Observation of exclusive production of a charmonium and a charmonium-like state in the reaction $\mu^+N \to \mu^+(J/\psi\pi^+\pi^-)\pi^\pm N'$

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on behalf of the COMPASS collaboration

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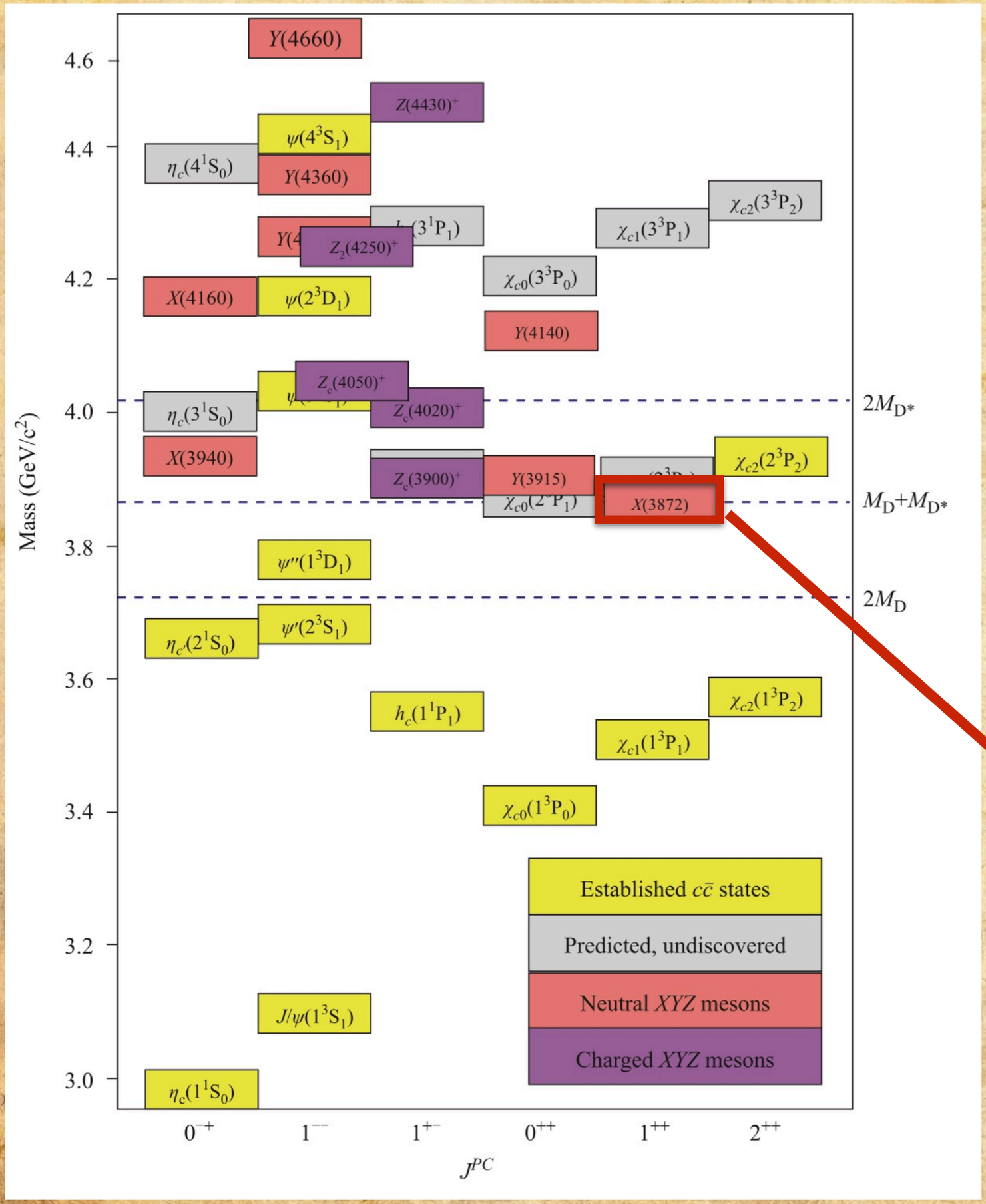


Charmonium and charmonium-like states

The first charmonium-like exotic hadron discovered by the Belle collab. in 2003

X(3872)

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 %	†
$\gamma J/\psi$	$> 6 \times 10^{-3}$	697
$\gamma\psi(2S)$	> 3.0 %	181
$\pi^+\pi^-\eta_c(1S)$	not seen	746
$p\overline{p}$	not seen	1693

Strong isospin violation:

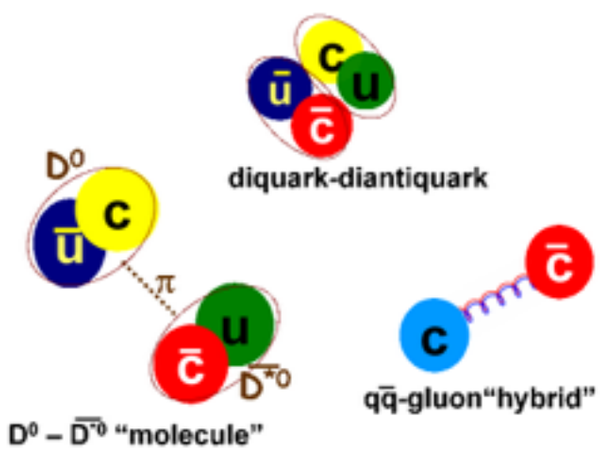
$$\frac{Br(X \to \pi^+\pi^-\pi^0 J/\psi)}{Br(X \to \pi^+\pi^- J/\psi)} = 1.0 \pm 0.4 \pm 0.3$$

- pure $c\bar{c}$ state ($\chi_{c1}(2P)$)
- tetraquark
- $D\bar{D}^*$- molecule
- $c\bar{c}g$ state
- threshold effects
- ...

?

$m_X - m_{DD^*} =$ 0.11 ± 0.21 MeV

State	M /MeV	Γ /MeV	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.68±0.17	< 1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle [95, 102], BaBar [98], LHCb [103]
				$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + \ldots$	CDF [96, 104, 105, 160], D0 [97]
				$B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$	Belle [107], BaBar [72, 73]
				$B \to K + (D^0\bar{D}^0\pi^0)$	Belle [108, 109], BaBar [110]
				$B \to K + (J/\psi\,\gamma)$	BaBar [137], Belle [138], LHCb [141]
				$B \to K + (\psi'\,\gamma)$	BaBar [137], Belle [138], LHCb [141]
				$pp \to (J/\psi\,\pi^+\pi^-) + \ldots$	LHCb [99], CMS [100] ATLAS
				$e^+e^- \to \gamma X(3872)$	BES-III



The COMPASS experiment

COMPASS (COmmon Muon Proton Apparatus for Structure and Spectroscopy)

is a fixed target experiment on a secondary beam of Super Proton Synchrotron at CERN

13 countries,
24 institutions,
~220 physicists

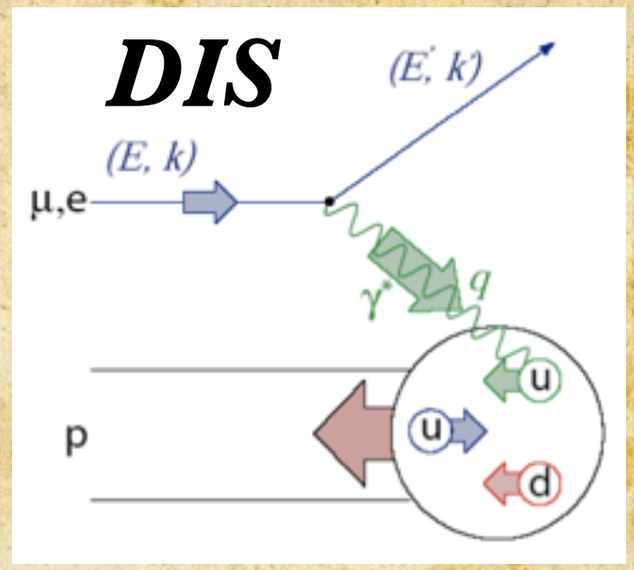
1996 - Proposal
2002-2016 - Physical data taking

