# Search for Exotic Heavy- and Light-Quark Mesons at COMPASS

Boris Grube*

for the COMPASS Collaboration

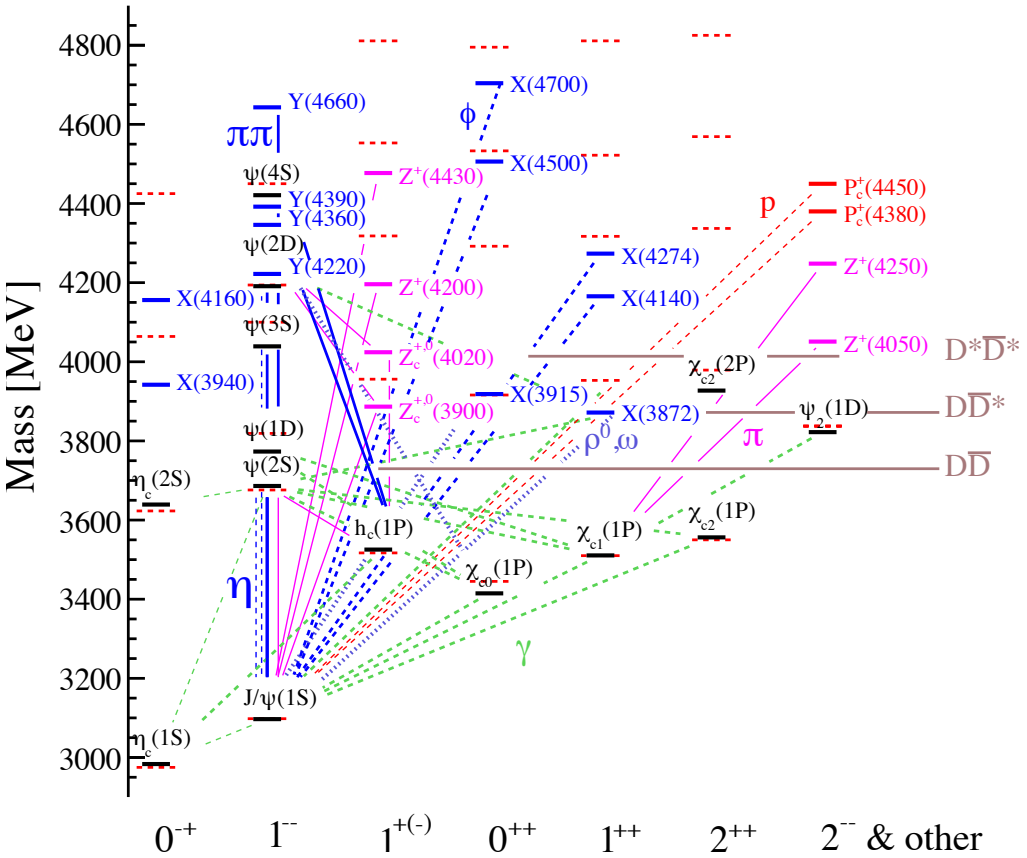
*Jefferson Lab

Workshop on
Exotic heavy meson spectroscopy and structure with EIC
15. August 2022, CFNS Stony Brook University, NY

# Part I

# Exotic Heavy-Quark Mesons

# Exotic Charmonium-Like States




S.L. Olsen, T. Skwarnicki, D. Zieminska,
Rev. Mod. Phys. **90** (2018) 015003

## Observed in various production mechanisms

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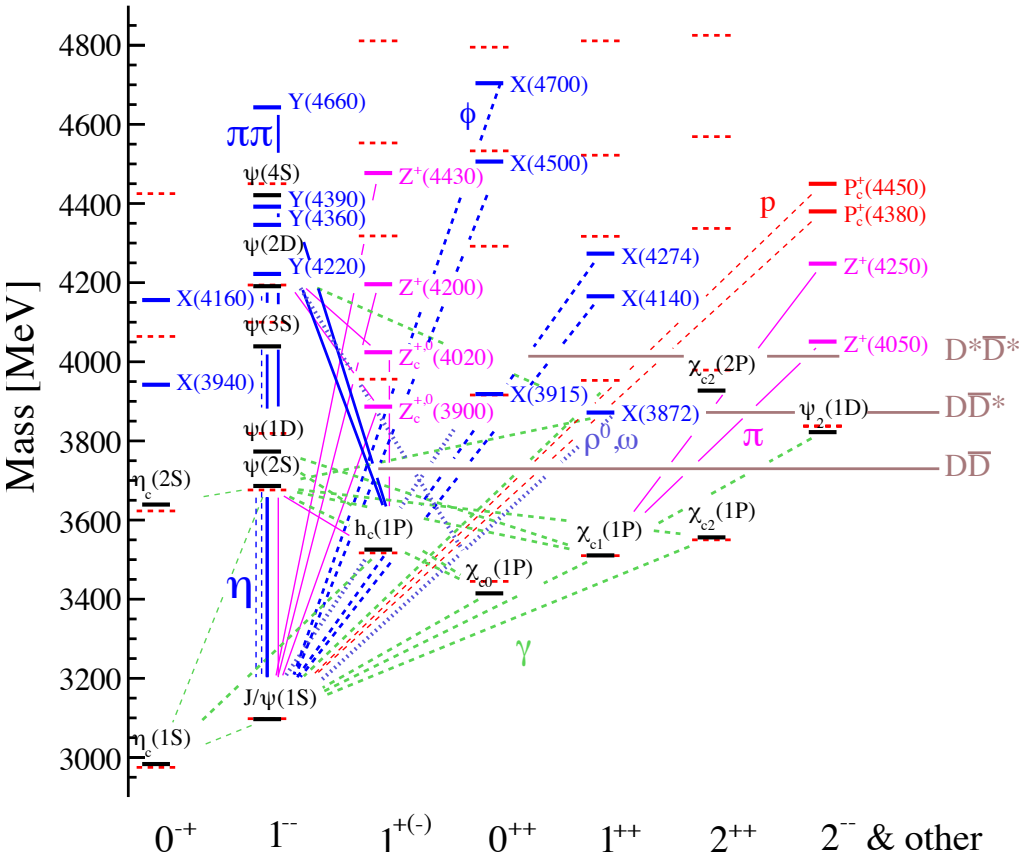


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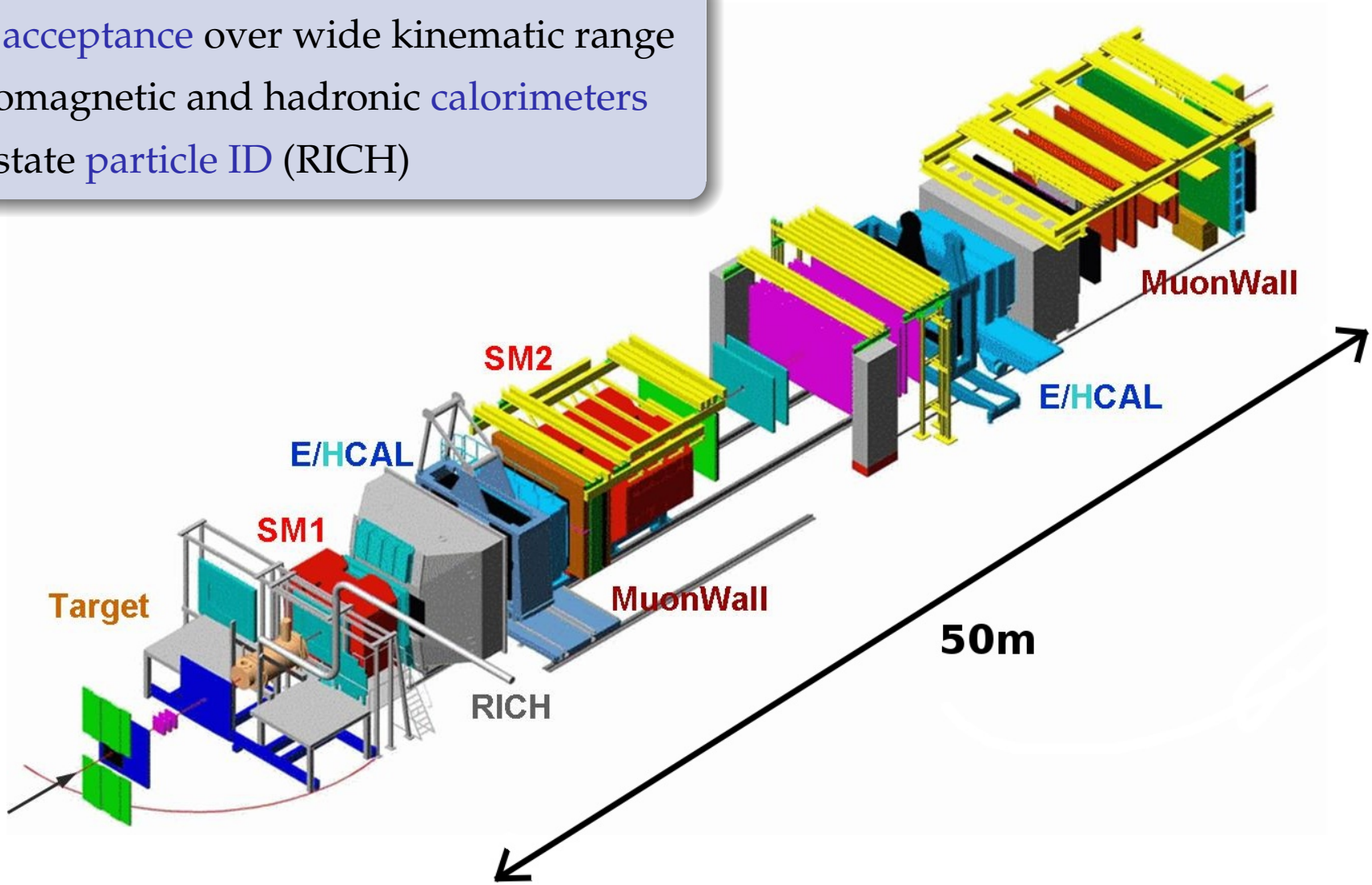
## Fixed-target experiment

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



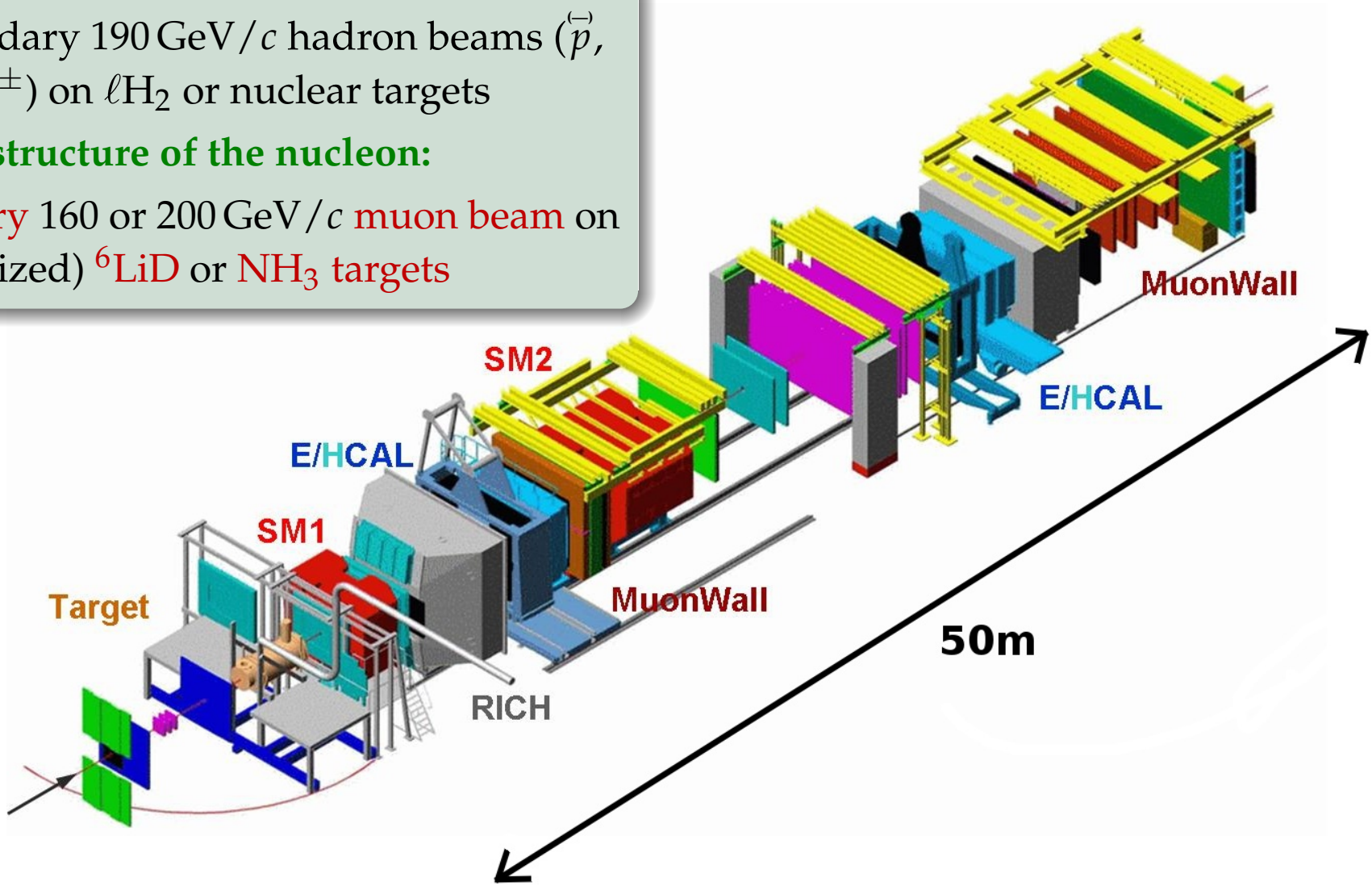
## Physics goals

- **Spectroscopy of light mesons:**

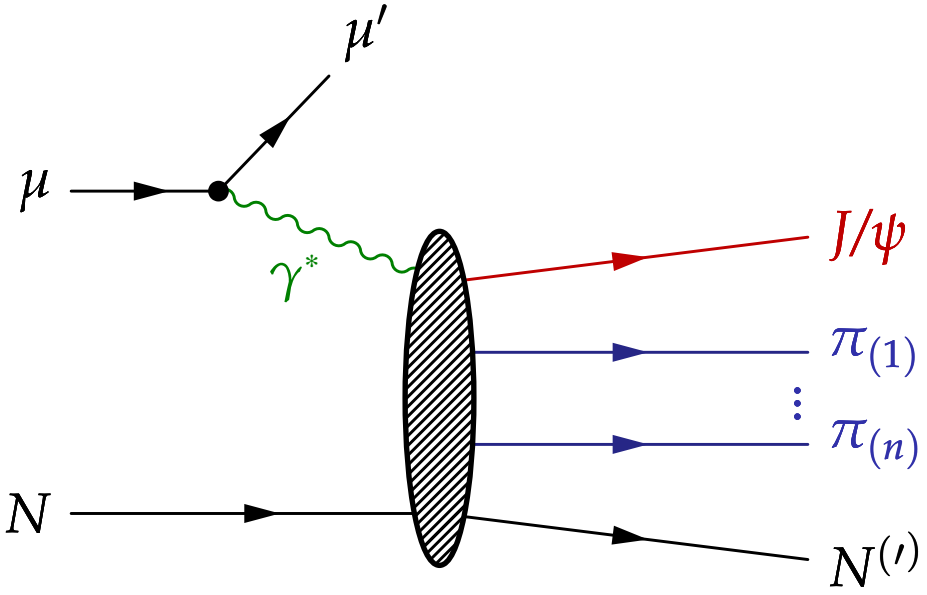
  Secondary 190 GeV/$c$ hadron beams ($\overset{(-)}{p}$, $\pi^{\pm}$, $K^{\pm}$) on $\ell H_2$ or nuclear targets

- **Spin structure of the nucleon:**

  Tertiary 160 or 200 GeV/$c$ muon beam on (polarized) $^6$LiD or $NH_3$ targets



# (Associated) Muoproduction of Charmonium(-Like) States




## Measure exclusive events

- Production of $J/\psi$ in association with $n$ charged pions by virtual photons
  - Here: $n = 0, 1, 2, 3$
- Search for exotic states in $J/\psi\pi^{\pm}$ and $J/\psi\pi^{+}\pi^{-}$ decay channels
- Target recoil $N^{(\prime)}$ unobserved

## COMPASS data from 7 years

| Year | Beam | Target |
|---|---|---|
| 2002 | $\mu^+$, 160 GeV/$c$ | $^6$LiD |
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| 2004 | $\mu^+$, 160 GeV/$c$ | $^6$LiD |
| 2006 | $\mu^+$, 160 GeV/$c$ | $^6$LiD |
| 2007 | $\mu^+$, 160 GeV/$c$ | $NH_3$ |
| 2010 | $\mu^+$, 160 GeV/$c$ | $NH_3$ |
| 2011 | $\mu^+$, 200 GeV/$c$ | $NH_3$ |

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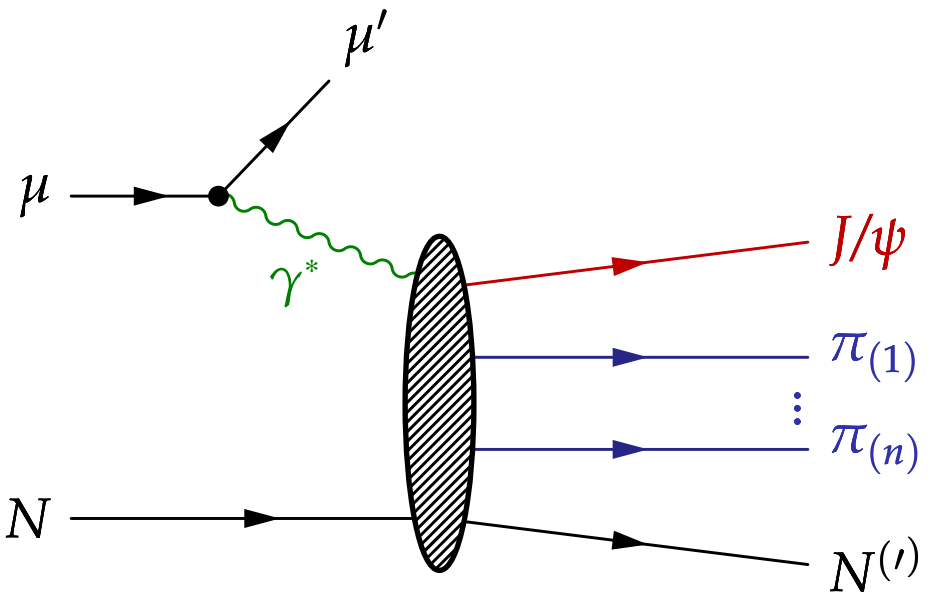


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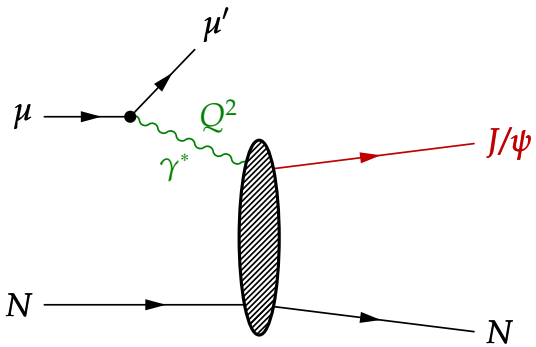
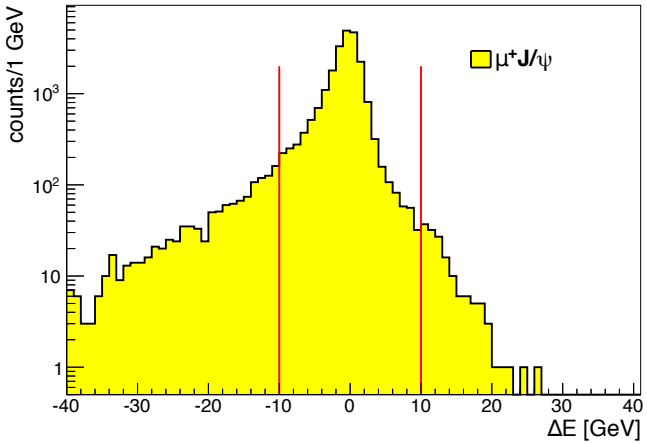
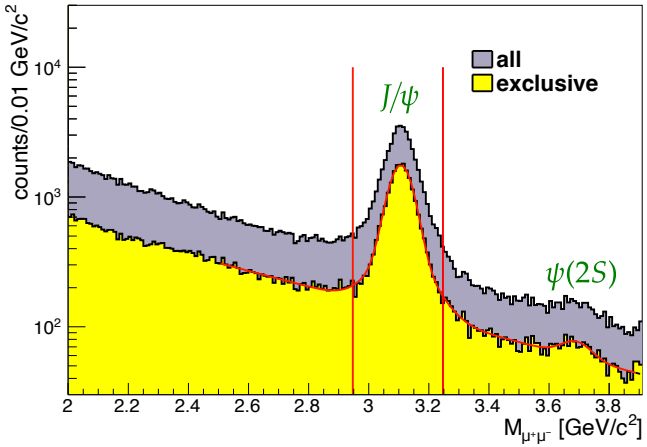
# Exclusive Muoproduction of $J/\psi$

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




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

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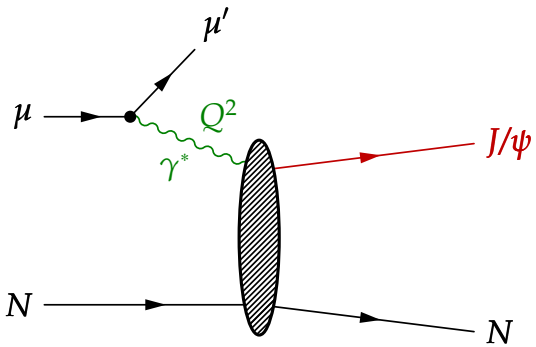


