Search for photoproduction of exotic charmonia X(3872) at COMPASS and indication of a new state $\tilde{X}(3872)$

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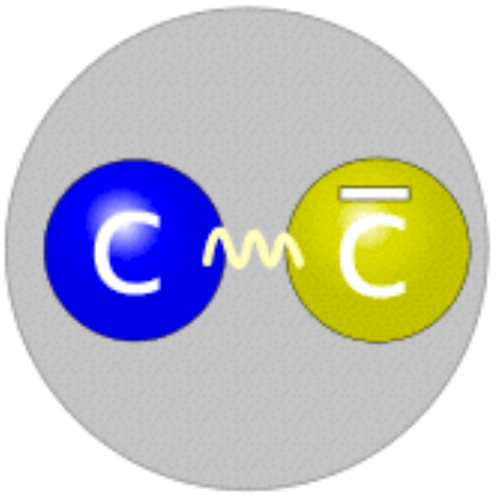
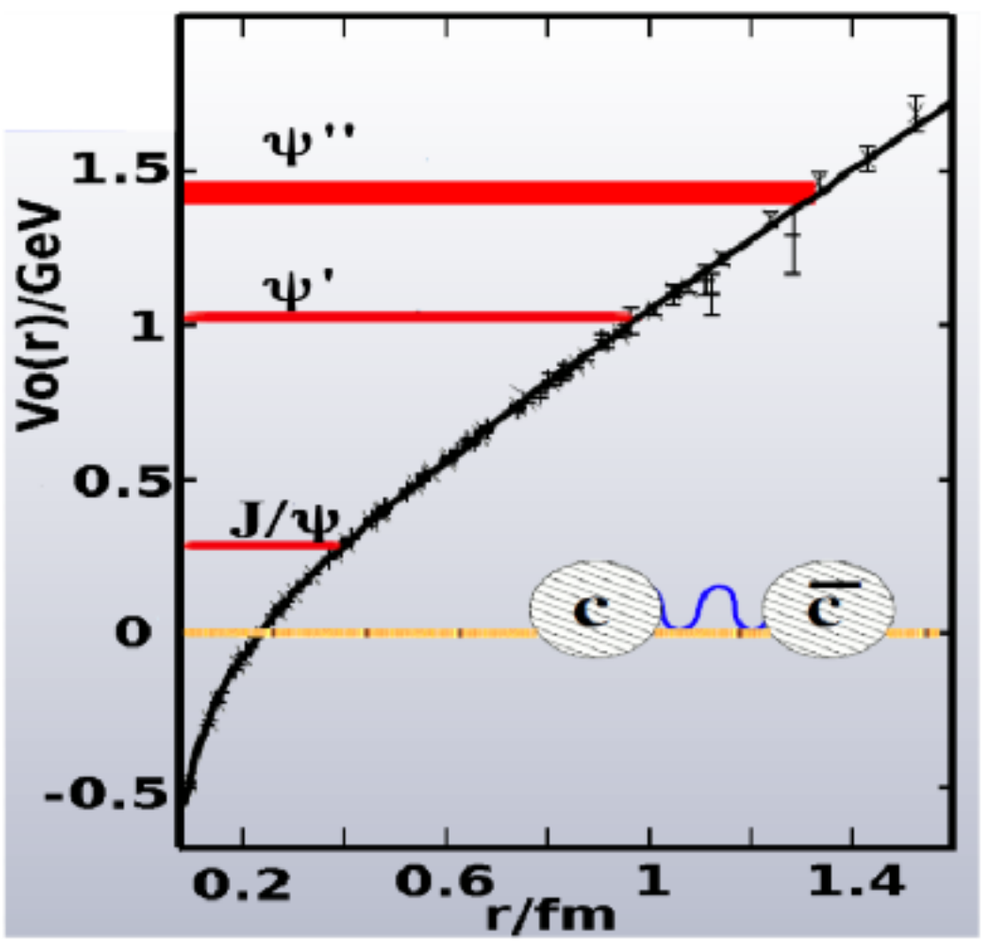
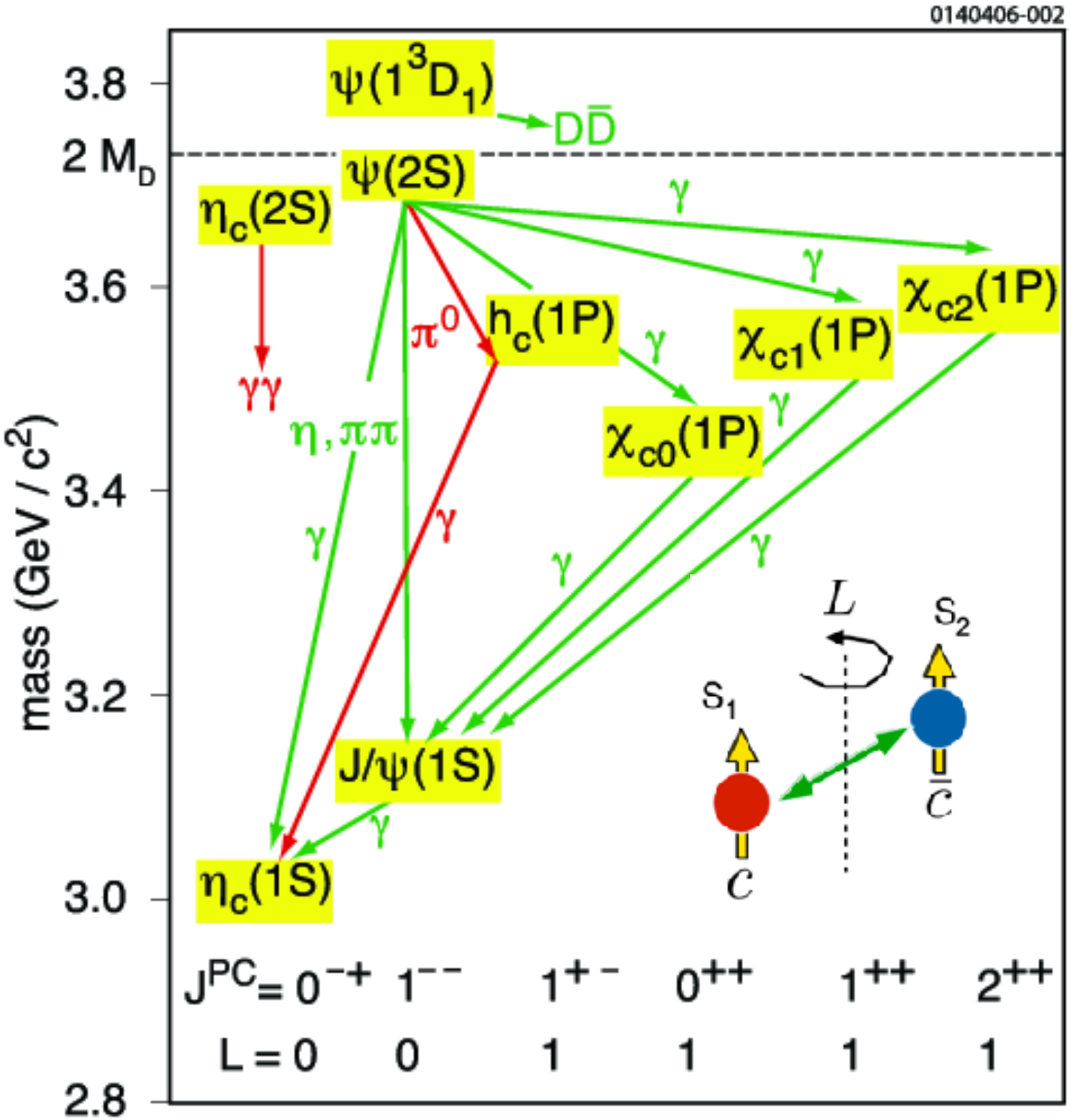
Charmonium spectrum

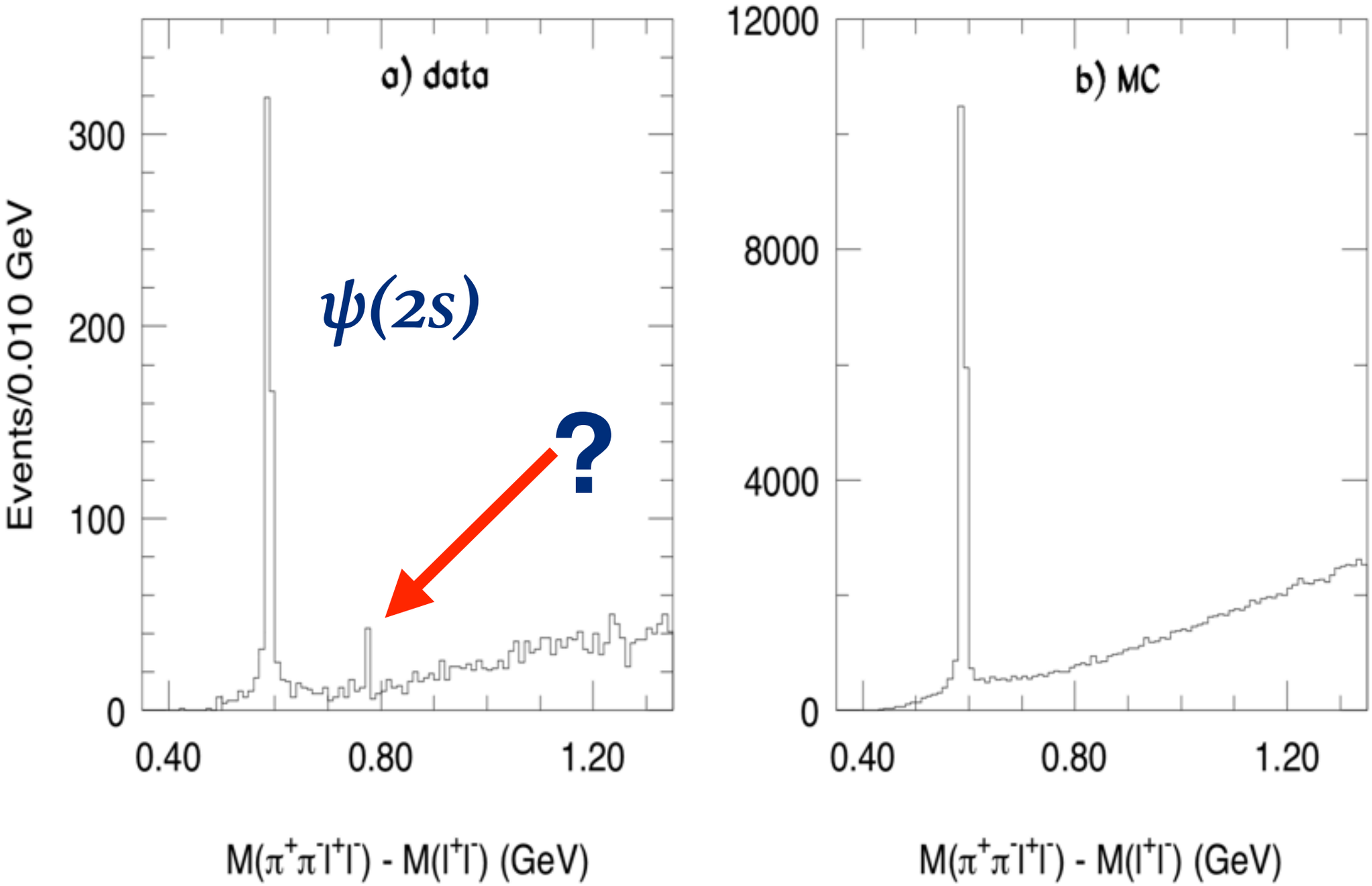






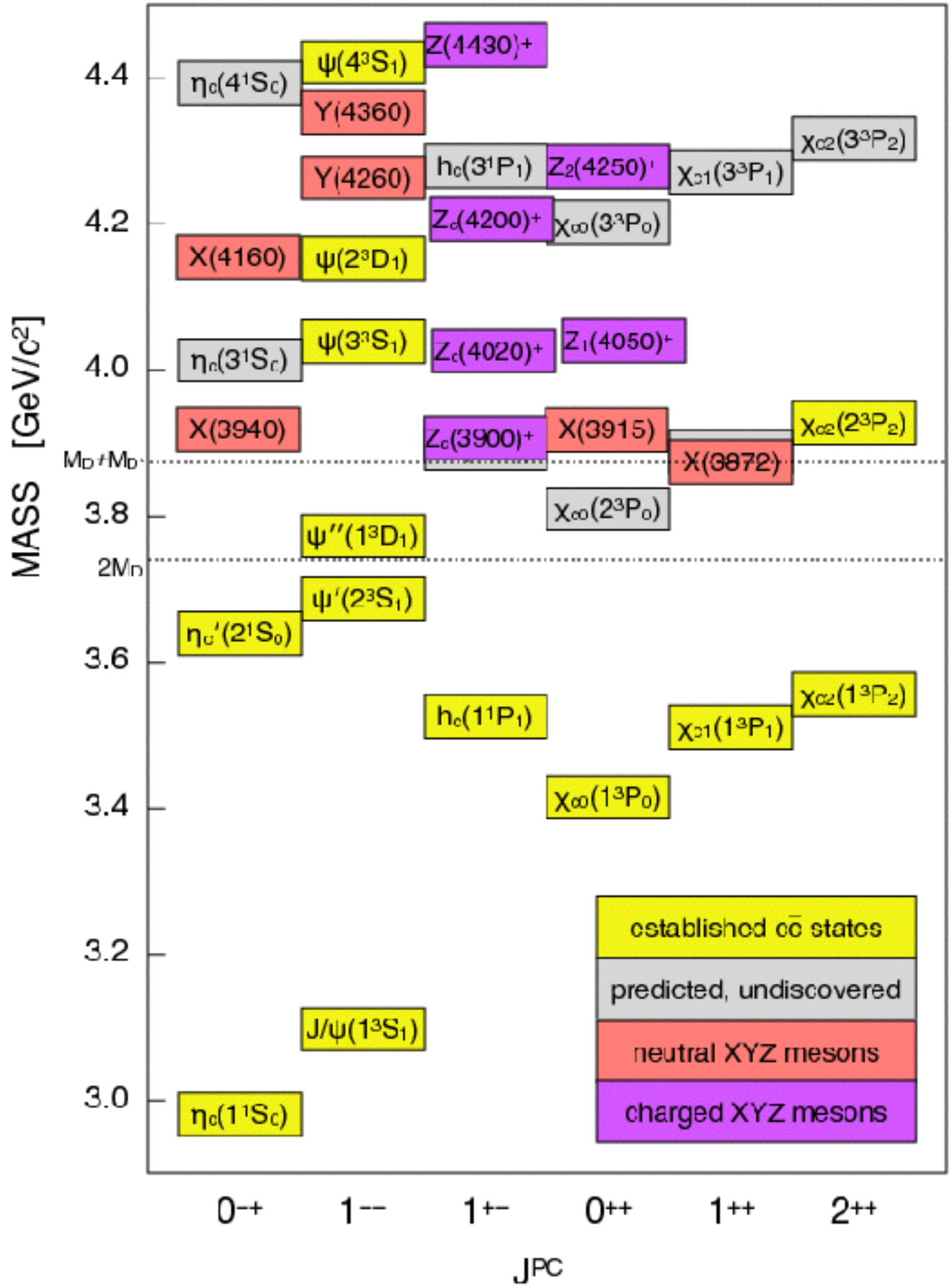
But…

$B^{\pm} \to K^{\pm}(\pi^{+}\pi^{-}J/\psi)$ *(Belle, 2003)*

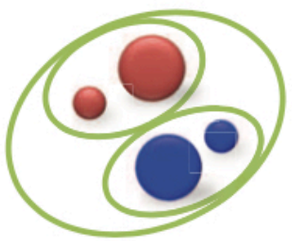


Charmonia today

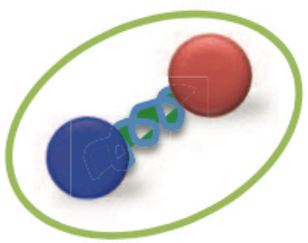
More than 20 exotic charmonium states, neutral and charged, were reported till now with different level of statistical significance



What is their nature?

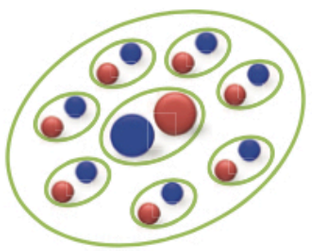


tetraquark (or diquark-antidiquark)



hybrid meson

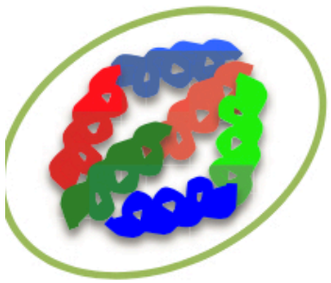
threshold effect in mass spectrum



normal charmonium

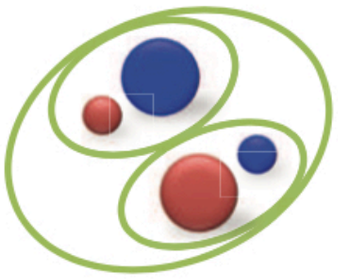
hadro-quarkonium

...



glueball

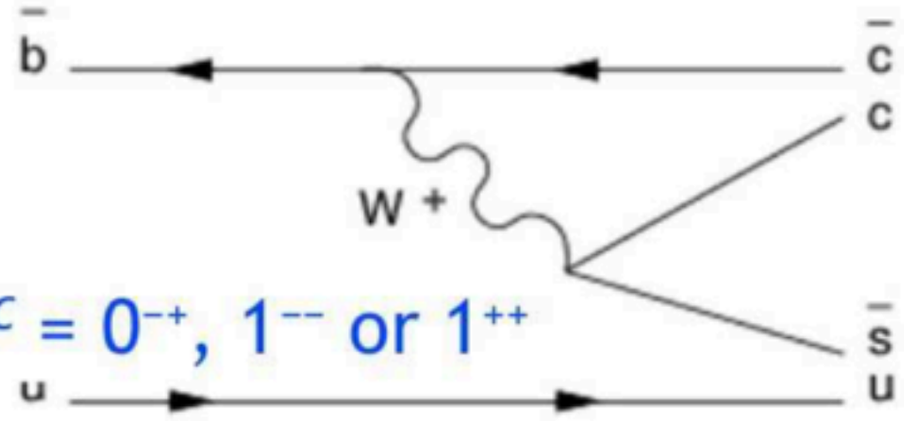
Actually the nature of exotic charmonia is still unknown



mesonic molecule (pure or with admixture of normal charmonium)

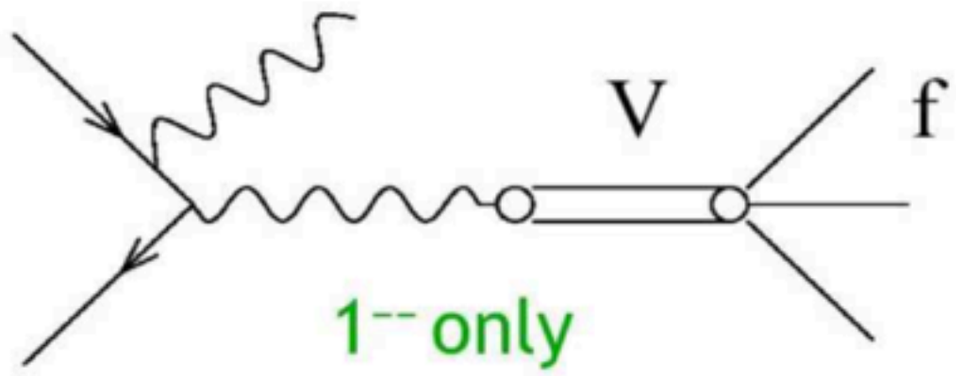
Production mechanisms

$B \to c\bar{c}\, K^{(*)}$ decays



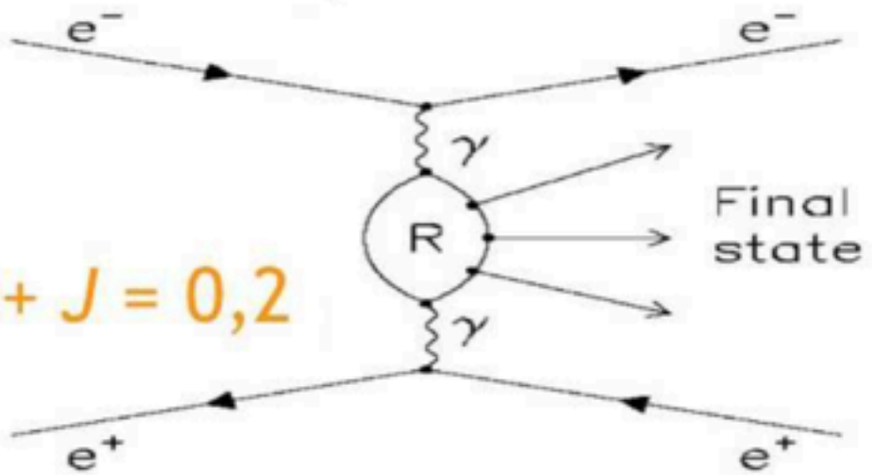
$J^{PC} = 0^{-+}, 1^{--}$ or 1^{++}

Initial State Radiation (*ISR*)



1^{--} only

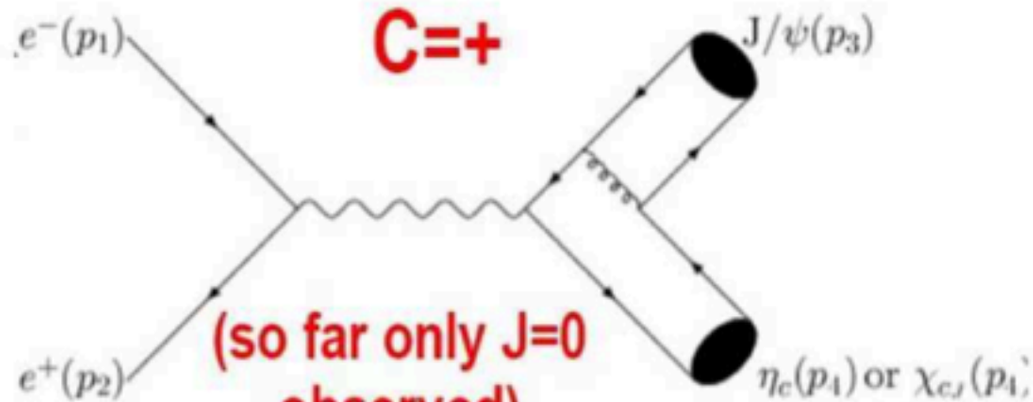
Two-photon fusion



C=+ J = 0,2

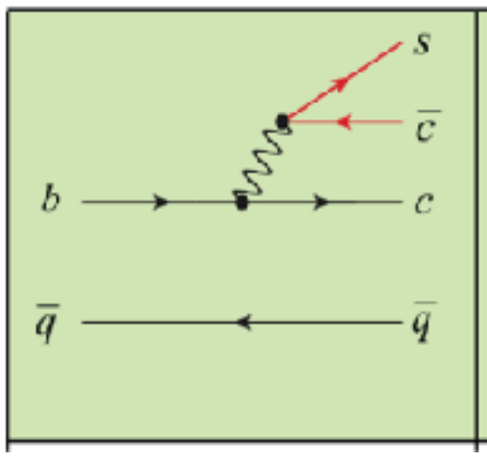
Double charmonium

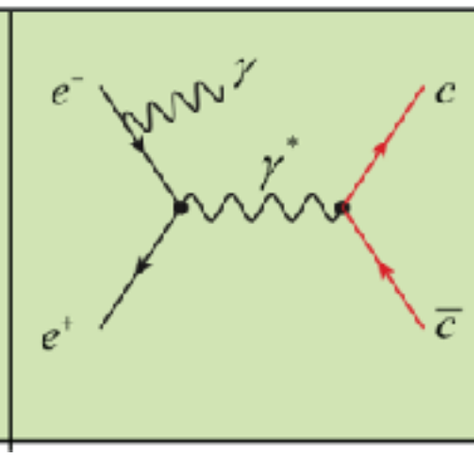
C=+

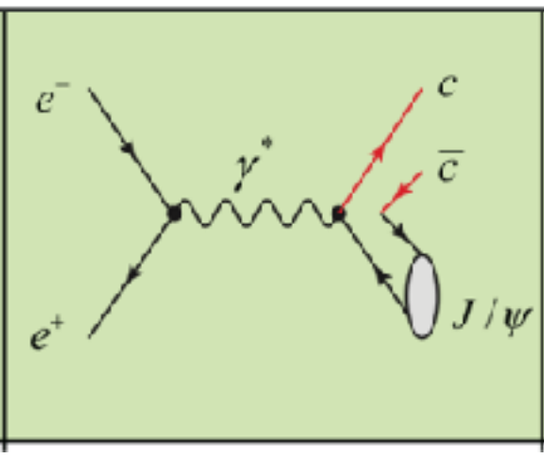


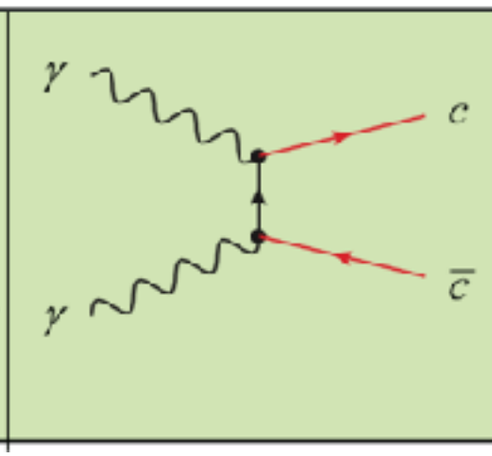
(so far only J=0 observed)

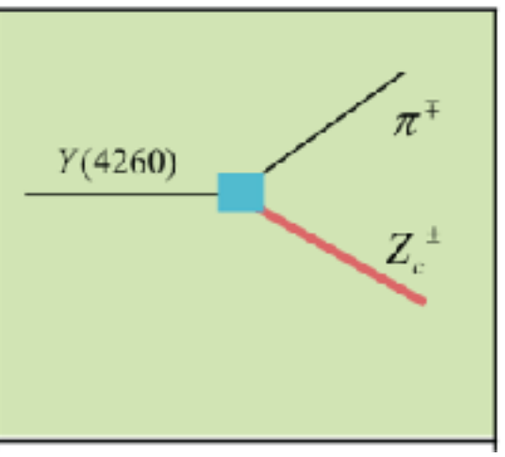
Production mechanisms











Belle II Belle II Belle II Belle II Belle II

BABAR ATLAS BABAR BABAR CESR CLEO

LHCb CESR CLEO BESIII

BESIII

+ *inclusive production in hadronic collisions:*

CDF DØ LHCb CMS ATLAS

Photoproduction!