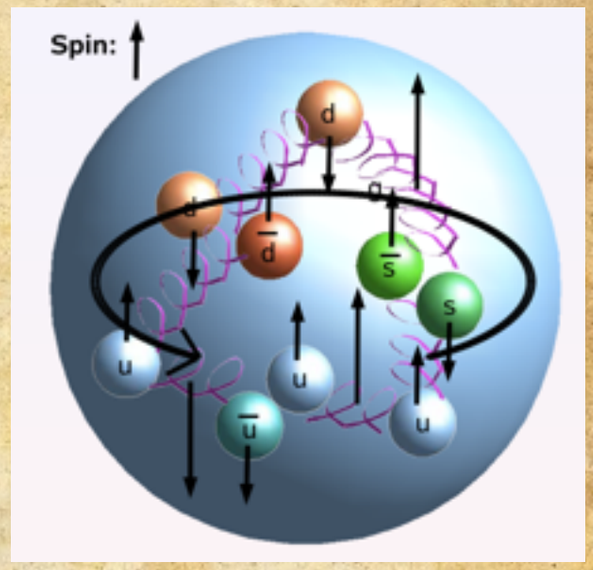
COMPASS: physics with muon and hadron beam

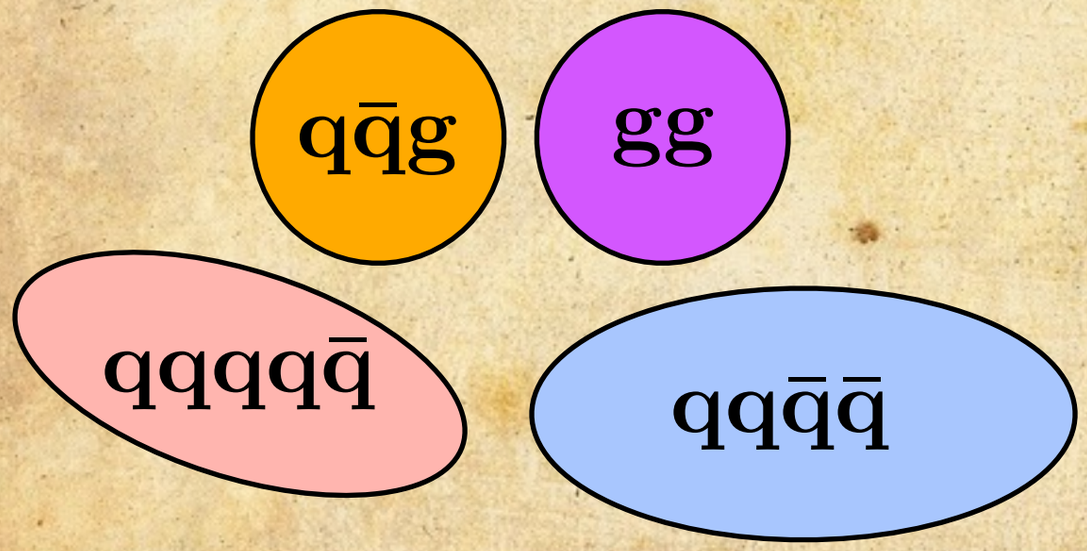
COMPASS ≈ SPIN PHYSICS + SPECTROSCOPY

Study of spin structure of nucleon with muon beam and polarized target:

- (un)polarized and TMD PDFs and FFs
- Generalized PDFs







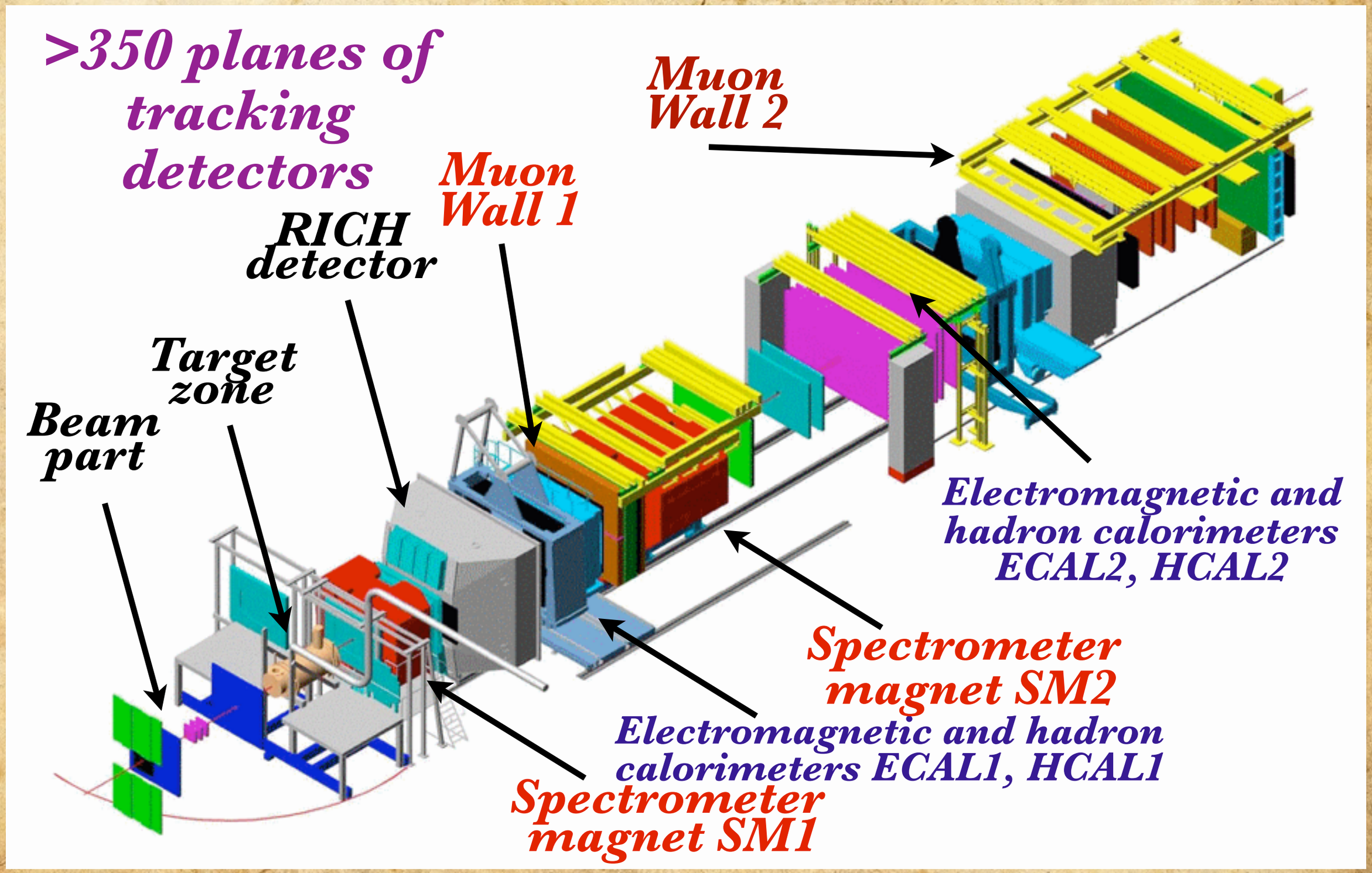
Study of hadron structure and hadron spectroscopy with hadron beam:

- Primakoff reactions
- diffractive and central production
- k_T-dependent PDFs via Drell-Yan process

