Quarkonia and Exotics at LHCb

Philippe Ghez, LAPP
on behalf of the LHCb collaboration
BEACH 2014, Birmingham

the return of Quarkonia*

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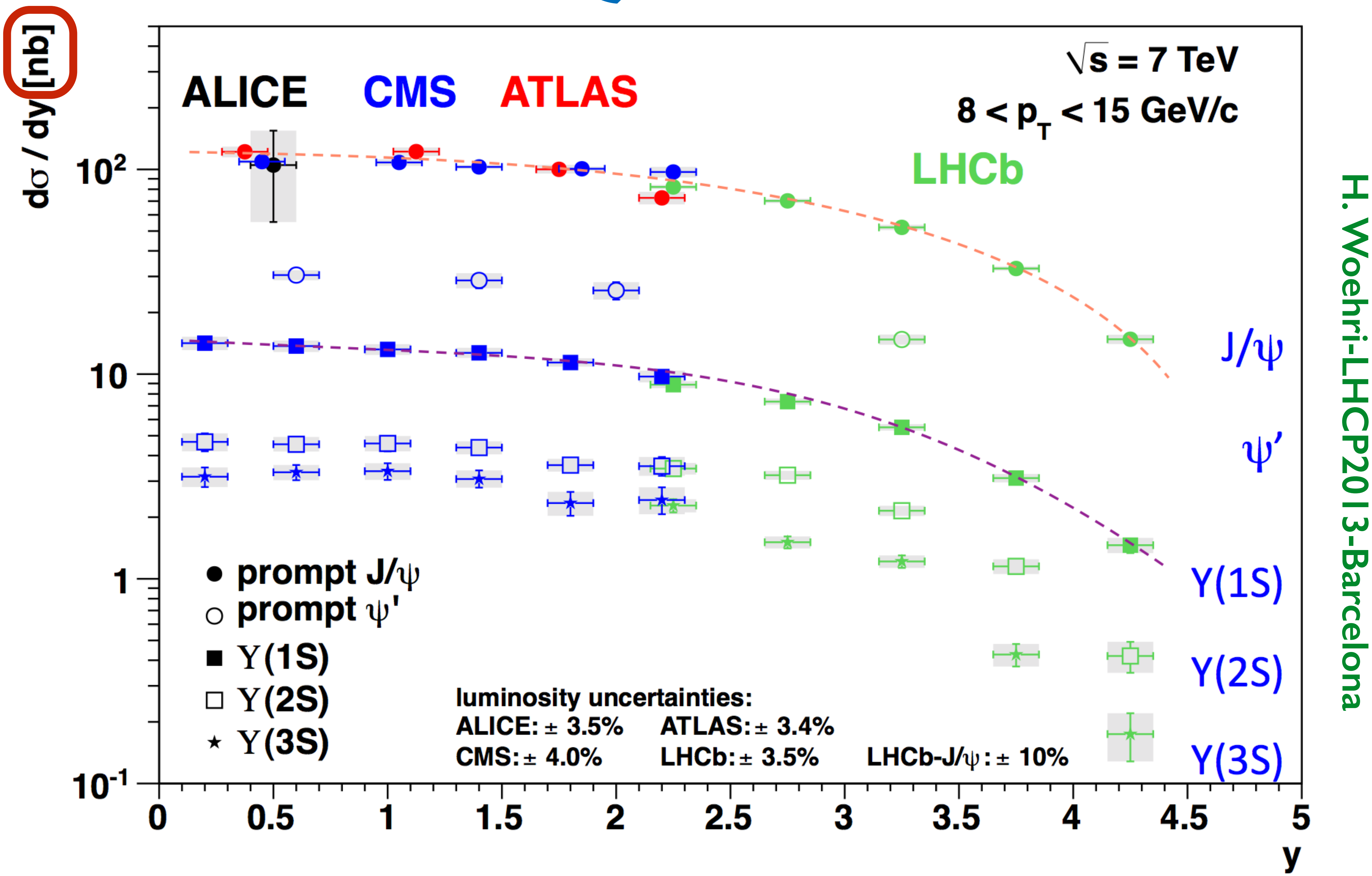

* CERN Courier July 2013

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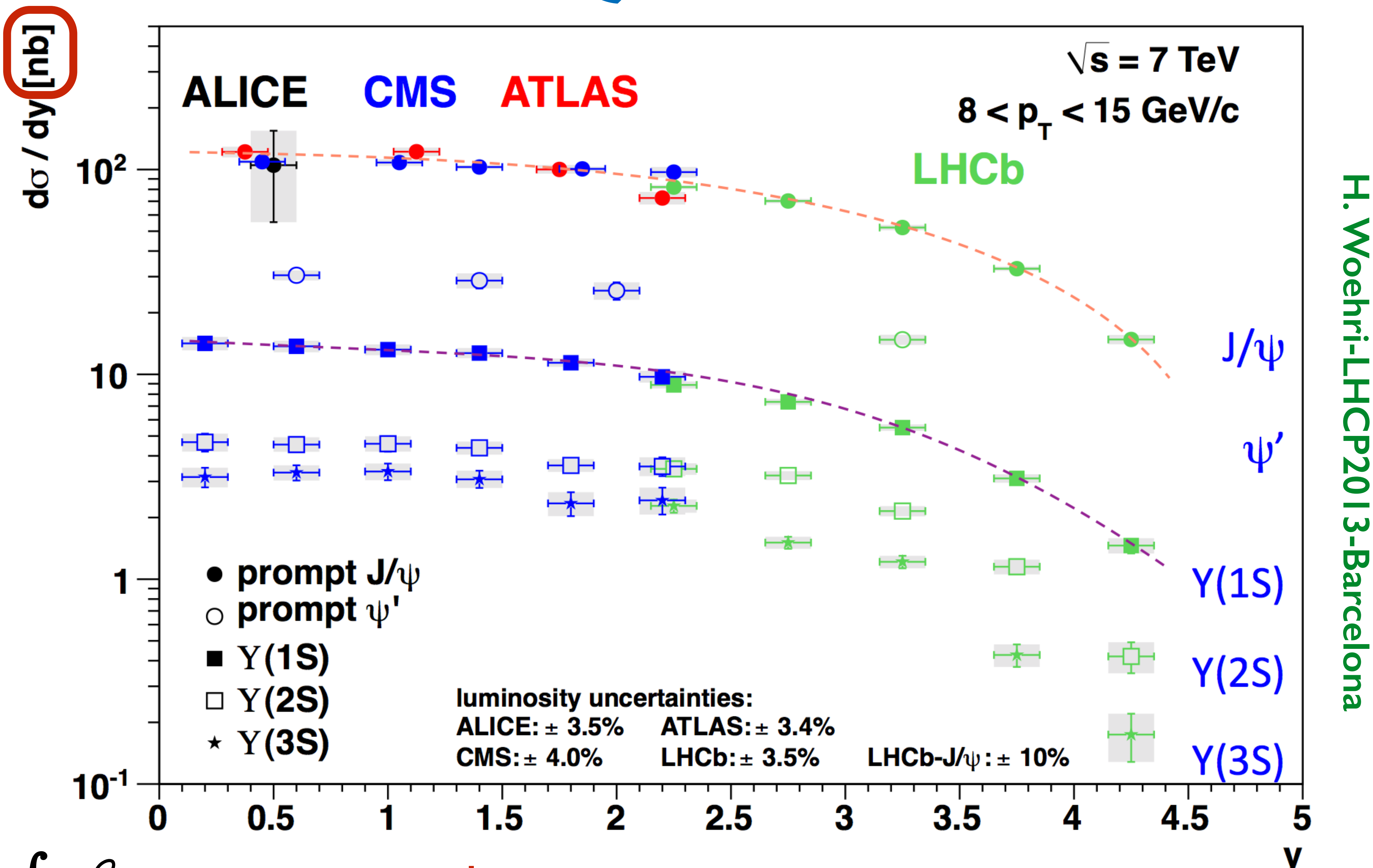
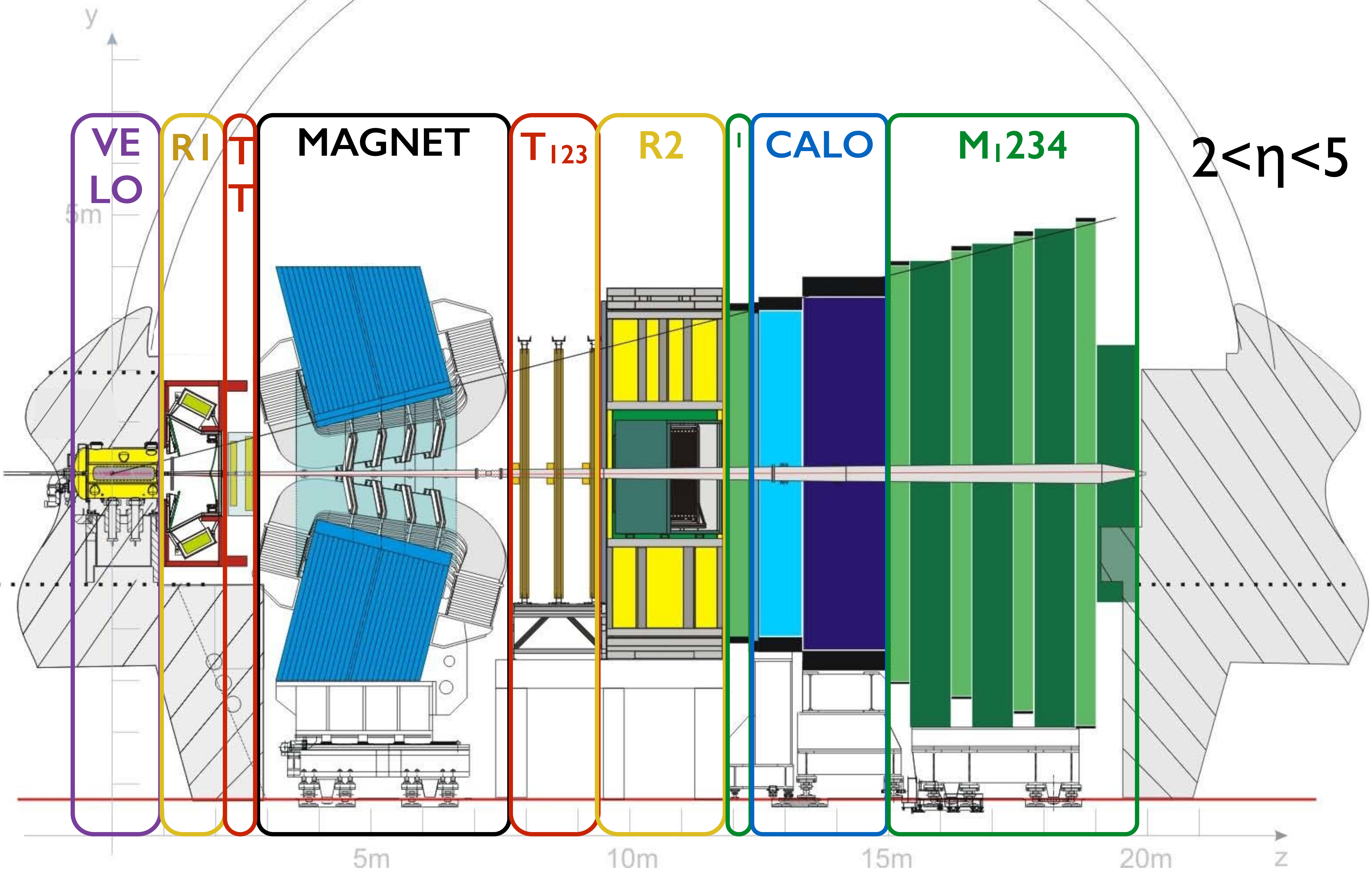


$\int \mathscr{L}$(LHCb) ~ **3 fb^{-1}** (~ 25 fb^{-1} for ATLAS and CMS)

⇒ the LHC is a **Quarkonia Factory !**

LHCb : a Quarkonia Detector/1



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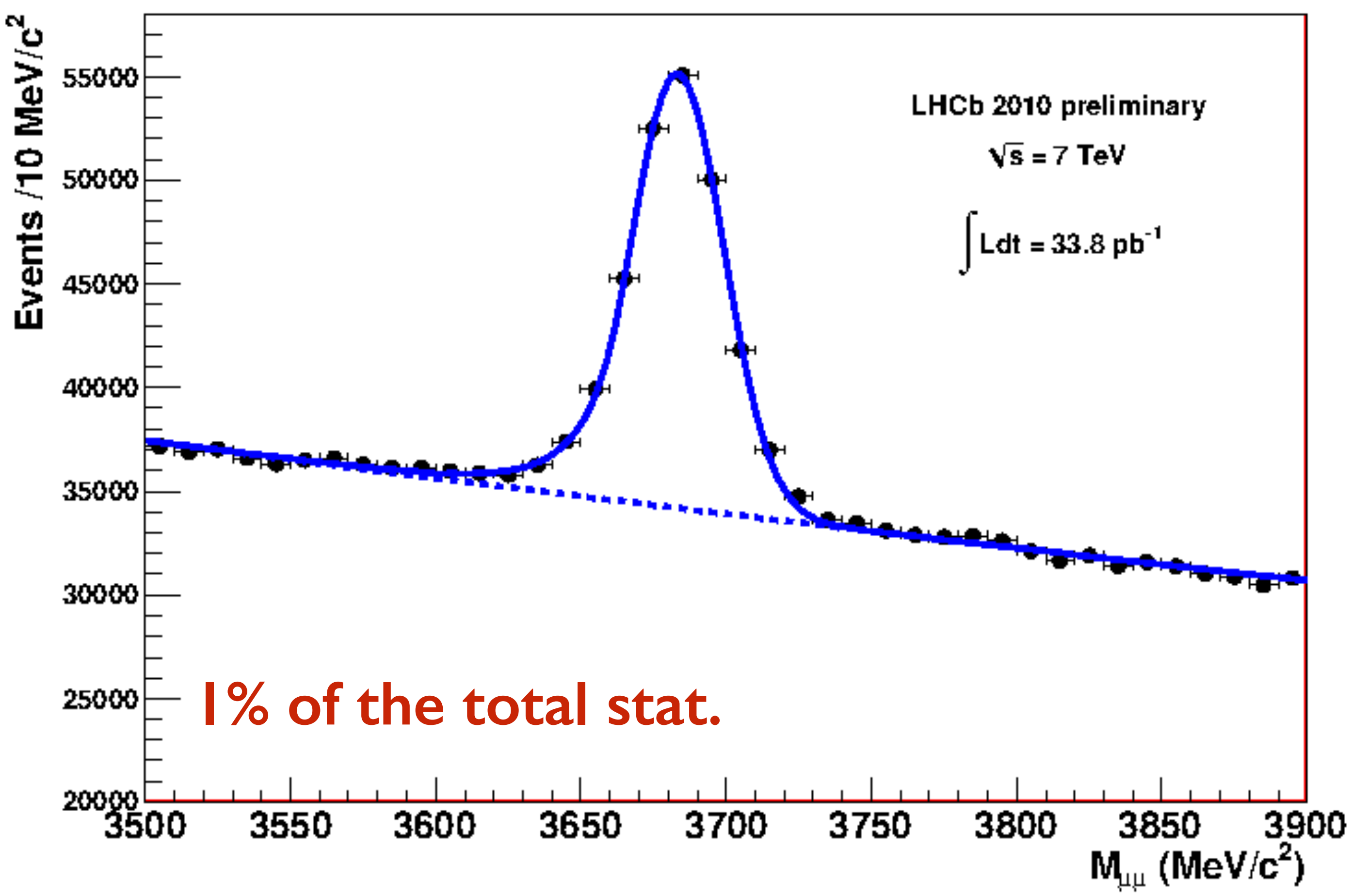
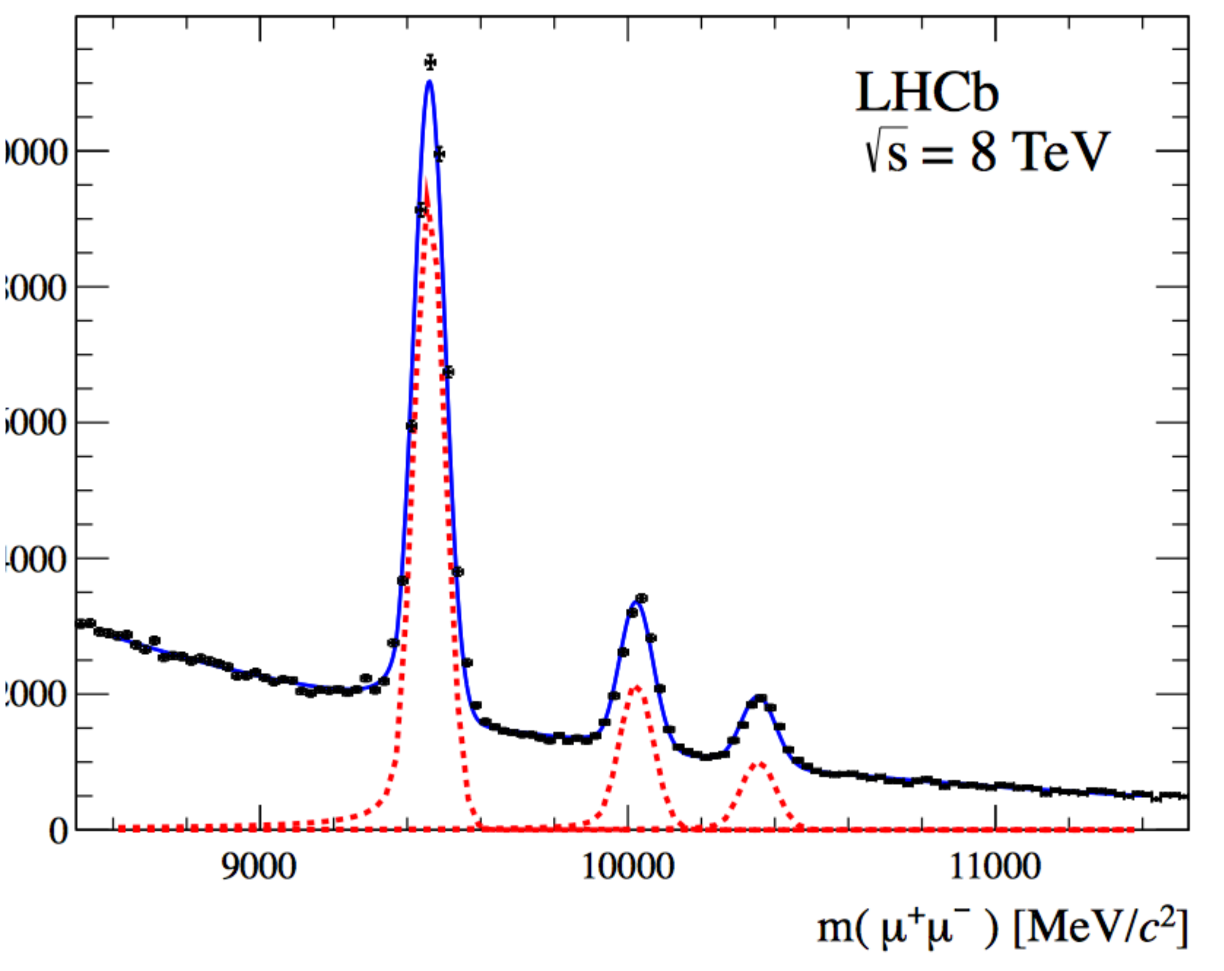
LHCb : a Quarkonia Detector/2

EPJ C72(2012)2100



JHEP 06(2013)064



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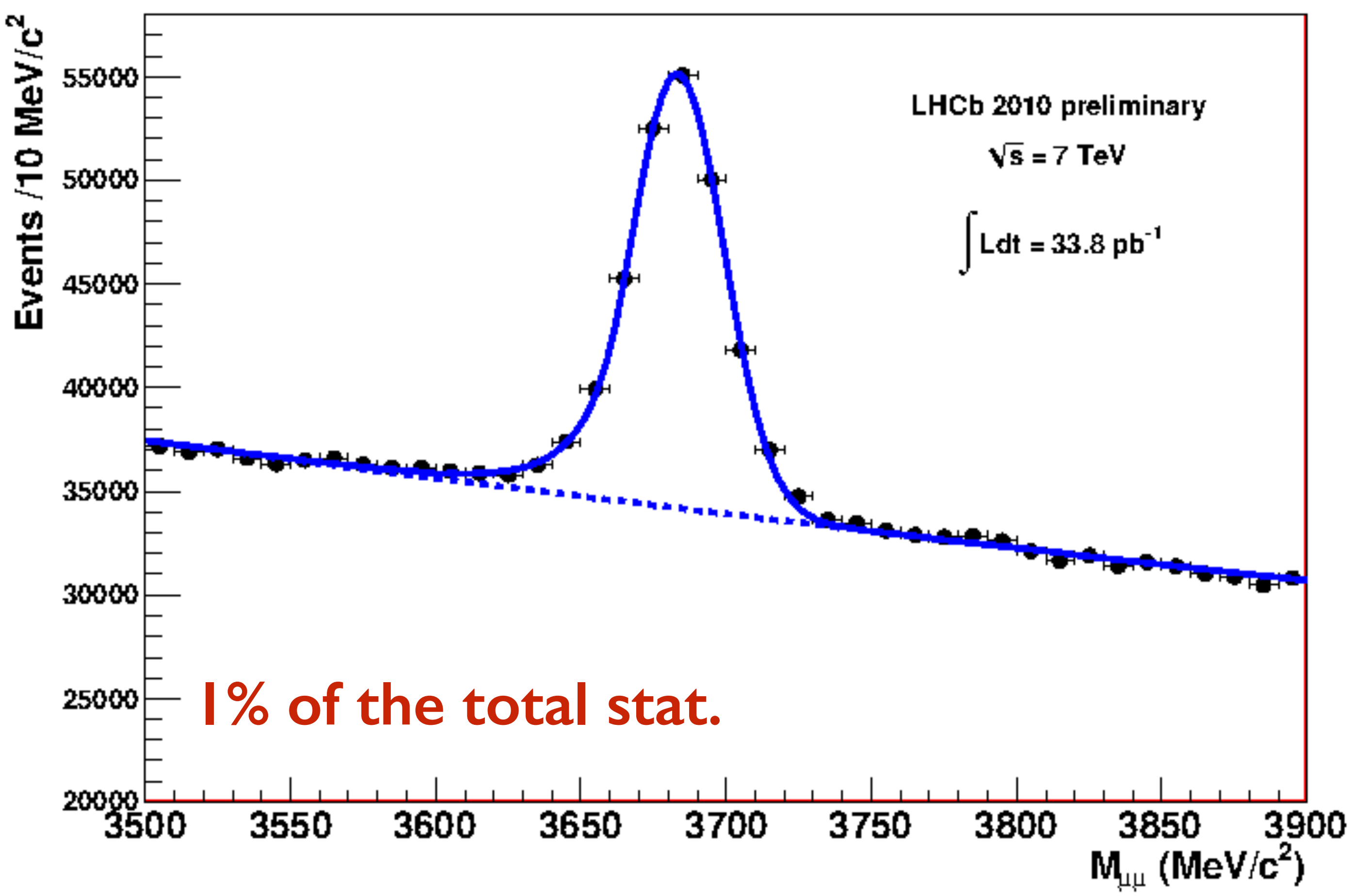

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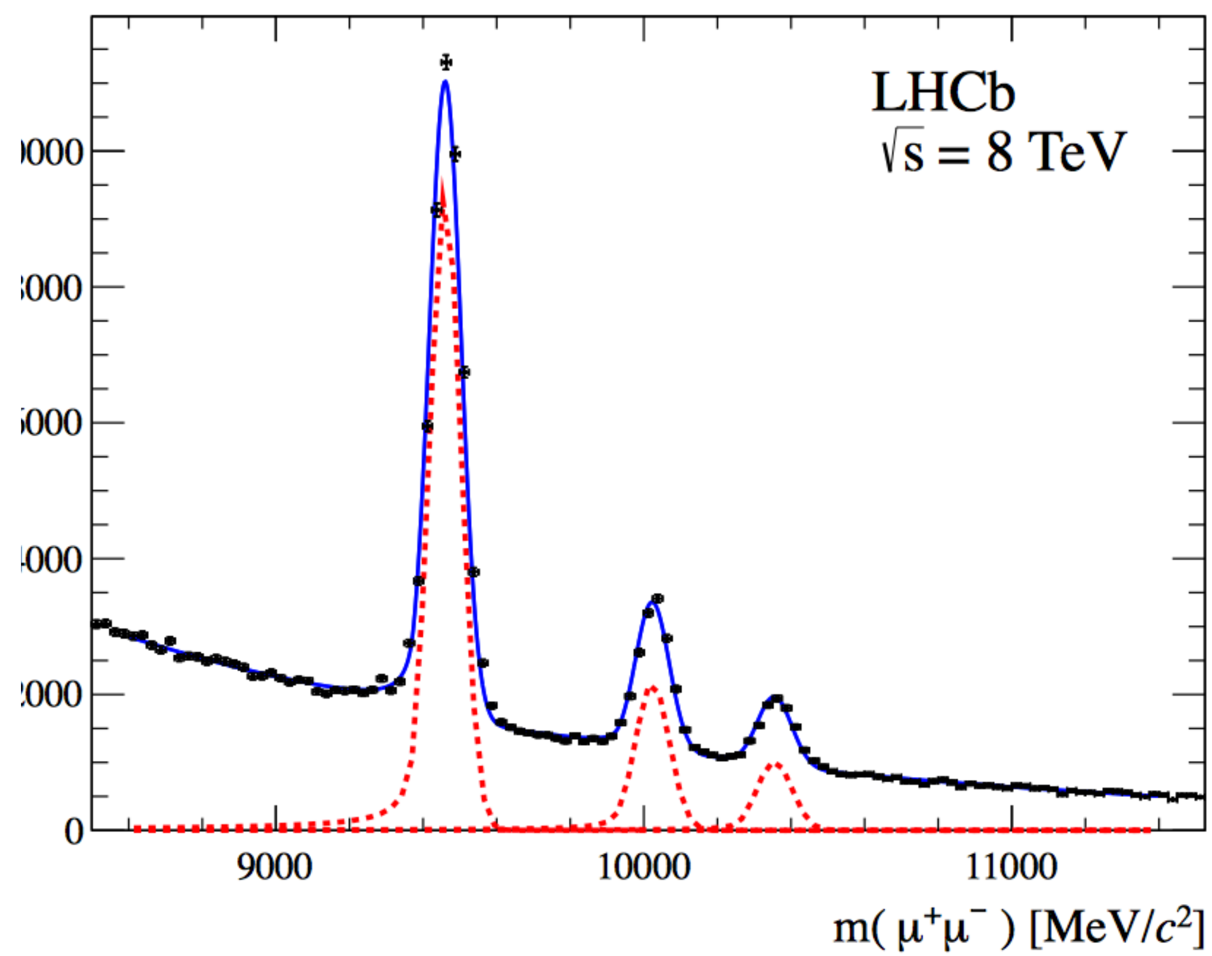


