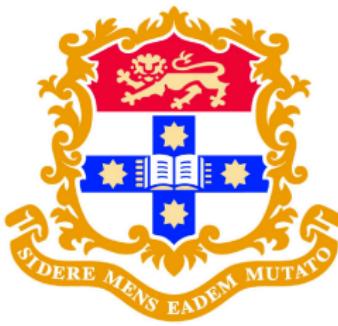


# Conventional and exotic charmonium production at the ATLAS experiment

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(<http://www.coepp.org.au/>)

CHARM 2015, 18th May, Wayne State University, Detroit



ARC Centre of Excellence for  
Particle Physics at the Terascale

# Outline

## 1 Hidden flavour production at ATLAS

- physics motivation
- experimental environment and techniques

## 2 $\Upsilon(nS)$ production cross-sections at 7 TeV

## 3 Search for a $X_b \rightarrow \pi^+ \pi^- \Upsilon$ signal

- summary of the analysis
- results as a function of mass
- interpretation and plans

## 4 $\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$ at 7 TeV

## 5 $\chi_{c1}$ and $\chi_{c2}$ production at 7 TeV

## 6 Summary

- 
- lots in the backup: ask me a question!

# Hidden flavour production

from CHARM 2013 / Manchester:

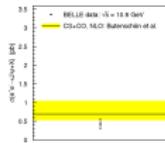


## Overview: Three J/ $\psi$ Production Works

e+e- yield:

**Butenschön, Kniehl:**

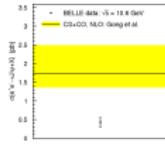
$$\begin{aligned}\langle O_0^{(v)}(^1S_0) \rangle &= 0.0497 \text{ GeV}^2 \\ \langle O_1^{(v)}(^3S_1) \rangle &= -0.0022 \text{ GeV}^2 \\ \langle O_2^{(v)}(^3P_0) \rangle &= -0.0181 \text{ GeV}^2\end{aligned}$$



yp yield:

**Gong, Wan, J.-X. Wang,  
H.-F. Zhang:**

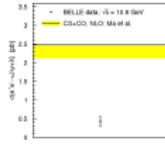
$$\begin{aligned}\langle O_0^{(v)}(^1S_0) \rangle &= -0.097 \text{ GeV}^2 & \langle O_0^{(v)}(^1S_0) \rangle &= -0.0001 \text{ GeV}^2 \\ \langle O_1^{(v)}(^3S_1) \rangle &= -0.0046 \text{ GeV}^2 & \langle O_1^{(v)}(^3S_1) \rangle &= 0.0034 \text{ GeV}^2 \\ \langle O_2^{(v)}(^3P_0) \rangle &= -0.0214 \text{ GeV}^2 & \langle O_2^{(v)}(^3P_0) \rangle &= 0.0095 \text{ GeV}^2 \\ \langle O_3^{(v)}(^3S_1) \rangle &= 0.0022 \text{ GeV}^2\end{aligned}$$



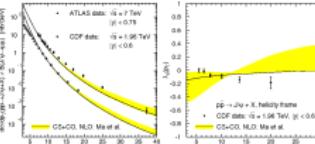
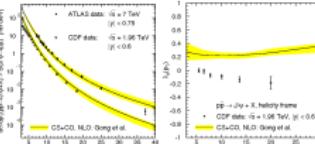
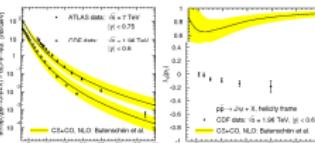
pp yield:

**Chao, Ma, Shao, K. Wang,  
Y.-J. Zhang:**

$$\begin{aligned}\langle O_0^{(v)}(^1S_0) \rangle &= -0.089 \text{ GeV}^2 \\ \langle O_1^{(v)}(^3S_1) \rangle &= -0.003 \text{ GeV}^2 \\ \langle O_2^{(v)}(^3P_0) \rangle &= 0.0126 \text{ GeV}^2\end{aligned}$$



CDF polariz.:



M. Butenschön

Theory of Charmonium Production

15/21

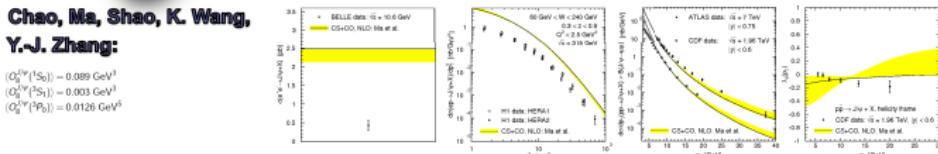
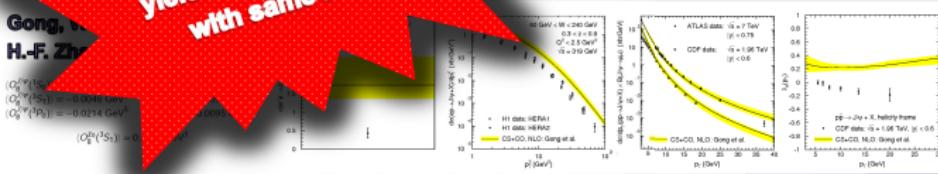
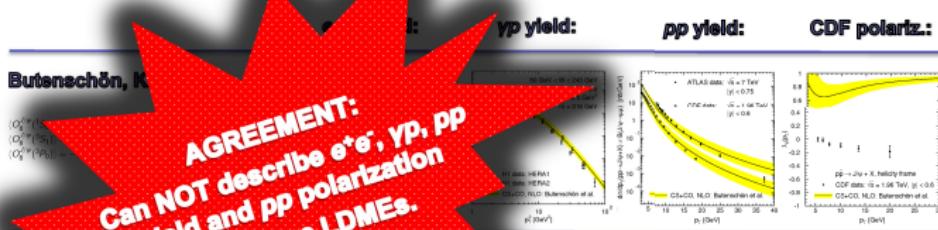
## Hidden flavour production

from CHARM 2013 / Manchester:



## Overview: Three J/ $\psi$ Production Works

Can NOT describe  $e^+e^-$ ,  $pp$ ,   
yield and  $pp$  polarization  
with same LDMEs.



M. Butenschön

Theory of Charmonium Production

15/21



from CHARM 2013 / Manchester:

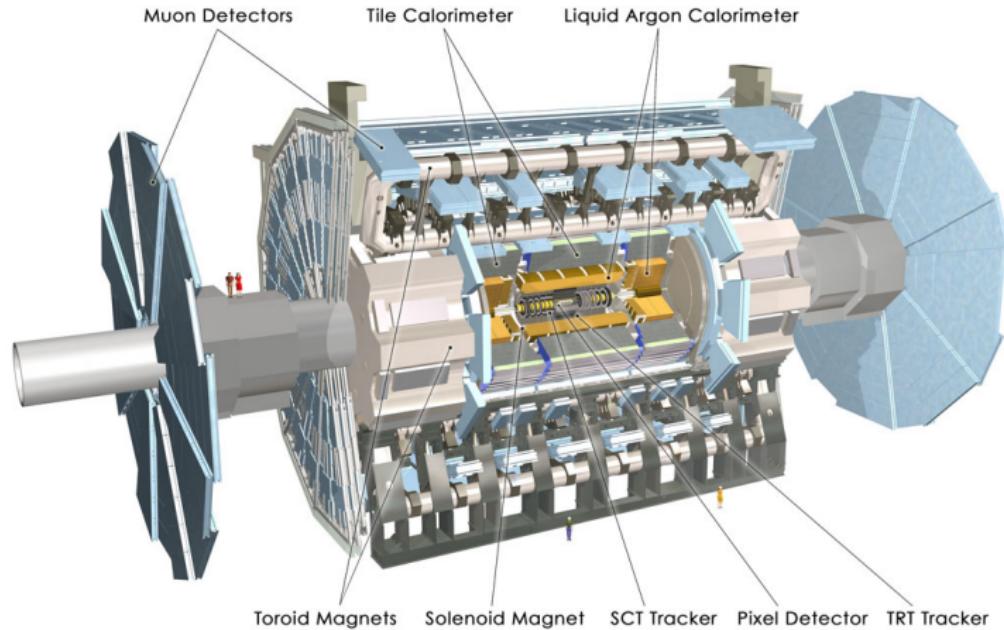


## Summary

- 40 years after  $J/\psi$  discovery:  
Still **no successful description** of charmonium production!
- Traditional color singlet model:
  - Can successfully describe **only  $e^+e^-$  data**
  - Theoretically **incomplete** due to uncancelled IR divergences
- **NRQCD factorization** based on solid effective field theory approach, but
  - Factorization theorem not yet proven (IR safe to all orders?)
  - Current NLO analyses in combination with recent polarization measurements cast doubt on LDME universality.
- Possible **ways out**:
  - NRQCD factorization **may not hold** in all kinematic regions / for all observables
  - Resummation of **large logarithms**  $p_T^2/m_c^2$  (large  $p_T$  resummation)
  - Apply  **$k_T$  dependent** PDFs.

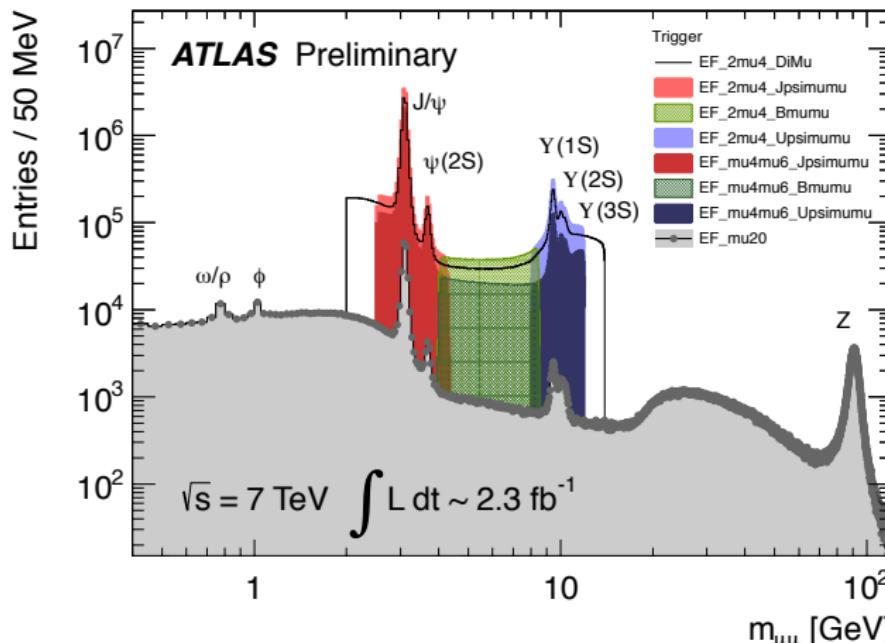
# Hidden flavour at ATLAS: experimental environment

high production rates for signal and background, in a detector optimized for high- $p_T$  discovery physics at  $\sqrt{s} = 14 \text{ TeV}$



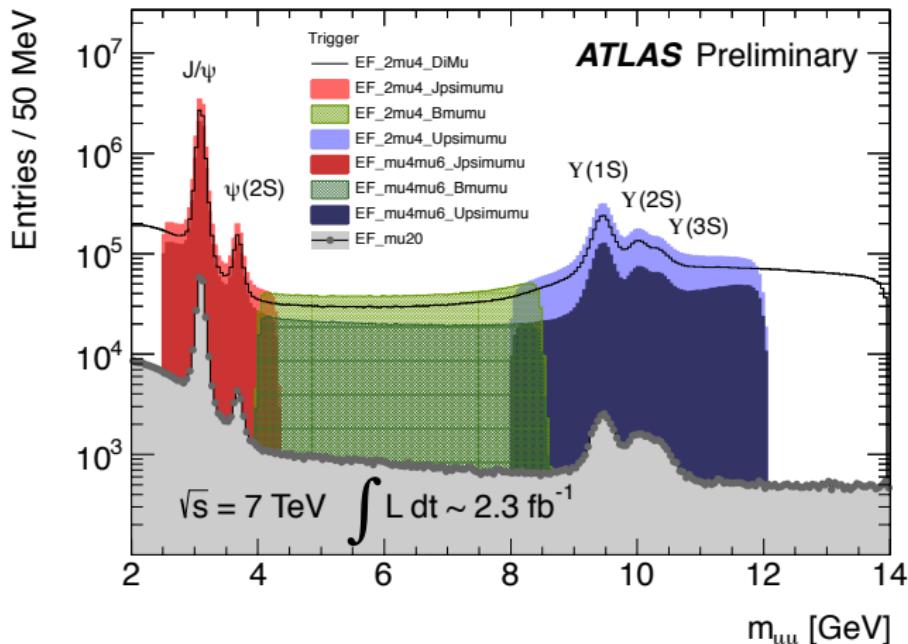
# Hidden flavour at ATLAS: experimental techniques

- rate limited by trigger bandwidth, especially at Level 1 (hardware)
- $B$ -physics & onia: high- $p_T \mu$ ,  **$M(\mu\mu)$ -restricted-dimuon**, ... triggers
- increasing  $\mathcal{L} \rightarrow$  higher- $p_T$  triggers, prescaling, ...



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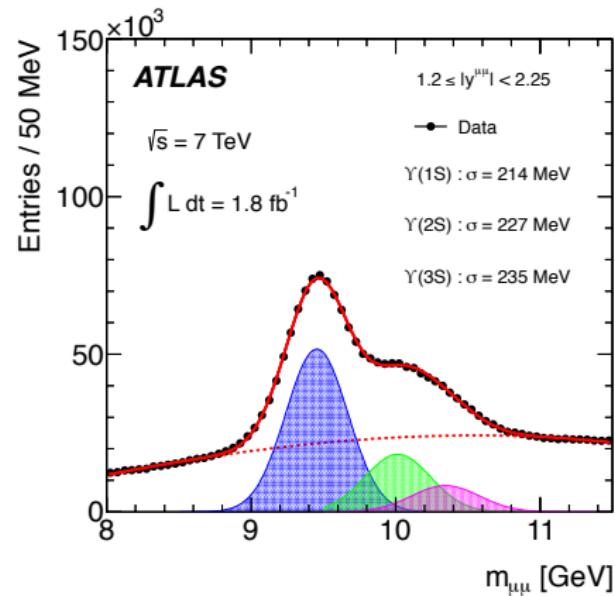


# $\Upsilon(nS)$ production cross-sections

ATLAS Collaboration, PRD 87, 052004 (2013)

dimuon trigger:  $p_T^\mu > 4 \text{ GeV}$ ,  $|\eta^\mu| < 2.3$ ; largely un-prescaled,  $1.8 \text{ fb}^{-1}$

- resolution differs at high  $|y|$

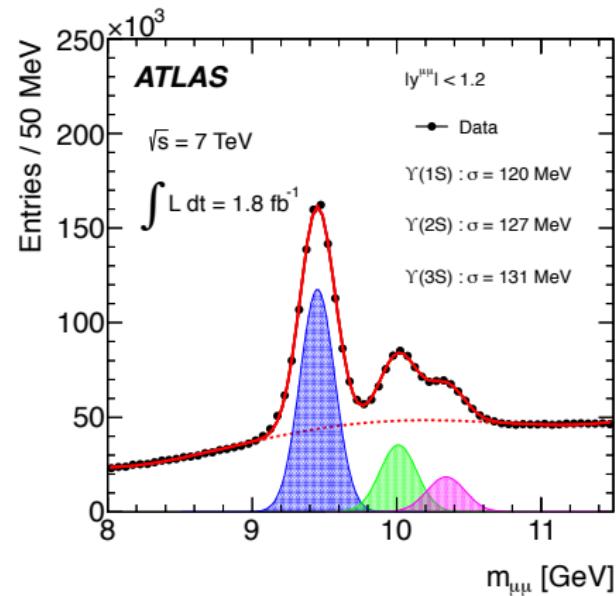


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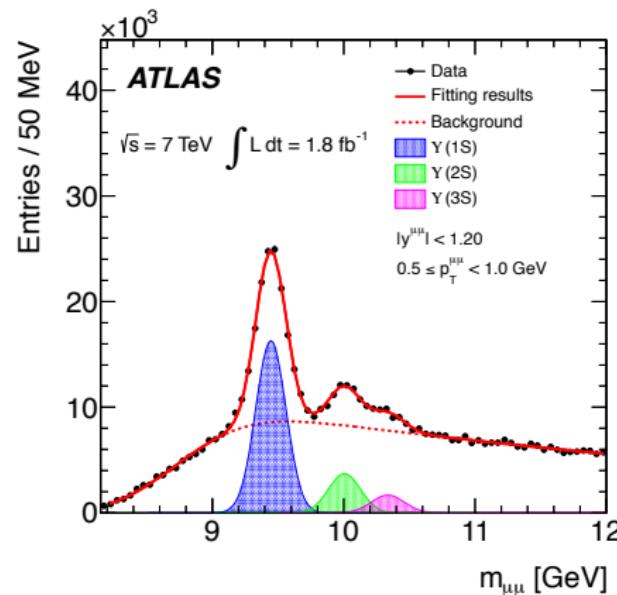


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- resolution differs at high  $|y|$  and at central  $|y|$
- weighted event-by-event for  $\epsilon$ ; fits in  $p_T$  bins: e.g.  $[0.5, 1.0]$

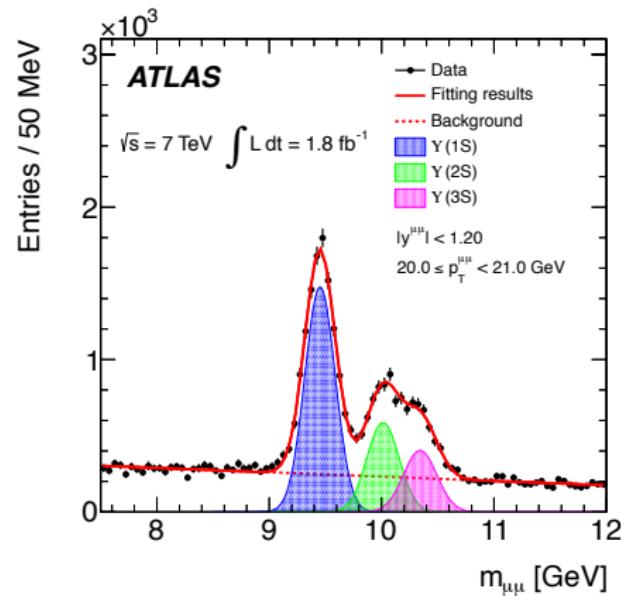


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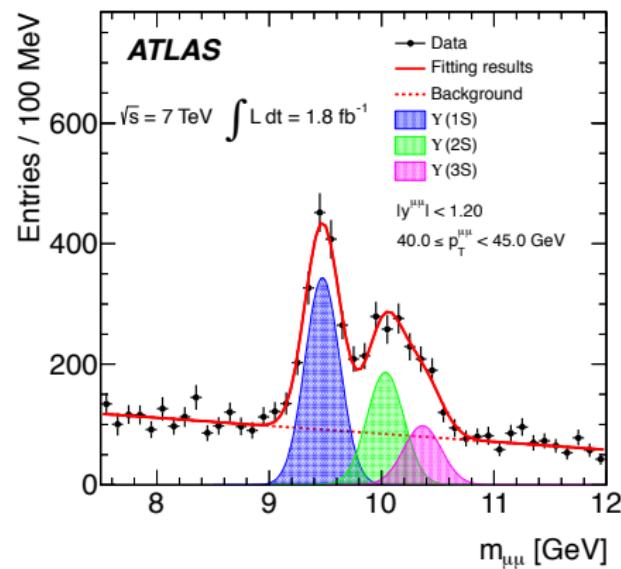


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- resolution differs at high  $|y|$  and at central  $|y|$
- weighted event-by-event for  $\epsilon$ ; fits in  $p_T$  bins: e.g. [40.0, 45.0]

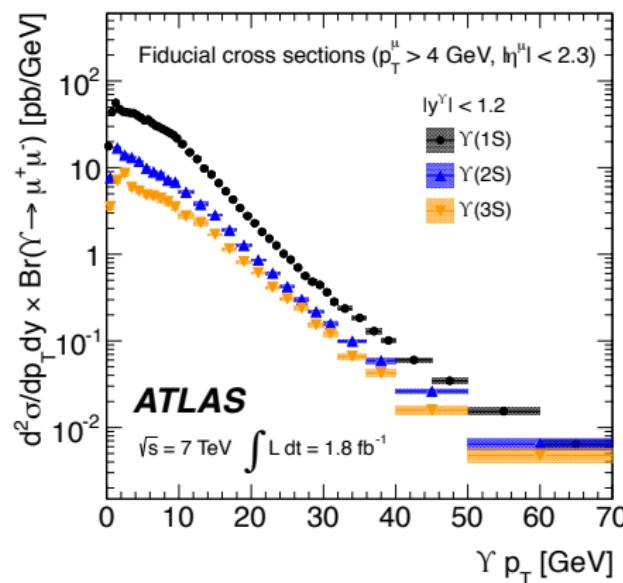


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- fiducial cross-sections: no spin-alignment uncertainty

