Heavy Quarkonia Production at LHCb

International Workshop on Heavy Quarkonium 2011
Darmstadt, Germany

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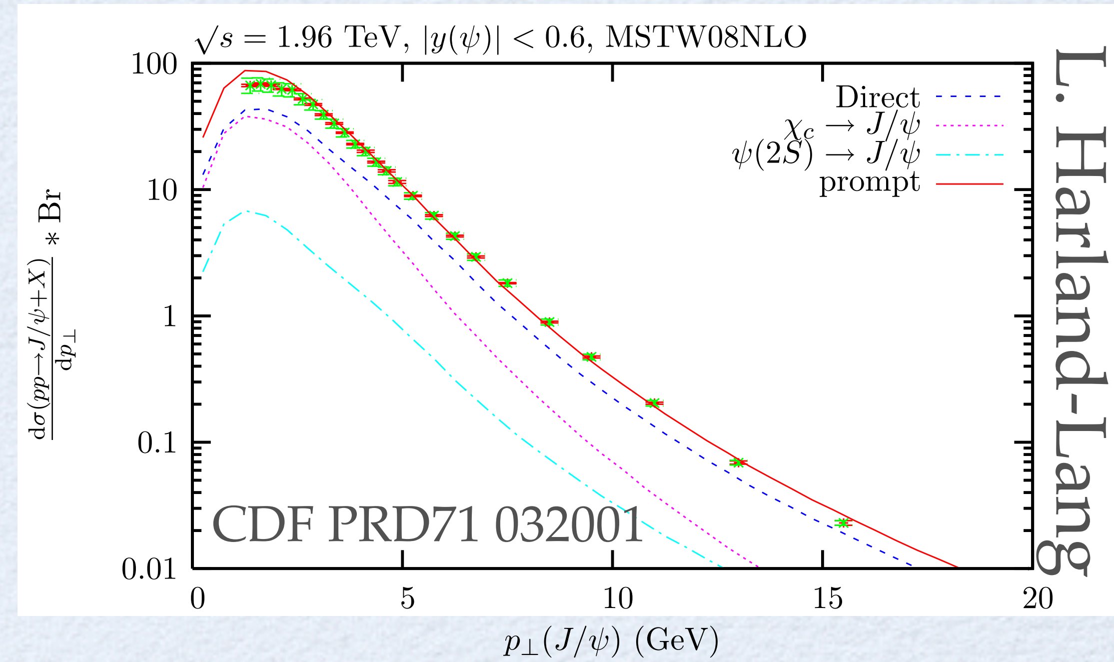
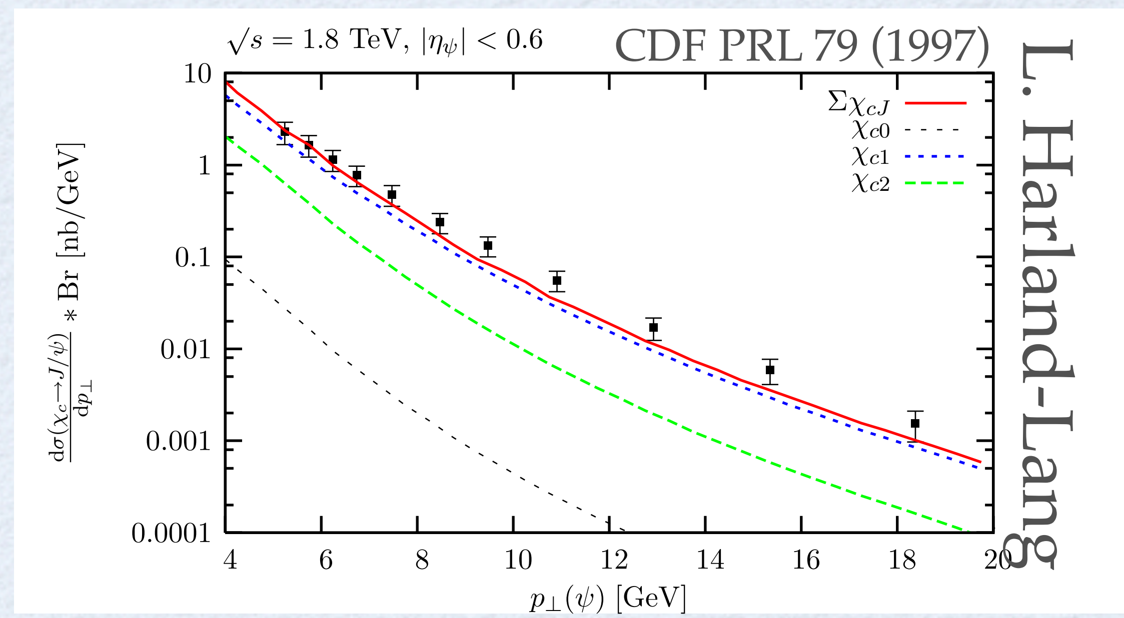
INTRODUCTION

- Quarkonia production mechanism challenging for theory
- Several theoretical models
  - Colour Singlet (CS)
  - Colour Octet (CO)
  - Colour Evaporation (CE)
  - Inclusion of higher order terms (NRQCD)





- NRQCD prediction at LO in αs:
  - CS scales as $1/p_t^6$
  - CO scales as $1/p_t^4$

  (e.g. fair agreement with
  CDF RunI data for leading order colour singlet)

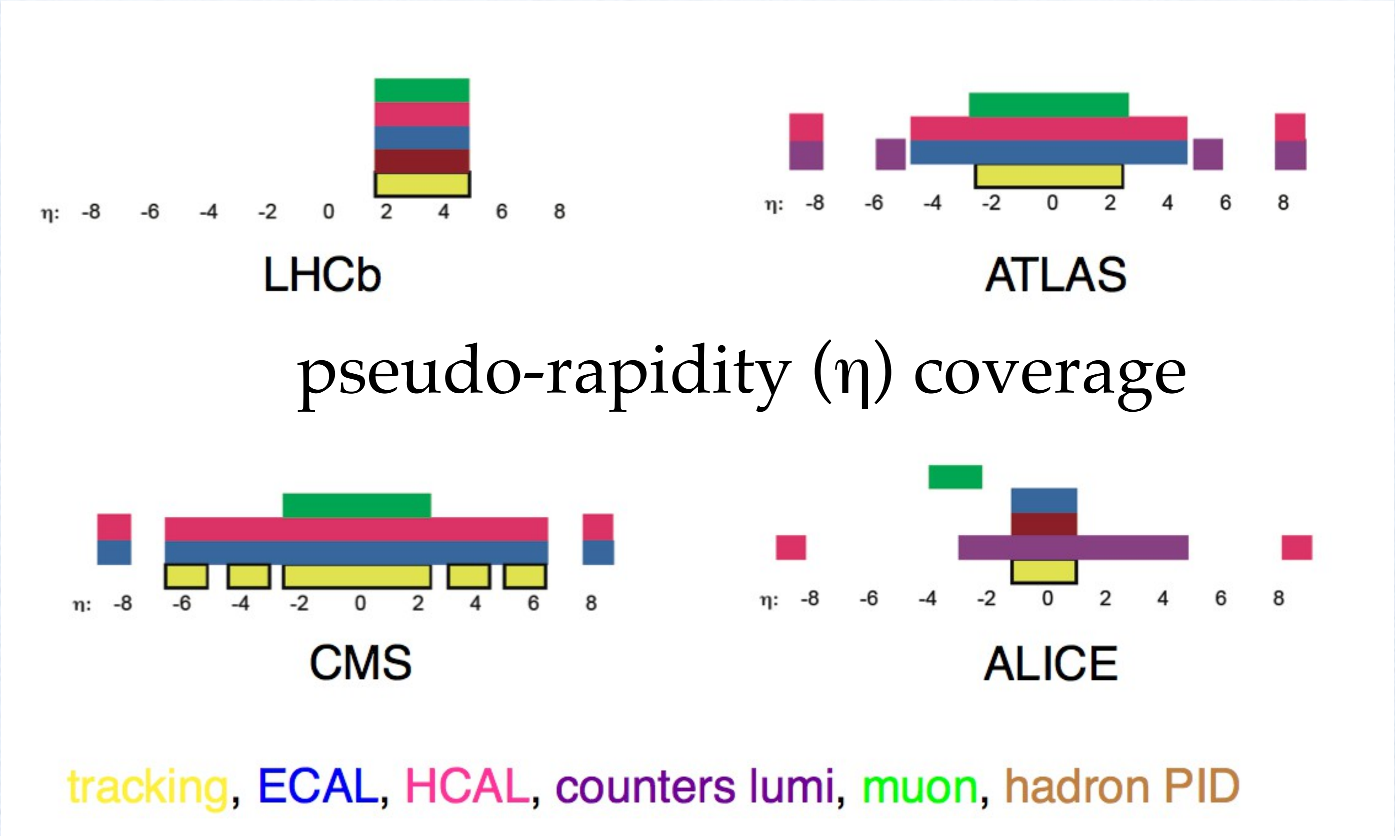
INTRODUCTION II

- However:
  - LO CS does not describe J/ψ production
    - Undershoots measured cross-section
  - LO can be fitted to data, but does not provide scale
    - Also predicts wrong polarisation
  - NRQCD factorisation valid at very low values of p_t ?
  - χ_c feed-down predictions compatible both with low energy (e.g. PHENIX) and high energy (Tevatron, LHC)?
  - Recent NLO corrections at high p_t for χ_c:
    - NLO corrections become large
    - Make CS contribution negative and comparable to CO
    - NLO scale as $1/p_t^4$ → NNLO probably small
- → Further charmonium studies needed

