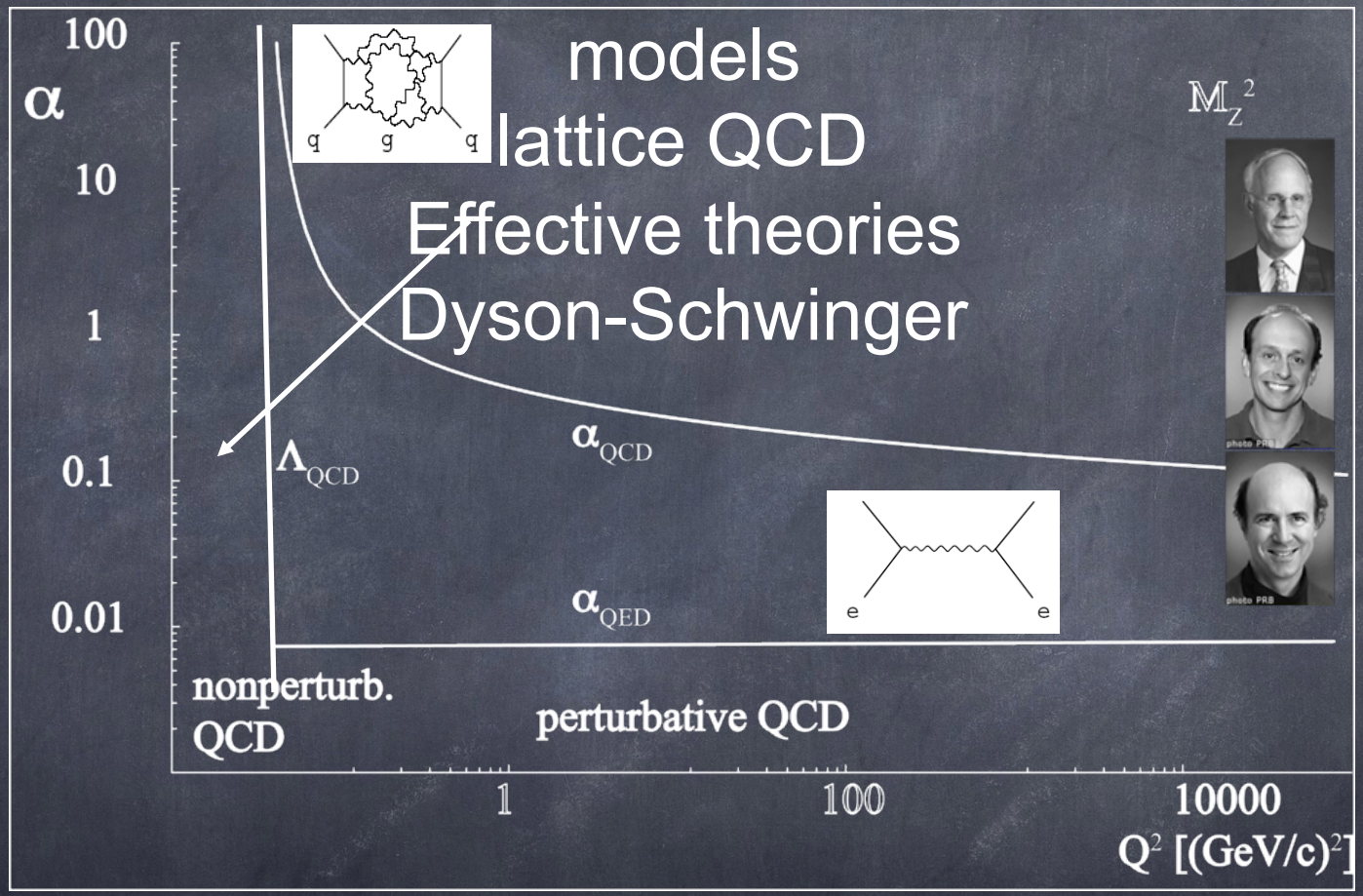
Hadron structure and spectroscopy from antiproton annihilations

International School of Nuclear Physics (37th Course)
Probing Hadron Structure with Lepton and Hadron Beams
Erice-Sicily, September 16-24, 2015

Frank Maas
GSI / HIM / U Mainz

QCD



Bound states of hadrons
Structure of hadrons
Interaction of hadrons

PANDA Program: 2 GeV – 5.5 GeV

I: Hadron spectroscopy

light mesons, baryons, charmonium, open charm,

QCD exotics: glueballs, hybrid states, X,Y,Z-states,…

II: Electromagnetic processes

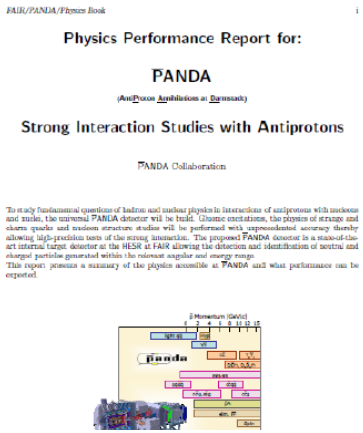
time like form factors, transition distribution

amplitudes, TMDs, …

III:Hadronic interactions:

Hyperons, Hypernuclei,

In medium-effects


FAIR/PANDA/Physics Book

Physics Performance Report for:

PANDA

(AntiProton Annihilation at Darmstadt)

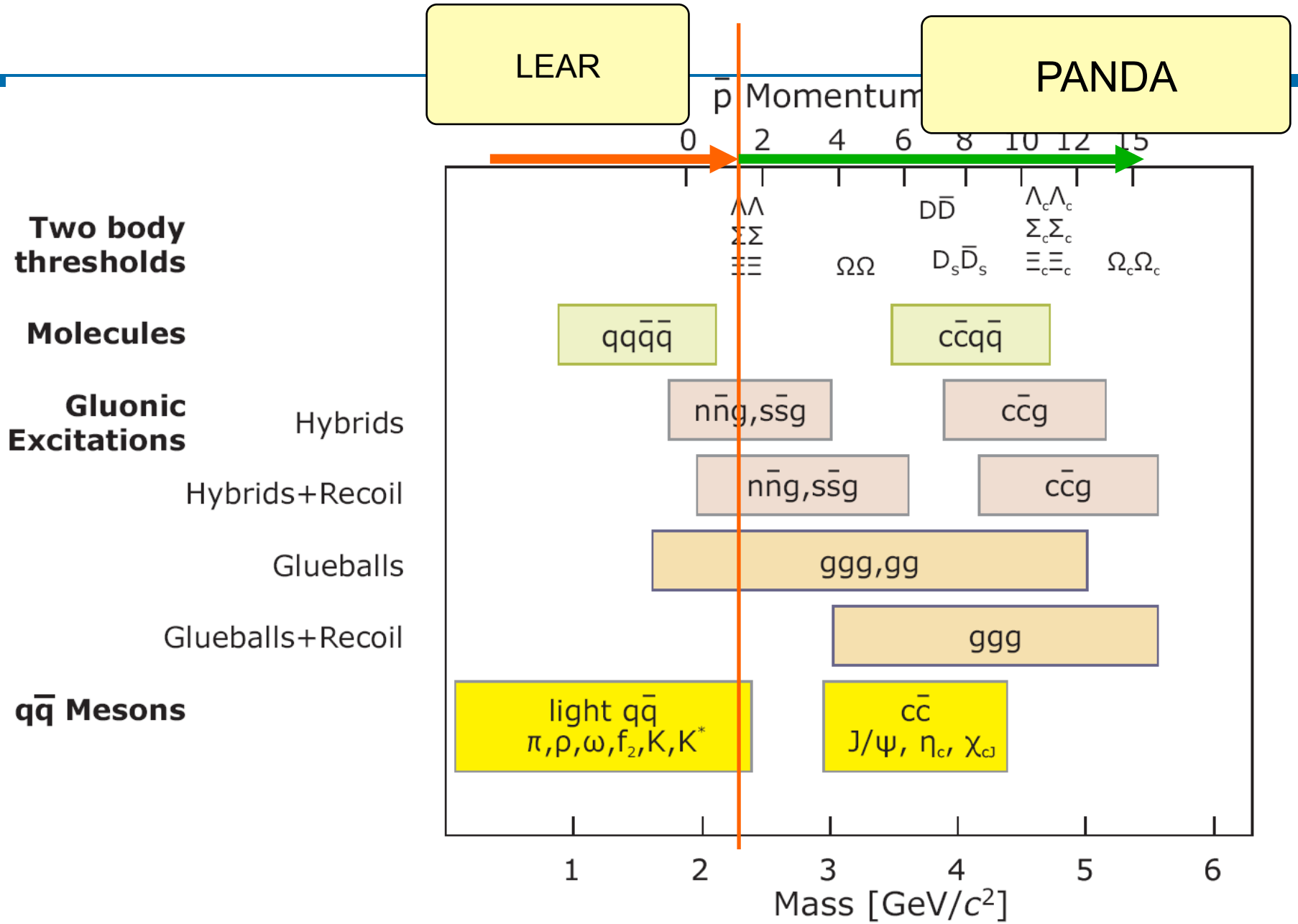
Strong Interaction Studies with Antiprotons

PANDA Collaboration

To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal PANDA 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 PANDA 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 PANDA and what performance can be expected.

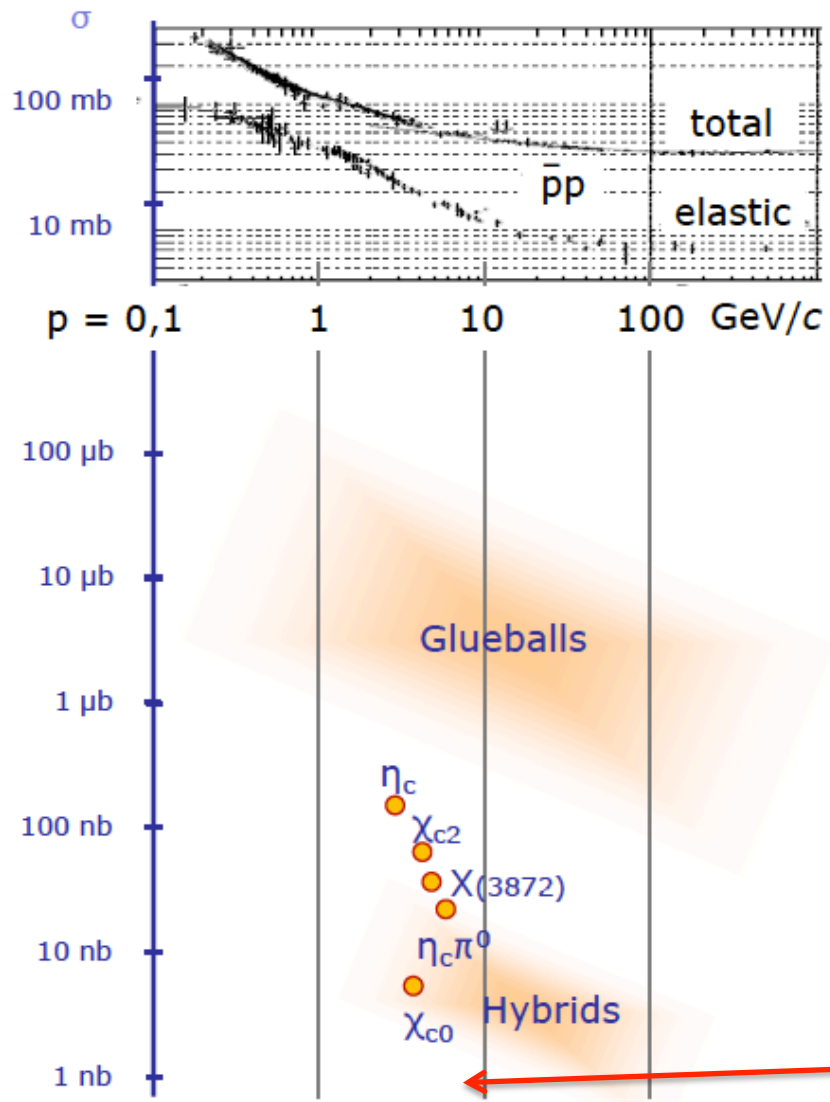
ArXiV:0903.3905

PANDA physics workshop in Uppsala, June 8 – 12, 2015



Physics performance report: arXiv:0903.3905v1

Detector Requirements from Physics Case



High luminosity and hadronic cross sections

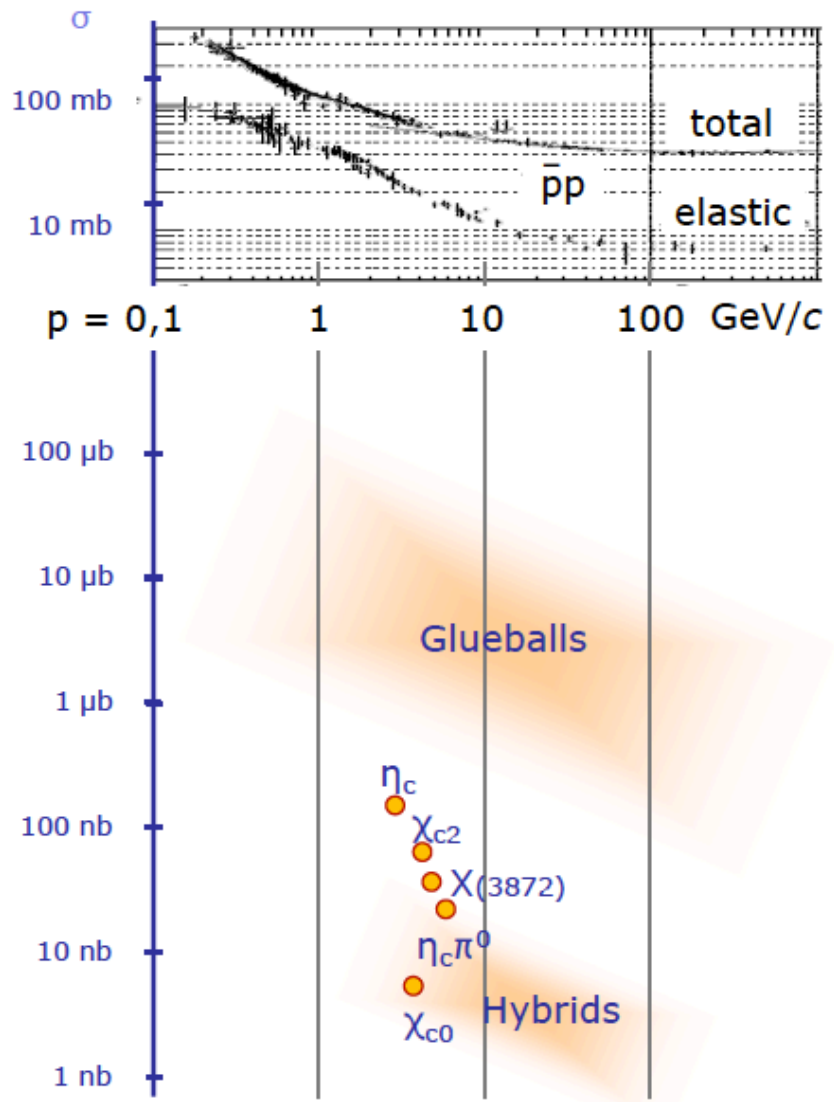
High rate capability, $2 \cdot 10^7\ s^{-1}$ interactions

High data rate

High degree of radiation resistance

Cross section for electromagnetic Processes

Detector Requirements from Physics Case



4π acceptance

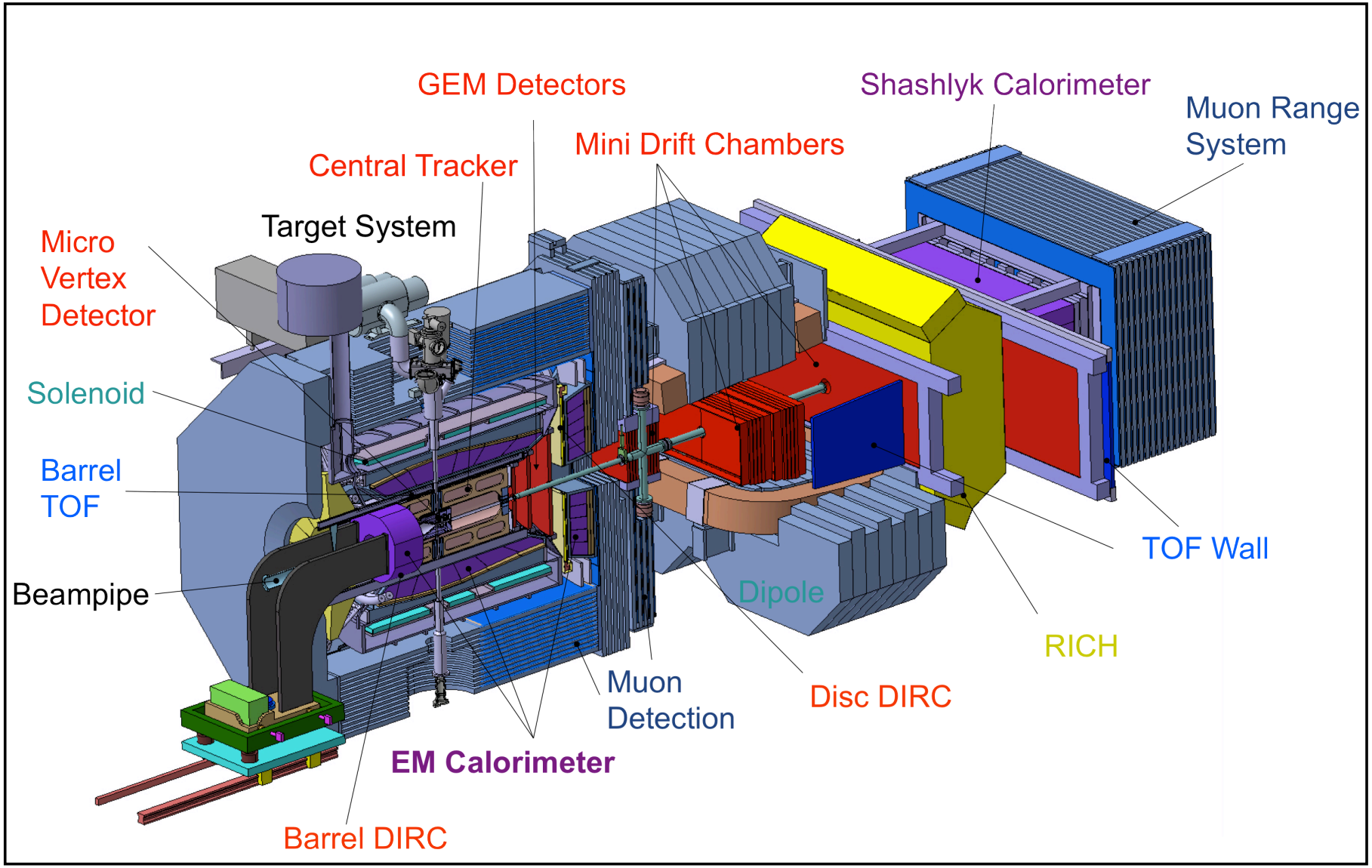
Momentum resolution: 1%
central tracker in magnetic field

Photon detection: 1 MeV - 10 GeV
high dynamic range
good energy resolution

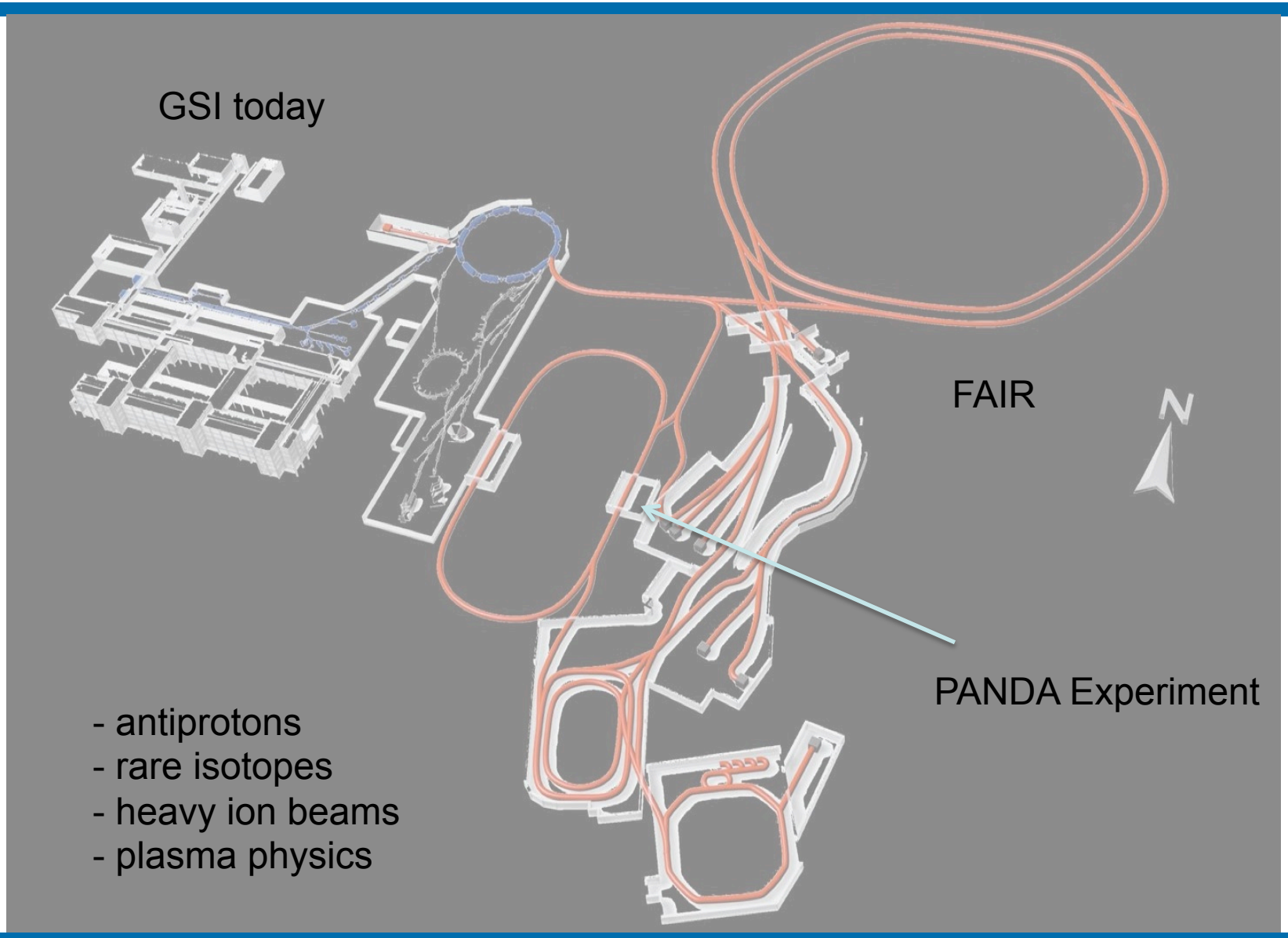
Particle identification: γ, e, μ, π, K, p
Cherenkov detector
time of flight, dE/dx, muon counter