Bing An Li Is $X(3872)$ a possible candidate of hybrid meson // Phys. Lett. B. 2005. V. 605. P. 306-310.

$$\gamma p \to X(3872)p \qquad \gamma p \to X(3872)n\pi^+$$

Liu X.-H. Qiang Zhao, Frank E. Close. Search for tetraquark candidate Z(4430) in meson photoproduction // Phys. Rev. D. 2008. V. 77. P. 094005

$$\gamma p \to Z_c^+(4430)n \to \psi(2S)\pi^+ n$$

He J., Liu X. Discovery potential for charmonium-like state Y(3940) by the meson photoproduction // Phys. Rev. D. 2009. V. 80. P. 114007

$$\gamma p \to Y(3940)p$$

Lin Q.-Y., Liu X., Xu H.-S. Charged charmoniumlike state $Z_c^{\pm}(3900)$ via meson photoproduction // Phys. Rev. D. 2013. V. 88. P. 114009

$$\gamma p \to Z_c^+(3900)n$$

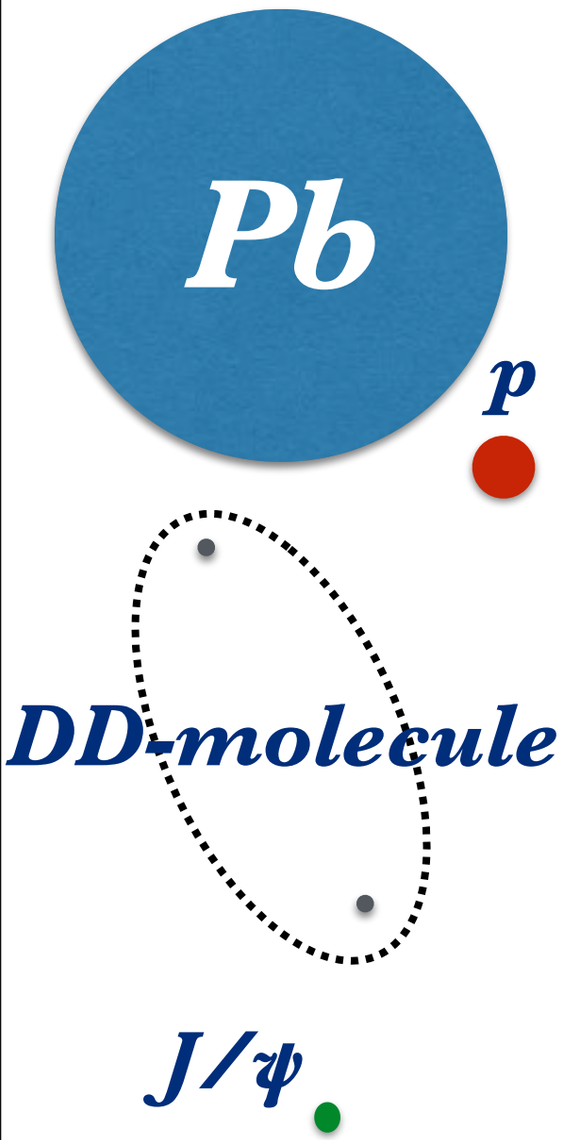
Lin Q.-Y., Liu X., Xu H.-S. Probing charmoniumlike state X(3915) through meson photoproduction // Phys. Rev. D. 2014. V. 89. P. 034016

$$\gamma p \to X(3915)p \to J/\psi\omega p$$

Wang X.-Y., Chen X.-R., Guskov A. Photoproduction of the charged charmoniumlike $Z_c^+(4200)$ // Phys. Rev. D. 2015. V. 92. P. 094017

$$\gamma p \to Z_c^+(4360)n$$

■ ■ ■



The COMPASS experiment












COMPASS (COmmon Muon Proton Apparatus for Structure and Spectroscopy)

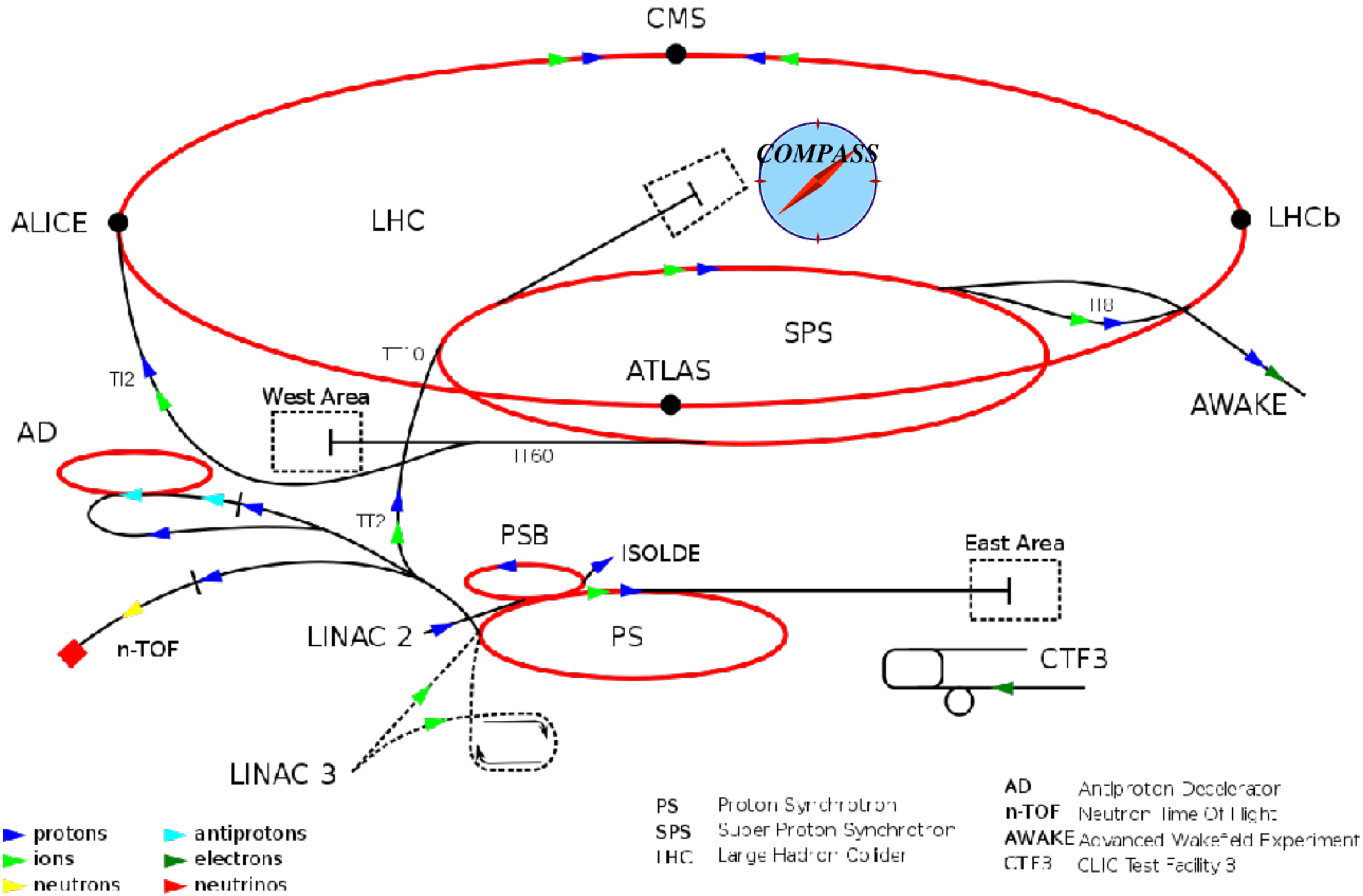
is a fixed target experiment on a secondary beam of Super Proton Synchrotron at CERN

1996 - Proposal

2002-now - Physical data taking

13 countries,
24 institutions,
~220 physicists

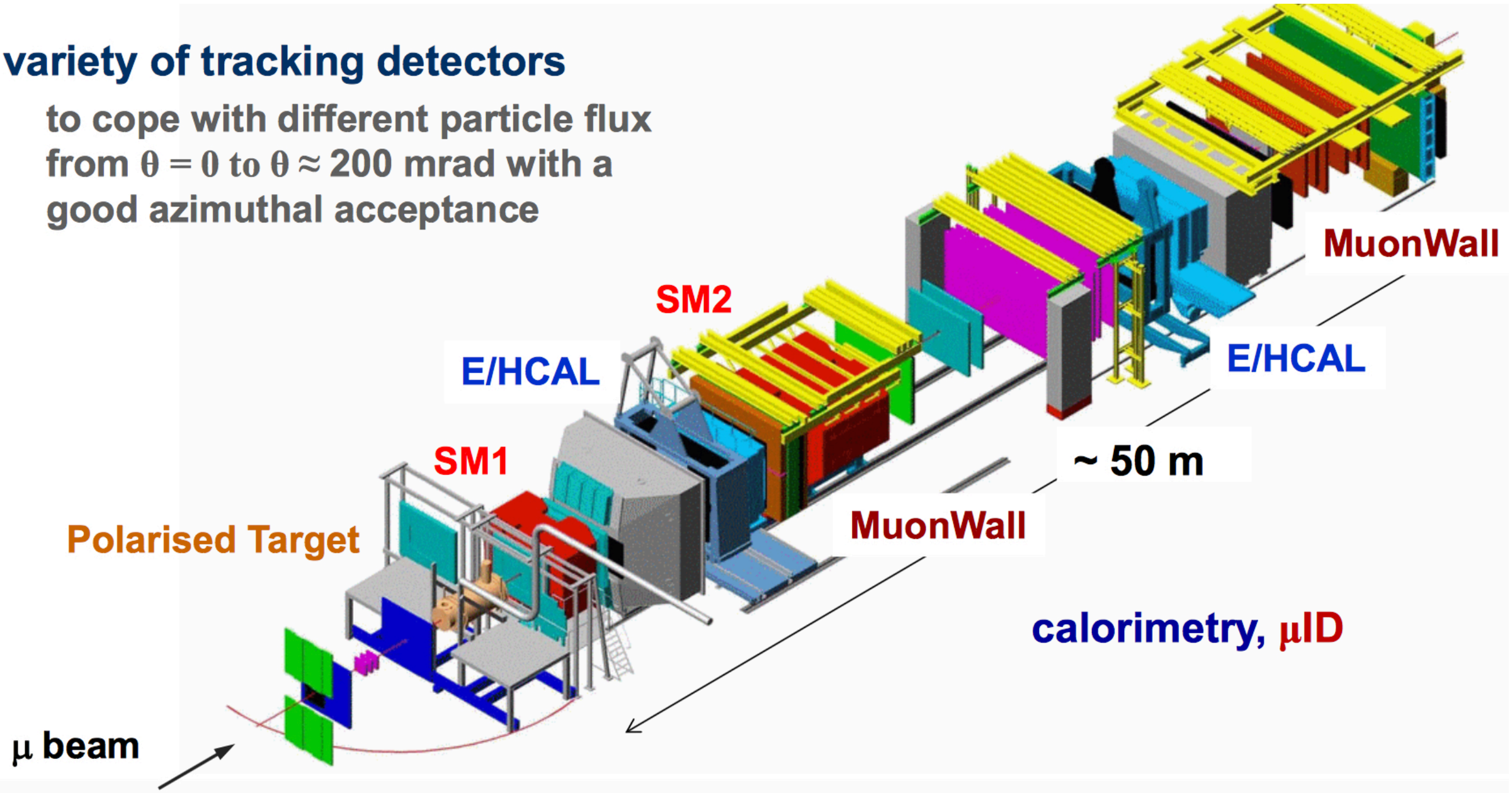
COMPASS at CERN



The COMPASS setup

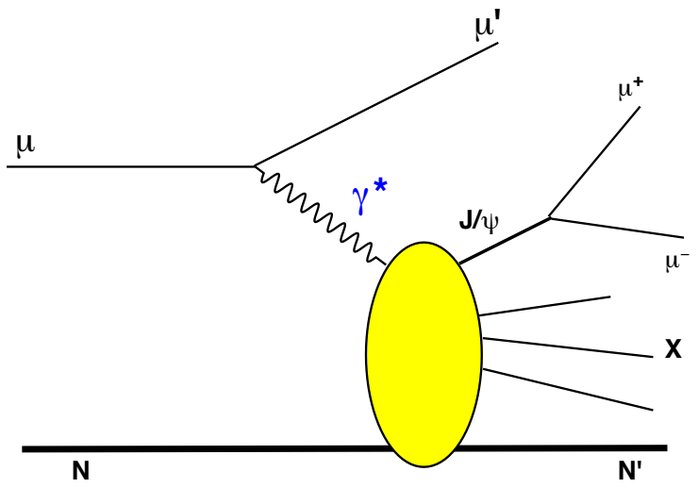
variety of tracking detectors

to cope with different particle flux
from $\theta = 0$ to $\theta \approx 200$ mrad with a
good azimuthal acceptance

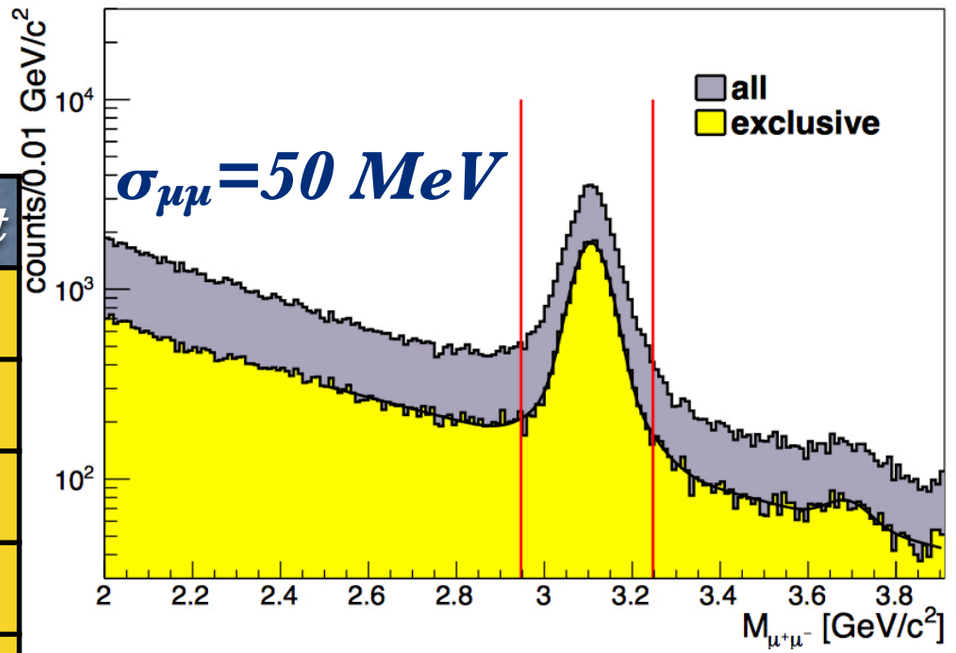


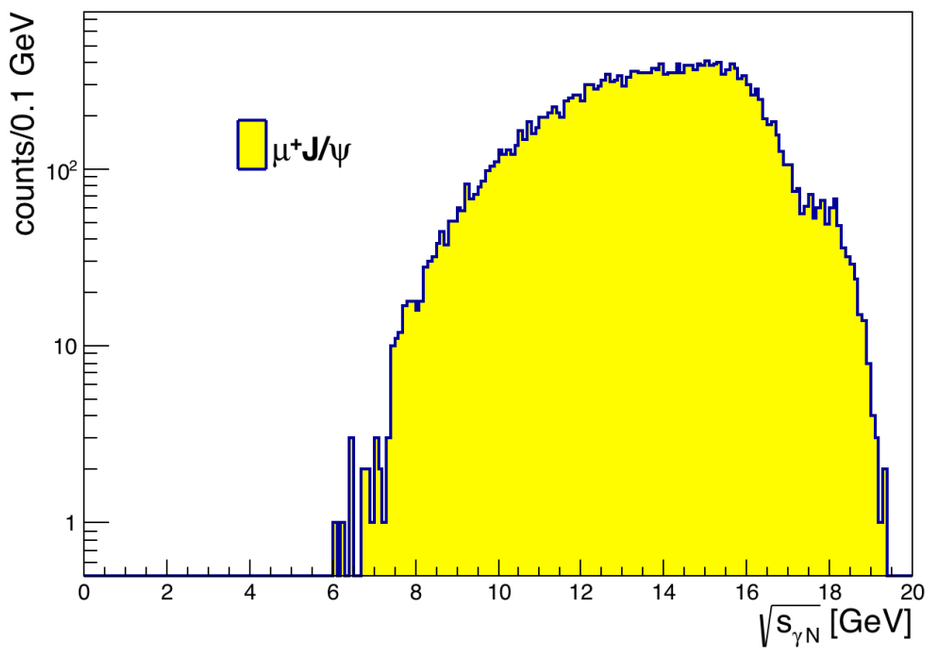
Configuration of the beam and target region depends on the particular physics programme

Muoproduction at COMPASS



Years	P, GeV/c	Target
2002	μ^+,160	^{6}LiD
2003	μ^+,160	^{6}LiD
2004	μ^+,160	^{6}LiD
2006	μ^+,160	^{6}LiD
2007	μ^+,160	NH_3
2010	μ^+,160	NH_3
2011	μ^+,200	NH_3
2016	$\mu^\pm$,160	LH_2
2017	$\mu^\pm$,160	LH_2



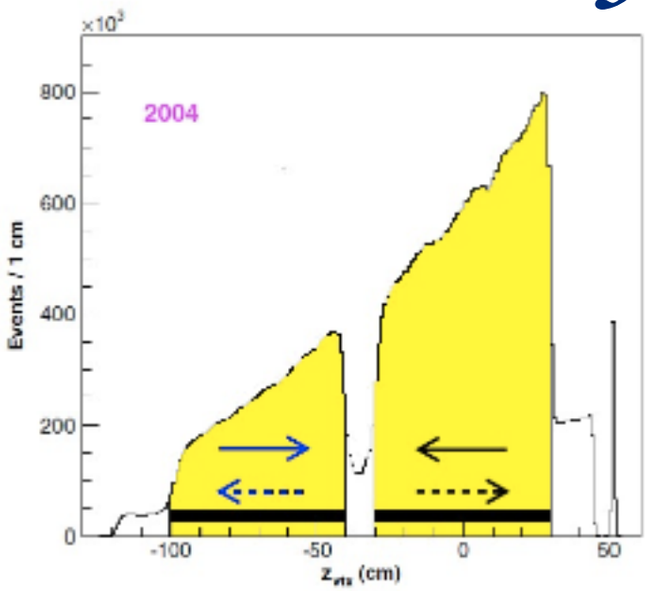


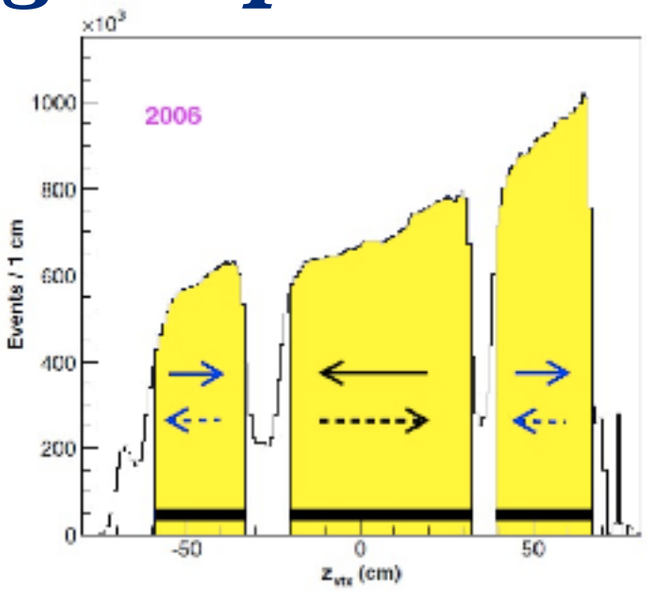
~50 000 $J/\psi \to \mu^+\mu^-$ events after 7 years of DIS running

Effective γ^*N statistics accumulated by COMPASS is equivalent to about $L=14\ pb^{-1}$ of the integrated luminosity, when considering a real-photon beam of about 100 GeV incident energy scattering off free nucleons

