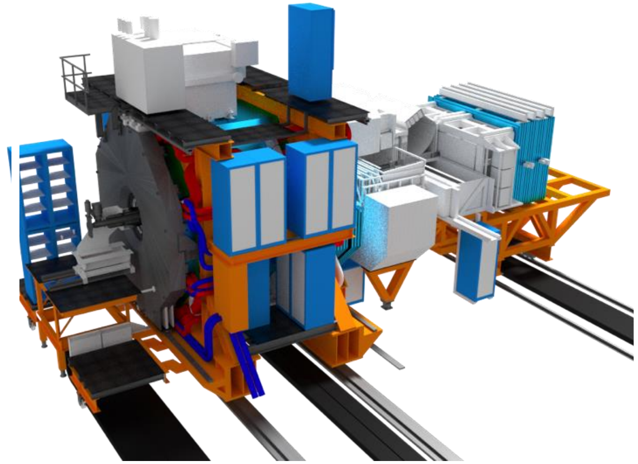


Initial Measurements of Hadron Spectroscopy and Nucleon Structure with Antiprotons by PANDA

COMPASS Beyond 2020 Workshop

J. Ritman Forschungszentrum Juelich

Outline

- Overview of PANDA Physics Program
- Nucleon Structure Measurements
  examples: Time-like nucleon FF, TDAs
- Hadron Spectroscopy
  → X,Y, Z States, Hyperons, Open Charm
- Status of Detector systems
- Summary

PANDA Objectives

HEP: interference of coupled channels

HEP: underlying elementary processes

Spectroscopy

New narrow XYZ: Search for partner states

Production of exotic QCD states: Glueballs & hybrids

Bound States of Strong Interaction

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

Strangeness

Strange baryons: Spectroscopy Polarisation

Astro physics: Strange n-stars

Nuclear physics: Hypernuclear spectroscopy

Nuclear Physics

Hypernuclear physics: Double Λ hypernuclei Hyperon interaction

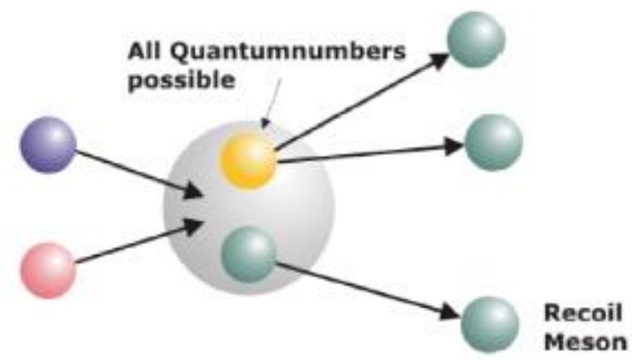
Hadrons in nuclei: Charm and strangeness in the medium

HI collisions comparing QGP to elementary reactions

Antiproton Annihilations: Gluon Rich Environment

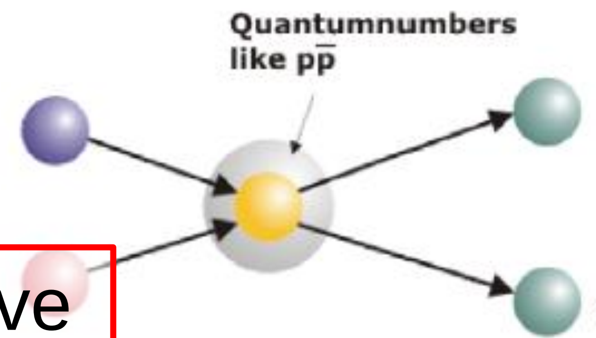
Production: all states with exotic and non-exotic quantum numbers accessible with a recoil
- high discovery potential

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 and decisive

PANDA: Comparison with other Techniques

- e^+e^- (BaBar, BES-III, CLEO-C, Belle II)
  - direct formation limited to $J^{PC}=1^{--}$
  - sub-MeV for masses and widths close to impossible
  - high L not accessible

- high-energy (several TeV) hadroproduction (LHC)
  - high combinatorial background: discovery very difficult
  - Width measurements limited by detector resolution

- B-decays (both for e^+e^- and hadroproduction)
  - limited J^{PC}
  - C cannot be determined (not conserved in weak decay)

Key-Experiments of the Start Phase

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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

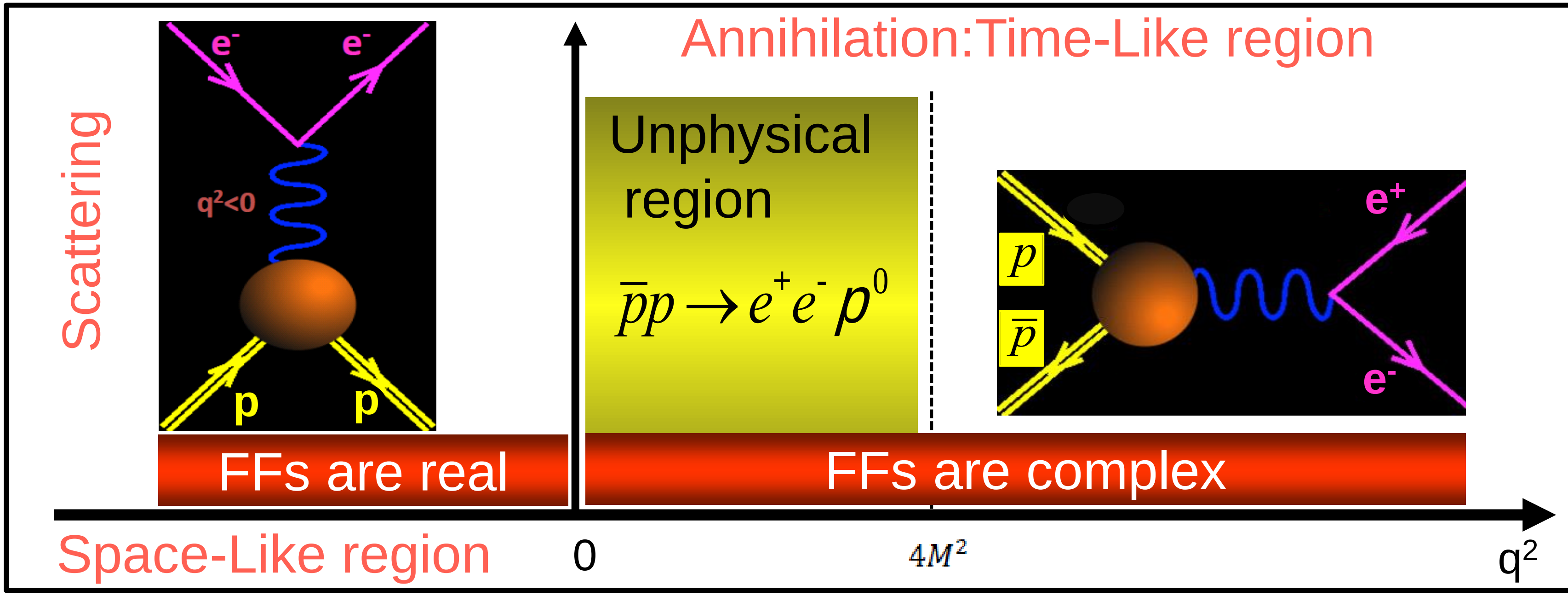
- Measurement of the electromagnetic form factors of the proton in the time-like domain with muons in the final state

XYZ-, hyperon factory

Proton Electromagnetic Form Factors

Jim Ritman

Electromagnetic Form Factors: the Analyticity



At the threshold: $G_E(4M^2)=G_M(4M^2)$ (only s-wave)

Point-like proton: $G_E(4M^2)=G_M(4M^2)=1$

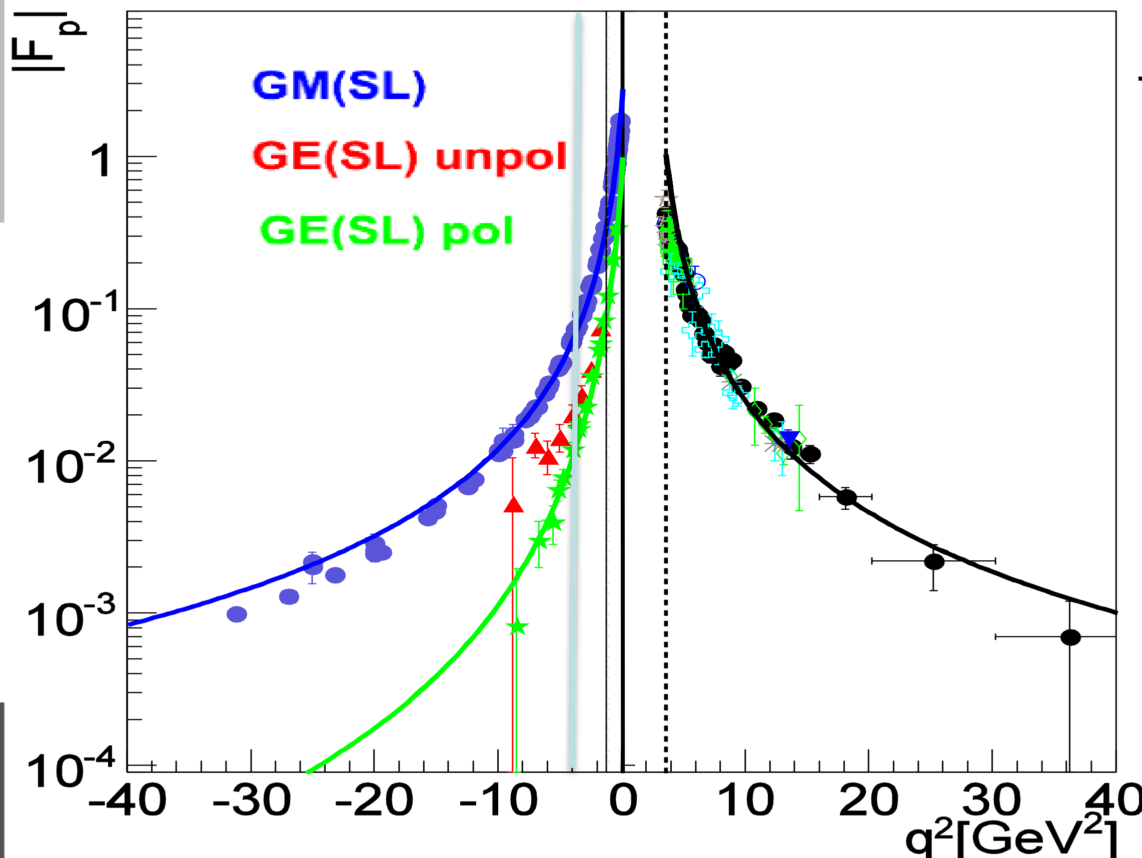
Unified frame for the description of FFs:

$$G(q^2)=\frac{1}{\pi}\left[\int_{4m_\pi^2}^{4m_p^2}\frac{\mathrm{Im}\,G(s)ds}{s-q^2}+\int_{4m_p^2}^{\infty}\frac{\mathrm{Im}\,G(s)ds}{s-q^2}\right]$$

$$\lim_{q^2\to-\infty}G^{SL}_{E,M}(q^2)=\lim_{q^2\to+\infty}G^{TL}_{E,M}(q^2)$$

The measurement of the Form Factors at large q^2 and in all the kinematical region: test of the analytical nature of the FFs

Data on Proton Electromagnetic Form Factors



The Experimental Status (TL)

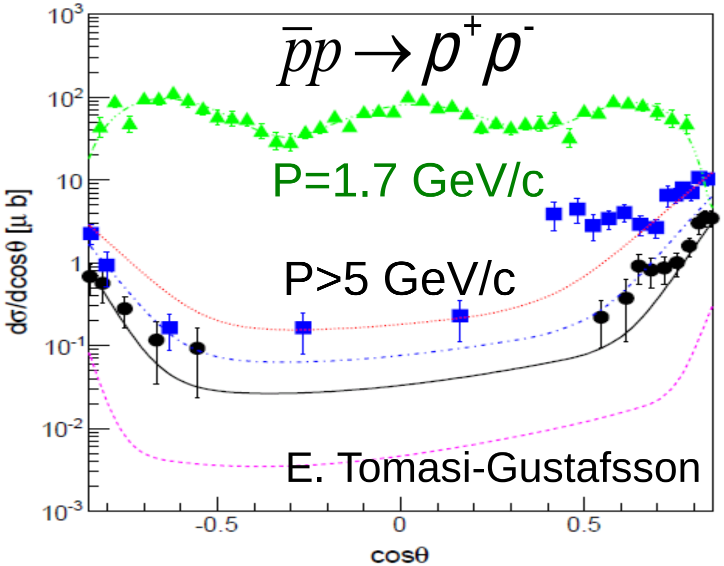
- No individual determination of G_E and G_M
- TL proton FFs twice larger than in SL at the same Q^2
- Steep behaviour at threshold
- Babar:Structures? Resonances?

