“Relativistic Nuclear Physics and Quantum Chromodynamics”

XXII International Baldin Seminar on High Energy Physics Problems

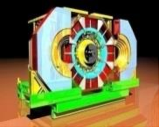
15th - 20th September 2014

JINR - Dubna (RUSSIA)

The PANDA Project @ FAIR

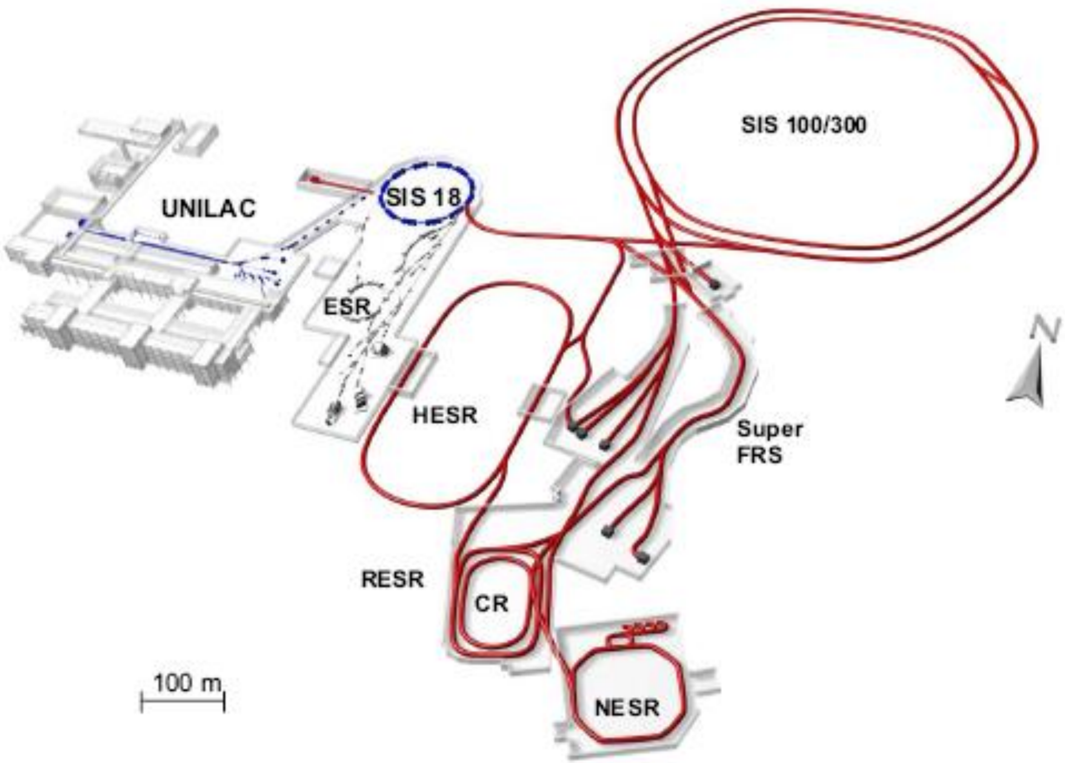
Marco Maggiora on behalf of the PANDA Collaboration

Department of Physics and INFN – Turin, Italy



The future FAIR facility

Facility for Antiproton and Ion Research



Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- Factor 100-1000 present in intensity
- 2(4)x10^{13}/s 30 GeV protons
- 10^{10}/s $^{238}U^{73+}$ up to 25 (- 35) GeV/u

Secondary Beams

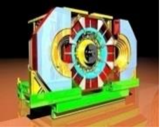
- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
- Antiprotons 3 (0) - 30 GeV

Storage and Cooler Rings

- Radioactive beams
- e – A collider
- 10^{11} stored and cooled 0.8 - 14.5 GeV antiprotons

Key Technical Features

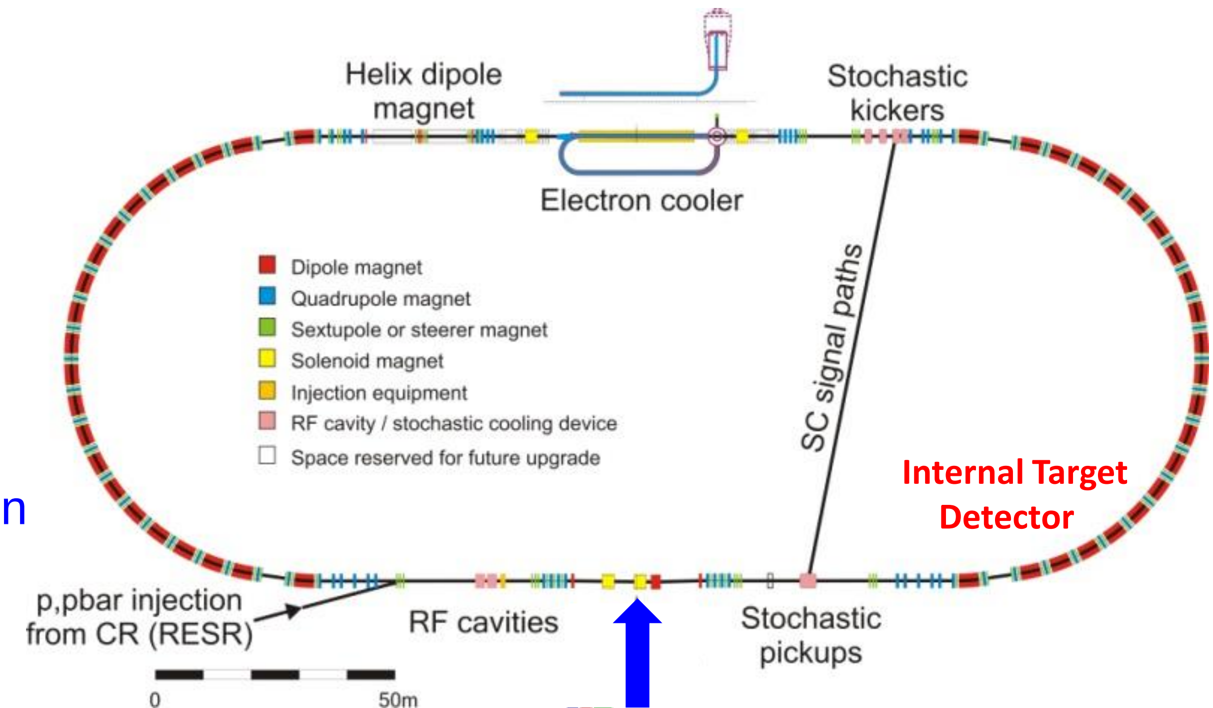
- Cooled beams
- Rapidly cycling superconducting magnets

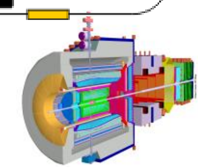


HESR - High Energy Storage Ring

- Production rate 2×10^7/sec
- P_{beam} = 1 - 15 GeV/c
- N_{stored} = 5×10^{10} $\bar{p}$
- Internal Target

$2.3 \leq \sqrt{s} \leq 5.5$ GeV





High resolution mode

- $\delta p/p$ ~ 10^{-5} (electron coolin
- Lumin. = 10^{31} cm^{-2} s^{-1}

High luminosity mode

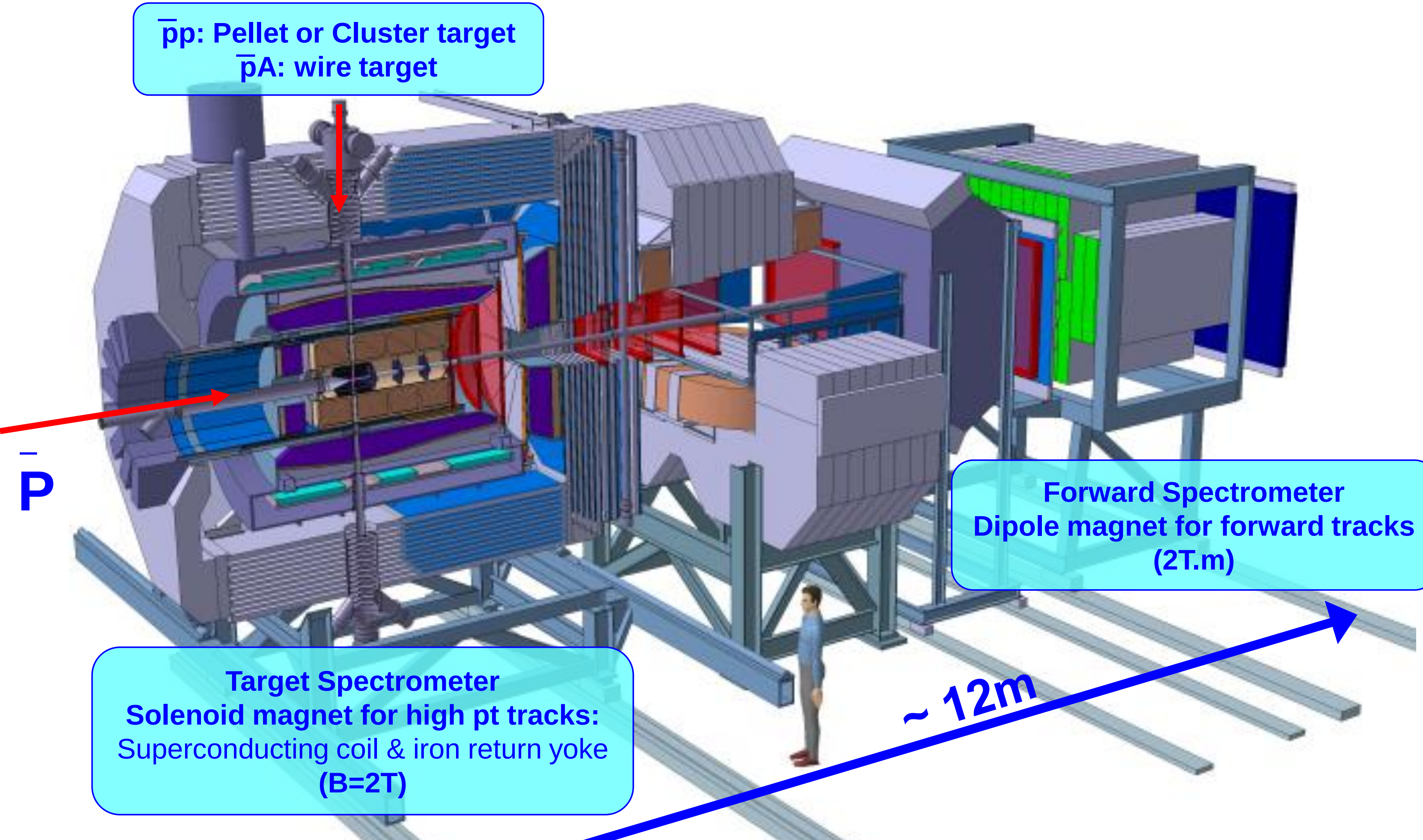
- Lumin. = 2×10^{32} cm^{-2} s^{-1}
- $\delta p/p$ ~ 10^{-4} (stochastic cooling)

The Collaboration

At present 520 physicists from 67 institutions in 17 countries

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, KVIGroningen, 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, Sydney, Dep. A. Avogadro Torino, Dep. Fis. Sperimentale Torino, Torino Politecnico, Trieste, TSL Uppsala, Tübingen, Uppsala, Valencia, NCBJ Warsaw, TU Warsaw, AAS Wien

PANDA spectrometer

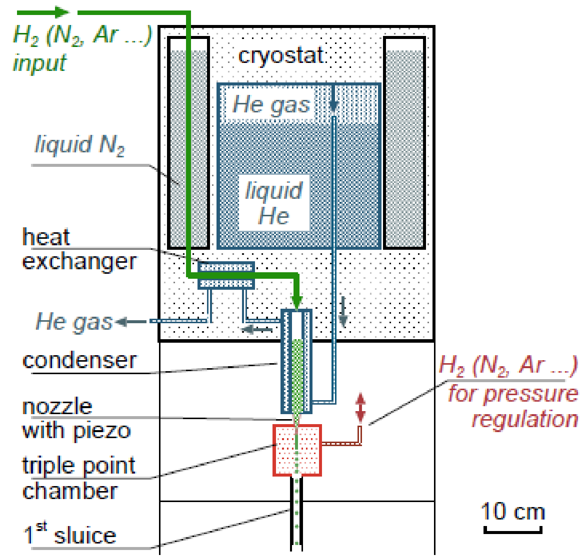


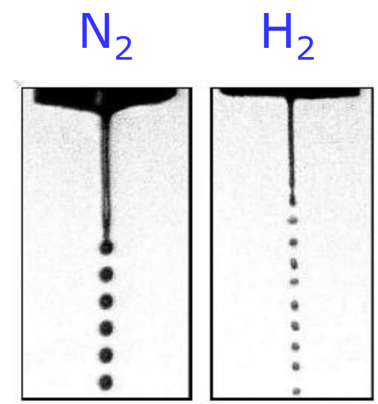
Physics Performance Report for PANDA arXiv:0903.3905 [hep-ex]

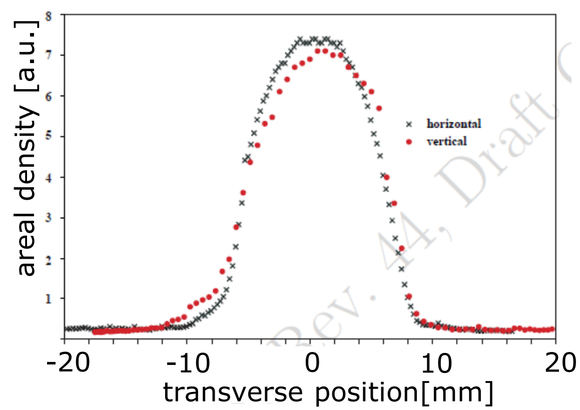
PANDA Magnet TDR http://www-panda.gsi.de/archive/public/P_magn_TDR.pdf

Target system

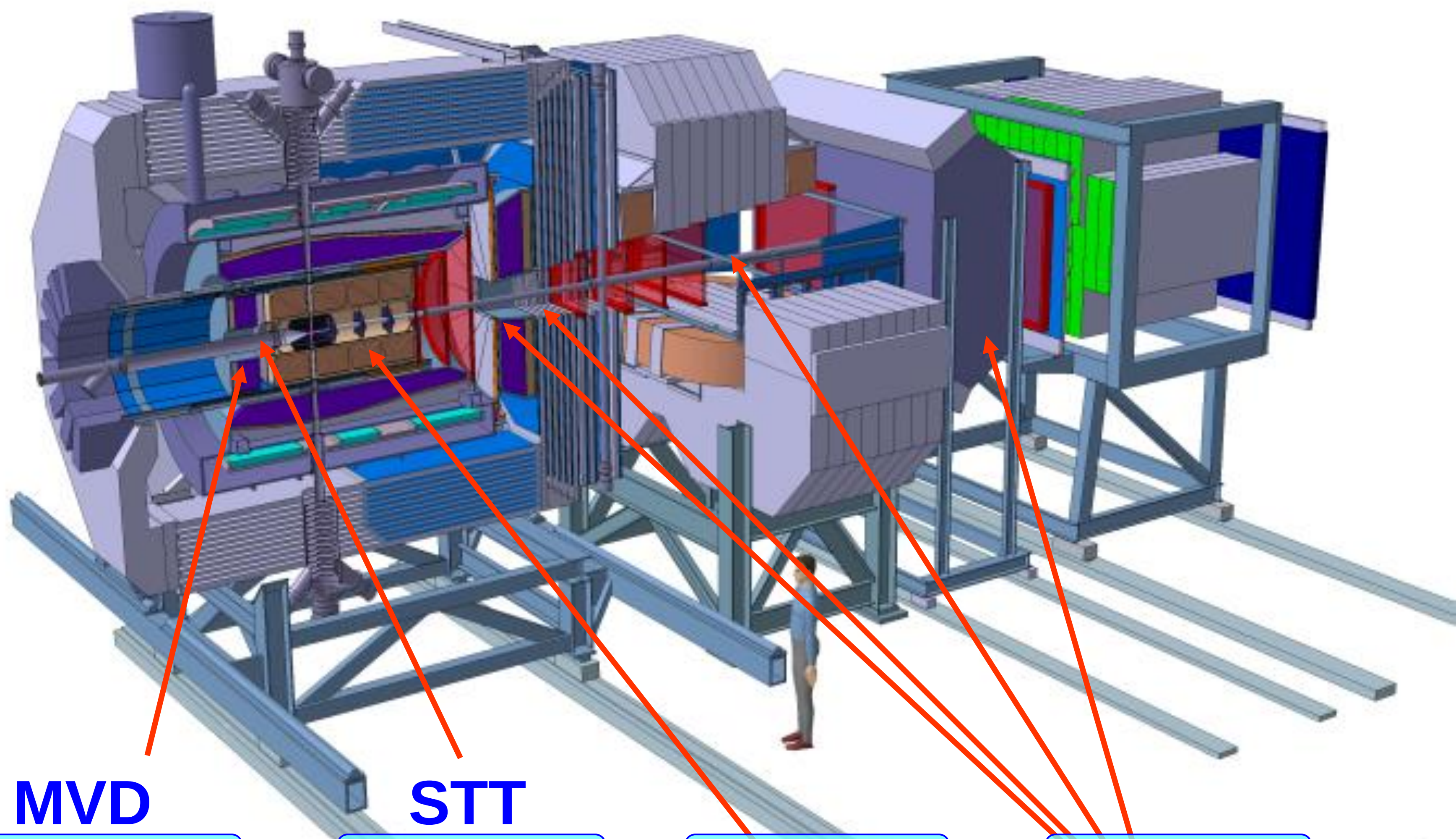
- **Requirements**
  - Proton Target
  - 5×10^{15} cm^{-2} for maximum luminosity
- **Pellet Target**
  - Frozen droplets ∅ 20µm
  - also possible: D_2, N_2, Ne, ...
  - Status: $\rho \sim 5 \times 10^{15}$
- **Cluster Jet Target**
  - Dense gas jet
  - also D_2, N_2, Ne, ...
  - Status: $\rho \sim 8 \times 10^{14}$



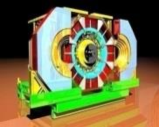




PANDA spectrometer: Tracking



Physics Performance Report for PANDA arXiv:0903.3905
PANDA STT TDR arXiv:1205.5441v1 [physics.ins-det]



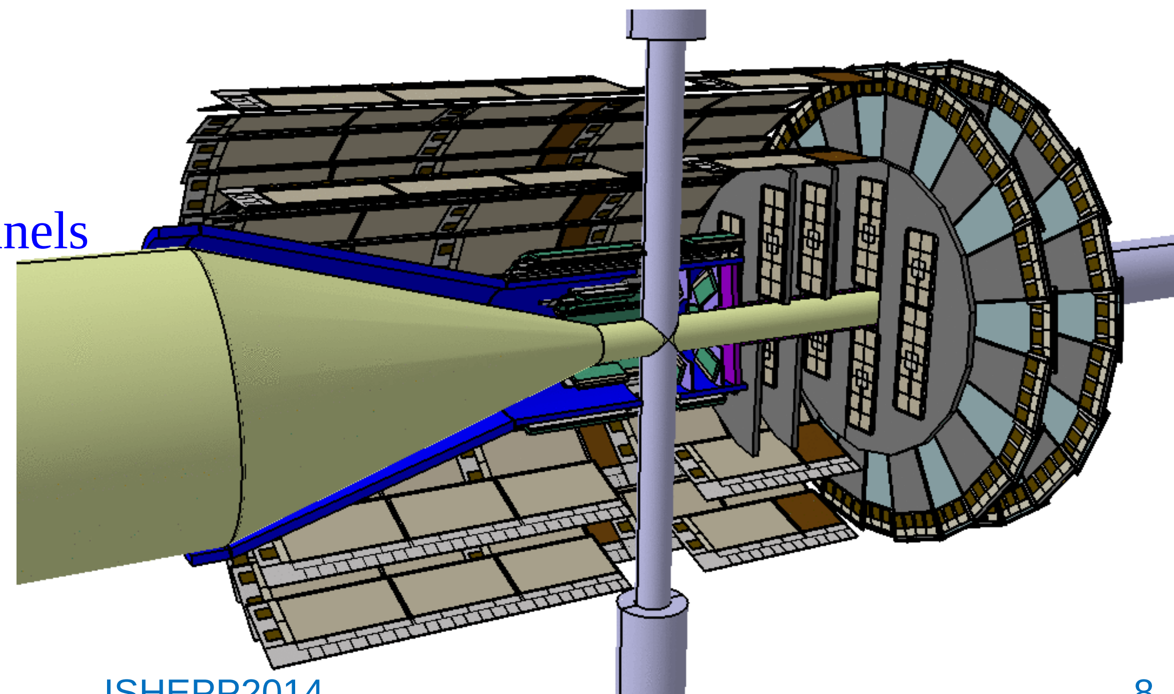
Silicon Microvertex Detector

Micro Vertex Detector

- 4 barrels and 6 disks
- Inner layers:
  hybrid pixels (100x100 μm^2)
  - 140 module, 12M channels
- Outer layers:
  silicon strip detectors
  - double sided strips
  - 400 modules, 200k channels
- Mixed forward disks
- Continuous readout

Requirements

- $c\tau(D^{\pm}) \sim 312\ \mu m$
  $c\tau(D_s^{\pm}) \sim 147\ \mu m$
- Vertex resolution ~ 50 µm



