Studying nucleon structure with time like processes

IPN Orsay activities for PANDA

QCD-GDR meeting, 10 November 2016 , Orsay

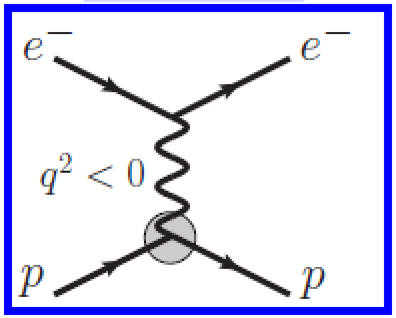
Outline

- Nucleon structure studies in time-like processes
- FAIR and PANDA
- Technical and software developments of IPNO
- Time Like Electromagnetic form factors
- Feasibility studies for TDA measurements in $\bar{p}p \rightarrow J/\psi\pi^0$ with PANDA

Using time-like electromagnetic processes for nucleon structure studies

- Access to nucleon structure observables currently limited to lepton/photon scattering on protons (JLab, Compass, Mainz. . .)

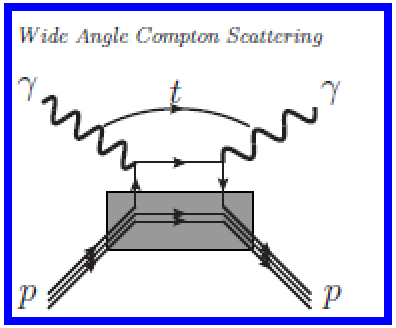
$e^- p \to e^- p$



Space-Like

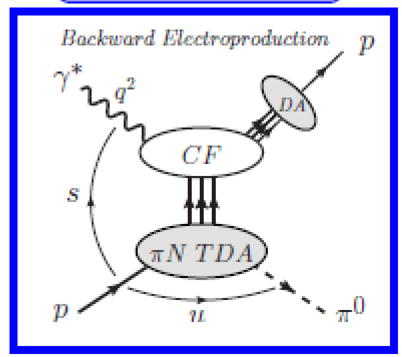
Elastic Scattering
Electromagnetic Form Factors (FF)

$\gamma p \to \gamma p$



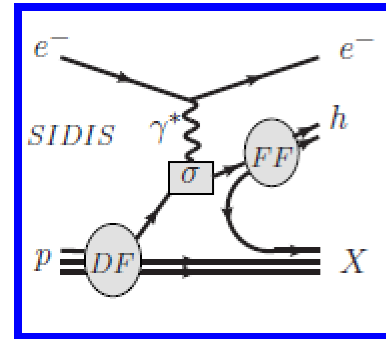
Large angle compton scattering
Generalized Parton Distribution (GPD)

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



Backward electroproduction
Transition Distribution Amplitude (TDA)

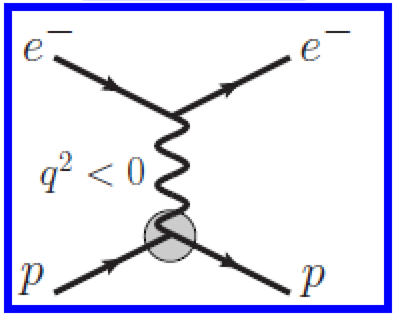
$e^- p \to e^- hX$



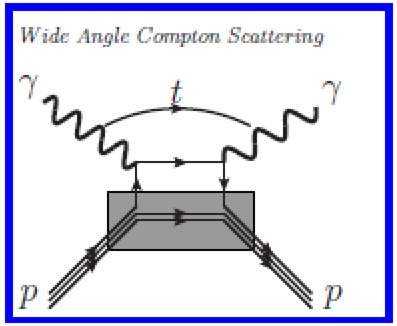
Semi-inclusive DIS
Parton Distribution Functions (PDF)

Using time-like electromagnetic processes for nucleon structure studies

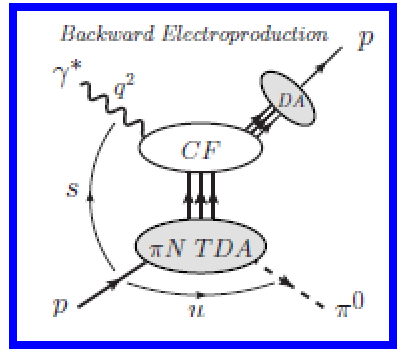
$e^- p \to e^- p$



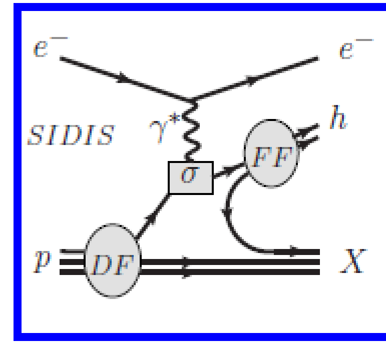
$\gamma p \to \gamma p$



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

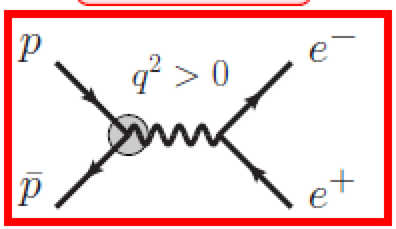


$e^- p \to e^- hX$

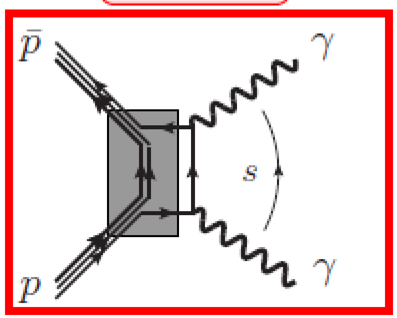


Space-Like

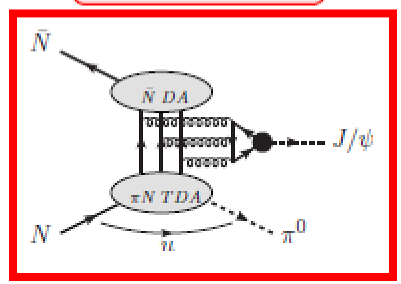
$\bar{p}p \to e^+ e^-$



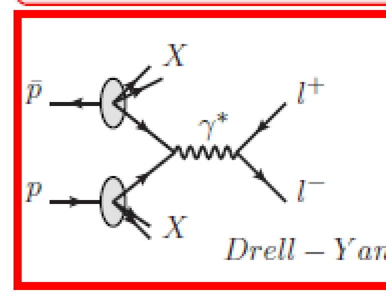
$\bar{p}p \to \gamma\gamma$



$\bar{p}p \to \pi^0 J/\psi$



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



Time-Like

Electromagnetic Form Factors (FF)

Generalized Parton Distribution (GPD)

Transition Distribution Amplitude (TDA)

Parton Distribution Functions (PDF)

- ✓ Crossing symetry: same or complementary information available in electron scattering and p̄p annihilation
- ✓ Only Time-like form factors measured in p̄p (LEAR,Fermilab)
- ✓ Novel opportunity with Panda: high precision and large kinematic coverage

Challenge of e^+e^- exit channels: pionic background !