S. Pacetti et al., Physics Reports, 514 (2014) 1

QCD based model is not able to reproduce the polarized SL data
VMD model is not able to reproduce the TL data at large momenta

Feasibility Studies for $\bar{p}p \rightarrow e^+e^-$ at PANDA

- Main issue: signal identification from the huge hadronic background



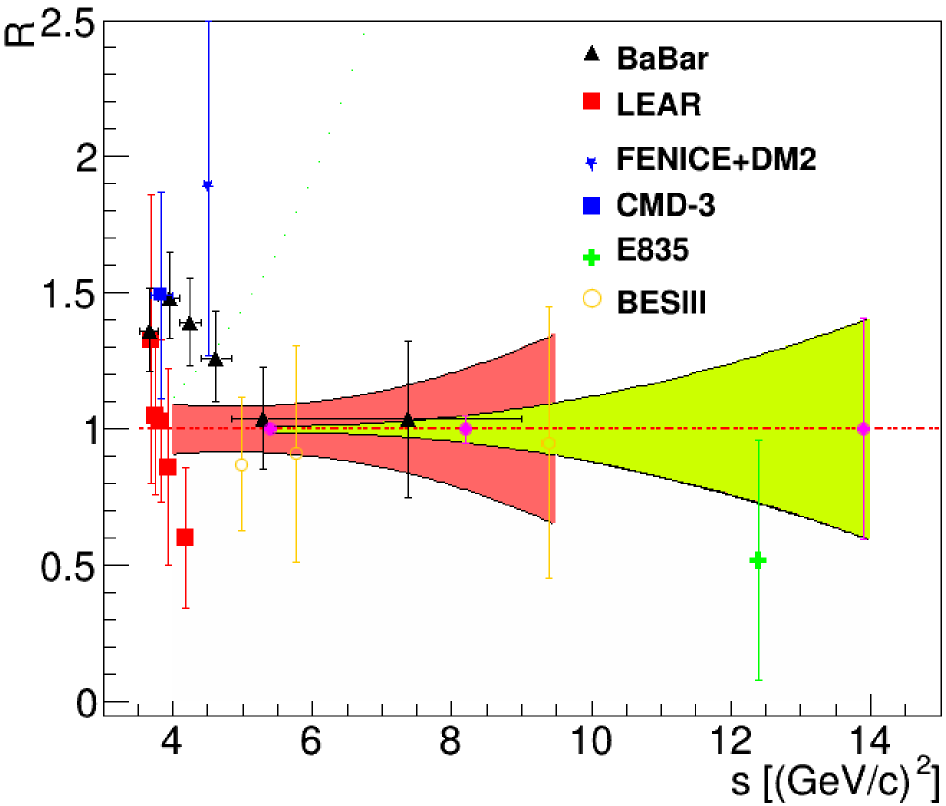
Reaction mechanism changes with the energy and the angle:

- **Low energy**: Legendre polynomials
- **High energy**: Regge inspired parametrization

$$\frac{s(p^+p^-)}{s(e^+e^-)} @ [10^5 - 10^6]$$

A background rejection at the order of 10^{-8} is achieved

Expected Reach: Full Luminosity



21 scan points 2015 (552 pb^{-1})

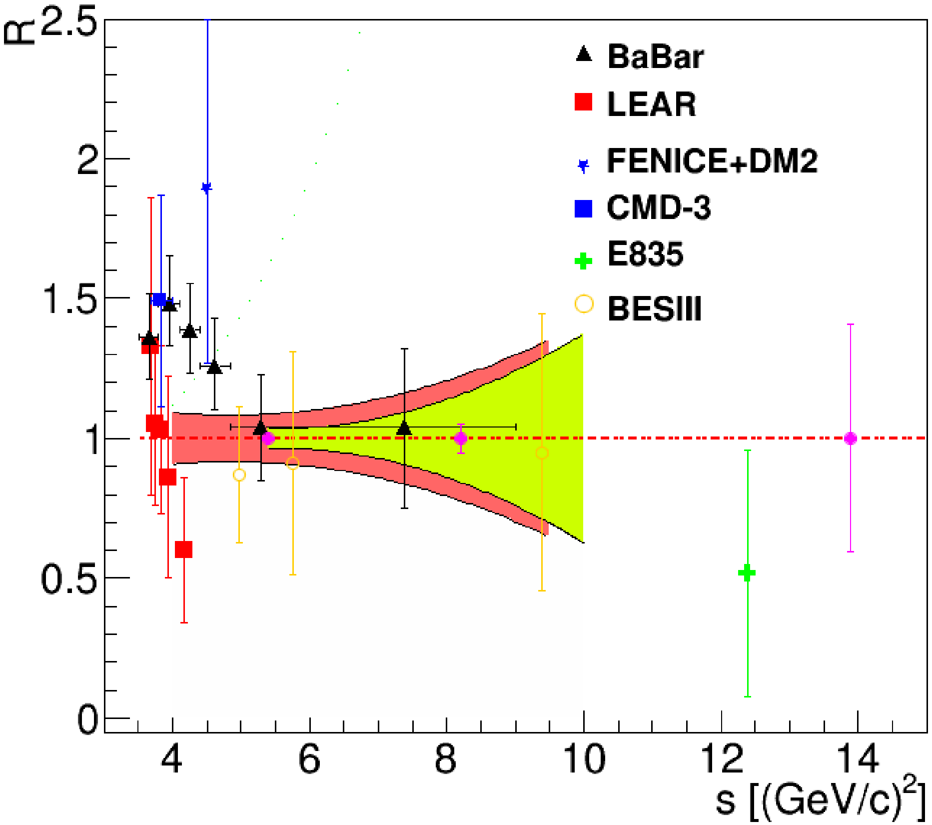
Monte Carlo Sim., R=1 (C. Morales)

L=2 fb^{-1}
$2x10^{32}$ cm^{-1} s^{-1}

~5 months data taking /point

	BESIII	PANDA (e^+e^-)	PANDA (mu^+mu^-)
s [(GeV/c)^2]	4 - 9.5	5 - 14	5 - ~9
$R=\|G_E\|/\|G_M\|$	9 % - 35 %	1.4 % - 41 %	5 % - 18.7 %

Expected Reach: Starting Luminosity



BESIII

21 scan points 2015 (552 pb^{-1})

Monte Carlo Sim., R=1 (C. Morales)

panda

L=0.2 fb^{-1}

2×10^{31} cm^{-1} s^{-1}

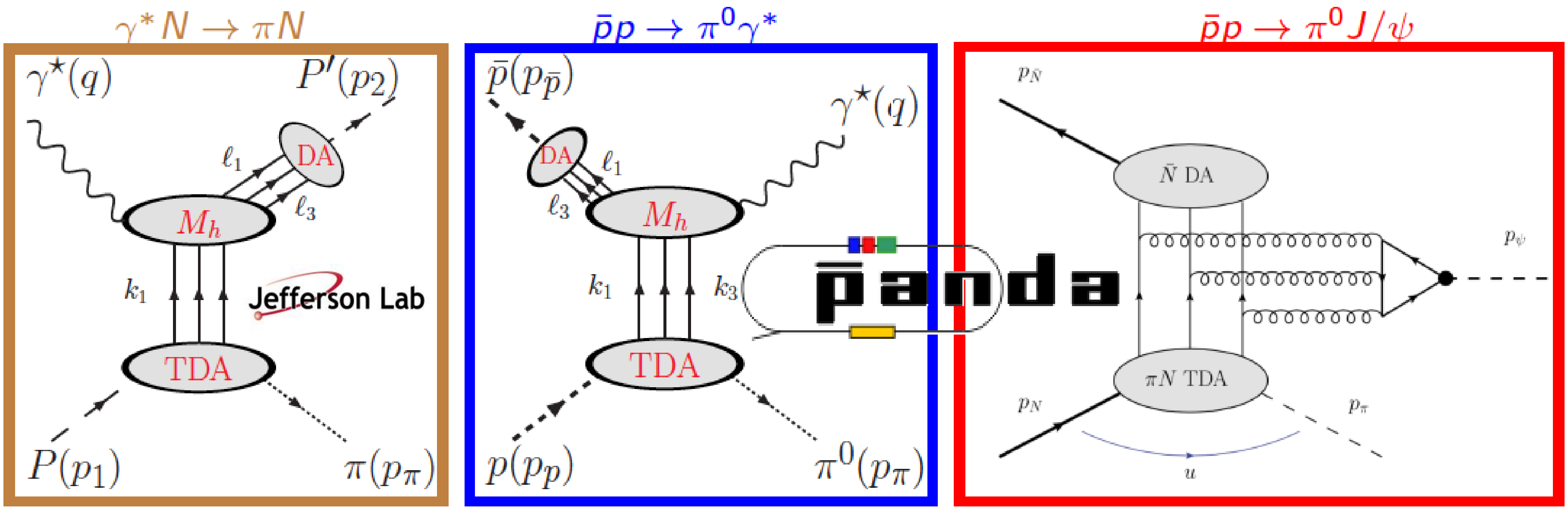
~5 months data taking /point

	BESIII	PANDA (e^+e^-)	PANDA (mu^+mu^-)
s [(GeV/c)^2]	4 - 9.5	5 - ~10	@ 5.4
$R=\|G_E\|/\|G_M\|$	9 % - 35 %	3.5 % - 38 %	13.3 %

Study for a polarized target → 1st measurement of the relative phase G_E/G_M

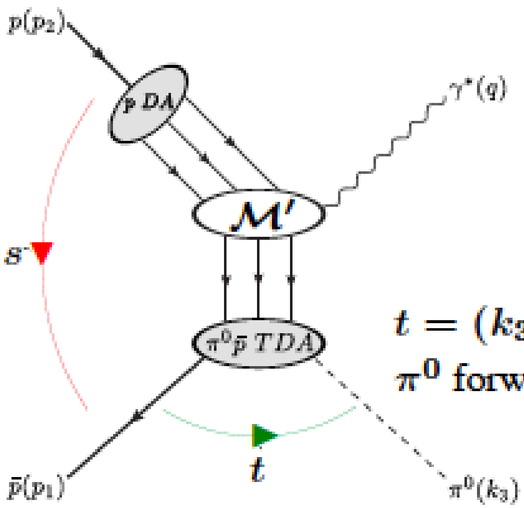
Transition Distribution Amplitudes

Nucleon to meson TDAs



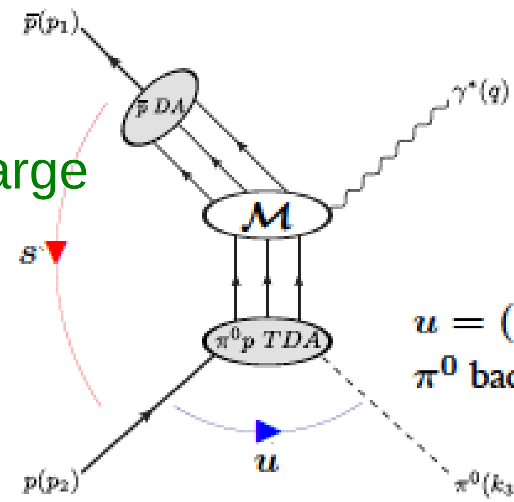
- Occur in collinear factorization description of various hard exclusive processes
- Parameterized as a function of momentum fraction (x_i), skewness (ξ) and momentum transfer squared (t,u)
- Independent of reaction type, s and q^2
- Give information on pionic components of the nucleon wave-function

