Spectroscopy at ATLAS

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Quarkonium Working Group, 8th June 2016,
Pacific Northwest National Laboratory, Richland WA

Outline

Previously at this meeting:

- quarkonium production at ATLAS: Elisa's talk on Monday
- new $X(3872)$-*vs*-$\psi(2S)$ prod^n results: Vato's talk (also on Monday)
- those analyses use weighted events, the usual ATLAS-Onia approach; today's use *unweighted events*

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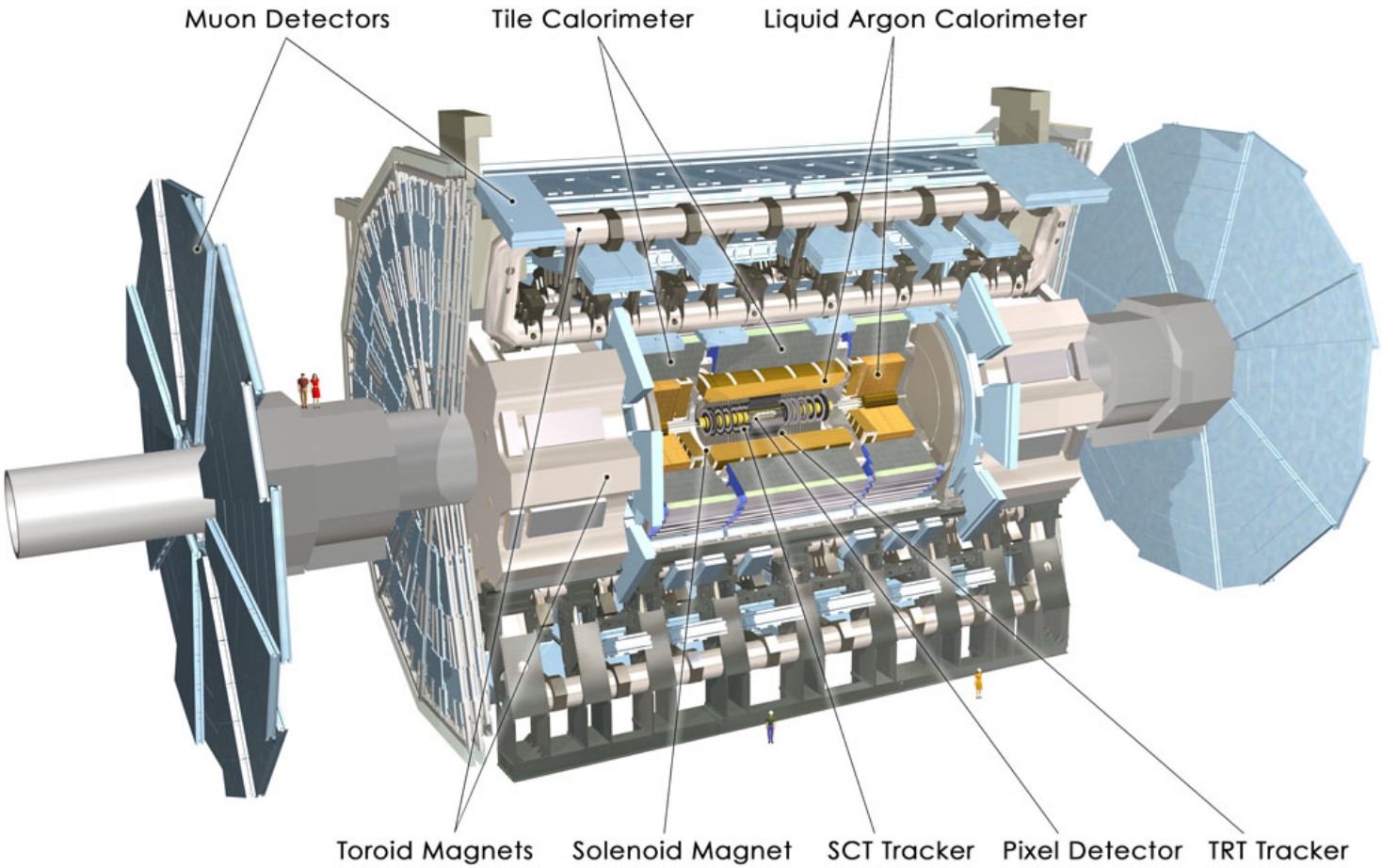
1. **ATLAS: detector, trigger, dataset, program**
2. **Observation of the $B_c(2S)$**
3. **Observation of the $\chi_b(3P)$**
4. **Search for an X_b state**
5. **Summary, and Run 2 plans**

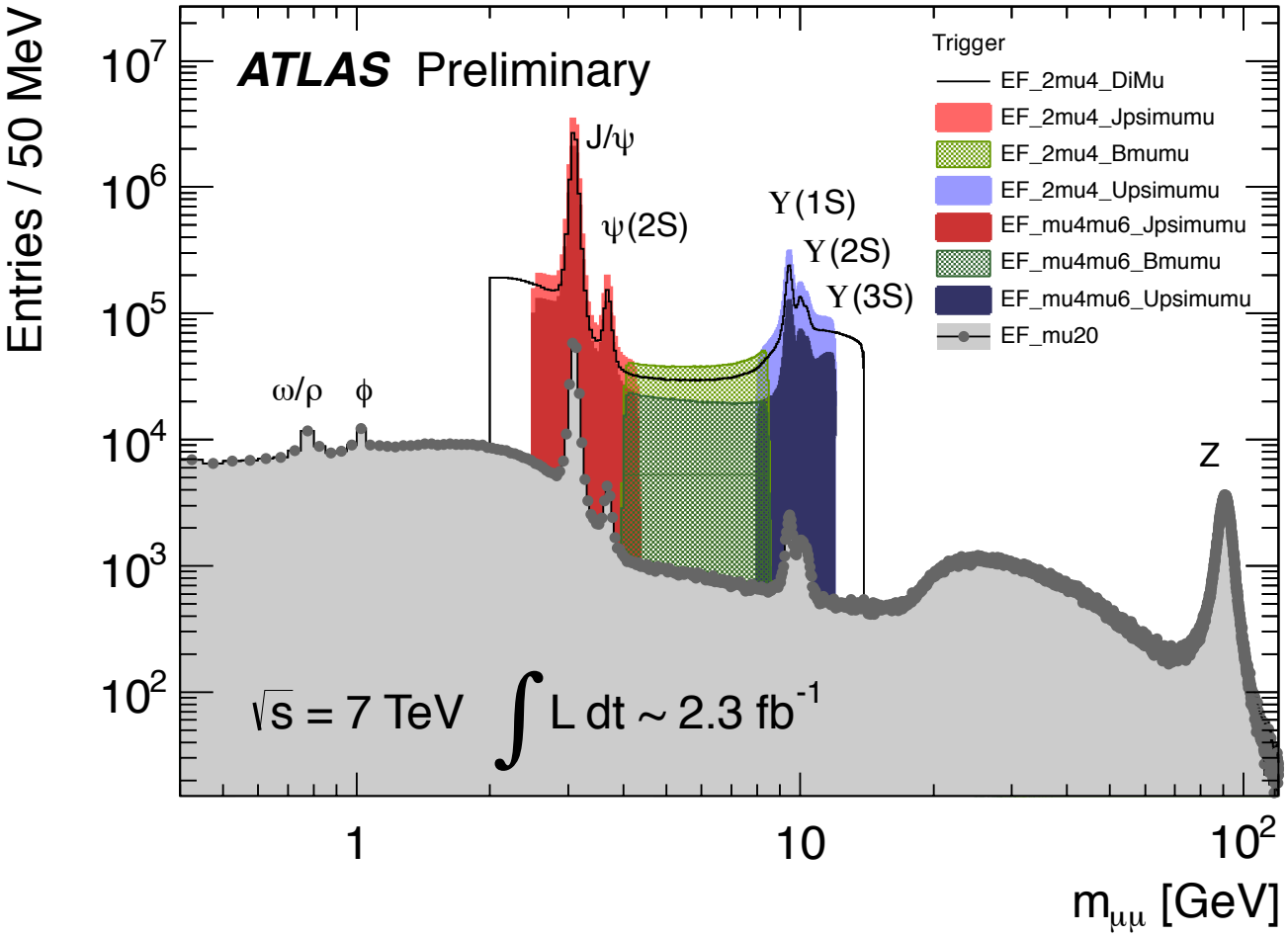
ATLAS: (1) detector and trigger

copious quarkonium production, but with strongly falling $\frac{\mathrm{d}\sigma}{\mathrm{d}p_T}$,
in high track-multiplicity events,
in a detector optimized for high-p_T discovery physics at $\sqrt{s} = 14\,\mathrm{TeV}$



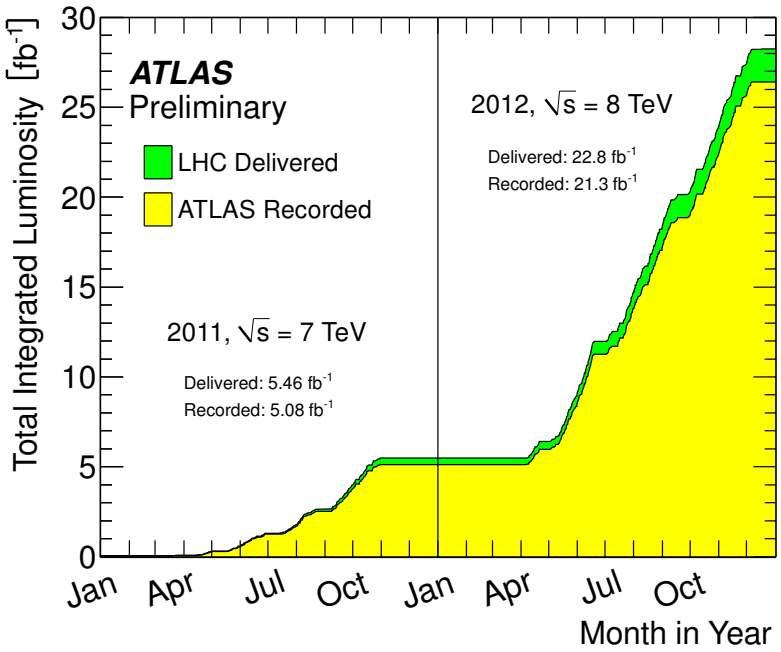
ATLAS: (1) detector and trigger

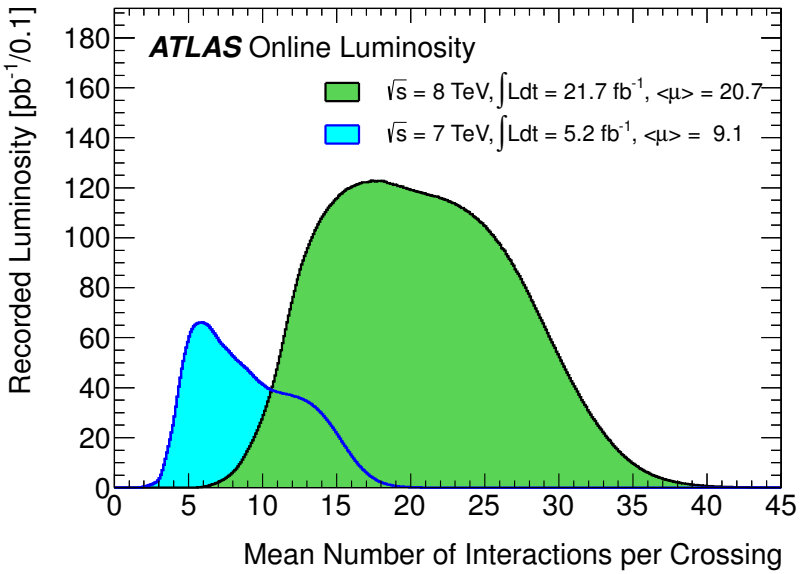
- rate limited by trigger bandwidth, especially at Level 1 (hardware)
- for quarkonia: high-p_T μ & $M(\mu\mu)$-restricted-dimuon triggers
- increasing $\mathcal{L} \longrightarrow$ higher-p_T triggers, prescaling, ...



ATLAS: (2) dataset and research program

- **Run 1 dataset:**
  $5\,\mathrm{fb}^{-1}$ at $7\ \mathrm{TeV}$ (2011)
  $21\,\mathrm{fb}^{-1}$ at $8\ \mathrm{TeV}$ (2012)
- analyses presented here use large subsets, depending on trigger availability & prescaling
- conditions change over the run, esp. the rate of *in-time pileup*: additional pp interactions in the same bunch-crossing
- less $\int \mathcal{L}\,\mathrm{d}t$ at $7\ \mathrm{TeV}$; harsher conditions at $8\ \mathrm{TeV}$
- affects track multiplicity, combinatorial background, and (via bkgd suppression) efficiency





Observation of the $B_c(2S)$: (1) selection

ATLAS Collaboration, Physical Review Letters 113, 212004 (2014)

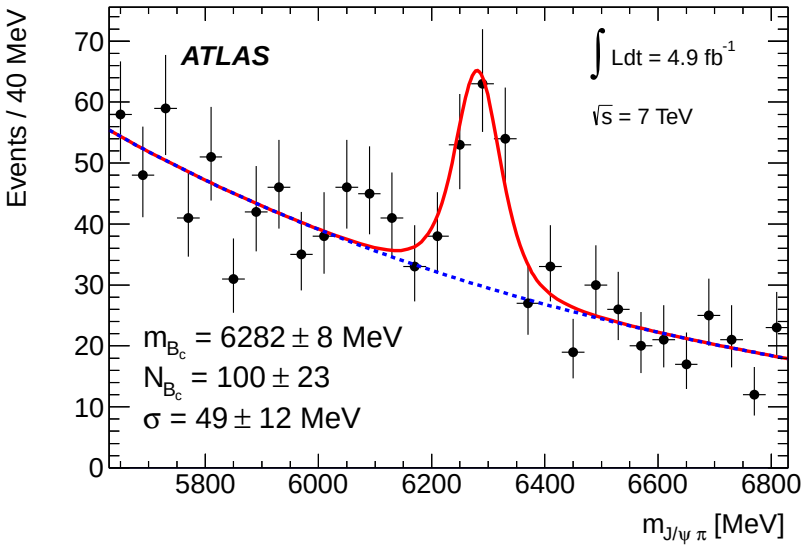
$4.9\,\mathrm{fb}^{-1}$ (7 TeV) & $19.2\,\mathrm{fb}^{-1}$ (8 TeV)

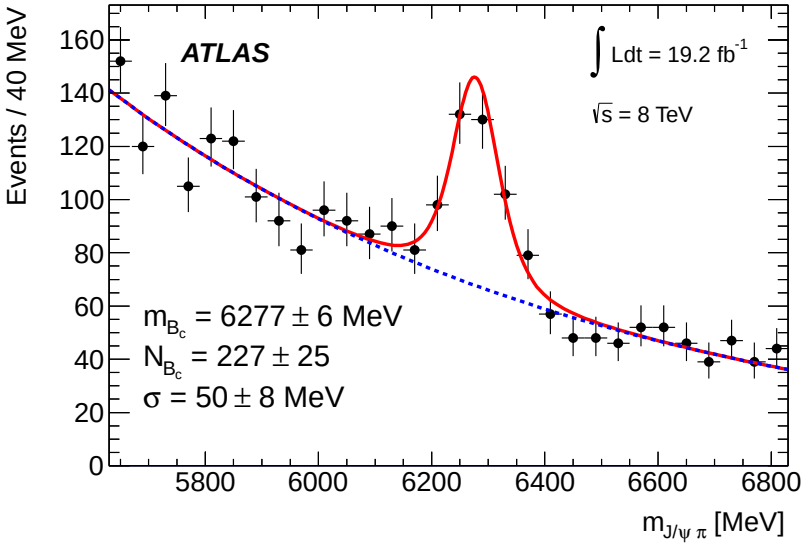
first collect $J/\psi \to \mu^+\mu^-$:

- $p_T^{\mu 1} > 6\,\mathrm{GeV}$, $p_T^{\mu 2} > 4\,\mathrm{GeV}$
- common vertex fit, $\chi^2/n_{dof} < 15$
- better **B**arrel ($|\eta^\mu| < 1.05$) resol^n than **E**ndcap ($|\eta^\mu| \in (1.05, 2.5)$); distinct **B+B**, **B+E**, **E+E** samples

then form $B_c \to \pi J/\psi$ at 7 & 8 TeV:

- $|m_{\mu\mu} - m_\psi| < 3\sigma$ (σ : $40 \sim 90\,\mathrm{MeV}$)
- $p_T^\pi > 4.0\,\mathrm{GeV}$; $d_0/\sigma(d_0) > 5$, 4.5
- $\pi\psi$ vertex fit, $m_{\mu\mu} \to m_\psi$ constraint
- $\chi^2/n_{dof} < 2$, 1.5; $p_T^{B_c} > 15$, $18\,\mathrm{GeV}$
- extended UML bkgd exp $+\,\mathcal{G}$ signal fit





Observation of the $B_c(2S)$: (2) result

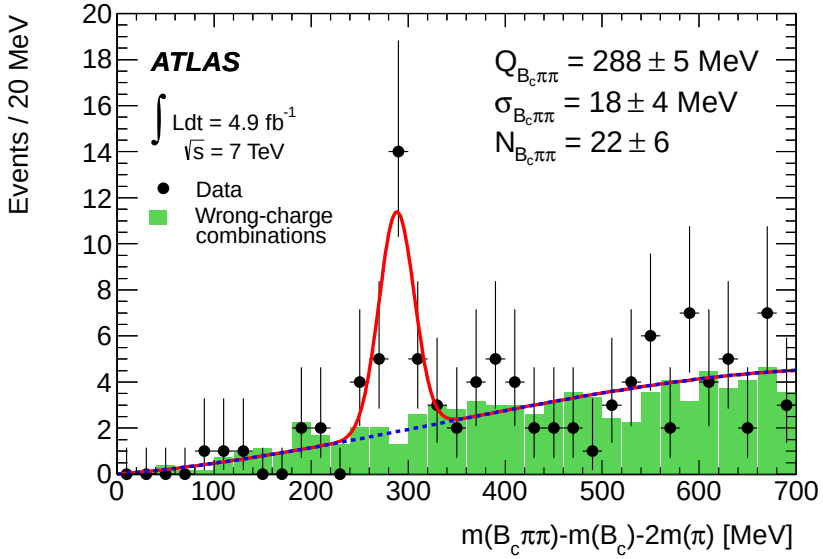
ATLAS Collaboration, Physical Review Letters 113, 212004 (2014)

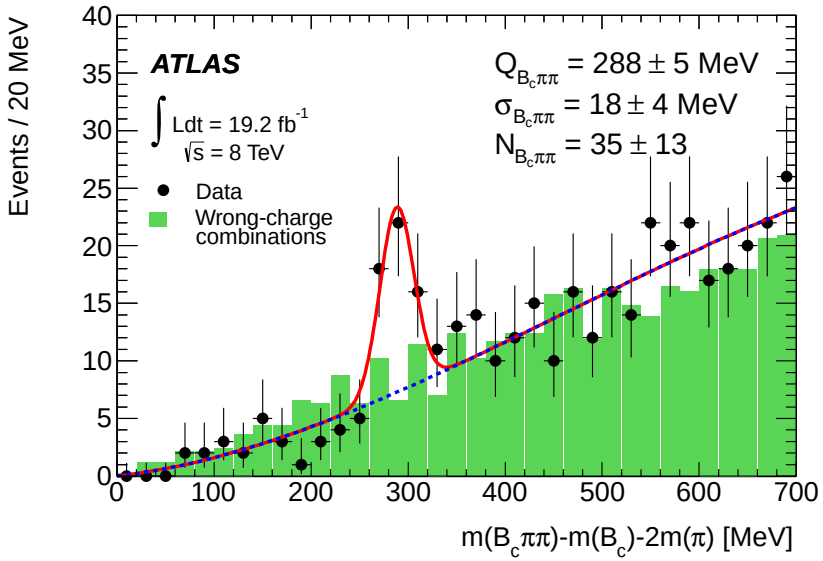
form $B_c(2S) \to \pi\pi B_c$ candidates:

- $|m_{\pi\psi} - m_{B_c}| < 3\sigma$
- combine with π^+, π^- candidate tracks from same vtx; $p_T^\pi > 0.4\,\mathrm{GeV}$
- refit with constraints:
  - $m_{\mu\mu} \to m_\psi$
  - separate B_c, $B_c(2S)$ vertices; $\vec{p}(B_c)$ points to $B_c(2S)$ vertex
- UML bkgd P3 + $\mathcal{G}$ signal fit to $Q_{B_c\pi\pi} = m(B_c\pi\pi) - m_{B_c} - 2m_\pi$:
- *cf.* wrong-charge combinations

significant, consistent signal seen:

- $3.7\,\sigma$ & $4.5\,\sigma \to 5.2\,\sigma$ (pseudo-exp^{ts})
- $m(B_c(2S)) = 6842 \pm 4 \pm 5\ \mathrm{MeV}$



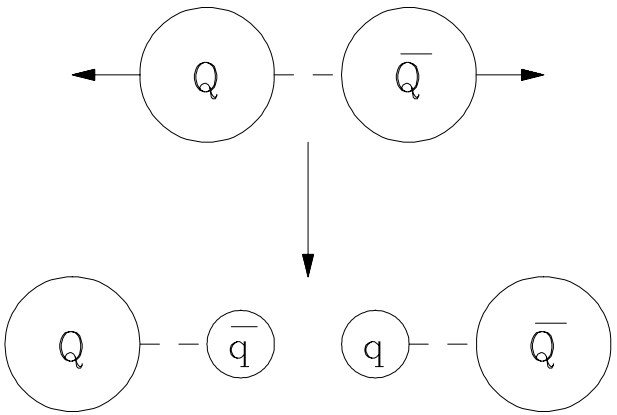


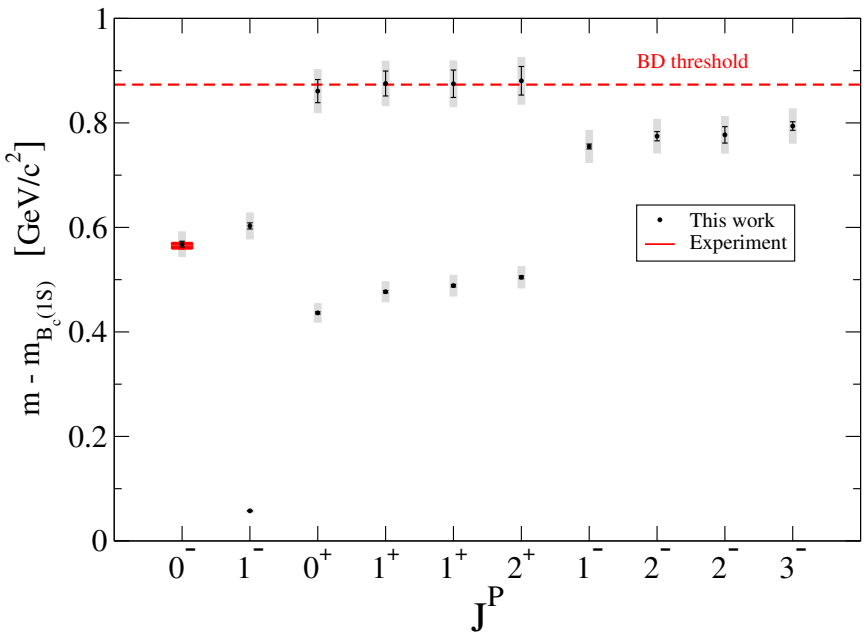
Observation of the $B_c(2S)$: (3) appropriation

ATLAS Collaboration, Physical Review Letters 113, 212004 (2014)

the B_c system is still relatively poorly-known:

- B_c & its decay modes studied
- $^3S_1$ not yet seen ($B_c^* \to \gamma_{\text{soft}} B_c$)
- $B_c(2S)$ is the only other datapoint; 2S−1S: $\mathbf{567.4 \pm 3.5 \pm 4.1\,MeV}$
- *cf.* 605.9 ($c\bar{c}$) & 572.5 ($b\bar{b}$) [using centroids; private calc^n]
- Rosner, *PRD* **90**, 117902 (2014) uses this for flavour-indep^{ce} of $Q\bar{Q}$ potential, *re* pp scattering
- Wurtz, Lewis, and Woloshyn, *PRD* **92**, 054504 (2015) lattice study of the B_c system (first for 2P & 1D); *cf.* **ATLAS**



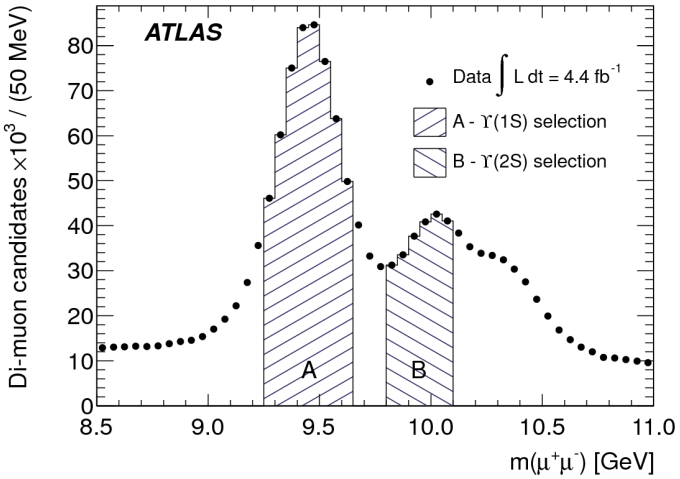


Observation of the $\chi_b(3P)$: (1) selection

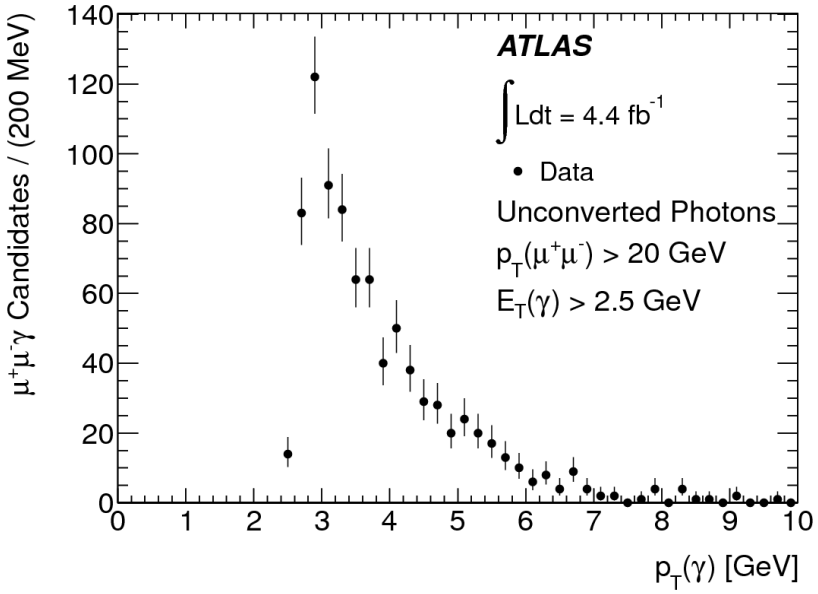
ATLAS Collaboration, Physical Review Letters 108, 152001 (2012)

$\mu^+\mu^-\gamma$ recon in 4.4 fb^{-1} (7 TeV):

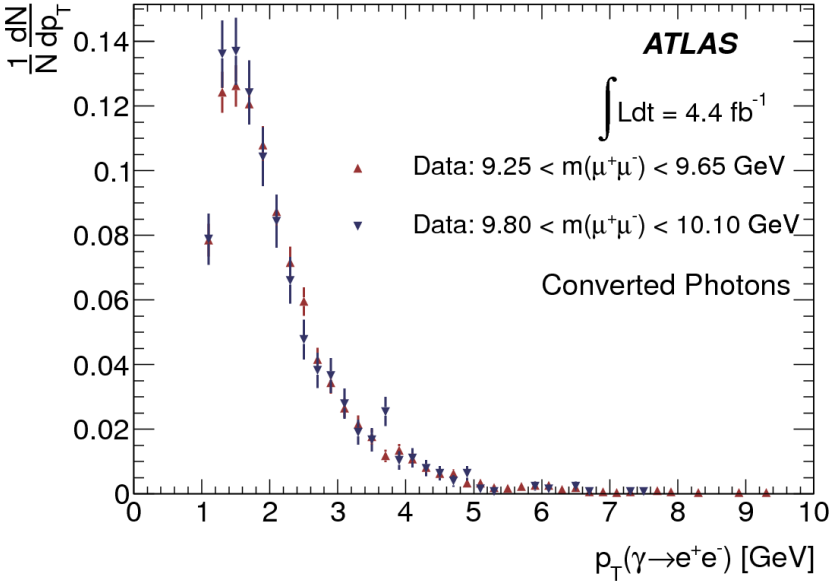
- "combined" μ tracks, $p_T > 4\,\mathrm{GeV}$, $|\eta| < 2.3$
- well-vertexed $\mu^+\mu^-$, $p_T > 12\,\mathrm{GeV}$, $|y| < 2.0$
- selected $\Upsilon(1S)$ and $\Upsilon(2S) \to \mu^+\mu^-$:
- combine with a photon:



unconverted



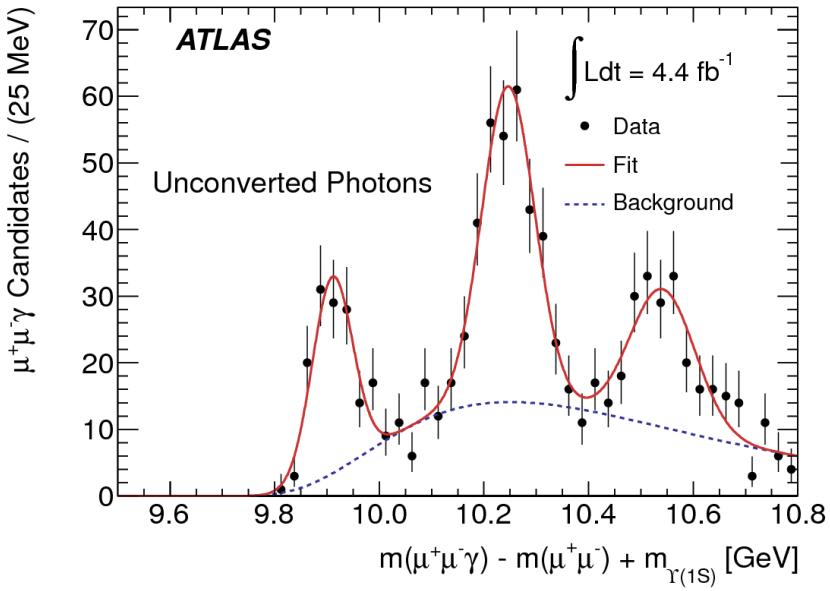
converted



Observation of the $\chi_b(3P)$: (2) result

ATLAS Collaboration, Physical Review Letters 108, 152001 (2012)

$\chi_b \to \gamma_{uncon}\Upsilon(1S)$ fit

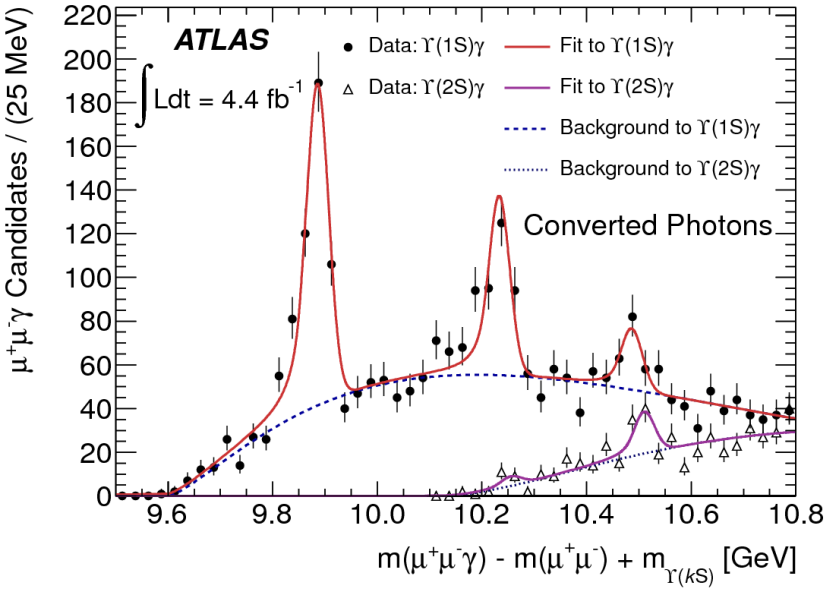


bkgd: $N_B \exp(A\Delta m + B\Delta m^{-2})$

signal: three Gaussians

$$\bar{m}_3 = 10.541 \pm 0.011 \pm 0.030\,\mathrm{GeV}$$

$\chi_b \to \gamma_{convert}\Upsilon(1S, 2S)$ fit



$$N_B^k(\Delta m - q_k^0)^{A_k} \exp\left[B_k(\Delta m - q_k^0)\right]$$

$3 \times$ (doublet of CB fns [for $\chi_{b1,b2}$])

(WA masses & equal $\chi_{b1,b2}$ norms for 1P, 2P)

$$\bar{m}_3 = 10.530 \pm 0.005 \pm 0.009\,\mathrm{GeV}$$

Observation of the $\chi_b(3P)$: (3) confirmation ...

