Searches for charmonium-like (exotic) XYZ states decaying to light hadrons at BESIII

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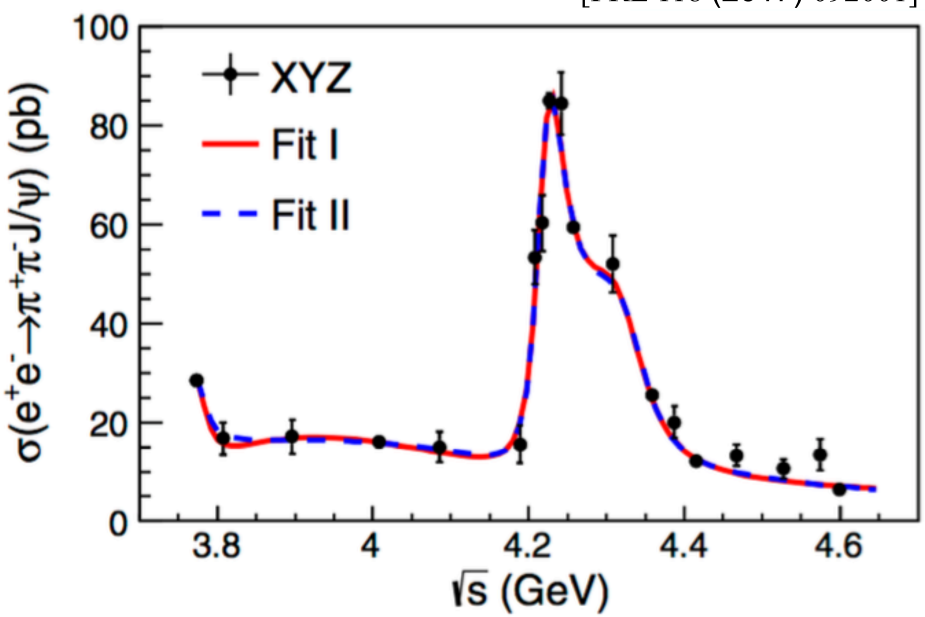
Outline

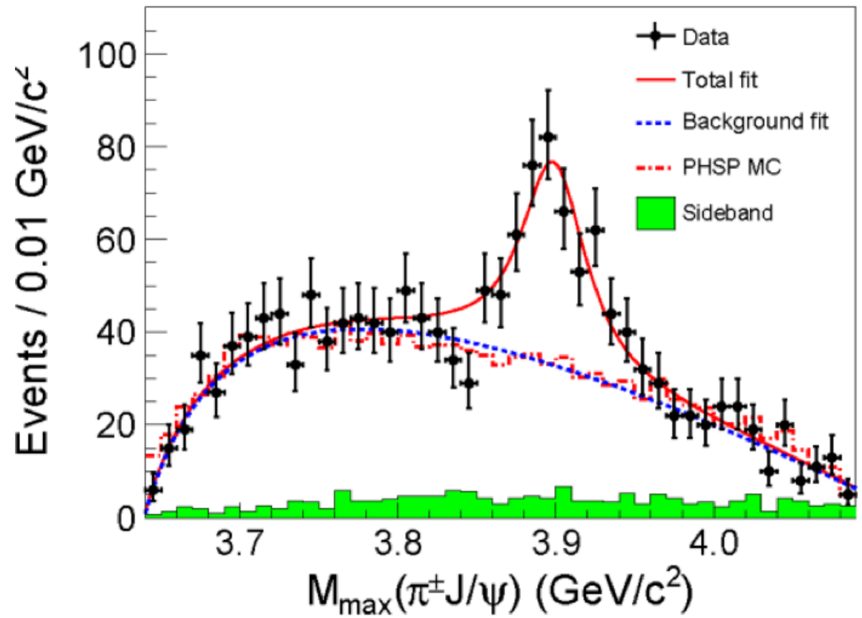
- **Introduction & motivation**
- **Searches for charmless decays**
  - Searches for Y(4260) via cross-section line-shapes
  - Searches for $Z_c(3900)$ decays to light hadrons
- **Summary**

Famous exotic (?) XYZ states

[PRL 118 (2017) 092001]



[PRL 110 (2013) 252001]

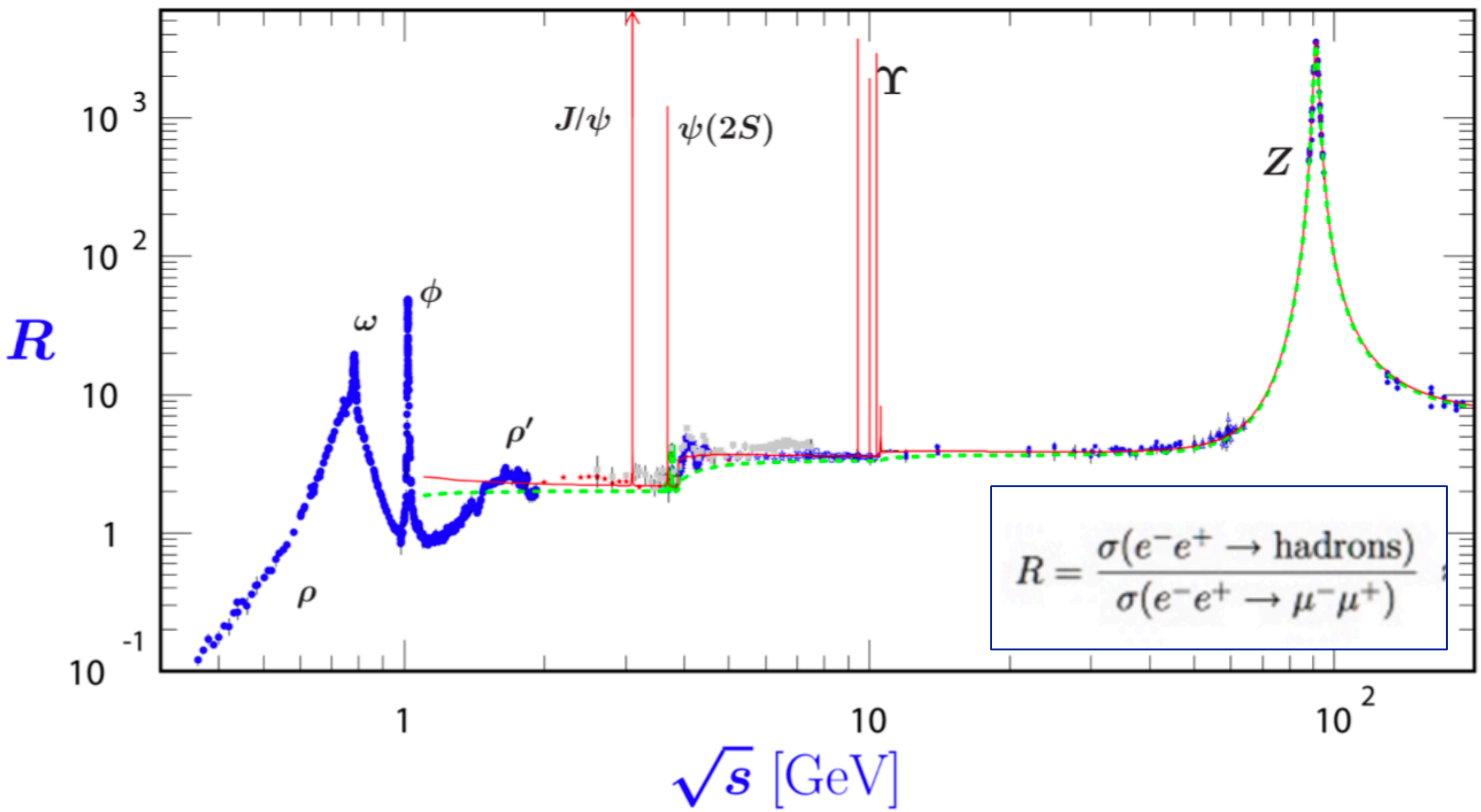


$Y(4260) \rightarrow J/\psi\pi\pi$

$Z_c(3900) \rightarrow J/\psi\pi$

Motivation

- Series of unexpected vector charmonium-like states
  - (mainly) observed in decays associated with charmonia
- *R*-value at 4.0 – 4.6 GeV is about ~ 4 => total cross-section 16 nb



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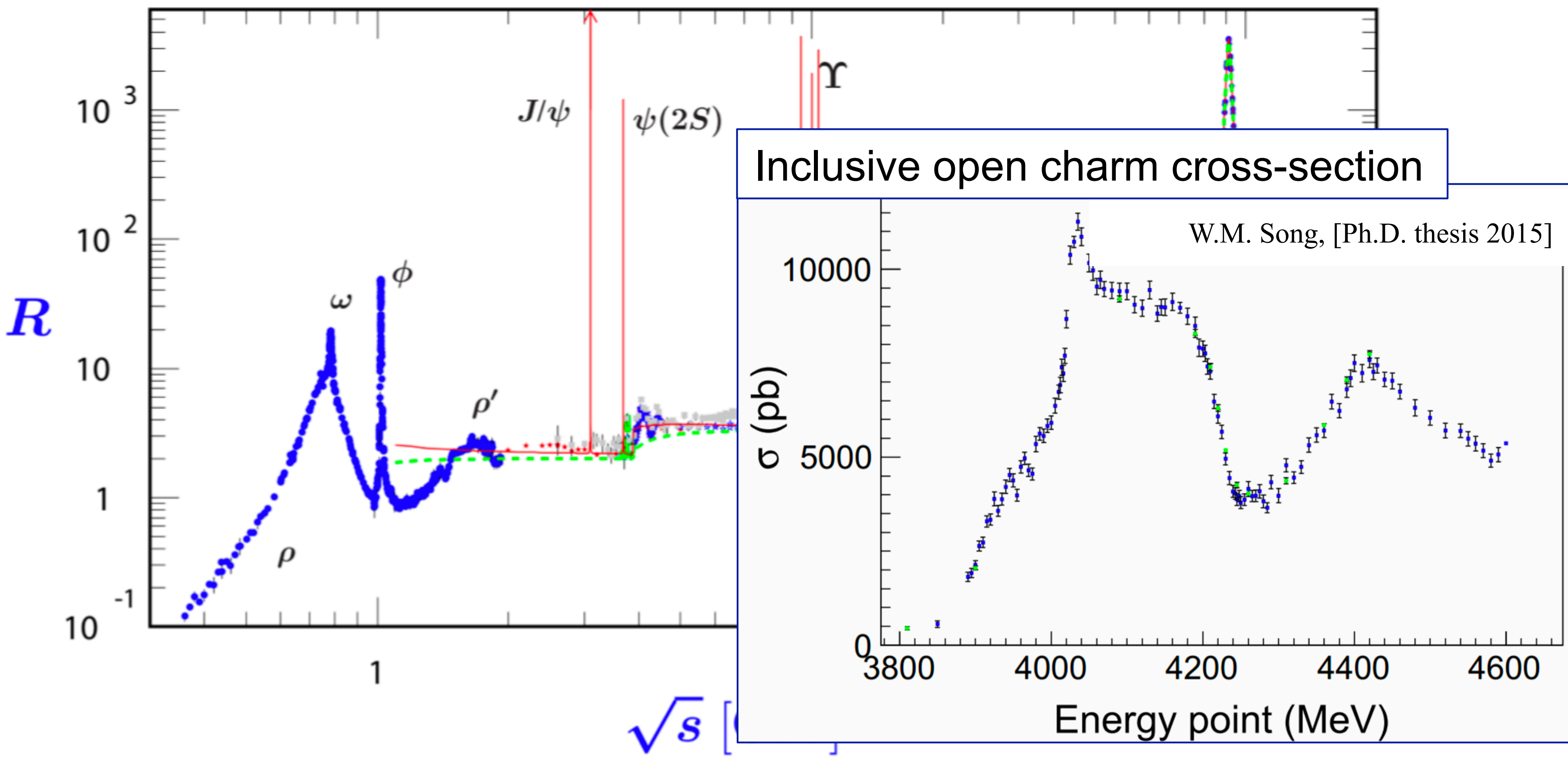
  - Open charm: 10 nb => The other 6 nb only charmonium transition?



