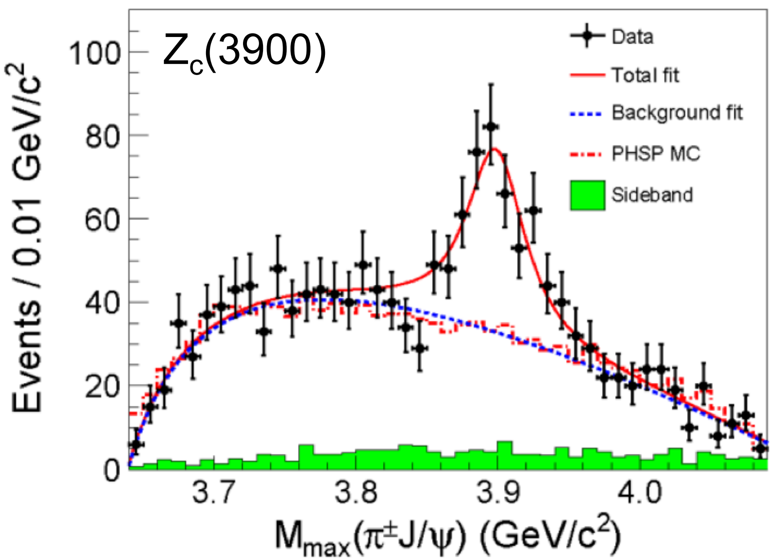
Outline

- **Introduction**
  - Motivation, physics programme
  - Advantage of anti-protons
  - Resonance scan method
- **Hadron spectroscopy**
  - Exotic hadrons
  - Open charm
  - Charmonium-like exotics
  - Baryon spectroscopy
- **Nucleon spin structure**
  - EM form factors
  - GPDs, TDAs
  - Drell-Yan
- **Summary & outlook**

Recent Hot Topics

Hadron Spectroscopy

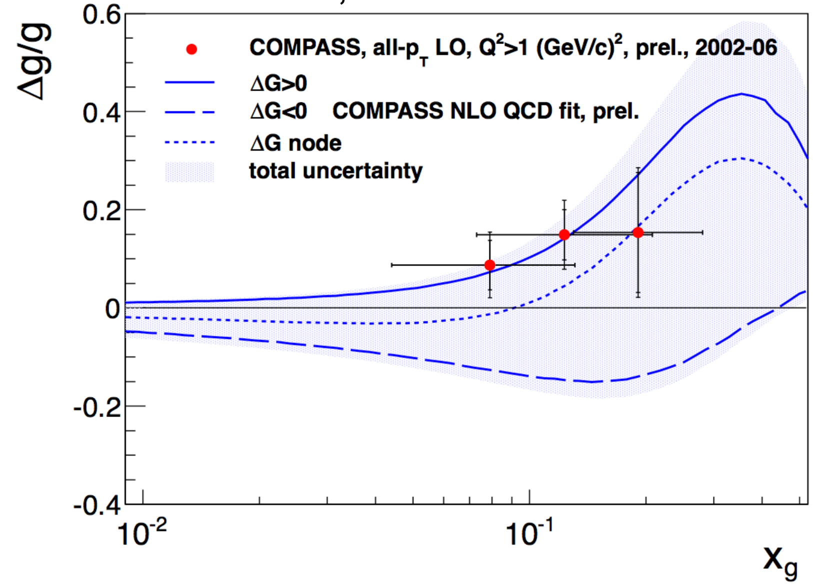
BESIII, arXiv:1303.5949



**unexpected,
manifestly exotic!**

Nucleon Structure

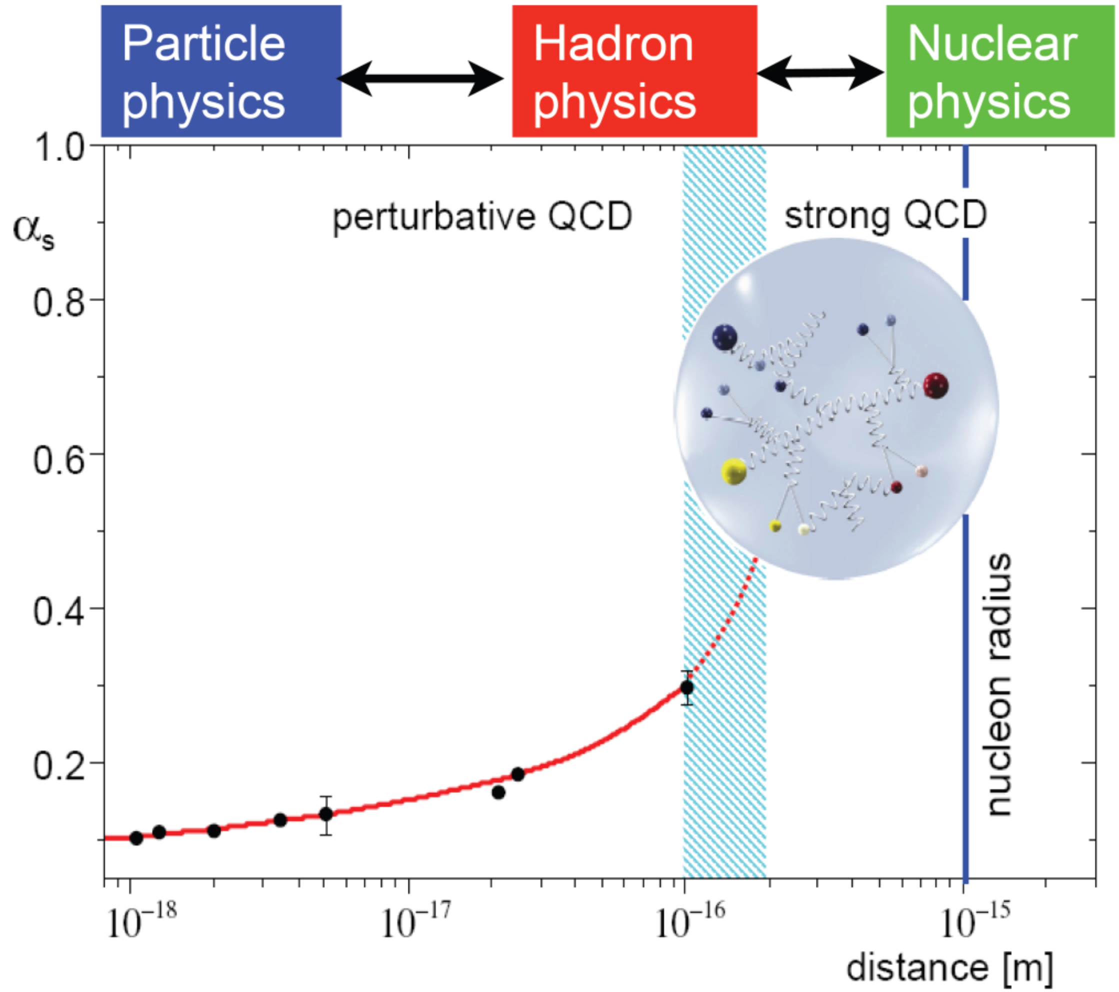
M.Stolarski, DIS 2014



**proton spin ½
not yet understood**

Hadron Physics and QCD

- Why are there no free quarks?
- Are there other colour neutral objects?
- What is the structure of the nucleon?
- What are the spin degrees of freedom?



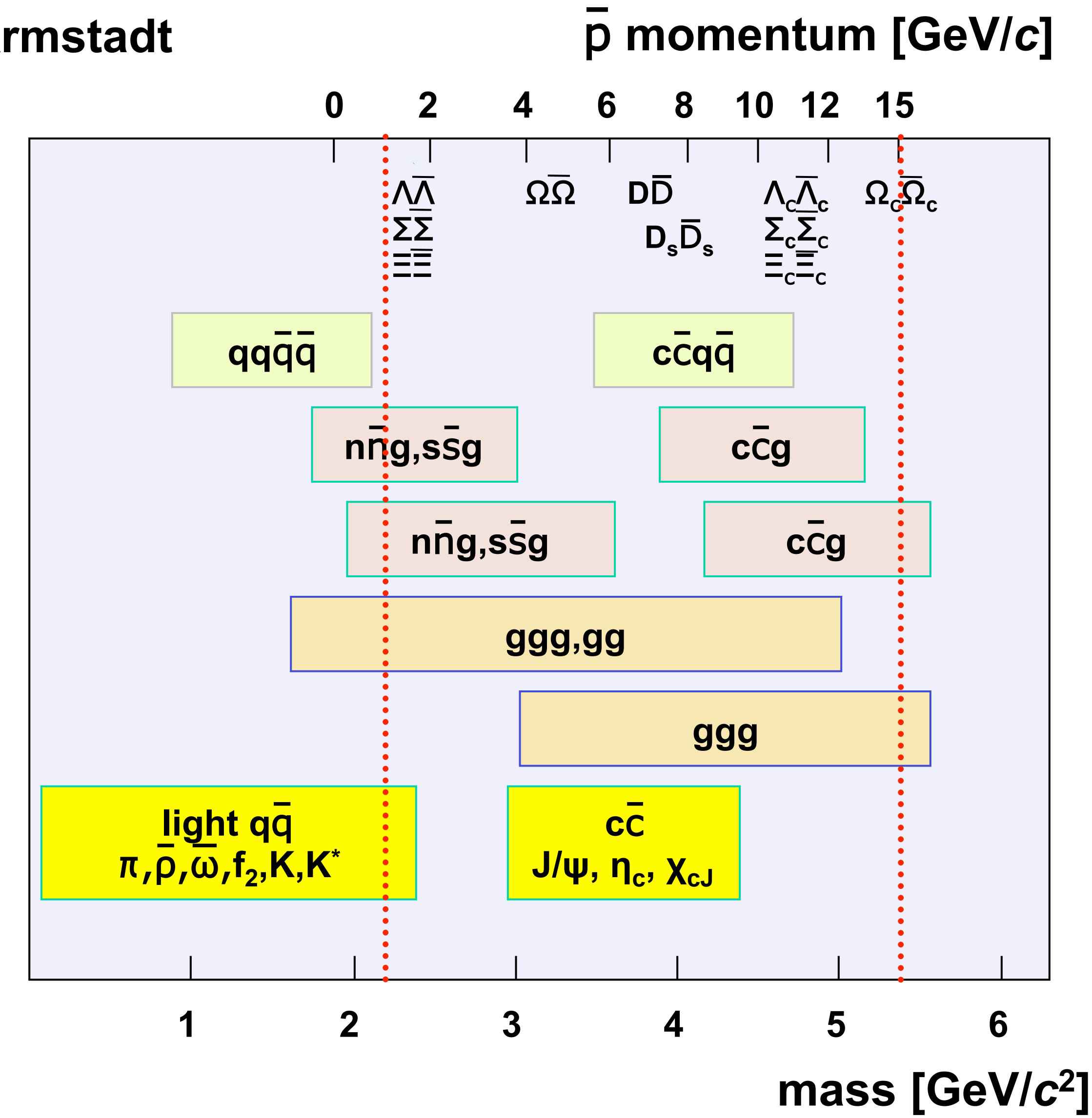
PANDA Physics Programme

anti-**P**roton **AN**nihilation in **DA**rmstadt

- **Meson spectroscopy**
  - light mesons
  - charmonium
  - exotic states:

    glue-balls, hybrids,

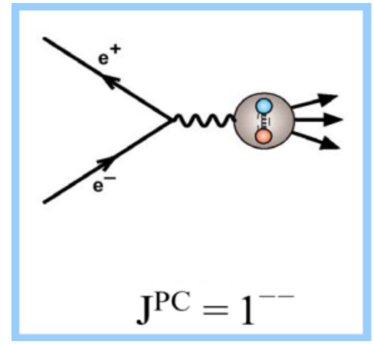
    molecules / multi-quarks
- **(Anti-) Baryon production**
- **Nucleon structure**
- **Charm in nuclei**
- **Strangeness physics**
  - hypernuclei,
  - S = -2 nuclear system



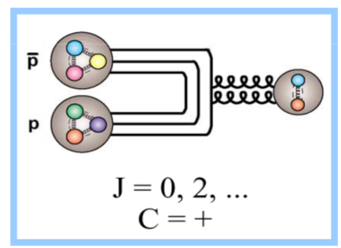
Advantages of Anti-Protons

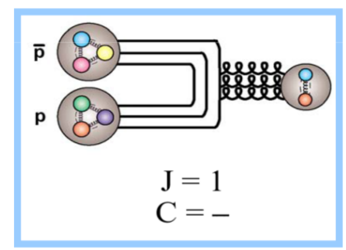
- Gluon rich process
- Gain ~2GeV in annihilation
  (low momentum transfer)
- B = 0 system
- Access to all fermion-antifermion quantum numbers *(not in e+e-)*
- Access to states of high spin J
- Precise mass resolution in formation reactions

Formation:



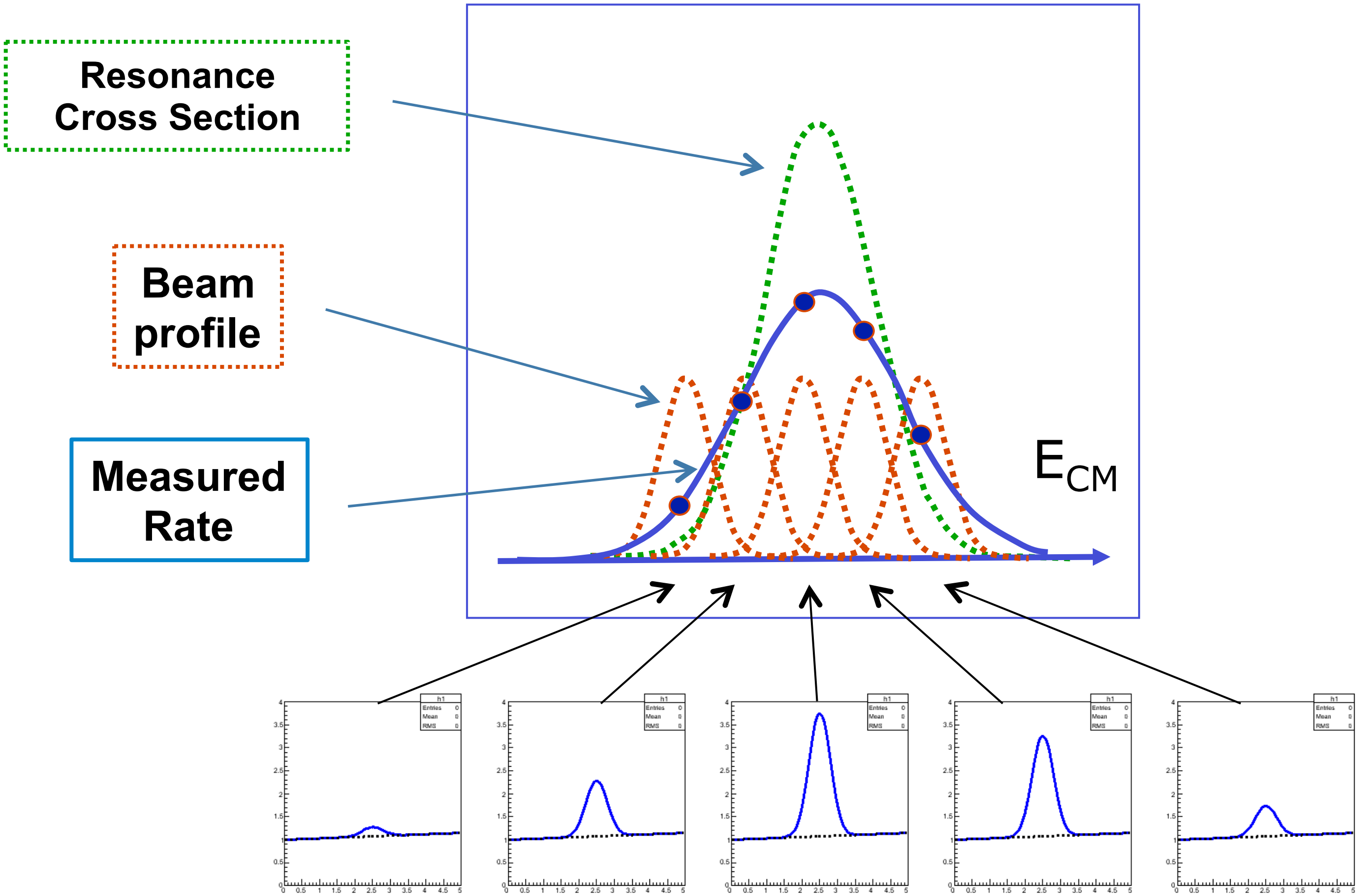
→ Only $J^{PC} = 1^{-}$ allowed in e^+e^-





→ All J^{PC} allowed for ($q\bar{q}$) accessible in $p\bar{p}$

Anti-Protons – Resonance Scan Method



- Cooled $\bar{p}$ beam: Excellent energy resolution!
- Production rate: Convolution of resonance and beam profile
- Principle has been proven to work ...

Resonance Scan Method -- an example: $\chi_{c1,2}$

Production:

$$e^+e^- \to \psi' \to \gamma\chi_{1,2} \to \gamma(\gamma J/\psi) \to \gamma\gamma e^+e^-$$

- Invariant mass reconstruction depends on the detector resolution ≈ 10 MeV

$e^+e^- \to \psi(2S)$
↳ $\gamma\ \chi_c$
↳ $\gamma\gamma\ J/\psi$
↳ $\gamma\gamma e^+e^-$

Formation:

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

- Resonance scan:
  → mass resolution depends on the beam resolution

$\bar{p}p \to \chi_c$
↳ $\gamma\ J/\psi$
↳ γe^+e^-

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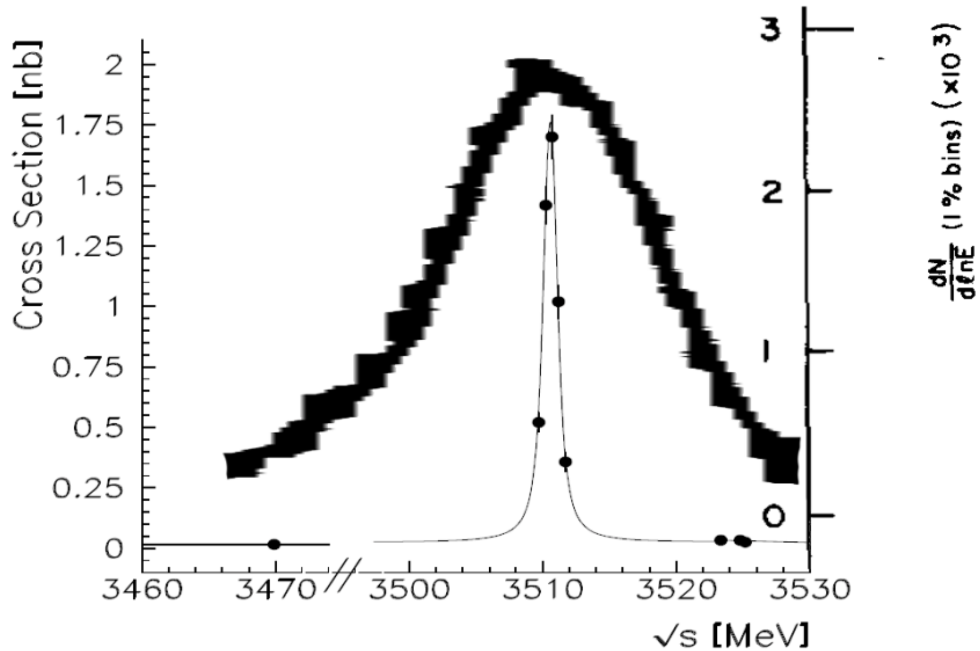

Gaiser et al., Phys. Rev. D34 (1986) 711:
CrystalBall (SLAC): 3512.3 ± 4 MeV/c^2
Andreotti et al., Nucl. Phys. B717 (2005) 34-47:
E835 (Fermilab): 3510.641 ± 0.074 MeV/c^2

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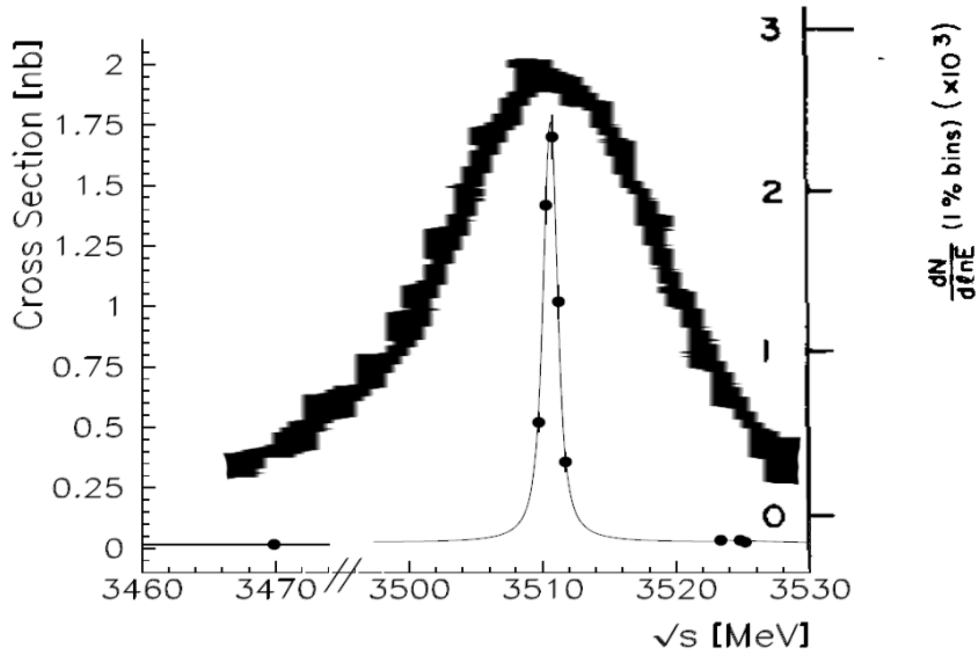