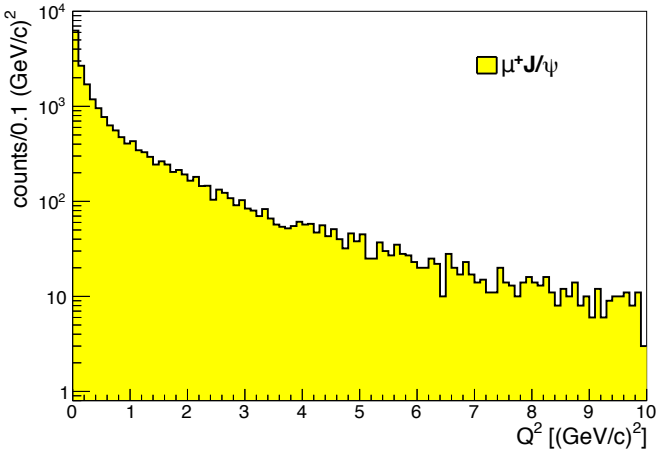


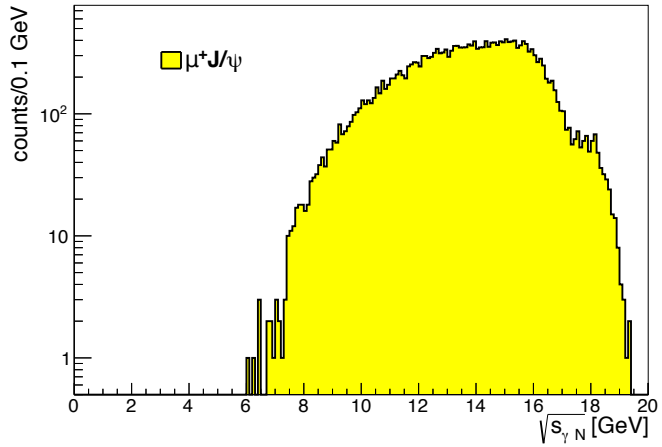


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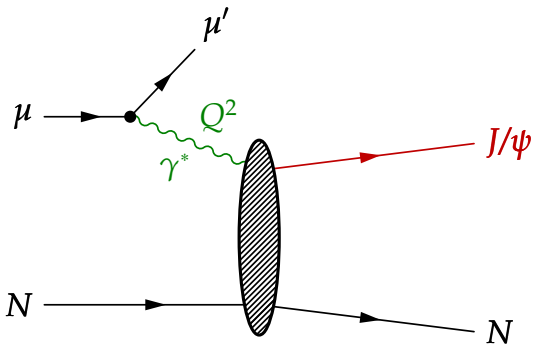


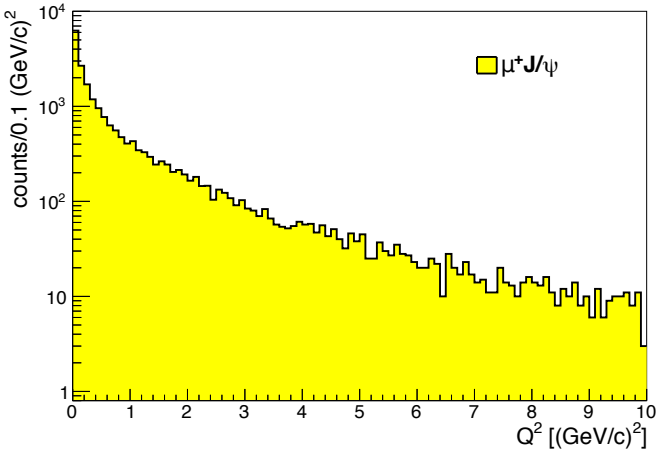


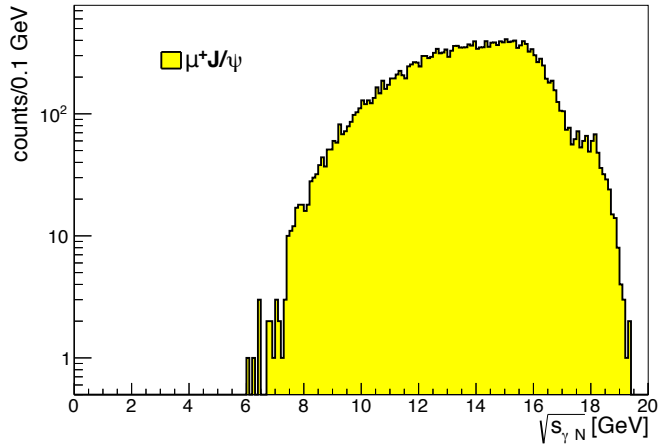


## Incoherent exclusive $J/\psi$ production used as normalization

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

  NA-14 (CERN), ZPC **33** (1987) 505
- Corrected by factor 0.8 to take into account $Q^2$ dependence using parametrization from ZEUS, NPB **695** (2004) 3
- Separate incoherent from coherent scattering off target nuclei by fitting sum of 2 exponentials to $p_T^2$ spectrum

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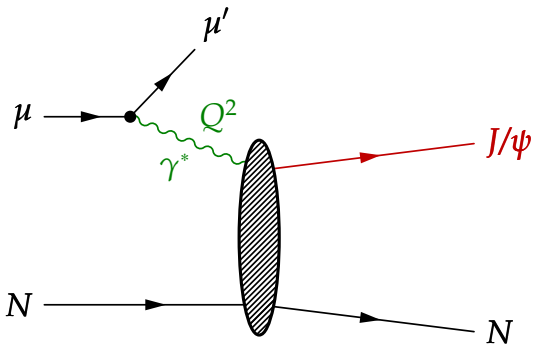


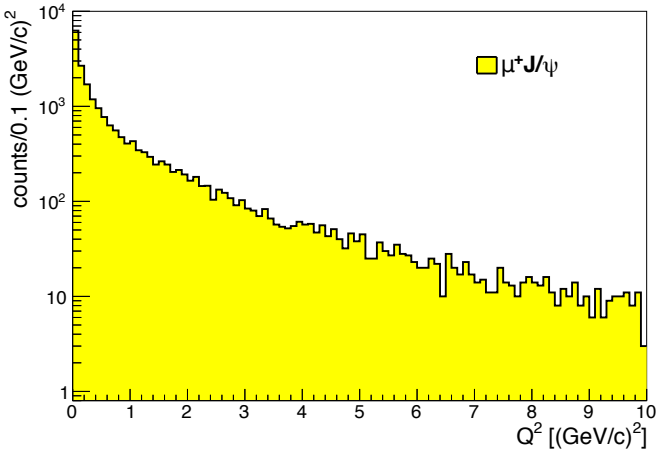


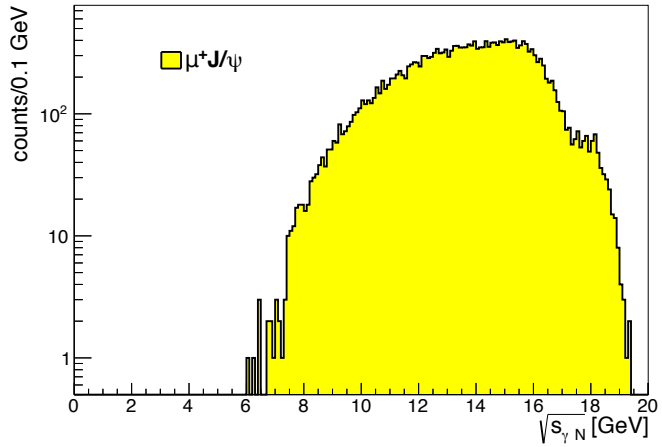


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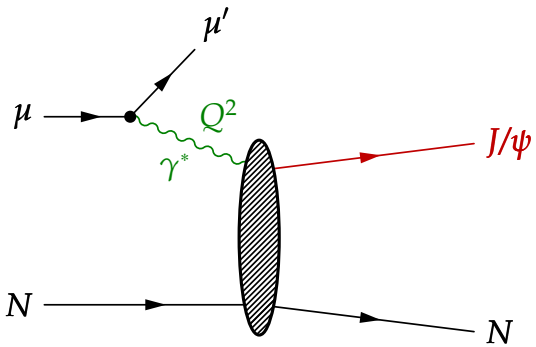


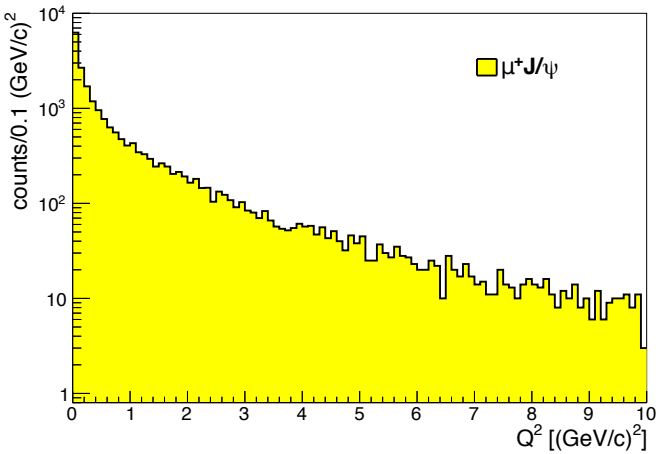


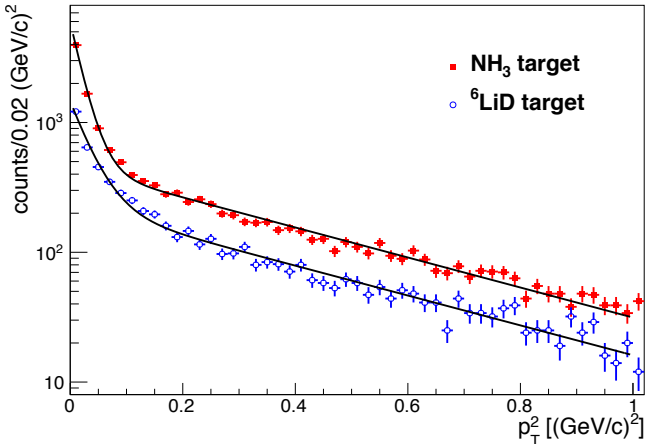


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**$Z_c(3900)$** $I^G(J^{PC}) = 1^+(1^{+-})$

was $X(3900)$

Mass $m = 3887.1 \pm 2.6$ MeV (S = 1.7)
Full width $\Gamma = 28.4 \pm 2.6$ MeV

| **$Z_c(3900)$ DECAY MODES** | Fraction ($\Gamma_i/\Gamma$) | $p$ (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 | – |
| $D^0D^{*-}$ + c.c. | seen | 152 |
| $D^-D^{*0}$ + c.c. | seen | 143 |
| $\omega\pi^{\pm}$ | not seen | 1862 |
| $J/\psi\eta$ | not seen | 510 |
| $D^+D^{*-}$ + c.c | seen | – |
| $D^0\overline{D}^{*0}$ + c.c | seen | – |

- $Z_c^{\pm}(3900)$ discovered 2013 by BESIII and Belle
- $Z_c^0(3900)$ observed in CLEO-c data and by BESIII experiment
- $J^P = 1^+$ determined by BESIII
- Nature unclear
  - Tetraquark?
  - $D\overline{D}^*$ molecule?
  - Cusp effect? Triangle singularity?
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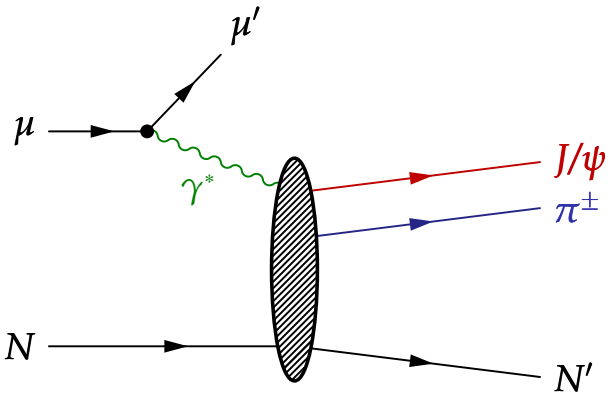
COMPASS, PLB **742** (2015) 330




## 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** (2013) 114009
- No $Z_c^{\pm}(3900)$ signal observed

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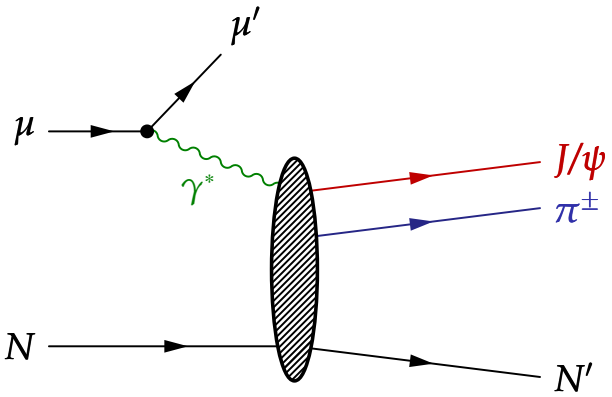


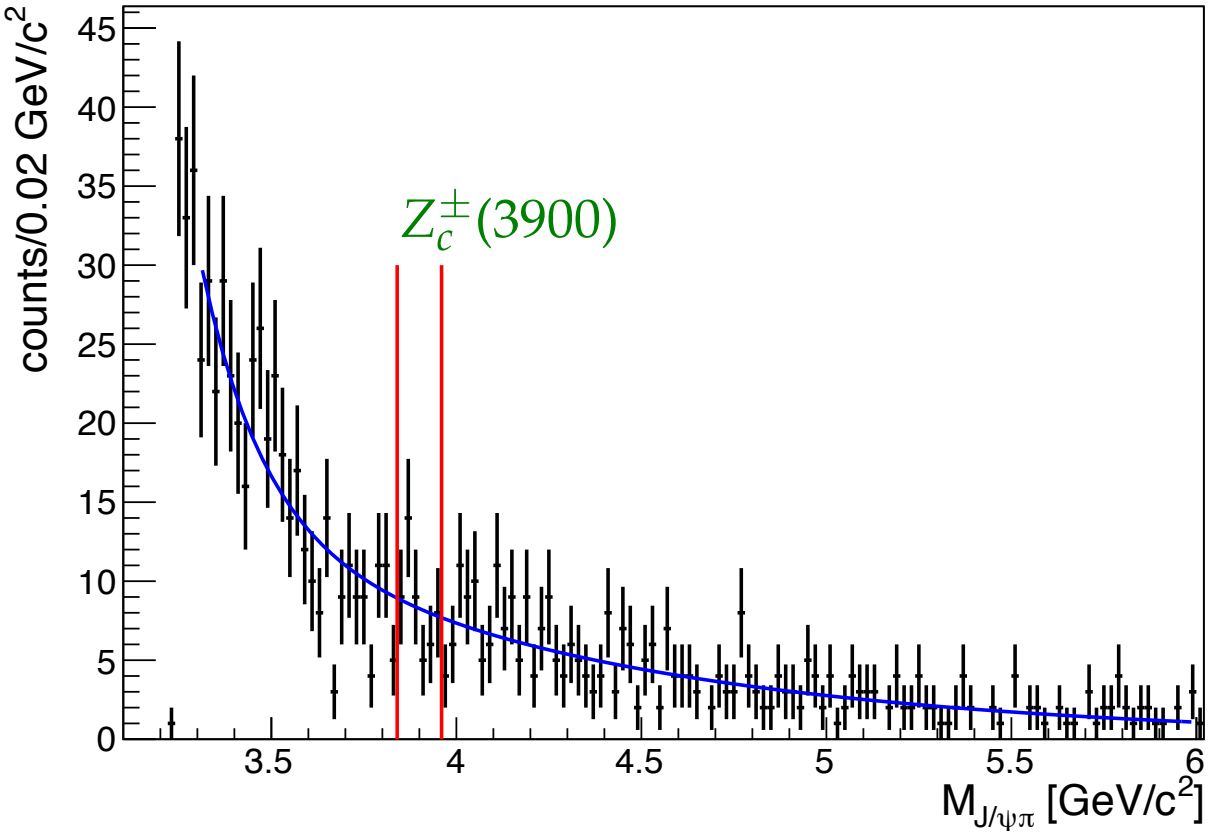


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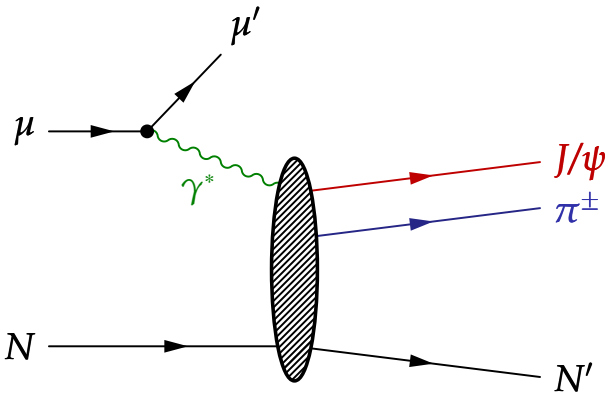


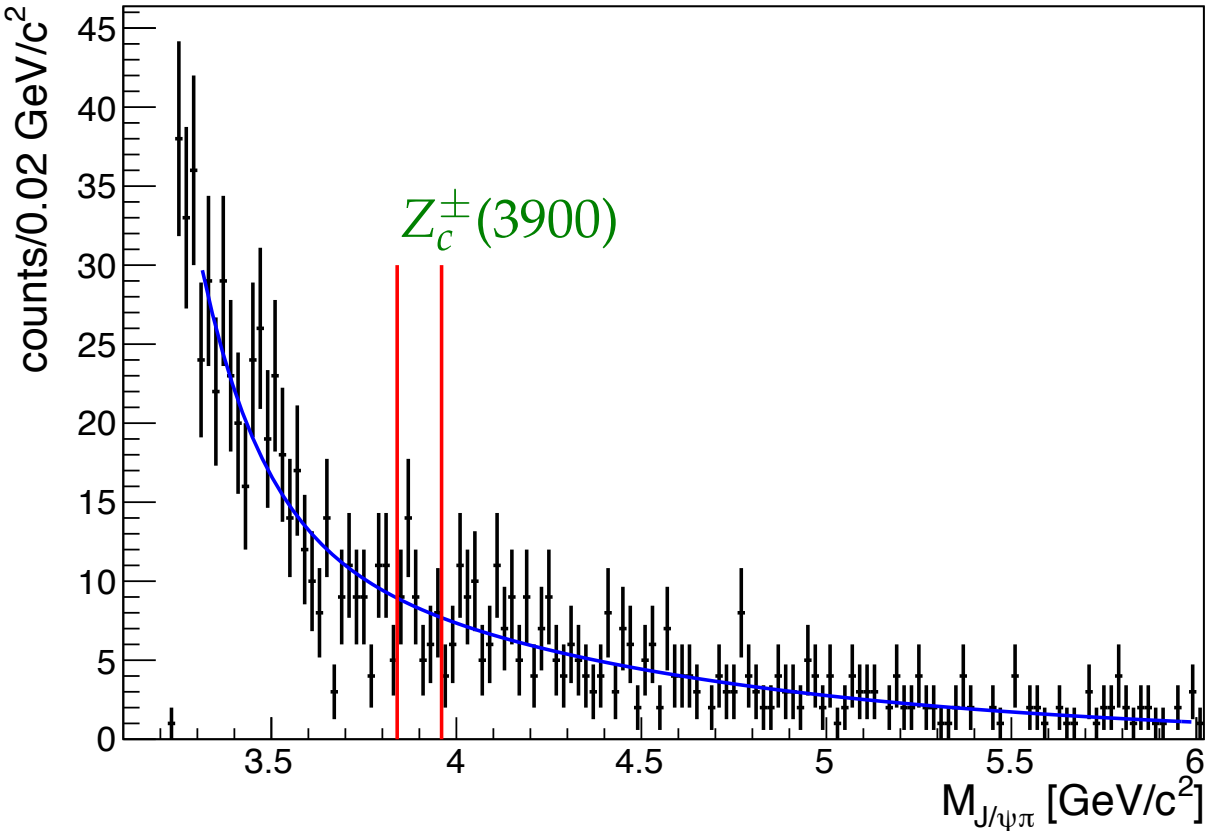


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- $$\frac{\sigma_{\gamma N \to Z_c^{\pm}(3900) N'} \times \mathcal{B}[Z_c^{\pm}(3900) \to J/\psi\, \pi^{\pm}]}{\sigma_{\gamma N \to J/\psi N'}} < 3.7 \times 10^{-3}$$

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

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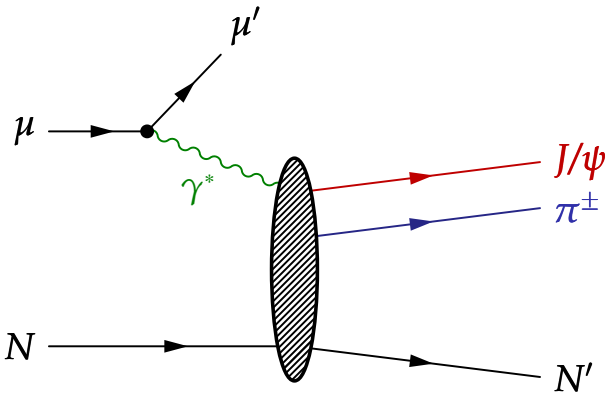


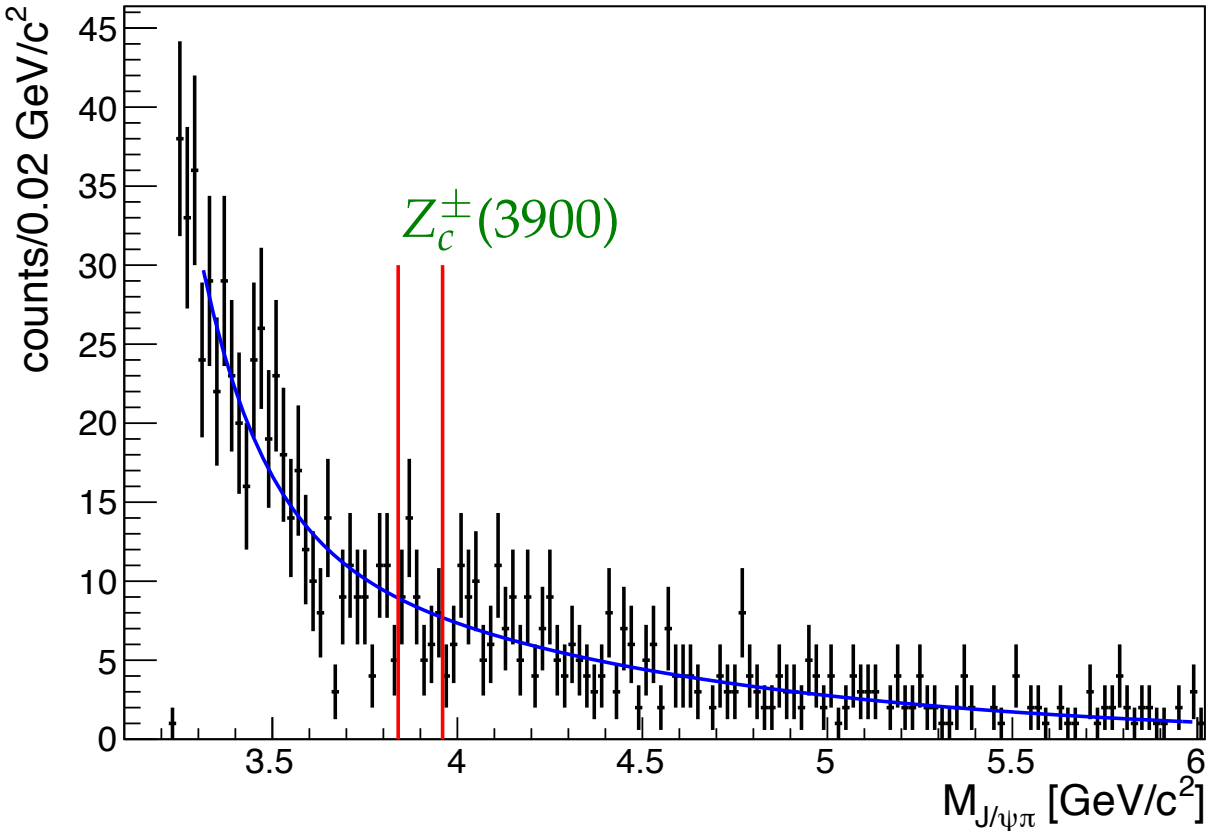


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- $\sigma_{\gamma N \to Z_c^{\pm}(3900) N'} \times \mathcal{B}[Z_c^{\pm}(3900) \to J/\psi\,\pi^{\pm}] < 52\,\text{pb}$

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

## $Z_c(4200)$

$I^G(J^{PC}) = 1^+(1^{+-})$
$I$, $G$, $C$ need confirmation.

