

Antiproton annihilation studies with the PANDA-Experiment at FAIR

"668. WE-Heräus-Seminar: Baryon Form Factors: Where do we stand?"

Physikzentrum Bad Honnef, Germany, April 23.-27., 2018

Frank Maas

HI Mainz, PANDA contact person



PANDA Program: 2 GeV – 5.5 GeV

I: Hadron spectroscopy

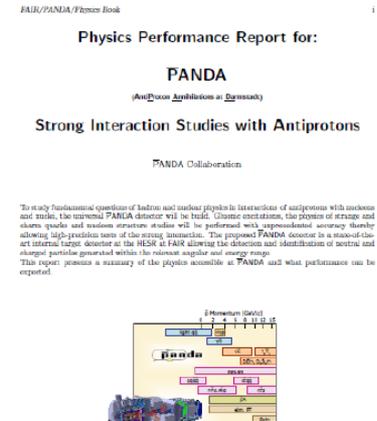
light mesons, baryons, charmonium, open charm,
QCD exotics: glueballs, hybrid states, X,Y,Z-states,...

II: Electromagnetic processes

time like form factors, transition distribution
amplitudes, TMDs, ...

III: Hadronic interactions:

Hyperons, Hypernuclei,
In medium-effects



ArXiv:0903.3905

PANDA Objectives

HEP: interference of coupled channels

Spectroscopy

New narrow XYZ:
Search for partner states

Production of exotic QCD states:
Glueballs & hybrids

Astro physics:
Strange n-stars

Strangeness

Strange baryons:
Spectroscopy
Polarisation

Nuclear physics:
Hypernuclear spectroscopy

HI collisions: Connecting to Quark Gluon Plasma
“crossing over” through baryon resonances

Bound States of Strong Interaction

Nuclear Physics

Hypernuclear physics:
Double Λ hypernuclei
Hyperon interaction

Hadrons in nuclei:
Charm and strangeness in the medium

HEP: underlying elementary processes

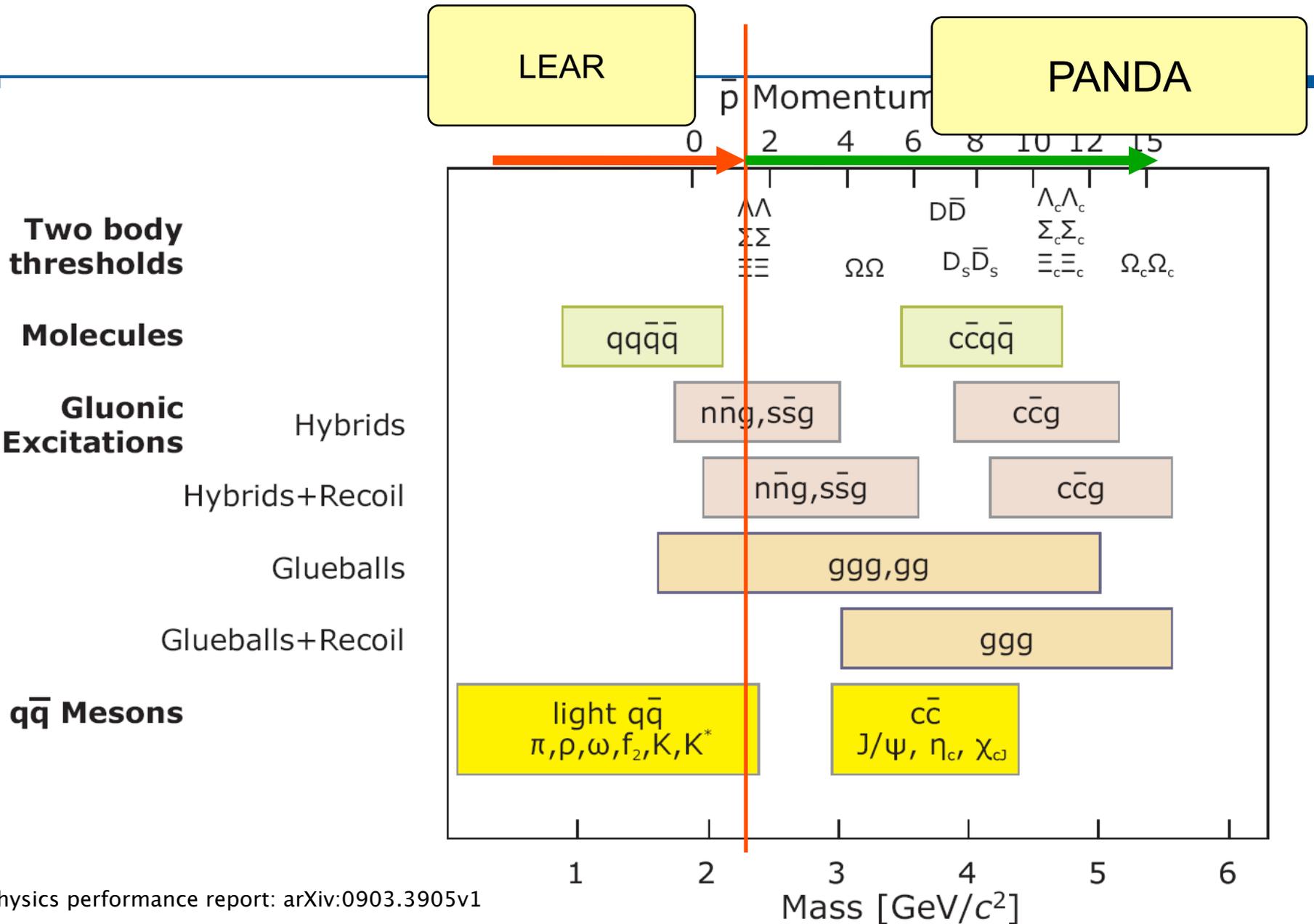
Nucleon Structure

Generalized parton distributions:
Orbital angular momentum

Drell Yan process:
Transverse structure, valence anti-quarks

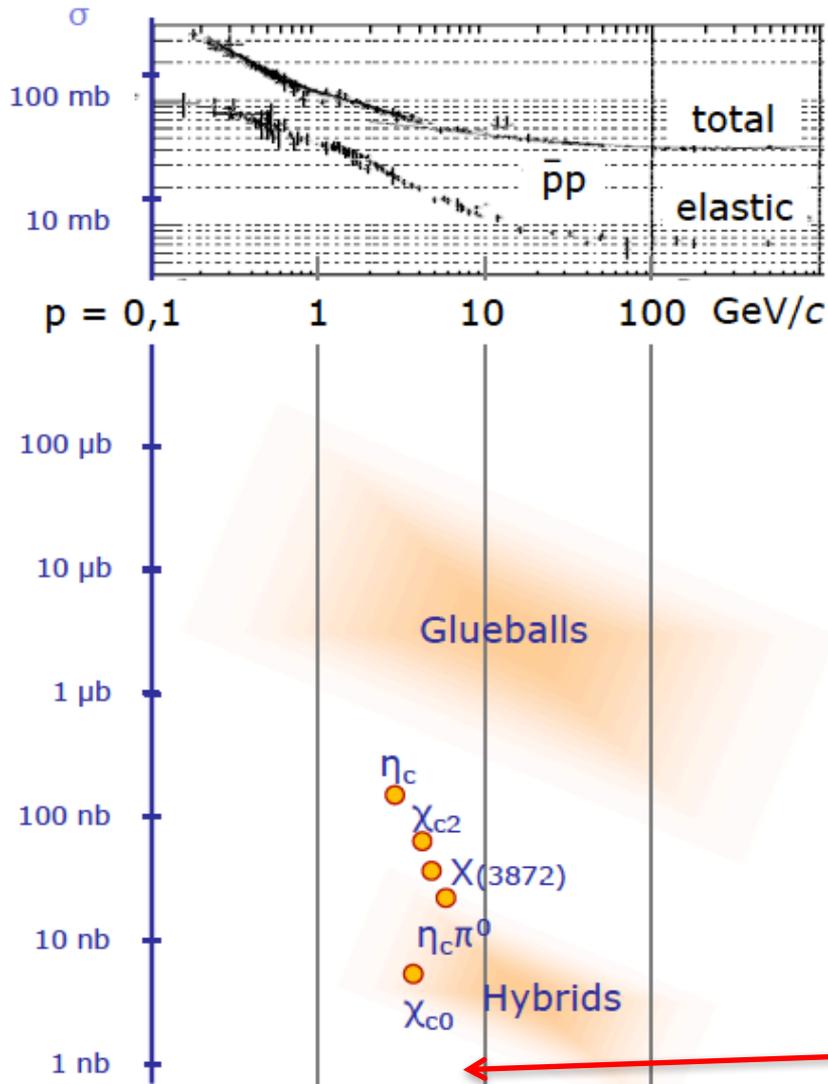
Timelike formfactors:
Low and high E,
e and μ pairs

HI collisions comparing QGP to elementary reactions



Physics performance report: arXiv:0903.3905v1

Detector Requirements from Physics Case



High luminosity and hadronic cross sections

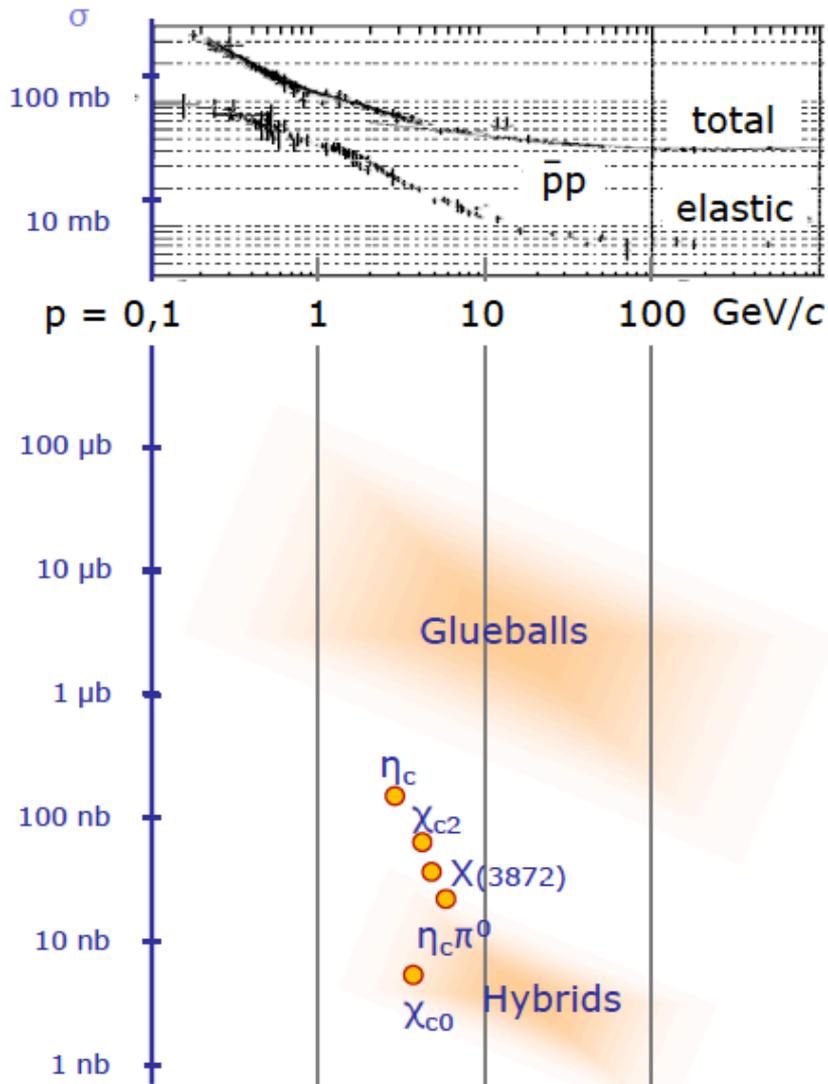
High rate capability, $2 \cdot 10^7 \text{ s}^{-1}$ interactions

