Charmonium Spectroscopy with the PANDA experiment at FAIR

Frank Nerling
Helmholtz Institute Mainz, GSI Darmstadt
on behalf of the PANDA Collaboration

Workshop on Physics at Future High Intensity e^+e^- Collider,
Hefei, China, January 13th – 17th 2015

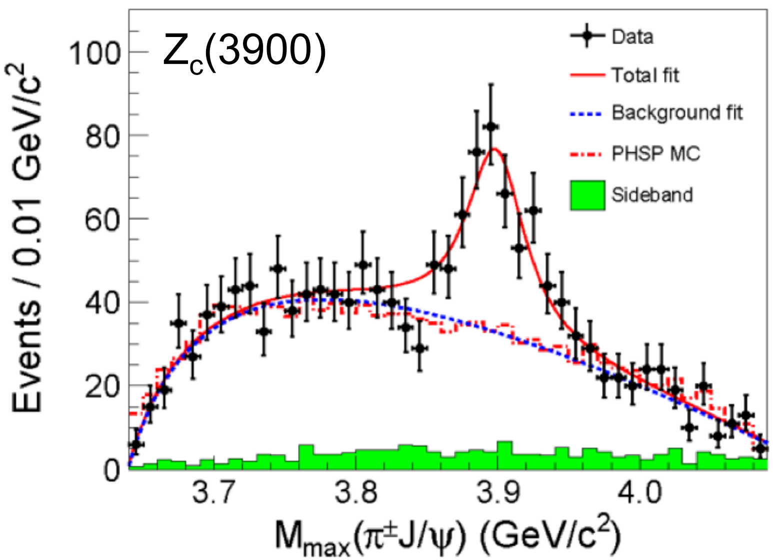
Outline

- **Introduction**
  - Motivation, physics programme
  - Advantage of anti-protons
  - Resonance scan method
- **Hadron spectroscopy**
  - Exotic hadrons
  - Open charm
  - Charmonium-like exotics
- **Summary & outlook**

Recent Hot Topics

Hadron Spectroscopy

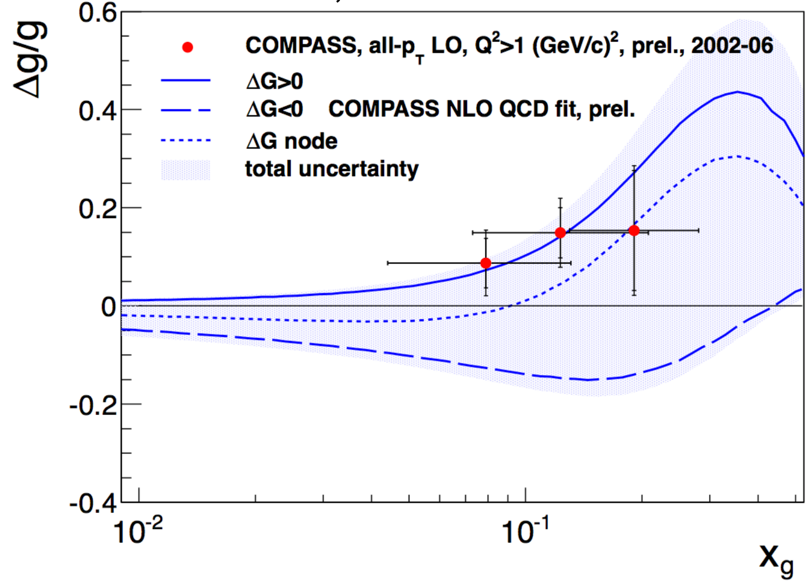
BESIII, arXiv:1303.5949



unexpected,
manifestly exotic!

Nucleon Structure

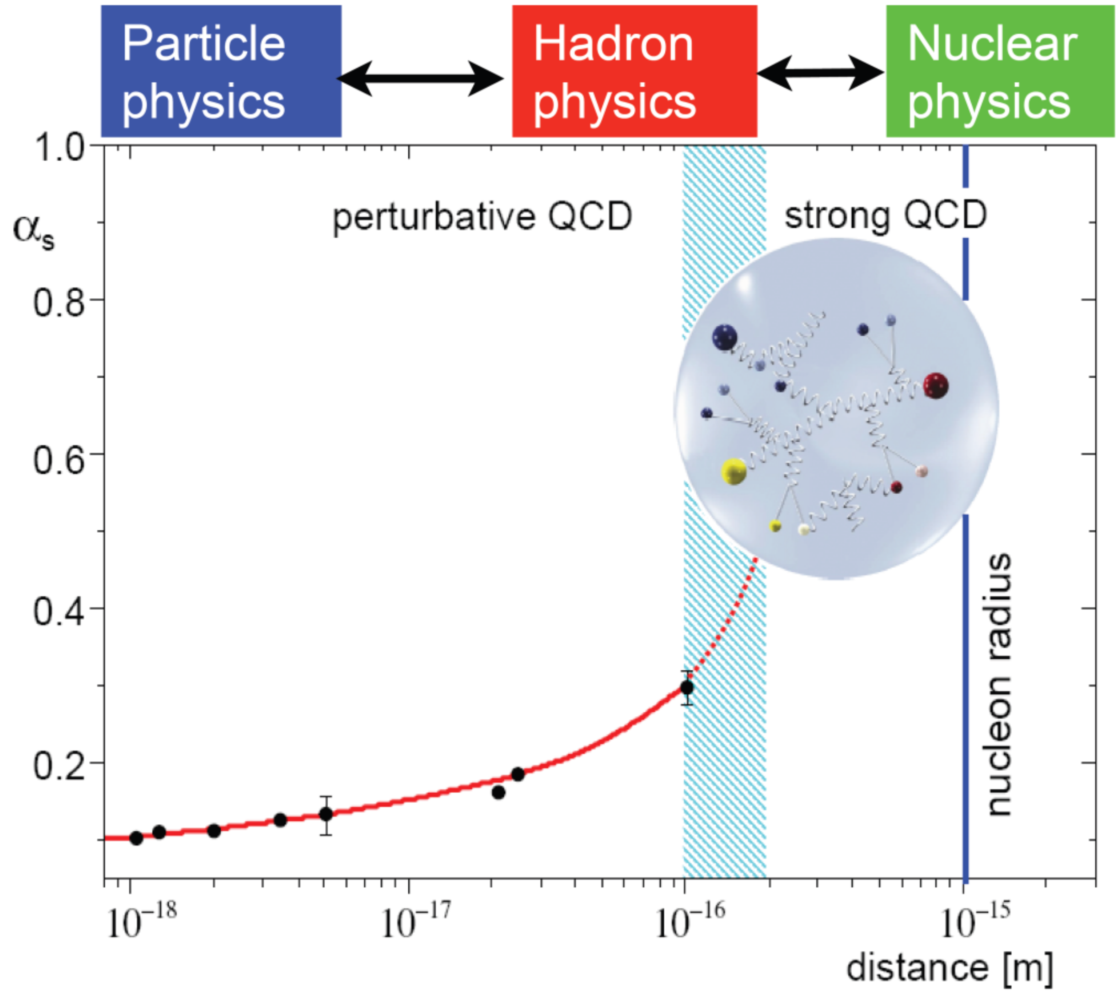
M.Stolarski, DIS 2014



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?



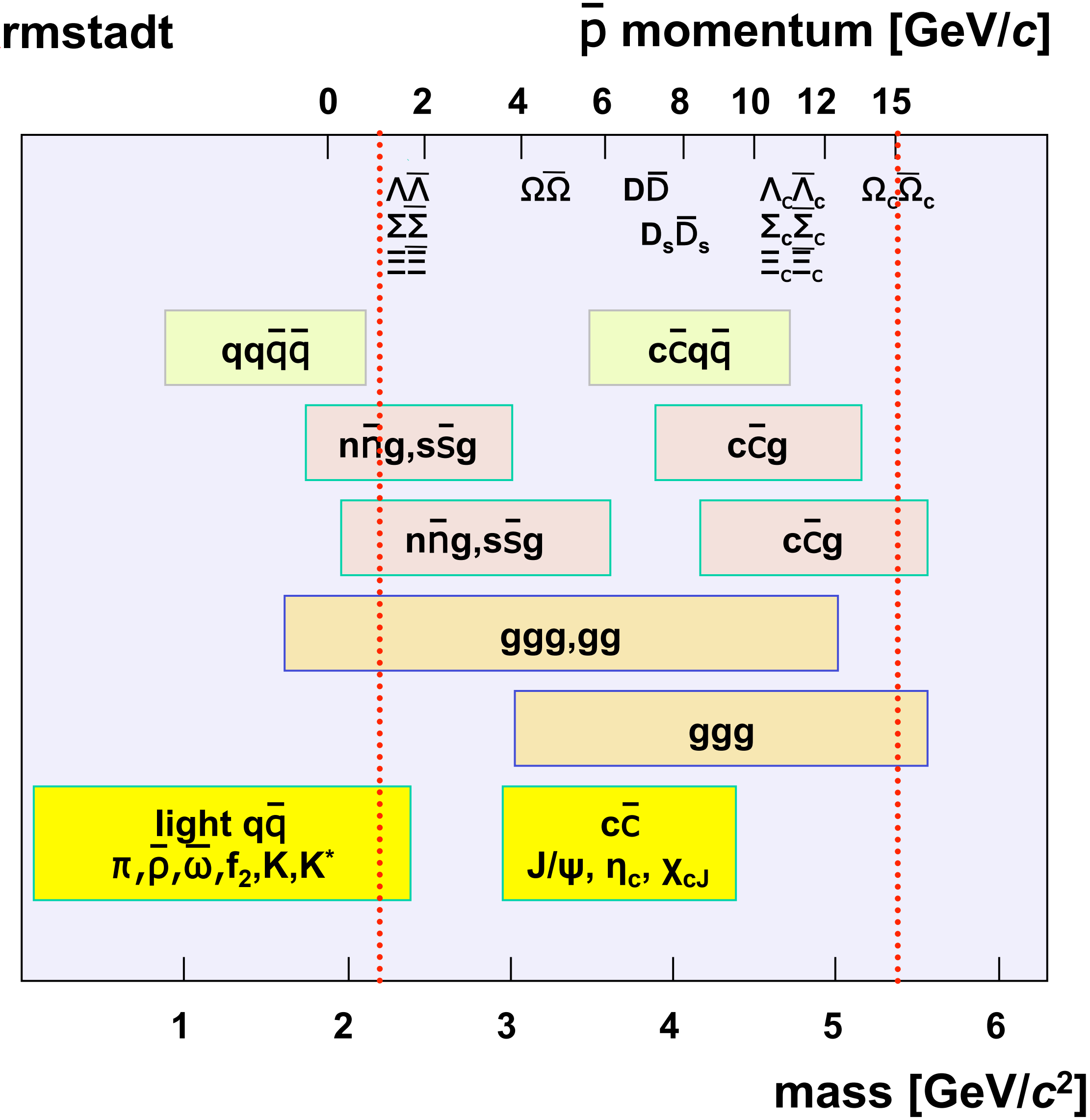
PANDA Physics Programme

Anti-Proton ANnihilation in DArmstadt

- **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



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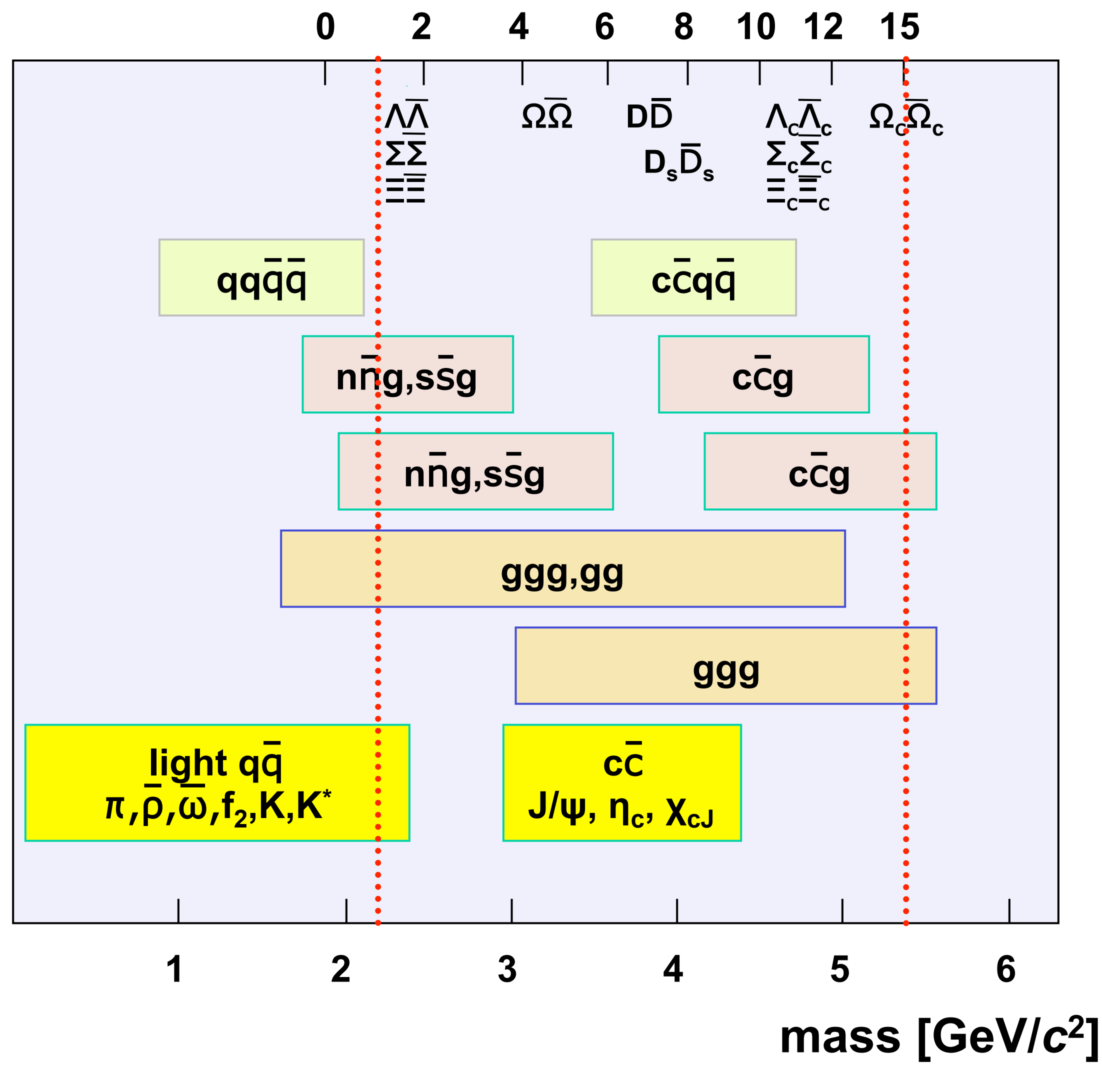
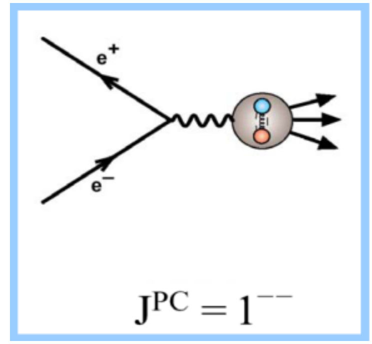


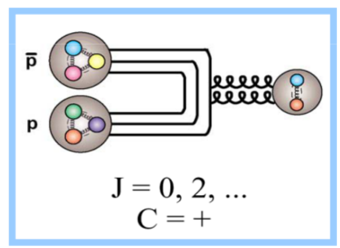
Advantages of Anti-Protons

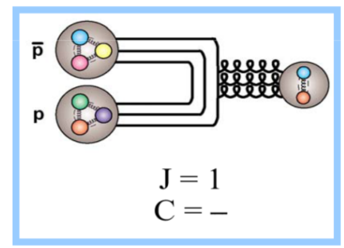
- Gluon rich process
- Gain ~ 2 GeV in annihilation *(low momentum transfer)*
- B = 0 system
- Access to all fermion-antifermion quantum numbers *(not in e+e-)*
- Access to states of high spin J
- Precise mass resolution in formation reactions

Formation:



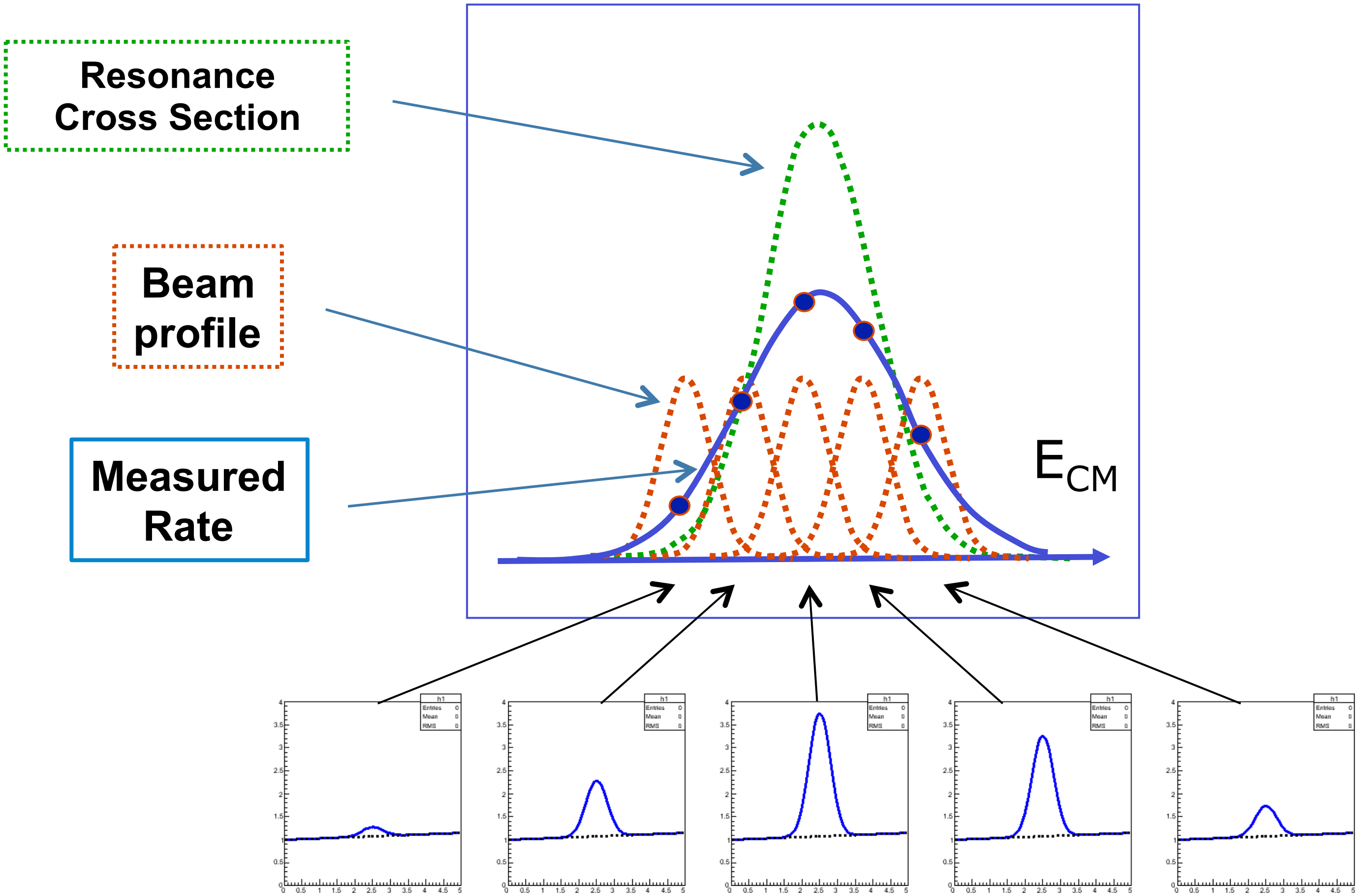
→ Only $J^{PC} = 1^{-}$ allowed in e^+e^-





→ 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

$\bar{p}p \to \chi_c$
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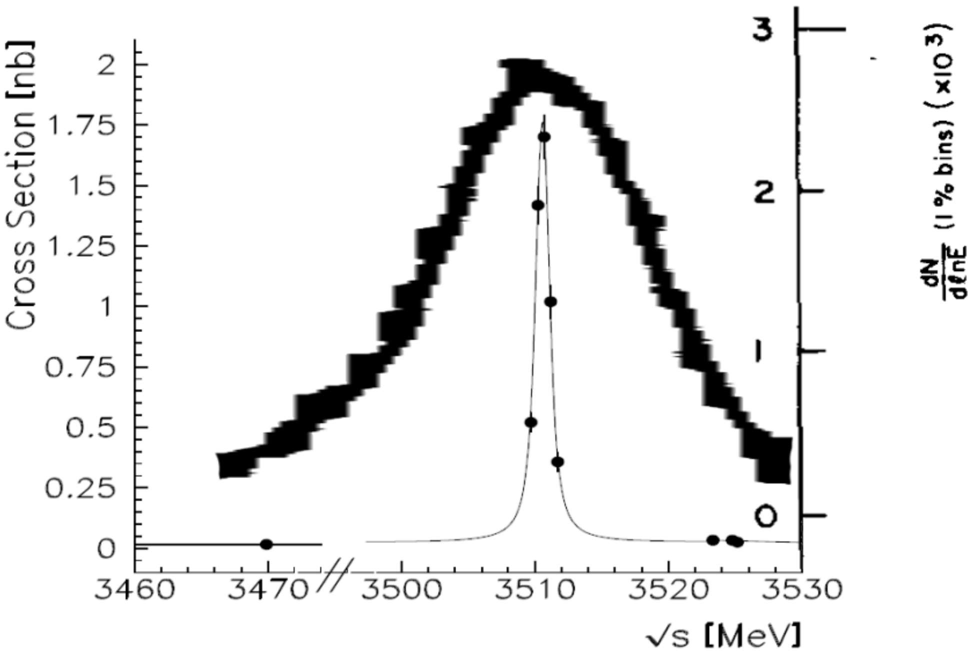

Gaiser et al., Phys. Rev. D34 (1986) 711:
CrystalBall (SLAC): 3512.3 ± 4 MeV/c^2
Andreotti et al., Nucl. Phys. B717 (2005) 34-47:
E835 (Fermilab): 3510.641 ± 0.074 MeV/c^2

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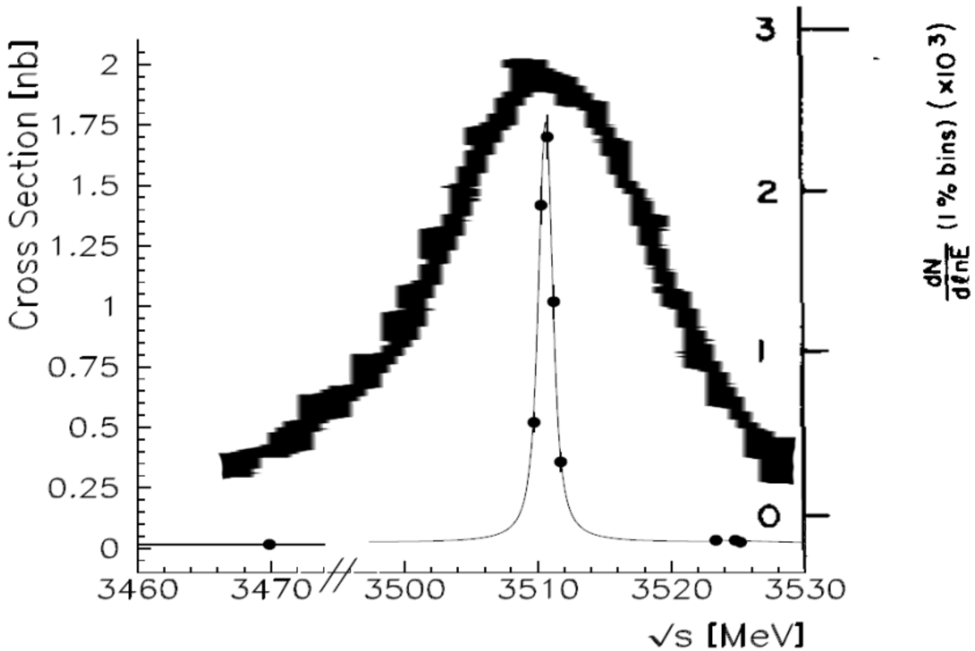
Formation:

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

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

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



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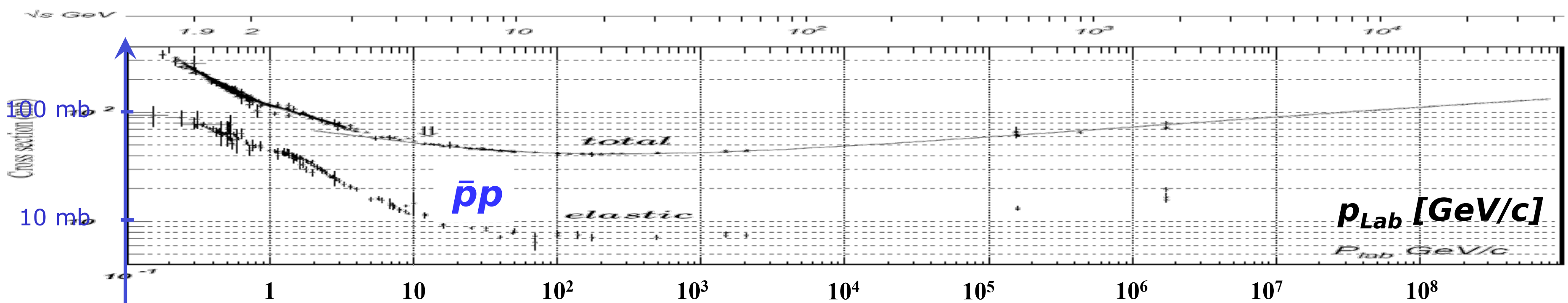
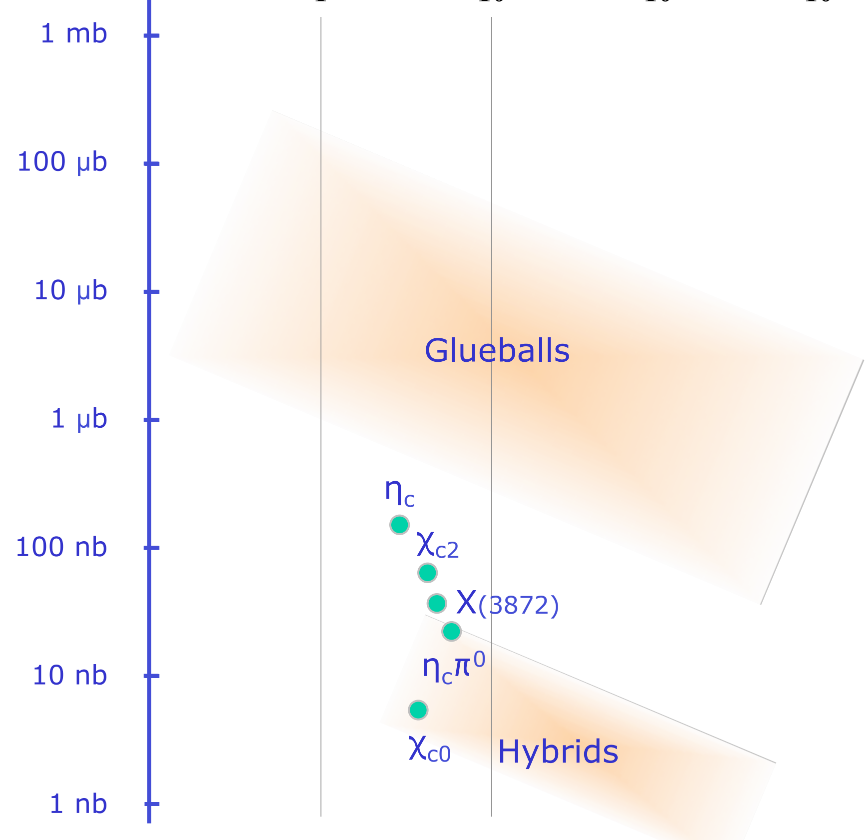
NB: Interpretation of many states depends on width of states!

$\bar{p}p$ 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*

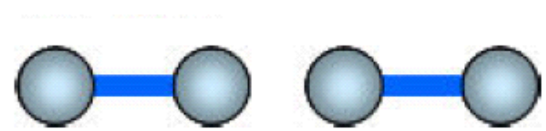
Spectroscopy – Exotic Hadrons

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



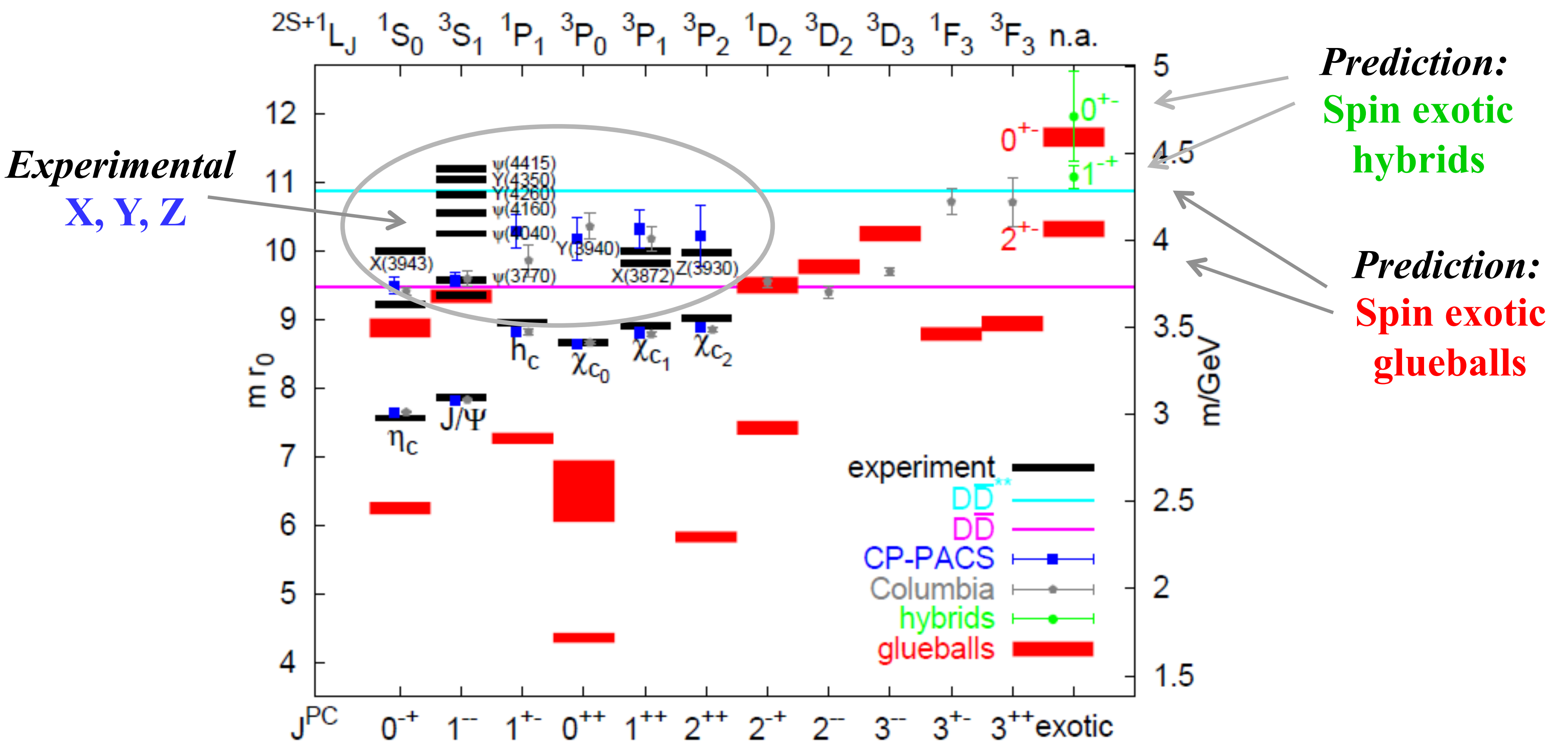
Three categories of exotics:

- 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

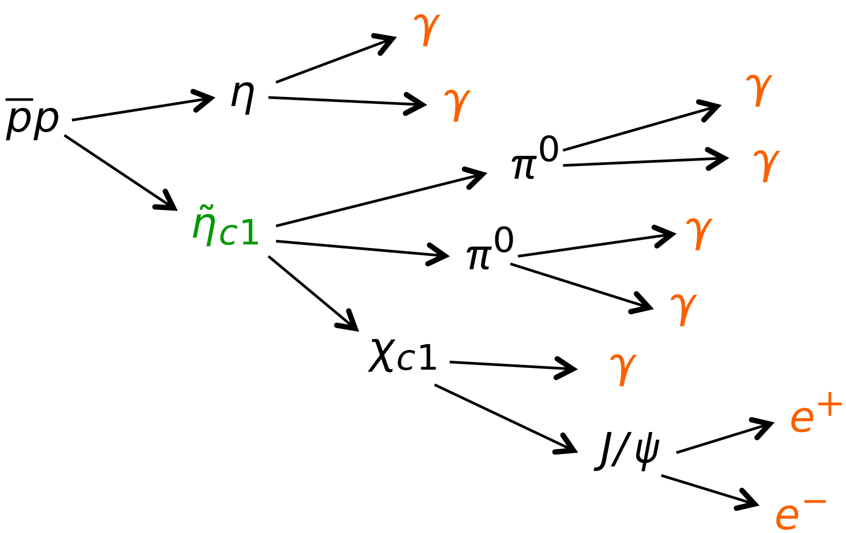


G. S. Bali, Int.J.Mod.Phys. A21 (2006) 5610-5617

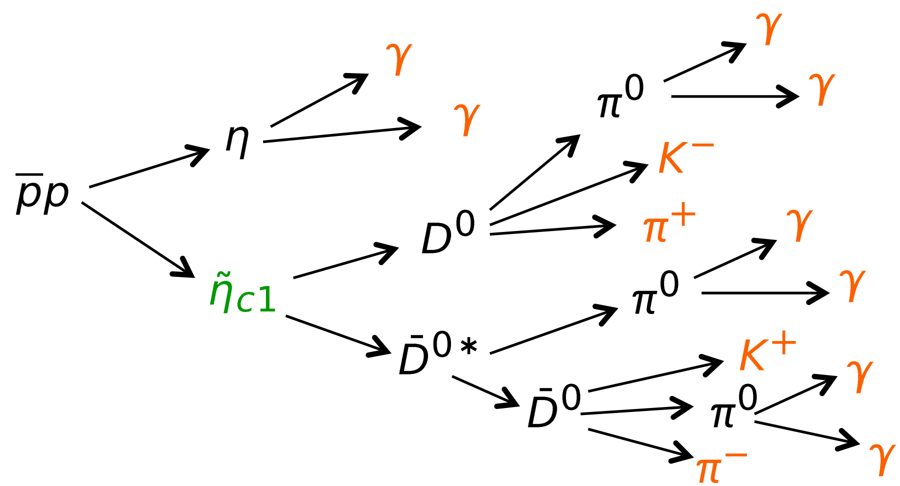
Charmonium Hybrid Candidate $\tilde{\eta}_{c1}$