Muon beam: μ^+, P=160-200 GeV/c

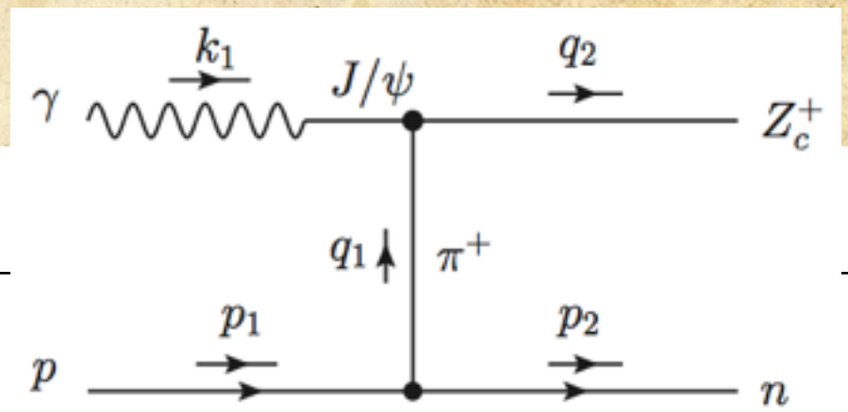
Hadron beam: π^-,K^-, p P=190 GeV/c

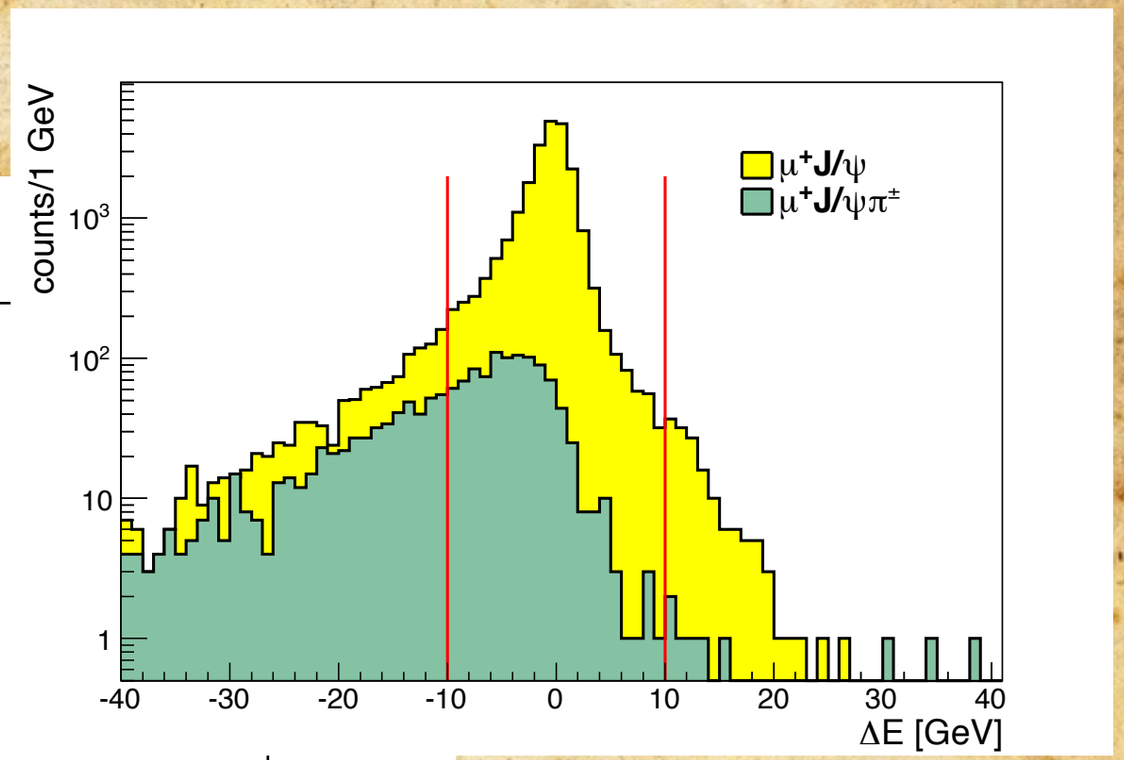
The COMPASS setup

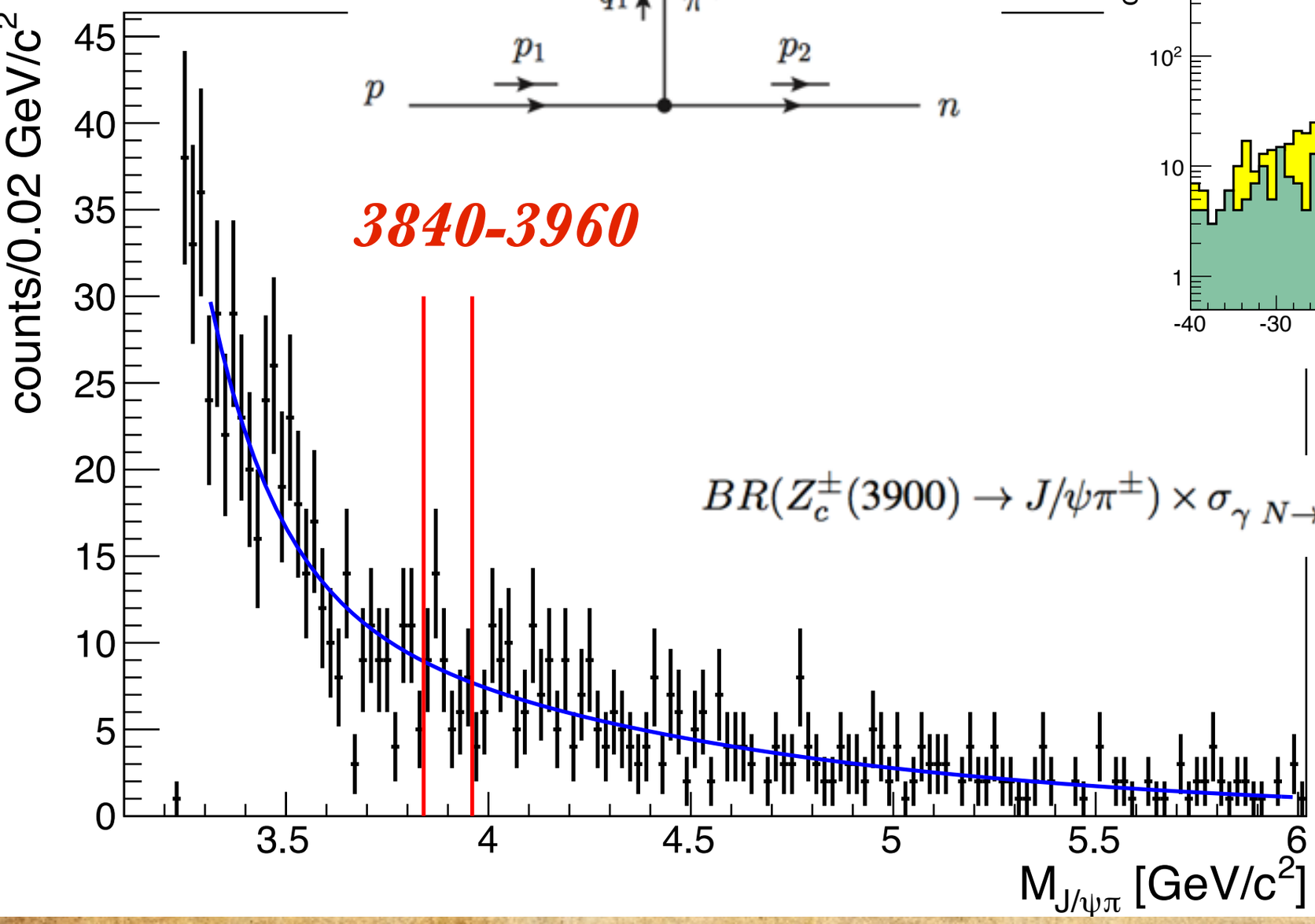


COMPASS and XYZ hadrons

COMPASS has addressed charmonia production







$$BR(Z_c^\pm(3900) \to J/\psi\pi^\pm) \times \sigma_{\gamma\, N \to Z_c^\pm(3900)\, N}\Big|_{\langle\sqrt{s_{\gamma N}}\rangle = 13.8\ \mathrm{GeV}} < 52\ \mathrm{pb}.$$

