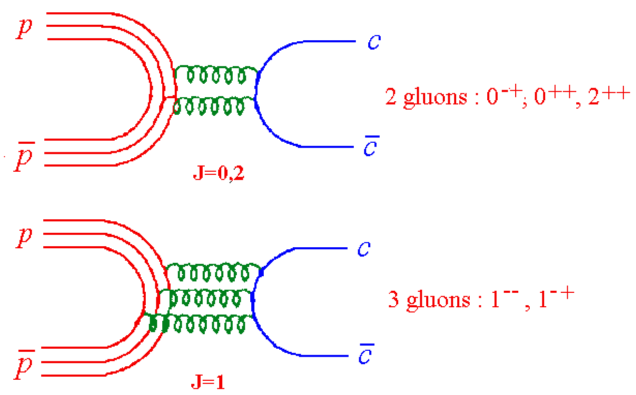
$N_{stored} = 10^{10}\ \bar{p}$
$dp/p \sim 3 \times 10^{-5}$ (electron cooling)
Lumin. = 10^{31} cm^{-2} s^{-1}

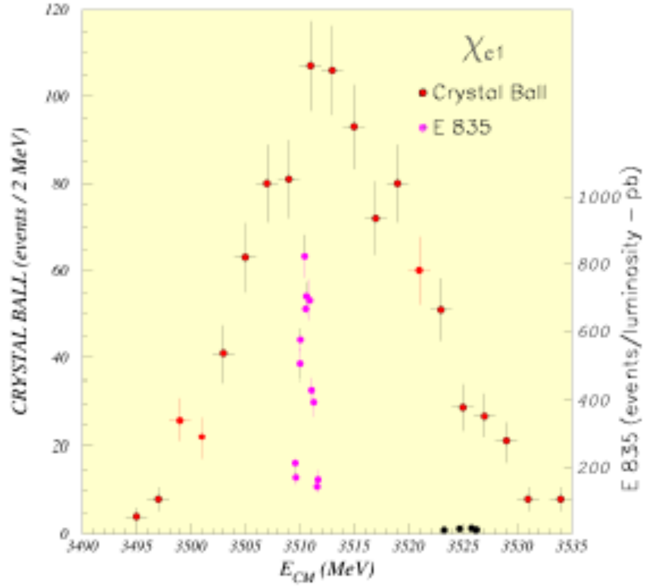
High luminosity mode

$N_{stored} = 10^{11}\ \bar{p}$
Lumin. = 2×10^{32} cm^{-2} s^{-1}
$dp/p \sim 10^{-4}$ (stochastic cooling)

p̄p Annihilation

In p̄p collisions the coherent annihilation of the 3 quarks in the p with the 3 antiquarks in the p̄ makes it possible to form directly states with all non-exotic quantum numbers.





The measurement of masses and widths is very accurate because it depends only on the beam parameters, not on the experimental detector resolution, which determines only the sensitivity to a given final state.

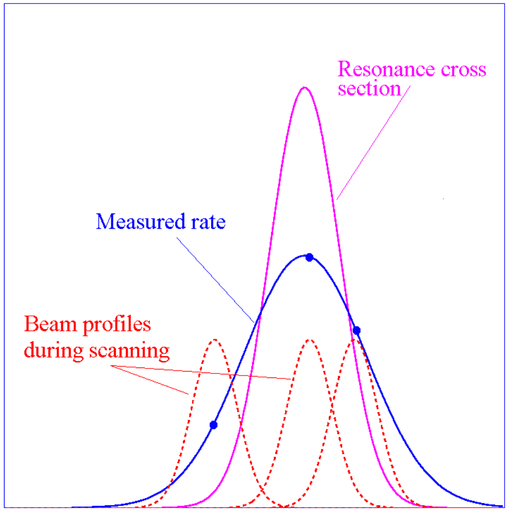
Experimental Method

The cross section for the process:

$\bar{p}p \rightarrow R \rightarrow$ final state

is given by the Breit-Wigner formula:

$$\sigma_{BW} = \frac{2J+1}{4}\frac{\pi}{k^2}\frac{B_{in}B_{out}\Gamma_R^2}{(E-M_R)^2+\Gamma_R^2/4}$$



The production rate ν is a convolution of the BW cross section and the beam energy distribution function $f(E,\Delta E)$:

$$\nu = L_0\left\{\varepsilon\int dE f(E,\Delta E)\sigma_{BW}(E)+\sigma_b\right\}$$

The resonance mass M_R, total width Γ_R and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy E.
With the PANDA setup widths down to ≈50 KeV will be accessible.

The $\bar{\text{P}}$ANDA Experiment

The $\bar{\text{P}}$ANDA Physics Program

The $\bar{\text{P}}$ANDA Detector

P̄ANDA Physics Program

- HADRON SPECTROSCOPY
  - CHARMONIUM
  - GLUONIC EXCITATIONS
  - OPEN CHARM
  - STRANGE AND CHARMED BARYONS
- NUCLEON STRUCTURE
  - GENERALIZED DISTRIBUTION AMPLITUDES (GDA)
  - DRELL-YAN
  - ELECTROMAGNETIC FORM FACTORS
- HYPERNUCLEAR PHYSICS
- HADRONS IN THE NUCLEAR MEDIUM

FAIR/PANDA/Physics Book i

Physics Performance Report for:

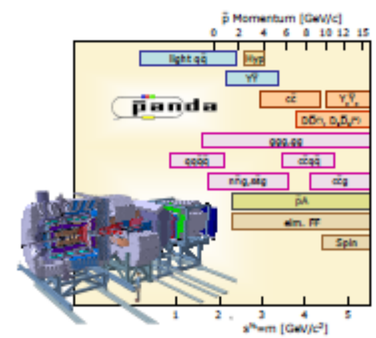
P̄ANDA

(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

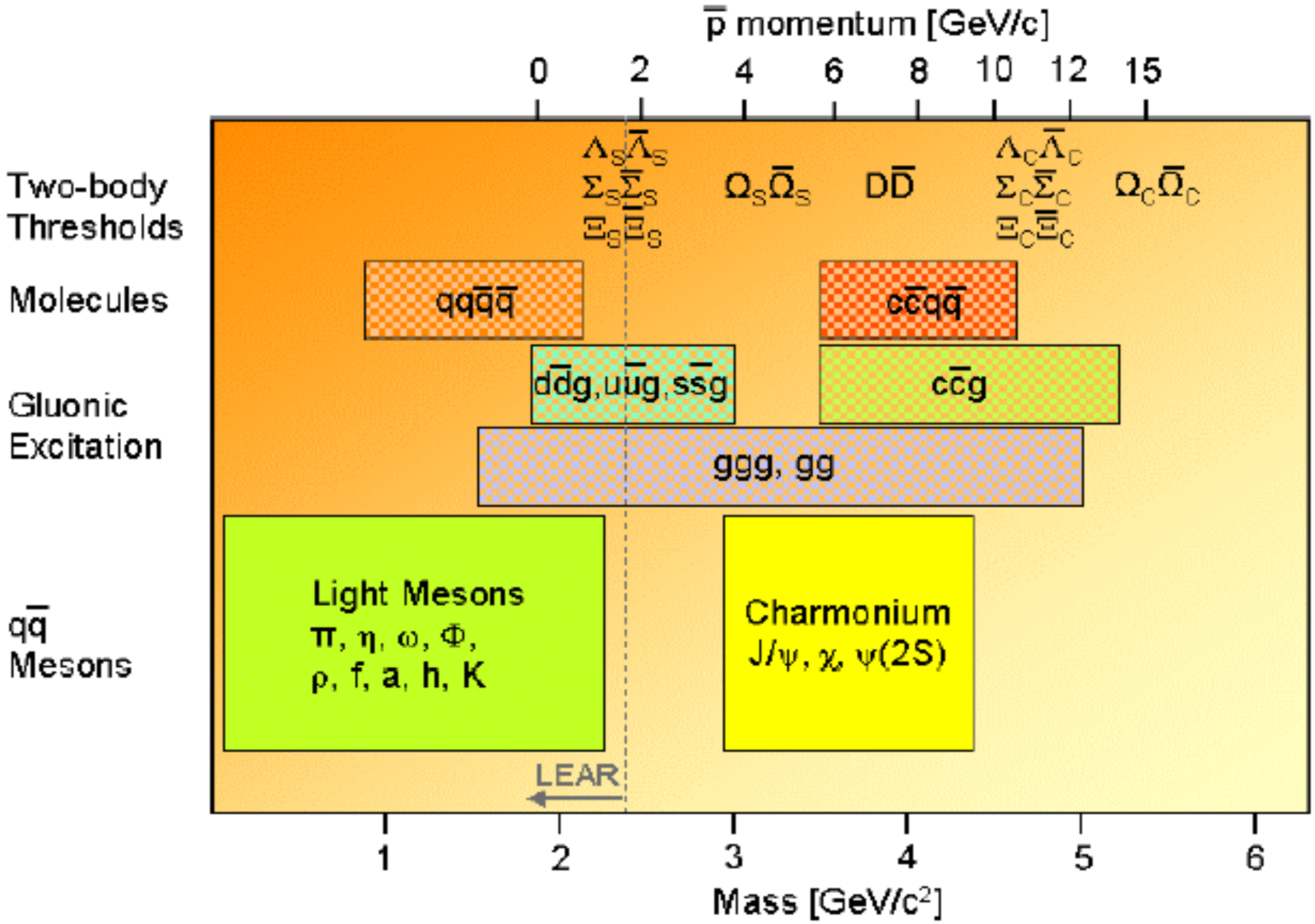
P̄ANDA Collaboration

To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal P̄ANDA detector will be build. Gluonic excitations, the physics of strange and charm quarks and nucleon structure studies will be performed with unprecedented accuracy thereby allowing high-precision tests of the strong interaction. The proposed P̄ANDA detector is a state-of-the-art internal target detector at the HESR at FAIR allowing the detection and identification of neutral and charged particles generated within the relevant angular and energy range.
This report presents a summary of the physics accessible at P̄ANDA and what performance can be expected.



ArXiV:0903.3905

QCD Systems to be Studied by P̄ANDA



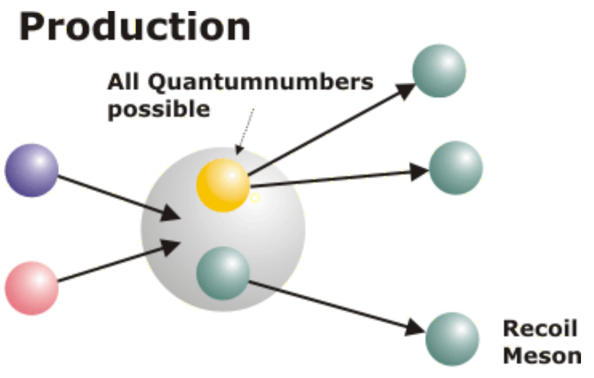
Hadron Spectroscopy

The study of QCD bound states is of fundamental importance for a better, quantitative understanding of QCD. Particle spectra can be computed within the framework of non-relativistic potential models, effective field theories and Lattice QCD. Precision measurements are needed to distinguish between the different approaches and identify the relevant degrees of freedom.

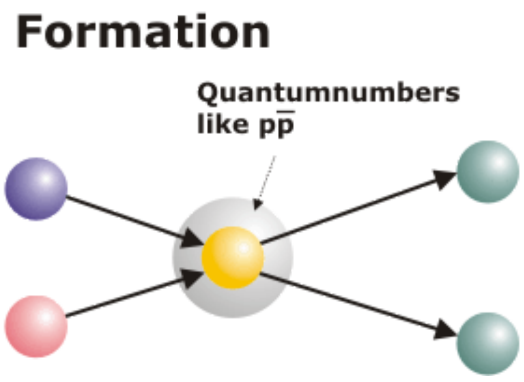
- Charmonium Spectroscopy
- Gluonic Excitations
- Open Charm
- Strange and Charmed Baryons

Spectroscopy with Antiprotons

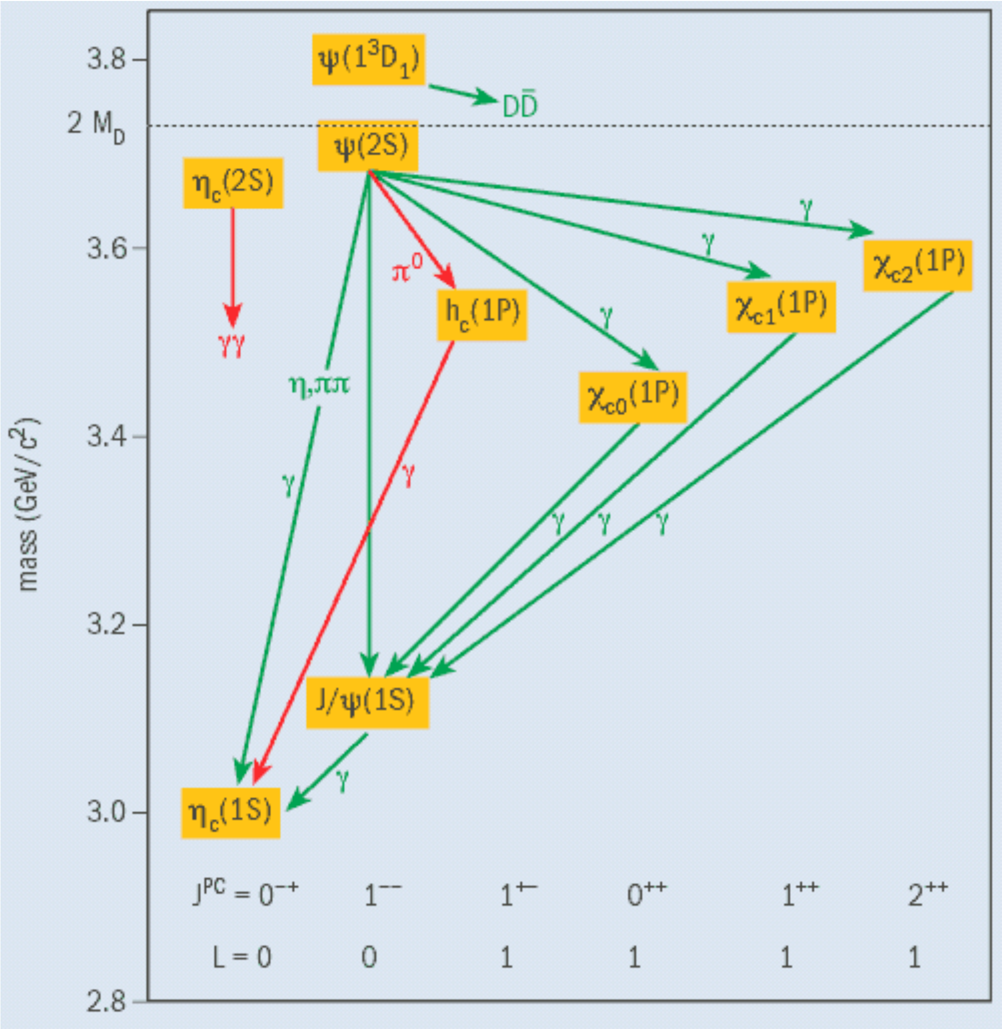
all J^{PC} available



only selected J^{PC}



Charmonium Spectroscopy



All 8 states below open charm threshold are well established experimentally, although some precision measurements still needed (e.g. $\eta_c(2S)$, h_c)

The region above threshold still to be understood:

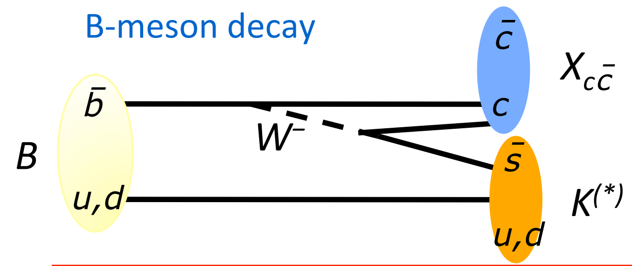
- find missing states (e.g. D-wave)
- understand nature of newly discovered states (e.g. X Y Z)

Hyperfine splitting of quarkonium states gives access to V_{SS} component of quark potential model

The XYZ States

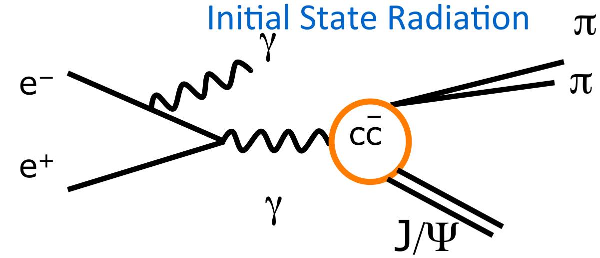
Over past few years a wealth of new states has been discovered, mostly at the B-factories, in the region above open charm threshold. These states are usually associated to charmonium, because they decay into charmonium, but their nature is not at all understood.

