The Abdus Salam
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United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1942-47

Sixth International Conference on Perspectives in Hadronic Physics

12 - 16 May 2008

Experimental prospects at GSI (Panda and PAX).

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UK

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PANDA & PAX @ FAIR

Exploring Nucleon Structure with Antiprotons

Ralf Kaiser, University of Glasgow

- The High Energy Storage Ring at FAIR
- The PANDA Experiment
- The PAX Experiment
- Nucleon Structure with PANDA & PAX

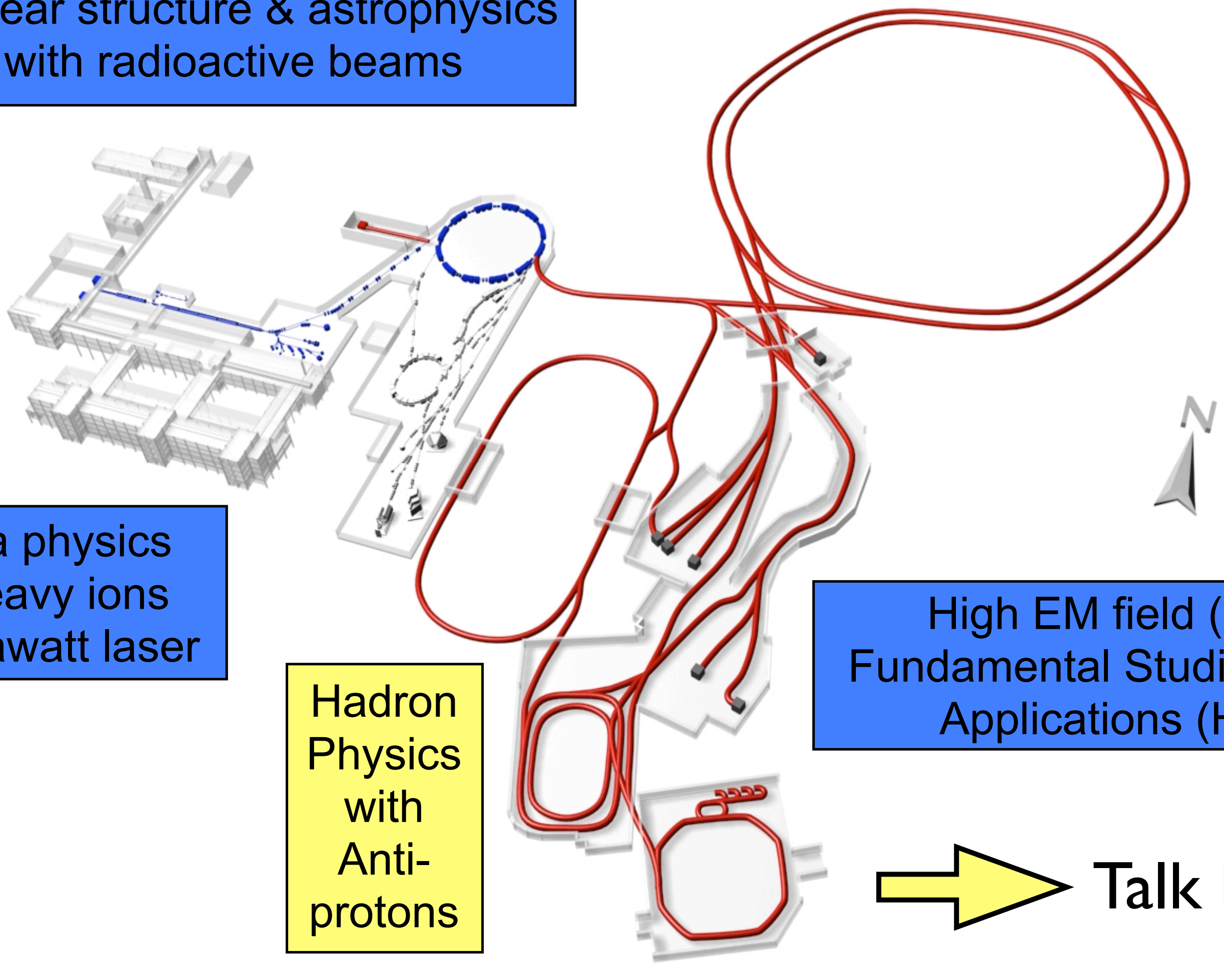
Thanks to P.Lenisa & F.Rathmann for Material on PAX

UNIVERSITY of GLASGOW

Research at FAIR

Nuclear matter physics with 35-45 GeV/u HI beams

Nuclear structure & astrophysics with radioactive beams



Plasma physics with heavy ions and petawatt laser

Hadron Physics with Anti-protons

High EM field (HI)
Fundamental Studies (HI)
Applications (HI)

→ Talk by K.Peters

HESR - High Energy Storage Ring

- Circumference 442.5 m
- Production rate 2x10^7/sec
- P_{beam} = 1 - 15 GeV/c
- N_{stored} = 5x10^{10}
- Internal Target

