Light-meson spectroscopy and search for exotic heavy-quark states at COMPASS

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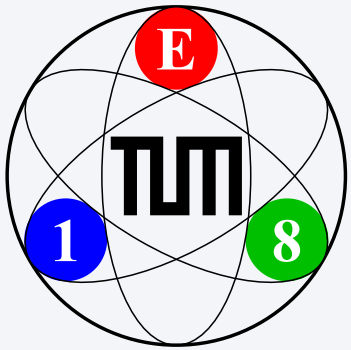
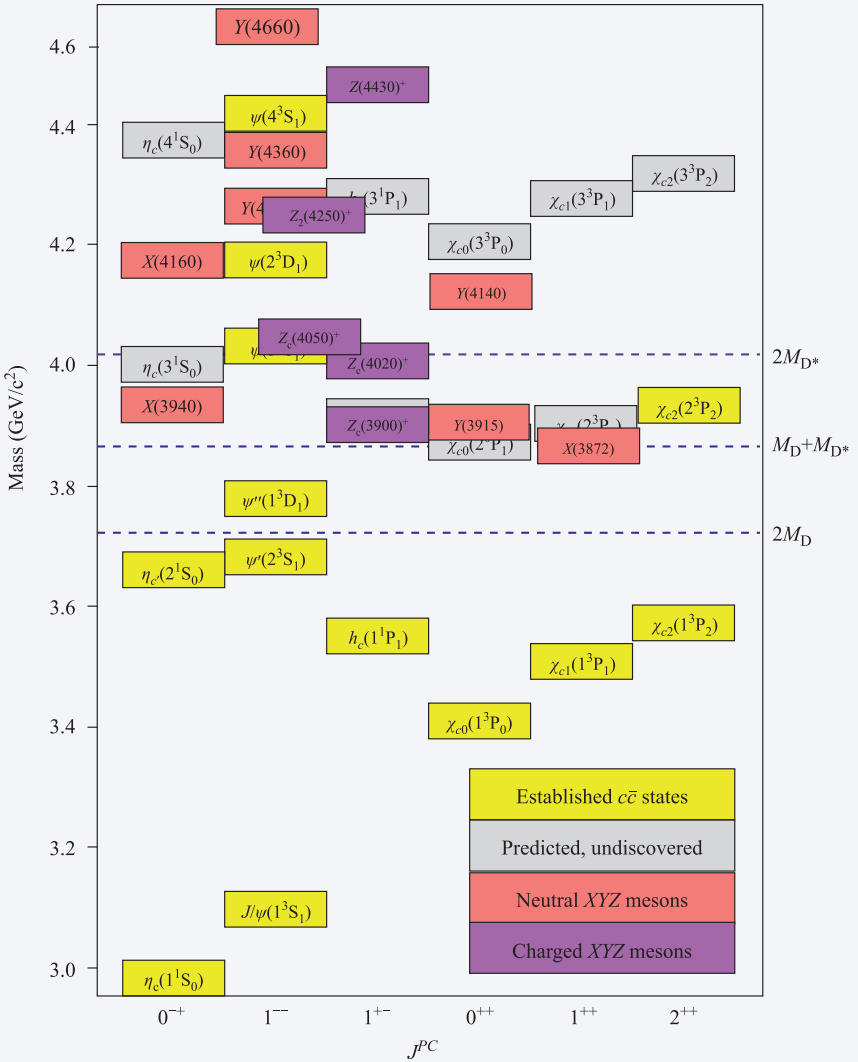
for the COMPASS Collaboration

Institute for Hadronic Structure and Fundamental Symmetries
Technische Universität München

Workshop on exotic hadron spectroscopy
Edinburgh, 12. Dec 2017



Exotic Charmonia



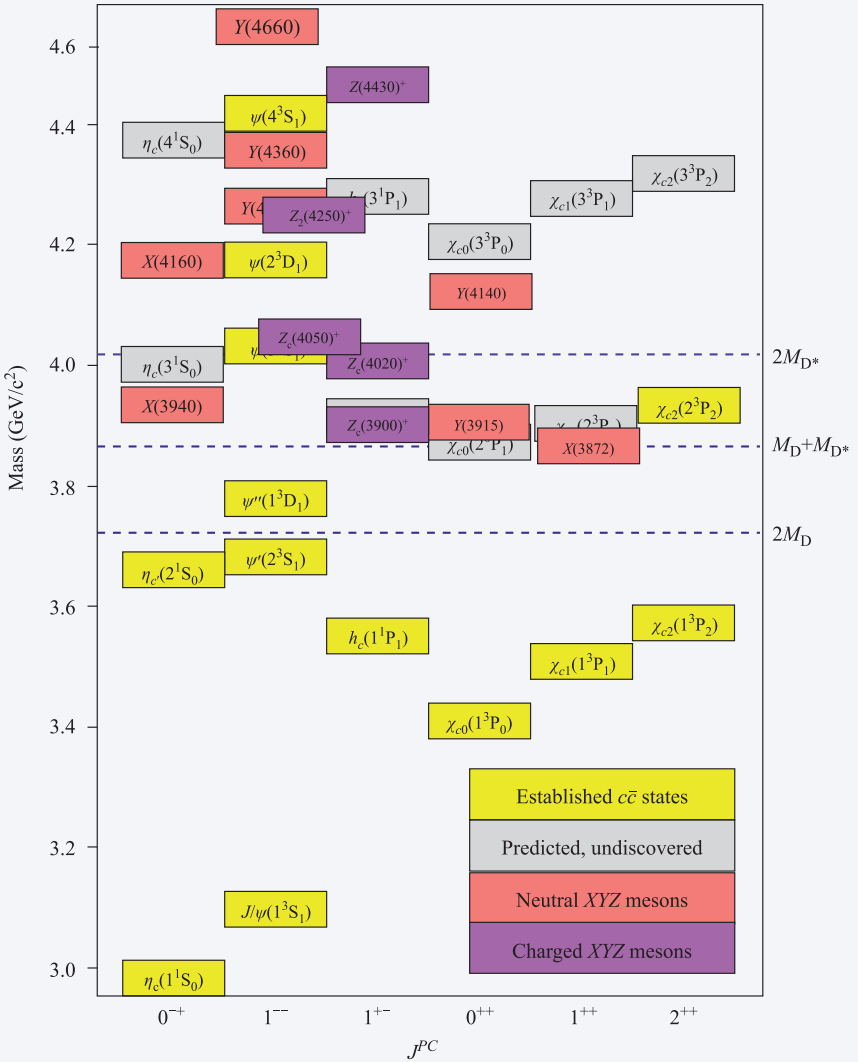
S.L. Olsen, Front. Phys. **10** (101401) 2015

Observed in various production mechanisms

- Direct production in e^+e^- collisions at CLEO, BESIII, BABAR, and Belle
- Direct production in hadron collisions at DØ, CDF, ATLAS, and CMS
- *B* decays at BABAR, Belle, LHCb, and ATLAS
- Two-photon collisions at BABAR and Belle

What about photo/leptoproduction?

Exotic Charmonia



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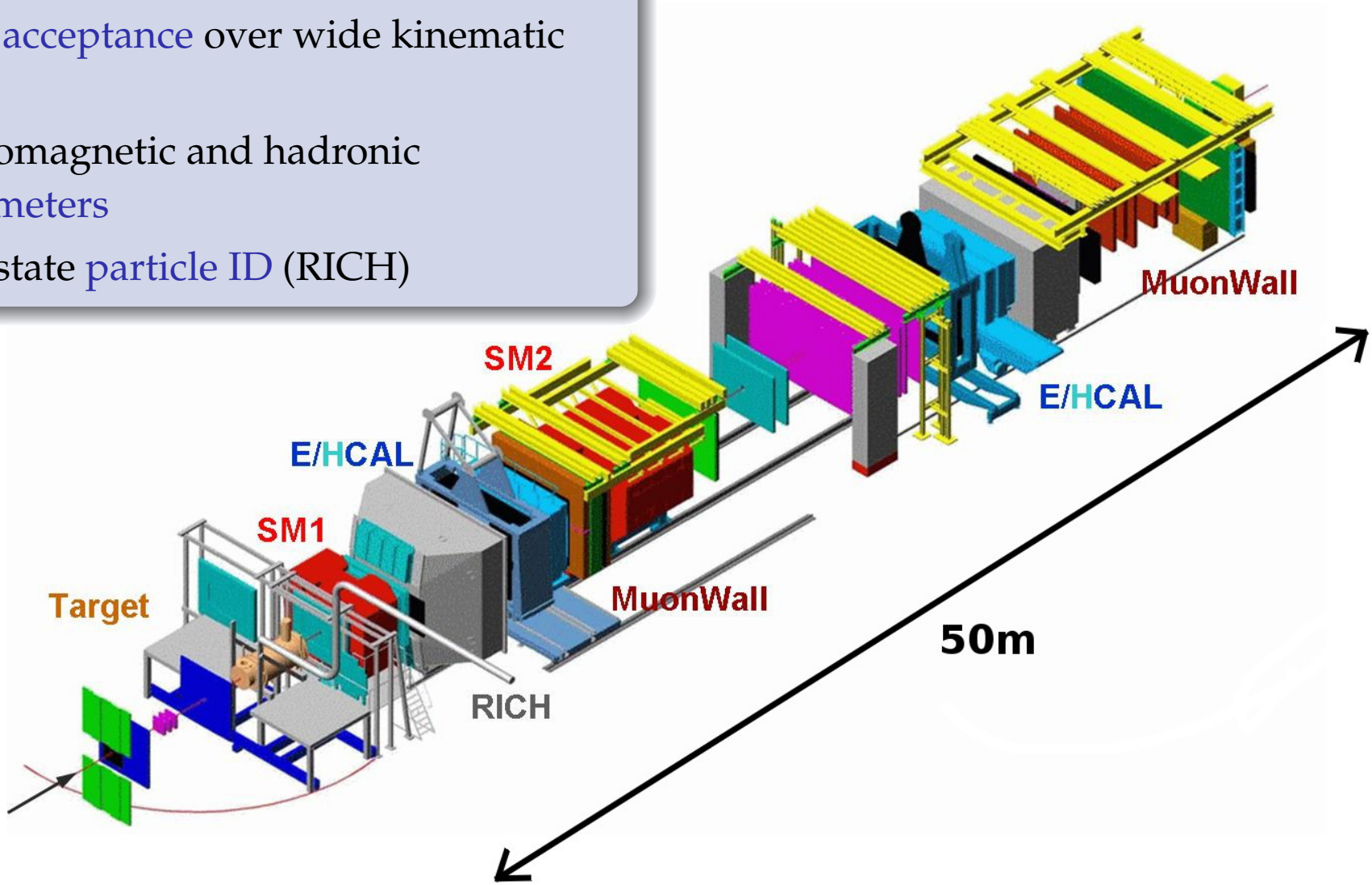
What about photo/leptoproduction?

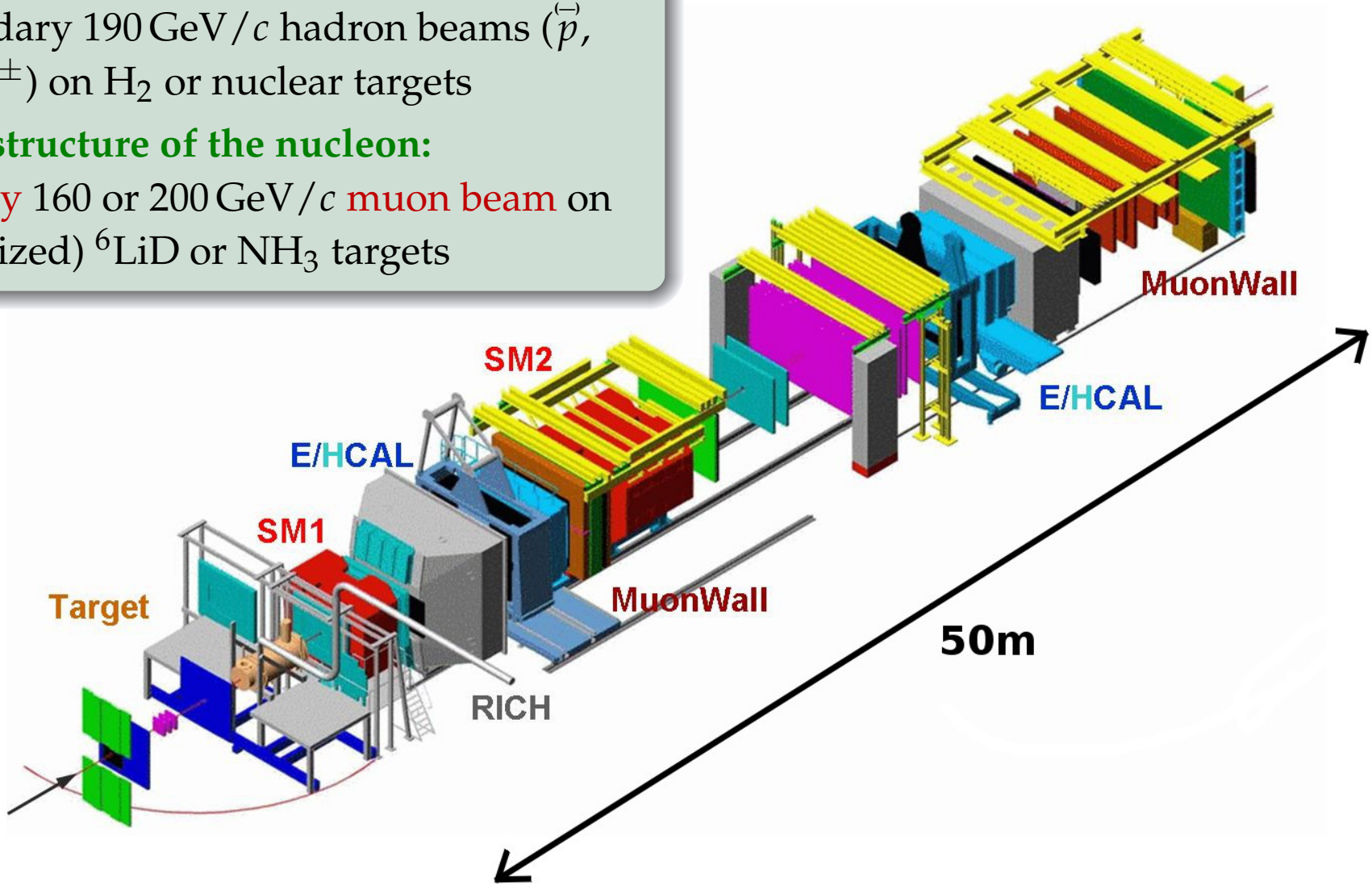
Fixed-target experiment

- Two-stage spectrometer
- Large acceptance over wide kinematic range
- Electromagnetic and hadronic calorimeters
- Final-state particle ID (RICH)

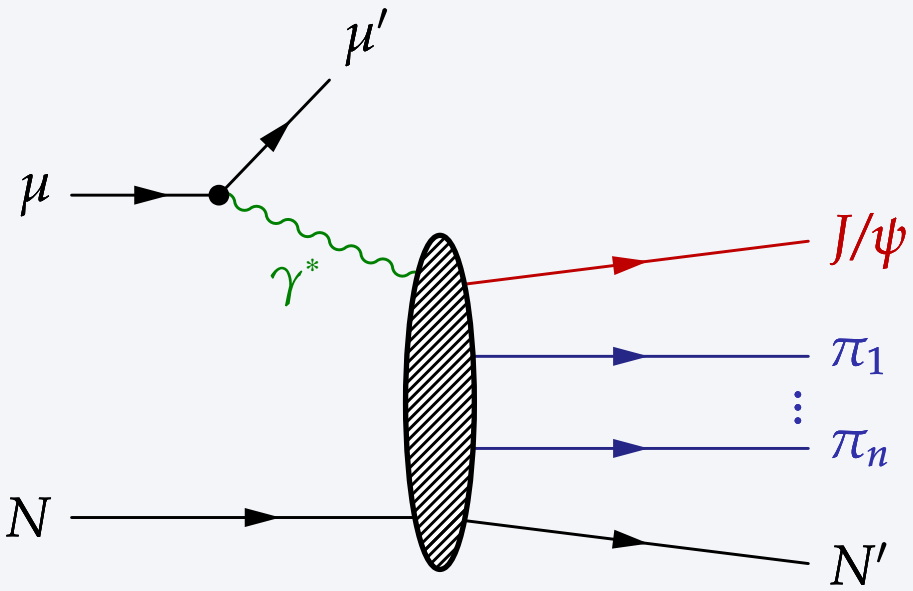


Physics goals

- **Spectroscopy of light mesons:**
  secondary 190 GeV/c hadron beams ($\overset{(-)}{p}$, $\pi^{\pm}$, $K^{\pm}$) on H_2 or nuclear targets
- **Spin structure of the nucleon:**
  tertiary 160 or 200 GeV/c muon beam on (polarized) ^{6}LiD or NH_3 targets



(Associated) Muoproduction of Charmonia



Measure exclusive events

- Production of J/ψ and n charged pions by virtual photons, $n = 0, \ldots, 3$
- Search for exotic charmonia in $J/\psi\pi$ and $J/\psi\pi\pi$ channels
- Target recoil N' unobserved

Data set from 7 years

2002	μ^+, 160 GeV/c	^{6}LiD
2003	μ^+, 160 GeV/c	^{6}LiD
2004	μ^+, 160 GeV/c	^{6}LiD
2006	μ^+, 160 GeV/c	^{6}LiD
2007	μ^+, 160 GeV/c	NH_3
2010	μ^+, 160 GeV/c	NH_3
2011	μ^+, 200 GeV/c	NH_3

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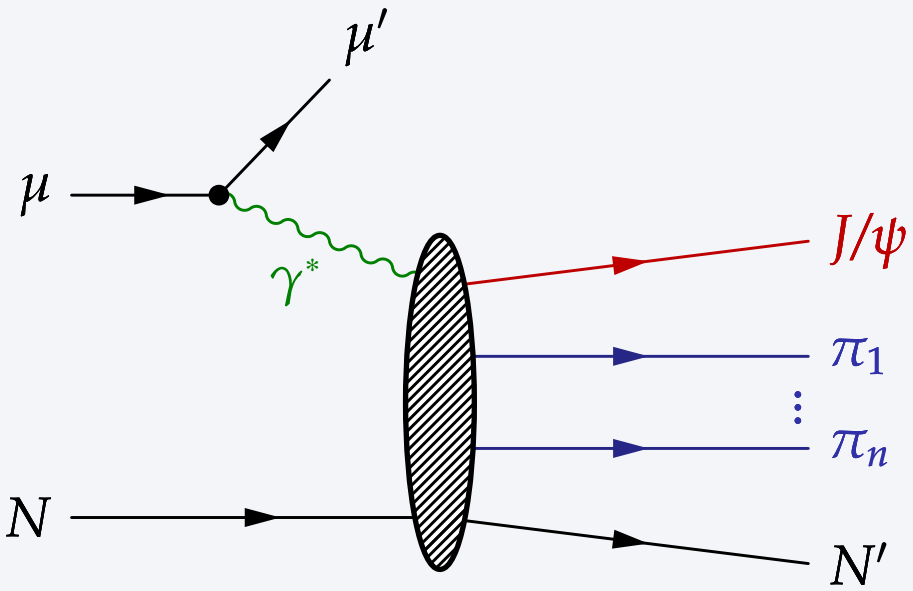

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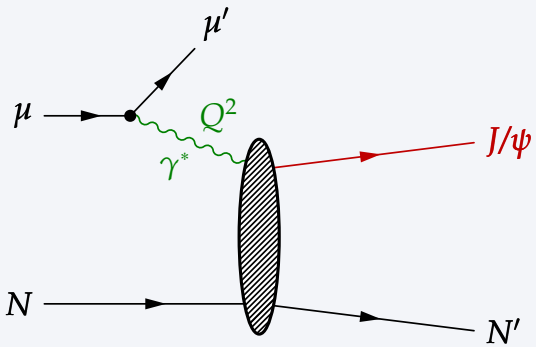
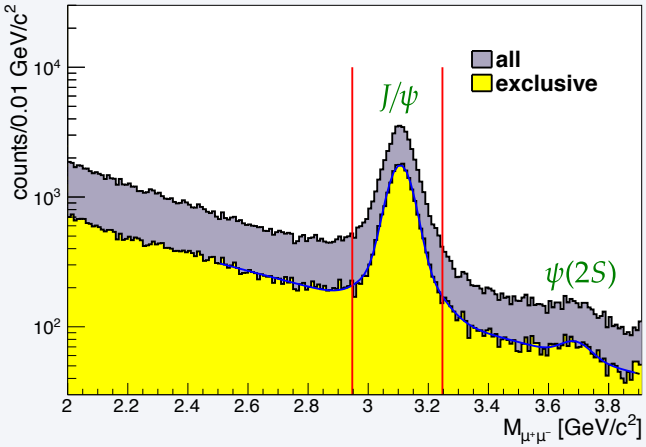
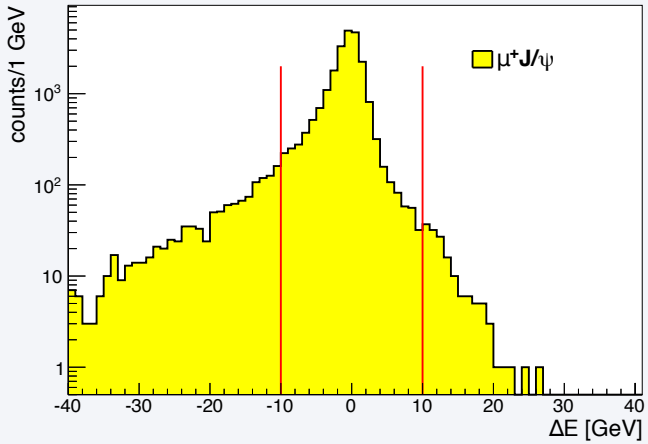
Exclusive Muoproduction of J/ψ