L0Muon : P_T > 1.5 GeV + HLT (soft)

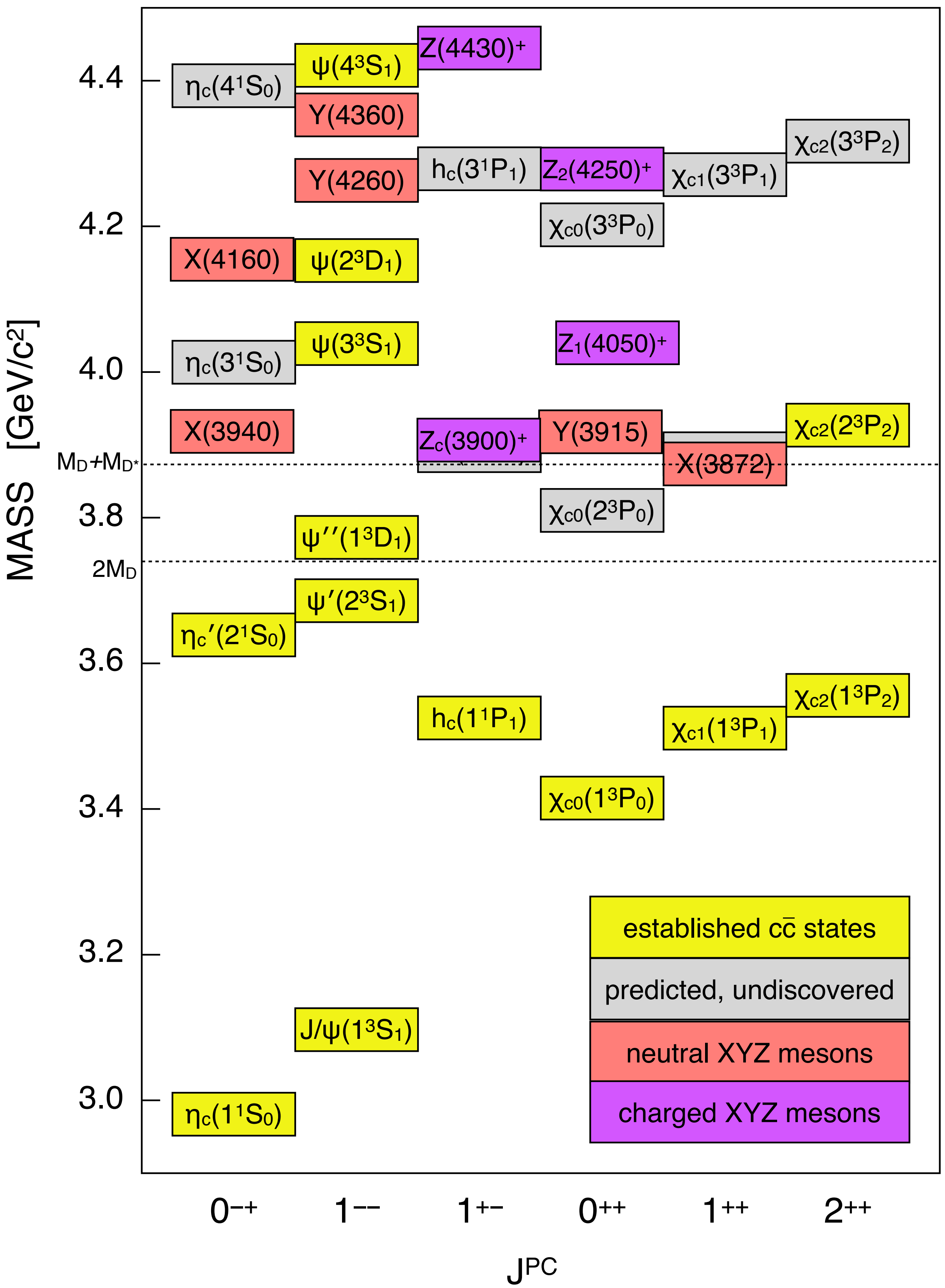
Impact parameter resolution (high pT tracks) : 20µm

Decay time resolution : 45 fs (for Bs → J/ψ φ and for Bs → Ds π)

µ ID efficiency : 97% (1-3% π-µ mis-ID)

J/Ψ (µµ) mass resolution : 8 MeV (B → J/Ψ X with constrains)

Outline



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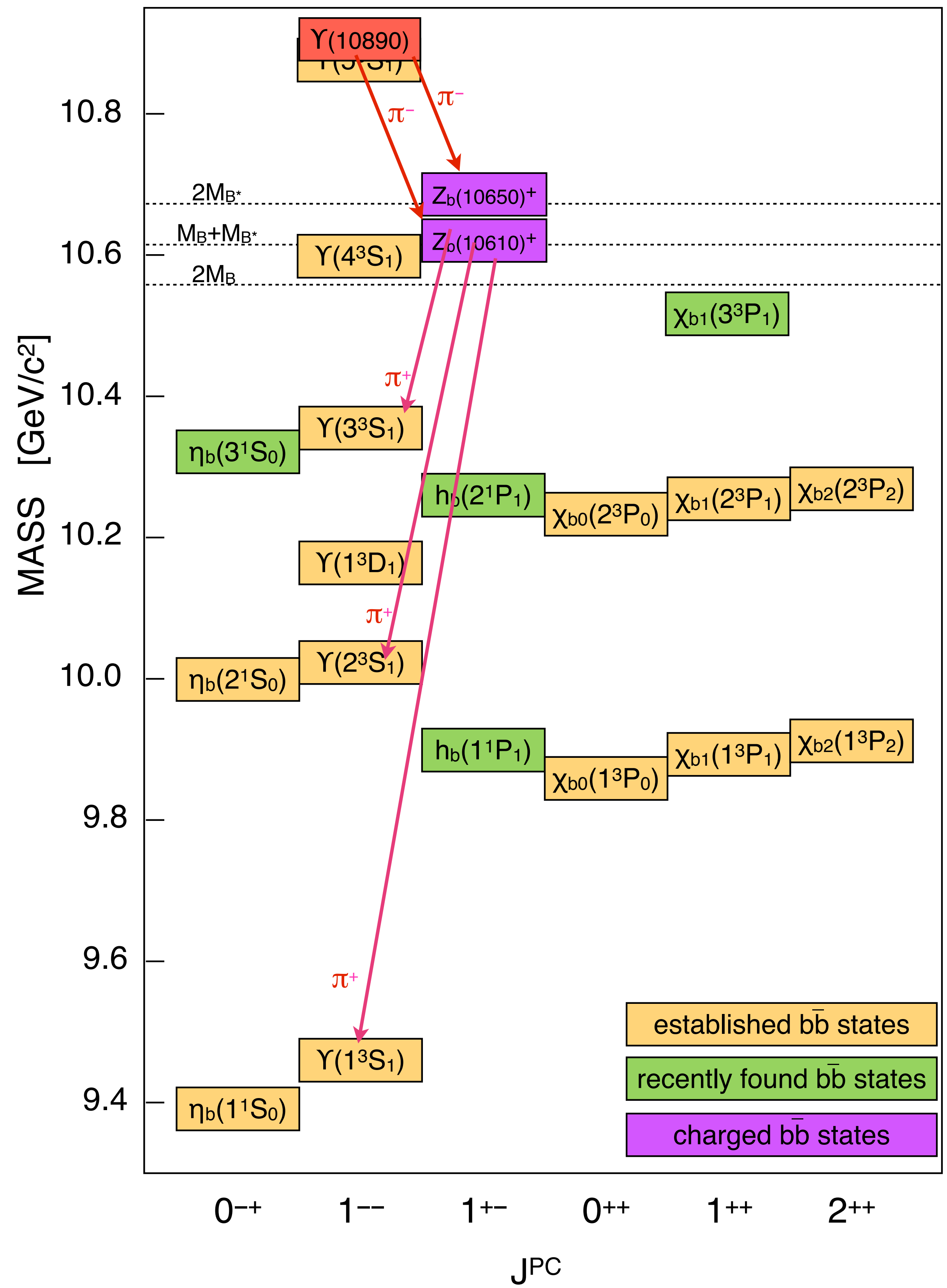

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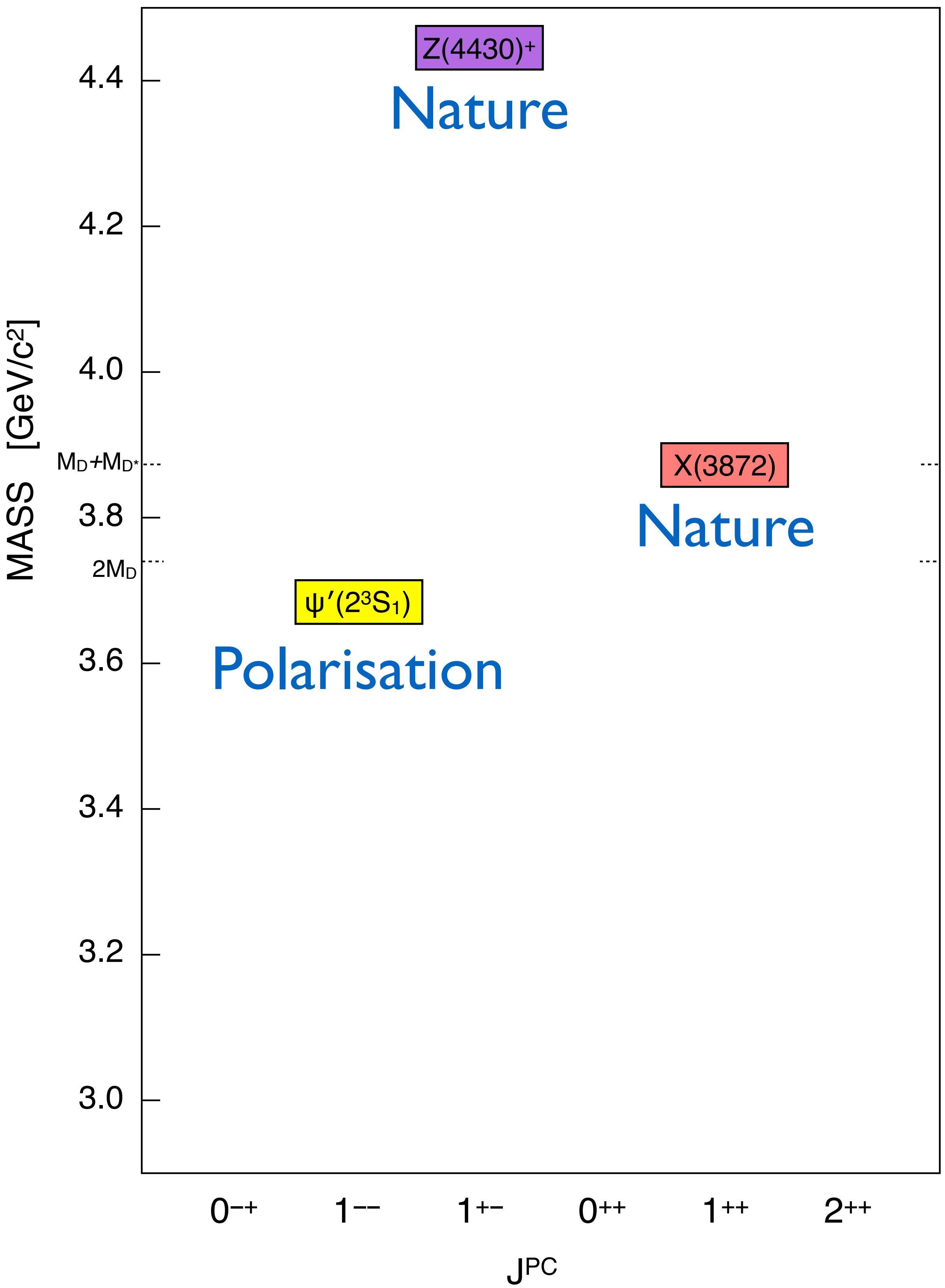

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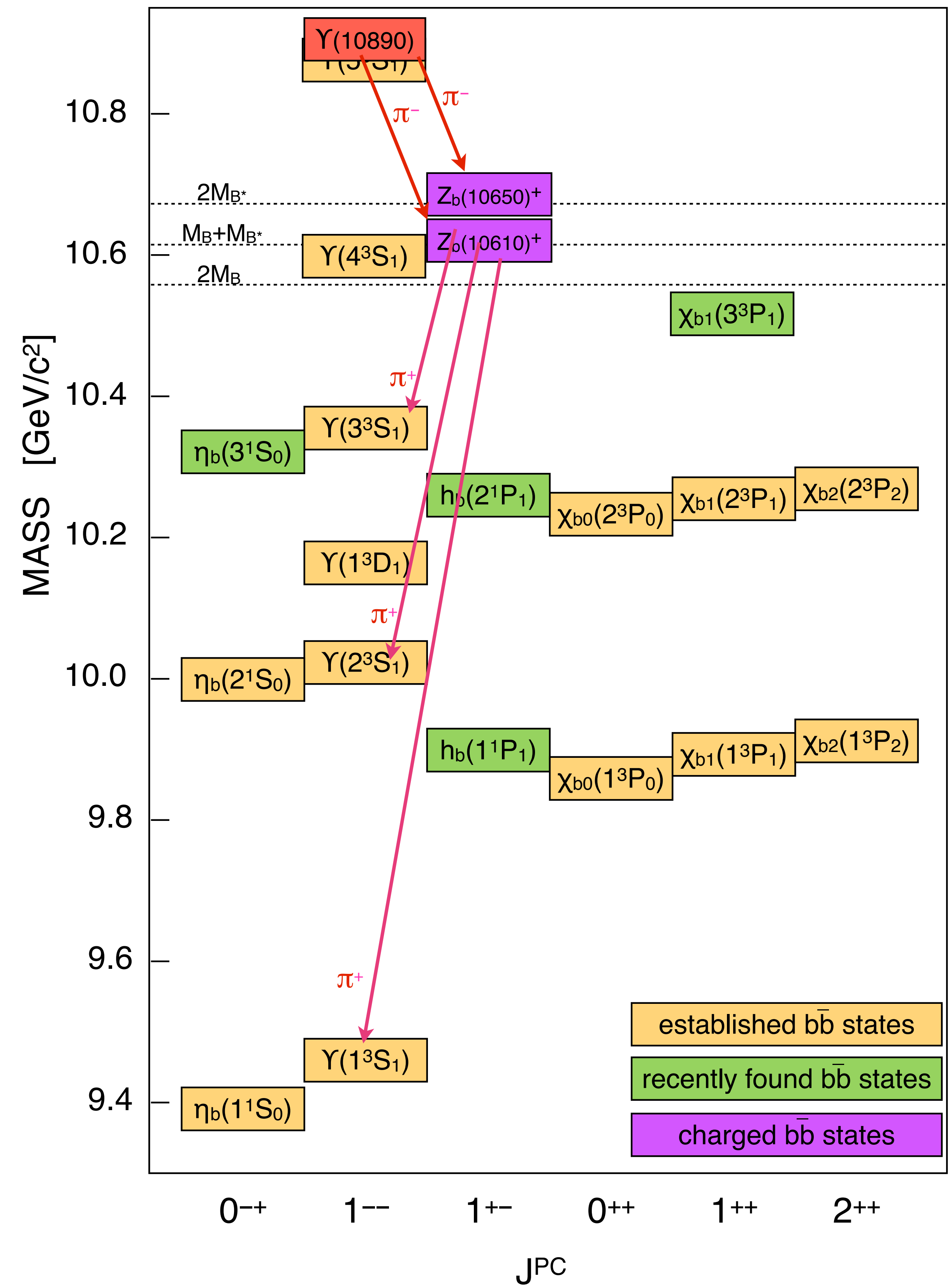

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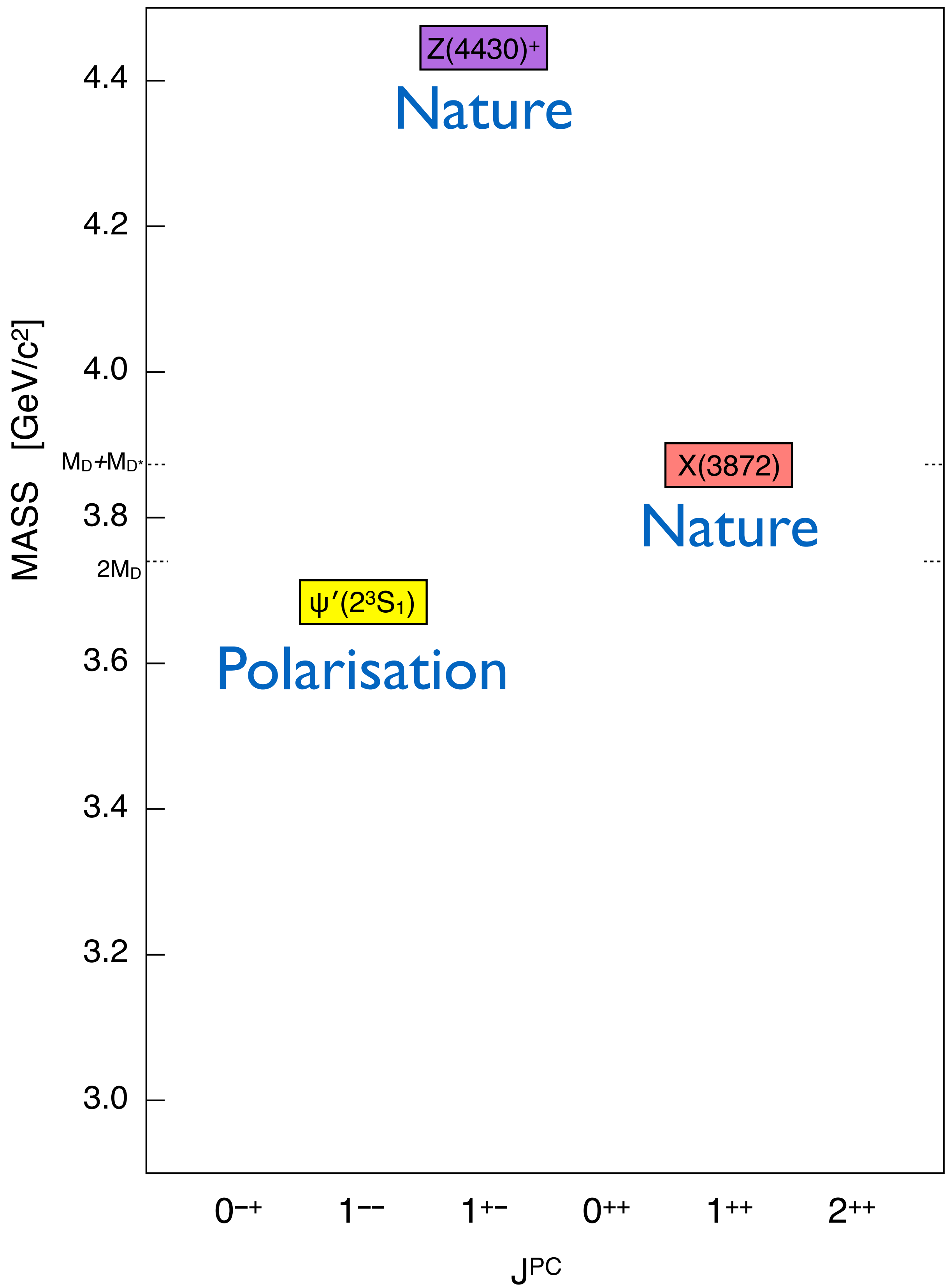
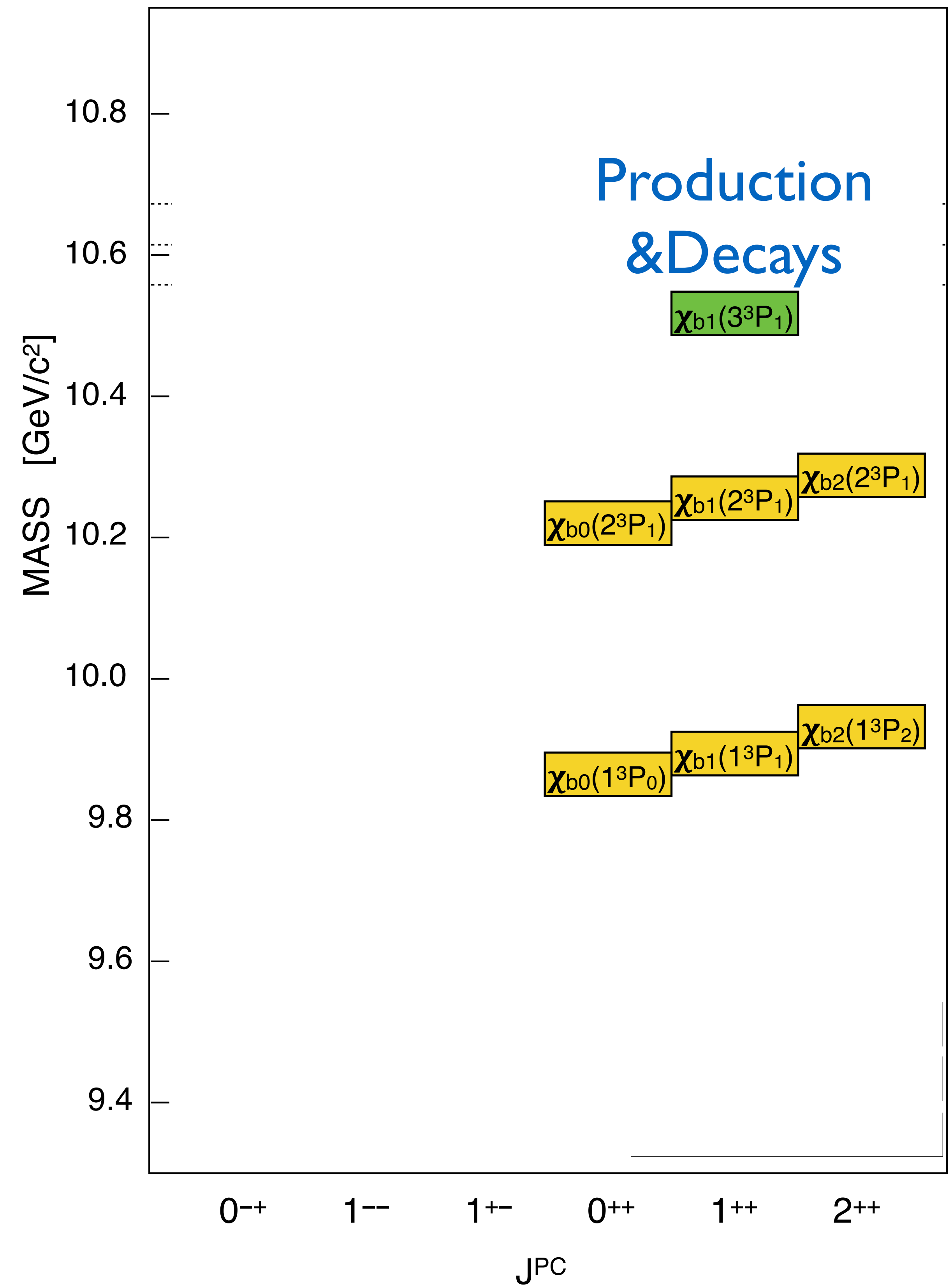


Z(4430)+
Nature
X(3872)
Nature
ψ′(2³S₁)
Polarisation
MASS [GeV/c²]
MD+MD*
2MD
JPC
0−+ 1−− 1+− 0++ 1++ 2++

arXiv:1403.1254



Production
&Decays
χb1(3³P₁)
χb0(2³P₁)
χb1(2³P₁)
χb2(2³P₁)
χb0(1³P₀)
χb1(1³P₁)
χb2(1³P₂)
MASS [GeV/c²]
JPC
0−+ 1−− 1+− 0++ 1++ 2++

Prompt Ψ' polarisation/1

EPJ C73(2013)11
arXiv:1403.1339

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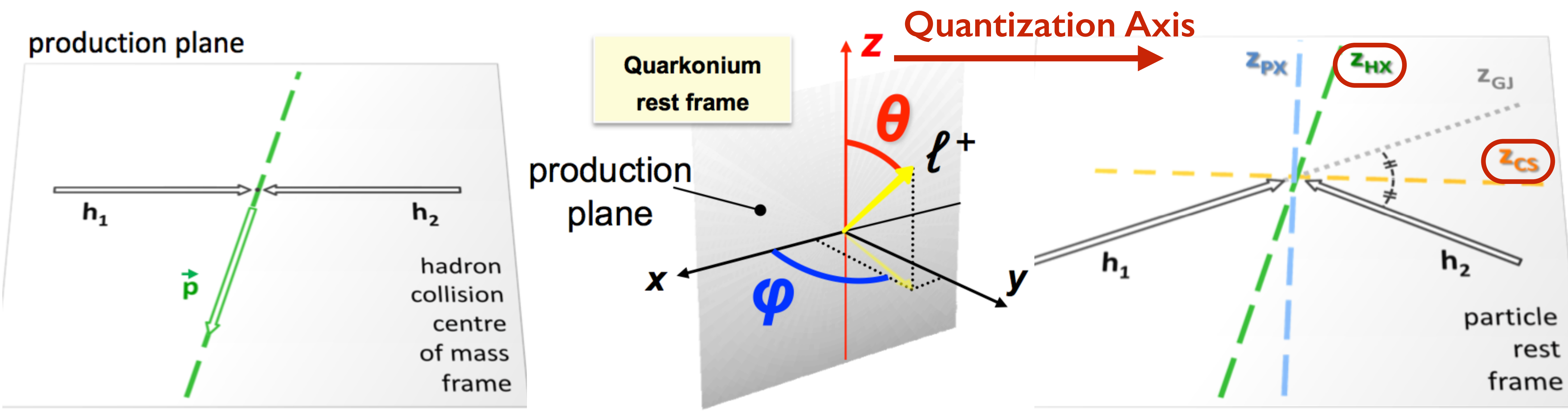
  - (λ_θ, λ_φ, $\lambda_{\theta\varphi}$) pol. angles from $\Psi'_{\to\mu\mu}$ (η, p_T) bins