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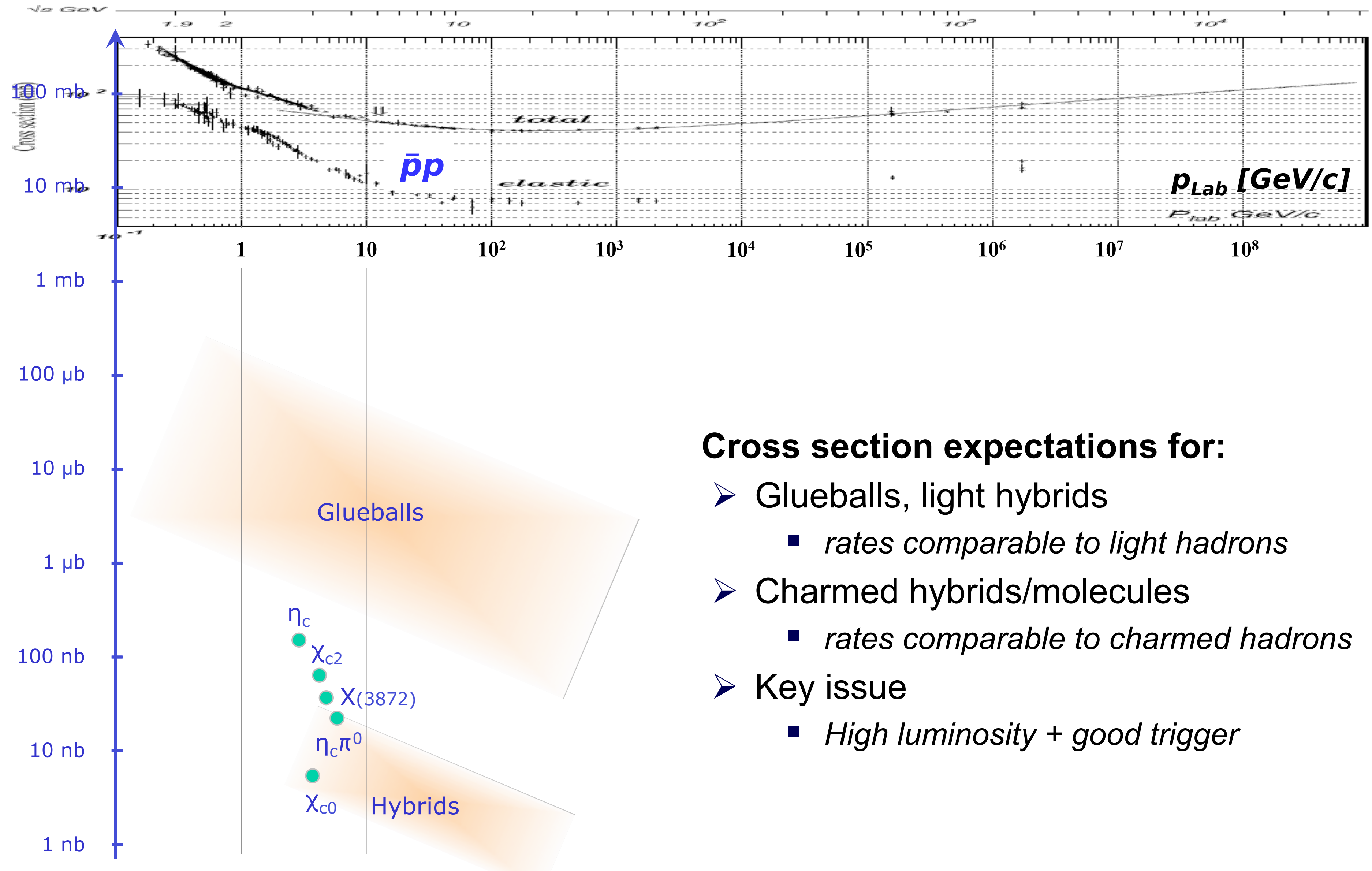
E760/835@Fermilab ≈ 240 keV
PANDA@FAIR ≈ 50 keV

NB: Interpretation of many states depends on width of states!

$\bar{p}p$ Production Cross Sections



Cross section expectations for:

- Glueballs, light hybrids
  - *rates comparable to light hadrons*
- Charmed hybrids/molecules
  - *rates comparable to charmed hadrons*
- Key issue
  - *High luminosity + good trigger*

Spectroscopy – Exotic Hadrons

Mesons and (Spin) Exotic States

Constituent quark model

- color neutral $q\bar{q}$ systems
- quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$ $C = (-1)^{L+S}$ $G = (-1)^{I+L+1}$
- J^{PC} *multiplets:* $0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}, \ldots$
- *Forbidden:* $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

QCD: meson states beyond

Three categories of exotics:

- Glueballs → gg, ggg

- Hybrids → $(q\bar{q})g$

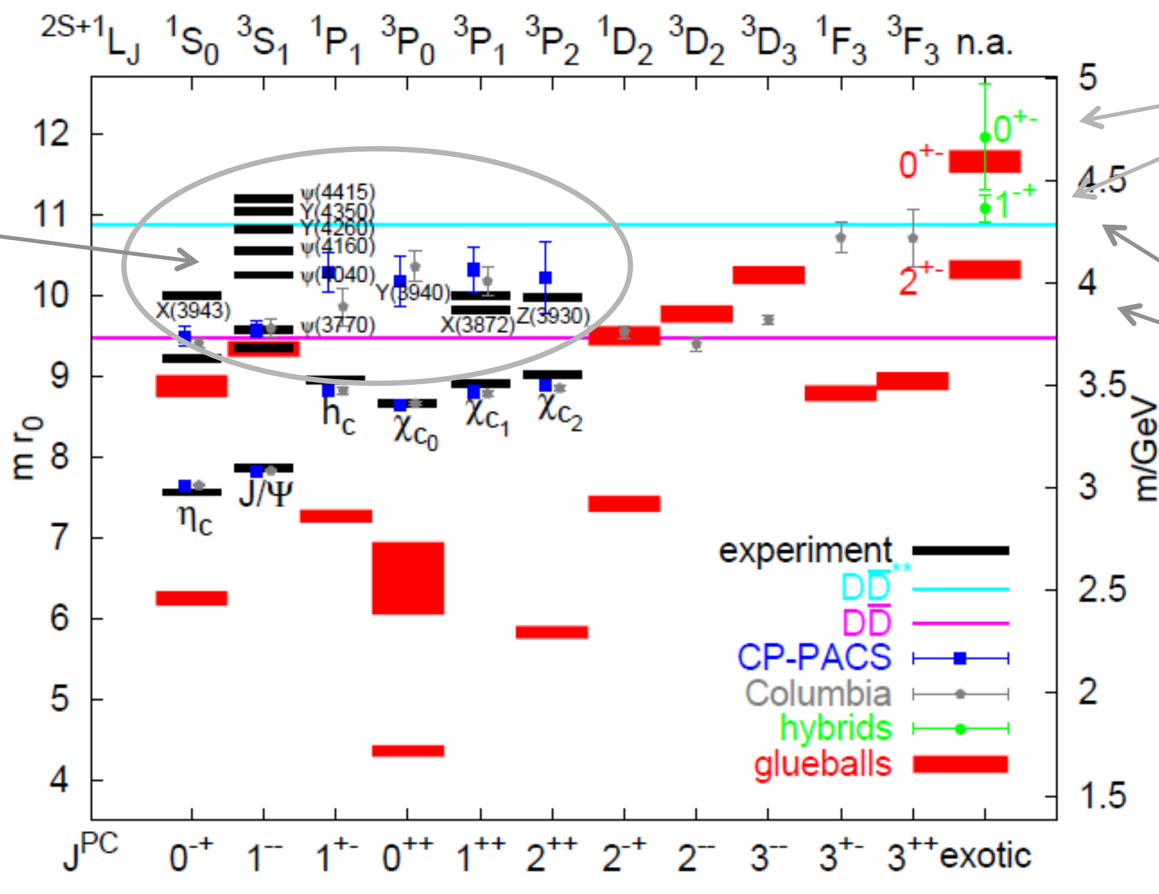
- Molecules / multiquarks
  → $(qqq)(q\bar{q})$, $(q\bar{q})(q\bar{q})$ or: $qq\bar{q}\bar{q}$, $qqqq\bar{q}$

→ **The observation of exotic hadrons would be a confirmation of QCD**

Lattice Predictions

- Lattice QCD → Predictions for masses/properties
- Current predictions for mesons, glueballs, hybrids

Experimental
X, Y, Z



Prediction:
Spin exotic hybrids

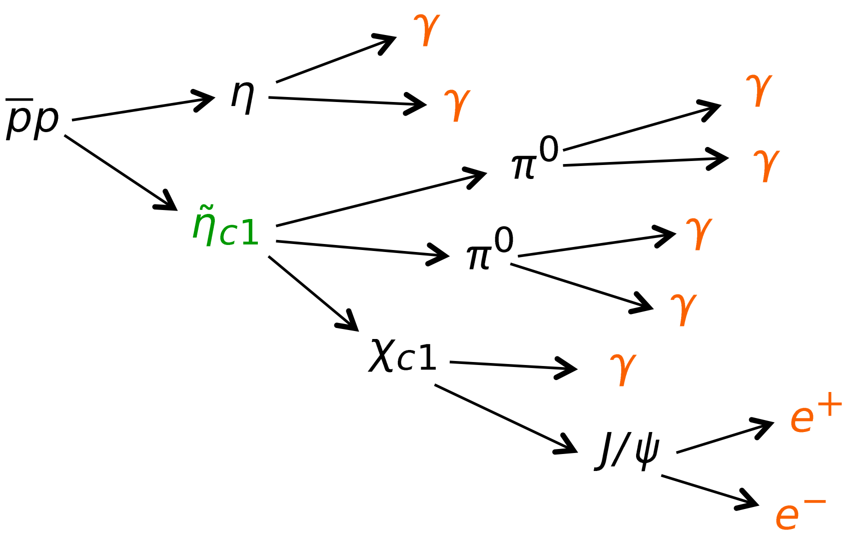
Prediction:
Spin exotic glueballs

G. S. Bali, Int.J.Mod.Phys. A21 (2006) 5610-5617

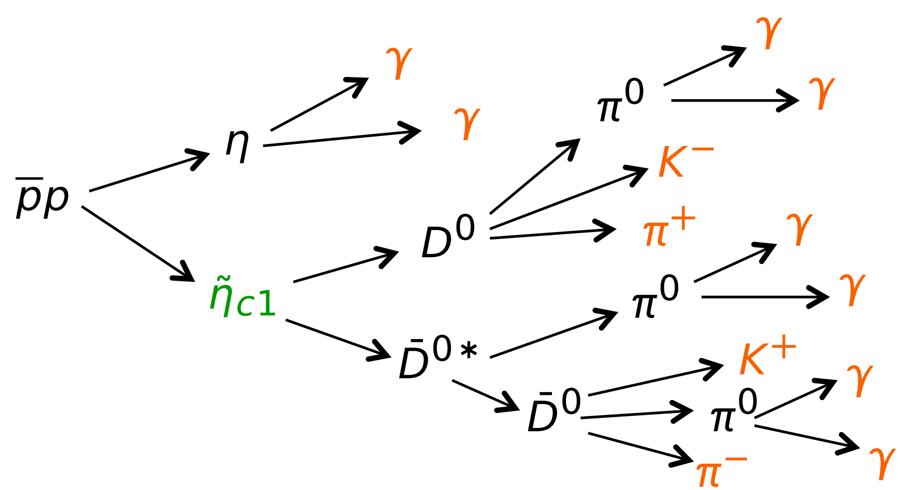
Charmonium Hybrid Candidate $\tilde{\eta}_{c1}$

- From LQCD calculations:
  Spin-exotic hybrid candidate $\tilde{\eta}_{c1}$ with m ≈ 4.3GeV/c², $J^{PC} = 1^{-+}$
- Exclusive reconstruction in two favoured channels:

$$\bar{p}p \rightarrow \tilde{\eta}_{c1}\,\eta \rightarrow \chi_{c1}\pi^0\pi^0\eta$$



$$\bar{p}p \rightarrow \tilde{\eta}_{c1}\,\eta \rightarrow D^0\bar{D}^{0*}\,\eta$$



- Production X-section assumed similar to $\bar{p}p \rightarrow \psi(2S)\,\eta$ (33pb)
  → *Need good calorimetry + good particle identification*

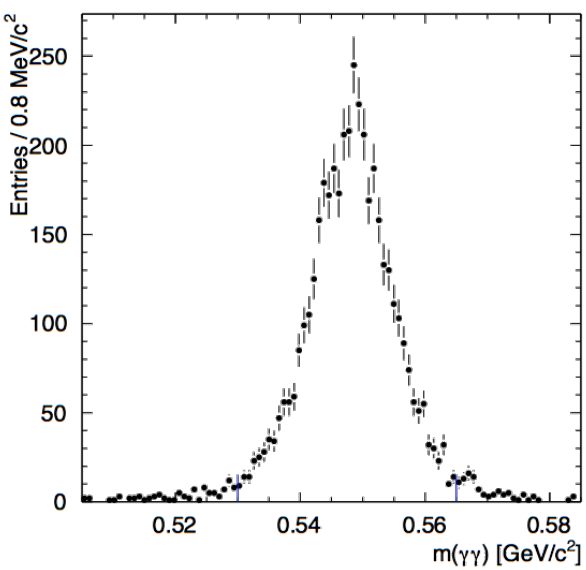
$\bar{p}p \rightarrow \tilde{\eta}_{c1}\,\eta \rightarrow \chi_{c1}\pi^0\pi^0\eta$

- Simulation @ 15 GeV/c
  - 80k signals + 80k each background, e.g.

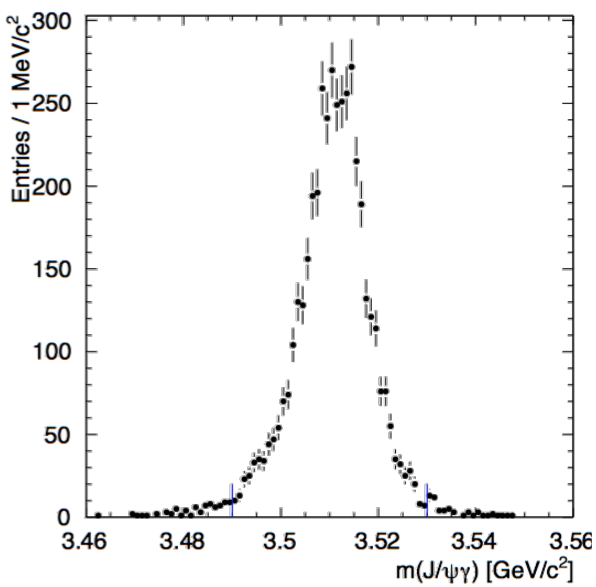
    $$\bar{p}p \rightarrow J/\psi\,\pi^0\pi^0\pi^0\,\eta,\ \bar{p}p \rightarrow \chi_{c1}\pi^0\eta\eta$$

  - 9C kinematic fit (mass constraints, 4C energy momentum)

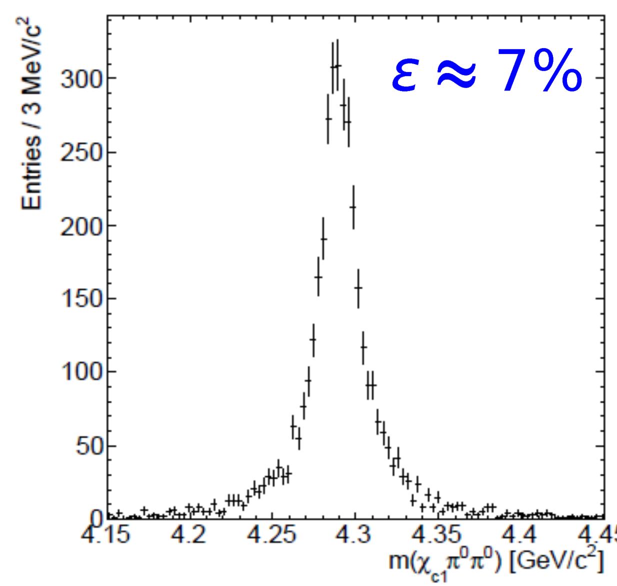
$\eta \rightarrow \gamma\gamma$



$\chi_{c1} \rightarrow J/\psi\gamma$



$\tilde{\eta}_{c1} \rightarrow \chi_{c1}\pi^0\pi^0$



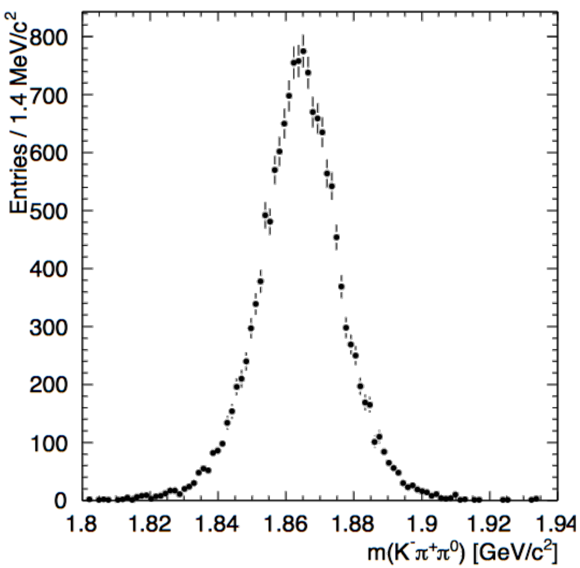
- Signal to noise: $\frac{S}{N} > 250 \cdot \frac{\sigma_S}{\sigma_B}$ => well feasible for σ_B ≈< 10 σ_S !

[arXiv:0903.3905, hep-ex]

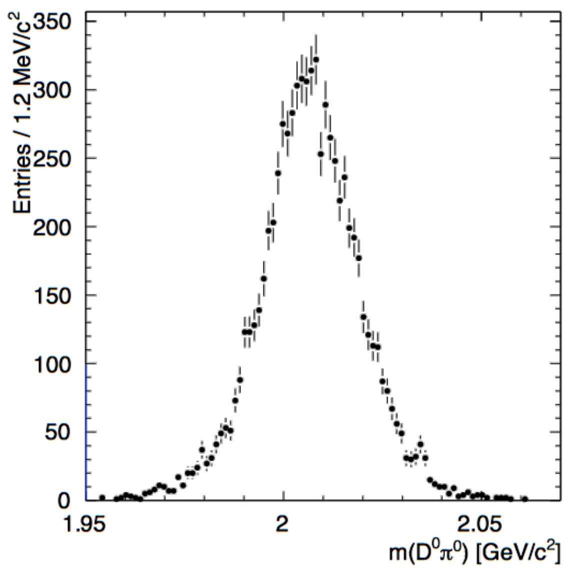
$\bar{p}p \rightarrow \tilde{\eta}_{c1}\,\eta \rightarrow D^0\bar{D}^{0*}\eta$

- Simulation @ 15 GeV/c
  - ➢ 200k signals + background, e.g. $\bar{p}p \rightarrow D^0\bar{D}^{0*}\pi^0$
  - ➢ 11C kinematic fit (mass constraints, 4C energy momentum)

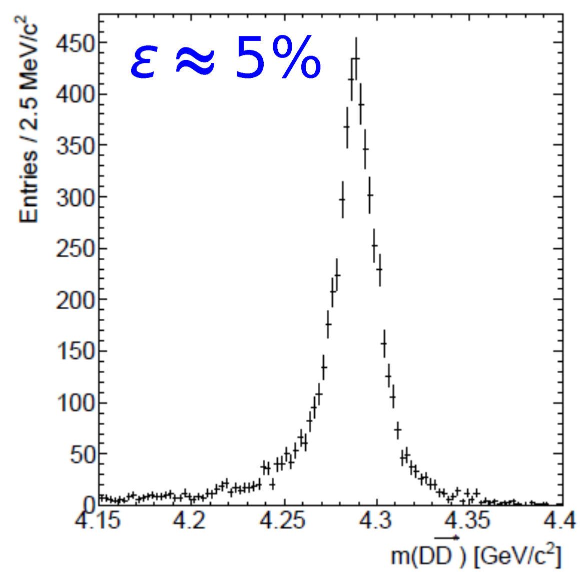
$D^0 \rightarrow K^-\pi^+\pi^0$



$D^{0*} \rightarrow D^0\pi^0$



$\tilde{\eta}_{c1} \rightarrow D^0\bar{D}^{0*}$

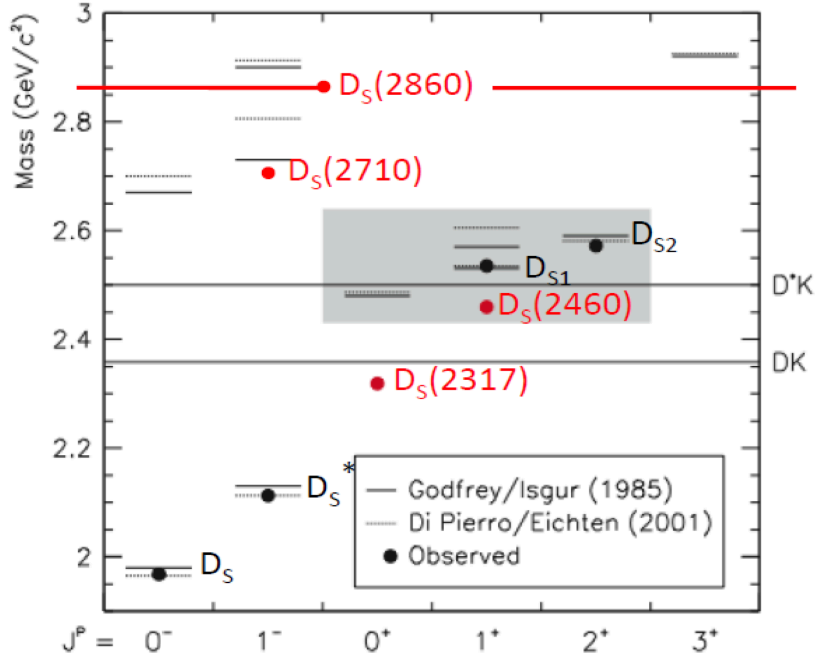


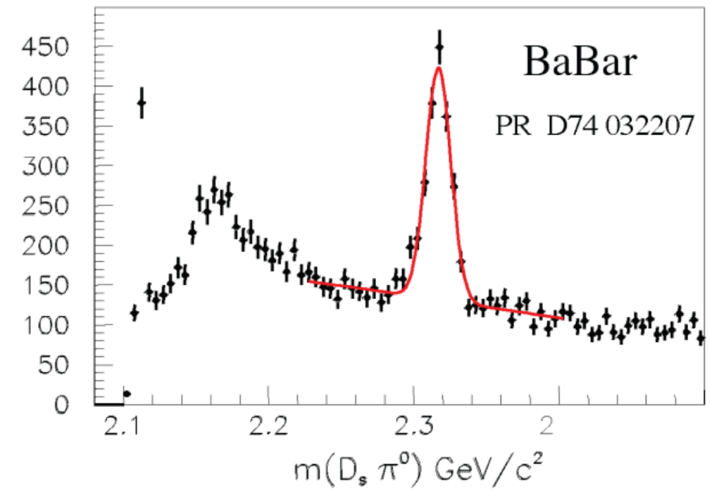
- Signal to noise: $\frac{S}{N} > 2900 \cdot \mathcal{B}(\tilde{\eta}_{c1} \rightarrow D^0\bar{D}^{0*})$ => feasible for non-vanishing BR