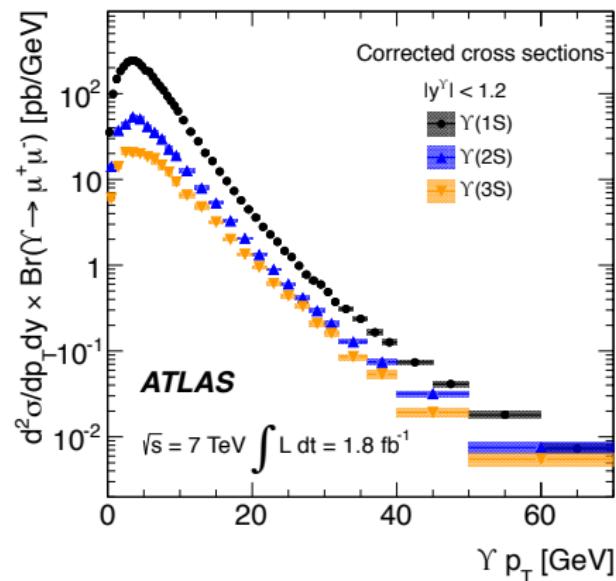


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- resolution differs at high  $|y|$  and at central  $|y|$
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- fiducial cross-sections: no spin-alignment uncertainty
- corrected cross-sections: full  $\Upsilon$  decay parameter space

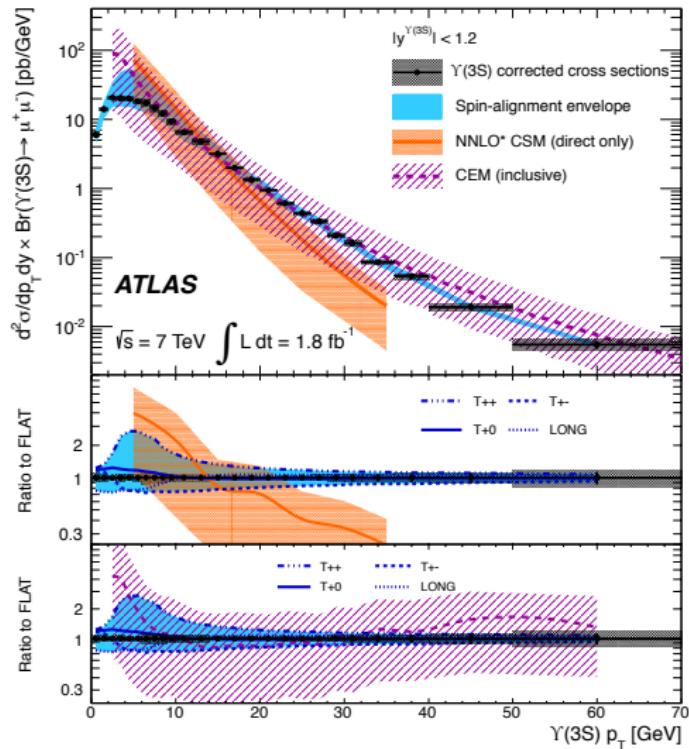


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- fiducial cross-sections: no spin-alignment uncertainty
- corrected cross-sections: full  $\Upsilon$  decay parameter space
- data disagrees w predictions;  
**NNLO\* CSM:** at high  $p_T$ ;  
**colour evaporation:** on shape;  
note  $p_T$  dependence of the  
**spin-alignment uncertainty**



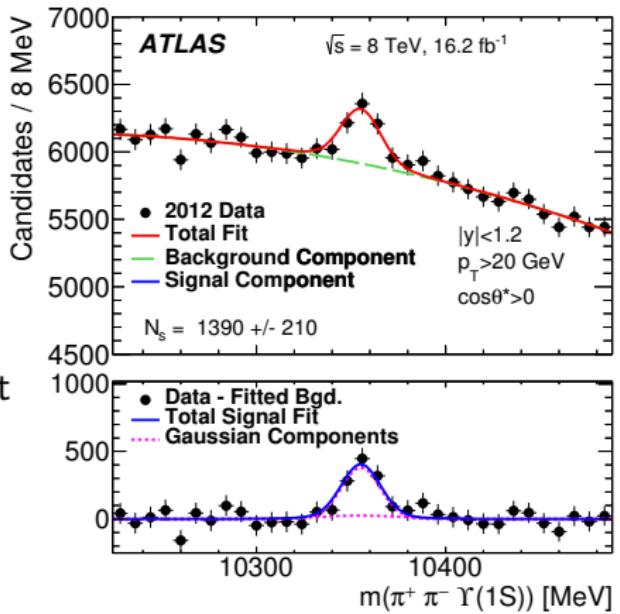
# Search for a $X_b \rightarrow \pi^+ \pi^- \Upsilon$ signal

ATLAS Collab., Physics Letters B 740, 199–217 (2015); arXiv:1410.4409 [hep-ex]

- hidden-beauty analogue of  $X(3872) \rightarrow \pi^+ \pi^- J/\psi$
- $16.2 \text{ fb}^{-1}$  of  $\sqrt{s} = 8 \text{ TeV}$  data;  $2 \times (p_T > 4 \text{ GeV} \text{ muon})$  trigger
- fit in  $2 \times 2 \times 2$  bins of ( $|y|$ ,  $p_T$ ,  $\cos \theta^*$ ) to discriminate vs bkgd
- kinematics: ATLAS/CMS  
 $\Upsilon(nS) \frac{d^2\sigma}{dy dp_T}$ ; validated on  
 $34300 \pm 800$   $\Upsilon(2S)$  signal
- $\Upsilon(3S)$ : model for  $X_b$  search
- significance  $z = 8.7$ ;  
most sensitive bin  $z = 6.5 \rightarrow$
- $\chi^2/n_{dof} = 1.0$  for simultaneous fit

$$N_{3S}^{fit} = 11600 \pm 1300$$

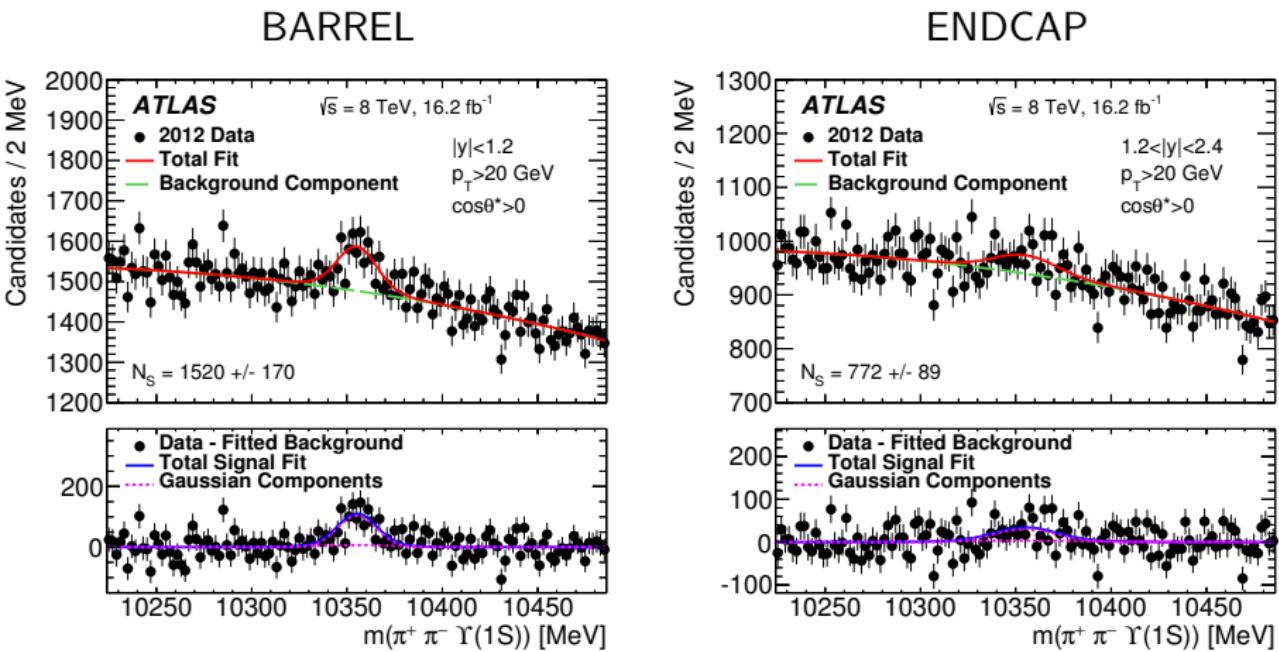
$$\begin{aligned} N_{3S}^{pred} &= (\sigma \mathcal{B})_{3S} \cdot \mathcal{L} \cdot \mathcal{A} \cdot \epsilon \\ &= 11400 \pm 1500 \end{aligned}$$



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ATLAS Collab., Physics Letters B 740, 199–217 (2015); arXiv:1410.4409 [hep-ex]

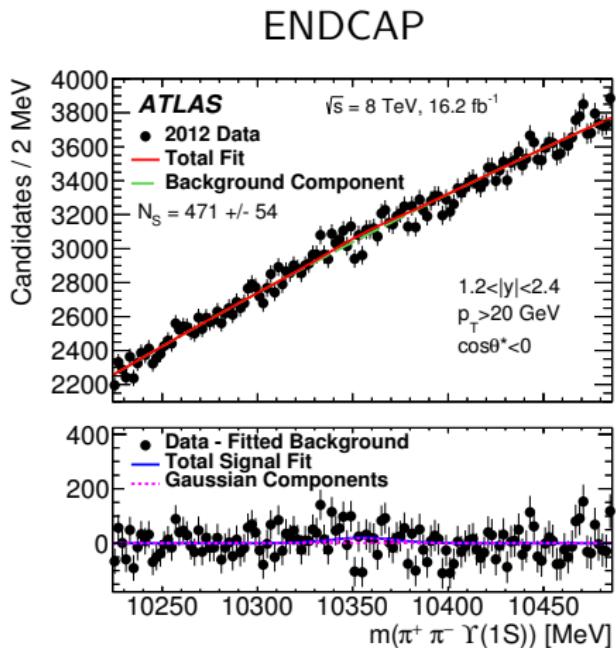
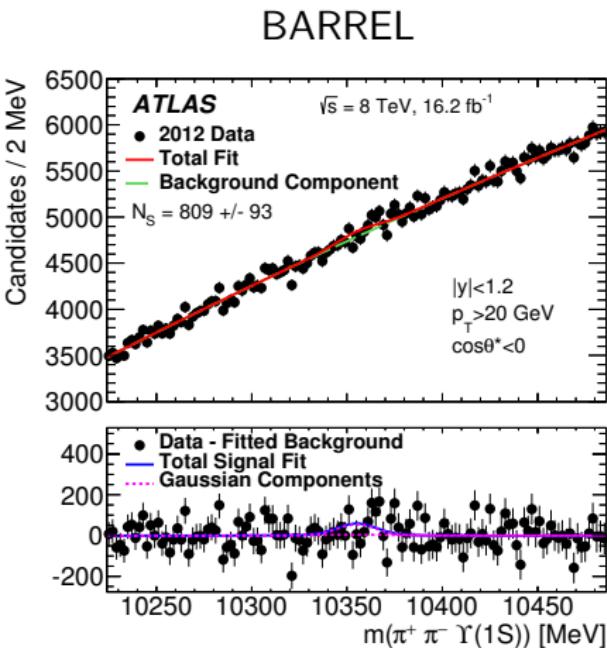
- $p_T > 20 \text{ GeV}$ ,  $\cos \theta^* > 0$  (most sensitive bin):



# Search for a $X_b \rightarrow \pi^+ \pi^- \Upsilon$ signal

ATLAS Collab., Physics Letters B 740, 199–217 (2015); arXiv:1410.4409 [hep-ex]

- $p_T > 20 \text{ GeV}$ ,  $\cos \theta^* < 0$  (top-left bin):

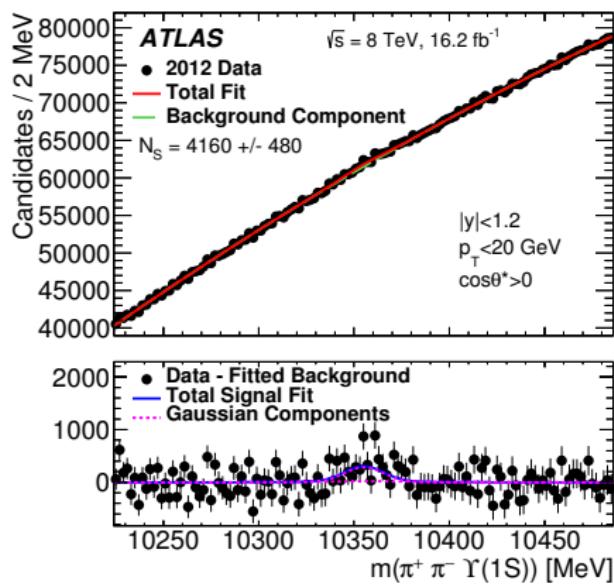


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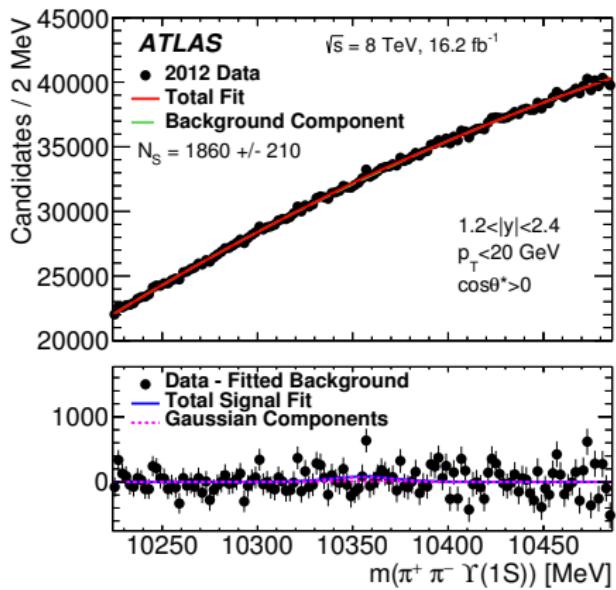
ATLAS Collab., Physics Letters B 740, 199–217 (2015); arXiv:1410.4409 [hep-ex]

- $p_T < 20 \text{ GeV}$ ,  $\cos \theta^* > 0$  (bottom-right bin):

BARREL



ENDCAP

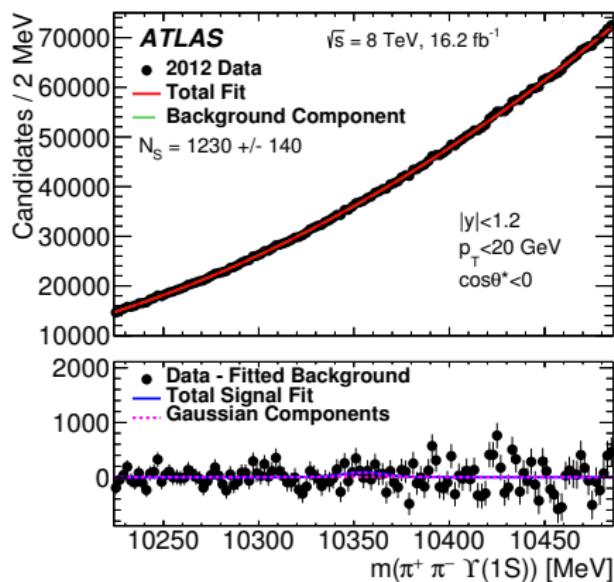


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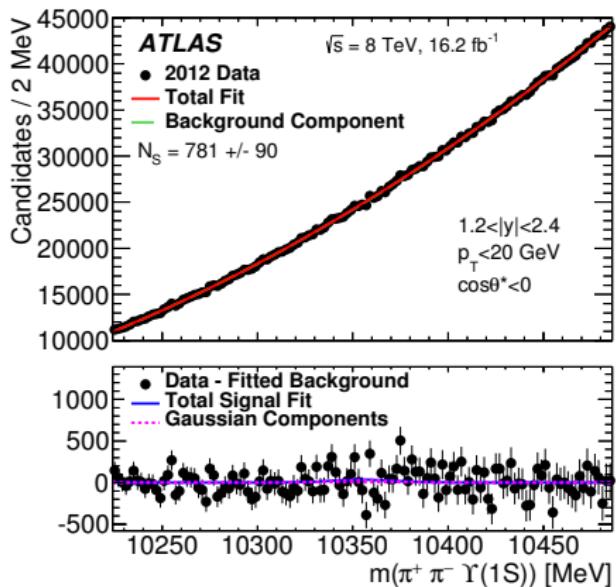
ATLAS Collab., Physics Letters B 740, 199–217 (2015); arXiv:1410.4409 [hep-ex]

- $p_T < 20 \text{ GeV}$ ,  $\cos \theta^* < 0$  (least sensitive bin):

BARREL



ENDCAP



# $X_b \rightarrow \pi^+ \pi^- \Upsilon$ : results as a function of mass

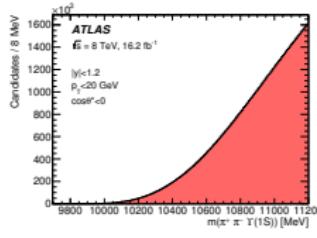
ATLAS Collab., Physics Letters B 740, 199–217 (2015); arXiv:1410.4409 [hep-ex]

- hypothesis test every 10 MeV from 10–11 GeV, excluding  $\Upsilon(2S, 3S)$
- fit range  $m \pm 8\sigma_{\text{endcap}}$ :  $\pm 72$  MeV at 10 GeV;  $\pm 224$  MeV at 10.9 GeV
- simultaneous fit to the 8 ( $|y|$ ,  $p_T$ ,  $\cos \theta^*$ ) bins, for  $R = \sigma \mathcal{B}/(\sigma \mathcal{B})_{2S}$

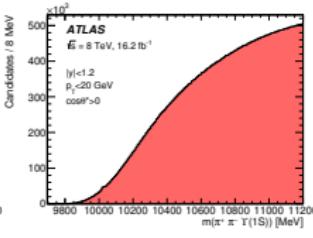
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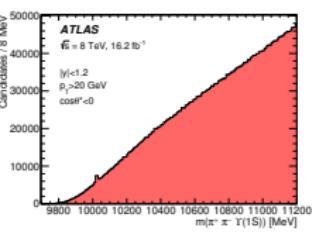
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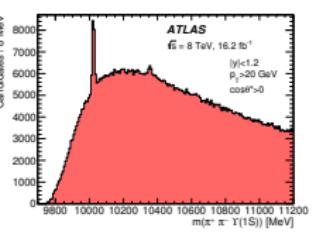
(a) Barrel, low  $p_T$ , low  $\cos \theta^*$



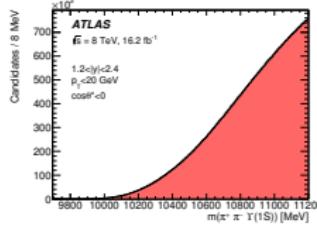
(b) Barrel, low  $p_T$ , high  $\cos \theta^*$



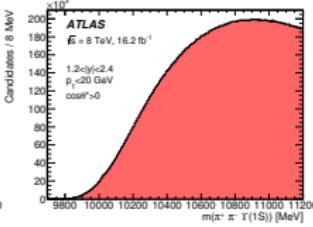
(c) Barrel, high  $p_T$ , low  $\cos \theta^*$



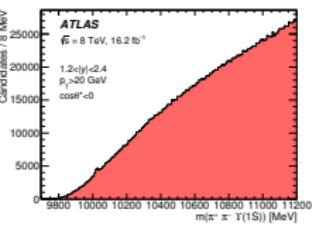
(d) Barrel, high  $p_T$ , high  $\cos \theta^*$



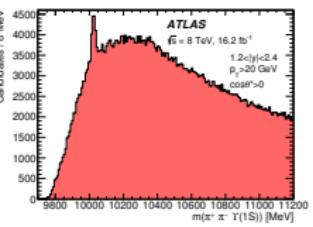
(e) Endcap, low  $p_T$ , low  $\cos \theta^*$



(f) Endcap, low  $p_T$ , high  $\cos \theta^*$



(g) Endcap, high  $p_T$ , low  $\cos \theta^*$

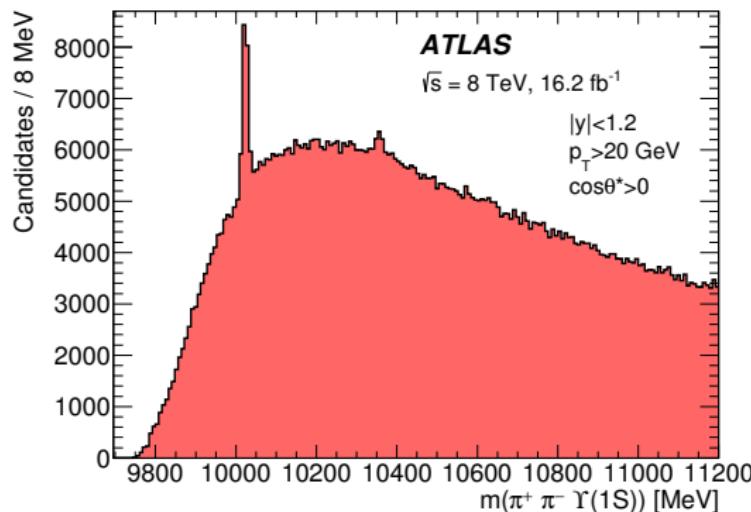


(h) Endcap, high  $p_T$ , high  $\cos \theta^*$

# $X_b \rightarrow \pi^+ \pi^- \Upsilon$ : results as a function of mass

ATLAS Collab., Physics Letters B 740, 199–217 (2015); arXiv:1410.4409 [hep-ex]