Displaced vertex info
cτ = 317 μm for $D^{\pm}$
$\gamma\beta \approx 2$

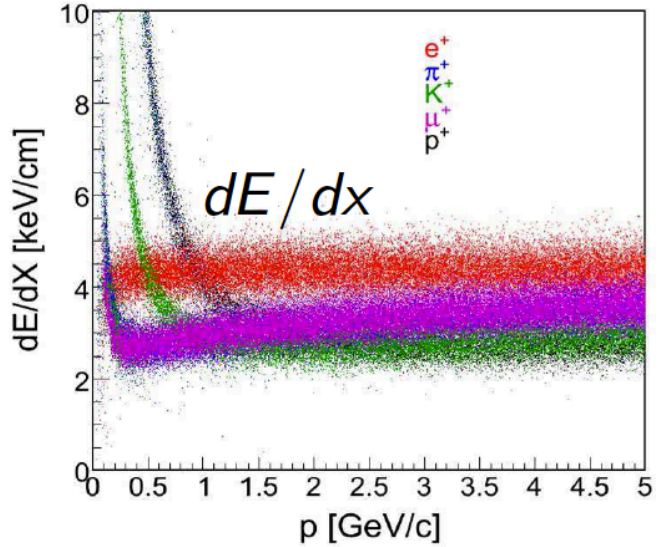
PANDA Detector

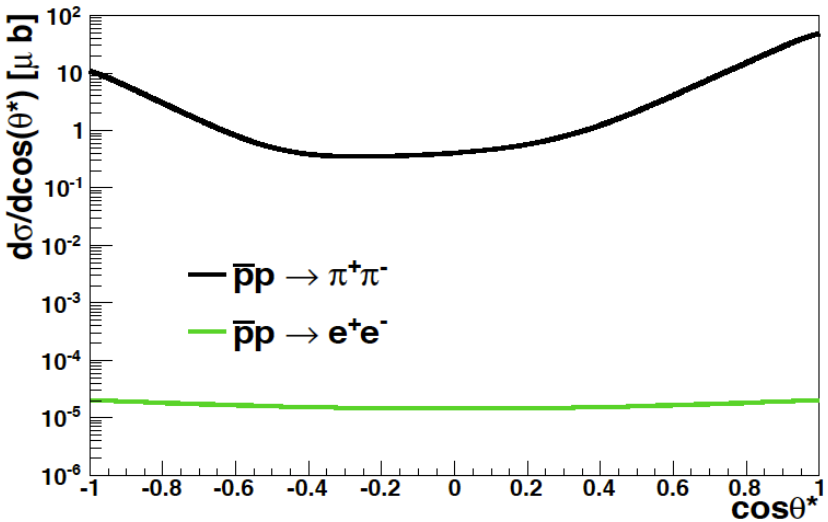


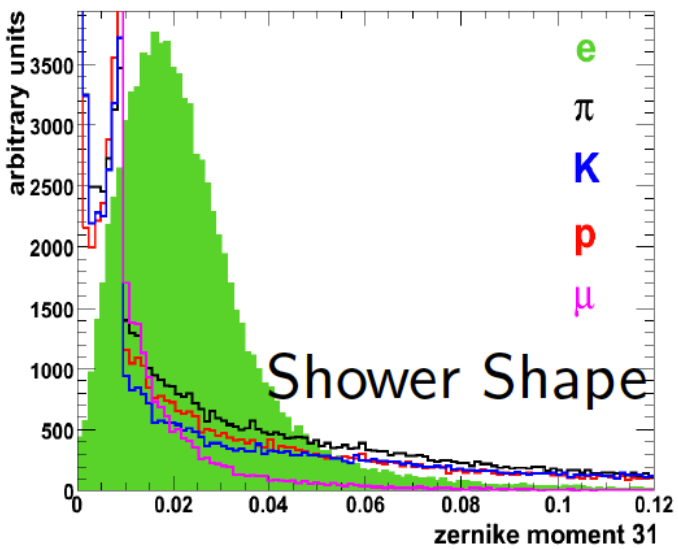
FAIR Facility Darmstadt

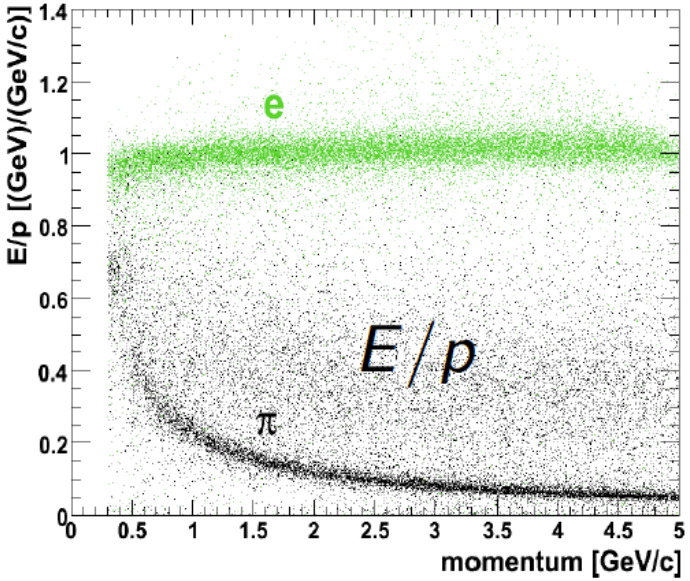


Particle Identification in PANDA









I. Spectroscopy

Elisa Fioravanti, Johan Meschendorp,
Frank Nerling, Marc Pelizäus

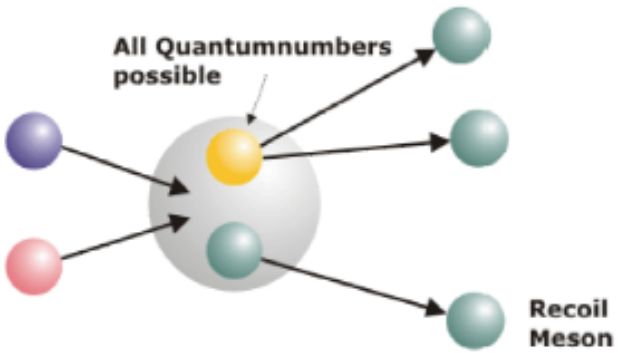
PANDA physics workshop in Uppsala, June 8 – 12, 2015

Antiproton annihilations: gluon rich environment

Production: all states with exotic and non-exotic quantum numbers accessible with a recoil

- high discovery potential

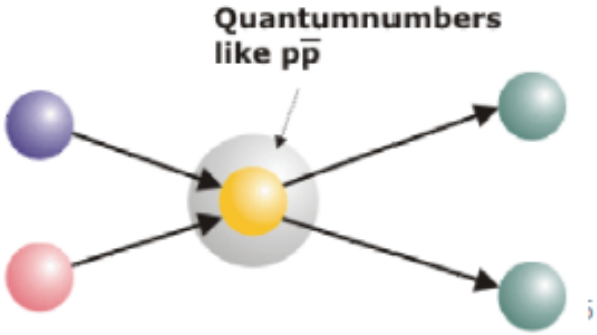
Associated, access to all quantum numbers (exotic)



Formation: all states with non-exotic quantum numbers accessible

- not only limited to 1^{--} as e^+e^- colliders
- precision physics of known states

Resonant, high statistics, extremely good precision in mass and width



antiproton probe unique

Comparision with other techniques

- e^+e^-
  - direct formation limited to $J^{PC} = 1^{--}$
  - limited resolution for masses and widths for non vector states
  - sub-MeV widths very difficult or impossible
  - high L not accessible
- high-energy (several TeV) hadroproduction
  - high combinatorial background makes discovery of new states very difficult
  - width measurements limited by detector resolution
- B decays (both for e^+e^- and hadroproduction)
  - limited J^{PC}
  - C cannot be determined since not conserved in weak decay

Energy scan of HESR-storage ring

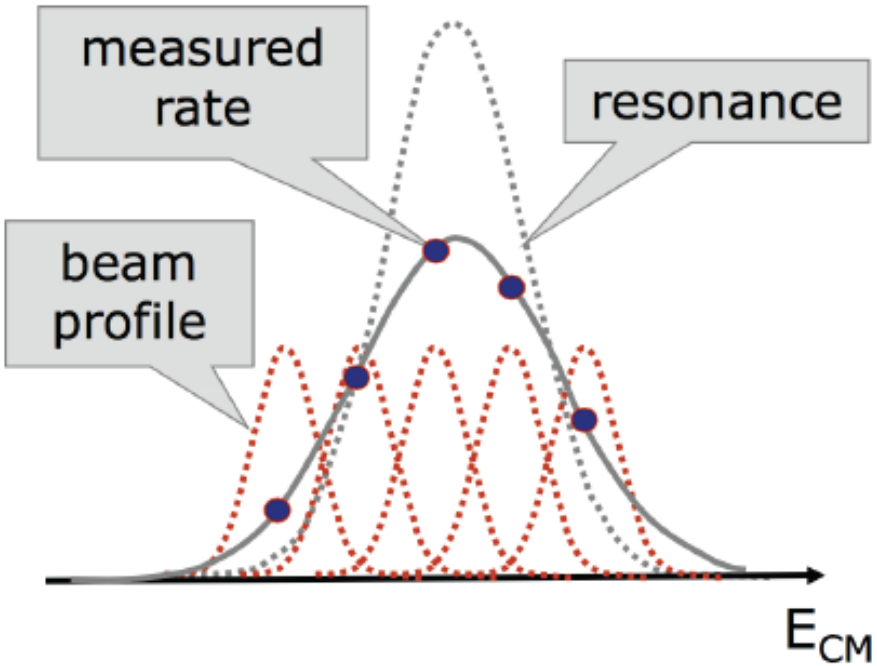
High resolution mode of HESR

- Stochastic and electron cooling of beam for p < 8.9 GeV/c
- Momentum resolution: $\Delta p/p \leq 4 \times 10^{-5}$
- Peak luminosity: 10^{31} cm^{-2} s^{-1}

Precise measurement of masses and widths of resonances

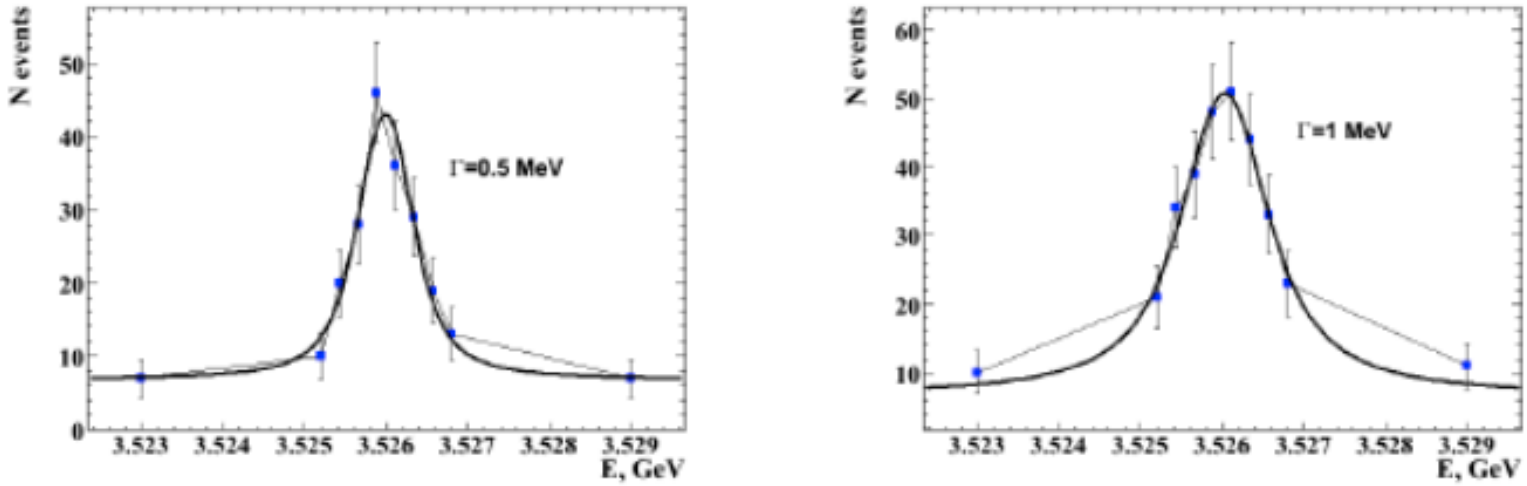
- only dependent on beam momentum resolution

→ unique at PANDA



$h_c(1^1P_1)$ Energy Scan At PANDA

$h_c \rightarrow \eta_c\gamma \rightarrow \phi\phi\gamma \rightarrow 4K\,\gamma$



- Scan at 10 energy points around the h_c mass
- Each point corresponds to 5 days of data taking in high resolution mode

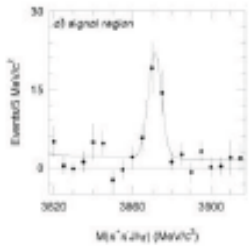
$\Gamma_{R,MC}$ [MeV]	$\Gamma_{R,reco}$ [MeV]	$\Delta\Gamma_R$ [MeV]
1	0.92	0.24
0.75	0.72	0.18
0.5	0.52	0.14

PANDA, arXiv:0903.3905 [hep-ex]

X.Y.Z

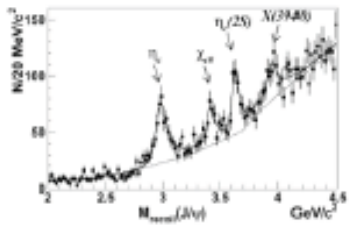
X(3872)

PRL 91,262001 (2003)



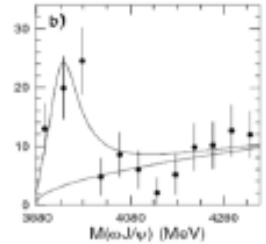
X(3940)

PRL 98,082001 (2007)



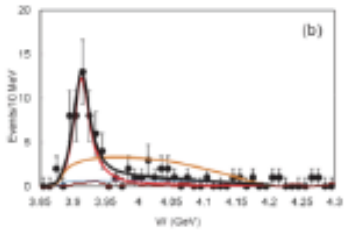
Y(3940)

PRL 94,182002 (2005)



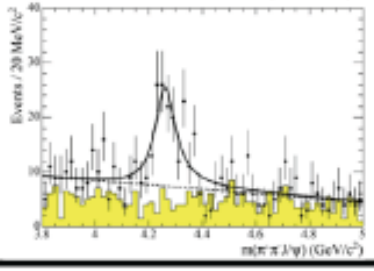
X(3915)

PRL 104,092001 (2010)



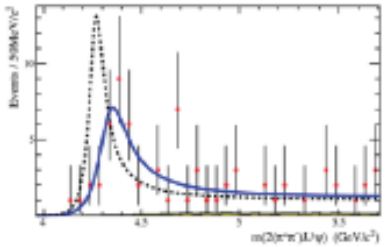
Y(4260)

PRL 95,142001 (2005)



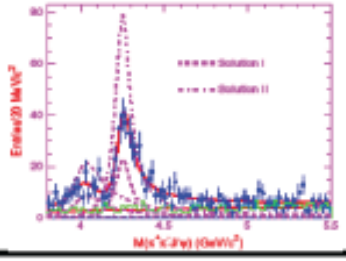
Y(4350)

PRL 98,212001 (2007)



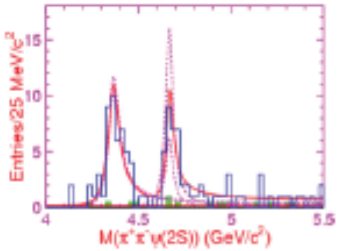
Y(4008)

PRL 99,182004 (2007)



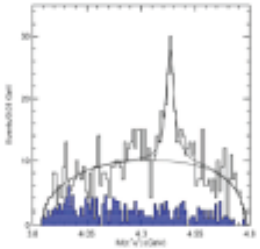
Y(4660)

PRL 99,142002 (2007)



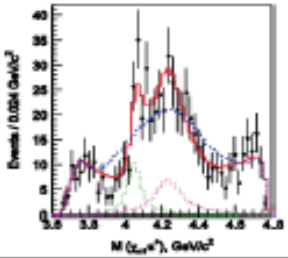
Z(4430)$^-$

PRL 100,142001 (2008)



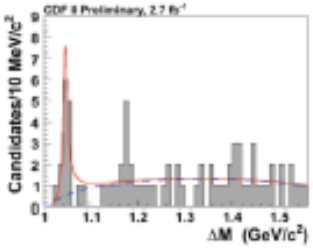
Z_1^- & Z_2^-

PRD 78,072004 (2008)



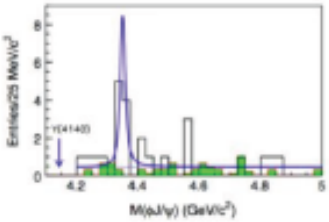
Y(4140)

PRL 102,242002 (2009)



X(4350)

PRL 104,112004 (2010)



X(3872): PANDA vs. Belle II And BES III

Some numbers, considering $J/\psi\ \pi^+\pi^-$ decay mode only:

- PANDA, assume $\sigma(pp \to X(3872))=50$ nb
  statistics ~130 (1300) per day on peak for $\mathcal{L}=2 \times 10^{31}$ (10^{32}) $cm^{-2}\ s^{-1}$
  efficiency ~50% (4 charged, exclusive)
  high boost β_{γ} ~0.89 (fixed target) → $\beta\gamma$~1.95
  mass
- Belle
  statis
  effien
  small boost $p\gamma$=0.45 (Belle), $p\gamma$=0.28 (Belle II)
  mass resolution ~10-20 MeV (unfitted)
- BESIII
  $e^+e^- \to Y(4260) \to \gamma X(3872)$ BESIII, Phys. Rev. Lett. 112(2014)092001
  ≃1200 Y(4260) per day (σ≃60 pb, integrated luminosity ≃20 pb^{-1}/day)
  but branching fraction small, only ≃0.5% (≃20 events in ~4 weeks)
  rare

350 X(3872)/day
820 Y(4260)/day
176 Z(3900)/day

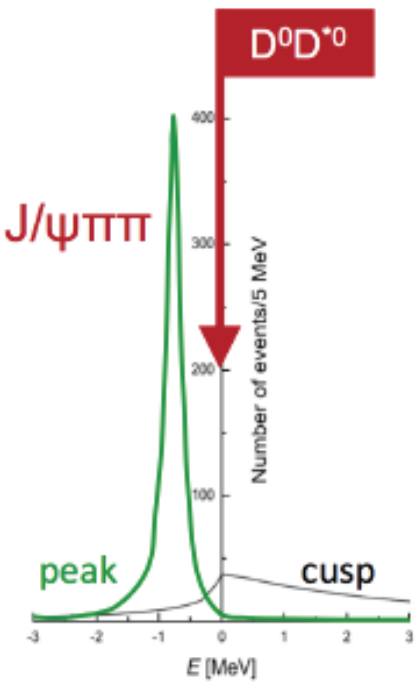
$\bar{P}$ANDA is an X Y Z factory

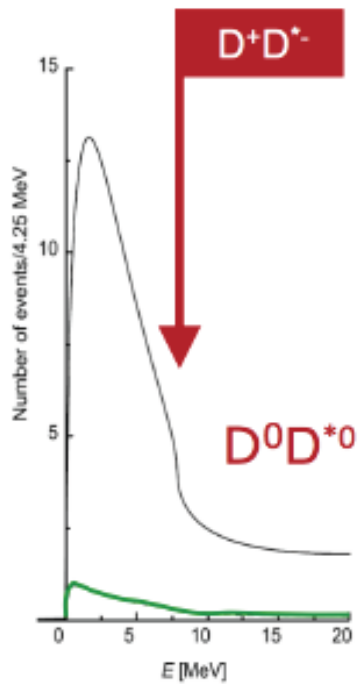
) measurement
ie X(3872),
: lineshape!

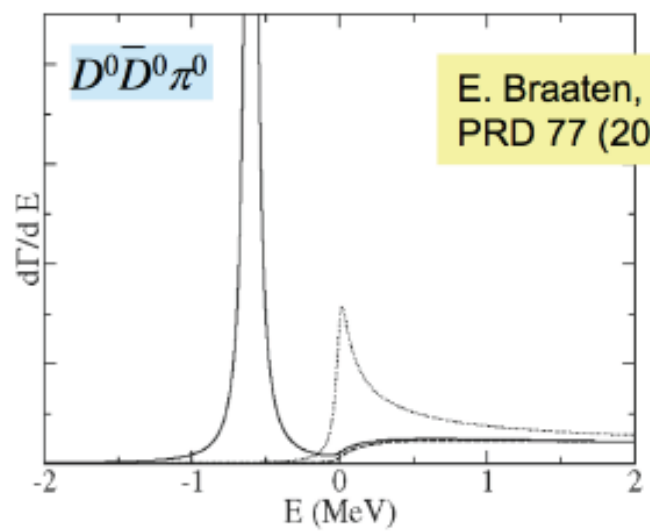
[S.Lange, Worms 2014]

PANDA: Study of Lineshapes

- Panda: Final states including neutral & charged particles
  - e.g. $J/\psi\ \pi^-\pi^+$, $J/\psi\ \pi^0\pi^0$, $\chi_\chi\gamma \rightarrow J/\psi\ \gamma\gamma$, $J/\psi\ \gamma$, $J/\psi\ \eta$, $\eta_\chi\gamma$, ...
- Direct formation in $\bar{p}p$ → *lineshapes*
- Example: X(3872)







E. Braaten, M. Lu, PRD 77 (2008) 014029

virtual state
binding state

C. Hanhart *et al.*, PRD 76 (2007) 034007

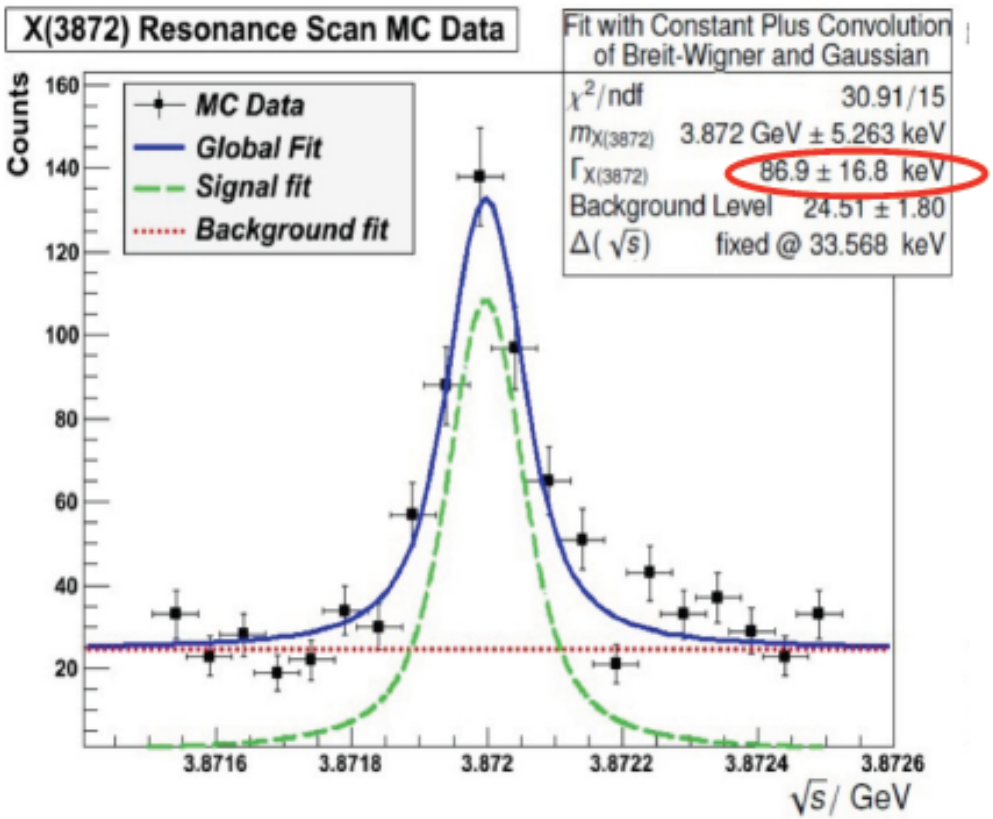
Compare lineshapes in different final states

