Helmholtz Forschungsakademie Hessen für FAIR

JOHANN WOLFGANG GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Review on Hadron Spectroscopy

Frank Nerling
HFHF, GU Frankfurt & GSI Darmstadt

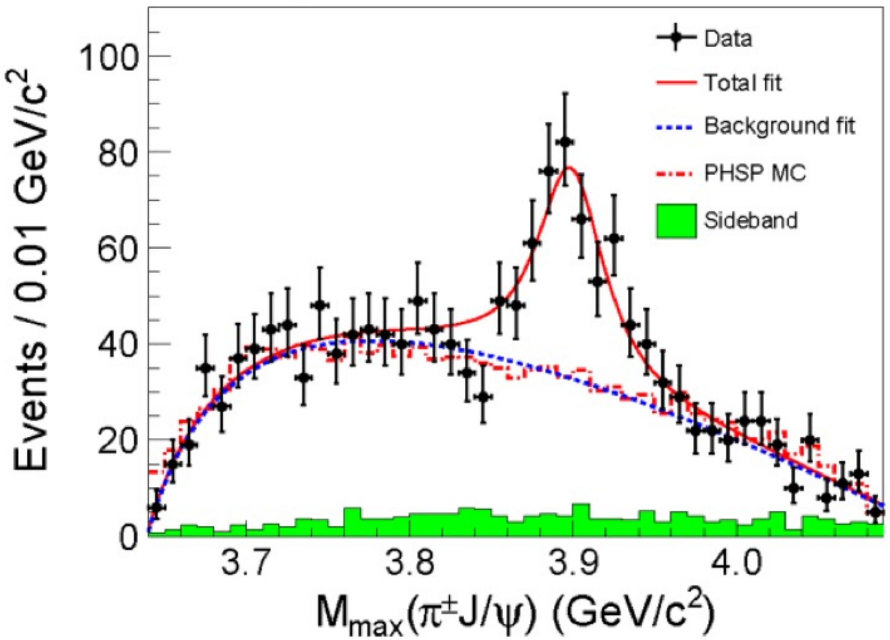
10th International Symposium on Non-equilibrium Dynamics –
NED2024, Krabi, Thailand, Nov 25th - 29th 2024

Outline

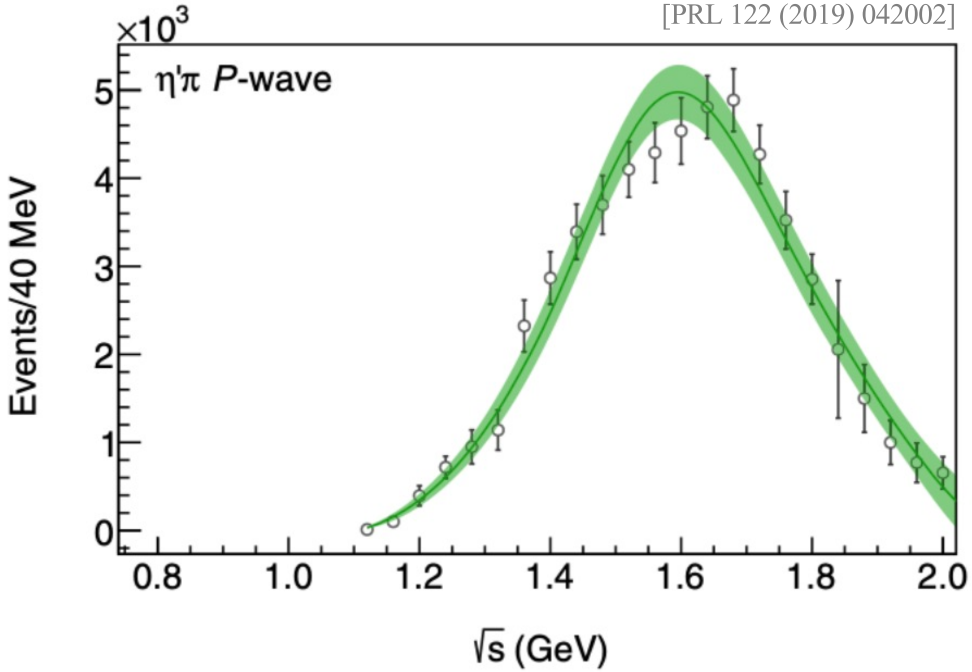
- **Introduction: From cosmic rays to hadrons**
- **The powerful Quark Model and QCD**
- **A selection of recent results at BESIII**
  - Supernumerary vector Y states
  - Manifestly exotic Z_c states)
  - The X(3872) and other X states
- **Ongoing analysis at GlueX:**
  - Search for the Y(2175) in photoproduction
- **Summary & prospectives**

Recent hot topics

[PRL 110 (2013) 252001]

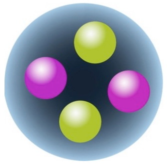


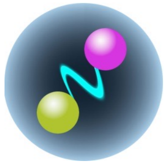
[PRL 122 (2019) 042002]



$Z_c(3900)^{+/-} \rightarrow J/\psi\pi^{+/-}$

$\pi_1(1600) \rightarrow \eta'\pi$





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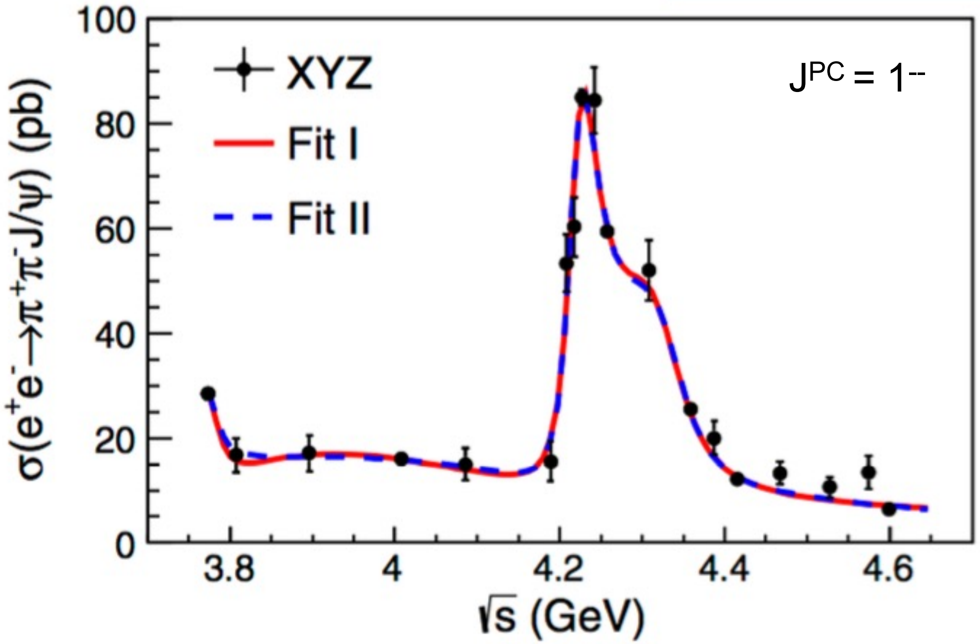

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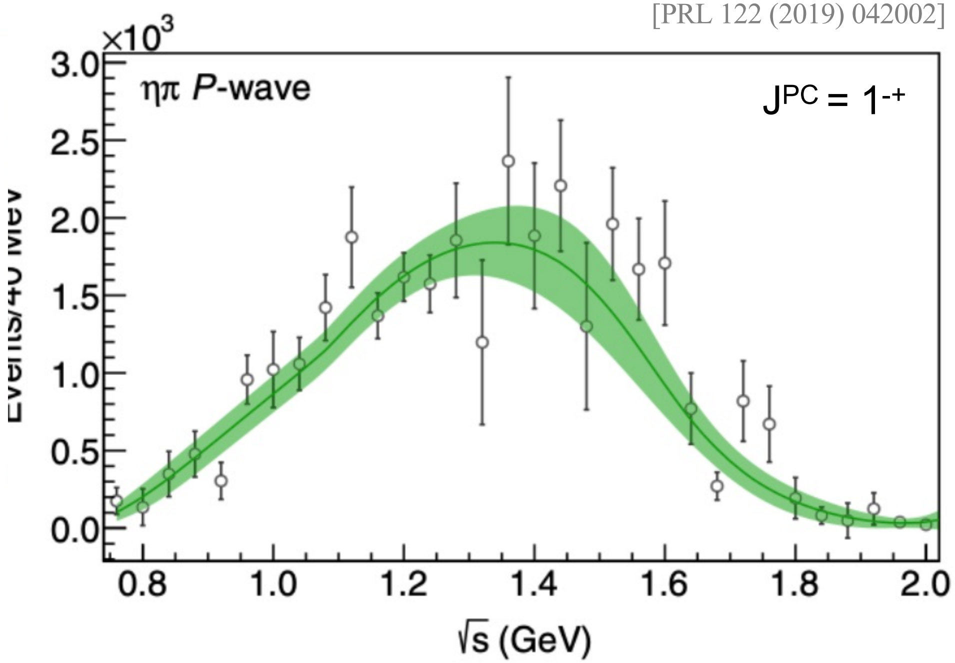


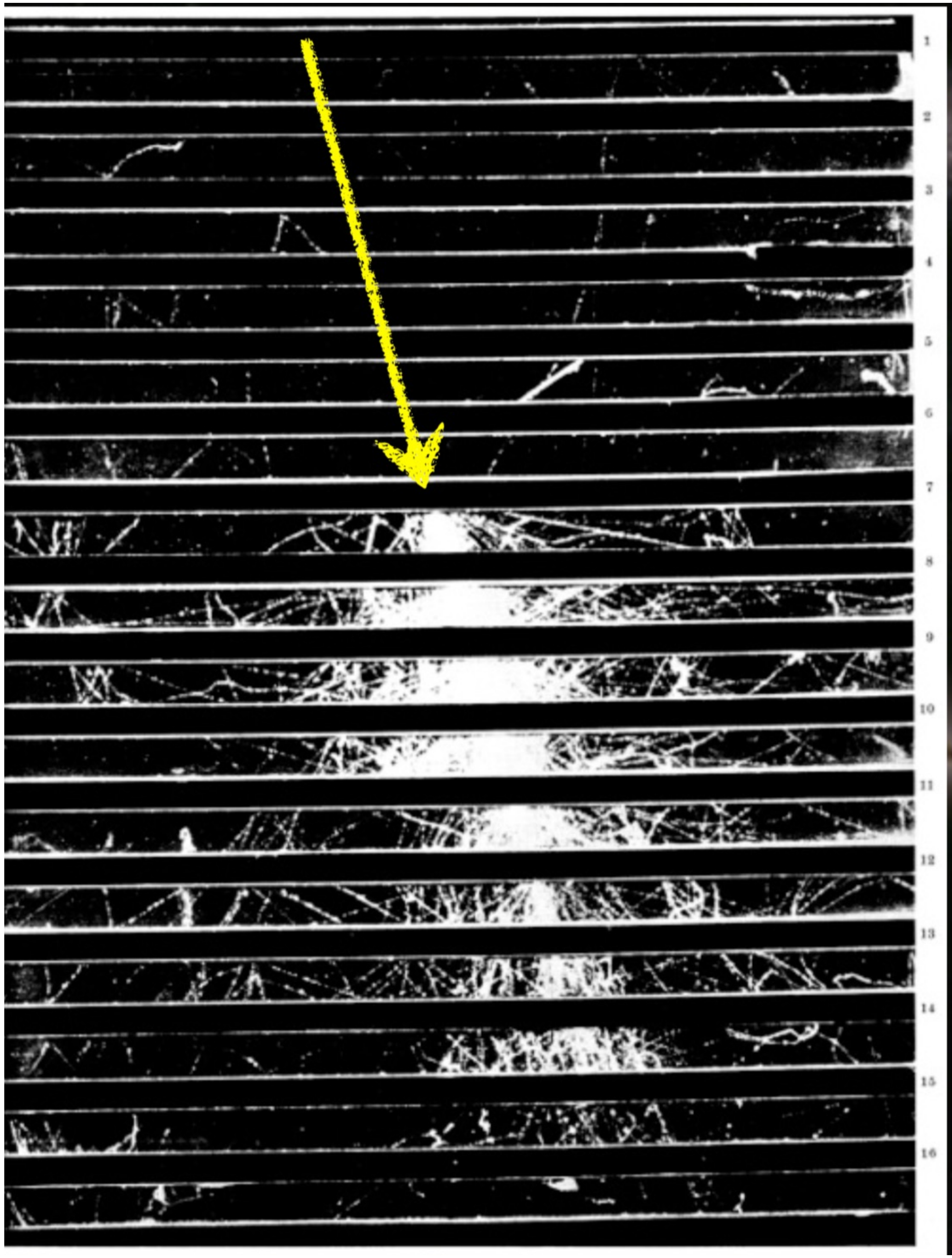
$Z_c(3900)^{+/-} \rightarrow J/\psi\pi^{+/-}$

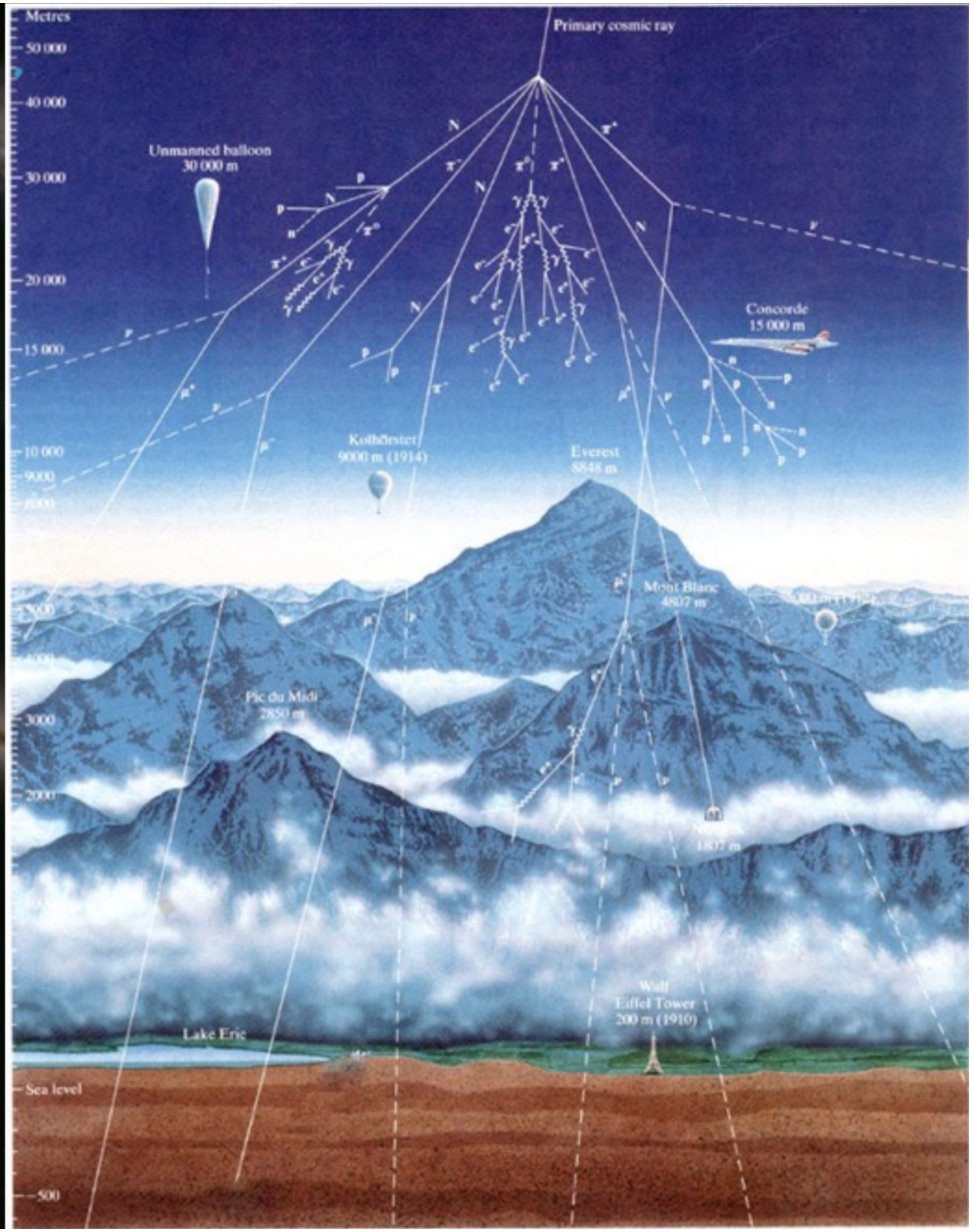
$Y(4230) \rightarrow J/\psi\pi^+\pi^-$

$\pi_1(1600) \rightarrow \eta'\pi$

$\pi_1(1400) = \pi_1(1600) \rightarrow \eta\pi$

Extensive air showers (1938)





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GSI
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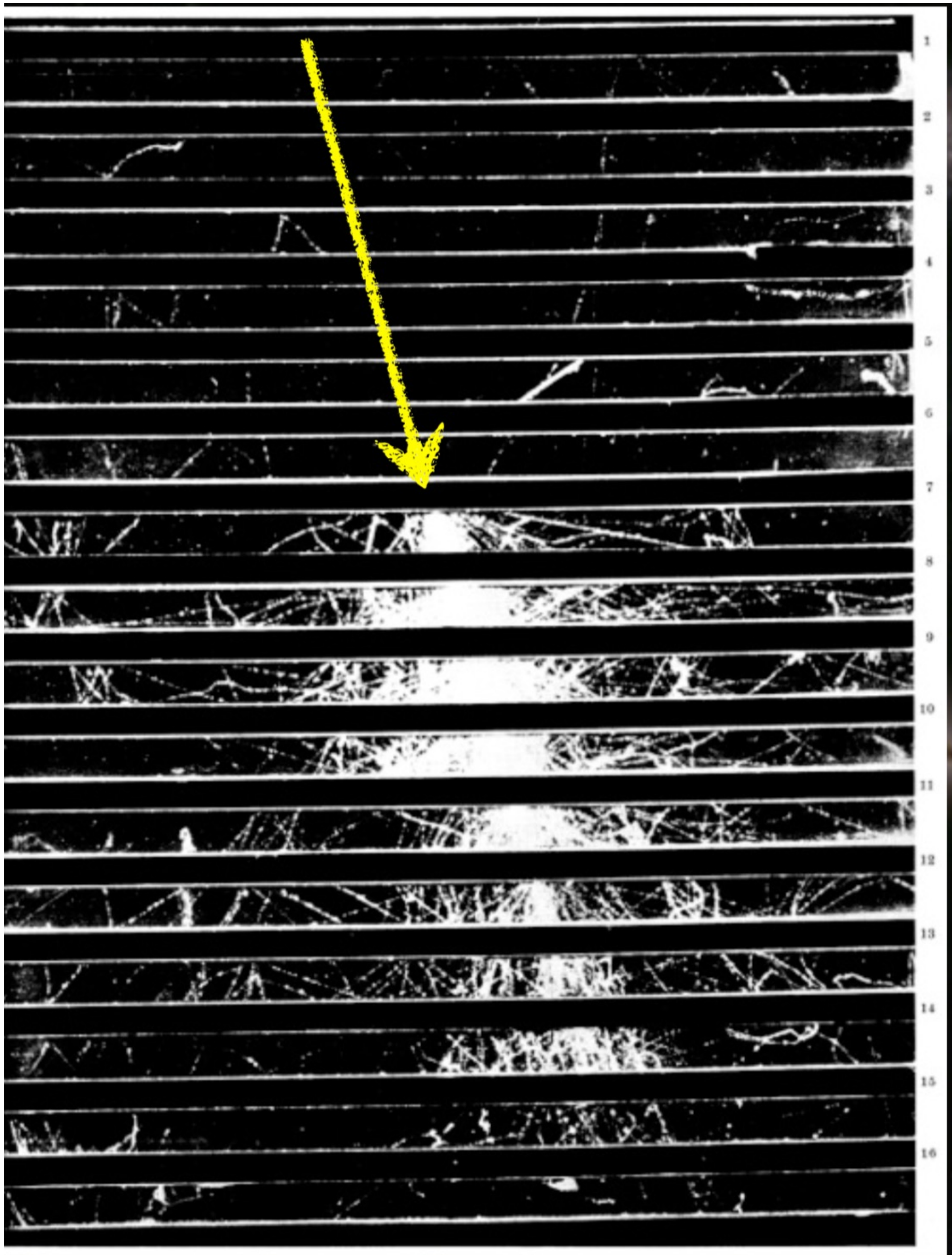
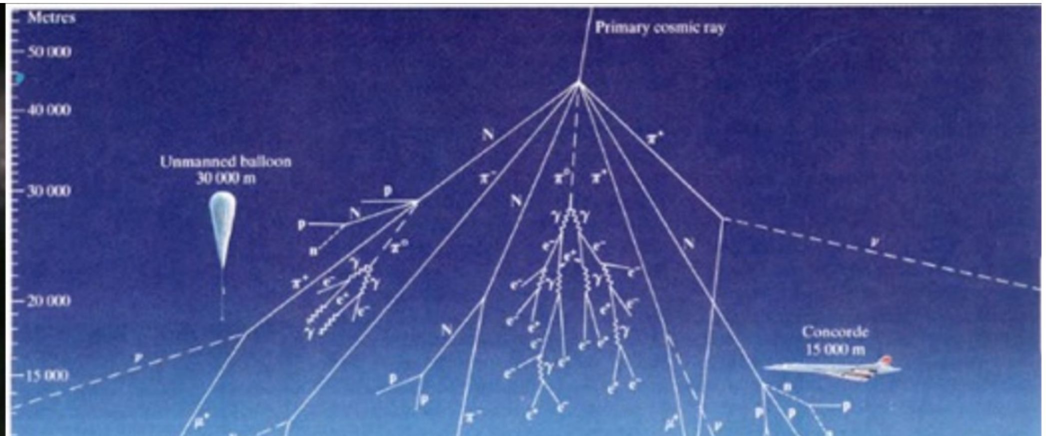
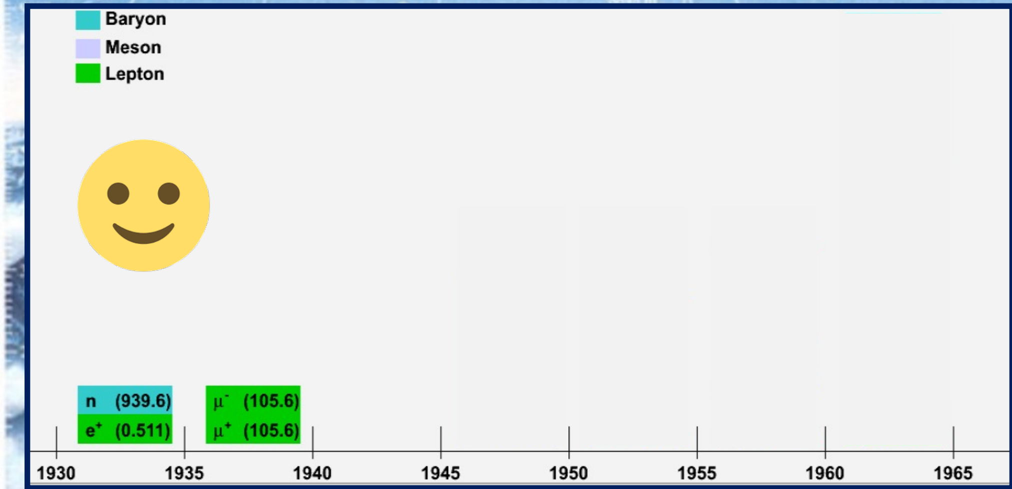
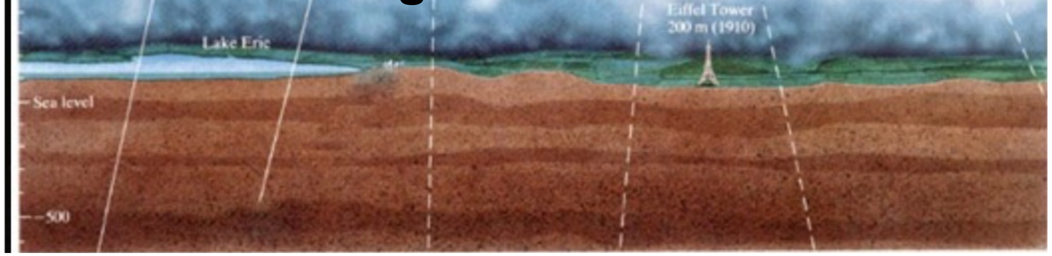




- **Particle Discoveries since 1930 – 1965**



- **Since then it got more and more ...**



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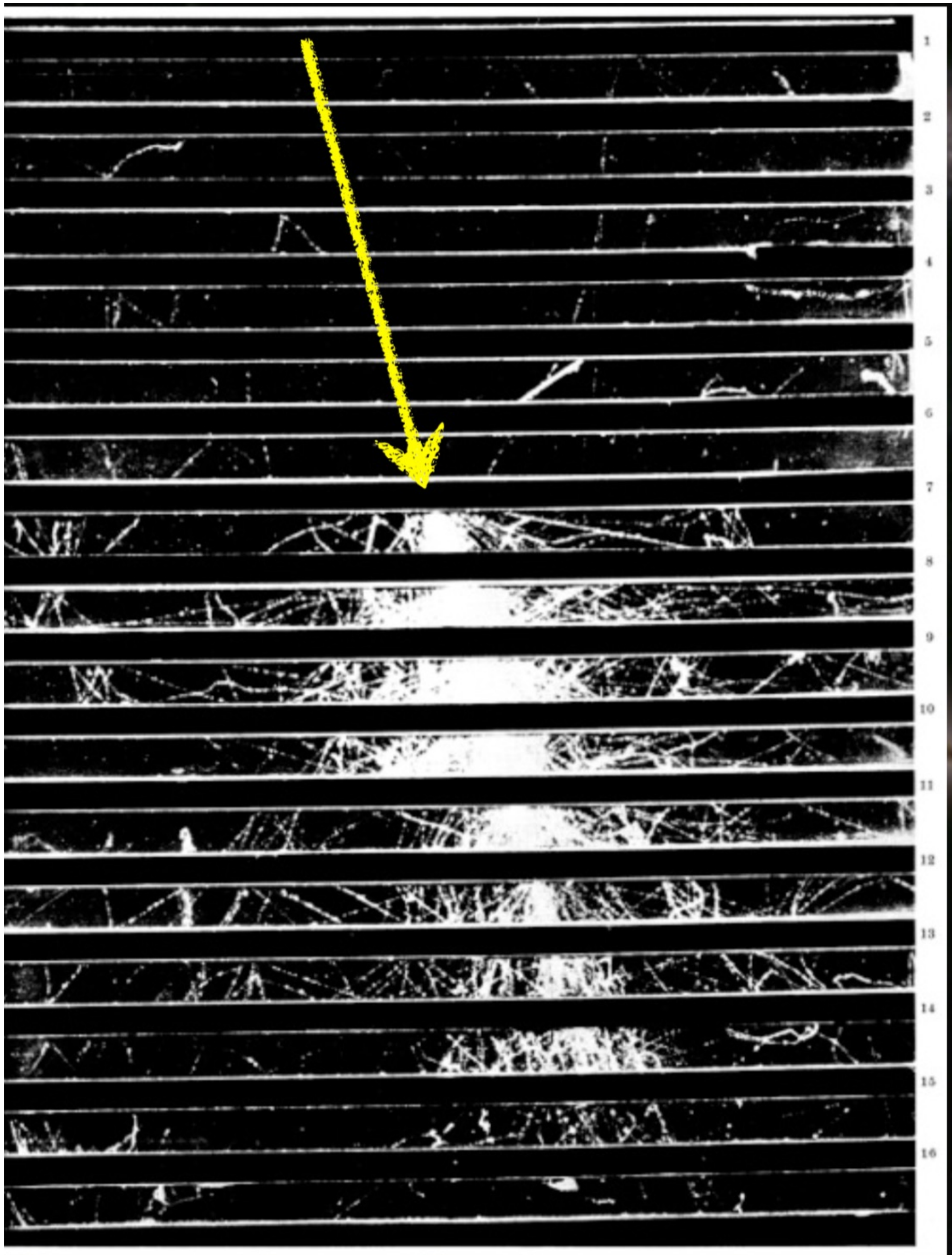