- From LQCD calculations:
  Spin-exotic hybrid candidate $\tilde{\eta}_{c1}$ with m ≈ 4.3GeV/c^2, J^{PC} = 1^{-+}
- Exclusive reconstruction in two favoured channels:

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



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



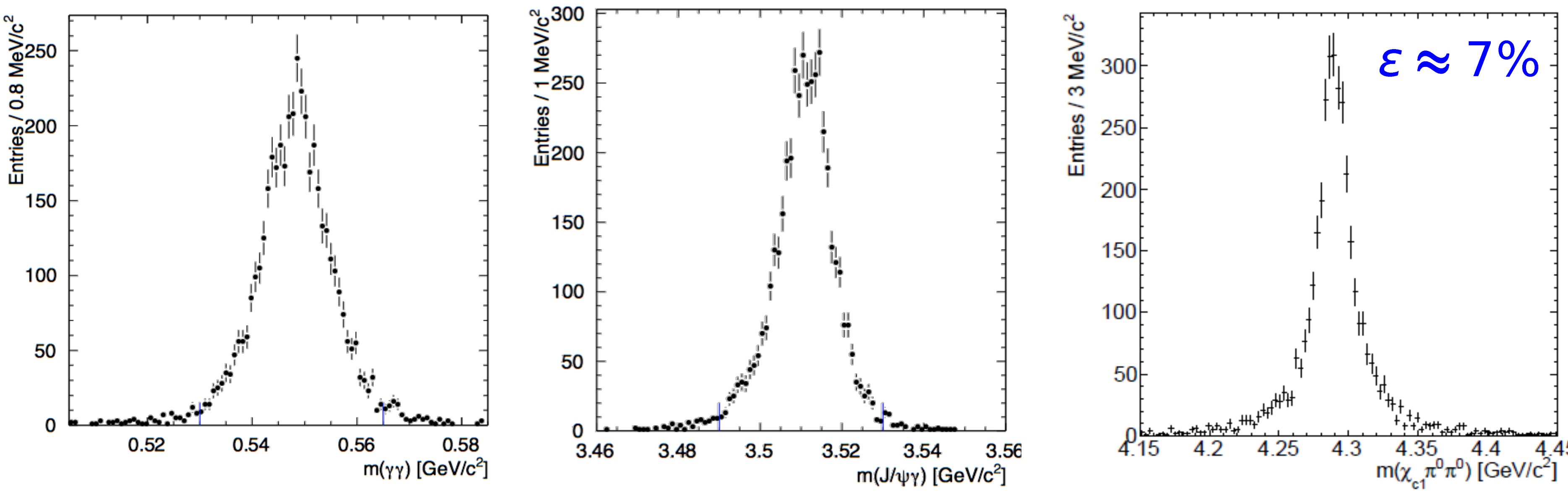
- Production X-section assumed similar to $\bar{p}p \rightarrow \psi(2S)\,\eta$ (33pb)
  → *Need good calorimetry + good particle identification*

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

- 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)

$\eta \rightarrow \gamma\gamma$ $\quad\quad$ $\chi_{c1} \rightarrow J/\psi\gamma$ $\quad\quad$ $\tilde{\eta}_{c1} \rightarrow \chi_{c1}\pi^0\pi^0$



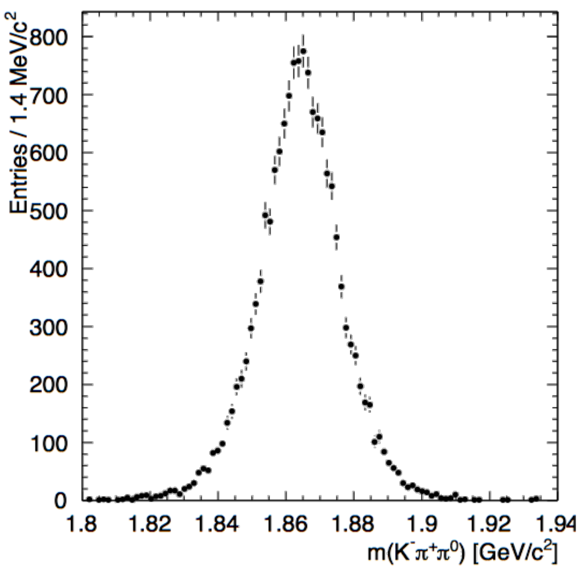
- Signal to noise: $\frac{S}{N} > 250 \cdot \frac{\sigma_S}{\sigma_B}$ => well feasible for σ_B ≈< 10 σ_S !

[arXiv:0903.3905, hep-ex]

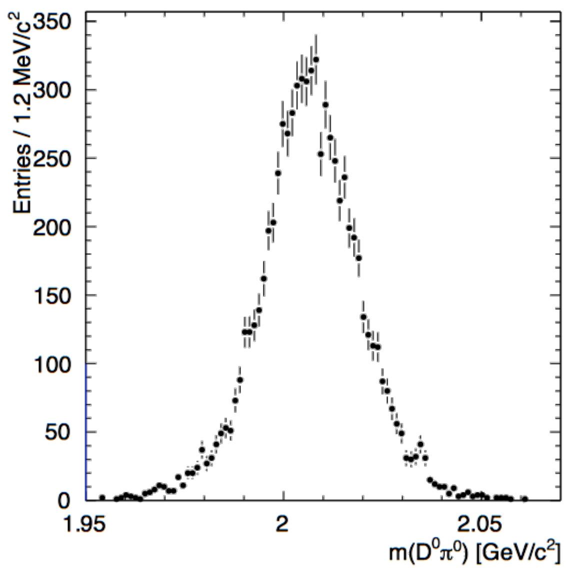
$\bar{p}p \to \tilde{\eta}_{c1}\eta \to D^0\bar{D}^{0*}\eta$

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

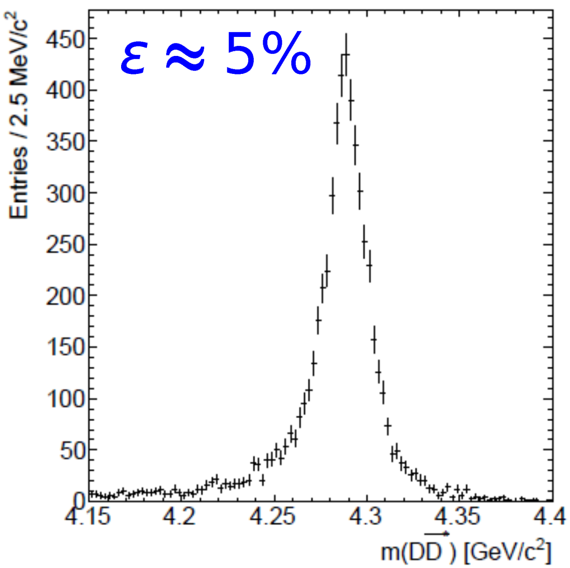
$D^0 \to K^-\pi^+\pi^0$



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



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

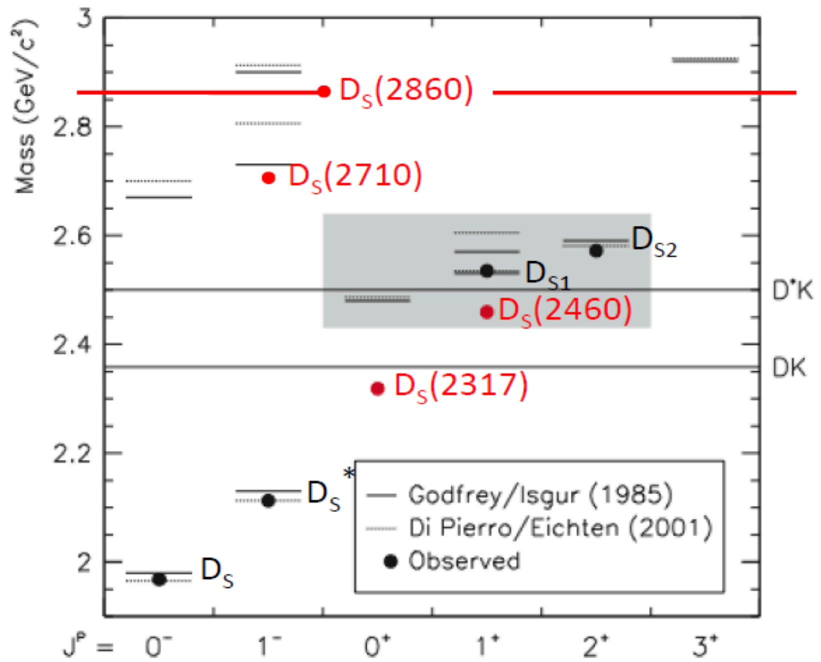


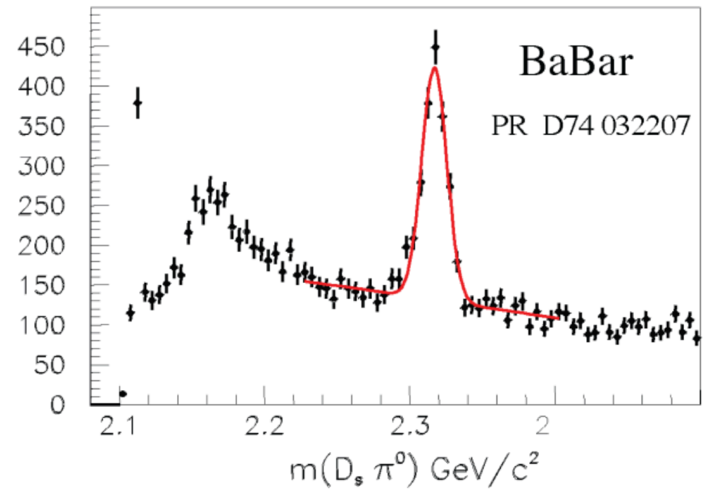
- Signal to noise: $\frac{S}{N} > 2900 \cdot \mathcal{B}(\tilde{\eta}_{c1} \to D^0\bar{D}^{0*})$ => feasible for non-vanishing BR

[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





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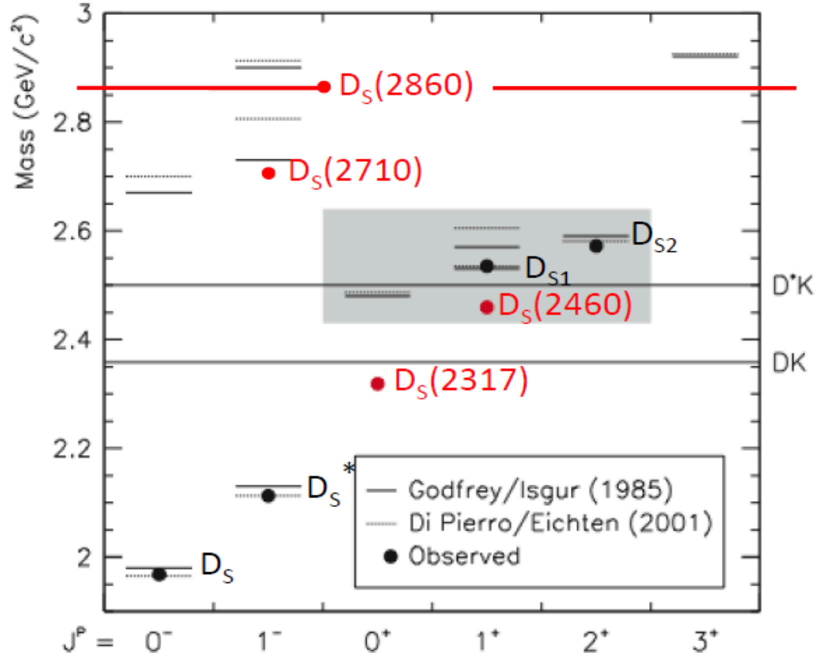
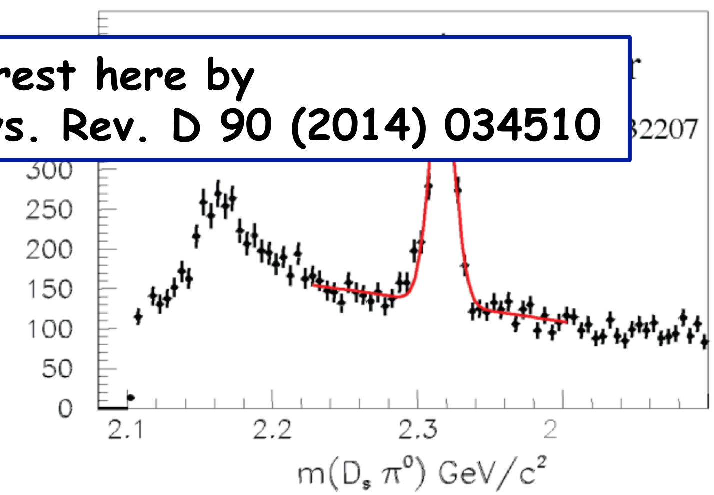




Recent paper of interest here by C.B. Lang et al.: Phys. Rev. D 90 (2014) 034510

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 $D_{s0}^*(2317)$

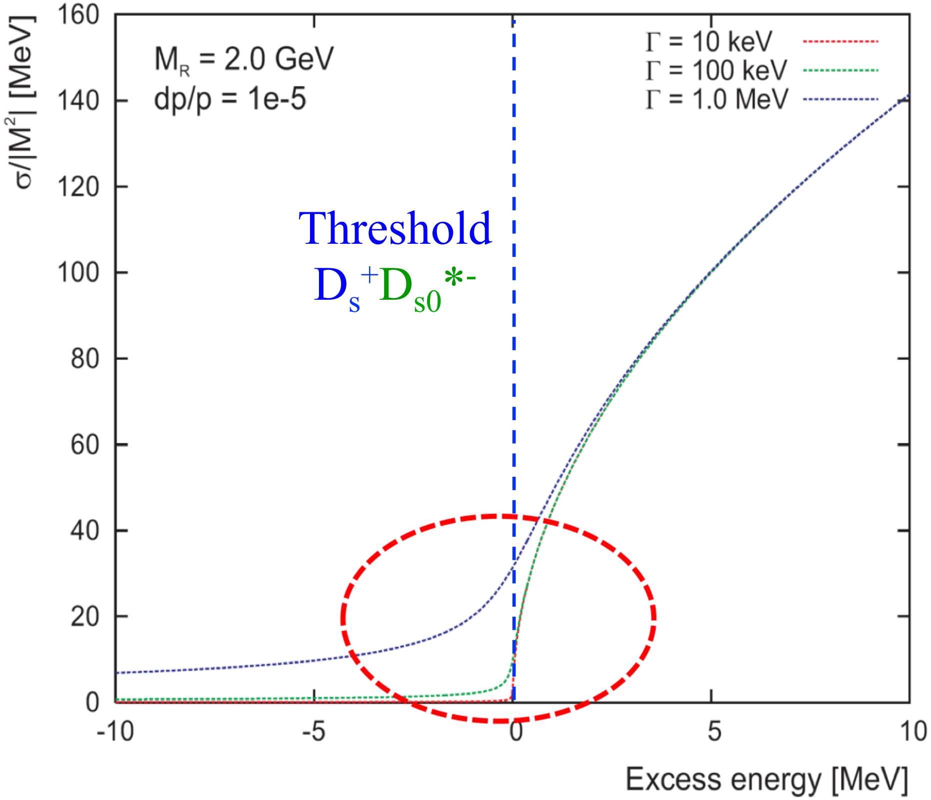
- Theoretical interpretations very sensitive for $\Gamma(D_{s0}^*(2317))$
- Formation reaction not possible: $\bar{p}p \not\to D_{s0}^*(2317)$

  → *Energy-scan with recoil @ threshold:* $\bar{p}p \to D_s^+ D_{s0}^*(2317)^-$

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

[C. Hanhart]