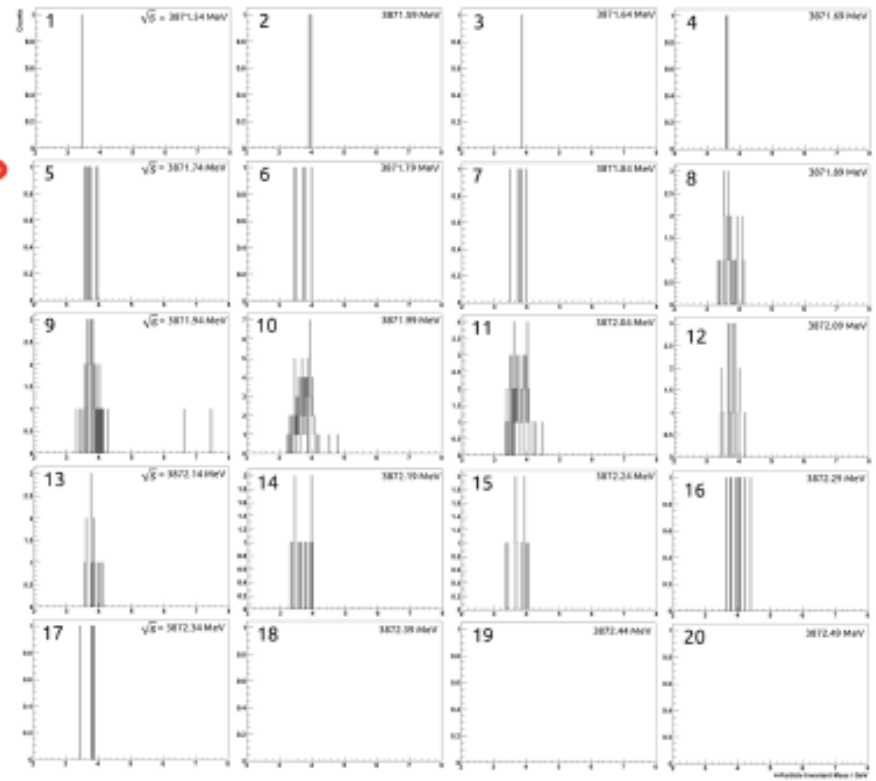
X(3872): Lineshape Scan at PANDA

- Upper limit on branching ratio by LHCb:

$BR(X \to \bar{p}p) < 0.002 * BR(X \to J/\psi \pi\pi^+)$ → $\Gamma < 1.2$ MeV EPJ C73 (2013) 2462

- And $BR(X \to J/\psi \pi^-\pi^+) > 0.026$ (PDG 12) => $\sigma(\bar{p}p \to X(3872)) < 67$ nb





→ 40 days of data taking

[M.Galuska, PhD thesis]

X, Y, Z Studies At PANDA

[F. Nerling, K. Goetzen, R. Kliemt]

$\sigma_s = 10$ nb, $E_{cms} = 5.5$ GeV

10nb	L/cms			
E_cm	detopt	Full		
	mode	t [d]	S/B	Dal QA

$\sigma_s = 1$ nb, $E_{cms} = 5.5$ GeV

1nb	L/cms			
E_cm	detopt	Full		
	mode	t [d]	S/B	Dal QA

- Many more charged and neutral states predicted than observed
  - 67 among 80 ground states still to be discovered
- Only PANDA: discovery potential for high spin states *(angular momentum barrier)*
  - e.g. predicted J = 3 state
- Observation of complete multiplet pattern needed to solve X,Y,Z puzzle

Jpsi(2e) 2eta	3,8	0,57	✓
Jpsi(2e) 2K	0,7	2,7	✓
Jpsi(2mu) 2pi	0,6	3,1	✓
Jpsi(2mu) 2pi0	0,6	3,0	✓
Jpsi(2mu) 2eta	2,3	0,82	✓
Jpsi(2mu) 2K	0,5	3,8	✓

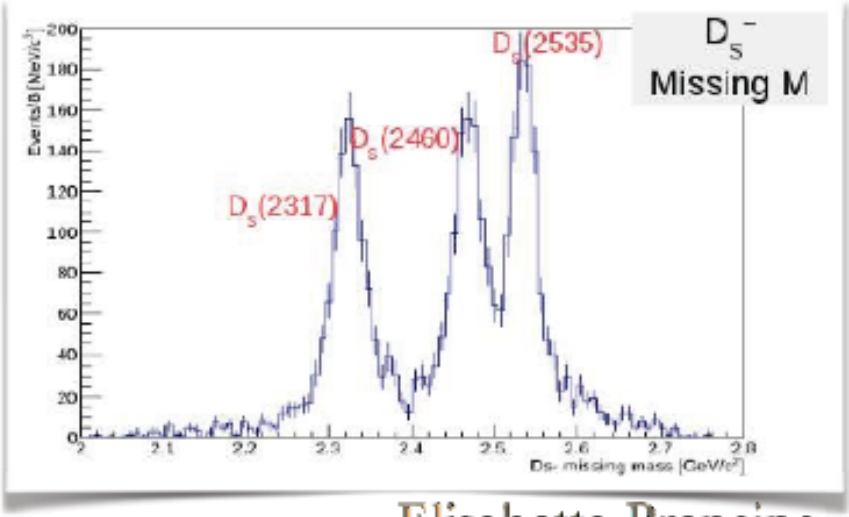
Jpsi(2e) 2eta	38	0,057	✓
Jpsi(2e) 2K	7,2	0,27	✓
Jpsi(2mu) 2pi	6,3	0,31	✓
Jpsi(2mu) 2pi0	6,4	0,30	✓
Jpsi(2mu) 2eta	24	0,082	✓
Jpsi(2mu) 2K	5,1	0,38	✓

Required Beam Time (days)
green < 30 yellow < 365 red >= 365

Signal / Background
green > 1 yellow > 0.1 red <= 0.1

Homogeneity of Dalitz plot
ok < 1.5

PANDA Opportunities



Elisabetta Prencipe

- **Radiative transitions**
  - limited data available
  - model sensitive and calculable as well!
- **Soft pion transitions**
  - isospin breaking mechanism in D_s
  - low-energy with Goldstone bosons
  - mixing of 1+ states: f.e, D_{sJ}(2460,2536)—>D*pi
- **Search for D-waves and "exotics"**
  - expect higher production rate in p-pbar than in e+e-
  - determine spin-parity of existing candidates
  - *new* discovery from LHCb: D^*_{s1}(2860) mixture with D^*_{s3}(2860) - arXiv:1407.7574

Light Mesons in $\bar{p}p$ Annihilation at PANDA

- Light meson production cross sections in $\bar{p}p$ are huge
  - 100 nb … 10 μb

- Neutral resonances with m>2.25 GeV/c^2 and non-exotic quantum numbers accessible in formation
  - all others accessible in production with at least one recoil meson and variable center-of-mass energy (→ tuneable phasespace)

- Many broad and overlapping states
  - requires (often) partial wave analysis techniques to identify resonances

Y(2175) Studies at PANDA

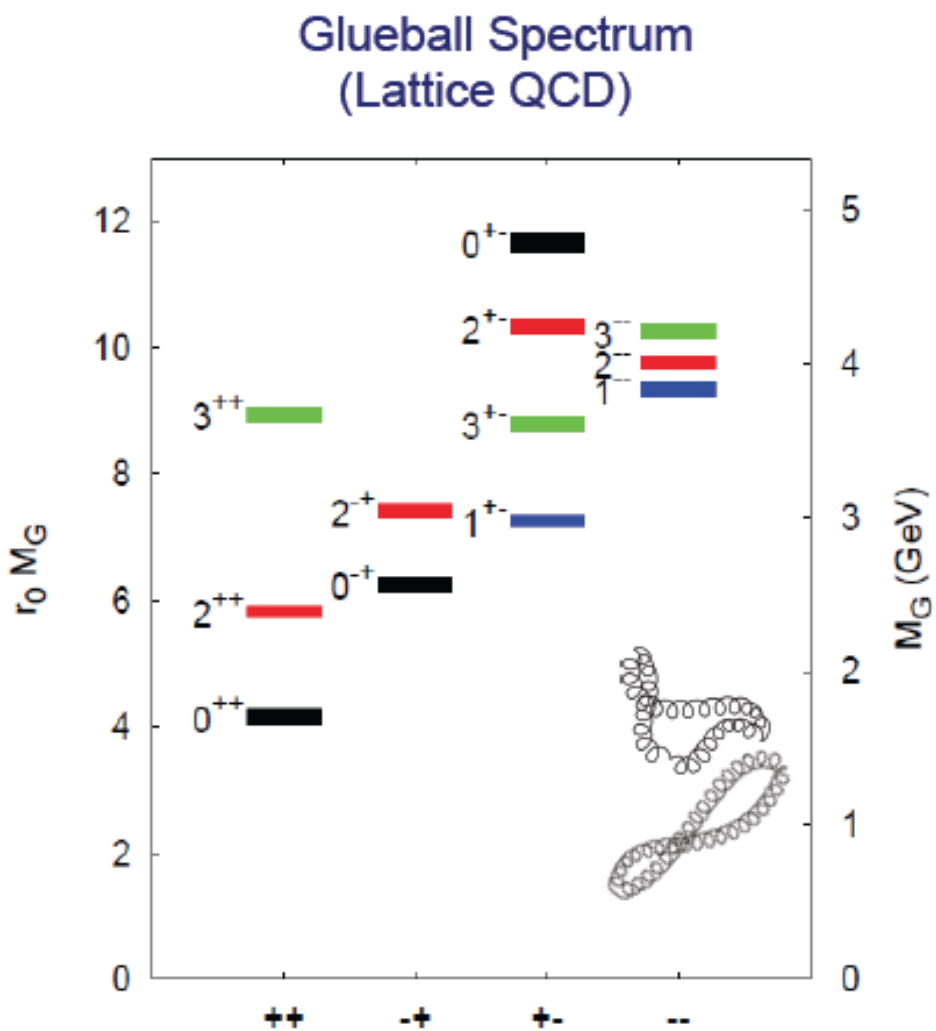
- $\bar{p}p \to Y(2175)\pi\pi, Y(2175)\pi^0$ at E_{CMS}= 3 GeV
  - Y(2175) reconstructed in $\Phi\pi^+\pi^-$ and $\Phi\pi^0\pi^0$
  - assumed signal cross section: 100 nb
  - background cross section: 70 mb

Beam-time to record 1000 reconstructed events in the $\Phi\pi^+\pi^-\pi^0$ decay mode

	$f_{BR} = 5\,\%$	$f_{BR} = 10\,\%$	$f_{BR} = 30\,\%$
$L = 2{\cdot}10^{30}$	99.5 d	24.9 d	2.8 d
$L = 2{\cdot}10^{31}$	9.95 d	2.49 d	0.28 h
$L = 2{\cdot}10^{32}$	0.995 d	0.249 d	0.028 h

[Ch. Motzko]

Glueballs



C. Morningstar, M. Peardon, Phys. Rev. D60, 34509 (1999)

C. Morningstar, M. Peardon, Phys. Rev. D56, 4043 (1997)

Glueball Studies at PANDA

- Study of glueball production in $K^+K^-\pi^0$, $K^+K^-\pi^0\pi^0$, and $\Phi\Phi\pi^0$
  - assuming cross section of 10 nb (including decay to final state)
  - background cross sections 50 to 80 mb

- "Light" glueball m = 2400 MeV/c^2 (could be 2^{++} or 0^{-+})
  - E_{CMS} = 2.57 GeV and 5.47 GeV
  - could be broad, study final states w/o intermediate resonances

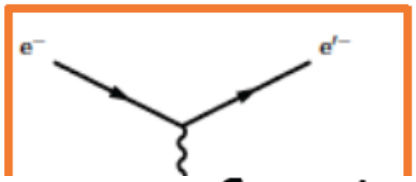
- "Heavy" glueball m = 3900 MeV/c^2
  - E_{CMS} = 5.47 GeV
  - could be narrow, assume Γ=10 MeV
  - search for narrow signal in production followed by detailed studies in formation [unique at PANDA]

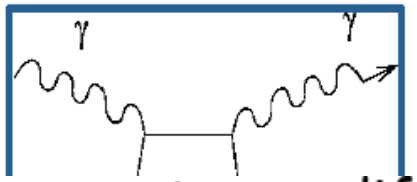
II. Electromagnetic Processes

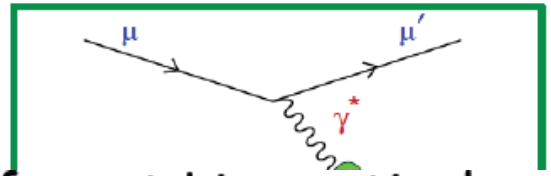
PANDA physics workshop in Uppsala, June 8 – 12, 2015

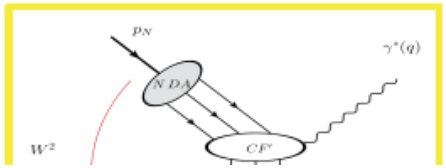
Alaa Dbeyssi

(Virtual) photon in intermediate state



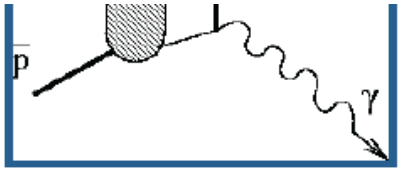


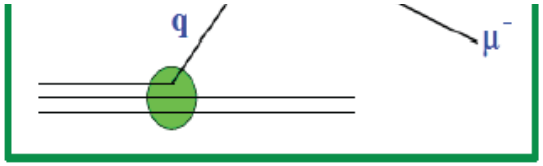


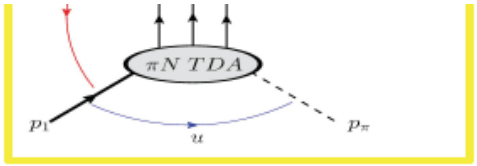


Crossing symmetry: - different kinematical regions
- observables are counterparts

A high quality and energy antiproton beam will be an excellent tool for a complementarity study of the nucleon structure with electron or photon experiments





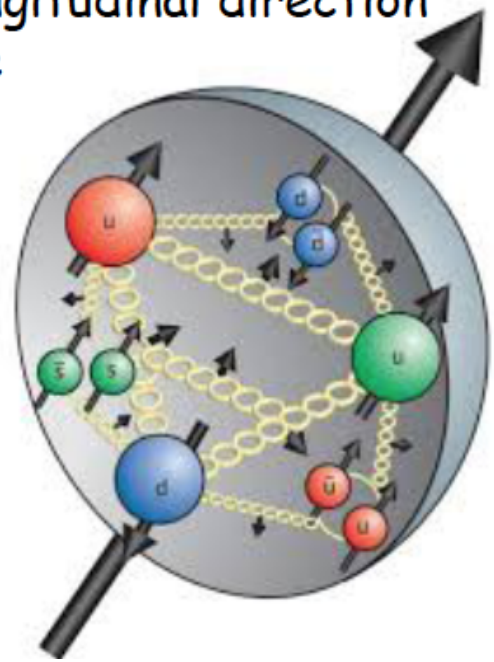


Wide selection of structure functions acessible

- The nucleon size, the charge and magnetization distributions with the electromagnetic Form Factors (FFs)

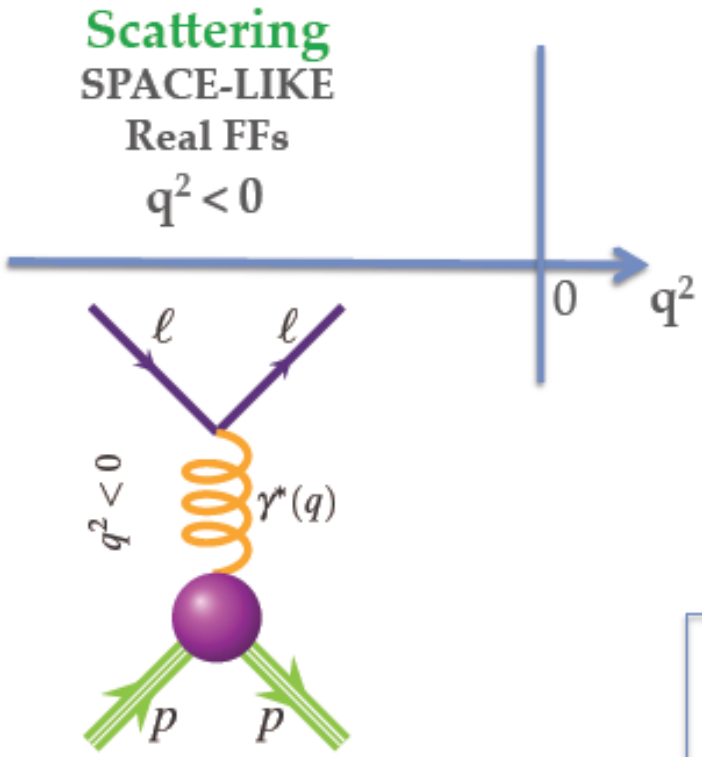
- Distribution of partons in the transverse plane and longitudinal direction with the Parton Distribution Functions (PDFs) and the Generalized Parton Distributions (GPDs)

- The spin dependent properties of the nucleon and its transverse degree of freedom with the transverse Momentum Dependence PDFs (TMDs)



Extended feasibility studies in simulations based on present PANDA design

Electromagnetic Form Factors of the Proton



- **Internal structure and dynamics** of the proton
- **Hadronic vertex can be parametrized in terms of two Form Factors F_1 & F_2:**

$$\Gamma^\mu = F_1(q^2)\,\gamma^\mu + \frac{i\kappa}{2m_p} F_2(q^2)\,\sigma^{\mu\nu} q_\nu$$

- **Sachs Form Factors G_E & G_M**

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4m_p^2} F_2(q^2), \quad G_E(0) = 1$$

$$G_M(q^2) = F_1(q^2) + F_2(q^2), \quad G_M(0) = \mu_p$$

- In the Breit frame q=(0,**q**) and in non relativistic approach, G_E and G_M are the Fourier transforms of the **charge and magnetic spatial distributions** of the nucleon

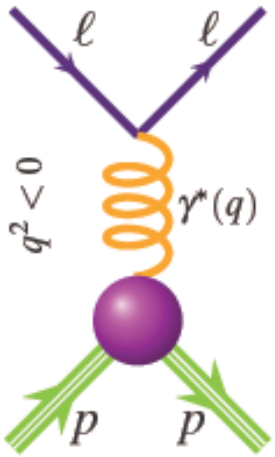
Electromagnetic Form Factors of the Proton

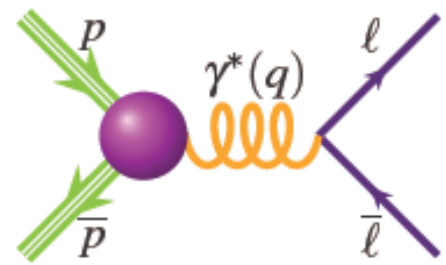
Scattering
SPACE-LIKE
Real FFs
$q^2 < 0$

Annihilation
TIME-LIKE
Complex FFs
$q^2 > 0$

„Unphysical region"
$\bar{p}p \rightarrow \pi^0 e^+ e^-$

0 | $4\,M_p^2$ | q^2





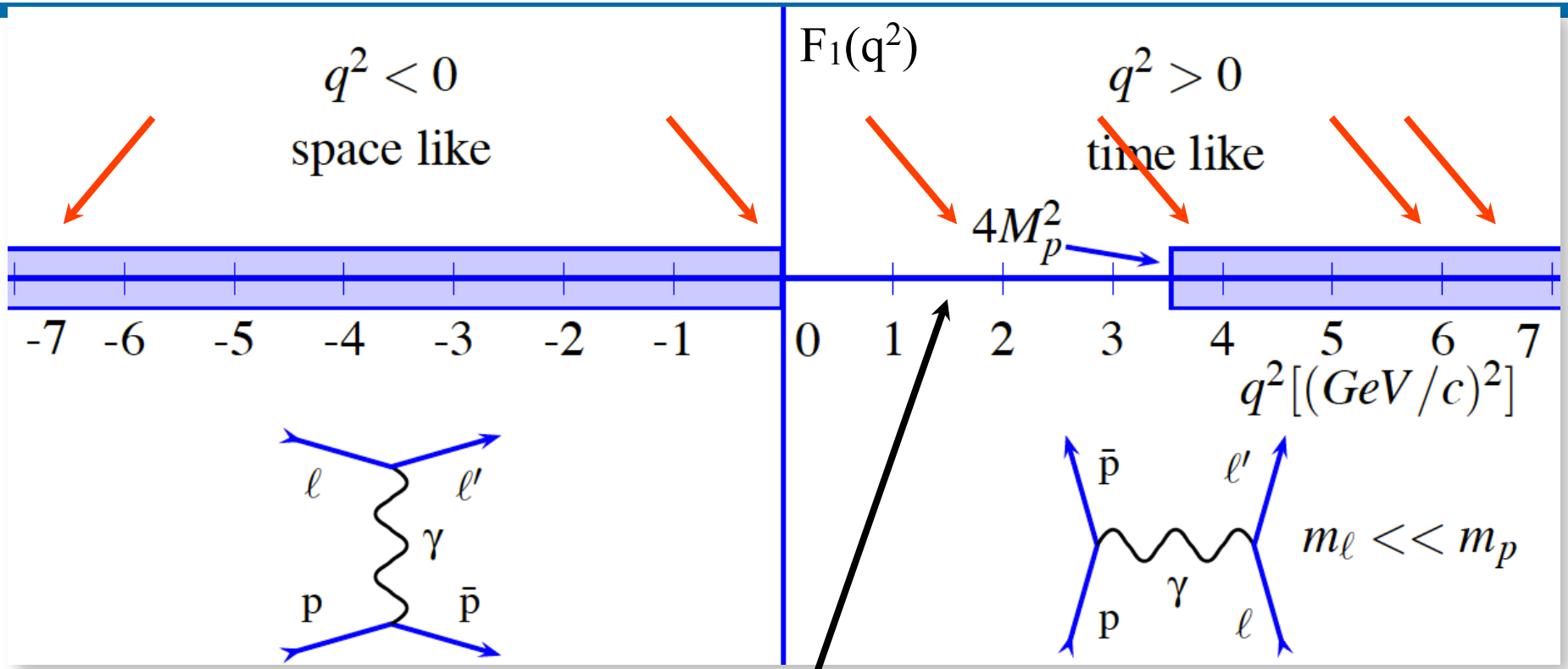
- **Only few experiments** so far
- **Scarce data, low statistics**
- **No individual measurement** of G_E and G_M

