Experimental Techniques & Methods in Hadron Spectroscopy

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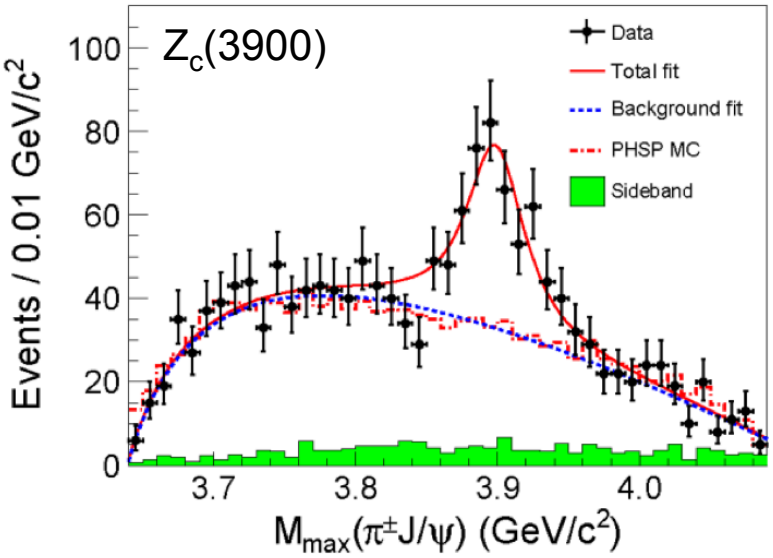
Outline

- **Introduction**
  - Mesons & exotics
  - Properties & dynamics
  - Resonance scan method
- **Experimental status**
  - Light meson sector
  - Charmonium region
  - Running & future experiments
- **Summary & outlook**

Hadron Spectroscopy -- Recent Highlights

Meson Spectroscopy

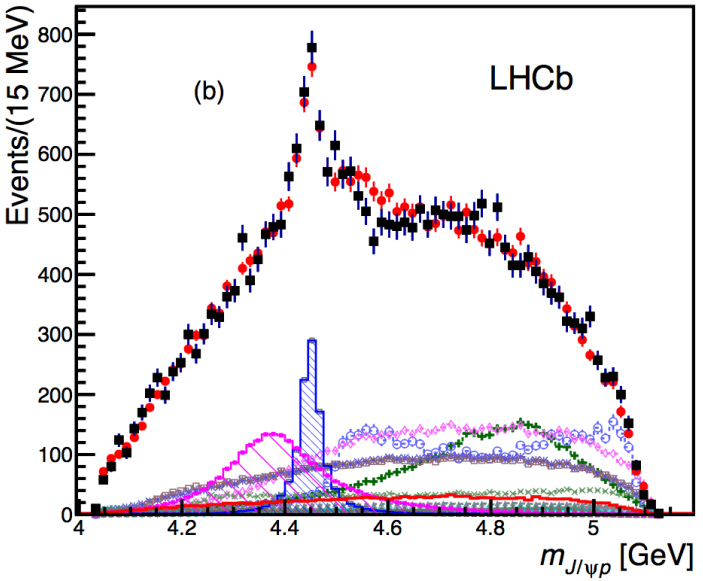
BESIII, arXiv:1303.5949



unexpected,
manifestly exotic!

Baryon Spectroscopy

LHCb, arXiv:1507.03414



pentaquarks
-- revival (!?)

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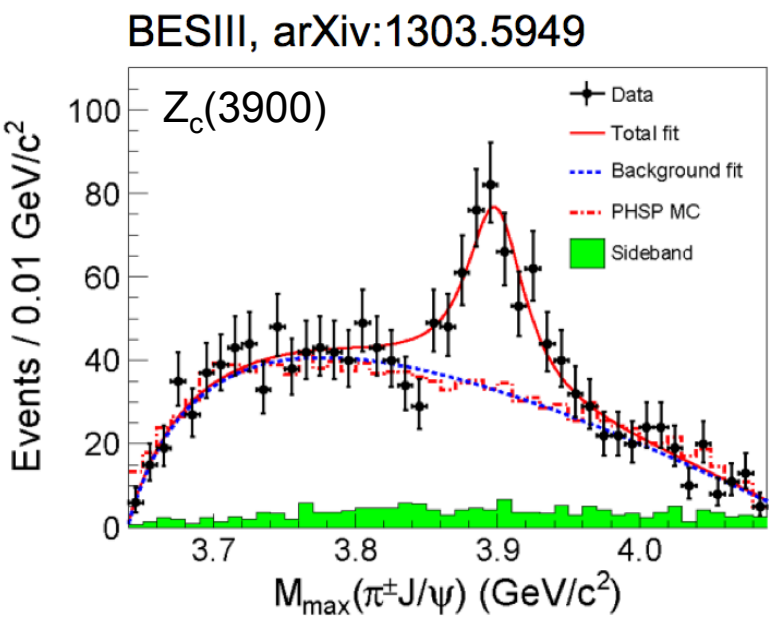

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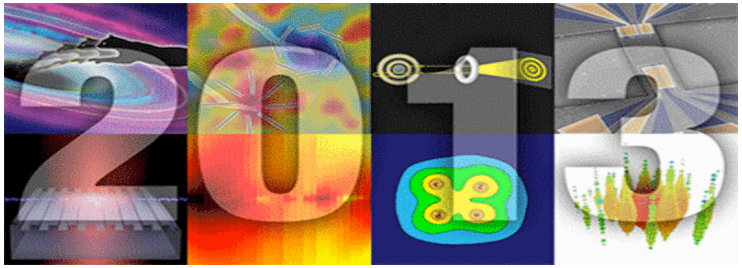
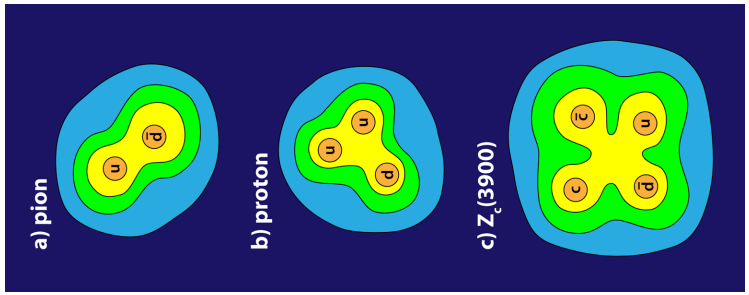
American Physical Society:



pion: proton: $Z_c(3900)$:



Viewpoint: New Particle Hints at Four-Quark Matter → *Highlight 2013!*

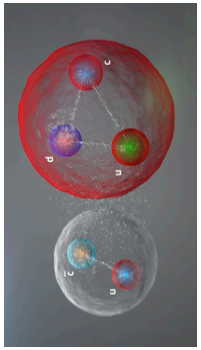
[http://physics.aps.org/articles/v6/139]

Hadron Spectroscopy -- Recent Highlights

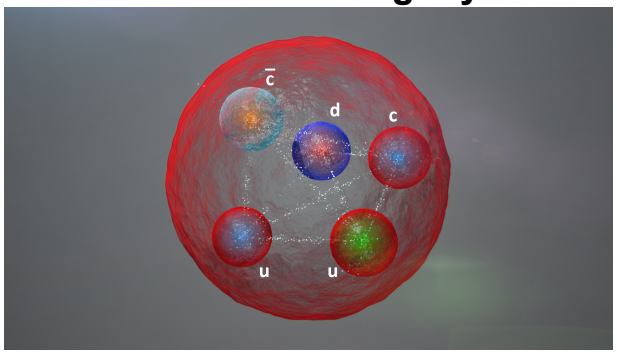
After 4 quark state, now 5 quark state

Quark interactions inside pentaquarks, two possibilities

Meson-baryon molecule:



Pentaquark state, tightly bound:



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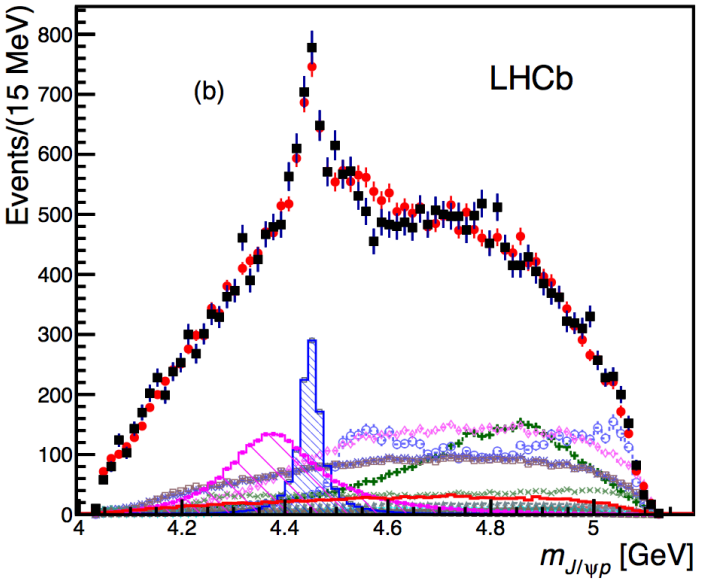

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[http://lhcb-public.web.cern.ch/lhcb-public/Welcome.html#Penta]

Hadron Spectroscopy -- Recent Highlights

Focus in this talk

Meson Spectroscopy

Baryon Spectroscopy

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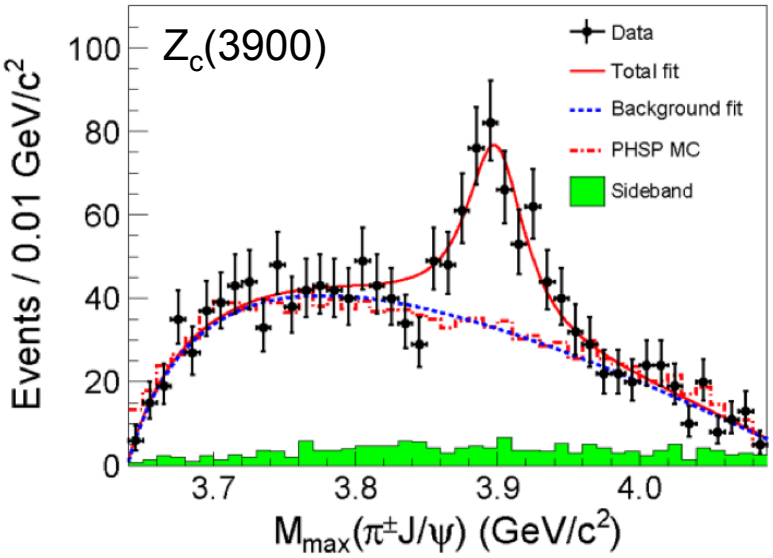

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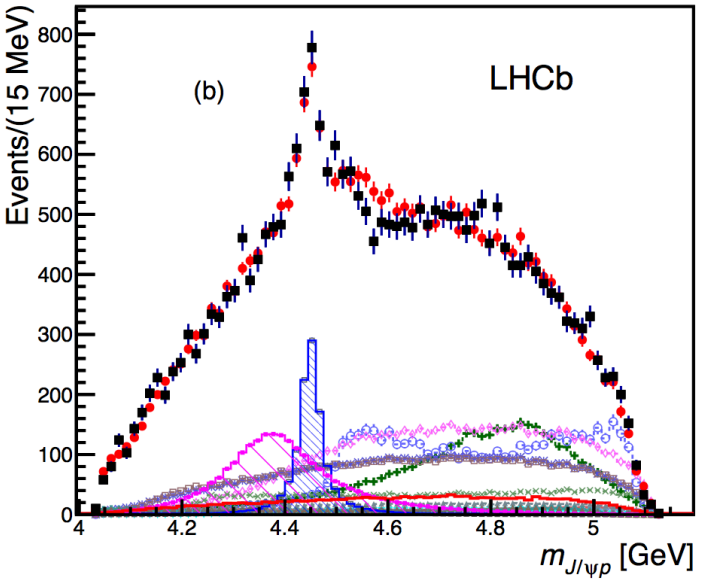

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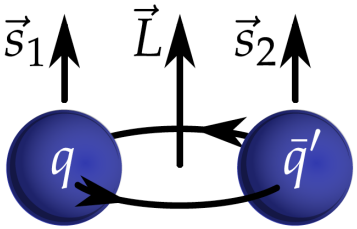
Mesons and (Spin) Exotic States

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: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$



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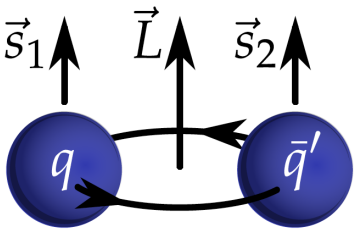
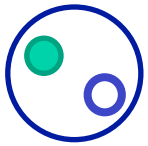


Meson



Conventional $(q\bar{q})_1$

QCD: Meson states beyond

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- In contrast to simple $q\bar{q}$ allows for **=> huge variety of states:**

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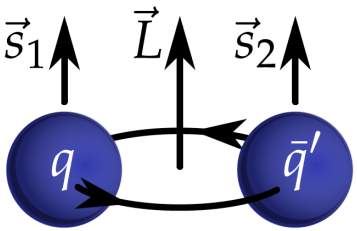

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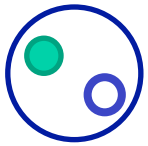

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Tetraquark $(q\bar{q}q\bar{q})_1$

Glue-ball $(gg)_{\bar{1}}$ or $(ggg)_1$

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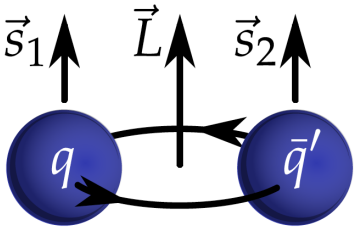

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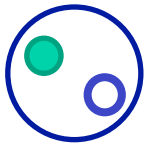

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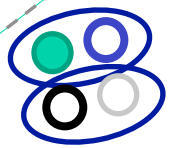
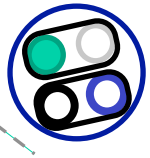
Further 4-quark-configurations:



Molecule $(q\bar{q})_1(q\bar{q})_1$

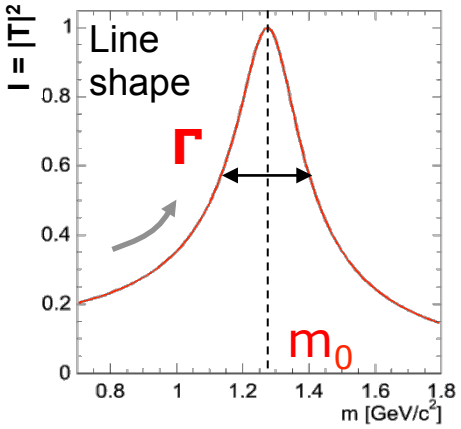
Hadro-quarkonium $(Q\bar{Q})_1(q\bar{q})_1$

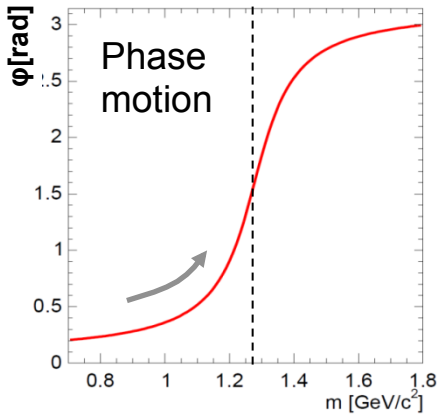


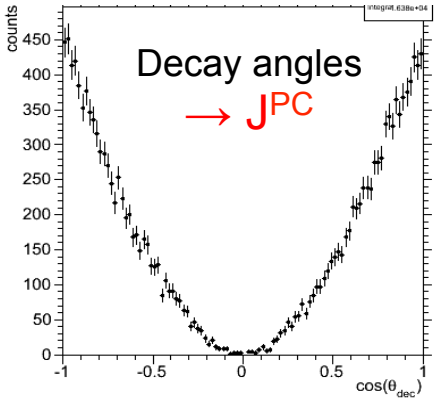
Di-quarkonium $(qq)_{\bar{3}}(\bar{q}\bar{q})_3$

[e.g. Braaten, PRD 90 (2014) 014044]

Properties and Dynamics of Mesons







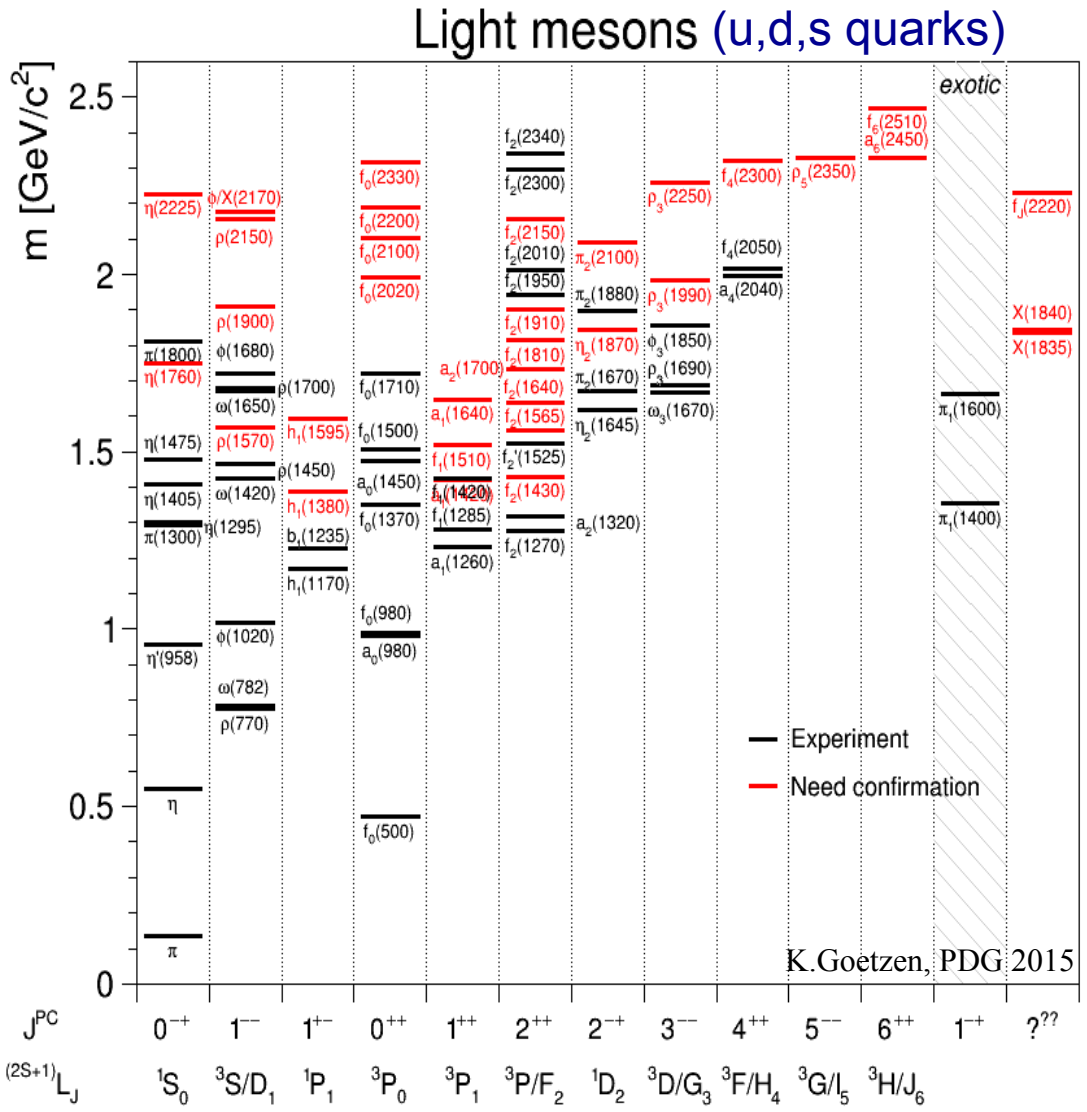
- Main properties: Mass m, width Γ, Spin-Parity J^{PC}, decays $B(M \to f_i)$
- Complex dynamics, e.g. $T(m) = \dfrac{\Gamma/2}{m_0 - m - i\,\Gamma/2} = A \cdot e^{i\phi}$, $I = |T|^2$
- Multiple resonances T_i interfere => $I = |\Sigma c_i T_i|^2$ (strength c_i)

=> **Typically:** Amplitude Analysis (or Partial Wave Analysis) needed to disentangle signals and determine resonance properties

Light quark sector

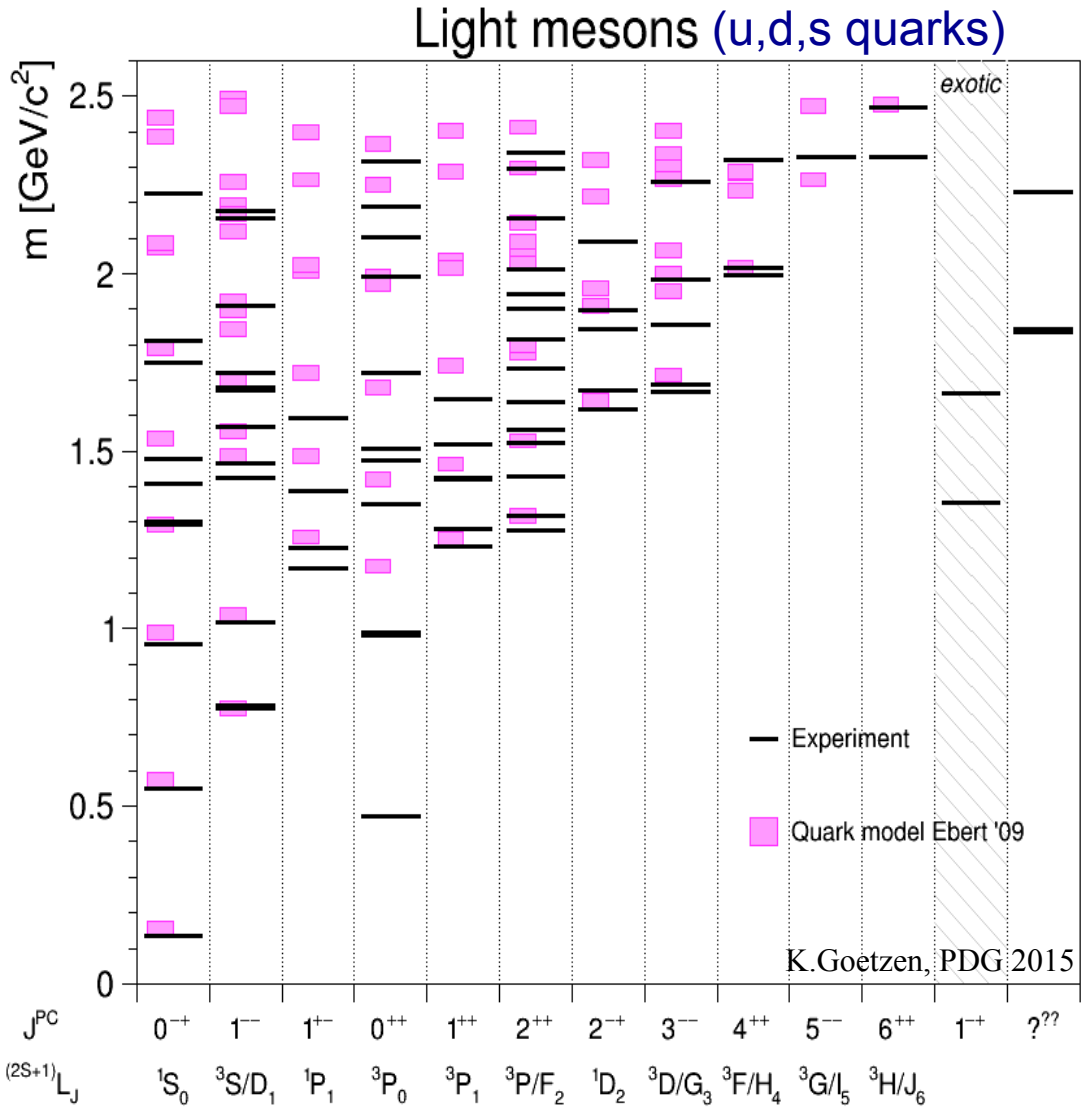
Light Meson Spectrum

- Many states observed



Light Meson Spectrum

- Many states observed
- Predictions not perfect, some predicted states not (yet) observed