COMPASS, PLB **742** (330) 2015







- J/ψ reconstructed via decay to $\mu^+\mu^-$
- Exclusivity: $\Delta E \equiv E_{\mu'} + E_{J/\psi} - E_{\text{beam}}$
  - Energy transfer to nucleon negligible
  - ΔE resolution $\approx 3\,\text{GeV}$
- 18 200 exclusive J/ψ events
- Dominated by quasi-real photons: $\langle Q^2 \rangle \approx 1\,(\text{GeV}/c)^2$
- $\gamma^* N'$ center-of-mass energy $8 \lesssim \sqrt{s_{\gamma N}} \lesssim 18\,\text{GeV}$

Exclusive Muoproduction of J/ψ

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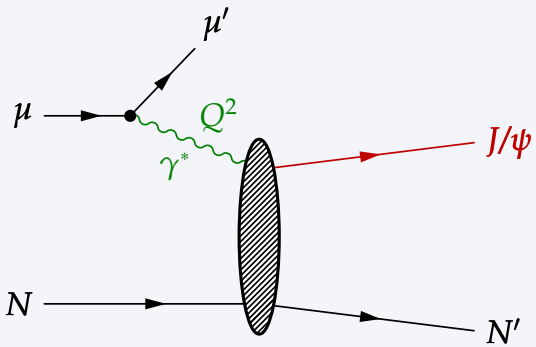

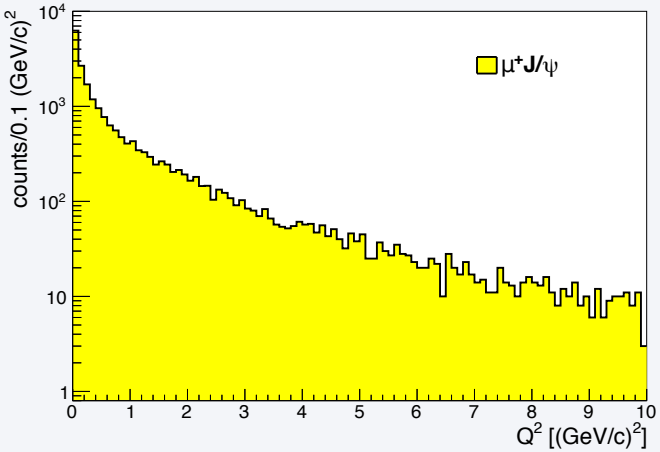

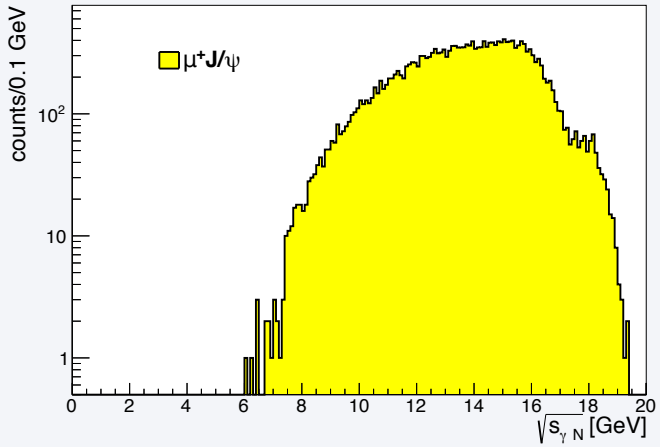

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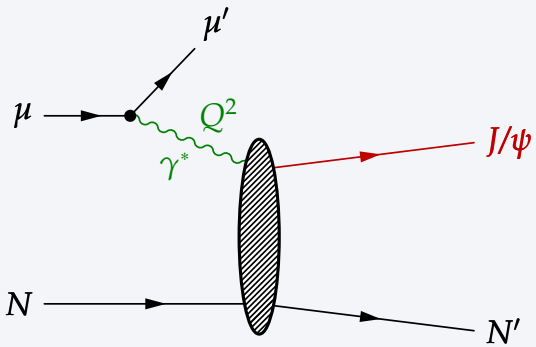

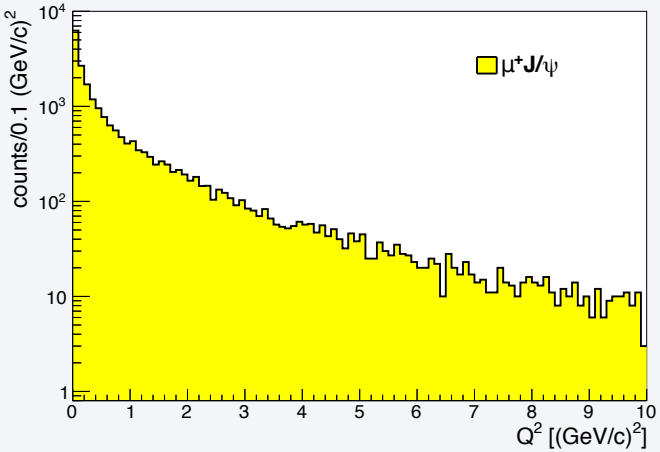

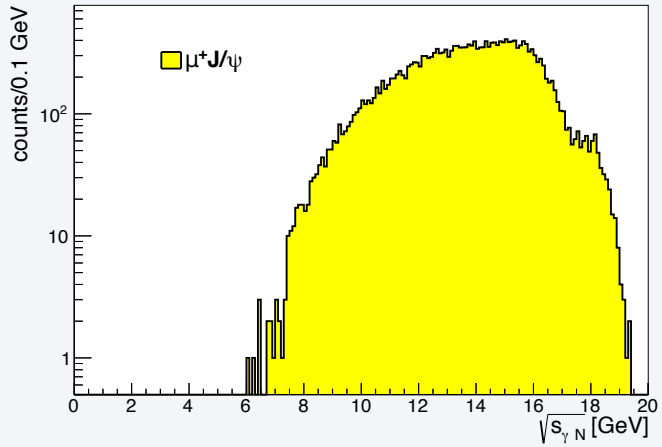

Incoherent exclusive J/ψ production used as normalization

- Known cross section for $\gamma\, N \to J/\psi\, N$:
  $(14.0 \pm 1.6_{\text{stat.}} \pm 2.5_{\text{sys.}})$ nb at $\sqrt{s_{\gamma N}} = 13.7\,\text{GeV}$

  NA-14 Collaboration, ZPC **33** (505) 1987
- Corrected by factor 0.8 to take into account Q^2 dependence

  ZEUS, NPB **695** (3) 2004
- Contribution from coherent scattering on target nuclei separated by fit to p_T^2 spectrum

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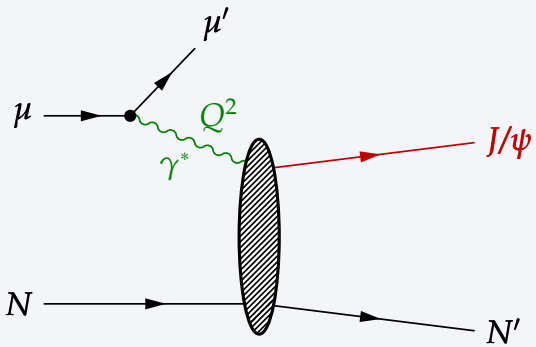

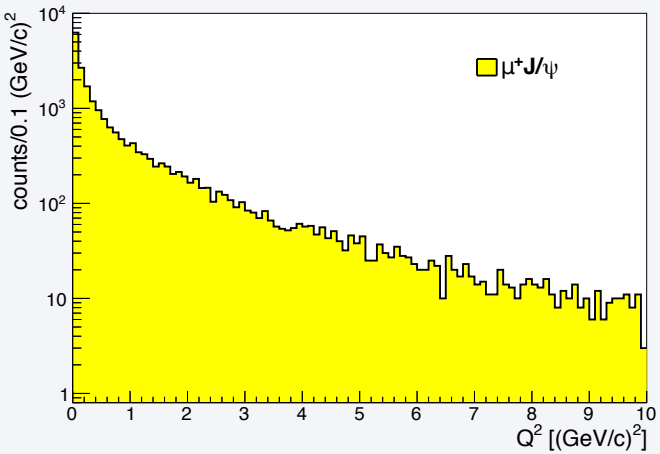

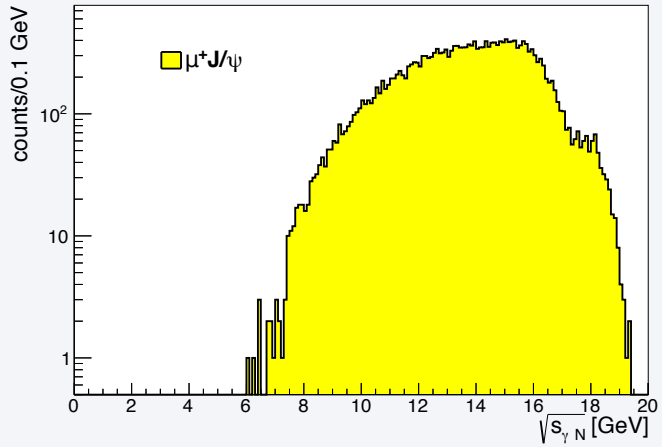

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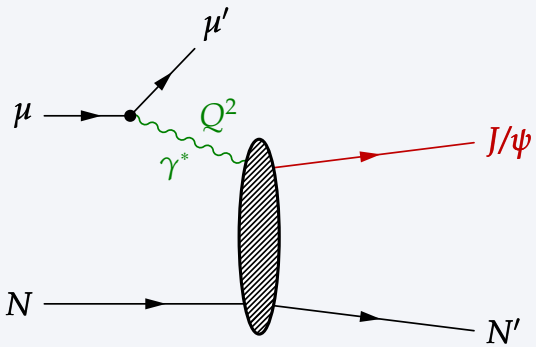

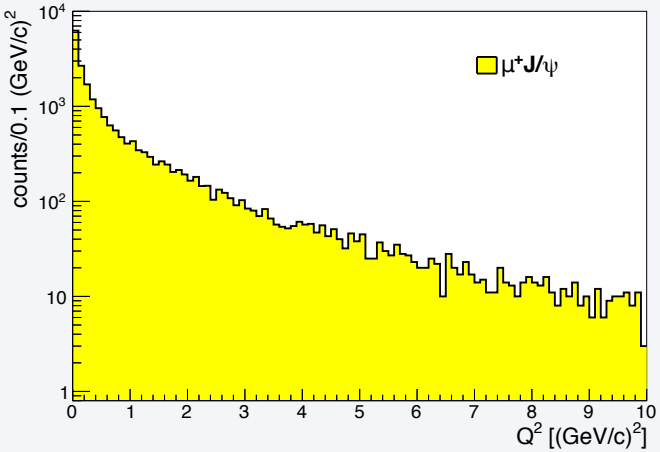

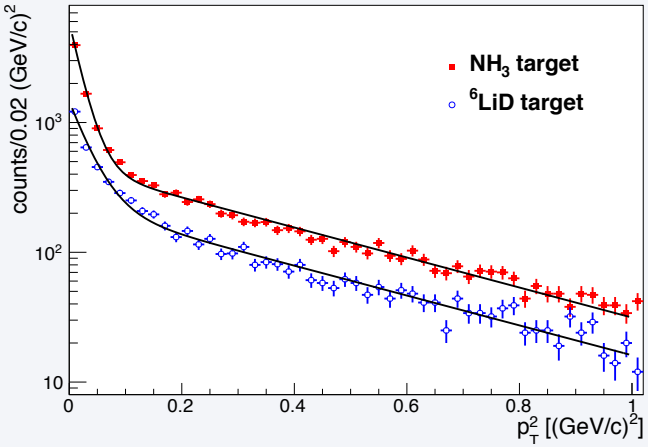

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$Z_c^{\pm}(3900)$

X(3900) $I^G(J^{PC}) = 1^+(1^{+-})$

Mass $m = 3886.6 \pm 2.4$ MeV (S = 1.6)
Full width $\Gamma = 28.1 \pm 2.6$ MeV

X(3900) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$J/\psi\pi$	seen	699
$h_c\,\pi^{\pm}$	not seen	318
$\eta_c\,\pi^+\pi^-$	not seen	759
$(D\overline{D}^*)^{\pm}$	seen	–
$D^0\,D^{*-}$ + c.c.	seen	150
$D^-\,D^{*0}$ + c.c.	seen	141
$\omega\pi^{\pm}$	not seen	1862
$J/\psi\eta$	not seen	509
$D^+\,D^{*-}$ + c.c	seen	–
$D^0\,\overline{D}^{*0}$ + c.c	seen	–

- Discovered 2013 by BESIII and Belle
- Up to now only seen in $e^+e^- \to \pi^{\mp} Z_c^{\pm}$
- $Z_c^0(3900) \to J/\psi\pi^0$ observed in CLEO-c data and by BESIII experiment
- Nature unclear
  - Tetraquark?
  - $D\overline{D}^*$ molecule?
  - Cusp effect? Triangle singularity?
  - ...

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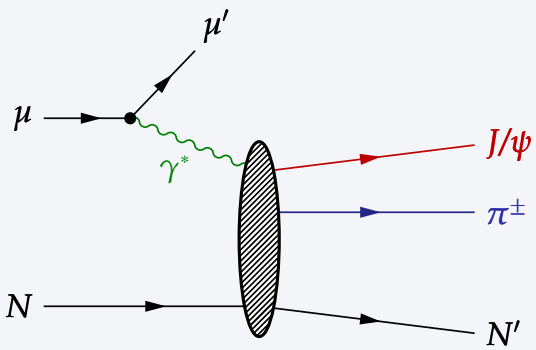
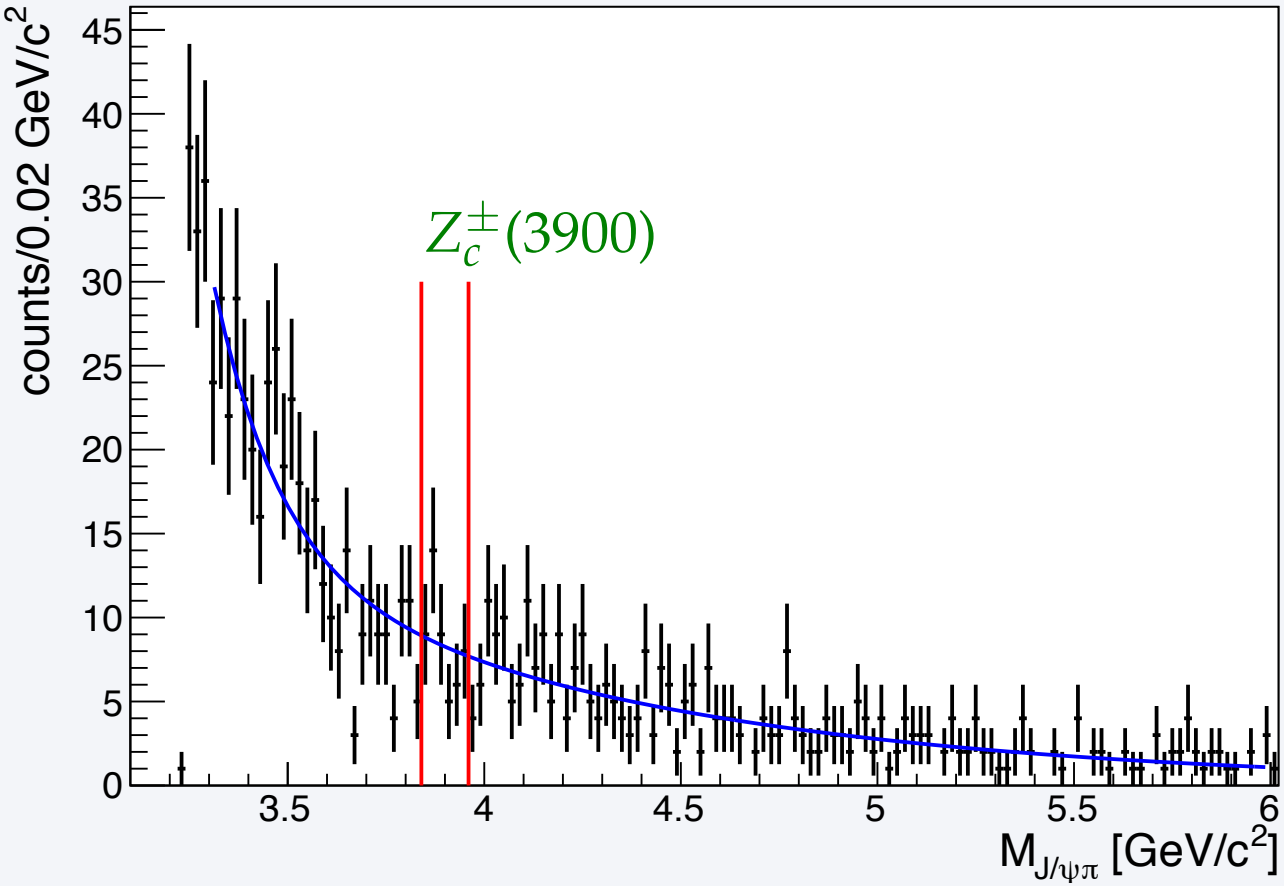
Exclusive Muoproduction of $J/\psi\pi^{\pm}$

COMPASS, PLB **742** (330) 2015





Search for $Z_c^{\pm}(3900)$ in $J/\psi\pi^{\pm}$ invariant mass spectrum

- Prediction: 50 to 100 nb $Z_c^{\pm}(3900)$ production cross section at $\sqrt{s_{\gamma N}} = 7\,\text{GeV}$

  Q.-Y. Lin *et al.*, PRD **88** (114009) 2013
- No signal observed

Exclusive Muoproduction of $J/\psi\pi^{\pm}$

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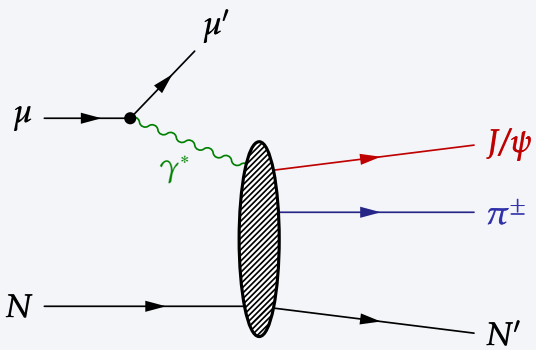

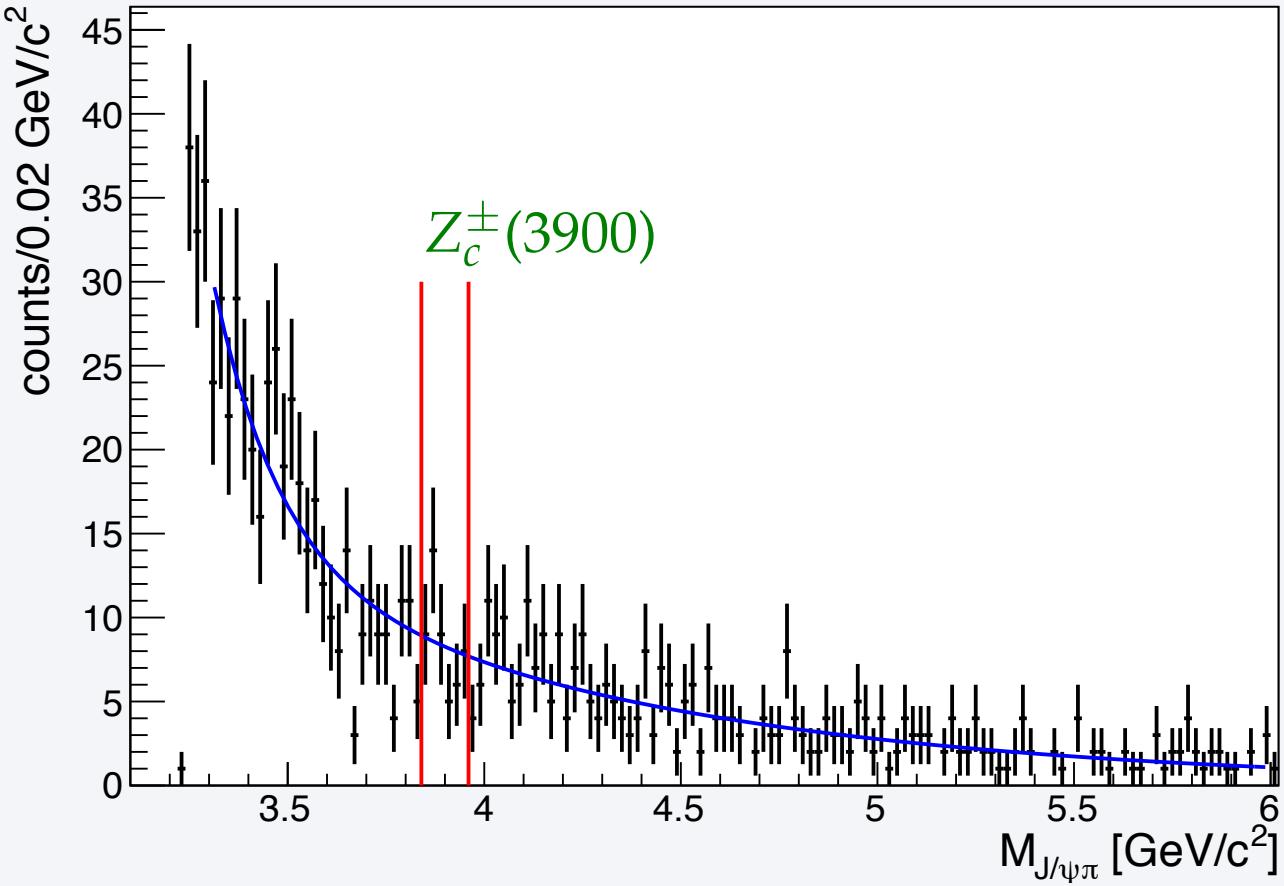

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- $$\frac{\sigma_{\gamma N \to Z_c^{\pm}(3900)\, N'}}{\sigma_{\gamma N \to J/\psi\, N'}} \mathrm{BR}[Z_c^{\pm}(3900) \to J/\psi\, \pi^{\pm}] < 3.7 \times 10^{-3}$$

  at $\sqrt{s_{\gamma N}} = 13.8\,\mathrm{GeV}$ and 90 % C.L.