B-meson decay



X(3872) Belle, Babar, Cleo, CDF, D0
Y(3940) Belle, Babar
Y(4140)? CDF
Z(4430), $Z_1(4050)$, $Z_2(4250)$ — Belle

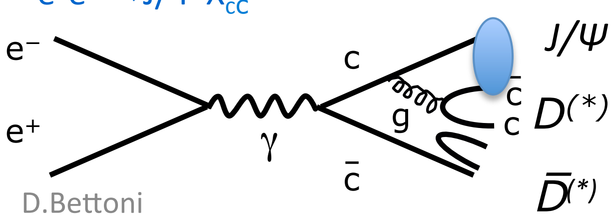
Initial State Radiation



1^{--} states
X(4008)? Belle
Y(4260) BaBar, Belle, Cleo
Y(4350) BaBar, Belle
Y(4660) Belle

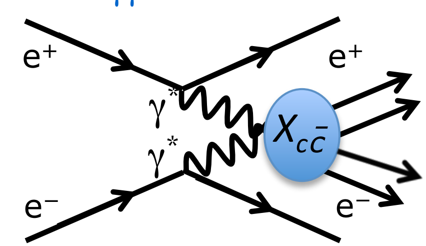
X(3915) Belle
Z(3930) Belle
Y(4350) Belle

Associate production
$e^+e^- \longrightarrow J/\Psi\ X_{c\bar{c}}$



X(3940) Belle
X(4160) Belle

γγ-collisions



The XYZ States

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (#σ)	1st observation
$X(3823)$	3823.1±1.9	< 24	$??^{-}$	$B \to K + (\chi_{c1}\gamma)$	Belle [4] (3.8)	Belle 2013
$\boldsymbol{X(3872)}$	3871.68±0.17	< 1.2	1^{++}	$B \to K + (J/\psi\, \pi^+\pi^-)$	Belle [5, 6] (12.8), *BABAR* [7] (8.6)	Belle 2003
				$p\bar{p} \to (J/\psi\, \pi^+\pi^-) + ...$	CDF [8–10] (np), DØ [11] (5.2)	
				$B \to K + (J/\psi\, \pi^+\pi^-\pi^0)$	Belle [12][a] (4.3), *BABAR* [13][a] (4.0)	
				$B \to K + (D^0\bar{D}^0\pi^0)$	Belle [14, 15][a] (6.4), *BABAR* [16][a] (4.9)	
				$B \to K + (J/\psi\, \gamma)$	Belle [17][a] (4.0), *BABAR* [18, 19][a] (3.6)	
				$B \to K + (\psi(2S)\, \gamma)$	*BABAR* [19][a] (3.5), Belle [17][a] (0.4)	
				$pp \to (J/\psi\, \pi^+\pi^-) + ...$	LHCb [20] (np)	
$\boldsymbol{X(3915)}$	3917.5 ± 1.9	20±5	0^{++}	$B \to K + (J/\psi\, \omega)$	Belle [21] (8.1), *BABAR* [22] (19)	Belle 2004
				$e^+e^- \to e^+e^- + (J/\psi\, \omega)$	Belle [23] (7.7), *BABAR* [13, 24](7.6)	
$\boldsymbol{\chi_{c2}(2P)}$	3927.2 ± 2.6	24±6	2^{++}	$e^+e^- \to e^+e^- + (D\bar{D})$	Belle [25] (5.3), *BABAR* [26] (5.8)	Belle 2005
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$??^{+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27] (6.0)	Belle 2007
				$e^+e^- \to J/\psi + (...)$	Belle [28] (5.0)	
$\boldsymbol{G(3900)}$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma + (D\bar{D})$	*BABAR* [29] (np), Belle [30] (np)	*BABAR* 2007
$Y(4008)$	4008^{+121}_{-49}	226±97	1^{--}	$e^+e^- \to \gamma + (J/\psi\, \pi^+\pi^-)$	Belle [31] (7.4)	Belle 2007
$\boldsymbol{Y(4140)}$	4144.5 ± 2.6	15^{+11}_{-7}	$??^{+}$	$B \to K + (J/\psi\, \phi)$	CDF [32, 33] (5.0), CMS [34] (>5)	CDF 2009
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$??^{+}$	$e^+e^- \to J/\psi + (D^*\bar{D}^*)$	Belle [27] (5.5)	Belle 2007

G.T. Bodwin et al., arXiv:1307.7425v3 [hep-ph]

The XYZ States

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (#σ)	1st observation
$\boldsymbol{Y(4260)}$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	*BABAR* [35, 36] (8.0), CLEO [37] (5.4)	*BABAR* 2005
					Belle [31] (15)	
				$e^+e^- \to (J/\psi\,\pi^+\pi^-)$	CLEO [38] (11)	
				$e^+e^- \to (J/\psi\,\pi^0\pi^0)$	CLEO [38] (5.1)	
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [33] (3.1)	CDF 2010
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(J/\psi\,\phi)$	Belle [39] (3.2)	Belle 2009
$\boldsymbol{Y(4360)}$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$	*BABAR* [40] (np), Belle [41] (8.0)	*BABAR* 2007
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [42] (8.2)	Belle 2007
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$	Belle [41] (5.8)	Belle 2007
$\boldsymbol{Z_c^+(3900)}$	3898 ± 5	51 ± 19	$1^{?-}$	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [43] (np), Belle [44] (5.2)	BESIII 2013
				$e^+e^- \to \pi^- + (J/\psi\,\pi^+)$	Xiao *et al.* [45][a] (6.1)	
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K + (\chi_{c1}(1P)\,\pi^+)$	Belle [46] (5.0), *BABAR* [47] (1.1)	Belle 2008
$Z_2^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K + (\chi_{c1}(1P)\,\pi^+)$	Belle [46] (5.0), *BABAR* [47] (2.0)	Belle 2008
$Z^+(4430)$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$B \to K + (\psi(2S)\,\pi^+)$	Belle [48, 49] (6.4), *BABAR* [50] (2.4)	Belle 2007
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle [51, 52] (2.0)	Belle 2010
$Z_b^+(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+),\ n=1,2,3$	Belle [53, 54] (16)	Belle 2011
				$\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+),\ n=1,2$	Belle [53, 54] (16)	
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+),\ n=1,2,3$	Belle [53, 54] (16)	Belle 2011
				$\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+),\ n=1,2$	Belle [53, 54] (16)	

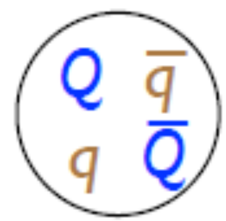
G.T. Bodwin et al., arXiv:1307.7425v3 [hep-ph]

Models for XYZ Mesons

- conventional quarkonium

- quarkonium hybrids

- quarkonium tetraquarks
  - compact tetraquark
  - meson molecule
  - diquark-onium
  - hadro-quarkonium

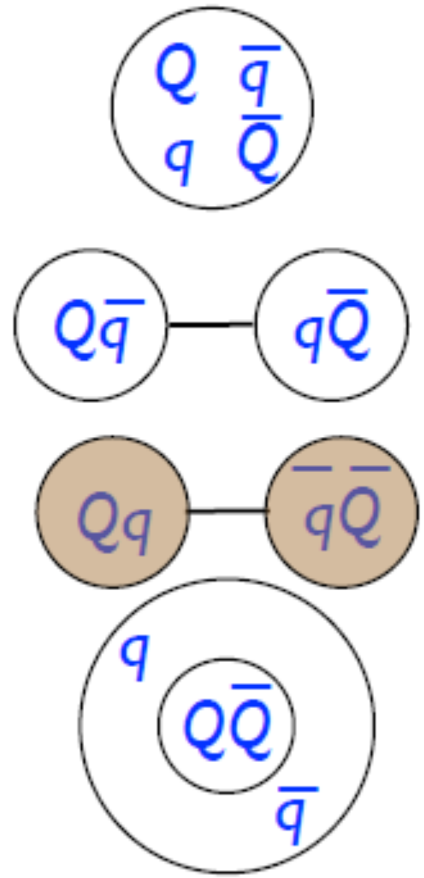


Eric Braaten – Charm 2013

Models for XYZ Mesons

quarkonium tetraquarks

- compact tetraquark
- meson molecule
- diquark-onium
- hadro-quarkonium
- Born-Oppenheimer tetraquark! arXiv:1305.6905



Eric Braaten – Charm 2013

Charmonium at $\bar{\text{P}}$ANDA

- At $2\times10^{32}\text{cm}^{-2}\text{s}^{-1}$ accumulate 8 pb^{-1}/day (assuming 50 % overall efficiency) $\Rightarrow$ $10^4 \div 10^7$ ($c\bar{c}$) states/day.
- Total integrated luminosity 1.5 fb^{-1}/year (at $2\times10^{32}\text{cm}^{-2}\text{s}^{-1}$, assuming 6 months/year data taking).
- Improvements with respect to Fermilab E760/E835:
  - Up to ten times higher instantaneous luminosity.
  - Better beam momentum resolution $\Delta p/p = 10^{-5}$ (GSI) vs 2×10^{-4} (FNAL)
  - Better detector (higher angular coverage, magnetic field, ability to detect hadronic decay modes).
- Fine scans to measure masses to $\approx$ 100 KeV, widths to $\approx$ 10 %.
- Explore entire region below and above open charm threshold.
- Decay channels
  - J/ψ+X , $J/\psi \to e^+e^-$, $J/\psi \to \mu^+\mu^-$
  - $\gamma\gamma$
  - hadrons
  - $D\bar{D}$

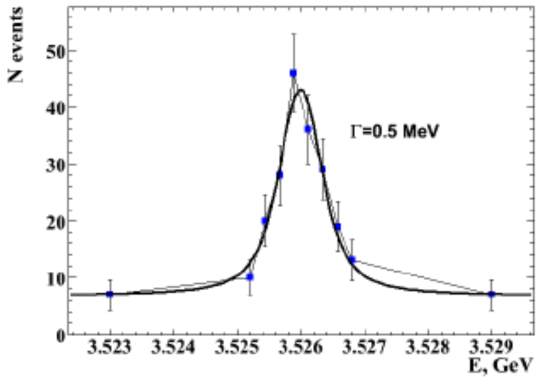
•Precision measurement of known states
•Find missing states (e.g. D states)
•Understand newly discovered states

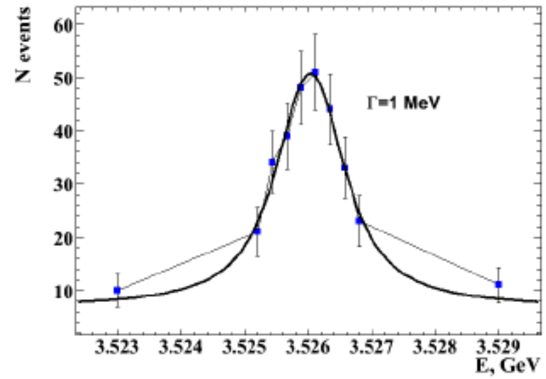
Get a complete picture of the dynamics of the $c\bar{c}$ system.

Sensitivity to h_c Width Measurement

$$p\bar{p} \rightarrow h_c \rightarrow \eta_c + \gamma \rightarrow K^+K^-K^+K^-\gamma$$

$$\nu_i = [\varepsilon \times \int Ldt]_i \times [\sigma_{bkgd}(E) + \frac{\sigma_p \Gamma_R^2/4}{(2\pi)^{1/2}\sigma_i} \times \int \frac{e^{-(E-E')^2/2\sigma_i^2}}{(E'-M_R)^2 + \Gamma_R^2/4} dE'],$$





signal efficiency ε=0.24

each point corresponds to 5 days of data taking

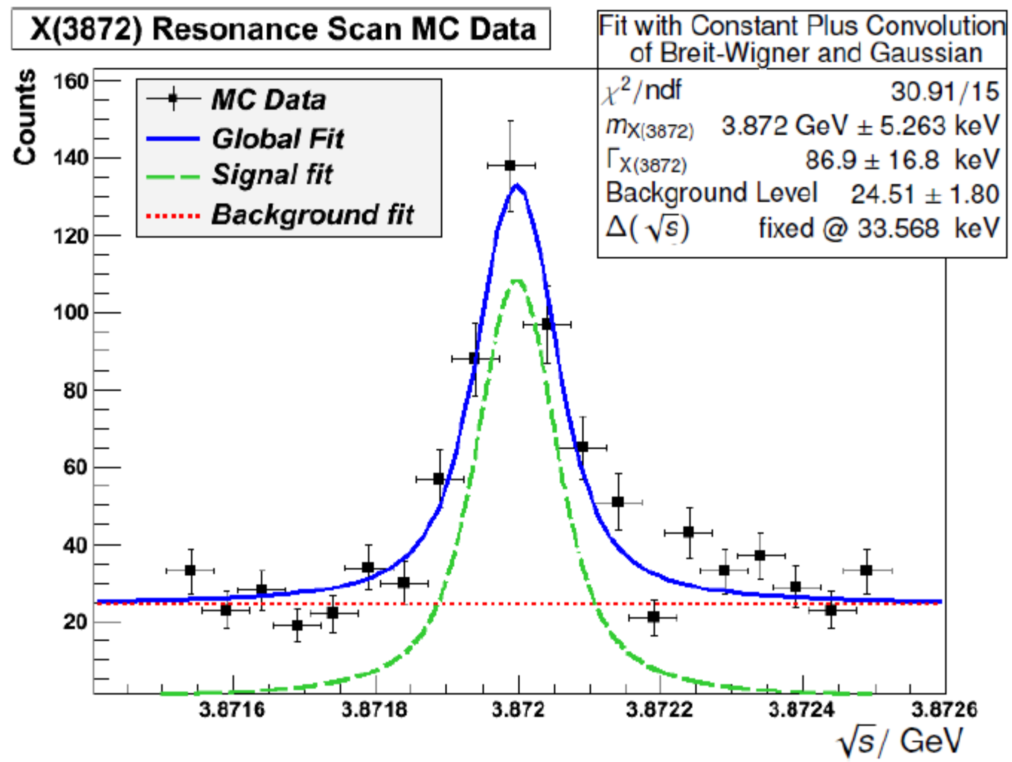
Likelihood function:

$$\mathcal{L} = \prod_{j=1}^{N} \frac{\nu_j^{n_j} e^{-\nu_j}}{n_j!}.$$

$\Gamma_{R,MC}$, MeV	$\Gamma_{R,reco}$, MeV	$\Delta\Gamma_R$, MeV
1	0.92	0.24
0.75	0.72	0.18
0.5	0.52	0.14