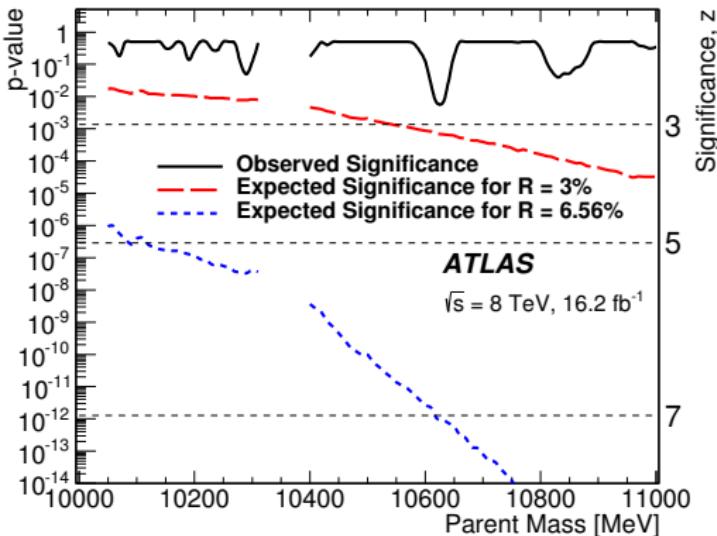
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- local signif.  $z < 3$  by asymptotic formulae



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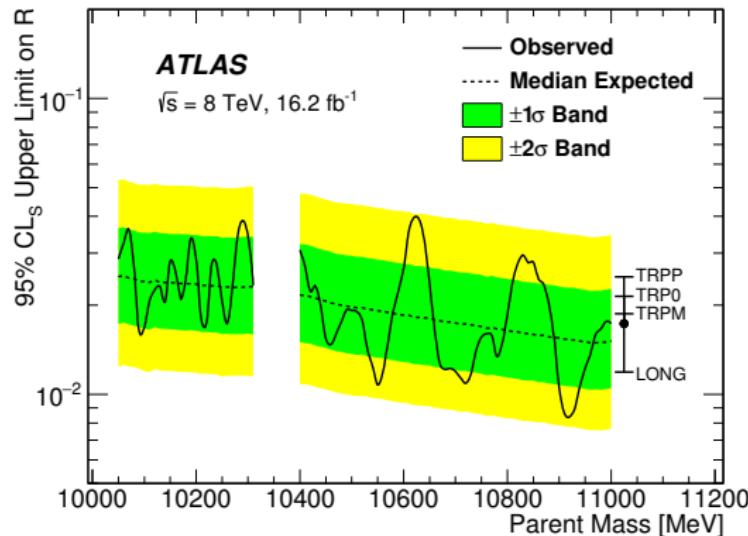
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- local signif.  $z < 3$  by asymptotic formulae
- cf.  $R = 3\%$ ,  $6.56\%$



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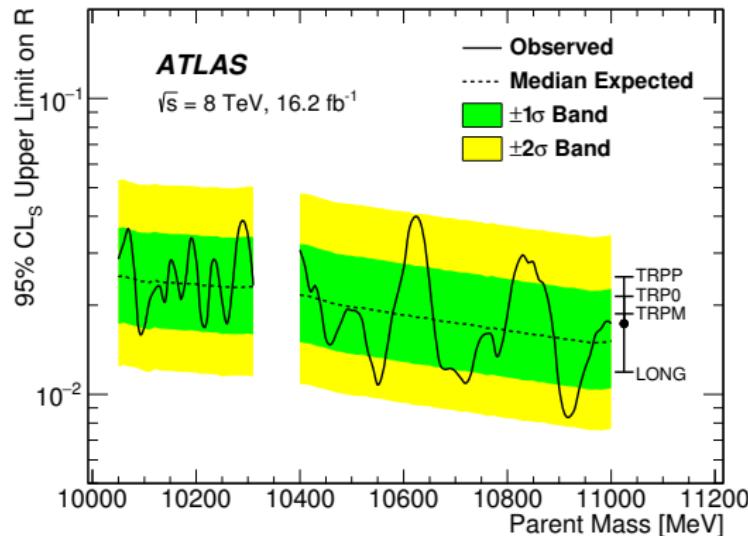
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- local signif.  $z < 3$  by asymptotic formulae
- cf.  $R = 3\%$ , 6.56%
- set ULs using  $CL_S$



# $X_b \rightarrow \pi^+ \pi^- \Upsilon$ : results as a function of mass

ATLAS Collab., Physics Letters B 740, 199–217 (2015); arXiv:1410.4409 [hep-ex]

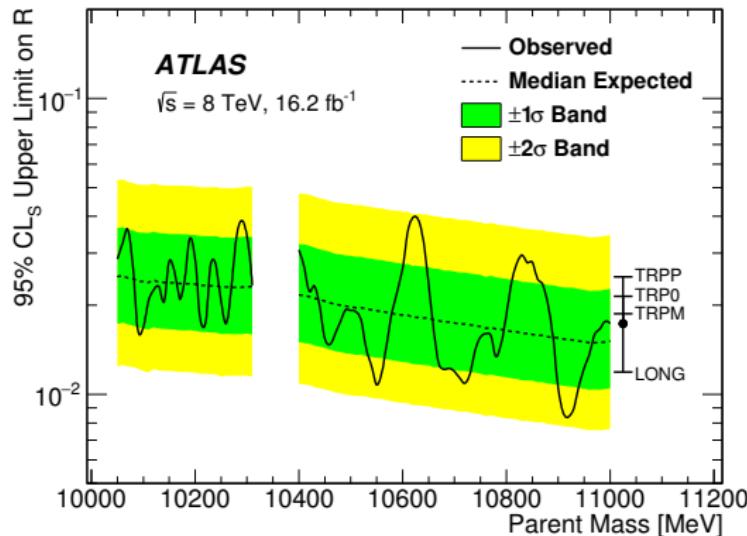
- hypothesis test every 10 MeV from 10–11 GeV, excluding  $\Upsilon(2S, 3S)$
- fit range  $m \pm 8\sigma_{\text{endcap}}$ :  $\pm 72$  MeV at 10 GeV;  $\pm 224$  MeV at 10.9 GeV
- simultaneous fit to the 8 ( $|y|$ ,  $p_T$ ,  $\cos \theta^*$ ) bins, for  $R = \sigma \mathcal{B}/(\sigma \mathcal{B})_{2S}$
- local signif.  $z < 3$  by asymptotic formulae
- cf.  $R = 3\%$ , 6.56%
- set ULs using  $CL_S$
- syst's first added:
  - using  $\mathcal{G}$  constraints
  - increases limits  $\lesssim 13\%$
  - inflates  $\pm 1\sigma$  bands 9.5–25%



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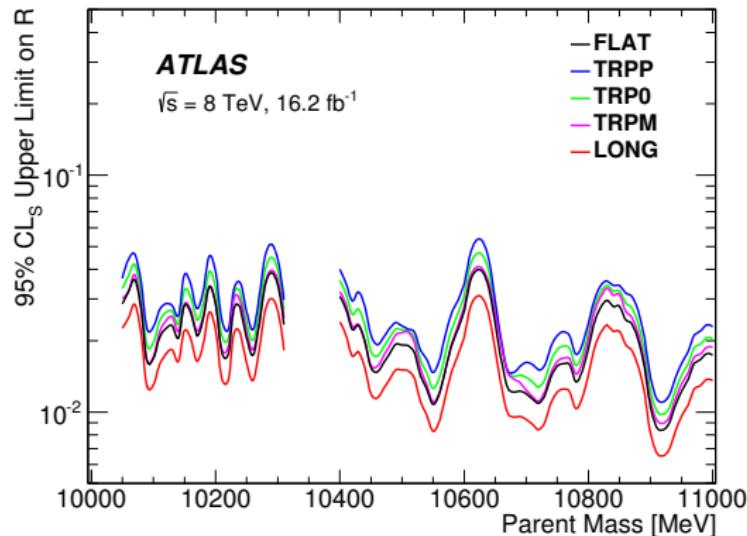
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- reported in detail



# $X_b \rightarrow \pi^+ \pi^- \Upsilon$ : interpretation and plans

- this is the most sensitive  $X_b$  production search for  $m > 10.1$  GeV
- excludes  $R = \sigma\mathcal{B}/(\sigma\mathcal{B})_{\Upsilon(2S)} = 6.56\%$  throughout search range
  - cf.  $\pi\pi\psi$  [CMS, JHEP 04 (2013) 154]:  $(\sigma\mathcal{B})_{X(3872)}/(\sigma\mathcal{B})_{\psi(2S)} = 6.56\%$
  - if  $X_b$  exists, relative production  $\sigma/\sigma_{2S}$  or branching  $\mathcal{B}/\mathcal{B}_{2S}$ , or both, are weaker than for  $X(3872)$
- an  $X_b$  is not in general a carbon copy of the  $X(3872)$ :
  - $X(3872)$  is within sub-MeV resolution of  $D^0 \bar{D}^{*0}$  threshold
  - even a molecular  $X_b$  is bound by tens of MeV
  - further, large  $D\bar{D}^*$  isospin breaking ( $m_\pm - m_{00} = +8.08 \pm 0.11$  MeV) is absent for  $B\bar{B}^*$  ( $m_\pm - m_{00} = -0.64 \pm 0.12$  MeV)<sup>‡</sup>
  - stressed by theorists [Guo/Meißner/Wang, 1204.2158; Karliner ...]

$X(3872)$ :  $|m_\pm - m_{00}| \gg E_b$ ;  $\approx$  pure  $D^0 \bar{D}^{*0}$  state;  $\mathcal{B}_{\rho\psi} \simeq \mathcal{B}_{\omega\psi}$

$X_b$ :  $|m_\pm - m_{00}| \ll E_b$ ;  $\approx$  pure  $I = 0$  state;  $\mathcal{B}_{\rho\Upsilon}$  "strongly" suppressed

- $I$ -allowed modes —  $\{\gamma, \pi\pi\pi^0\}\Upsilon, \pi\pi\chi_b$  — have severe  $\mathcal{A} \cdot \epsilon$  problems; further searches are under investigation

# $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$ at 7 TeV

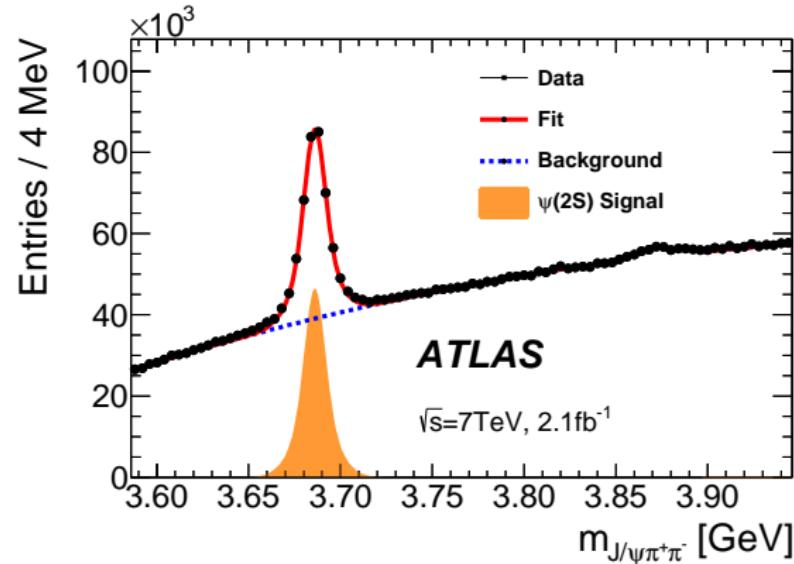
ATLAS Collaboration, JHEP 09 (2014) 079

little feed-down from higher states: test of direct charmonium production  
also constrains feed-down to  $J/\psi$  if measured in bins of  $J/\psi$  ( $p_T, y$ )

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dimuon trigger:  $p_T^\mu > 4$  GeV,  $|\eta^\mu| < 2.3$ ; un-prescaled,  $2.1 \text{ fb}^{-1}$

- full spectrum;  
note the  $X(3872)$



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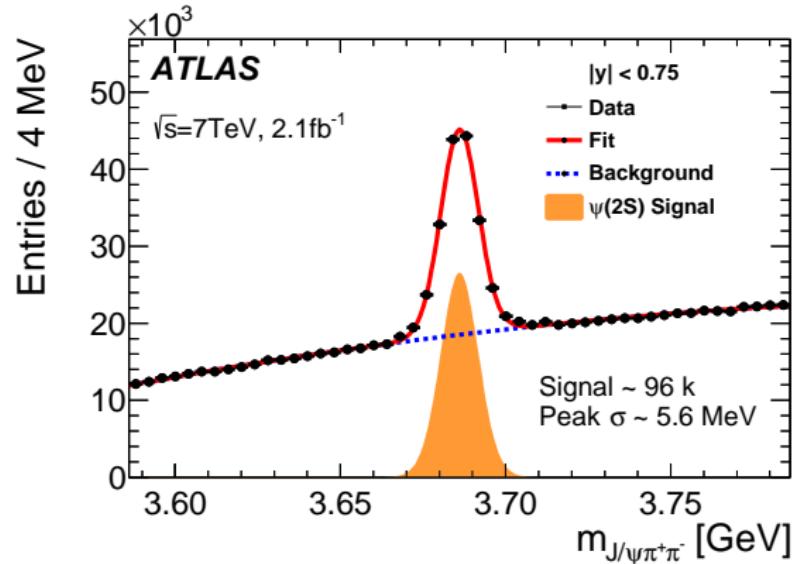
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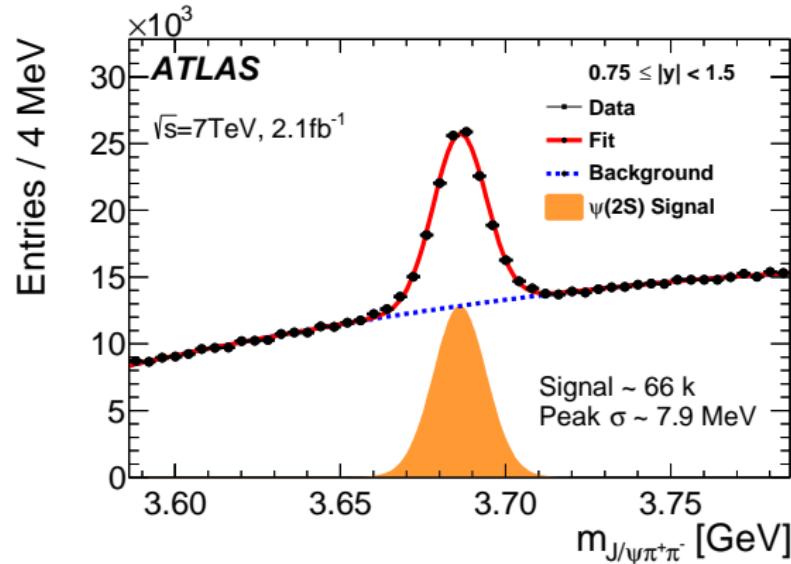
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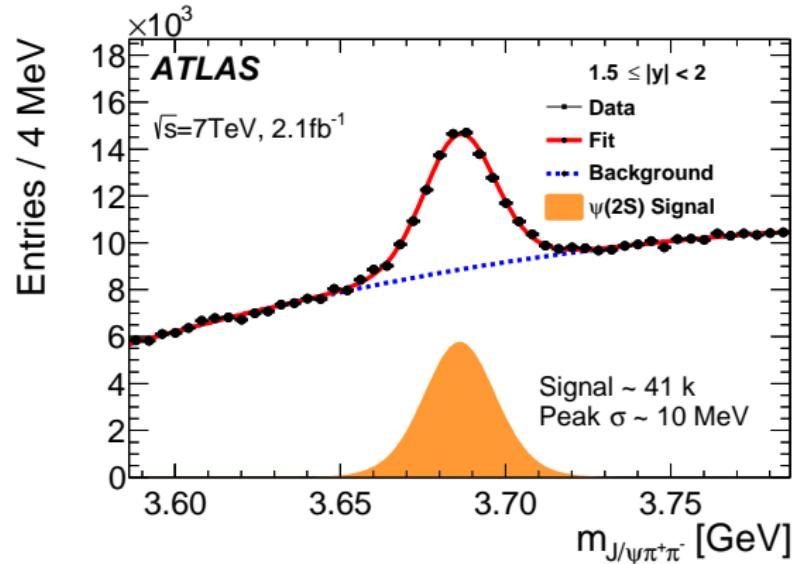
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# $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$ at 7 TeV: 2D fit to (m, $\tau$ )

ATLAS Collaboration, JHEP 09 (2014) 079

## mass:

prompt:  $f\mathcal{G}_1(m) + [1 - f]\mathcal{G}_2(m)$

non-prompt:  $f\mathcal{G}_1(m) + [1 - f]\mathcal{G}_2(m)$

bkgds:  $P_2(m)$

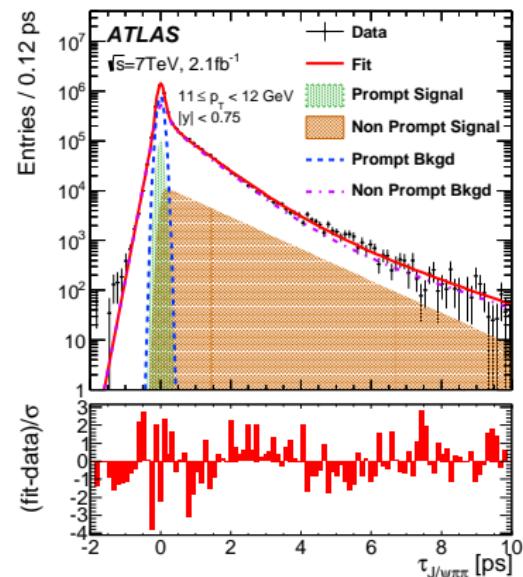
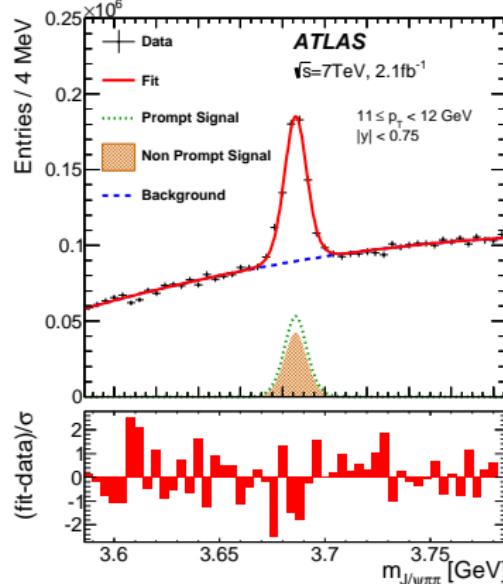
## pseudo proper time:

$$\delta(\tau) \otimes \mathcal{G}_{\text{res}}(\tau)$$

$$(E_1(\tau) \equiv \exp(-\tau/\tau_1)\Theta(\tau)) \otimes \mathcal{G}_{\text{res}}(\tau)$$

$$\{\delta(\tau), \sum_i k_i E_i(\tau), E_4(|\tau|)\} \otimes \mathcal{G}_{\text{res}}(\tau)$$

in bins of  
the  $\psi(2S)$   
( $p_T, |y|$ );  
representative  
examples at  
**low**  $y, p_T$



likewise for  
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mid  $y, p_T$