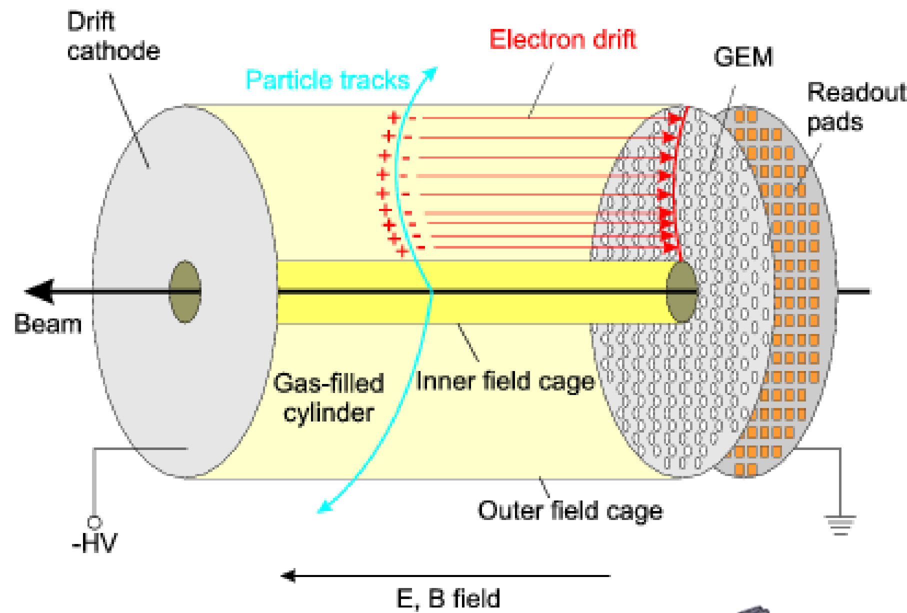
Central Tracker

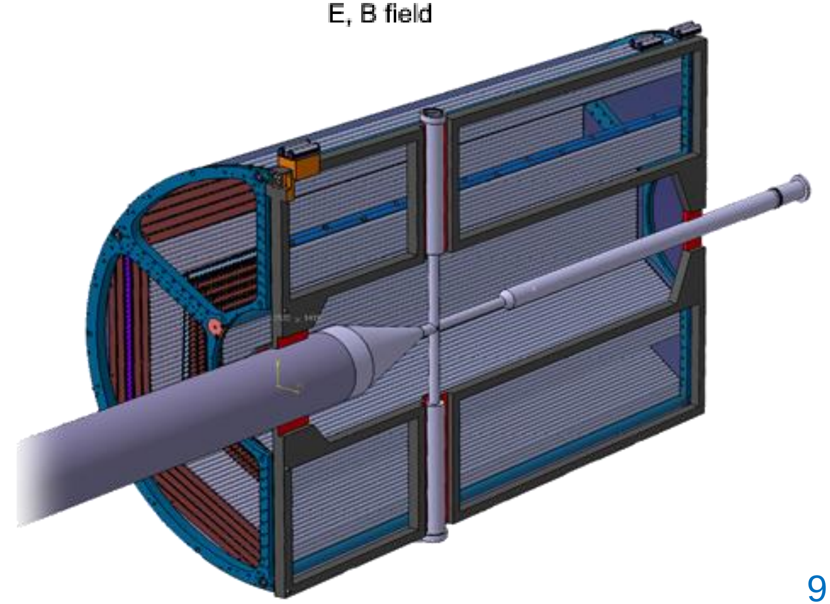
- Design figures:
  - $\sigma_{r\varphi} \sim 150\mu m$, $\sigma_z \sim 1mm$
  - $\delta p/p \sim 1\div 2\%$ (with MVD)
  - Material budget ~ 2% X_0

2 Alternatives:

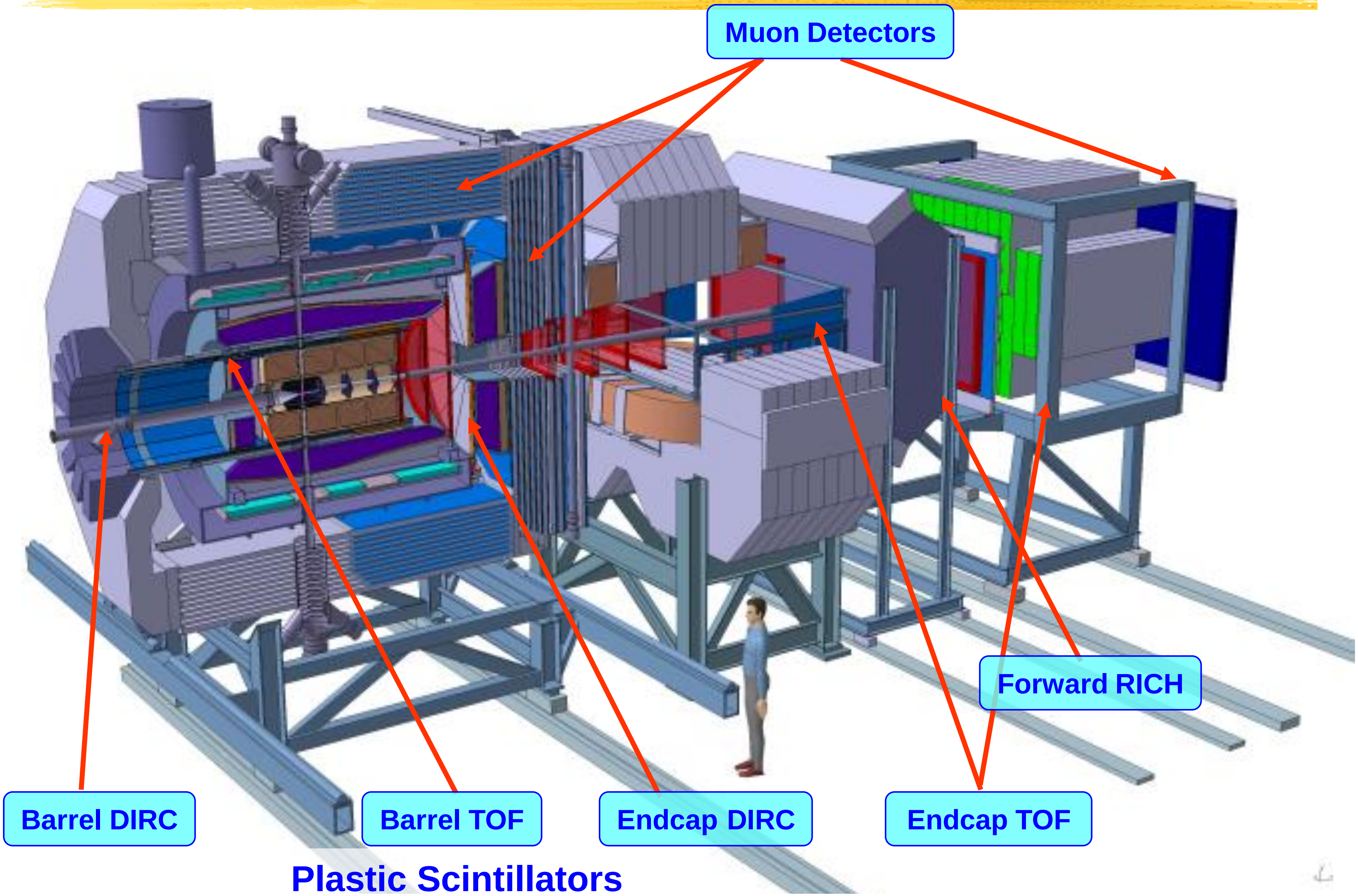
- **Time Projection Chamber (phased out)**
  - Continuous sampling
    GEMs readout plane
    (Ion feedback suppression)
    Online tracklet finding

- **Straw Tube Tracker (selected!)**
  - about 4000 straws
  - 27 μm thin mylar tubes, 1 cm Ø
  - Stability by 1 bar overpressure





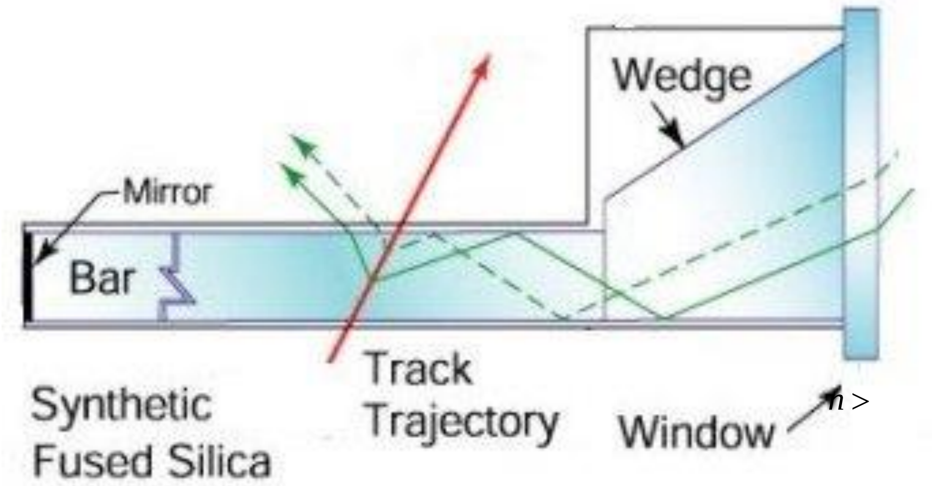
PANDA spectrometer: Particle IDentification

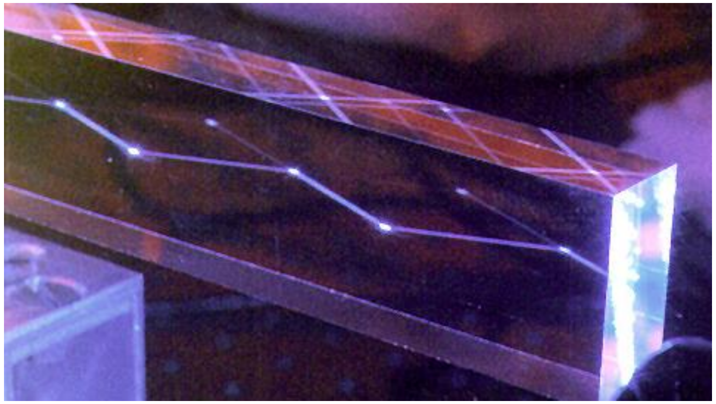


Plastic Scintillators

Physics Performance Report for PANDA arXiv:0903.3905 [hep-ex]

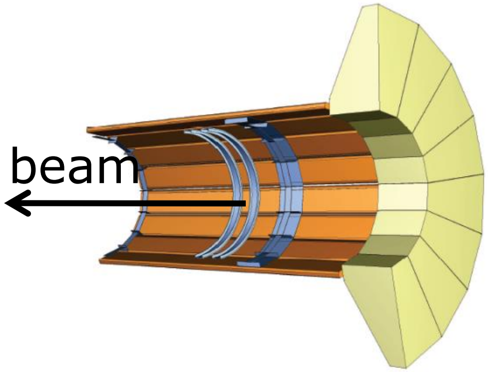
DIRC



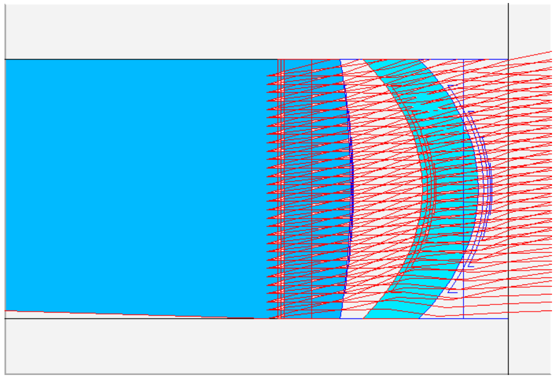


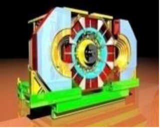
PANDA DIRC

- Lens focussing
- shorter radiator
- no water tank
- compact pixel readout (CP-PMTs or APDs)



Lens Focussing





Muon detector

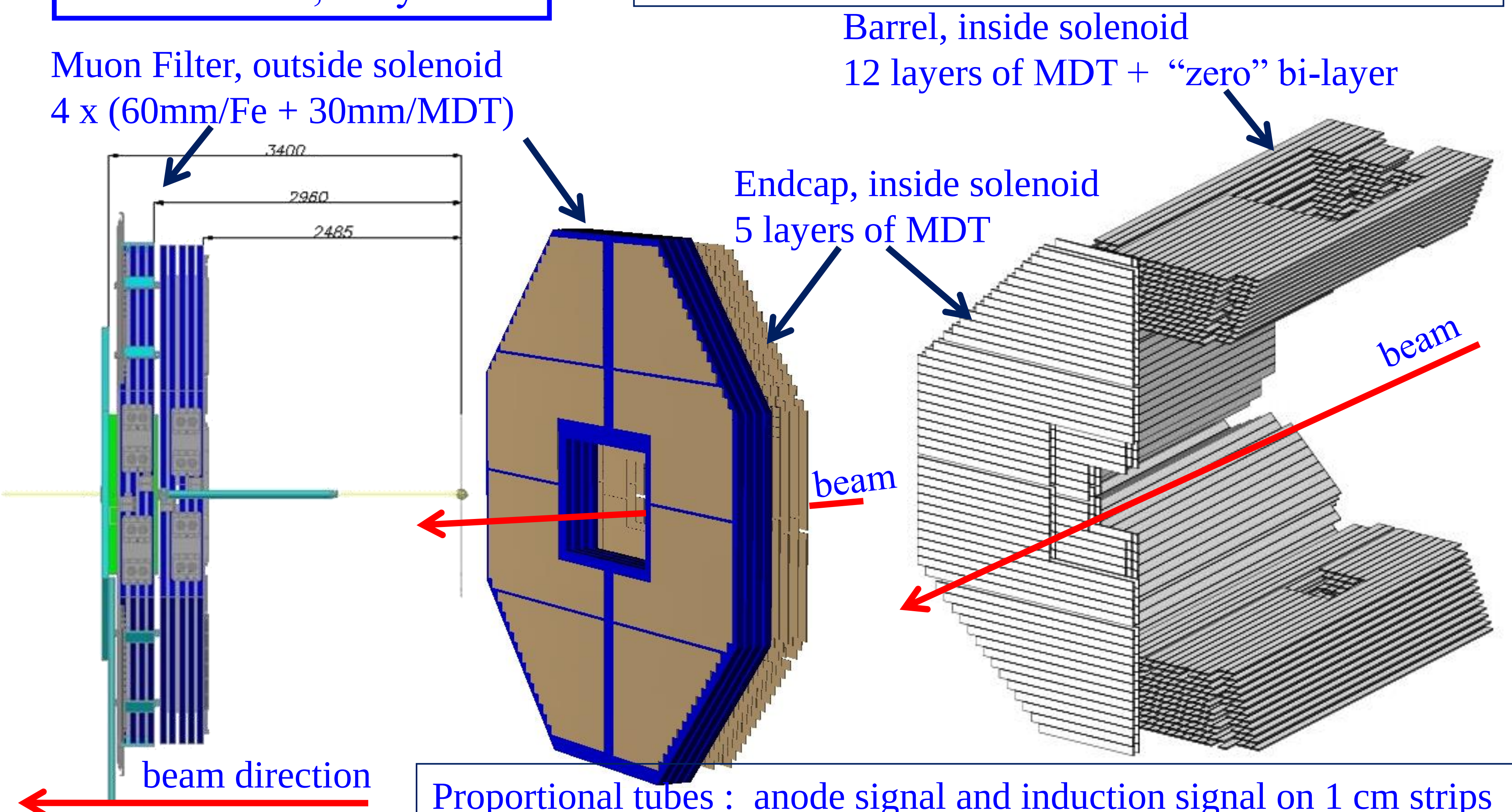
Inside the solenoid

Barrel: 12 layers inside the yoke + 1 bi-layer ("zero" bi-layer) in before iron

Endcap: 5 layers + "zero" bi-layer before iron

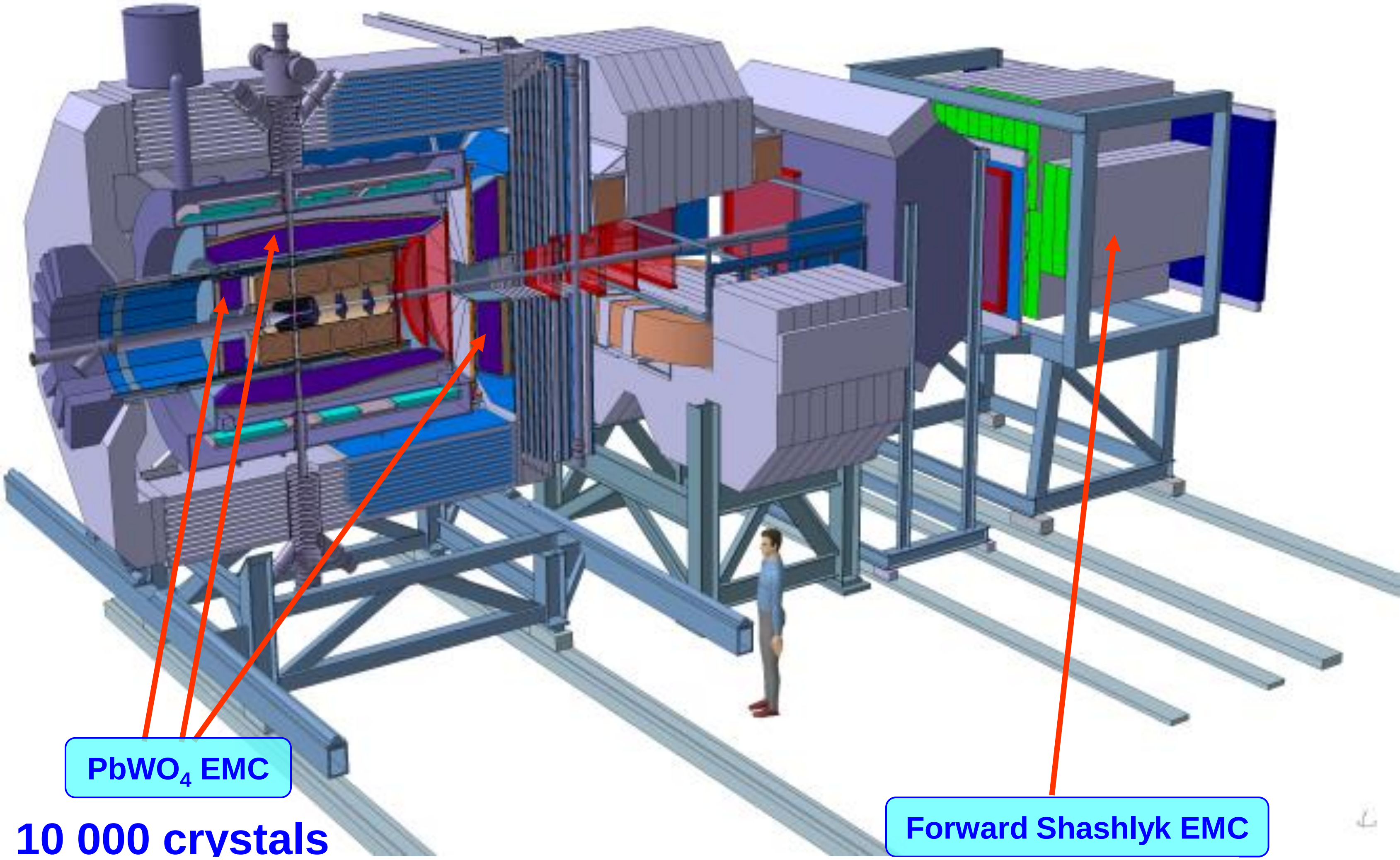
Outside the solenoid

"Muon Filter", 4 layers



Proportional tubes : anode signal and induction signal on 1 cm strips

PANDA spectrometer: Particle IDentification



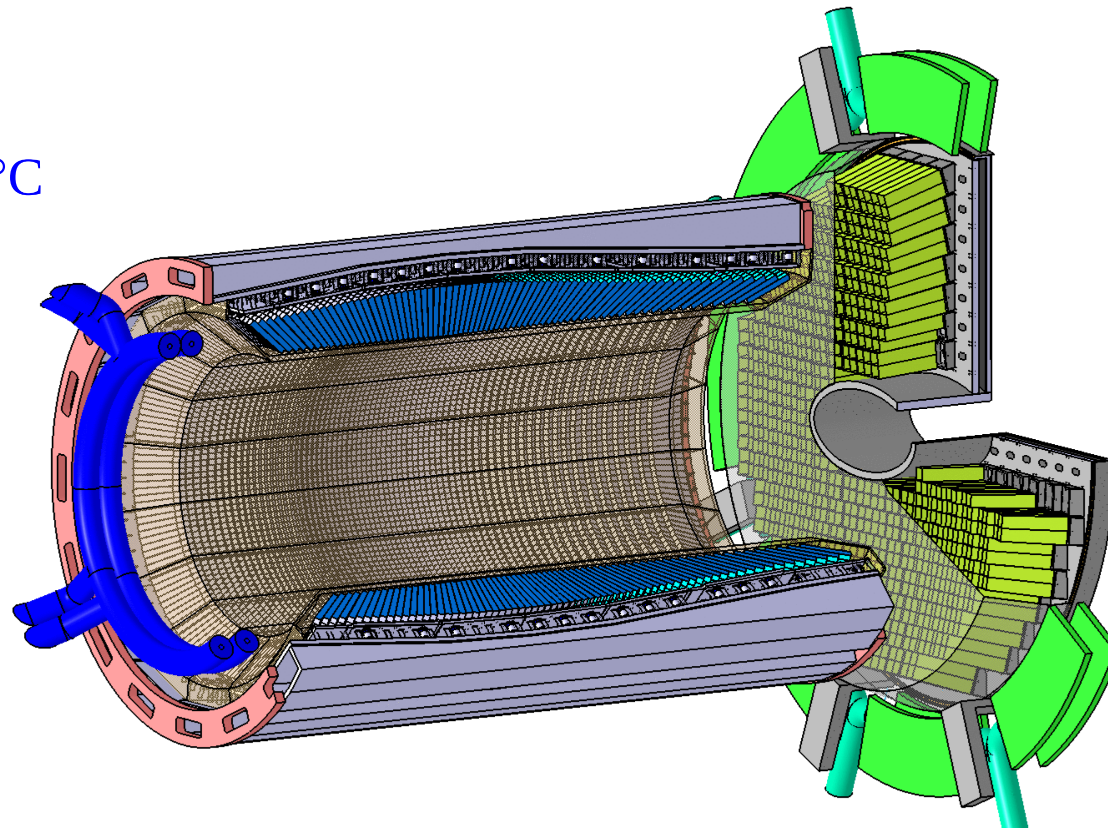
Physics Performance Report for PANDA arXiv:0903.3905 [hep-ex]
PANDA EMC TDR arXiv:0810.1216v1 [physics.ins-det]

PANDA PWO Calorimeters

- PWO is dense and fast
- Increase light yield:
  - improved PWO II
  - operation at -25°C
- Challenges:
  - temperature stable to 0.1°C
  - control radiation damage
  - low noise electronics
- Delivery of crystals started

