Spectroscopy of Exotic XYZ States at GSI

Klaus Götzen

GSI Darmstadt

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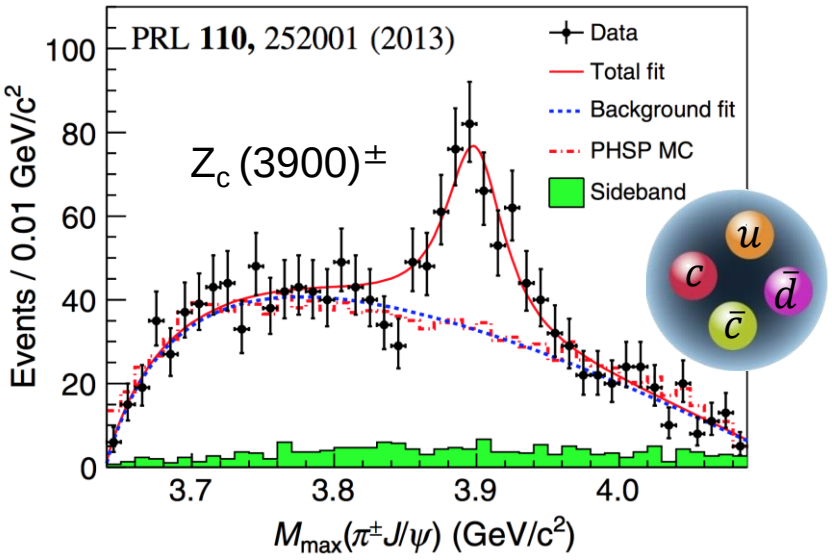
Why hunt for XYZ States?

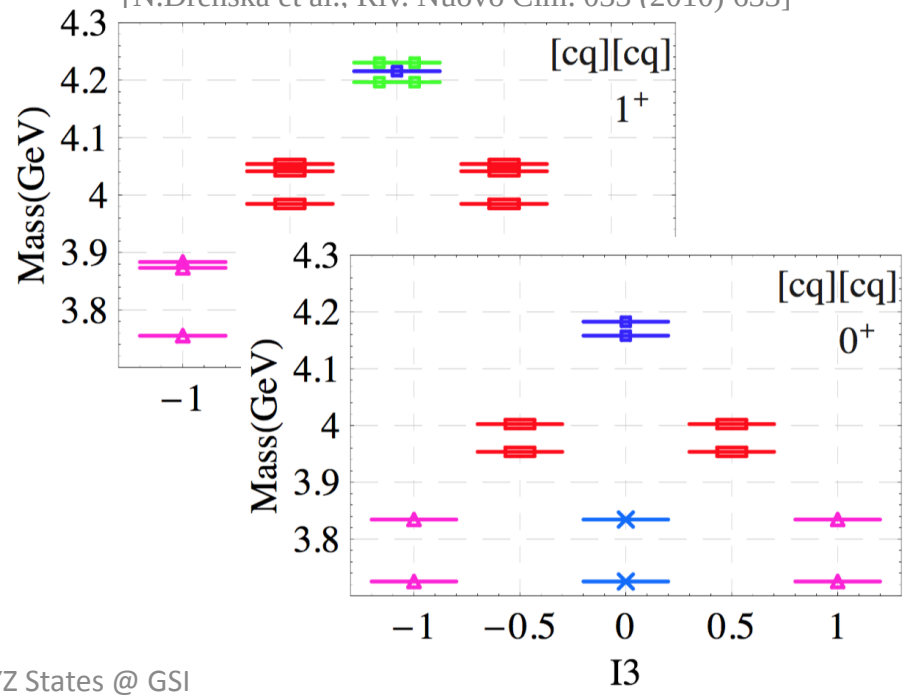
- BESIII 2013: Discovery of manifestly exotic $Z_c(3900)^{\pm}$!
  - Decay to J/ψ requires $c\bar{c}$ content
  - Charge requires $u\bar{d}$ content

  } Minimal quark content: $c\bar{c}u\bar{d}$

- Need complete multiplets to understand inner structure
  - ➢ Identify more states
  - ➢ Establish additional decay channels

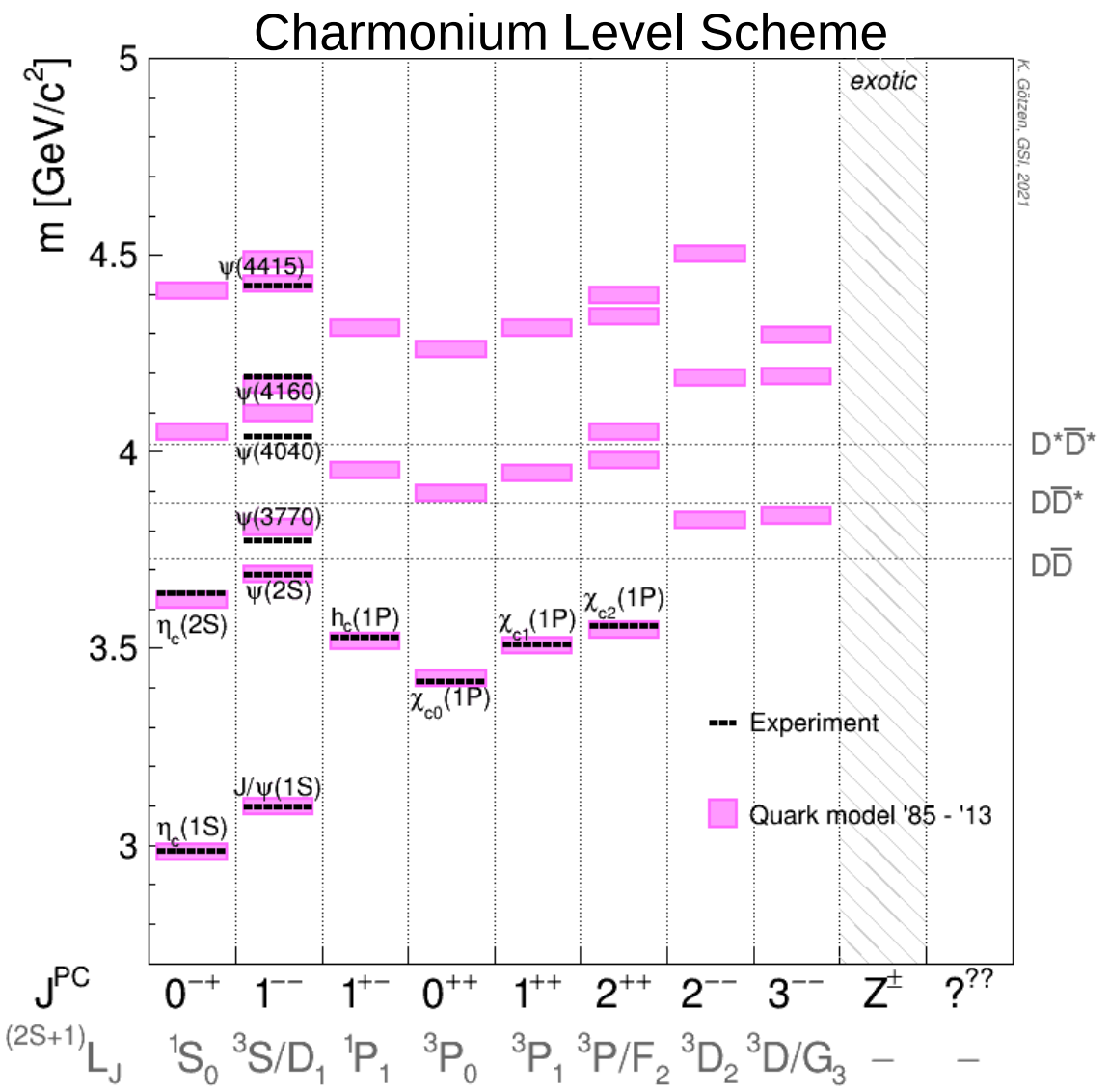


[N.Drenska et al., Riv. Nuovo Cim. 033 (2010) 633]