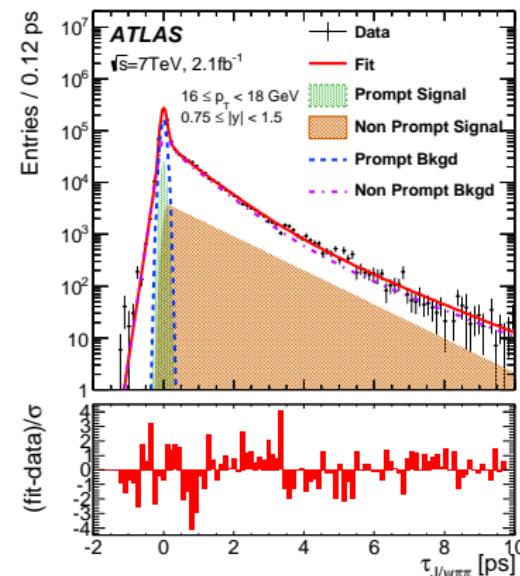
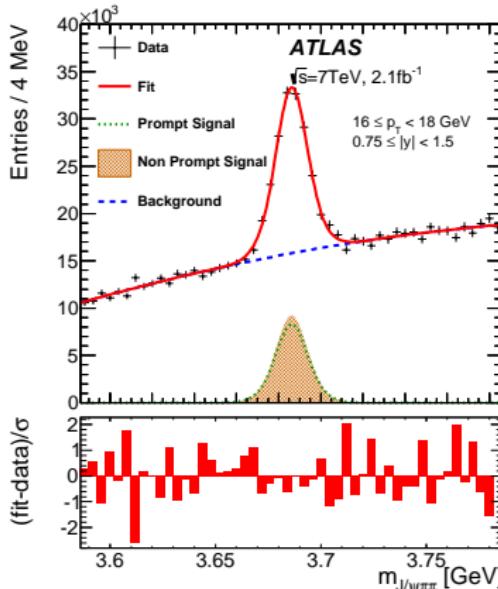
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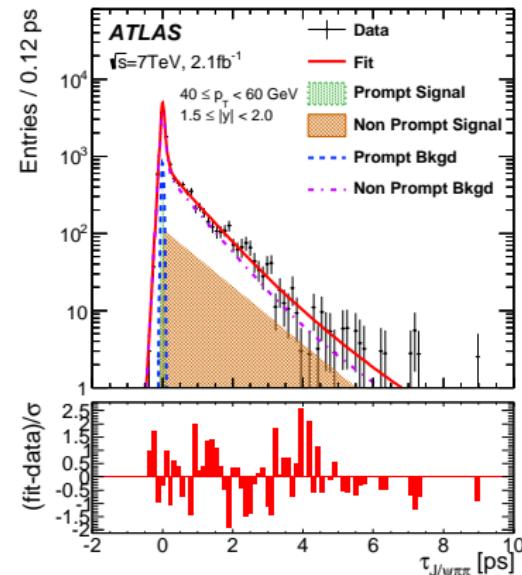
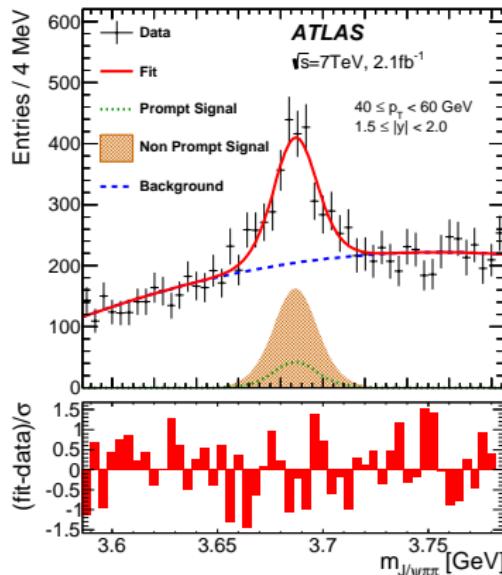
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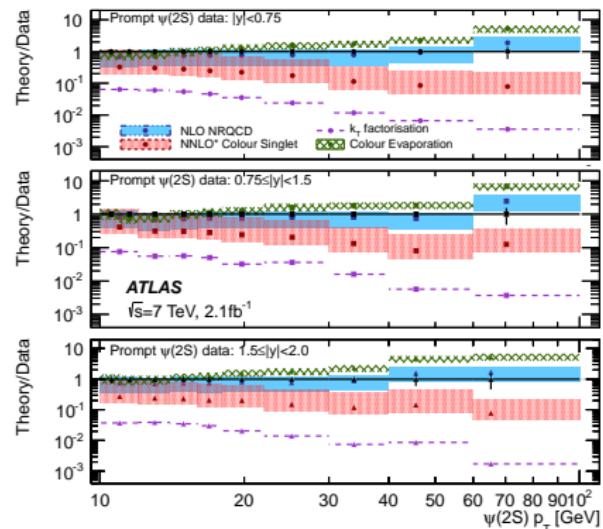
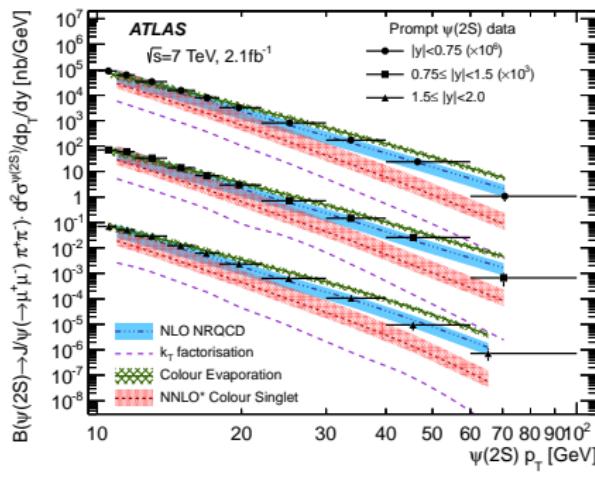
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ATLAS Collaboration, JHEP 09 (2014) 079

## prompt production:

NNLO\* CS undershoots (esp. at high  $p_T$ ); NLO NRQCD  $\approx$  matches data;  
colour evaporation predicts a harder spectrum than seen;  
 $k_T$  factorization significantly (and as a fn of  $p_T$ ) underestimates data

cf. spin-alignment uncertainty:  $(^{+62}_{-32})\%$  at 10 GeV  $\rightarrow (^{+8}_{-12})\%$  at high  $p_T$

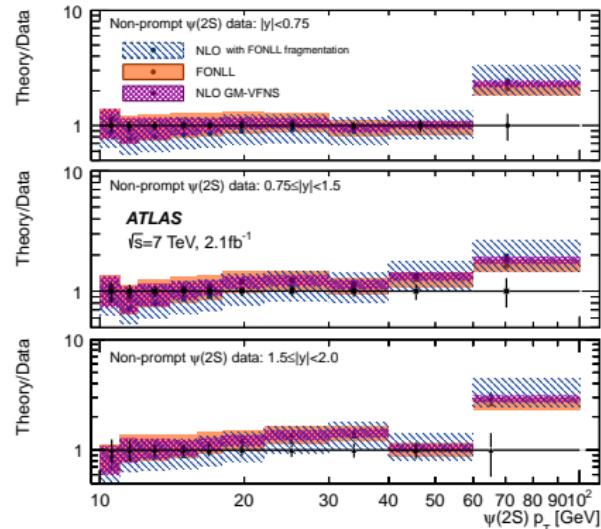
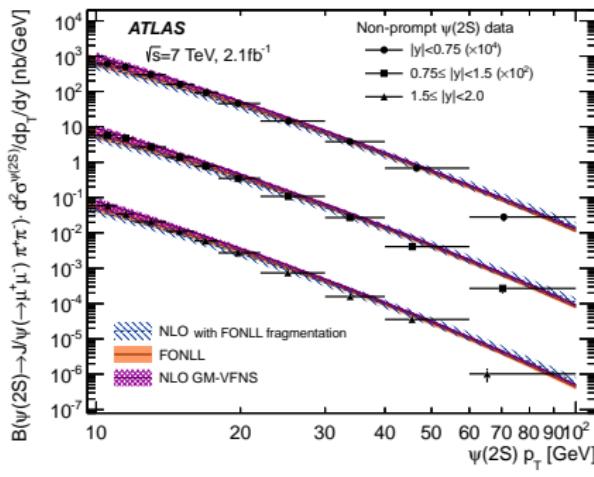


# $\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$ at 7 TeV: comparison w theory

ATLAS Collaboration, JHEP 09 (2014) 079, &  $B^+$ : JHEP 10 (2013) 042

**non-prompt production:** reasonable agreement with both general-mass variable-flavour-number scheme (GM-VFNS) at NLO, and fixed-order next-to-leading logarithm (FONLL) calculations, but both predict production that's harder in  $p_T$ ;

FONLL reproduces  $B^+ \xrightarrow{?} \exists b$ -hadron composition & decay mismodelling?  
[for same trigger & dataset]

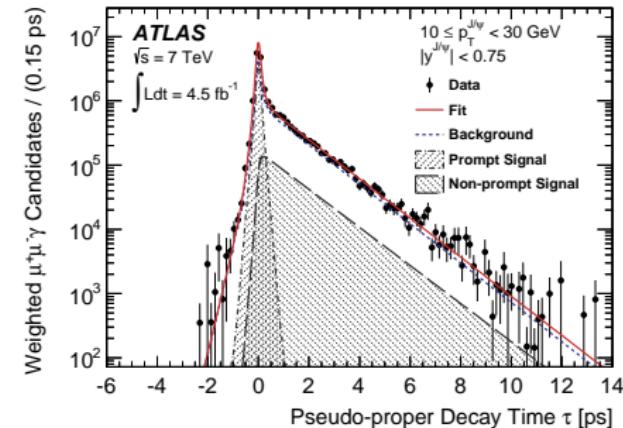
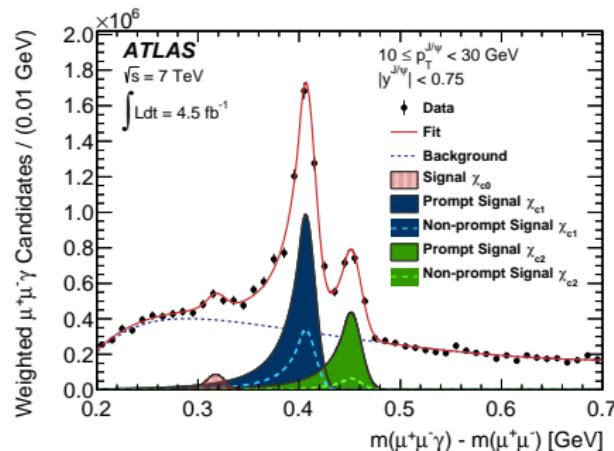


# $\chi_{c1}$ and $\chi_{c2}$ production at 7 TeV

ATLAS Collaboration, JHEP 07 (2014) 154

- example of  $P$ -wave quarkonium production
- significant source of feed-down to  $J/\psi$
- multiple states  $\rightarrow \chi_{c2}/\chi_{c1}$  ratios provide precision tests

cf.  $\psi(2S)$ :  $\pi\pi$  replaced by  $\gamma \rightarrow e^+e^-$  in pixels,  $p_T^\gamma > 1.5$  GeV,  $|\eta^\gamma| < 2.0$   
again, 2D fit in mass and pseudo-proper time:

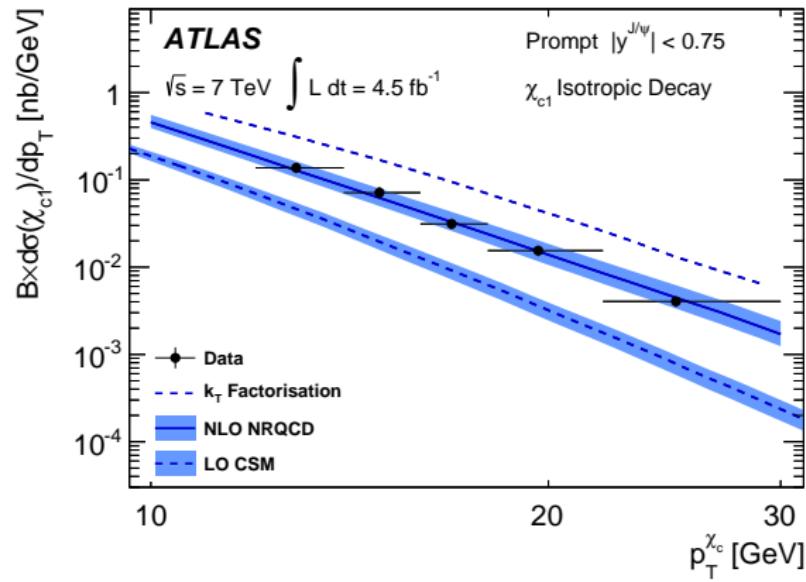


# $\chi_{c1}$ and $\chi_{c2}$ production at 7 TeV

ATLAS Collaboration, JHEP 07 (2014) 154

a series of absolute cross-section  $\times \mathcal{B}_{\chi_{c1,c2}} \times \mathcal{B}_{J/\psi}$  measurements in

- $\chi_{c1,c2} p_T$  bins, for  $\chi_{c1,c2}$  production studies
- $J/\psi p_T$  bins, for constraint of feed-down to  $J/\psi$ ; examples:
- prompt  $\chi_{c1}$  and



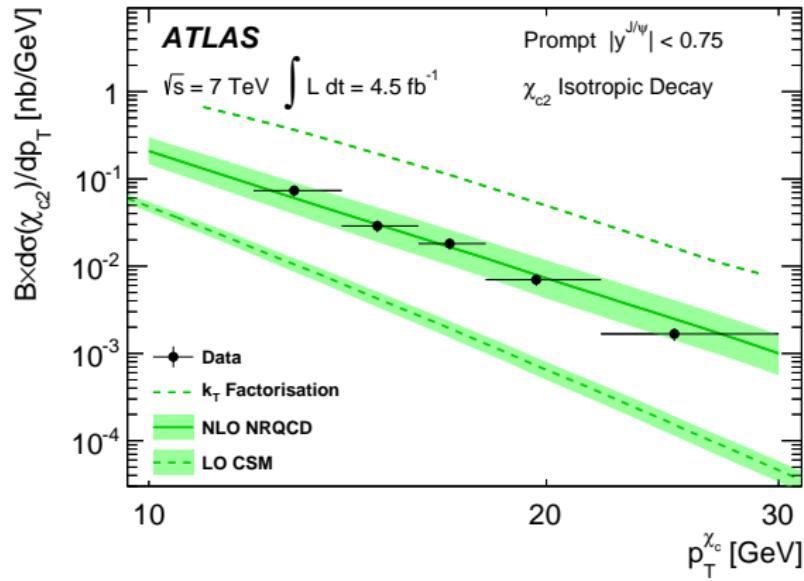
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prompt  $\chi_{c2}$ :  
good agreement w/  
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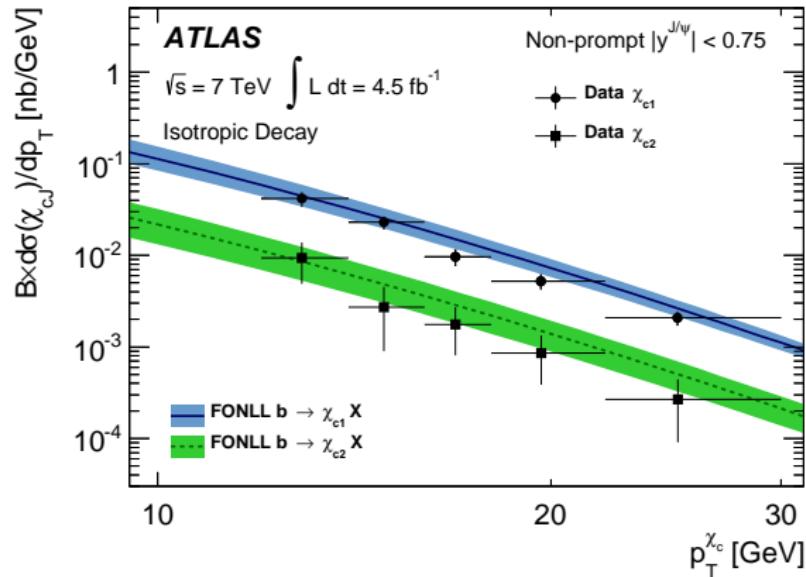


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- non-prompt  $\chi_{c1}$ ,  $\chi_{c2}$ :  
FONLL does well;  
overshoots at high  $p_T$



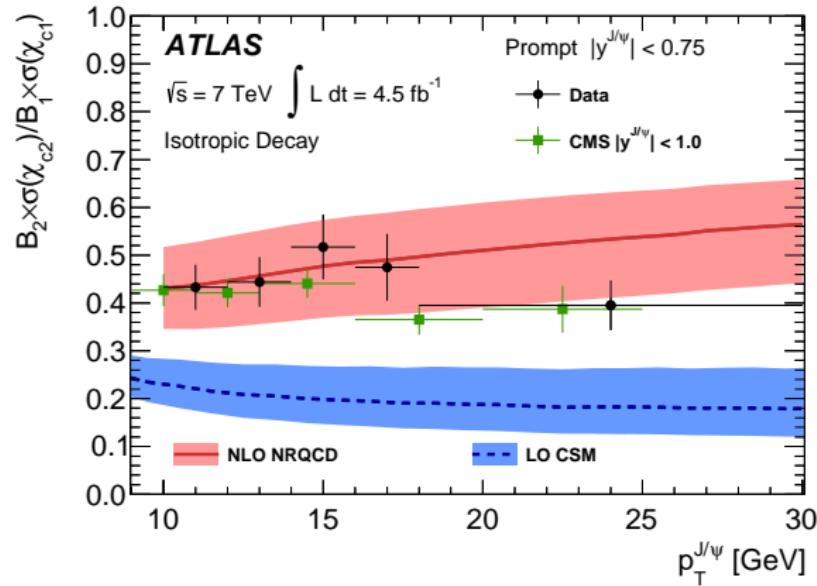
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- NLO NRQCD matches well
- results, including ?NRQCD high- $p_T$  over-prediction?, consistent w CMS



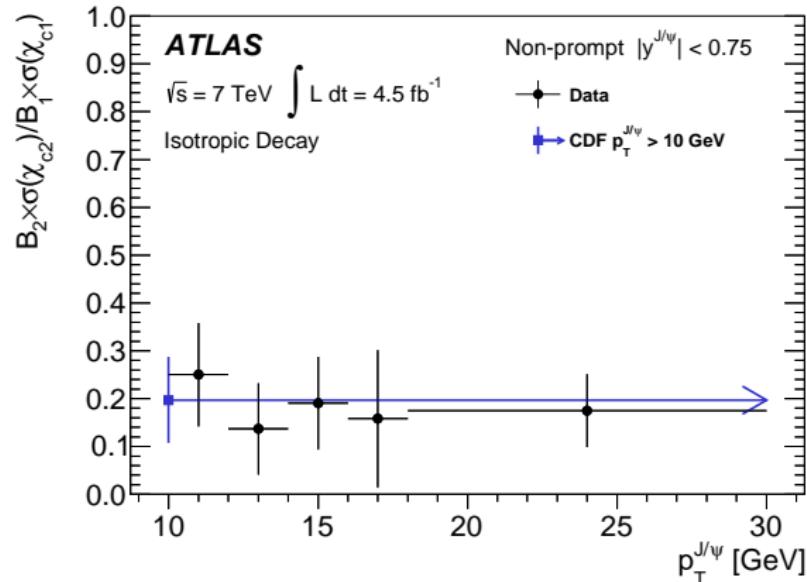
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## non-prompt:

- agrees with CDF  $\sqrt{s} = 1.96 \text{ TeV}$   $p\bar{p}$  measurement

# Summary

ATLAS has an active programme measuring charmonium production, featuring

- differential cross-section measurements in  $|y|$  and  $p_T$
- careful treatment and reporting of spin-alignment uncertainties
- both prompt and non-prompt production for hidden charm
- a reasonably comprehensive set of states:
  - $J/\psi$  (older results not shown here)
  - $\chi_{c1}$  and  $\chi_{c2}$
  - $\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$
  - $\Upsilon(1S)$ ,  $\Upsilon(2S)$ ,  $\Upsilon(3S)$
  - $\chi_{bJ}(mP)$  measurements (not shown here)
- a sensitive  $X_b$  production test has also been performed

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Further measurements, on 8 TeV and 13 TeV data,  
will be released in the next year or so.

