Exotic Mesons: Measurements and Searches at ATLAS and CMS

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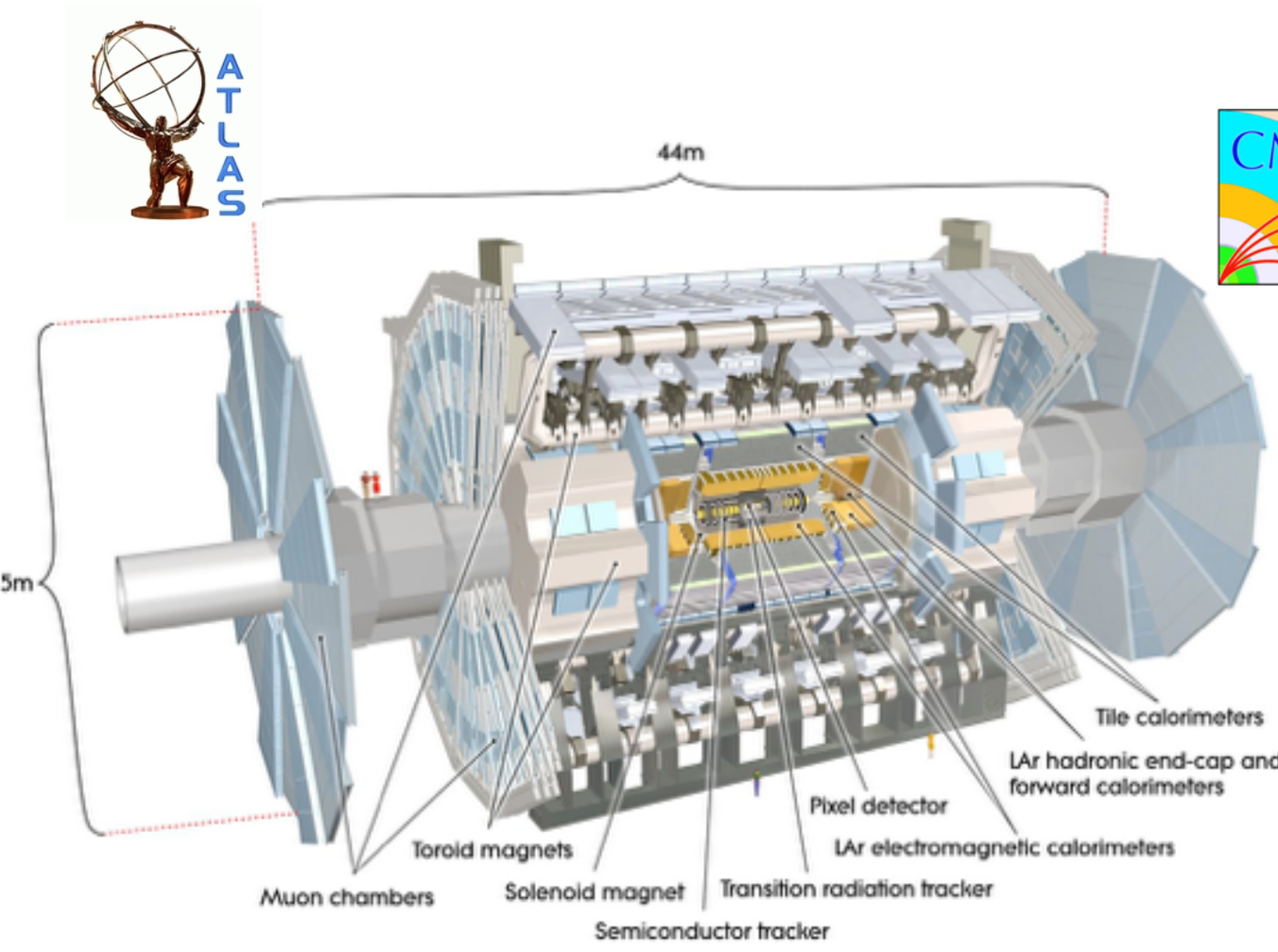
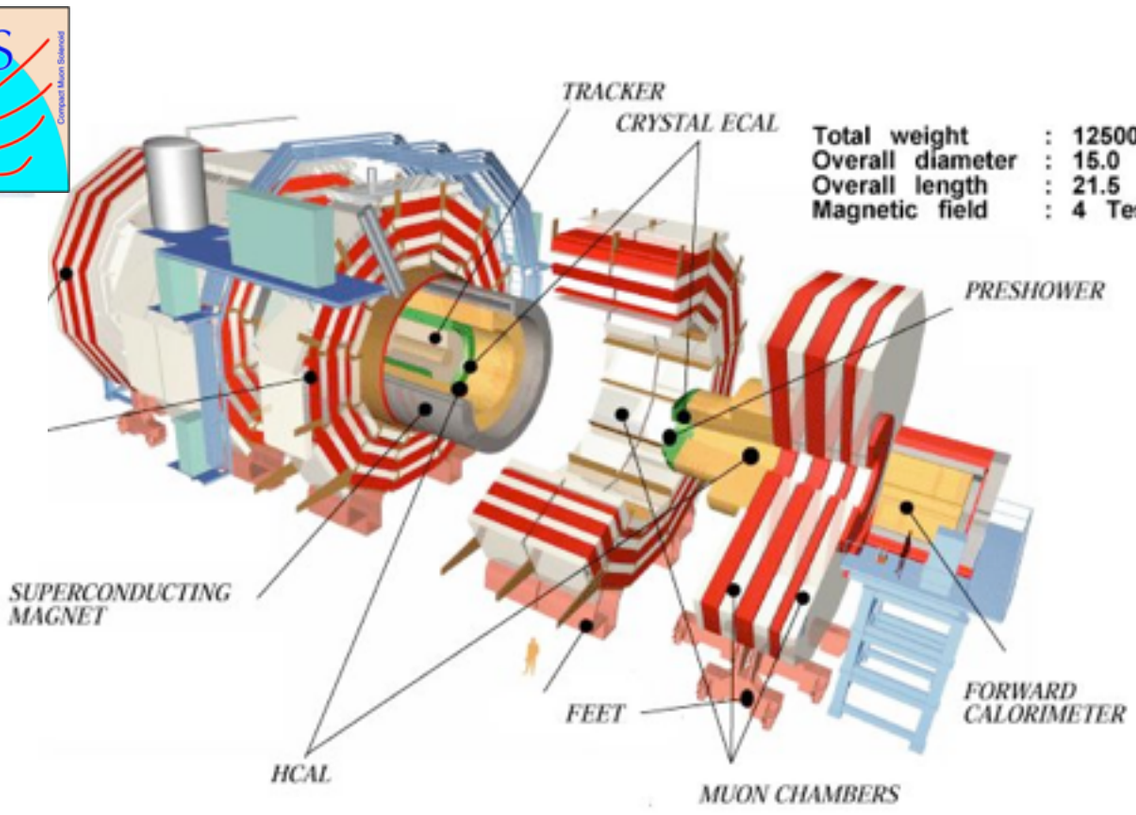
On behalf of the ATLAS and CMS Collaborations

23/07/2015 – EPS, Vienna

LHC GPD Detectors: ATLAS and CMS

- General Purpose Detectors





	ATLAS	CMS
Axial Magnetic field	2 T	3.8 T
Track momentum resolution σ/p_T^2 [GeV]$^{-1}$	~0.05%p_T + 0.015	~0.015%p_T + 0.005
Lifetime resolution	~100 fs	~70 fs
ID tracking $\lvert\eta_{max}\rvert$	2.5	2.5
Muon System $\lvert\eta_{max}\rvert$	2.7	2.4

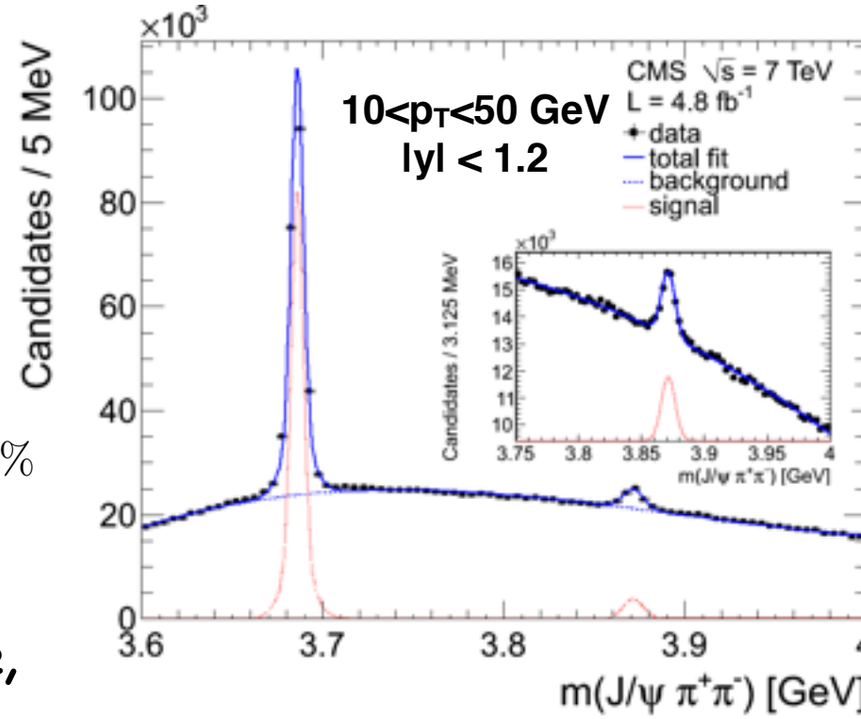
JHEP04(2013)154

X(3872) Production

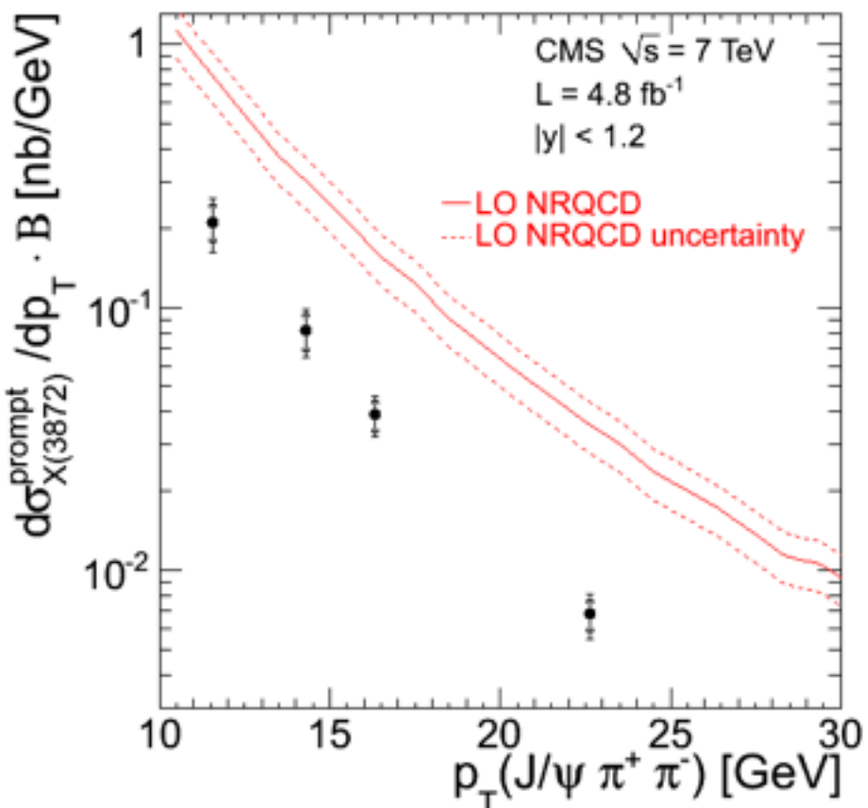
- CMS measurement of X(3872) production cross-section in the decay $J/\Psi\pi\pi$
  - Under assumptions of: Unpolarised, $J^{PC}=1^{++}$
- Inclusive ratio R: (in corrected region)

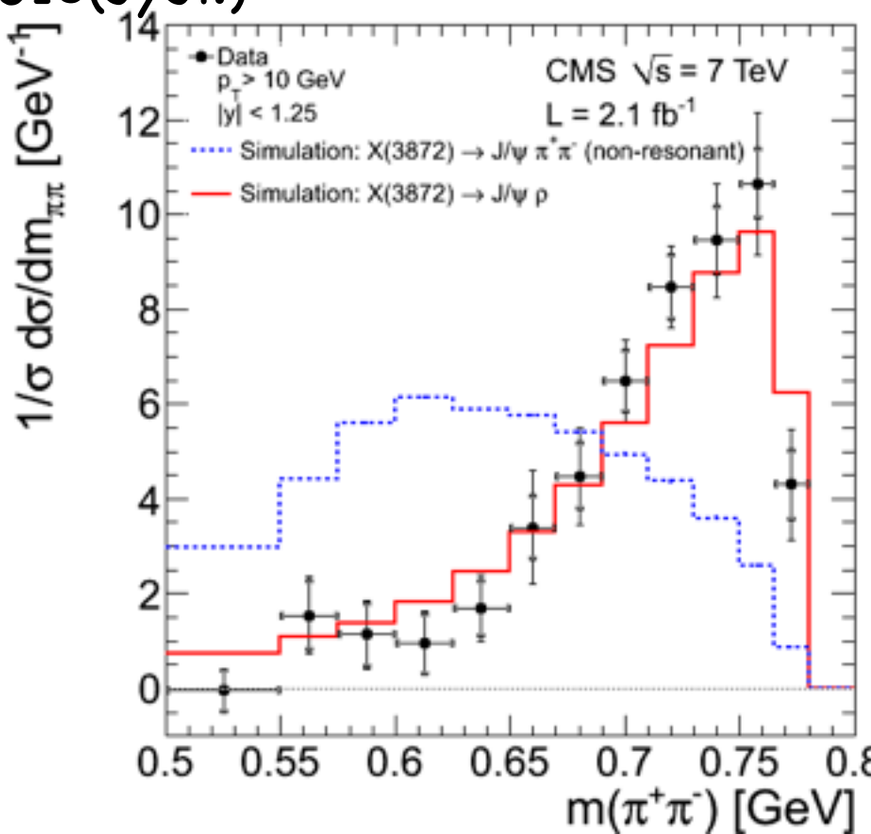
$$R = \frac{\sigma(\mathrm{pp} \to \mathrm{X}(3872) + \mathrm{anything}) \cdot \mathcal{B}(\mathrm{X}(3872) \to \mathrm{J}/\psi\pi^+\pi^-)}{\sigma(\mathrm{pp} \to \psi(2\mathrm{S}) + \mathrm{anything}) \cdot \mathcal{B}(\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^-)} = \quad (6.56 \pm 0.29\,(\mathrm{stat.}) \pm 0.65\,(\mathrm{syst.}))\%$$

  - Intermediate ρ^0 state favoured
- Prompt cross-section: NRQCD – reasonable in shape, – overestimation to data



- Average Non-prompt fraction 0.263±0.023(stat.)± 0.016(syst.)