Motivation

- Series of unexpected v
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- *R*-value at 4.0 – 4.6 Ge
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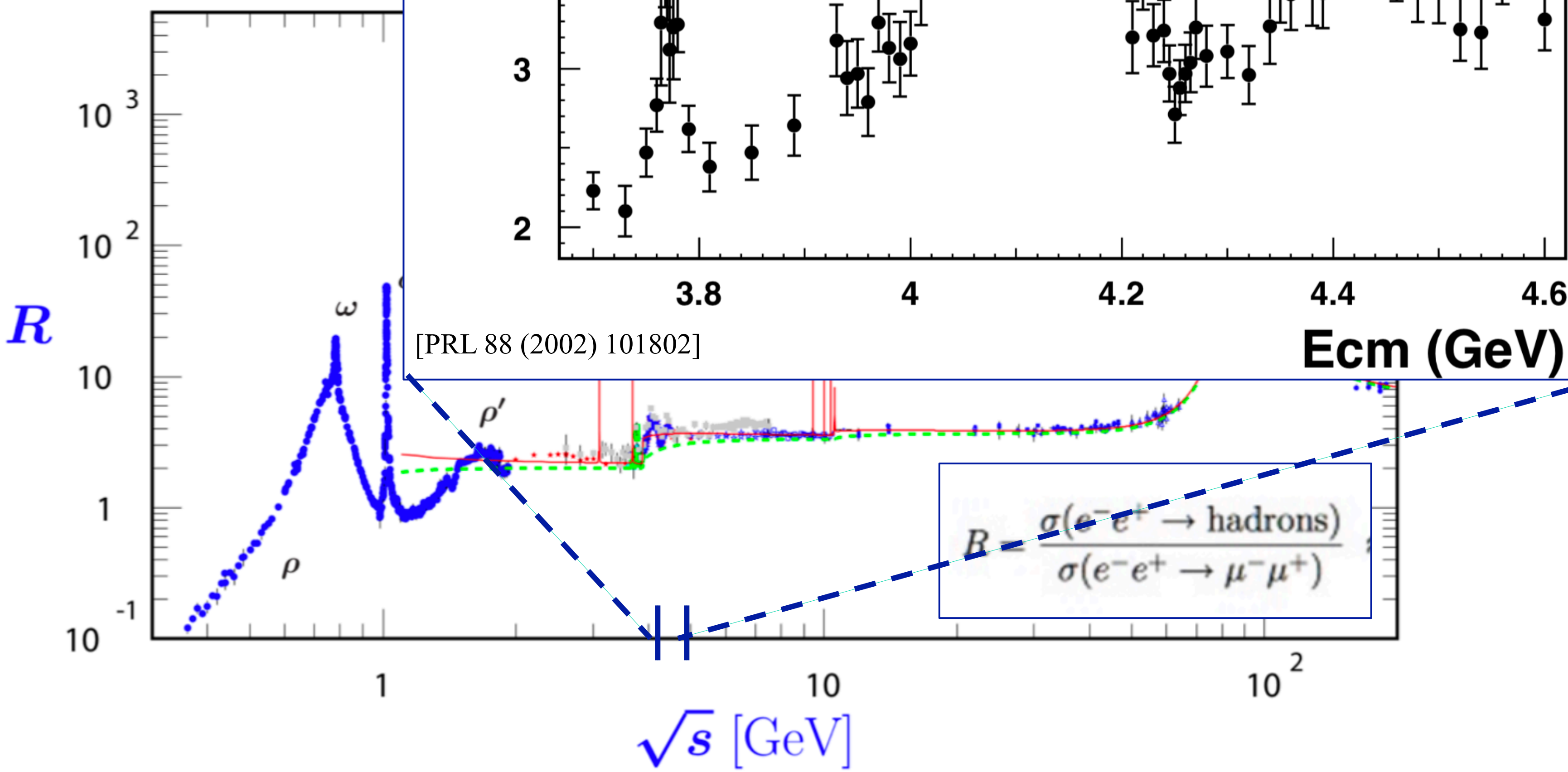

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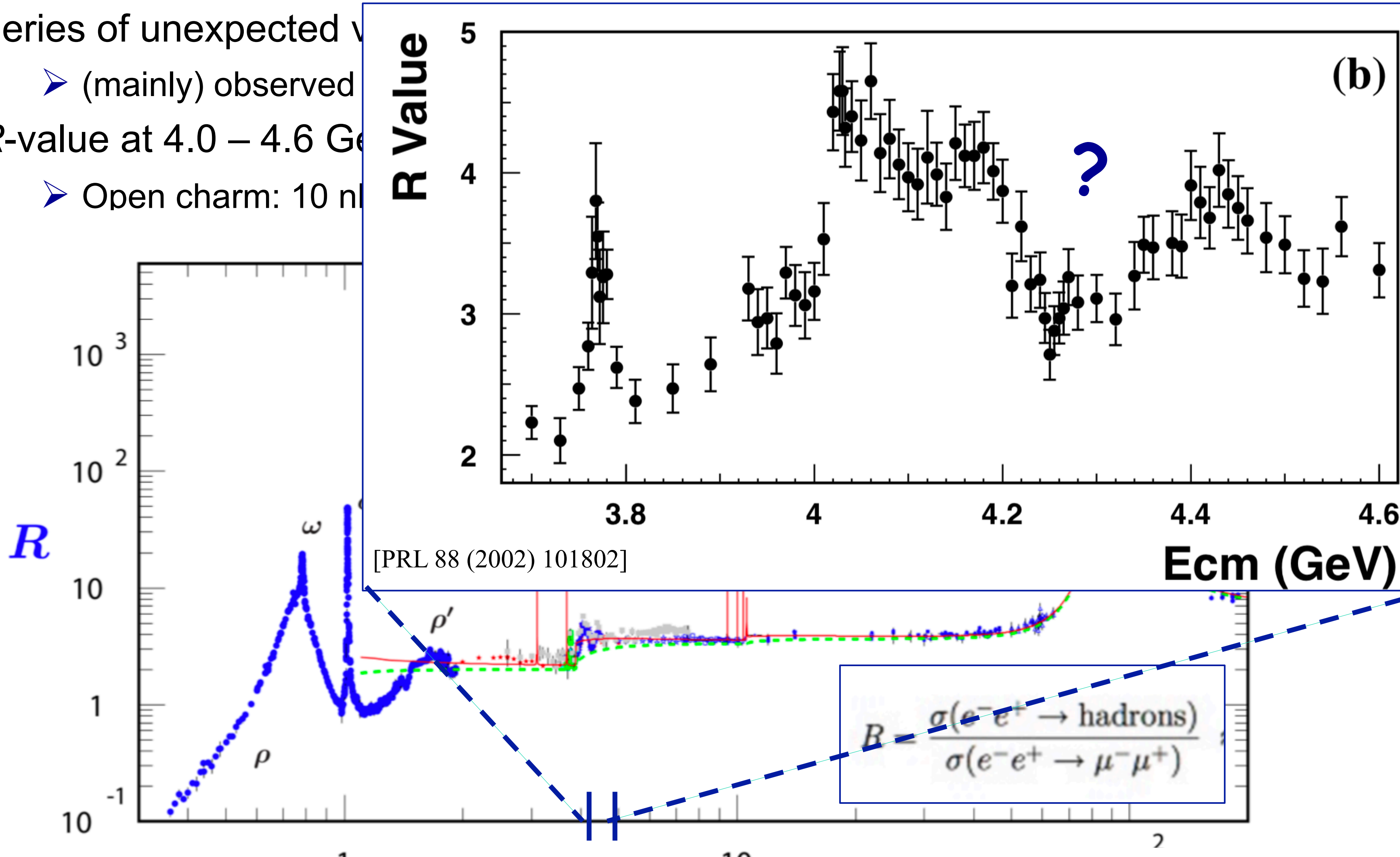


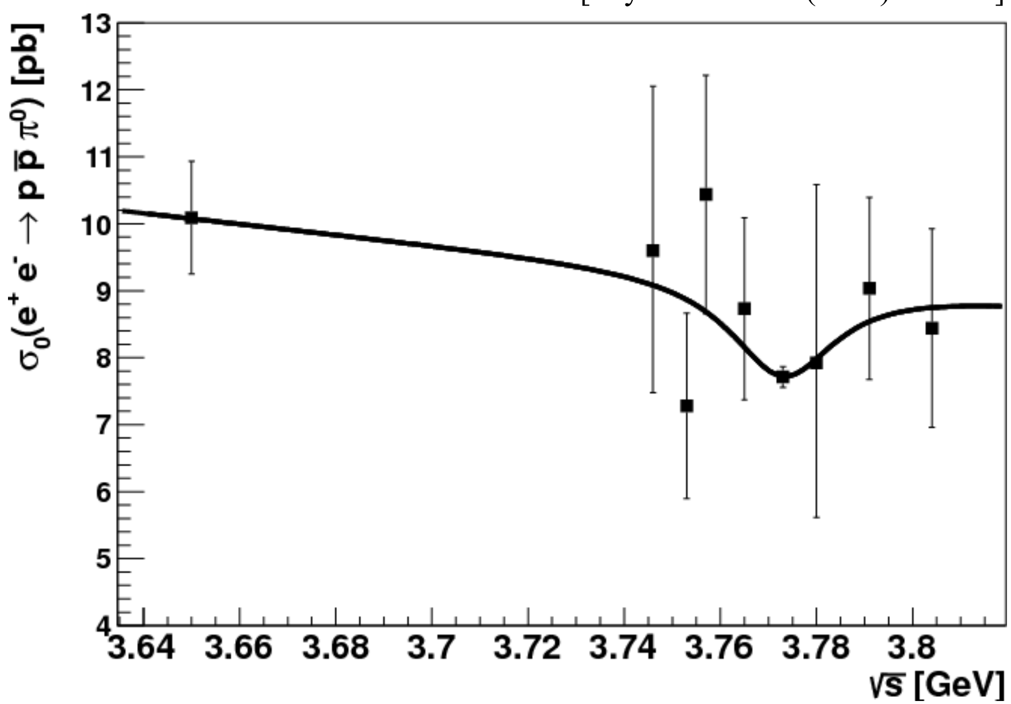
-> What about charmless decays of Y(4260) & Co?

As predicted e.g. by:
PLB 628 (2005) 215, or
CPC 39 (2015) 063102

Cross-section measurement $\sigma_B(e^+e^- \to p\bar{p}\pi^0)$ between 4.0 – 4.6 GeV

- Cross-sections $e^+e^- \to \psi(3770) \to p\bar{p}\pi^0$ around 3.77 GeV measured previously, interferences included (resonant with continuum production):
  - Two solutions of same probability
    a) 33.8 ± 1.8 ± 2.1 pb, and
    b) < 0.22 pb at 90% CL
  - Both fit solutions consistent with destructive interference (270°)

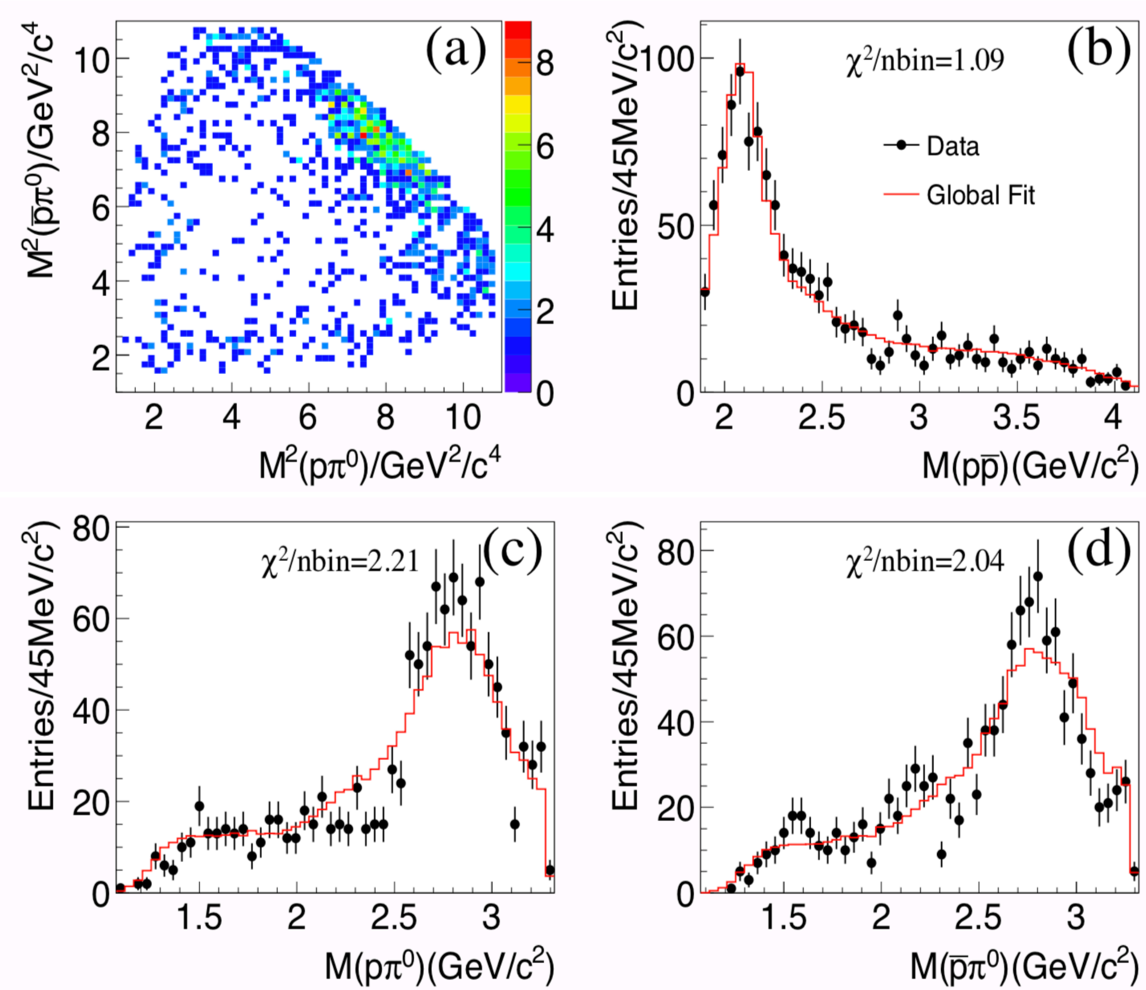
[Phys. Rev. D 90 (2014) 032007]



