Resonance Production with LHCb Experiment

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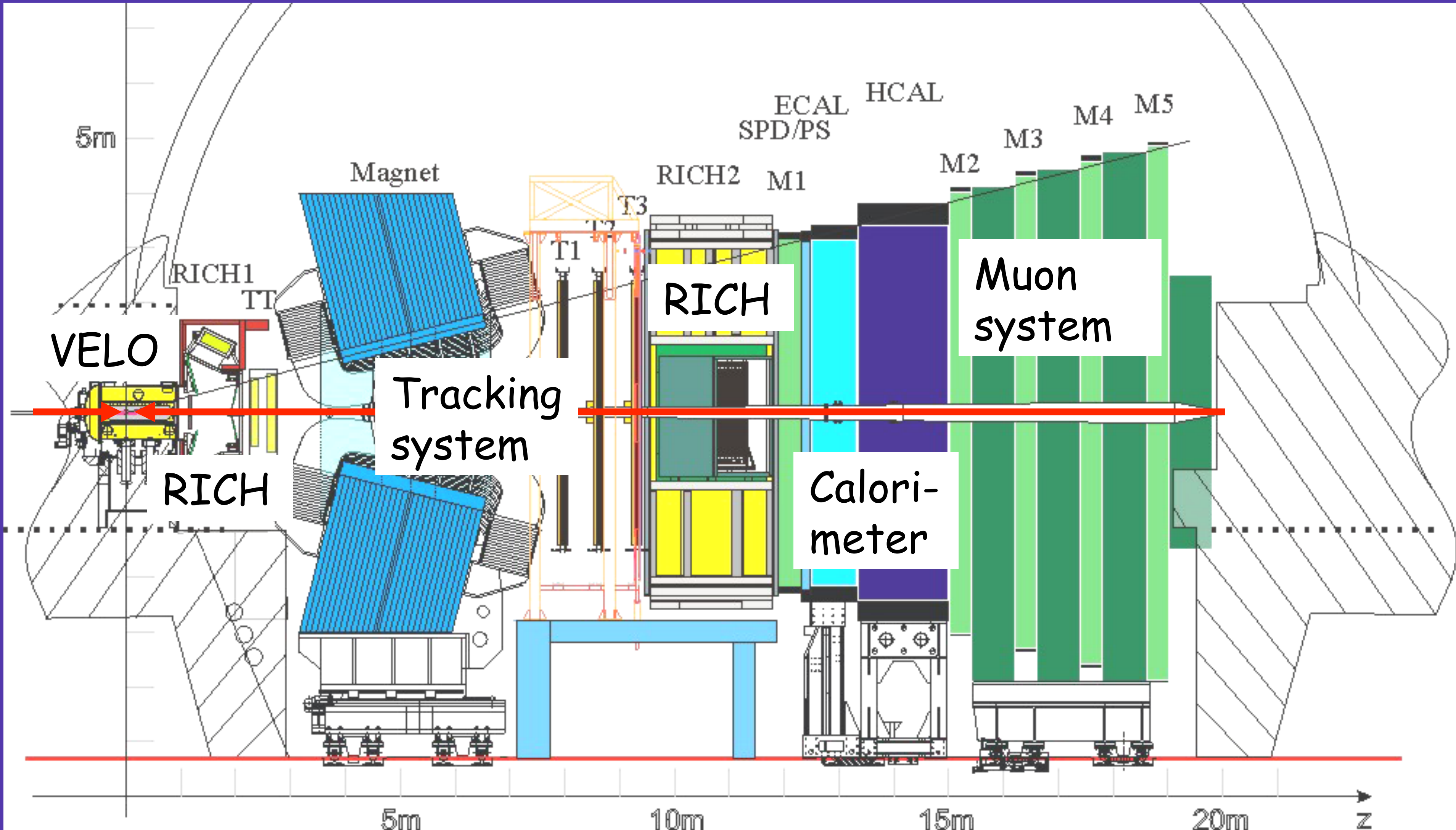
Outline

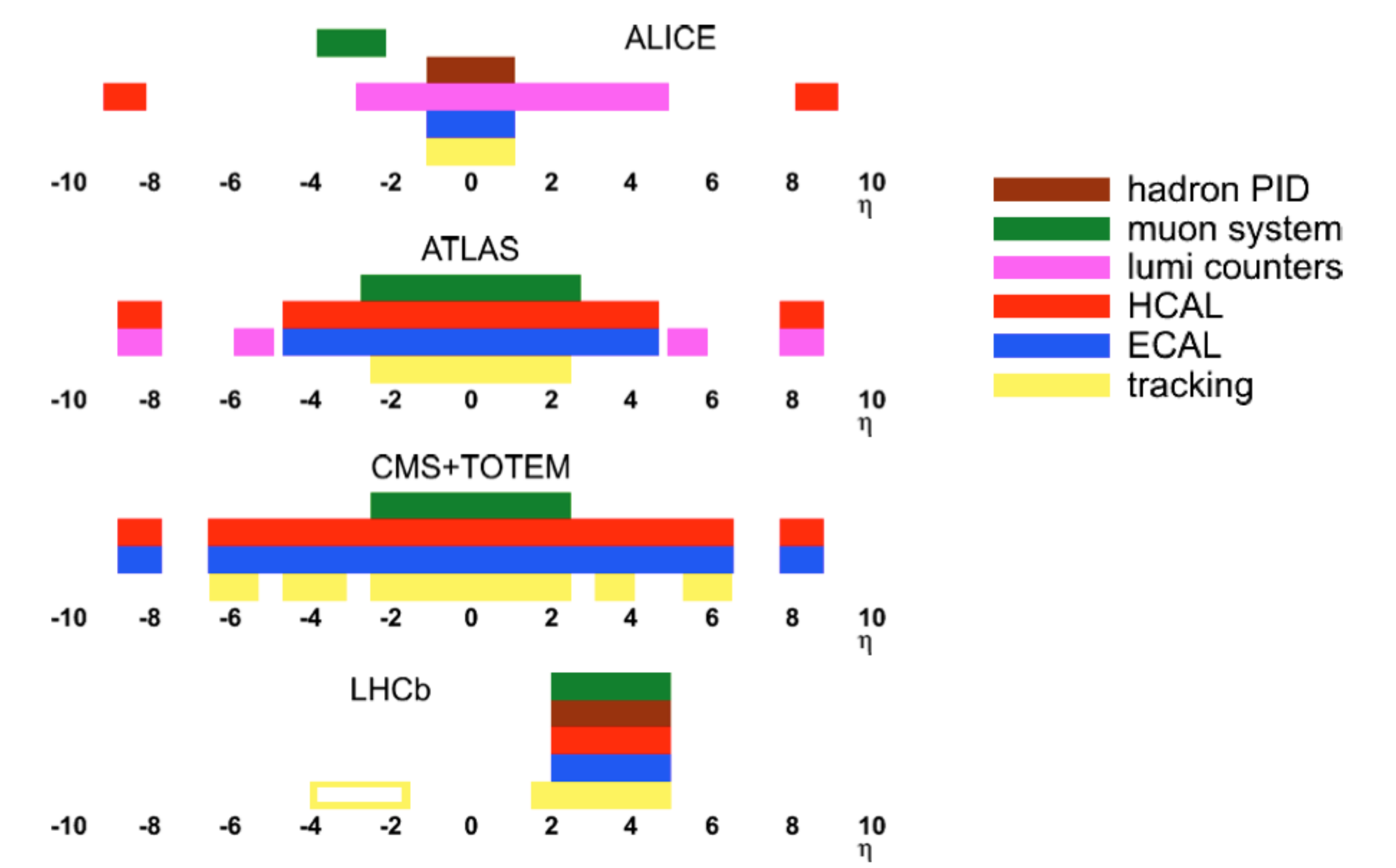
- LHCb detector
- Quarkonia production
    - p+p (polarisation)
    - p+Pb (Pb+p)
- Exotic Mesons

LHCb spectrometer

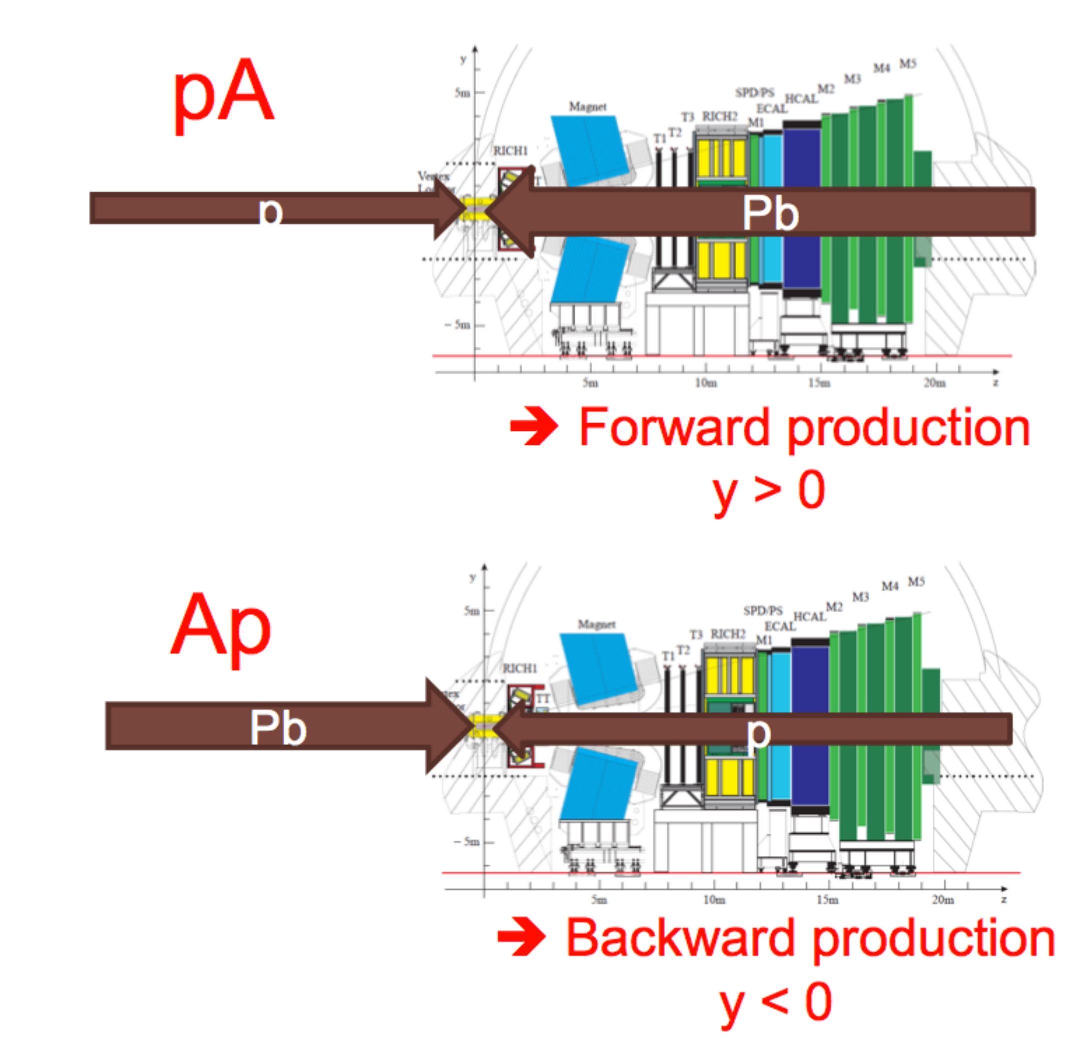
JINST 3 (2008) S08005



Acceptance of LHC Expts



Running configuration



$\sqrt{s_{NN}}$= 5 TeV

Different rapidity range (in CoM)