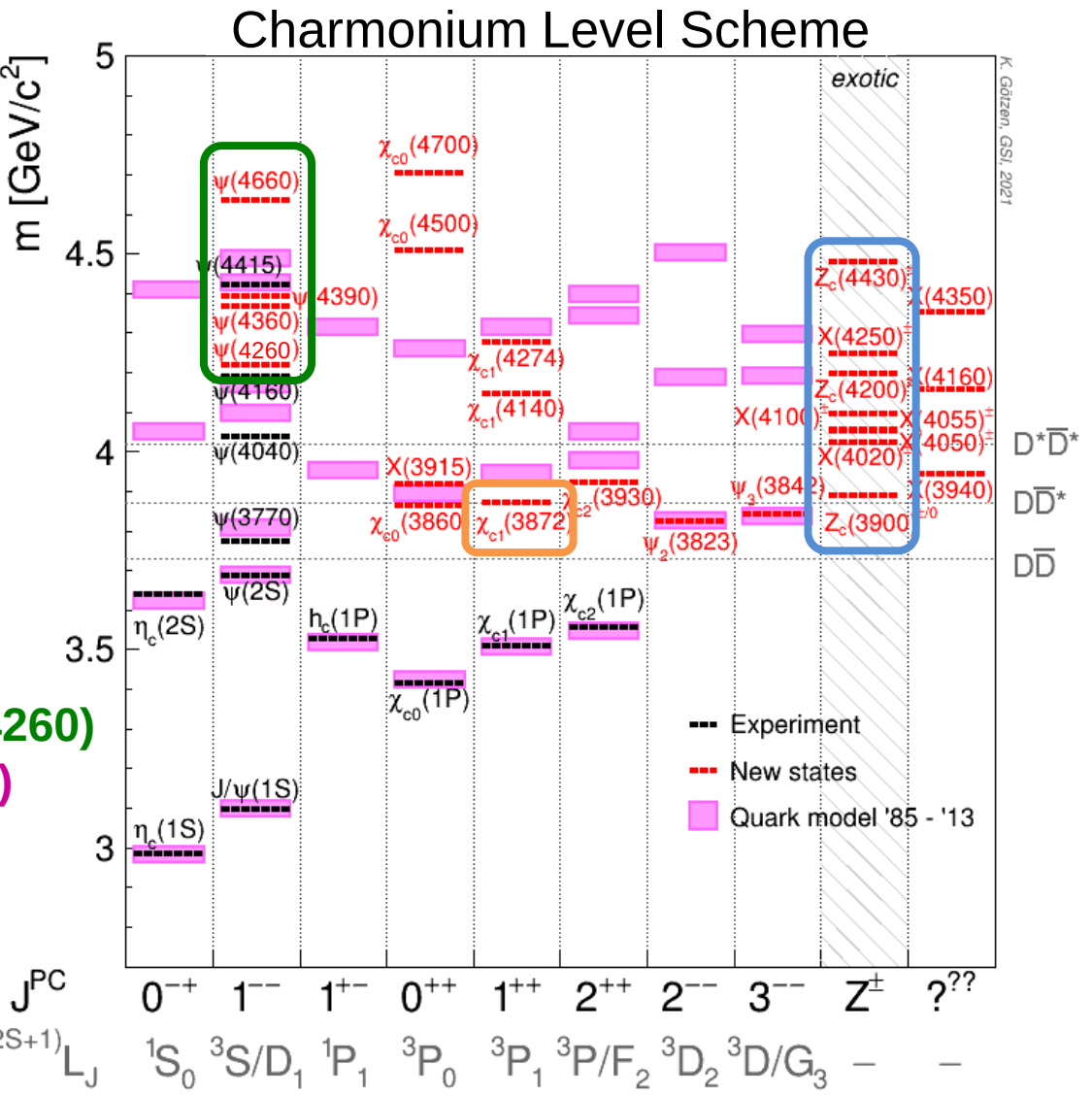
The Charmonium Spectrum

- Charmonium predictions fitted well until 2003



XYZ - Status

- Charmonium predictions fitted well until 2003
- Since 2003: >20 new charmonium-like states not fitting well the predictions
- Extremly narrow **X(3872)**
- Seven charged states: **Z(3900)⁺, ..., Z(4430)⁺**
- Supernumerary 1^{--} states like **Y(4260)**
  Possible strange partner: **Y(2175)**



Hadronspectroscopy at GSI

Involved in 3 Experiments for "XYZ-Hunting"

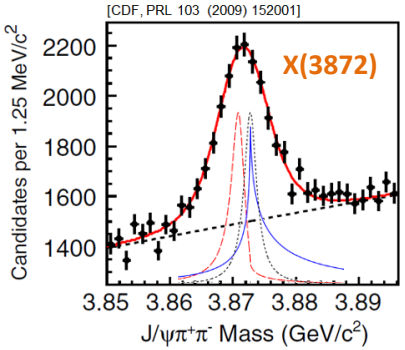
- **PANDA @ FAIR**: Experimental antiproton-pillar of FAIR
  - Precise energy scan of X(3872) line shape

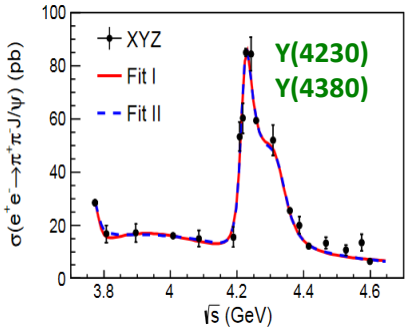
    [Eur. Phys. J. A 55 (2019) 3, 42, arXiv:1812.05132]

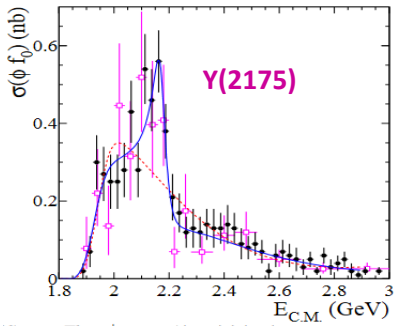
- **BESIII @ IHEP**: Beijing BEPC (e^+e^- collider)
  - Search for Y(4260) decays and connected Z states

    [Phys. Rev. D 103, 032006 (2021), arXiv:2010.14415]

- **GlueX @ JLab**: High energy photo production
  - Search for strange partner state Y(2175)







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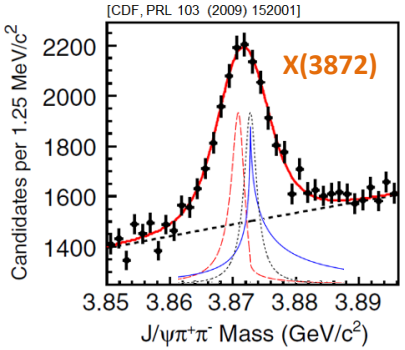

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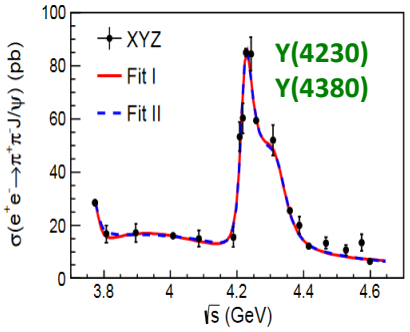

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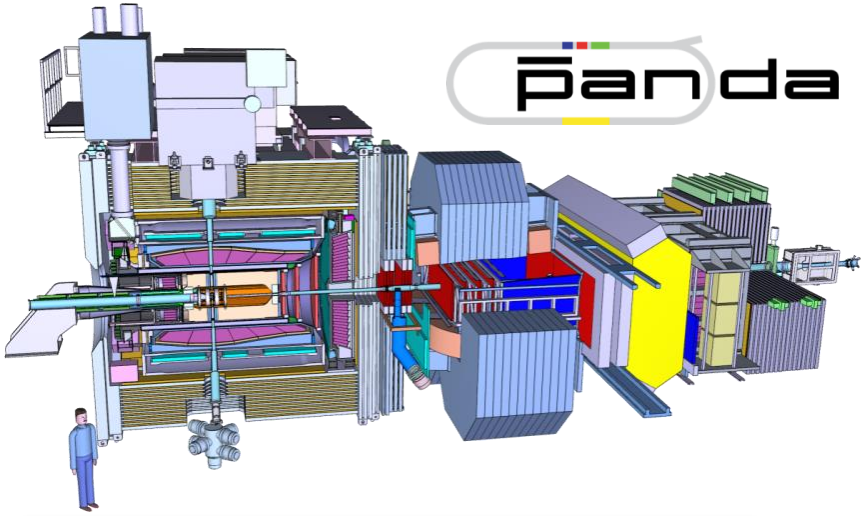
  - Search for strange partner state Y(2175)

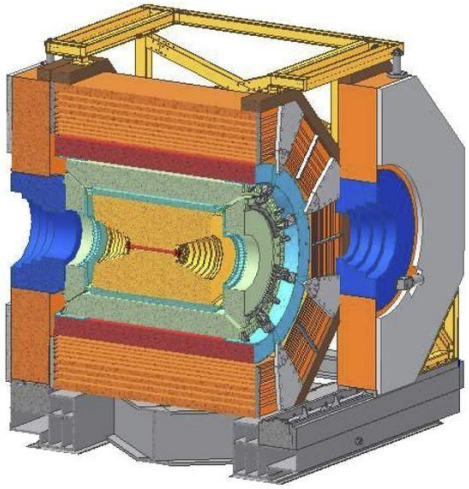
Will skip this due to limited time!