Light Meson Spectrum

- Many states observed
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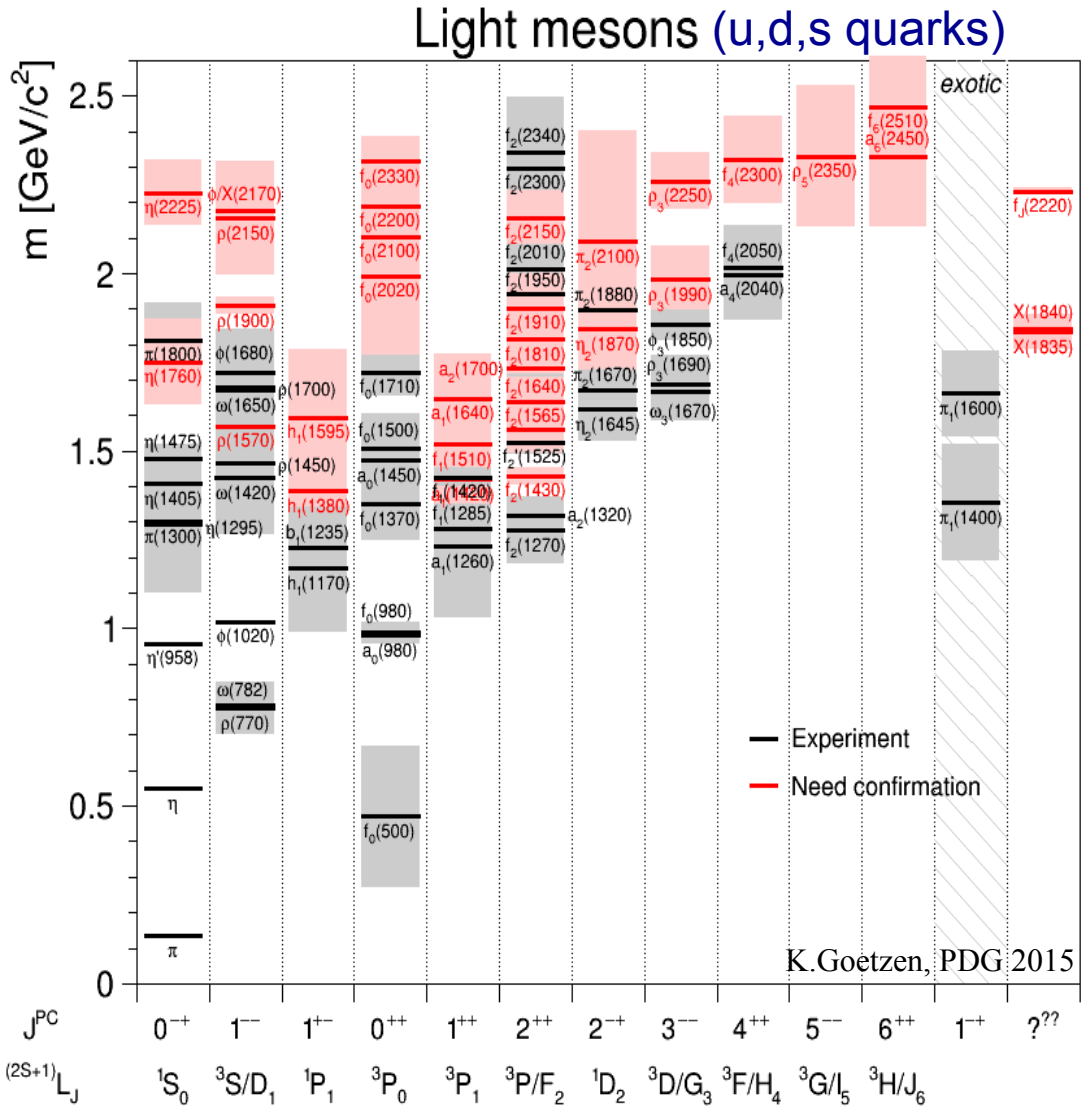
- Broad states
  => Strong overlap & mixing



Light Meson Spectrum -- Multiplets

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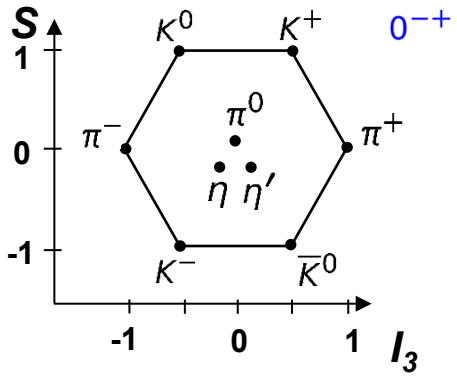
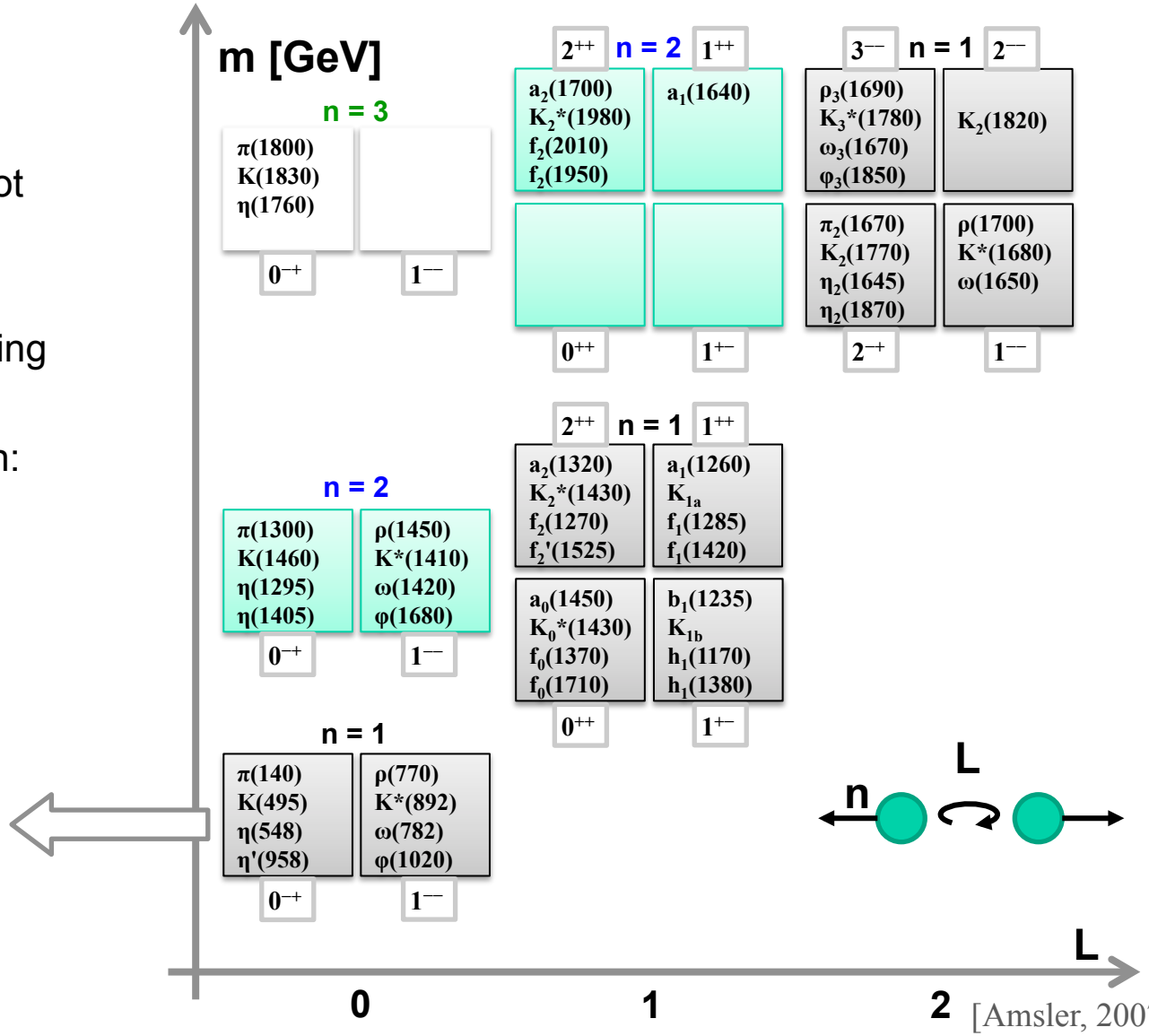
- Eightfold way, Gell-Mann:
  => J^{PC} multiplets





[Amsler, 2007]

Light Meson Spectrum -- Multiplets

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  some predicted states not
  (yet) observed
- Broad states
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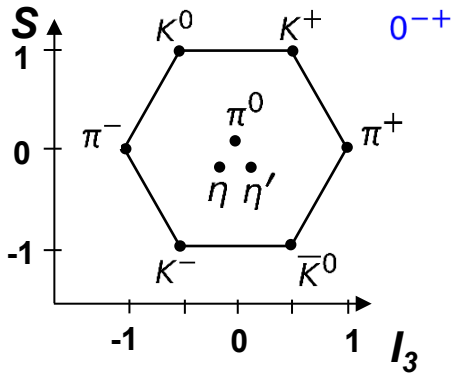
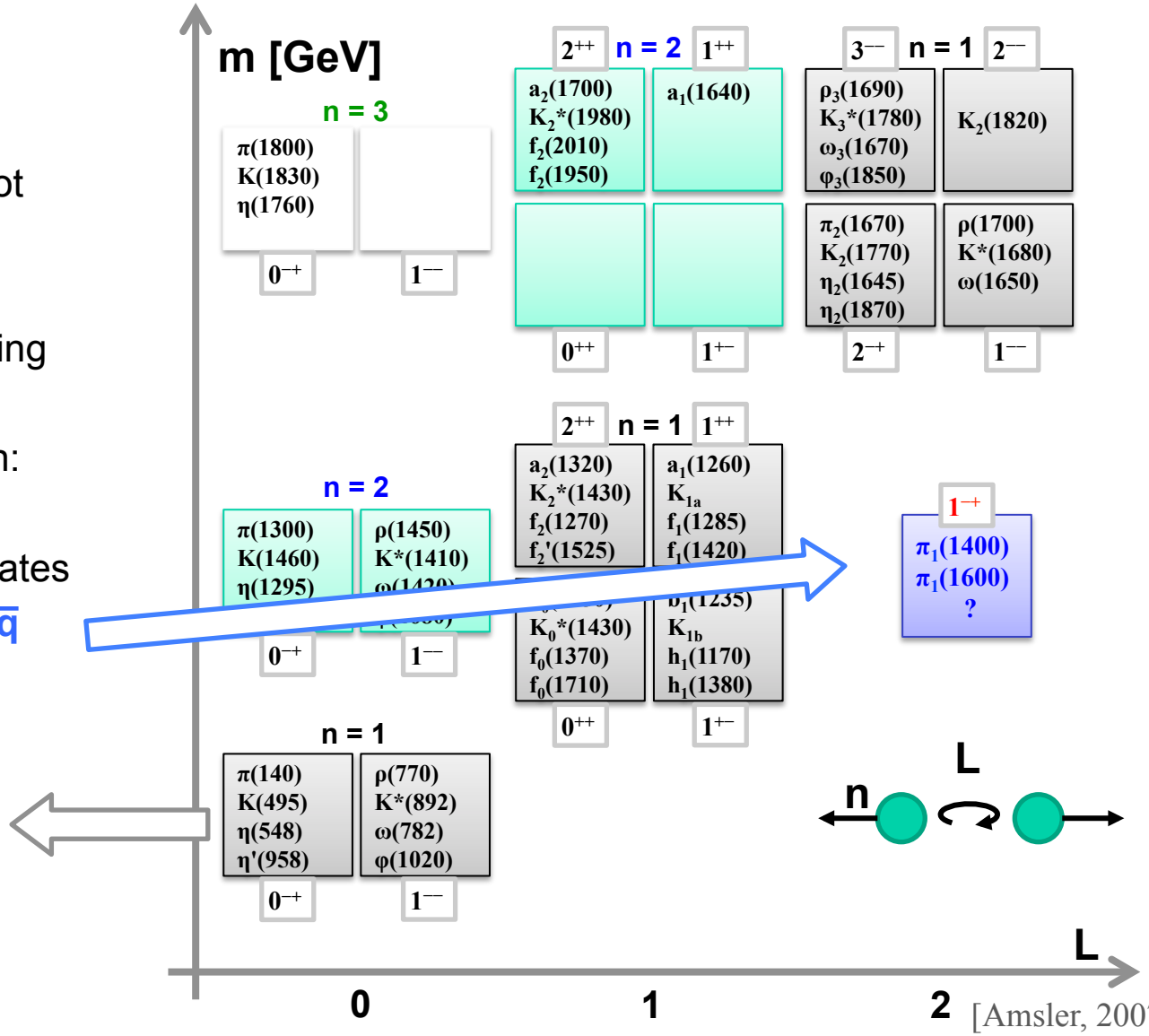
- Eightfold way, Gell-Mann:
  => J^{PC} **multiplets**
- Search for spin-exotic states
  => **avoid mixing with $q\bar{q}$**





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Dalitz Plot Analysis $\pi_1(1400)$ -- Crystal Barrel

- 3-body reaction: $\bar{p}n \rightarrow \pi^-\pi^0\eta$ (at rest)

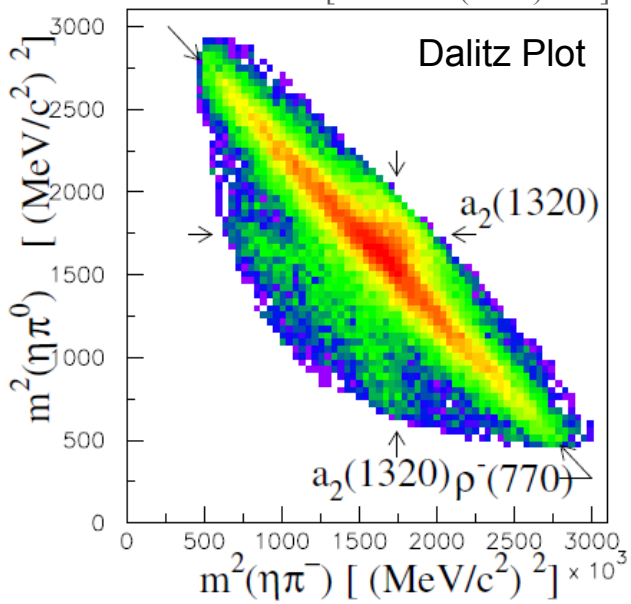
- Dalitz Plot Analysis:
  - 2D intensity study in 3-body reactions
  - 2 variables describe complete dynamics
  - reveals 2-body resonances in the system

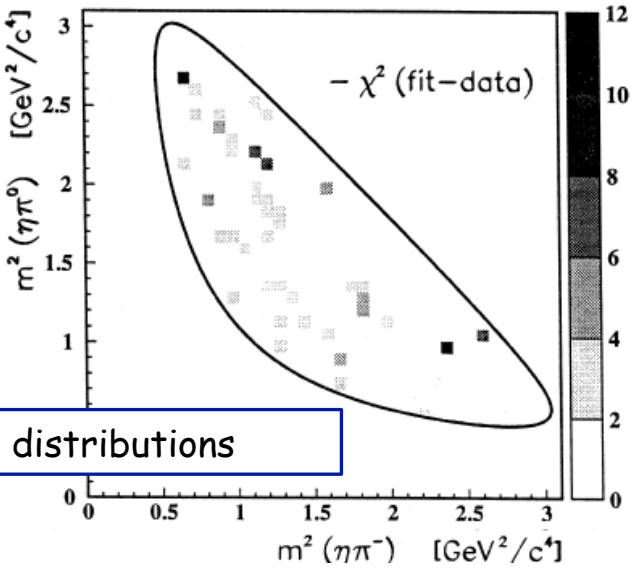
- Find set of resonances T_i and coefficients c_i, such that $I = |\Sigma c_i T_i|^2$ describes the data

- Fit demands $X \rightarrow \eta\pi$ (both 0^{-+}) with L=1
  (m_X = 1400±30 MeV, Γ_X = 310±70 MeV)

=> The so-called $\pi_1(1400)$, with $J^{PC} = 1^{-+}$

[PLB 423 (1998) 175]





-> flat χ^2 distributions

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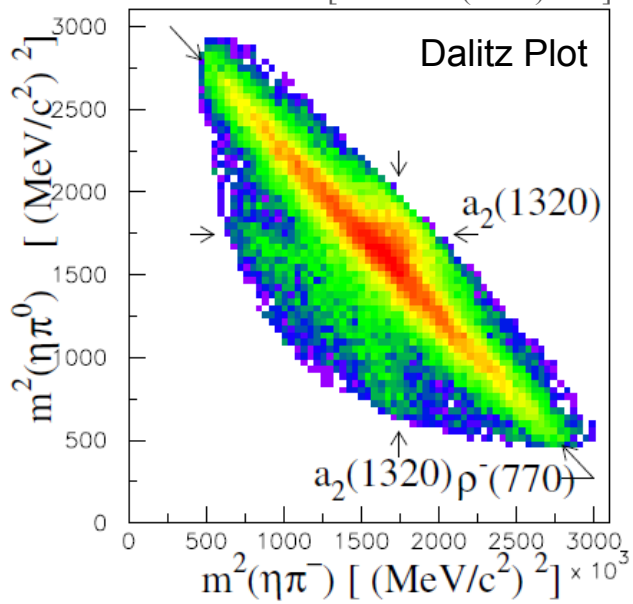

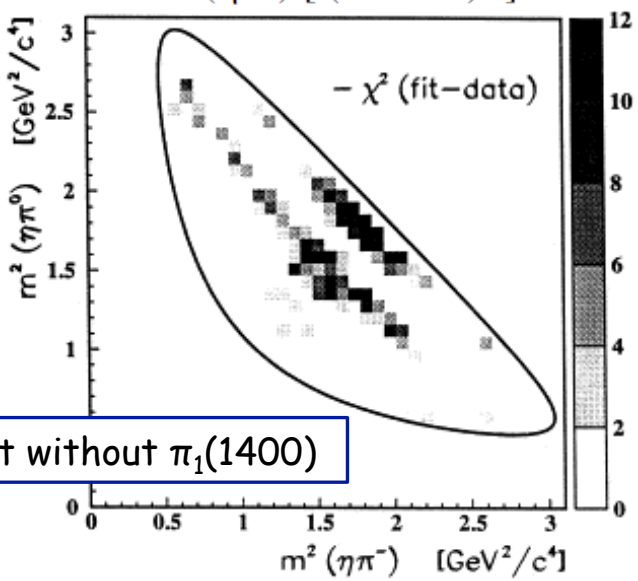

-> bad fit without $\pi_1(1400)$

Partial Wave Analysis $\pi_1(1600)$ -- COMPASS

- Observation of hybrid candidate $\pi_1(1600)$
- Diffractive pion dissociation into 3π final states,
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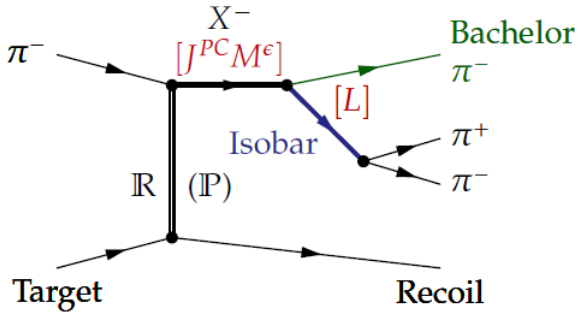
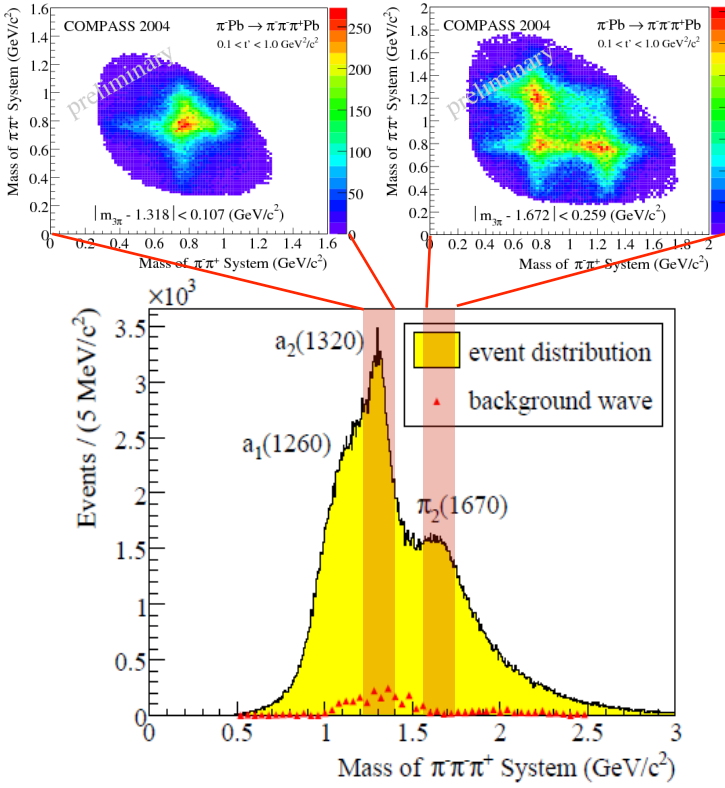


Partial-wave analysis *(isobar model)*:

- All possible isobars, $J \leq J_{max}$: 41+1 (87+1) partial-waves
- Acceptance corrections included *(normalisation integrals)*



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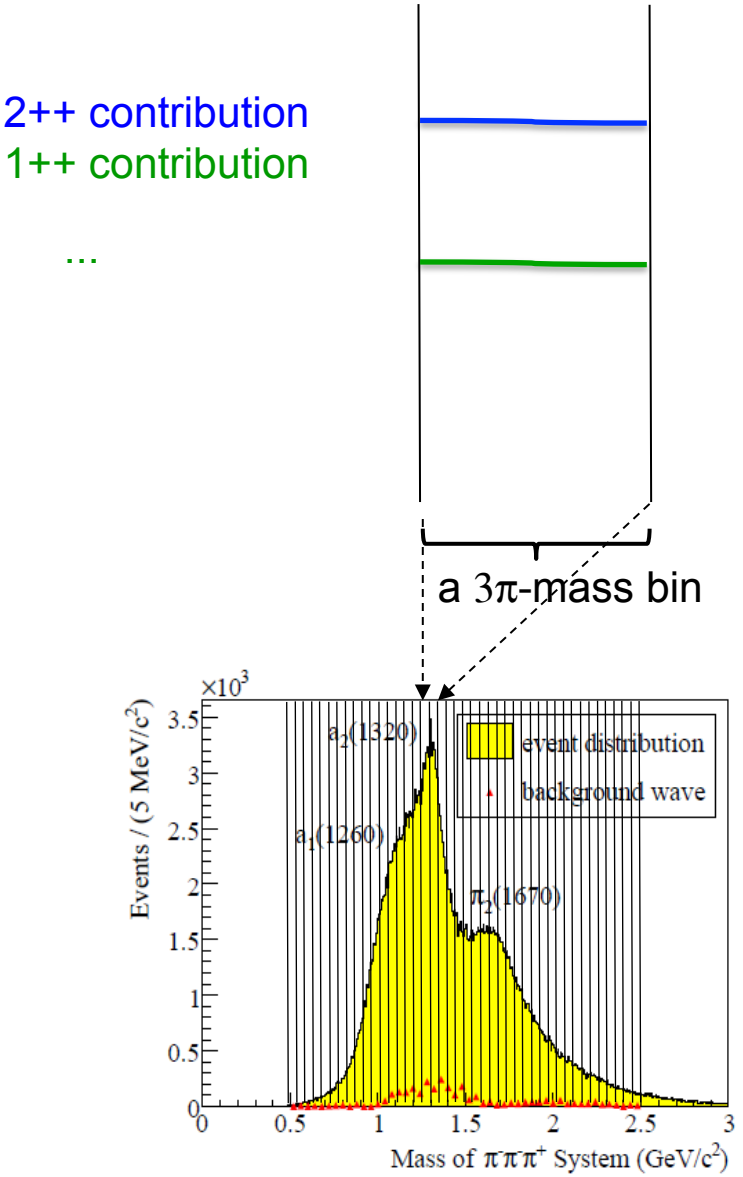
  - Extract production amplitudes and interferences