Exclusive Muoproduction of $J/\psi\pi^{\pm}$

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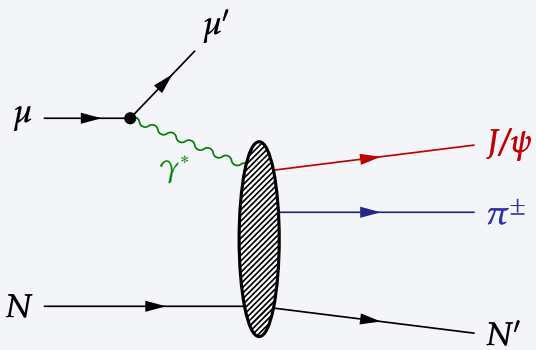

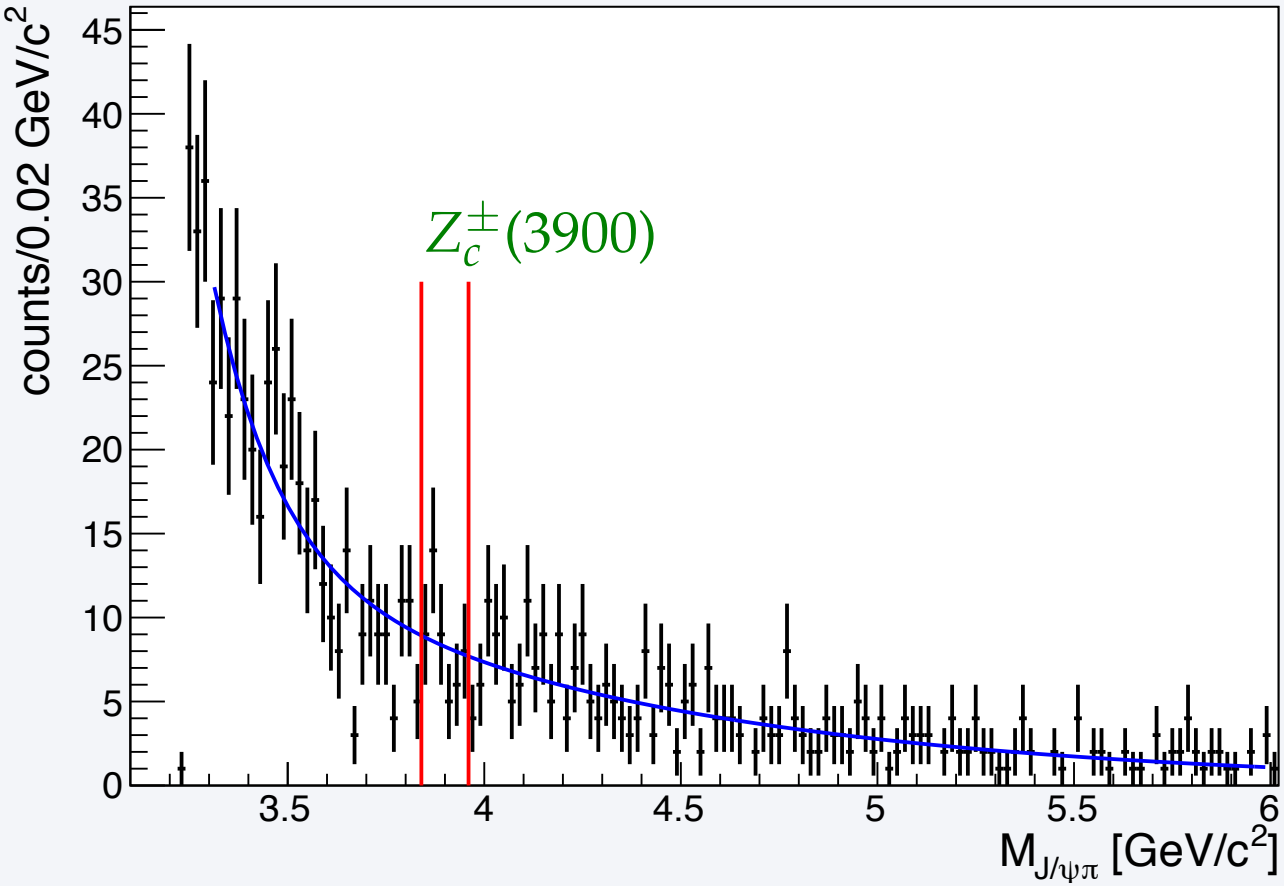

Search for $Z_c^{\pm}(3900)$ in $J/\psi\pi^{\pm}$ invariant mass spectrum

- $\sigma_{\gamma N \to Z_c^{\pm}(3900) N'} \, \mathrm{BR}[Z_c^{\pm}(3900) \to J/\psi \, \pi^{\pm}] < 52\,\mathrm{pb}$

  at $\sqrt{s_{\gamma N}} = 13.8\,\mathrm{GeV}$ and 90 % C.L.

$Z_c^{\pm}(4200)$

$X(4200)^{\pm}$

$I(J^P) = ?(1^+)$

OMITTED FROM SUMMARY TABLE

Reported by CHILIKIN 14 in $J/\psi\pi^+$ at a significance of 6.2σ. Assignments of 0^-, 1^-, 2^-, and 2^+ excluded at 6.1σ, 7.4σ, 4.4σ, and 7.0σ level, respectively. Needs confirmation.

$X(4200)^{\pm}$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4196^{+31+17}_{-29-13}	CHILIKIN	14	BELL	$\overline{B}^0 \to J/\psi K^- \pi^+$

$X(4200)^{\pm}$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$370 \pm 70^{+70}_{=132}$	CHILIKIN	14	BELL	$\overline{B}^0 \to J/\psi K^- \pi^+$

$X(4200)^{\pm}$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$J/\psi\pi^+$	seen

- Reported 2014 by Belle in $B \to K Z_c^{\pm}$ with $Z_c^{\pm} \to J/\psi\pi^{\pm}$
- Needs confirmation
- Unclear, whether neutral partner $Z_c^0(4200)$ exists

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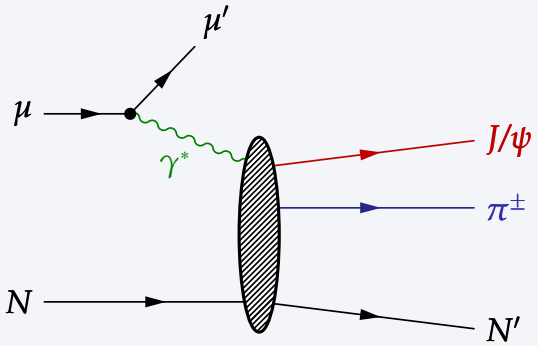
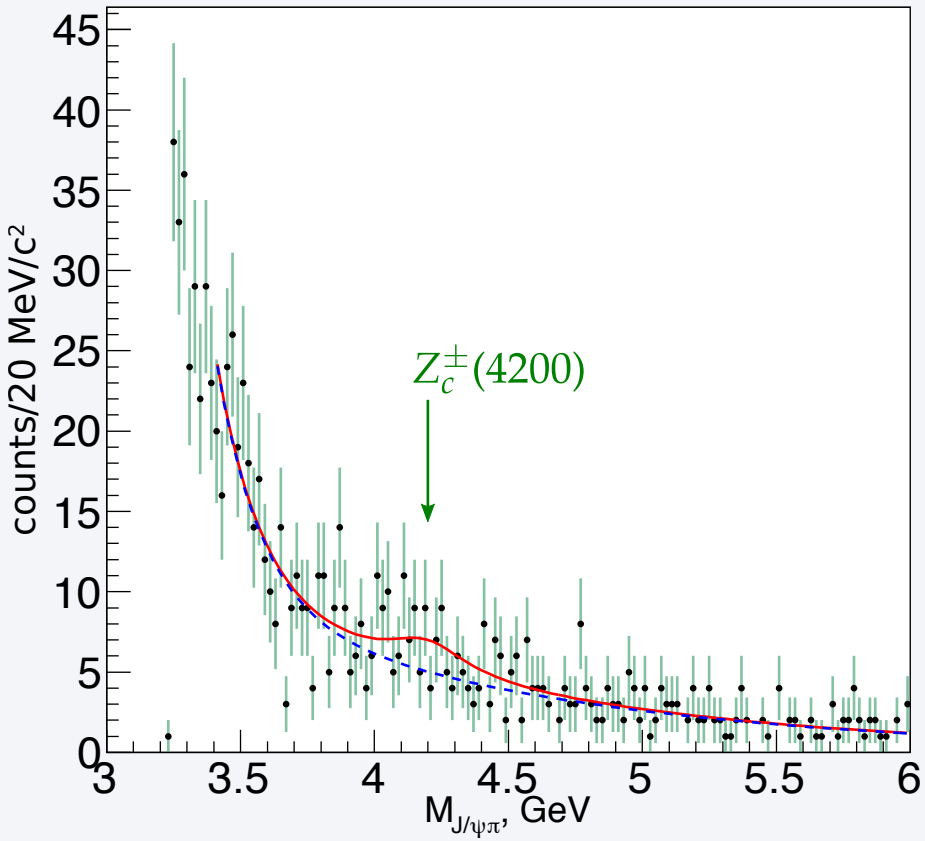
Exclusive Muoproduction of $J/\psi\pi^{\pm}$

X. Y. Wang *et al.*, PRD **92** (094017) 2015





Search for $Z_c^{\pm}(4200)$ in $J/\psi\pi^{\pm}$ invariant mass spectrum

- No signal observed
- $\sigma_{\gamma N \to Z_c^{\pm}(4200) N'} \, \mathrm{BR}[Z_c^{\pm}(4200) \to J/\psi \, \pi^{\pm}] < 340\,\mathrm{pb}$
  at $\sqrt{s_{\gamma N}} = 13.8\,\mathrm{GeV}$ and 90 % C.L.

$X(3872)$

$X(3872)$ $\quad I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 3871.69 \pm 0.17$ MeV
$m_{X(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
$m_{X(3872)} - m_{\psi(2S)}$
Full width $\Gamma < 1.2$ MeV, CL = 90%

$X(3872)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi^+\pi^- J/\psi(1S)$	> 2.6 %	650
$\omega J/\psi(1S)$	> 1.9 %	†
$D^0\overline{D}{}^0\pi^0$	>32 %	117
$\overline{D}{}^{*0}D^0$	>24 %	3
$\gamma J/\psi$	$> 6 \times 10^{-3}$	697
$\gamma\psi(2S)$	> 3.0 %	181
$\pi^+\pi^-\eta_c(1S)$	not seen	746
$p\overline{p}$	not seen	1693

- Discovered 2003 by Belle
- Best studied exotic charmonium-like state
- Mass at $D^0\bar{D}^{0*}$ threshold
- Narrow $\Rightarrow$ so far only upper limit for width
- LHCb: $J^{PC} = 1^{++}$
- $$\frac{\mathrm{BR}[X \to J/\psi\omega]}{\mathrm{BR}[X \to J/\psi\pi^+\pi^-]} = 0.8 \pm 0.3$$
- Nature still unclear

$X(3872)$

X(3872) $I^G(J^{PC}) = 0^+(1^{++})$

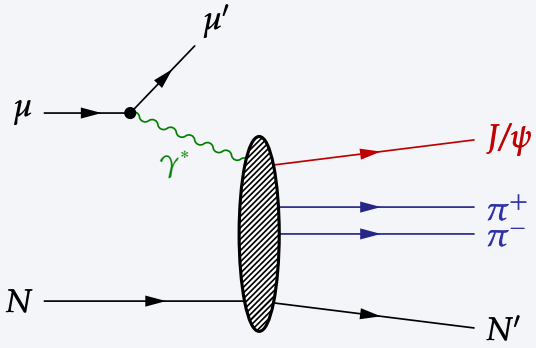
Mass $m = 3871.69 \pm 0.17$ MeV
$m_{X(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
$m_{X(3872)} - m_{\psi(2S)}$
Full width $\Gamma < 1.2$ MeV, CL = 90%

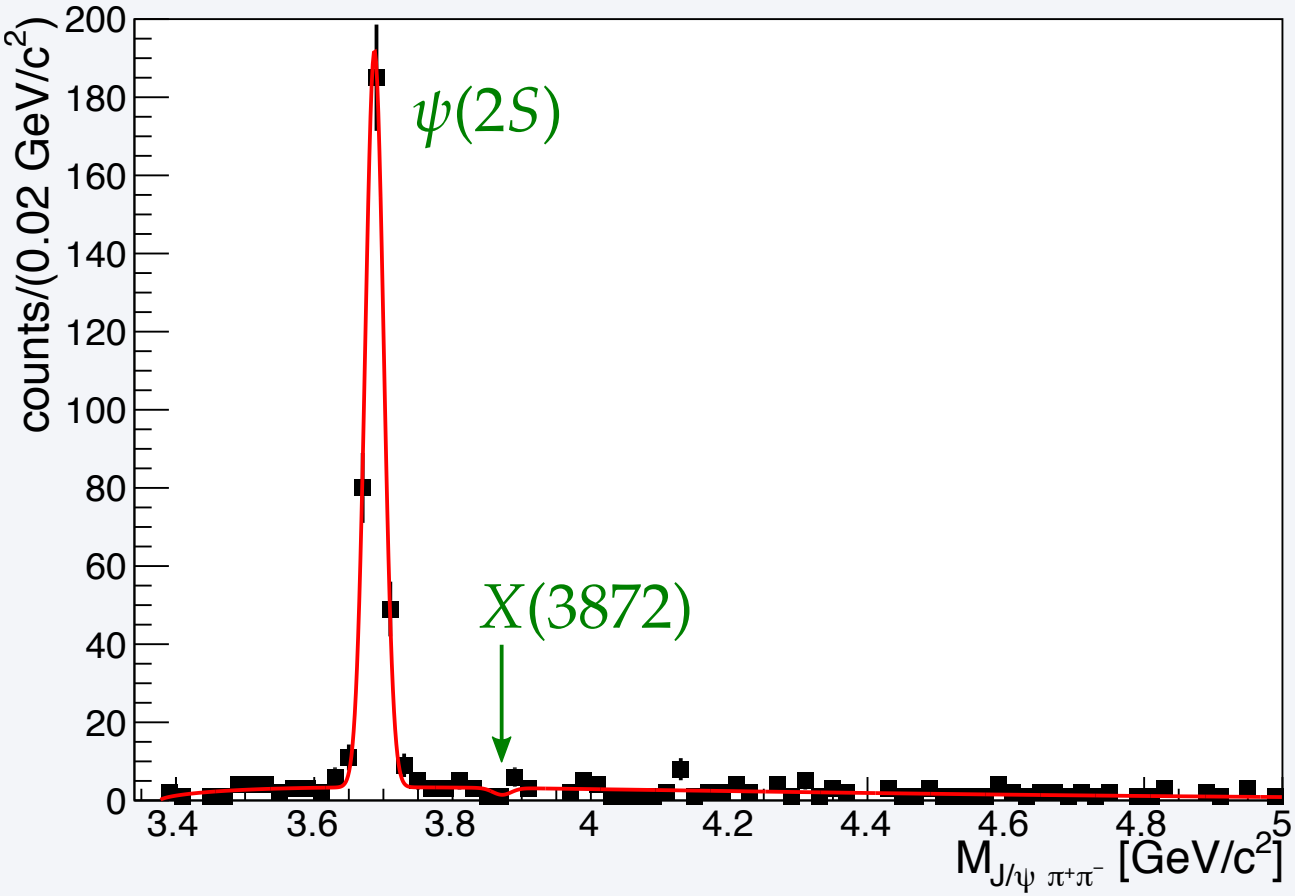
X(3872) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi^+\pi^- J/\psi(1S)$	> 2.6 %	650
$\omega J/\psi(1S)$	> 1.9 %	†
$D^0\overline{D}{}^0\pi^0$	>32 %	117
$\overline{D}{}^{*0}D^0$	>24 %	3
$\gamma J/\psi$	$> 6 \times 10^{-3}$	697
$\gamma\psi(2S)$	> 3.0 %	181
$\pi^+\pi^-\eta_c(1S)$	not seen	746
$p\overline{p}$	not seen	1693

- Discovered 2003 by Belle
- Best studied exotic charmonium-like state
- Mass at $D^0\overline{D}{}^{0*}$ threshold
- Narrow $\Rightarrow$ so far only upper limit for width
- LHCb: $J^{PC} = 1^{++}$
- $$\frac{\mathrm{BR}[X \to J/\psi\omega]}{\mathrm{BR}[X \to J/\psi\pi^+\pi^-]} = 0.8 \pm 0.3$$
- Nature still unclear

Exclusive Muoproduction of $J/\psi\pi^+\pi^-$

[arXiv:1707.01796]



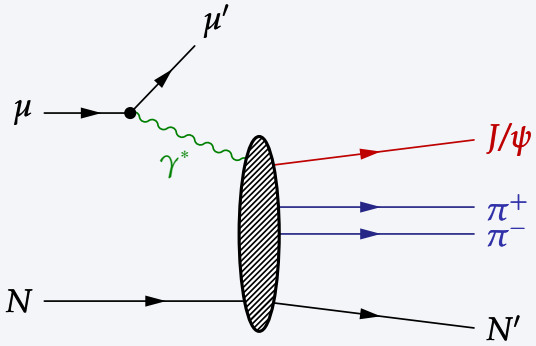


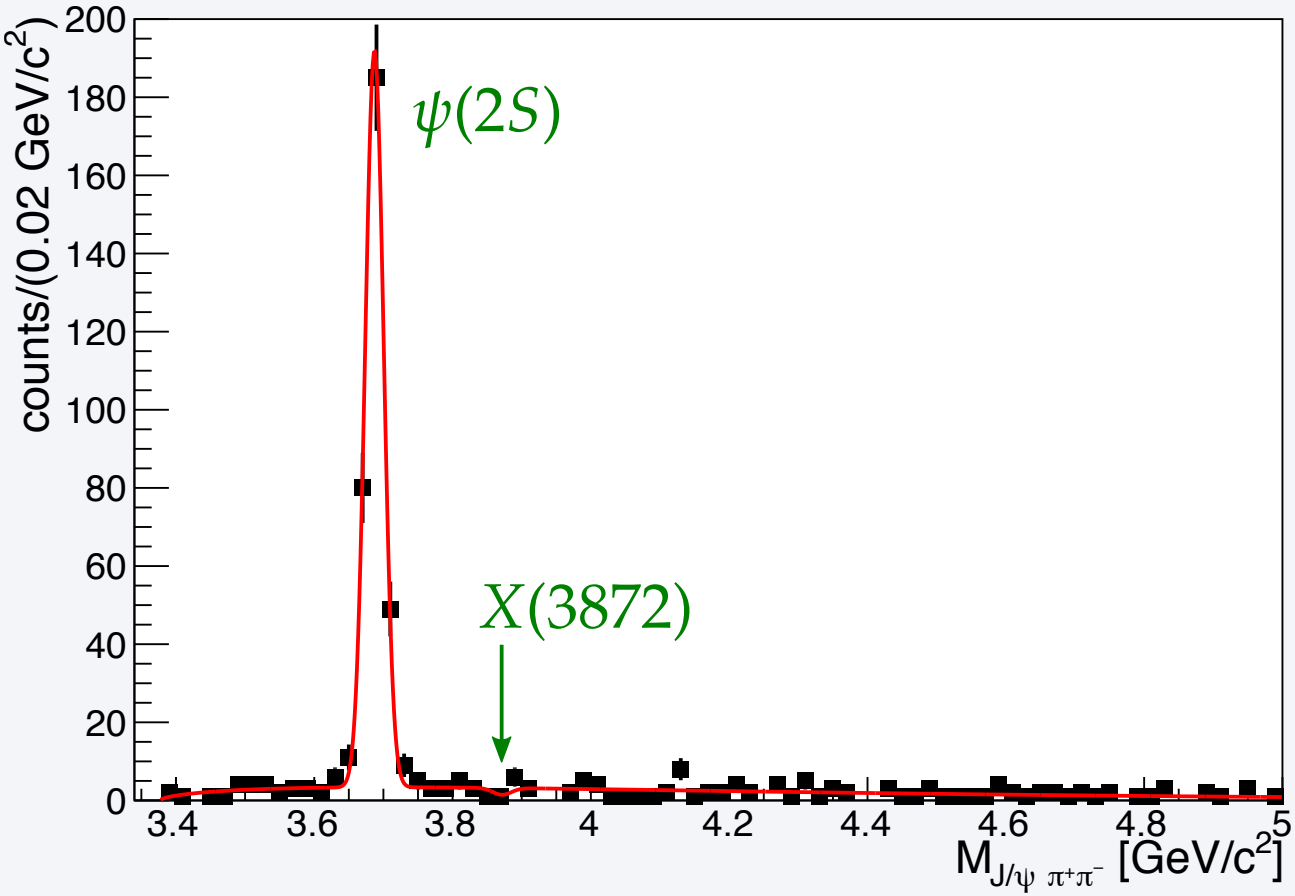
Search for $X(3872)$ in $J/\psi\pi^+\pi^-$ invariant mass spectrum

- $\psi(2S)$ peak at $(3687.1 \pm 0.8)\,\mathrm{MeV}/c^2$ (good agreement with PDG)
- No $X(3872)$ signal

Exclusive Muoproduction of $J/\psi\pi^+\pi^-$

[arXiv:1707.01796]