The Experiments: PANDA and BESIII



$\bar{p}p$ collisions @ $\sqrt{s}$ = 2.2 ... 5.5 GeV
$\mathcal{L}$ = 2 · 10^{31} $cm^{-2}s^{-1}$ ... 2 · 10^{32} $cm^{-2}s^{-1}$
dp/p = 2 · 10^{-5} ... 1 · 10^{-4}

- Physics Programme
  - Hadron Spectroscopy
  - Hadron Structure
  - Hypernuclei and more
- Target and Forward Spectrometer
  - Tracking (Straws) and Vertexing (Pixel/Strip)
  - EM Calorimetry
  - Particle Ident. (dE/dx, DIRC, ToF, Muo)



e^+e^- collisions @ $\sqrt{s}$ = 2.0 ... 4.6 GeV
$\mathcal{L}$ = 1 · 10^{33} $cm^{-2}s^{-1}$
dp/p = 5 · 10^{-4}

- Physics Programme
  - Hadron Spectroscopy
  - CP Physics
  - Tau Physics
- Symmetric Detector
  - Tracking (Drift Chamber)
  - EM Calorimetry
  - Particle Identification (dE/dx, ToF, Muo)

BESIII: Study Y and Z states

BESIII: Search for Y(4260) ⟶ η_c + recoil

- Large dataset of ~18 fb^{-1} in XYZ energy region [4.0 - 4.6 GeV]
- Search for $Z^{\pm/0}$ decaying to charmonium ground state η_c (0^{-+} $c\bar{c}$)
- Measure energy dependent production cross section

$$e^+e^- \to \boldsymbol{Y(4260)} \begin{cases} \boldsymbol{Z_c^+}\pi^- & \to \boldsymbol{\eta_c}\boldsymbol{\pi^+}\,\pi^- \\ \boldsymbol{Z_c^+}\pi^-\pi^0 & \to \boldsymbol{\eta_c}\boldsymbol{\pi^+}\,\pi^-\pi^0 \\ \boldsymbol{Z_c^0}\pi^+\pi^- & \to \boldsymbol{\eta_c}\boldsymbol{\pi^0}\,\pi^+\pi^- \\ \boldsymbol{Z_c^0}\gamma & \to \boldsymbol{\eta_c}\boldsymbol{\pi^0}\,\gamma \end{cases}$$ same final state

- **Analysis strategy:**
  - Investigate largest six data samples between $\sqrt{s}$ = 4.18 ... 4.6 GeV
  - Reconstruct 16 different decay channels of η_c
  - Perform simultaneous fit (η_c/Z_c + recoil) to all spectra for each energy
  - Study possible intermediate states in energy dependent cross section

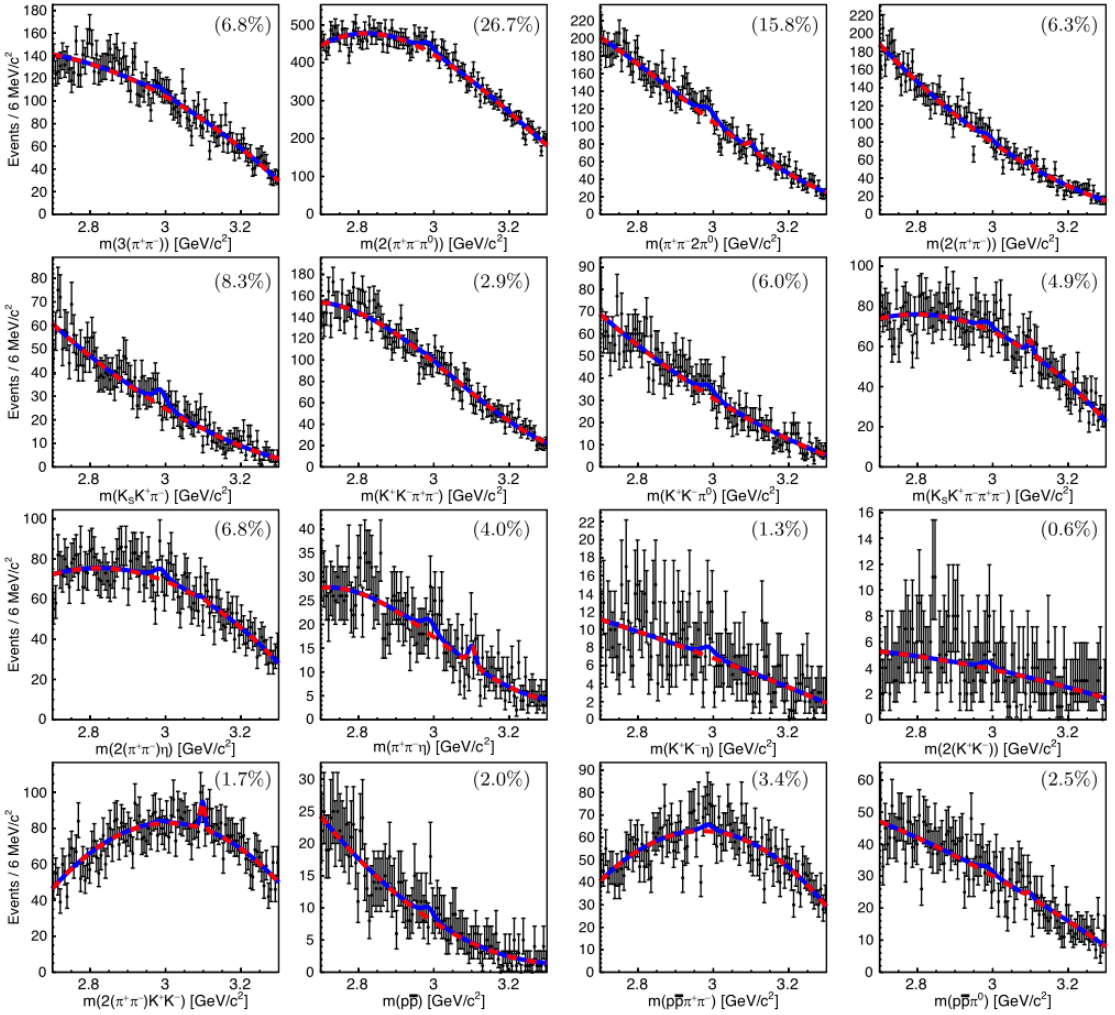
[Phys. Rev. D 103, 032006 (2021), arXiv:2010.14415]

Simultaneous fit of 16 decay channels

- Simultaneous fit example: $\eta_c\pi^+\pi^-\pi^0$ @ E_{cm} = 4.23 GeV
- Signal(s) barely visible

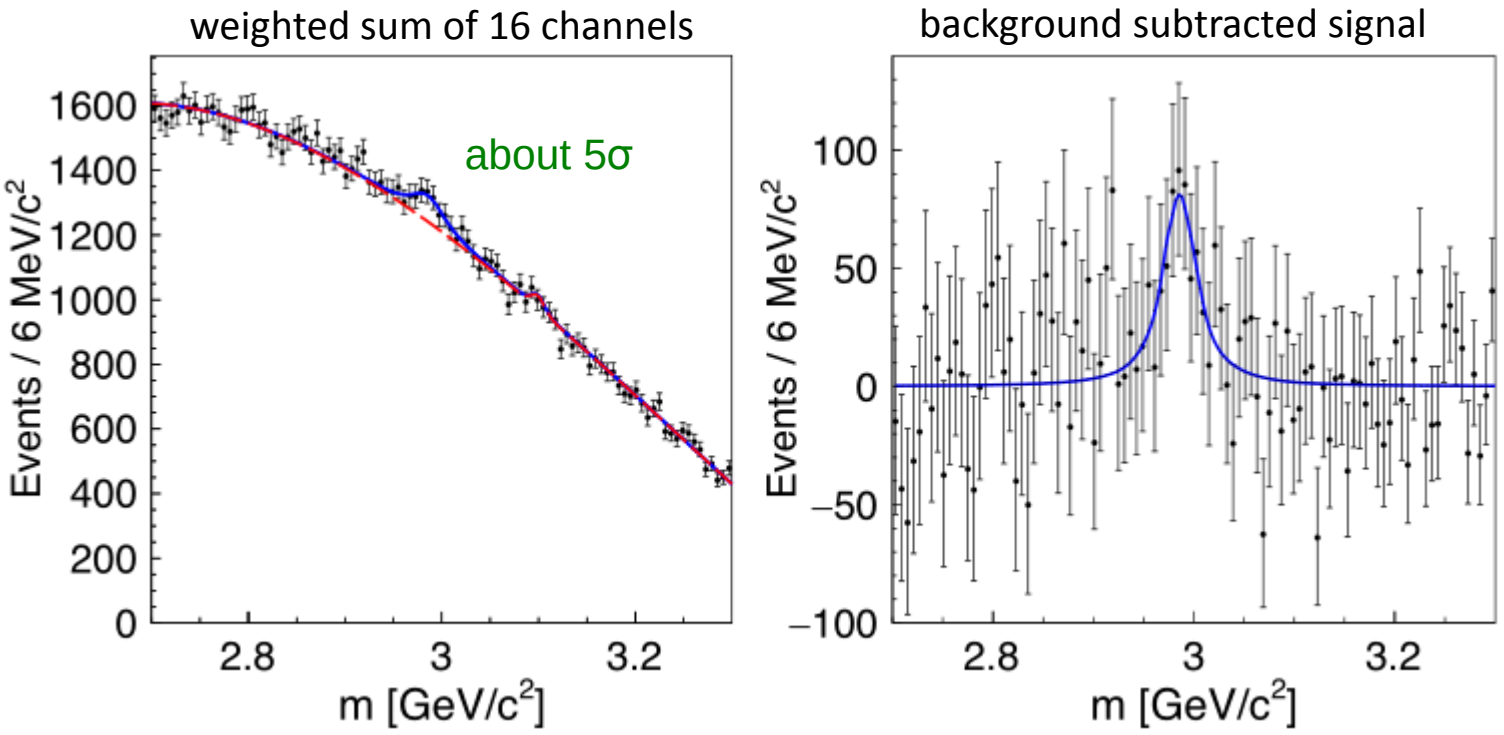
[Phys. Rev. D 103, 032006 (2021), arXiv:2010.14415]