- Cross-section $p\bar{p} \to \psi(3770)\pi^0$
  - Using constant decay amplitude approximation: 122 ± 10 nb, and
    < 0.79 nb at 90% CL at 5.26 GeV (PANDA)

Cross-section measurement
$\sigma_B(e^+e^- \to p\bar{p}\pi^0)$ between 4.0 – 4.6 GeV

- PWA to correctly determine detection efficiencies
  - ➢ Dalitz plot at 4.26 GeV
  - ➢ MC data generated from PWA result vs. real data
- Multi intermediate baryons:
  - ➢ $N^*, \Delta^* \to p\bar{p}\pi^0, p\pi^0, \bar{p}\pi^0$
  - ➢ $\rho^*, \omega^* \to p\bar{p}$
- Partial wave analysis:
  - ➢ Covariant tensor formalism [J. Phys. G28,233]
  - ➢ Breit-Wigner param. of $\rho^* N^*, \Delta^*$ [RPD80,052004]
  - ➢ Direct process $e^+e^- \to p\bar{p}\pi^0$: 1^{--} or 3^{--} $p\bar{p}$ system
  - ➢ Resonance > 5σ are retained



[Phys. Lett. B771 (2017) 45]

Cross-section measurement $\sigma_B(e^+e^- \to p\bar{p}\pi^0)$ between 4.0 – 4.6 GeV

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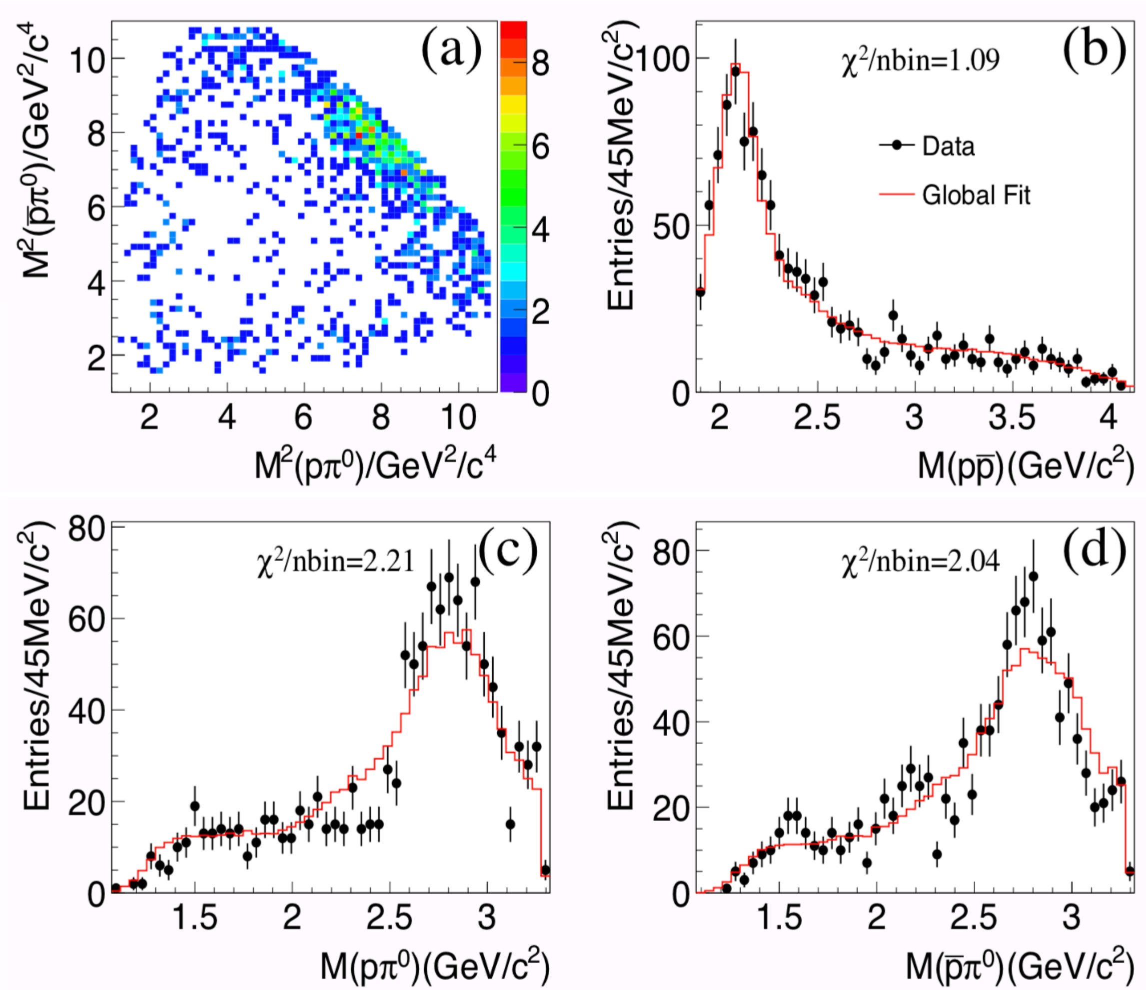

- Multi intermediate baryons:
  - $N^*, \Delta^* \to p\bar{p}\pi^0, p\pi^0, \bar{p}\pi^0$
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- Partial wave analysis:
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Cross-section measurement $\sigma_B(e^+e^- \to p\bar{p}\pi^0)$ between 4.0 – 4.6 GeV

- Born cross section:
  - radiative correction factor $(1+\delta^r)$
  - vacuum polarisation factor $(1+\delta^v)$

$$\sigma^B = \frac{N^{\text{obs}}}{\mathcal{L}\cdot(1+\delta^r)\cdot(1+\delta^v)\cdot\epsilon\cdot\mathcal{B}_{\pi^0}}$$

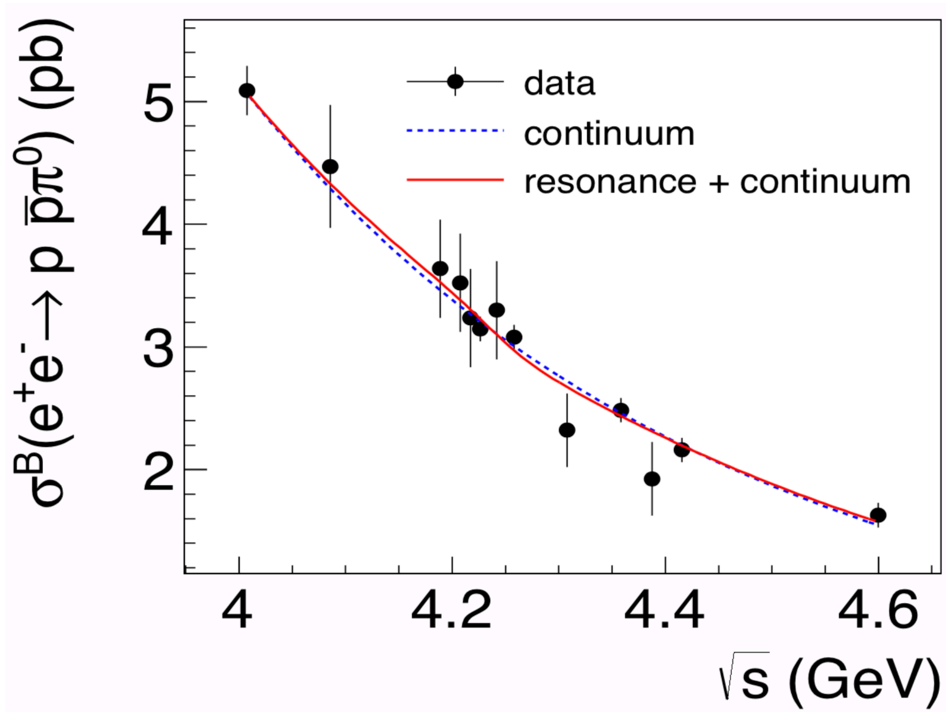
$\sqrt{s}$ (GeV)	$\mathcal{L}$ [pb^{-1}]	$(1+\delta^r)$	$(1+\delta^v)$	N^{obs}	ϵ[%]	σ^B[pb]
4.008	482.0	0.967	1.044	1074 ± 33	43.9 ± 0.9	$5.09 \pm 0.18^{+0.26}_{-0.24}$
4.085	52.6	0.992	1.052	106 ± 11	43.7 ± 1.4	$4.47 \pm 0.46^{+0.27}_{-0.21}$
4.189	43.1	1.025	1.056	75 ± 9	44.7 ± 1.0	$3.64 \pm 0.43^{+0.18}_{-0.19}$
4.208	54.6	1.031	1.057	93 ± 10	44.9 ± 1.6	$3.52 \pm 0.39^{+0.17}_{-0.22}$
4.217	54.1	1.034	1.057	82 ± 10	43.4 ± 1.3	$3.24 \pm 0.37 \pm 0.18$
4.226	1047.3	1.037	1.056	1611 ± 41	45.2 ± 0.5	$3.15 \pm 0.08 \pm 0.14$
4.242	55.6	1.042	1.056	89 ± 9	44.6 ± 1.1	$3.30 \pm 0.36^{+0.19}_{-0.15}$
4.258	825.6	1.048	1.054	1203 ± 35	43.4 ± 0.5	$3.08 \pm 0.10^{+0.14}_{-0.15}$
4.308	44.9	1.063	1.053	53 ± 8	46.0 ± 1.4	$2.32 \pm 0.33^{+0.15}_{-0.10}$
4.358	539.8	1.081	1.051	668 ± 26	44.7 ± 1.1	$2.48 \pm 0.11^{+0.13}_{-0.12}$
4.387	55.2	1.087	1.051	57 ± 8	47.5 ± 1.8	$1.92 \pm 0.26 \pm 0.10$
4.416	1028.9	1.098	1.053	1133 ± 34	44.6 ± 0.6	$2.16 \pm 0.10^{+0.10}_{-0.11}$
4.600	566.9	1.124	1.055	474 ± 22	43.8 ± 0.8	$1.63 \pm 0.08 \pm 0.08$

[Phys. Lett. B771 (2017) 45]

Cross-section measurement $\sigma_B(e^+e^- \to p\bar{p}\pi^0)$ between 4.0 – 4.6 GeV

- No significant resonant structure
  - Least square fit to cross-section: $$\sigma(s) = \left| \sqrt{\sigma_{\rm con}} + \sqrt{\sigma_Y}\frac{m\Gamma}{s - m^2 + im\Gamma}\exp(i\phi) \right|^2$$
  - Continuum process: $\sqrt{\sigma_{\rm con}} \propto \frac{1}{s^n}$
  - Y(4260) with (m,Γ) from PDG
  - $\phi = 3.4 \pm 1.0$, $\sigma_{\rm Y} = (1.6 \pm 5.9) \times 10^{-3}$ pb (0.5σ)
  - No multiple solutions