X(3872)

Mass $m_{X(3872)}$	3.872 GeV
Width $\Gamma_{X(3872)}$	100 keV
Production	$p\bar{p} \rightarrow X(3872)$ ($\sigma_{BW} = 50$ nb)*
Decay	$X(3872) \rightarrow J/\psi\, \pi^+\pi^-$ (BR = 0.1)
Subsequent Decay	$J/\psi \rightarrow e^+e^-$ (BR = 0.06)†
Time Requirement	$20 \cdot 2$ days
Accelerator duty factor	50%
Luminosity	0.864 pb^{-1}/day
HESR	High resolution mode
p_{beam} distribution	Gaussian, rms $\simeq 2 \cdot 10^{-5} \cdot p_{beam}$
$\sqrt{s}$ distribution	Gaussian, rms $\simeq$ 33.6 keV



Reconstructed width $\Gamma_{X(3872)}$ is consistent with input width of 100 keV.*

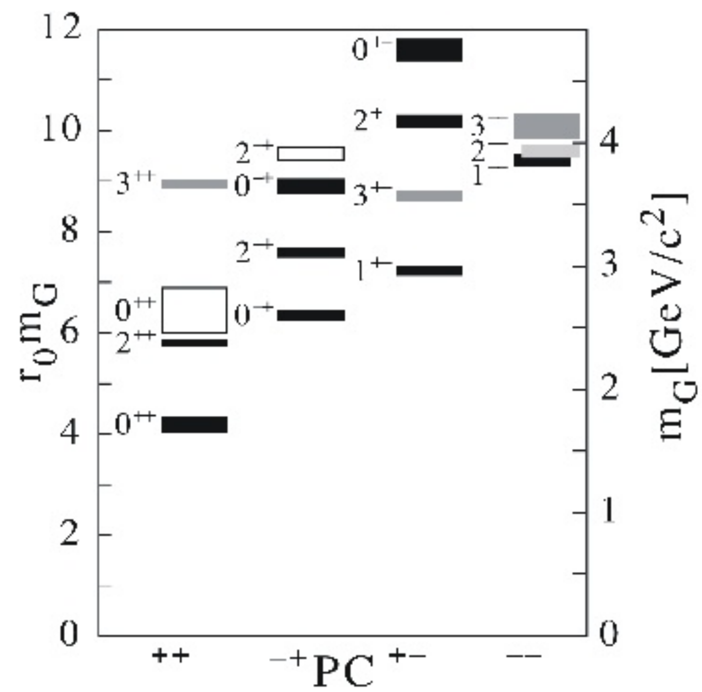
Hybrids and Glueballs

The QCD spectrum is much richer than that of the quark model as the gluons can also act as hadron components.

Glueballs states of pure glue

Hybrids $q\bar{q}g$

- Spin-exotic quantum numbers J^{PC} are a powerful signature of gluonic hadrons.
- In the light meson spectrum exotic states overlap with conventional states.
- In the $c\bar{c}$ meson spectrum the density of states is lower and the exotics can be resolved unambiguously.
- $\pi_1(1400)$ and $\pi_1(1600)$ with $J^{PC}=1^{-+}$.
- $\pi_1(2000)$ and $h_2(1950)$
- Narrow state at 1500 MeV/c^2 seen by Crystal Barrel best candidate for glueball ground state ($J^{PC}=0^{++}$).



Morningstar und Peardon, PRD60 (1999) 034509
Morningstar und Peardon, PRD56 (1997) 4043

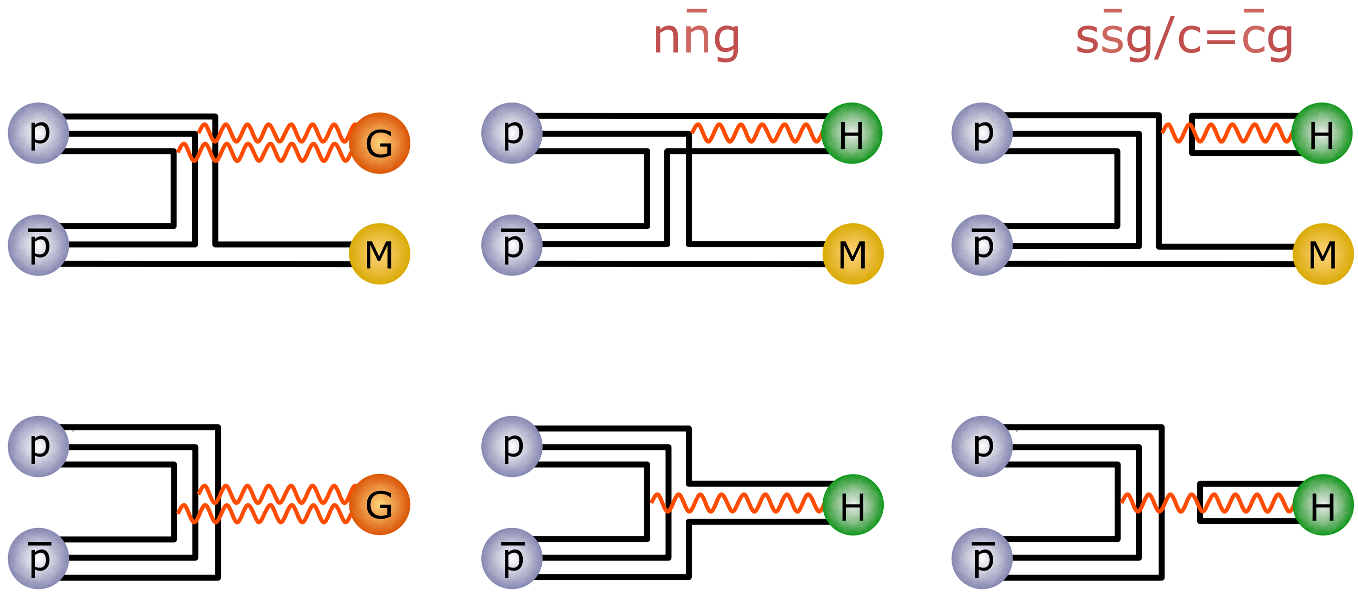
Hybrids and Glueballs in $\bar{p}p$ Annihilation

Production

all J^{PC} available

Formation

only selected J^{PC}

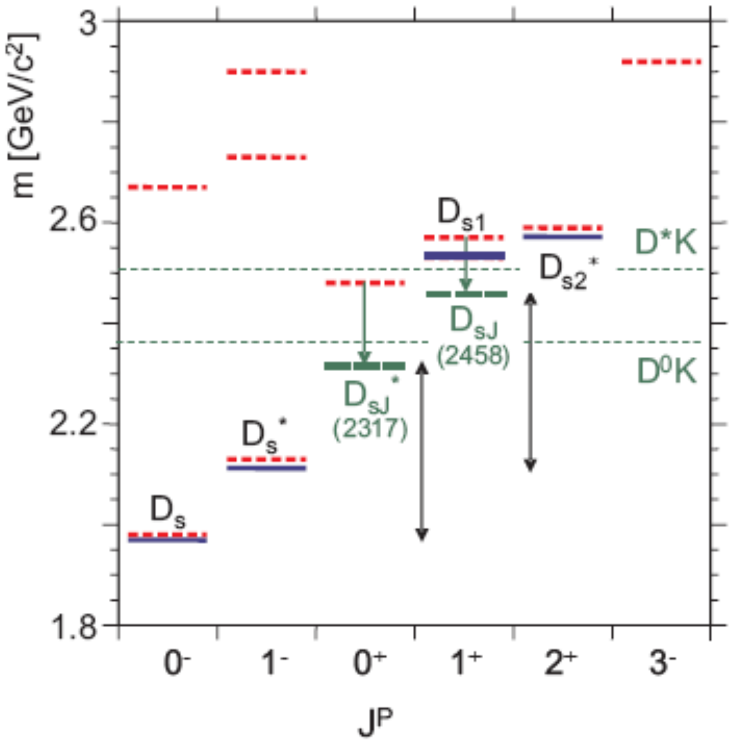


Gluon rich process creates gluonic excitation in a direct way

- $c\bar{c}$ requires the quarks to annihilate (no rearrangement)
- yield comparable to charmonium production
- even at low momenta large exotic content has been proven
- Exotic quantum numbers can only be achieved in production mode

Open Charm Physics

- New narrow states D_{sJ} recently discovered at B factories do not fit theoretical calculations.
- At full luminosity at $\bar{p}$ momenta larger than 6.4 GeV/c PANDA will produce large numbers of $D\bar{D}$ pairs.
- Despite small signal/background ratio (5×10^{-6}) background situation favourable because of limited phase space for additional hadrons in the same process.



Baryon Spectroscopy

An understanding of the baryon spectrum is one of the primary goals of non-perturbative QCD. In the nucleon sector, where most of the experimental information is available, the agreement with quark model predictions is astonishingly small, and the situation is even worse in the strange baryon sector.

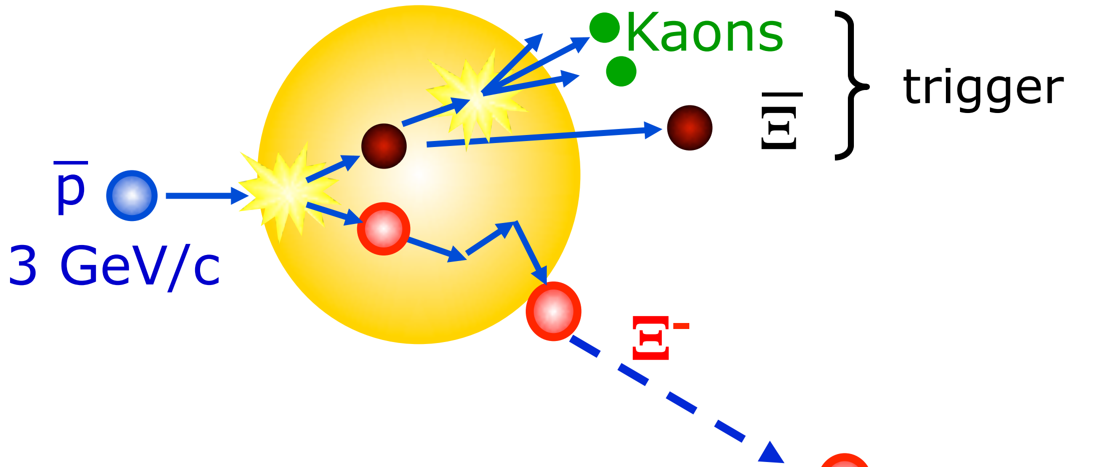
- In $\bar{p}p$ collisions a large fraction of the inelastic cross section is associated to channels with a baryon-antibaryon pair in the final state.
- This opens up the opportunity for a comprehensive baryon spectroscopy program at PANDA.
- Example: $\bar{p}p \to \bar{\Xi}\Xi$ cross section up to 2 μb, expect sizeable population of excited Ξ states. In PANDA these excited states can be studied by analyzing their various decay modes e.g. $\Xi\pi$, $\Xi\pi\pi$, $\Lambda\bar{K}$, $\Sigma\bar{K}$, $\Xi\eta$ ...
- Ω baryons can also be studied, but cross sections lower by approximately two orders of magnitude.

Hypernuclear Physics

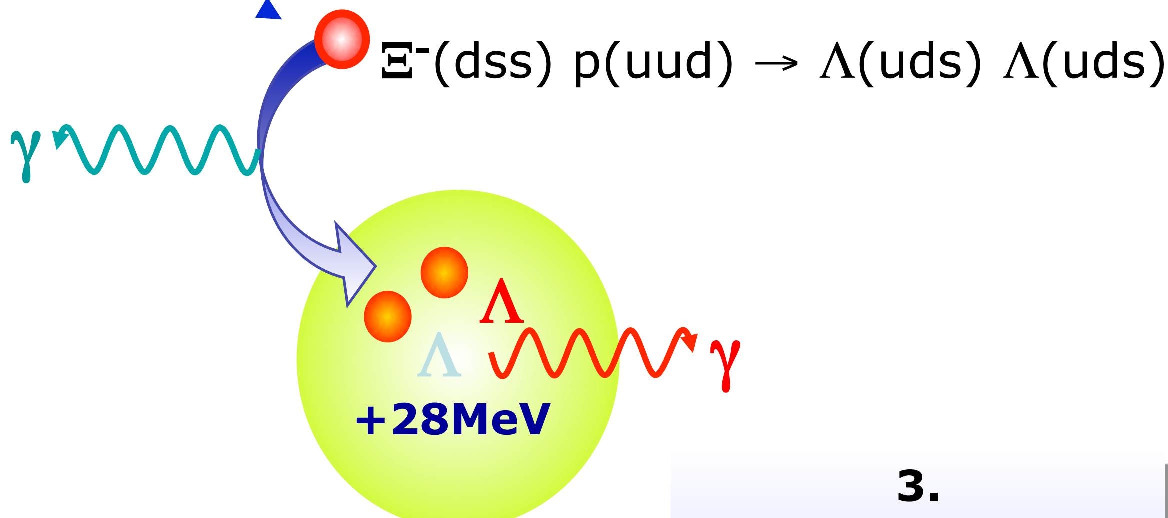
Hypernuclei, systems where one (or more) nucleon is replaced by one (or more) hyperon(s) (Y), allow access to a whole set of nuclear states containing an extra degree of freedom: strangeness.

- Probe of nuclear structure and its possible modifications due to the hyperon.
- Test and define shell model parameters.
- Description in term of quantum field theories and EFT.
- Study of the YN and YY forces (single and double hypernuclei).
- Weak decays ($\Lambda \rightarrow \pi N$ suppressed, but $\Lambda N \rightarrow NN$ and $\Lambda\Lambda \rightarrow NN$ allowed $\Rightarrow$ four-baryon weak interaction)
- Hyperatoms
- Experimentally: in 50 years of study 35 single, 6 double hypernuclei established

Production of Double Hypernuclei



2.
Slowing down and capture of Ξ^- in secondary target nucleus



1.
Hyperon-antihyperon production at threshold

3.
γ-spectroscopy with Ge-detectors

Nucleon Structure Using Electromagnetic Processes

- The electromagnetic form factors of the proton in the time-like region can be extracted from the cross section for the process:

$$\bar{p}p \rightarrow e^+e^-$$

  - Moduli of form factors using angular distribution
  - Extend q^2 range
  - Improve accuracy of measurement
- Hard Scattering Processes ($pp \rightarrow \gamma\gamma$)
  (test of factorization)
- Transverse parton distribution functions in Drell-Yan production.