Effective Form Factor: $|F_p|^2 \propto \sigma_{tot}$

Dispersion relations based on

Unitarity & Analyticity

Electromagnetic Form factors of the Nucleon



unphysical region

Form Factor real

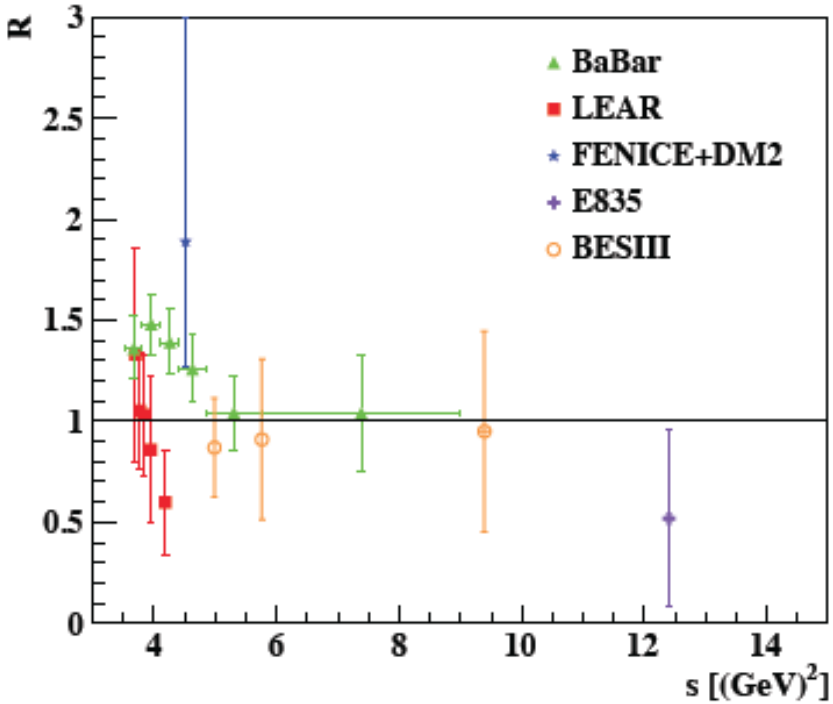
cross section (Rosenbluth)
no single spin observables
double spin observables

Form Factor complex

cross section (angular Distr.)
single spin observables (P_y)
double spin observables

connected by dispersion relations

Data on the time-like proton form factor ratio $R=|G_E|/|G_M|$



@ BaBar (SLAC): $e^+e^- \rightarrow \bar{p}p\gamma$

- data collection over wide energy range
- 10%-24% statistical uncertainties

@ PS 170 (LEAR): $\bar{p}p \rightarrow e^+e^-$

- data collection at low energies

Data from BaBar & LEAR show inconsistencies

@ BESIII: $e^+e^- \rightarrow \bar{p}p$

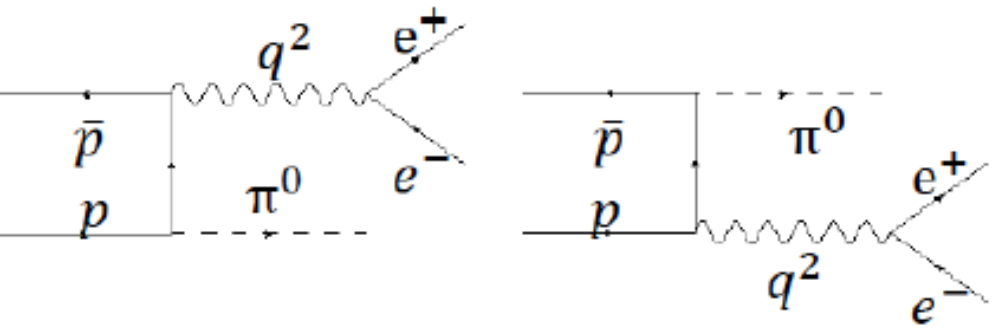
- Measurement at different energies
- Uncertainties comparable to previous experiments

BaBar: Phys. Rev. D88 072009
LEAR: Nucl.Phys.J., B411:3-32. 1994
BESIII: arXiv:1504.02680. 2015

PANDA: Measurement up to large q^2 with unprecedented precision

Electro magnetic form factors in the time like regime in PANDA

- Measurements of the proton effective form factor in the TL region over a large kinematical region through: $\bar{p}p \rightarrow e^+e^-$ $\bar{p}p \rightarrow \mu^+\mu^-$
- Individual measurement of $|G_E|$ and $|G_M|$ and their ratio
- Possibility to access the relative phase of proton TL FFs
  - Polarization observables (**Born approximation**) give access to $G_E G_M{}^*$
  - Development of a transverse polarized proton target for PANDA in Mainz
- Measurement of proton FFs in the unphysical region: $\bar{p}p \rightarrow e^+e^-\pi^0$

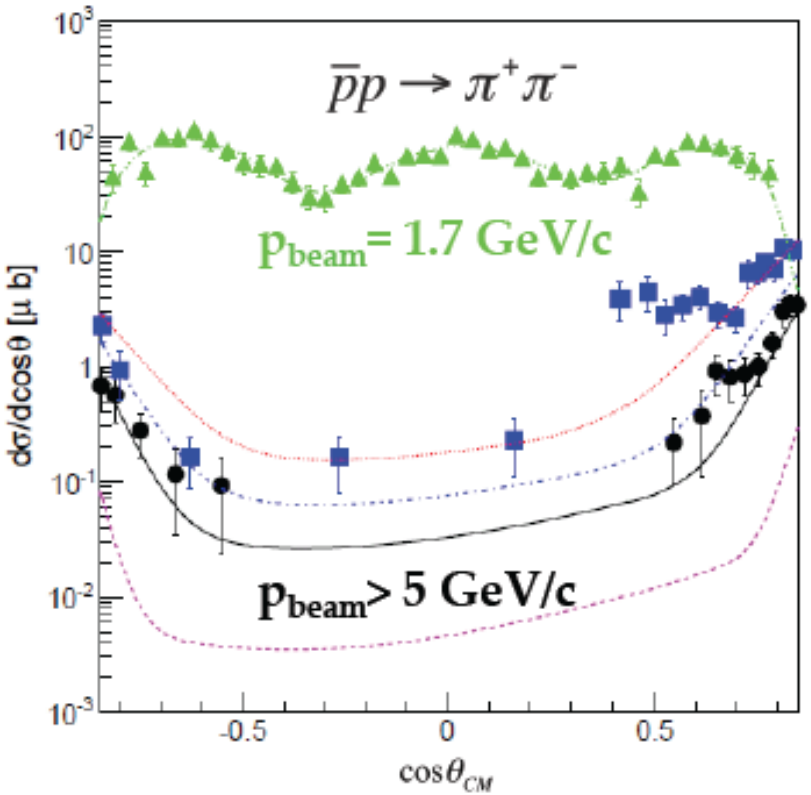


- M.P. Rekalo. Sov. J. Nucl. Phys., 1:760, 1965
- Adamuscin, Kuraev, Tomasi-Gustafsson and F. Maas, Phys. Rev. C 75, 045205 (2007)
- C. Adamuscin, E.A. Kuraev, G. I. Gakh, ...
- Feasibility studies (J. Boucher, M. C. Mora-Espi PhD)

Feasibility studies: time-like proton form factors @ PANDA

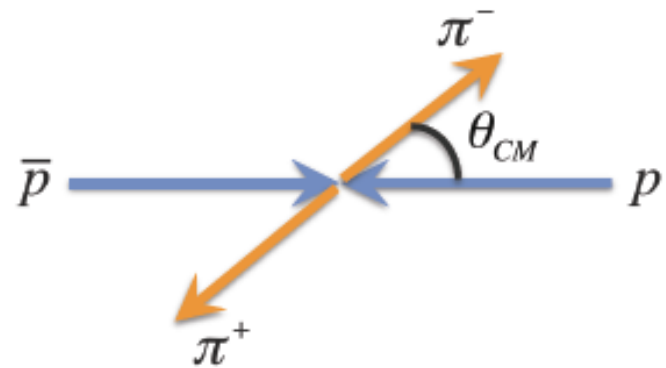
Background studies

- **New event generator** developed by Mainz working group (M. Zambrana et al.)



- J. Van de Wiele and S. Ong: Eur.Phys.J. A 46, 291-298 (2010)
- M. Sudol et al. EPJA44, 373 (2010)
- A. Dbeyssi, D. Khaneft, M. Zambrana et al.: Paper will be published soon (2015)

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



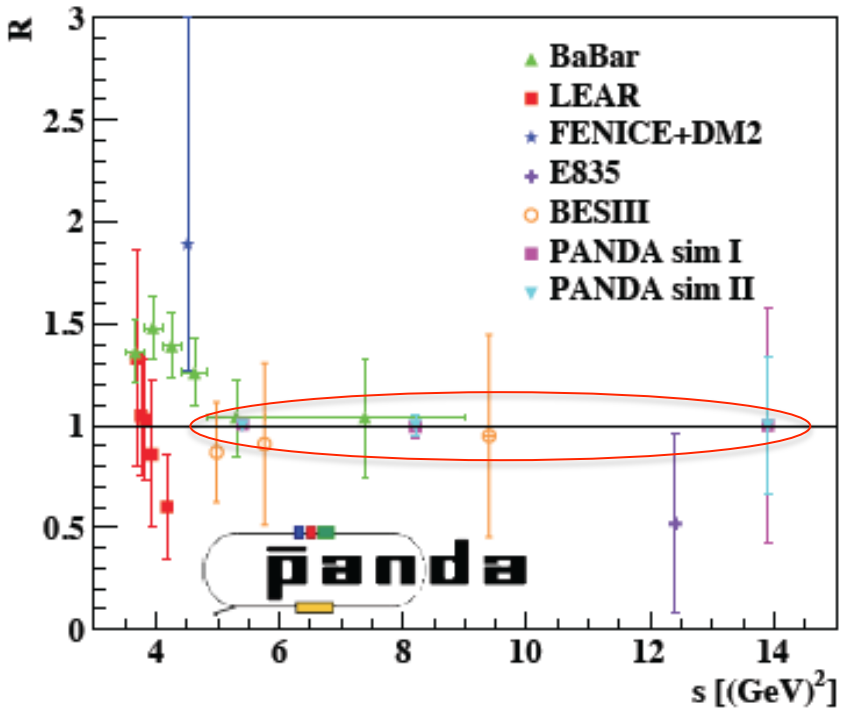
$$\frac{\sigma(\bar{p}p \rightarrow \pi^+\pi^-)}{\sigma(\bar{p}p \rightarrow l^+l^-)} \propto [10^5 - 10^6]$$

- **Background rejection ~10^{-8} needed: Pollution < 1%**
- **For e^+e^-: A background rejection** of the order of **10^{-8}** will be achieved @ PANDA
- **For $\mu^+\mu^-$: background rejection** of the order of ~**10^{-6}** will be achieved @ PANDA

(I) Feasibility studies: time-like proton form factors @ PANDA

Precision of $|G_E|$, $|G_M|$ and R

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



Sim. I: Determination precision

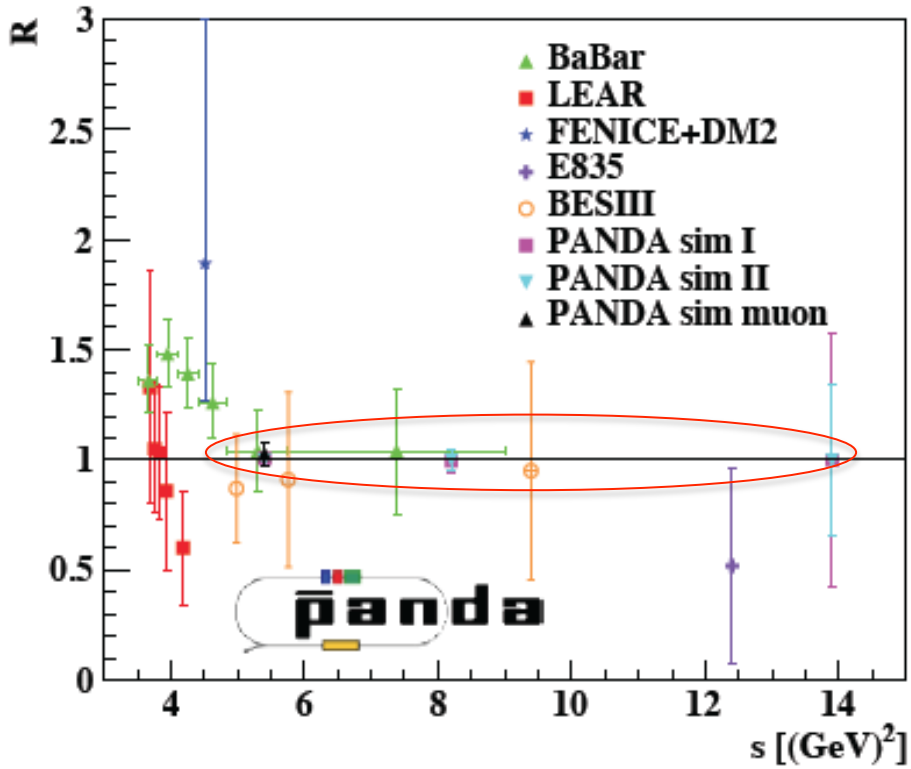
s (GeV)²	5.4	8.2	13.9
$R=\|G_E\|/\|G_M\|$	1.5 %	5.3 %	57 %
$\|G_E\|$	3.3 %	6.8%	45%
$\|G_M\|$	1.7%	2.3 %	9%

- Integrated luminosity of L=2 fb^{-1}
  $2*10^{32}$ cm^{-2} s^{-1}-> 4 months data taking
- The determination precisions obtained at 5.4 GeV^2 and 8.2 GeV^2 are compatible between sim I & sim II
- At 13.9 GeV^2 the error of R was studied.

- The effective FF can be measured with good precision ranging from 0.3% up to 62.4% (at q^2 ~28 GeV^2)

(II) Feasibility studies: time-like proton form factors @ PANDA

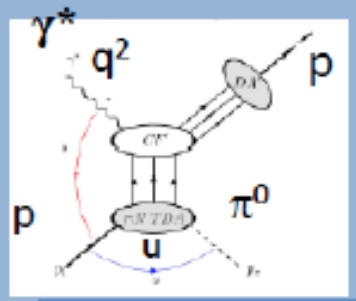
Precision of $|G_E|$, $|G_M|$ and R



s (GeV)^2	5.4	8.2	13.9
sim I	$\bar{p}p \rightarrow e^+e^-$		
$R=\|G_E\|/\|G_M\|$	1.5 %	5.3 %	57 %
$\|G_E\|$	3.3 %	6.8%	45%
$\|G_M\|$	1.7%	2.3 %	9%
MVA	$\bar{p}p \rightarrow \mu^+\mu^-$		
$R=\|G_E\|/\|G_M\|$	5.1%	-	-
$\|G_E\|$	8.6%	-	-
$\|G_M\|$	4.1%	-	-

Transition Distribution Amplitudes (TMDs)

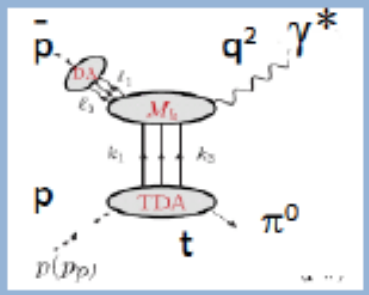
$e^- p \to e^- p \pi^0$ Bwd electroproduction



Large q^2 small u

Transition Distrib. Amplitudes

$\bar{p} p \to e^+ e^- \pi^0$ Fwd/bwd



Large q^2 small t or u

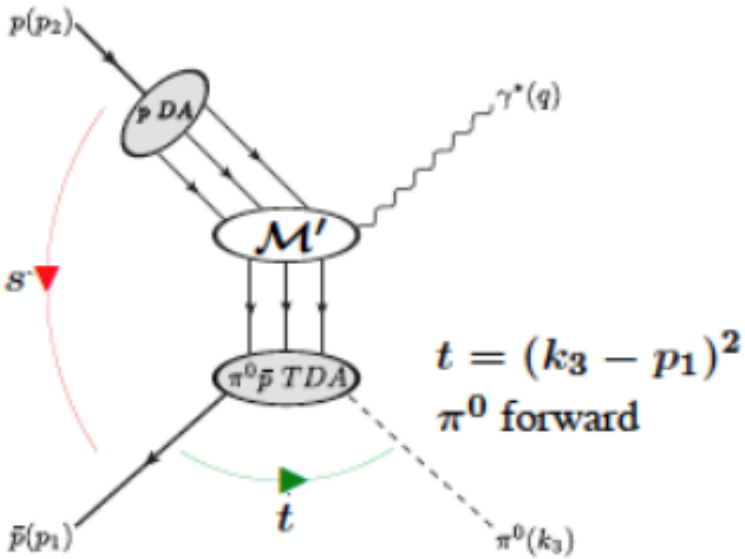
Transition Distrib. Amplitudes

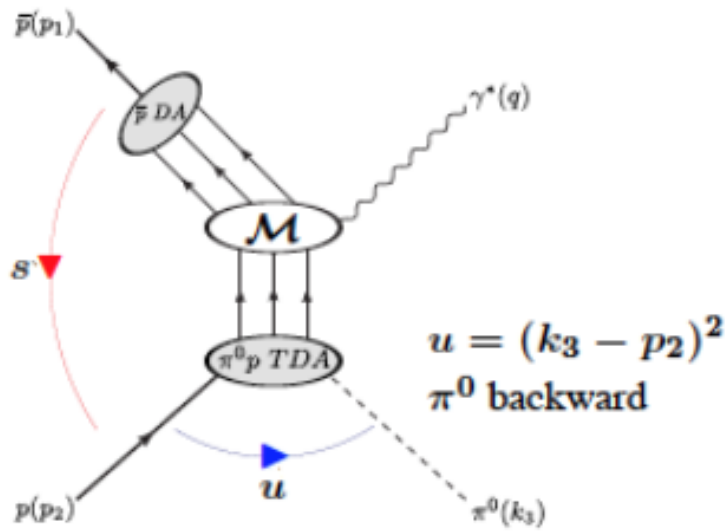
Transitions Distribution Amplitudes: $\bar{p}p \to e^+e^-\pi^0, e^+e^-\rho^0, e^+e^-\eta, \ldots$

- Describe the transition between two particles
- Explore pionic components in the nucleon wave function
- Transverse picture of the pion cloud
- Universality: the same TDA could be measured in different kinematics or different reactions

Transition Distribution Amplitudes (TMDs)

Signal channel: $\bar{p}p \rightarrow \gamma^* \pi^0 -> e^+ e^- \pi^0$





$$\mathcal{M}(\bar{p}p \rightarrow \gamma^* \pi^0) = \mathcal{M}_{\text{parton, parton}} \otimes \text{distribution amplitude (DA) and TDA}$$

B. Pire et al. PRD 76, 111502 (2007)

- Admits a factorized description when:
  - q^2 is large ($q^2 \approx s$)
  - *t* is small (forward kinematics, pi-N TDAs) , or *u* is small (backward, pi-Nbar TDAs)
    [check the symmetry violation between proton and antiproton]
- TDAs are related to the proton FFs by integration over all variables but q^2.

Transition Distribution Amplitudes (TMDs)

Feasibility studies of measuring $\bar{p}p \rightarrow \gamma^* \pi^0 -> e^+ e^- \pi^0$ at PANDA

i) $s = 5\ \mathrm{GeV}^2 \rightarrow 3.0 < q^2 < 4.3\ \mathrm{GeV}^2, \quad |\cos\theta_{\pi^0}| > 0.5$

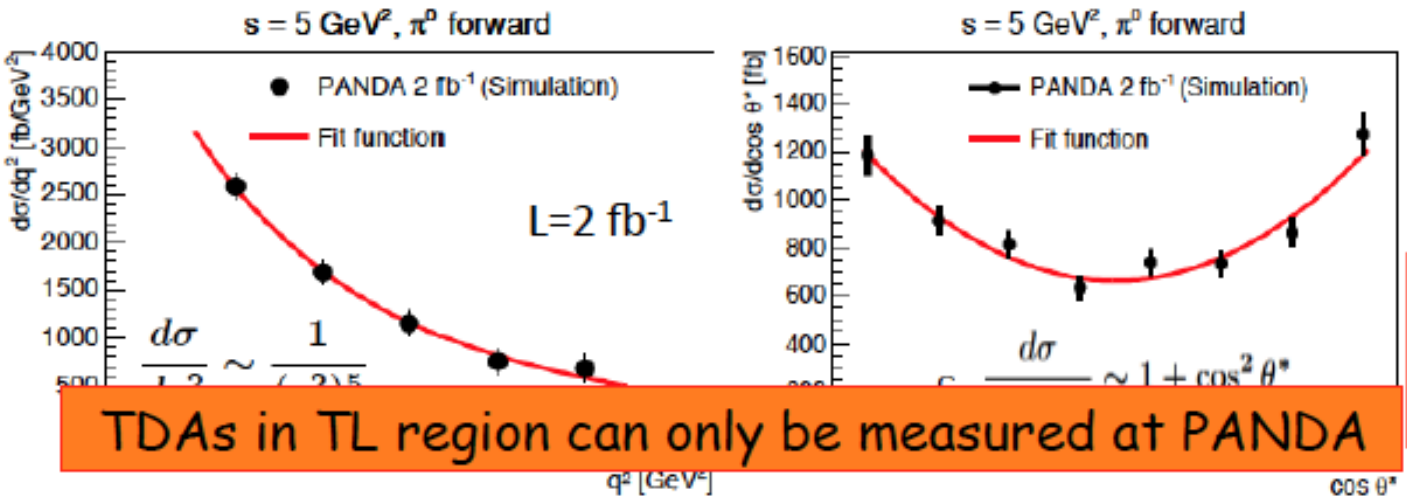
ii) $s = 10\ \mathrm{GeV}^2 \rightarrow 5 < q^2 < 9\ \mathrm{GeV}^2, \quad |\cos\theta_{\pi^0}| > 0.5$

- Background suppression of the $\bar{p}p \rightarrow \pi^+\pi^-\pi^0$ and measurement precision:

s = 5 GeV^2: $5 \cdot 10^7$ ($1 \cdot 10^7$) $\Delta\sigma/\sigma \sim 12\%$

s = 10 GeV^2: $1 \cdot 10^8$ ($6 \cdot 10^6$) $\Delta\sigma/\sigma \sim 24\%$

- Test of the QCD factorization/access TDAs



TDAs in TL region can only be measured at PANDA

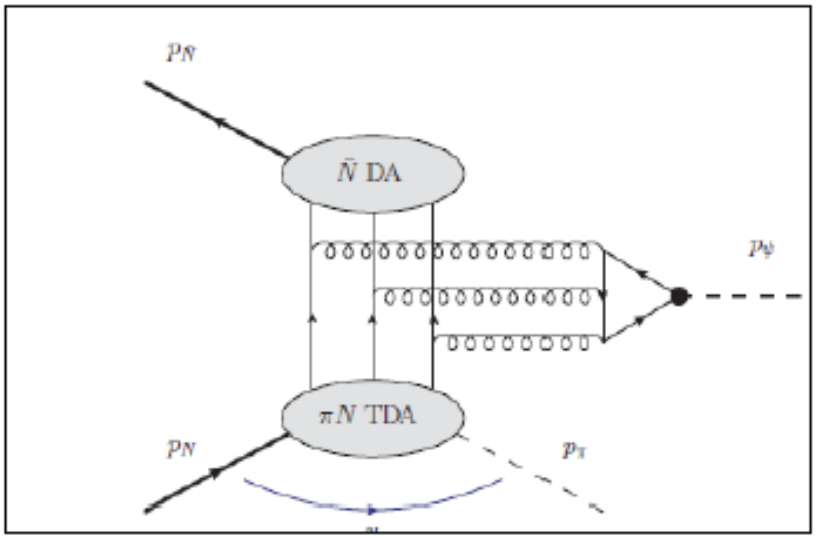
M. Carmen Mora Espi *et al.* (HIM). Submitted to EPJA