High Resolution Mode

$$\delta p/p \sim 10^{-5}$$

electron cooling

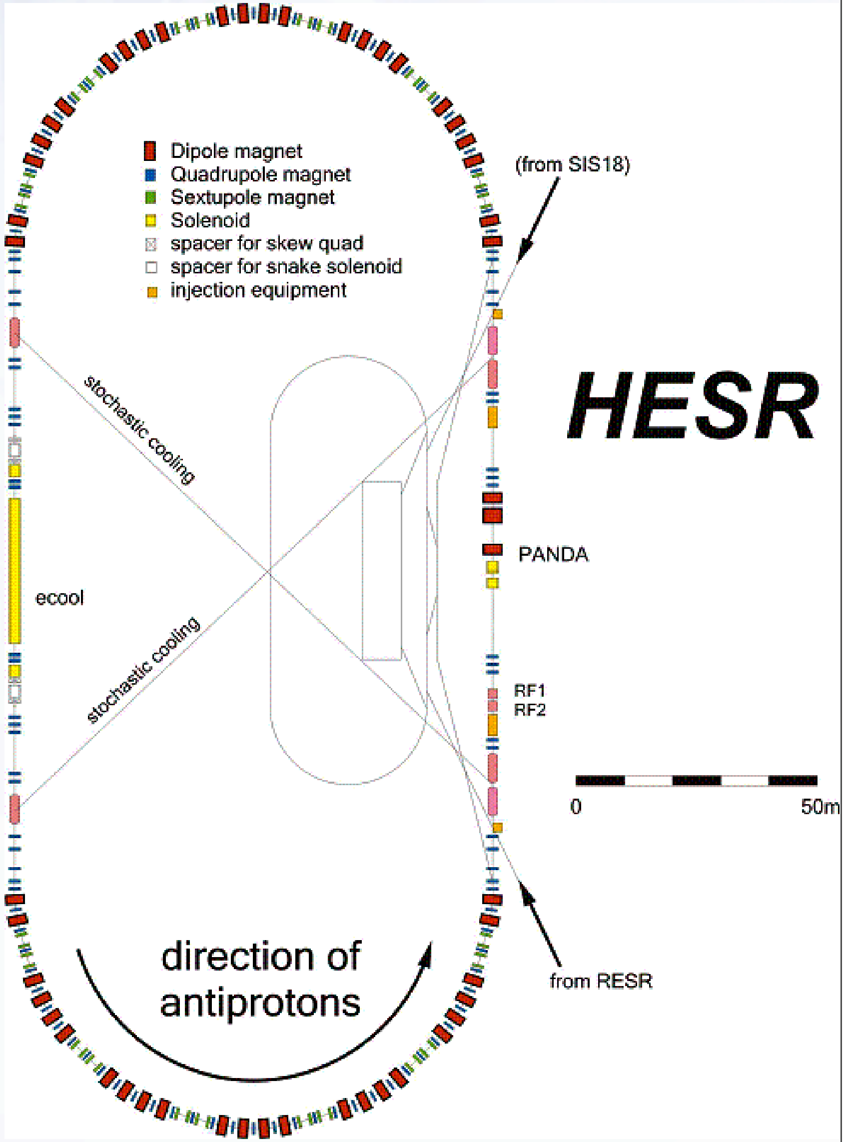
Luminosity: $10^{31} cm^{-2} s^{-1}$

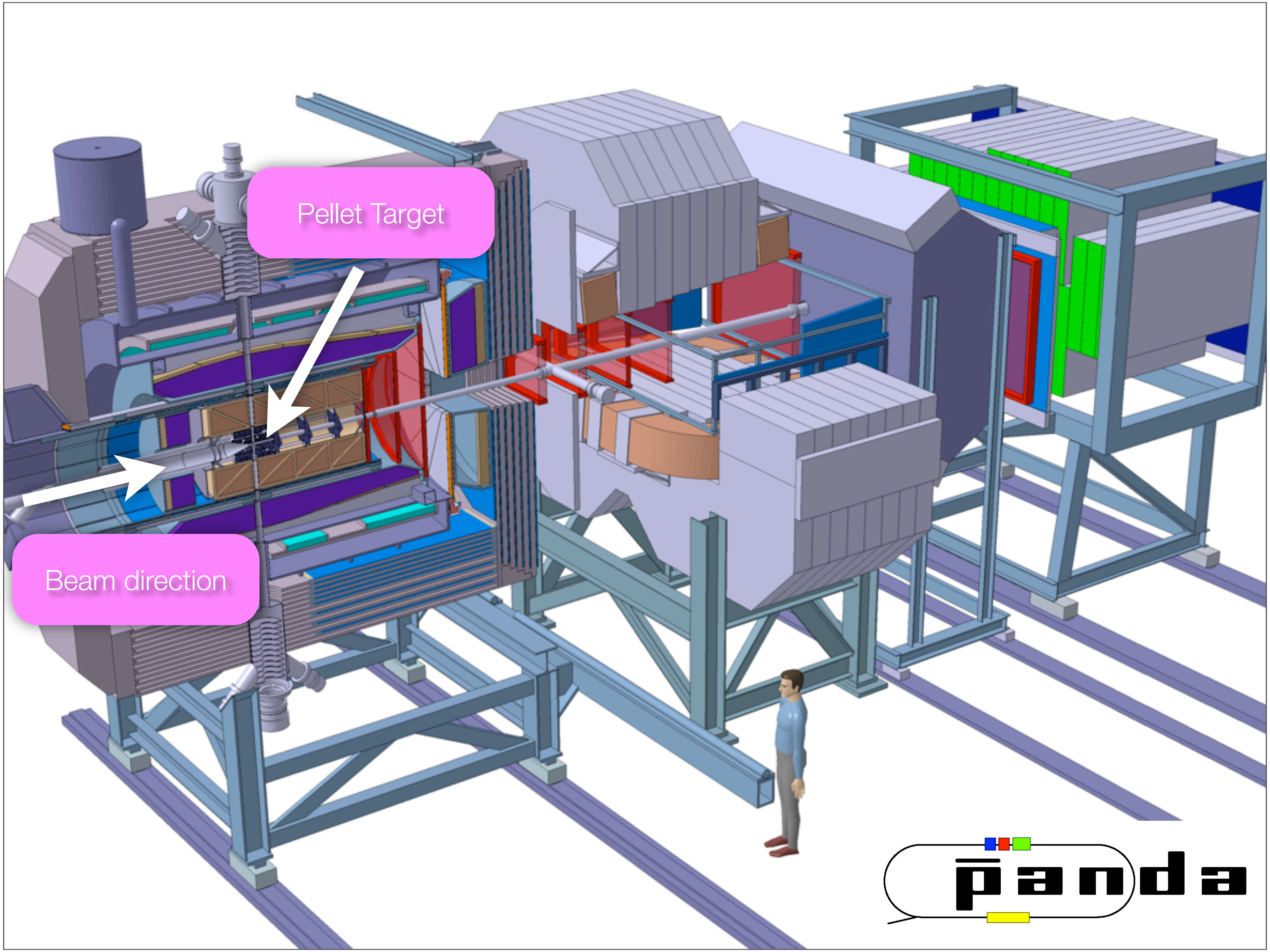
High Luminosity Mode

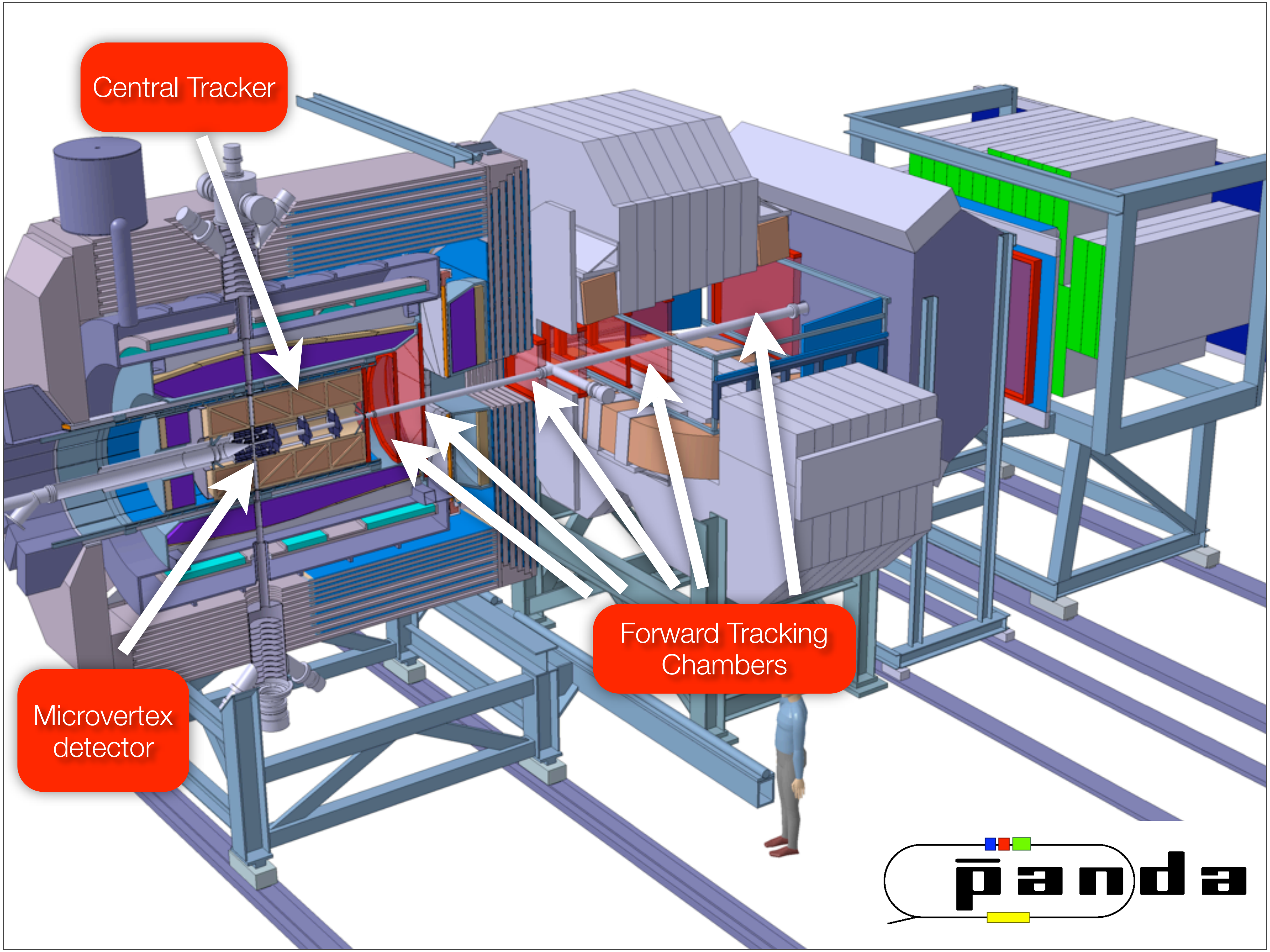
$$\delta p/p \sim 10^{-4}$$

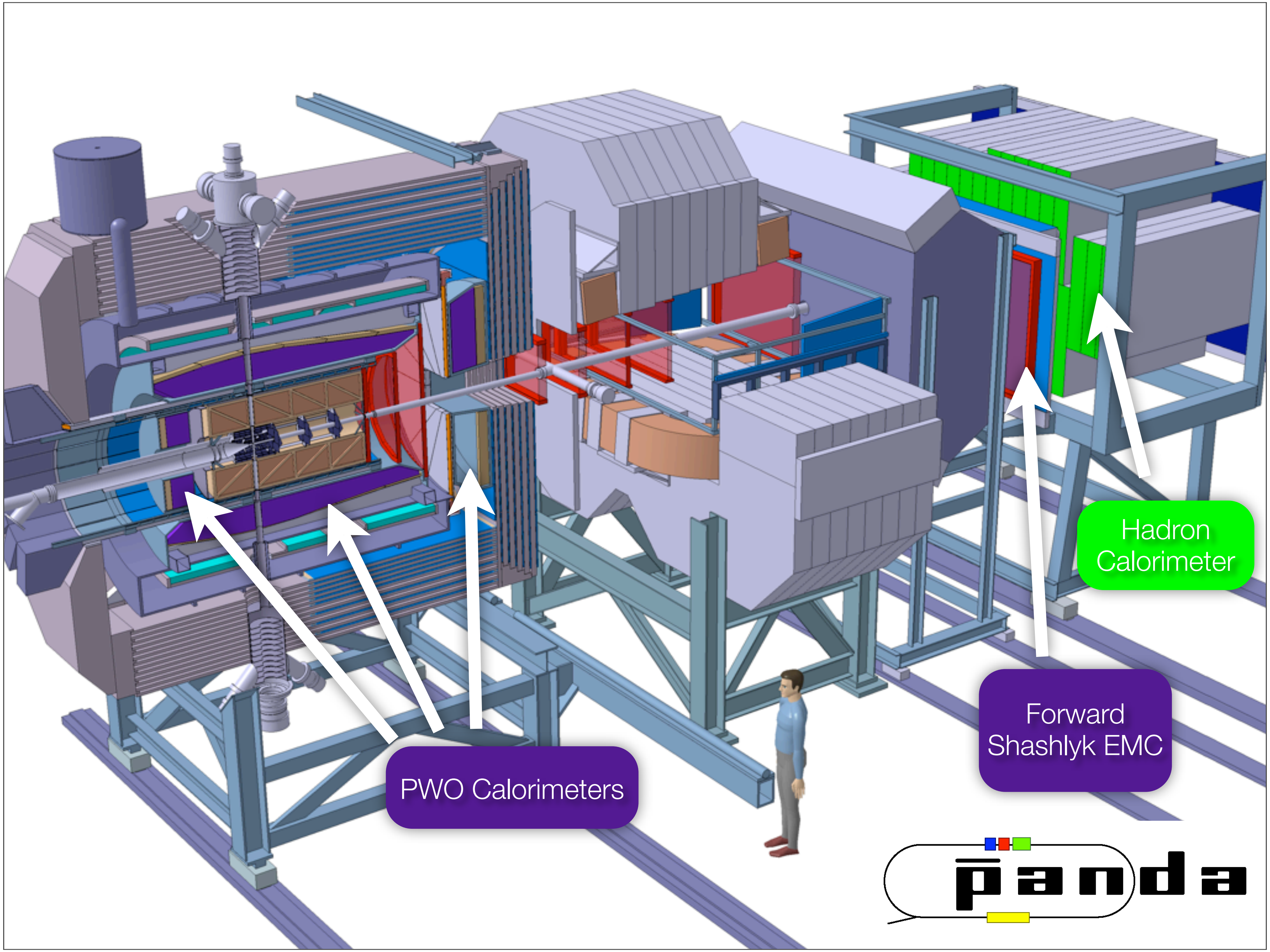
stochastic cooling

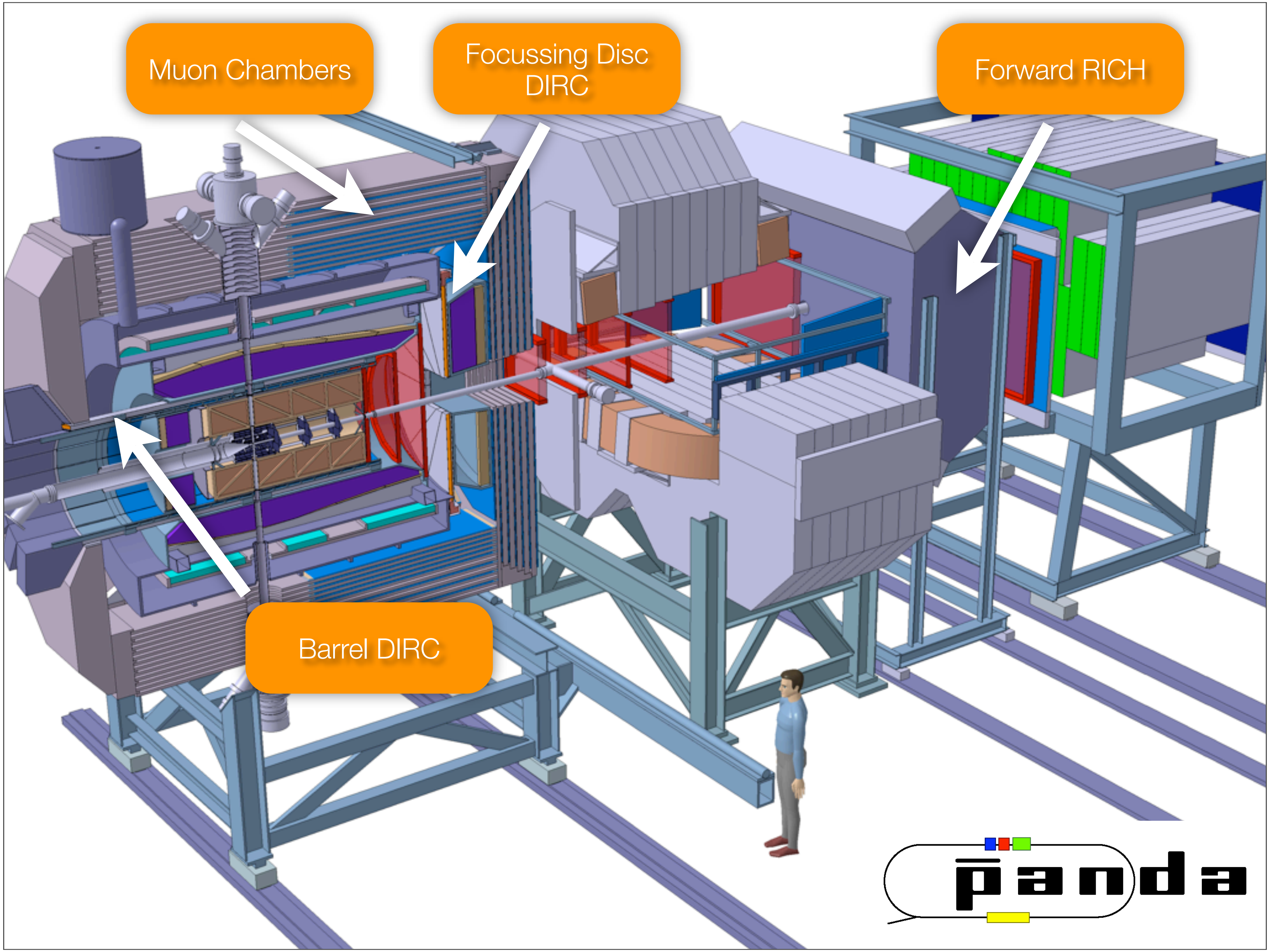
Luminosity: $2 \cdot 10^{32} cm^{-2} s^{-1}$



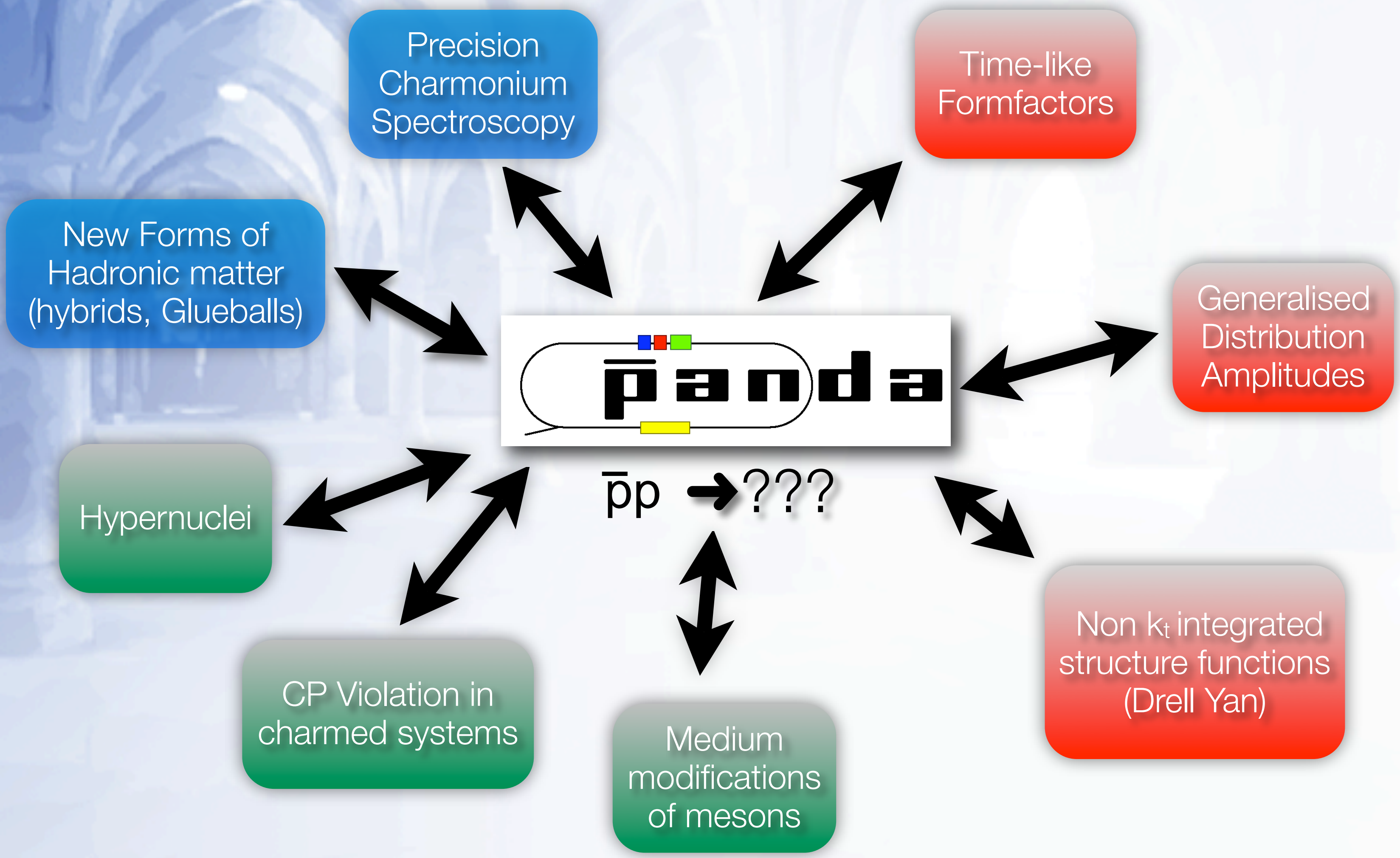

Pellet Target
Beam direction
panda


Central Tracker
Microvertex detector
Forward Tracking Chambers
panda


Hadron
Calorimeter
Forward
Shashlyk EMC
PWO Calorimeters


Muon Chambers
Focussing Disc DIRC
Forward RICH
Barrel DIRC
panda

Physics at PANDA

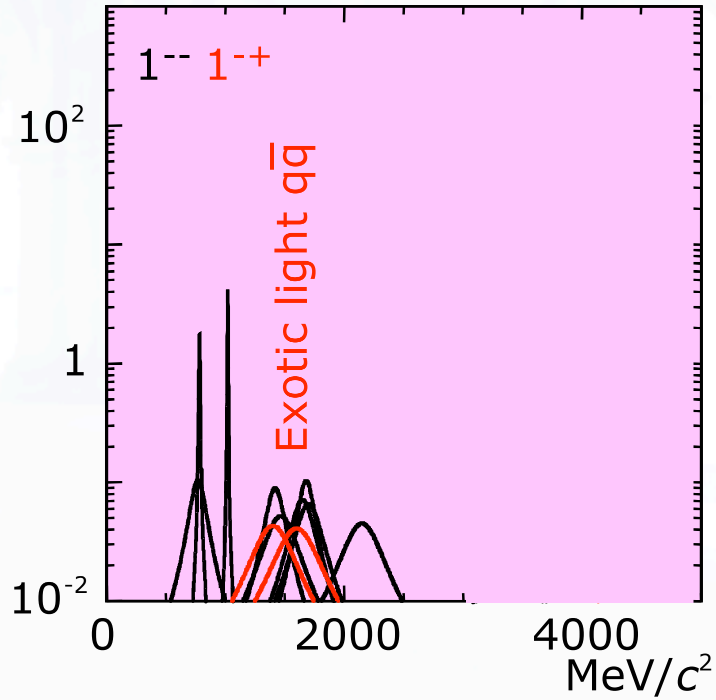


Exotic Hadrons

The QCD spectrum is much richer than expected from the naive quark model, because also gluons can act as hadron components

The "exotic hadrons" fall in 3 general categories:

Multiquarks	$qq\bar{q}\bar{q}$	
Hybrids	$qg\bar{q}$	
Glueballs	gg	



In the light meson spectrum exotic states overlap with conventional states

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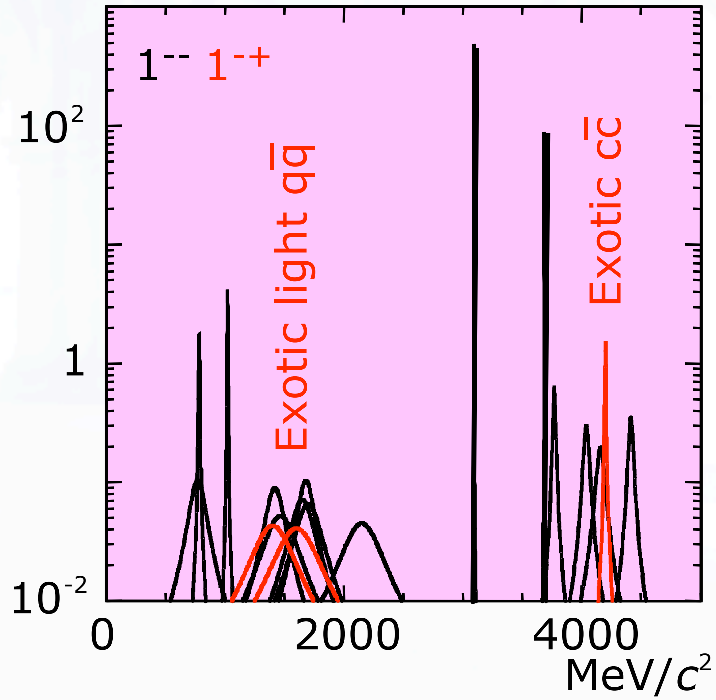
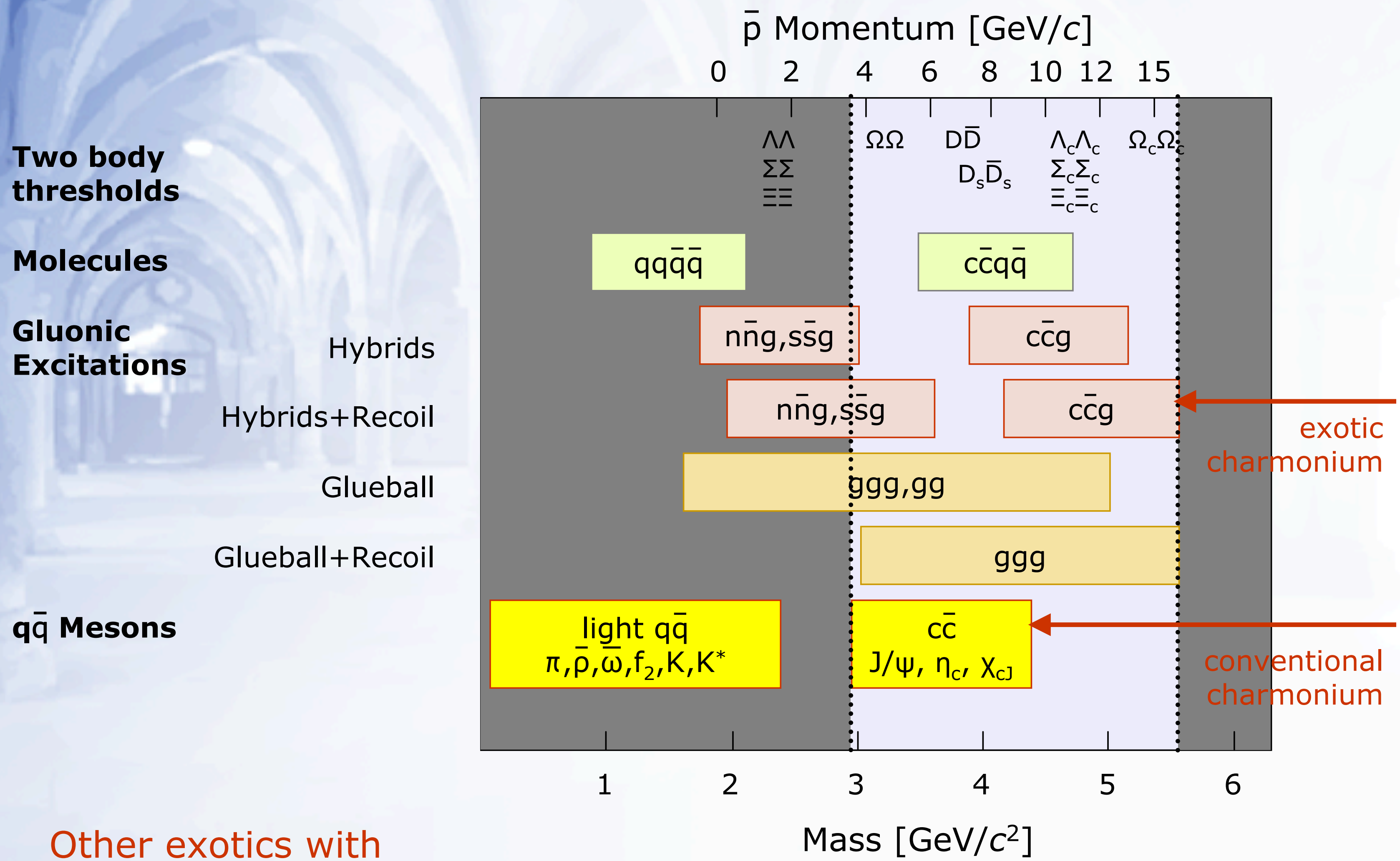
Hybrids $qg\bar{q}$ 

Glueballs gg 



In the light meson spectrum exotic states overlap with conventional states, while in the cc meson spectrum the density of states is lower ⇒ less overlap

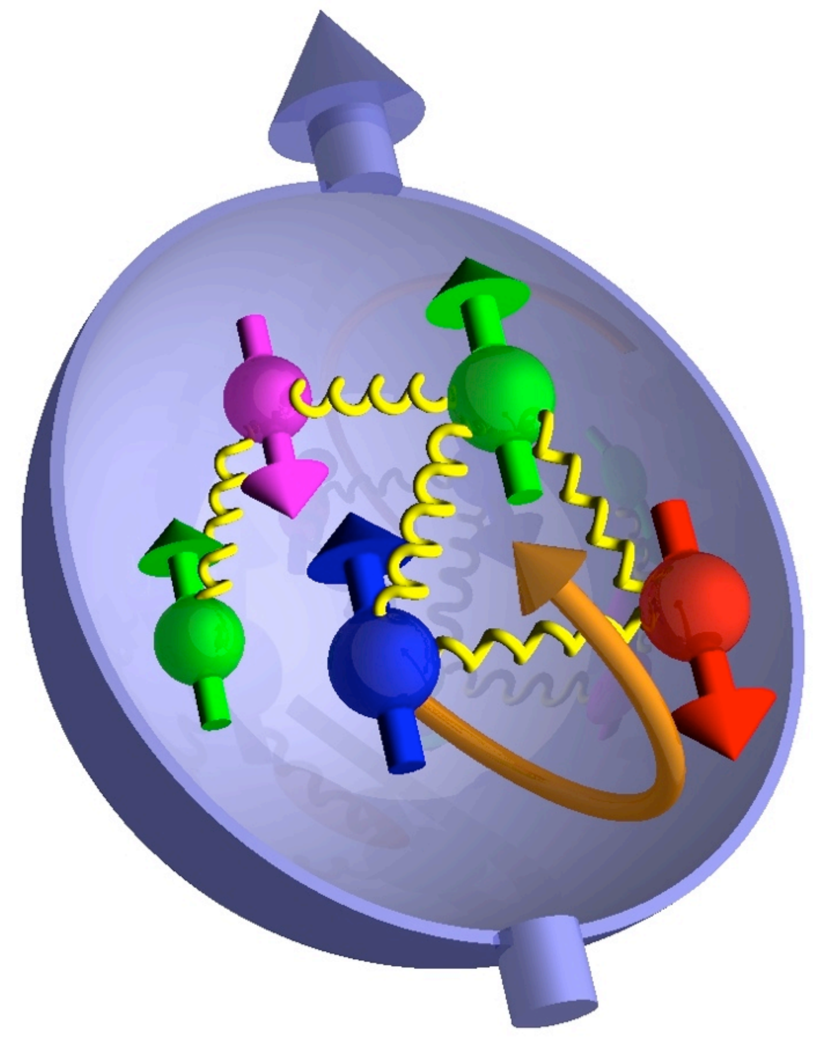
Accessible Mass Range at PANDA



Other exotics with identical decay channels → same region

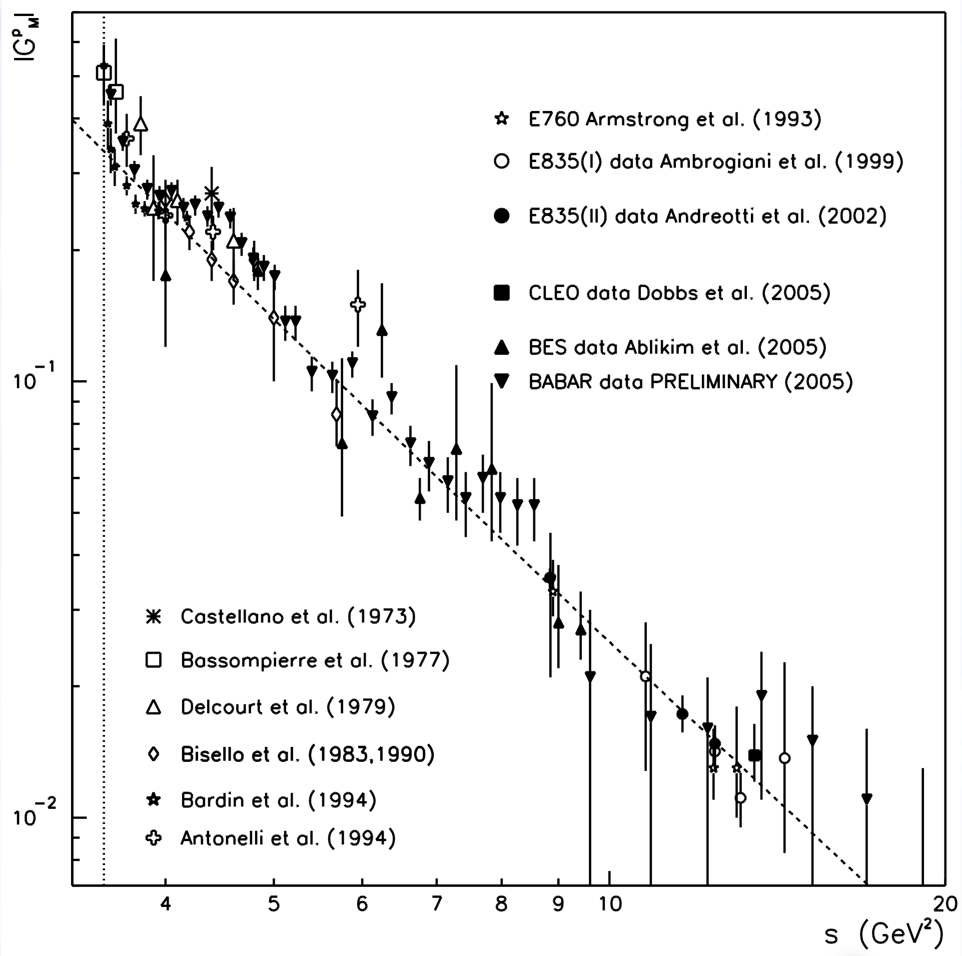
Nucleon Structure at PANDA

- Timelike Form Factors
- Transition Distribution Amplitudes
- Boer-Mulders Parton Distribution Function