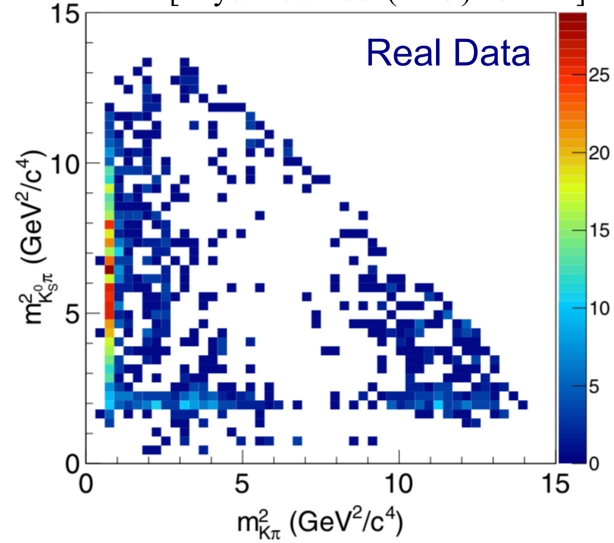
- Obtained upper limit at 90% CL on $e^+e^- \to Y(4260) \to p\bar{p}\pi^0$ (most conservative) estimate:
  => σ < 0.01 pb

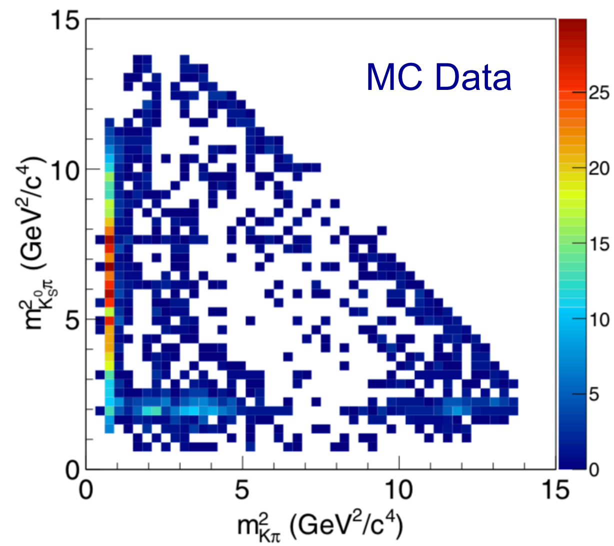


Precision measurement of $\sigma_B(e^+e^- \to K_s K^{+/-}\pi^{-/+})$ between 3.8 – 4.6 GeV

- Based on 5.0 fb^{-1} between 3.8 – 4.6 GeV
  → *energy-dependent Born cross-section*
- Dalitz plots for $e^+e^- \to K_s K^+\pi^-$ at 4.23 GeV, real vs MC data generated from PWA result
- Various bands visible:
  - $K^*(892), K_2^*(1430) \to K^{+/-}\pi^{-/+}$ *(vertical)*
  - $K_2^*(1430)^{+/-} \to K_s\pi^{-/+}$ *(horizontal)*
  - e.g. excited $\rho^{+/-*}$, $a_2(1320)^{+/-} \to K_s K^-$ *(diagonal)*
- PWA of $K_s K^+\pi^-$ system at different E_{cms} (relativistic BWs, covariant helicity method)
  - determination of reconstruction efficiencies

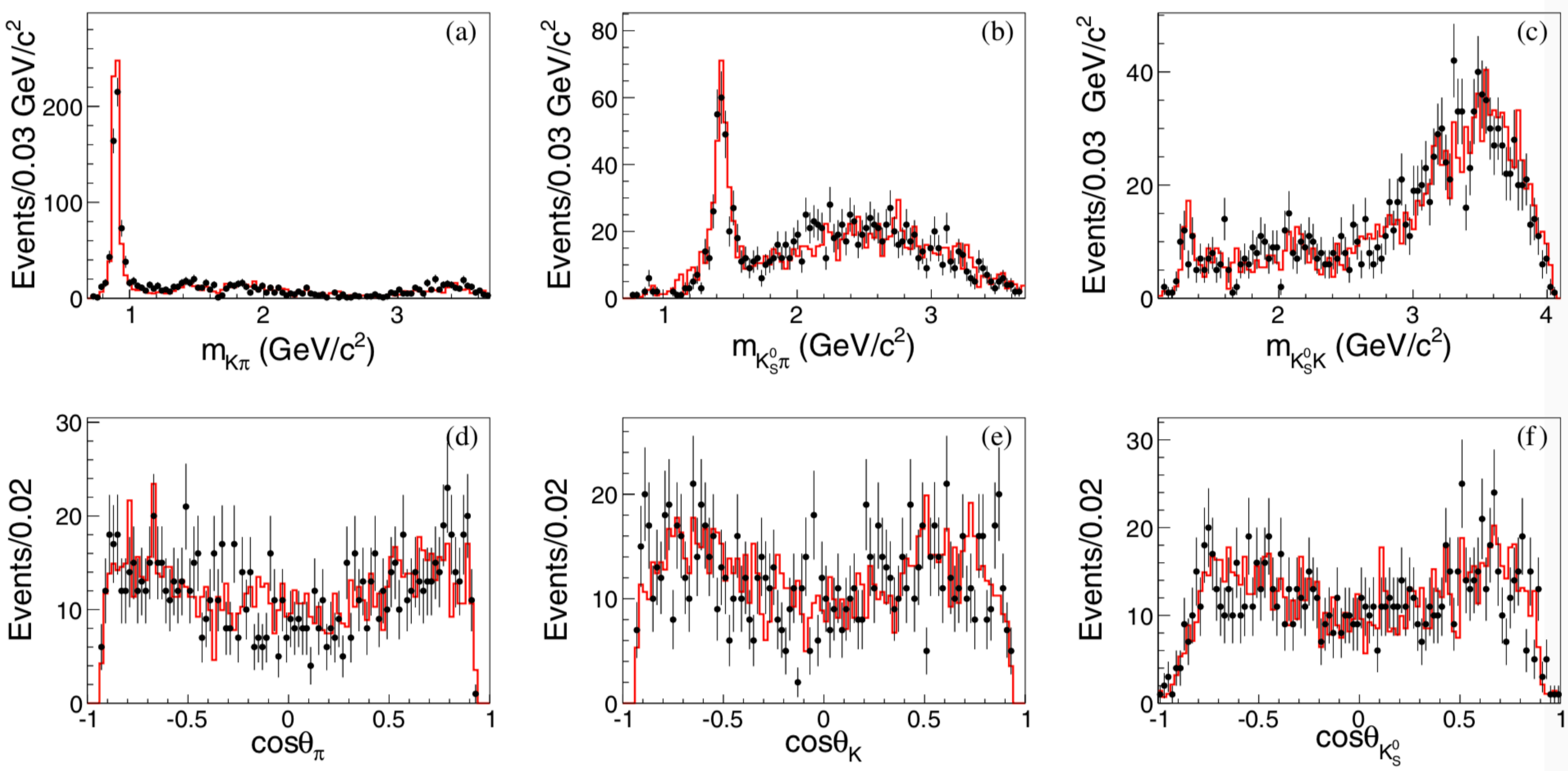
[Phys. Rev. D99 (2019) 072005]





Precision measurement of $\sigma_B(e^+e^- \to K_s K^{+/-}\pi^{-/+})$ between 3.8 – 4.6 GeV

- Amplitude fit result at 4.23 GeV *(MC projections according to PWA result)*



- Inv. masses for $K^+\pi$, $K_s\pi$ and K_sK and polar angle distributions for π, K and K_s

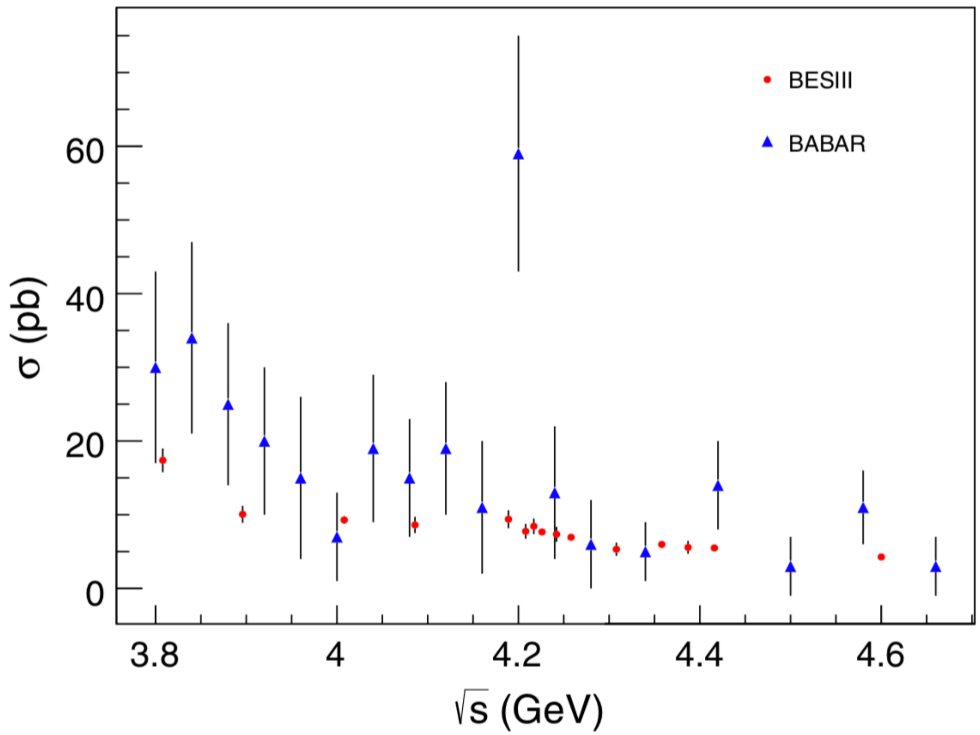
  → *Good agreement to data*

[Phys. Rev. D99 (2019) 072005]

Precision measurement of $\sigma_B(e^+e^- \to K_s K^{+/-}\pi^{-/+})$ between 3.8 – 4.6 GeV

- Energy dependent cross section of $e^+e^- \to K_s K^+\pi^-$

→ *In agreement to BaBar but much higher precision*



[BarBar: PRL 95 (2005) 142001]

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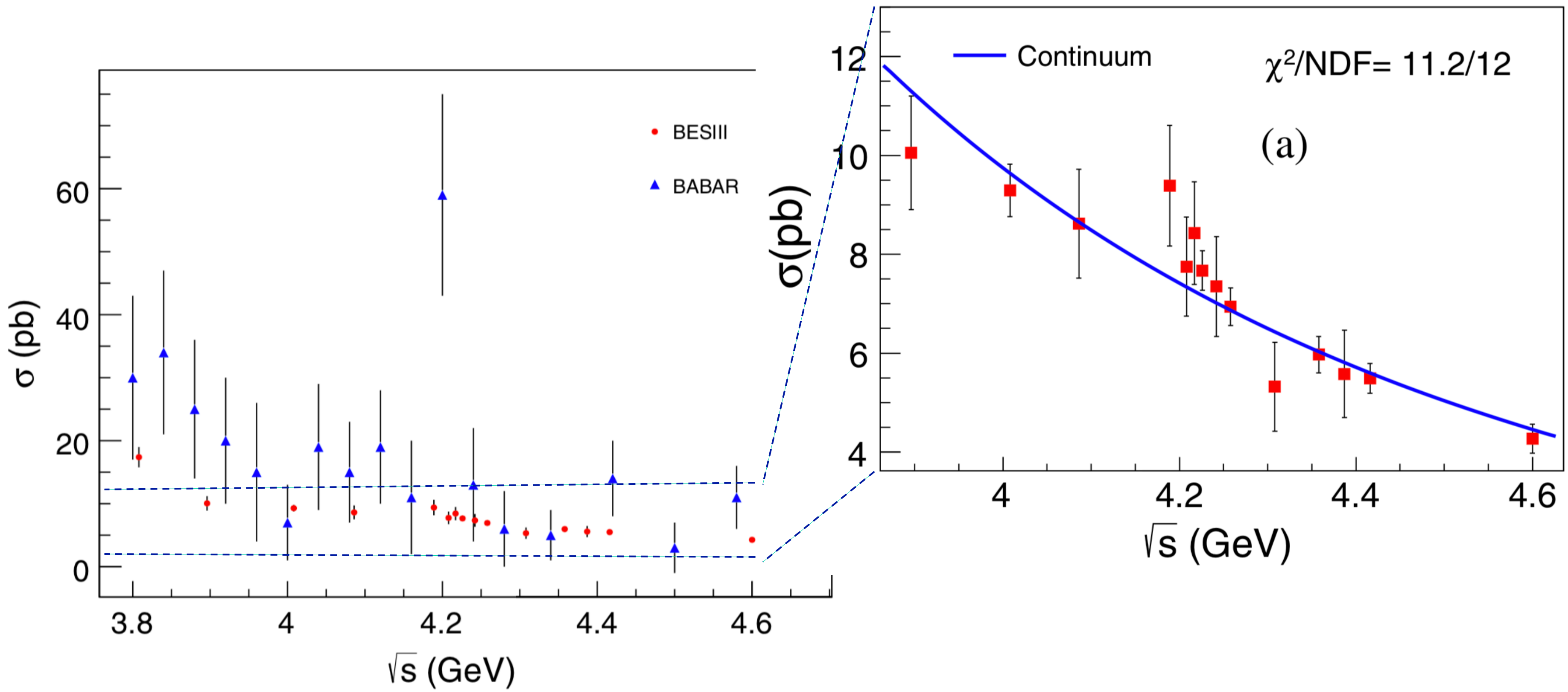