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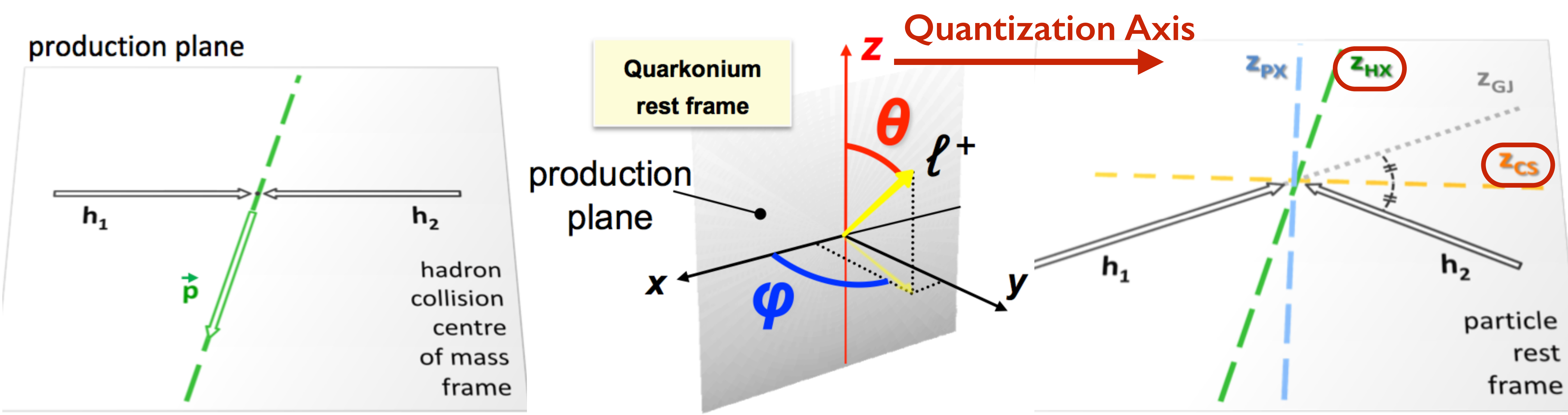

  - use HX AND CS (≠ ε)
  - $\lambda_{inv} = (\lambda_\theta + \lambda_\varphi)/(1-\lambda_\varphi)$ frame independent and (theory) predicted

Prompt Ψ' polarisation/2

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7 TeV / 1fb^{-1}

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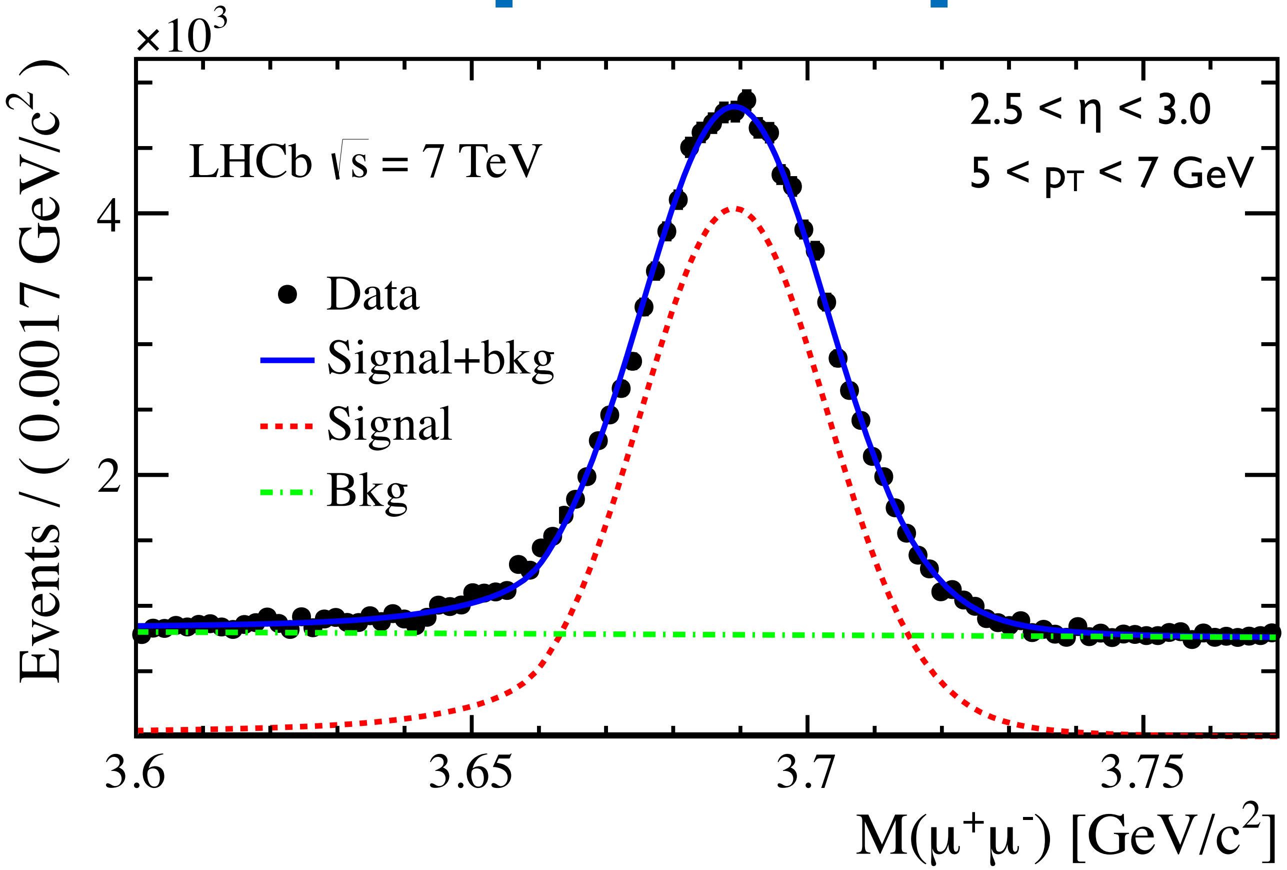

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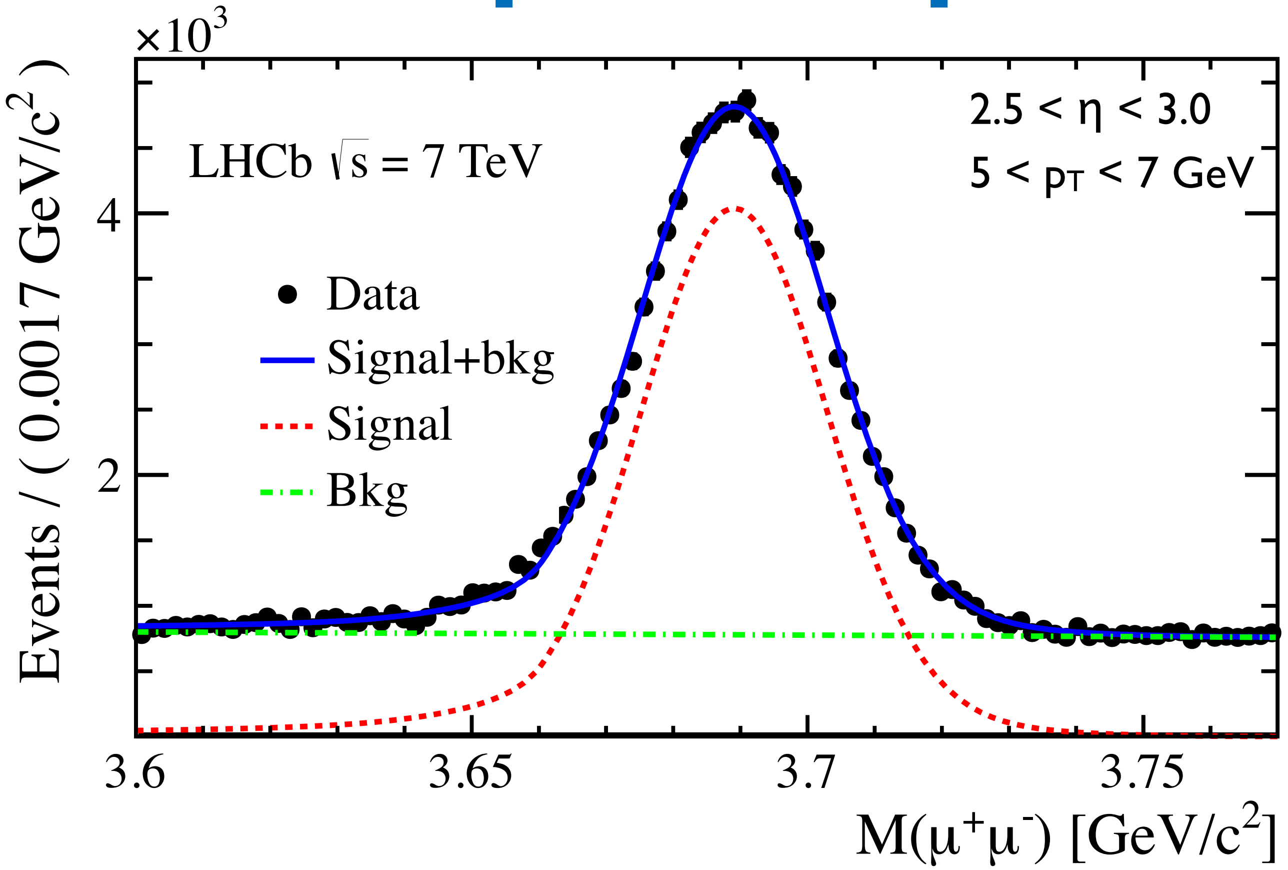

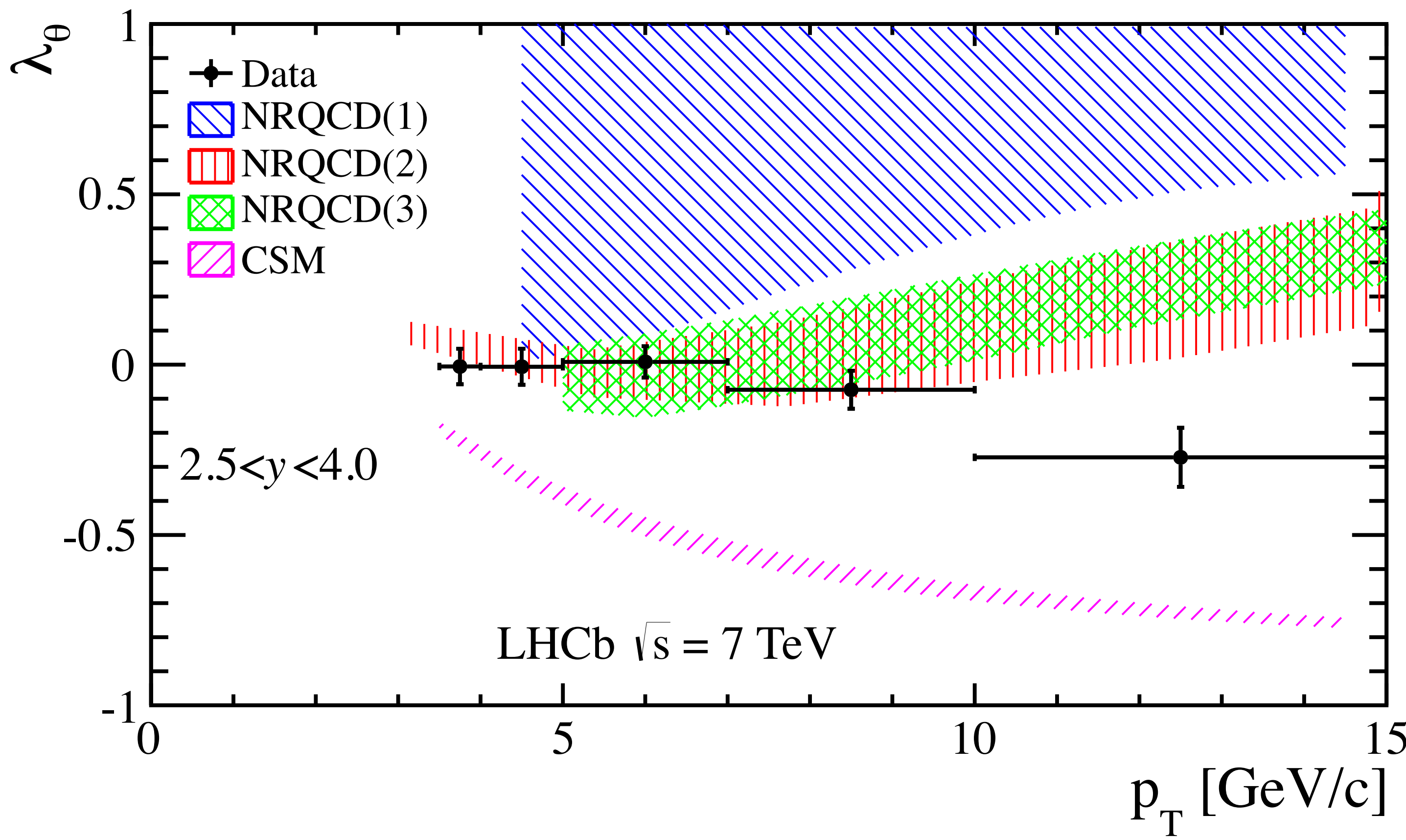

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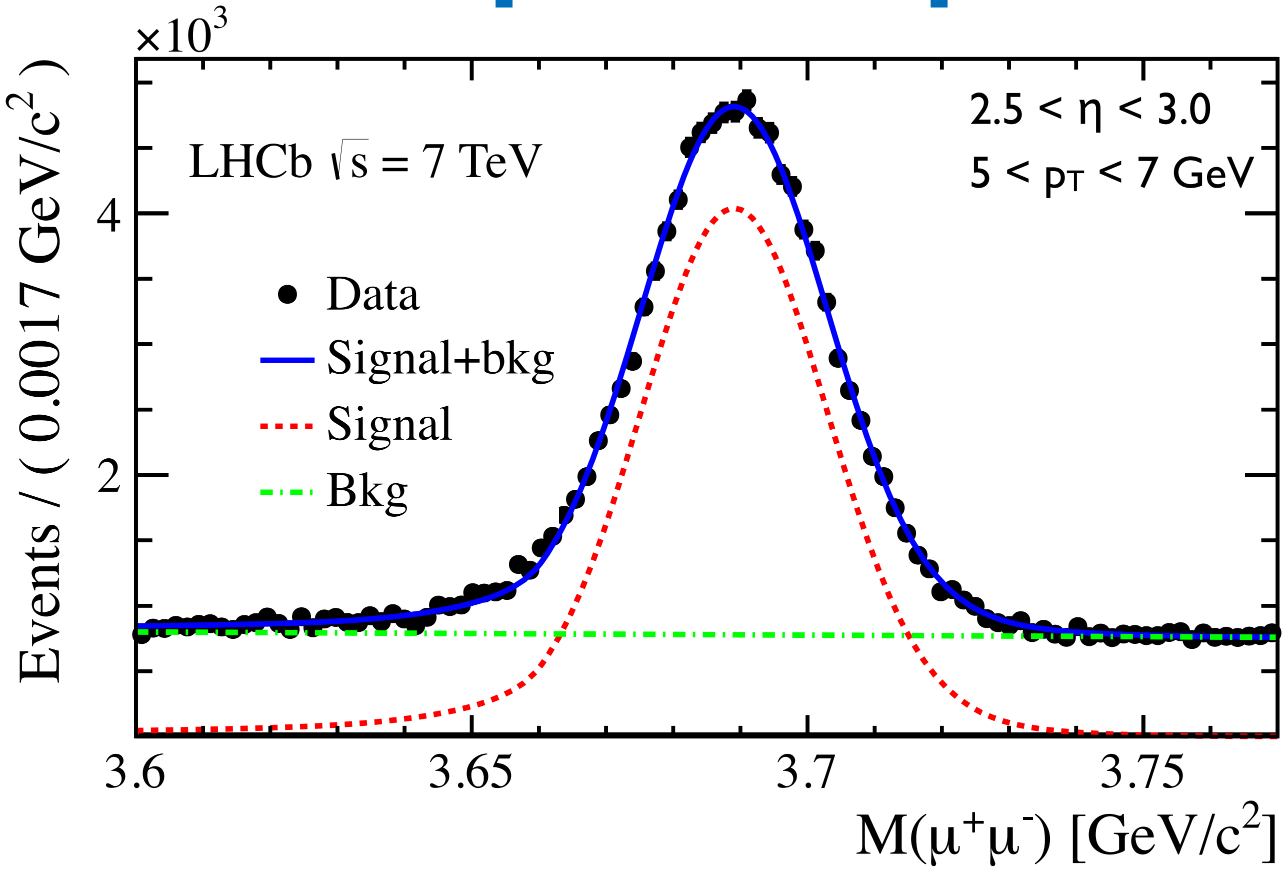

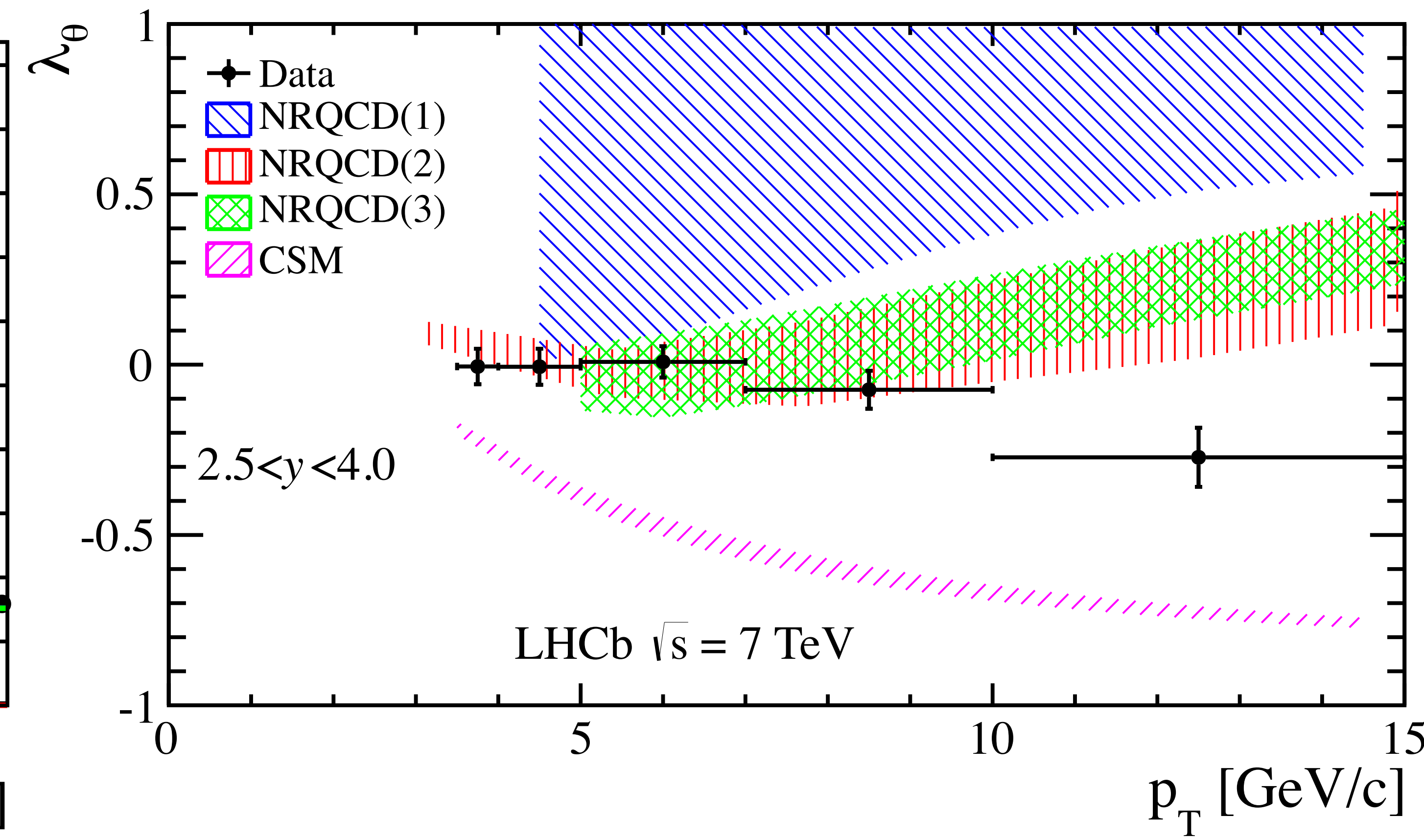

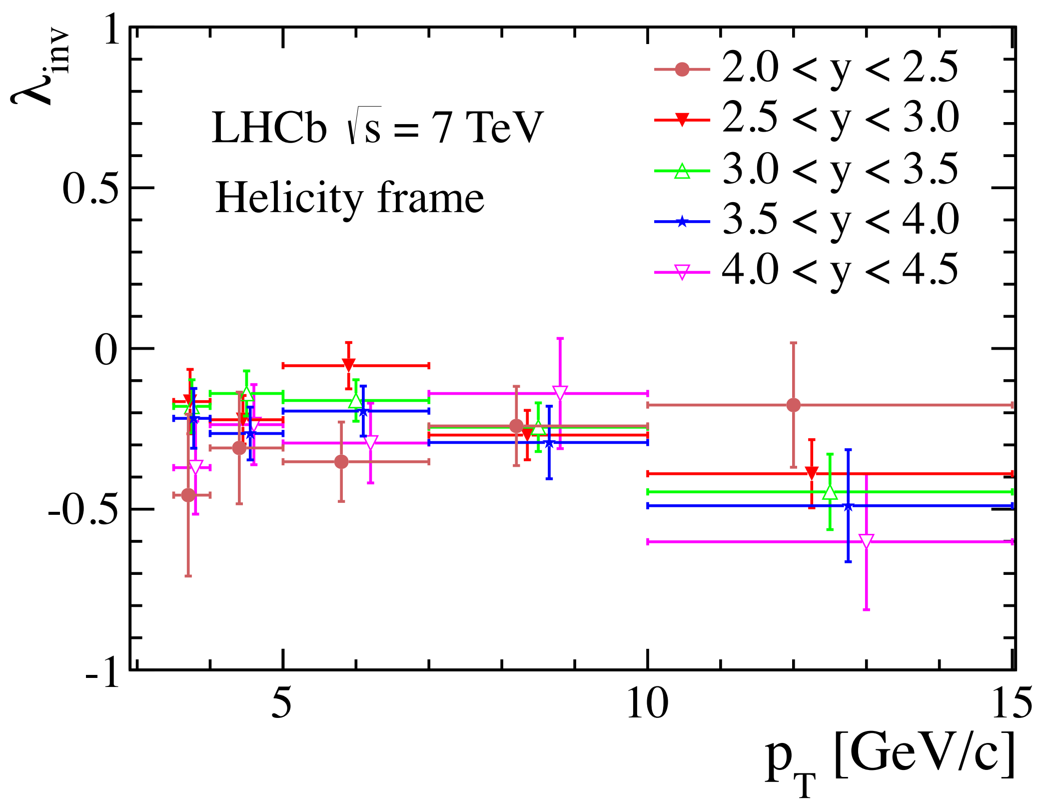

HX/CS consistent

λ_φ, $\lambda_{\theta\varphi}$ ~ 0 , λ_{inv} < 0

λ_θ : no model fits high p_T

arXiv:1404.0275

Exotics : X(3872) nature/1

arXiv:1404.0275

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- Question : what is it ?