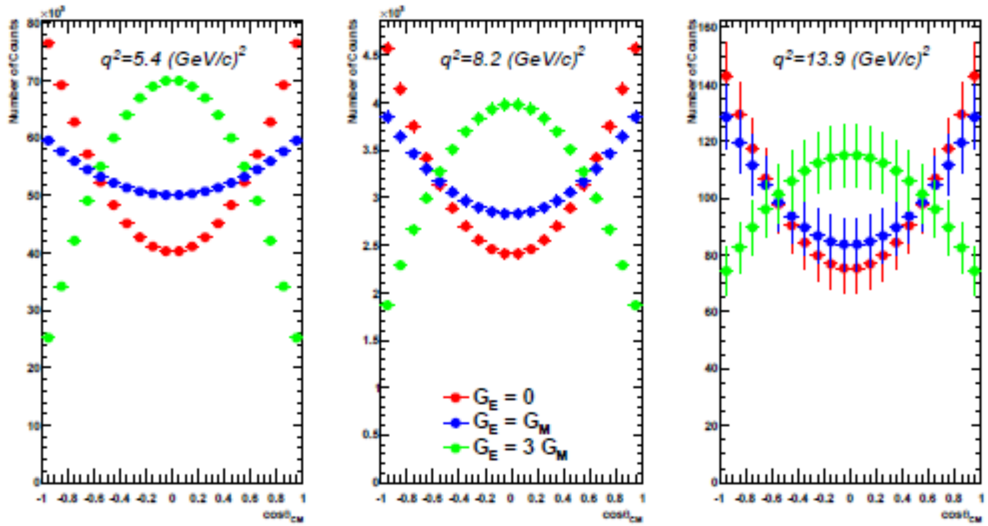
Form Factors in P̄ANDA

The PANDA experiment will determine the moduli of the proton form factors in the time-like region by measuring the angular distribution of the process

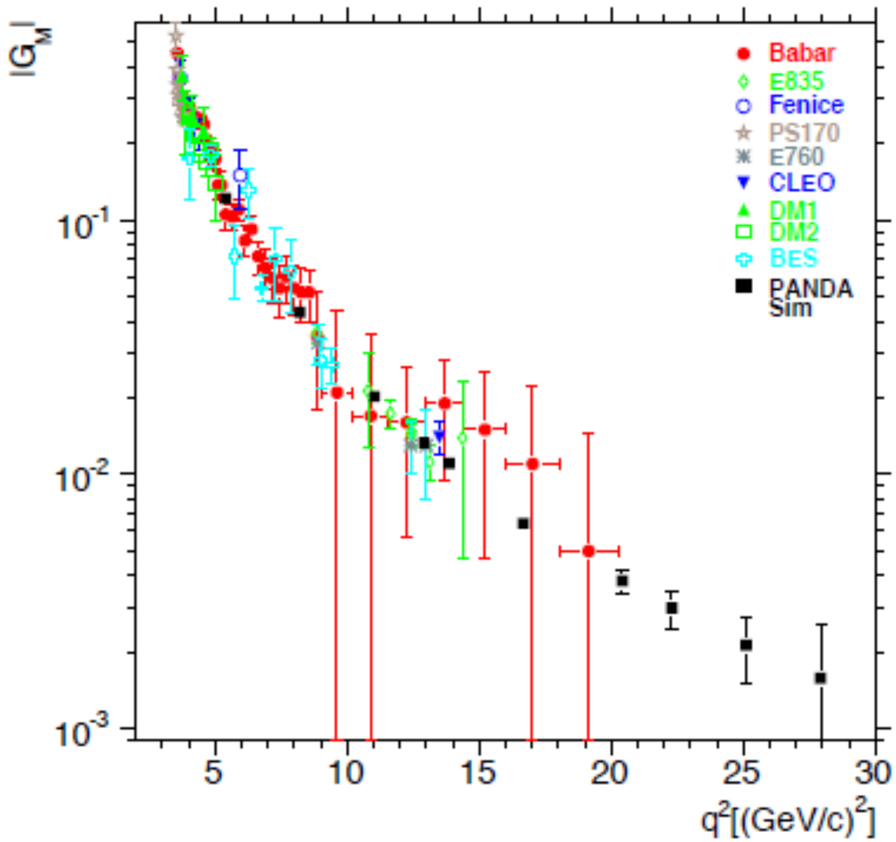
$$\bar{p}p \rightarrow e^+e^-$$

in a q^2 range from 5 $(GeV/c)^2$ up to 14 $(GeV/c)^2$. A determination of the form factor up to a q^2 of 22 $(GeV/c)^2$ will be possible by measuring the total cross section.

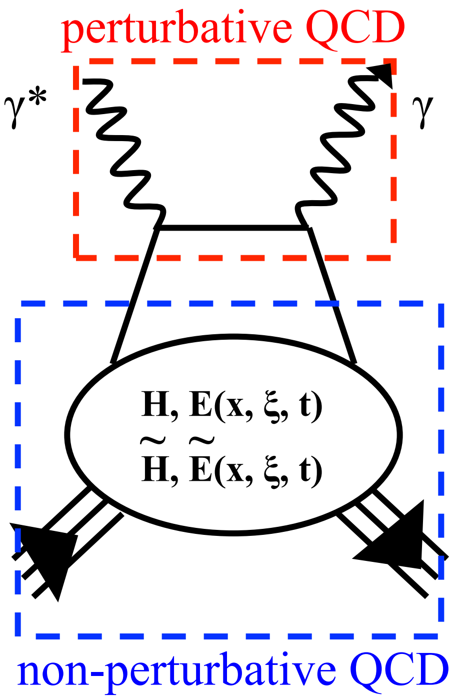
$$\frac{d\sigma}{d\left(\cos\theta^*\right)} = \frac{\pi\alpha^2\hbar^2c^2}{2xs}\left[\left|G_M\right|^2\left(1+\cos^2\theta^*\right) + \frac{4m_p^2}{s}\left|G_E\right|^2\left(1-\cos^2\theta^*\right)\right]$$



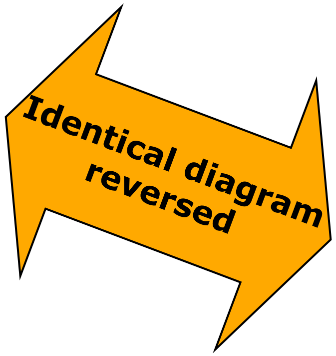
Projected $\bar{P}$ANDA $|G_M|$ Measurement

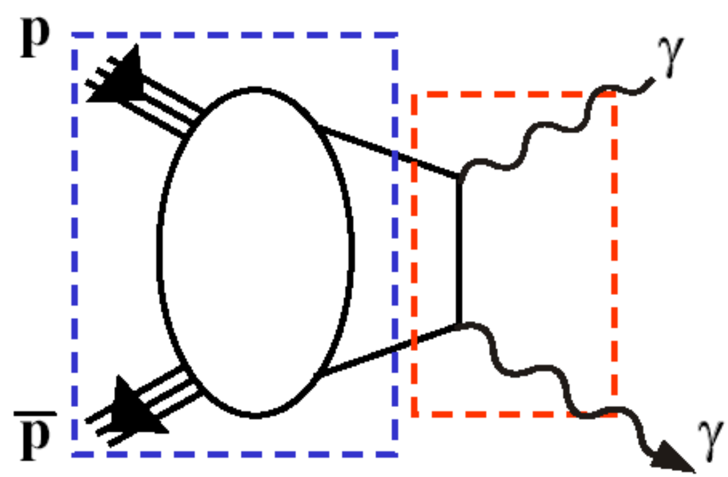


Hard Scattering Processes and $\bar{p}p \rightarrow \gamma\gamma$



Wide angle Compton scattering
factorisation into hard amplitude
(calculable in perturbative QCD)
and soft amplitude
(information on parton distributions)



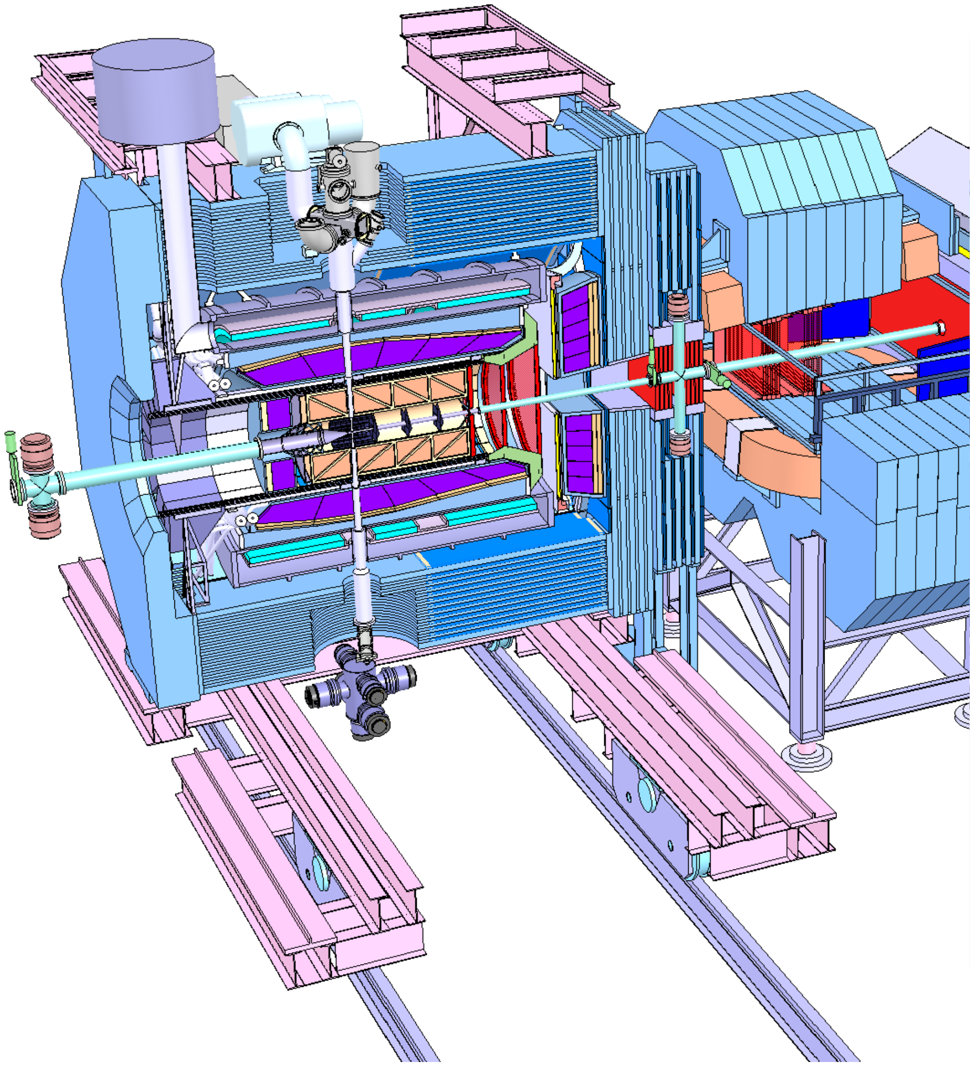


Crossed Diagram

$\bar{p}p \rightarrow \gamma\gamma$

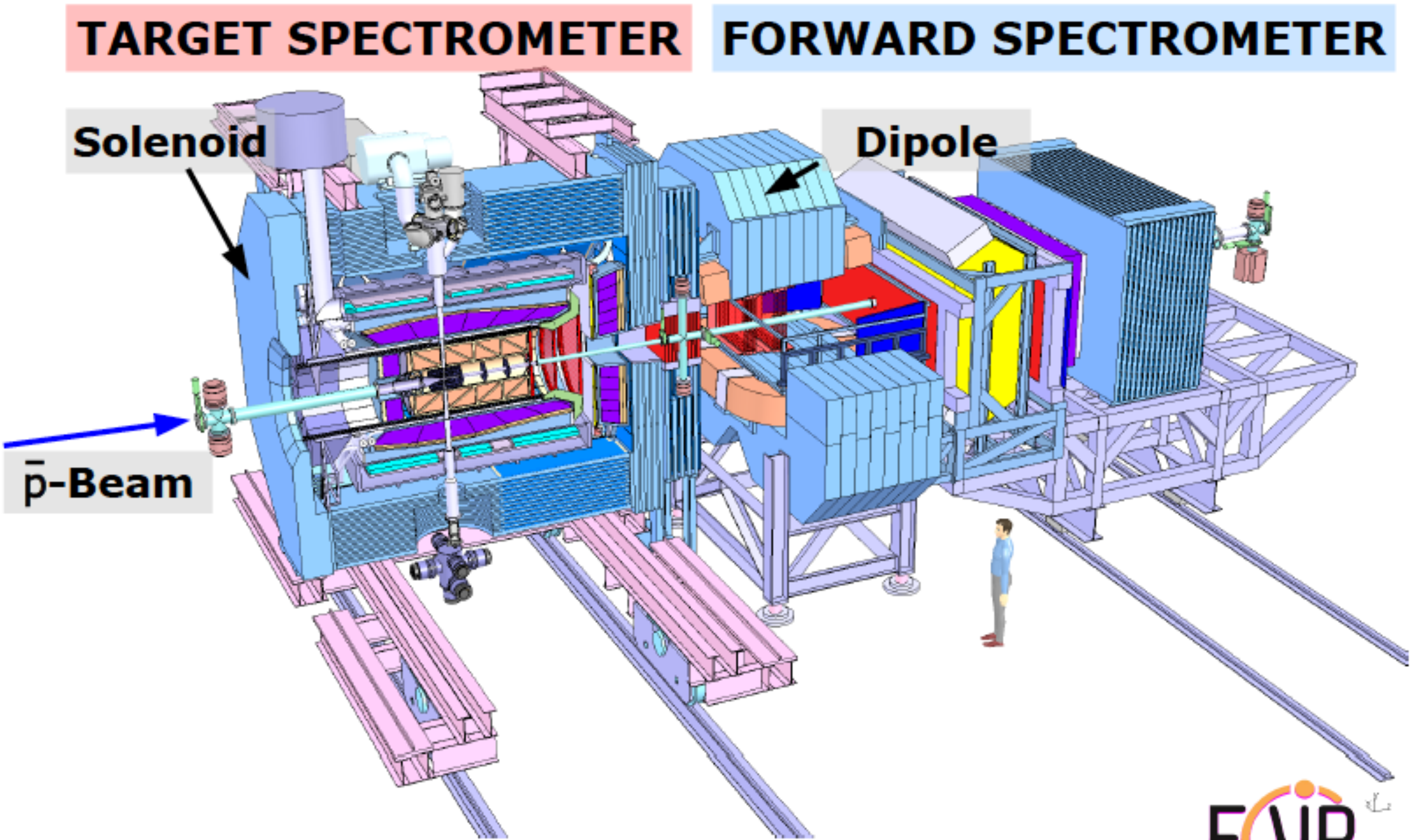
clear experimental signature
both baryons in ground state
$\sigma \approx 2.5\text{pb}$ @ $s \approx 10\ \text{GeV}^2$
$L = 2\cdot10^{32}\ \text{cm}^{-2}\ \text{s}^{-1} \rightarrow 10^3$ events per month