[arXiv:0903.3905, hep-ex]

Open charm: The D_s spectrum

- Qualitative agreement theory vs. experiment on D states – details however still open
- Many new D_J mesons *(LHCb)*
- Narrow states *(2003)*: D_s*(2317) and D_s*(2416) still under discussion *(and other broad states recently)*
- Masses: Significantly lower than expected *(quark potential model*), and just below DK and D*K threshold
- Widths: Only upper limits
- Interpretation unclear: DK / D*K molecules, tetraquarks, chiral doublers, ...? Sensitive to width





Interpretation ←→ Width of $D_{s0}^*(2317)$

Different theoretical approaches, different interpretations	$\Gamma(D_{s0}^*(2317)^+ \to D_s\pi^0)$ (keV)	
M. Nielsen, Phys. Lett. B 634, 35 (2006)	**6 ± 2**	
P. Colangelo and F. De Fazio, Phys. Lett. B 570, 180 (2003)	**7 ± 1**	
S. Godfrey, Phys. Lett. B 568, 254 (2003)	**10**	Pure $\bar{c}s$ state
Fayyazuddin and Riazuddin, Phys. Rev. D 69, 114008 (2004)	**16**	
W. A. Bardeen, E. J. Eichten and C. T. Hill, Phys. Rev. D 68, 054024 (2003)	**21.5**	
J. Lu, X. L. Chen, W. Z. Deng and S. L. Zhu, Phys. Rev. D 73, 054012 (2006)	**32**	
W. Wei, P. Z. Huang and S. L. Zhu, Phys. Rev. D 73, 034004 (2006)	**39 ± 5**	
S. Ishida, M. Ishida, T. Komada, T. Maeda, M. Oda, K. Yamada and I. Yamauchi, AIP Conf. Proc. 717, 716 (2004)	**15 - 70**	
H. Y. Cheng and W. S. Hou, Phys. Lett. B 566, 193 (2003)	**10 - 100**	Tetraquark state
A. Faessler, T. Gutsche, V.E. Lyubovitskij, Y.L. Ma, Phys. Rev. D 76 (2007) 133	**79.3 ± 32.6**	DK had. molecule
M.F.M. Lutz, M. Soyeur, Nucl. Phys. A 813, 14 (2008)	**140**	Dynamically gen. resonance
L. Liu, K. Orginos, F. K. Guo, C. Hanhart, Ulf-G. Meißner Phys. Rev. D 87, 014508 (2013)	**133 ±22**	DK had. molecule
M. Cleven, H. W. Giesshammer, F. K. Guo, C. Hanhart, Ulf-G. Meißner hep-ph: arXiV 1405.2242 (2014)	NEW! Strong and radiative decays of $D_{s0}^*(2317)$ and $D_{s1}(2460)$	

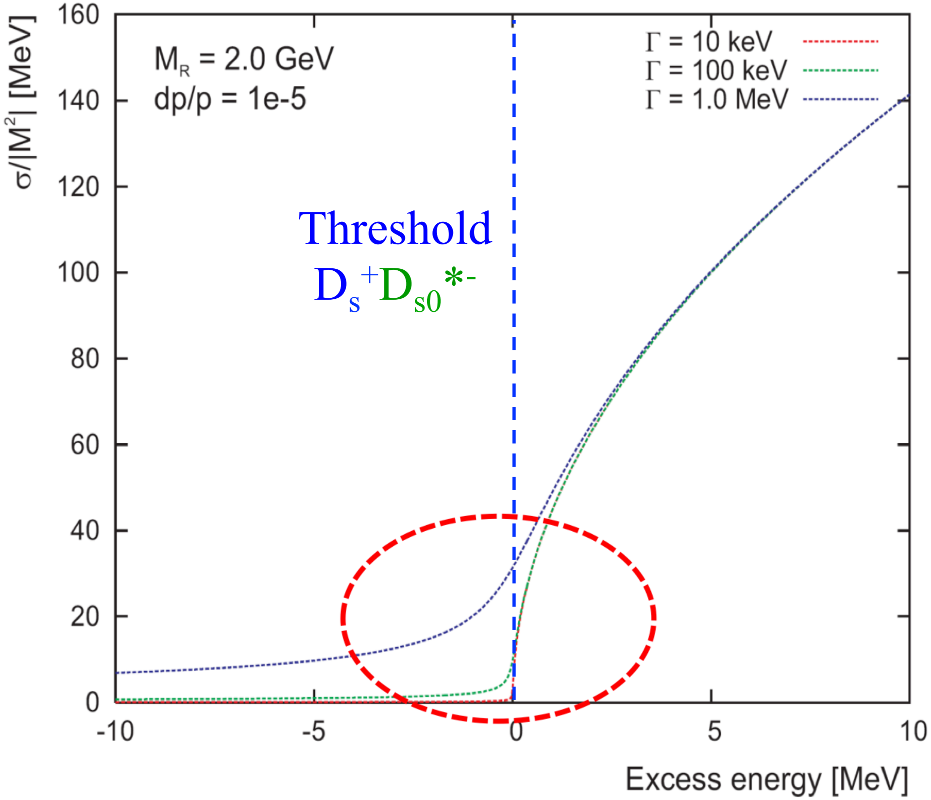
Width of D_{s0}*(2317)

- Theoretical interpretations very sensitive for $\Gamma(D_{s0}^*(2317))$
- Formation reaction not possible: $\bar{p}p \not\rightarrow D^*_{s0}(2317)$
  → *Energy-scan with recoil @ threshold:* $\bar{p}p \rightarrow D_s^+ D^*_{s0}(2317)^-$

$$\frac{\sigma(s)}{|M^2|} = \frac{\Gamma}{4\pi\sqrt{s}} \int_{-\infty}^{\sqrt{s}-m_{D_s}} \mathrm{d}m \frac{\sqrt{\left(s-(m+m_{D_s})^2\right)\left(s-(m-m_{D_s})^2\right)}}{\left(m-m_{D(2317)}\right)^2+(\Gamma/2)^2}$$

[C. Hanhart]

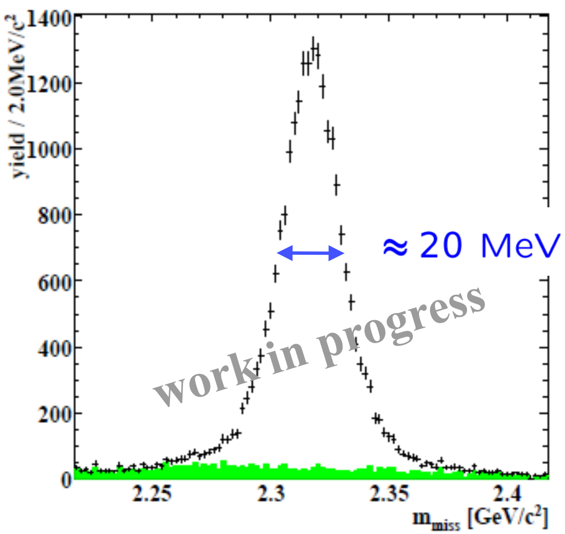
→ **Lineshape at threshold depends on $\Gamma(D_{s0}(2317)^*)$**



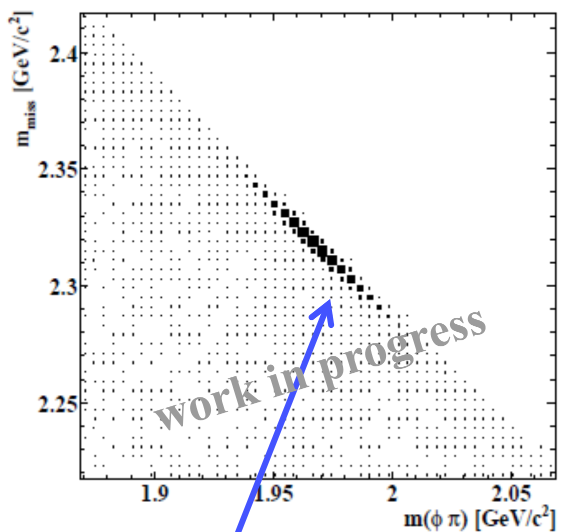
Reconstruction of $\bar{p}p \to D_s^+ D_{s0}^*(2317)^-$

- Simulation @ 8.8 GeV/c
  - 40k signals, 40k each background, e.g. $\bar{p}p \to D_s^+ D_s^- \pi^0$
  - 10M generic background events
  - Inclusive reconstruction of $D_s^\pm$, missing mass technique

m_{miss}

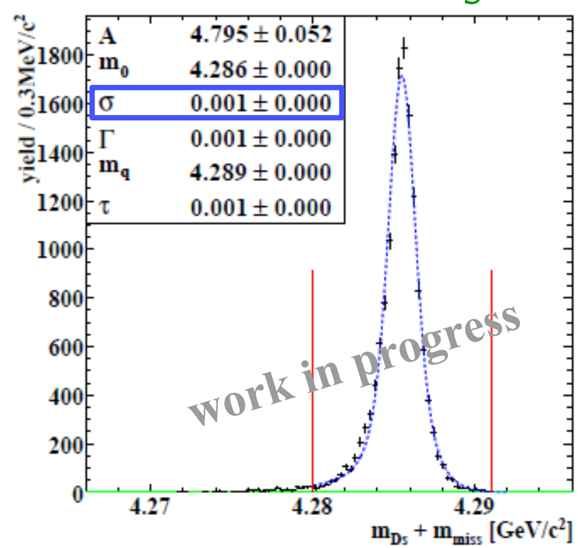


m_{miss} vs. m_{D_s}



make use of strong correlation between masses

$m_{miss} + m_{D_s}$



efficiency

$\varepsilon \approx 20\% - 36\%$

[arXiv:0903.3905, hep-ex]

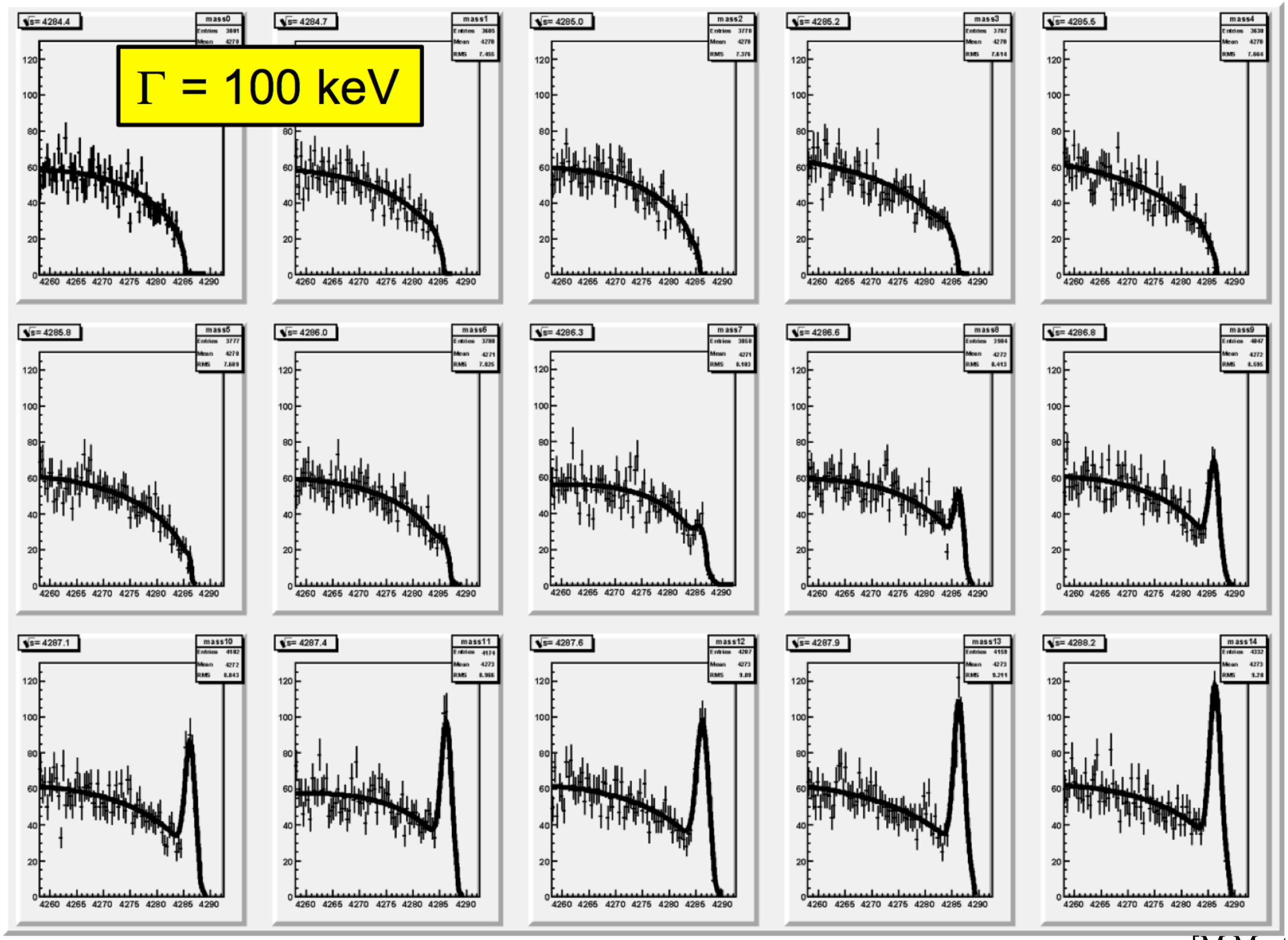
Energy scan simulation around threshold

$\bar{p}p \rightarrow D_s^{\pm} D_{s0}^{*}(2317)^{\mp}$

$M_{sum} = M_{miss}(D_s) + M(D_s)$

15 measured points within 4 MeV window

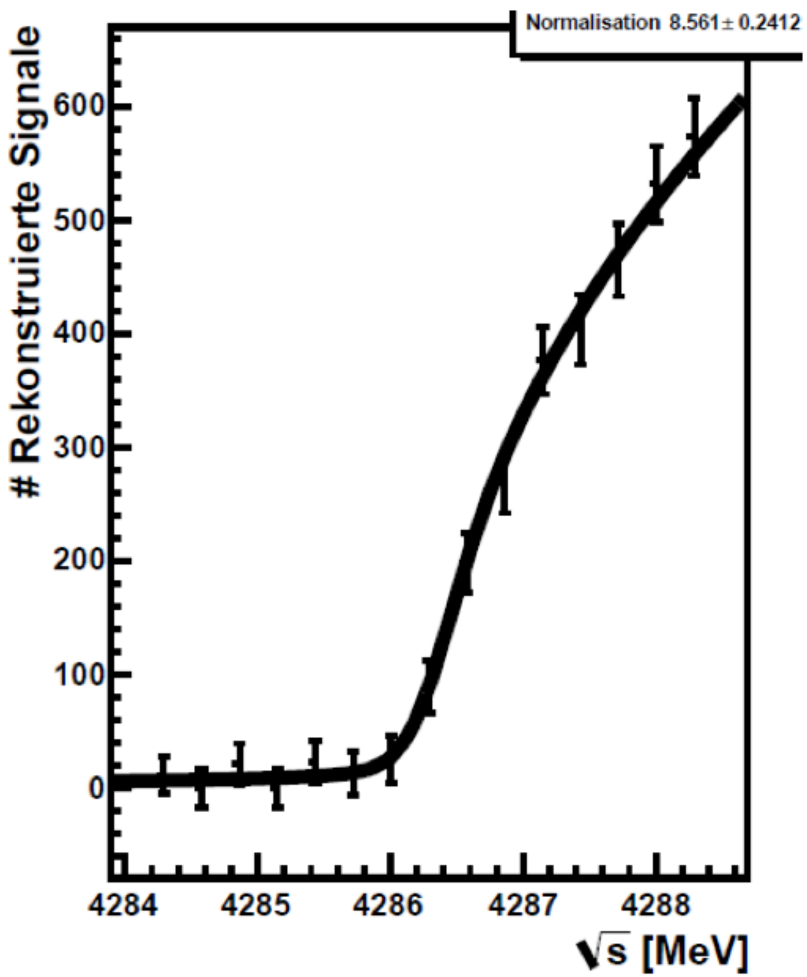
Γ = 100 keV



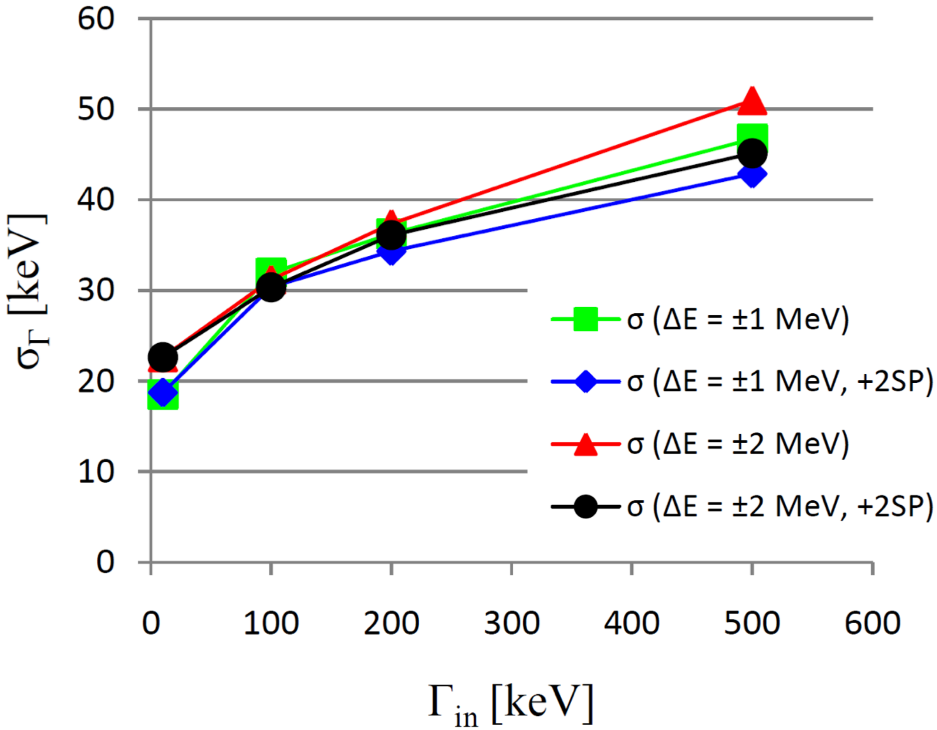
[M.Mertens, PhD thesis]

Energy scan simulation around threshold

Extracted excitation function



Sensitivity of width Measurement



Relative accuracy $\sigma_\Gamma/\Gamma < 1/3$ for $\Gamma > 100$

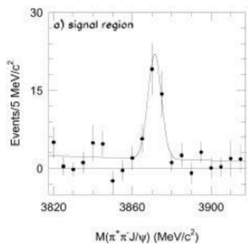
[M.Mertens, PhD thesis]

Meson Spectroscopy – Charmonium-like (exotics)

X,Y,Z

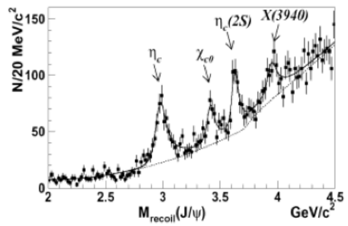
X(3872)

PRL 91,262001 (2003)



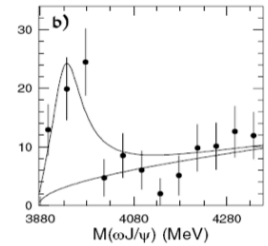
X(3940)

PRL 98,082001 (2007)



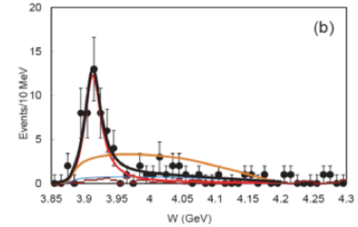
Y(3940)

PRL 94,182002 (2005)



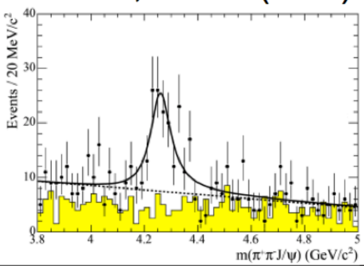
X(3915)

PRL 104,092001 (2010)