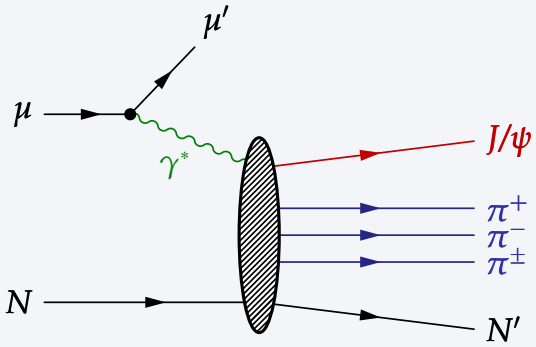


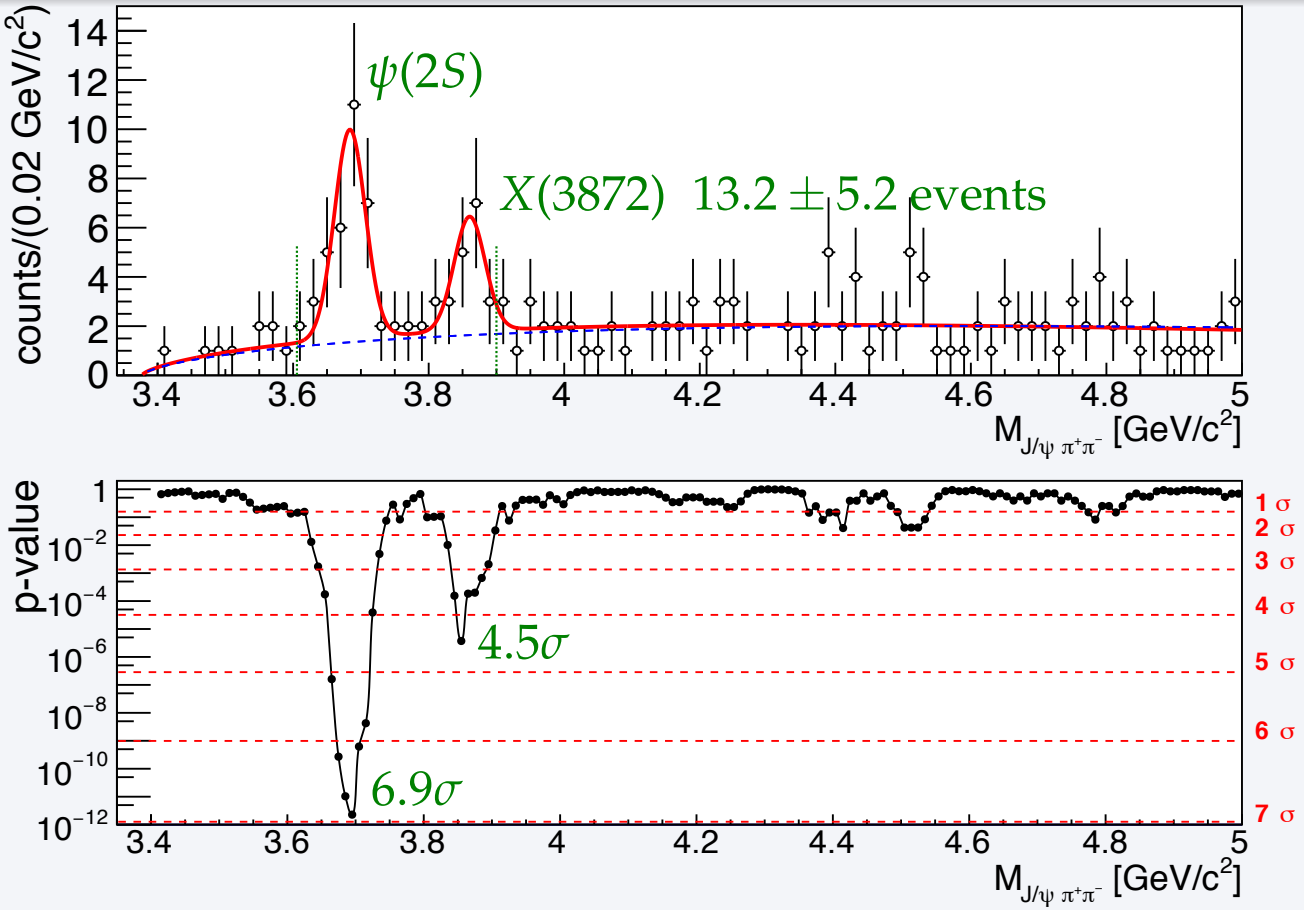
Search for $X(3872)$ in $J/\psi\pi^+\pi^-$ invariant mass spectrum

- $\sigma_{\gamma N \to X(3872) N'} \, \mathrm{BR}[X(3872) \to J/\psi \, \pi^+\pi^-] < 2.9\,\mathrm{pb}$ at 90 % C.L.

Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$

[arXiv:1707.01796]



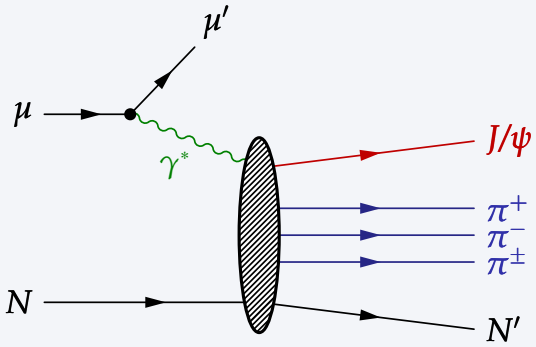


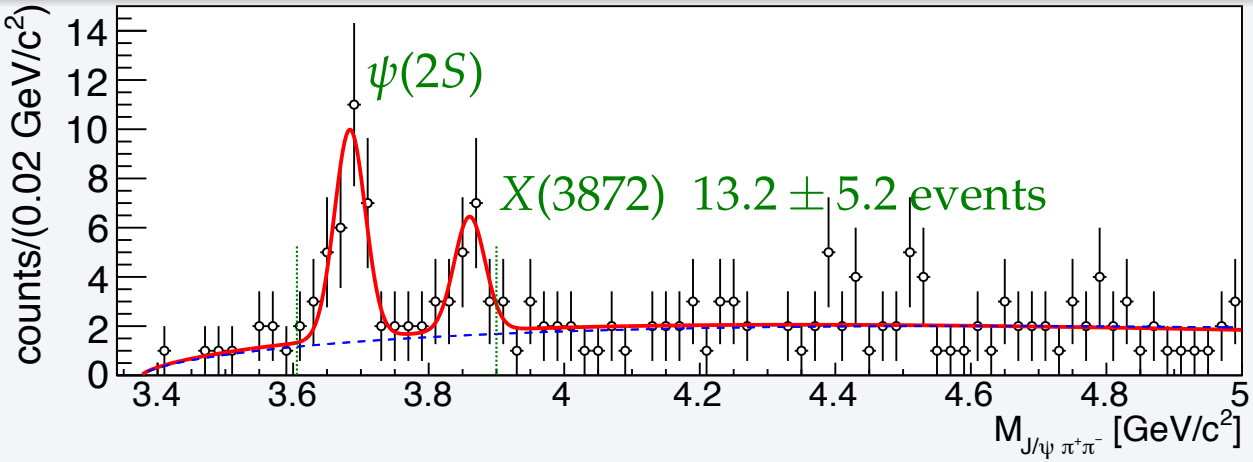
Search for $X(3872)$ in $J/\psi\pi^+\pi^-$ invariant mass spectrum

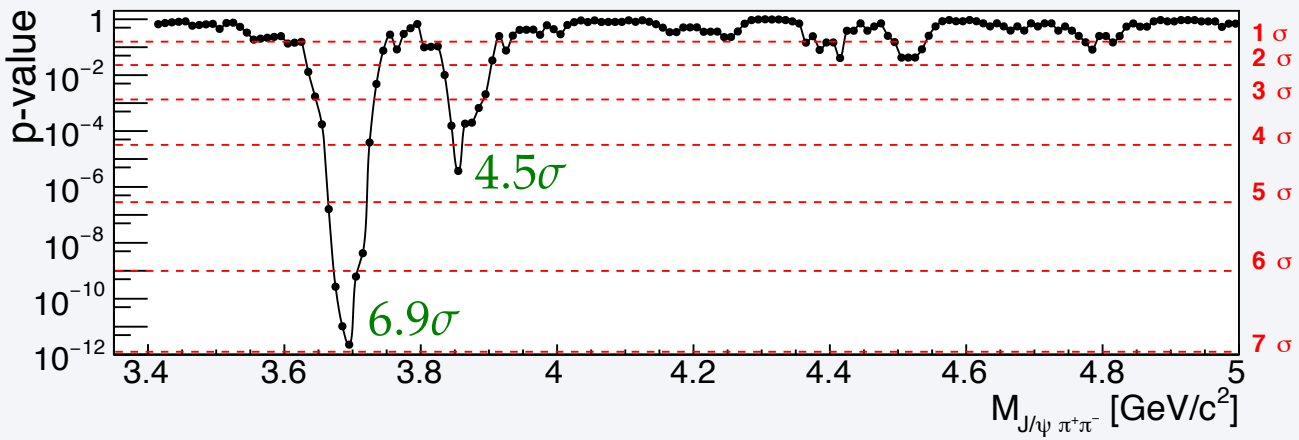
- $\psi(2S)$ peak at $(3683.7 \pm 6.5)\,\mathrm{MeV}/c^2$ (good agreement with PDG)
- Peak at $(3860.4 \pm 10.0)\,\mathrm{MeV}/c^2$ consistent with $X(3872)$
- $\sigma = (22.8 \pm 6.9)\,\mathrm{MeV}/c^2$ for both peaks; dominated by resolution

Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$

[arXiv:1707.01796]





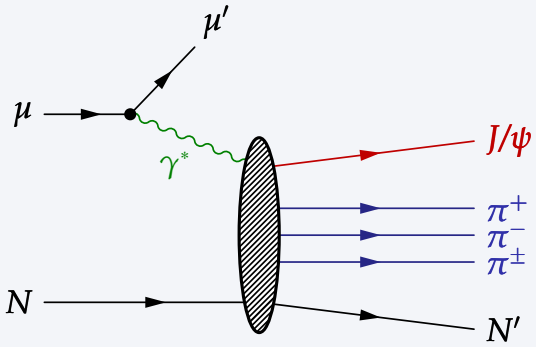


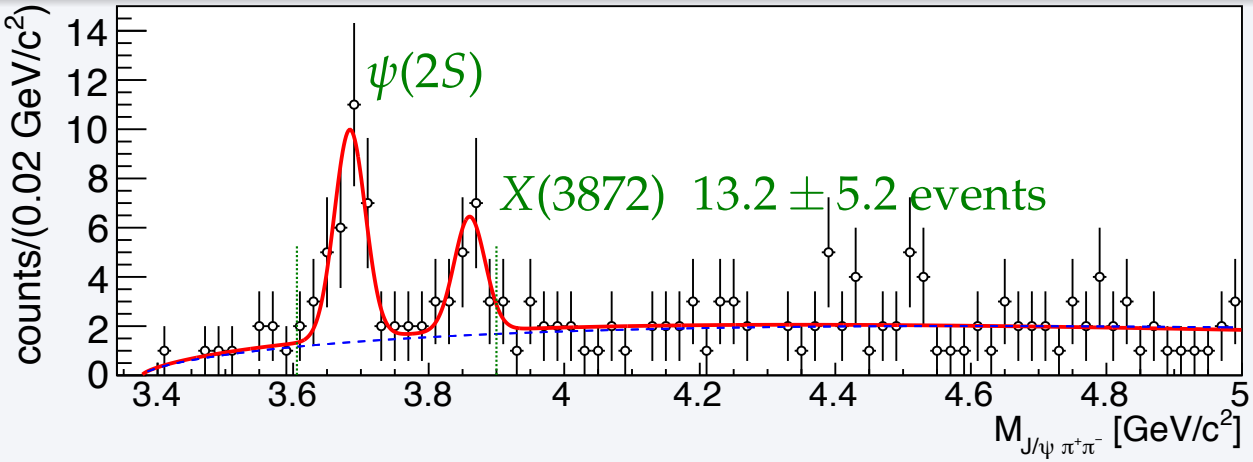
Significance

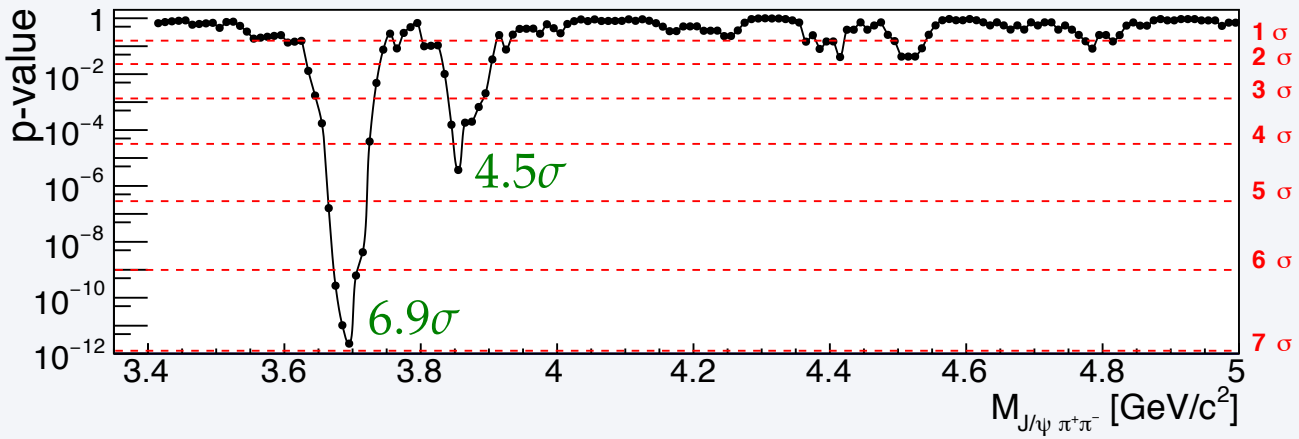
- Integrate background curve over 60 MeV/c^2 wide mass window
  $\Rightarrow$ expected number of background events
- Assume Poisson distribution $\Rightarrow$ p-value for BG fluctuation

Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$

[arXiv:1707.01796]





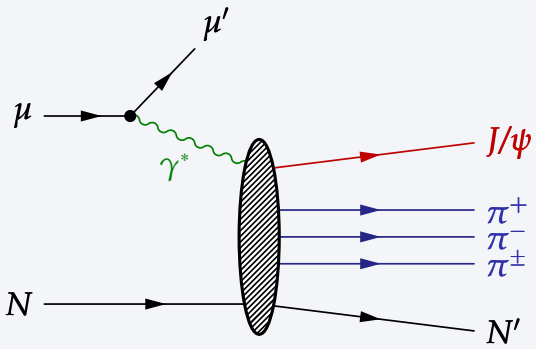


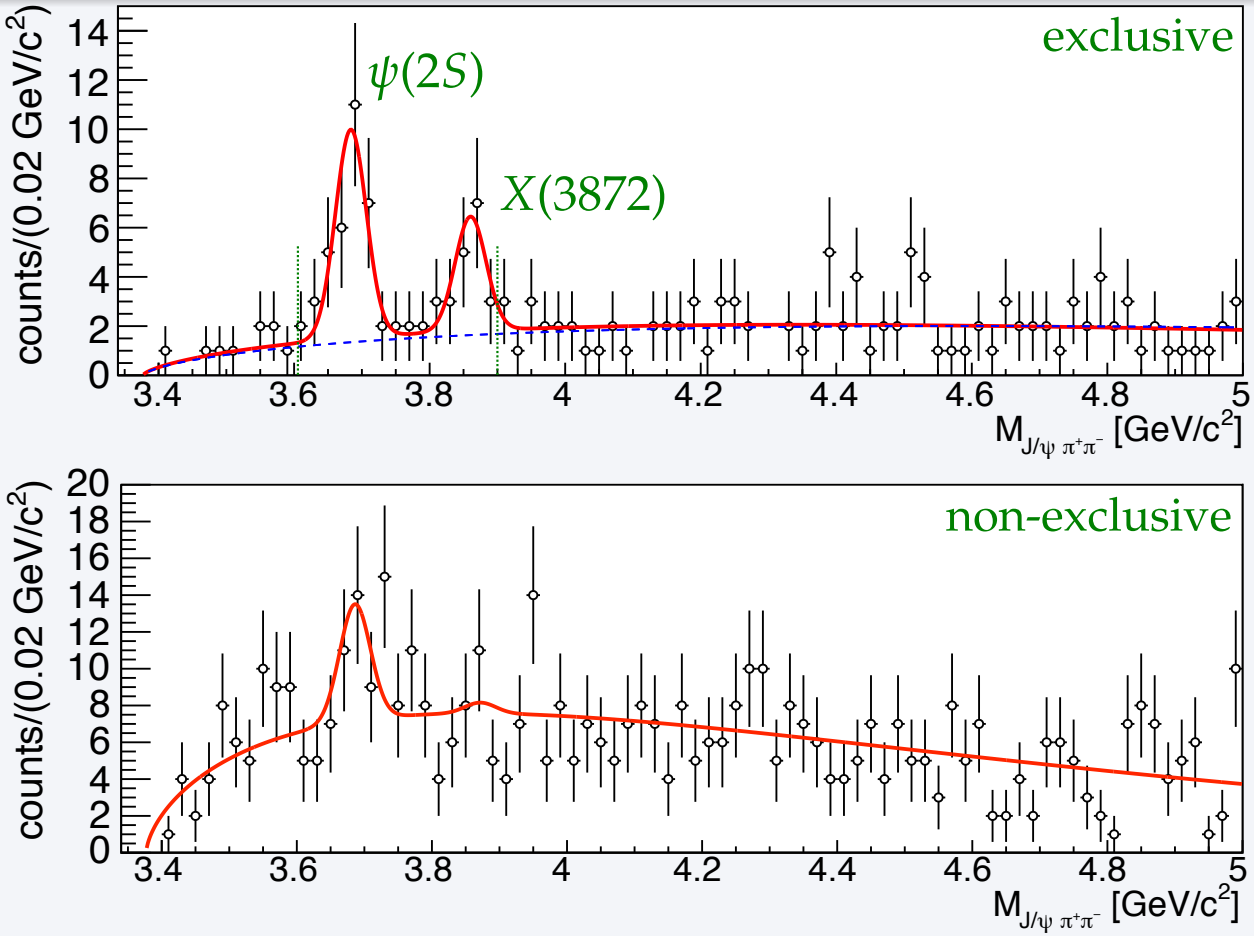
Production rate

- $\sigma_{\gamma N \to X(3872)\,\pi N'}\,\mathrm{BR}[X(3872) \to J/\psi\,\pi^+\pi^-]$
  $= (71 \pm 28_{\,\mathrm{stat.}} \pm 39_{\,\mathrm{sys.}})\,\mathrm{pb}$

Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$

[arXiv:1707.01796]



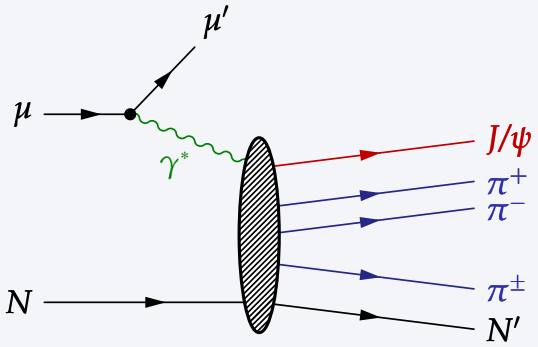


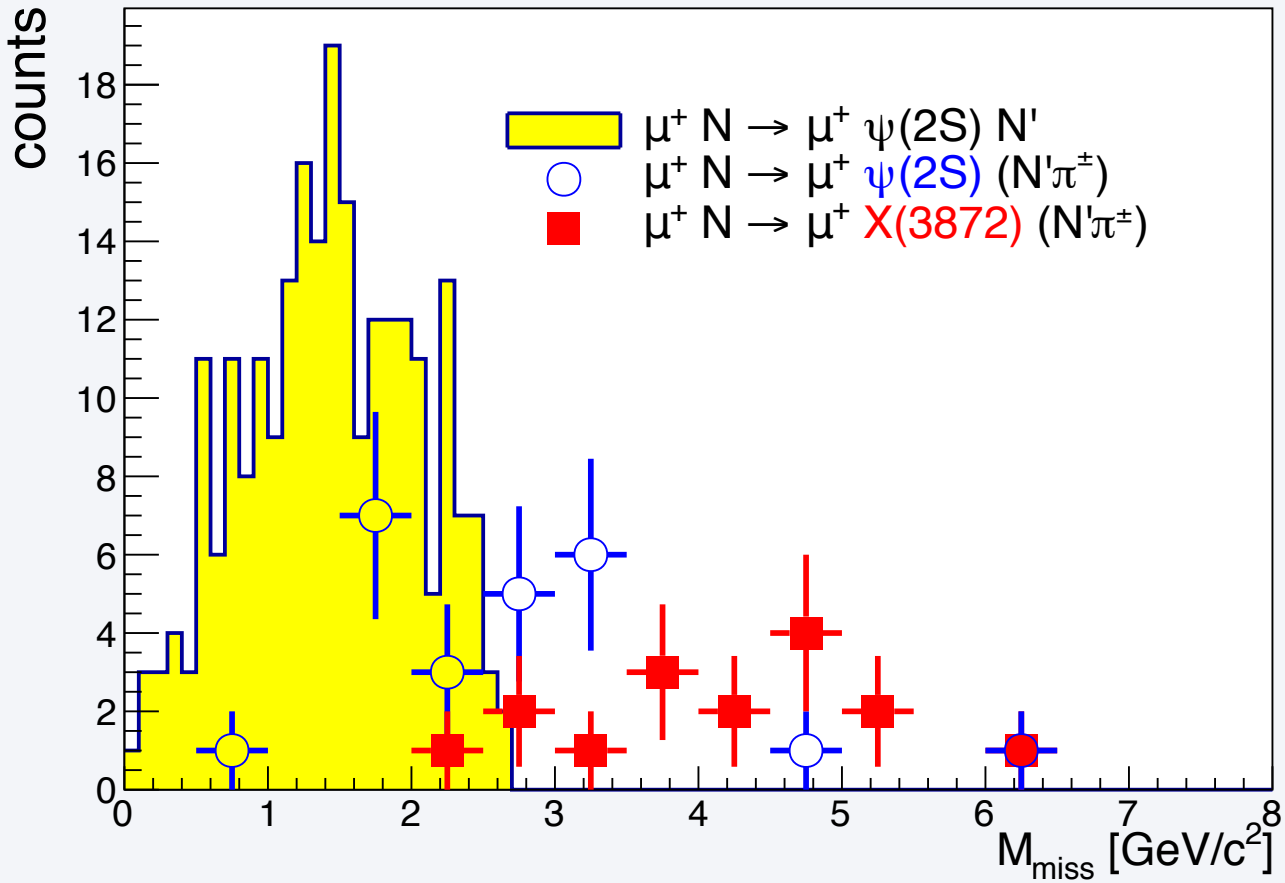
Production of $X(3872)$ is exclusive

- Exclusive events: $|\Delta E| < 4\,\mathrm{GeV}$
- Non-exclusive events: $-12 < \Delta E < -4\,\mathrm{GeV}$
  - $X(3872)$ signal disappears

Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$

[arXiv:1707.01796]



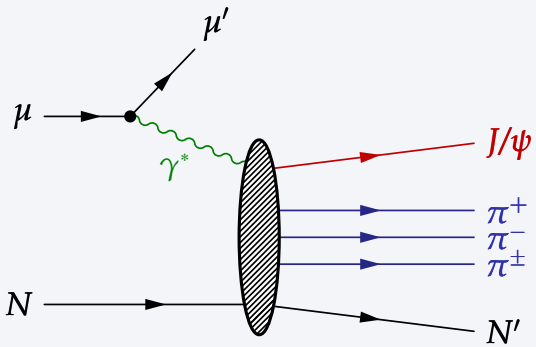


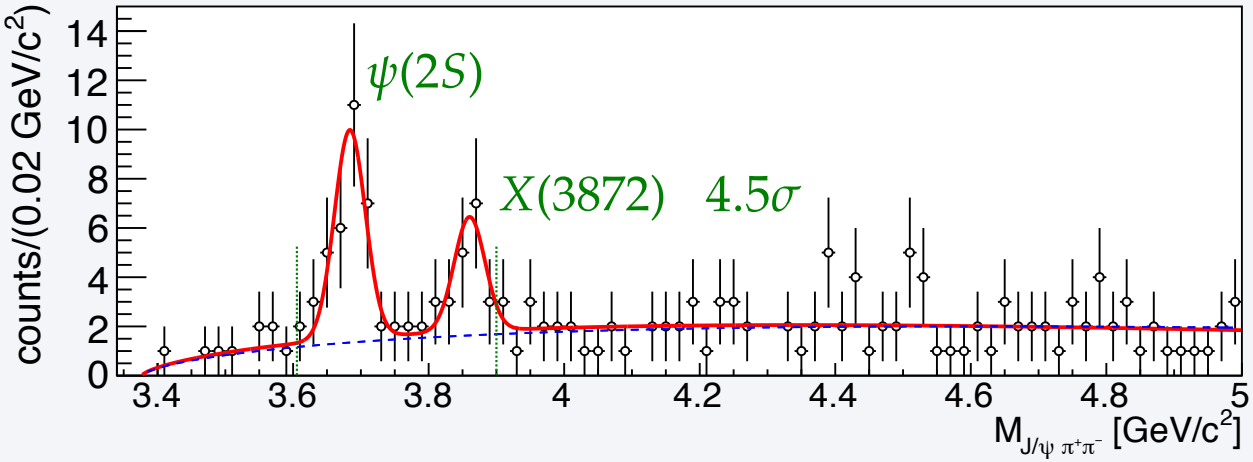
Mass spectrum of $\pi^\pm N'$ system

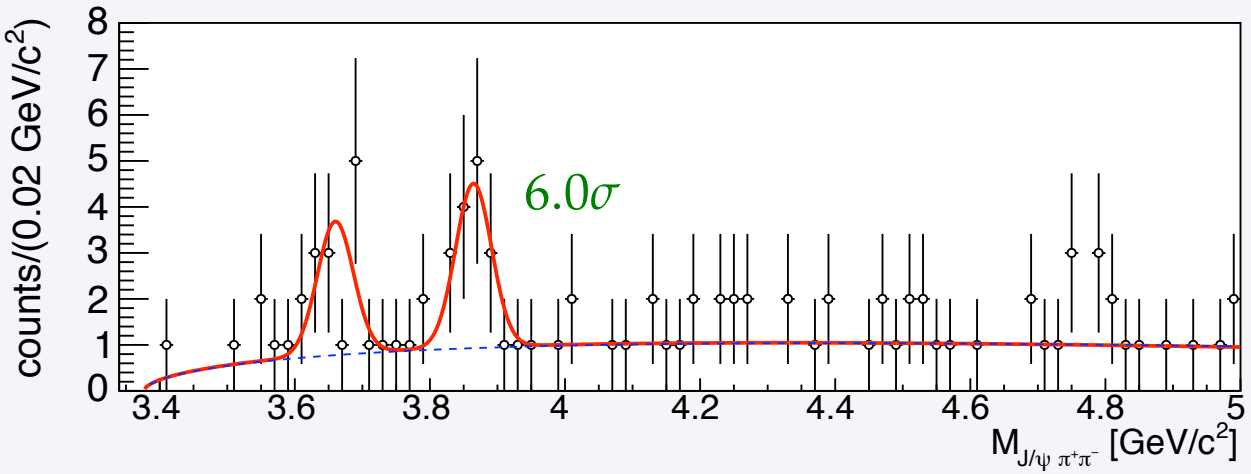
- Mass region $\pm 30\,\mathrm{MeV}/c^2$ around $\psi(2S)$ and $X(3872)$ peaks
- Smaller $\pi^\pm N'$ masses for $\psi(2S)$
  - Hint for different production mechanism

Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$

[arXiv:1707.01796]







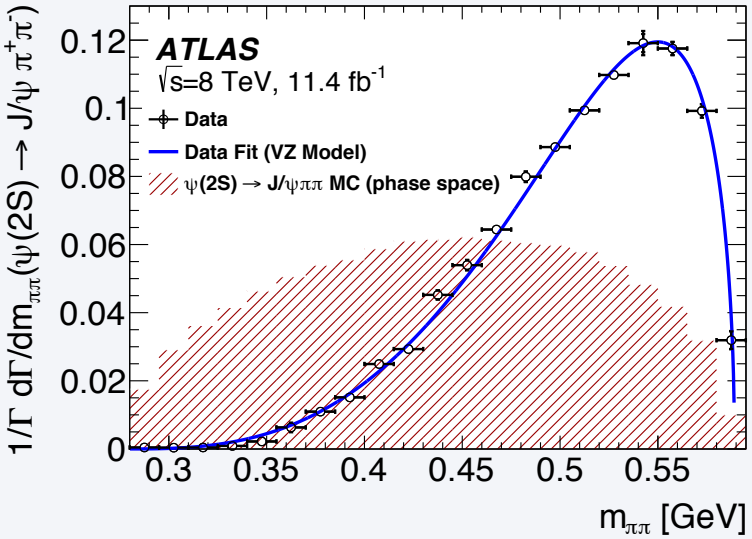
- Require $\pi^\pm N'$ mass $> 3\,\mathrm{GeV}/c^2$
  - Larger significance of $X(3872)$ signal

Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$

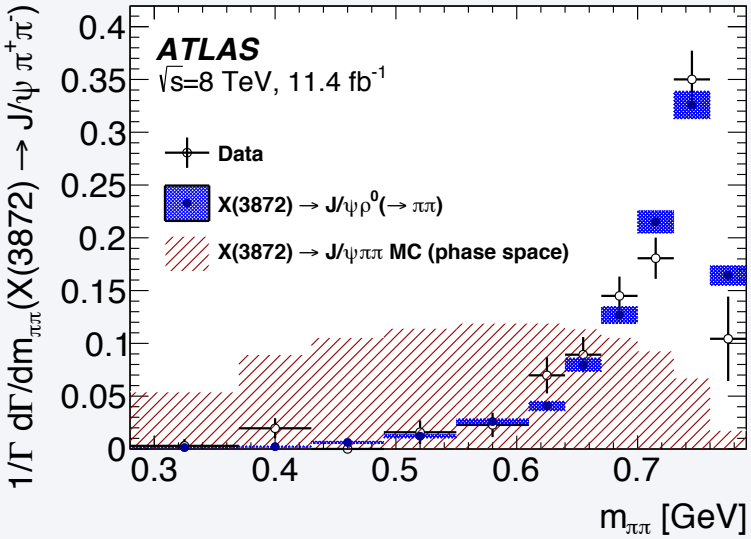
[arXiv:1707.01796]

$\pi^+\pi^-$ Mass Spectrum for $\psi(2S)$ and $X(3872)$ Peaks

$\psi(2S)$



$X(3872)$



ATLAS, JHEP **1701** (117) 2017

Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$

[arXiv:1707.01796]

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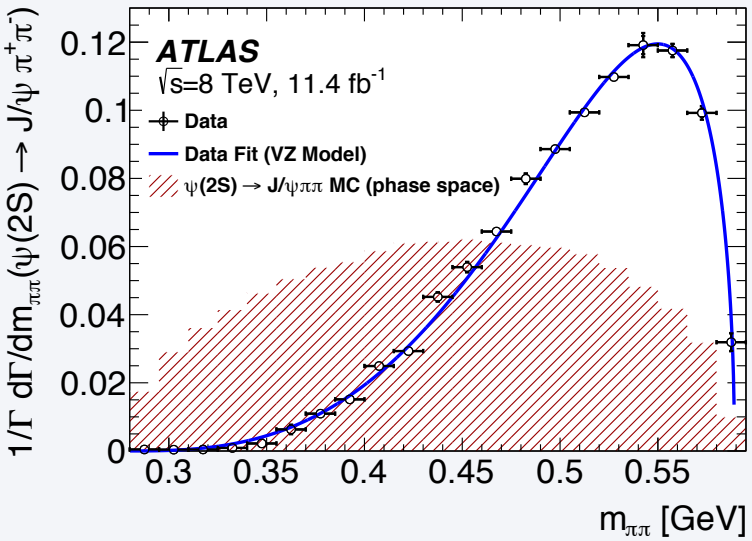
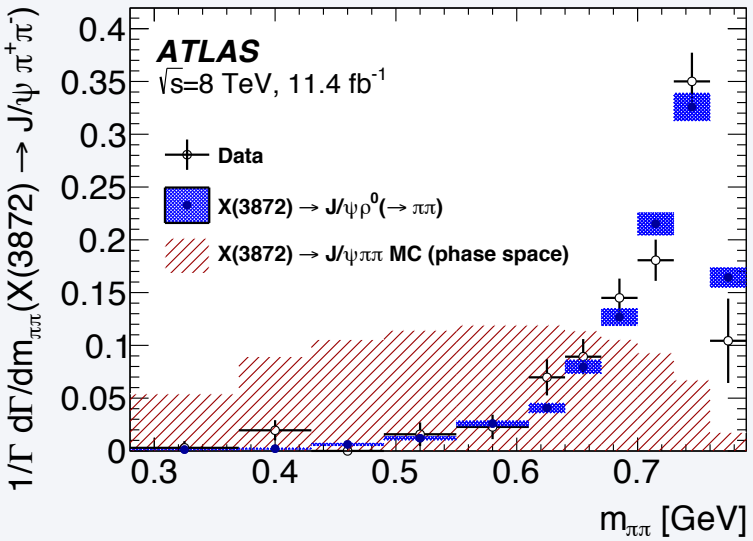


$X(3872)$



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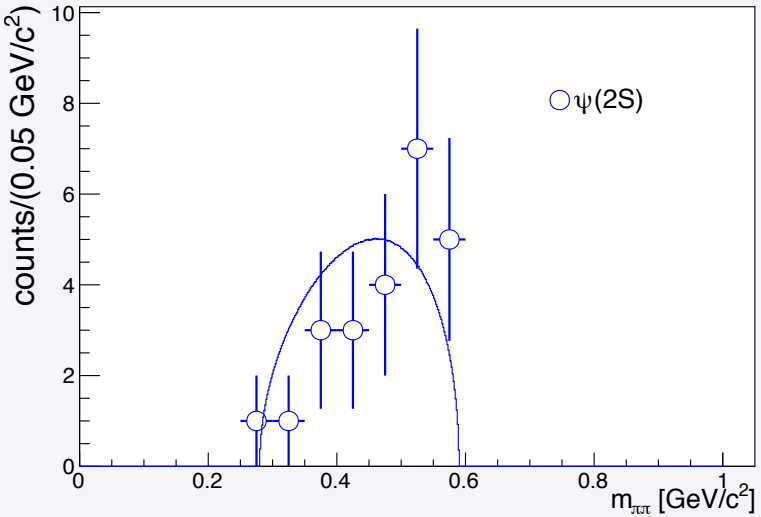

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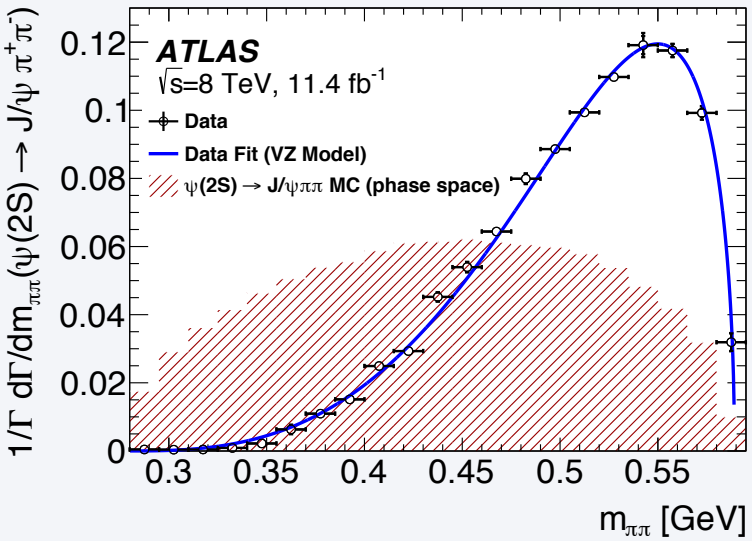
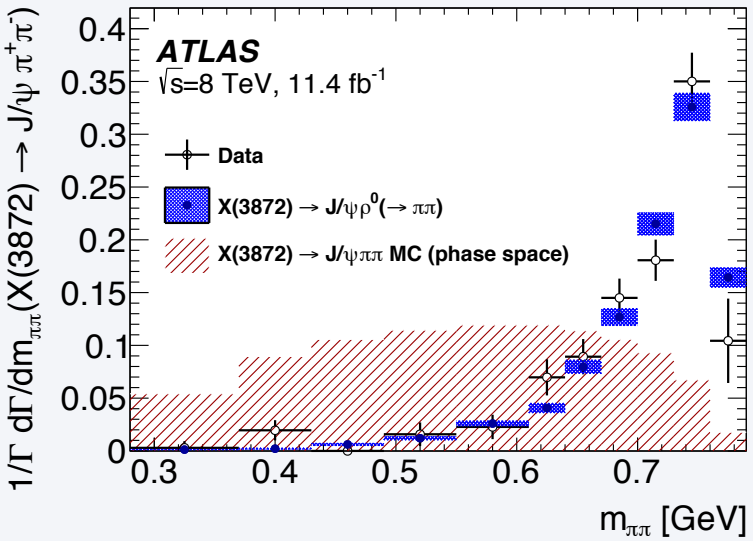


$X(3872)$



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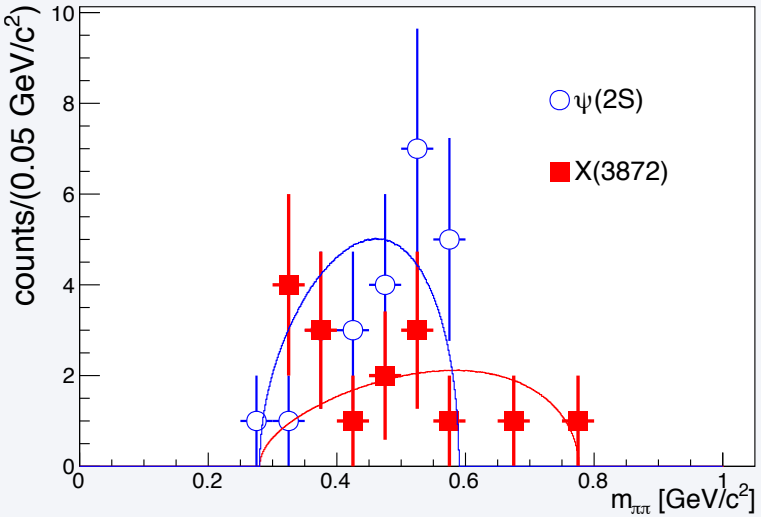

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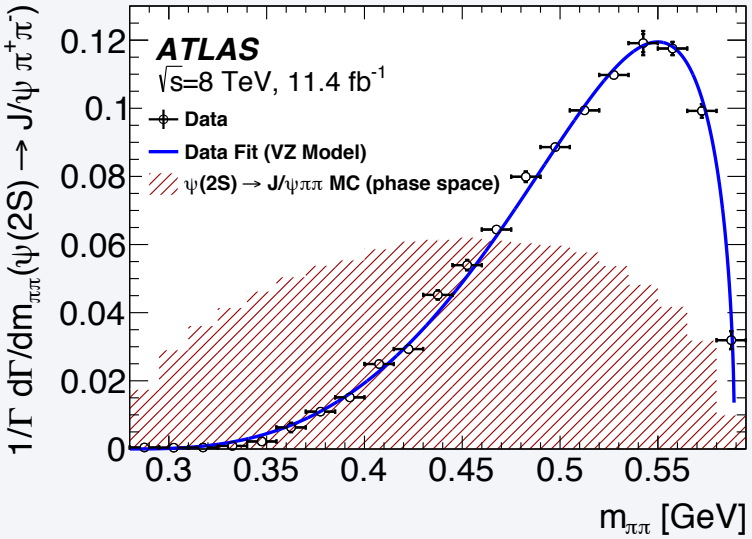

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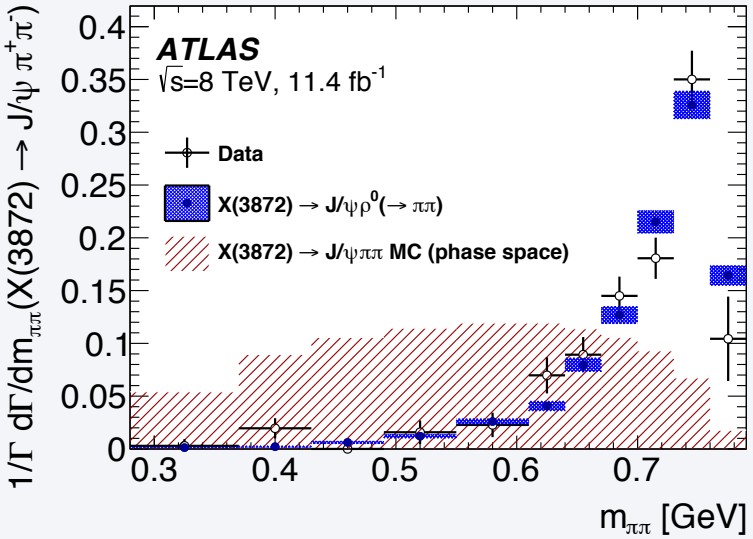