« The X(3872) occupies a unique niche in the menagerie (…) as both the first and the **most intriguing** (…)quantum numbers, mass, and decay patterns make it an unlikely conventional charmonium candidate, and **no consensus explanation** has been found. » (Brambilla et al. (2011) **EPJ C71(2011)1534**)

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- The X(3872) physics case
  - born in 2003 (Belle - **PRL 91(2003)262001**)
  - $J^{PC}=1^{++}$, possible interpretation : **$c\bar{c}u\bar{u}$**, D^0D^{0*},$c\bar{c}g$, …
  - $R_{\psi\gamma}$ = Br(X→Ψ'γ **(to be confirmed)**) / Br(X→J/Ψγ) to discriminate
  - this analysis : $B^+ \to X K^+$ with $X \to (\Psi'$ or $J/\Psi)_{(\to\mu\mu)}\ \gamma$
  - this analysis : extract signal yields from mass fits (**ε** corrections very ≠)

Exotics : X(3872) nature/2

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7+8 TeV / 3 fb^{-1}

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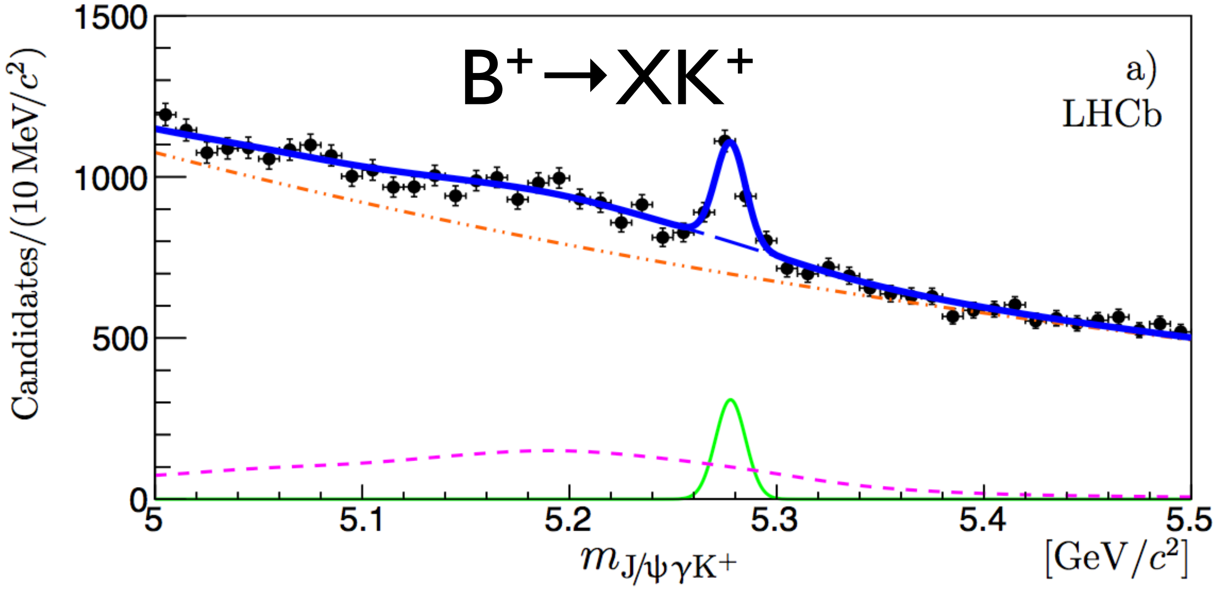

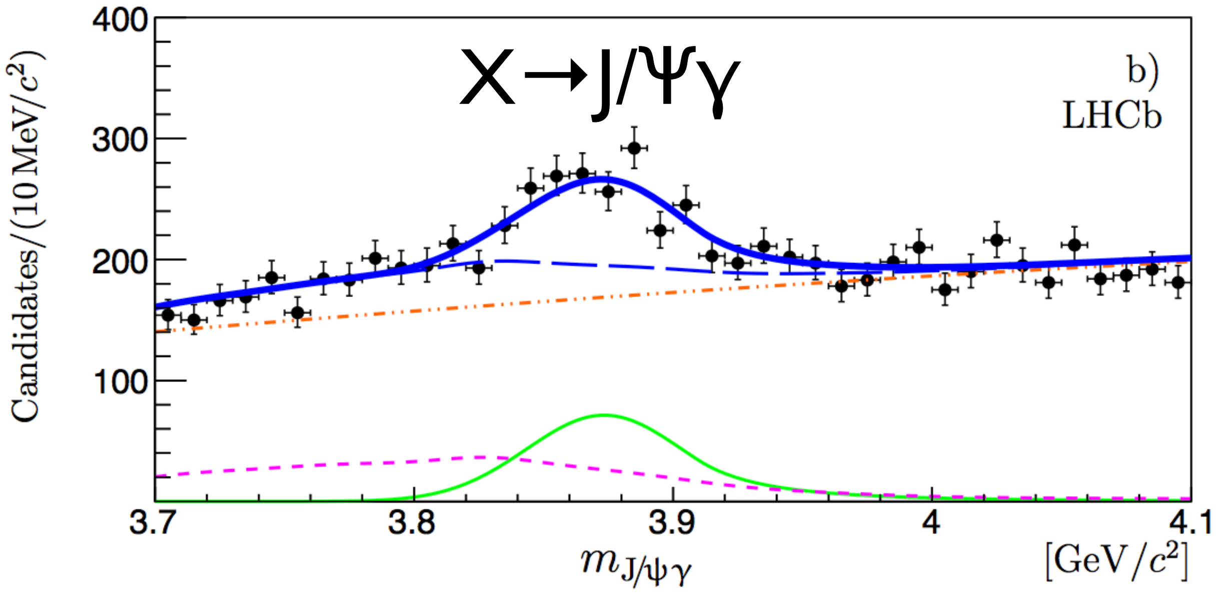

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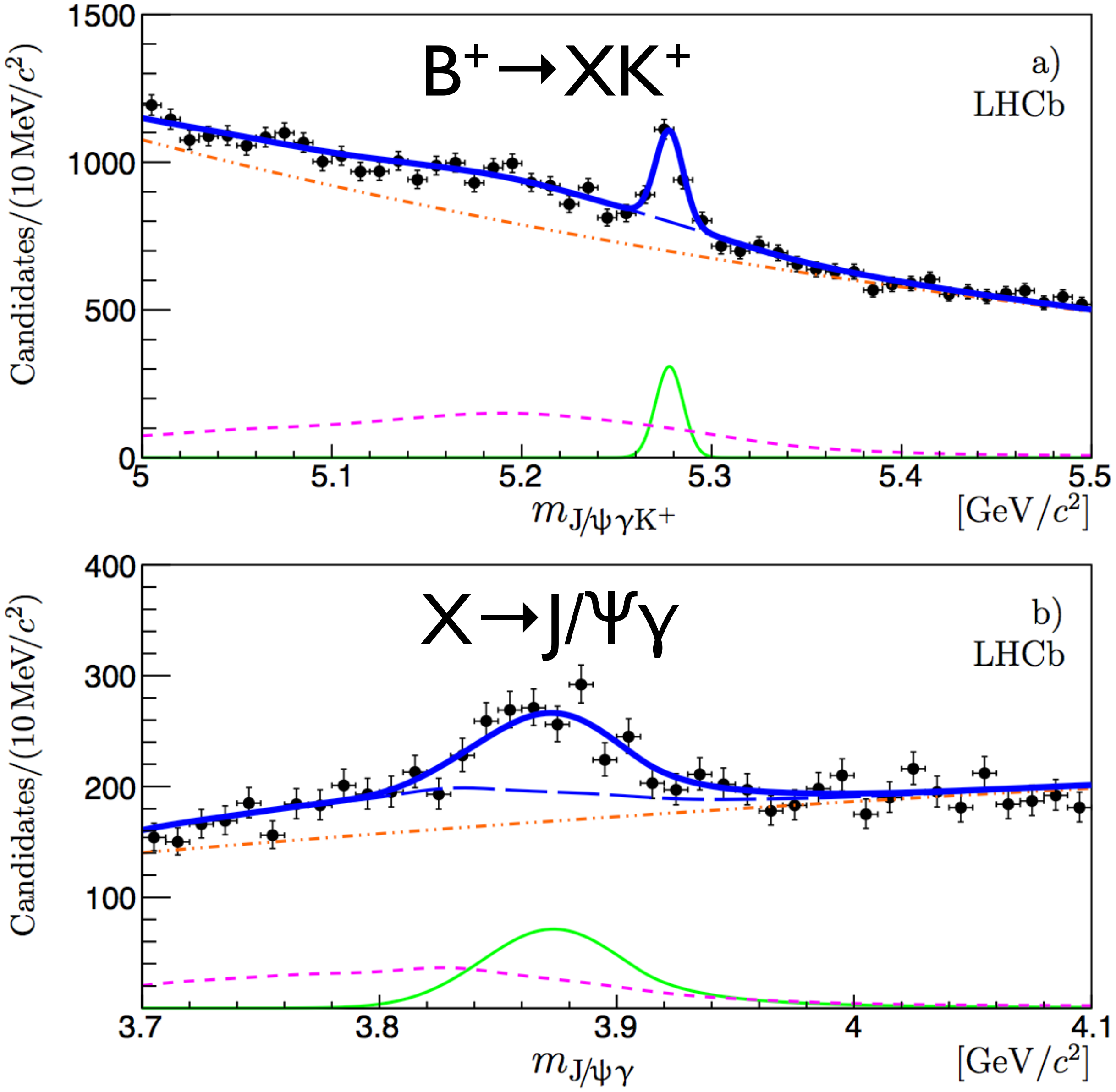
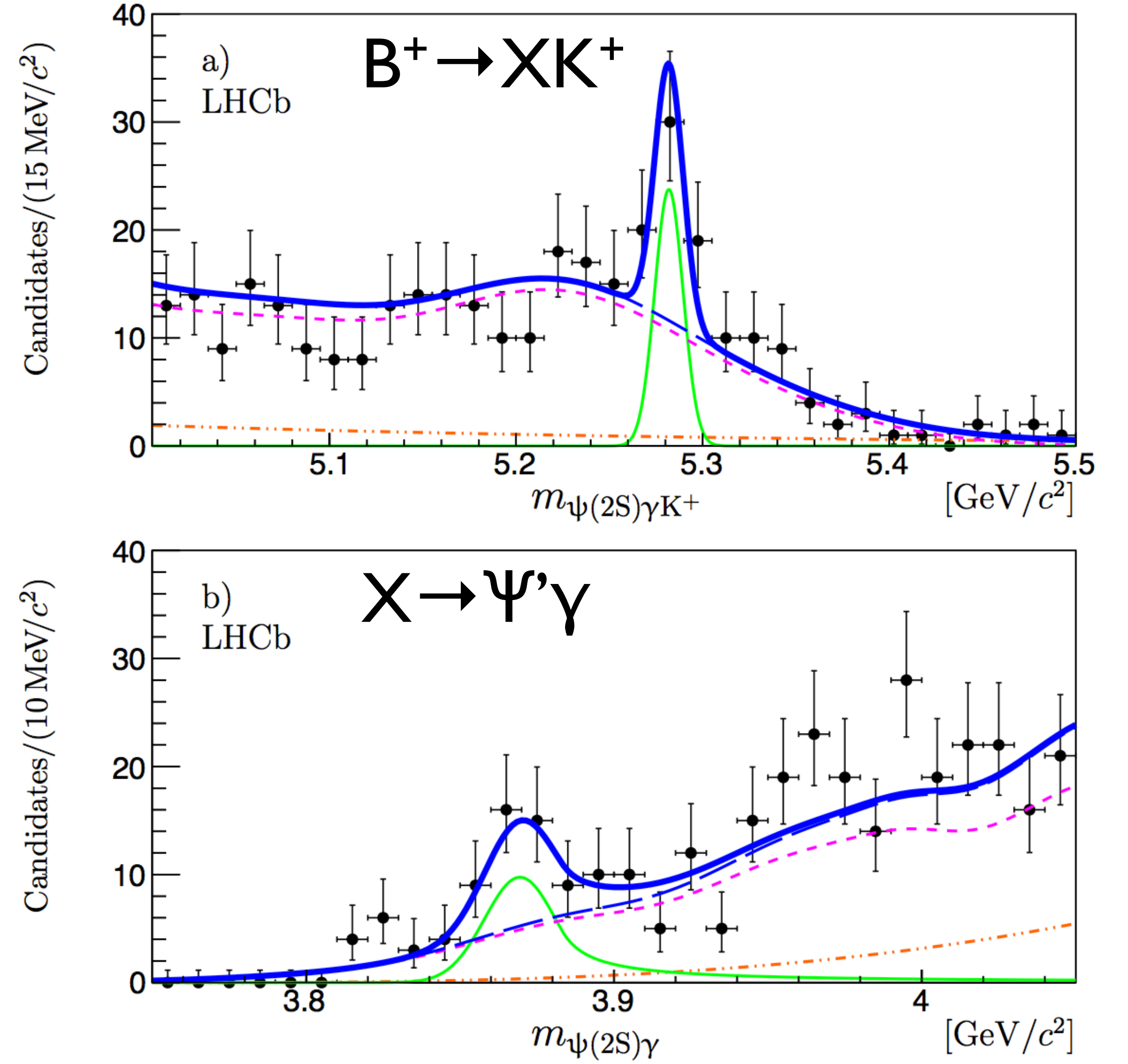
7+8 TeV / 3 fb⁻¹





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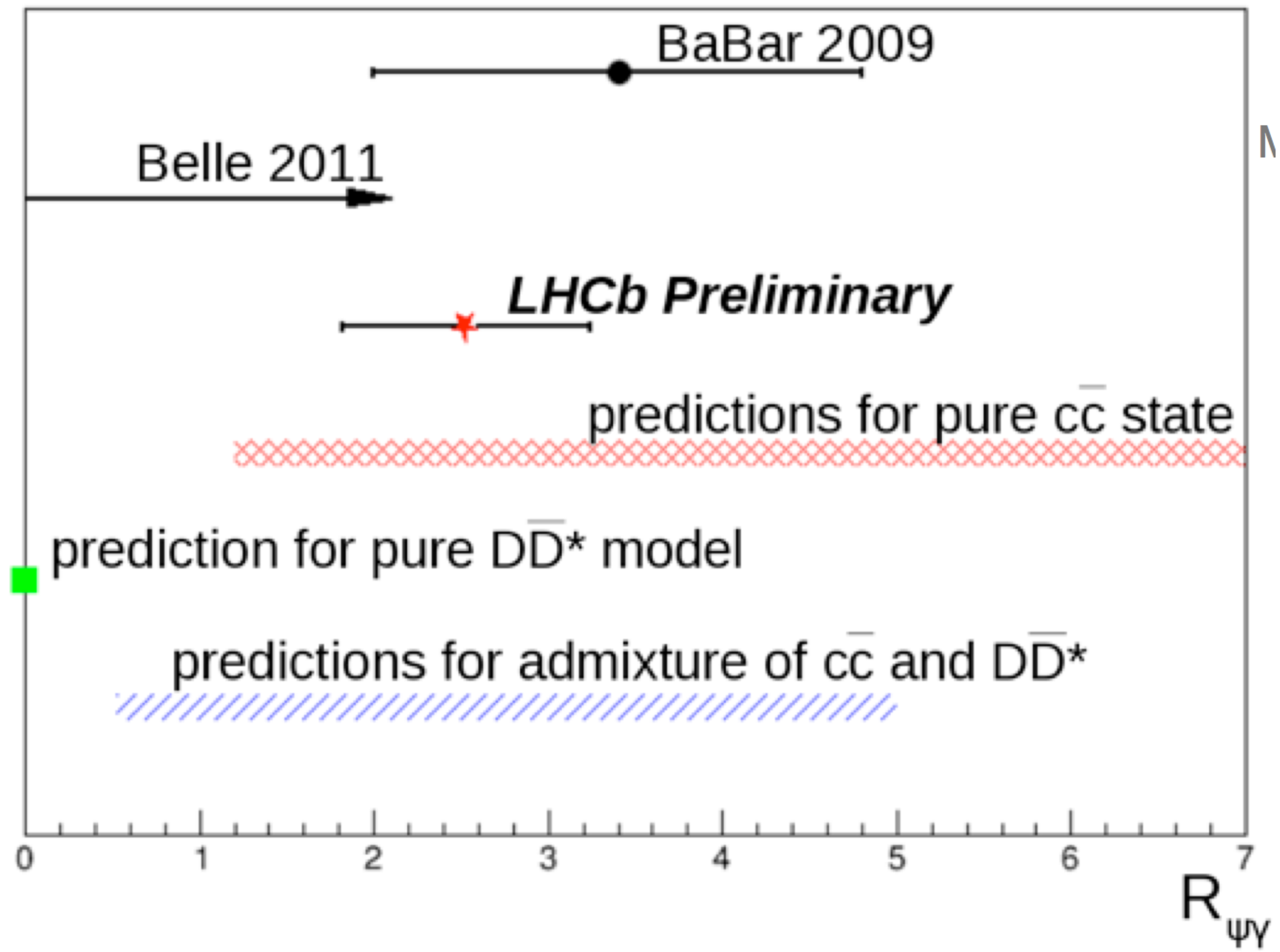

$X \to \Psi'\gamma$ confirmed

$R_{\psi\gamma} = Br(X \to \Psi'\gamma)/Br(X \to J/\Psi\gamma) = 2.46 \pm 0.64\ (stat.) \pm 0.29\ (syst.)$

$D\bar{D}^*$ molecule ruled out

Exotics : Z(4430) nature/1

PRL 112(2014)222002
arXiv:1404.1903

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- Question : if it exists, what is it ?

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- Question : if it exists, what is it ?

- The Z(4430) physics case
  - born in 2007 (Belle - **PRL100(2008)142001** - but not BaBar (2009))
  - $J^P = 1^+$ favored / minimal quark content : **$c\bar{c}d\bar{u}$!**
  - this analysis : $B^0 \to \Psi'_{\to\mu\mu}\, \pi^- K^+$
  - this analysis : **4D amplitude** = $(m^2_{K^+\pi^-}, m^2_{\Psi'\pi^-}, \cos\theta_{\Psi'}, \varphi)$ fit (à la Belle)
    - $B^0 \to Z^- K^+ + B^0 \to \Psi' K^{*0}$ (all known $K^{*0} \to K^+\pi^-$ included)
    - each resonance = BW
    - etc …

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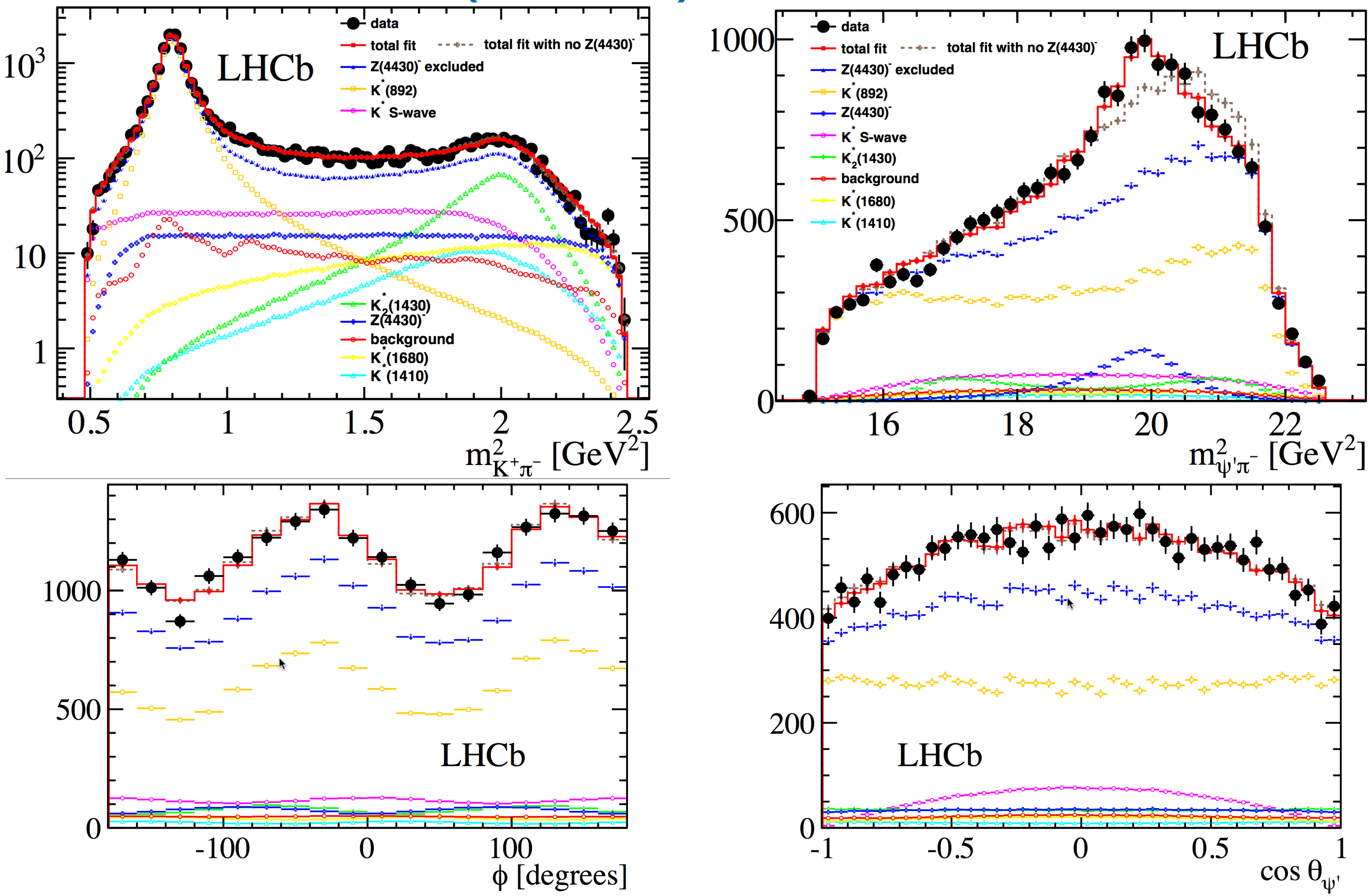

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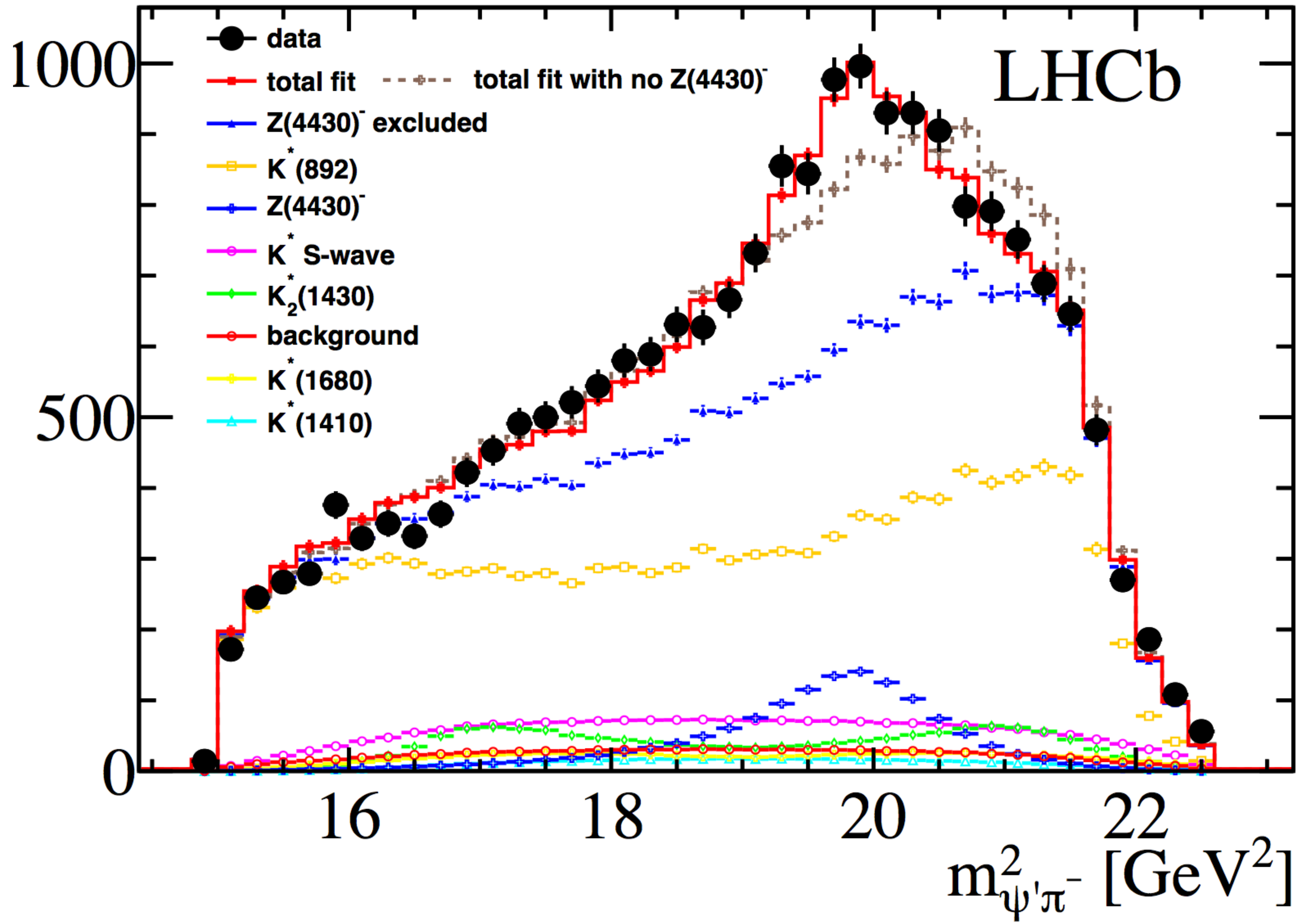

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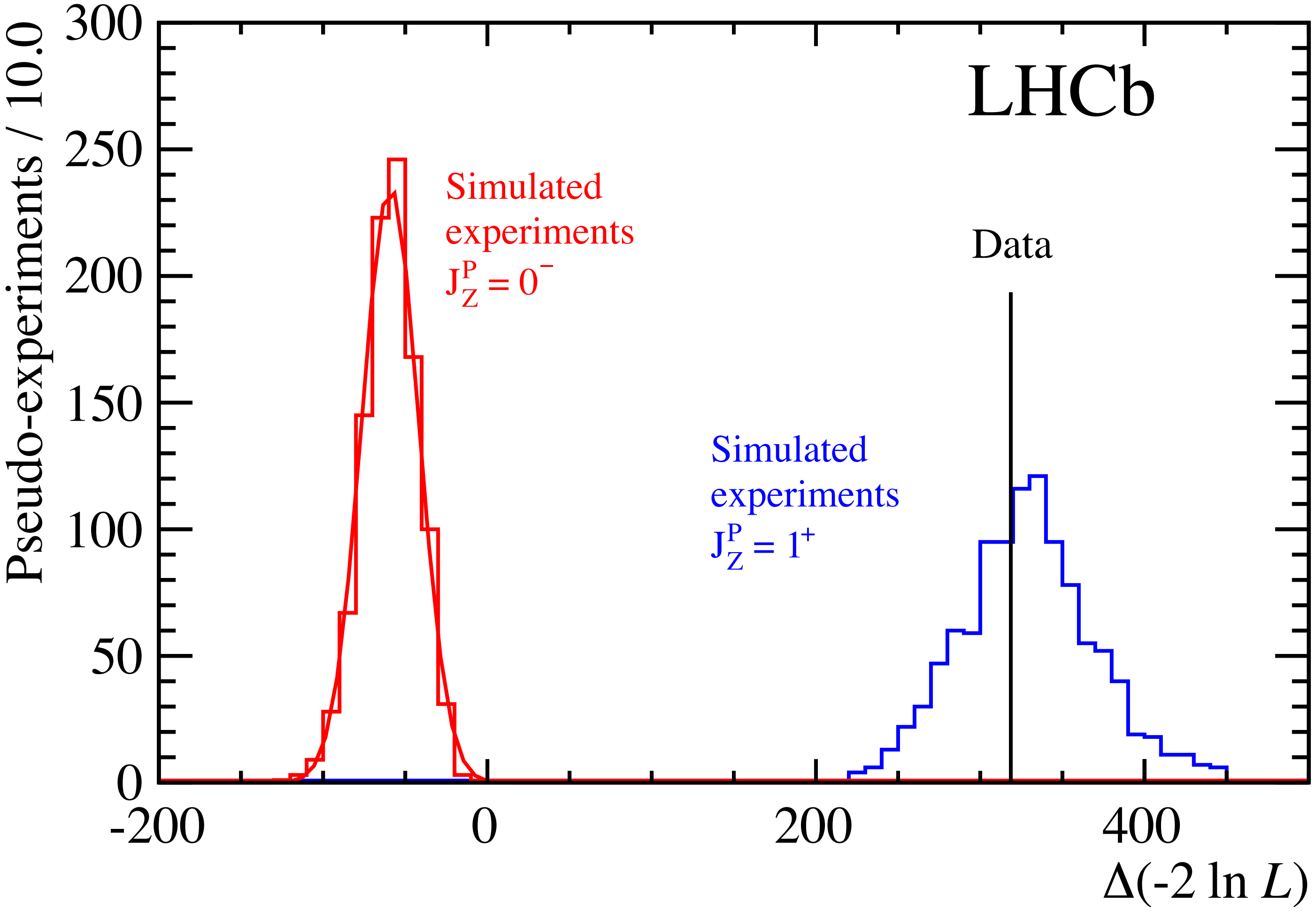