Decay	$\mathcal{B}_i$[%] [39]
$3(\pi^+\pi^-)$	1.8 ± 0.4
$2(\pi^+\pi^-\pi^0)$	17.4 ± 3.3
$\pi^+\pi^-\pi^0\pi^0$	4.7 ± 1.0
$2(\pi^+\pi^-)$	0.97 ± 0.12
$K^0_S K^+\pi^-$	2.43 ± 0.17
$K^+K^-\pi^+\pi^-$	0.69 ± 0.11
$K^+K^-\pi^0$	1.21 ± 0.83
$K^0_S K^+\pi^-\pi^+\pi^-$	2.75 ± 0.74
$2(\pi^+\pi^-)\eta$	4.4 ± 1.3
$\pi^+\pi^-\eta$	1.7 ± 0.5
$K^+K^-\eta$	1.35 ± 0.16
$K^+K^-K^+K^-$	0.146 ± 0.030
$K^+K^-2(\pi^+\pi^-)$	0.75 ± 0.24
$p\bar{p}$	0.150 ± 0.016
$p\bar{p}\pi^+\pi^-$	0.53 ± 0.18
$p\bar{p}\pi^0$	0.36 ± 0.13
Summed up	$\sum_i \mathcal{B}_i = 41.34 \pm 3.93$



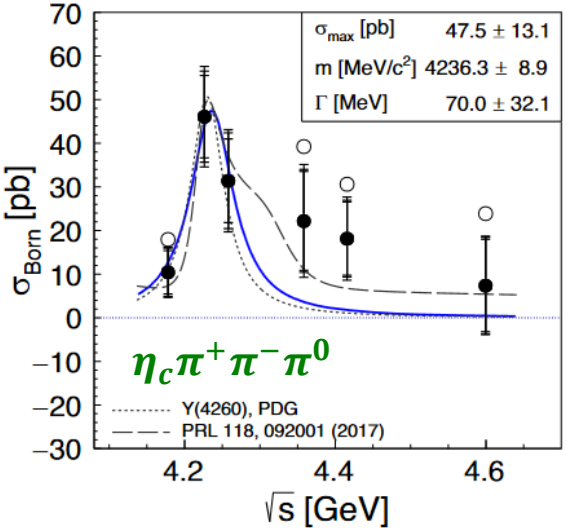
Signal in $\eta_c\pi^+\pi^-\pi^0$ @ 4.23 GeV

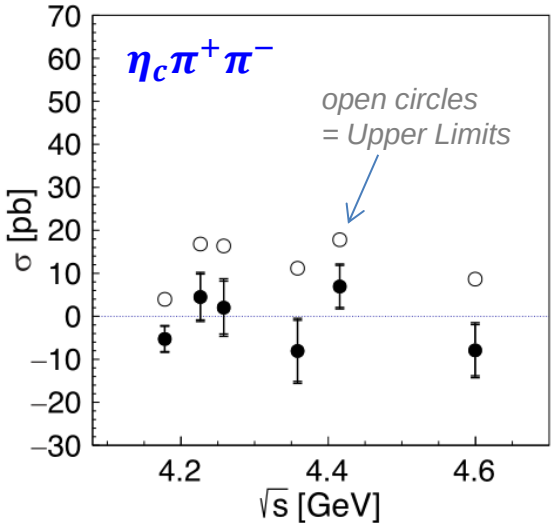
- Sum of spectra @ E_{cm} = 4.23GeV: Visible peak in $\eta_c\pi^+\pi^-\pi^0$ reactions
- About 5σ statistical significance
- Cases with no signal observed → Provide upper limit with CL_{90}

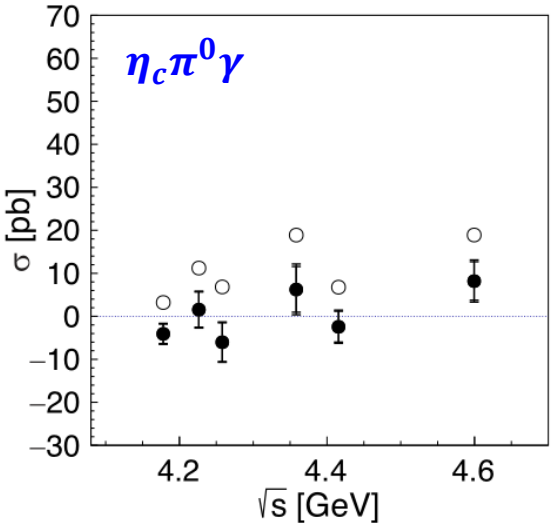


Energy Dependent Cross Section

- Significant cross section for $e^+e^- \rightarrow \eta_c\pi^+\pi^-\pi^0$
- Fit to distribution suggest intermediate Y(4260)
- Parameters consistent with PDG



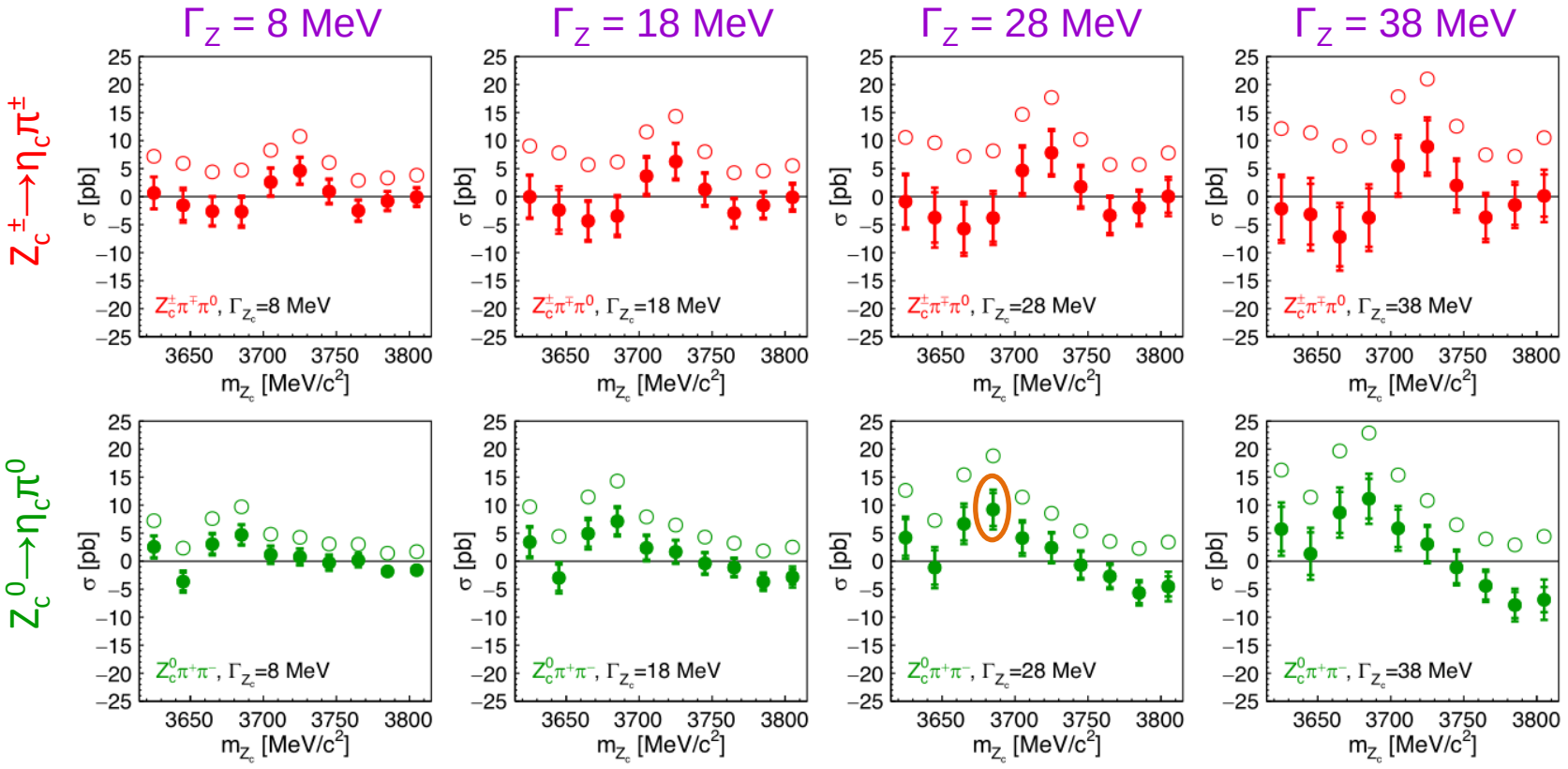




$\psi(4230)$ Decay Modes (new PDG entries)			
...			
Γ_{12}	$\pi^+\pi^-\pi^0\eta_c$	seen	992
Γ_{13}	$\pi^+\pi^-\eta_c$	not seen	1027
Γ_{14}	$\gamma\pi^0\eta_c$	not seen	1049