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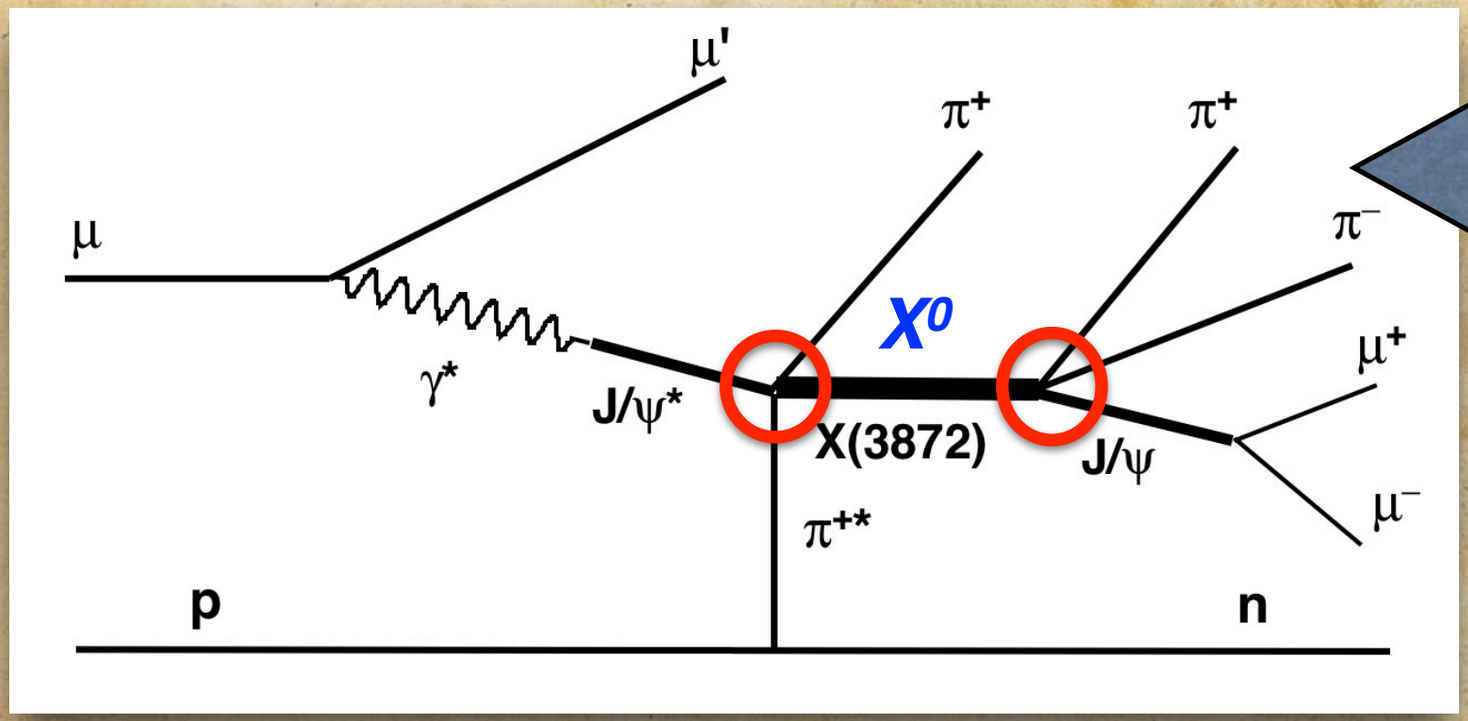
ψ(2S) and X(3872) at COMPASS

Now study $J/\psi\pi^+\pi^-$ subsystem of exclusive final state $J/\psi\pi^+\pi^-\pi^\pm$



Possible production mechanism

$$N \sim \Gamma_{J/\psi\pi\pi} \times B_{J/\psi\pi\pi} = \Gamma^2_{J/\psi\pi\pi}/\Gamma$$

$$\mu^+ N \to \mu^+ N' \pi^\pm X^0 \to \mu^+ N' \pi^\pm \pi^+ \pi^- J/\psi$$

X0: 1^{--} for J/ψ family and 1^{++} for X family (no G-parity eigenstate)

	$\psi(2S)$	$\psi(3770)$	X(3872)	$\psi(4040)$	$\psi(4160)$	X(4260)	X(4360)	X(4660)
M, MeV	3686	3773	3872	4039	4191	4251	4354	4665
Γ, MeV	0.3	27.2	<1.2	80±10	70±10	120±12	78±16	53±16
$\Gamma_{J/\psi\pi\pi}$, MeV	0.103	0.052	seen	<0.32	<0.21	seen	seen	seen

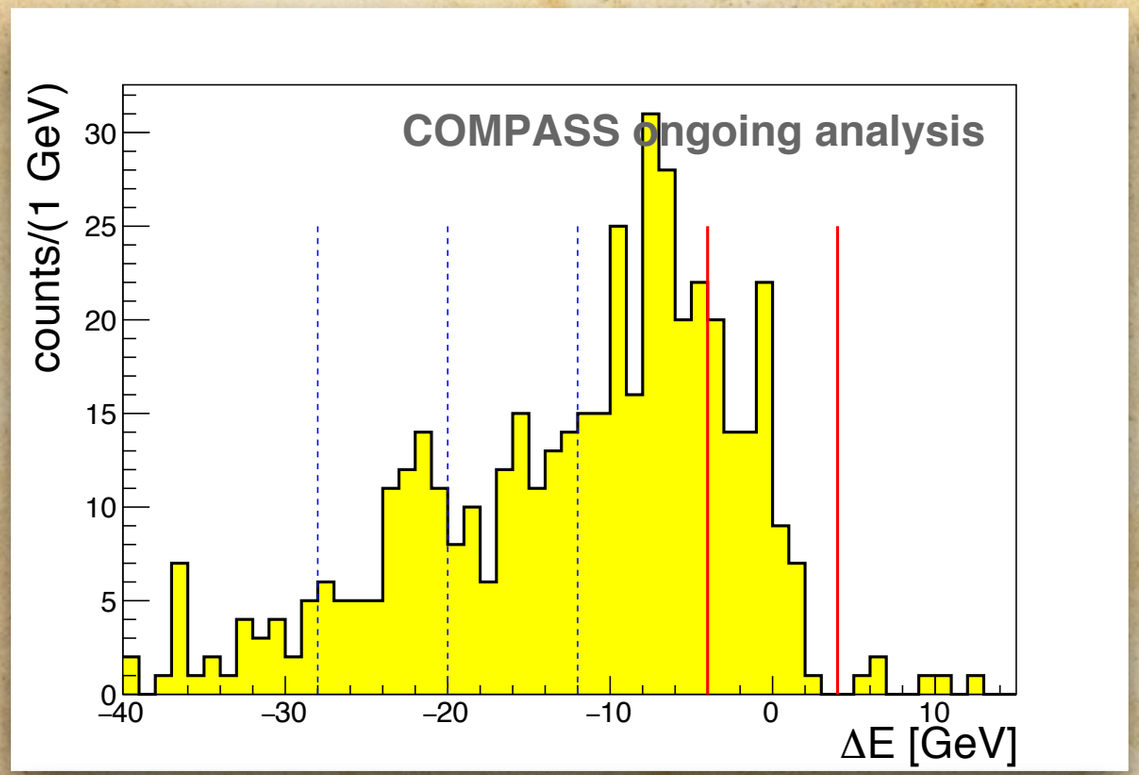
Event selection

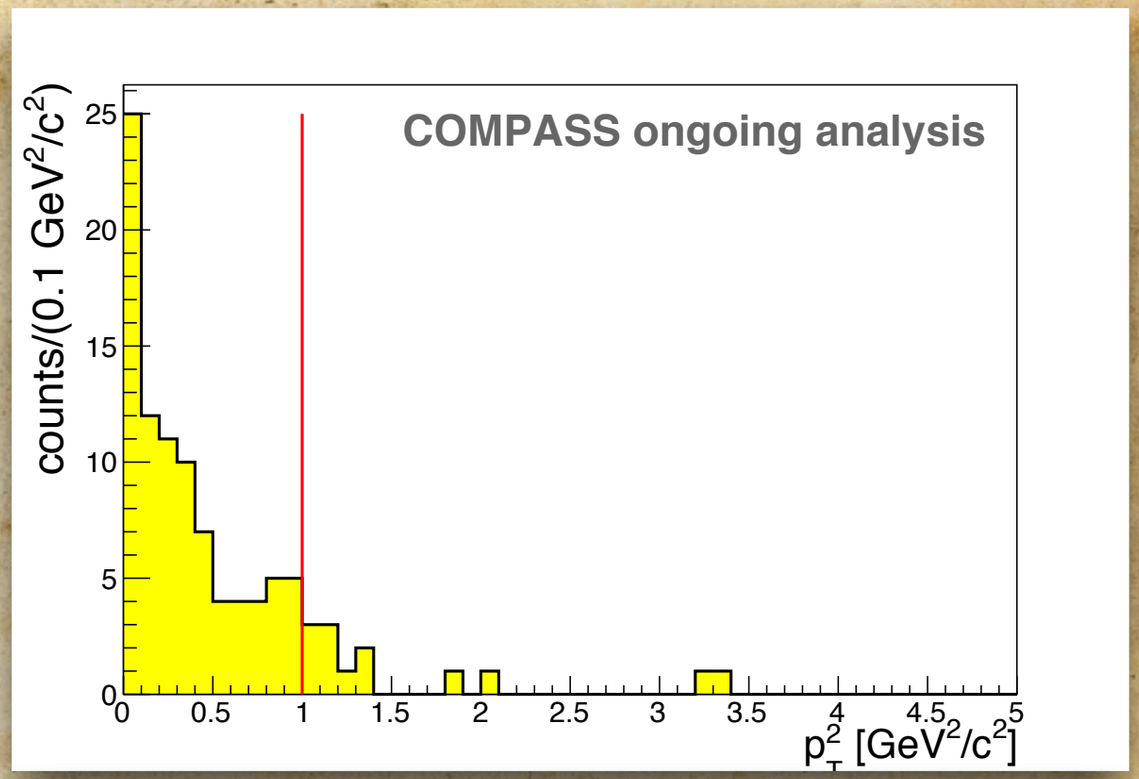
- Primary vertex in the target region
- $\mu^+\mu^-\mu^+$ in the primary vertex with $P>8$ GeV/c
- Just 1 J/ψ candidate in mass range 3.02-3.18 GeV
- Additional $\pi^+\pi^-\pi^\pm$ in the primary vertex
- No background tracks
- p_T cut: $p_T<1$ GeV/c
- Exclusivity cut $|\Delta E|<4$ GeV