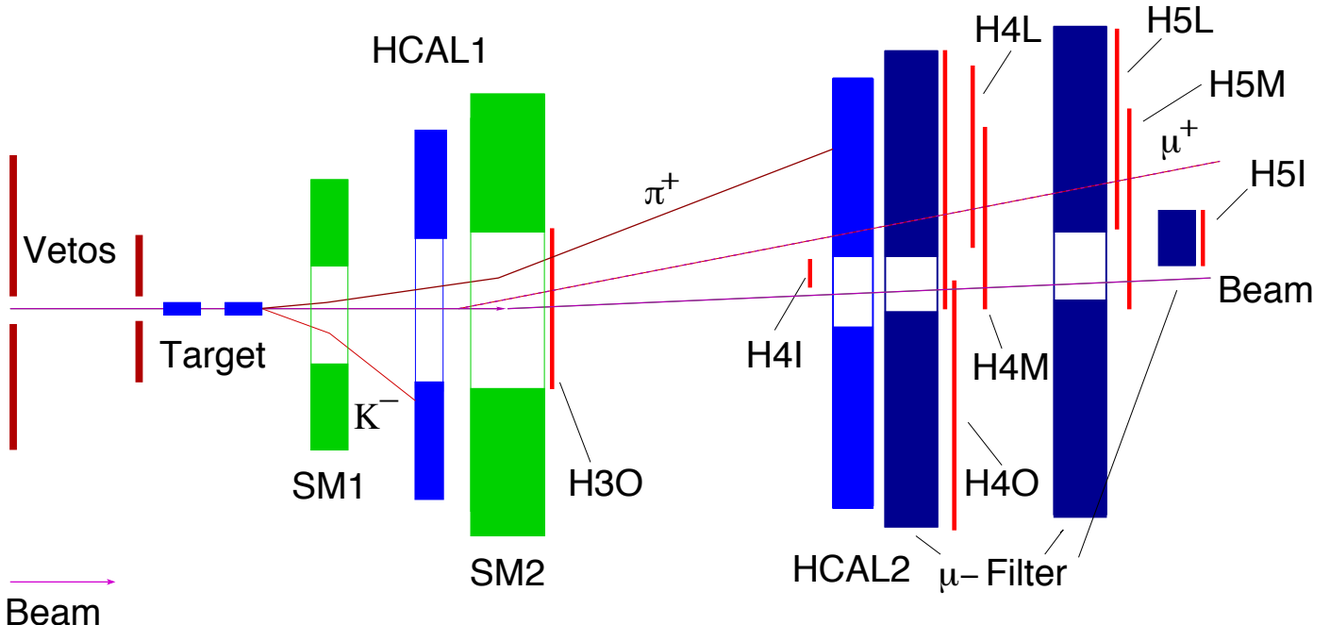
Target and trigger

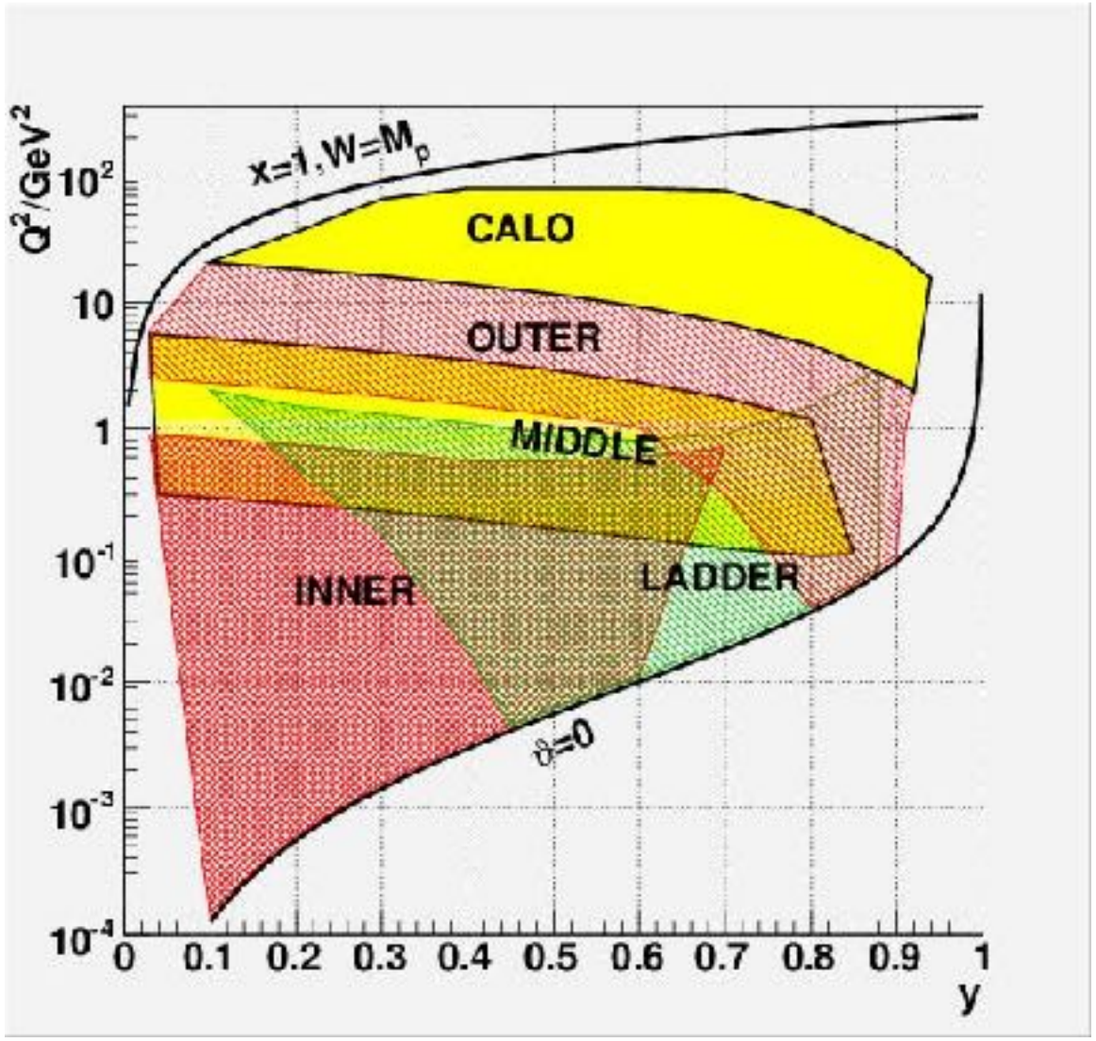
2 or 3 cell cryogenic polarized target





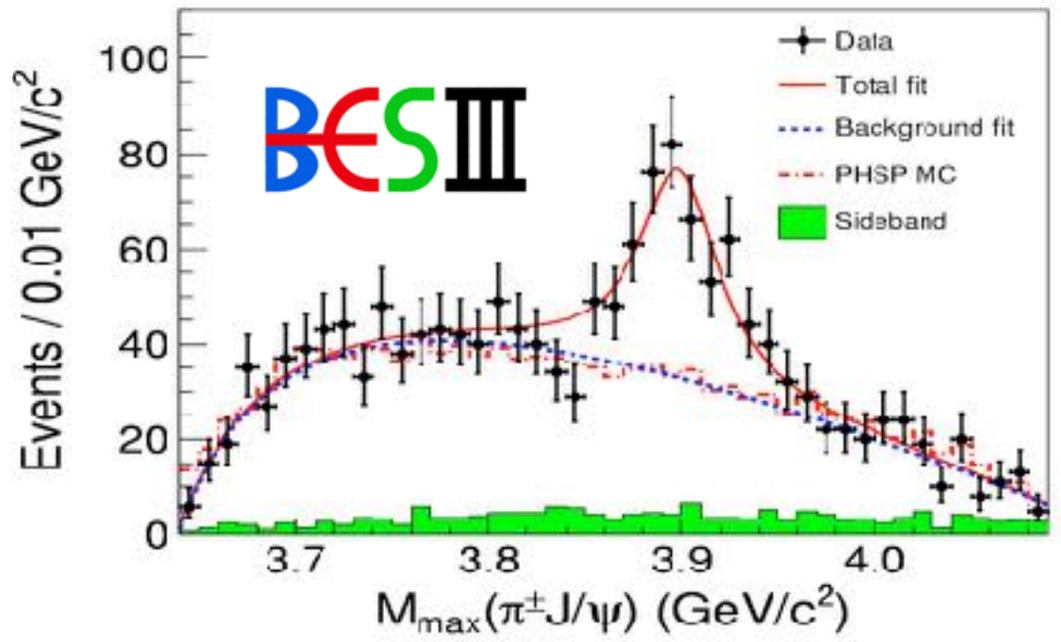
Hodoscope-based trigger on scattered muons





Search for $Z_c(3900)^{\pm}$

COMPASS already has experience with the search for exotic charmonia

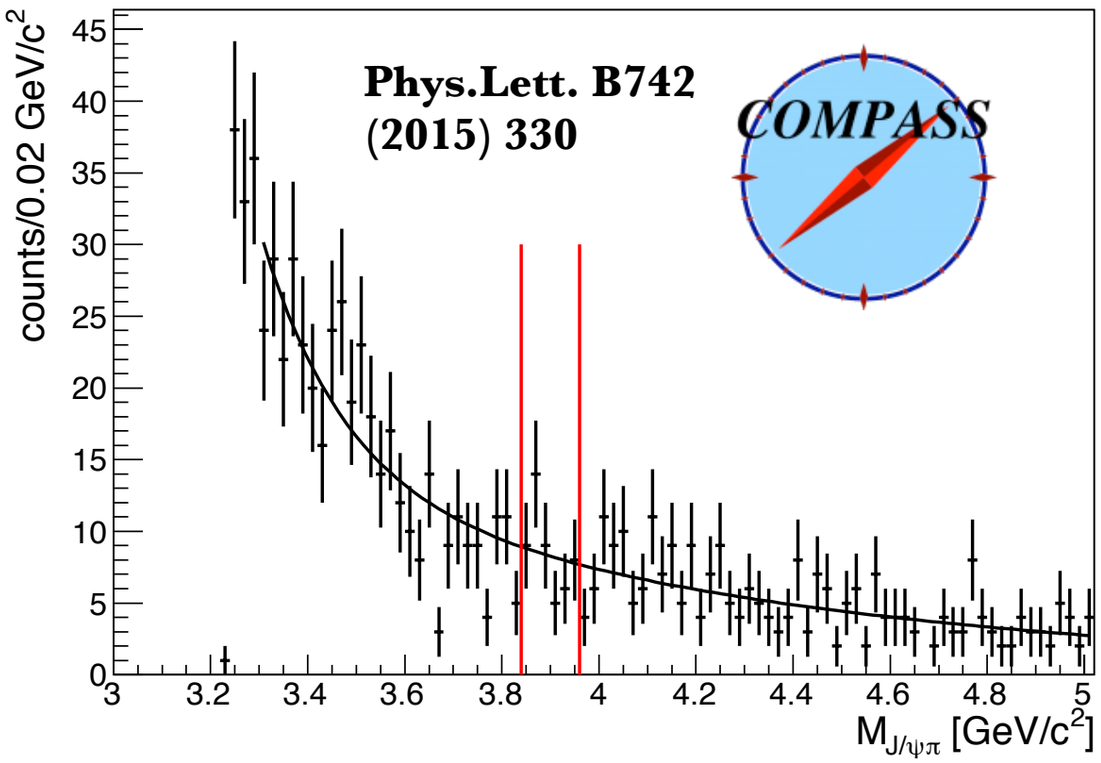


$Z_c(3900)$

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

Mass $m = 3886.6 \pm 2.4$ MeV (S = 1.6)
Full width $\Gamma = 28.2 \pm 2.6$ MeV

$Z_c(3900)$ 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	758
$(D\overline{D}^*)^{\pm}$	seen	–
D^0D^{*-} + c.c.	seen	150
D^-D^{*0} + c.c.	seen	140
$\omega\pi^{\pm}$	not seen	1862
$J/\psi\eta$	not seen	509
D^+D^{*-} + c.c	seen	–
$D^0\overline{D}^{*0}$ + c.c	seen	–



X(3872)

Surprisingly narrow:

$$\Gamma < 1.2\,\mathrm{MeV} \quad (\Gamma(\psi'') = 27\,\mathrm{MeV})$$

Suspiciously close to DD* threshold:

$$M(D^0) + M(\bar{D}^{*0}) = 3871.81 \pm 0.36\,\mathrm{MeV}$$

Large isospin breaking:

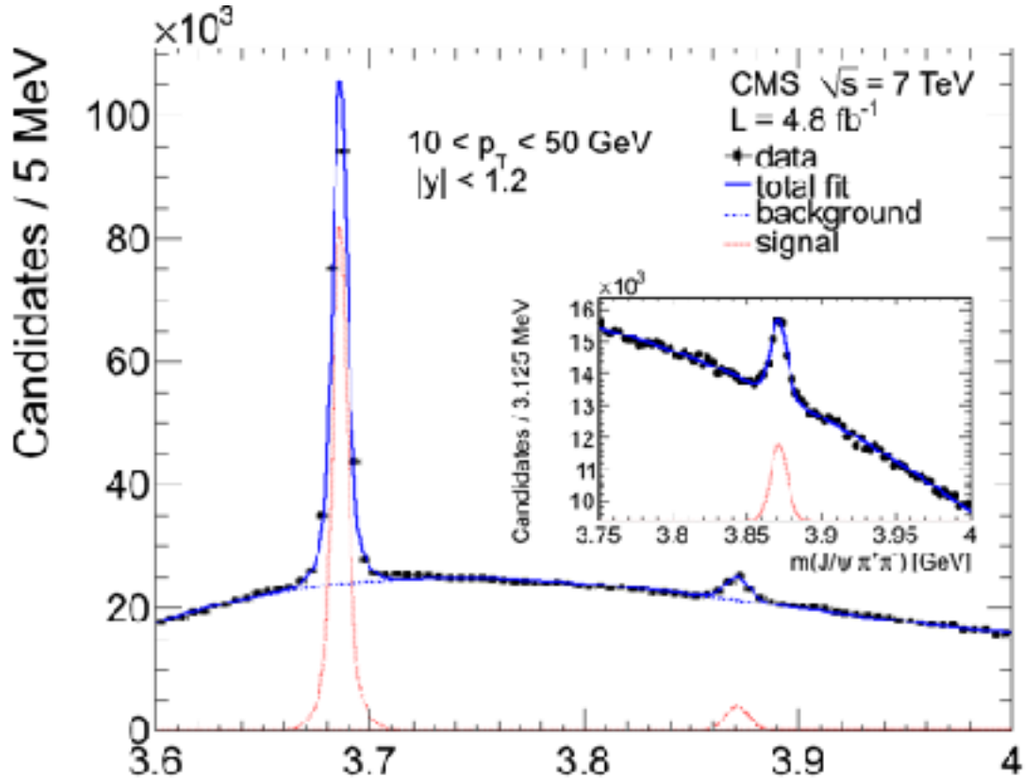
$$B(X \to \rho J/\Psi) \approx B(X \to \omega J/\Psi)$$

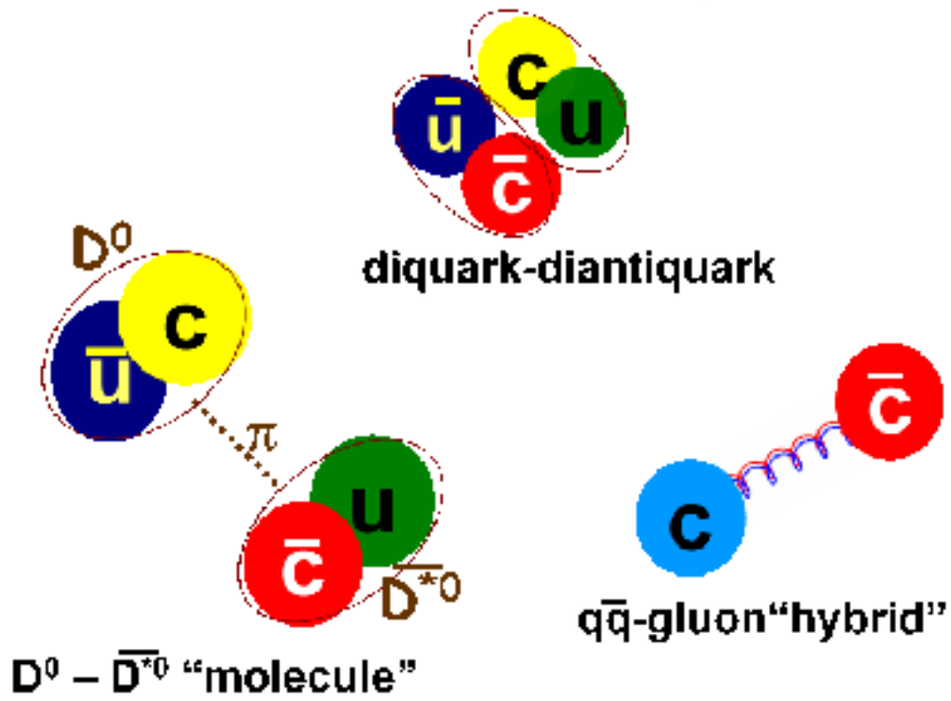
Spin-parity (recent LHCb study):

$$J^{PC} = 1^{++}$$ LHCb:PRL110, 222001 (2013)

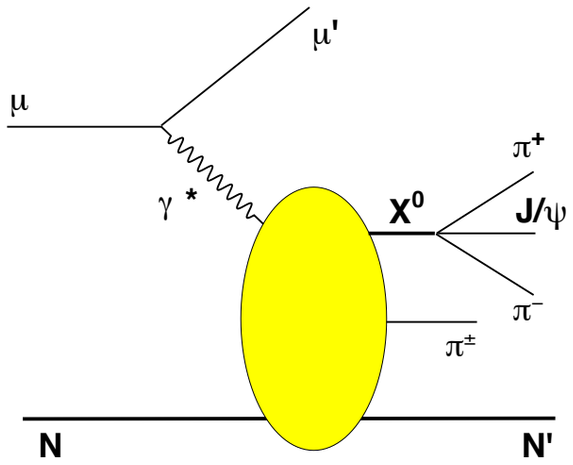
What is its nature?

What is it?!



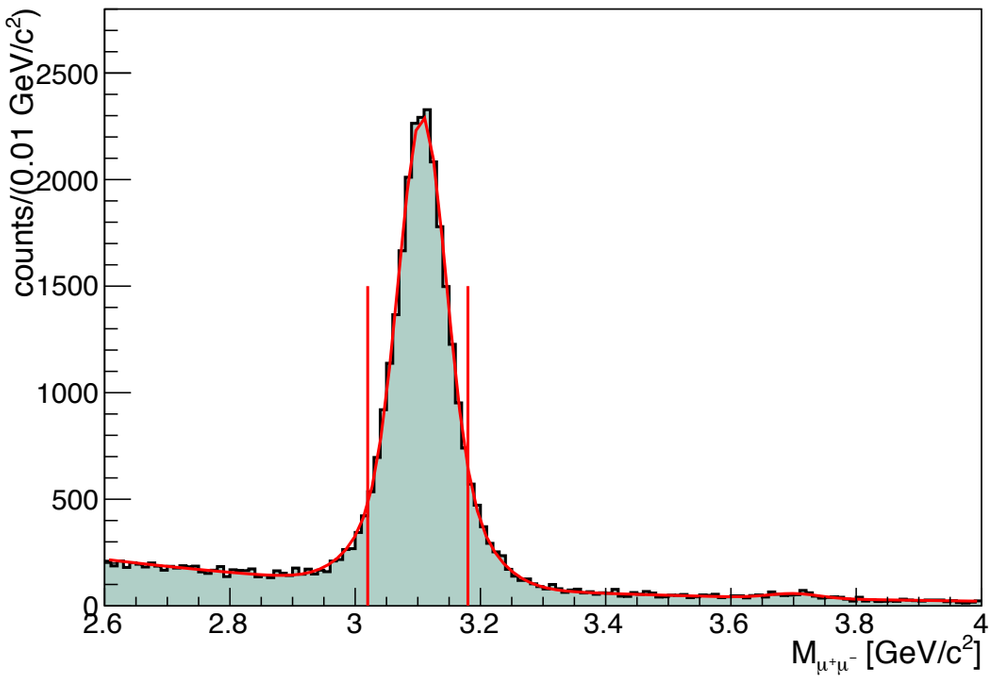


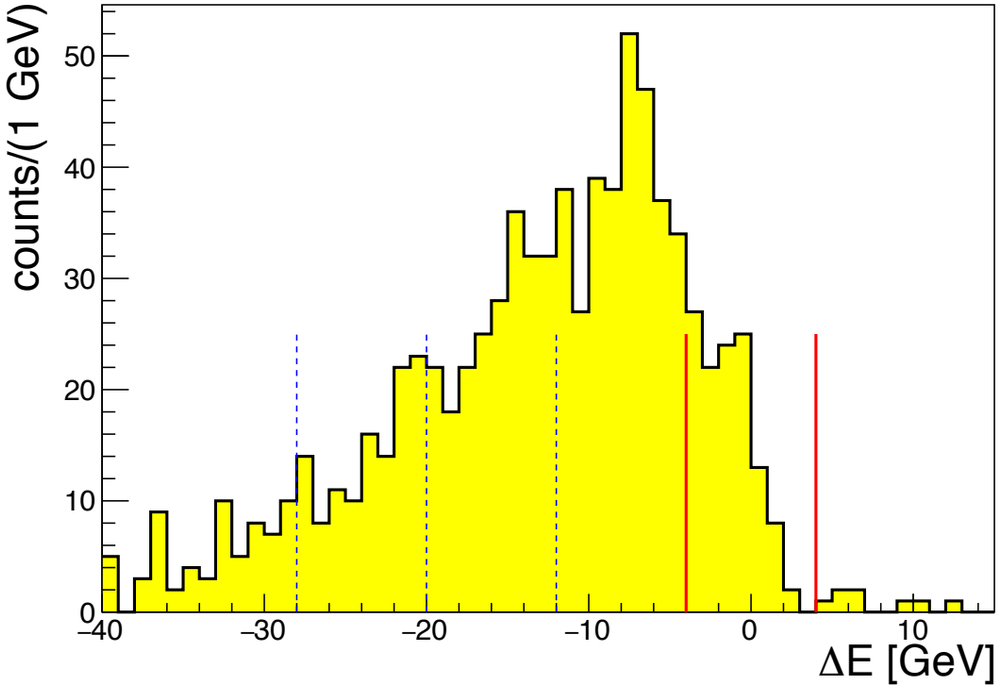
Event selection



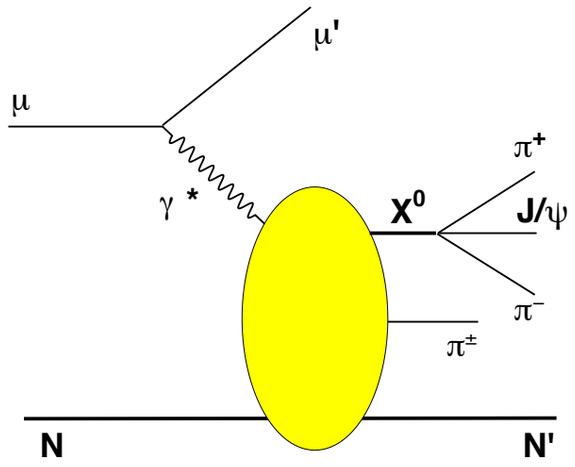
1) Primary vertex in the target region
2) 6 outgoing tracks: $\mu^+\mu^+\mu^-X^+X^-X^\pm$ ($X\equiv\pi$)
3) $P_\mu > 8$ GeV/c
4) $\mu^+\mu^+\mu^- = \mu^+ J/\psi$ - just one combination

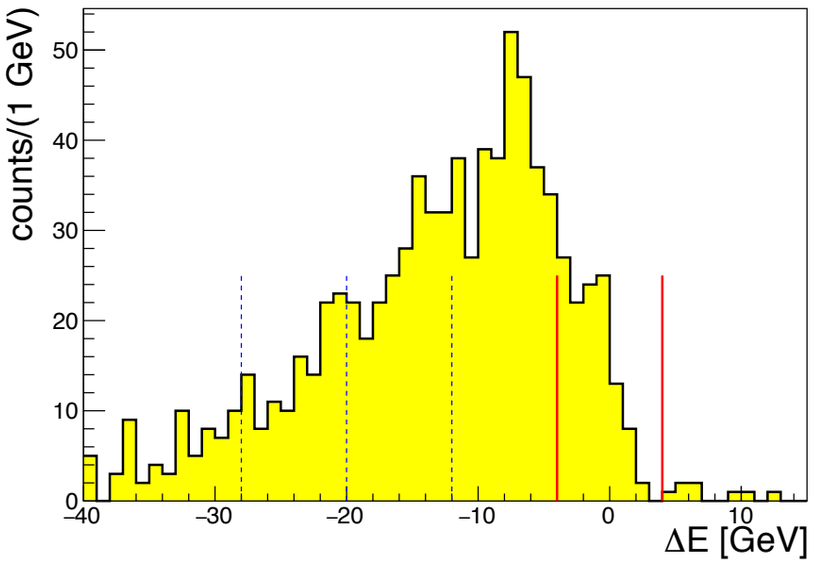
5) Exclusivity ΔE is controlled on the level of ± 4 GeV