Search for $Z_c \longrightarrow \eta_c \pi^{\pm/0}$

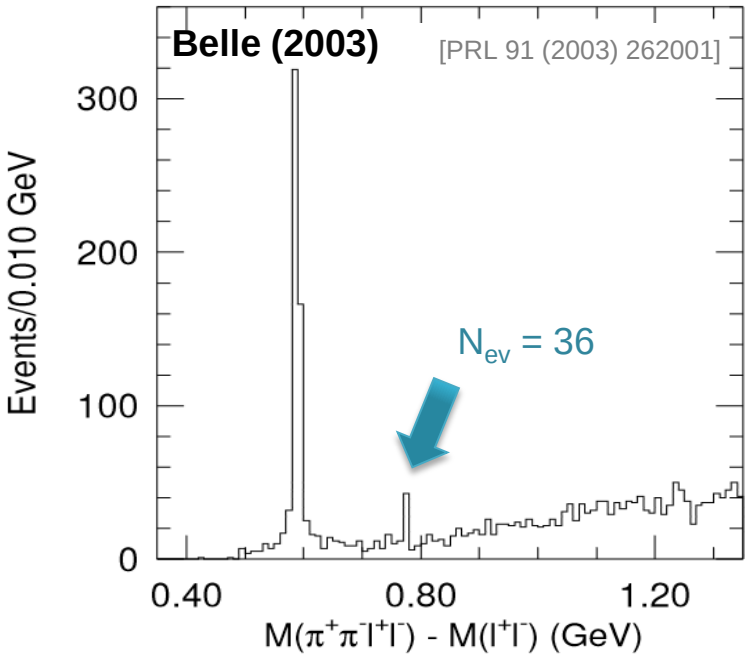
- In dataset with largest η_c production: Find $Z_c(3900)$ partner with $J^P = 0^+$?
- Scan for various mass/width combinations
- See 2.8σ enhancement - but with Look-Elsewhere-Effect reduced to 2.0σ
- No evidence for $Z_c^{\pm/0} \longrightarrow \eta_c \pi^{\pm/0}$ decays at present statistics

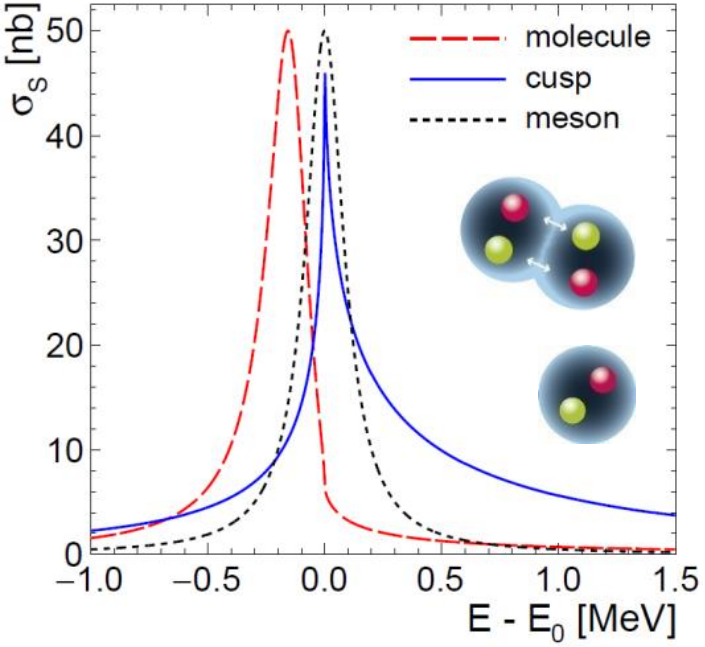


PANDA: X(3872) Lineshape

PANDA: Energy Scan of X(3872)

- Nature of first observation X(3872) in 2003 still not fixed!
- Idea to a solution:
  - Different internal structure → different production/decay dynamics
  - Line shape of resonance reveals nature!





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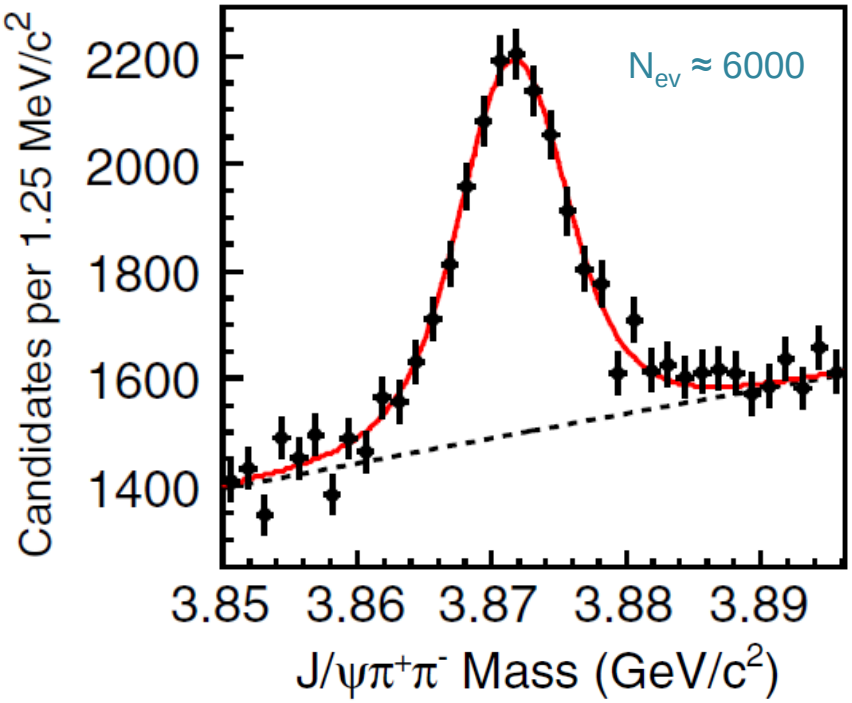
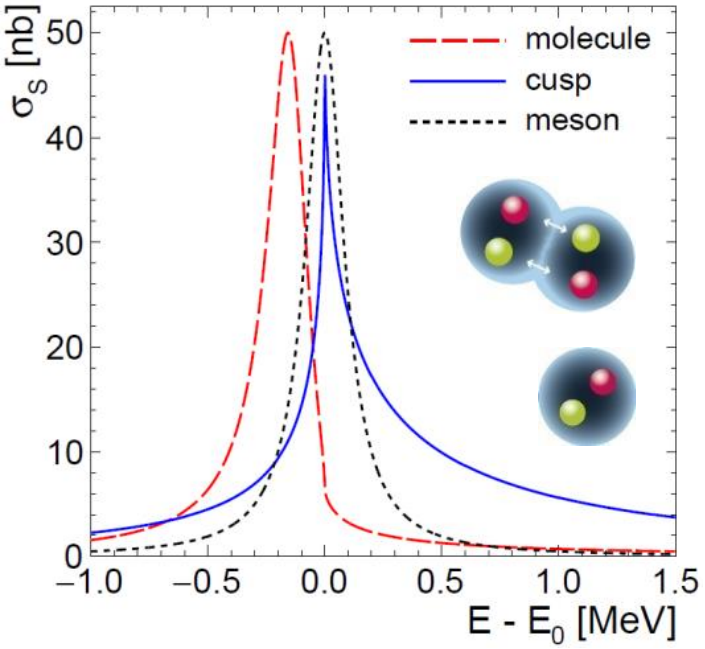
[CDF, PRL 103 (2009) 152001]