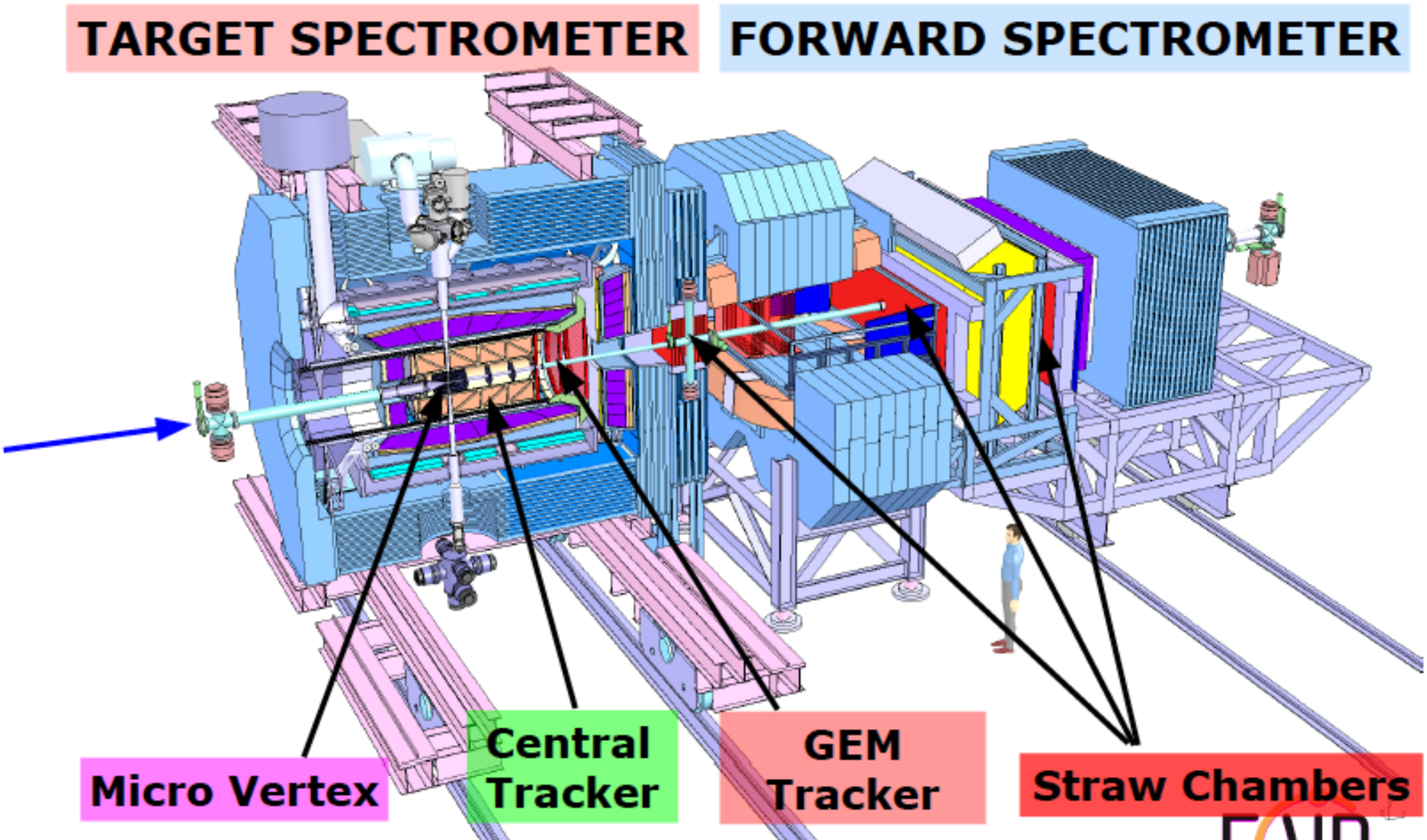
$\bar{\text{P}}$ANDA Spectrometer

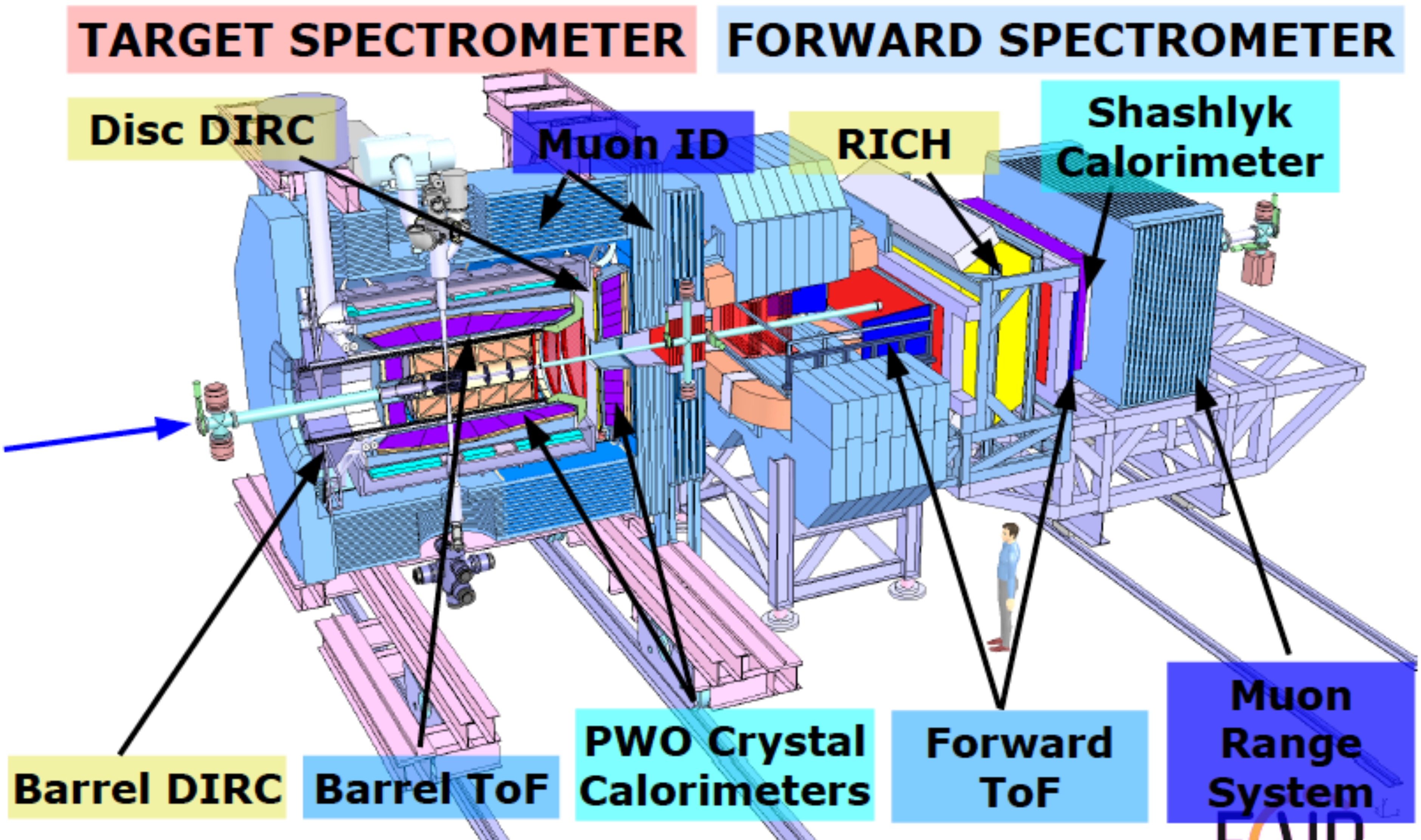


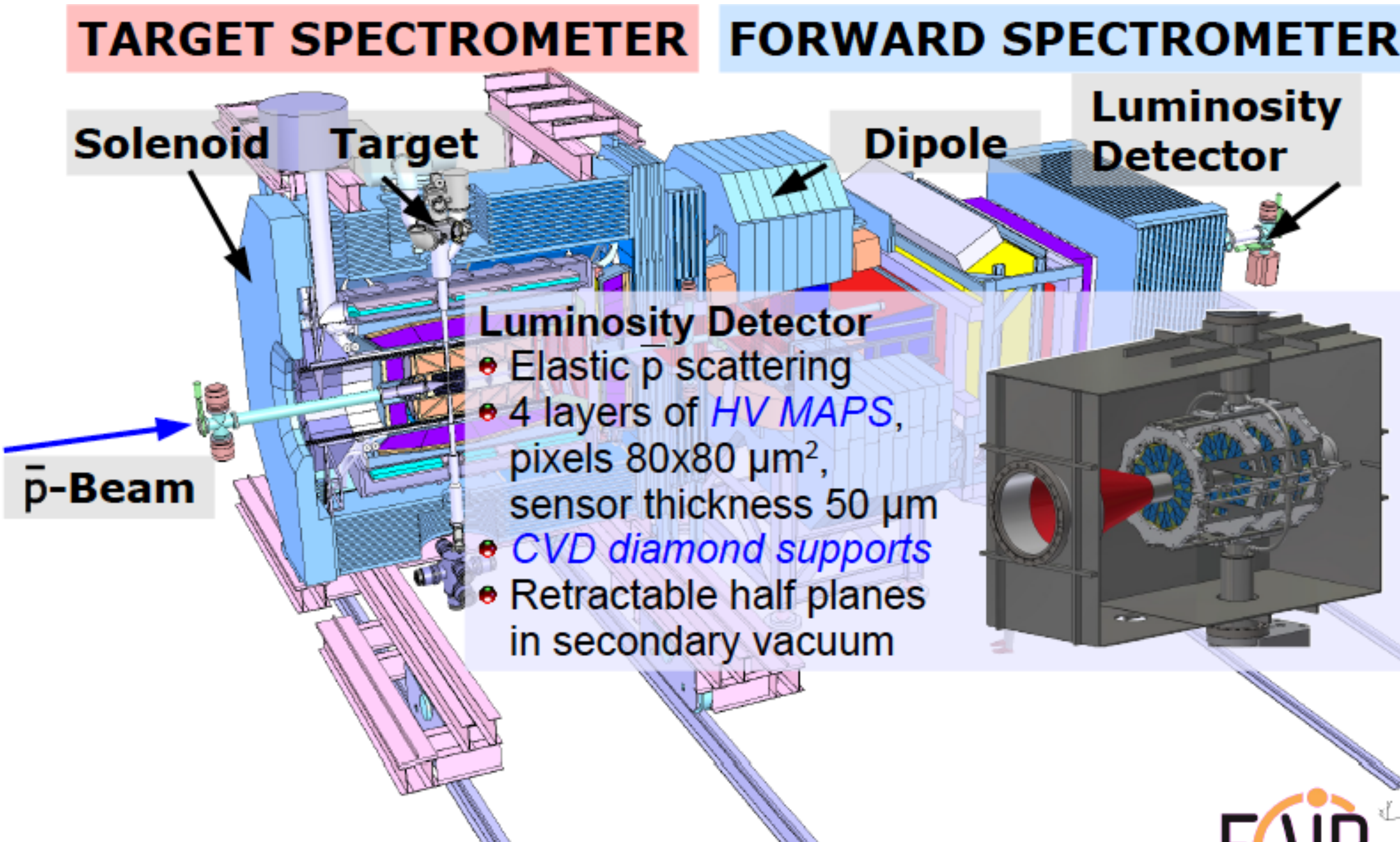
Detector requirements:

- 4π acceptance
- High rate capability: $2\times10^{7}\ s^{-1}$ interactions
- Efficient event selection
  - ➔ *Continuous acquisition*
- Momentum resolution ~1%
- Vertex info for D, K^0_S, Y ($c\tau$ = 317 μm for $D^{\pm}$)
  - ➔ *Good tracking*
- Good PID (γ, e, μ, π, K, p)
  - ➔ *Cherenkov, ToF, dE/dx*
- γ-detection 1 MeV – 10 GeV
  - ➔ *Crystal Calorimeter*


TARGET SPECTROMETER
FORWARD SPECTROMETER
Solenoid
Dipole
$\bar{p}$-Beam


TARGET SPECTROMETER
FORWARD SPECTROMETER
Micro Vertex
Central Tracker
GEM Tracker
Straw Chambers

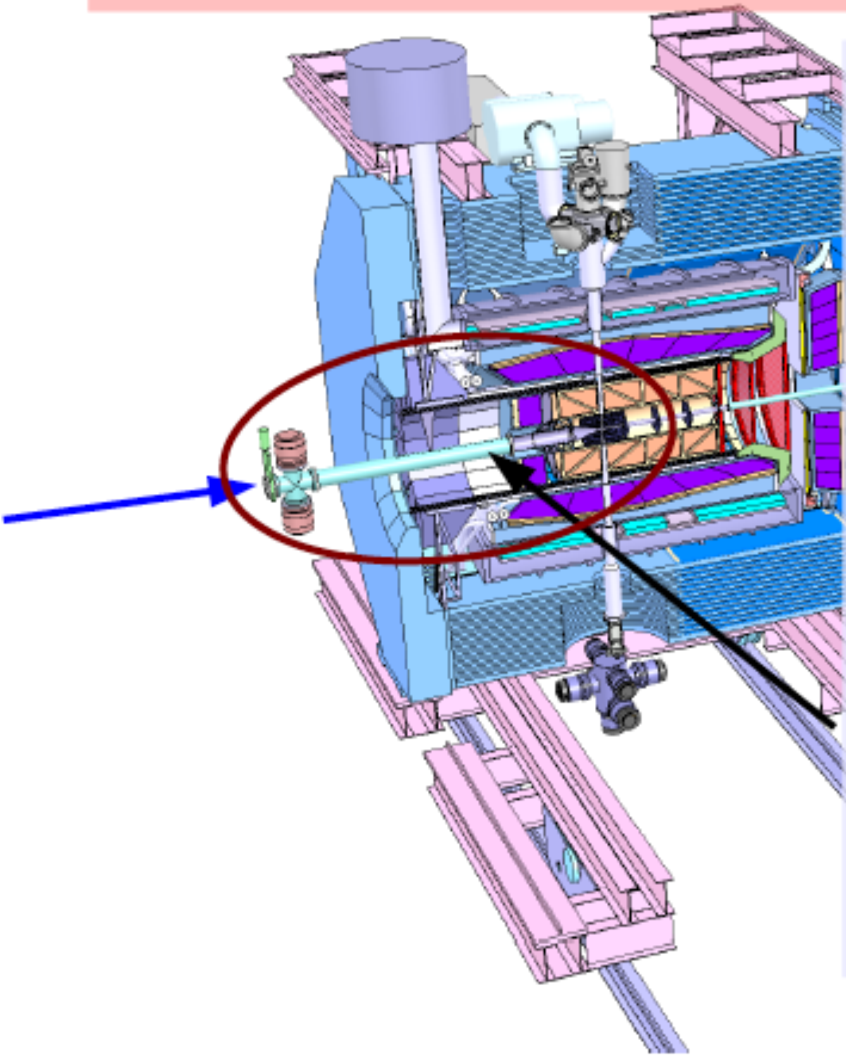

TARGET SPECTROMETER
FORWARD SPECTROMETER
Disc DIRC
Muon ID
RICH
Shashlyk Calorimeter
Barrel DIRC
Barrel ToF
PWO Crystal Calorimeters
Forward ToF
Muon Range System



Luminosity Detector

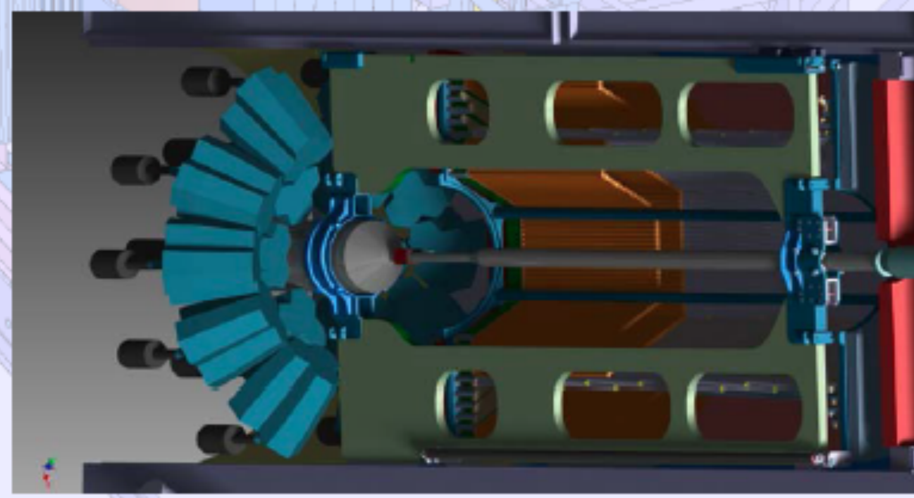
- Elastic p̄p scattering
- 4 layers of *HV MAPS*, pixels 80x80 μm^2, sensor thickness 50 μm
- *CVD diamond supports*
- Retractable half planes in secondary vacuum

TARGET SPECTROMETER **FORWARD SPECTROMETER**



Modified Hypernuclear Setup

- Primary retractable wire/foil target
- Secondary active target to capture Ξ and track products with Si strips
- HP Ge detector for γ-spectroscopy
- Mod. central tracker and beam pipe