OMITTED FROM SUMMARY TABLE
was $X(4200)^{\pm}$

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

### $Z_c(4200)$ MASS

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

### $Z_c(4200)$ WIDTH

| *VALUE* (MeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| $\mathbf{370\pm70^{+70}_{-132}}$ | CHILIKIN | 14 | BELL | $\overline{B}^0 \to J/\psi K^-\pi^+$ |

### $Z_c(4200)$ DECAY MODES

| | Mode | Fraction ($\Gamma_i/\Gamma$) |
|---|---|---|
| $\Gamma_1$ | $J/\psi\pi^+$ | seen |

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

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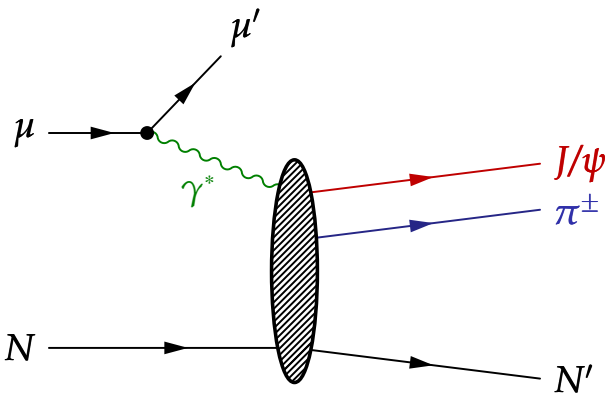
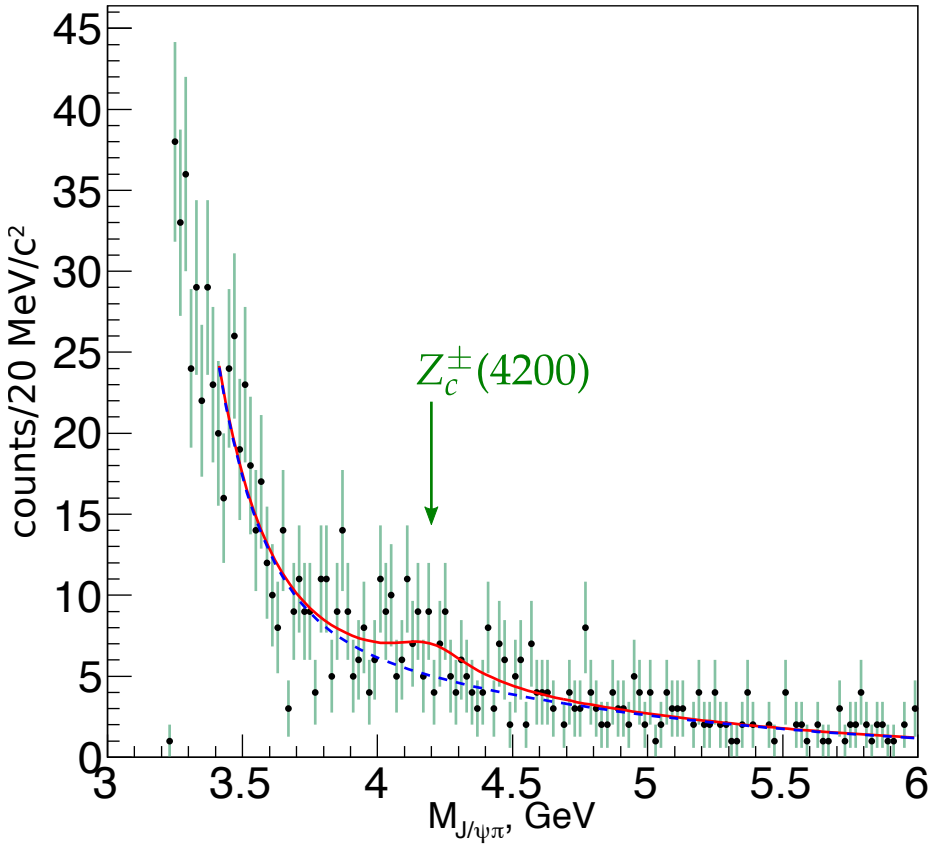
# Exclusive Muoproduction of $J/\psi\pi^{\pm}$

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




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

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

## $\chi_{c1}(3872)$

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

also known as $X(3872)$

Mass $m = 3871.65 \pm 0.06$ MeV
$m_{\chi_{c1}(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
Full width $\Gamma = 1.19 \pm 0.21$ MeV (S = 1.1)

| $\chi_{c1}(3872)$ DECAY MODES | Fraction ($\Gamma_i/\Gamma$) | Confidence level | $p$ (MeV/$c$) |
|---|---|---|---|
| $e^+e^-$ | $< 2.8 \times 10^{-6}$ | 90% | 1936 |
| $\pi^+\pi^- J/\psi(1S)$ | $( 3.8 \pm 1.2)$ % | | 650 |
| $\pi^+\pi^-\pi^0 J/\psi(1S)$ | not seen | | 588 |
| $\omega\eta_c(1S)$ | $< 33$ % | 90% | 368 |
| $\omega J/\psi(1S)$ | $( 4.3 \pm 2.1)$ % | | † |
| $\phi\phi$ | not seen | | 1646 |
| $D^0\overline{D}^0\pi^0$ | $(49\ ^{+18}_{-20})$ % | | 116 |
| $\overline{D}^{*0}D^0$ | $(37 \pm 9)$ % | | † |
| $\gamma\gamma$ | $< 11$ % | 90% | 1936 |
| $D^0\overline{D}^0$ | $< 29$ % | 90% | 519 |
| $D^+D^-$ | $< 19$ % | 90% | 502 |
| $\pi^0\chi_{c2}$ | $< 4$ % | 90% | 273 |
| $\pi^0\chi_{c1}$ | $( 3.4 \pm 1.6)$ % | | 319 |
| $\pi^0\chi_{c0}$ | $< 70$ % | 90% | – |
| $\pi^+\pi^-\eta_c(1S)$ | $< 14$ % | 90% | 745 |
| $\pi^+\pi^-\chi_{c1}$ | $< 7 \times 10^{-3}$ | 90% | 218 |
| $p\overline{p}$ | $< 2.4 \times 10^{-5}$ | 95% | 1693 |
| **Radiative decays** | | | |
| $\gamma D^+D^-$ | $< 4$ % | 90% | 502 |
| $\gamma\overline{D}^0D^0$ | $< 6$ % | 90% | 519 |
| $\gamma J/\psi$ | $( 8 \pm 4 ) \times 10^{-3}$ | | 697 |
| $\gamma\chi_{c1}$ | $< 9 \times 10^{-3}$ | 90% | 344 |

- Discovered 2003 by Belle
- Best studied exotic charmonium-like state
- Mass at $D^0\overline{D}^{0*}$ threshold
- Extremely narrow
- LHCb: $J^{PC} = 1^{++}$
- Nature still unclear

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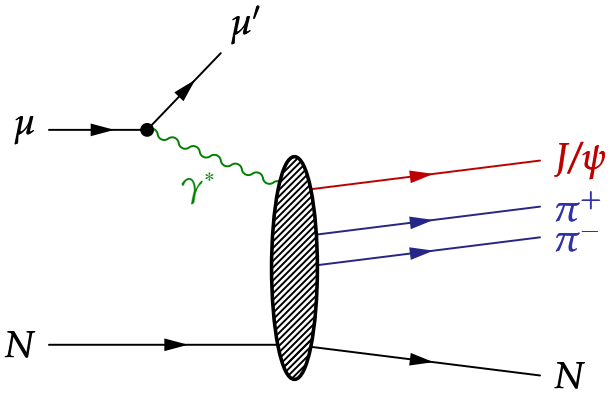
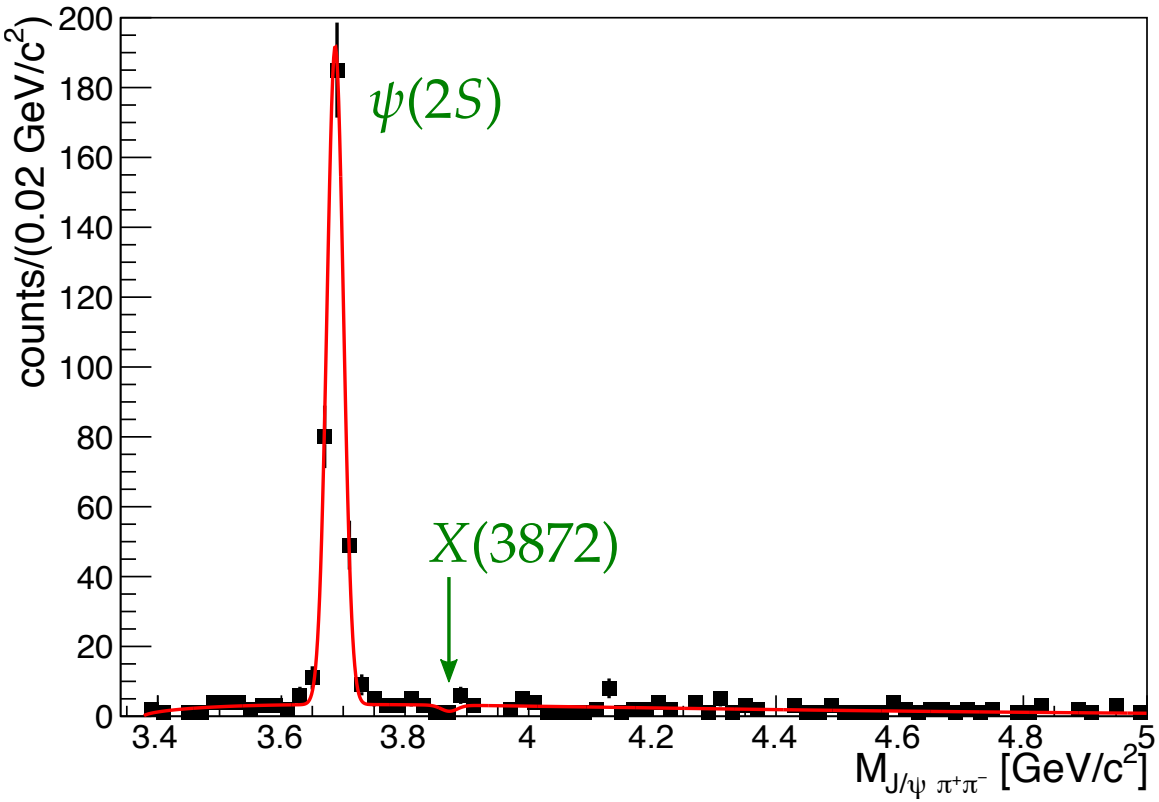
# Exclusive Muoproduction of $J/\psi\pi^+\pi^-$

COMPASS, PLB **783** (2018) 334



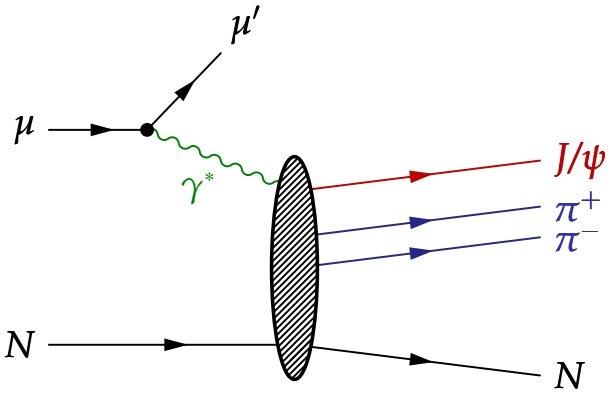



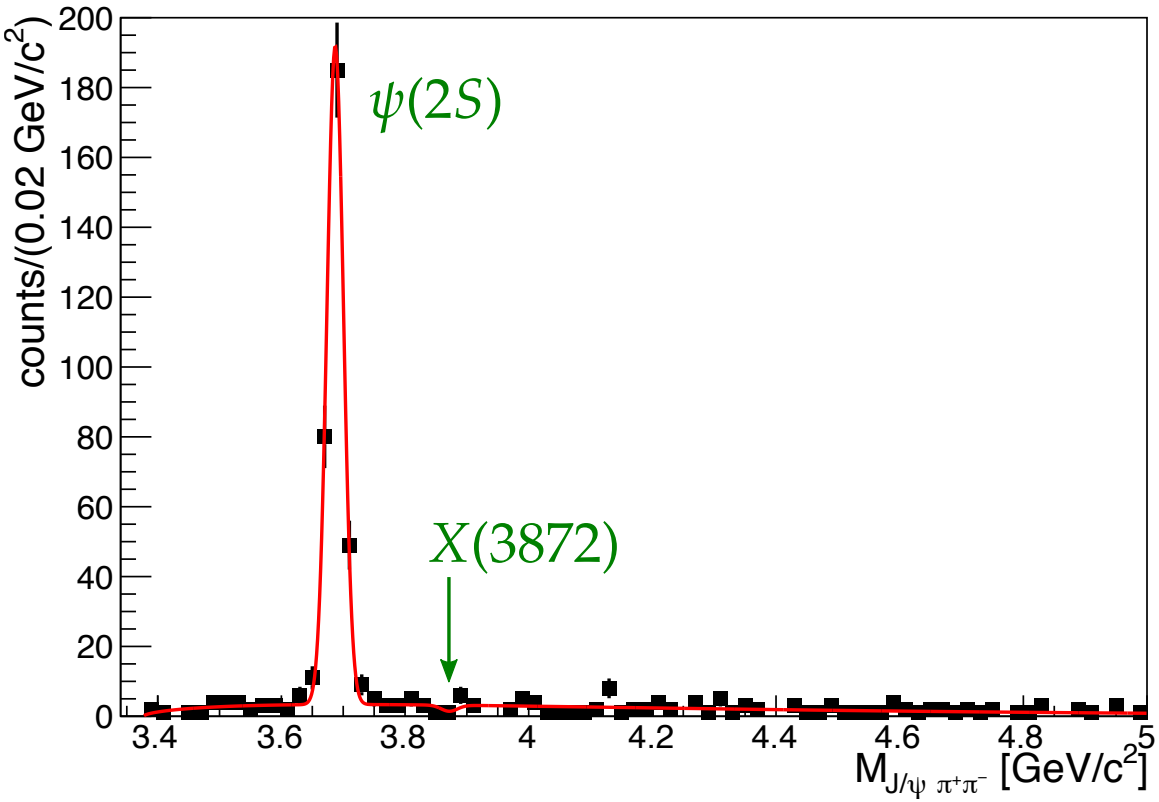

## Search for $X(3872)$ in $J/\psi\pi^+\pi^-$ invariant mass spectrum

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

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

COMPASS, PLB **783** (2018) 334

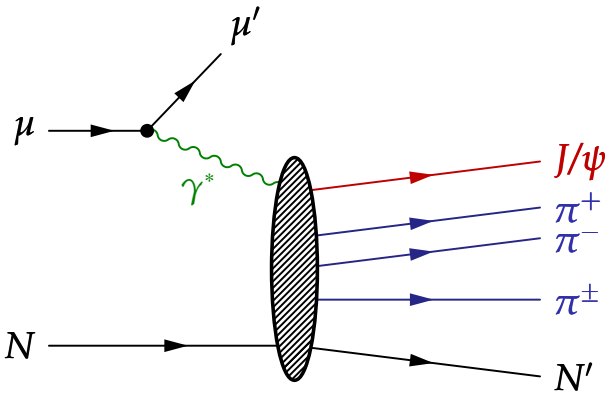


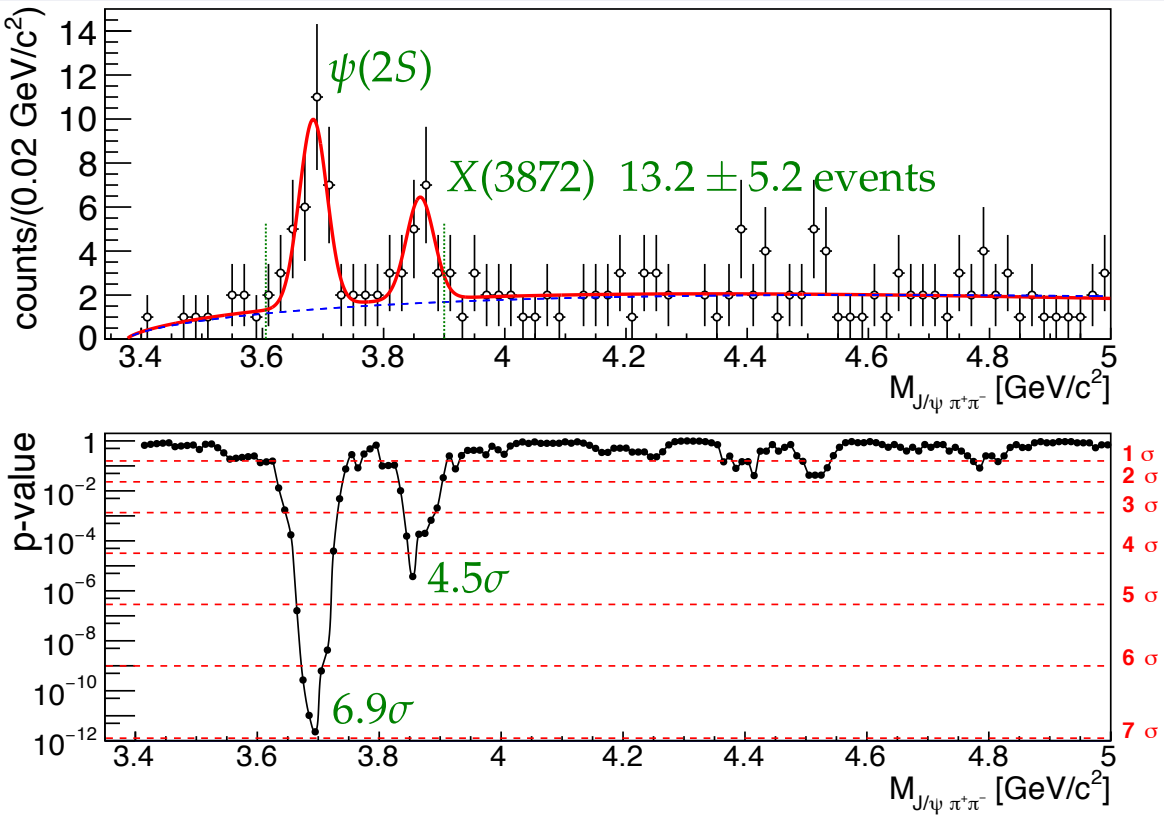




## Search for $X(3872)$ in $J/\psi\pi^+\pi^-$ invariant mass spectrum

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

# Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$ COMPASS, PLB **783** (2018) 334