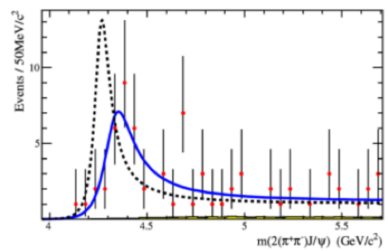
Y(4260)

PRL 95,142001 (2005)



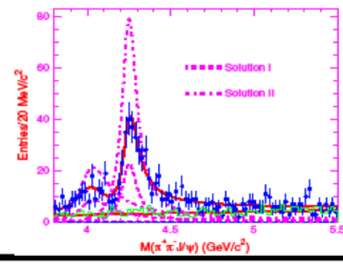
Y(4350)

PRL 98,212001 (2007)



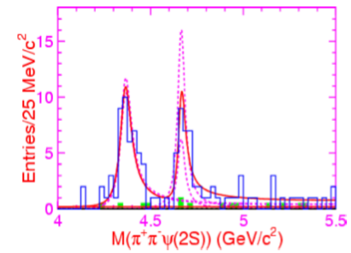
Y(4008)

PRL 99,182004 (2007)



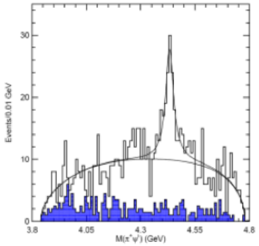
Y(4660)

PRL 99,142002 (2007)



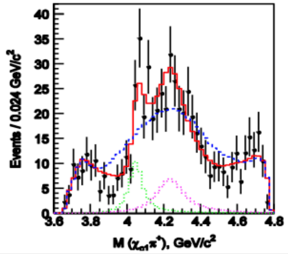
Z(4430)⁻

PRL 100,142001 (2008)



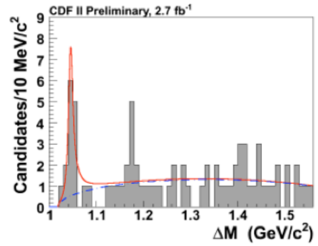
Z_1^- & Z_2^-

PRD 78,072004 (2008)



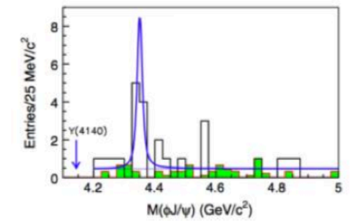
Y(4140)

PRL 102,242002 (2009)

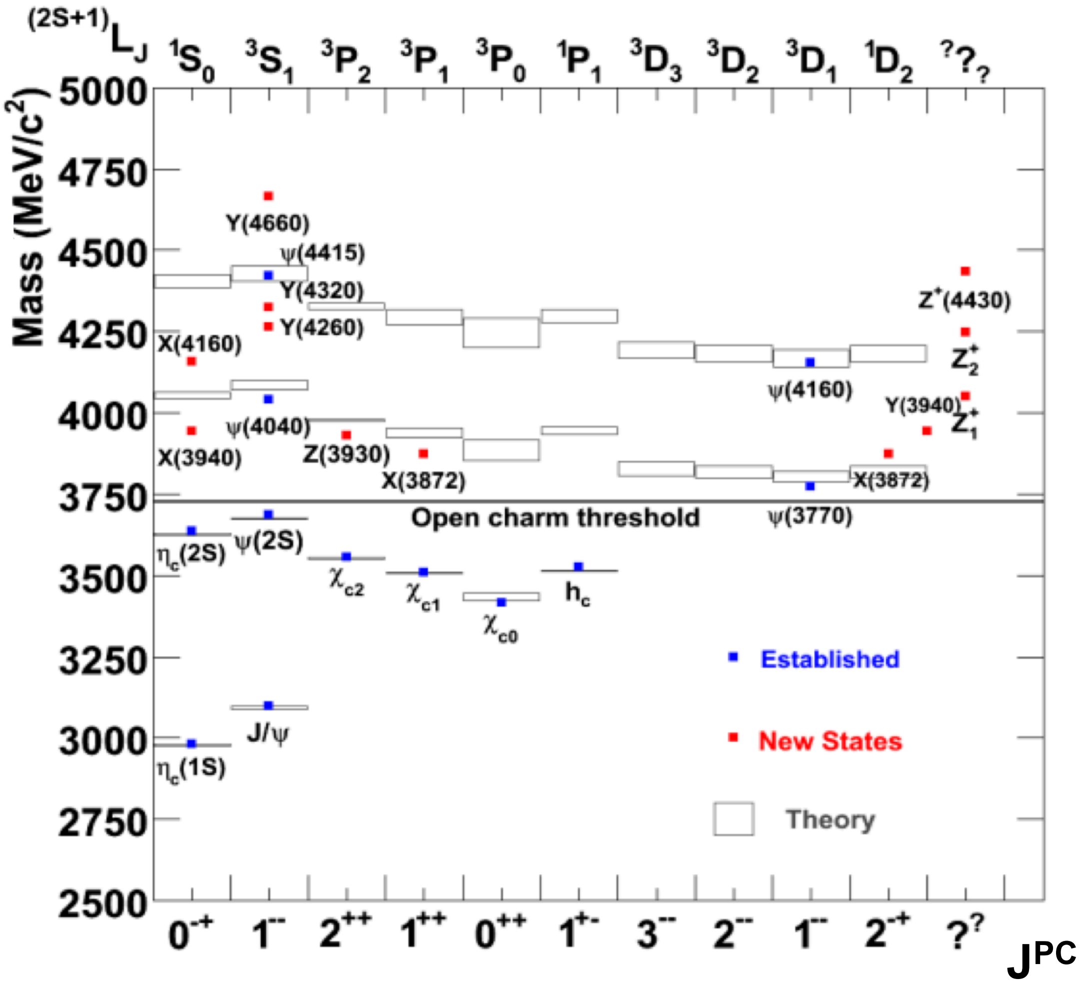


X(4350)

PRL 104,112004 (2010)



Charmonium(-like) Spectrum



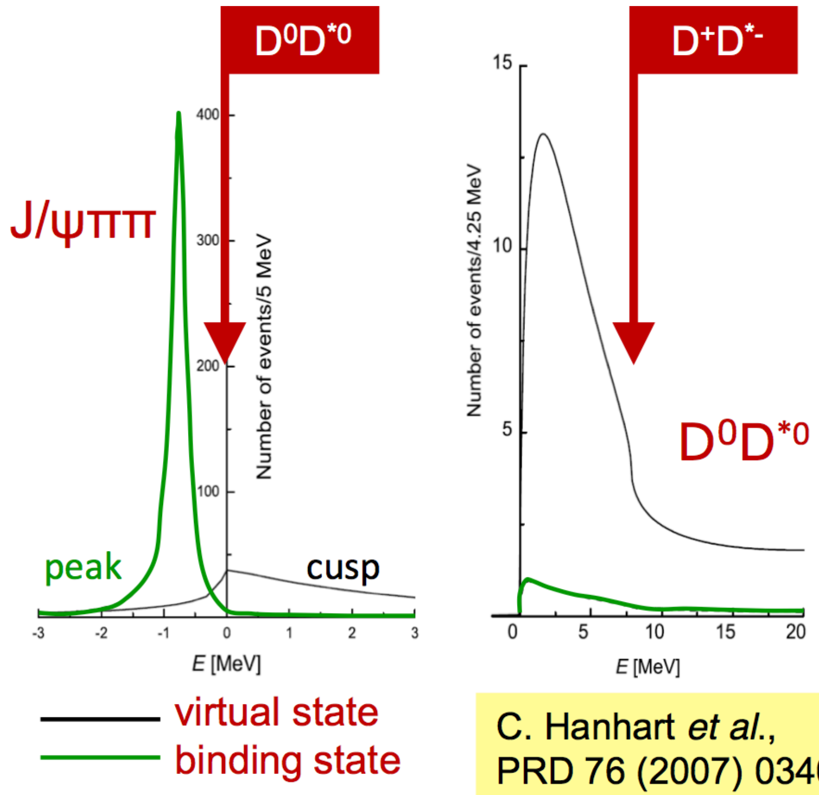
- Since 2003 charmonium-like spectrum found richer as expected
- Observation of states that do not fit theoretical models/predictions
- The case of the X(3872):
  - isospin violating, very narrow
  - quantum numbers known (1^{++}, LHCb)
  - width unclear

  → *nature not yet clear..*

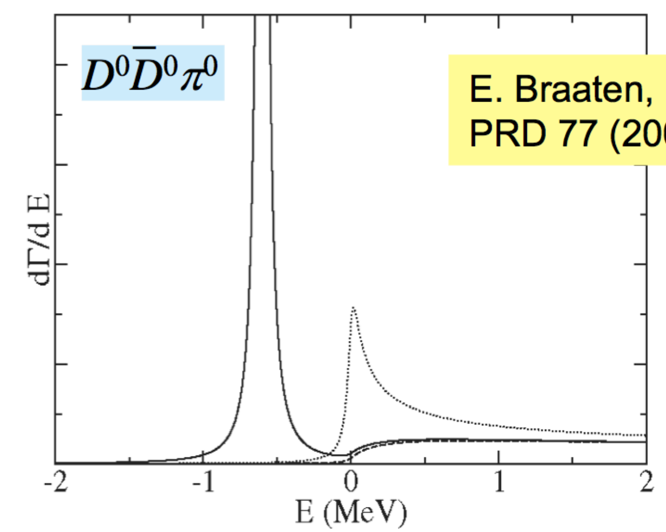
  needed: measurement of width
- X,Y,Z states:
  - some need still confirmation
  - masses poorly known
  - statistics poor, nature unclear:
    Molecules, tetraquarks, hybrids, ..?
    Z_c(3900): First order exotic?

How PANDA can contribute: Study lineshapes

- Panda: Neutral & charged, e.g. $J/\psi\pi^-\pi^+$, $J/\psi\pi^0\pi^0$, $\chi_c\gamma \rightarrow J/\psi\gamma\gamma$, $J/\psi\gamma$, $J/\psi\eta$, $\eta_c\gamma$, ...
- Direct formation in $\bar{p}p$ → *lineshapes*
- Example: X(3872)



C. Hanhart *et al.*, PRD 76 (2007) 034007



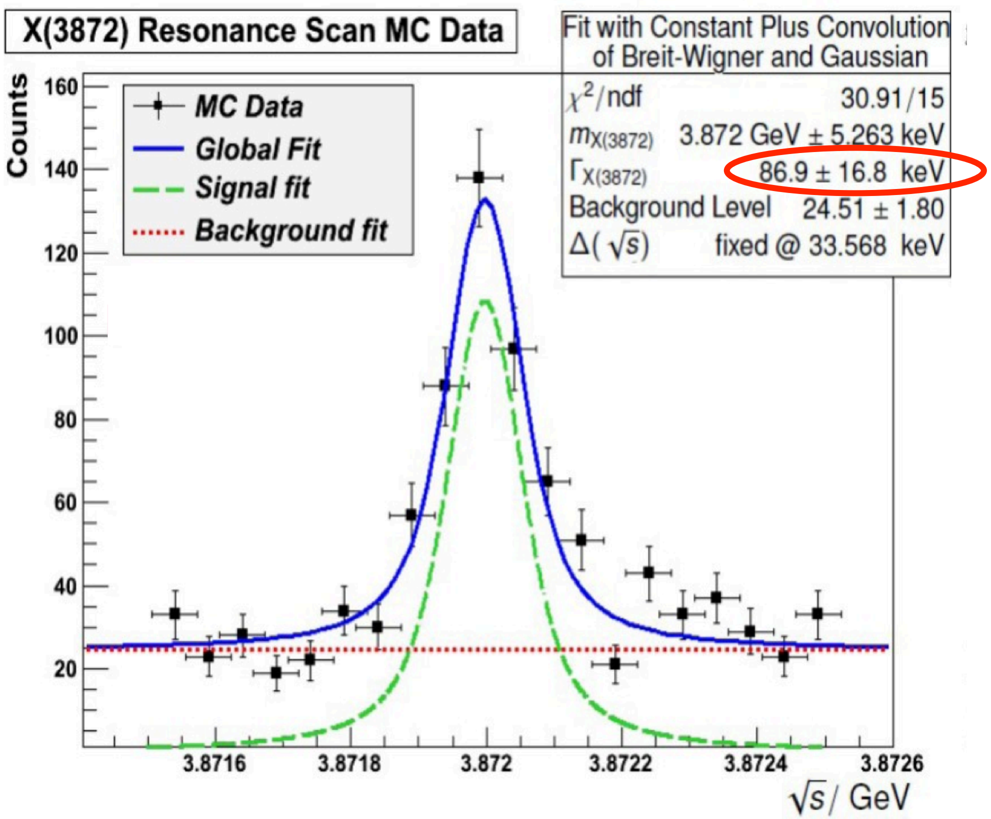
E. Braaten, M. Lu, PRD 77 (2008) 014029

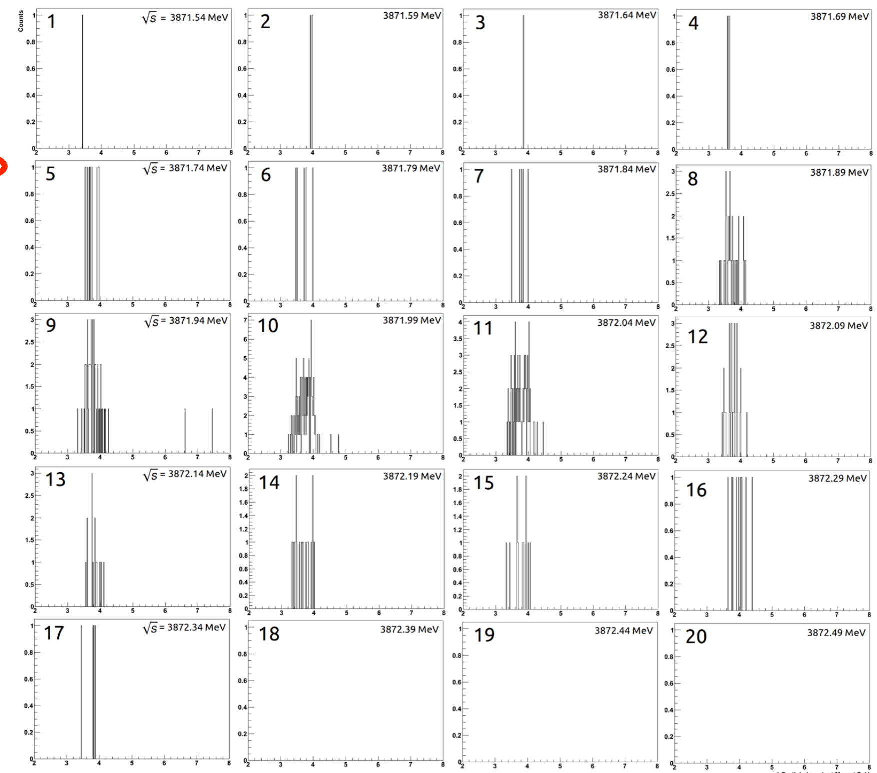
Compare lineshapes in different final states

X(3872)

- Upper limit on branching ratio by LHCb:

  $BR(X \to \bar{p}p) < 0.002 * BR(X \to J/\psi \pi^- \pi^+)$ → $\Gamma < 1.2$ MeV   EPJ C73 (2013) 2462
- And $BR(X \to J/\psi \pi^- \pi^+) > 0.026$ (PDG 12) => $\sigma(\bar{p}p \to X(3872)) < 67$ nb





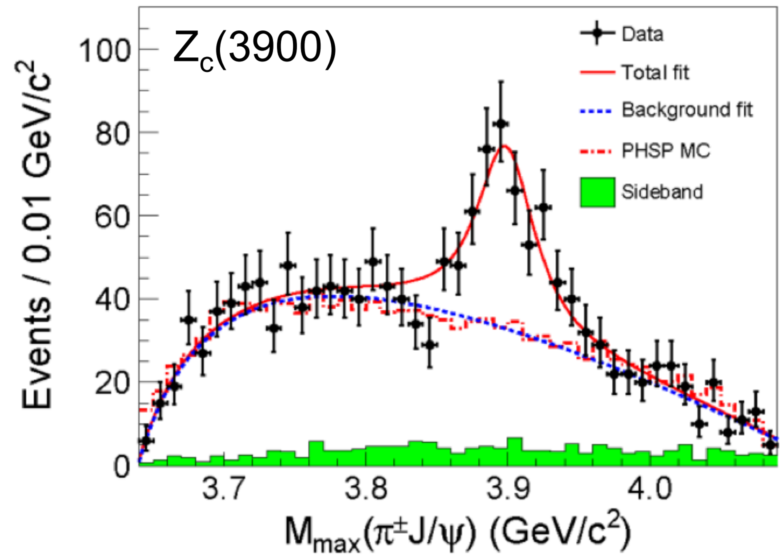
- Here: Assume σ = 50 nb, Luminosity: 2×10^{31} cm^{-2}s^{-1}
- Width resolution < 100 keV

[M.Galuska, PhD thesis]

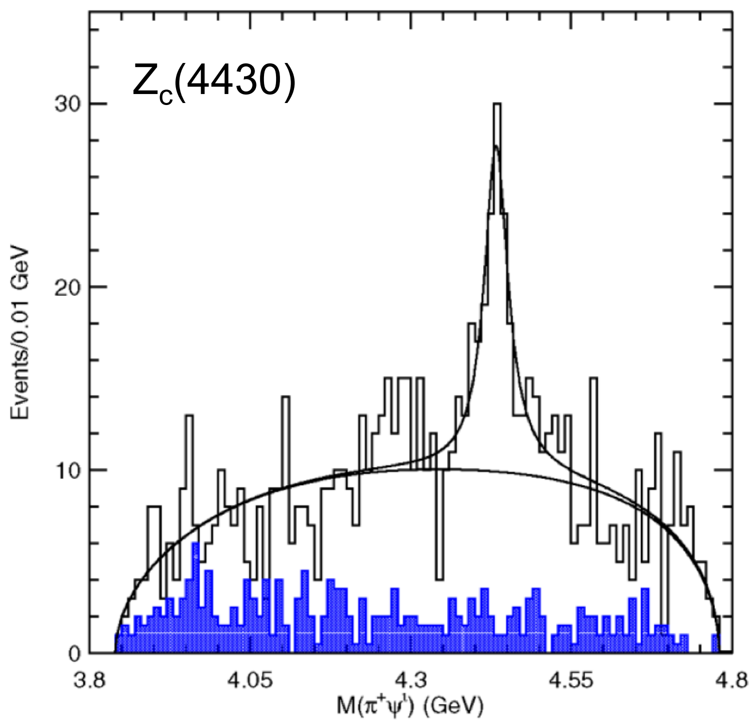
Non-$q\bar{q}$ mesons: Charged $c\bar{c}$-like states

- Manifestly exotic: tetra-quark or molecular nature
- $Z(4430)^{\pm}$ seen by Belle, confirmed by LHCb
- $Z(3900)^{\pm}$ seen by BESIII, Belle
- $Z(4020)^{\pm}$, $Z(4040)^{\pm}$ seen by BESIII
- $Z(4050)^{\pm}$, $Z(4250)^{\pm}$ seen by Belle

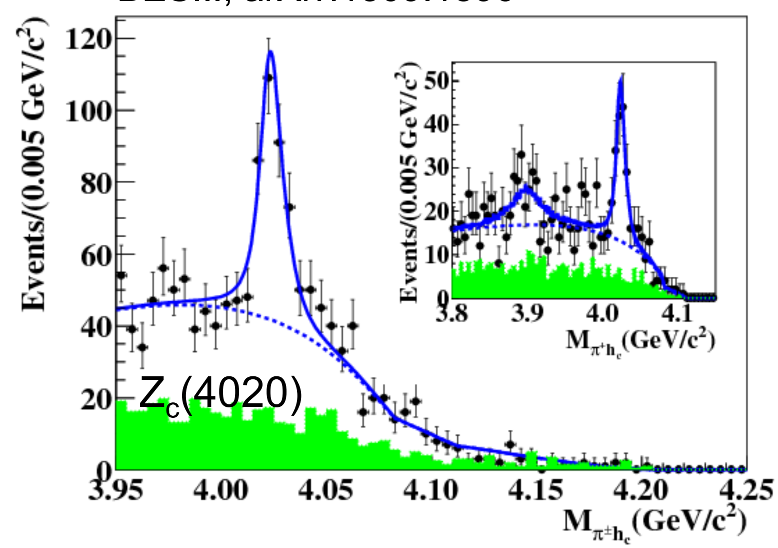
BESIII, arXiv:1303.5949



Belle, PRL 100 (2008) 142001



BESIII, arXiv:1309.1896



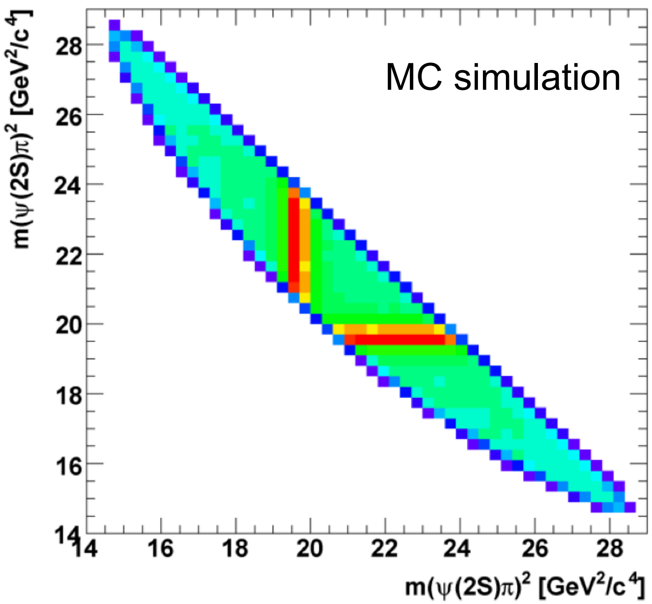
Non-$q\bar{q}$ mesons: Charged $c\bar{c}$-like states

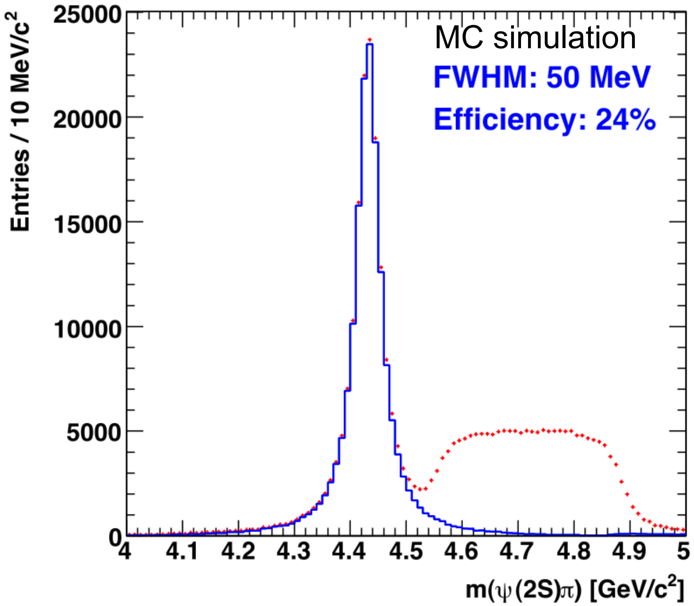
Studies planned with PANDA:

- *production* in $\bar{p}p$:
  $\bar{p}p \rightarrow Z(4430)^{\pm}\,\pi^{\mp}$
  $Z(4430)^{\pm} \rightarrow \psi(2S)\,\pi^{\pm}$

- *formation* in $\bar{p}n$:
  $\bar{p}d \rightarrow Z(4430)^{-}\,p_{spectator}$
  $\rightarrow \psi(2S)\,\pi^{-}\,p_{spectator}$

spectator proton needed to reconstruct
→ *reduced mass resolution*



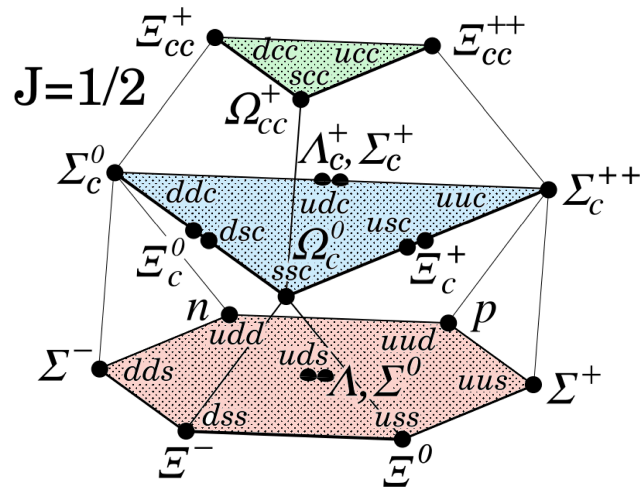


Further Branches of the PANDA Physics Programme ...