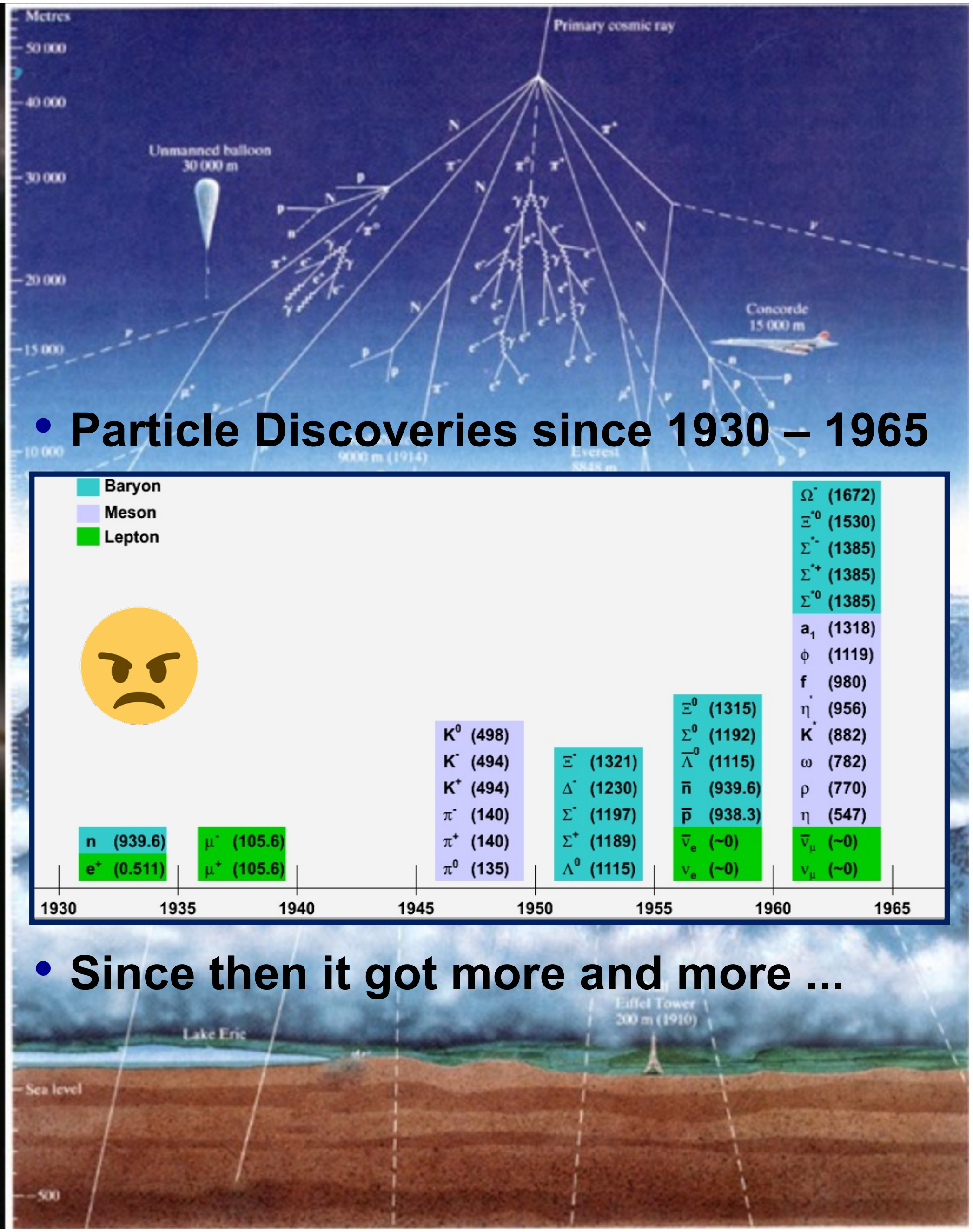

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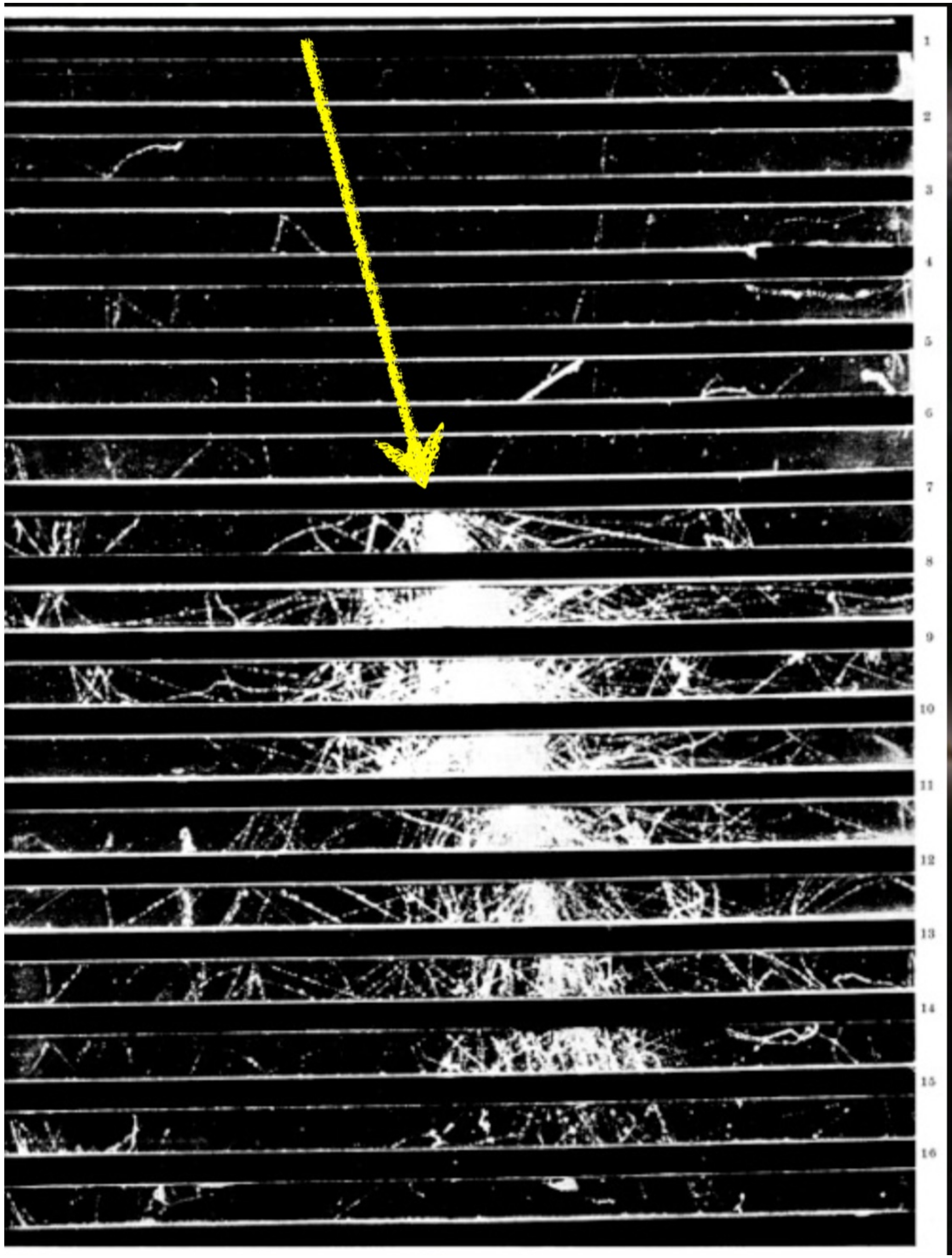

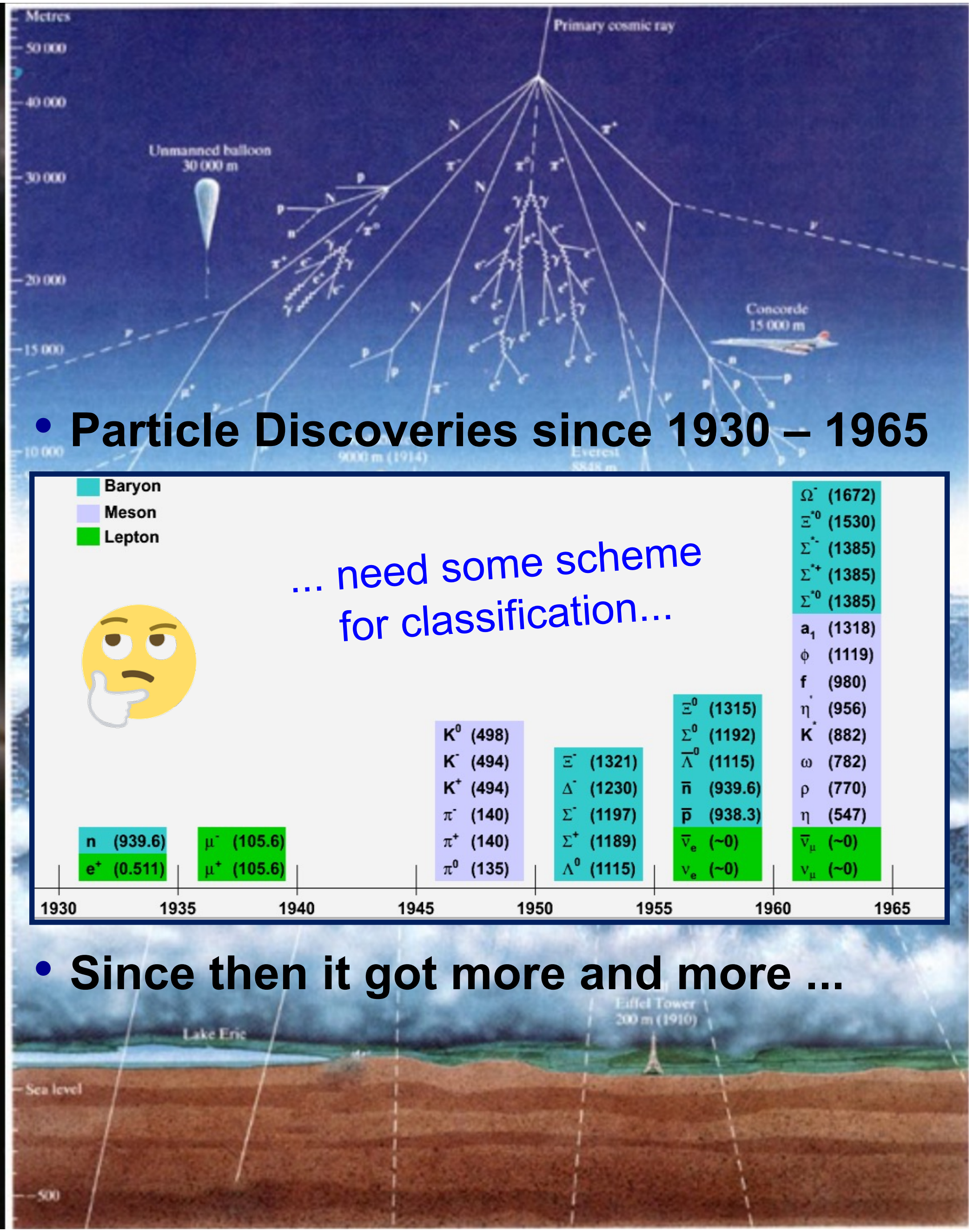

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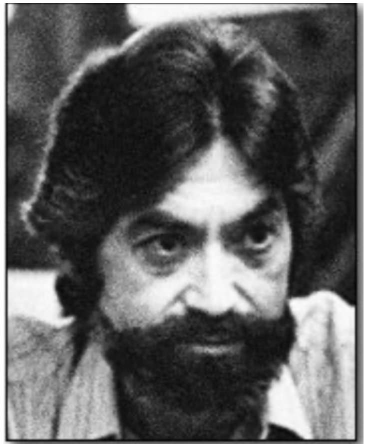
The successful Quark Model

1964



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

. . .

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while

8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

G. Zweig
CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

. . .

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $AAAA\bar{A}$, $AAAAA\bar{A}\bar{A}$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $A\bar{A}$, $AA\bar{A}\bar{A}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $A\bar{A}$ and AAA, that is, "deuces and treys".

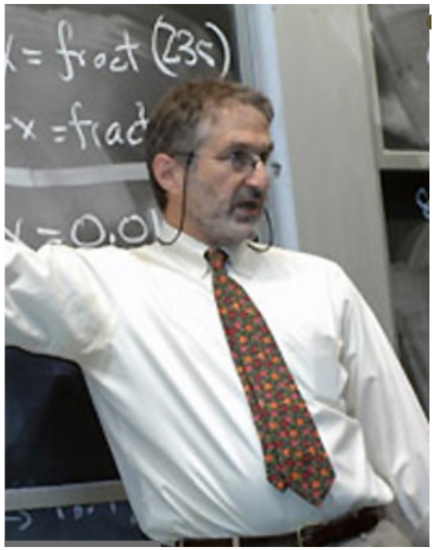
Hadrons beyond the Quark Model

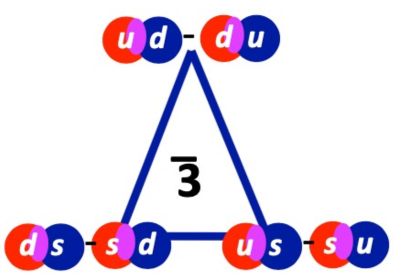
PHYSICAL REVIEW D VOLUME 15, NUMBER 1 1 JANUARY 1977

Multiquark hadrons. I. Phenomenology of $Q^2\bar{Q}^2$ mesons*

R. J. Jaffe†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
and Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 15 July 1976)

The spectra and dominant decay couplings of $Q^2\bar{Q}^2$ mesons are presented as calculated in the quark-bag model. Certain known 0^+ mesons $[\epsilon(700), S^*, \delta, \kappa]$ are assigned to the lightest cryptoexotic $Q^2\bar{Q}^2$ nonet. The usual quark-model 0^+ nonet ($Q\bar{Q}$ $L=1$) must lie higher in mass. All other $Q^2\bar{Q}^2$ mesons are predicted to be broad, heavy, and usually inelastic in formation processes. Other $Q^2\bar{Q}^2$ states which may be experimentally prominent are discussed.



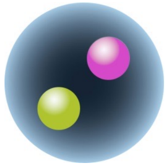


Antisymmetric in:
color
flavor
spin (S=0)

Mesons and exotic states

Simple Quark model

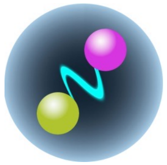
- Mesons: Color neutral $q\bar{q}$ systems



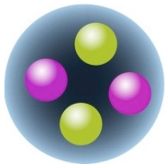
Conventional ($q\bar{q}$)

QCD

- Meson states beyond $q\bar{q}$



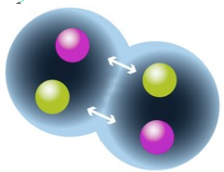
Hybrid ($q\bar{q}$) g



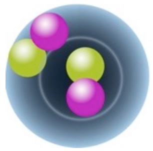
Tetraquark ($q\bar{q}q\bar{q}$)

Glue-ball (gg) or (ggg)

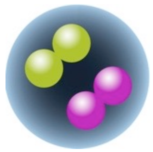
Alternative 4-quark configurations:



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



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



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

Mesons and exotic states

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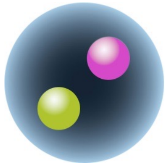

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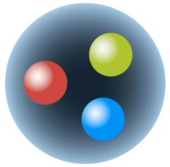
- Baryons: (qqq) / $(\bar{q}\bar{q}\bar{q})$



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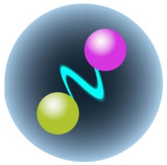

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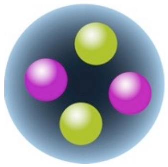

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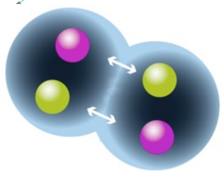

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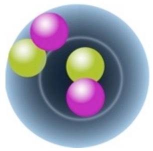

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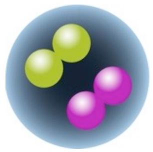

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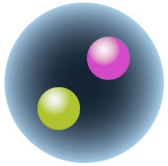

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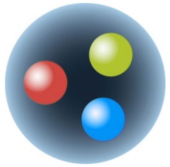
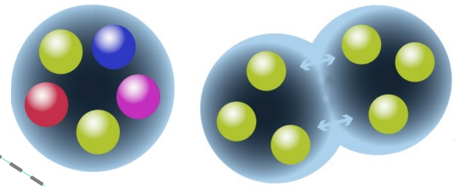


Lead to further alternative multi-quark configurations:



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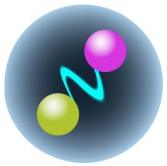

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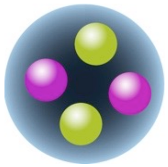

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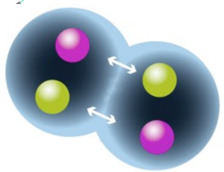

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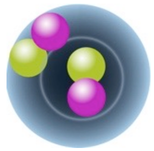

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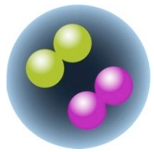

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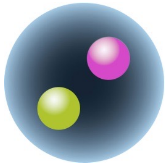

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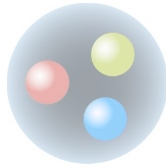

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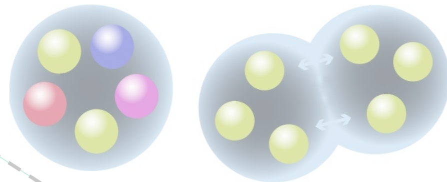

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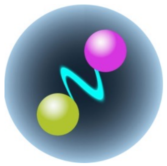

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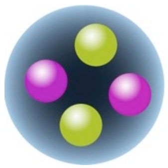

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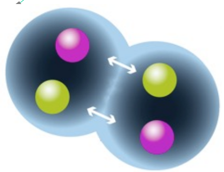

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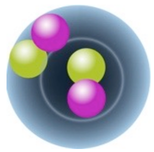

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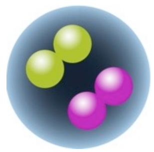
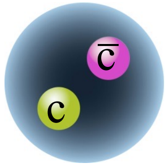
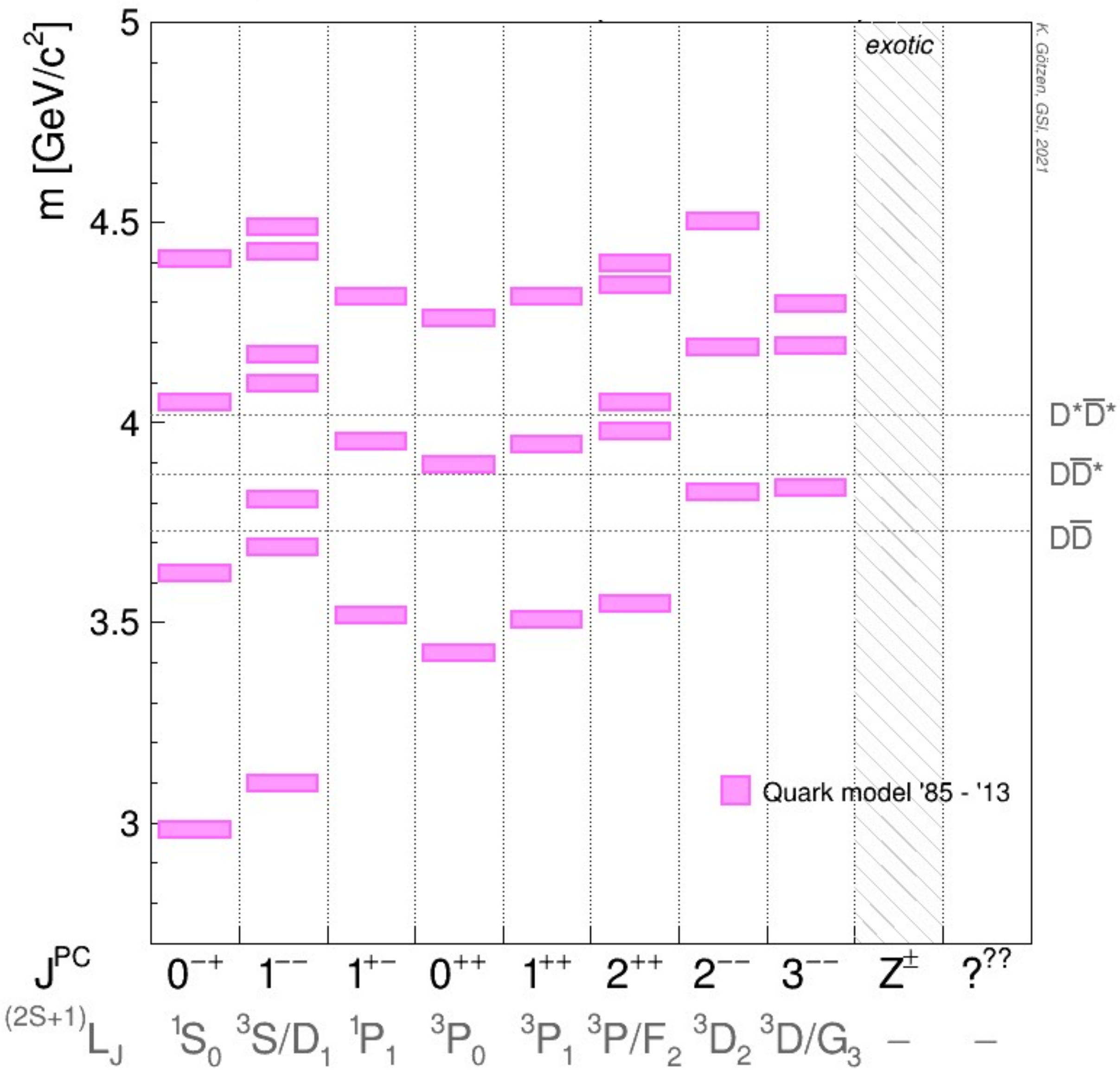


Di-quarkonium $(qq)(\bar{q}\bar{q})$

Charmonium spectrum ($c\bar{c}$)





Potential model:

$$V_0^{c\bar{c}} = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\delta(r)\vec{S}_c\vec{S}_{\bar{c}}$$

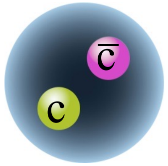
$$V_{\text{spin-dep.}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

+ relativistic corrections!

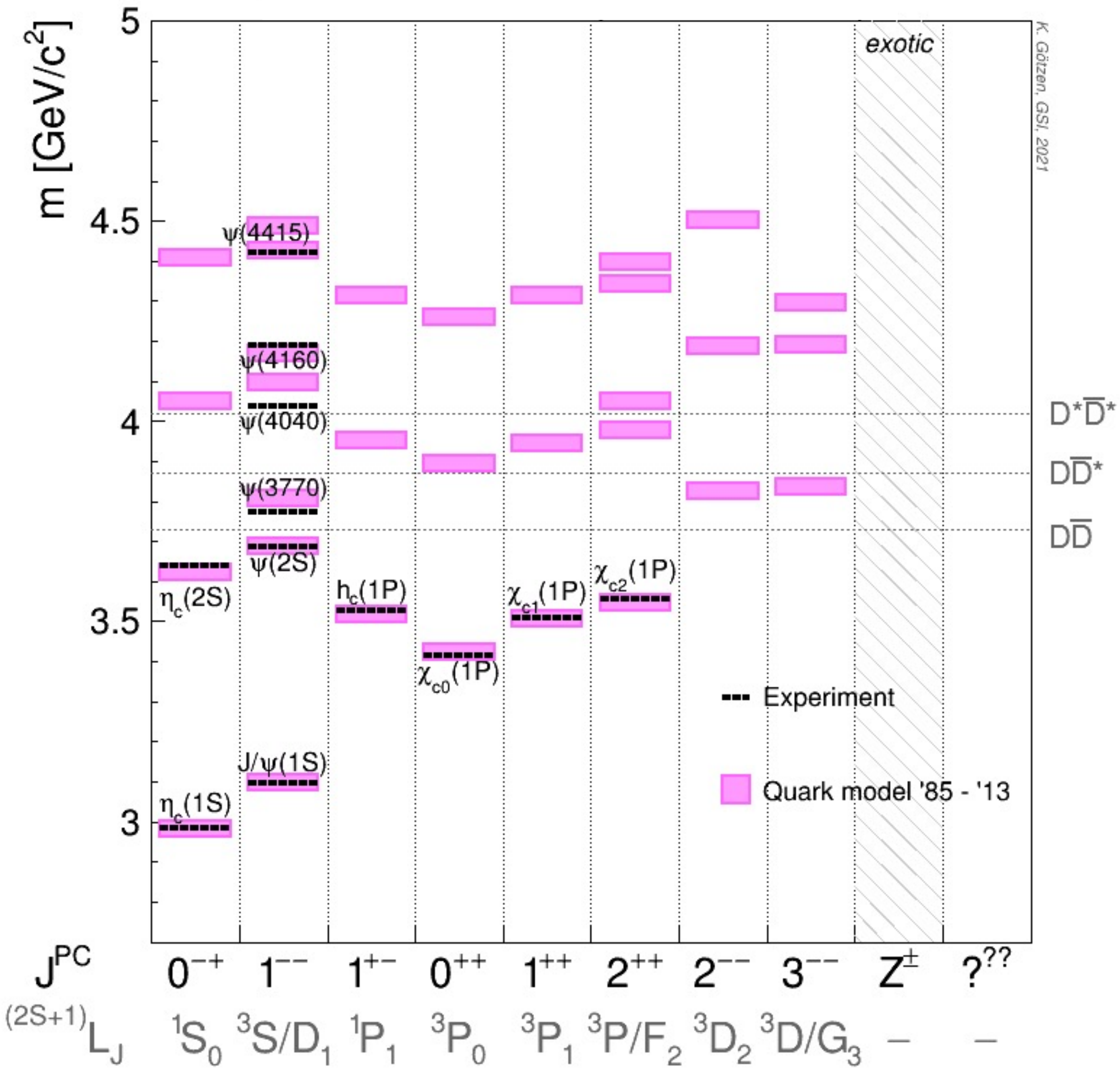
[Godfrey & Isgur, PRD 32 (1985) 189]

[Barnes, Godfrey & Swanson, PRD 72 (2005) 054026]

Charmonium spectrum ($c\bar{c}$)



- Before 2003:
  - Good agreement between theory and experiment, particularly beneath open charm thresholds



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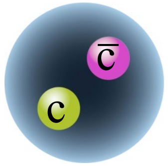


- Before 2003:
  - Good agreement between theory and experiment, particularly beneath open charm thresholds
- After 2003:
  - Severe mismatch between predicted and observed spectrum

Potential model:

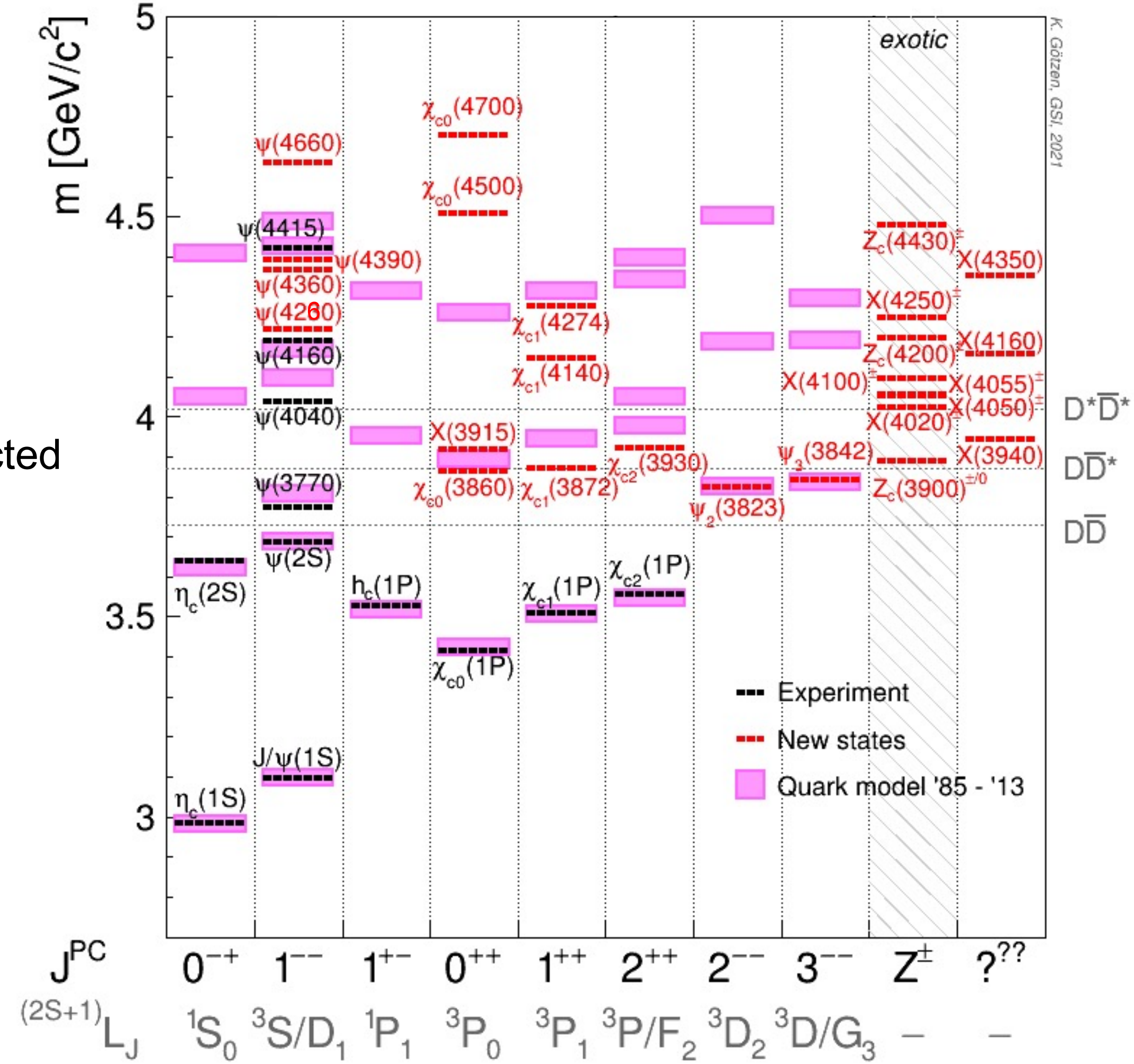
$$V_0^{c\bar{c}} = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\delta(r)\vec{S}_c\vec{S}_{\bar{c}}$$

$$V_{\text{spin-dep.}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

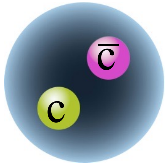
+ relativistic corrections!