OUTLINE

- LHCb:
  - forward arm spectrometer: unique rapidity range

    ➥ complementary to ATLAS/CMS/ALICE



- In this talk:
  - $\psi(2S)$ cross-section
  - $\Upsilon(1S)$ cross-section
  - Ratio of $\sigma(\chi_{c2})/\sigma(\chi_{c1})$
  - Exclusive χ_c Production
  - χ_b

χ c relative cross section

- Measure production cross section:

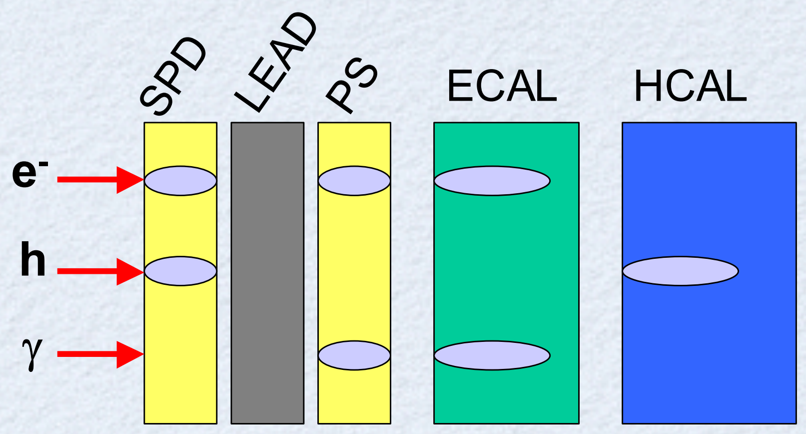
$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = \frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} \cdot \frac{\epsilon^{\chi_{c1}}_{J/\psi}\epsilon^{\chi_{c1}}_{\gamma}\epsilon^{\chi_{c1}}_{sel}}{\epsilon^{\chi_{c2}}_{J/\psi}\epsilon^{\chi_{c2}}_{\gamma}\epsilon^{\chi_{c2}}_{sel}} \cdot \frac{B(\chi_{c1} \to J/\psi\gamma)}{B(\chi_{c2} \to J/\psi\gamma)}$$

in bins of $p_t(J/\psi)$ in the range: $2 < p_t(J/\psi) < 15$ GeV/c

- Simultaneous fit to extract χ_{c0}, χ_{c1}, χ_{c2} yield + BG
  - Fit to mass difference $\Delta m = m(\chi_c) - m(J/\psi)$
    ➥ limit effect of detector resolution, absolute mass scale
  - Assume unpolarised states and investigate effect of polarisation
  - Key ingredient: Determination of the various efficiencies

Photon Identification

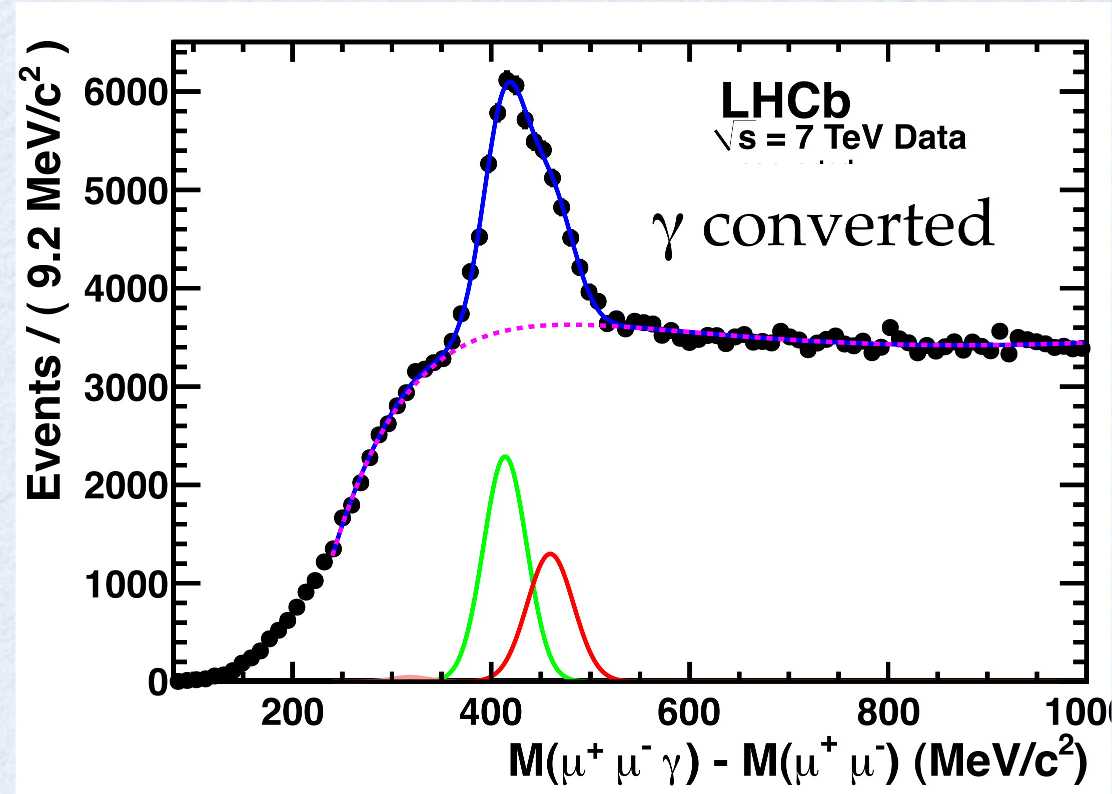
- Photons are reconstructed using the Calorimeter
  - Unconverted photons
  - Converted photons ($\gamma \rightarrow e^+e^-$) *after the magnet*
  - The converted photons are identified by requiring a signal in the Scintillating Pad Detector (SPD)

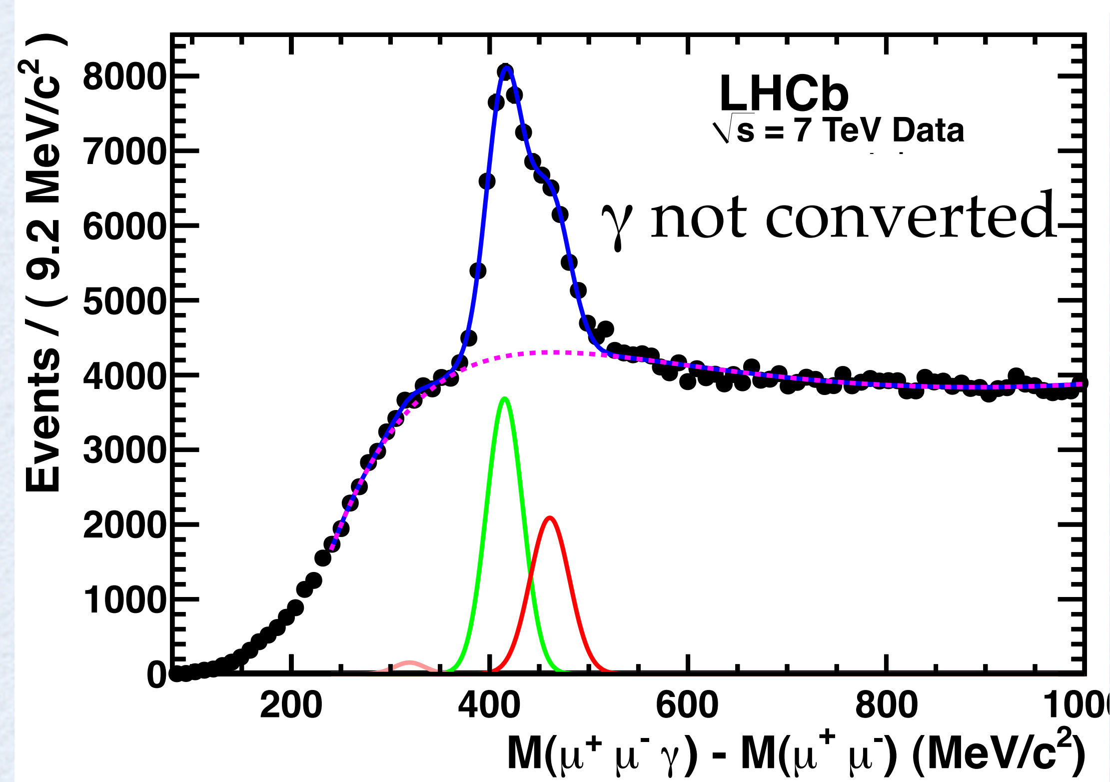


- Photons from χ_c are identified using a Confidence Likelihood (CL):
  - Calorimeter information
  - Tracking information
  - Ratio of track seed energy to ECAL cluster energy
- Additional $e^{\pm}$ rejection: no match between any track and ECAL cluster