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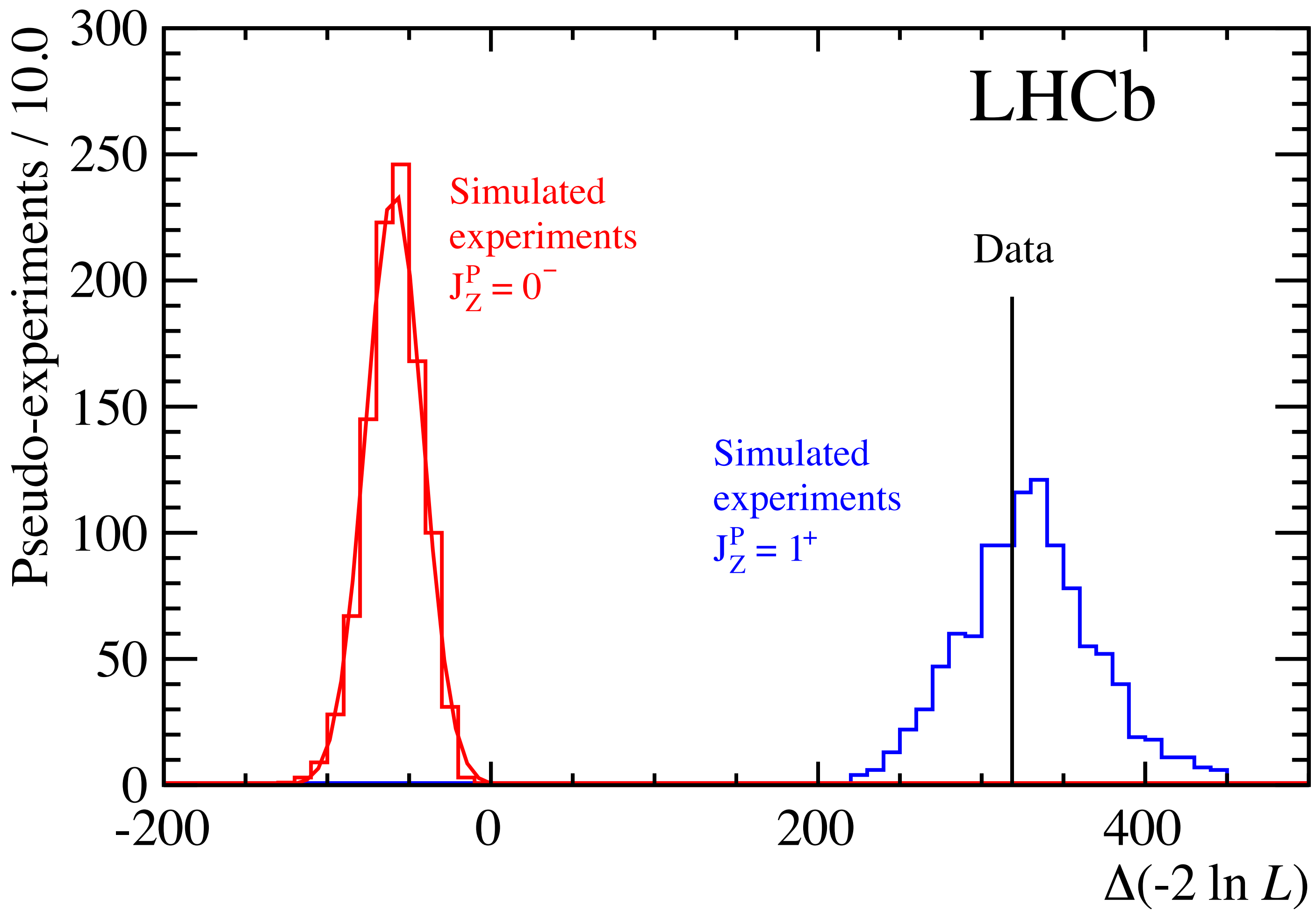

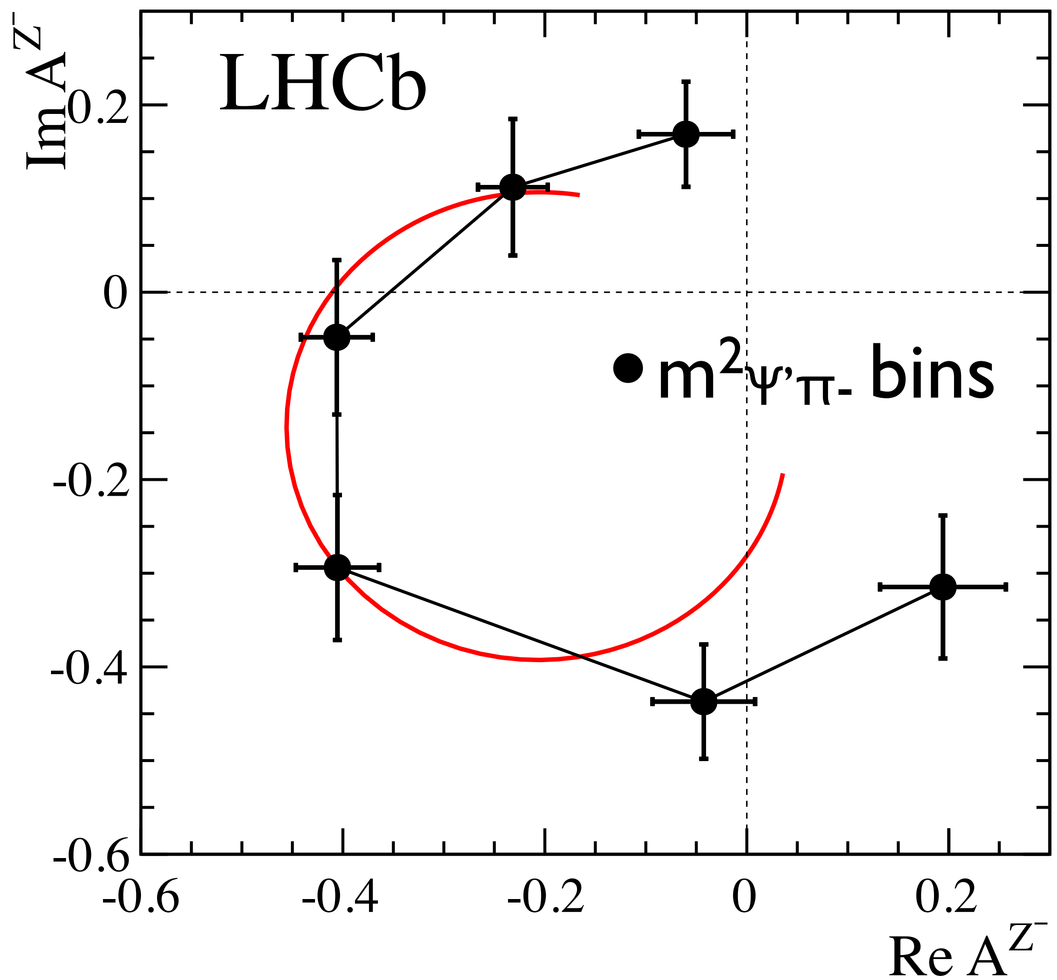

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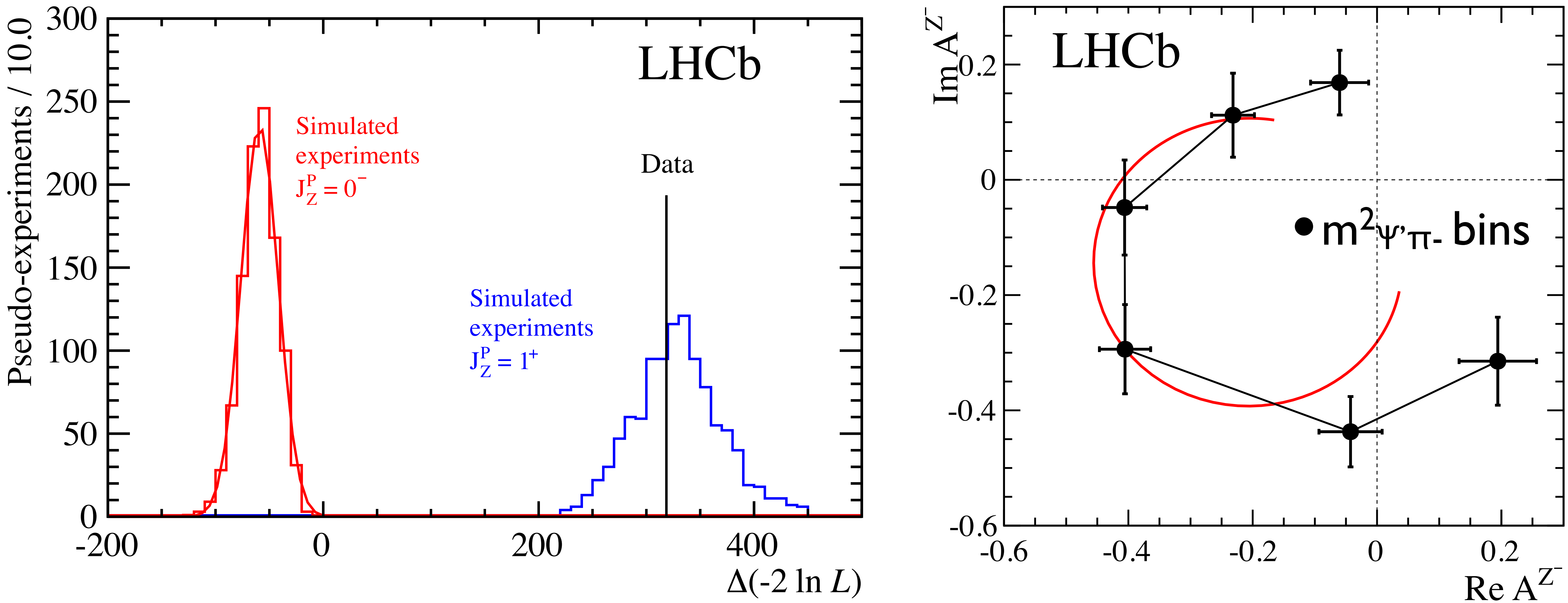

confirm Z existence : no Z : $p_{\chi 2} < 2\text{x}10^{-6}$ / with Z : $p_{\chi 2}$ = 12%

confirm ($\geq 10\sigma$) $J^P = 1^+$

M(Z)[MeV] = $4475 \pm 7\ ^{+15}_{-25}$, Γ(Z)[MeV] = $172 \pm 13\ ^{+37}_{-34}$

establish : Z is a (4-quarks) resonant state !!!

LHCb-PAPER-2014-031

χ_b's production & decays/1

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- Question : feed-down contributions of (P) to (S) quarkonia ?
  - mandatory to compare exp./theo. for prompt (S) production
  - possible impact on (S) polarisation interpretation

χ_{b}'s production & decays/1

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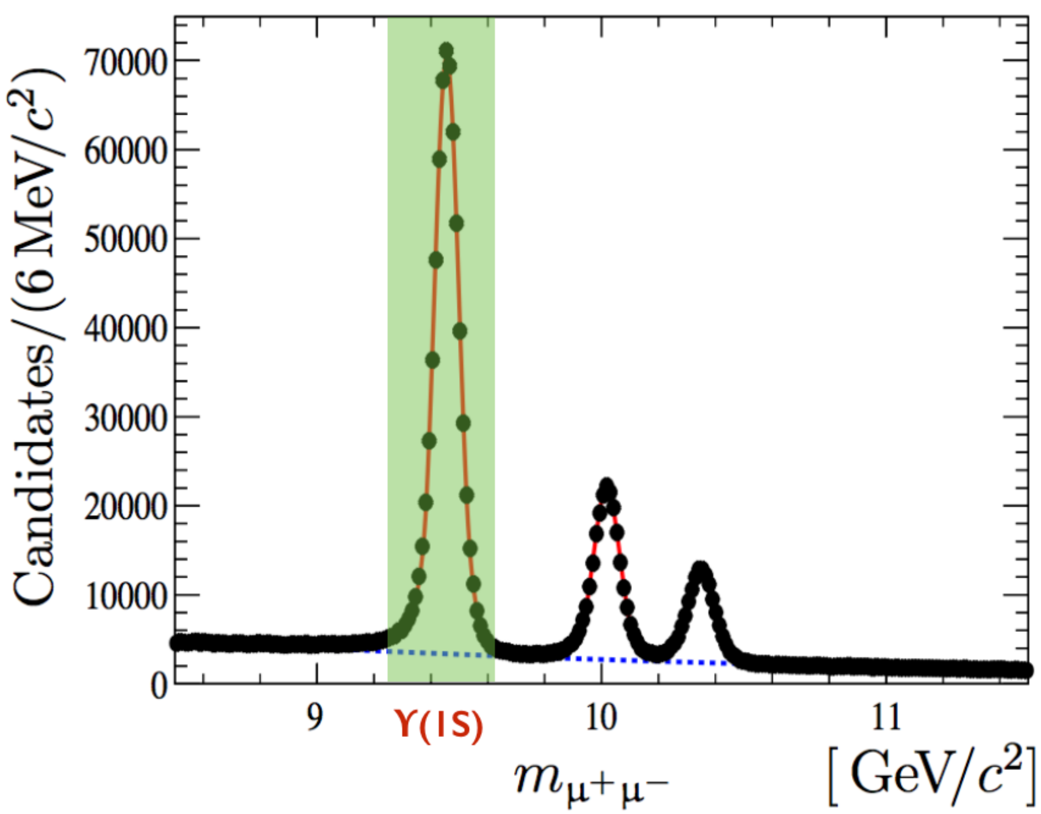
- The χ_b physics case
  - S = 1, L = 1 → J = (0,1,2) → (χ_{b0},χ_{b1},χ_{b2})
  - (1P , 2P) found and …
  - $\chi_{b1}(3^3P_1)$: born in 2011(ATLAS - **PRL 108(2012)152001**)
    - **first particle discovered @ LHC !**
  - radiative decays : χ_b(mP) → ϒ(nS) (n,m = 1,2,3) → ϒ's origin

LHCb-PAPER-2014-031

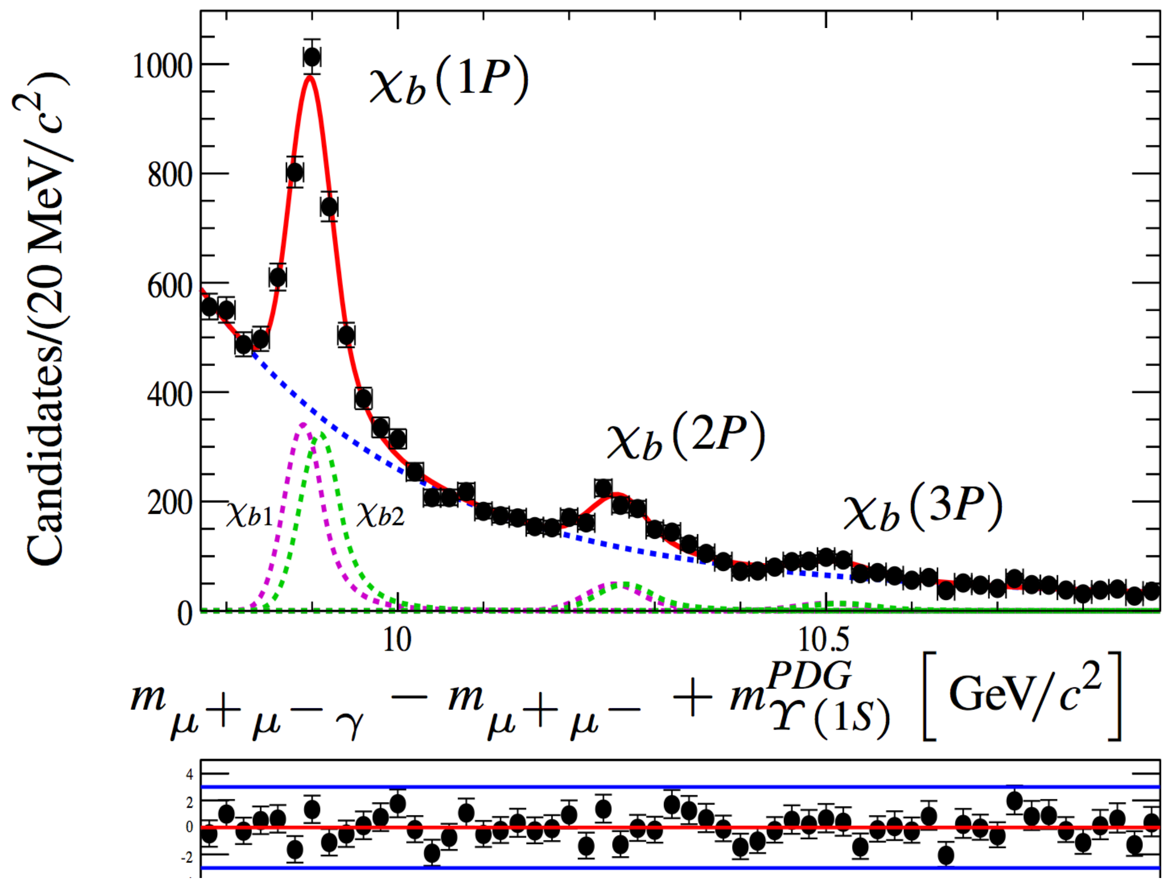
χ_b's production & decays/2

χ_b's production & decays/2

- the « method » :



+ γ →



χ_{b}'s production & decays/2

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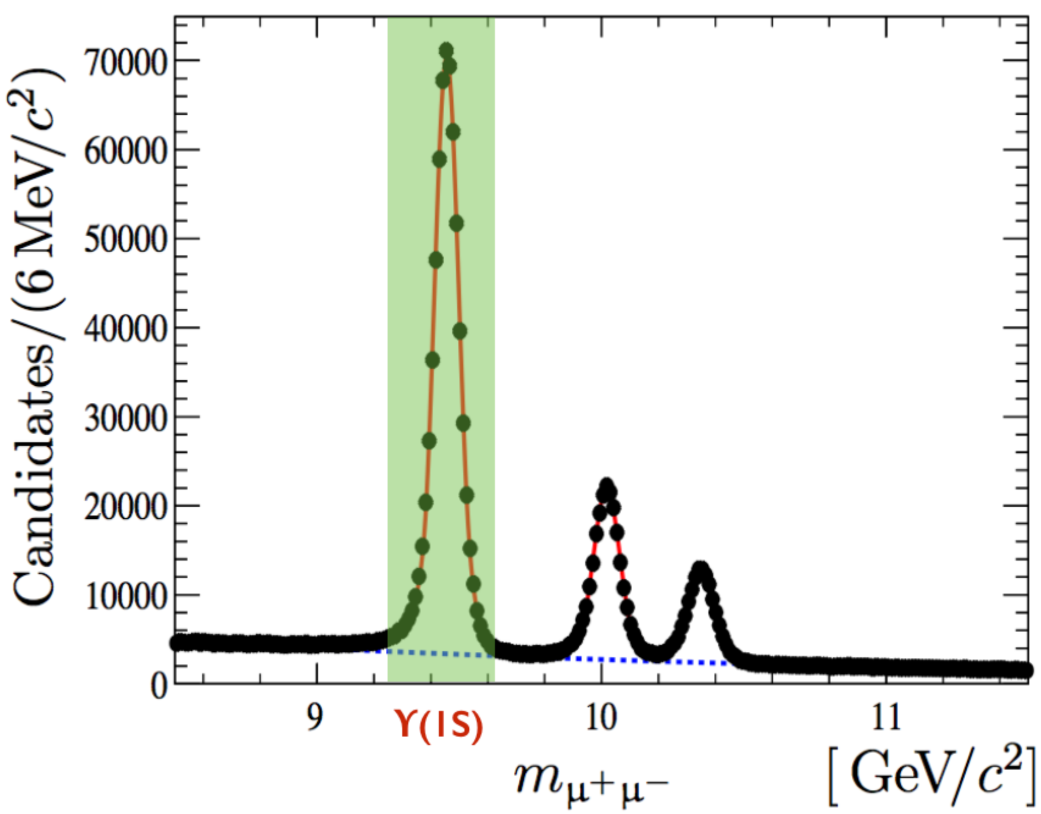

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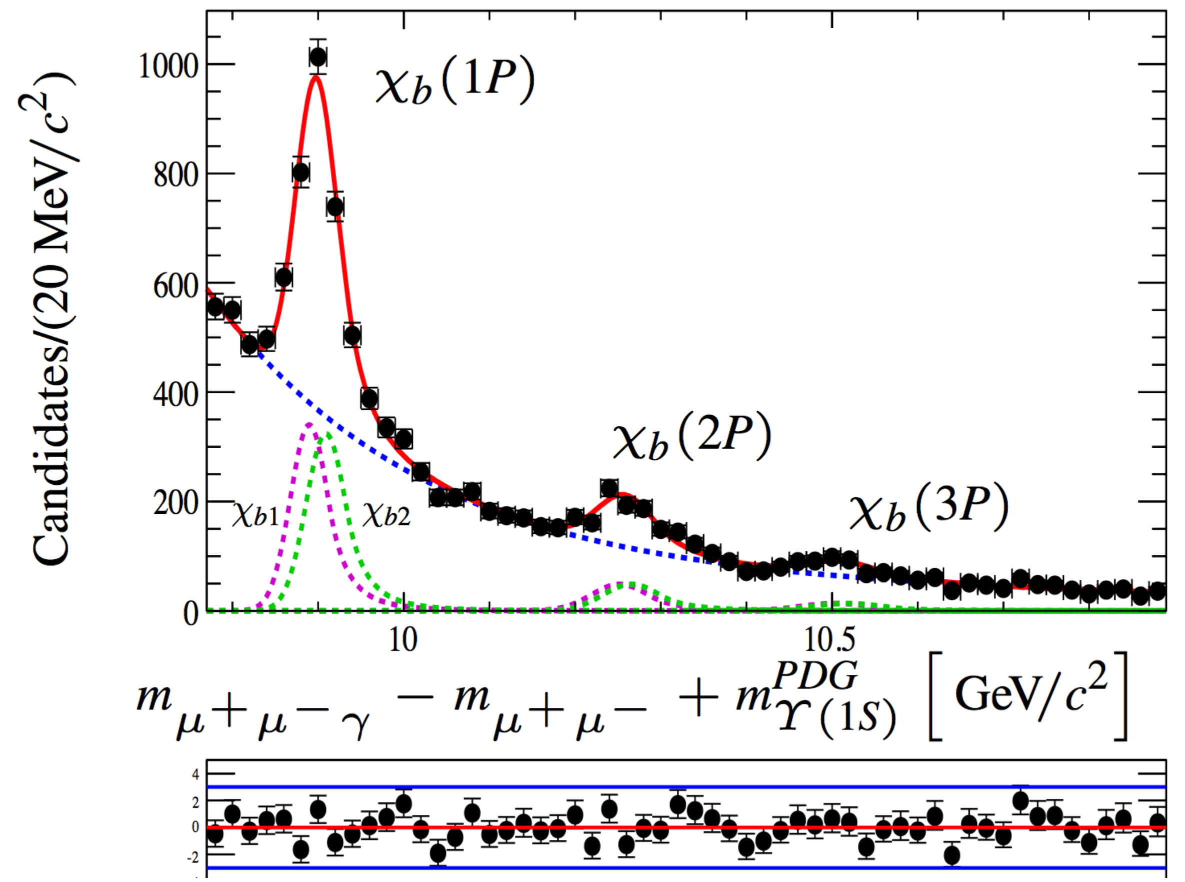
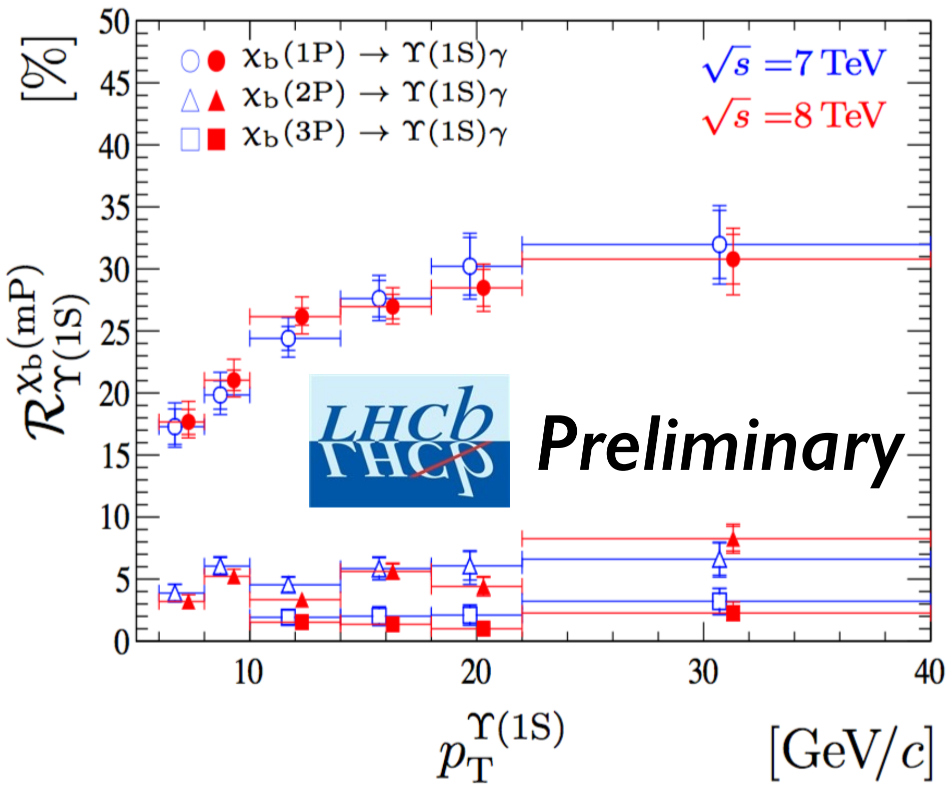
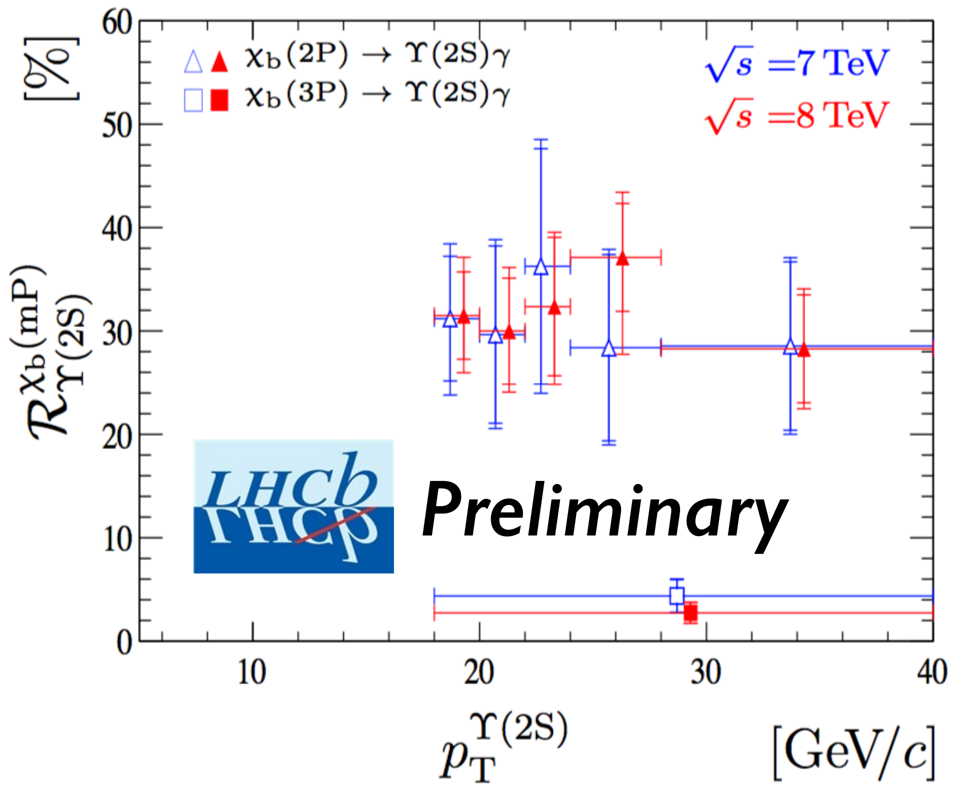