ATLAS Collaboration, Physical Review Letters 108, 152001 (2012)

ATLAS unconverted	$\bar{m}_3$	10541 $\pm$ 11	$\pm$ 30 MeV	higher syst; not combined
ATLAS converted	$\bar{m}_3$	10530 $\pm$ 5	$\pm$ 9 MeV	principal result
DØ converted	$\bar{m}_3$	10551 $\pm$ 14	$\pm$ 17 MeV	*PRD* **86**, 031103 (2012)
LHCb combined	$m_{\chi_{b1}}$	10512.1 $\pm$ 2.1	$\pm$ 0.9 MeV	($\pm$ exp-total $\pm$ model)
LHCb converted	$m_{\chi_{b1}}$	10515.7 $^{+2.2}_{-3.9}$	$^{+1.5}_{-2.1}$ MeV	*JHEP* **10** (2014) 088
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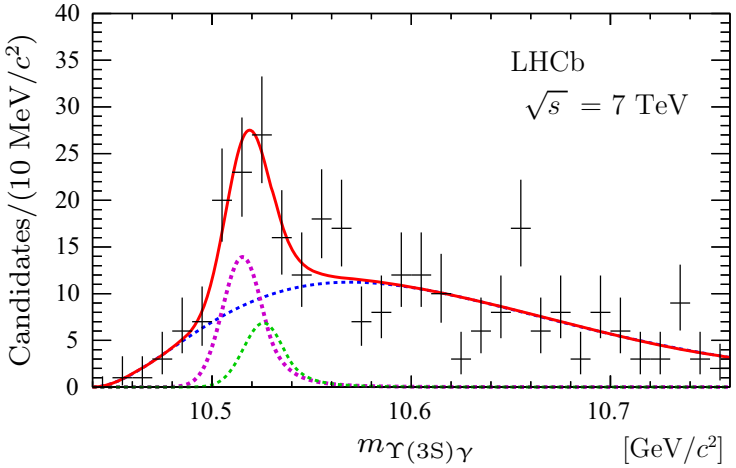

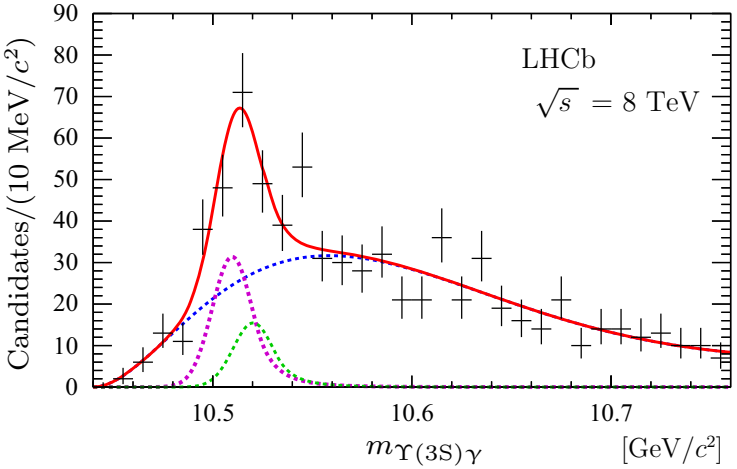

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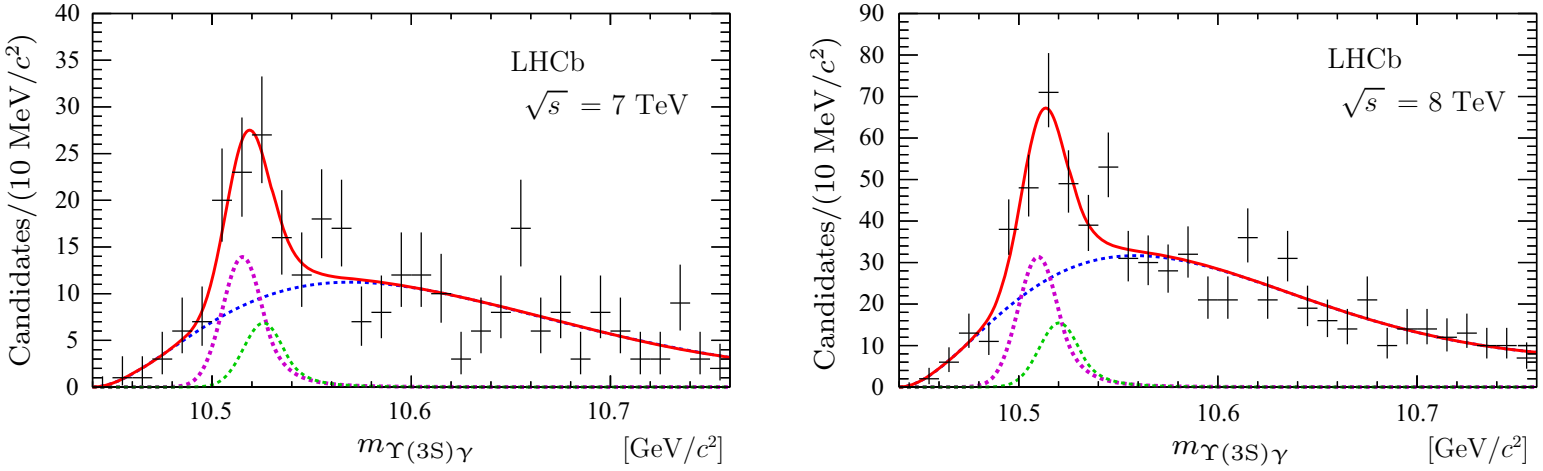

- $\bar{m}_3 \simeq m_{\chi_{b1}} + 6\,\mathrm{MeV}$ given ATLAS assumptions

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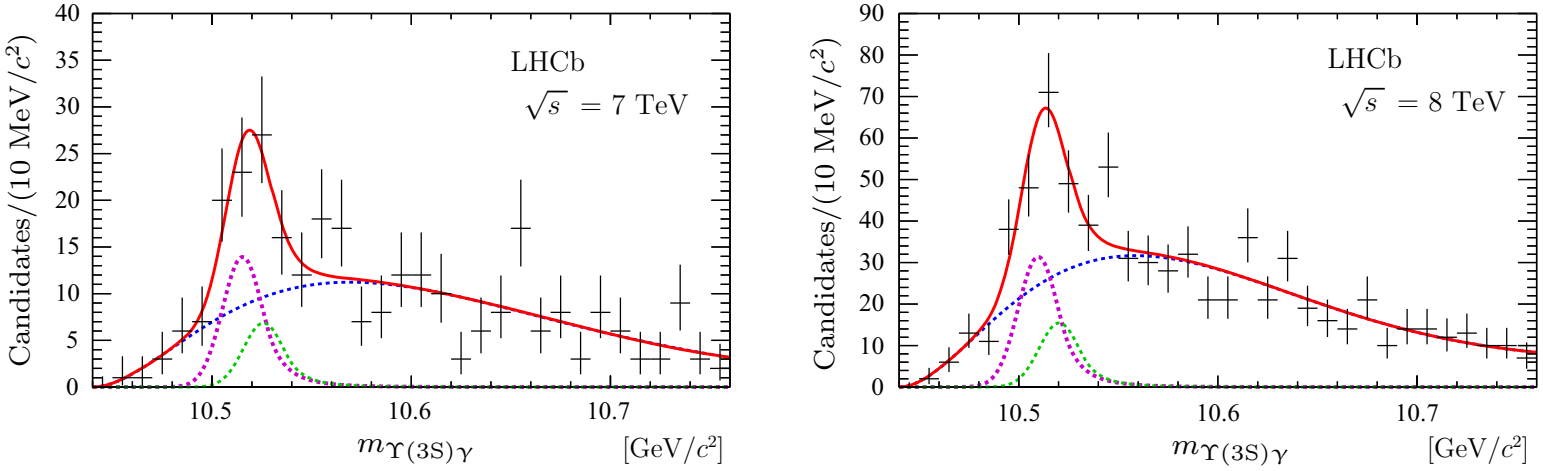

- $\bar{m}_3 \simeq m_{\chi_{b1}} + 6\,\mathrm{MeV}$ given ATLAS assumptions
- on experimental/completeness grounds, more measurements desirable

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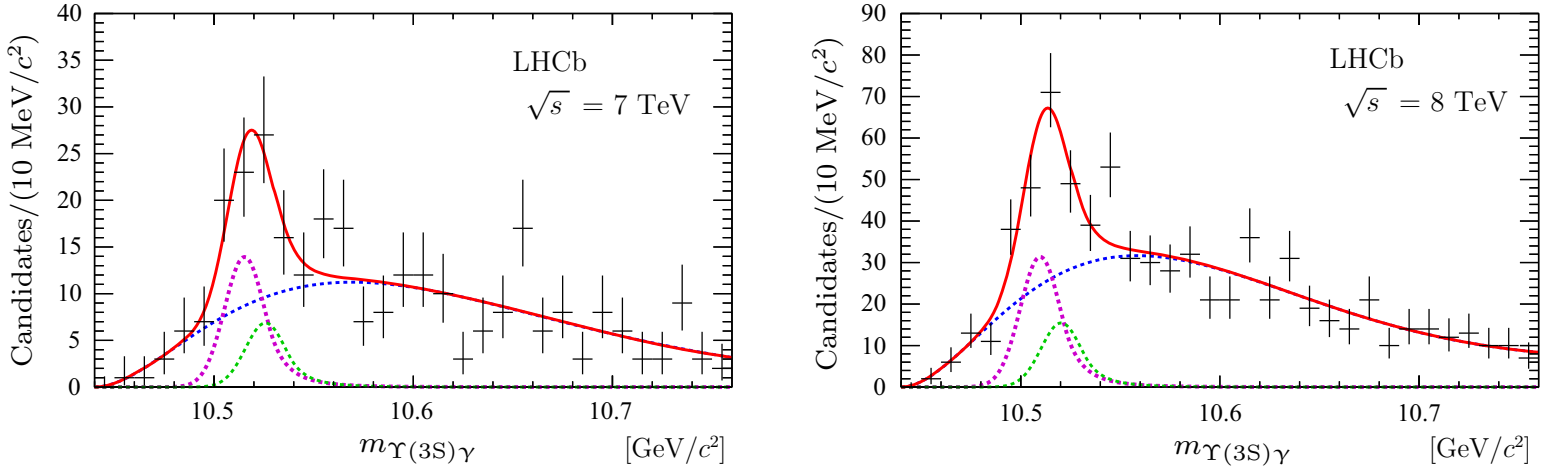


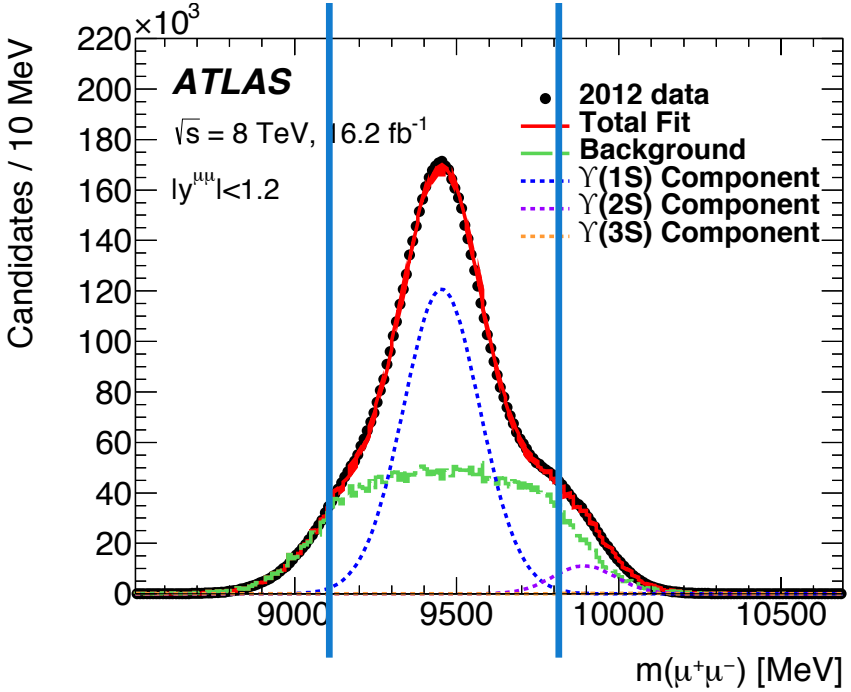
- $\bar{m}_3 \simeq m_{\chi_{b1}} + 6\,\mathrm{MeV}$ given ATLAS assumptions
- on experimental/completeness grounds, more measurements desirable
- is "$\chi_b(3P)$" a $\chi_b(3P)$-X_b mix? Karliner/Rosner, *PRD* **91**, 014014 (2015)
  — argument for further $\gamma\Upsilon(nS)$ measurments; will return to this ...

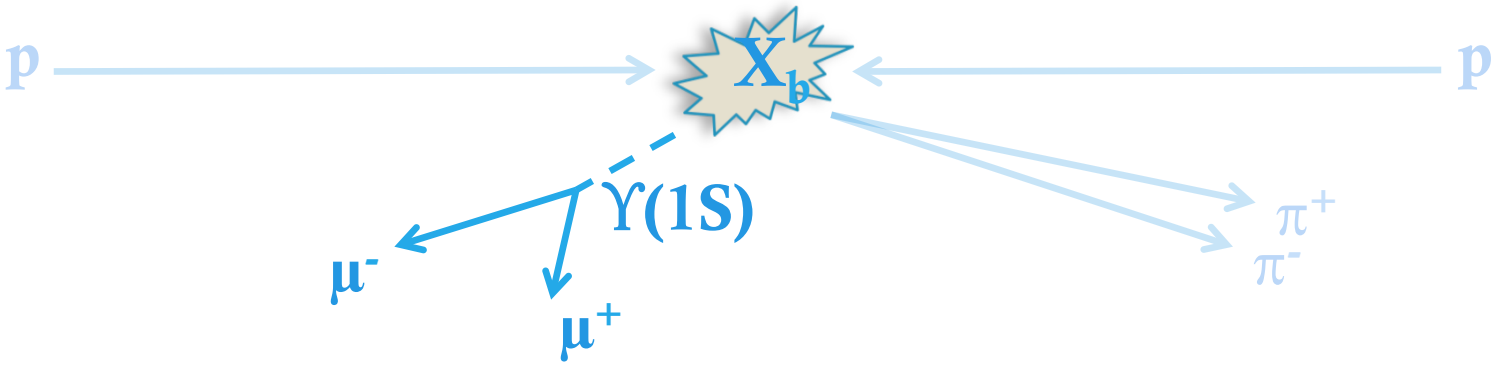
Search for an X_b: (1) $X_b \to \pi\pi\Upsilon$ selection

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

I. **Find $\Upsilon \to \mu^+\mu^-$ candidates:**

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





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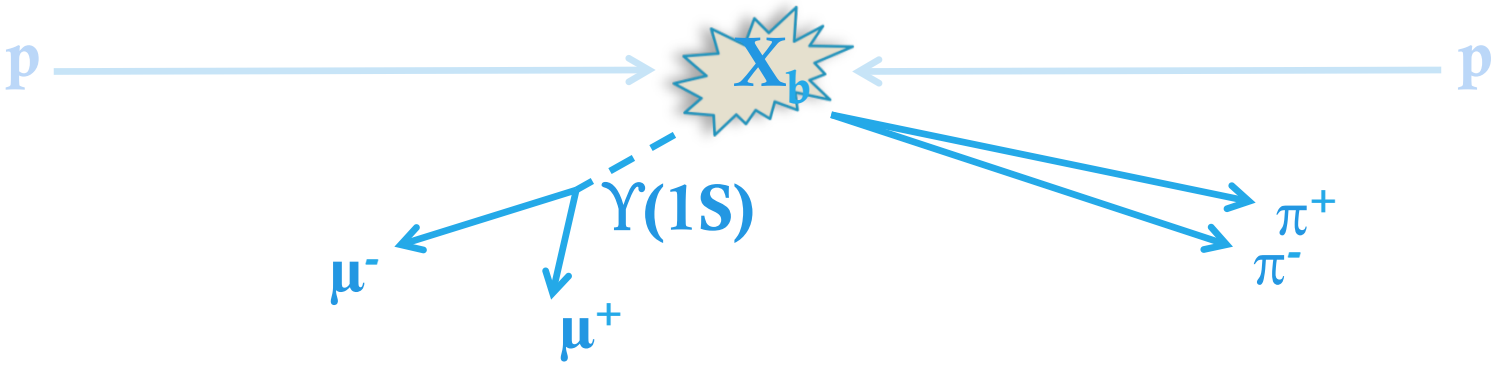
- two "combined" μ tracks
- $|\eta(\mu)|<2.3$
- $|m(\mu\mu)-m_{1S}|<350$ MeV

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

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

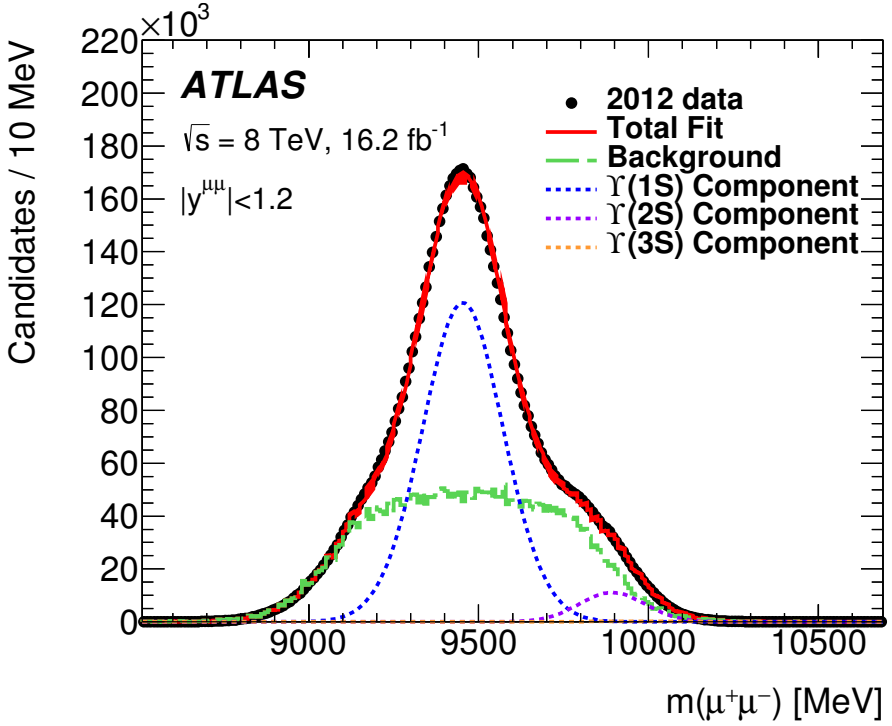


Search for an X_b: (2) ($|y|$, p_T, $\cos\theta^*$) binning

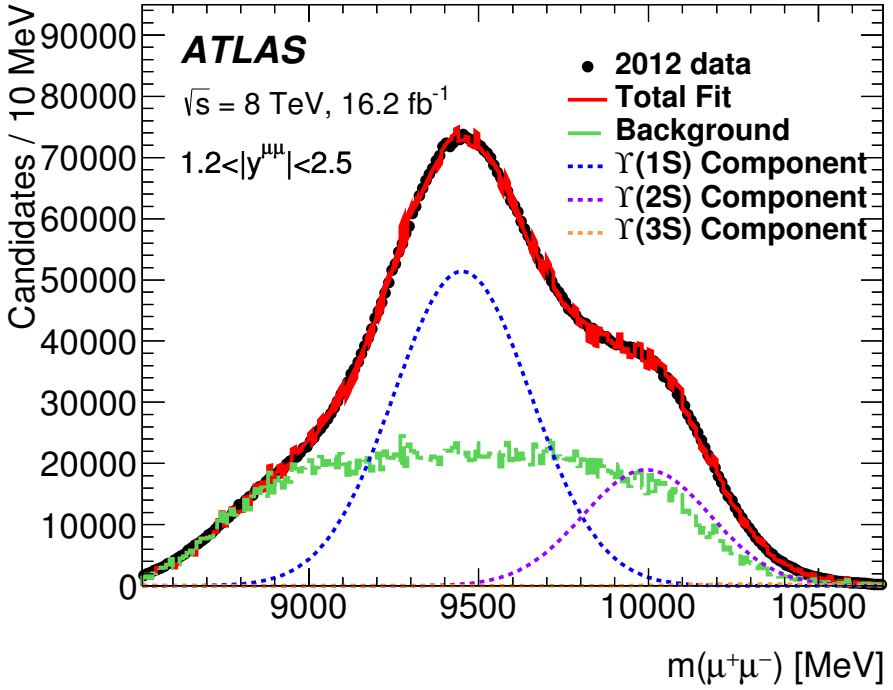
ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

- **barrel ($|y| < 1.2$) resolut^n better than endcap ($1.2 < |y| < 2.4$)**
  $\longrightarrow$ perform the analysis in bins of rapidity

BARREL



ENDCAP



[soft cutoff is an effect of χ^2 cut in subsequent $\pi\pi\Upsilon$ candidate selection; background shape taken from data]

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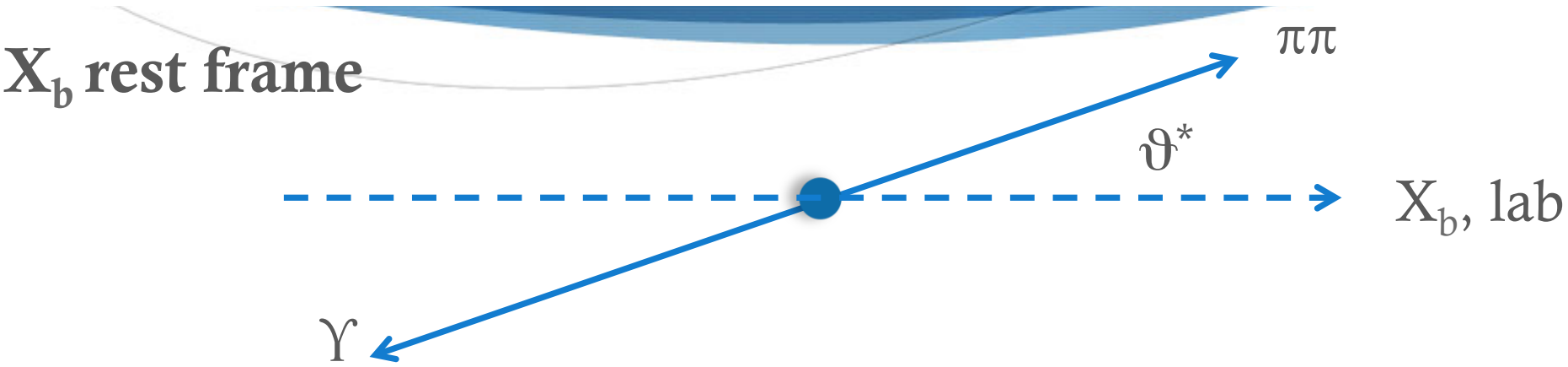
- **barrel ($|y| < 1.2$) resolut^n better than endcap ($1.2 < |y| < 2.4$)**
  $\longrightarrow$ perform the analysis in bins of rapidity
- **different signal and background distributions in (p_T, $\cos\theta^*$):**
  - in signal, $\cos\theta^*(\pi^+\pi^-)$ flat in parent rest frame [for unpolarized prod^n]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



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

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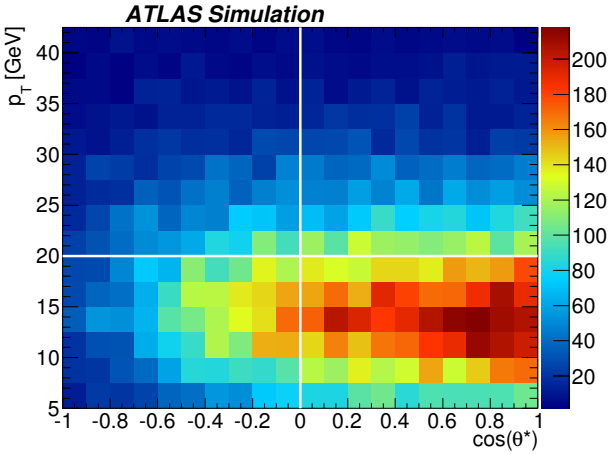
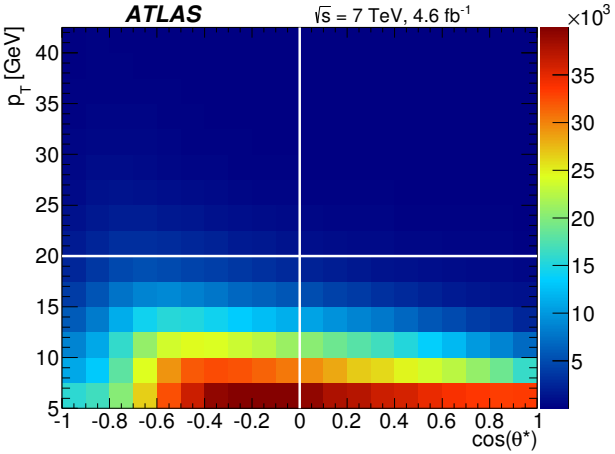
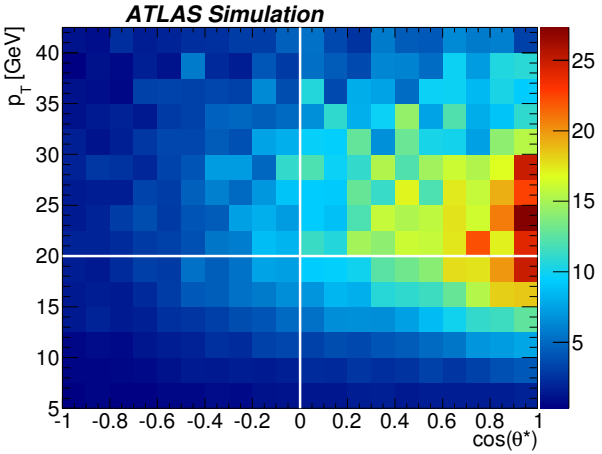
    $\longrightarrow$ background is lower in p_T, more backward in $\cos\theta^*$
  - bin in ($|y|$, p_T, $\cos\theta^*$): boundaries at $p_T = 20\,\mathrm{GeV}$, and $\cos\theta^* = 0$



SIGNAL



BACKGROUND



$S/\sqrt{B}$

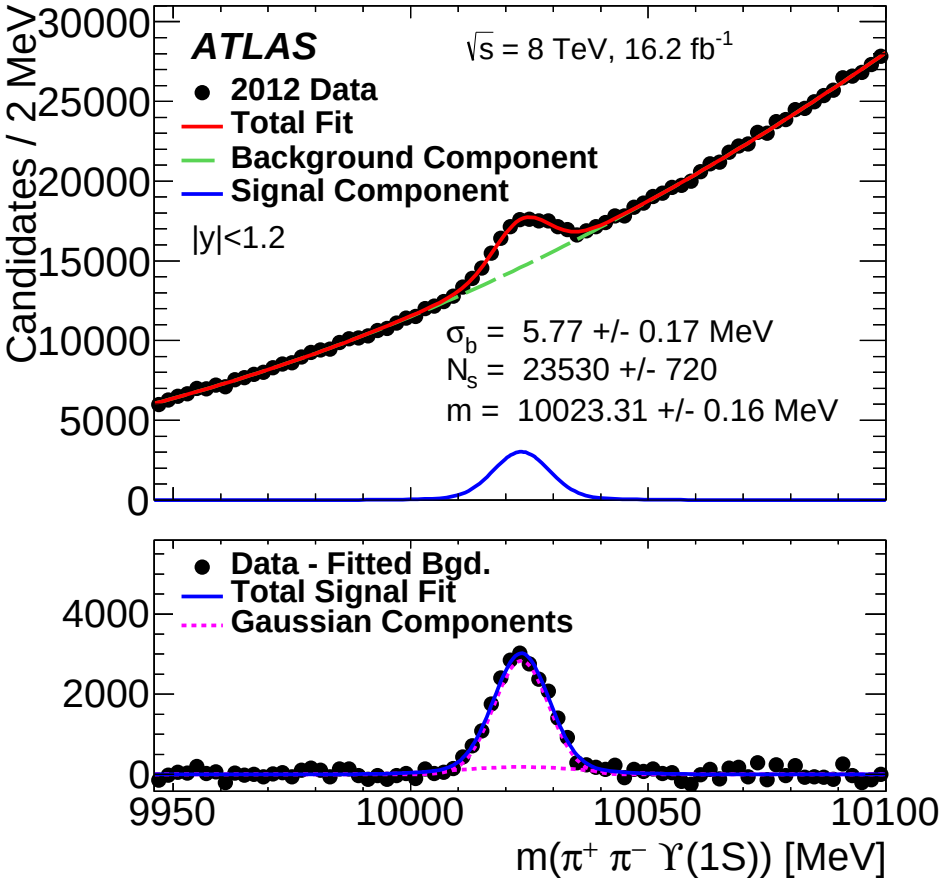
[reconstructed distributions, reflecting trigger effects *etc.*]