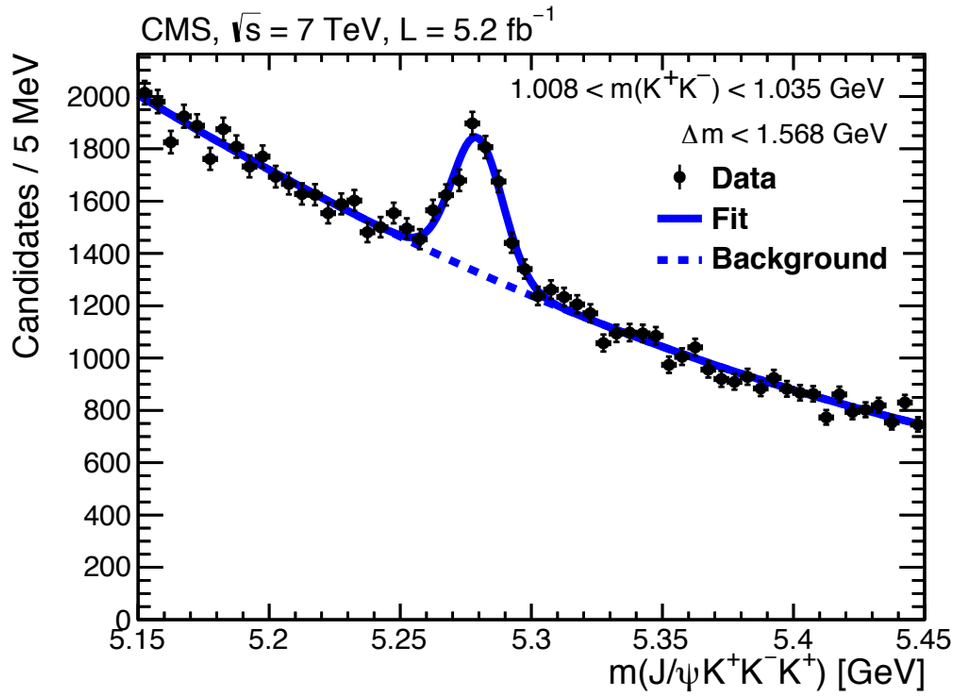


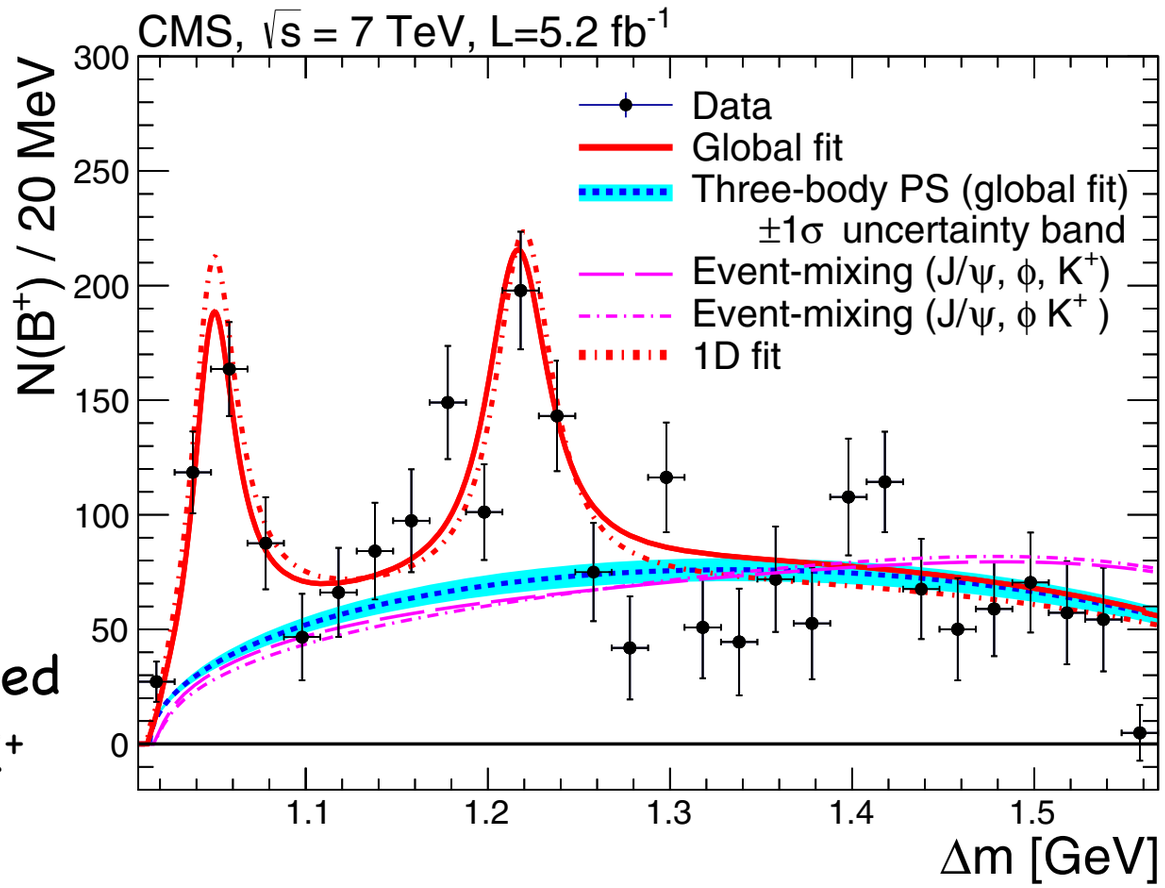


PLB 734(2014)261-281

Peaking Structures in Decays of $B^{\pm} \to J/\Psi \phi K^{\pm}$

- First seen at CDF: arXiv: 0903.2229v2
- Identified through 5-track vertex fit, m(J/Ψ) constraint,
  - 1008 < m(K^+K^-) < 1035 MeV, using KK combination with min. mass.
- Analysis performed in bins of rel. eff. corrected $\Delta m = m(\mu\mu KK) - m(\mu\mu)$; $B^{\pm}$ yields in 20MeV slices
- Observation (>5σ) of peaking structure at:
  - M = 4148.0 ± 2.4 (stat.) ± 6.3 (syst.) MeV
  - Γ = 28^{+15}_{-11} (stat.) ± 19 (syst.) MeV
- First structure consistent with X(4140)
  - and rel. Br = 0.1±~0.3, consistent with CDF and LHCb upper limits.
- Evidence of second structure at:
  - M = 4313.8 ± 5.3 (stat.) ± 7.3 (syst.) MeV
  - Γ = 38^{+30}_{-15} (stat.) ± 16 (syst.) MeV
    - Possible complications from φK resonances
- Full amplitude analysis for J/ΨKKK needs increased statistics and improved knowledge on φK^+ or $J/\psi K^+$ resonances,





Search for Exotic Bottomonium-like States

- X_b : Analogue of X(3872) expected in bottomonium sector
  - Various theoretical models / approaches to explore sector
    - 10,562 GeV ($B\bar{B}$) , 10,604 GeV ($B\bar{B}^*$) thresholds
    - Alternative possibilities also allowed in ranges 10 – 11 GeV.

- CMS: $\sqrt{s}$ = 8 TeV, L = 20.7 fb^{-1} ; PLB 727 (2013) 57–76
- ATLAS: $\sqrt{s}$ = 8 TeV, L = 16.2 fb^{-1} ; PLB 740 (2015) 199–217

  - ATLAS and CMS performed search for X_b in the decays of $\Upsilon(1S)\pi\pi$
    - cf: X(3872) to $J/\Psi\pi\pi$: Branching Ratio of 6.56% relative to $\Psi(2S)$ to $J/\Psi\pi\pi$

$$R = \frac{\sigma(\mathrm{pp} \to X_b \to \Upsilon(1\mathrm{S})\pi^+\pi^-)}{\sigma(\mathrm{pp} \to \Upsilon(2\mathrm{S}) \to \Upsilon(1\mathrm{S})\pi^+\pi^-)} = \frac{\sigma \cdot \mathcal{B}}{\sigma_{2\mathrm{S}} \cdot \mathcal{B}_{2\mathrm{S}}}$$

ATLAS search also for $\Upsilon(1^3D_J)$, $\Upsilon(10860)$ and $\Upsilon(11020)$

Sample Selection

- Selection optimised to maximise expected significance near Υ(2S)

	ATLAS	CMS	
$p_T(\Upsilon(1S)\pi\pi) >$	**5**	**13.5**	GeV
$\lvert y(\Upsilon(1S)\pi\pi)\rvert <$	**2.4**	**2.0**	
$\chi^2(\Upsilon(1S)\pi\pi) <$	20	P>10%	
$p_T(\mu) >$	4	2.5	GeV
$\lvert\eta(\mu)\rvert <$	2.3	2.1	
$p_T(\mu\mu) >$	–	**13.5**	GeV
$\lvert y(\mu\mu)\rvert <$	–	2.0	
$\chi^2(\mu\mu) <$	100	P>1%	
$p_T(\pi) >$	400	400	MeV
$\lvert\eta(\pi)\rvert <$	2.5	2.5	
$p(\chi^2(\pi\pi)) >$	–	10%	
$\Delta R(\pi, \Upsilon(1S)) <$	**–**	**0.7**	

- For efficiency determinations, MC is reweighted to CLEO di-pion mass distributions.
- Central results is presented under assumption of zero polarisation (isotropic).
  - Variations of spin-alignment envelope considered:
    - CMS: systematic from fully transverse or longitudinal.
    - ATLAS: reassessed for different spin-alignment hypotheses.
  - All candidates passing selections retained in analysis
    - CMS: ~2.3 candidates per-event
    - ATLAS: ~19.5 candidates per-event

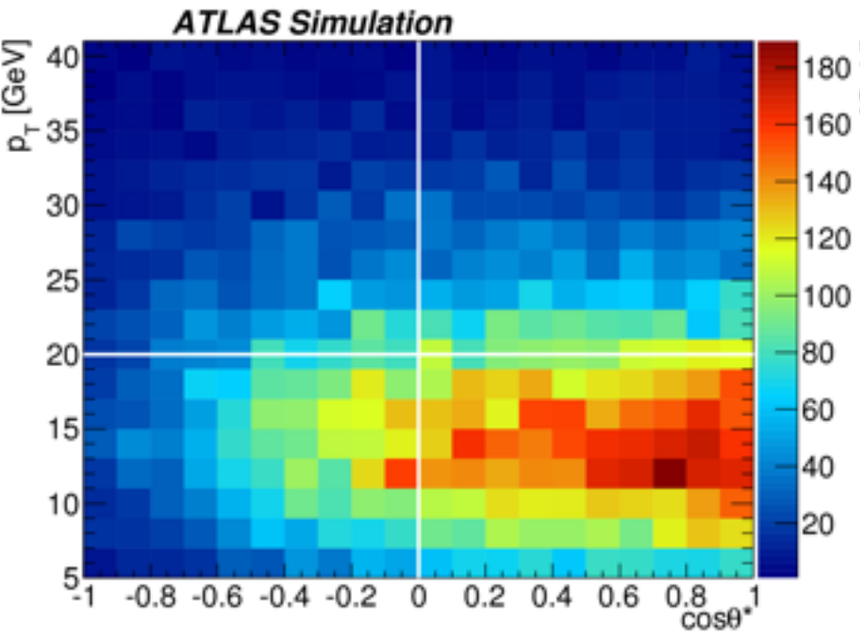
Sensitivities (I)

- ATLAS studied data according to:
  - cos θ* vs pT(Υ(1S)ππ)
    - Retain all data,

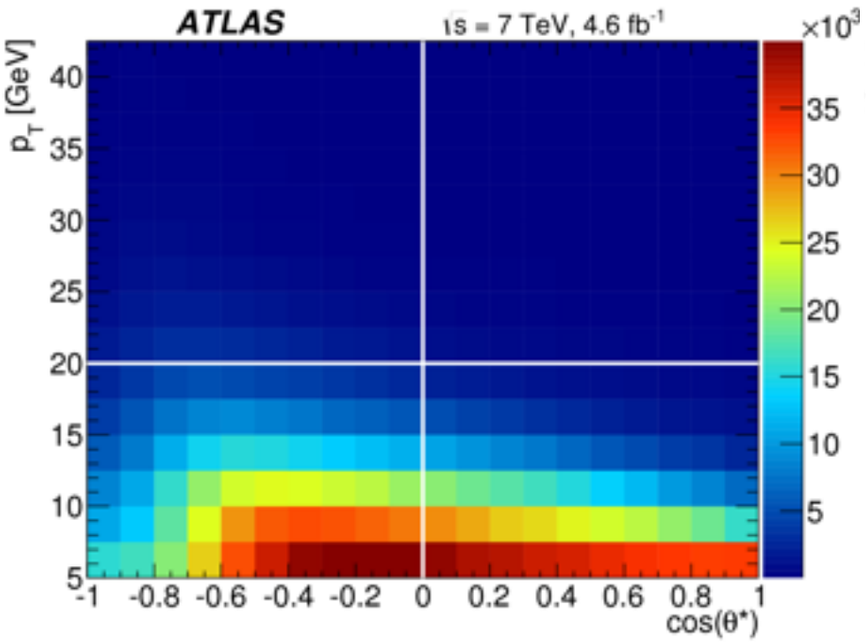
- maximise significance for weak signal at M = 10.561 GeV

- θ* angle between di-pion momentum in parent rest-frame and parent lab-momentum

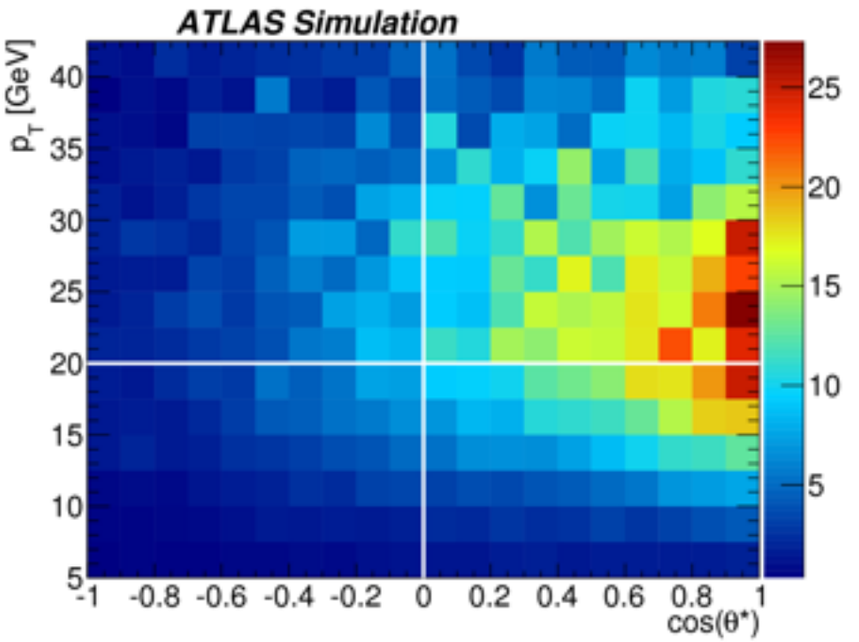
M = 10.561 GeV



Background

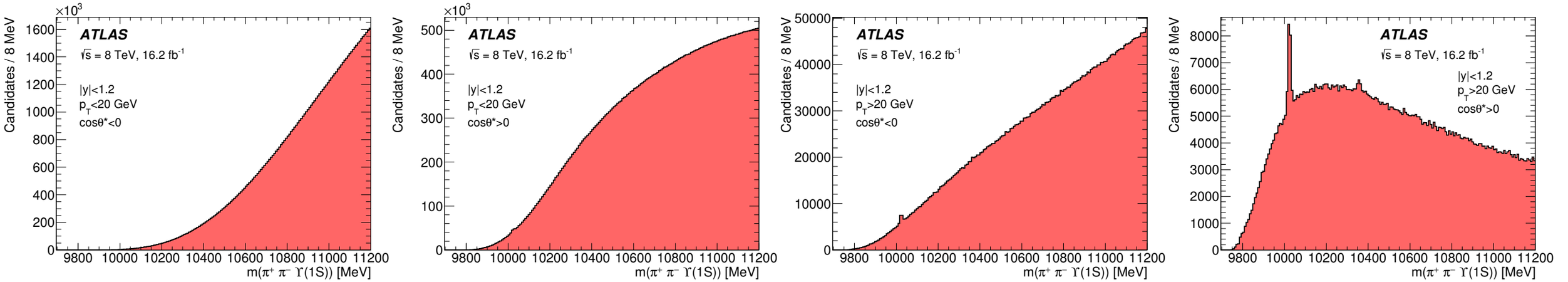


Significance



Sensitivities (II)

- Data sample separated into 2^3 regions:
  - 2x Rapidity:
    - Mass resolution varies with parent rapidity |y| due to detector effects
  - 2x pT:
  - 2x cos θ^*;
- highest S/B at high-pT, large cos θ^*, small |y|
- Simultaneous fits to all regions

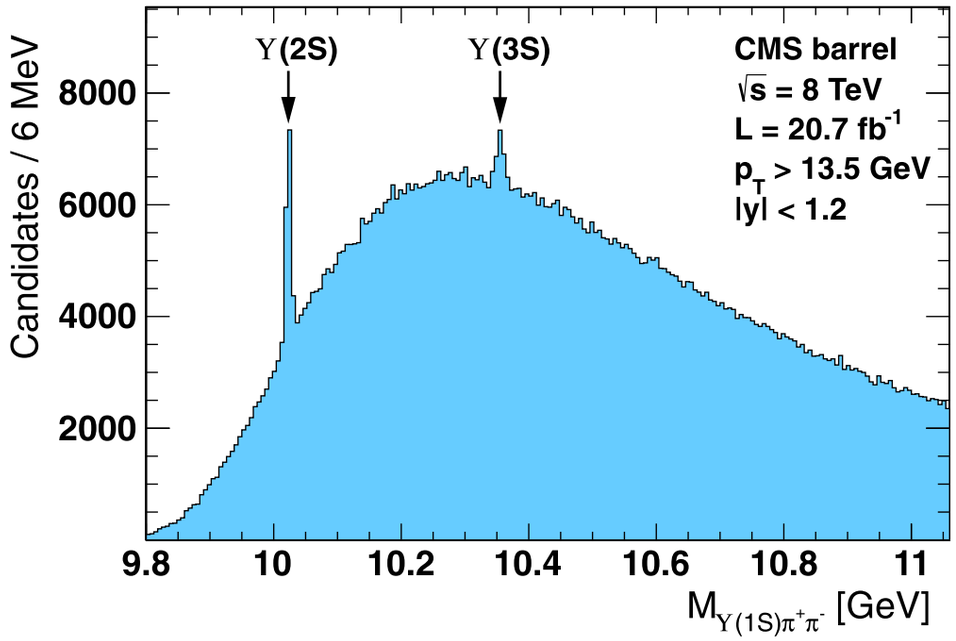


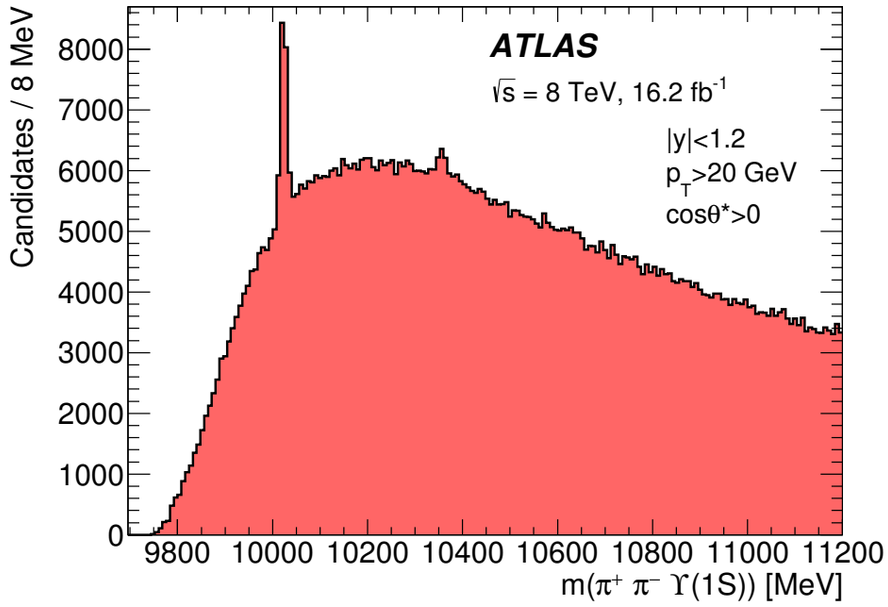
(a) Barrel, low p_{T}, low $\cos\theta^*$ **(b)** Barrel, low p_{T}, high $\cos\theta^*$ **(c)** Barrel, high p_{T}, low $\cos\theta^*$ **(d)** Barrel, high p_{T}, high $\cos\theta^*$

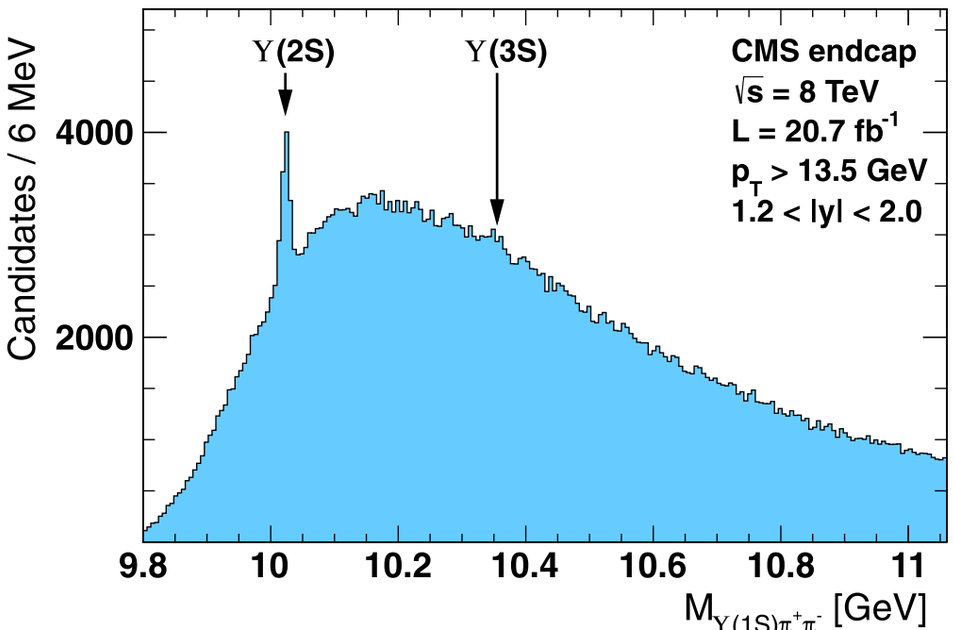
(e) Endcap, low p_{T}, low $\cos\theta^*$ **(f)** Endcap, low p_{T}, high $\cos\theta^*$ **(g)** Endcap, high p_{T}, low $\cos\theta^*$ **(h)** Endcap, high p_{T}, high $\cos\theta^*$