Baryon Spectroscopy

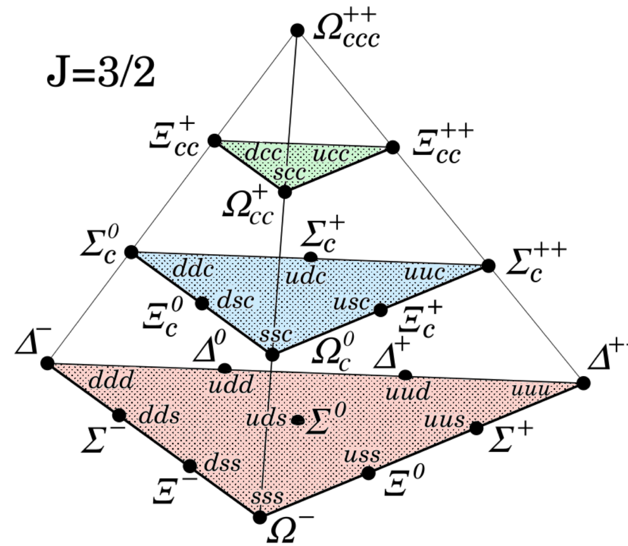
Baryon spectroscopy in PANDA

- Large cross-section, no extra mesons
- 4π acceptance for charged and neutral
- Displaced vertex tagging



N and Δ baryons

- N* spectrum not understood
- Missing resonances
- Progress basically in photoproduction only



Charmed baryons

- Narrow widths of resonances
- Rich spectrum of states
- J^{PC} quantum numbers not yet all measured
- Testing ground for HQET

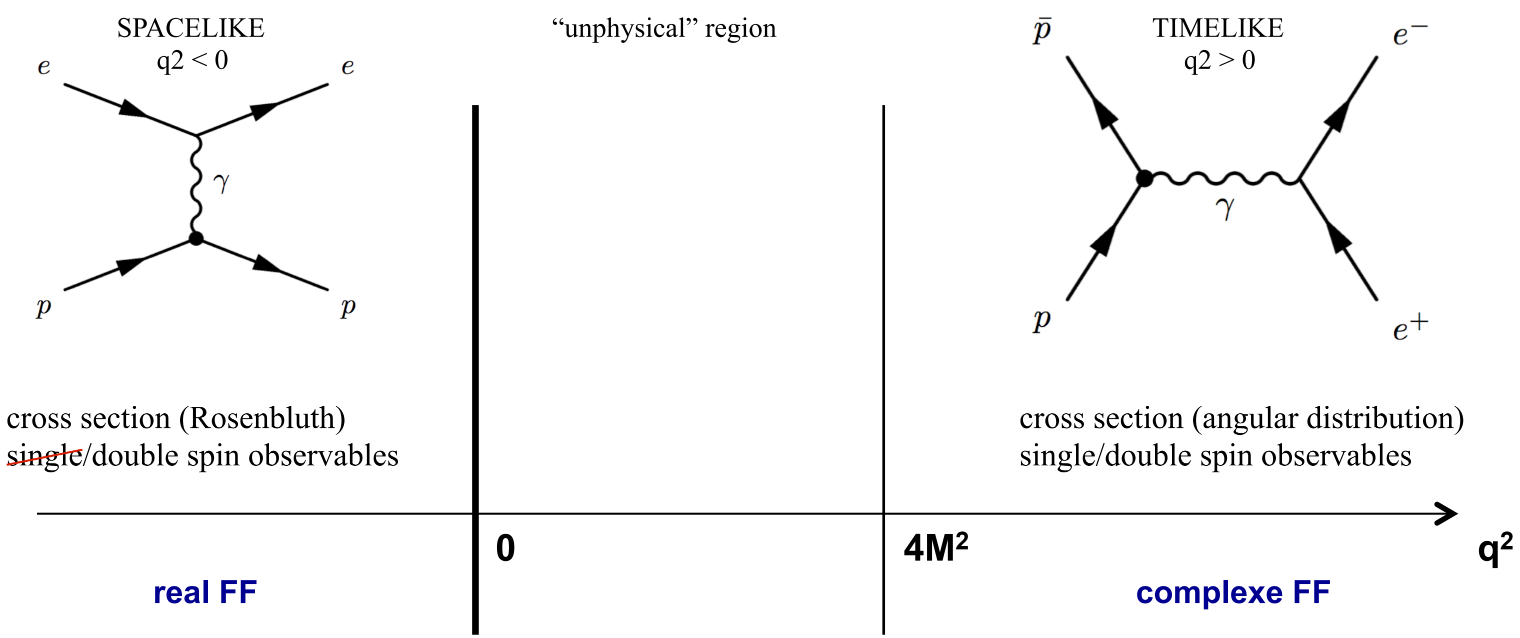
Nucleon spin structure

Basics of nucleon spin structure studies

- Bjorken scaling
  - At high Q^2 dependence only on x: scatter off partons
- Parton distributions
  - Valence quarks
  - Sea: quarks & anti-quarks
  - Gluons
- Structure functions
  - Unpolarised, f_1
  - Polarised, g_1 (and g_2)
  - Tranverse polarised, h_1
- Proton spin status: $\langle s_z \rangle = \frac{1}{2} = \frac{1}{2} (\Delta u+\Delta d+\Delta s) + L_q + \Delta G + L_g$
  - Quark contribution: $\Delta\Sigma = (\Delta u+\Delta d+\Delta s) \approx 0.3$ (Expt.)
  - Gluon polarisation: $|\Delta G/G| < 0.3$ (Expt.)
  - Other contributions: Orbital angular momentum

Electromagnetic proton form factor

scattering: **annihilation:**

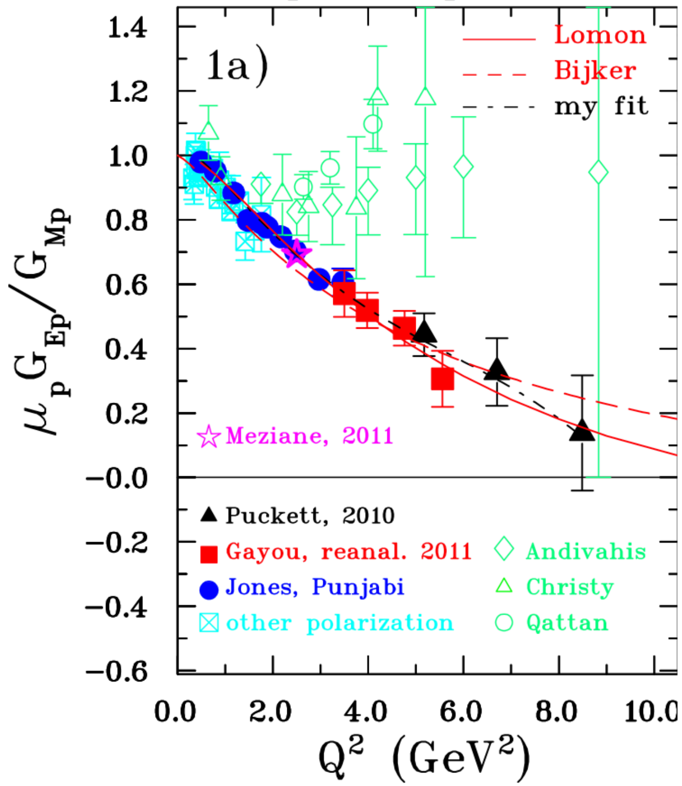


- Access to the charge radius of the proton
- Incompatibility of Rosenbluth and polarisation data in spacelike region
- Same matrix element: Highly explored in spacelike region, almost unknown in timelike

Electromagnetic proton form factor

SPACELIKE, $q^2 < 0$

Rosenbluth separation / polarization transfer

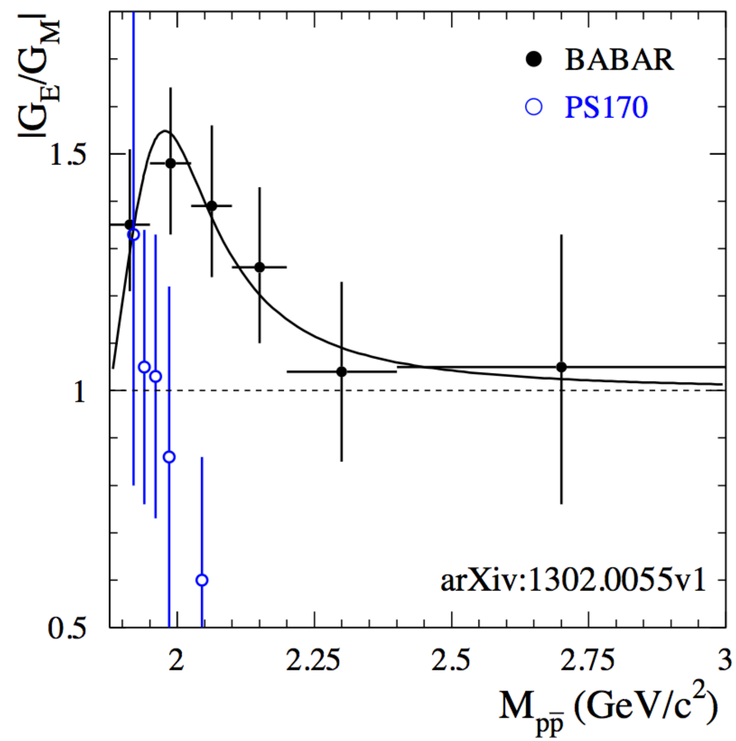


Rosenbluth: $\mu G_E/G_M \sim 1$

polarisation: $G_E/G_M \sim a + bq^2$

TIMELIKE, $q^2 > 0$

cross section (angular distribution)



Timelike EM form factor

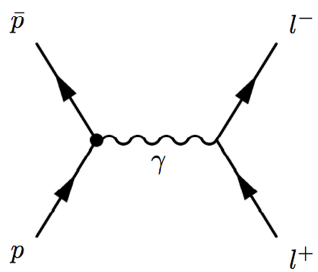
- **at the lowest order (one-photon exchange approximation):**

  A.Zichichi et al., Nuovo Cimento XXIV, 170 (1962)

$$\frac{d\sigma}{d\cos\theta^*} = \frac{\pi\alpha^2}{2s}\frac{1}{\beta}\left\{(1+\cos^2\theta^*)\,|G_M|^2 + \frac{1}{\tau}(1-\cos^2\theta^*)|G_E|^2\right\}$$

$$= \frac{\pi\alpha^2}{2s\tau}\frac{1}{\beta}\,|G_M|^2\left\{\tau\,(1+\cos^2\theta^*) + (1-\cos^2\theta^*)\frac{|G_E|^2}{|G_M|^2}\right\}$$

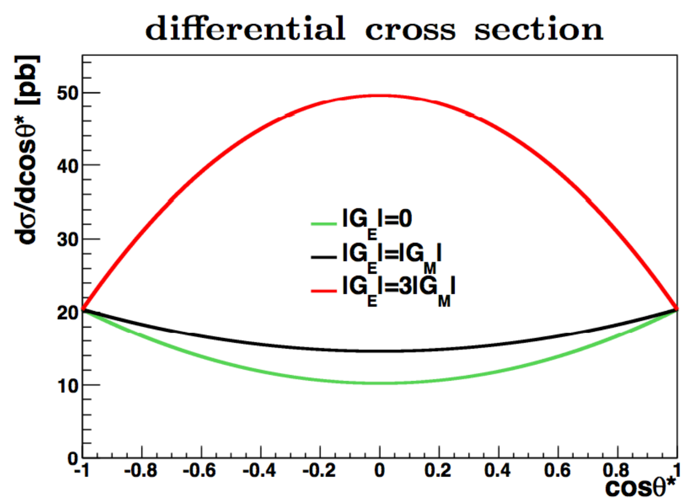
$$\tau = q^2/4M^2$$

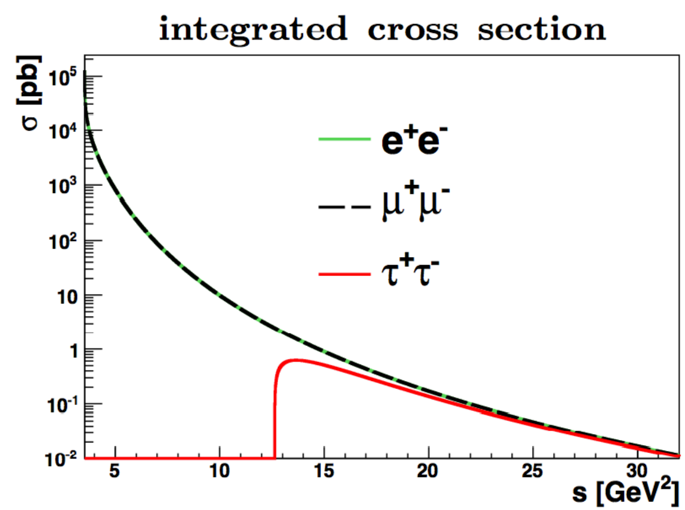


$\rightarrow$ **extract $|G_E|$ and $|G_M|$: with luminosity measurement, low q^2 (no $|G_E|$ suppression)**

$\rightarrow$ **extract $|G_E|/|G_M|$**

- **integrated cross section:** $\sigma = \frac{4}{3}\frac{\pi\alpha^2}{\beta s}\left[|G_M|^2 + \frac{1}{2\tau}|G_E|^2\right]$ $\Rightarrow$ **effective FF**





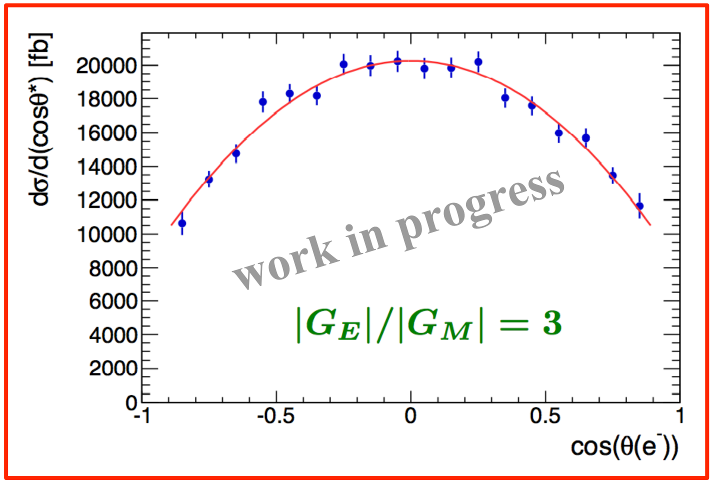
[M.Zambrana, Photon 2013]

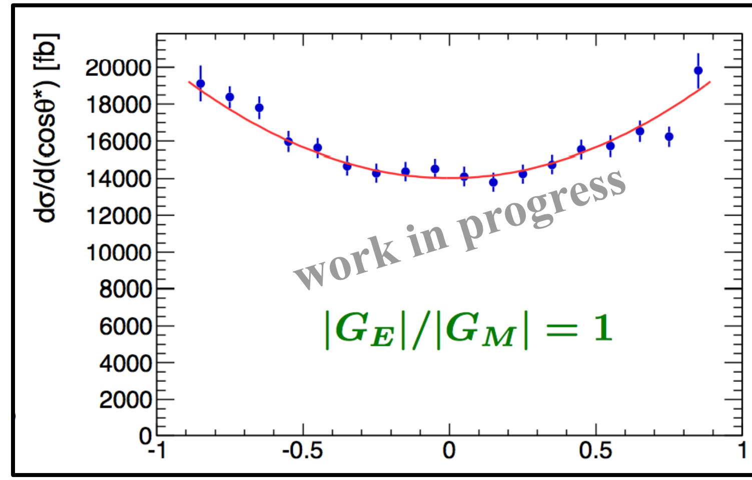
Timelike EM form factor

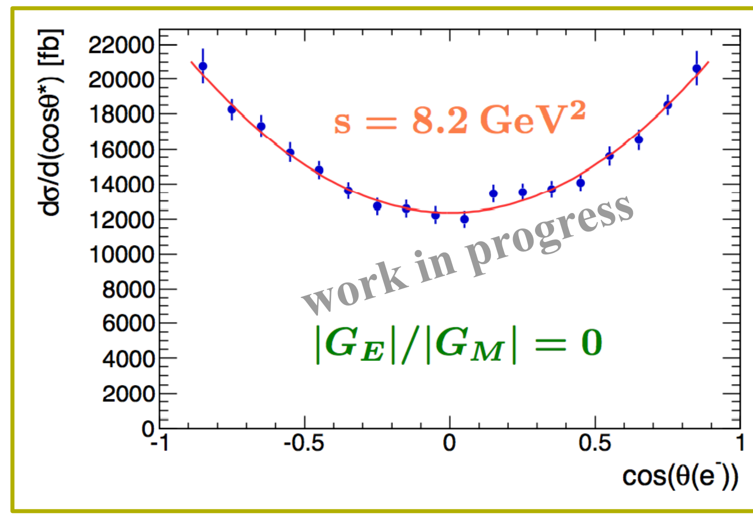
- simulations with $L = 2\ \mathrm{fb}^{-1}$, several s, $|G_E|/|G_M| = 0, 1, 3$
- signal corrected by efficiency ϵ_i
- measure cross section:

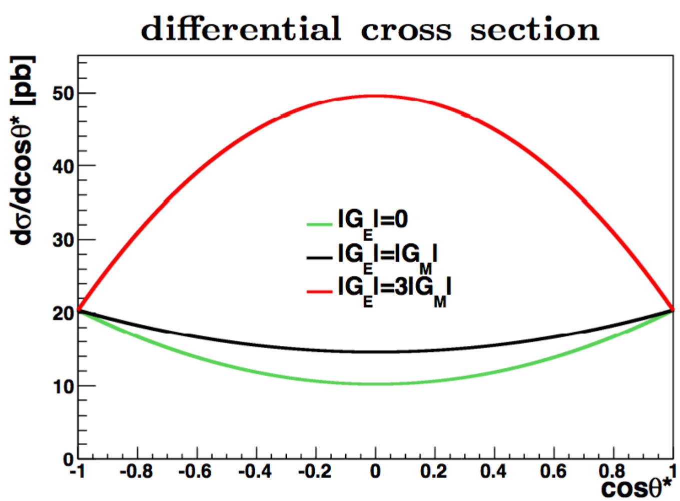
$$\sigma_i = \frac{N_i}{\epsilon_i\, L}$$