Search for an X_b: (3) calibration & validation, $\Upsilon(2S)$

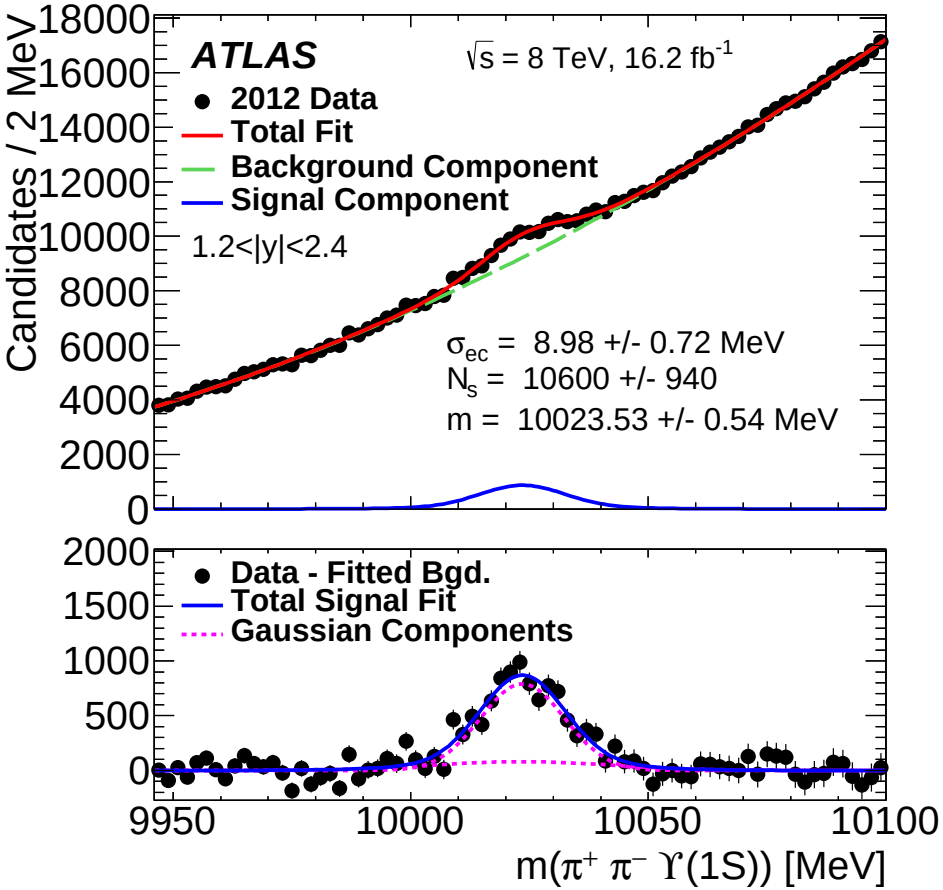
ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

1. **fit in 2 |y| bins, floated params:** m matches w.a.; σ matches MC

BARREL



ENDCAP



Search for an X_b: (3) calibration & validation, $\Upsilon(2S)$

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

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\begin{aligned}
N_{2S}^{fit} &= 34300 \pm 800 \\
N_{2S}^{pred} &= (\sigma\mathcal{B})_{2S} \cdot \mathcal{L} \cdot \mathcal{A} \cdot \epsilon \\
&= (0.504 \pm 0.038)\,\mathrm{nb} \cdot (16.2 \pm 0.3)\,\mathrm{fb}^{-1} \cdot (1.442 \pm 0.004)\% \cdot (0.283 \pm 0.002) \\
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4. **perform all subsequent fits**
   - simultaneously over the $2 \times 2 \times 2$ bins
   - using MC division of signal between the bins (as a function of mass)
   - (see backup for fits)

Search for an X_b: (3) calibration & validation, $\Upsilon(3S)$

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

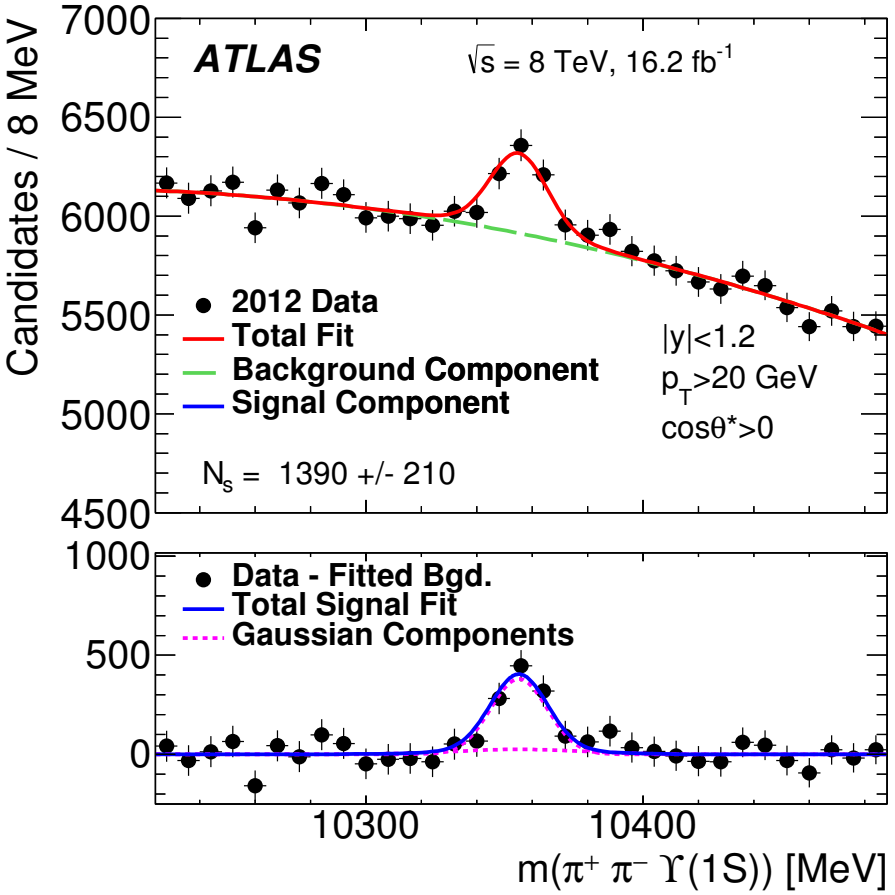
$\Upsilon(3S)$ provides a clear signal, but is not overwhelming
$\longrightarrow$ **validation for X_b search**

- significance $z = 8.7$
- most sensitive bin $z = 6.5 \longrightarrow$:
  (for clarity: rebinned $2 \rightarrow 8\,\mathrm{MeV}$)
- $\chi^2/n_{dof} = 1.0$ for simult. fit:
  good signal division among bins
- overall fitted yield:

$$N_{3S}^{fit} = 11600 \pm 1300$$
$$N_{3S}^{pred} = (\sigma\mathcal{B})_{3S} \cdot \mathcal{L} \cdot \mathcal{A} \cdot \epsilon$$
$$= 11400 \pm 1500$$

- full set of fits in backup

BARREL, HIGH-p_T, HIGH-$\cos\theta^*$



Search for an X_b: (4) results as a function of mass

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

- hypothesis test every $10\,\mathrm{MeV}$ from 10–11 GeV, excluding $\Upsilon(2S, 3S)$
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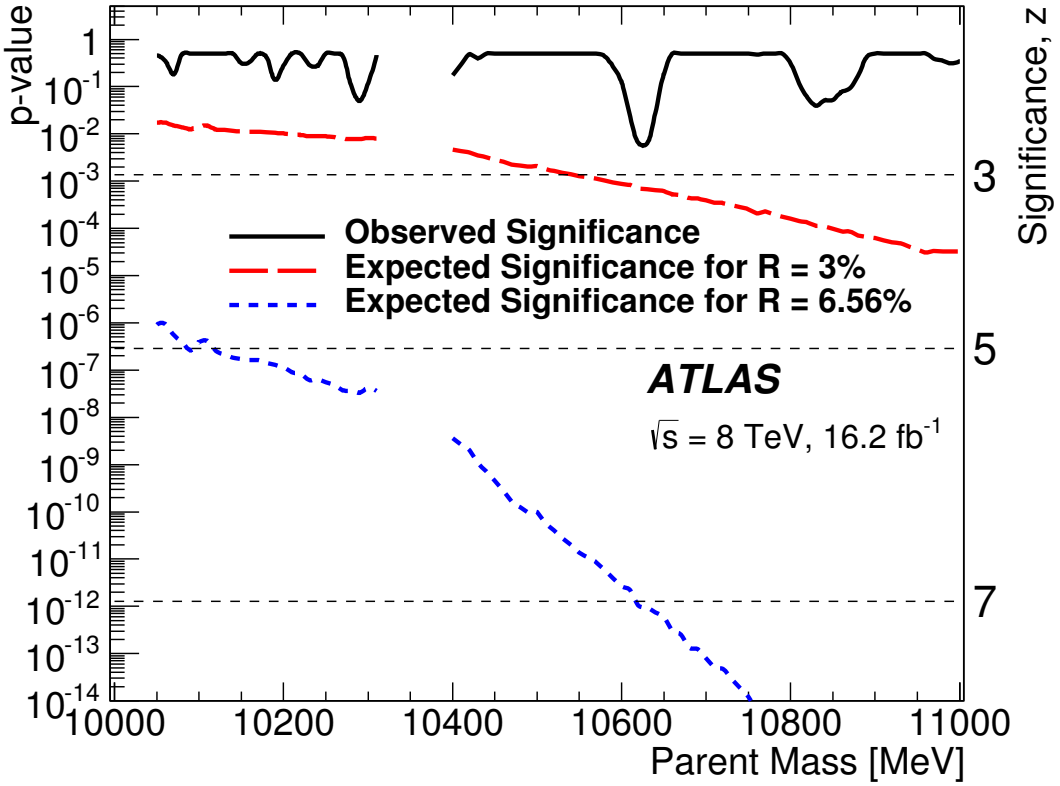
- local significance $z < 3$ by asymptotic formulae; *cf.* $R = 3\%$, 6.56%



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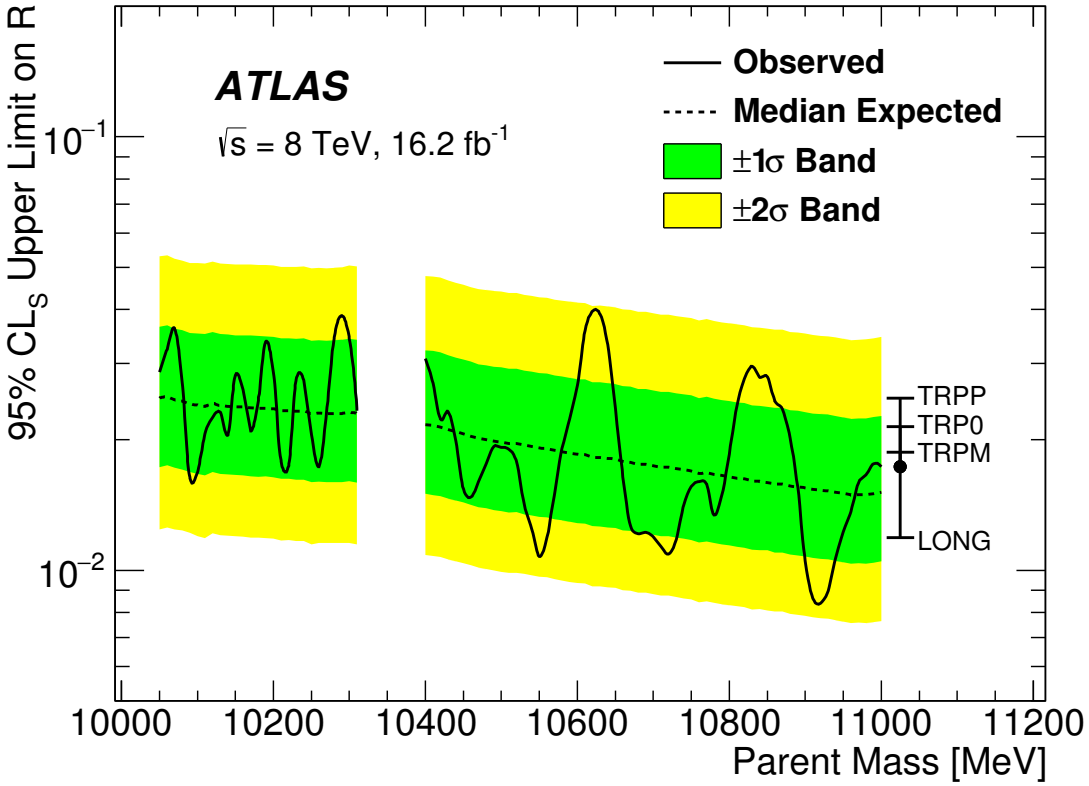

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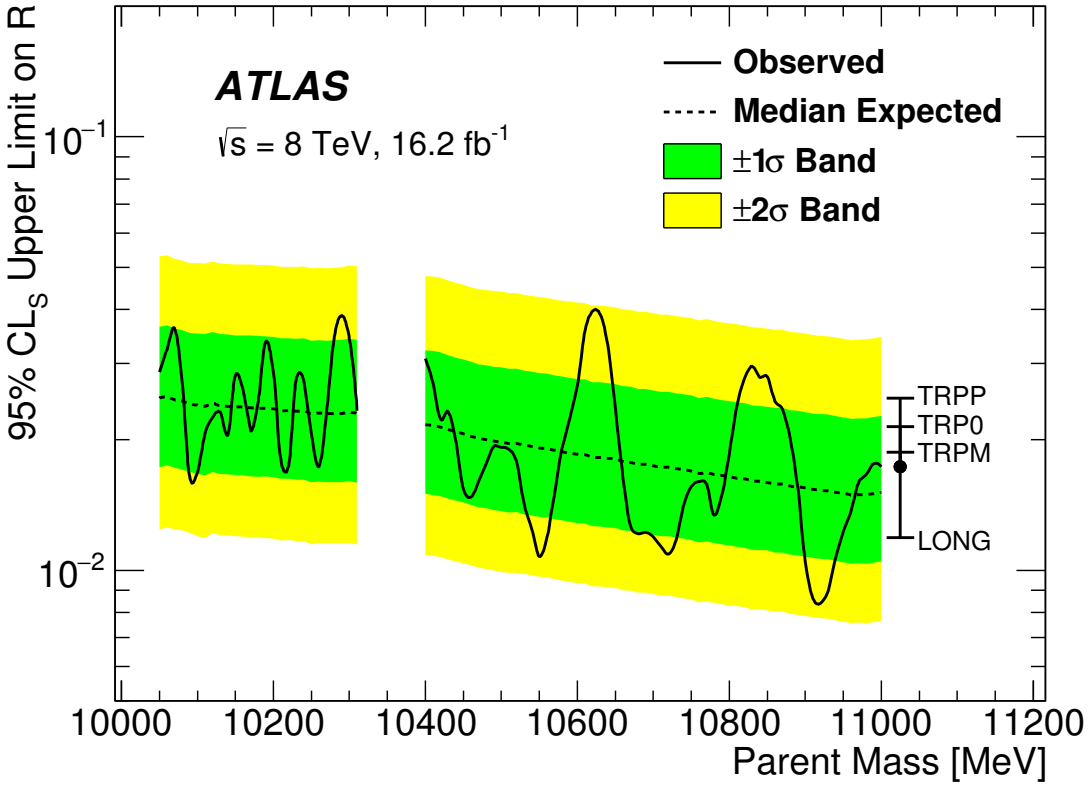

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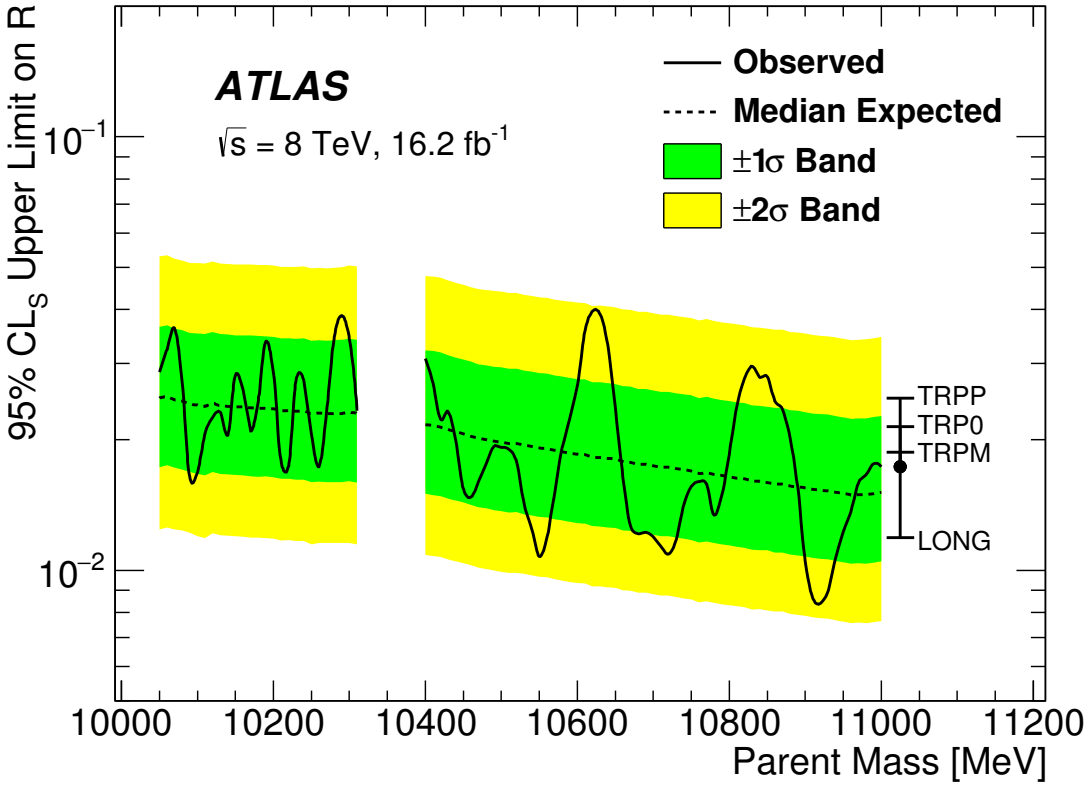

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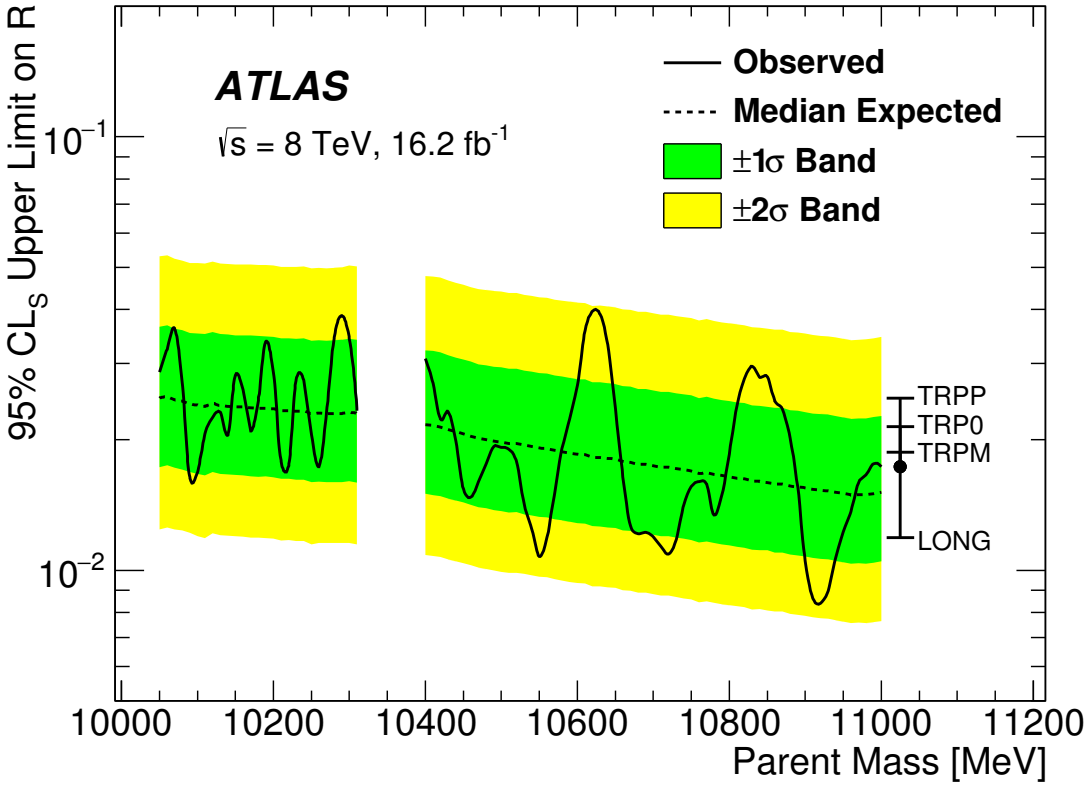
- I-allowed modes have acceptance problems: *e.g.* $X_b \to \pi\pi\chi_{b1}(\to \gamma\Upsilon)$



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Padmanath, Lang, Prelovsek, PRD 92, 034501 (2015), & others in backup

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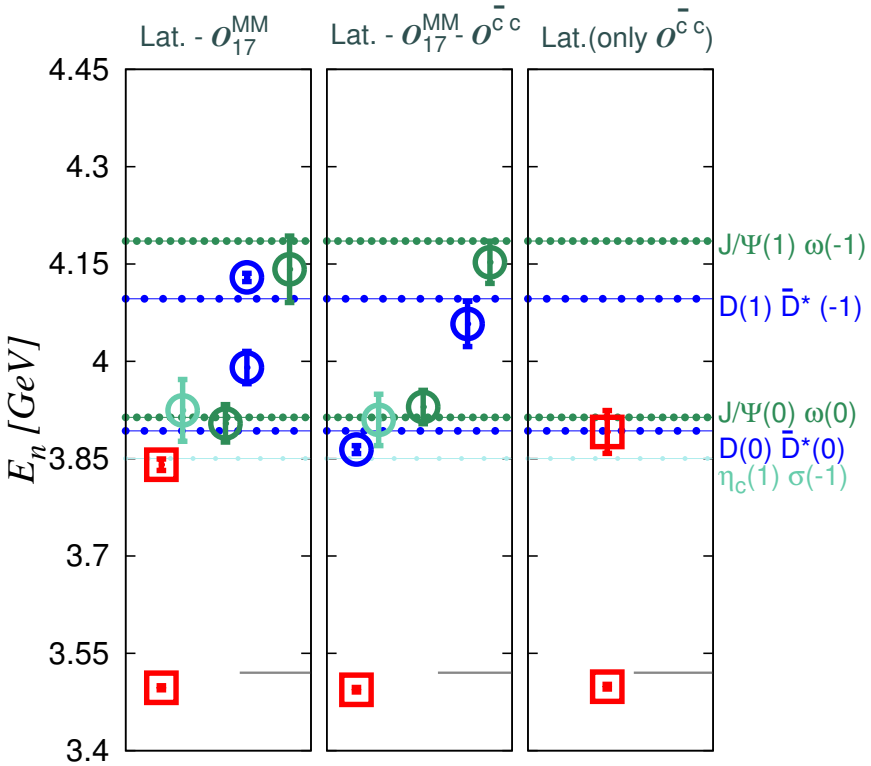

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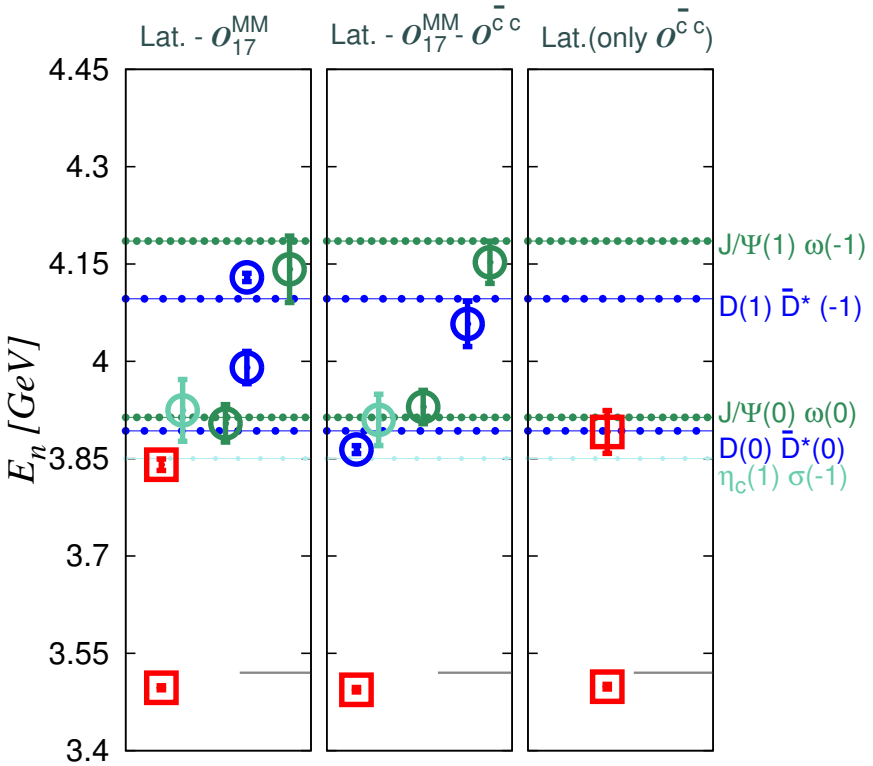

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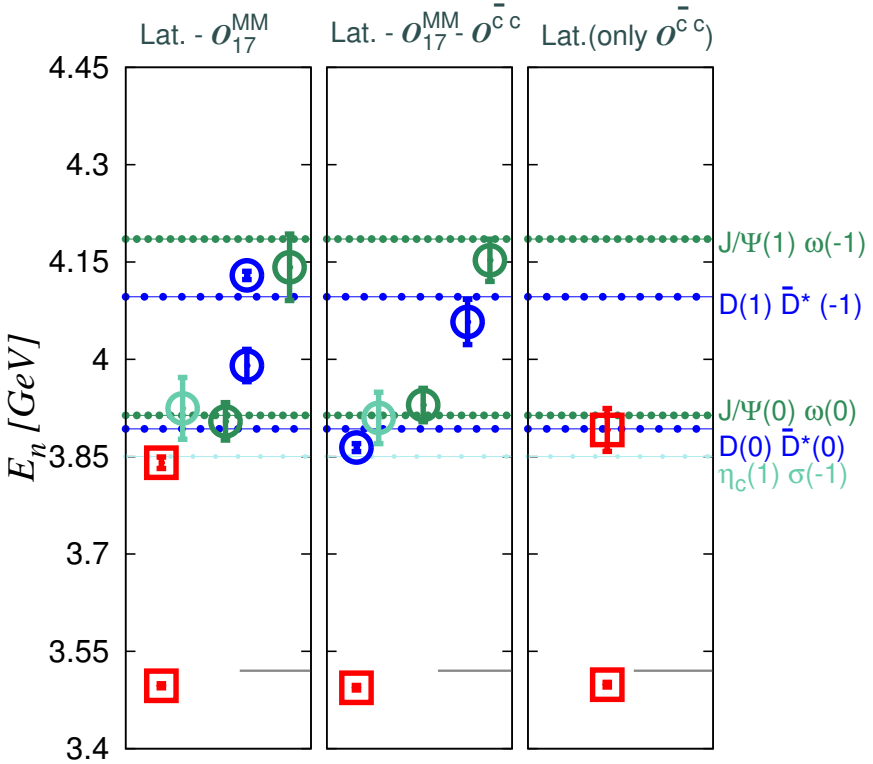

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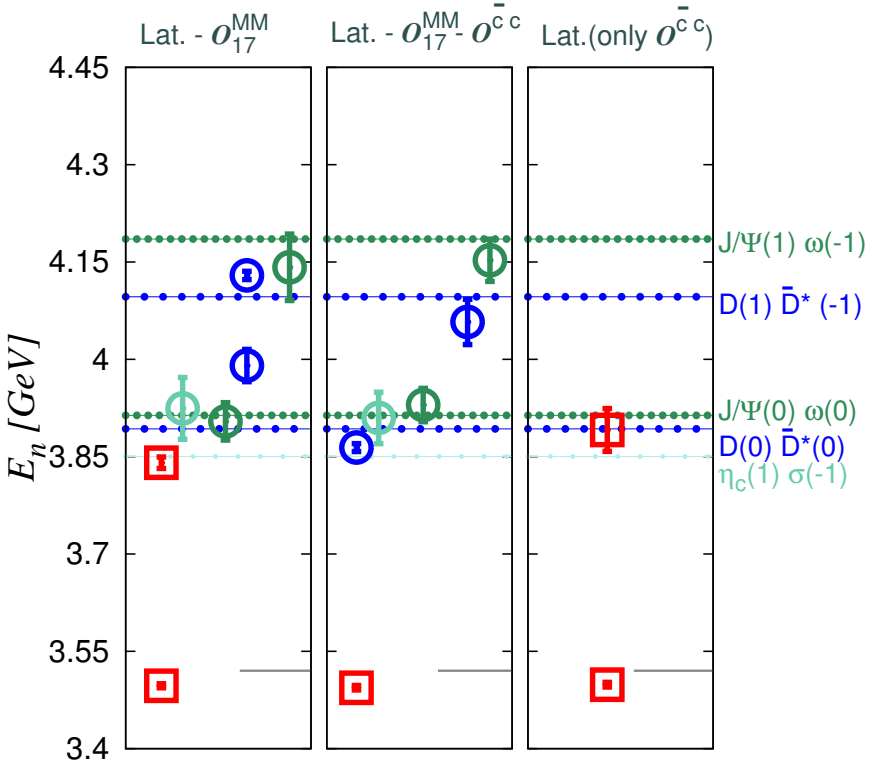

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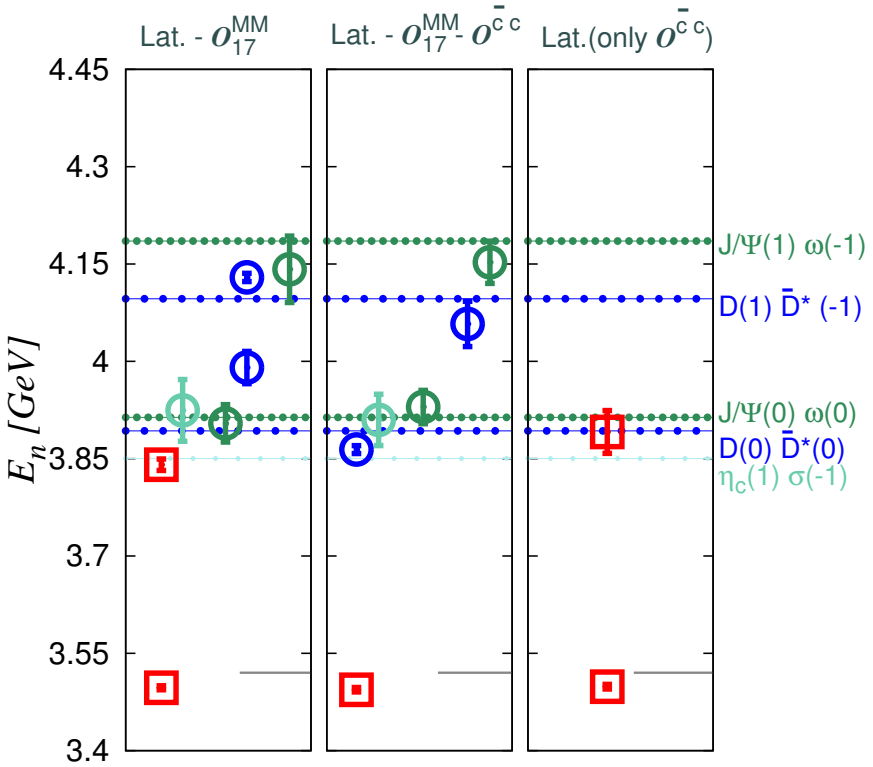