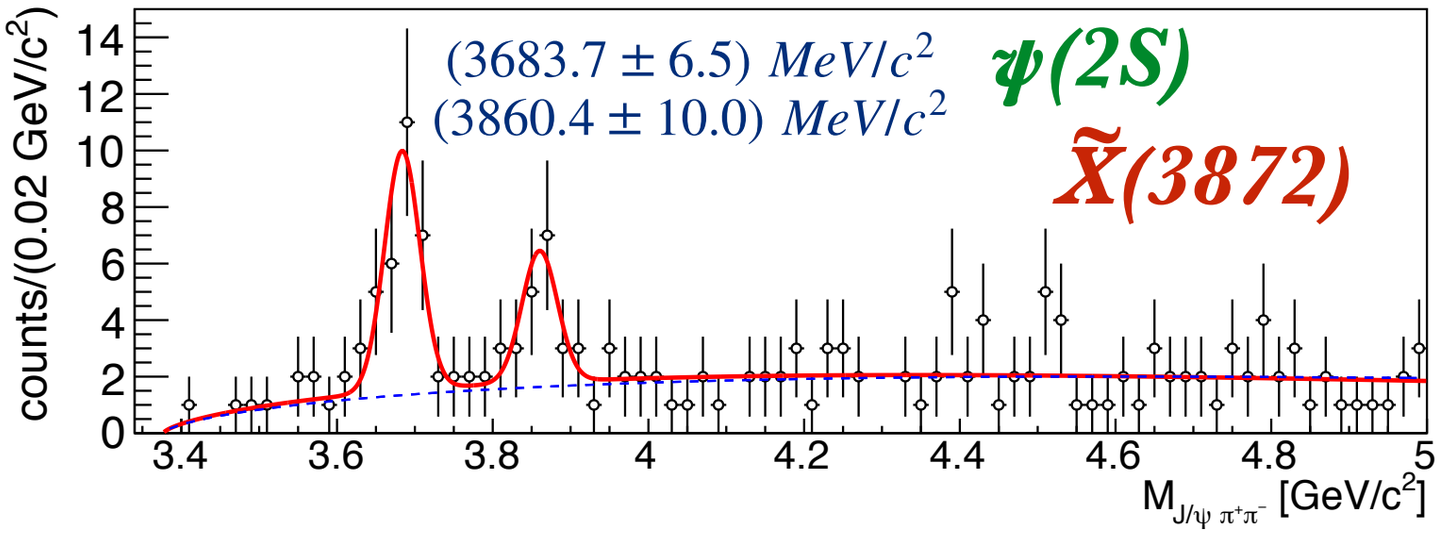


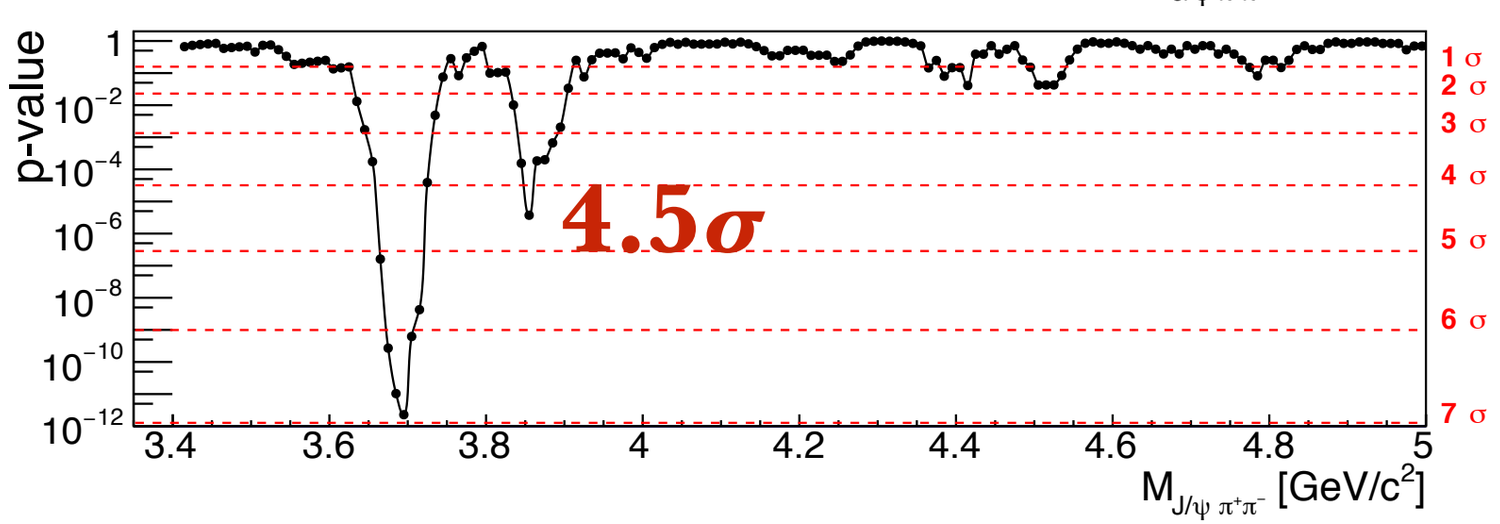


$\gamma^* N \to (J/\psi \pi^+ \pi^-) \pi^\pm N'$







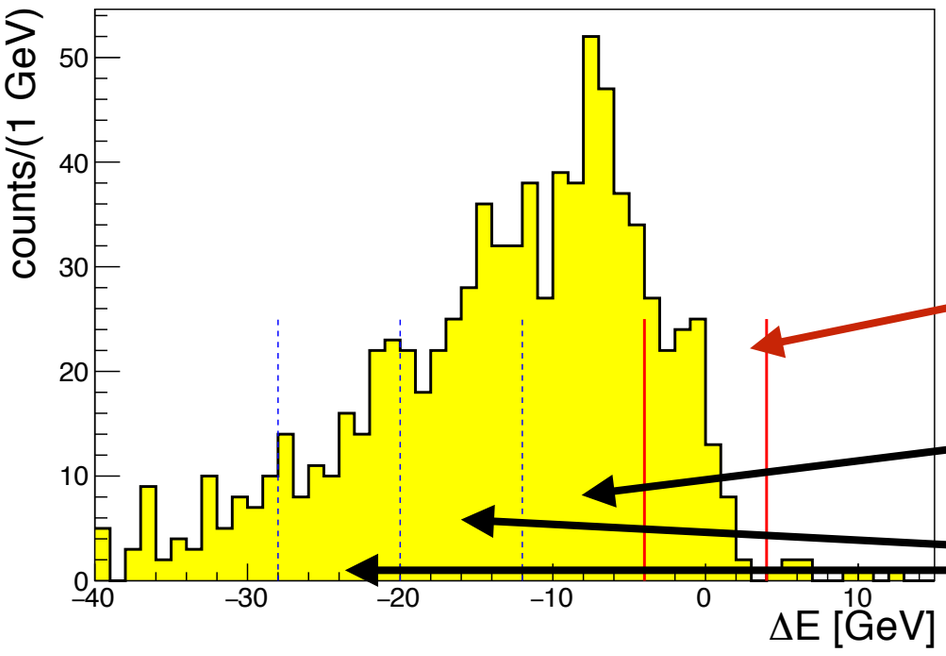


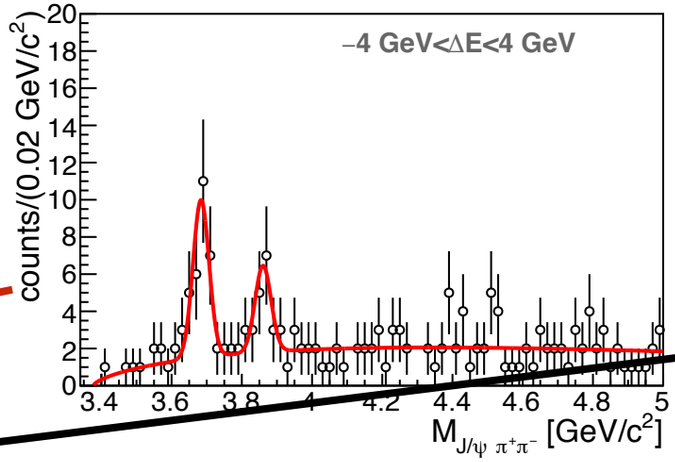
$$f(m) = \text{Gauss}(N_{J/\psi(2S)}, M_{\psi(2S)}, \sigma_M) + \text{Gauss}(N_{\tilde{X}(3872)}, M_{\tilde{X}(3872)}, \sigma_M) + c_1(m - m_0)^{c_2} e^{-c_3 m}$$

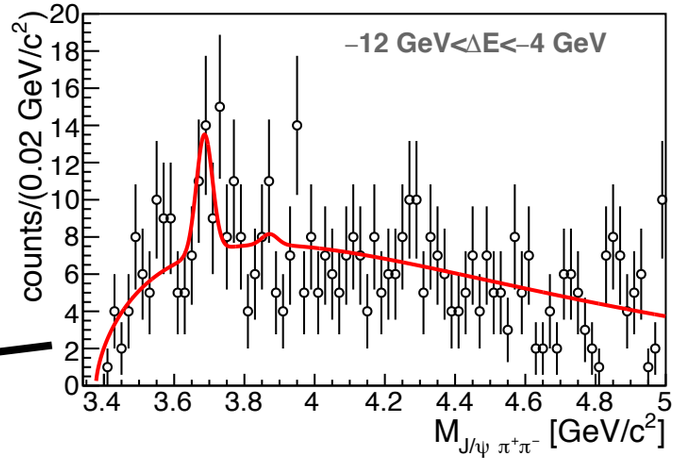
$\sigma_M = (22.8 \pm 6.9)\ MeV/c^2$

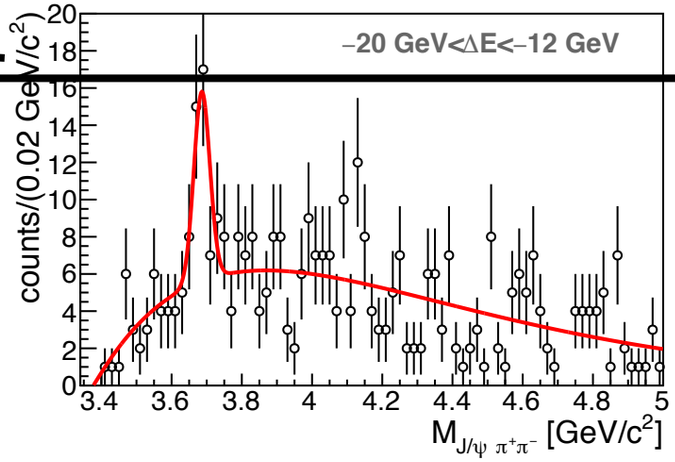
$N_{(\tilde{X}3872)} = (13.2 \pm 5.2)\ events$

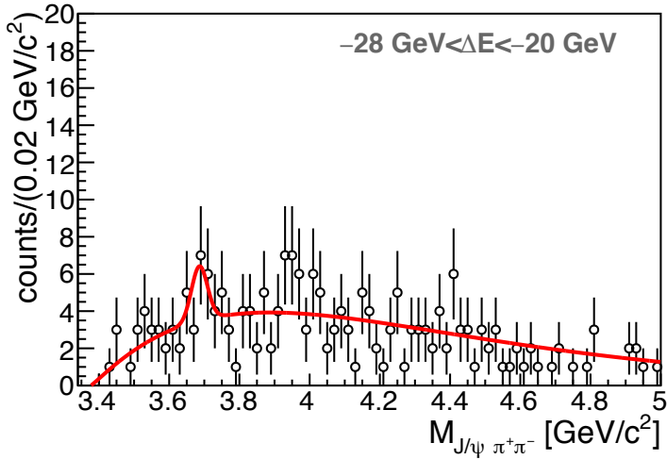
More kinematics



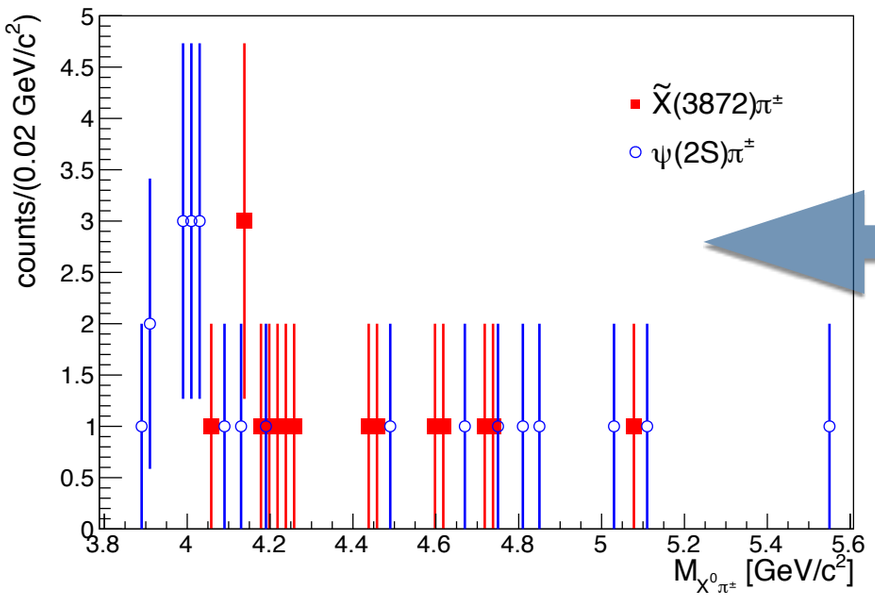






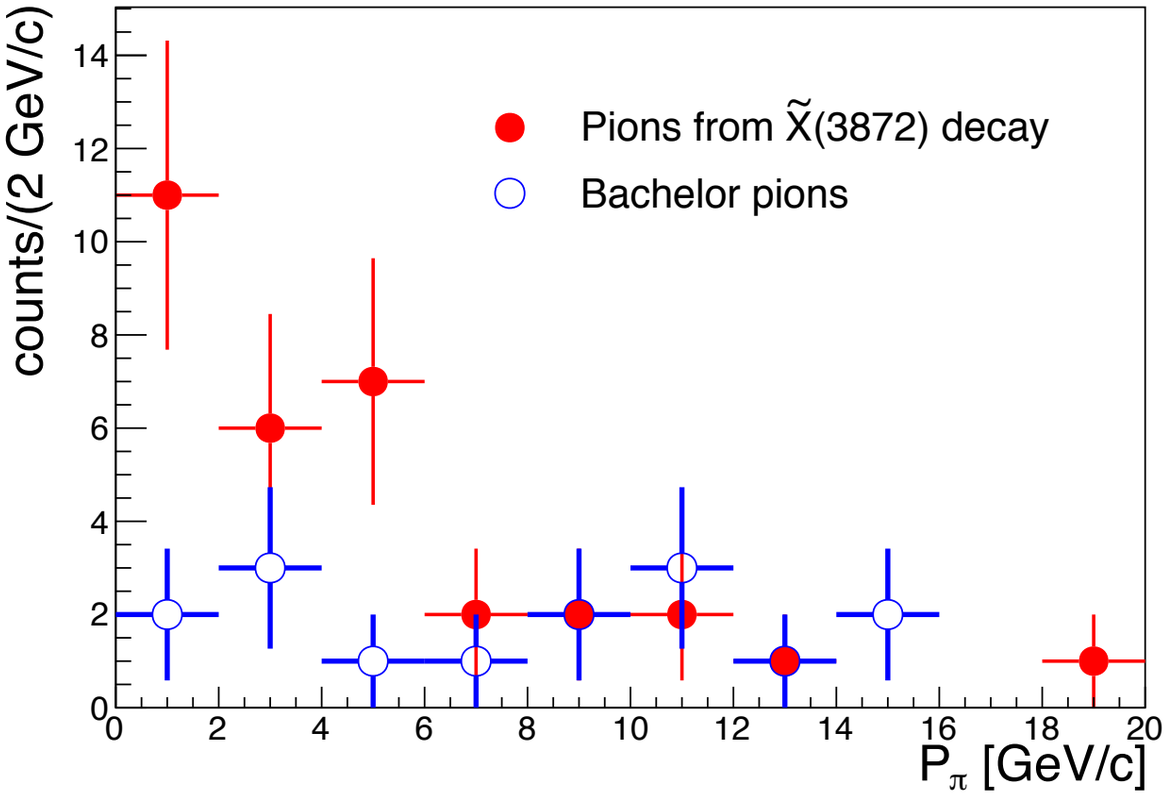


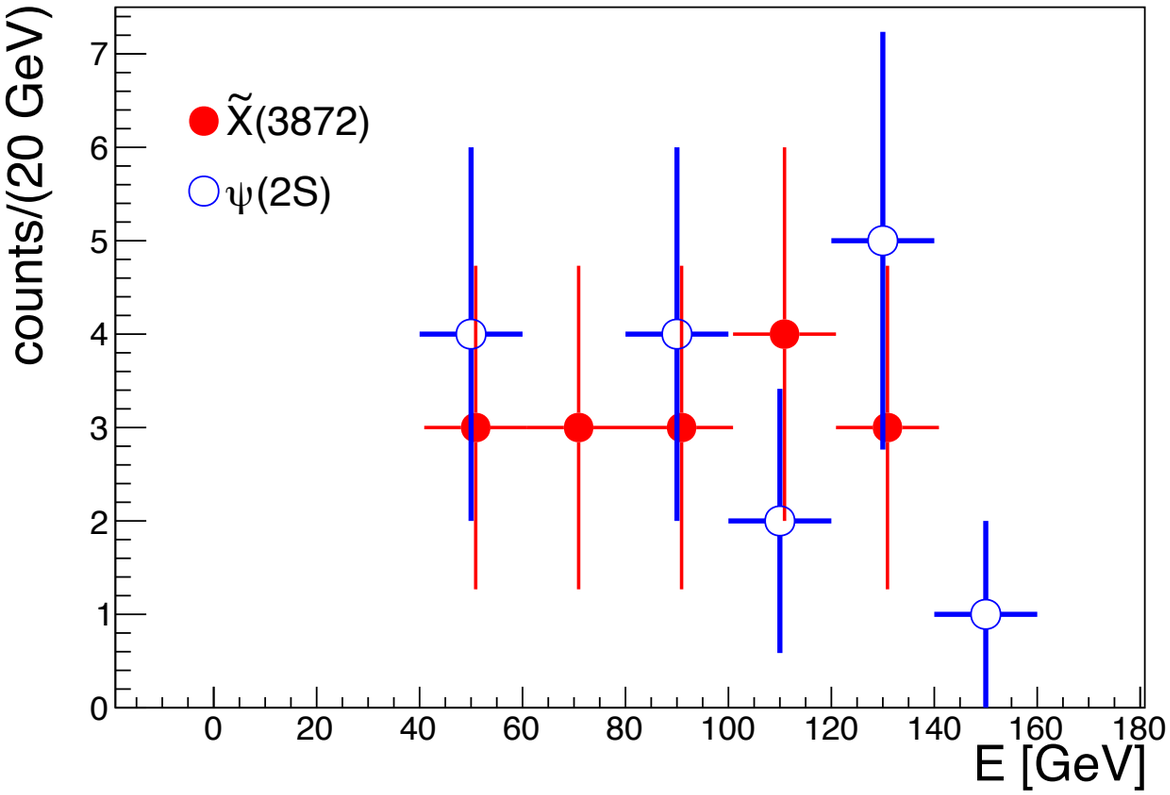
No statistically significant evidence of a peak at 3872 MeV/c^2 in our nonexclusive sample



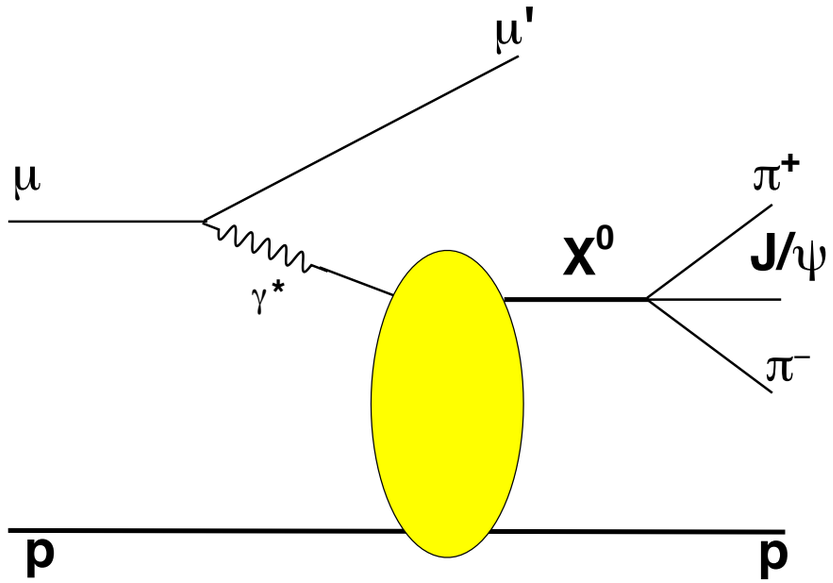
No statistically significant resonances in the corresponding $J/\psi\pi^+\pi^-\pi^\pm$ mass spectra