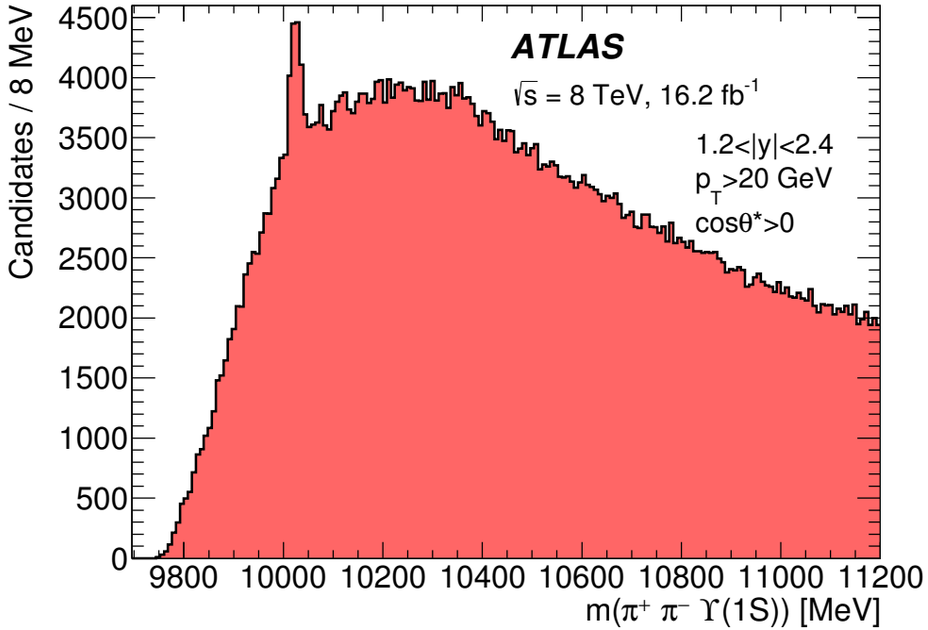
Mass Distributions

- Selected Υ(1S)ππ distributions for the central and forward regions of the detectors (ATLAS shown for most sensitive pT and cos θ* bins).
  - Clear Υ(2S) and Υ(3S)
    - No obvious additional structures seen.







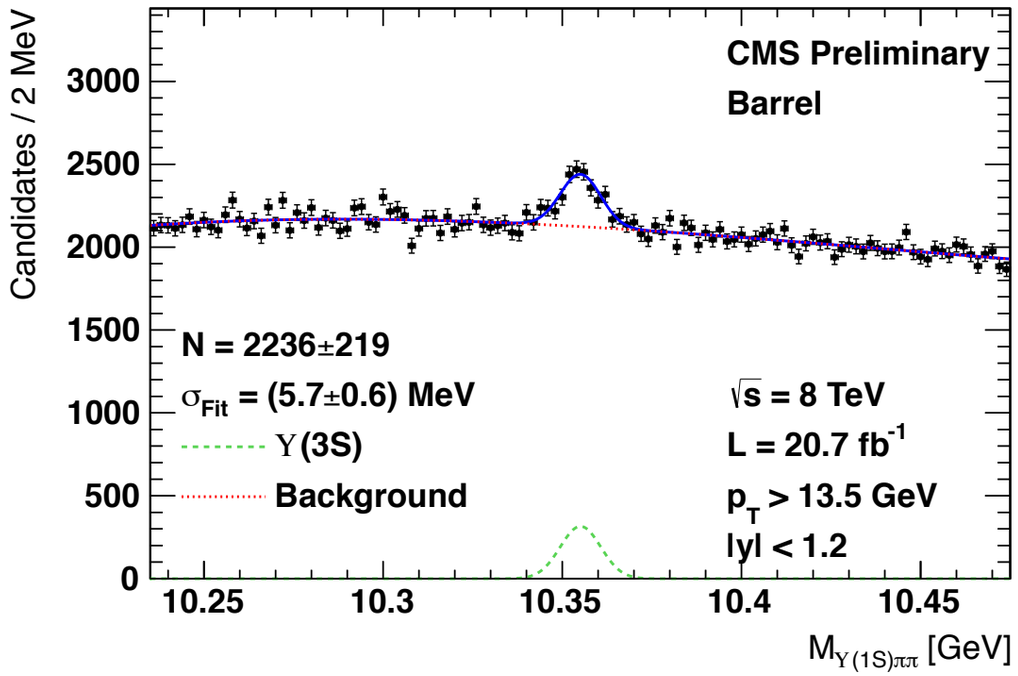


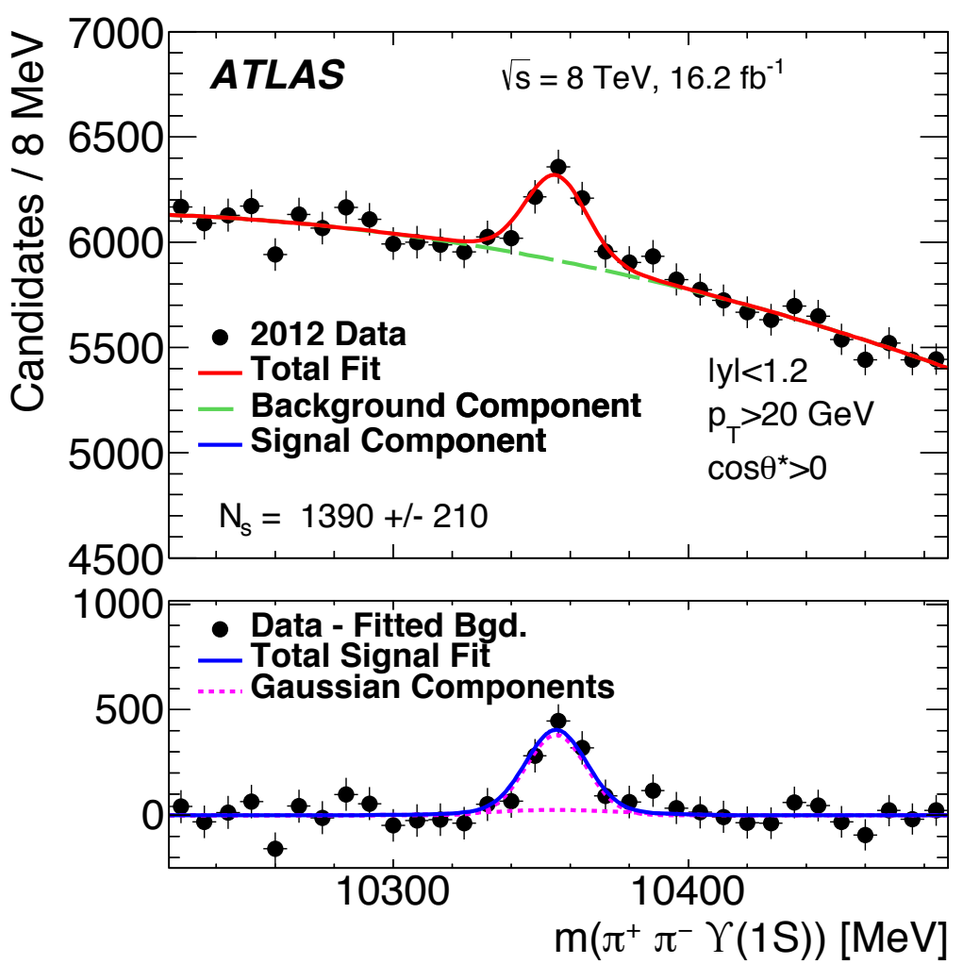
Signal Extraction

$$R = \frac{\sigma(\mathrm{pp} \to X_b \to \Upsilon(1\mathrm{S})\pi^+\pi^-)}{\sigma(\mathrm{pp} \to \Upsilon(2\mathrm{S}) \to \Upsilon(1\mathrm{S})\pi^+\pi^-)} = \frac{\sigma \cdot \mathcal{B}}{\sigma_{2\mathrm{S}} \cdot \mathcal{B}_{2\mathrm{S}}}$$

$$N^{\mathrm{obs}}_{\mathrm{X_b}} = R \times N^{\mathrm{obs}}_{\Upsilon(2\mathrm{S})} \times \frac{\epsilon_{\mathrm{X_b}}}{\epsilon_{\Upsilon(2\mathrm{S})}}$$

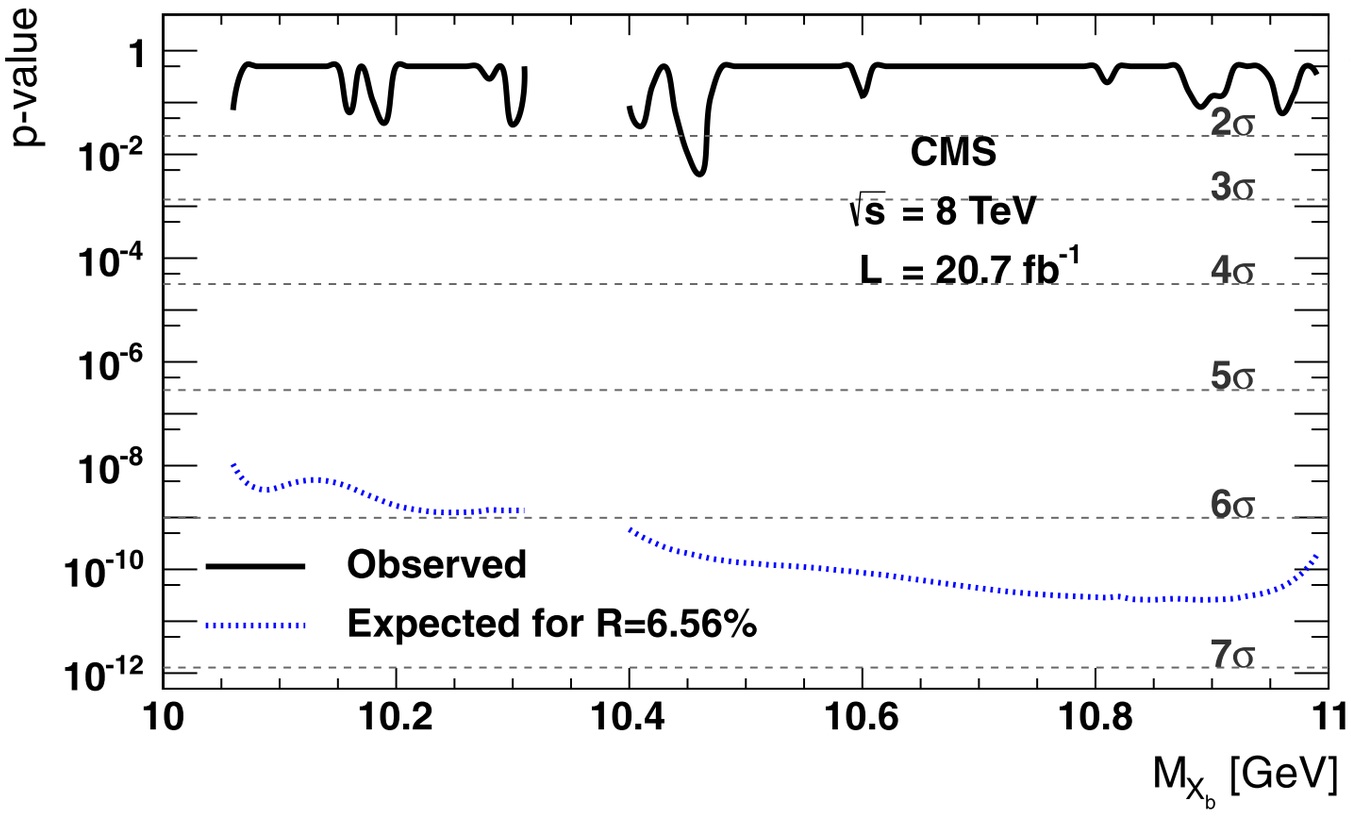
- Efficiency x Acceptance corrections from MC
- Perform hypothesis test, 10 MeV intervals: ~10-11 GeV (veto Υ(2,3S))
  - Signal shape parameters fixed to simulation;
    - signal strength allow to float
- Normalised to Υ(2S) yields:
  - validated on Υ(3S) :
    - ATLAS: predicted: 11,400 ± 1,500
    - ATLAS: fitted: 11,600 ± 1,300
- ATLAS: Fit is performed simultaneously to the 8 (2x2x2) |y|,pT,cosθ* bins

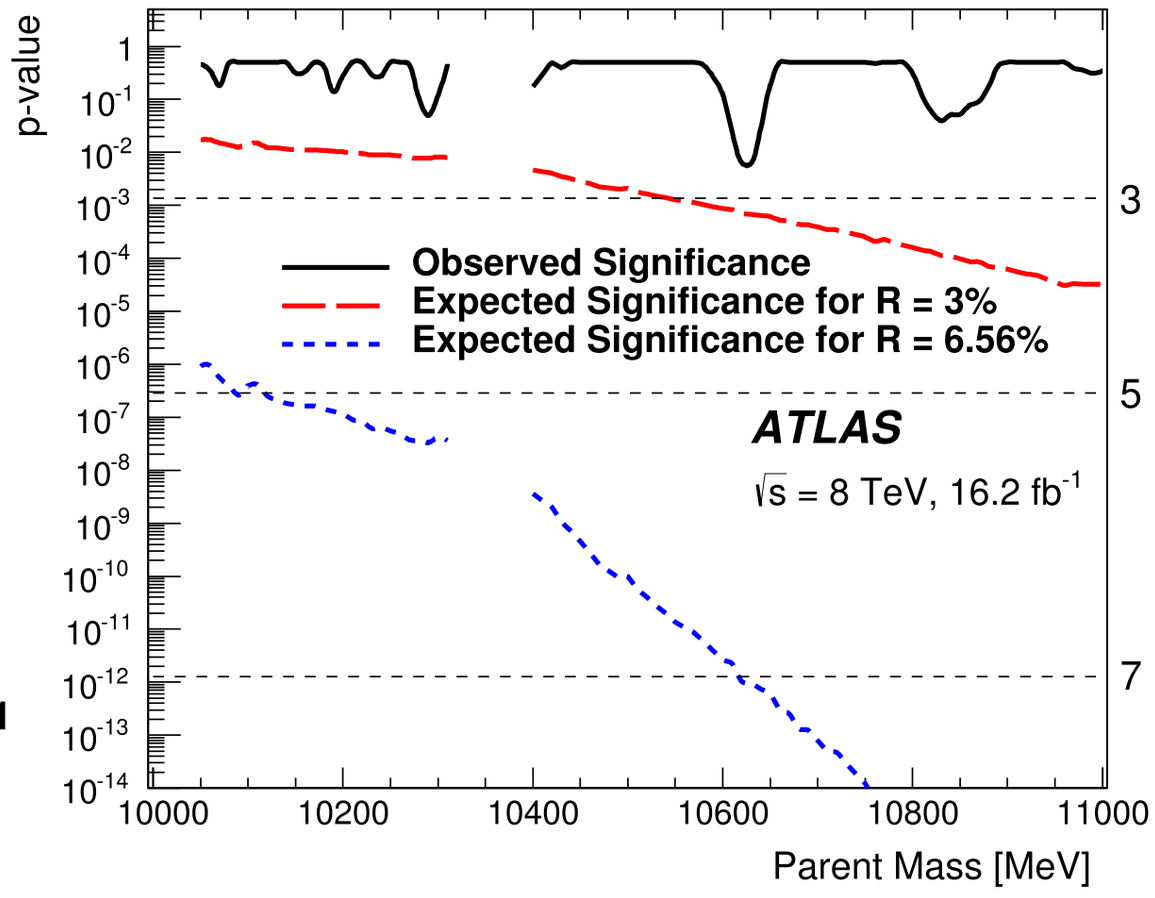




Results

- Local p-value significance (background-only hypothesis) and expected values for analogous X(3872) Branching ratio R, and weaker (3%) value (ATLAS).