Forward Endcap

- 4000 PWO crystals
- High occupancy in center
- LAAPD readout



Barrel Calorimeter

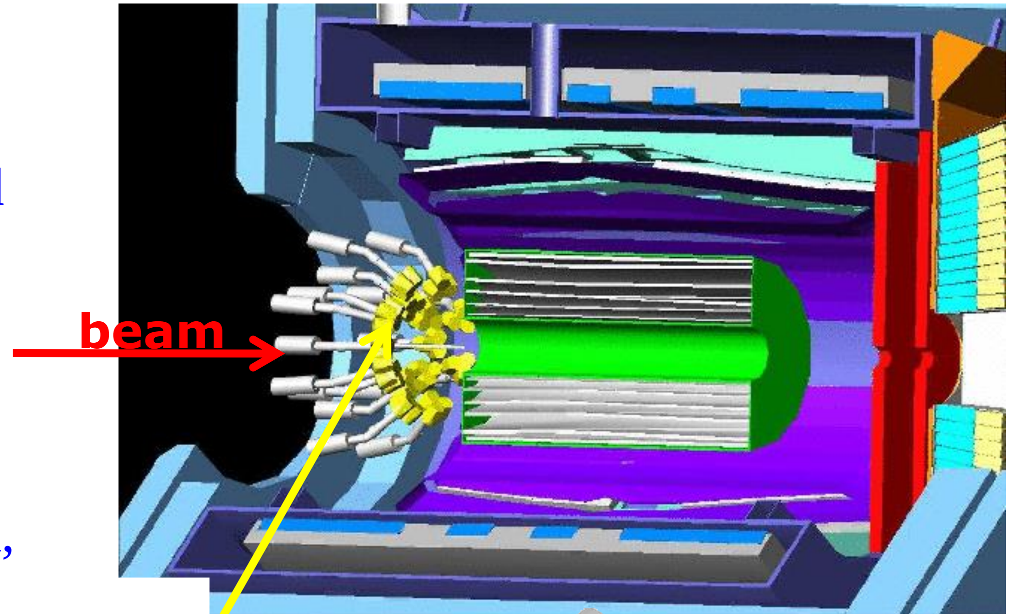
- 11000 PWO Crystals
- LAAPD readout, 2 x 1cm^2
- $\sigma(E)/E \sim 1.5\%/\sqrt{E} + \sim 1\%$

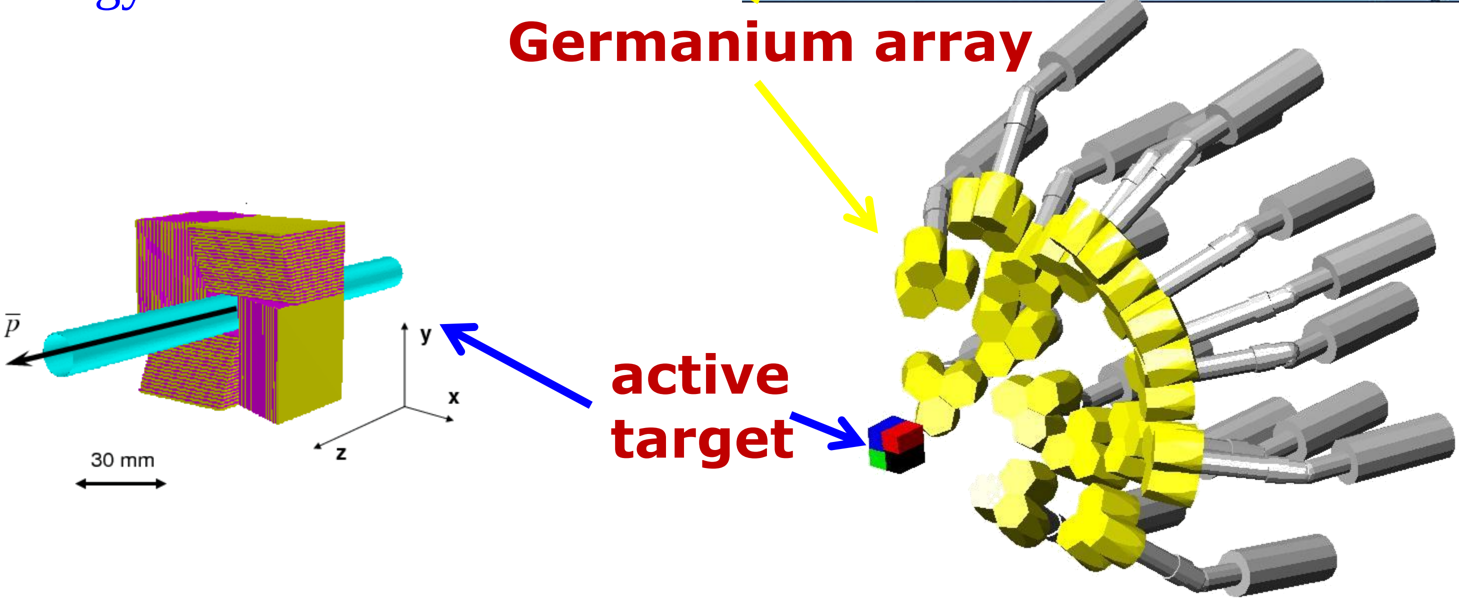
Hypernuclear Detector

Internal C target to produce $\Xi\bar{\Xi}$
Active silicon target to stop the Ξ and detect the hypenuclei decay products

Germanium γ array detector, with 15 clusters of 3 gemanium

Foreseeen 2 KeV γ energy resolution, 1.3 MeV π energy resolution





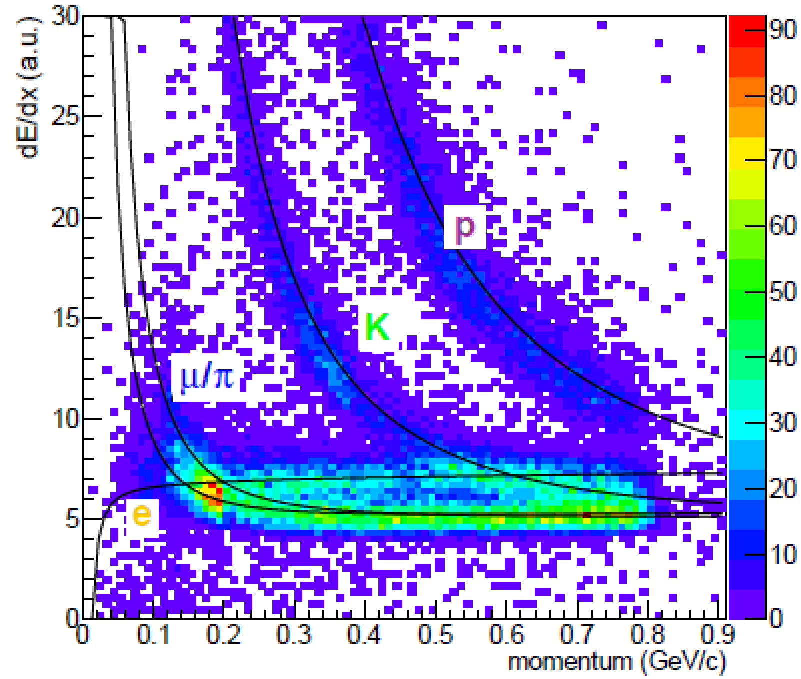
PANDA PID requirements

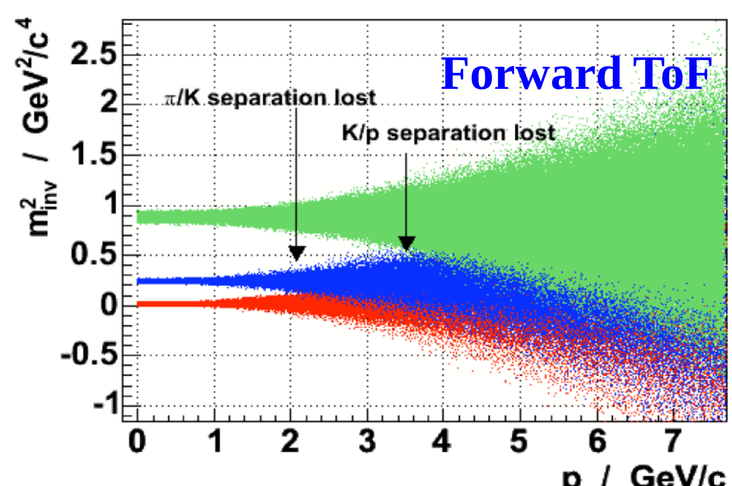
- Particle identification essential tool
- Momentum range 200 MeV/c – 10 GeV/c
- Different processes for PID needed

PID Processes

- Čerenkov radiation:
  Radiators: quartz, aerogel, C_4F_{10}
- Energy loss: p < 1 GeV
  Good accuracy with TPC,
  Stt system dE/dx under study
- Time of flight:
  needs a start detector
- Electromagnetic showers:
  EMC for e and γ

dE/dx of STT

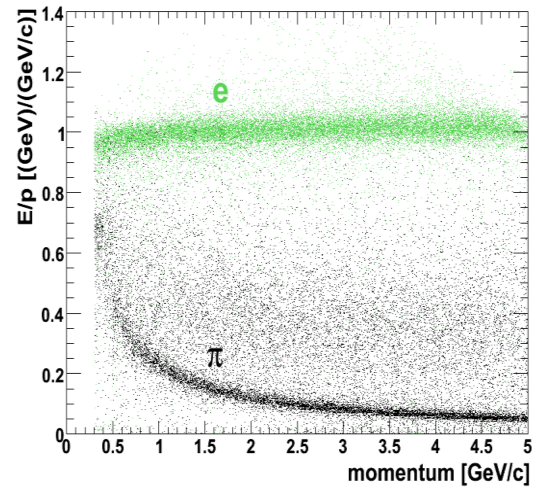




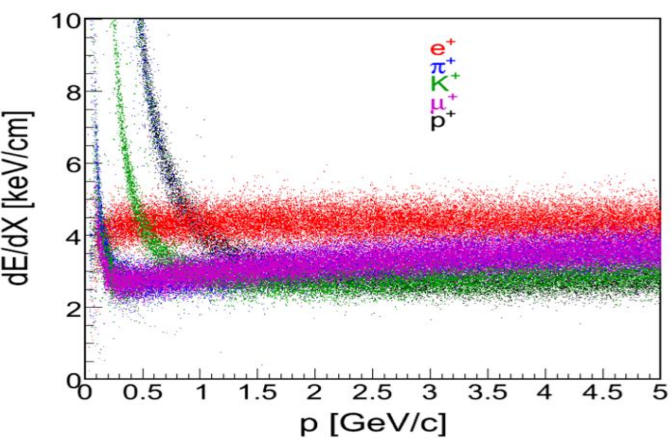
PANDA PID Requirements:

- particle identification essential for PANDA
- momentum range 200 MeV/c – 10 GeV/c
- Extreme high rates $2 \cdot 10^7$ Hz
- **good particle separation (K-π, e–π)**
  - different detectors needed for PID

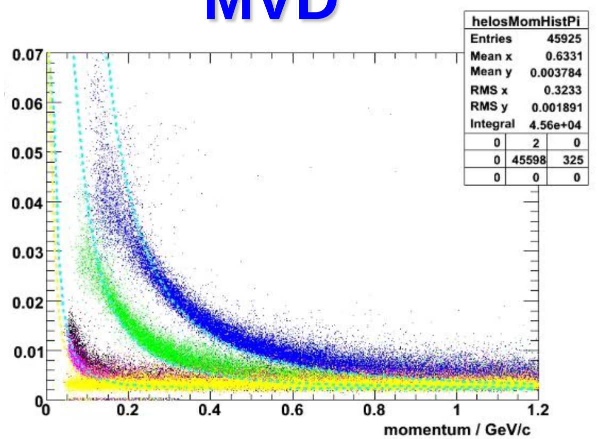
EMC



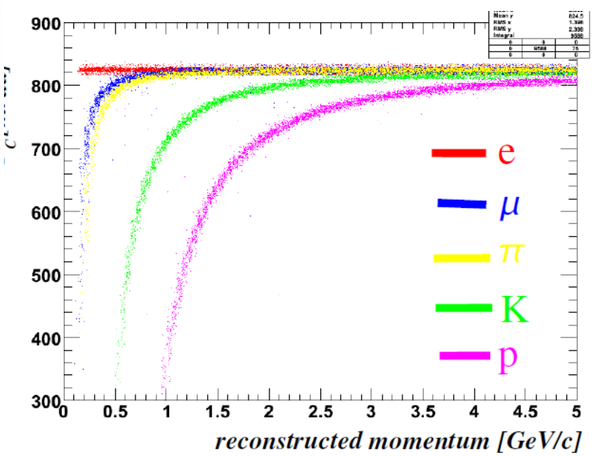
STT



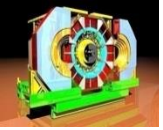
MVD



DIRC

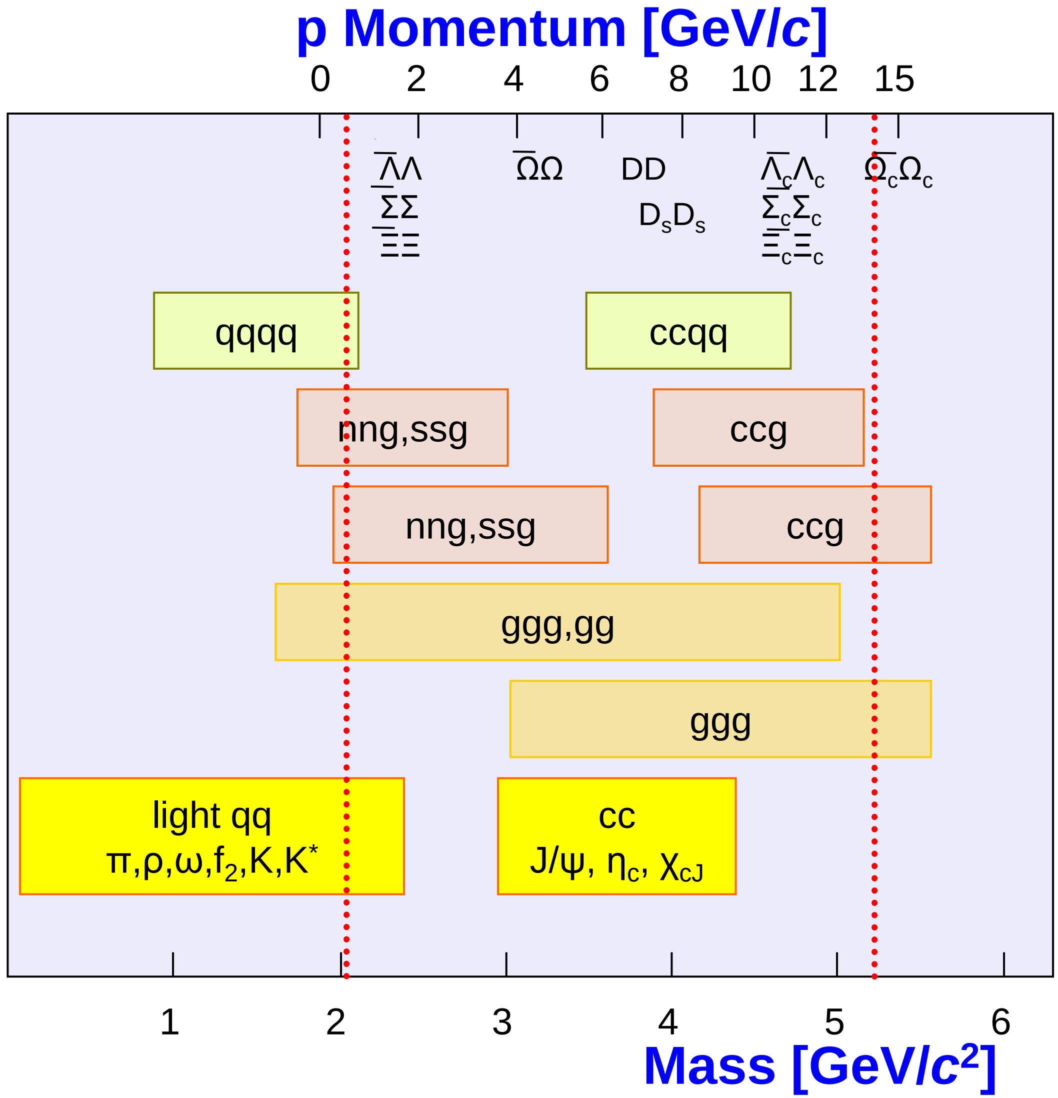


Physics Performance Report for PANDA arXiv:0903.3905



PANDA scientific program

- **baryon/antybaryon production**
- **EM processes:**
  - TL form factos
  - Drell-Yan and TMDS
  - GPDs
  - TDA
- **strangeness physics**
  - hyperatoms
  - S=-2 nuclear system
    - Ξ^- nuclei
    - $\Lambda\Lambda$ hypernuclei
- **meson spectroscopy**
  - light mesons
  - charmonium
  - exotics states
    - glueballs
    - hybrids
    - molecules/multiquarks
  - open charm
- **charm in nuclei**



Time-Like EM proton form factors in $\bar{p} + p \rightarrow e^- + e^+$

$\mathscr{L} = 2 \cdot 10^{32}\ cm^{-2}\ s^{-1} \rightarrow 2\ fb^{-1}$ in ~ 100 days

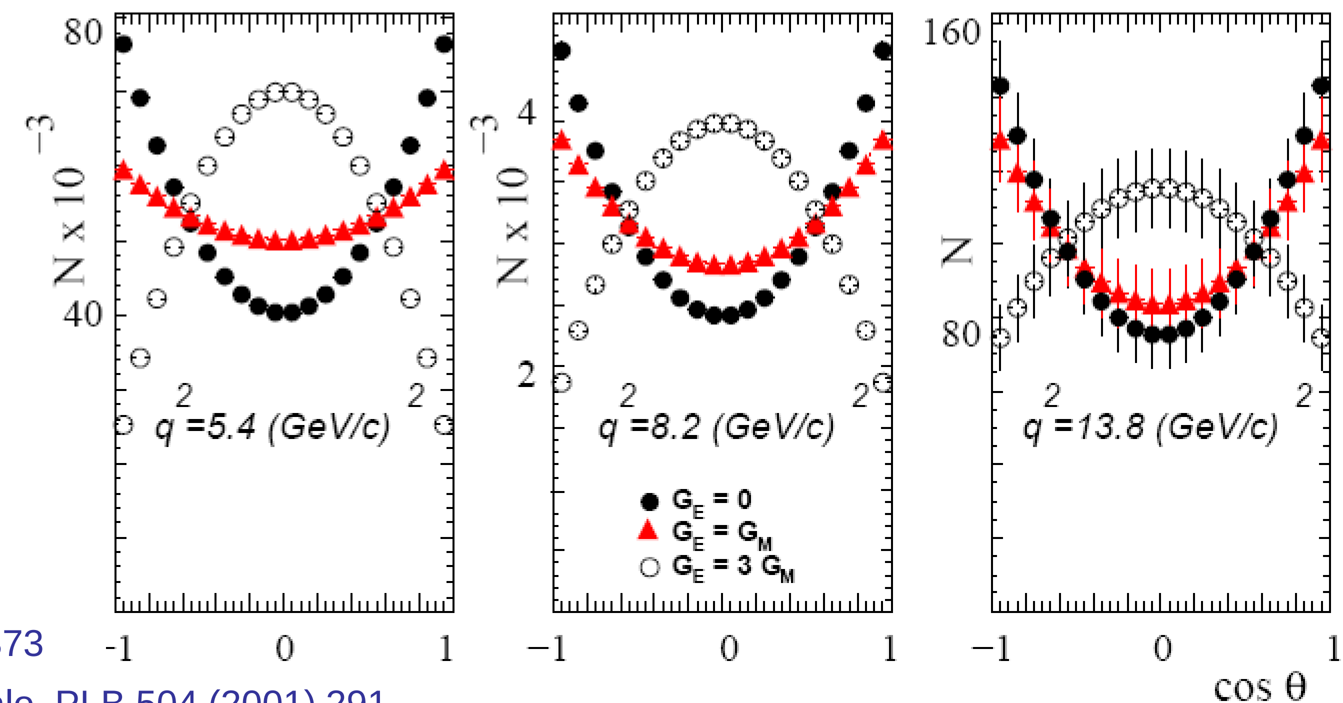
Generator:

- $|G_M| = 22.5\ (1 + q^2 / 0.71)^{-2}\ (1 + q^2 / 3.6)^{-1}$

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

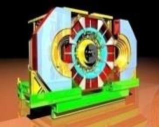
- $\Re = |G_E|/|G_M|$

lower sensitivity @ higher q^2



M. Sudol et al., EPJ A44 (2010) 373

E. Tomasi-Gustafsson, M.P. Rekalo, PLB 504 (2001) 291



PANDA scenario: expected results

$\mathscr{L} = 2 \cdot 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} \rightarrow 2\ \mathrm{fb}^{-1}$ in ~ 100 days

$$N(\cos\theta) = \alpha[\tau(1+\cos^2\theta) + \mathcal{R}^2 \sin^2\theta]$$

BABAR:

B. Aubert et al. PRD 73 (2006) 012005

PS170:

G. Bardin et al., NPB 411 (1994) 3

pQCD inspired:

V. A. Matveev et al., LNC 7 (1973) 719

S. J. Brodsky et al., PRL 31 (1973) 1153

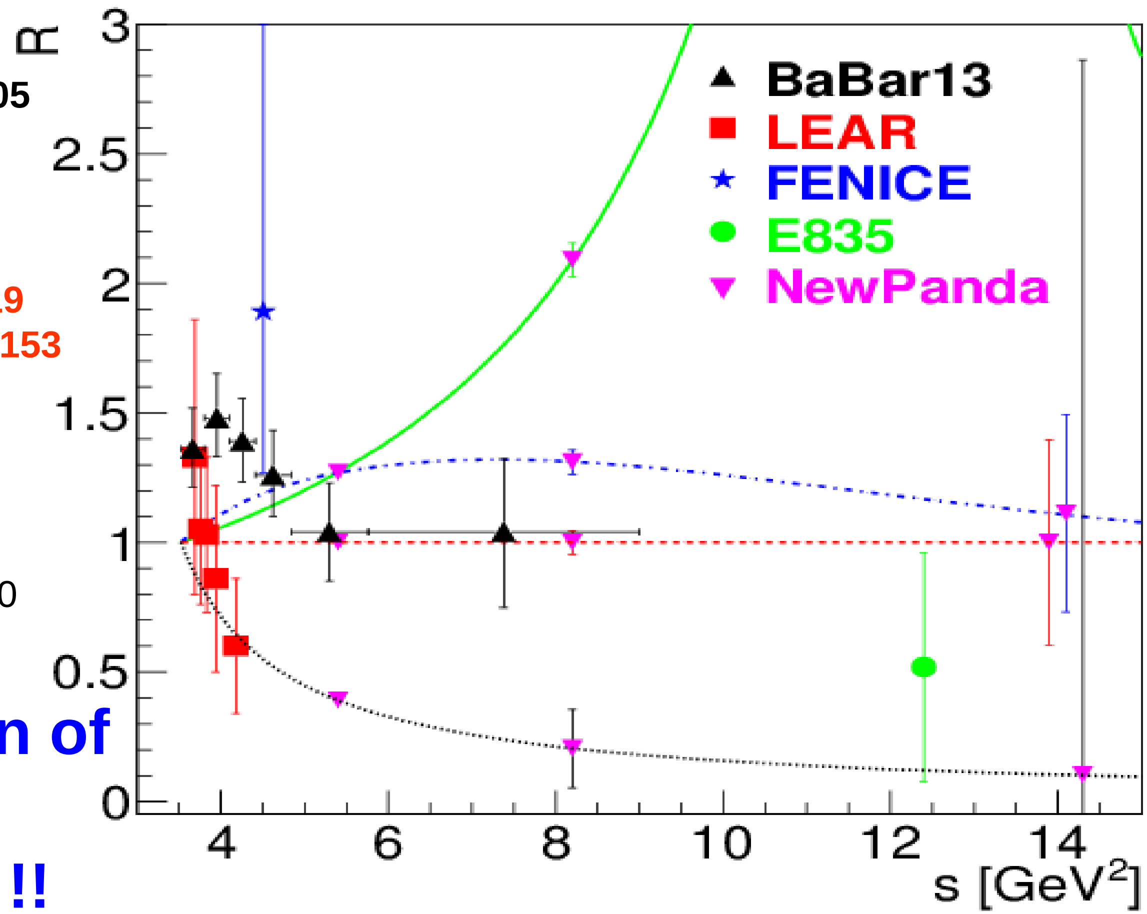
VDM:

F. Iachello, PLB 43 (1973) 191

Extended VDM:

E.L.Lomon, PRC 66 (2002) 045501

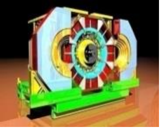
E. A. Kuraev et al., PLB 712 (2012) 240



Individual determination of $|G_E|$ and $|G_M|$ up to $q^2 \sim 14\ (\mathrm{GeV}/c)^2$!!