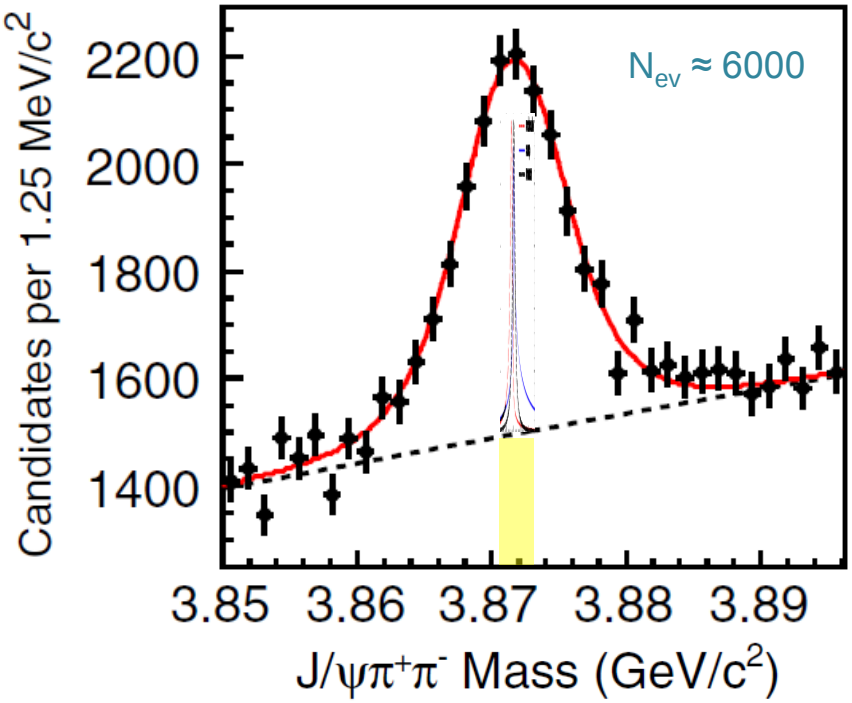


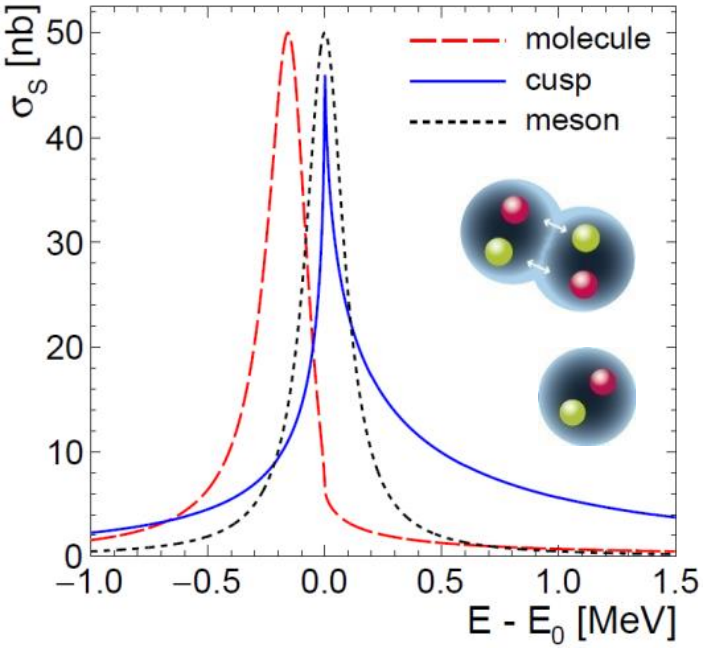


PANDA: Energy Scan of X(3872)

- Nature of first observation X(3872) in 2003 still not fixed!
- Idea to a solution:
  - Different internal structure → different production/decay dynamics
  - Line shape of resonance reveals nature!
  - High resolution needed to resolve structures!

[CDF, PRL 103 (2009) 152001]

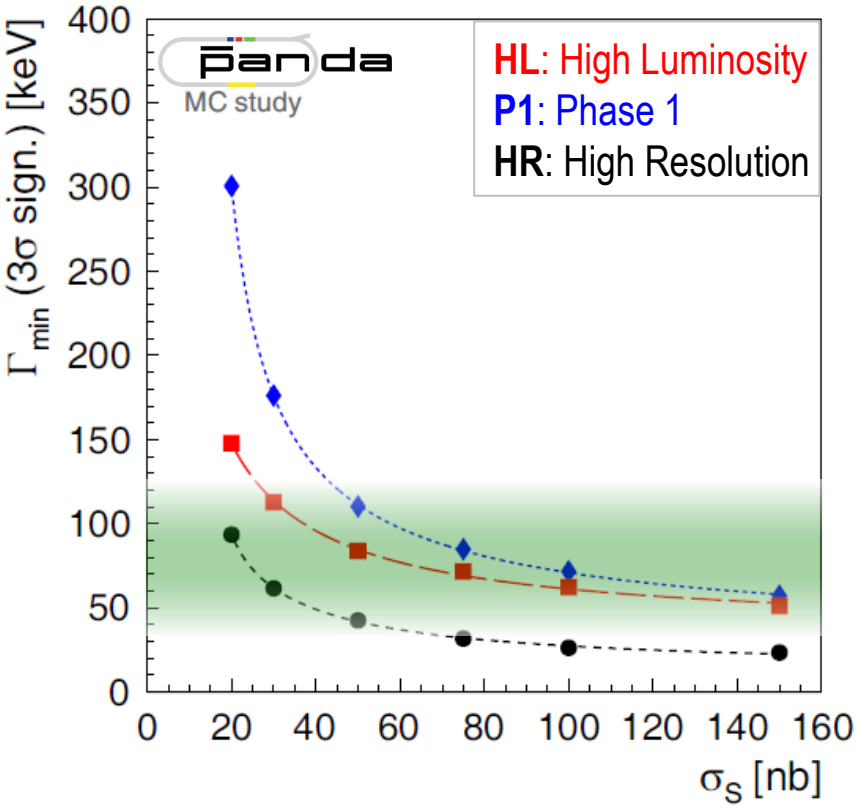


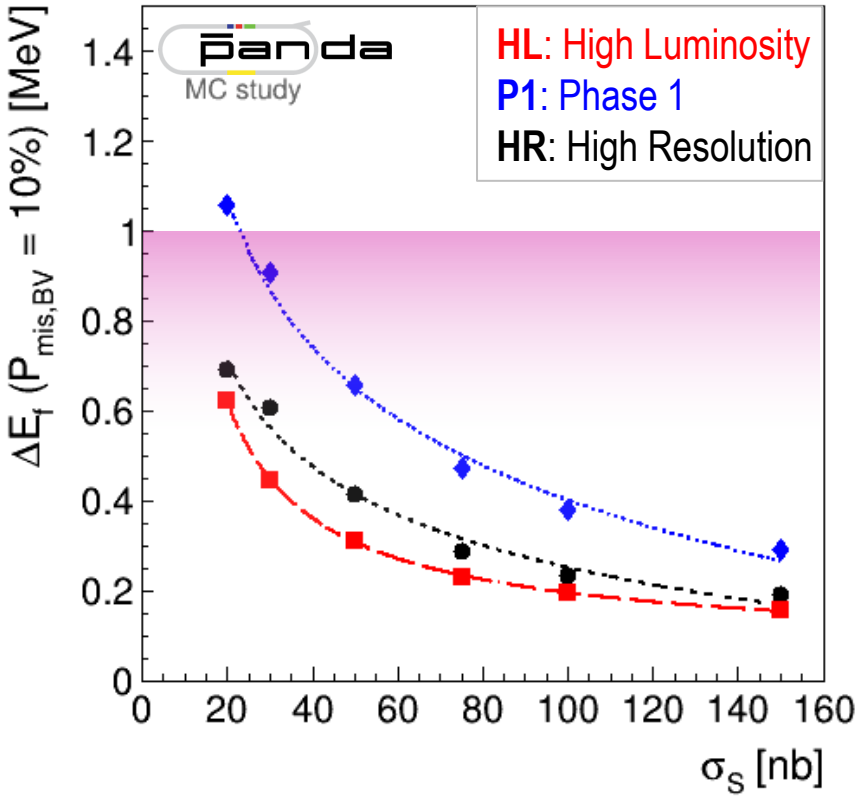


PANDA: Precise Line Shape Sensitivity Study

- Comprehensive simulation study carried out and published
  → Expected sensitivity for BW Width Γ & Flatté Parameter E_f @ PANDA
- Breit-Wigner: 3σ precision at down to Γ = O(50 − 100) keV!
- Flatté: Precision in sub-MeV range!

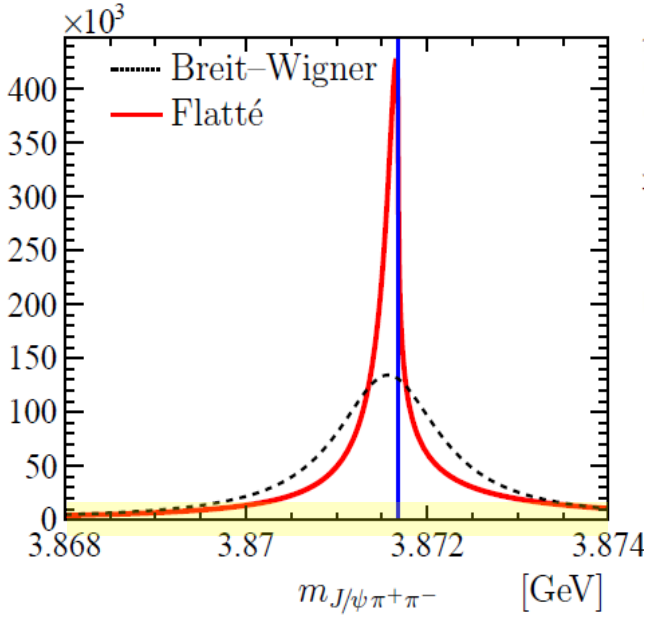
[Eur. Phys. J. A 55 (2019) 3, 42, arXiv:1812.05132]



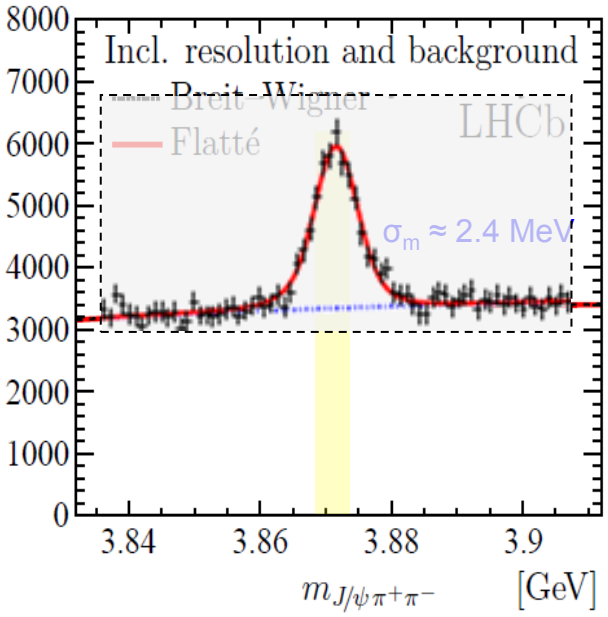


Recent LHCb Measurement (2020)

Original lineshapes



LHCb Lineshapes with resolution



[PRD 102 (2020) 9, 092005]

7.3 Comparison between Breit–Wigner and Flatté lineshapes

Figure 4 shows the comparison between the Breit–Wigner and the Flatté lineshapes. While in both cases the signal peaks at the same mass, the Flatté model results in a signifcantly narrower lineshape. However, after folding with the resolution function and adding the background, the observable distributions are indistinguishable.