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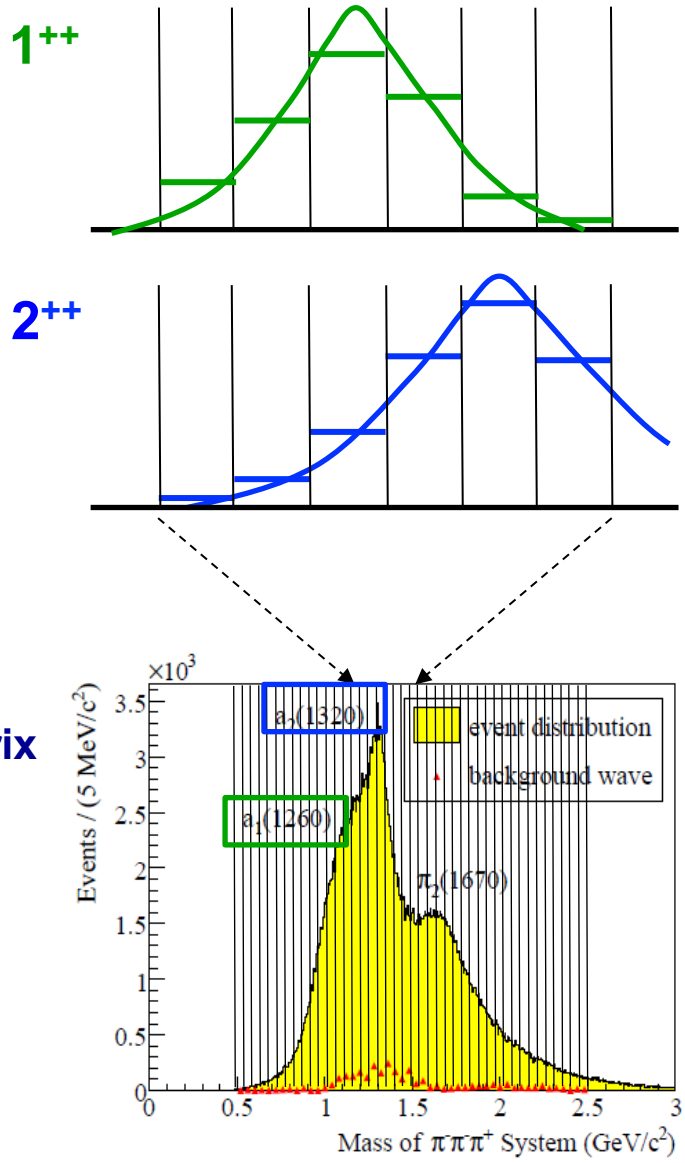
- **Step 2) χ^2 fit of mass dependence of spin-density matrix**
  - Main partial waves chosen, parameterised by Breit-Wigner fctns. fit to first step result
  - Non-resonant background for some waves



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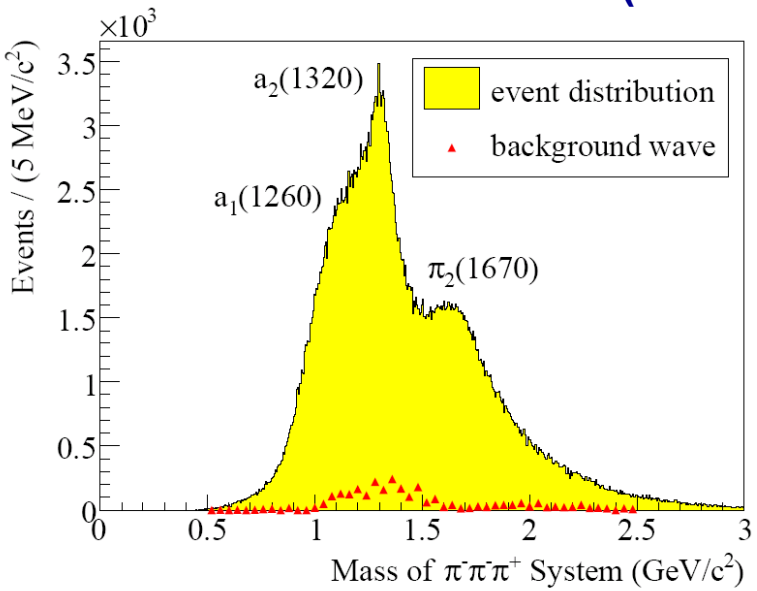
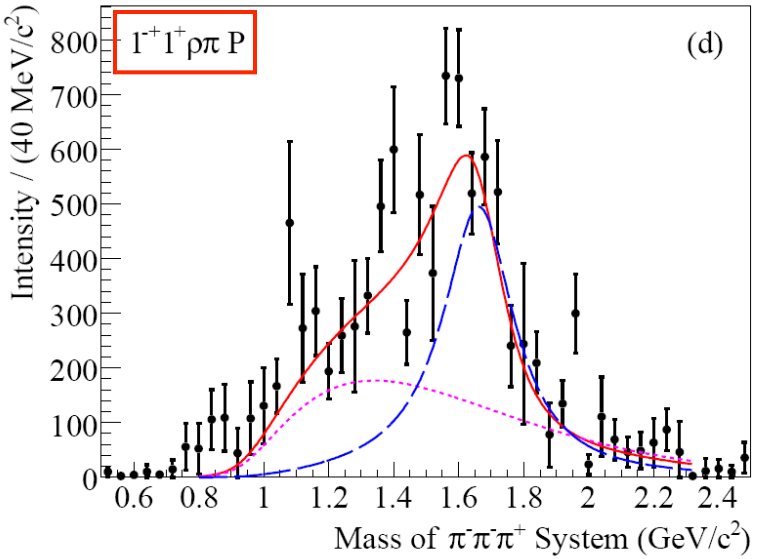
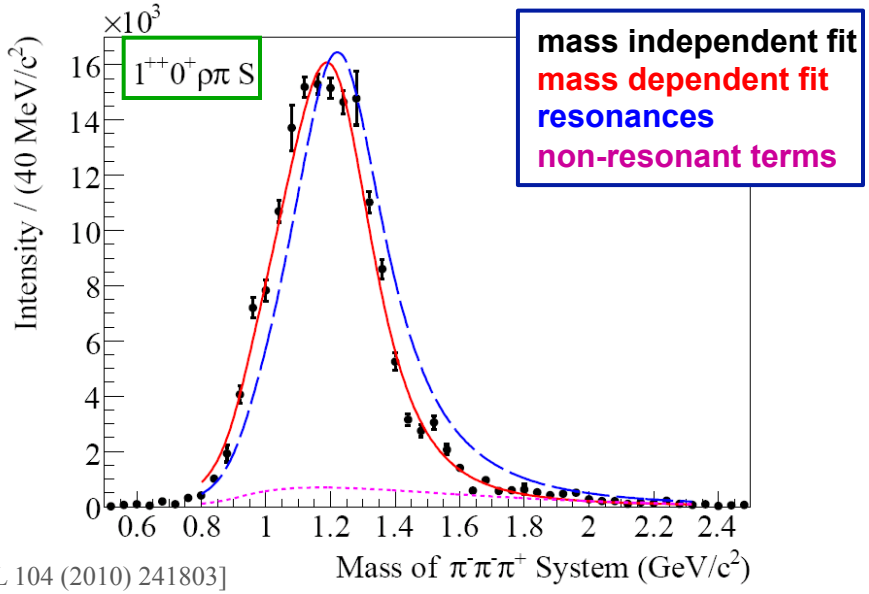
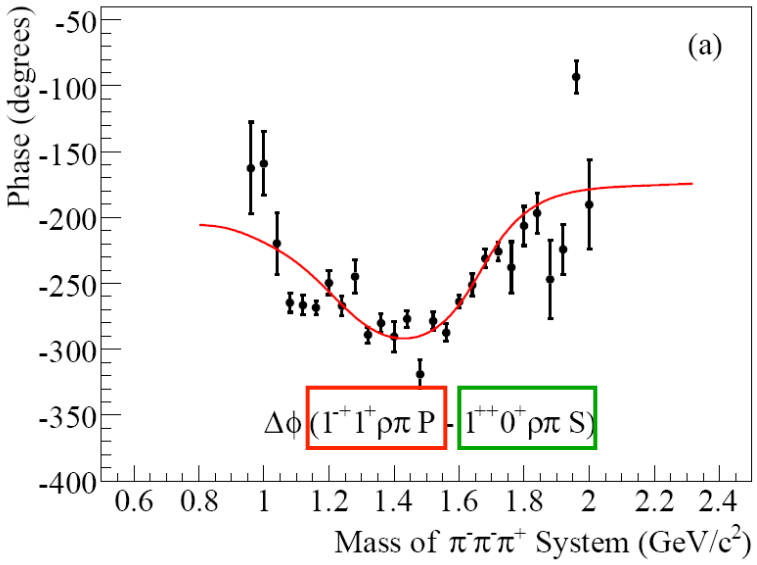
(2004 Pb target data)







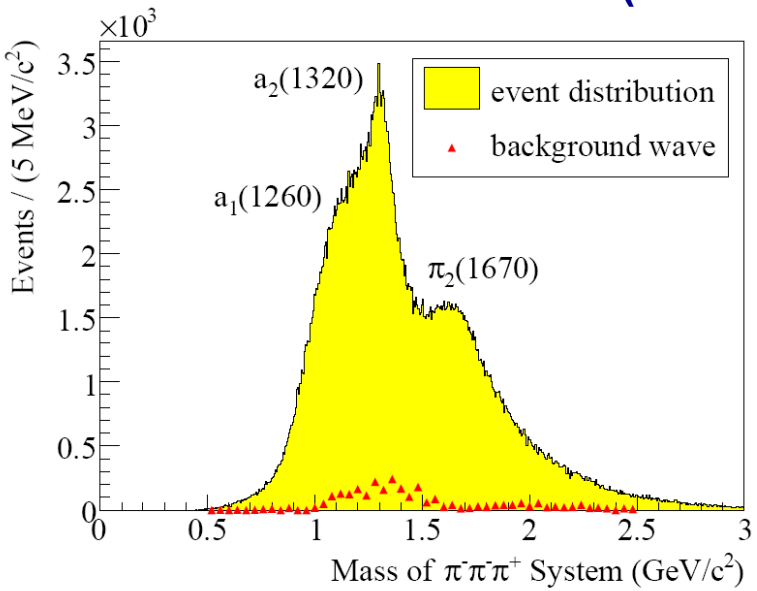
mass independent fit
mass dependent fit
resonances
non-resonant terms

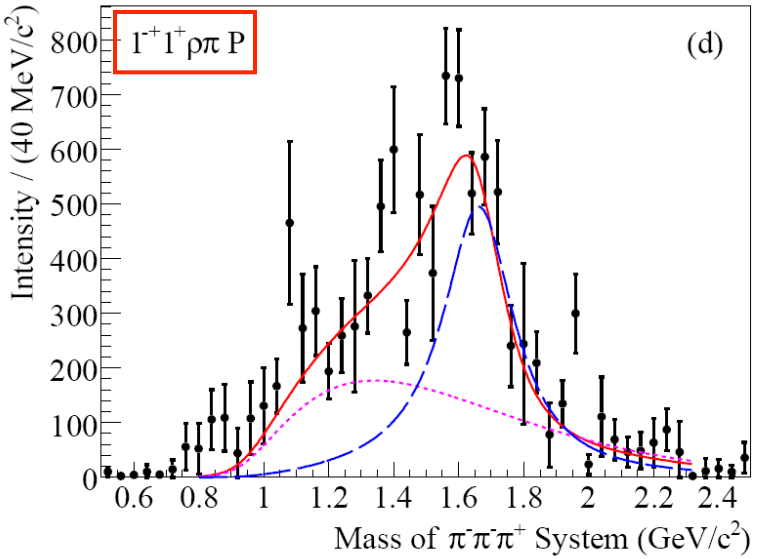


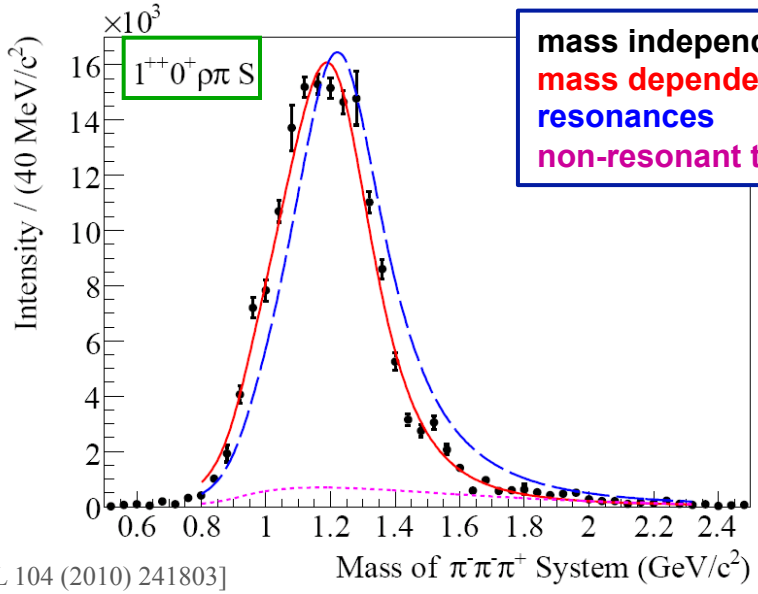
[PRL 104 (2010) 241803]

Partial Wave Analysis $\pi_1(1600)$ -- COMPASS

(2004 Pb target data)







mass independent fit
mass dependent fit
resonances
non-resonant terms

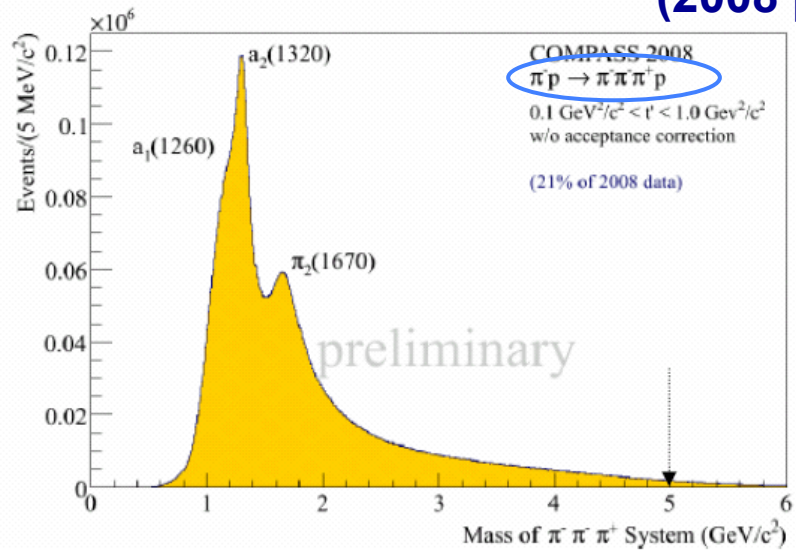
[PRL 104 (2010) 241803]

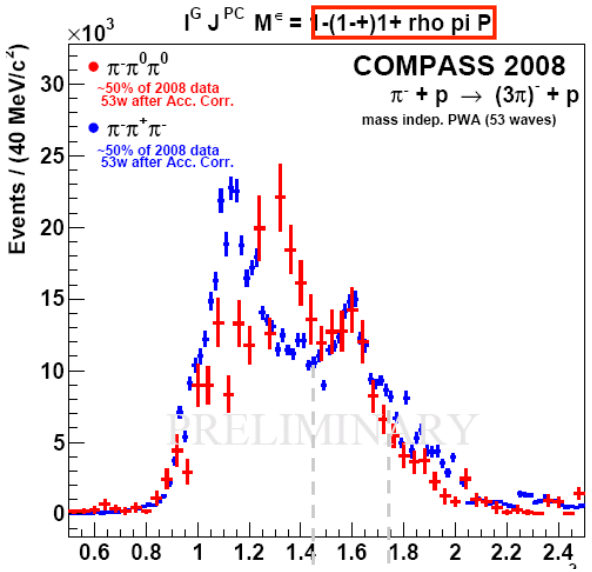
BW parameters for the $\pi_1(1600)$:

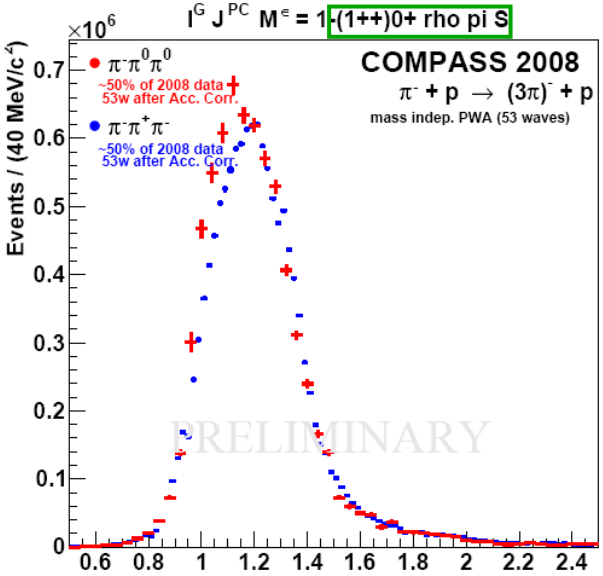
- $M = \left(1660 \pm 10^{+0}_{-64}\right) \mathrm{MeV}/c^2$
- $\Gamma = \left(269 \pm 21^{+42}_{-64}\right) \mathrm{MeV}/c^2$
- Leakage negligible (< 5%)

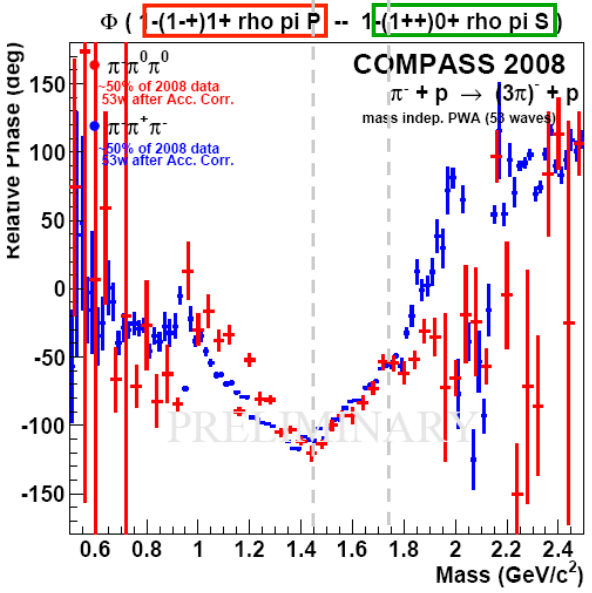
Partial Wave Analysis $\pi_1(1600)$ – COMPASS

(2008 proton target data)









[Nerling et al, Proc. MESON 2012]

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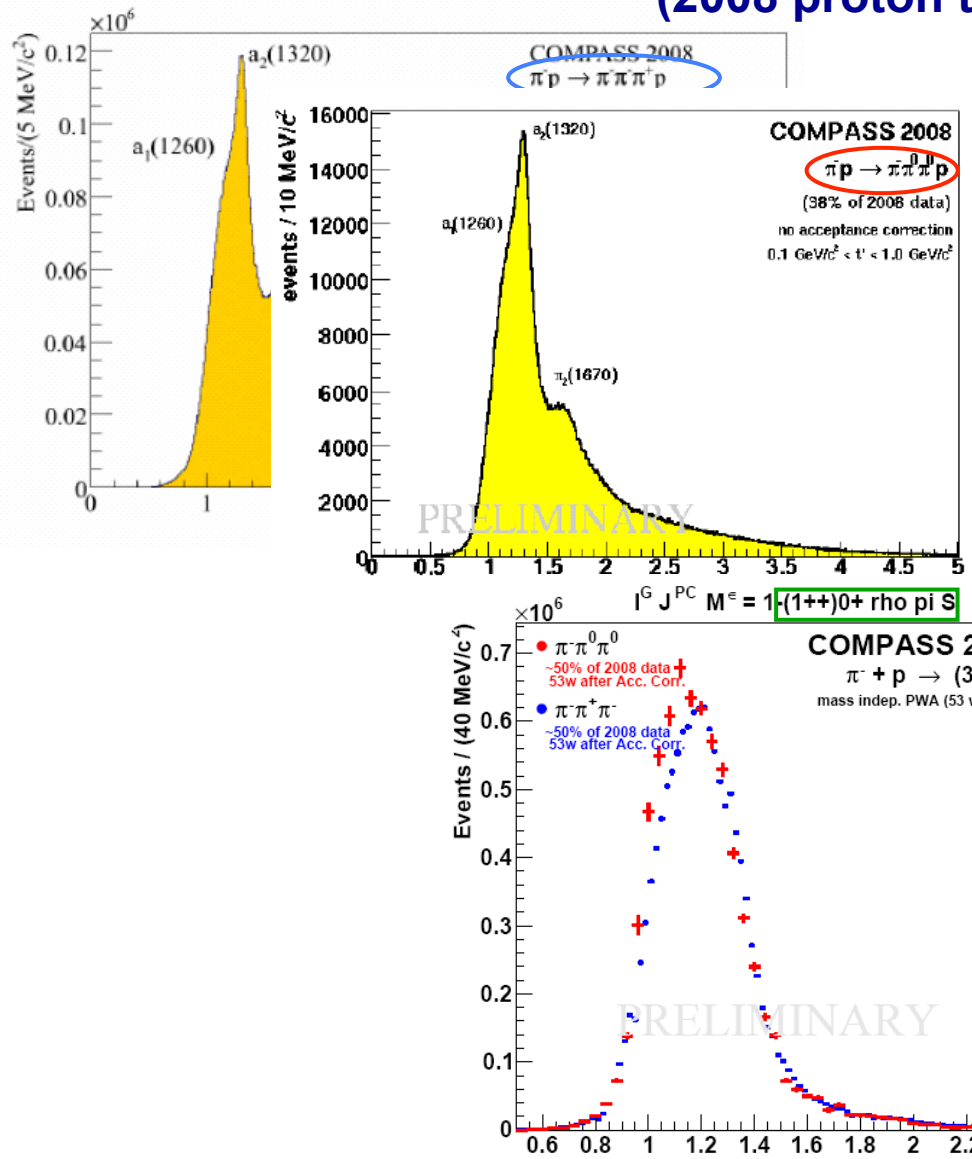

[Nerling et al, Proc. MESON 2012]

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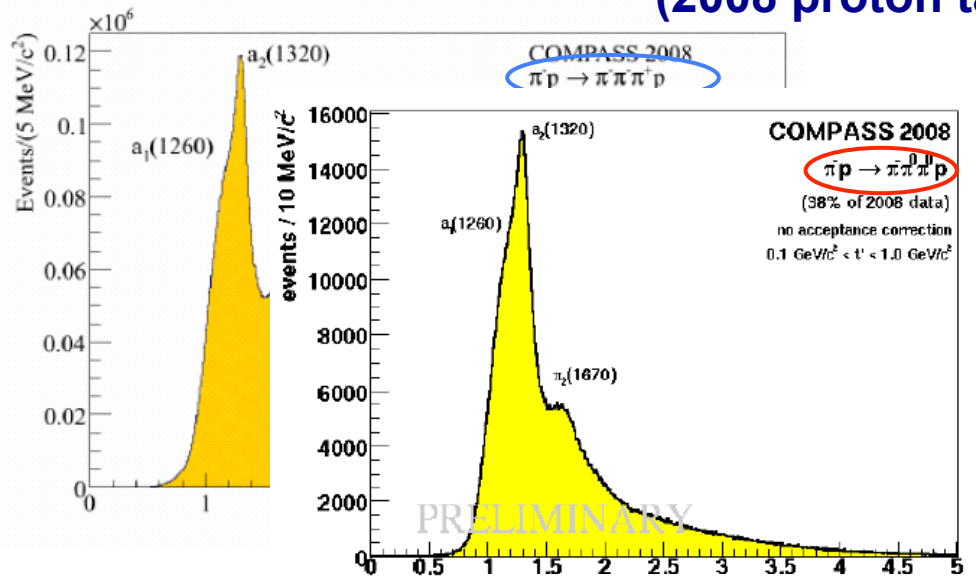
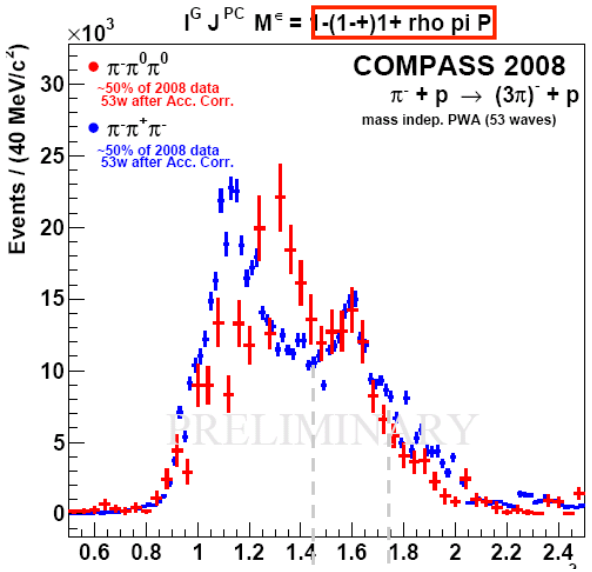
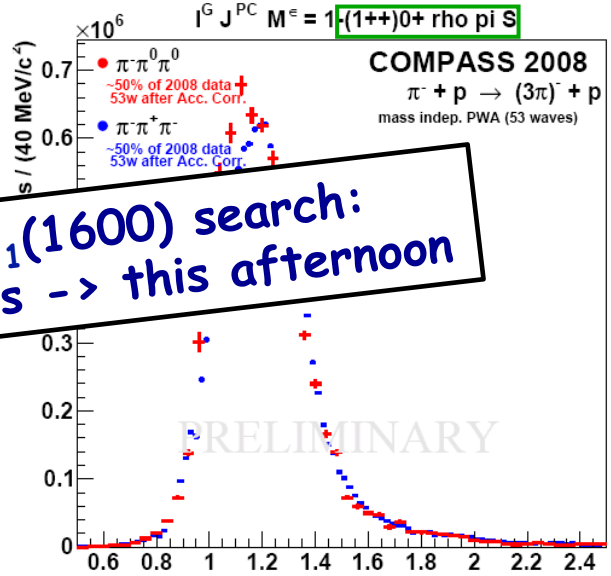
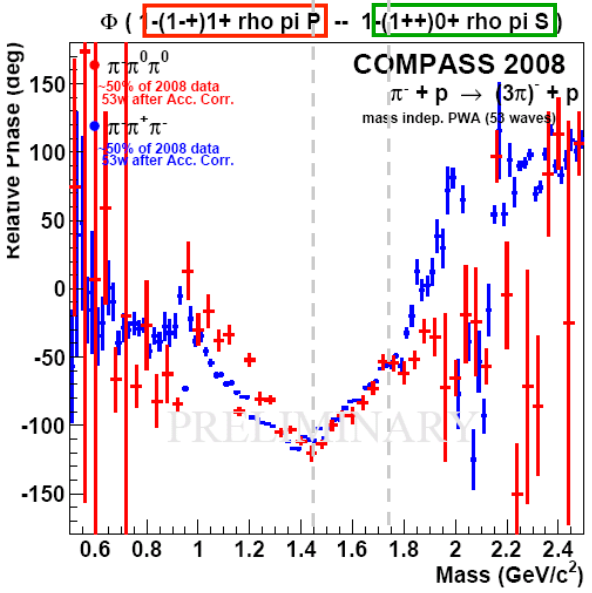