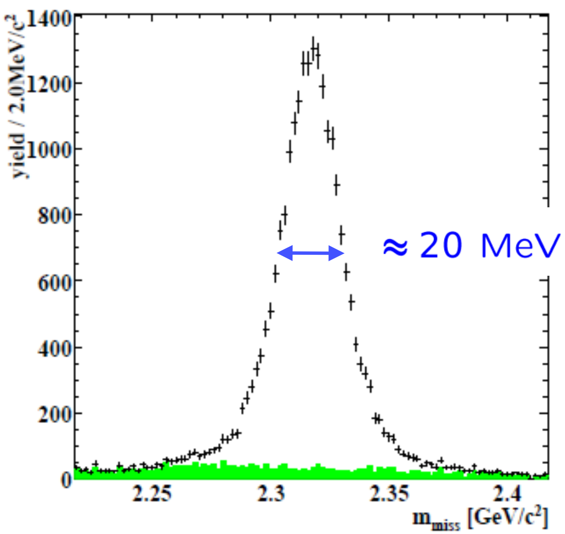
→ **Lineshape at threshold depends on $\Gamma(D_{s0}(2317)^*)$**



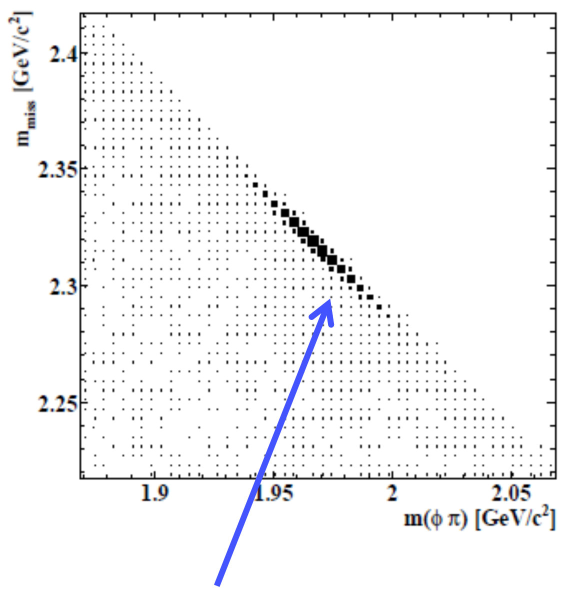
Reconstruction of $p\bar{p} \rightarrow D_s^+ D_{s0}^*(2317)^-$

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

m_{miss}

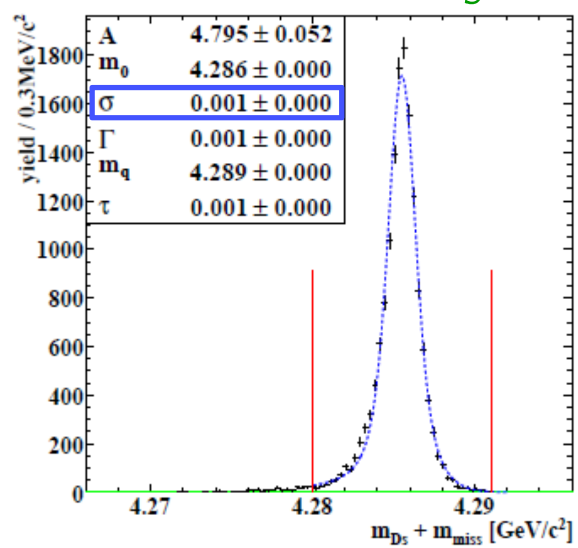


m_{miss} vs. m_{D_s}



make use of strong correlation between masses

$m_{miss} + m_{D_s}$



efficiency

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

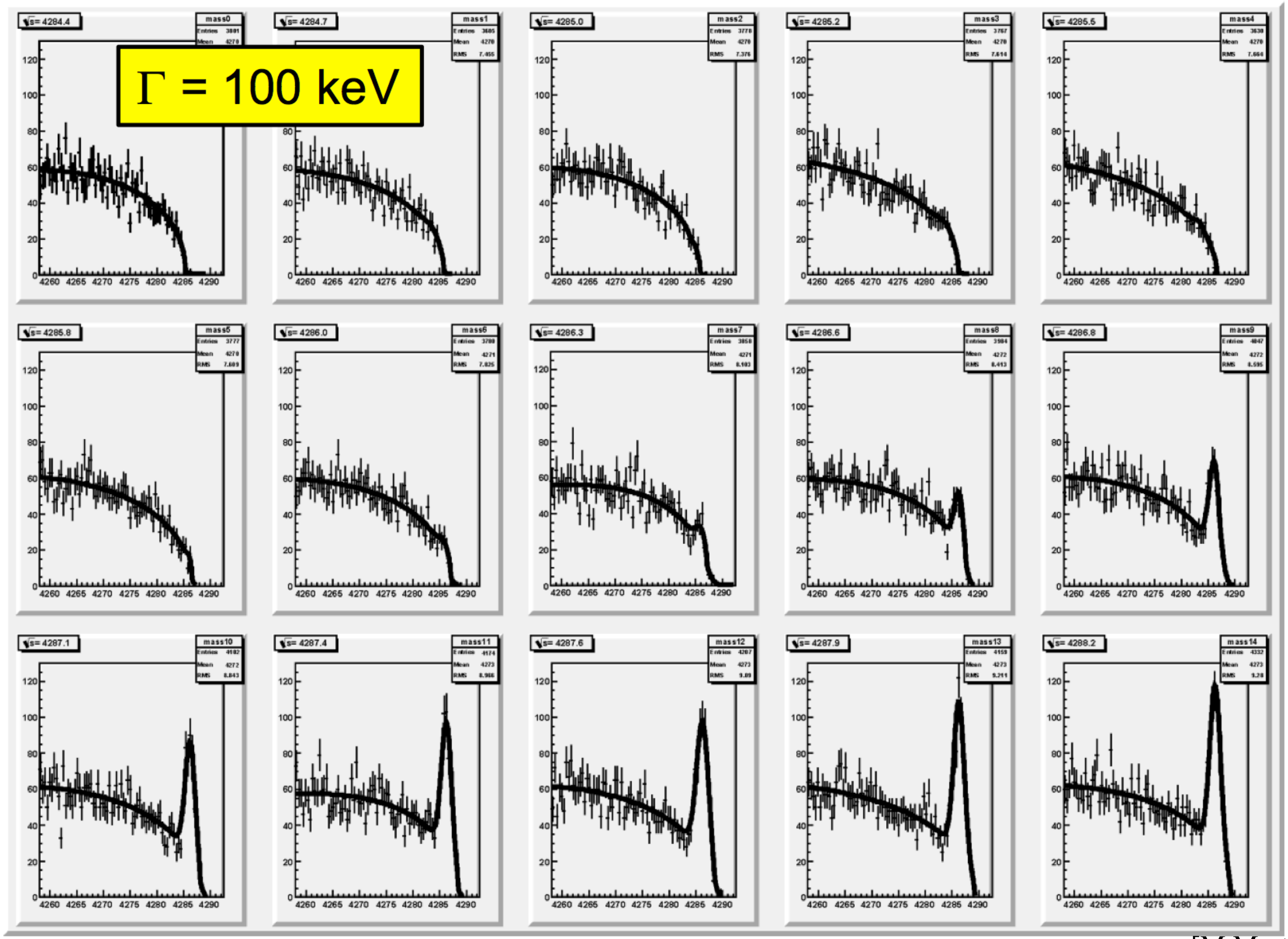
[arXiv:0903.3905, hep-ex]

Energy scan simulation around threshold

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

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

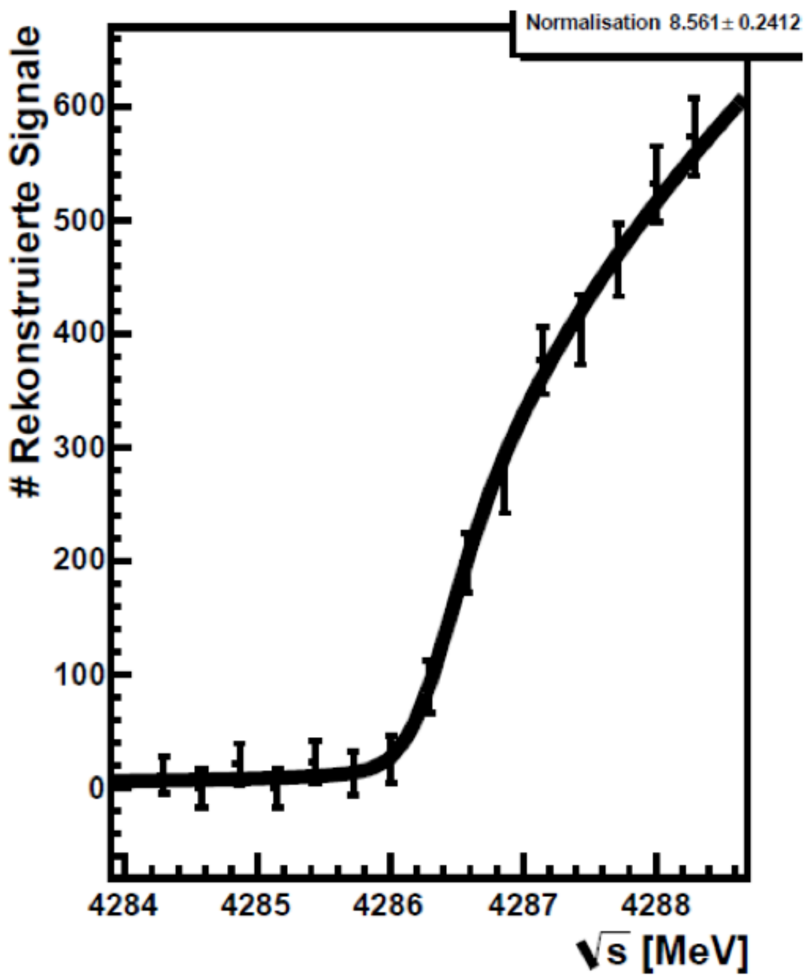
15 measured points within 4 MeV window



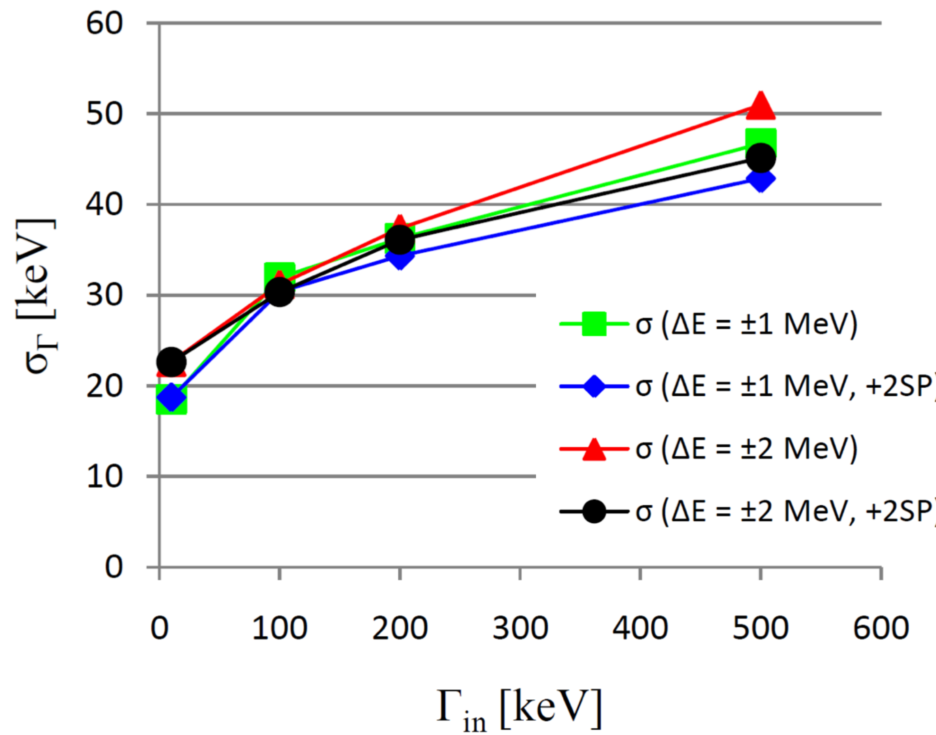
[M.Mertens, PhD thesis]

Energy scan simulation around threshold

Extracted excitation function



Sensitivity of width Measurement

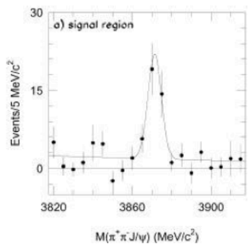
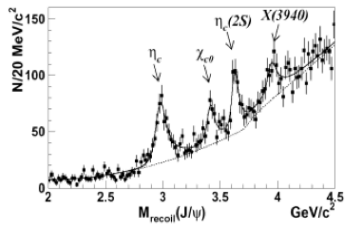
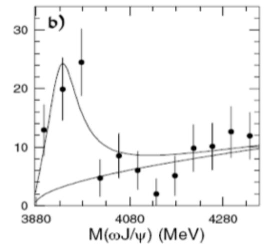
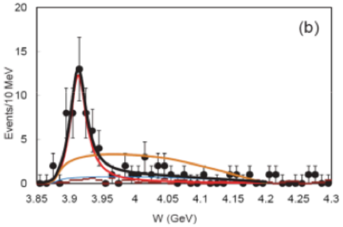
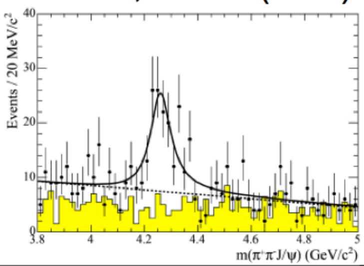
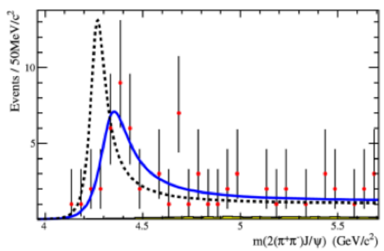
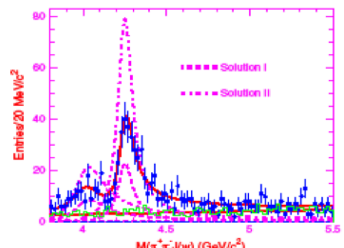
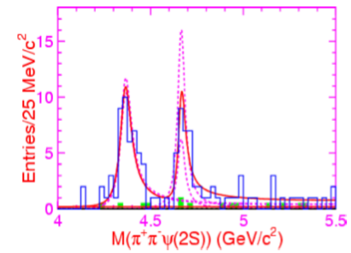
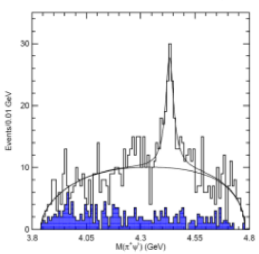
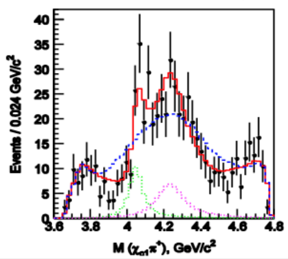
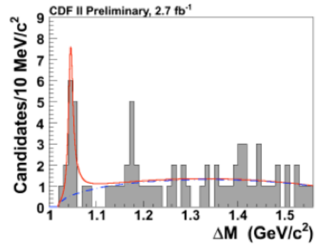
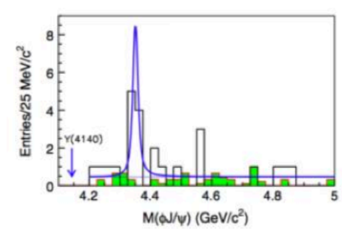


Relative accuracy $\sigma_\Gamma/\Gamma < 1/3$ for $\Gamma > 100$

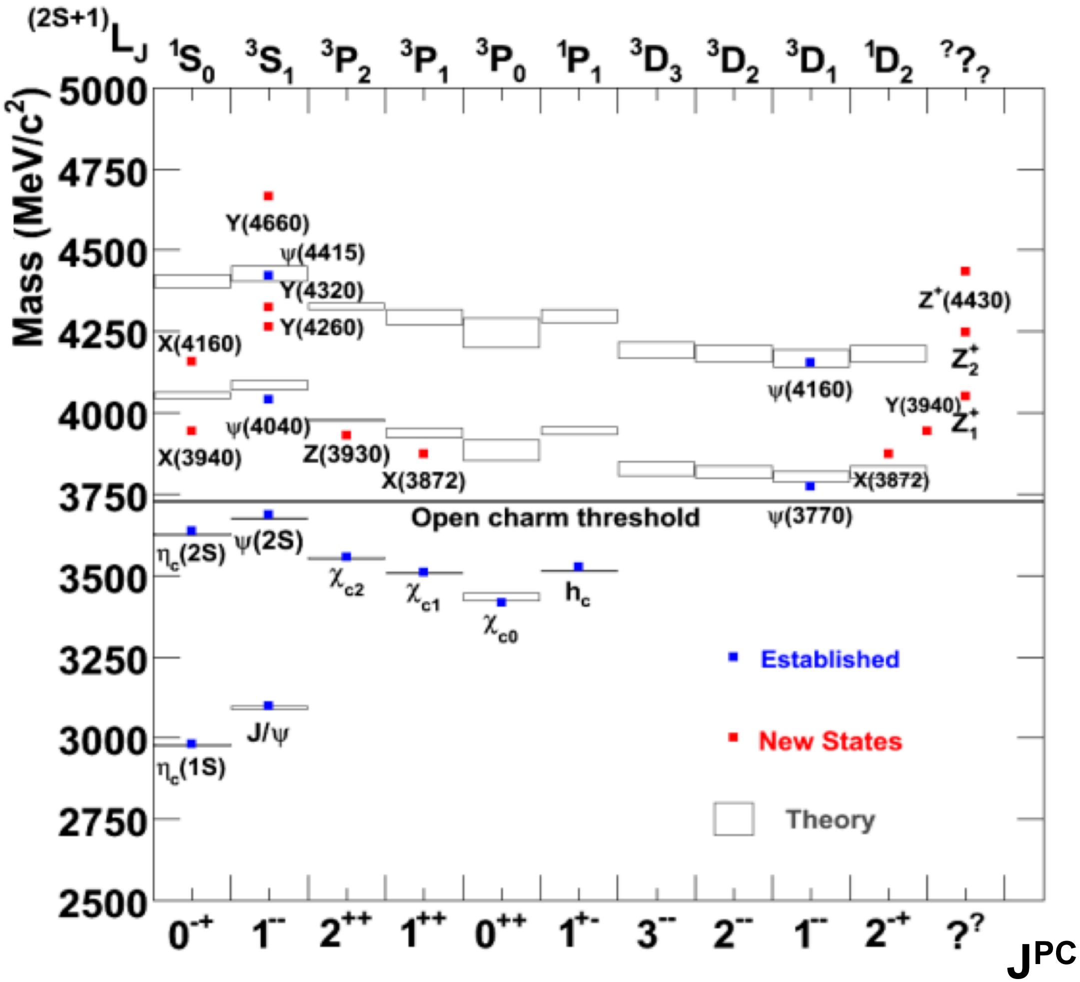
[M.Mertens, PhD thesis]