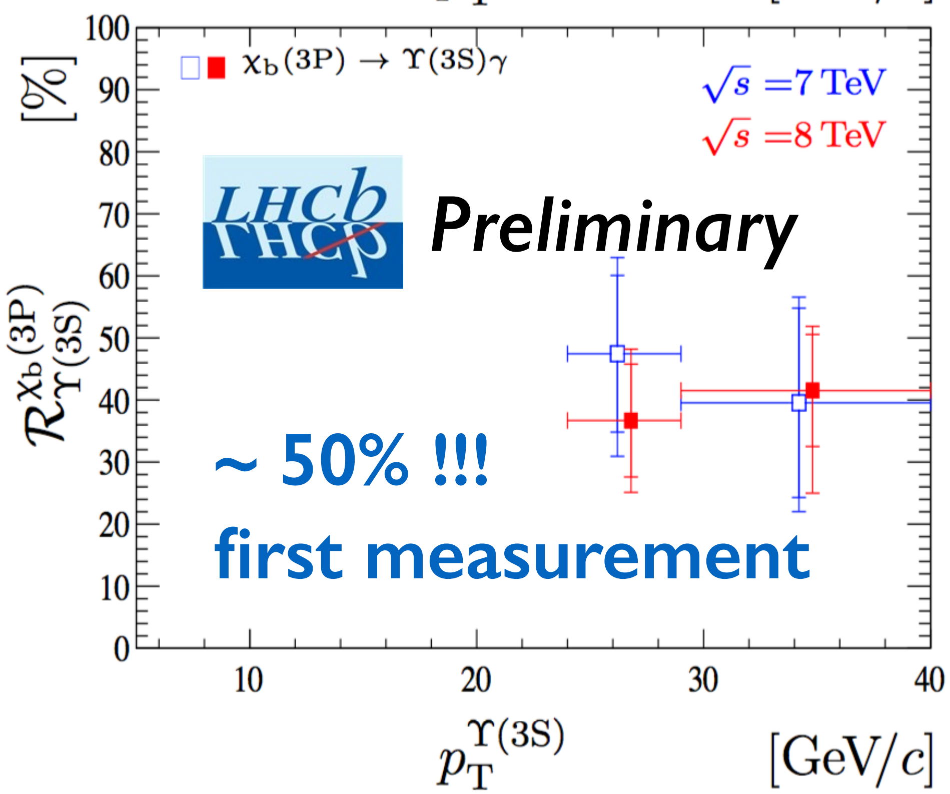
- **calorimetric** γ : « high » stat. / « low » resol.
- b_0 neglected, b_1 and b_2 fitted simultaneously (assume Δm_{12} and N_{b2}/N_{b1})
- main systematics : fit model and γ reconstruction
- analysis with **converted** γ (« low » stat. / « high » resol.) coming soon …

LHCb-PAPER-2014-031
7+8 TeV / 3 fb^{-1}

χ_b's production & decays/3







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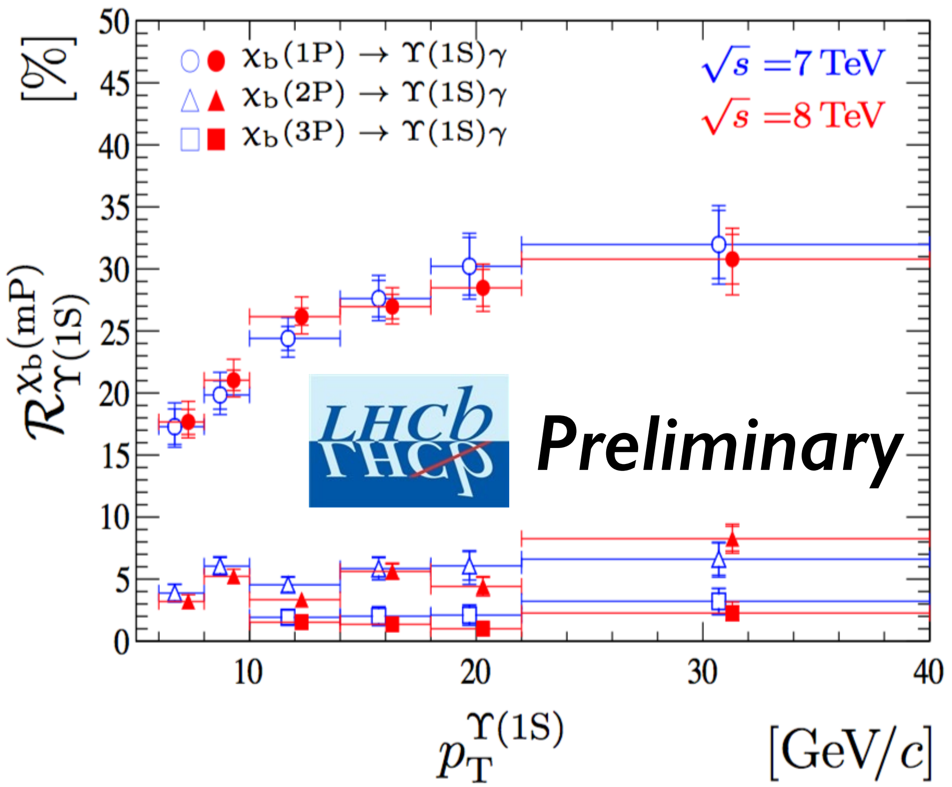
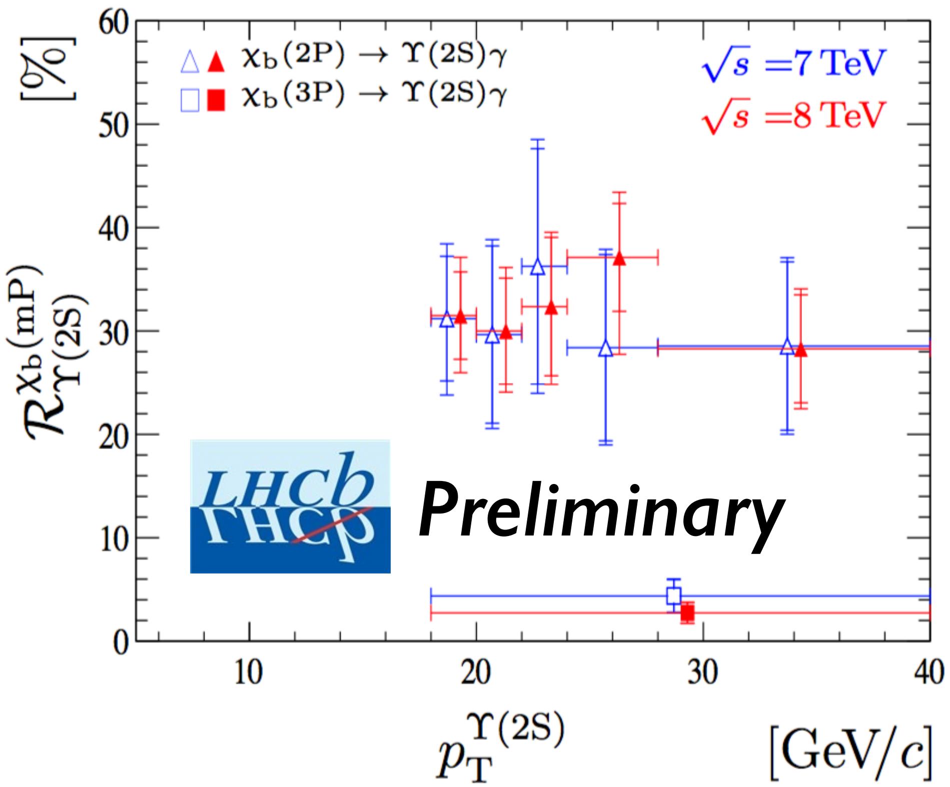
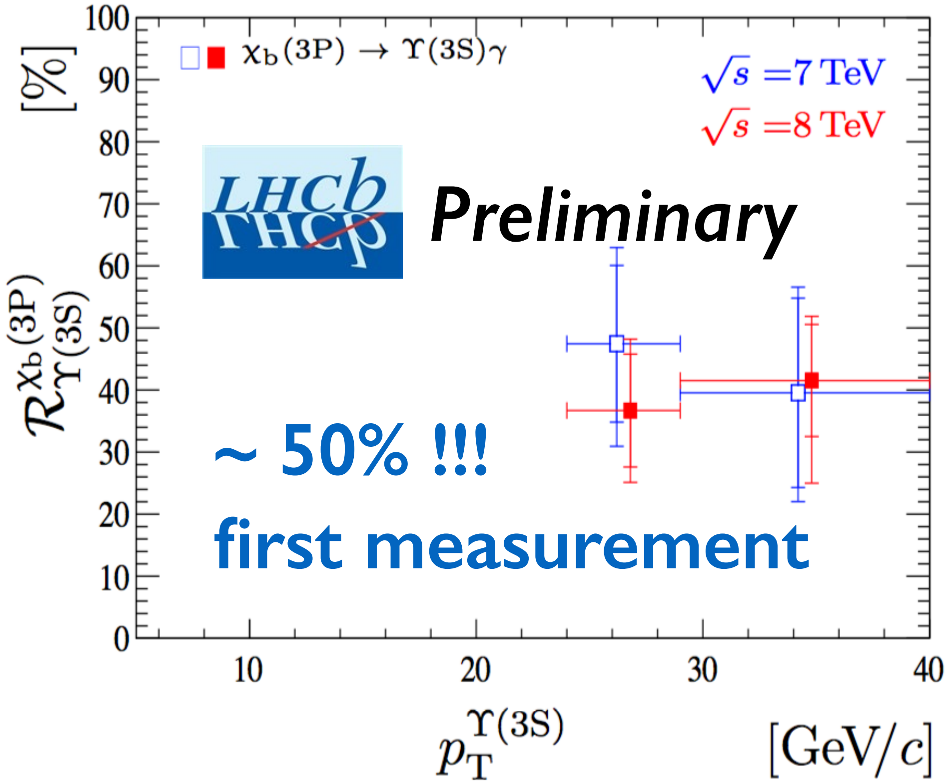






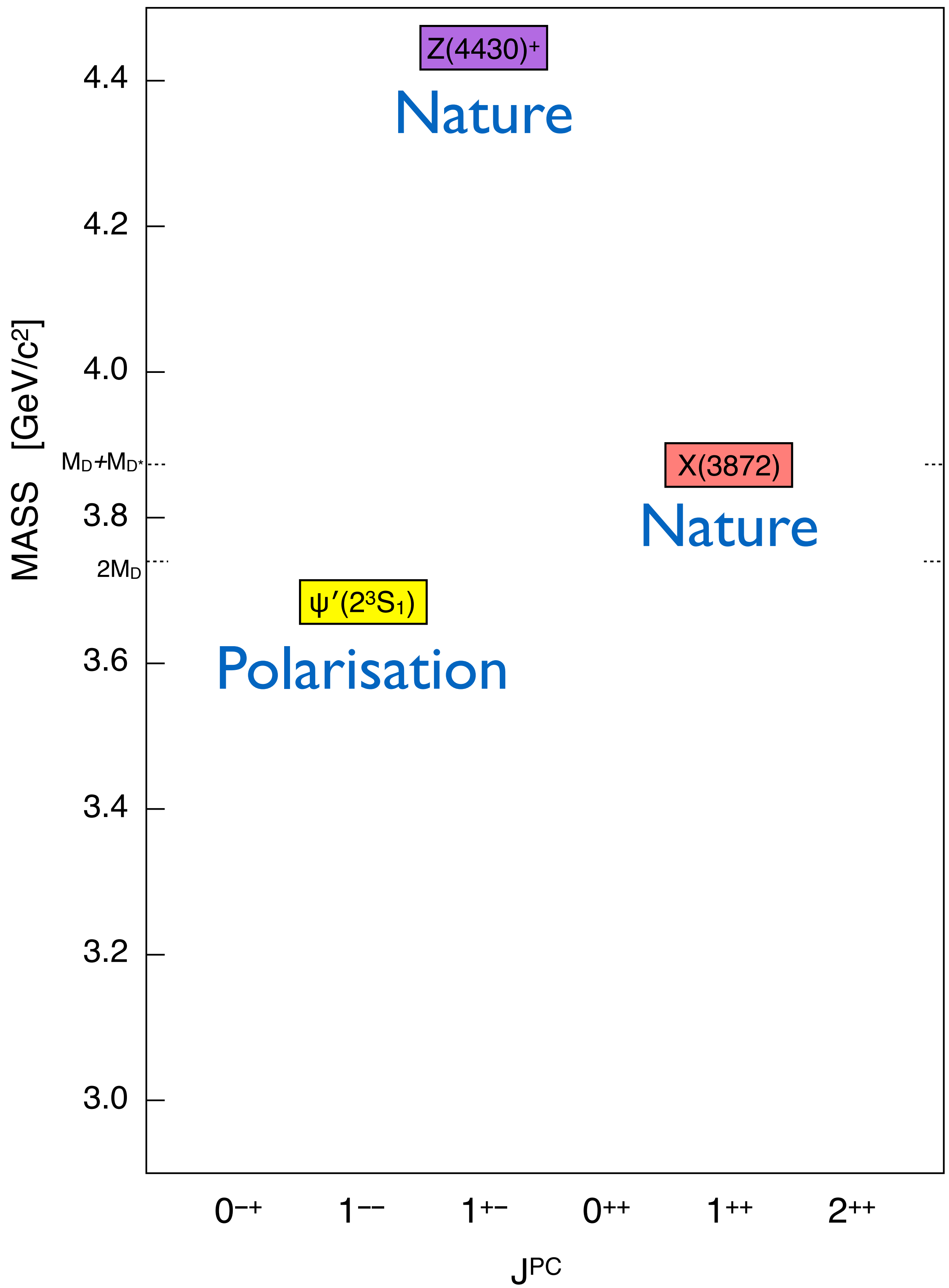
6 χb(mP) → Y(nS) feed-down fractions

including (first) χ_b(3P) → Y(3S)

→ ~ > 30% of Y's are coming from χ_b's

$m_{\chi_{b1}(3P)}$ = 10 511.3 ± 1.7 ± 2.4 MeV/c^2

Conclusions



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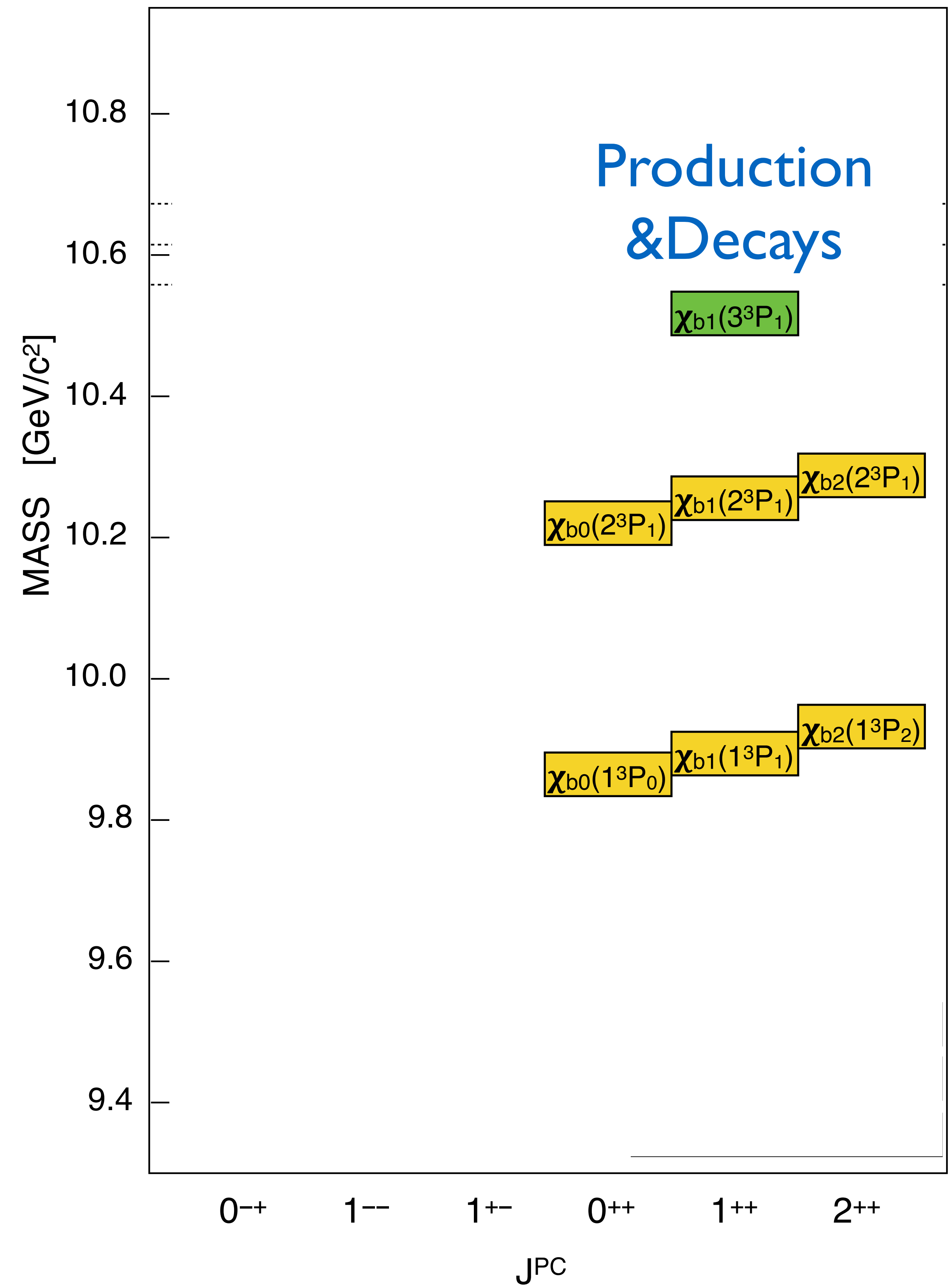
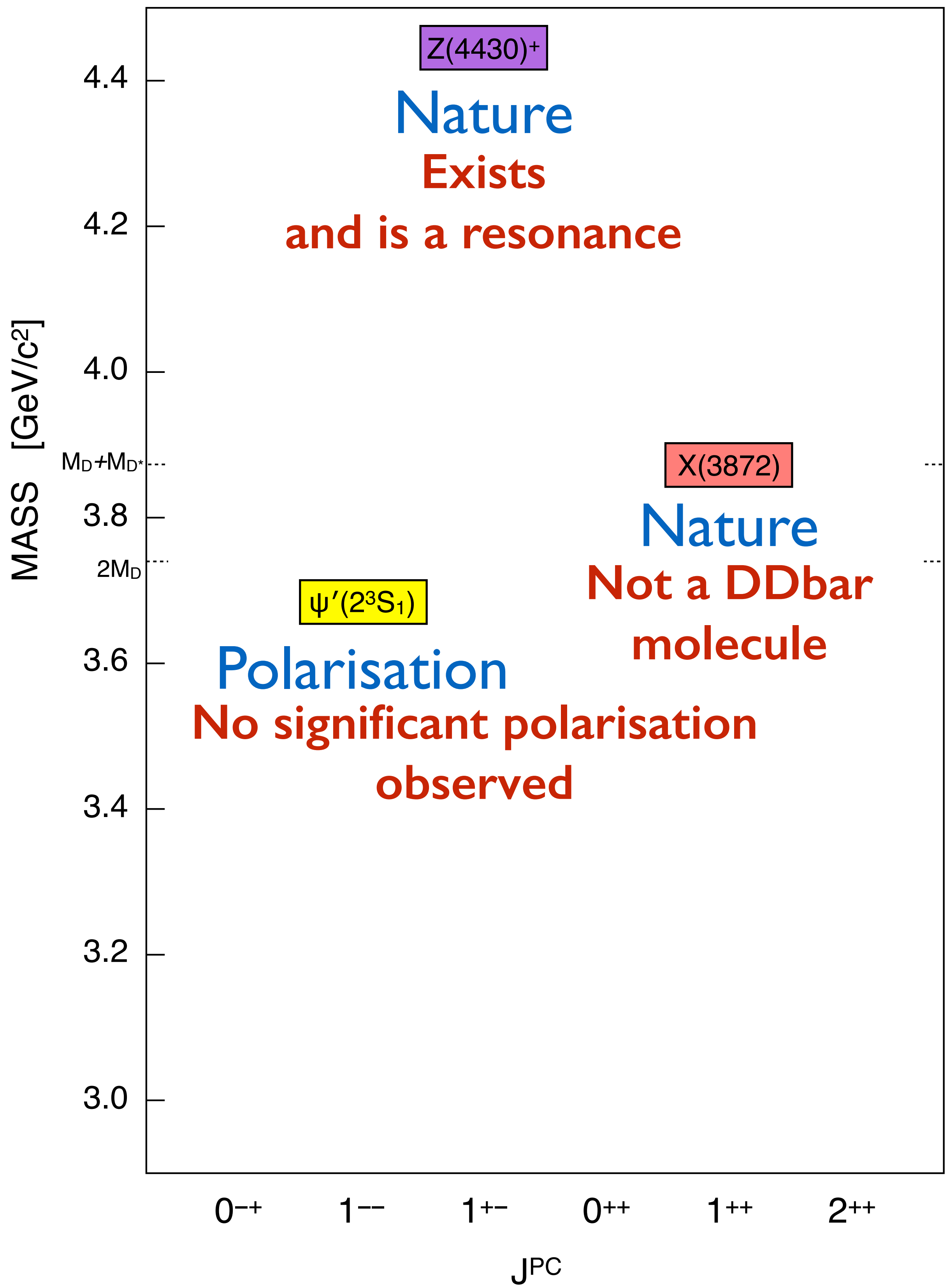


Conclusions



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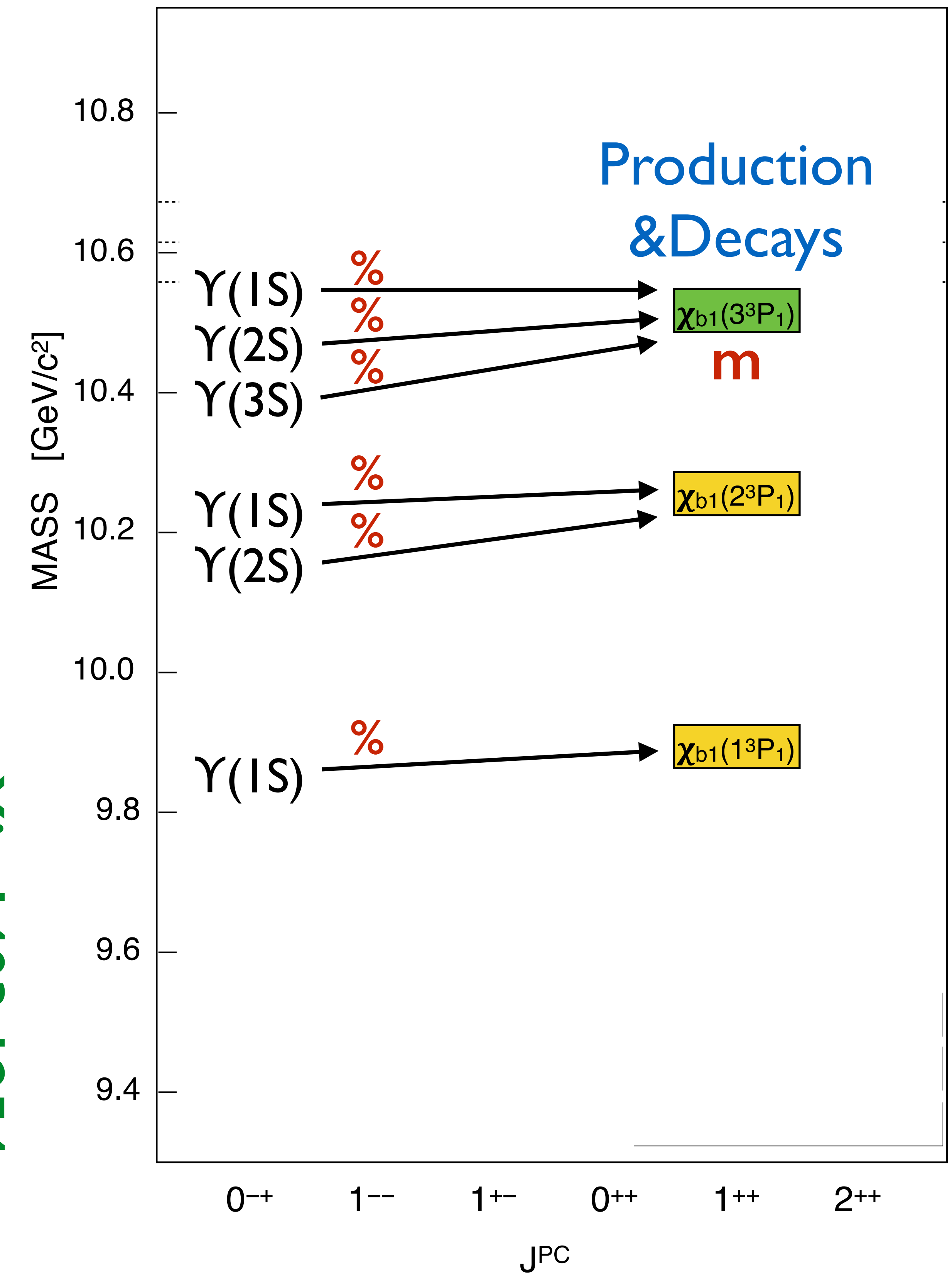