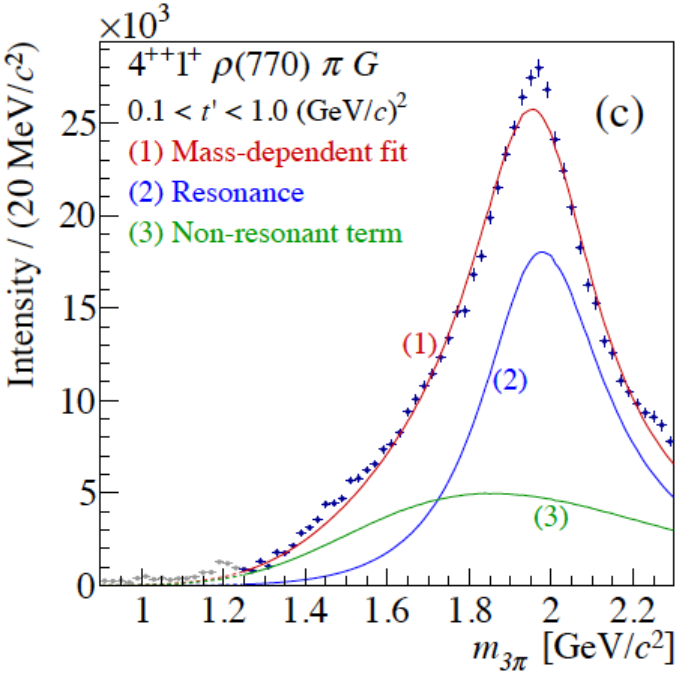


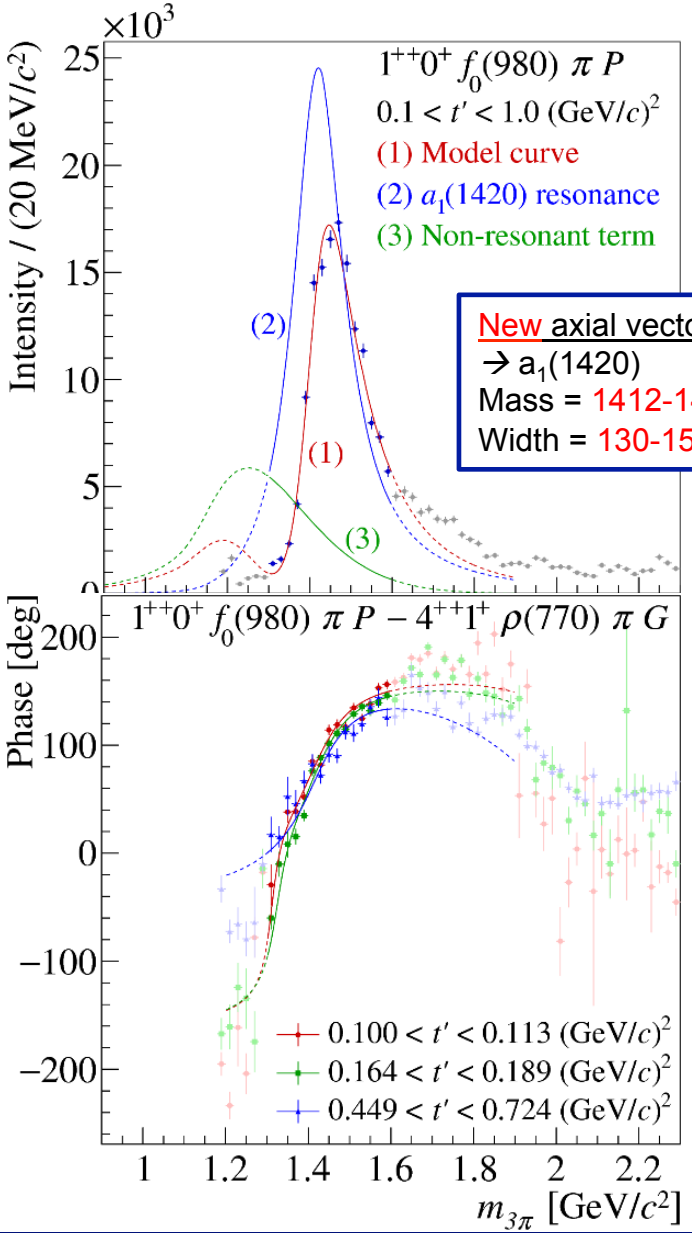


COMPASS $\pi_1(1600)$ search:
Latest status -> this afternoon

[Nerling et al, Proc. MESON 2012]

A new axial vector resonance found?





New axial vector state:
→ $a_1(1420)$
Mass = 1412-1422 MeV/c^2
Width = 130-150 MeV/c^2

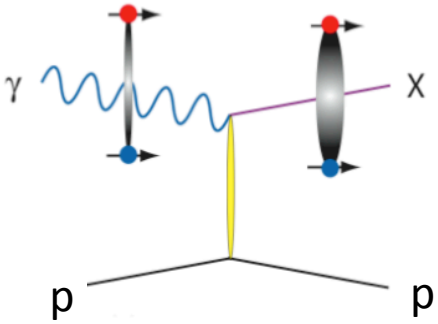
- 2nd step analysis result overlaid
  (charged mode only presently)
- New axial vector state observed
- Coupling to $K\bar{K}\pi$, and not seen in $\rho\pi$
  → *isospin partner of $f_1(1420)$?*

[Acc. PRL; hep-ex/1501.05732]

Search for spin-exotics – GlueX / JLab

Goal: Map the spectrum of spin-exotic hybrid mesons

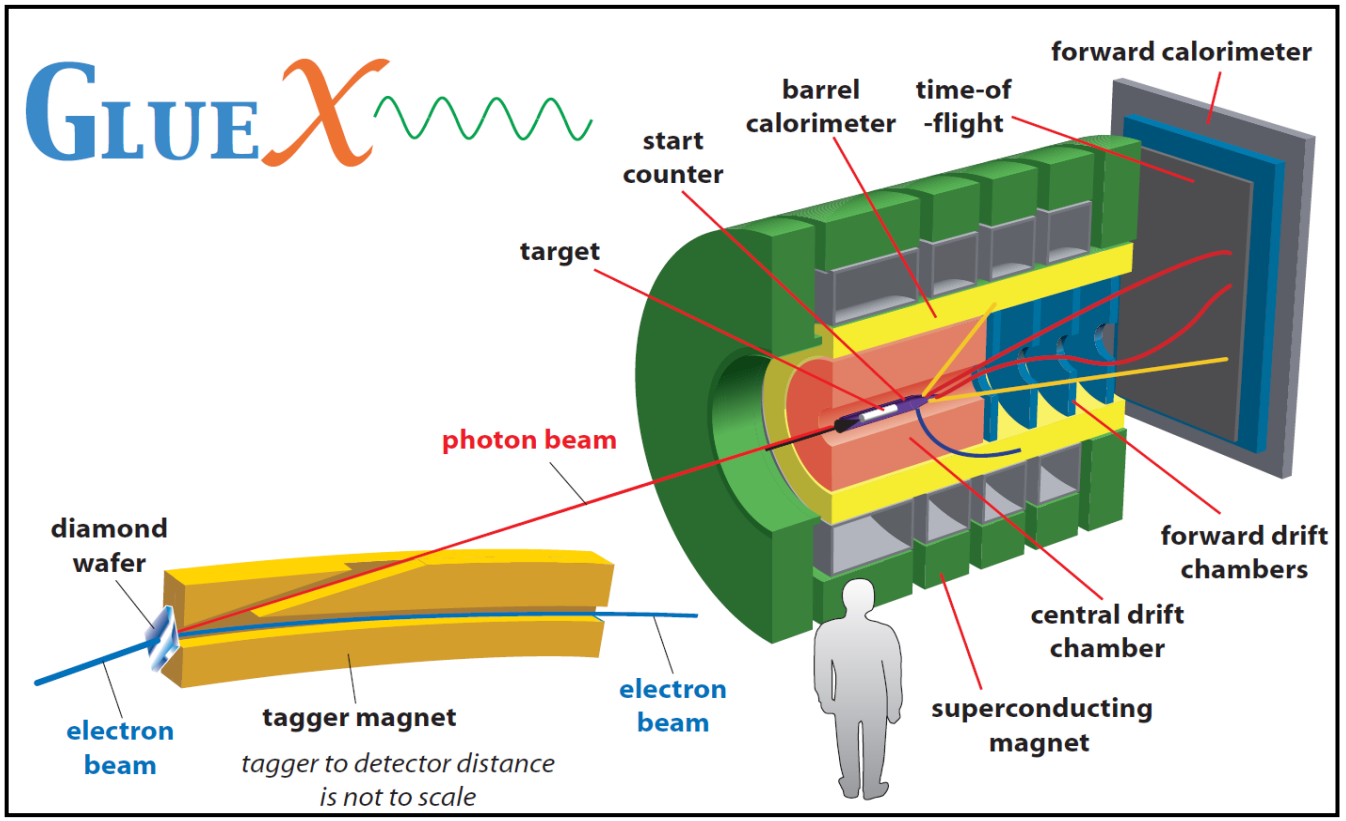
Method: Photo-production of spin-exotics (proton target),



$\gamma + p \rightarrow X + p$, where

$X \rightarrow b_1\pi$
$X \rightarrow f_1\pi$
$X \rightarrow \eta'/\eta\,\pi$
....

[courtesy C.Meyer]



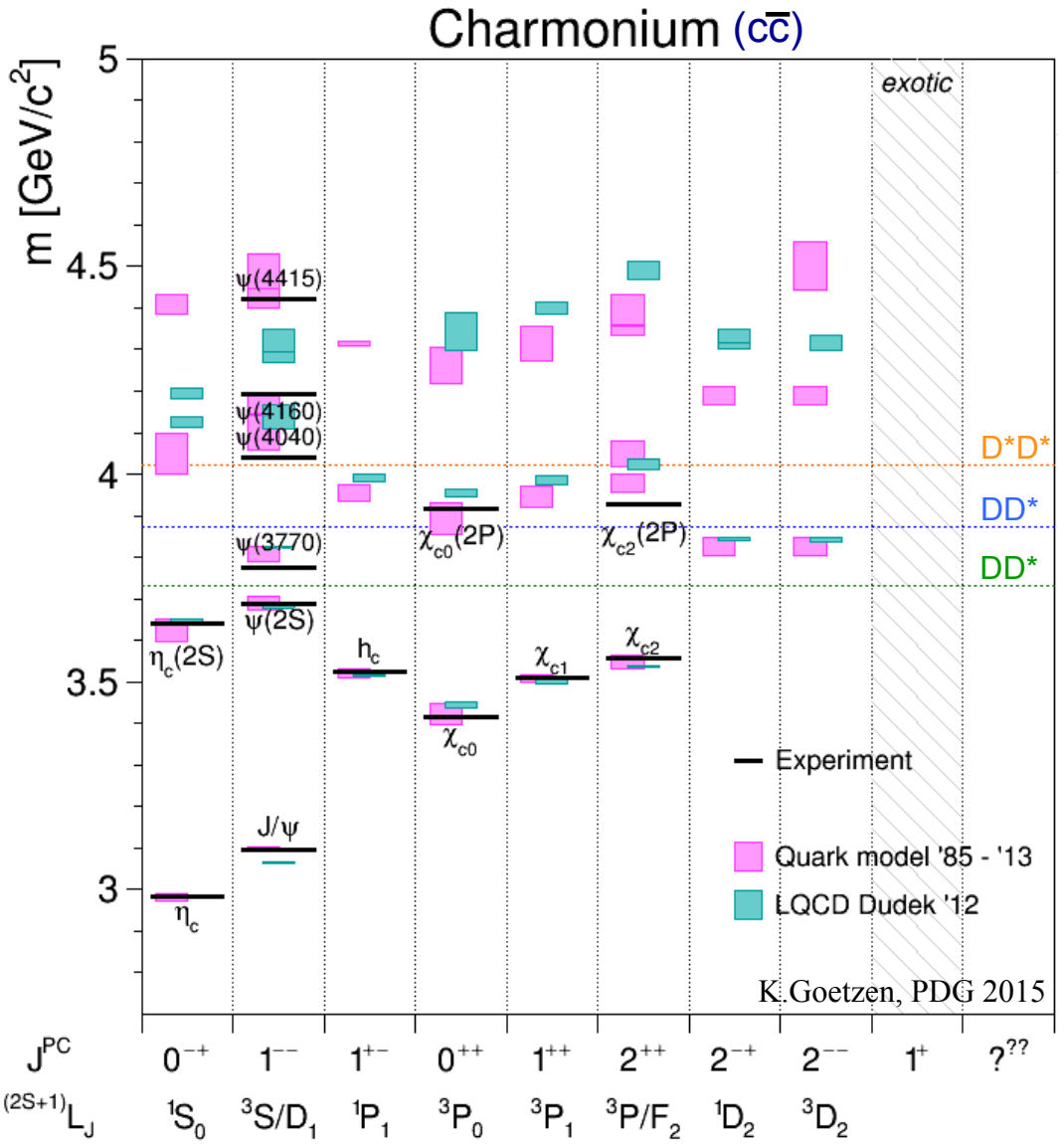
Polarised photon beam:
- 10^8 tagged γ/s (8.4 - 9.0GeV)
- Exploiting polarization

→ *π/K PID for 2017,*
→ *K_L beam proposed for future upgrade*

Heavy quark sector -- Charmonium

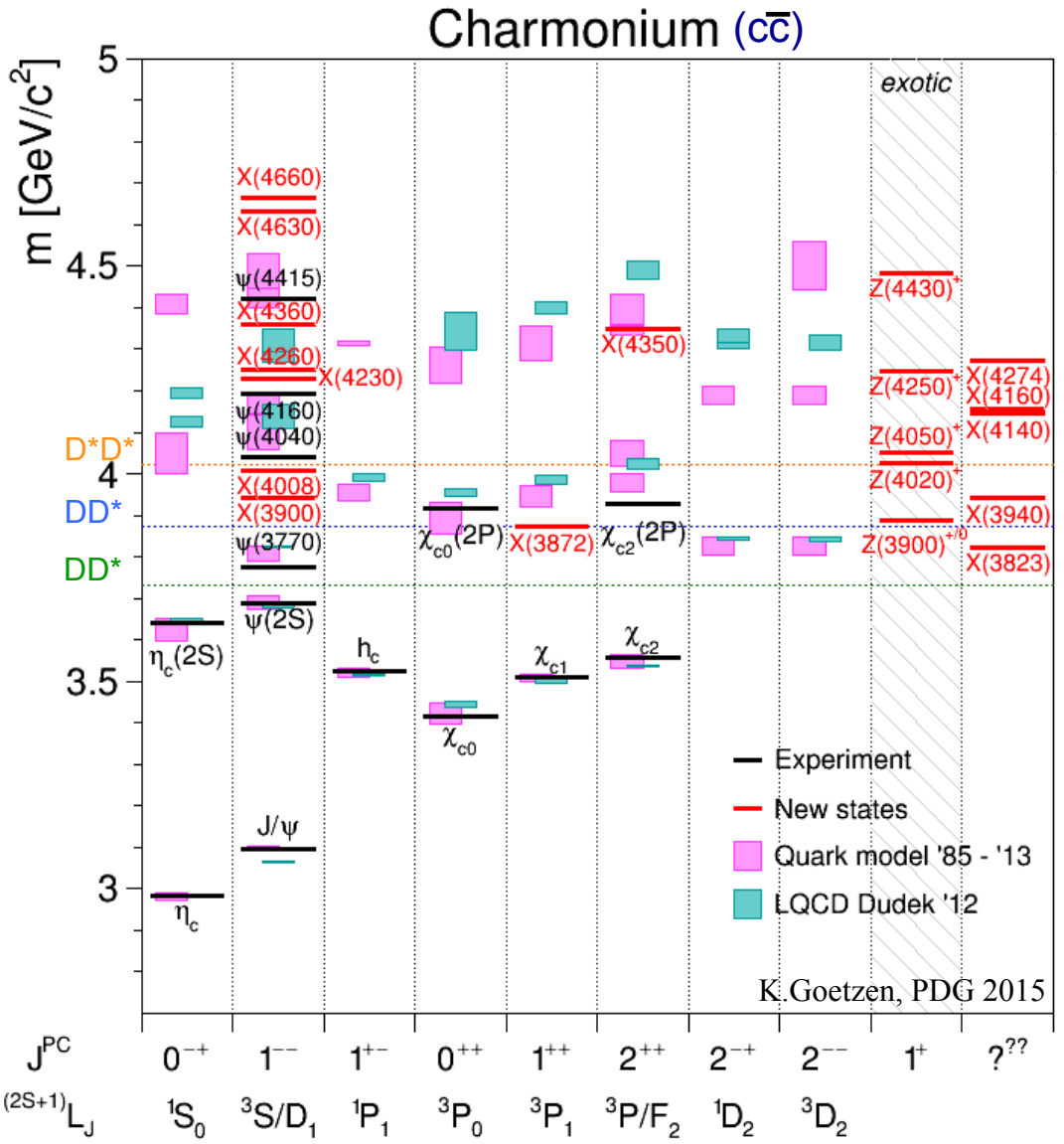
Charmonium region

- Advantages:
  - lower level density
  - longer lifetime (small width)
- Charmonium predictions fitted well until 2003



Charmonium region

- Advantages:
  - lower level density
  - longer lifetime (small width)
- Charmonium predictions fitted well until 2003
- Since 2003: ≈ 20 new states not fitting well the patterns
- Five (almost) 1st order exotics $Z(3900)^+$ ... $Z(4430)^+$
- Some suspiciously close to DD-like thresholds X(3872), Z(3900), Z(4020), ...



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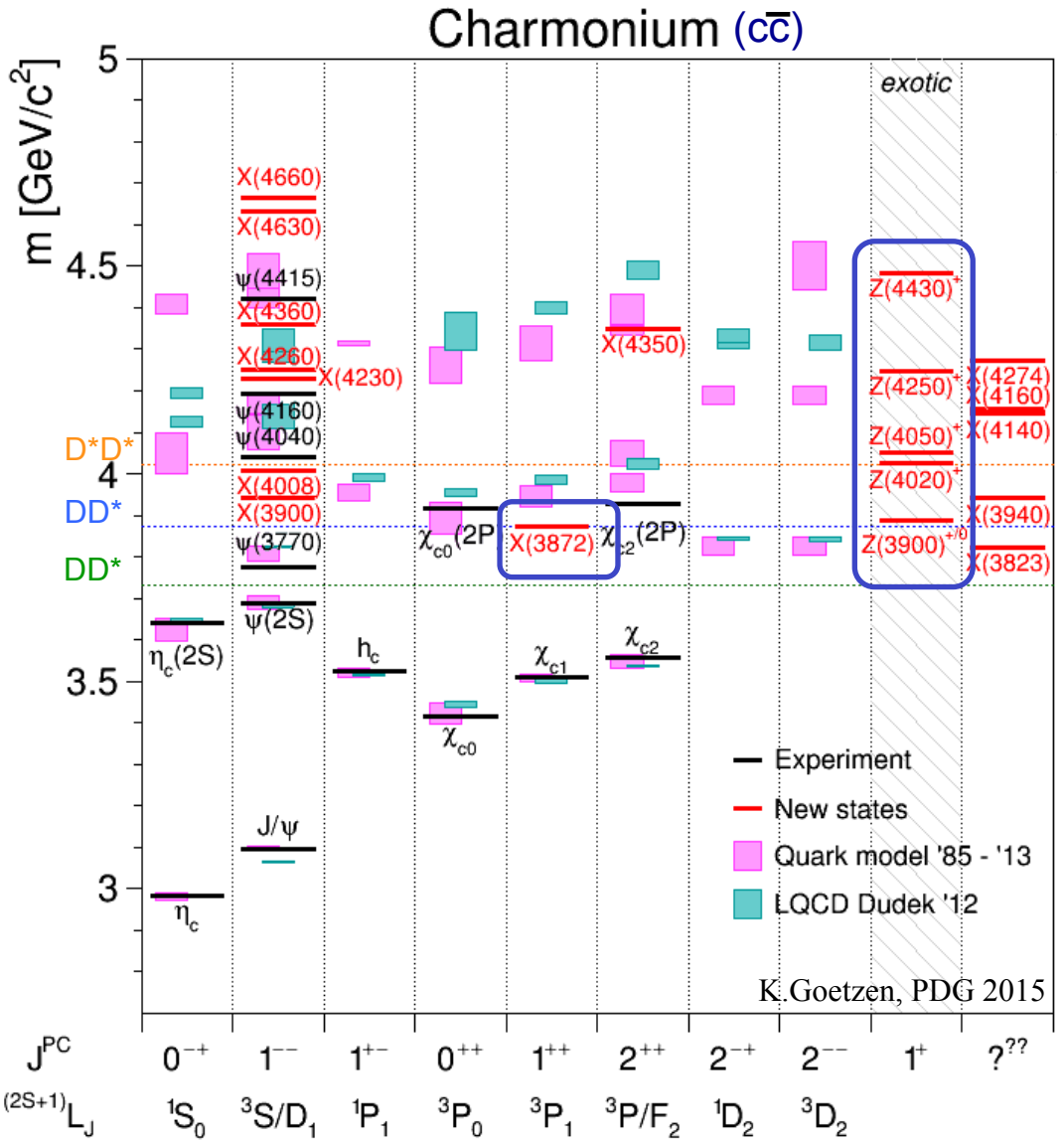


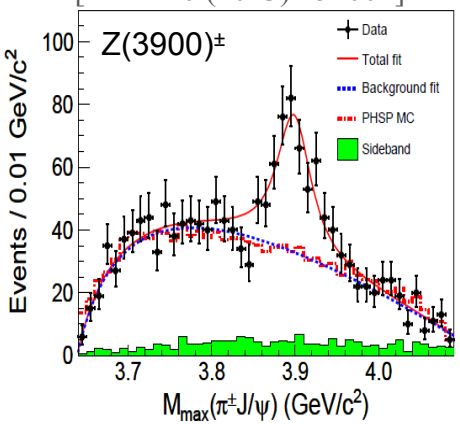
Charmonium-like exotics: Charged Z states

- All Z_c states decay to $c\bar{c}\ \pi^{+/-}$
- Manifestly exotic: tetra-quark or molecular nature

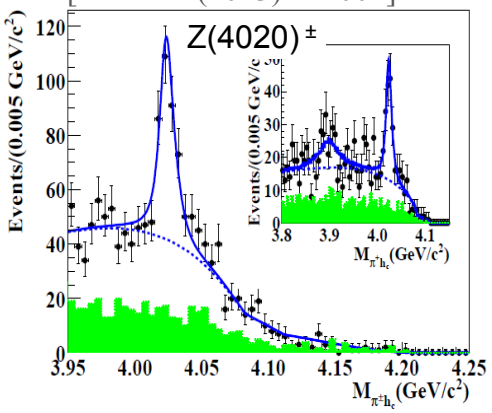
  → *Charged and too heavy for excited light* meson => Minimum quark content $c\bar{c}u\bar{d}$

  NB: First proof of exotic matter!