Time-like Proton Form Factors

- All existing data measure absolute cross section $G_E = G_M$
- PANDA will provide independent measurements of G_E and G_M
- widest kinematic range in a single experiment
- Time-like form factors are complex
- precision experiments will reveal these structures

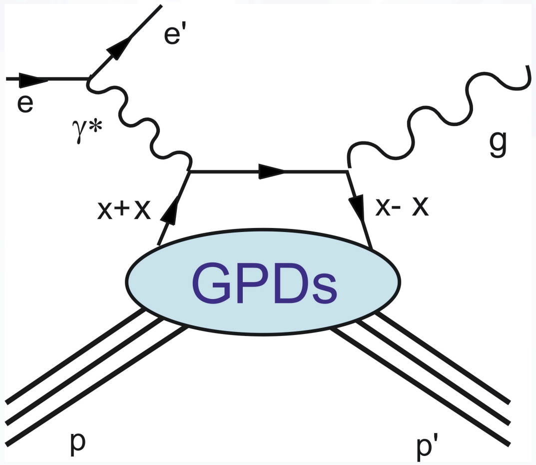


PANDA range

up to 25 GeV^2

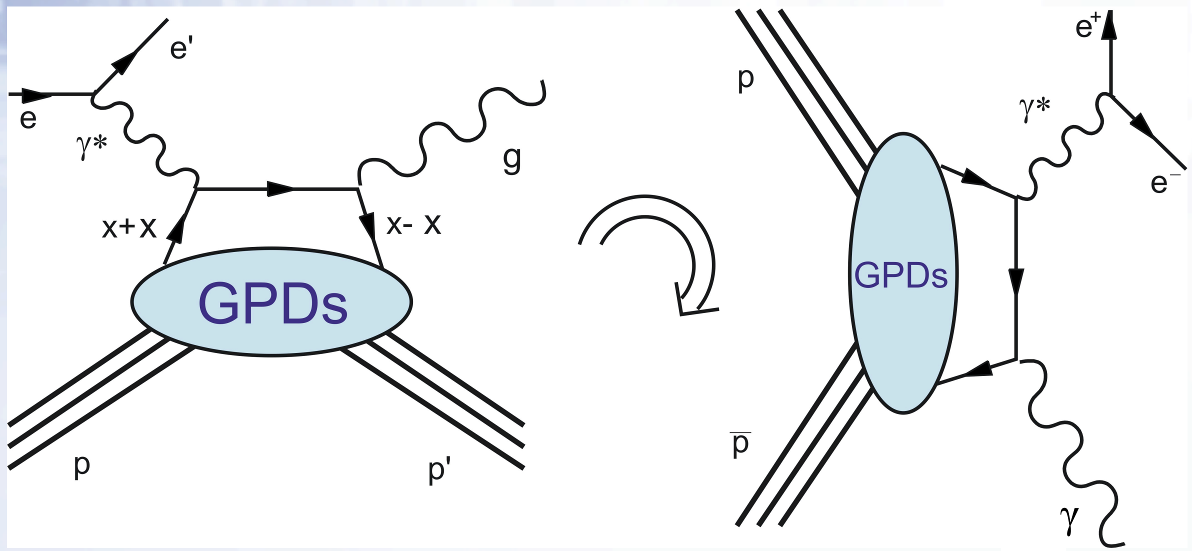
Hard Exclusive Reactions

- The prototype of all hard exclusive reactions is Deeply Virtual Compton Scattering.
- DVCS is one of the modern tools to explore the structure of the nucleon.
- Simplest process to measure Generalised Parton Distributions
- Allows to access the orbital angular momentum of quarks.
- Current and future experiments at HERMES, COMPASS and JLAB

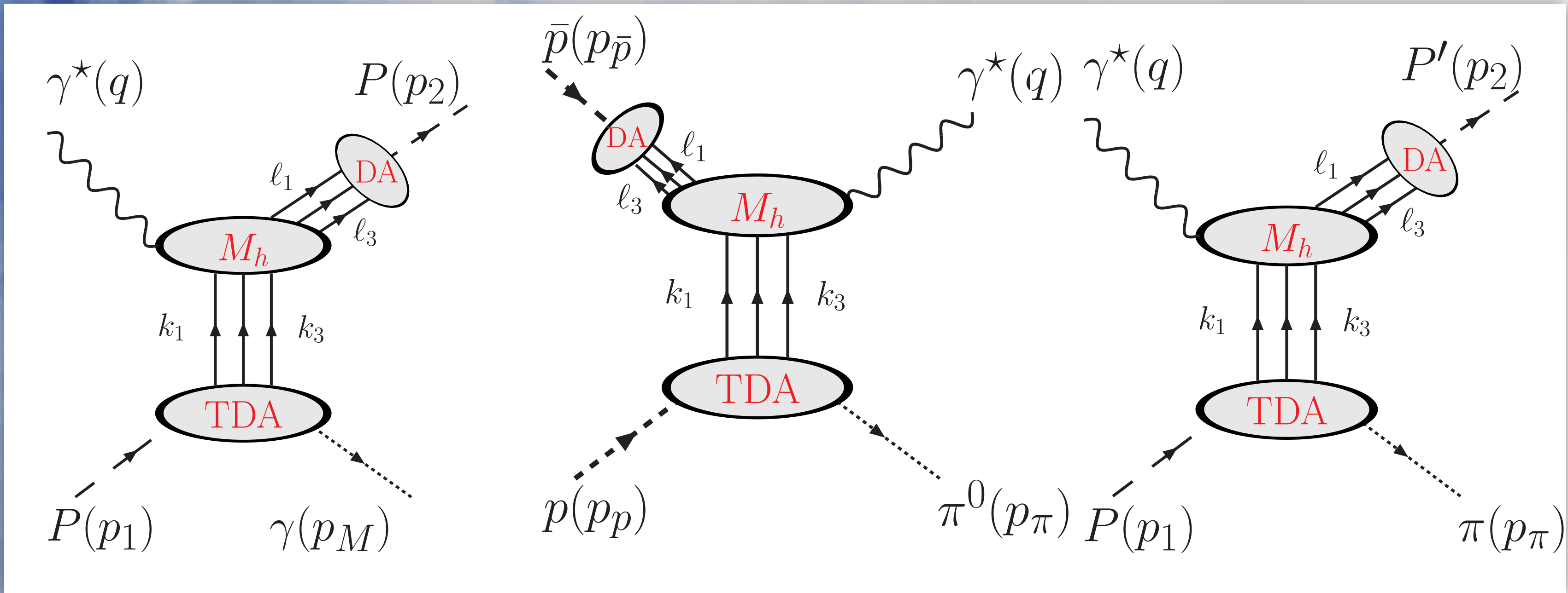


DVCS at PANDA

- PANDA can measure the ‘cross channel’ or ‘time-like’ version of the same process, that depends on the same GPDs
- More precisely on Generalised Distribution Amplitutes, introduced by M.Diehl et.al. to describe the inverse process [PRL.81:1782 (1998)].



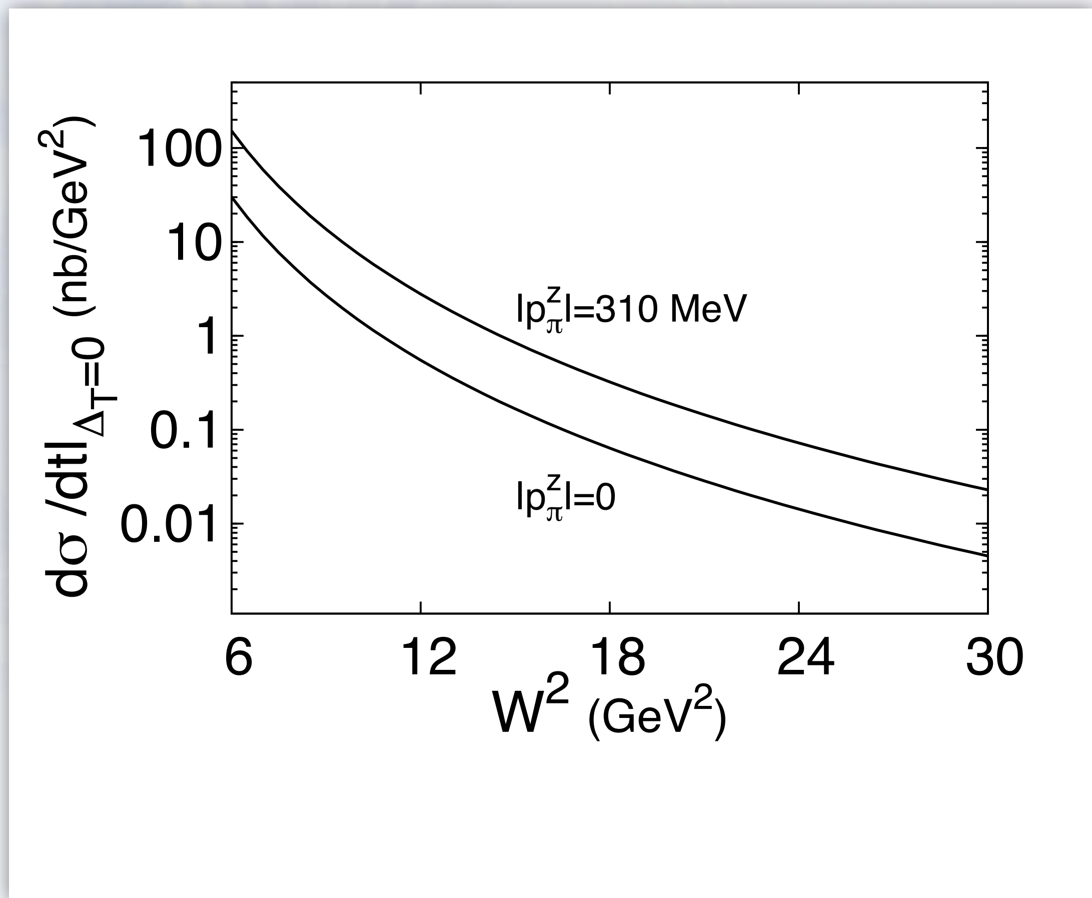
Transition Distribution Amplitudes



- TDAs extend the GPD concept to transitions
  [B.Pire, L.Szymanowski, PLB 622 (2005) 83, J.P.Lansberg et al. Nucl.Phys. A782 (2007) 16-23]
- Impact parameter space interpretation as for GPDs
- Fourier transform gives a transverse picture of the pion cloud in the proton

Transition Distribution Amplitudes

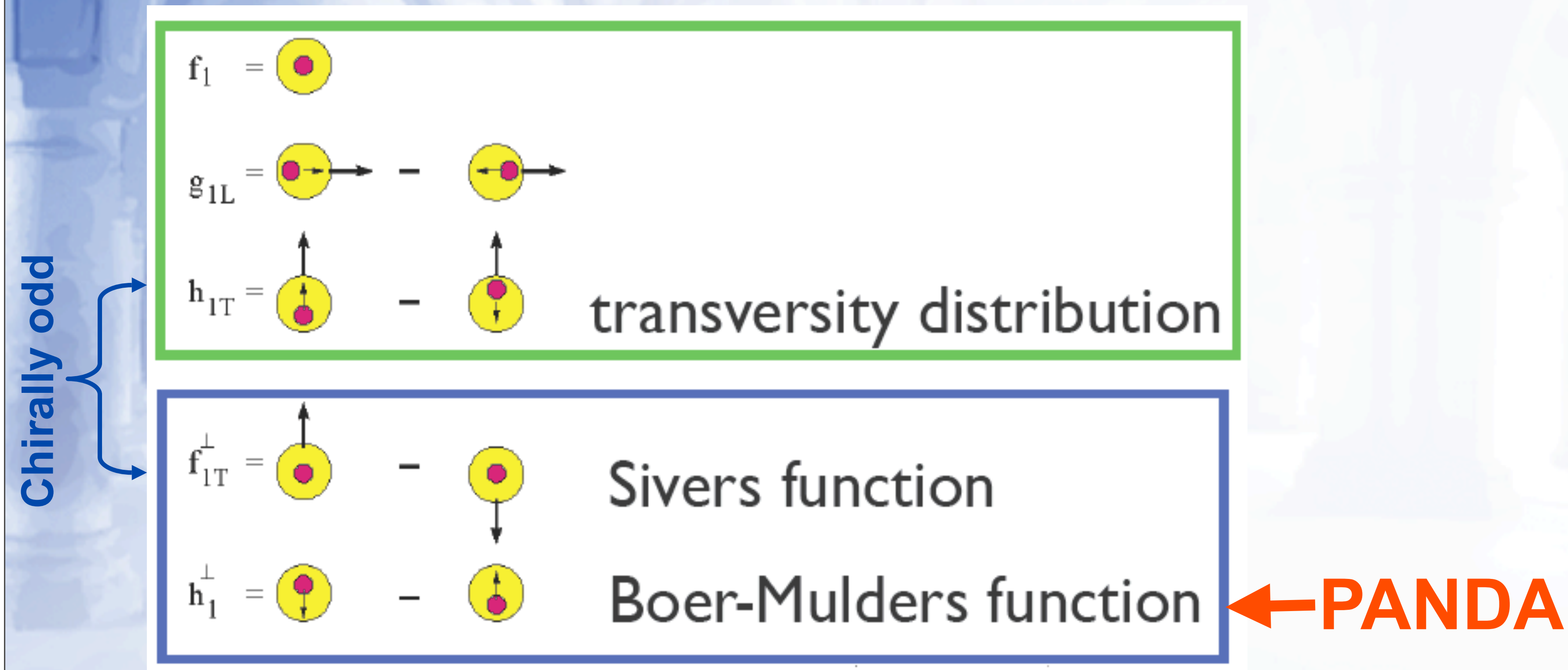
- Current models of TDA predict small cross section (~100 fb)
- Need excellent detector system to remove background
- Measurement feasible with PANDA



J. P. Lansberg et al. arXiv: 0710.1267v1

Parton Distribution Functions

Leading twist



T-odd

Drell-Yan angular distribution

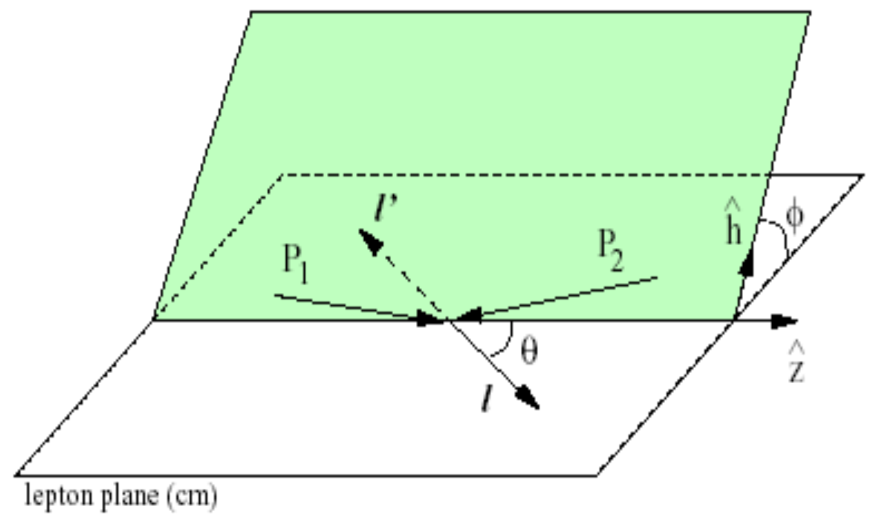
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

- Experimentally, a violation of the Lam-Tung sum rule is observed by sizeable cos2Φ moments
- Several model explanations
  - higher twist
  - spin correlation due to non-trival QCD vacuum
  - Non-zero Boer Mulders function

$$\text{Lam} - \text{Tung SR}: \; 1-\lambda = 2\nu$$

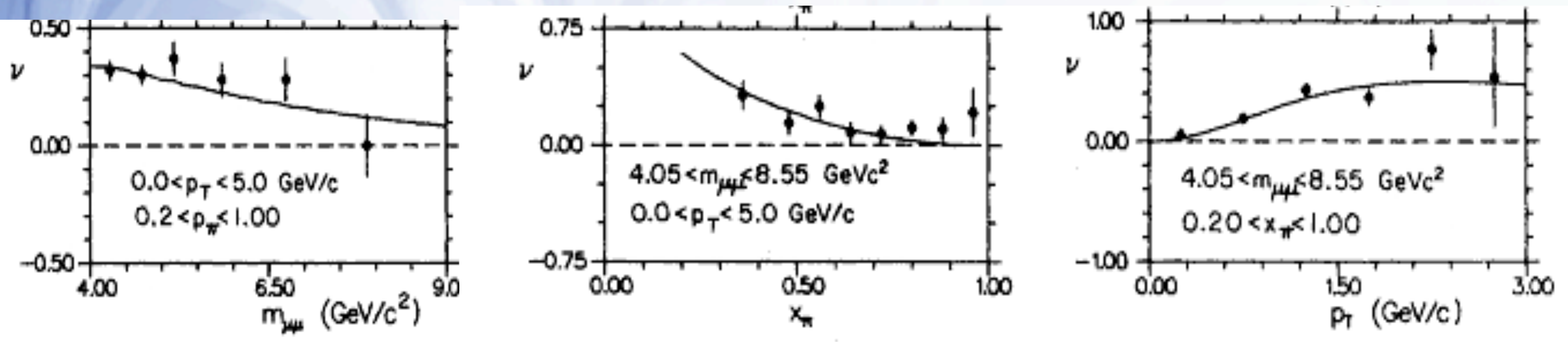
$$\text{NLO pQCD}: \lambda \approx 1 \; \mu \approx 0 \; \nu \approx 0$$

$$\text{experiment}: \; \nu \approx 0.3$$

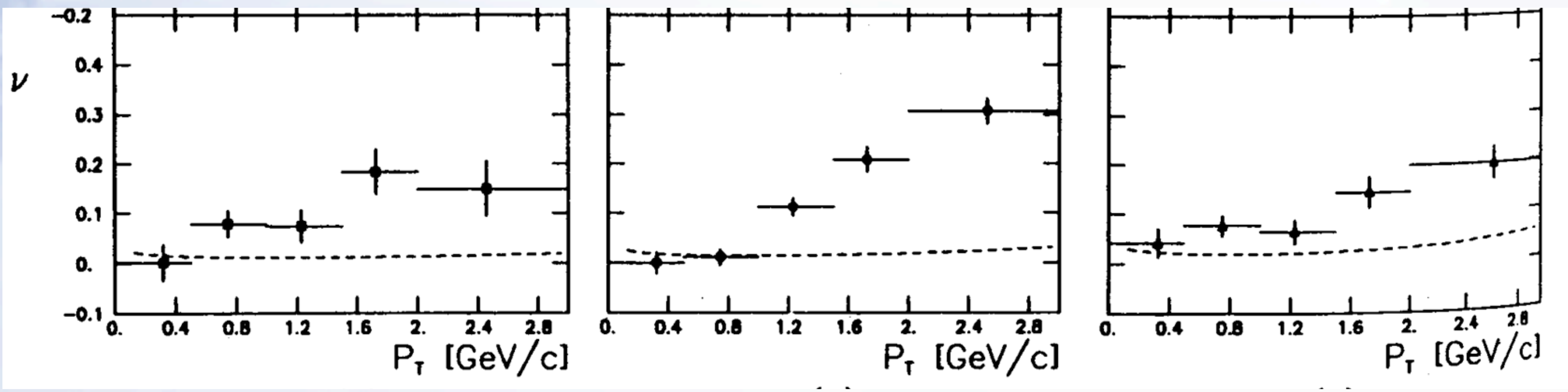


Azimuthal cos2φ Distribution in π-N Drell Yan

E615 at Fermilab: 252 GeV π^- + W Conway et al., PRD39,92(1989)



NA10 at CERN: 140/194/286 GeV π- + W Z. Phys. C37, 545 (1988)

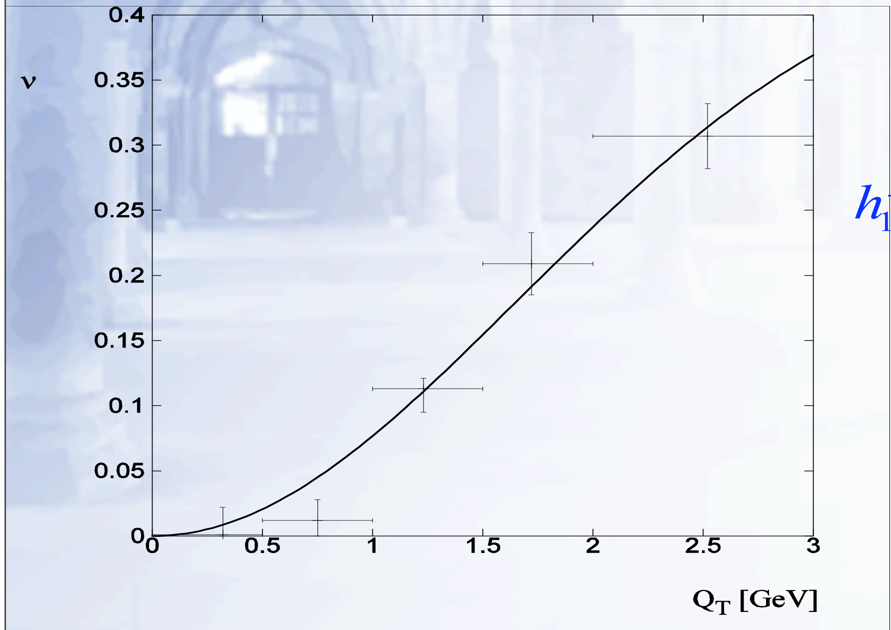


Boer-Mulders Function and NA10 Data

An approach in terms of $h_1^\perp$ can fit the NA10 data at 194 GeV.