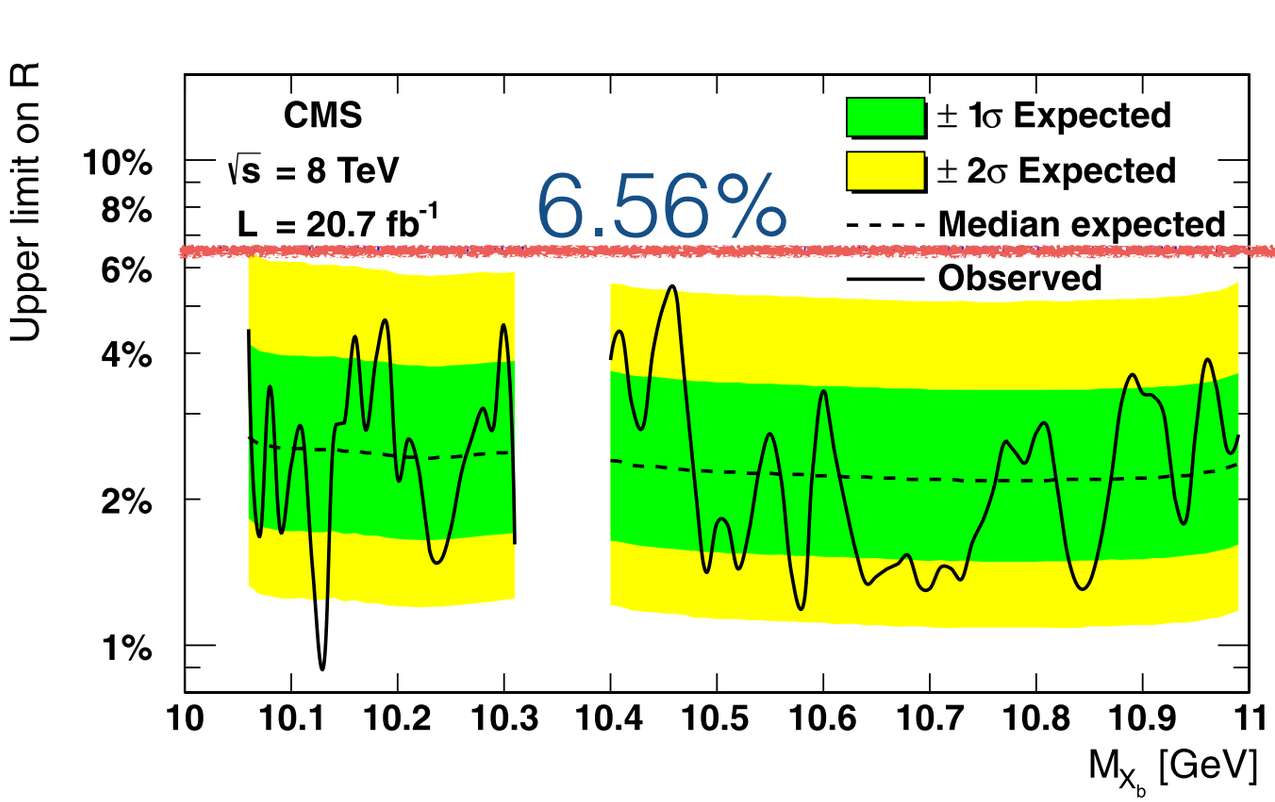


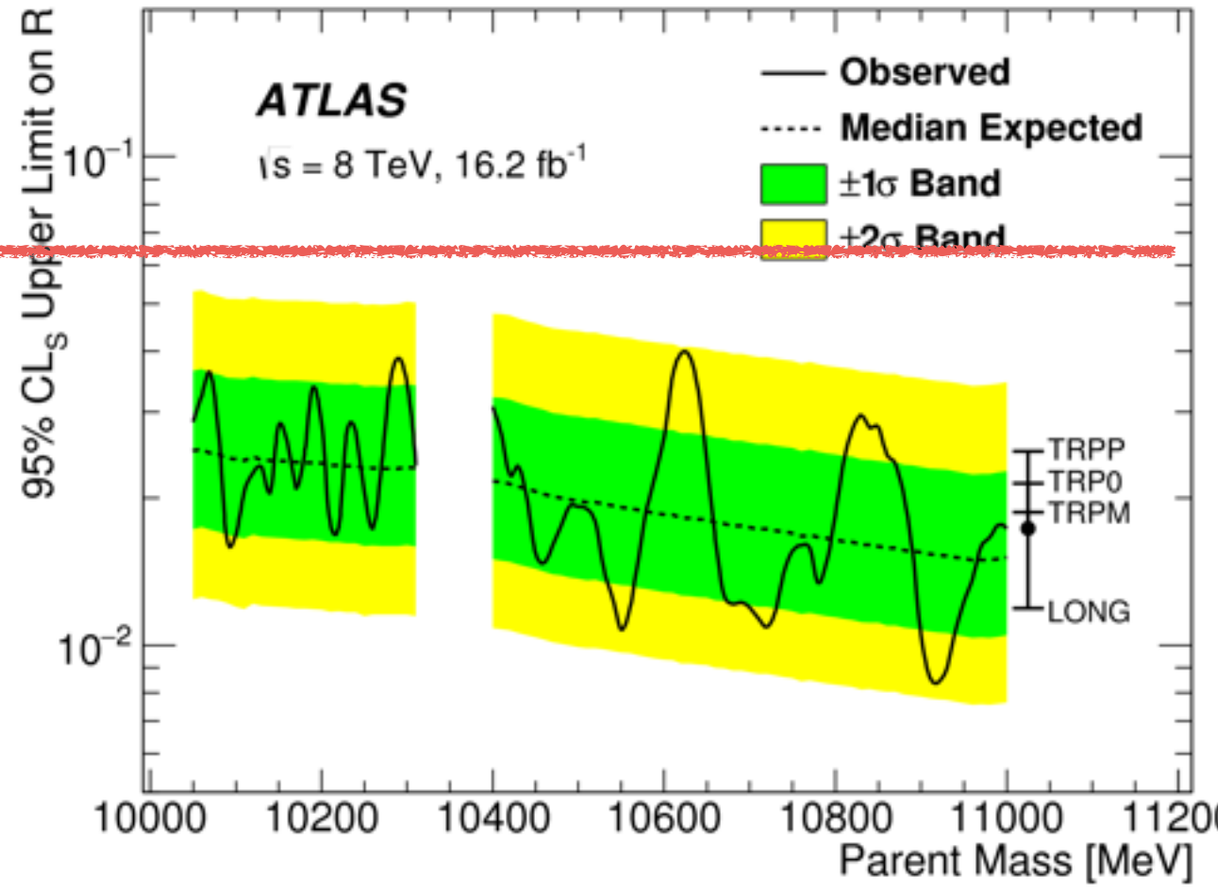


- Expected significance for R = 6.56% exceeds 5σ across range.
  - CMS - largest statistical significance of 0.8σ, including 'look-elsewhere-effect'

Production Rate Upper Limits

- In absence of signal, upper limits on relative production rates are set:





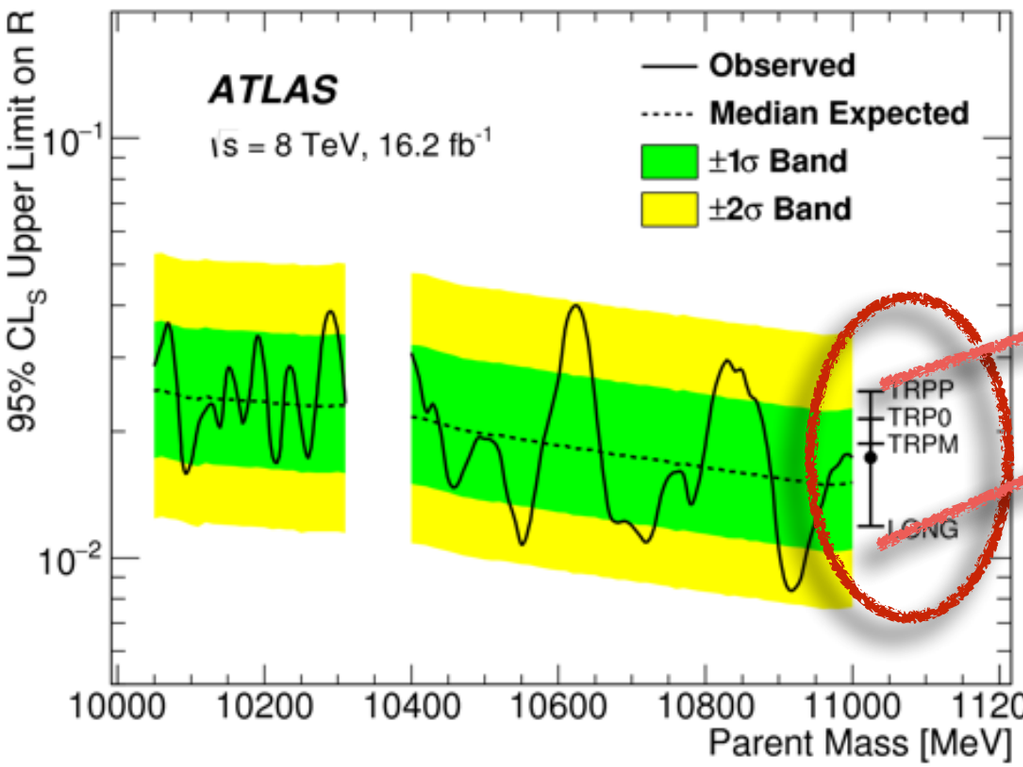
- Upper limits on the production rate R (relative to the $\Upsilon(2S)$ rate):
  - CMS: 0.9 – 5.4 % (m > 10.06 GeV)
  - ATLAS: 0.8 – 4.0% (m >10.1 GeV)
    - at 95% CL_s. ($\Upsilon(2S)$ and $\Upsilon(3S)$ mass regions excluded).
- Increased sensitivity with increasing mass for ATLAS data due to splitting up of data (most sensitive bin with falling background mass-shape)

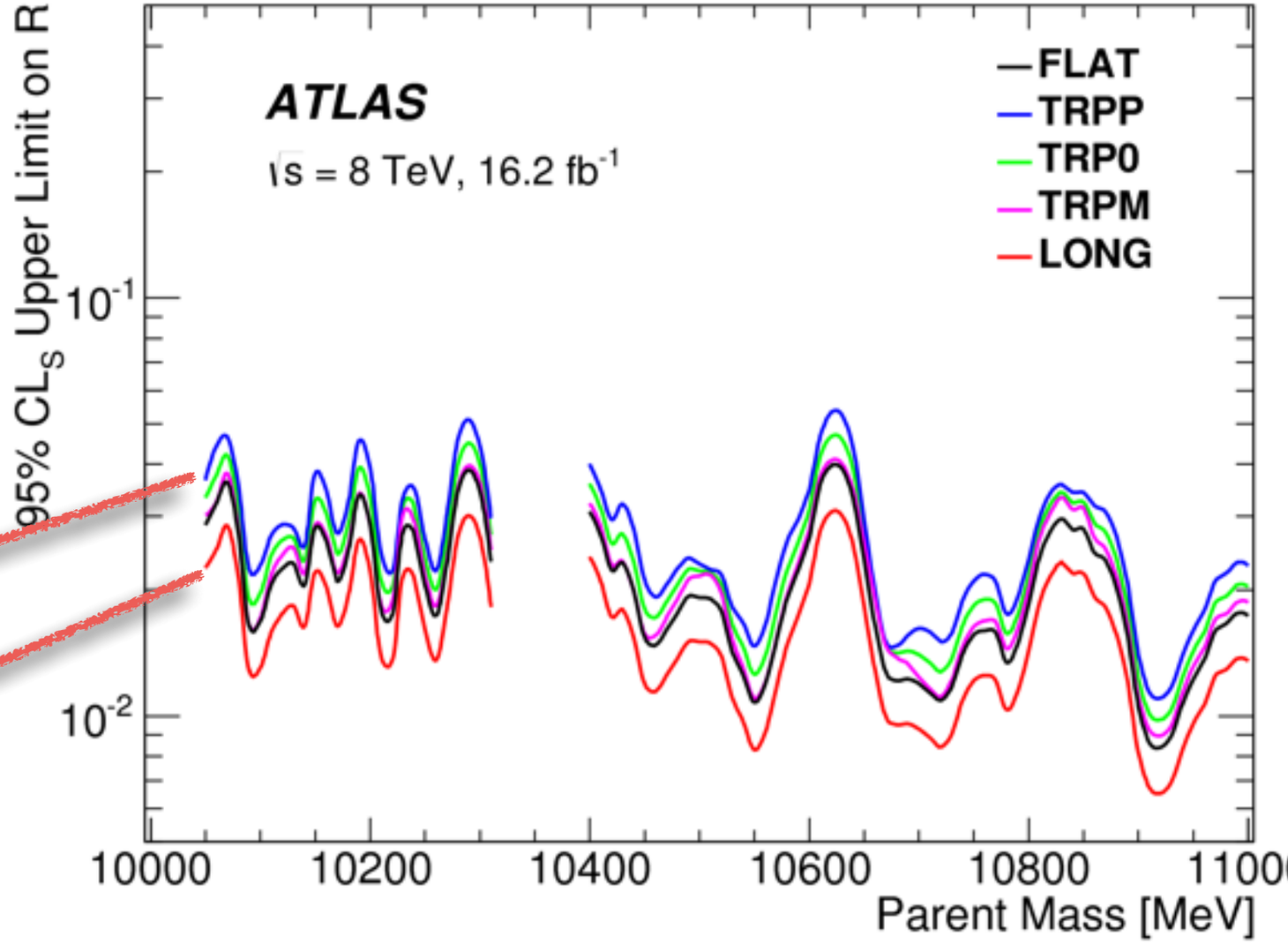
Limits under Spin-Alignment Variation

- Υ(2S) measured to have negligible polarisation, arXiv:1209.2922
  - expected that produced Υ(1S) similarly polarised.
- X_b however is unknown.

- ATLAS presents upper limits for longitudinal and three transverse spin-alignment scenarios.

- CMS assigns 25% systematic –
  - MC Eff. differences between fully trans. and fully long.





d

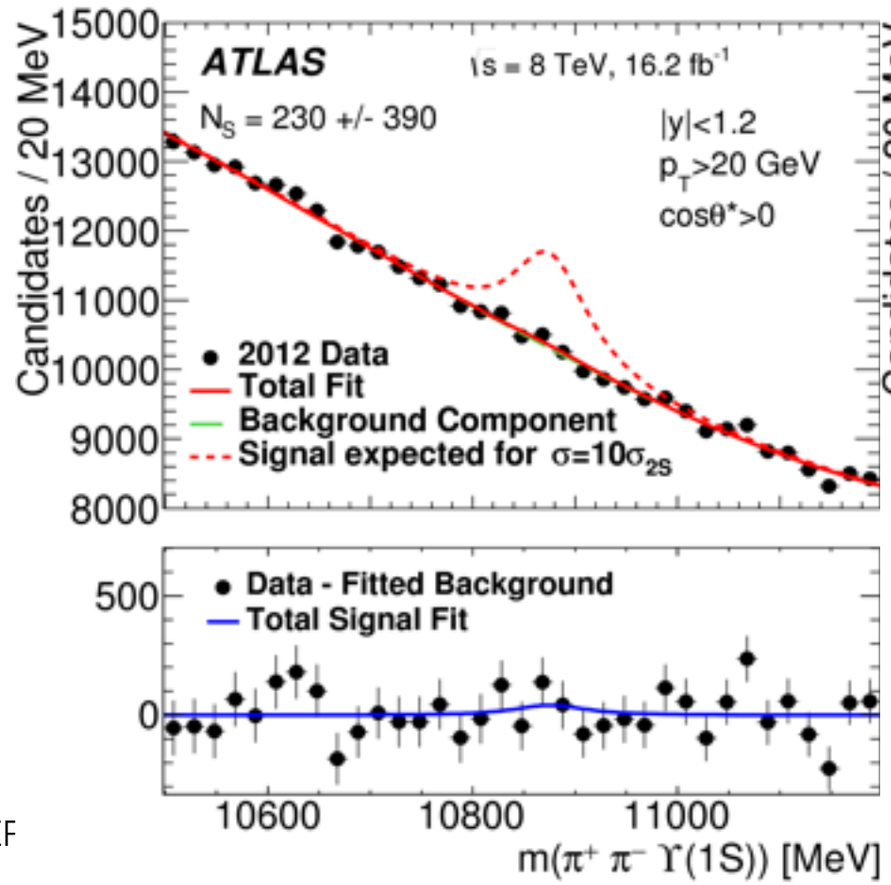
Search for $\Upsilon(1^3D_J)$, $\Upsilon(10860)$ and $\Upsilon(11020)$

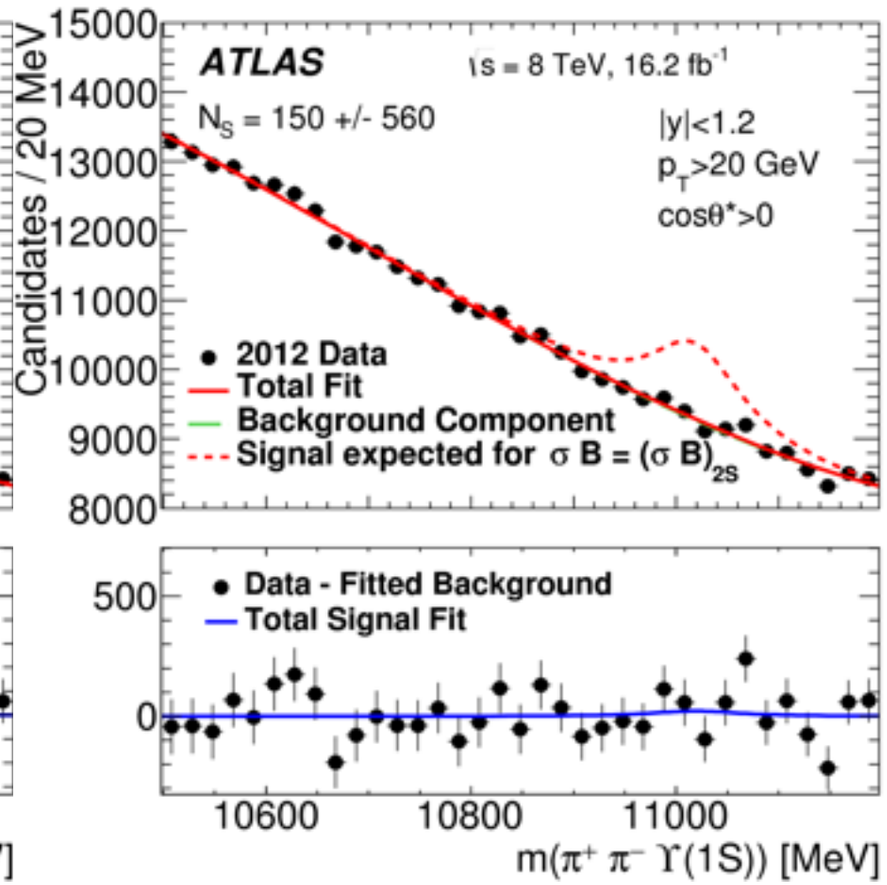
- $\Upsilon(1^3D_J)$ triplet fit attempted with additional signal shapes for the three masses: 10,156, 10,164, and 10,170 MeV.
  - **No excess of events over background observed.**
    - Upper limit of relative cross-section: $\sigma(\Upsilon(1\,^3D_J)) / \sigma(\Upsilon(2S)) < 0.55$.
      - (using $Br(\Upsilon(1\,D_J) \to \Upsilon(1S)\pi\pi = (6.6\pm1.6)\times10^{-3}$)

- Broad resonances $\Upsilon(10860)$ and $\Upsilon(11020)$ searched for in grid of mass and width, (using world-average masses and uncertainties).
  - largest significances of z=1.1 and 0.6 found,

- **No evidence for the production of $\Upsilon(10860)$ of $\Upsilon(11020)$.**

- Plots shown with rates
  $\sigma_{10860} = 10\sigma(2S)$
  $\sigma_{11020} = \sigma(2S)\times B(2S)$





Summary

- In the production and decays of Exotic mesons at ALTAS and CMS:
- CMS reports: JHEP04(2013)154
  - Measurement of inclusive, and prompt differential cross-section of X(3872), and NPF.
  - Measurement of peaking structure in $B^{\pm} \rightarrow J/\Psi\varphi K^{\pm}$ PLB 734(2014)261-281
    - Mass consistent with previously observed X(4140).