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) 

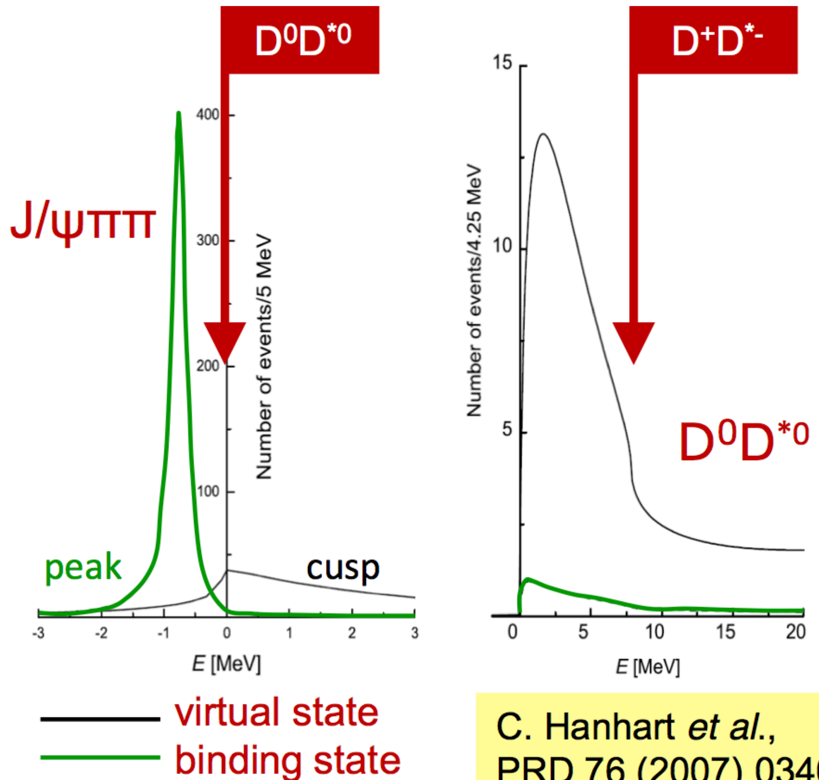
Charmonium(-like) Spectrum



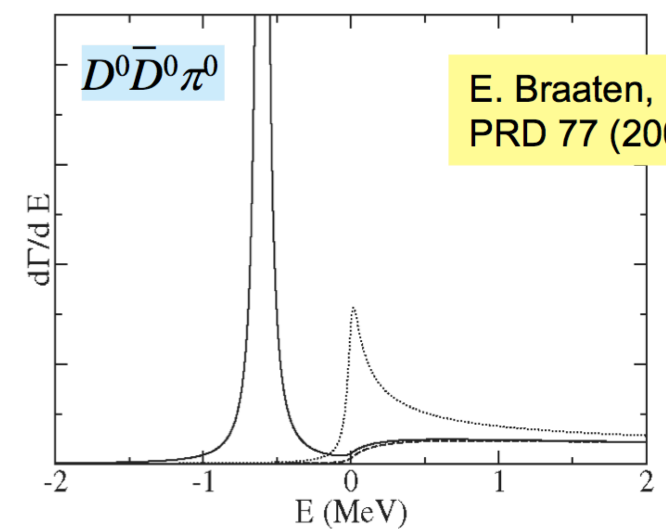
- Since 2003 charmonium-like spectrum found richer as expected
- Observation of states that do not fit theoretical models/predictions
- The case of the X(3872):
  - ➢ isospin violating, very narrow
  - ➢ quantum numbers known (1^{++}, LHCb)
  - ➢ width unclear
  - → *nature not yet clear..*
    needed: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



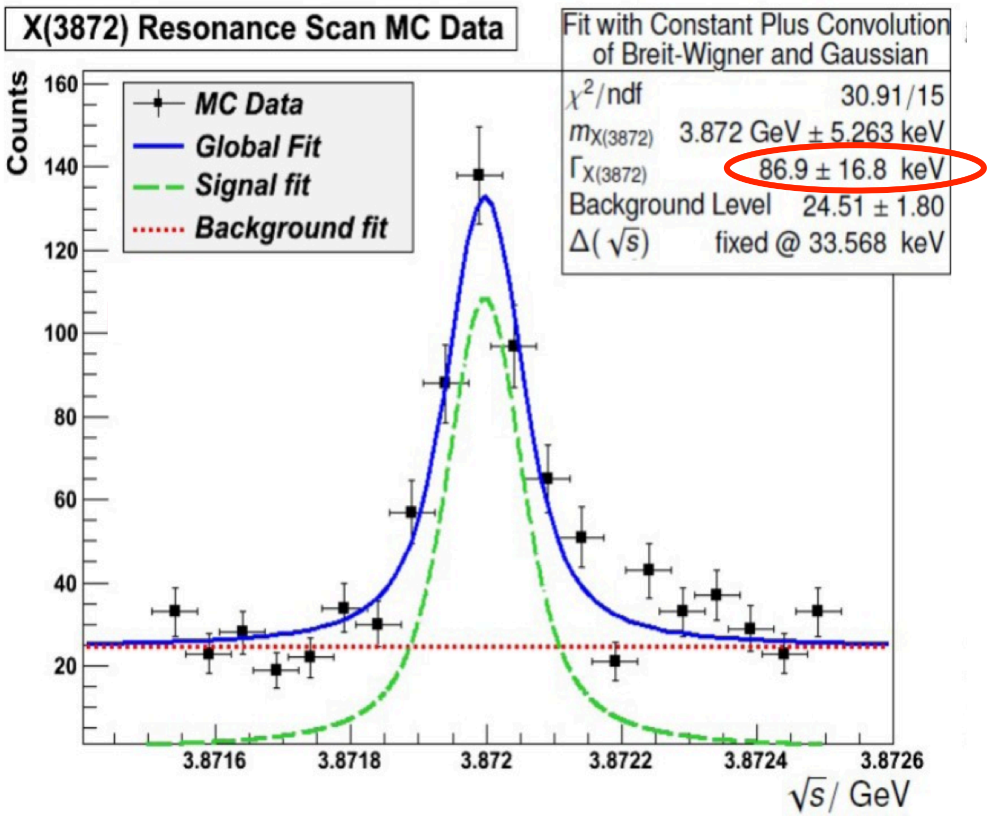
E. Braaten, M. Lu,
PRD 77 (2008) 014029

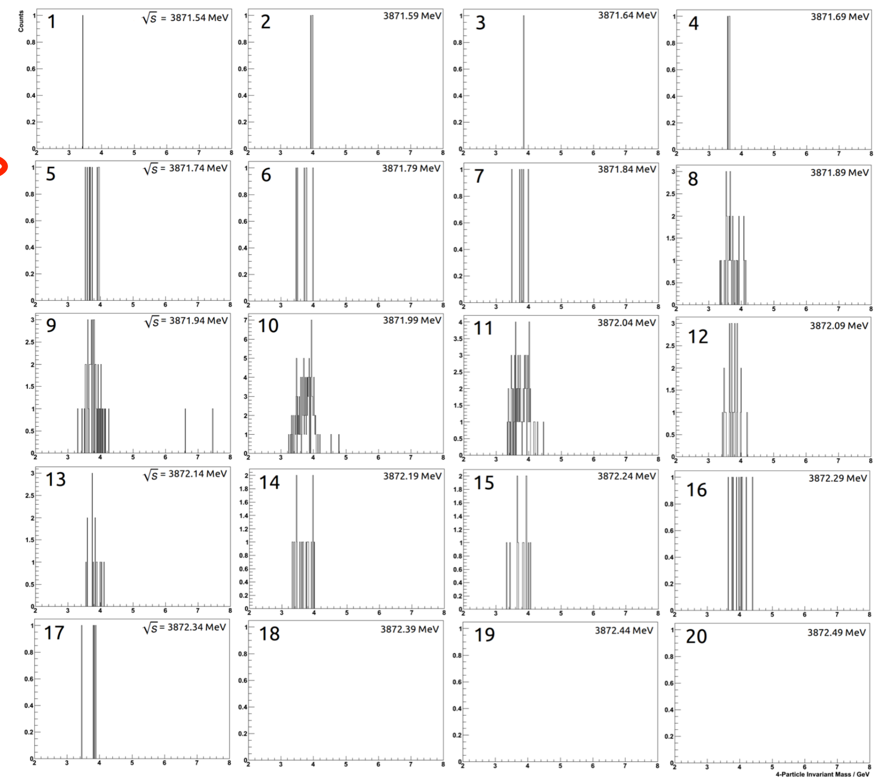
Compare lineshapes in different final states

X(3872)

- Upper limit on branching ratio by LHCb:

  *BR(X→p̄p) < 0.002*BR(X→J/ψπ⁻π⁺)* → *Γ < 1.2 MeV*   EPJ C73 (2013) 2462
- And BR(X→J/ψπ⁻π⁺) > 0.026 (PDG 12) => *σ(p̄p→X(3872)) < 67 nb*





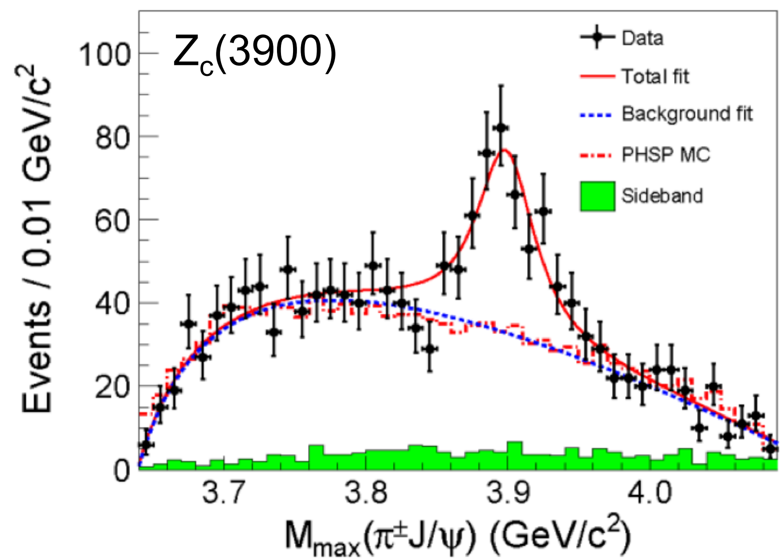
- Here: Assume σ = 50 nb, Luminosity: 2×10^{31} $cm^{-2}s^{-1}$
- Width resolution < 100 keV

[M.Galuska, PhD thesis]

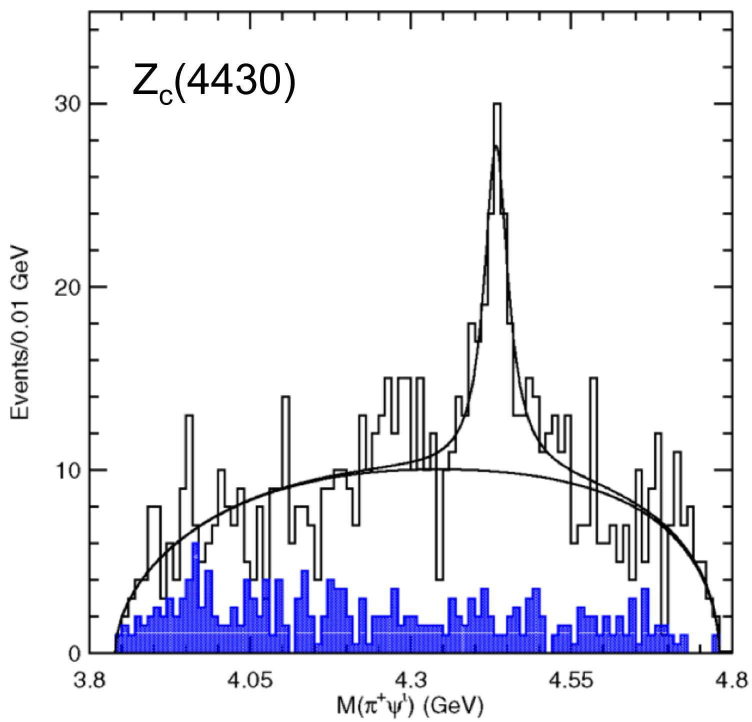
Non-$q\bar{q}$ mesons: Charged $c\bar{c}$-like states

- 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

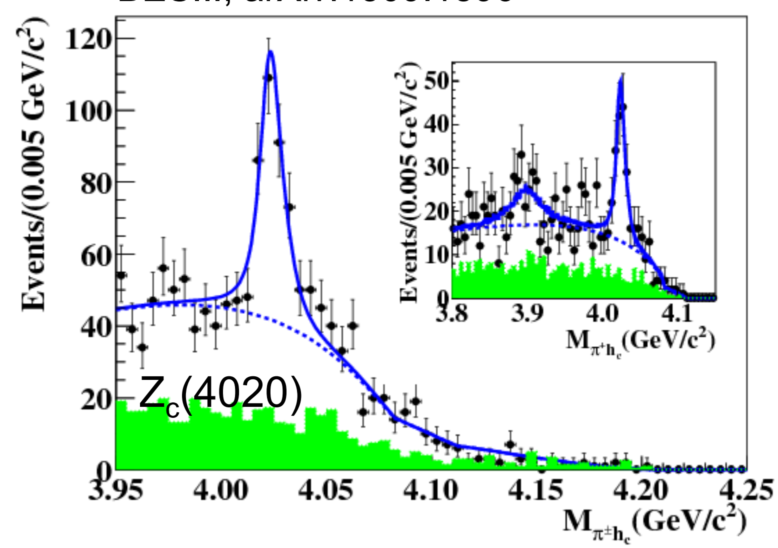
BESIII, arXiv:1303.5949



Belle, PRL 100 (2008) 142001



BESIII, arXiv:1309.1896



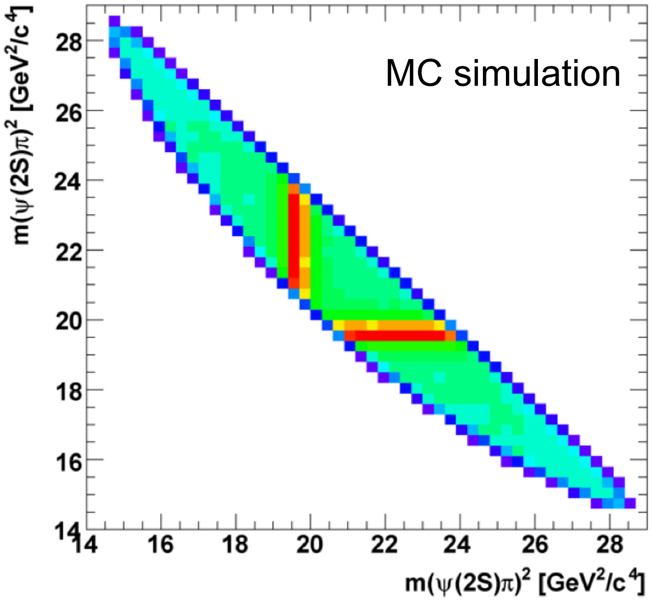
Non-$q\bar{q}$ mesons: Charged $c\bar{c}$-like states