χ_c Selection

- J/ψ
  - ➥ same selection as in J/ψ analysis
- Photon Selection:
  - γ CL > 0.5 (from Calorimeter)
  - $p(\gamma) > 5$ GeV/c, $p_t(\gamma) > 0.65$ GeV/c
- Fit model
  - Gaussian for χ_{c1} and χ_{c2} (χ_{c0} as well but hardly visible)
  - Mass-difference function for BG (RooDstD0BG)
- N.B. Calorimeter resolution too coarse to resolve χ_c states





Efficiencies

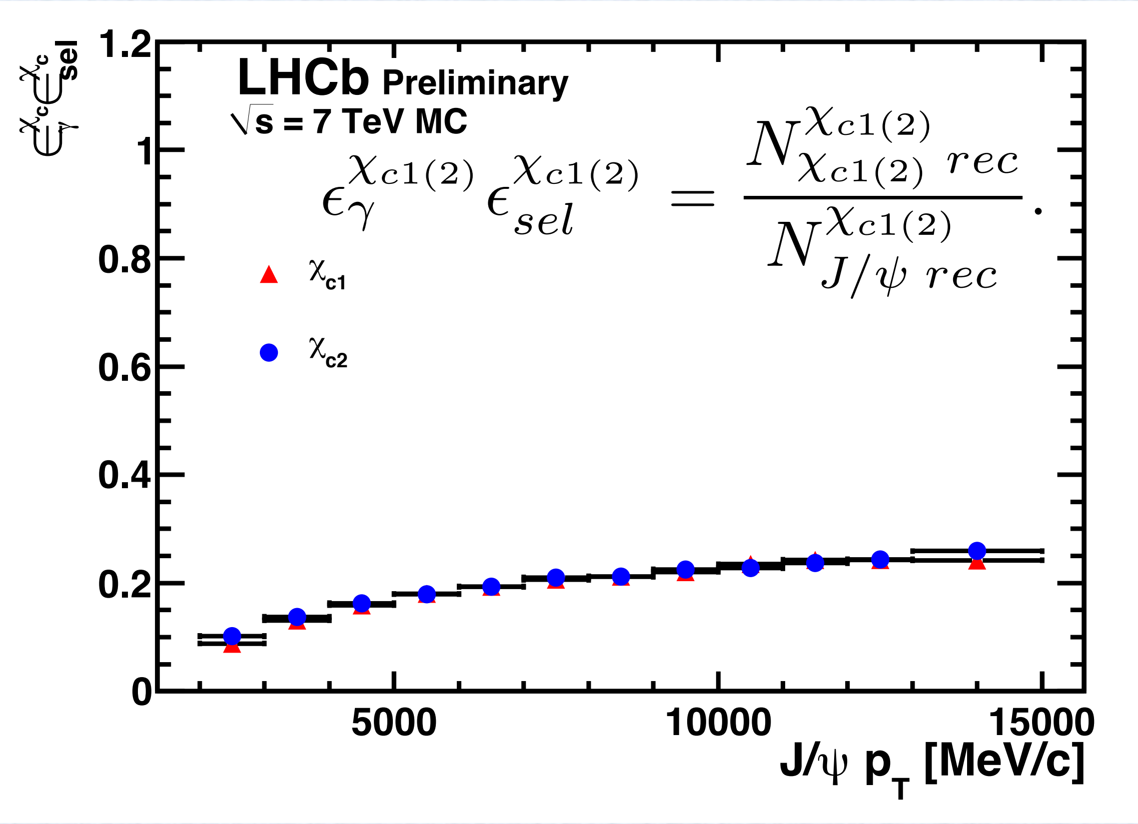
- The following efficiencies enter the ratio of production cross-sections

$$\frac{\epsilon^{\chi_{c1}}_{J/\psi}\,\epsilon^{\chi_{c1}}_{\gamma}\,\epsilon^{\chi_{c1}}_{sel}}{\epsilon^{\chi_{c2}}_{J/\psi}\,\epsilon^{\chi_{c2}}_{\gamma}\,\epsilon^{\chi_{c2}}_{sel}}$$

- Efficiencies are determined using fully simulated events
- Two components:
  - J/ψ reconstruction:
    ➡ ratio consistent with 1 for all $p_t(J/\psi)$

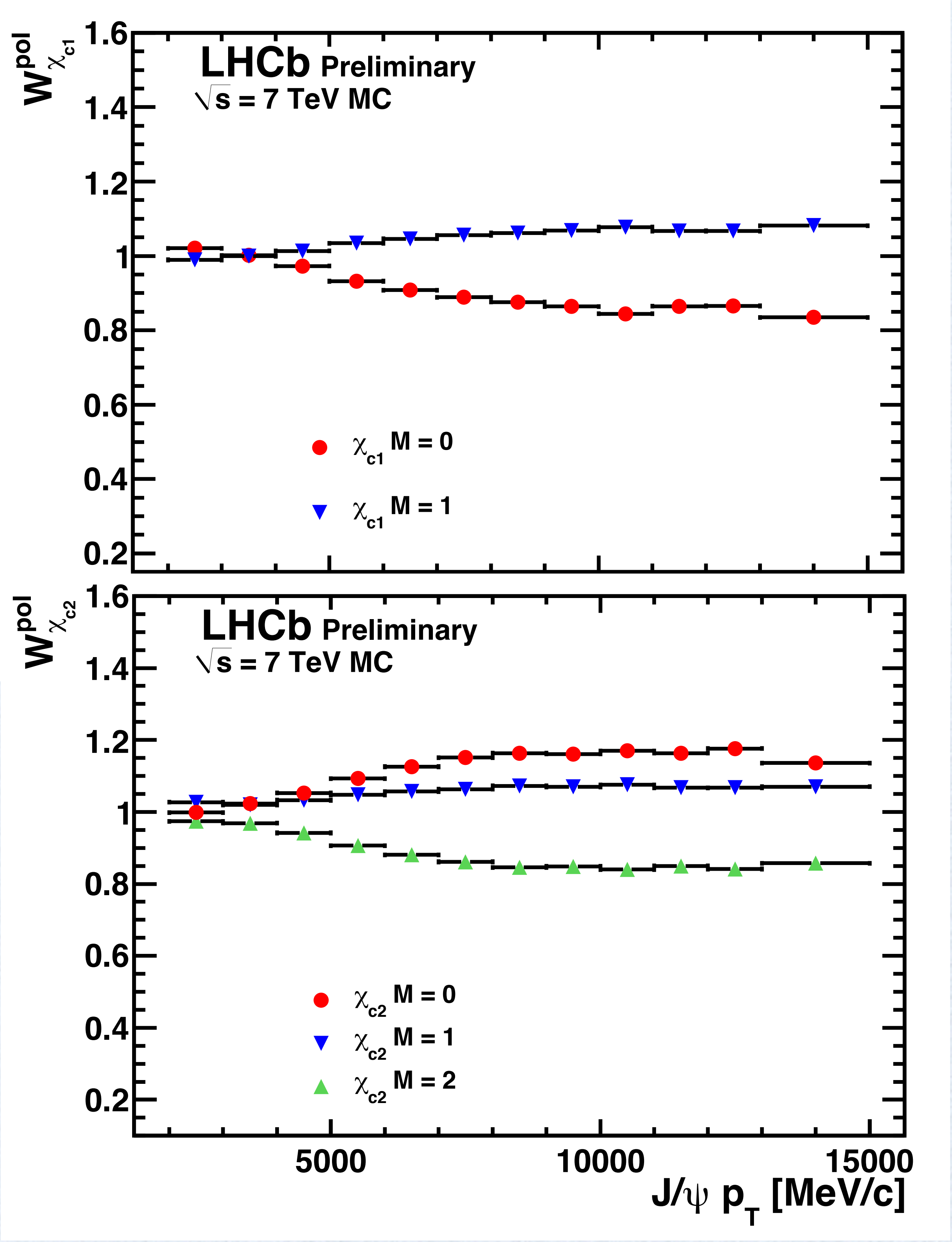
$$\frac{\epsilon^{\chi_{c2}}_{J/\psi}}{\epsilon^{\chi_{c1}}_{J/\psi}} = \frac{N^{\chi_{c2}}_{J/\psi\ rec}}{N^{\chi_{c1}}_{J/\psi\ rec}} \cdot \frac{N^{\chi_{c1}}_{J/\psi\ gen}}{N^{\chi_{c2}}_{J/\psi\ gen}}.$$