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

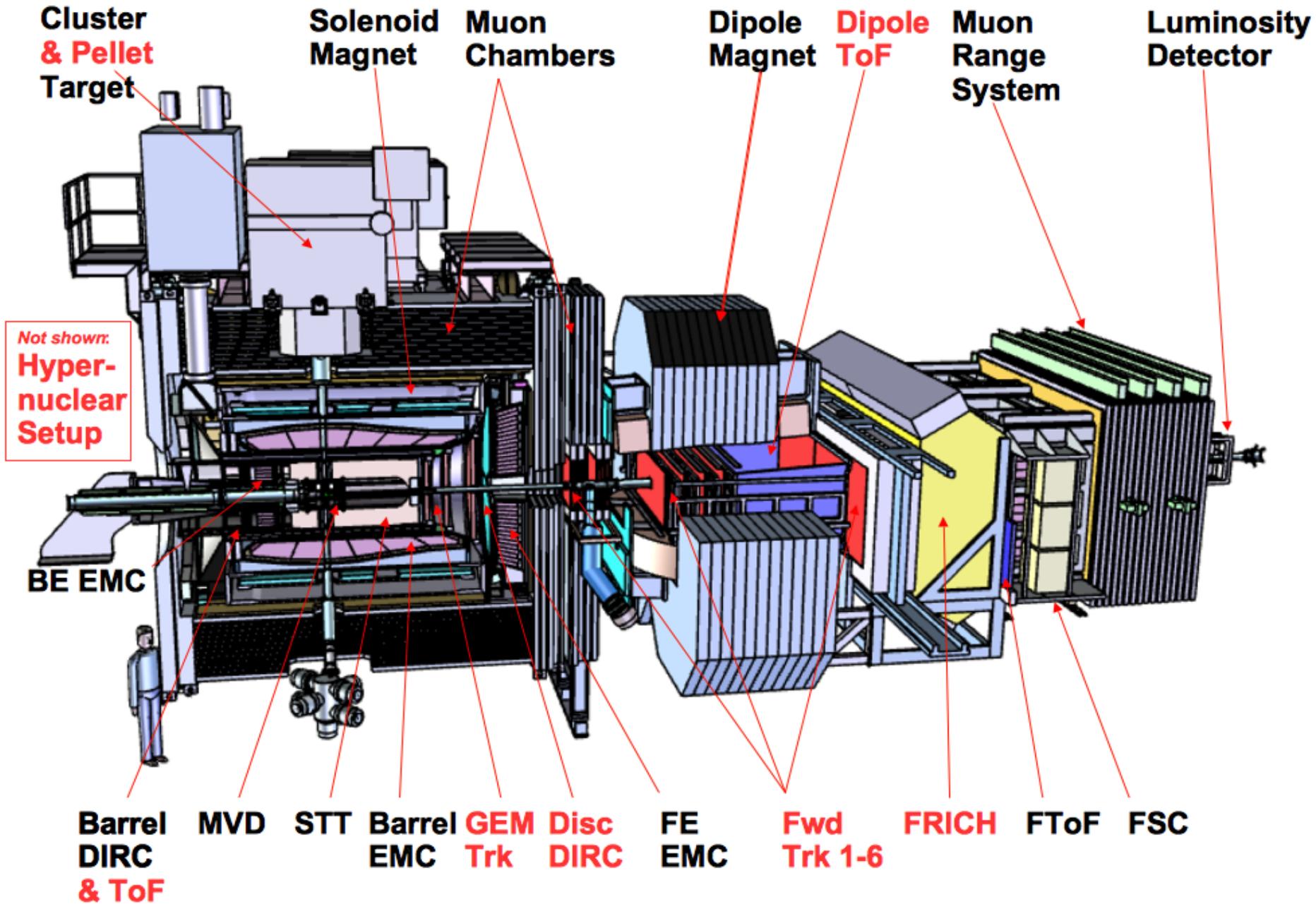
time of flight, dE/dx , muon counter

Displaced vertex info

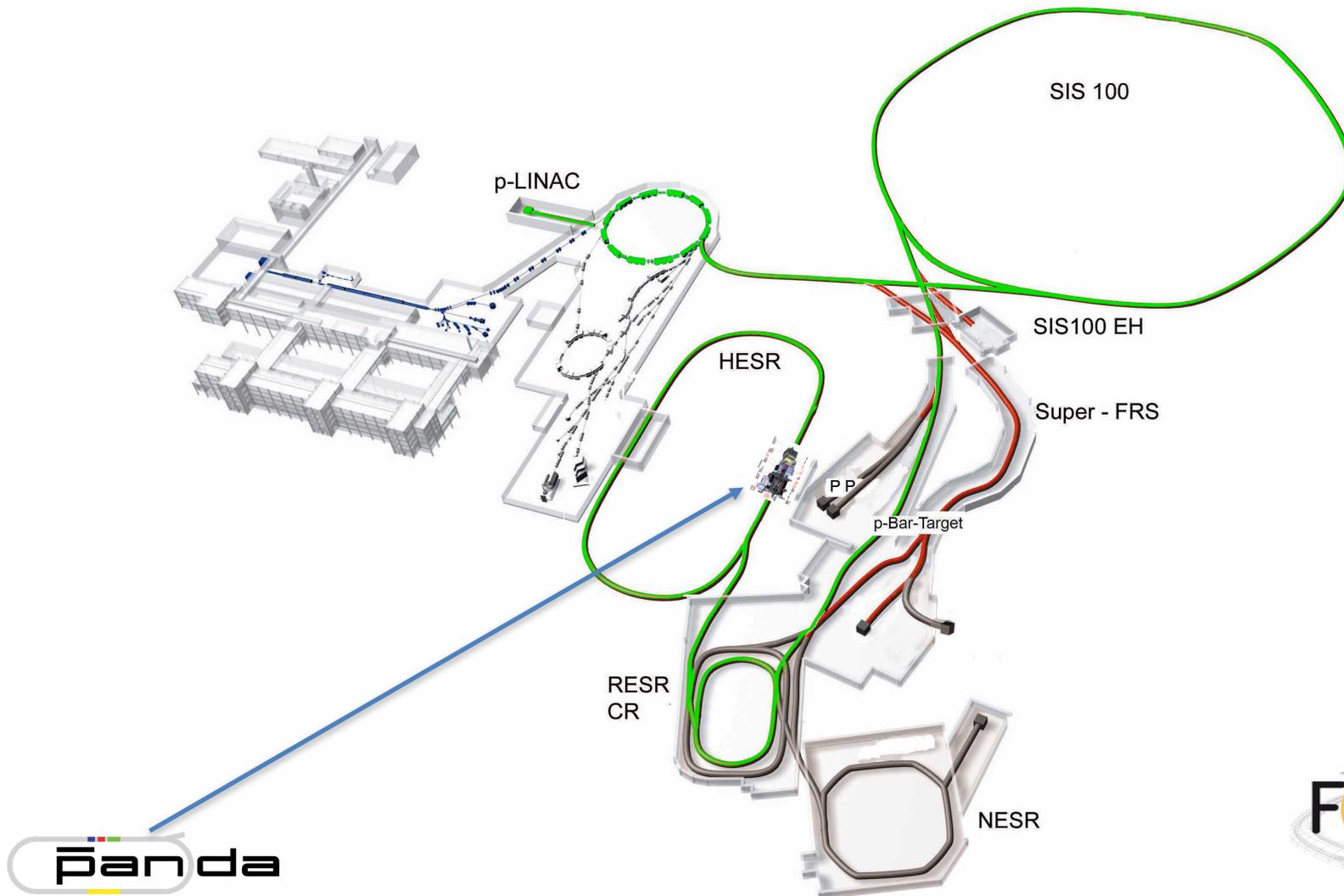
$c\tau = 317 \mu\text{m}$ for D^\pm

$\gamma\beta \approx 2$

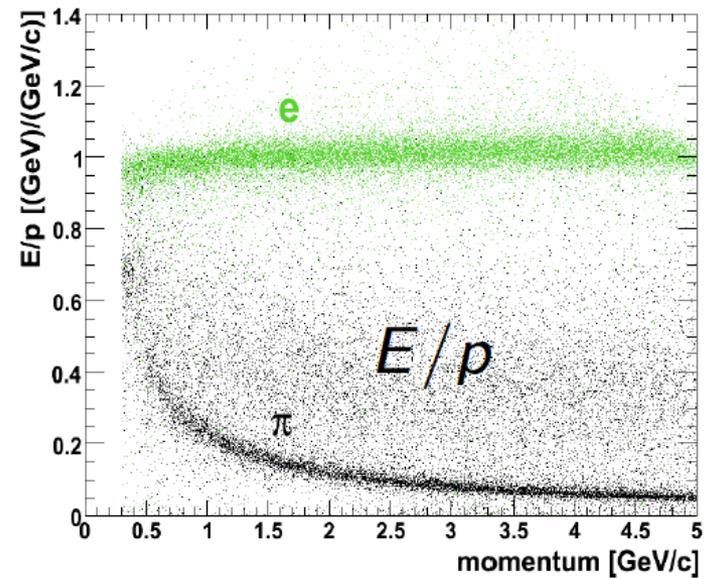
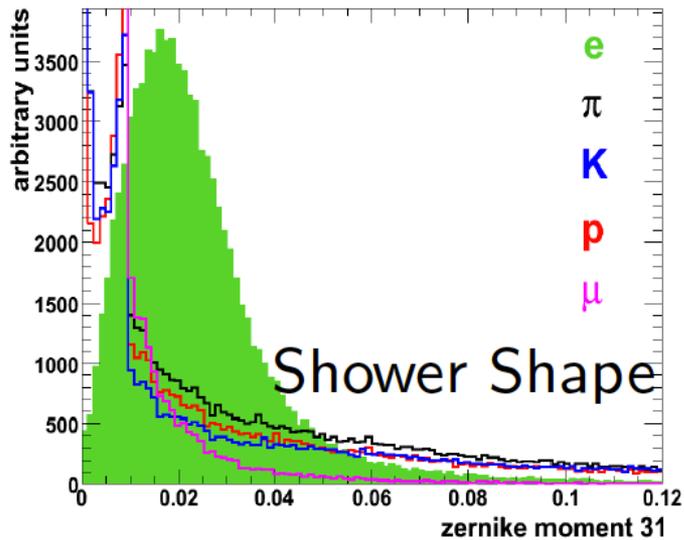
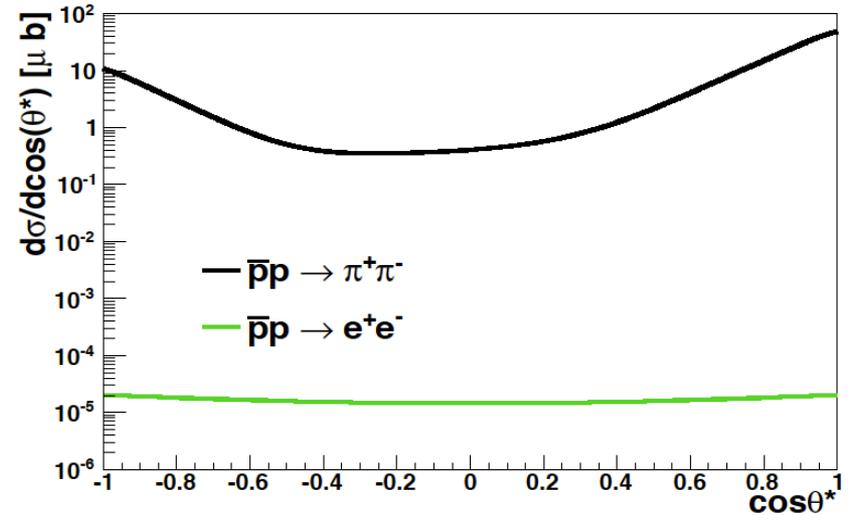
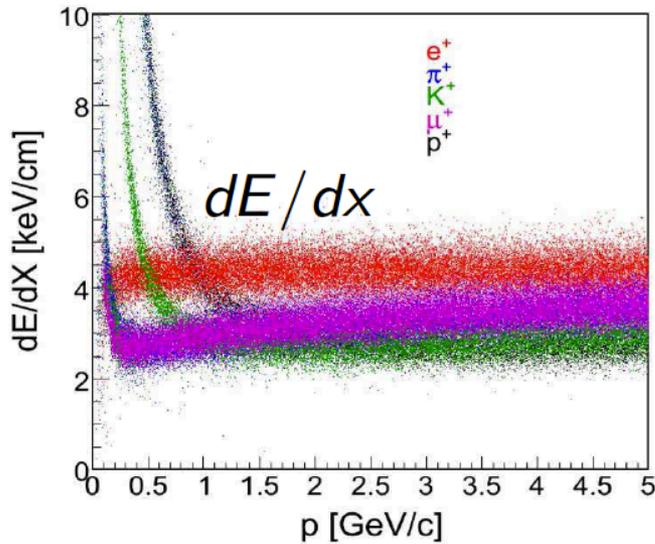
Full Setup



FAIR Facility Darmstadt



Particle Identification in PANDA



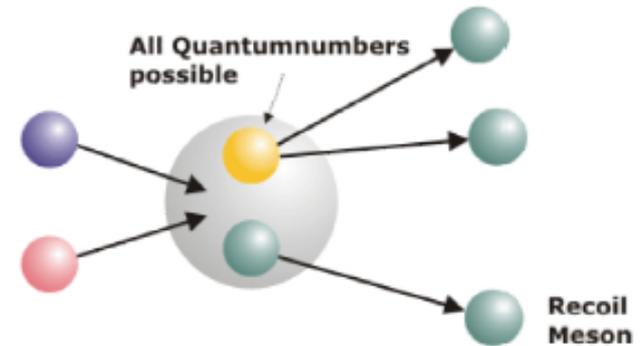
I. Spectroscopy

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)

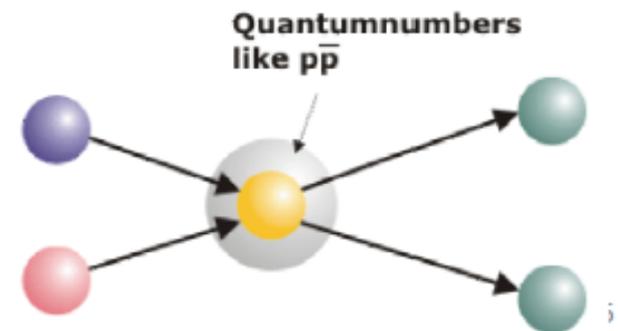


Formation: all states with non-exotic quantum numbers accessible

- 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

Comparison 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

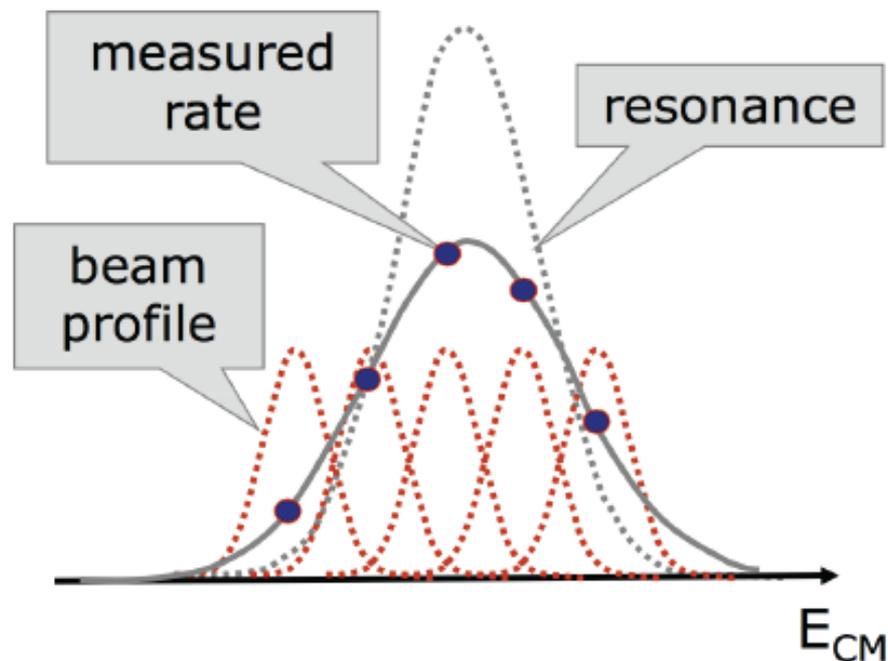
High resolution mode of HESR

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

Precise measurement of masses and widths of resonances

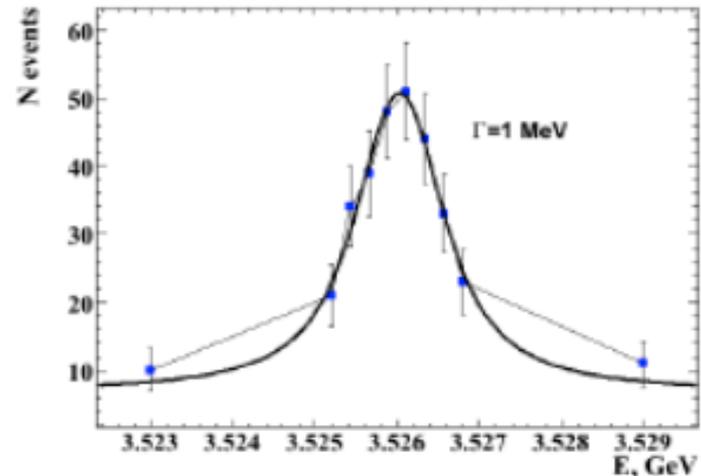
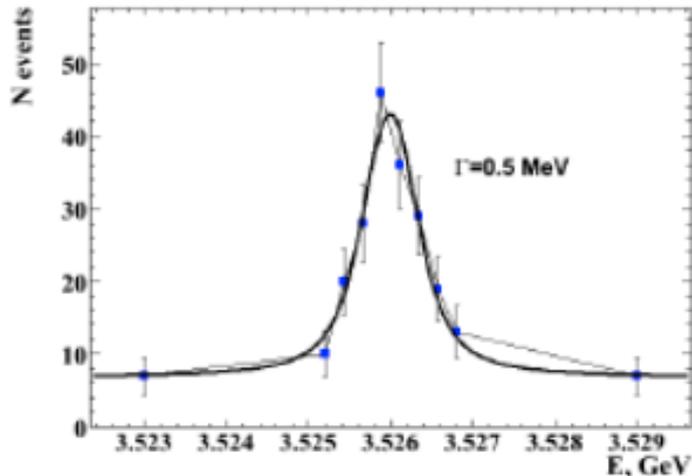
- only dependent on beam momentum resolution

→ **unique at PANDA**



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

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



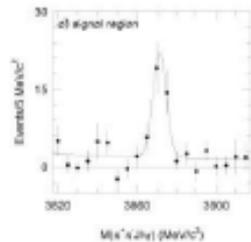
- Scan at 10 energy points around the h_c mass
- Each point corresponds to 5 days of data taking in high resolution mode

$\Gamma_{R,MC}$ [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



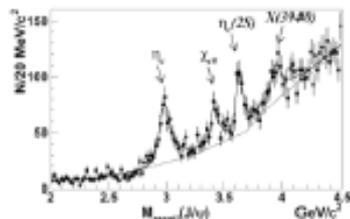
X(3872)

PRL 91,262001 (2003)



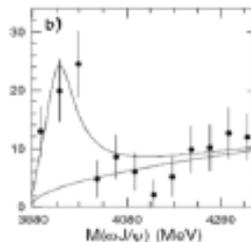
X(3940)

PRL 98,082001 (2007)



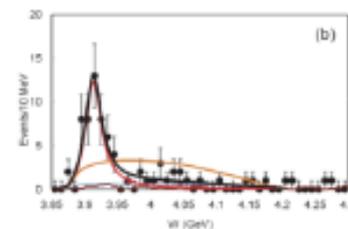
Y(3940)

PRL 94,182002 (2005)



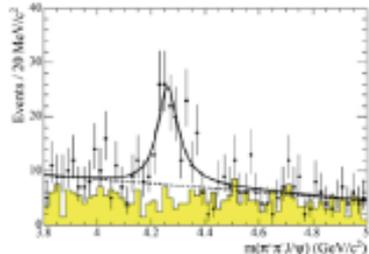
X(3915)

PRL 104,092001 (2010)



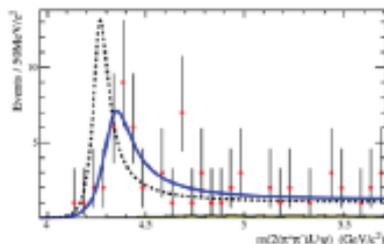
Y(4260)

PRL 95,142001 (2005)



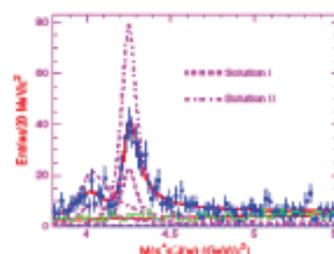
Y(4350)

PRL 98,212001 (2007)



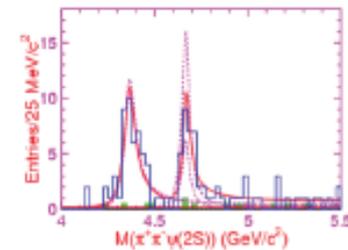
Y(4008)

PRL 99,182004 (2007)



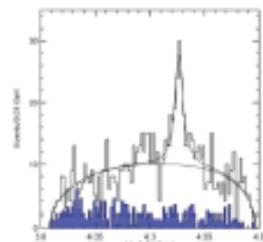
Y(4660)

PRL 99,142002 (2007)



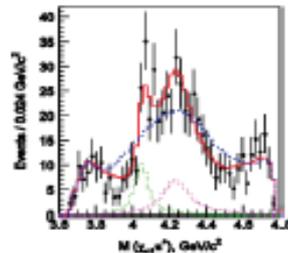
Z(4430)⁻

PRL 100,142001 (2008)



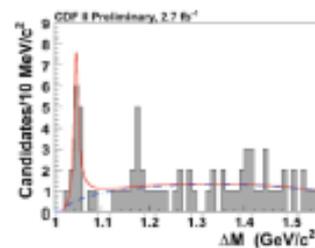
Z₁⁻ & Z₂⁻

PRD 78,072004 (2008)



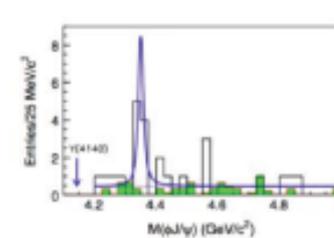
Y(4140)

PRL 102,242002 (2009)



X(4350)

PRL 104,112004 (2010)



Energy scans

HESR: average luminosity 1170 nb⁻¹/d (MSV0-3, no RESR)

- **PANDA:** estimate of cross section:
 $\sigma(\text{pbar } p \rightarrow X(3872)) = 100\text{nb}$ i.e. 1.17×10^5 $X(3872)$ produced per day
 $X(3872) \rightarrow J/\psi \rho^0 \rightarrow e^+e^-/\mu^+\mu^- \pi^+\pi^-$ only:
statistics: **~120 reconstructed events per day (full simulation)**
with RESR: factor 10 more
precise measurement of width/line shape by energy scan **~100keV**,
decisive for 4 quark states
- **BELLE II:**
estimated statistics: 1500 events in 4 years
- **BES III:**
statistics: ~20 events in 4 weeks

PANDA: ~120 $X(3872)$ /day, 820 $Y(4260)$ /day, 180 $Z(3900)$ /day

PANDA is a X,Y,Z factory
high statistics X,Y,Z data sample

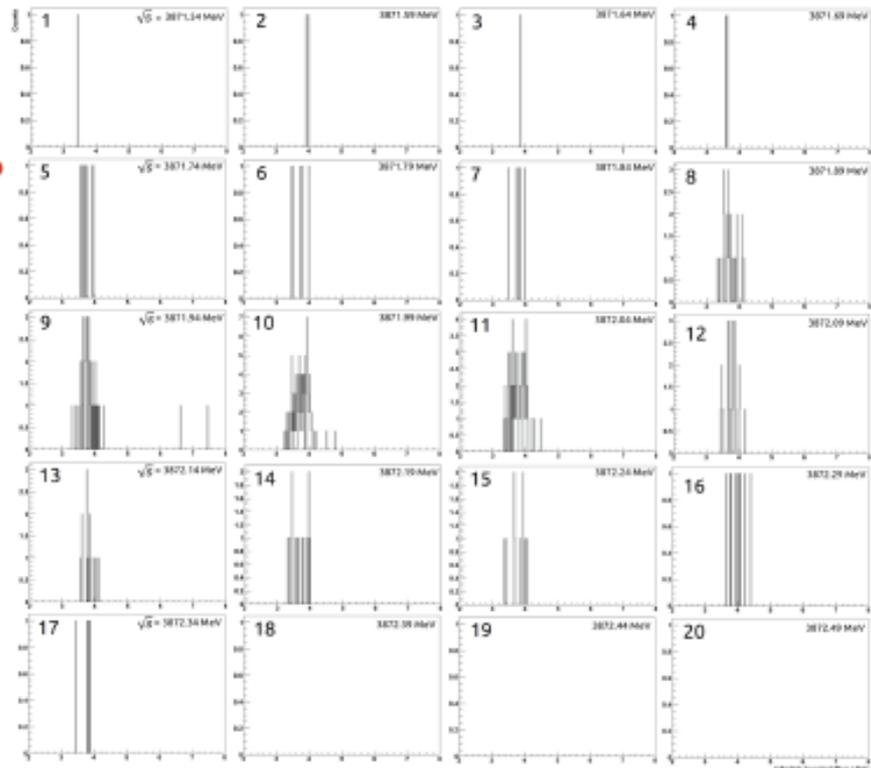
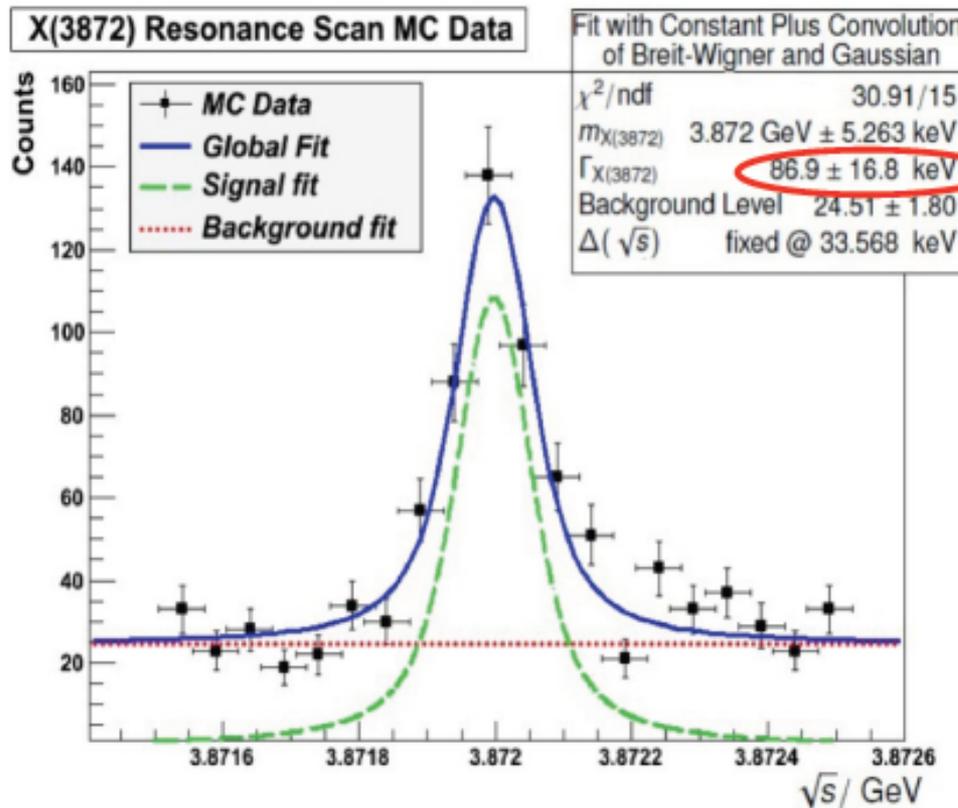
PANDA Release Note
RN-QCD-2016-002, QWG 2016

X(3872): Lineshape Scan at PANDA

Upper limit on branching ratio by LHCb:

$$BR(X \rightarrow \bar{p}p) < 0.002 \cdot BR(X \rightarrow J/\psi \pi \pi^+) \rightarrow \Gamma < 1.2 \text{ MeV} \quad \text{EPJ C73 (2013) 2462}$$

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

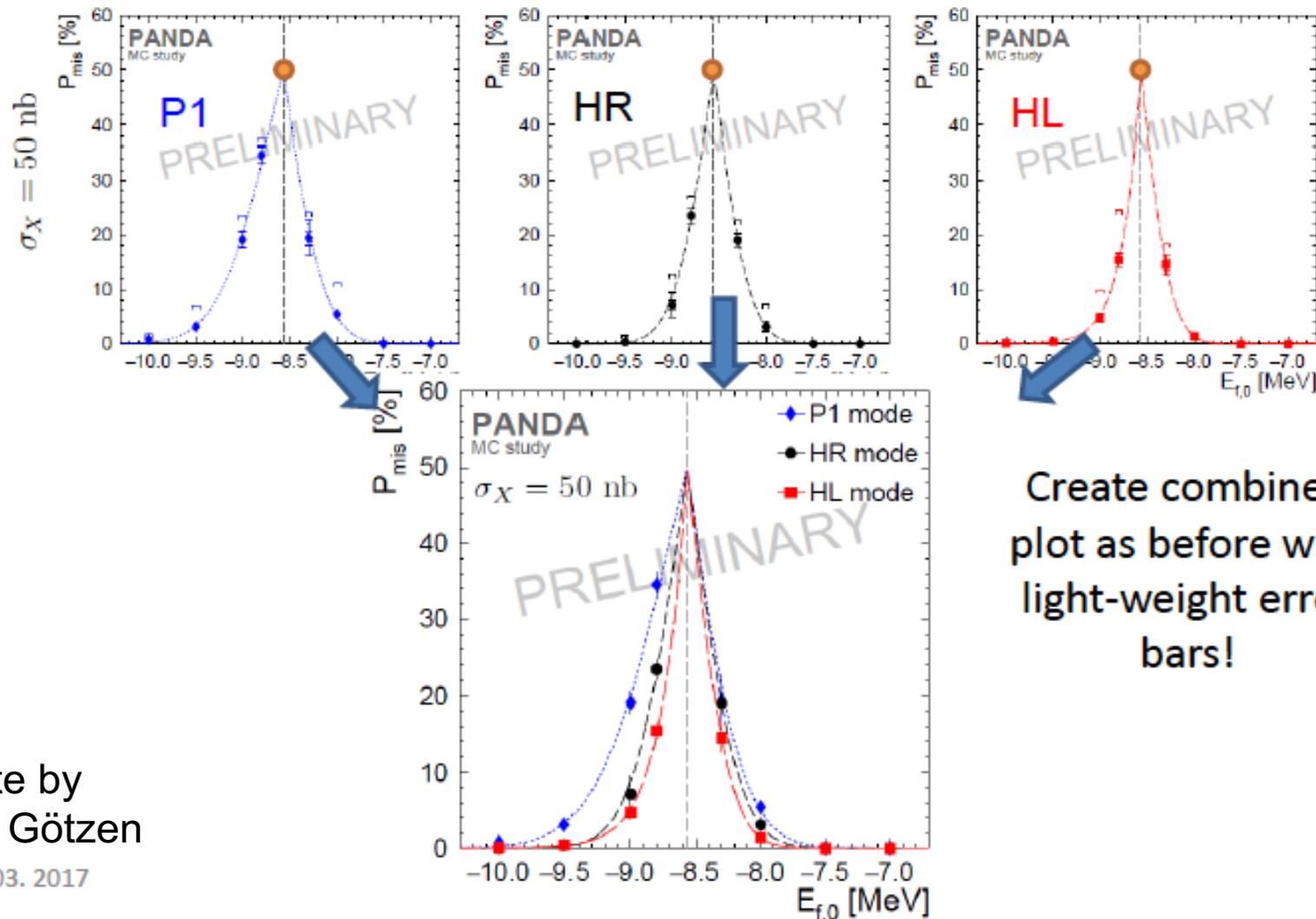


→ 40 days of data taking

[M.Galuska, PhD thesis]

Display of Results (Mol. P_{mis})

- Assume mis-id probability to be 50% at $E_f = E_{f,\text{thres}}$
- Fit gaussian tails to both sides, fixing the point ($E_{f,\text{thres}}$; 50%)



Create combined plot as before with light-weight error bars!

Update by
Klaus Götzen

09. 03. 2017

21

X, Y, Z Studies At PANDA

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

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

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

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

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) Zeta	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) Zeta	2,3	0,82	✓
Jpsi(2mu) 2K	0,5	3,8	✓

Jpsi(2e) Zeta	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) Zeta	24	0,082	✓
Jpsi(2mu) 2K	5,1	0,38	✓

Required Beam Time (days)

green < 30 yellow < 365 red >= 365

Signal / Background

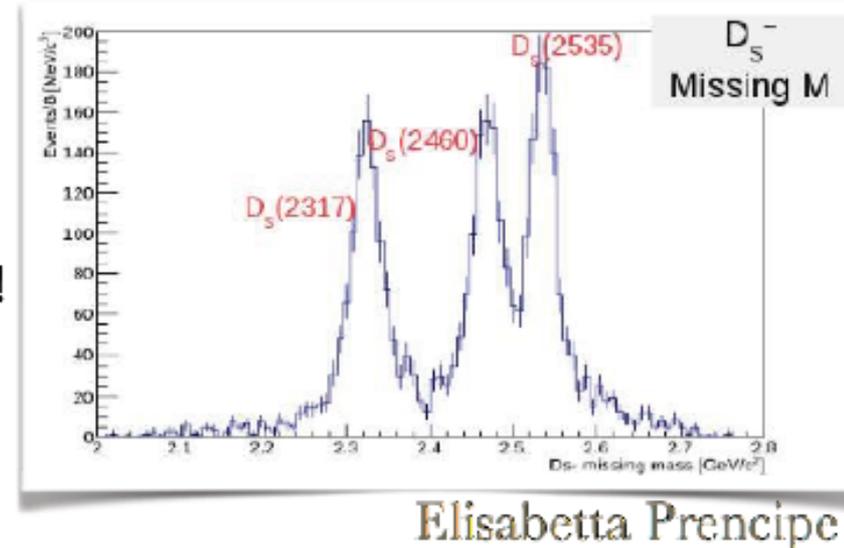
green > 1 yellow > 0.1 red <= 0.1

Homogeneity of Dalitz plot

ok < 1.5

PANDA Opportunities

- **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, $D_{sJ}(2460,2536) \rightarrow D^* \pi$
- **Search for D-waves and “exotics”**
 - expect higher production rate in $p\text{-}\bar{p}$ 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



Elisabetta Prencipe

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

- Light meson production cross sections in $\bar{p}p$ are huge
 - 100 nb ... 10 μ b
- 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 (\rightarrow tuneable phasespace)
- Many broad and overlapping states
 - requires (often) partial wave analysis techniques to identify resonances

Y(2175) Studies at PANDA

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

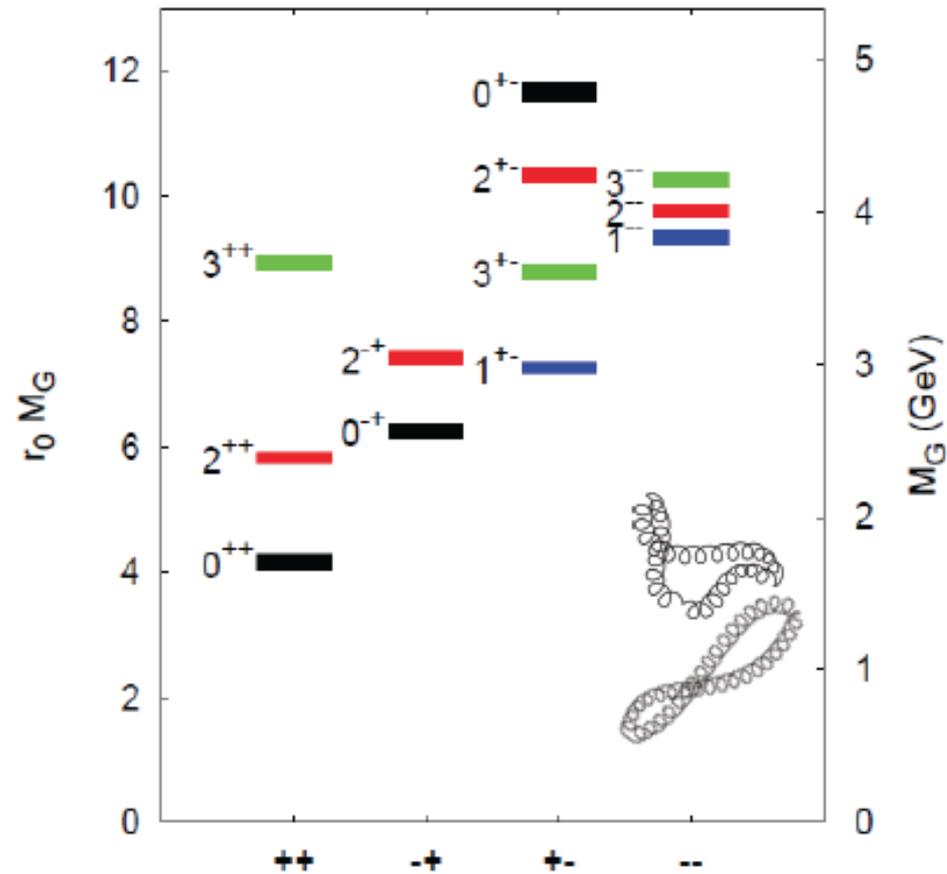
Beam-time to record 1000 reconstructed events in the $\Phi\pi^+\pi^-\pi^0$ decay mode

	$f_{BR} = 5 \%$	$f_{BR} = 10 \%$	$f_{BR} = 30 \%$
$L = 2 \cdot 10^{30}$	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

Glueball Spectrum
(Lattice QCD)



Higher spin
Glueballs only
accessible with PANDA

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

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

Glueball Studies at PANDA

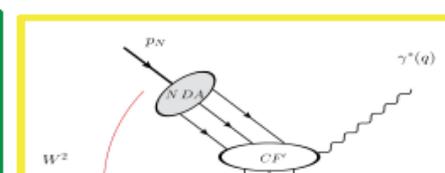
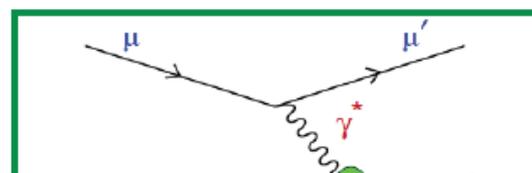
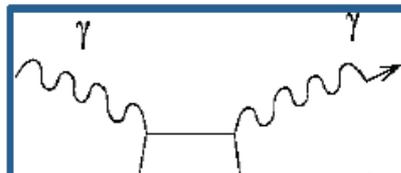
- Study of glueball production in $K^+K^-\pi^0$, $K^+K^-\pi^0\pi^0$, and $\Phi\Phi\pi^0$
 - assuming cross section of 10 nb (including decay to final state)
 - background cross sections 50 to 80 mb
- “Light” glueball $m = 2400 \text{ MeV}/c^2$ (could be 2^{++} or 0^{-+})
 - $E_{\text{CMS}} = 2.57 \text{ GeV}$ and 5.47 GeV
 - could be broad, study final states w/o intermediate resonances
- “Heavy” glueball $m = 3900 \text{ MeV}/c^2$
 - $E_{\text{CMS}} = 5.47 \text{ GeV}$
 - could be narrow, assume $\Gamma = 10 \text{ MeV}$
 - search for narrow signal in production followed by detailed studies in formation [unique at PANDA]

II. Electromagnetic Processes

Alaa Dbeyssi

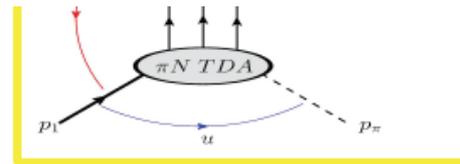
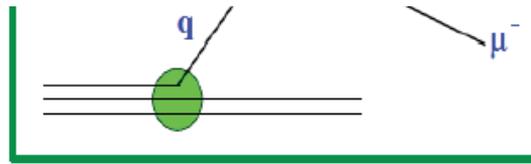
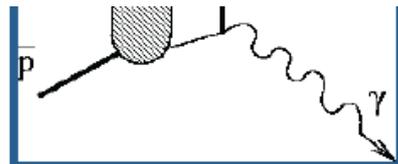
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(Virtual) photon in intermediate state



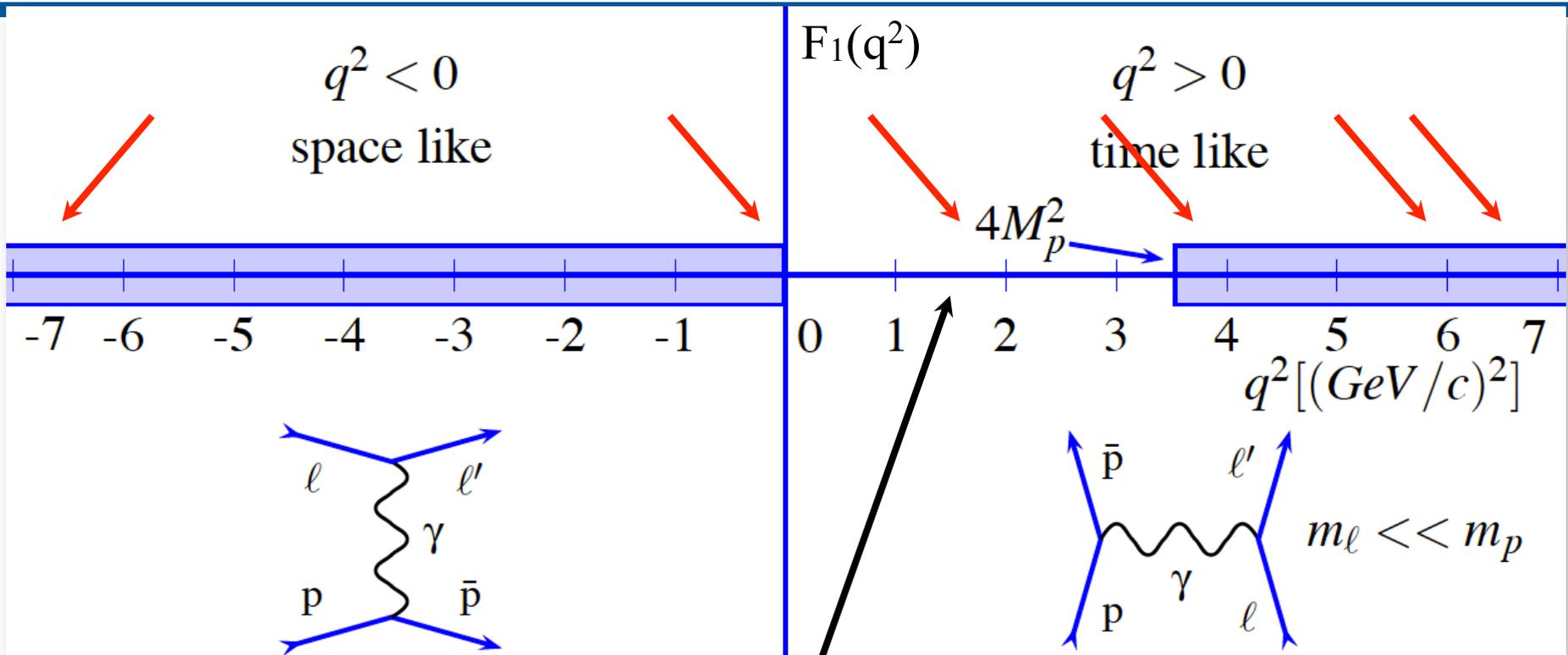
Crossing symmetry: - different kinematical regions
- observables are counterparts

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



Extended feasibility studies in simulations based on present PANDA design

Electromagnetic Form factors of the Nucleon



Form Factor real

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

unphysical region

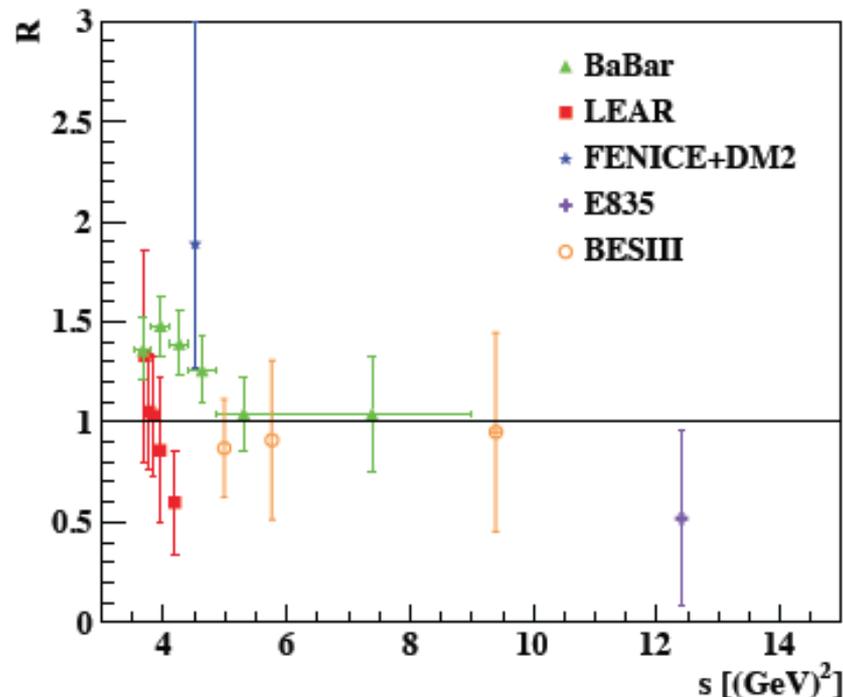
Form Factor complex

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

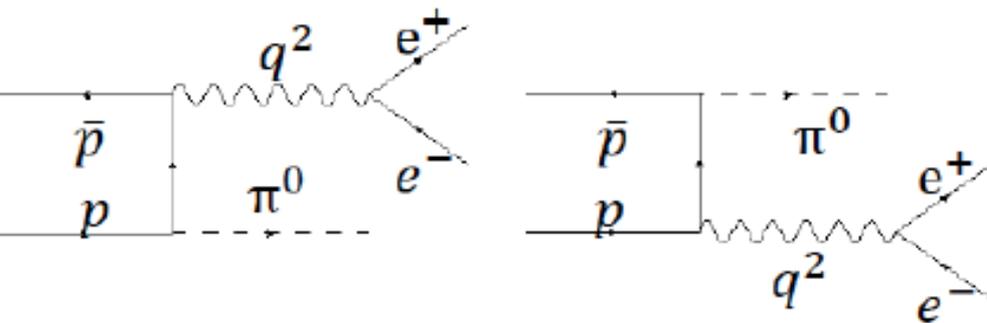
LEAR: Nucl.Phys.J., B411:3-32. 1994

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

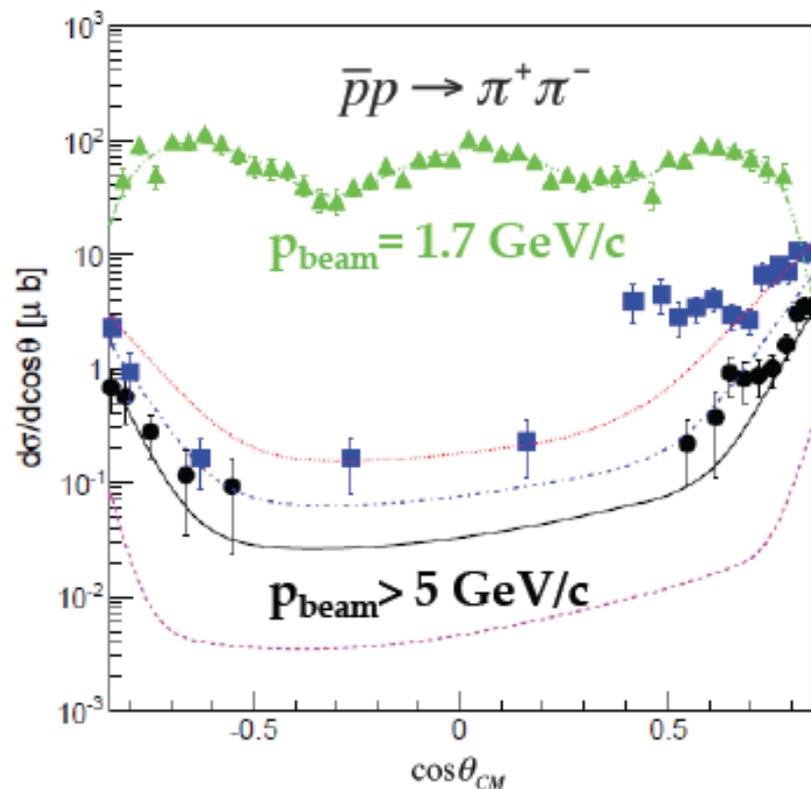


- M.P. Rekalo. Sov. J. Nucl. Phys., 1:760, 1965
- Adamuscin, Kuraev, Tomasi-Gustafsson and F. Maas, Phys. Rev. C 75, 045205 (2007)
- C. Adamuscin, E.A. Kuraev, G. I. Gakh, ...
- Feasibility studies (J. Boucher, M. C. Mora-Espi PhD)

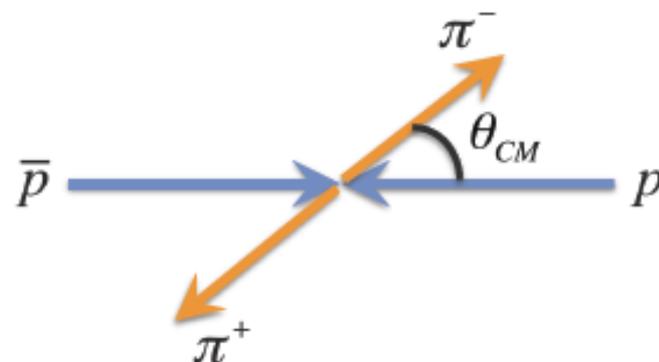
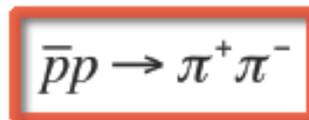
Feasibility studies: time-like proton form factors @ PANDA

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. Khanef, M. Zambrana et al.: Paper will be published soon (2015)



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

- Background rejection $\sim 10^{-8}$ 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 $\sim 10^{-6}$ will be achieved @ PANDA

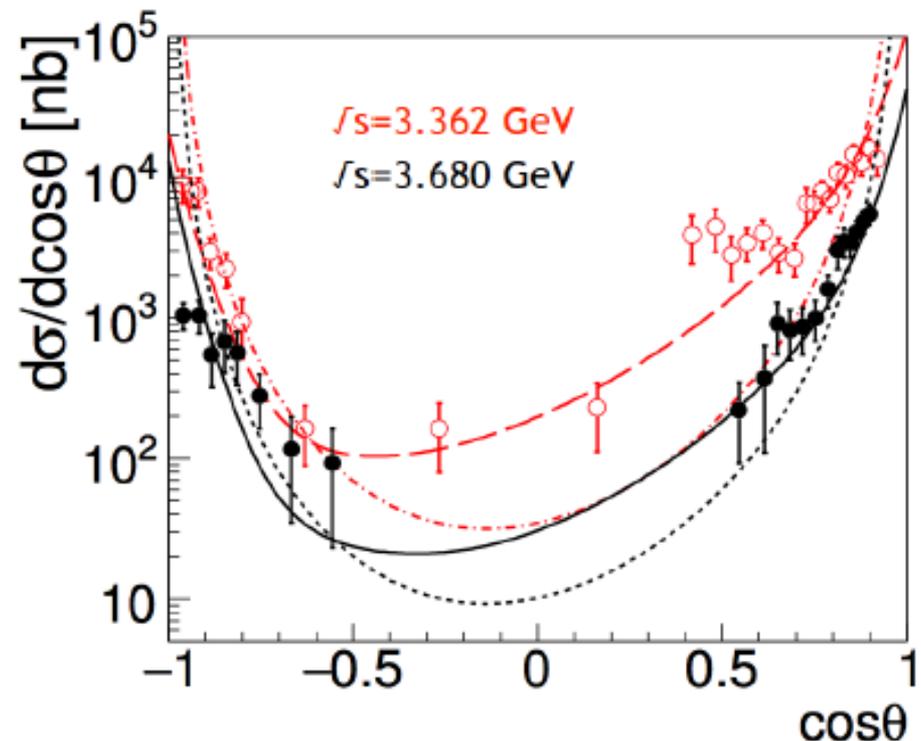
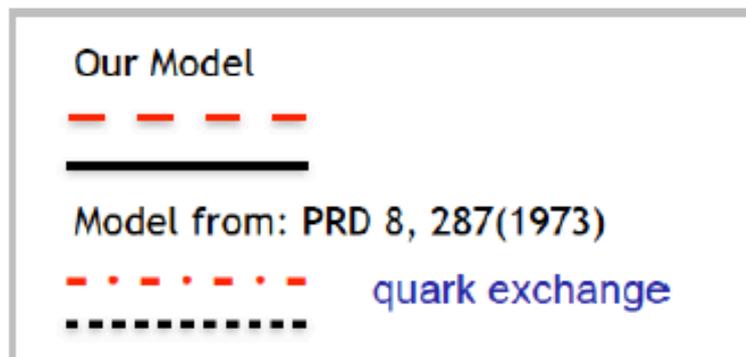
Charged and Neutral light meson pair production at PANDA

Egle Tomasi-Gustafsson (CEA, IRFU, DPhN, University Paris-Saclay)

Effective Lagrangian Model for $\pi^+ + \pi^-$

A promising model based on effective Lagrangian has been built to describe 2 meson production in $p\bar{p}$ annihilation:

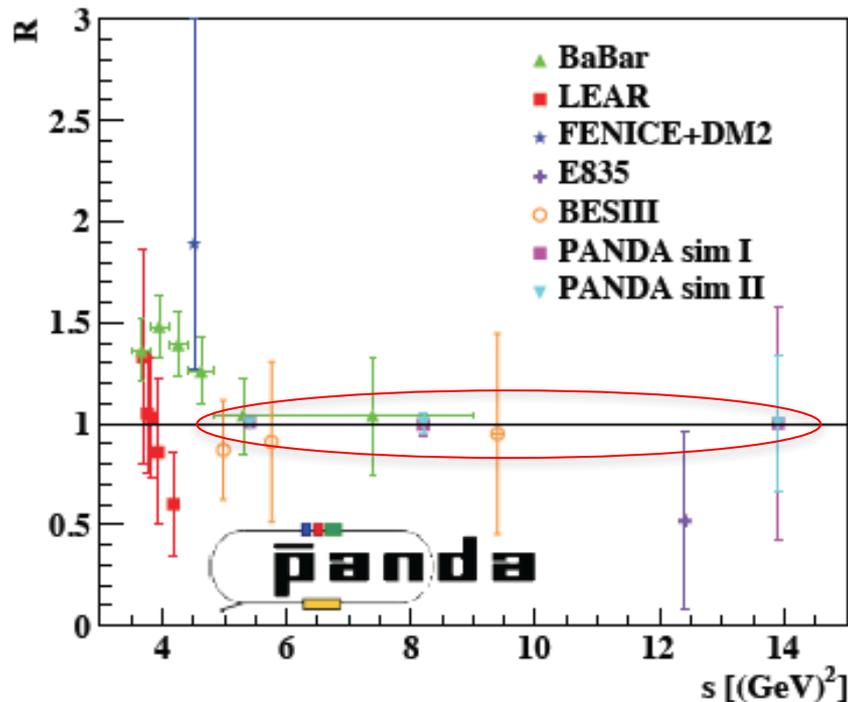
- logarithmic form factors
- no Regge factors



(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

$s \text{ (GeV)}^2$	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 $L=2 \text{ fb}^{-1}$
 $2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow 4 \text{ months data taking}$
- The **determination precisions** obtained at **5.4 GeV²** and **8.2 GeV²** are **compatible** between sim I & sim II
- At 13.9 GeV² the error of R was studied.

- The **effective FF** can be measured with good precision ranging from 0.3% up to 62.4% (at $q^2 \sim 28 \text{ GeV}^2$)

Electro magnetic form factors in the time like regime in PANDA

EPJ A Highlight

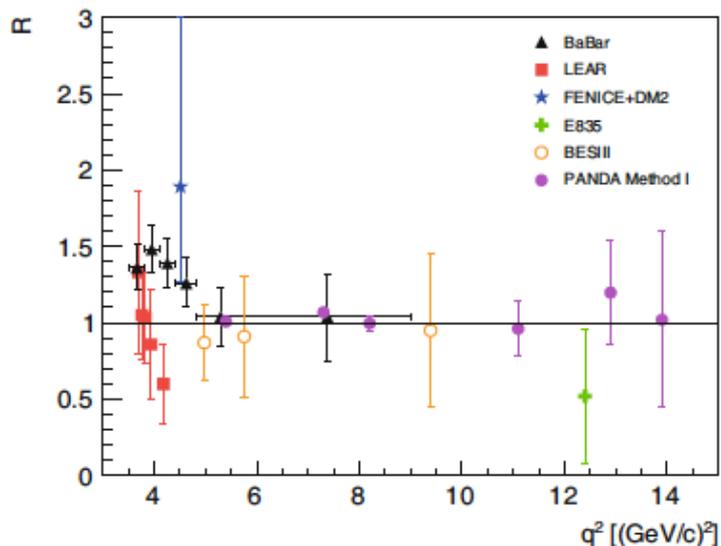
COVER EPJA October issue (2016)

“Feasibility studies of time-like proton electromagnetic form factors at PANDA at FAIR”

Corresponding author:

D. Khanef (PhD-Student HIM)

A. Dbeyssi (Helmholtz-Postdoc HIM)



The European Physical Journal

volume 52 · number 10 · october · 2016

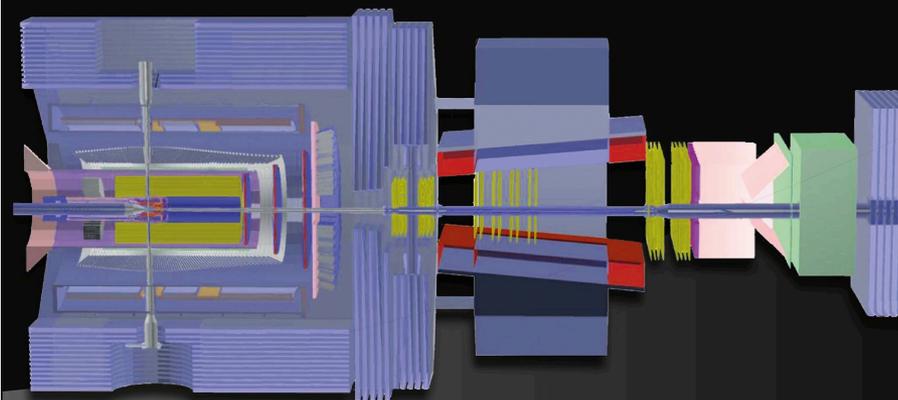
EPJ A



Recognized by European Physical Society

Hadrons and Nuclei

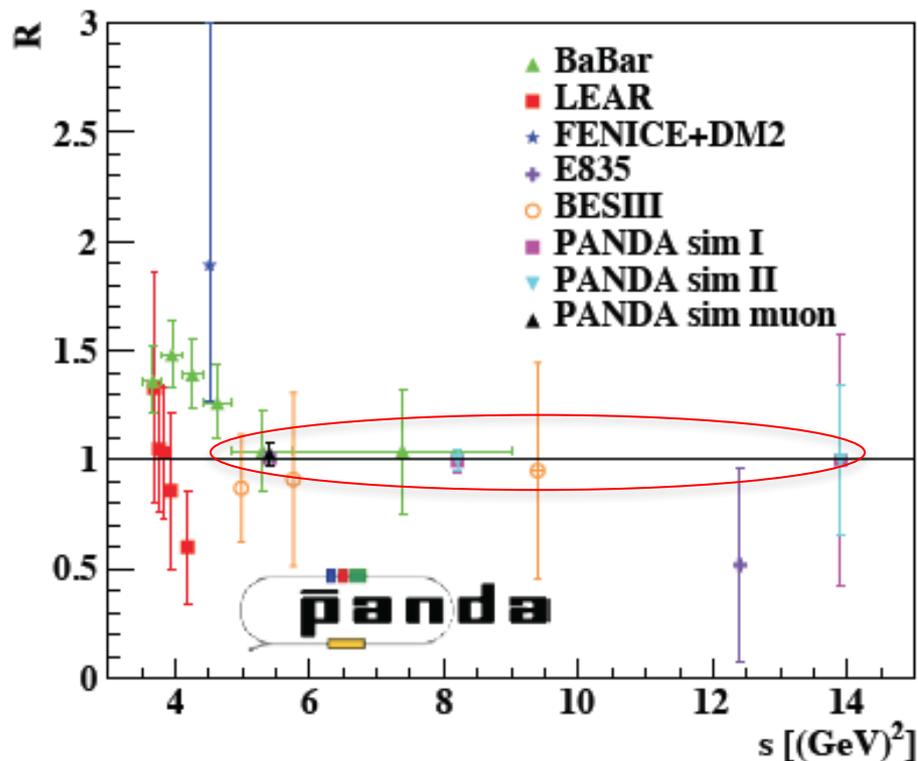
From: Feasibility studies of time-like proton electromagnetic form factors at PANDA at FAIR by The PANDA Collaboration



Springer

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

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

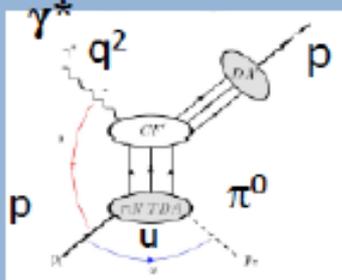


$s \text{ (GeV)}^2$	5.4	8.2	13.9
sim I	$\bar{p}p \rightarrow e^+e^-$		
$R= G_E / G_M $	1.5 %	5.3 %	57 %
$ G_E $	3.3 %	6.8%	45%
$ G_M $	1.7%	2.3 %	9%
MVA	$\bar{p}p \rightarrow \mu^+\mu^-$		
$R= G_E / G_M $	5.1%	-	-
$ G_E $	8.6%	-	-
$ G_M $	4.1%	-	-

Transition Distribution Amplitudes (TMDs)

$$e^-p \rightarrow e^-p\pi^0$$

Bwd
electroproduction

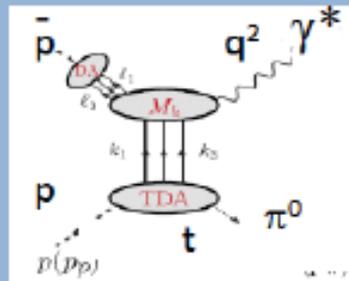


*Large q^2
small u*

Transition **D**istrib.
Amplitudes

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

Fwd/bwd



*Large q^2
small t or u*

Transition **D**istrib.
Amplitudes

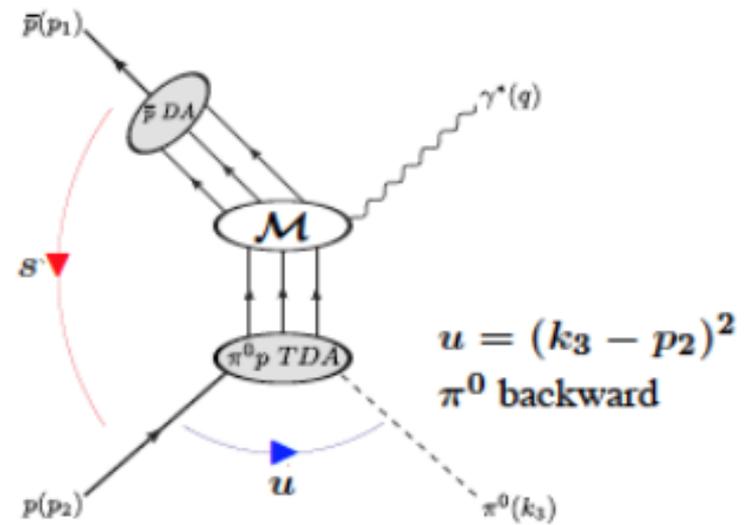
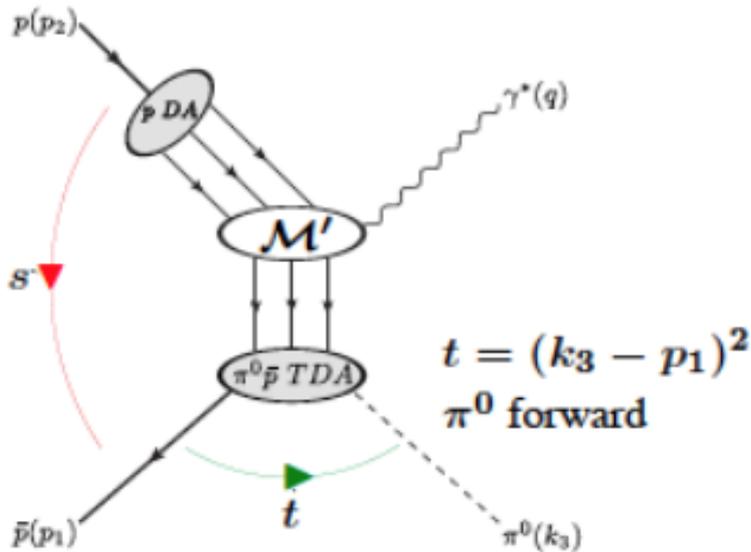
Transitions Distribution Amplitudes:

$$\bar{p}p \rightarrow e^+e^-\pi^0, e^+e^-\rho^0, e^+e^-\eta, \dots$$

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



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

- Admits a factorized description when:

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

- q^2 is large ($q^2 \approx s$)
- t is small (forward kinematics, π -N TDAs), or u is small (backward, π -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 $\bar{p}p \rightarrow \gamma^* \pi^0 \rightarrow e^+e^-\pi^0$ at PANDA

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

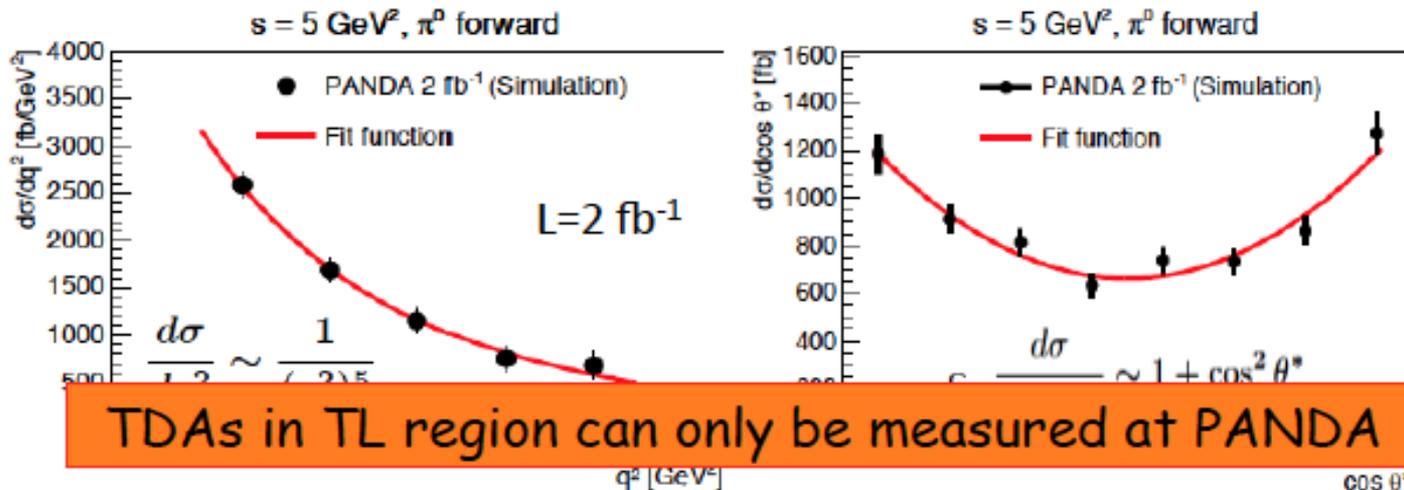
ii) $s = 10 \text{ GeV}^2 \rightarrow 5 < q^2 < 9 \text{ GeV}^2, |\cos \theta_{\pi^0}| > 0.5$

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

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

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

- Test of the QCD factorization/access TDAs



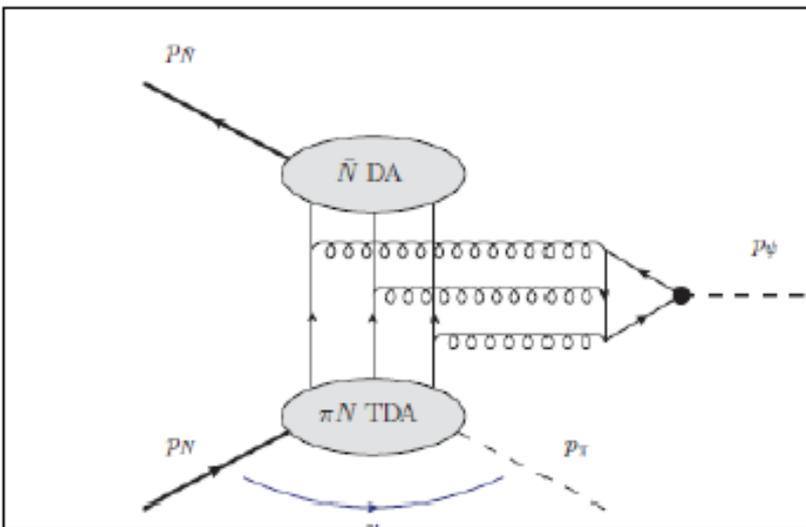
TDA's in TL region can only be measured at PANDA

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

Transition Distribution Amplitudes (TMDs)

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

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



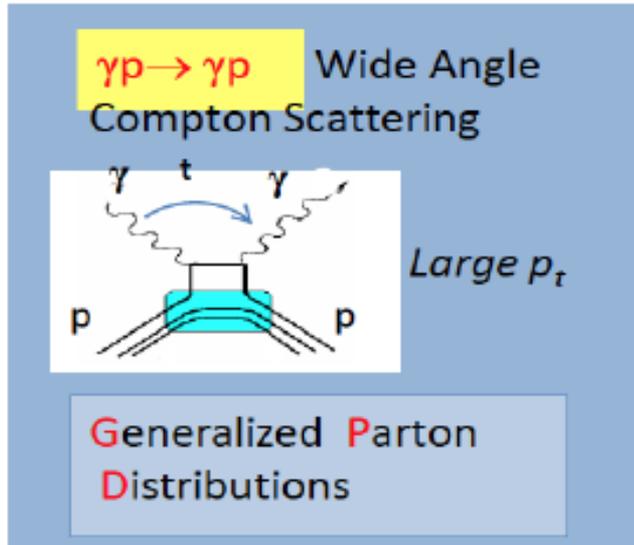
Feasibility studies for PANDA @ $p=5.513, 8.0$
and $12.0 \text{ GeV}/c$:

$S/B > 8, 70, 600$

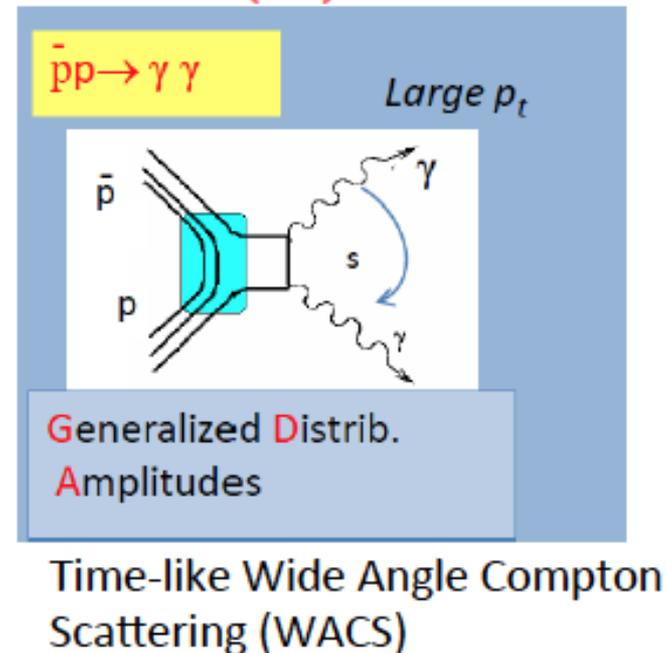
Binsong Ma, PhD thesis, IPNO 2014
Ongoing work by Ermias Atomsa et al. (IPNO)

Generalized Distribution Amplitudes (GDAs)

(SL)



(TL)



The QCD factorization theorem allows us to calculate high 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

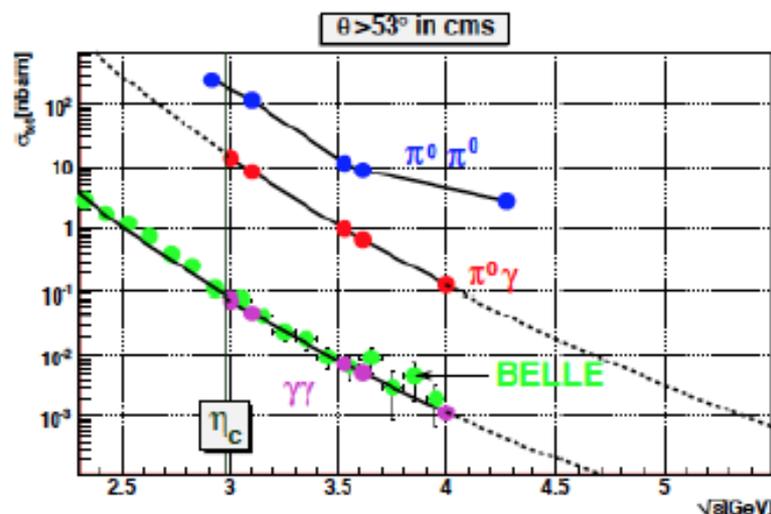
Feasibility studies for $\bar{p}p \rightarrow \gamma\gamma$ and $\bar{p}p \rightarrow \pi^0\gamma$ at PANDA

PANDARoot simulations:

- 4 different CM energies
- Main background channels:

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

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



Events left after Separation looking for $\gamma\gamma$ -events

Events left after Separation looking for $\gamma\pi^0$ -events

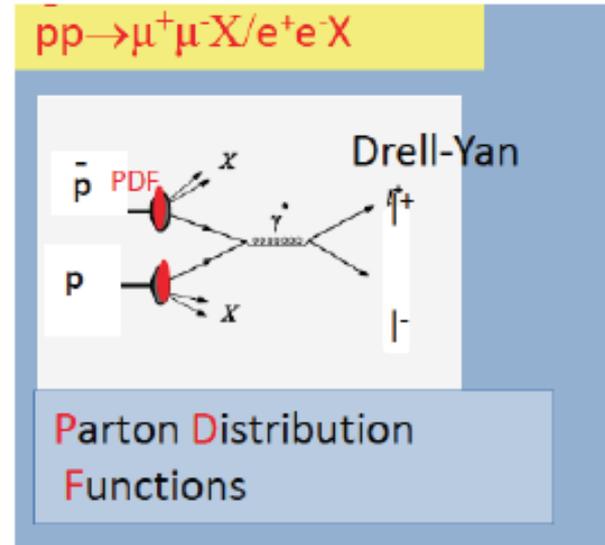
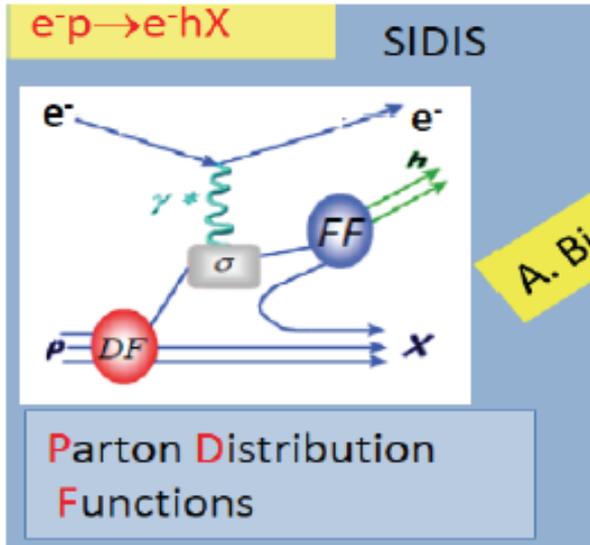
Time-like wide angle Compton scattering and hard exclusive meson production can be measured at PANDA

$S/B \sim 1$ for $\bar{p}p \rightarrow \gamma\gamma$ (25% efficiency)

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

Further studies are required for precise predictions

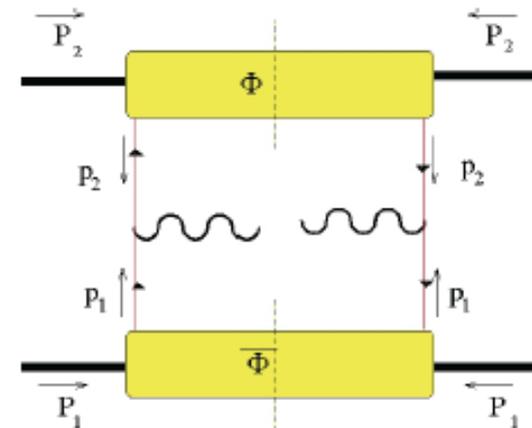
Drell-Yan Process



PDFs are convoluted with the fragmentation functions

- @ FAIR unique energy range up to $s \sim 30 \text{ GeV}^2$ with PANDA up to $s \sim 200 \text{ GeV}^2$ with PAX
- @ much higher energies \rightarrow big contribution from sea-quarks
- @ $p\bar{p}$ 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 $\sim 10^7$
- Simulations @ $s=30 \text{ GeV}^2$ and $1.5 \leq M_\gamma \leq 2.5$ (non resonance region, large cross section)
 $N_{\text{gen}}=480 \cdot 10^3$, 5 months with $L=2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ **PANDA Physics Performance Report**
[arXiv:0903.3905](https://arxiv.org/abs/0903.3905)

Acceptance, efficiency corrections, background rejection are still
Under investigation: expectation: $130 \cdot 10^3 \text{ DY/month}$

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

Torino group, Marco Maggiora

Electromagnetic processes in PANDA

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

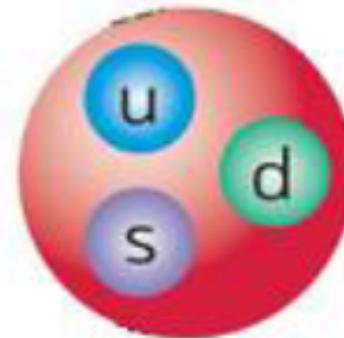
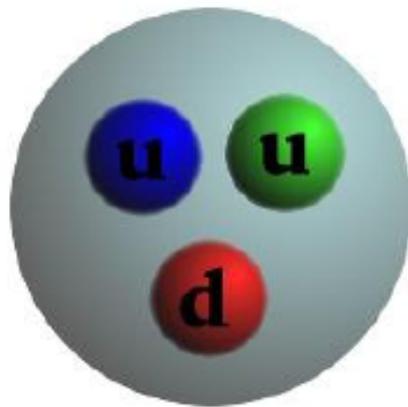
Signal	Physics	s [Gev ²]	S/B	Status
$\bar{p}p \rightarrow e^+e^-$	FFs	5.4, 8.2, 13.9	>100	Feasible
$\bar{p}p \rightarrow \mu^+\mu^-$	FFs	5.4	¼	Feasible
$\bar{p}p \rightarrow \gamma^* \pi^0$	TDAs	5.0 10.0	$5 \cdot 10^7$ ($1 \cdot 10^7$) $1 \cdot 10^8$ ($6 \cdot 10^6$)	Feasible
$\bar{p}p \rightarrow J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

III. Hyperons, Hypernuclei, In-medium effects

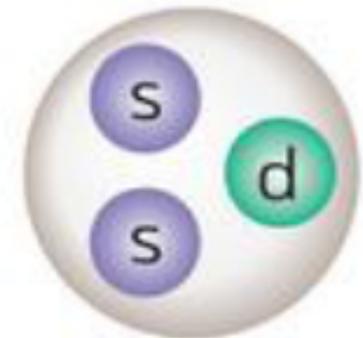
Karin Schöning (Uppsala)
Alicia Sanchez (HI Mainz)

Strange (and charmed) hyperons

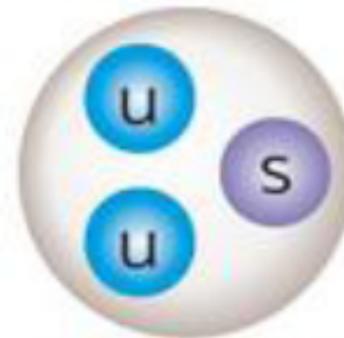
What happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)?



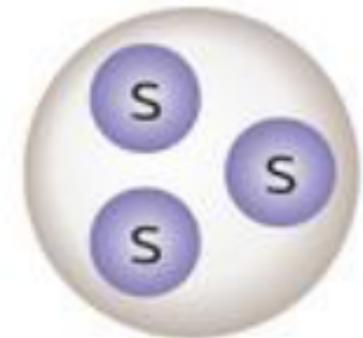
Lambda (Λ)



Xi (Ξ)



Sigma (Σ)



Omega (Ω)

Strange hyperons

Excited strange hyperon spectrum:

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

- 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

J^P	$(D, L_N^P) S$	Decuplet members			
$9/2^+$	$(56, 4_4^+)$	$1/2 N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$
$3/2^+$	$(56, 0_0^+)$	$3/2 \Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$
$3/2^+$	$(56, 0_2^+)$	$3/2 \Delta(1600)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$1/2^-$	$(70, 1_1^-)$	$1/2 \Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$3/2^-$	$(70, 1_1^-)$	$1/2 \Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$5/2^+$	$(56, 2_2^+)$	$3/2 \Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$7/2^+$	$(56, 2_2^+)$	$3/2 \Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$
$11/2^+$	$(56, 4_4^+)$	$3/2 \Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$

Baryon spectroscopy subtopics with PANDA

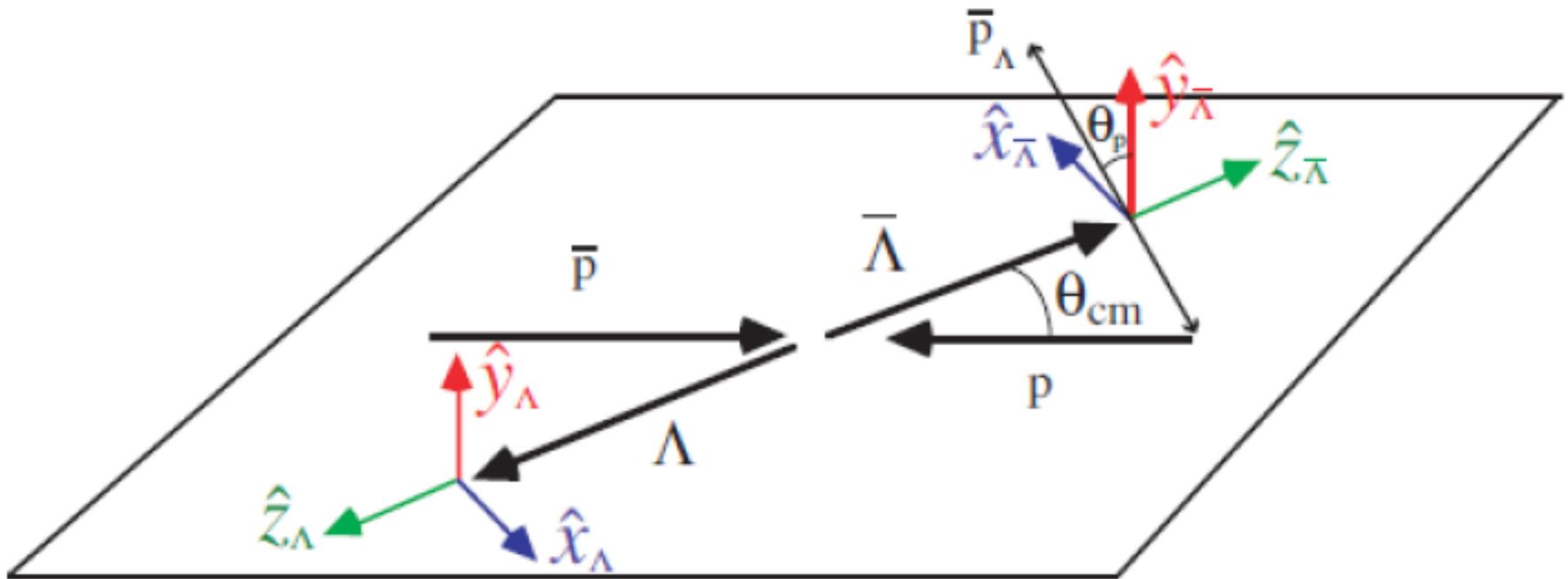
Study excited states of

**PANDA is a
strangeness factory!**

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

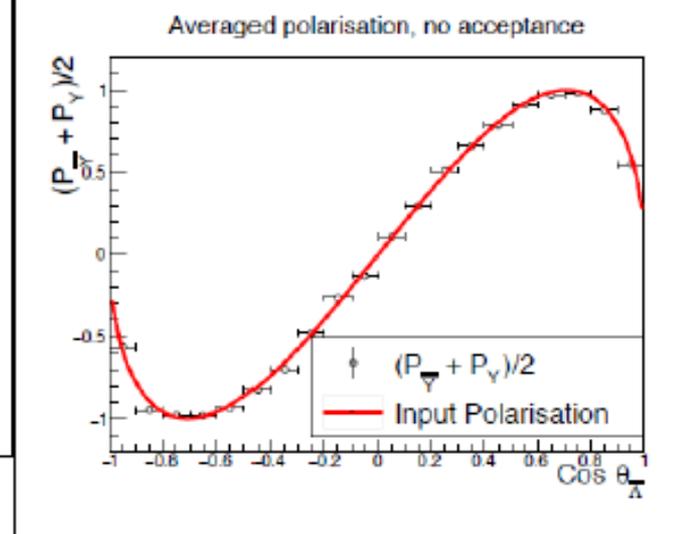
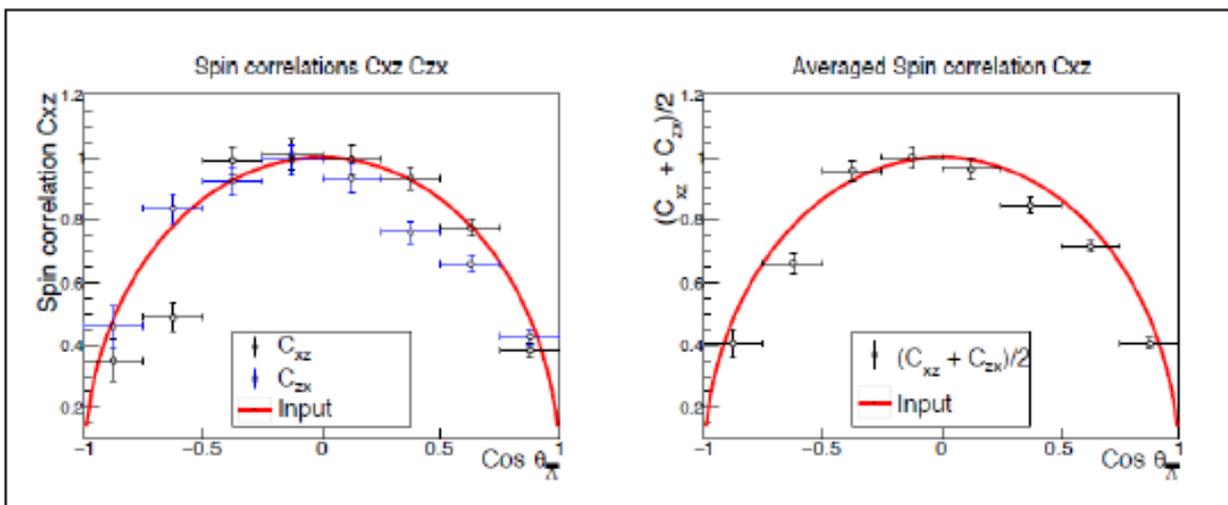
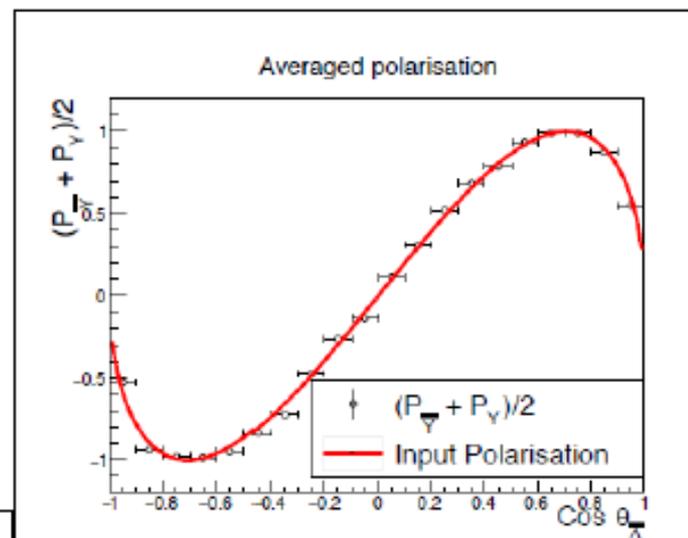
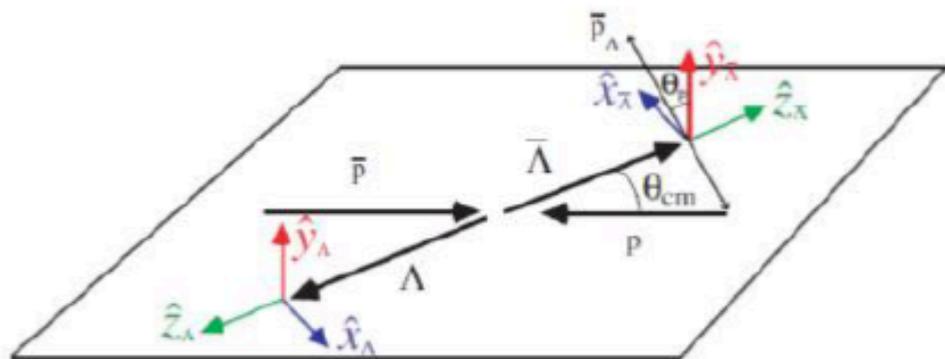
Spin observables in hyperon production

- *Vector polarisation* P the most straight-forward observable for spin $\frac{1}{2}$ hyperons.
- Strong interactions: normal to the production plane (y-direction)





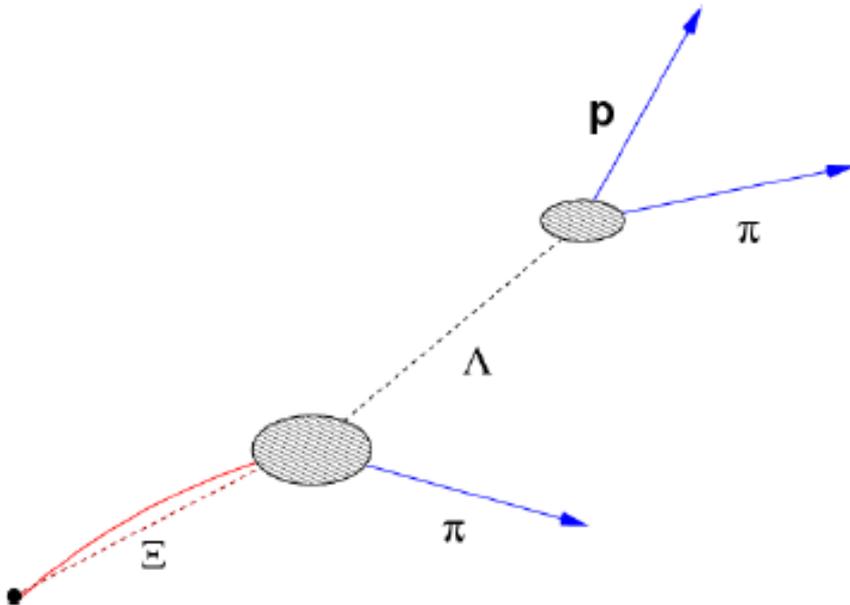
Update on hyperon spin observables



Spin observables in hyperon production

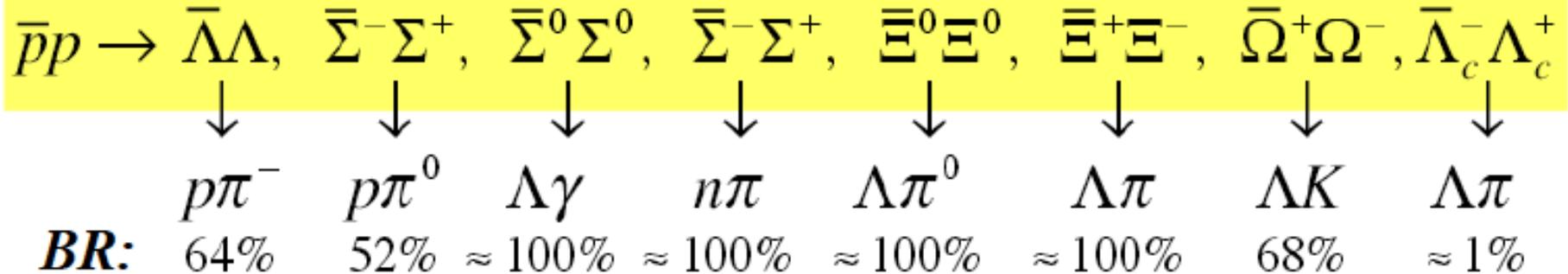
If the decay product of the hyperon is a hyperon, e.g. $\Xi \rightarrow \Lambda \pi$, then also β and γ can be obtained from the decay protons of the Λ .

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



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

Spin observables in hyperon production



- Simulation studies using a simplified MC framework (smearing and acceptance included)
- Quoted rates are valid for day one luminosity of the HESR ($10^{31} \text{ cm}^{-2} \text{ s}^{-1}$).
- Cross sections of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0$ 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 $10^{31} \text{ cm}^{-2}\text{s}^{-1}$)
1.64	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64	10	28 s^{-1}
4	$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0$	~ 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	$\sim 4 \text{ h}^{-1}$
12	$\bar{p}p \rightarrow \bar{\Lambda}_c^-\Lambda_c^+$	~ 0.1	35	$\sim 2 \text{ day}^{-1}$

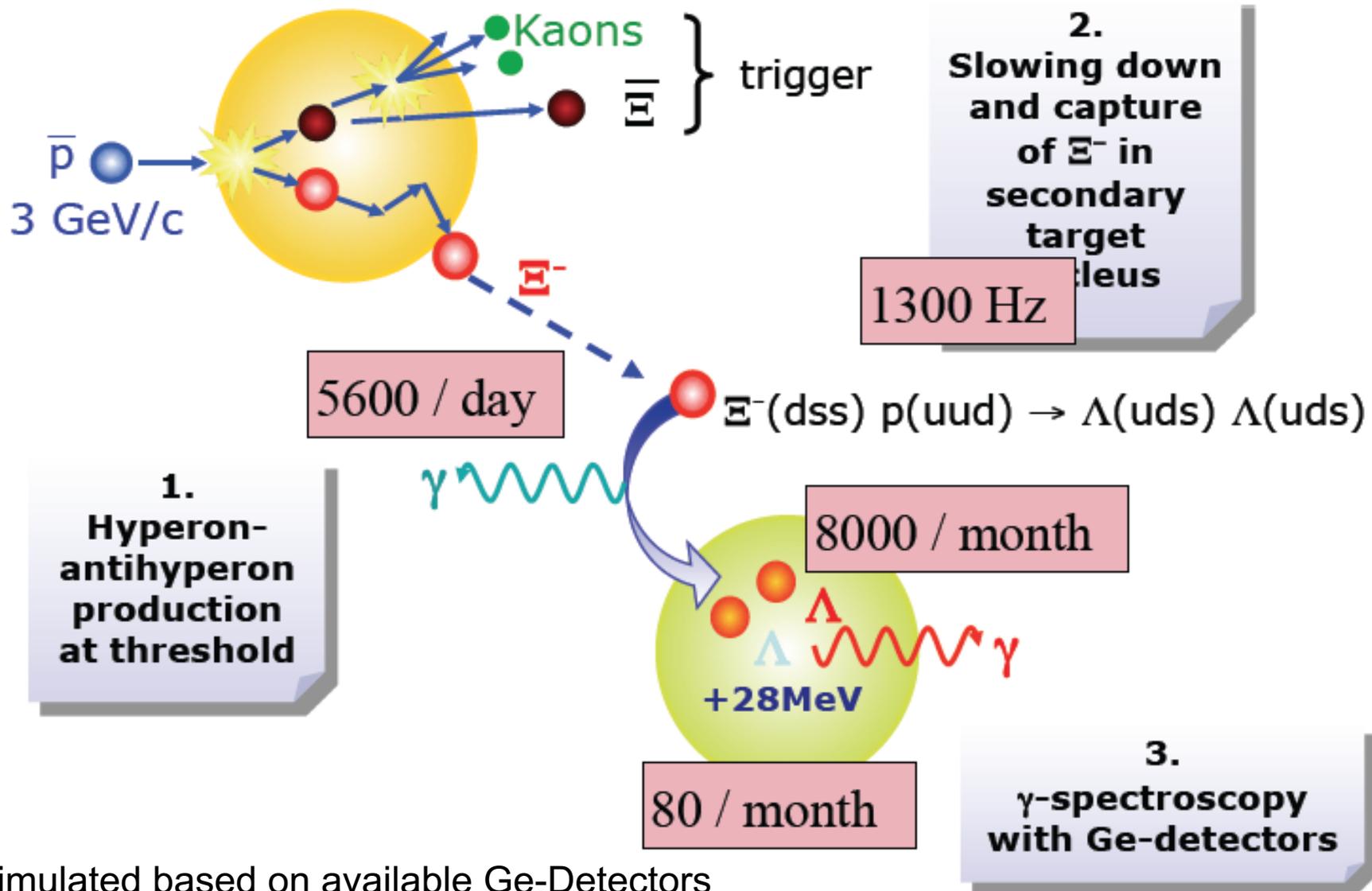
- High event rates for Λ and Σ^* .
- Low background for Λ and Σ^* .
- Ω channel feasible
- Λ_c requires high luminosity **
- New efficiencies obtained with a more sophisticated MC framework are underway.

Gain a factor of 100 with inclusive measurement

*Sophie Grape, Ph. D. Thesis, Uppsala University 2009

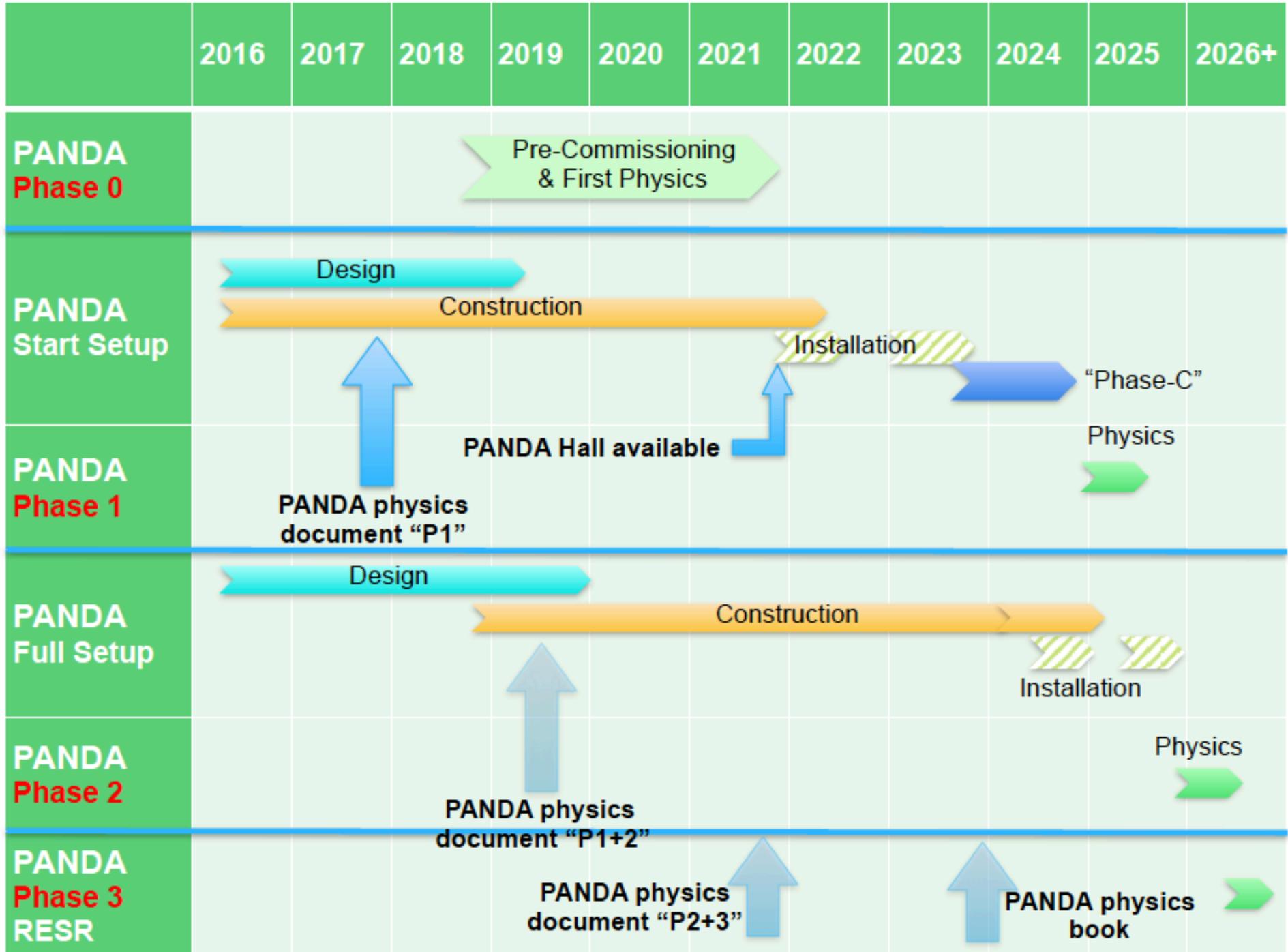
** Erik Thomé, Ph. D. Thesis, Uppsala University 2012

Production of Double Hypernuclei



Fully simulated based on available Ge-Detectors

Time Line



Physics Groups and Convenors

Johann Messchendorp/Karin Schönning: Physics coordinators

Baryons	<i>Albrecht Gillitzer (FZJ)</i>
Hyperon Dynamics	<i>Karin Schoenning (Uni Uppsala)</i>
Hypernuclear Physics	<i>Felice Iazzi (INFN-Torino)/Josef Pochodzalla (Mainz)</i>
Hadrons in nuclei	<i>Albrecht Gillitzer (FZJ)</i>
Charmonium-like exotics	<i>Frank Nerling (GSI)</i>
Charmonium	<i>Frank Nerling/Marc Pelizaeus (ad-interim)</i>
Light Meson Exotics	<i>Marc Pelizaeus (Uni Bochum)</i>
Timelike Form Factors	<i>Alaa Dbeyssi (HIM)</i>
Hard Exclusive Processes	<i>Alaa Dbeyssi (HIM)</i>
Drell-Yan	<i>Anna Skachkova (JINR-Dubna)</i>
Heavy-light Systems	<i>Johan Messchendorp (KVI-CART)</i>
Electroweak	<i>Lars Schmitt (GSI)</i>

High profile P₁ projects

1. **charm** d.o.f.

- ✓ Charmonium-like spectroscopy...
- ✓ ... X(3872) line shape and decays – *precision (?) + uniqueness*
- ✓ ... Charged Z-states spectroscopy – *uniqueness*
- ✓ ... high-spin states – *uniqueness*

2. **strangeness** d.o.f.

- ✓ Hyperon structure: spectroscopy – *uniqueness*
- ✓ Hyperon production observables: xsecs, spin, CP, ... – *precision + uniqueness*
- ✓ Hyperon/anti-Hyperon production (pbar-A) – *uniqueness*

3. **light(-quark)** systems

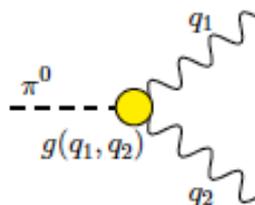
- ✓ Nucleon structure: EMFF in time-like regime
- ✓ Form factors in unphysical regime via π^0 production – *uniqueness*
- ✓ Light-meson spectroscopy: glueballs, etc.. – *precision*

PANDA Phase 0

Primakoff π^0 electroproduction

Interesting parameter:

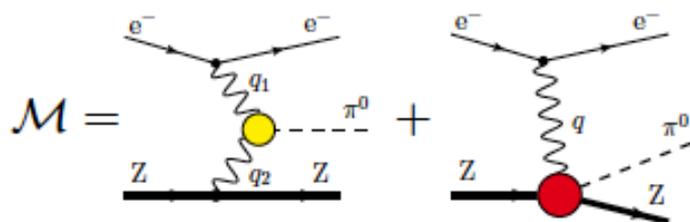
- ▶ $\pi^0\gamma\gamma$ effective coupling



$$\mathcal{L}_{\pi^0\gamma\gamma} = g(q_1^2, q_2^2) \pi^0 \epsilon_{\mu\nu\kappa\lambda} F^{\mu\nu} F^{\kappa\lambda}$$

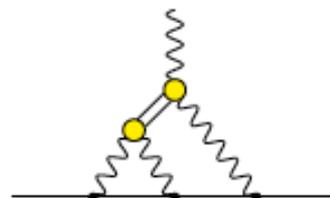
$$\left(\Rightarrow \Gamma_{\pi^0\gamma\gamma} = \frac{g^2 m_\pi^3}{\pi} \right)$$

Cross section contributions



Motivation:

- ▶ hadronic correction to $g - 2$ of the muon (light by light scattering)



- ▶ constraints on g for $q_{1,2}^2 \neq 0$ needed

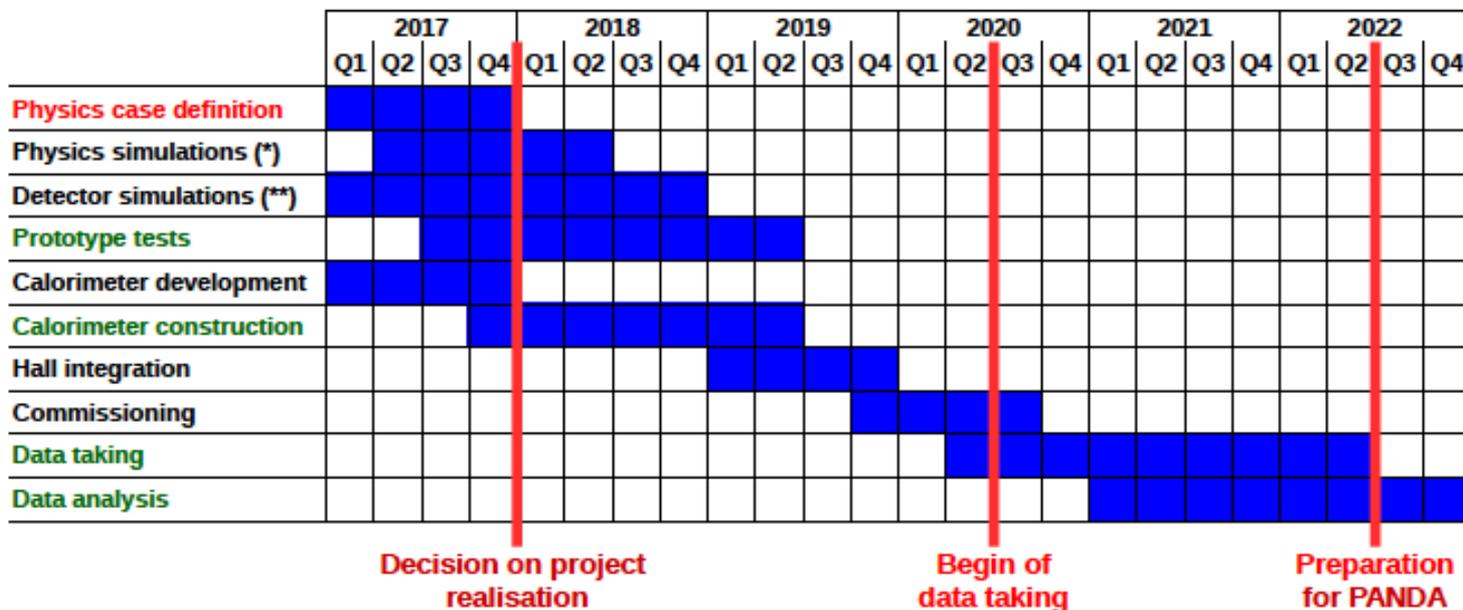
- ▶ estimation of g from π^0 decay constant

$$g(q_1^2, q_2^2) \simeq g(0, 0) \simeq 3.17 \cdot 10^{-6} \text{MeV}^{-1}$$

- ▶ “strong” π^0 prod. background to be estimated
- ▶ effect enhanced for $q_2^2 \rightarrow 0$

Current time line

Phase 0: at MAMI

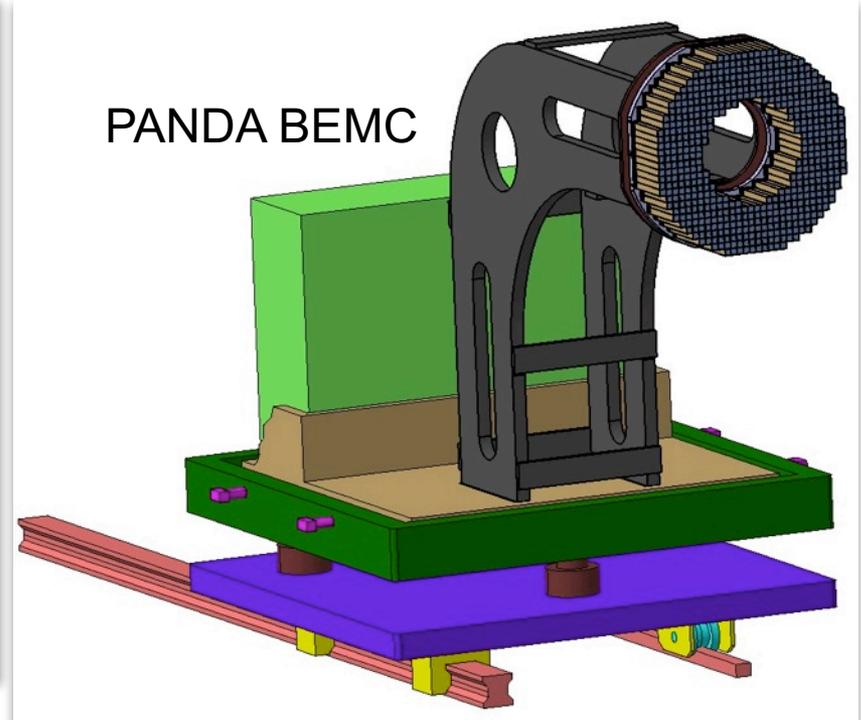
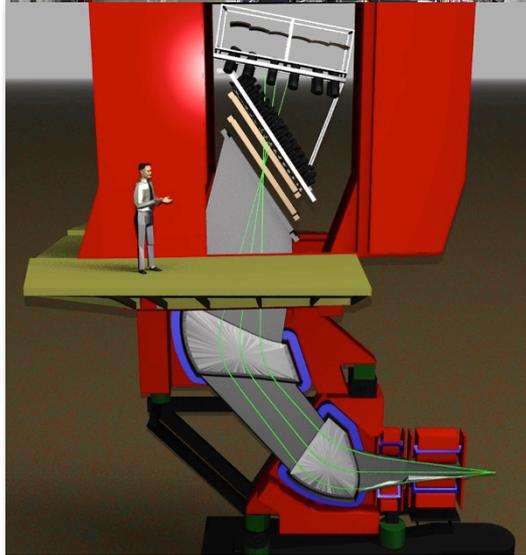


- ▶ Development of backward EMC continuing at normal pace
- ▶ Not all resources redirected to phase0
- ▶ Hardware development mostly overlaps with the phase0 project
- ▶ Physics programme definition requires a reasonable time
- ▶ Beam tests will also be decisive for the feasibility
- ▶ Decision on project realisation probably during the first months of 2018

Phase 0: BEMC@MAMI



A1-3 Spectrometer Setup



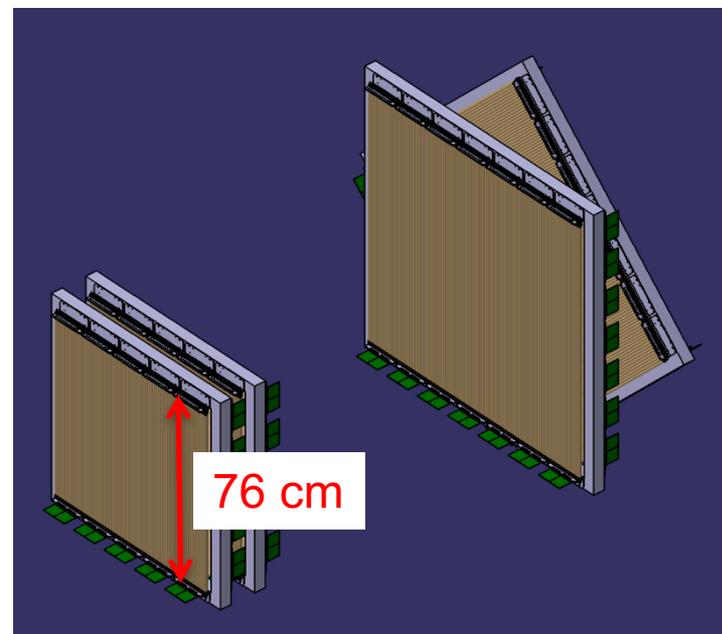
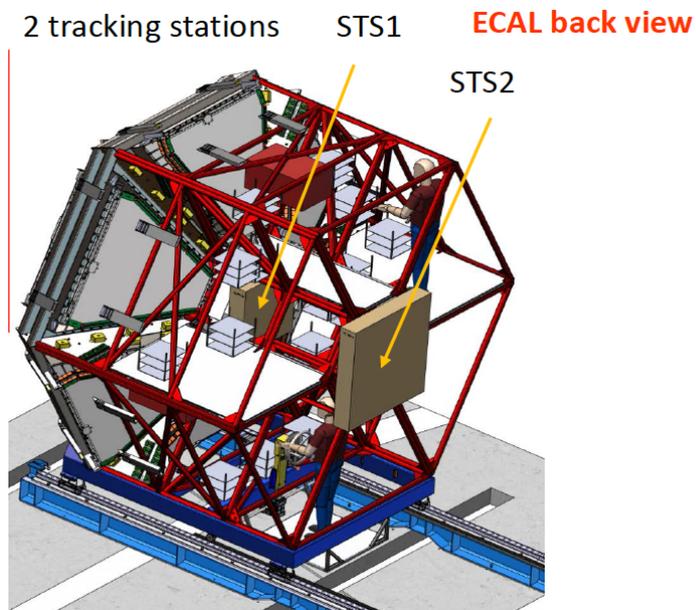
PANDA BEMC

- A1: 3 Magnetic Spectrometer setup
- Momentum Resolution: $\Delta p/p < 10^{-4}$ in each spectrometer
- Coincident detection of three charged particles.
- MAMI: 180 MeV – 1.6 GeV electron accelerator

PANDA Phase 0 Experiments with HADES *Detectors*

PANDA pre-series and prototype detectors for STS1/2

- **HADES** measures the dileptons & mesons
- **PANDA** Straw Trackers for the baryon ($\Theta < 7^\circ$)



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

- 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

Key-Experiments of the phase 1

Concentration on unique and forefront physics topics

- Precise measurement of the **line shape of narrow XYZ-states**, e.g. X(3872)
(only possible in proton–antiproton, counting experiment, clarification of the nature of the states)
- Resonant formation of the **negative and uncharged partners of the Z-States**
(only possible in proton–antiproton, clarification of the nature of the states)
- (Parasitic) production of **multi-strangeness baryons**
(unexplored, new territory, „Strangeness-Factory“)
- Parasitic production of **high spin charmonia** (only possible in proton–antiproton)
light mesons, baryons and production of hybrids und glueballs
- Measurement of **the electromagnetic form factors of the proton** in the time-like domain with **electrons and muons** in the final state

XYZ-, hyperon factory