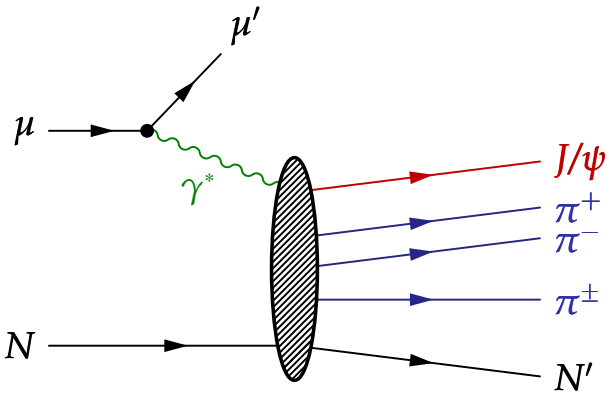


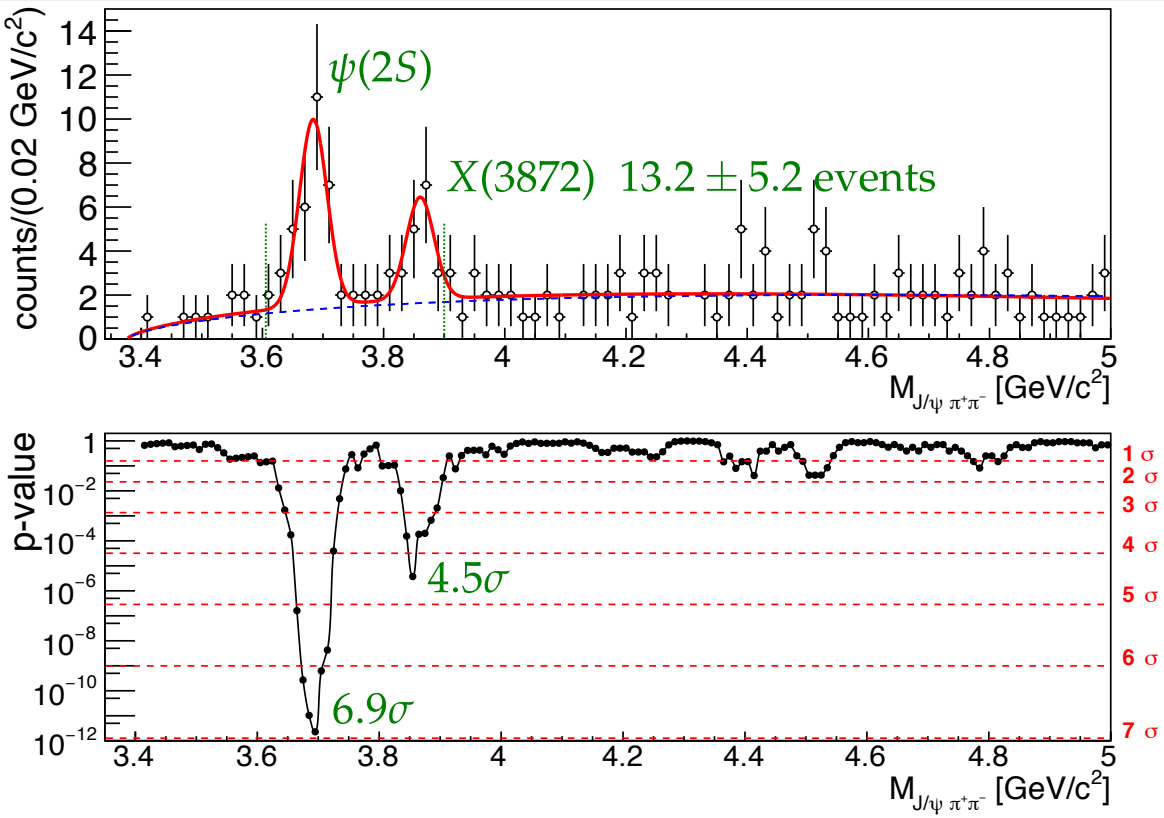




## Search for $X(3872)$ in invariant mass spectrum of $J/\psi\pi^+\pi^-$ subsystem

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

# Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$ COMPASS, PLB **783** (2018) 334

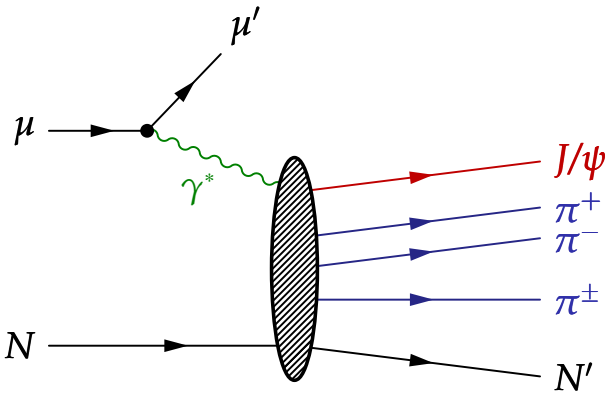


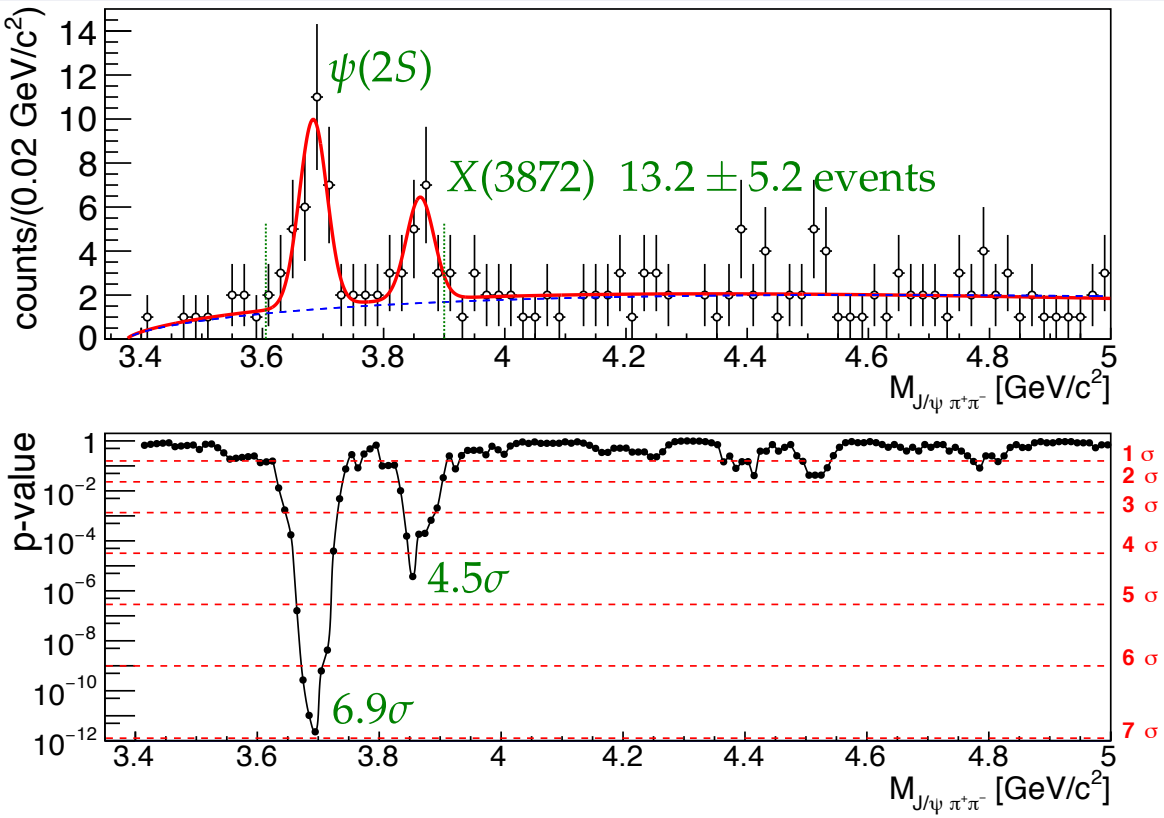




## Significance of $X(3872)$ signal

- Integrate background curve over 60 MeV/$c^2$ wide mass window $\Longrightarrow$ expected number of background events
- $p$-value for BG to fluctuate to observed count (assume Poisson)
- $4.1\sigma$ including systematics

# Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$ COMPASS, PLB **783** (2018) 334

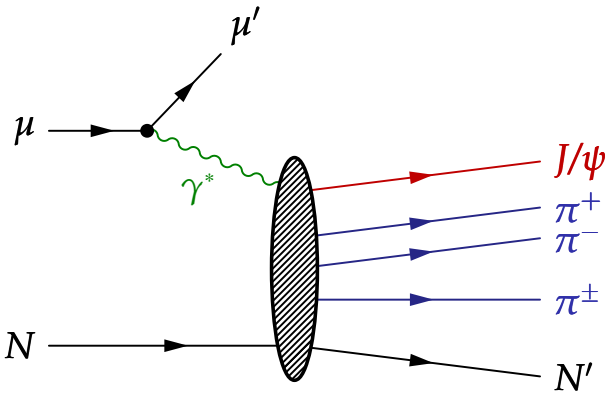


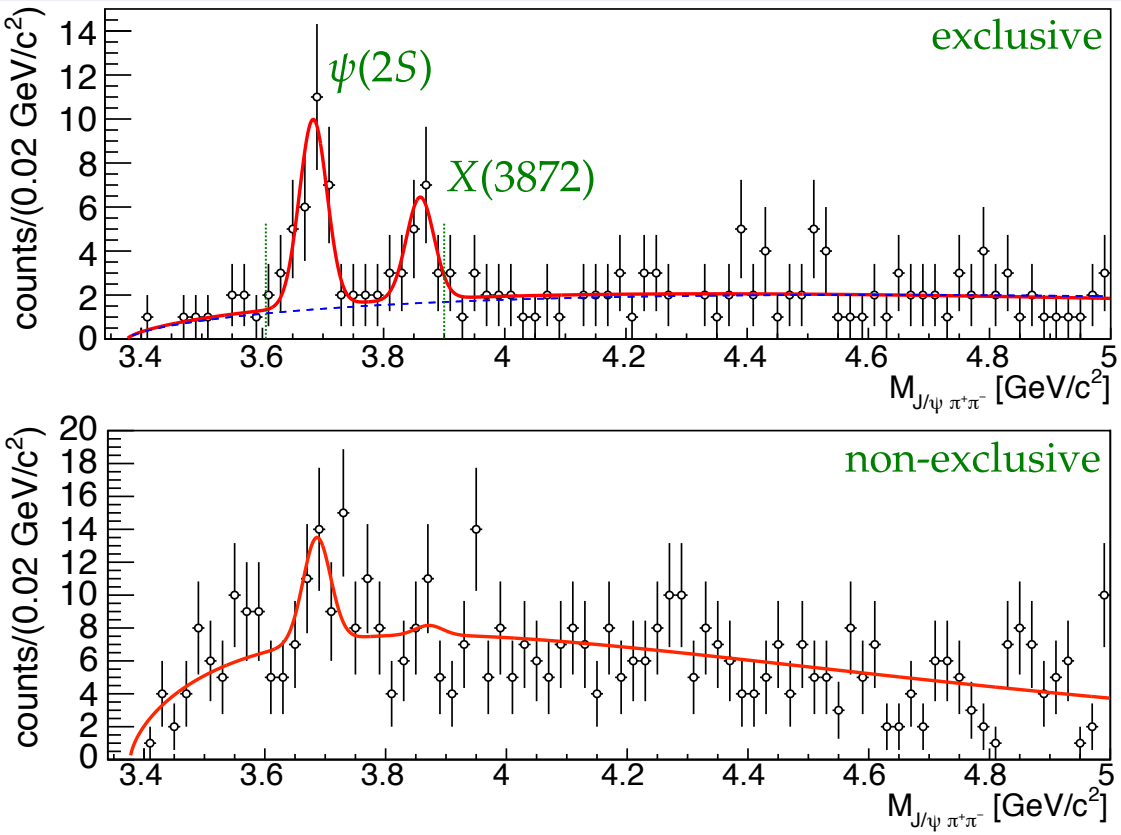




## Production rate

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

# Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$ COMPASS, PLB **783** (2018) 334

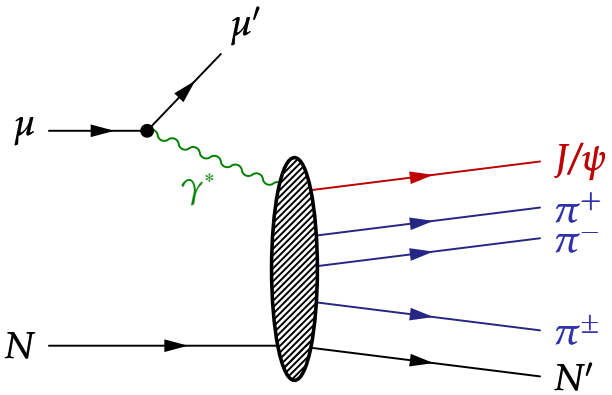


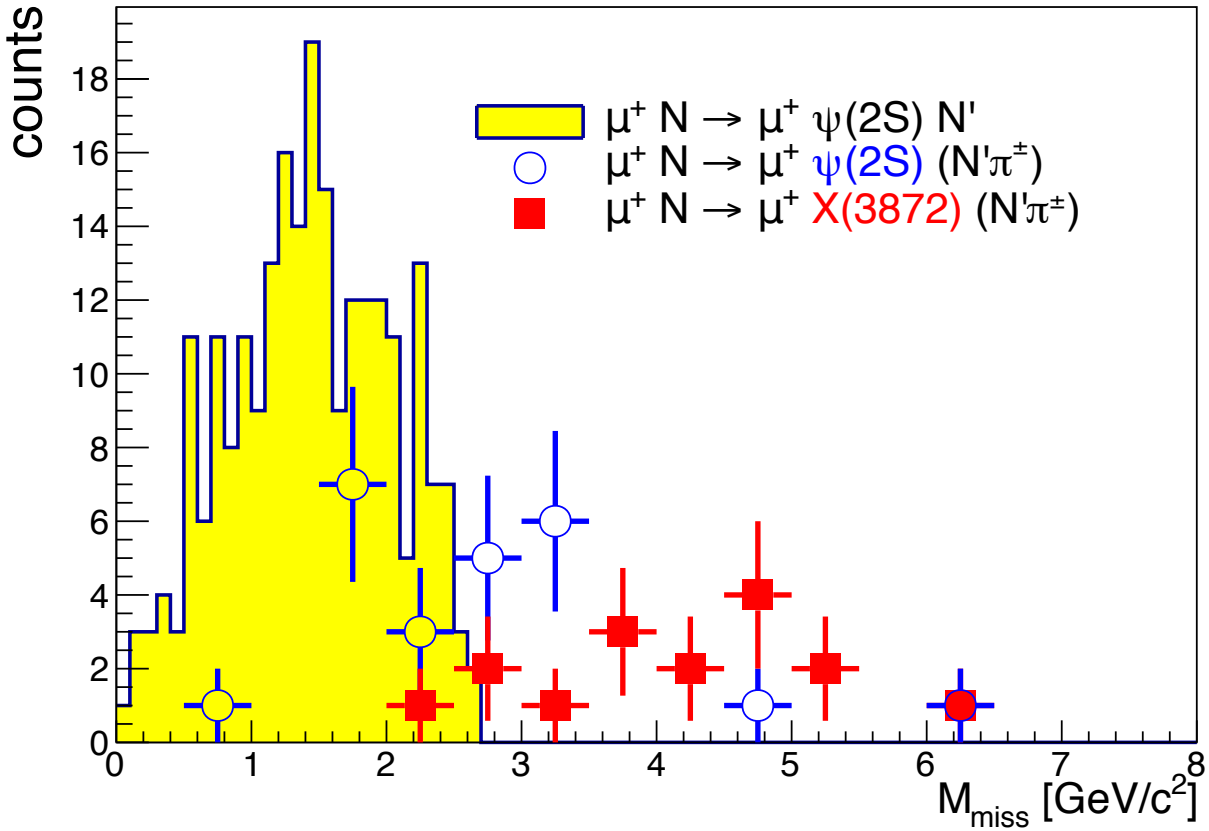




## Production of $X(3872)$ is exclusive

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

# Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$ COMPASS, PLB **783** (2018) 334



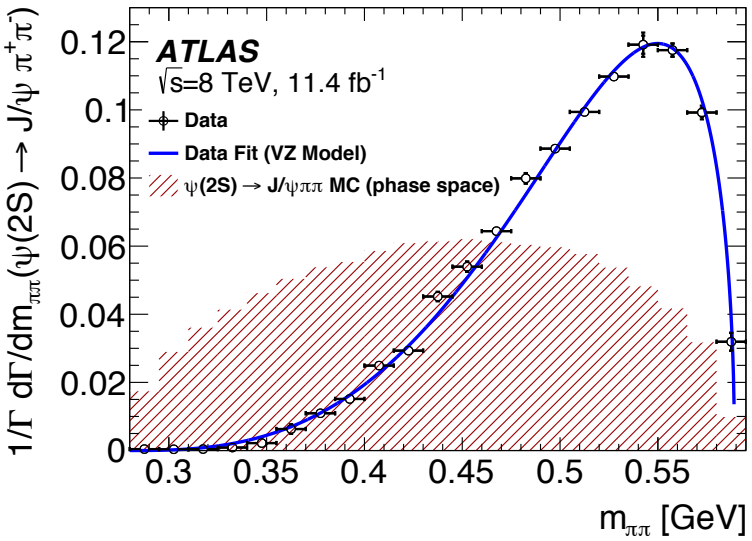

## Mass spectrum of $\pi^\pm N'$ system

- 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 $J/\psi\pi^+\pi^-\pi^\pm$ COMPASS, PLB **783** (2018) 334

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

$\psi(2S)$




ATLAS, JHEP **01** (2017) 117

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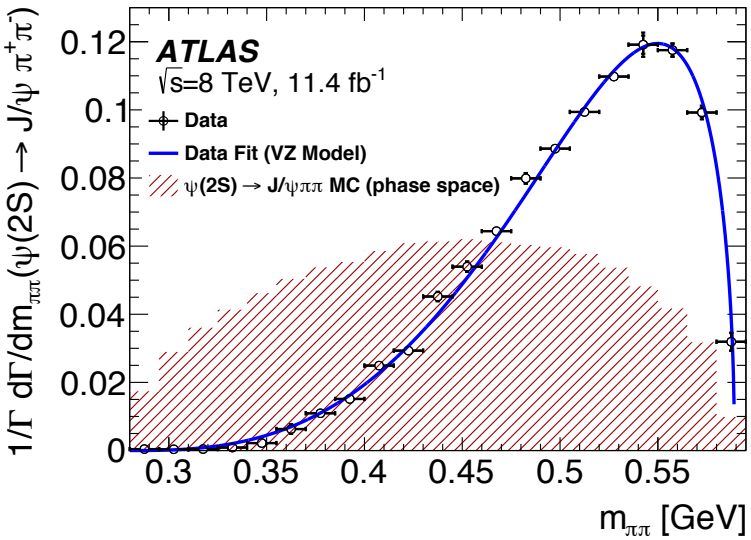
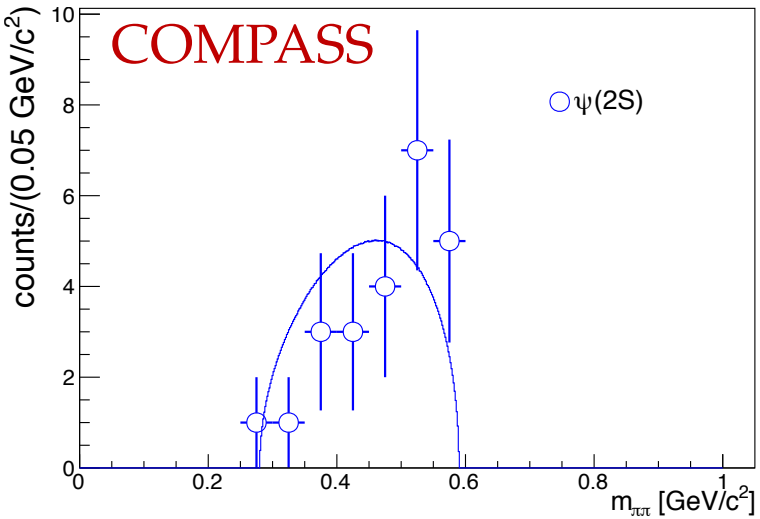



ATLAS, JHEP **01** (2017) 117



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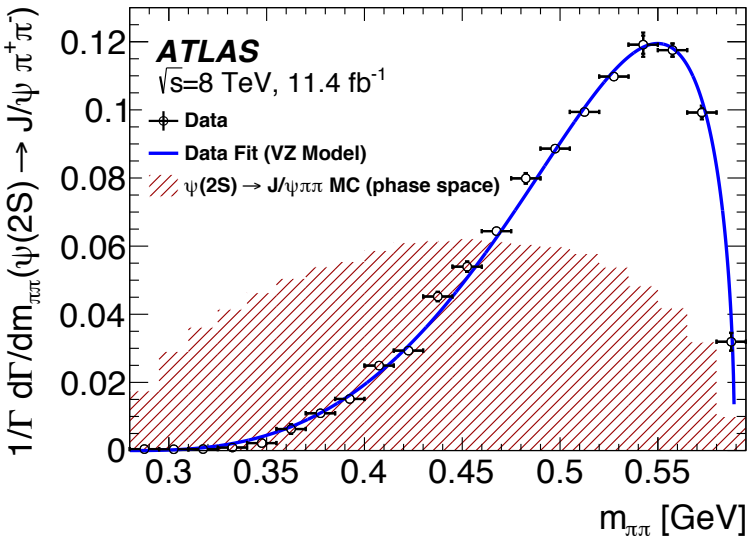
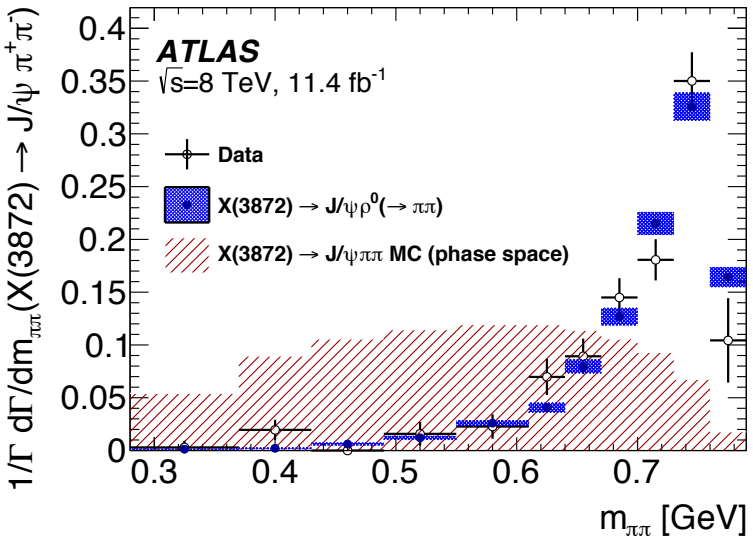
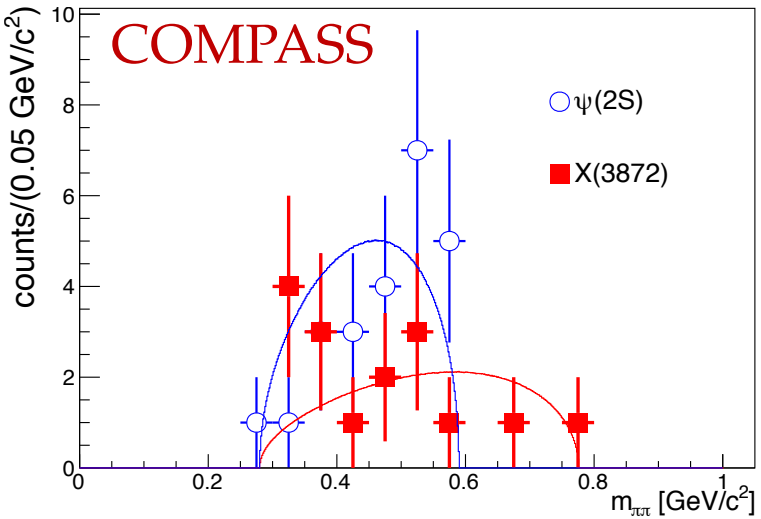