TDAs with the $\bar{p}p \to \gamma^* \pi^0 \to e^+e^- \pi^0$ channel



$t = (k_3 - p_1)^2$
π^0 forward

Hard scale: q^2 is large



$u = (k_3 - p_2)^2$
π^0 backward

t is small (forward kinematics, pi-N TDAs)

u is small (backward, pi-Nbar TDAs

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

Luminosity= 2 fb^{-1}

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

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

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

s = 5 GeV^2: 5 $x10^7$ (1 $x10^7$)
s = 10 GeV^2: 1 $x10^8$ (6 $x10^6$)

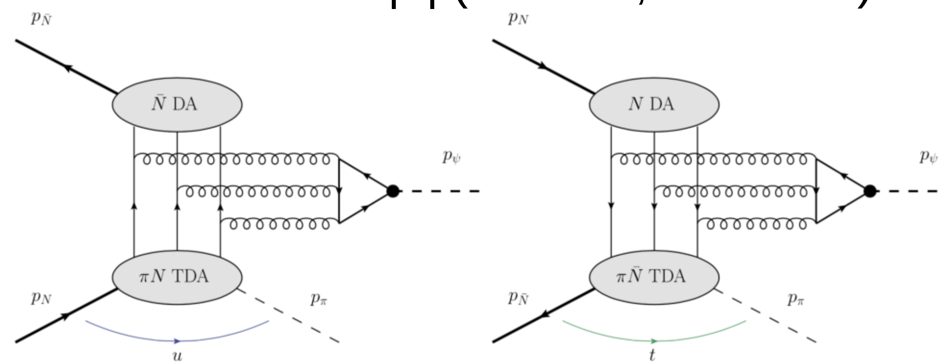
$\Delta s / s \sim 12\%$
$\Delta s / s \sim 24\%$

Published in
Eur.Phys.J. A51 (2015) 8, 107

Accessing TDAs in the $\bar{p}p \rightarrow J/yp^0 - > e^+e^- p^0$ Channel

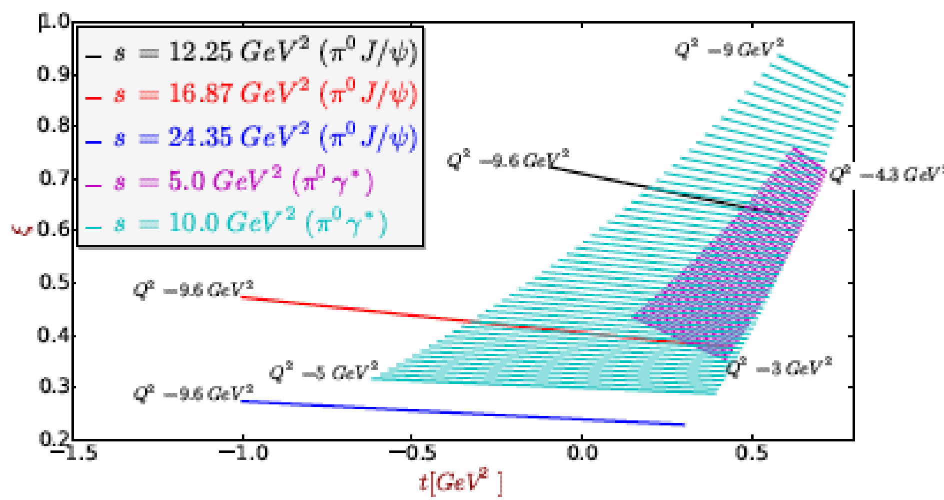
- **Test of universality of TDAs**
  - Validate independence on reaction type, Q^2 and s
  - Complementary to $\pi^0\gamma^*$
  - Different phase-space coverage in skewness (ξ) vs momentum transfer (t) space

- **Two validity regimes**
  - Small |t| (Fwd. π^0, πNbar TDAs)
  - Small |u| (Bwd. π^0, πN TDAs)



- **Additional Items being discussed**
  - Other potential background sources
    - $\pi^0\pi^0\pi^+\pi^-$, $\pi^0\pi^+\pi^-\pi^+\pi^-$
    - $\pi^0\pi^0 J/\psi$
  - 4C kinematic fitting
    - Signal hypothesis
    - $\pi^0\pi^0 J/\psi$ bkg hypothesis
  - Signal purity
  - MSV luminosity

Phase space coverage for $\pi^0\gamma*$ and $\pi^0 J/\psi$



Efficiency, Purity, Precision for $\pi^0 J/\psi \rightarrow \gamma\gamma e^+e^-$

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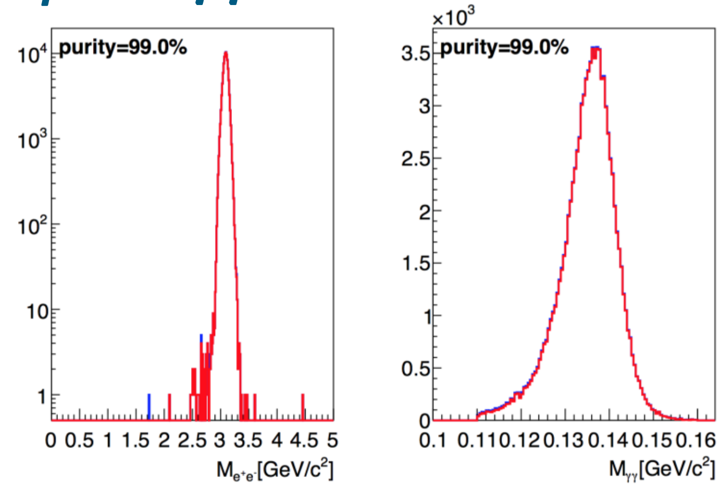
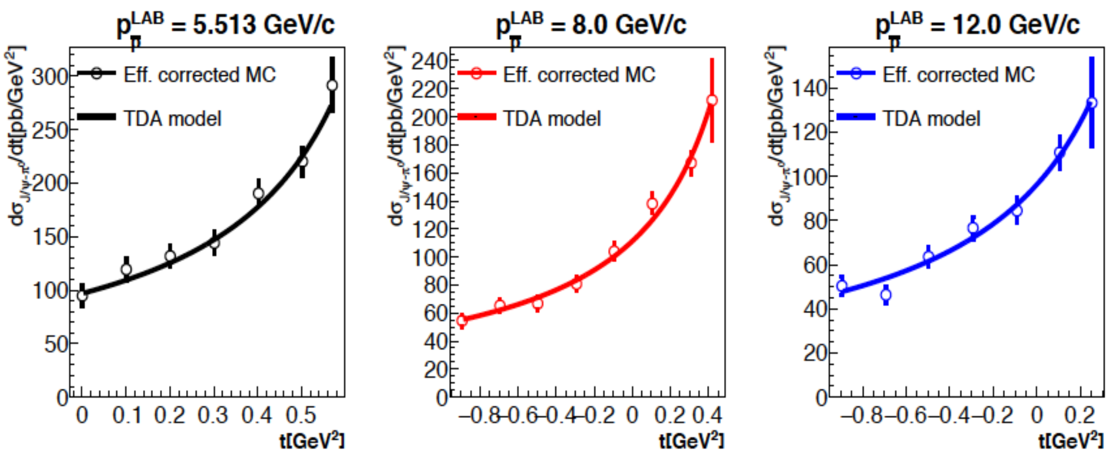
- New set of cuts including kinematic fit implemented:
  - Background contamination <~ 1% attained for all sources
  - Signal efficiency sufficient to attain 5-10% relative uncertainty with full setup ($2 fb^{-1}$, 5 months)





- MSV setup (4 months)
  - Statistics will be too low even for single differential cross-section measurement, but useful for
    - Checking order of magnitude of cross-sections
    - Constraining pionic background sources with cross-sections in the mb range

Many More Measurements Have Been Studied

Signal	Physics	s [Gev²]	S/B	Status
$\bar{p}p \to e^+e^-$	FFs	5.4, 8.2, 13.9	>100	Feasibile
$\bar{p}p \to \mu^+\mu^-$	FFs	5.4	¼	Feasibile
$\bar{p}p \to \gamma^*\pi^0$	TDAs	5.0 10.0	5 x 10^7 (1 x10^7) 1 x10^8 (6 x10^6)	Feasibile
$\bar{p}p \to J/\psi\pi^0$	TDAs	P=5.513 P=8.0 P=12.0	>8 >70 >600	Feasibile
$\bar{p}p \to \gamma\gamma$ $\bar{p}p \to \pi^0\gamma$	GDAs	2.5, 3.5, 4.0, 5.5	1 2	Feasibile
$\bar{p}p \to \mu^+\mu^- X$	TMD PDFs	30	in progress	Feasibile

Hadron Spectroscopy

Jim Ritman

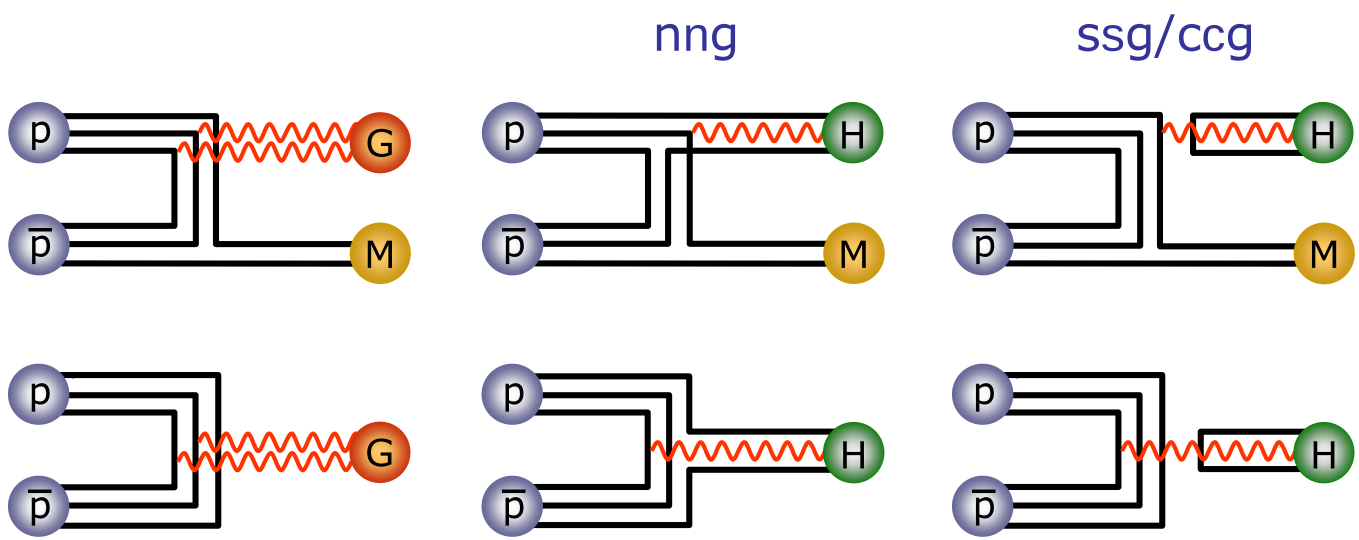
Exotic Hadrons I: Hybrids and Glueballs

Production

all J^{PC} available

Formation

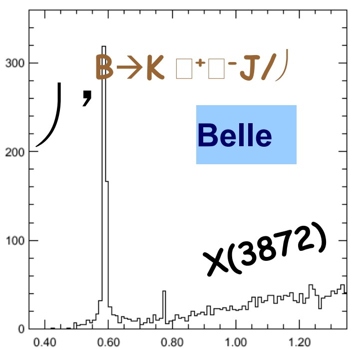
only selected J^{PC}



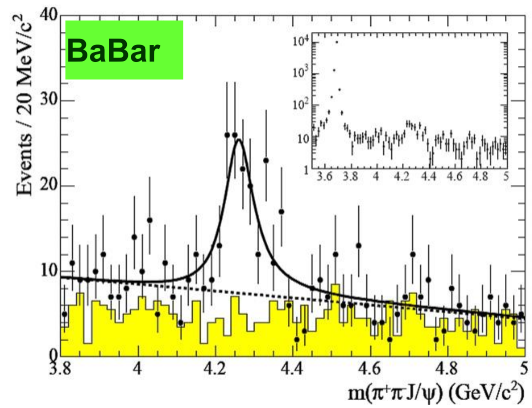
- Sound theoretical predictions from models and LQCD
- Gluon rich process creates gluonic excitation in a direct way
- Access to both exotic and non-exotic quantum numbers
- Highest precision for direct formation
- Access to both light and charm energy range
- UNIQUE to PANDA