- χ_c reconstruction:
  - $N(\chi_c)$: generated χ_c
    → reconstructed and selected
  - $N(J/\psi)$: #J/ψ from a χ_{cJ} state
    - Very similar (but not identical)
    - Cut $p_t(\gamma)$ introduces edge at low $p_t(J/\psi)$

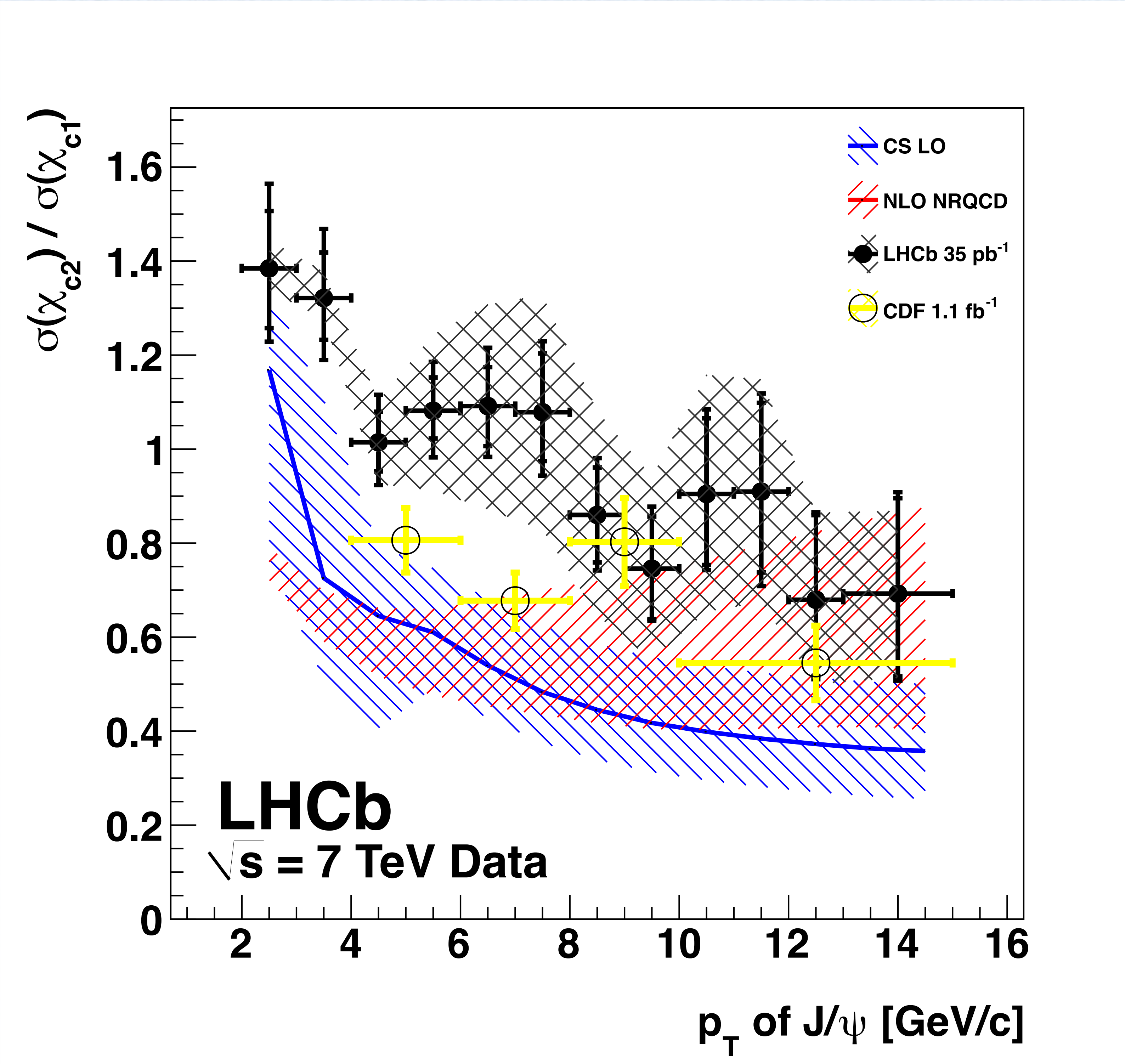


χ_c: J/ψ and χ_c polarisation

- Both the polarisation of J/ψ and χ_c states are unknown
  - Events are simulated assuming no polarisation
  - Effect of polarisation: ➡ Change in efficiencies obtained from sim. events.
- Evaluate by re-weighting simulated events:
  - Fully longitudinal / transverse polarisation of J/ψ
  - According to z component of χ_{cJ} states: M = 0 ... J