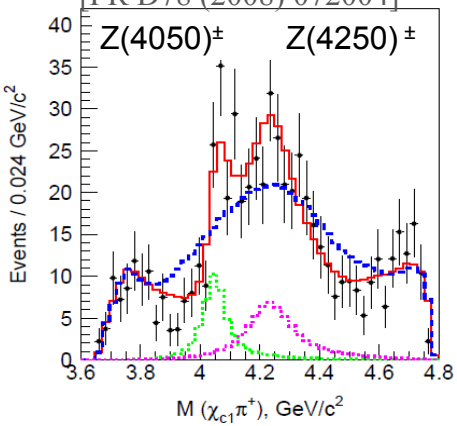
[PRL 110 (2013) 252001]



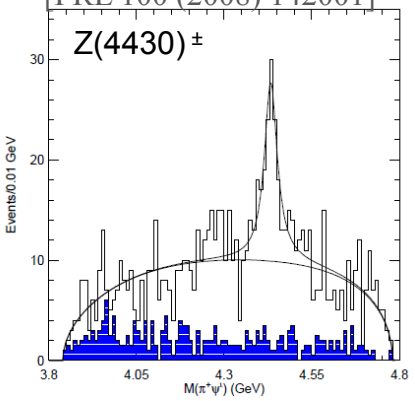
[PRL 111 (2013) 242001]



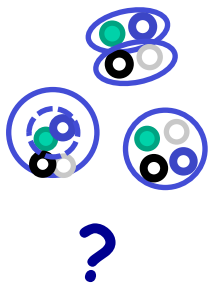
[PR D78 (2008) 072004]



[PRL 100 (2008) 142001]



Name	Γ [MeV]	cc̄ decay	open charm	closeby DD	Δm to DD [MeV]
$Z(3900)^+$	35 ± 7	$J/\psi\ \pi^+$	$(D\bar{D}^*)^+$	$D^0\bar{D}^{*+}$	9.3 ± 3.4
$Z(4020)^+$	10 ± 6	$h_c\ \pi^+$	$(D^*\bar{D}^*)^+$	$D^{*0}\bar{D}^{*+}$	6.7 ± 2.4
$Z(4050)^+$	82 ± 40	$\chi_c(1P)\ \pi^+$	?	$D^0\bar{D}^{*+}$	34 ± 2.4
$Z(4250)^+$	177 ± 100	$\chi_c(1P)\ \pi^+$	?	$D^0\bar{D}^{*+}$	-38 ± 50
$Z(4430)^+$	200 ± 50	$\psi(2S)\ \pi^+$	?	$D^{*+}\bar{D}_1$	12 ± 40

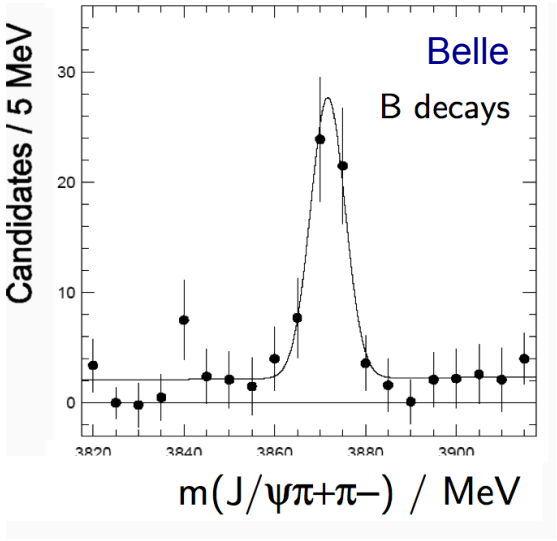


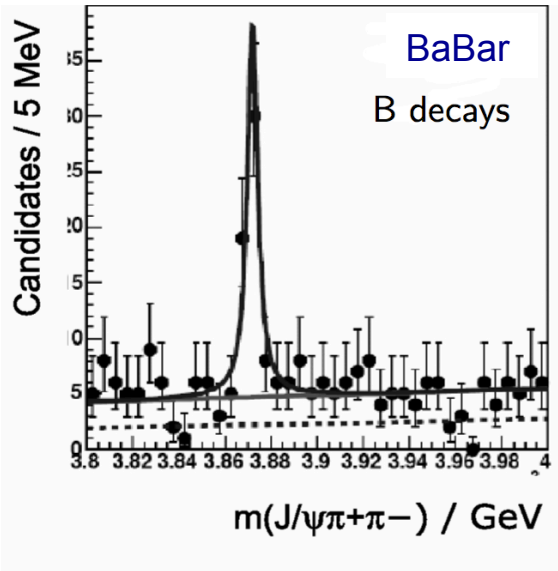
The *mysterious* X(3872)

Already known:

- Observed by (in) 7 (6) experiments (decay channels)
  (J/ψρ, J/ψω, J/ψγ, ψ'γ, $D\bar{D}\pi^0$, $D^*\bar{D}$)
- Quantum numbers $J^{PC}=1^{++}$, charmonium potential model: χ_{c1}'
  → *predicted mass ≥ 50 MeV larger*
  [Barnes, Godfrey, Swanson, Phys. Rev. D72 (2005) 054026]
- Not produced in $e^+e^- \to \gamma^* \to X(3872)$
  ($e^+e^- \to \gamma^*\gamma^* \to X(3872)$ possible but suppressed)
- Pecularities:
  - 50 - 100 MeV too light for $\chi_{c1}(2P)$
  - extremly close to DD* threshold:
    $m_X - m_{DD^*} = 0.11 \pm 0.21$ MeV

  } -> molecule ?!

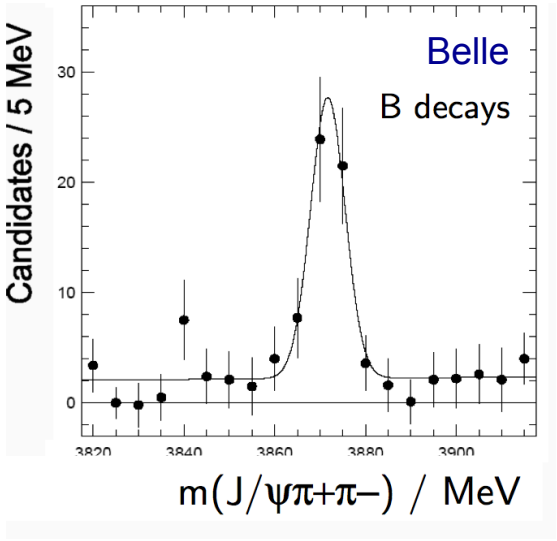




The *mysterious* X(3872)

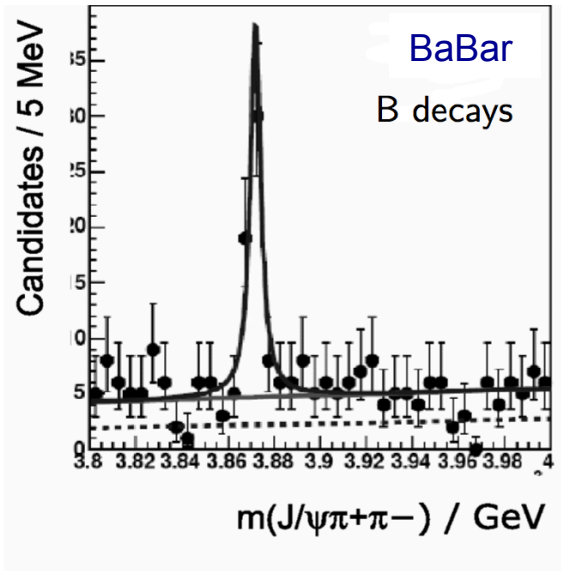
Important knowledge missing & needed:

- Width, only upper limit (BelleI): $\Gamma < 1.2\,\mathrm{MeV}$
  → *prediction for pure charmonium state χ_{c1}':*
  $\Gamma = 40\,keV$ [G.Y. Chen, J.P. Ma, Phys. ReV. D77 (2008) 034019]
  → *prediction for molecule, must be larger than width of D*:*
  $\Gamma > 82.3 \pm 1.2 \pm 1.4\,keV$ [E.Braaten, Phys. Rev. D77 (2008) 034019]



A word on statistics:

- Belle II: ~1500 by the year 2020
- BESIII: ~20 per month
- PANDA: ~130 (1300) per day
  in high resolution (luminosity) mode



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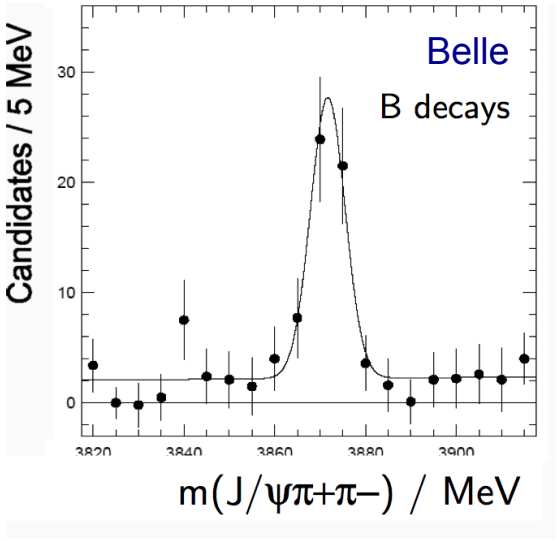

=> Precise (sub-MeV) measurement of the width of the X(3872), indeed needed the lineshape!

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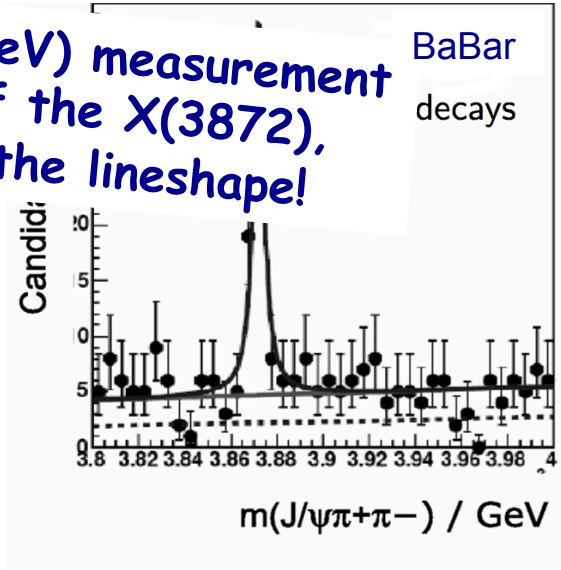
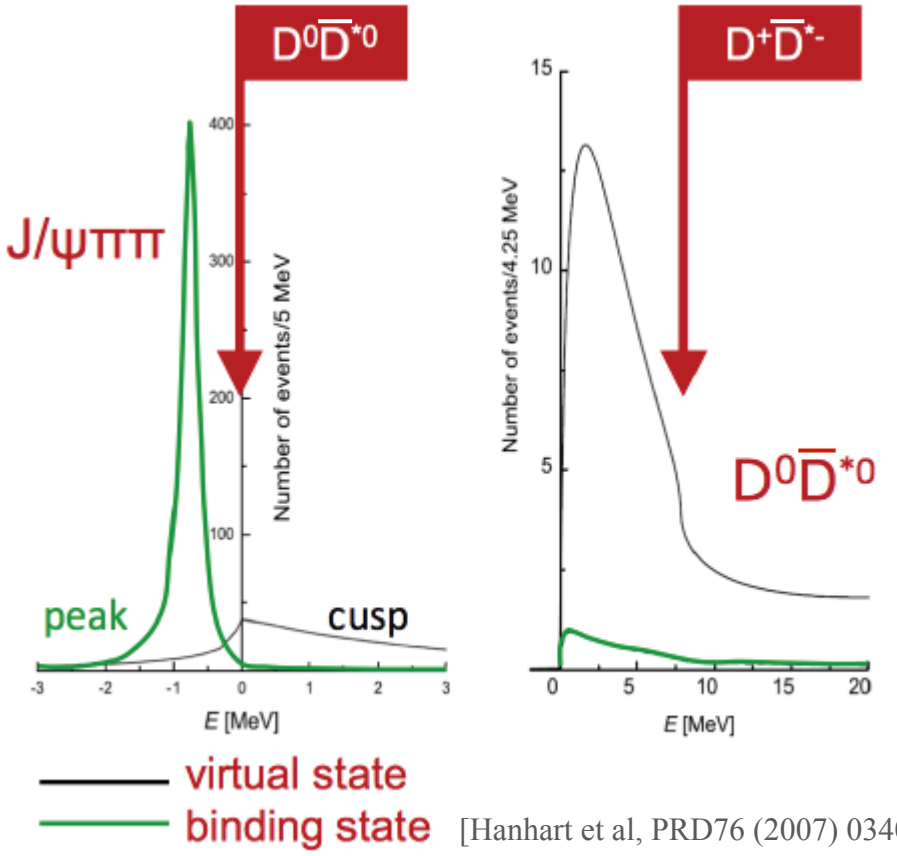
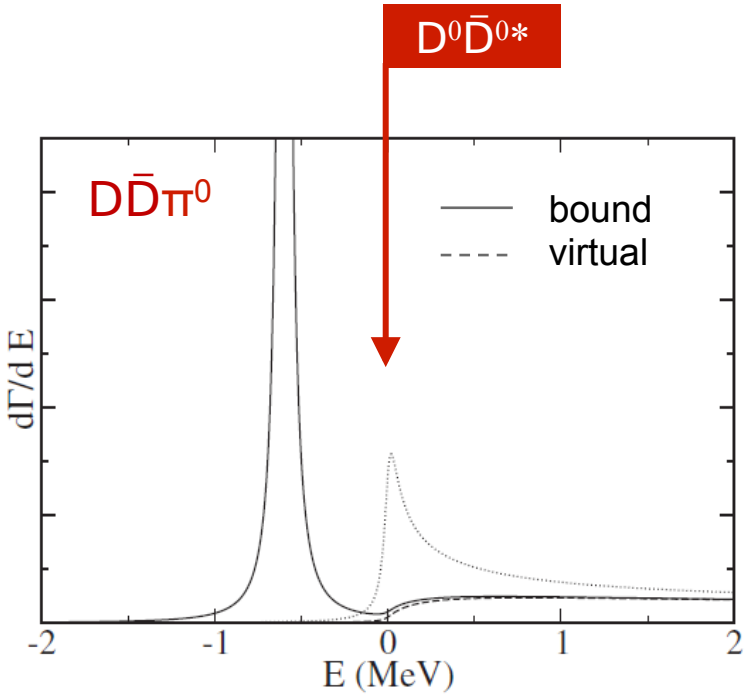


What is the nature of the X(3872)?

- For clarification: Measurement of width & line shape essential



[Hanhart et al, PRD76 (2007) 034007]



[E.Braaten, M.Lu, PRD77 (2008) 014029]

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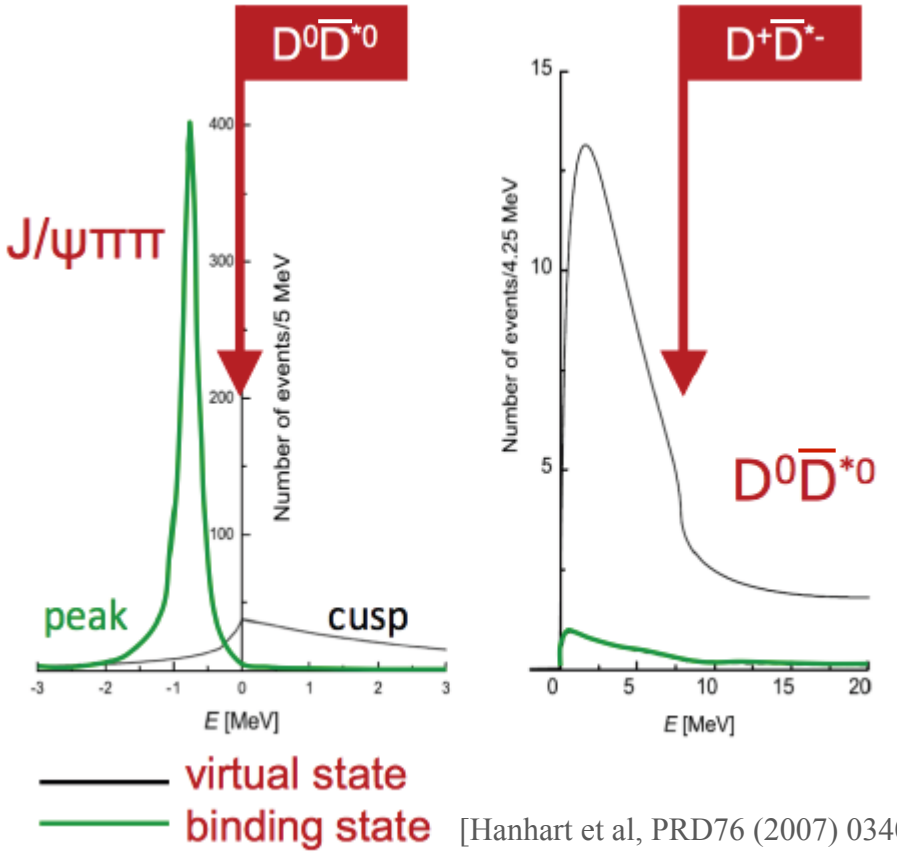

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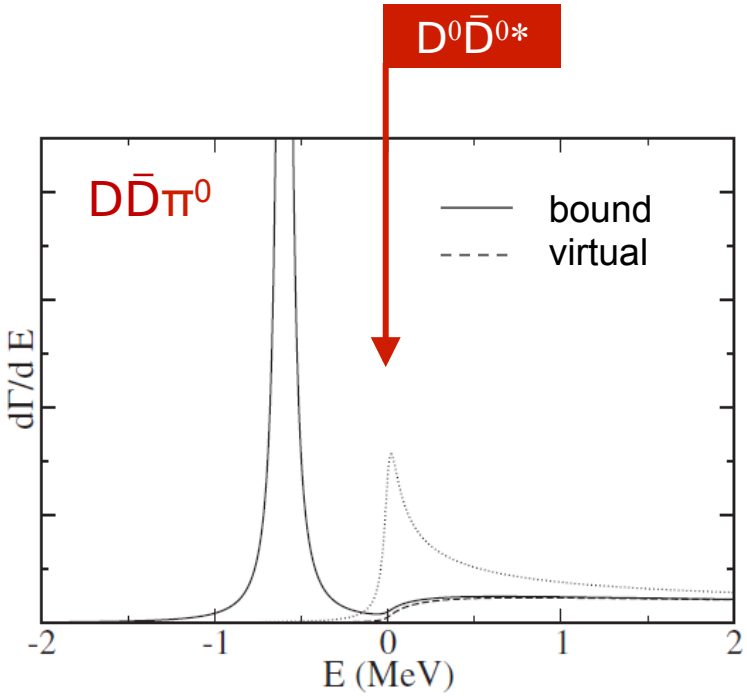
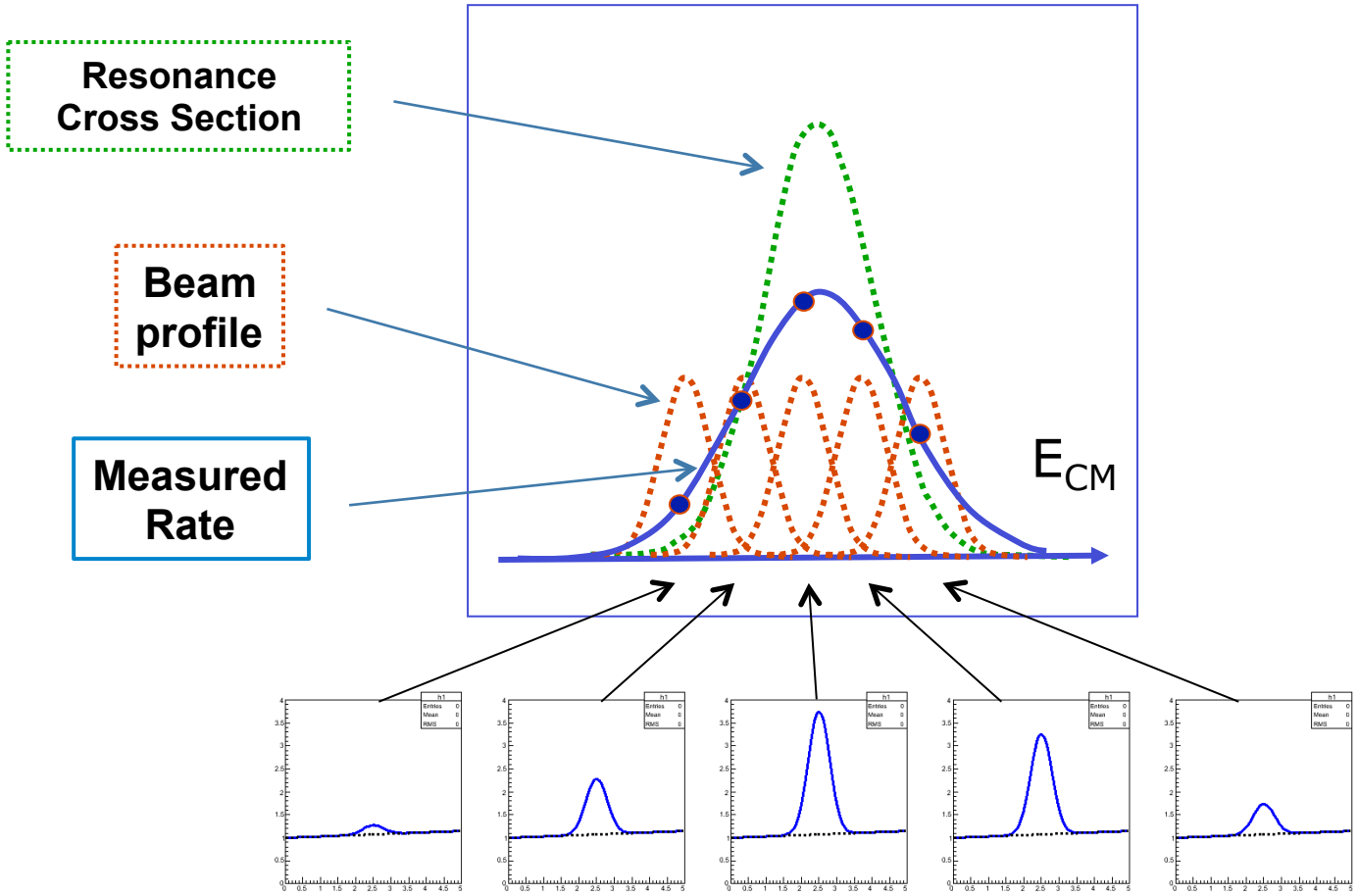


[E.Braaten, M.Lu, PRD77 (2008) 014029]

=> Need $\bar{p}p$ scan experiment to access the line shape!

(NB: 1^{++} state not possible in formation for e^+e^-)

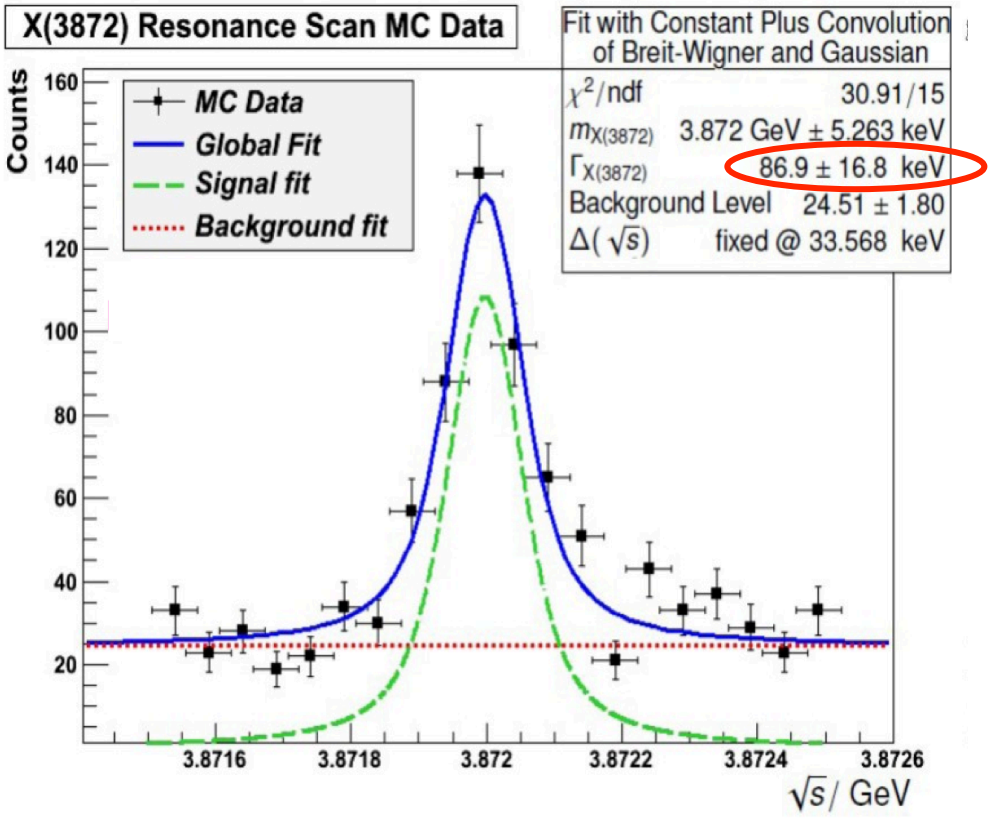
Anti-Protons – Resonance Scan Method

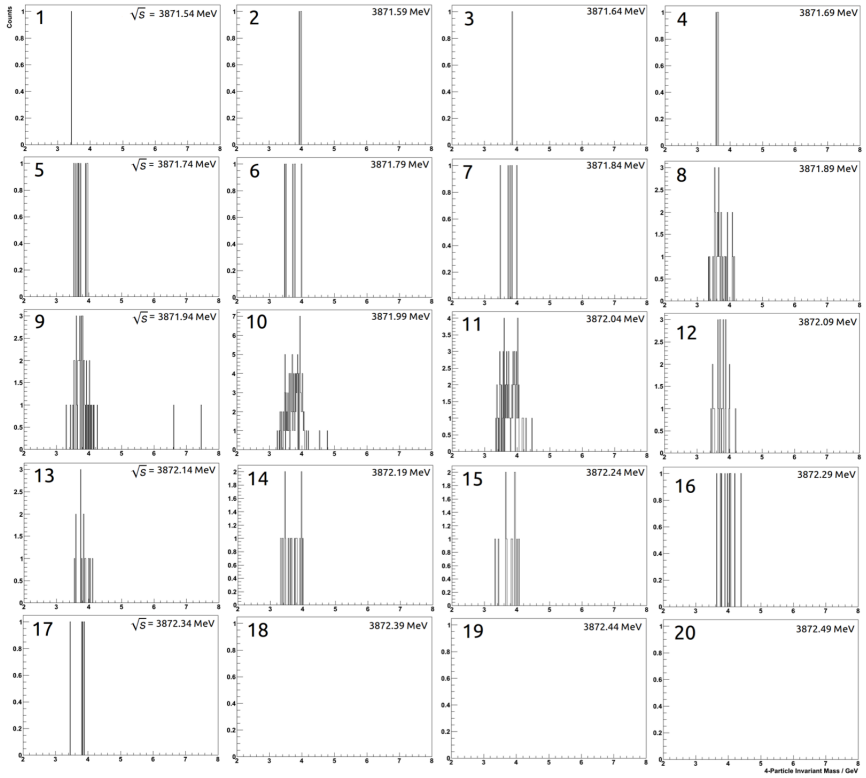


- Cooled $\bar{p}$ beam: Excellent energy resolution!
- Production rate: Convolution of resonance and beam profile
- Principle has been proven to work ...