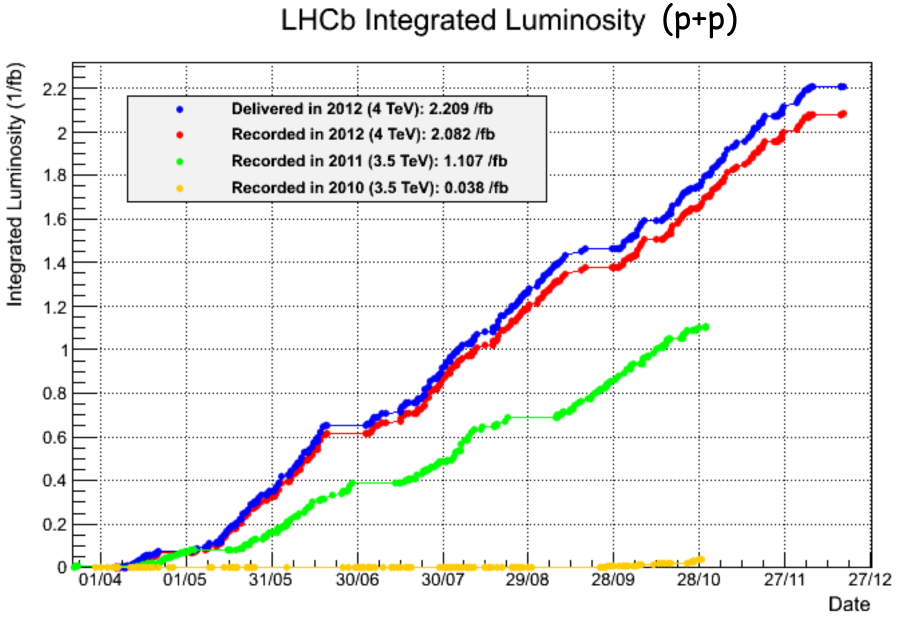
pp: 2.0 < η < 5.0

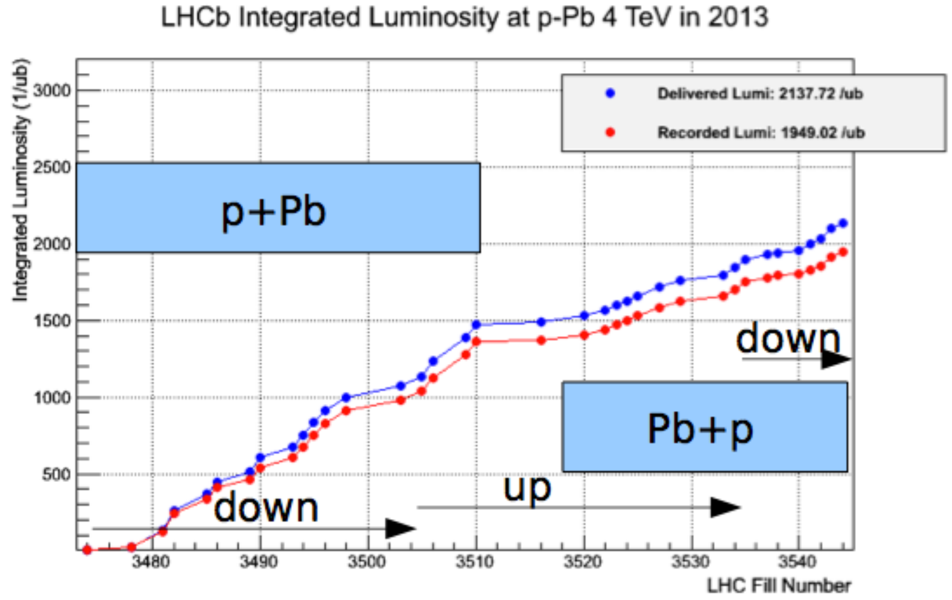
p-Pb: 1.5 < η < 4.5

Pb-p: -5.5 < η < -2.5

(rapidity wrt proton direction)

Luminosity





p+p: collected ~3.2 fb^{-1}

2012: ~2.1 fb^{-1} @ 8 TeV

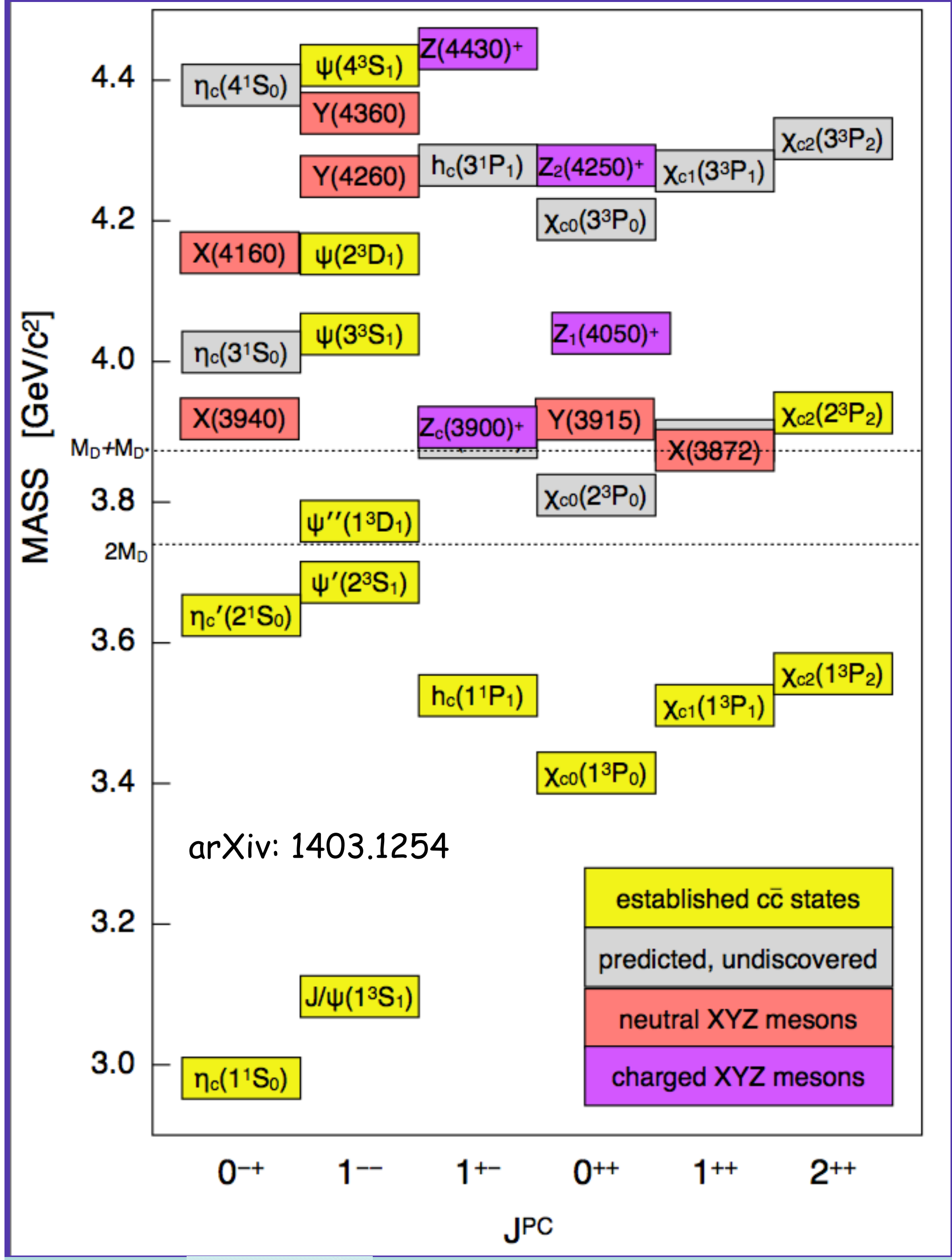
2011: ~1.1 fb^{-1} @ 7 TeV

Low instantaneous luminosity
$\mathcal{L} = 5.10^{-27} cm^{-2} s^{-1}$

p+Pb: $\mathcal{L}$ = 1.1 nb^{-1}

Pb+p: $\mathcal{L}$ = 0.5 nb^{-1}

Charmonium(-like) mesons



Questions:

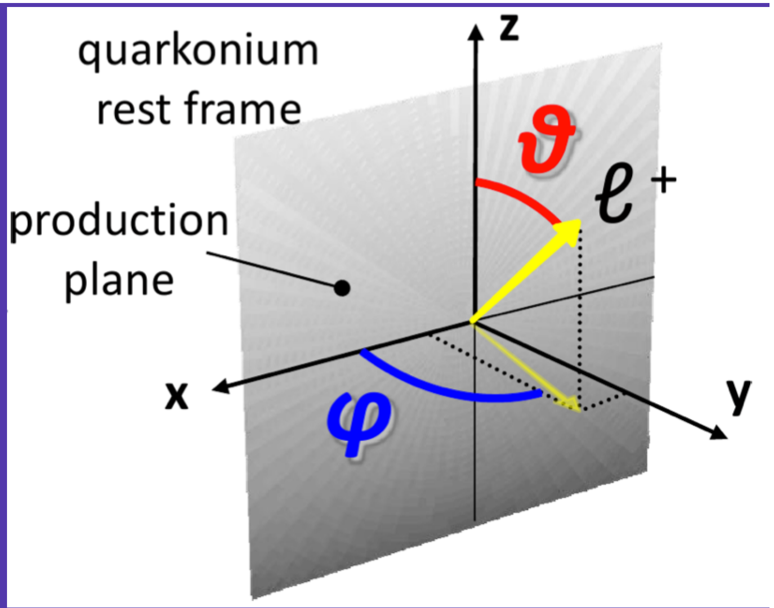
1. How do you reconcile the tension for charmonium production and polarisation measurements & theory ?
2. What are the charmonium production measurements: prompt ~(hard scatter); feed down (from higher states); from b-states ?
3. What are the exotic states ?