- fit distribution and extract $|G_E|$ and $|G_M|$ or ratio $|G_E|/|G_M|$





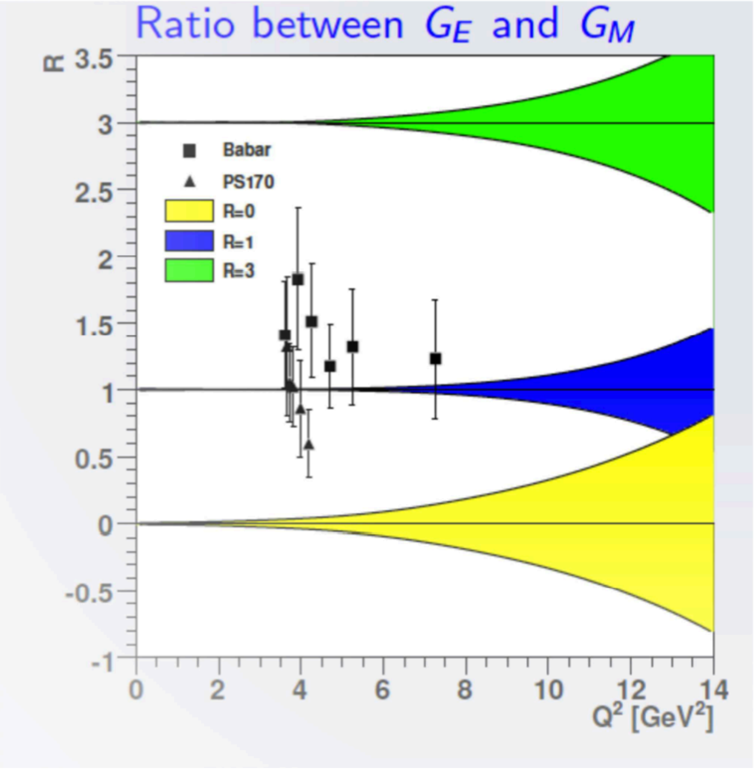




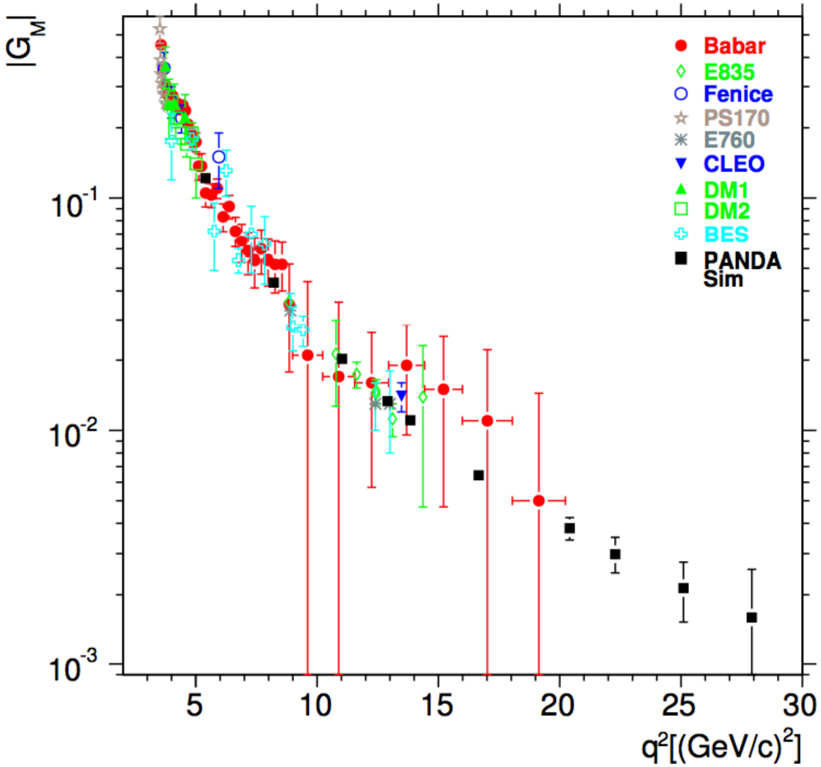
[M.Zambrana, Photon 2013]

Measurement of EM proton formfactor

from angular distribution



from total cross section
assumption : $|G_E| = |G_M|$



M. Sudol et al., Eur. Phys. J. A 44, 373-384 (2010)
M.C. Mora Espí, PhD thesis (2012)

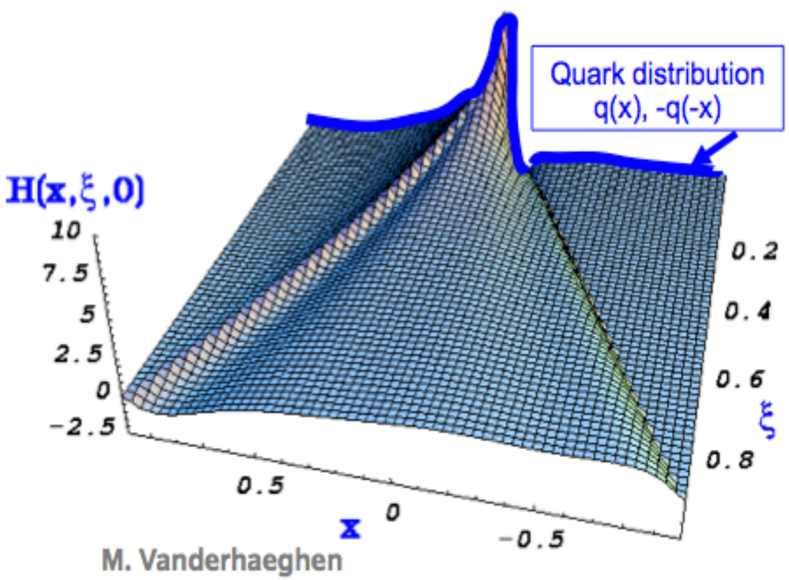
Unprecedented precision in PANDA measuremen: 50% → 3-5%

[M.Zambrana, Photon 2013]

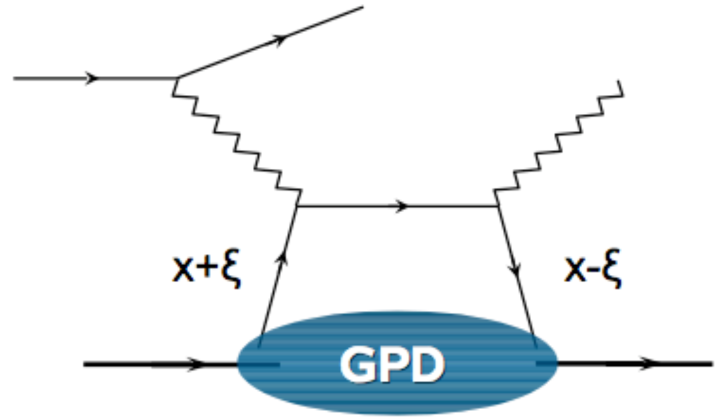
Generalised Parton Distributions (GPDs)

What GPDs are:

- A fractional momentum ξ is taken out
- GPDs: 4 functions
  - H(x,ξ,t), E(x,ξ,t)
  - $\tilde{H}$(x,ξ,t), $\tilde{E}$(x,ξ,t) *(polarised)*



Handbag Diagram



Properties of GPDs:

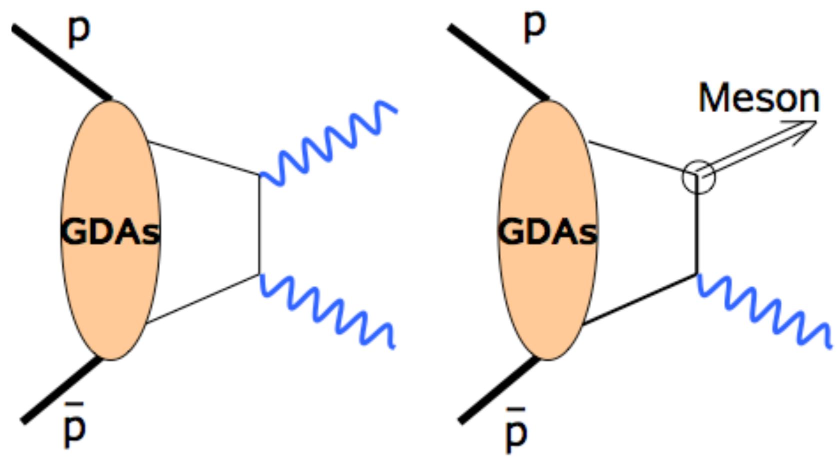
- GPDs carry information on both distribution of partons: *longitudinal & transverse*
- GPDs contain also information on quark (orbital) angular momentum
- H(x,0,0) = q(x) *structure functions of DIS*
- ∫H(x,0,t) dx = F(t) *nucleon formfactor*

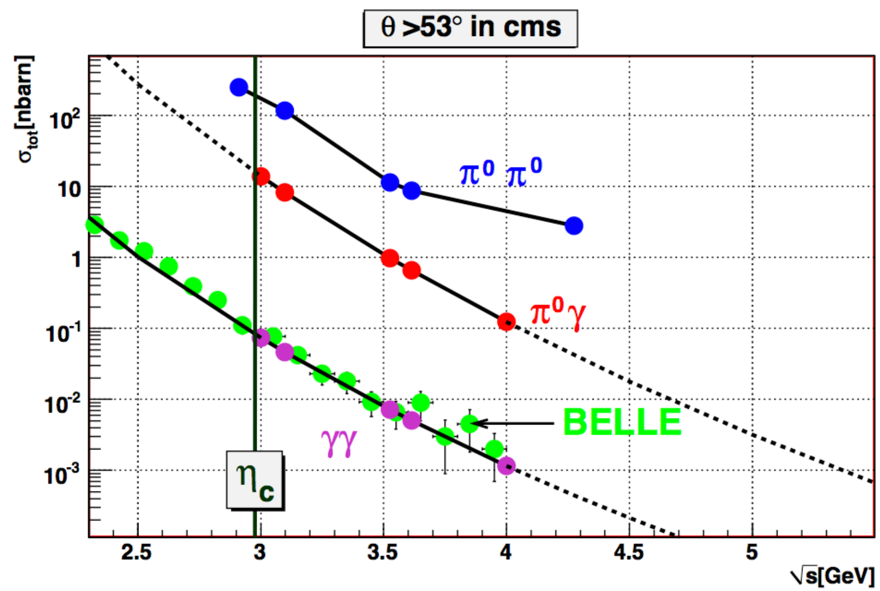
GPDs with PANDA

Generalised Parton Distributions
- Deeply Virtual Compton Scattering (DVCS)
- Hard Exclusive Meson Production (HEMP)

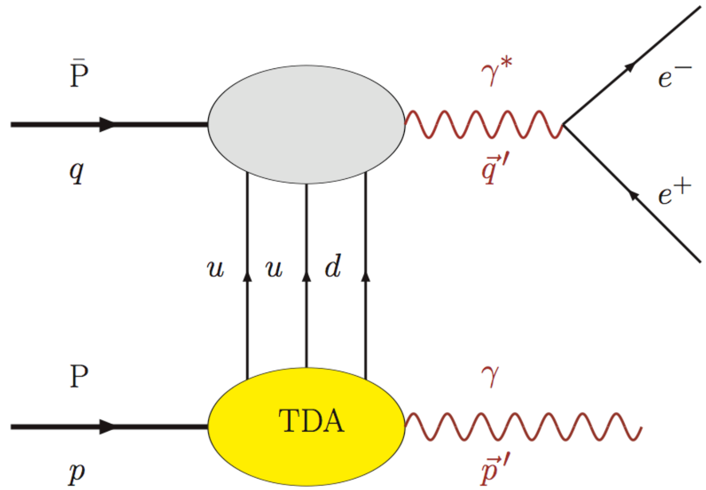
Crossed Channel with p̄: GDAs
- Wide angle compton scattering
- Hard Exclusive Meson Production

Simulation
- Signal: $\bar{p}p \to \gamma\gamma$
- Backgrounds: $\bar{p}p \to \gamma\pi^0, \bar{p}p \to \pi^0\pi^0$





Transition Distribution Amplitudes (TDAs)



From GPDs to TDAs:

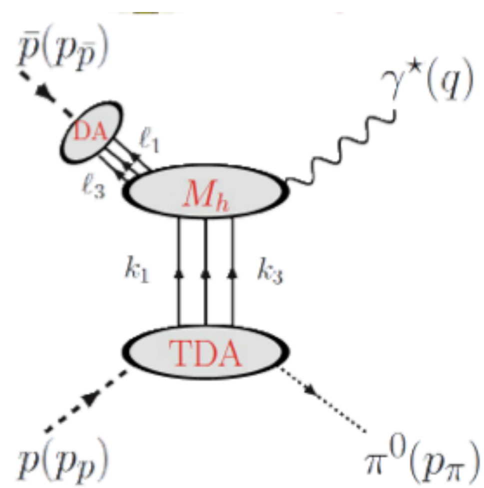
- GPDs describe $q\bar{q}$ exchange
- TDAs describe qqq exchange

→ *Backward exclusive meson production*

→ *Process: $\bar{p}p \rightarrow \gamma\gamma^*$*

Properties of TDAs:

- Universal non-perturbative objects describing e.g. $p \rightarrow \pi$ and $p \rightarrow \gamma$
- Obey QCD evolution equations



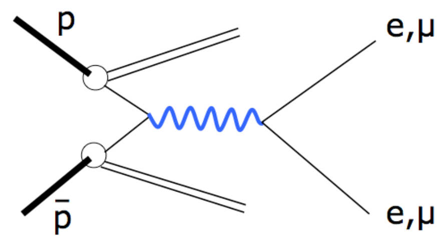
Feasibility Studies

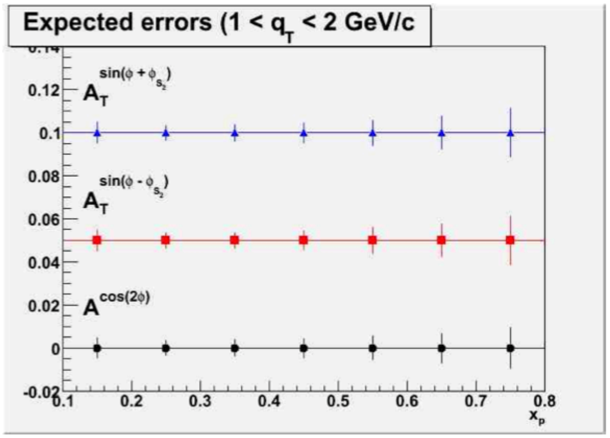
- Cross section in reach for PANDA
- Signal: $\bar{p}p \rightarrow \gamma e^+e^-$ and $\bar{p}p \rightarrow \gamma\pi^0$
- Backgrounds: $\bar{p}p \rightarrow \pi^0$, $\bar{p}p \rightarrow \pi^0\pi^0$

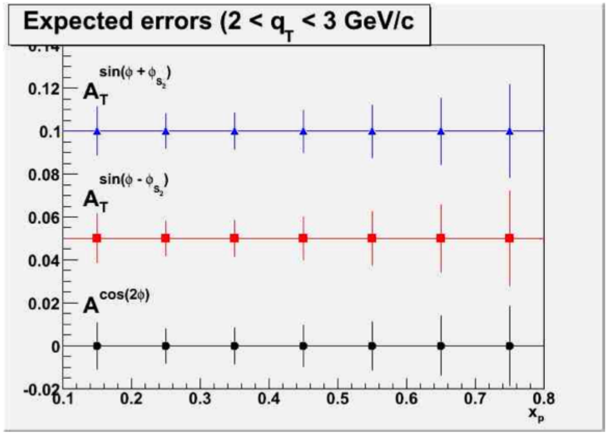
Drell-Yan process with PANDA

<u>Transverse nucleon spin</u>

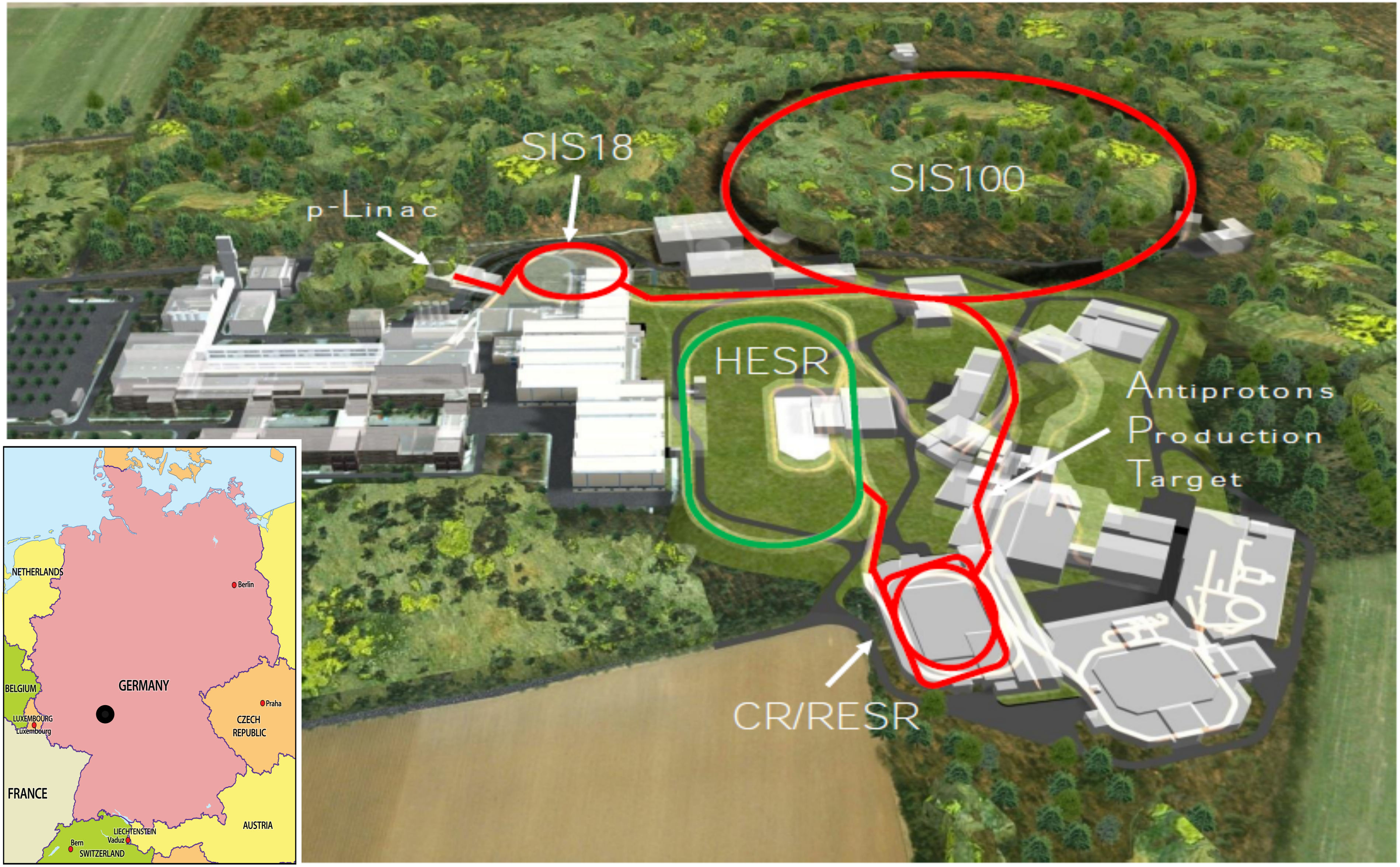
- Drell-Yan process
  (full PWA or polarised beam/target)
- No helicity flip fragmentation function needed as in DIS
- With p̄p access to valence antiquarks
- High x, high cross-section, high sensitivity
- First: *Unpolarised only*
- Later: *Single spin asymmetry also*