# BACKUP SLIDES

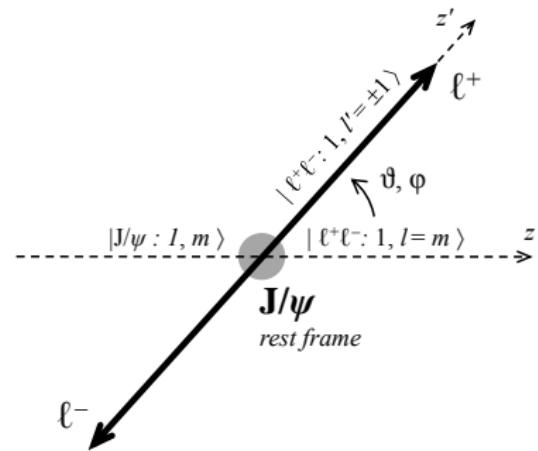
# BACKUP: polarization for $V \rightarrow \mu^+ \mu^-$

Faccioli, Lourenço, Seixas, and Wöhri, EPJC 69, 657–673 (2010)

for ( $J^{PC} = 1^{--}$ )  $|V\rangle = b_{+1}|+1\rangle + b_{-1}| -1\rangle + b_0|0\rangle$  decaying  $\rightarrow \ell^+ \ell^-$ ,

- the angular distribution  $W(\cos \vartheta, \varphi)$

$$\propto \frac{\mathcal{N}}{(3 + \lambda_\vartheta)} (1 + \lambda_\vartheta \cos^2 \vartheta + \lambda_\varphi \sin^2 \vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos \varphi + \lambda_\varphi^\perp \sin^2 \vartheta \sin 2\varphi + \lambda_{\vartheta\varphi}^\perp \sin 2\vartheta \sin \varphi)$$



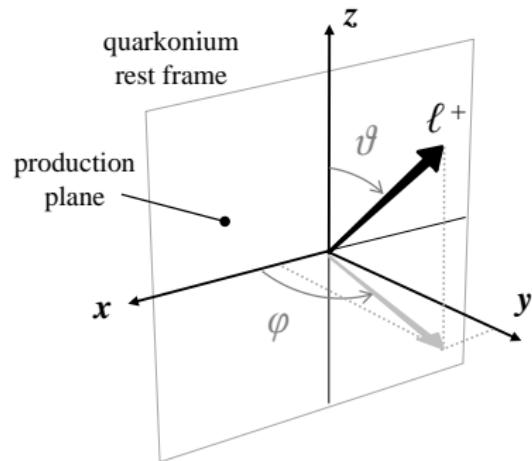
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- inclusive production:  $p_1$ ,  $p_2$ , and  $V$  only;  
we ( $\sim$  must) choose  $(x, z)$ : production plane

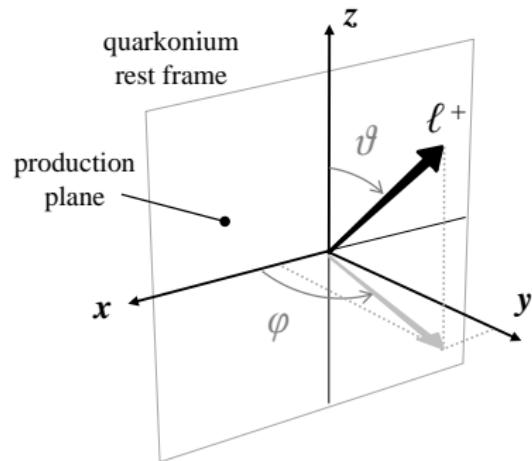
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- reflection-odd terms unobservable (parity)

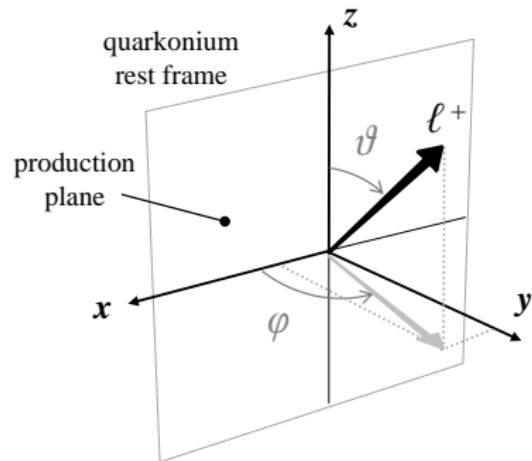
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Faccioli, Lourenço, Seixas, and Wöhri, EPJC 69, 657–673 (2010)

for ( $J^{PC} = 1^{--}$ )  $|V\rangle = b_{+1}|+1\rangle + b_{-1}| -1\rangle + b_0|0\rangle$  decaying  $\rightarrow \ell^+ \ell^-$ ,

- the angular distribution  $W(\cos \vartheta, \varphi)$

$$\propto \frac{\mathcal{N}}{(3 + \lambda_\vartheta)} (1 + \lambda_\vartheta \cos^2 \vartheta + \lambda_\varphi \sin^2 \vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos \varphi + \lambda_\varphi^\perp \sin^2 \vartheta \sin 2\varphi + \lambda_{\vartheta\varphi}^\perp \sin 2\vartheta \sin \varphi)$$



- inclusive production:  $p_1$ ,  $p_2$ , and  $V$  only;  
we ( $\sim$  must) choose  $(x, z)$ : production plane
- reflection-odd terms unobservable (parity)

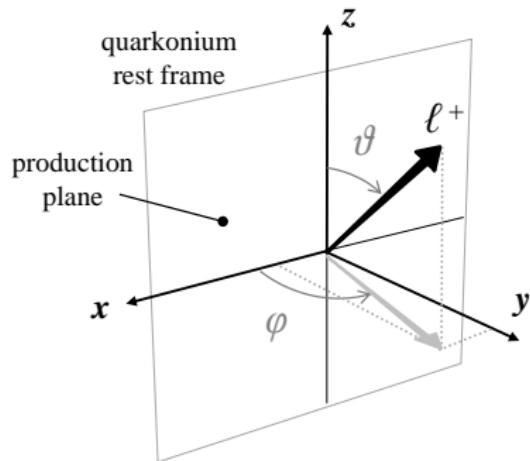
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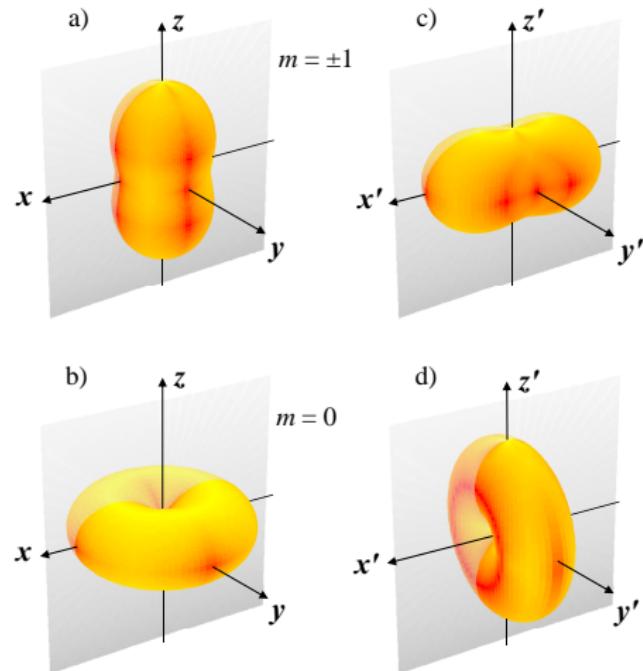


- inclusive production:  $p_1$ ,  $p_2$ , and  $V$  only;  
we ( $\sim$  must) choose  $(x, z)$ : production plane
- reflection-odd terms unobservable (parity)
- full angular distributions ( $\lambda_\vartheta$ ,  $\lambda_\varphi$ ,  $\lambda_{\vartheta\varphi}$ ) in general needed ...

# BACKUP: polarization for $V \rightarrow \mu^+ \mu^-$

Faccioli, Lourenço, Seixas, and Wöhri, EPJC 69, 657–673 (2010)

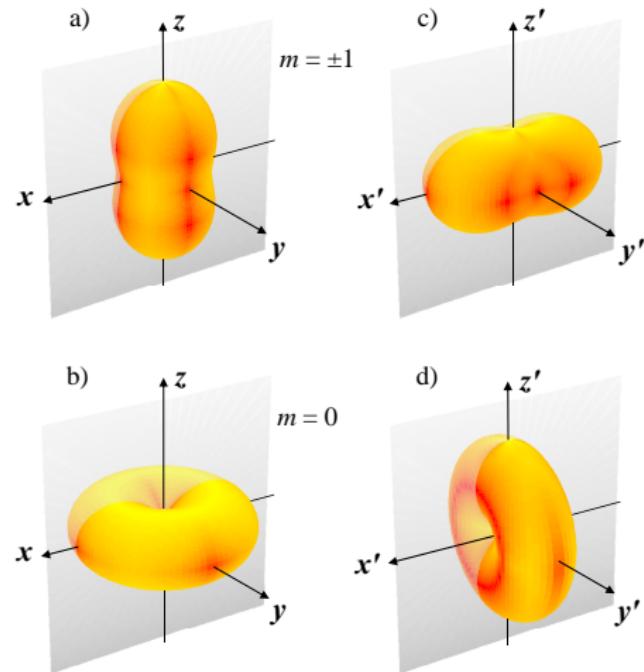
- L: polarized
  - transversely
  - longitudinally



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Faccioli, Lourenço, Seixas, and Wöhri, EPJC 69, 657–673 (2010)

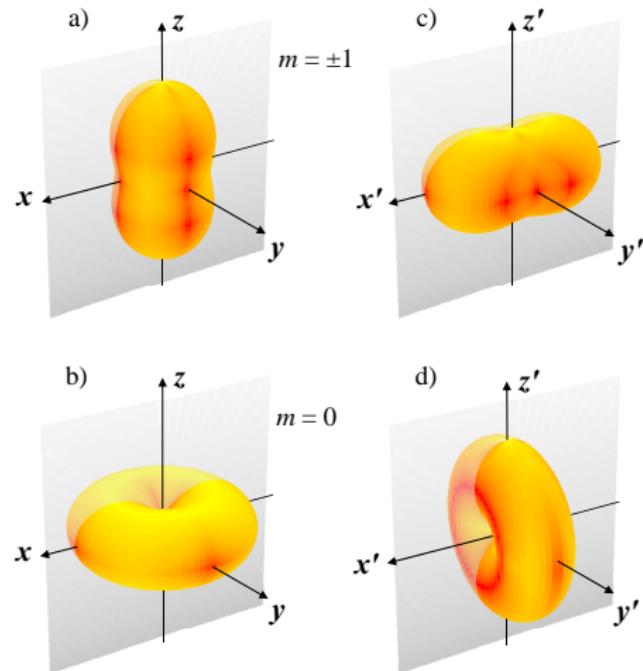
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- R: meas<sup>t</sup> frame rotated by 90°



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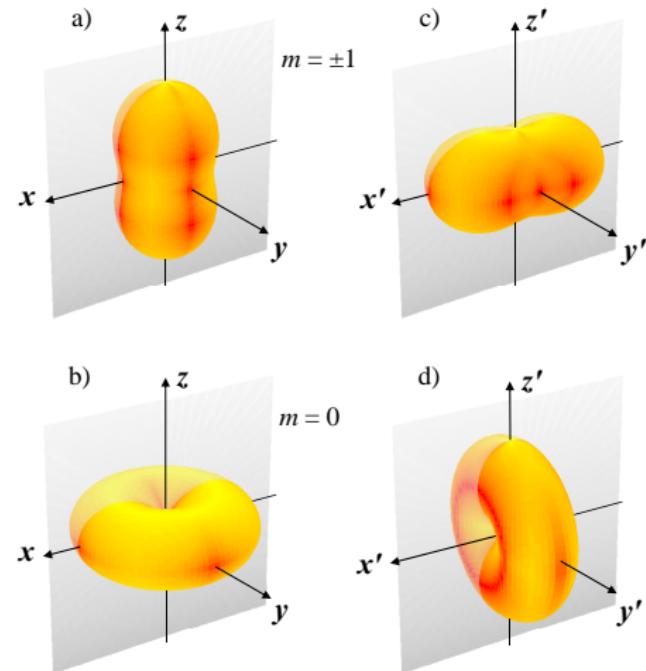
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- integration over azimuth  $\varphi \longrightarrow$



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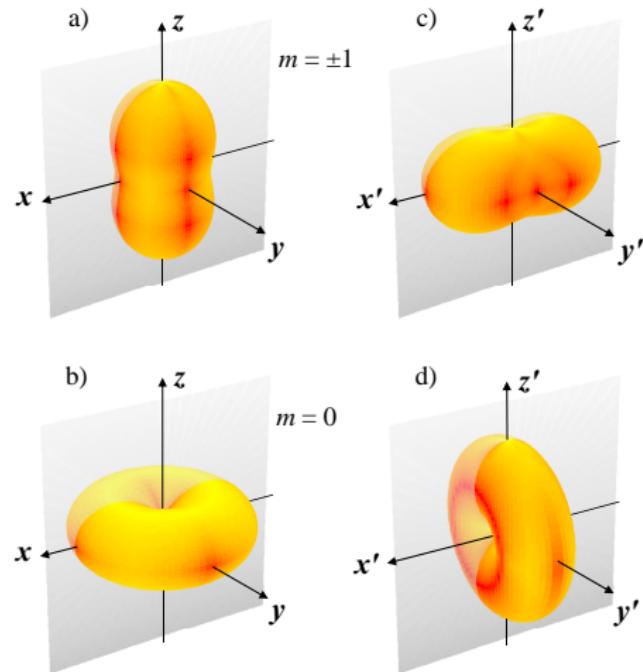
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longitudinal dist<sup>n</sup> (d) looks like



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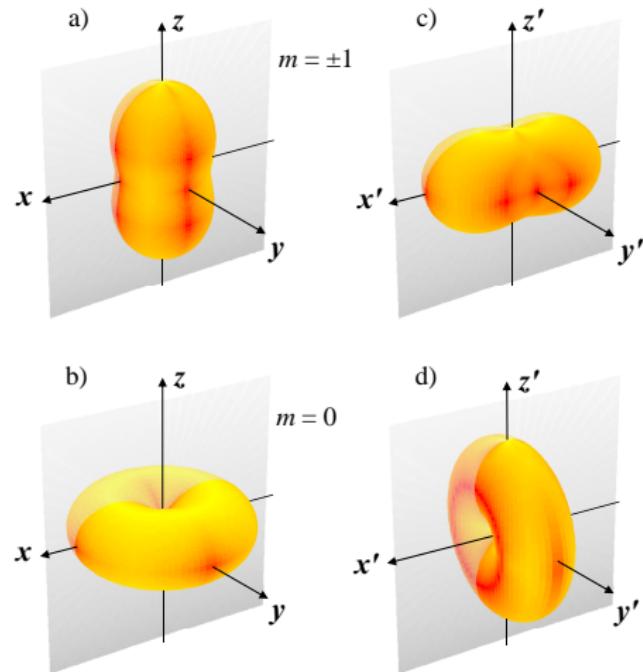
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*transverse dist<sup>n</sup>* (a)



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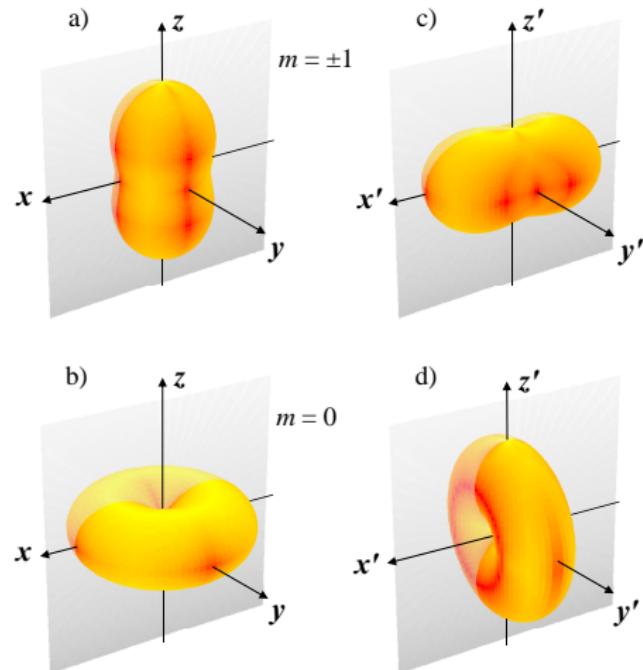
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- integration over azimuth  $\varphi \rightarrow$  longitudinal dist<sup>n</sup> (d) looks like transverse dist<sup>n</sup> (a)
- $\lambda_\vartheta$ -only measurements  
(à la TeVatron Run I)  
can't be compared without assumptions about pol<sup>n</sup> frame



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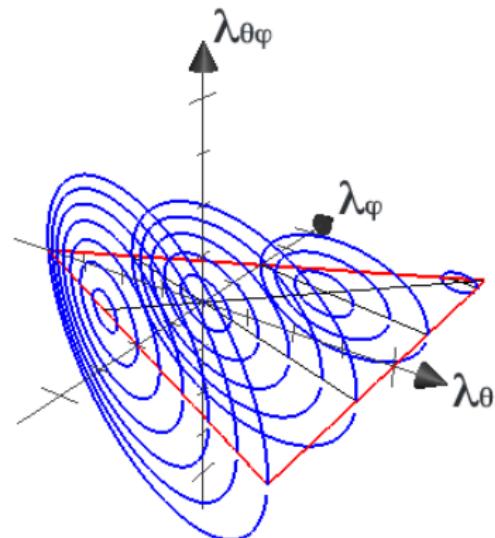
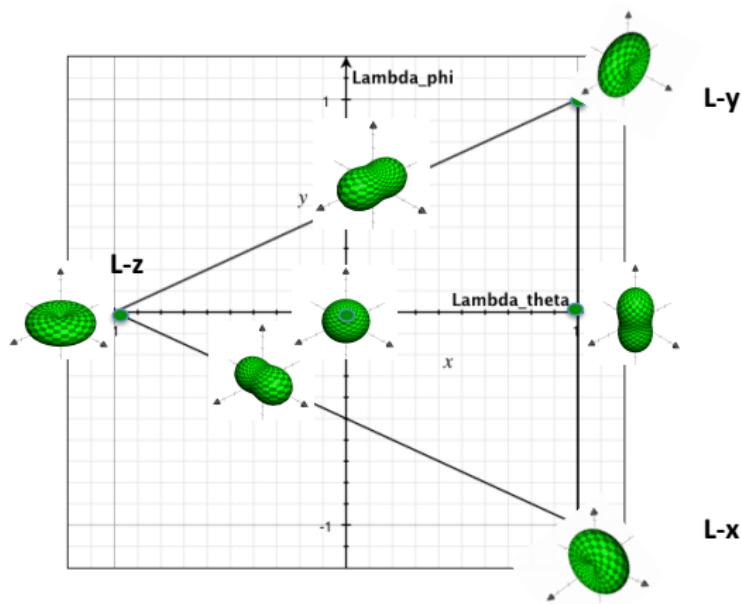
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- $\lambda_\vartheta$ -only measurements  
(à la TeVatron Run I)  
can't be compared without assumptions about pol<sup>n</sup> frame
- *experimental acceptance* is also typically a f<sup>n</sup> of  $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$



# BACKUP: polarization for $V \rightarrow \mu^+ \mu^-$

Sandro Palestini, Physical Review D 83, 031503(R) (2011)

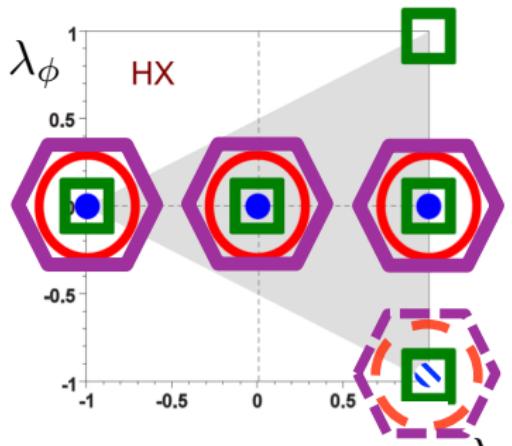
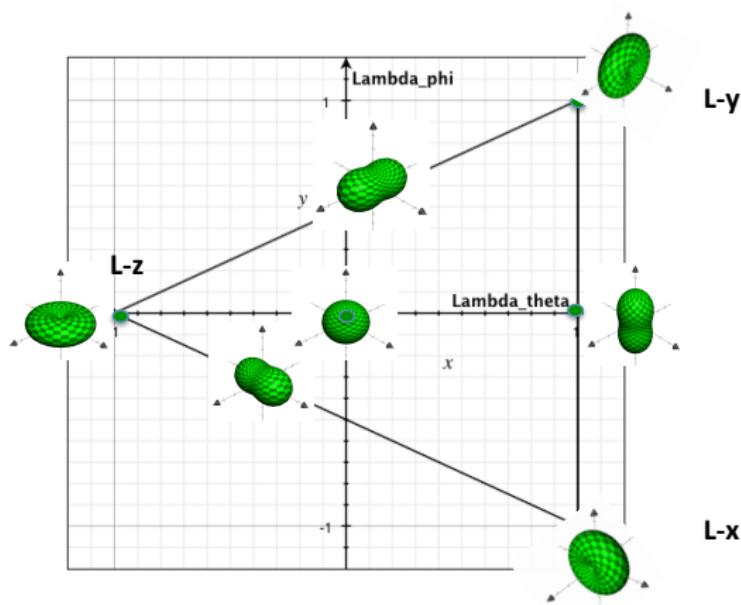
- limited range of  $(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi})$  values allowed



# BACKUP: polarization for $V \rightarrow \mu^+ \mu^-$

Sandro Palestini, Physical Review D 83, 031503(R) (2011)

- limited range of  $(\lambda_\theta, \lambda_\varphi, \lambda_{\vartheta\varphi})$  values allowed
- LHC experiments quote results for each of a set of working points



ATLAS CMS  
LHCb ALICE

# BACKUP: $\Upsilon(nS)$ production cross-sections

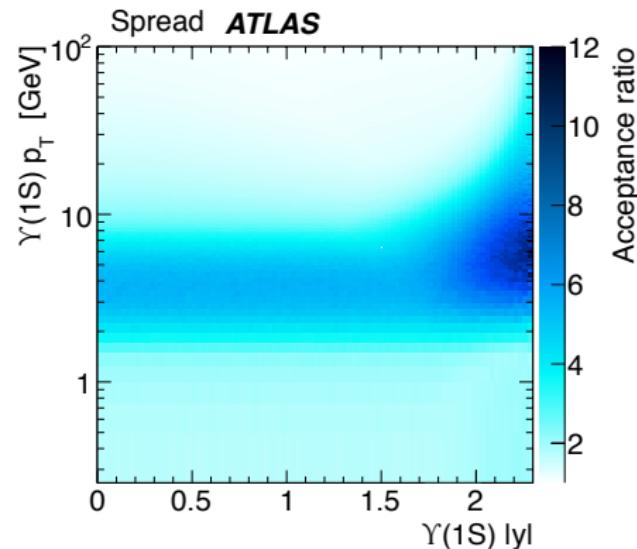
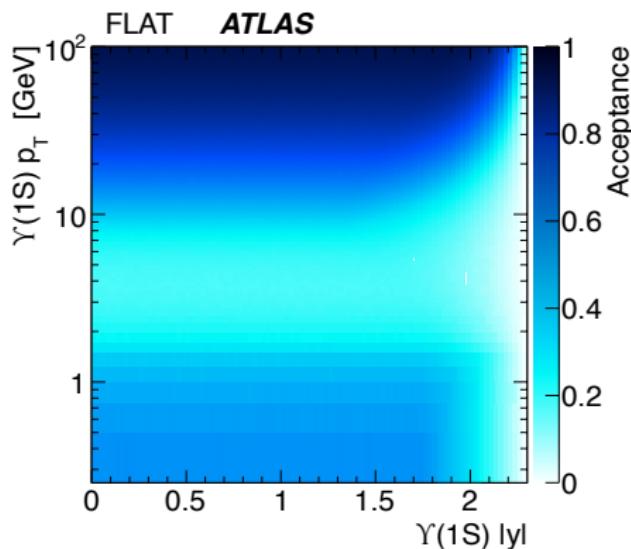
ATLAS Collaboration, PRD 87, 052004 (2013)

acceptance  $\mathcal{A}(p_T^\Upsilon, y^\Upsilon) = P(\text{both muons pass } p_T^\mu > 4 \text{ GeV}, |\eta^\mu| < 2.3)$

function of  $\Upsilon$  spin alignment: isotropic (default) +4 working points in