The FAIR facility at Darmstadt

FAIR = Facility for Antiproton and Ion Reserach

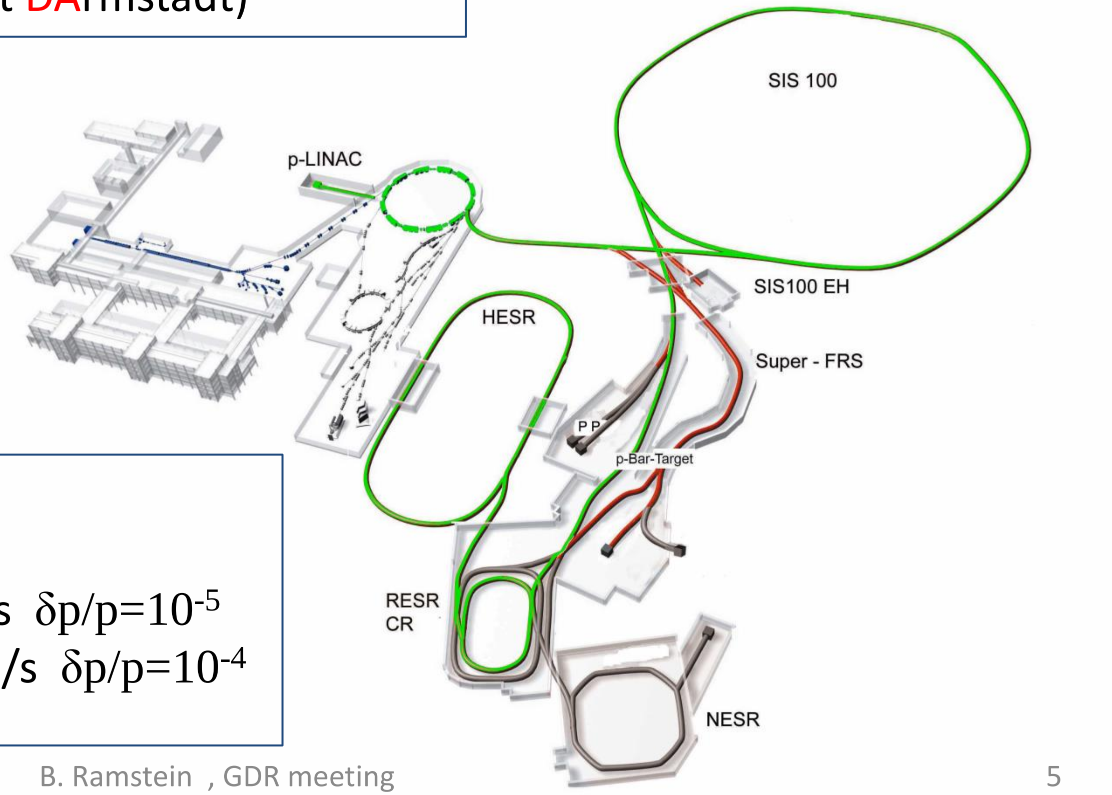
4 pillars

APPA (Atomic, Plasma Physics and Applications)

CBM (Compressed Baryonic Matter)

NUSTAR (NUclear, STructure, Astrophysics and Reactions)

$\bar{P}$ANDA (AntiProton ANnihilation at DArmstadt)



High Energy Storage Ring

Antiprotons p= 1.5-15 GeV/c

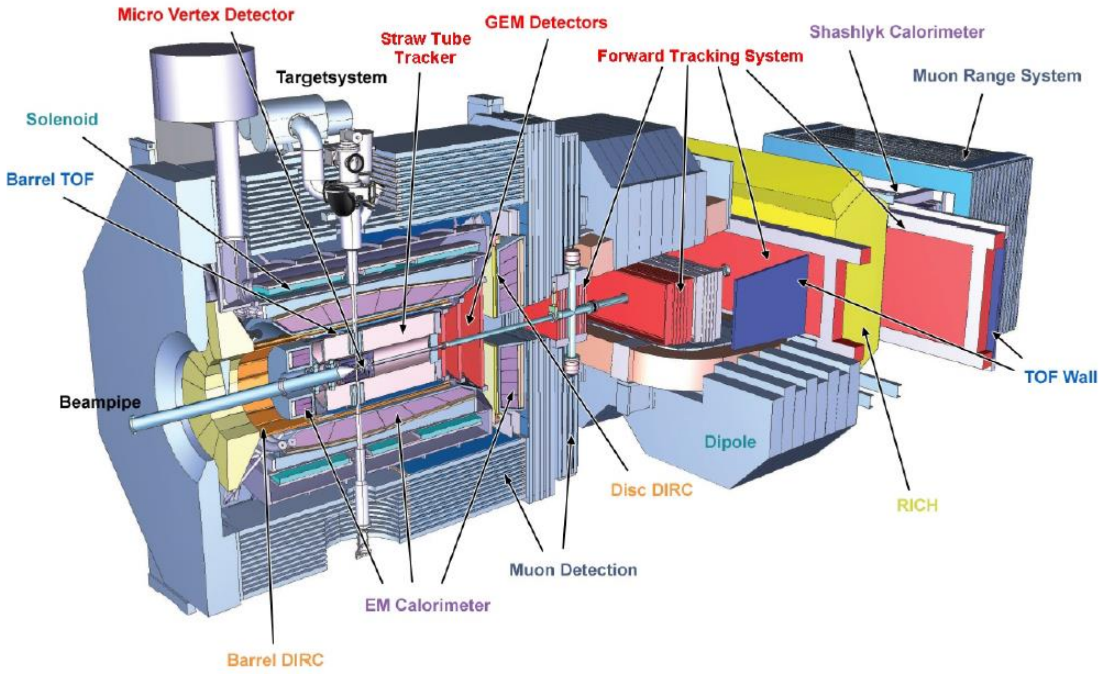
High res. mode $L_{peak}=2x10^{31}/cm^2/s$ $\delta p/p=10^{-5}$

High lumi mode $L_{peak}=2x10^{32}/cm^2/s$ $\delta p/p=10^{-4}$

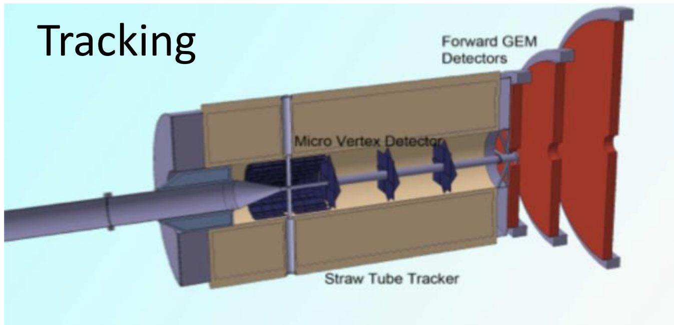
The PANDA multipurpose detector

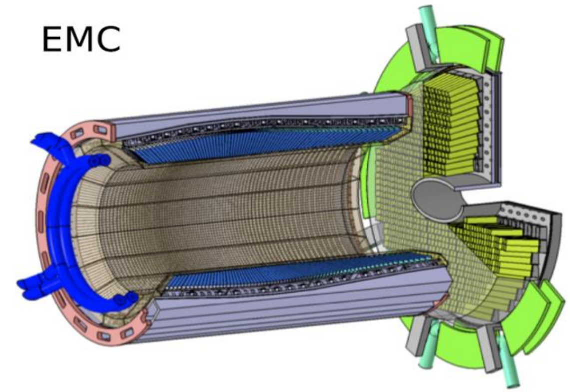
- Meson spectroscopy: D mesons, charmonia
- Search for exotic QCD states: glueballs, tetraquarks, hybrids, molecules…
- Single and Double hypernuclei
- Hadrons in nuclear matter
- Nucleon structure

AntiProton ANnihilation at Darmstadt



Tracking and PID for nucleon structure studies

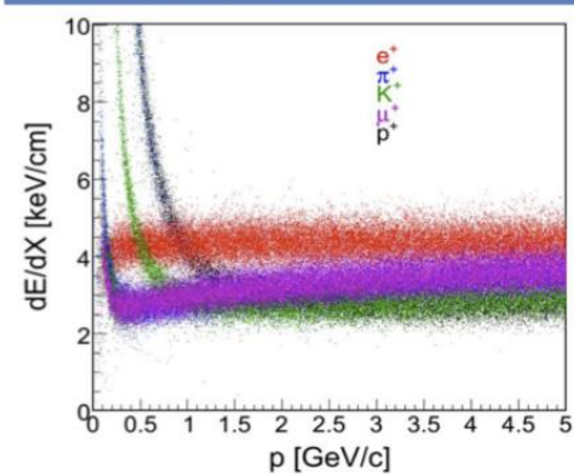


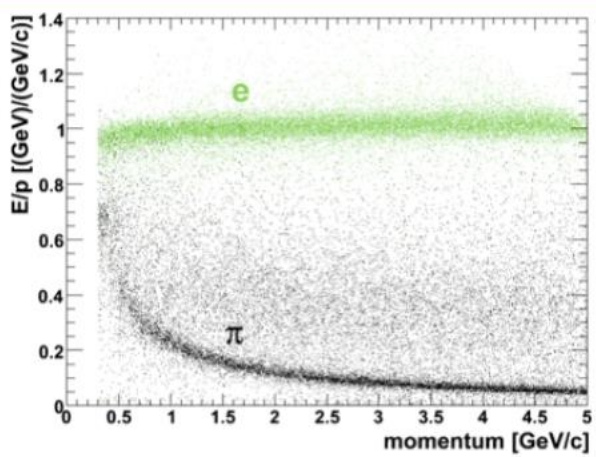


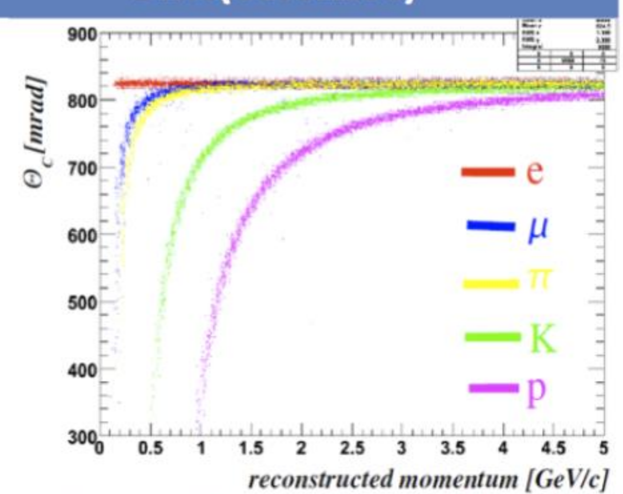
Target spectrometer:
Large coverage (2π, $5° < \theta < 145°$)
Silicon MVD, Straw Tube and GEM
dE/dx for PID from STT and MVD