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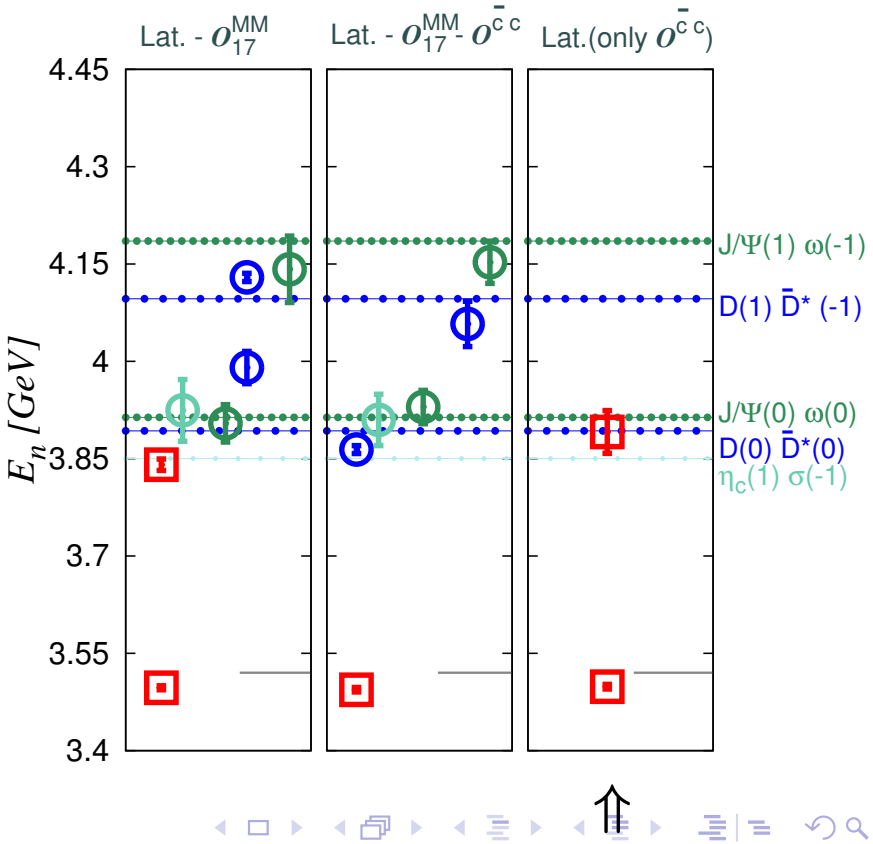

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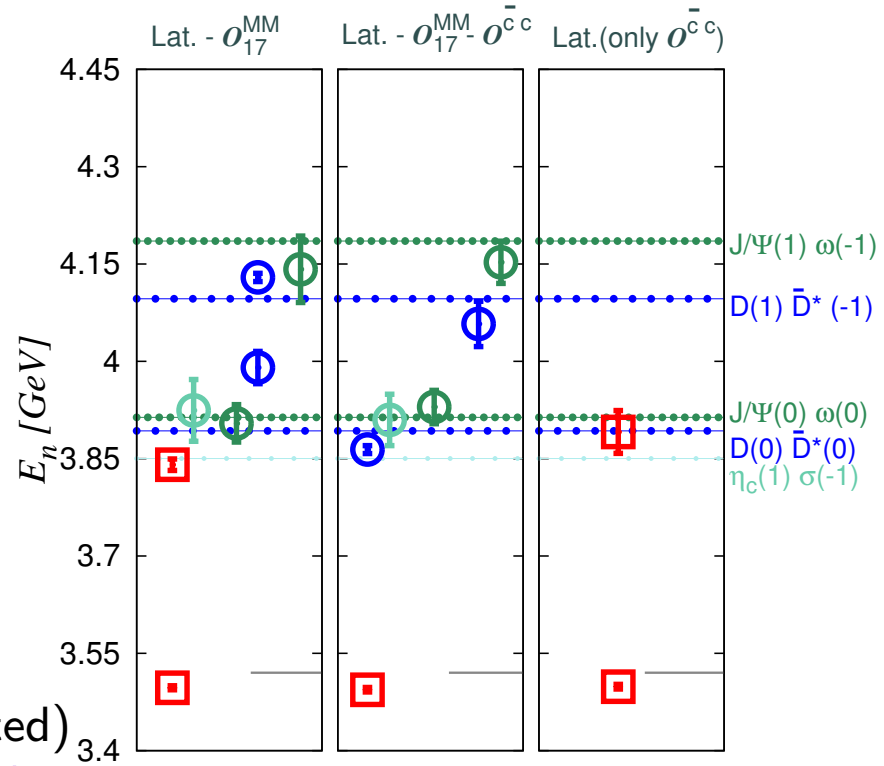
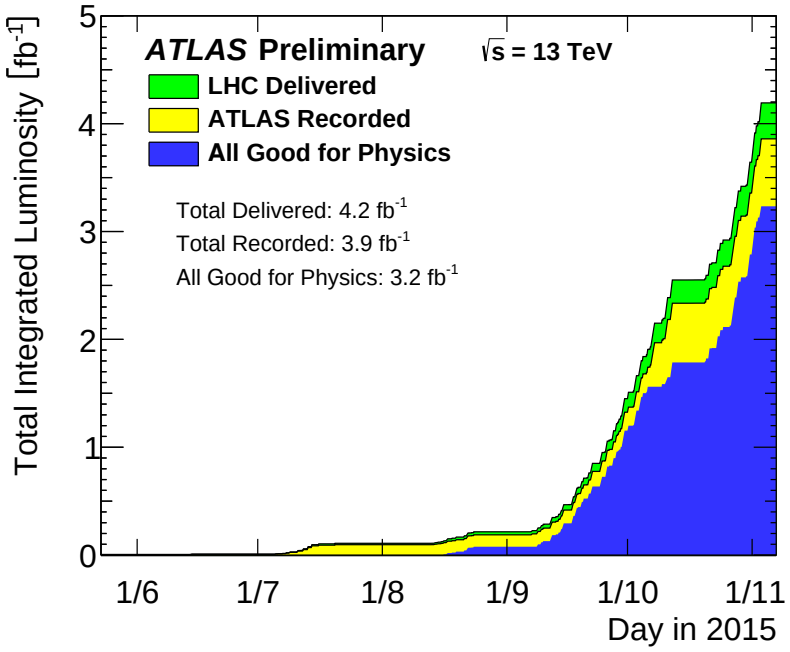
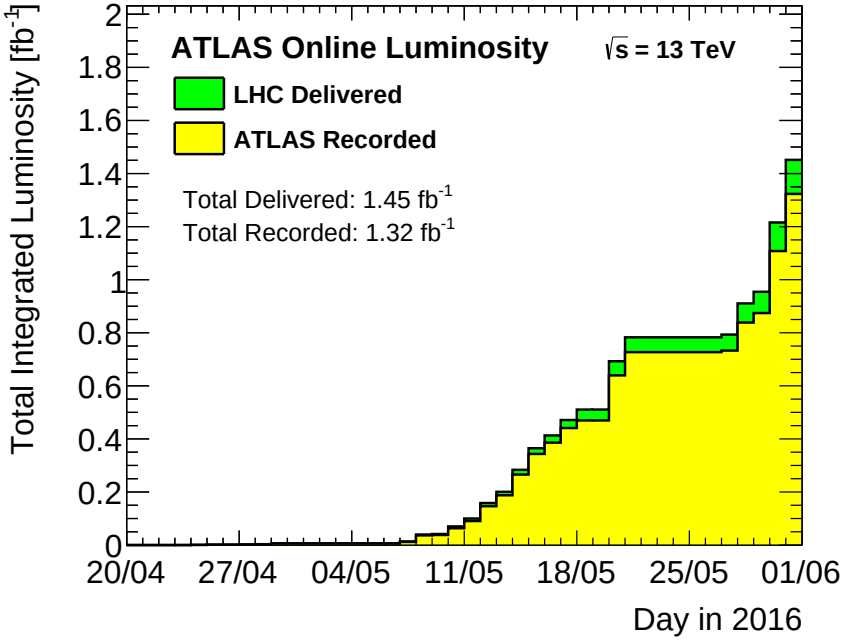
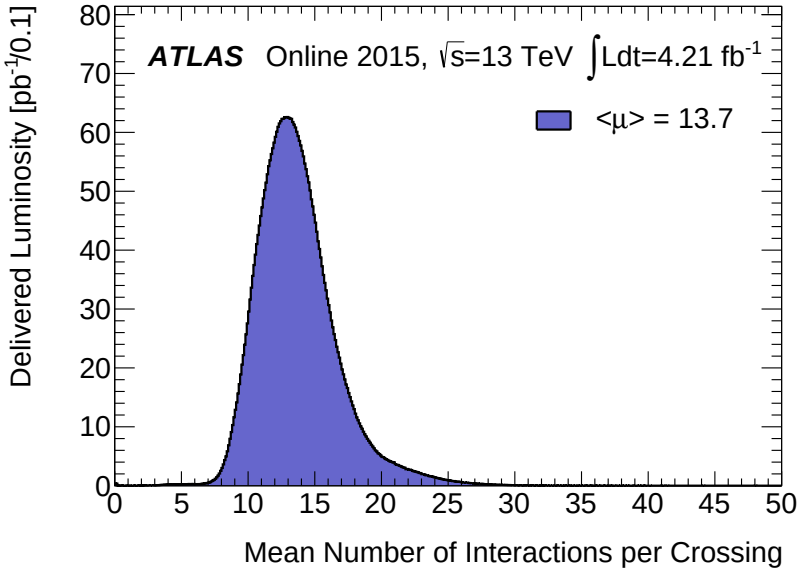


future analysis priority? (personpower-limited)
$X_b \rightarrow \pi\pi\chi_{b1}$? $\chi_{bJ}(3P)$? associated $X(3872)$ prod^n? other?

Run 2 datataking







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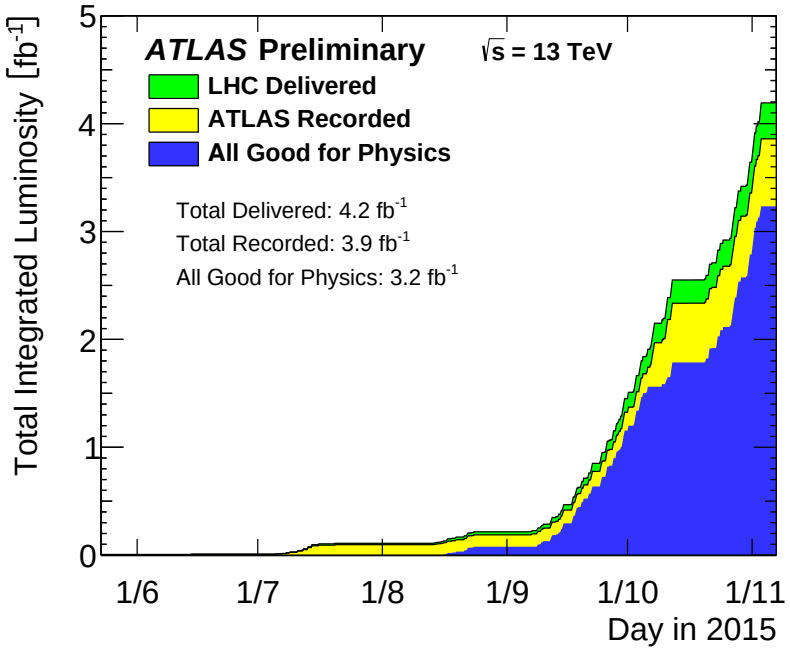
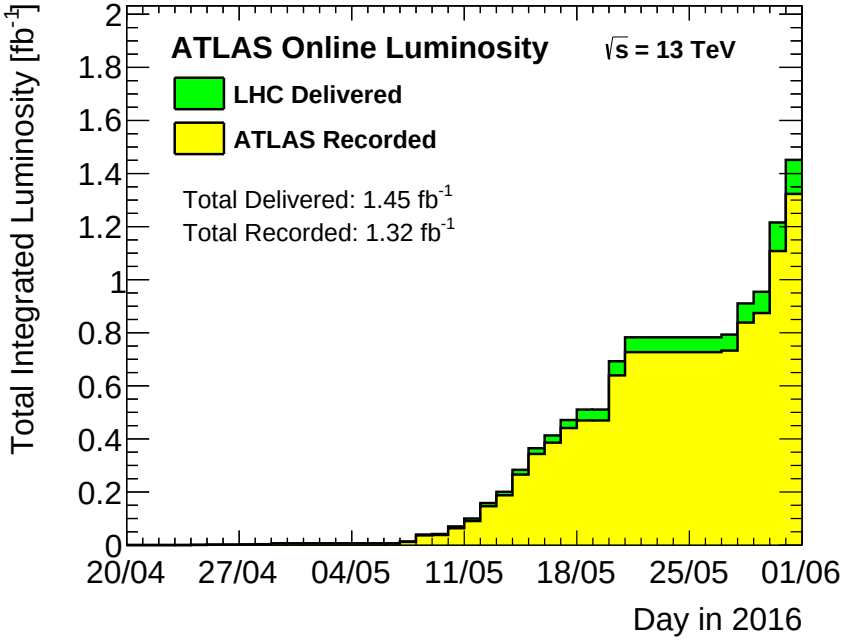
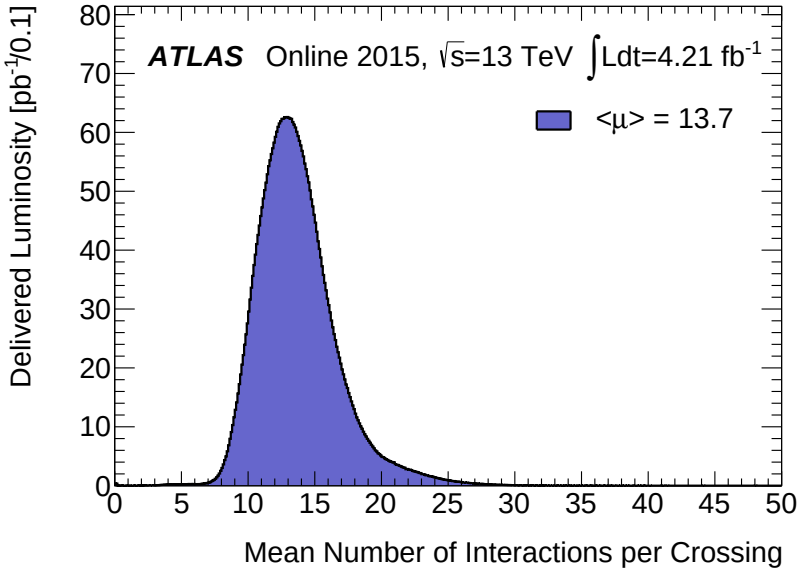
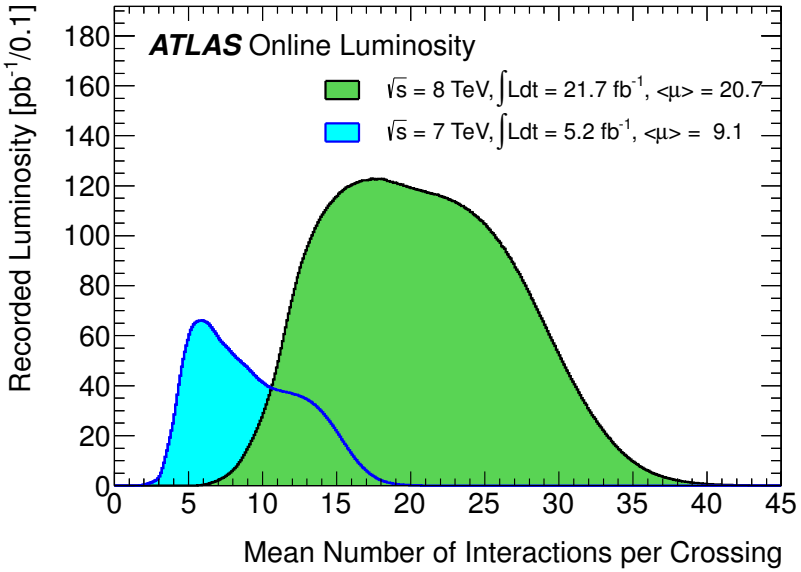








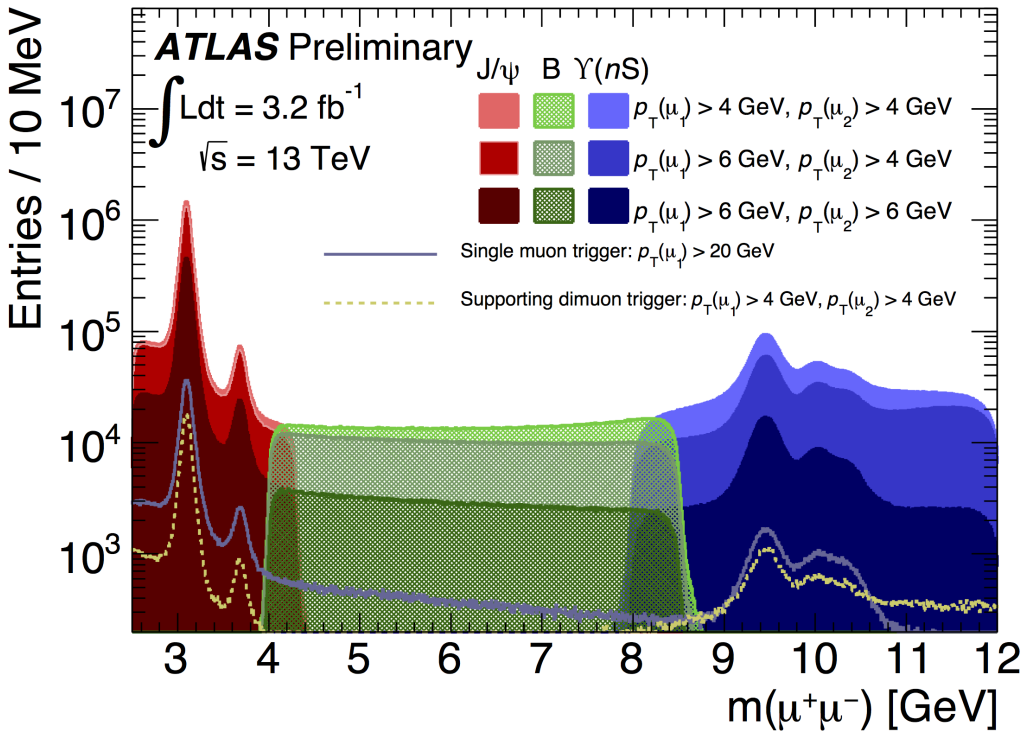
Summary and Run 2 prospect

ATLAS has contributed to spectroscopy through a range of ψ and $\Upsilon \to \mu^+\mu^-$-based analyses from Run 1:

- $B_c(2S) \to \pi^+\pi^- B_c(\to \pi^+\psi)$ observation
- $\chi_b(3P) \to \gamma\Upsilon(1S, 2S)$ observation
- $\psi(2S)$, $X(3872) \to \pi^+\pi^-\psi$ production
- search for X_b production with $X_b \to \pi^+\pi^-\Upsilon(1S)$

A further program is now underway at Run 2:

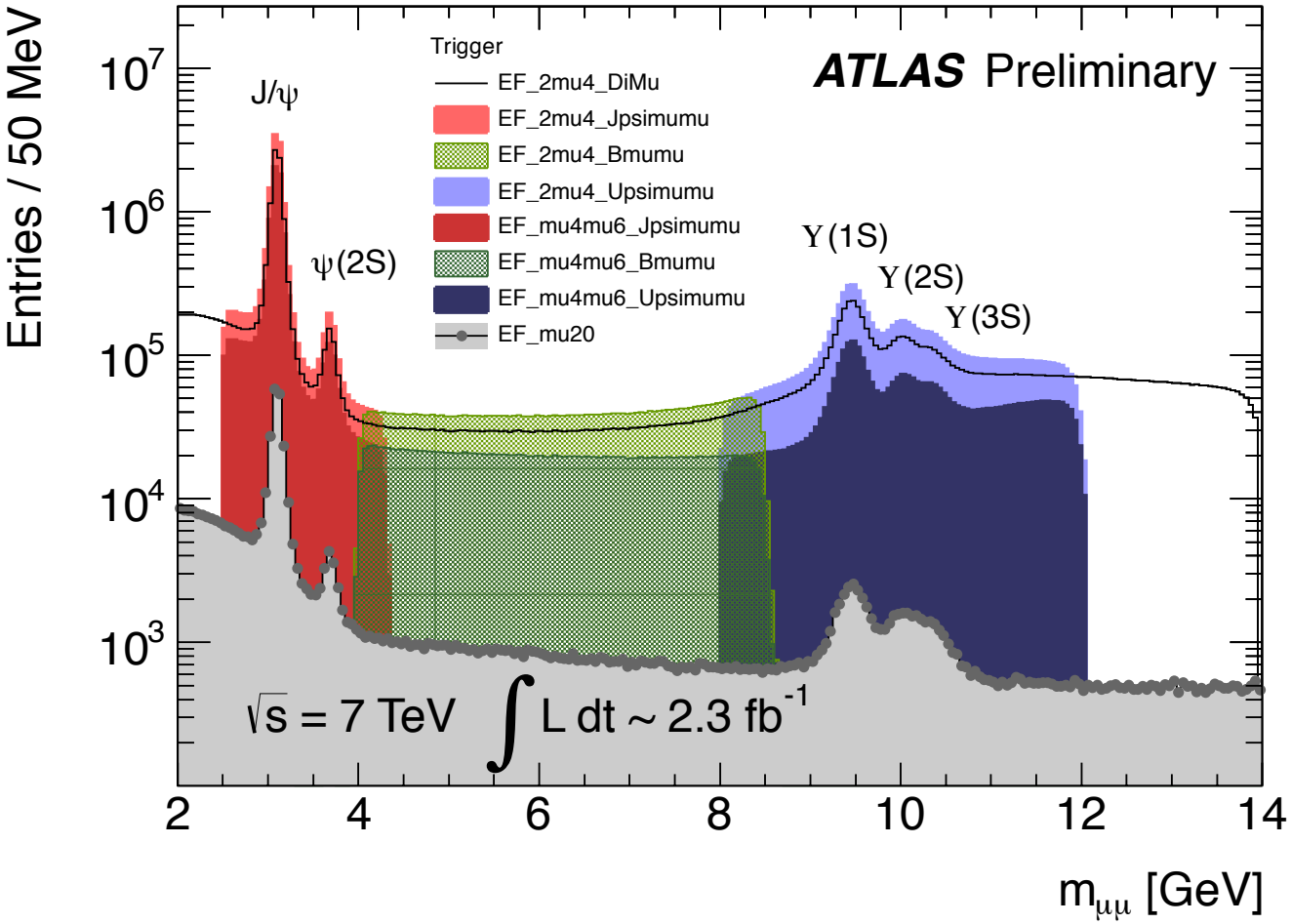
- $> 5\,\mathrm{fb}^{-1}$ taken at 13 TeV
- an order of magnitude more data is foreseen
- ψ and Υ oriented $\mu^+\mu^-$ triggers developed for the new datataking conditions
- watch for new results soon; feedback/requests welcome



BACKUP SLIDES:

BACKUP: ATLAS detector, trigger; expanded scale

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

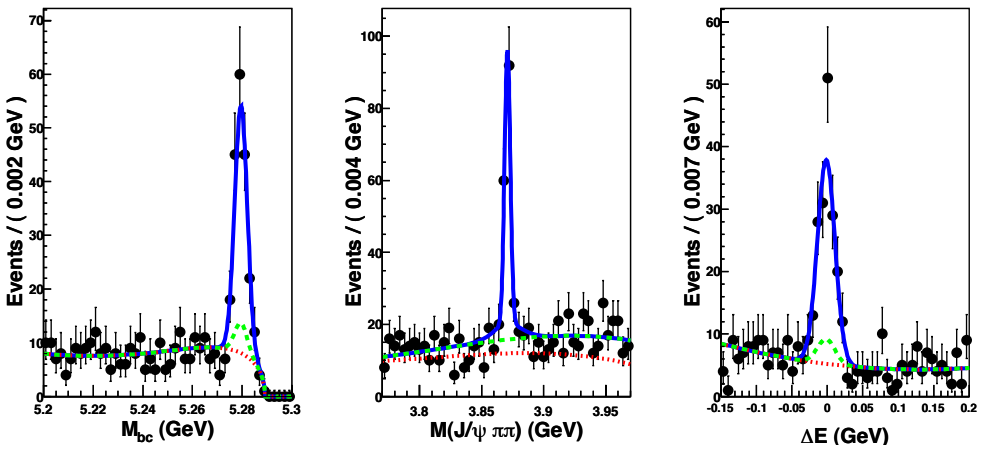


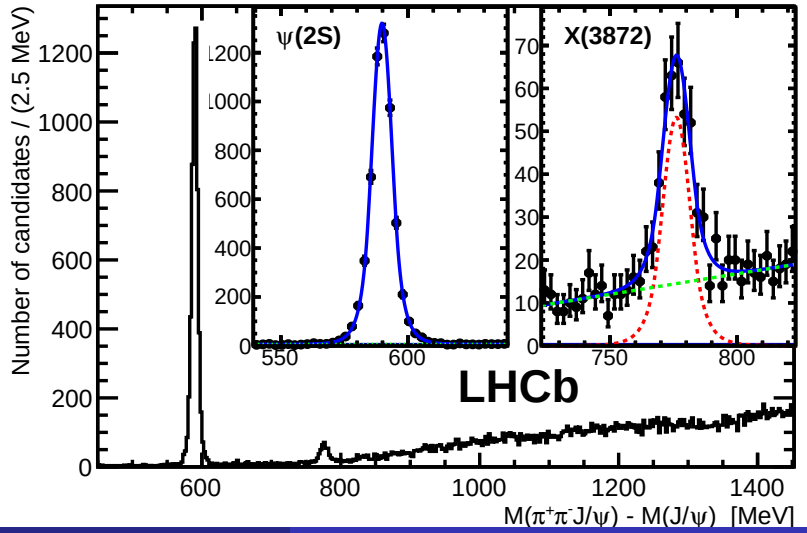
BACKUP: Search for an X_b: motivation

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

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

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





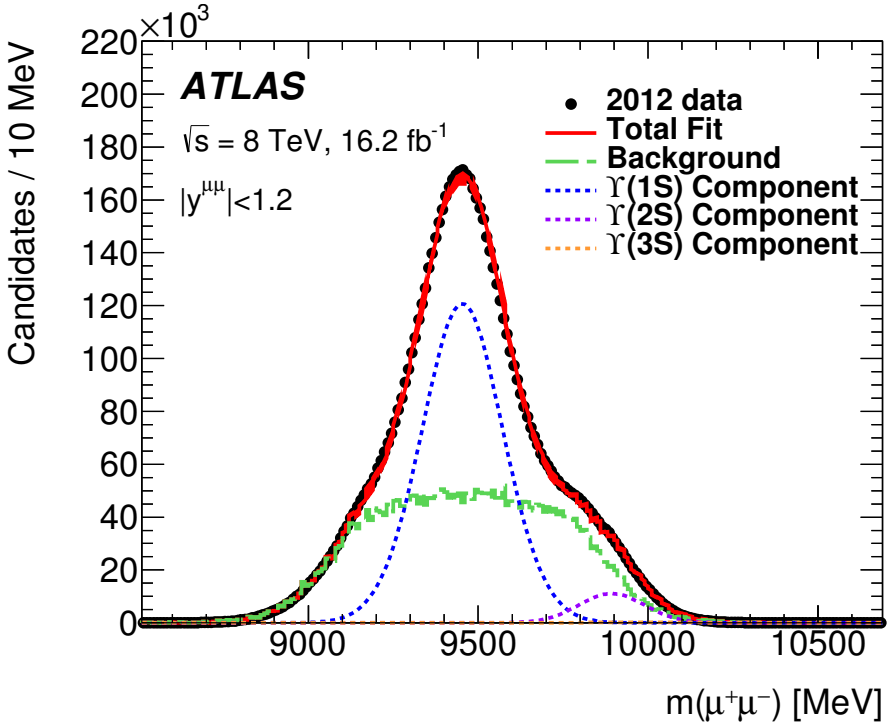
BACKUP: Search for an X_b: ($|y|$, p_T, $\cos\theta^*$) binning

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

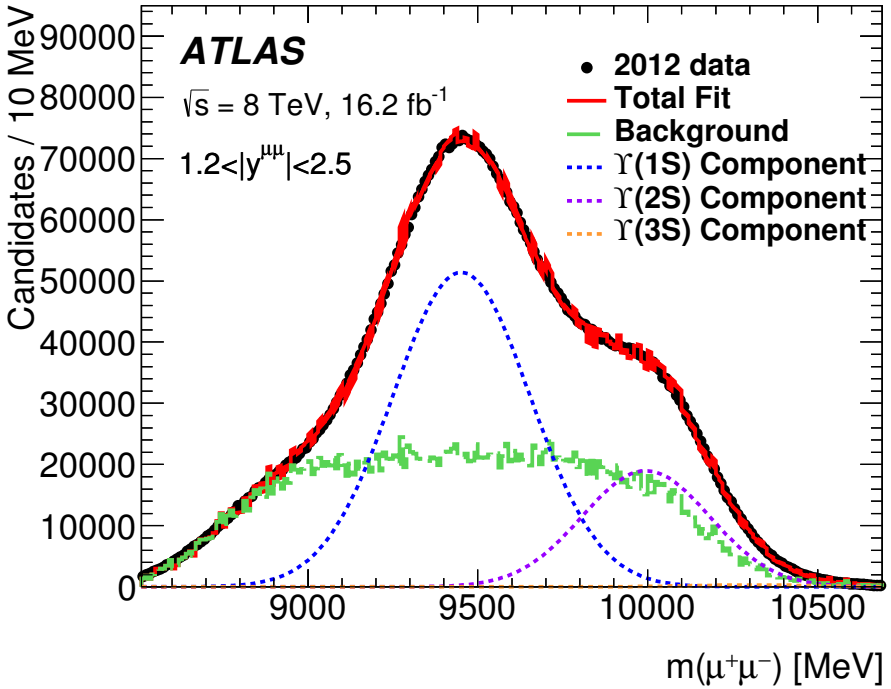
- **barrel ($|y| < 1.2$) resolut^n better than endcap ($1.2 < |y| < 2.4$)**
- constraint $\mu^+\mu^- \to \Upsilon$ mitigates this, but not higher bkgd under peak

$\longrightarrow$ perform the analysis in bins of rapidity

BARREL



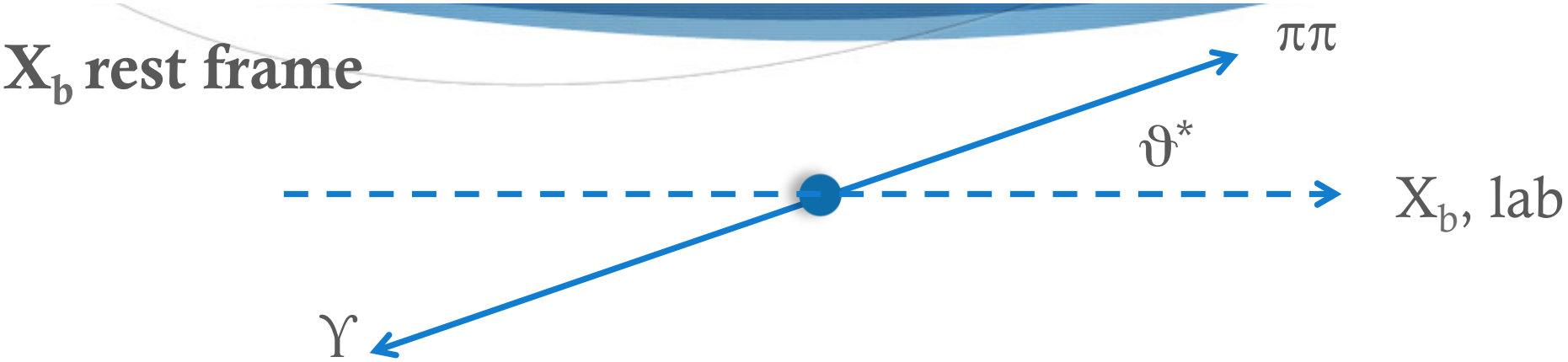
ENDCAP



BACKUP: Search for an X_b: ($|y|$, p_T, $\cos\theta^*$) binning

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

- **barrel ($|y| < 1.2$) resolut^n better than endcap ($1.2 < |y| < 2.4$)**
  $\longrightarrow$ 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 $p_T^{\pi\pi}$
    $\longrightarrow$ background is lower in p_T, more backward in $\cos\theta^*$