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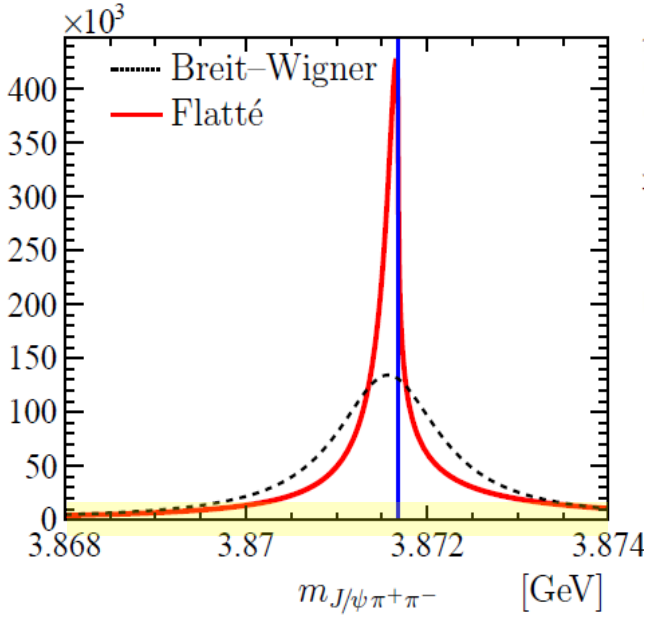

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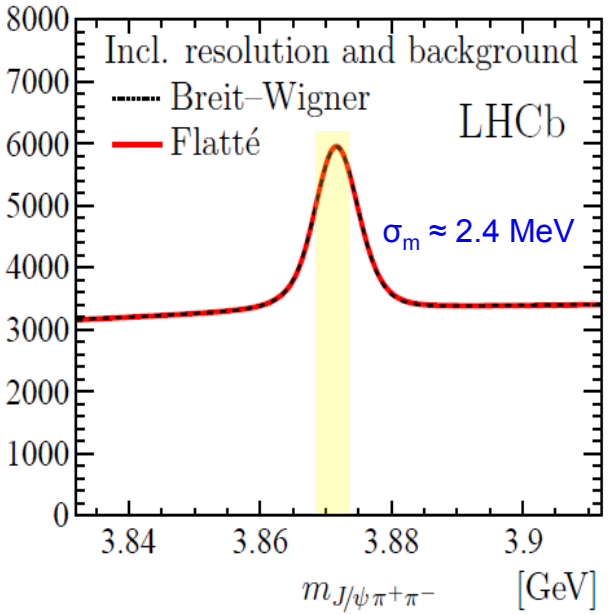

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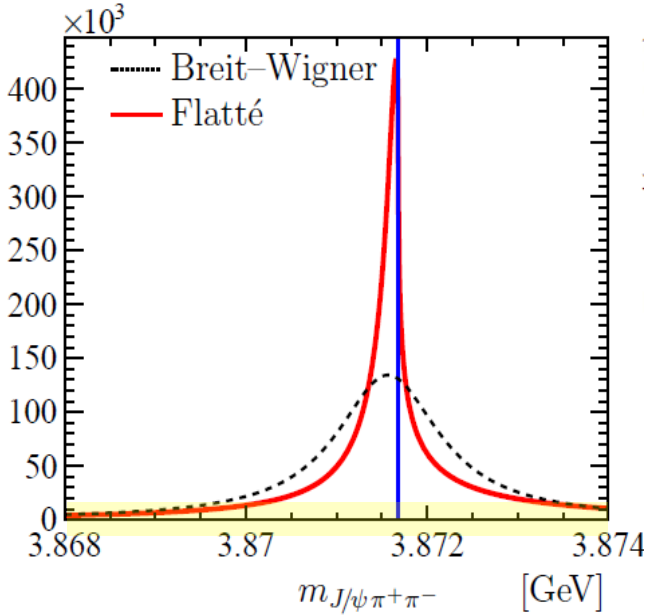
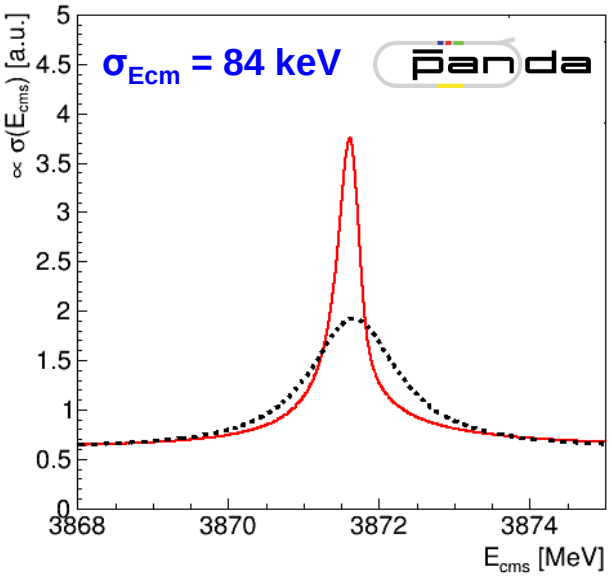


Lineshapes @ PANDA (Phase 1)



[PRD 102 (2020) 9, 092005]

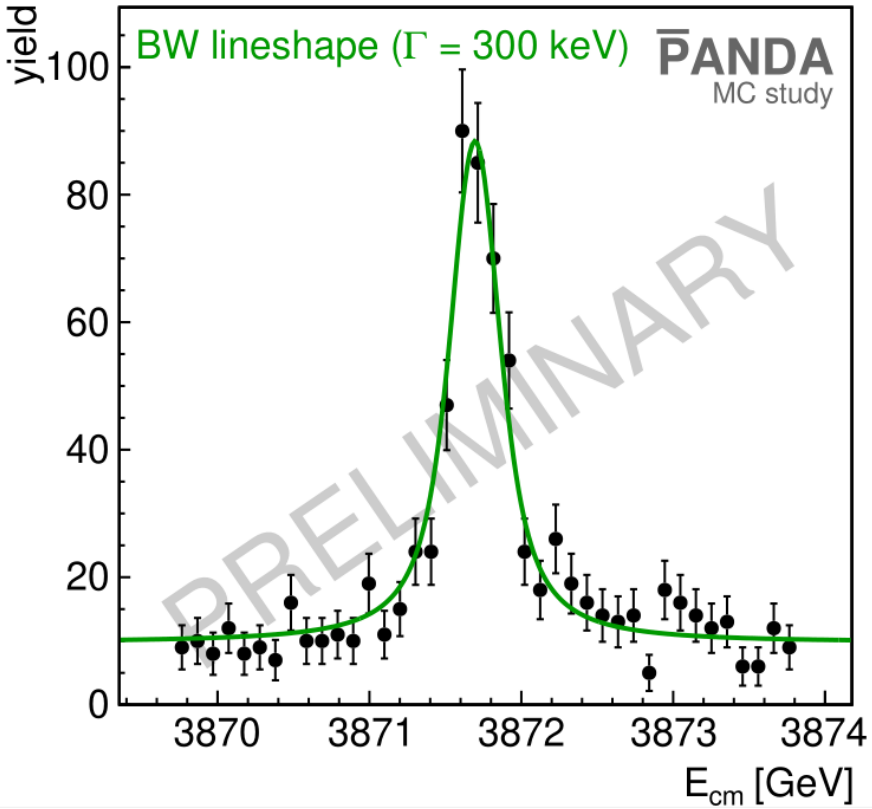
Due to precise beam resolution O(50 - 100 keV) @ PANDA