PbWO4 crystals, APDs (barrel), VPT(forward)
Operation at -25° for optimal light yield
Wide dynamic range >3 MeV
Excellent resolution $\sigma(E)/E \sim 1\% \oplus 2\%/\sqrt{E}$

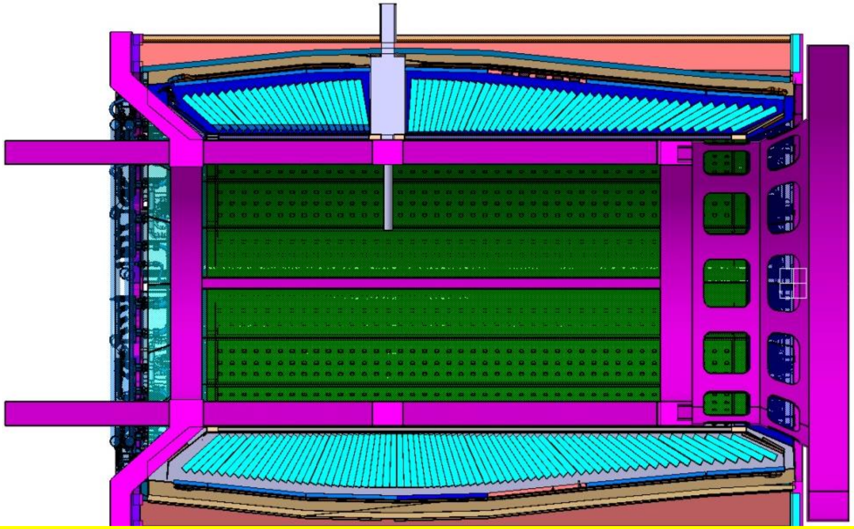
Straw Tube Tracker	ElectroMagneticCalorimeter	DIRC(Cerenkov)







Technical contribution of IPNO



The barrel calorimeter: 11520 PbWO4 crystals

1/3 of the 120 crystal prototype

R & D on the barrel calorimeter

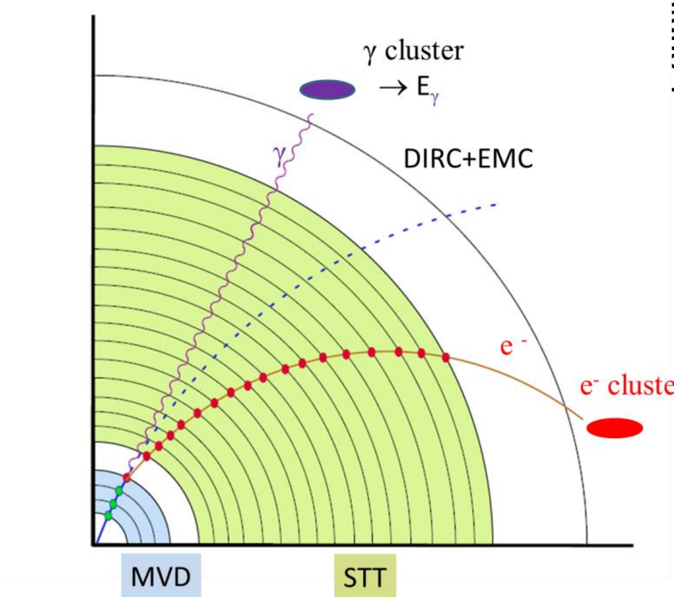
- General layout and integration (EMC TDR)
- Design of the cooling system (-25°C)

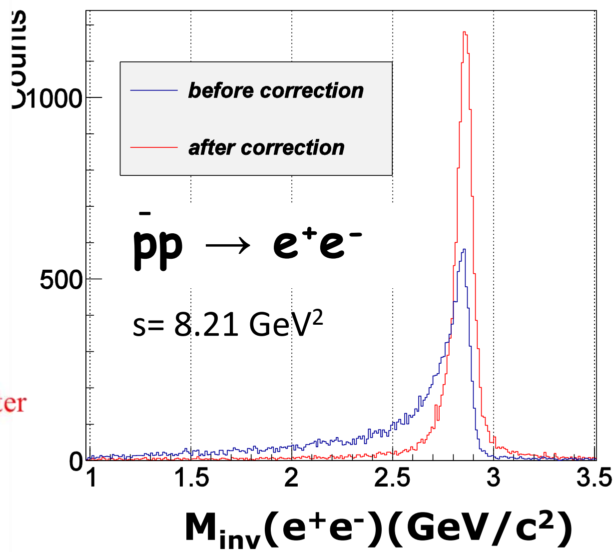
tests of chiller → transfer of know-how to Bochum/Giessen in Spring 2015

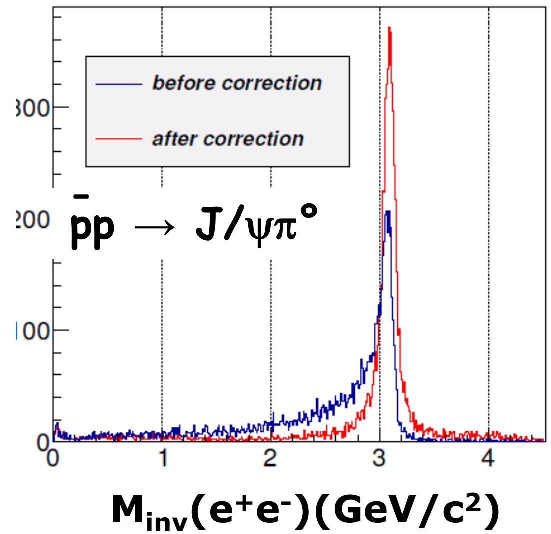
- Optical glue studies *(A. Dbeyssi et al; NIM A722 (2013) 82)*
- Participation in construction and tests of two prototypes

Simulation and analysis code developments for PANDA

- **Particle IDentification** (Bayesian methods/ GEANT hadronic models sensitivity)
- **Bremsstrahlung correction** using photon detection in EMC
  B. Ma, PhD, Univ. Paris-Sud, Sept 2014.







- **Event Filtering** (trigger): fast selection of em channels/suppression of hadronic channels

Time Like Electromagnetic proton form factors with PANDA

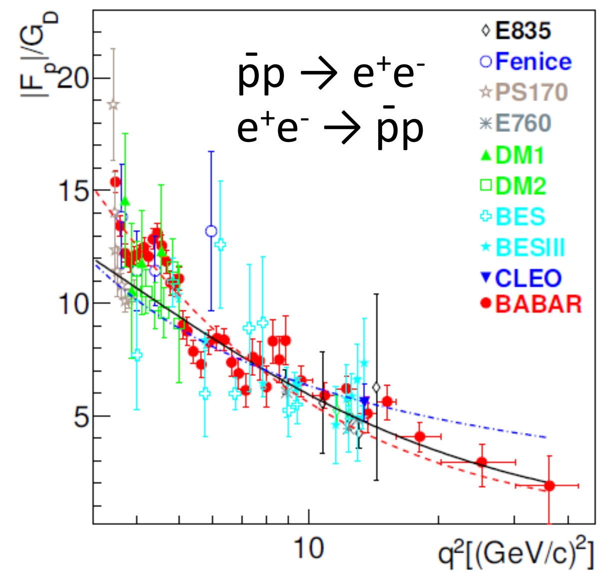
$\bar{p}p \to e^+e^-$, $\bar{p}p \to \mu^+\mu^-$