Exotic Hadrons II: X, Y, Z

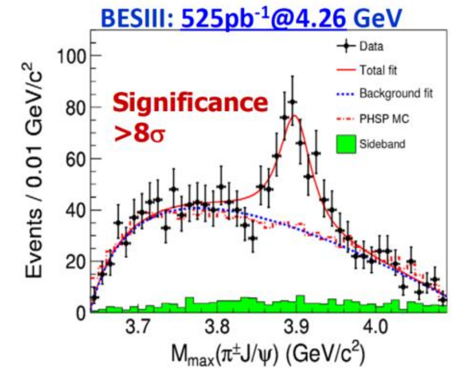
X(3872)



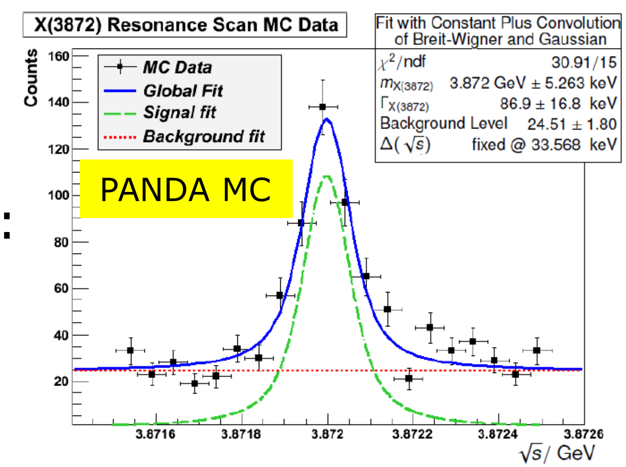
Y(4260)



Zc(3900) at BESIII



Need systematic approach with the capability to carry out high-precision measurements to map out completely the spectrum of these news states, in order to understand their nature: **PANDA will be unique in achieving this**.



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

PANDA is an X Y Z factory (reco)

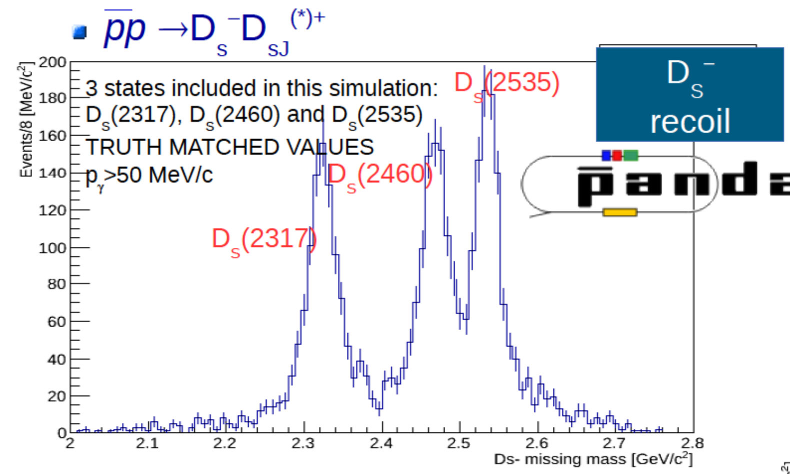
350 X(3872)/day — widths

820 Y(4260)/day — rare decays

176 Z(3900)/day — neutral partner

Open Charm

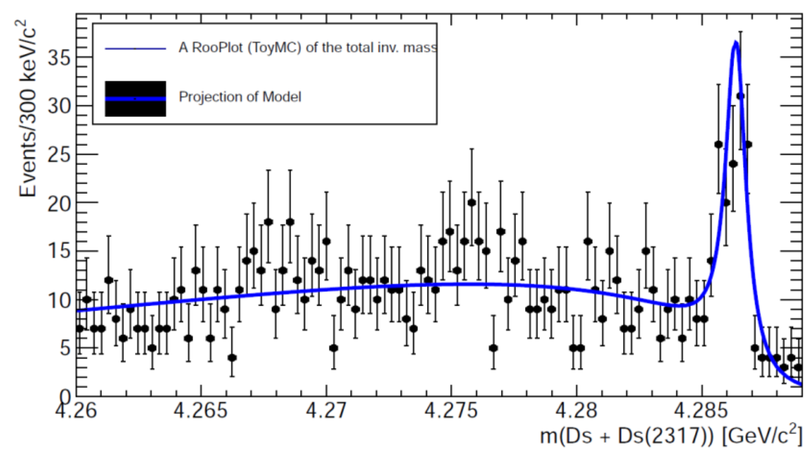
- QCD laboratory
- Intermediate case between heavy and light quarks
- Interesting spectroscopy
- Weak interactions



Unique features at PANDA:

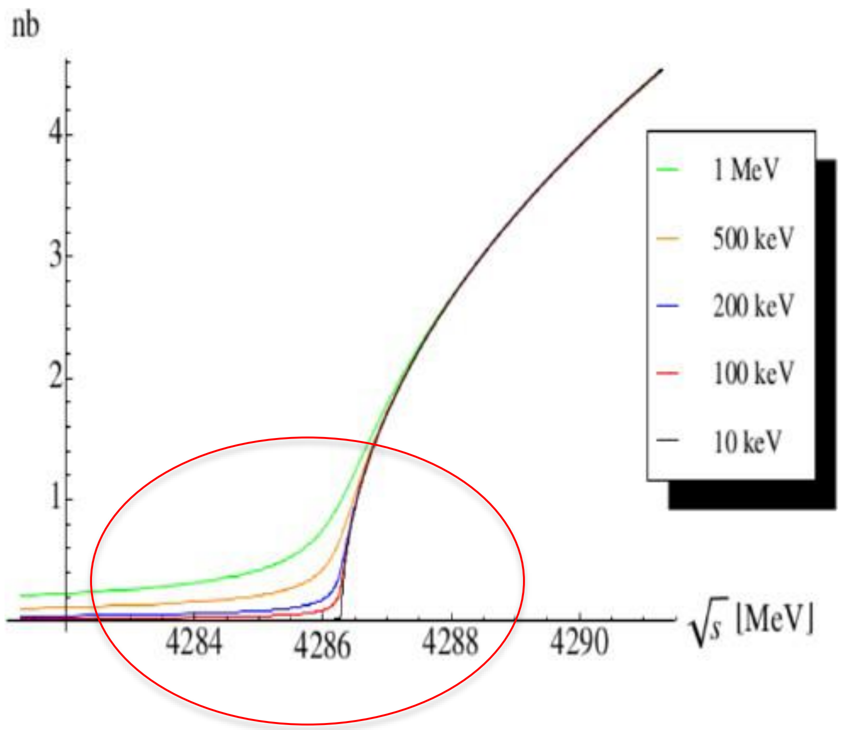
- width measurement of $D_{sJ}(2317)$ (30-100 keV) (threshold scan)
- Access to high L (available in pp, suppressed in B decays)