χ_c Results

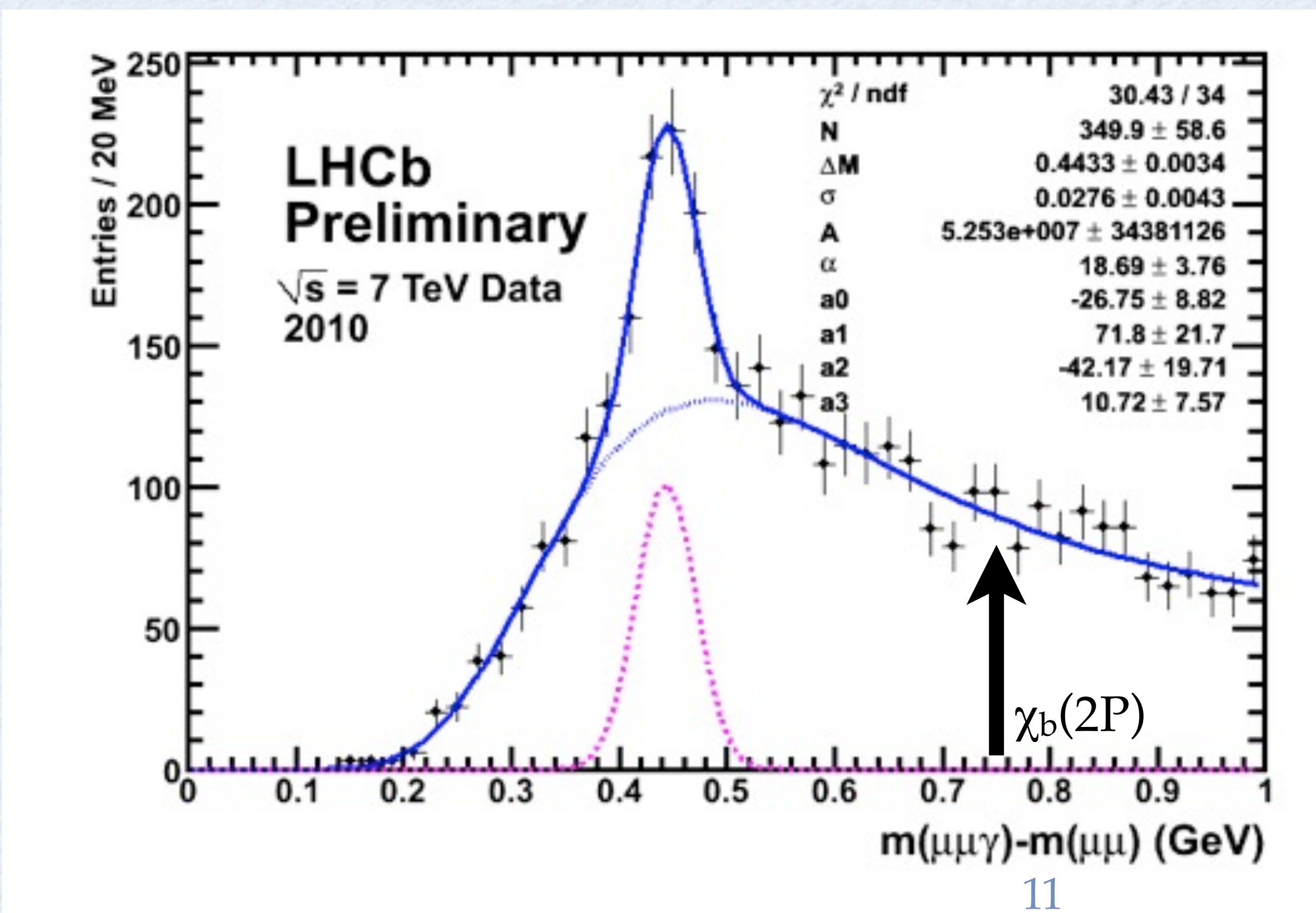


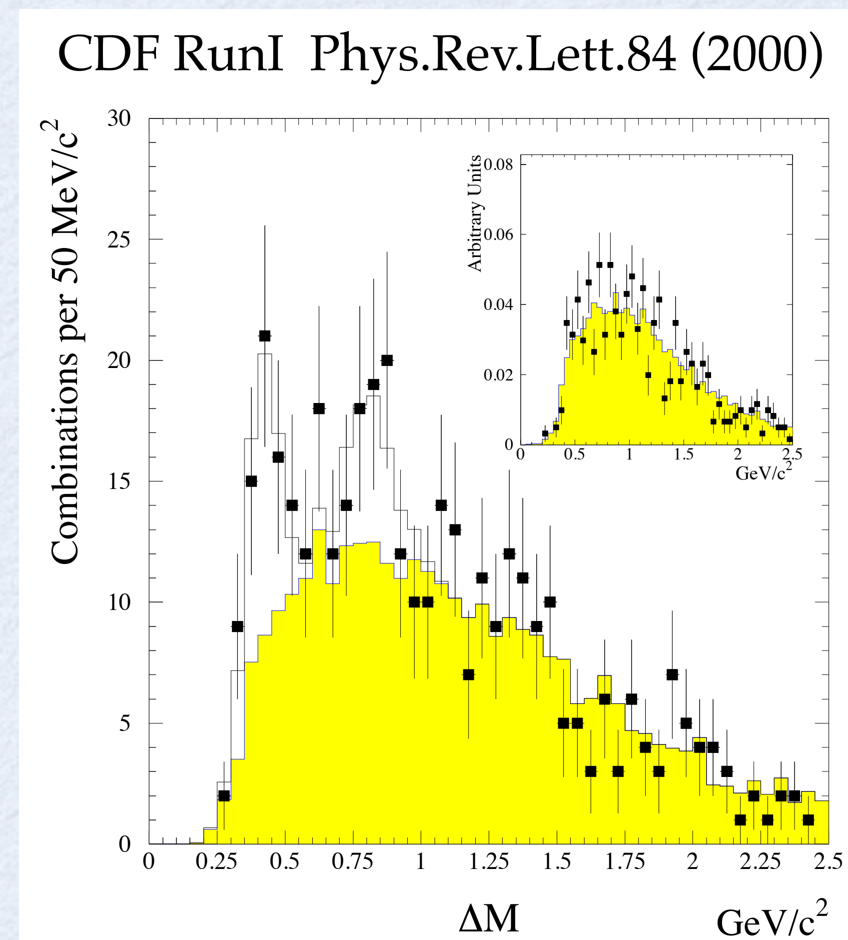
- LHCb:
  - Error bars: stat. and syst. uncertainties
  - Shaded area: Polarisation
- CDF: PRL 98:232001 (2007)

- Blue: Prediction from ChiGen event simulation
- Red : NLO NRQCD PRD 83 111503 (2011)

$\chi_B \rightarrow \Upsilon(1S)\ \gamma$

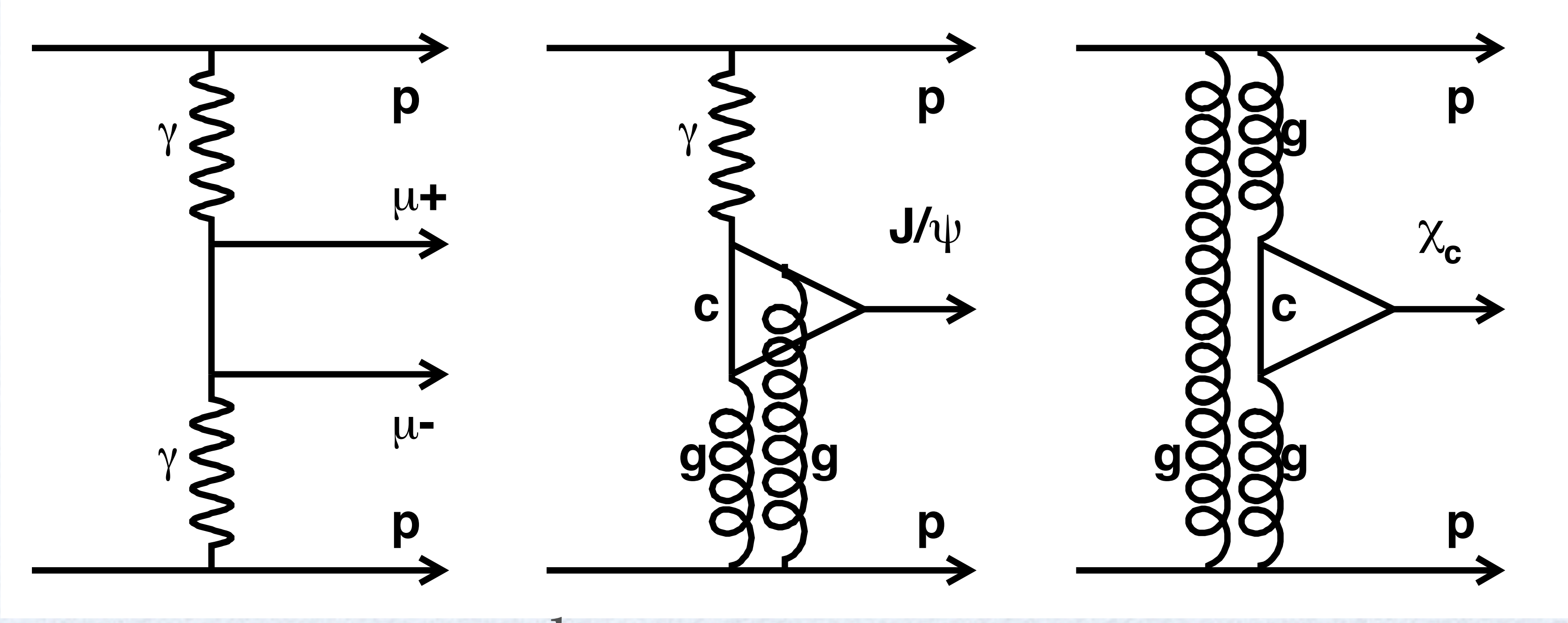
- Analysis in progress: challenging hadronic environment
- Data between April - September 2010: ~ 37 pb^{-1}
- $\Upsilon(1S) \rightarrow \mu^+\mu^-$, photon from calorimeter system
- Present statistics does not allow to distinguish between χ_{b0}, χ_{b1}, χ_{b2}
- However, no $\chi_b(2P)$ state as hinted in CDF RunI measurement, though ~30 times $\Upsilon(1S)$ yield in LHCb 2010 data.