Angular distributions:

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

Total cross sections:

$$\sigma_{tot} \sim |G_{eff}|^2 \qquad G_{eff}^2 = \frac{2\tau|G_M|^2 + |G_E|^2}{2\tau+1} \qquad \tau = \frac{q^2}{4M_p^2}$$

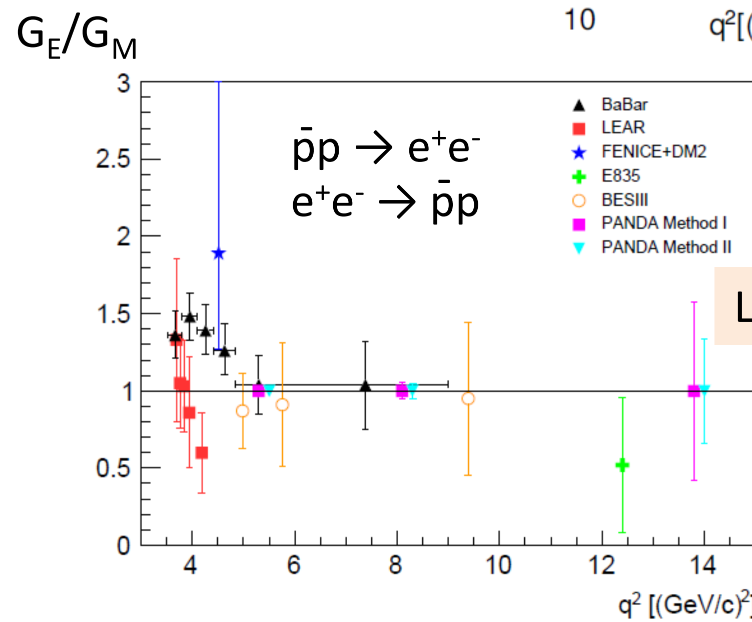


Feasibility studies for PANDA in $\bar{p}p \to e^+e^-$

Rejection of $\bar{p}p \to \pi^+\pi^-$ 10^8-5.10^7
Efficiency for $\bar{p}p \to e^+e^-$ ~ 40%

$q^2 < 14$ GeV^2 : $|G_M|$ with precision 2%-10%
$|G_E|$ with precision 2%-60%
$q^2 > 14$ GeV^2 : $|G_{eff}|$ can be measured

M. Sudol et al. EPJA44,373 (2010).
A. Dbeyssi 's PhD (2013) Orsay
PANDA collab: Eur.Phys.J. A52 (2016), 325



L_{int}=2fb^{-1}

Further prospects for TL form factor studies with PANDA

- Measurement of $|G_E|$ and $|G_M|$ in $\bar{p}p \rightarrow \mu^+\mu^-$
  On-going PhD work I.Zimmermann (Mainz)
  Contamination by $\bar{p}p \rightarrow \pi^+ \pi^-$ S/B~1/4

- Measurements of the proton form factors in the unphysical region $q^2 < 4\ m_p^2$
  $\bar{p}d \rightarrow ne^+e^-$ *H. Fonvieille and V.A. Karmanov EPJA42 (2009) 287-298.*
  $\bar{p}p \rightarrow \pi^0\ e^+e^-$ Feasibility studies by *J. Boucher , PhD University Paris-Sud, 2011).*
- Possibility to access the relative phase of G_E and G_M:
  Transverse spin asymmetry$\rightarrow$ $Im(G_E G_M^*)$
  Development of a transverse polarized proton target for PANDA in Mainz
  on-going PhD work B. Fröhlich (Mainz)

- Study of hadronic channels: background for electromagnetic channels and reaction mechanisms *on-going PhD work Wang Ying (Orsay)*

Phenomenological works related to TL form factors

- Radiative Corrections

  J. Van de Wiele and S. Ong, EPJ A 49 (2013) 18.

  E. Tomasi-Gustafsson et al, PRC83 (2011) 04520.

- Heavy leptons and Polarisation

  E. Tomasi-Gustafsson et al, NPA 894 (2012) 20 and PRC83 (2011) 025202.

- Crossed channels and TL-SL Unification

  E. Tomasi-Gustafsson et al, PLB 712 (2012) 240.

- Reaction mechanisms

  E. Tomasi-Gustafsson et al, NPA 920 (2013) 45.

- Hadronic channels

  E. Tomasi-Gustafsson et al, EPJA 46 (2011) 91.

  J. Van de Wiele and S. Ong, EPJA 46 (2010) 291 and EPJ C73 (2013) 2640.

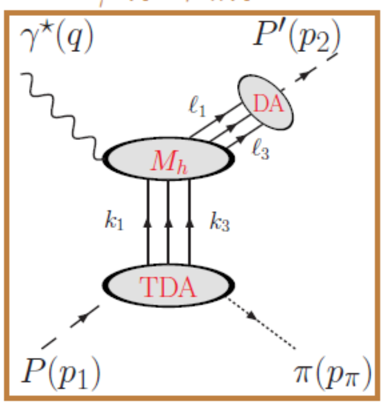
  W. Ying et al. arXiv:1512.05520, subm. to Phys. Lett. B

  W. Ying JPCS 742 ,012021

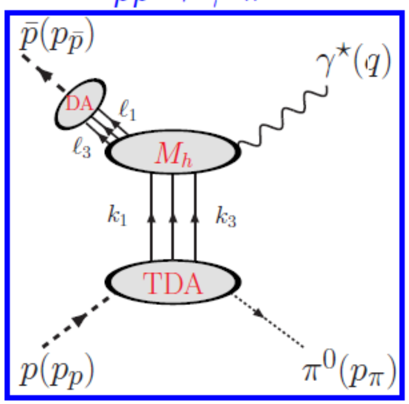
π-N Transition Distribution Amplitudes (TDA)

- TDA=Fourier transforms of non diagonal hadronic matrix elements of three (anti) quark operators on the light cone
- Occur in collinear factorization description of various reactions:
  - Backward hard electroproduction of mesons: $\gamma^* N \to \pi N$
  - Associated meson production in $\bar{p}p$ annihilation: $\bar{p}p \to e^+e^- \pi^0$, $\bar{p}p \to J/\psi\, \pi^0$

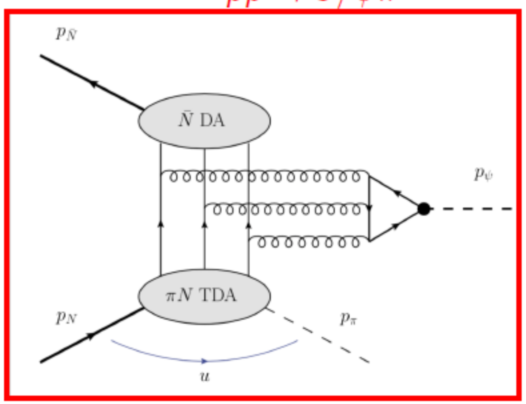
$\gamma^* N \to \pi N$



$\bar{p}p \to \gamma^* \pi^0$



$\bar{p}p \to J/\psi \pi^0$



- large q^2
- t or u $\ll q^2$

(θ_π close to 0^0 or 180^0)
$\to$ two kinematical regimes in $\bar{p}p$
πp-TDA or $\pi\bar{p}$-TDA

- Parametrized as a function of momentum fractions (x_i), skewness (ξ) and momentum transferred squared (Δ^2= t or u)
- independent of reaction type, s and q^2
- πN-TDA: information on the pionic components of the nucleon wave function