Simulation:
1 week data, S/B 0.2 eff ~ 3%

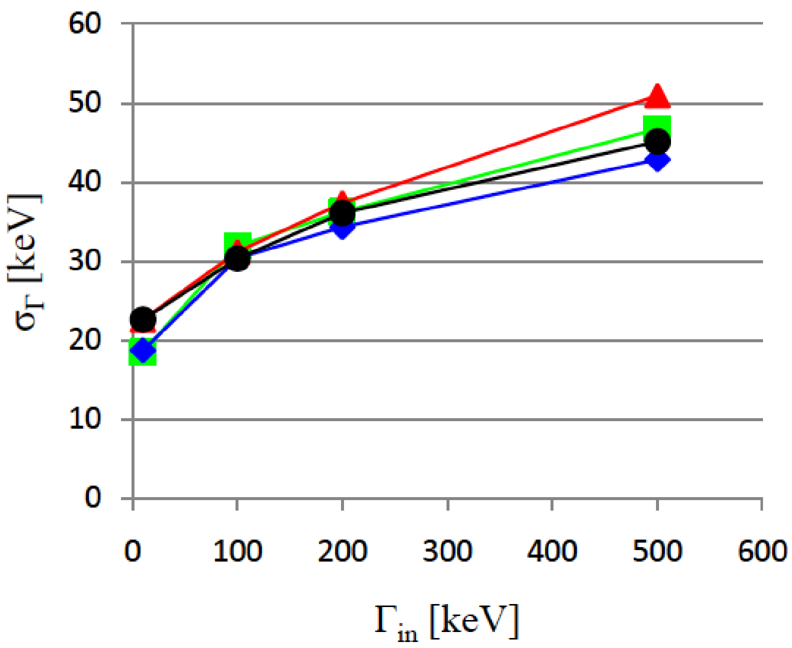


Threshold Scans of e.g. Open Charm

Width strongly effects rates near threshold

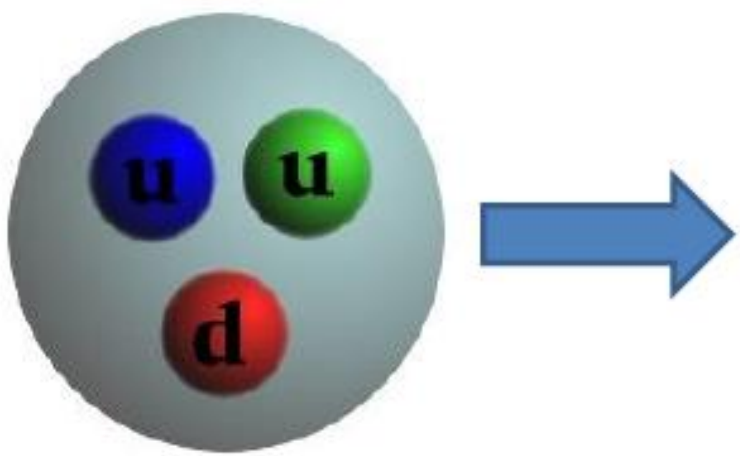


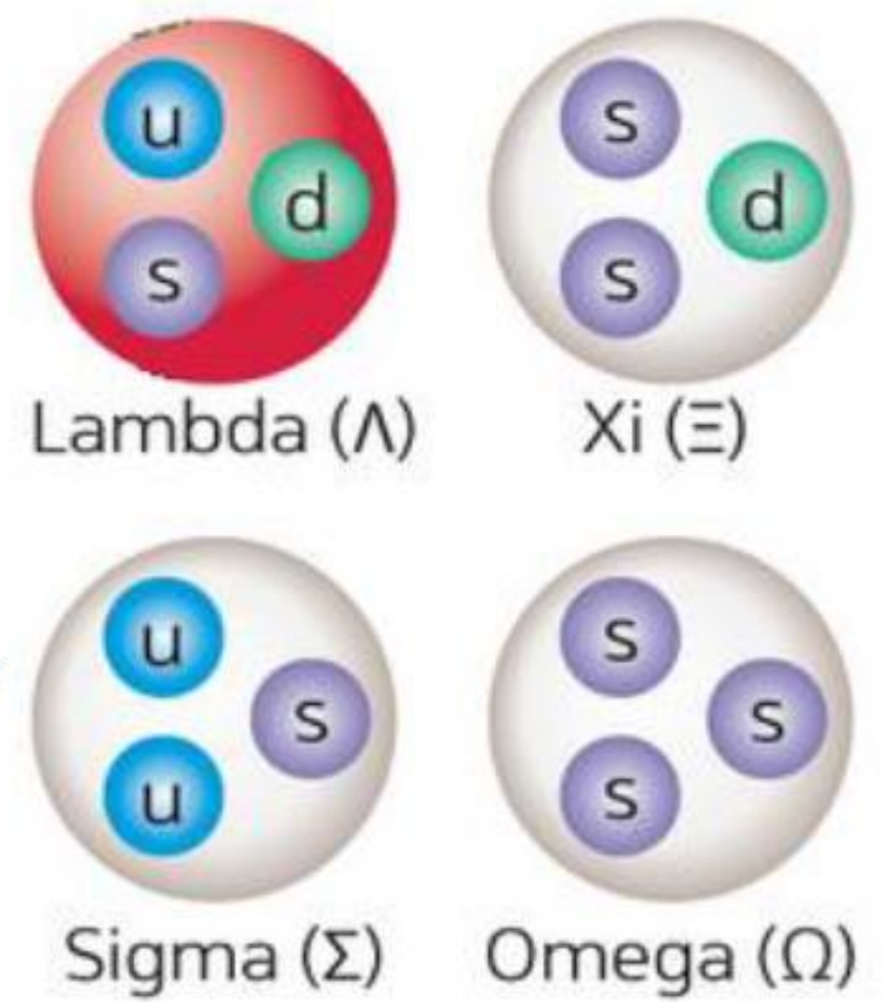
Resolution ~ 50 keV



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 and Charmed Baryons

- Light quark (*u*, *d*) systems:
  - Highly non-perturbative interactions.
  - Relevant degrees of freedom are hadrons.
- Systems with strangeness
  - Scale: $m_s \approx 100$ MeV ~ $\Lambda_{QCD} \approx 200$ MeV.
  - Relevant degrees of freedom?
  - **Probes QCD in the intermediate domain.**
- Systems with charm
  - Scale: $m_c \approx 1300$ MeV.
  - Quark and gluon degrees of freedom more relevant.
  - **By comparing strange and charmed hyperons we learn about QCD at two different energy scales.**

Baryon Spectroscopy

- New baryon states ?
- Properties of already known states.
- Symmetries in observed spectrum.

Baryons in PANDA

- Large cross section s for $\bar{p}p \rightarrow \bar{Y}Y$
  - $\bar{p}p \rightarrow \Xi\bar{\Xi} \approx \mu b$
  - $\bar{p}p \rightarrow \Omega\bar{\Omega} \approx 0.002 \div 0.06\ \mu b$
- No extra mesons in final state needed for strangeness or charm conservation
- Symmetry in hyperon and antihyperon
- PANDA detector versatile

Prospects for PANDA

S=2 hyperons (Ξ)
S=0 baryons (N)
S=1 hyperons (Λ)

S=3 hyperons (Ω)

Charmed (Λ_c, Σ_c)
Hidden charm (N_{cc})

PANDA is a Strangeness Factory

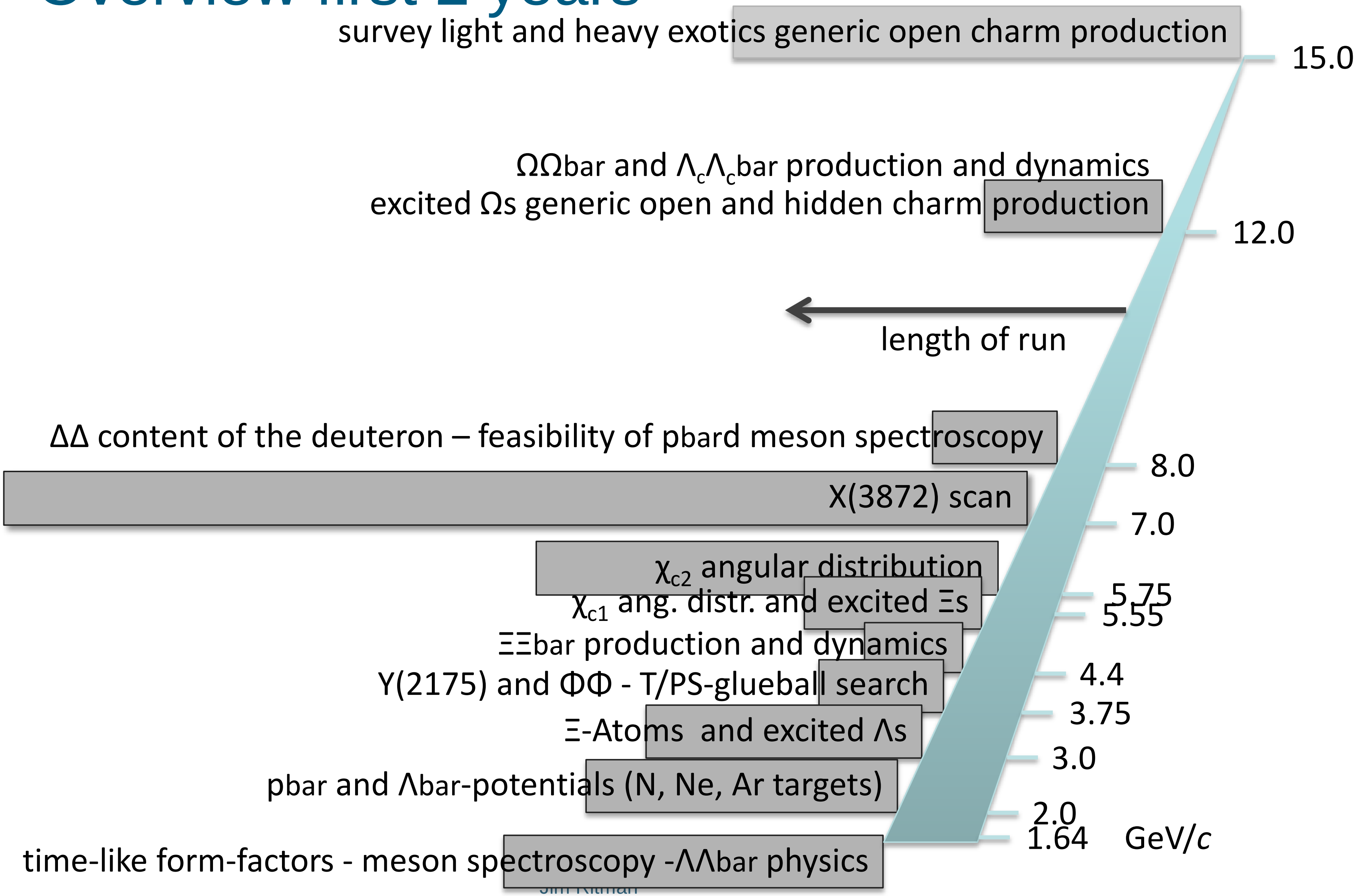
Spin Observables in Hyperon Production

The parity-violating weak decay of hyperons gives access to spin observables even for unpolarised beam/target. These observables give insight in the production mechanism of hyperons (e.g. the role of spin in strangeness and charm production).
Unique to PANDA: the study of these observables and especially the hyperon-antihyperon spin correlations.