Boer, PRD60,014012(1999)

$$\nu = 2\kappa = 4\kappa_1 \frac{Q_T^2 M_C^2}{(Q_T^2 + 4M_C^2)^2}; \quad \lambda = 1; \mu = 0$$



$$\nu \propto h_1^\perp(x_1)\bar{h}_1^\perp(x_2)$$

$$h_1^\perp(x, k_T^2) = \frac{\alpha_T}{\pi} c_H \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x)$$

$\kappa_1=0.5$

$m_C=2.3$

$\alpha_T=C_H=1$

Boer-Mulders Function

- Boer-Mulders distribution function $\mathbf{h_1}^{\perp}$ can be measured in unpolarised Drell-Yan at PANDA

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \sim \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

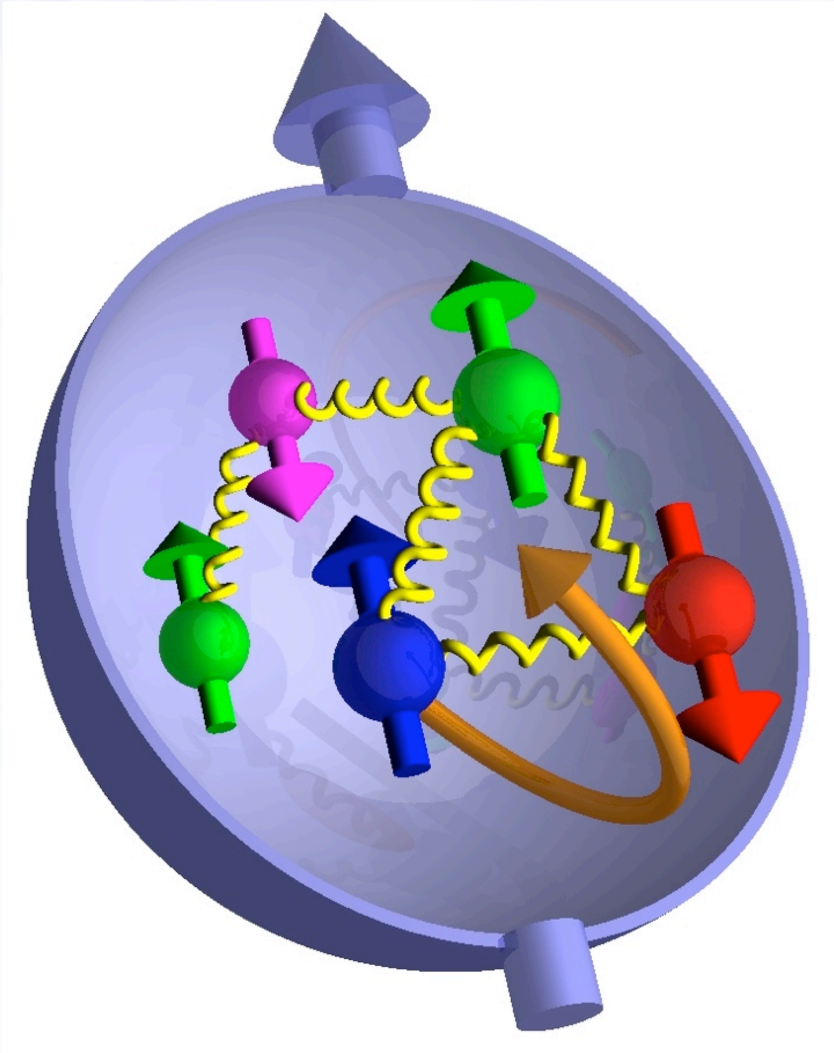
$$\nu \sim \sum_a e_a^2 \frac{h_1^{\perp} \bar{h}_1^{\perp}}{f_1 \bar{f}_1}$$

- Boer-Mulders function expected to be larger than Sivers function (measured at HERMES)

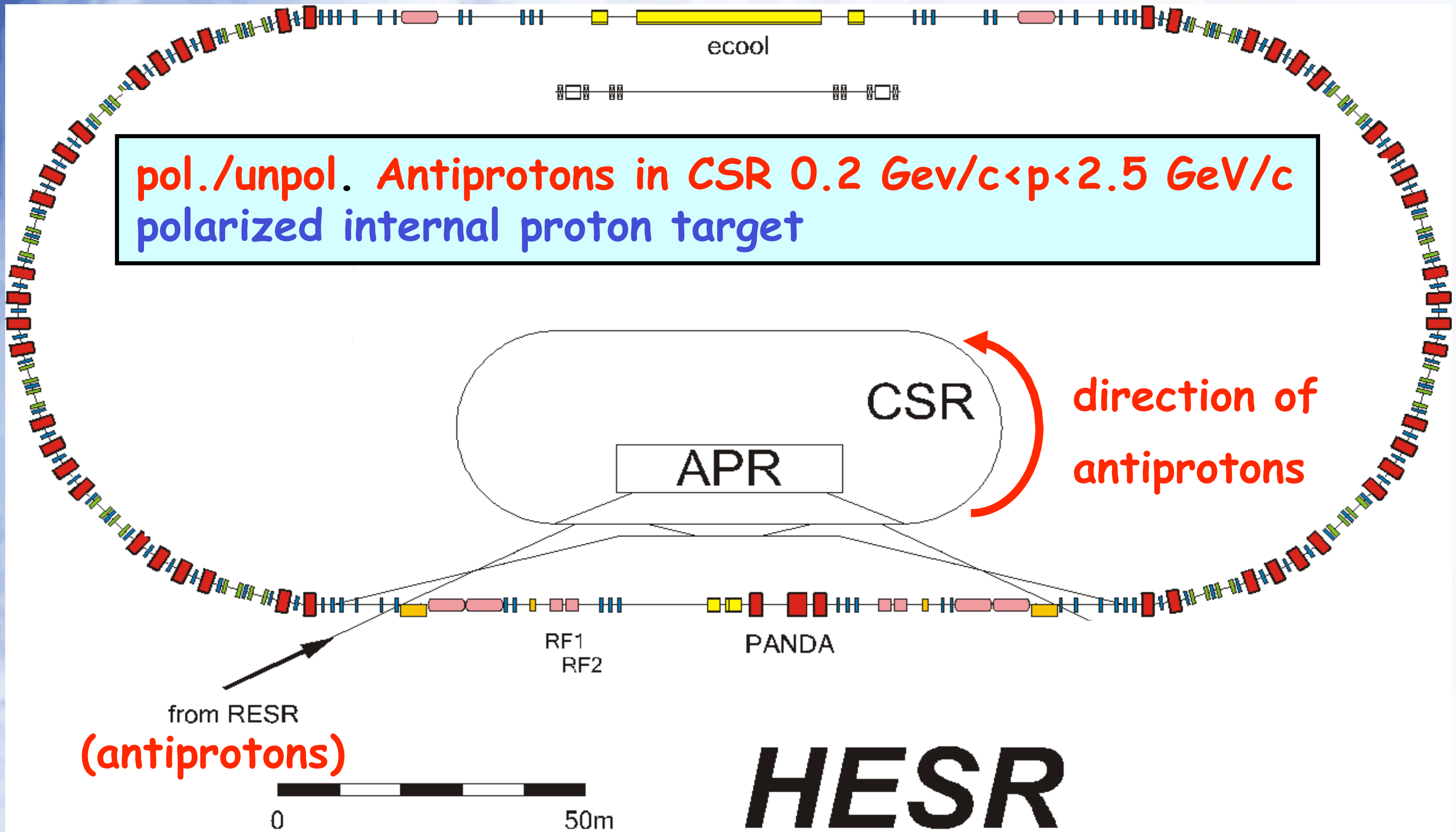
[M.Burkhardt, hep-ph/0611256]

Nucleon Structure at PAX

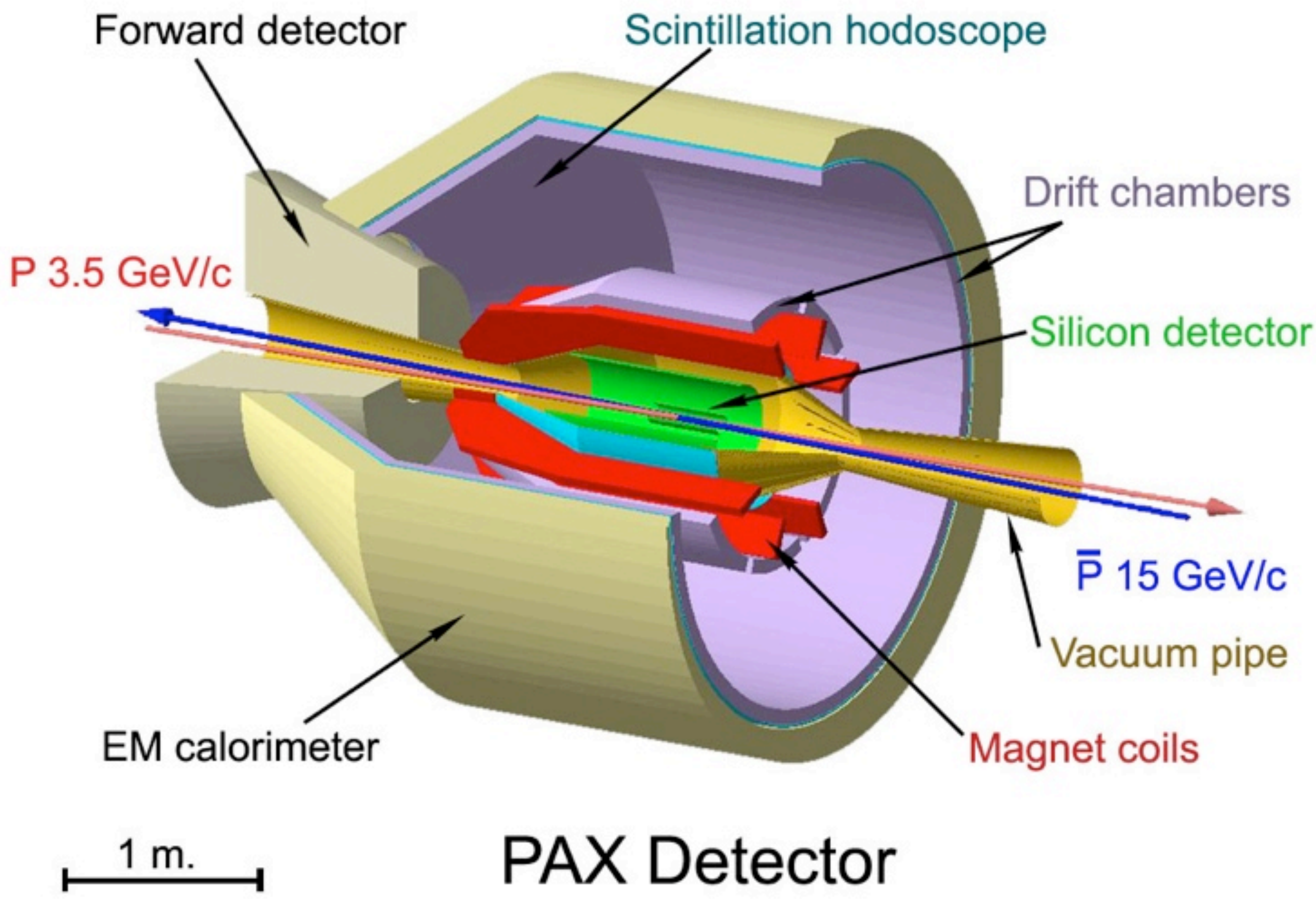
- Timelike Form Factors with relative Phase
- Direct Measurement of the Transversity Distribution



PAX - Phase I - Fixed Target

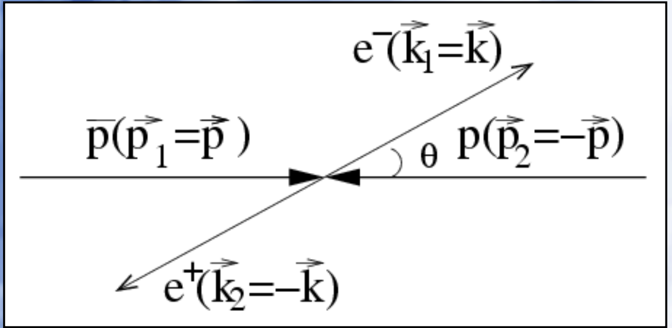


Independent from HESR running



PAX Detector

Timelike FF in double polarised p̄p-Annihilation



$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{xx} = \sin^2\theta\left(|G_M|^2+\frac{1}{\tau}|G_E|^2\right)\mathcal{N},$$

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{yy} = -\sin^2\theta\left(|G_M|^2-\frac{1}{\tau}|G_E|^2\right)\mathcal{N},$$

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{zz} = \left[(1+\cos^2\theta)|G_M|^2-\frac{1}{\tau}\sin^2\theta|G_E|^2\right]\mathcal{N},$$

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{xz} = \left(\frac{d\sigma}{d\Omega}\right)_0 A_{zx} = \frac{1}{\sqrt{\tau}}\sin 2\theta\, Re\, G_E G_M^* \mathcal{N}.$$

E. Tomasi, F. Lacroix, C. Duterte, G.I. Gakh, EPJA 24, 419(2005)

- Most asymmetries contain moduli of G_E,G_M, allowing an independent measurement and a test of Rosenbluth separation in the time-like region
- Access to the G_E-G_M phase
- Sensitive to different models

Form Factor Models

Spacelike

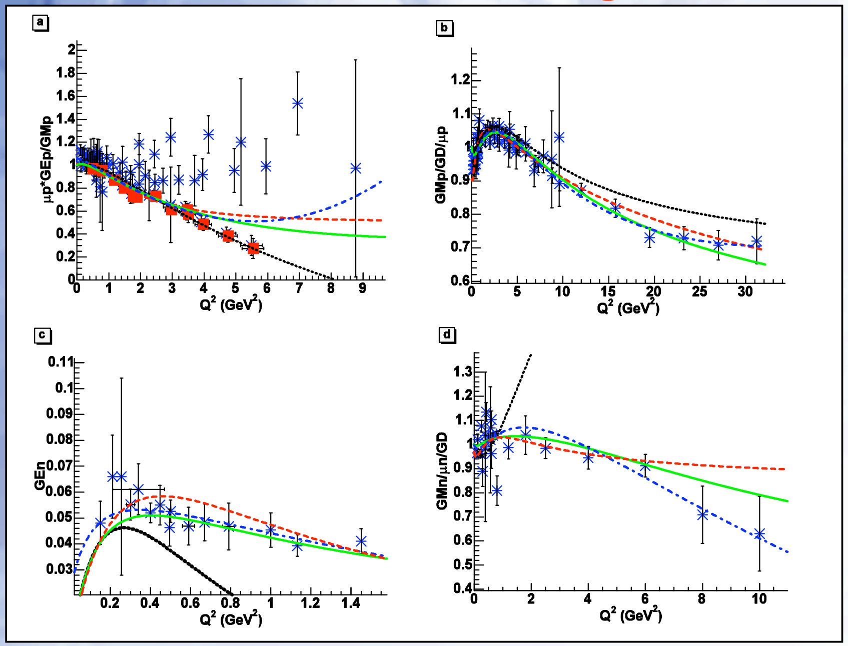
Electric Magnetic

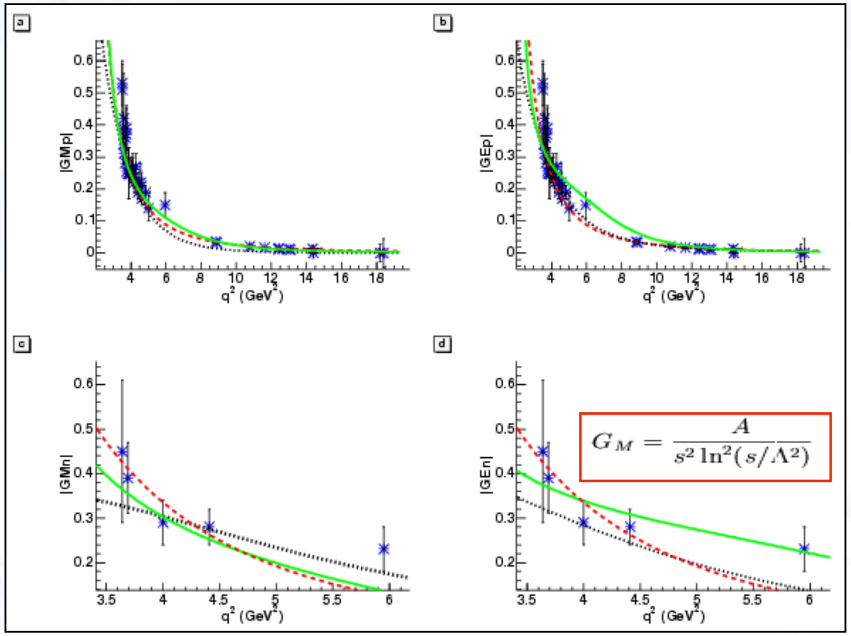
Timelike

Electric Magnetic

proton

neutron





QCD inspired
Bosted PRC 51, 409 (1995)

Extended VDM
E.L.Lomon PRC 66, 045501 2002)

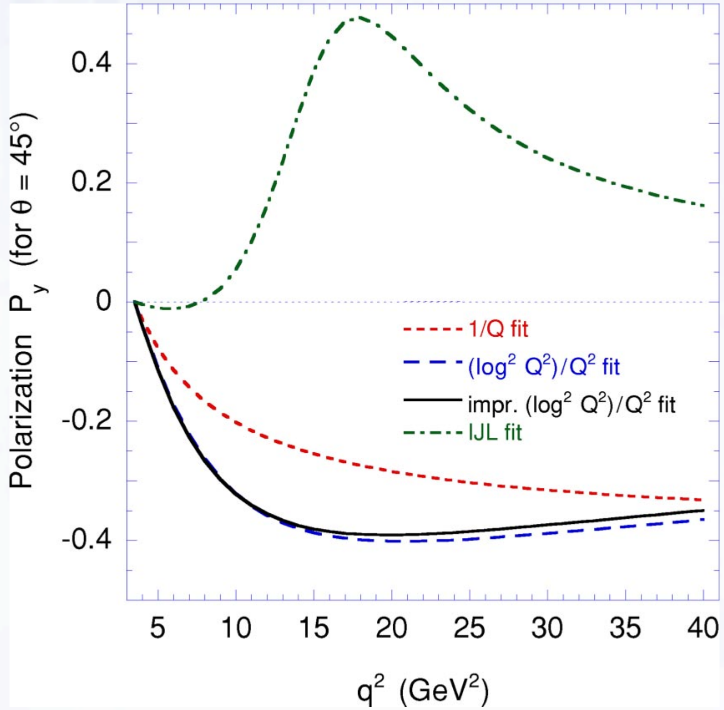
VDM : IJL
F. Iachello..PLB 43, 191 (1973)