TDA using $\bar{p}p \rightarrow e^+e^- \pi^0$ with PANDA

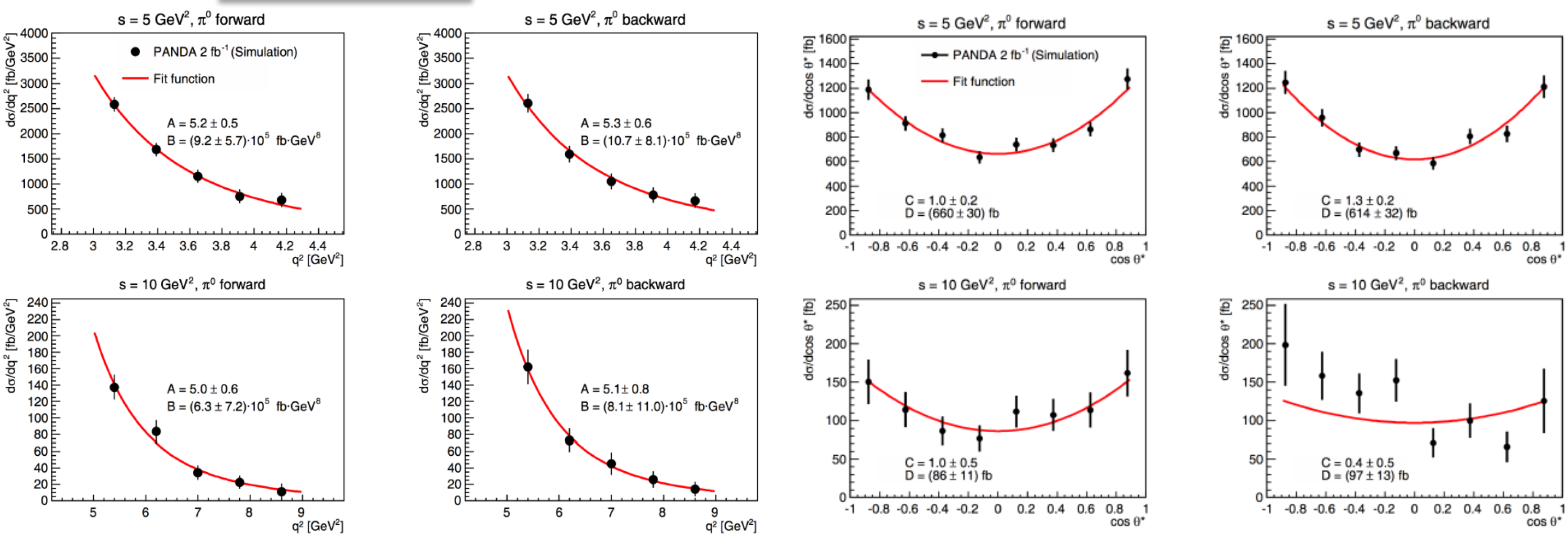
J.-P. Lansberg et al., Phys. Rev. D 76, 111502 (2007).
J.-P. Lansberg et al., Phys. Rev. D85, 054021 (2012)

Feasibility tested at s=5 GeV^2 (p=1.45 GeV/c) and 10 GeV^2 (p=4.3 GeV/c)
L_{int}=2 fb^{-1} (~5 months at High lumi)

$$\frac{d\sigma}{dq^2} \sim \frac{1}{(q^2)^5}$$

Scaling properties of cross section

$$\frac{d\sigma}{d\theta_e} \sim 1 + \cos^2\theta_e$$

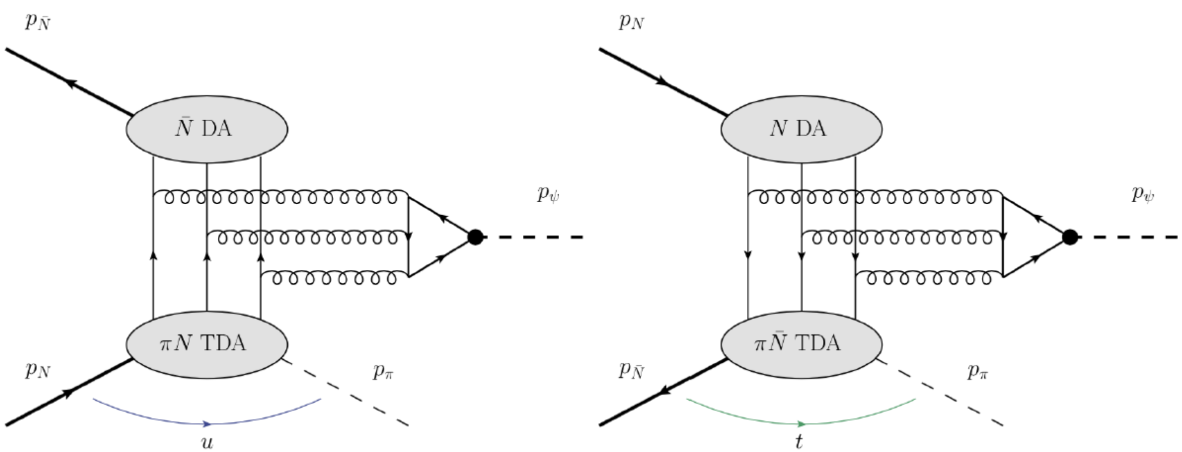


B. P. Singh et al. [PANDA collaboration] Eur. Phys. J. A (2015) 51:107.

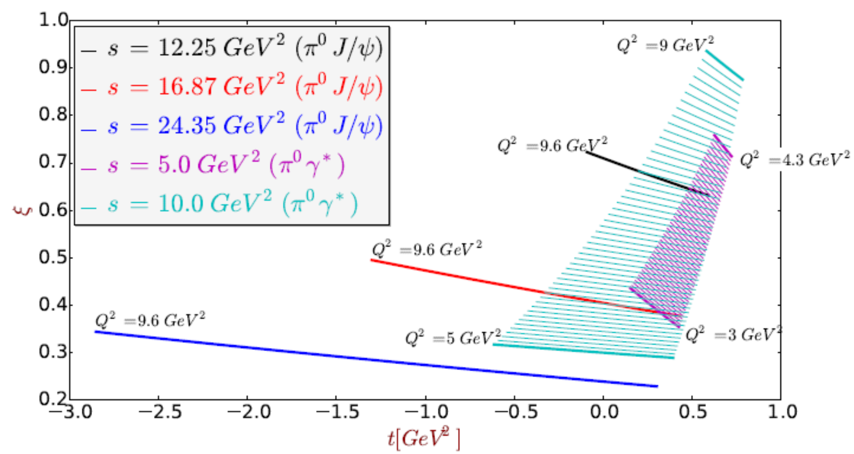
TDA using $\bar{p}p \rightarrow J/\psi\, \pi^0$ ($J/\psi \rightarrow e^+e^-$) with PANDA

B. Pire et al. Phys. Lett. B 724 99-107 (2013)

TDA from nucleon exchange model



- Hard scale provided by $Q^2=M^2_{J/\psi}$=9.6 GeV/c^2
- $\Gamma(J/\psi\rightarrow\bar{p}p)$ used as a constraint
- Complementary to $\bar{p}p \rightarrow e^+e^-\, \pi^0$
- Larger cross section and easier pionic background subtraction (side-band)
- Q^2 is fixed, but $1+\cos^2\theta$ trend of $J/\psi\rightarrow e^+e^-$ decay can be checked