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

BACKUP: Search for an X_b: ($|y|$, p_T, $\cos\theta^*$) binning

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

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  - $\cos\theta^*(\pi^+\pi^-)$ flat in parent rest frame for unpolarized signal
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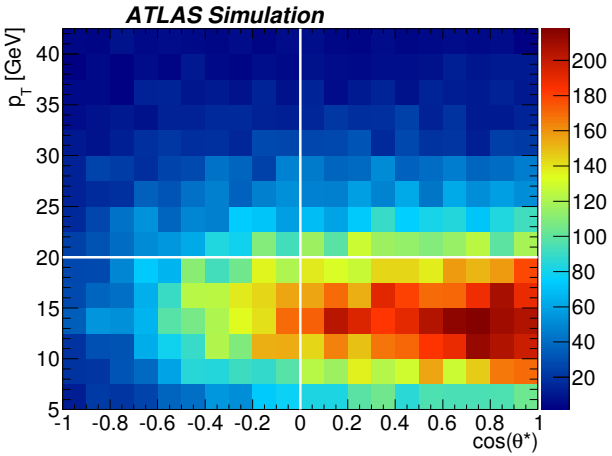
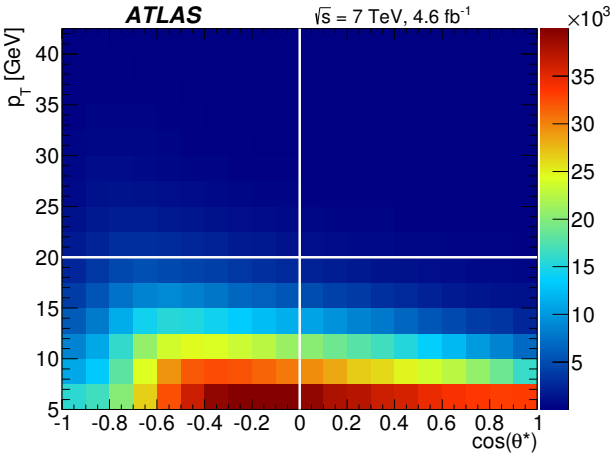
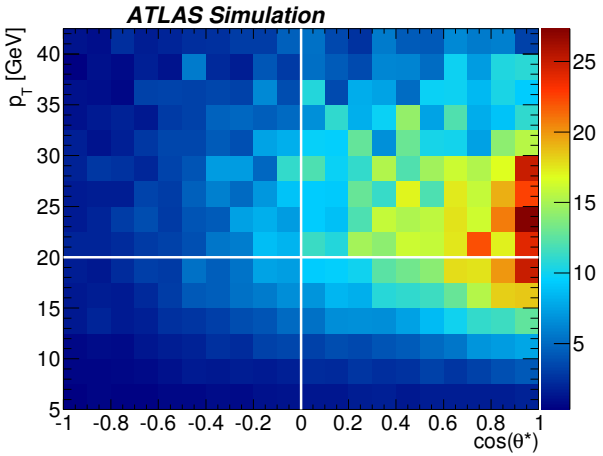
    $\longrightarrow$ background is lower in p_T, more backward in $\cos\theta^*$
  - trigger threshold effects
    $\longrightarrow$ distributions change but discrimination remains



SIGNAL



BACKGROUND



$S/\sqrt{B}$

BACKUP: Search for an X_b: ($|y|$, p_T, $\cos\theta^*$) binning

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

- **barrel ($|y| < 1.2$) resolut^n better than endcap ($1.2 < |y| < 2.4$)**
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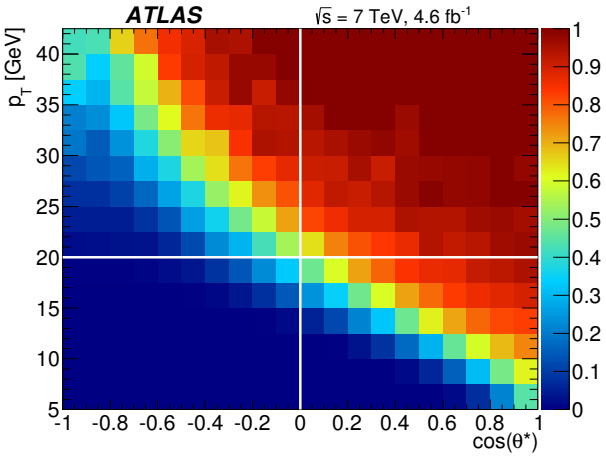
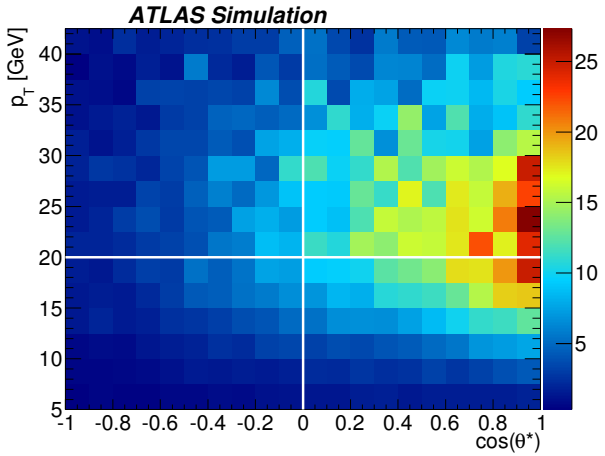


we chose bin boundaries at $(p_T, \cos\theta^*) = (20\,\mathrm{GeV}, 0)$
$\longrightarrow$ simult. fit to $2 \times 2 \times 2$ bins in ($|y|$, p_T, $\cos\theta^*$):

considered ΔR cut [CMS]: less sensitive than binning



ΔR cut à la CMS

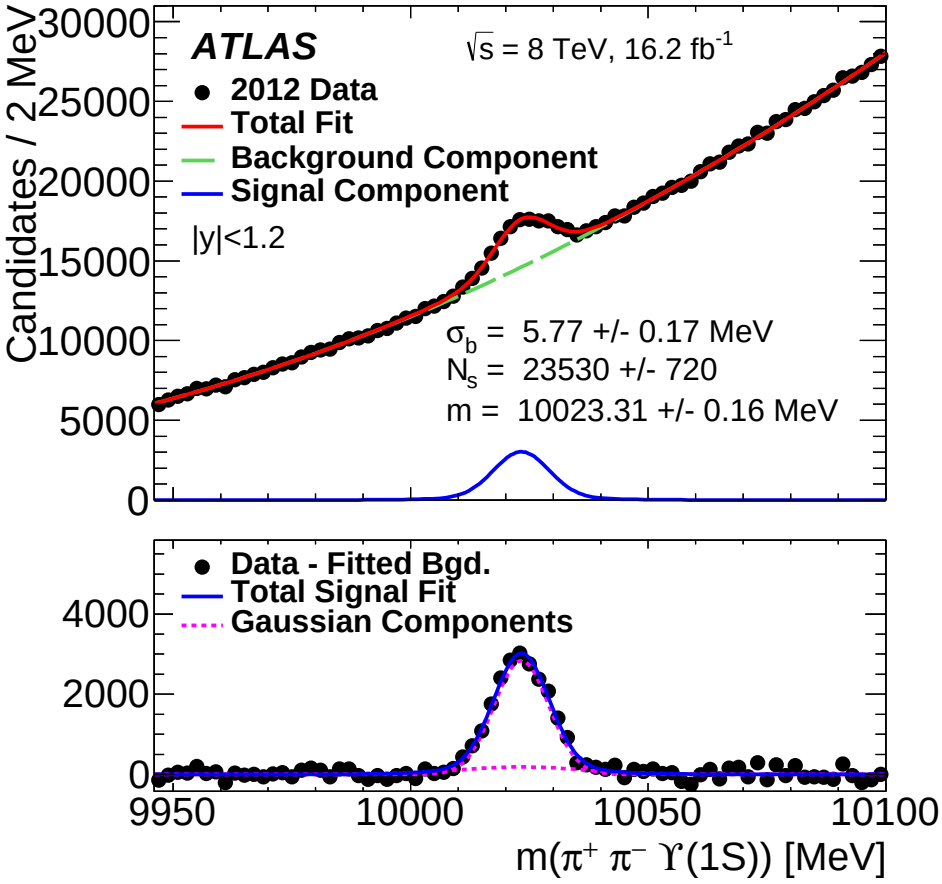
$S/\sqrt{B}$

BACKUP: Search for an X_b: calibration & validation, $\Upsilon(2S)$

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

1. **fit in 2 |y| bins, floated params:** m matches w.a.; σ matches MC

BARREL



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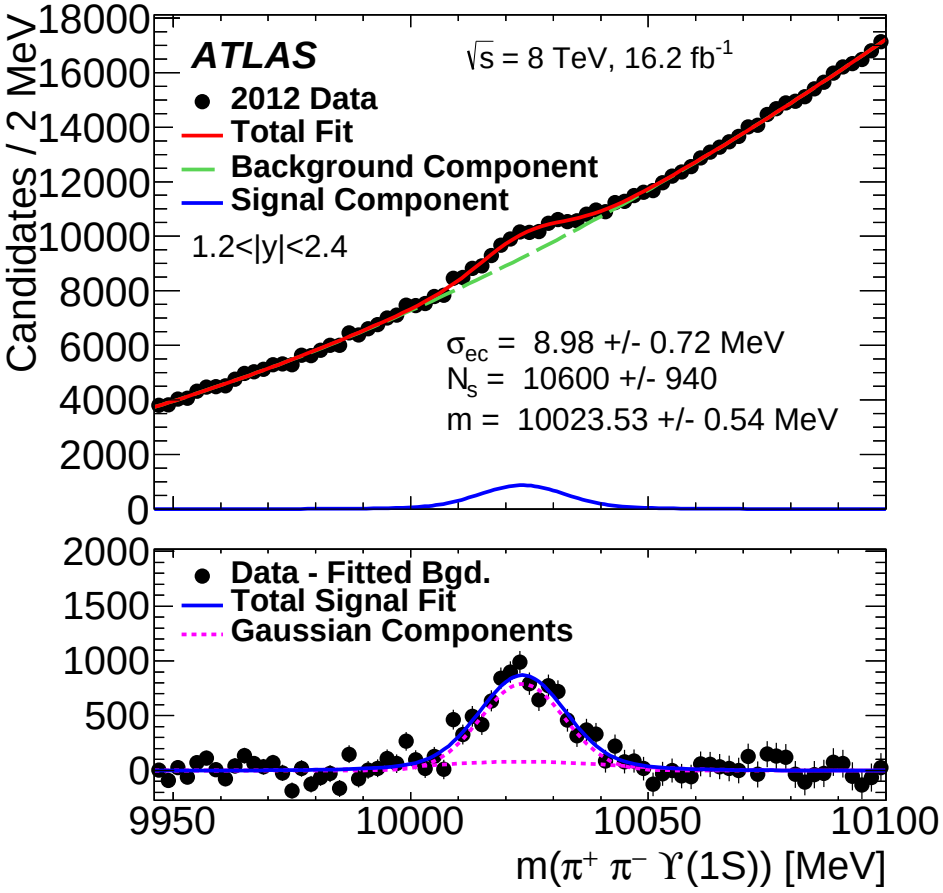


BACKUP: Search for an X_b: calibration & validation, $\Upsilon(2S)$

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

1. **fit in 2 $|y|$ bins, floated params:** m matches w.a.; σ matches MC

2. **separate fits in $2 \times 2 \times 2$ bins in ($|y|$, p_T, $\cos\theta^*$), fixed params:**
   - barrel fraction 0.67 ± 0.04 exceeds MC value 0.606 ± 0.004
   - in all subsequent fits, MC barrel fractions *rescaled* by $0.67/0.606$
   - division of signal among $2 \times 2 \times 2$ bins consistent with rescaled MC
   - sum of the eight yields:

$$
\begin{aligned}
N_{2S}^{fit} &= 34300 \pm 800 \\
N_{2S}^{pred} &= (\sigma\mathcal{B})_{2S} \cdot \mathcal{L} \cdot \mathcal{A} \cdot \epsilon \\
&= (0.504 \pm 0.038)\,\mathrm{nb} \cdot (16.2 \pm 0.3)\,\mathrm{fb}^{-1} \cdot (1.442 \pm 0.004)\% \cdot (0.283 \pm 0.002) \\
&= 33300 \pm 2500
\end{aligned}
$$

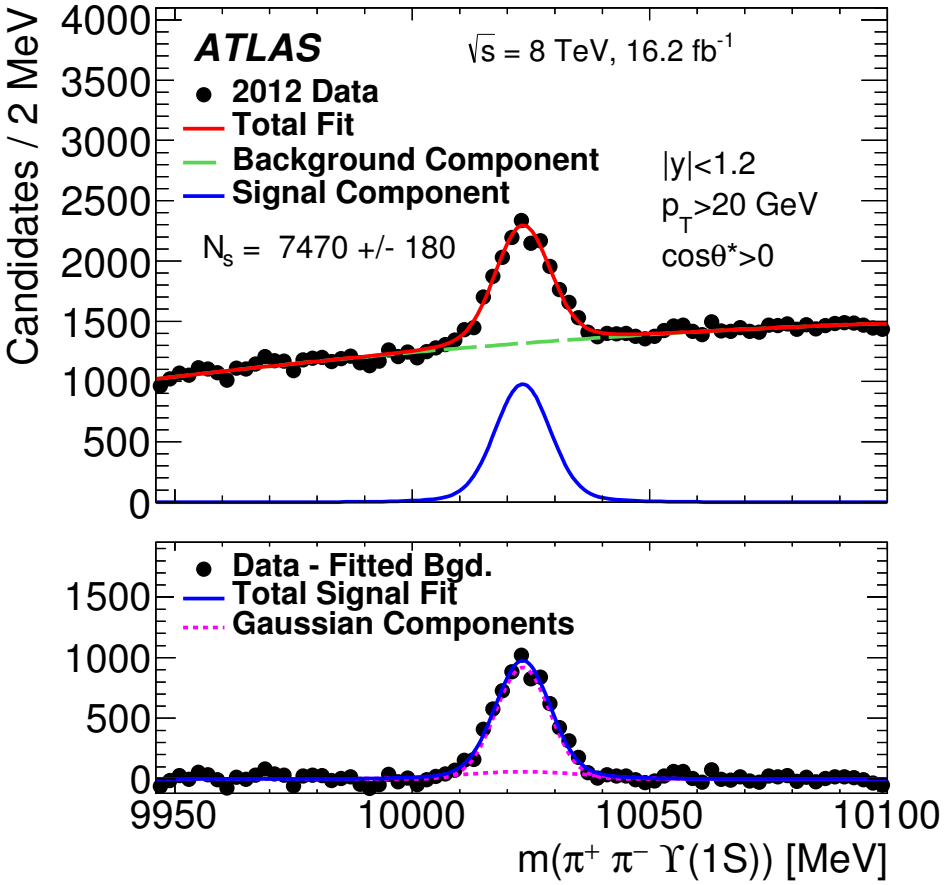
   - all subsequent fits are performed
     - simultaneously over the $2 \times 2 \times 2$ bins
     - using the division of signal between the bins (as a function of mass) determined from MC

BACKUP: Search for an X_b: calibration & validation, $\Upsilon(2S)$

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

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

BARREL



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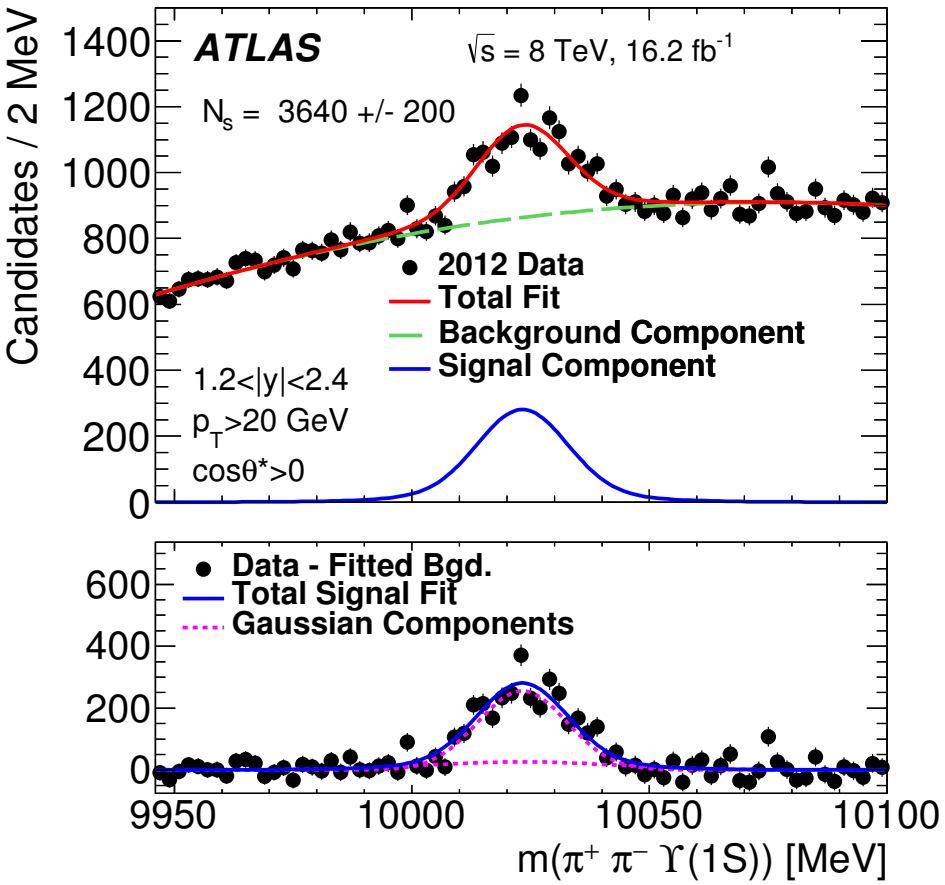
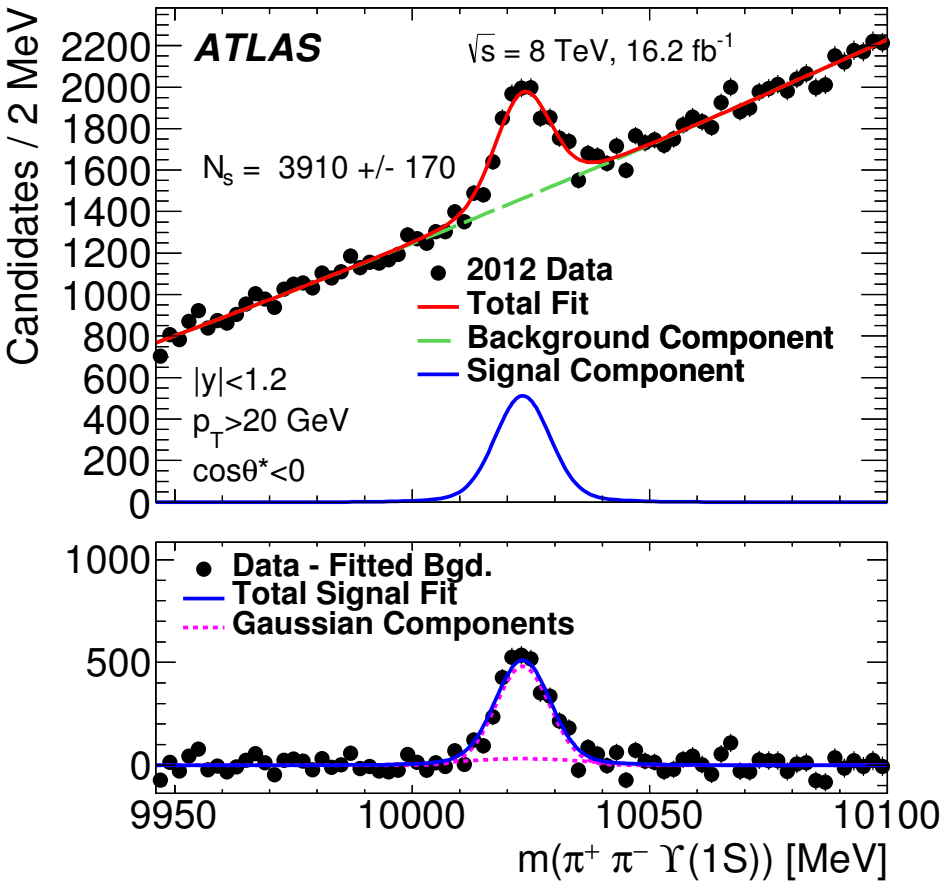


BACKUP: Search for an X_b: calibration & validation, $\Upsilon(2S)$

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

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

BARREL



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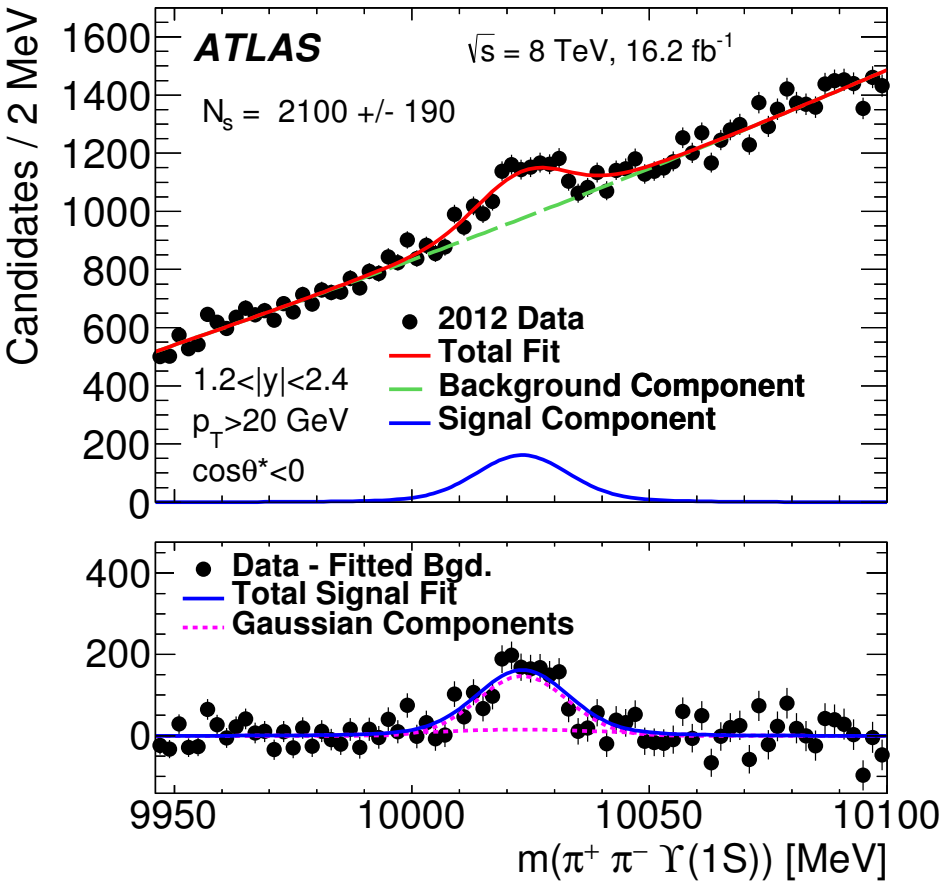
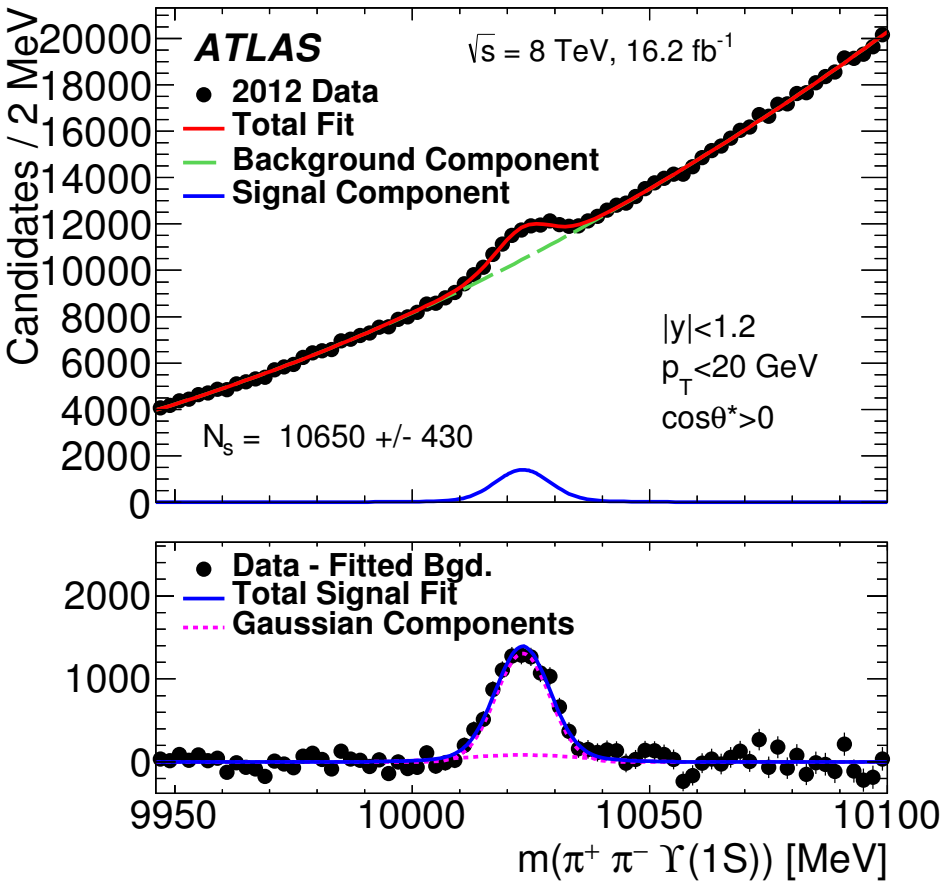


BACKUP: Search for an X_b: calibration & validation, $\Upsilon(2S)$

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

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

BARREL



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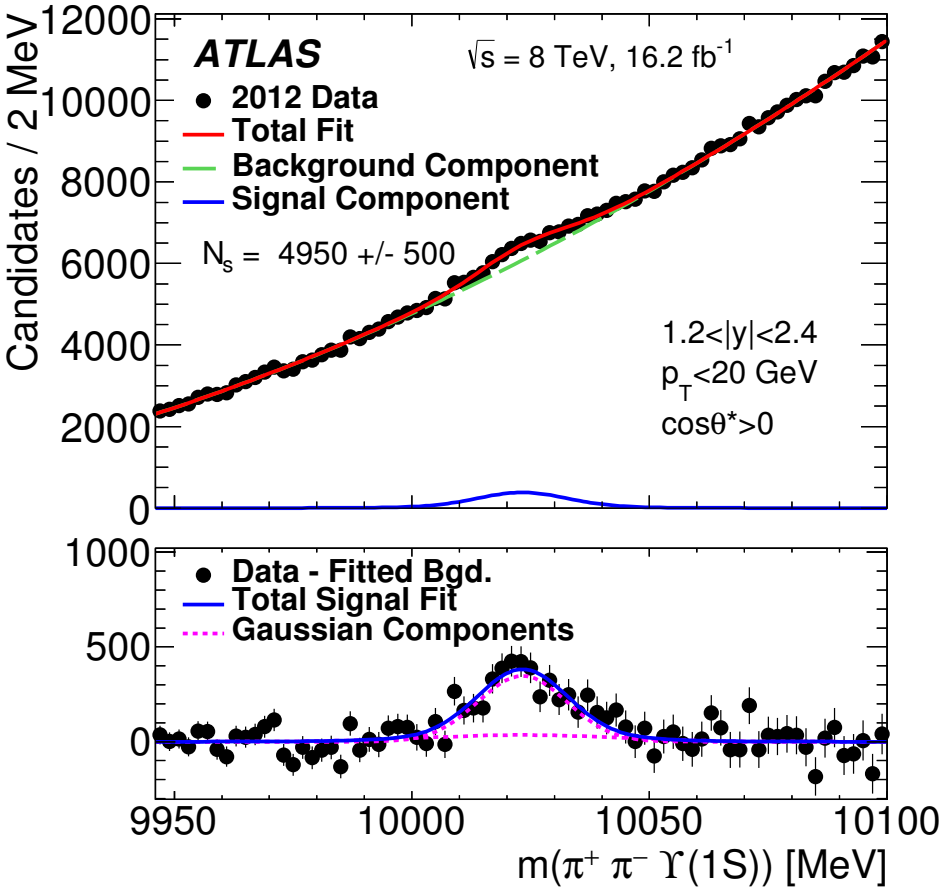
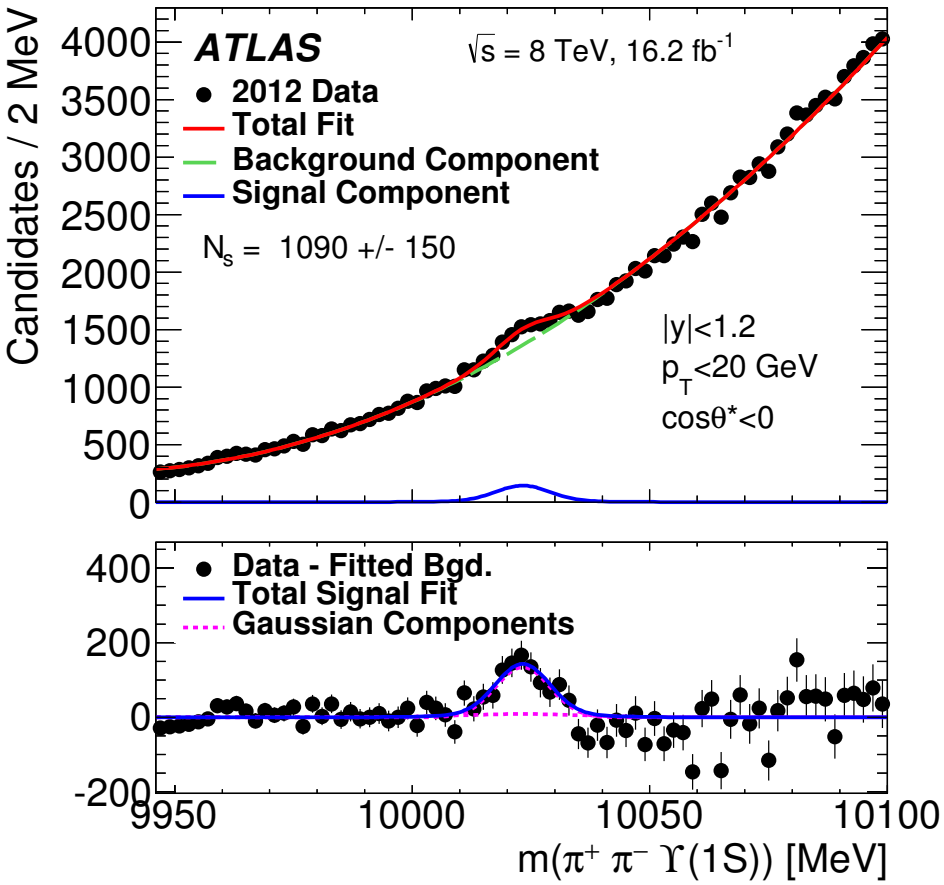