PANDA Collaboration (B.P. Singh et al.) Eur.Phys.J. A51 (2015) 8, 107

Transition Distribution Amplitudes (TMDs)

Signal channel: $\bar{p}p \rightarrow J/\psi\pi^0 -> e^+e^-\pi^0$

- High signal cross section
- Large q^2 fixed to $M^2_{J/\psi}$ (facorization theorem is likely reached)
- Reduces uncertainty on DAs by using the data on the $J/\psi -> pp$ partial decay modes
- Test of universality of TDAs by comparing to $\bar{p}p \rightarrow \gamma^*\pi^0 -> e^+e^-\pi^0$ at different q^2



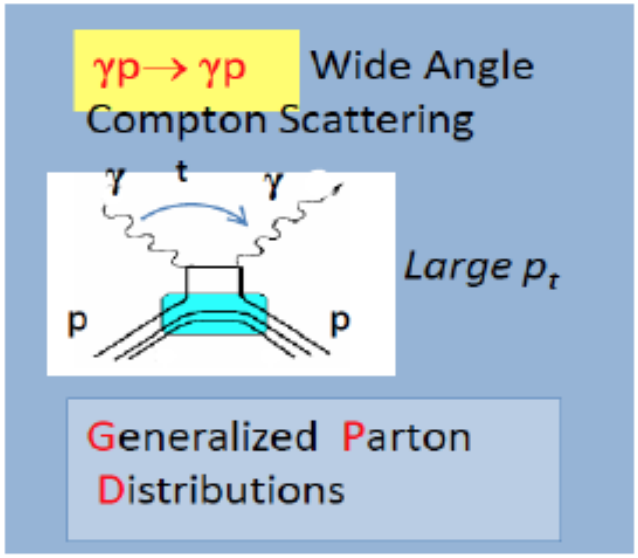
Feasibility studies for PANDA @ p=5.513, 8.0 and 12.0 GeV/c:

S/B> 8, 70, 600

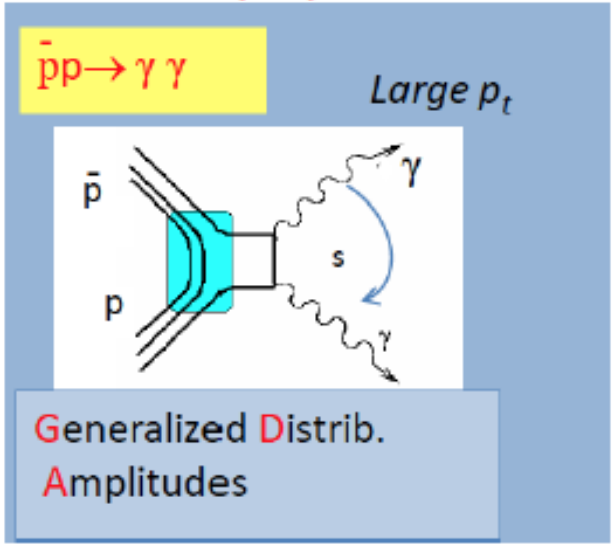
Binsong Ma, PhD thesis, IPNO 2014
Ongoing work by Ermias Atomsa et al. (IPNO)

Generalized Distribution Amplitudes (GDAs)

(SL)



(TL)



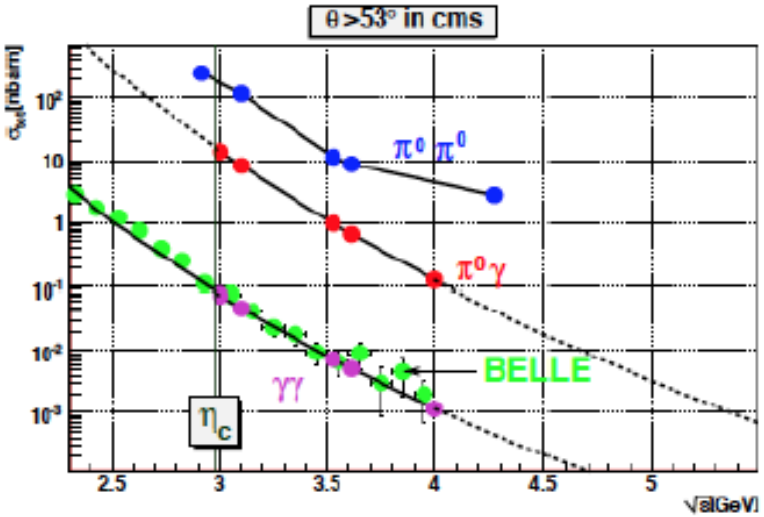
Time-like Wide Angle Compton Scattering (WACS)

The QCD factorization theorem allows us to calculate hign energy cross sections separating short-distance process with long-distance non perturbative functions

Hard scale is defined by the large transverse momentum of the final state photon

WACS process: give access to the GDAs, the counterpart of the GPDs

Feasibility studies for $\bar{p}p \rightarrow \gamma\gamma$ and $\bar{p}p \rightarrow \pi^0\gamma$ at PANDA

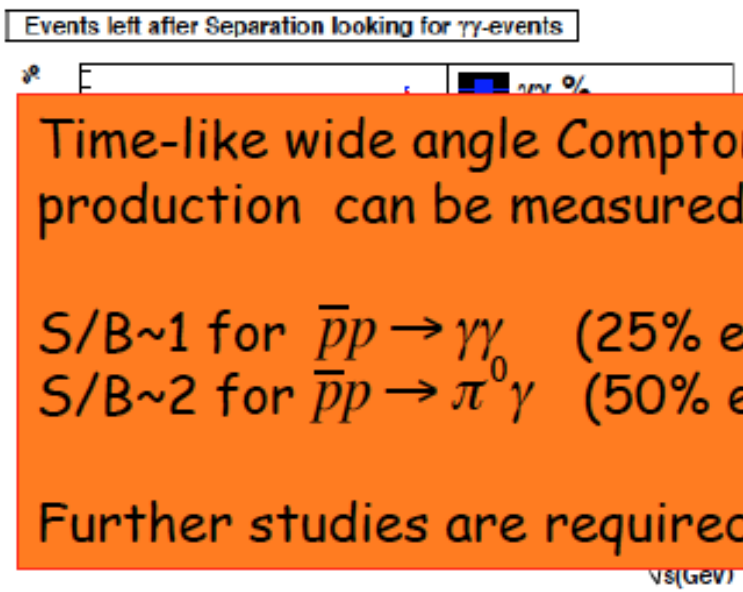


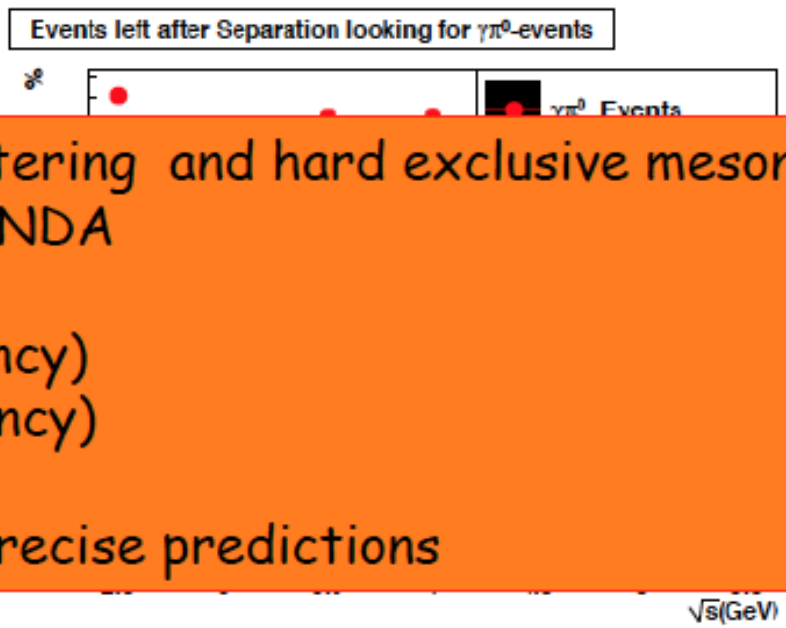
PANDARoot simulations:

- 4 different CM energies
- Main background channels:

$\bar{p}p \rightarrow \pi^0\pi^0$ (for both signals)

$\bar{p}p \rightarrow \pi^0\gamma$ (for signal1: $\bar{p}p \rightarrow \gamma\gamma$)



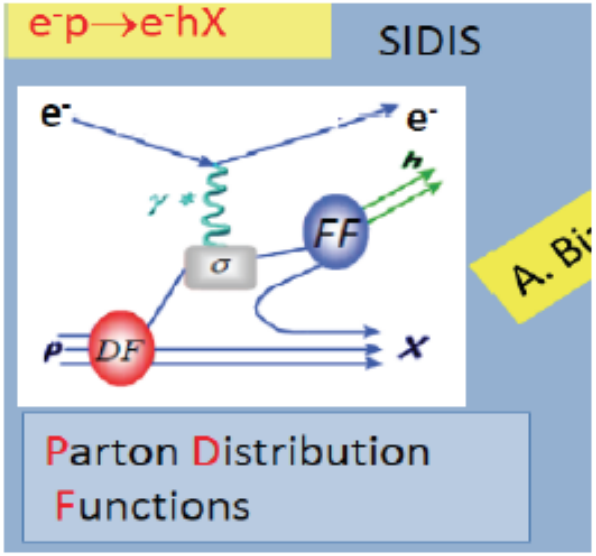


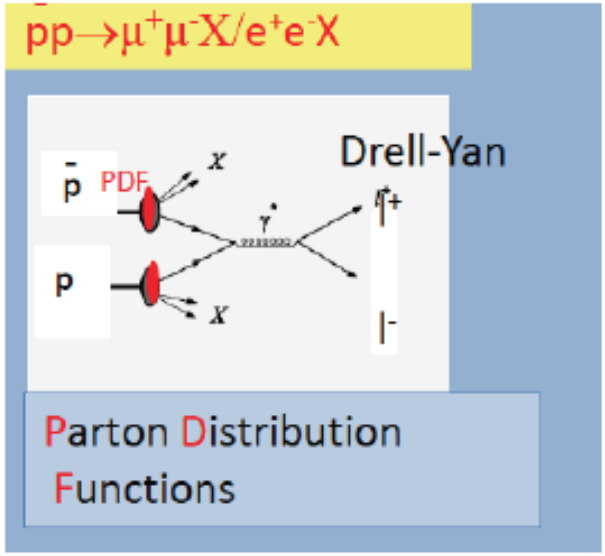
Time-like wide angle Compton scattering and hard exclusive meson production can be measured at PANDA

S/B~1 for $\bar{p}p \rightarrow \gamma\gamma$ (25% efficiency)
S/B~2 for $\bar{p}p \rightarrow \pi^0\gamma$ (50% efficiency)

Further studies are required for precise predictions

Drell-Yan Process





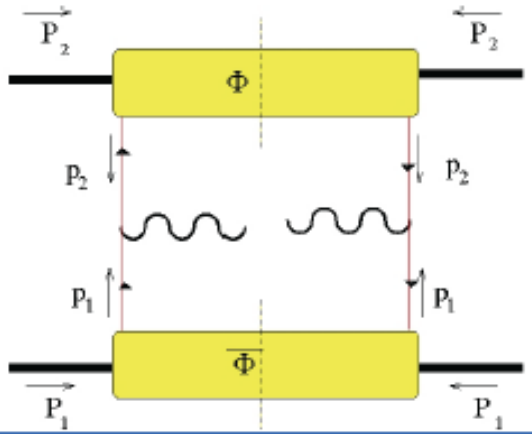
PDFs are convoluted with the fragmentation functions

@ FAIR unique energy range
up to s~30 GeV2 with PANDA
up to s~200 GeV2 with PAX

@ much higher energies
→ big contribution from sea-quarks

@ppbar annihilation each valence quark contribute to the diagram

Handbag diagram: $s \gg M_h^2$



Feasibility measurement of DYs at PANDA

Feasibility studies using Monte-Carlo simulation:

- Signal: $\bar{p}p \rightarrow \mu^+\mu^- X$ Unpolarized DY

  $\bar{p}p^\uparrow \rightarrow \mu^+\mu^- X$ Single-polarized DY

- Main background: $\bar{p}p \rightarrow n(\pi^+\pi^-)X$, required rejection factor ~10^7

- Simulations @ s=30 GeV^2 and $1.5 \leq M_{\gamma^*} \leq 2.5$ (non resonance region, large cross section)

  N_{gen}=480 . 10^3, 5 months with L=2 . 10^{32} cm^{-2} s^{-1}

PANDA Physics Performance Report
arXiv:0903.3905

Acceptance, efficiency corrections, background rejection are still Under unvestigation: expectation: 130. 10^3 DY/month

One year data taking: azimuthal asymmetries with uncertainties of The order of the presented one

Torino group, Marco Maggiora

Electromagnetic processes in PANDA

Feasibilty study for the measurement of many electromagnetic processes at PANDA are done

Signal	Physics	s [Gev^2]	S/B	Status
$\bar{p}p \rightarrow e^+e^-$	FFs	5.4, 8.2, 13.9	>100	Feasibile
$\bar{p}p \rightarrow \mu^+\mu^-$	FFs	5.4	¼	Feasibile
$\bar{p}p \rightarrow \gamma^*\pi^0$	TDAs	5.0 10.0	$5 . 10^7$ ($1 . 10^7$) $1 . 10^8$ ($6 . 10^6$)	Feasibile
$\bar{p}p \rightarrow J/\psi\pi^0$	TDAs	P=5.513 P=8.0 P=12.0	>8 >70 >600	Feasibile
$\bar{p}p \rightarrow \gamma\gamma$ $\bar{p}p \rightarrow \pi^0\gamma$	GDAs	2.5, 3.5, 4.0, 5.5	1 2	Feasibile
$\bar{p}p \rightarrow \mu^+\mu^-X$	TMD PDFs	30	in progress	Feasibile

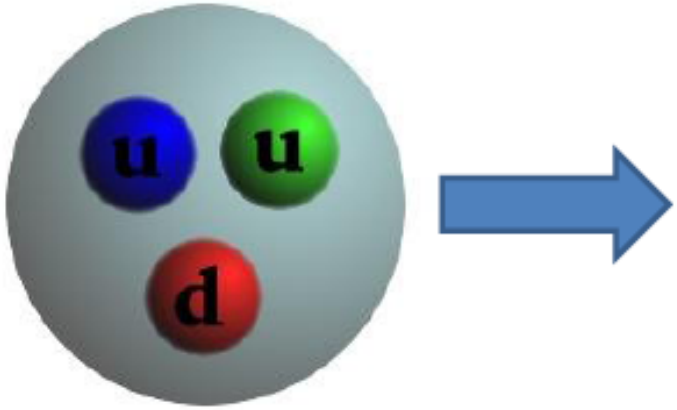
III. Hyperons, Hypernuclei, In-medium effects

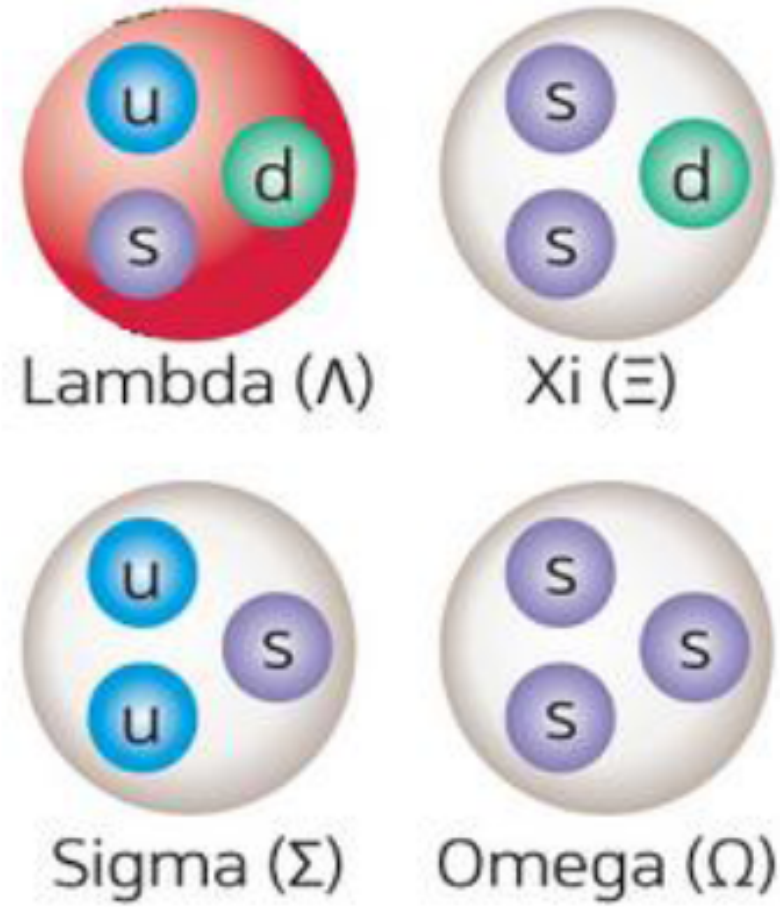
Karin Schöning (Uppsala)
Alicia Sanchez (HI Mainz)

PANDA physics workshop in Uppsala, June 8 – 12, 2015

Strange (and charmed) hyperons

What happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)?





Strange hyperons

Excited strange hyperon spectrum:

J^P	(D, L_N^P)	S	Octet members				Singlets
$1/2^+$	$(56,0_0^+)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$1/2^+$	$(56,0_2^+)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
$1/2^-$	$(70,1_1^-)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
$9/2^+$	$(56,4_4^+)$	1/2	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	

			Decuplet members			
$3/2^+$	$(56,0_0^+)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$
$3/2^+$	$(56,0_2^+)$	3/2	$\Delta(1600)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$1/2^-$	$(70,1_1^-)$	1/2	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$3/2^-$	$(70,1_1^-)$	1/2	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$5/2^+$	$(56,2_2^+)$	3/2	$\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$7/2^+$	$(56,2_2^+)$	3/2	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$
$11/2^+$	$(56,4_4^+)$	3/2	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$

- PANDA can fill the gap in the strange sector

→ the full Ξ and Ω spectra are accessible with PANDA!

strangeness

- Octet Ξ* partners of *N** ?
  - Only a few found
- Decuplet Ξ* and Ω* partners of Δ*?
  - Nothing found

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Baryon spectroscopy subtopics with PANDA

Study excited states of

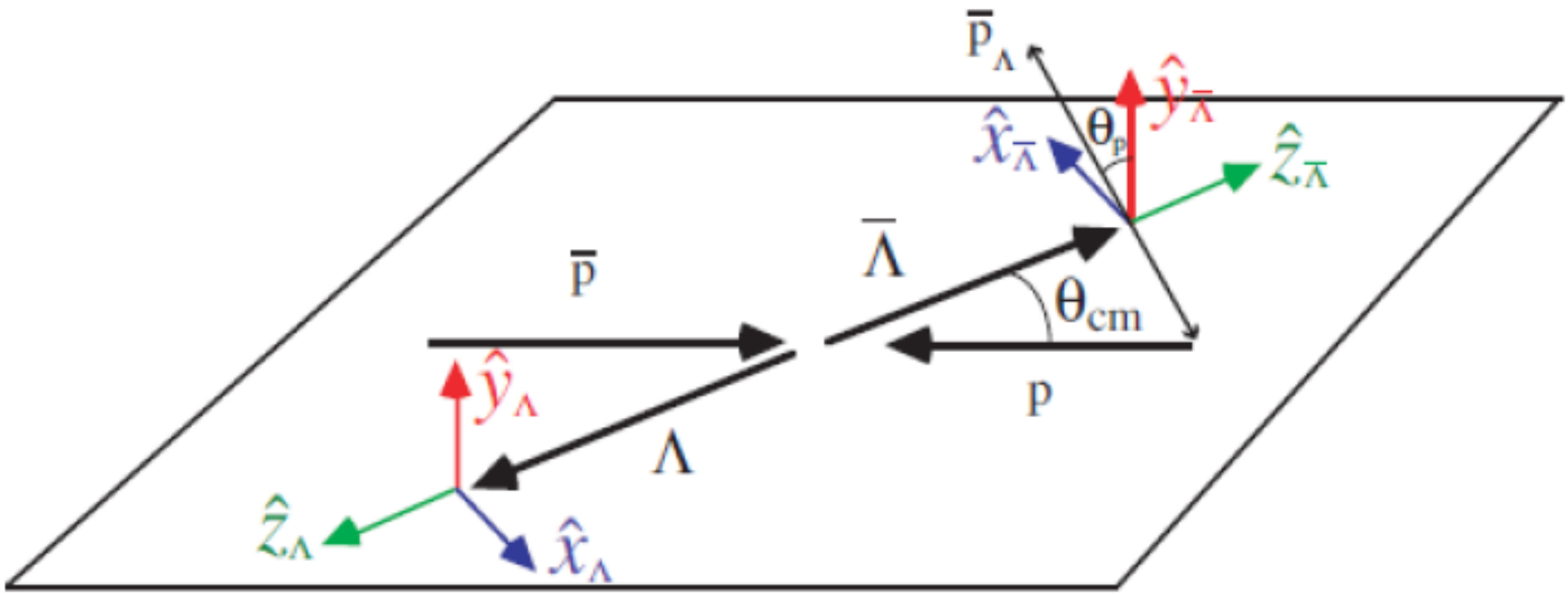
PANDA is a strangeness factory!

- hidden-charm nucleons ($N_{c\bar{c}}$)
- non-strange baryons (N^*)
- single-strange hyperons (Λ^*, Σ^*)

Spin observables in hyperon production

- *Vector polarisation* P the most straight-forward observable for spin $\frac{1}{2}$ hyperons.