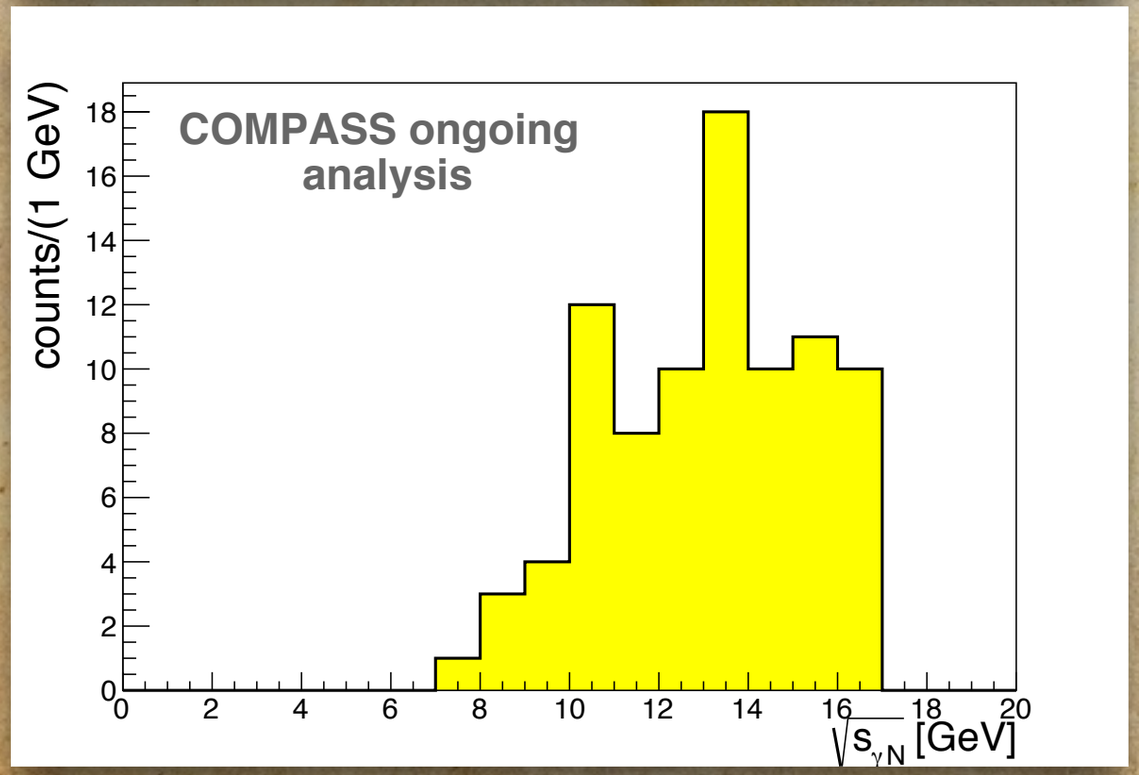
87 events after selection:

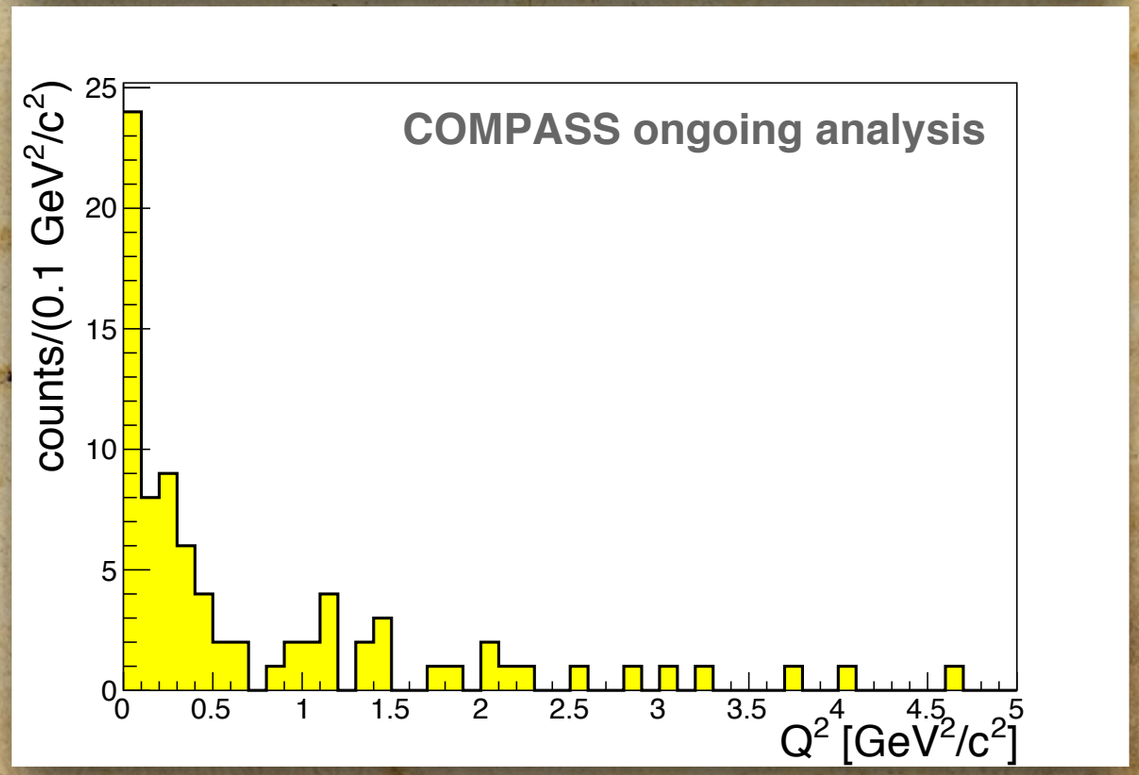
52 $J/\psi\ \pi^+\pi^-\pi^+$ and 35 $J/\psi\ \pi^+\pi^-\pi^-$