ATLAS, JHEP **01** (2017) 117

$X(3872)$



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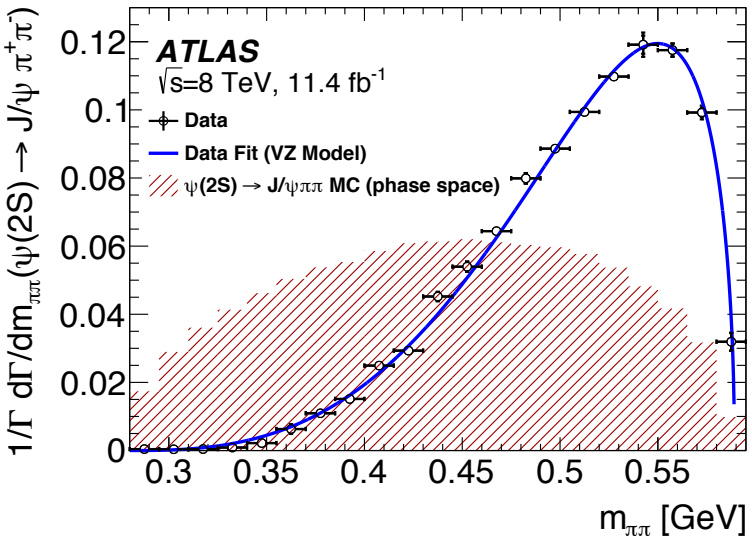


ATLAS, JHEP **01** (2017) 117

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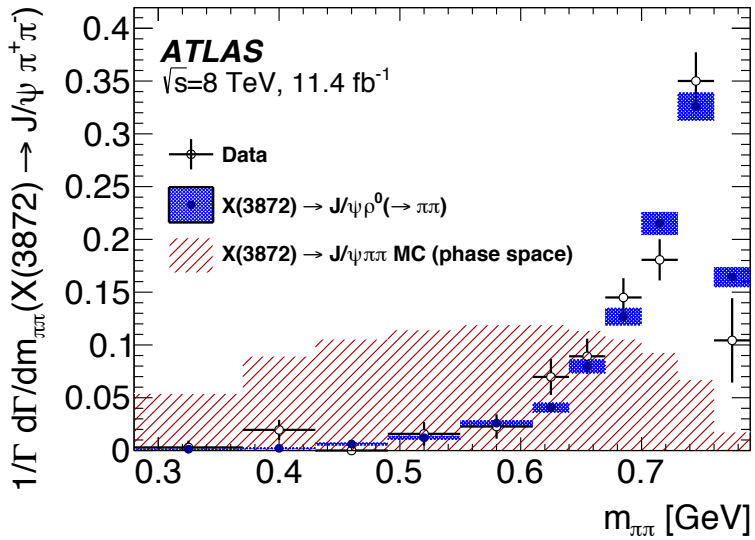


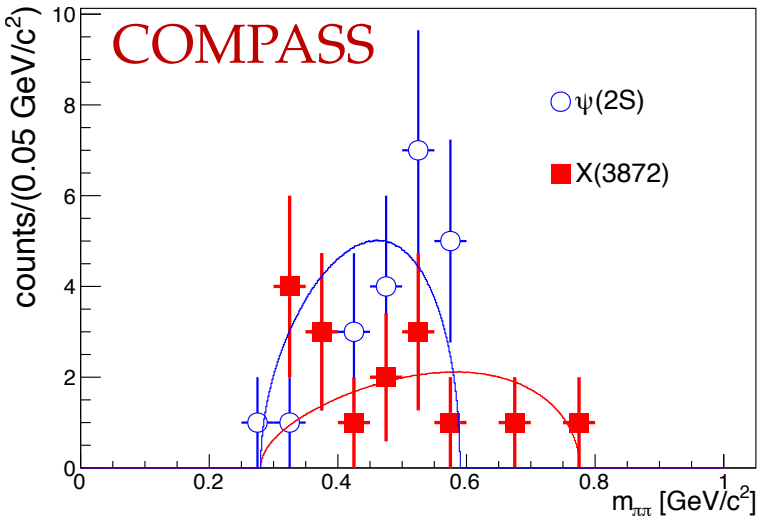


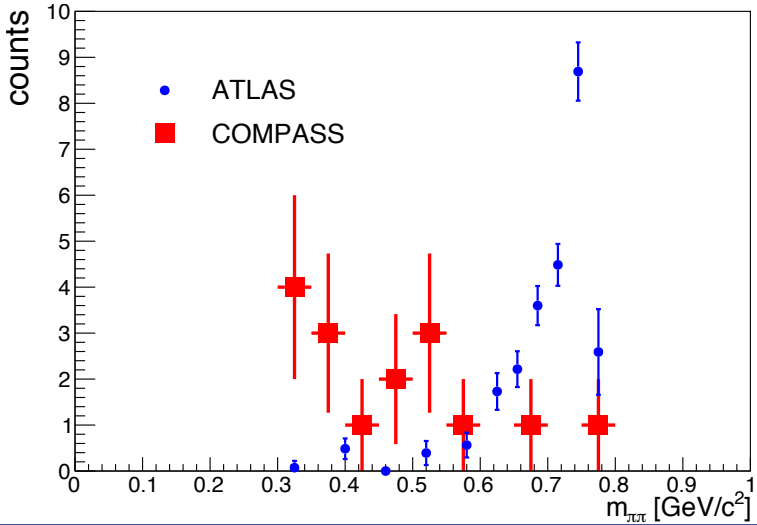

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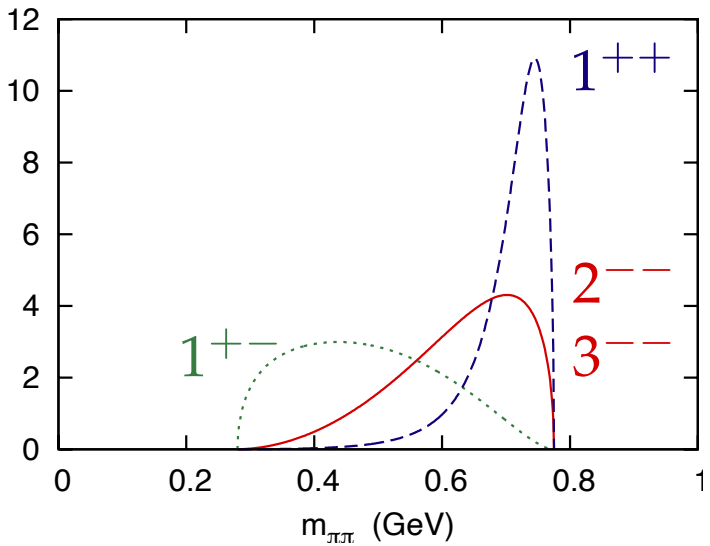
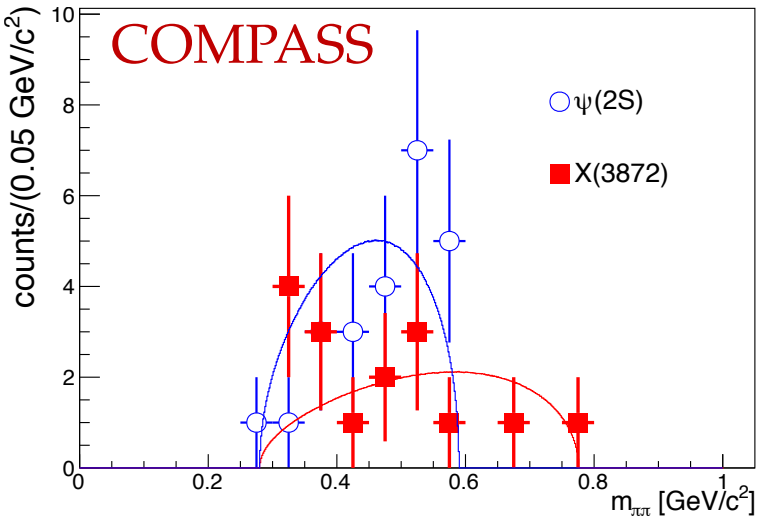


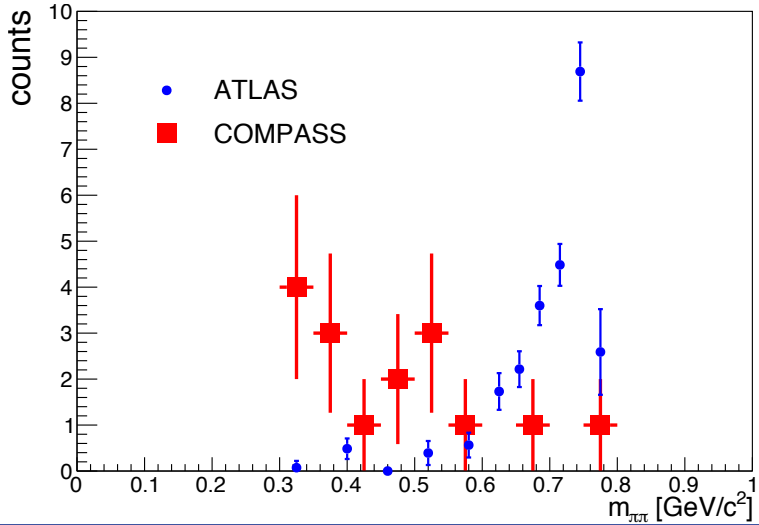

T. Kim, P. Ko, PRD **71** (2005) 034025, PRD **71** (2005) 099902

### A new state $\widetilde{X}(3872)$?

- $4.7\sigma$ to $7.3\sigma$ tension with $1^{++} \rightarrow J/\psi\,\rho(770)$
- $m_{\pi^-\pi^+}$ distribution compatible with $1^{+-} \rightarrow J/\psi\,[\pi\pi]_S$
- Degenerate $C = -1$ partner state of $X(3872)$ predicted by tetraquark model?

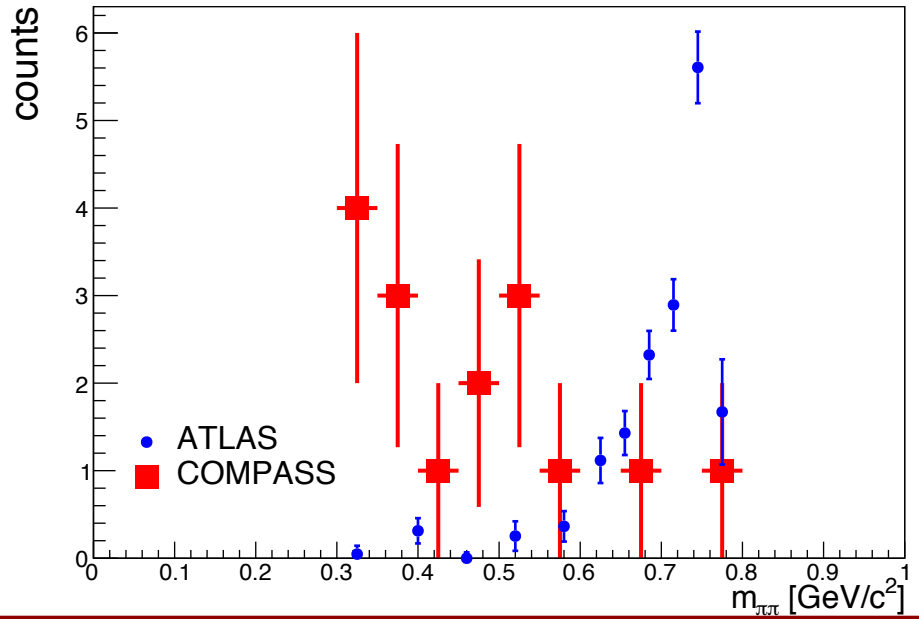
L. Maiani *et al.*, PRD **71** (2005) 014028
L. Maiani *et al.*, PRD **89** (2014) 114010



# Exclusive Muoproduction of $J/\psi\pi^+\pi^-\pi^\pm$ COMPASS, PLB **783** (2018) 334

## $\pi^+\pi^-$ Mass Distribution for $X(3872)$ Peak in Tension with previous Observations



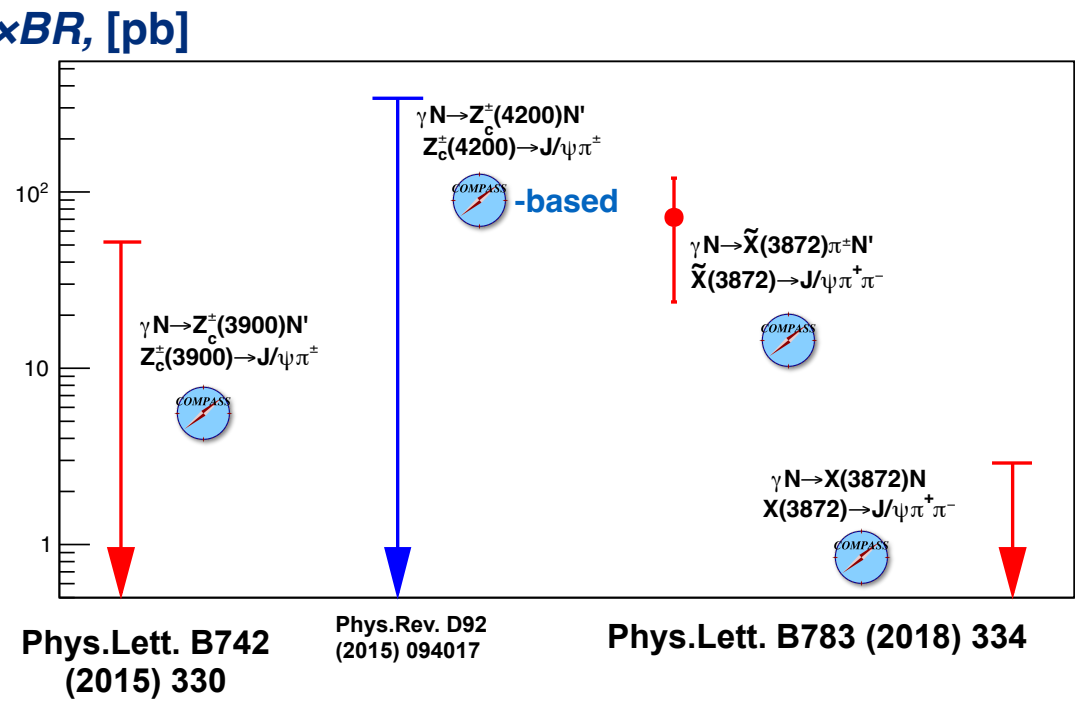

### Performed several studies

- Used sPlot technique to remove effect of background (ca. 40 %) $\Longrightarrow$ same result
- Excluded acceptance effects
- Excluded lost $\pi^0$ 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

## Photoproduction

- New opportunity to study exotic charmonium-like states
- Provides additional information to clarify nature of $XYZP$ states

**COMPASS:**




*Outlook:* More data from COMPASS runs in 2016, 17, 21, and 22

- Increase data sample by about 30 %
- Access to final states with photons: e.g. $J/\psi\pi^0$, $J/\psi\eta$, $J/\psi\omega$, $\chi_{c0,1,2}$

# Exotic Heavy-Quark States

## Summary and Outlook

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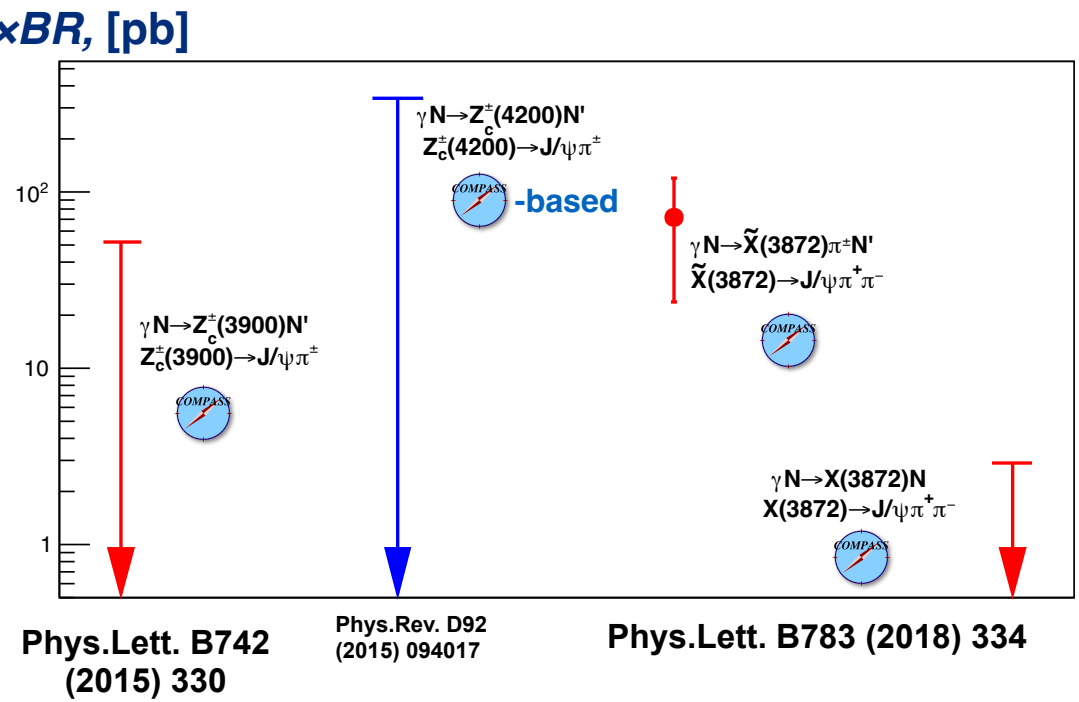


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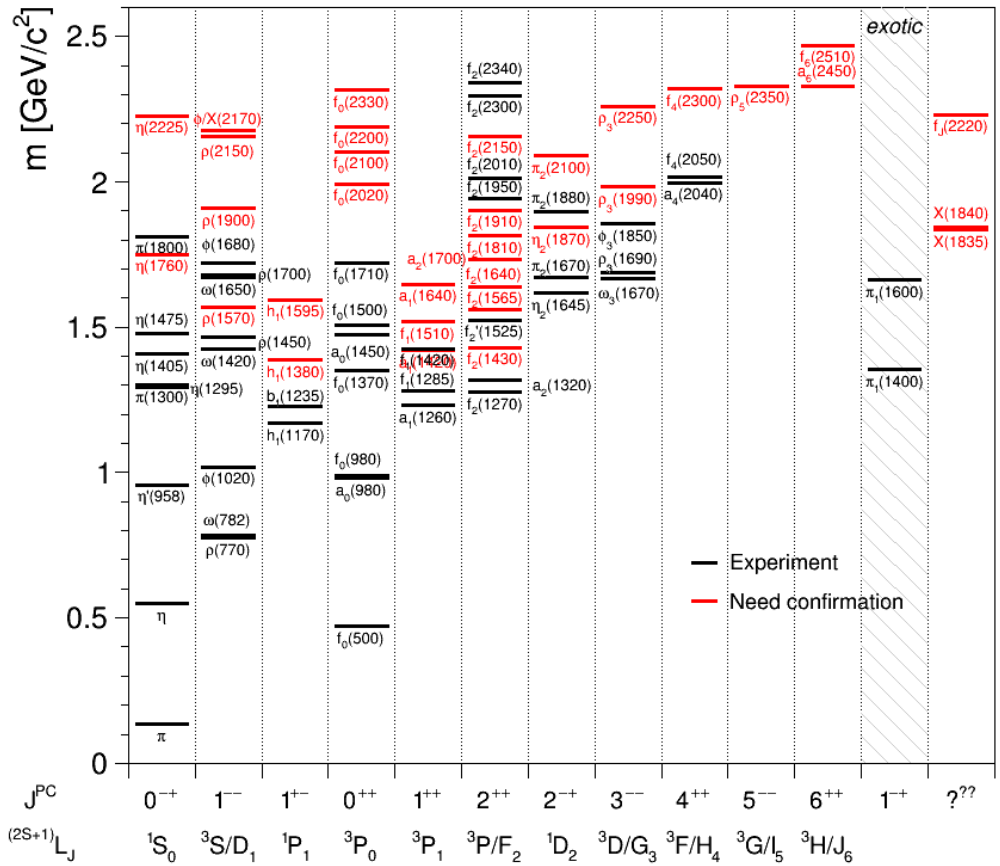
# Part II