A bit more kinematics

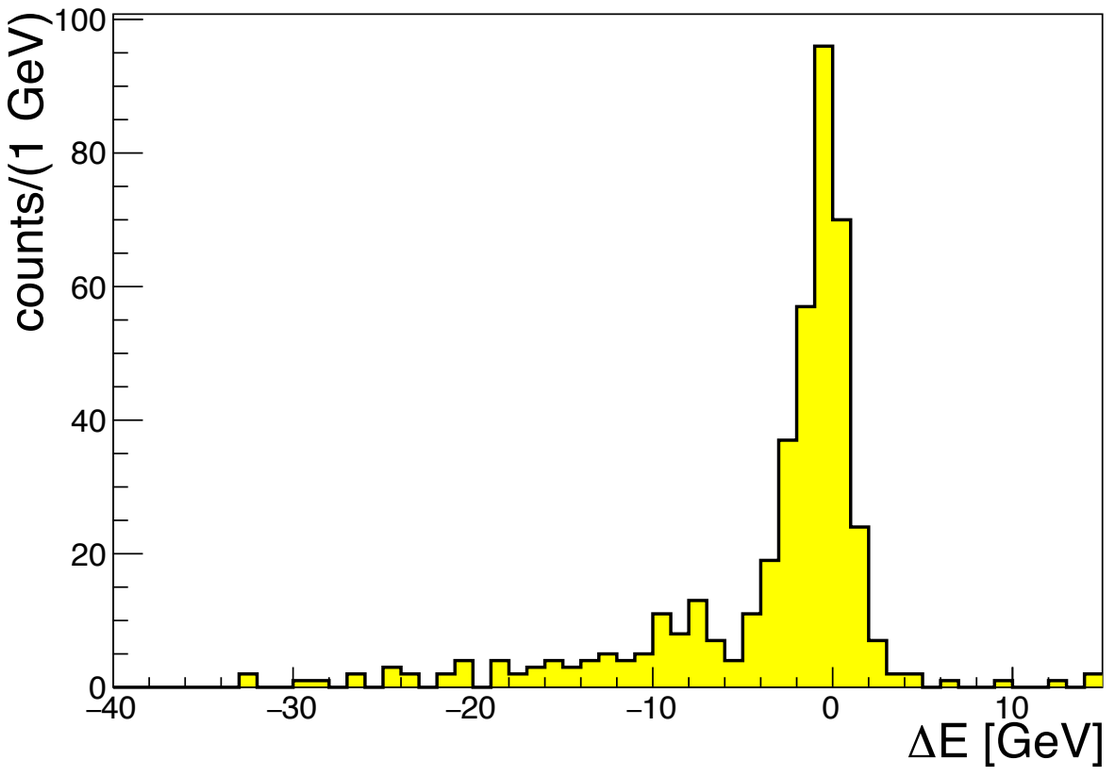


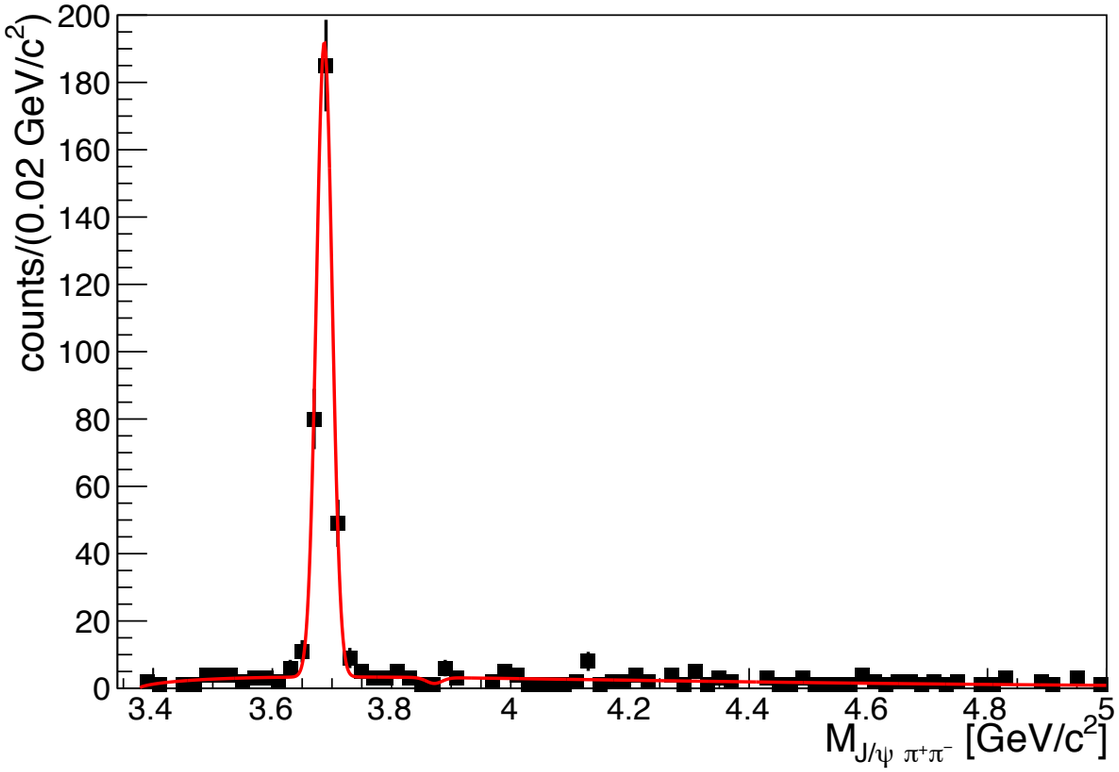


$\gamma^* N \to (J/\psi \pi^+ \pi^-) N$

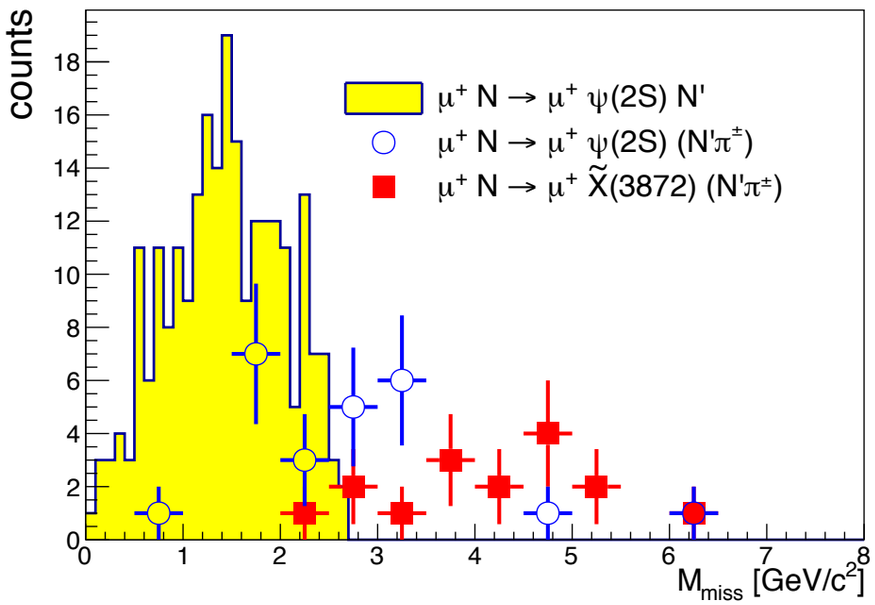


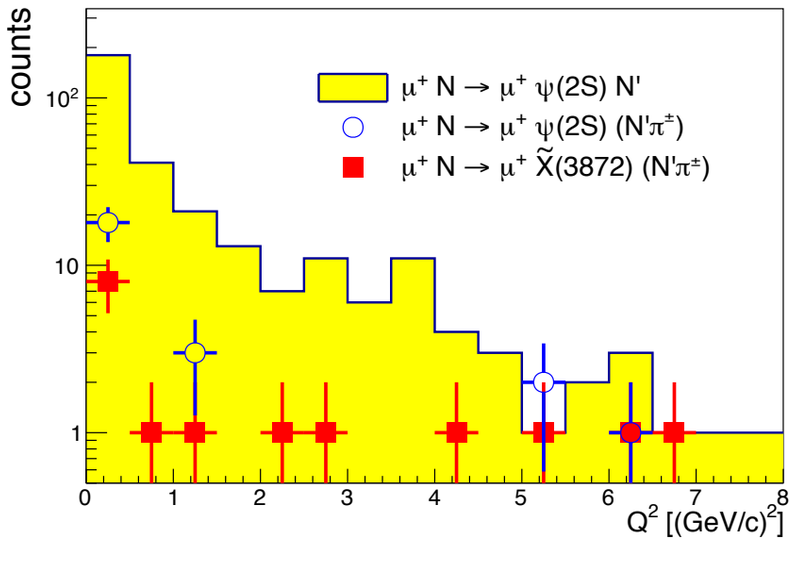
No any evidence of a peak at 3872 MeV/c^2

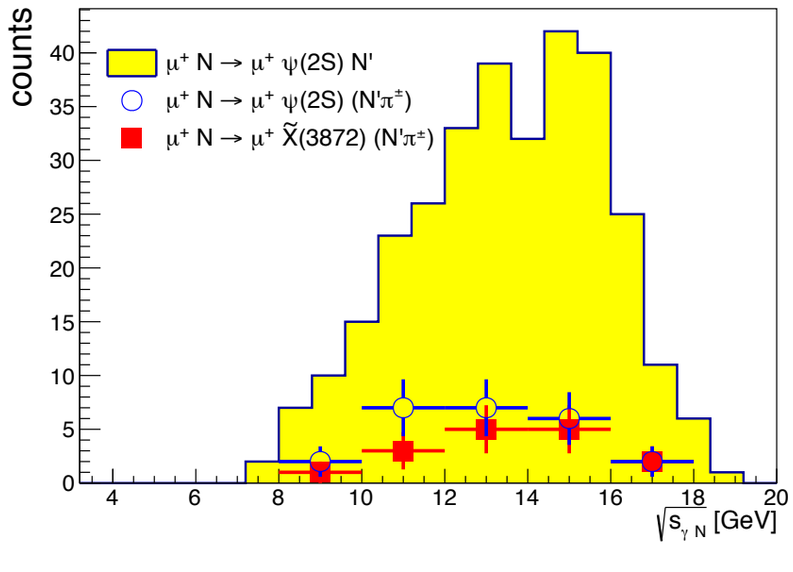


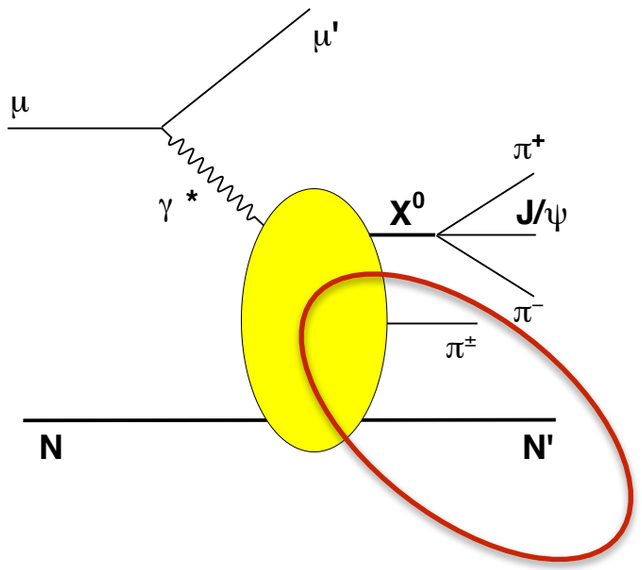


Production kinematics



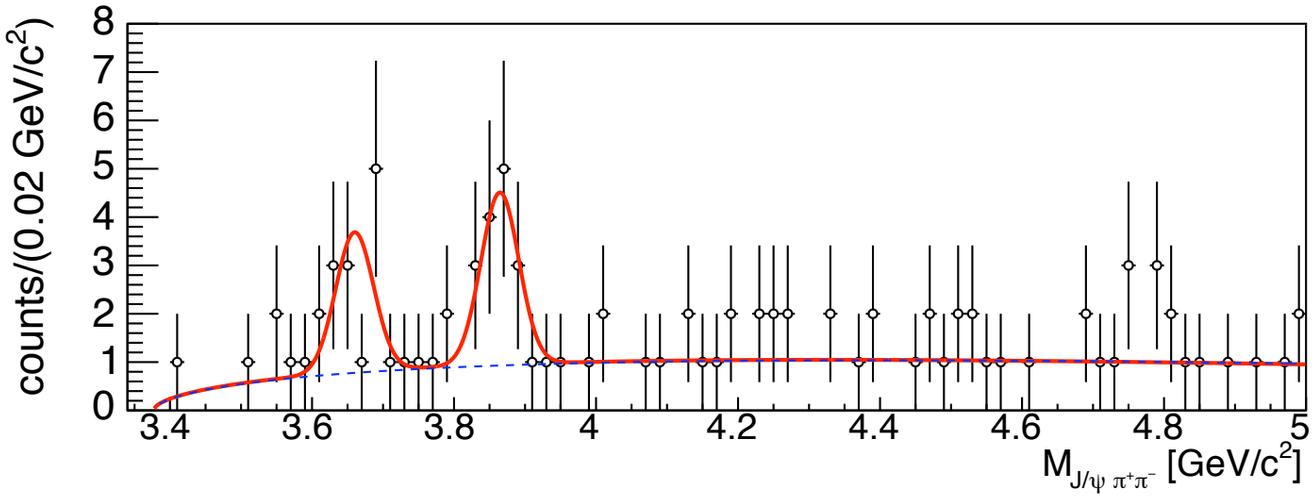






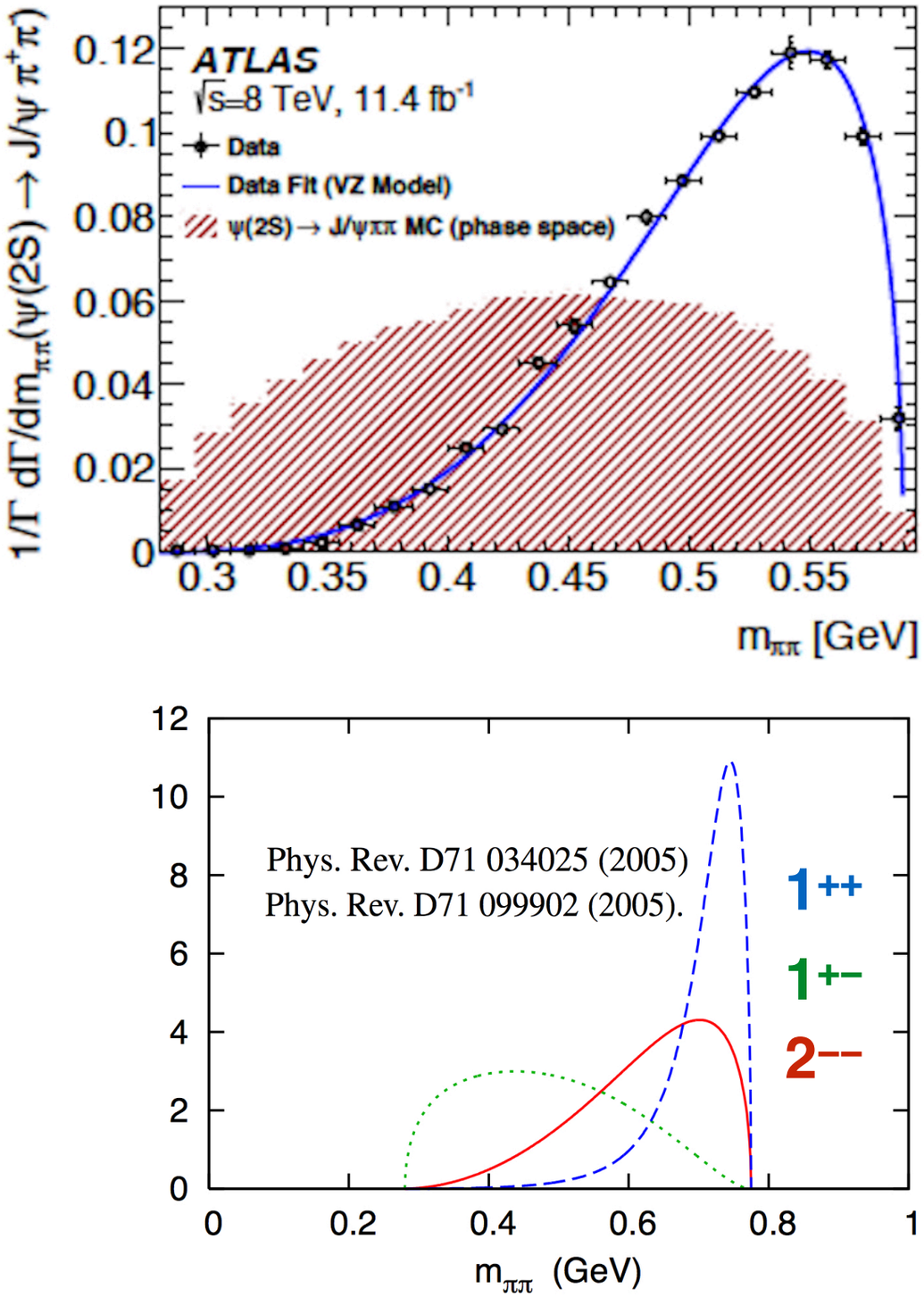
M_{miss}

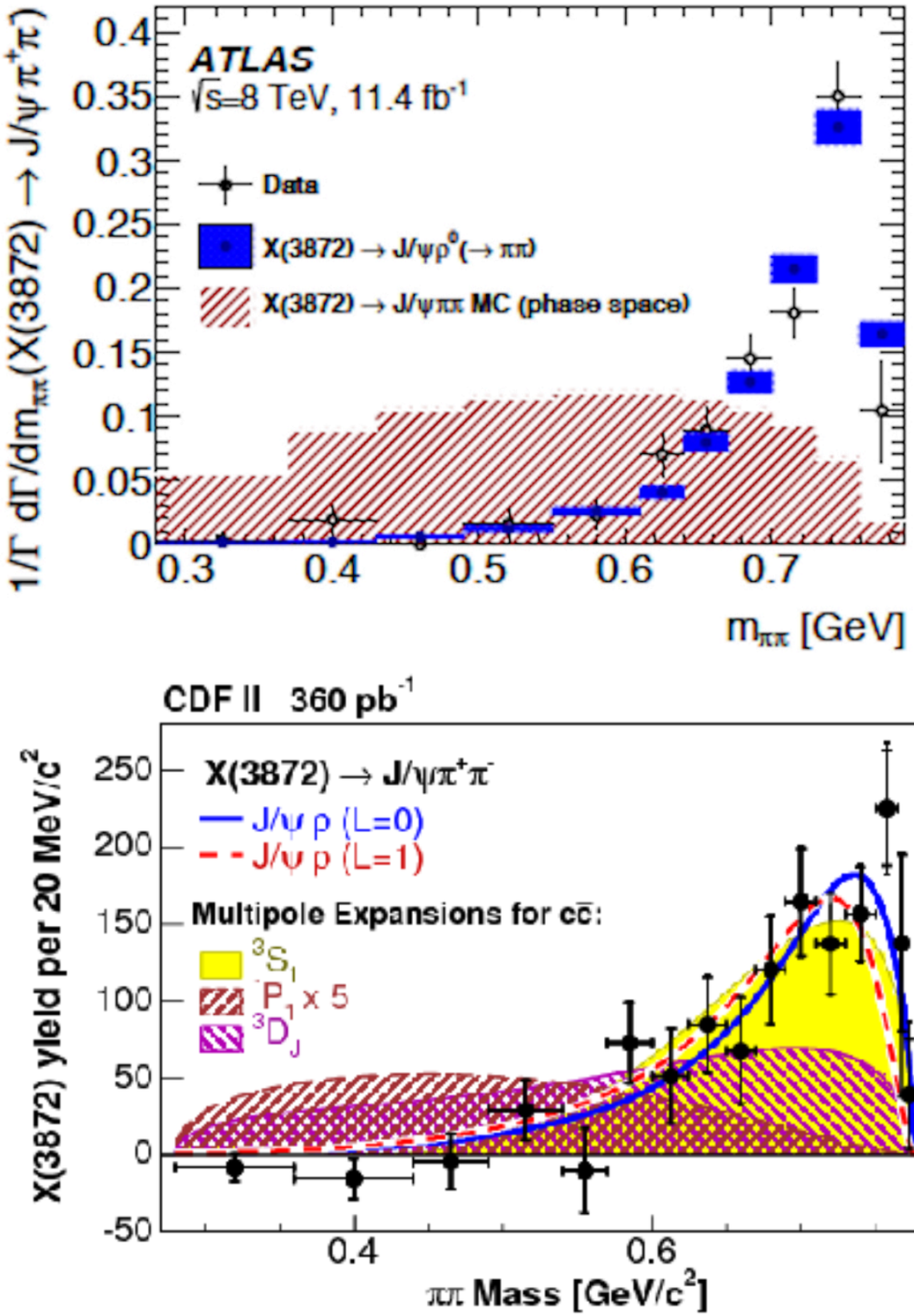
M_{miss}>3 GeV/c^2



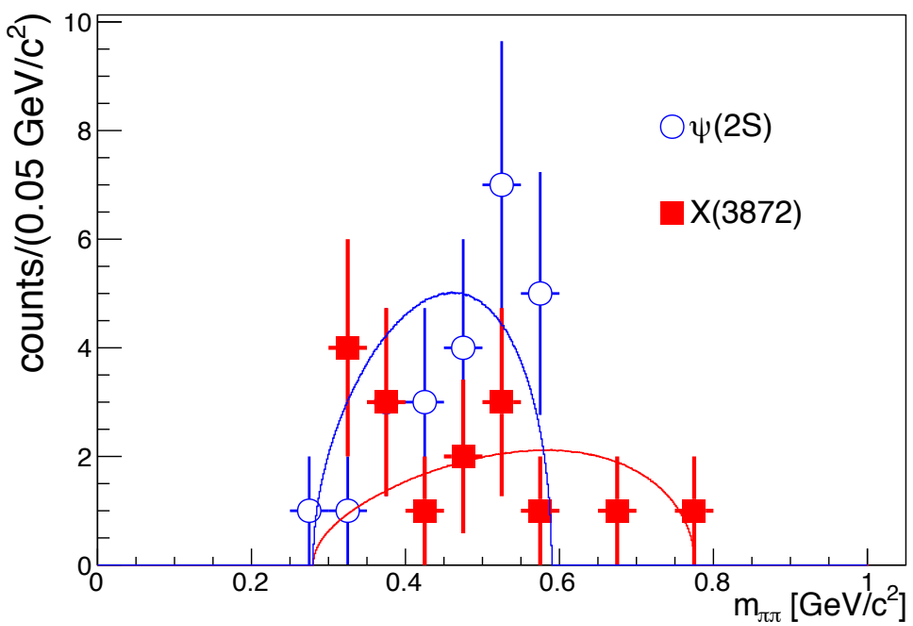
It seems, $\tilde{X}(3872)\pi^{\pm}$ and $\psi(2S)\pi^{\pm}$ are produced via different mechanisms

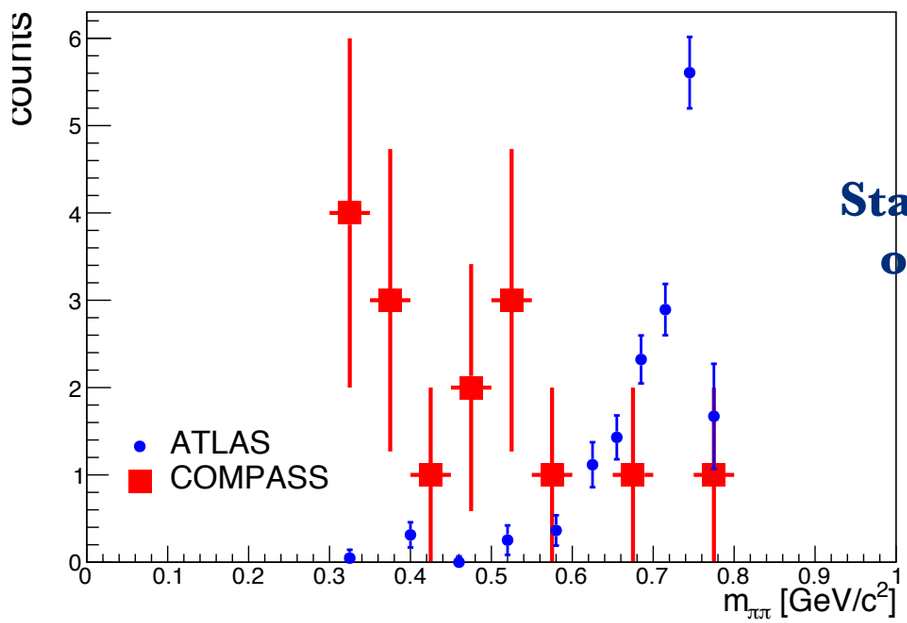
Two pion mass spectrum





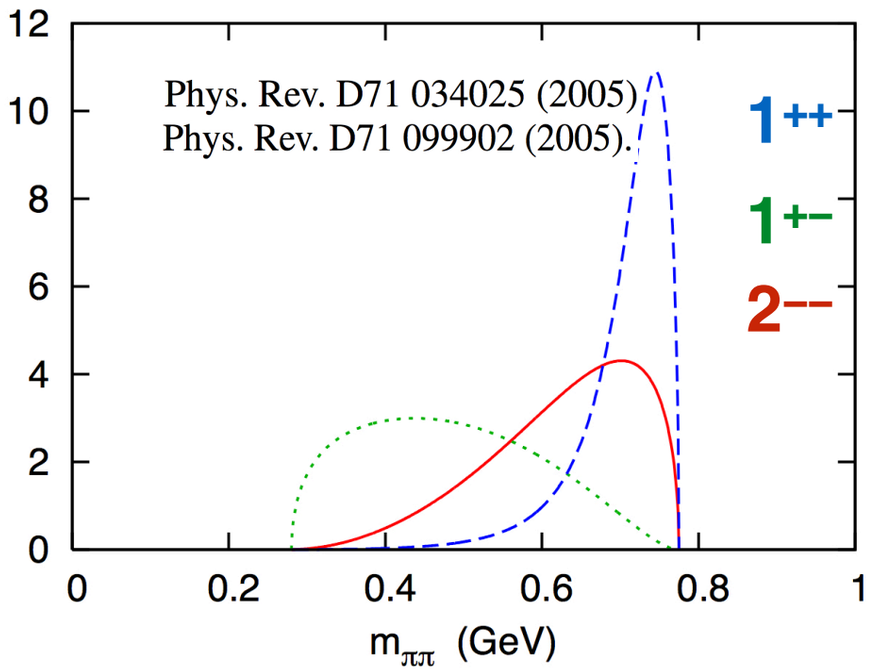
Two pion mass spectrum

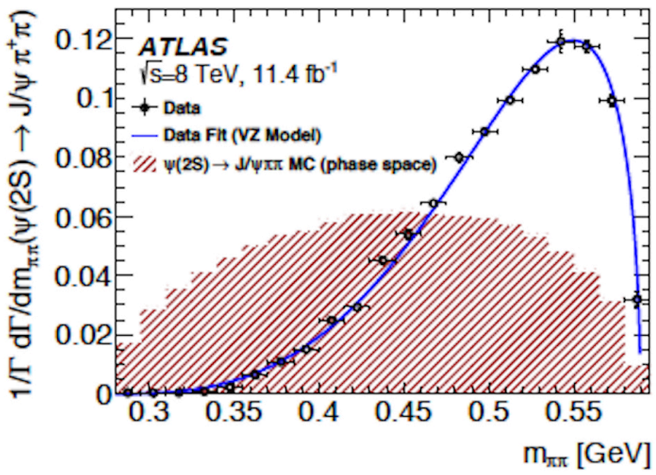


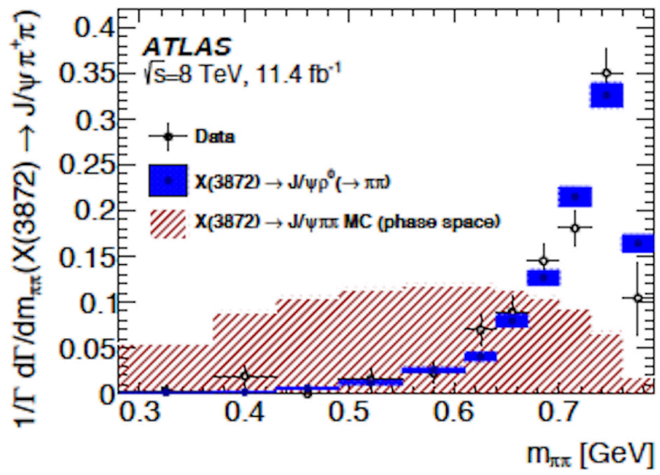


Statistical significance of the difference is $(4.7-7.3)\sigma$

The shape of the ππ-mass spectrum observed by COMPASS for ψ(2S) is in agreement with previous results while our result for $\tilde{X}(3872)$ is in tension with previous observations.