- Zoomed in BESIII data together with fit of continuum process only
  → *does not describe access at about 4.2 GeV*

[Phys. Rev. D99 (2019) 072005]

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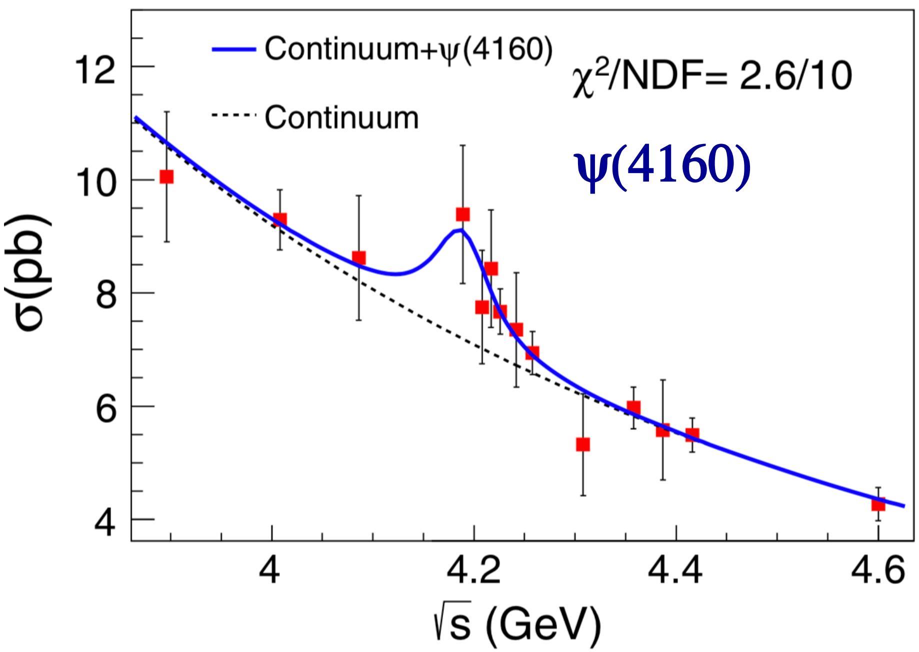

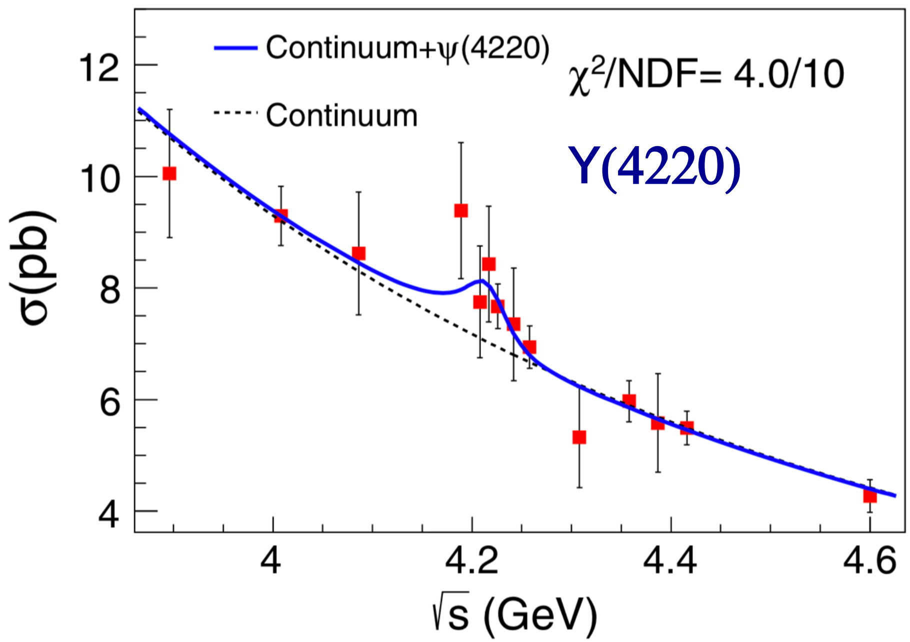

- Zoomed in BESIII data together with fit of continuum process
  → *and additional resonance, ψ(4160) (left) or Y(4220) (right)*

[Phys. Rev. D99 (2019) 072005]

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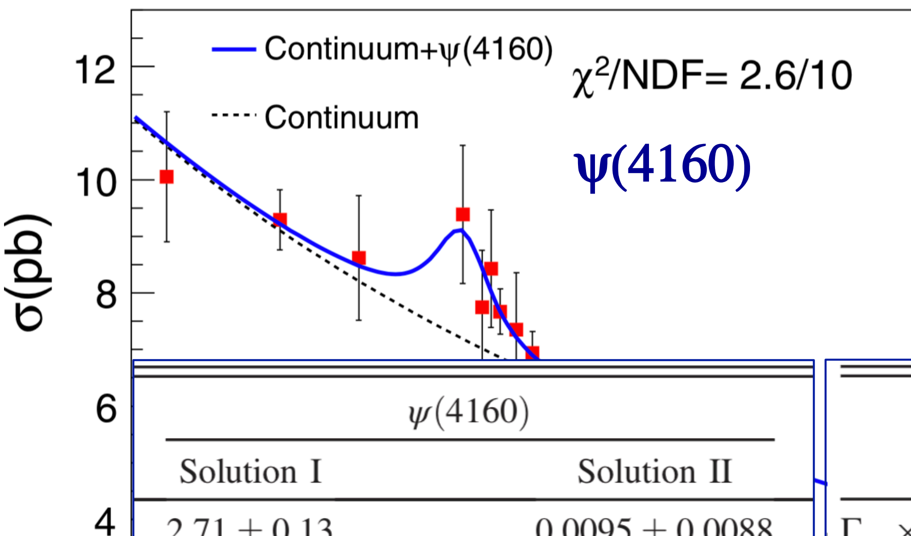

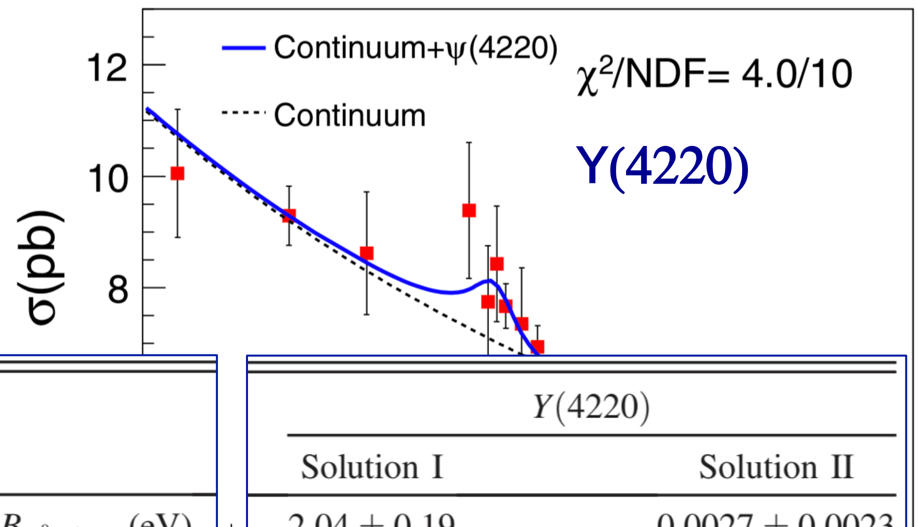

	$\psi(4160)$		$Y(4220)$	
	Solution I	Solution II	Solution I	Solution II
$\Gamma_{ee} \times B_{K_S^0 K^+ \pi^-}$ (eV)	2.71 ± 0.13	0.0095 ± 0.0088	2.04 ± 0.19	0.0027 ± 0.0023
ϕ (rad)	-1.60 ± 0.03	1.67 ± 0.44	-1.60 ± 0.02	2.00 ± 0.53
Significance	2.5σ		2.2σ	

- Zoomed in BESIII data together with fit of continuum process
  → *and additional resonance, ψ(4160) (left) or Y(4220) (right)*

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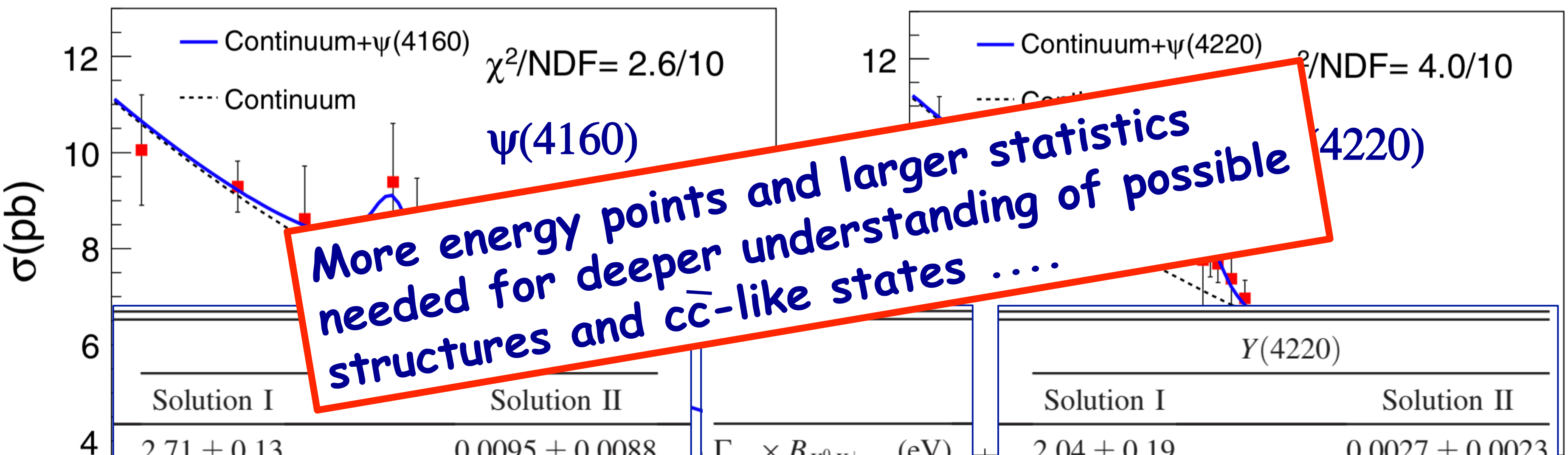

More energy points and larger statistics needed for deeper understanding of possible structures and $c\bar{c}$-like states ….