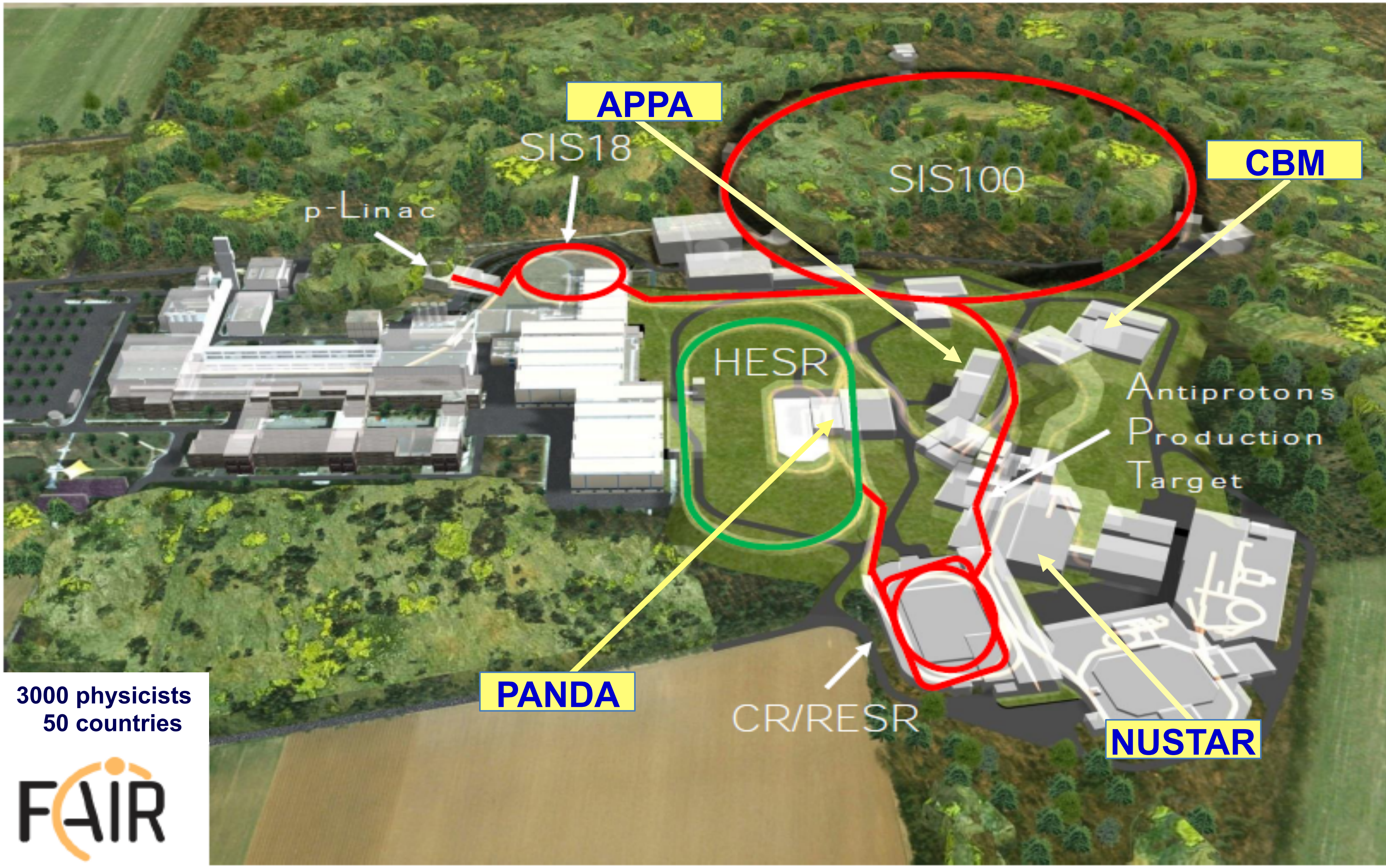




Facility for Antiproton and Ion Research

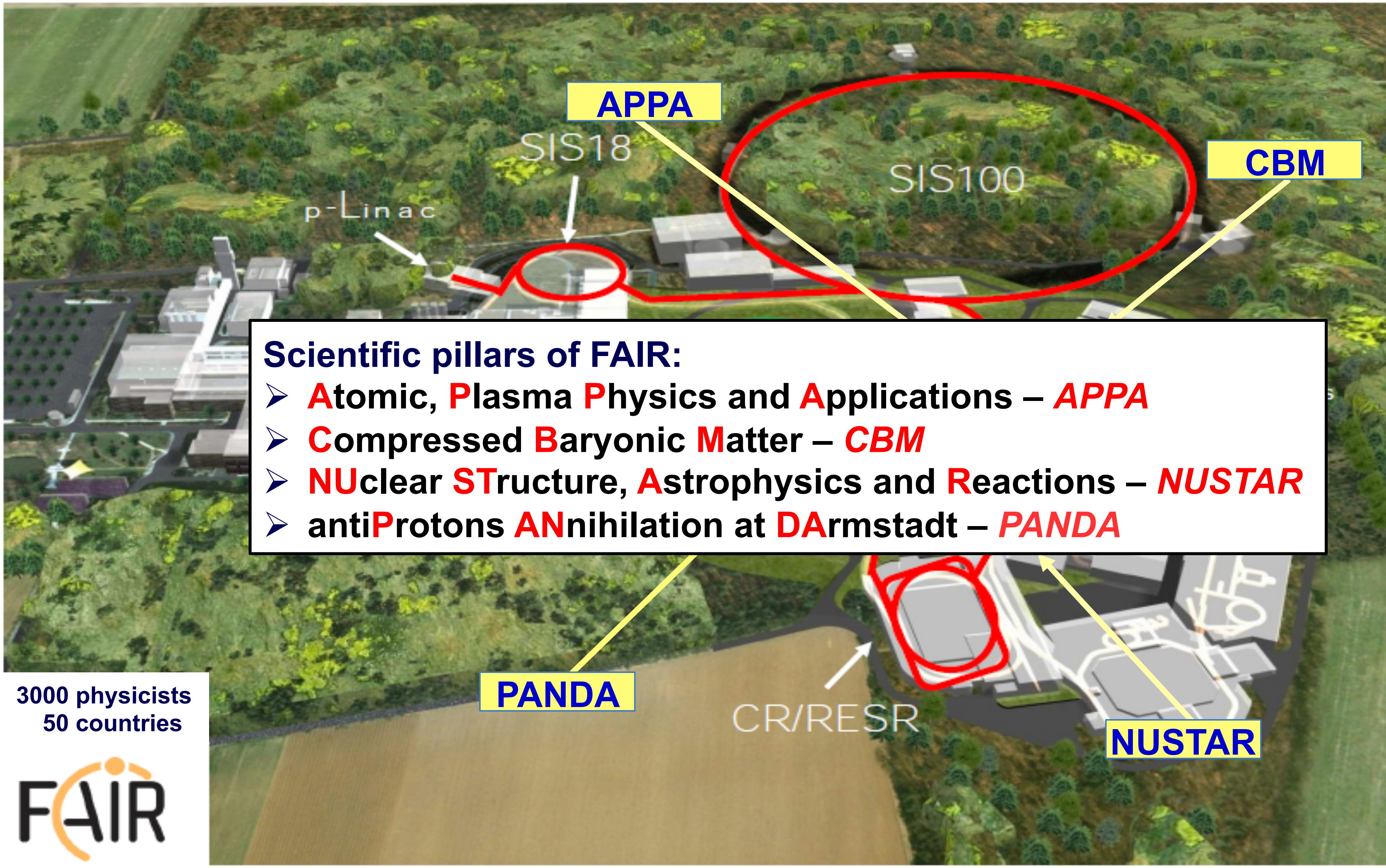


Facility for Antiproton and Ion Research



3000 physicists
50 countries

Facility for Antiproton and Ion Research

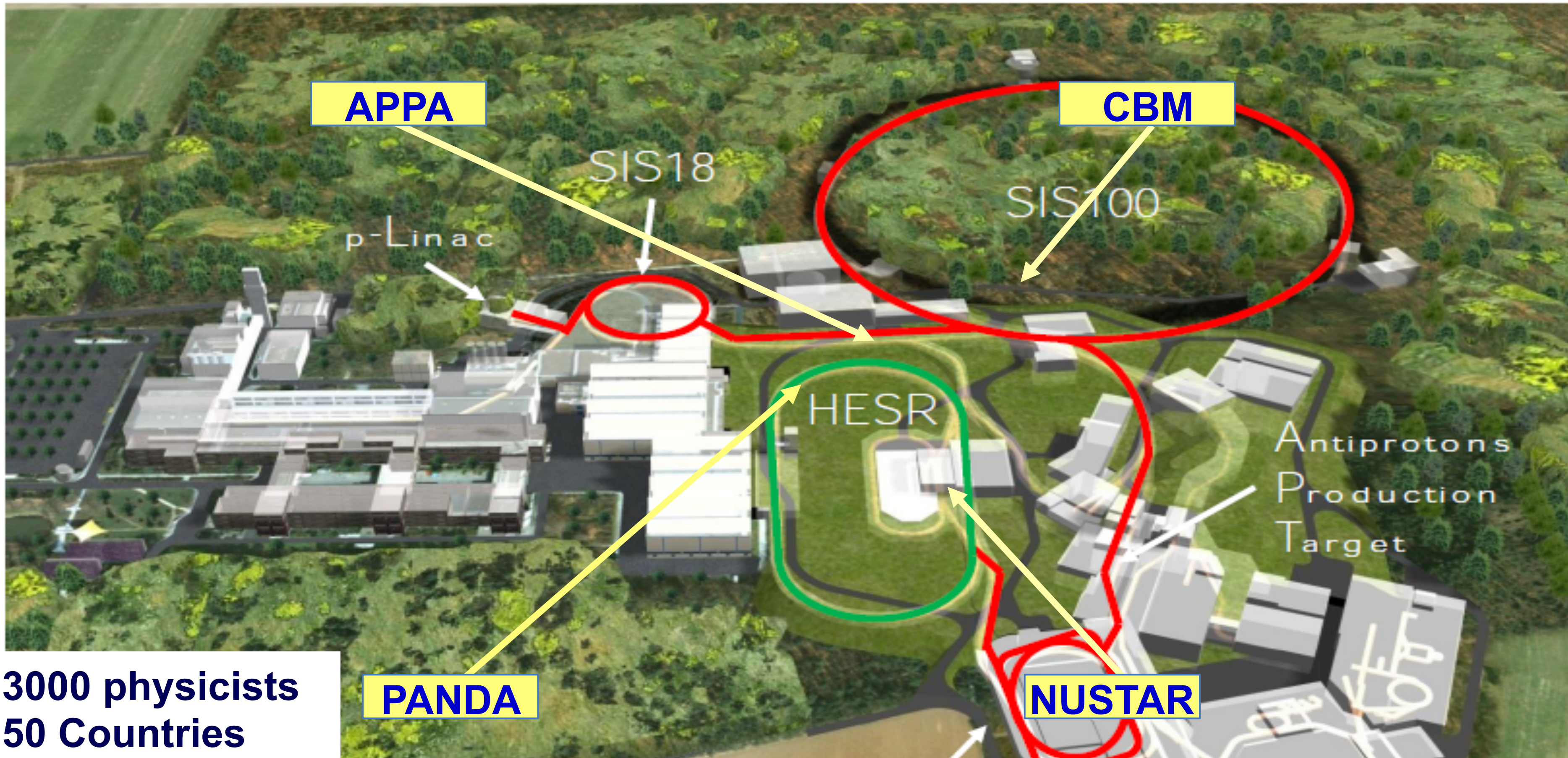


Scientific pillars of FAIR:

- **Atomic, Plasma Physics and Applications – *APPA***
- **Compressed Baryonic Matter – *CBM***
- **NUclear STructure, Astrophysics and Reactions – *NUSTAR***
- **antiProtons ANnihilation at DArmstadt – *PANDA***

3000 physicists
50 countries

Facility for Antiproton and Ion Research



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Scientific pillars of FAIR:

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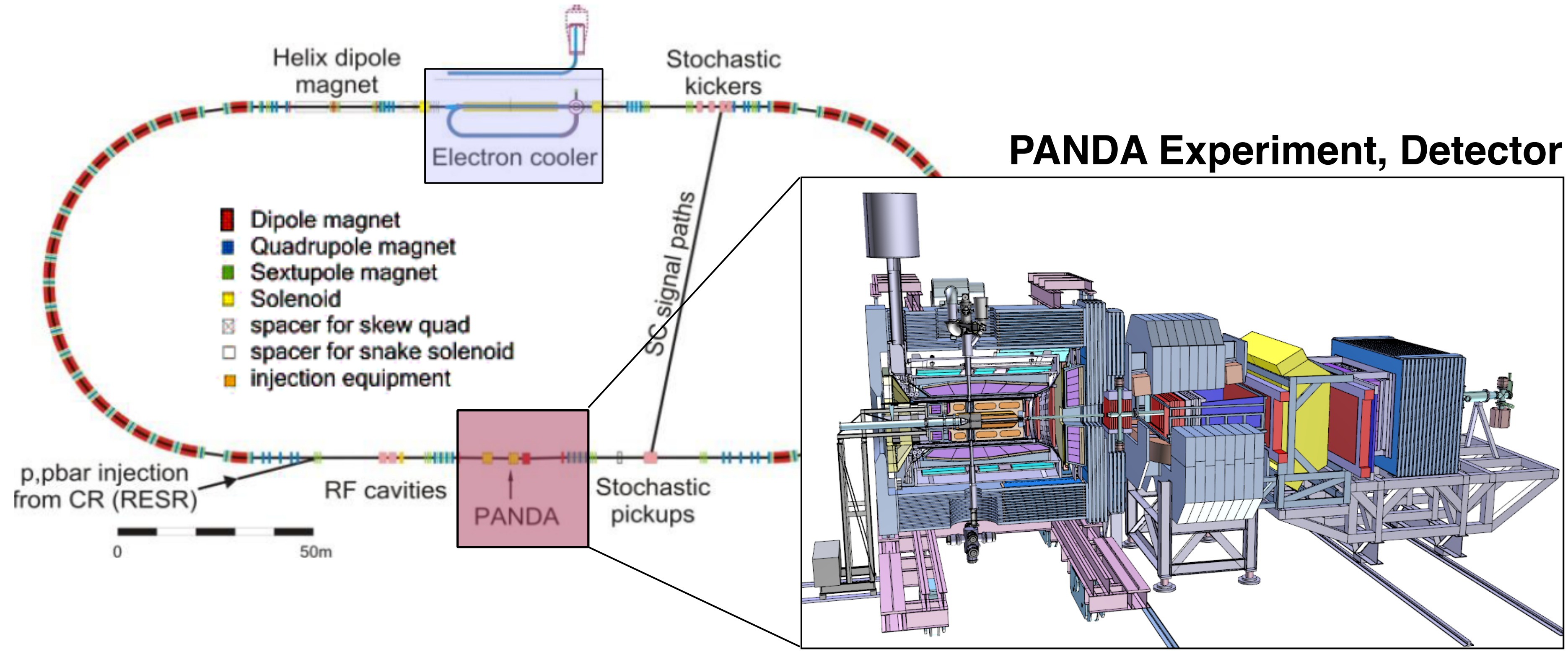
Facility for Antiproton and Ion Research

High Energy Storage Ring -- HESR

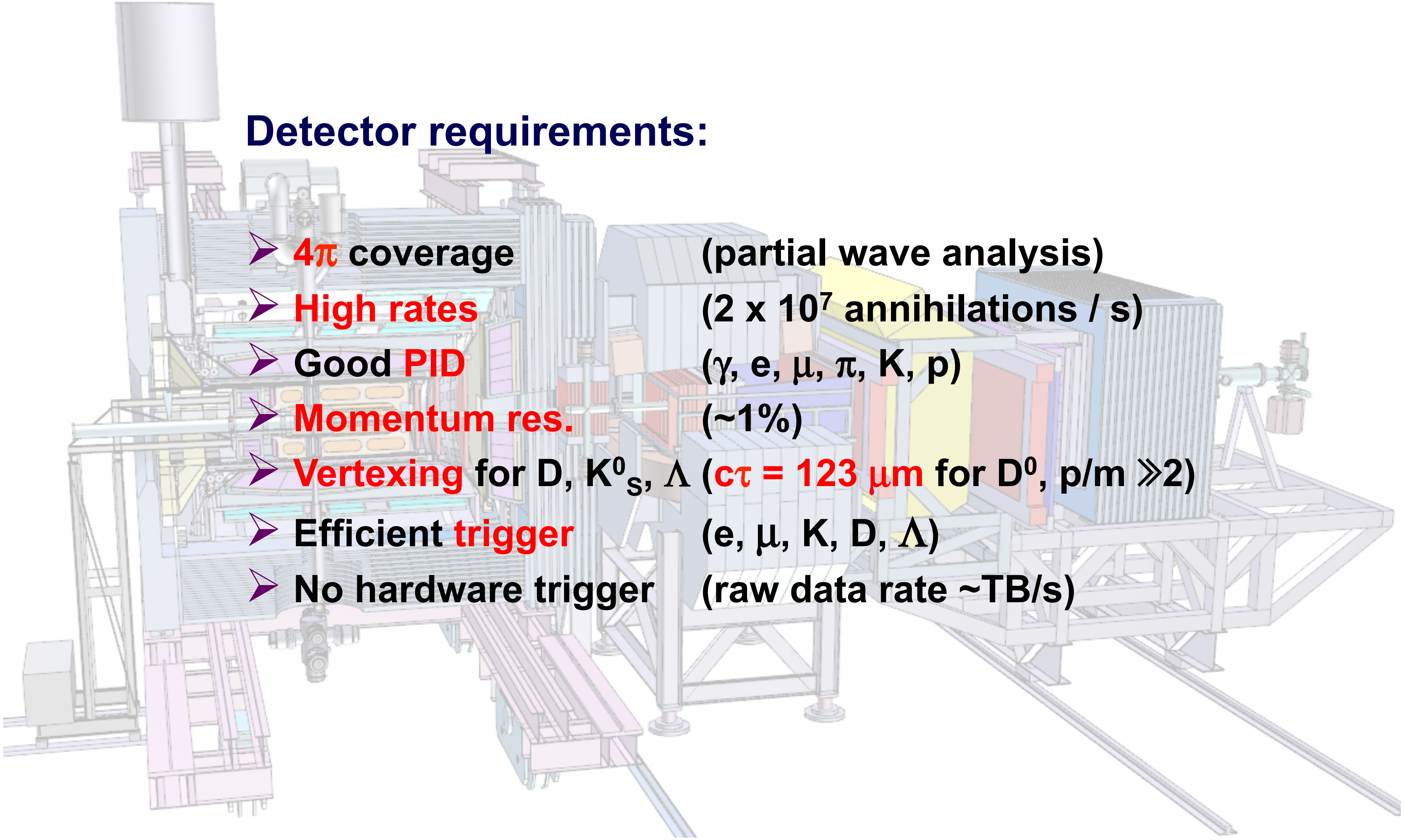


High resolution mode:

- e^- cooling: $p \leq 8.9$ GeV/c
- 10^{10} anti-protons stored
- Luminosity up to 2×10^{31} cm^{-2} s^{-1}
- $\Delta p/p = 4 \times 10^{-5}$

High intensity mode:

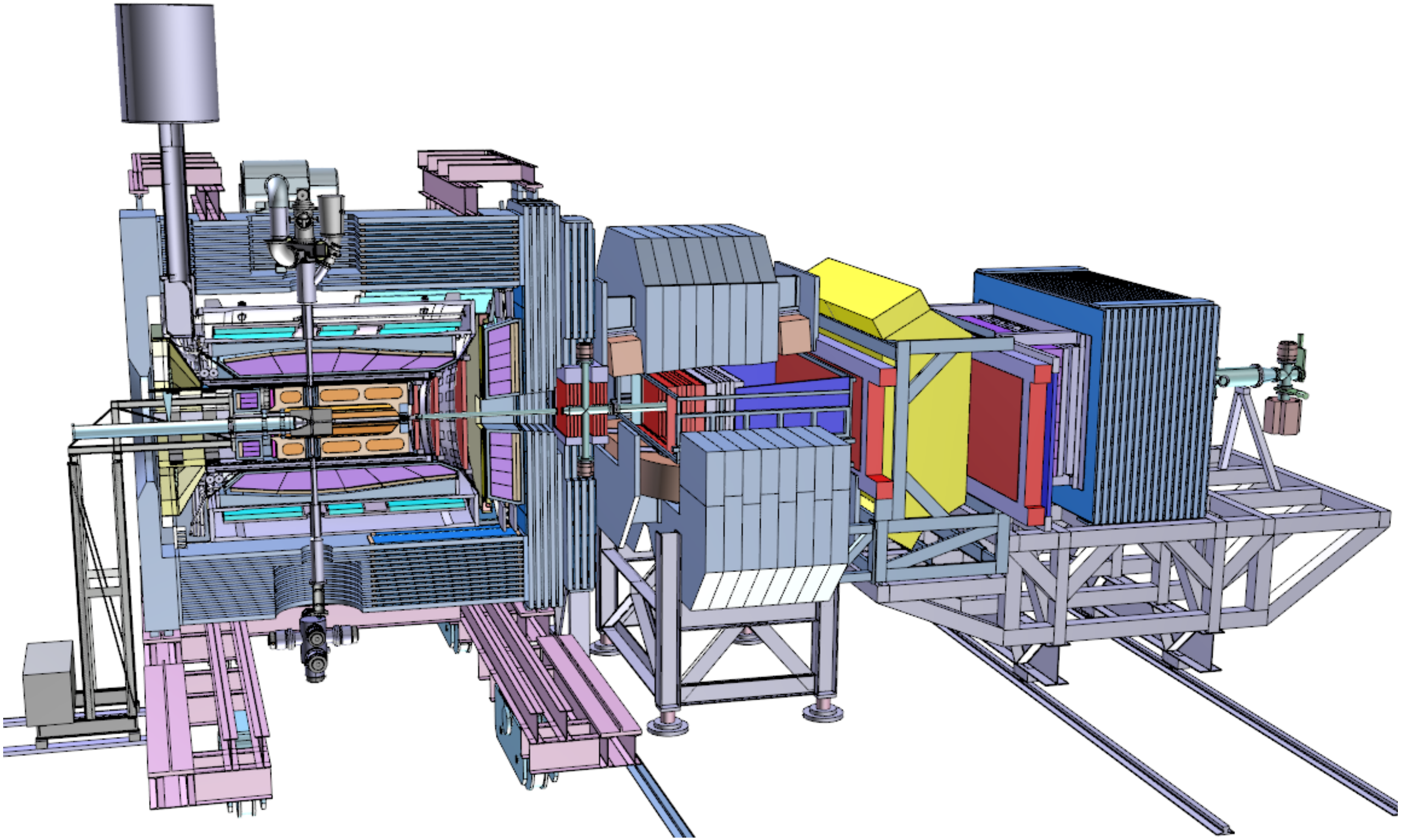
- Stochastic cooling
- 10^{11} anti-protons stored
- Luminosity up to 2×10^{32} cm^{-2} s^{-1}
- $\Delta p/p = 2 \times 10^{-4}$