X(3872) – Energy scan at PANDA (MC study)

- Upper limit on branching ratio by LHCb:
  $BR(X \to \bar{p}p) < 0.002 * BR(X \to J/\psi \pi\pi^+) \rightarrow \Gamma < 1.2$ MeV EPJ C73 (2013) 2462
- And $BR(X \to J/\psi \pi^-\pi^+) > 0.026$ (PDG 12) $\Rightarrow \sigma(\bar{p}p \to X(3872)) < 67$ nb





- Here: Input width = 100 keV, assume σ = 50 nb, luminosity: 2×10^{31} cm^{-2}s^{-1}
- Width resolution < ~20 keV, mass resolution ~5 keV/c^2

[M.Galuska, PhD thesis]

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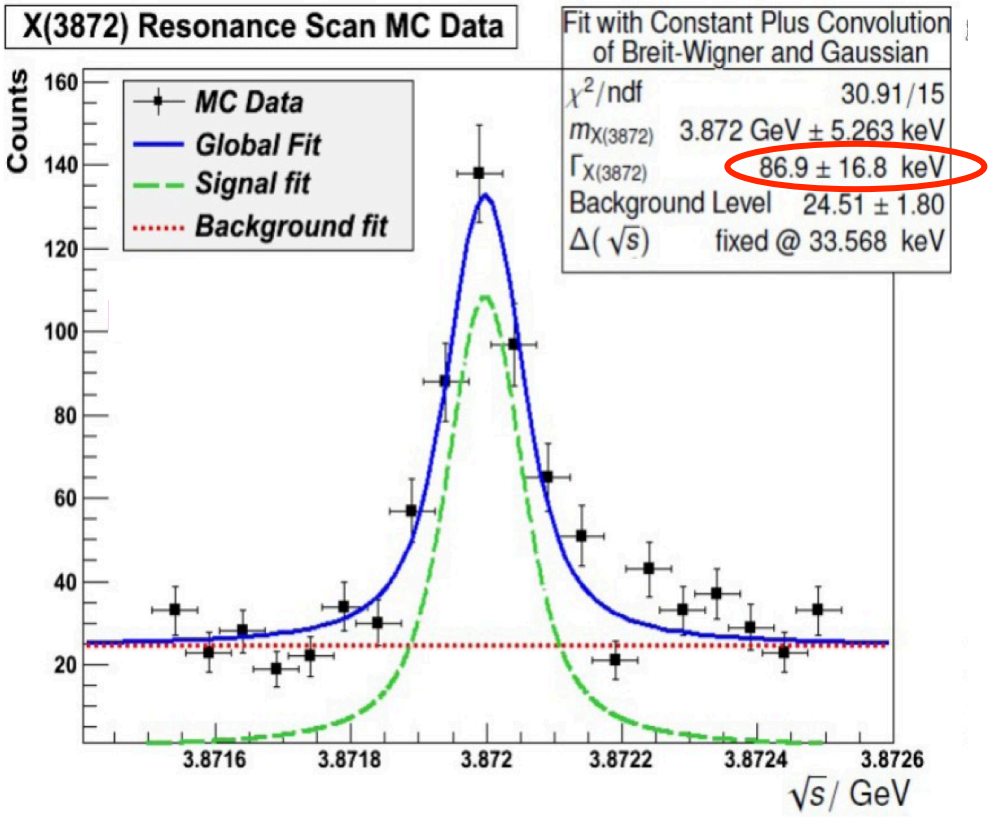

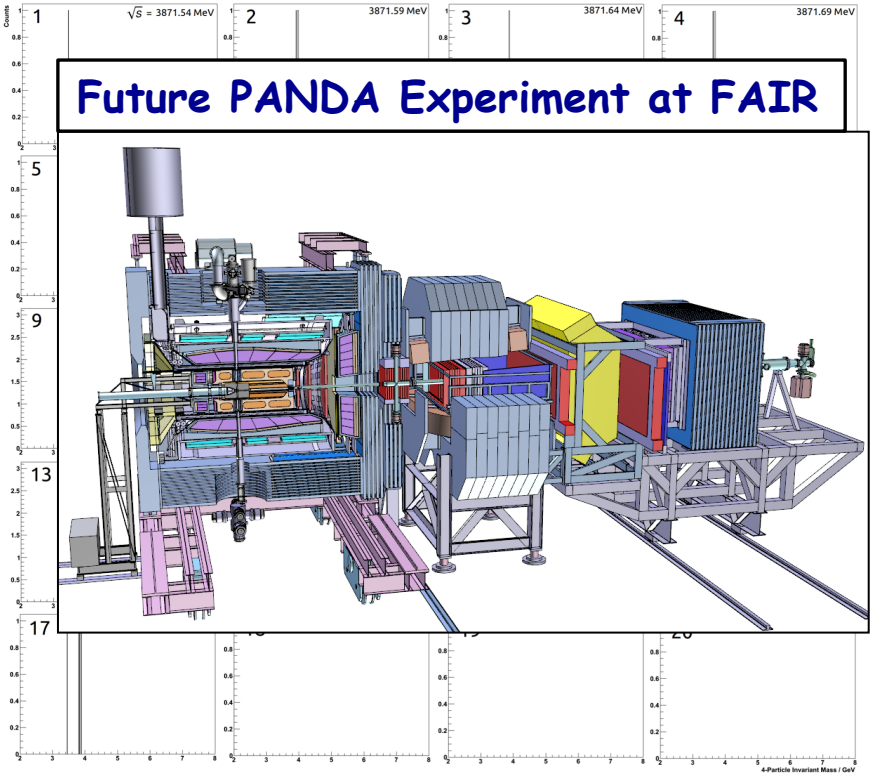

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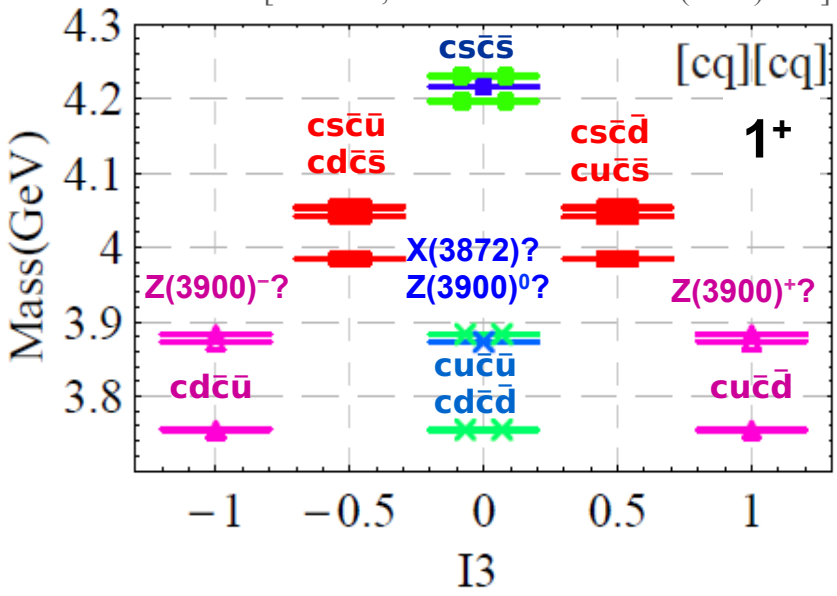
[M.Galuska, PhD thesis]

Models and Multiplets for XYZ

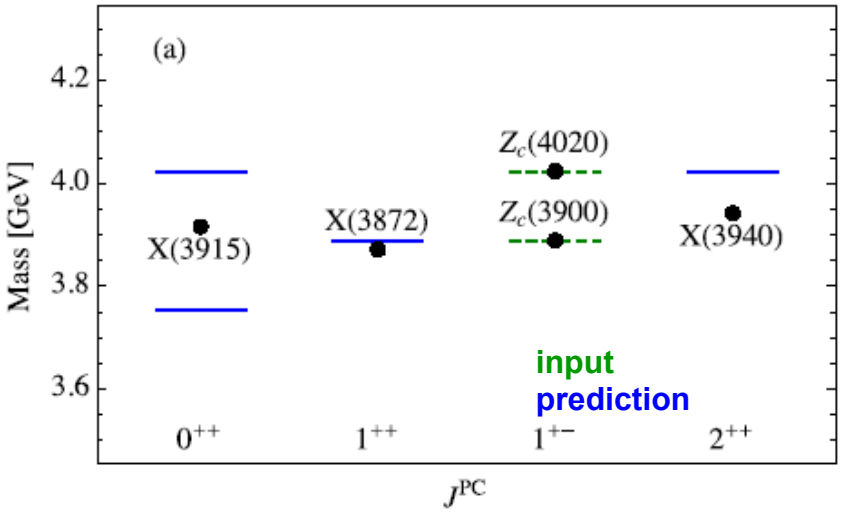
- need to measure complete multiplets
  → *to really understand XYZ nature*

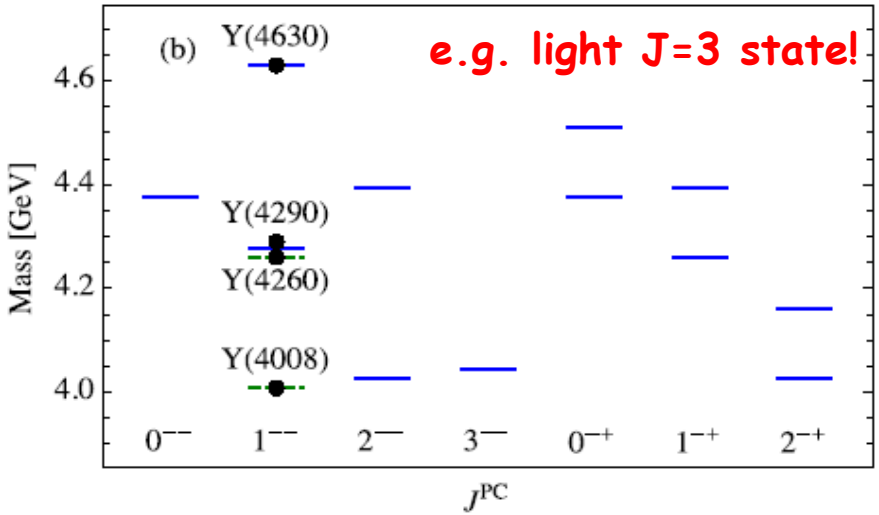
- e.g. di-quarkonium [cq][c̄q̄] models provide predictions
  - ➢ Look for stranged partners
  - ➢ Look for light high spin states

[Drenska, Riv. Nuovo Cim. 033 (2010) 633]



[Cleven et al., arXiv:1505.01771]



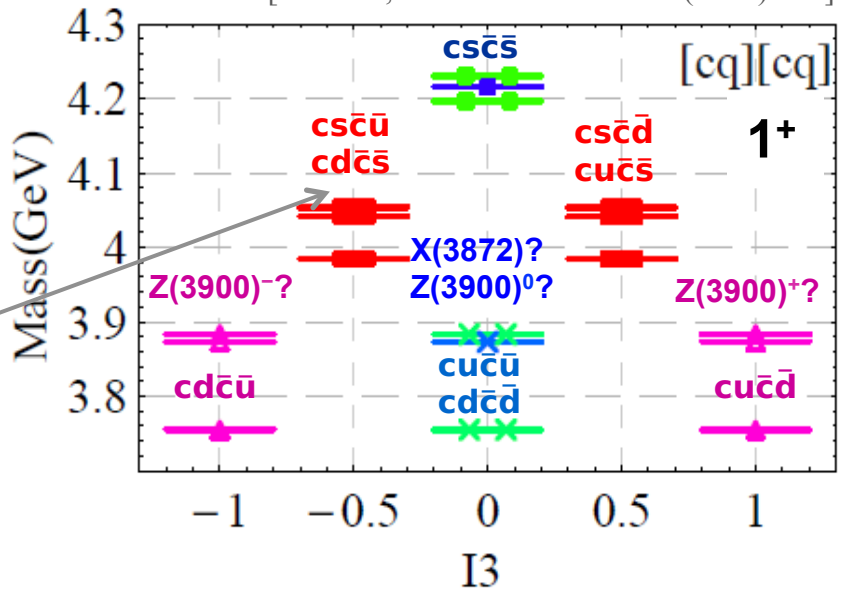


Models and Multiplets for XYZ

- need to measure complete multiplets
  → *to really understand XYZ nature*

- e.g. di-quarkonium [cq][c̄q̄] models provide predictions
  - ➢ Look for stranged partners
  - ➢ Look for light high spin states

[Drenska, Riv. Nuovo Cim. 033 (2010) 633]



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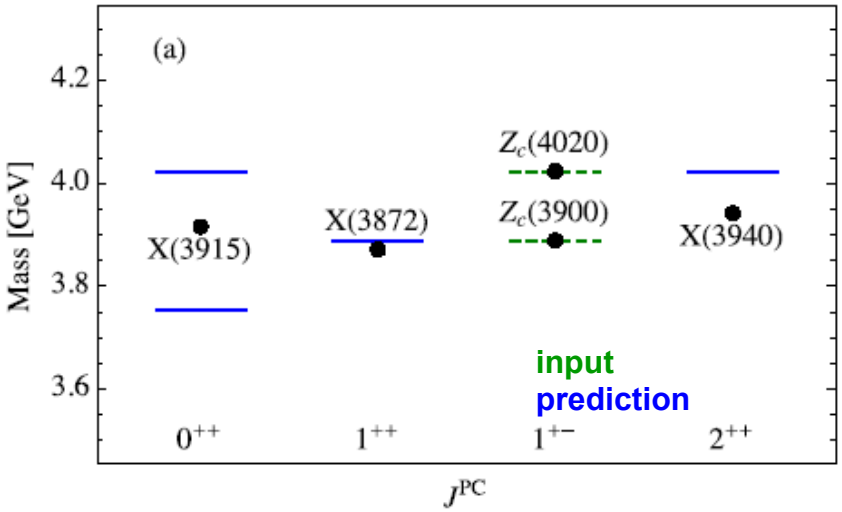

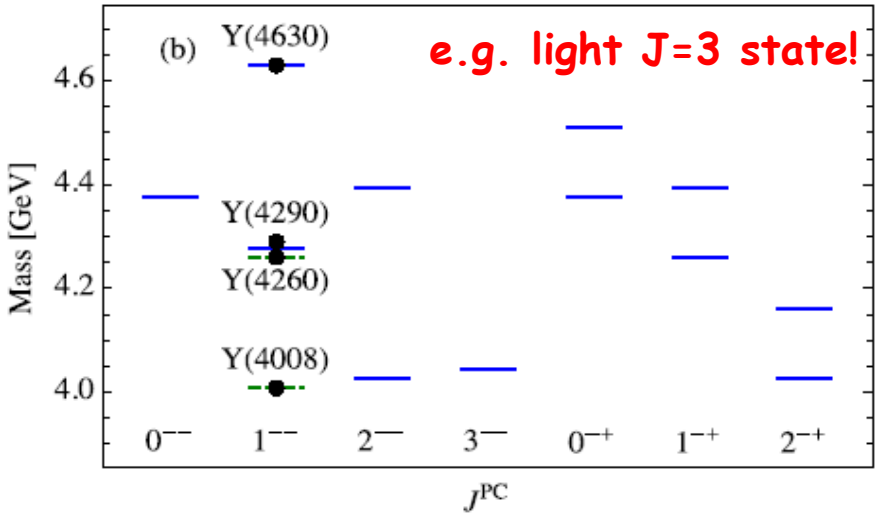

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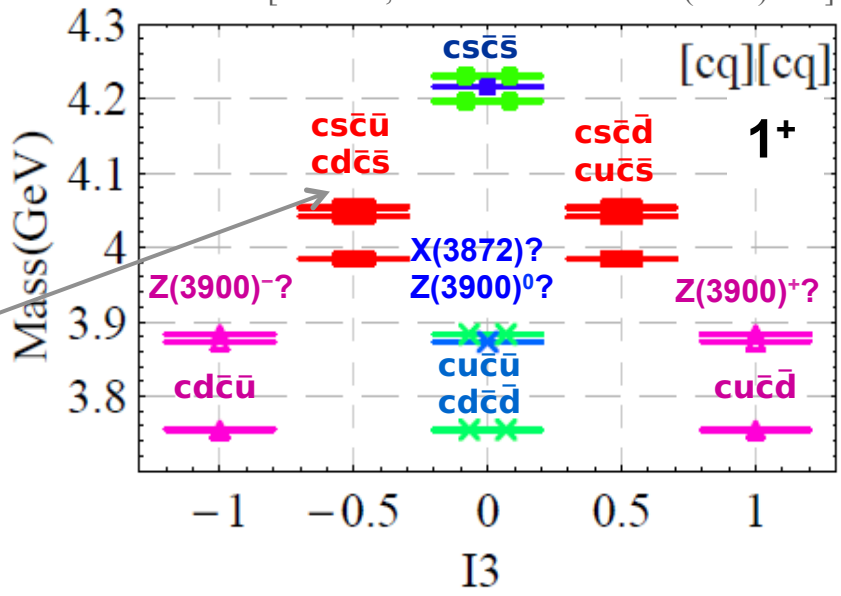

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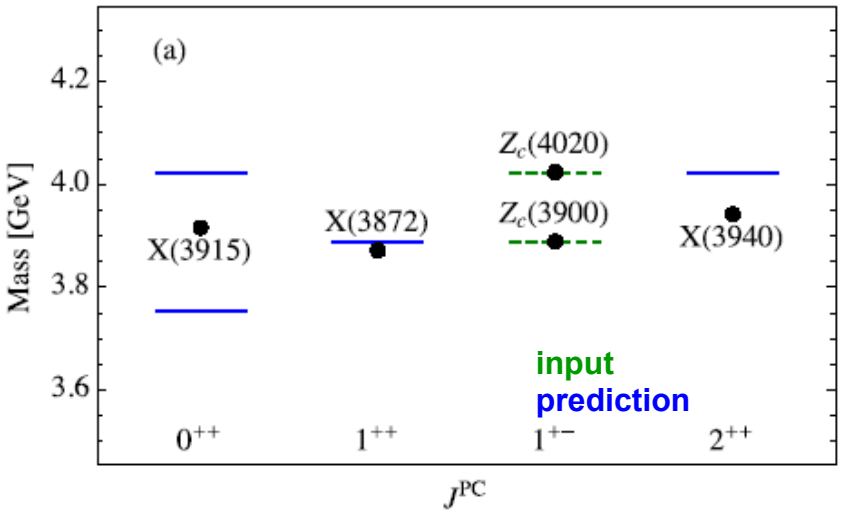
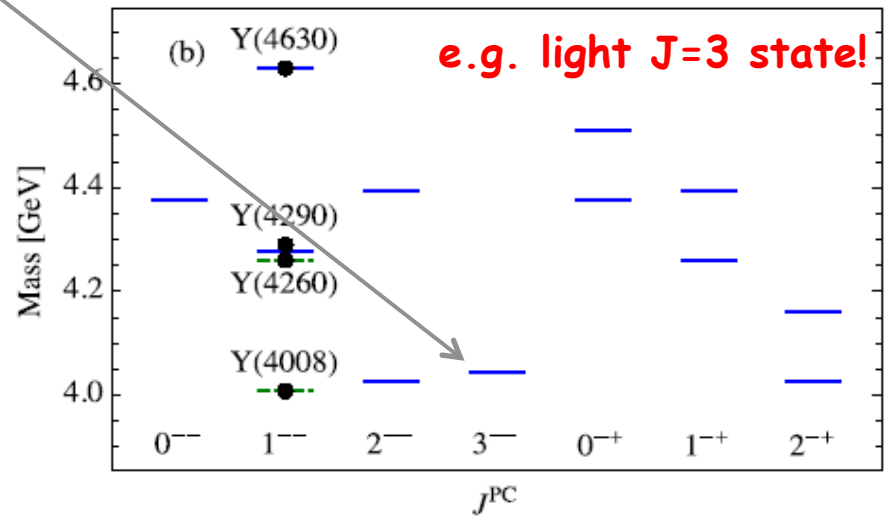
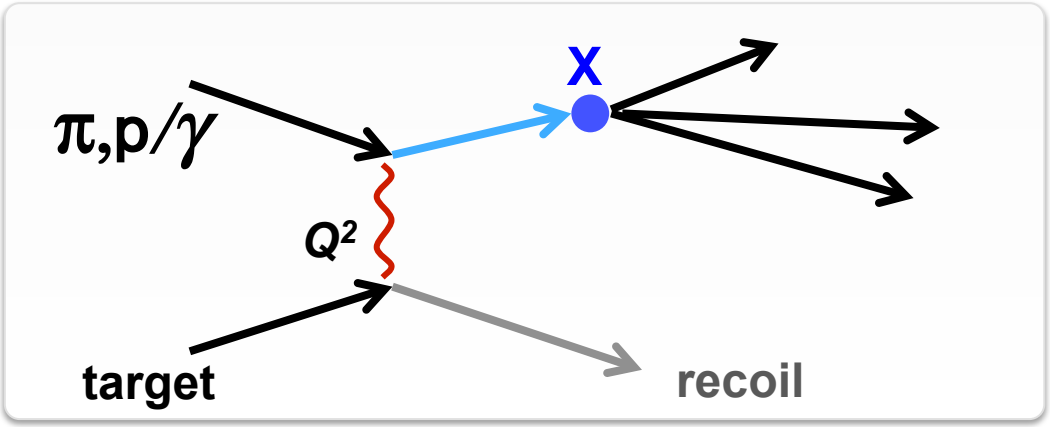




Running & future experiments

Production mechanisms & experiments (I)

- **Fixed-target, hadron/photon beam on proton/nuclear targets**
  - GlueX: γp (9 GeV/c), COMPASS: π/K/p p (190-270 GeV/c)



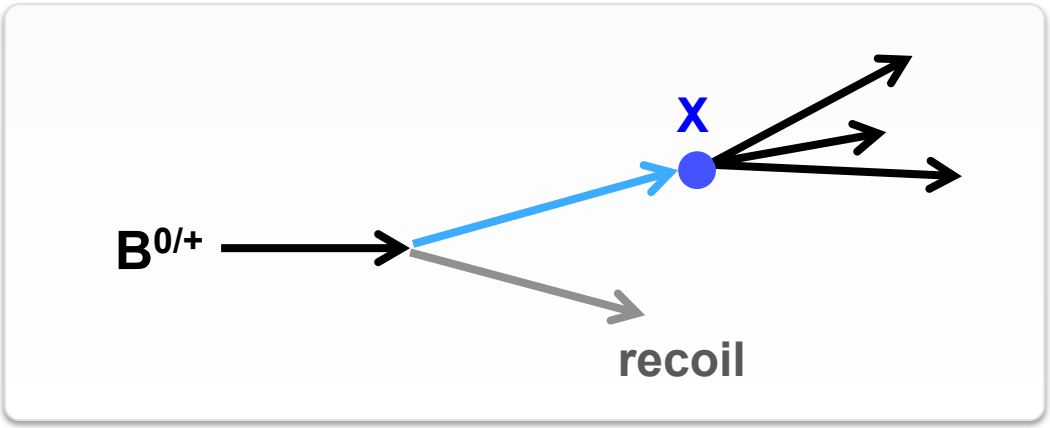
COMPASS **Status: Running**

GlueX **Status: Started**

- **Light quark sector (mainly)**
- **Spin-exotics directly accessible** ☺
- **Always against target recoil particle (complicates analysis)** ☹