Polarisation Measurement

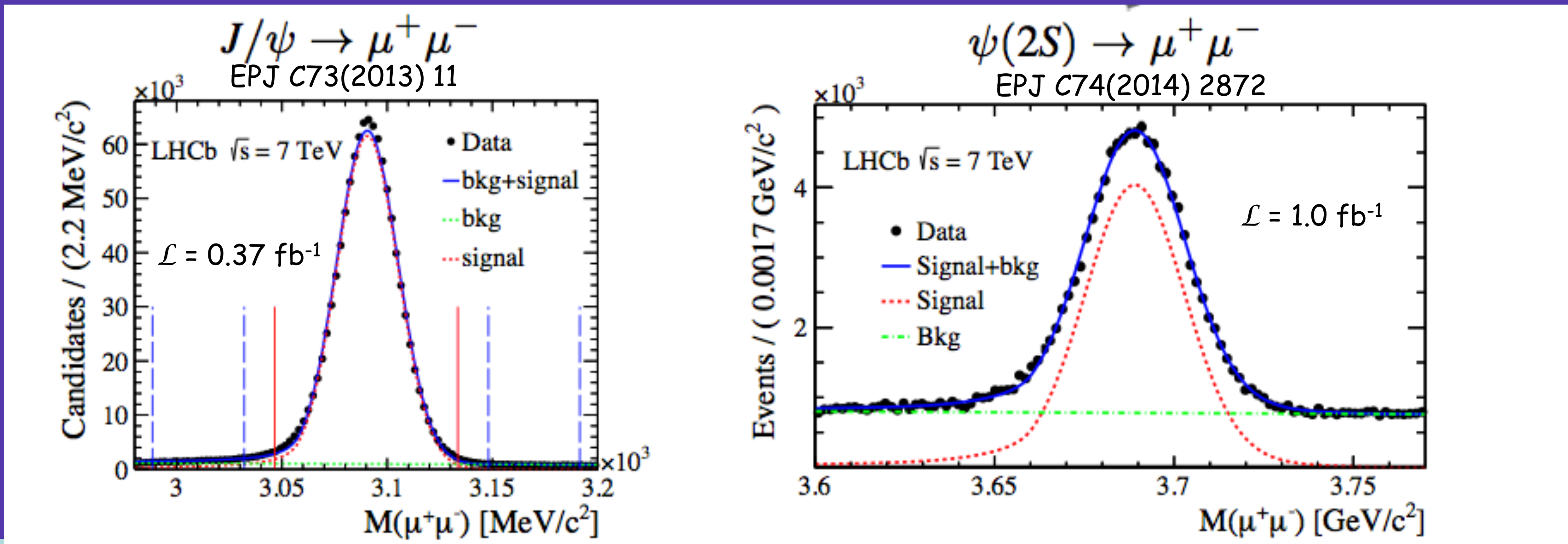
Polarisation

Fit angular decay of di-muon decay

Angular decay measured in Helicity frame

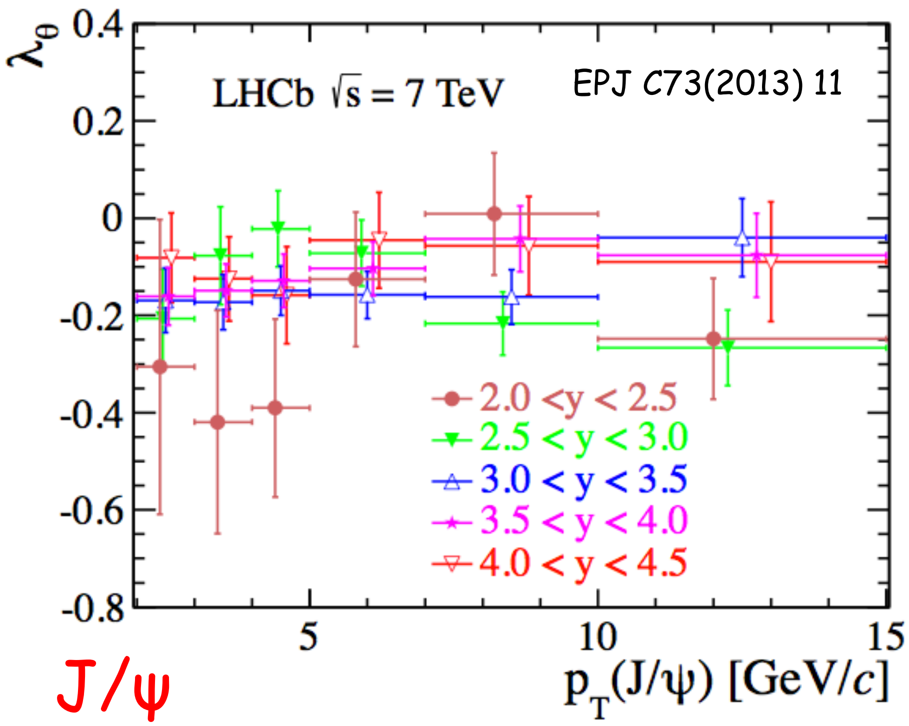


$$\frac{d^2N}{d\cos\theta d\phi} = 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\phi} \sin 2\theta \cos\phi + \lambda_\phi \sin^2\theta \cos 2\phi$$

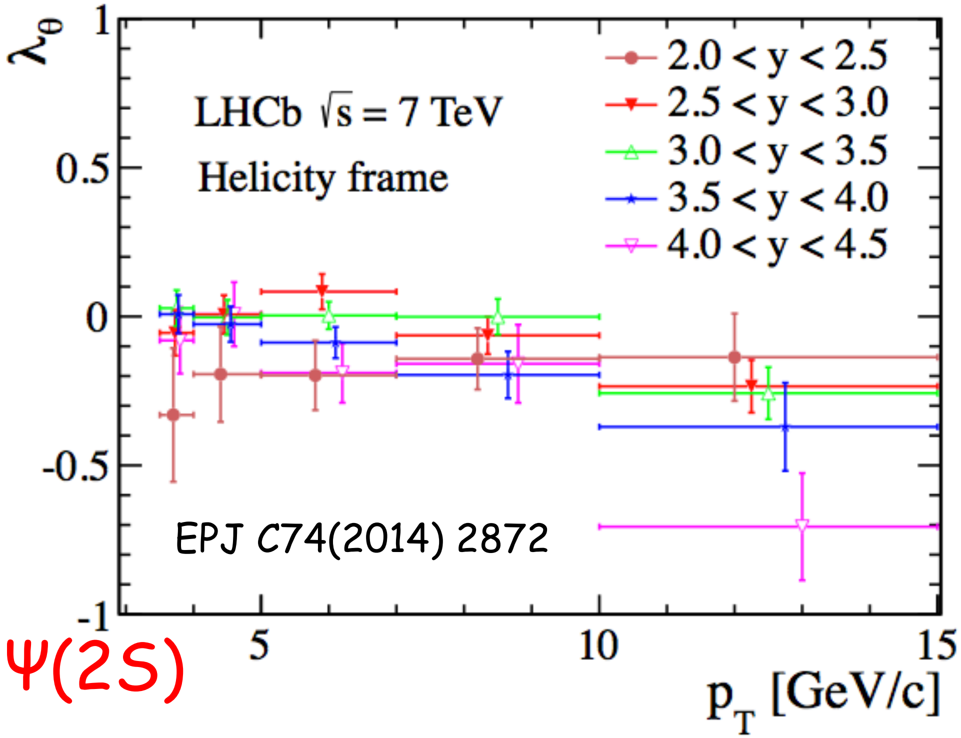


Polarisation

$$\frac{d^2N}{d\cos\theta d\phi} = 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\phi}\sin 2\theta\cos\phi + \lambda_\phi \sin^2\theta\cos 2\phi$$



J/ψ



Ψ(2S)

λ_ϕ , $\lambda_{\vartheta\phi}$ consistent with zero within uncertainties

Average λ_ϑ = -0.145±0.027

λ_ϕ , $\lambda_{\vartheta\phi}$ are small over measured range

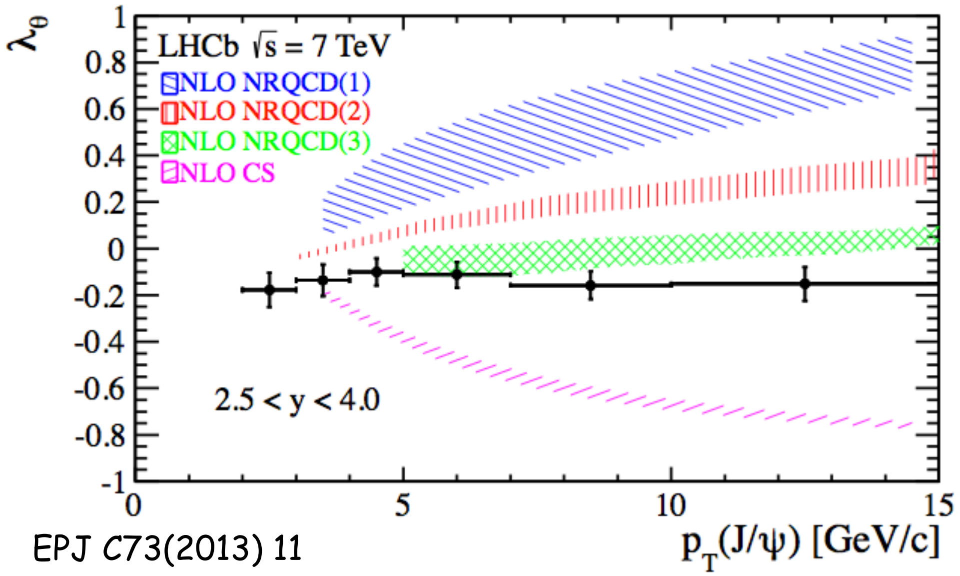
λ_ϑ has neither large transverse or longitudinal polarisation

$$\lambda_{\text{inv}} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi} < 0.0$$

Polarisation

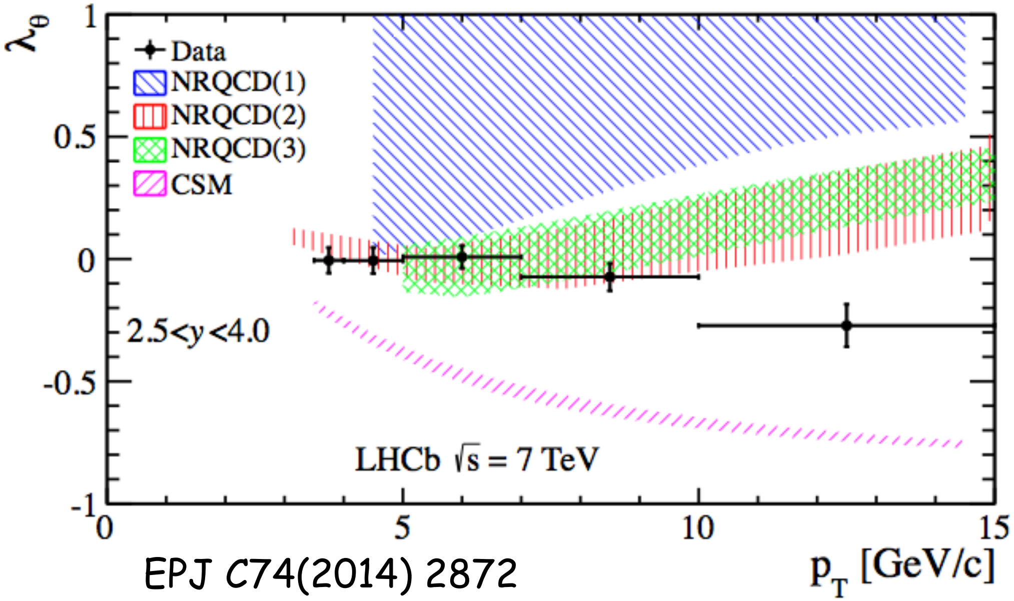
$$\frac{d^2N}{d\cos\theta d\phi} = 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\phi}\sin 2\theta\cos\phi + \lambda_\phi \sin^2\theta\cos 2\phi$$

$J/\psi \to \mu^+\mu^-$



EPJ C73(2013) 11

$\psi(2S) \to \mu^+\mu^-$



EPJ C74(2014) 2872

NLO CS & NLO NRQCD(1) – PRL 108 (2012) 172002

NLO NRQCD(2) – PRL 110 (2013) 042002

NLO NRQCD(3) – PRL 108 (2012) 242004

- CSM disfavoured by data
- NLO NRQCD(3) best description
  - Though poor description at high p_T for $\psi(2S)$