# Exotic Light-Quark Mesons

# Spectrum of Light Non-Strange Mesons

## Light-Meson Frontier




[Courtesy K. Götzen, GSI]

- Rich spectrum
- Many states in mass region $\gtrsim 2\,\mathrm{GeV}/c^2$ need confirmation
- Many wide states
  - Identification requires partial-wave analysis (PWA)
  - Overlap and mixing of states with same $J^{PC}$

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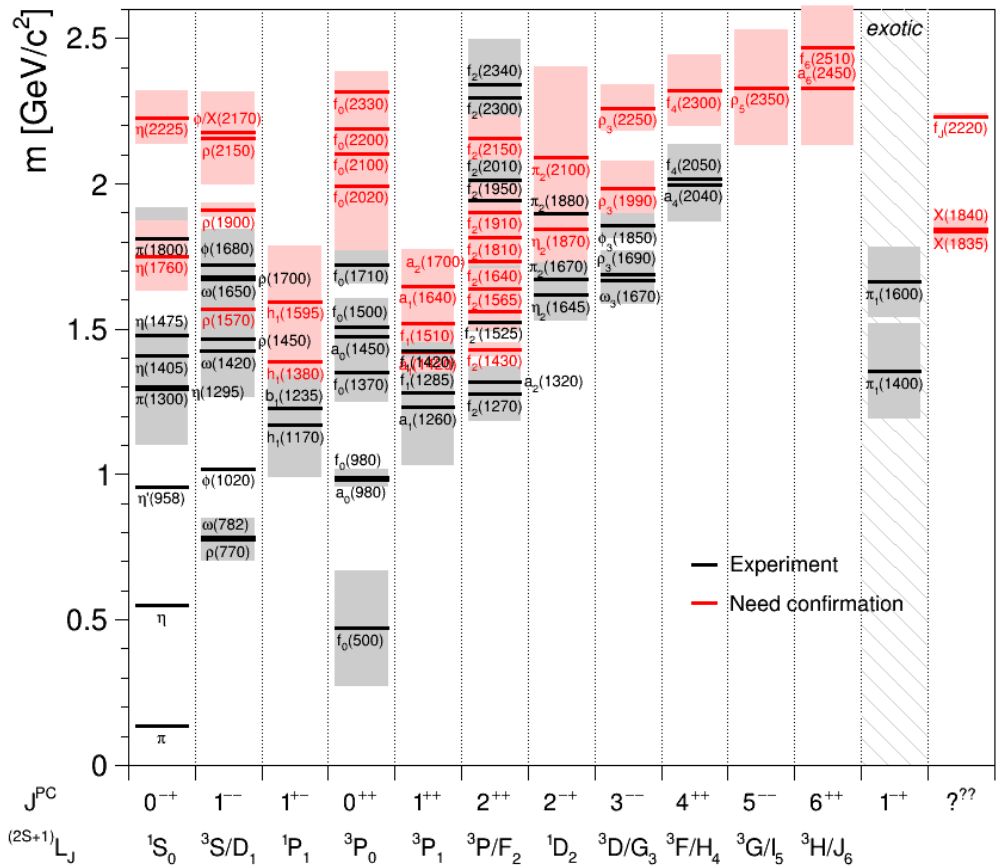


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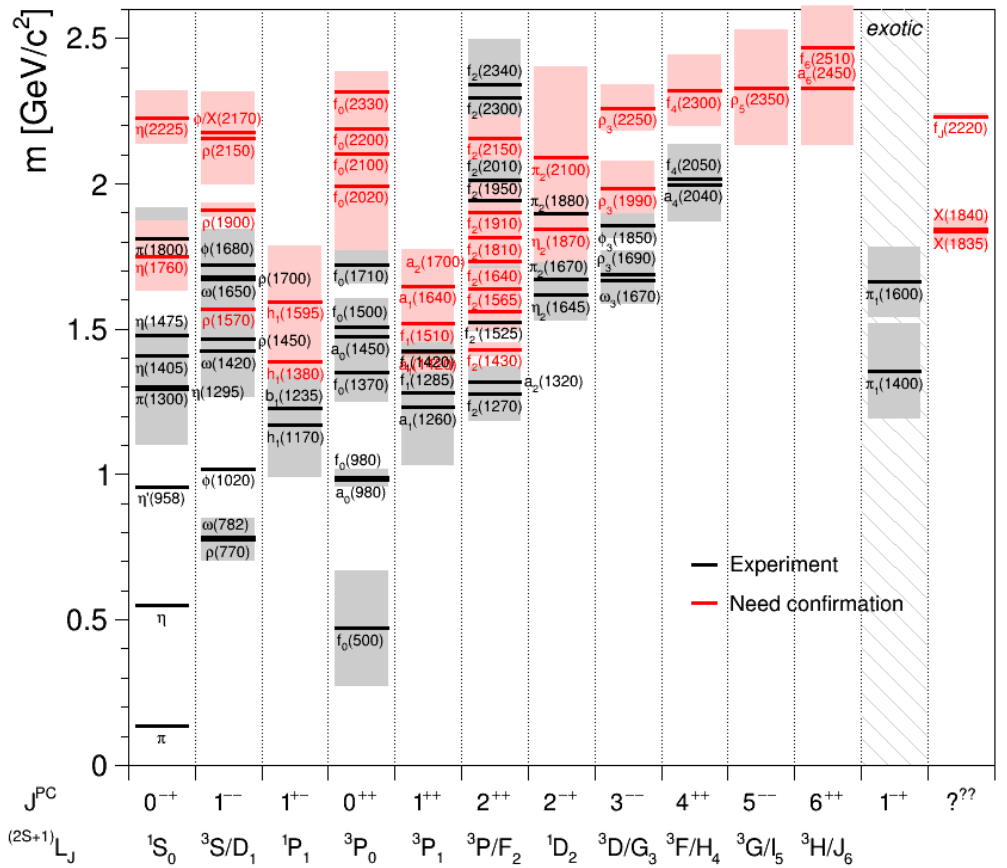
# Spectrum of Light Non-Strange Mesons

## Light-Meson Frontier




[Courtesy K. Götzen, GSI]

- Rich spectrum
- Many states in mass region $\gtrsim 2\,\mathrm{GeV}/c^2$ need confirmation
- Many wide states
  - Identification requires partial-wave analysis (PWA)
  - Overlap and mixing of states with same $J^{PC}$

**_Goal:_ precision measurement**

- Confirm higher excitations
- Complete $SU(3)_{\text{flavor}}$ nonets
- Search for exotic states

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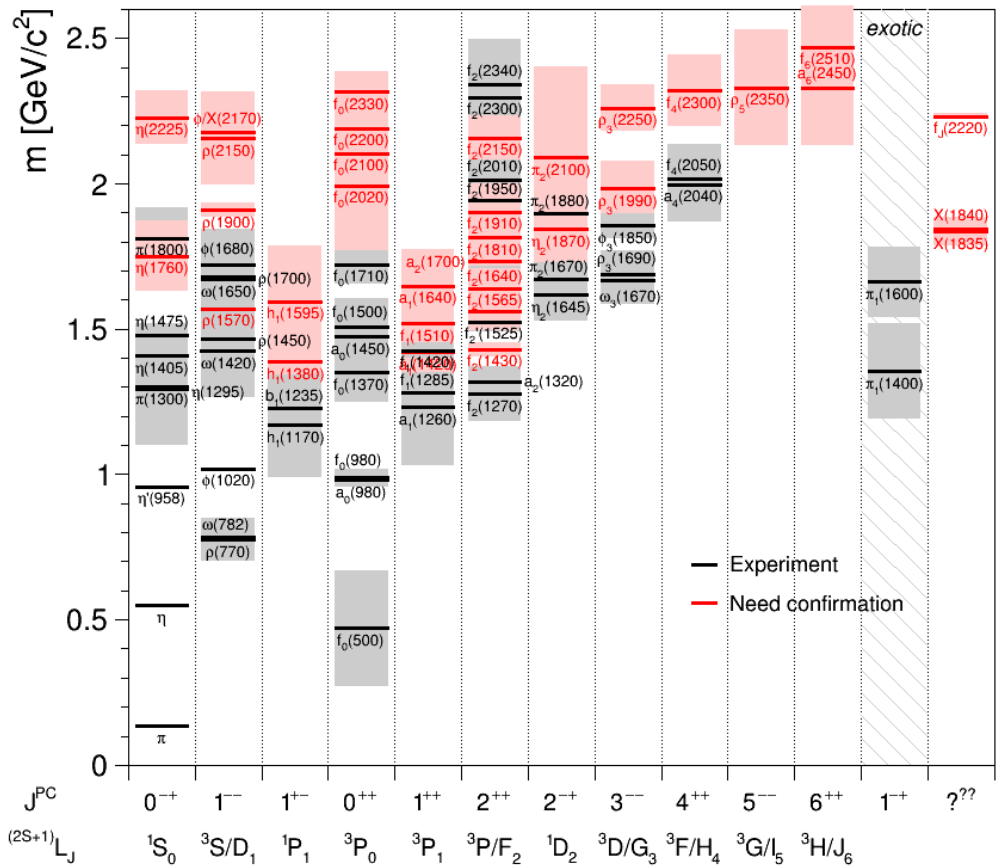


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- Important input for theory and phenomenology
- Understand QCD at low energies, i.e. nature of confinement

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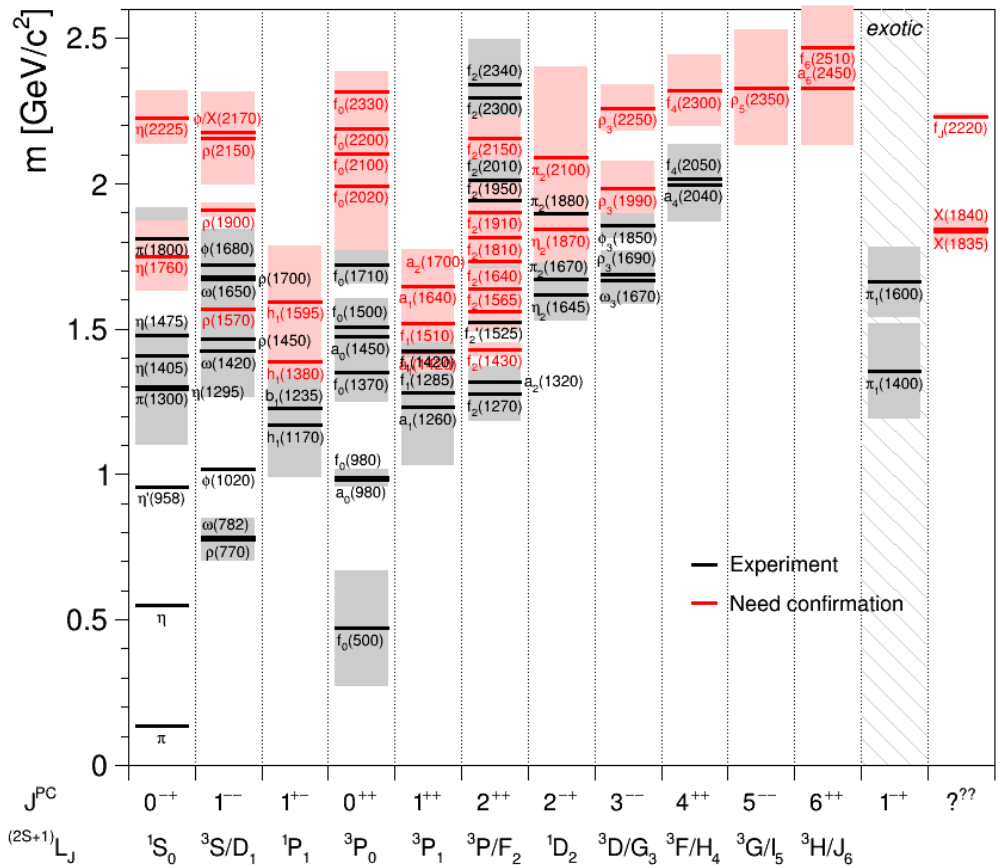


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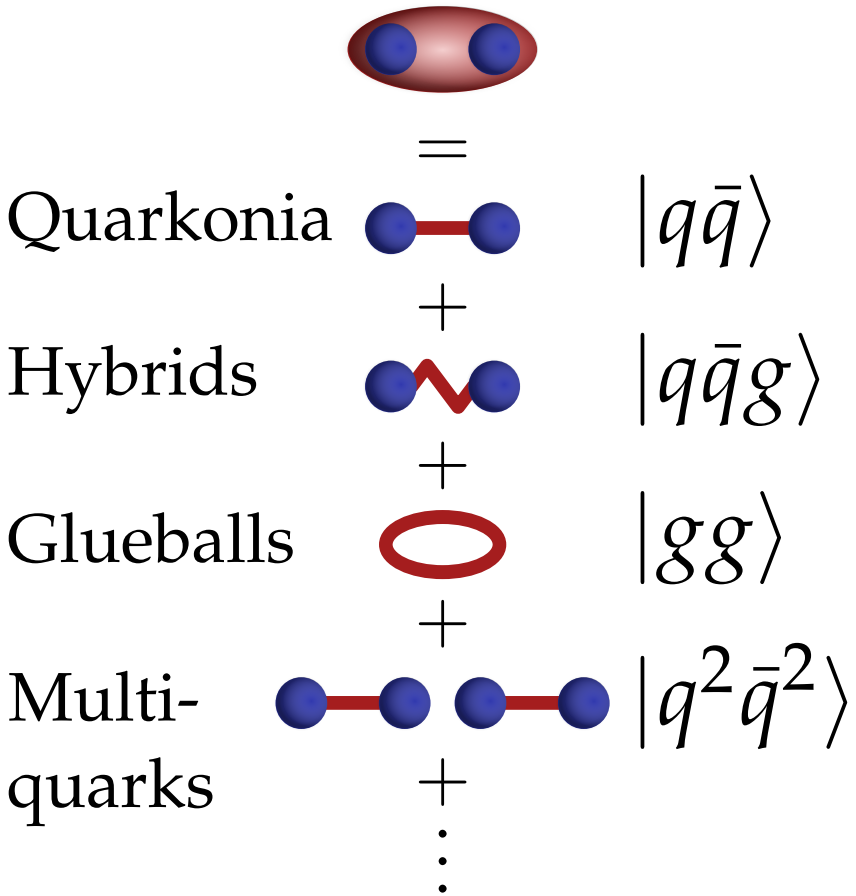
**Analyses driven by**

- High-quality data
- Advancements in analysis techniques
- More rigorous theoretical PWA models

# Beyond the Constituent Quark Model

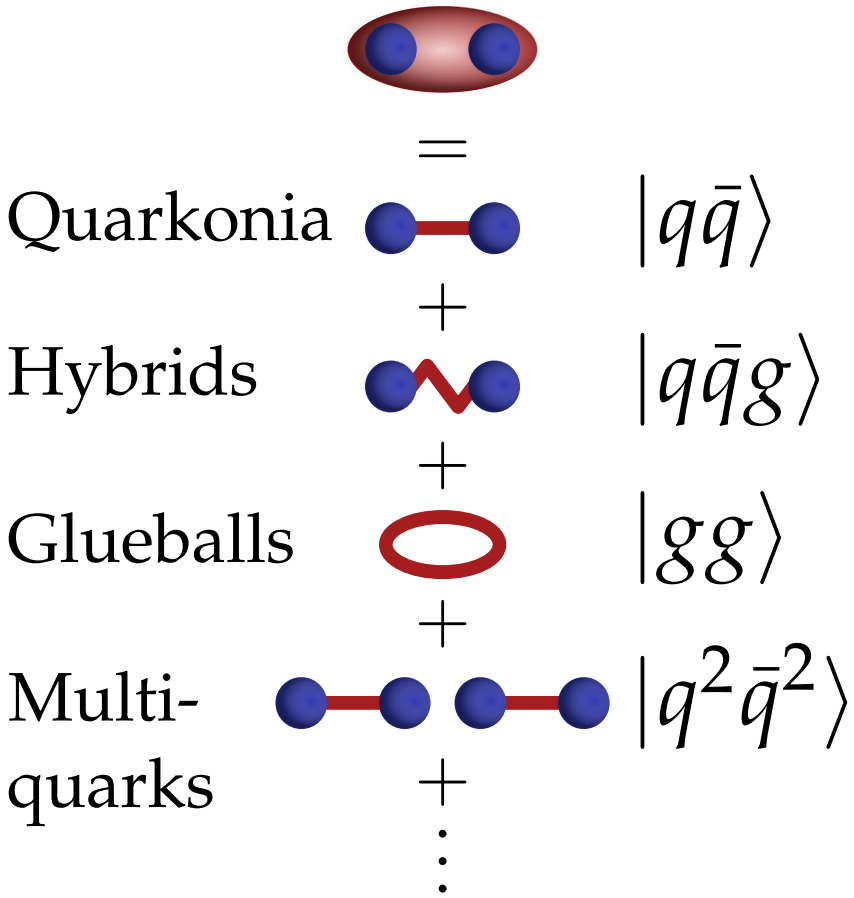
## Exotic Mesons




QCD permits additional color-singlet mesonic configurations

### Physical mesons

- Linear superpositions of *all* allowed basis states
- "Configuration mixing"
- Disentanglement of contributions difficult
  - Detailed information about couplings to production and decay channels required

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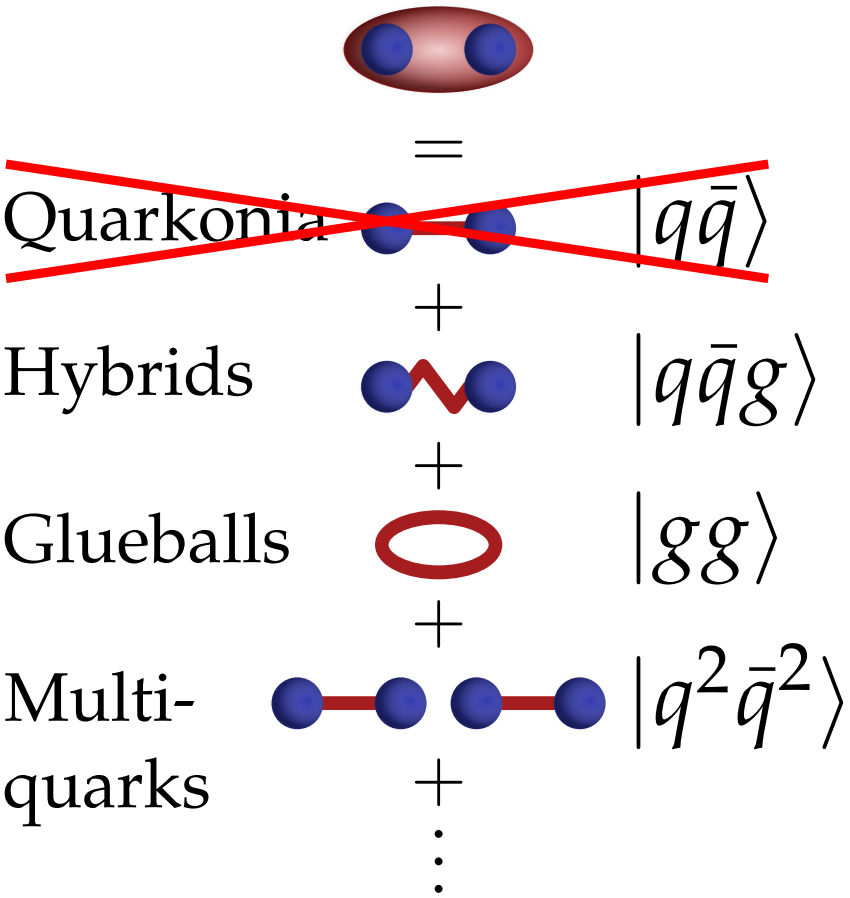


- States with $J^{PC} = 0^{--}$, $(\text{even})^{+-}$, or $(\text{odd})^{-+}$ forbidden for $|q\bar{q}\rangle$
- Finding them would be unambiguous proof for configurations beyond $|q\bar{q}\rangle$

**So far 3 exotic light-meson candidates**

1. $\pi_1(1400)$: seen only in $\eta\pi$
2. $\pi_1(1600)$: seen in $\rho(770)\pi$, $\eta'\pi$, $b_1(1235)\pi$, and $f_1(1285)\pi$
3. $\pi_1(2015)$ (needs confirmation): seen in $b_1(1235)\pi$, and $f_1(1285)\pi$

- All have $J^{PC} = 1^{-+}$
- Some claims are controversial

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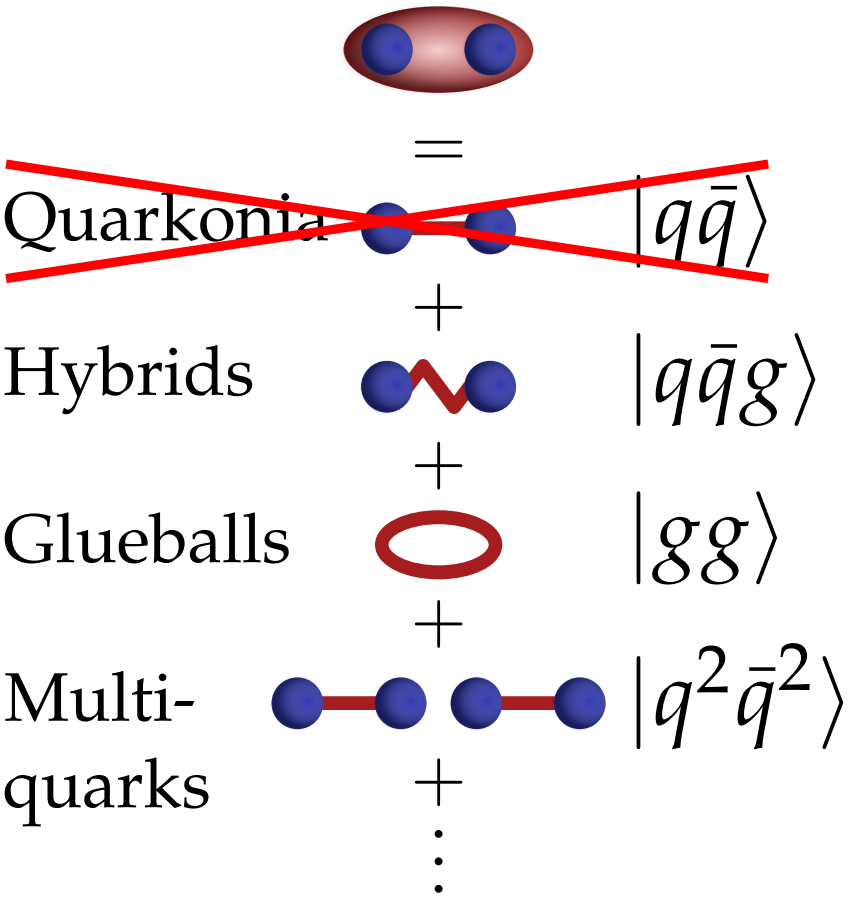