- ATLAS and CMS present limits:
  - search for X_b in the decays of $\Upsilon(1S)\pi\pi$
    - CMS: PLB 727 (2013) 57–76
    - ATLAS: PLB 740 (2015) 199–217
- No evidence of Narrow resonance that decays into $\Upsilon(1S)\pi\pi$
  - Upper limit on Production Ratio set (95% CL):
    - 0.9–5.4% (CMS) and 0.8–4.0% (ATLAS) dependent on mass.
      - Analogous value R=6.56% excluded.
  - Limit calculations under spin-alignment scenarios computed
      - No evidence for $\Upsilon(1^3D_J)$, $\Upsilon(10860)$ and $\Upsilon(11020)$

- Expected isospin suppression of $\Upsilon(1S)\pi^+\pi^-$ limit yields (cf X(3872)),
  - Isospin allowed modes present greater challenges to GPD detectors (low acceptance)
- Turn over all 'stones', revisit $\chi_b(3P)$ for possible mixing scenarios.

M. Karliner, J. Rosner, PRD91 (2015) 014014; 1410.77293 [hep-ph]

Backup

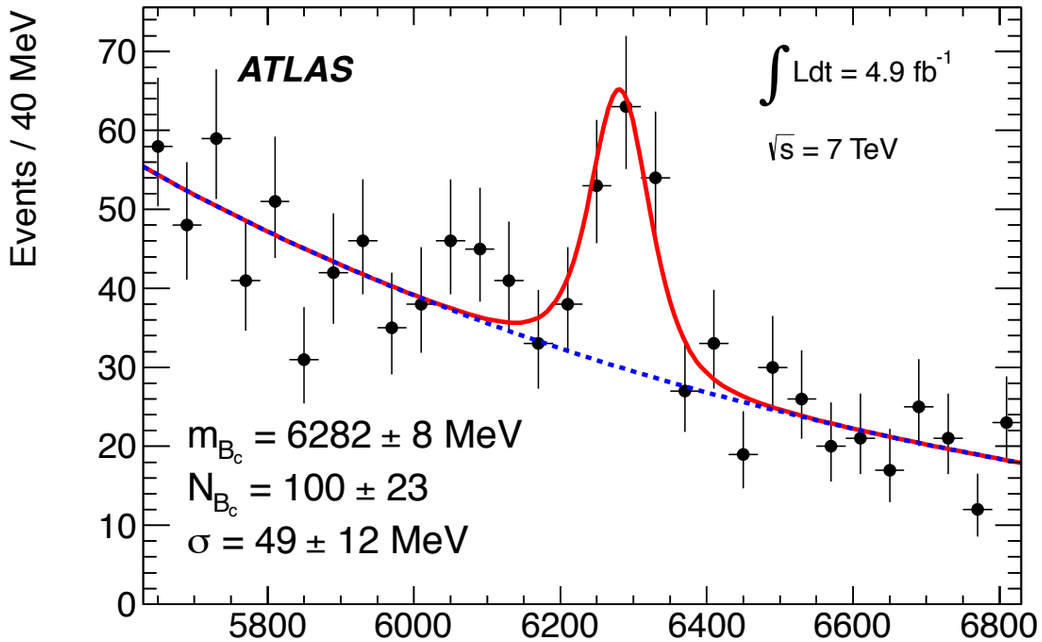
Results from ATLAS and CMS

Experiment	Luminosity [fb^{-1}]	Energy [TeV]	Title
CMS	4.8	7	Measurement of the X(3872) production cross section JHEP 04 (2013) 154, arXiv:1302.3968
CMS	5.2	7	Observation of a peaking structure in the J/ψφ mass spectrum from B± decays arXiv:1309.6920
CMS	20.7	8	Search for a new bottomonium state decaying to Y(1S) π+π- in pp collisions at $\sqrt{s}$= 8 TeV PLB 727 (2013) 57, arXiv:1309.0250
ATLAS	16.2	8	Search for the Xb and other hidden-beauty states in the π+π- Y(1S) channel at ATLAS PLB 740 (2015), pp. 199-217, arXiv:1410.4409

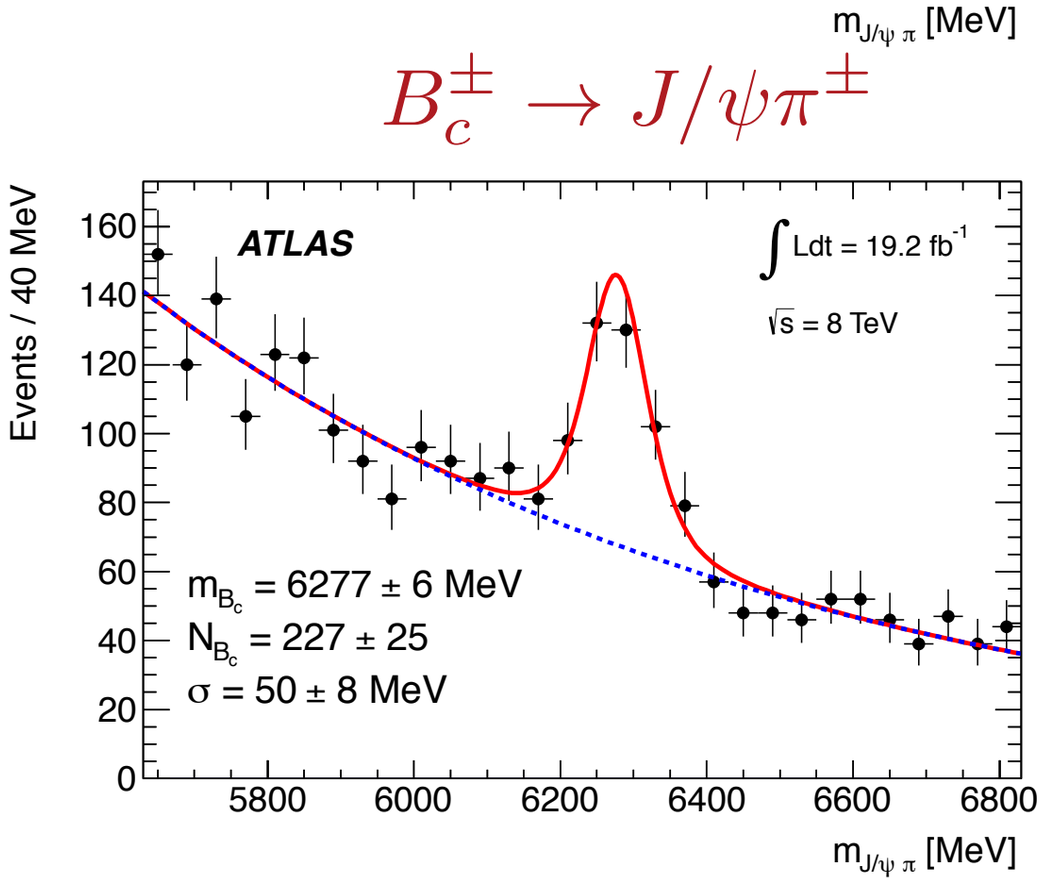
Observations: Excited Bc Meson

Phys. Rev. Lett. 113 (2014) 212004

- Predicted to sit below the B-D strong threshold between charmonium and bottomonium states.
- Dataset: 7 TeV (4.9 fb^{-1}) + 8 TeV (19.2 fb^{-1}).
- $B^{\pm}_c$ reconstructed in $J/\Psi(\mu\mu)\ \pi^{\pm}$ decay mode
  - di-muon system constrained to $m(J/\Psi)_{PDG}$
- Selection criteria optimised (separately) on $S/\sqrt{(S+B)}$ at each energy from MC.
  - Main analysis selections:
    - $pT(\mu 2) > 6$, $pT(\mu 1) > 4$ GeV
    - $pT(\pi) > 400$ MeV
    - Pion d_0 significance cuts
    - $pT(B^{\pm}_c) > 15$ (18) GeV at 7 (8) TeV
- $B^{\pm}_c$ system then combined with two additional charged pions, :
    - $pT(\pi) > 400$ MeV



$B_c^{\pm} \to J/\psi\pi^{\pm}$



Observations: Excited Bc

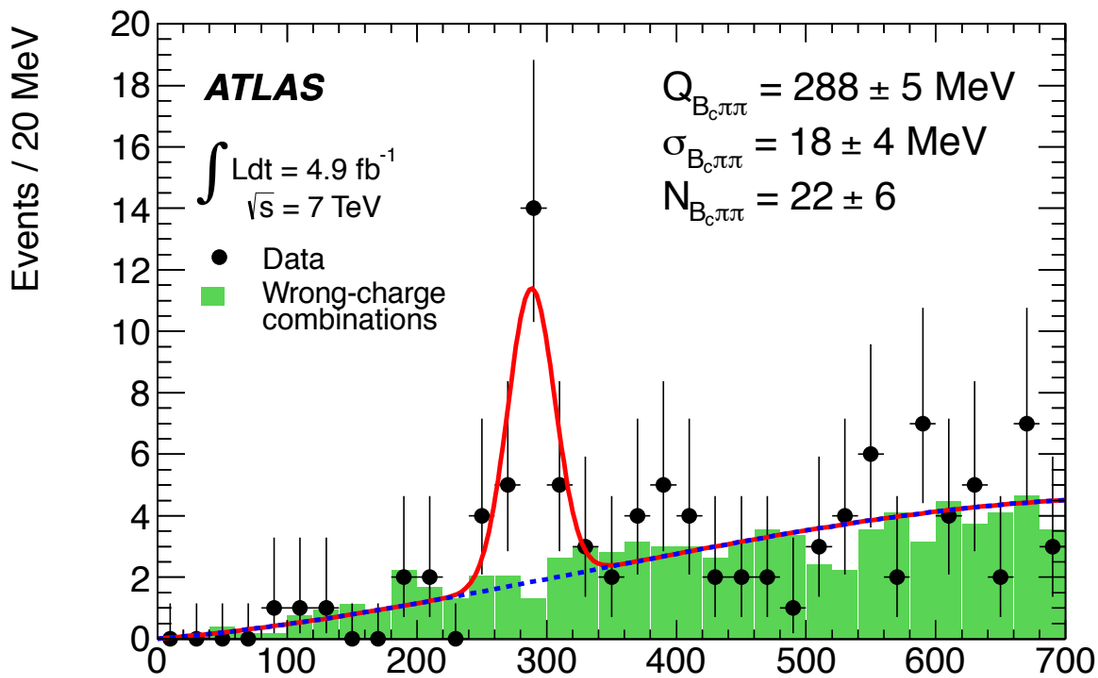
- Define the mass-difference:

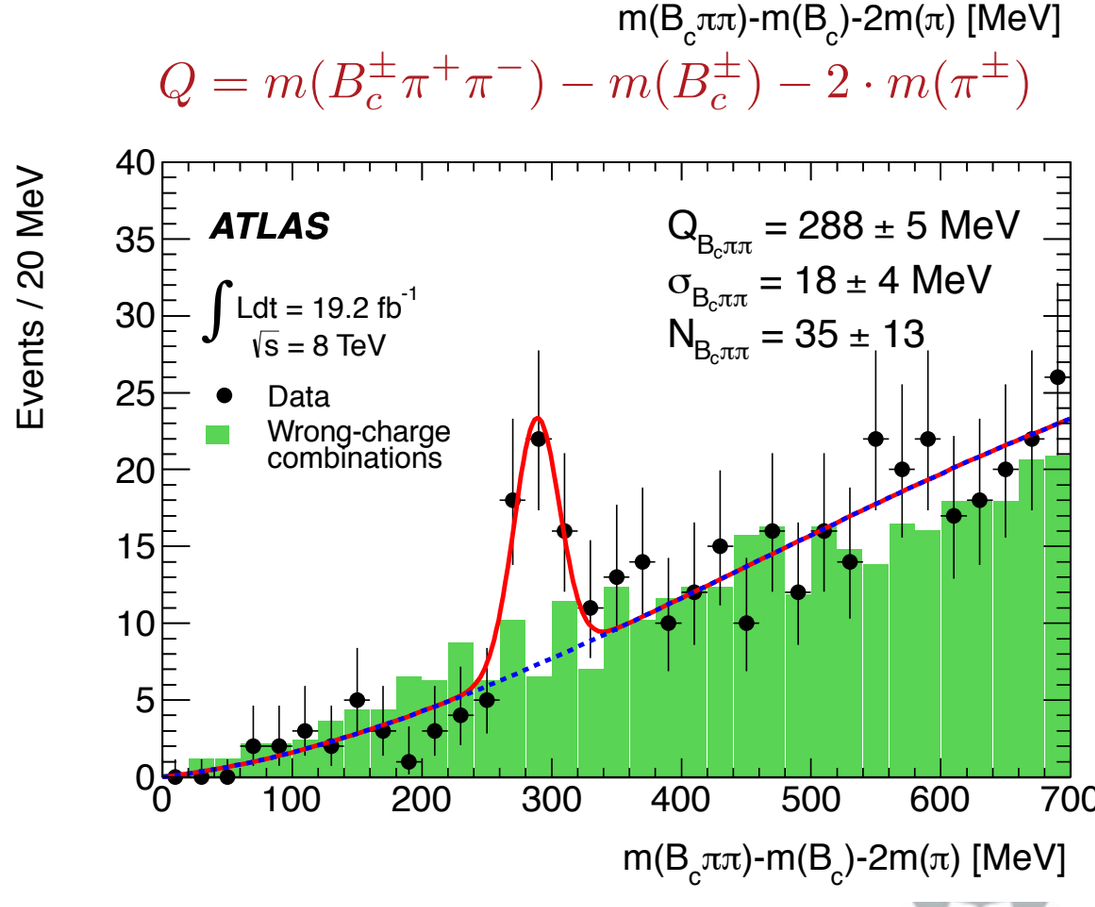
$$Q = m(B_c^{\pm}\pi^+\pi^-) - m(B_c^{\pm}) - 2 \cdot m(\pi^{\pm})$$

  - to reduce effects of detector resolution

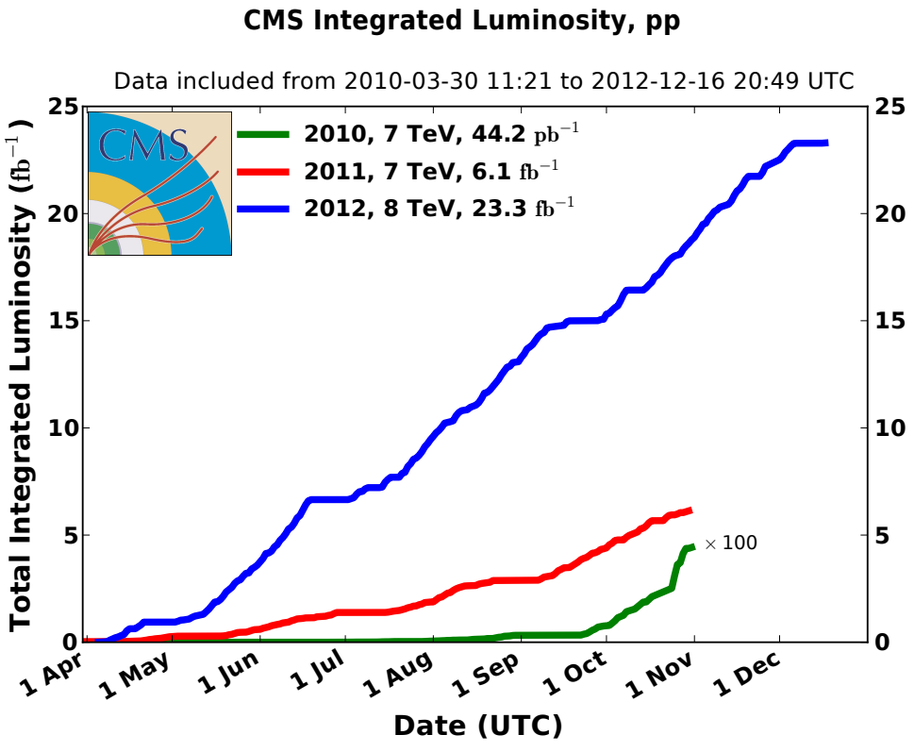
- Total significance 5.2σ (incl. 'look-elsewhere effect')
  - 3.7σ @ 7TeV, 4.5σ @ 8TeV
  - Established using ΔlnL through
  - Pseudo-experiments

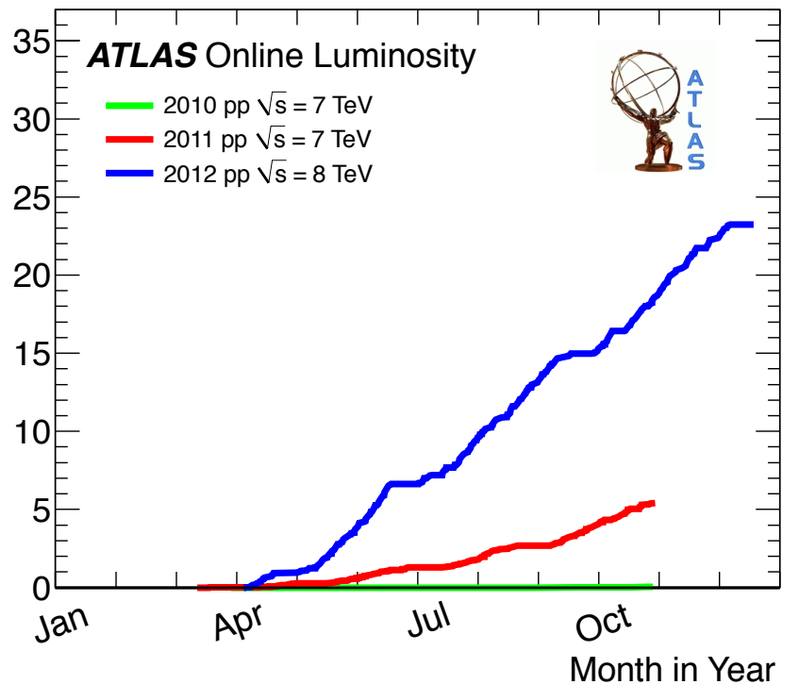
- New structure observed at mass:
- $M(B_c\pi\pi)$ = 6,842 ± 4 (stat.) ± 5 (syst.) MeV
  - Consistent with predictions of $B_c^{\pm}(2S)$ meson.