M. Sudol et al., EPJ A44 (2010) 373

A. Dbeyssi, PhD Thesis: PANDA unofficial results



PANDA scenario: expected results

$\mathscr{L} = 2 \cdot 10^{32}\ \mathrm{cm^{-2}\,s^{-1}} \rightarrow 2\ \mathrm{fb^{-1}}$ in ~ 100 days

BABAR:
- **B. Aubert et al. PRD 73 (2006) 012005**

E835:
- **M. Andreotti et al., PLB 559 (2003) 20**
- **M. Ambrogiani et al., PRD 60 (1999) 032002**

Fenice:
- **A. Antonelli et al., NPB 517 (1998) 3**

PS170:
- **G. Bardin et al., NPB 411 (1994) 3**

E760:
- **T. A. Armstrong et al., PRD 56 (1997) 2509**

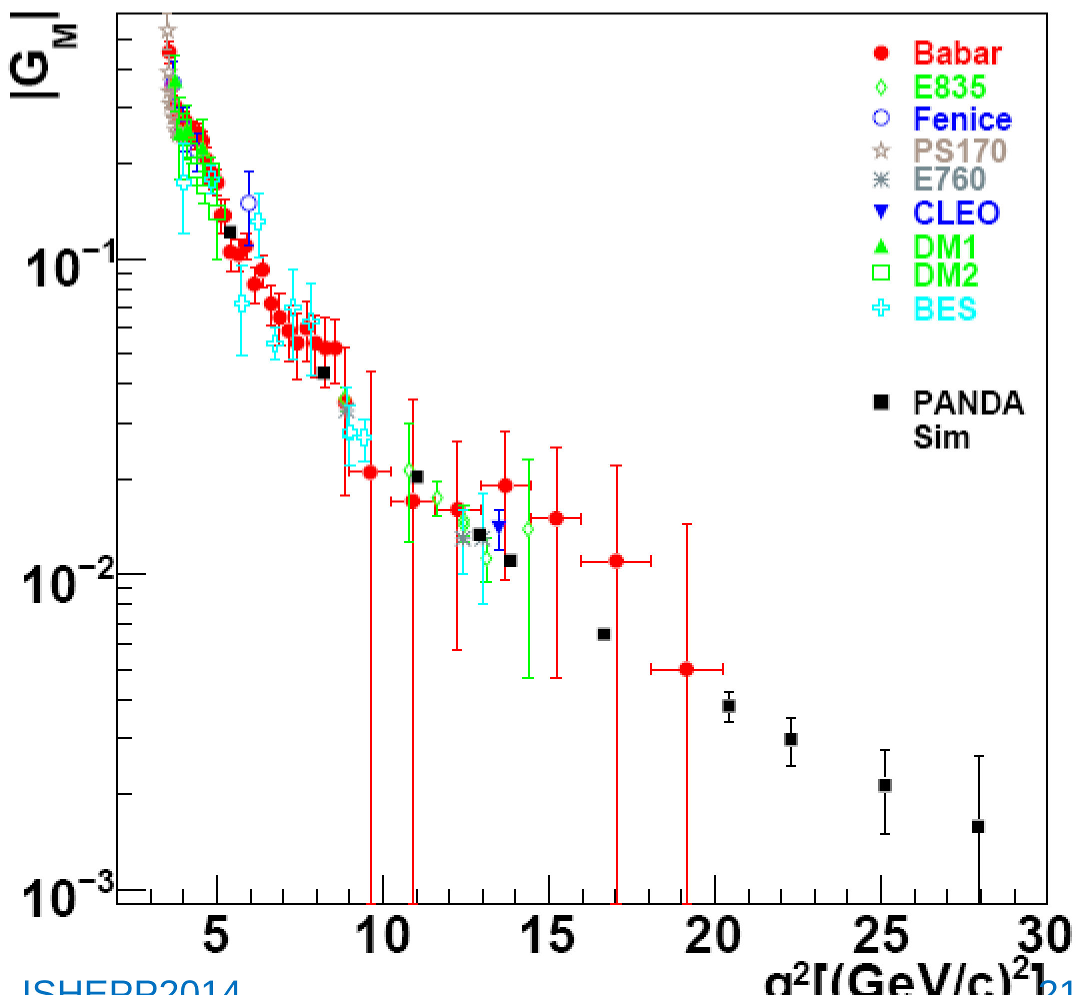
CLEO:
- **T. K. Pedlar et al. , PRL 95 (2005) 261803**

DM1:
- **B. Delcourt et al., PLB 86 (1979) 395**

DM2:
- **D. Bisello et al., NPB 224 (1983) 379**

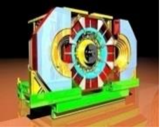
BES:
- **M. Ablikim et al., PLB 630 (2005) 14**

$\mathcal{R} = 1$



Absolute σ accessible up to $q^2 \sim 28\ (GeV/c)^2$

M. Sudol et al., EPJ A44 (2010) 373



PANDA scenario: asymptotic behaviours

$\mathscr{L} = 2 \cdot 10^{32}\ cm^{-2}\ s^{-1} \rightarrow 2\ fb^{-1}$ in ~ 100 days

BABAR:
B. Aubert et al. PRD 73 (2006) 012005
E835:
M. Andreotti et al., PLB 559 (2003) 20
M. Ambrogiani et al., PRD 60 (1999) 032002
Fenice:
A. Antonelli et al., NPB 517 (1998) 3
PS170:
G. Bardin et al., NPB 411 (1994) 3
E760:
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CLEO:
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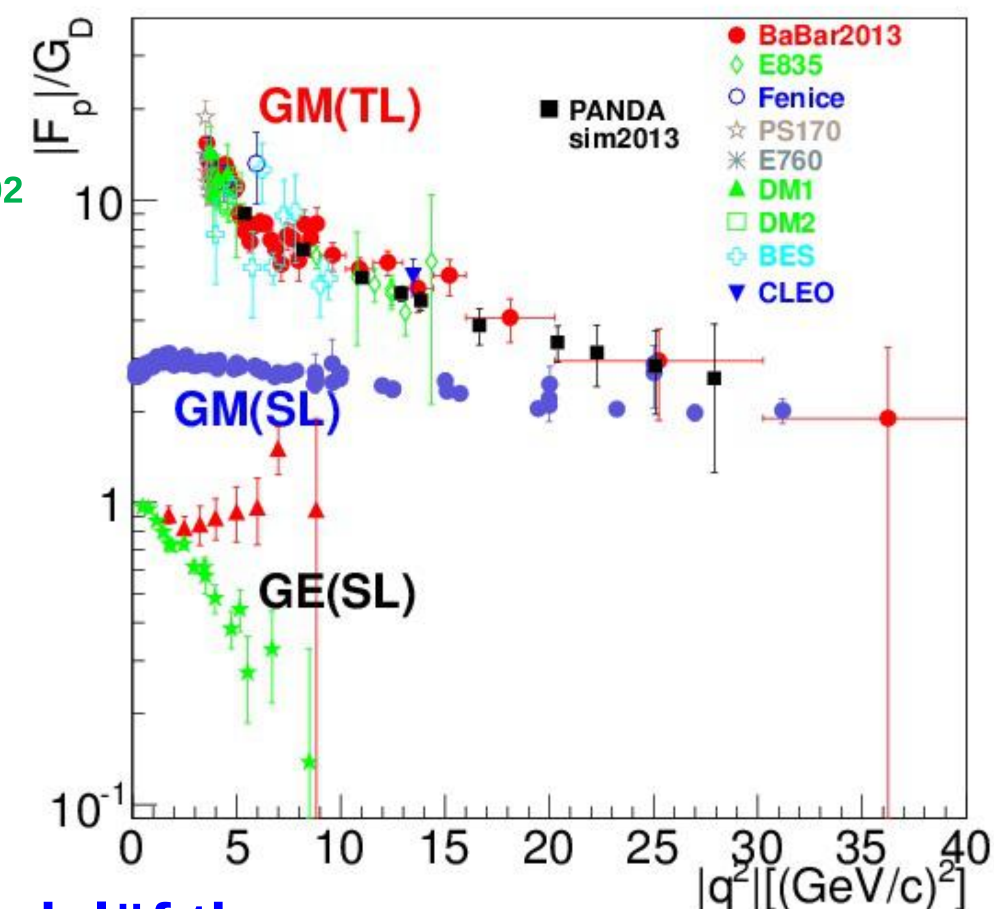
DM1:
B. Delcourt et al., PLB 86 (1979) 395
DM2:
D. Bisello et al., NPB 224 (1983) 379
BES:
M. Ablikim et al., PLB 630 (2005) 14



Probing the Phragmèn-Lindelöf theorem:

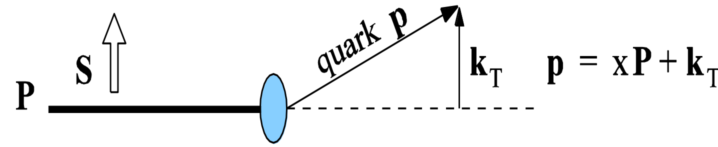
$$\lim_{q^2 \to -\infty} F^{(SL)}(q^2) = \lim_{q^2 \to \infty} F^{(TL)}(q^2) \qquad ImF_i(q^2) \to 0, \quad q^2 \to \infty$$

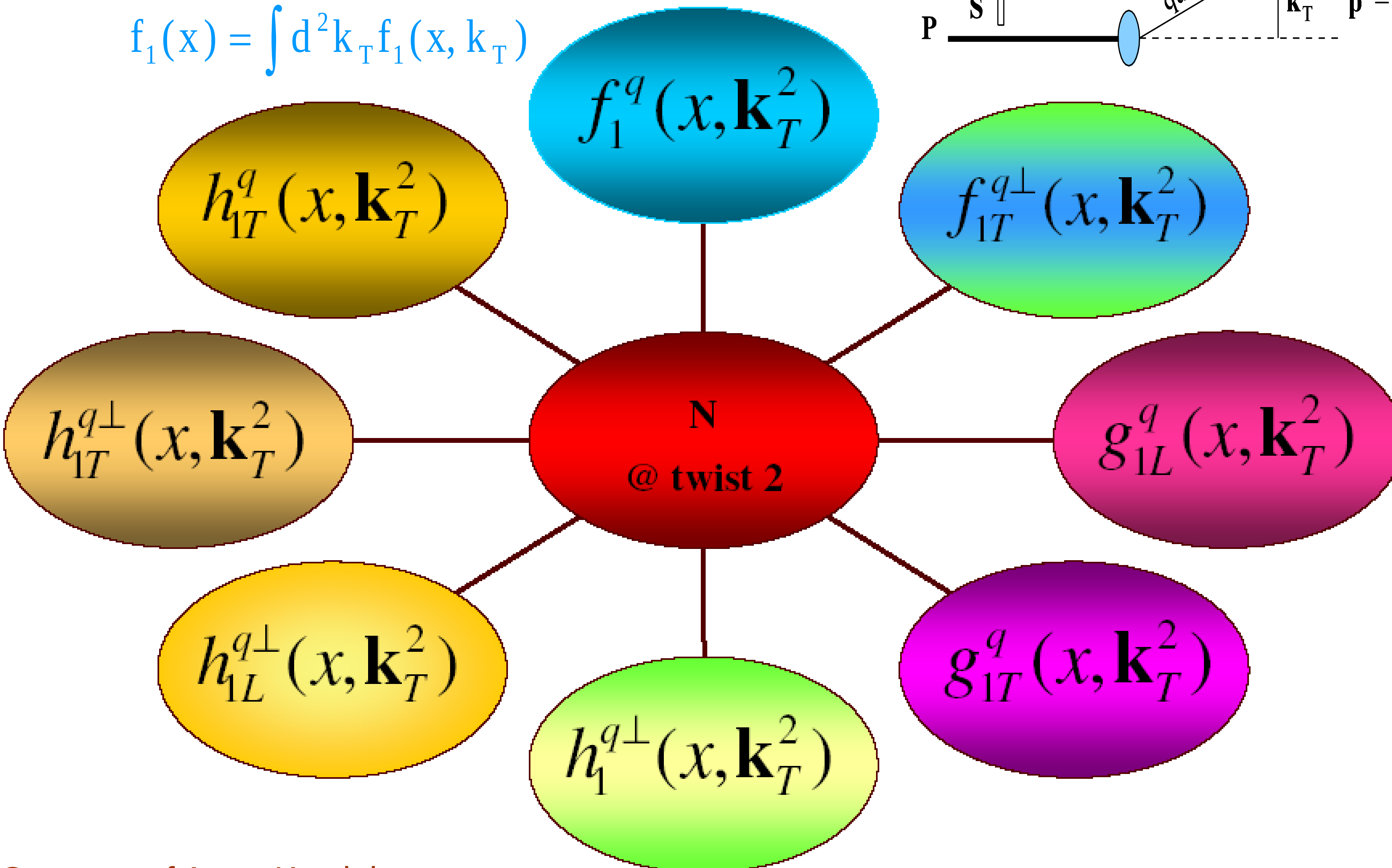
E. Tomasi-Gustafsson, 12th International Conference on Nuclear Reaction Mechanisms, Villa Monastero, Varenna, Italy, 15 - 19 Jun 2009, pp.447, arXiv:0907.4442v1 [nucl-th]

TMD: κ_T-dependent Parton Distributions

Twist-2 PDFs:

$$f_1(x) = \int d^2k_T f_1(x, k_T)$$



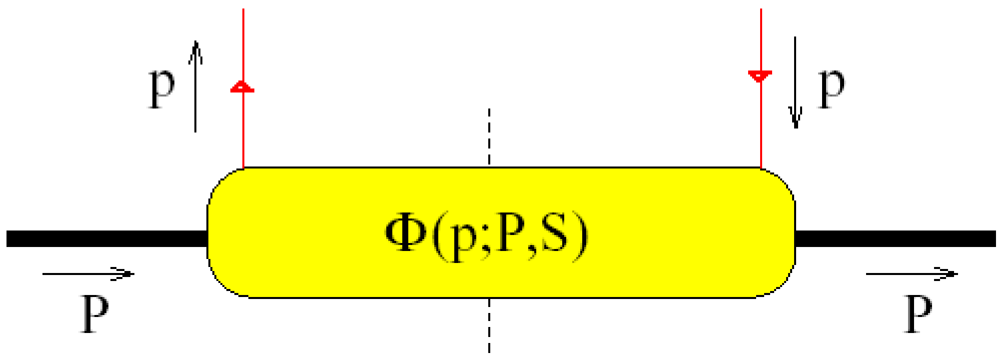


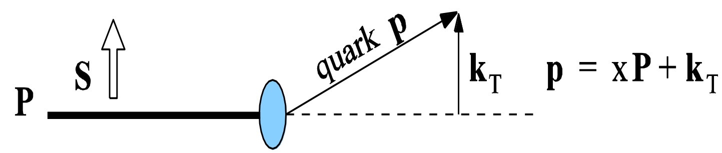
Courtesy of Aram Kotzinian

TMD: κ_T-dependent Parton Distributions

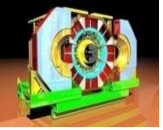
Leading-twist correlator depends on

five more distribution functions:



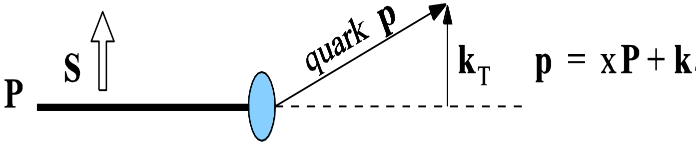


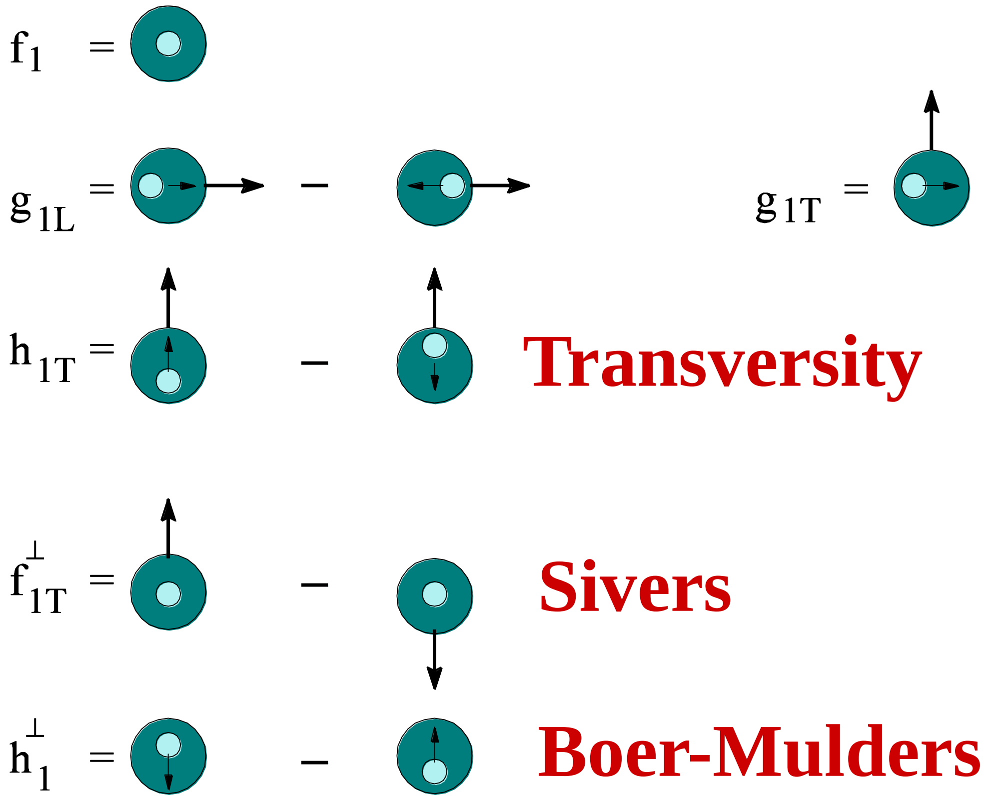
$$\Phi(x_a, \boldsymbol{k}_{\perp a}) = \frac{1}{2}\Big[f_1 \not{n}_+ + f_{1T}^{\perp} \frac{\epsilon_{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu k_{\perp a}^\rho (P_T^A)^\sigma}{M} + \Big(P_L^A g_{1L} + \frac{\boldsymbol{k}_{\perp a}\cdot \boldsymbol{P}_T^A}{M} g_{1T}^{\perp} \Big)\gamma^5 \not{n}_+$$
$$+ h_{1T}\, i\sigma_{\mu\nu}\gamma^5 n_+^\mu (P_T^A)^\nu + \Big(P_L^A h_{1L}^{\perp} + \frac{\boldsymbol{k}_{\perp a}\cdot \boldsymbol{P}_T^A}{M} h_{1T}^{\perp} \Big) \frac{i\sigma_{\mu\nu}\gamma^5 n_+^\mu k_{\perp a}^\nu}{M}$$
$$+ h_1^{\perp} \frac{\sigma_{\mu\nu} k_{\perp a}^\mu n_+^\nu}{M} \Big] .$$



TMD: κ_T-dependent Parton Distributions

Twist-2 PDFs $\qquad f_1(x) = \int d^2k_T f_1(x,k_T)$





Distribution functions		Chirality even	Chirality odd
Twist-2	U	f_1	$h_1^{\perp}$
	L	g_1	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}, g_{1T}$	$h_1, \; h_{1T}^{\perp}$

Drell-Yan Di-Lepton Production — $\bar{p}p \rightarrow \ell^+\ell^- X$

Why Drell Yan?