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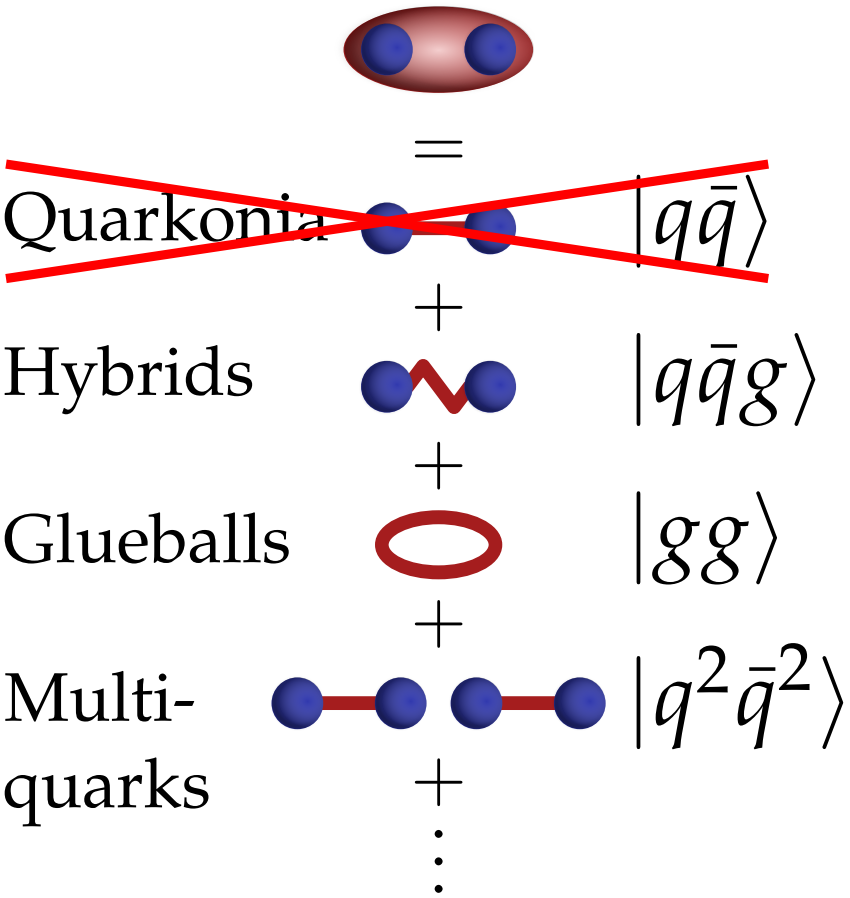


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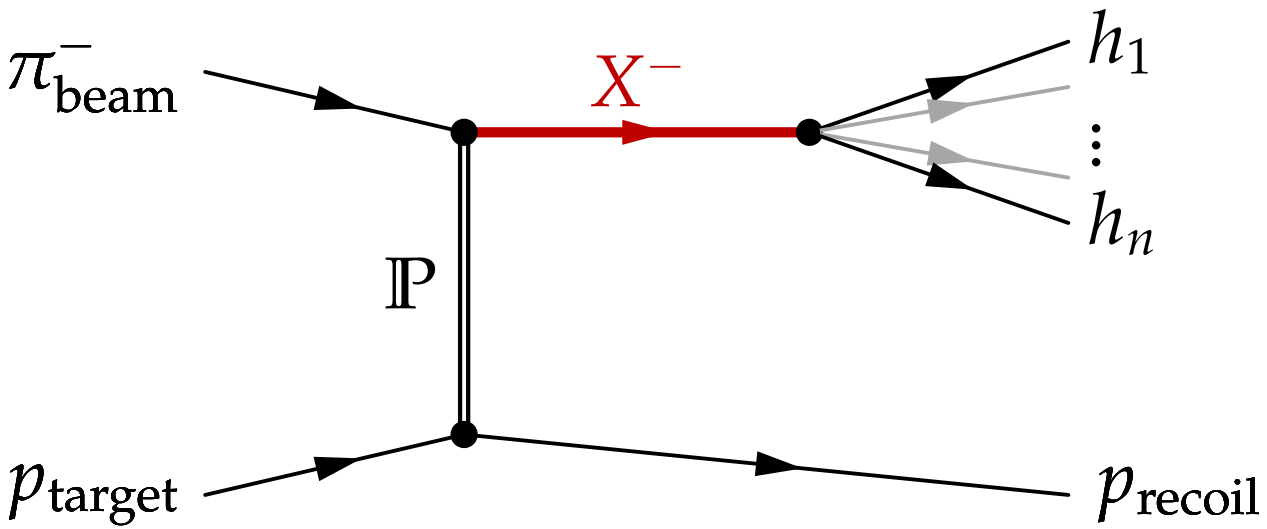
# Diffractive Production of light Mesons at COMPASS




- Soft scattering of 190 GeV pion beam off proton target
  - Target proton remains intact
  - Excitation of beam pion into some higher state $X$
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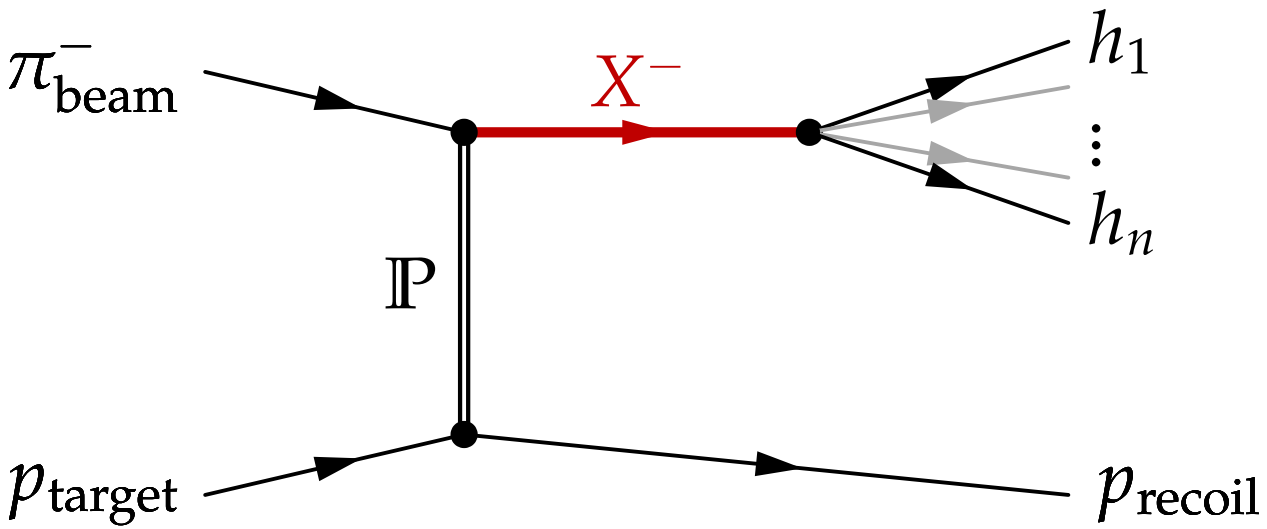


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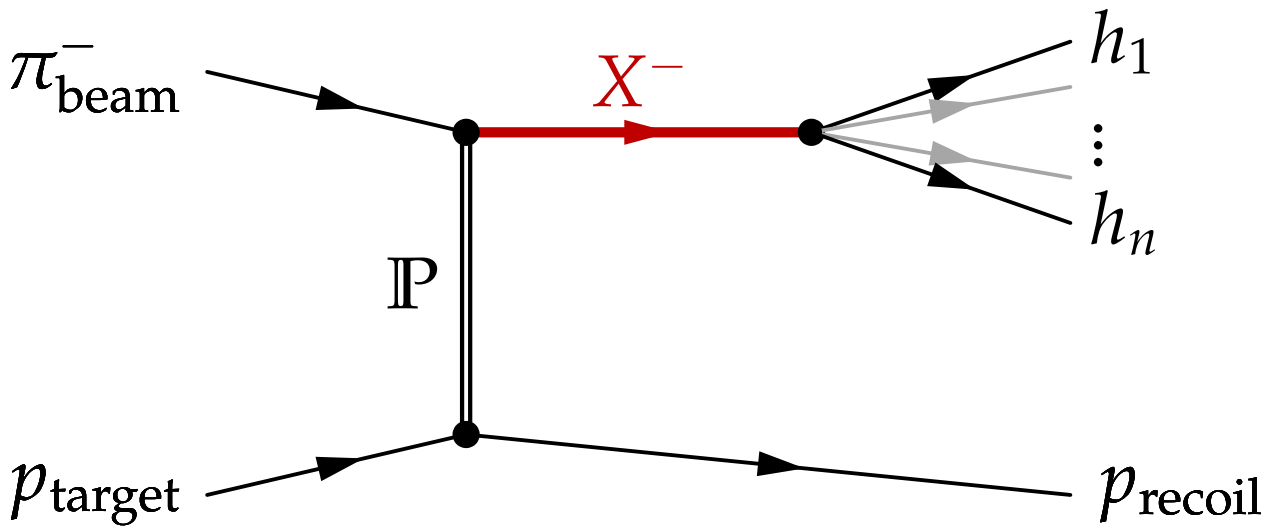


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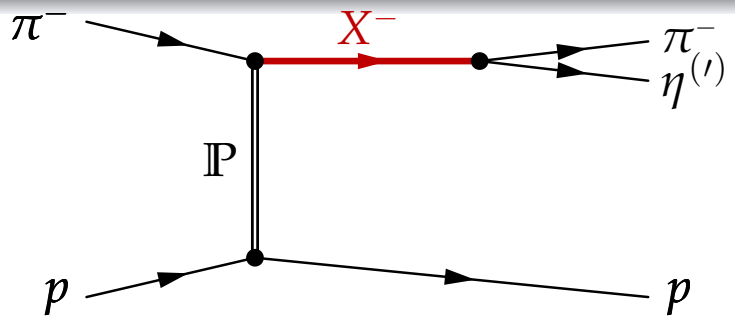
# *Example:* Diffractive Production of $\eta\pi$ and $\eta'\pi$

COMPASS, PLB **740** (2015) 303

- 116 000 $\eta\pi$ events
  - With $\eta \to \pi^+\pi^-\pi^0$ and $\pi^0 \to \gamma\gamma$
  - Dominated by well-known $a_2(1320)$ with $J^{PC} = 2^{++}$
- 39 000 $\eta'\pi$ events
  - With $\eta' \to \pi^+\pi^-\eta$ and $\eta \to \gamma\gamma$
  - Small $a_2(1320)$ signal




- For both systems, odd-$J$ waves have spin-exotic quantum numbers
- Previous experiments:
  - Puzzling $J^{PC} = 1^{-+}$ resonance signals
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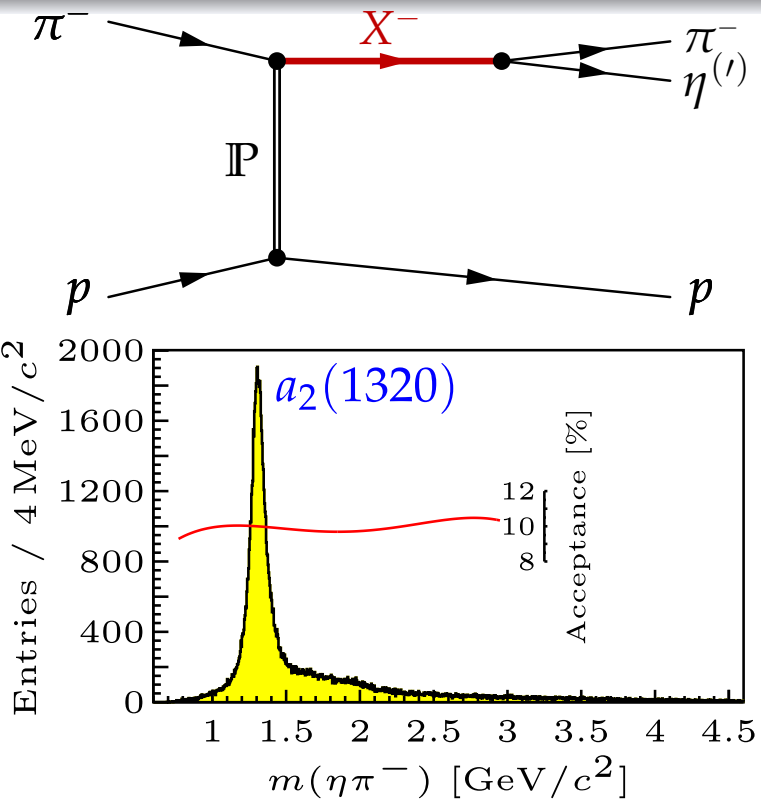

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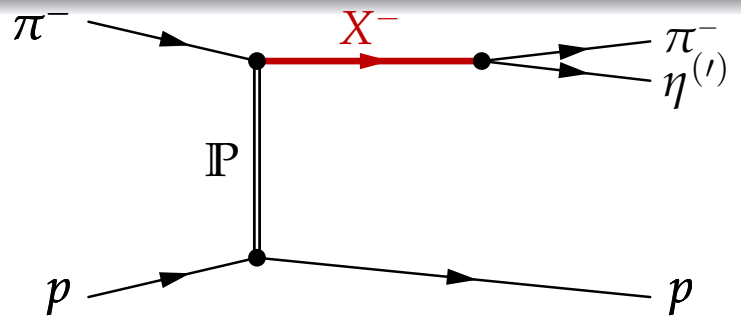


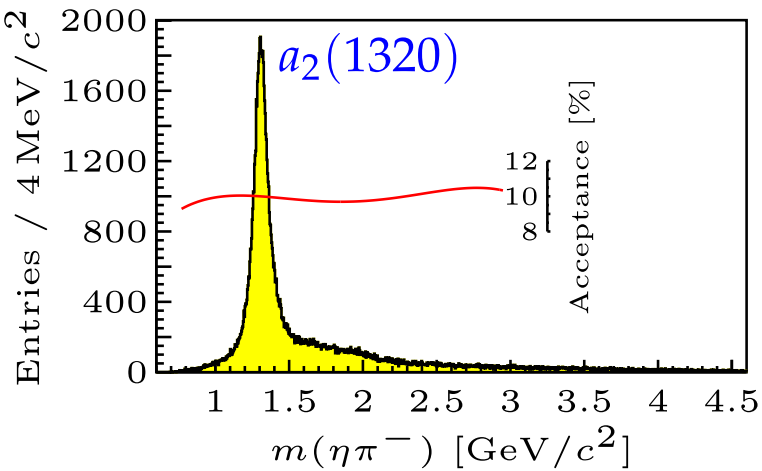


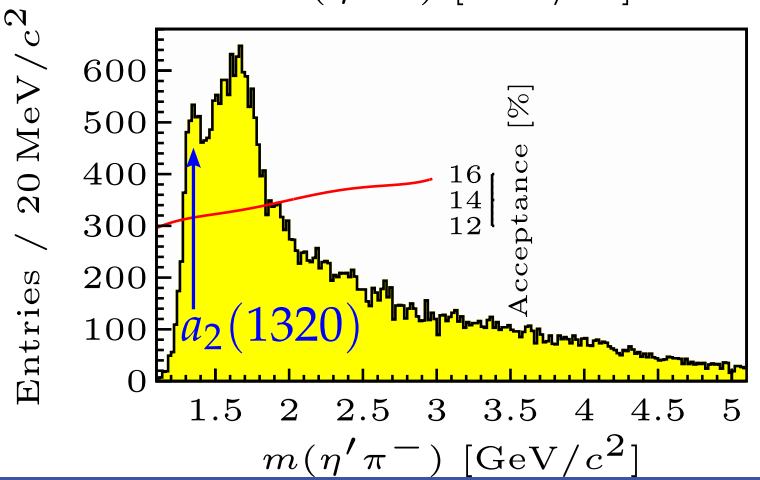

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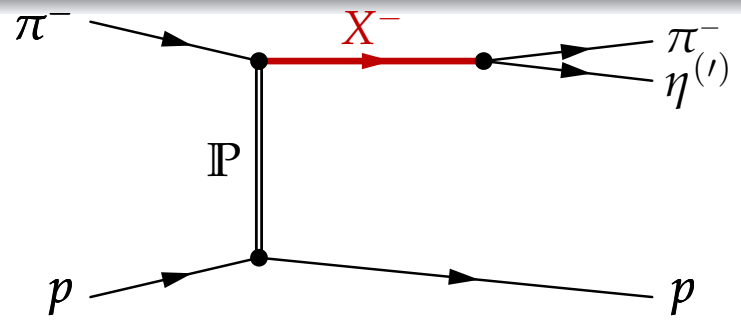
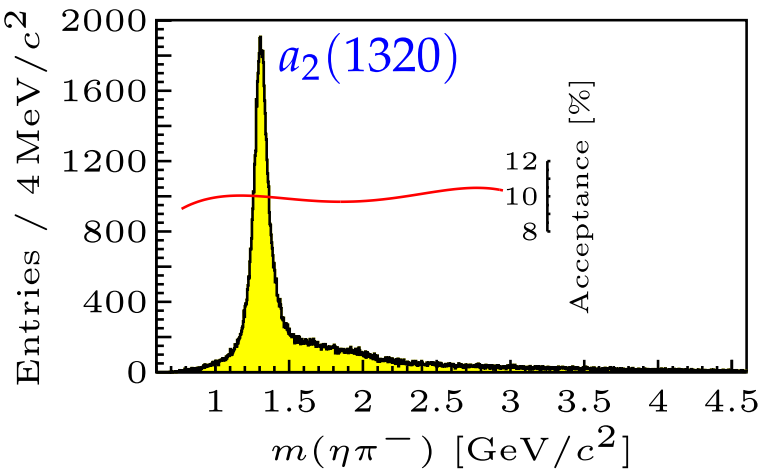
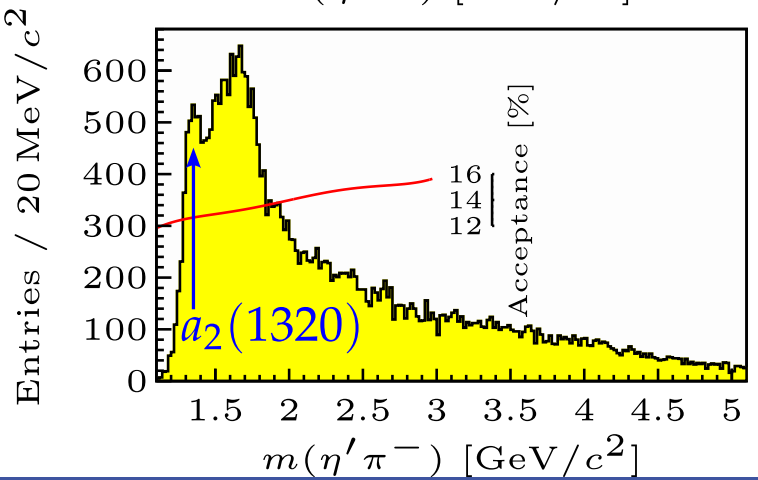
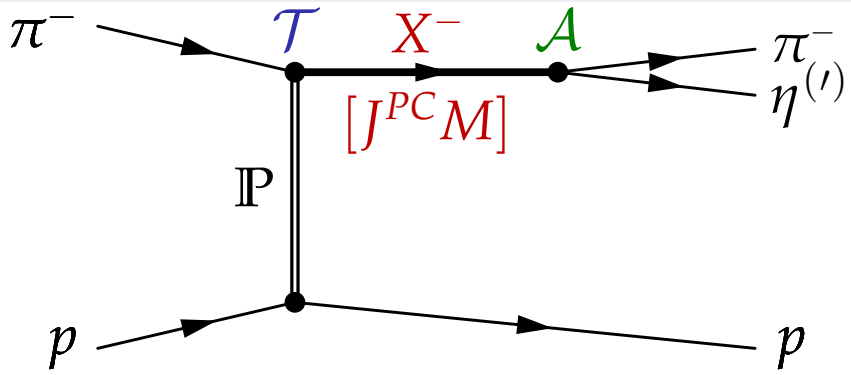


# Partial-Wave Analysis Method




**(Simplified) ansatz:** Factorization of production and decay

$$\sigma(\tau; m_X) \propto \left| \sum_{i}^{\text{waves}} \mathcal{T}_i(m_X)\, \mathcal{A}_i(\tau; m_X) \right|^2$$

- Transition amplitude $\mathcal{T}_i(m_X)$: strength and phase of wave $i$
- Decay amplitude $\mathcal{A}_i(\tau; m_X)$
  - Describes kinematic distribution of final-state particles in phase-space variables $\tau$ for wave $i$
  - For 2-body system of spinless particles: $\mathcal{A}_i(\tau) = Y_J^M(\theta, \phi)$