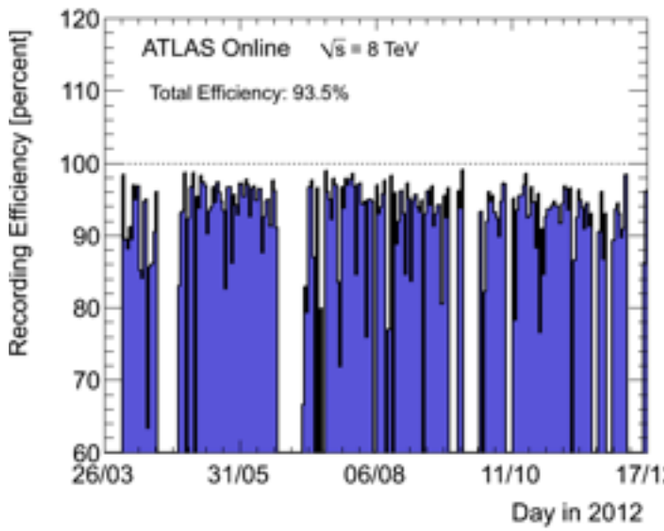




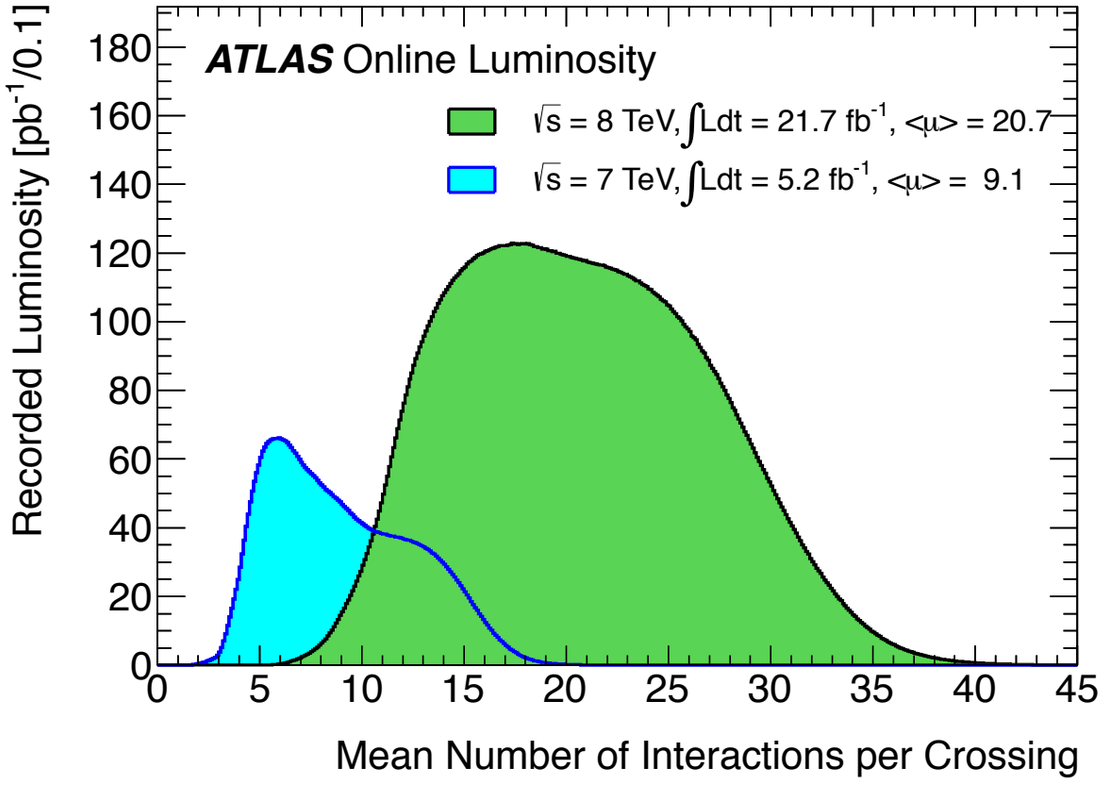
Data-taking in 2011–2012





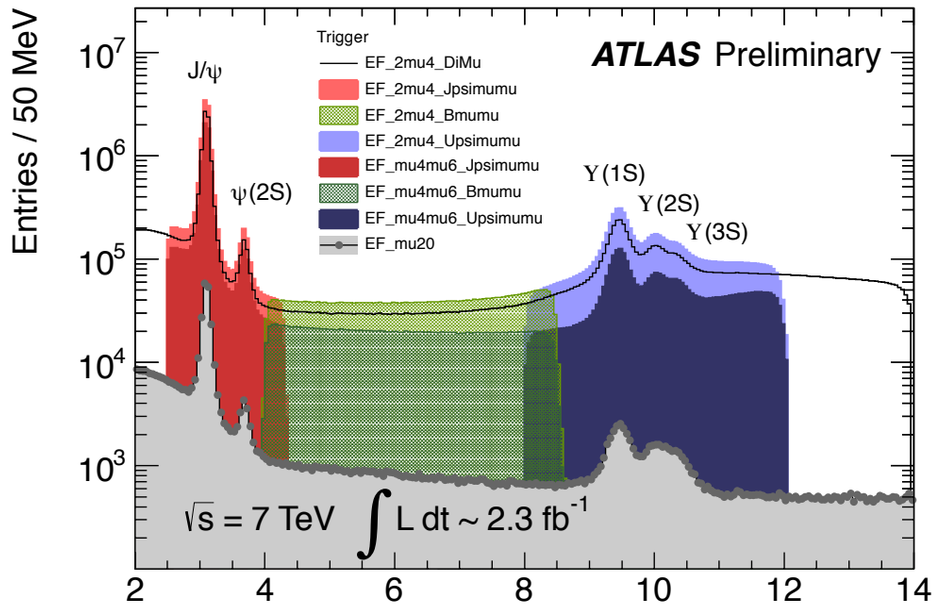


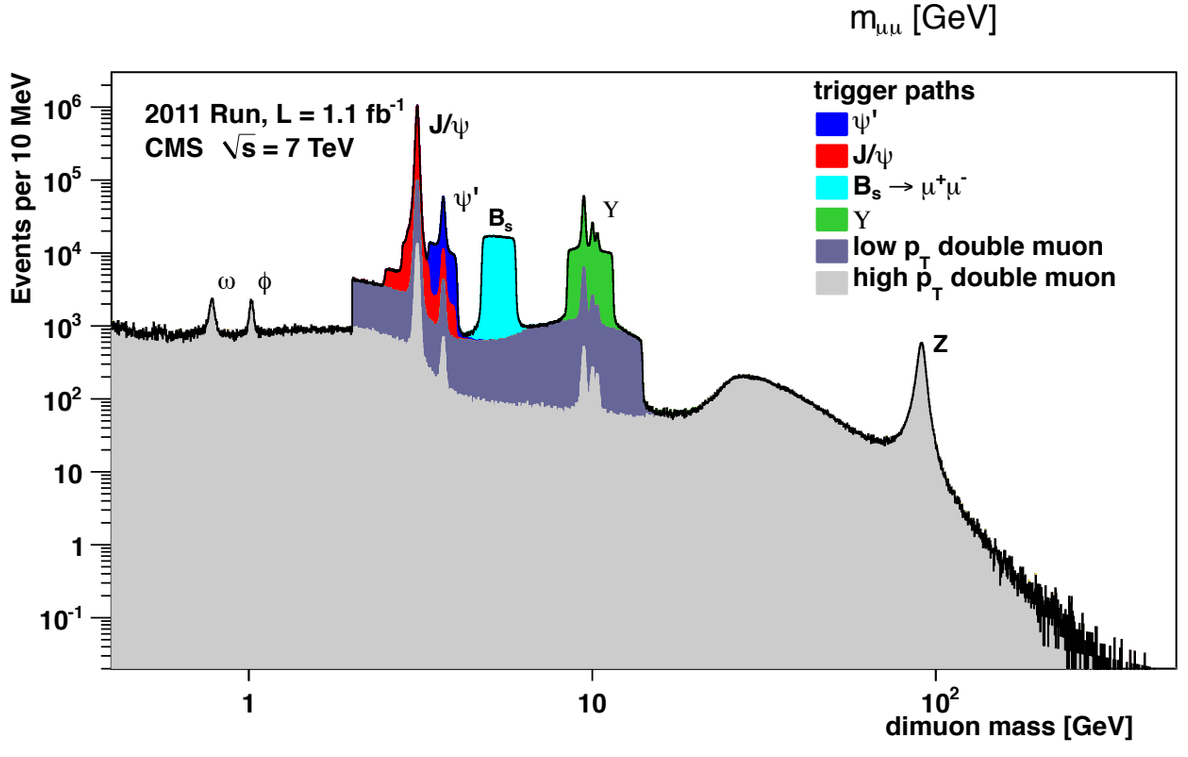
- B-physics sensitive to correct choice of primary interaction vertex
- Detector data taking efficiency > 93%



Triggering for B-physics

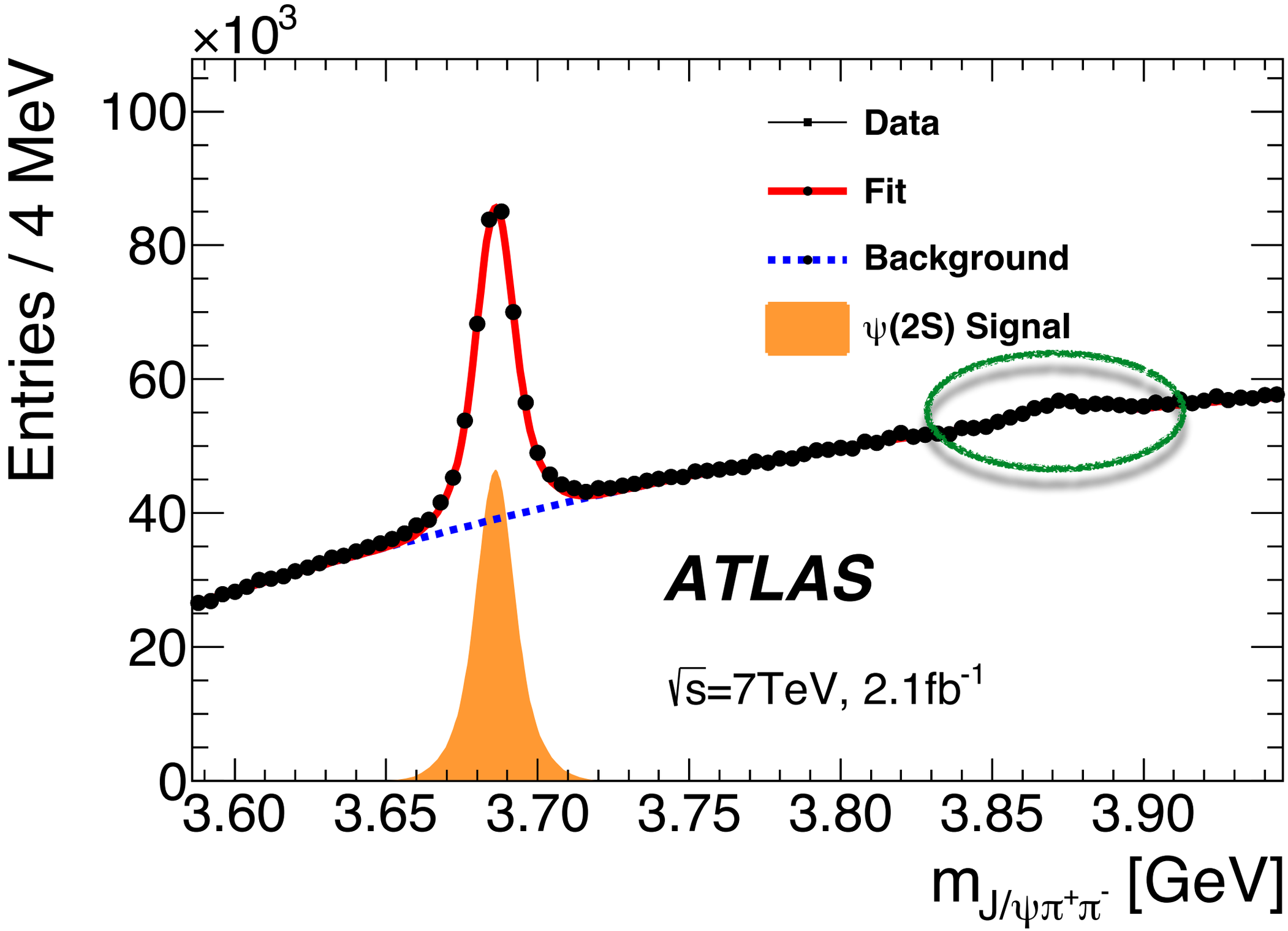
- 3-level system O(20MHz) -> O(200Hz)
  - Level 1 - hardware O(75)KHz
  - Level 2 and Event Filter
    - Software-based
    - Offline-like reconstruction software
- B-physics statistics typically low-pT
- Primary B-physics triggers:
  - Two muon signals at L1
  - confirmed at L2/EF with vertexing and invariant mass criteria applied
  - Varying thresholds and prescaling applied to maximise signal rate
    - For analyses presented here - typically $\mu 4\mu 4$ or $\mu 6\mu 4$ thresholds used:
      $\mu 4\mu 4$ ($\mu 6\mu 4$) un-prescaled for majority of 7 (8) TeV data-taking.