Production mechanisms & experiments (II)

- **B meson decays**
  - LHCb: pp (7 TeV/c), BelleII: e^+e^- (≤ 11 GeV)



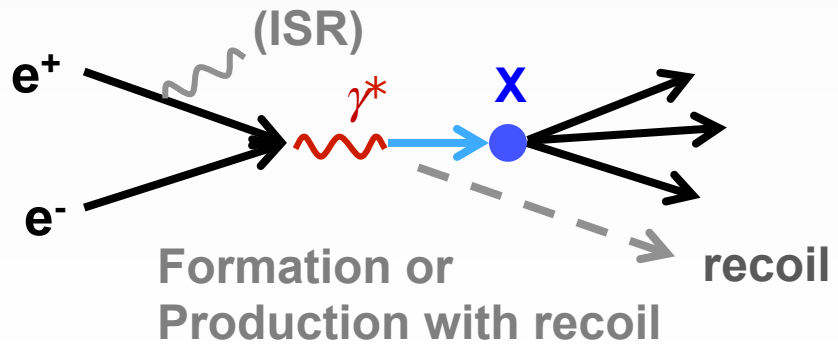
Status: Running

Status: Future

- **Charmonium & light quark sector**
- **Exclusive systems for Dalitz plot analysis** ☺
- **Suppression of higher spins J** ☹

Production mechanisms & experiments (III)

- **Formation & Production against recoil particle(s) in e^+e^-**
  - BESIII: $E_{cms} \leq 4.6$ GeV, BelleII: $E_{cms} \leq 11$ GeV



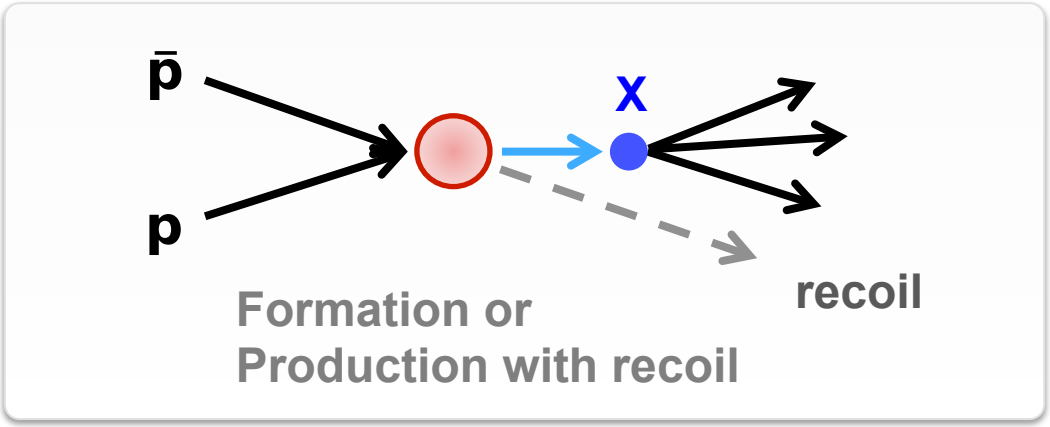
Status: Running

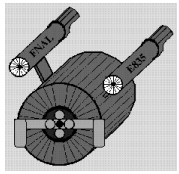
Status: Future

- **Bottomonium, Charmonium & light quark sector**
- **High precision mass & width resolution (formation)** ☺
- **Suppression of higher spins J && J^{PC} limited to 1^{--} (Formation)** ☹

Production mechanisms & experiments (IV)

- **Formation & Production against recoil particle(s) in $\bar{p}p$**
  - PANDA: E ≤ 5.5 GeV, E835: E ≤ 4.3 GeV





FERMILAB E835
CHARMONIUM

Status: Past

p̄anda

Status: Future

- **Charmonium & light quark sector**
- **High precision mass & width resolution, all ($\bar{q}q$) J^{PC} (formation) and also spin-exotic J^{PC} (production) possibe** ☺
- **No running experiment** ☹

Summary and Prospectives

- **Hadron physics -- Spectroscopy**
  - Recent hot discoveries in (baryon and) meson spectroscopy
  - Opportunity to understand and quantify QCD binding

- **New exotic states observed during last decade**
  - Proof validity of fundamental QCD principles
  - Light meson sector:

    → *New axial-vector* $a_1(1420)$, $\pi_1(1600)$ *re-adressed*
  - Charmonium-like exotics:

    → *Charged states manifestly exotic matter*
  - Precise knowledge of decay width and line shape essential!

- **Running & new experiments**
  - Complementary production mechanisms and measurements needed
  - Complete the exotic multiplets

- **Quite some way still to go ...**

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- **Quite some way still to go ...** ... stay tuned for further exciting discoveries!

Last remark. citation of Paola G., ICNFP2014:

The Phaistos Disc is a disk of fired clay from the Minoan palace of Phaistos of Crete (2 millenium B.C.). It is covered on both sides with a spiral of stamped symbols. Its purpose and meaning, and even its original geographical place of manufacture, remain disputed, making it one of the most famous mysteries of archaeology.

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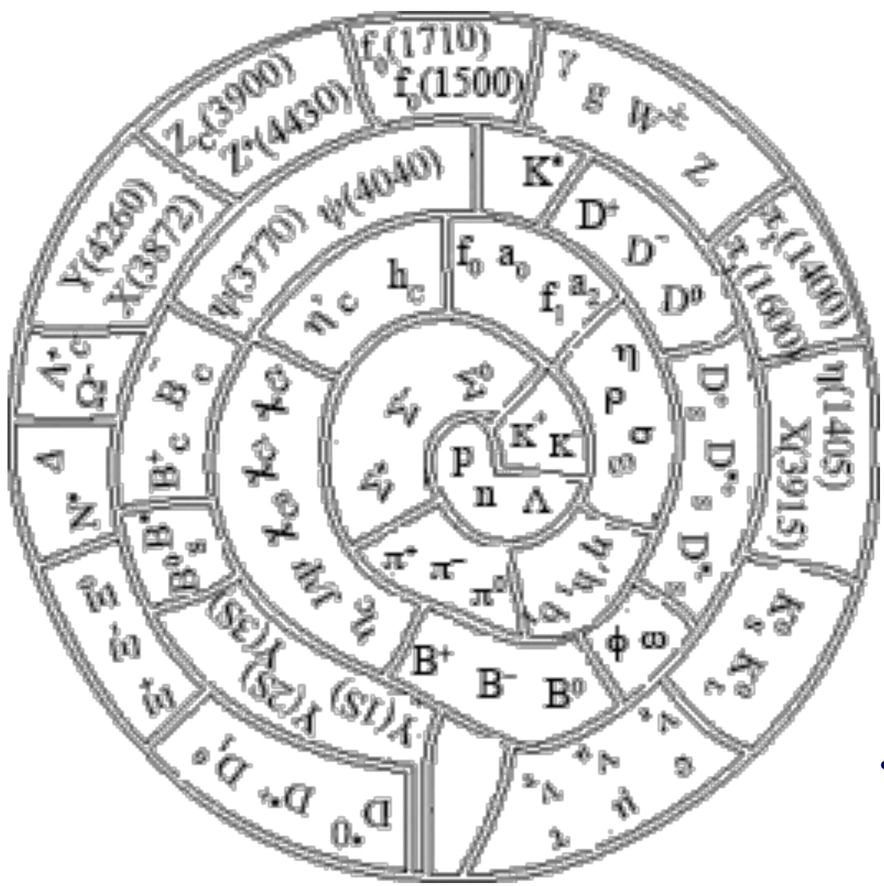
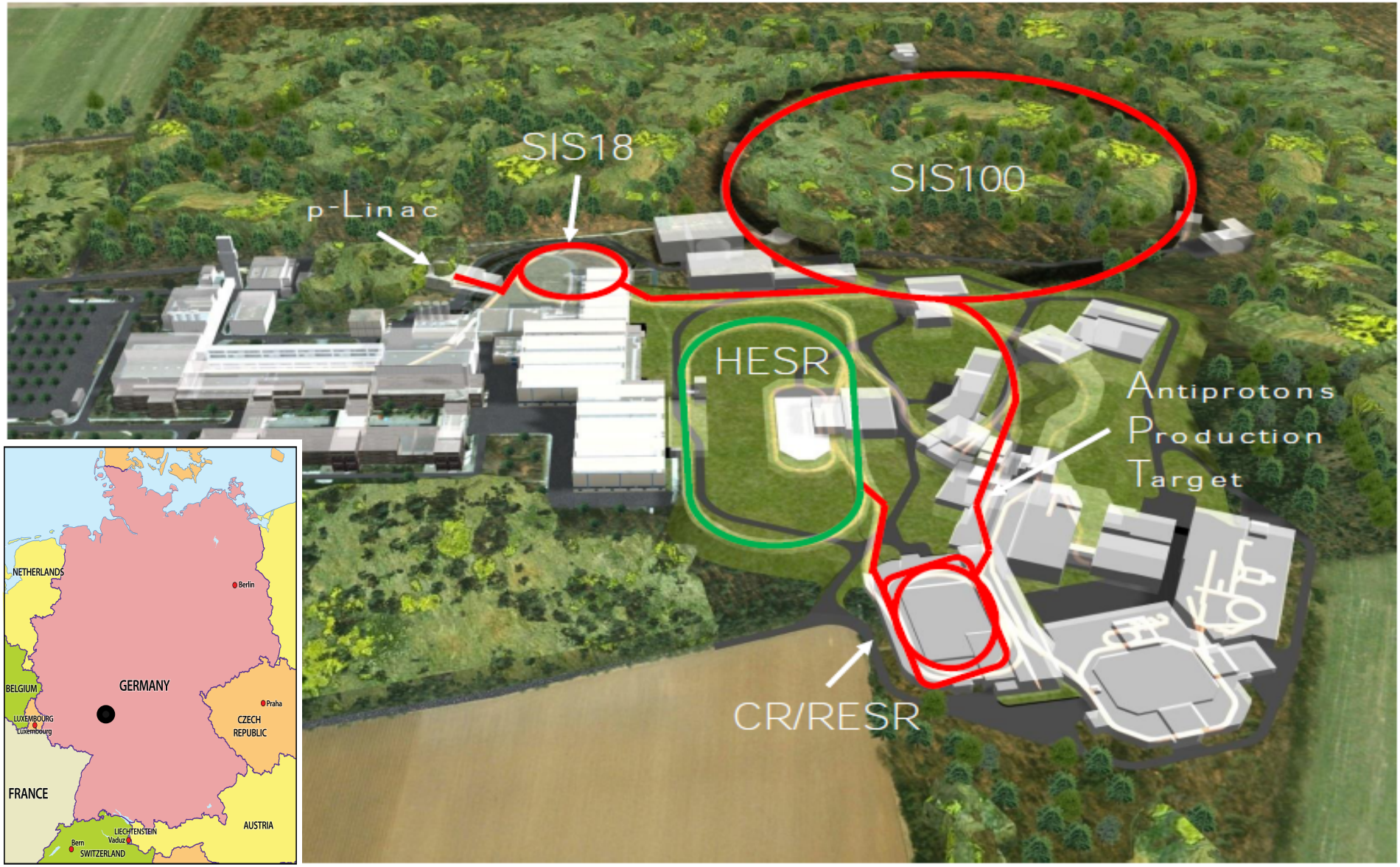
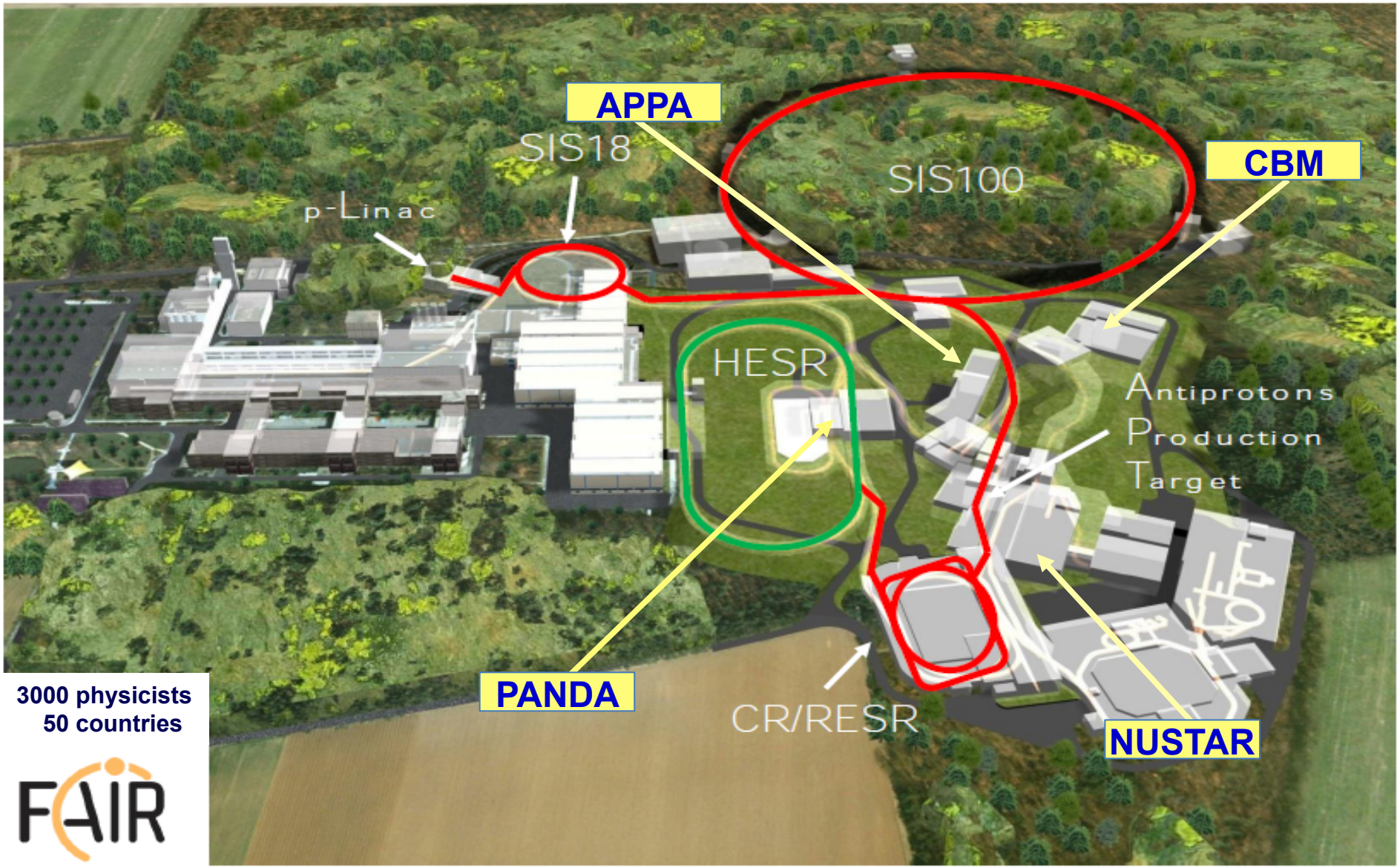


Thank you for your attention !

Facility for Antiproton and Ion Research

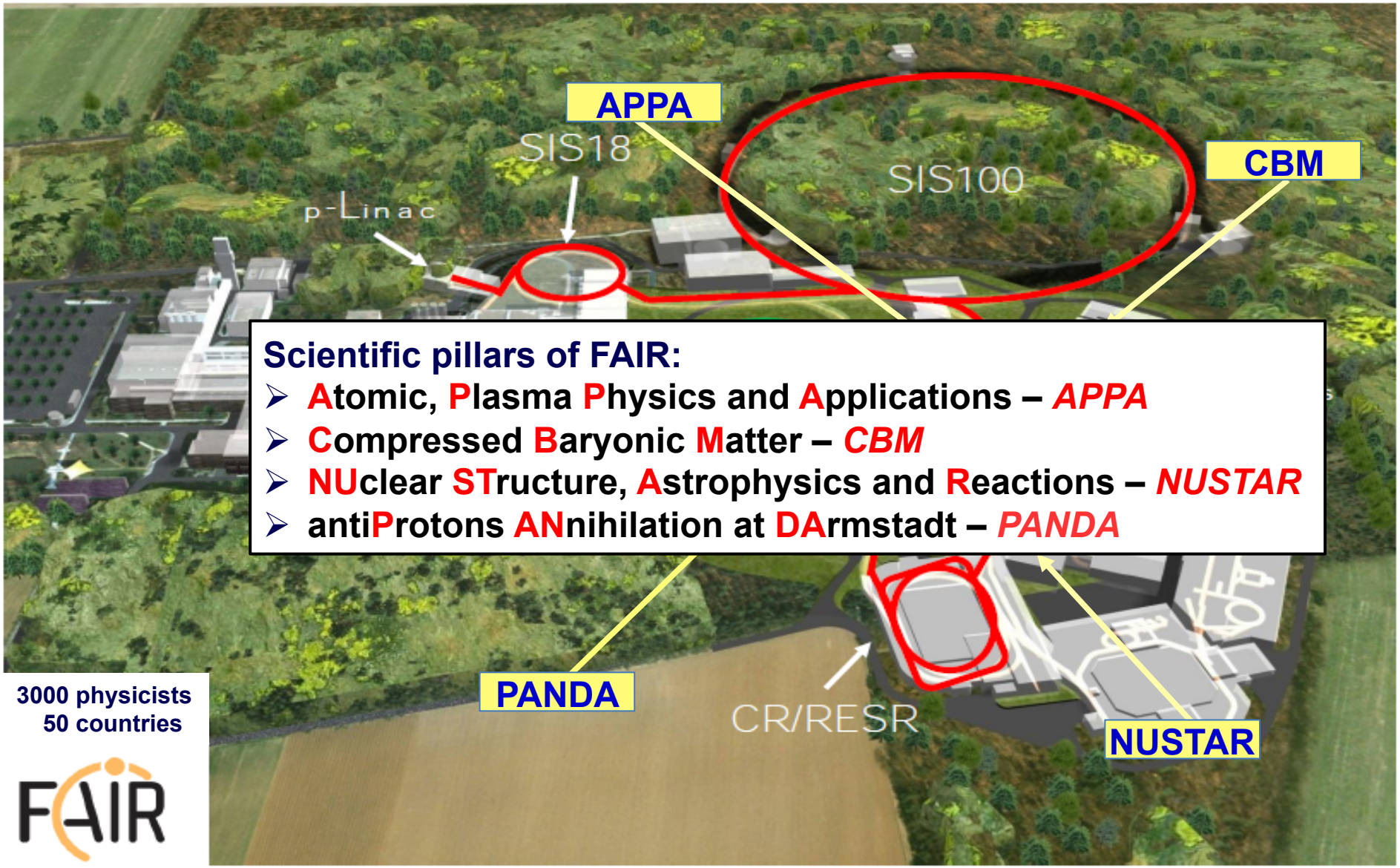


Facility for Antiproton and Ion Research



3000 physicists
50 countries

Facility for Antiproton and Ion Research



Scientific pillars of FAIR:

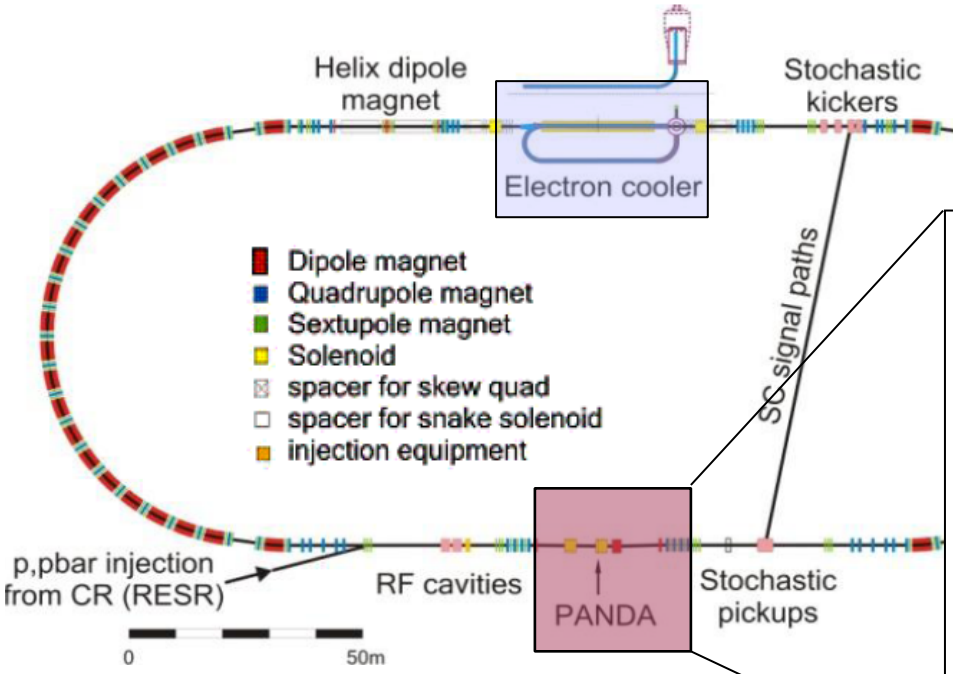
- **A**tomic, **P**lasma **P**hysics and **A**pplications – ***APPA***
- **C**ompressed **B**aryonic **M**atter – ***CBM***
- **NU**clear **ST**ructure, **A**strophysics and **R**eactions – ***NUSTAR***
- anti**P**rotons **AN**nihilation at **DA**rmstadt – ***PANDA***

3000 physicists
50 countries

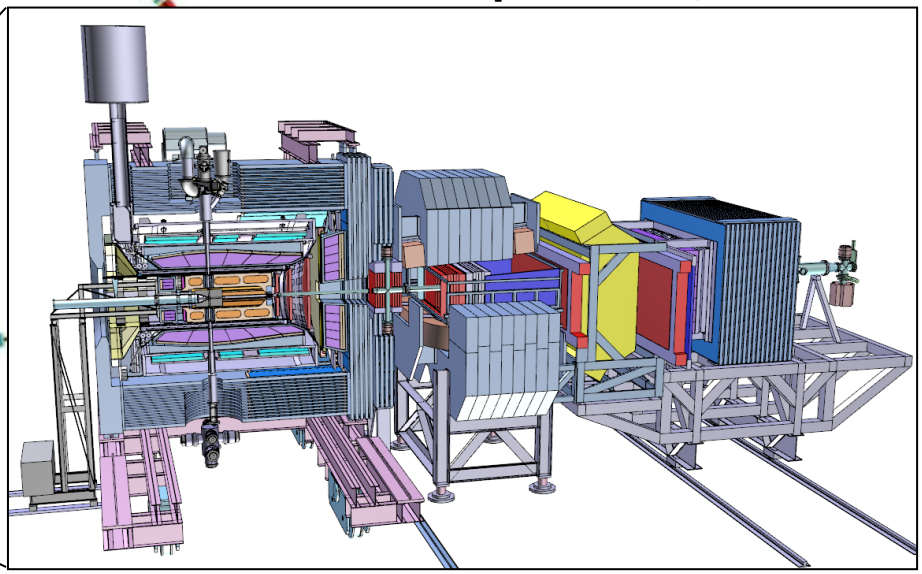
Facility for Antiproton and Ion Research