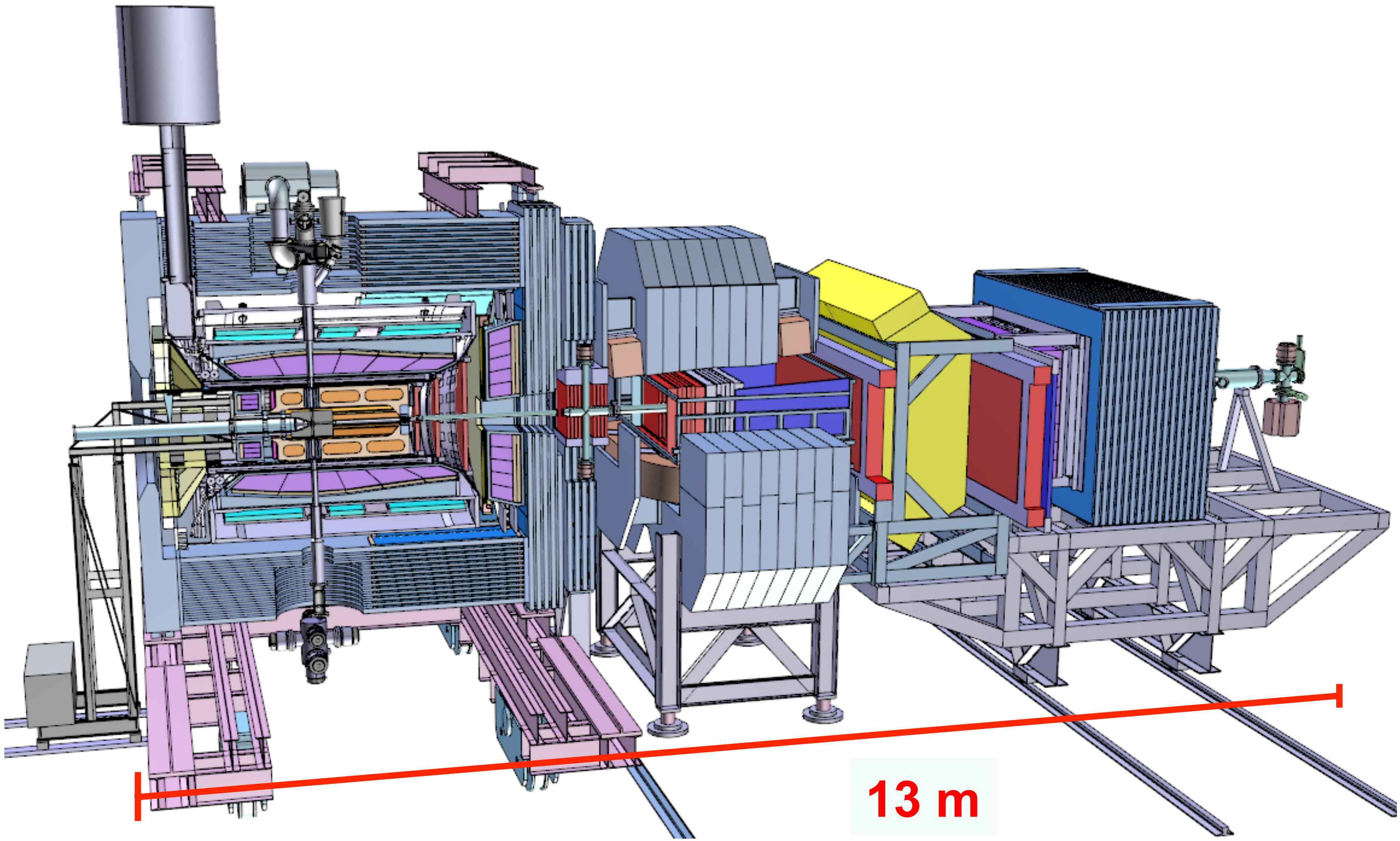
Detector requirements:

- **4π coverage** (partial wave analysis)
- **High rates** (2 x 10^7 annihilations / s)
- **Good PID** (γ, e, μ, π, K, p)
- **Momentum res.** (~1%)
- **Vertexing for D, K^0_S, Λ** (cτ = 123 μm for D^0, p/m ≫2)
- **Efficient trigger** (e, μ, K, D, Λ)
- **No hardware trigger** (raw data rate ~TB/s)

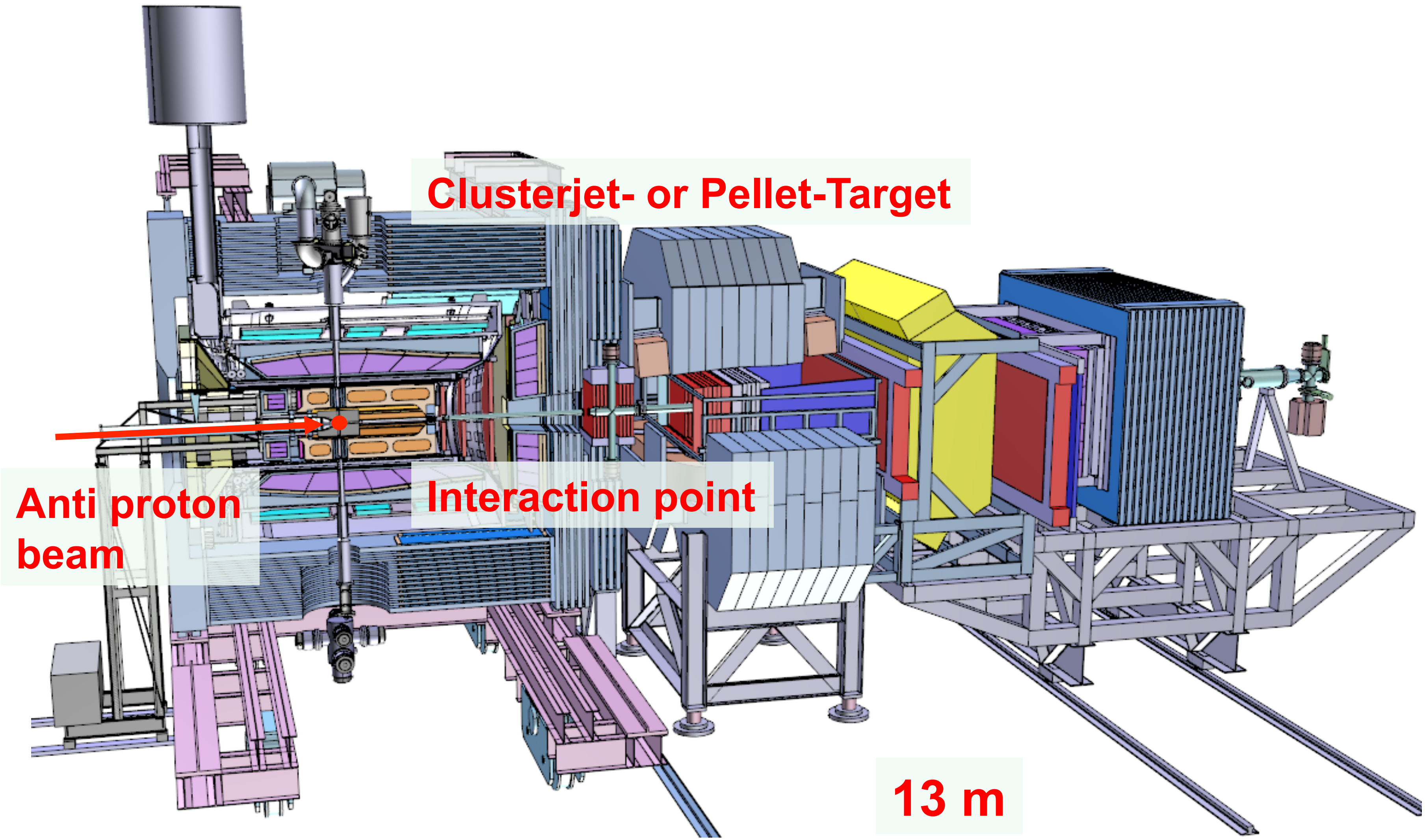
AntiProton Annihilation at Darmstadt



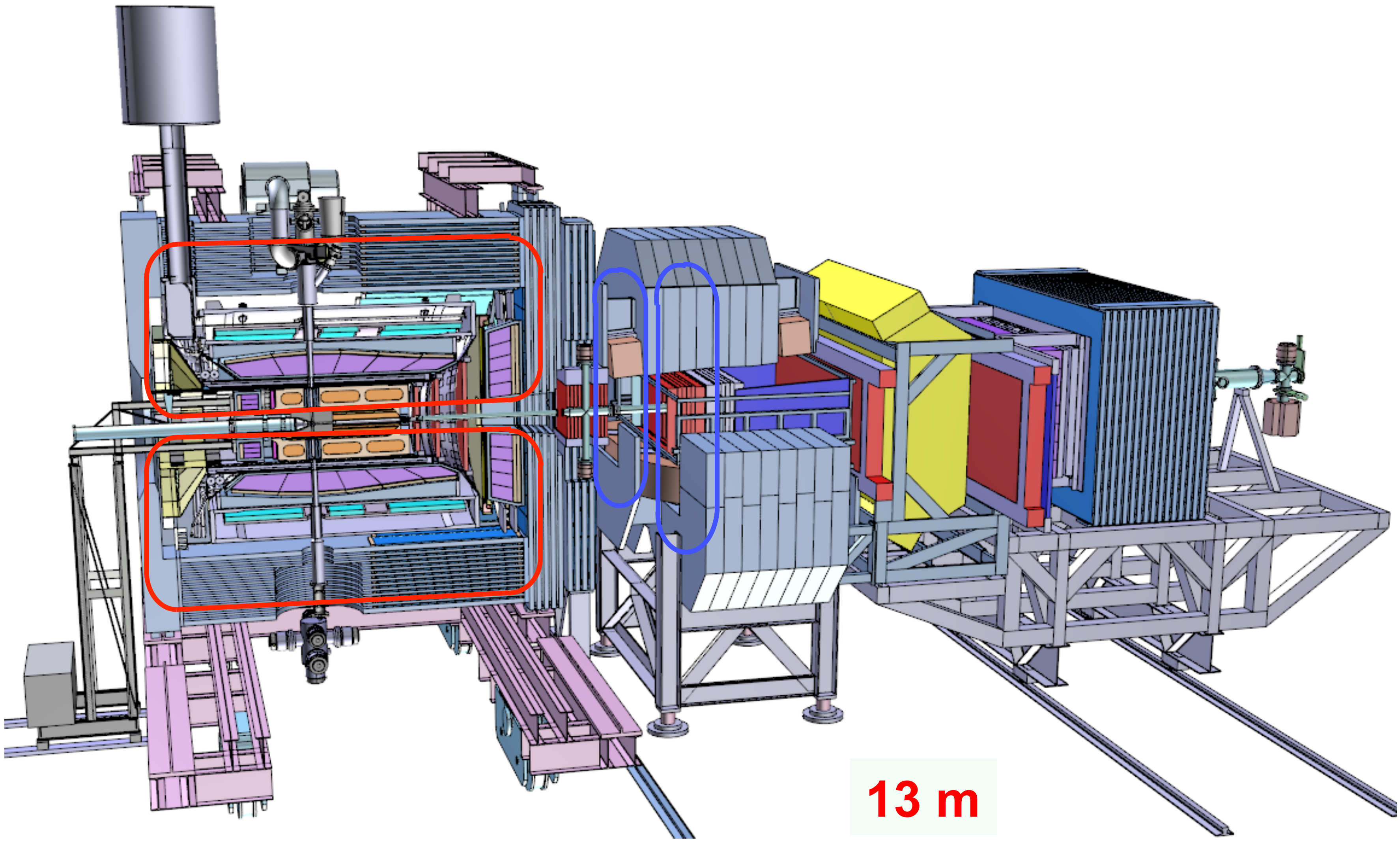
AntiProton Annihilation at Darmstadt



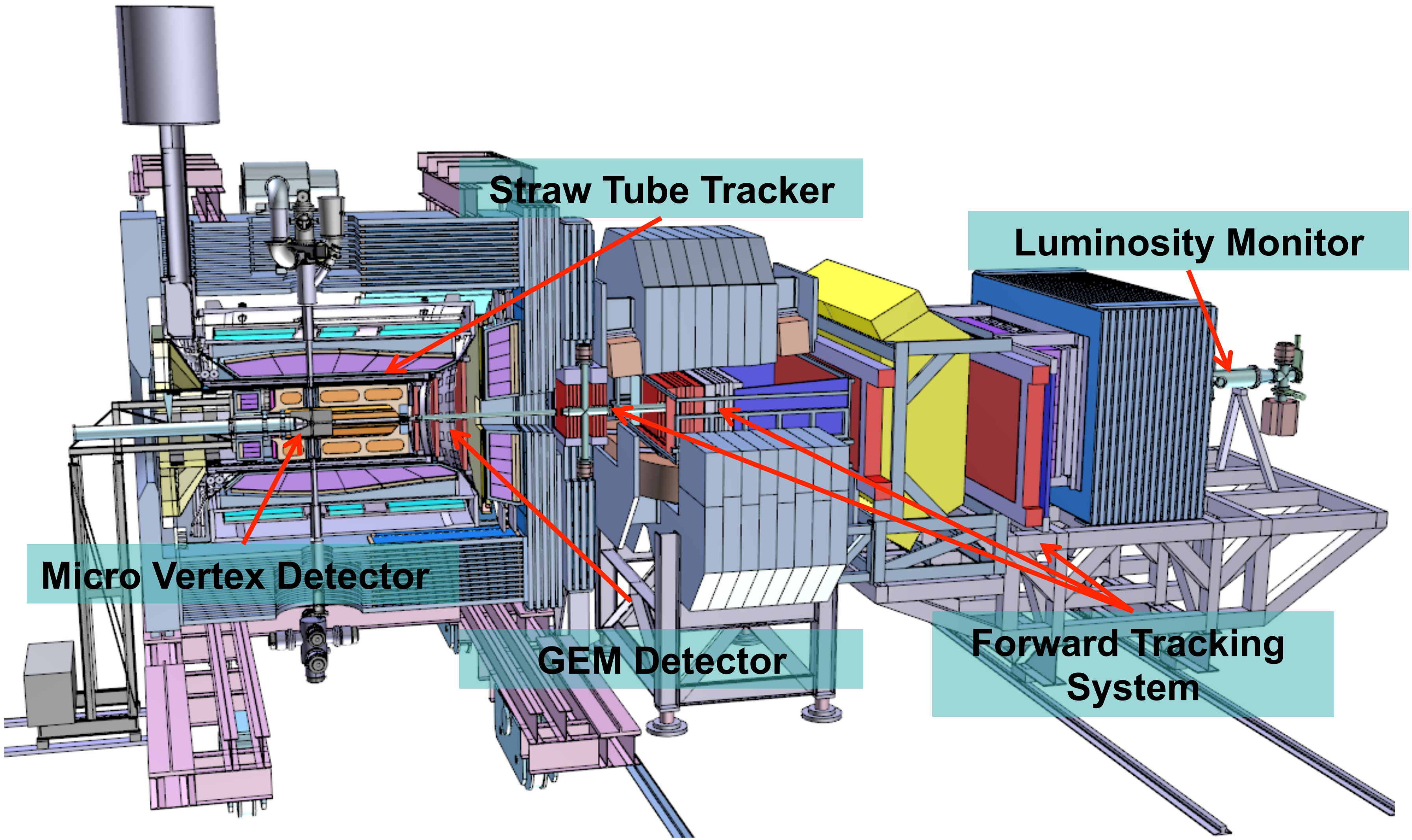
AntiProton Annihilation at Darmstadt



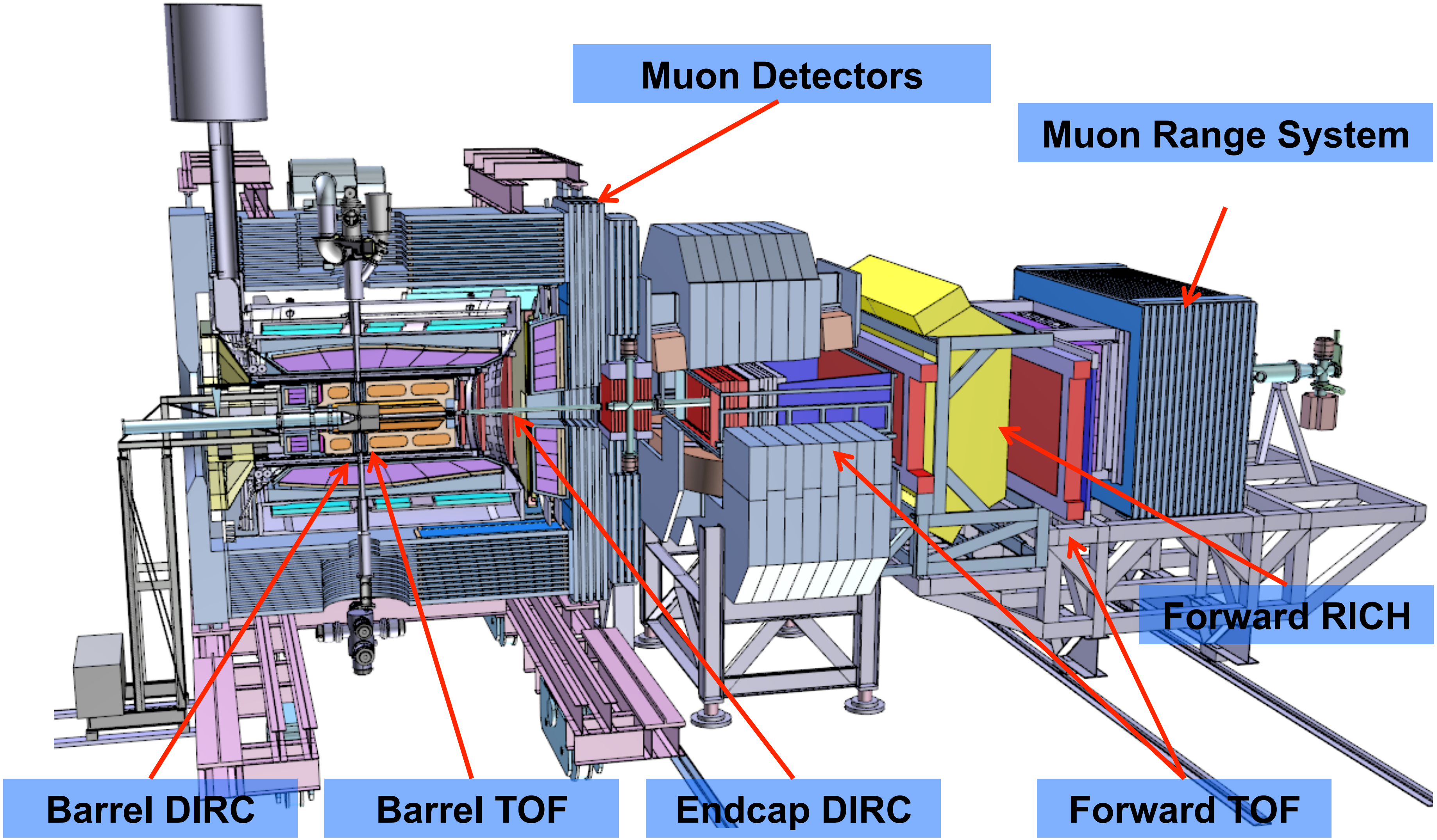
AntiProton Annihilation at Darmstadt



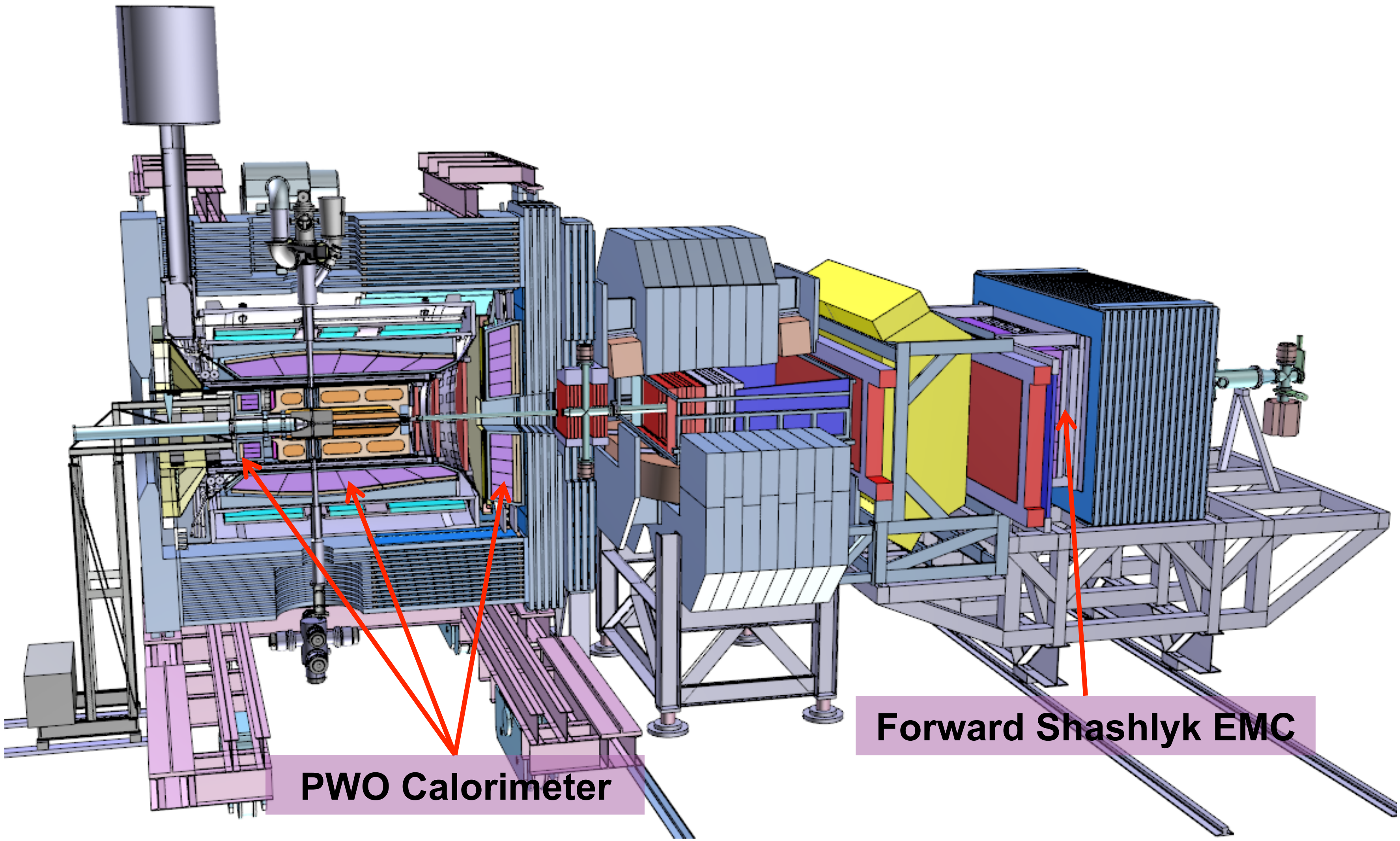
AntiProton Annihilation at Darmstadt



AntiProton Annihilation at Darmstadt



AntiProton Annihilation at Darmstadt



Summary & conclusions

- Broad & fascinating physics programme at PANDA
- Anti-protons provide experimental key technique
- Accelerator and detector are on track

PANDA will be the facility to study QCD -- nucleon structure and spectroscopy

Thank you for your attention!

The PANDA collaboration:
~ 520 Members, 69 Institutes, 18 Countries

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