Differential Cross-section $\Psi(2S)$ in $J/\Psi\pi\pi$

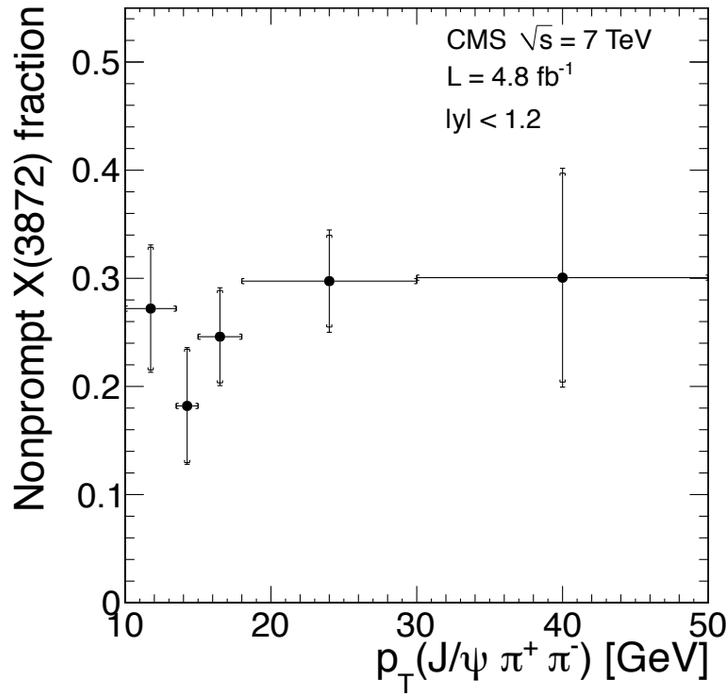
JHEP09(2014)079

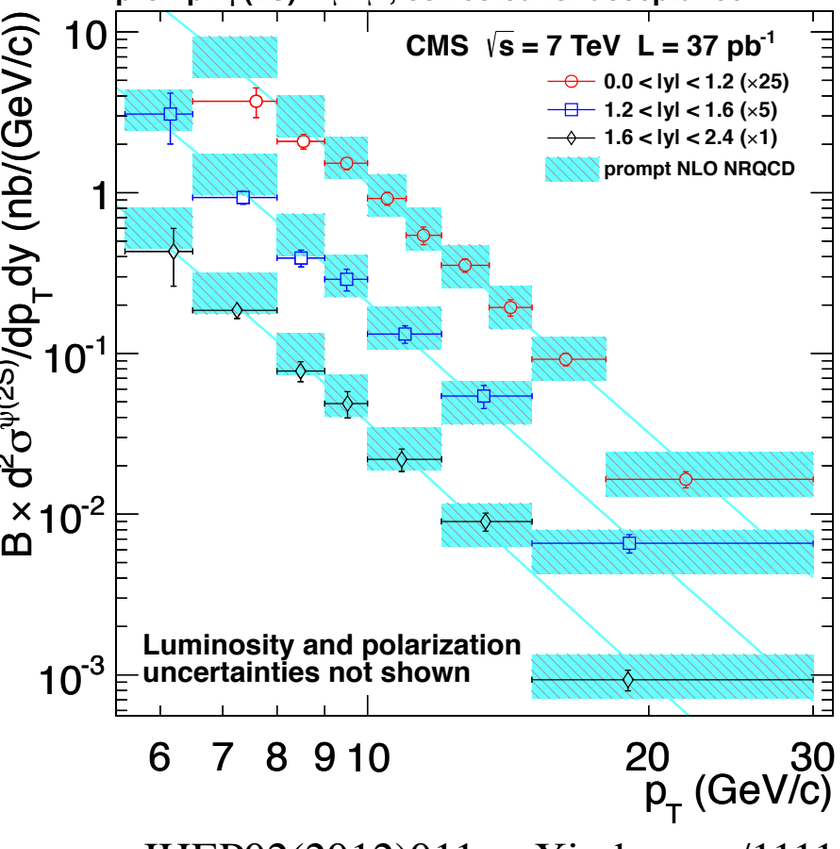


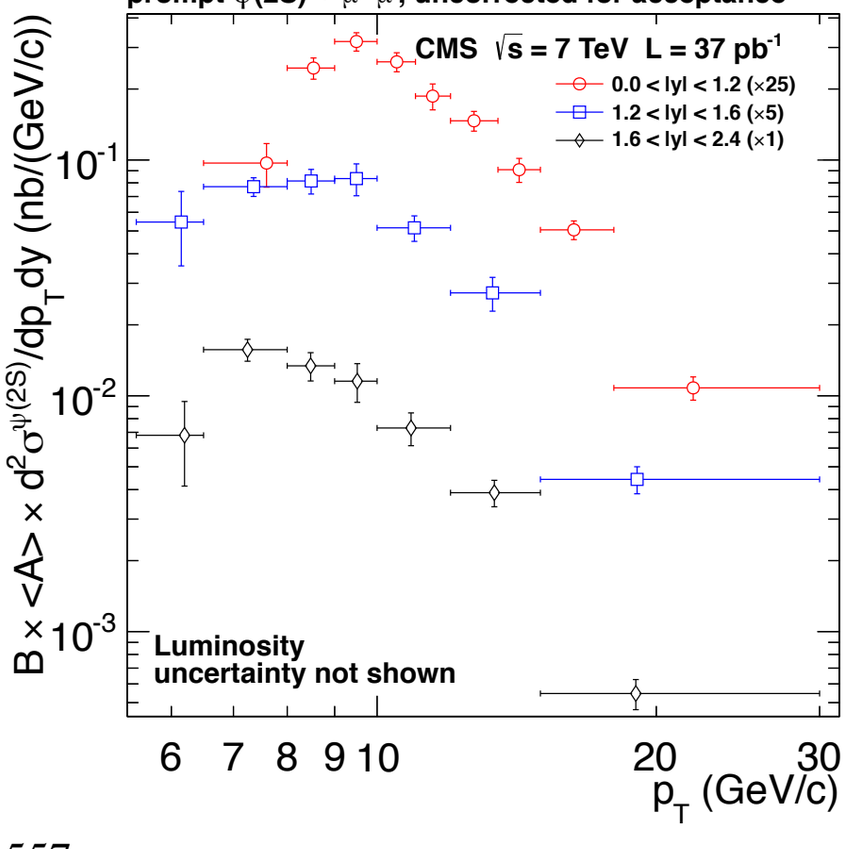
CMS: X(3872) Cross-section and NPF

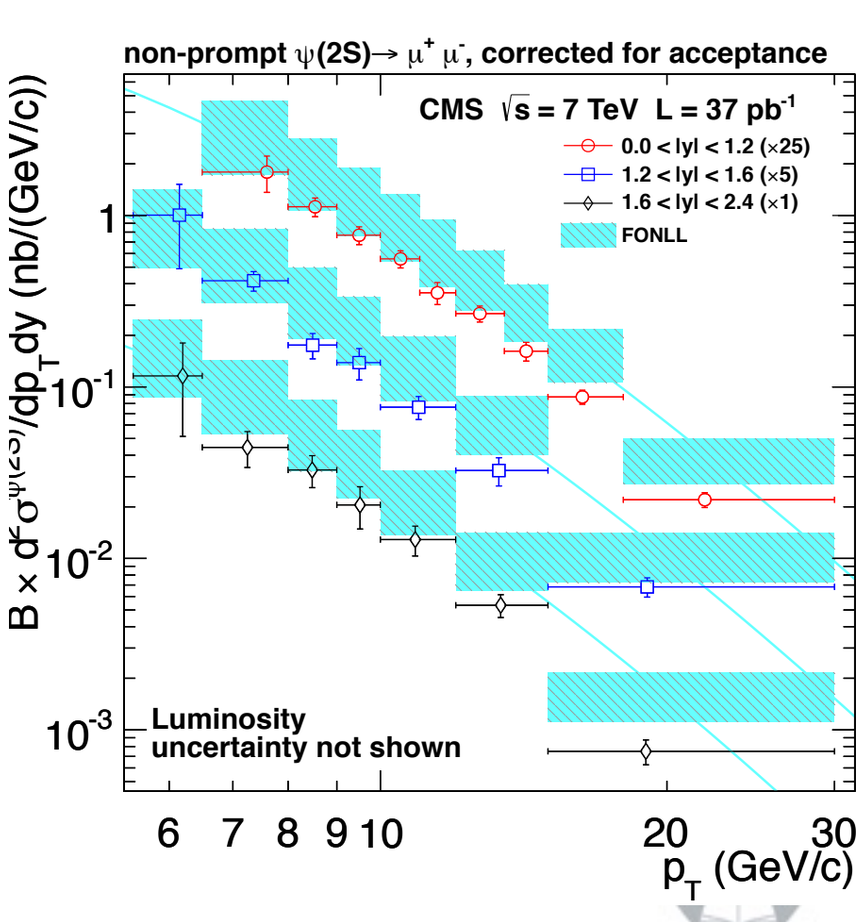
$$\sigma^{\text{prompt}}_{\text{X(3872)}} \cdot \mathcal{B}(\text{X(3872)} \to \text{J}/\psi\pi^+\pi^-) = \frac{1 - f^B_{\text{X(3872)}}}{1 - f^B_{\psi(2\text{S})}} \cdot R \cdot \left(\sigma^{\text{prompt}}_{\psi(2\text{S})} \cdot \mathcal{B}(\psi(2\text{S}) \to \mu^+\mu^-)\right) \cdot \frac{\mathcal{B}(\psi(2\text{S}) \to \text{J}/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2\text{S}) \to \mu^+\mu^-)},$$

$$\sigma^{\text{prompt}}(\text{pp} \to \text{X(3872)} + \text{anything}) \cdot \mathcal{B}(\text{X(3872)} \to \text{J}/\psi\pi^+\pi^-) = 1.06 \pm 0.11\,(\text{stat.}) \pm 0.15\,(\text{syst.})\,\text{nb}.$$









. JHEP02(2012)011, arXiv:hep-ex/1111.1557.

CMS: X(3872) Systematics

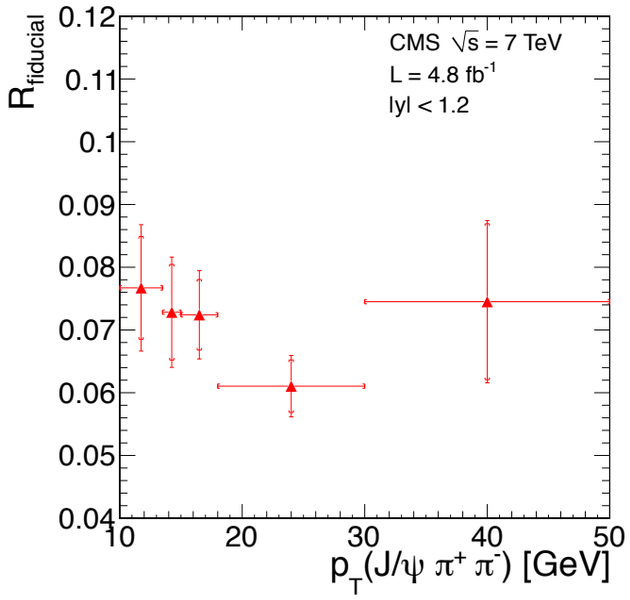
$$R = \frac{\sigma(\mathrm{pp} \to \mathrm{X}(3872) + \text{anything}) \cdot \mathcal{B}(\mathrm{X}(3872) \to \mathrm{J}/\psi\pi^+\pi^-)}{\sigma(\mathrm{pp} \to \psi(2\mathrm{S}) + \text{anything}) \cdot \mathcal{B}(\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^-)} = \frac{N_{\mathrm{X}(3872)} \cdot A_{\psi(2\mathrm{S})} \cdot \epsilon_{\psi(2\mathrm{S})}}{N_{\psi(2\mathrm{S})} \cdot A_{\mathrm{X}(3872)} \cdot \epsilon_{\mathrm{X}(3872)}}$$

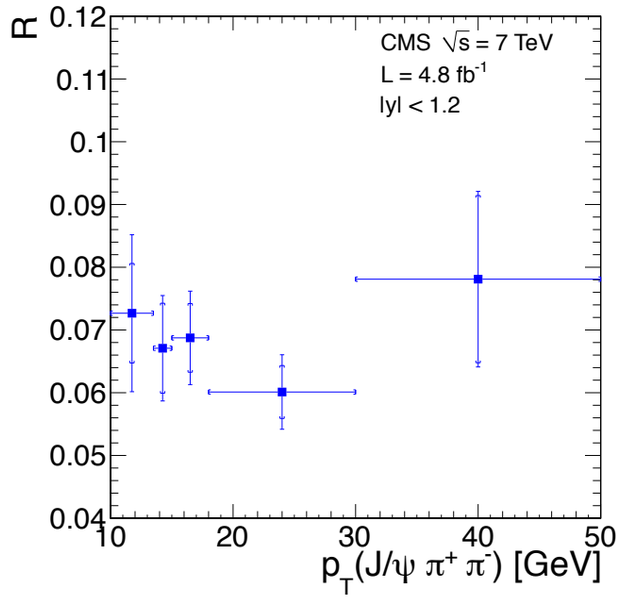
$$R_{\text{fiducial}} = \frac{N_{\mathrm{X}(3872)} \cdot \epsilon_{\psi(2\mathrm{S})}}{N_{\psi(2\mathrm{S})} \cdot \epsilon_{\mathrm{X}(3872)}},$$

Weight correction

$$\left\langle \frac{1}{A \cdot \epsilon} \right\rangle_{\text{bin}} \equiv \sum_{i=1}^{N_{\text{fine}}^{\text{bin}}} \frac{N_i}{A^i \cdot \epsilon^i} \Bigg/ \sum_{i=1}^{N_{\text{fine}}^{\text{bin}}} N_i,$$

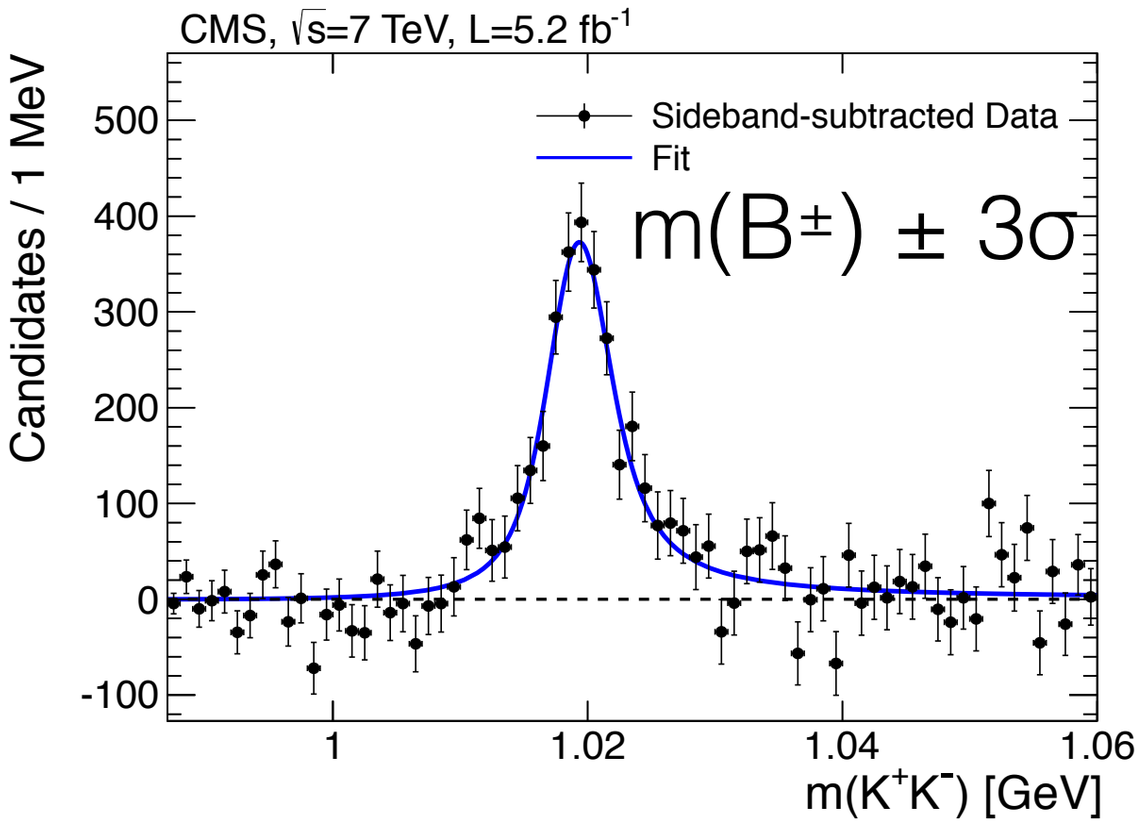
Source	Relative uncertainty (%)
Common to R_{fiducial} and R	
Fit functions	1–2
$\epsilon(\mu^+\mu^-)$	< 1
$\epsilon(\pi^+\pi^-)$	1–5
Efficiency statistical precision	1–3
Specific to R_{fiducial}	
X(3872) p_{T} spectrum	2–5
$\psi(2\mathrm{S})$ p_{T} spectrum	1–4
Total systematic uncertainty in R_{fiducial}	4–8
Specific to R	
X(3872) p_{T} spectrum	1–11
$\psi(2\mathrm{S})$ p_{T} spectrum	1–4
$m(\pi^+\pi^-)$ spectrum	1–2
Acceptance statistical precision	1–3
Total systematic uncertainty in R	5–13

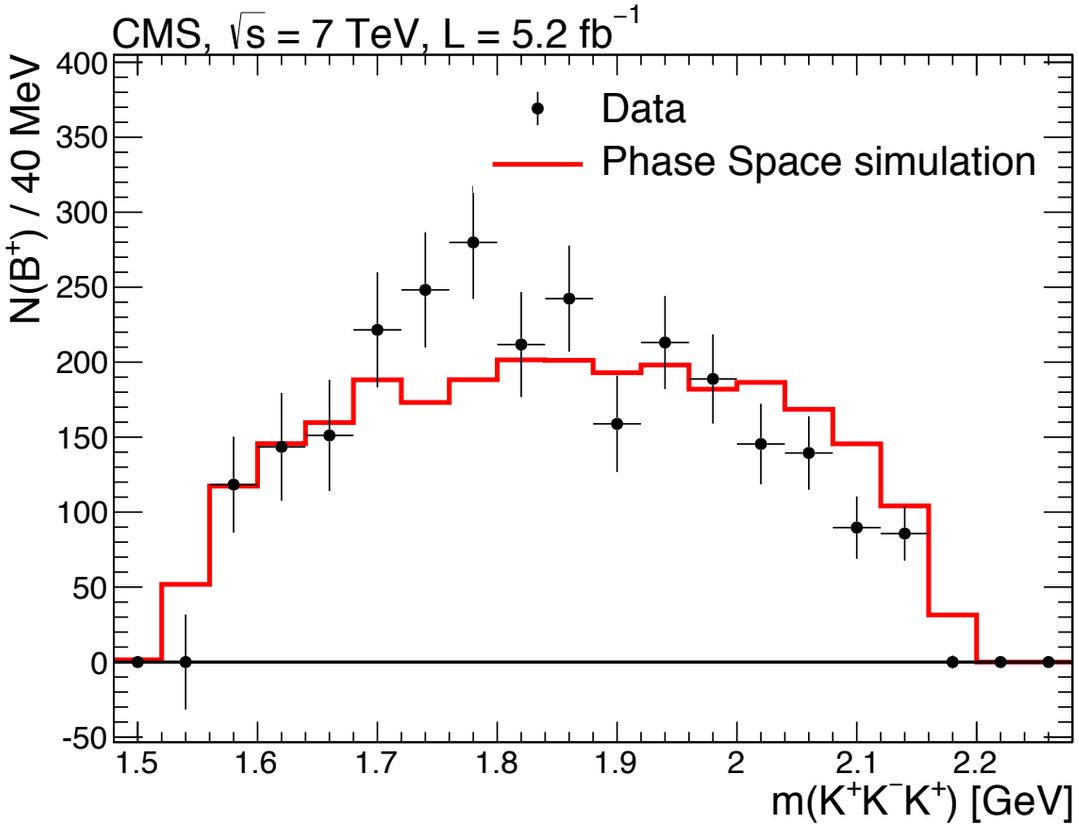




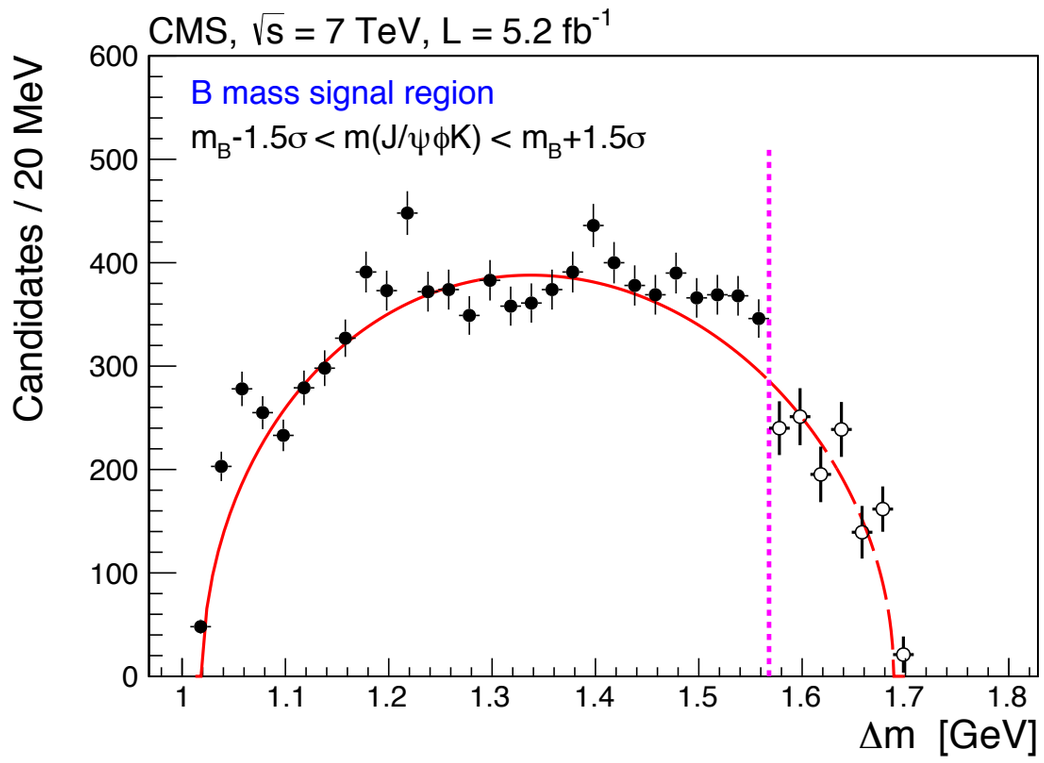
Polarization X(3872)	Polarization $\psi(2\mathrm{S})$	Relative shifts (%)	Polarization X(3872)	Polarization $\psi(2\mathrm{S})$	Relative shifts (%)
CST	CSL	-28	CST	unpol	-8
CSL	CST	$+31$	CSL	unpol	$+22$
HXT	HXL	$+86$	HXT	unpol	$+28$
HXL	HXT	-49	HXL	unpol	-31
CST	CST	-1	unpol	CST	$+8$
CSL	CSL	-5	unpol	CSL	-22
HXT	HXT	-6	unpol	HXT	-27
HXL	HXL	-1	unpol	HXL	$+25$

Peaking structures in decays of $B^{\pm} \to J/\Psi\Phi K^{\pm}$





	m_1 (MeV)	Γ_1 (MeV)	m_2 (MeV)	Γ_2 (MeV)
B^+ background PDF	0.8	7.4	2.6	9.9
B^+ signal PDF	0.2	3.6	2.7	0.2
Relative efficiency	4.8	6.0	0.9	10.0
Δm binning	3.7	1.5	2.7	0.2
Δm structure PDF	0.8	9.3	0.6	4.9
Δm mass resolution	0.8	6.4	0.6	4.6
Δm background shape	0.2	7.0	0.3	0.2
Selection requirements	0.8	7.8	5.5	1.8
Total	6.3	19	7.3	16