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- Zoomed in BESIII data together with fit of continuum process

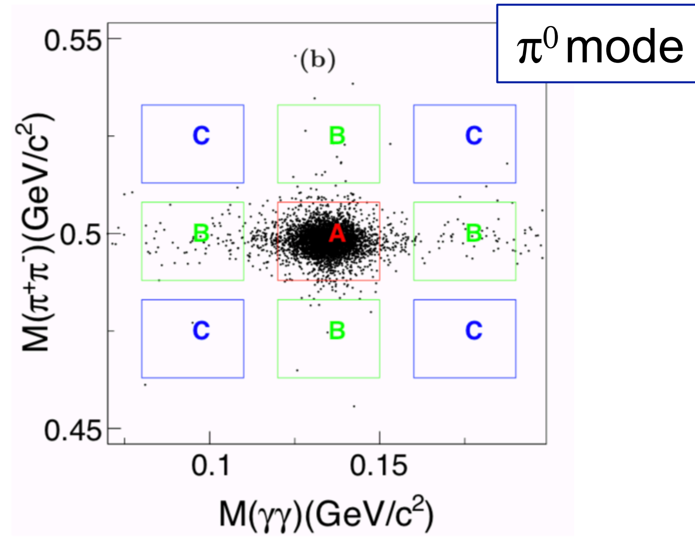
  → *and additional resonance, ψ(4160) (left) or Y(4220) (right)*

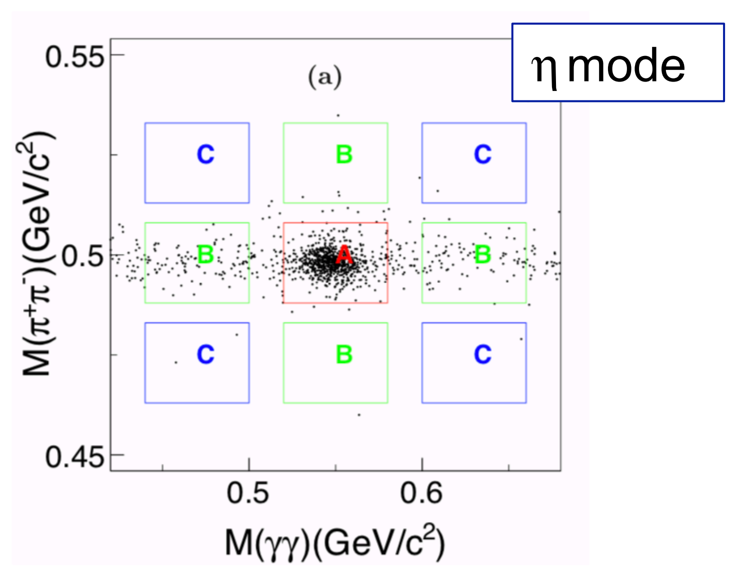
[Phys. Rev. D99 (2019) 072005]

Search for Y(4260) and $Z_c(3900)$ in $e^+e^- \to K_s K \pi \pi^0$ and $K_s K \pi \eta$

- Based on 17 E_{cms} points, in the range of 3.8 – 4.6 GeV
- Invariant mass distributions ππ vs. γγ at $\sqrt{s}$ = 4.26 GeV
  → *clear K_s and π/η peaks*
- Sidebands:

$$N_{\rm sig} = N_{\rm A} - \sum N_{\rm B}/2 + \sum N_{\rm C}/4$$



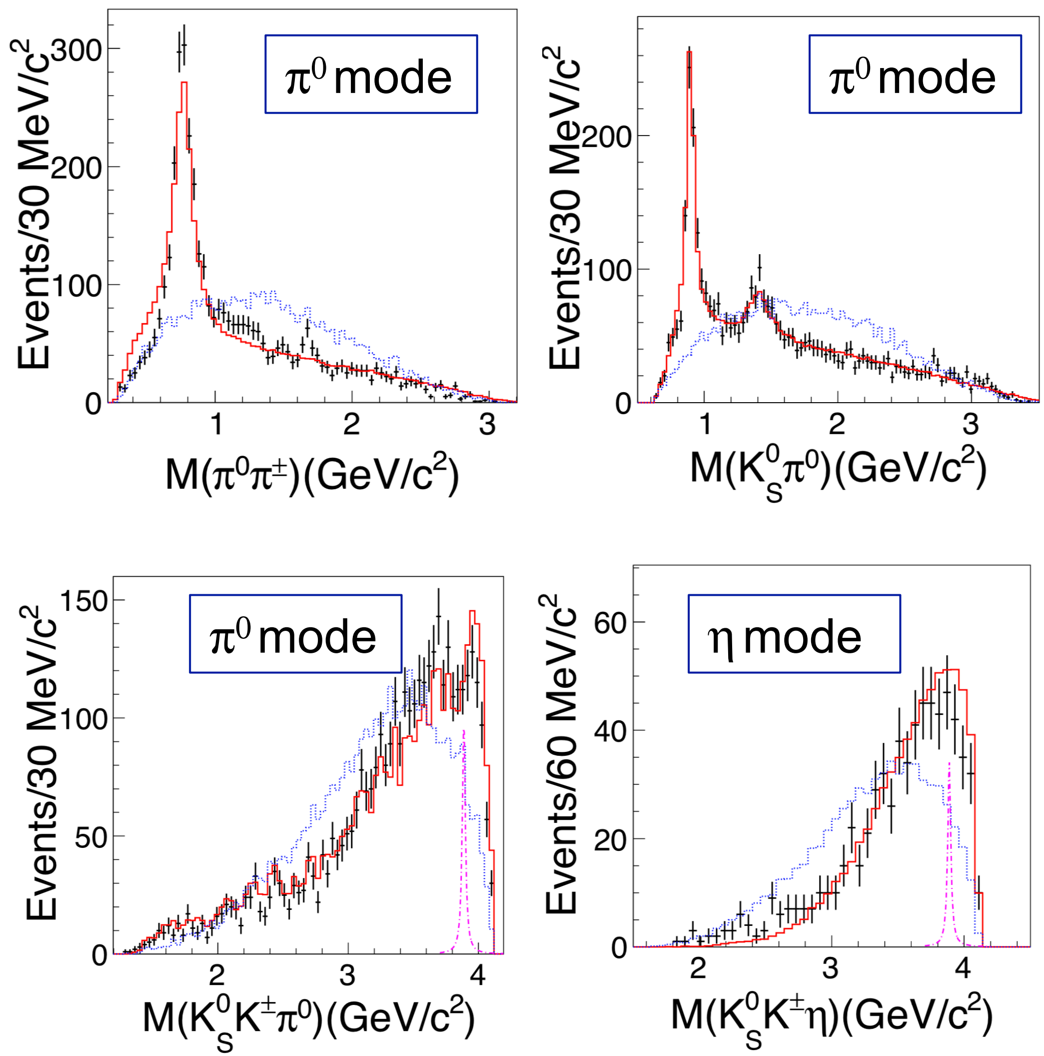


[Phys. Rev. D99 (2019) 012003]

Search for Y(4260) and Z_c(3900) in $e^+e^- \to K_s K \pi \pi^0$ and $K_s K \pi \eta$

- Examples of invariant masses for 2- and 3-body final states, here at 4.26 GeV
  → *intermediate resonances such as $\rho(770)$ or $K^*(890)$*

- MC shape of Z_c(3900) as pink dash-dotted line, arbitrary scale



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Search for Y(4260) and Z_c(3900) in $e^+e^- \to K_s K \pi \pi^0$ and $K_s K \pi \eta$

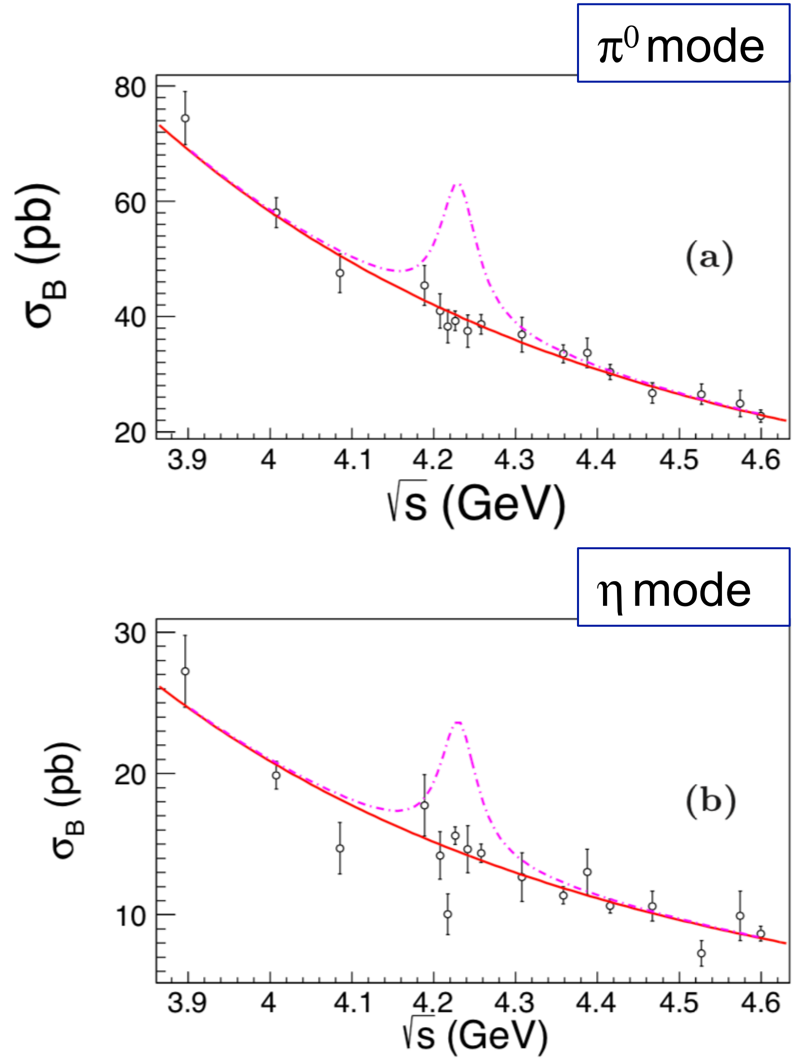
- Energy-dependent Born cross-sections:

$$\sigma_B = \frac{N_{sig}}{\mathcal{L} \cdot \mathcal{B} \cdot \epsilon \cdot (1+\delta^{ISR}) \cdot \frac{1}{|1-\Pi(s)|^2}}$$

- MC shape of Y(4220) as pink dash-dotted line, arbitrary scale

- No clear structure observed, CL90 ULs
  - BR x Γ_{e+e-} < 0.05 eV (π^0 mode)
  - BR x Γ_{e+e-} < 0.19 eV (η mode)

- Comparing to $J/\psi\pi\pi$ (1.5 – 13.3 eV), much smaller possible couplings for decays to light hadrons



[Phys. Rev. D99 (2019) 012003]

Search for Y(4260) and $Z_c(3900)$ in $e^+e^- \to K_s K \pi \pi^0$ and $K_s K \pi \eta$

- Search for and upper limits on $Z_c(3900)$ production at 5 E_{cms}
- And ratios $R = \dfrac{\sigma_B(e^+e^- \to \pi Z_c(3900) \to \pi K_S^0 K\pi/\eta)}{\sigma_B(e^+e^- \to \pi Z_c(3900) \to \pi\pi J/\psi)}$
- No obvious signal observed in charged nor neutral mode
- Unbinned max. likelihood fit to $K_s K \pi \pi^0/\eta$, 3.7 – 4.1 GeV
- CL90 ULs provided at 5 E_{cms}

=> Cross section for decays to light hadrons small

	$\sqrt{s}$ (GeV)	σ_B (pb)	R
$e^+e^- \to \pi^0 Z_c(3900)^0$, $Z_c(3900)^0 \to K_S^0 K^\pm \pi^\mp$	4.226	< 0.24	$< 2.5 \times 10^{-2}$
	4.258	< 0.38	$< 1.2 \times 10^{-1}$
	4.358	< 0.51	$< 2.6 \times 10^{-1}$
	4.416	< 0.27	-
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[Phys. Rev. D99 (2019) 012003]

Search for Y(4260) and Z_c(3900) in $e^+e^- \to K_s K \pi \pi^0$ and $K_s K \pi \eta$

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- No obvious signal observed in charged nor neutral mode
- Unbinned max. likelihood fit to $K_s K \pi \pi^0/\eta$, 3.7 – 4.1 GeV
- CL90 ULs provided at 5 E_{cms}