Central Exclusive Production

- Elastic process in which protons remain intact



di-photon

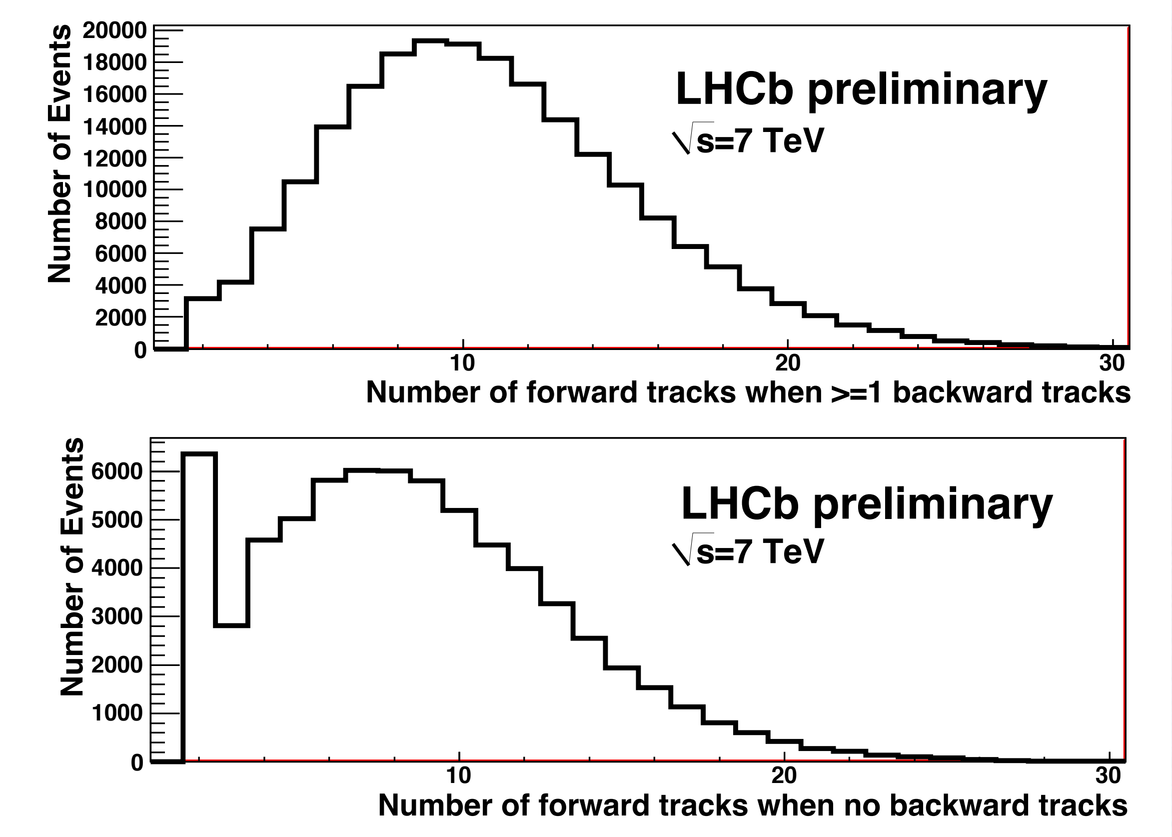
photon-pomeron fusion

double-pomeron exchange

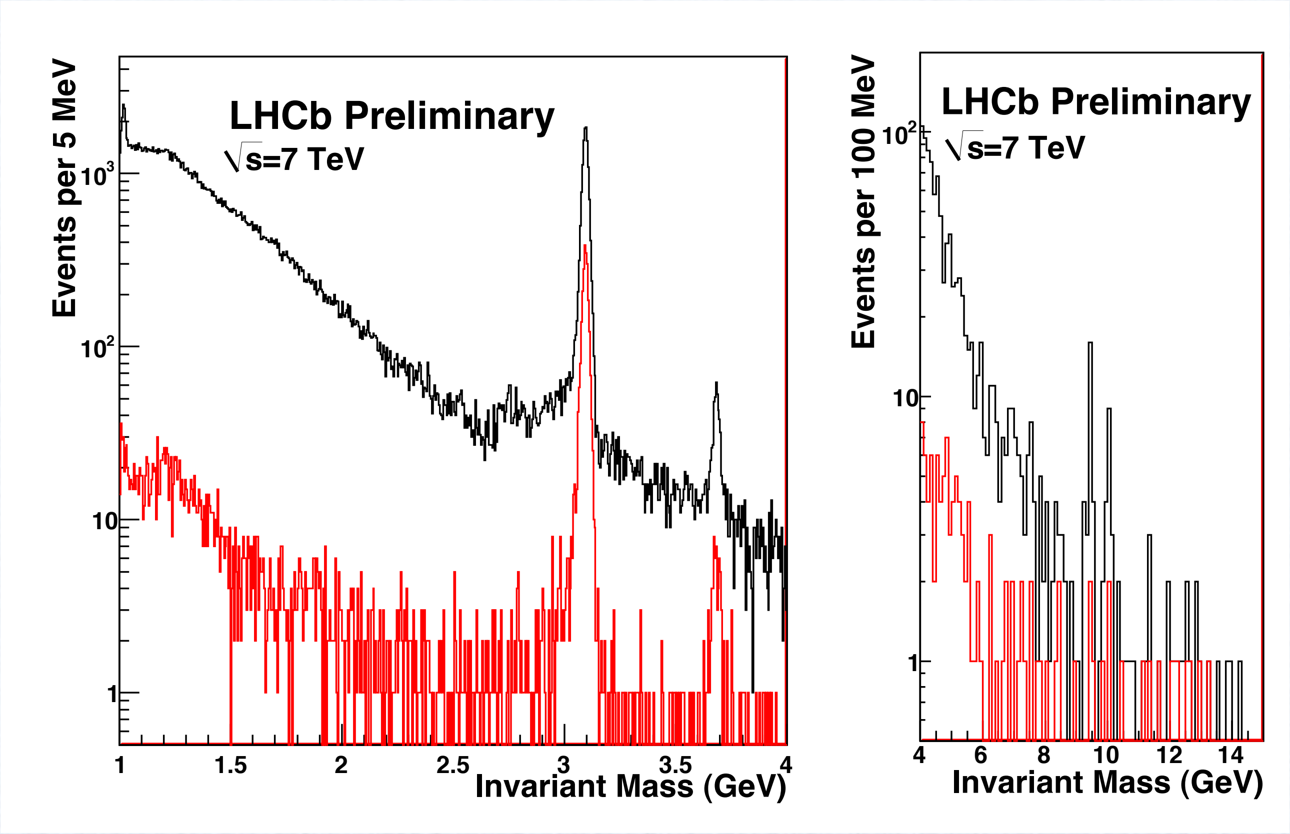
- Analysis performed on 2010 dataset: ~37pb^{-1}
  - Veto multiple interactions: effectively ~3pb^{-1}
- Trigger: require single muon, very low overall multiplicity

CENTRAL EXCLUSIVE PRODUCTION

- Track multiplicity (triggered events)



- Invariant mass spectrum (triggered events)

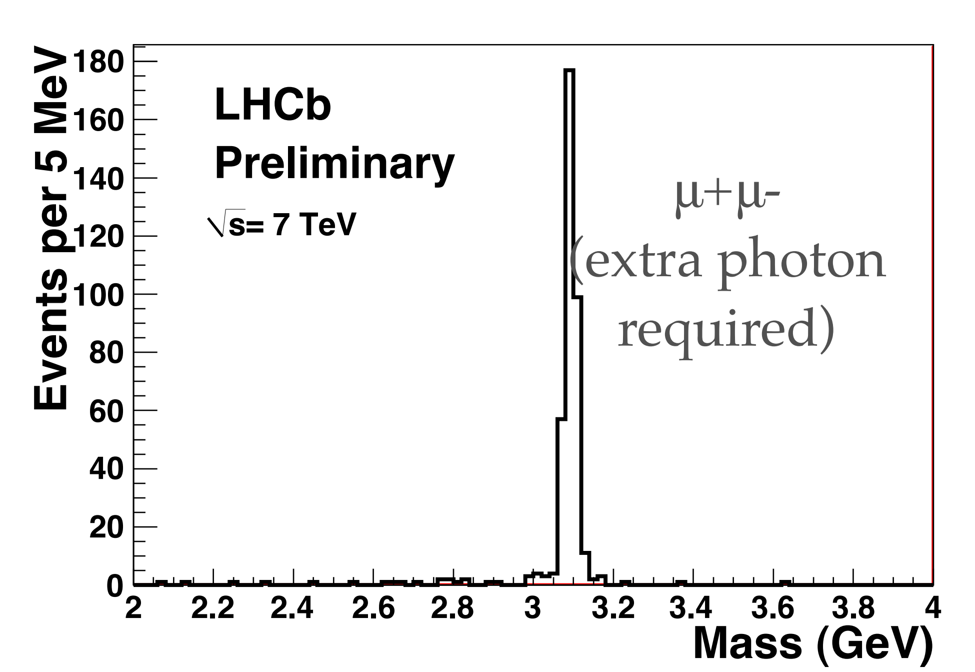


black: all

red: no backward tracks, 2 forward tracks

Central Exclusive Production

- Very clean signals
- Measured cross-sections:



$$\sigma_{J/\psi\to\mu^+\mu^-}(2 < \eta_{\mu+}, \eta_{\mu-} < 4.5) = 474 \pm 12 \pm 51 \pm 92 \text{ pb}$$

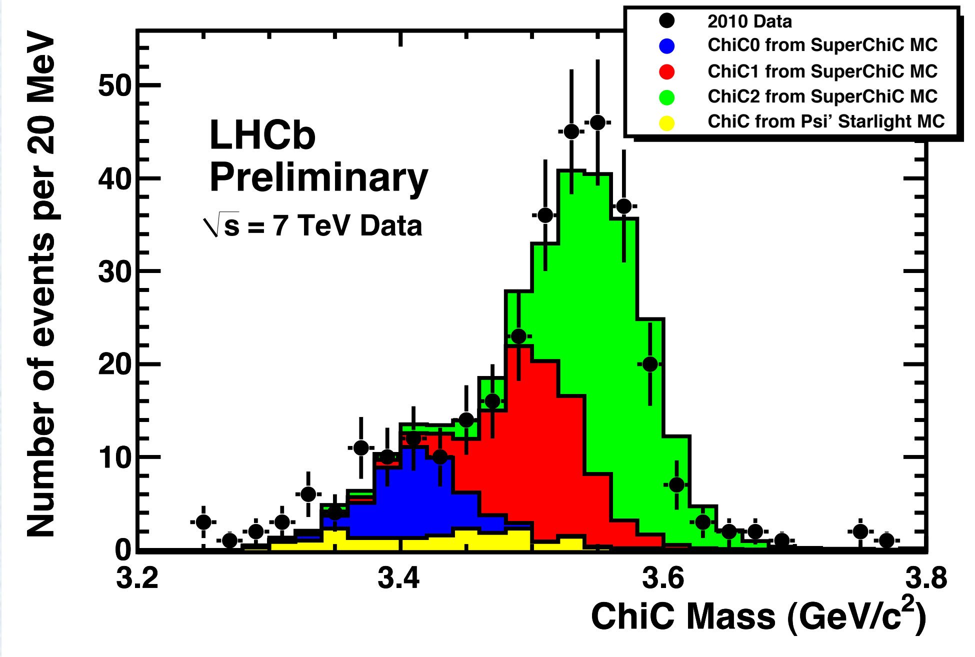
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2 < \eta_{\mu+}, \eta_{\mu-} < 4.5) = 12.2 \pm 1.8 \pm 1.3 \pm 2.4 \text{ pb}$$

$$\sigma_{\chi_{c0}\to J/\psi\gamma\to\mu^+\mu^-\gamma}(2 < \eta_{\mu+}, \eta_{\mu-}, \eta_\gamma < 4.5) = 9.3 \pm 2.2 \pm 3.5 \pm 1.8 \text{ pb}$$

$$\sigma_{\chi_{c1}\to J/\psi\gamma\to\mu^+\mu^-\gamma}(2 < \eta_{\mu+}, \eta_{\mu-}, \eta_\gamma < 4.5) = 16.4 \pm 5.3 \pm 5.8 \pm 3.2 \text{ pb}$$

$$\sigma_{\chi_{c2}\to J/\psi\gamma\to\mu^+\mu^-\gamma}(2 < \eta_{\mu+}, \eta_{\mu-}, \eta_\gamma < 4.5) = 28.0 \pm 5.4 \pm 9.7 \pm 5.4 \text{ pb}$$

$$\sigma_{pp\to p\mu^+\mu^-p}(2 < \eta_{\mu+}, \eta_{\mu-} < 4.5; m_{\mu+\mu-} > 2.5 \text{ GeV/c}^2) = 67 \pm 10 \pm 7 \pm 15 \text{ pb}$$



- σ ± (stat.) ± (syst.) ± (luminosity)
- Results agree with theoretical expectations
  - However, further theoretical work welcome

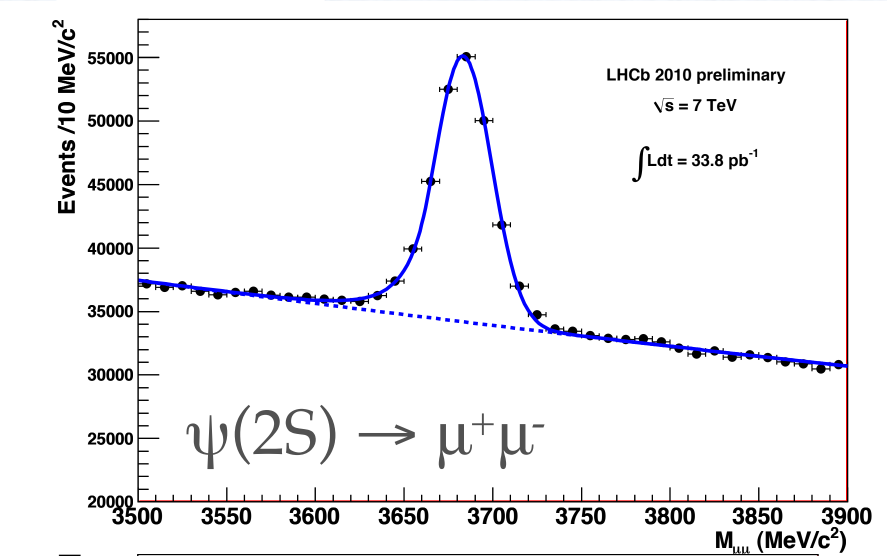
ψ(2S) cross section

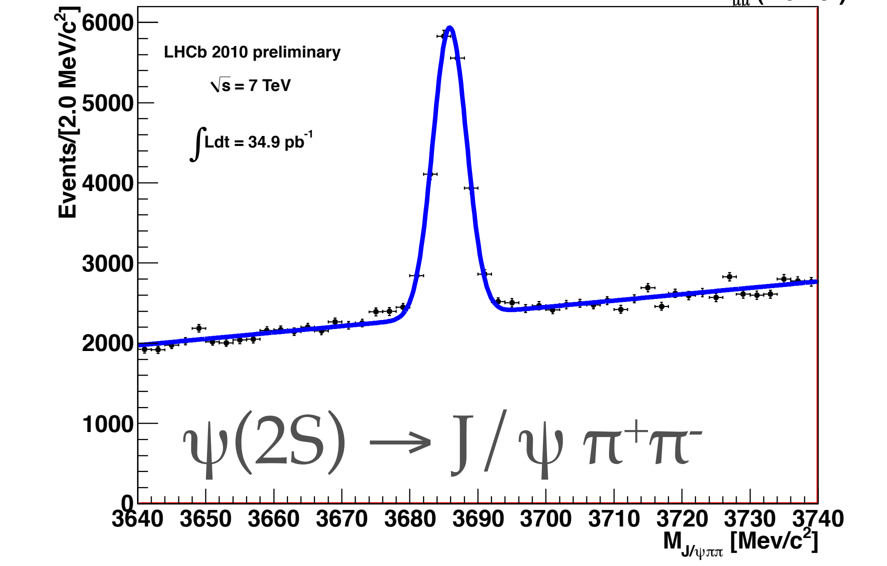
$L = 34\ \mathrm{pb}^{-1}$

- Analyse two decay modes
    - $2 < y < 4.5$
    - $\psi(2S) \rightarrow \mu^+\mu^-$ $(0 < p_t < 12\ \mathrm{GeV}/c)$
    - $\psi(2S) \rightarrow J/\psi\, \pi^+\pi^-$ $(3 < p_t < 16\ \mathrm{GeV}/c)$
- Double ($\mu^+\mu^-$ mode) or single (hadronic mode) differential cross section

$$\frac{d^2\sigma}{dp_T dy}(p_T, y) = \frac{N_{\psi(2S)}(p_\mathrm{T}, y)}{\mathcal{L}_{int}\ \epsilon(p_\mathrm{T}, y)\ \mathcal{B}(\psi(2S) \to e^+e^-)\ \Delta p_\mathrm{T}\ \Delta y},$$

$$\frac{d\sigma}{dp_T}(p_T) = \frac{N_{\psi(2S)}(p_\mathrm{T})}{\mathcal{L}_{int}\ \epsilon(p_\mathrm{T})\ \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)\ \mathcal{B}(J/\psi \to \mu^+\mu^-)\ \ \Delta p_\mathrm{T}},$$