CMS: Signal Extraction

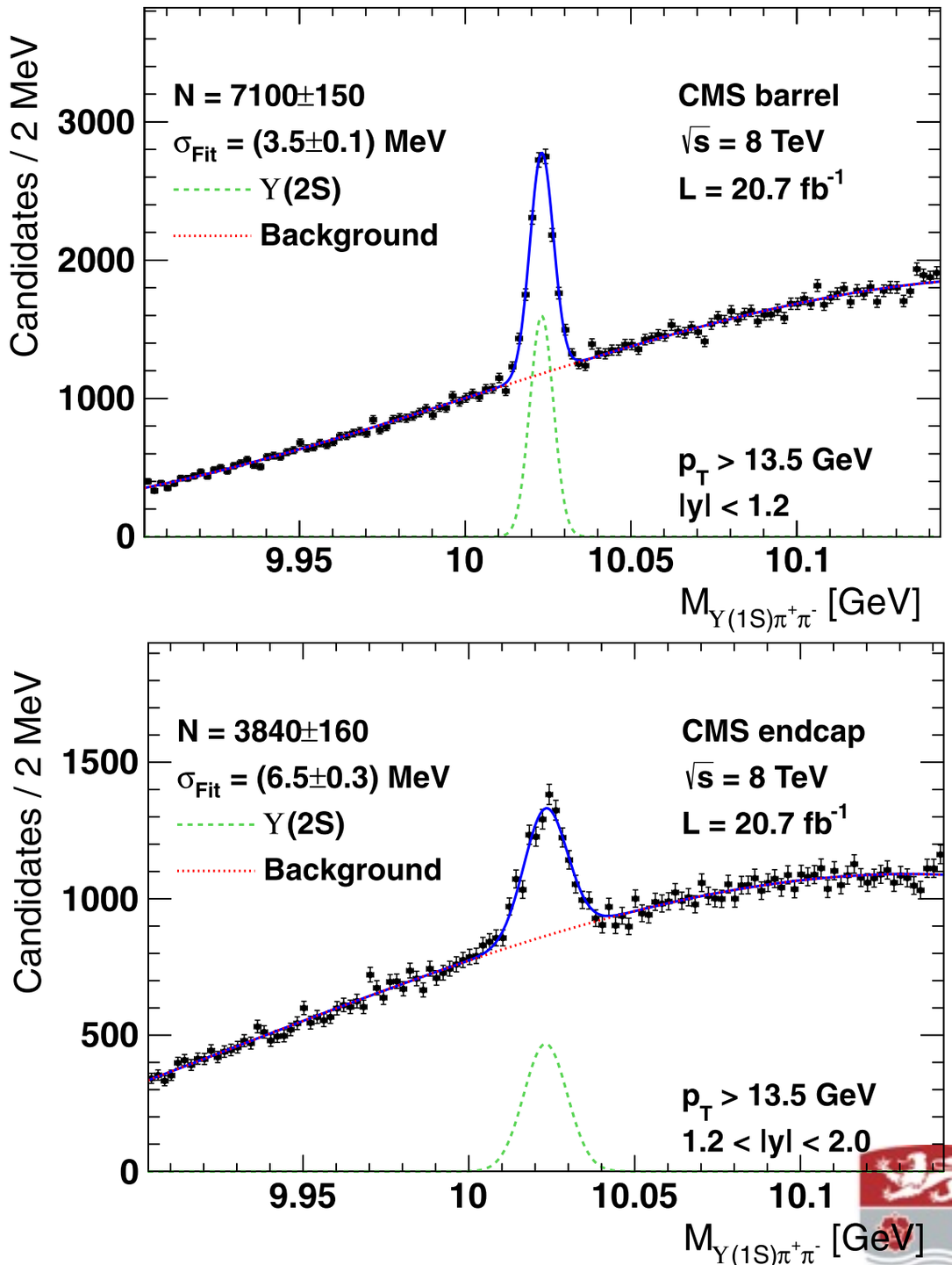
$$R = \frac{\sigma(\mathrm{pp} \to X_b \to \Upsilon(1\mathrm{S})\pi^+\pi^-)}{\sigma(\mathrm{pp} \to \Upsilon(2\mathrm{S}) \to \Upsilon(1\mathrm{S})\pi^+\pi^-)} = \frac{\sigma \cdot \mathcal{B}}{\sigma_{2\mathrm{S}} \cdot \mathcal{B}_{2\mathrm{S}}}$$

$$N^{\mathrm{obs}}_{\mathrm{X_b}} = R \times N^{\mathrm{obs}}_{\Upsilon(2\mathrm{S})} \times \frac{\epsilon_{\mathrm{X_b}}}{\epsilon_{\Upsilon(2\mathrm{S})}}$$

- Efficiency ratio from MC,
  - MC dipion mass distributions reweighted according to CLEO data

- Signal shape parameters fixed to simulation;
  - signal strength allow to float
- Fits performed at each mass-hypothesis point.

- Assumption of zero polarisation is treated in systematics.



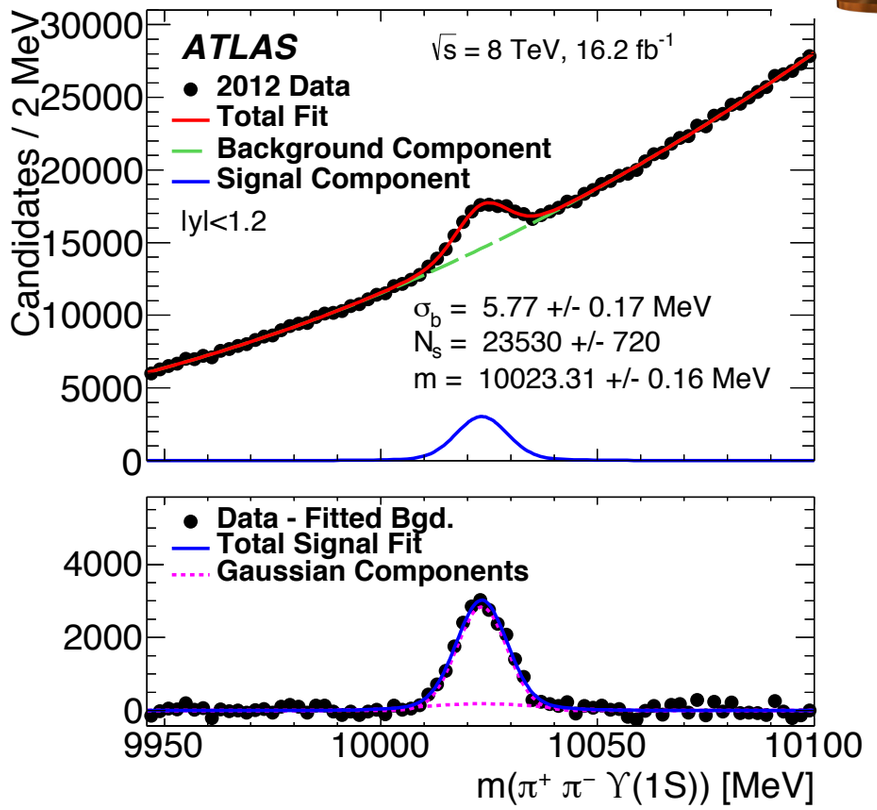
ATLAS: Signal Extraction

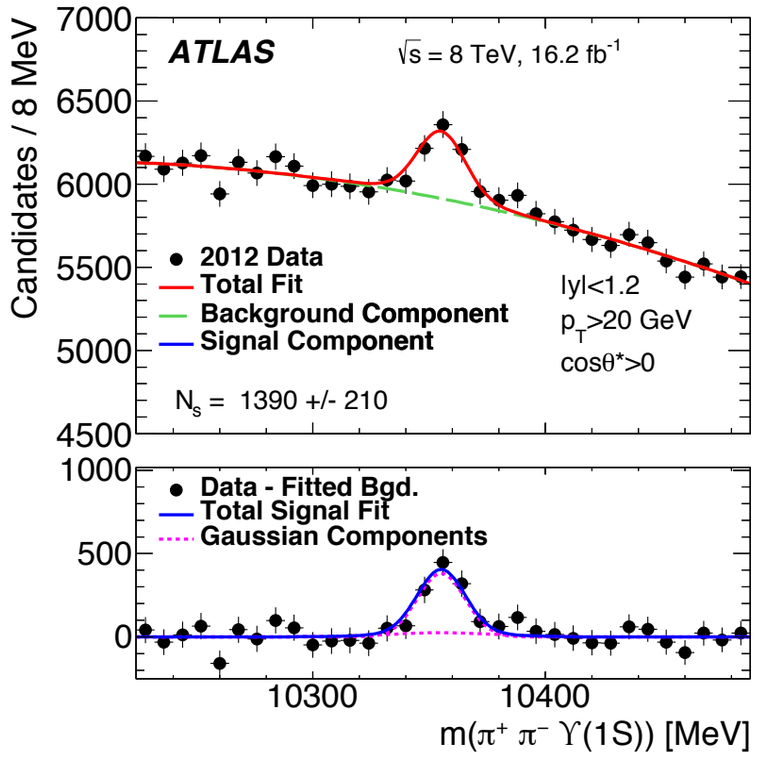
- Extracted yields normalised to fitted Υ(2S)

$$N = N_{2S} \cdot R \cdot \frac{\mathcal{A}}{\mathcal{A}_{2S}} \cdot \frac{\epsilon}{\epsilon_{2S}}$$

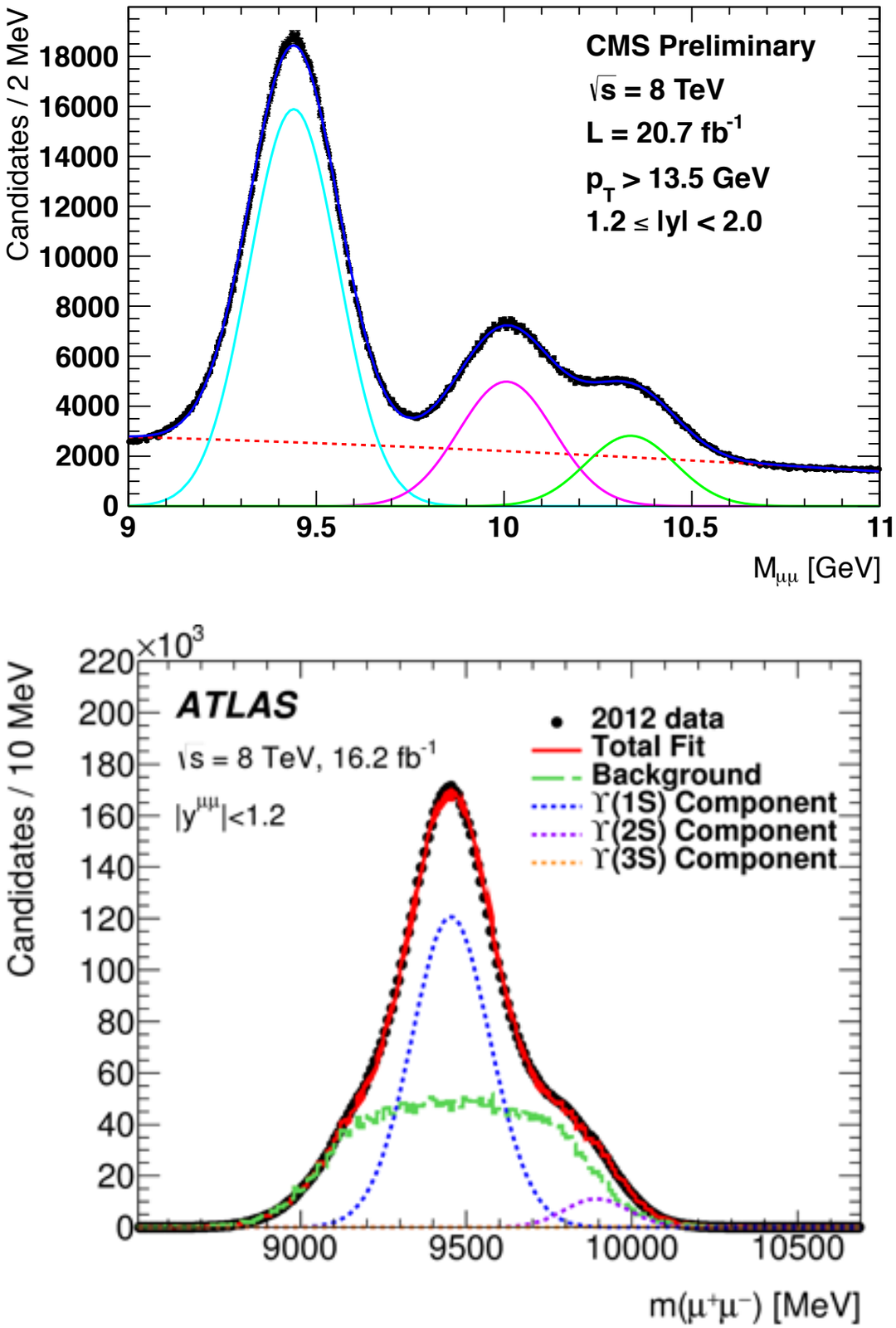
$$R = \frac{\sigma(\mathrm{pp} \to X_b \to \Upsilon(1\mathrm{S})\pi^+\pi^-)}{\sigma(\mathrm{pp} \to \Upsilon(2\mathrm{S}) \to \Upsilon(1\mathrm{S})\pi^+\pi^-)} = \frac{\sigma \cdot \mathcal{B}}{\sigma_{2\mathrm{S}} \cdot \mathcal{B}_{2\mathrm{S}}}$$

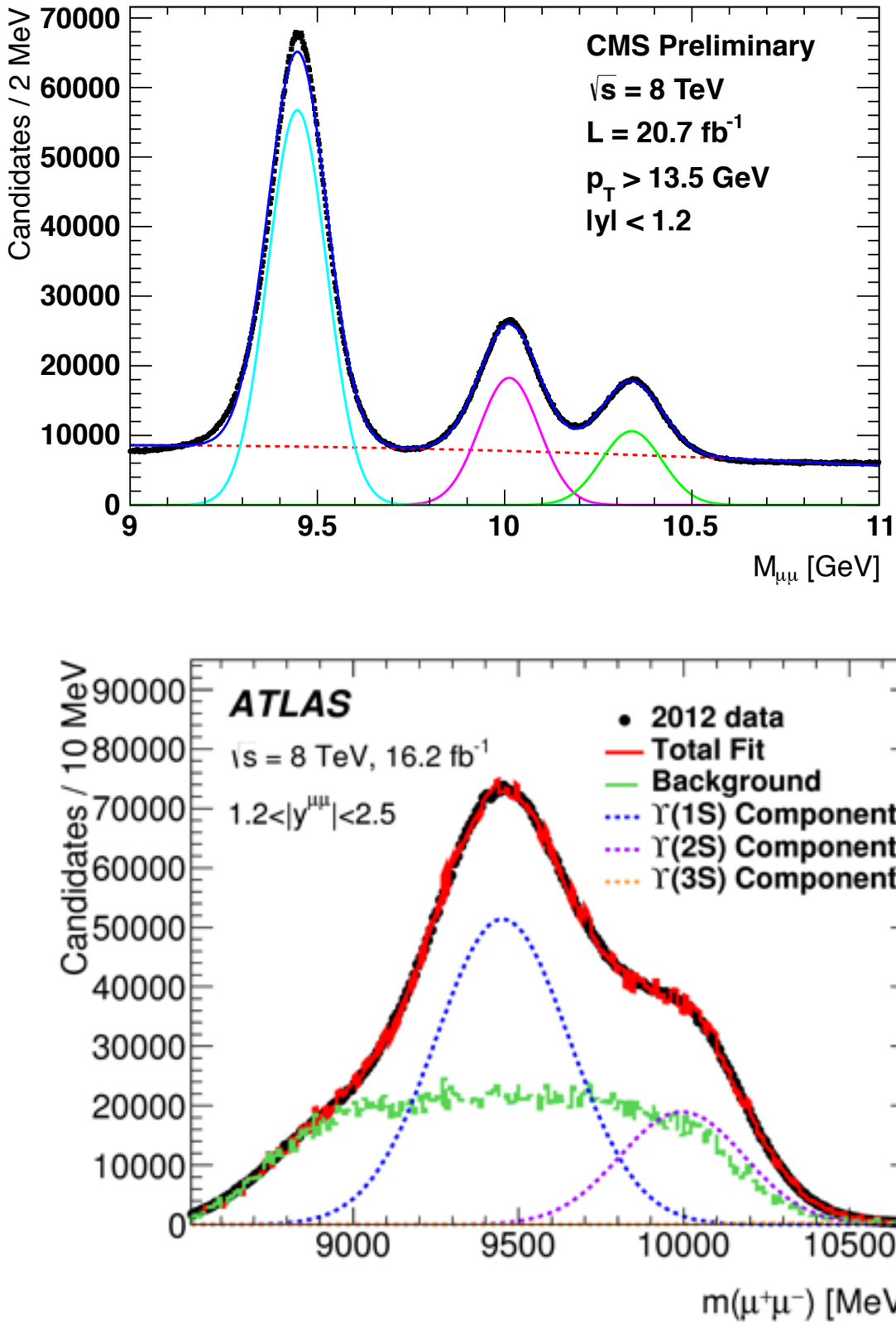
- Validated on Υ(3S)
  - predicted: 11,400 ± 1,500
  - fitted: 11,600 ± 1,300
- Perform hypothesis test, 10 MeV intervals: 10–11 GeV (veto Υ(2,3S))
    - Mass window for each fit: m±8σ:
      - σ: 72MeV@ 10 GeV – 224MeV @10.9 GeV
  - Fit is performed simultaneously to the 8 (2x2x2) |y|,pT,cosθ* bins





M(μμ) Υ distributions





Observations: $\chi_b(3P)$

Phys. Rev. Lett. 108 (2012) 152001

- First published observation of a new '*particle*' by LHC, reported by media.

- χ_b; J^{++} triplet states of bound b b-bar pairs of Bottomonium system:
  - Studies of QCD close to the strong decay threshold

- Observation of a new state through radiative transitions to $\Upsilon(1S)$, $\Upsilon(2S)$
  - $\Upsilon(nS) \rightarrow \mu\mu$
- Photons reconstructed as:
  - Unconverted photons (Calorimetry)
  - Converted photons (ID)

- Mass consistent with predictions of $\chi_b(3P)$ multiplet:
  - 10.530 ± 0.005 (stat.) ± 0.009 (syst.) GeV.

PRD 91, 014014 (2015)

- Possible scenarios for mixing of $\chi_b(3P)$ with exotic X_b states – interesting further studies.