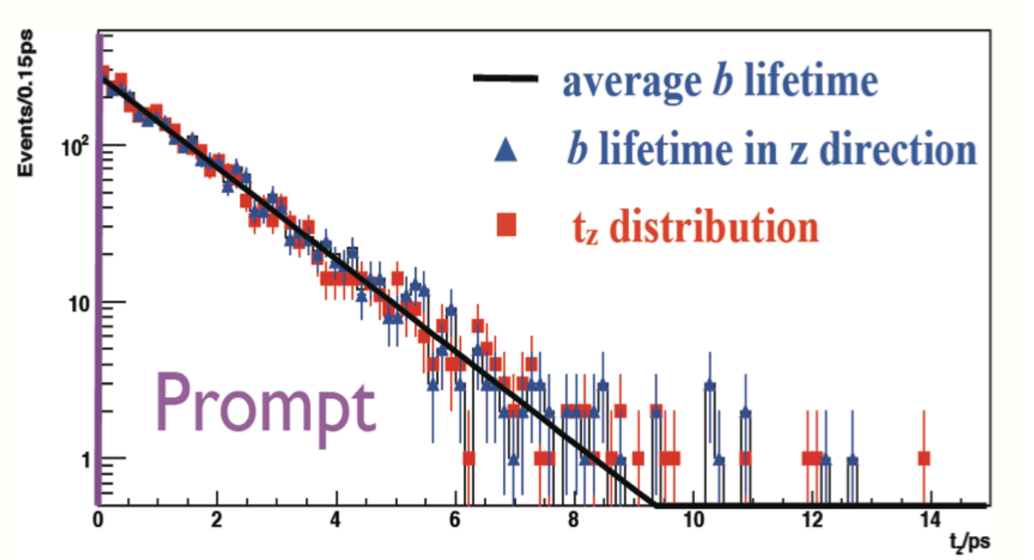
Heavy Ion Charmonium Production

Analysis Strategy

- Reconstruct J/ψ in p-Pb Pb-p data (dimuon decay)
- Separate prompt charmonium from secondaries
- Total prompt x-section
- Nuclear modification effect
- Determine FB asymmetry

LHCb-TALK-2013-286

$$t_z = \frac{(z_{J/\psi} - z_{PV})M_{J/\psi}}{p_z}$$

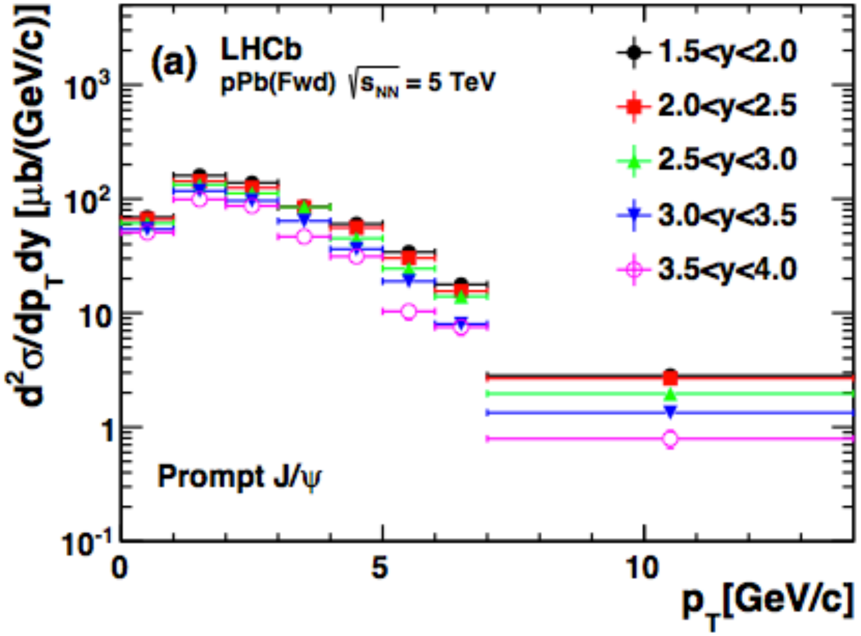


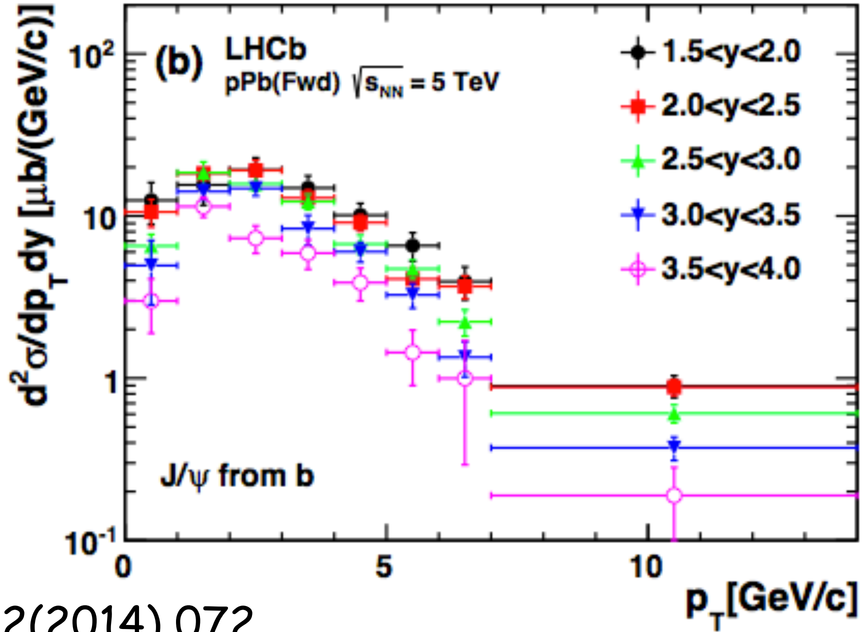
generator level distribution of t_z

Good approx. of average b-lifetime

Well described by exponential distbn

J/ψ results





JHEP 02(2014) 072

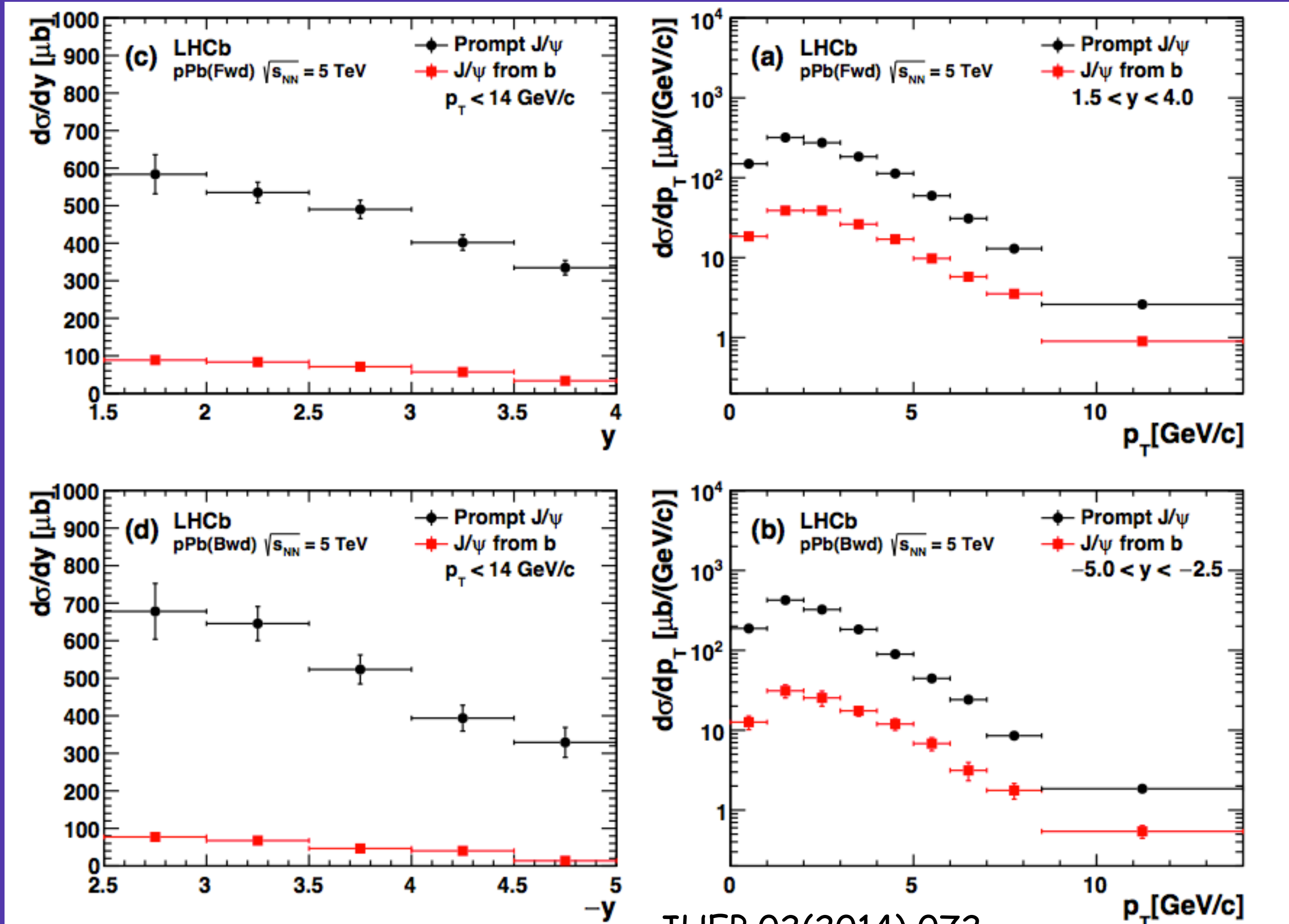
$$\sigma_{pA} = 1168 \pm 15(\text{stat}) \pm 60(\text{sys})\ \mu b$$ prompt