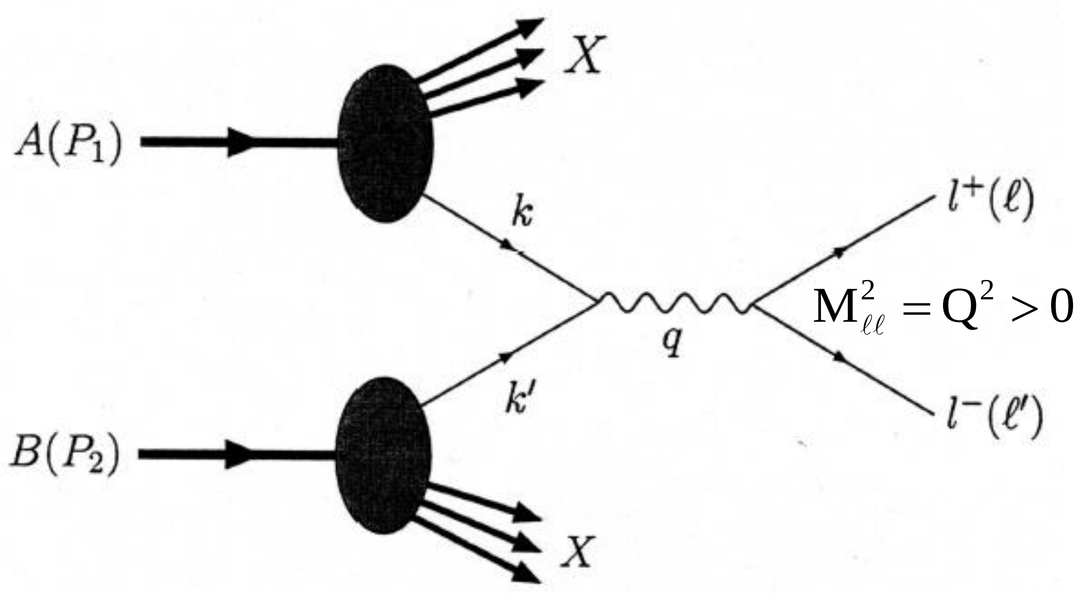
Asymmetries depend on PD only (SIDIS→convolution with QFF)

3 planes: plane ⊥ to polarisation vectors
$p - \gamma^*$ plane
$\ell^+\ell^-\gamma^*$ plane

→ plenty of (single) spin effects

Why $\bar{p}$?

Each valence quark can contribuite to the diagram



Kinematics

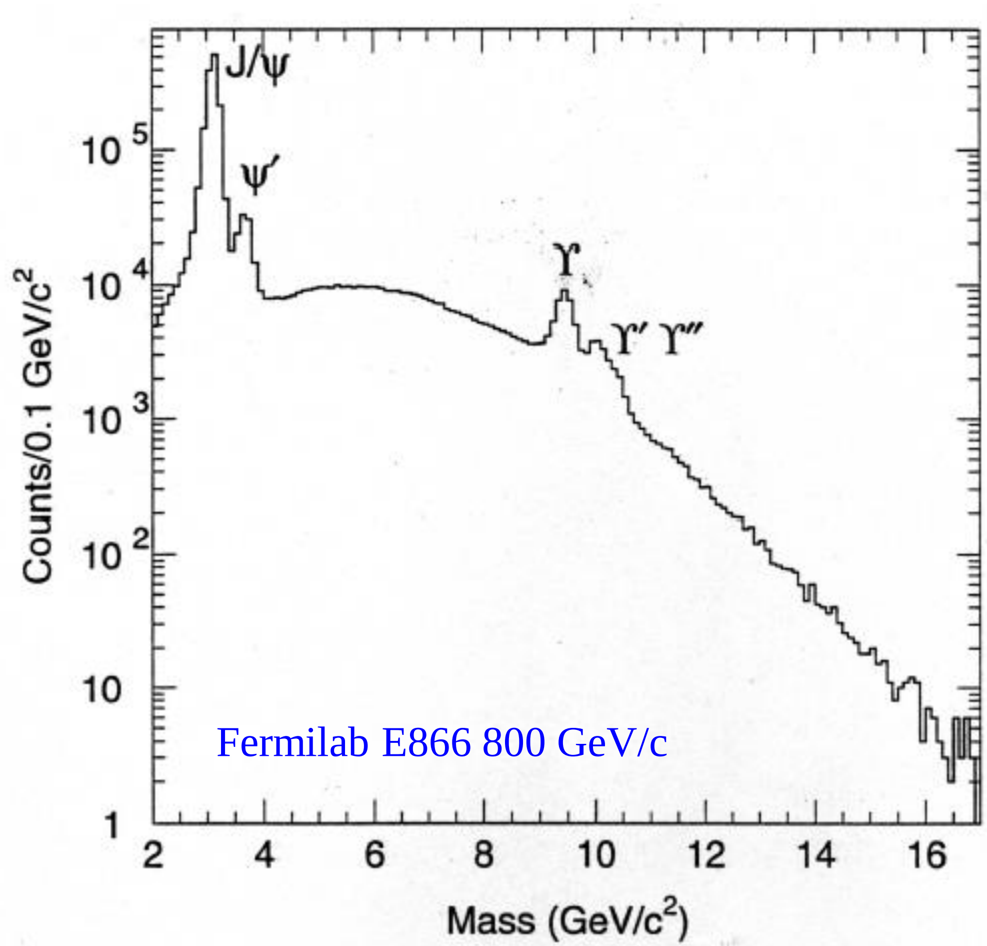
$$x_1 = \frac{M^2}{2P_1 \bullet q} \qquad x_2 = \frac{M^2}{2P_2 \bullet q}$$

$$x_F = x_1 - x_2$$

$$\tau = x_1 x_2 = \frac{M^2}{s}$$

Drell-Yan Di-Lepton Production — $\bar{p}p \rightarrow \ell^+\ell^- X$

$$\frac{d^2\sigma}{dM^2 dx_F} = \frac{4\alpha^2\pi}{9M^2 s}\frac{1}{x_1 + x_2}\sum_a e_a^2\left[f^a(x_1)f^{\bar{a}}(x_2) + f^{\bar{a}}(x_1)f^a(x_2)\right]$$



0

Scaling:

$$\frac{d^2\sigma}{d\sqrt{\tau}\,dx_F} \propto \frac{1}{s}$$

Full x_1, x_2 range $\Rightarrow \tau \in [0,1]$

Kinematics

$$x_1 = \frac{M^2}{2P_1 \bullet q} \qquad x_2 = \frac{M^2}{2P_2 \bullet q}$$

$$x_F = x_1 - x_2$$

$$\tau = x_1 x_2 = \frac{M^2}{s}$$

Experimental Asymmetries @ PANDA — $\bar{p}\, p^{(\uparrow)} \to \mu^+\mu^- X$

Unpolarised:

$$A^{\cos 2\phi}$$

$$\frac{d\sigma^0}{d\Omega dx_1 dx_2 d\boldsymbol{k}_T} = \frac{\alpha^2}{12Q^2}\sum_a e_a^2 \left\{ \left(1+\cos^2\theta\right)\mathcal{F}\left[\bar{f}_1^a f_1^a\right] + \sin^2\theta\cos 2\phi\,\mathcal{F}\left[\left(2\boldsymbol{h}\cdot\boldsymbol{p}_{1T}\,\boldsymbol{h}\cdot\boldsymbol{p}_{2T} - \boldsymbol{p}_{1T}\cdot\boldsymbol{p}_{2T}\right)\frac{\bar{h}_1^{\perp a} h_1^{\perp a}}{M_1 M_2}\right]\right\}$$

$$\mathcal{F}\left[\bar{f}_1^a f_1^a\right] \equiv \int d\boldsymbol{p}_{1T} d\boldsymbol{p}_{2T}\,\delta\left(\boldsymbol{p}_{1T}+\boldsymbol{p}_{2T}-\boldsymbol{k}_T\right)\left[\bar{f}_1^a\left(x_1,\boldsymbol{p}_{1T}\right) f_1^a\left(x_2,\boldsymbol{p}_{2T}\right) + \left(1\leftrightarrow 2\right)\right]$$

Single Spin:

$$A^{\sin\left(\phi-\phi_{S_2}\right)}$$

$$\frac{d\Delta\sigma^\uparrow}{d\Omega dx_1 dx_2 d\boldsymbol{k}_T} = \frac{\alpha^2}{12sQ^2}\sum_a e_a^2 \left|\boldsymbol{S}_{2T}\right| \left\{ \left(1+\cos^2\theta\right)\sin\left(\phi-\phi_{S_2}\right)\mathcal{F}\left[\boldsymbol{h}\cdot\boldsymbol{p}_{2T}\frac{\bar{f}_1^a f_{1T}^{\perp a}}{M_2}\right] + \right.$$

$$-\sin^2\theta\sin\left(\phi+\phi_{S_2}\right)\mathcal{F}\left[\boldsymbol{h}\cdot\boldsymbol{p}_{1T}\frac{\bar{h}_1^{\perp a} h_{1T}^a}{M_1}\right]$$

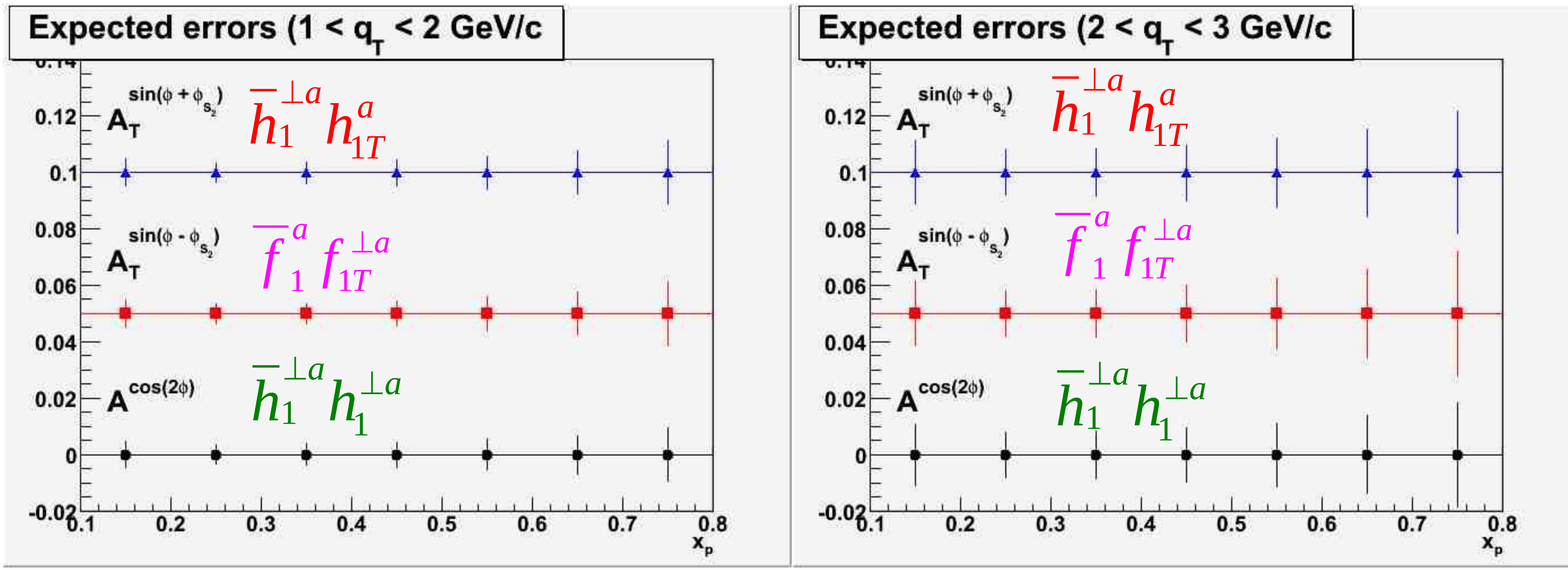
$$A^{\sin\left(\phi+\phi_{S_2}\right)}$$

$$\left. -\sin^2\theta\sin\left(3\phi-\phi_{S_2}\right)\mathcal{F}\left[\left(4\boldsymbol{h}\cdot\boldsymbol{p}_{1T}\left(\boldsymbol{h}\cdot\boldsymbol{p}_{2T}\right)^2 - 2\boldsymbol{h}\cdot\boldsymbol{p}_{2T}\,\boldsymbol{p}_{1T}\cdot\boldsymbol{p}_{2T} - \boldsymbol{h}\cdot\boldsymbol{p}_{1T}\,\boldsymbol{p}_{2T}^2\right)\frac{\bar{h}_1^{\perp a} h_{1T}^{\perp a}}{2M_1 M_2^2}\right]\right\}$$

Experimental Asymmetries @ PANDA — $\bar{p}\, p^{(\uparrow)} \to \mu^+\mu^- X$

480K ev[1] with $E_{\bar{p}} = 15$ GeV on fixed target, $1.5 < M_{\mu\mu} < 2.5$ GeV/c^2

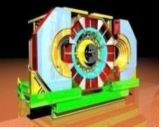
$$\text{Eff } R_{DY\text{-}\mu\mu}{}^{[2]} \left(1.5 < M_{\mu\mu} < 2.5 \text{ GeV/c}^2\right) = 0.16 \text{ s}^{-1} \times \frac{1}{2} = 0.08 \text{ s}^{-1} \approx 200\text{K Ev month}^{-1}$$



$s \sim 30$ GeV^2

[1]A. Bianconi and M. Radici, Phys. Rev. D71 (2005) 074014

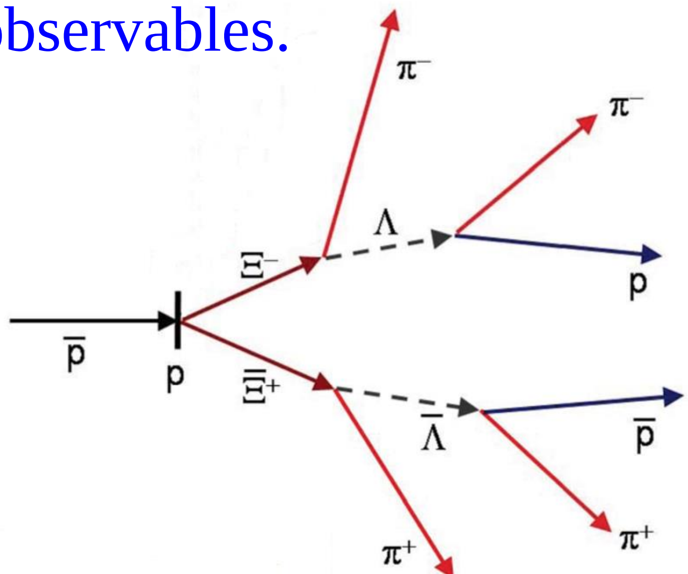
[2]Physics Performance Report for PANDA, arXiv: 0903.3905



QCD dynamics

The experimental data set available is far from being complete. All strange hyperons and single charmed hyperons are energetically accessible in $p\bar{p}$ collisions at PANDA.

In PANDA $p\bar{p} \rightarrow \Lambda\Lambda$, $\Lambda\Xi$, $\Lambda\Xi$, $\Xi\Xi$, $\Sigma\Sigma$, $\Omega\Omega$, $\Lambda_c\Lambda_c$, $\Sigma_c\Sigma_c$, $\Omega_c\Omega_c$ can be produced allowing the study of the dependences on spin observables.

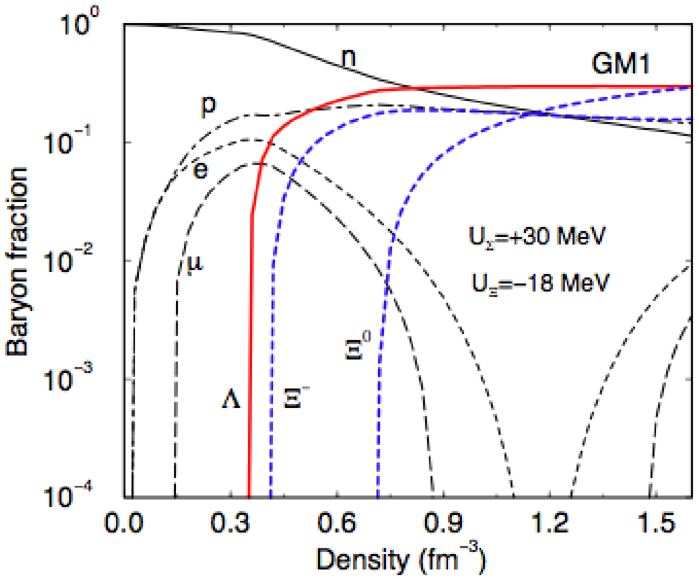


Channel 1.64 GeV/c	Rec. eff.	σ [μb]	Signal
$\bar{p}p \rightarrow \Lambda\bar{\Lambda}$	0.11	64	1
$\bar{p}p \rightarrow \bar{p}p\pi^+\pi^-$	$1.2 \cdot 10^{-5}$	~ 10	$4.2 \cdot 10^{-5}$
Channel 4 GeV/c			
$\bar{p}p \rightarrow \Lambda\bar{\Lambda}$	0.23	~ 50	1
$\bar{p}p \rightarrow \bar{p}p\pi^+\pi^-$	$< 3 \cdot 10^{-6}$	$3.5 \cdot 10^3$	$< 2.2 \cdot 10^{-3}$
$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0$	$5.1 \cdot 10^{-4}$	~ 50	$2.2 \cdot 10^{-3}$
$\bar{p}p \rightarrow \bar{\Lambda}\Sigma(1385)$	$< 3 \cdot 10^{-6}$	~ 50	$< 1.3 \cdot 10^{-5}$
$\bar{p}p \rightarrow \bar{\Sigma}^0\Sigma^0$	$< 3 \cdot 10^{-6}$	~ 50	$< 1.3 \cdot 10^{-5}$
Channel 15 GeV/c			
$\bar{p}p \rightarrow \Lambda\bar{\Lambda}$	0.14	~ 10	1
$\bar{p}p \rightarrow \bar{p}p\pi^+\pi^-$	$< 1 \cdot 10^{-6}$	$1 \cdot 10^3$	$< 2 \cdot 10^{-3}$
$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0$	$2.3 \cdot 10^{-3}$	~ 10	$1.6 \cdot 10^{-2}$
$\bar{p}p \rightarrow \bar{\Lambda}\Sigma(1385)$	$3.3 \cdot 10^{-5}$	60	$1.4 \cdot 10^{-3}$
$\bar{p}p \rightarrow \bar{\Sigma}^0\Sigma^0$	$3.0 \cdot 10^{-4}$	~ 10	$2.1 \cdot 10^{-3}$
DPM	$< 1 \cdot 10^{-6}$	$5 \cdot 10^4$	$< .09$
Channel 4 GeV/c	Rec. eff.	σ (μb)	Signal
$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	0.19	~ 2	1
$\bar{p}p \rightarrow \bar{\Sigma}^+(1385)\Sigma^-(1385)$	$< 1 \cdot 10^{-6}$	~ 60	$< 2 \cdot 10^{-4}$

By comparing several reactions involving different quark flavours the OZI rule and its possible violation, can be tested

Baryon-baryon interaction

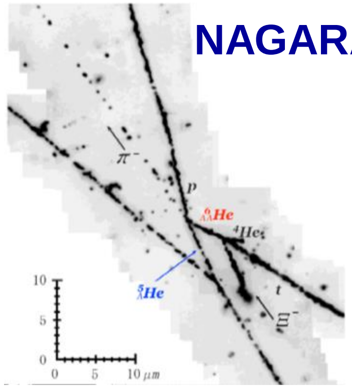
The knowledge of Baryon-Baryon potential is essential for the understanding of the composition of nuclear matter.



The fraction of baryons and leptons in neutron star matter arXiv:0801.3791v1

Nuclear *NN* forces are known, *YN* interaction, thanks to hypernuclear physics, is relatively known, but *YY* interaction is completely unknown, there are just a few double Λ hypernuclear events.

NAGARA



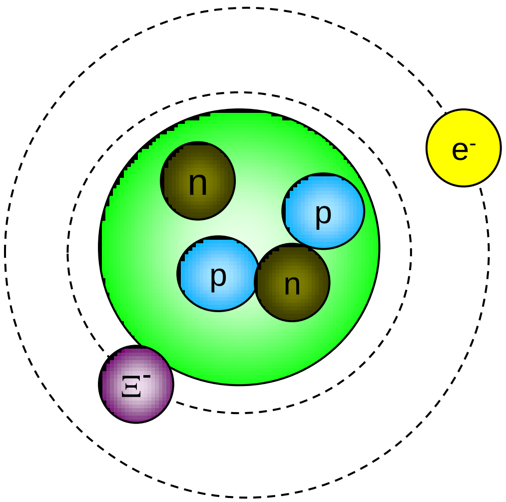
ΛΛ-hypernuclei, Ξ-atoms, Ω-atoms allow to have an insight to more complex nuclear systems containing strangeness (neutron stars, hyperon-stars, strange-quark stars, ...)

Double Strange Systems (DDS)

(S=±2) hyperon – antihyperon systems are fully accessible at PANDA

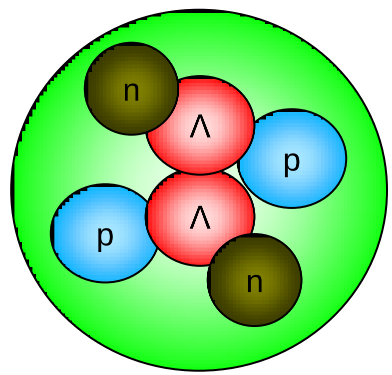
Exotic hyperatom:

Ξ^- occupies an atomic level



Double Λ Hypernucleus:

2 Λ's replace 2 nucleons in a nucleu



ΛΛ strong interaction

- only possible in double hypernuclei
- YY potential: attractive/repulsive?
- hyperfragments probability dependence on YY potential

One Boson Exchange features

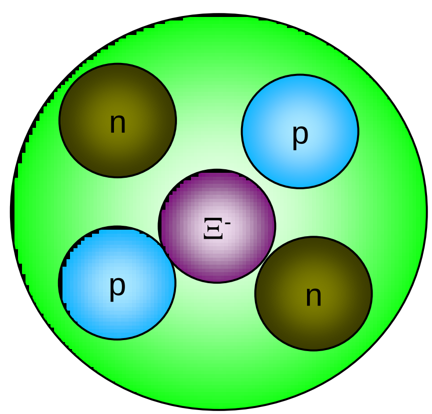
ΛΛ → ΛΛ: only *non strange, I =0 meson* exchange (ω,η...)