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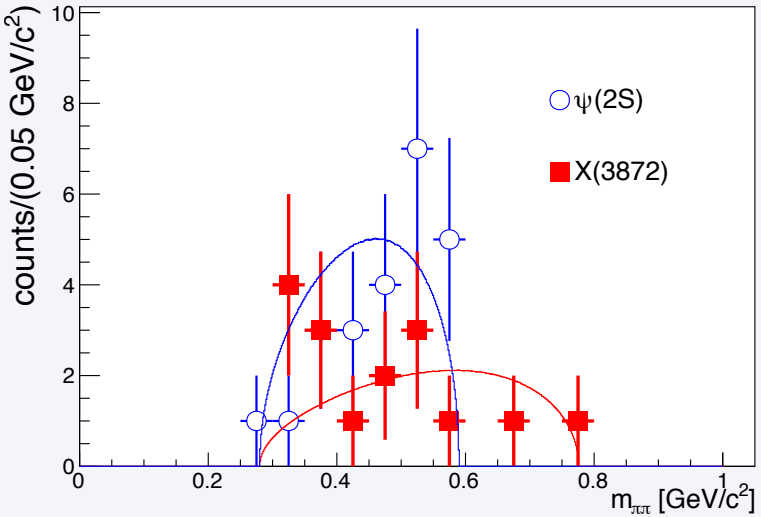
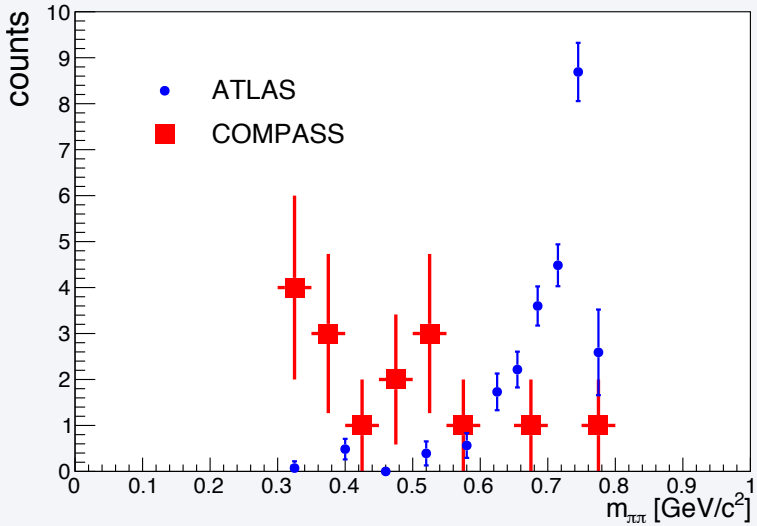
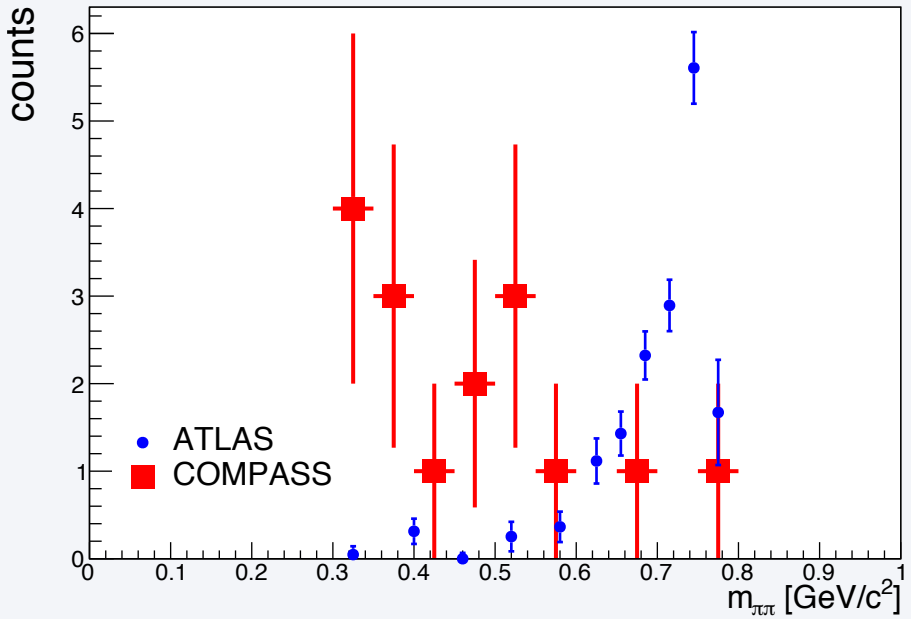




Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$

[arXiv:1707.01796]

$m_{\pi^+\pi^-}$ Distribution for $X(3872)$ Peak in Tension with previous Observations



Performed several studies

- Used sPlot technique to remove effect of background (ca. 40 %) $\Rightarrow$ same result
- Excluded acceptance effects
- Excluded lost π^0 in $X(3872) \to J/\psi\omega$
- Excluded $\chi_{c0,1,2} \to J/\psi\gamma$ with $\gamma \to e^+e^-$ misidentified as $\pi^+\pi^-$
- Excluded that $X(3872)$ peak is faked by $\psi(2S)N^*$ production

Exotic Heavy-Quark States

Summary and Outlook

Photoproduction

- Additional process to study production of exotic charmonia

COMPASS

- First measurements of (associated) photoproduction of
  - $X(3872)$
  - $Z_c^{\pm}(3900)$
  - $Z_c^{\pm}(4200)$
- Based on 7 years worth of data

Outlook

- More data from COMPASS runs in 2016 and 2017
- Exotic charmonia can also be studied with high-intensity photon beams at GlueX and CLAS12

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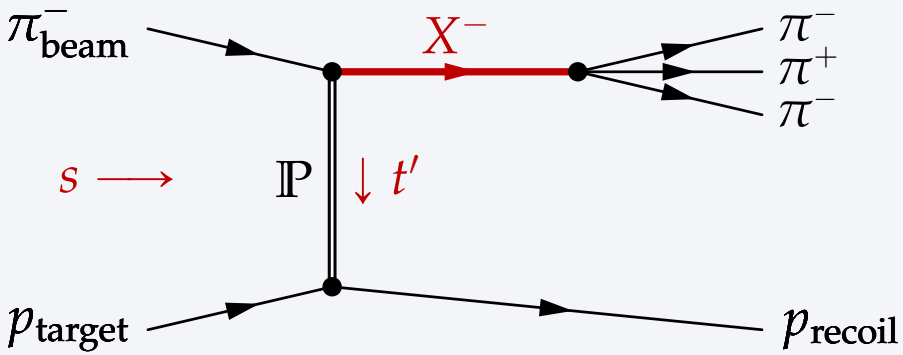
Meson Production in Diffractive Dissociation

Example: $\pi^-\pi^-\pi^+$ final state at COMPASS

COMPASS, PRD **95** (2017) 032004



Soft scattering of 190 GeV/c π^- beam off proton target

- Interaction dominated by space-like pomeron exchange
- Excitation of beam pion into intermediate resonances X
- X dissociate into forward-going $\pi^-\pi^-\pi^+$ final state
- Target proton stays intact

Rich spectrum of intermediate states X

- Disentangle all contributing X by **partial-wave analysis** (PWA)

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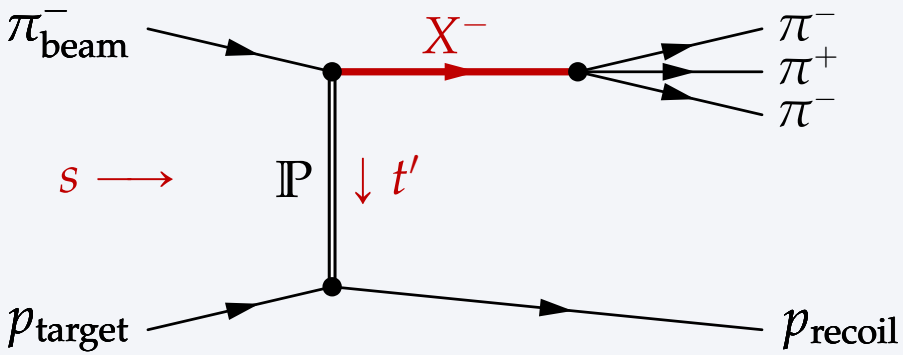

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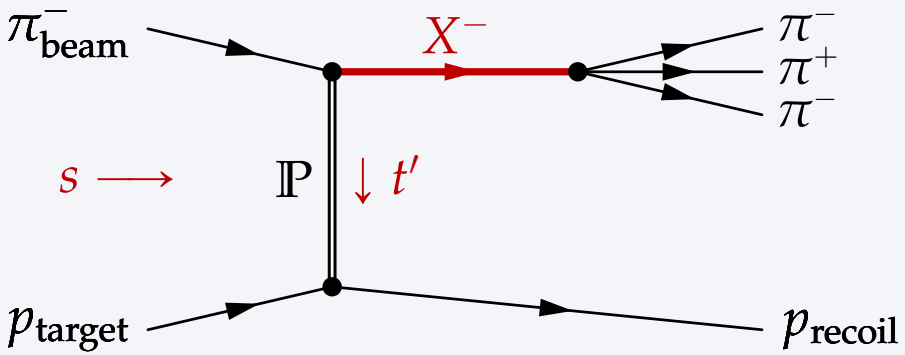
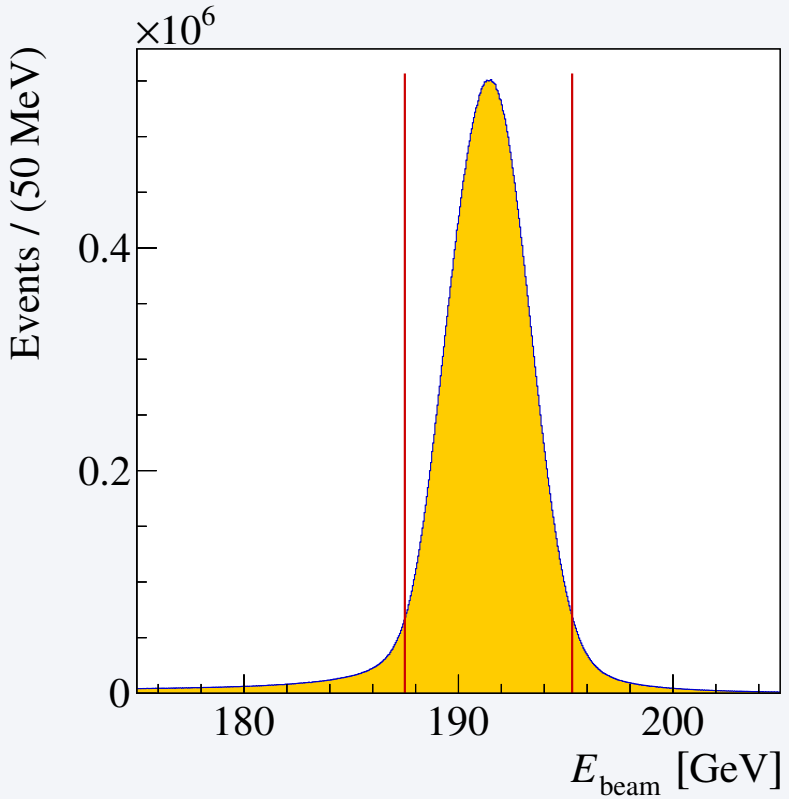


- Exclusive measurement
- Squared four-momentum transfer $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- Well-known 3π resonances appear in $m_{3\pi}$
- 46 M $\pi^-\pi^-\pi^+$ events spectrum



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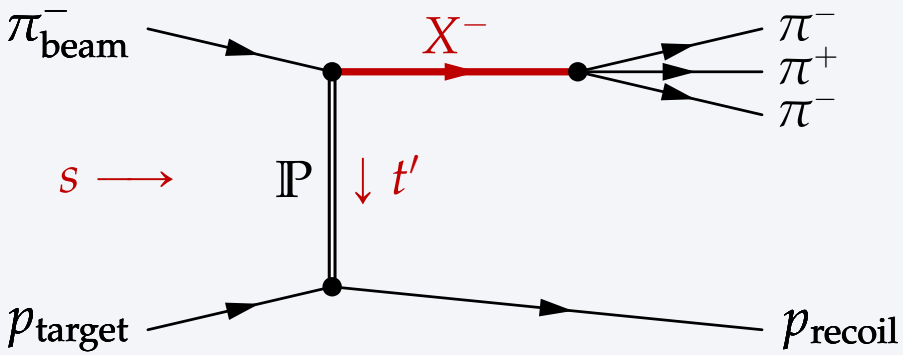

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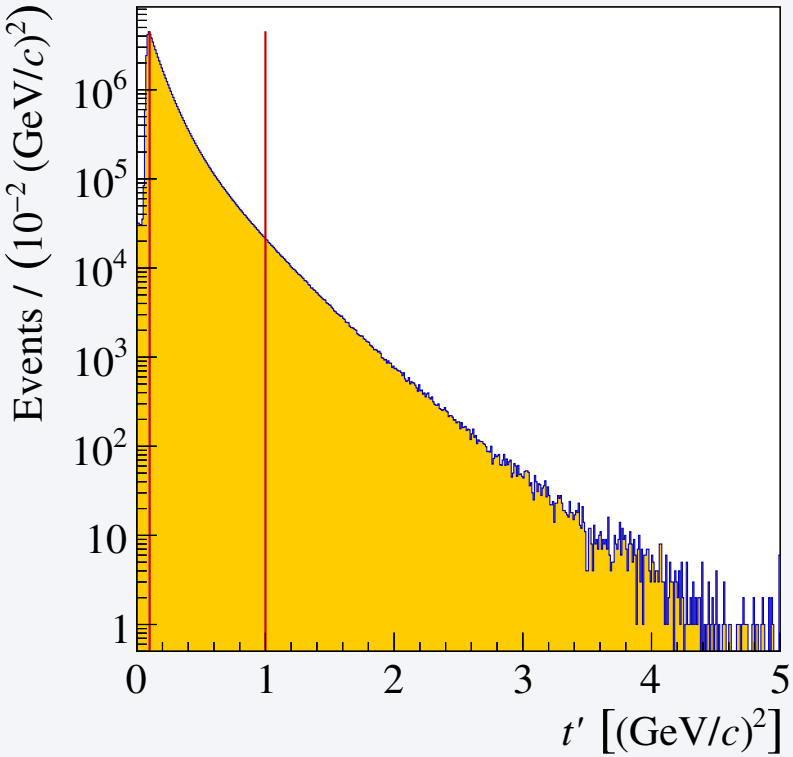

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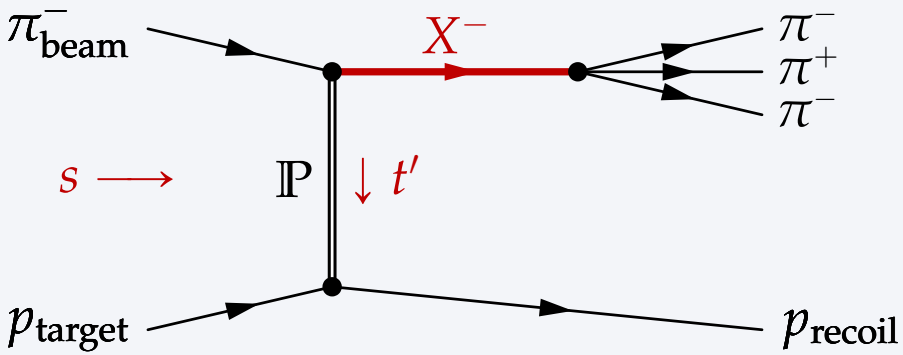

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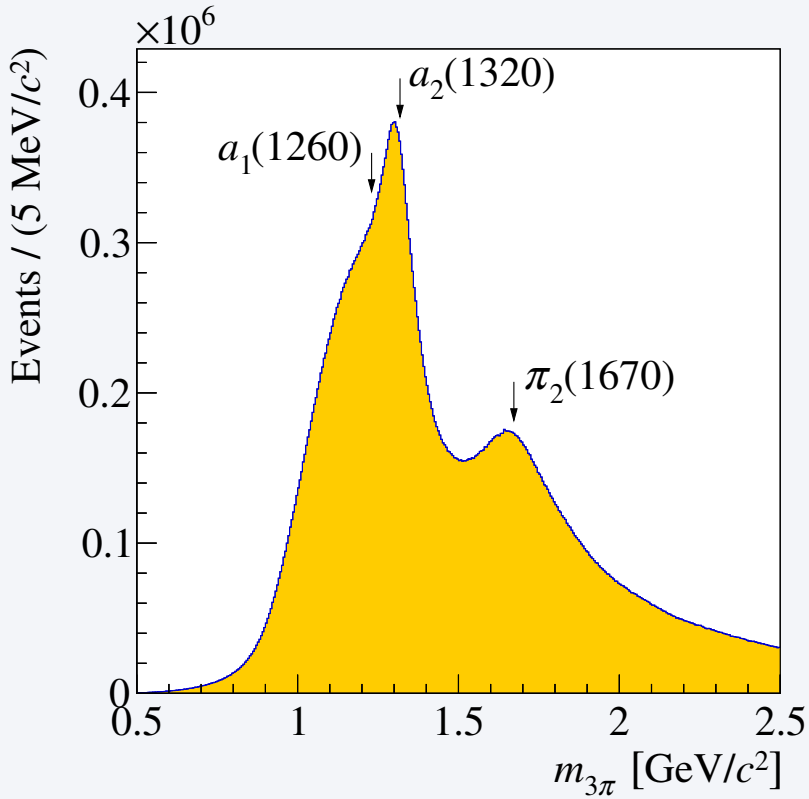

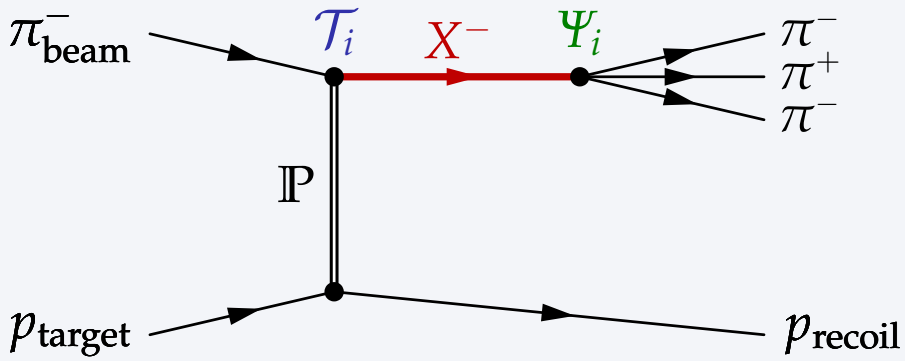

Ansatz: Factorization of production and decay

$$\mathcal{I}(\tau; m_{3\pi}) = \left| \sum_{i}^{\text{waves}} \mathcal{T}_i(m_{3\pi})\, \Psi_i(\tau; m_{3\pi}) \right|^2$$

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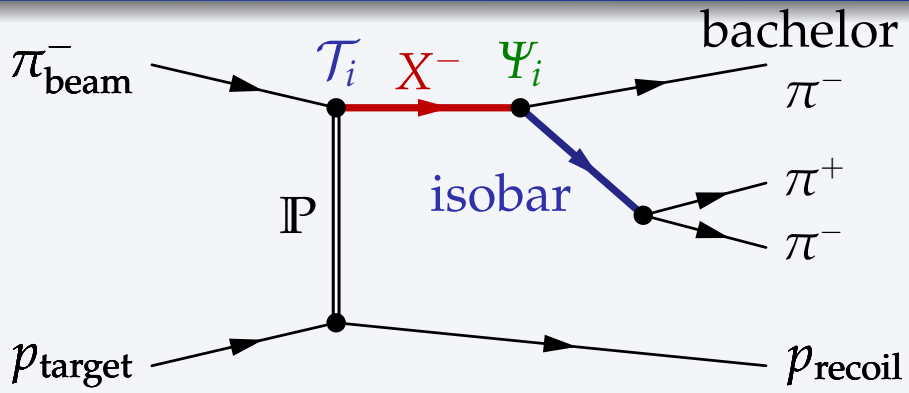

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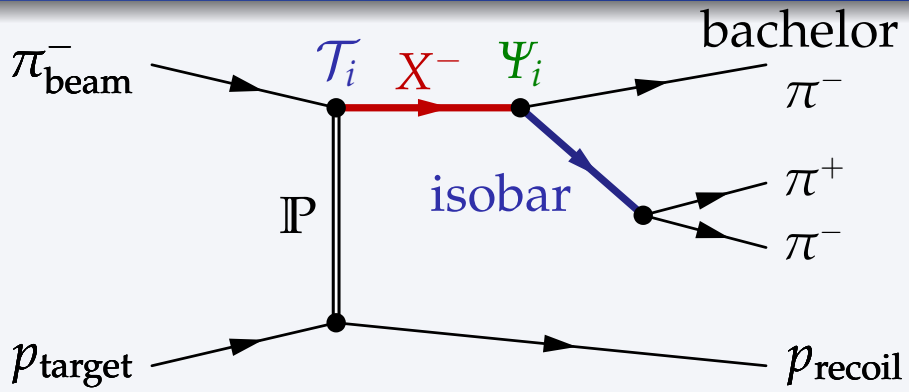
COMPASS, PRD **95** (2017) 032004



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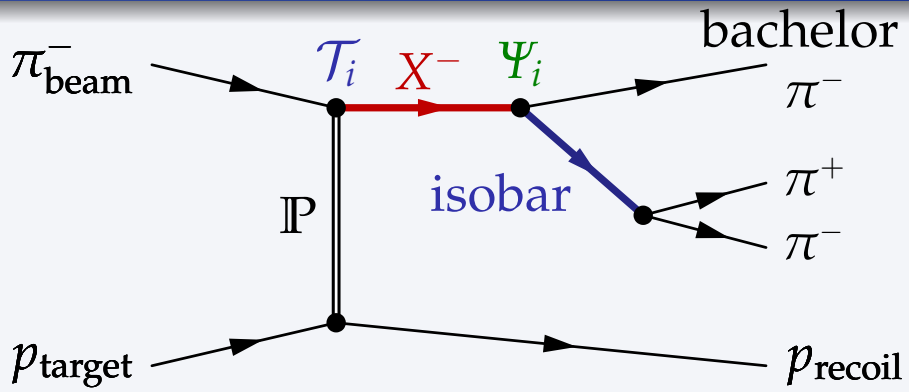

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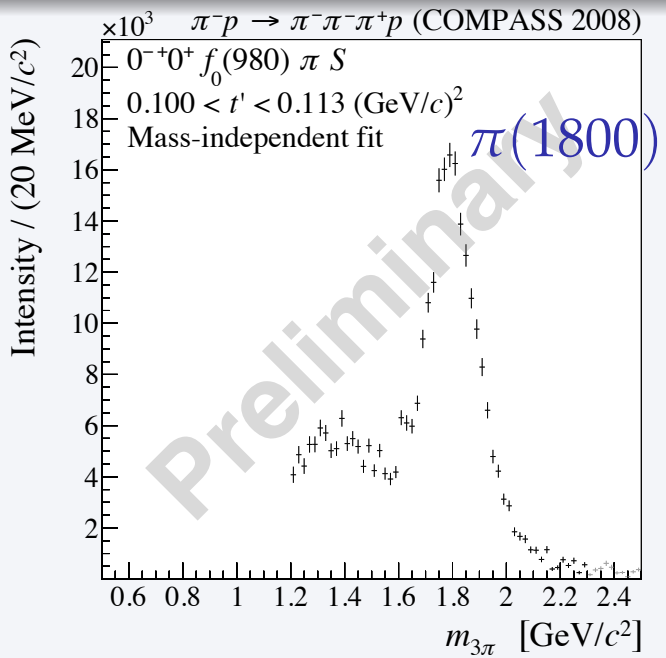