BACKUP

Intro

Charmonium

Term symbol $n^{2S+1}L_J$	$I^G(J^{PC})$	Particle	mass (MeV/c²) [1]
1^1S_0	$0^+(0^{-+})$	$\eta_c(1S)$	2 980.3 ±1.2
1^3S_1	$0^-(1^{--})$	$J/\psi(1S)$	3 096.916 ±0.011
1^1P_1	$0^-(1^{+-})$	$h_c(1P)$	3 525.93 ±0.27
1^3P_0	$0^+(0^{++})$	$\chi_{c0}(1P)$	3 414.75 ±0.31
1^3P_1	$0^+(1^{++})$	$\chi_{c1}(1P)$	3 510.66 ±0.07
1^3P_2	$0^+(2^{++})$	$\chi_{c2}(1P)$	3 556.20 ±0.09
2^1S_0	$0^+(0^{-+})$	$\eta_c(2S)$, or η'_c	3 637 ±4
2^3S_1	$0^-(1^{--})$	$\psi(3686)$	3 686.09 ±0.04
1^1D_2	$0^+(2^{-+})$	$\eta_{c2}(1D)^\dagger$	
1^3D_1	$0^-(1^{--})$	$\psi(3770)$	3 772.92 ±0.35
1^3D_2	$0^-(2^{--})$	$\psi_2(1D)$	
1^3D_3	$0^-(3^{--})$	$\psi_3(1D)^\dagger$	
2^1P_1	$0^-(1^{+-})$	$h_c(2P)^\dagger$	
2^3P_0	$0^+(0^{++})$	$\chi_{c0}(2P)^\dagger$	
2^3P_1	$0^+(1^{++})$	$\chi_{c1}(2P)^\dagger$	
2^3P_2	$0^+(2^{++})$	$\chi_{c2}(2P)^\dagger$	
$?^??_?$	$1^{++\dagger}$	$X(3872)$	3 872.2 ±0.8
$?^??_?$	$?^?(1^{--})$	$Y(4260)$	$4\,263\ ^{+8}_{-9}$

Bottomonium

Term symbol $n^{2S+1}L_J$	$I^G(J^{PC})$	Particle	mass (MeV/c²)[2]
1^1S_0	$0^+(0^{-+})$	$\eta_b(1S)$	9 390.9 ±2.8
1^3S_1	$0^-(1^{--})$	$\Upsilon(1S)$	9 460.30 ±0.26
1^1P_1	$0^-(1^{+-})$	$h_b(1P)$	
1^3P_0	$0^+(0^{++})$	$\chi_{b0}(1P)$	9 859.44 ±0.52
1^3P_1	$0^+(1^{++})$	$\chi_{b1}(1P)$	9 892.76 ±0.40
1^3P_2	$0^+(2^{++})$	$\chi_{b2}(1P)$	9 912.21 ±0.40
2^1S_0	$0^+(0^{-+})$	$\eta_b(2S)$	
2^3S_1	$0^-(1^{--})$	$\Upsilon(2S)$	10 023.26 ±0.31
1^1D_2	$0^+(2^{-+})$	$\eta_{b2}(1D)$	
1^3D_1	$0^-(1^{--})$	$\Upsilon(1D)$	
1^3D_2	$0^-(2^{--})$	$\Upsilon_2(1D)$	10 161.1 ±1.7
1^3D_3	$0^-(3^{--})$	$\Upsilon_3(1D)$	
2^1P_1	$0^-(1^{+-})$	$h_b(2P)$	
2^3P_0	$0^+(0^{++})$	$\chi_{b0}(2P)$	10 232.5 ±0.6
2^3P_1	$0^+(1^{++})$	$\chi_{b1}(2P)$	10 255.46 ±0.55
2^3P_2	$0^+(2^{++})$	$\chi_{b2}(2P)$	10 268.65 ±0.55
3^3S_1	$0^-(1^{--})$	$\Upsilon(3S)$	10 355.2 ±0.5
3^3P_J	$0^+(J^{++})$	$\chi_b(3P)$	10 530 ±5 (stat.) ± 9 (syst.)[4]
4^3S_1	$0^-(1^{--})$	$\Upsilon(4S)$ or $\Upsilon(10580)$	10 579.4 ±1.2
5^3S_1	$0^-(1^{--})$	$\Upsilon(10860)$	10 865 ±8
6^3S_1	$0^-(1^{--})$	$\Upsilon(11020)$	11 019 ±8

This is Wikipedia !!!

Intro

L0

	global	all muons	L0Muon	L0DiMuon
$B^+ \to J/\psi K^+$	$92.5 \pm 0.7\%$	$91.6 \pm 0.7\%$	$91.0 \pm 0.7\%$	$63.3 \pm 2.6\%$

HLT1

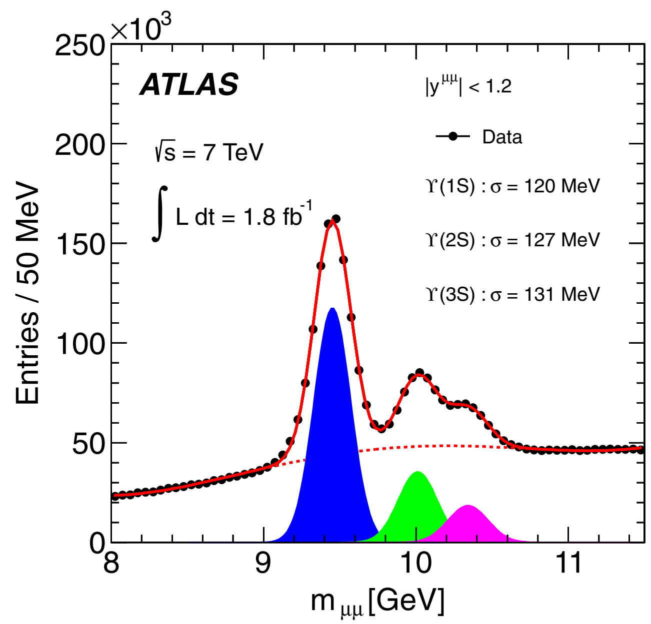
line	prescale	rate [Hz]	$\epsilon(B^+ \to J/\psi K^+)$
Hlt1Physics	1	36 000	$95.1 \pm 0.6\%$
Hlt1TrackMuon	1	5000	$80.5 \pm 1.0\%$
Hlt1SingleMuonHighPT	1	700	$23.9 \pm 1\%$
Hlt1DiMuonHeavy	1	1200	$75.5 \pm 1.0\%$
Hlt1DiMuonLowMass	1	1300	$71.2 \pm 1.1\%$

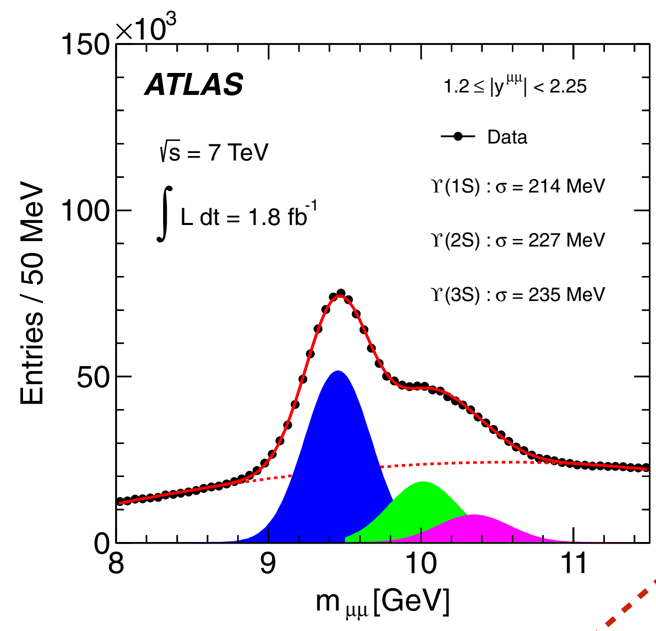
HLT2

line	prescale	rate [Hz]	$\epsilon(B^+ \to J/\psi K^+)$
Hlt2Physics	-	3200	$96.5 \pm 0.5\%$
Hlt2SingleMuon	0.5	483	$34.0 \pm 1.5\%$
Hlt2SingleMuonHighPT	1	45	$4.7 \pm 0.5\%$
Hlt2DiMuonJPsi	0.2	51	$91.0 \pm 0.7\%$
Hlt2DiMuonJPsiHighPT	1	113	$59.4 \pm 1.2\%$
Hlt2DiMuonDetached	1	71	$69.2 \pm 1.1\%$
Hlt2DiMuonDetachedHeavy	1	75	$87.6 \pm 0.8\%$
Hlt2DiMuonDetachedJPsi	1	36	$88.9 \pm 0.8\%$
Hlt2DiMuonPsi2S	1	4	-
Hlt2DiMuonPsi2SHighPT	1	15	-
Hlt2DiMuonB	1	81	-
Hlt2TriMuonDetached	1	2	-
Hlt2TriMuonTau	1	1	-

Intro

Comparison of mass resolutions (with Υ) 6

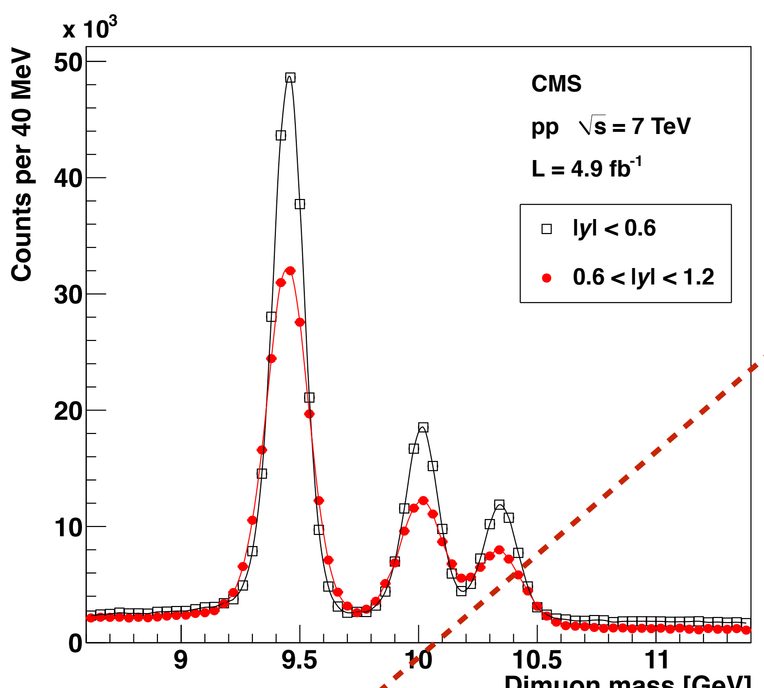




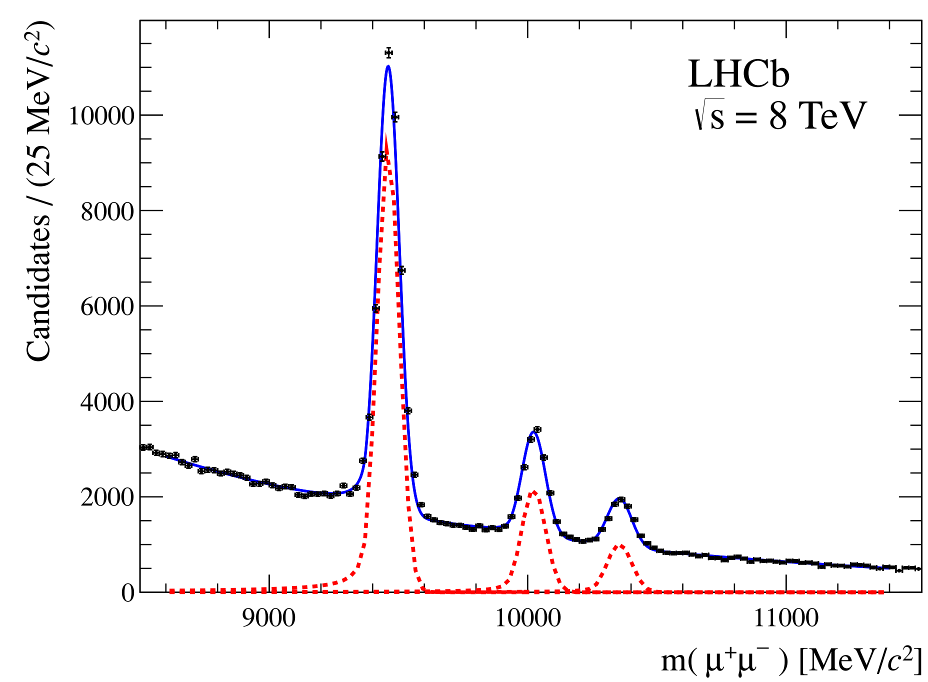
Good…

J. Catmore is NOT a member of LHCb

…better…

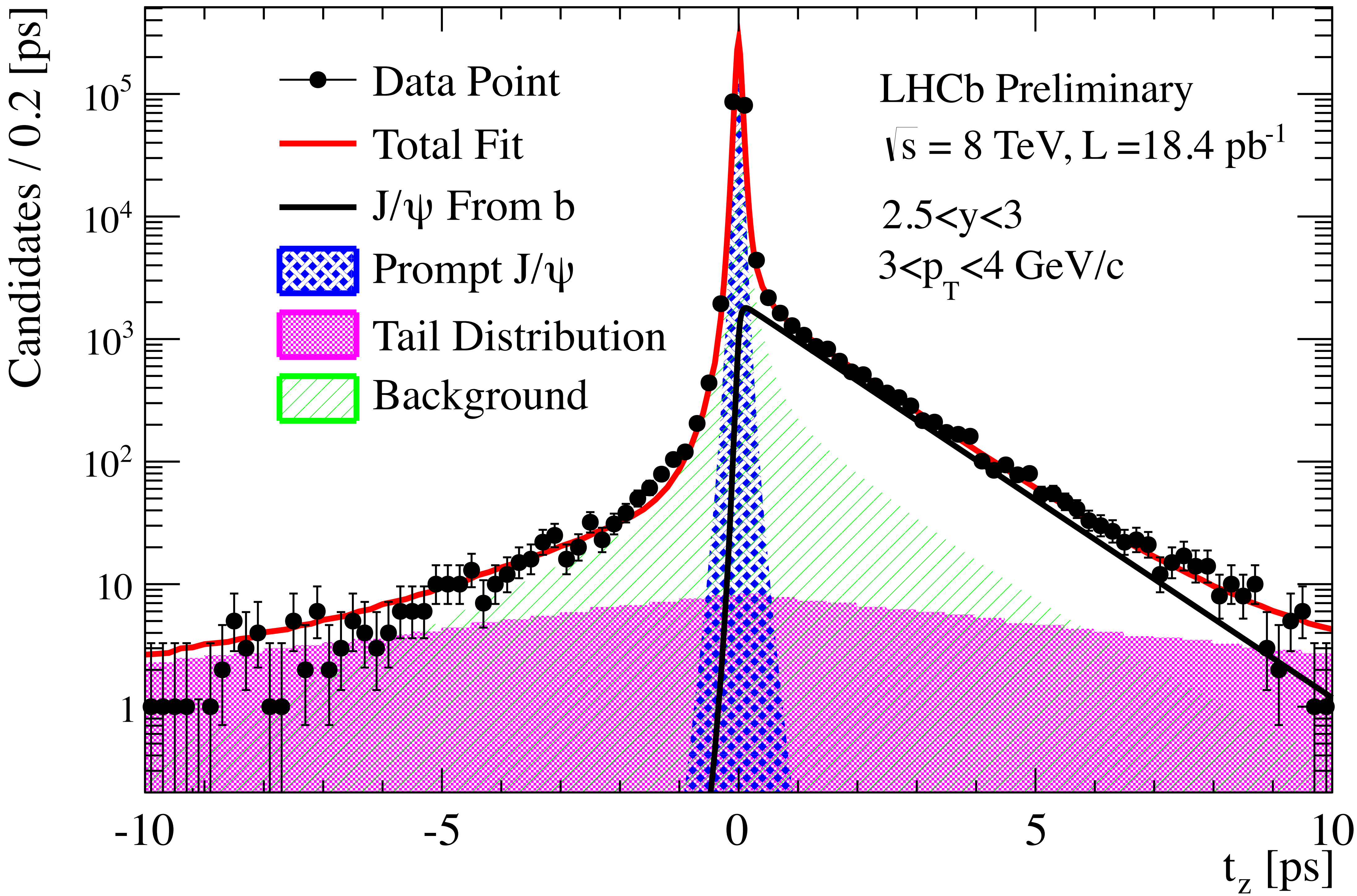


…best



James Catmore Quarkonia measurements: the State of the Art FPCP 2014 - Marseille, France

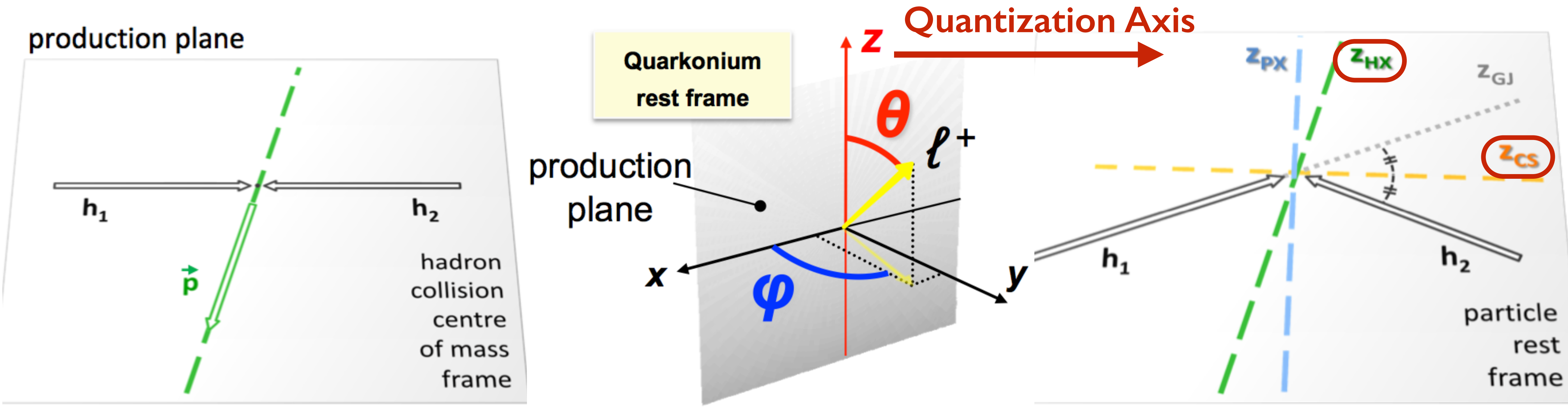
Intro



J/Ψ proper time :

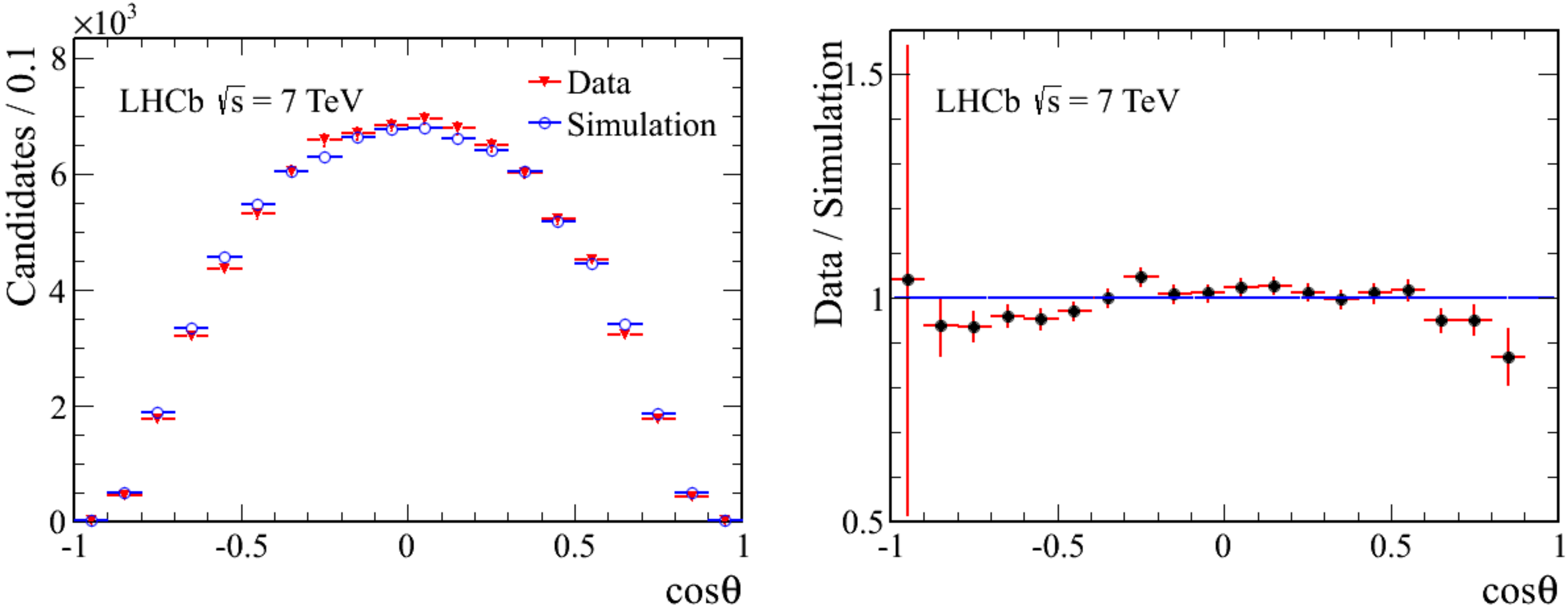
$t_z = (z_{J/\psi} - z_{PV}) \times M_{J\psi} / p_z$

Ψ'



Helicity Axis (HX): quarkonium momentum direction
Gottfried-Jackson Axis (GJ): direction of one or other beam
Collins-Soper Axis (CS): average of the two beam directions
Perpendicular Helicity Axis (PX): perpendicular to CS

Ψ'



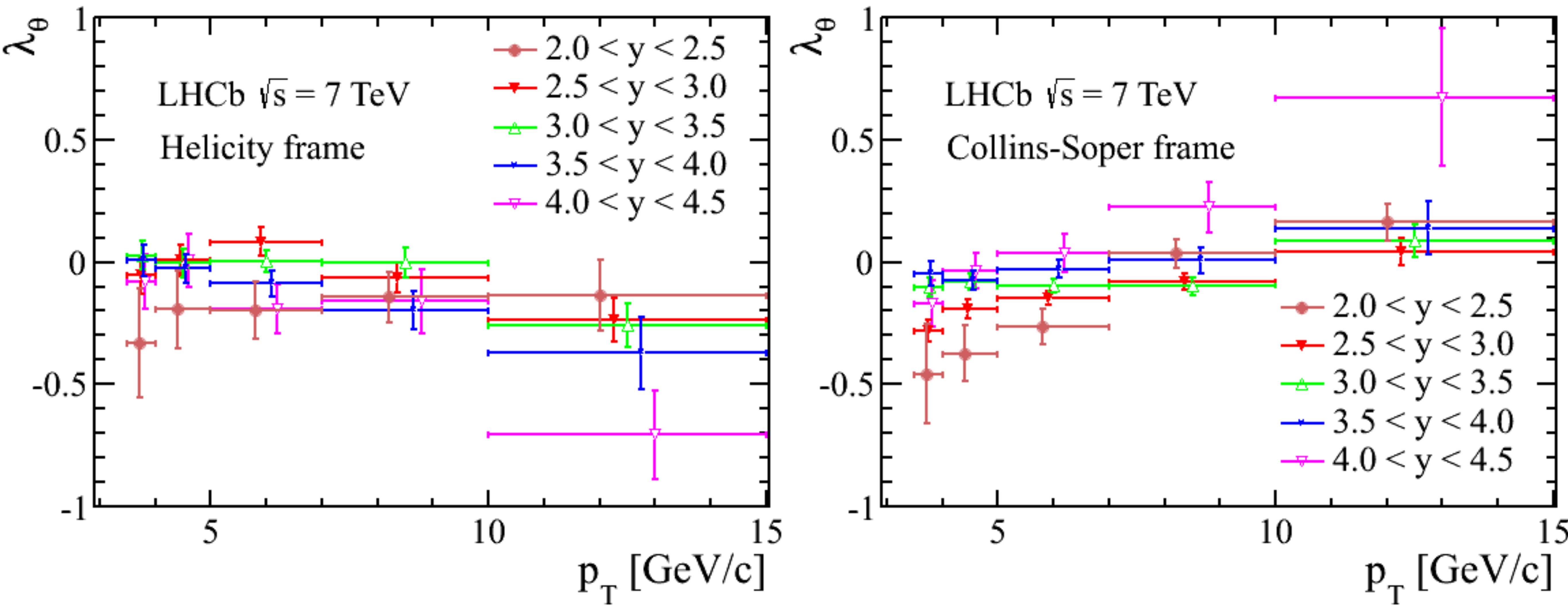
HX frame : for J/Ψ from $B^+ \rightarrow J/\Psi\, K^+$

(J/Ψ long. polar. in B^+ rest frame)

Ratio : after reweighting for B^+ and J/Ψ kinematics

remaining ≠ : detector response modeling

ψ'