Kinematic distributions

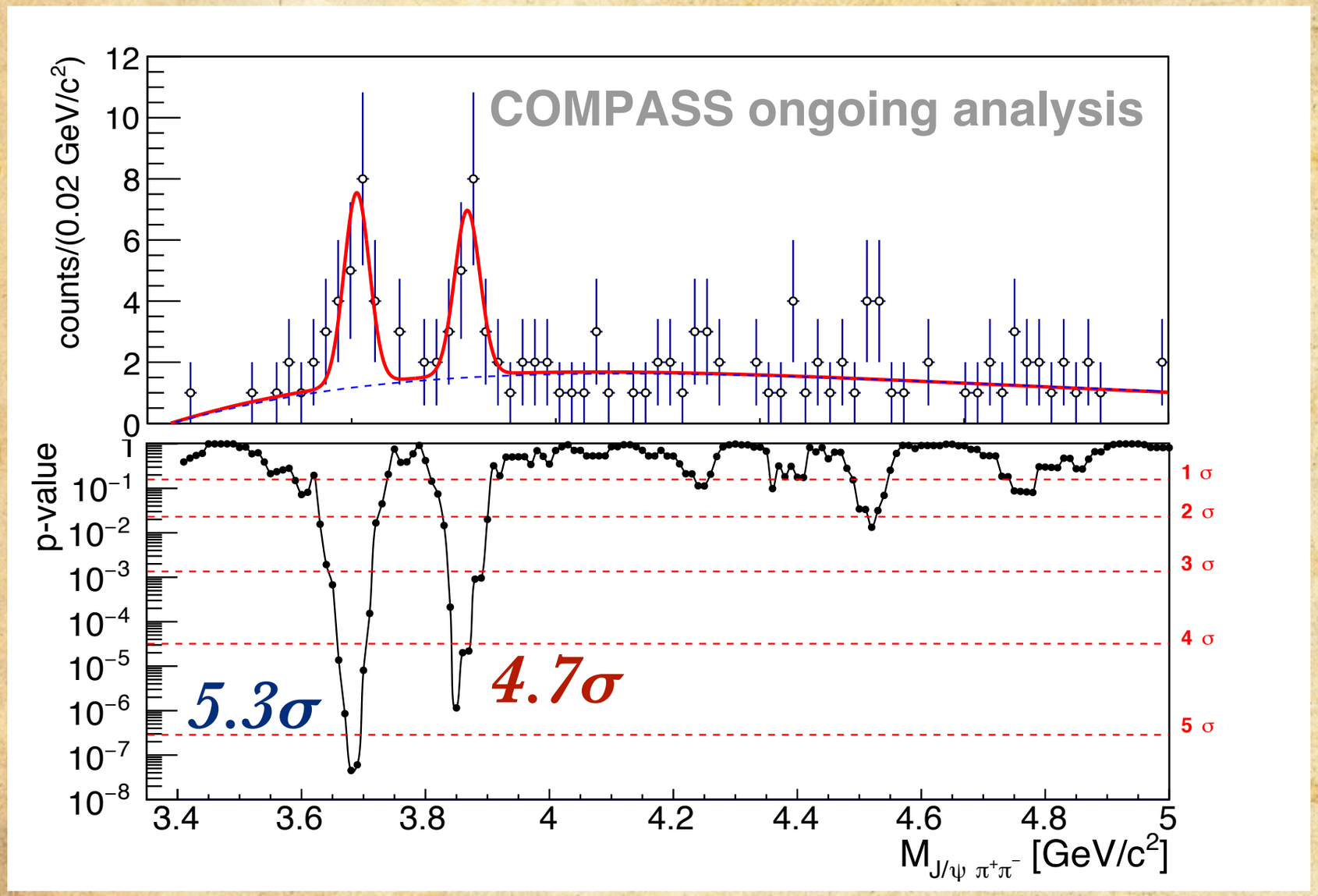


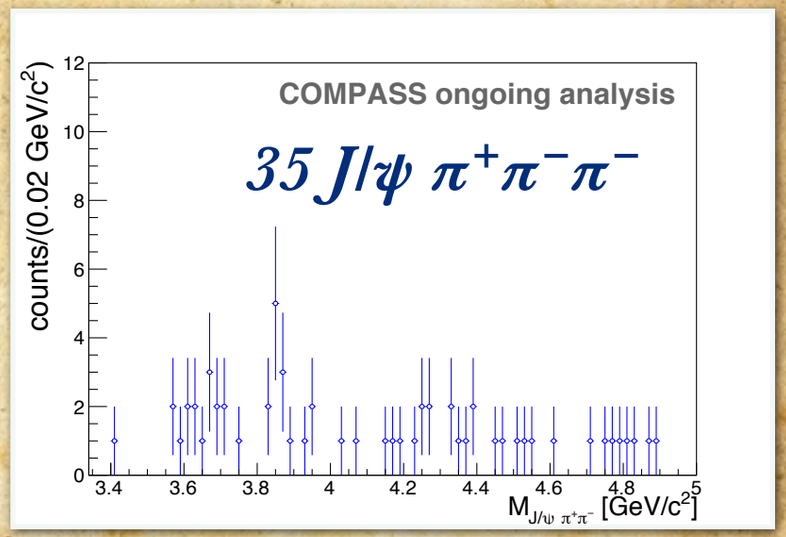


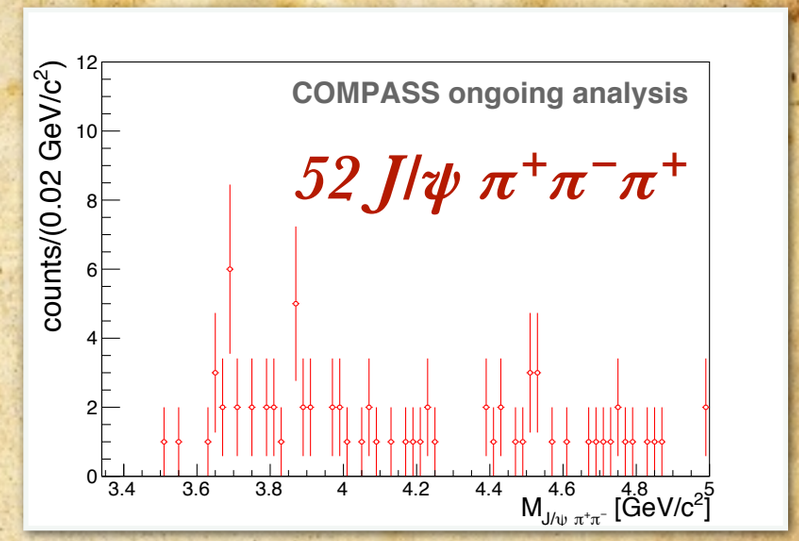




$J/\psi\pi^+\pi^-$ mass spectrum







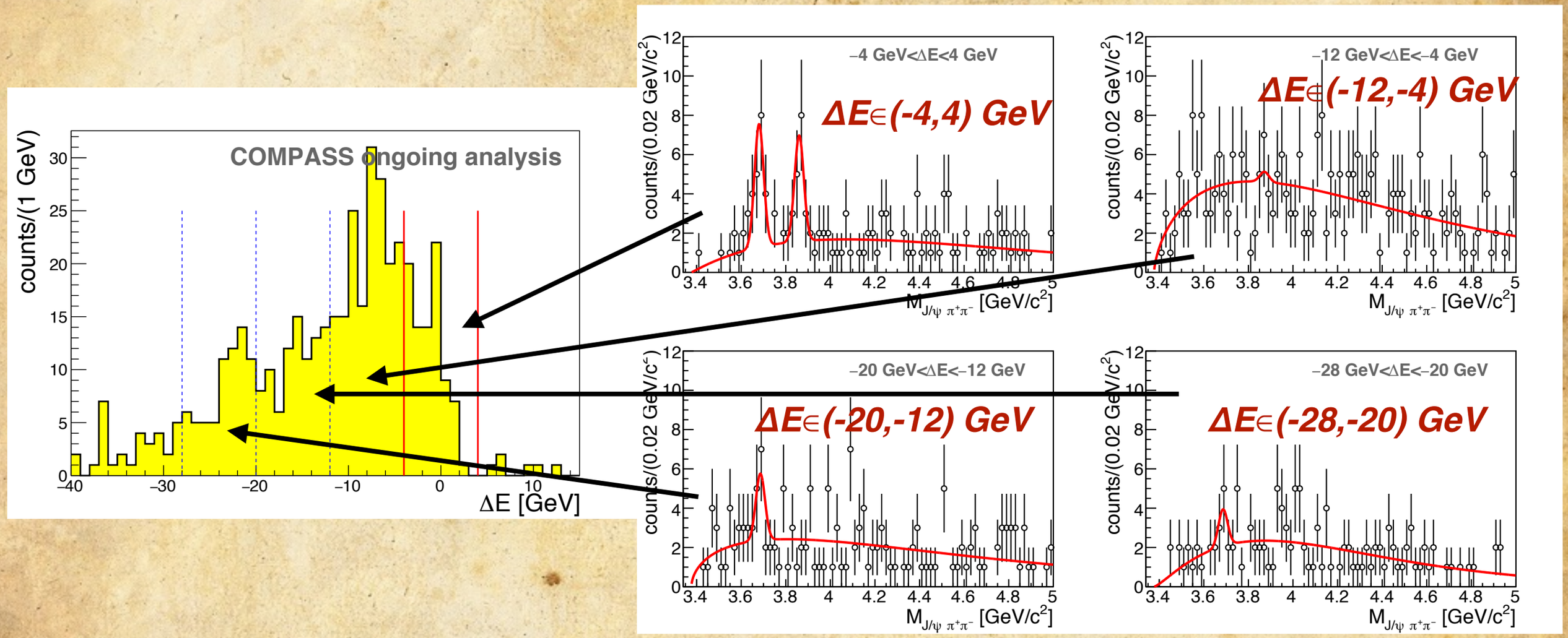
8-parameter fit

$N_{\psi(2S)}=16.1\pm5.2$
$N_{X(3872)}=13.9\pm4.9$

$M_{\psi(2S)}=3680\pm8$ MeV (nominal 3686.1)
$M_{X(3872)}=3860\pm8$ MeV (nominal 3871.7)

$$f(m) = Gaus(N_{\psi(2S)}, M_{\psi(2S)}, \sigma_M) + Gaus(N_{X(3872)}, M_{X(3872)}, \sigma_M) + c_1(m-m_0)^{c_2}e^{-c_3 m}$$