$$\sigma_{pA} = 166 \pm 4.1(\text{stat}) \pm 9.2(\text{sys})\ \mu b$$ from b's

$$\sigma_{Ap} = 1293 \pm 49.8(\text{stat}) \pm 82(\text{sys})\ \mu b$$ prompt

$$\sigma_{Ap} = 118 \pm 6.8(\text{stat}) \pm 12.2(\text{sys})\ \mu b$$ from b's

J/ψ results

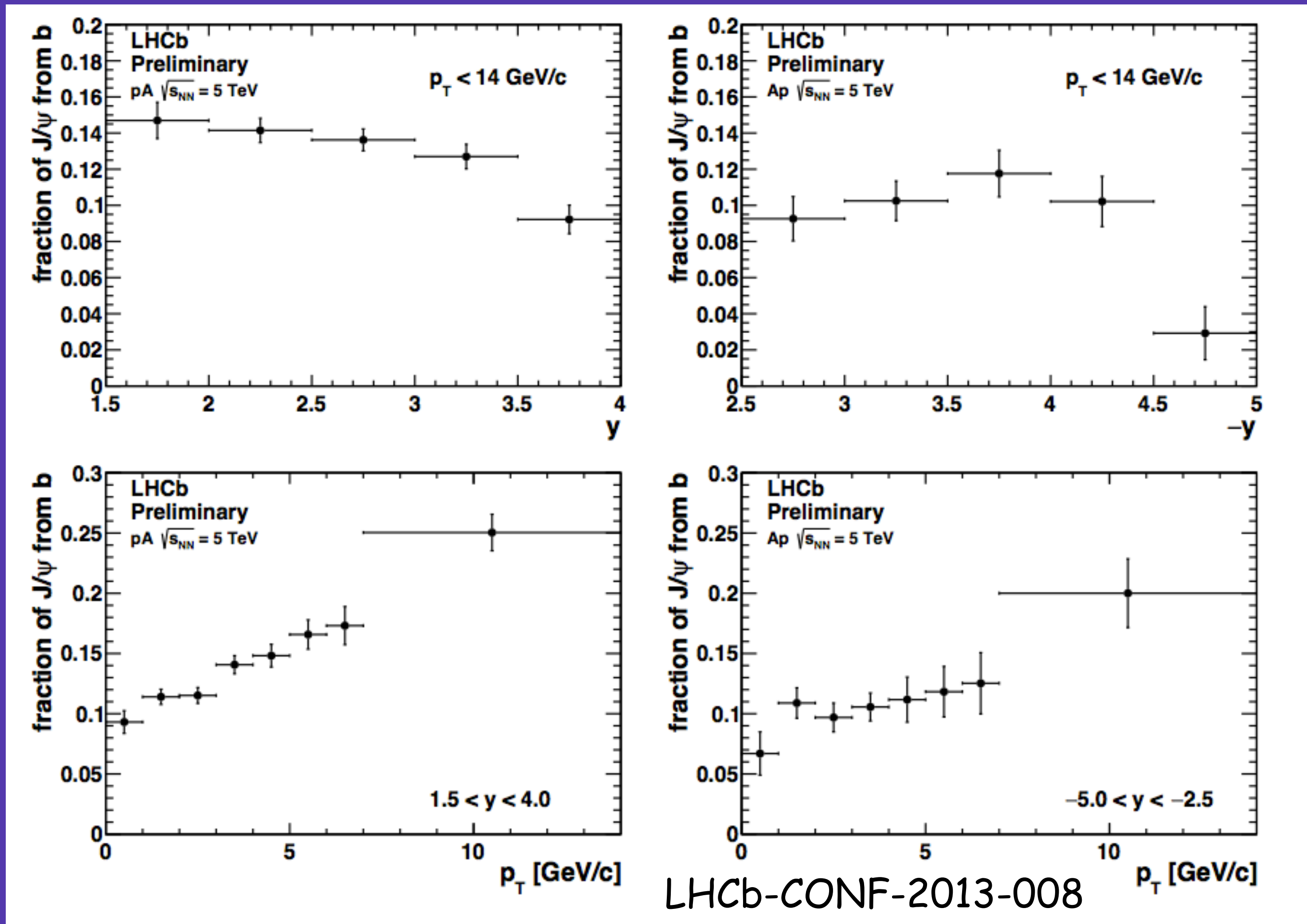


JHEP 02(2014) 072

Fraction of J/ψ from b increases with p_T - as expected

Larger fraction of J/ψ from b in pA than Ap – as predicted

J/ψ results



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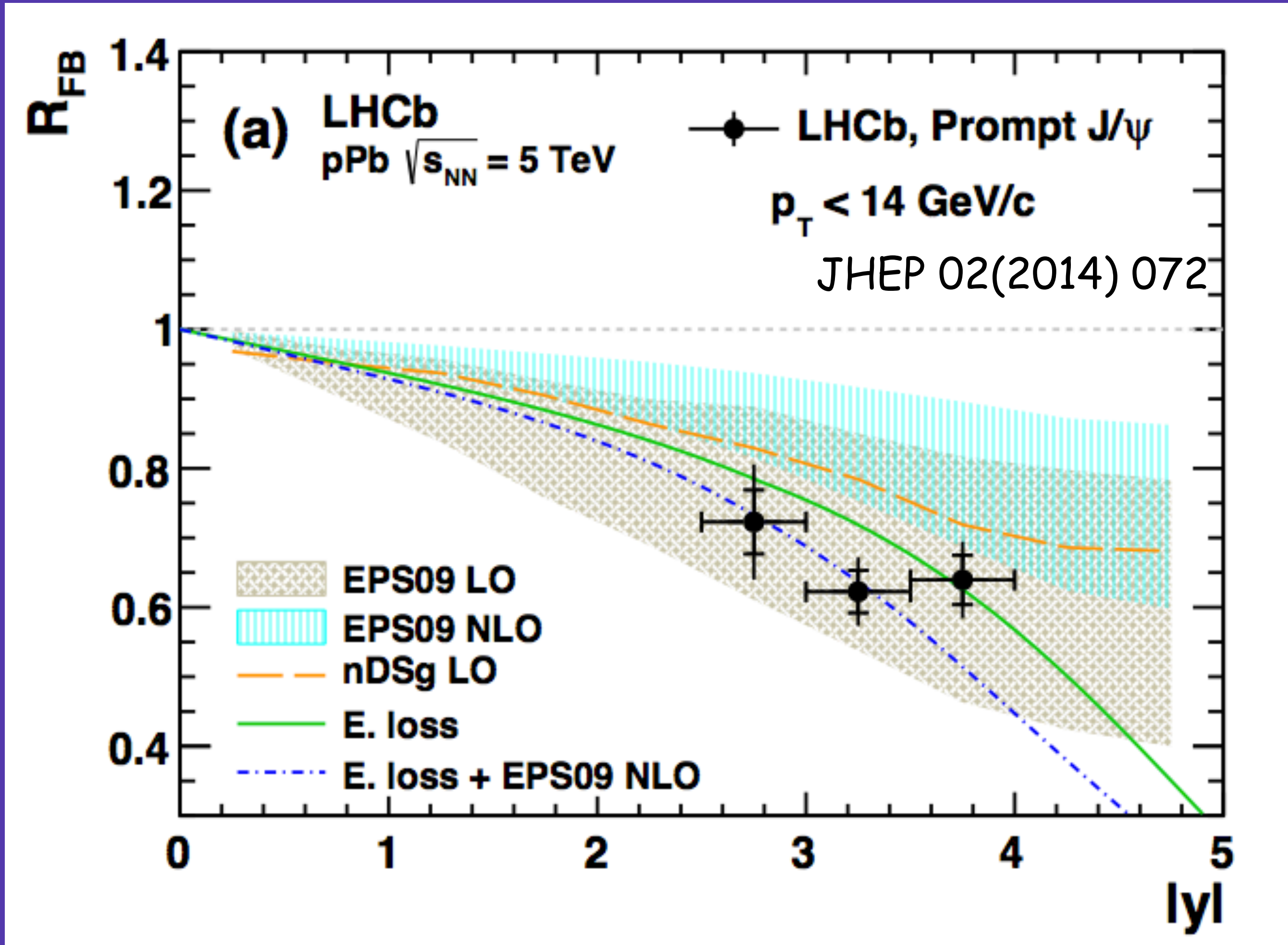
J/ψ results



$$R_{FB} = \frac{R_{pA}(y)}{R_{Ap}(-y)}$$

Theory:

Phys.Rev. C88 (2013) 047901

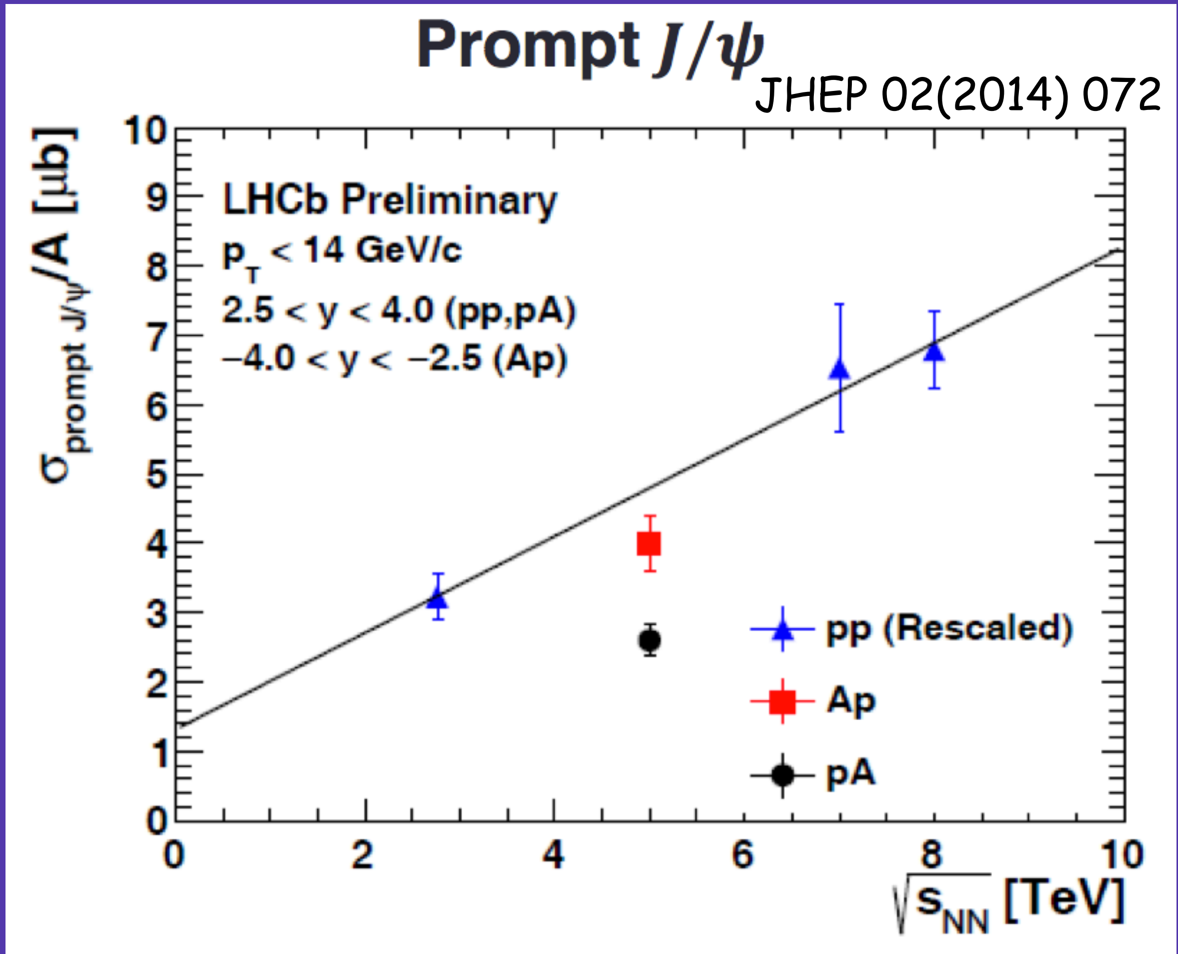
Int.J.Mod.Phys. E22 (2013) 13300007

JHEP 03 (2013) 122

Clear forward-backward asymmetry

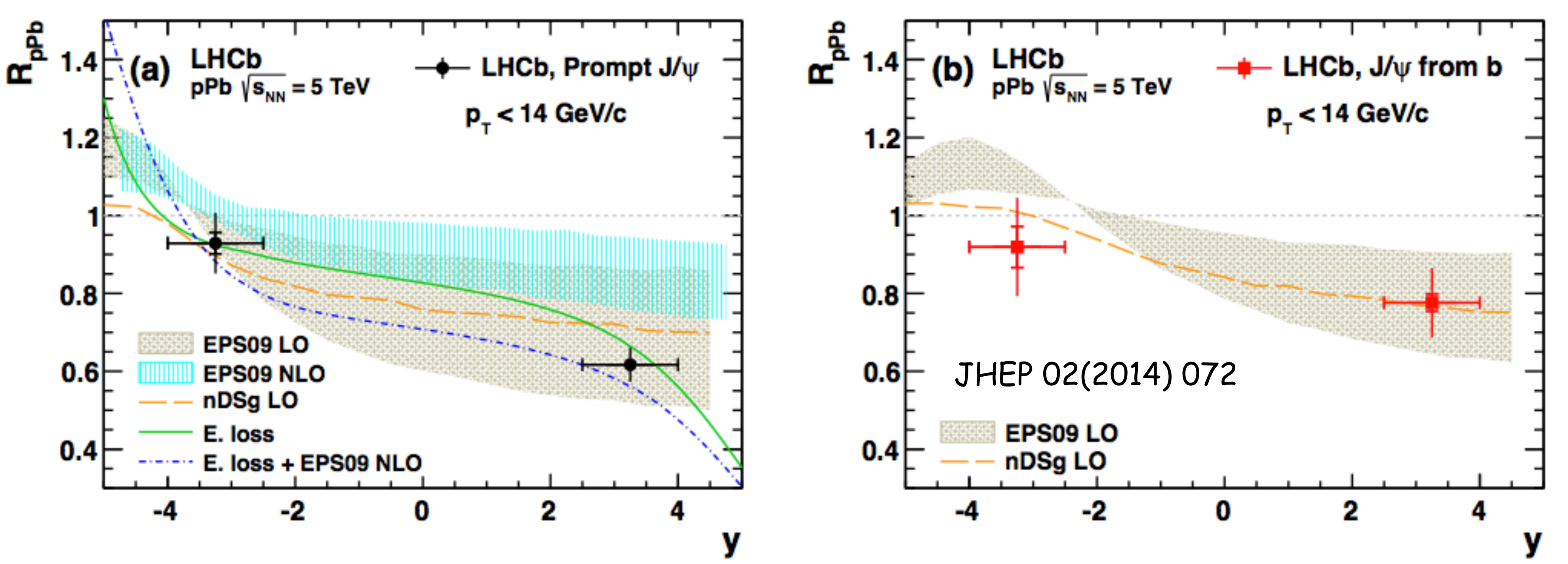
Currently unable to distinguish nuclear effects with or w/o saturation