Hohler
NPB 114, 505 (1976)

E. Tomasi, F. Lacroix, C. Duterte, G.I. Gakh, EPJA 24, 419(2005)

Measurement of Phase Difference

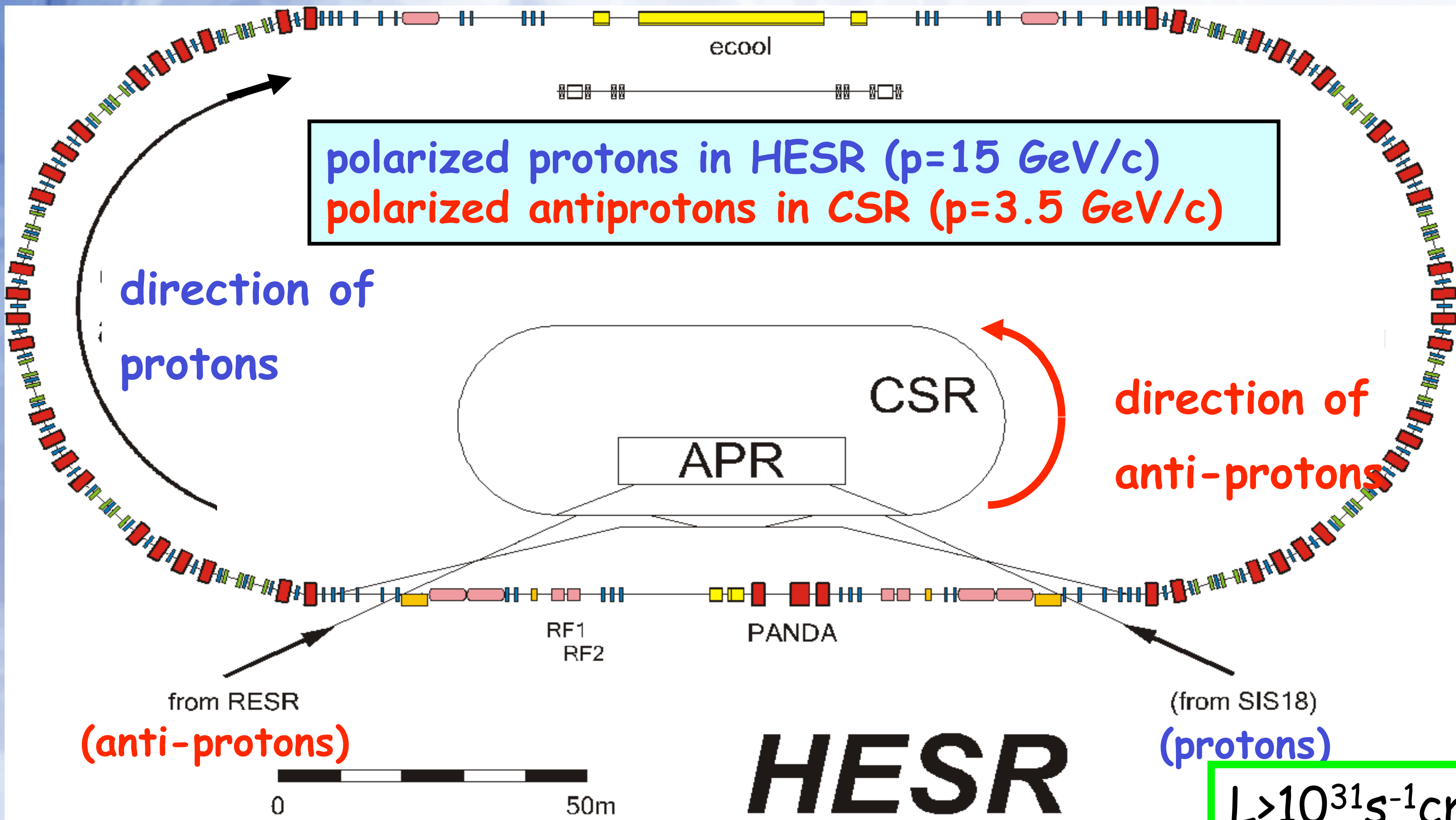
- Timelike formfactors are complex
- Single spin asymmetries in $e^+e^- \to pp$ and $pp \to e^+e^-$ are sensitive to complex phase
- sizeable asymmetry predicted in models



S. Brodsky et al.
Phys Rev. D 69 (2004) 054022

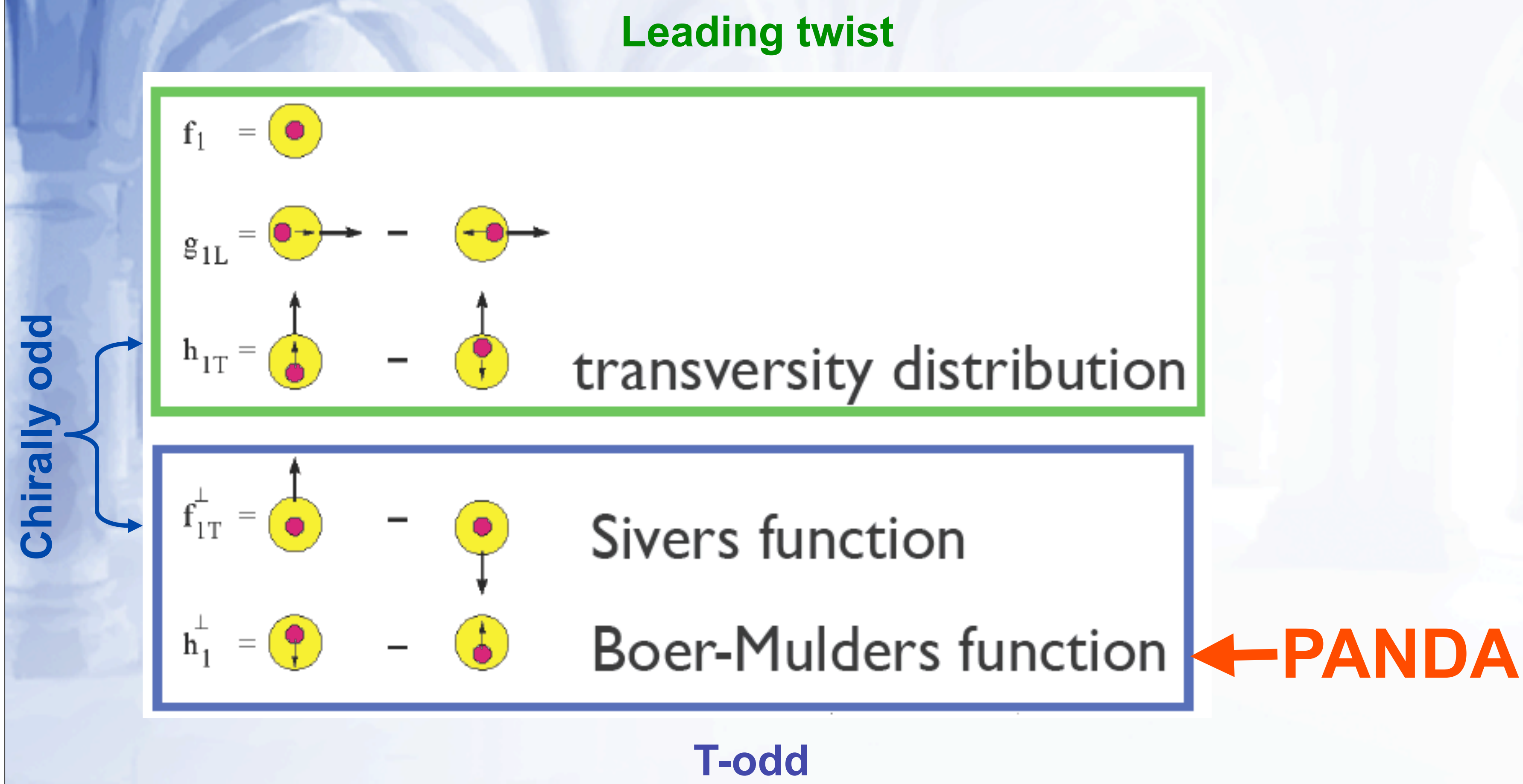
$$A_y = \frac{\sin 2\theta \cdot Im(G_E^* G_M)}{[(1+\cos^2\theta)|G_M|^2 + \sin^2\theta |G_E|^2/\tau]\sqrt{\tau}}$$

PAX - Phase II - Asymmetric $\bar{p}p$-Collider

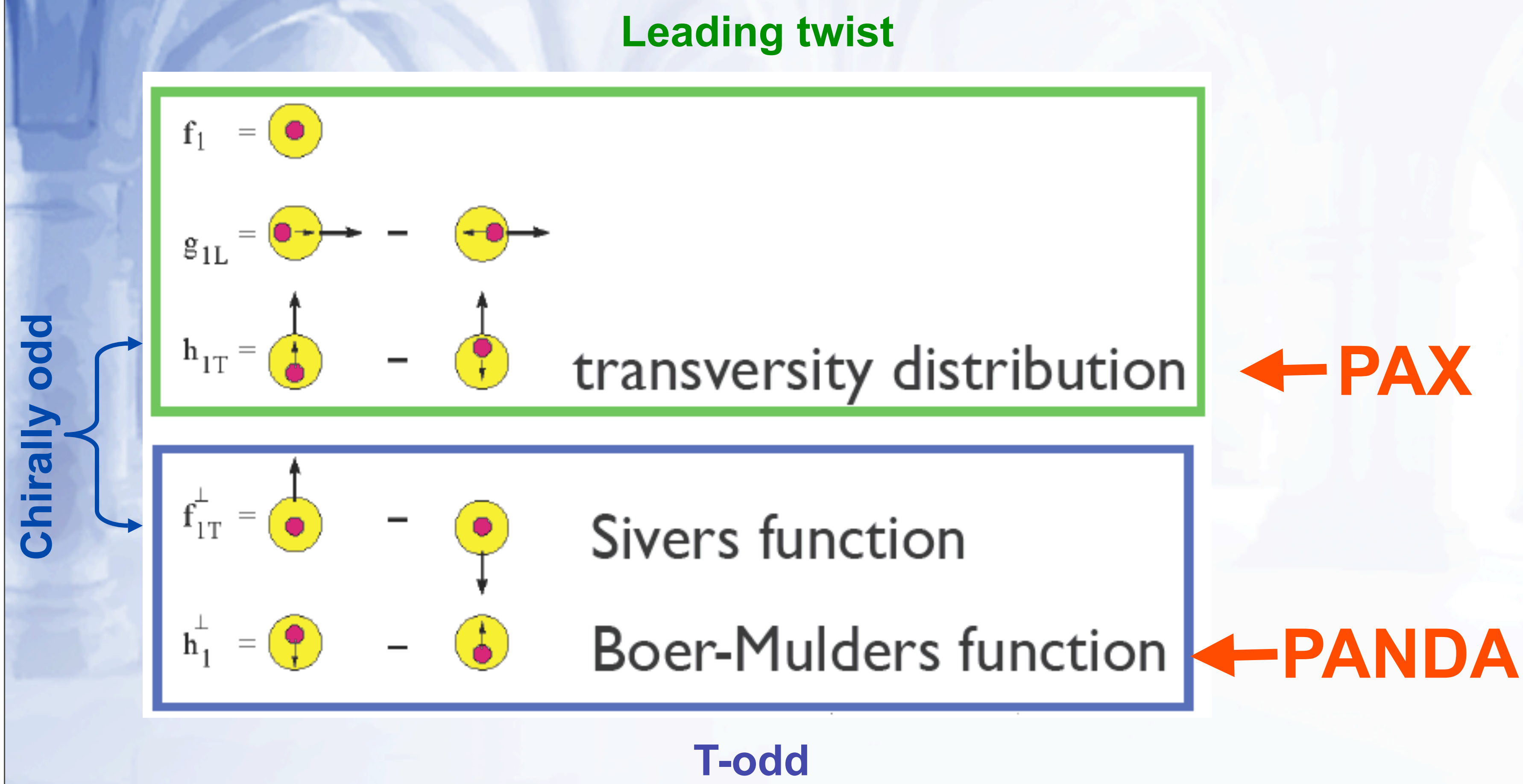


$L>10^{31}s^{-1}cm^{-2}$

Parton Distribution Functions



Parton Distribution Functions



Transversity

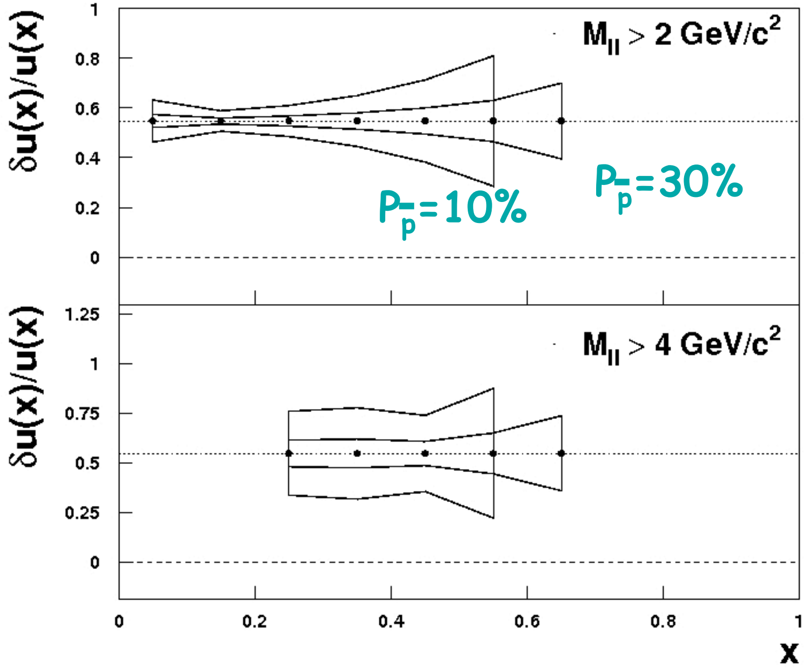
$$A_{TT} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 \left[h_{1q}(x_1) h_{1q}(x_2) + h_{1\bar{q}}(x_1) h_{1\bar{q}}(x_2)\right]}{\sum_q e_q^2 \left[q(x_1) q(x_2) + \bar{q}(x_1) \bar{q}(x_2)\right]}$$

- **u-dominance**
- **$|h_{1u}| > |h_{1d}|$**

$$A_{TT} \approx \hat{a}_{TT} \frac{h_{1u}(x_1) h_{1u}(x_2)}{u(x_1) u(x_2)}$$

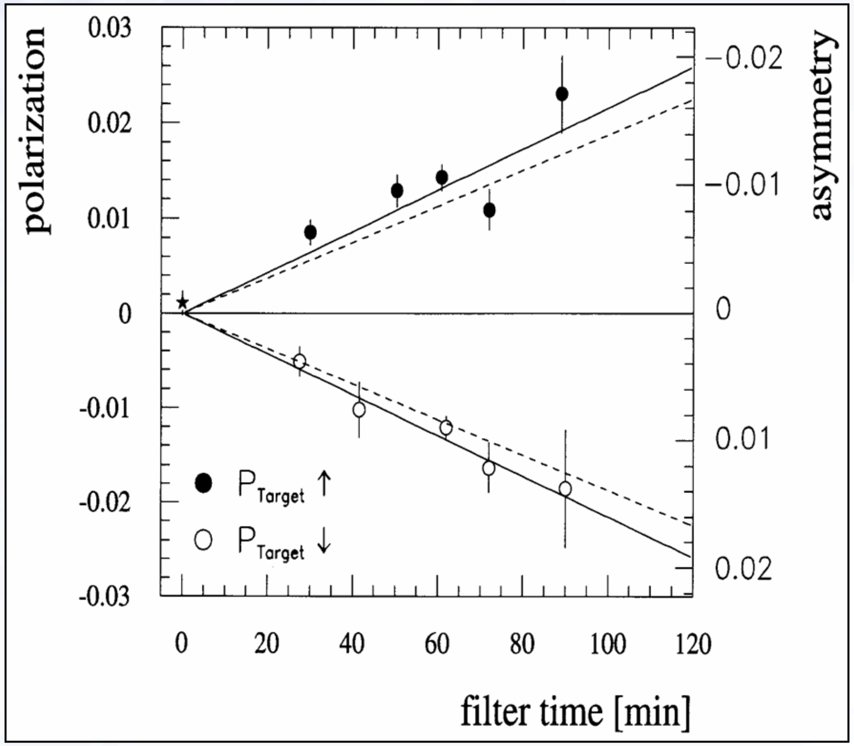
PAX : $M^2/s = x_1 x_2 \sim 0.02-0.3$
valence quarks
(A_{TT} large ~ 0.2-0.3)

1year run: 10 % precision on the $h_{1u}(x)$ in the valence region



Polarised Antiprotons

- Spin filtering using an internal polarised proton target is the most promising method to polarise the antiproton beam
- Positive results in pp-scattering from the FILTEX experiment at the TSR in Heidelberg in 1992
- Test experiments planned at COSY and AD/CERN



F. Rathmann. et al.,
PRL 71, 1379 (1993)

Polarised Antiprotons - Timeline

Fall 2008	Technical Proposal to COSY PAC for spin filtering experiment
	Technical Proposal to SPSC for spin filtering at AD
2008 - 2009	Design and construction phase
2009	Spin filtering studies at COSY
	Commissioning of AD experiment
> 2010	Installation at AD
	Spin filtering studies at AD

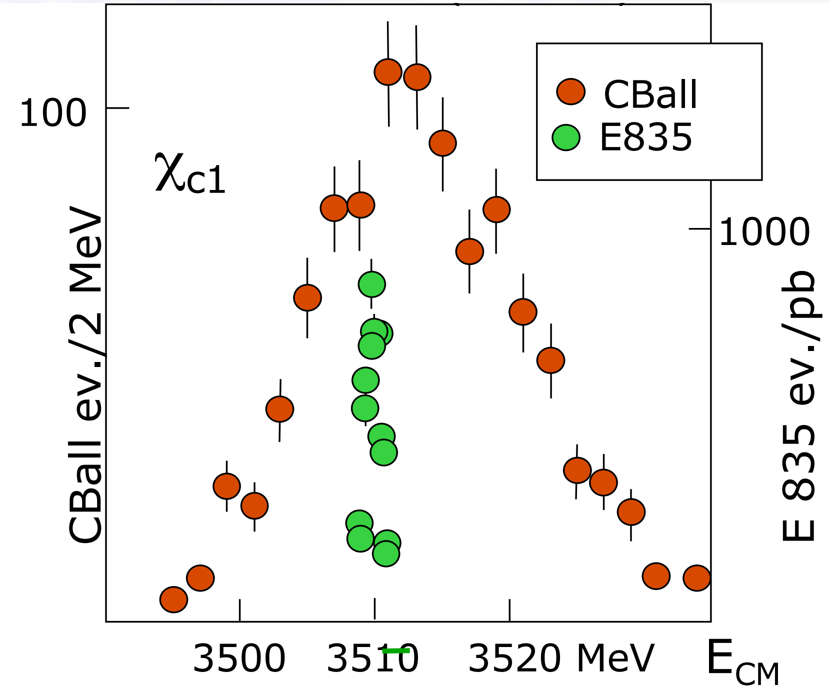
Summary

- In the coming decade FAIR will be one of the leading facilities in hadron physics worldwide
- PANDA at FAIR will be a versatile multi purpose detector open to a wide physics program: search for particles with exotic quantum numbers, charmonium spectroscopy and nucleon structure
- PAX at FAIR will extend the measurements of time-like form factors and provide the first direct measurement of the transversity distribution