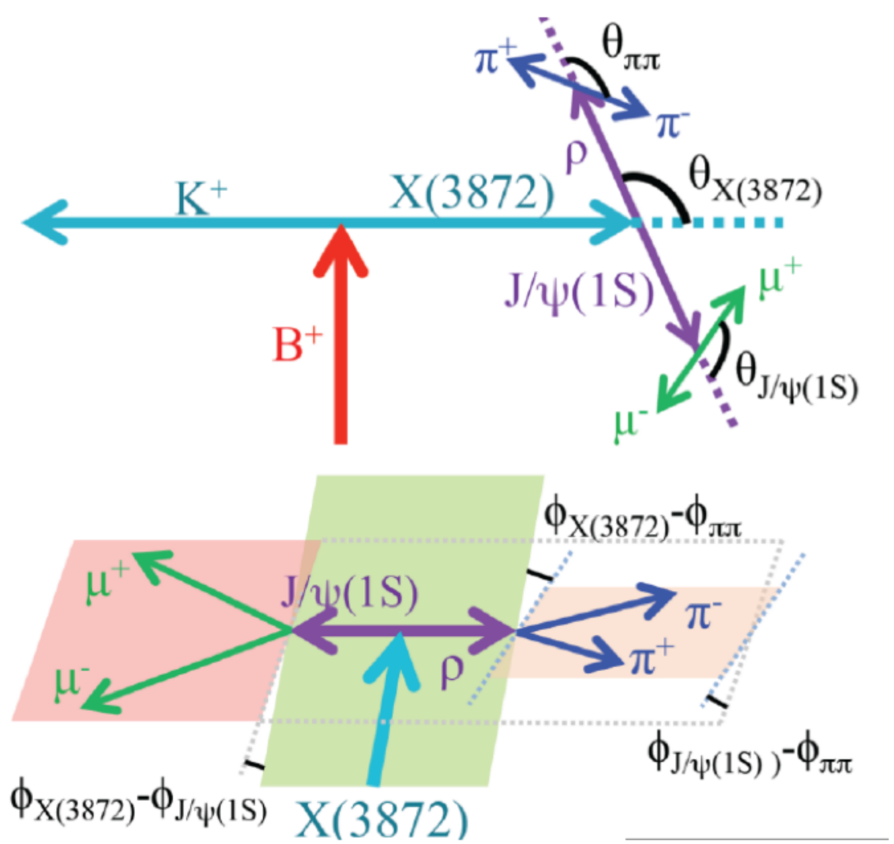
LHCb $\sqrt{s}$ = 7 TeV
Helicity frame
λ_θ
p_T [GeV/c]
2.0 < y < 2.5
2.5 < y < 3.0
3.0 < y < 3.5
3.5 < y < 4.0
4.0 < y < 4.5
LHCb $\sqrt{s}$ = 7 TeV
Collins-Soper frame
λ_θ
p_T [GeV/c]
2.0 < y < 2.5
2.5 < y < 3.0
3.0 < y < 3.5
3.5 < y < 4.0
4.0 < y < 4.5

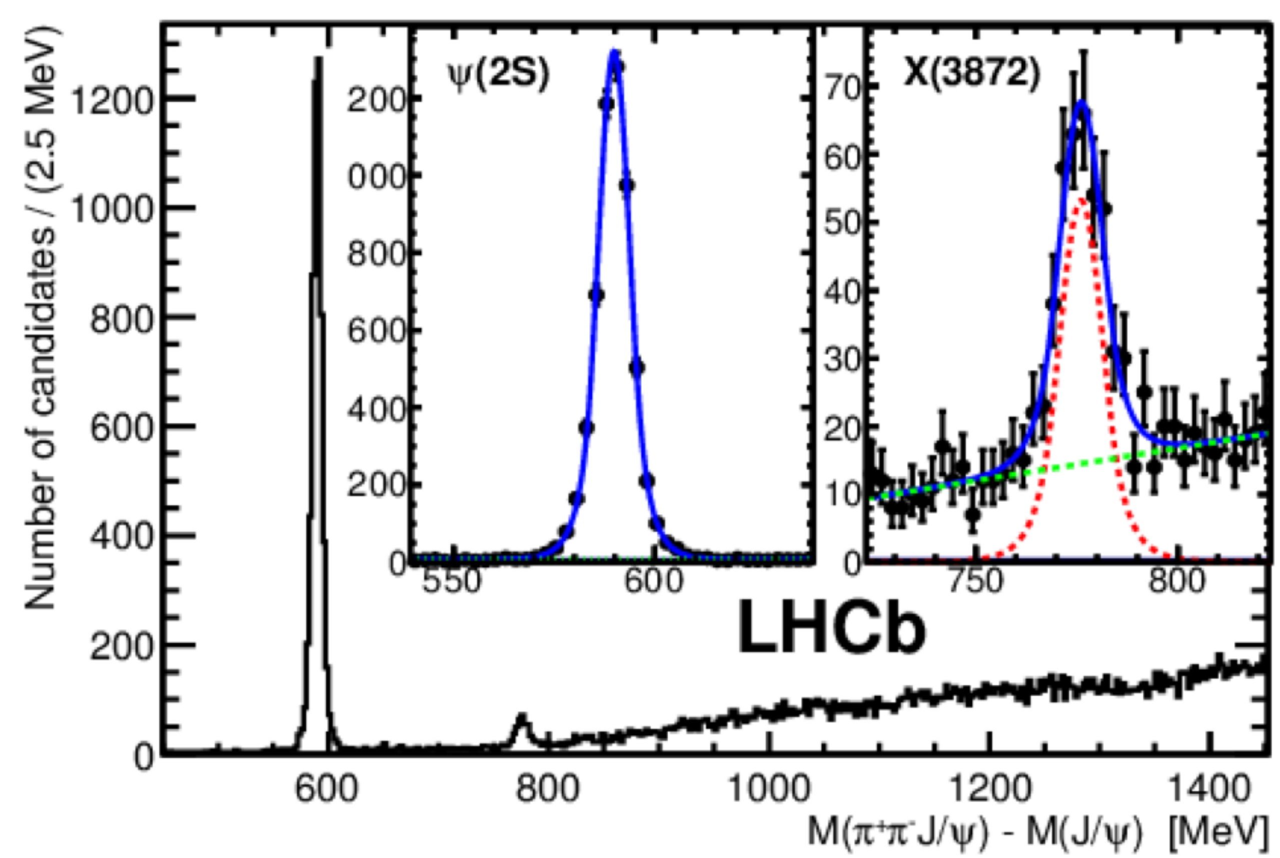
X(3872)

X(3872) quantum numbers determination

Phys. Rev. Lett. 110, 222001 (2013)

- Using the 1.0 fb^{-1} dataset recorded by LHCb in 2011
- 313 ± 26 $B^+ \to K^+ X(3872)$ with $X(3872) \to J/\psi\pi^+\pi^-$.
- 5642 ± 76 $B^+ \to K^+ \psi(2S)$ with $\psi(2S) \to J/\psi\pi^+\pi^-$.
- 5D analysis: all angular correlations used to measure X(3872) J^{PC}

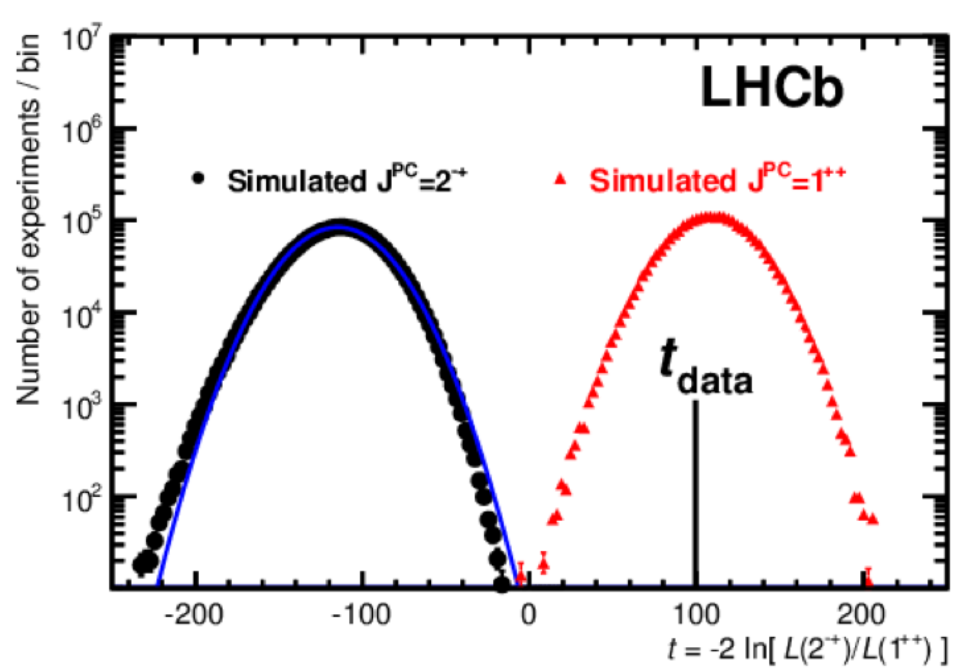


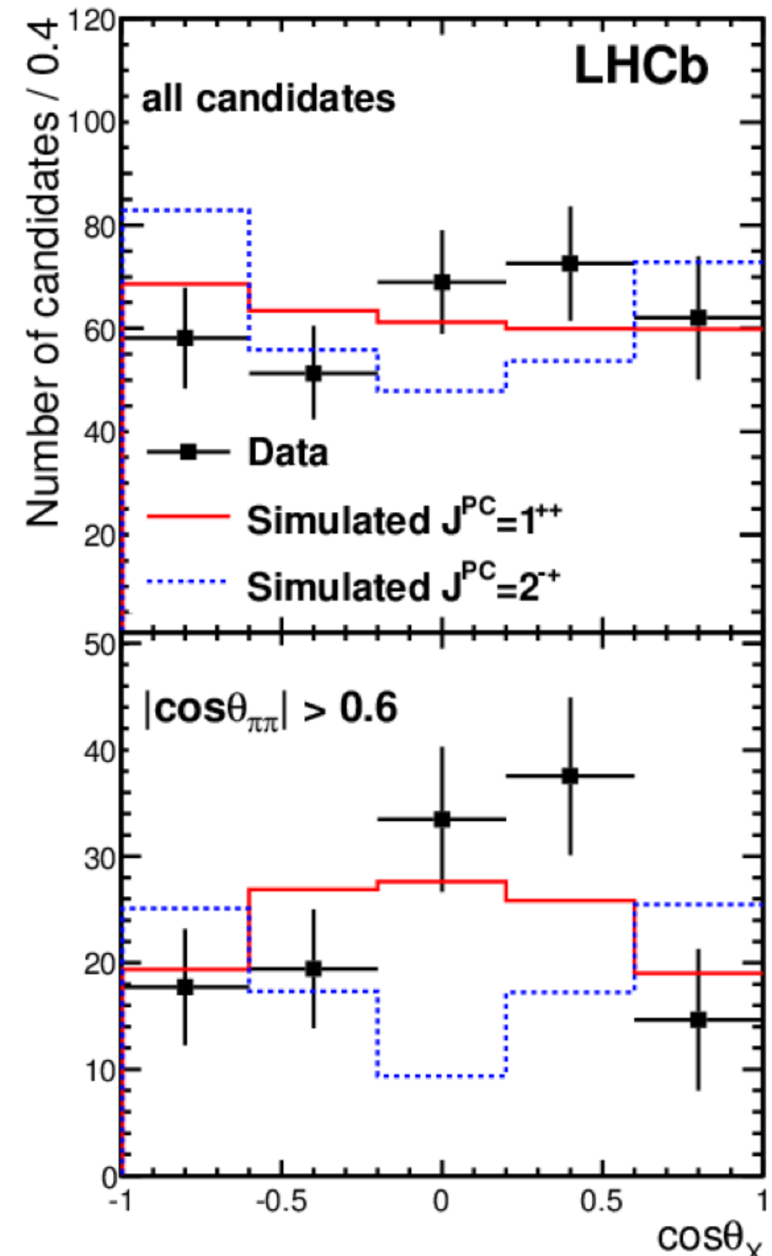


X(3872) quantum numbers determination

Phys. Rev. Lett. 110, 222001 (2013)

- Two X(3872) J^{PC} configurations are considered: 1^{++} and 2^{-+};
- Likelihood-ratio test, to discriminate between the assignments;
- Compare the results to simulated experiments;
- Data favour the 1^{++} over the 2^{-+} hypothesis at 8.4σ;

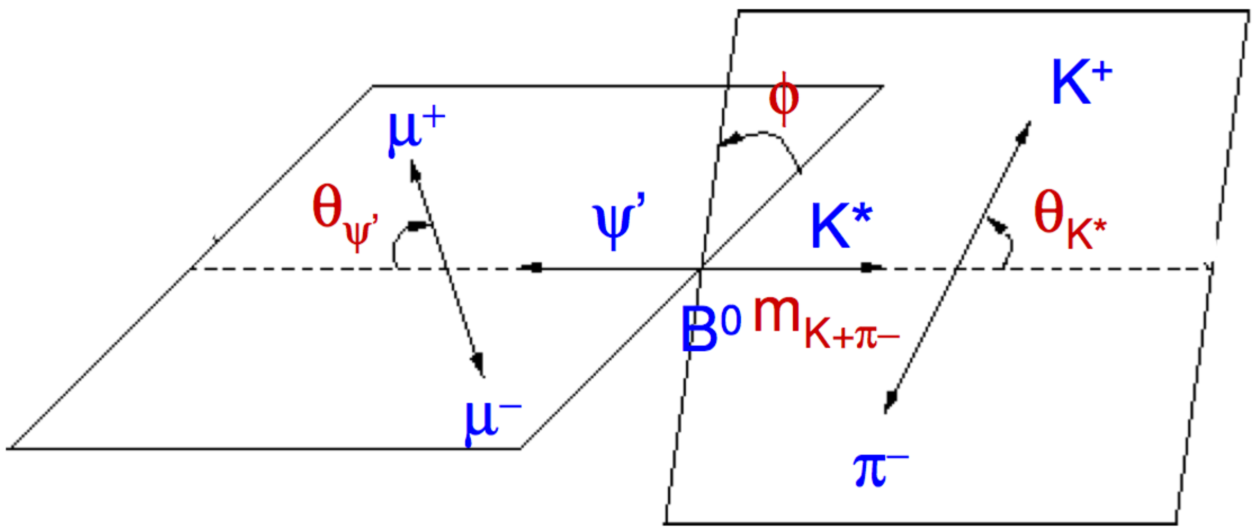




This result favours the interpretations of X(3872) as an exotic state.

Z(4430)

$Z(4430)^-$ in LHCb:
4D model dependent amplitude analysis (a la Belle)



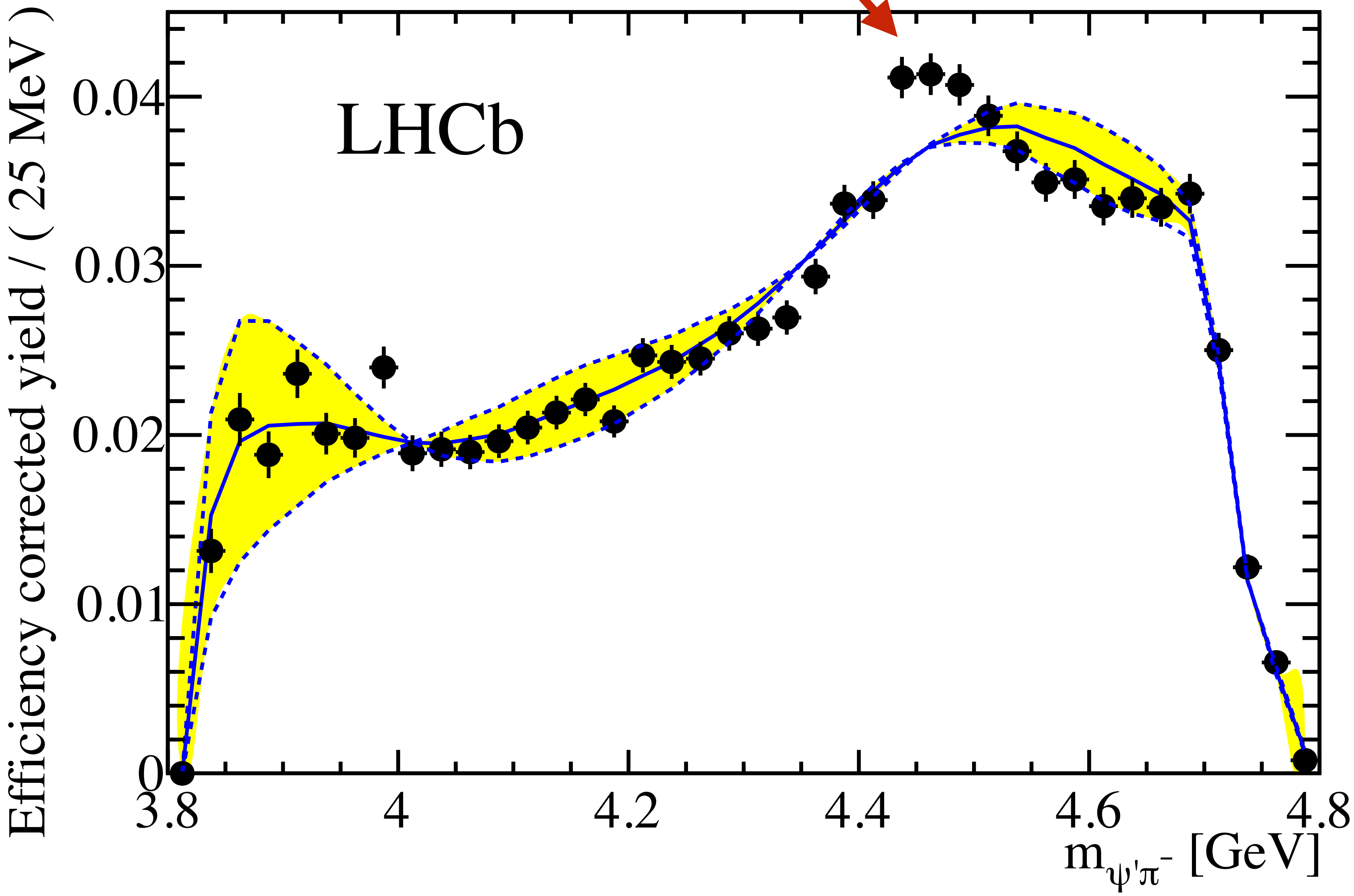
(or $m_{K+\pi-}{}^2$, $m_{\psi'\pi-}{}^2$)

$Z(4430)^-$ amplitude parameterized in different angles derivable from the angles in the K* decay chain

- Amplitude model:
  - Construct decay matrix elements as a sum of quasi-two-body $B^0 \to \psi' K^{*0}$ and $B^0 \to Z^- K^+$ components.
  - Each resonance represented as Breit-Wigner amplitude ("Isobar model") and J dependent angular terms.
  - Allow all known $K^{*0} \to K^+\pi^-$ resonances with $J \leq 3$ (higher J states are above the kinematic K* mass limit and suppressed by orbital angular momentum barrier in the B^0 decay) with masses and widths constrained to the PDG values; fit their complex helicity amplitudes.
  - Two different J=0 ("S-wave") parameterizations (Isobar and LASS).
  - Study K* model dependence for systematic errors.
- Fit method:
  - Use two different methods of implementing efficiency corrections and of non-B^0 background parameterization.
  - Perform unbinned maximum likelihood fit of free model parameters to the 4D data.
  - Discriminate between various amplitude models using the likelihood ratio test:
    - $\Delta(-2\ln L)$ is a test statistic
    - generate and fit pseudo-experiment to predict probability density distribution under each amplitude hypothesis
  - Also evaluate goodness-of-fit by calculating a χ^2 value between the data and the fit using adaptive 4D binning.

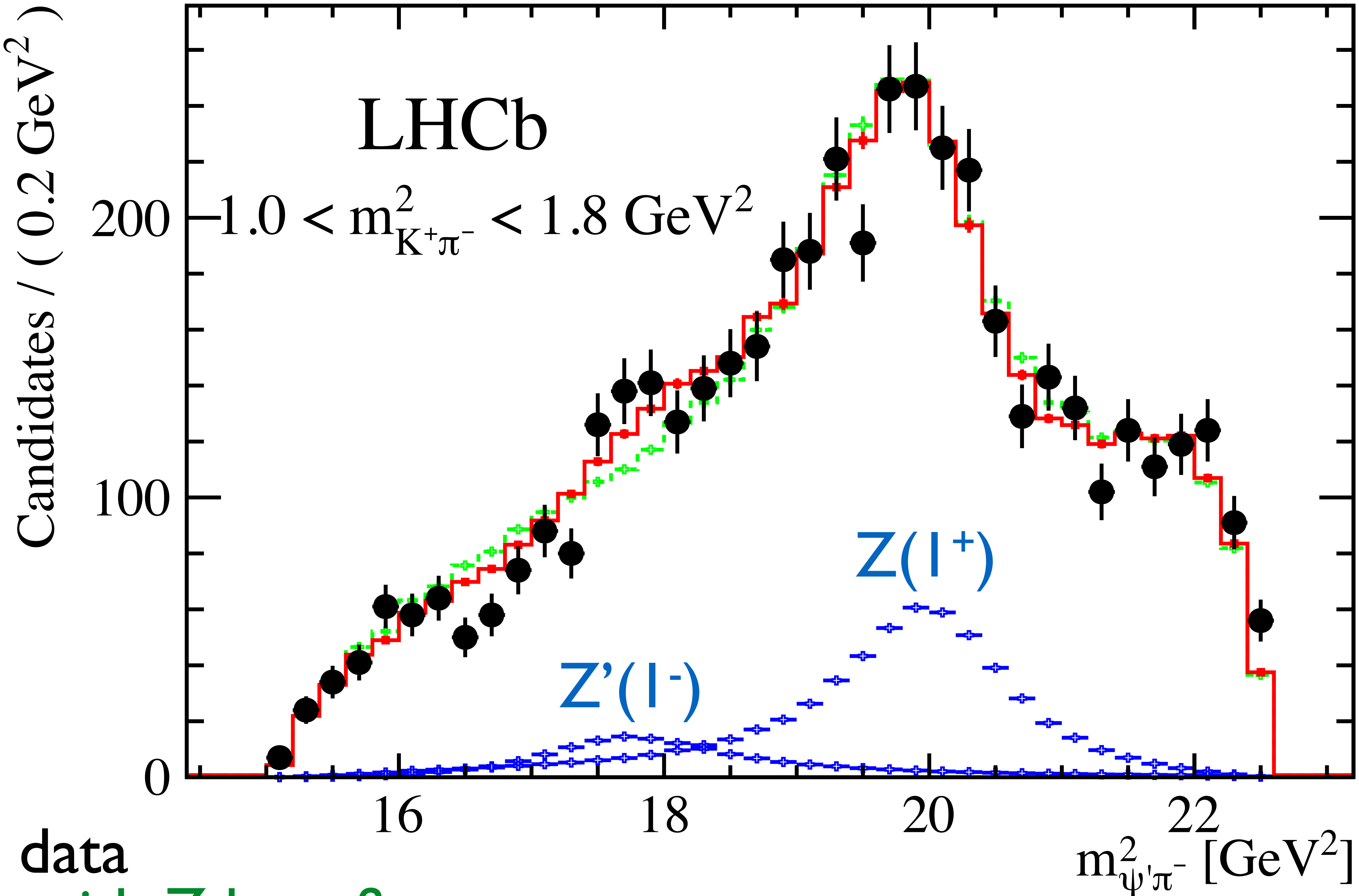
Z(4430)

Independent analysis (à la Babar)
No constrains on combinations of K^*
But $J(K^*) \leq 2$



Black dots : data
Blue line : reflections of $\cos\theta_{K^*}$ moments
Yellow band : (stat.) errors

Z(4430)

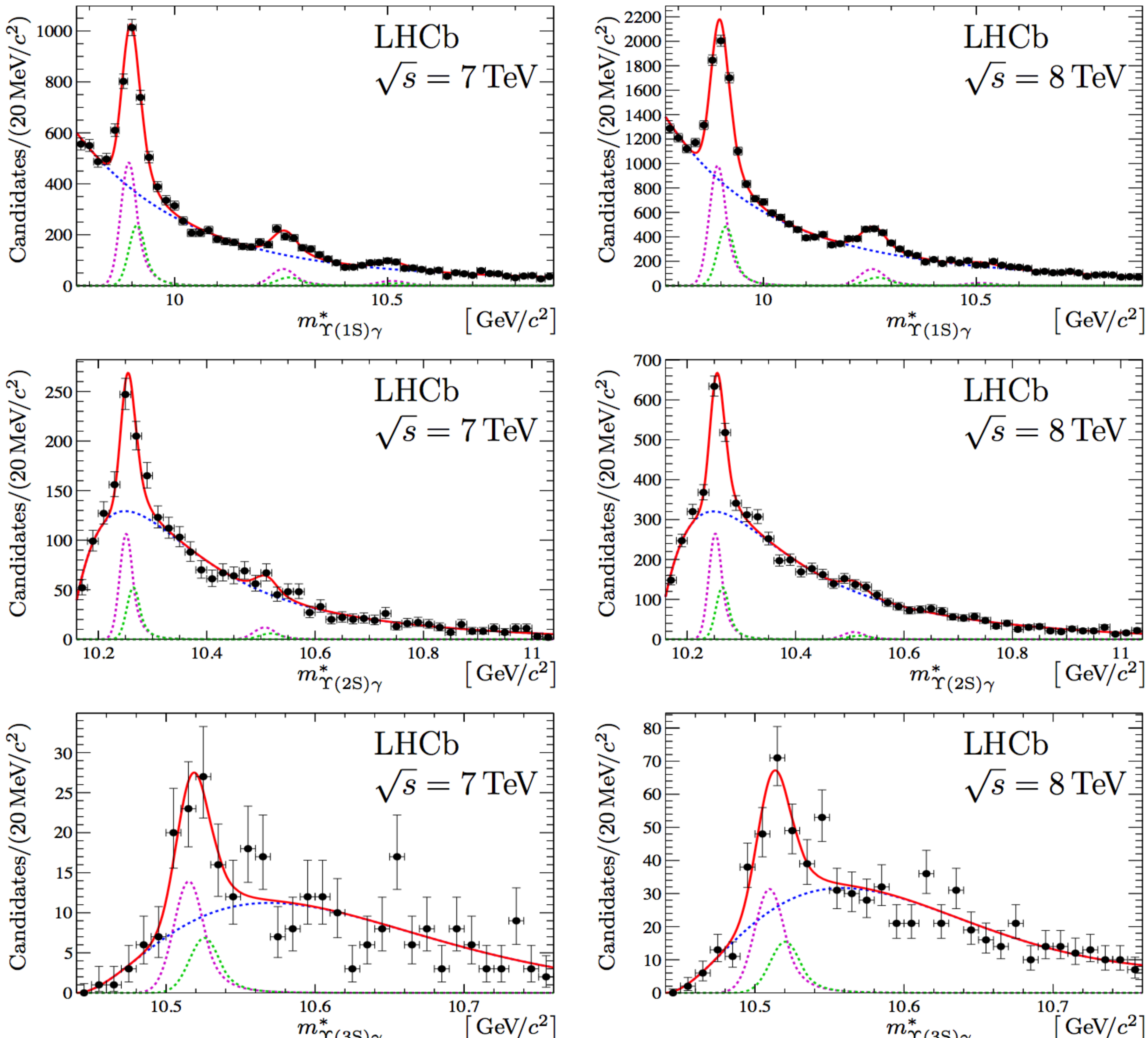


- data

with Z best fit

with Z and Z' best fit (better $p_{\chi 2}$ but … mod. indepdt, Argand plot, etc …)

χ_b's



with $m^*_{\Upsilon(nS)\gamma} = m_{\Upsilon(nS)\gamma} - (m_{\Upsilon(nS)} - m^0_{\Upsilon(nS)})$ - $m^0_{\Upsilon(nS)}$ from PDG

LHCb luminosity projection