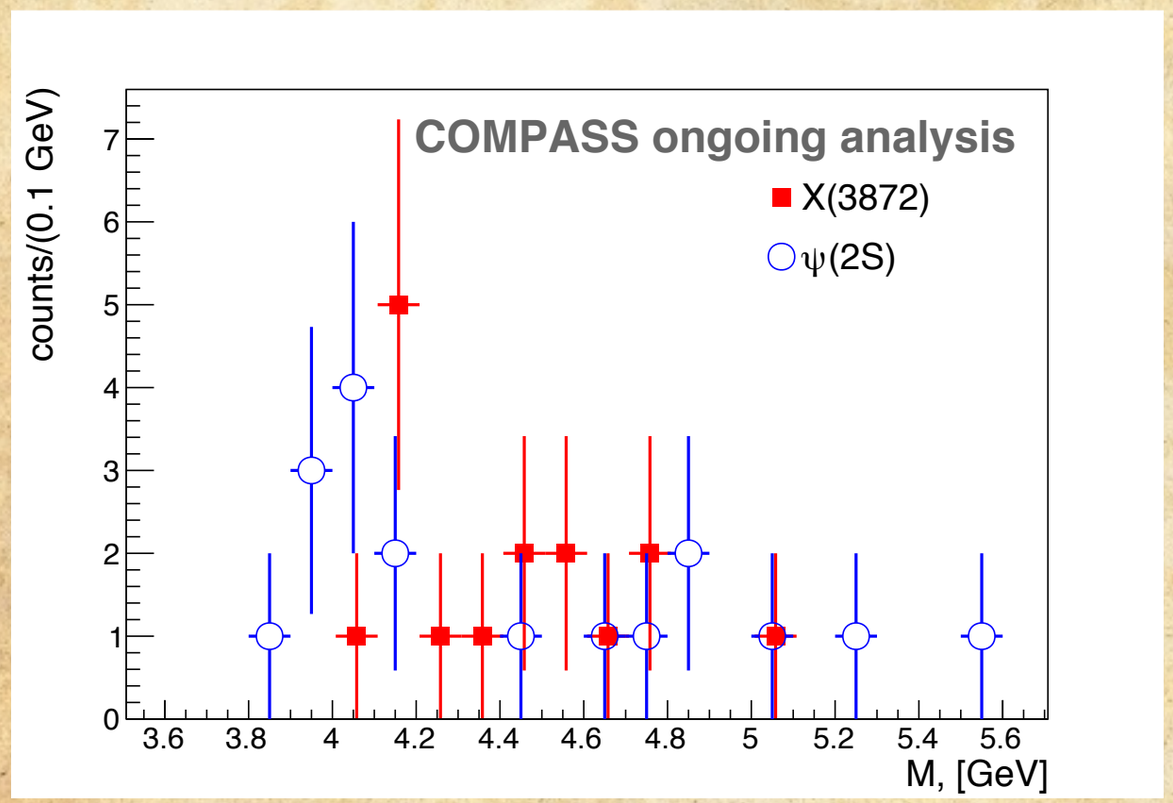
$J/\psi\pi^+\pi^-$ mass spectrum

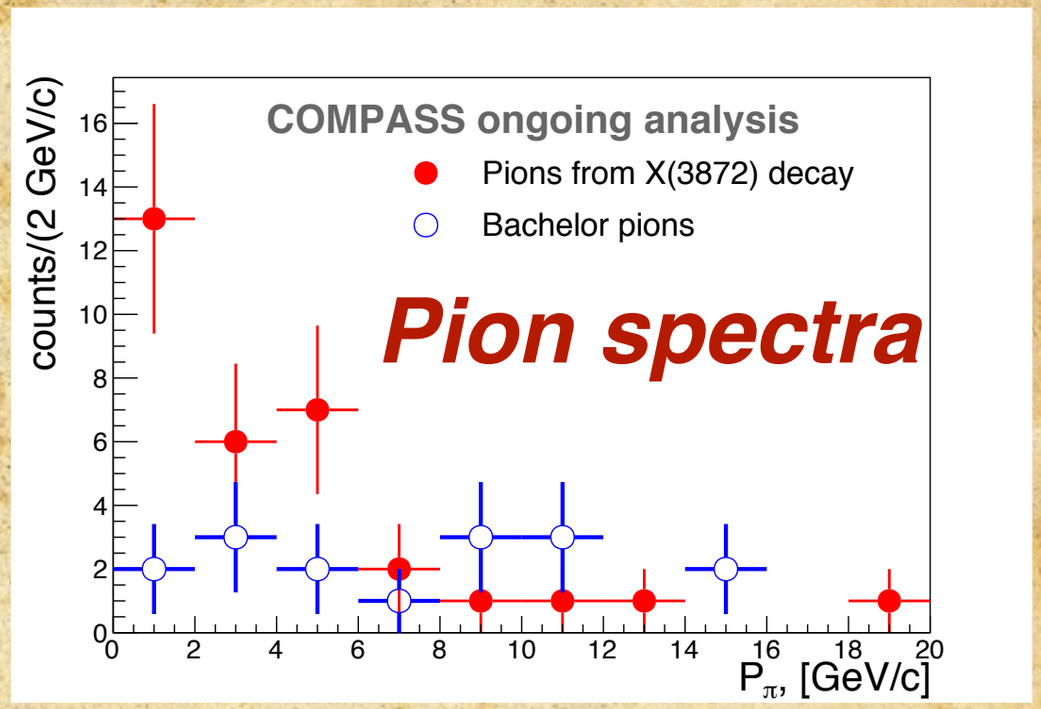


Exclusive production of X(3872)