Additional Slides

Advantages of PANDA

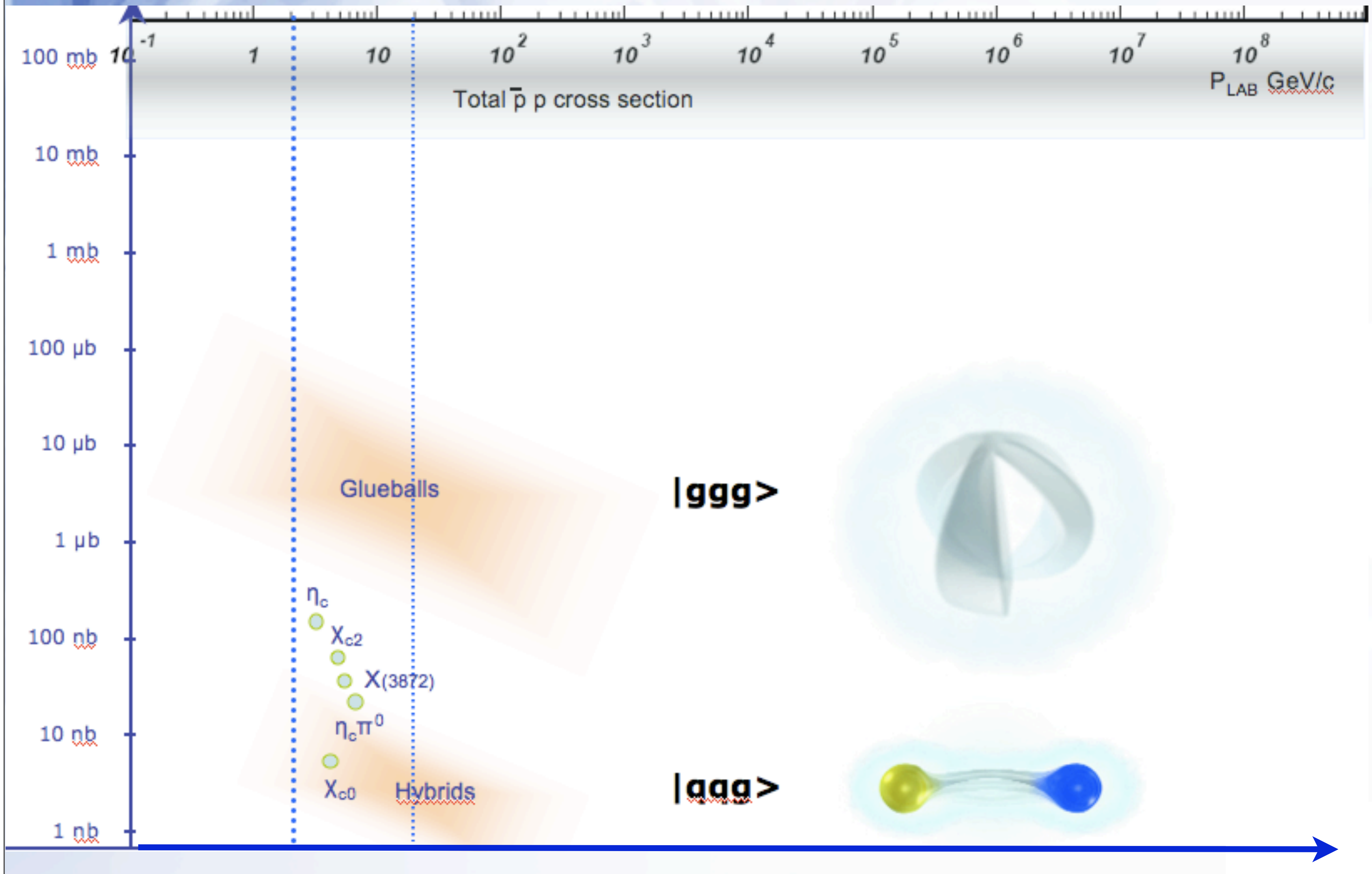
- e^+e^- annihilation fixes quantum numbers of initial state $J^{PC} = 1^{--}$
- Other states by decays leading to moderate mass resolution
- States directly formed in $p\bar{p}$ annihilation
- Excellent mass resolution given by beam



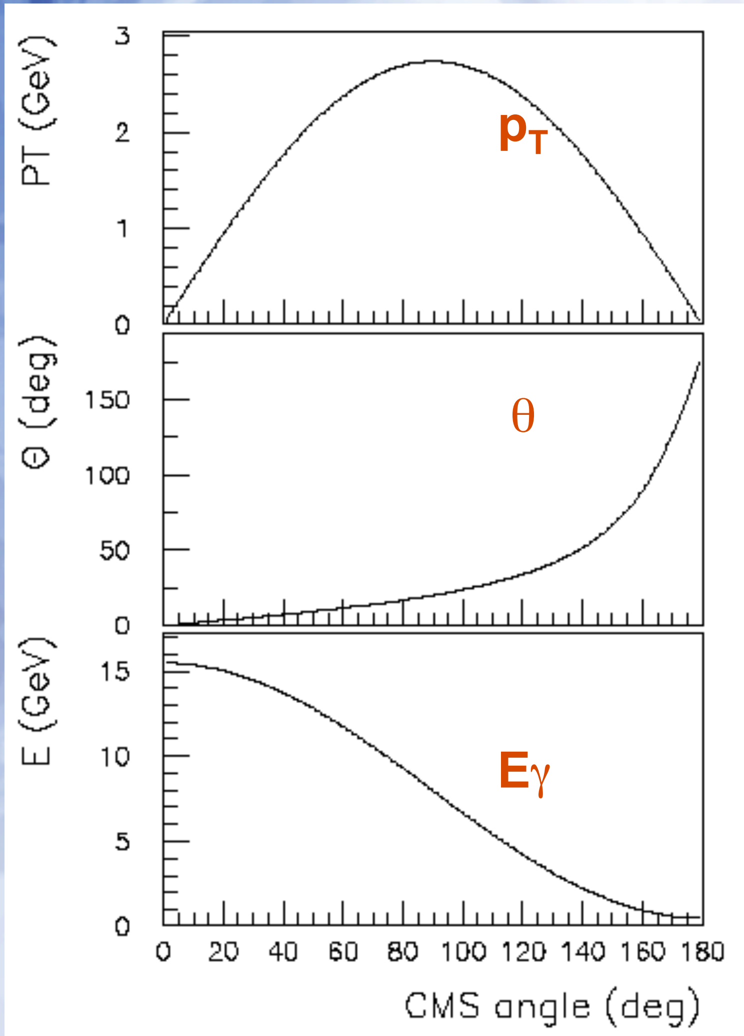
$$p\bar{p} \to \chi_{c1} \to \gamma J/\Psi \to \gamma e^+e^-$$

$$e^+e^- \to \Psi' \to \gamma\chi_{c1} \to \gamma\gamma J/\Psi \to \gamma\gamma e^+e^-$$

Cross Section



Experimental Requirements



p_{beam}=15 GeV/c, s=30 GeV²

Estimates for p_{beam} = 15 GeV/c

- Photon kinematics:

  E_γ = 15.5 .... 0.5 GeV @ 0°...180°
- Photon angle in CMS and transverse momentum are 'large' for wide angle Compton:
  p_T = few 100 MeV ... 2.7 GeV
- Interesting range in Lab around
  E_γ = 8 GeV and θ = 20°

➡ 4π calorimeter needed !

- Background suppression by
  - Large acceptance charged particle detector veto
  - Good resolution calorimeter for check of exclusivity (momentum balance)
  - Large acceptance neutral particle veto (neutrons)

Transition Distribution Amplitudes

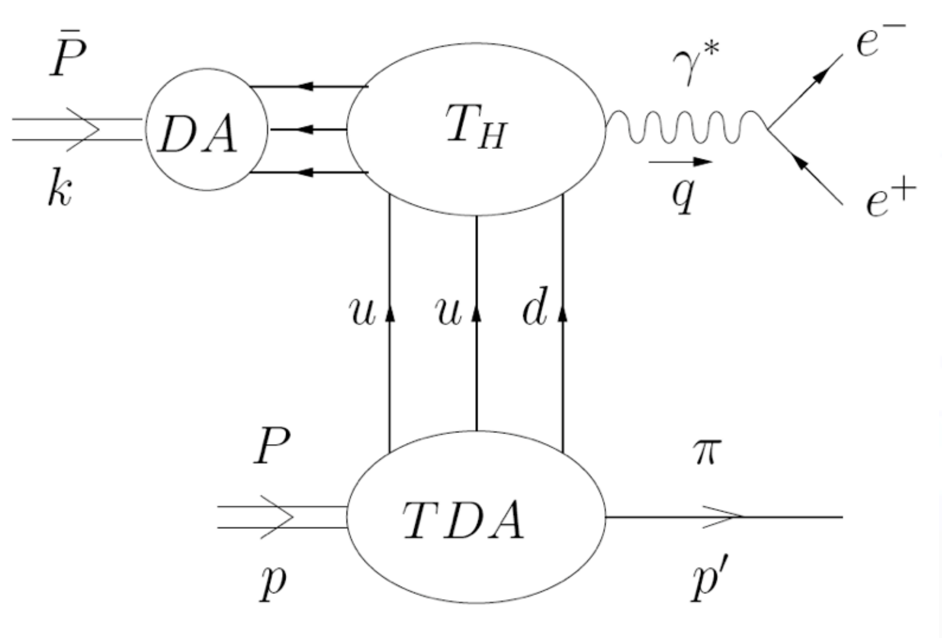
$$\bar{p}p \to \gamma^*\pi^0 \to e^+e^-\gamma\gamma$$ proton - pion

$$\bar{p}p \to \gamma^*\gamma \to e^+e^-\gamma$$ proton - photon

- TDAs extend the GPD concept further, to non-diagonal matrix elements [B.Pire, L.Szymanowski, PLB 622 (2005) 83]

- Impact parameter space interpretation as for GPDs

- Fourier transform gives a transverse picture of the pion cloud in the proton



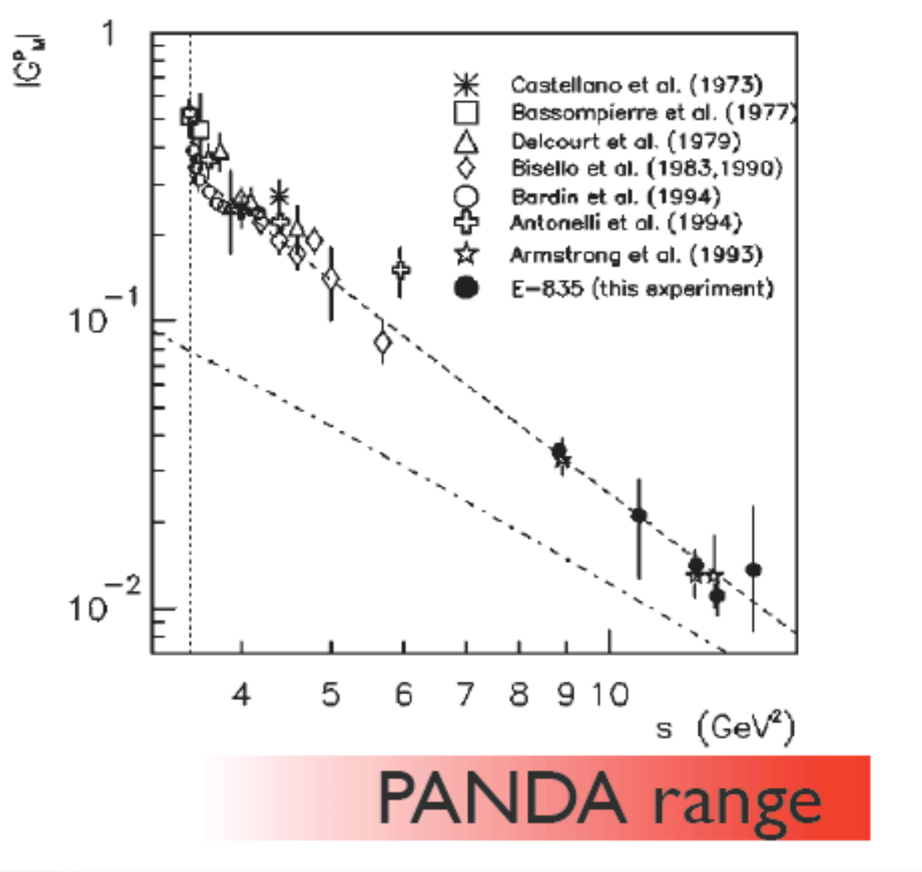
Time-like Proton Form Factors

Crossed channel
$p\bar{p} \longrightarrow e^+e^-$

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

- PANDA:
  - Wide kinematical range
  - Large solid angle coverage
  - Large statistics
- Goals:
  - To measure time-like FF from threshold up to high s = q^2 in one experiment (reduced systematic error)
  - To compare with space-like FFs (pQCD at large s?)

➡ High-quality measurement of both G_E and G_M



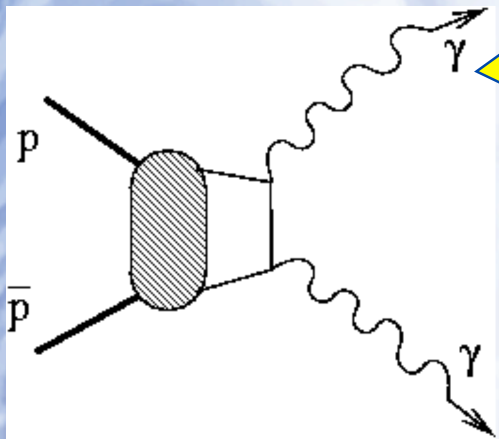
PANDA Collaboration

- At present a group of **350 physicists** from 47 institutions of 15 countries

Austria – Belaruz - China - Finland - France - Germany – Italy – Poland – Romania - Russia – Spain - Sweden – Switzerland - U.K. – U.S.A..

Basel, Beijing, Bochum, Bonn, IFIN Bucharest, Catania, Cracow, Dresden, Edinburg, Erlangen, Ferrara, Frankfurt, Genova, Giessen, Glasgow, GSI, Inst. of Physics Helsinki, FZ Jülich, JINR Dubna, Katowice, Lanzhou, LNF, Mainz, Milano, Minsk, TU München, Münster, Northwestern, BINP Novosibirsk, Pavia, Piemonte Orientale, IPN Orsay, IHEP Protvino, PNPI St. Petersburg, Stockholm, Dep. A. Avogadro Torino, Dep. Fis. Sperimentale Torino, Torino Politecnico, Trieste, TSL Uppsala, Tübingen, Uppsala, Valencia, SINS Warsaw, TU Warsaw, AAS Wien

Hard Exclusive Reactions at PANDA

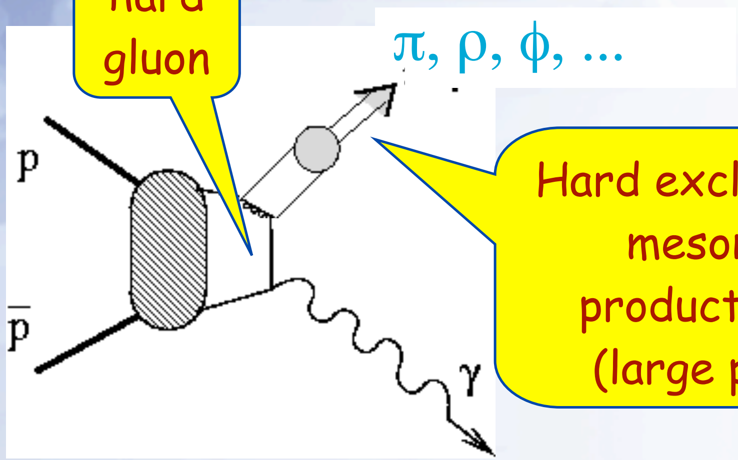


Timelike wide angle Compton scattering (large p_T)

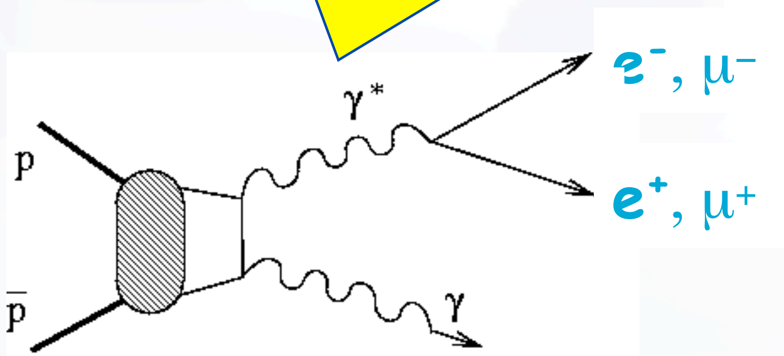
Q^2 large: DVCS

Q^2 small: Wide angle Compton scattering (large p_T)

hard gluon

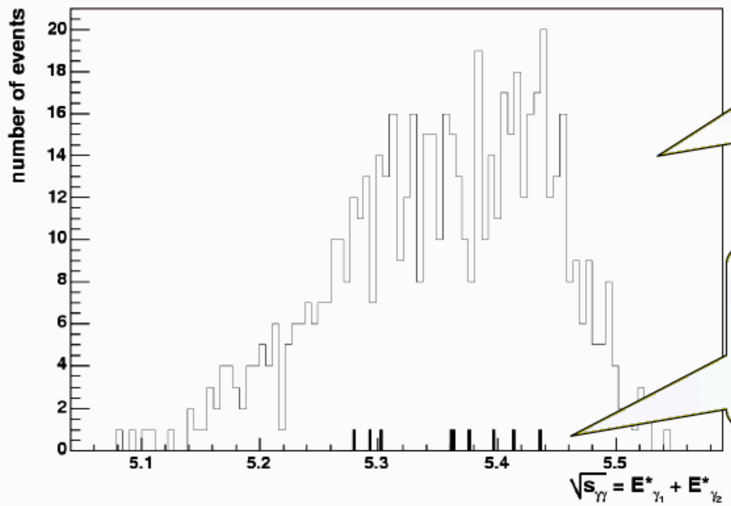


Hard exclusive meson production (large p_T)



First Simulation Results (G.Serbanut)

	$\gamma\gamma$	$\pi^0\gamma$	$\pi^0\pi^0$
generated events	10 000	10 000	100 000
events with 2 clusters	7 081	982	1 404
events after all cuts	5675	91	17
surviving yield	56.7%	0.9%	0.017%
estimated cross section (pb)	15	420	17 500
accepted cross section after cuts (pb)	8.5	3.78	2.98
relative contributions	55%	25%	20%



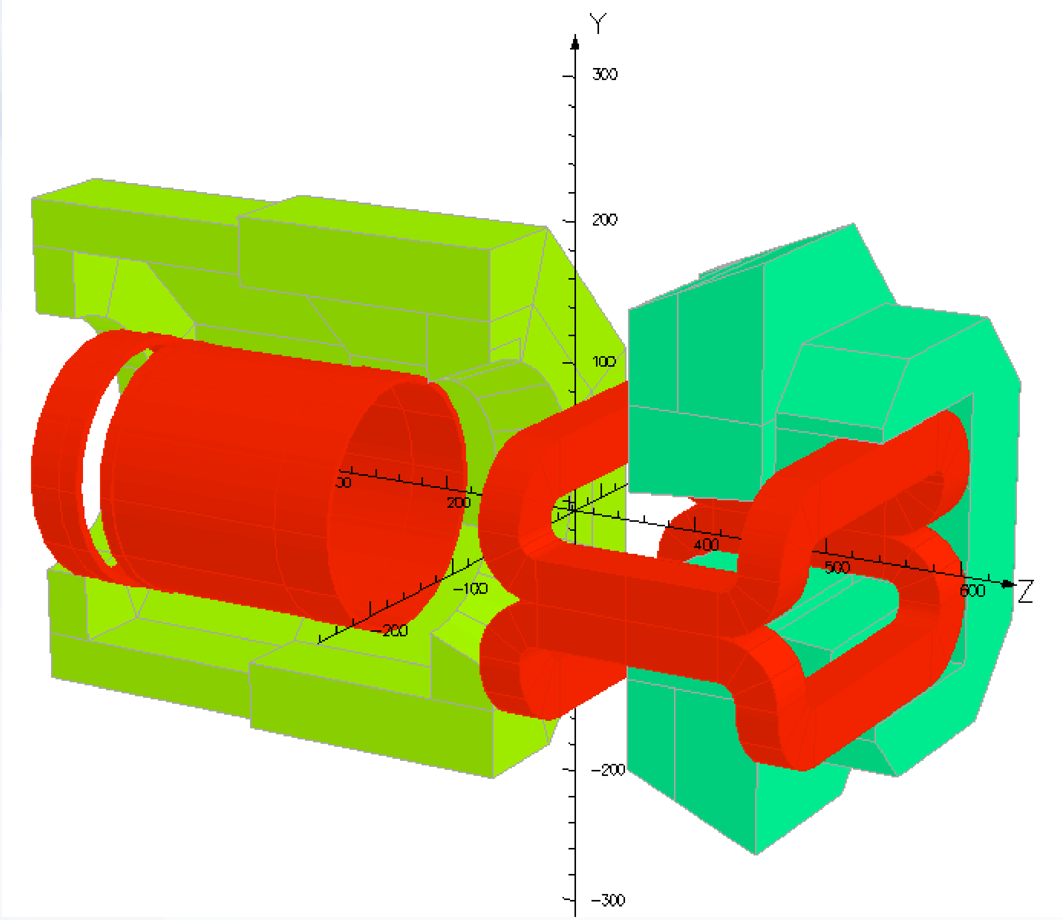
Reconstructed invariant mass of 5.5 GeV $\gamma\gamma$ events

Feed-down of 5.5 GeV $\pi\gamma$ events are strongly suppressed; $\pi\pi$ is zero in this simulation of 10000 ev.