ΛΛ weak interaction: hyperon induced decay:

- ΛΛ →Λ n: $\Gamma_{\Lambda n}$ << Γ_{free} (expected)
- ΛΛ → Σ^-p: $\Gamma_{\Sigma p}$ << Γ_{free} (expected)

Doubly Strange Hypernucleus:

Ξ^- occupies a nuclear level



Ξ^- -nucleus interaction

- Atomic orbits overlap nucleus
- Strong interaction and Coulomb force interplay
- Lowest atomic levels are shifted and broadened
- Potential: Coulomb + optical

Ξ -N interaction:

- short range interaction
- long range interaction
- .....

A new way for double strange systems

✓ **Up to now double strange systems have been produced by K^- beams in the reaction:**

K^- (N, Ξ^-) K^+ (N- quasi free or bound in nucleus)

➢ **S=-2 baryon can be produced via:**

$$\bar{p} + p \longrightarrow \Xi^- + \Xi^+$$

$$\bar{p} + n \longrightarrow \Xi^- + \bar{\Xi}^0$$

$\sigma_{reaction}$ = 2μb at 3GeV/c

700.000∈□∈bar /h

Goal:

maximize the "stopped Ξ^-" with a suitable set-up

✓ **Choice of the target:**

free protons (hydrogen target) **or** protons and neutrons in a **nucleus** (quasi-free reactions)

➤ **Advantages of nuclear target** ☺ :

a) higher cross section (scaling as ~$A^{2/3}$)

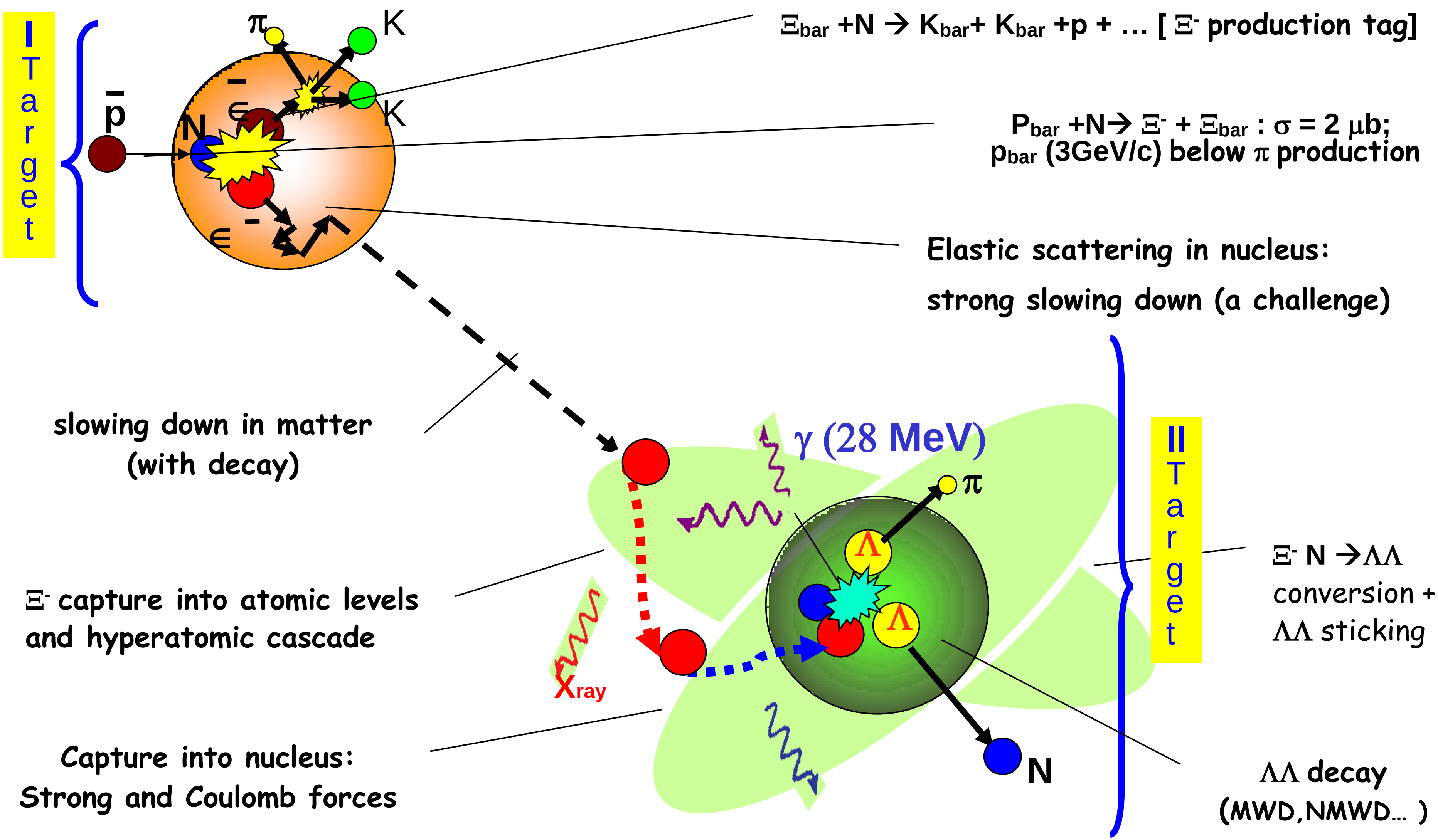
b) Ξ^- slowing down in dense (nuclear) matter

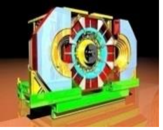
➤ **Disadvantages of nuclear target** ☹ :

c) high background (annihilation)

d) high beam consuming (beam losses)

A new way for double strange systems





ΛΛ Hypernuclei

Status of the art:

Nucleus	$B_{\Lambda\Lambda}({}_{\Lambda\Lambda}{}^{A}Z)$ [MeV]	$\Delta B_{\Lambda\Lambda}({}_{\Lambda\Lambda}{}^{A}Z)$ [MeV]	Reference	Reaction
${}_{\Lambda\Lambda}{}^{10}Be$	17.7± 0.4	4.3±0.4	M.Danysz et al., PRL.11(1963) 29	$K^- + A \rightarrow K^+ + \Xi^-$
${}_{\Lambda\Lambda}{}^{6}He$	10.9±0.5	4.6±0.5	D.J.Prowse, PRL.17(1966) 782	$K^- + A \rightarrow K^+ + \Xi^-$
${}_{\Lambda\Lambda}{}^{10}Be$	8.5±0.7	-4.9±0.7	KEK-E176	$K^- + p \rightarrow K^+ + \Xi^-$ (q.f)
${}_{\Lambda\Lambda}{}^{13}B$	27.6±0.7	4.9±0.7	S.Aoki et al., PTP.85(1991) 1287	$K^- + p \rightarrow K^+ + \Xi^-$ (q.f)
${}_{\Lambda\Lambda}{}^{12}B$		4.5±0.5	P.Khaustov et al., PRC.61(2000)027601	$({}^{12}C)_{atom}\Xi^- \rightarrow {}^{12}B_{\Lambda\Lambda} + n$
${}_{\Lambda\Lambda}{}^{6}He$	$7.25 \pm 0.19^{+0.18}_{-0.11}$	$1.01 \pm 0.2^{+0.18}_{-0.11}$	KEK-E373,NAGARA H.Takahashi et al., PRL.87(2001)212502-1	$K^- + p \rightarrow K^+ + \Xi^-$ (q.f)
${}_{\Lambda\Lambda}{}^{12}B$		$\sigma (\theta<8^0) \approx$ 6-10nb	K.Yamamoto et al., PLB.478(2000) 401	$K^- + {}^{12}C \rightarrow K^+ + {}^{12}B_{\Lambda\Lambda}$

Up to know these systems have been studied in cosmic rays or using kaon-beams:

$K^- + p \rightarrow \Xi^- + K^+$ *From Ξ^- to Double Hypernuclei*

KEK, BNL-AGS, have demonstrated that the systems are produced.

At JPARC with high intensity kaon-beams the goal is to stop 10^4 Ξ^- in a nuclear target.

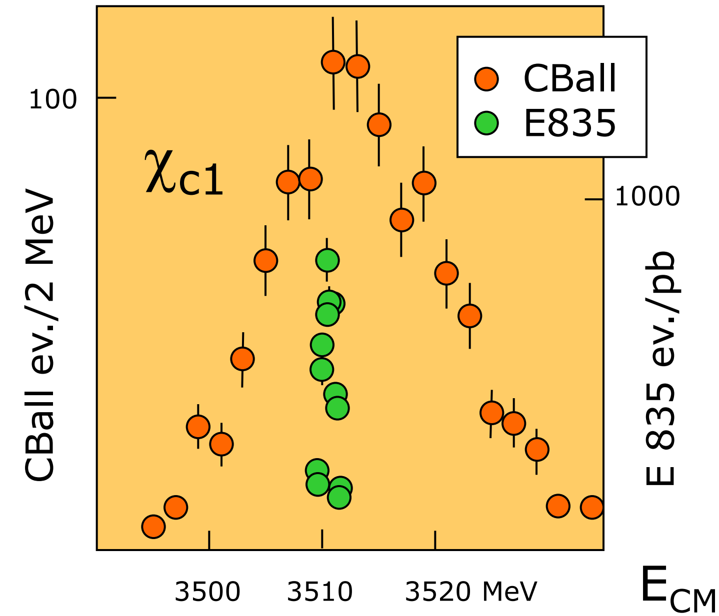
At PANDA the same amount of data will be collected, with the possibility to run with different nuclear targets at the same time.

Antiproton power

$e^+e^- \rightarrow \Psi' \rightarrow \gamma\chi_{1,2} \rightarrow \gamma\gamma J/\psi \rightarrow \gamma\gamma e^+e^-$

$\bar{p}\,p \rightarrow \chi_{1,2} \rightarrow \gamma J/\psi \rightarrow \gamma e^+e^-$

- e^+e^- interactions:
  - Only 1^{--} states are formed
  - Other states only by secondary decays (moderate mass resolution related to the detector)
- $p\bar{p}$ reactions:
  - Most states directly formed (very good mass resolution; $\bar{p}$-beam can be efficiently cooled)



$Br(p\bar{p} \rightarrow \eta_c) = 1.2\ 10^{-3}$

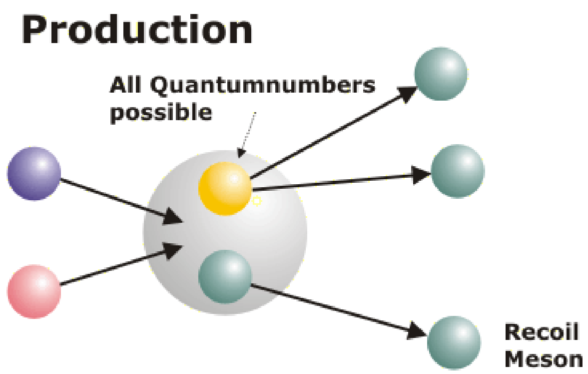
$Br(e^+e^- \rightarrow \psi) \cdot Br(\psi \rightarrow \gamma\eta_c) = 2.5\ 10^{-5}$

Spectroscopy with antiprotons

There are two mechanisms to access particular final states:

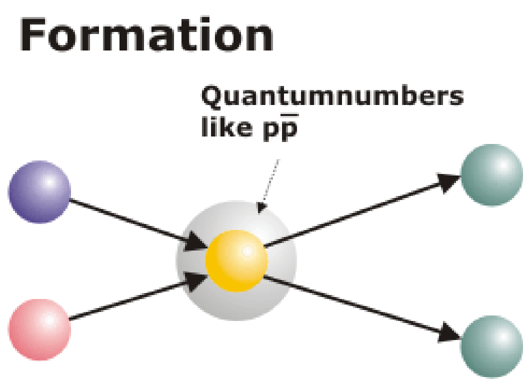
Production

all J^{PC} available



Formation

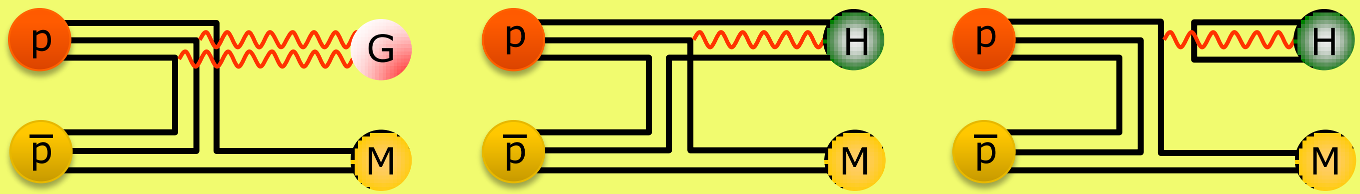
only selected J^{PC}



Spectroscopy with antiprotons

There are two mechanisms to access particular final states:

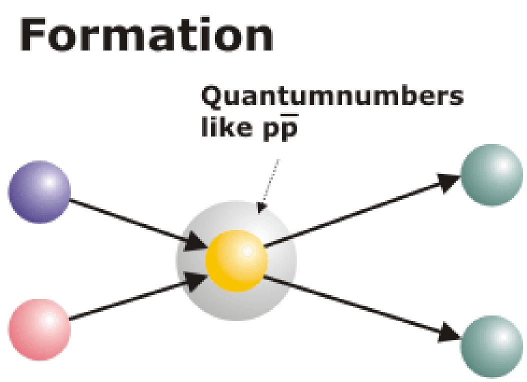
Production



Even exotic quantum numbers can be reached σ ~100 pb

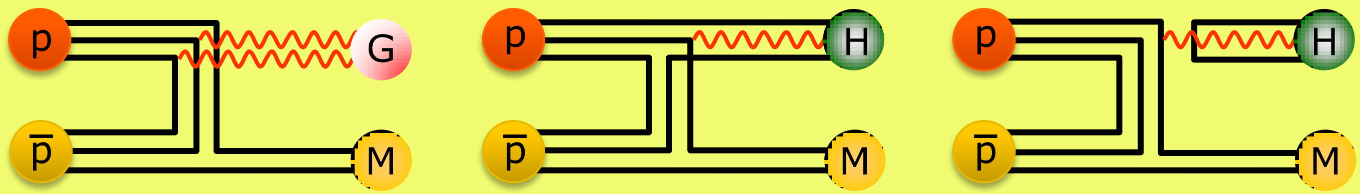
Formation

only selected J^{PC}



Spectroscopy with antiprotons

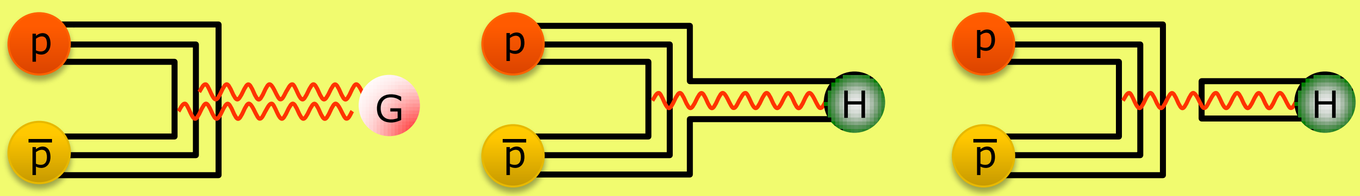
Production



Even exotic quantum numbers can be reached σ ~100 pb

All ordinary quantum numbers can be reached σ ~1 μb

Formation



Exotic hadrons

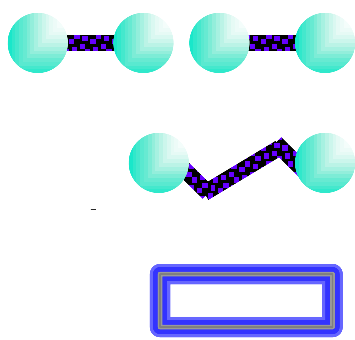
The QCD spectrum is much rich than that of the naive quark model also the gluons can act as hadron components

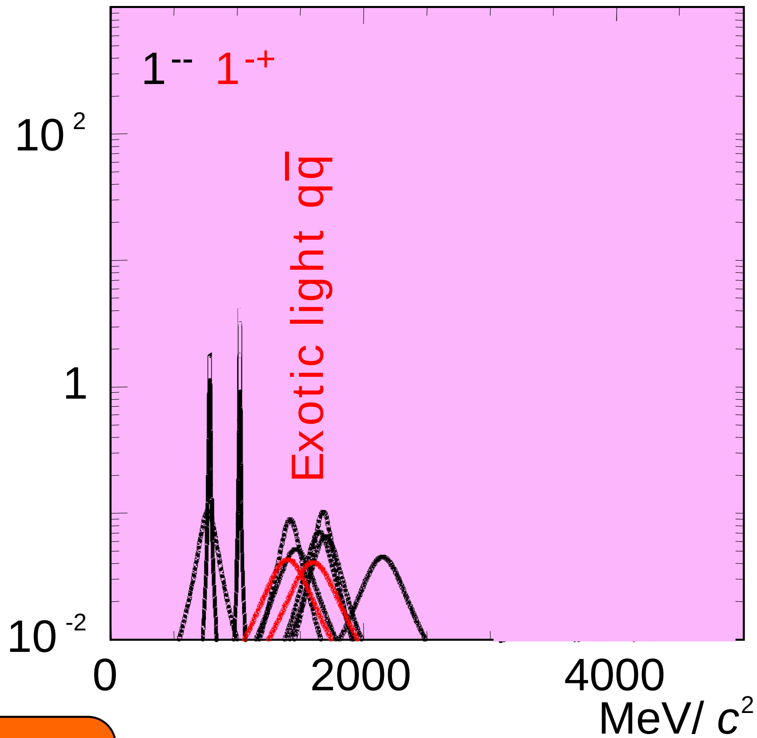
The “exotic hadrons” fall in 3 general categories:

Multiquarks (qq)(qq)

Hybrids (qq) g

Glueballs gg



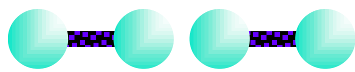


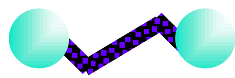
In the light meson spectrum exotic states overlap with conventional states

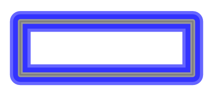
Exotic hadrons

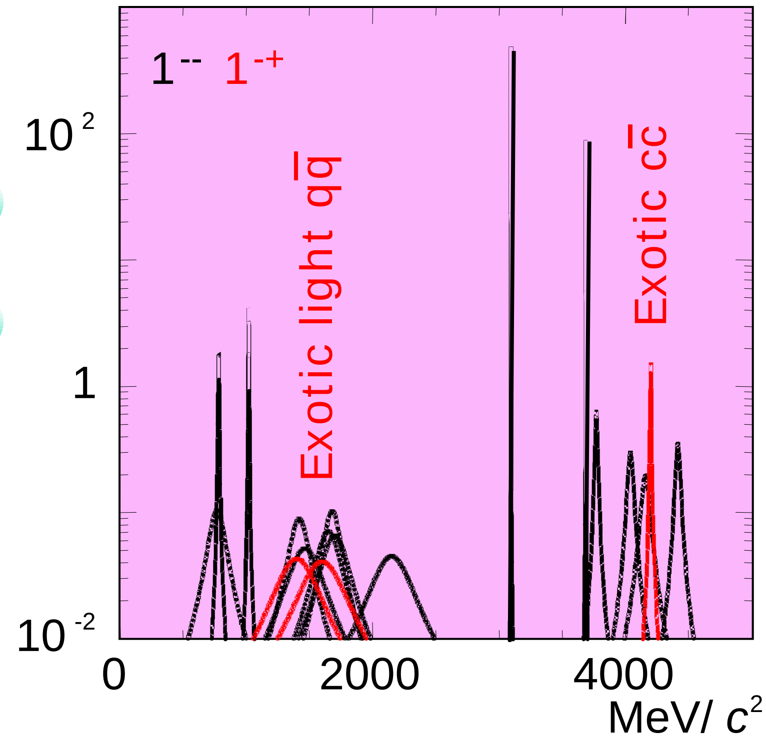
The QCD spectrum is much rich than that of the naive quark model
also the gluons can act as hadron components

The "exotic hadrons" fall in 3 general categories:

Multiquarks (qq)(qq) 

Hybrids (qq) g 

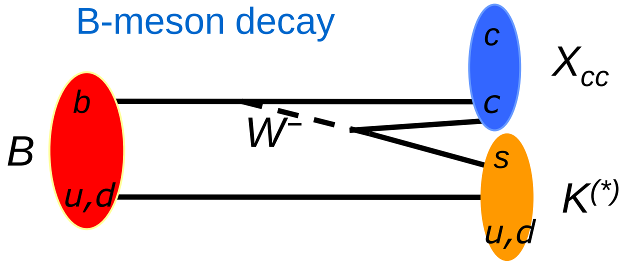
Glueballs gg 



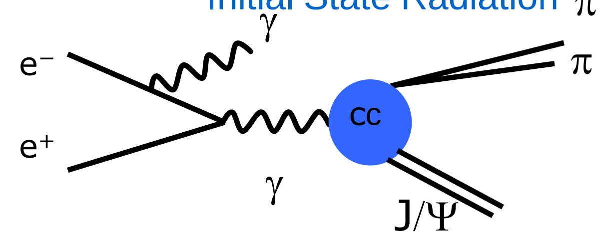
In the $c\bar{c}$ meson spectrum the density of states is lower and therefore so the overlap

XYZ Mesons

B-meson decay



Initial State Radiation

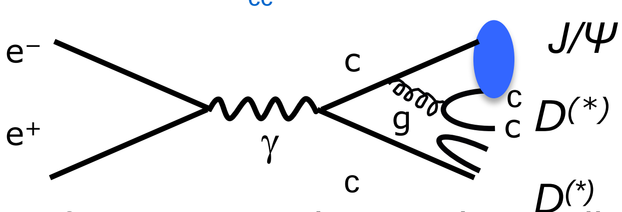


X(3872) Belle, Babar, Cleo, CDF, D0
Y(3940) Belle, Babar
Y(4140)? CDF
Z(4430)
Z_1(4050) } Belle
Z_2(4250)