BACKUP: Search for an X_b: calibration & validation, $\Upsilon(2S)$

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

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

BARREL



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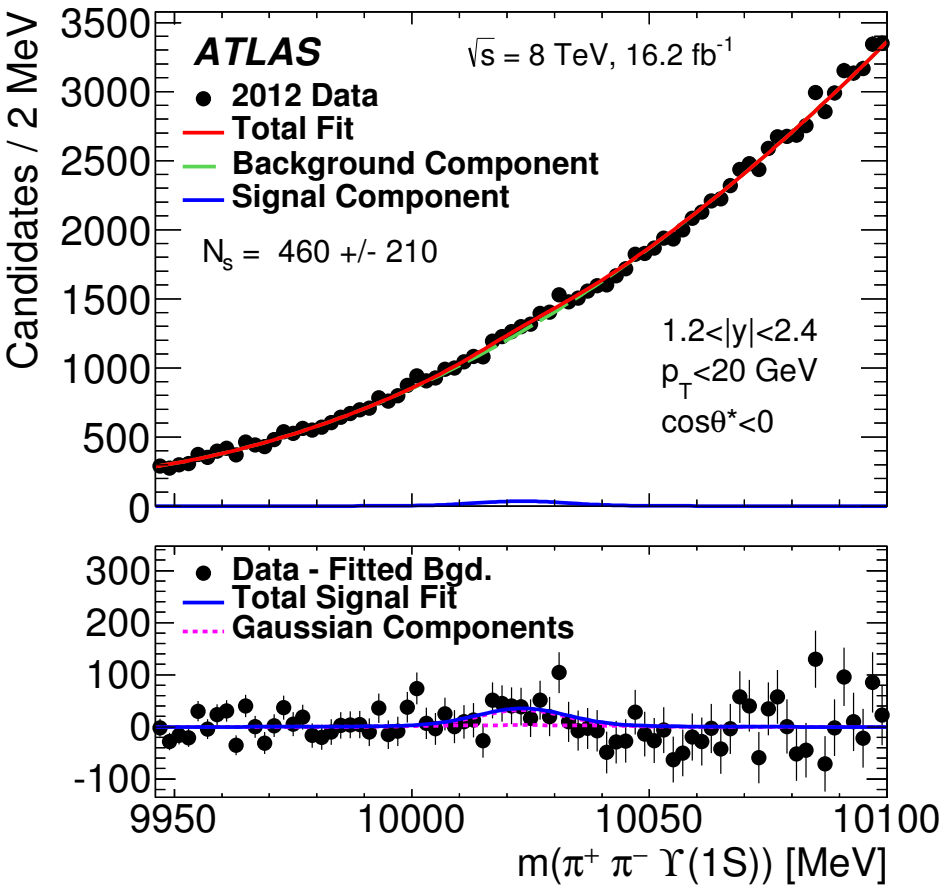


BACKUP: Search for an X_b: calibration & validation, $\Upsilon(3S)$

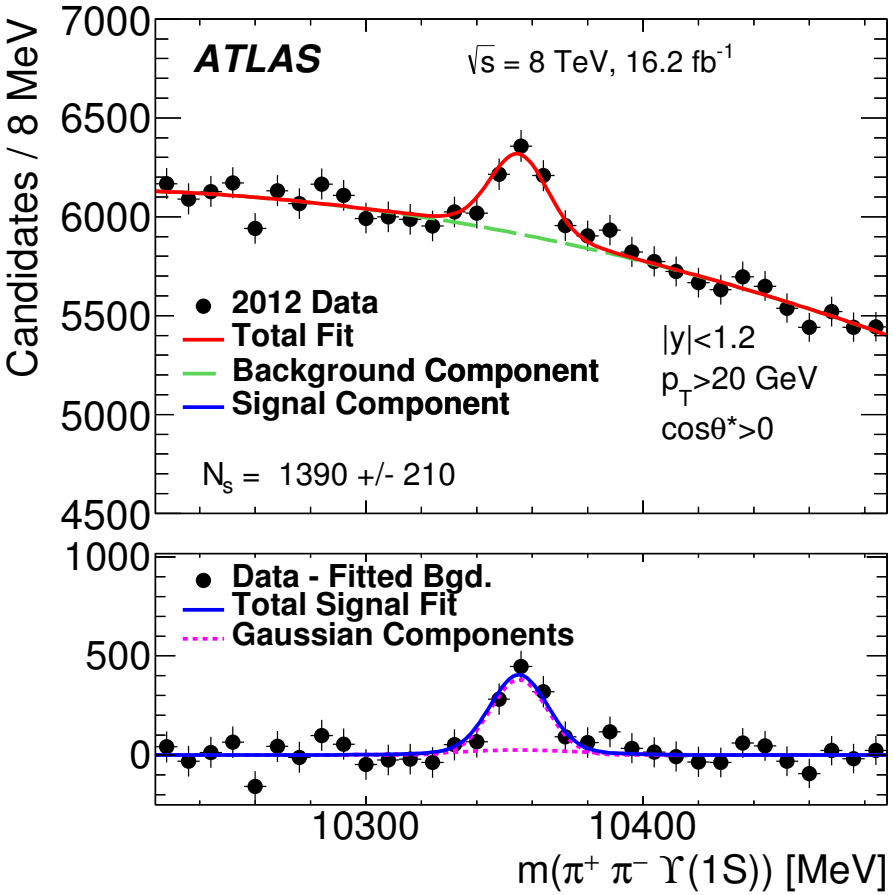
ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

3. **simultaneous fit to $2 \times 2 \times 2$ bins with fixed params:**

- strong but not overwhelming signal: model for X_b search
- significance $z = 8.7$
- most sensitive bin $z = 6.5 \longrightarrow$: (for clarity: rebinned $2 \rightarrow 8\,\mathrm{MeV}$)
- $\chi^2/n_{dof} = 1.0$ for simult. fit: good signal division among bins
- overall fitted yield:

$$N_{3S}^{fit} = 11600 \pm 1300$$
$$N_{3S}^{pred} = (\sigma\mathcal{B})_{3S} \cdot \mathcal{L} \cdot \mathcal{A} \cdot \epsilon$$
$$= 11400 \pm 1500$$

BARREL, HIGH-p_T, HIGH-$\cos\theta^*$

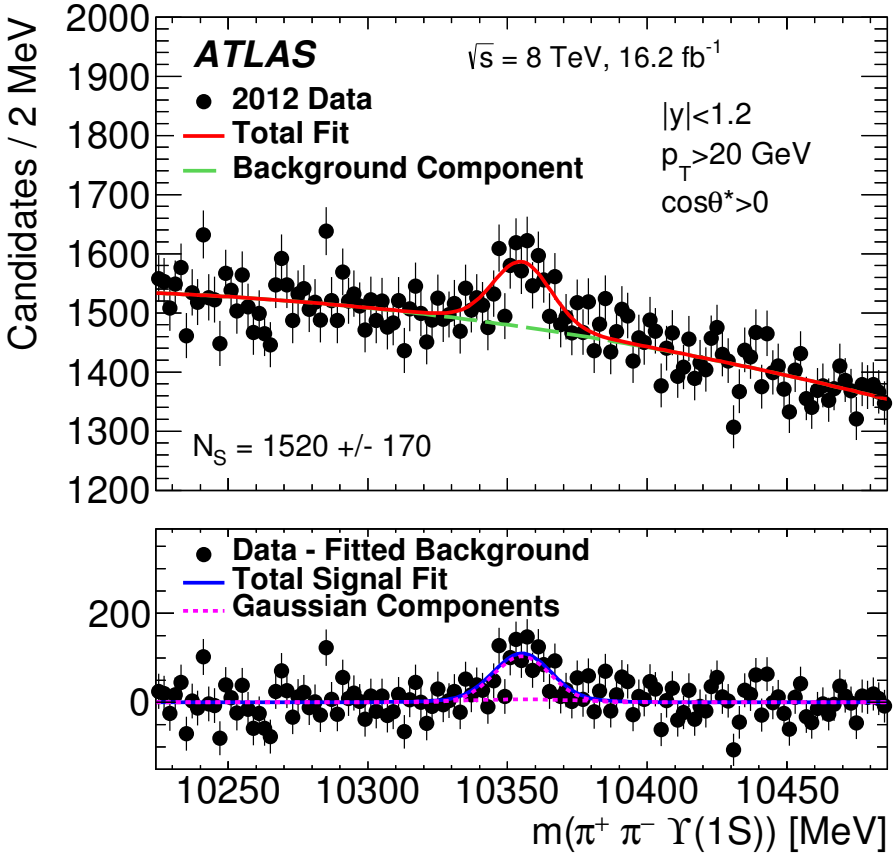


BACKUP: Search for an X_b: calibration & validation, $\Upsilon(3S)$

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

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

BARREL



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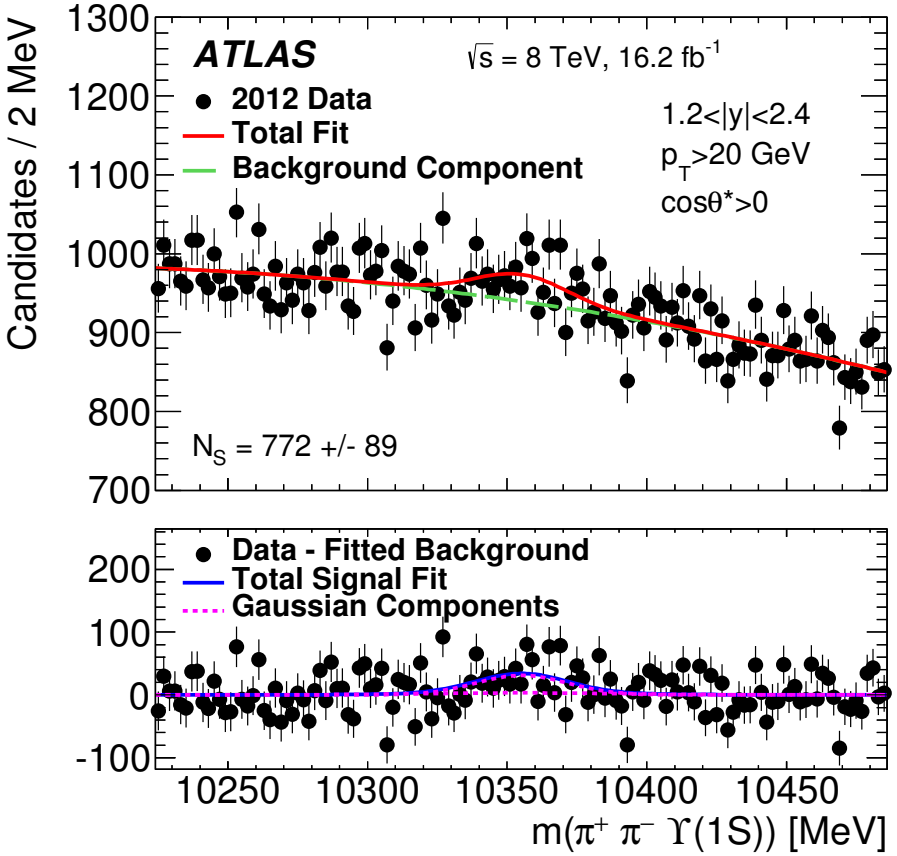
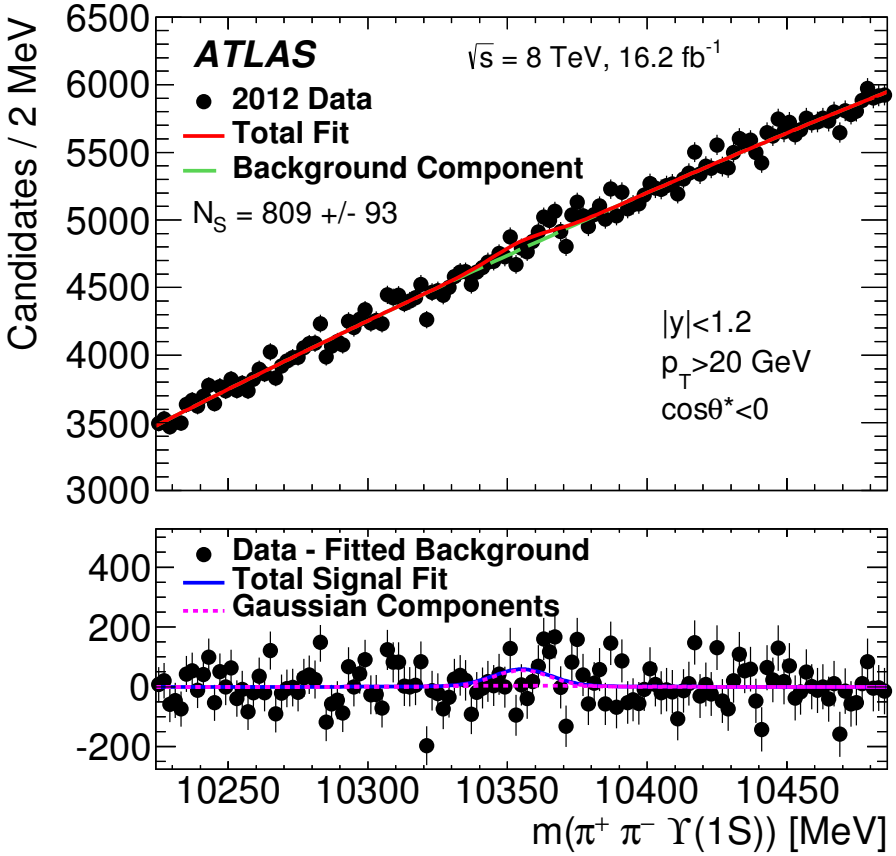


BACKUP: Search for an X_b: calibration & validation, $\Upsilon(3S)$

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

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

BARREL



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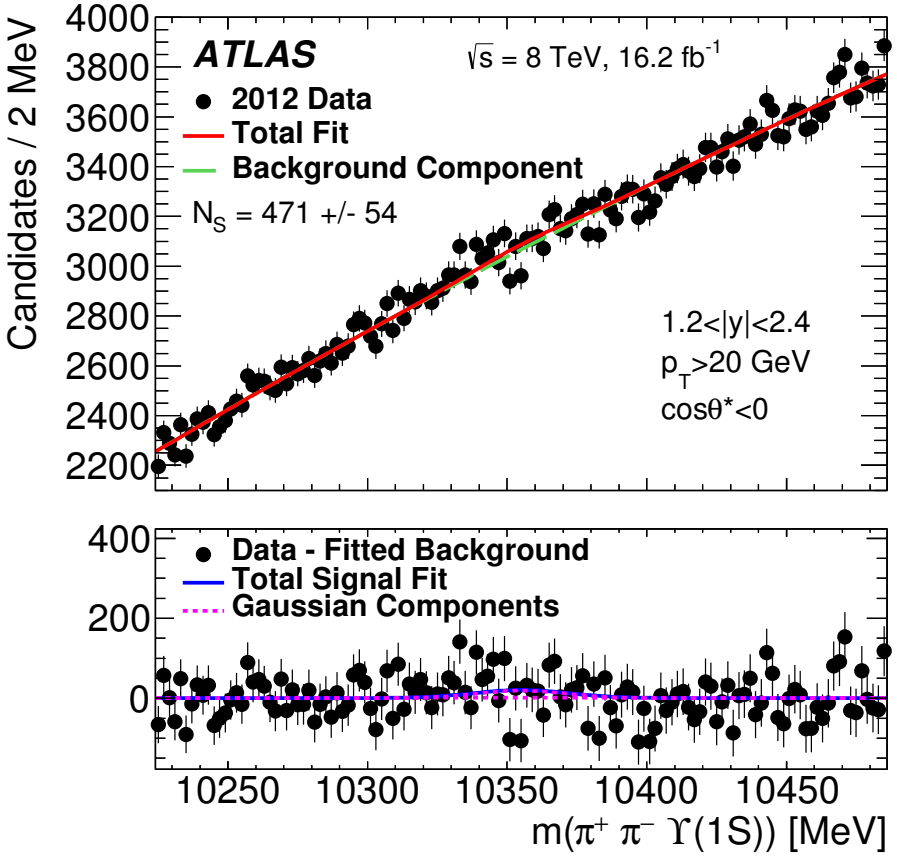
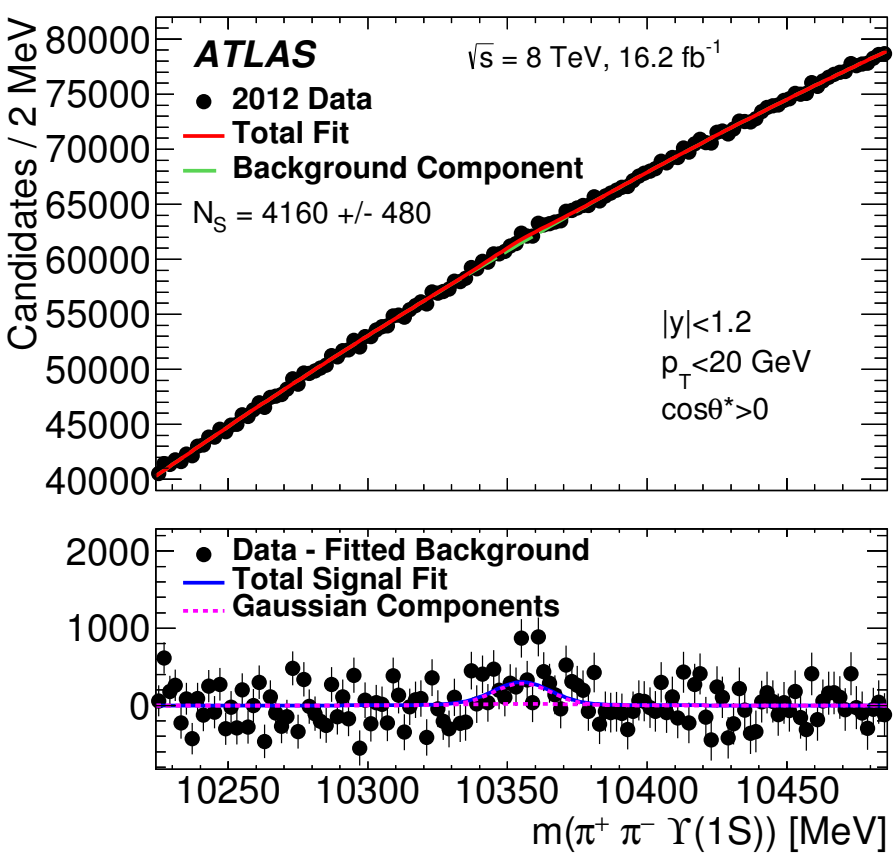


BACKUP: Search for an X_b: calibration & validation, $\Upsilon(3S)$

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

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

BARREL



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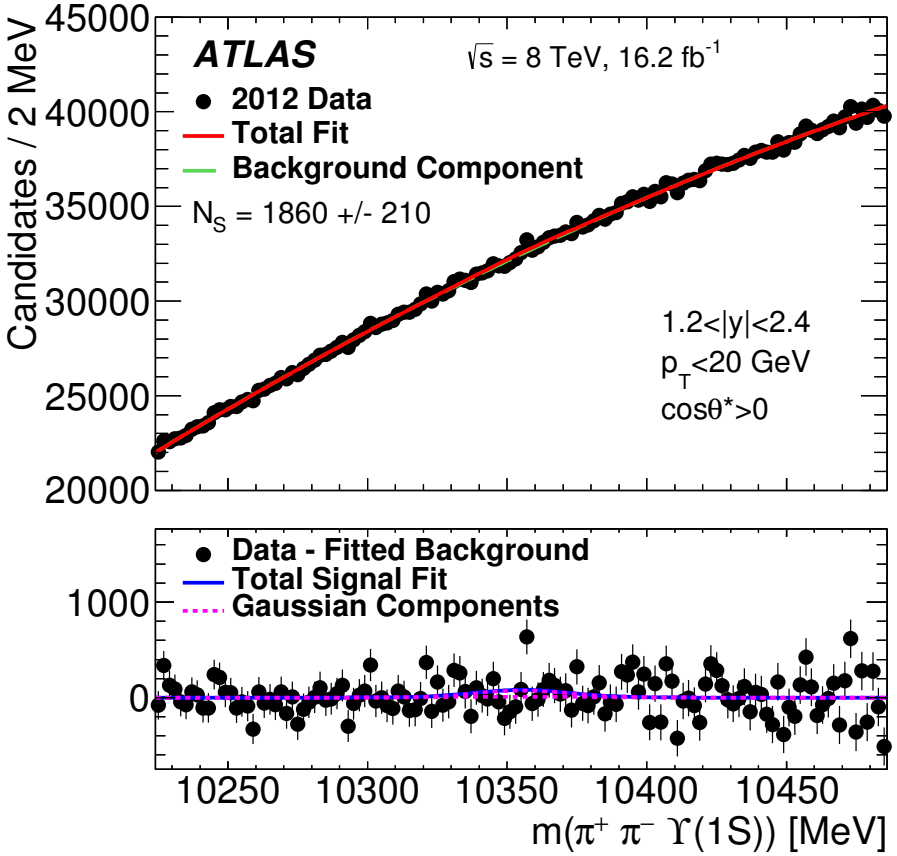

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ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

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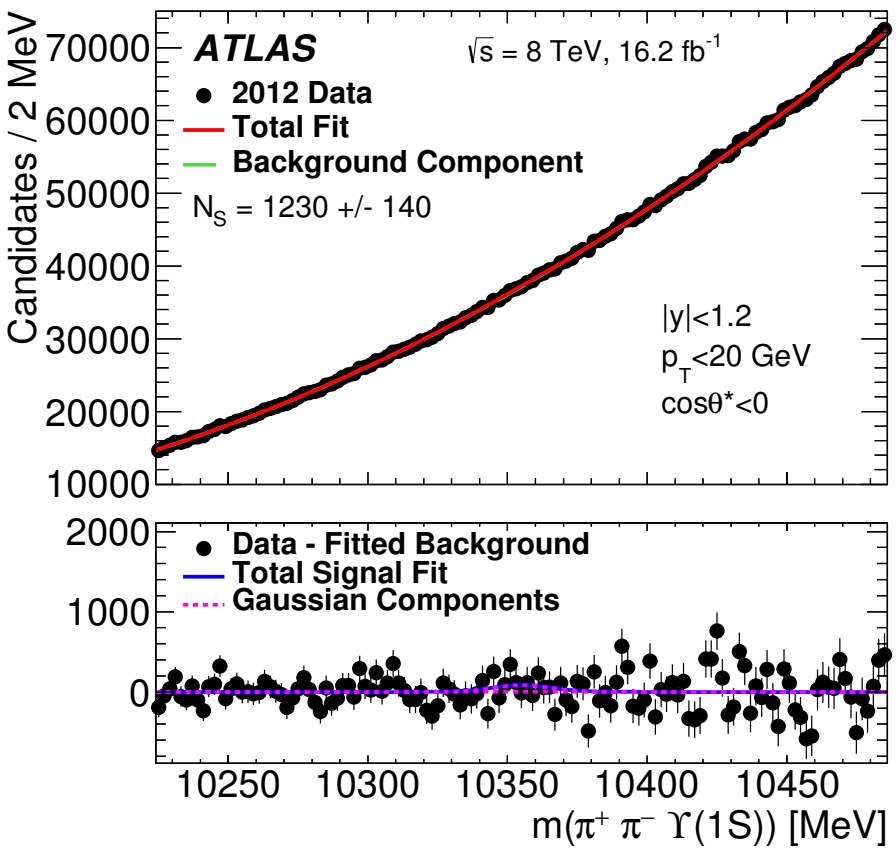
BARREL



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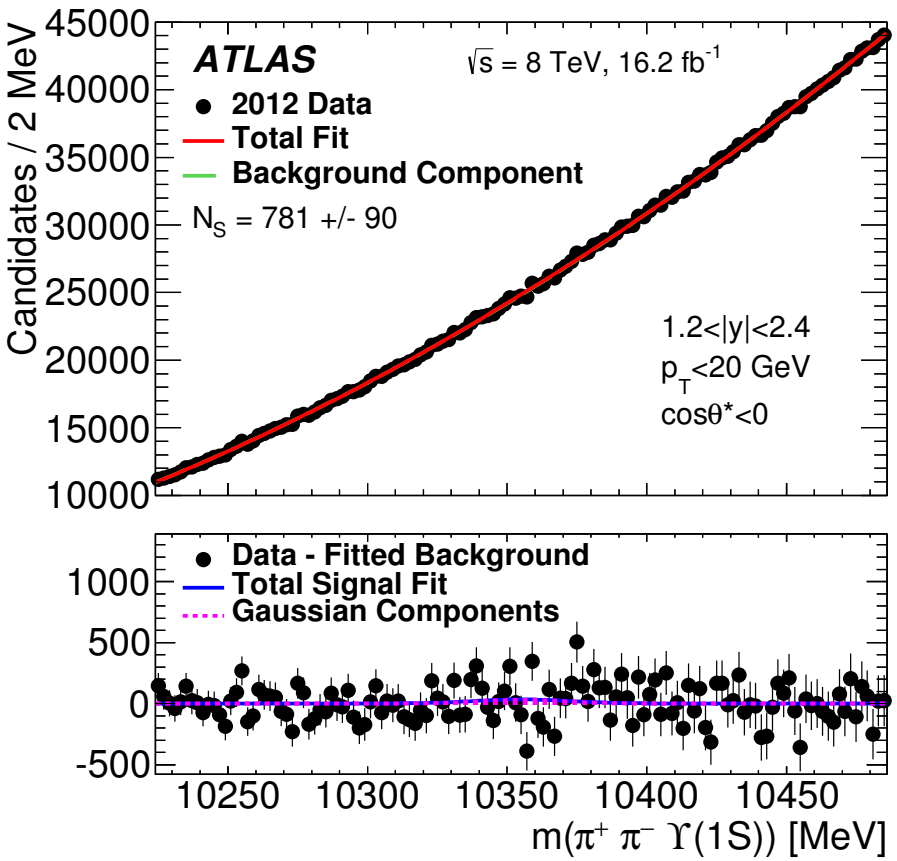


BACKUP: Search for an $X_b \to \pi^+\pi^-\Upsilon$ signal

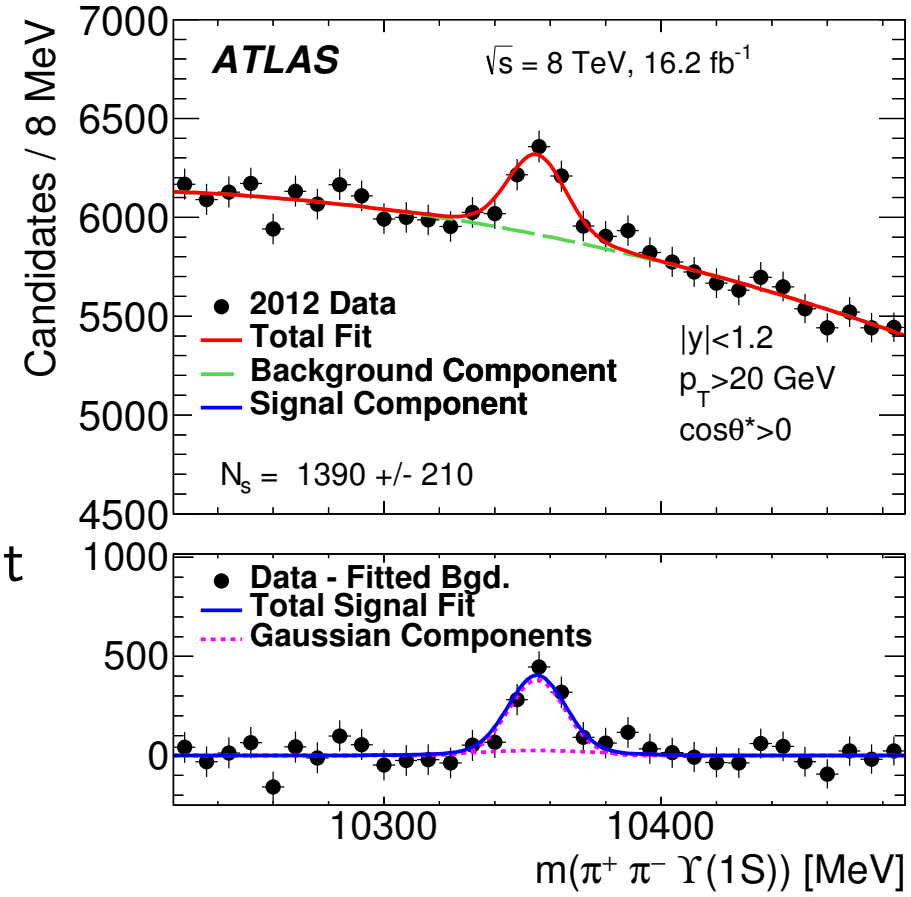
ATLAS Collab., Physics Letters B 740, 199–217 (2015); arXiv:1410.4409 [hep-ex]

- hidden-beauty analogue of $X(3872) \to \pi^+\pi^- J/\psi$
- $16.2\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 8\,\mathrm{TeV}$ data; $2 \times (p_T > 4\,\mathrm{GeV}$ muon) trigger
- fit in $2 \times 2 \times 2$ bins of $(|y|,\ p_T,\ \cos\theta^*)$ to discriminate *vs* bkgd

- kinematics: ATLAS/CMS $\Upsilon(nS)\ \frac{\mathrm{d}^2\sigma}{\mathrm{d}y\mathrm{d}p_T}$; validated on $34300 \pm 800\ \Upsilon(2S)$ signal
- $\Upsilon(3S)$: model for X_b search
- significance $z = 8.7$; most sensitive bin $z = 6.5 \longrightarrow$
- $\chi^2/n_{dof} = 1.0$ for simultaneous fit

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

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



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 ($7\,\mathrm{TeV}$) data: lower-sideband $\mu^+\mu^-$ and same-sign $\mu^\pm\mu^\pm$ samples
- $m(\pi^+\pi^-\Upsilon)$ distributions featureless above 9800 MeV
- confirmed in $\Upsilon \to \mu^+\mu^-$ signal region for various $m(\pi^+\pi^-\Upsilon)$ ranges

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

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

signal:

- narrow state search: fit with $\mathbf{f \cdot \mathcal{G}(m, \sigma) + (1 - f) \cdot \mathcal{G}(m, r\sigma)}$
- f, $r \sim$ indep^t of mass; fixed to average over MC samples
- σ 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]

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signal:

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

BACKUP: Search for an X_b: results as a fn of mass

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

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

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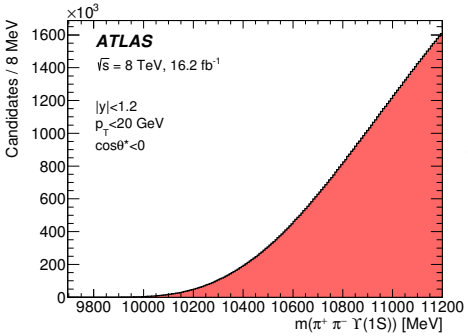
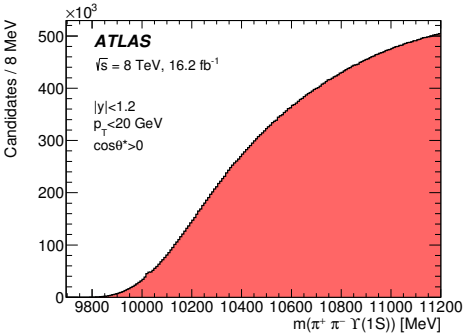
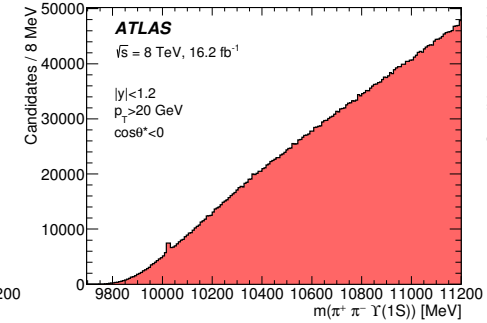


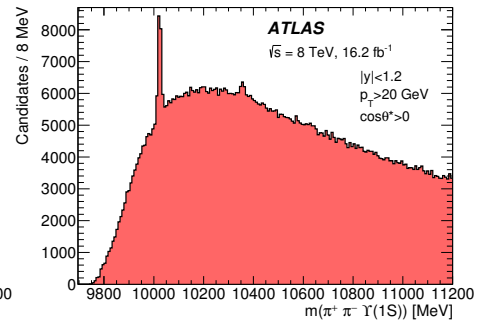
(a) Barrel, low p_T, low $\cos\theta^*$



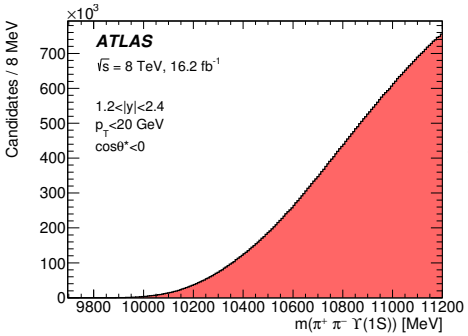
(b) Barrel, low p_T, high $\cos\theta^*$



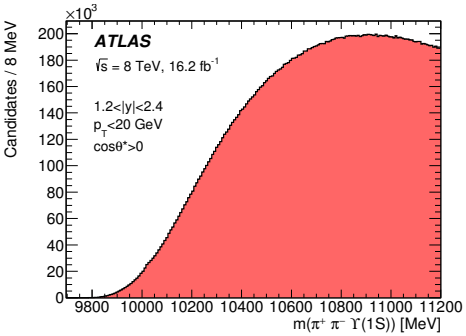
(c) Barrel, high p_T, low $\cos\theta^*$



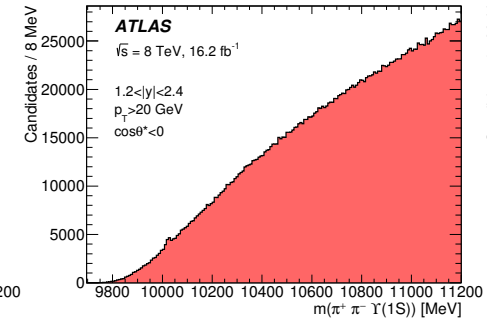
(d) Barrel, high p_T, high $\cos\theta^*$



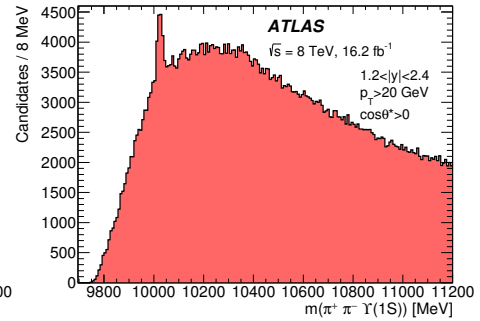
(e) Endcap, low p_T, low $\cos\theta^*$



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



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



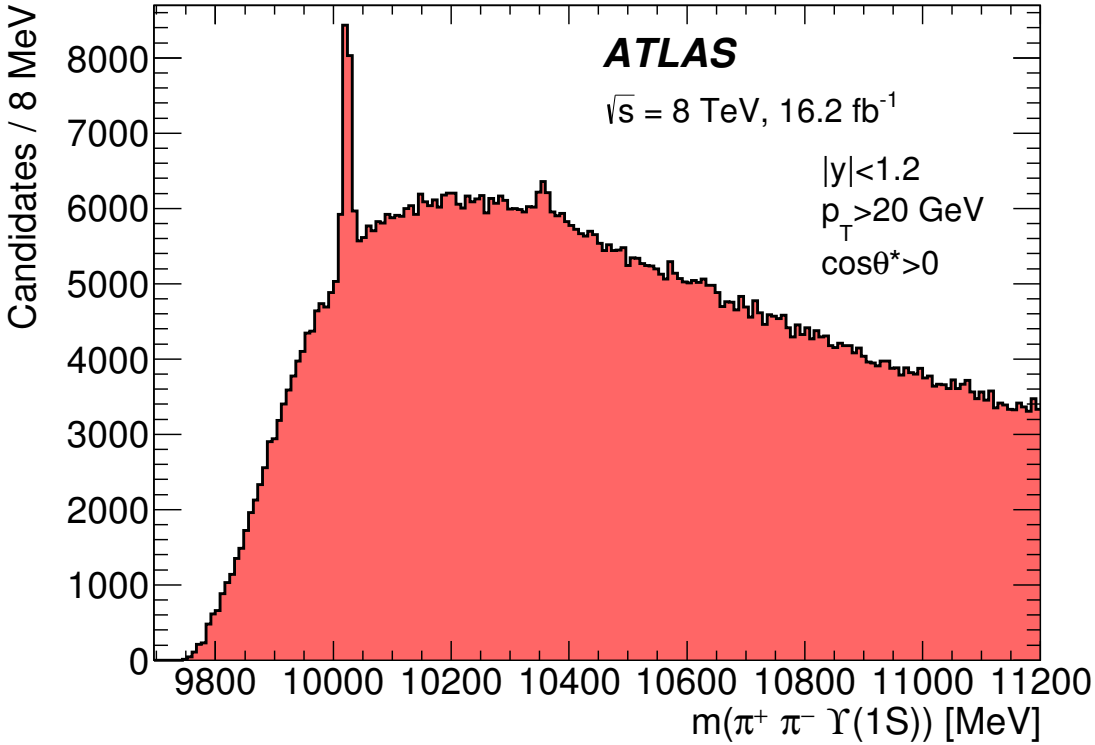
(h) Endcap, high p_T, high $\cos\theta^*$

BACKUP: Search for an X_b: results as a fn of mass

ATLAS Collaboration, Physics Letters B 740, 199–217 (2015)

- hypothesis test every $10\,\mathrm{MeV}$ from 10–11 GeV, excluding $\Upsilon(2S, 3S)$
- fit range $m \pm 8\sigma_{\text{endcap}}$: $\pm 72\,\mathrm{MeV}$ at $10\,\mathrm{GeV}$; $\pm 224\,\mathrm{MeV}$ at $10.9\,\mathrm{GeV}$
- 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



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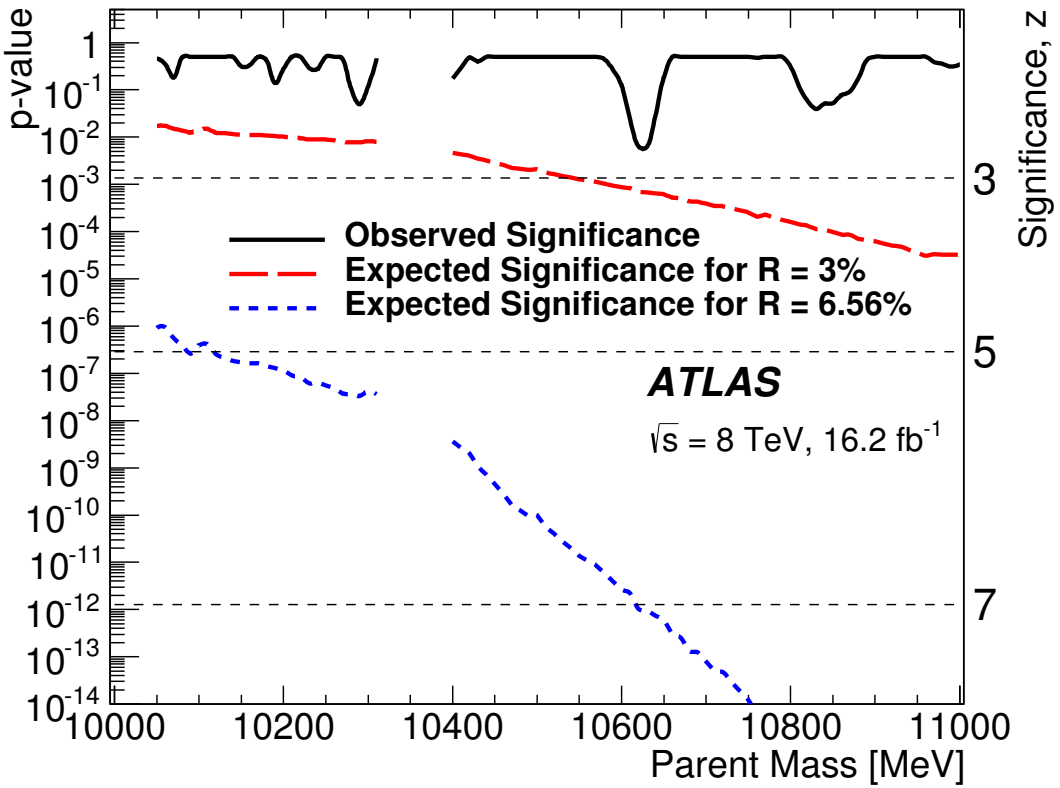

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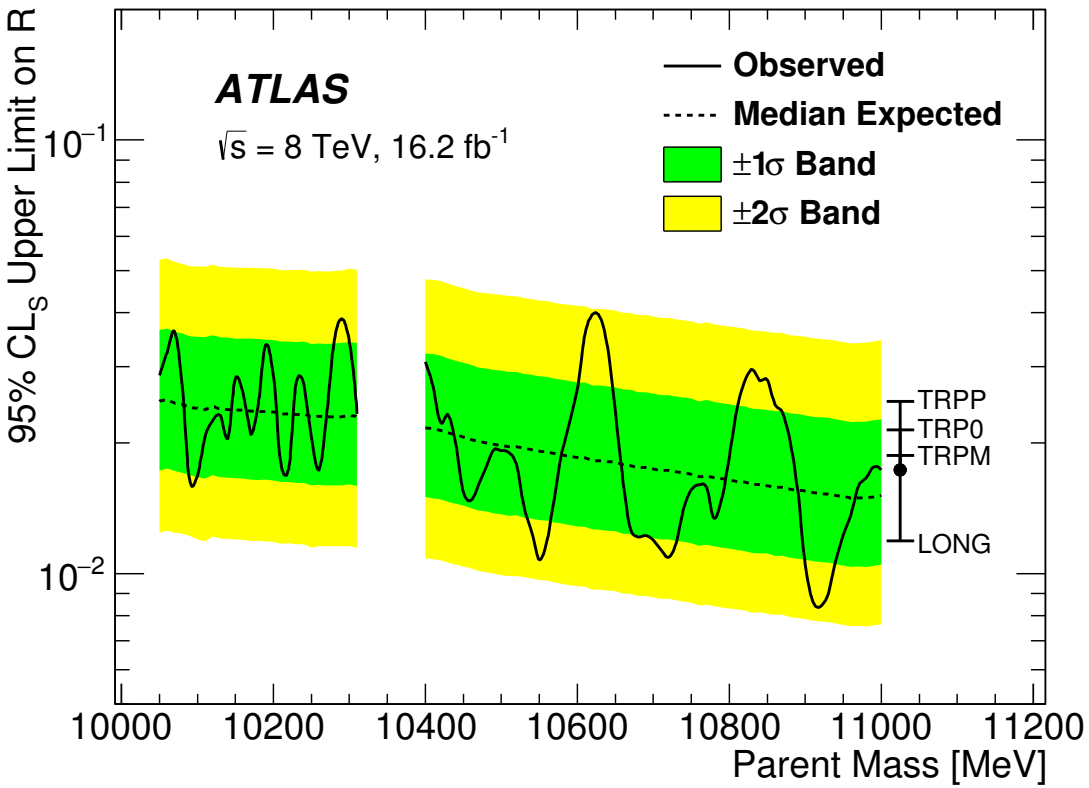

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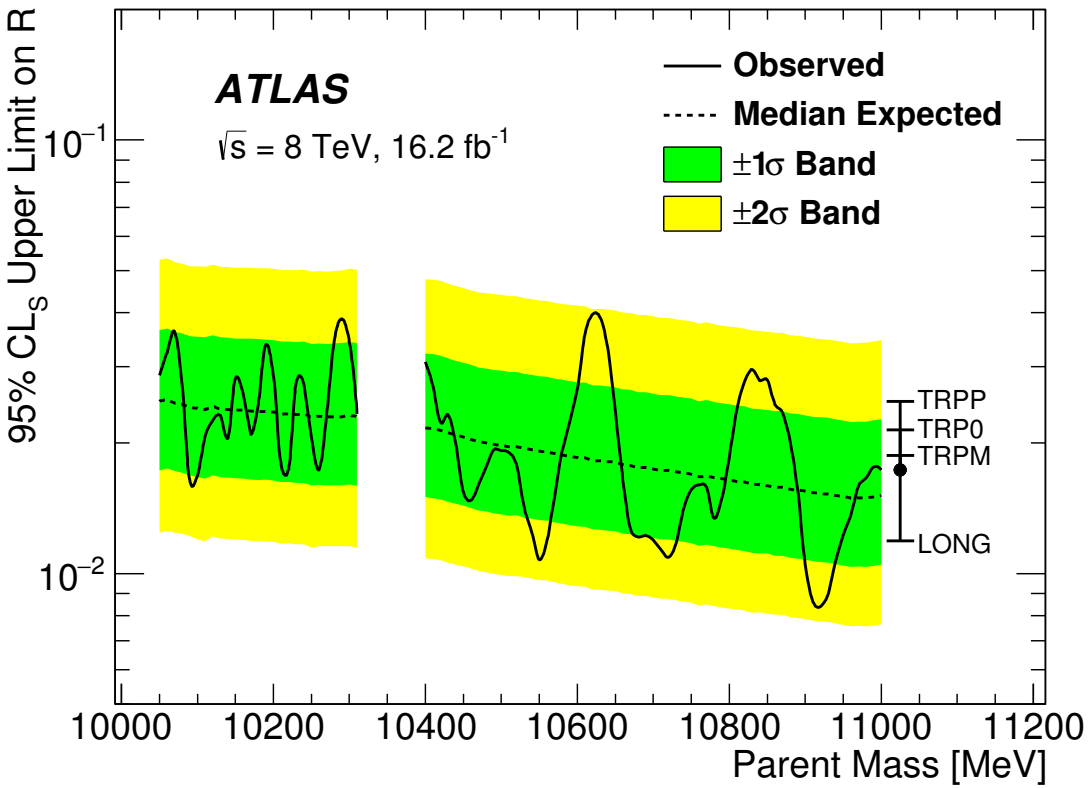
  - increases limits $\lesssim 13\%$
  - inflates $\pm 1\sigma$ bands 9.5–25%



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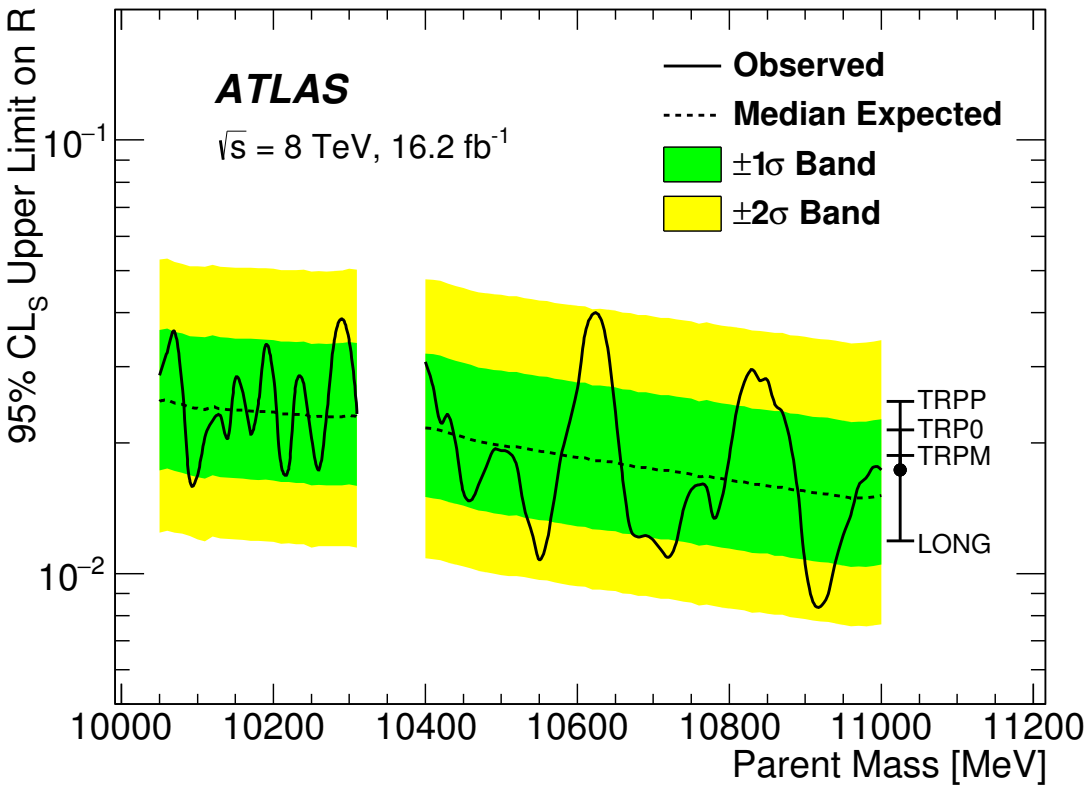

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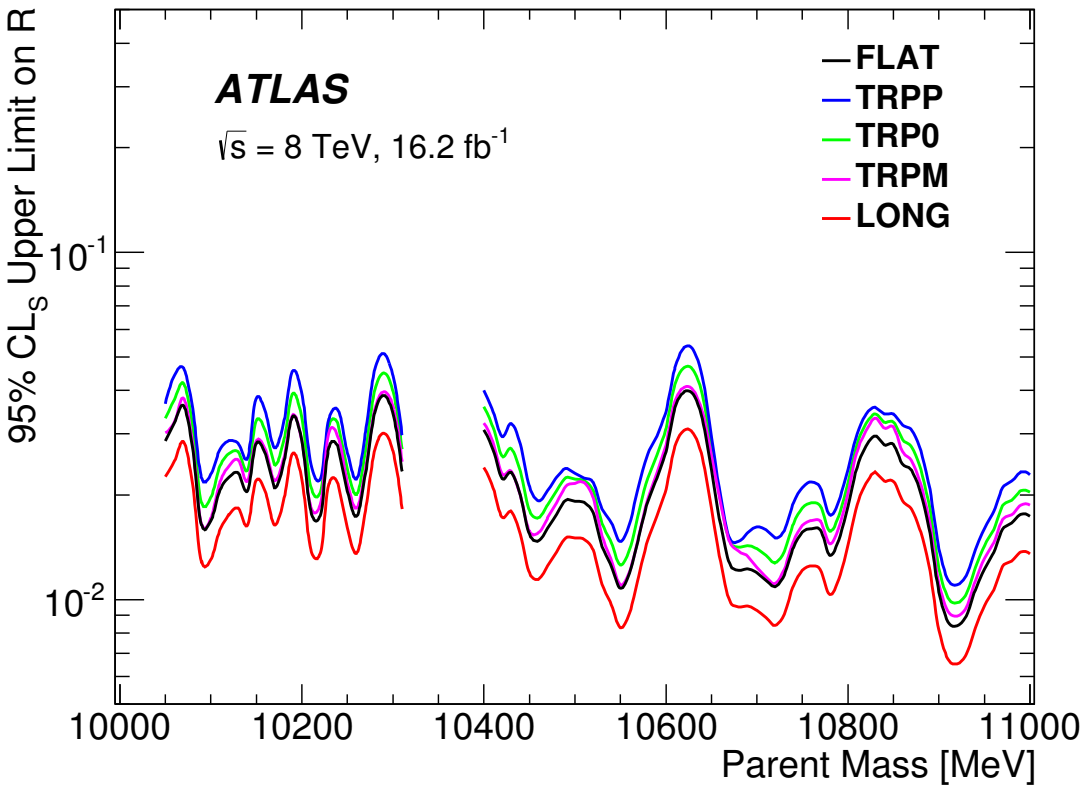


BACKUP: $X_b \to \pi^+\pi^-\Upsilon$: interpretation and plans

- this is the most senstitive X_b production search for $m > 10.1\,\mathrm{GeV}$
- 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 σ/σ_{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 $D^0\overline{D}^{*0}$ threshold
  - even a molecular X_b is bound by tens of MeV
  - further, large $D\overline{D}^*$ isospin breaking ($m_\pm - m_{00} = +8.08 \pm 0.11\,\mathrm{MeV}$) is absent for $B\overline{B}^*$ ($m_\pm - m_{00} = -0.64 \pm 0.12\,\mathrm{MeV}$)‡
  - stressed by theorists [Guo/Meißner/Wang, 1204.2158; Karliner ...]

X(3872): $|m_\pm - m_{00}| \gg E_b$; $\approx$ pure $D^0\overline{D}^{*0}$ 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

BACKUP: Search for an X_b: reassessing the motivation

Padmanath, Lang, Prelovsek, PRD 92, 034501 (2015), & others in backup [HERE]

some models with accidental $\chi_{c1}(2P)$-threshold overlap,
or attraction of resonance to threshold,
or other effects without straightforward $c \to b$ analogues:

- Yu. S. Kalashnikova, *PRD* **72**, 034010 (2005) *et passim*
- Danilikin, Simonov, *PRL* **105**, 102002 & *PRD* **81**, 074027 (2010)
- Coito, Rupp, van Beveren, *EPJC* **71**, 1762 (2011) & **73**, 2351 (2013)
- Caramés, Valcarce, Vijande, *PLB* **709**, 358 (2012) [constituent quark]
- Ferretti, Galatà, Santopinto, *PRC* **88**, 015207 (2013)
  & *PRD* **90**, 054010 (2014)
- Takizawa, Takeuchi, *PTEP* **2013**, 093D01.
- Takeuchi, Shimizu, Takizawa, *PTEP* **2014**, 123D01.

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

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

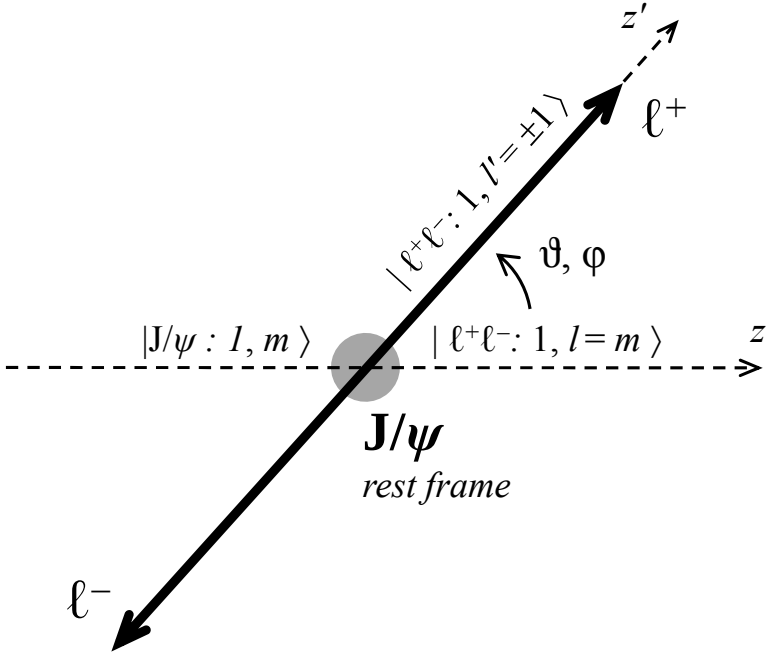
for ($J^{PC} = 1^{--}$) $|V\rangle = b_{+1}\,|+1\rangle + b_{-1}\,|-1\rangle + b_0\,|0\rangle$ decaying $\rightarrow \ell^+\ell^-$,

- 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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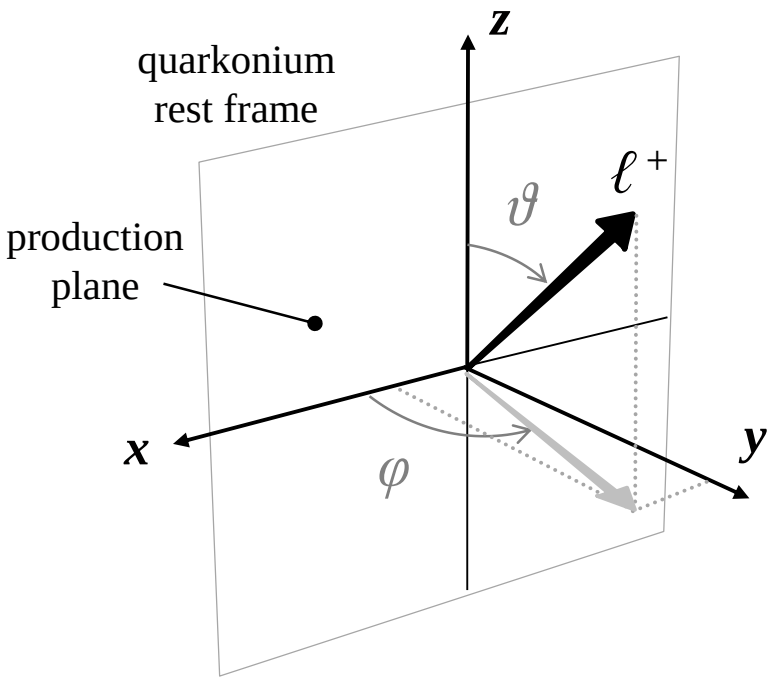

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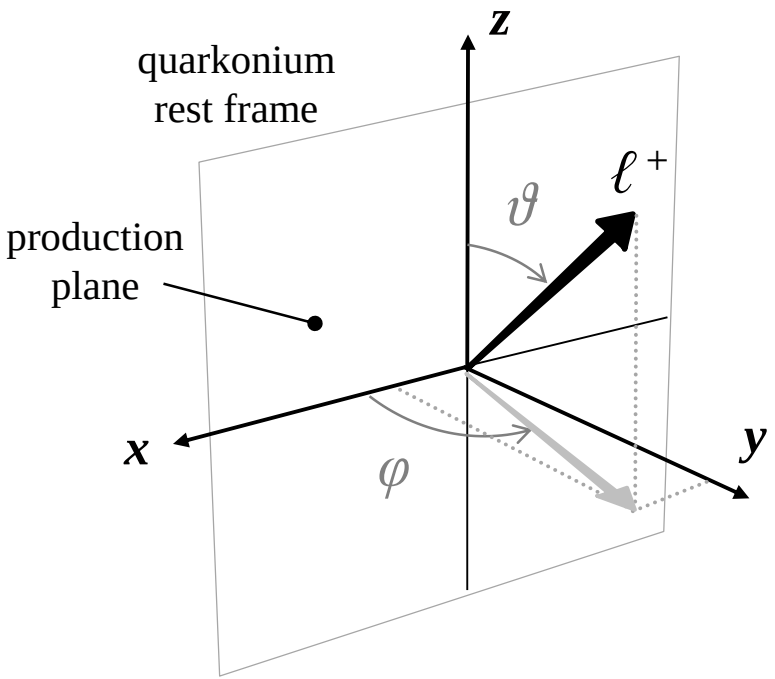

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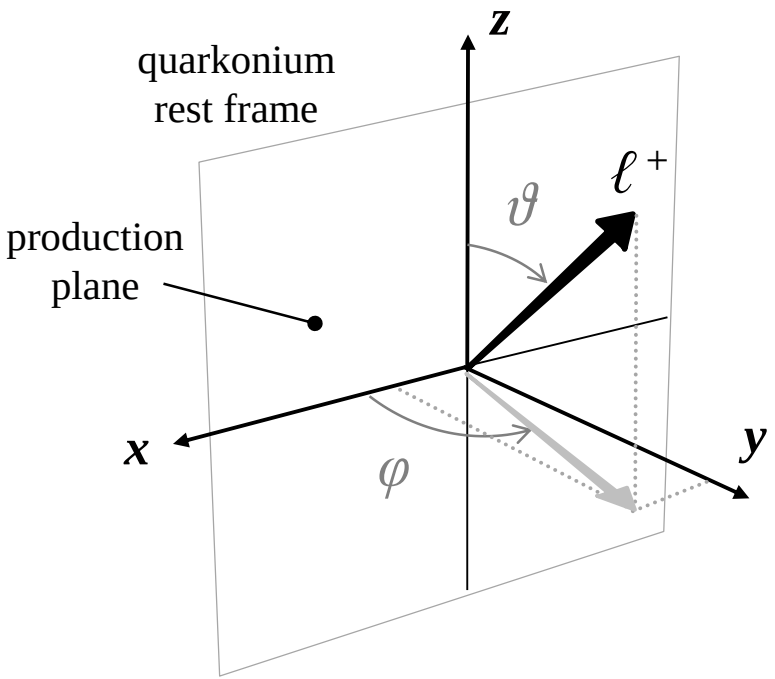

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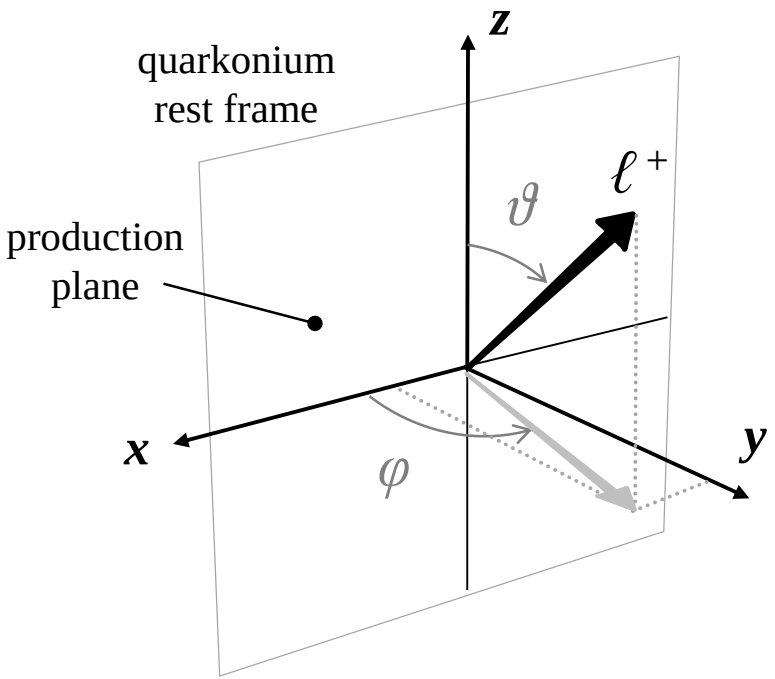

- inclusive production: p_1, p_2, and V only;
  we ($\sim$ must) choose (x, z) : production plane
- reflection-odd terms unobservable (parity)
- full angular distributions (λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$) in general needed ...