[Godfrey & Isgur, PRD 32 (1985) 189]

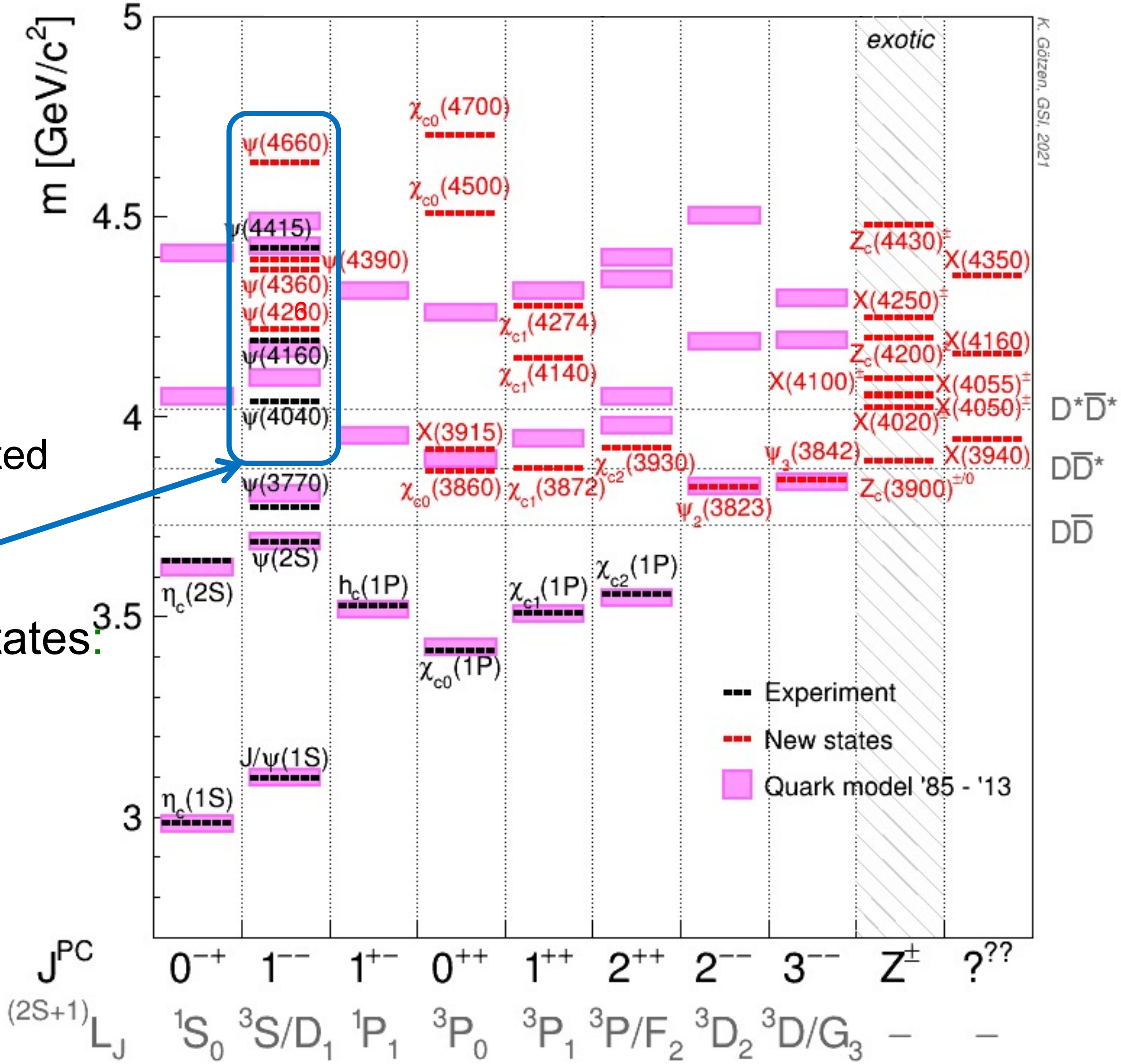
[Barnes, Godfrey & Swanson, PRD 72 (2005) 054026]



Charmonium spectrum ($c\bar{c}$)



- Before 2003:
  - Good agreement between theory and experiment, particularly beneath open charm thresholds
- After 2003:
  - Severe mismatch between predicted and observed spectrum
- Several supernumerary vector states: Y(4260), ..., Y(4660)



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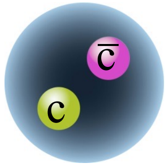

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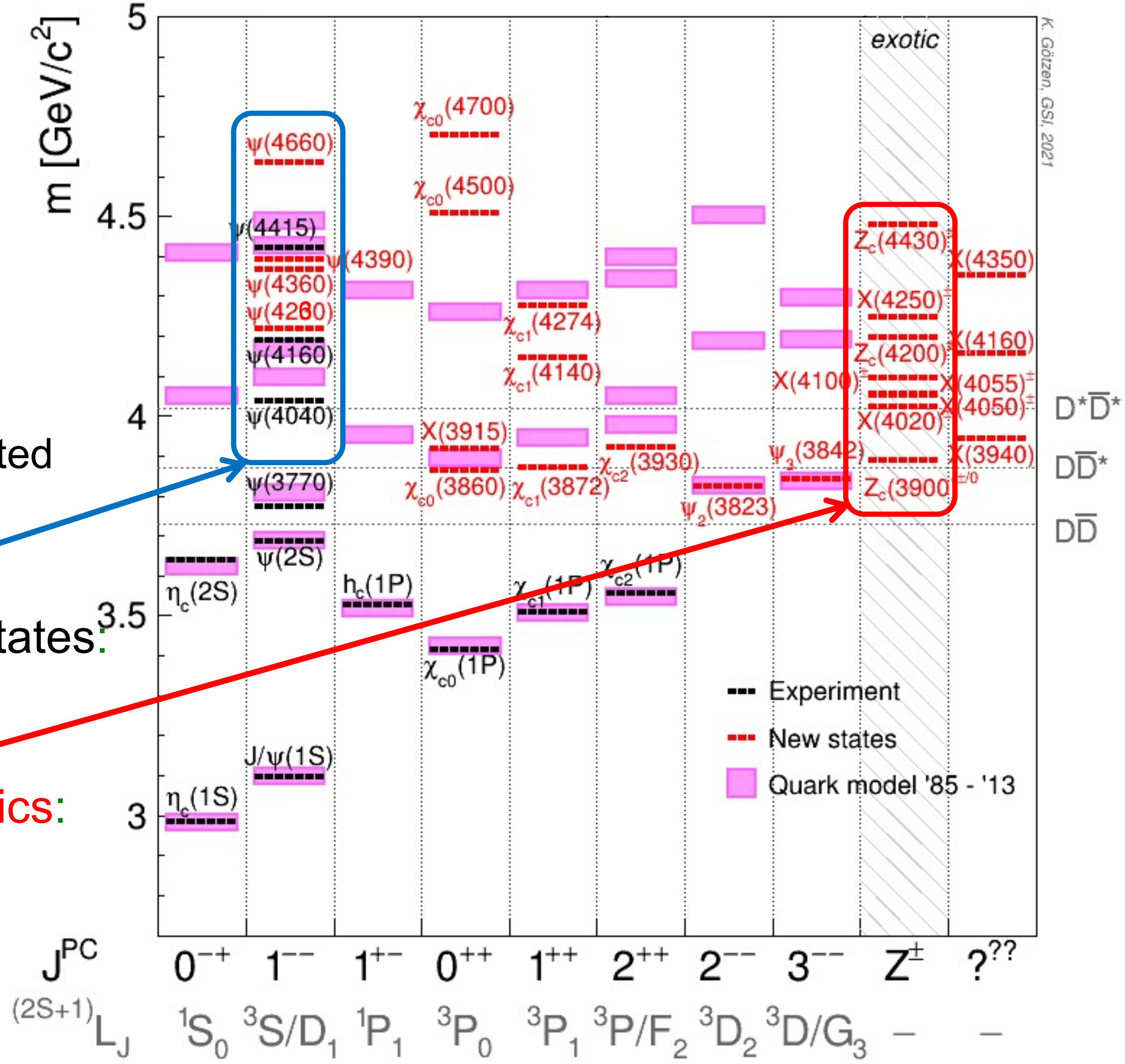

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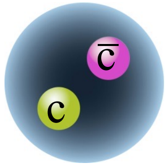

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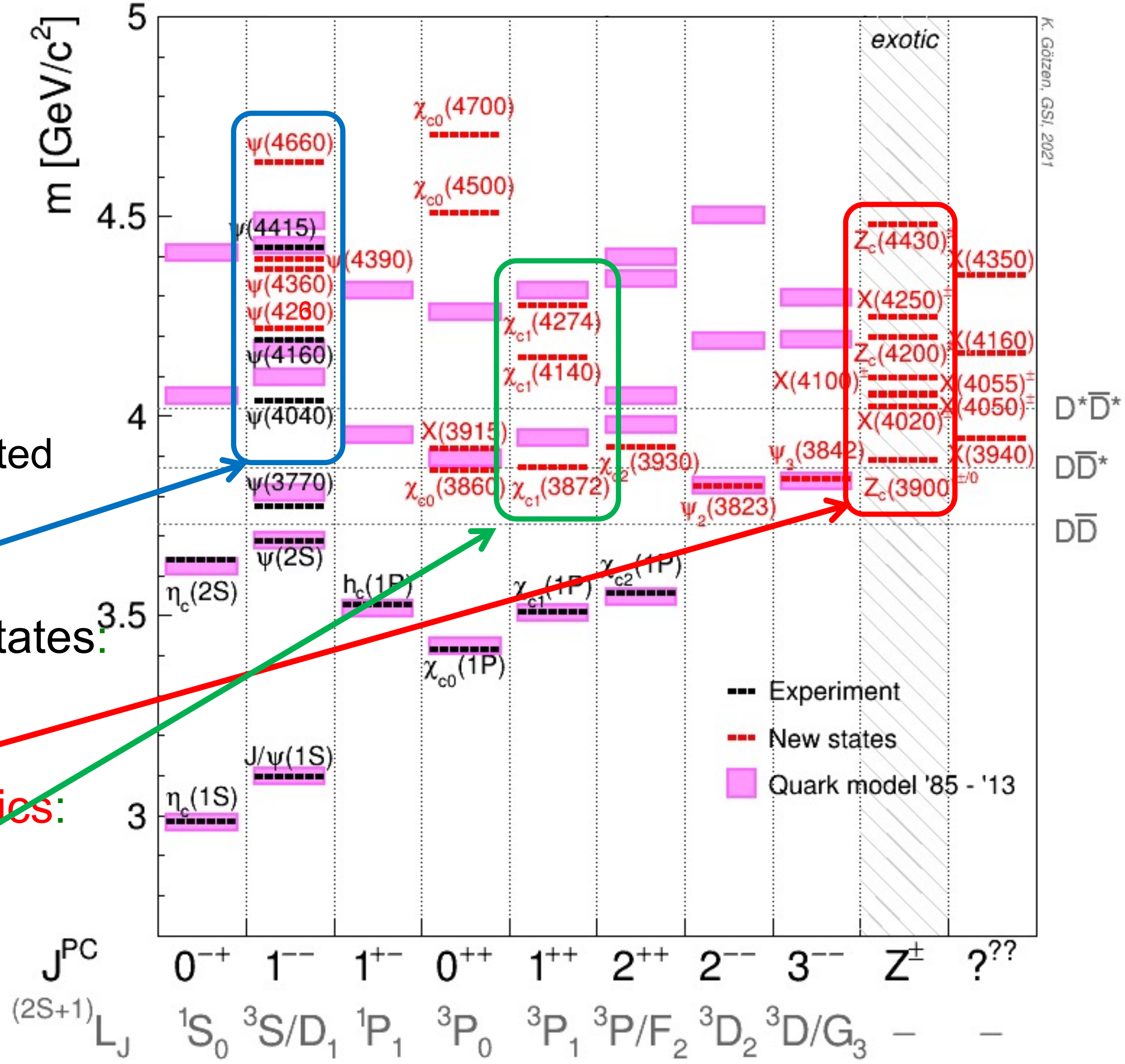
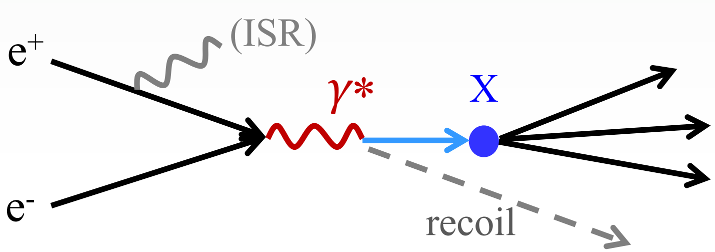
- Several supernumerary vector states: Y(4260), ..., Y(4660)
- Several charged manifestly exotics: $Z_c(3900)^{+/-}$, ..., $Z_c(4430)^{+/-}$
- The X states – the $\chi_{c1}(3872)$ was the first observed in 2003

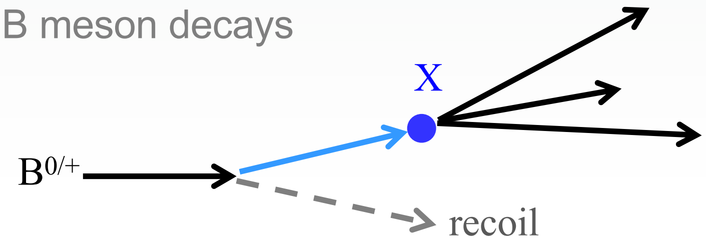


Production mechanisms of hadrons

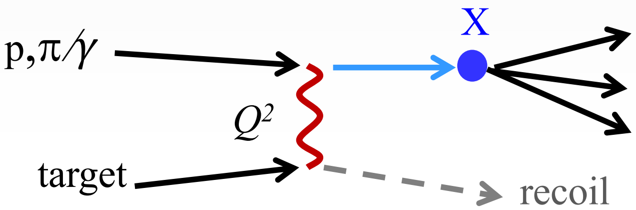
Formation or production with recoil



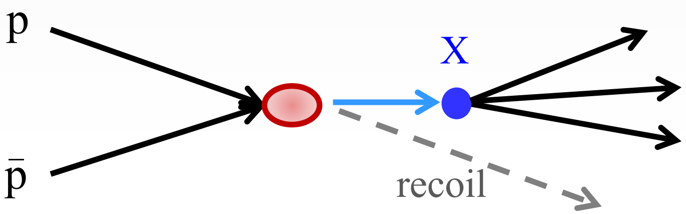
B meson decays



Hadron/photon beam on fixed-targets

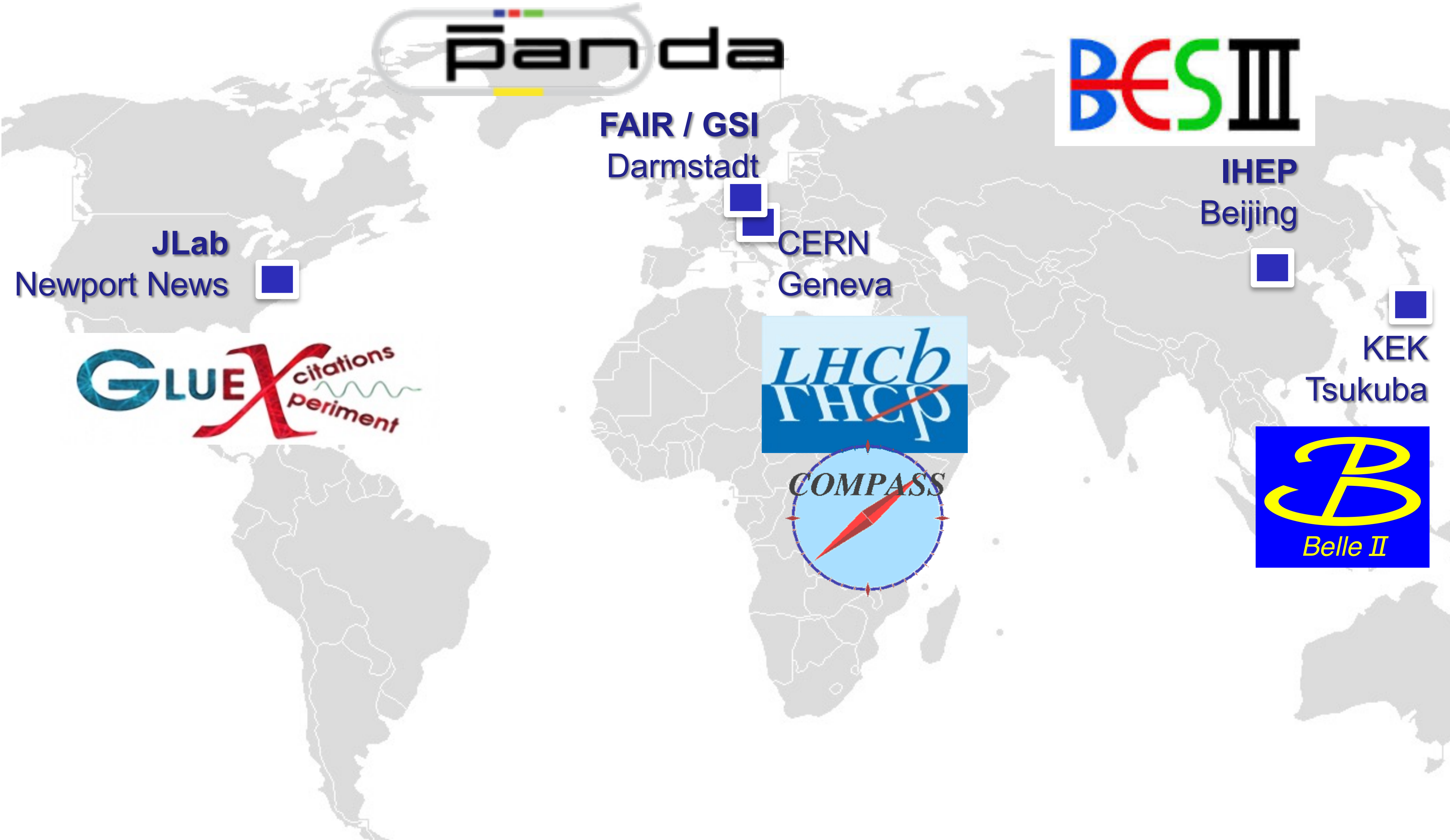


Formation or production with recoil

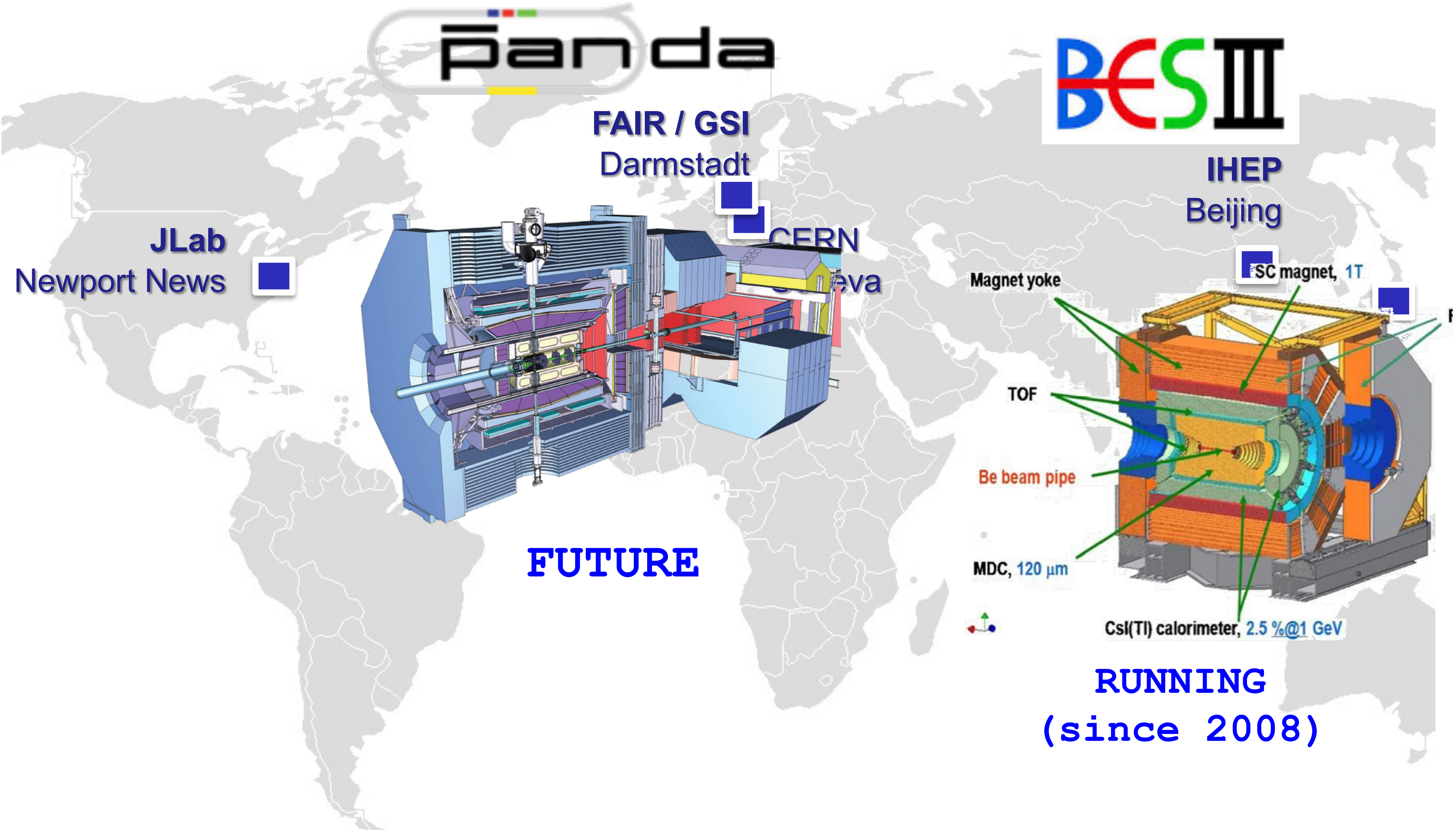


- Formation & Production with recoil particle(s)
  - CLEO(-c), BaBar, Belle(II) ($E_{cms} \leq 12$ GeV)
  - BESI-III ($E_{cms} \leq 4.9$ GeV)
- B meson decays
  - CLEO, BaBar, Belle(II) ($E_{cms} \leq 12$ GeV)
  - LHCb: pp (7 TeV/c)
- Diffractive, photoproduction
  - GlueX: γ p (9 GeV/c),
  - COMPASS: π/K/p p (190-270 GeV/c)
- Formation & Production with recoil particle(s)
  - E760/E835, PANDA ($E_{cms} \leq 5.5$ GeV)
  - No running experiment presently

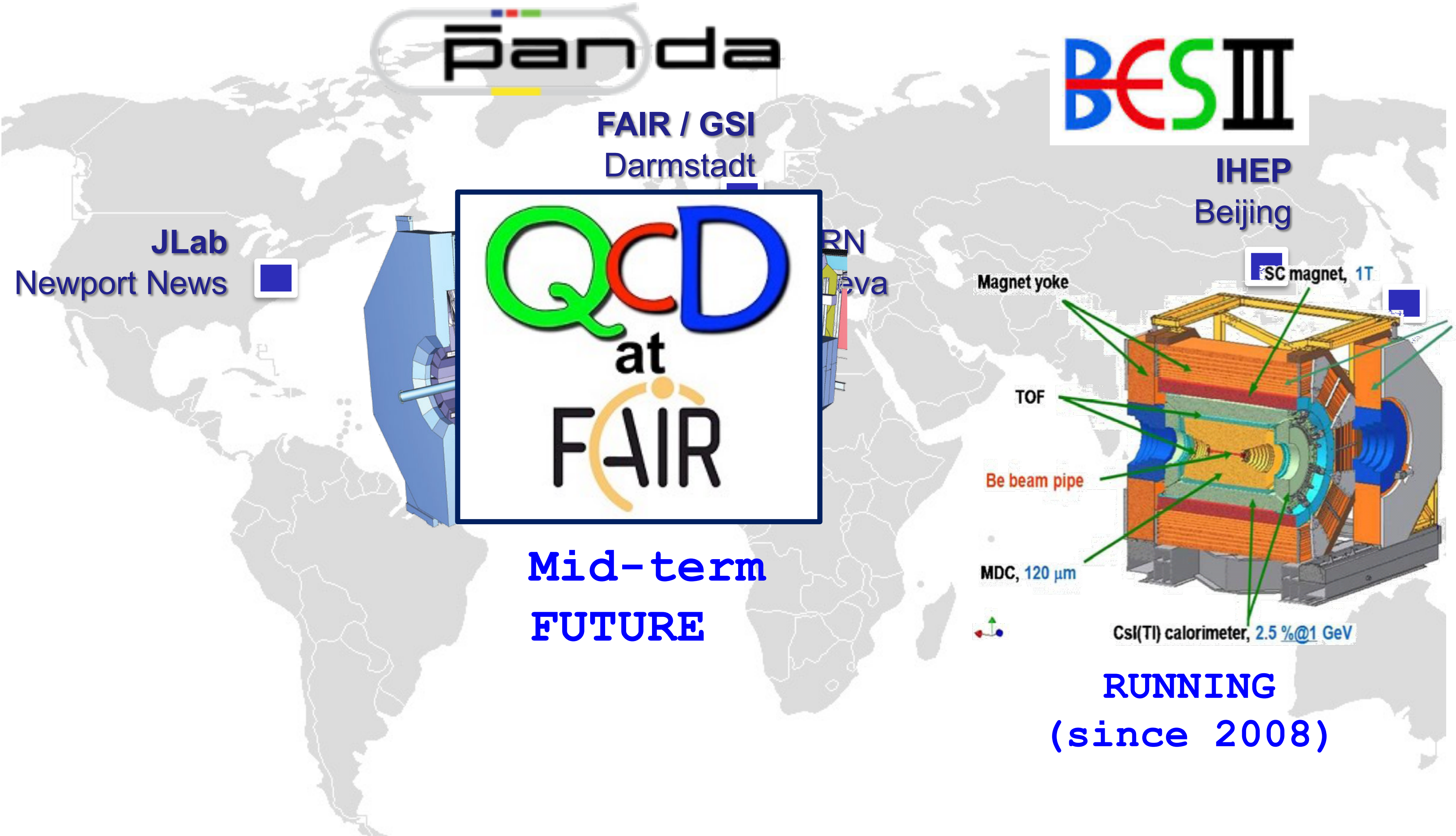
Hadron physics – Major labs and experiments



Hadron physics – Major labs and experiments



Hadron physics – Major labs and experiments



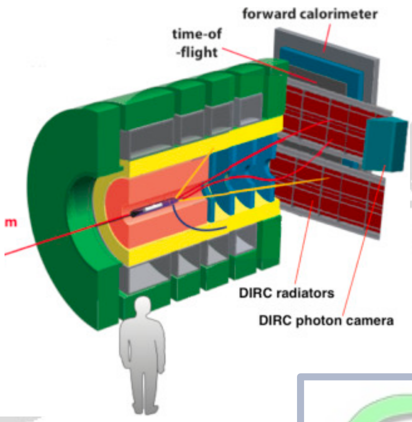
Hadron physics – Major labs and experiments

HFHF Helmholtz Forschungsakademie Hessen für FAIR

GSI

JOHANN WOLFGANG GOETHE UNIVERSITÄT FRANKFURT AM MAIN

GlueX



JLab
Newport News

RUNNING
(since 2016)

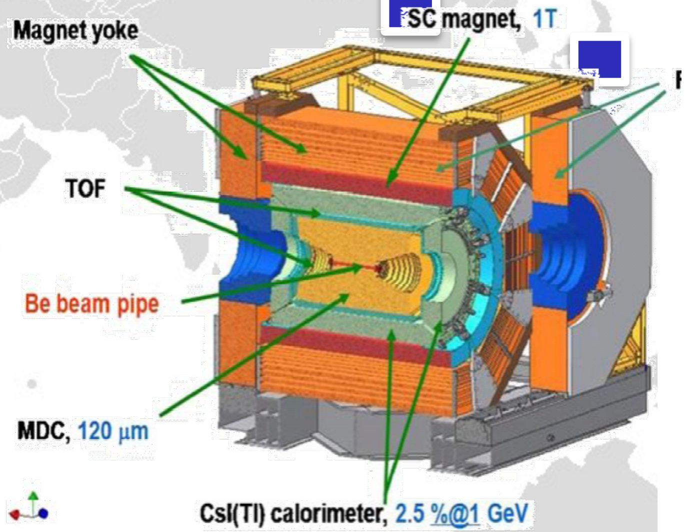
FAIR / GSI
Darmstadt

QCD at FAIR

Mid-term
FUTURE

BESIII

IHEP
Beijing



RUNNING
(since 2008)

BESIII at BEPCII

- Symmetric e^+e^- collider:
  - $\sqrt{s}$ = 2.0 - 4.6 GeV
- Design luminosity:
  - $1x10^{33}$ $cm^{-2}s^{-1}$ (at $\psi(3770)$, achieved in 04/2016)

- Multi-purpose 4π detector with
  - good tracking
  - calorimetry
  - PID and muon detection
- Operating since March 2008

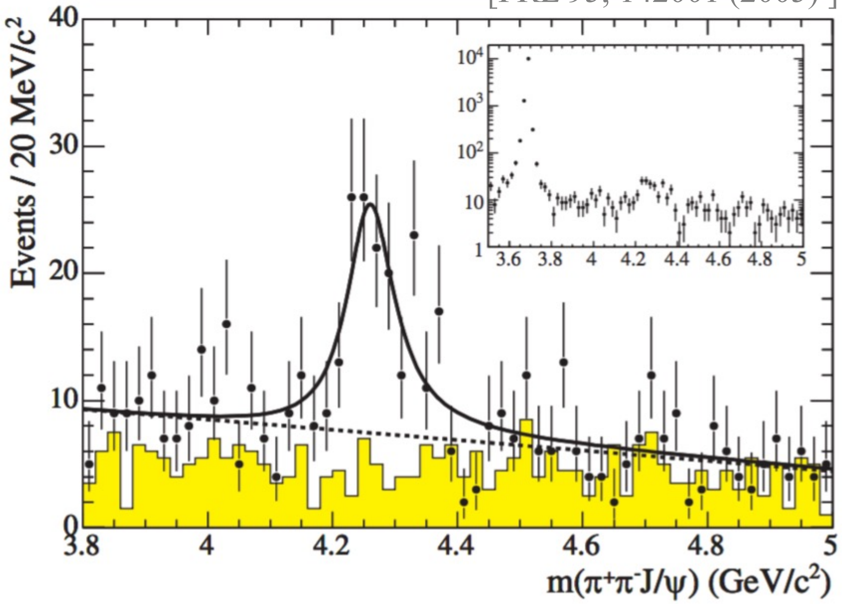
The Y(4260) and further supernumerary vector states