1^{--} states
X(4008)? Belle
Y(4260) BaBar, Belle,CLEO
Y(4350) BaBar, Belle
Y(4660) Belle

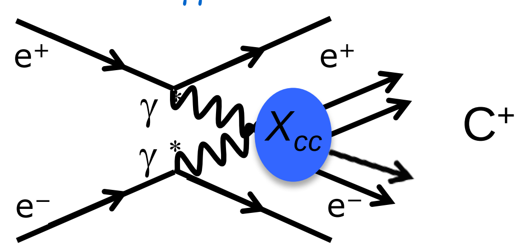
X(3915) Belle
Z(3930) Belle
Y(4350) Belle

Associate production
$e^+e^- \longrightarrow J/\Psi\ X_{cc}$



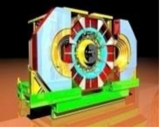
X(3940) Belle
X(4160) Belle

γγ-collisions



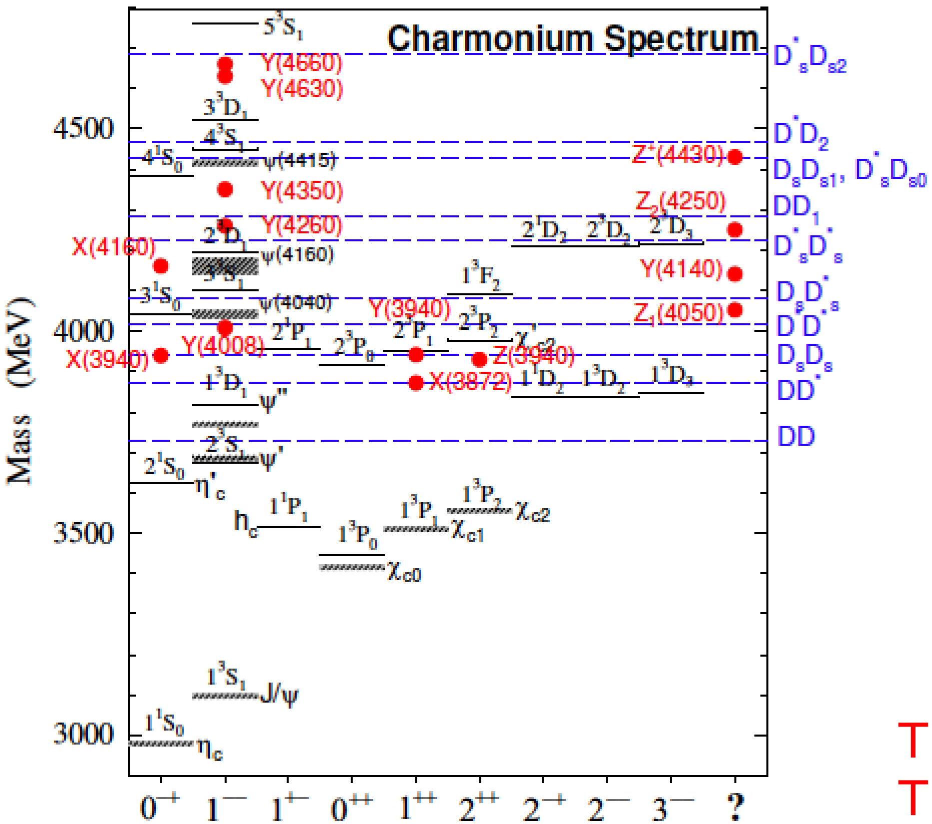
The B-factory experiments have discovered a large number of candidates for charmonium and charmonium-like meson states, many of which can not be easily accommodated by theory. State parameters are still largely unknown. Few events collected in 10 years of running

PANDA will detect 100 events per day



XYZ Mesons

Without entering into the details of each state some general consideration can be drawn.



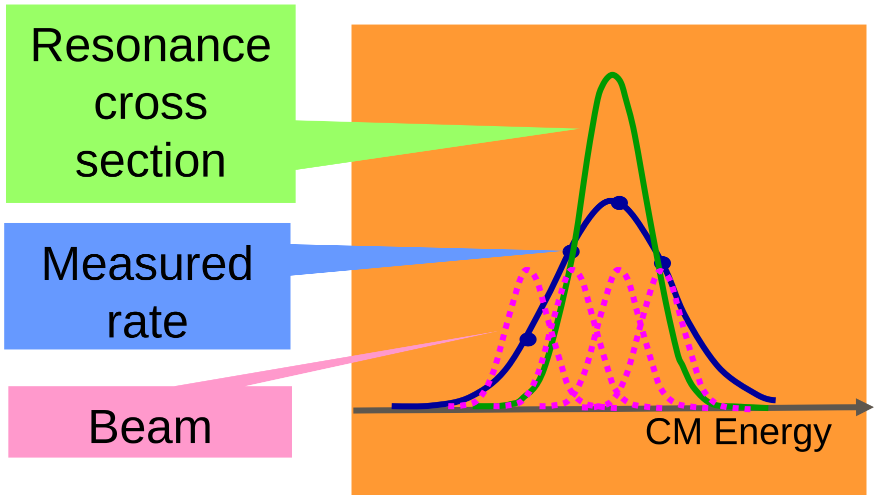
Arxiv:09010.3409v2 [hep-th]

- masses are barely known;
- often widths are just upper limits;
- few final states have been studied;
- statistics are poor;
- quantum number assignment is possible for few states;
- some resonances need confirmation…

There are problems of compatibility Theory - Experiment

Quantum numbers assignment and structure become clear only with high statistics, different final states and very precise energy measurements,.

Antiproton power

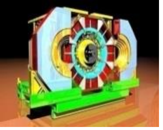


- e^+e^-: typical mass res. ~ 10 MeV
- Fermilab: 240 keV
- HESR: ~30 keV

The production rate of a certain final state ν is a convolution of the BW cross section and the beam energy distribution function $f(E,\Delta E)$:

$$\nu = L_0 \left\{ \varepsilon \int dE f(E,\Delta E) \sigma_{BW}(E) + \sigma_b \right\}$$

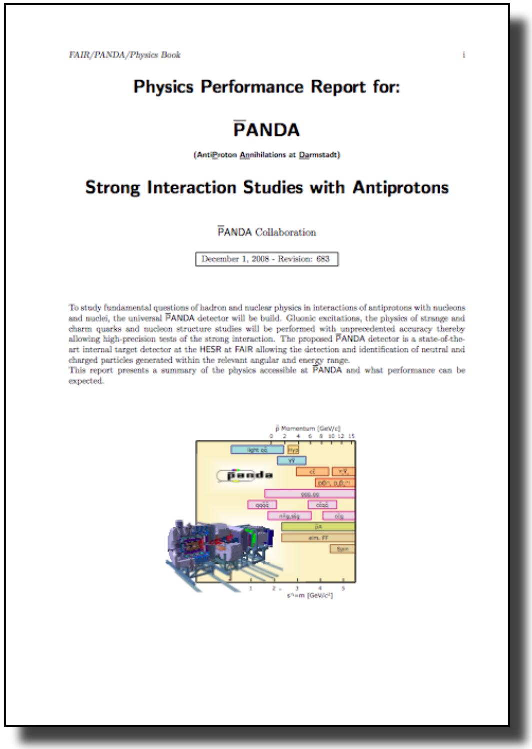
The resonance mass M_R, total width Γ_R and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy E.



PANDA Physics Performance Report

All the details of the PANDA experimental program are reported in the “Physics Performance Report”.

Within this document, we present the results of detailed simulations performed to evaluate detector performance on many benchmark channels.



FAIR/PANDA/Physics Book i

Physics Performance Report for:

$\overline{\text{P}}$ANDA

(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

$\overline{\text{P}}$ANDA Collaboration

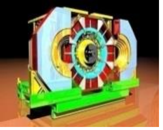
December 1, 2008 - Revision: 683

To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal $\overline{\text{P}}$ANDA detector will be build. Gluonic excitations, the physics of strange and charm quarks and nucleon structure studies will be performed with unprecedented accuracy thereby allowing high-precision tests of the strong interaction. The proposed $\overline{\text{P}}$ANDA detector is a state-of-the-art internal target detector at the HESR at FAIR allowing the detection and identification of neutral and charged particles generated within the relevant angular and energy range.
This report presents a summary of the physics accessible at $\overline{\text{P}}$ANDA and what performance can be expected.

arXiv:0903.3905v1

on behalf of the PANDA Collaboration

THANK YOU!



Drell-Yan Asymmetries — $\bar{p}p \rightarrow \mu^+\mu^- X$

Di-Lepton Rest Frame

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

NLO pQCD: $\lambda \sim 1,\ \mu \sim 0,\ \upsilon \sim 0$

Lam-Tung sum rule: $1-\lambda = 2\nu$

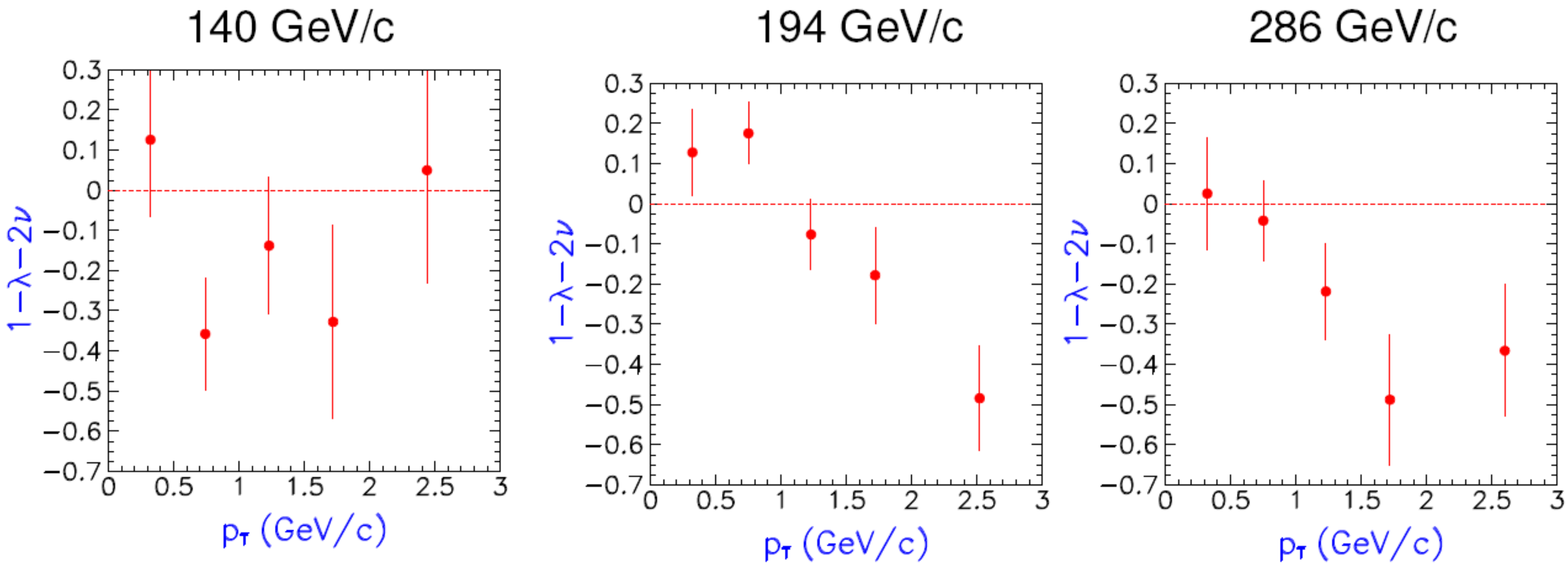
- reflects the spin-½ nature of the quarks
- insensitive top QCD-corrections

Experimental data [1]: $\upsilon \sim 30\ \%$

[1] J.S.Conway et al., Phys. Rev. D39 (1989) 92.

Remarkable and unexpected violation of Lam-Tung rule

λ, μ, ν measured in $\pi N \rightarrow \mu^+\mu^- X$ NA10 @ CERN



υ involves transverse spin effects at leading twist [2]

If unpolarised DY σ is kept differential on k_T ,

cos2φ contribution to angular distribution provide:

$$h_1^{\perp}(x_{2},\kappa_{\perp}^{2}) \times \bar{h}_1^{\perp}(x_1,\kappa_{\perp}'^{2})$$

[2] D. Boer et al., Phys. Rev. D60 (1999) 014012.

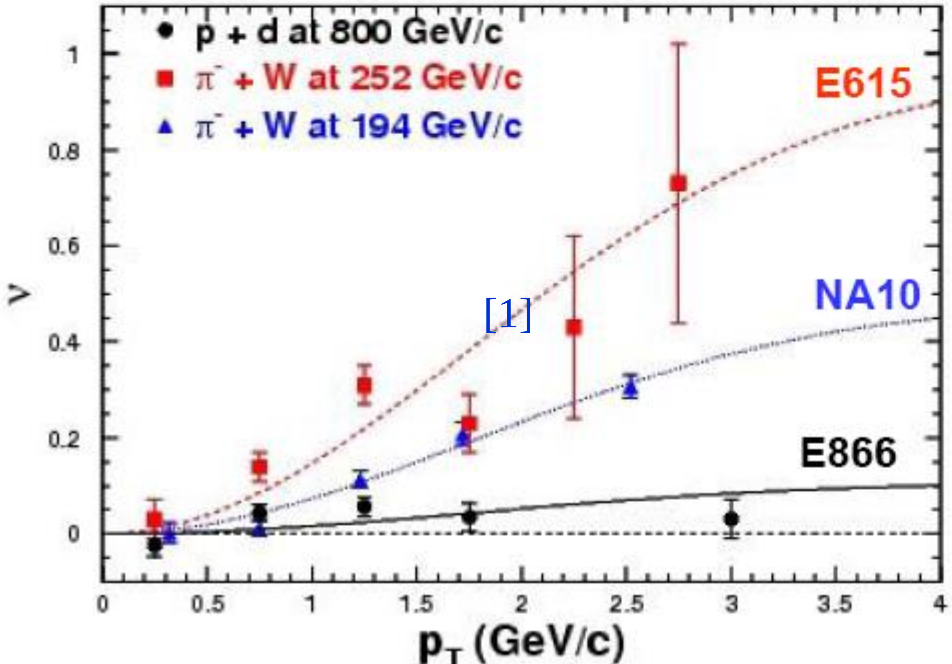
[1] NA10 coll., Z. Phys. C37 (1988) 545

Drell-Yan Asymmetries — $\bar{p}p \rightarrow \mu^+\mu^-X$

Boer-Mulders

$h_1^\perp =$ 

T-odd Chiral-odd TMD



- $\nu > 0 \rightarrow$ valence $h_1^\perp$ has same sign in π and N
- $\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim h_1^\perp(\pi)_{valence}$ x $h_1^\perp(p)_{valence}$
- $\nu(pd \rightarrow \mu^+\mu^- X) \sim h_1^\perp(p)_{valence}$ x $h_1^\perp(p)_{sea}$
- $\nu > 0 \rightarrow$ valence and sea $h_1^\perp$ has same sign, but sea $h_1^\perp$ should be significantly smaller

[1] L. Zhu et al, PRL 99 (2007) 082301; [12 D. Boer, Phys. Rew. D60 (1999) 014012.

All these effects may may lead to Single Spin Asymmetries (SSA):

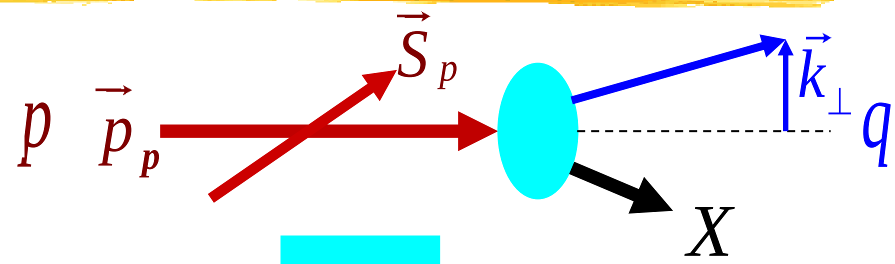
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

Transverse Single Spin Asymmetries: correlation functions

Sivers effect

# of partons in polarized proton depends on

$\vec{S}_p \bullet \left(\vec{p}_p \times \vec{k}_\perp \right)$



part

$$f_{q/p,\boldsymbol{s}}(x,\boldsymbol{k}_\perp) = f_{q/p}(x,k_\perp) - \frac{k_\perp}{M} f_{1T}^{\perp q}(x,k_\perp)\, \boldsymbol{S}\cdot(\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp)$$

Collins effect

fr

$$f_{q,\boldsymbol{s}_q/p}(x,\boldsymbol{k}_\perp) = \frac{1}{2} f_{q/p}(x,k_\perp) - \frac{1}{2}\frac{k_\perp}{M} h_1^{\perp q}(x,k_\perp)\, \boldsymbol{s}_q \cdot(\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp)$$

Polarising Fragmentation Function

$$D_{h/q,\boldsymbol{s}_q}(z,\boldsymbol{p}_\perp) = D_{h/q}(z,p_\perp) + \frac{p_\perp}{z\, M_h} H_1^{\perp q}(z,p_\perp)\, \boldsymbol{s}_q \cdot(\hat{\boldsymbol{p}}_q \times \hat{\boldsymbol{p}}_\perp)$$

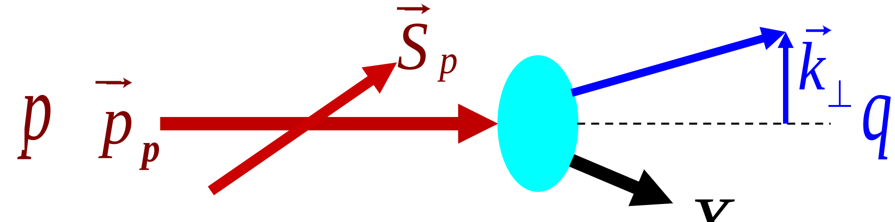
$\vec{S}_\Lambda \bullet \left(\vec{p}_q \times \vec{p}_\perp \right)$

Transverse Single Spin Asymmetries: correlation functions

Sivers effect

# of partons in polarized proton depends on

$$\vec{S}_p \bullet \left(\vec{p}_p \times \vec{k}_\perp\right)$$

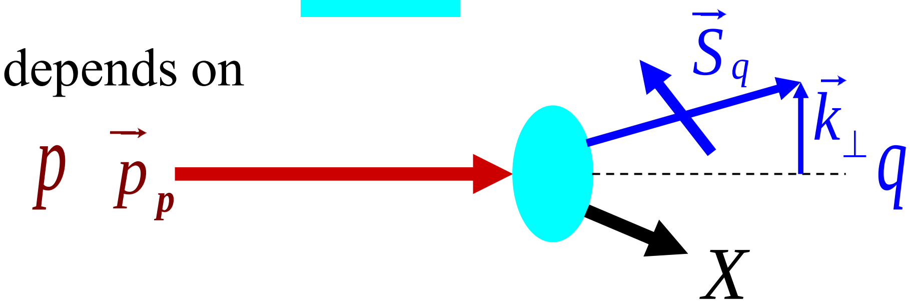


PDF

Boer – Mulders effect

partons' polarisation in unpolarized proton depends on

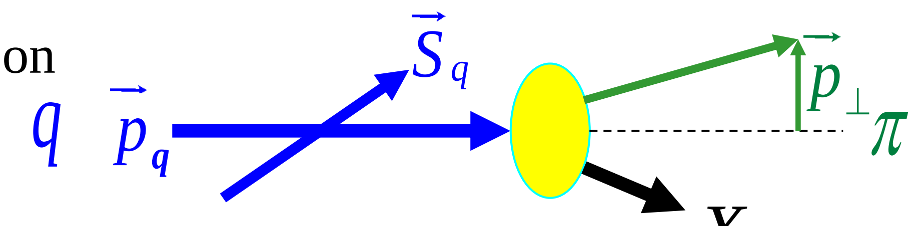
$$\vec{S}_q \bullet \left(\vec{p}_q \times \vec{k}_\perp\right)$$



Collins effect

fragmentation of polarised quark depends on

$$\vec{S}_q \bullet \left(\vec{p}_q \times \vec{p}_\perp\right)$$



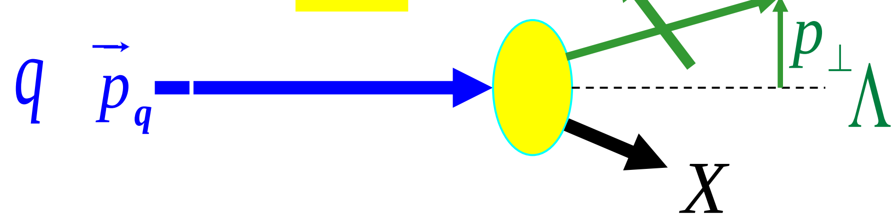
FF

Polarising Fragmentation Function

Hadrons' polarisation coming from

Unpolarised quarks depends on

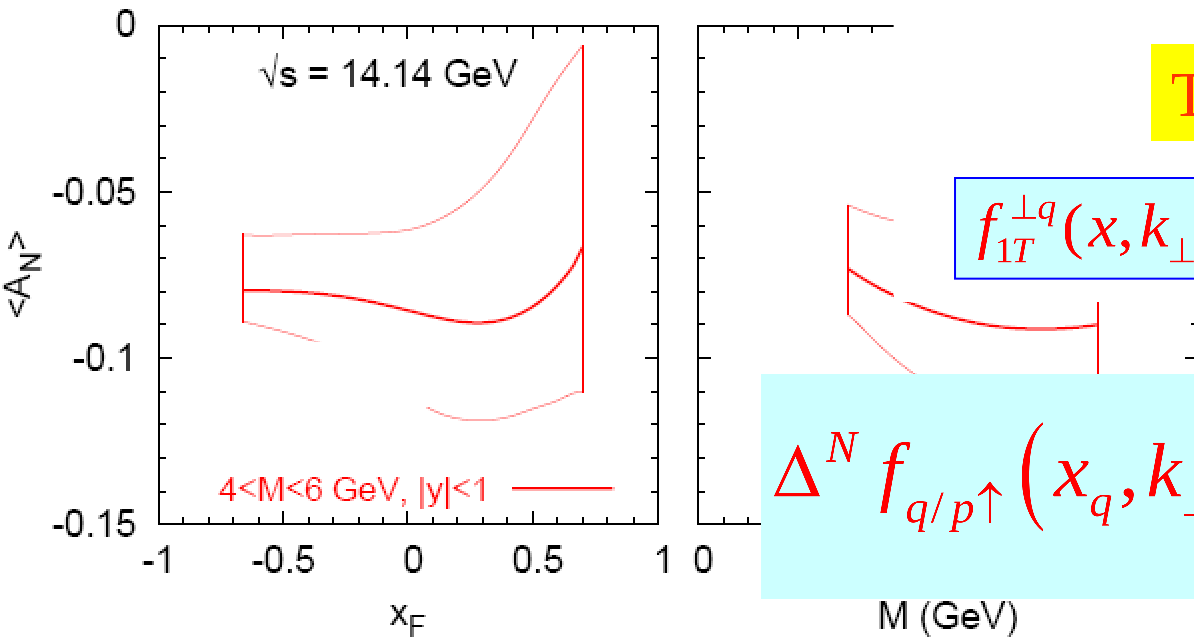
$$\vec{S}_\Lambda \bullet \left(\vec{p}_q \times \vec{p}_\perp\right)$$