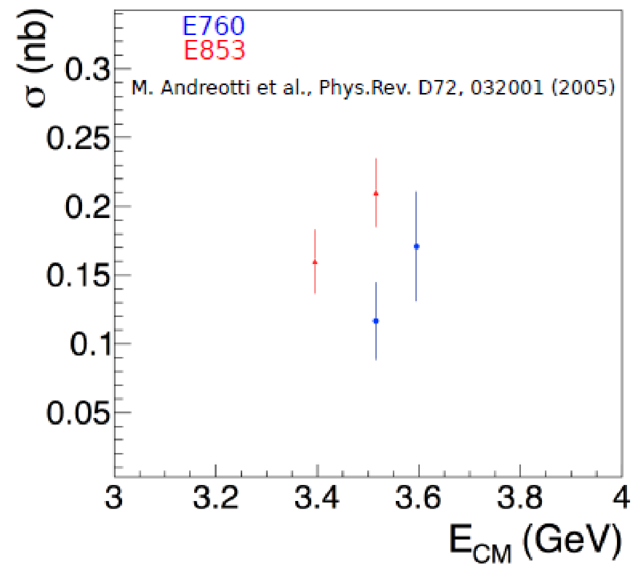


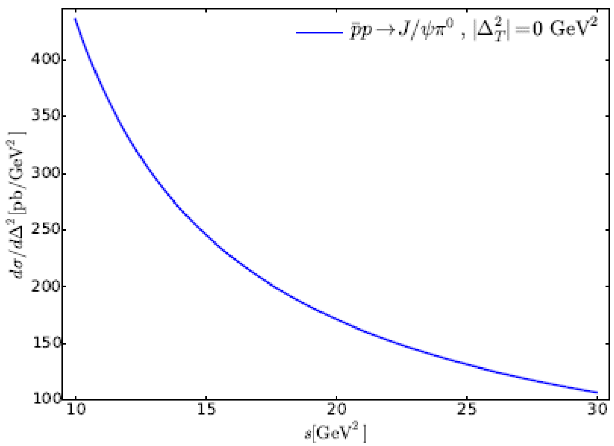
Cross section estimates with TDA model

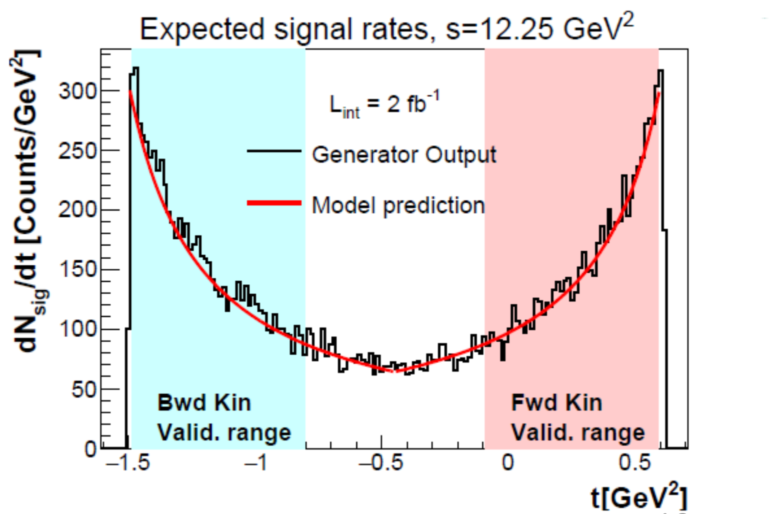
- Event generator for $\bar{p}p \to J/\psi\, \pi^0$ ($J/\psi \to e^+e^-$) based on TDA model

  B. Pire et al. Phys. Lett. B 724 99-107 (2013)

  B. Ma's PhD, université Paris-Sud, Orsay, 2014
- Cross sections consistent with scarce existing data
- Weak dependence of cross sections as a function of $\sqrt{s}$
- Full feasibility study at s= 12.3, 16.9 ,24.3 GeV^2 (p_p= 5.5, 8, 12 GeV/c) (E. Atomssa post doc work)







Background sources

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

- contaminates signal if (π^+, π^-) misidentified as (e^+,e^-) and invariant mass close to J/ψ mass
- Total cross sections based on existing data *V. Flaminio et al. CERN HERA 79-03 (1984).*
- Hadronic event generator DPM used for distributions

$p_{\bar{p}}$ (GeV/c)	S/B (production rate)
5.5	1.5×10^{-6}
8.0	1.0×10^{-5}
12.0	3.6×10^{-5}

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

- cross sections even larger than for $\pi^+\pi^- \pi^0$: $\sigma(\pi^+\pi^- \pi^0 \pi^0)$~ 3 x $\sigma(\pi^+\pi^- \pi^0)$ $\sigma(\pi^+\pi^- \pi^+\pi^- \pi^0)$~ (8-15) x $\sigma(\pi^+\pi^- \pi^0)$
- simulation based on DPM

$\bar{p}p \to J/\psi\, \pi^0 \pi^0$

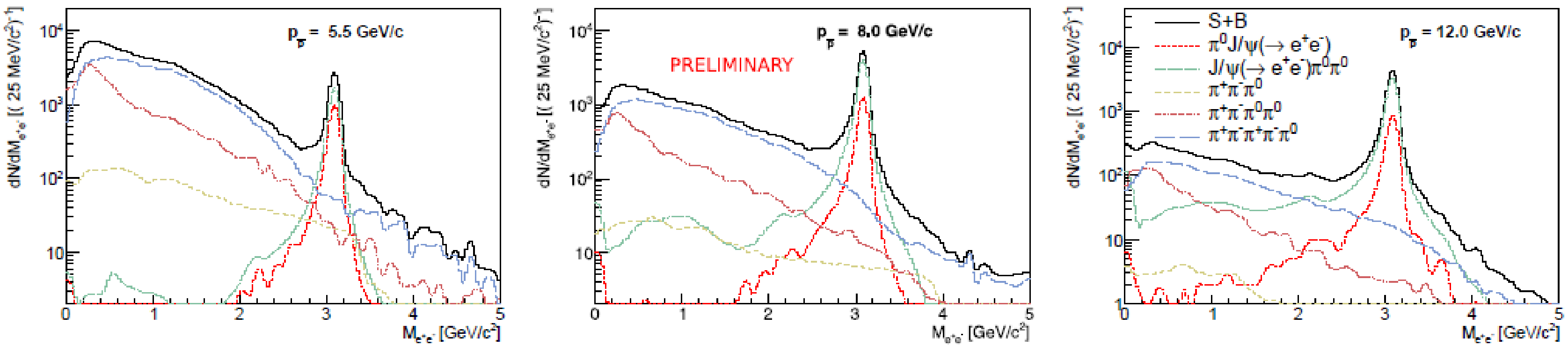
- Cross sections not known (will be measured by PANDA) input for simulations: σ= 35 , 52 and 40 pb at p= 5.5, 8 and 12 GeV/c respectively (= 3-4 x signal) based on conservative estimates

Rough estimate from Fermilab : σ < 3 pb at p=5.5 GeV/c

Cross section deduced from model at p= 7 GeV/c 30 pb (Chen et al. hep-ph:0802.2982)

Analysis procedure for $\bar{p}p \rightarrow J/\psi\ \pi^0$ ($J/\psi \rightarrow e^+e^-$) Particle IDentification

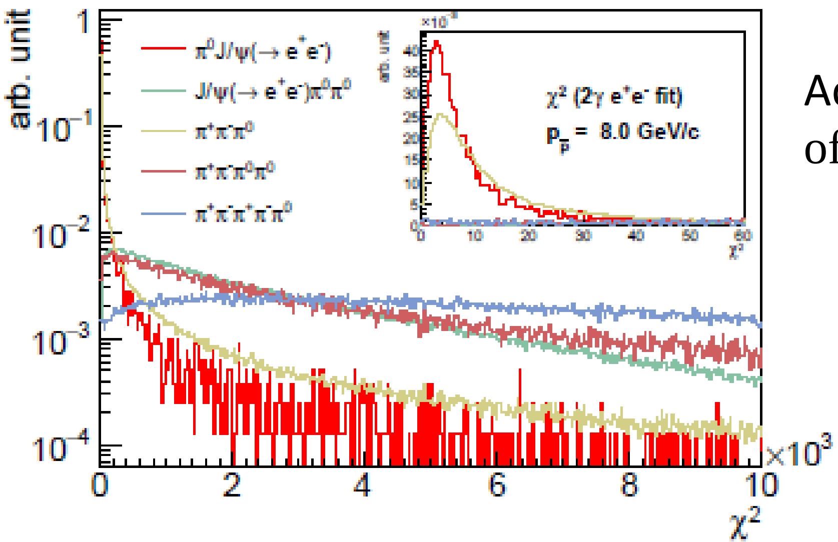
- Selection of all possible charged track pairs
- Cut on electron identification probability (using information from all detectors)
- π^0 selection ($\gamma\gamma$ kinematical correlation)
- Pick most back-to-back π^0-(e^+e^-) pair



Before 4 constraint kinematic fit:

- Background with pions in final states reduced to < 20 % level and can be further subtracted using side-band analysis
- Signal eff. ~ 18% (p=5.5 GeV/c)-9%(p=12 GeV/c)
- $\bar{p}p \rightarrow J/\psi\ \pi^0\ \pi^0$ larger (X3) than the signal in our conservative estimates

Analysis procedure for $\bar{p}p \to J/\psi\ \pi^0$ ($J/\psi \to e^+e^-$) kinematical fits



Additionnal cuts on χ^2 for 4 constraint kinematic fitting of $\bar{p}p \to e^+e^-\gamma\gamma$ and $\bar{p}p \to e^+e^-\gamma\gamma\ \gamma\gamma$:

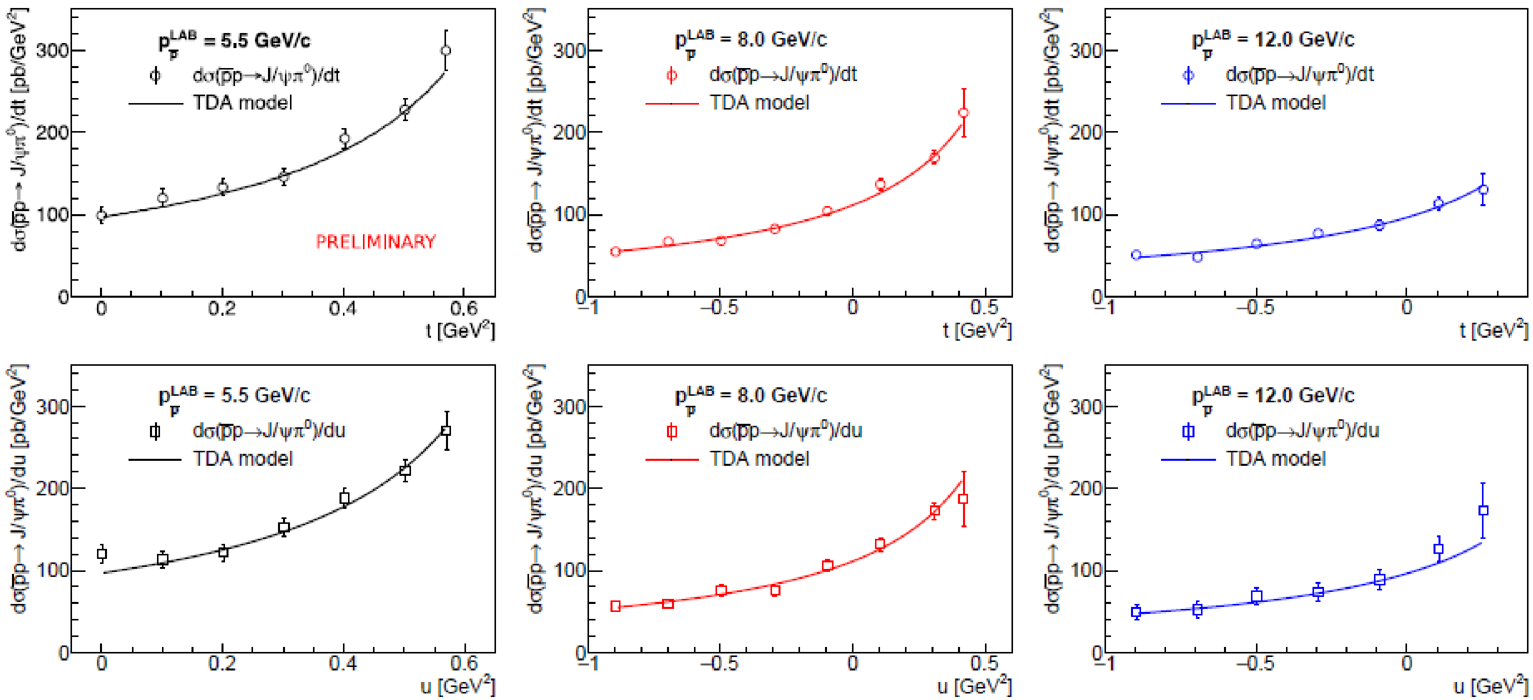
Final contamination results

- multipion channels < 4 % (can be further subtracted by side-band analysis)
- $\bar{p}p \to J/\psi\ \pi^0\pi^0$ <2% (conservative estimates, will be measured by PANDA)

Signal efficiency 11% (p=5.5 GeV/c)- 7% (p=12 GeV/c)

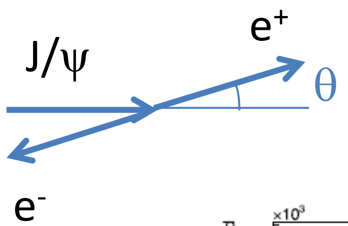
N. B. Possibility of measurement in parallel with charmonium studies: X(3872), Y(4260),…
(no or rare decay to $J/\psi\ \pi^0$, $J/\psi\ \pi^0\ \pi^0$ or multipion channels)

Precision on cross section measurement

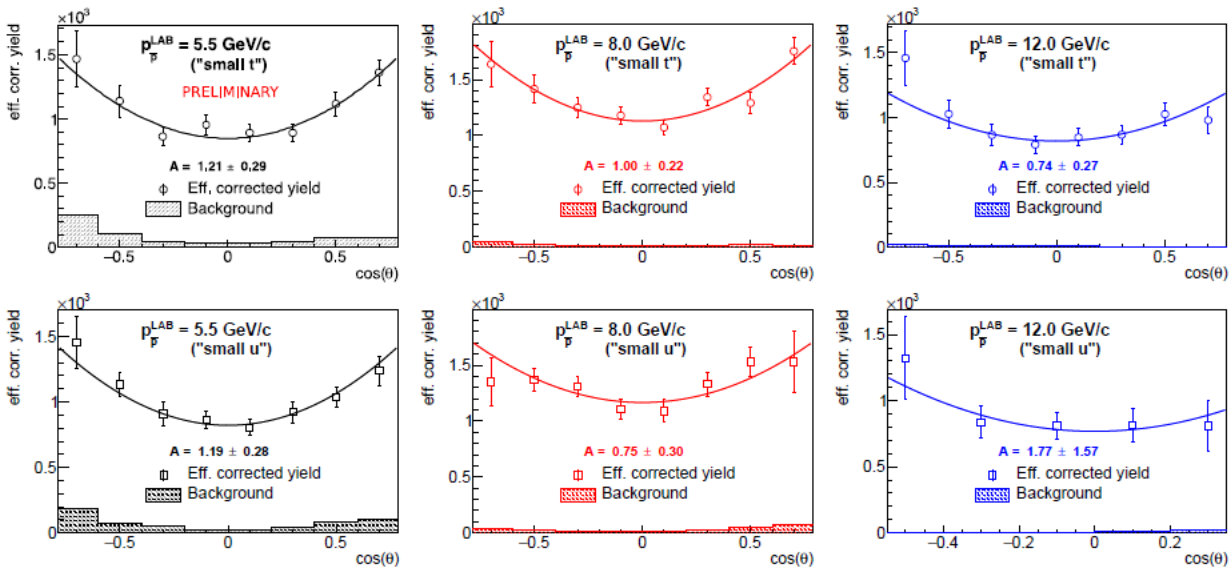


Integrated luminosity of L_{int}=2 fb^{-1} *(5 months in high luminosity mode)*
Efficiency correction based on a separated high statistics signal simulation
→ Differential distribution reconstructed with good precision
→ Very promising results for TDA studies

e^+/e^- angular distributions



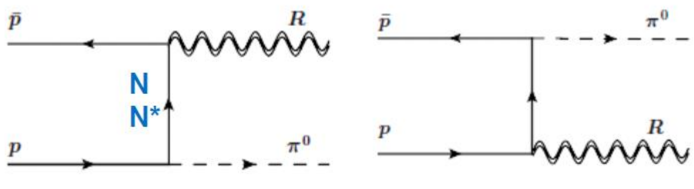
Expected in collinear factorized description $\frac{d\sigma}{d\theta_e} \sim 1 + \cos^2\theta_e$



- Check of collinear factorization accessible for forward emitted π^0.
- Could be accessed also for backward emitted π^0 by including tracking in the most forward angles.

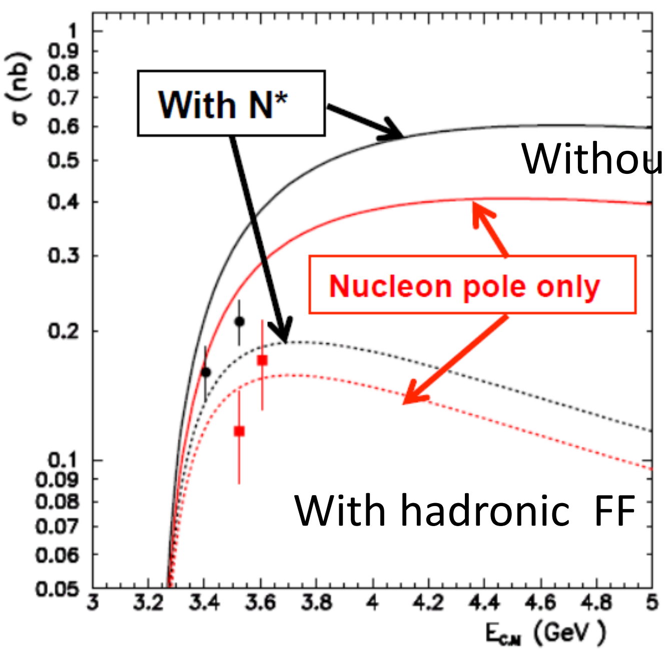
Subm. to PRD, Oct. 2016

$\bar{p}p \to J/\psi\ \pi^0$ in Lagrangian models



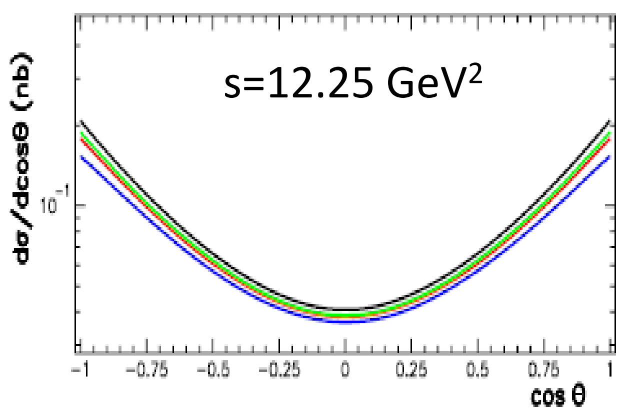
*J. Van de Wiele and S. Ong Eur. Phys. J. C (2013) **73**: 2640*