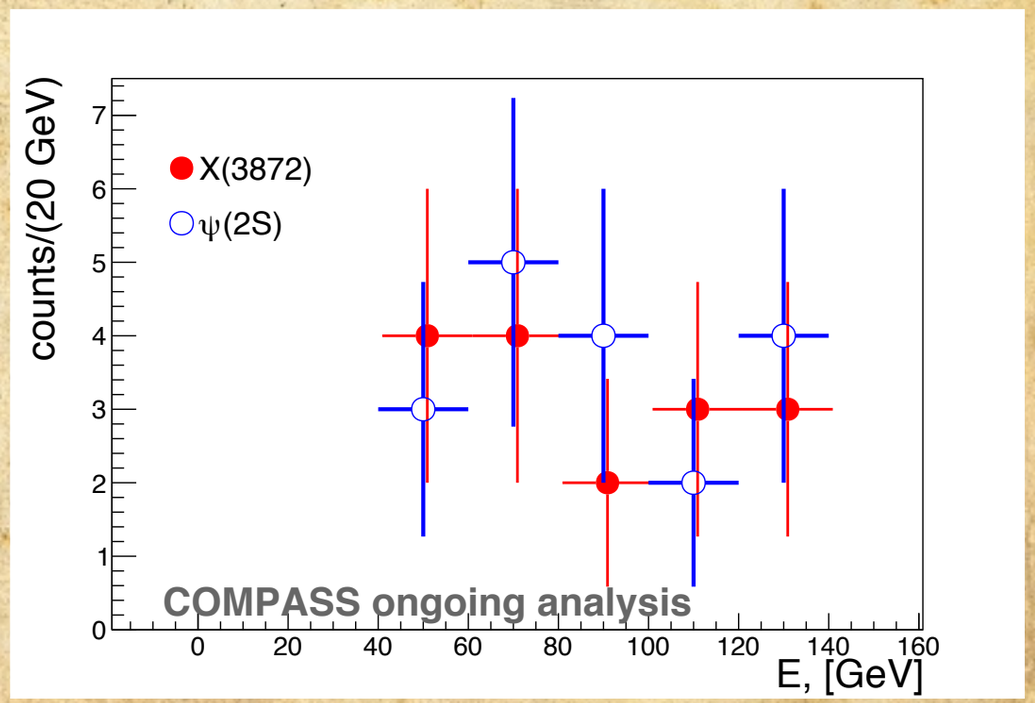
Details of the production

Total mass of ψ(2S)π and X(3872)π systems



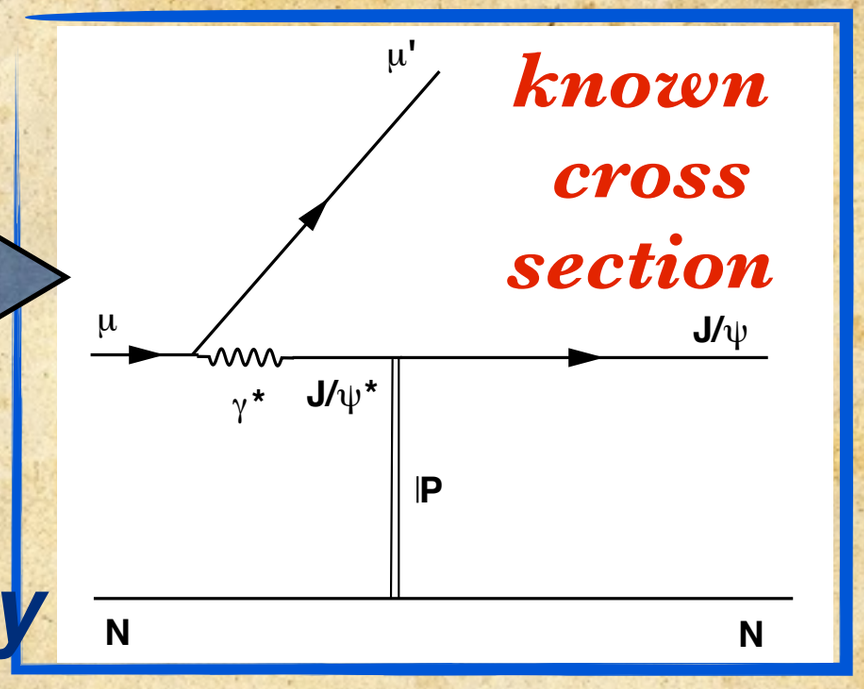


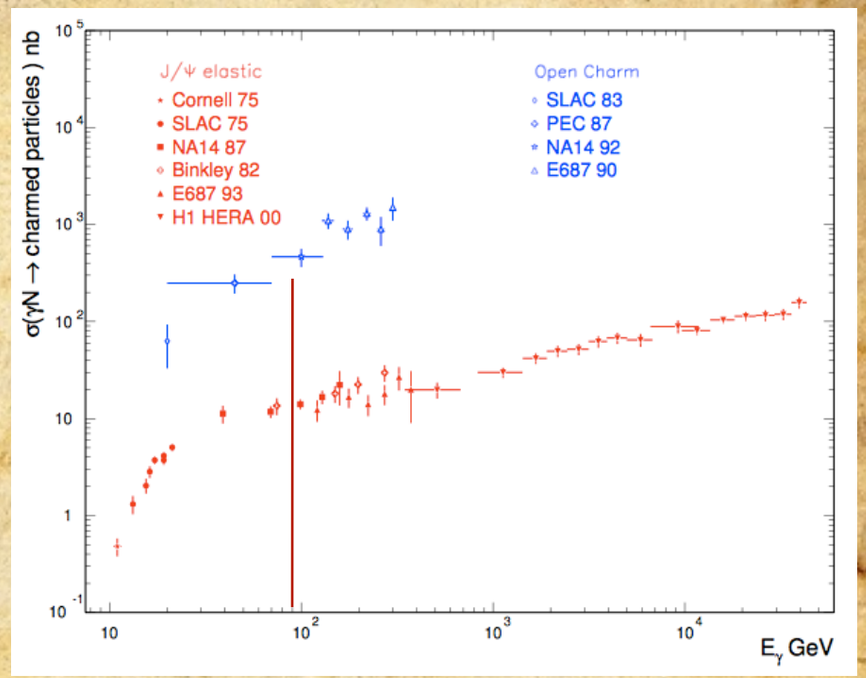
Yield of ψ(2S) and X(3872)



Absolute production rate

Use exclusive J/ψ production as a reference: $\mu^+N \to \mu^+ J/\psi N$





Same data set - same γ* luminosity

$$\frac{\sigma_{\mu\, N\to\mu X(3872)\pi\, N'}}{\sigma_{\mu\, N\to\mu J/\psi\, N}} = \frac{\sigma_{\gamma\, N\to X(3872)\pi\, N'}}{\sigma_{\gamma\, N\to J/\psi\, N}}$$

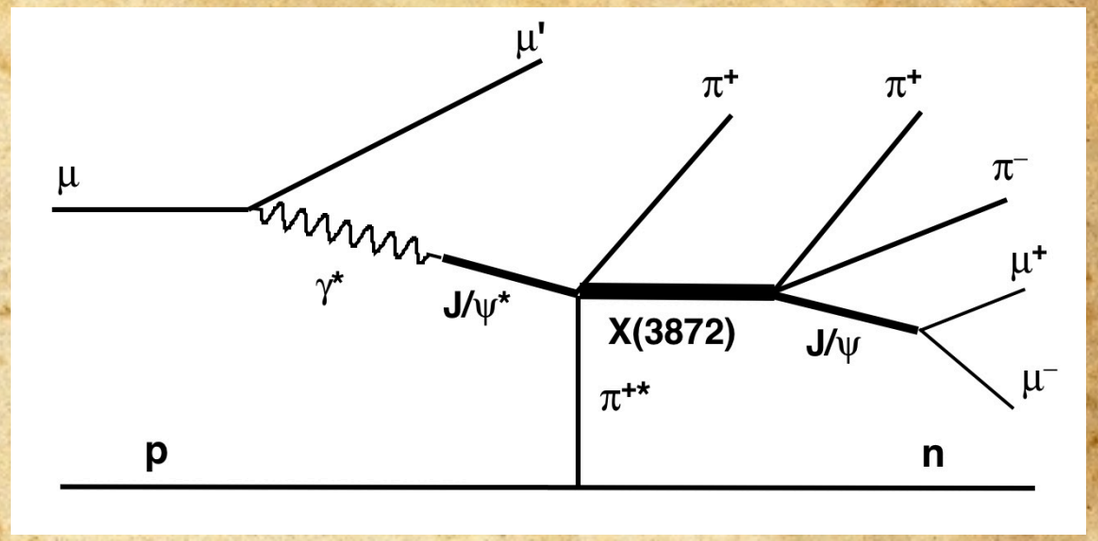
$\sigma_{\gamma N\to J/\psi N}$=(14.0±1.6$_{stat}$±2.5$_{syst}$) nb (NA14)

$$\frac{\sigma_{\gamma N\to X(3872)\pi N'} \times \mathcal{B}_{X(3872)\to J/\psi\pi\pi}}{\sigma_{\gamma N\to J/\psi N}} = \frac{N_{X(3872)}}{a_\pi^3 N_{J/\psi}}$$

a_π=0.6±0.1 acceptance for soft pion

$$\sigma_{\gamma N\to X(3872)\pi N'} \times \mathcal{B}_{X(3872)\to J/\psi\pi\pi} = 130 \pm 50(stat) \pm 80(syst)\ \text{pb}.$$

Width of X(3872)



Assumption: X(3872) produced via CEX reaction

N ~ Flux of virtual photons | Flux of virtual pions | Production phase space | Acceptance | $\Gamma_{J/\psi\pi\pi}$ | $BR_{J/\psi\pi\pi}$

Equal for X(3872) and ψ(2S)

$$\frac{N_{X(3872)}}{N_{\psi(2S)}} = \frac{\Gamma_{X(3872)\to J/\psi\pi\pi} BR_{X(3872)\to J/\psi\pi\pi}}{\Gamma_{\psi(2S)\to J/\psi\pi\pi} BR_{\psi(2S)\to J/\psi\pi\pi}} = \frac{\Gamma^2_{X(3872)\to J/\psi\pi\pi}\Gamma_{\psi(2S)}}{\Gamma^2_{\psi(2S)\to J/\psi\pi\pi}\Gamma_{X(3872)}}$$

=0.9±0.4

For ψ(2S): $\Gamma_{\psi(2S)}$=298 keV, $\Gamma_{\psi(2S)\to J/\psi\pi\pi}$=103 keV

$$\Gamma_{X(3872)\to J/\psi\pi\pi} BR_{X(3872)\to J/\psi\pi\pi} = 32 \pm 14\ keV.$$

$\Gamma_{X(3872)}$<1.2 MeV CL=90% → **$\Gamma_{X(3872)\to J/\psi\pi\pi}$ <210 keV, CL=90%**

$$BR_{X(3872)\to J/\psi\pi\pi} = 1 - \sum BR_i < 0.625$$ → **$\Gamma_{X(3872)}$ > 80 keV**

Summary

- ***COMPASS observed lepto(photo-)production of exotic charmonium X(3872) in exclusive reaction $\mu N \to \mu N'(J/\psi\pi^+\pi^-)\pi^\pm$ together with the well-known charmonium $\psi(2S)$***

- ***We measured $\sigma_{\gamma N \to X\pi N'} \times B_{J/\psi\pi\pi} = 130 \pm 50(stat) \pm 80(syst)$ pb (input for Glue-X and CLAS-12)***

- ***Assuming the same production mechanism for X(3872) and $\psi(2S)$ we extract upper limit of the partial width $\Gamma_{J/\psi\pi\pi} < 210$ keV and lower limit of the full width $\Gamma_X > 80$ keV***

- ***Further input for modeling of X(3872)***