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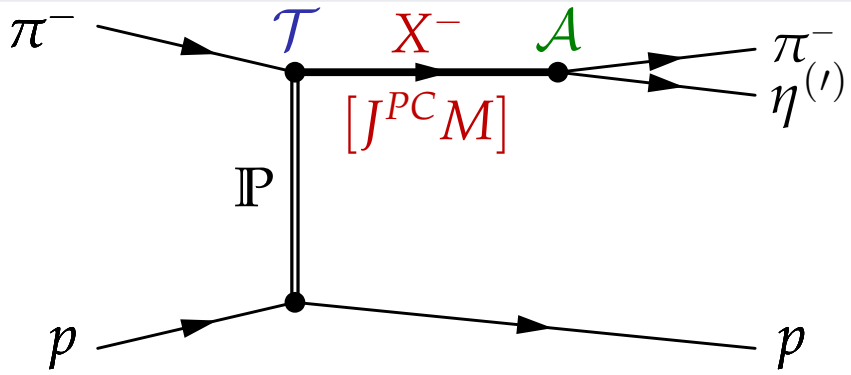


## Two-stage analysis

$$\sigma(\tau; m_X) \propto \left| \sum_{i}^{\text{waves}} \mathcal{T}_i(m_X)\, \mathcal{A}_i(\tau; m_X) \right|^2$$

1. **Partial-wave decomposition**
   - Independent maximum likelihood fits to $\tau$ distributions in narrow $m_X$ bins
   - Take into account detection efficiency
   - No assumptions about resonance content of $X$
2. **Resonance-model fit**
   - $\chi^2$ fit of resonance model to $m_X$ dependence of (selected) transition amplitudes

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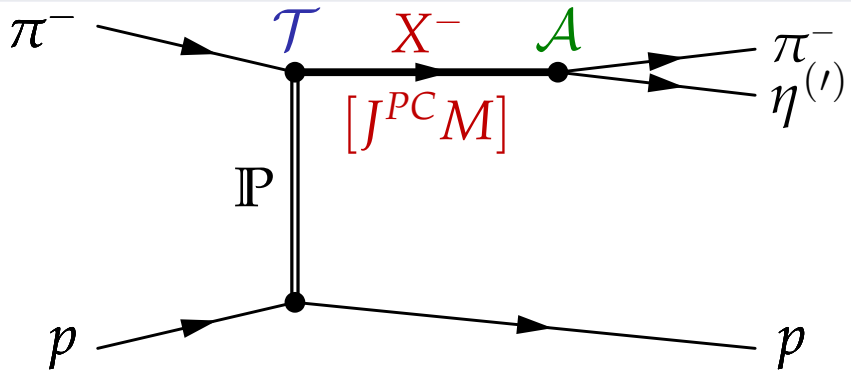


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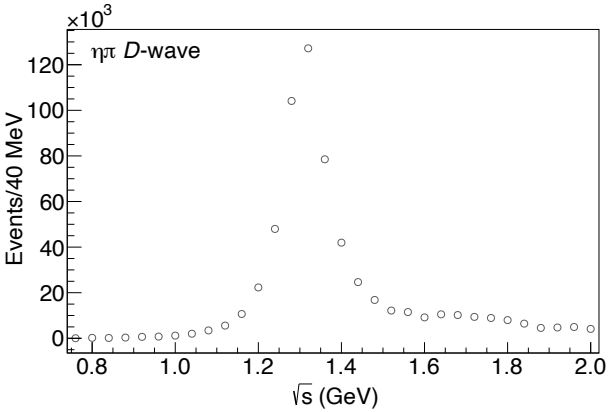
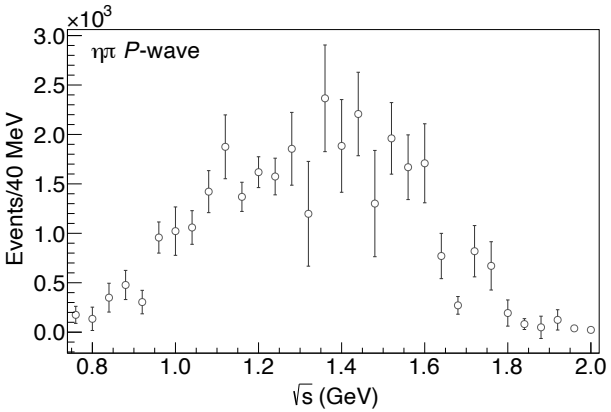
COMPASS, PLB **740** (2015) 303

Rodas *et al.* [JPAC], PRL **122** (2019) 042002

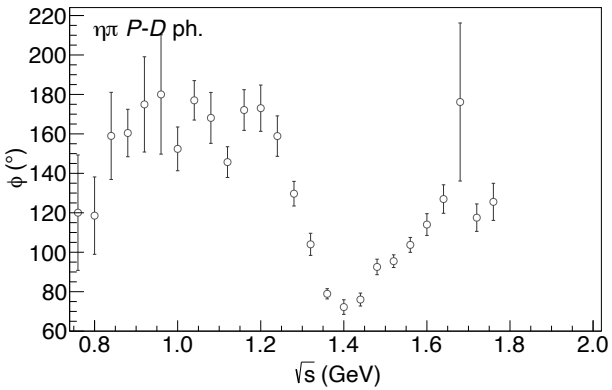
$\eta\pi$: $2^{++}$




$1^{-+}$




$\Delta\phi(1^{-+} - 2^{++})$

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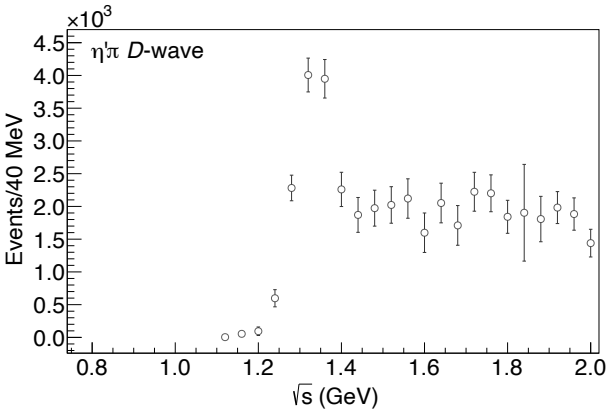


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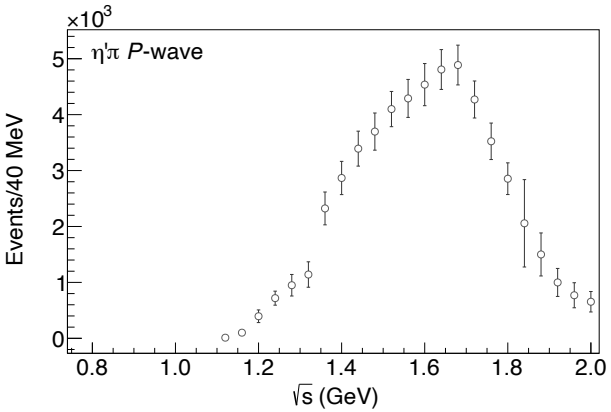


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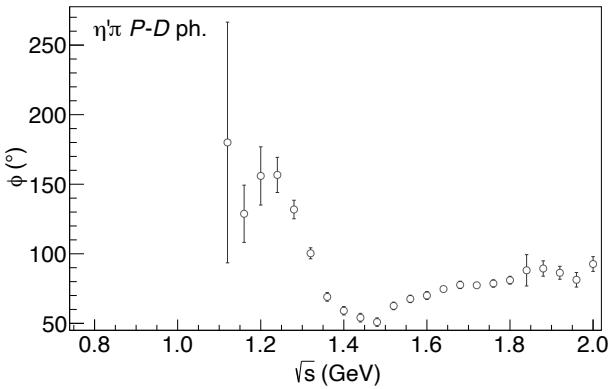


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- Analytical and unitary model based on $S$-matrix principles

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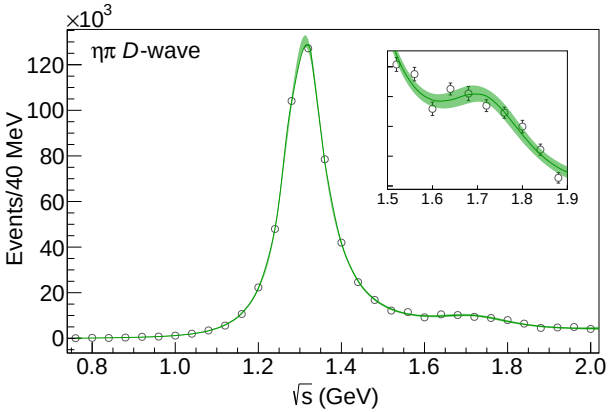


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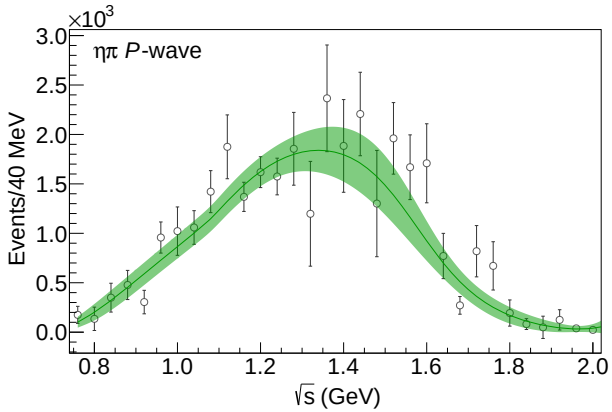


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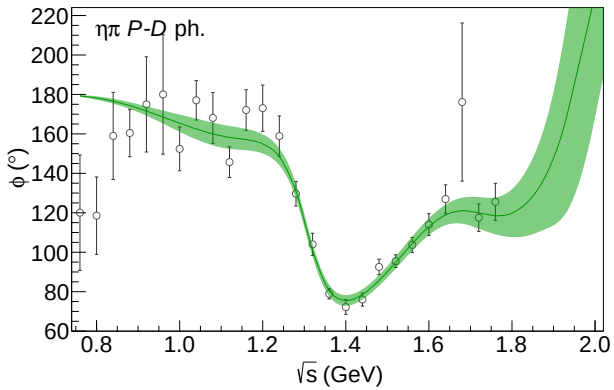


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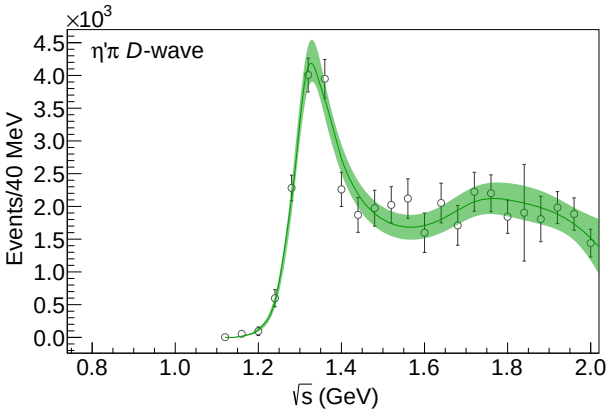


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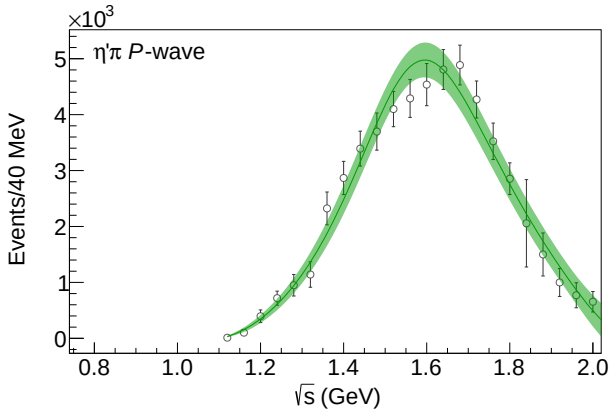


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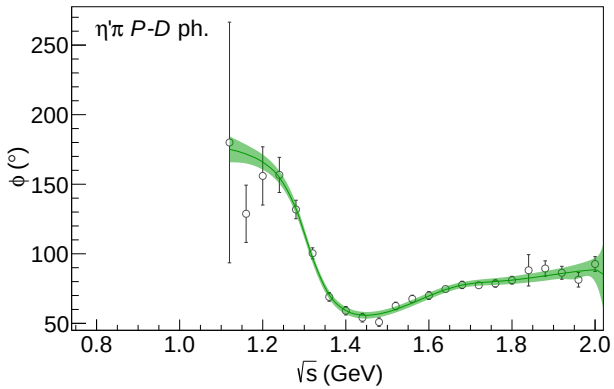


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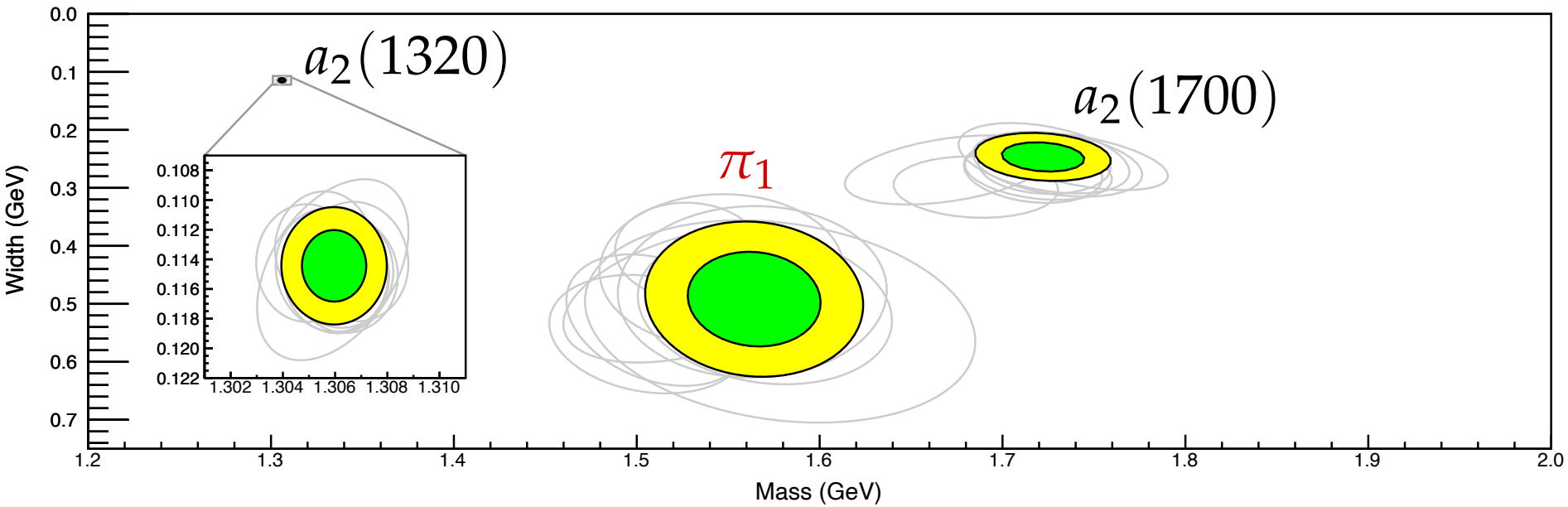
## Resonance Pole Parameters

Rodas *et al.* [JPAC], PRL **122** (2019) 042002




- Only single pole required to describe peaks in $\eta\pi$ and $\eta'\pi$ $1^{-+}$ waves:
  - $m_0 = (1564 \pm 24_{\text{stat.}} \pm 86_{\text{sys.}})\,\text{MeV}/c^2$
  - $\Gamma_0 = (492 \pm 54_{\text{stat.}} \pm 102_{\text{sys.}})\,\text{MeV}/c^2$
  - Consistent with $\pi_1(1600)$
  - First measurement of pole parameters of $\pi_1(1600)$
- Raises serious doubts about existence of $\pi_1(1400)$

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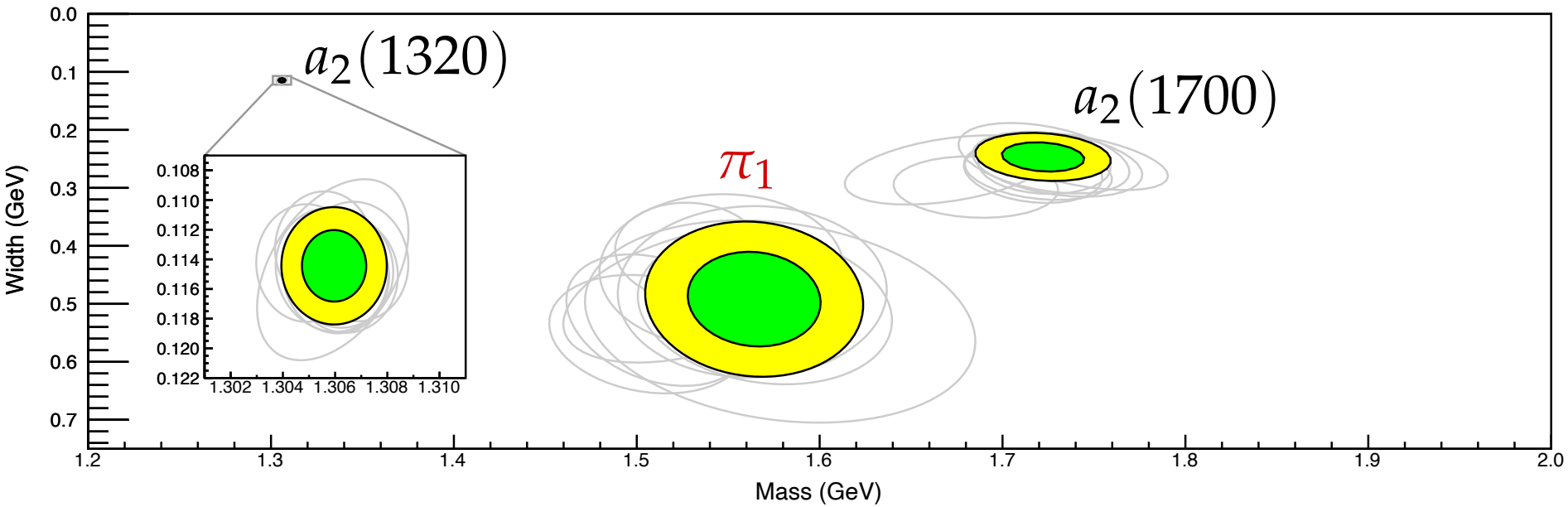


- Only single pole required to describe peaks in $\eta\pi$ and $\eta'\pi$ $1^{-+}$ waves:
  - $m_0 = (1564 \pm 24_{\text{stat.}} \pm 86_{\text{sys.}})\,\text{MeV}/c^2$
  - $\Gamma_0 = (492 \pm 54_{\text{stat.}} \pm 102_{\text{sys.}})\,\text{MeV}/c^2$
  - Consistent with $\pi_1(1600)$
  - First measurement of pole parameters of $\pi_1(1600)$
- Raises serious doubts about existence of $\pi_1(1400)$

# JPAC Coupled-Channel Analysis of $\eta\pi$ and $\eta'\pi$

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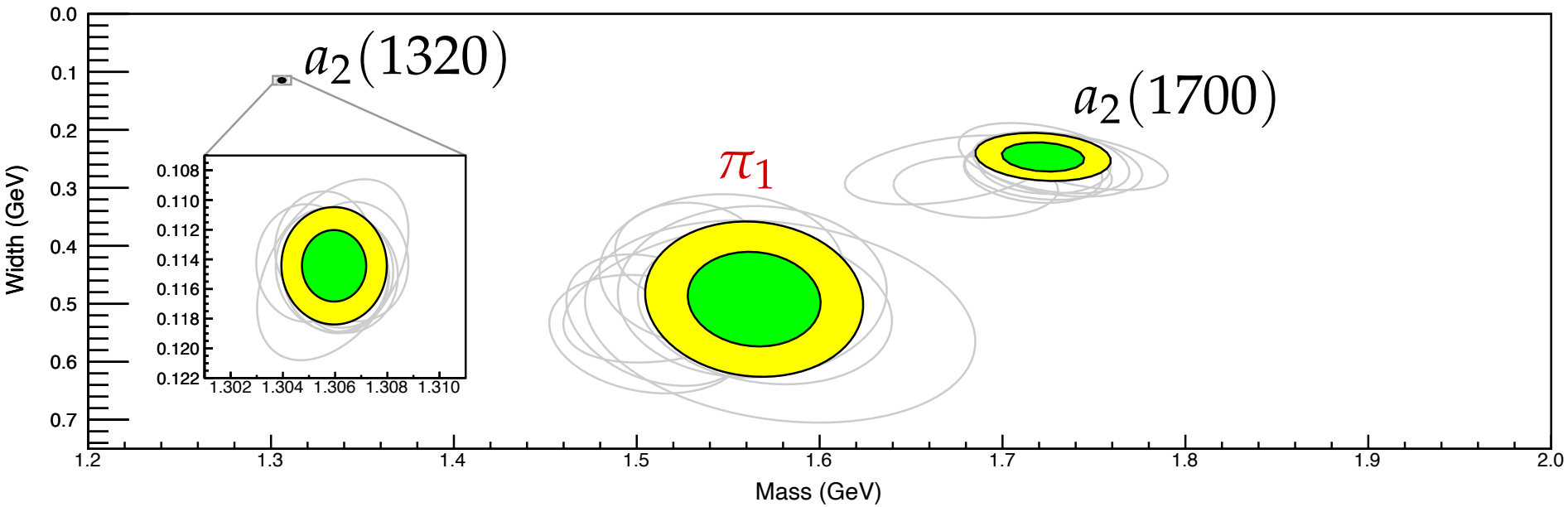


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# Light-Meson Spectroscopy at COMPASS

## Summary and Conclusions

### COMPASS has high-precision data on pion and kaon diffraction

- Performed so far most detailed and comprehensive PWA of $\eta^{(\prime)}\pi$, $\pi^-\pi^-\pi^+$, and $K^-\pi^-\pi^+$ channels
- Confirmed disputed $\pi_1(1600) \to \rho(770)\pi$ and explained seemingly contradictory results from previous experiments
- JPAC: $\pi_1(1400)$ does not exist and is identical to $\pi_1(1600)$

### Some lessons for heavy-meson spectroscopy

- Amplitude analysis is a powerful tool
  - But systematic uncertainties due to model assumptions may be sizable
  - Statistical(-only) significances may be deceiving
- Too simplistic resonance models may lead to duplication of states
- Similar challenges in formulating PWA models for multi-body decays of heavy and light meson
  - High-precision data require more advanced PWA models that take into account final-state interactions and non-resonant contributions

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