=> Cr… ligh… mall

Annihilation of $c\bar{c}$ quarks in Y(4260) & Z_c(3900) suppressed

	$\sqrt{s}$ (GeV)	σ_B (pb)	R
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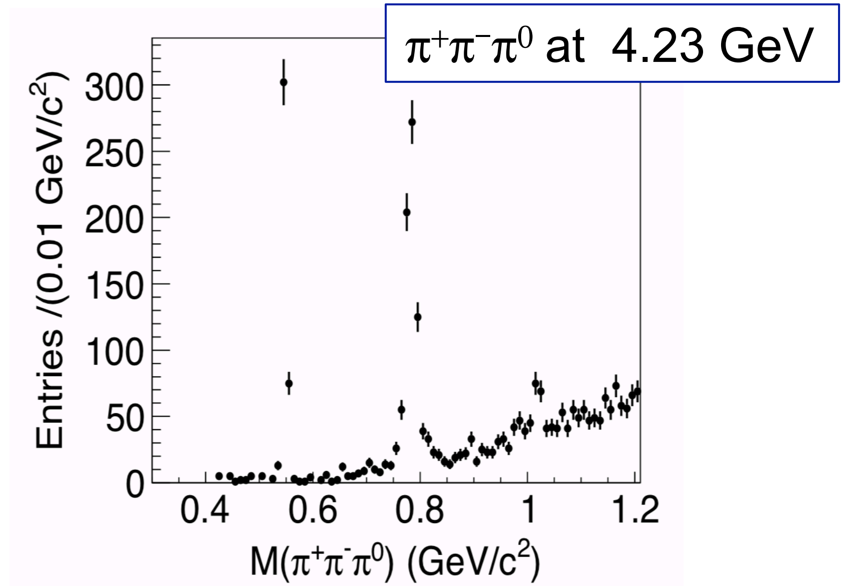
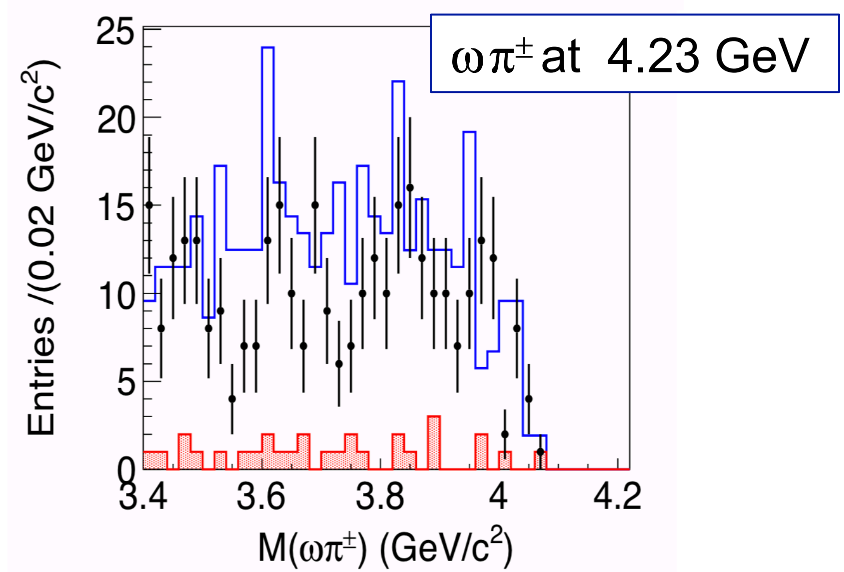
Search for $Z_c(3900)$ in $e^+e^- \rightarrow \omega\pi^+\pi^-$

- Invariant $\pi^+\pi^-\pi^0$ mass distribution for selected $\pi^+\pi^-\pi^+\pi^-\pi^0$ events at $\sqrt{s}$ = 4.23 GeV
  → *clear η, ω and ϕ peaks*



- Invariant $\omega\pi^\pm$ mass distribution at $\sqrt{s}$ = 4.23 GeV
  - Data events in ω region
  - Events selected from sidebads
  - Inclusive MC events (blue) dominated by continuum



[Phys. Rev. D 92 (2015) 032009]

Search for $Z_c(3900)$ in $e^+e^- \to \omega\pi^+\pi^-$

- Unbinned, extended maximum lilelihood fit to $\omega\pi^\pm$ system
  - Separately at $\sqrt{s}$ = 4.23 and 4.26 GeV
  - Signal PDF parameterisation S-wave BW convolved with Gaussian
  - Background described by ARGUS function

- Results, Born cross sections and ULs:
  - $\sqrt{s}$ = 4.23 GeV: 14 ± 11 events, 1.2σ
    $\sqrt{s}$ = 4.26 GeV: 2.2 ± 8.1 events, 0.1σ
  - CL90 upper limits, Bayesian method: 33.5 and 18.8 events
  - ULs: σ_B < 0.26 and 0.18 pb

$$\sigma(e^+e^- \to Z_c(3900)^\pm\pi^\mp, Z_c(3900)^\pm \to \omega\pi^\pm) = \frac{N^{\mathrm{UL}}}{\mathcal{L}_{\mathrm{int}}(1+\delta)\frac{1}{|1-\Pi|^2}\epsilon(1-\sigma_\epsilon)\mathcal{B}_\omega\mathcal{B}_{\pi^0}}$$

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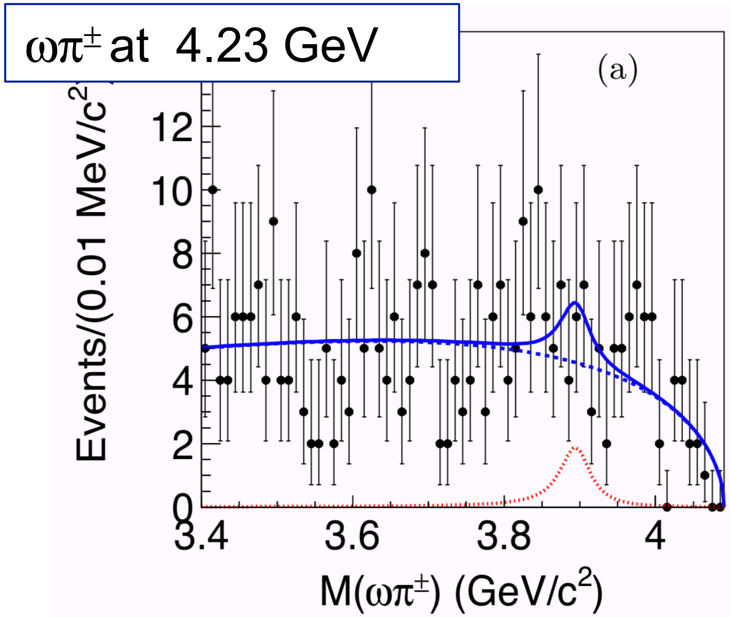

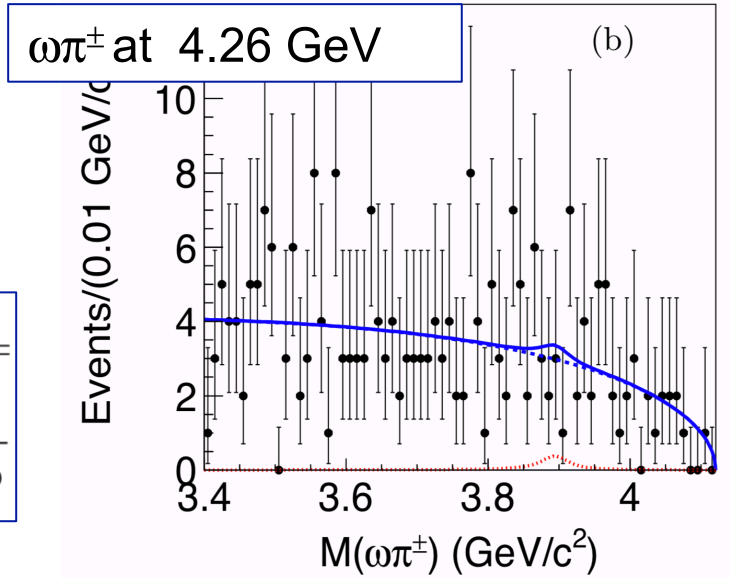

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Non-observation of $Z_c(3900) \to \omega\pi^\pm$
-> typical decay channel for a 1^+ resonance,
indicates $c\bar{c}$ annihilation in $Z_c(3900)$ suppressed

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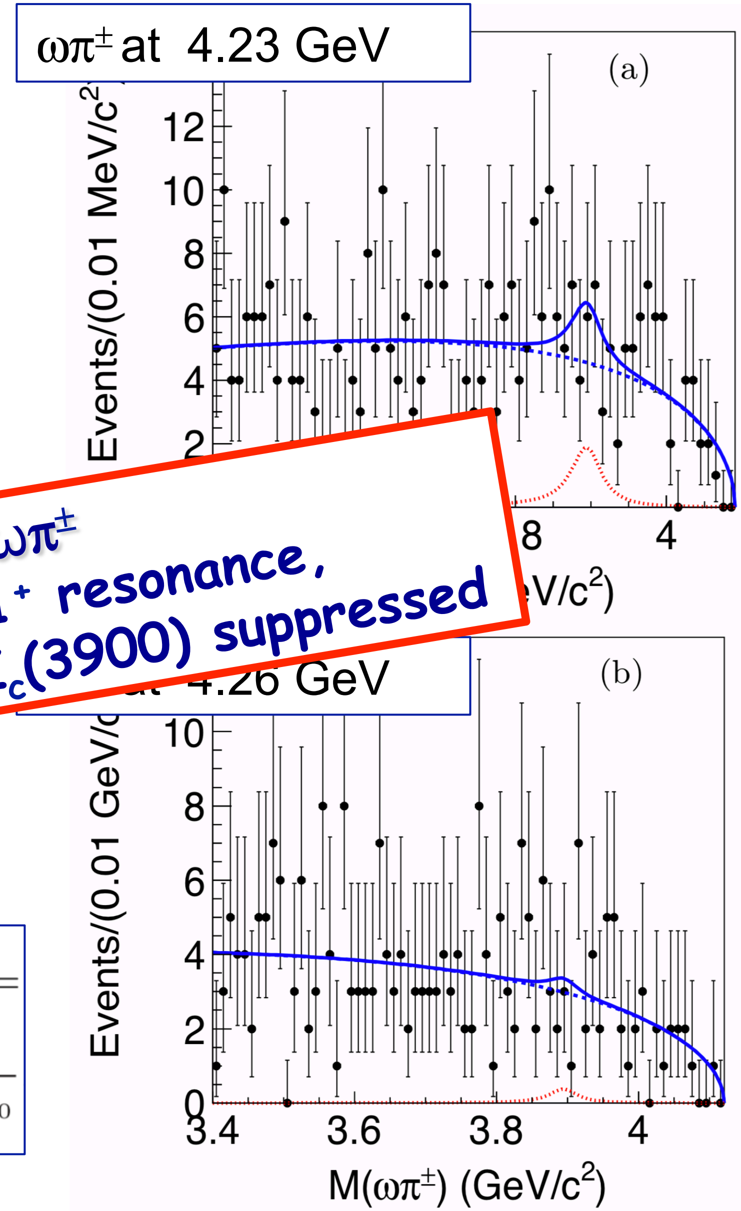

[Phys. Rev. D 92 (2015) 032009]

Summary & outlook

- BESIII major contributions to XYZ puzzle
  - Charmless decays predicted for various nature interpretations for both, Y(4260) and $Z_c(3900)$
  - Several possible decay channels for light hadrons checked

  => No obvious signals observed

- Annihilation of $c\bar{c}$ quarks in Y(4260) & $Z_c(3900)$ seems to be heavily suppressed

	Y(4260)	$Z_c(3900)$
$p\bar{p}\,\pi^0$	✓	
$K_sK\,\pi$	✓	
$K_sK\,(\pi)\,\pi^0$	✓	✓
$K_sK\,(\pi)\,\eta$	✓	✓
$\omega\,\pi$		✓
$p\,\bar{n}\,K_sK$	✓	✓

Outlook:

- More precision (energy scan) data around Y(4220) and further vector states needed (4.1 – 4.4 GeV)