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

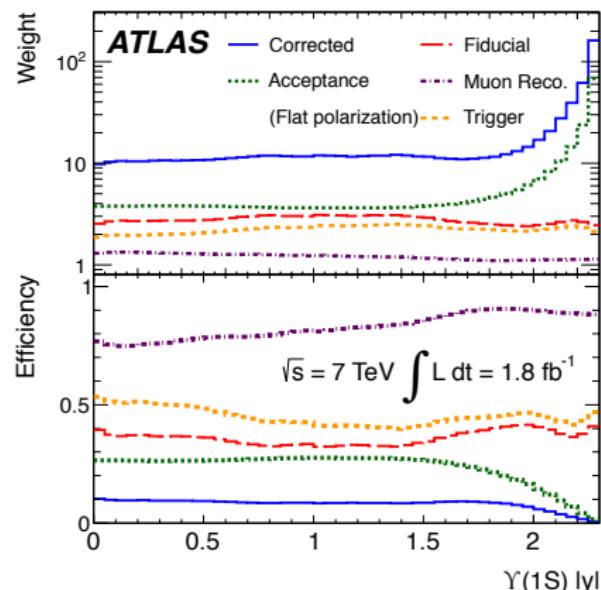
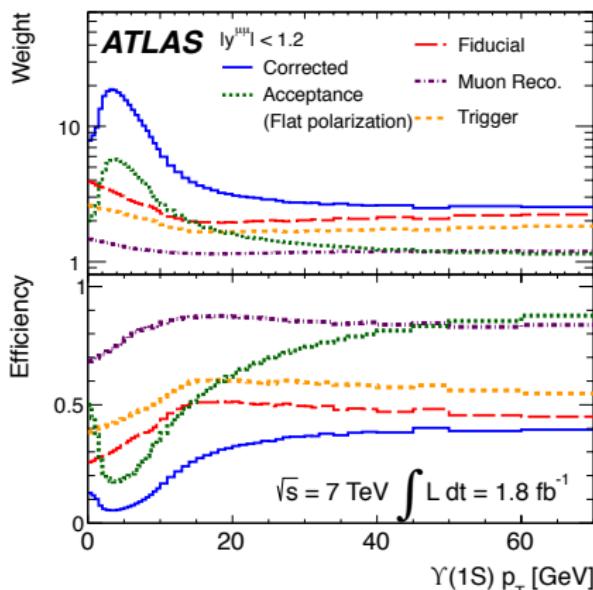
Lowest  $\mathcal{A}$ , and largest variation, for  $p_T \simeq \frac{1}{2}m_\Upsilon$  (consider "backward"  $\mu$ )



# BACKUP: $\Upsilon(nS)$ production cross-sections

ATLAS Collaboration, PRD 87, 052004 (2013)

**fiducial cross-sections** (no theoretical predictions to compare to so far!):  
little  $(p_T, y)$  structure in the weight,  $w_{\text{fid}} = (\epsilon_{\text{reco}} \cdot \epsilon_{\text{trig}})^{-1}$ ; dominated by  
trigger efficiency  $\epsilon_{\text{trig}} = \epsilon_{\text{RoI}}(p_T, q \cdot \eta)_{\mu_1} \cdot \epsilon_{\text{RoI}}(p_T, q \cdot \eta)_{\mu_2} \cdot c_{\mu\mu}(\Delta R, |y^{\mu\mu}|)$ ;  
see paper & <http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/BPHY-2011-06/>

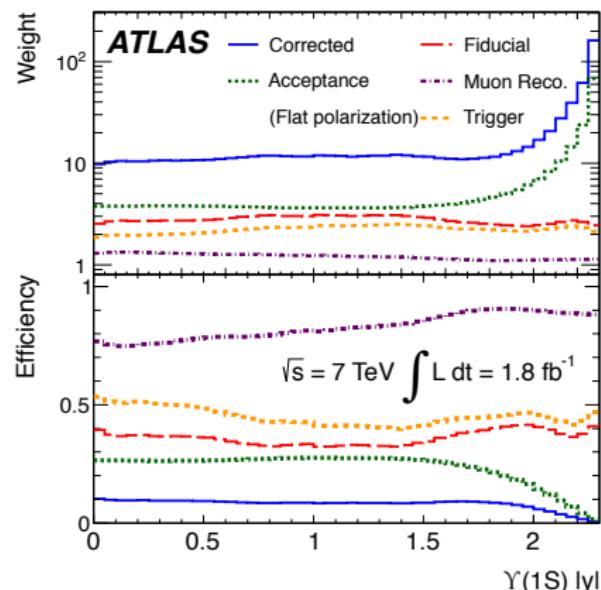
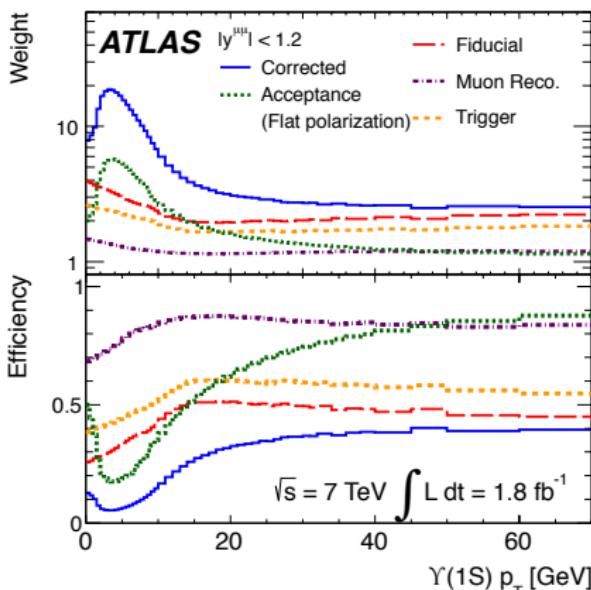


# BACKUP: $\Upsilon(nS)$ production cross-sections

ATLAS Collaboration, PRD 87, 052004 (2013)

## corrected cross-sections:

weight  $w_{\text{tot}} = (\mathcal{A} \cdot \epsilon_{\text{reco}} \cdot \epsilon_{\text{trig}})^{-1}$  dominated by acceptance at low  $p_T$   
⇒ spin-alignment dependence



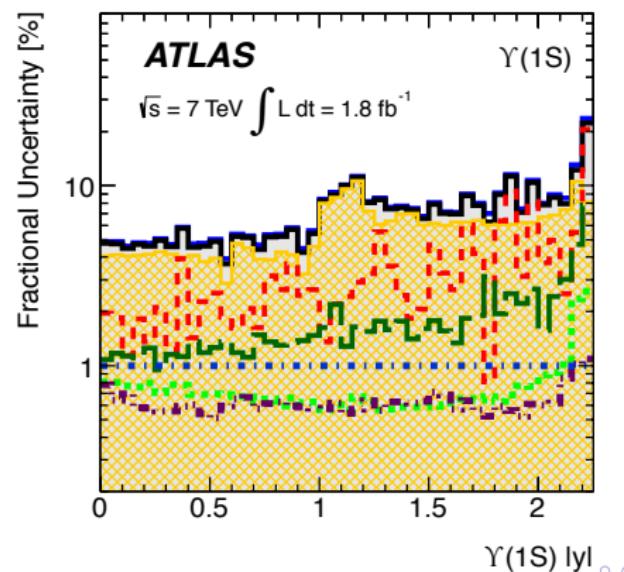
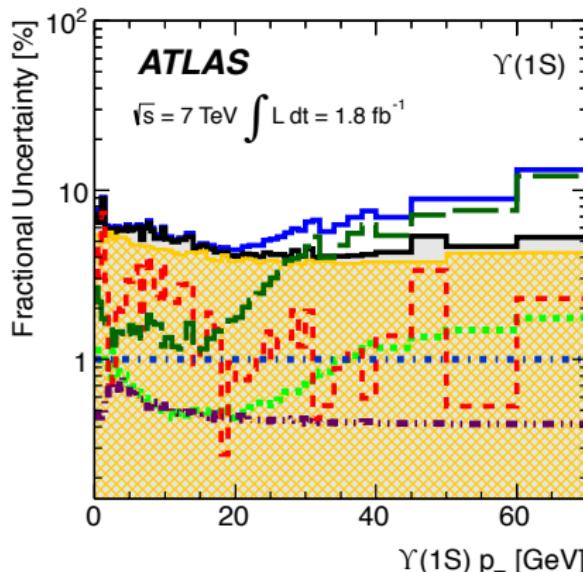
# BACKUP: $\Upsilon(nS)$ production cross-sections

ATLAS Collaboration, PRD 87, 052004 (2013)

systematics dominated by trigger efficiency and fit modelling;

— falls below stat/<sup>l</sup> uncert<sup>y</sup> for  $p_T \gtrsim 30$  (20) GeV for  $\Upsilon(1S)$  ( $\Upsilon(2S, 3S)$ )

low acceptance correction uncertainties due to spread in interaction point  
(subleading: statistical noise due to very fine binning)



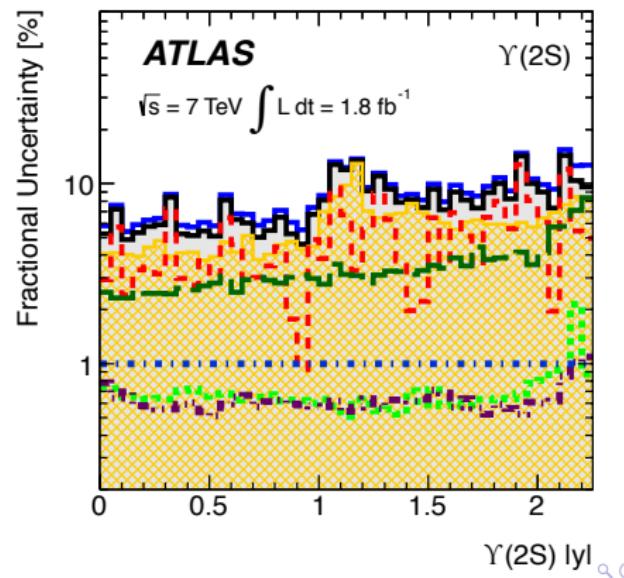
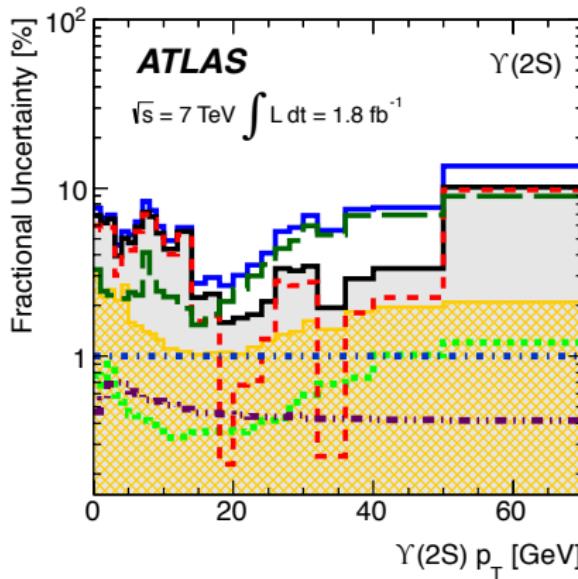
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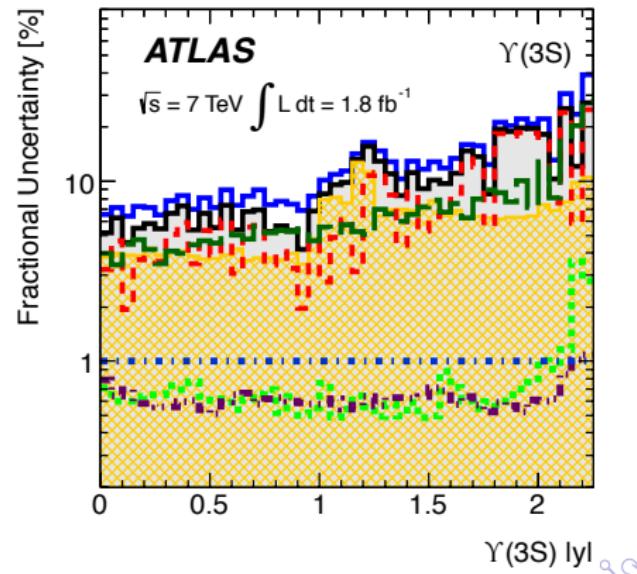
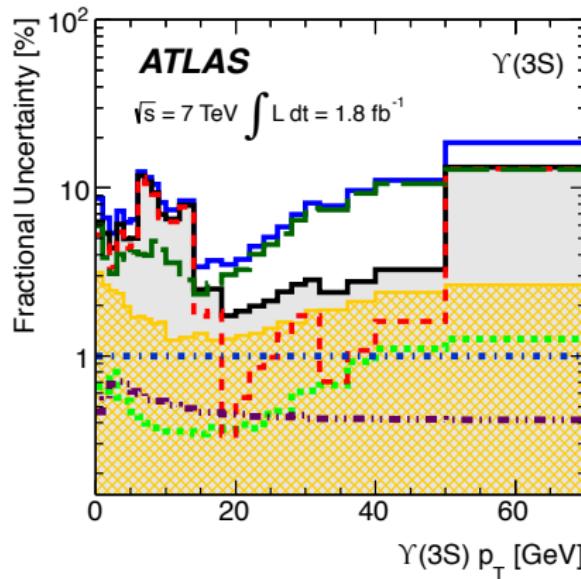
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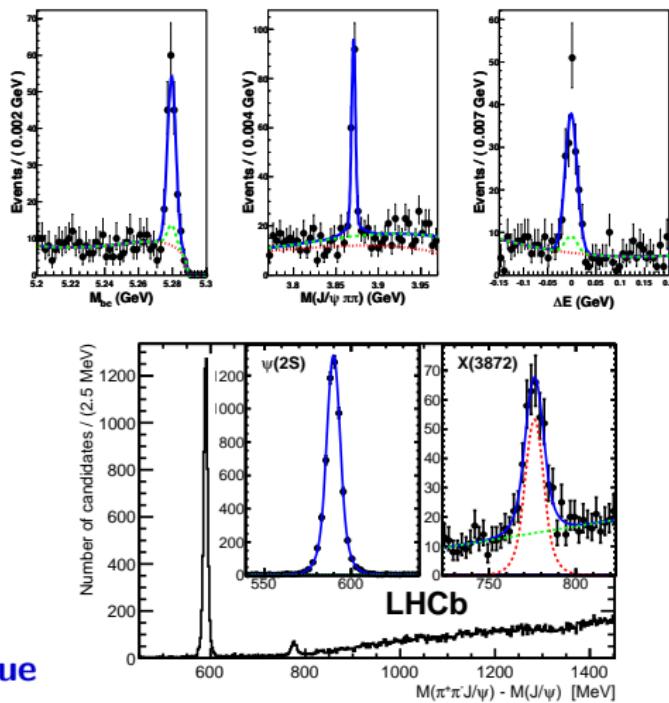
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# BACKUP: The X(3872) and the “X<sub>b</sub>”

The X(3872) is the first (2003) & best-studied ( $> 25$  exp<sup>tal</sup> papers) of the new hidden-charm states seen in the last decade.

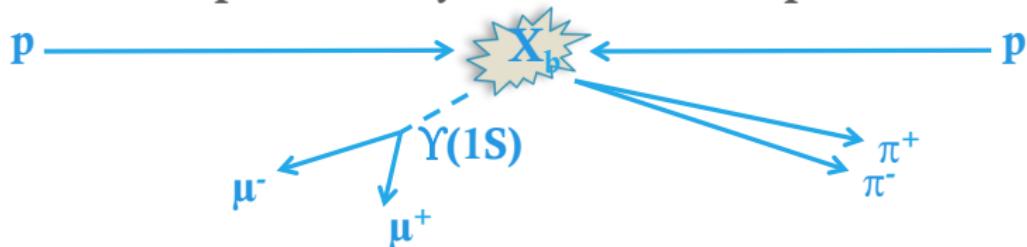
- $\pi\pi\psi$  [discovery] & other decays
- narrow:  $\Gamma < 1.2$  MeV, 90% C.L.
- $J^{PC} = 1^{++}$  ( $2^{-+}$  finally excluded)
- direct  $p\bar{p}$  &  $pp$  production seen
- very poor match to  $c\bar{c}$  structure
- very close to  $D^{*0}\bar{D}^0$  threshold:
  - $D^{*0}\bar{D}^0$  molecule,  
very weak  $E_b \approx \frac{1}{10} E_b(^2H)$ ?
  - $\exists$  tetraquark, other models
- heavy-flavour symmetry:  
**expect a hidden-beauty analogue**



# BACKUP: $X_b$ search: outline

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

The  $\pi^+\pi^-Y(1S)$  (c.f.  $\pi^+\pi^-J/\psi$ ) channel provides an experimentally feasible search option:



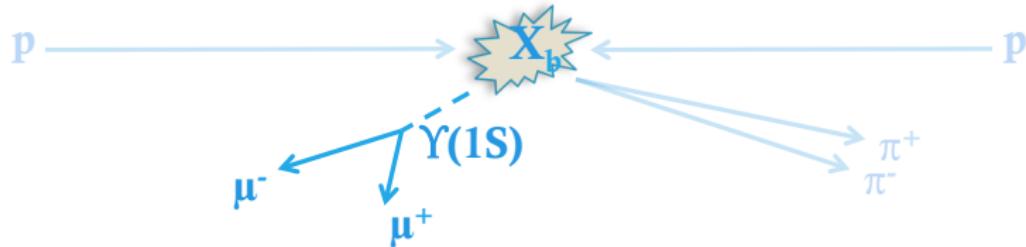
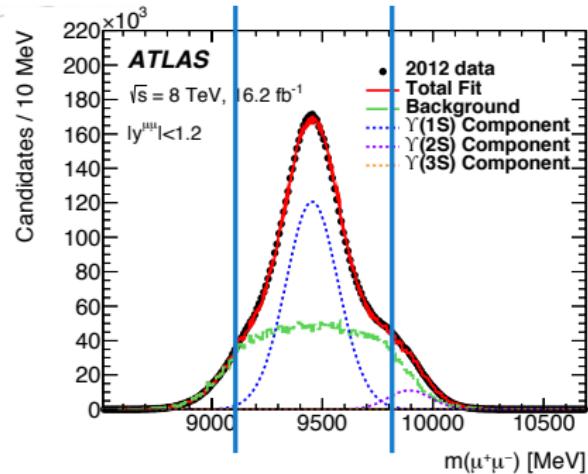
1. Reconstruct  $X_b \rightarrow \pi^+\pi^-Y(\mu\mu)$  using large ATLAS  $Y(\mu\mu)$  sample
2. Either observe  $X_b$  at mass  $M$  with significance  $z$ , or
3. Set upper limits for  $X_b \rightarrow \pi^+\pi^-Y(\mu\mu)$  production
4. Also look for  $Y(1^3D_J)$ ,  $Y(10860)$ , and  $Y(11020)$  decays

# BACKUP: $X_b \rightarrow \pi^+\pi^-\Upsilon(\rightarrow \mu^+\mu^-)$ reconstruction

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

## I. Find $\Upsilon \rightarrow \mu^+\mu^-$ candidates:

- $p_T(\mu) > 4$  GeV  $\Upsilon$  trigger
- two “combined”  $\mu$  tracks
- $|\eta(\mu)| < 2.3$
- $|m(\mu\mu) - m_{1S}| < 350$  MeV



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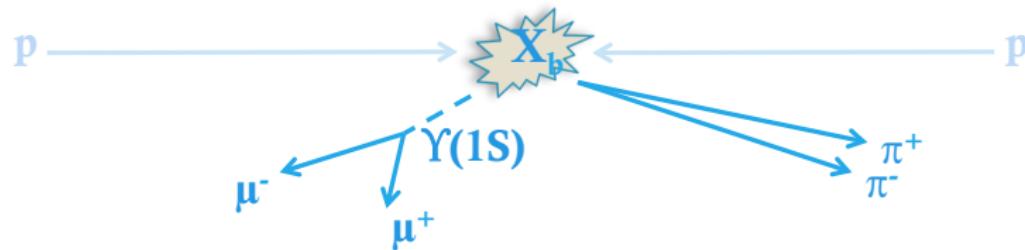
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- two “combined”  $\mu$  tracks
- $|\eta(\mu)| < 2.3$
- $|m(\mu\mu) - m_{1S}| < 350 \text{ MeV}$