P̄ANDA Target

Luminosity Considerations

- Goal: $2x10^{32}$ $cm^{-2}s^{-1}$ (HL mode)
- With 10^{11} stored $\bar{p}$ and 50 mb: $4x10^{15}$ cm^{-2} target density

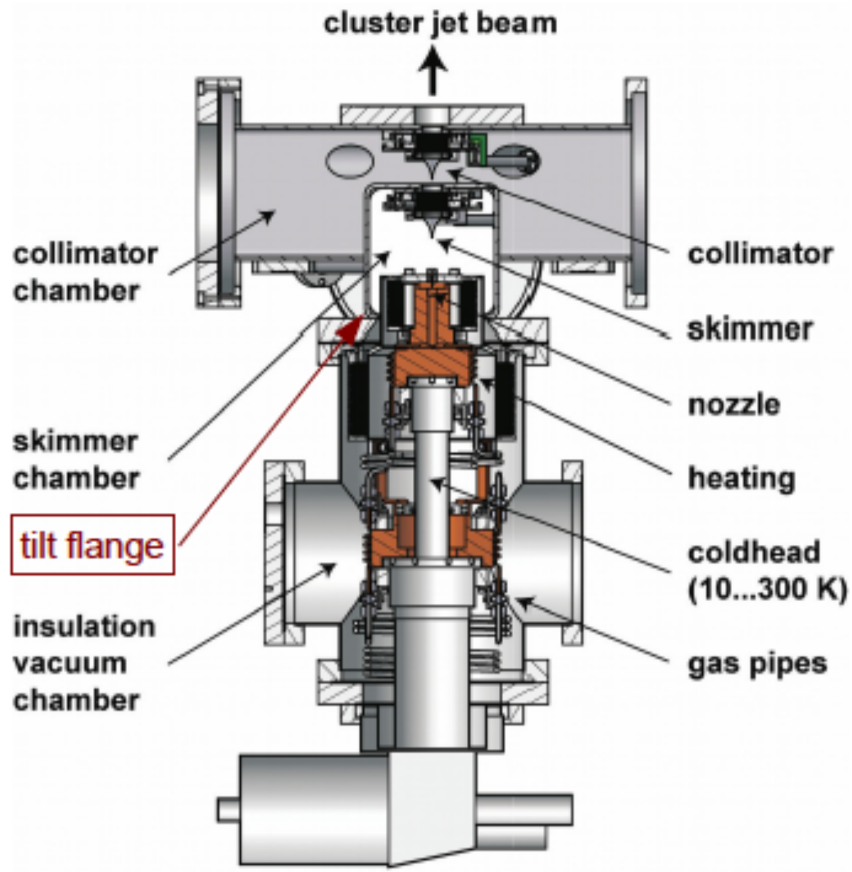
Cluster Jet Target

- Continuous development
  - Nozzle improvement
  - Better alignment by tilt device
  - ~$2x10^{15}$ cm^{-2} reached
- TDR completed

Pellet Target

- >$4x10^{15}$ cm^{-2} feasible
- Prototype under way
- Pellet tracking prototype
- Second TDR part to come

Latest version of the cluster jet target



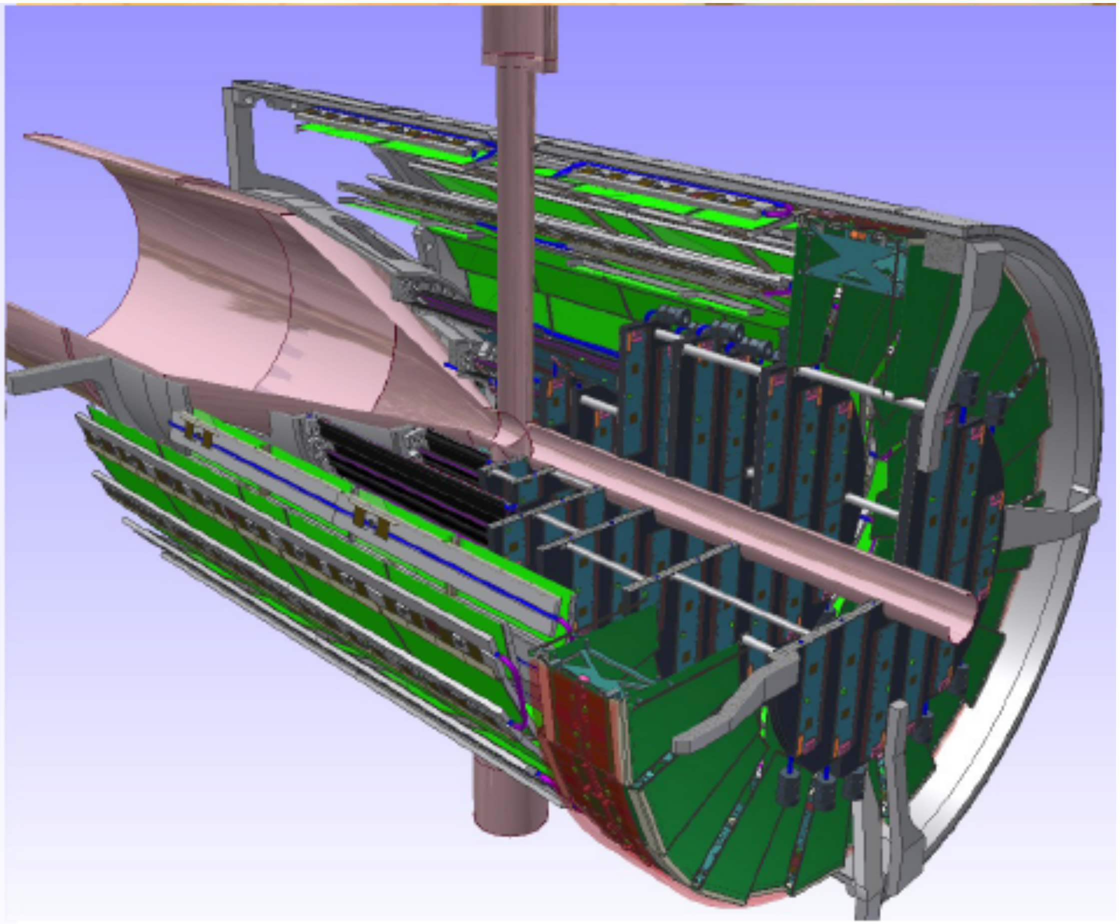
Micro Vertex Detector

Design of the MVD

- 4 barrels and 6 disks
- Continuous readout
- *Inner layers*: hybrid pixels (100x100 μm^2)
  - ToPiX chip, 0.13µm CMOS
  - Thinned sensor wafers
- *Outer layers*: double sided strips
  - Rectangles & trapezoids
  - 128 channel readout ASIC
- Mixed forward disks (pixel/strips)

Challenges

- Low mass supports
- Cooling in a small volume
- Radiation tolerance



Straw Tube Tracker

Detector Layout

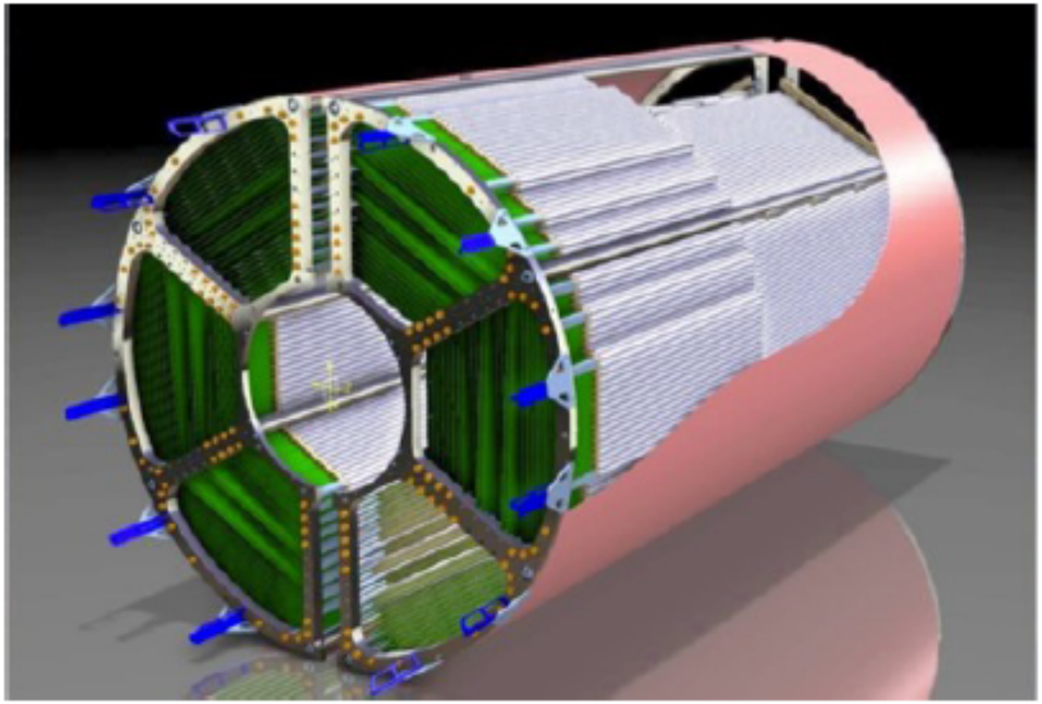
- 4600 straws in 21-27 layers, of which 8 layers skewed at ~3°
- Tube made of 27 µm thin Al-mylar, Ø=1cm
- R_{in}= 150 mm, R_{out}= 420 mm, l=1500 mm
- Self-supporting straw double layers at ~1 bar overpressure (Ar/CO_2)
- Readout with ASIC, TDC, FADC

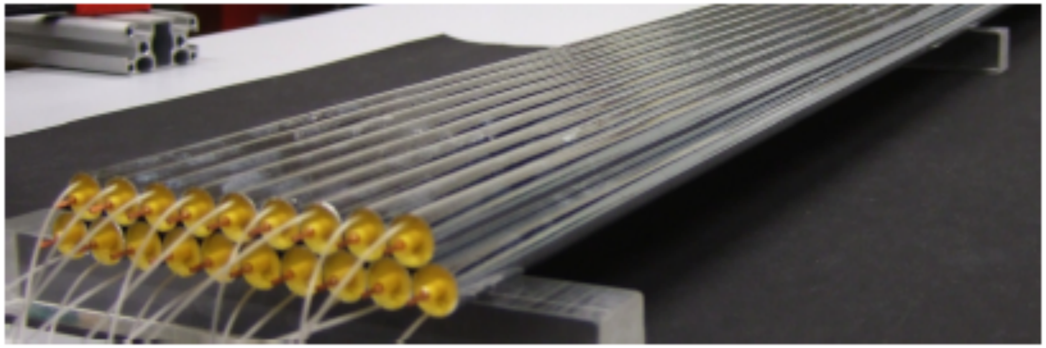
Material Budget

- Max. 26 layers,
- 0.05 % X/X_0 per layer
- Total 1.3% X/X_0

Detector Studies

- Prototype construction & tests
- Aging tests: up to 1.2 C/cm^2
- Cosmic tests for dE/dx
- Simulations of field and detector

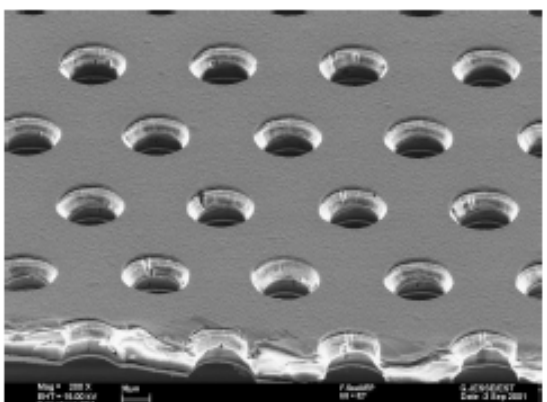


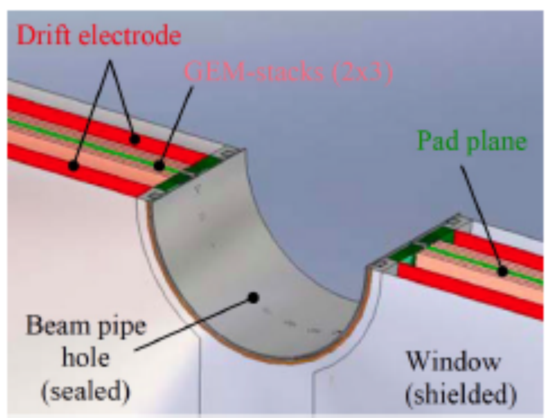


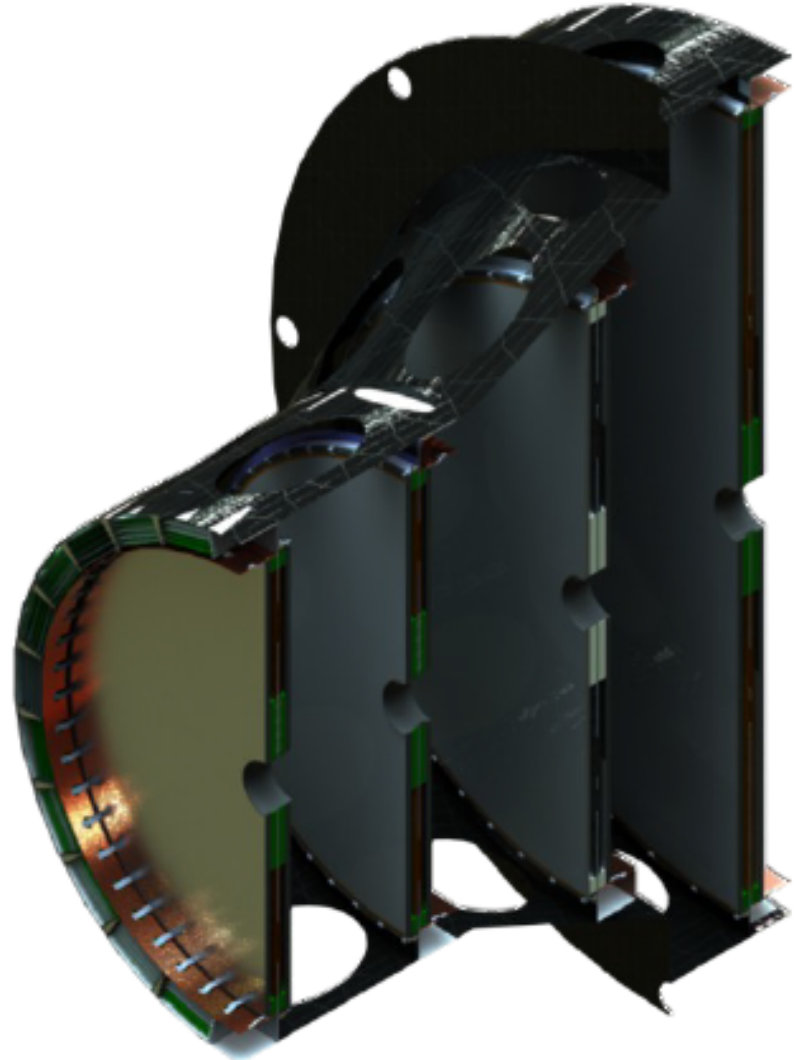
Forward GEM Tracker

Forward Tracking inside Solenoid

- 3-4 stations with 4 projections each
  - ➔ Radial, concentric, x, y
- Central readout plane for 2 GEM stacks
- Large area GEM foils from CERN (50µm Kapton, 2-5µm copper coating)
- ADC readout for cluster centroids
  - ➔ Approx. 35000 channels total
- Challenge to minimize material