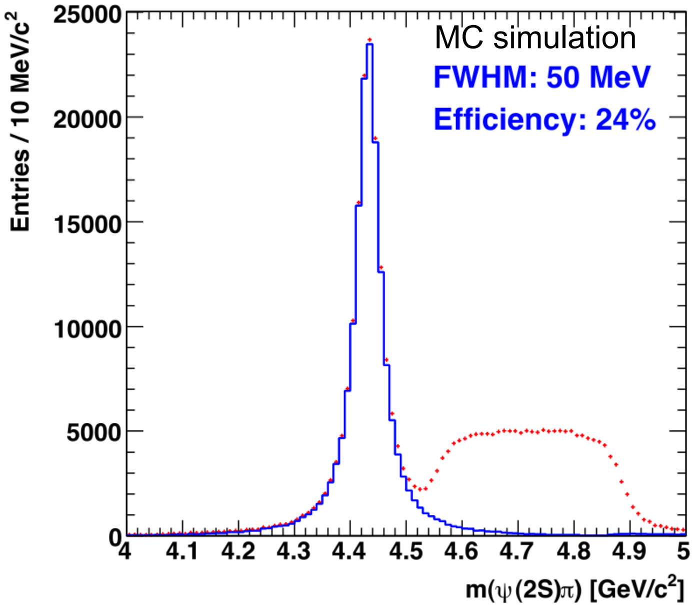
Studies planned with PANDA:

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

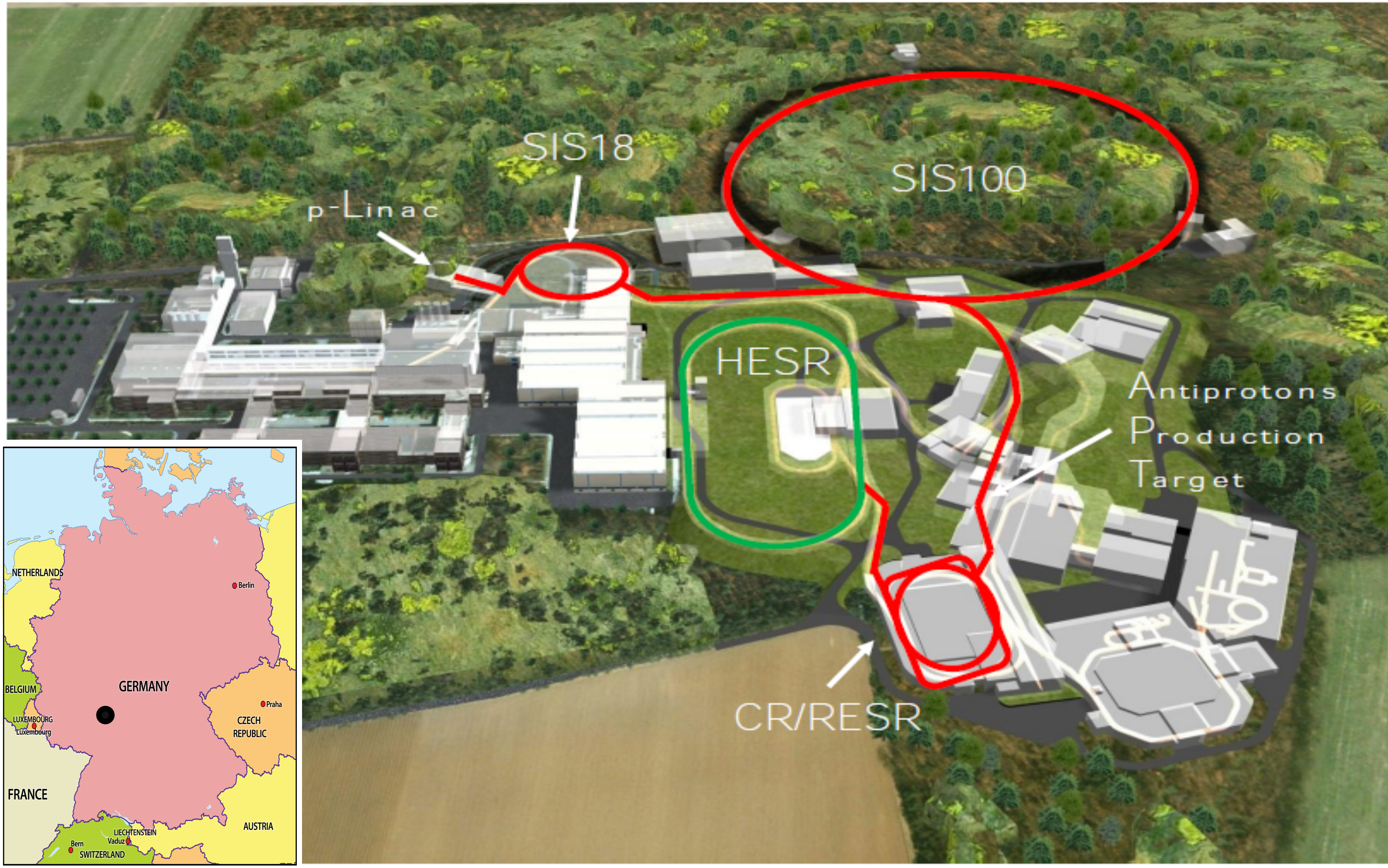
- *formation* in $\bar{p}n$:
  $\bar{p}d \rightarrow Z(4430)^{-}\, p_{spectator}$
  $\rightarrow \psi(2S)\, \pi^{-}\, p_{spectator}$

spectator proton needed to reconstruct
→ *reduced mass resolution*

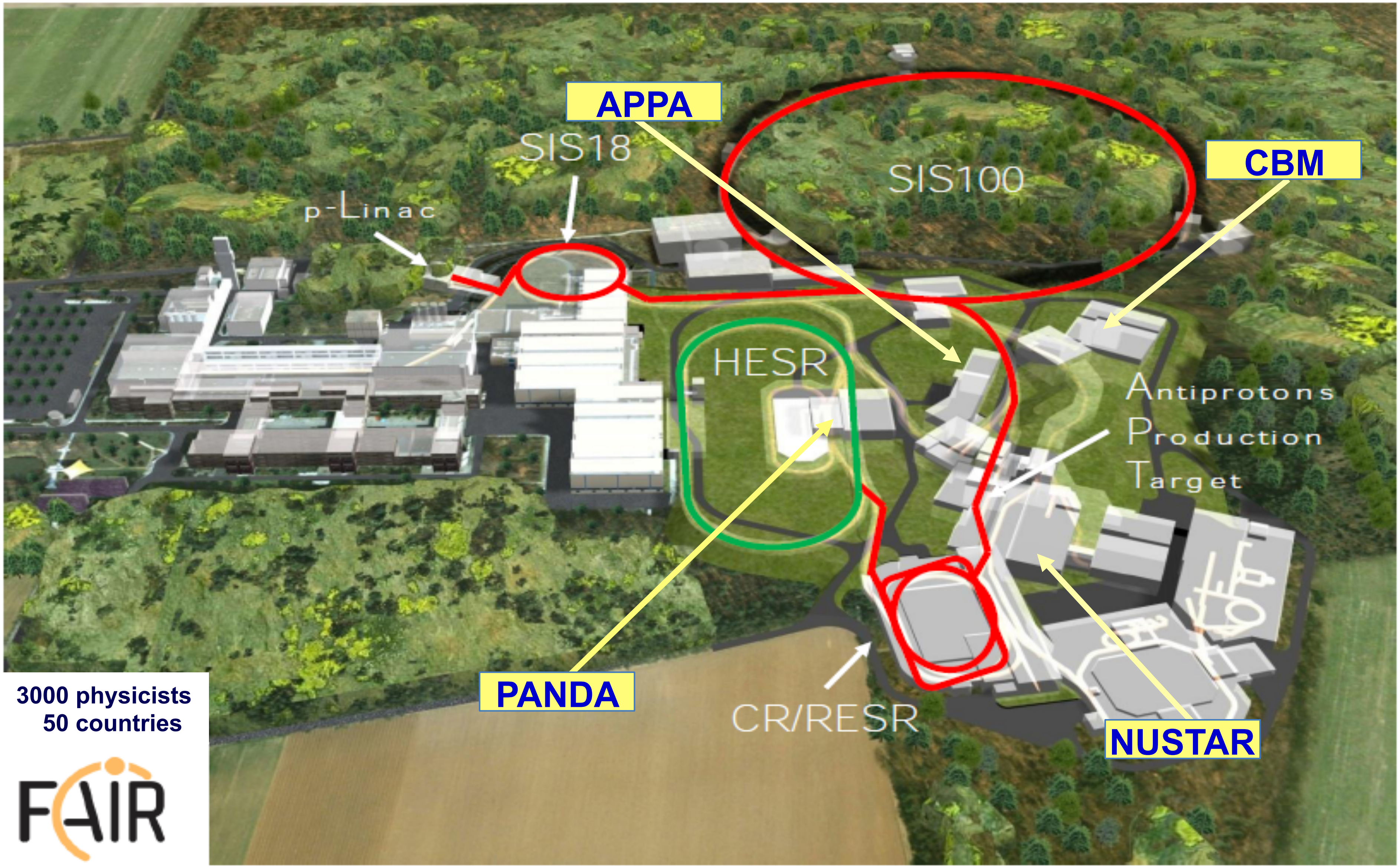




Facility for Antiproton and Ion Research



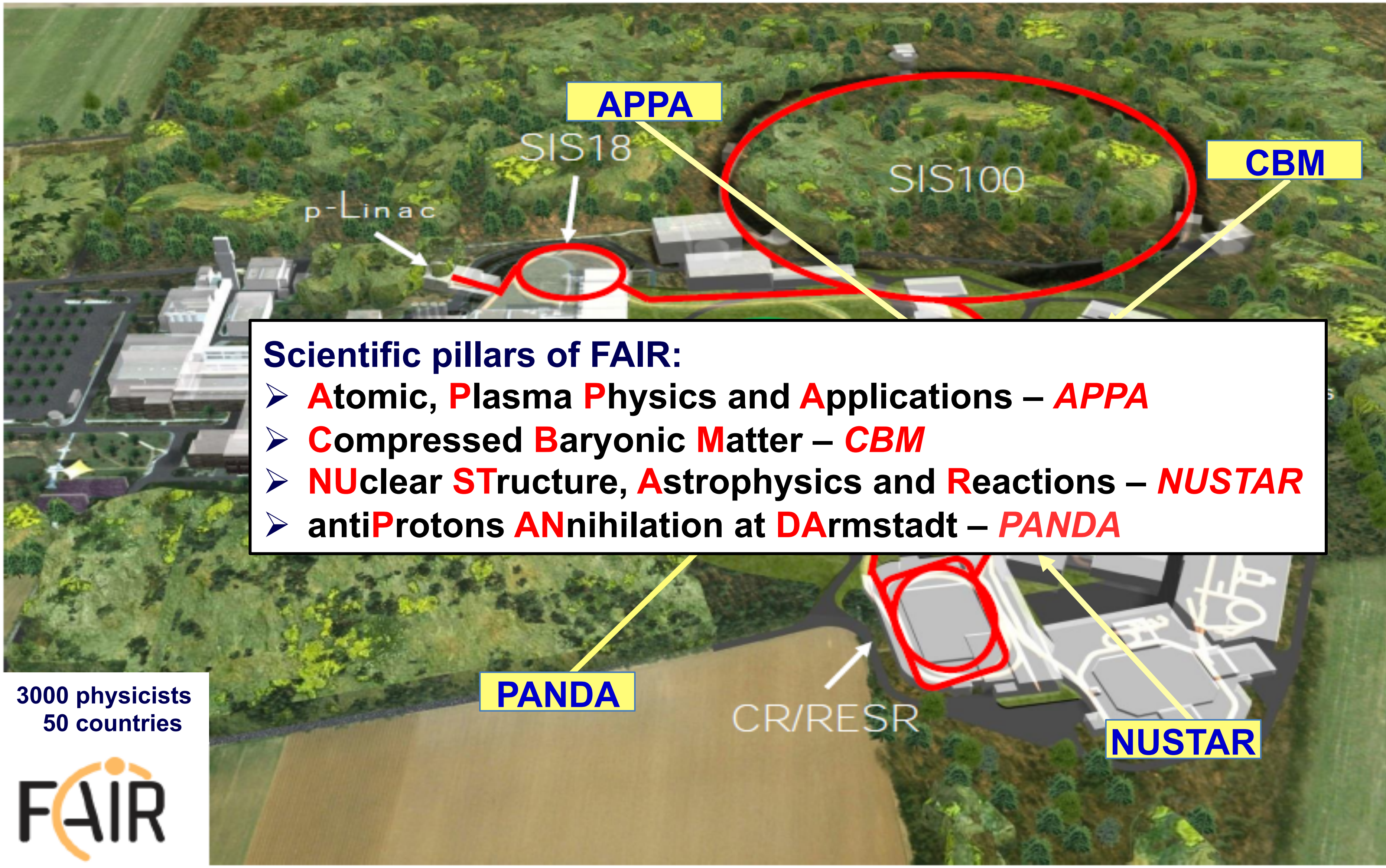
Facility for Antiproton and Ion Research



3000 physicists
50 countries

FAIR

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***

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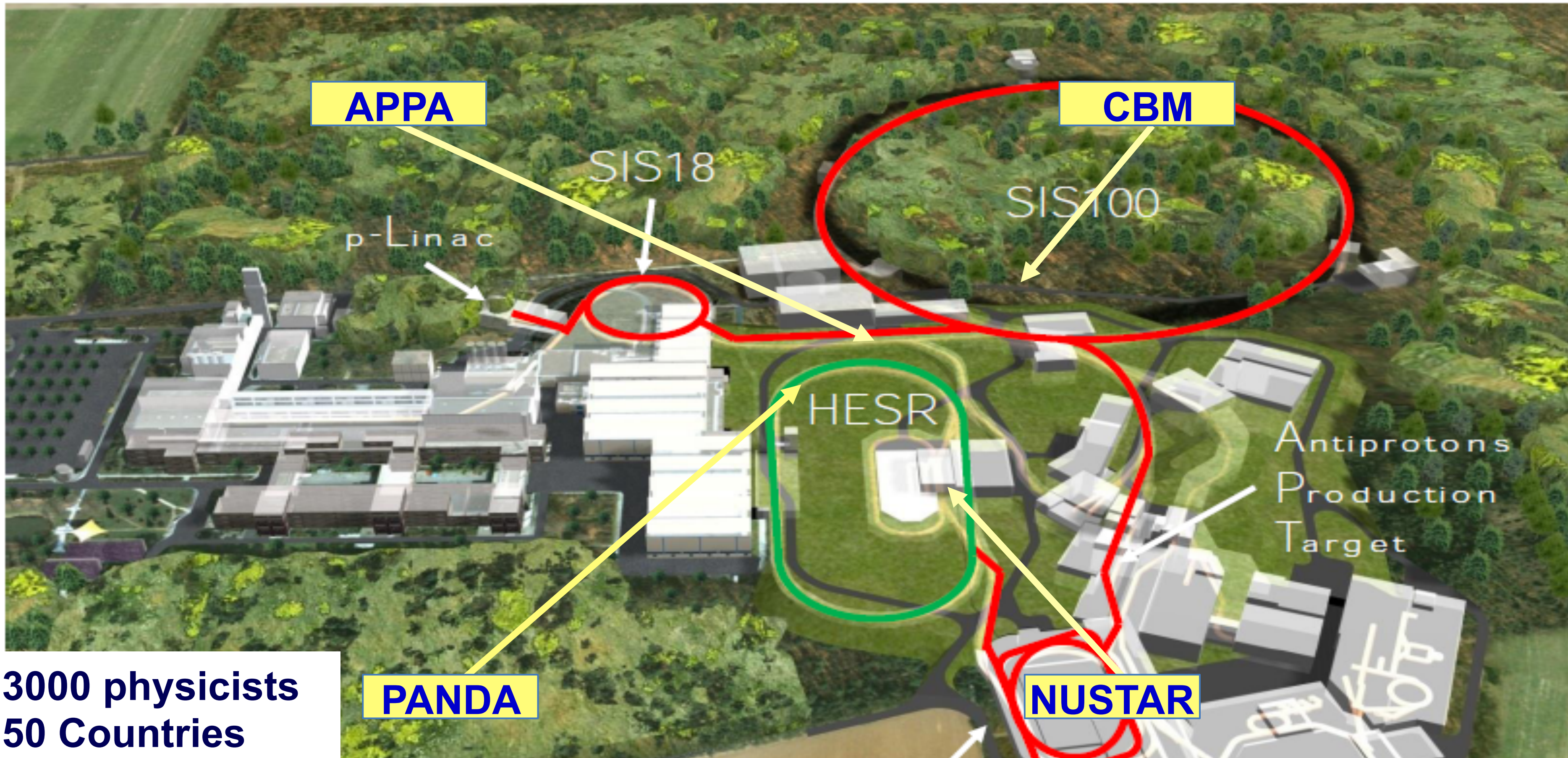