The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

Some history:

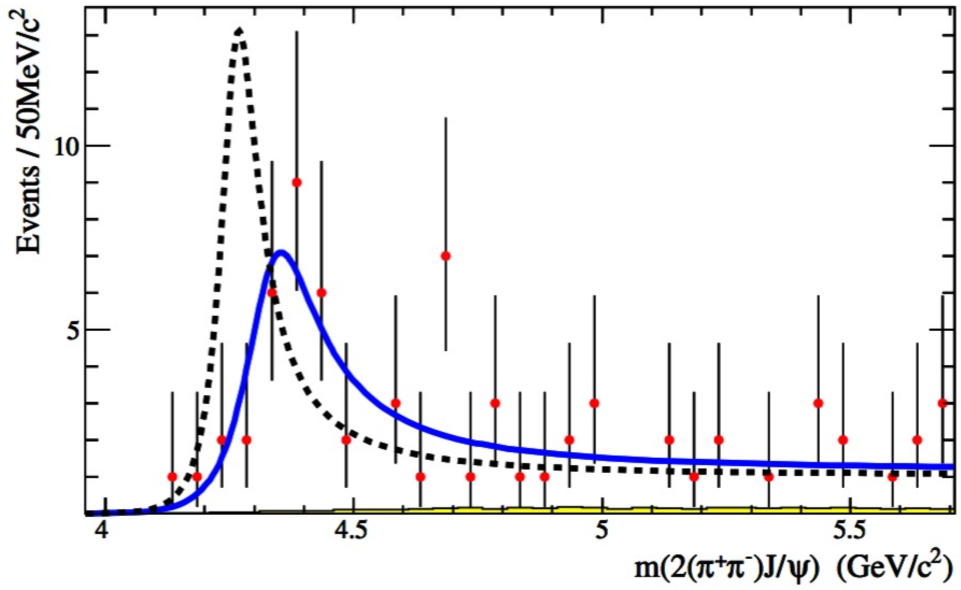
$e^+e^- \to J/\psi\pi^+\pi^-$

[PRL 95, 142001 (2005)]



$e^+e^- \to \psi(2S)\pi^+\pi^-$

[PRL 98, 212001 (2007)]



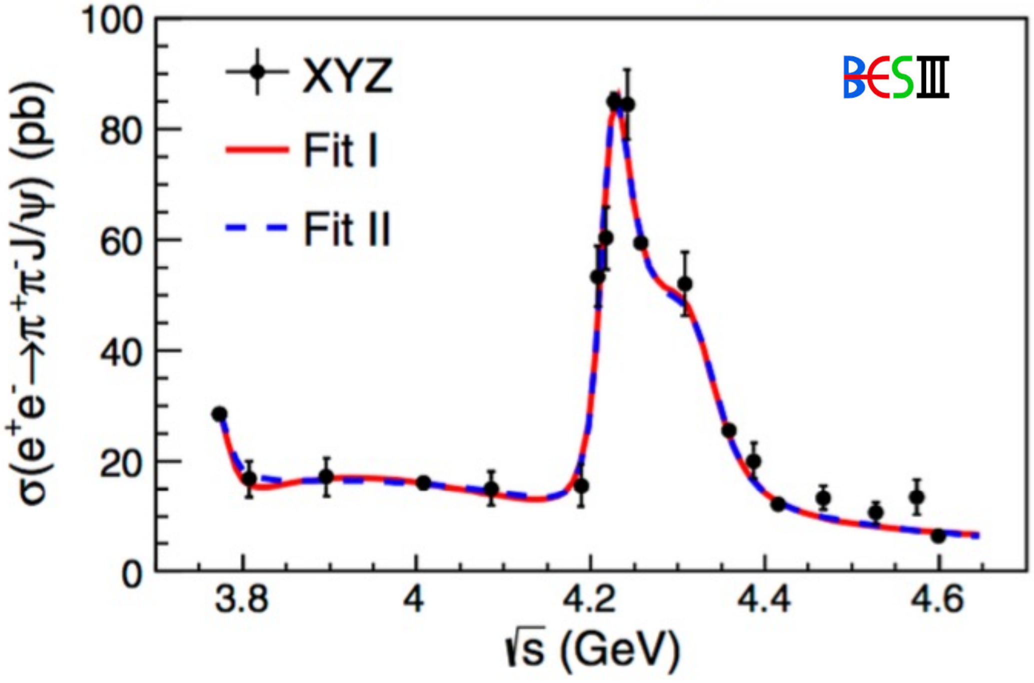
- Discovery of the Y(4260) using ISR by BaBar in $J/\psi\pi^+\pi^-$
- Discovery of the Y(4360) using ISR by BaBar in $\psi(2S)\pi^+\pi^-$

The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

BESIII result, published

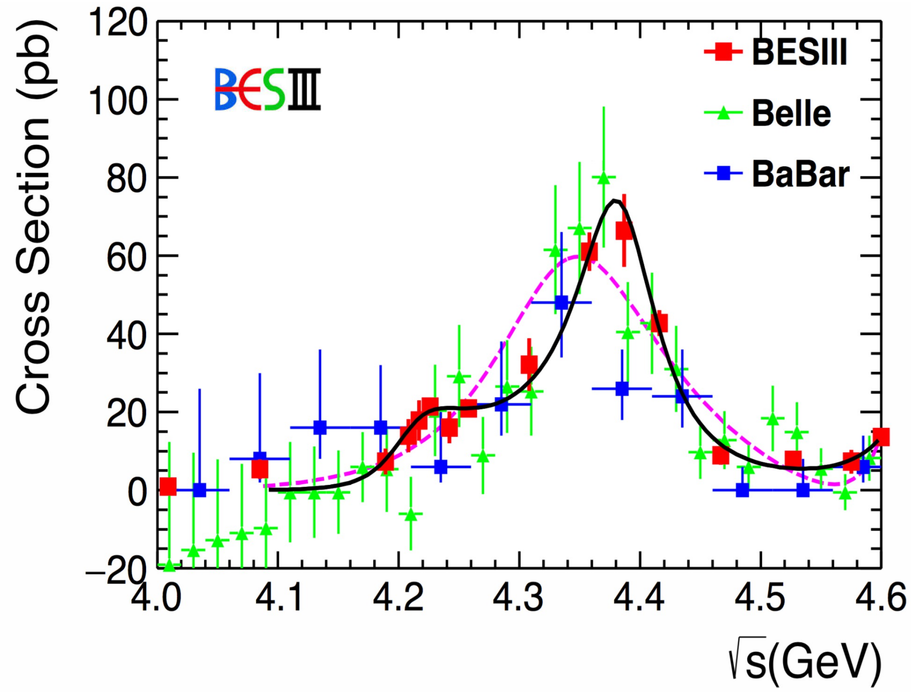
$e^+e^- \to J/\psi\pi^+\pi^-$

[PRL 118, 092001 (2017)]



$e^+e^- \to \psi(2S)\pi^+\pi^-$

[Phys. Rev. D 96, 032004 (2017)]



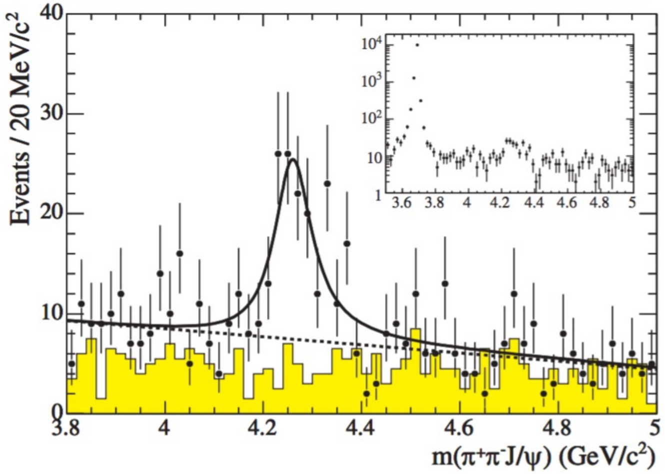
- Cross-section inconsistent with the single resonance Y(4260)!
  - ➢ Two favoured over one by >7σ

- BESIII: Much higher precision (5.8σ)
- Coherent BW fit: Y(4230) and Y(4390)

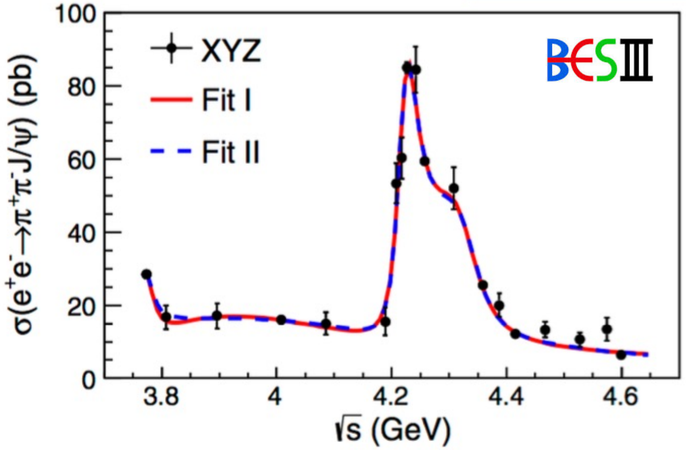
What happened to the Y states?

$e^+e^- \rightarrow J/\psi\pi^+\pi^-$

[BaBar, PRL 95, 142001 (2005)]

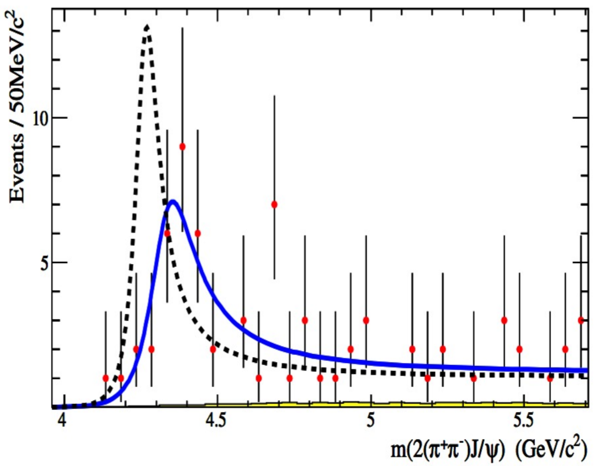


[PRL 118, 092001 (2017)]

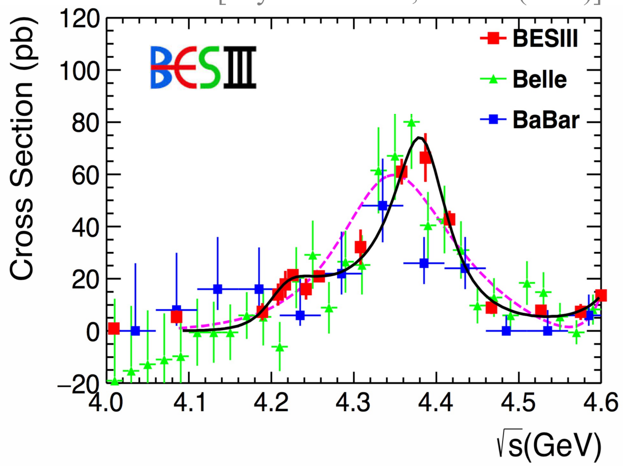


$e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$

[BaBar, PRL 98, 212001 (2007)]



[Phys. Rev. D 96, 032004 (2017)]



Two structures now resolved: Y(4260) → Y(4230) , Y(4360) → Y(4390)

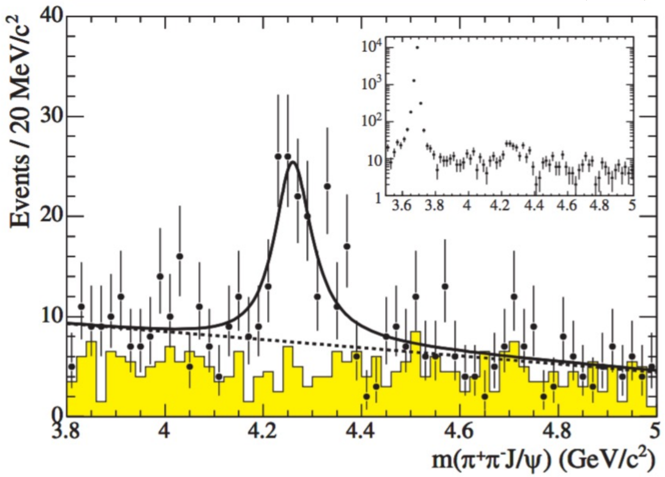
What happened to the Y states?

$e^+e^- \to J/\psi\pi^+\pi^-$

$e^+e^- \to \psi(2S)\pi^+\pi^-$

$e^+e^- \to h_c\pi^+\pi^-$

[BaBar, PRL 95, 142001 (2005)]



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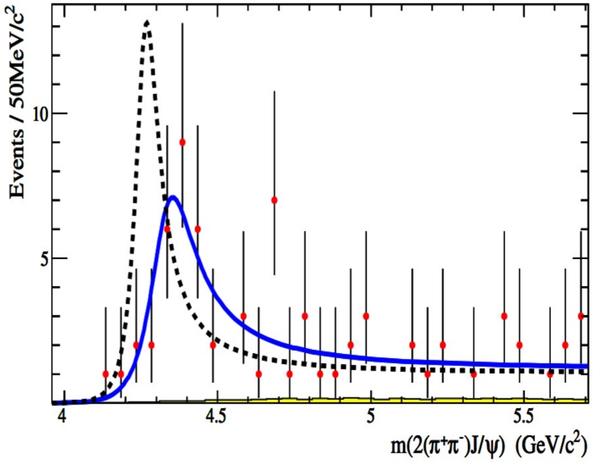
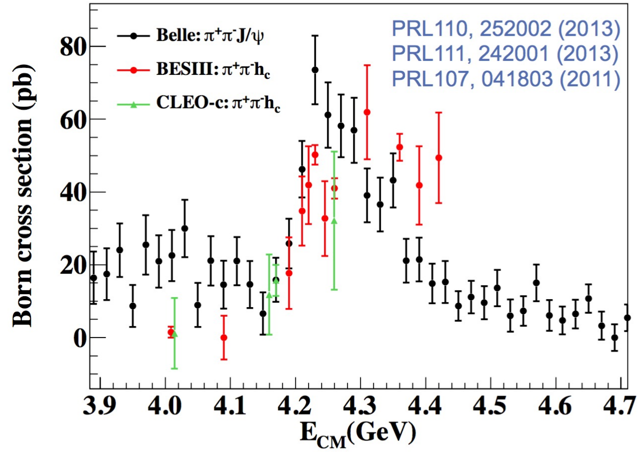
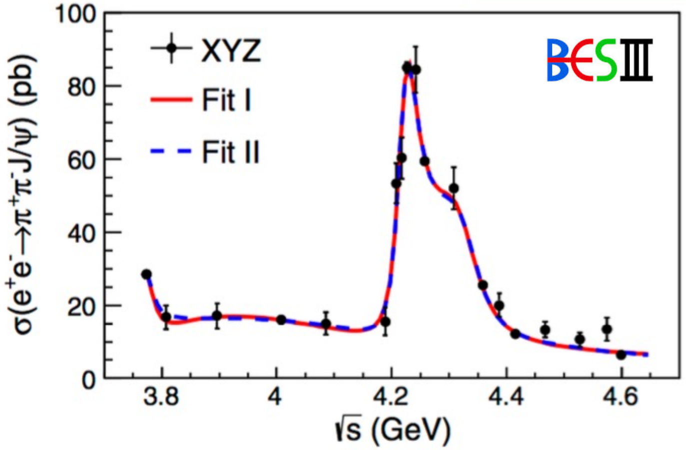




[PRL 118, 092001 (2017)]



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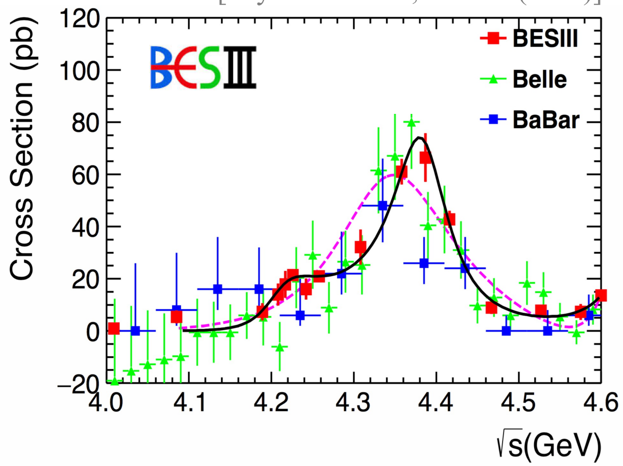
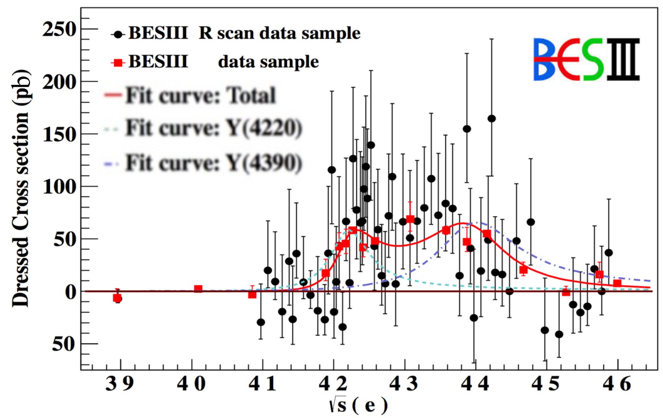


[Phys. Rev. Lett. 118 092002 (2017)]

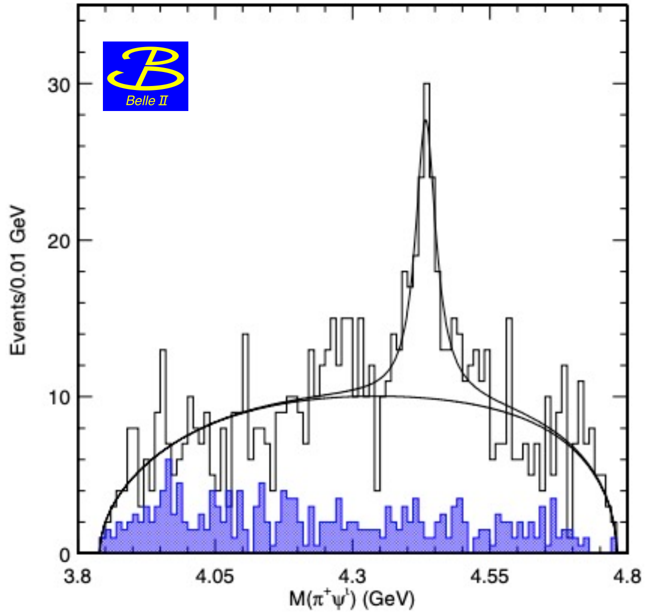


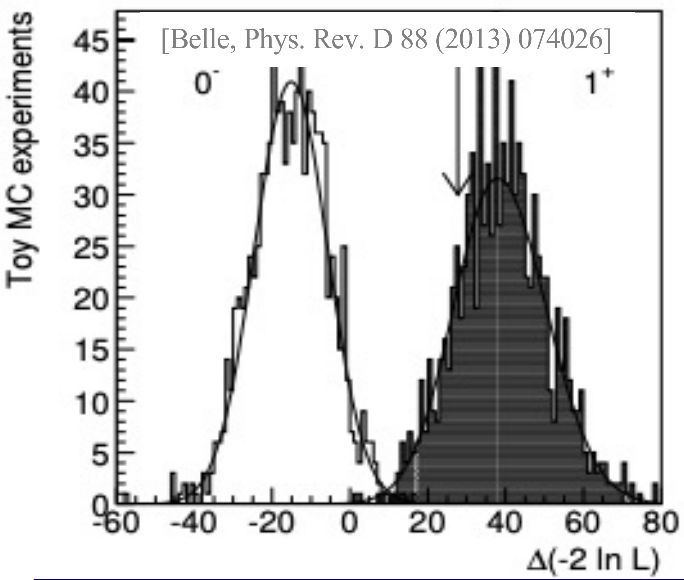
Two structures now resolved: Y(4260) → Y(4230) , Y(4360) → Y(4390)

The Z(4430) and further (charged) Z_c states

Experimental review of the Z(4430)

[Belle, Phys. Rev. Lett., 100 (2008) 142001]





- First observed by Belle in 2008
  - ➢ $B \to K^{\mp} Z(4430)^{\pm} \to K^{\mp}\pi^{\pm}\psi'$
  - ➢ relatively narrow state, 6.5 σ
  - ➢ first charmonium-like state with a non-zero electric charge

=> Minimal quark content [$c\bar{c}u\bar{d}$] = manifestly exotic

- BaBar searched for it, however, does not confirm [PRD 79, 112001 (2009)]

- Decay to J/ψ/π seen in B decays by Belle [PRD 90, 112009 (2014)], and not seen by BaBar [PRD 79, 112001 (2009)]

- LHCb confirms and showed resonant behavior in argand plot [PRL 112, 222002 (2014)]

- Spin-parity constrained by Belle: $J^P = 1^+$, confirmed by LHCb [PRL 112, 222002 & PRD 92, 112009 (2015)]

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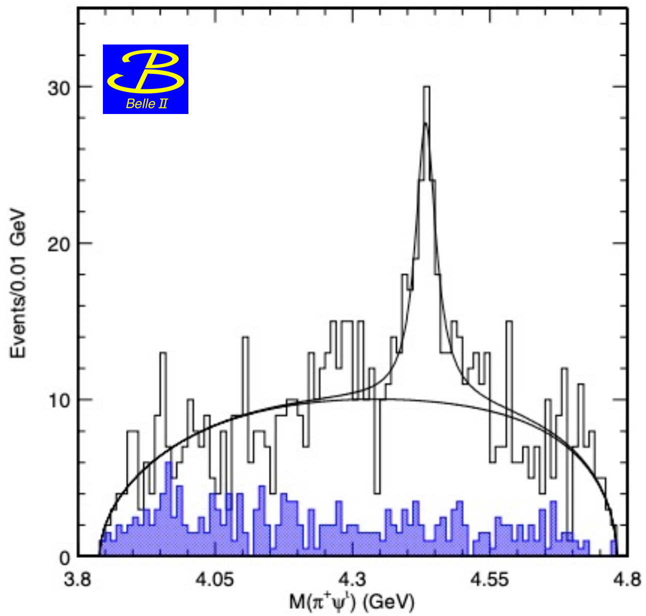

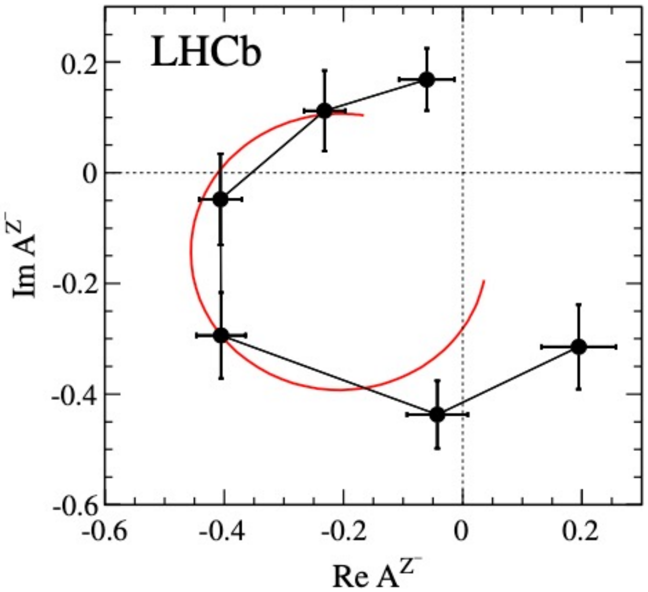

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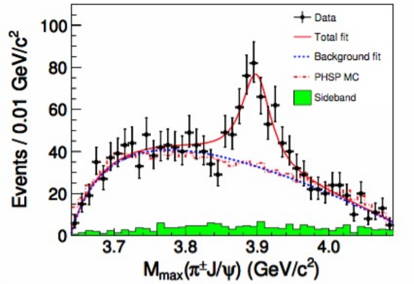
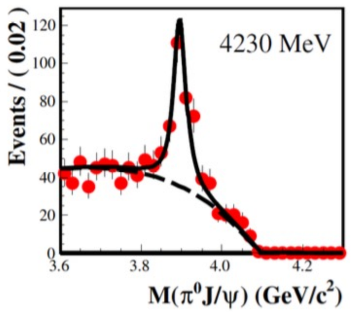
Two Z_c triplets established at BESIII

[PRL 110 (2013) 252001]



$e^+e^- \to \pi^-\pi^+J/\psi$

[PRL 115 (2015) 112003]



$e^+e^- \to \pi^0\pi^0J/\psi$

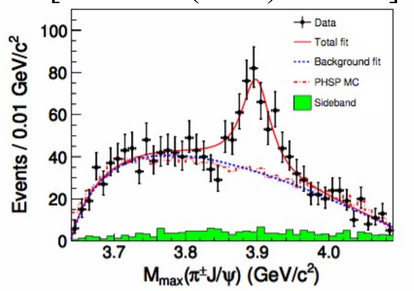
Charged **Neutral**

$Z_c(3900)^{\pm,0}$?

- The charged $Z_c(3900)^{\pm}$, and meanwhile also the neutral partner $Z_c(3900)^0$

Two Z_c triplets established at BESIII

[PRL 110 (2013) 252001]



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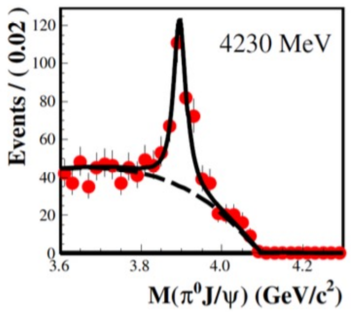
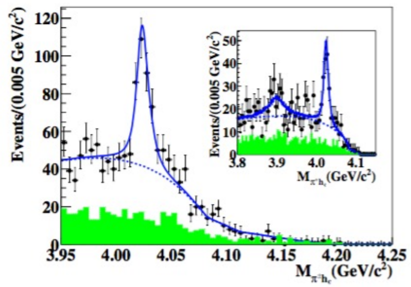


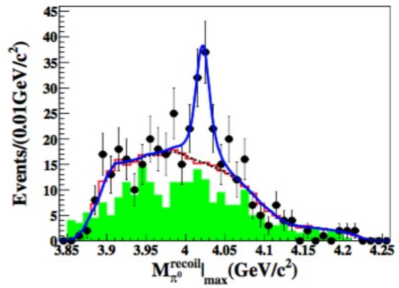
$e^+e^- \to \pi^0\pi^0J/\psi$

[PRL 111 (2013) 242002]



$e^+e^- \to \pi^-\pi^+h_c$

[PRL 113 (2014) 212002]



$e^+e^- \to \pi^0\pi^0h_c$

Charged Neutral → $Z_c(3900)^{\pm,0}$?

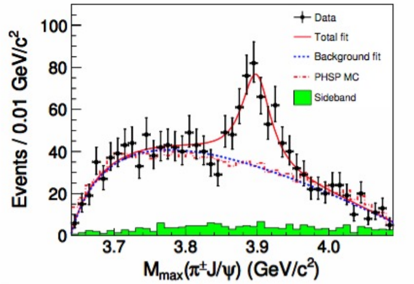
Charged Neutral → $Z_c(4020)^{\pm,0}$?

- The charged $Z_c(3900)^{\pm}$, and meanwhile also the neutral partner $Z_c(3900)^0$
- Two isospin triplets of charmonium-like exotic states established

Two Z_c triplets established at BESIII

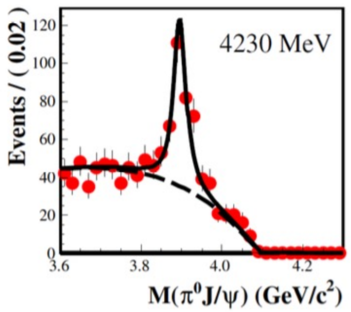
Hidden Charm

[PRL 110 (2013) 252001]



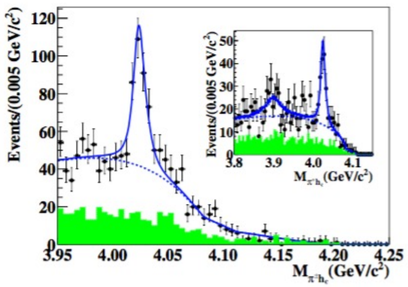
$e^+e^- \rightarrow \pi^-\pi^+J/\psi$

[PRL 115 (2015) 112003]



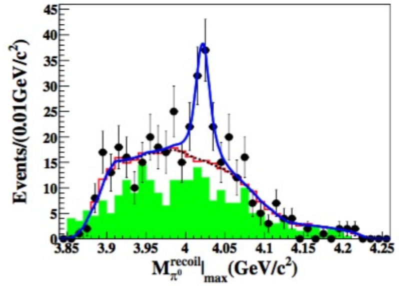
$e^+e^- \rightarrow \pi^0\pi^0J/\psi$

[PRL 111 (2013) 242002]



$e^+e^- \rightarrow \pi^-\pi^+h_c$

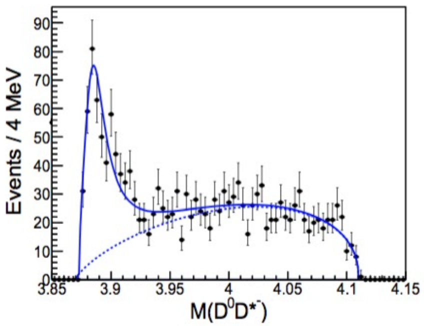
[PRL 113 (2014) 212002]



$e^+e^- \rightarrow \pi^0\pi^0h_c$

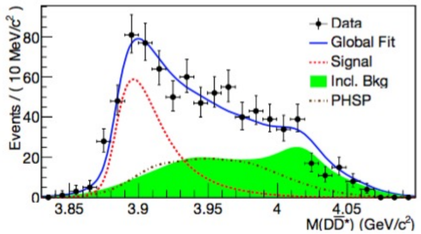
Open Charm

[PRL 112 (2014) 022001]

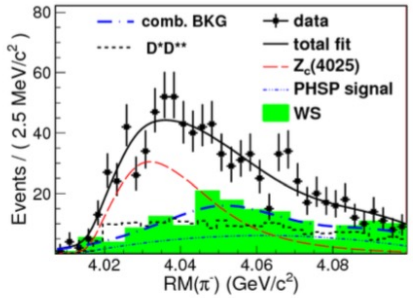


$e^+e^- \rightarrow \pi^-(D\bar{D}^*)^+$

[PRL 115 (2015) 222002]

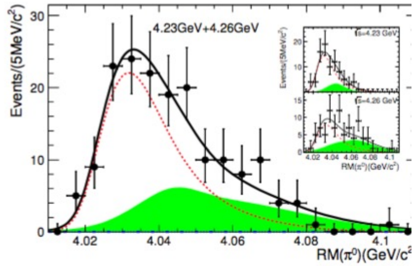


[PRL 112 (2013) 132001]



$e^+e^- \rightarrow \pi^-(D^*\bar{D}^*)^+$

[PRL 115 (2015) 182002]



Charged — Neutral: $Z_c(3900)^{\pm,0}$?

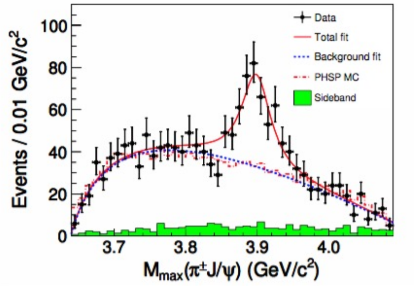
Charged — Neutral: $Z_c(4020)^{\pm,0}$?

- Two isospin triplets of charmonium-like exotic states established
- Different decay *(hidden vs. open charm)* of same state observed?

Two Z_c triplets established at BESIII

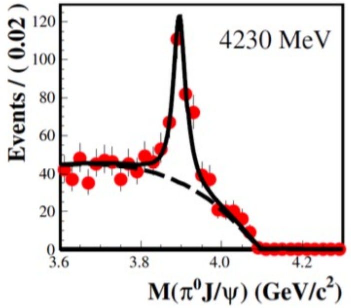
Hidden Charm

[PRL 110 (2013) 252001]



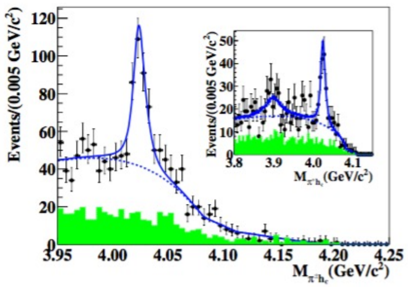
$e^+e^- \to \pi^-\pi^+J/\psi$

[PRL 115 (2015) 112003]



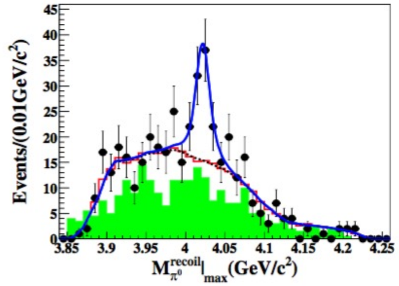
$e^+e^- \to \pi^0\pi^0J/\psi$

[PRL 111 (2013) 242002]



$e^+e^- \to \pi^-\pi^+h_c$

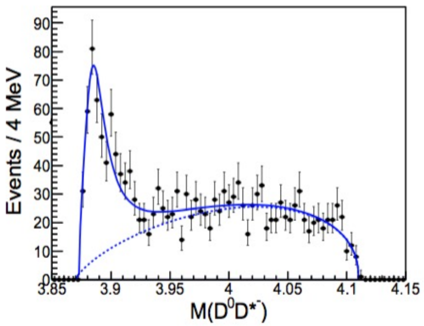
[PRL 113 (2014) 212002]



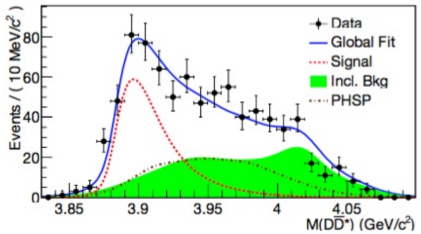
$e^+e^- \to \pi^0\pi^0h_c$

Open Charm

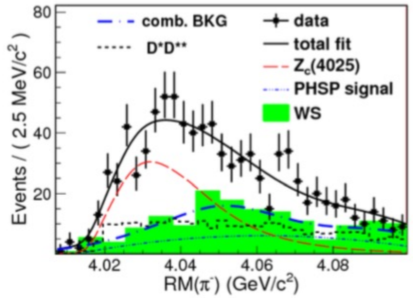
[PRL 112 (2014) 022001]



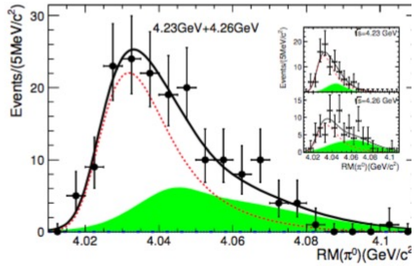
[PRL 115 (2015) 222002]



[PRL 112 (2013) 132001]



[PRL 115 (2015) 182002]



$\pi^-(D^*\bar{D}^*)^+$

harged

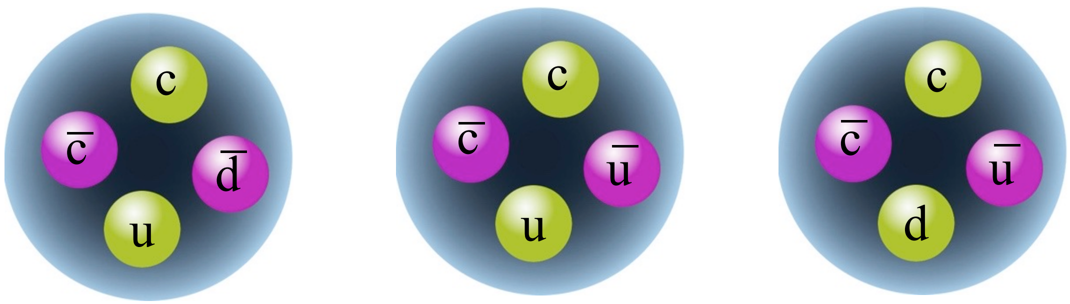
Neutral

$Z_c(4020)^{\pm,0}$?

es established

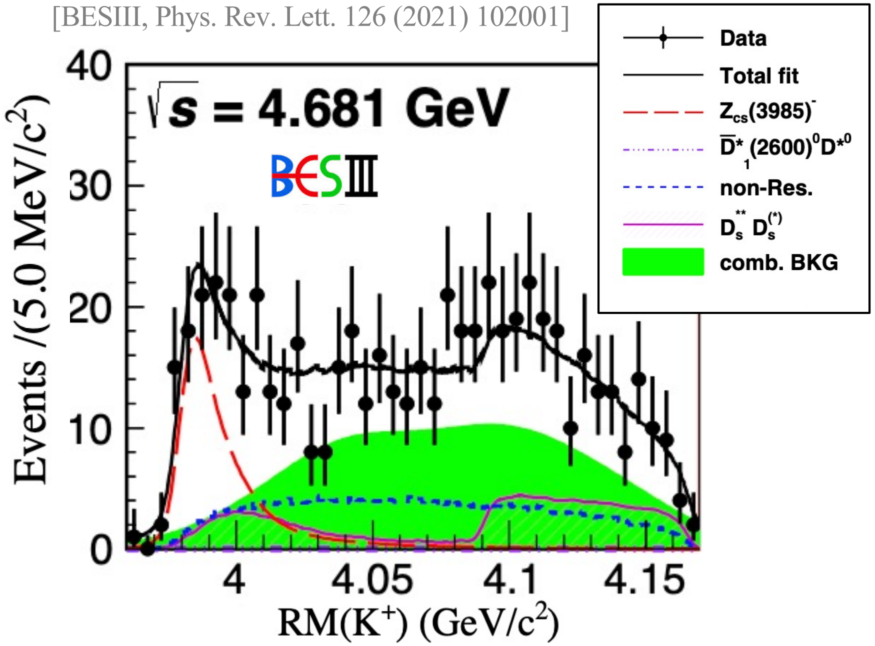
state observed?

$Z_c(3900)^+$ $Z_c(3900)^0$ $Z_c(3900)^-$

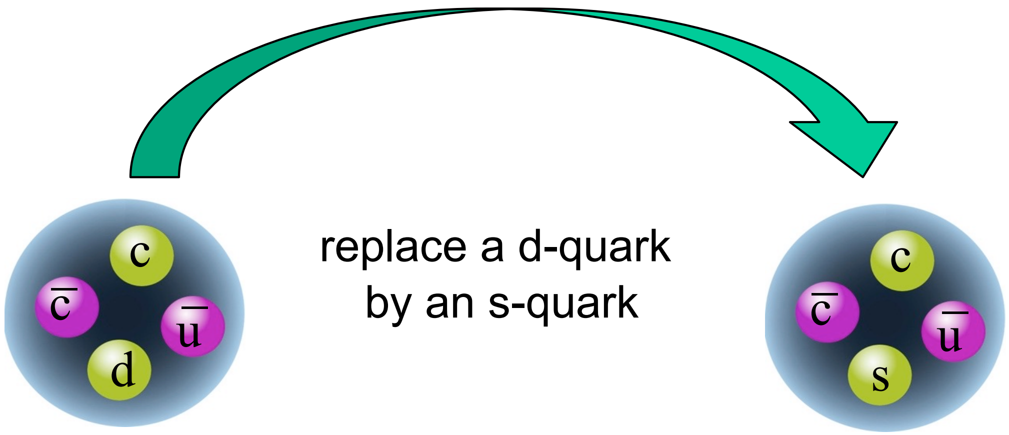


First Z_{cs} candidates Z(3985) reported

[BESIII, Phys. Rev. Lett. 126 (2021) 102001]



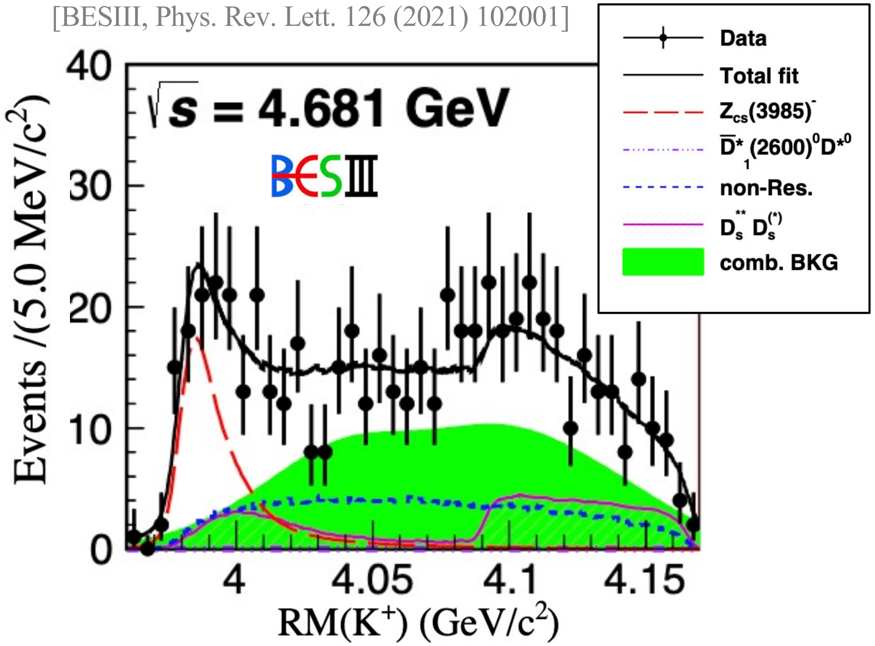
- Search for strange partner of $Z_c(3900)$
  - Containing s quark in open charm decay
  - $e^+e^- \to K^+(D_sD^*/D_s^*D)^-$
  - Narrow threshold enhancement (5.3σ)
  - $M = (3982.5^{+1.8}_{-2.6} \pm 2.1)\mathrm{MeV}/c^2$, $\Gamma = (12.8^{+5.3}_{-4.4} \pm 3.0)\mathrm{MeV}$
- Manifestly exotic charged hidden-charm tetraquark candidate with strangeness
  - With a non-zero electric charge
  - Thus, minimal quark content => [$c\bar{c}s\bar{u}$]

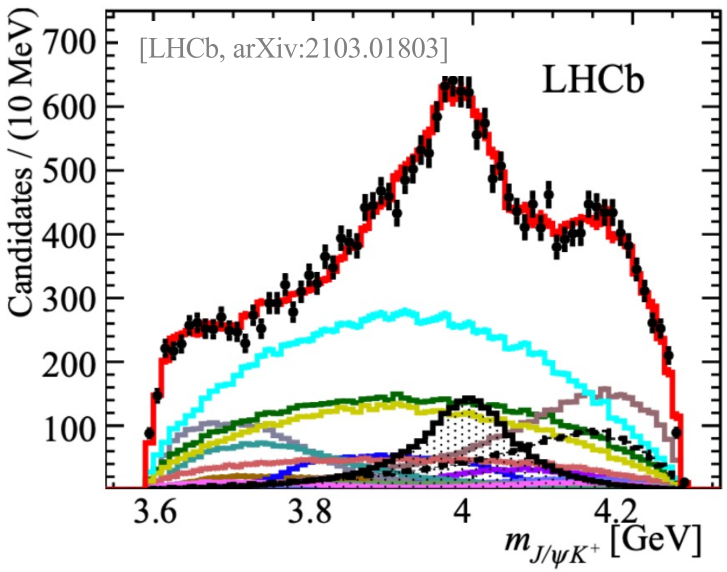


$Z_c(3900)$ $Z_{cs}(3985)$

First Z_{cs} candidates Z(3985) reported

[BESIII, Phys. Rev. Lett. 126 (2021) 102001]





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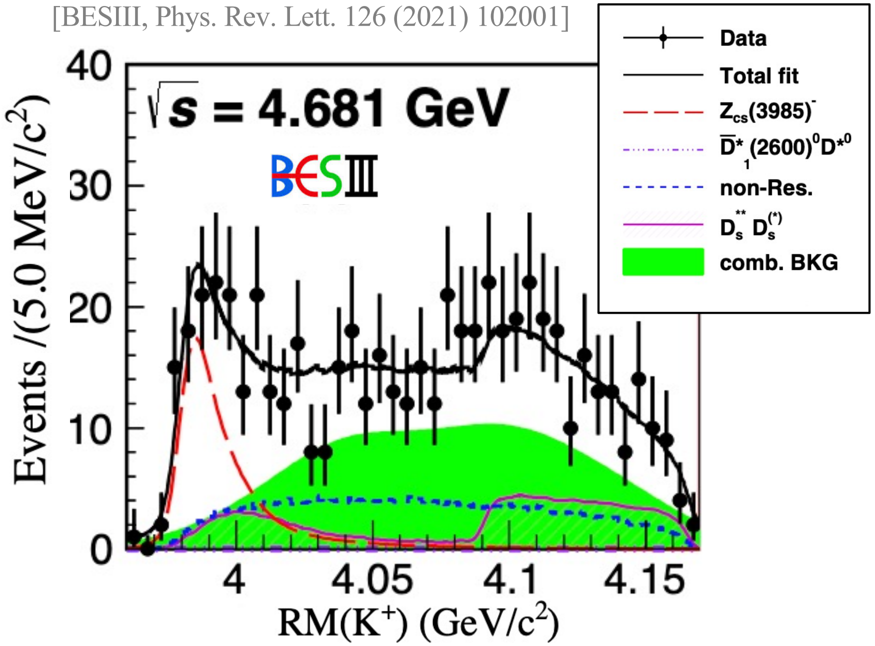
- Manifestly exotic charged hidden-charm tetraquark candidate with strangeness
  - With a non-zero electric charge
  - Thus, minimal quark content => [$c\bar{c}s\bar{u}$]
- LHCb reports a $Z_{cs}(4000)$ in $B \to \phi(J/\psi K^+)$
  - $M = (4000.3 \pm 6^{+4}_{-14})\mathrm{MeV}/c^2,$ $\Gamma = (131 \pm 15 \pm 26)\mathrm{MeV}$
  - $J^P = 1^+$, hidden charm final state
  - 10x broader …

=> Same state observed in different decays (open/hidden charm) at two experiments?

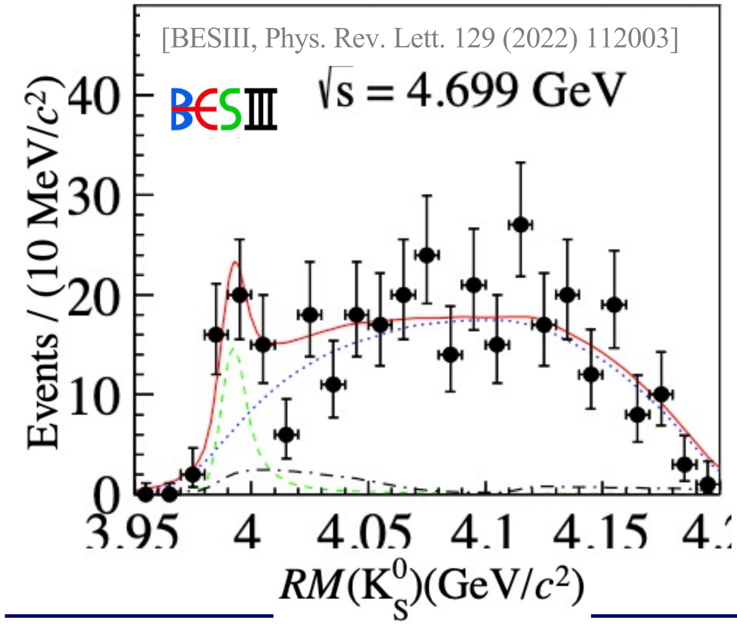
HFHF Helmholtz Forschungsakademie Hessen für FAIR

First Z_{cs} candidates Z(3985) reported

Johann Wolfgang Goethe Universität Frankfurt am Main



[BESIII, Phys. Rev. Lett. 126 (2021) 102001]



[BESIII, Phys. Rev. Lett. 129 (2022) 112003]

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  - Containing s quark in open charm decay
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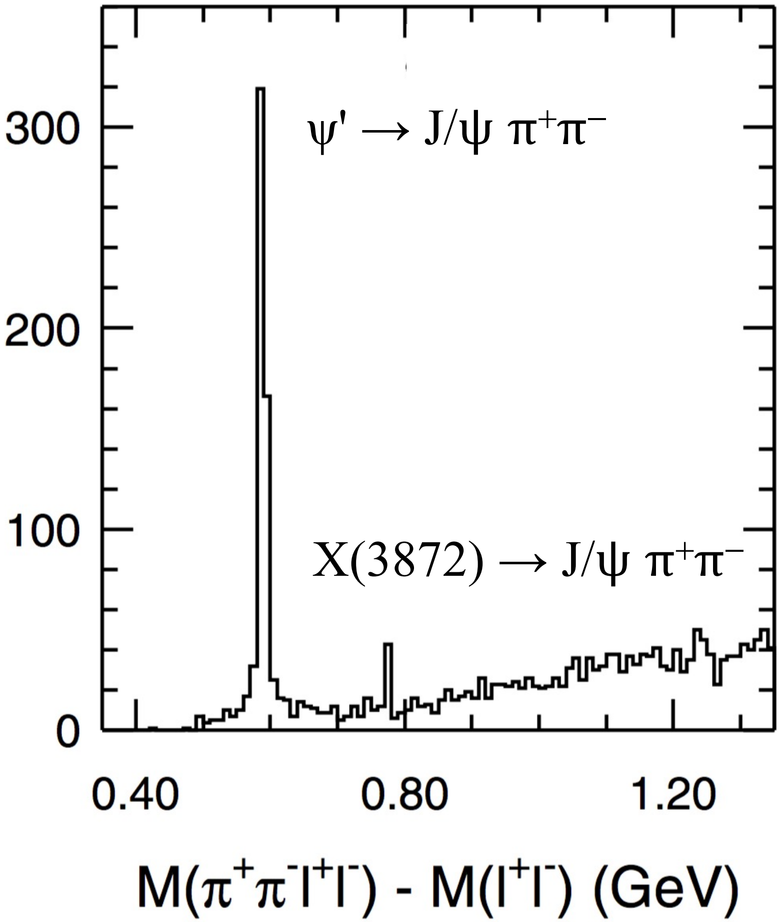
  - With a non-zero electric charge
  - Thus, minimal quark content => [$c\bar{c}s\bar{u}$]
- Search for neutral partner of $Z_{cs}(3985)$
  - Containing s quark in open charm decay
  - $e^+e^- \to K^0_S(D_s^+ D^{*-} + D_s^{*+} D^-)$
  - Narrow threshold enhancement (4.6σ)
  - $M = (3992.2 \pm 1.7 \pm 1.6)\ \mathrm{MeV}/c^2$, $\Gamma = (7.7^{+4.1}_{-3.8} \pm 4.3)\ \mathrm{MeV}$

=> Seem to be isospinpartners

The X(3872)
and further X states

Experimental review of the X(3872)

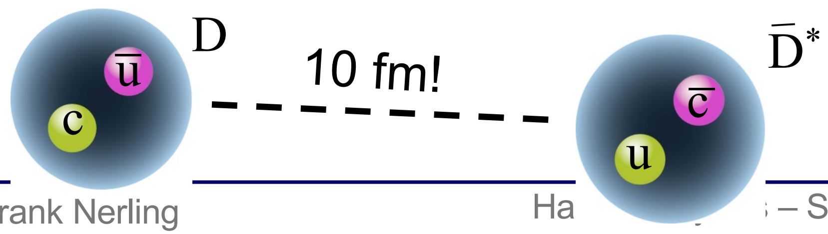
[Belle Collab., PRL 91 (2003) 262001]



- First observed by Belle in 2003
  - $X(3872) \rightarrow J/\psi\pi^+\pi^-$
  - very narrow state with $J^{PC} = 1^{++}$
- Belle & BaBar report signal in
  - $X(3872) \rightarrow D^0\bar{D}^{*0}$
- Mass $m[X(3872)] - m[D^{*0}] - m[D^0]$

  $= (-0.07 \pm 0.12)$ MeV/c^2 (LHCb 2020)
- Width measurement:
  - $\Gamma_{X(3872)} < 1.2$ MeV (2011, Belle)
  - $\Gamma_{X(3872)} = 1.13$ MeV (2020, LHCb)

Analogy to deuteron:



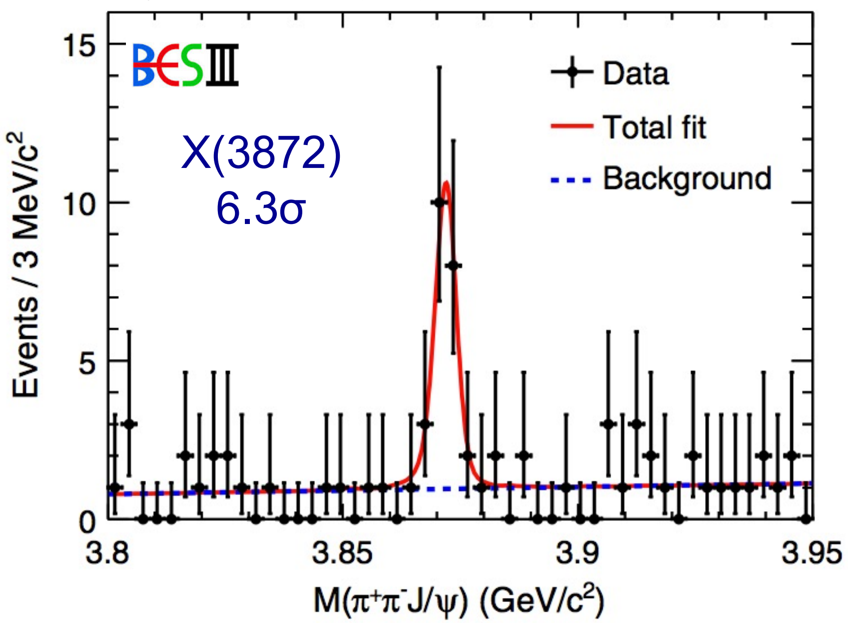
For clarification:
=> Precision measurement with
sub-MeV resolution needed!

First observation of $e^+e^- \to \gamma X(3872)$

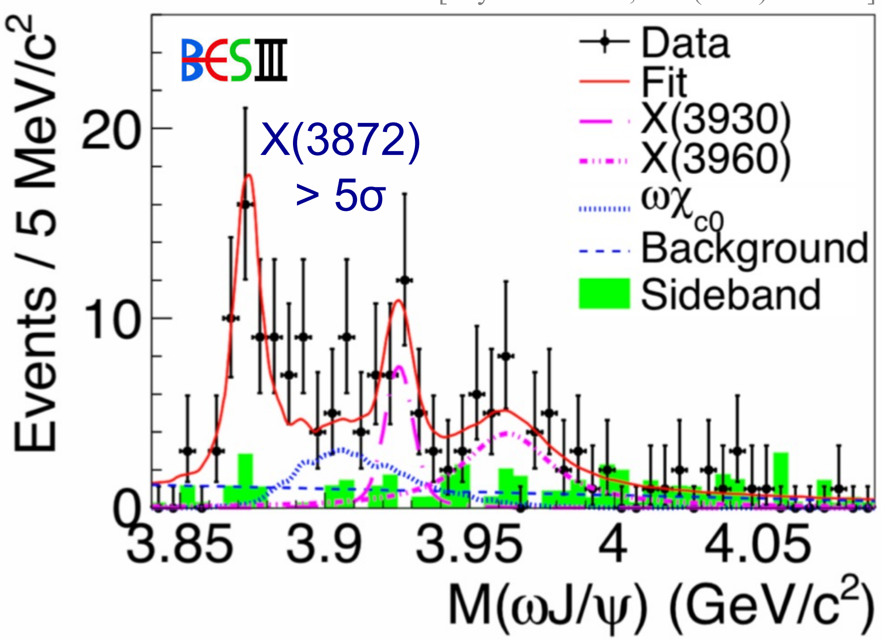
BESIII: First observation of $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$

First observation of $e^+e^- \to \gamma X(3872) \to \gamma\omega J/\psi$

[Phys. Rev. Lett. 112 (2014) 092001]



[Phys. Rev. Lett., 122 (2019) 232002]



- $m = (3871.9 \pm 0.7 \pm 0.2)\,\mathrm{MeV}/c^2$
- $\Gamma < 2.4\,\mathrm{MeV}$ (90% CL)

- Fit with three Breit-Wigner resonances
  => *Evidence for two more structures*

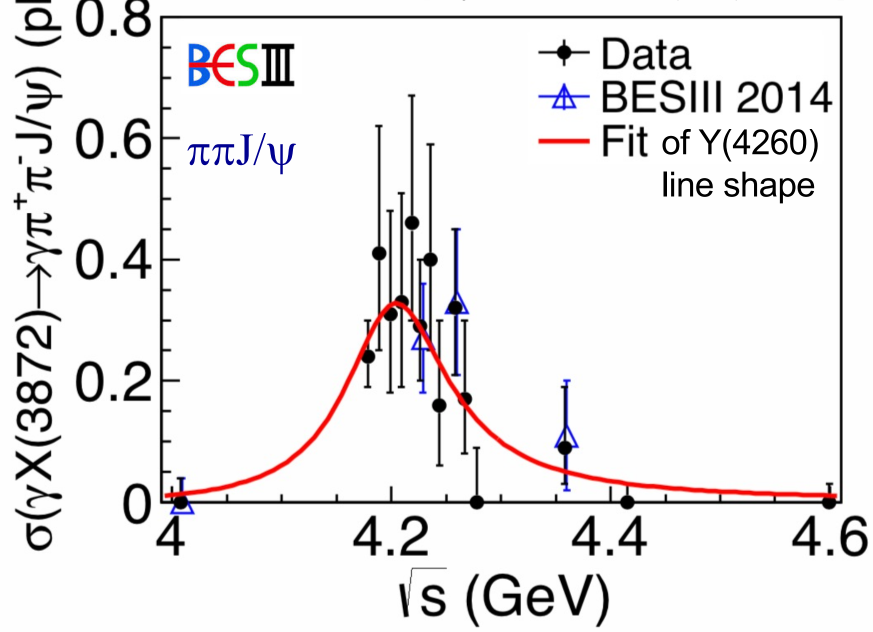
First observation of $e^+e^- \to \gamma X(3872)$

BESIII: First observation of $e^+e^- \to Y(4260) \to \gamma X(3872) \to \gamma\omega J/\psi$

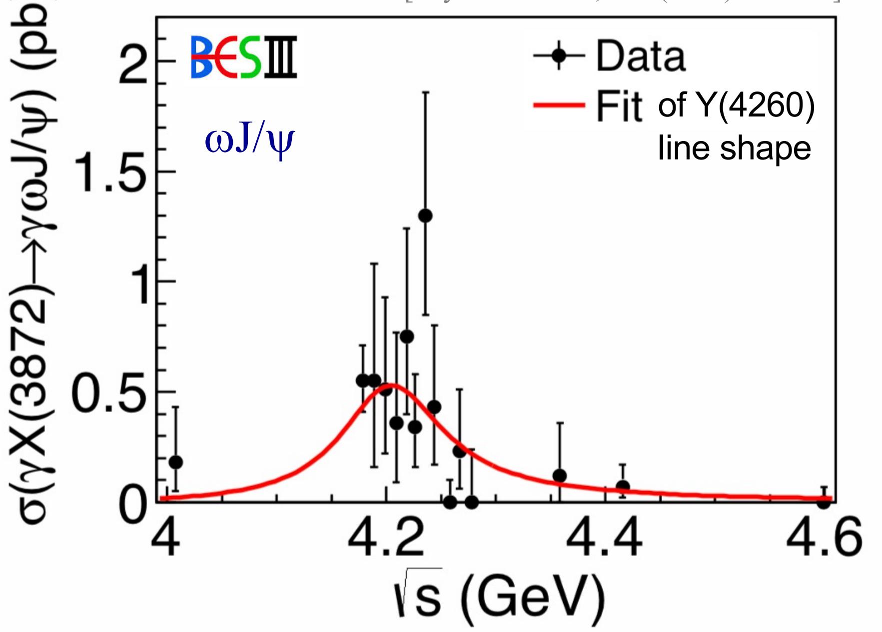
First observation of $e^+e^- \to Y(4260) \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$

cross section

[Phys. Rev. Lett. 112 (2014) 092001]



[Phys. Rev. Lett., 122 (2019) 232002]

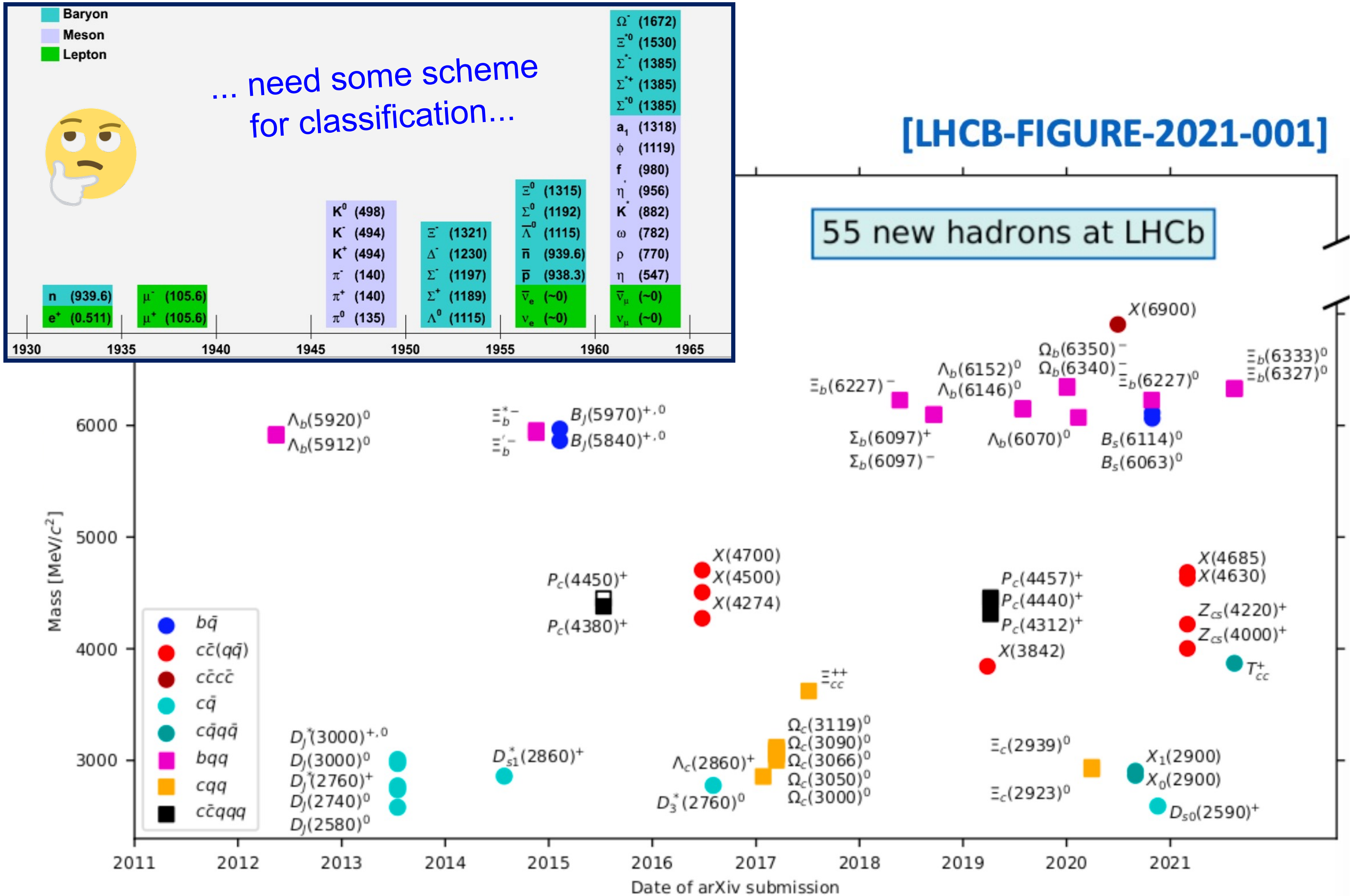


- $m = (4200.6^{+7.9}_{-13.3} \pm 3.0)\ \mathrm{MeV}/c^2$
- $\Gamma = (115^{+38}_{-26} \pm 12)\ \mathrm{MeV}/c^2$

- Shape consistent with production via a Y(4260) state

[Subm. to Phys. Rev. Lett., arXiv:1903.04695 [hep-ex]]

Again a Zoo of (exotic) hadrons ...

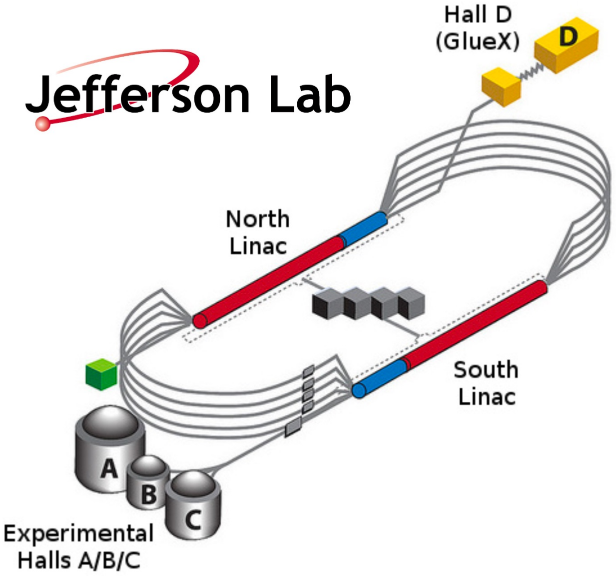


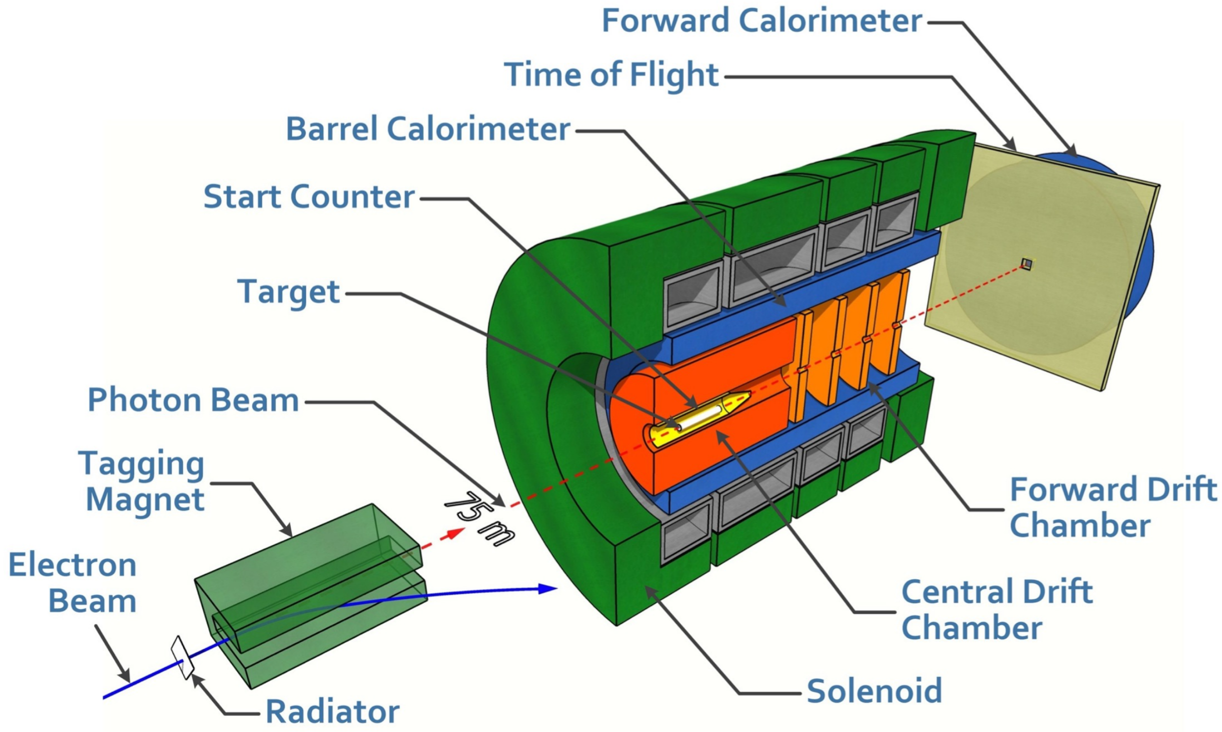
[Polyakov, EPS-HEP-2021]

Search for the Y(2175) in photo-production at GlueX

CEBAF at JLab

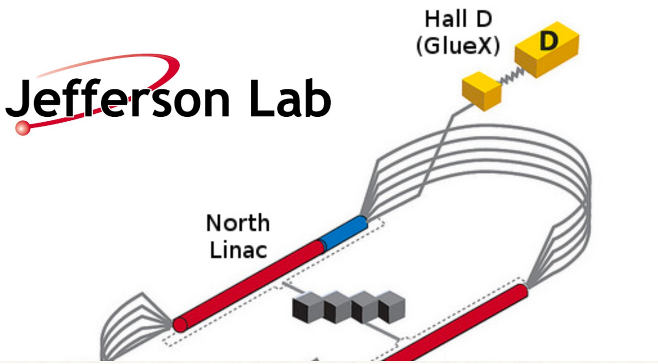
GlueX in Hall D at CEBAF, JLab

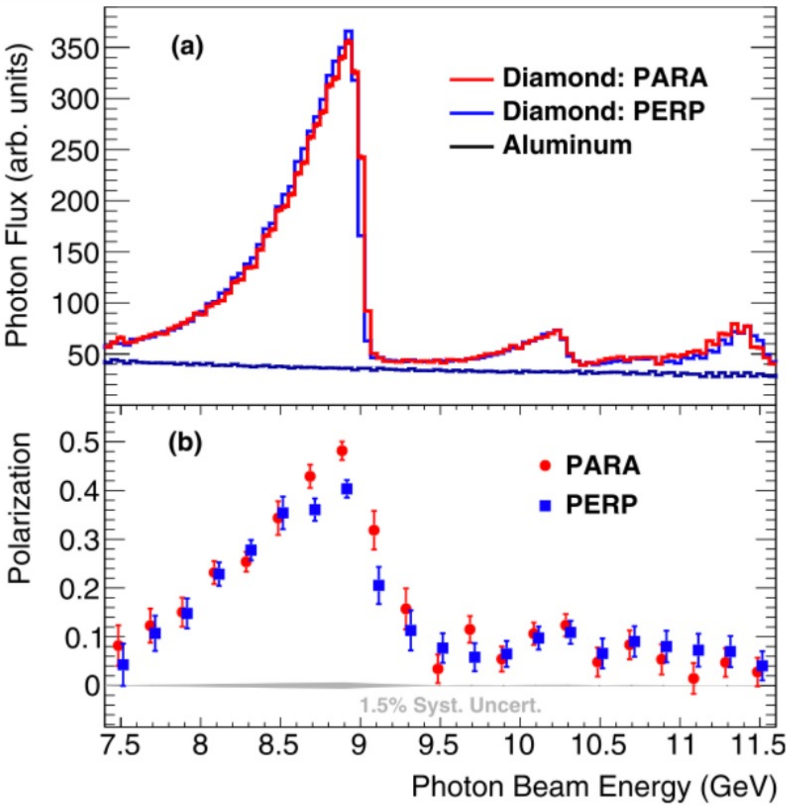


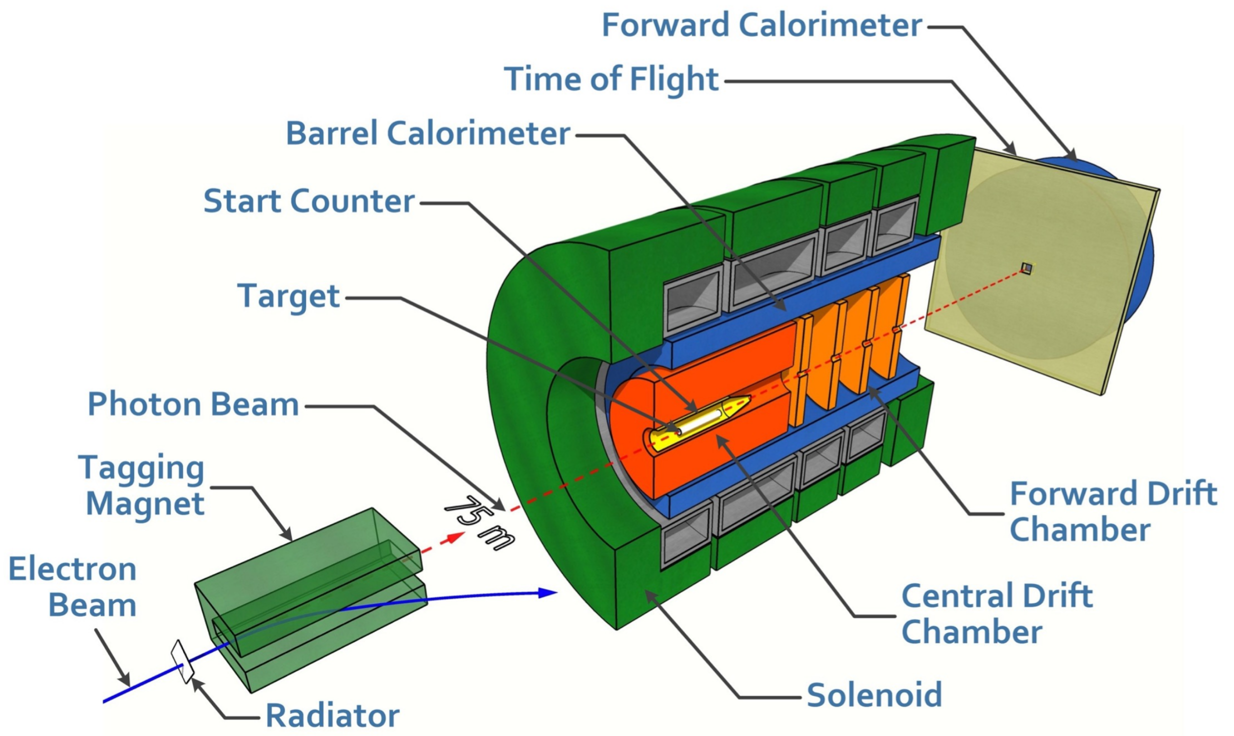


- 12 GeV electron beam from CEBAF accelerator
- Coherent Bremsstrahlung on diamond radiator
- Linear polarization in peak at ~9 GeV: $P\gamma \sim 40\%$
- Energy tagged by scattered electrons
- Beam intensity: $1 - 5 \cdot 10^7$ γ/s in peak

GlueX in Hall D at CEBAF, JLab







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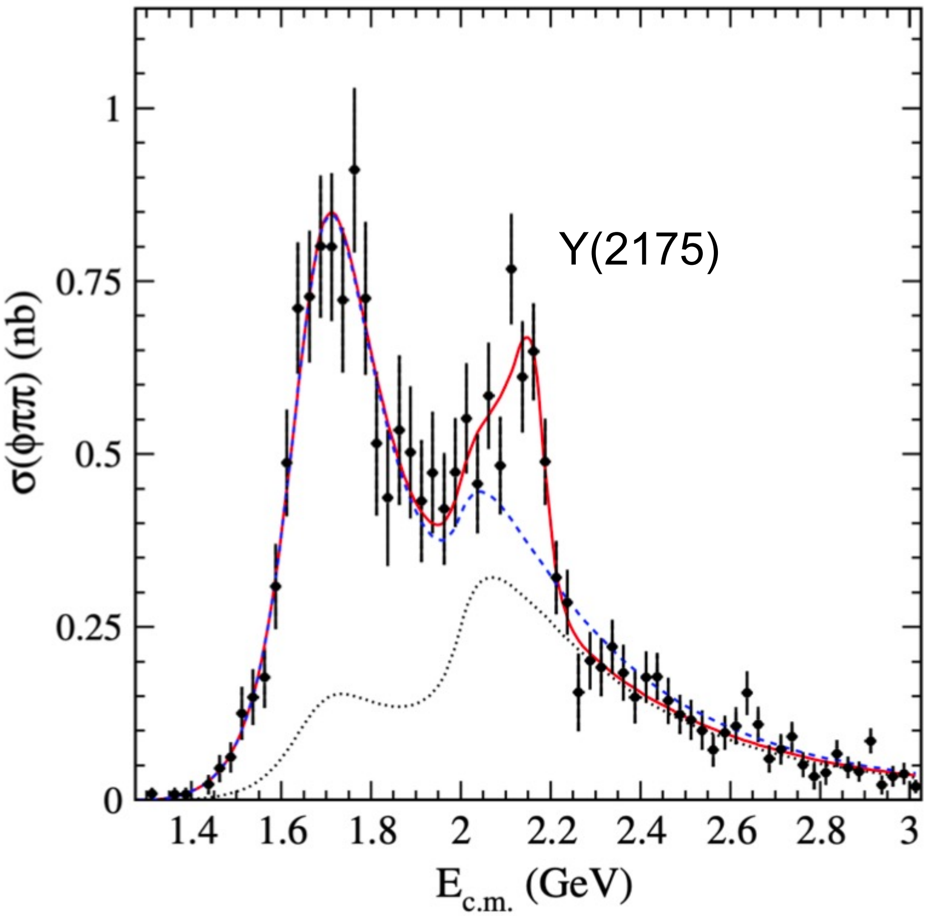
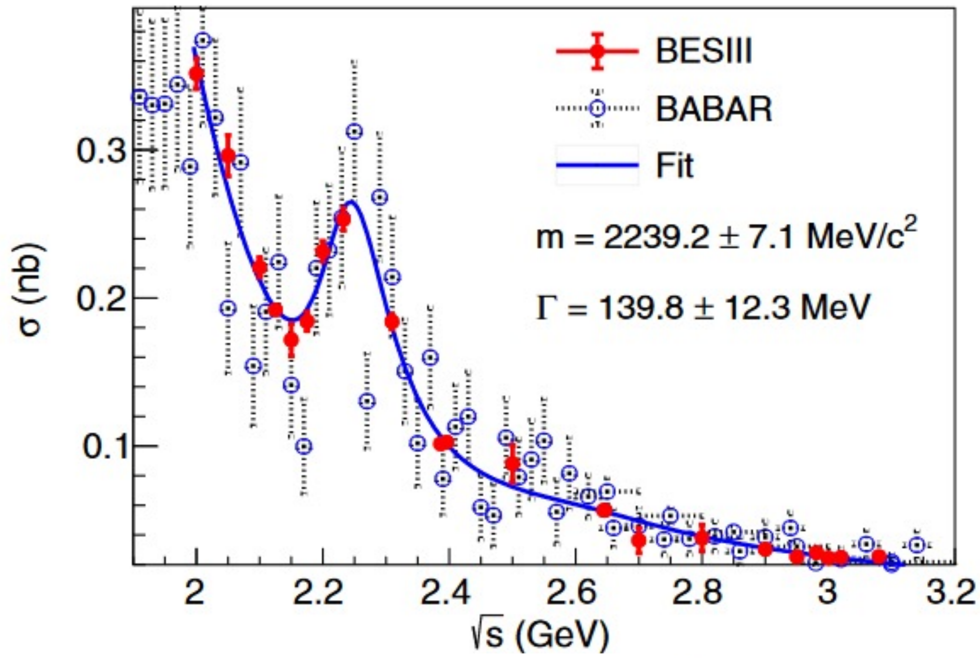
The Y(2175) – strange partner of Y(4230)

[Phys. Rev. D. 74 (2006) 091103]



[Phys. Rev. D 99, (2019) 032001]



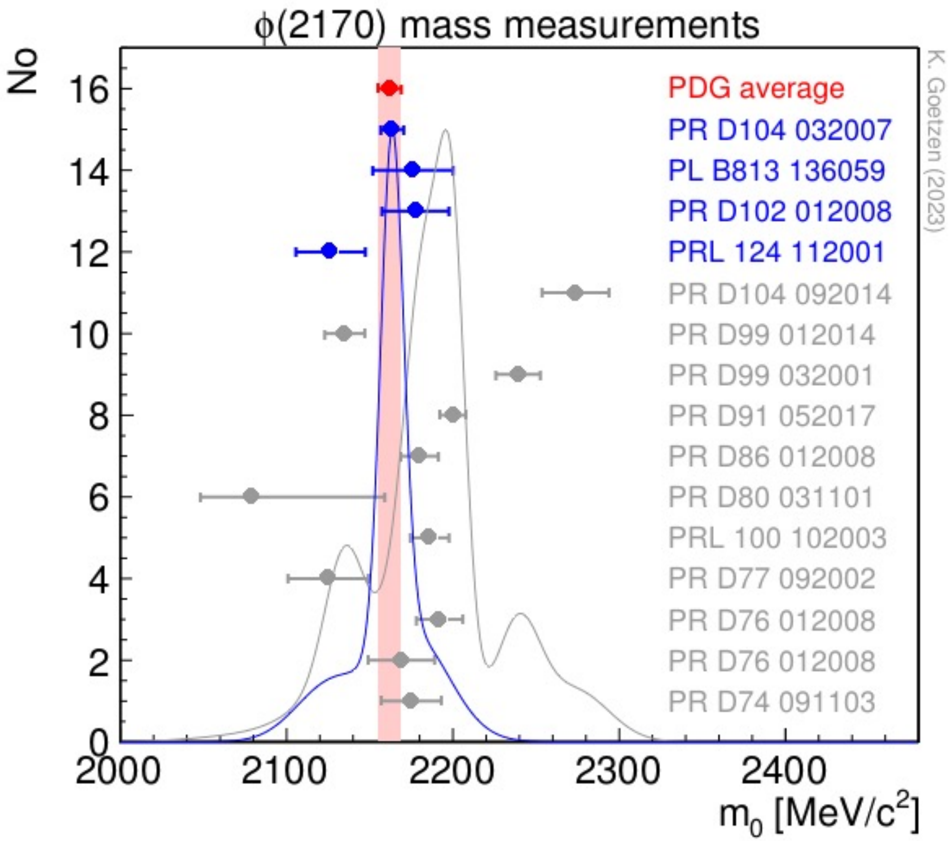
$e^+e^- \rightarrow K^+K^-$ cross section at $\sqrt{s} = 2.00 - 3.08$ GeV

$$M = 2239.2 \pm 7.1 \pm 11.3 \text{ MeV}/c^2$$
$$\Gamma = 139.8 \pm 12.3 \pm 20.6 \text{ MeV}$$

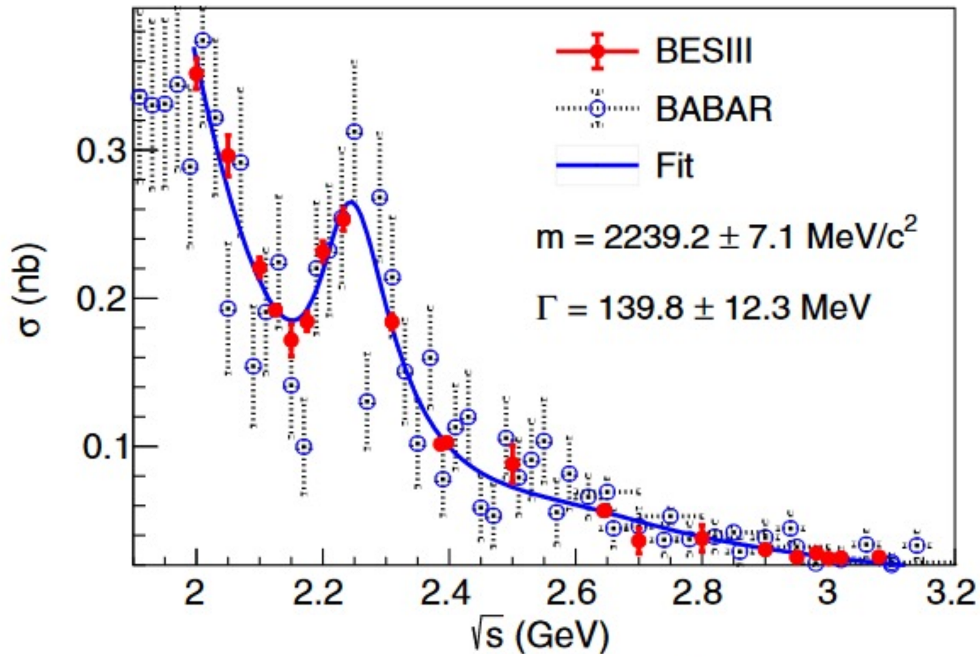
First observed in ISR, BaBar

PDG: Larger spread in individual resonance parameter measurements, e.g. above

The Y(2175) – strange partner of Y(4230)



[Phys. Rev. D 99, (2019) 032001]



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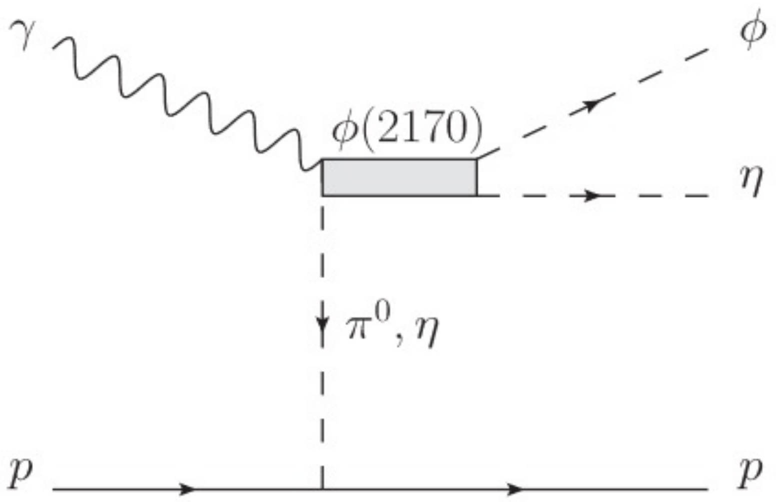
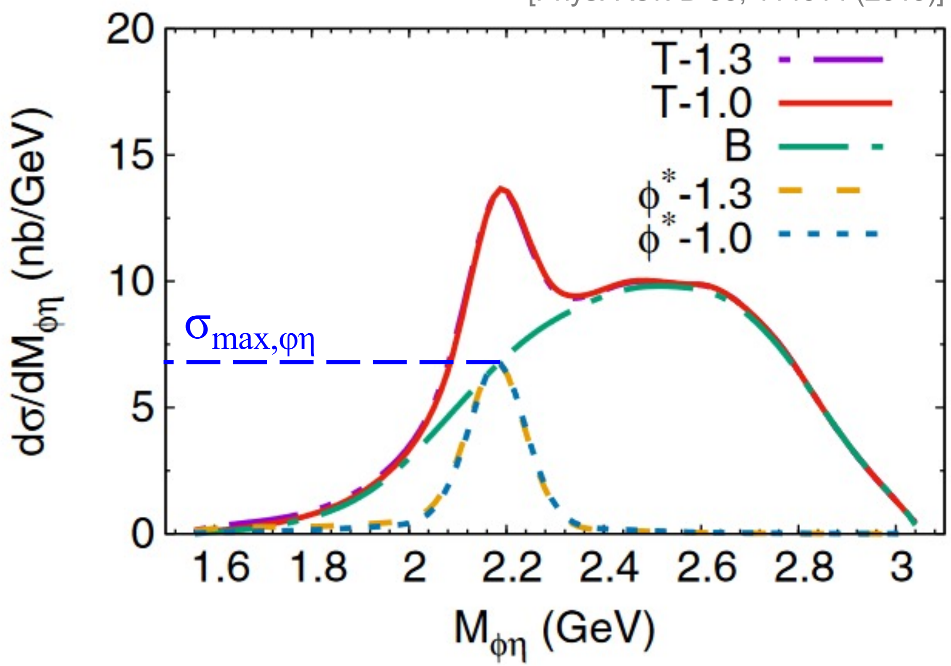
Prediction for photoproduction

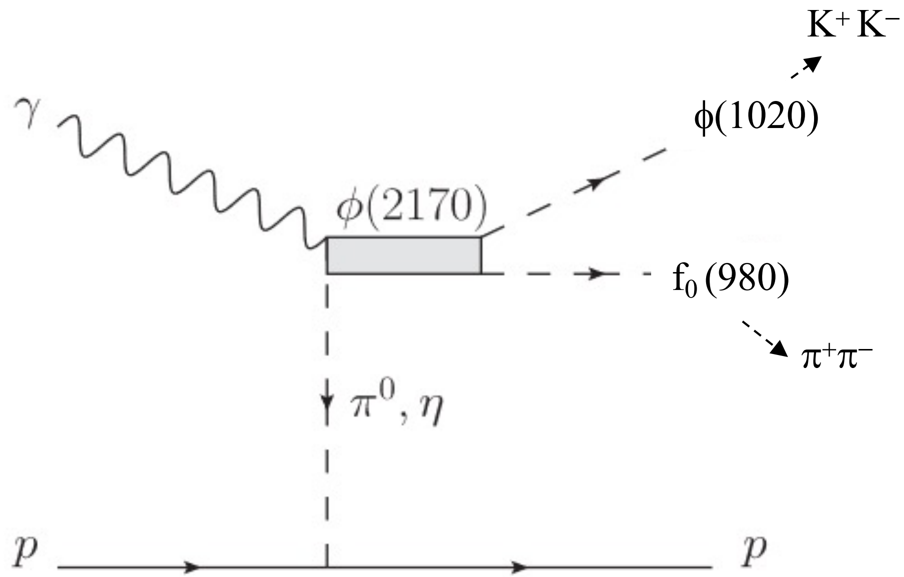


[Phys. Rev. D 99, 114014 (2019)]

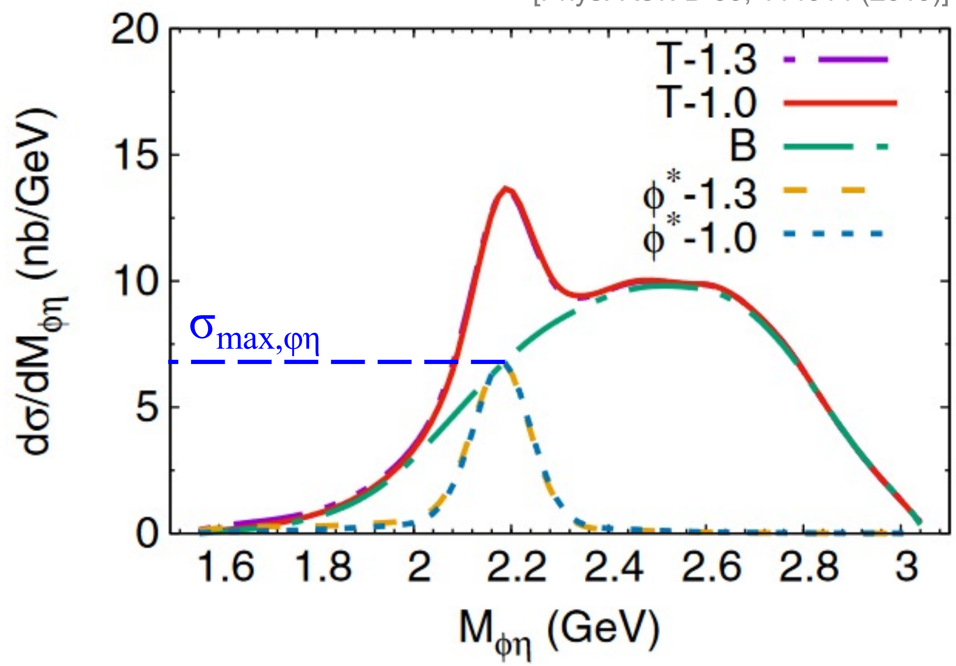


- Investigation of reaction $\gamma p \rightarrow \varphi\eta p$ @ E_γ = 8 GeV
- Assumption: $\Gamma(Y(2175) \rightarrow \varphi\eta) \approx 6.6$ MeV (quark model)
- Peak integral: $\sigma_{\varphi\eta} \approx 885$ pb (with $\sigma_{max} \approx 7$nb, $\Gamma = 83$ MeV/c^2)

Study $\phi\pi\pi$ photoproduction



[Phys. Rev. D 99, 114014 (2019)]



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- $\Gamma(Y(2175) \to \varphi f_0(980) / \Gamma(Y(2175) \to \varphi\eta)) \approx 1.37$
  - For $Y(2175) \to \varphi f_0(980)$: $\sigma_{\varphi f0} \approx 1212$ pb

Timeline	$\int \mathcal{L}$ (pb^{-1})
2017	22
2018	103
2020	132
2023	
2024	

Event selection

I)

- Apply loose PID selection (dE/dx, ToF)
- Form $\gamma\, K^+K^-\pi^+\pi^-\, p$ candidates
- Perform 4C of $K^+K^-\pi^+\pi^-\, p$ to γp_{target} system together with
- Vertex fit of $K^+K^-\pi^+\pi^-\, p$ system

} event candidates

II)

- Apply beam energy cut $E_\gamma > 8$ GeV
- Apply momentum transfer cut $-t < 1\ \mathrm{GeV}^2/c^4$ (fiducial)
- Apply veto cut for $\Delta^{++}(1232)$: $m > 1.35\ \mathrm{GeV}/c^2$
- Require $|MM^2| < 50\ \mathrm{MeV}^2/c^4$ for missing mass squared
- Require $\chi^2_{4C+vtx} < 70$

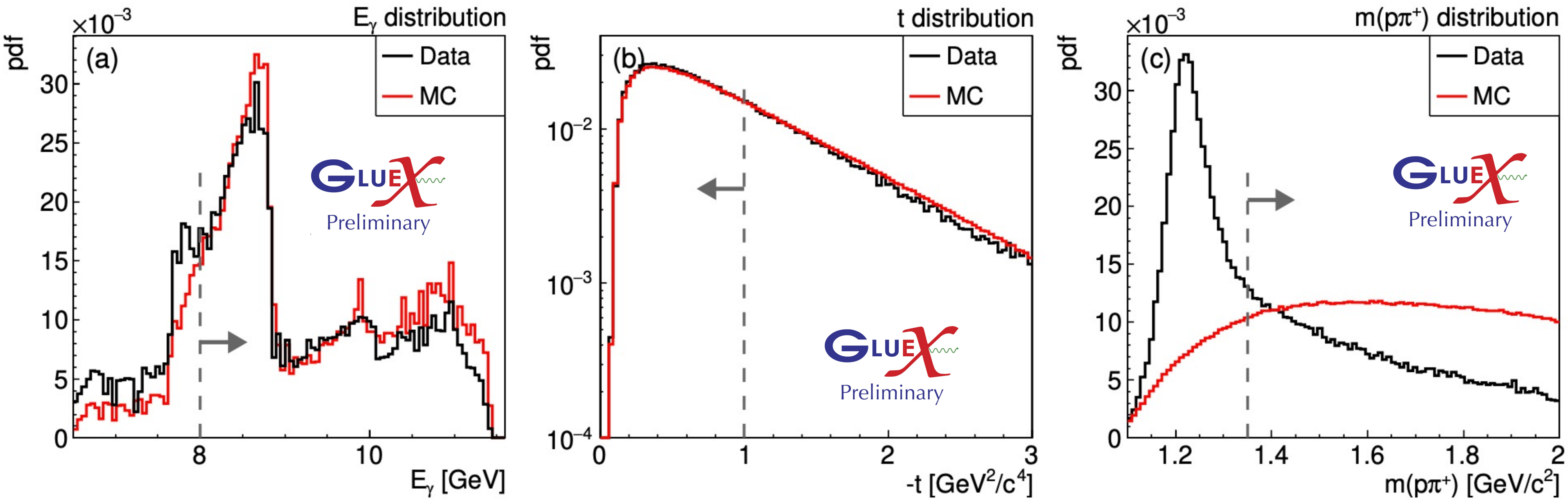
} event selection cuts

III)

- Determine $\phi(1020)$ yield using a Voigtian fctn.

[K. Goetzen and F. Nerling, behalf of GlueX, Conf. Proc. HADRON2023 & MESON2023]

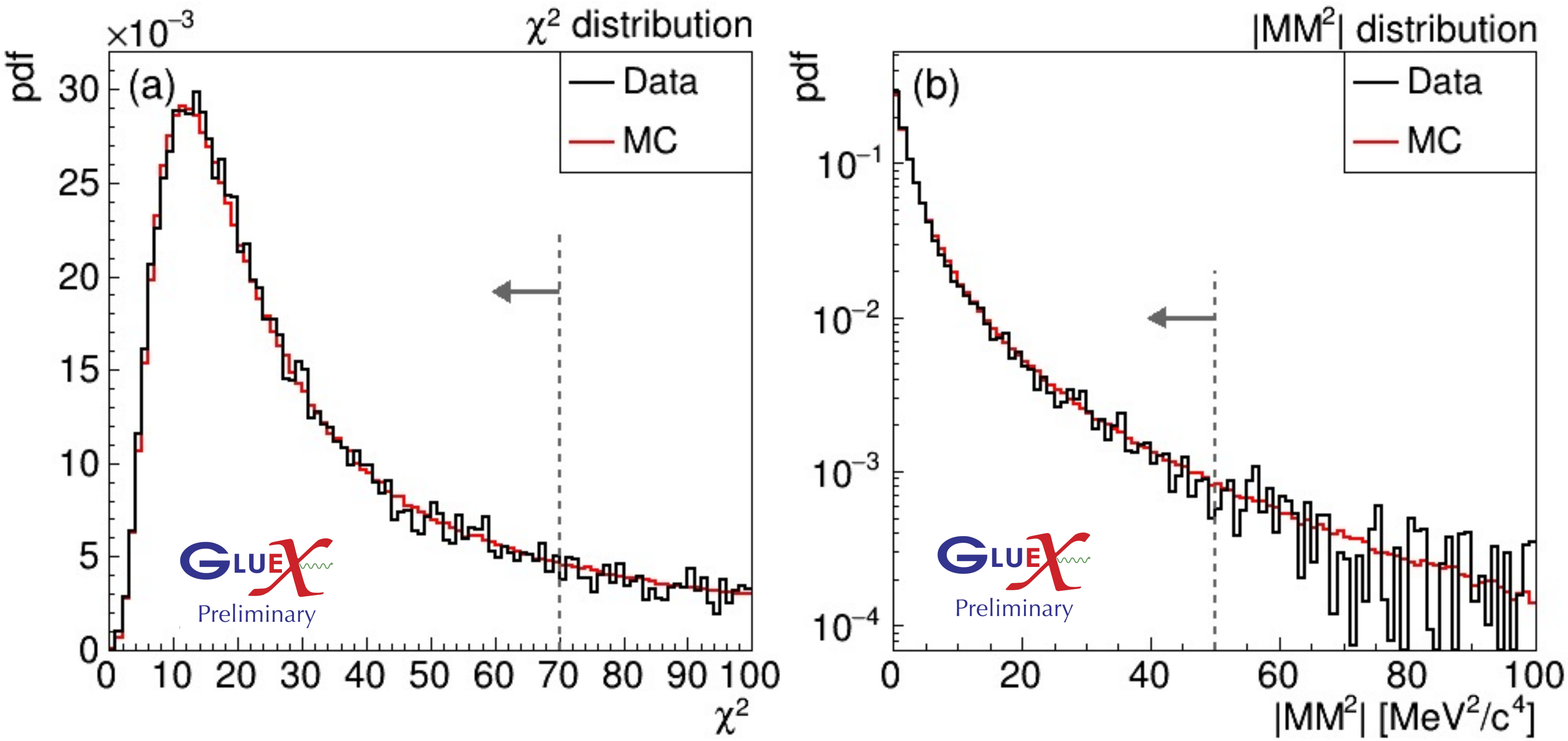
Event selection (II): MC vs. Data



- Photon energy:
  $E_\gamma > 8$ GeV
- Momentum transfer:
  $-t < 1$ GeV^2/c^4
- Veto $\Delta(1232)^{++}$:
  $m(\pi^+p) > 1.35$ GeV/c^2

[K. Goetzen and F. Nerling, Conf. Proc. HADRON2023 & MESON2023]

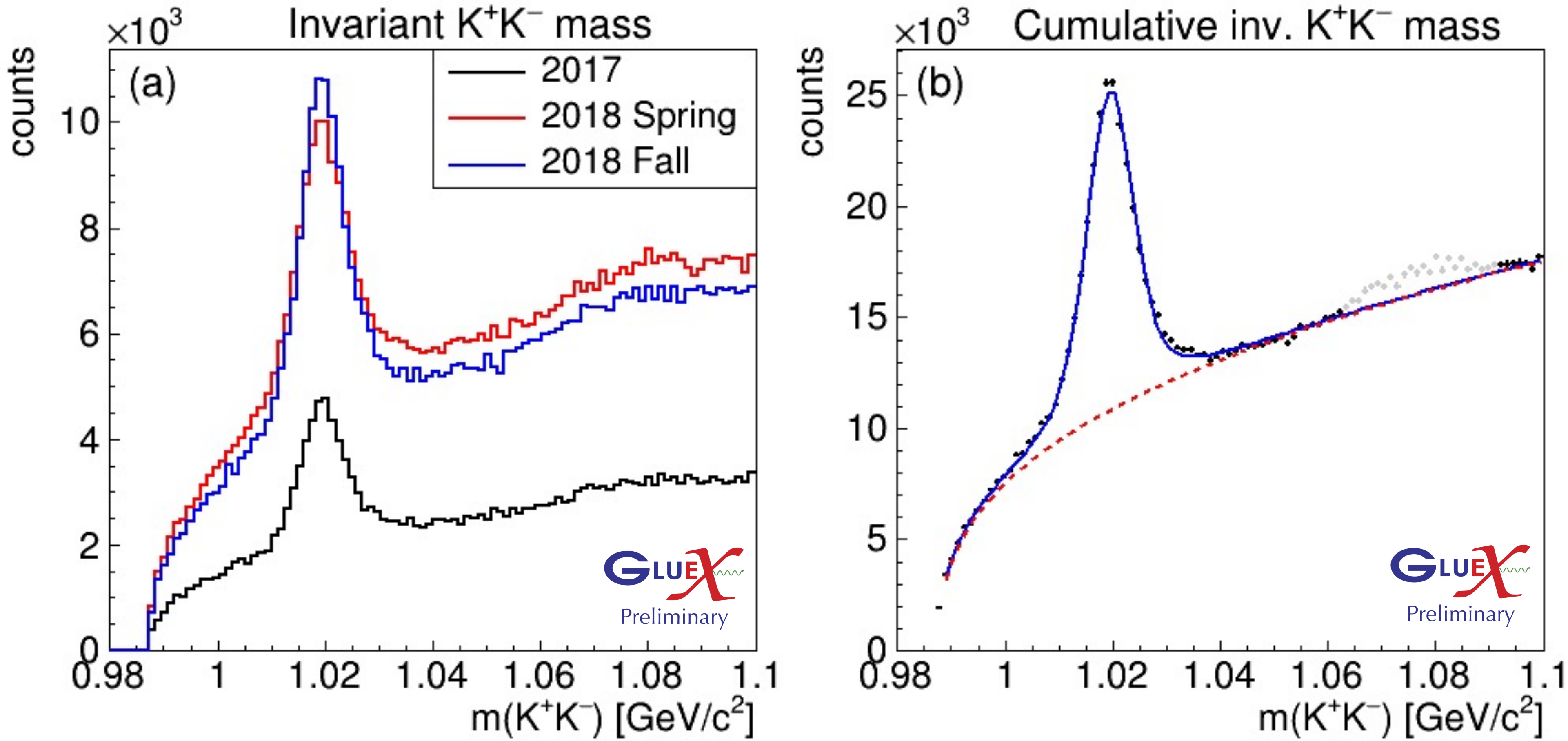
Event selection (II): Kinematics



- 4C and vertex fit quality:
  $\chi^2 < 70$ (ndf = 11)
- Missing mass:
  $|MM^2| < 50$ MeV^2/c^4

[K. Goetzen and F. Nerling, behalf of GlueX, Conf. Proc. HADRON2023 & MESON2023]

φ(1020) signal in different data sets



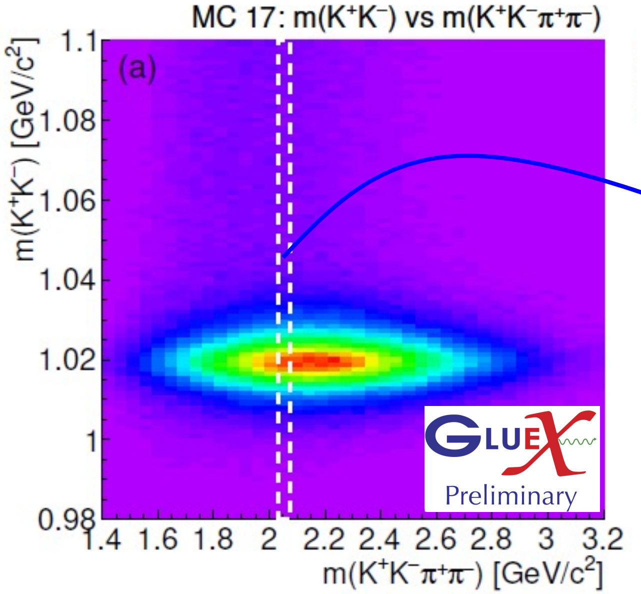
- Fit signal with function (V = Voigtian):

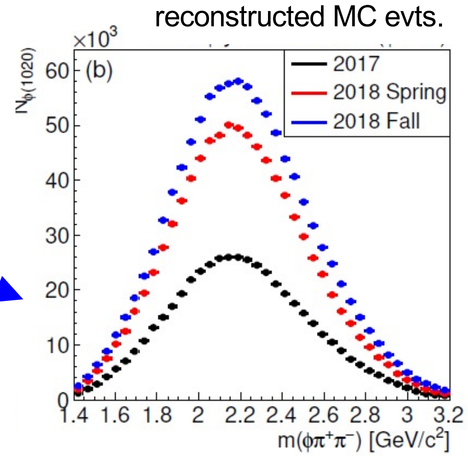
$$f(m) = V(m; m_0, \Gamma_0, \sigma_{\rm res}) + |m - m_t|^p \cdot e^{-\lambda m} \qquad \text{for } m > m_t,$$

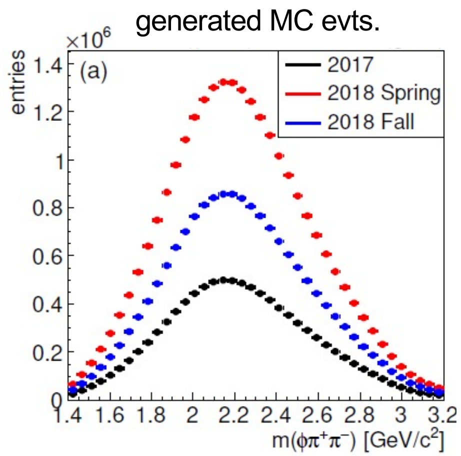
- Fix φ-shape parameters to extract distributions slice-wise

[K. Goetzen and F. Nerling, behalf of GlueX, Conf. Proc. HADRON2023 & MESON2023]

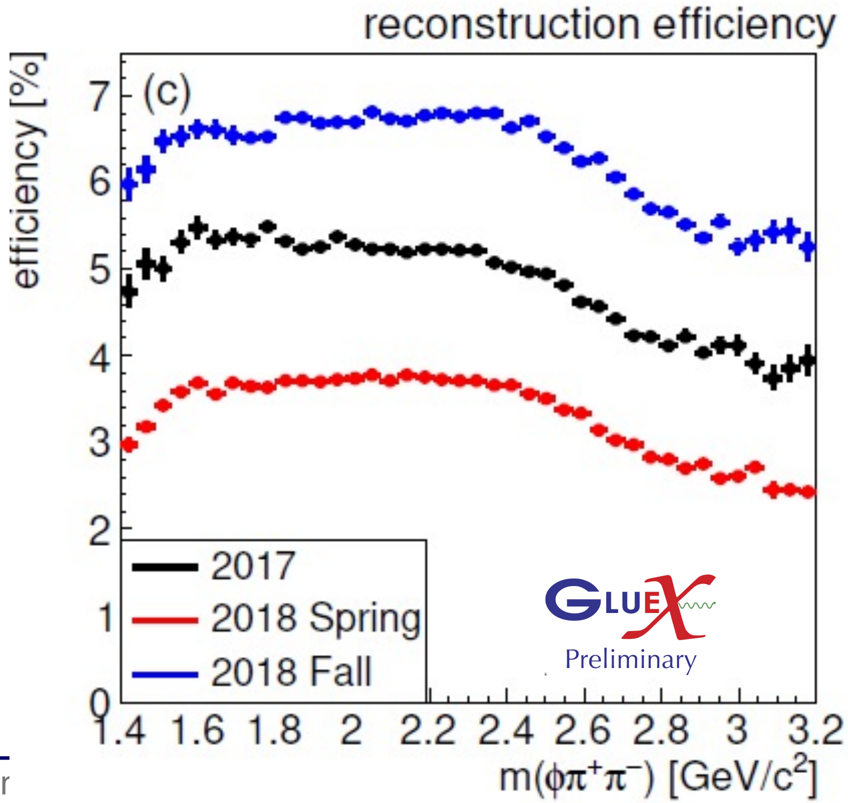
Slice-wise efficiency determination





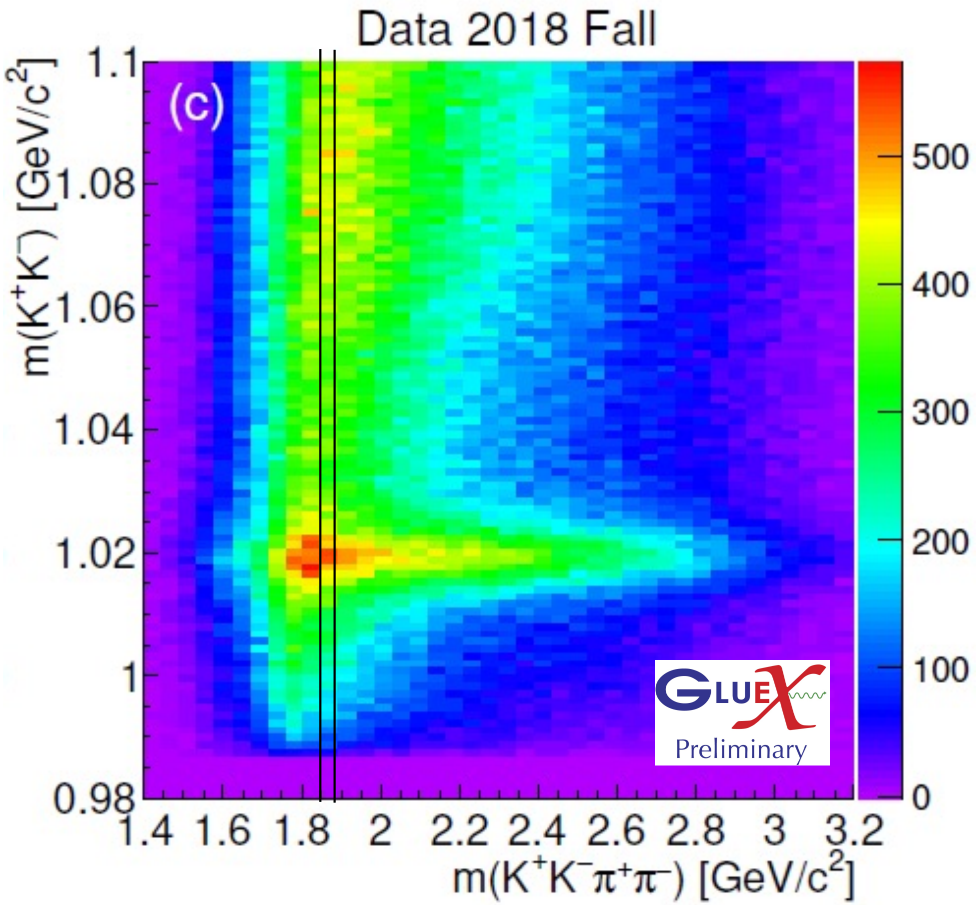


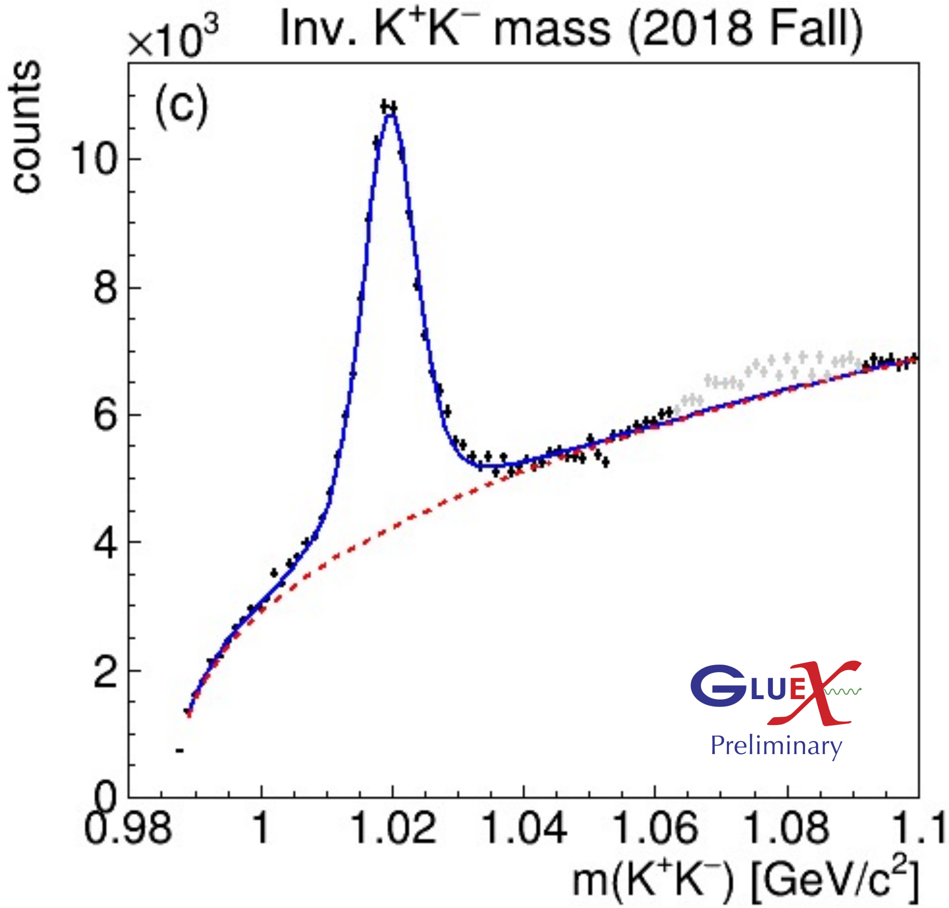
=>



[K. Goetzen and F. Nerling, behalf of GlueX, Conf. Proc. HADRON2023 & MESON2023]

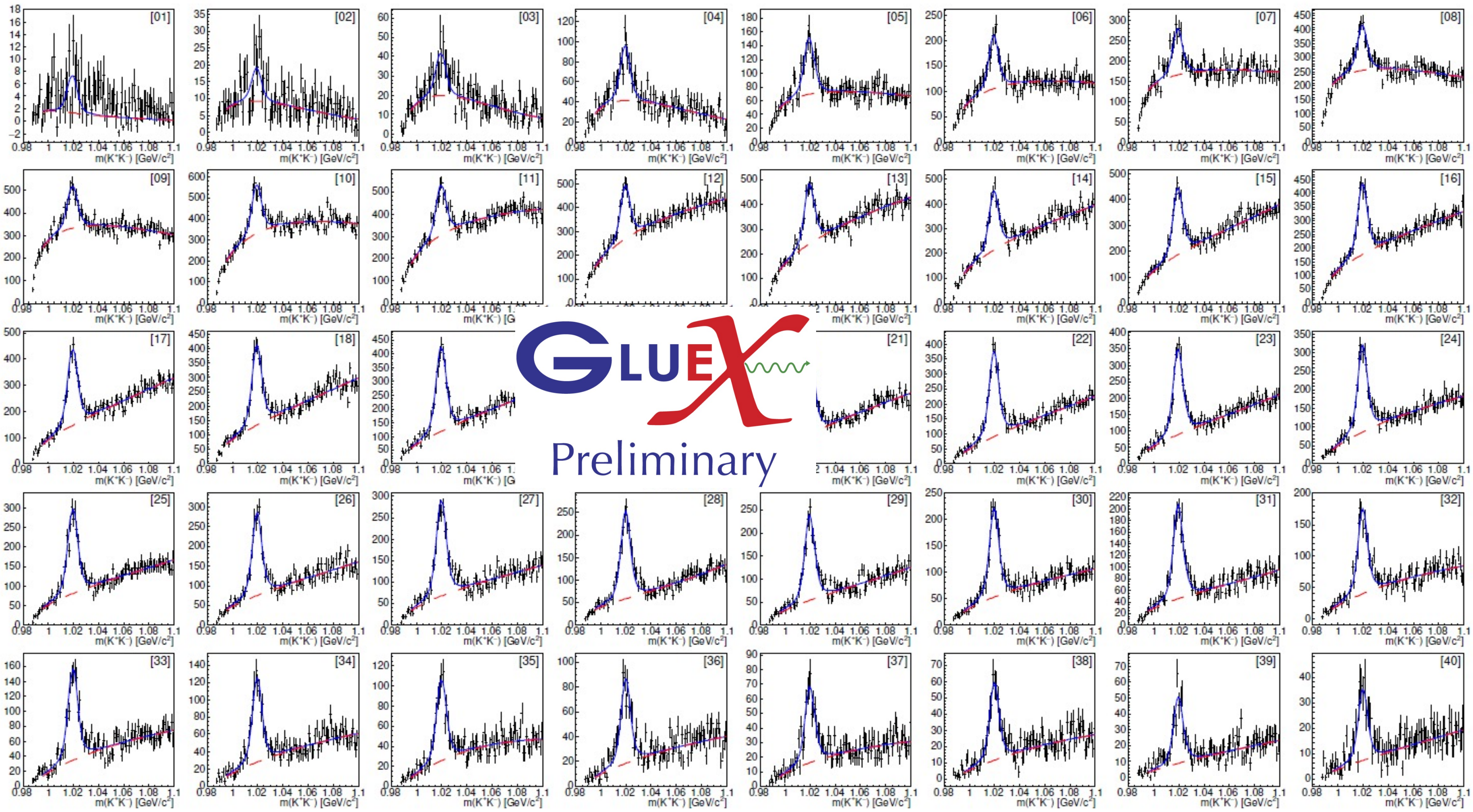
Slice-wise fits & φ signal shape parameters





- Fit yields in 45 MeV slices in 4-body mass with fixed signal shape
- Signal shape parameters m and σ_{res} determined from data (coarse scan)

„Slice-wise φ fits“, data



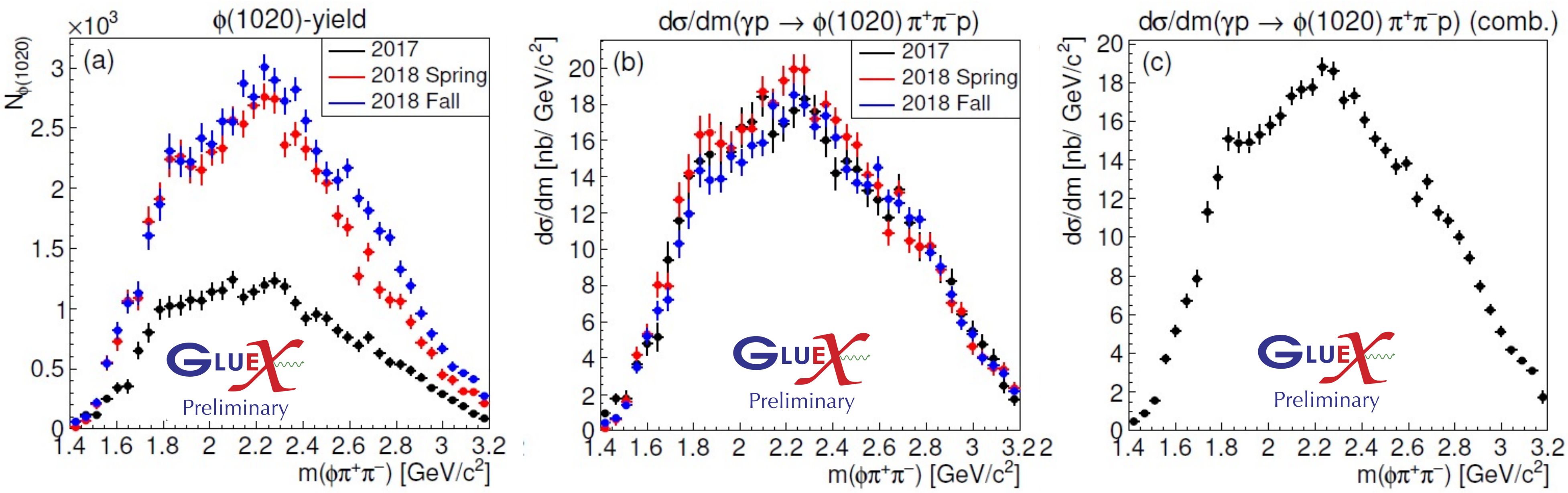
- Single slice fits data (here for 2018 Fall)

[K. Goetzen and F. Nerling, behalf of GlueX, Conf. Proc. HADRON2023 & MESON2023]

Differential cross section

- Determine mass-dependent cross section:

$$\frac{d\sigma}{dm}(m_i) = \frac{N_\phi(m_i)}{\varepsilon(m_i)\cdot F \cdot d_{\text{target}} \cdot \mathcal{B}(\phi(1020)\to K^+K^-)}$$



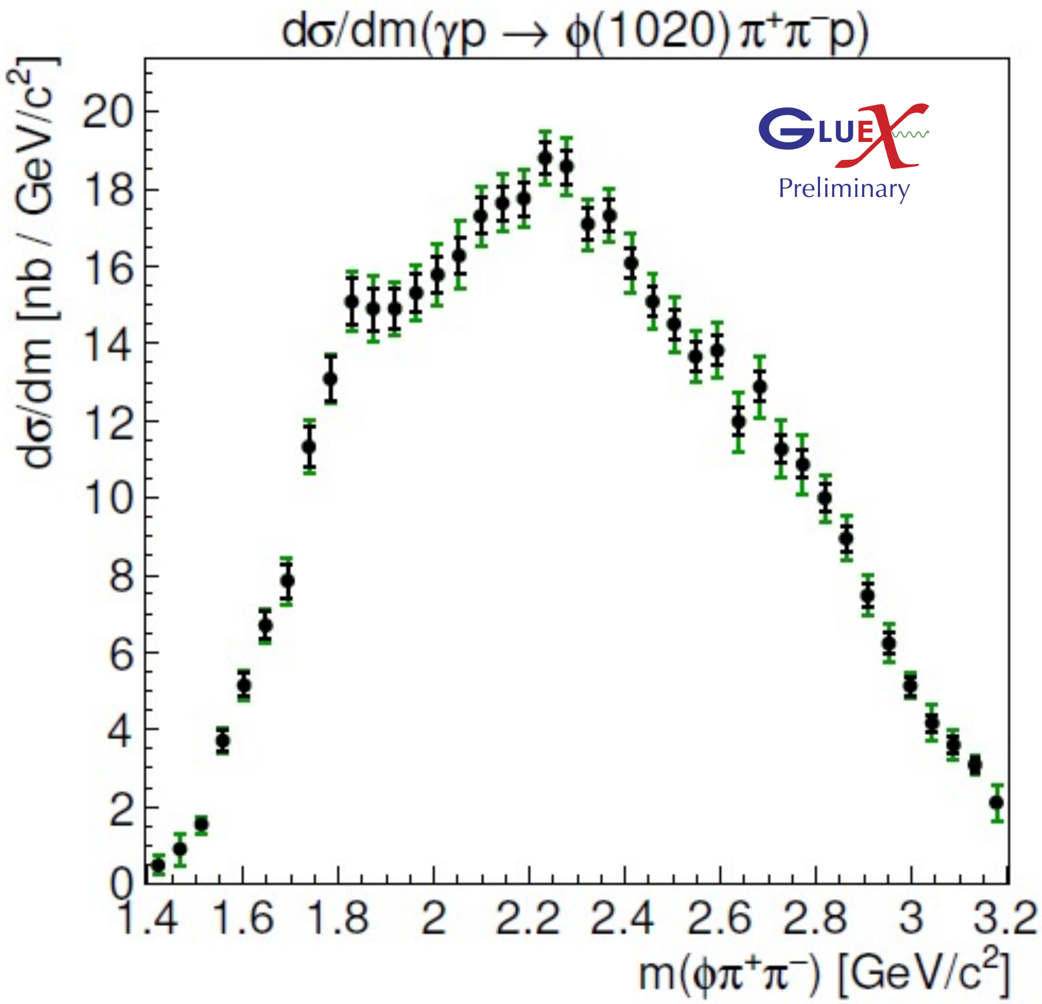
- Combine results by bin-wise via „weighted average“ method:

$$\hat{x} \pm \delta\hat{x} = \frac{\sum_i w_i x_i}{\sum_i w_i} \pm \left(\sum_i w_i^2\right)^{-1/2} \quad \text{with } w_i = 1/\delta x_i^2$$

Mass-dependent cross section result

=> Take differences in cross section of default vs. varied fit as systematics

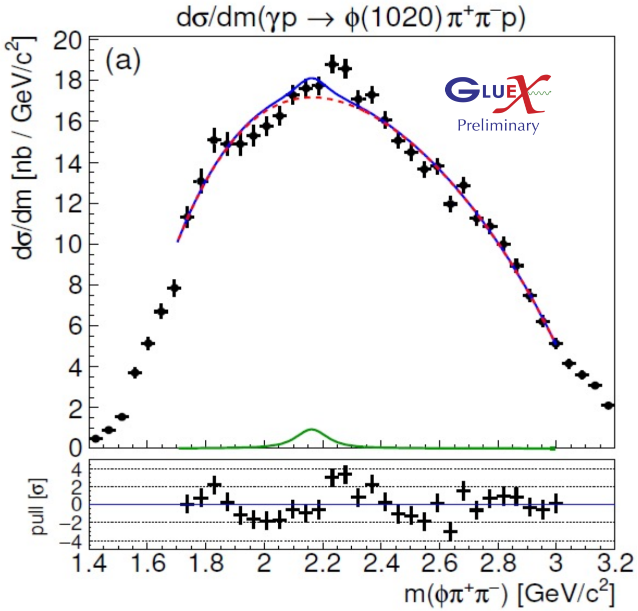
Source	$\delta_{\mathrm{sys,avg}}$ [%]
$\phi(1020)$ branching fraction	1.0
χ^2 requirement	0.9
MM^2 requirement	0.4
Accidentals	0.5
K^+K^- binning	0.7
$\Delta(1232)^{++}$ veto	2.8
$\phi(1020)$ fit model data	0.8
$\phi(1020)$ fit model MC	0.7
$\phi(1020)$ fit range	1.6
$\phi(1020)$ veto range MC	0.5
$\phi(1020)$ integral range MC	0.1
$\phi(1020)$ param. interpolation	0.5
Total systematic uncertainty	4.7



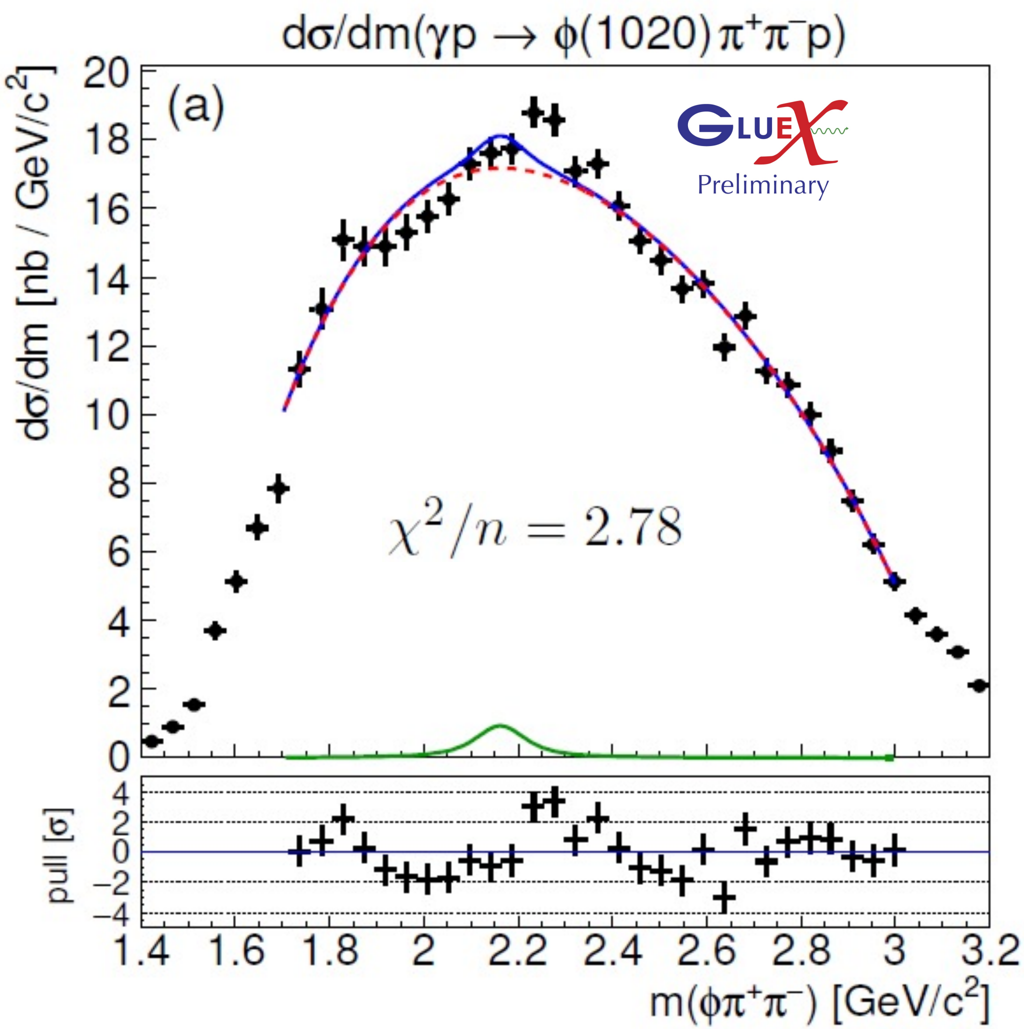
[K. Goetzen and F. Nerling, behalf of GlueX, Conf. Proc. HADRON2023 & MESON2023]

Search for resonances in $m(\phi\pi^+\pi^-)$

- Fit signal + background in combined spectrum
  - 1 Res.: $f(m) = V(m; m_1, \Gamma_1, \sigma_{\text{res}}) + T_4(m)$
  - 2 Res.: $f(m) = V_1(m; m_1, \Gamma_1, \sigma_{\text{res}}) + V_2(m; m_2, \Gamma_2, \sigma_{\text{res}}) + T_4(m)$
  - V = Voigtian, T_4 = 4th order Chebyshev polynomial
- Use weighted mass resolution from MC (σ_{res}= 24.6 MeV/c^2)
- Repeat for each systematic variation
- Systematic uncertainty: Difference to nominal result
- Additional systematics are:
  - $m(\phi\pi\pi)$ fit range
  - $m(\phi\pi\pi)$ fit model (degree of bkgd polynomial)
  - $\phi(2170)$ mass m_0 (by +/- 1σ)
  - $\phi(2170)$ width Γ_0 (by +/- 1σ)
- And we take the (larger) difference as systematic uncertainty



Fixed Y(2175) parameters – fit a_1)



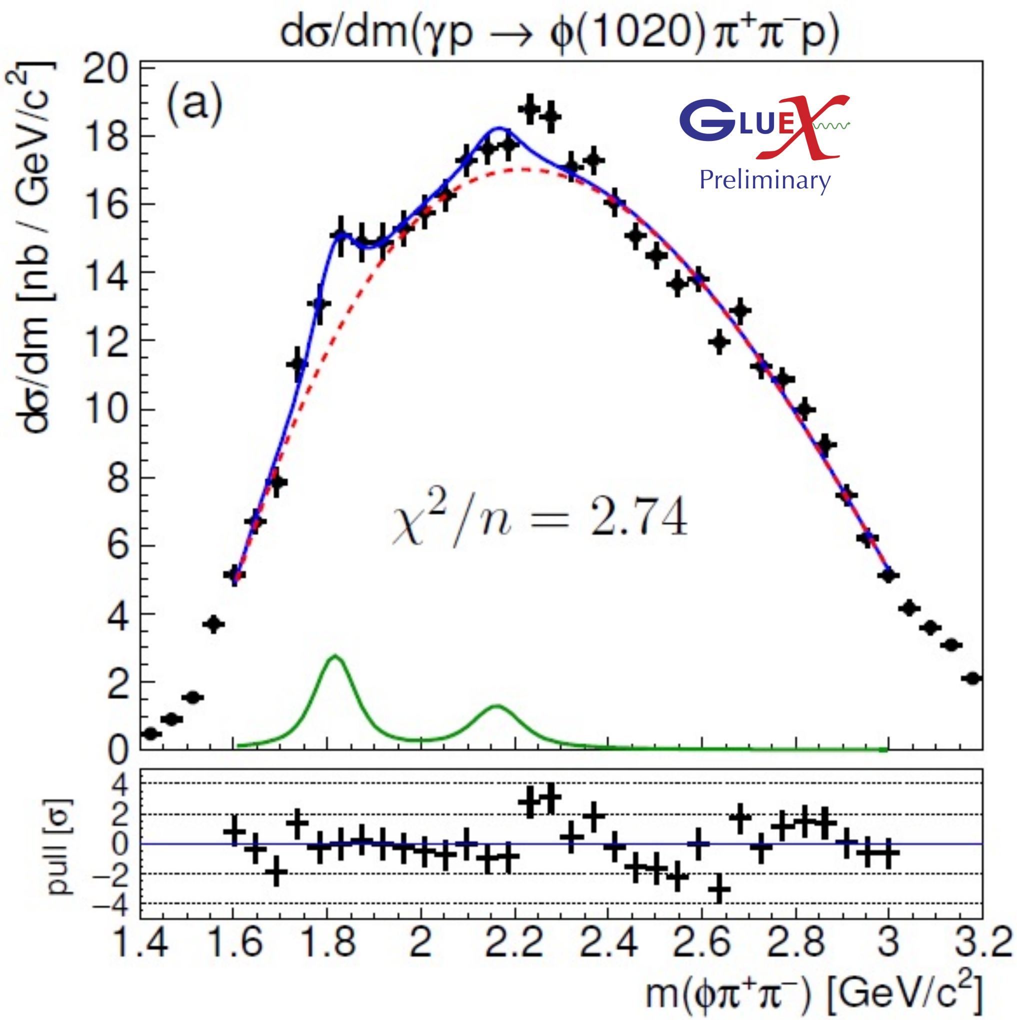
R1: Fixed PDG parameters Y(2175)

$$m_{\phi(2170)} = 2162 \pm 7 \text{ MeV}/c^2$$
$$\Gamma_{\phi(2170)} = 100^{+31}_{-21} \text{ MeV}/c^2$$

$$\sigma_{\phi(2170)} = 174 \pm 69\,(\text{stat.}) \pm 218\,(\text{sys.})\ \text{pb}$$
$$\sigma_{\phi(2170)} < 499\ \text{pb (CL90)} \quad [Z = 1.6\sigma\ (2.1\sigma)]$$

[K. Goetzen and F. Nerling, behalf of GlueX, Conf. Proc. HADRON2023 & MESON2023]

Fixed Y(2175) parameters – fit a_2)



R1: Fixed PDG parameters Y(2175)

$$m_{\phi(2170)} = 2162 \pm 7\ \mathrm{MeV}/c^2$$
$$\Gamma_{\phi(2170)} = 100^{+31}_{-21}\ \mathrm{MeV}/c^2$$

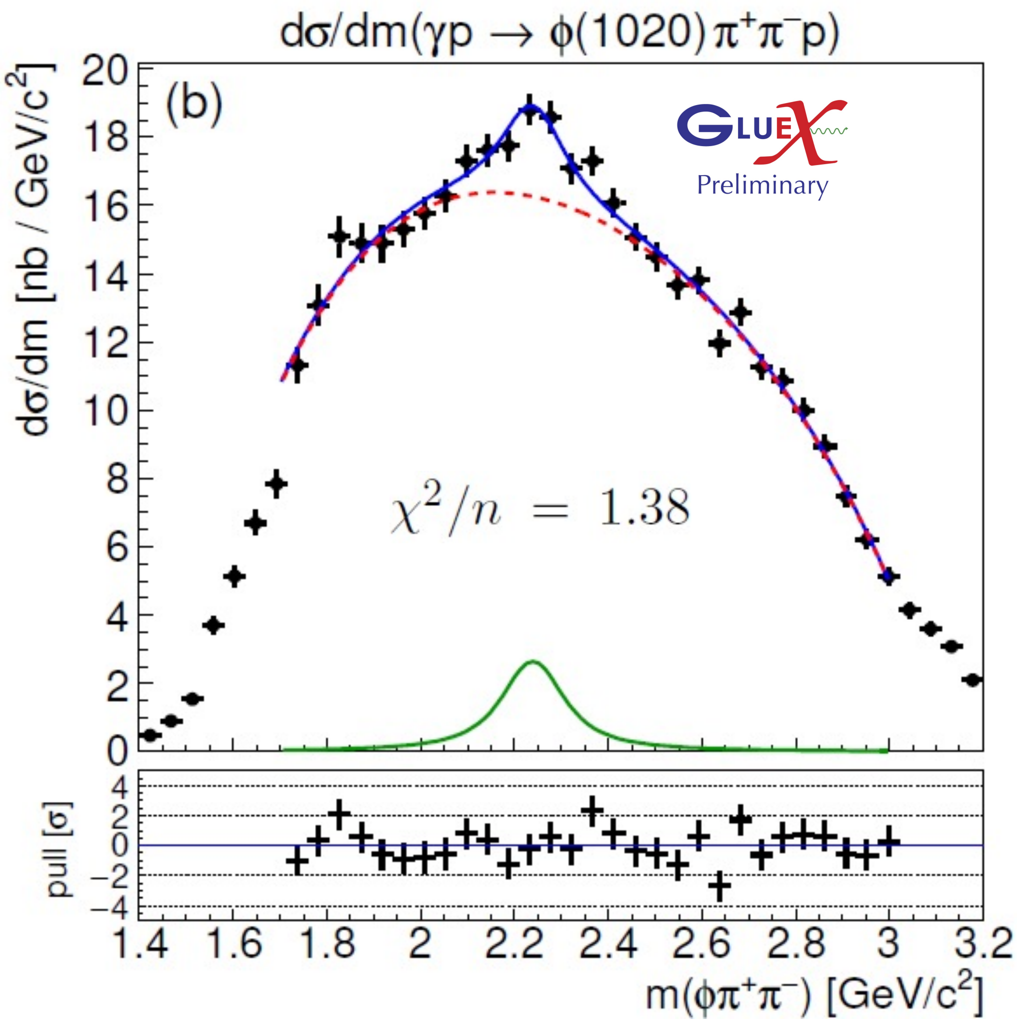
R2: Possible structure at m ~ 1.8 GeV

$$\sigma_{X(1800)} < 615\ \mathrm{pb}\ (\mathrm{CL90})$$

$$\sigma_{\phi(2170)} = 232 \pm 68\,(\mathrm{stat.}) \pm 91\,(\mathrm{sys.})\ \mathrm{pb}$$
$$\sigma_{\phi(2170)} < 379\ \mathrm{pb}\ (\mathrm{CL90})\quad [Z = 1.5\sigma\ (1.8\sigma)]$$

[K. Goetzen and F. Nerling, behalf of GlueX, Conf. Proc. HADRON2023 & MESON2023]

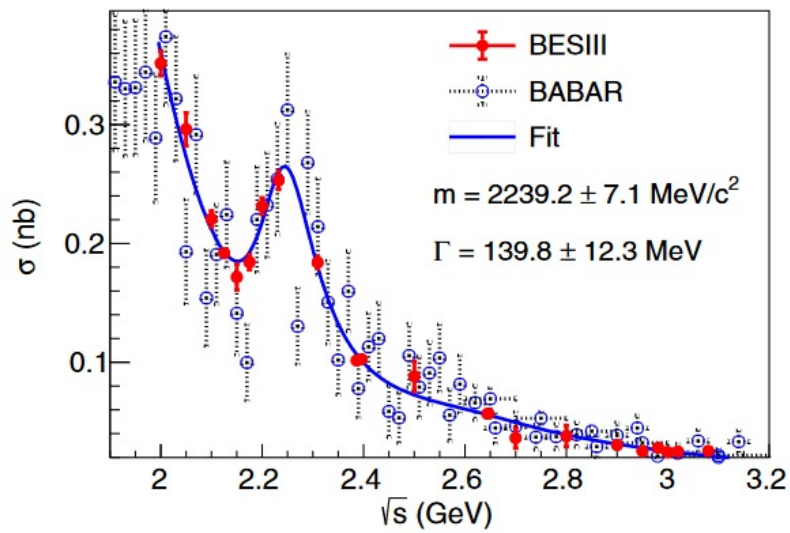
Fixed Y(2239) parameters – fit b_1)



R1: Fixed parameters Y(2239)

$$m_{Y(2239)} = 2239.2 \pm 13.4\ \mathrm{MeV}/c^2$$
$$\Gamma_{Y(2239)} = 139.8 \pm 24.0\ \mathrm{MeV}/c^2$$

[Phys. Rev. D 99, (2019) 032001]



$$\sigma_{Y(2239)} = 641 \pm 82\,(\mathrm{stat.}) \pm 181\,(\mathrm{sys.})\ \mathrm{pb}$$
$$\sigma_{Y(2239)} < 896\ \mathrm{pb}\ (\mathrm{CL90})\quad [Z = 5.7\sigma\ (6.0\sigma)]$$

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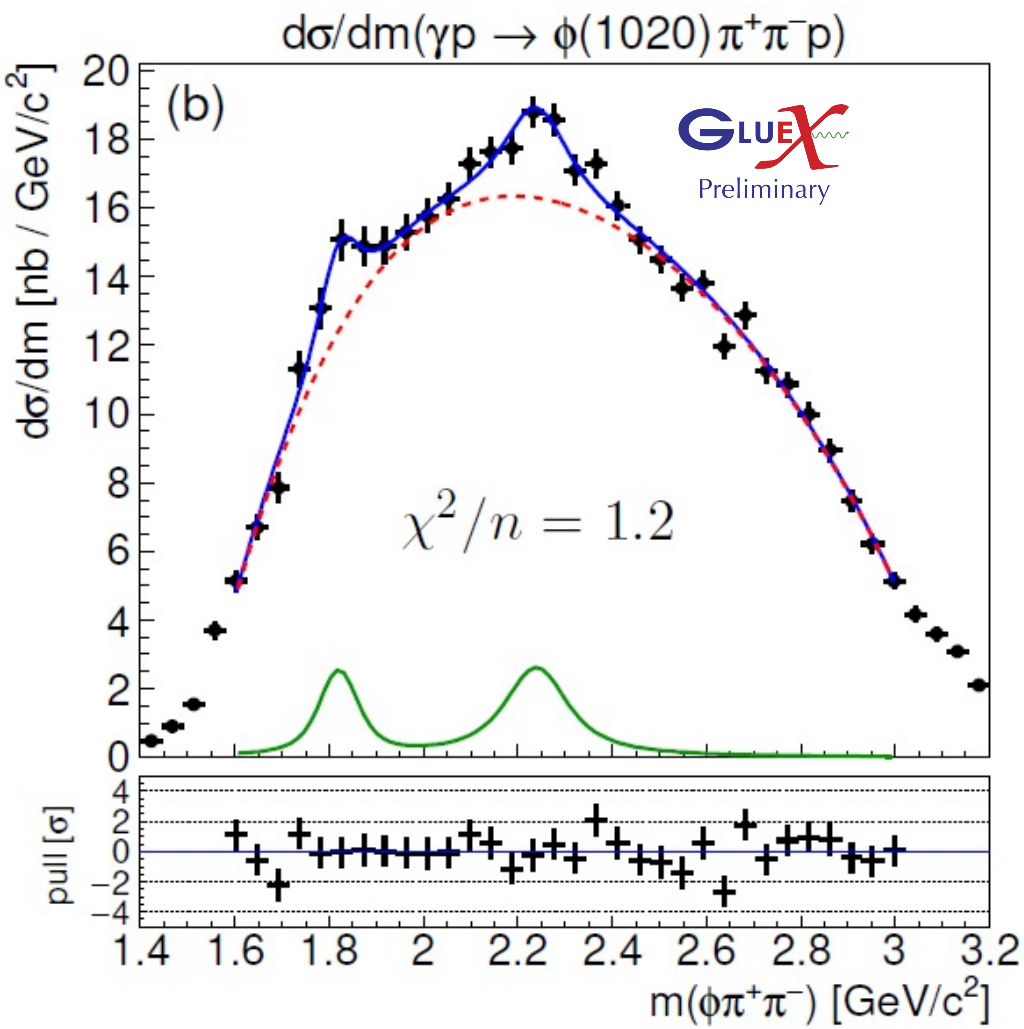
Fixed Y(2175)' parameters – fit b_2)



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R2: Possible structure at m ~ 1.8 GeV):

$$\sigma_{X(1800)} < 701 \text{ pb (CL90)}$$

$$\sigma_{Y(2239)} = 629 \pm 83\,(\text{stat.}) \pm 130\,(\text{sys.})\text{ pb}$$
$$\sigma_{Y(2239)} < 826 \text{ pb (CL90)} \quad [Z = 4.7\sigma\ (5.1\sigma)]$$

[K. Goetzen and F. Nerling, behalf of GlueX, Conf. Proc. HADRON2023 & MESON2023]

Summary

- Analysis of reaction $\gamma p \rightarrow K^+K^-\pi^+\pi^- p$
- Measurement of differential $\varphi\pi^+\pi^-$ production cross section $\sigma(\gamma p \rightarrow \varphi\pi^+\pi^- p)$
- Search for Y(2175) + other resonances gives

Case	Cross Section [pb]	UL [pb]	Z_{stat}	Z_{tot}
Fit a_1: Y(2175) fixed	174 ± 69 ± 218	499	2.1	1.6
Fit a_2: Y(2175) fixed	232 ± 68 ± 91	379	1.8	1.5
Fit b_1: Y(2239) fixed	641 ± 82 ± 181	896	6.0	5.7
Fit b_2: Y(2239) fixed	629 ± 83 ± 130	826	5.1	4.7

- Fit with Y(2175) PDG parameters → no evidence ($Z < 3\sigma$)
- Alternative fits with Y(2239) parameters (fixed) → evidence/observation ($Z > 3$)
- Signal strength of Y(2239) in ball-park of predicted $\sigma \approx 1200$ pb
- Find 2nd structure at around $m \approx 1.8$ GeV/c^2
    - UL(CL90): $\sigma < 615$ pb (fit a_2) and $\sigma < 701$ pb (fit b_2)

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Under internal review for publication
→ *paper submission to journal soon*

Summary and Prospectives

- New era of charmonium-like exotic states started two decades ago, and more than 20 unexpected XYZ states have been discovered
  - Supernumerary vector Y states consistently resolved (statistics)
    - *Two structures consistently resolved in all three systems*
    - *Y(4260) and Y(4360) → Y(4230), Y(4390)?*
  - Charged Z_c states are manifestly exotic states
    - *First complete isospin triplets established*
    - *First strange partner(s) reported, incl. neutral partner*
  - The first of the XYZ states discovered, the X(3872), still not understood
    - *Consistent picture in B decays and e^+e^- production*
    - *Line shape to be measured precisely → $p\bar{p}$ annihilation experiment*

–

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Thank you!

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Outlook: „QCD at FAIR“ initiative
→ *Synergies between hadron physics and heavy-ion communities*