Transverse Single Spin Asymmetries in Drell-Yan

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

expected[1] to be small but not negligible for HESR layout on fixed target



Test of Universality

$$f_{1T}^{\perp q}(x,k_\perp)_{SIDIS} = -f_{1T}^{\perp q}(x,k_\perp)_{DY} \quad [2]$$

$$\Delta^N f_{q/p\uparrow}\left(x_q,k_{\perp q}\right) = -\frac{2k_\perp}{m_p} f_{1T}^{\perp q}\left(x,k_\perp\right)$$

Originates from the Sivers function[1]:

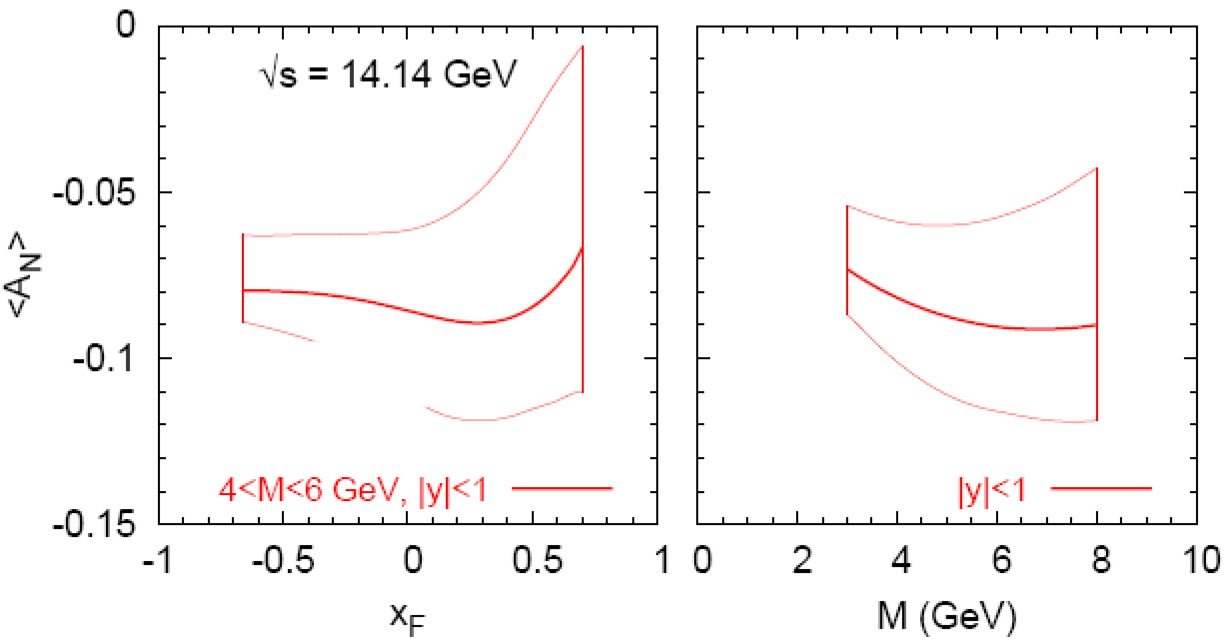
$$A_N = \frac{\sum_q e_q^2 \int d^2\mathbf{k}_{\perp q} d^2\mathbf{k}_{\perp\bar{q}} \delta^2\left(\mathbf{k}_{\perp q} + \mathbf{k}_{\perp\bar{q}} - q_T\right) \Delta^N f_{q/p\uparrow}\left(x_q,\mathbf{k}_{\perp q}\right) f_{\bar{q}/p}\left(x_{\bar{q}},\mathbf{k}_{\perp\bar{q}}\right)}{2\sum_q e_q^2 \int d^2\mathbf{k}_{\perp q} d^2\mathbf{k}_{\perp\bar{q}} \delta^2\left(\mathbf{k}_{\perp q} + \mathbf{k}_{\perp\bar{q}} - q_T\right) f_{q/p}\left(x_q,\mathbf{k}_{\perp q}\right) f_{\bar{q}/p}\left(x_{\bar{q}},\mathbf{k}_{\perp\bar{q}}\right)}$$

[1] Anselmino et al., Phys. Rev. D72, 094007 (2005).
[2] J.C. Collins, Phys. Lett. B536 (2002) 43

Transverse Single Spin Asymmetries in Drell-Yan

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

expected[1] to be small but not negligible for HESR layout on fixed target



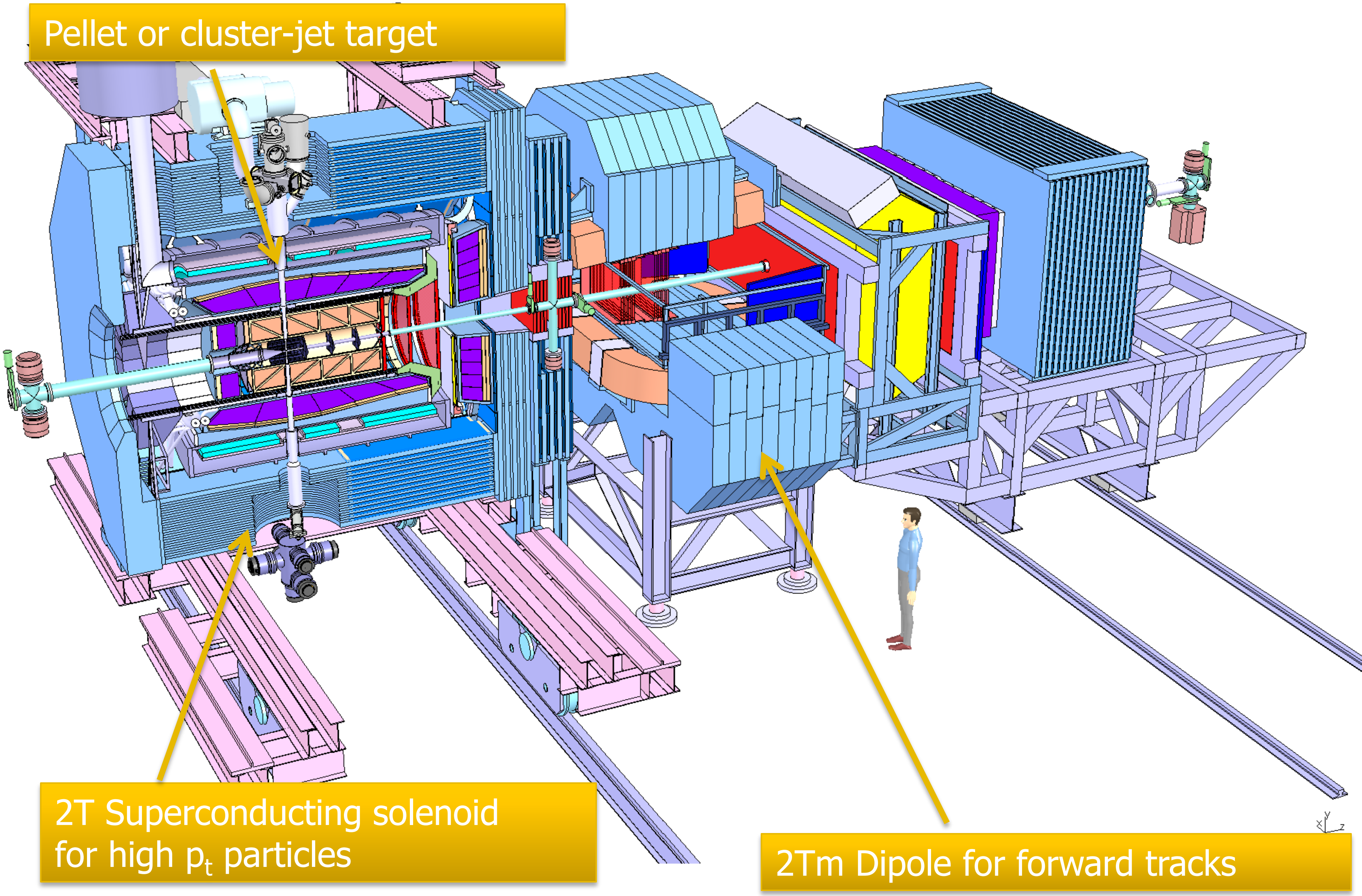
$0 \leq q_T \leq 1$ GeV/c

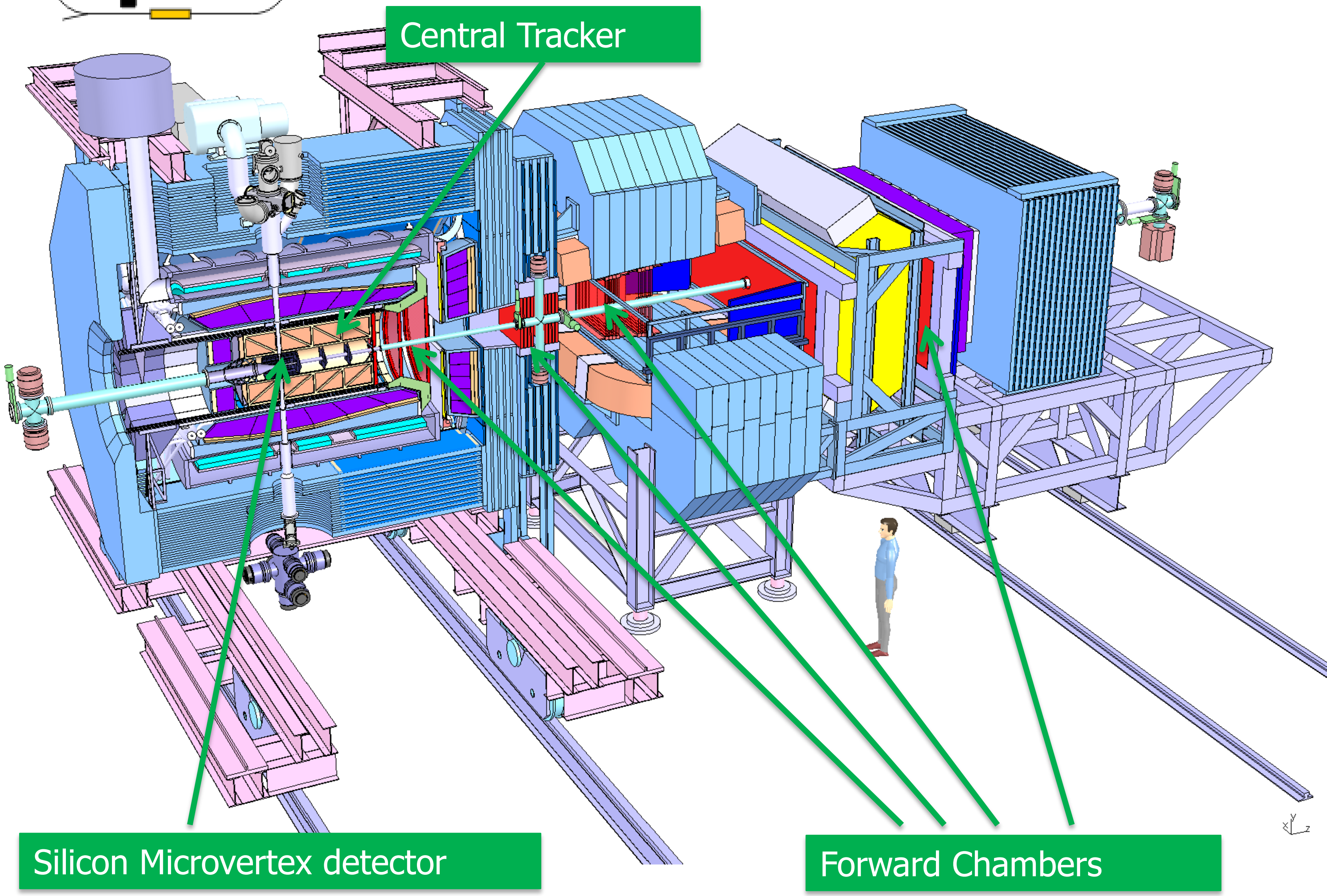
$\sqrt{s} = 14.14$ GeV

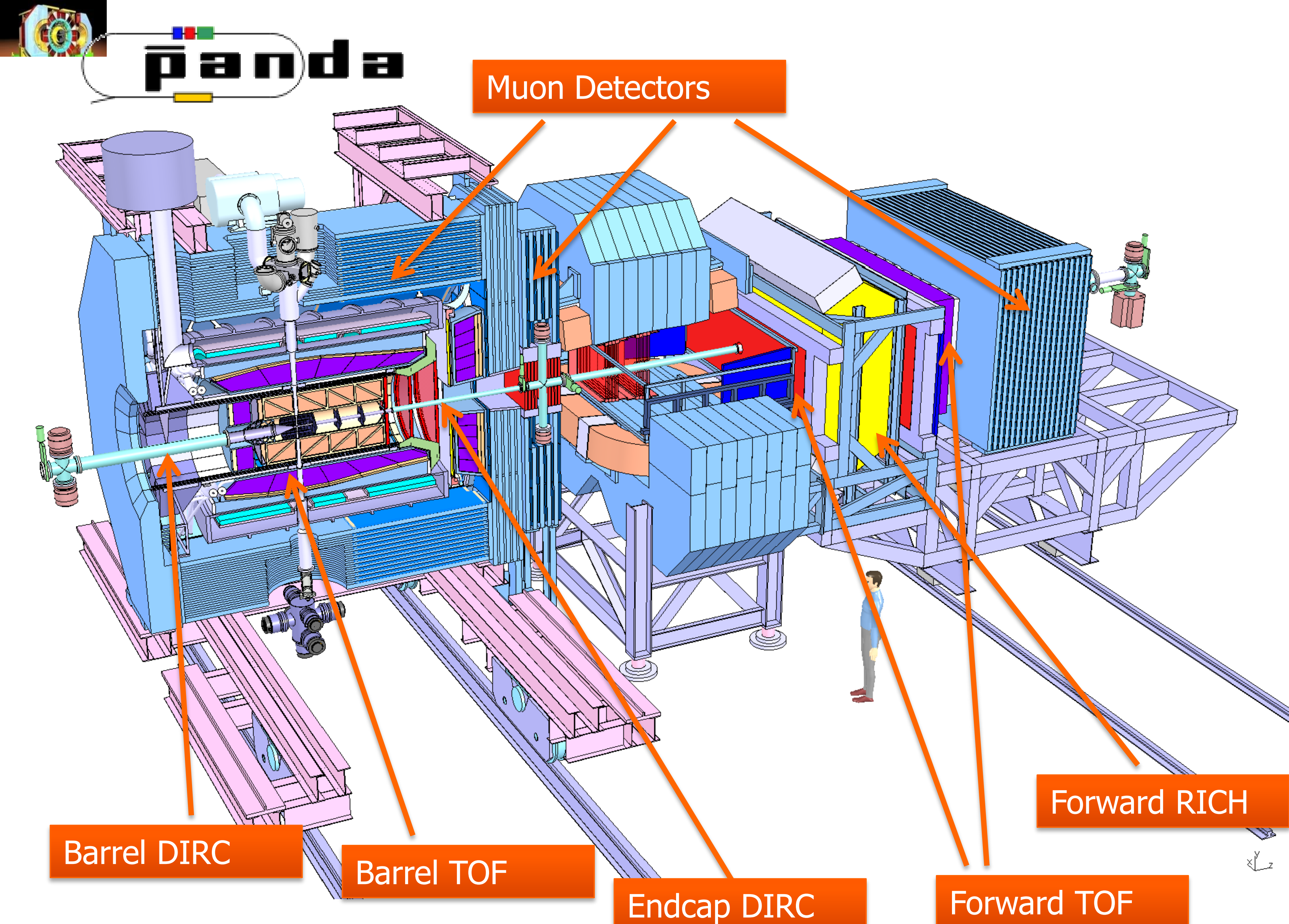
Originates from the Sivers function[1]:

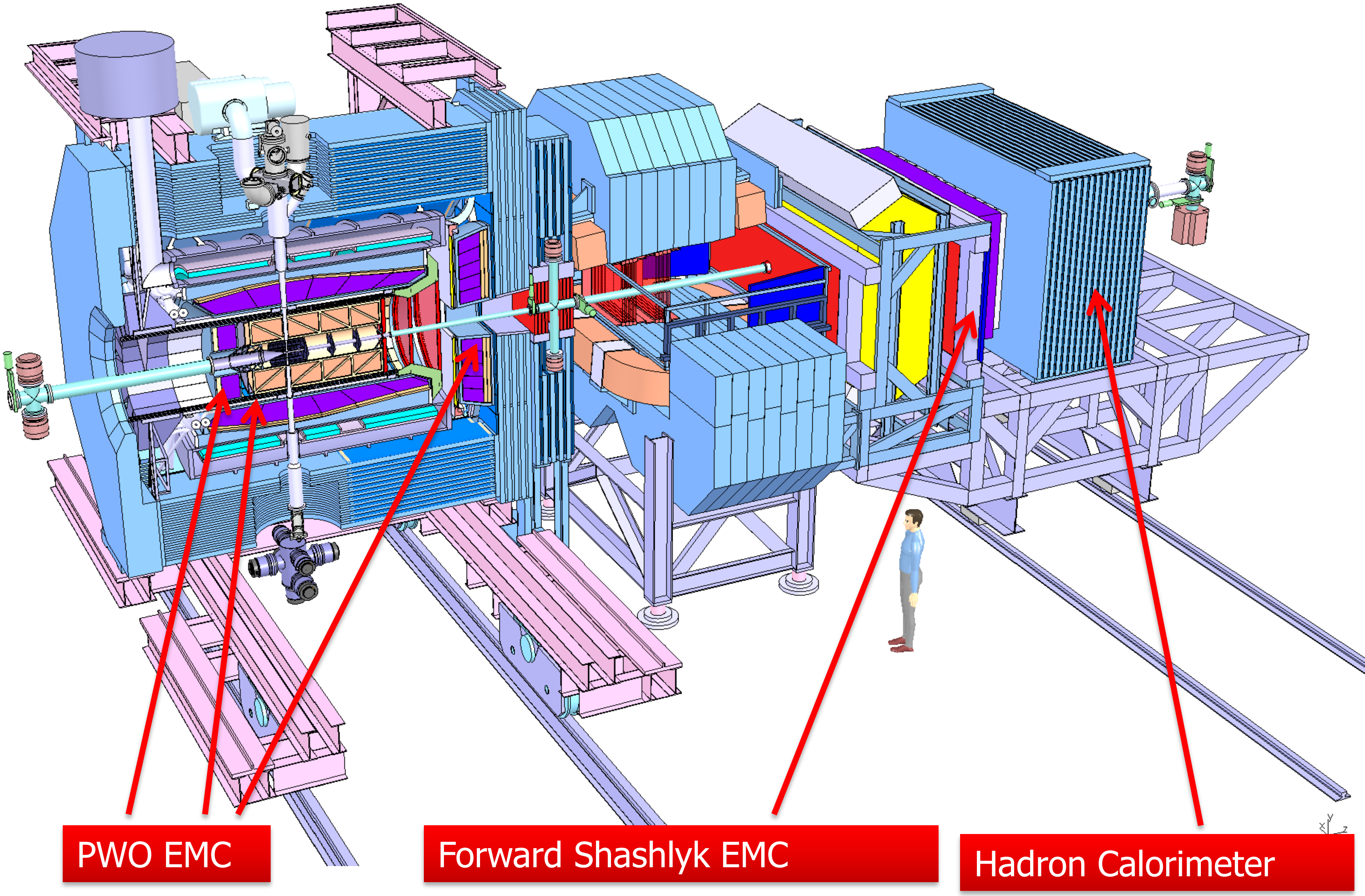
$$A_N = \frac{\sum_q e_q^2 \int d^2\mathbf{k}_{\perp q} d^2\mathbf{k}_{\perp \bar{q}} \delta^2\left(\mathbf{k}_{\perp q} + \mathbf{k}_{\perp \bar{q}} - q_T\right) \Delta^N f_{q/p\uparrow}\left(x_q, \mathbf{k}_{\perp q}\right) f_{\bar{q}/p}\left(x_{\bar{q}}, \mathbf{k}_{\perp \bar{q}}\right)}{2\sum_q e_q^2 \int d^2\mathbf{k}_{\perp q} d^2\mathbf{k}_{\perp \bar{q}} \delta^2\left(\mathbf{k}_{\perp q} + \mathbf{k}_{\perp \bar{q}} - q_T\right) f_{q/p}\left(x_q, \mathbf{k}_{\perp q}\right) f_{\bar{q}/p}\left(x_{\bar{q}}, \mathbf{k}_{\perp \bar{q}}\right)}$$

[1] Anselmino et al., Phys. Rev. D72, 094007 (2005).
[2] J.C. Collins, Phys. Lett. B536 (2002) 43


Pellet or cluster-jet target
2T Superconducting solenoid
for high p_t particles
2Tm Dipole for forward tracks


Central Tracker
Silicon Microvertex detector
Forward Chambers


panda
Muon Detectors
Barrel DIRC
Barrel TOF
Endcap DIRC
Forward TOF
Forward RICH


PWO EMC
Forward Shashlyk EMC
Hadron Calorimeter