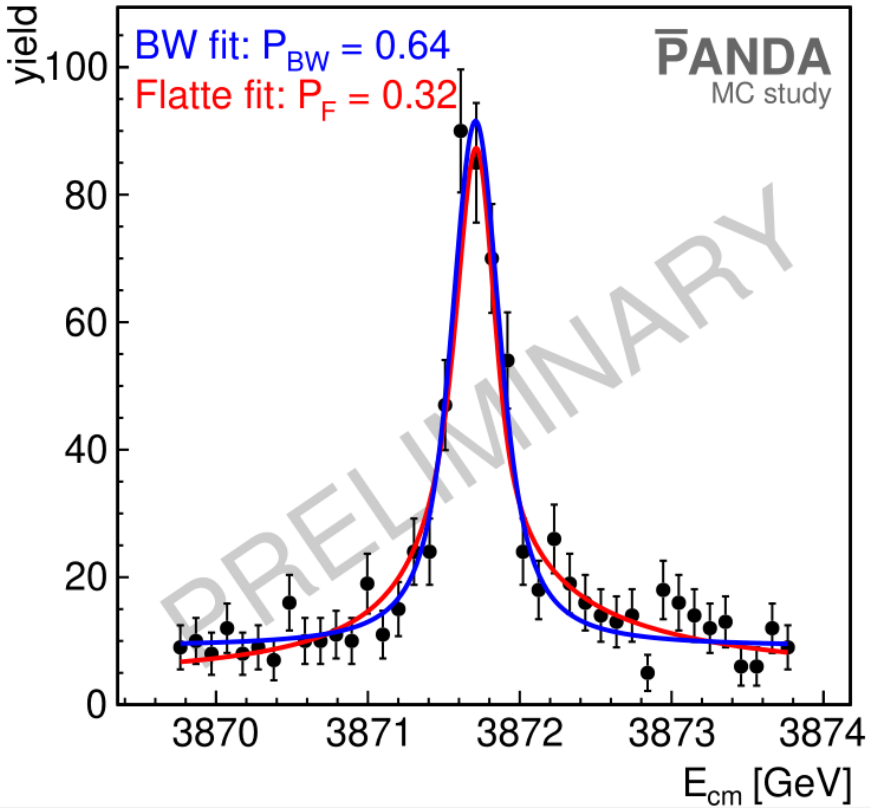
→ Models are well distinguishable!

→ Let us quantify how well!

Simulation Strategy

1. Generate spectra from chosen input line-shape (Breit-Wigner or Flatté)
2. Fit both models → Fit probabilities $P_{\text{Breit-Wigner}}$ and $P_{\text{Flatté}}$
3. If $P_{\text{input}} > P_{\text{other}}$ → identification correct
4. Repeat many times → number of correct / wrong ident. = F_{correct} and F_{wrong}

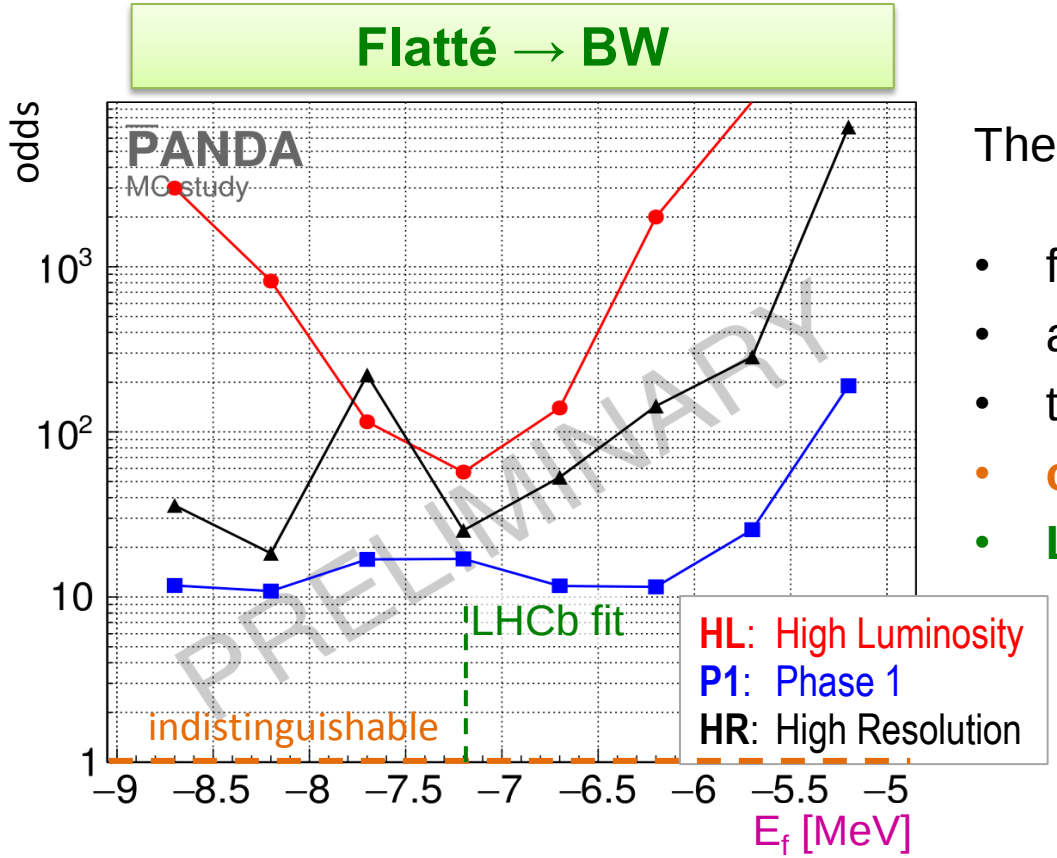




Performance

- How much better than "indistinguishable" is this now?
- Idea: Consider **odds** = ratio of correct and wrong identifications

$$\text{odds} = F_{\text{correct}} / F_{\text{wrong}}$$



The plot shows:

- for the three beam modes **HL**, **P1**, **HR**
- across range of input parameters E_f
- the odds $F_{\text{correct}} / F_{\text{wrong}}$ @ PANDA
- **odds = 1** for "indistinguishable"
- **LHCb** best fit E_f = -7.2 MeV

Performance

- How much better than "indistinguishable" is this now?
- Idea: Consider **odds** = ratio of correct and wrong identifications

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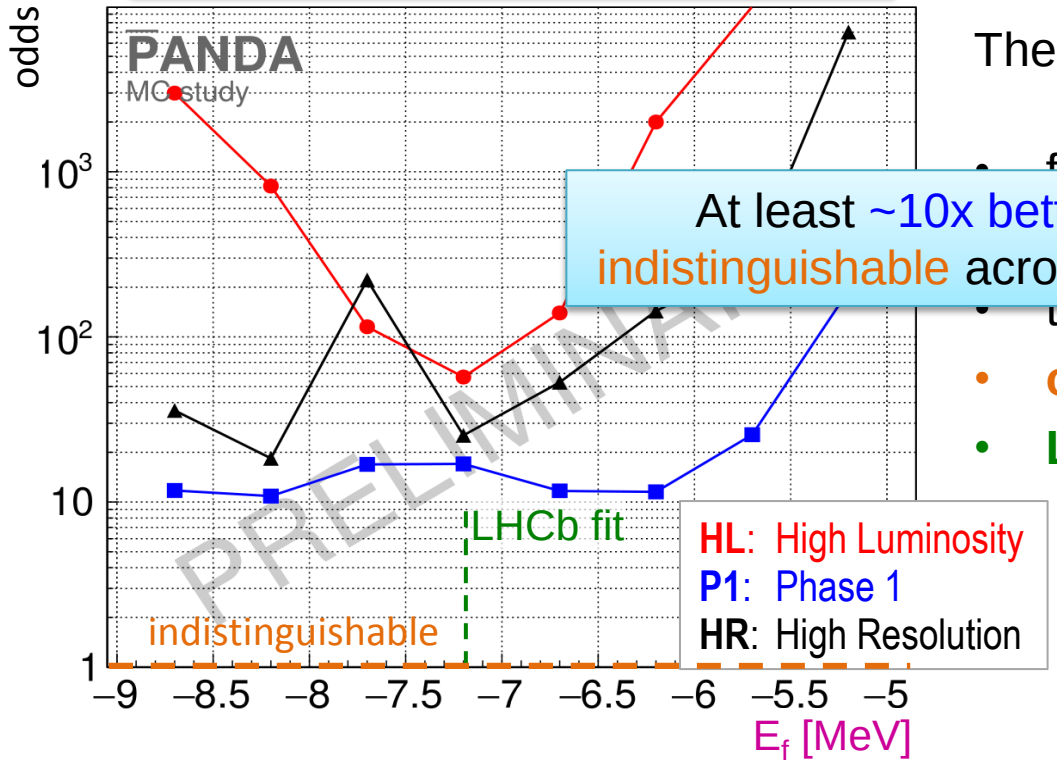
Flatté → BW



At least ~10x better than indistinguishable across full range!

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- f input parameters E_f
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Summary

- XYZ states great opportunity to further understand QCD bound states

- GSI group involved in PANDA, BESIII and GlueX

- **BESIII**: Published evidence for $e^+e^- \rightarrow Y(4230) \rightarrow \eta_c\pi^+\pi^-\pi^0$
  → No (clear) evidence found for Z_c decay with given data
  → Re-analyse with more data!

- **PANDA**: Published X(3872) lineshape scan simulation
  → Unprecedented precision expected!

- GlueX: Search for photo production of Y(2175) ongoing.