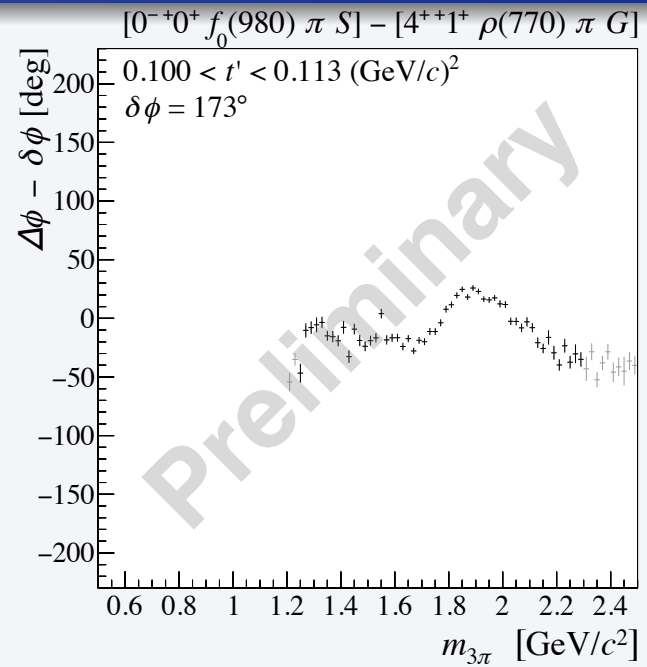

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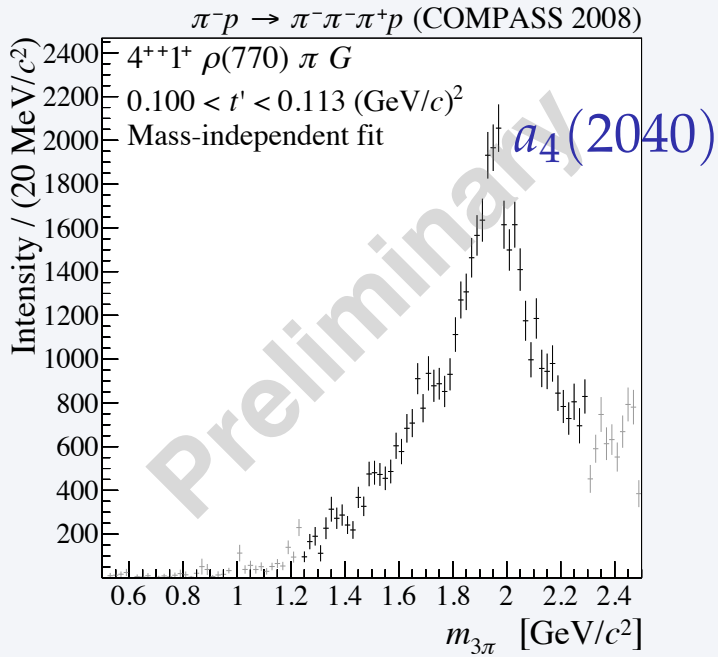

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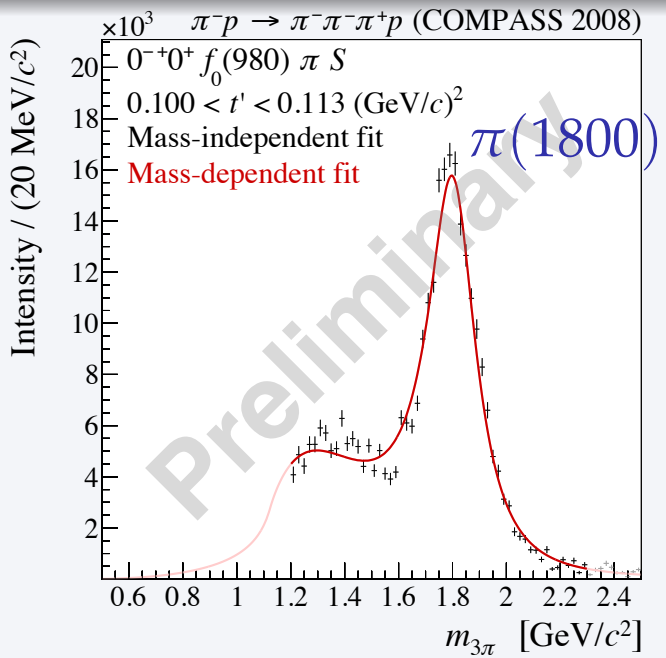

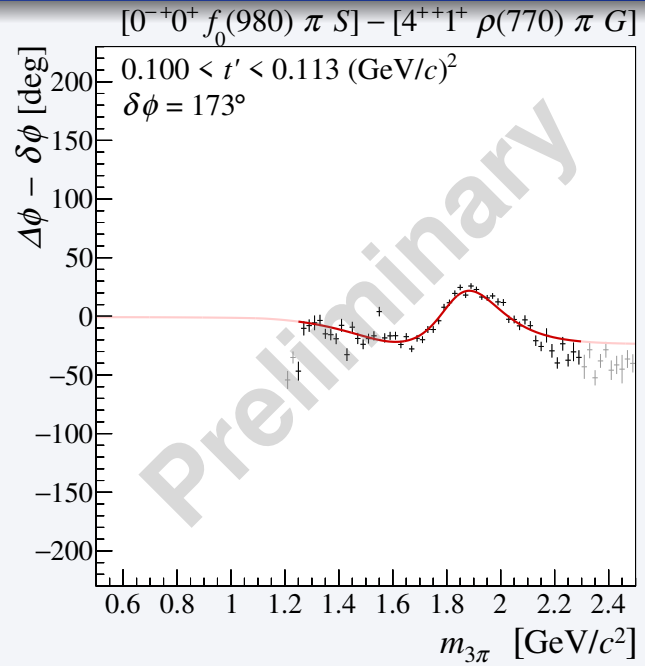

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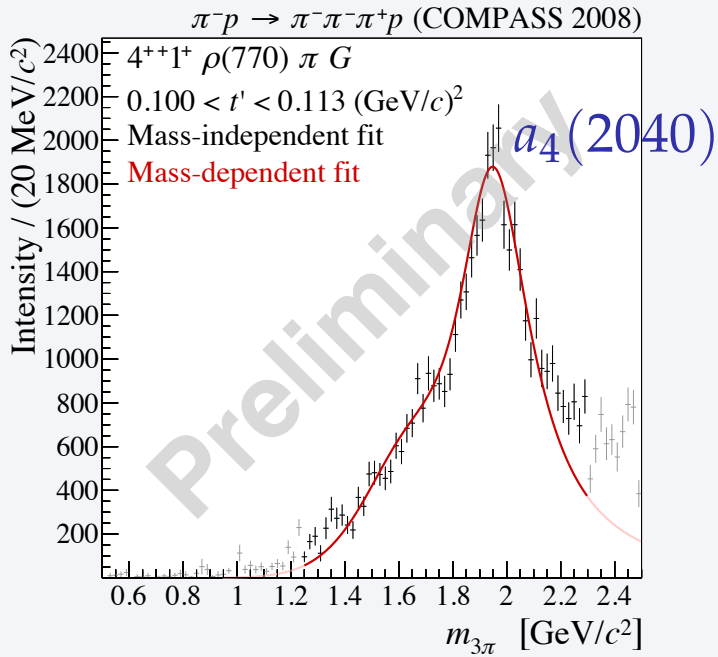

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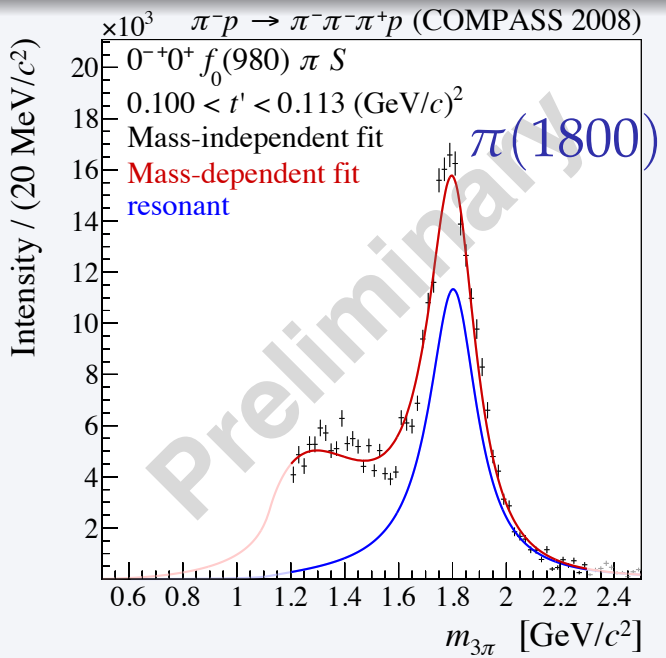

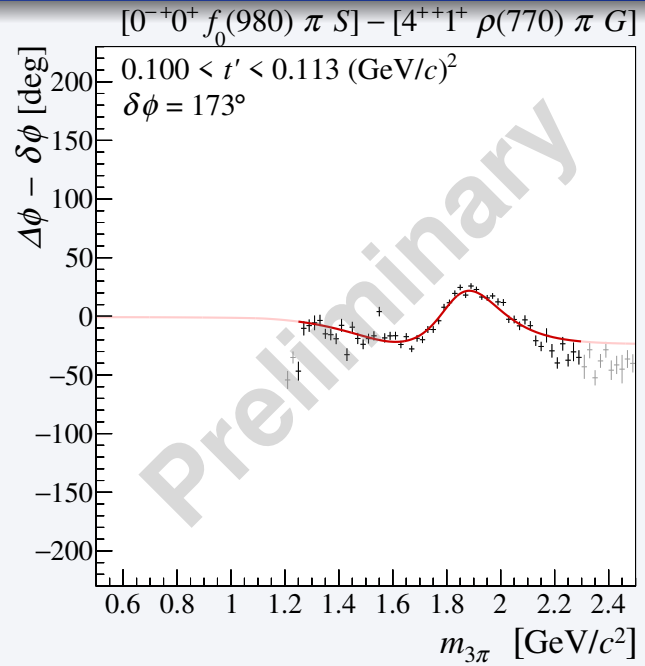

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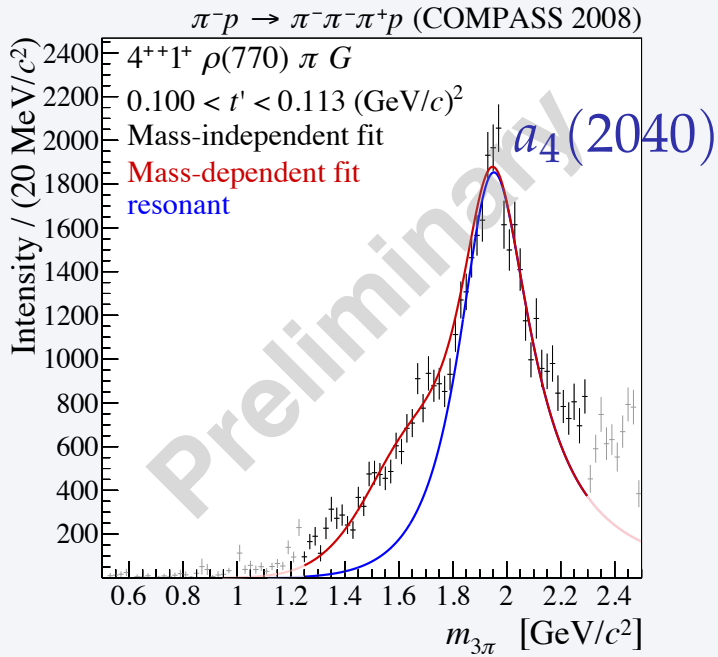

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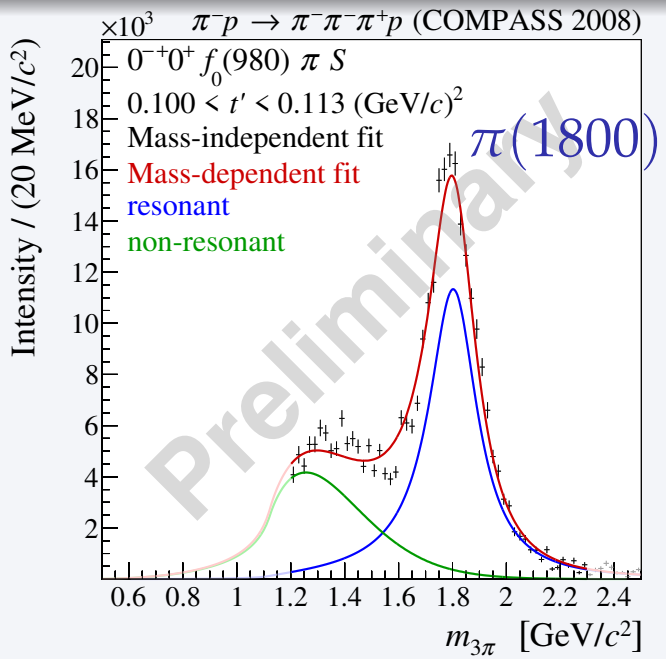

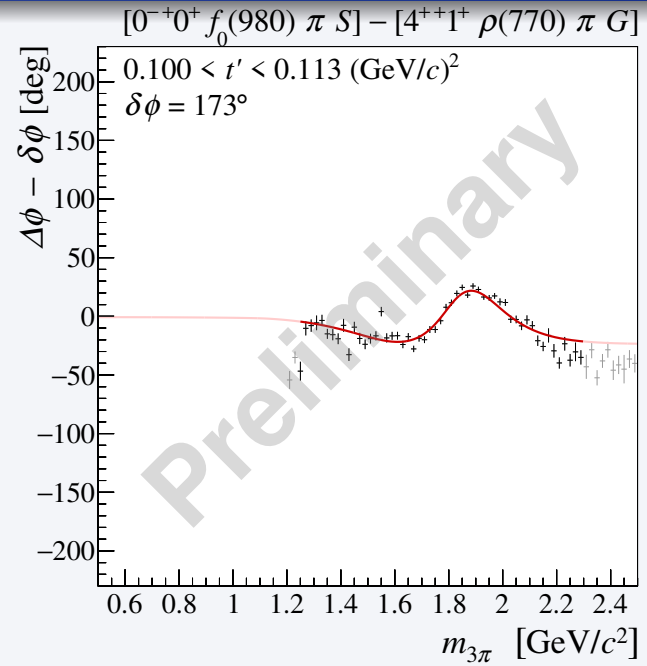

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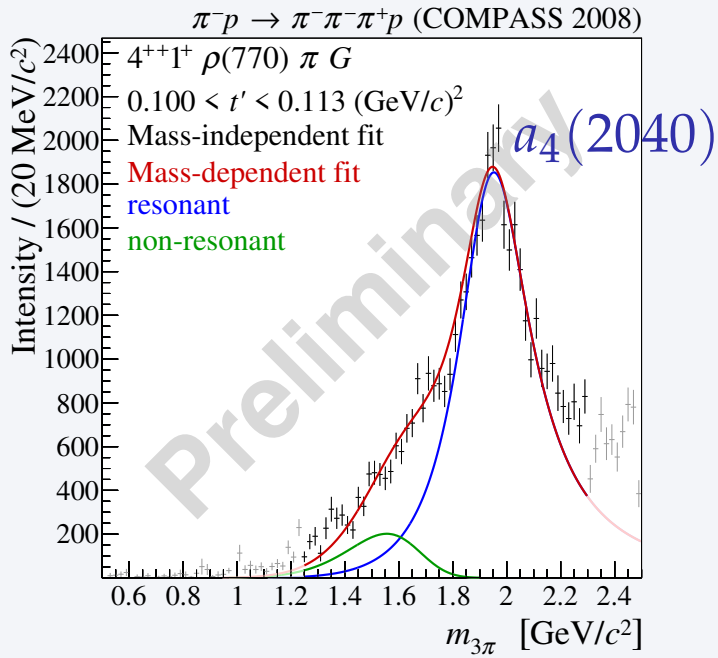
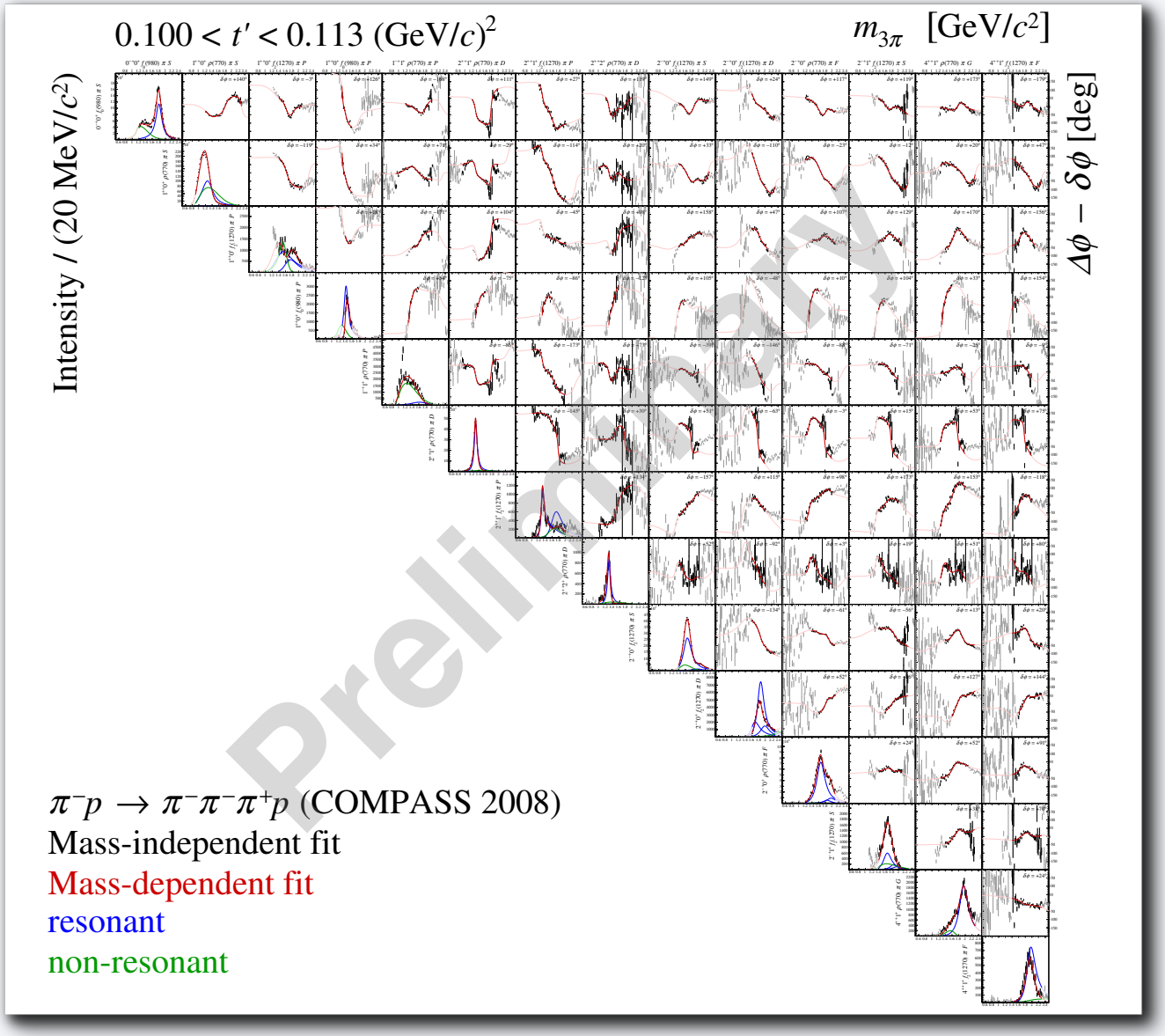