our ππ-mass spectrum looks similar to 1^{+-}

Consistency checks

We investigated many possible reactions which could imitate the observed $\tilde{X}(3872)$ signal:

$$\gamma^*N \to \psi(2S)\pi^\pm N' \to (J/\psi\pi^+\pi^-)\pi^\pm N'$$
$$\gamma^*N \to \psi(2S)N^* \to (J/\psi\pi^+\pi^-)(\pi^\pm N')$$
$$\gamma^*N \to X(3872)\pi^\pm N' \to (J/\psi\omega)\pi^\pm N' \to (J/\psi\pi^+\pi^-\pi^0)\pi^\pm N'$$
$$\gamma^*N \to \chi_{cJ}\pi^\pm N' \to (J/\psi\gamma)\pi^\pm N' \to (J/\psi e^+e^-)\pi^\pm N'$$
$$\gamma^*N \to J/\psi\pi^+\pi^-\pi^+\pi^- N'$$

$(J/\psi\eta)$, $(J/\psi\eta'(958))$, $(J/\psi\phi)$ subsystems in the final state were also considered.

But all the hypotheses were disproved.

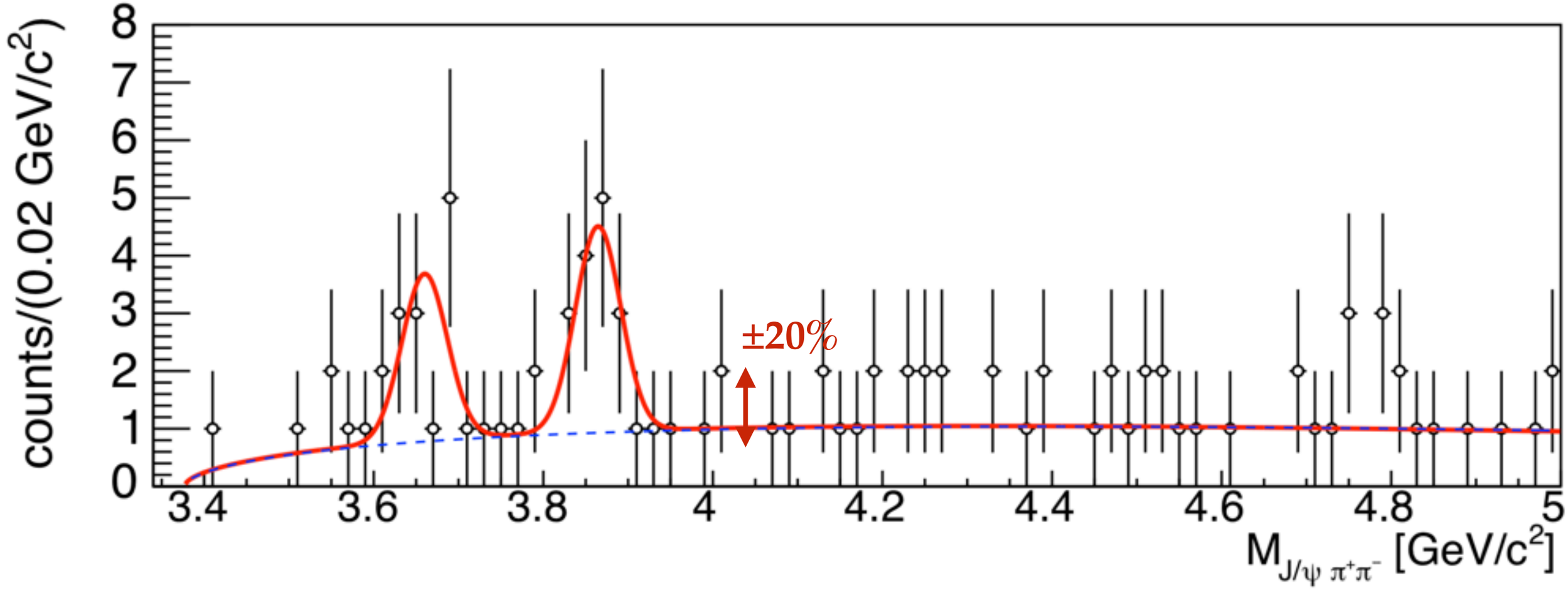
$\tilde{X}(3872)$ as a new state

$m_{X(\tilde{3872})} = (3860.0 \pm 10.4)\ MeV/c^2$

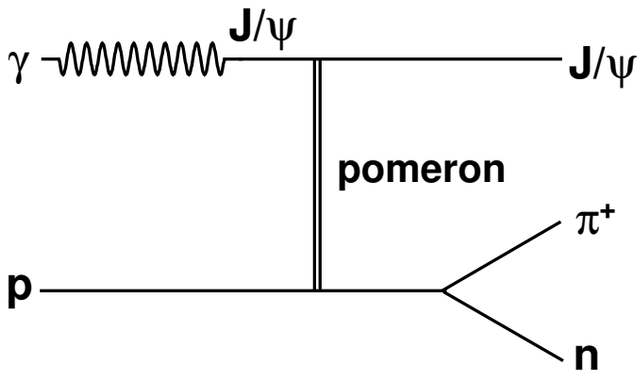
$\Gamma_{X(\tilde{3872})} < 51\ MeV/c^2\ (CL=90\%)$

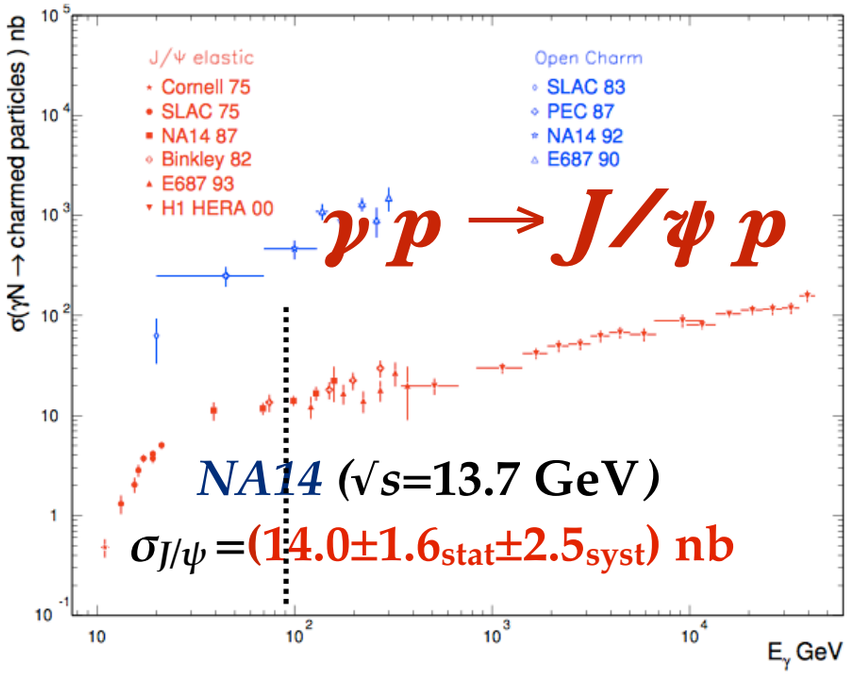
Significance (including systematics) is 4.1σ

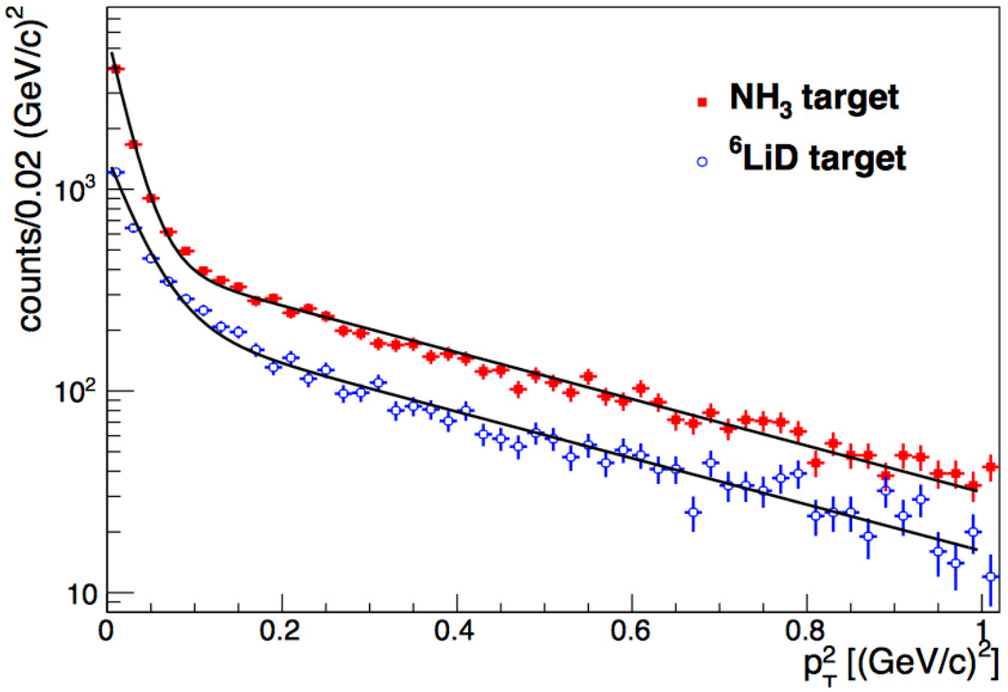
$C=-1$ (?)

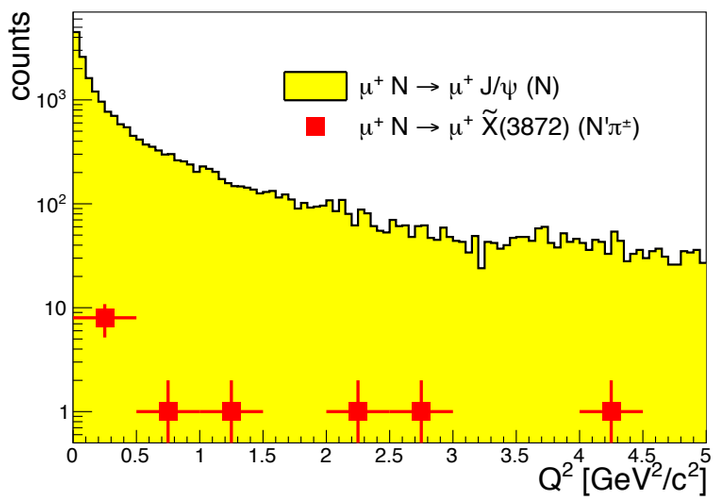


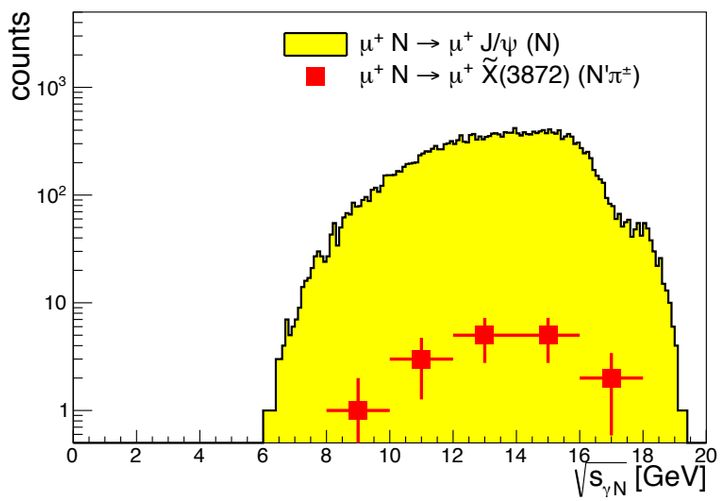
Absolute production rate











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

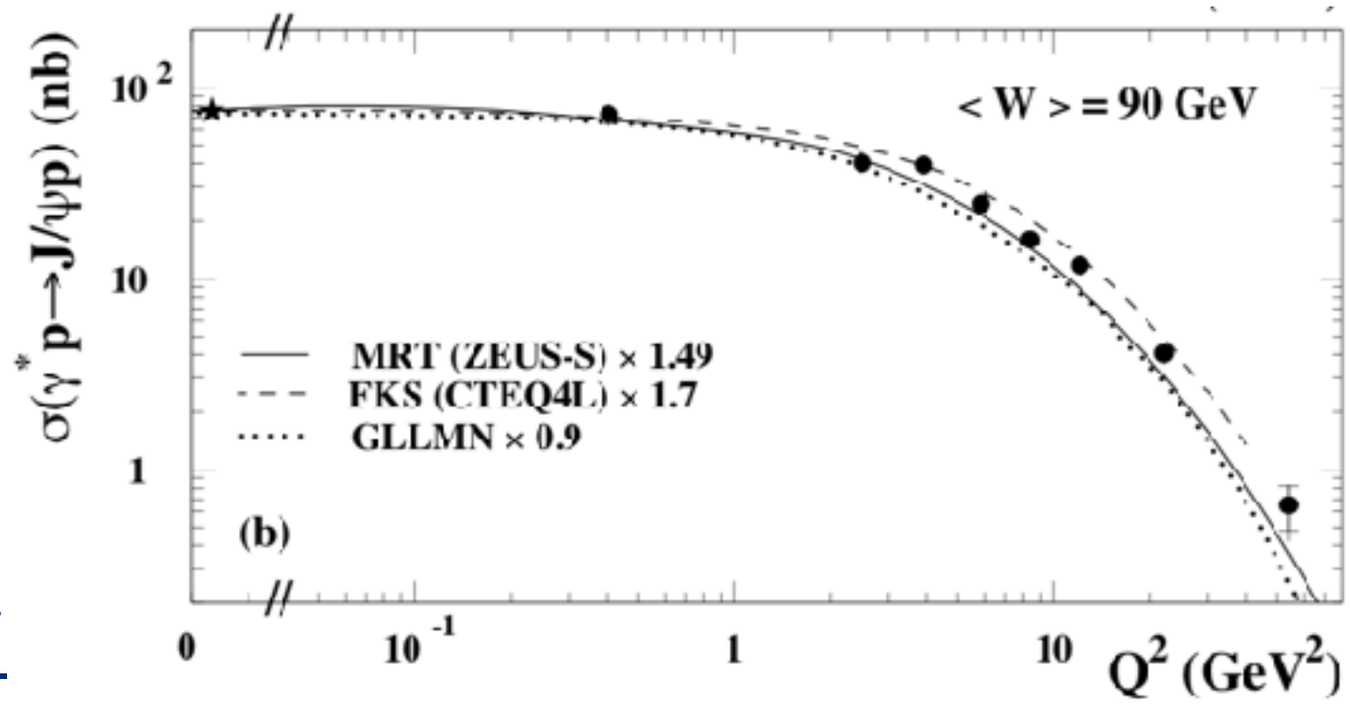
Absolute production rate

COMPASS

HERA:

$$\sigma_{\gamma^* p \to J/\psi} = \sigma_{\gamma p \to J/\psi} \times \left(\frac{M^2_{J/\psi}}{Q^2 + M^2_{J/\psi}} \right)^n$$

$$n = 2.44 \pm 0.08$$



$$\frac{\sigma_{\mu N \to \mu \widetilde{X}(3872) \pi N'}}{0.8 \sigma_{\mu N \to \mu J/\psi}} = \frac{\sigma_{\gamma N \to \mu \widetilde{X}(3872) \pi N'}}{\sigma_{\gamma N \to \mu J/\psi}}$$

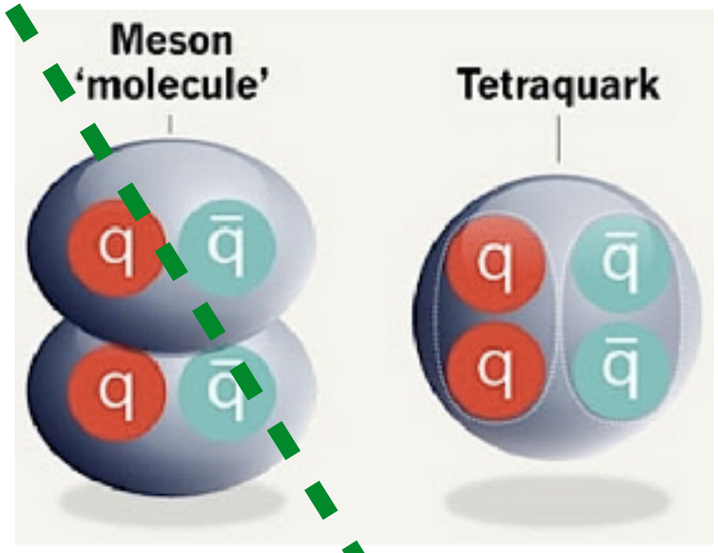
$$\frac{\sigma_{\gamma N \to \mu \widetilde{X}(3872) \pi N'} \times B_{\widetilde{X}(3872) \to J/\psi \pi\pi}}{\sigma_{\gamma N \to \mu J/\psi}} = 0.8 \frac{N_{\widetilde{X}(3872)}}{N_{J/\psi} a_\pi^3}$$

a_π=0.6±0.1

$$\sigma_{\gamma N \to \tilde{X}(3872) \pi N'} \times \mathcal{B}_{\tilde{X}(3872) \to J/\psi \pi\pi} = 71 \pm 28(\text{stat}) \pm 39(\text{syst}) \text{ pb}.$$
$$\sigma_{\gamma N \to X(3872) N'} \times \mathcal{B}_{X(3872) \to J/\psi \pi\pi} < 2.9 \text{ pb (CL} = 90\%).$$

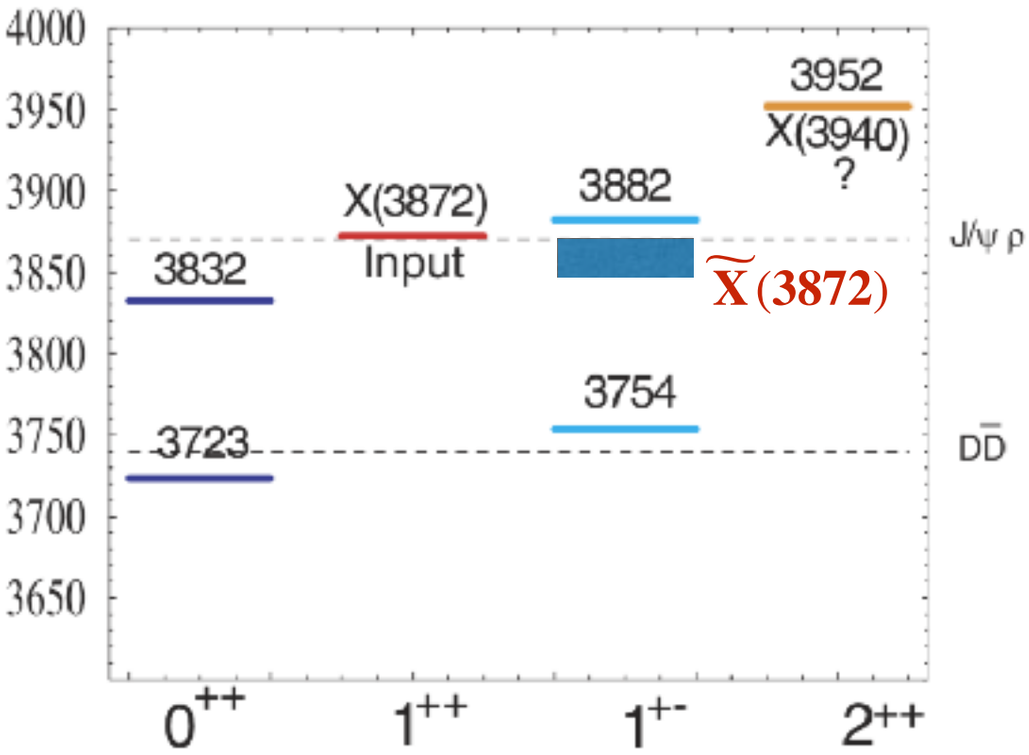
Tetraquark treatment

The X(3872) state, which mass is close to the X(3872) mass could be treated within the tetraquark model that predicts



L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. D71 (2005) 014028.

L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. D89 (2014) 114010.



$$X_u = [cu][\bar{c}\,\bar{u}]; \qquad X_d = [cd][\bar{c}\,\bar{d}];$$

$$M(X_h) - M(X_l) = 2(m_d - m_u)/\cos(2\theta) =$$

$$= (7 \pm 2)/\cos(2\theta)\ \text{MeV}$$

$X(3872) \to J/\psi\ \rho \to J/\psi\ \pi^+\pi^-$: $C=+1$

$\tilde{X}(3872) \to J/\psi\ \sigma \to J/\psi\ \pi^+\pi^-$: $C=-1$

Why not $h_c(2P)$?