Pseudo Scalar πNN coupling



Without hadronic FF

With hadronic FF



Expected precision on dσ/dcosθ better than 10% for 2 fb^{-1}
→PANDA can provide valuable tests of TDA/hadronic models for $\bar{p}p \to J/\psi\ \pi^0$

Conclusion

- PANDA: bright scientific program in $\bar{p}p$ annihilation
- Offers new possibilities to access nucleon observables
- IPN Orsay:
  - R&D studies for ElectroMagnetic Calorimeter
  - Software developments
  - Feasibility studies and phenomenological developments for time like electromagnetic form factors
  - Recent full scale feasibility study for $\bar{p}p \to J/\psi\ \pi^0$ (test of TDA or hadronic models)

IPNO PANDA team : E. Atomssa, J. Boucher, M. Gumberidze (Sudol), T. Hennino, R. Kunne, B. Ma, D. Marchand, S. Ong, B. R., E. Tomasi-Gustafsson, J. Van de Wiele , Wang Ying
R&D: B. Gajewski, M. Imre, C. Le Galliard, G. Minier, P. Rosier, L. Seminor
A. Maroni, C. Theneau…

PANDA collaboration

~ 520 physicists
~17 countries

52th PANDA collaboration meeting
organized by E. Tomasi-Gustafsson and D. Marchand in 2012

Thank you

Cross Section Estimates of TDA Model

B. Pire *et al.*, Phys. Lett. B. 724 99–107 (2013): $\bar{p}p \to J/\psi\pi^0$

$$\frac{d\sigma}{d\Delta^2} = \frac{1}{16\pi\Lambda^2(s,\ m_N^2,\ m_N^2)}|\overline{\mathcal{M}_T}|^2,$$

$$|\overline{\mathcal{M}_T}|^2 = \frac{1}{4}|\mathcal{C}|^2\frac{2(1+\xi)}{\xi\bar{M}^8}\left(|\mathcal{I}(\xi,\ \Delta^2)|^2 - \frac{\Delta_T^2}{m_N^2}|\mathcal{I}'(\xi,\ \Delta^2)|^2\right).$$

$$\mathcal{C} = (4\pi\alpha_s)^3\frac{f_N^2 f_\psi}{f_\pi}\frac{10}{81},\quad \mathcal{I}(\xi,\Delta^2) = \frac{f_\pi\, g_{\pi NN}\, m_N(1-\xi)}{(\Delta^2 - m_N^2)(1+\xi)}M_0,\quad \mathcal{I}'(\xi,\Delta^2) = \frac{f_\pi\, g_{\pi NN}\, m_N}{(\Delta^2 - m_N^2)}M_0,$$

- Collinear factorization (CF) approach prediction of differential cross section
- $\mathcal{I}(\xi,\Delta^2)$, $\mathcal{I}'(\xi,\Delta^2)$: convolutions of hard scattering kernels with πN TDAs and phenomenological solutions of the leading twist (anti)nucleon Distribution Amplitudes (DA).
- Strong coupling α_s fixed to reproduce $\Gamma(J/\psi \to \bar{p}p)$ together with selected DA

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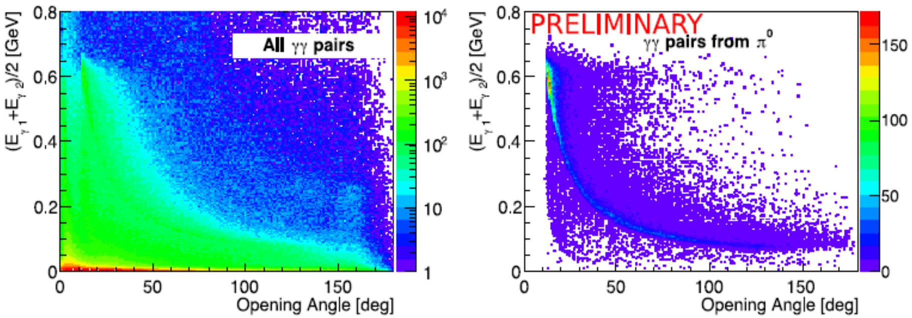
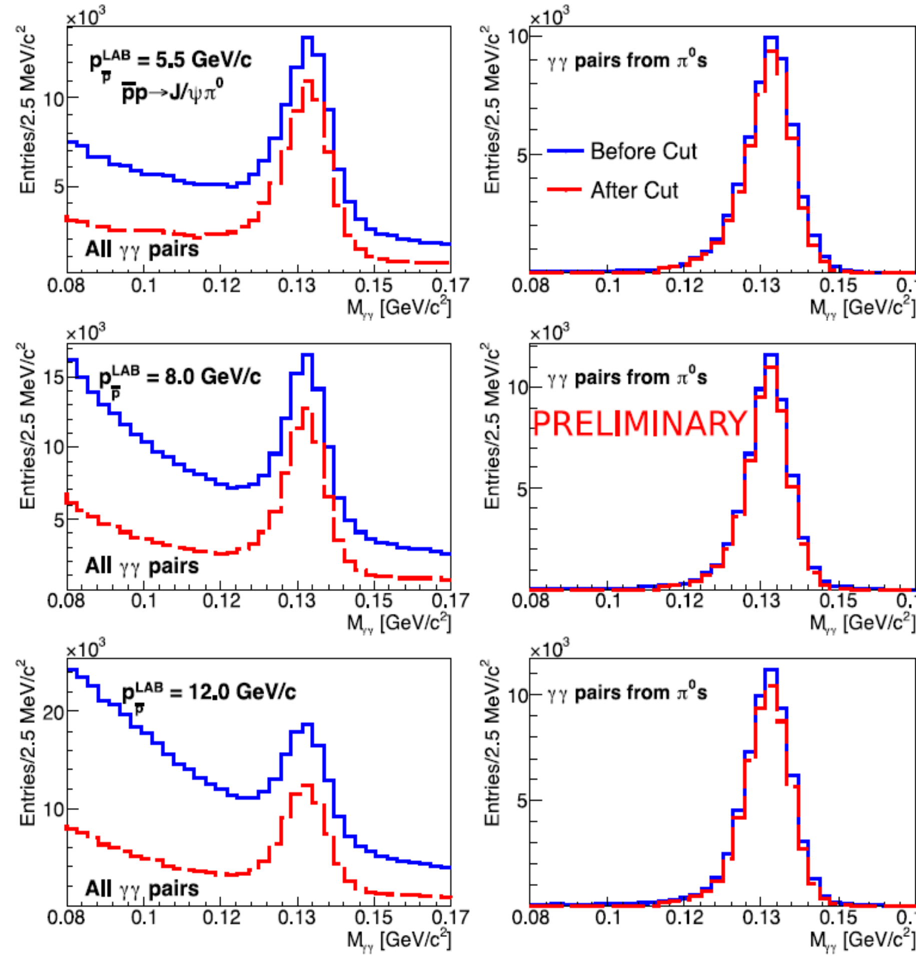
π^0 Selection in $\bar{p}p \rightarrow J/\psi\pi^0$





- Significant combinatorial background from uncorrelated $\gamma\gamma$ pairs
- Distinct signal opening angle – energy correlation from combinatorial background
- Sufficient to reduce background with minimal cost on true π^0's
- Mass cut $110 < M_{\gamma\gamma}[MeV/c^2] < 165$ is also applied