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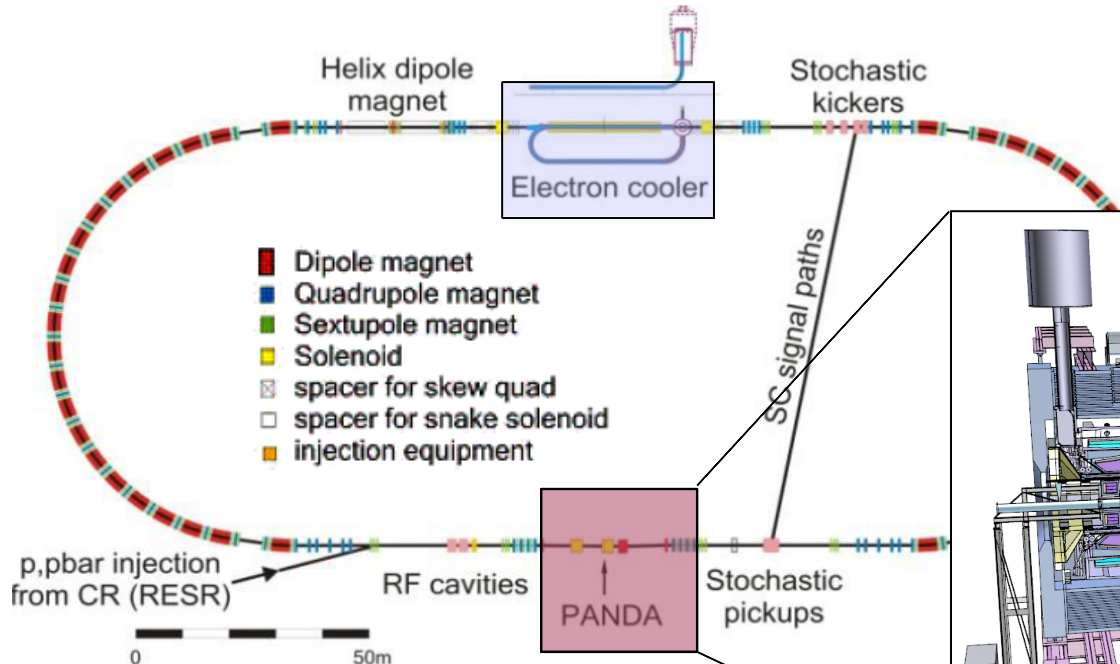
Facility for Antiproton and Ion Research

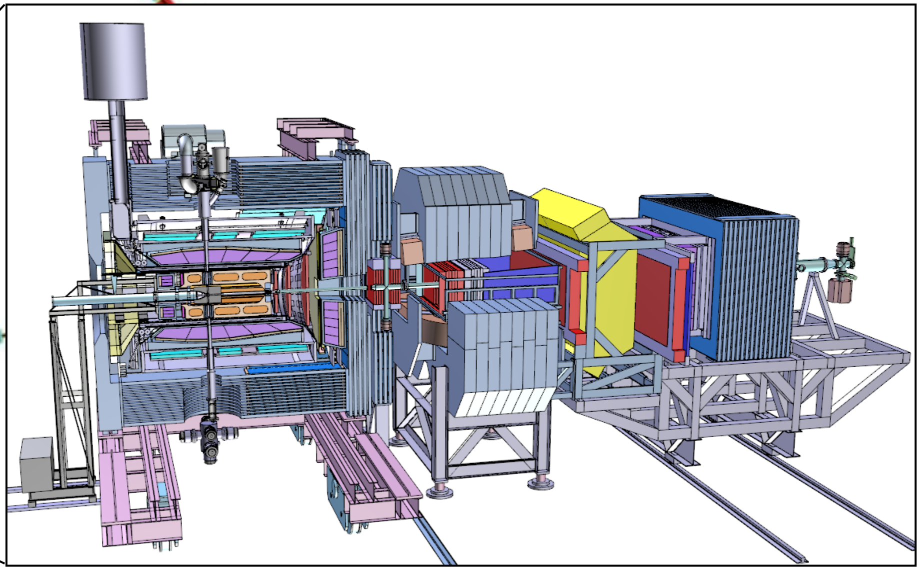
12 June 2014

Total area	> 200 000 m^2
Area buildings =	98 000 m^2
Usable area	= 135 000 m^2

High Energy Storage Ring -- HESR



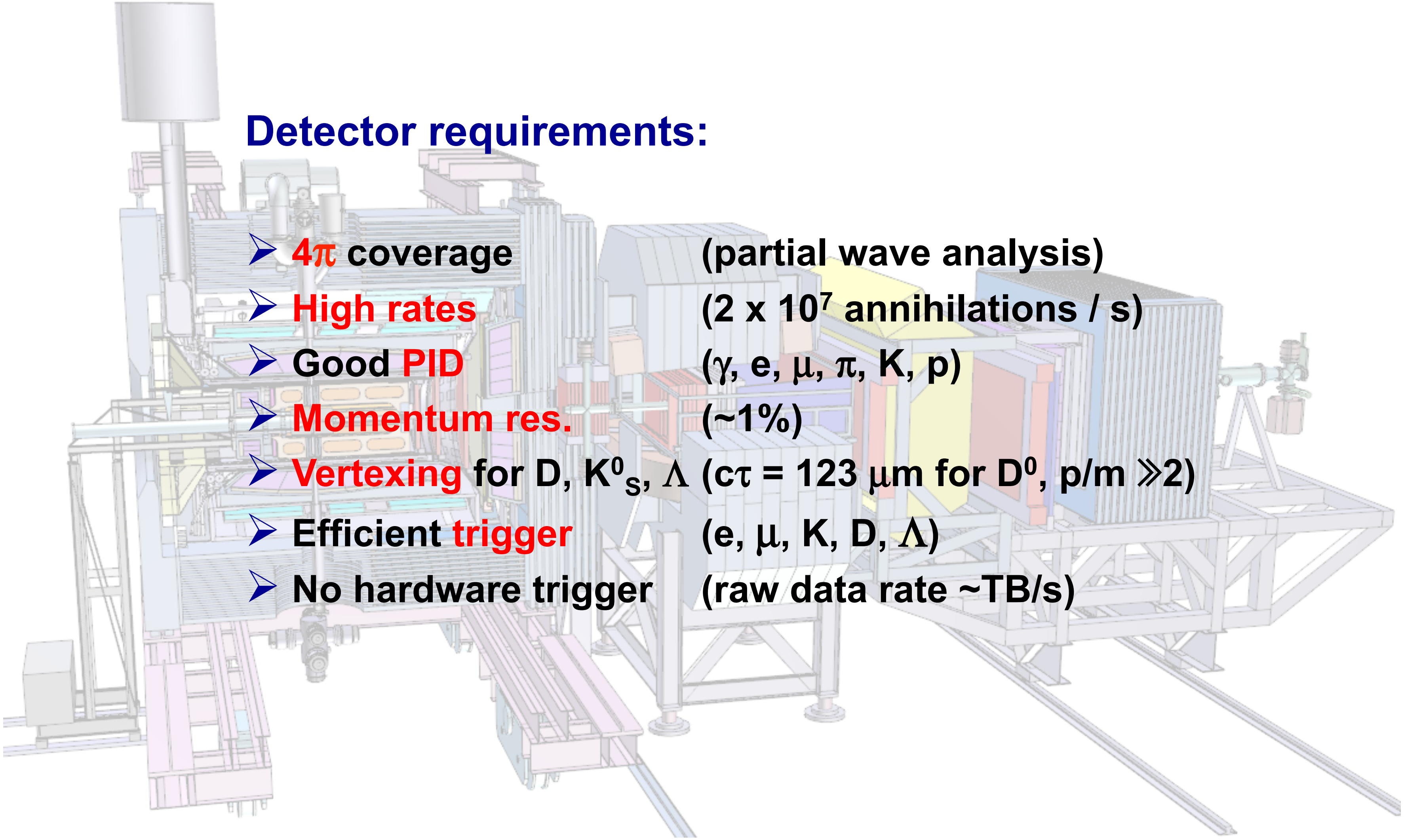
PANDA Experiment, Detector



High resolution mode:
- e^- cooling: p ≤ 8.9 GeV/c
- 10^{10} anti-protons stored
- Luminosity up to 2 x 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 x 10^{32} cm^{-2} s^{-1}
- $\Delta p/p = 2 \times 10^{-4}$

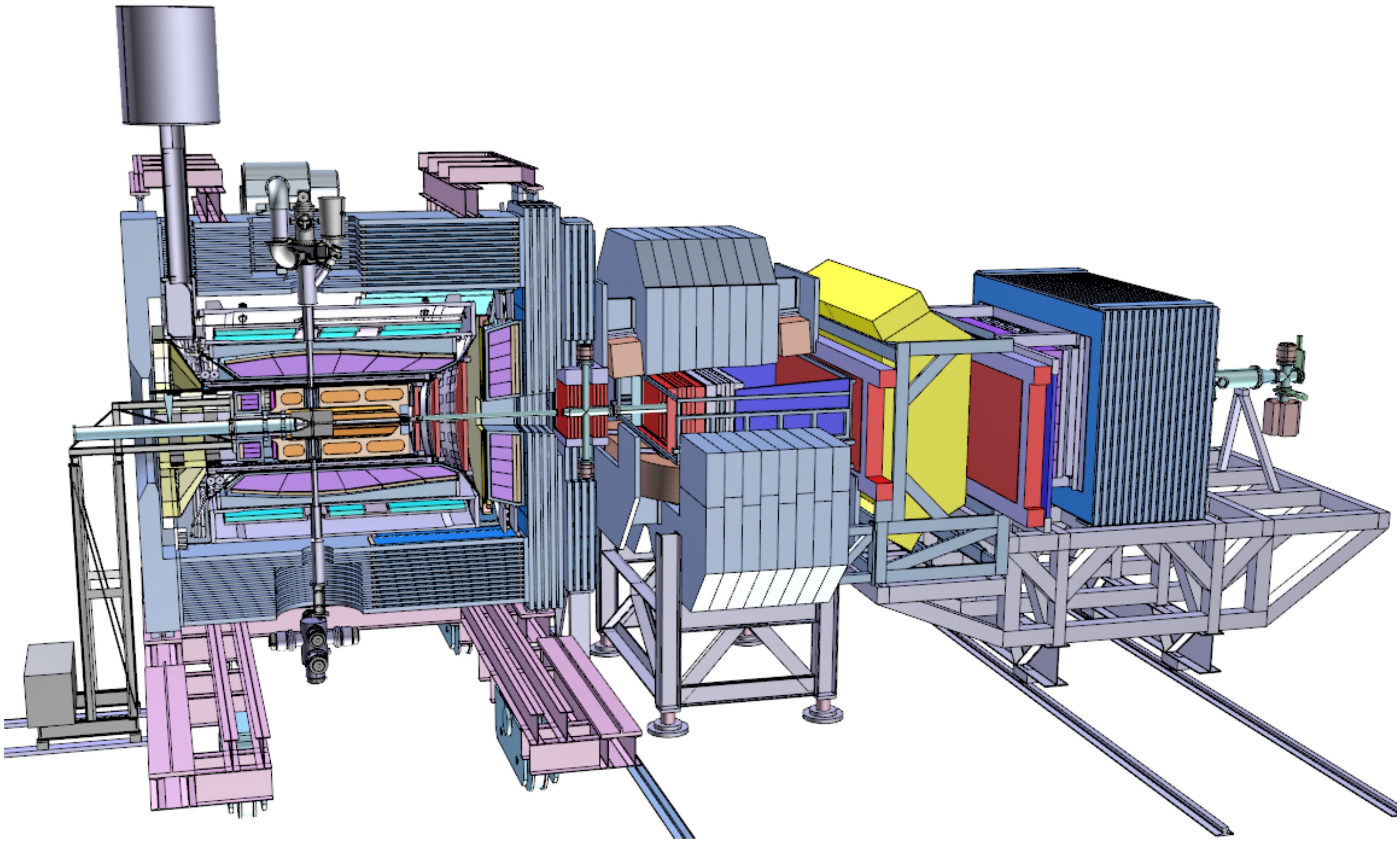
AntiProton Annihilation at Darmstadt



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** ($c\tau$ = 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



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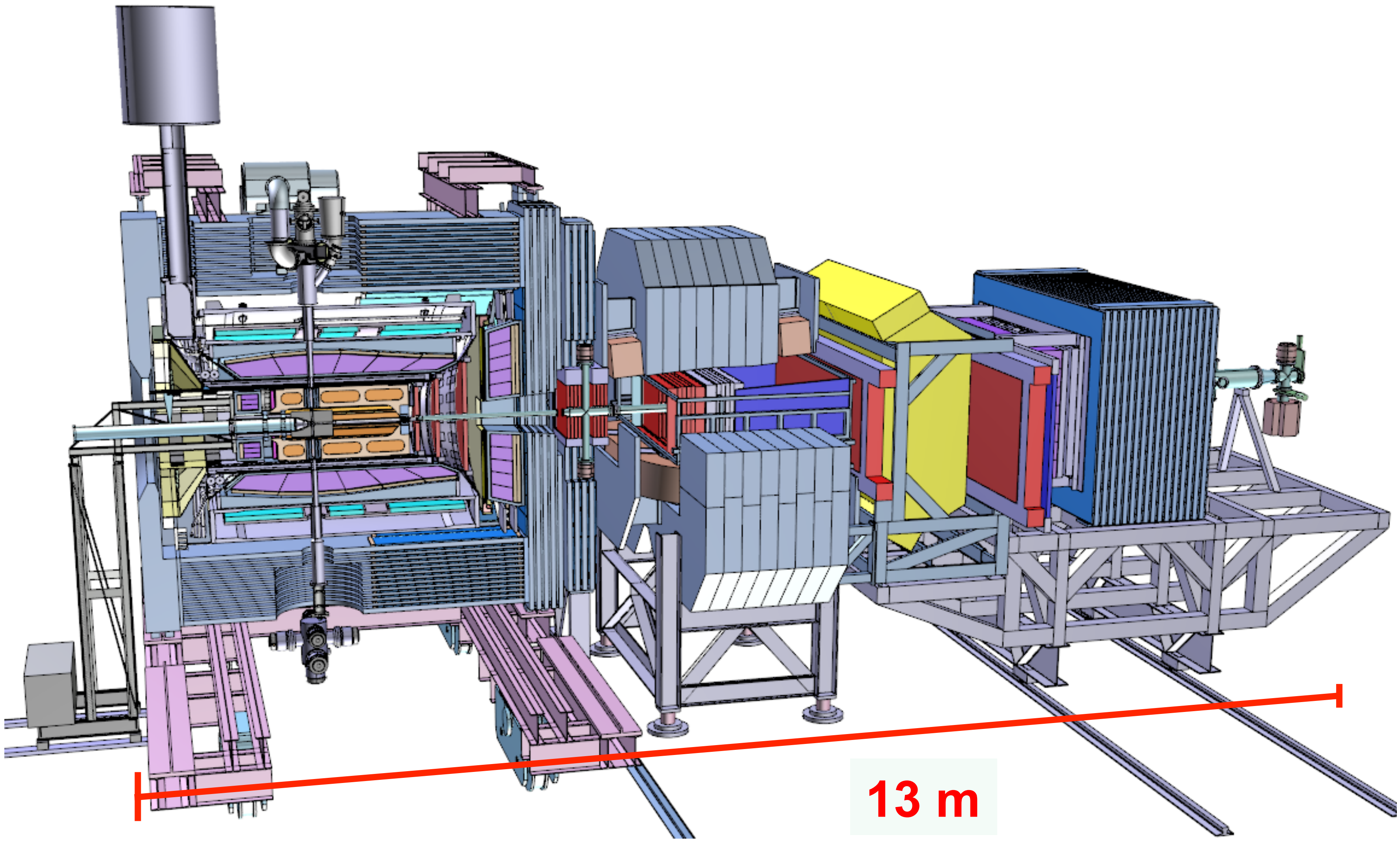
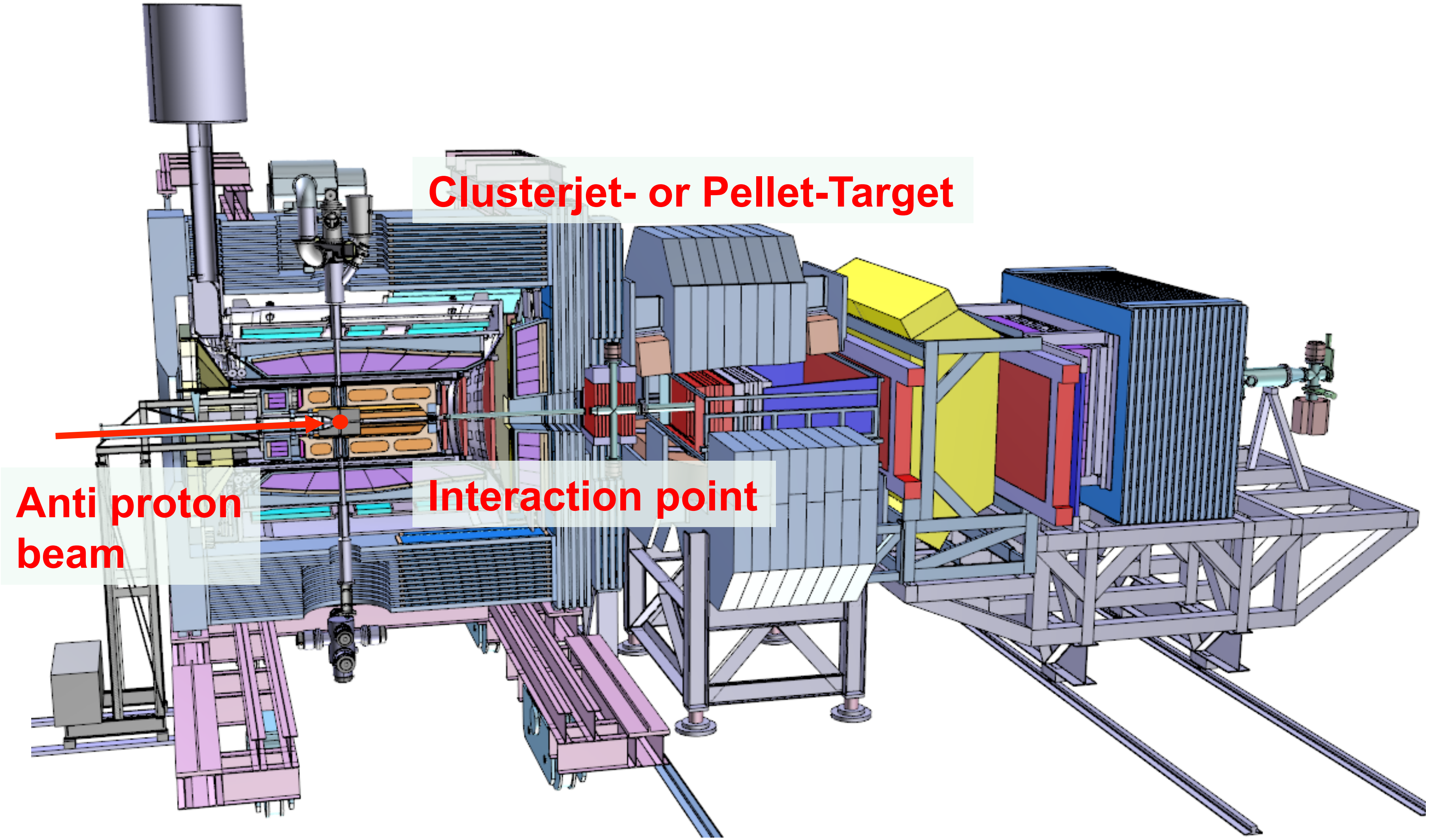