HIM Helmholtz-Institut Mainz
GSI

High Energy Storage Ring -- HESR



PANDA Experiment, Detector



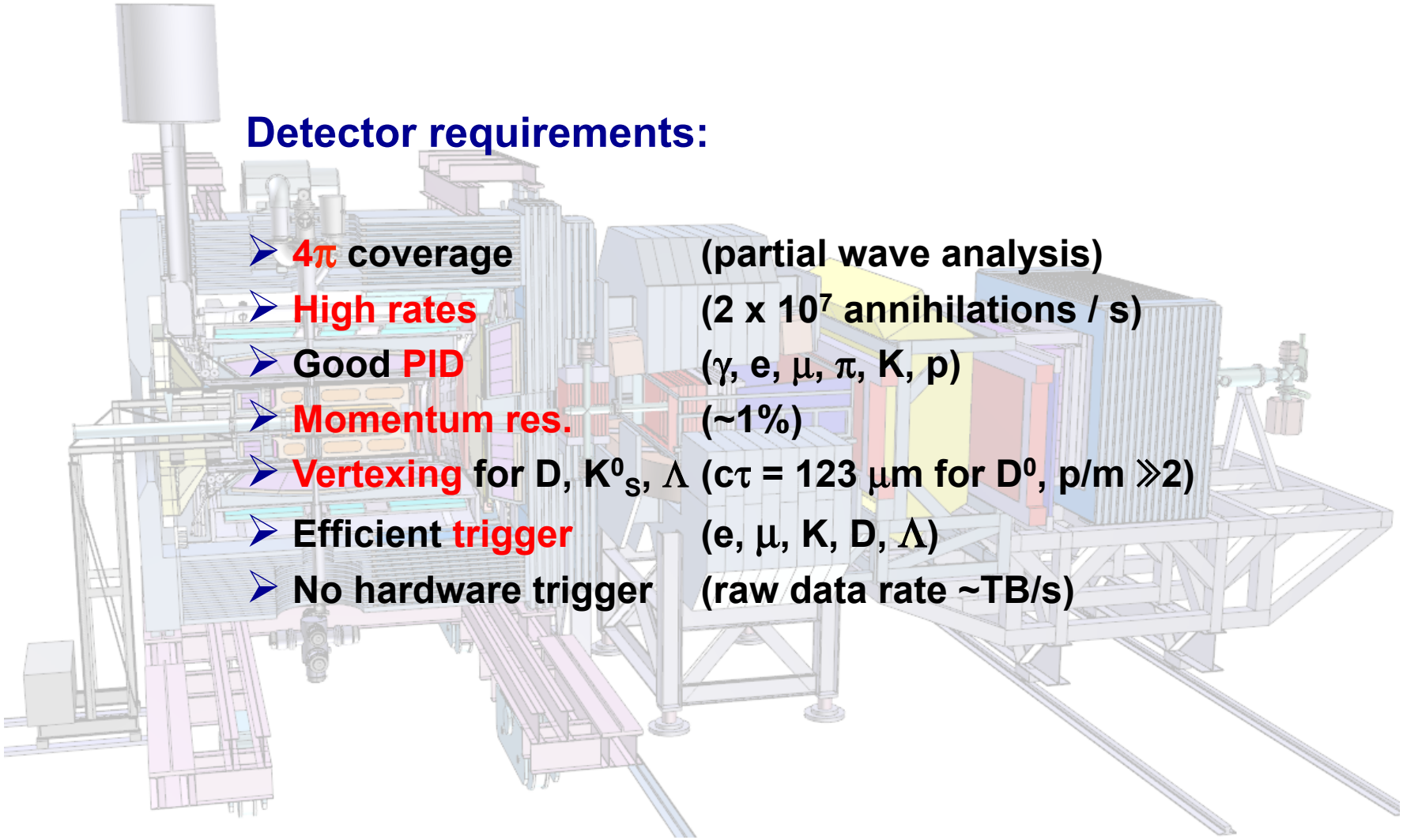
High resolution mode:

- 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}
- $\Delta p/p = 2 \times 10^{-4}$

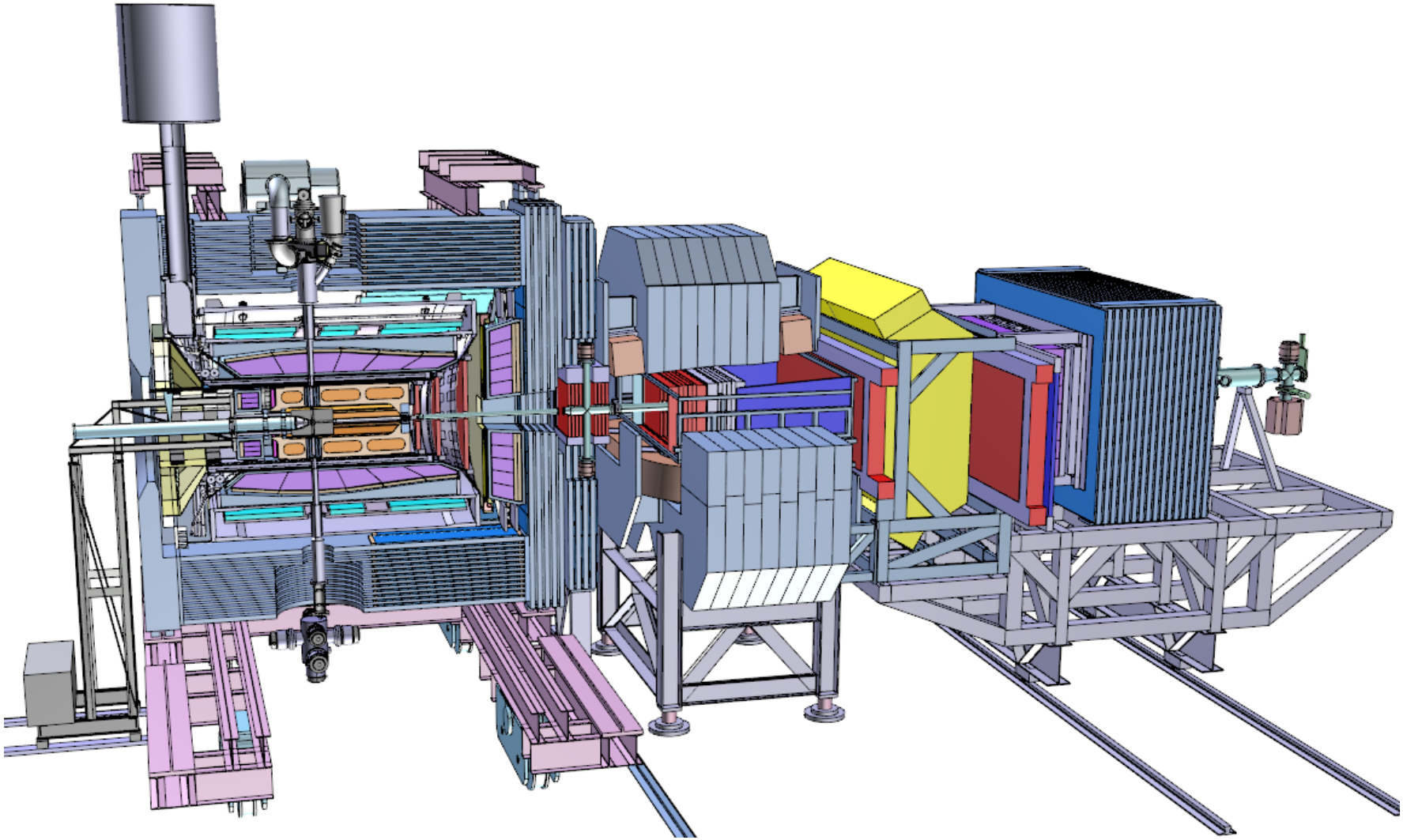
AntiProton Annihilation at Darmstadt



Detector requirements:

- 4π coverage (partial wave analysis)
- High rates (2×10^7 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 $\gg$2)
- Efficient trigger (e, μ, K, D, Λ)
- No hardware trigger (raw data rate ~TB/s)

AntiProton Annihilation at Darmstadt



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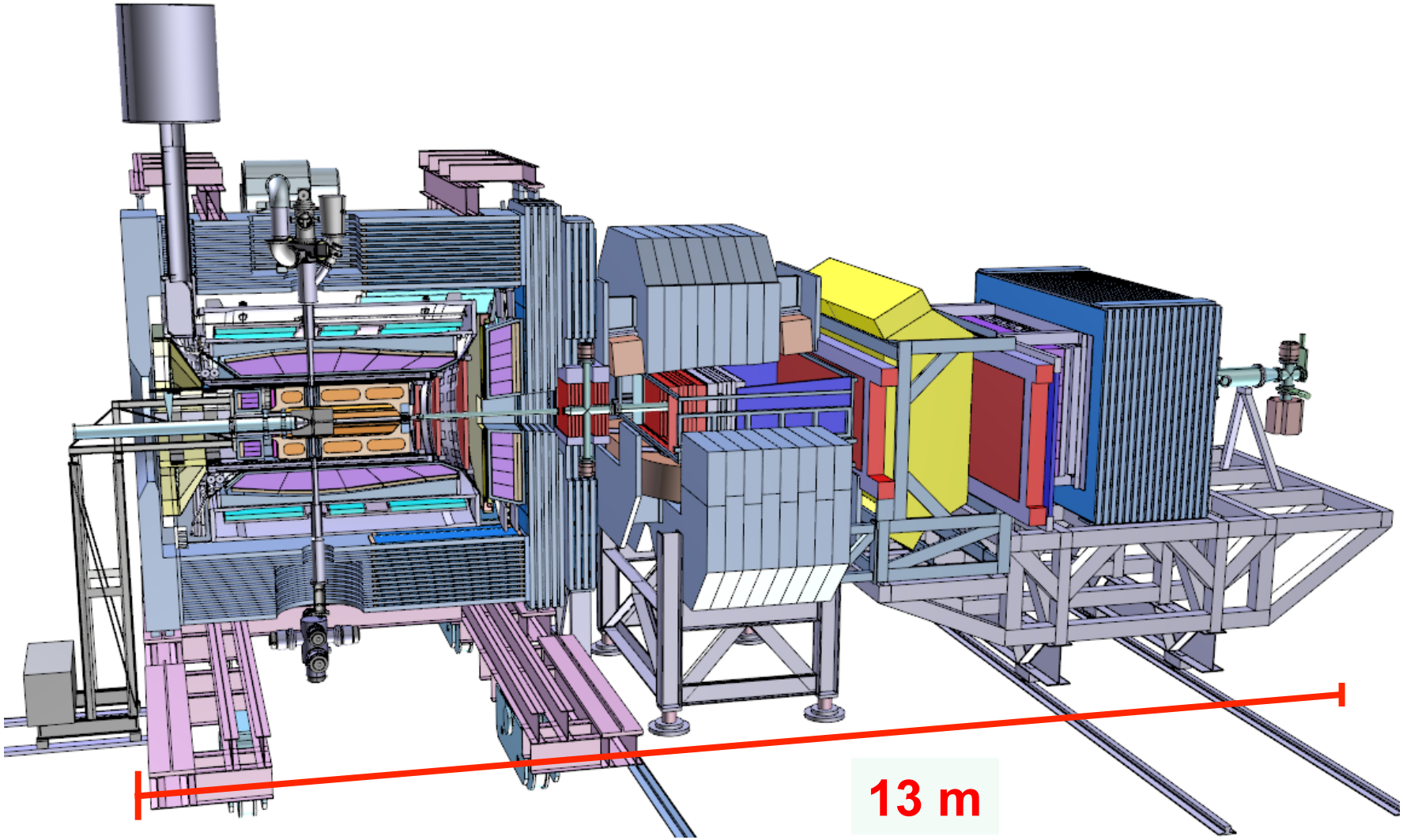

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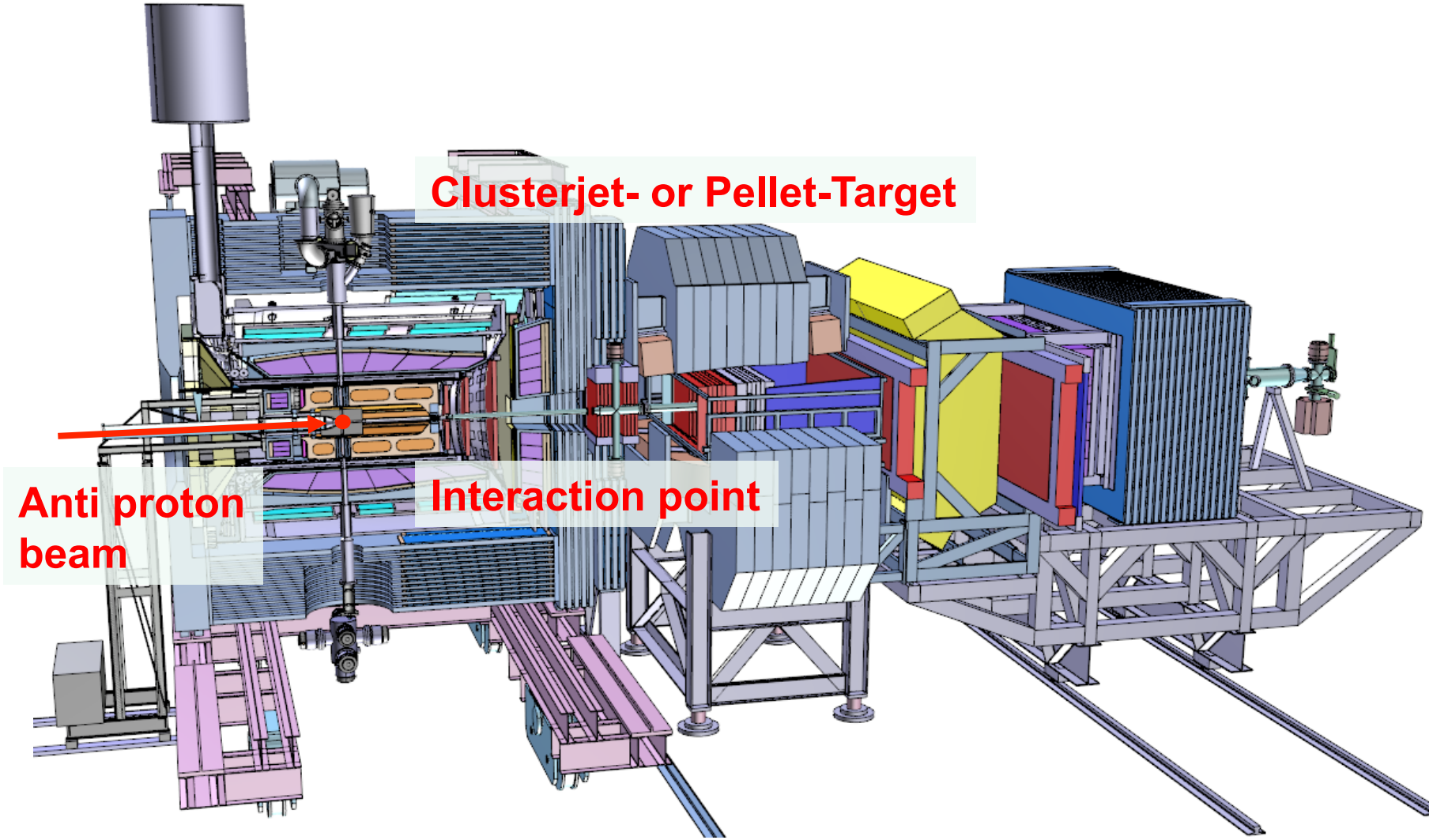

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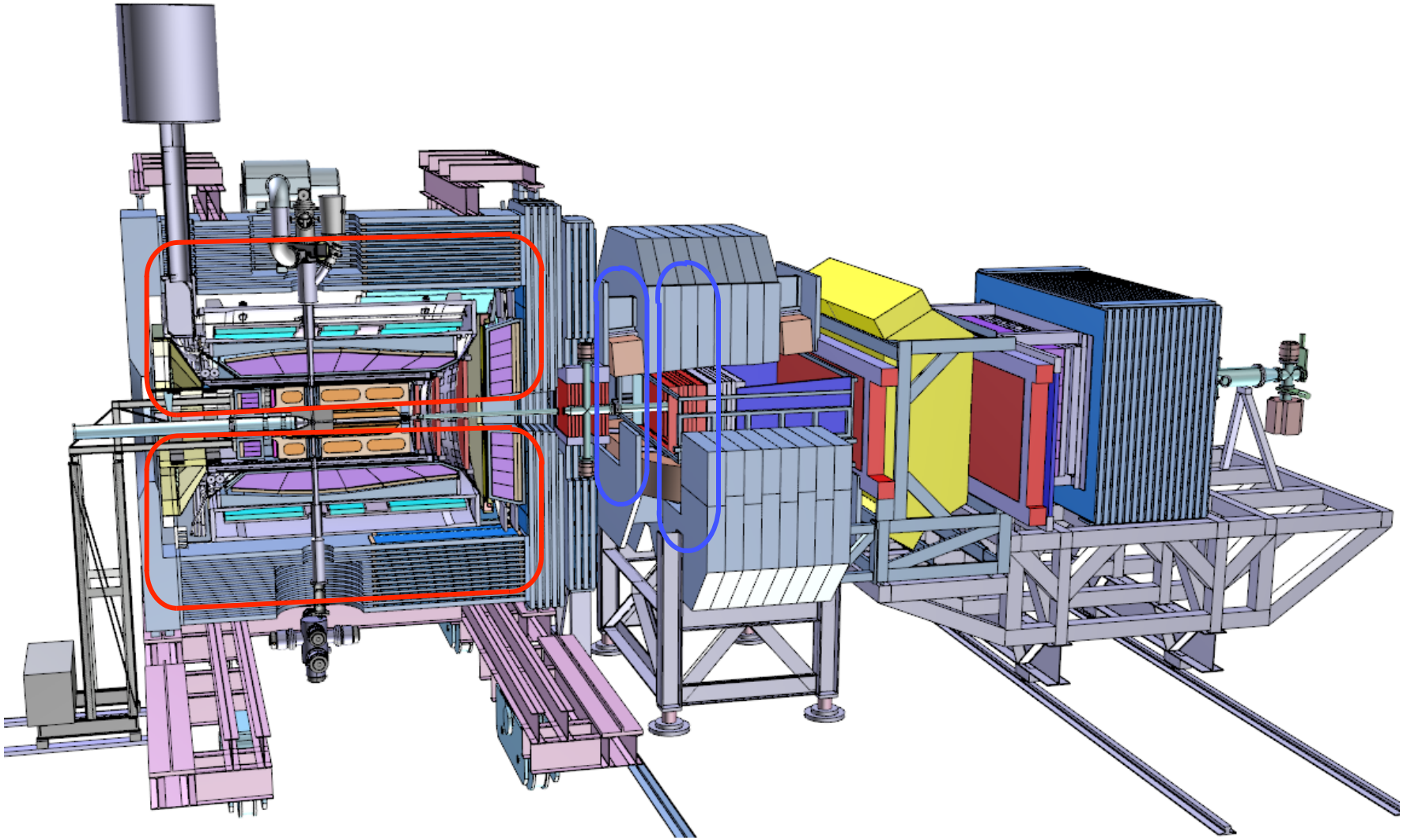

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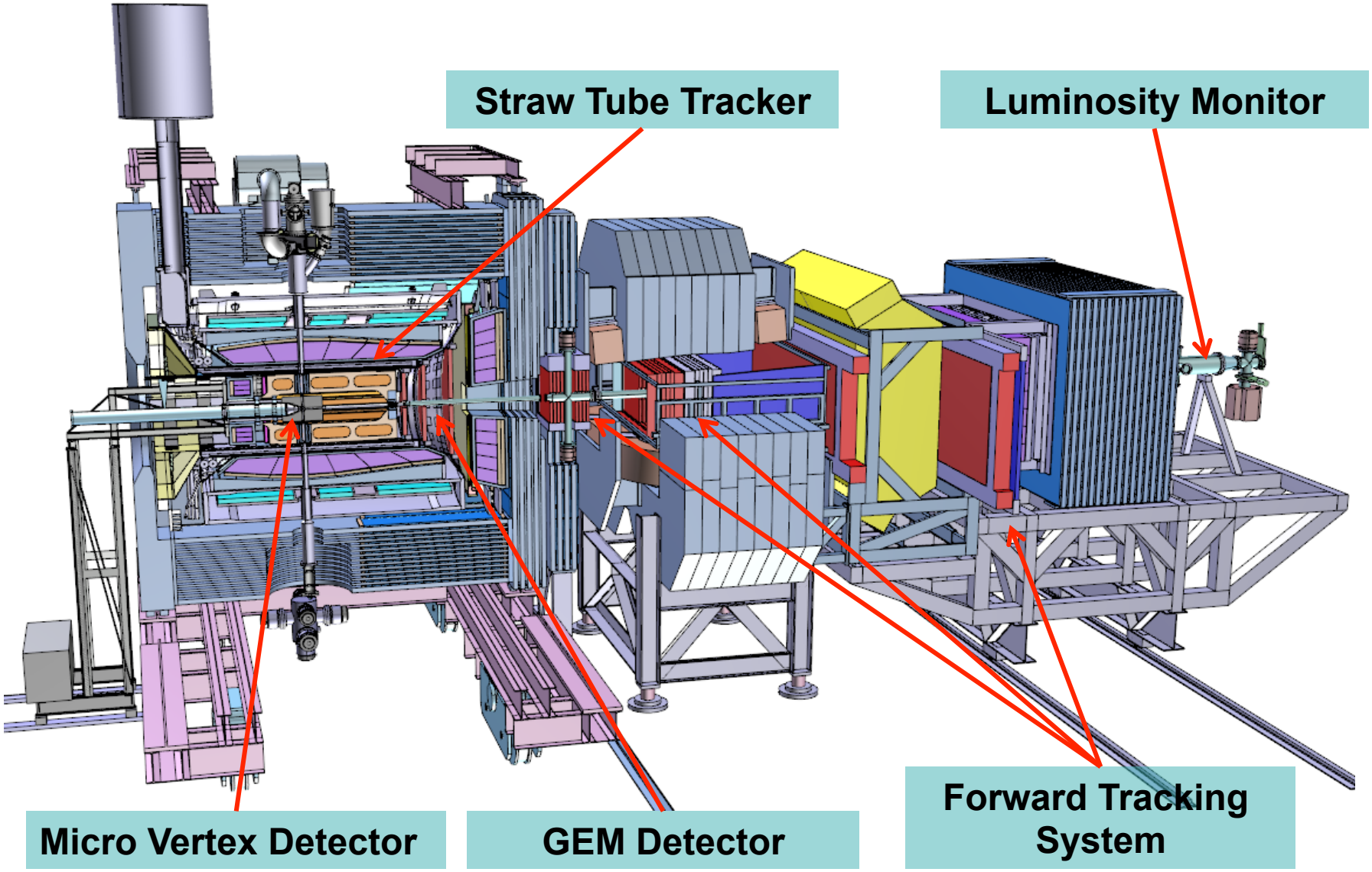

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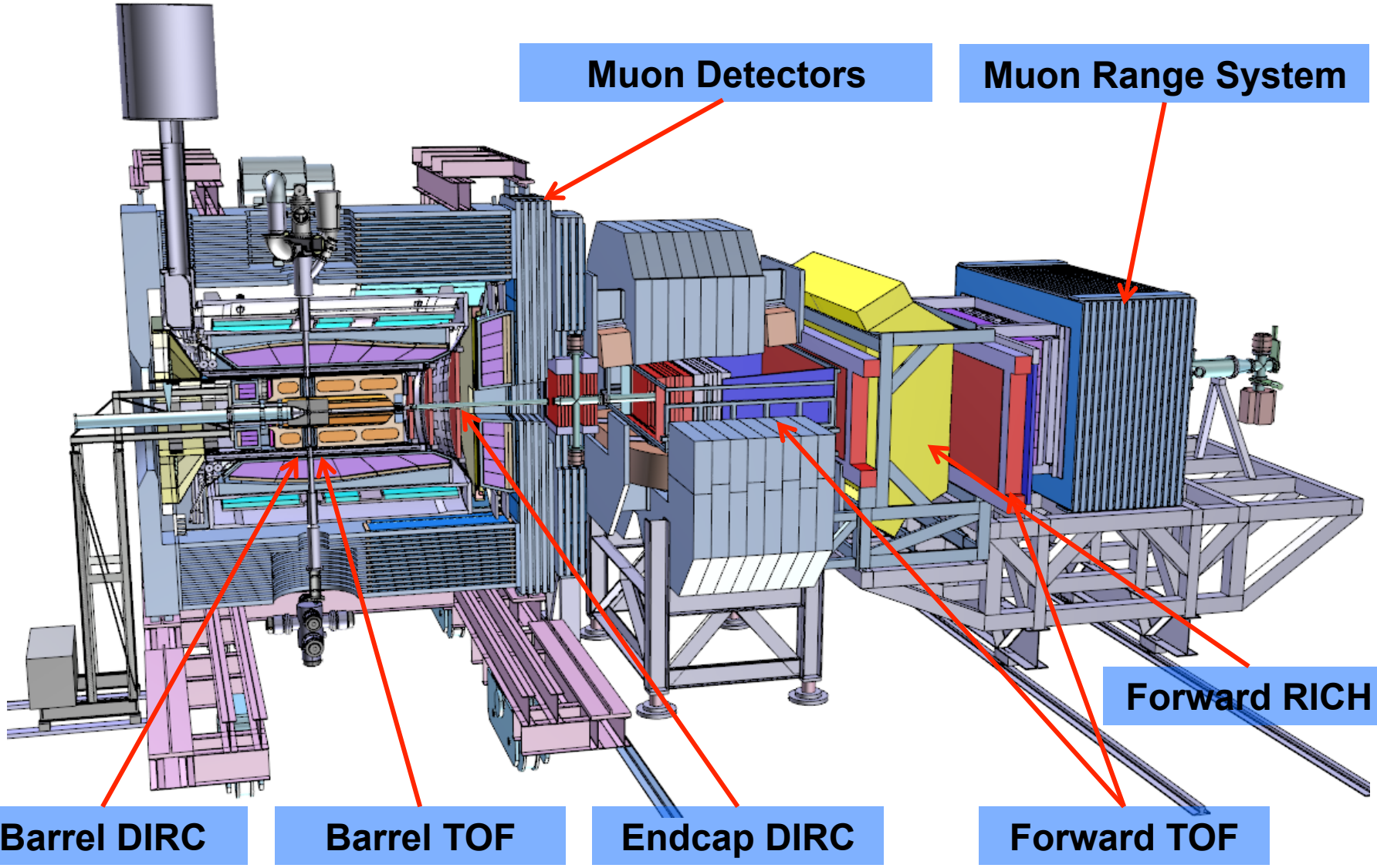

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