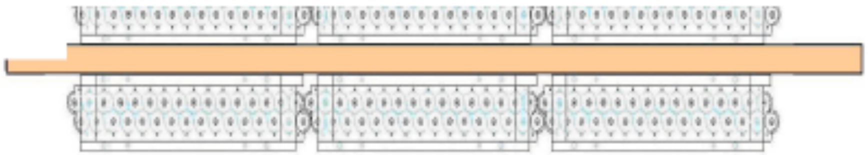


Forward Tracking

Tracking in Forward Spectrometer

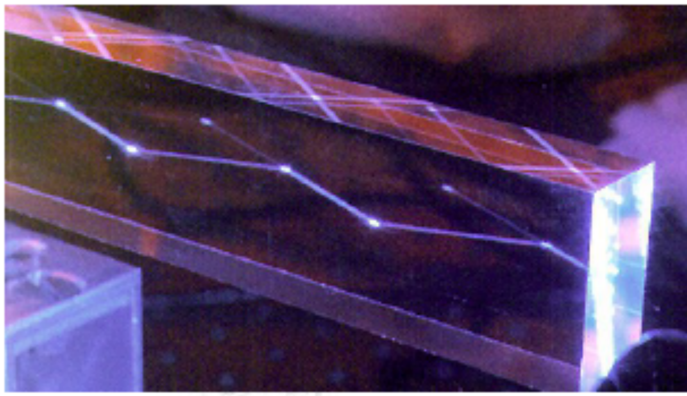
- 3 stations with 2 chambers each
  - FT1&2 : between solenoid and dipole
  - FT3&4 : in the dipole gap
  - FT5&6 : largest chambers behind dipole
- Straw tubes arranged in double layers
  - 27 µm thin mylar tubes, 1 cm Ø
  - Stability by 1 bar overpressure
- 3 projections per chamber (0°, ±5°)

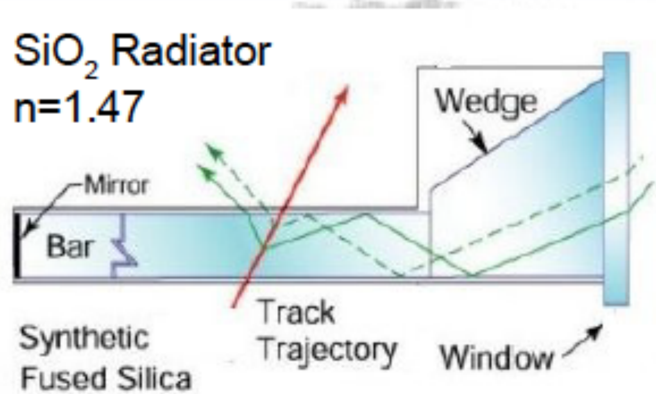
Modular layout of straws

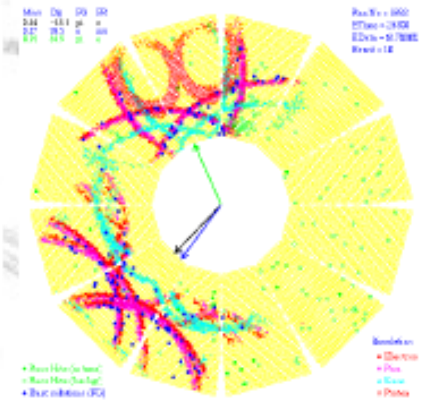


P̄ANDA DIRC Detectors

Detection of Internally Reflected Cherenkov light

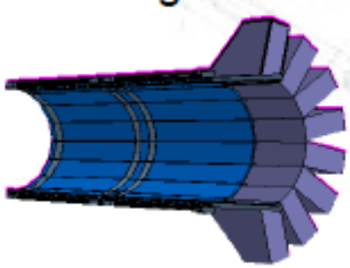






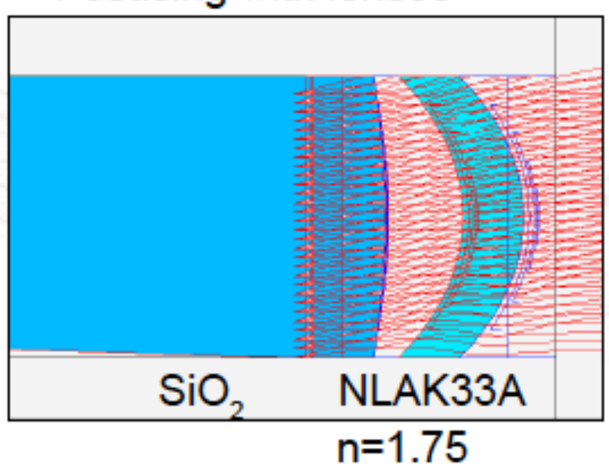
P̄ANDA Barrel DIRC

- Shorter radiator
- No large tank



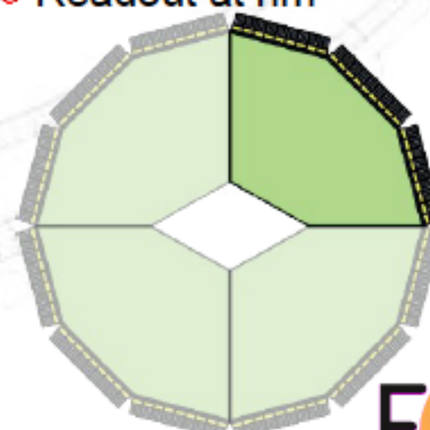
- Faster photo sensor

Focusing with lenses



P̄ANDA Disc DIRC

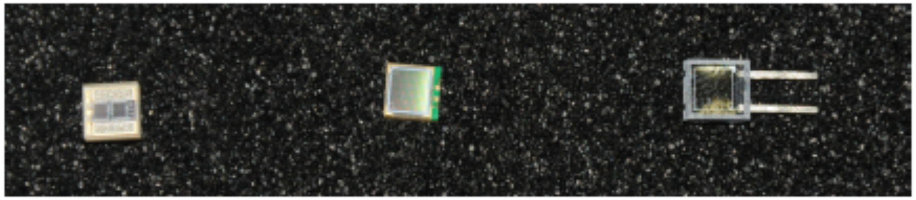
- Disc shaped radiator
- Readout at rim

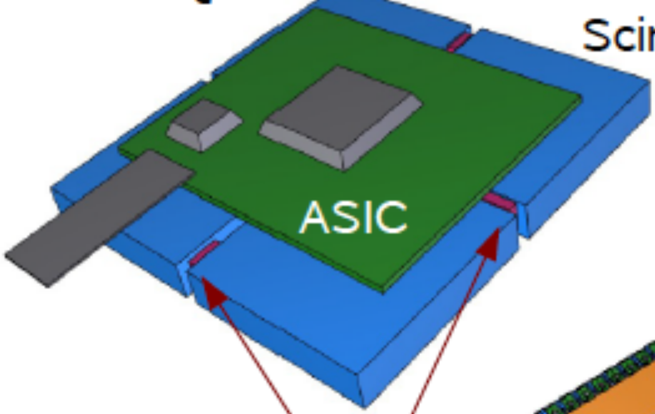


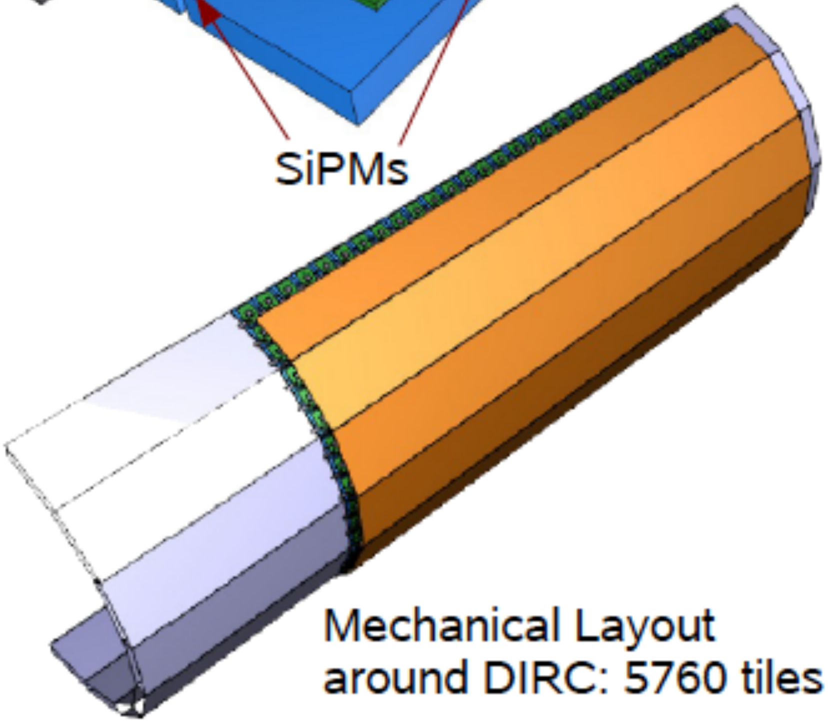
Scintillator Tile Hodoscope

Detector for ToF and event timing

- Scintillator tiles 3x3x0.5 cm^3
  - ➔ BC404, BC408 or BC420
  - ➔ Space points with precision timing
  - ➔ Lowest possible material budget
- Photon readout with 2 SiPMs (3x3 mm^2)
  - High PDE, time resolution, rate capability
  - Work in B-fields, small, robust, low bias
  - *High intrinsic noise*
  - *Temperature dependence*
- Goal for time resolution: 100 ps
- ASIC for SiPM readout







Electromagnetic Calorimeters

$\overline{\text{P}}$ANDA PWO Crystals

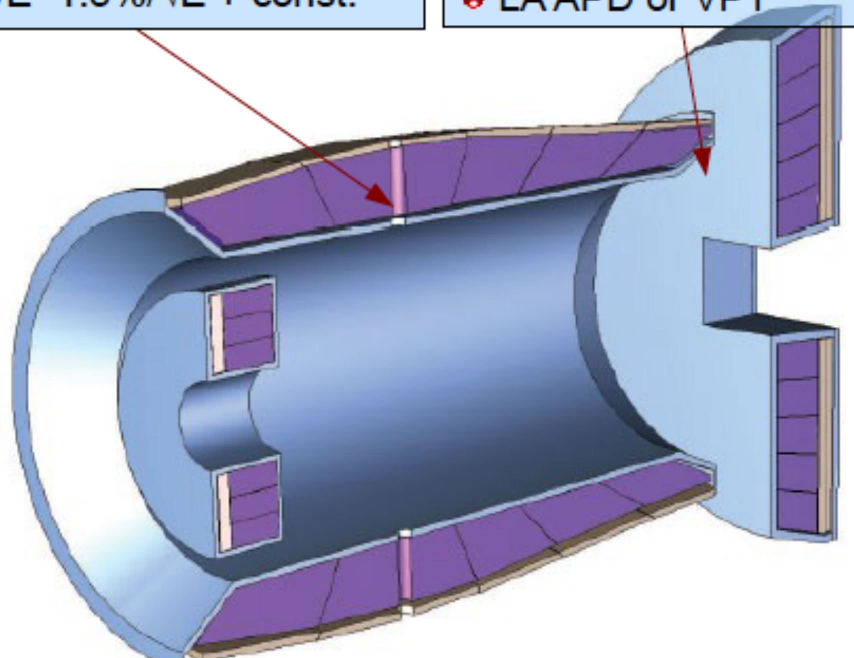
- PWO is dense and fast
- Low γ threshold is a challenge
- Increase light yield:
  - improved PWO II (2xCMS)
  - operation at -25°C (4xCMS)
- Challenges:
  - temperature stable to 0.1°C
  - control radiation damage
  - low noise electronics
- Delivery of crystals started

Barrel Calorimeter

- 11000 PWO Crystals
- LAAPD readout, 2x1cm²
- σ(E)/E~1.5%/√E + const.

Forward Endcap

- 4000 PWO crystals
- High occupancy in center
- LA APD or VPT



Large Area APDs

5x5 mm² 10x10 mm² and 7x14 mm²

Backward Endcap for hermeticity, 560 PWO crystals
Forward EMC shashlyk behind dipole

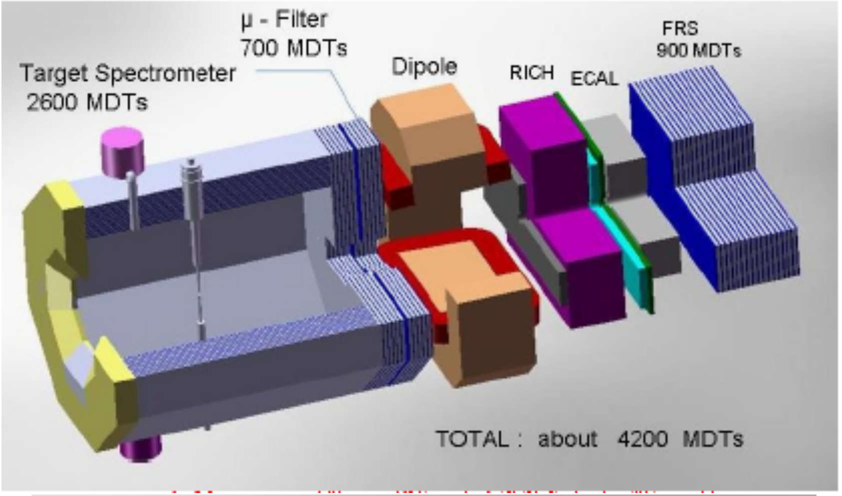
Muon Detection System

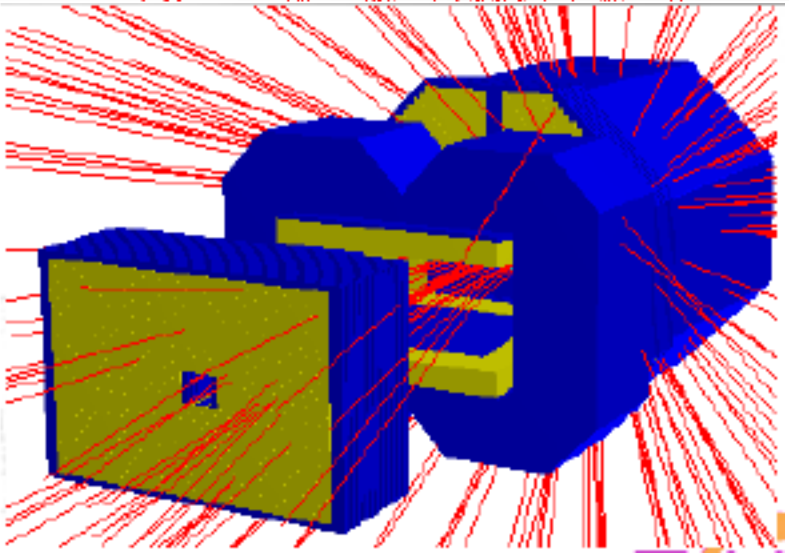
Muon system rationale:

- Low momentum particles
- High background of pions
- Multi-layer range system

Muon system layout:

- *Barrel*: 12+2 layers in yoke
- *Endcap*: 5+2 layers
- *Muon Filter*: 4 layers
- *Forward Range System*:
  - 16+2 layers
  - Iron absorbers
- *Detectors*: Drift tubes with wire & cathode strip readout