Resonance-Model Fit of $\pi^-\pi^-\pi^+$ Data



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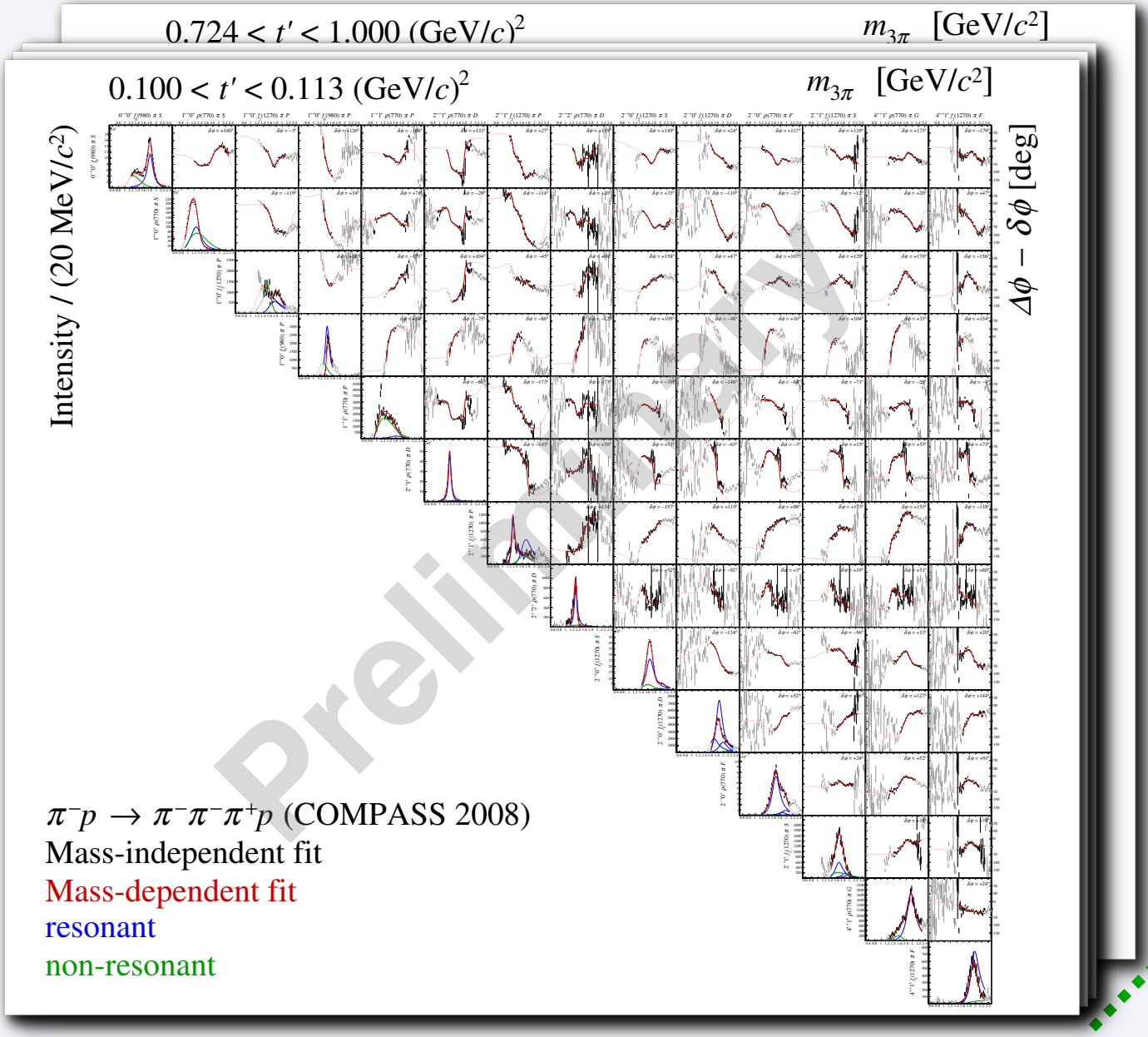
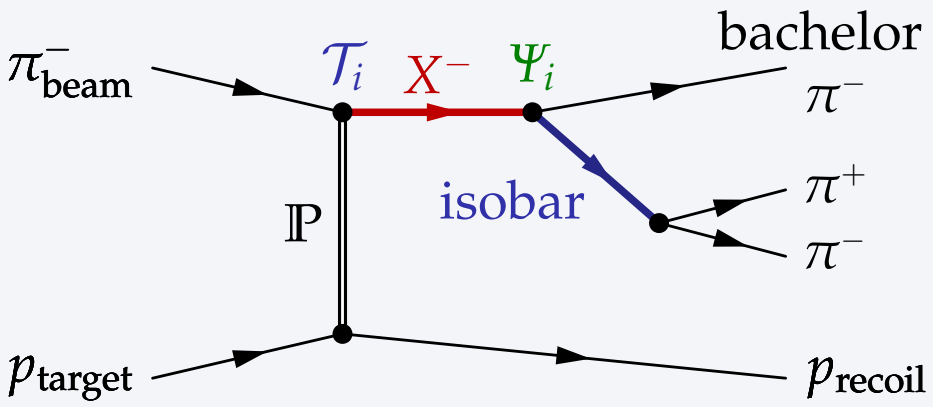


Reducing Bias due to Isobar Parametrizations



- Calculation of decay amplitudes $\Psi_i(\tau)$ needs precise knowledge of isobar $\to \pi^-\pi^+$ amplitude
- E.g. $J^{PC} = 0^{++}$: at least 3 isobars
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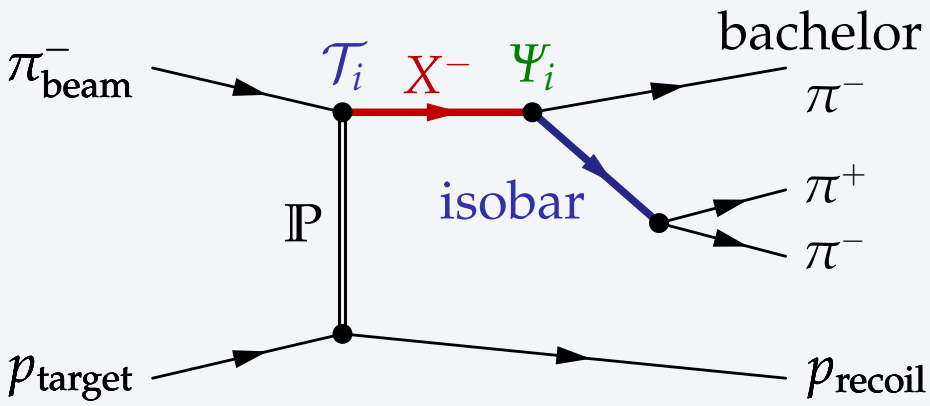

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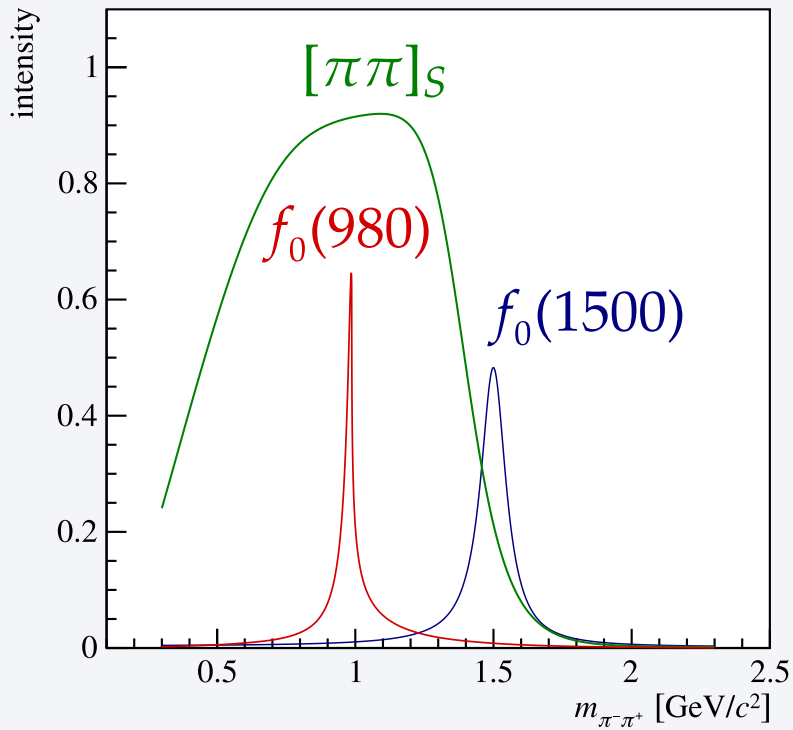

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Novel analysis method

inspired by E791, PRD **73** (2006) 032204

- Replace fixed $J^{PC} = 0^{++}$ isobar parametrizations by piece-wise constant amplitudes in $m_{\pi^-\pi^+}$ bins
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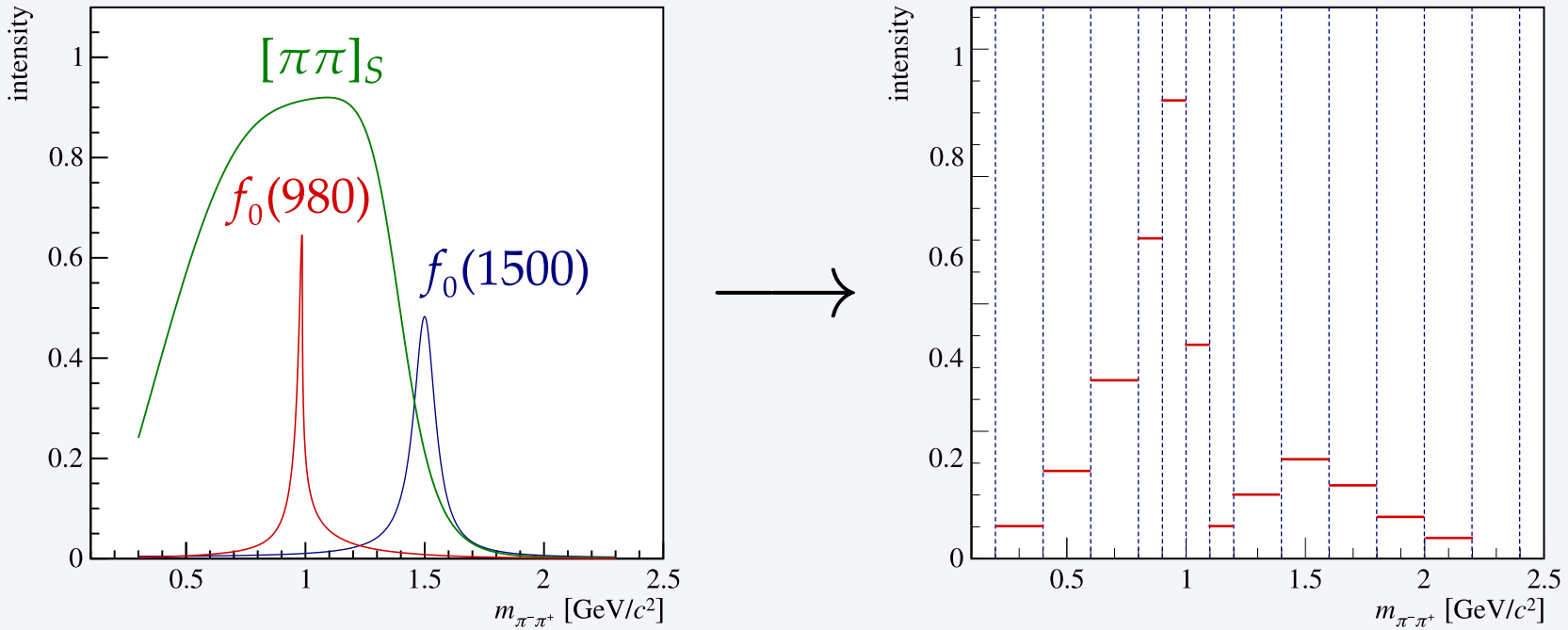

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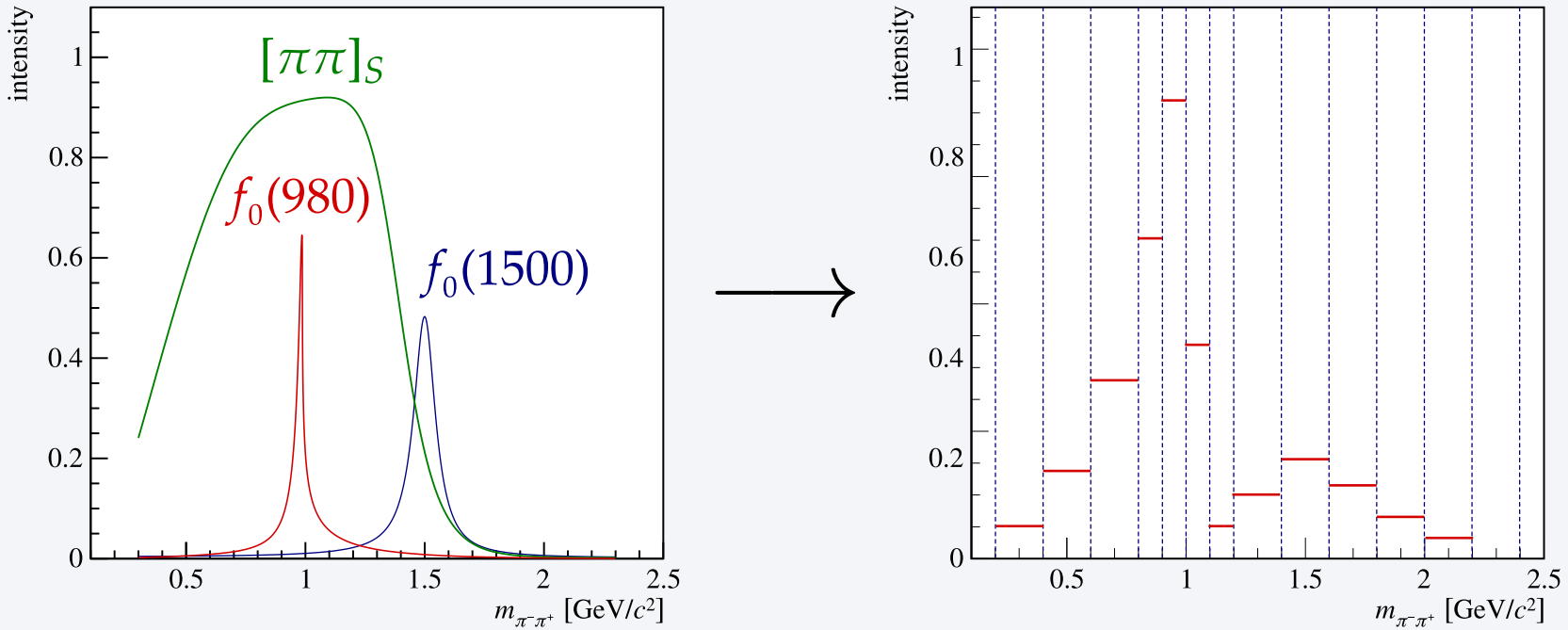
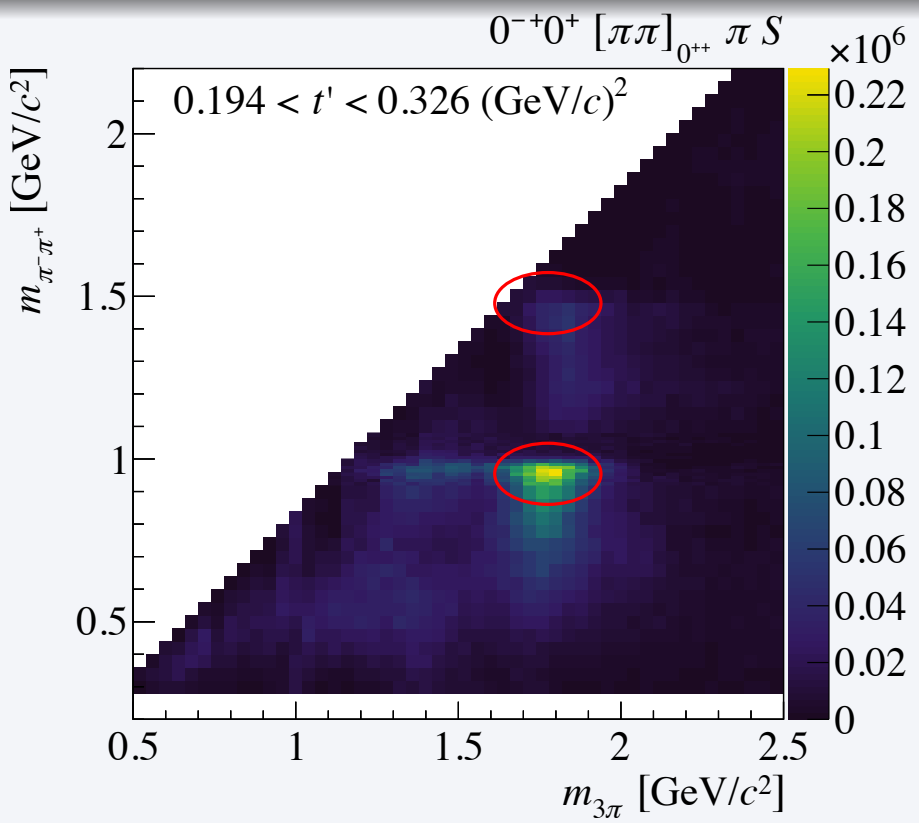
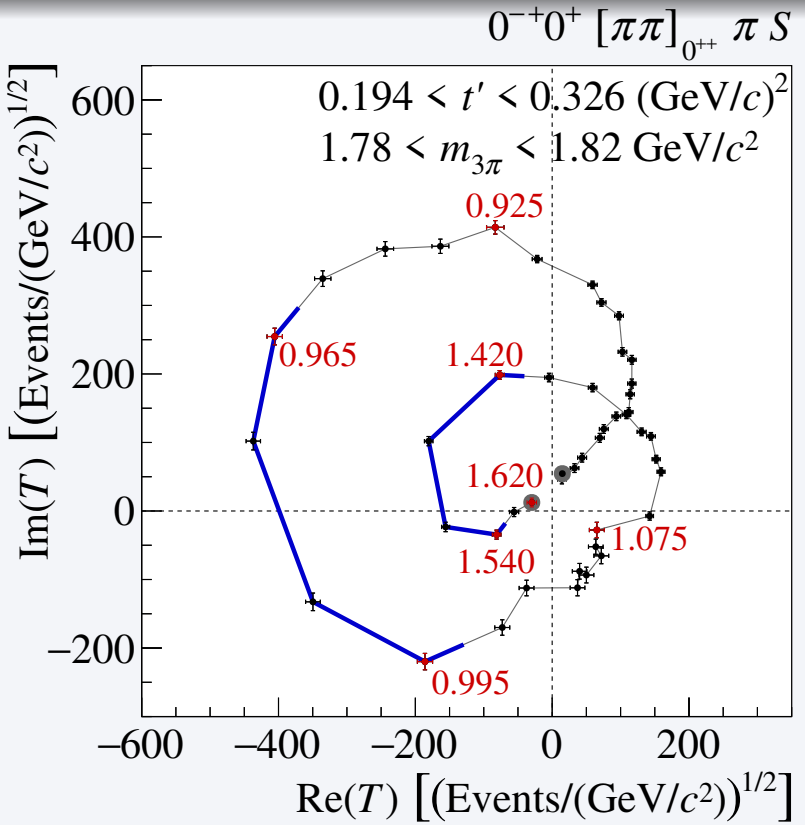


$\pi\pi$ S-Wave Amplitude in $J^{PC} = 0^{-+}$ 3π Wave

COMPASS, PRD **95** (2017) 032004





- Coupling of $\pi(1800)$ to $f_0(980)\pi$ and $f_0(1500)\pi$ decay modes
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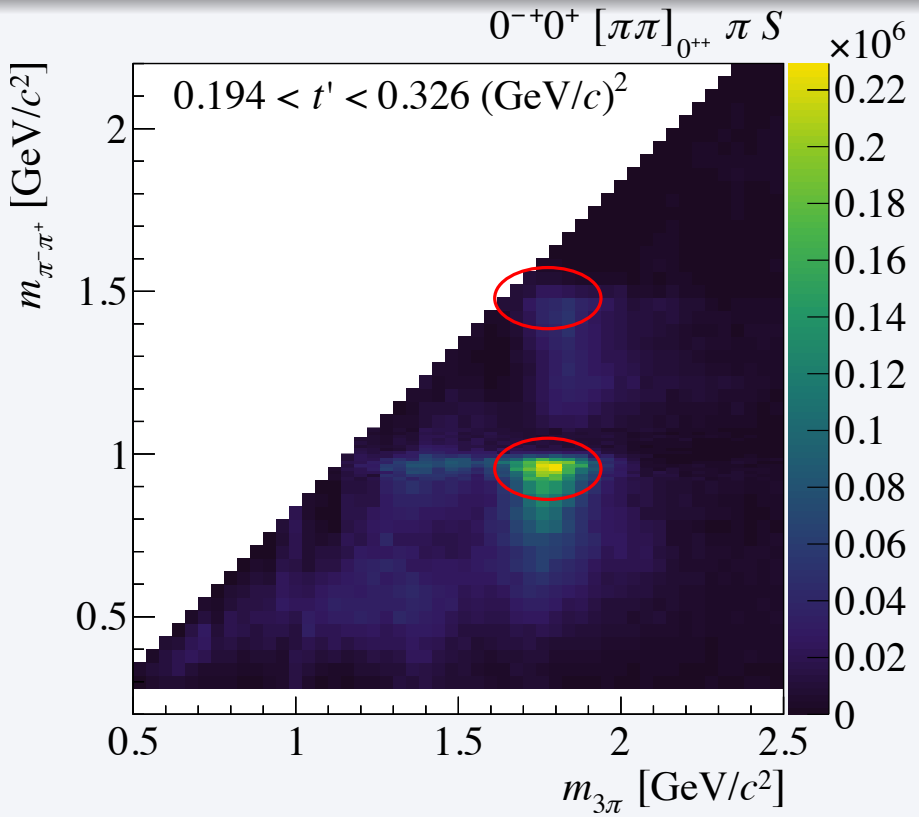

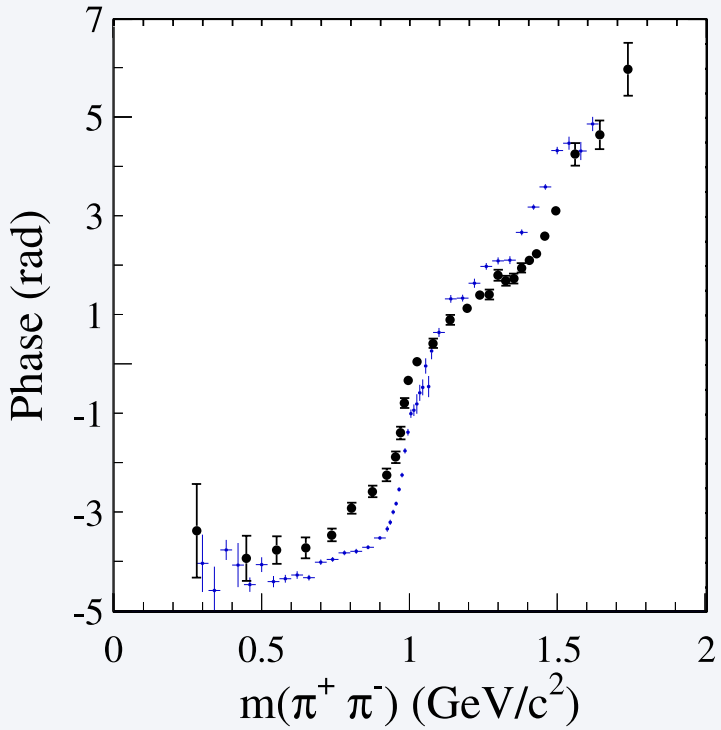

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- Paper about resonance-model fit in collaboration review

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  F. Krinner *et al. [arXiv:1710.09849]*
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