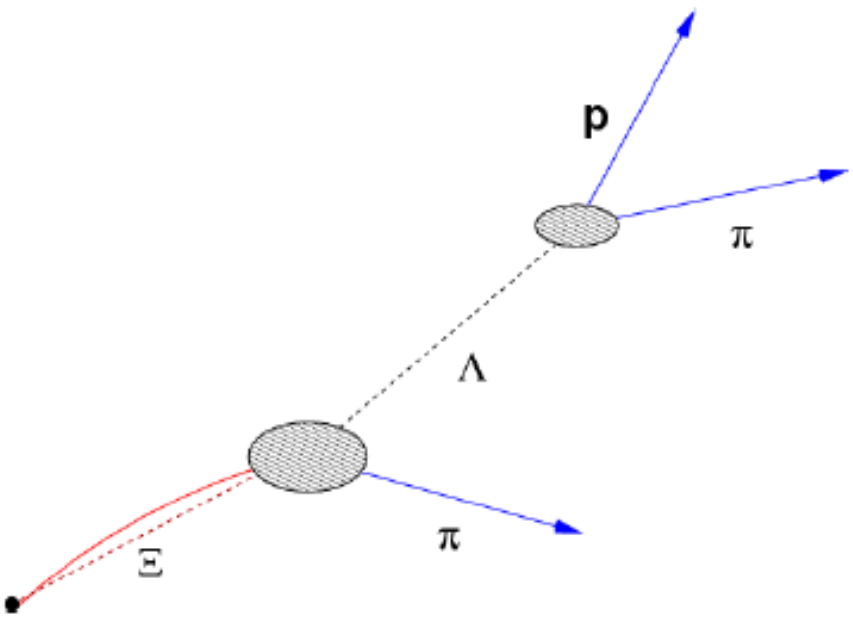
- Strong interactions: normal to the production plane (y-direction)



Spin observables in hyperon production

If the decay product of the hyperon is a hyperon, *e.g.* $\Xi \rightarrow \Lambda\pi$, then also β and γ can be obtained from the decay protons of the Λ.

$$I(\theta_p,\phi_p) = \frac{1}{4\pi}\left[1+\alpha_\Xi\alpha_\Lambda\cos\theta_p + \frac{\pi}{4}\alpha_\Lambda P\sin\theta_p(\beta_\Xi\sin\phi_p - \gamma_\Xi\cos\phi_p)\right]$$



α, β, γ decay parameters.
related to the decay amplitudes T_s and T_p

Spin observables in hyperon production

$\bar{p}p \rightarrow$	$\bar{\Lambda}\Lambda$,	$\bar{\Sigma}^-\Sigma^+$,	$\bar{\Sigma}^0\Sigma^0$,	$\bar{\Sigma}^-\Sigma^+$,	$\bar{\Xi}^0\Xi^0$,	$\bar{\Xi}^+\Xi^-$,	$\bar{\Omega}^+\Omega^-$,	$\bar{\Lambda}_c^-\Lambda_c^+$
	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
	$p\pi^-$	$p\pi^0$	$\Lambda\gamma$	$n\pi$	$\Lambda\pi^0$	$\Lambda\pi$	ΛK	$\Lambda\pi$
BR:	64%	52%	$\approx 100\%$	$\approx 100\%$	$\approx 100\%$	$\approx 100\%$	68%	$\approx 1\%$

- Simulation studies using a simplified MC framework (smearing and acceptance included)
- Quoted rates are valid for day one luminosity of the HESR (10^{31} cm^{-2} s^{-1}).
- Cross sections of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^o$ known near threshold, the $\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$ measured with large uncertainty.
- Only theoretical predictions of $\bar{p}p \rightarrow \bar{\Omega}^+\Omega^-$ and $\bar{p}p \rightarrow \bar{\Lambda}_c^-\Lambda_c^+$

Spin observables in hyperon production

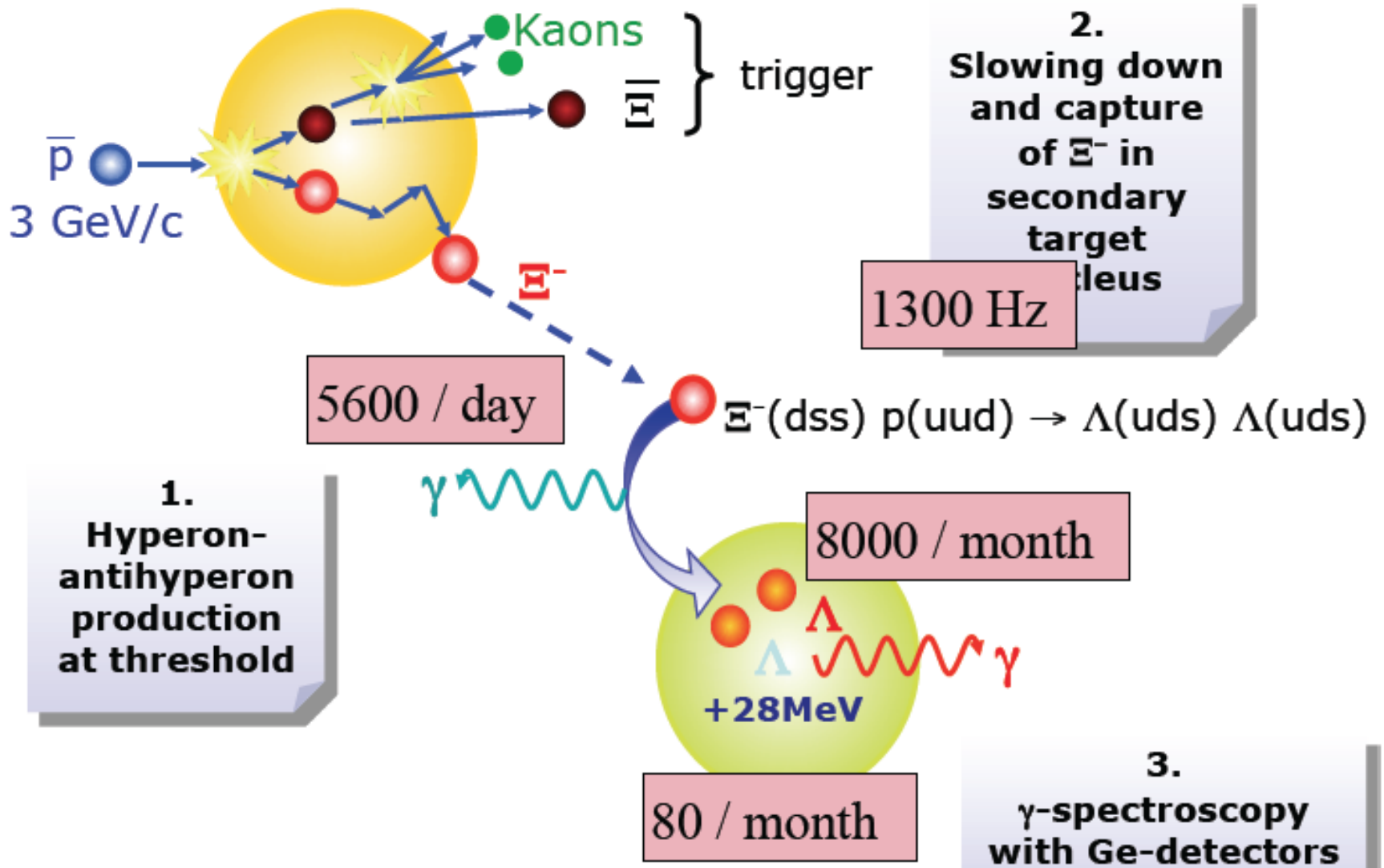
Momentum (GeV/c)	Reaction	σ (μb)	Efficiency (%)	Rate (with 10^{31} $cm^{-1}s^{-1}$)
1.64	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64	10	28 s^{-1}
4	$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^{o}$	~40	30	30 s^{-1}
4	$\bar{p}p \rightarrow \bar{\Xi}^{+}\Xi^{-}$	~2	20	1.5 s^{-1}
12	$\bar{p}p \rightarrow \bar{\Omega}^{+}\Omega^{-}$	~0.002	30	~4 h^{-1}
12	$\bar{p}p \rightarrow \bar{\Lambda}_{c}^{-}\Lambda_{c}^{+}$	~0.1	35	~2 day^{-1}

- High event rates for Λ and Σ *.
- Low background for Λ and Σ *.
- Ω channel feasible
- Λ_c requires high luminosity **
- New efficiencies obtained with a more sophisticated MC framework are underway.

Gain a factor of 100 with inclusive measurement

*Sophie Grape, Ph. D. Thesis, Uppsala University 2009
** Erik Thomé, Ph. D. Thesis, Uppsala University 2012

Production of Double Hypernuclei



Fully simulated based on available Ge-Detectors

PANDA: Excellent Physics-Opportunity

FAIR will be the main national laboratory for strong interaction Studies at all length scales: PANDA-experiment 1 of 4 Pillars

Antiproton beams for spectroscopy: X,Y,Z-factory, open charm, light mesons, baryons, glue-balls, hybrids, …
precision studies with large data samples, measurement of width and cross section

Explore electromagnetic probe in antiproton annihilation: many channels and reactions studied in detailed simulations, so far all accessible and measurable with high precision

Study of hyperon spectrum and hypernuclei with strangeness S=2

Backup Slides

Potential PANDA Run-Plan 1st year – 139 days net @ $10^{31}cm^{-2}s^{-1}$

part of machine development approx. 7 days @ J/ψ & ψ(2S) peaks

- calibration/commissioning

---

30 days @ 1.64 GeV/c

- time-like form-factors
- light meson spectroscopy and ΛΛbar physics

40 days @ 15 GeV/c

- survey of light and heavy exotics at max momentum (hybrids, tetraquarks)
- generic open charm production >10σ (yields and angular distributions)

14 days @ 12 GeV/c

- ΩΩbar and $\Lambda_c\Lambda_c$bar production and dynamics, excited Ωs
- generic open and hidden charm production

25 days $p_{bar}A$ @ 2 GeV/c

- pbar and Λbar-potentials incl. calibration (N, Ne, Ar targets)

10 days $p_{bar}d$ @ 8 GeV/c

- ΔΔ content of the deuteron and feasibility studies of pbard for spectroscopy (d-target)

13 days @ 5.55 GeV/c

- χ_{c1} angular distribution
- excited Ξs

7 days @ 3.75 GeV/c

- Investigate Y(2175) and ΦΦ resonances, T/PS-glueball search

Potential PANDA Run-Plan 2nd year – 144 days net @ $10^{31}cm^{-2}s^{-1}$

14 days @ 3 GeV/c

- Ξ-Atoms with hypernuclear setup and Ge-Counter

7 days @ 3 GeV/c

- excited Λs

7 days @ 4.4 GeV/c

- ΞΞbar production and dynamics

36 days @ 5.73 GeV/c

- χ_{c2} angular distribution

80 days @ 6.99++ GeV/c

- X(3872) scan

---

other options depending on PANDA results and the development of the field until 2020

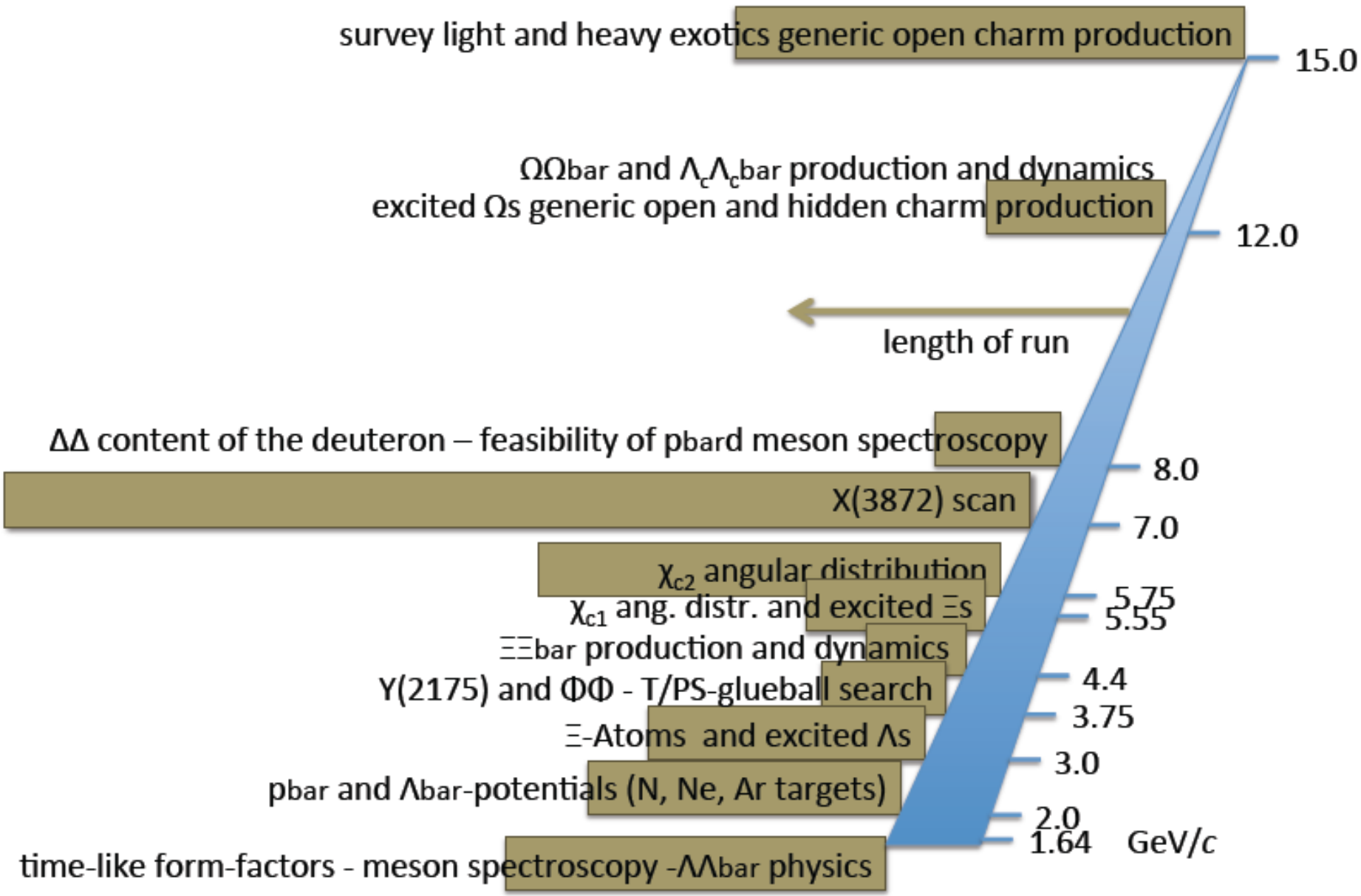
60 days – 5.61 GeV/c

- h_c width

30-80 days on various momenta

- detailed scans of potentially interesting signals

Potential PANDA Run-Plan – Overview first 2 years



R. Hofstadter (1956), Proton Electromagnetic Form Factor

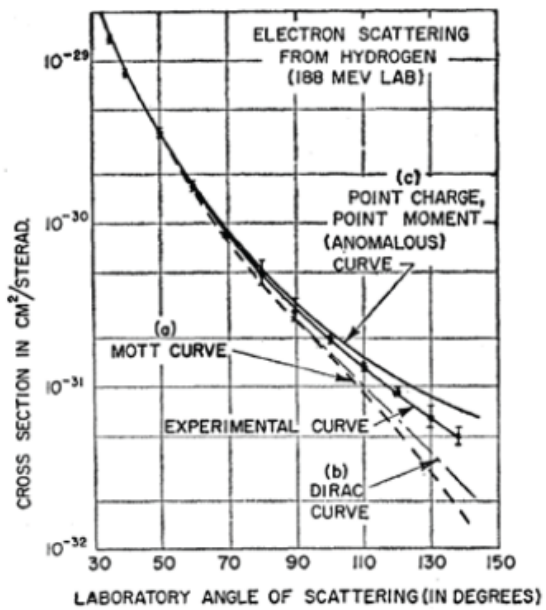


FIG. 24. Electron scattering from the proton at an incident energy of 188 Mev. The experimental points lie below the point-charge point-moment curve of Rosenbluth, indicating finite size effects.

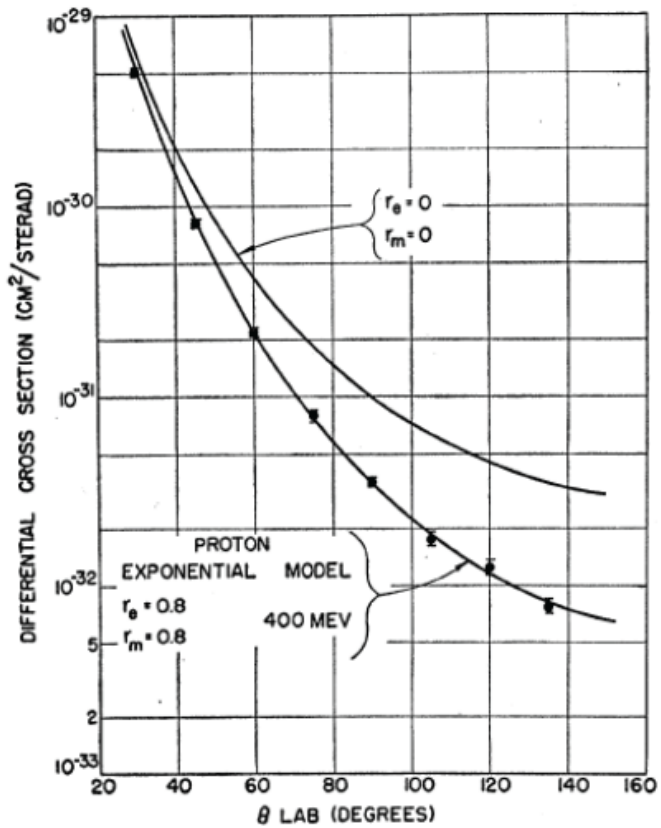
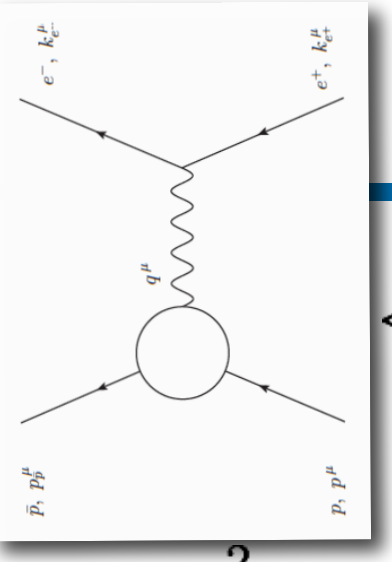


FIG. 26. Typical angular distribution for elastic scattering of 400-Mev electrons against protons. The solid line is a theoretical curve for a proton of finite extent. The model providing the theoretical curve is an exponential with rms radii $= 0.80 \times 10^{-13}$ cm.

Still today a hot topic of hadron physics. Electromagnetic form factors a testing ground for our understanding of QCD

R. Hofstadter, Rev. Mod. Phys. , 28 (1956), 243

Electromagnetic Form Factor (QED)



vector current of quarks

$$< \bar{N}(p')|q_u \bar{u}\gamma_\mu u + q_d \bar{d}\gamma_\mu d + \ldots |N(p) >$$

matrix element

$$\frac{e^2}{q^2}\ \bar{u}(k_2)\gamma_\mu u(k_1)\ \ \bar{u}(p_2)[F_1(q^2)\gamma_m u + i\kappa \frac{\sigma_{\mu\nu}q^\nu}{2m_p} F_2(q^2)]u(p_1)$$

Dirac

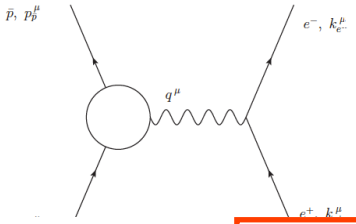
$G_E = F_1 + F_2$

$G_M = F_1 + \tau F_2$

Pauli

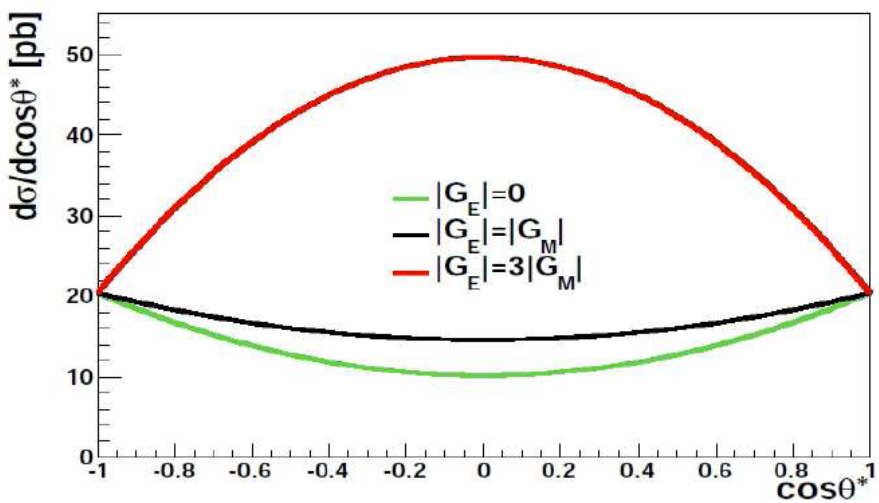
all hadronic structure and strong interaction in form factors,
but subject to electromagnetic (QED) radiative corrections
hadronic vector current: two form factors (2 s + 1)
internal structure of hadron ground state

Dirac	Pauli
$F_1^p(q^2=0) = 1$	$F_2^p(q^2=0) = 1$
$F_1^n(q^2=0) = 0$	$F_2^n(q^2=0) = 1$



Cross Section (pbar annihilation) (Angular Distribution)

$$\frac{d\sigma}{d\cos\theta_{CM}} = \frac{\pi\alpha^2}{8M_p\tau\sqrt{\tau(\tau-1)}}|G_M|^2\left[\tau\left(1+\cos^2\theta_{CM}\right)+\frac{|G_E|^2}{|G_M|^2}\left(1-\cos^2\theta_{CM}\right)\right]$$



$G_E = F_1 + F_2$

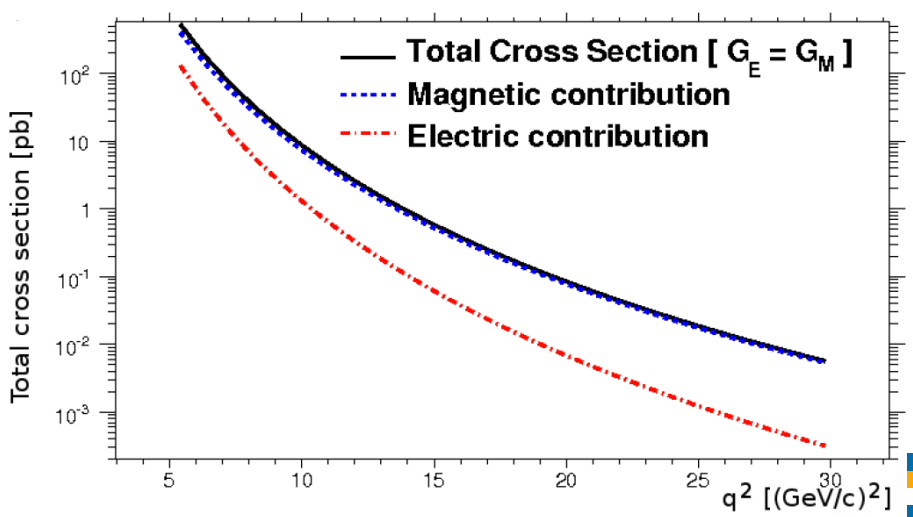
$G_M = F_1 + \tau F_2$

at threshold: $G_E = G_M$

two approaches:

assume G_E/G_M

extract G_E and G_M



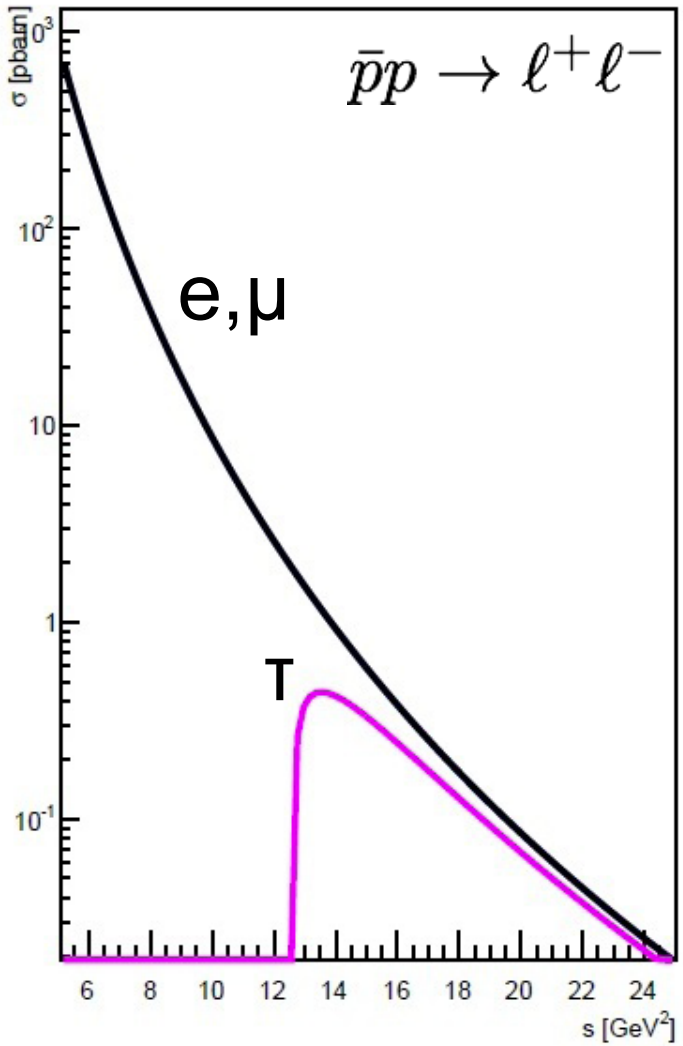
Integrated (Total) Cross Section:

$$\sigma = \frac{4\pi\alpha^2\beta C}{3q^2}\left[|G_M|^2 + \frac{1}{2\tau}|G_E|^2\right]$$

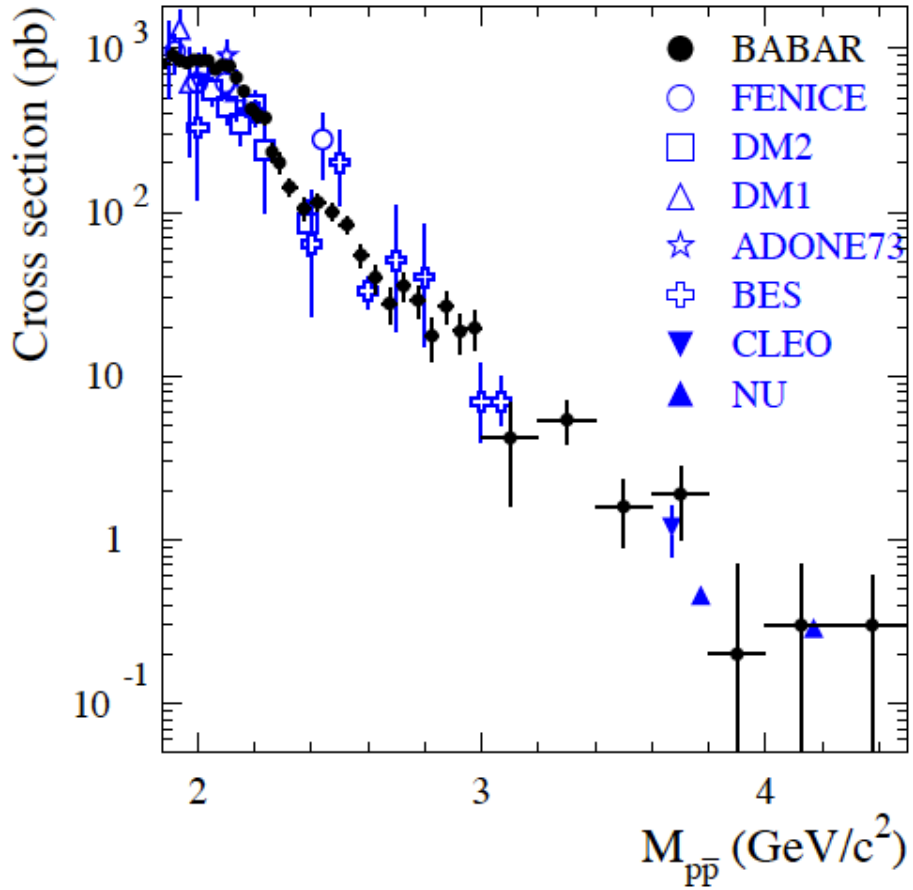
Effective FF

- Need Luminosity Measurement
- not on Resonance

Cross Section (pbar annihilation) (total cross section)



Cross section ($q^2 > 0$)



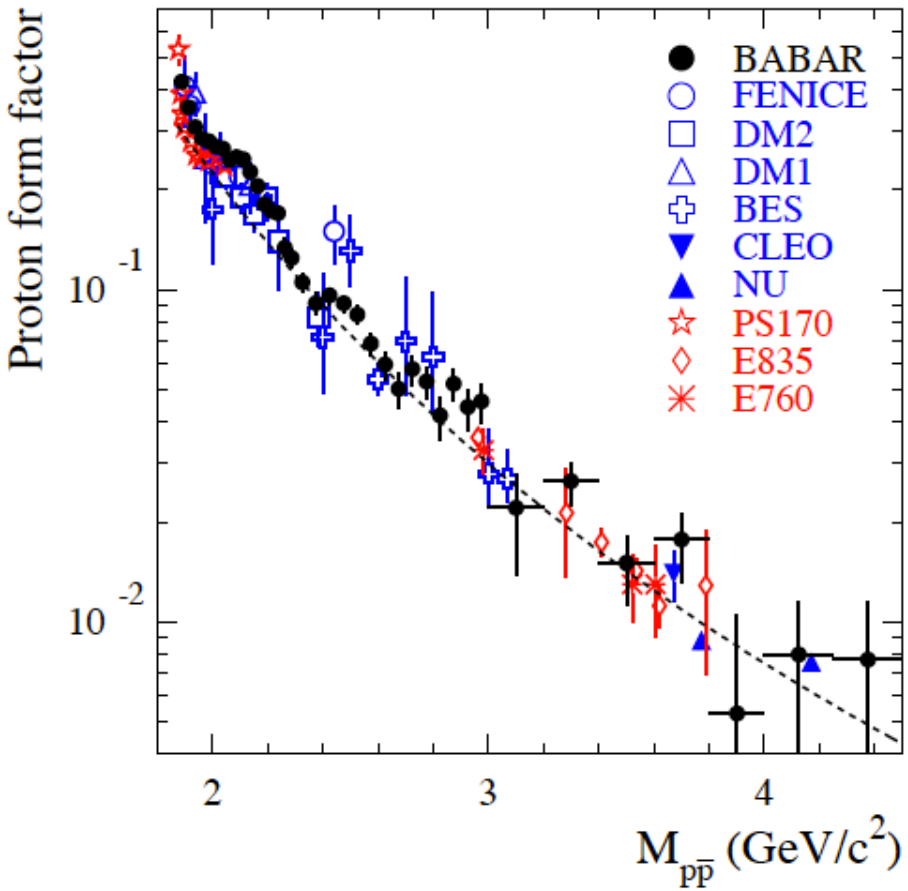
Adone e^+e^-: 25, 69 ev.
ELPAR $\bar{p}p$: 34 ev.
DM1,2 e^+e^-: 63, 172 ev.
$|G_E|/|G_M| = 0.34$
PS170 $\bar{p}p$: 3667 ev.
$|G_E|/|G_M| \approx 1$
E760 $\bar{p}p$: 29 ev.
E835 $\bar{p}p$: 206 ev.

CLEO e^+e^-: 14 ev.
BES e^+e^-: higher stat
BaBar e^+e^-: high stat

All data: Measure integrated cross section

new BABAR-Analysis: arxiv:1302.005

EM form factor ($q^2 > 0$)



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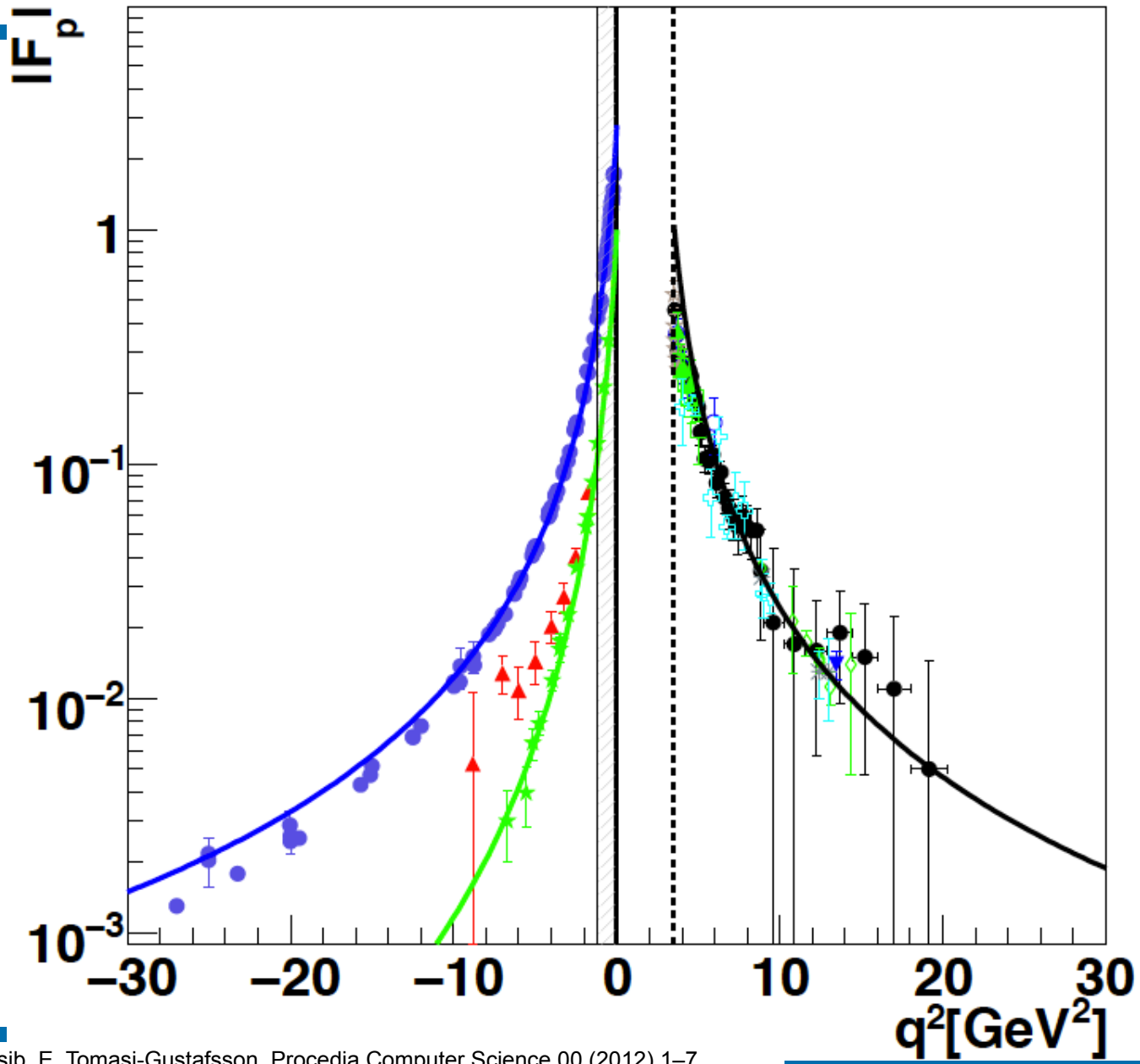
CLEO e^+e^-: 14 ev.
BES e^+e^-: higher stat
BaBar e^+e^-: high stat

All data: Measure integrated cross section

assume: $G_E = G_M$, or $F = (\sigma)^{0.5}$

new BABAR-Analysis: arxiv:1302.005

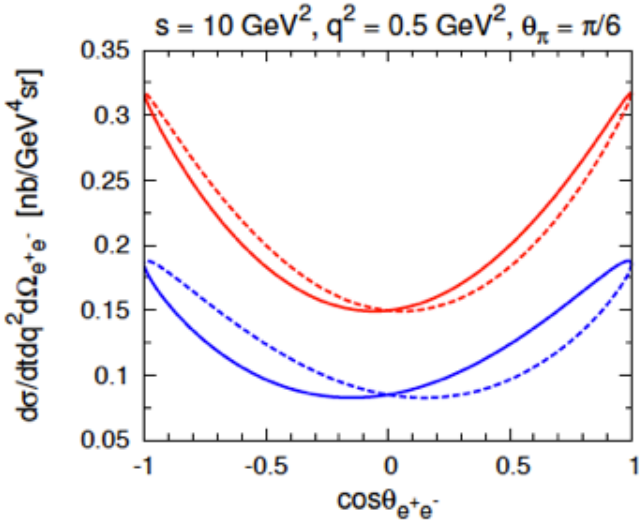
EM form factor ($q^2 > 0$)

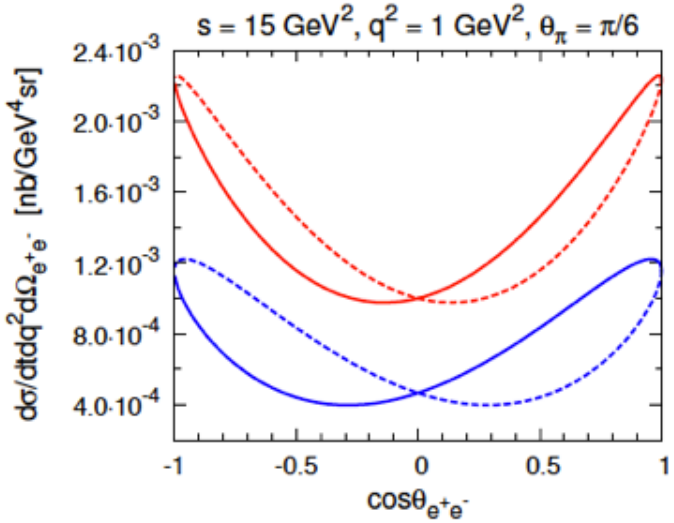


E.A.Kuraev, A.Dbeyssib, E. Tomasi-Gustafsson, Procedia Computer Science 00 (2012) 1–7

$p\bar{p} \to \pi^0 e^+ e^-$: Results in the Regge framework

Cross Section: $d\sigma/(dt dq^2 d\Omega_{e^+e^-})$ $[\mathrm{nb}/\mathrm{GeV}^4\mathrm{sr}]$





N-trajectory exchange: $\Phi_{e^+e^-} = 0$ (solid) and $\Phi_{e^+e^-} = \pi$ (dashed)

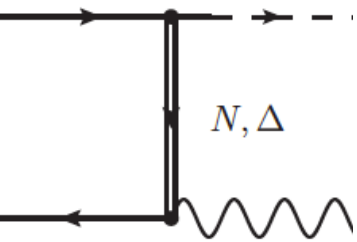
(N+Δ)-trajectory exchange: $\Phi_{e^+e^-} = 0$ (solid) and $\Phi_{e^+e^-} = \pi$ (dashed)

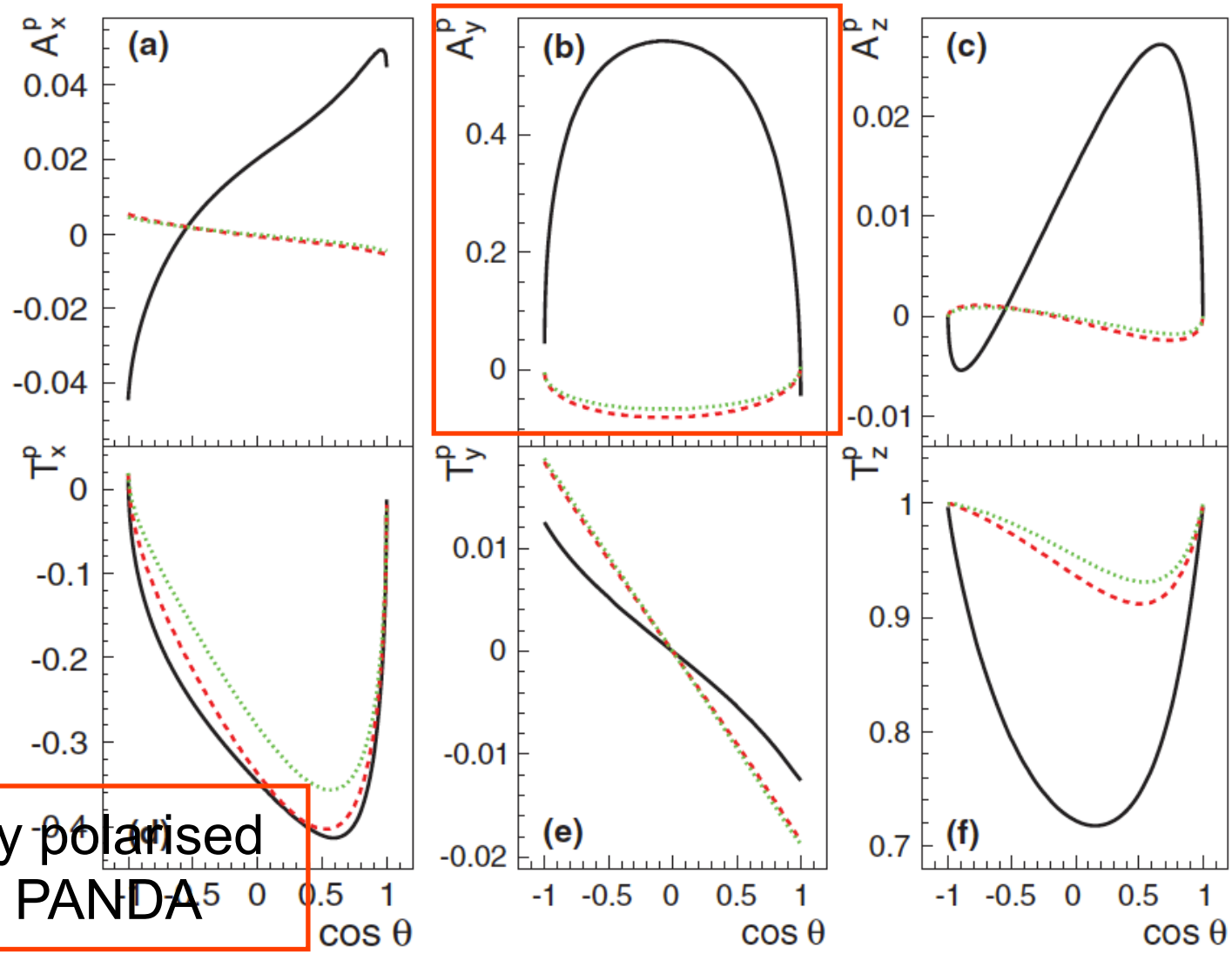
complementary approach to ff at and below threshold

interference terms (F_1F_2) in cross section

Target Asymmetry and Polarisation Transfer

$$\bar{p}p \to e^+e^-\pi^0$$

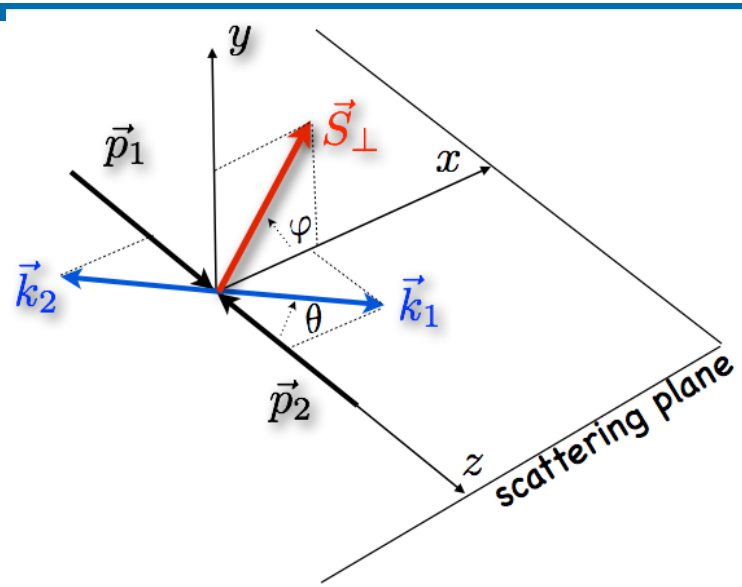




transversely polarised Target in PANDA

G. I. Gakh, E. Tomasi-Gustafsson, A. Dbeyssi, A. G. Gakh, Phys. Rev. C 86, 025204 (2012)

Imaginary Part of Time Like FF single spin target asymmetry



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

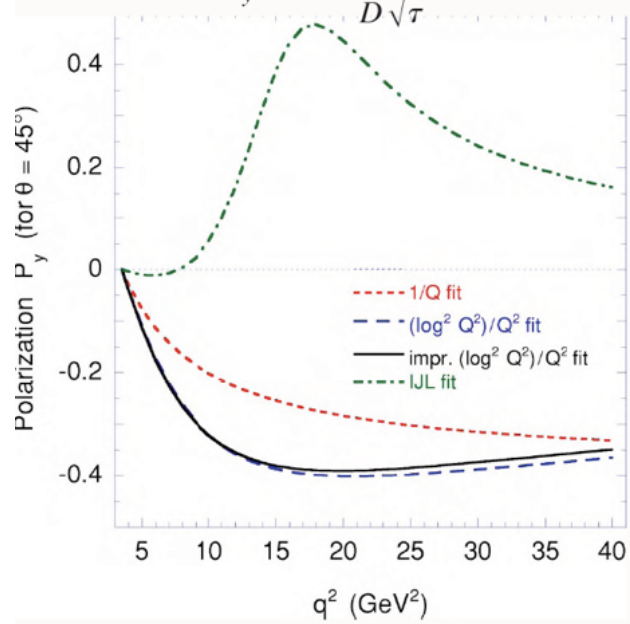
Single-spin polarization effects and the determination of timelike proton form factors

$$\mathcal{P}_y = \frac{\sin 2\theta \,\mathrm{Im}\, G_E^* G_M}{D\sqrt{\tau}} = \frac{(\tau-1)\sin 2\theta \,\mathrm{Im}\, F_2^* F_1}{D\sqrt{\tau}}$$

Carlson, Hiller, Hwang, sjb

$$D = |G_M|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E|^2\sin^2\theta;$$

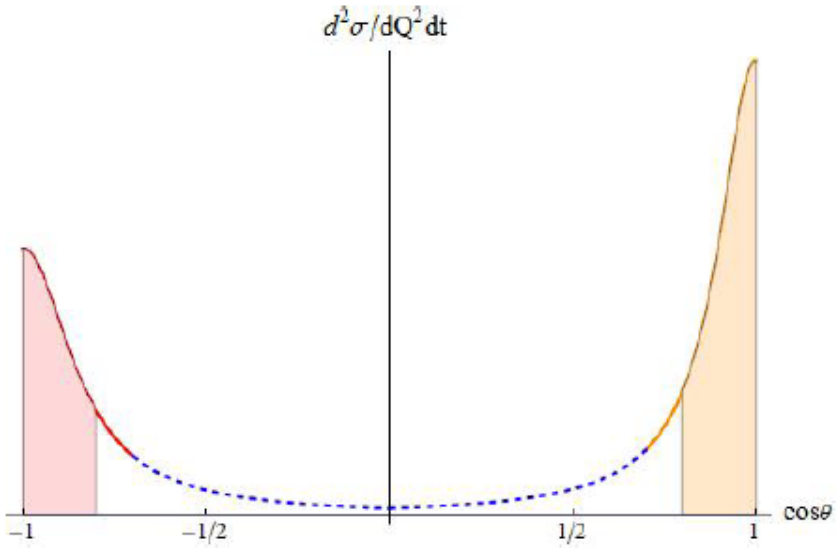
$$\tau \equiv q^2/4m_B^2$$

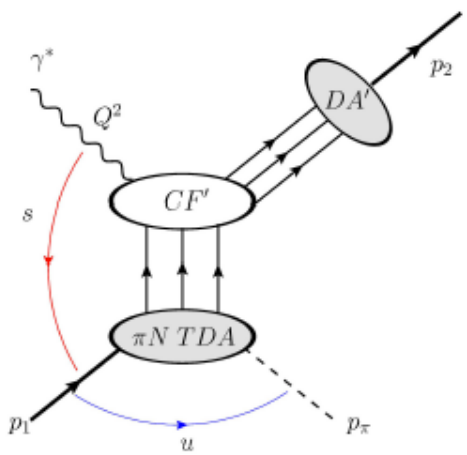


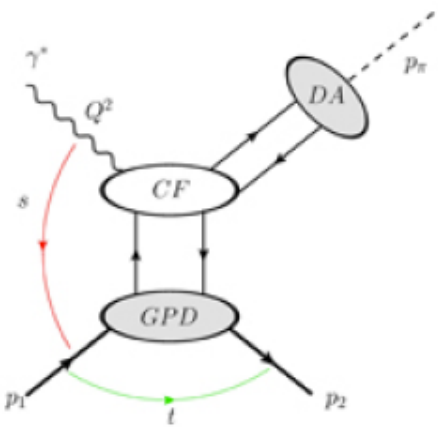
Measure relative phase of form factors

transversely polarised Target in PANDA

Generalized Parton Distributions and Transition Distribution Amplitudes (scattering)