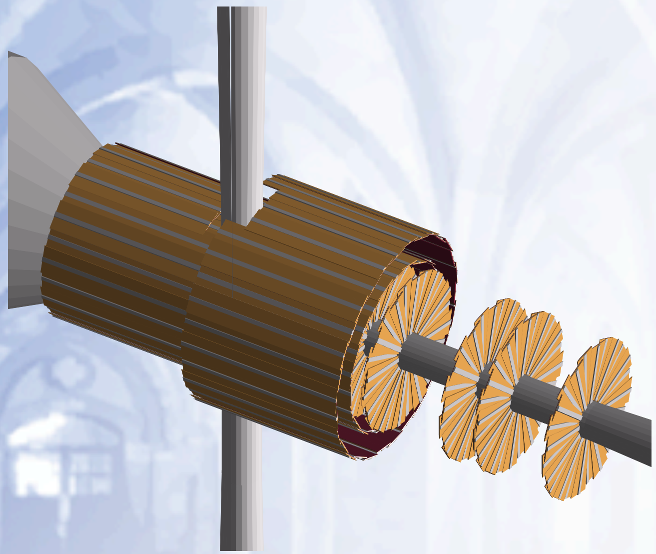
Experiment appears feasible

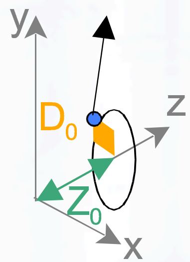
PANDA Magnet Design

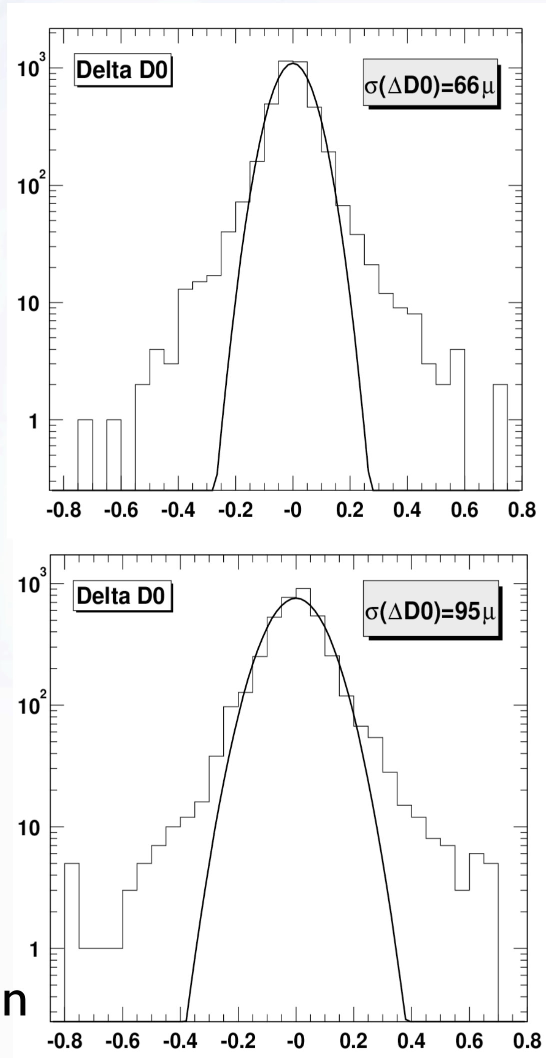
- Superconducting solenoid, inner radius 80 cm, length of 2.5 m, max field 2 T.
- The length forward of the target allows a reasonable momentum resolution even at the smallest polar angles (5°) detected only in the solenoid.
- Forward Spectrometer dipole magnet at 3.5 m to 5.5 m downstream of the target, with a 1 m gap and a maximum bending power of 2 Tm.



Micro Vertex Detector



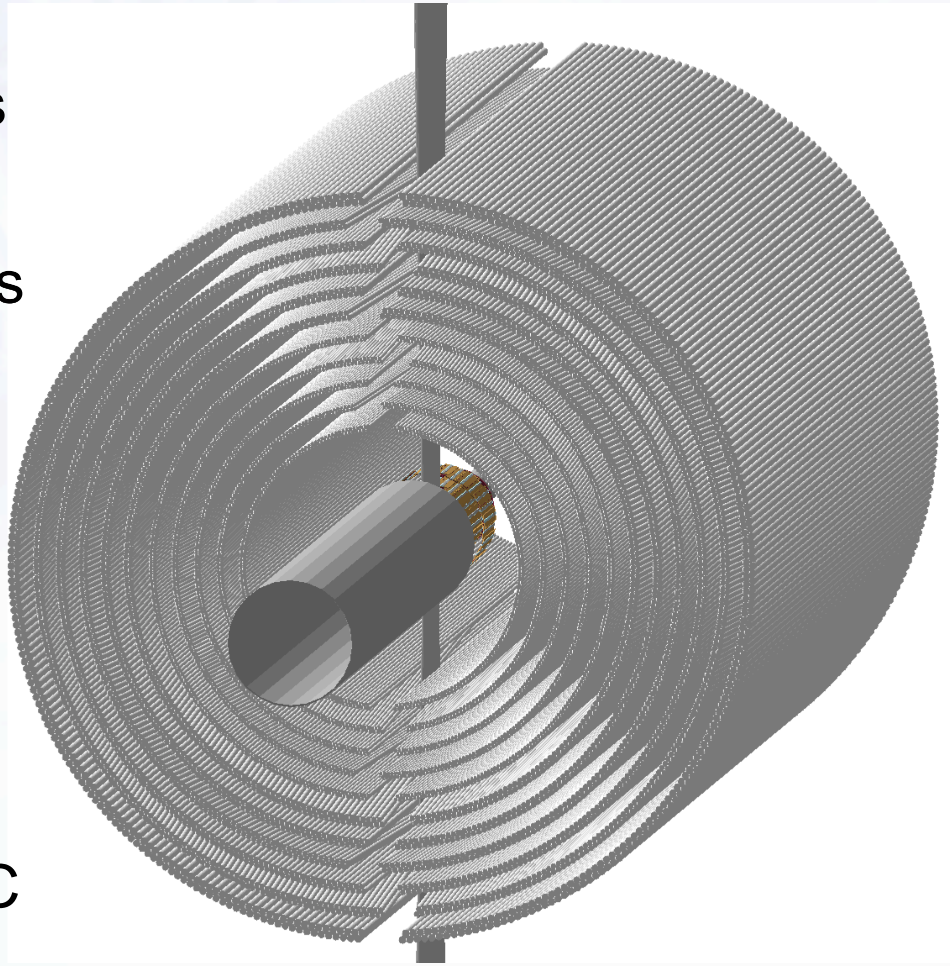




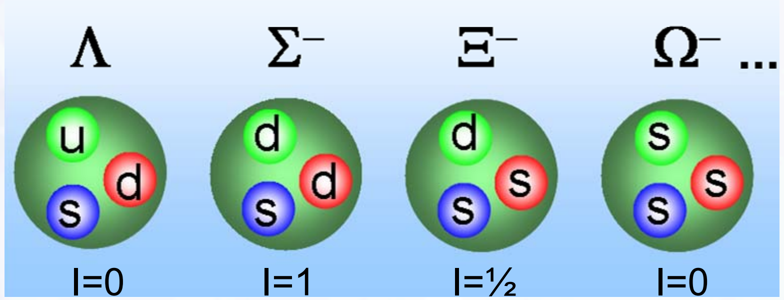
- good vertex reconstruction mandatory for wide variety of physics channels
- need to cover large momentum range and high rates
- low material budget and 100 μm resolution
- go for pixel detectors

Central Tracking System

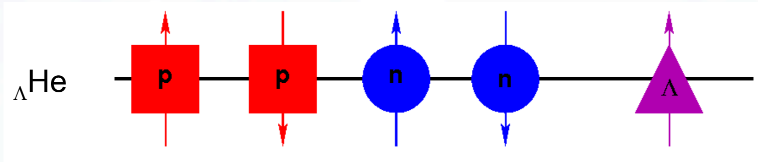
- large volume central tracker: 11 double layers Straw Tubes
- parallel and stereo layers for space point reconstruction
- small radiation length and reasonable resolution
- high rate capability
- possible alternative: TPC



Hypernuclei



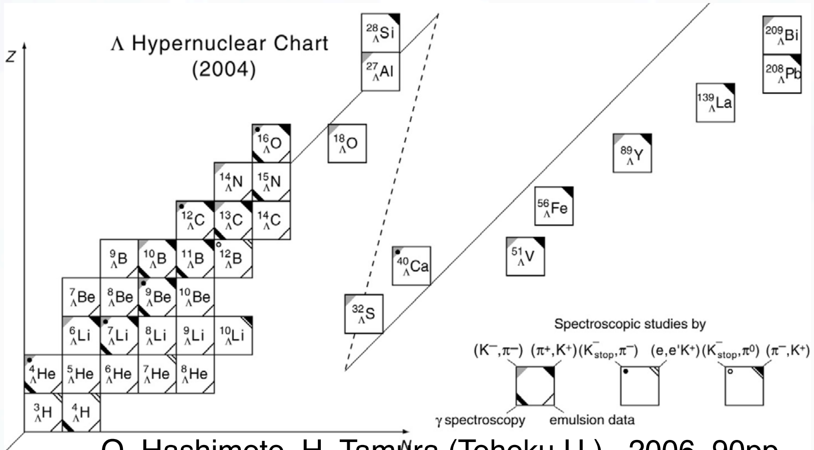
- Hypernuclei = nuclei containing hyperons



- Strangeness ⇒ study nuclear spectroscopy with and additional degree of freedom

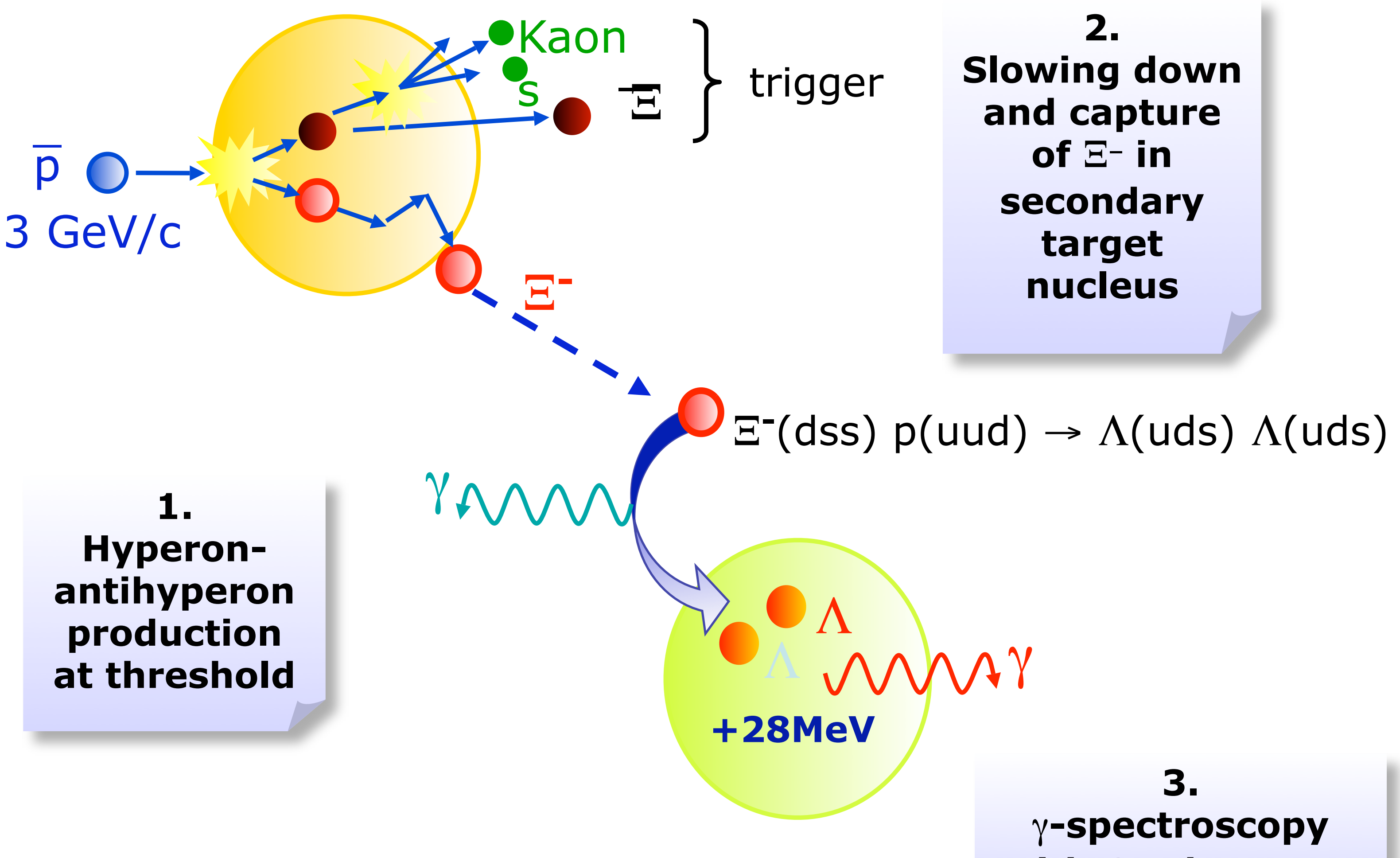
- Λ lifetime 2.6×10^{-10}s

- ~ 35 Λ and 6 ΛΛ hypernuclei experimentally established



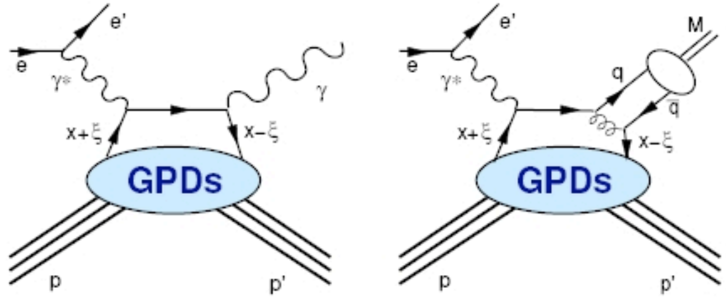
O. Hashimoto, H. Tamura (Tohoku U.) . 2006. 90pp.
Published in Prog.Part.Nucl.Phys.57:564-653,2006.

Production of ΛΛ Hypernuclei at PANDA



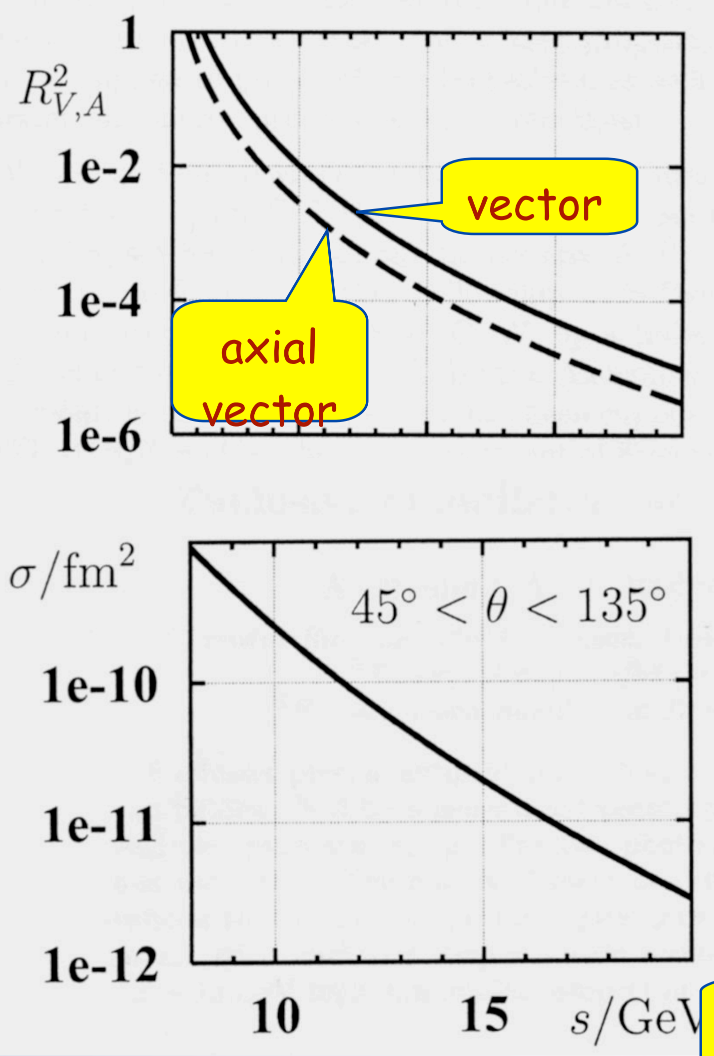
Expected Event Rate ~ 500/day

Generalised Parton Distributions



- functions of three variables: x, ξ, t
- H_q: nucleon spin preserved, E_q: nucleon spin flipped
- H_q: unpolarised $\tilde{H}_q$: polarised
- 4 (chirality conserving) quark GPDs: $H_q(x,\xi,t)$, $\tilde{H}_q(x,\xi,t)$, $E_q(x,\xi,t)$, $\tilde{E}_q(x,\xi,t)$
- parton distribution functions
  $q(x) = H_q(x,0,0)$
  $\Delta q(x) = \tilde{H}_q(x,0,0)$
- $q(-x) = -\bar{q}(x)$
  $\Delta q(-x) = \Delta\bar{q}(x)$
- form factors
  $F_1^q(t) = \int_{-1}^{1} dx H^q(x,\xi,t)$
  $F_2^q(t) = \int_{-1}^{1} dx E^q(x,\xi,t)$
  $g_a^q(t) = \int_{-1}^{1} dx \tilde{H}^q(x,\xi,t)$
  $h_a^q(t) = \int_{-1}^{1} dx \tilde{E}^q(x,\xi,t)$
- quark orbital angular momentum
  $J_q = \frac{1}{2}\int_{-1}^{1} x\, dx[H_q + E_q]$
  $= \frac{1}{2}\Delta\Sigma + L_q$ [X.Ji 1997]

Calculated cross section



$$\frac{d\sigma}{d\cos\theta} = \frac{2\pi\alpha_{em}^2}{s} \frac{R_V^2(s)\cos^2\theta + R_A^2(s)}{\sin^2\theta}$$

Assumptions :

$p_{beam} = 5\ \mathrm{GeV/c}$

$s = 10\ \mathrm{GeV}^2$

$L = 2\times10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Result :