## II. Add two tracks ( $\pi\pi$ ):

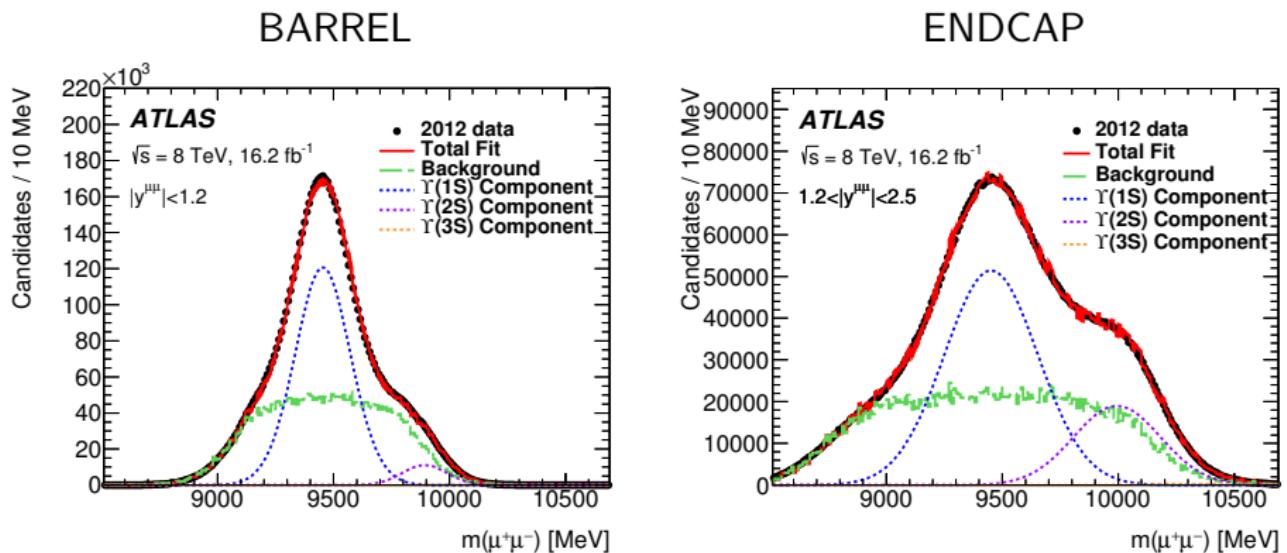
- $p_T(\pi) > 400 \text{ MeV}$
- $|\eta(\pi)| < 2.5$
- 4-track vertex fit
  - $m(\mu\mu) = m_{1S}$  constraint
  - $\chi^2 < 20$
  - masses  $< 11.2 \text{ GeV}$



# BACKUP: $X_b$ : discrimination in $(|y|, p_T, \cos \theta^*)$

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

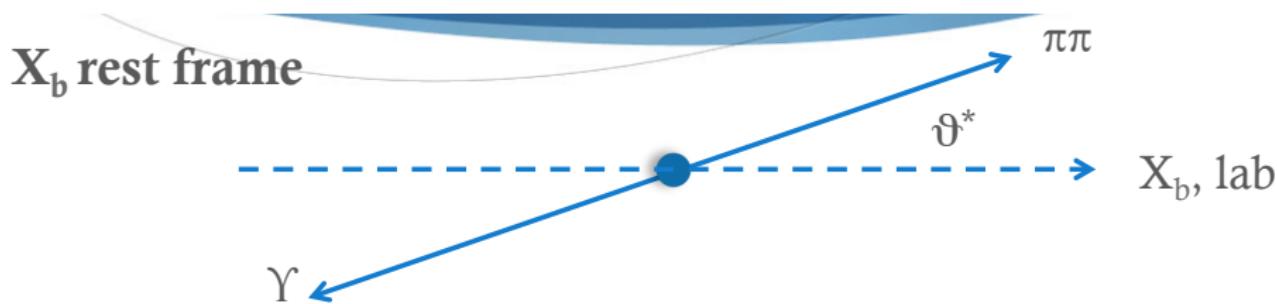
- barrel ( $|y| < 1.2$ ) resolut<sup>n</sup> better than endcap ( $1.2 < |y| < 2.4$ )
- constraint  $\mu^+ \mu^- \rightarrow \Upsilon$  mitigates this, but not higher bkgd under peak
- unknown  $X_b$  mass:  $\pi\pi$  effect on  $m(\pi\pi\Upsilon)$  resolution can't be removed  
→ perform the analysis in bins of rapidity



# BACKUP: $X_b$ : discrimination in $(|y|, p_T, \cos \theta^*)$

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

- barrel ( $|y| < 1.2$ ) resolut<sup>n</sup> better than endcap ( $1.2 < |y| < 2.4$ )  
→ perform the analysis in bins of rapidity
- different signal and background distributions in  $(p_T, \cos \theta^*)$ :
  - $\cos \theta^*(\pi^+ \pi^-)$  flat in parent rest frame for unpolarized signal
  - in background,  $\pi^+ \pi^-$  unrelated to  $\mu^+ \mu^-$ , and has low  $p_T^{\pi\pi}$   
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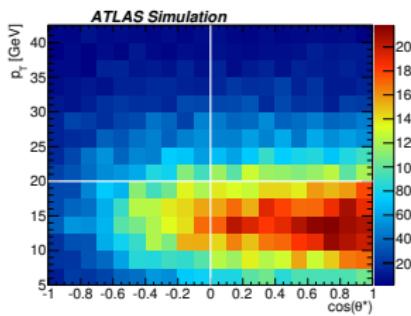


[classic discrimination by decay angle for (quasi-)2-body decays]

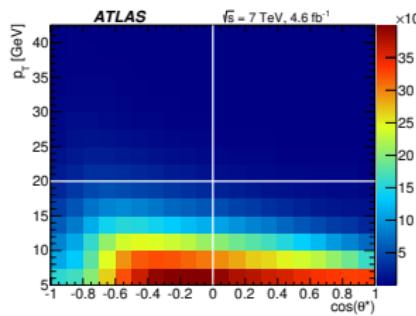
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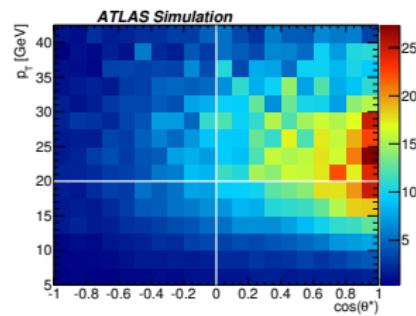
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→ distributions change but discrimination remains



SIGNAL



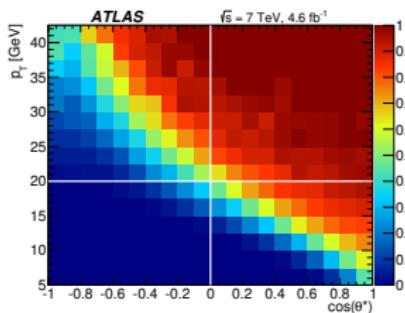
BACKGROUND



# BACKUP: $X_b$ : discrimination in $(|y|, p_T, \cos \theta^*)$

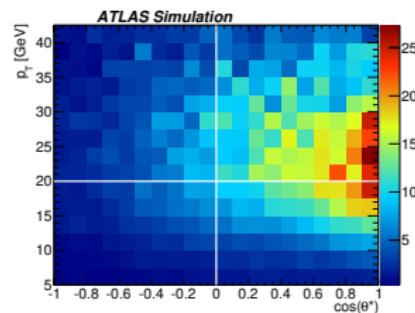
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→ distributions change but discrimination remains



$\Delta R$  cut à la CMS

we chose bin boundaries at  
 $(p_T, \cos \theta^*) = (20 \text{ GeV}, 0)$   
→ simult. fit to  $2 \times 2 \times 2$   
bins in  $(|y|, p_T, \cos \theta^*)$ :  
considered  $\Delta R$  cut [CMS]:  
less sensitive than binning



$S/\sqrt{B}$

# BACKUP: $X_b$ : background and signal modelling

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

## background:

- mix of inclusive  $\Upsilon(1S)$  and combinatorial  $\mu^+\mu^-$
- preliminary studies performed on 2011 (7 TeV) data:  
lower-sideband  $\mu^+\mu^-$  and same-sign  $\mu^\pm\mu^\pm$  samples
- $m(\pi^+\pi^-\Upsilon)$  distributions featureless above 9800 MeV
- confirmed in  $\Upsilon \rightarrow \mu^+\mu^-$  signal region for various  $m(\pi^+\pi^-\Upsilon)$  ranges  
→ **polynomial fit** to  $m(\pi^+\pi^-\Upsilon)$  region about each test mass

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→ **polynomial fit** to  $m(\pi^+\pi^-\Upsilon)$  region about each test mass

## signal:

- narrow state search: fit with  $f \cdot \mathcal{G}(m, \sigma) + (1 - f) \cdot \mathcal{G}(m, r\sigma)$
- $f, r \sim \text{indep}^t$  of mass; fixed to average over MC samples
- $\sigma$  then found to be linear in mass
- *remaining issues:* division among analysis bins, acceptance, efficiency

# BACKUP: $X_b$ : background and signal modelling

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

## background:

- mix of inclusive  $\Upsilon(1S)$  and combinatorial  $\mu^+\mu^-$
- preliminary studies performed on 2011 (7 TeV) data:  
lower-sideband  $\mu^+\mu^-$  and same-sign  $\mu^\pm\mu^\pm$  samples
- $m(\pi^+\pi^-\Upsilon)$  distributions featureless above 9800 MeV
- confirmed in  $\Upsilon \rightarrow \mu^+\mu^-$  signal region for various  $m(\pi^+\pi^-\Upsilon)$  ranges  
→ **polynomial fit** to  $m(\pi^+\pi^-\Upsilon)$  region about each test mass

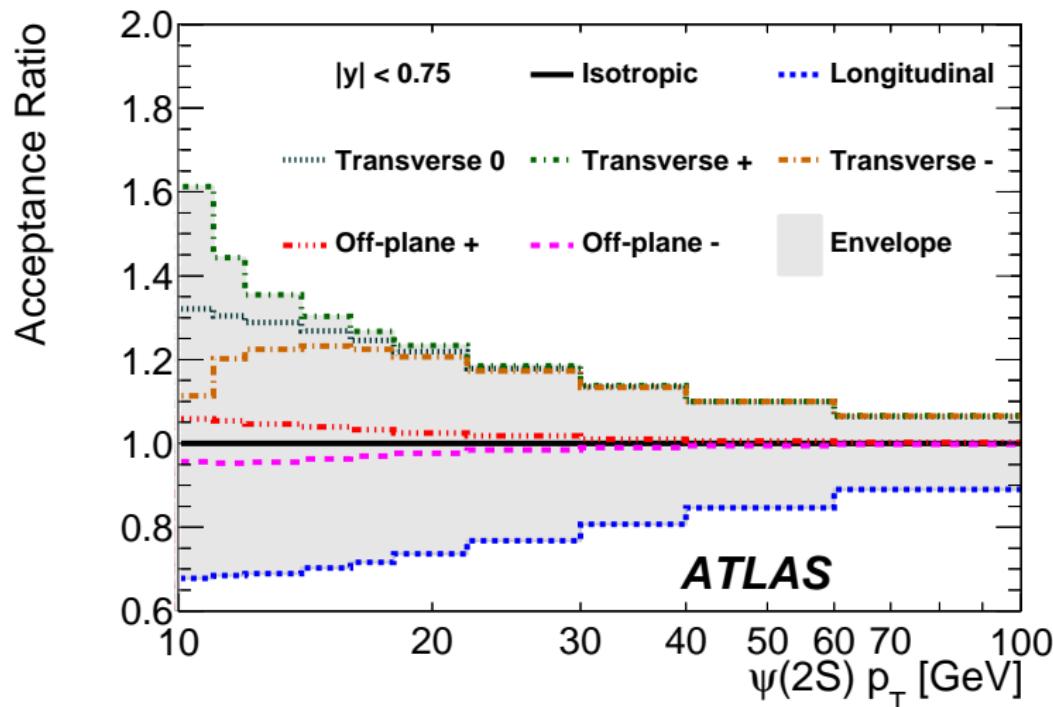
## signal:

- narrow state search: fit with  $f \cdot \mathcal{G}(m, \sigma) + (1 - f) \cdot \mathcal{G}(m, r\sigma)$
- $f, r \sim \text{indep}^t$  of mass; fixed to average over MC samples
- $\sigma$  then found to be linear in mass
- *remaining issues:* division among analysis bins, acceptance, efficiency  
— all depend on distribution of final-state particles in  $(\eta, p_T, \phi)$

# BACKUP: $\psi(2S) \rightarrow \pi^+ \pi^- \text{ J}/\psi$ at 7 TeV

ATLAS Collaboration, JHEP 09 (2014) 079

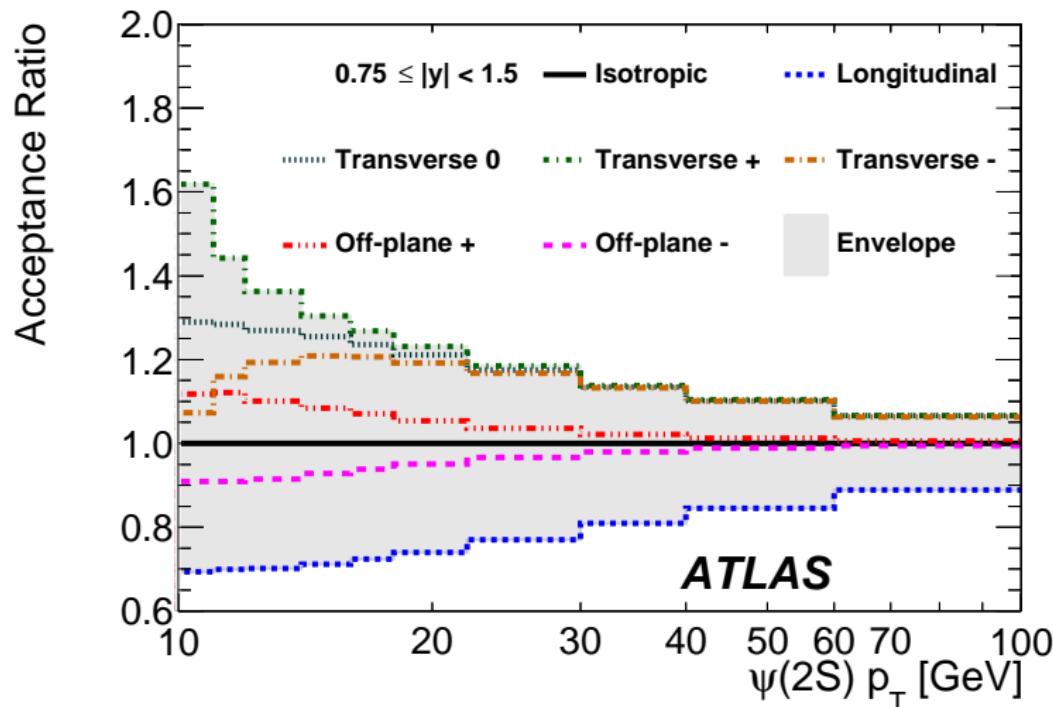
spin-alignment uncertainty:



# BACKUP: $\psi(2S) \rightarrow \pi^+ \pi^- \text{ J}/\psi$ at 7 TeV

ATLAS Collaboration, JHEP 09 (2014) 079

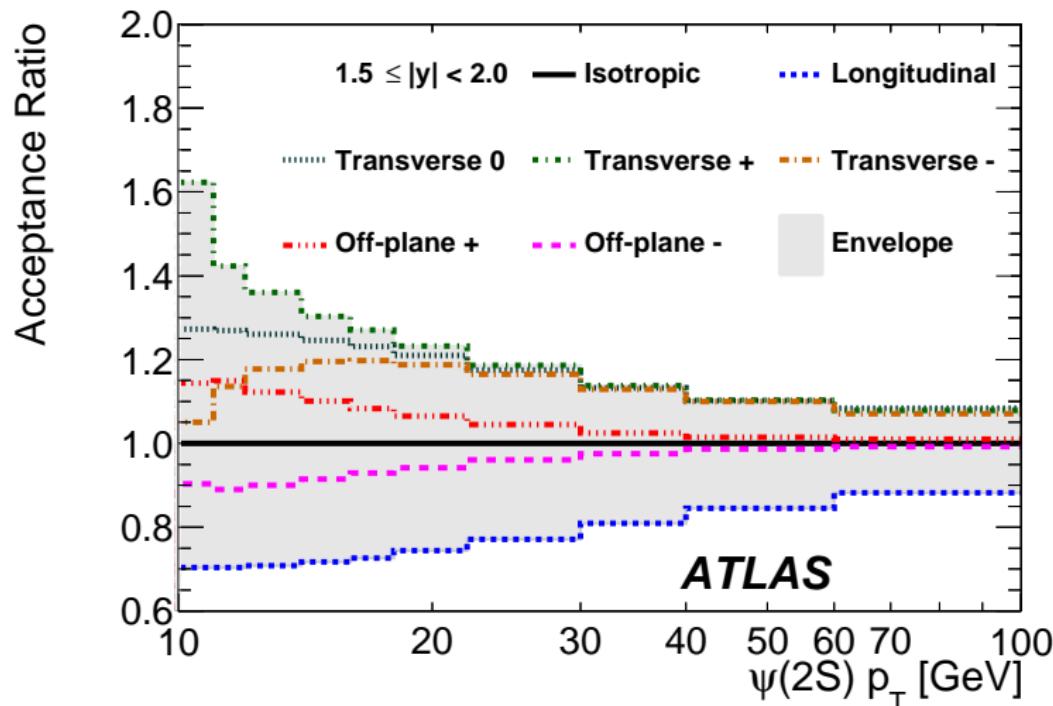
spin-alignment uncertainty:



# BACKUP: $\psi(2S) \rightarrow \pi^+ \pi^- \text{ J}/\psi$ at 7 TeV

ATLAS Collaboration, JHEP 09 (2014) 079

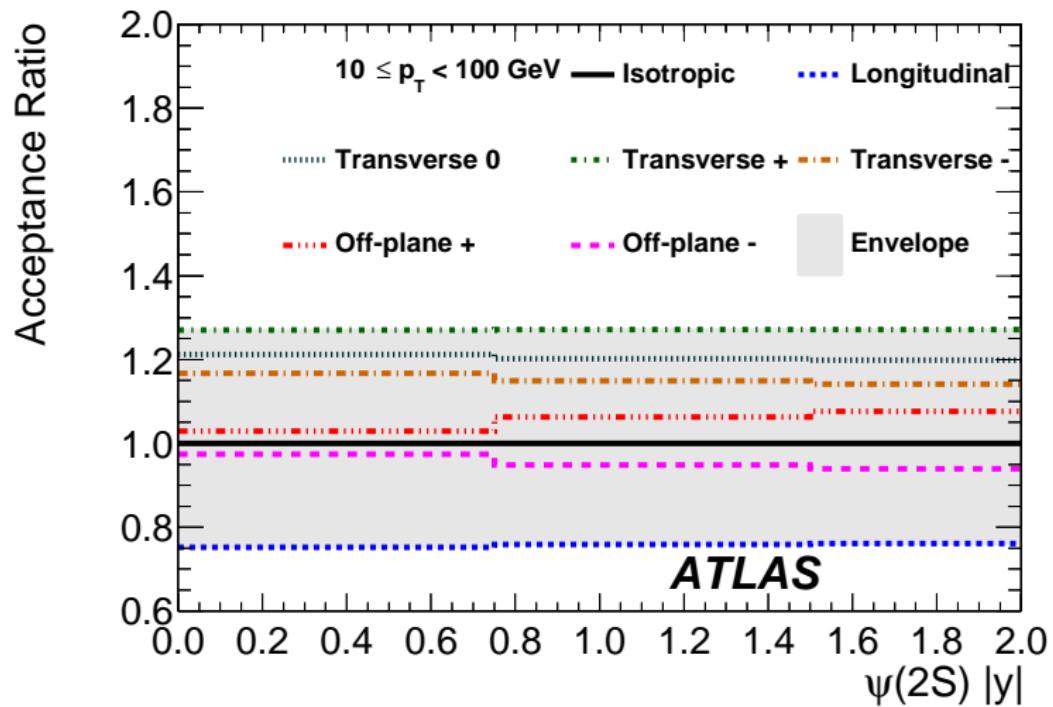
spin-alignment uncertainty:



# BACKUP: $\psi(2S) \rightarrow \pi^+ \pi^- \text{ J}/\psi$ at 7 TeV

ATLAS Collaboration, JHEP 09 (2014) 079

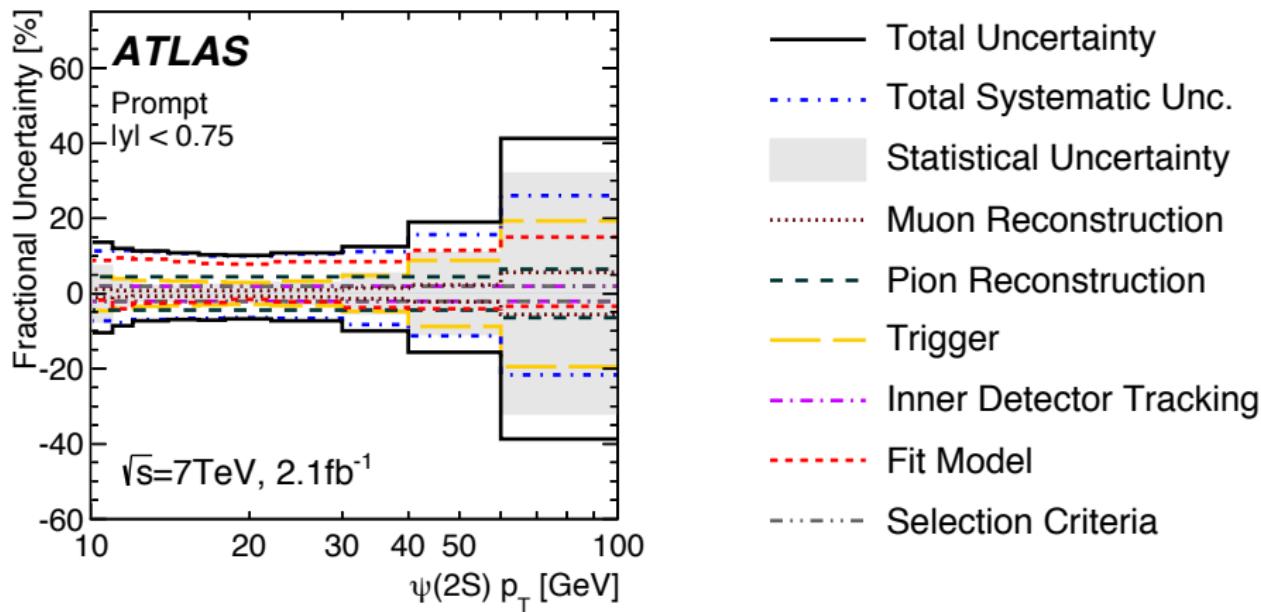
spin-alignment uncertainty:



# BACKUP: $\psi(2S) \rightarrow \pi^+ \pi^- \text{ J}/\psi$ at 7 TeV

ATLAS Collaboration, JHEP 09 (2014) 079

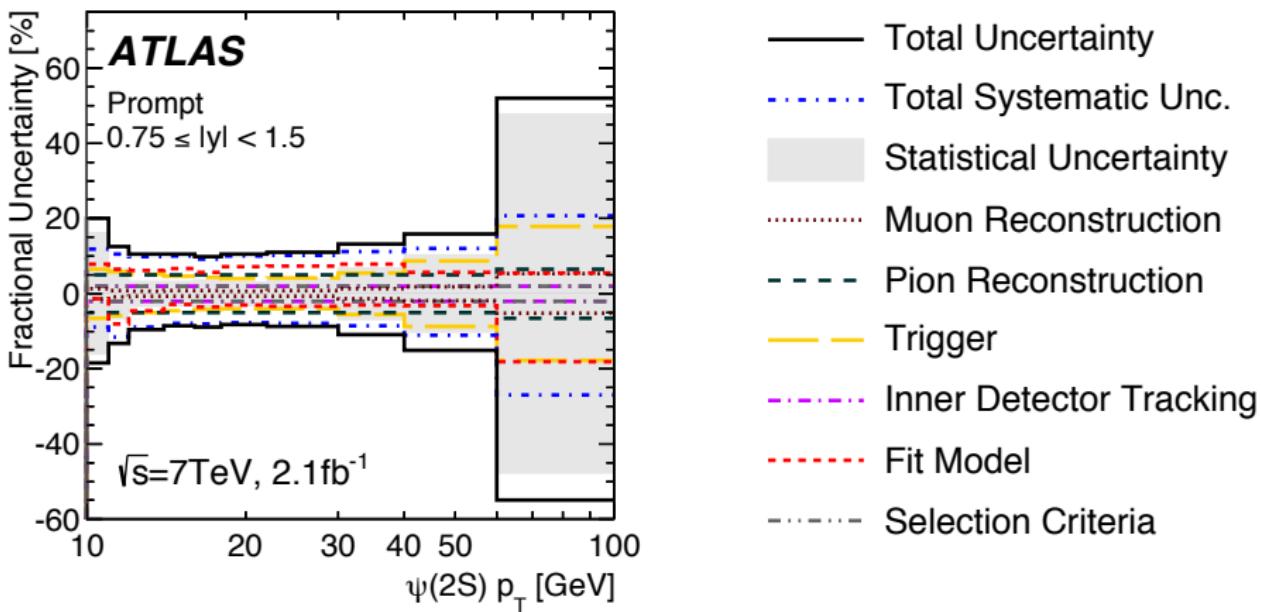
**prompt production uncertainty budget** (excluding spin alignment):



# BACKUP: $\psi(2S) \rightarrow \pi^+ \pi^- \text{ J}/\psi$ at 7 TeV

ATLAS Collaboration, JHEP 09 (2014) 079

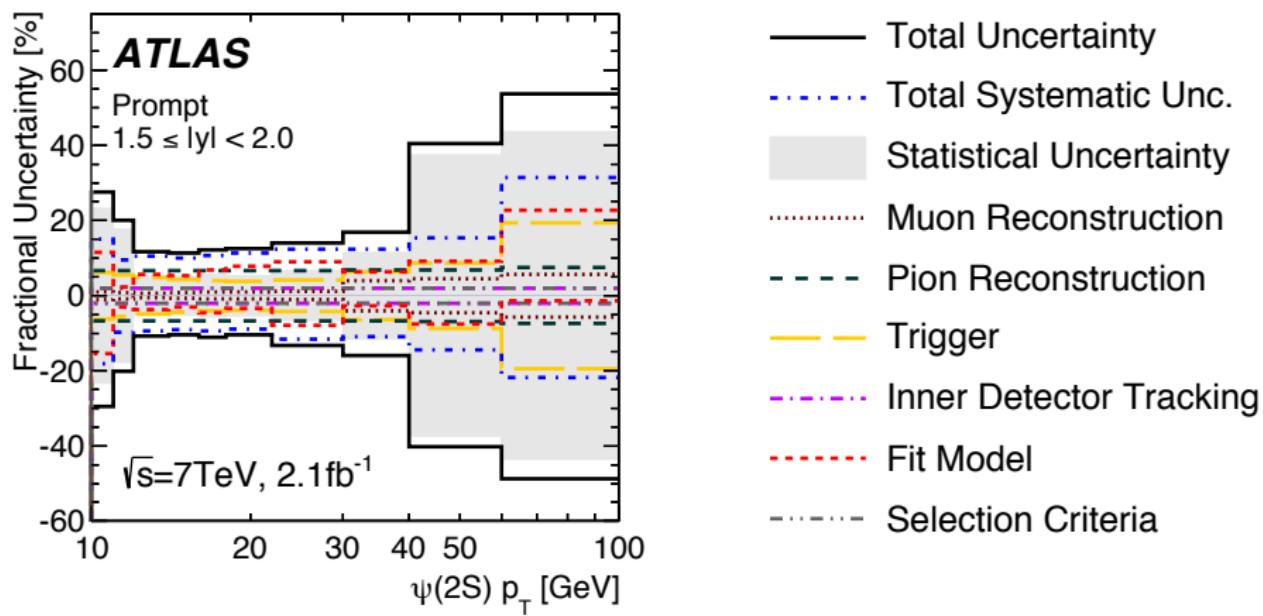
**prompt production uncertainty budget** (excluding spin alignment):



# BACKUP: $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$ at 7 TeV

ATLAS Collaboration, JHEP 09 (2014) 079

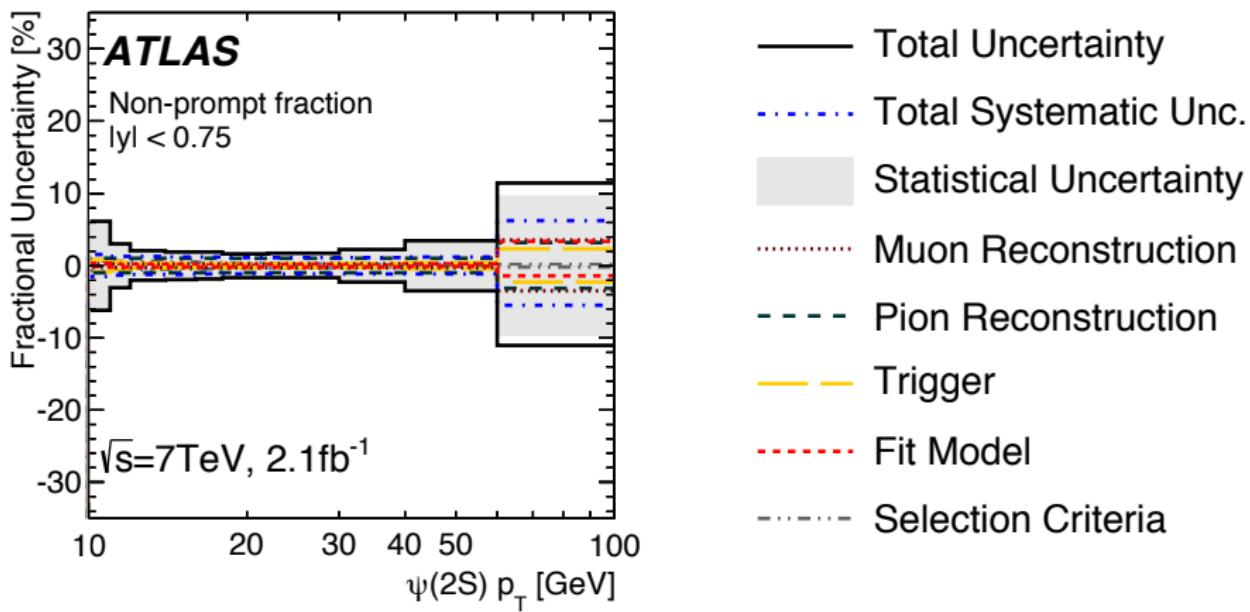
**prompt production uncertainty budget** (excluding spin alignment):



# BACKUP: $\psi(2S) \rightarrow \pi^+ \pi^- \text{ J}/\psi$ at 7 TeV

ATLAS Collaboration, JHEP 09 (2014) 079

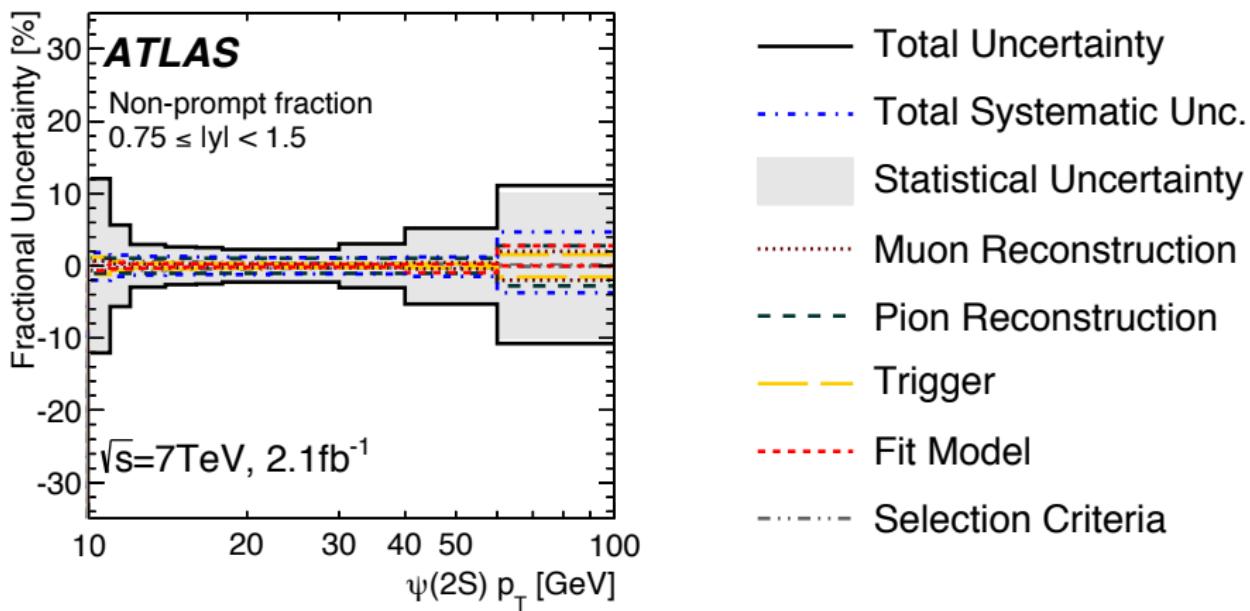
non-prompt uncertainty budget (excluding spin alignment):



# BACKUP: $\psi(2S) \rightarrow \pi^+ \pi^- \text{ J}/\psi$ at 7 TeV

ATLAS Collaboration, JHEP 09 (2014) 079

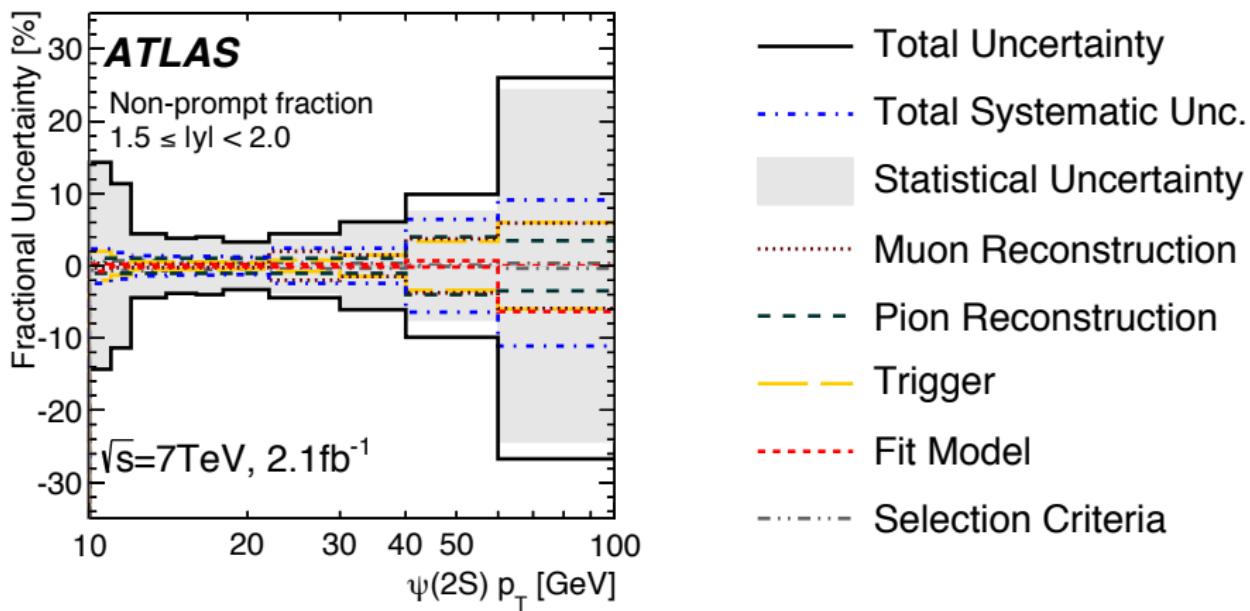
**non-prompt uncertainty budget** (excluding spin alignment):



# BACKUP: $\psi(2S) \rightarrow \pi^+ \pi^- \text{ J}/\psi$ at 7 TeV

ATLAS Collaboration, JHEP 09 (2014) 079

non-prompt uncertainty budget (excluding spin alignment):



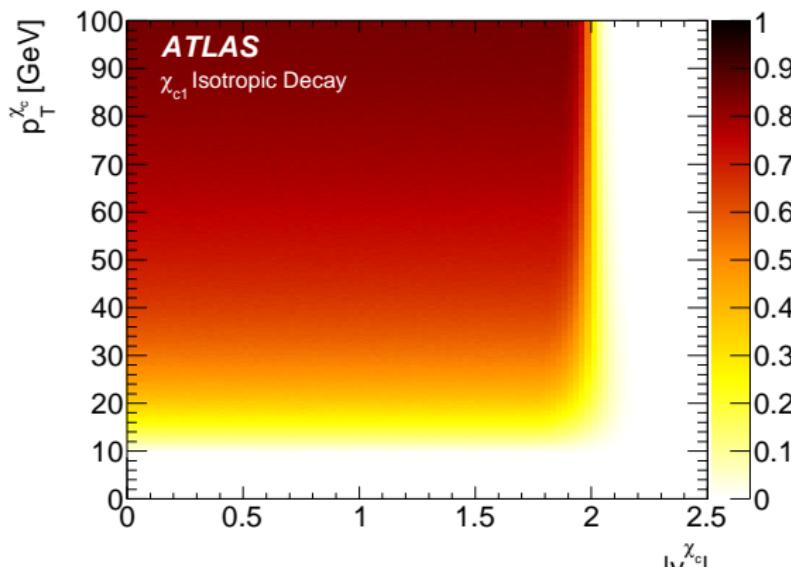
# BACKUP: $\chi_{c1}$ and $\chi_{c2}$ production at 7 TeV

ATLAS Collaboration, JHEP 07 (2014) 154

acceptance  $\mathcal{A}(p_T^\chi, y^\chi) = P(\text{both muons pass } p_T^\mu > 4 \text{ GeV}, |\eta^\mu| < 2.3,$   
and photon passes  $p_T^\gamma > 1.5 \text{ GeV}, |\eta^\gamma| < 2.0)$

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

treatment relies on Faccioli/Lourenco/Seixas/Wohri PRD 83, 096001 (2011)



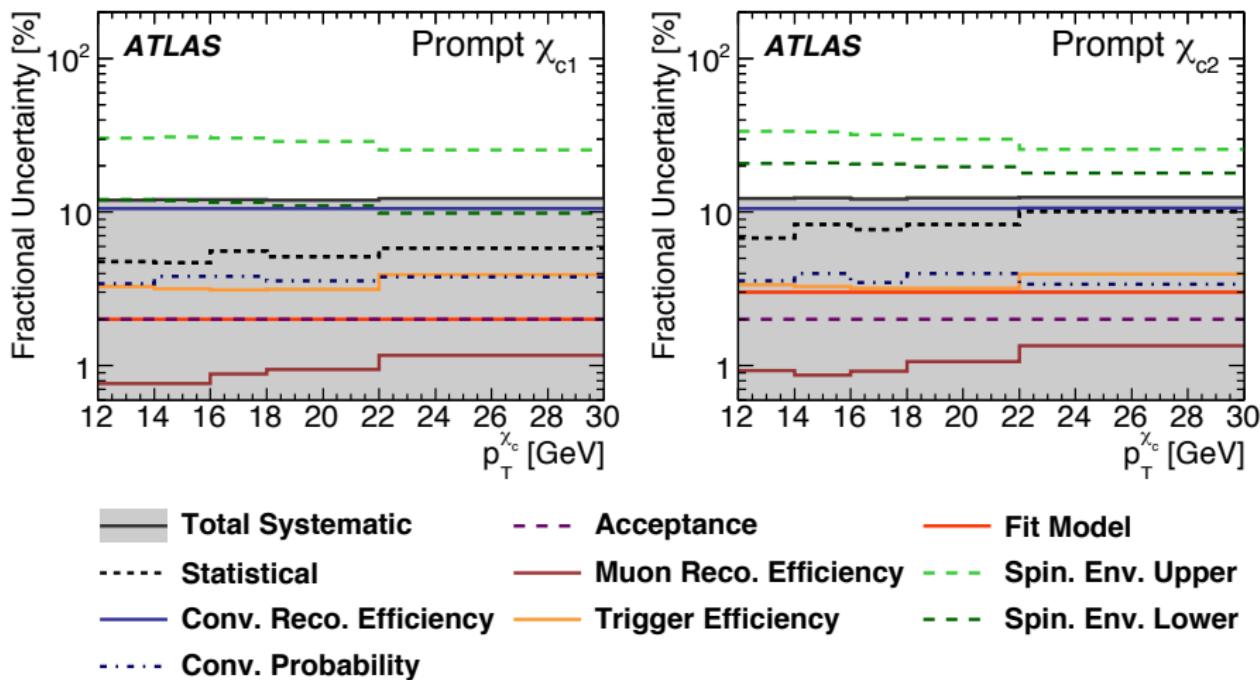
results, and neglect of the (suppressed) higher multipole contributions to  $\chi_{c2} \rightarrow \gamma J/\psi$

Note the high effective  $p_T$  threshold on the  $\chi$

# BACKUP: $\chi_{c1}$ and $\chi_{c2}$ production at 7 TeV

ATLAS Collaboration, JHEP 07 (2014) 154

**uncertainty budget** for the prompt measurement:



# BACKUP: $\chi_{c1}$ and $\chi_{c2}$ production at 7 TeV

ATLAS Collaboration, JHEP 07 (2014) 154

uncertainty budget for the non-prompt measurement:

