X(3872) and its bottomonium counterpart at ATLAS

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Overview

- X(3872) status

- Search for its bottomonium counterpart (Xb) and other hidden beaty states in ATLAS:
  - "Search for Xb and other hidden-beauty states using $\pi^+\pi^-\Upsilon(1S)$ channel"

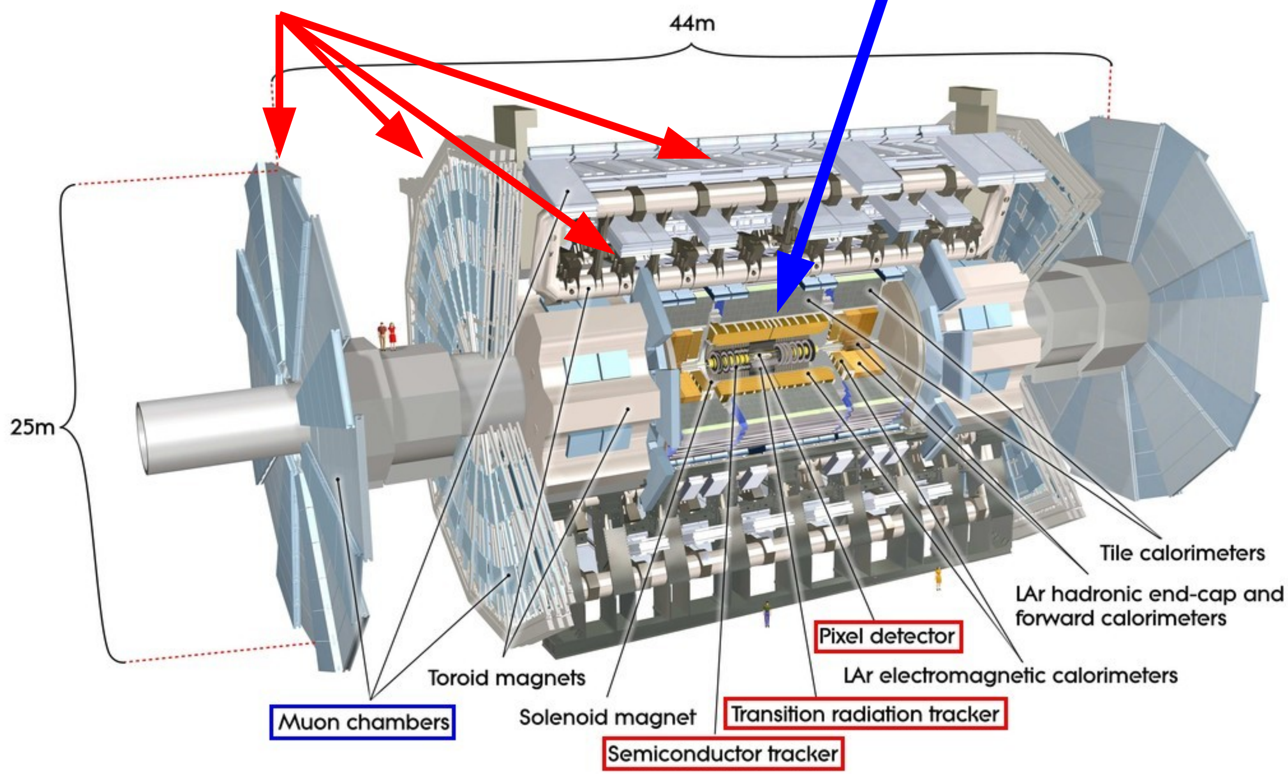
    Phys. Lett. B740 (2015) 199-217 , arXiv:1410.4409

    http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/BPHY-2013-07

ATLAS: detector & trigger for muons

- **Inner Detector:** |η|<2.5, 2T solenoid (1+3=4 Si pixels + 4 double Si strips, and Transition Radiation Tracker).
  $$\frac{\sigma_{p_T}}{p_T} \simeq 3.8\,x\,10^{-4}\, p_T[GeV] \oplus 0.015$$
- **Muon System:** $\frac{\sigma_p}{p} \simeq 10\,\%$

  |η|<2.7, Toroid <B>=0.5T



- **Trigger**:

  hardware Level-1, software High Level Trigger (HLT):in 2 stages for Run1 (7 & 8 TeV data) combined HLT in Run2 (13 TeV)

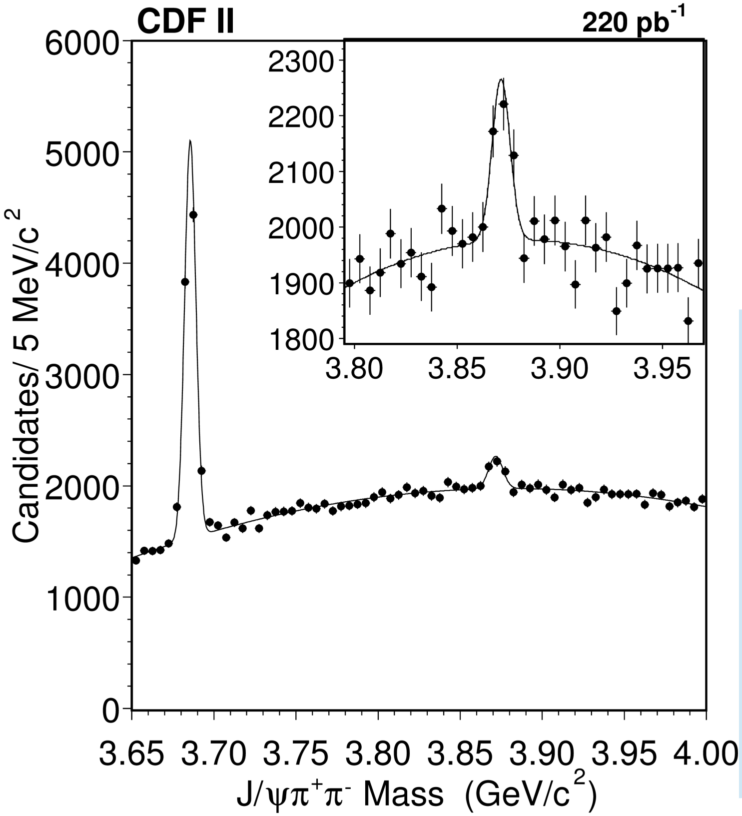
Heavy flavour studies use mostly $\mu^+ \mu^-$ signature

- pT(μ) > 4-6 GeV
- $\mu^+ \mu^-$ vertex
- $M(\mu^+ \mu^-)$ windows

1. Status of X(3872)

Brief history of X(3872)

- 2003 discovered by Belle in $B \to K\,X(3872),\, X(3872) \to J/\psi\,\pi^+\pi^-$
  - PRL 91, 262001 (2003)
- Confirmed soon after by CDF & D0 in $p\bar{p}$ at 1.96 TeV
  - CDF: PRL 93, 072001 (2004)



→ **prompt**: only ~16% of X(3872) from B's

→ **di-pion** seems from intermediate **ρ**

- LHCb: determined $J^{PC} = 1^{++}$
  - PRD 92 (2015) 011102
- CMS: detailed x-section, BR, etc
  JHEP 1304 (2013) 154

CMS: X(3872) in pp collisions @ 8 TeV

- CMS used the 7 TeV dataset (4.8 fb-1) to make detailed studies JHEP 1304 (2013) 154
- Ratio of X(3872) production compared to ψ(2S): ~7%

$$R = \frac{\sigma(pp \to X(3872) + anything) \cdot B(X(3872) \to J/\psi\, \pi^+ \pi^-)}{\sigma(pp \to \psi(2S) + anything) \cdot B(\psi(2S) \to J/\psi\, \pi^+ \pi^-)} = \underline{0.0694} \pm 0.0029(stat) \pm 0.0036(syst)$$

with no significant dependence on the pT of the system.

- m($\pi^+ \pi^-$) consistent with intermediate ρ^0 meson
- Non-prompt fraction: $\underline{0.263} \pm 0.023 \pm 0.016 (for\ 10 < p_T < 50\, GeV,\ |y| < 1.2)$

again no dependence on pT found

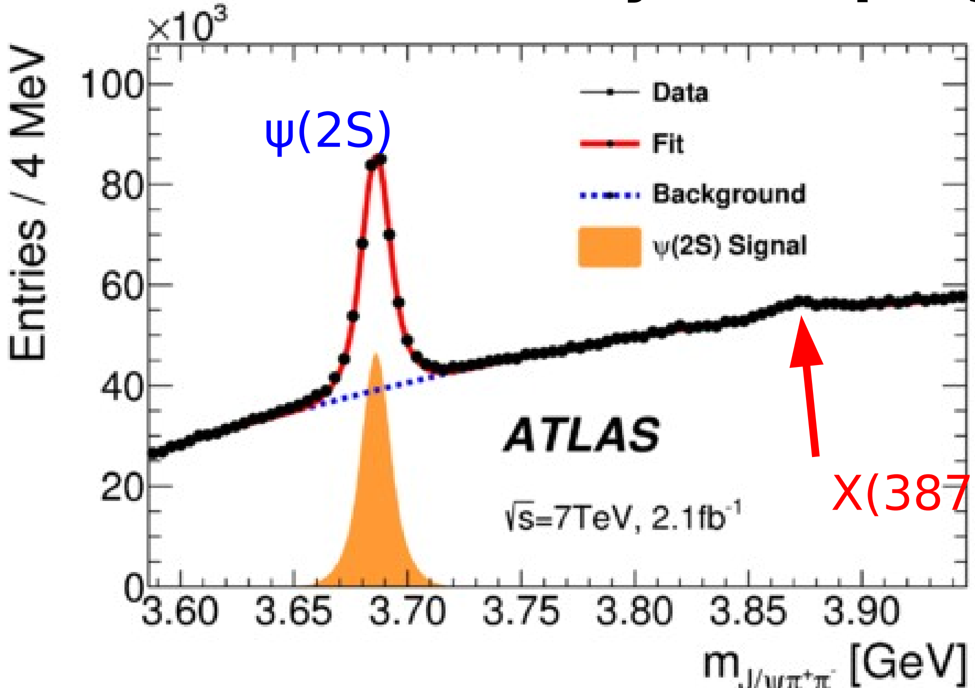
- Differential cross section vs. pT:
  - Shape is described reasonably by the theory, but the predicted cross section is overestimated by over 3σ.
- Integrated cross section * BR , for pT 10-30 GeV, |y|<1.2:

$$\sigma(pp \to X(3872) + anything) \cdot B(X(3872) \to J/\psi\, \pi^+ \pi^-) = (1.06 \pm 0.11 \pm 0.15)\, nb$$

ATLAS: X(3872) not released yet [reference channel **$\psi(2S) \to J/\psi\, \pi^+ \pi^-$** studied]

- X(3872) → $J/\psi\, \pi^+ \pi^-$ seen in **7 TeV** (2.1 fb-1);

  X(3872) on 8 TeV data: analysis in progress



JHEP09(2014)079 :
detailed measurement of the ψ(2S) production
10< pT < 100 GeV
|y|<2

- Prompt fraction of ψ(2S) : 40% to 80%, increasing with pT →
  non-prompt: 60% to 20%, decreasing with pT
  - significantly higher than the flat ~26% for X(3872)
- Theory (NLO NRQCD) gets absolute cross section and shape OK (shape slightly harder).

Nature of X(3872)

- Composition still unresolved. Main hypotheses:
  - **Tetraquark** (di-quak, di-antiquark) $J^{PC} = 1^{++}$ $(q\,c)(\bar{q}\,\bar{c})$
  - **Standard** $c\,\bar{c}$ (but $X(3872) \rightarrow J/\psi\,\rho$ violates isospin)

    [LHCb is 95% sure that D-wave does not contribute more than 4% : PRD 92 (2015) 011102]
  - **"Molecule"** of $D^0\,\overline{D}^{0*}$

    → X(3872) mass is very close to mass of $D^0\,\overline{D}^{0*}$

    → Binding energy by LHCb [new m(D^0): JHEP 06, 065 (2013)]

$$E_{binding}^{X(3872)} = m(D^0\,\overline{D}^{0*}) - m(X) = 2\,m(D^0) + \Delta m(D^{0*} - D^0) - m(X) = \underline{(0.09 \pm 0.28)\,MeV}$$

says that it would be a very loosely bound molecule

  - **Mixture of** $D^0\,\overline{D}^{0*}$ **and** $c\,\bar{c}$ is an option

    supported by LHCb [NPB 886 (2014) 665] seen $X(3872) \rightarrow \psi(2S)\,\gamma$

    [= 0 for a pure molecular state, Swanson, PLB 588 (2004) 189]

2. Search for Xb in ATLAS

Physics Letters B 740 (2015), pp. 199-217
arXiv:1410.4409

Search for $\mathbf{X_b}$

- Heavy quark theory suggests a counterpart of X(3872) in the b-sector: termed $\mathbf{X_b}$
- Molecular model suggests mass close to $B\overline{B}^{(*)}$ ~10.56 GeV
- Search for $X_b \to Y(1S)\pi^+\pi^-$ [analogous to $X(3872) \to J/\psi\,\pi^+\pi^-$]

  & compare to $Y(2S) \to Y(1S)\pi^+\pi^-$ [analogous to $\psi(2S) \to J/\psi\,\pi^+\pi^-$]
- CMS looked for this as well: PLB 727 (2013) 57-76
- ATLAS analysis [PLB 740(2015) 199-217] slightly more sensitive
  - ATLAS pp@8TeV: collected large Y(1S) & Y(2S) samples:

    Y(1S): (6.00 +- 0.01) M and Y(2S): (200 +- 2) k

Xb reconstruction and selection

Trigger:

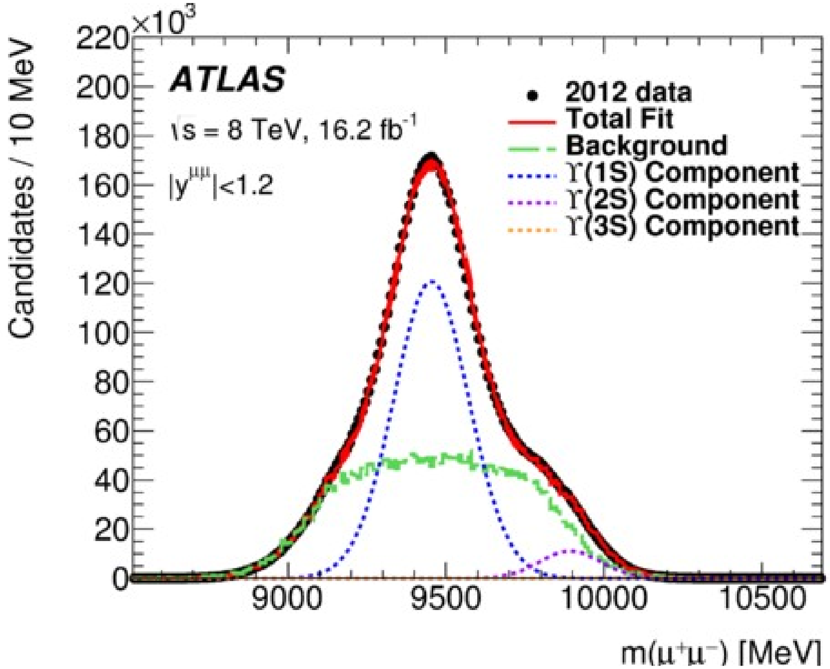
- Di-muon, each with pT(μ)>4 GeV
- common-vertex, m(μμ): 8-12 GeV
- Prescaled; got 16.2 fb^{-1}

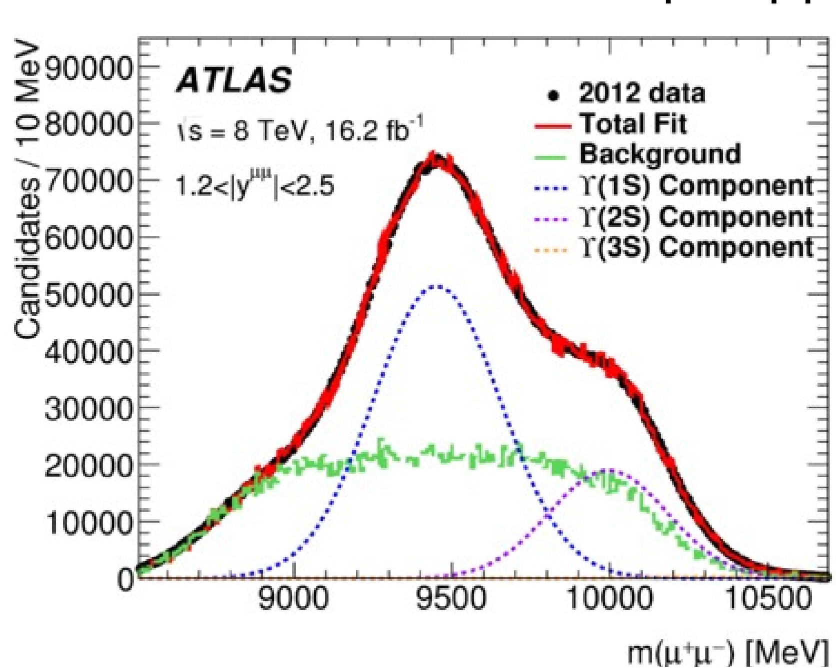
Y(1S):

- Two muons with pT>4 GeV , |η|<2.3
- common-vertex fit,
  m(μμ): +- 350 MeV from Y(1S)

Add π π to make: $\mu^+\mu^-\pi^+\pi^-$

- pT(π)>400 MeV , |η(π)|<2.5
- fit 4-track vertex
  - m(μμ) constraint to Y(1S) 10023.26 MeV
    RMS m(Y(2S)) : 147→9.7 MeV
  - X^2 < 20 , rejects 5% signal, 90% bkg
- m(Y(1S)ππ) < 11.2 GeV
  19.5 candidates per μμ





Central rapidity |y|<1.2 has better mass resolution & S/B than end-cap 1.2<|y|<2.5

Event binning: 8 bins (3 variables, each split in 2)

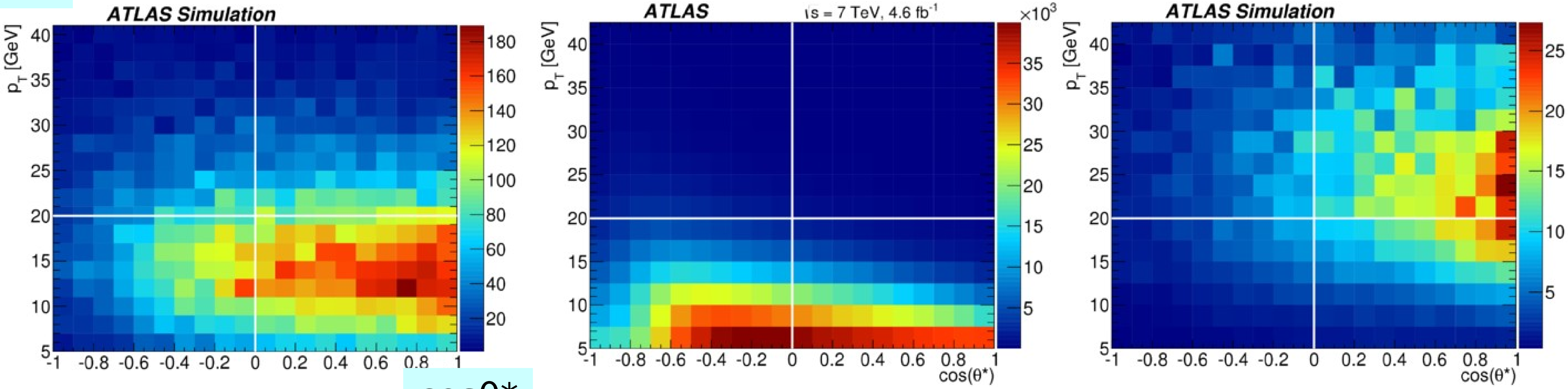
- **Y(1s) ππ system:** |y| < 2.4 , pT > 5 GeV.
- **Binning:** Rapidity: Barrel |y|<1.2 & Endcap 1.2<|y|<2.4

  pT: <20 GeV & >20 GeV , cosθ* : <0 & >0

  θ* = angle bw: {ππ momentum in the parent (4-body) rest frame} & {parent momentum in Lab}

  – Fraction of signal in each bin defined as "spliting functions". E.g, simulation says: S(|y|) = 0.606 +- 0.004 → signal in barrel |y|<1.2 region is 60.6% of all signal

pT



cosθ*

Signal

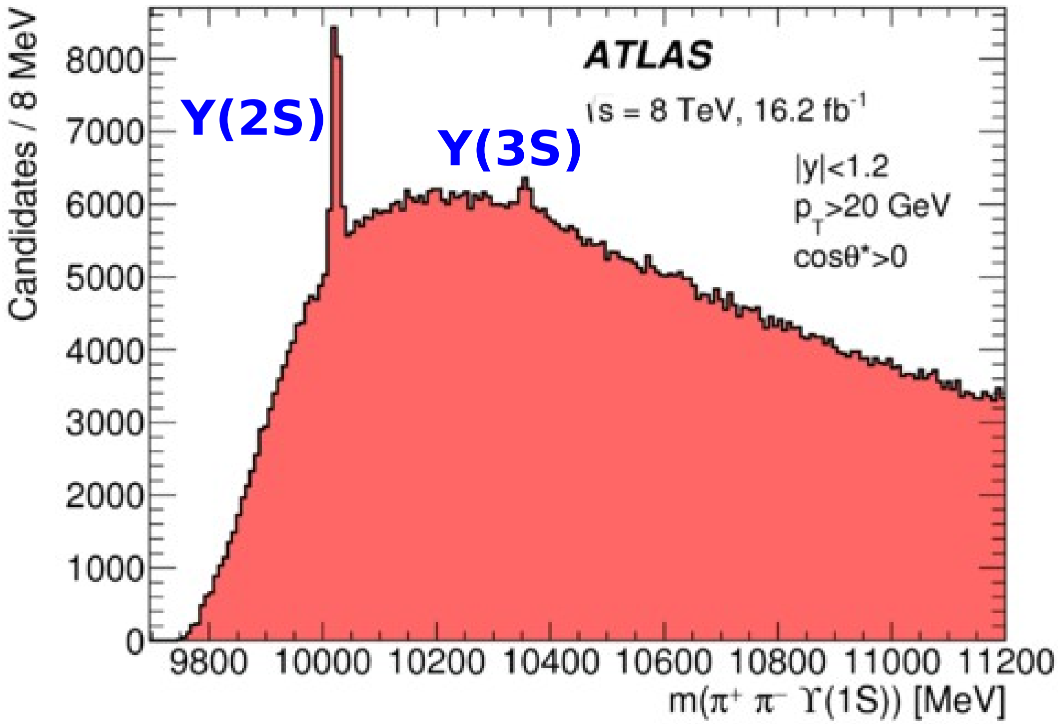
Background

$S/\sqrt{B}$ best in high cosθ*, high pT

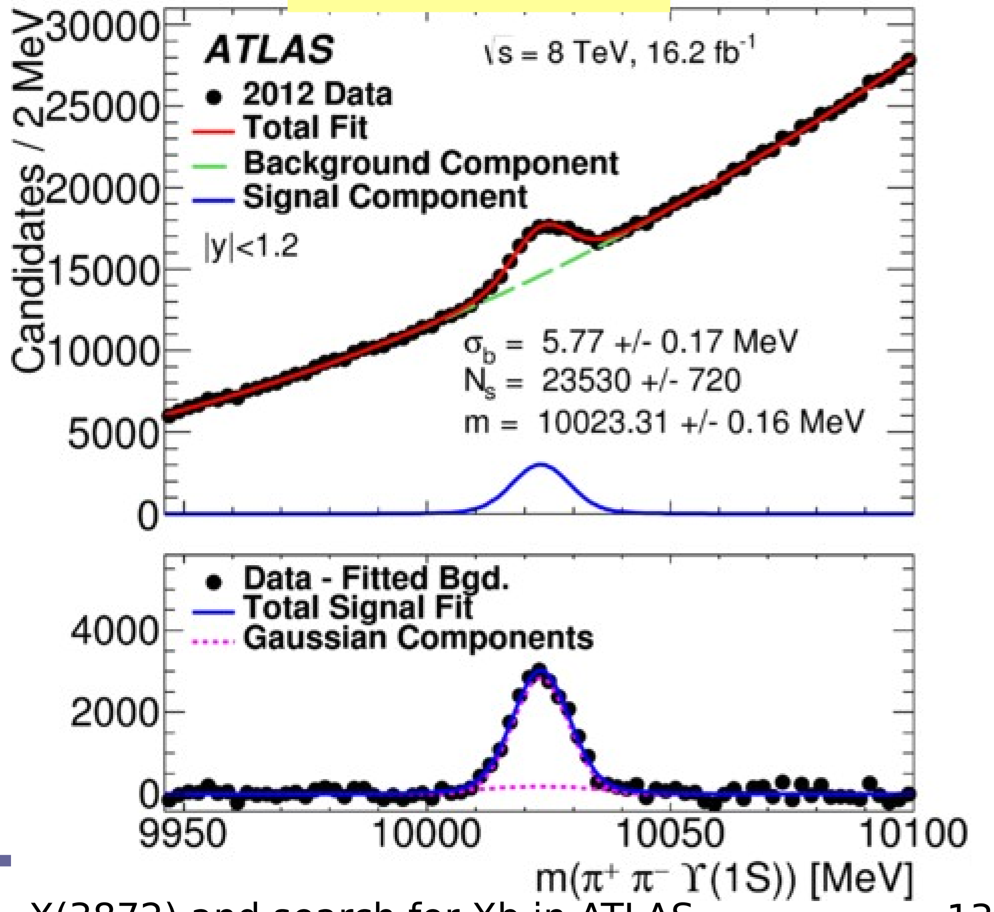
Υ(2S) and Υ(3S) signals (1/2)

- **Signal**: double Gaussian. **Bkg**: 2nd order Chebychev polynomials
- Acceptance = (1.442+- 0.004)% , Efficiency = (28.3 +- 0.2)%
- Nobs(Υ(2S)) used to rescale Spliting functions from MC for Xb:
  - e.g., S|y| = (0.67 / 0.606) * 0.606 = 0.67 from Υ(2S) in data

For best signal region:
Barrel, high cosθ*, high pT



Υ(2S) barrel



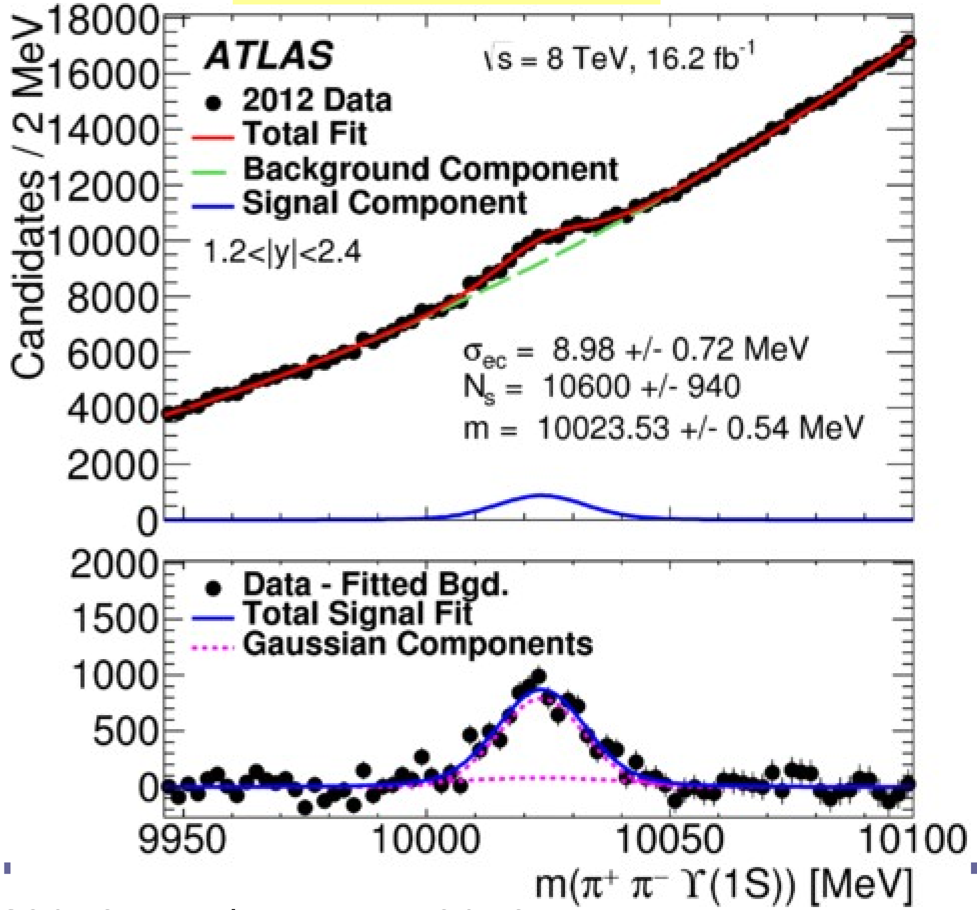
Υ(2S) and Υ(3S) signals (2/2)

- **Signal yields and shapes consistent with MC:**

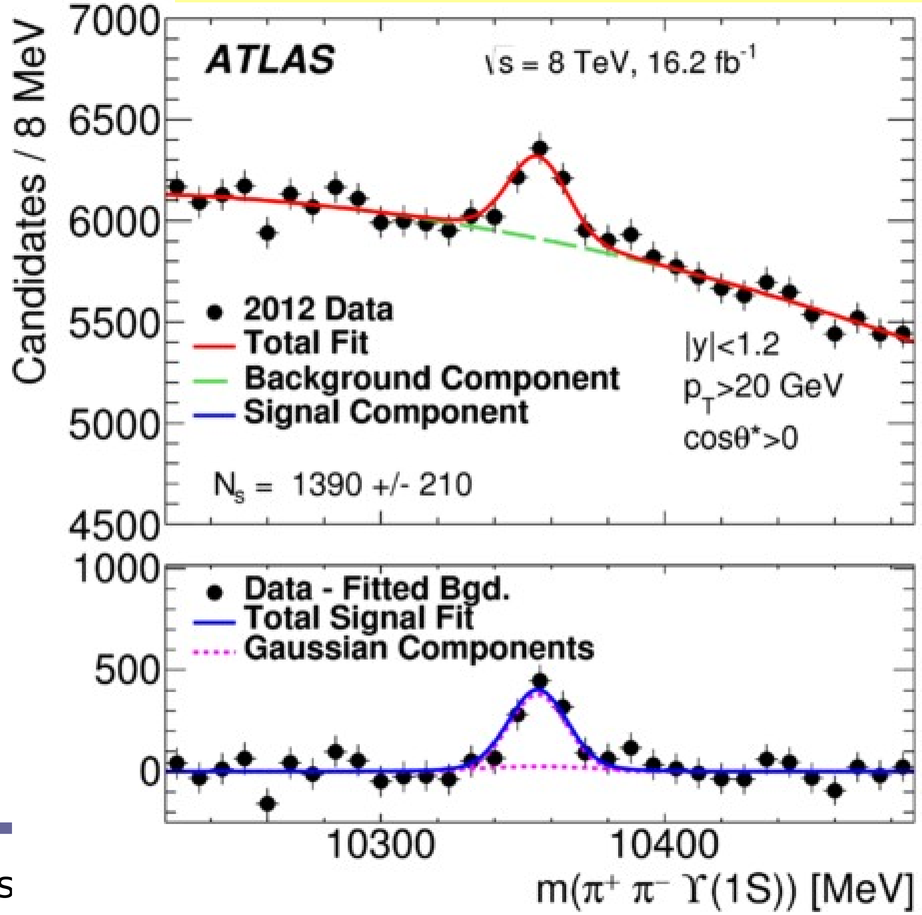
$$N_{2S}^{\exp}=(\sigma*B)_{2S}\cdot L\cdot A\cdot\varepsilon=33300\pm2500 . vs. N_{2S}^{obs}=34300\pm800\, events$$

$$N_{3S}^{\exp}=(\sigma*B)_{2S}\cdot L\cdot A\cdot\varepsilon=11400\pm1500 . vs. N_{3S}^{obs}=11600\pm1300\, events$$

Υ(2S) endcap



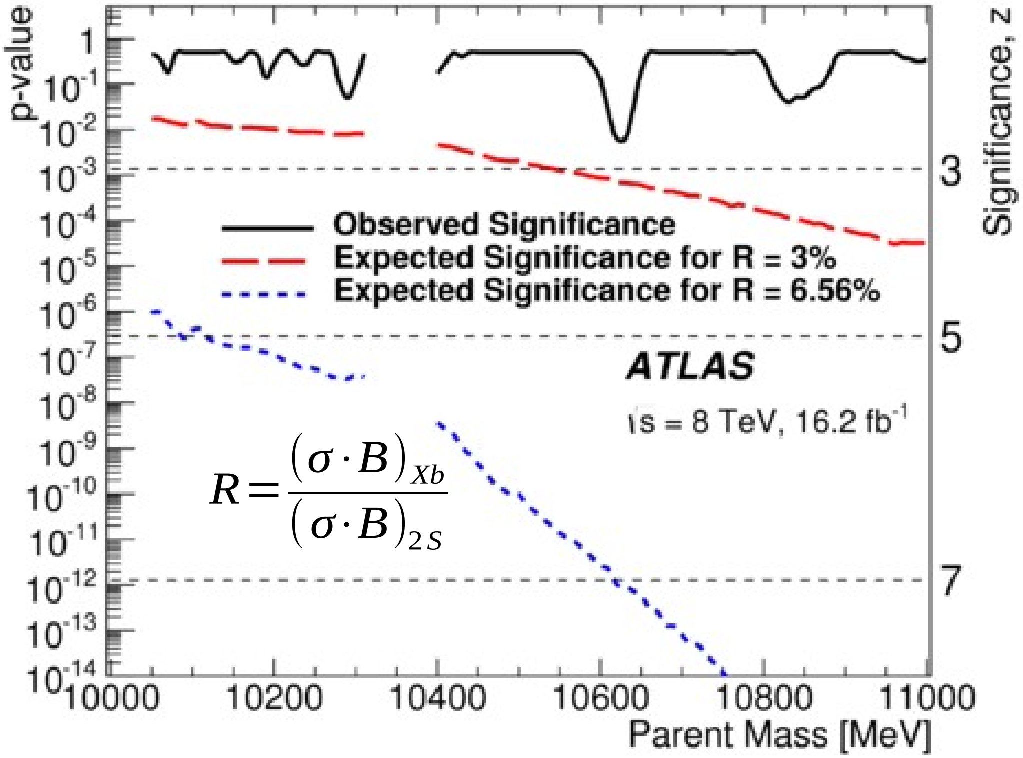
Υ(3S) best signal region:
Barrel, high cosθ*, high pT



Xb search in $X_b \to \Upsilon(1S)\pi^+\pi^-, \Upsilon(1S) \to \mu^+\mu^-$

Test hypotheses of Xb mass:

- Test from 10 GeV to 11 GeV, in steps of 10 MeV
- Assume (|y|, pT) distribution like Y(2S) and Y(3S), and a narrow state. Fit in window increasing with mass: +- 72 MeV for m=10 GeV to +- 224 for 10.9 GeV.
- Use phase-space shape for m(ππ)
- Binned Max Likelihood fit : Simultaneous in all 8 bins
- Limits include effect of systematics [increased limits by <13%, and the 1σ band by 9.5%-25% depending on Xb mass]



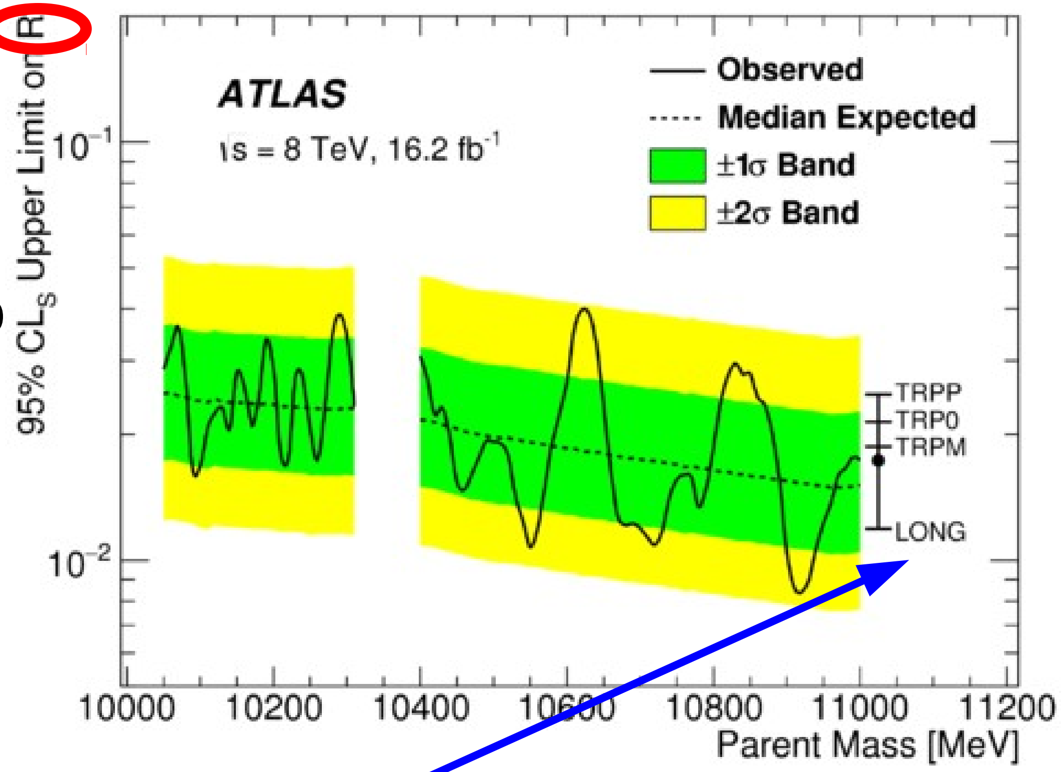
Exclude masses around Y(2S),Y(3S)
Fit: 10.05 -10.31 and 10.40-11.00 GeV

p-value from modified likelihood ratio [asymptotic formula, Cowan et. al. EPJ. C 71 (2011) 1554]: all regions consistent with bkg only → no evidence for new states with local significance >3.

Upper limit on Xb production

- The absence of signal sets upper limit on Xb production.
- Xb production compared to Y(2S)
- Impact of each systematic uncertainty on the factors to calculate R is included as Gaussian-constrained nuisance parameter
  - Xb assumed unpolarised, like the Y(2S) observation. different polarizations shift the limit equally for all masses

$$R = \frac{(\sigma \cdot B)_{Xb}}{(\sigma \cdot B)_{2S}} = \frac{(N / A\varepsilon)_{Xb}}{(N / A\varepsilon)_{2S}}$$



Best limits on R to date:
R< 0.8% to 4%, for m>10.1 GeV

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

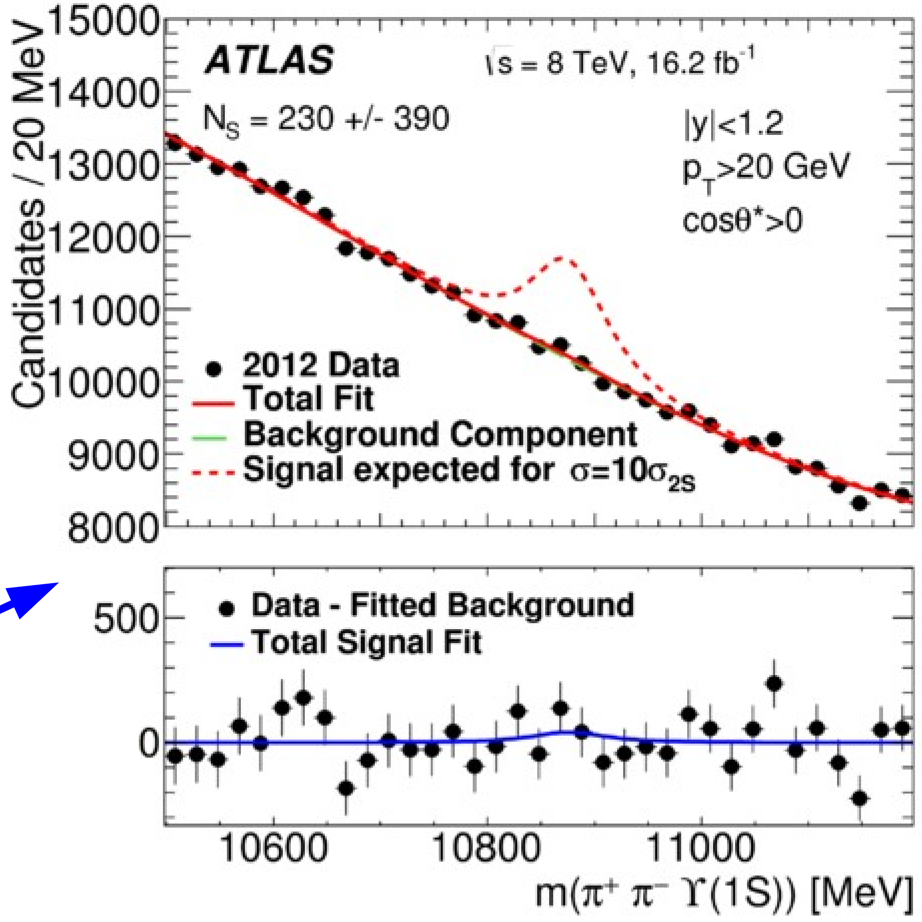
$\Upsilon(1^3D_J)$ Narrow states

- Two extra peaks in the fit. Models give triplet masses at

  10156, 10164 and 10170 MeV.

- Fixing to theses masses, and assuming common signal shapes and splitting functions, no evidence for the triplet.

- σ(triplet)/σ(Y2s) < 0.55 @ 95% CL, using BR from BaBar [PRD 82 (2010) 111102]



$\Upsilon(10860), \Upsilon(11020)$

- Broad states.

  No evidence either

Summary

- X(3872) studies in LHCb and CMS.

  ATLAS study is in progress.

  - Detailed study of the ref. channel [$\psi(2S) \to J/\psi\ \pi^+\ \pi^-$] is done.

- ATLAS searched for b-sector counterpart (Xb), PLB 740(2015) 199-217

  - found no evidence and released the most precise limit on the production of Xb to date:

$$R = \frac{(\sigma \cdot B)_{Xb}}{(\sigma \cdot B)_{2S}} < 0.8\% - 4\% \, (depending\ on\ parent\ mass)\ at\ 95\%\ C.L.$$

  - No evidence for $Y(1^3 D_J), Y(10860), Y(11020)$ either:

    σ(triplet)/σ(Y(2S)) < 0.55 @ 95% C.L.

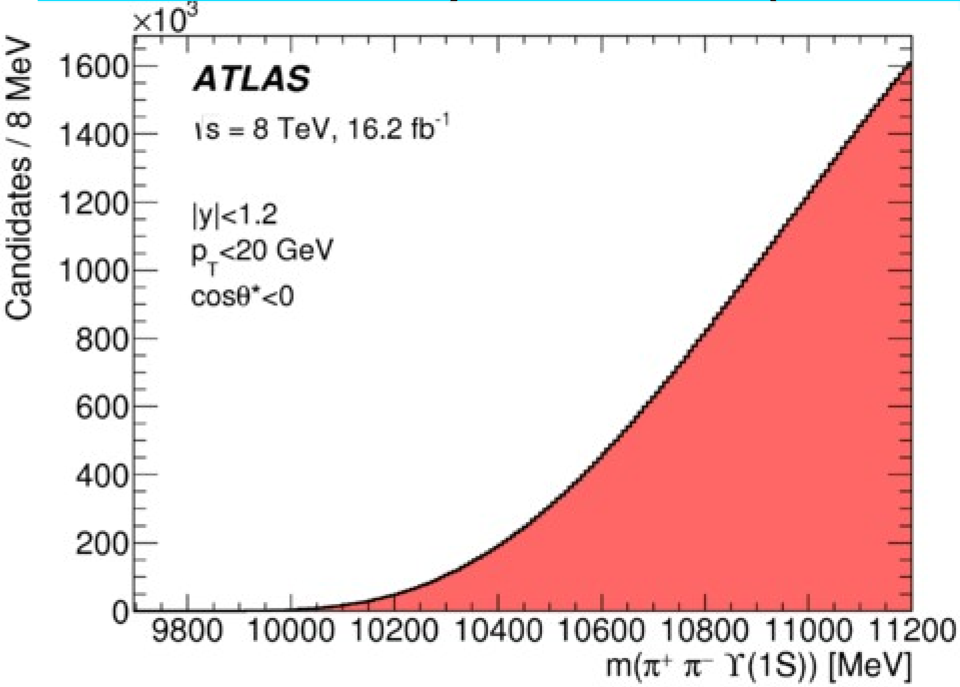
Thank you for your attention

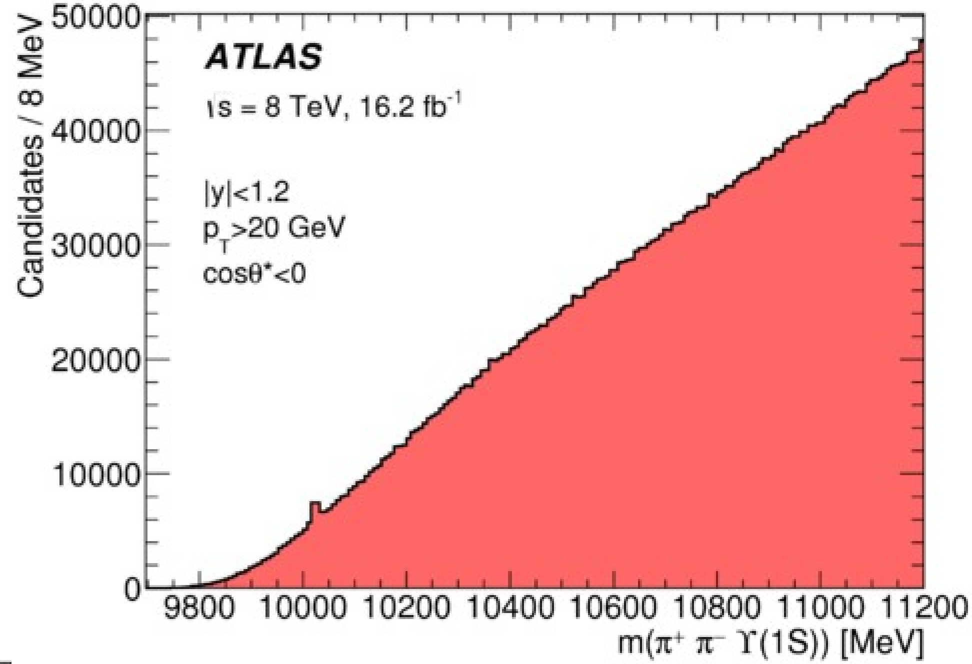
Systematics on R for Xb

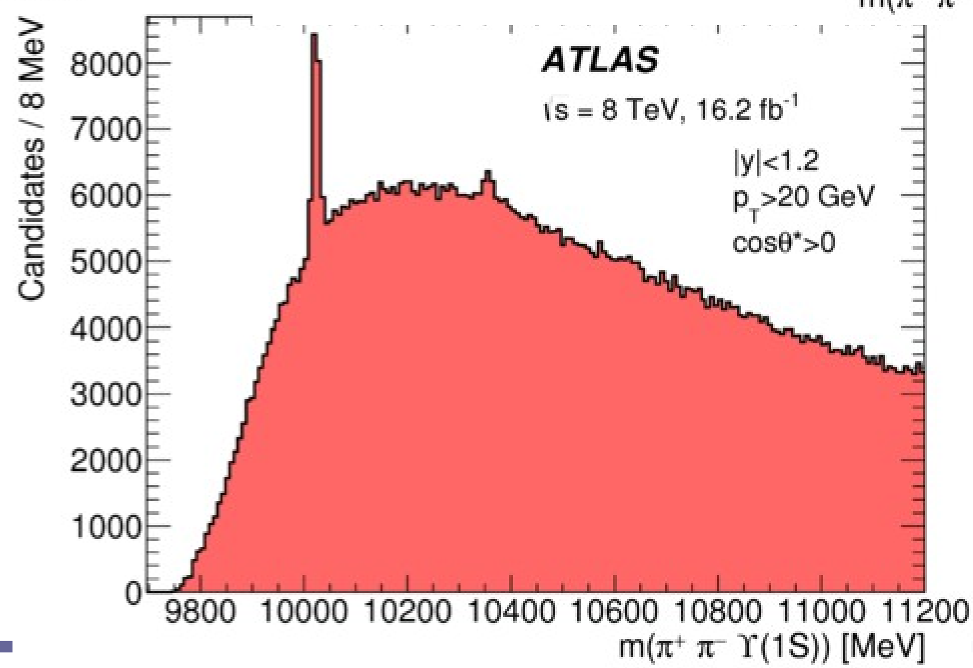
$$R = \frac{(\sigma \cdot B)_{Xb}}{(\sigma \cdot B)_{2S}} = \frac{(N/A\varepsilon)_{Xb}}{(N/A\varepsilon)_{2S}}$$

- Biggest systematics on R for Xb
  - m(ππ) shape:
    - Individual splitting functions change by up to 35%, but the ratio of $\varepsilon_{Xb}/\varepsilon_{2S}$ by up to 17%
  - Linear extrapolation of acceptance between the known Y(2S) and Y(3S): [if extrapolation from Y(1S) to Y(2S) and Y(1S) to Y(3S)]:
    - Change A_{Xb}/A_{2S} by up to 12%
  - Polarization model for Xb spin-alignment, alternative to isotropic (FLAT):
    - As shown in upper limit plot
  - Fitting parameters for signal model: splitting functions, widths of narrow and wide signal Gaussians, efficiency parameters: ~1% change

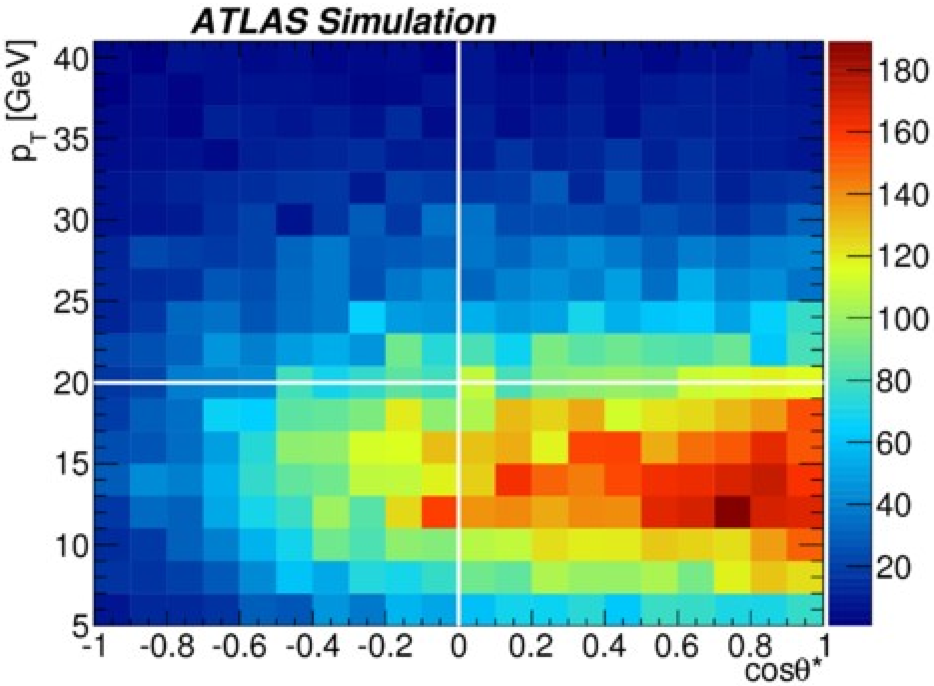
π+π-ϒ(1S) invariant mass distributions for some analysis bins (Barrel, low pT, low cos θ*)



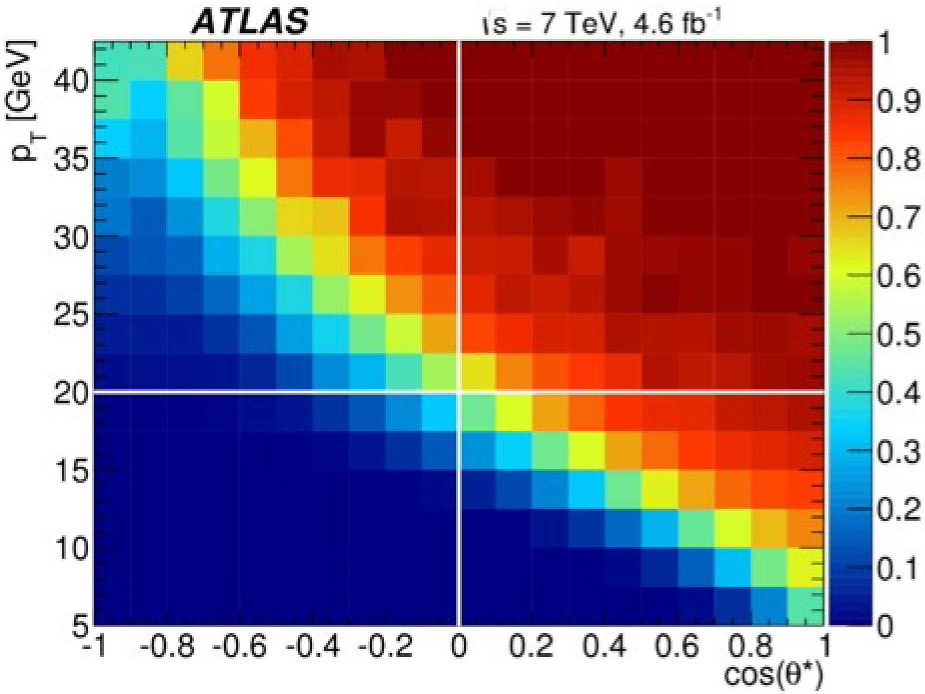




Effect of ΔR(π+, ϒ(1S)) < 0.7 and ΔR(π-, ϒ(1S)) < 0.7 requirements on the π+π-ϒ(1S) candidate. The fraction of combinations passing the requirements is shown.



Signal distribution
in the various bins (simulation)



ATLAS does simultaneous fit to
all bins, instead of applying DR cut
like CMS analysis

Fraction of Signal surviving the
DR(π, Y(1S))< 0.7 requirement