AntiProton Annihilation at Darmstadt



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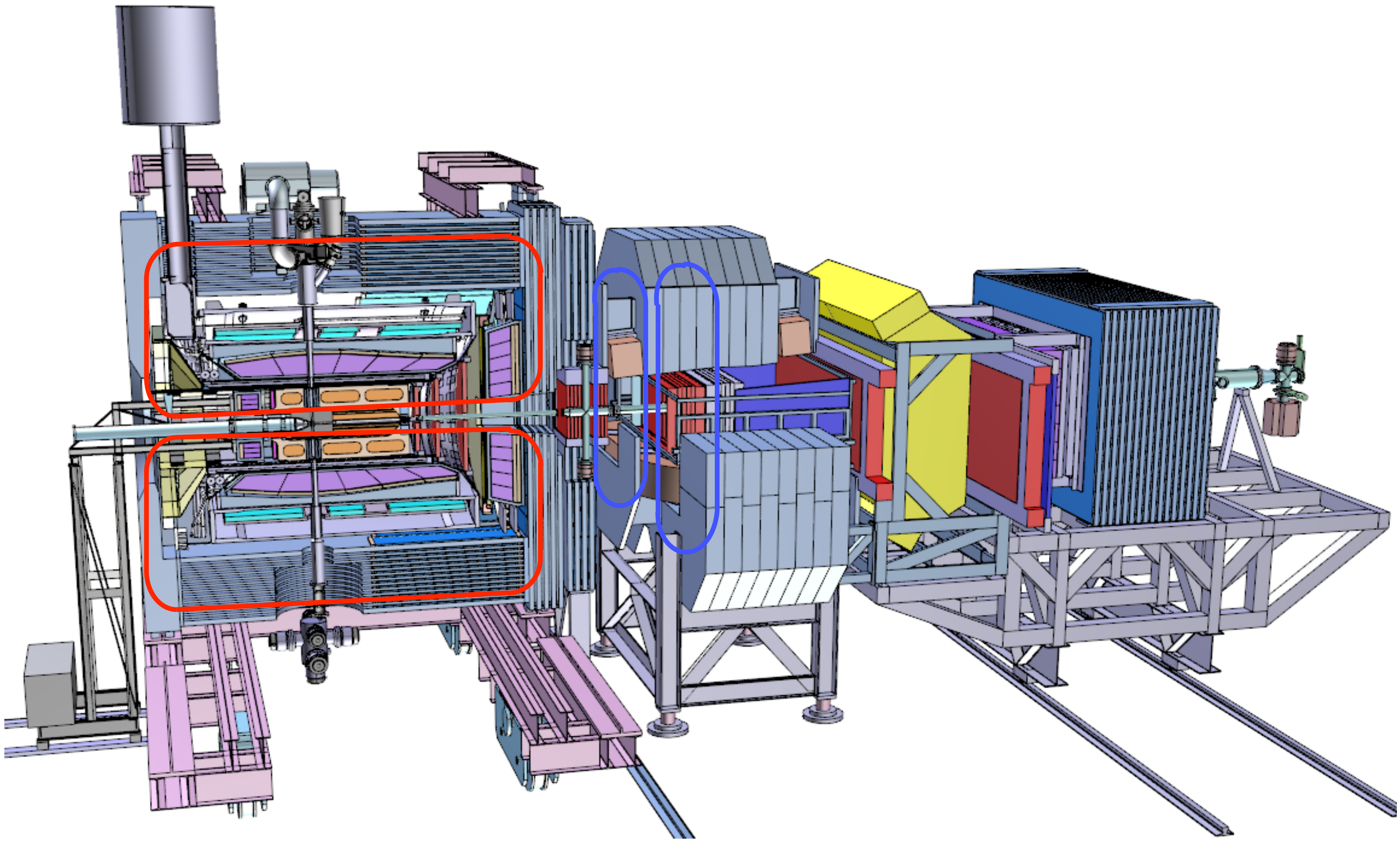

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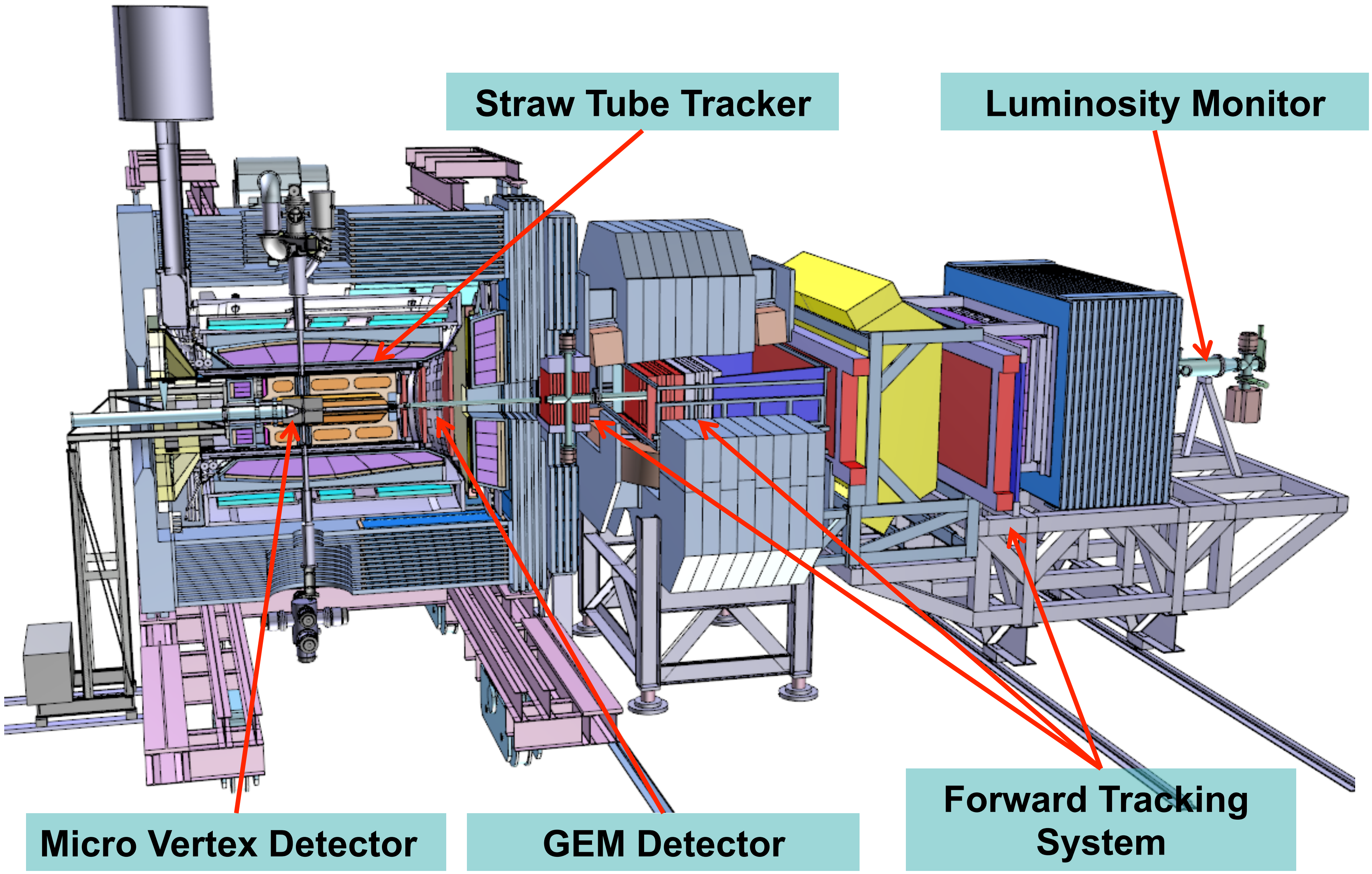

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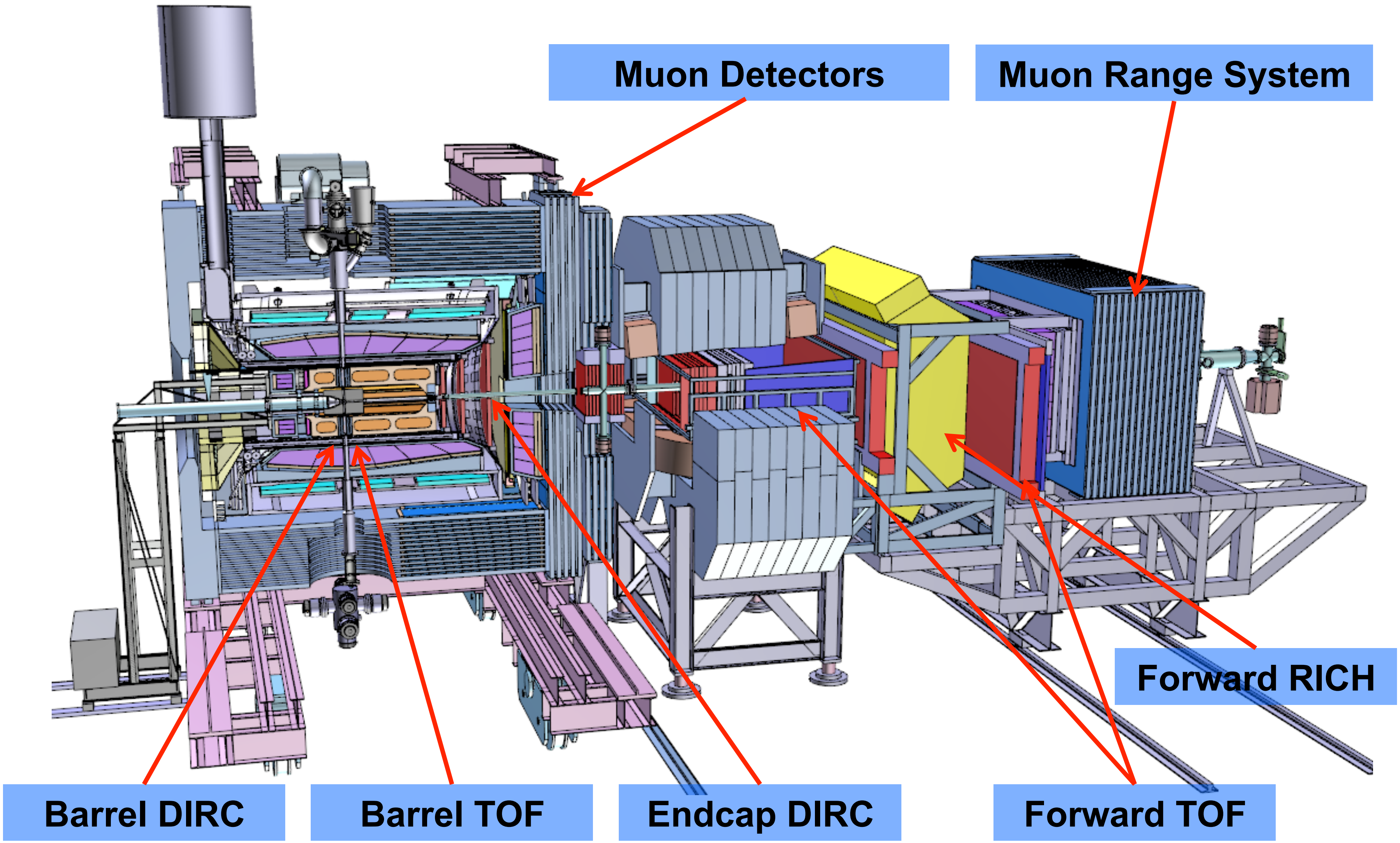

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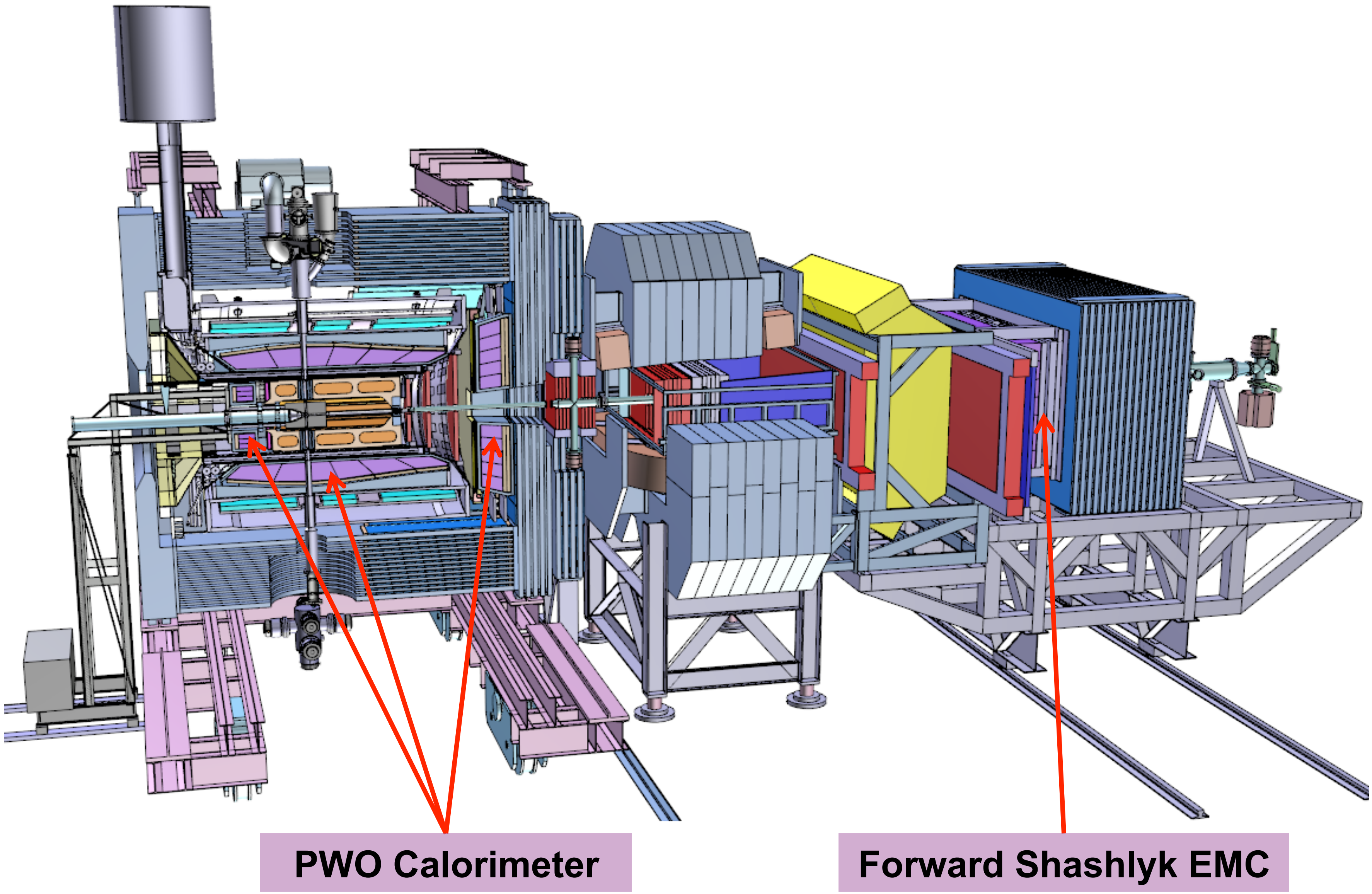

Summary & conclusions

- 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 -- hadron structure and spectroscopy

Thank you for your attention!

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

Austria, Australia, Belarus, China, France, Germany, India, Italy, Poland, Romania, Russia, Spain, Sweden, Switzerland, Thailand, Netherlands, USA, UK