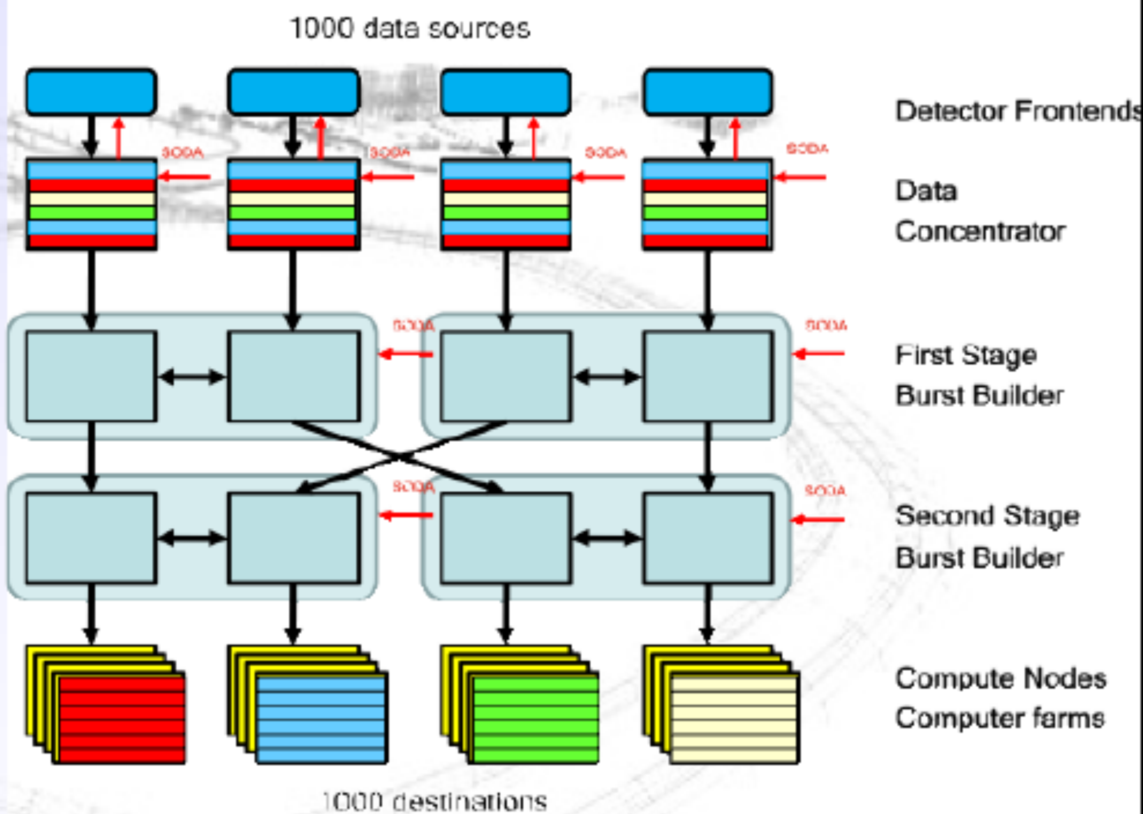


P̄ANDA Data Acquisition

Self triggered readout

- Components:
  - Time distribution system
  - Intelligent frontends
  - Powerful compute nodes
  - High speed network
- Data Flow:
  - Data reduction
  - Local feature extraction
  - Data burst building
  - Event selection
  - Data logging after online reconstruction

→ **Programmable Physics Machine**



The $\bar{\text{P}}$ANDA Collaboration

More than 520 physicists from 67 institutions in 17 countries

Aligarh Muslim University
U Basel
IHEP Beijing
U Bochum
Magadh U, Bodh Gaya
BARC Mumbai
IIT Bombay
U Bonn
IFIN-HH Bucharest
U & INFN Brescia
U & INFN Catania
NIT, Chandigarh
AGH UST Cracow
JU Cracow
U Cracow
IFJ PAN Cracow
GSI Darmstadt

Karnatak U, Dharwad
TU Dresden
JINR Dubna
U Edinburgh
U Erlangen
NWU Evanston
U & INFN Ferrara
FIAS Frankfurt
LNF-INFN Frascati
U & INFN Genova
U Glasgow
U Gießen
Birla IT&S, Goa
KVI Groningen
Sadar Patel U, Gujart
Gauhati U, Guwahati
IIT Guwahati

IIT Indore
Jülich CHP
Saha INP, Kolkata
U Katowice
IMP Lanzhou
INFN Legnaro
U Lund
U Mainz
U Minsk
ITEP Moscow
MPEI Moscow
TU München
U Münster
BINP Novosibirsk
IPN Orsay
U & INFN Pavia
IHEP Protvino

PNPI Gatchina
U of Silesia
U Stockholm
KTH Stockholm
Suranree University
South Gujarat U, Surat
U & INFN Torino
Politechnico di Torino
U & INFN Trieste
U Tübingen
TSL Uppsala
U Uppsala
U Valencia
SMI Vienna
SINS Warsaw
TU Warsaw

Summary and Outlook

The HESR at the GSI FAIR facility will deliver $\bar{p}$ beams of unprecedented quality with momenta up to 15 GeV/c ($\sqrt{s} \approx 5.5$ GeV). This will allow $\bar{P}$ANDA to shed light on many of today's QCD puzzles through measurements in hadron spectroscopy and nucleon structure.

Present status of $\bar{P}$ANDA:

- Several systems head for TDR submission
- Preparation for construction MoU
- Physics and detector topics

Timeline of $\bar{P}$ANDA:

- Many TDRs complete by end 2013
- Start of construction in 2014
- Start of preassembly at Juelich in 2016/17
- Mounting at FAIR in 2017/2018

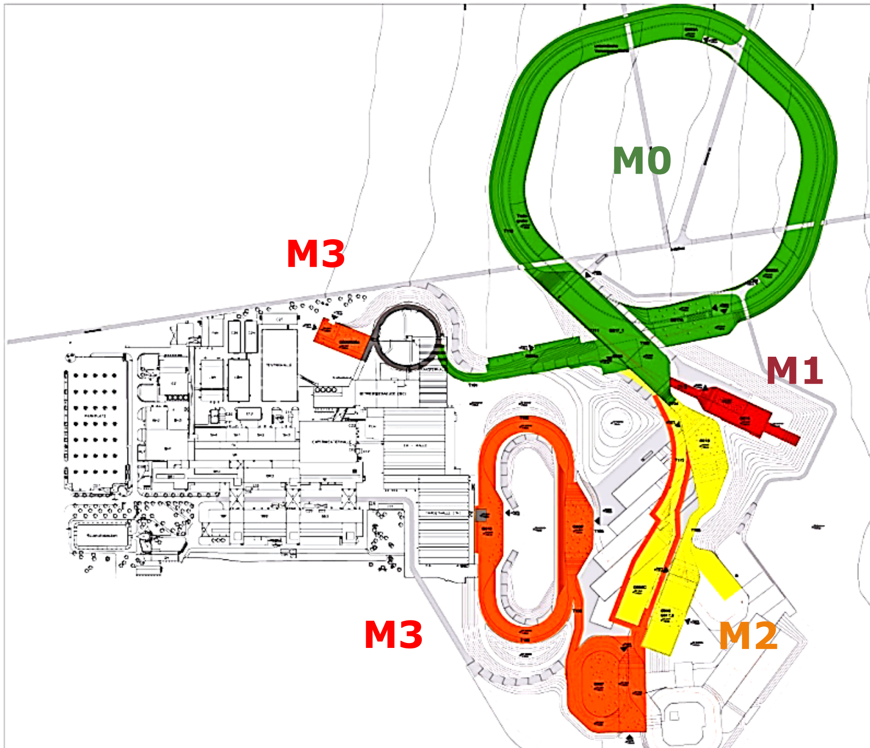
Backup

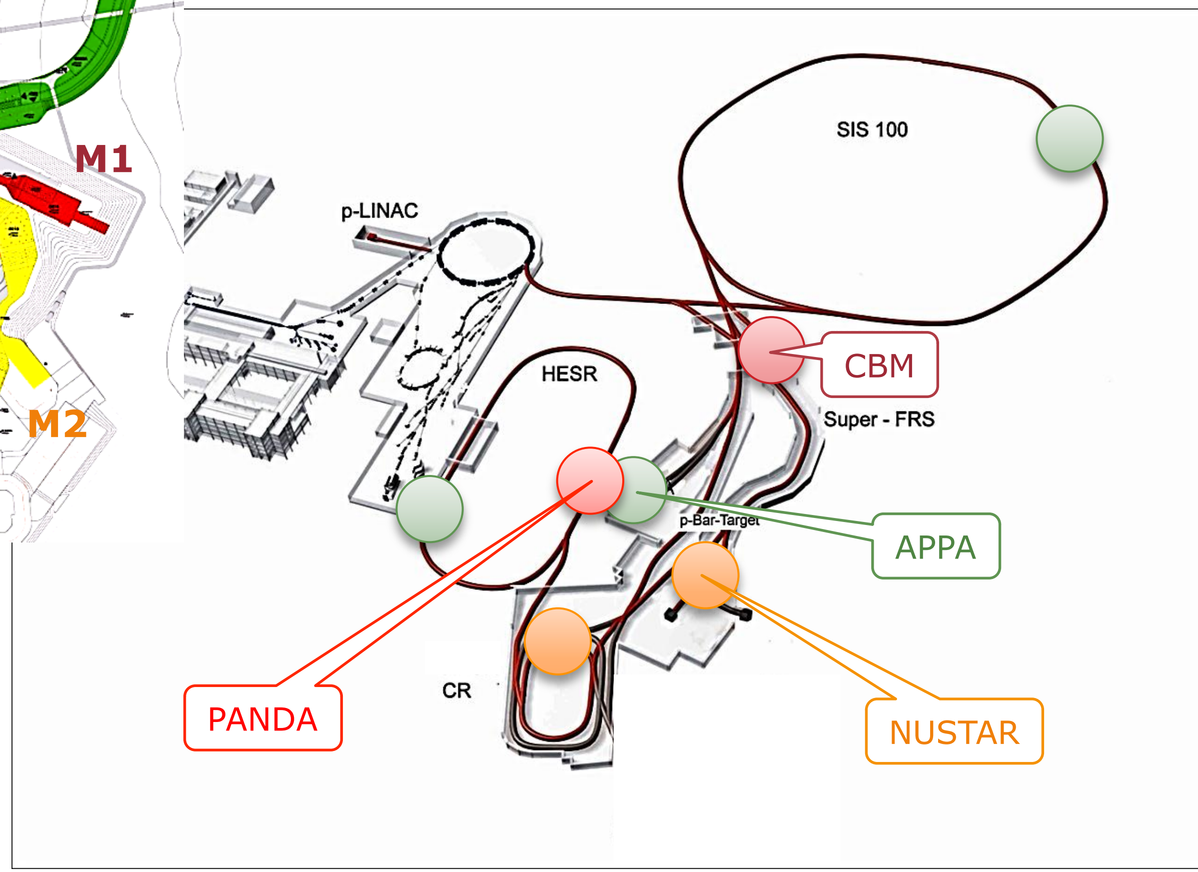
Staging

Start Version Phase A (SIS100)						**Phase B** (SIS300)
Modularised Start Version						
Module **0**	Module **1**	Module **2**	Module **3**	Module **4**	Module **5**	
SIS100	**Exp. halls** *CBM & APPA*	**Super-FRS** *NuSTAR*	**Antiproton Facility** *PANDA & options NuSTAR*	**LEB, NESR, FLAIR** *NuSTAR & APPA*	**RESR** *PANDA, NuSTAR & APPA*	

2018

FAIR Modularised Start Version





Experiments

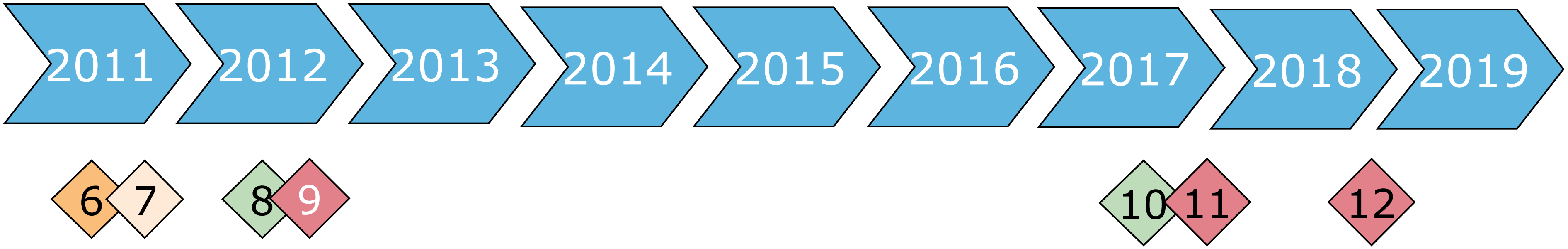
M0: APPA

M1: CBM

M2: NUSTAR

M3: PANDA

Timeline MSV



6 Submission of construction application

7 Start Site preparation

8 First civil construction contracts

9 Building of accelerator & detector components

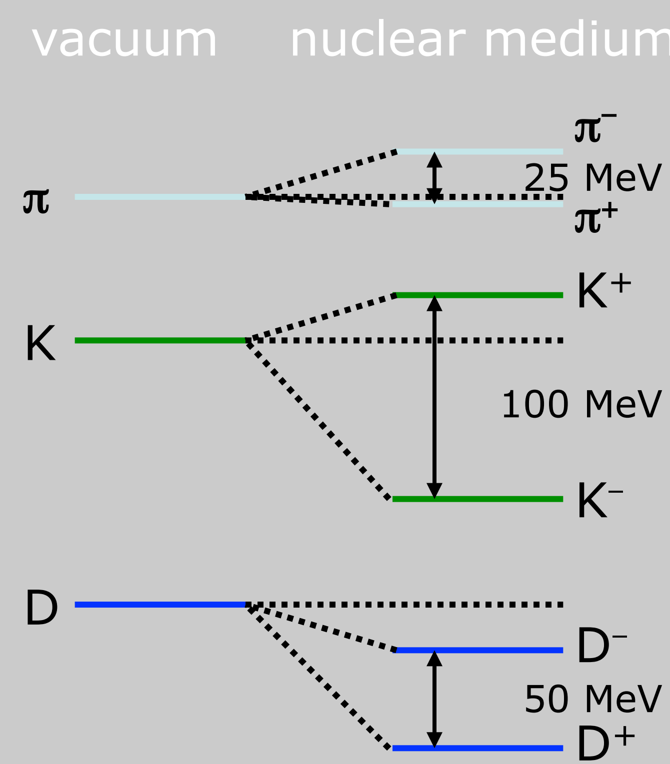
10 Civil construction work mostly finished

11 Start installing & commissioning accelerator and detector components

12 Start commissioning with beam

Hadrons in Nuclear Matter

- Partial restoration of chiral symmetry in nuclear matter
  - Light quarks are sensitive to quark condensate
- Evidence for mass changes of pions and kaons has been deduced previously:
  - deeply bound pionic atoms
  - (anti)kaon yield and phase space distribution
- $(c\bar{c})$ states are sensitive to gluon condensate
  - small (5-10 MeV/c^2) in medium modifications for low-lying $(c\bar{c})$ (J/ψ, η_c)
  - significant mass shifts for excited states: 40, 100, 140 MeV/c^2 for χ_{cJ}, ψ', $\psi(3770)$ resp.
- D mesons are the QCD analog of the H-atom.
  - chiral symmetry to be studied on a single light quark
  - theoretical calculations disagree in size and sign of mass shift (50 MeV/c^2 attractive – 160 MeV/c^2 repulsive)



Hayaski, PLB 487 (2000) 96
Morath, Lee, Weise, priv. Comm.

Charmonium in Nuclei

- Measure J/ψ and D production cross section in $\bar{p}$p annihilation on a series of nuclear targets.
- J/ψ nucleus dissociation cross section
- Lowering of the D^+D^- mass would allow charmonium states to decay into this channel, thus resulting in a dramatic increase of width

ψ(1D) 20 MeV → 40 MeV

ψ(2S) .28 MeV → 2.7 MeV

⇒Study relative changes of yield and width of the charmonium states.

- In medium mass reconstructed from dilepton ($c\bar{c}$) or hadronic decays (D)