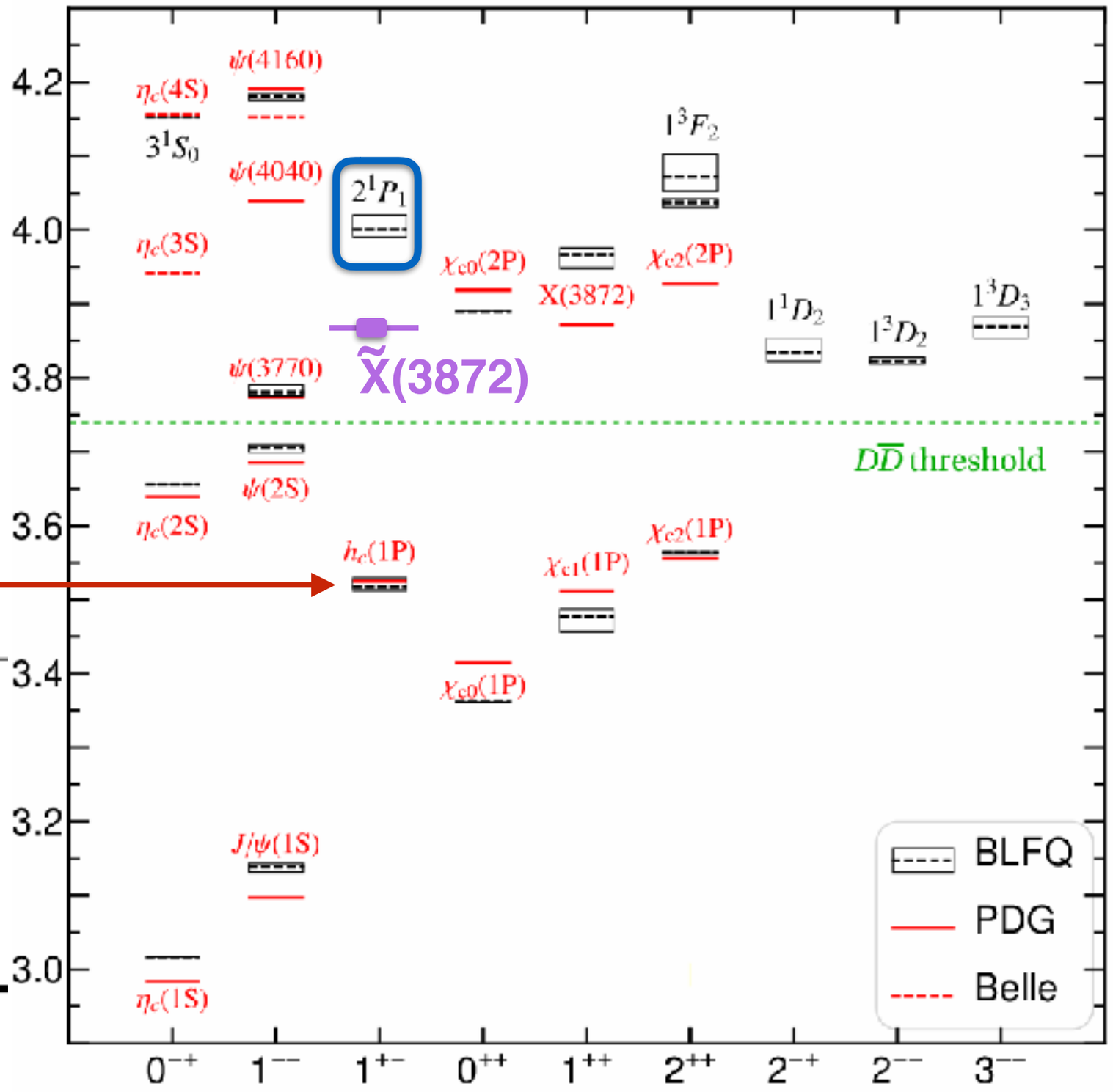
Predicted mass of $h_c(2P)$ is above 3.9 GeV. Our state is too low.

$h_c(1P)$

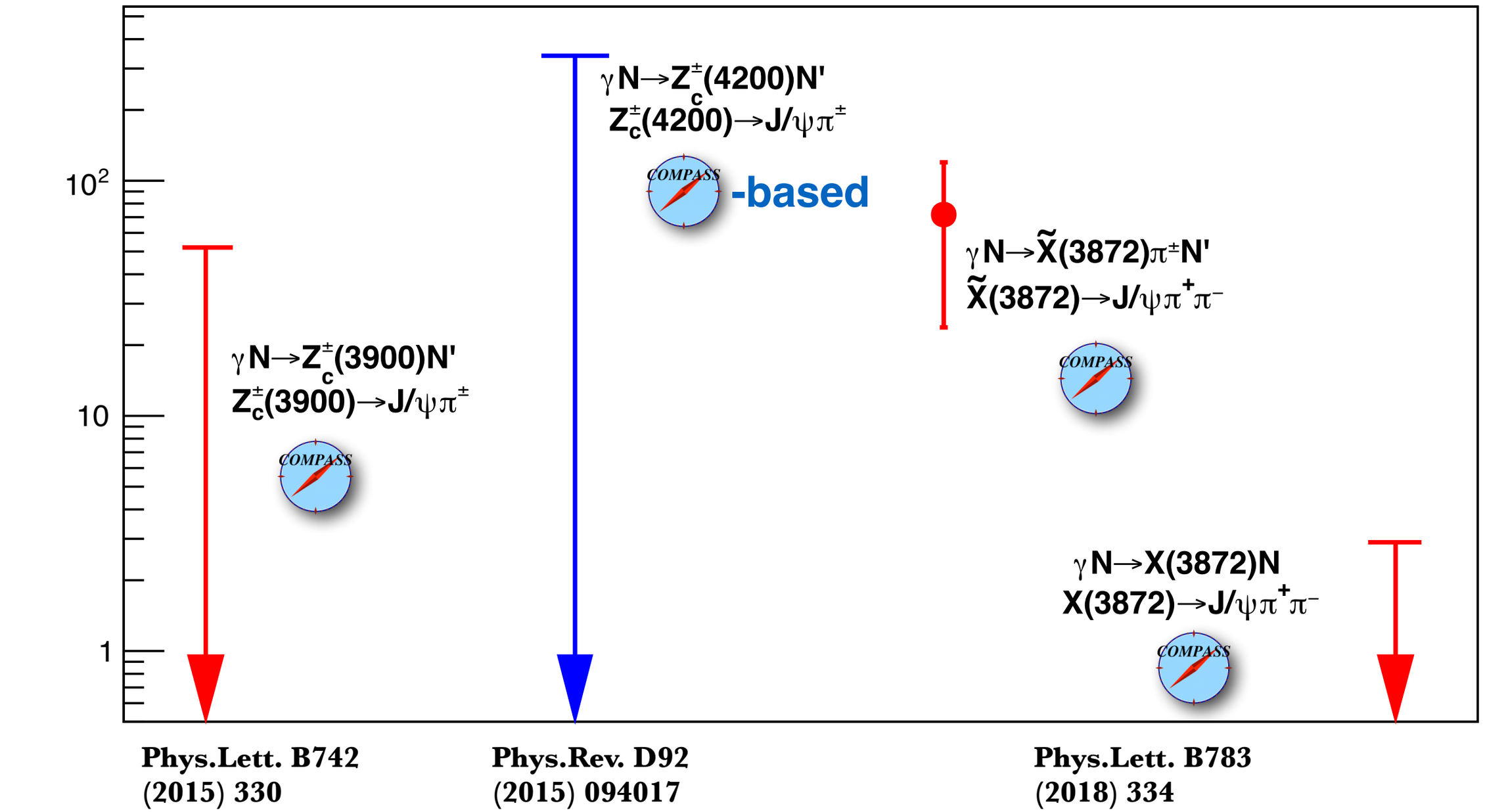
$I^G(J^{PC}) = ?^?(1^{+-})$

Mass $m = 3525.38 \pm 0.11$ MeV
Full width $\Gamma = 0.7 \pm 0.4$ MeV

$h_c(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level
$J/\psi(1S)\pi\pi$	not seen	
$p\overline{p}$	$< 1.5 \times 10^{-4}$	90%
$\pi^+\pi^-\pi^0$	$< 2.2 \times 10^{-3}$	
$2\pi^+2\pi^-\pi^0$	$(2.2^{+0.8}_{-0.7})$ %	
$3\pi^+3\pi^-\pi^0$	< 2.9 %	
Radiative decays		
$\gamma\eta$	$(4.7\pm2.1) \times 10^{-4}$	
$\gamma\eta'(958)$	$(1.5\pm0.4) \times 10^{-3}$	
$\gamma\eta_c(1S)$	(51 ±6) %	

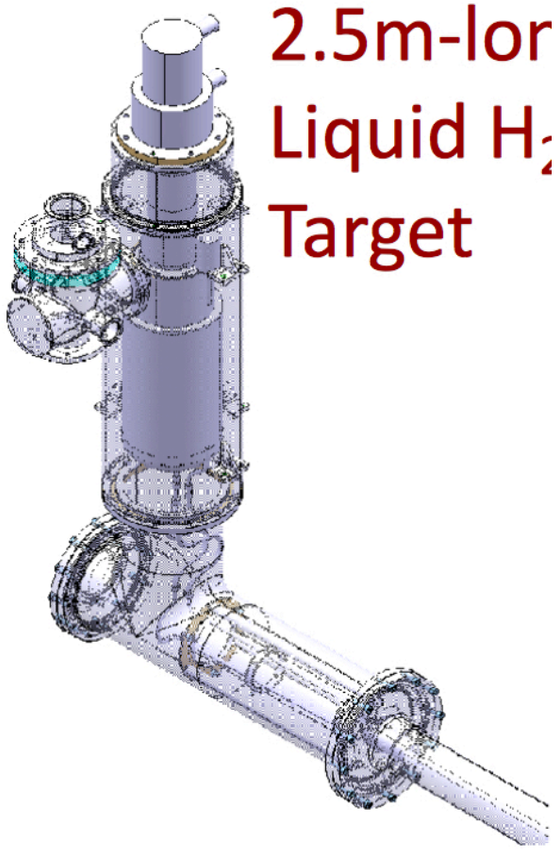


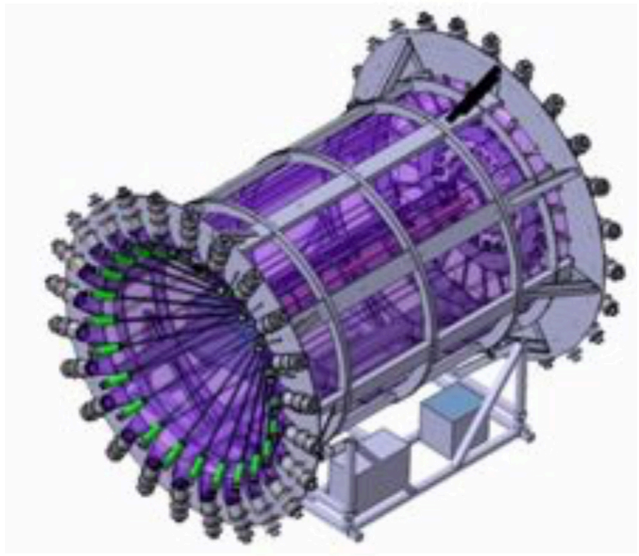
Photoproduction results for exotic charmonia



COMPASS run 2016-2017: new opportunities

- ***New 2.5 m long liquid hydrogen target transparent for photons ($0.27X_0$) surrounded by a recoil proton detector;***
- ***3 electromagnetic calorimeters covering a large aperture.***





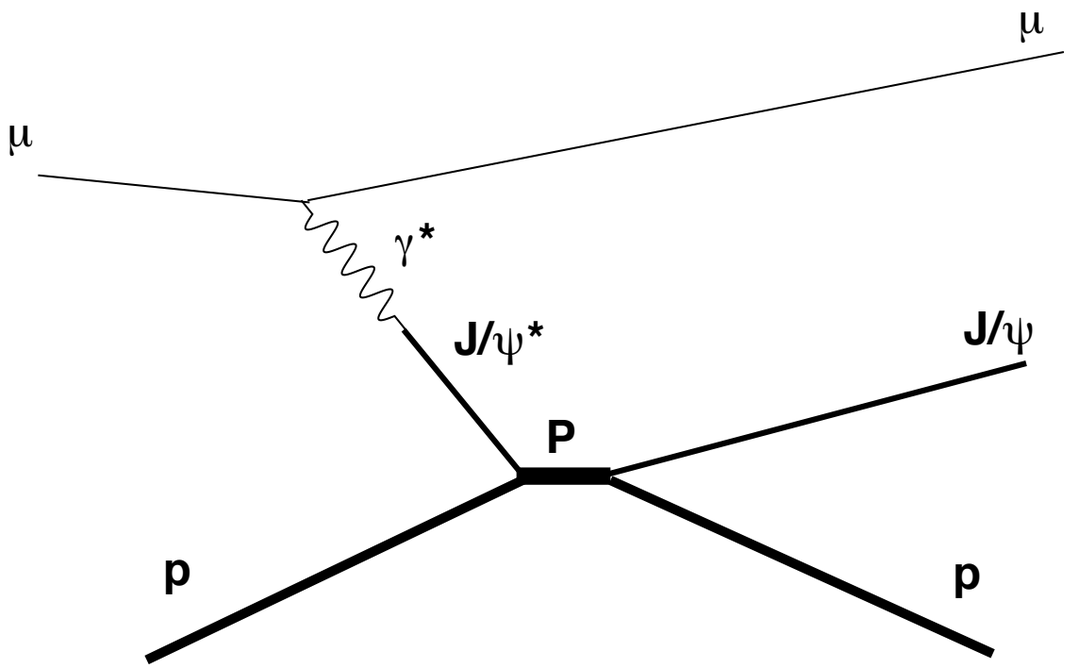
Состояние	M, МэВ/c^2	Γ, МэВ/c^2	J^{PC}	Каналы распада	Относительная вероятность распада,%
$\psi(2S)$	3686	0.286	1^{--}	$J/\psi\pi^0\pi^0$	18.17±0.31
				$J/\psi\eta$	3.36±0.05
				$J/\psi\pi^0$	0.1268±0.0032
$\psi(3823)$	3822.2±1.2	<16	2^{--}	$\chi_{c1}\gamma$	наблюдался
$X(3872)$	3871.69±0.17	<1.2	1^{++}	$J/\psi\omega$	>1.9
				$J/\psi\gamma$	>0.6
				$\psi(2S)\gamma$	>3
$Z_c^0(3900)$	3886.6±2.4	28.1±2.6	1^{+-}	$J/\psi\pi^0$	наблюдался
$X(3915)$	3919.4±2.9	20±5	$(0/2)^{++}$	$J/\psi\omega$	наблюдался
$\psi(4040)$	4039±1	80±10	1^{--}	$J/\psi\eta$	0.52±0.07
$X^{\pm}(4050)$	$4051\pm14^{+20}_{-41}$	82^{+21+47}_{-17-22}	$?^?$	$\chi_{c1}\pi^{\pm}$	наблюдался
$X(4230)$	4230±8±6	38±12±2	1^{--}	$\chi_{c0}\omega$	наблюдался
$X^{\pm}(4250)$	$4248^{+44+180}_{-29-35}$	$177^{+54+316}_{-39-61}$	$?^?$	$\chi_{c1}\pi^{\pm}$	наблюдался
$X(4260)$	4230±8	55±19	1^{--}	$J/\psi\pi^0\pi^0$	наблюдался

Possibility to search for and study of XYZ hadrons decaying to final states with photons like $J/\psi\pi^0$, $J/\psi\eta$, $J/\psi\omega$, $\chi_{c0,1,2}$ etc.

Exclusive photoproduction of pentaquarks P_c^+ in s-channel

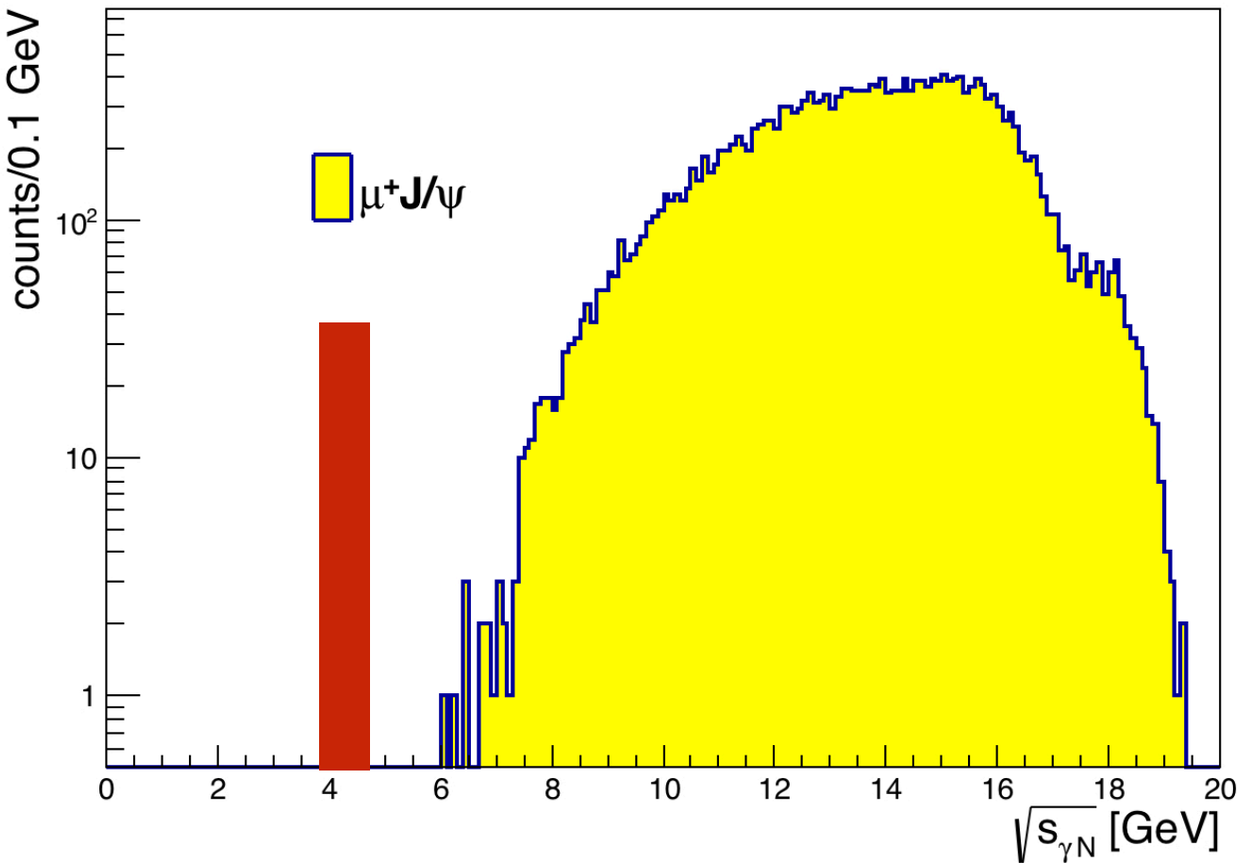
$P_c^+(4380)$ and $P_c^+(4450)$ were discovered by LHC-b in 2015 in the decay $\Lambda_b \to (J/\psi\, p)\, K^-$

$$\gamma\, p \to X \to J/\psi\, p$$



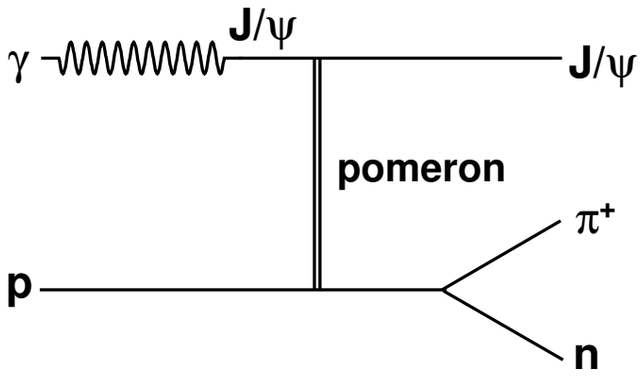
M. Karliner et. al. PLB 752 329 (2016)
arXiv:1508.01496v3

Q. Wang *et al.* Phys. Rev. D 92 034022 (2015)
arXiv:1508.00339



In present COMPASS data this process is out of trigger coverage

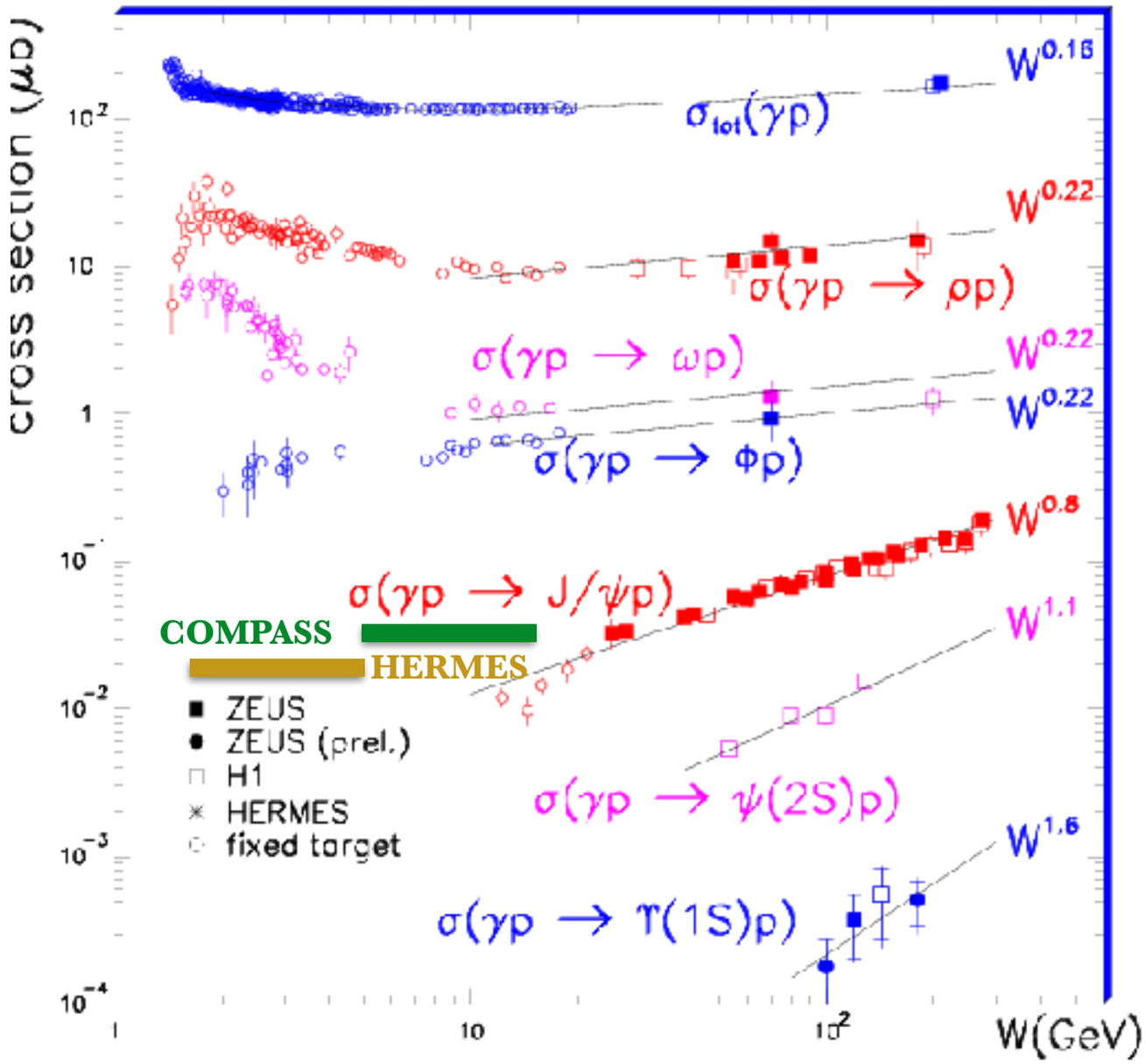
Possibilities to cross check our result



H1, ZEUS : a few thousands of exclusively produced $J/\psi \to \mu^+\mu^-$ events (vs 10k at COMPASS) but at higher $\sqrt{s_{\gamma N}}$