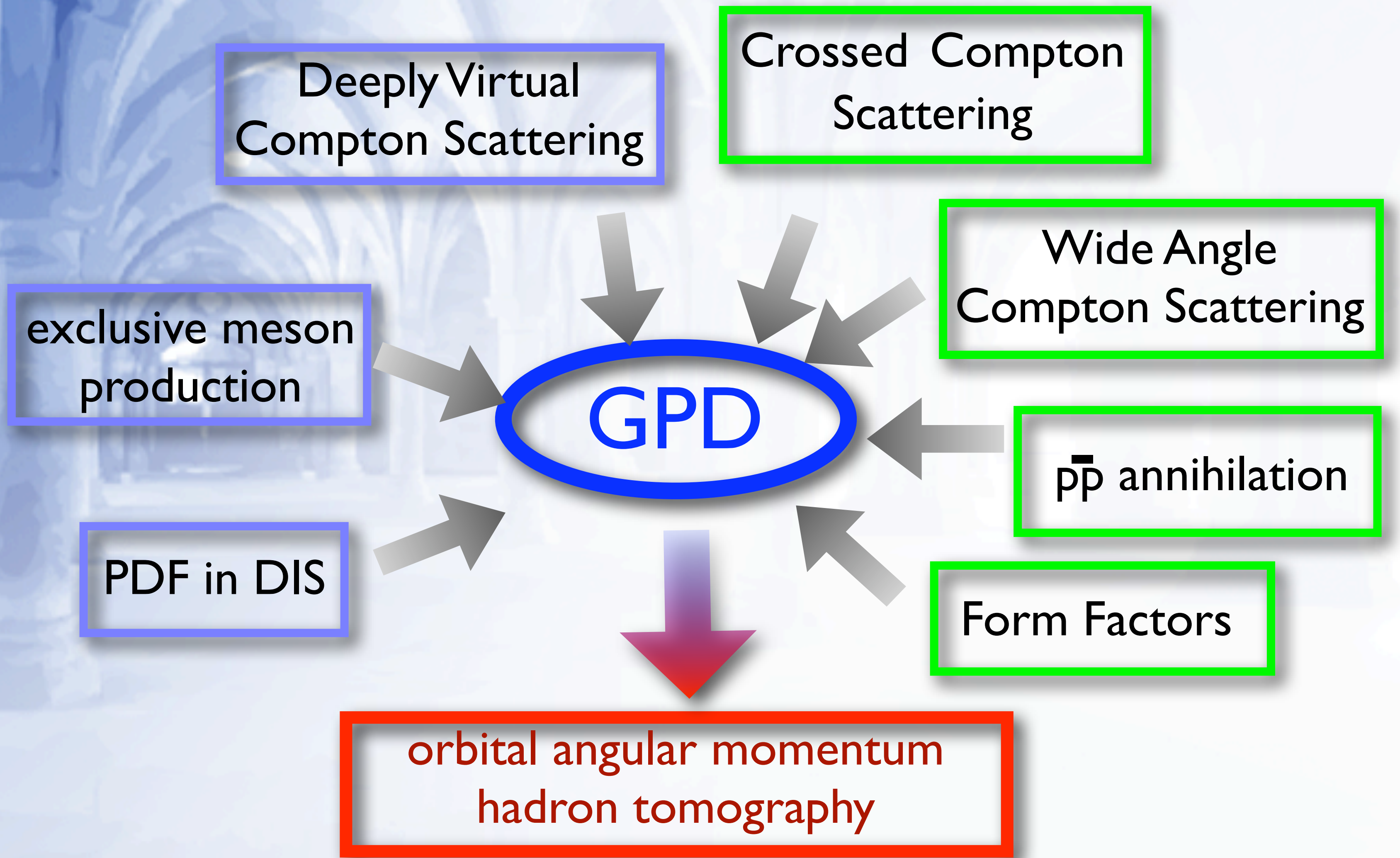
$\sigma = 0.25\times10^{-9}\ \mathrm{fm}^2$

$\mathrm{Rate} \approx 0.5\times10^{-3}/\mathrm{s} = \mathrm{few}\times10^3/\mathrm{month}$

Simple model by Freund, Radyushkin, Schäfer, Weiss PRL 90, 092001 (2003)

Data from e^+e^- suggest that the model underestimates the real rate by a large factor

GPDs – How it all fits together



Hadron Tomography

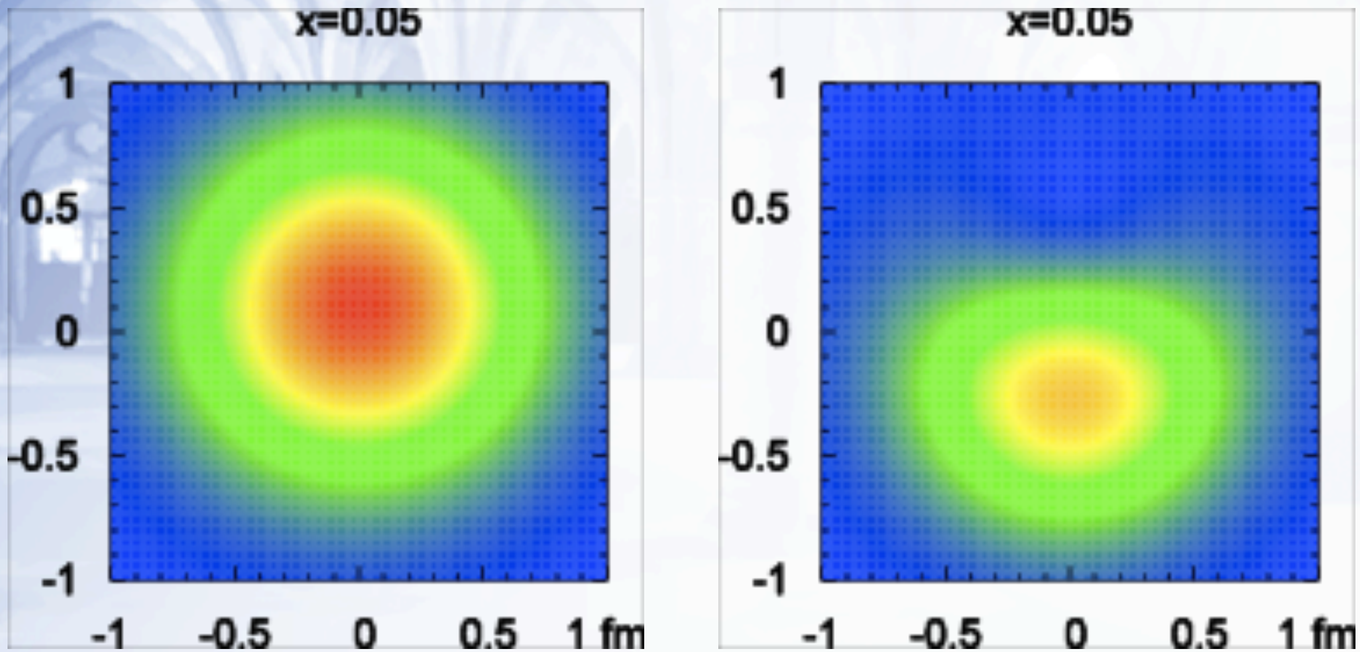
- GPDs at ξ =0 can be used to obtain quark densities in the mixed representation of longitudinal momentum and transverse position in the infinite momentum frame

$$q(x, b_\perp) = \int \frac{d^2\Delta_\perp^2}{(2\pi)^2} H(x, 0, -\Delta_\perp^2) e^{-i\Delta_\perp \cdot b_\perp}$$

- M.Burkhardt, PRD62 071503 (2000)
- J.R.Ralston, B.Pire, PRD66 111501 (2002)
- M.Burkhardt, hep-ph/0611256, 20.Nov.2006

Hadron Tomography

•GPD Model restricted by form factor data exists:
[P.Kroll, hep-ph/0612026, 4.Dec.2006]



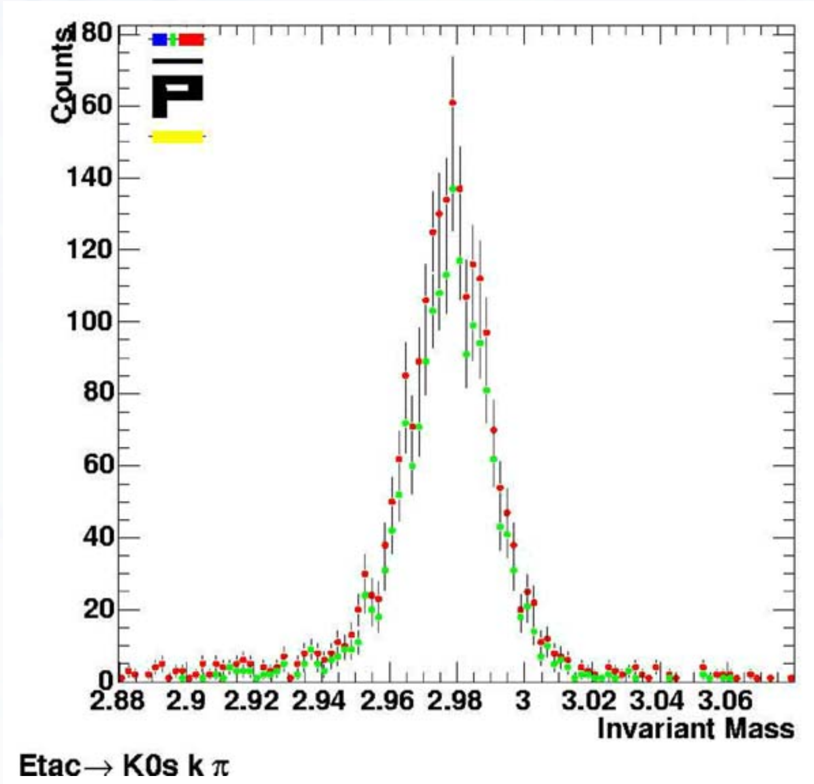
u-quark (left) and d-quark (right) density in impact parameter plane. Proton polarised in x-direction

PANDA Detector Requirements

- multi purpose modular detector for wide physics program
- capable of high reaction rates
- precise vertex reconstruction for fast decaying particles
- high momentum resolution in magnetic field
- Identification of charged particles in a large momentum range
- Energy reconstruction for neutral particles
- large angular and momentum acceptance (cover full solid angle)

Full PANDA Detector Simulation

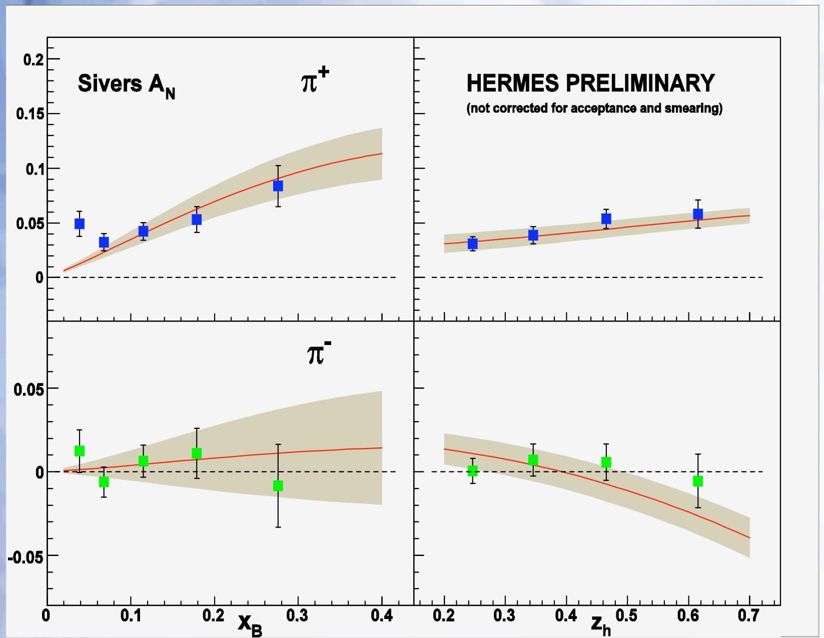
- relevant channel for Charmonium studies or exotics searches
- produced on resonance
- full detector simulation plus background
- large acceptance and reconstruction efficiency
- clear signal with good resolution



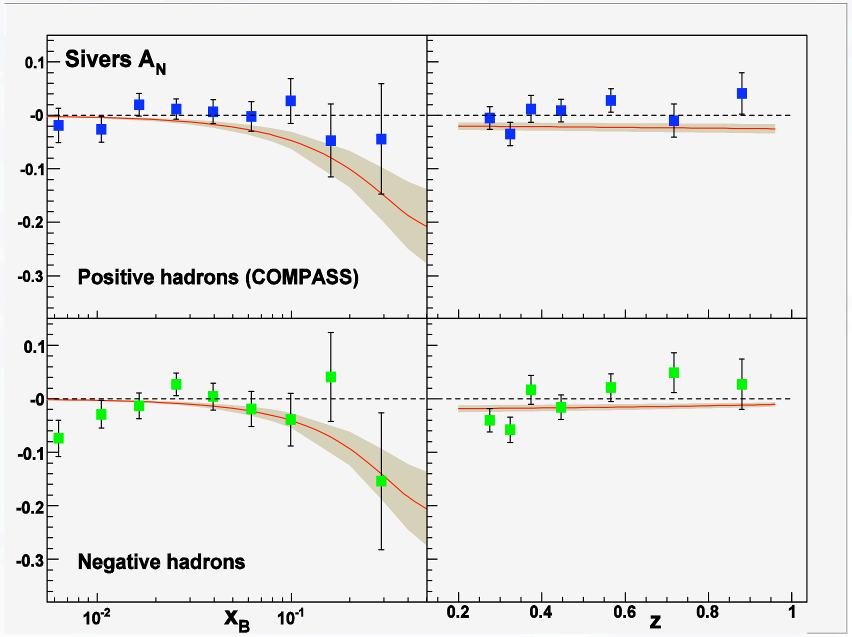
$$p\bar{p} \longrightarrow \eta_c \longrightarrow K^0_s K^{\pm} \pi^{\mp}$$

Sivers Function from HERMES Data

Fits to the Hermes data



"Prediction" of the Compass data



Assuming $f_{1T}^{\perp,u}(x) = S_u\, x(1-x)\,u(x); \quad f_{1T}^{\perp,d}(x) = S_d\, x(1-x)\,u(x)$

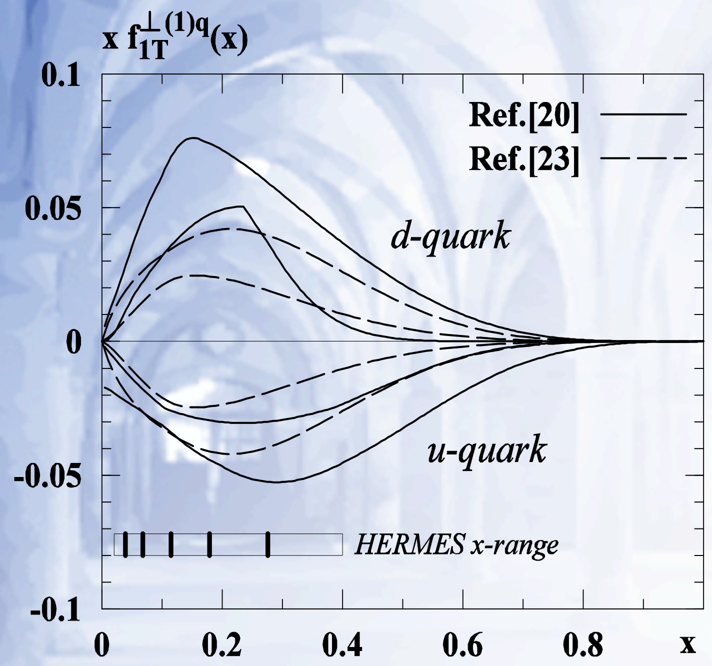
$S_u = -0.81 \pm 0.07, \quad S_d = 1.86 \pm 0.28$

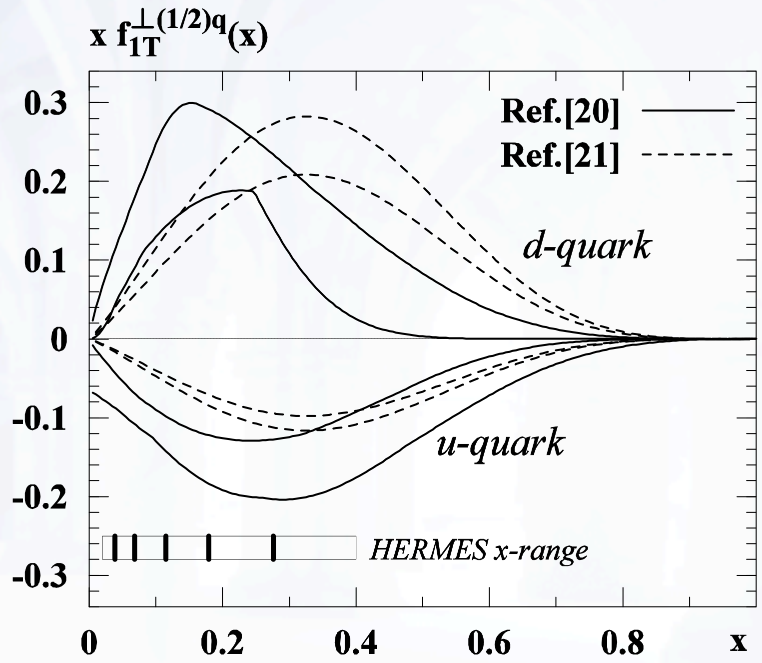
Vogelsang and Yuan, Phys.Rev.D72(2005)054028 [hep-ph/0507266]

Striking flavor dependence of the Sivers function

Different Sivers Function Extractions

M.Anselmino et al, hep-ph/0511017





Ref.[20] M.Anselmino et al, Phys.Rev.D72(2005)094007[hep-ph/0507181]

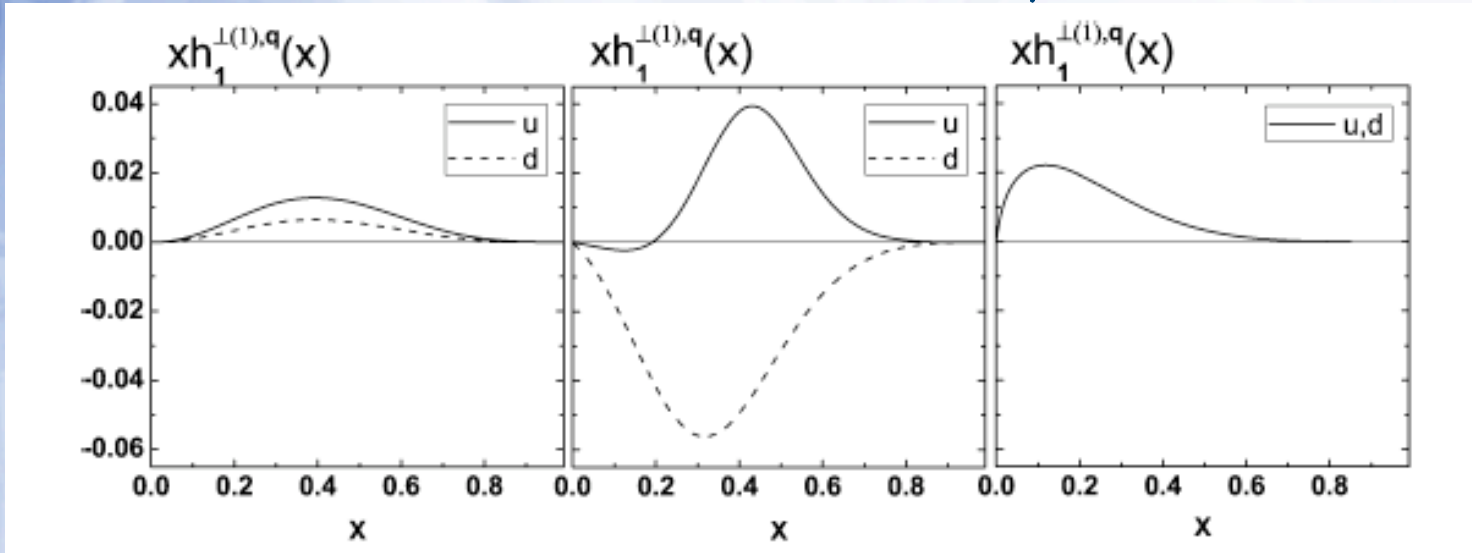
Ref.[21] W.Vogelsang & F.Yuan, Phys.Rev.D72(2005)054028[hep-ph/0507266]

Ref.[23] J.C.Collins et al, hep-ph/0510342

Satisfactory agreement between different models to fit HERMES data.

Comparing Boer-Mulders Function Models

Z. Lu, B.Q. Ma and I. Schmidt, Phys. Lett. B639(2006)494.



(a) (b) (c)

(a)MIT bag model: F. Yuan, Phys. Lett. B575,45(2003).

(b)Spectator model with axial-vector diquark: Bacchetta, Schaefer & Yang, Phys. Lett. B578,109(2004).

(c)Large-N_c limit, P.V. Pobylitsa, hep-ph/0301236

Knowledge of the Boer-Mulders functions is very poor.