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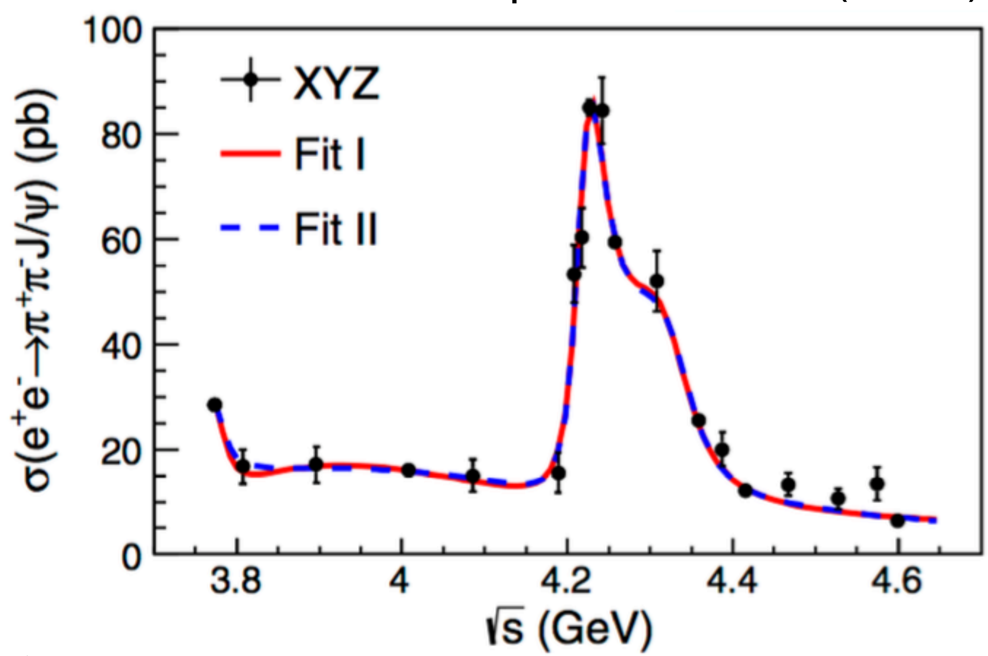

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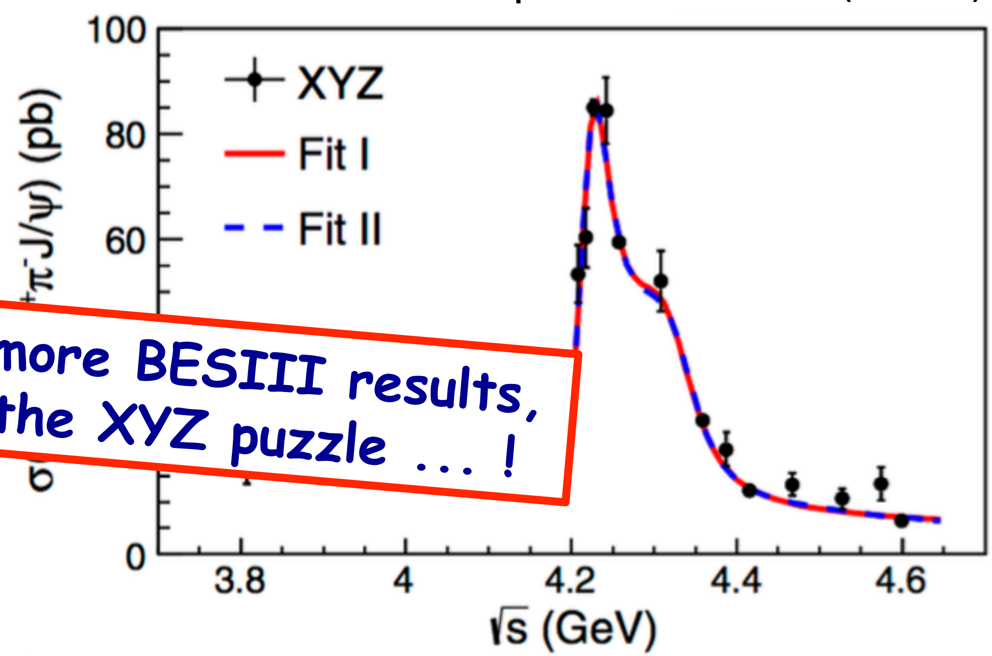

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Stay tuned for more BESIII results, helping to solve the XYZ puzzle ... !

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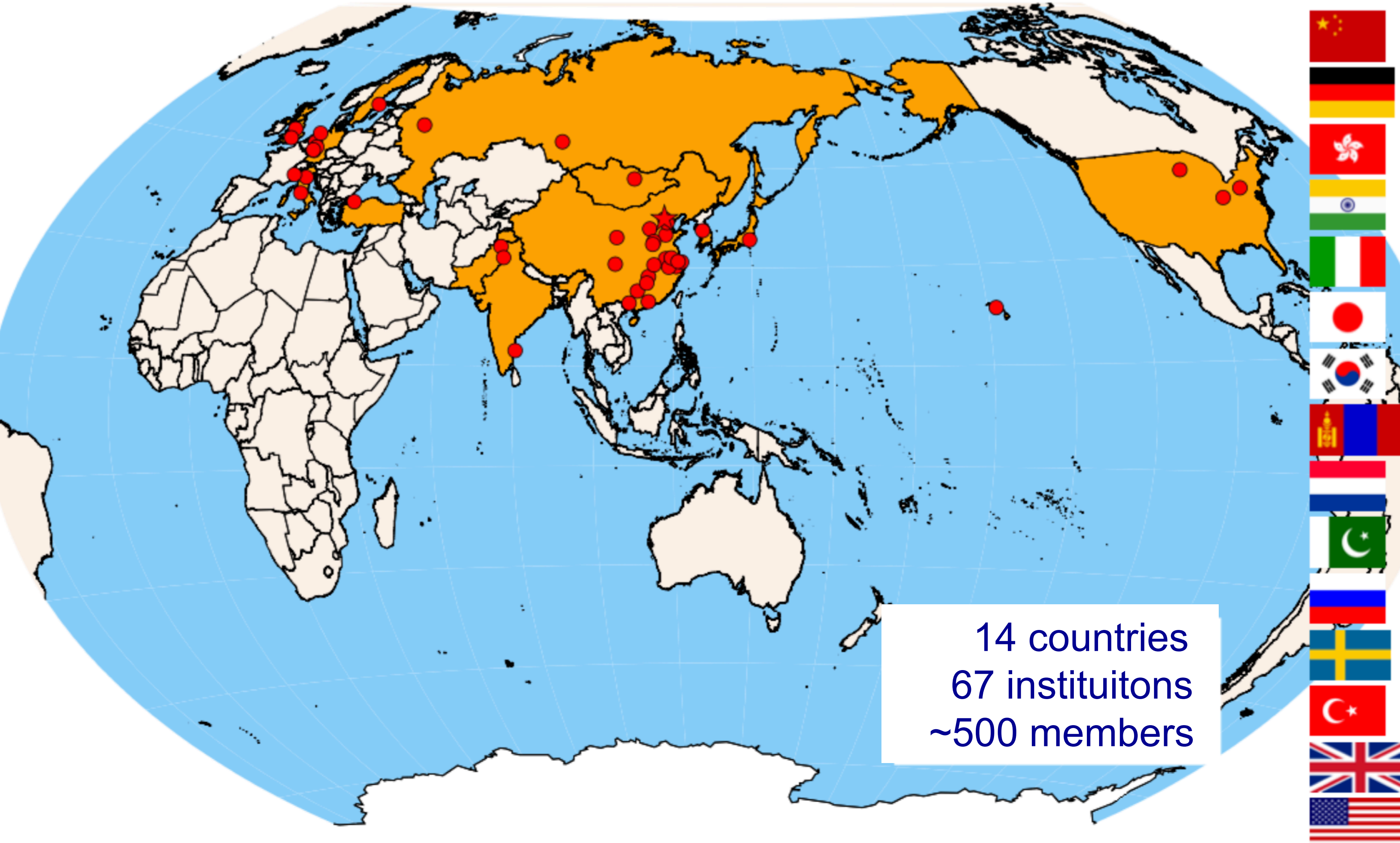
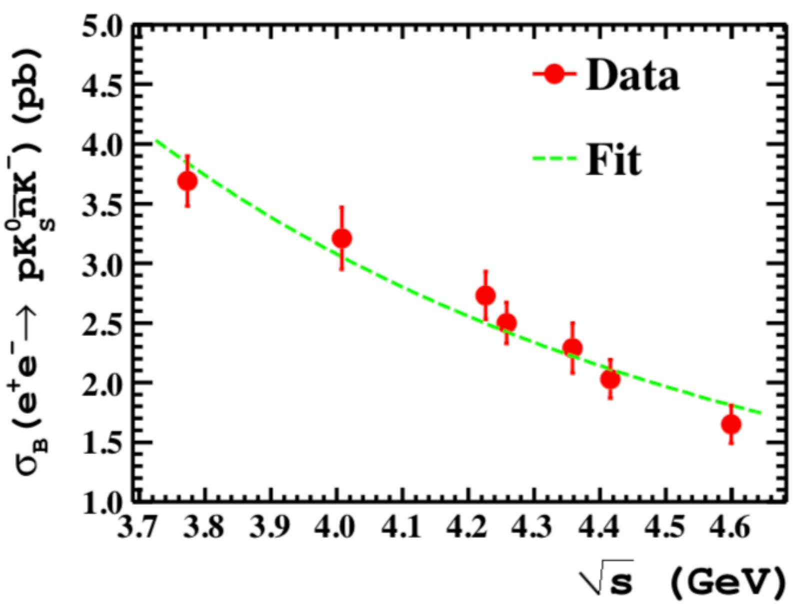
The BESIII Collaboration

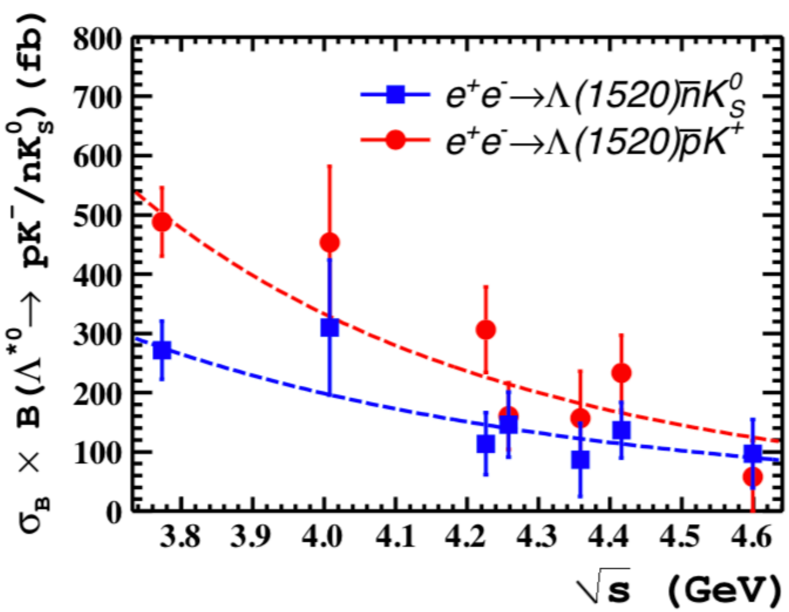


14 countries
67 instituitons
~500 members

First measurement of $e^+e^- \rightarrow pK_s\bar{n}K$ above open charm threshold

The process $e^+e^- \rightarrow pK_S^0\bar{n}K^- + c.c.$ and its intermediate processes are studied for the first time, using data samples collected with the BESIII detector at BEPCII at center-of-mass energies of 3.773, 4.008, 4.226, 4.258, 4.358, 4.416, and 4.600 GeV, with a total integrated luminosity of 7.4 fb^{-1}. The Born cross section of $e^+e^- \rightarrow pK_S^0\bar{n}K^- + c.c.$ is measured at each center-of-mass energy, but no significant resonant structure in the measured cross-section line shape between 3.773 and 4.600 GeV is observed. No evident structure is detected in the pK^-, nK_S^0, pK_S^0, nK^+, $p\bar{n}$, or $K_S^0K^-$ invariant mass distributions except for $\Lambda(1520)$. The Born cross sections of $e^+e^- \rightarrow \Lambda(1520)\bar{n}K_S^0 + c.c.$ and $e^+e^- \rightarrow \Lambda(1520)\bar{p}K^+ + c.c.$ are measured, and the 90% confidence level upper limits on the Born cross sections of $e^+e^- \rightarrow \Lambda(1520)\bar{\Lambda}(1520)$ are determined at the seven center-of-mass energies. There is an evident difference in line shape and magnitude of the measured cross sections between $e^+e^- \rightarrow \Lambda(1520)(\rightarrow pK^-)\bar{n}K_S^0$ and $e^+e^- \rightarrow pK^-\bar{\Lambda}(1520)(\rightarrow \bar{n}K_S^0)$.





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