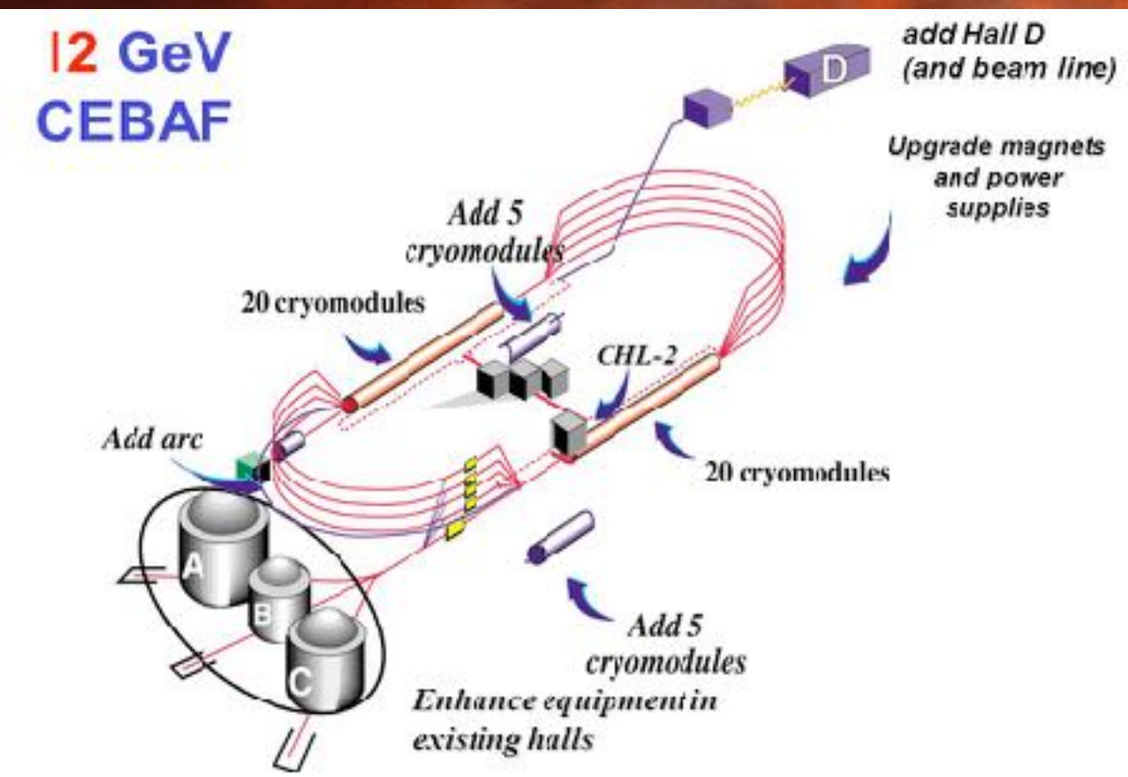
HERMES: just a few hundreds events at $\sqrt{s_{\gamma N}}$ below 7.1 GeV

Leptoproduction at HERA:

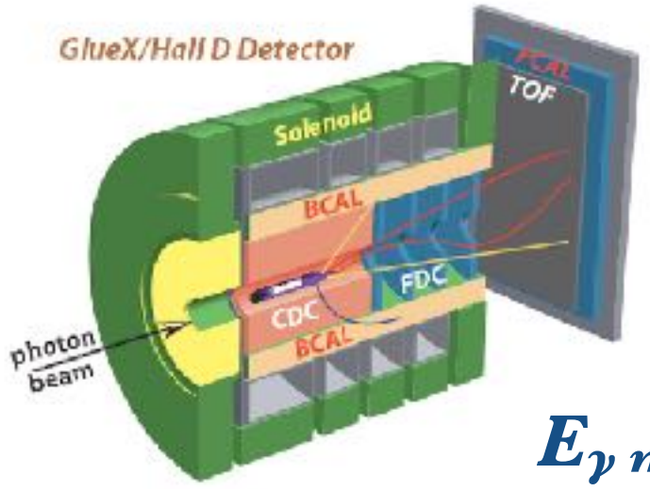


Possibilities to cross check our result

JLab



GlueX (JLab)



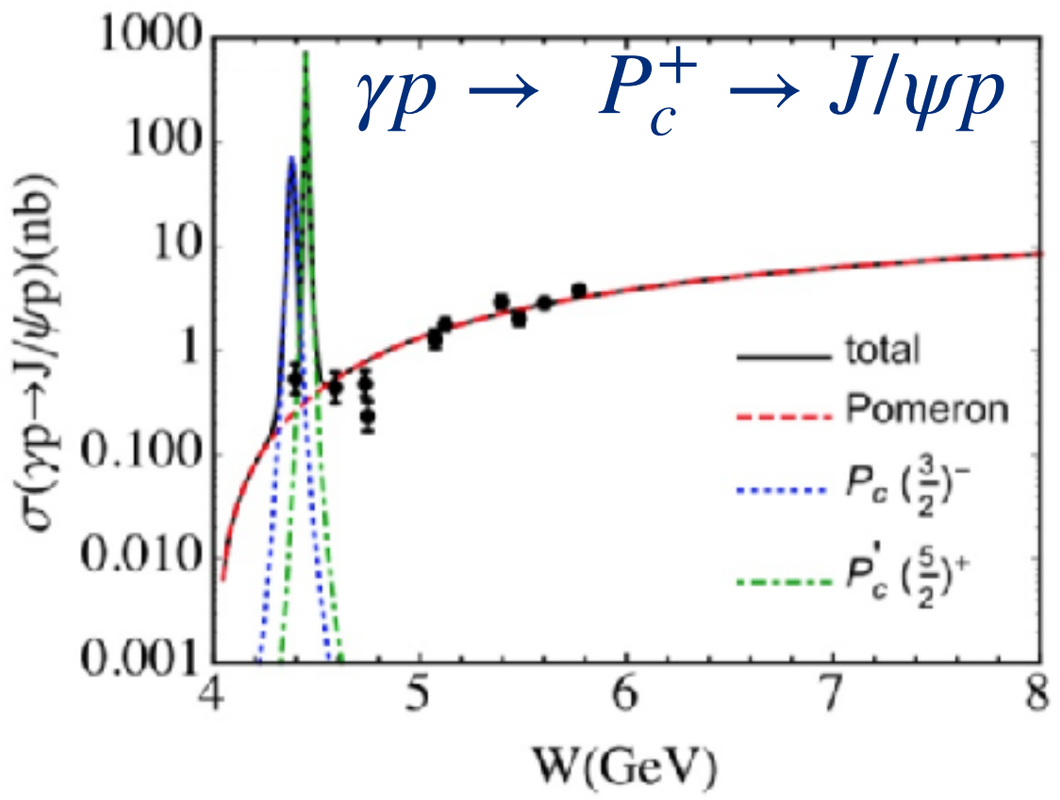
E_e=12 GeV

E_γ=9 GeV

but

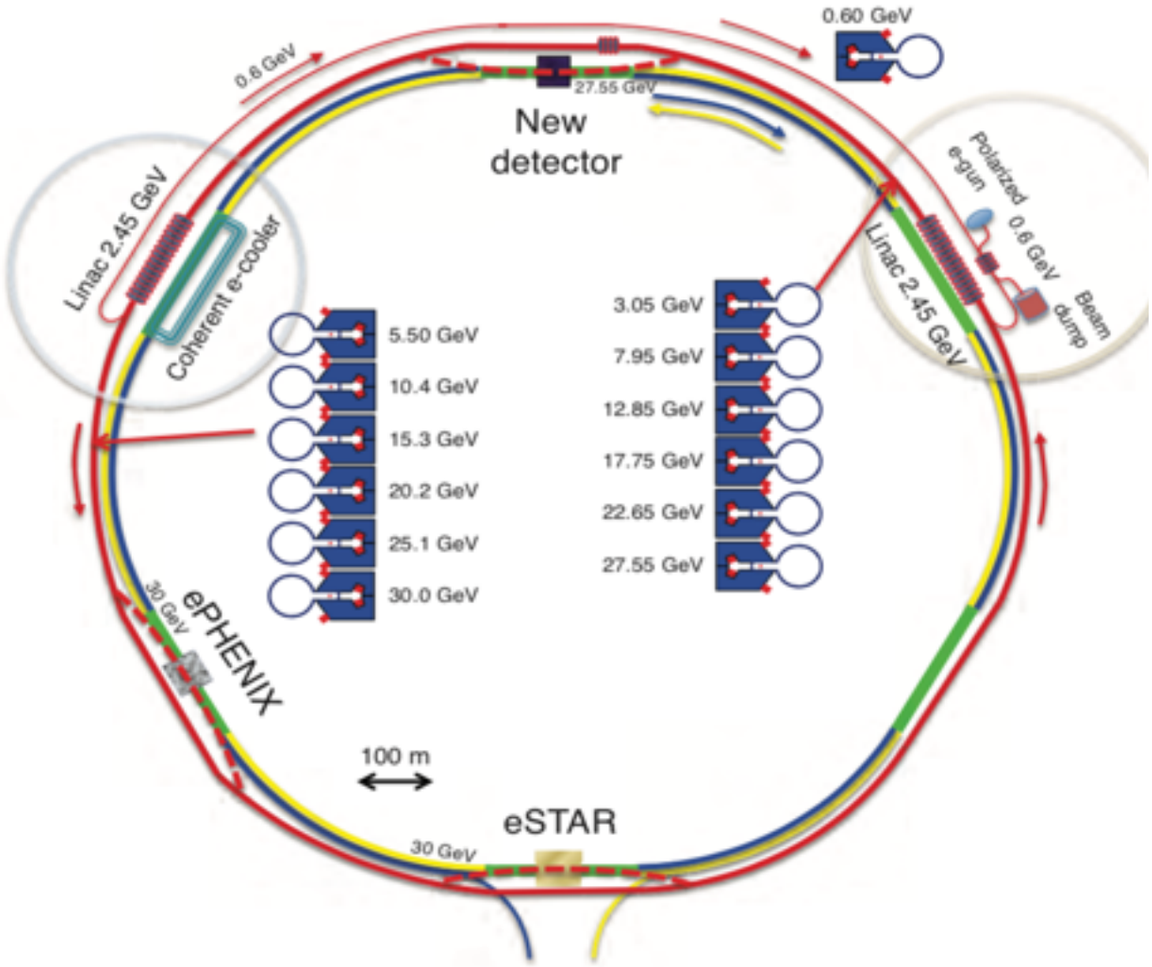
$E_{\gamma\ min}$ =13 GeV for

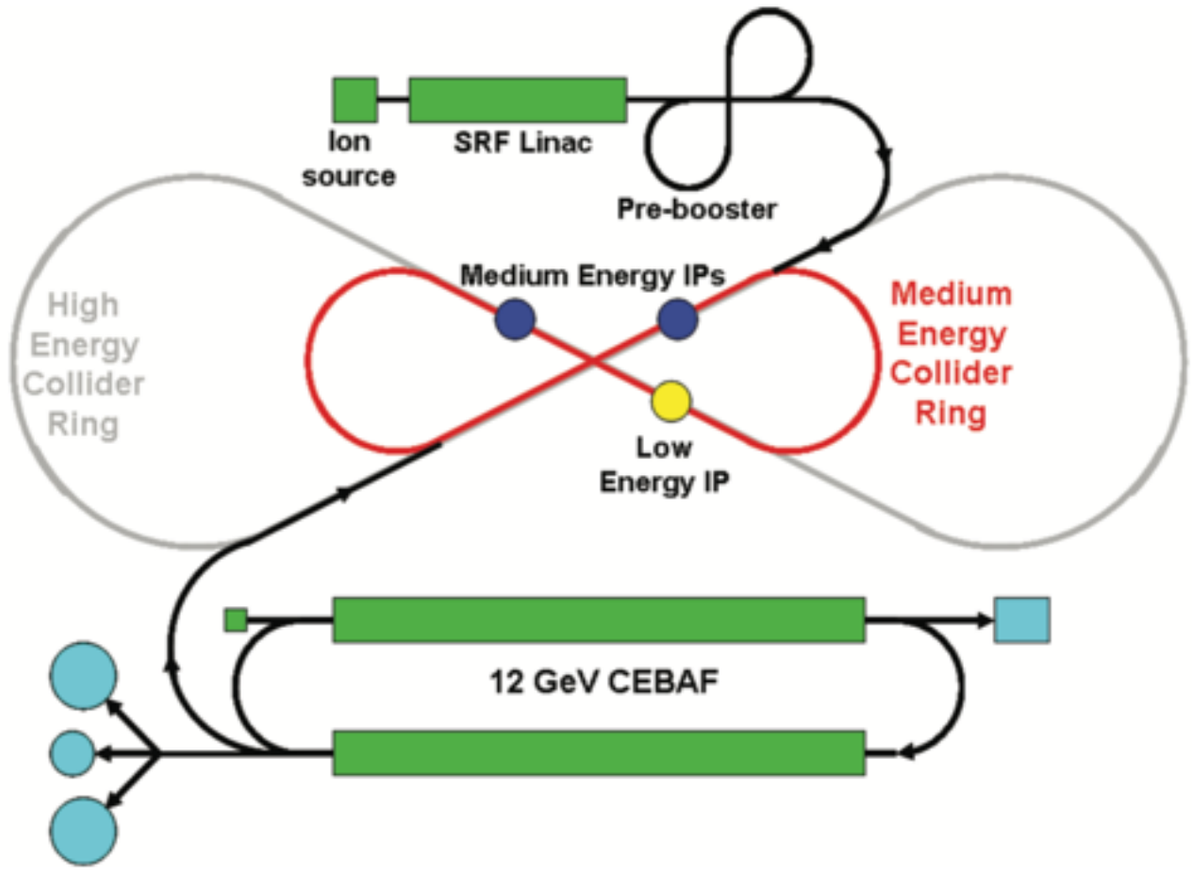
$\gamma p \to \widetilde{X}(3872)\pi^+ n$



Possibilities to cross check our result

Electron-Ion Collider (USA, planned)





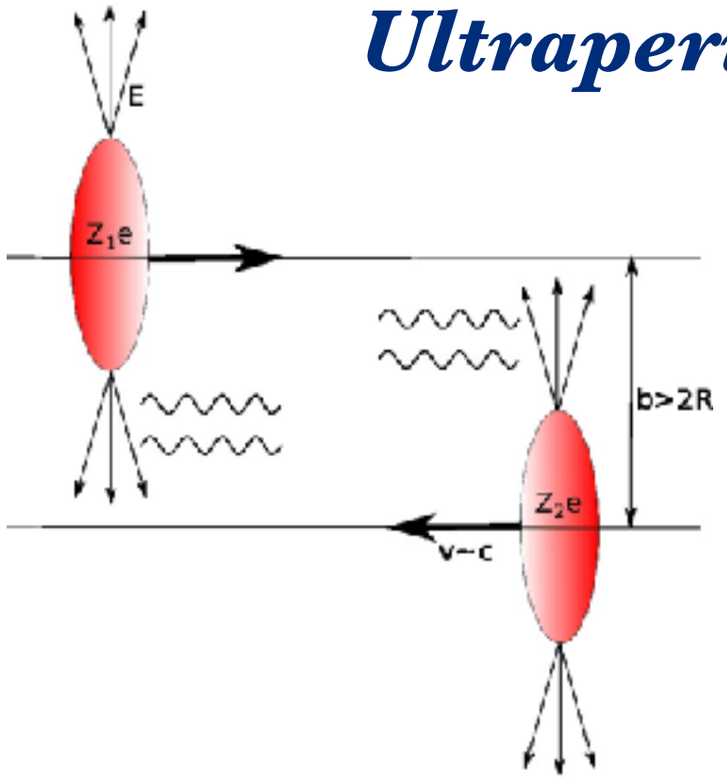
$\sqrt{s_{eN}} = 40 \div 100$ GeV

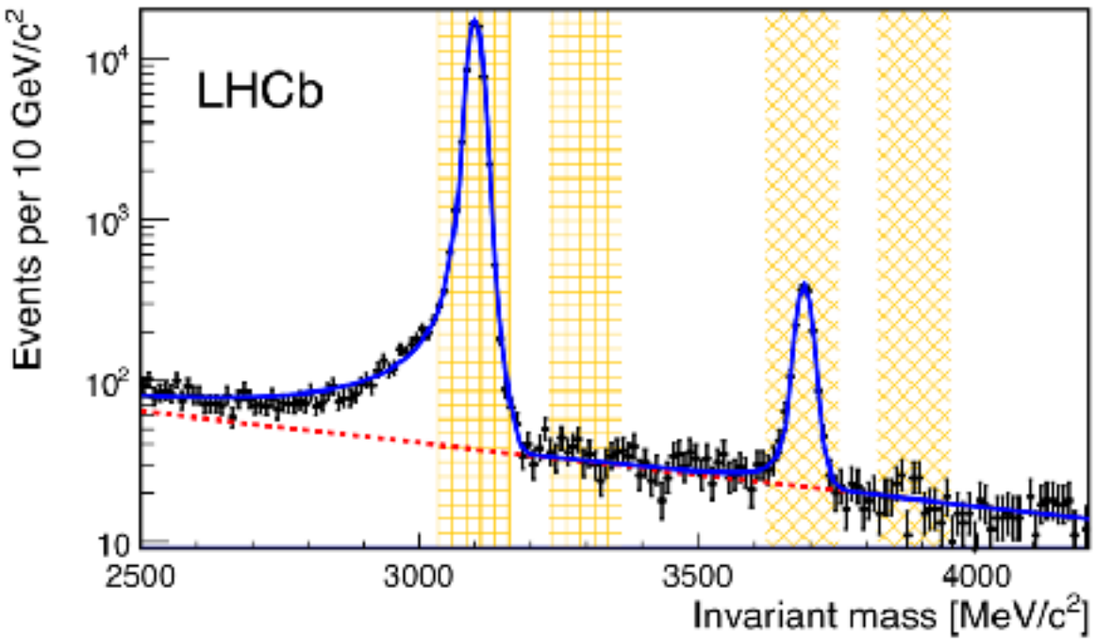
$L = 10^{34}$ cm^{-2} s^{-1}

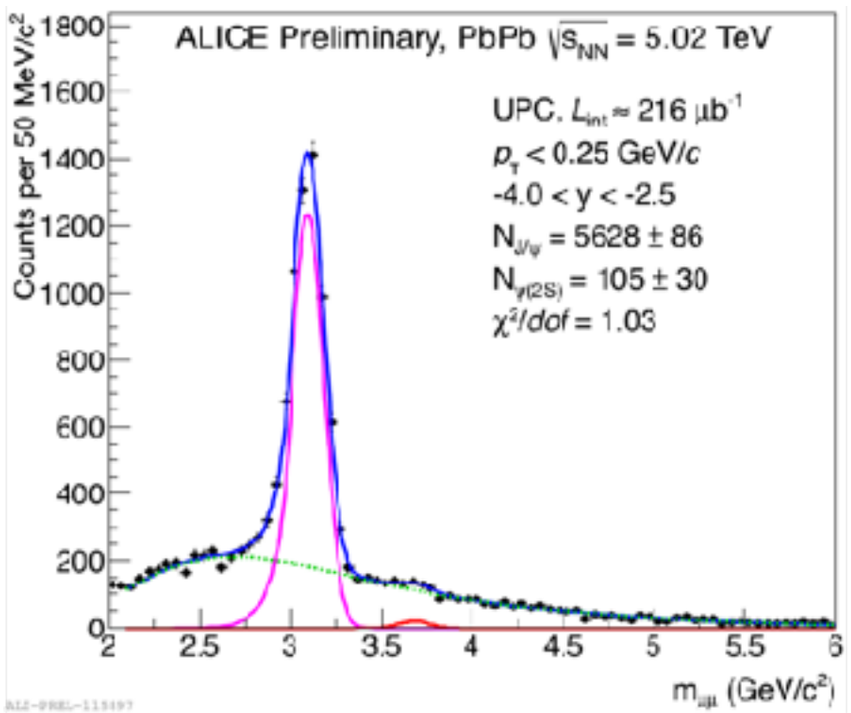
→ up to 1 $\tilde{X}(3872)$ per day

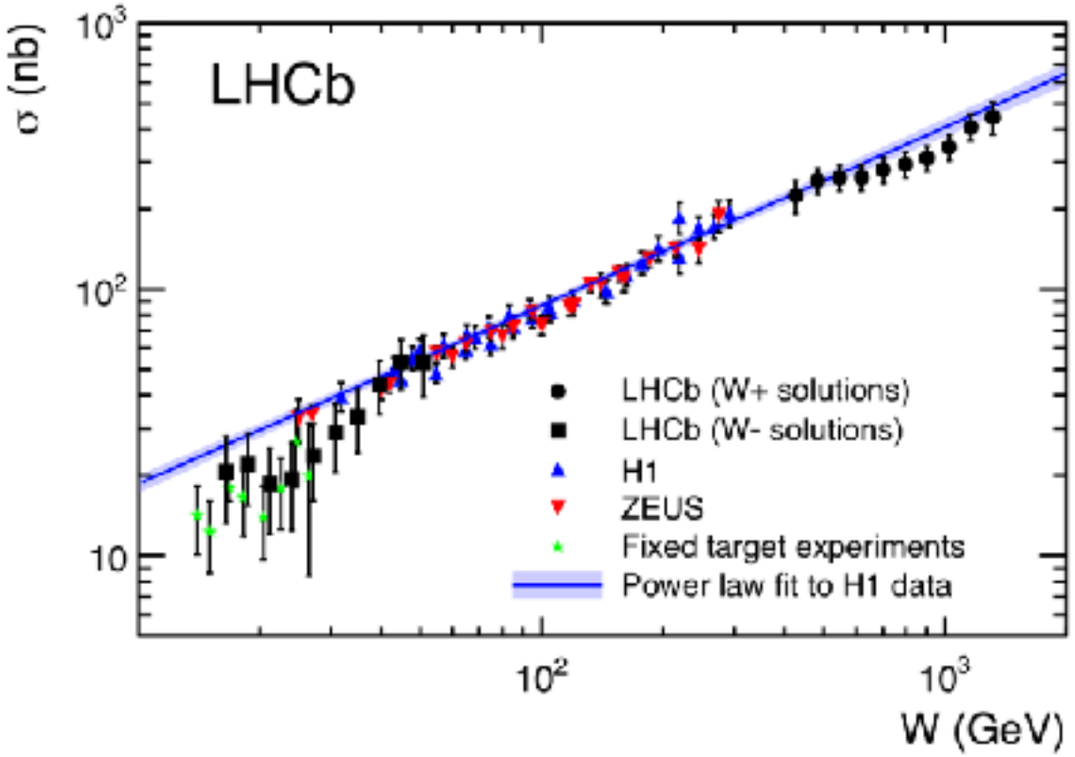
Possibilities to cross check our result

Ultraperipheral hadronic collisions at LHC









Summary

- In muoproduction at we found indications of a new state $\tilde{X}(3872)$ with a significance 4.1σ, which mass and width are compatible with those of X(3872) in the reaction $\gamma^*N \to (J/\psi\pi^+\pi^-)\pi^\pm N'$.
- Our observation for the two-pion mass spectrum shows significant disagreement with previous experimental results for X(3872).
- The mass and width of $X(3872)$ are (3860.0 ± 10.4) MeV/c^2 and <51 MeV/c^2 (CL=90%) respectively, quantum numbers, it seems, are different from 1^{++}.
- Absolute production rate was determined: $\sigma_{\gamma N \to \tilde{X}(3872)\pi^\pm N} \times B(\tilde{X}(3872) \to J/\psi\pi^+\pi^-) = 71 \pm 28_{stat} \pm 39_{syst}$ pb.
- New results from runs 2016-2017 for reactions with photons in the final state are expected.
- Search for photoproduction of exotic charmonia at COMPASS was proposed and performed by the DLNP JINR group. It is the result of close contacts with JINR BESIII group.