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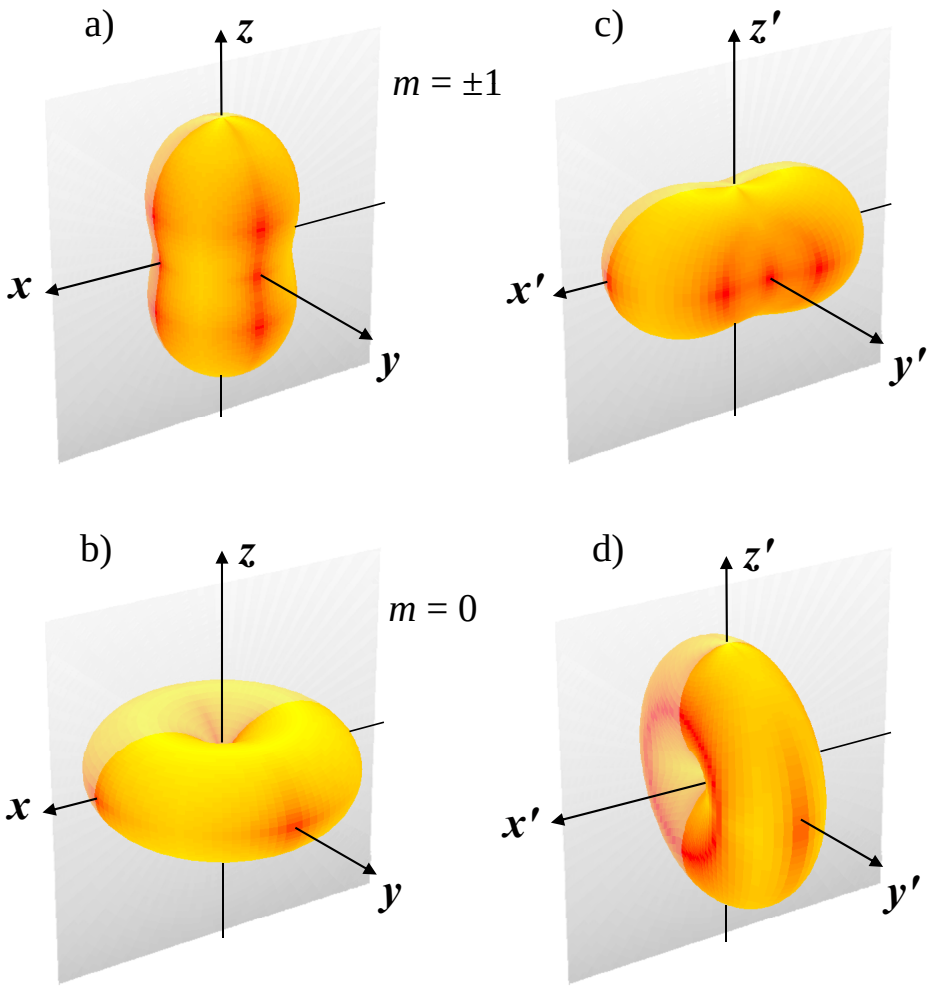

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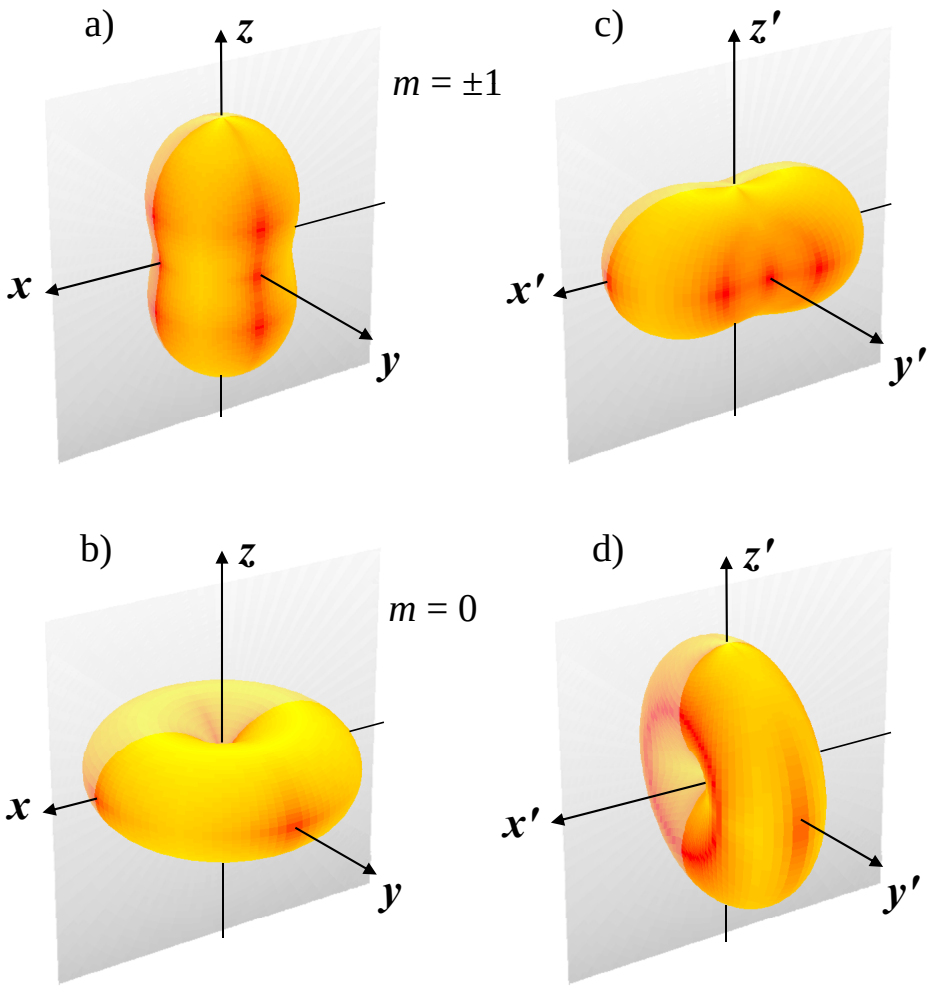

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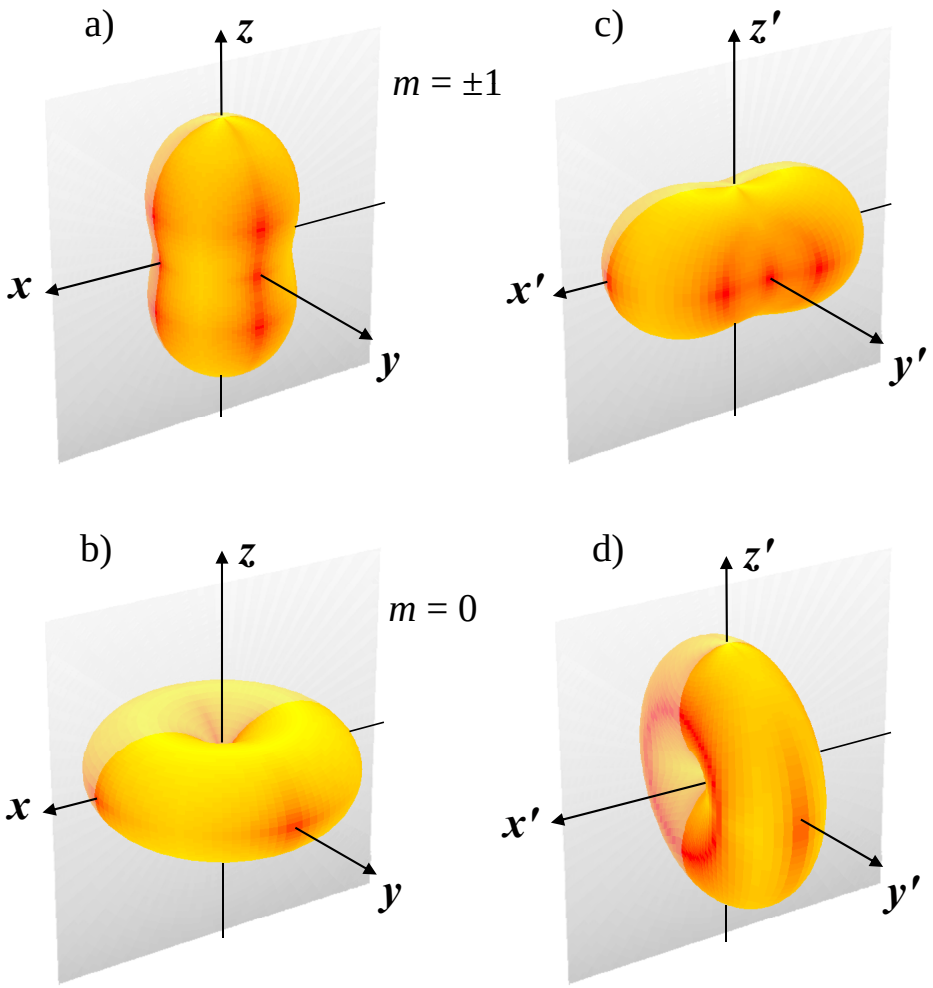

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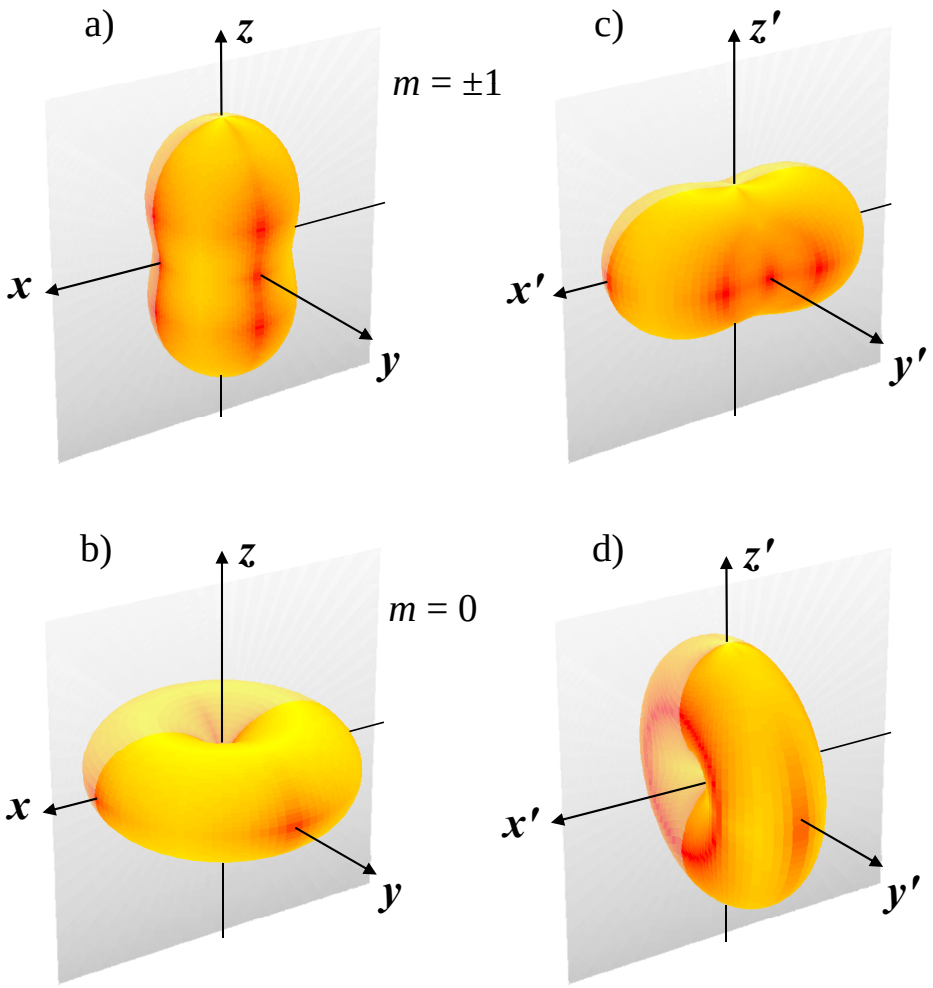
- integration over azimuth $\varphi \longrightarrow$ longitudinal dist^n (d) looks like



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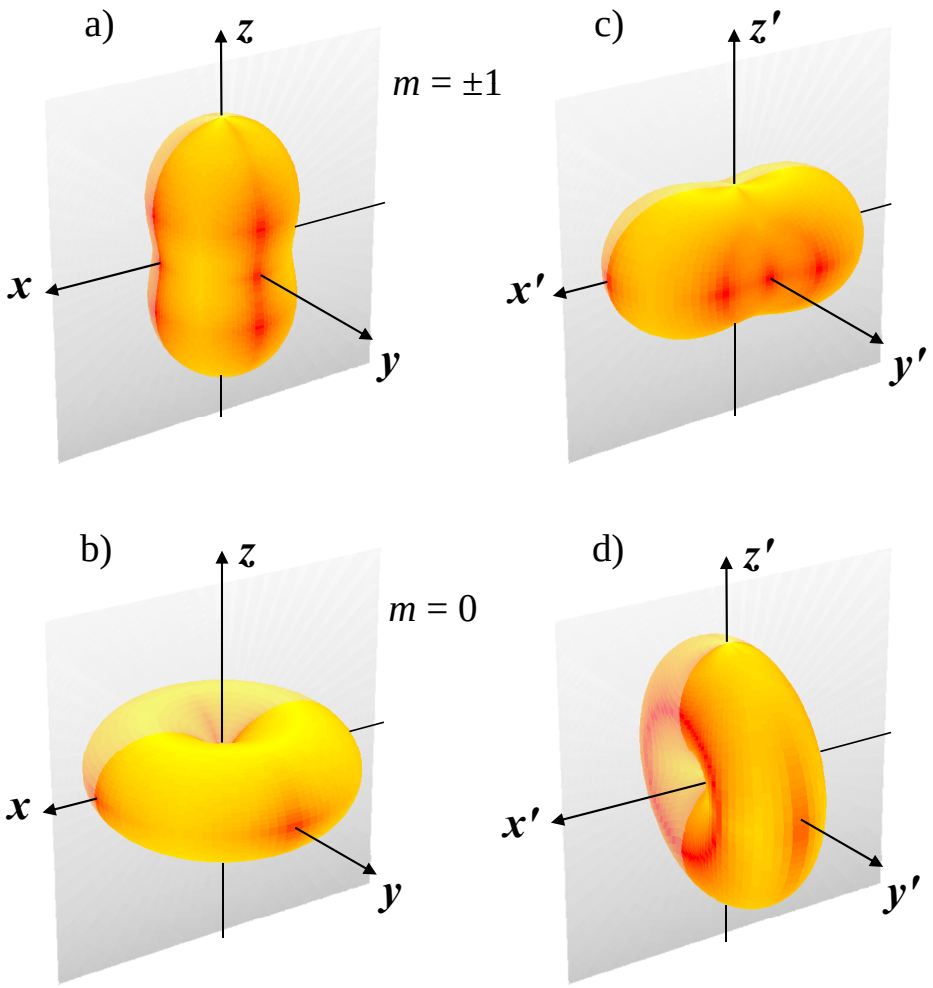
- integration over azimuth $\varphi \longrightarrow$ longitudinal dist^n (d) looks like *transverse* dist^n (a)



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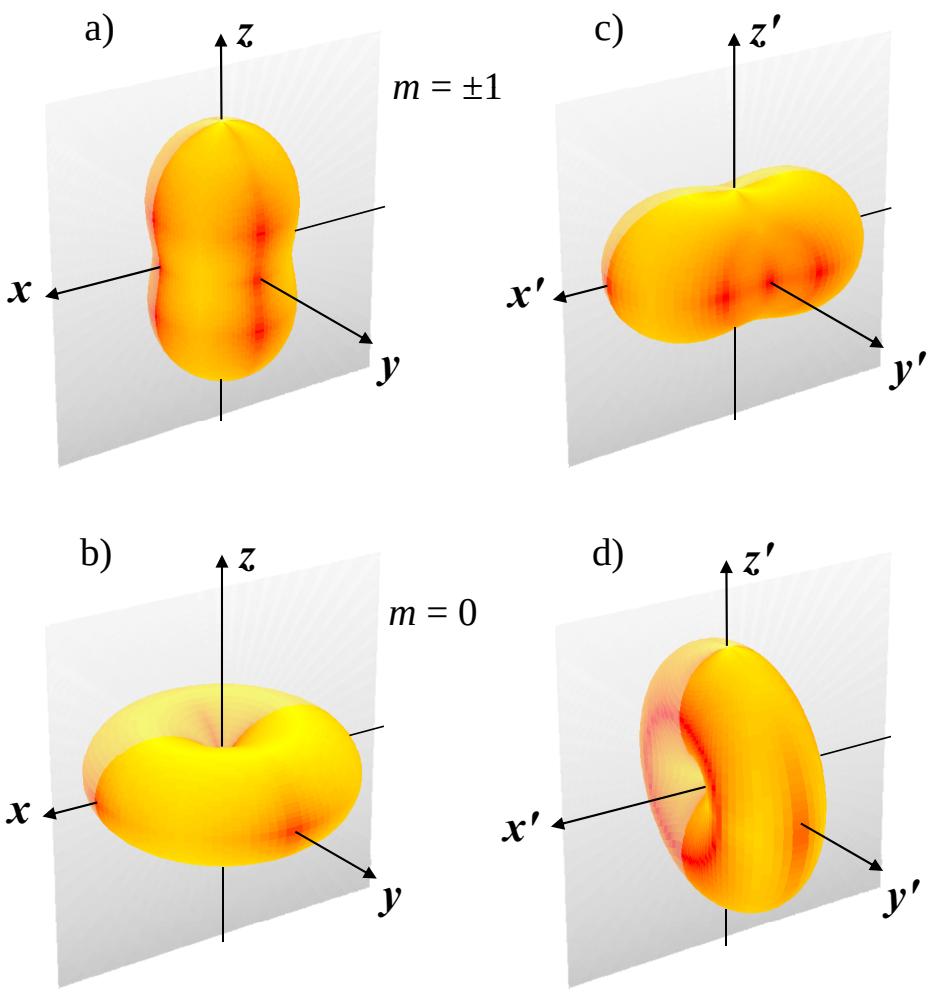

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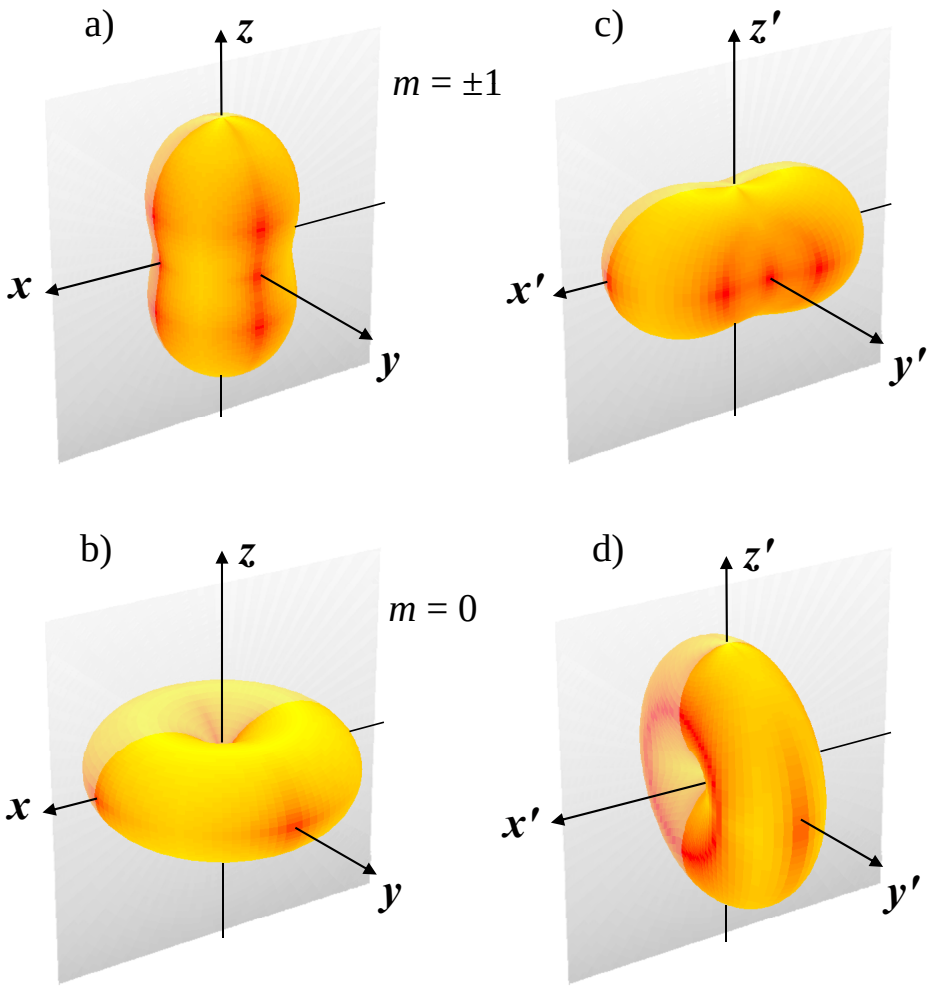
- λ_ϑ-only measurements (à la TeVatron Run I) can't be compared without assumptions about pol^n frame
- *experimental acceptance* is also typically a f^n of $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$



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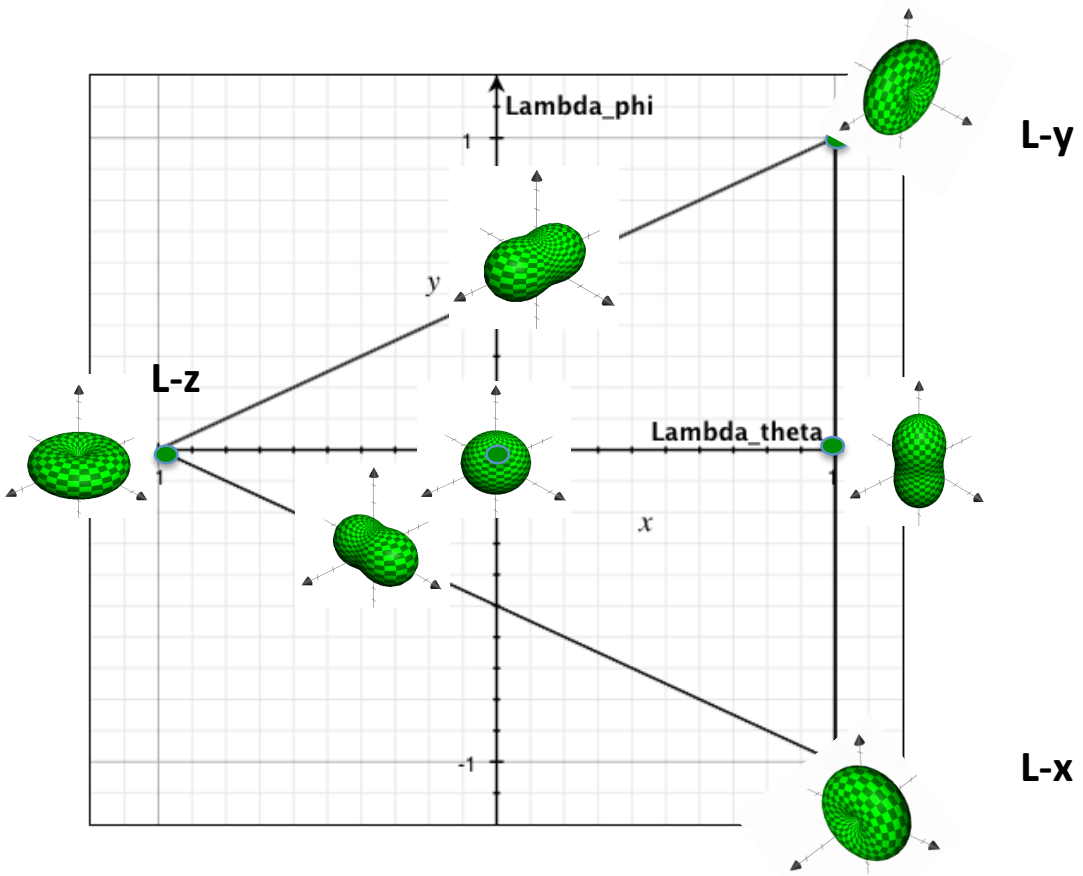
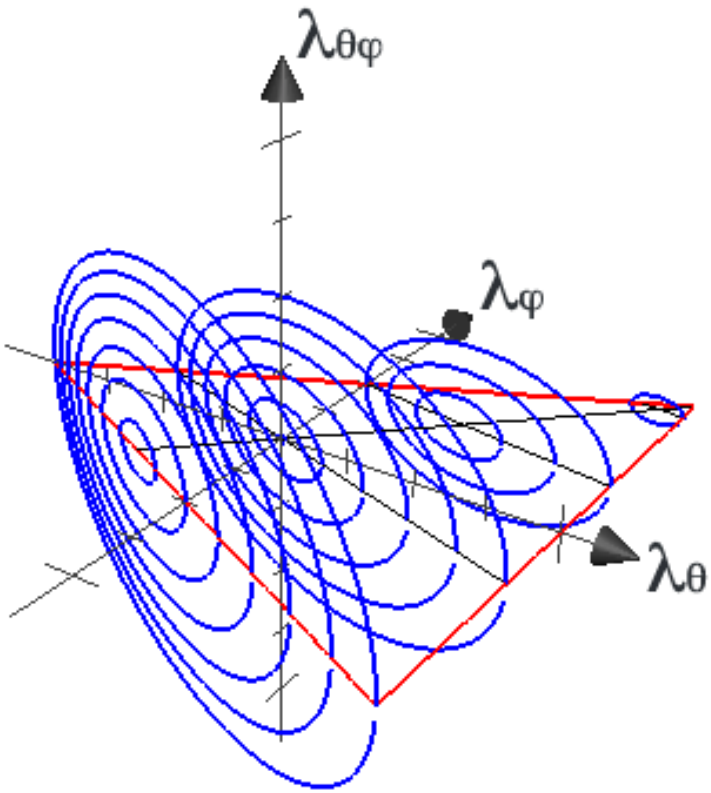
Sandro Palestini, Physical Review D 83, 031503(R) (2011)

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





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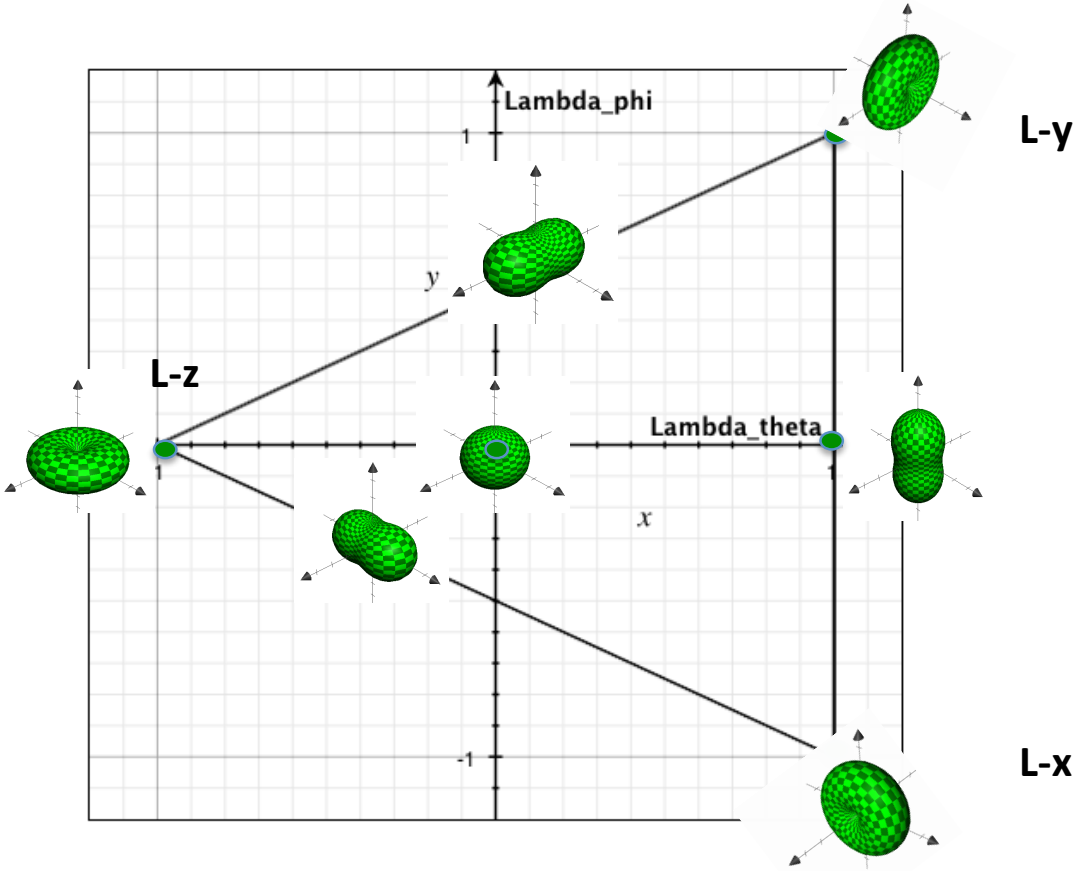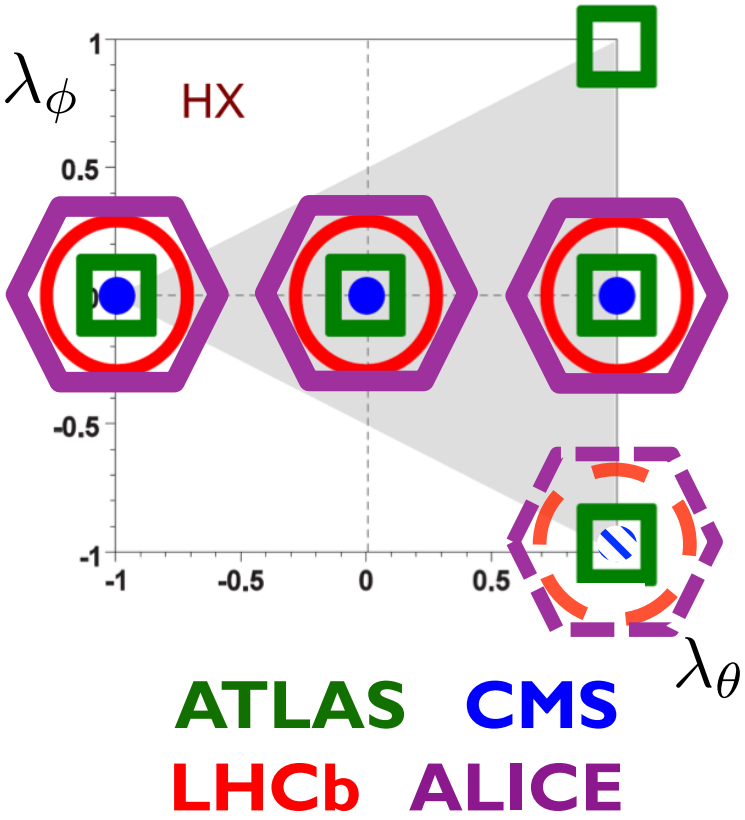
- limited range of $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$ values allowed
- LHC experiments quote results for each of a set of working points