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 **

Potential Run-Plan – Overview first 2 years



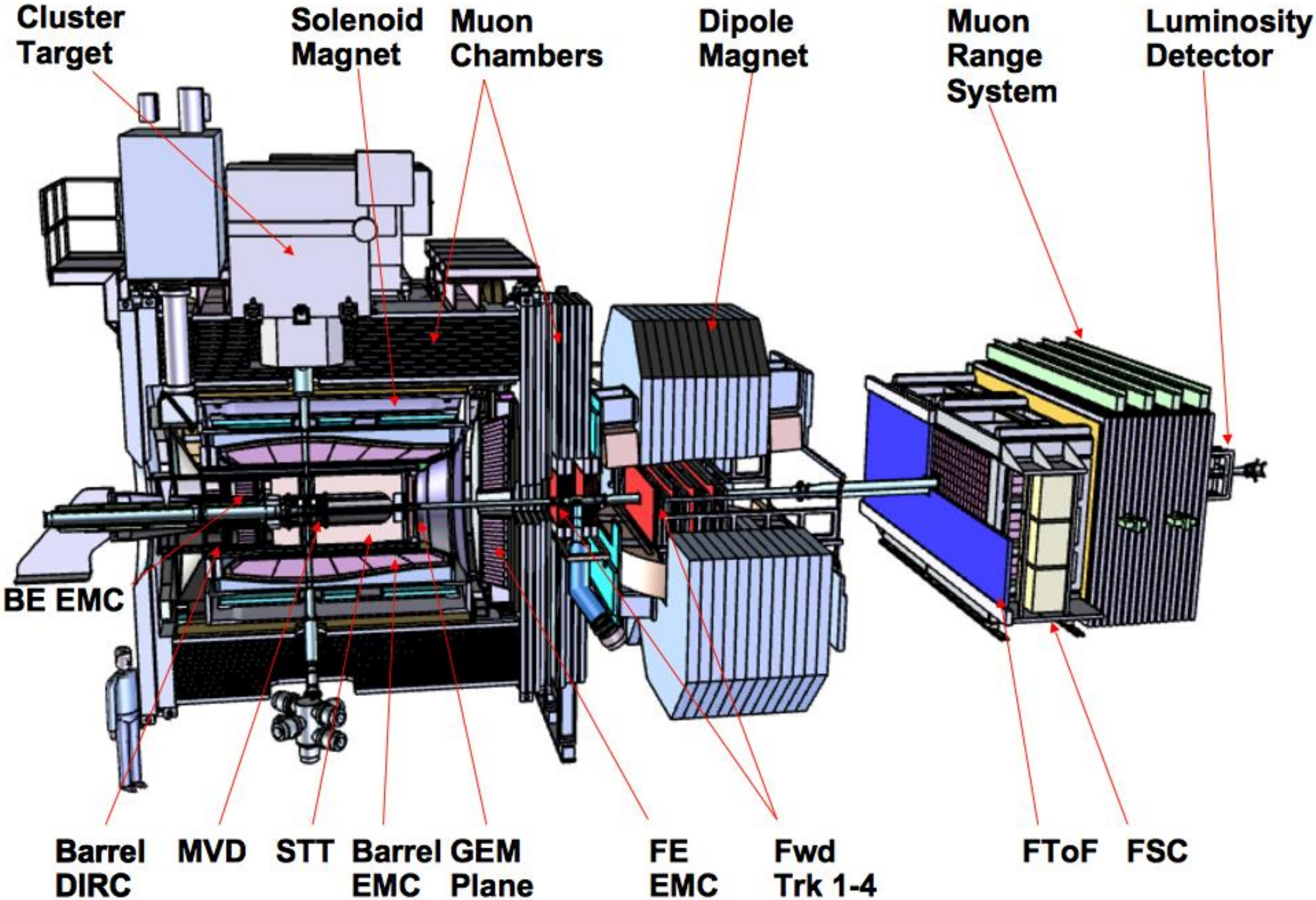
Status of the Detector System

Jim Ritman

HESR: On-time, On-budget

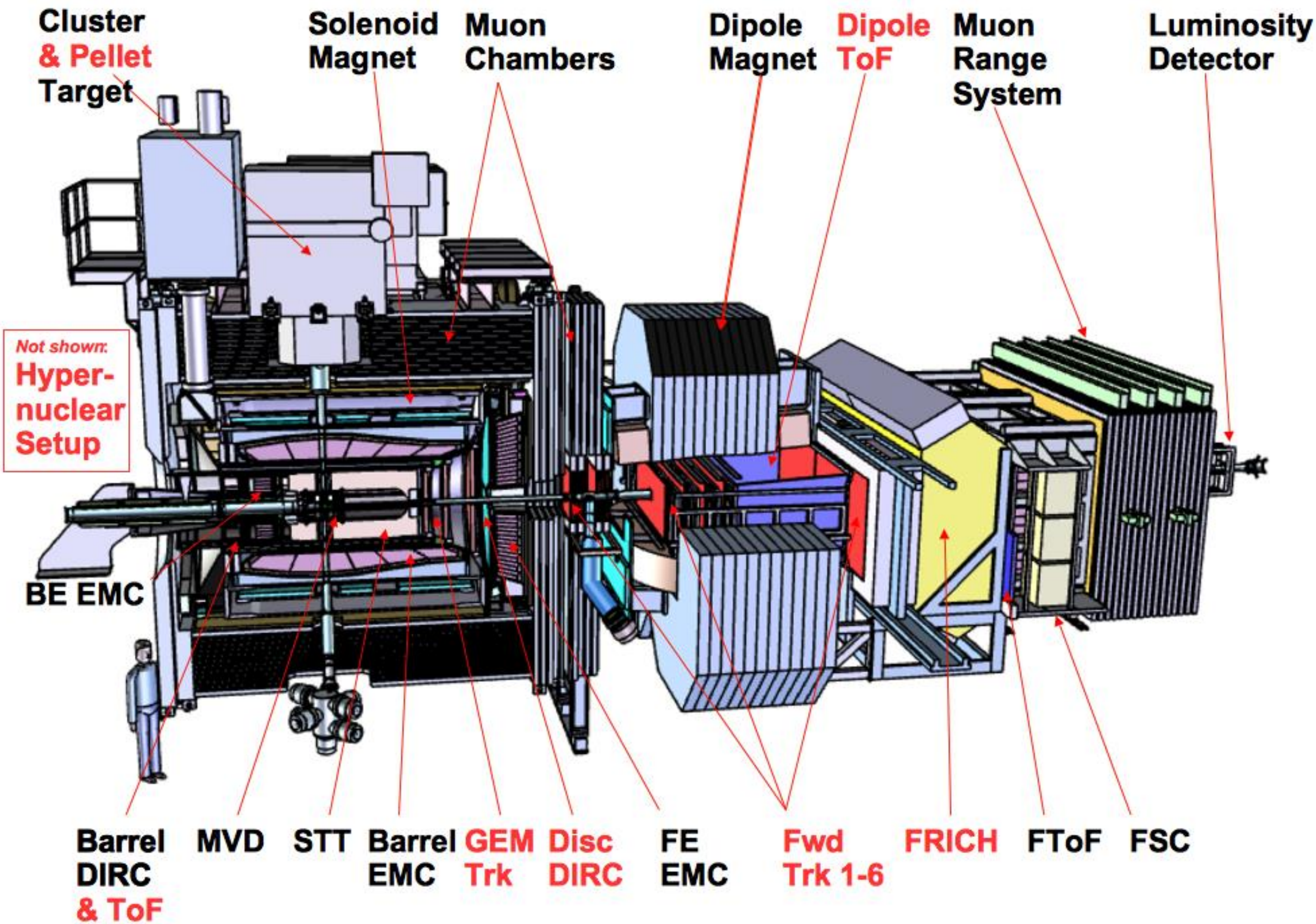
Dipole magnets in Jülich, first delivery of completed modules to Darmstadt

Start Setup



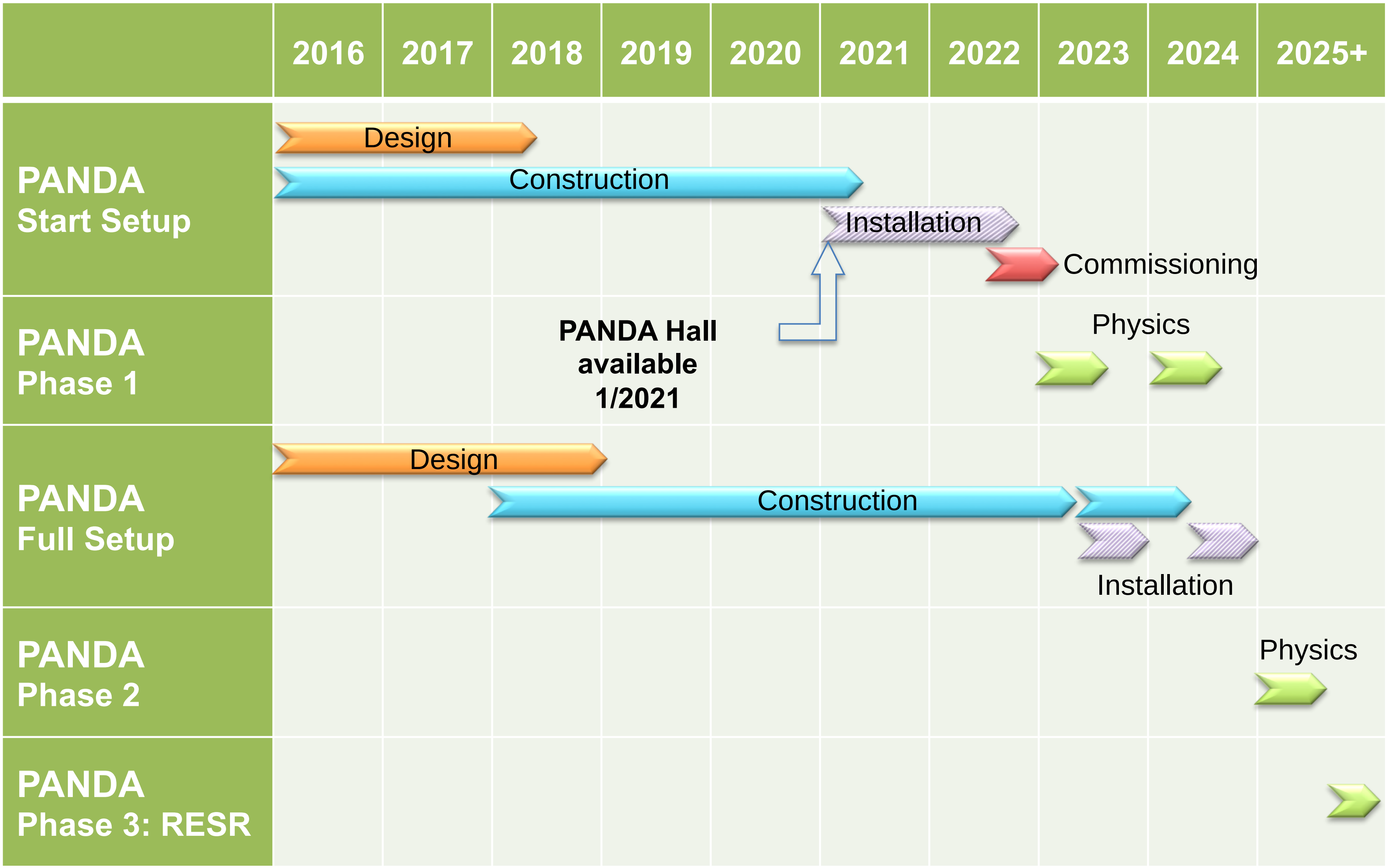
Cluster Target
Solenoid Magnet
Muon Chambers
Dipole Magnet
Muon Range System
Luminosity Detector
BE EMC
Barrel DIRC
MVD
STT
Barrel EMC
GEM Plane
FE EMC
Fwd Trk 1-4
FToF
FSC

Full Setup



Cluster
& Pellet
Target
Solenoid
Magnet
Muon
Chambers
Dipole
Magnet
Dipole
ToF
Muon
Range
System
Luminosity
Detector
Not shown:
Hyper-
nuclear
Setup
BE EMC
Barrel
DIRC
& ToF
MVD
STT
Barrel
EMC
GEM
Trk
Disc
DIRC
FE
EMC
Fwd
Trk 1-6
FRICH
FToF
FSC

PANDA Phases



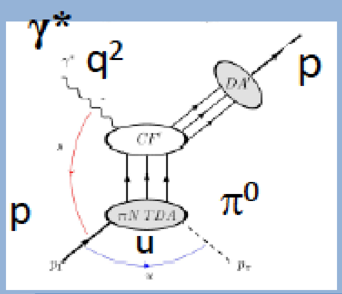
PANDA: Excellent Physics Opportunity

- FAIR will be the main international laboratory for strong interaction studies at all length scales:
  PANDA-experiment 1 of 4 Pillars
- Clear strategy for a strong PANDA physics case with high impact for the start phase
- PANDA detector for the start phase defined in line with FAIR high level time schedule
- PANDA Detector for the start phase already now: approved TDRs represent 86% of cost


Thank you!

Transition Distribution Amplitudes

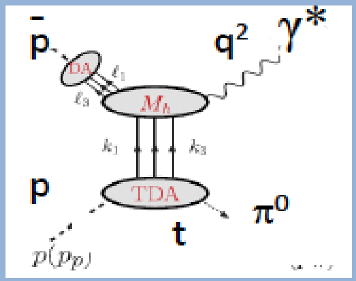
$e^-p \to e^-p\pi^0$ Bwd electroproduction



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

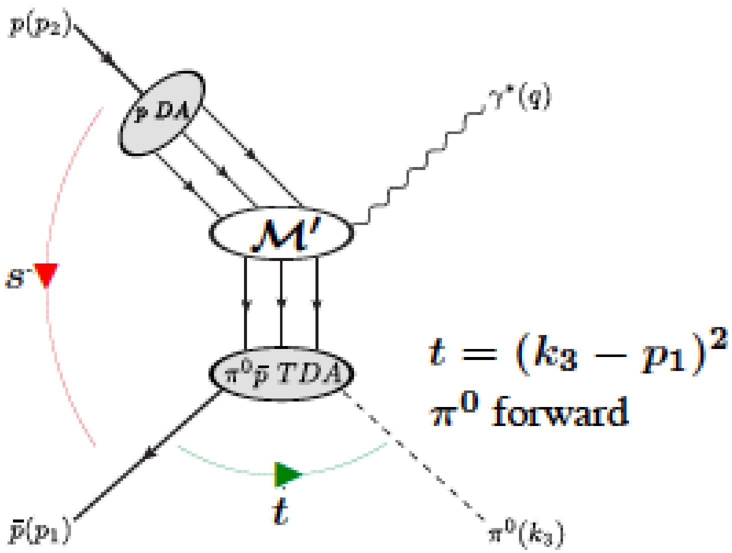
Transition Distrib. Amplitudes

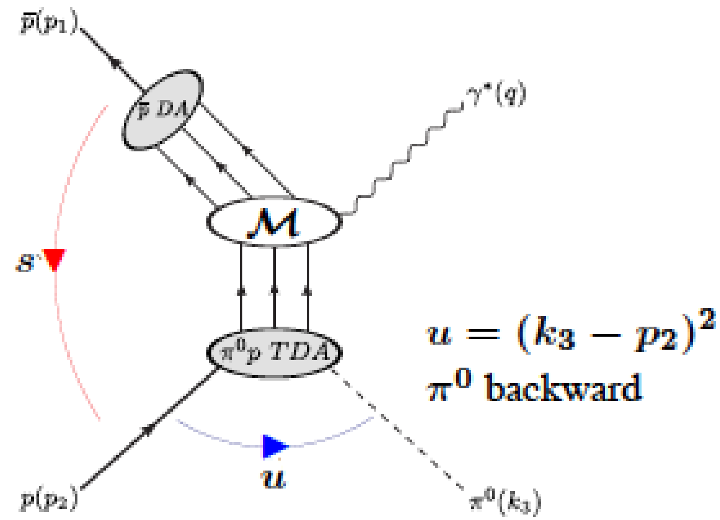
Transitions Distribution Amplitudes: $\bar{p}p \to e^+e^-\pi^0, e^+e^-\rho^0, e^+e^-\eta, \ldots$

- 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

Nucleon to meson TDAs

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





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

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.

Feasibility studies: nucleon to meson TDAs @ PANDA

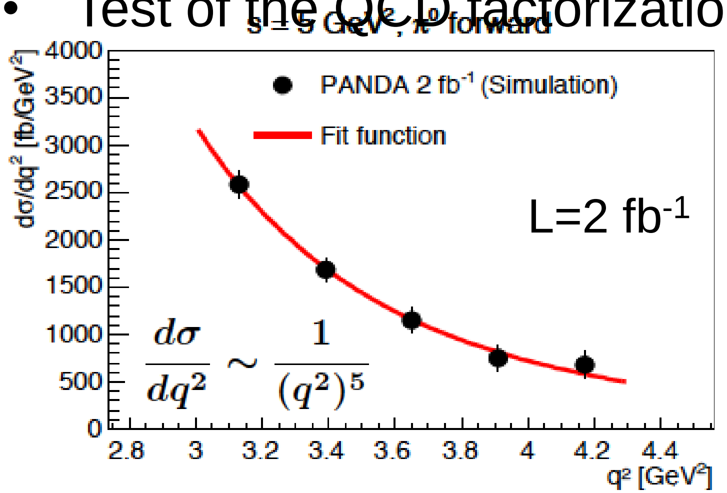
Feasibility studies of measuring $\bar{p}p \to \gamma^* \pi^0 \to e^+e^- \pi^0$ at PANDA

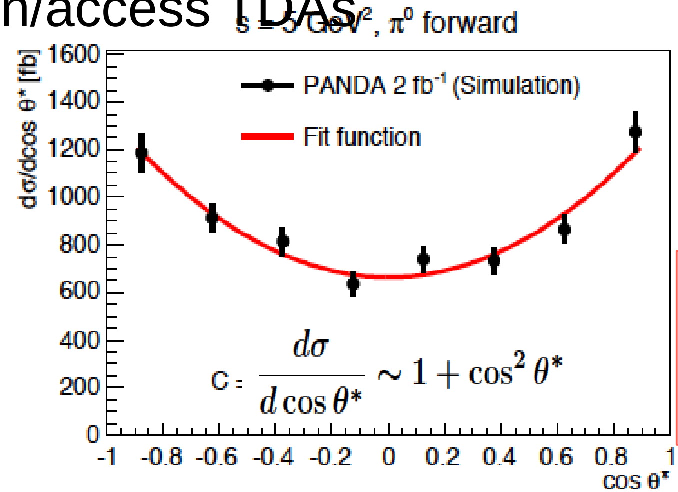
$$\mathrm{i)}\ s = 5\ \mathrm{GeV^2} \quad \to \quad 3.0 < q^2 < 4.3\ \mathrm{GeV^2}, \quad |\cos\theta_{\pi^0}| > 0.5$$
$$\mathrm{ii)}\ s = 10\ \mathrm{GeV^2} \quad \to \quad 5 < q^2 < 9\ \mathrm{GeV^2}, \quad |\cos\theta_{\pi^0}| > 0.5$$

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

s = 5 GeV^2: 5 . 10^7 (1 . 10^7) $\Delta\sigma/\sigma \sim 12\%$
s = 10 GeV^2: 1 . 10^8 (6 . 10^6) $\Delta\sigma/\sigma \sim 24\%$

- Test of the QCD factorization/access TDAs





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

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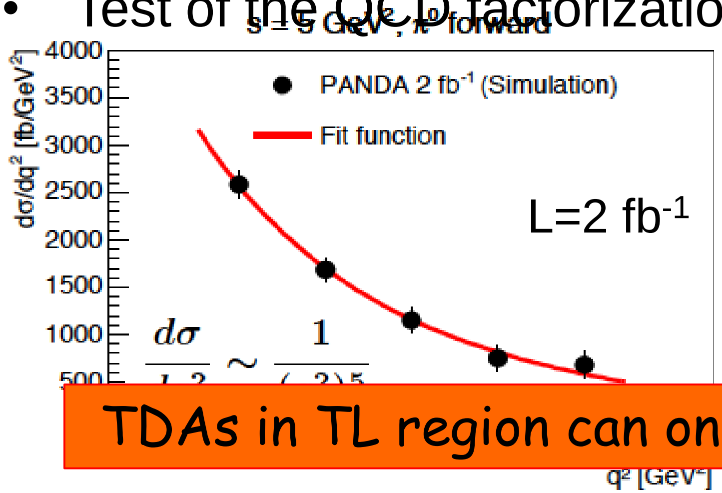
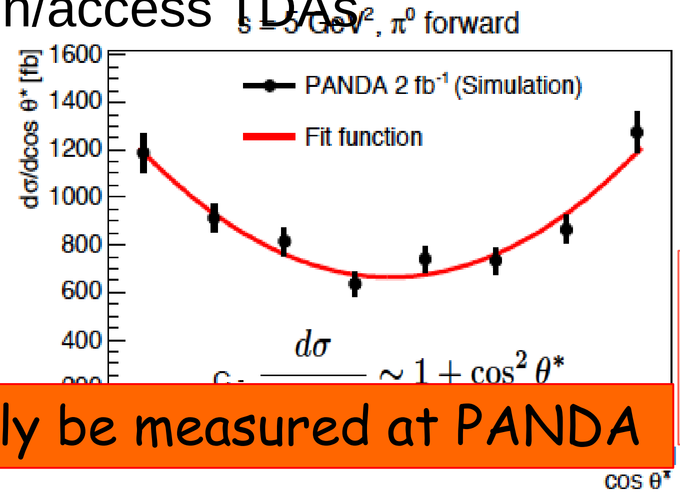




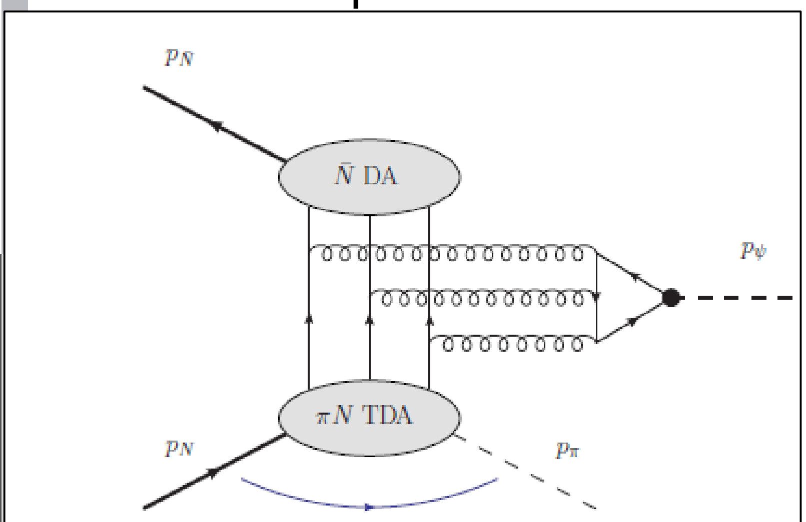
M. Carmen Mora Esp... *et al.* (HIM). Submitted to EPJA

TDAs in TL region can only be measured at PANDA

Nucleon to meson TDAs @ PANDA

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 $J/\psi -> \bar{p}p$ partial decay modes
- Test of universality of TDAs by comparing $\bar{p}p \rightarrow \gamma^* \pi^0 -> e^+e^- \pi^0$ at different q^2



Feasibility studies for PANDA @ p=5.513, 8 and 12.0 GeV/c:

S/B> 8, 70, 600

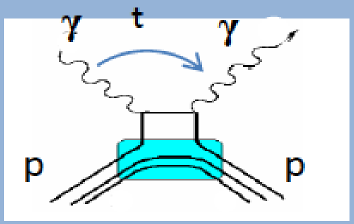
Binsong Ma, PhD thesis, IPNO 2014
Ongoing work by Ermias Atomsa et al. (IPNO

Generalized Distribution Amplitudes

Hard exclusive processes at large P_t: GDAs

(SL)

$\gamma p \rightarrow \gamma p$ Wide Angle Compton Scattering



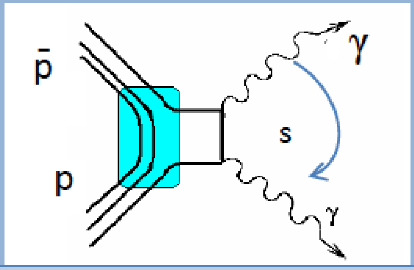
Large p_t

Generalized **P**arton **D**istributions

(TL)

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

Large p_t



Generalized **D**istrib. **A**mplitudes

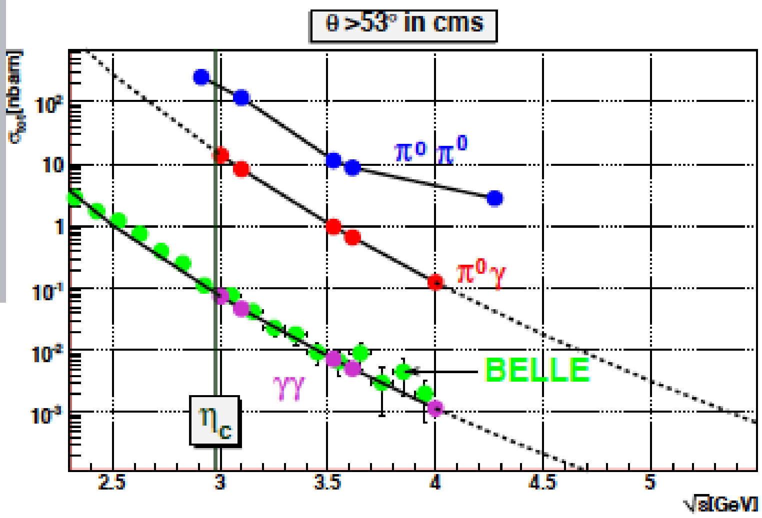
Time-like Wide Angle Compton Scattering (WACS)

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 $\bar{p}p \to gg$ and $\bar{p}p \to p^0 g$ at PANDA



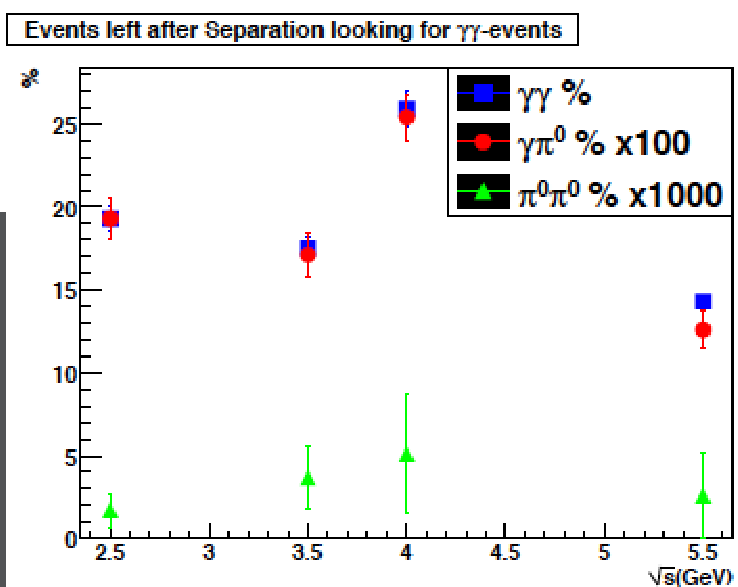
PANDARoot simulations:

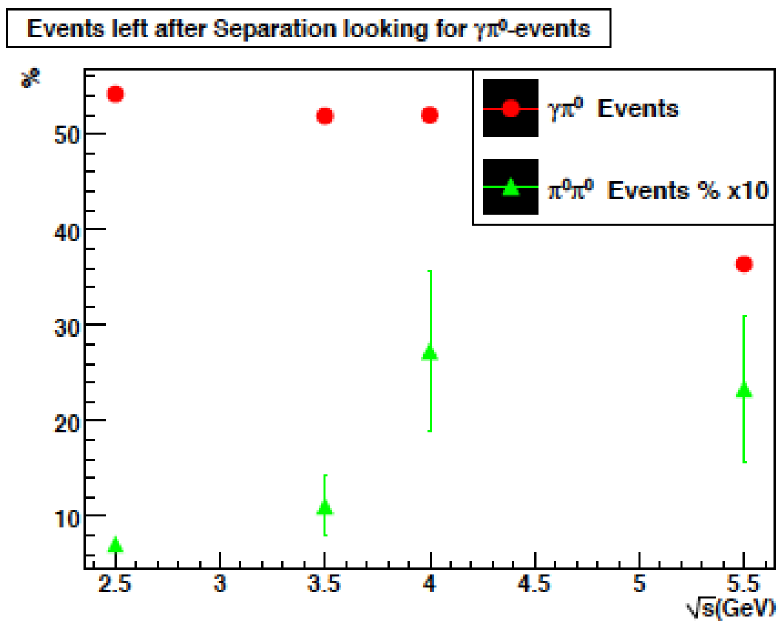
- 4 different CM energies
- Main background channels:

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

$\bar{p}p \to p^0 g$ (for signal1: $\bar{p}p \to gg$)

PANDA Physics Performance Report
arXiv:0903.3905





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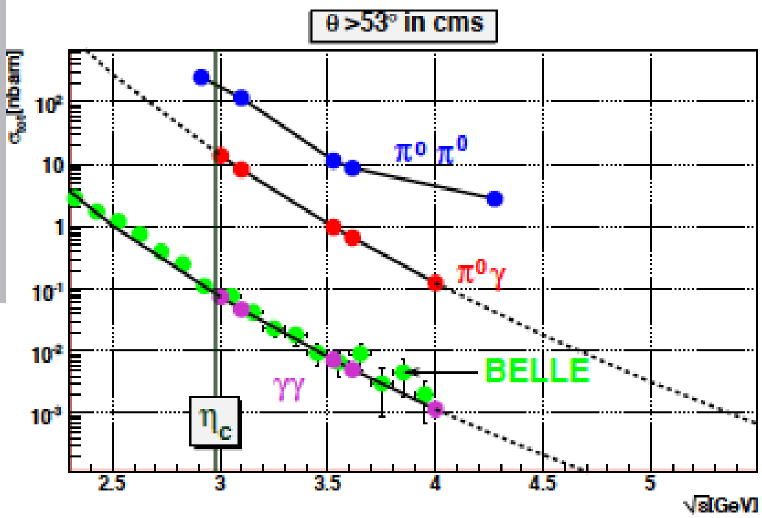

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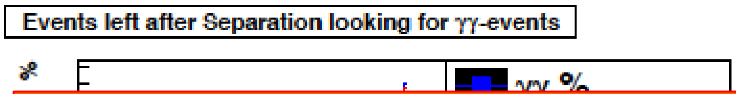


Time-like wide angle Compton scattering and hard exclusive meson production can be measured at PANDA

S/B~1 for $\bar{p}p \to gg$ (25% efficiency)
S/B~2 for $\bar{p}p \to p^0 g$ (50% efficiency)

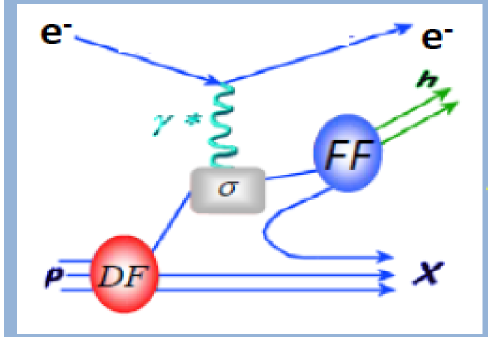
Further studies are required for precise predictions

Transverse Parton Distribution Functions

Drell-Yan processes at PANDA

$e^- p \rightarrow e^- hX$

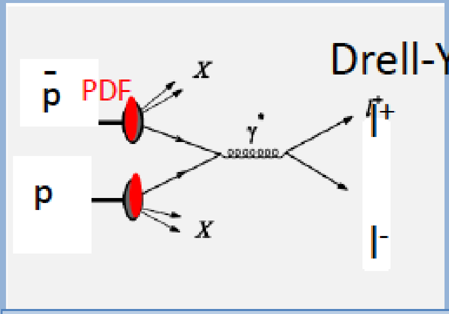
SIDIS



A. Bi

Parton Distribution Functions

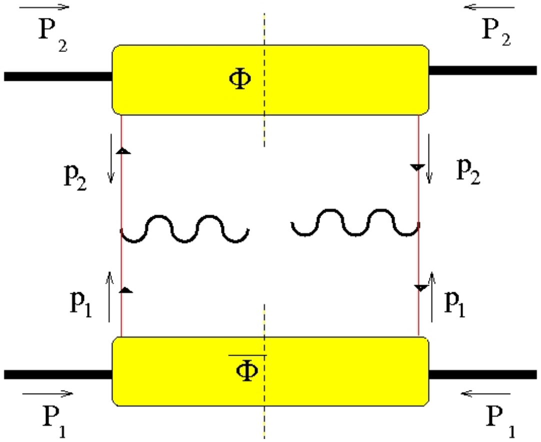
$\bar{p}p \rightarrow \mu^+\mu^- X / e^+e^- X$



Parton Distribution Functions

PDFs are convoluted with the fragmentation

Handbag diagram: $s >> M_h^2$



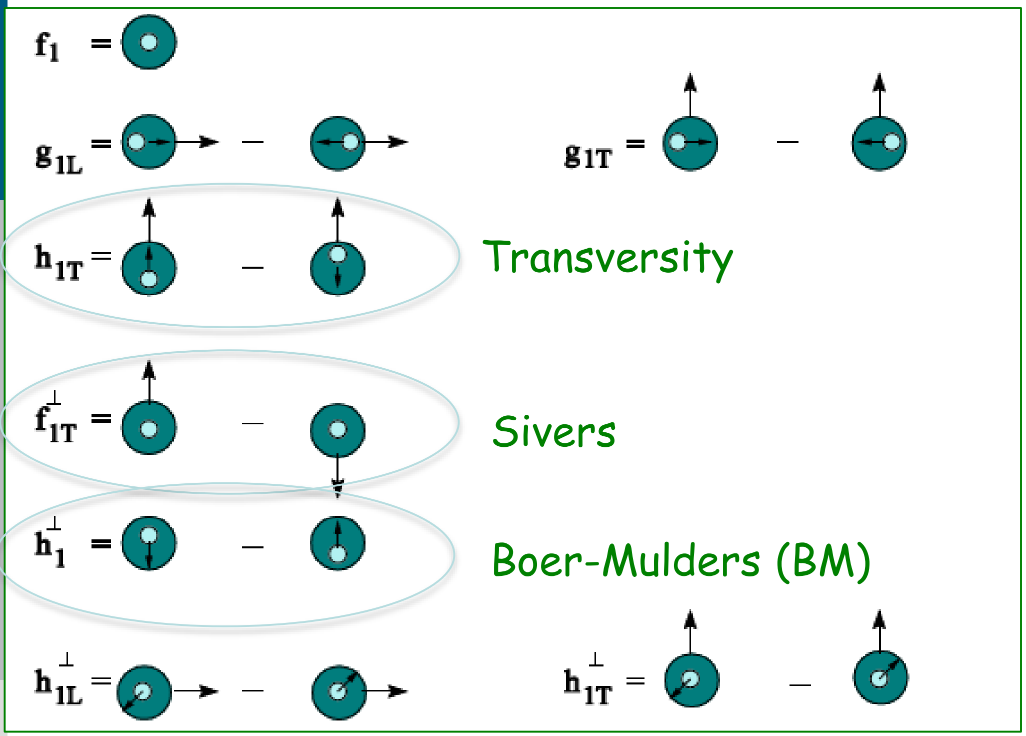
@ FAIR unique energy range
up to s~30 GeV2 with PANDA
up to s~200 GeV2 with PAX

@ much higher energies
→ big contribution from sea-quarks

@ppbar annihilation each valence quark contribute to the diagram

Transverse momentum dependence PDFs

Transverse Momentum Dependence (TMD leading-order) formalism:



Asymmetry measurements:

Unpolarized DY

$$A^{\cos 2\phi} \to h_1^{\perp}$$

Single-polarized DY

$$A^{\sin(\phi \pm \phi_{s2})} \to h_1^{\perp}, h_{1T}, f_{1T}^{\perp}$$

$$A = \frac{U - D}{U + D}$$

$U = N(\cos 2\phi > 0)$ $D = N(\cos 2\phi < 0)$	$U = N(\sin(\phi \pm \phi_{s2}) > 0)$ $D = N(\sin(\phi \pm \phi_{s2}) > 0)$

ϕ : angle between hadron and lepton planes

ϕ_{s2}: angle between hadron spin and lepton plane

Test of Universality
and the QCD TMD factorization:

$$f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SIDIS)$$

$$h_1^{\perp}(DY) = -h_1^{\perp}(SIDIS)$$

Feasibility measurement of DYs at PANDA

Feasibility studies using Monte-Carlo simulation:

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

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

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

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

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

PANDA Physics Performance Report
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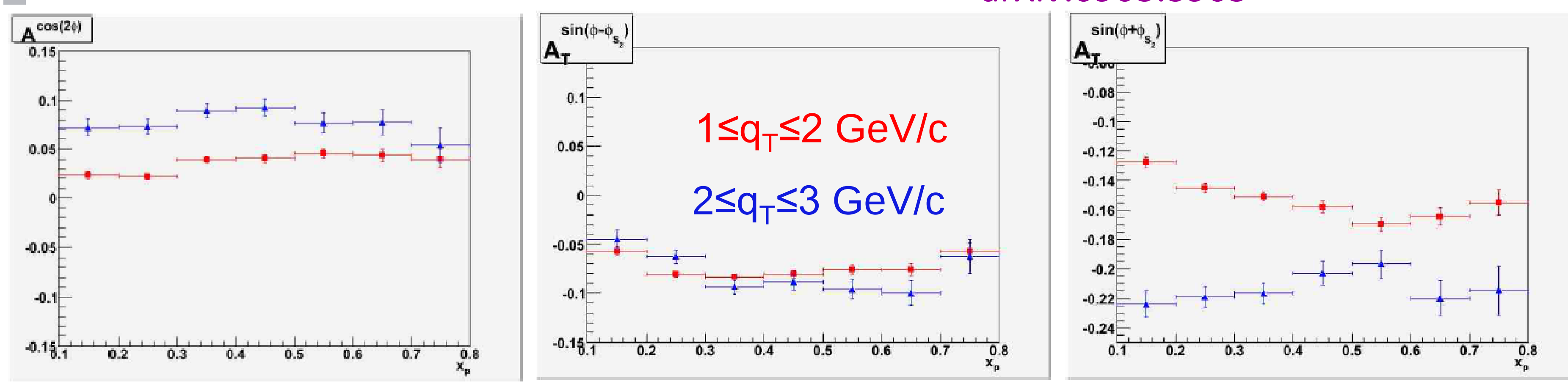

x_p: the longitudinal momentum of the hadronic probe

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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

A lot of progress

- Different event generators for signal and background channels are implemented in PANDARoot
- New method for correcting electron reconstruction for the Bremsstrahlung effect is developped
- Bayesian PID methods for the lepton/hadron separation have been developped
- Theoetical calculations on radiative corrections for the proton FFs measurement at PANDA are performed
  - New event generator is planned