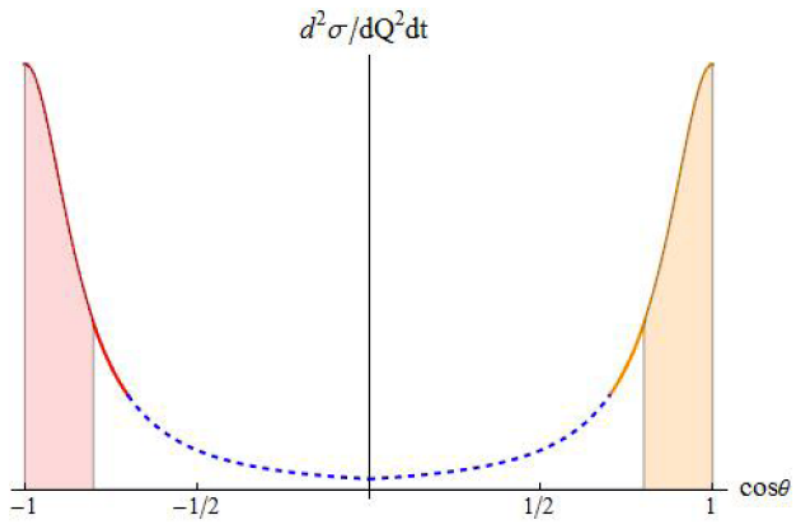


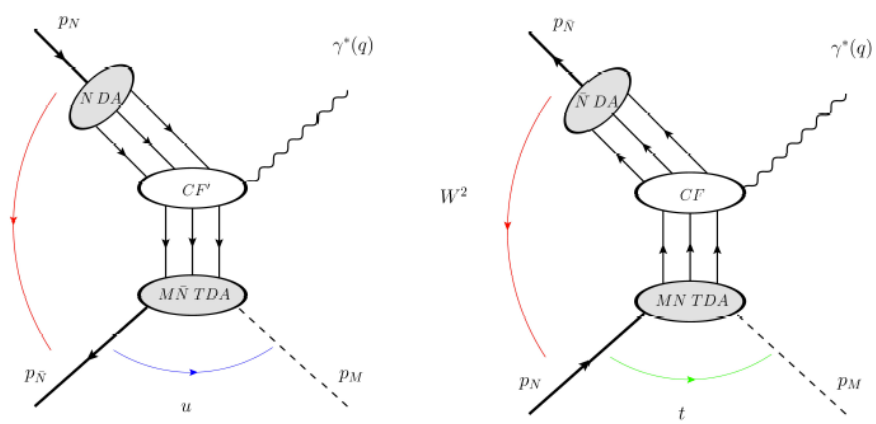




Generalized Parton Distributions and Transition Distribution Amplitudes (annihilation)

- Factorized description of $\bar{N}N \to \ell^+\ell^- M$ in terms of MN TDAs for near forward ($q^2 = Q^2$, W^2 – large, $\frac{q^2}{2p_N \cdot q}$ – fixed, $t \sim 0$) and near backward ($q^2 = Q^2$, W^2 – large, $\frac{q^2}{2p_{\bar{N}} \cdot q}$ – fixed, $u \sim 0$) regimes (Lansberg et al.'07)



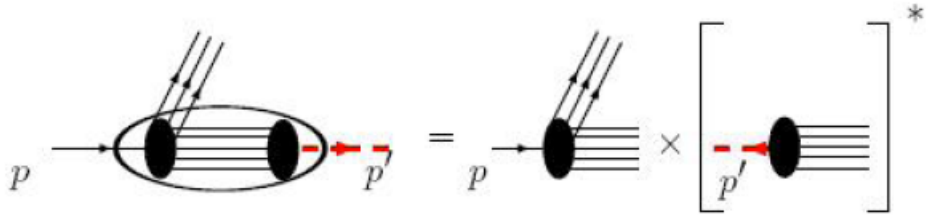


Generalized Parton Distributions and Transition Distribution Amplitudes (annihilation)

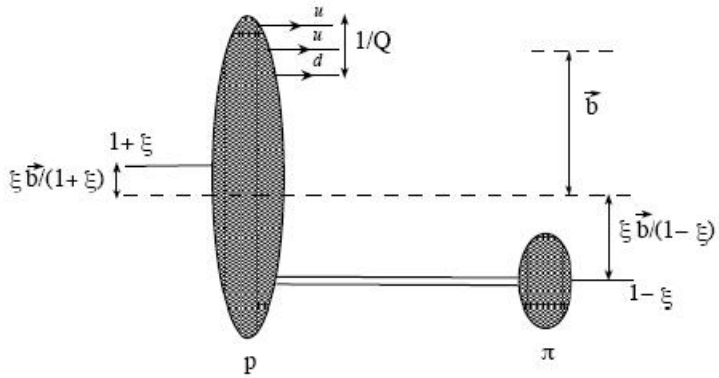
- develop the proton wave function as:

$$\underbrace{|qqq\rangle}_{\text{Described by nucleon DA}} \qquad +|qqq\,\pi\rangle + \ldots$$

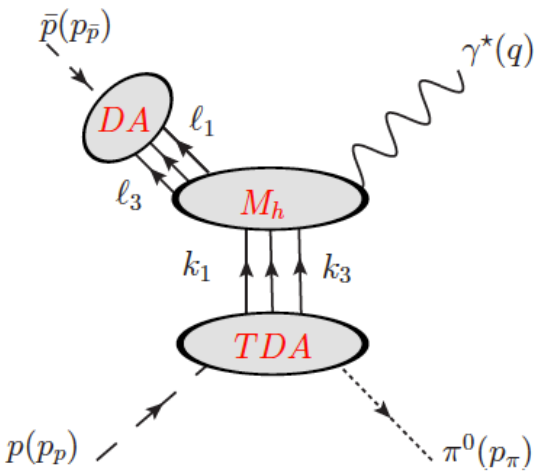
- πN TDAs provides information on the next to minimal Fock state in the baryon;



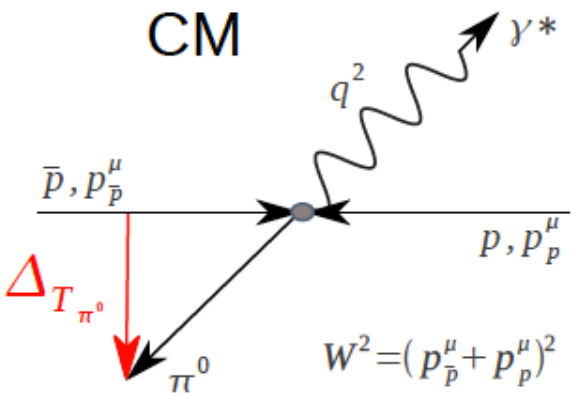
- Impact parameter space interpretation: the Fourier transform $\Delta_T \to b_T \Rightarrow$ transverse picture of pion cloud in the proton



Transition Distribution Amplitudes

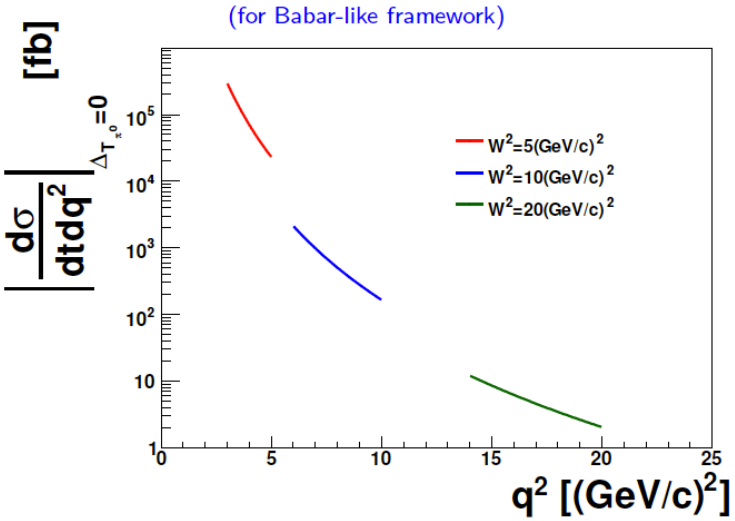


$\bar{p}p \to e^+e^-\pi^0$



Input for the Event Generator

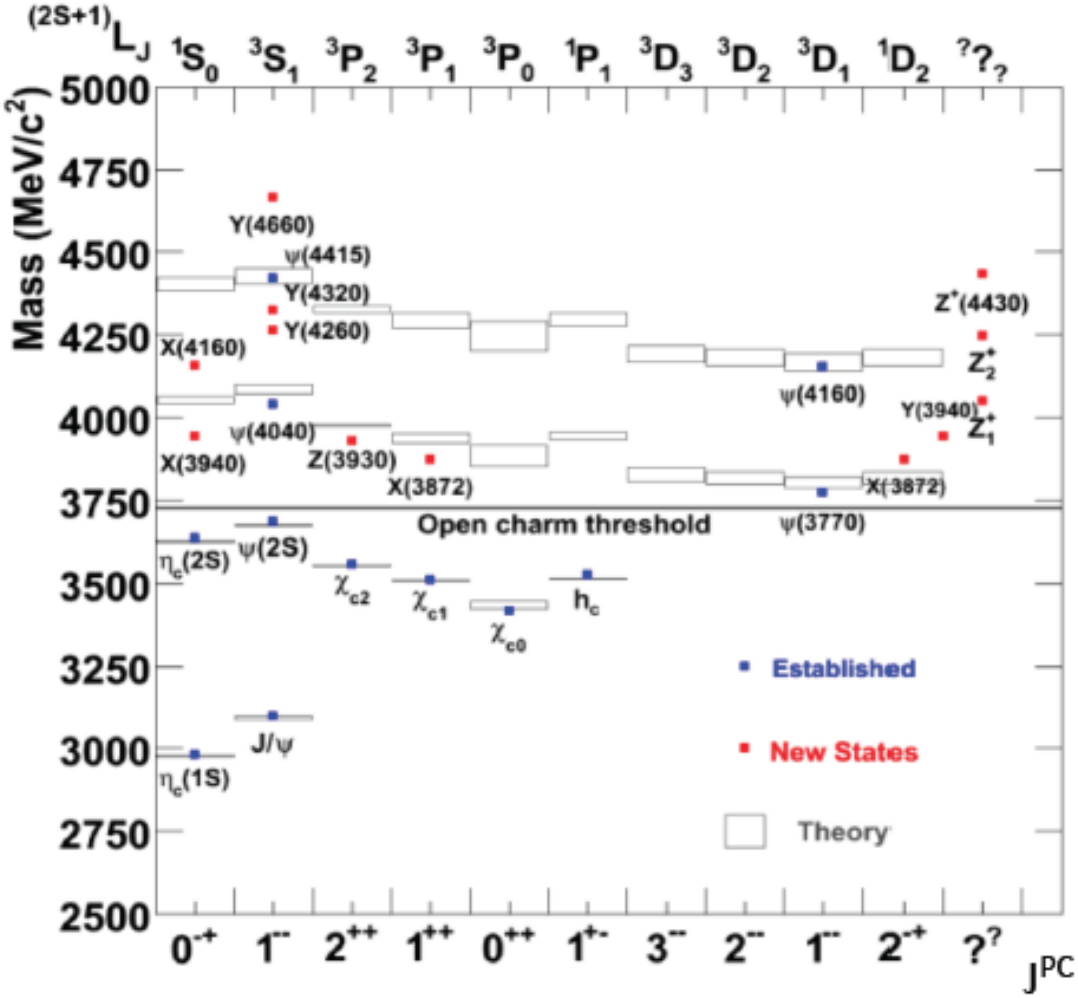
(for Babar-like framework)



Background: $\bar{p}p \to \pi^+\pi^-\pi^0$

- No data
- The same angular distribution as the signal
- 10^6 times higher

Charmonium(-like) Spectrum



- Observations that do not fit predictions
- The case of the X(3872):
  - isospin violating, very narrow
  - quantum numbers known (1^{++}, LHCb)
  - width: only upper limit

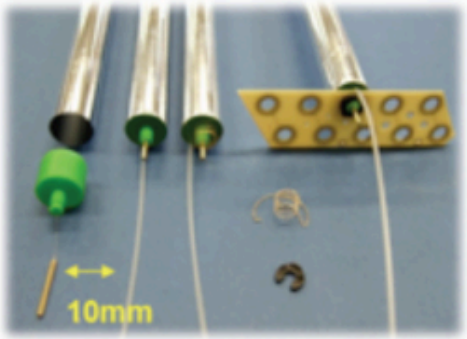
  → *nature not yet clear*

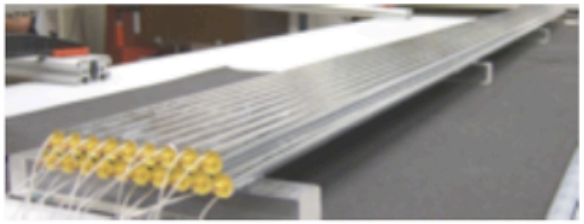
  needed: measurement of width
- X,Y,Z states:
  - some need still confirmation
  - masses poorly known
  - statistics poor, nature unclear:

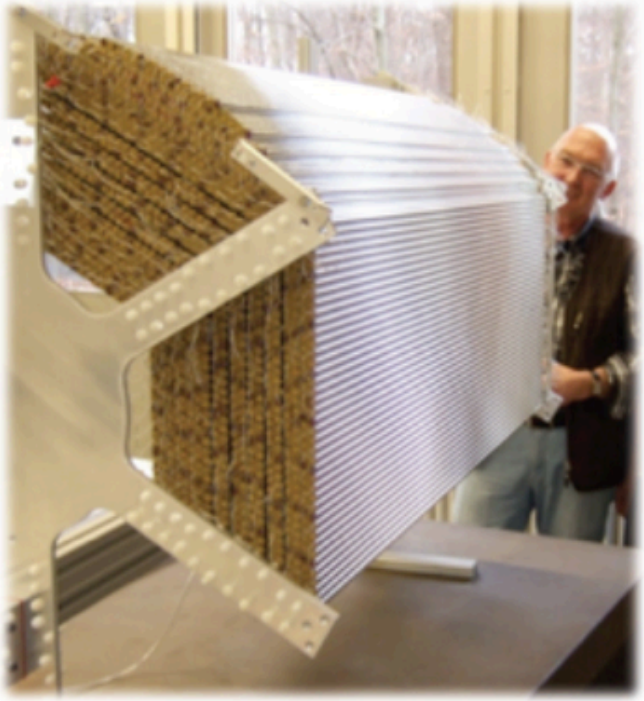
  Molecules, tetraquarks, hybrids, ..?

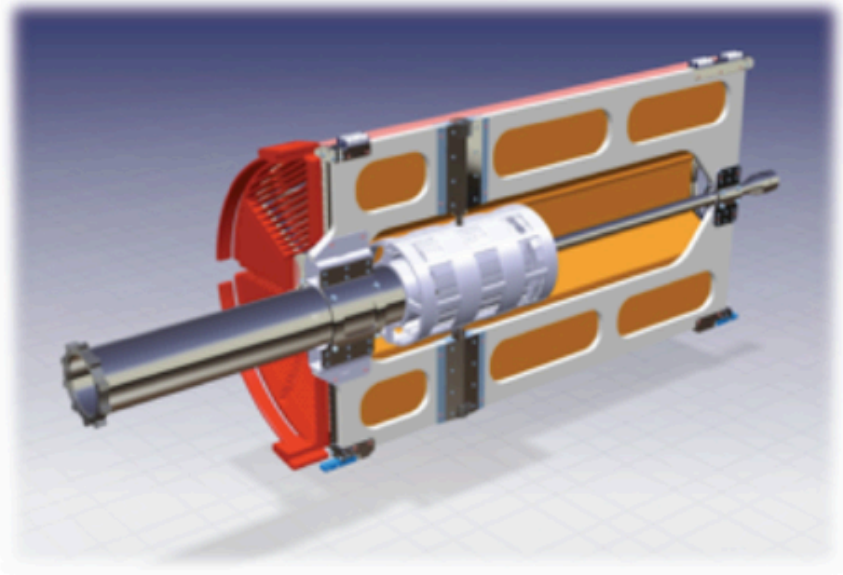
  $Z_c(3900)$: First order exotic?

The PANDA Central Tracker

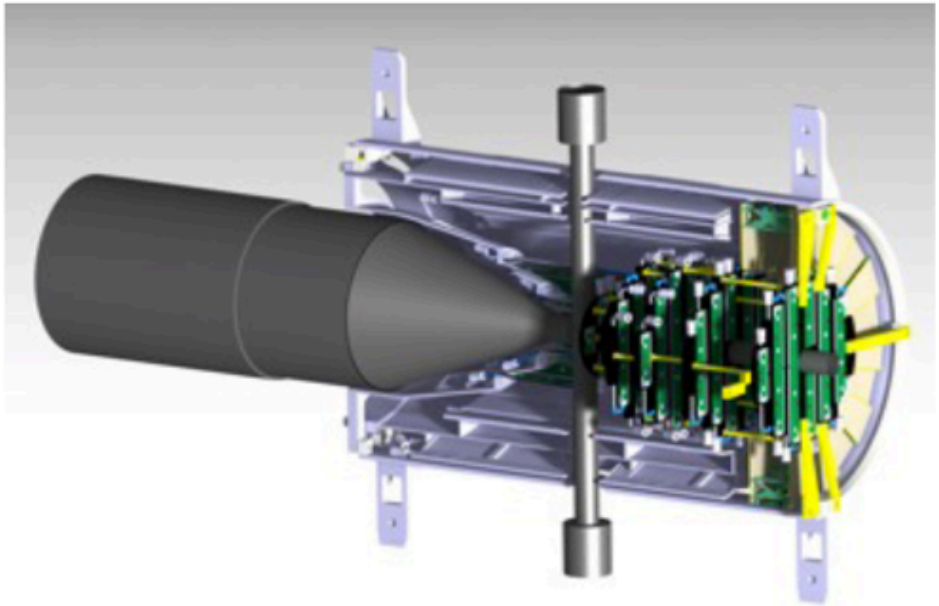




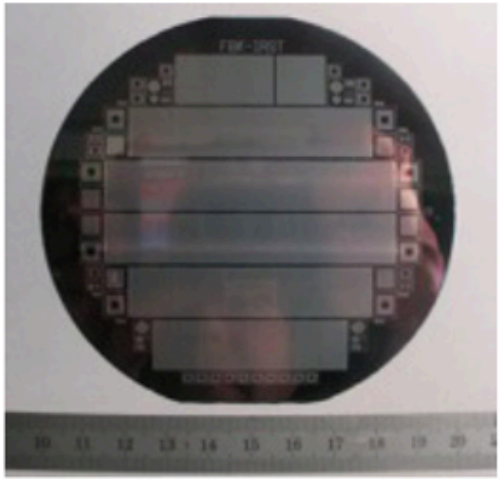




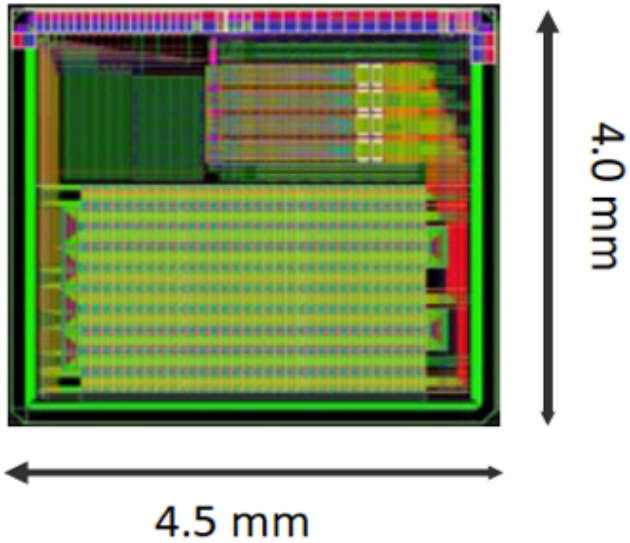
The PANDA MVD



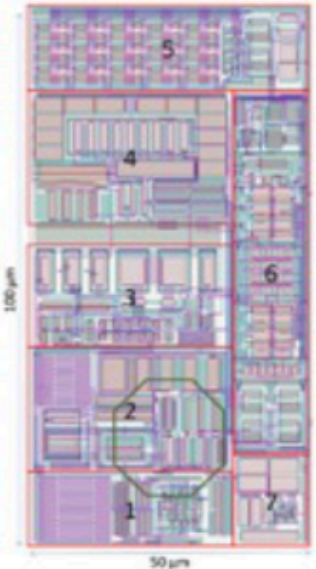
Full-Size Prototypes

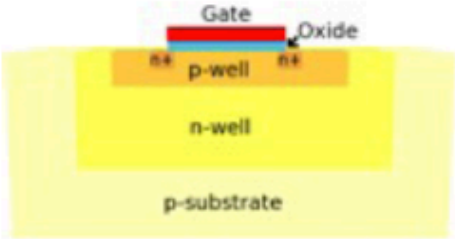


ASIC Prototypes



ToPix v3 Full-Feature Prototype





PANDA Collaboration

- At present a group of **500 physicists** from 62 institutions and 16 countries

Austria – Belaruz – China – France – Germany – India – Italy – The Netherlands – Poland – Romania – Russia – Spain – Sweden – Switzerland – U.K. – U.S.A.

AMU Aligarh, Basel, Beijing, BITS Pillani, Bochum, IIT Bombay, Bonn, Brescia, IFIN Bucharest, IIT Chicago, AGH-UST Cracow, JGU Cracow, IFJ PAN Cracow, Cracow UT, Edinburgh, Erlangen, Ferrara, Frankfurt, Gauhati, Genova, Giessen, Glasgow, GSI, FZ Jülich, JINR Dubna, Katowice, KVI Groningen, Lanzhou, Legnaro, LNF, Lund, Mainz, Minsk, ITEP Moscow, MPEI Moscow, TU München, Münster, BARC Mumbai, Northwestern, BINP Novosibirsk, IPN Orsay, Pavia, IHEP Protvino, PNPI St.Petersburg, South Gujarat University, SVNIT Surat, Sadar Patel University, KTH Stockholm, Stockholm, FH Südwestfalen, Suranaree University of Technology, Dep. A. Avogadro Torino, Dep. Fis. Sperimentale Torino, Torino Politecnico, Trieste, TSL Uppsala, Tübingen, Uppsala, Valencia, NCBJ Warsaw, TU Warsaw, AAS Wien

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