J/ψ results



Clear suppression in pA, slight suppression in Ap

J/ψ results



Theory confirmed by data

More data needed to separate saturation from energy loss

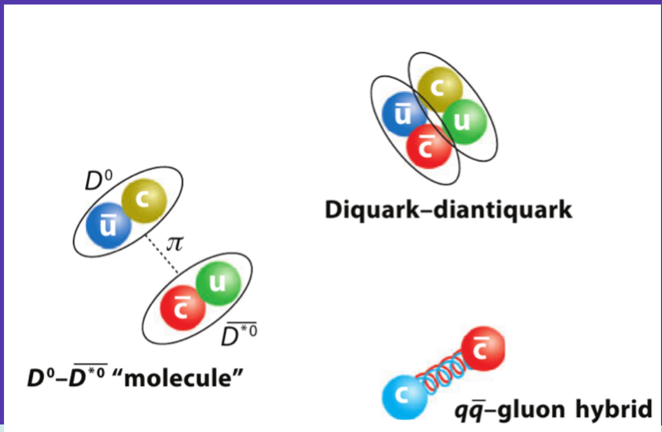
$$R_{pA}(y,\sqrt{s}) = \frac{1}{A}\frac{\frac{d\sigma_{pA}(y,\sqrt{s})}{dy}}{\frac{d\sigma_{pp}(y,\sqrt{s})}{dy}}$$

Theory: Phys.Rev. C88 (2013) 047901
Int.J.Mod.Phys. E22 (2013) 13300007 JHEP 03 (2013) 122

Exotic Mesons

XYZ States

- Many new states observed
  - Tevatron, B-factories, charm factories
  - Different production mechanisms
- Masses & properties not really consistent with charmonium picture

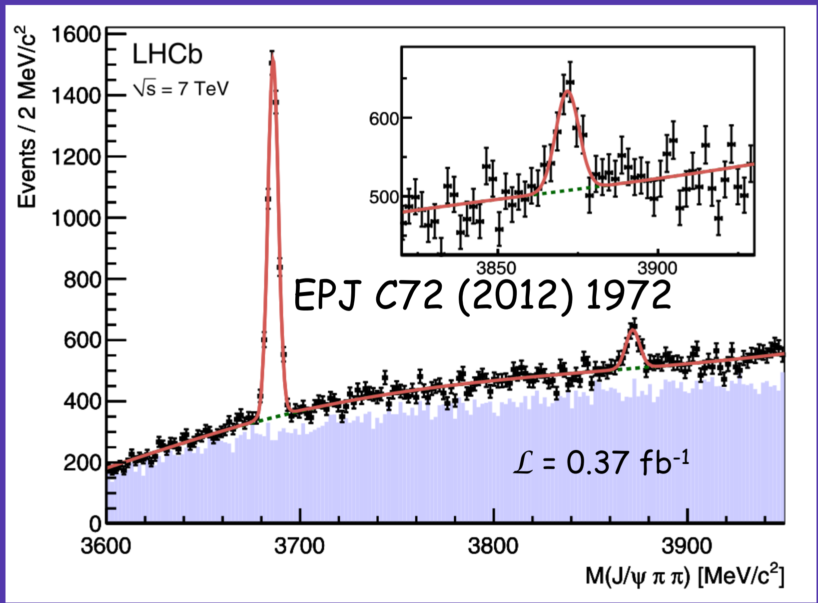


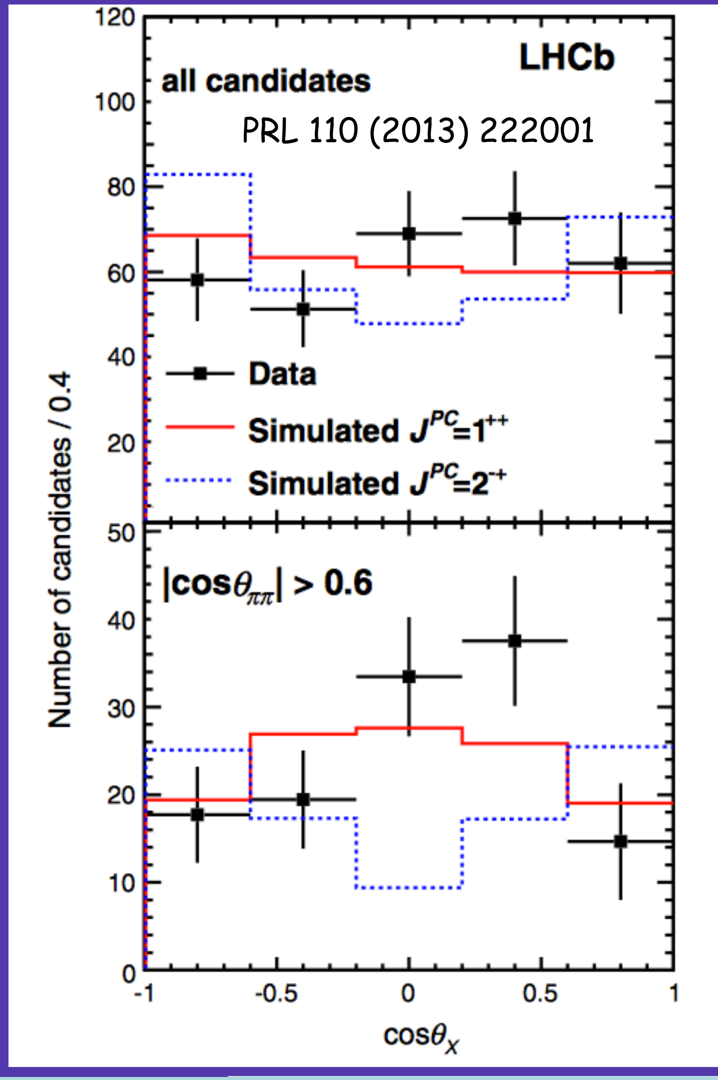
State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$
				$B \to K(\omega J/\psi)$
				$B \to K(D^{*0}\bar{D}^0)$
				$B \to K(\gamma J/\psi)$
				$B \to K(\gamma\psi(2S))$
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$
				$e^+e^- \to e^+e^-(\omega J/\psi)$
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
				$e^+e^- \to J/\psi\ (...)$
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$
$Y(4008)$	$4008^{+121}_{-\ 49}$	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4140)$	4143.4 ± 3.0	$15^{+11}_{-\ 7}$	$?^{?+}$	$B \to K(\phi J/\psi)$
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
$Z_2(4250)^+$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K(\pi^+\chi_{c1}(1P))$
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^+\pi^- J/\psi)$
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$
$Z(4430)^+$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$B \to K(\pi^+\psi(2S))$
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^- \Upsilon(nS))$

X(3872) state

- First observed by Belle (PRL 91 (2003) 262001)

$$\mathbf{B}^+ \to X(3872)K^+$$
$$X(3872) \to J/\psi\pi^+\pi^-$$
$$J/\psi \to \mu^+\mu^-$$

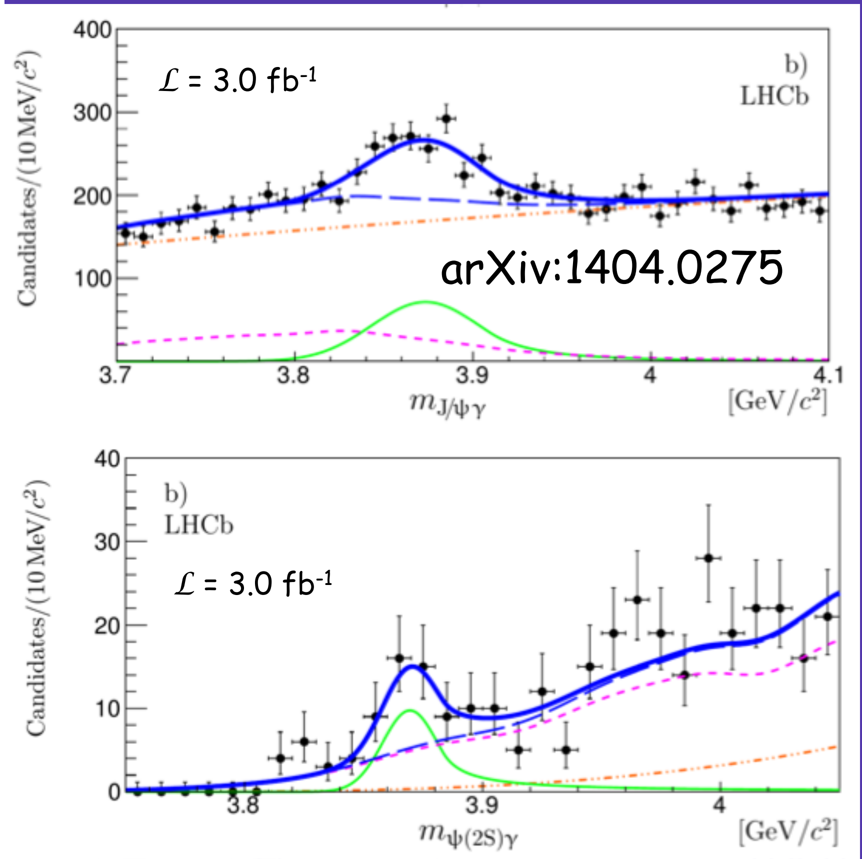


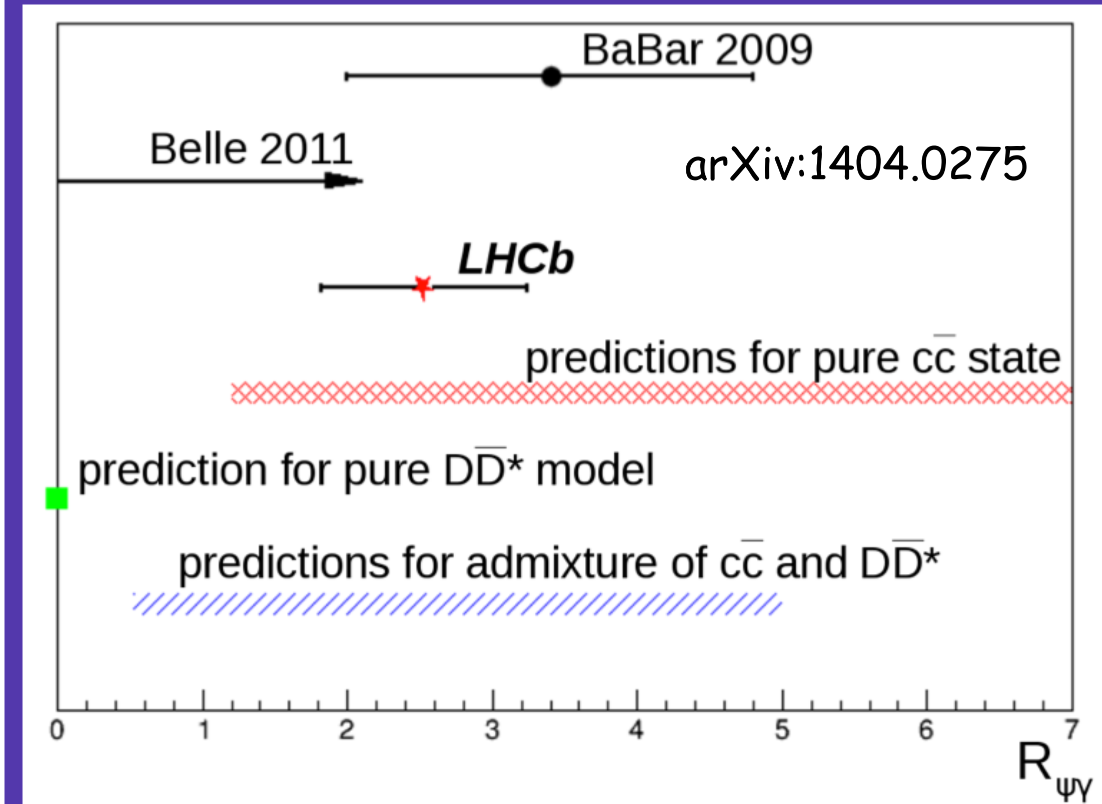


$$\sigma(\mathbf{pp} \to \mathbf{X(3872)} + \text{anything})$$
$$\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$$
$$= 5.4 \pm 1.3(\text{stat}) \pm 0.8(\text{syst})\ \text{nb}$$

$X(3872) \to \psi(2S)\gamma$

$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$





Disfavours $D^{\star 0}\bar{D}^0$ molecule hypothesis

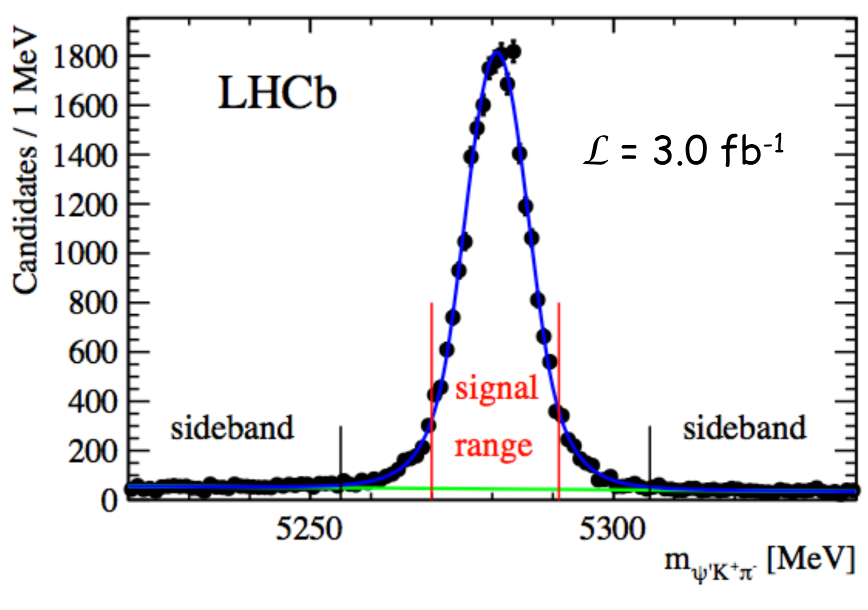
$Z(4430)^- \to \psi(2S)\pi^-$

PRL 112 (2014) 222002

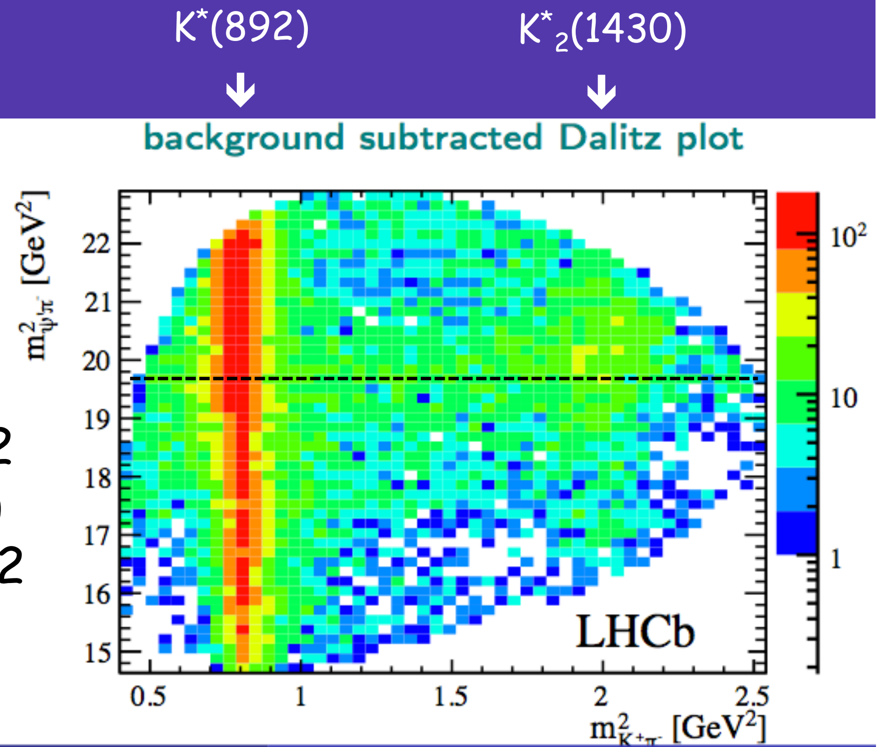
- Charged charmonium state observed by Belle (PRL 100 (2008) 142001)
  - Not confirmed (or ruled out) by BaBar
- LHCb sample > 25k $B^0 \to \psi(2S)\pi^- K^+$ candidates – factor 10 more than Belle/BaBar
- LHCb analysis
  - model dependent (4D amplitude fit c.f. Belle)
  - model independent (Legendre polynomial moments c.f. BaBar)
- Background extracted from sidebands
  - Estimated 4% of combinatorial bkgnd in signal region
- 4D efficiency calculated from full detector simulation

$Z(4430)^- \to \psi(2S)\pi^-$

- LHCb sample > 25k $B^0 \to \psi(2S)\pi^- K^+$ candidates – factor 10 than Belle/BaBar
- LHCb 4D amplitude fit analysis



PRL 112 (2014) 222002



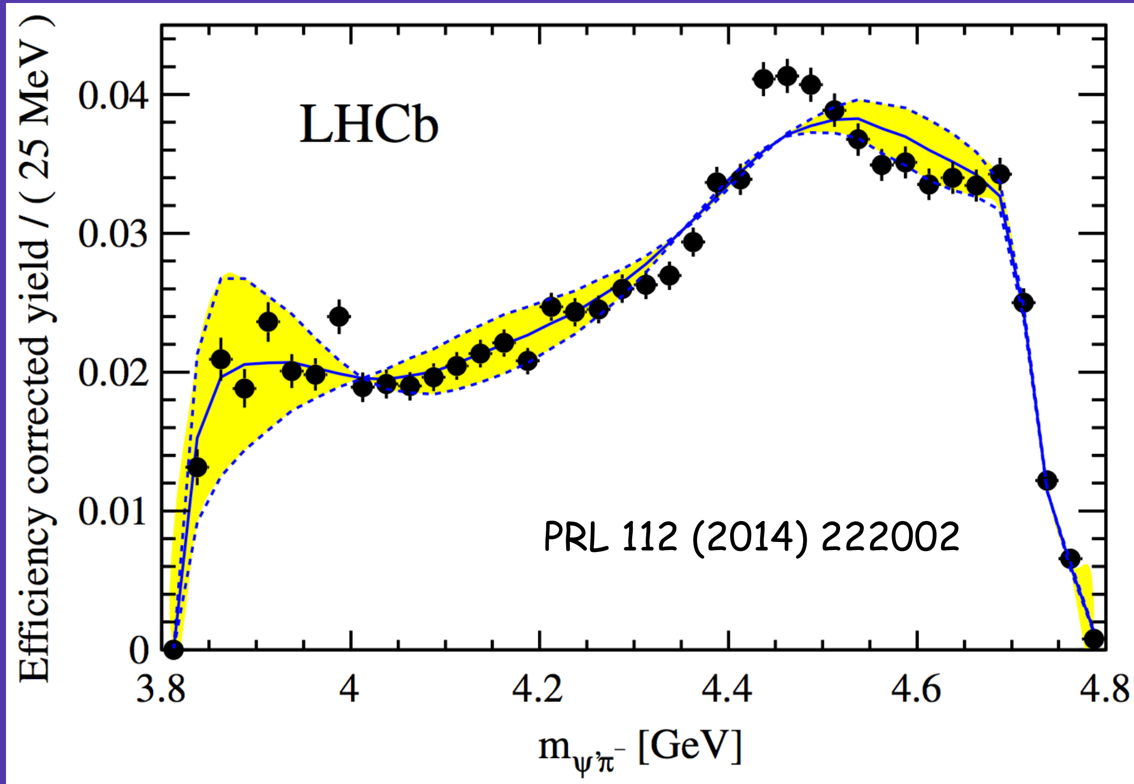
Model Independent Approach

(PRD 79 (2009) 112001)

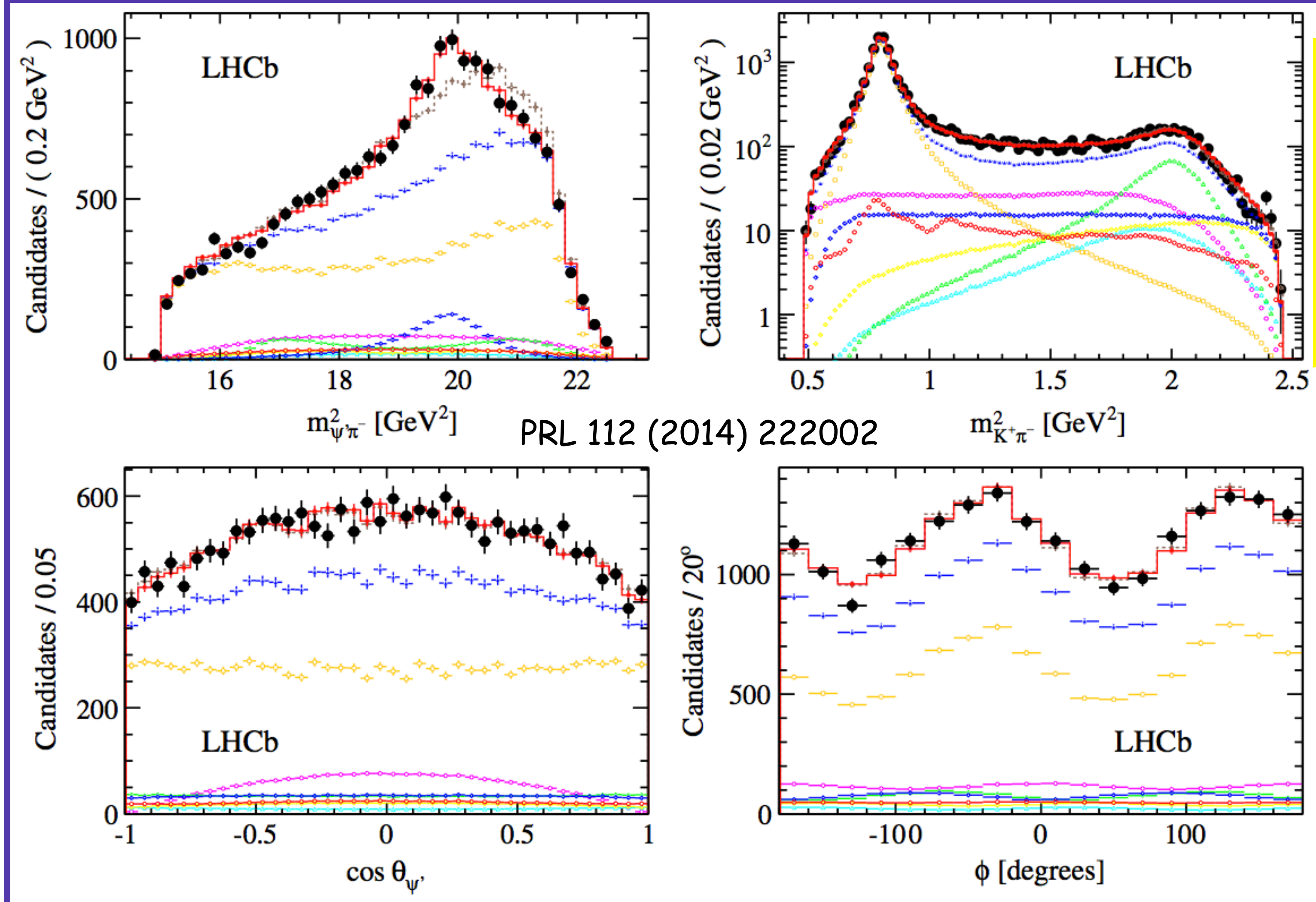
Analysis not constrained to K* combinations only restricted by maximal spin

Check if $m_{\psi'\pi}$ distribution can be explained in terms of structures caused by ang. mom. conservation

Approach doesn't describe the data



4D Amplitude Fit

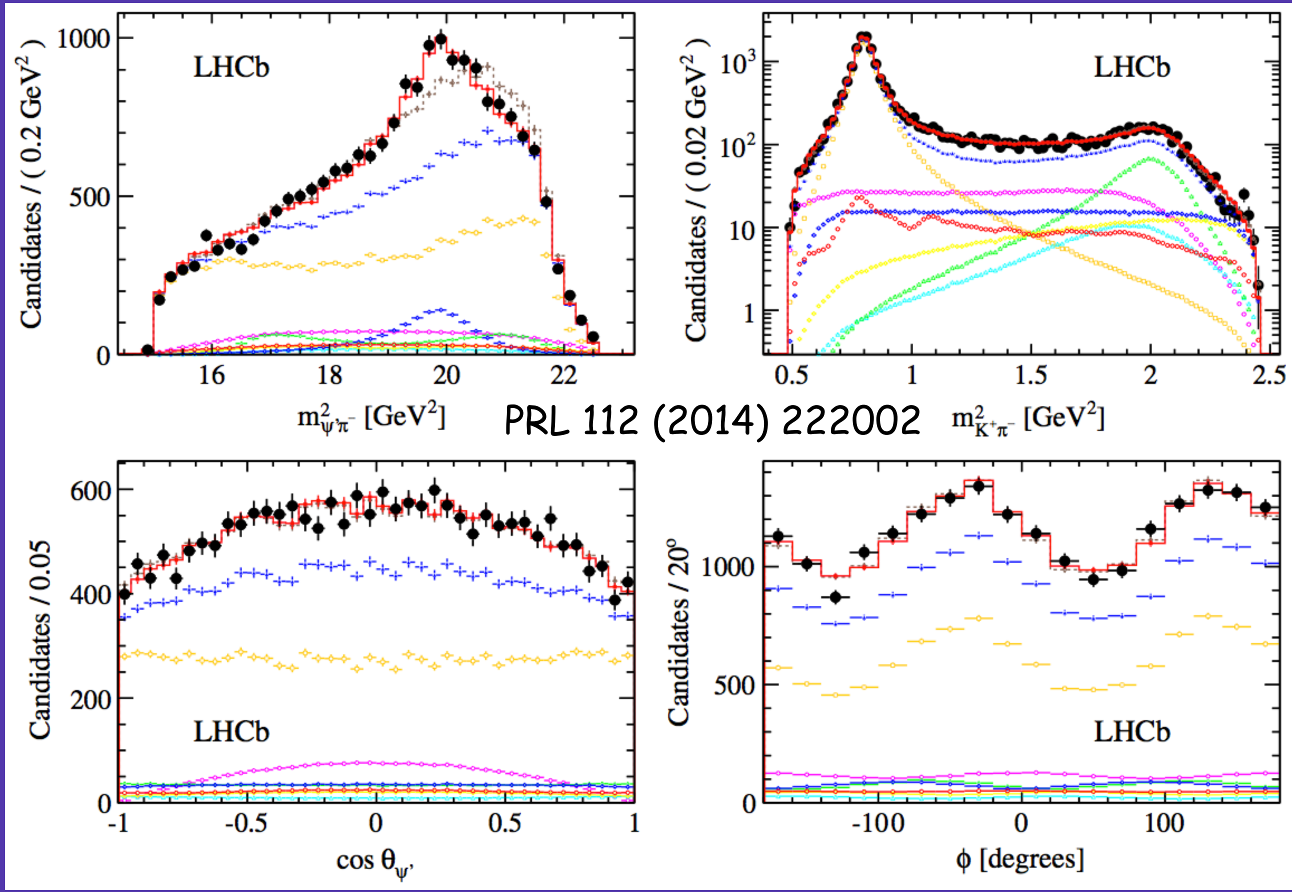


--- total fit with Z

--- total fit w/o Z

Fits need to include $Z(4330)^-$ component (with $J^P=1^+$)

4D Amplitude Fit



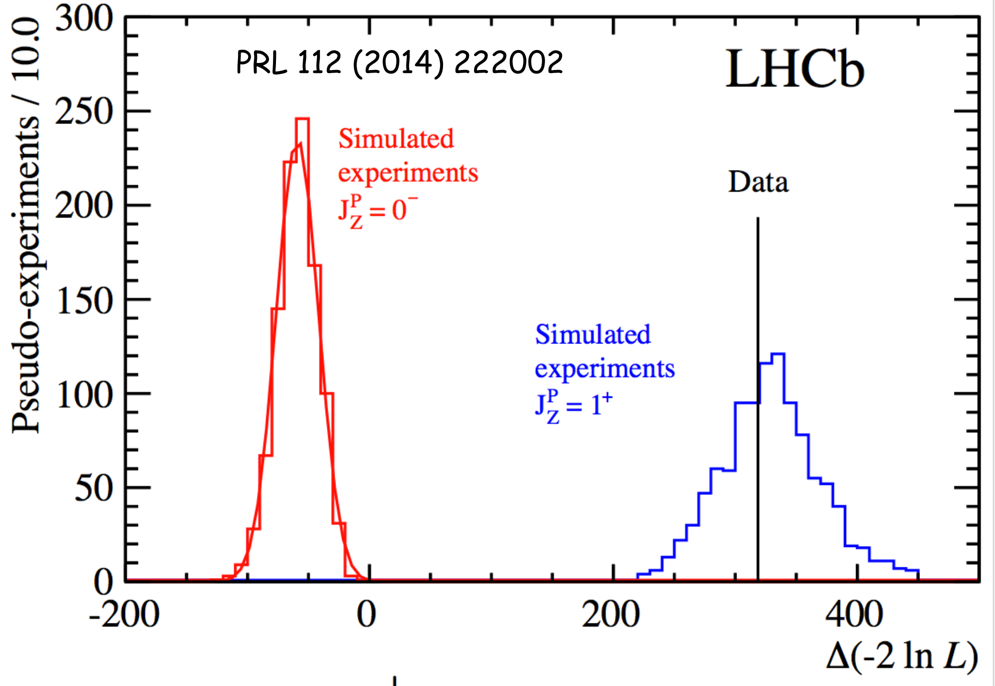
PRL 112 (2014) 222002

$$M_{Z(4330)^-} = 4475 \pm 7^{+15}_{-25}\ \mathrm{MeV/c^2}$$

$$\Gamma_{Z(4330)^-} = 172 \pm 13^{+37}_{-34}\ \mathrm{MeV/c^2}$$

$$f_{Z(4330)^-} = (5.9 \pm 0.9^{+1.5}_{-3.3})\%$$

Properties of Z(4430)$^-$

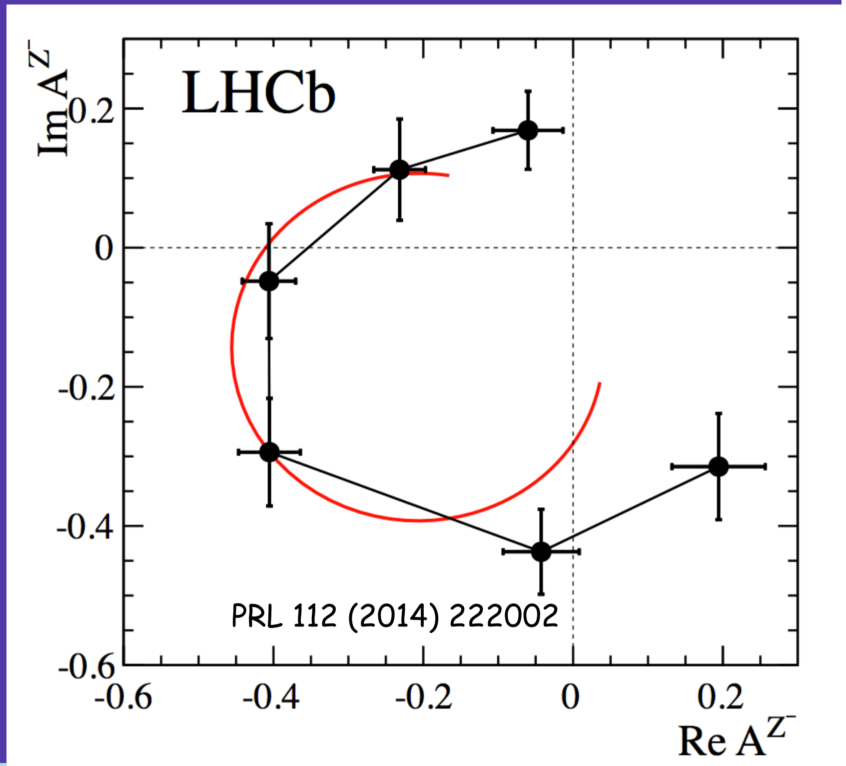


Clear preference for $J^P = 1^+$

Other J^P assignments ruled out

Replace in amplitude fit Breit-Wigner for Z (with circular trajectory in Argand plane) with 6 indep complex numbers

Resultant fit consistent with expected behaviour in Argand diagram of a resonance



Summary

- LHCb has some key results in charmonium production
  - Polarisation measuerments
  - FB asymmetry, nuclear modification factors in pA
- LHCb exciting results for exotic meson production
  - Clear evidence for $X(3872) \to \psi(2S)\gamma$
  - Ratio of X(3872) decays with γ disfavours $D^{\star 0}\bar{D}^0$ molecule
  - Confirmed existence of Z(4430) with $J^P=1^+$