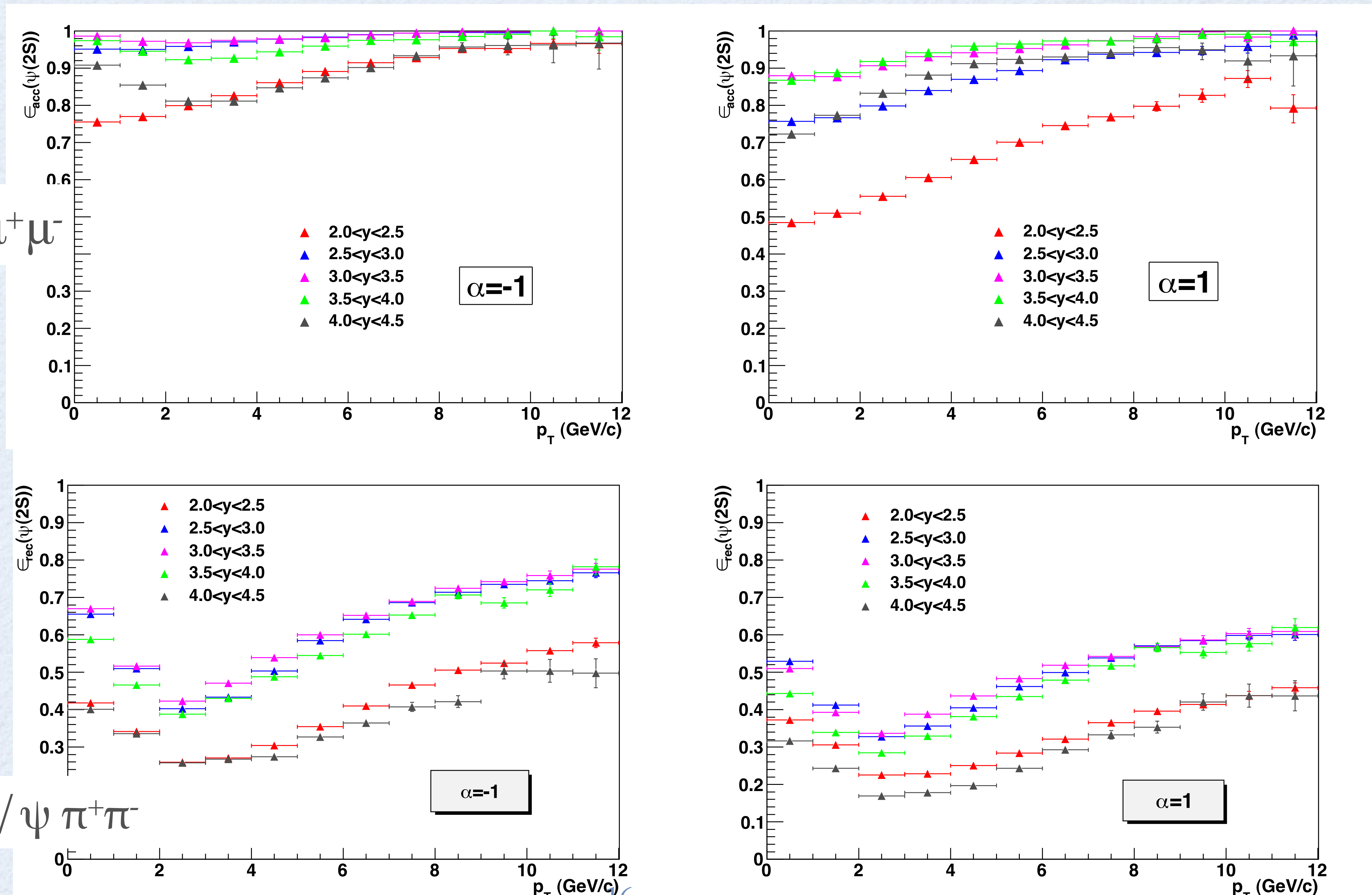




- Assume unpolarised ψ(2S) state
- Estimate efficiency due to acceptance, reconstruction, trigger from simulated events
- In progress: separate prompt and ψ from B decay

ψ (2S) Polarisation

Effect of ψ(2S) polarisation on cross-section measurement



$\psi(2S) \rightarrow \mu^+\mu^-$

$\psi(2S) \rightarrow J/\psi\, \pi^+\pi^-$

ψ (2S) RESULT

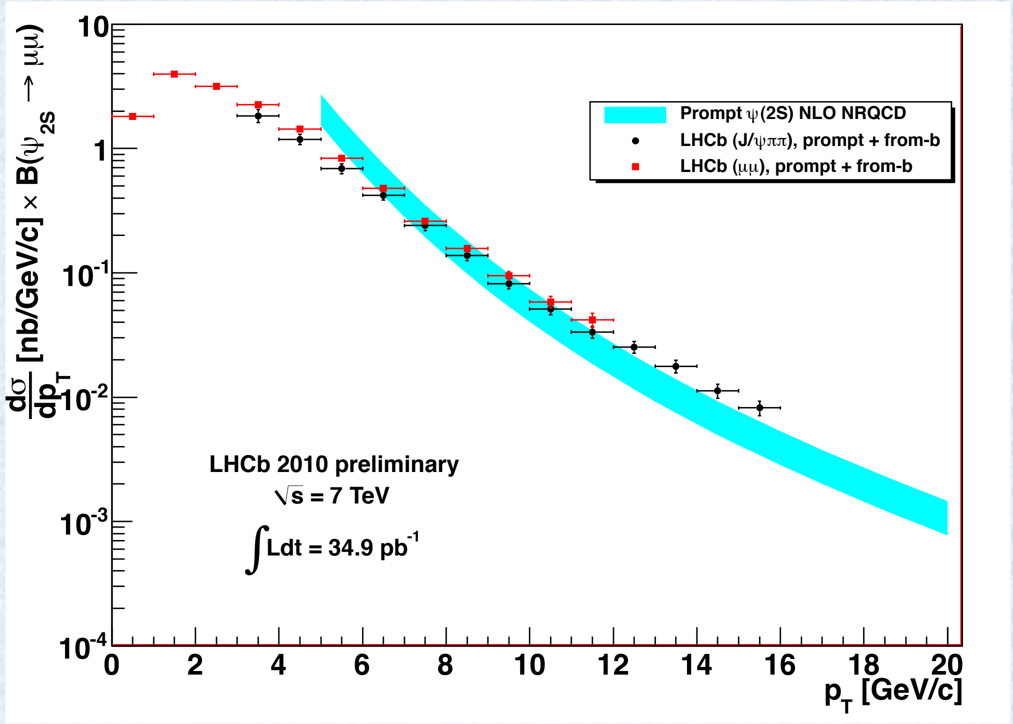
- Cross section measured as:
  - $\psi(2) \rightarrow \mu^{+}\mu^{-}$ $(0 < p_t < 12\ \mathrm{GeV}/c)$

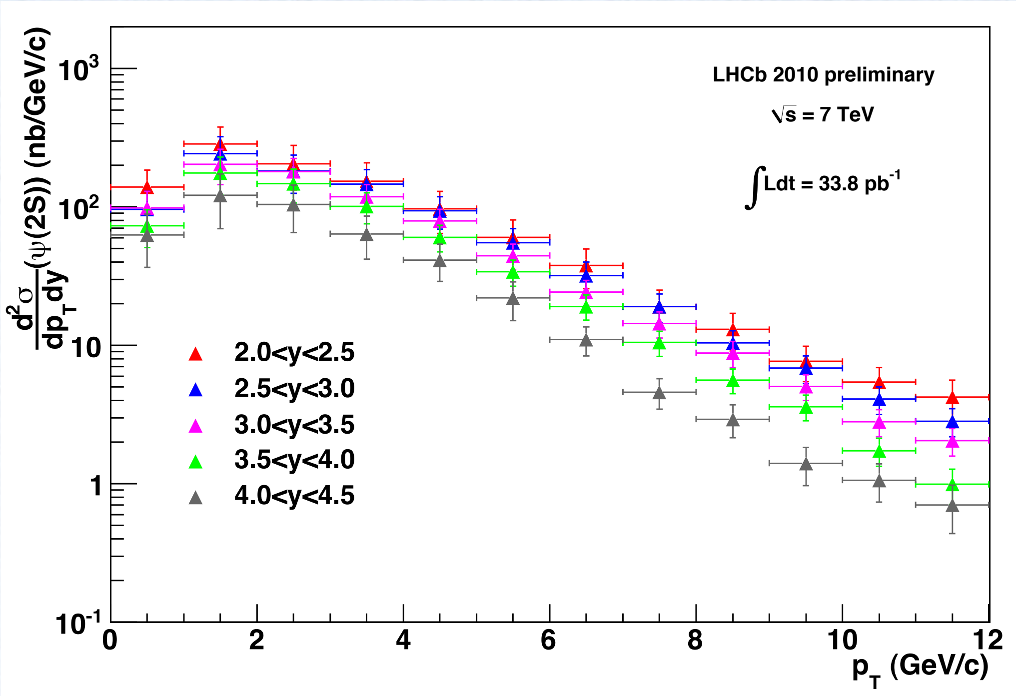
$$\sigma \;=\; 1.88 \pm 0.02 \pm 0.31^{+0.25}_{-0.48}\ \mu b$$

  - $\psi(2) \rightarrow J/\psi\pi^{+}\pi^{-}$ $(3 < p_t < 16\ \mathrm{GeV}/c)$

$$\sigma \;=\; 0.62 \pm 0.04 \pm 0.12^{+0.07}_{-0.14}\ \mu b$$

- Good agreement with recent NLO predictions
  - Need colour - octet contribution (see next slide)
  - Predictions for low p_t $(0 < p_t < 4\ \mathrm{GeV})$?

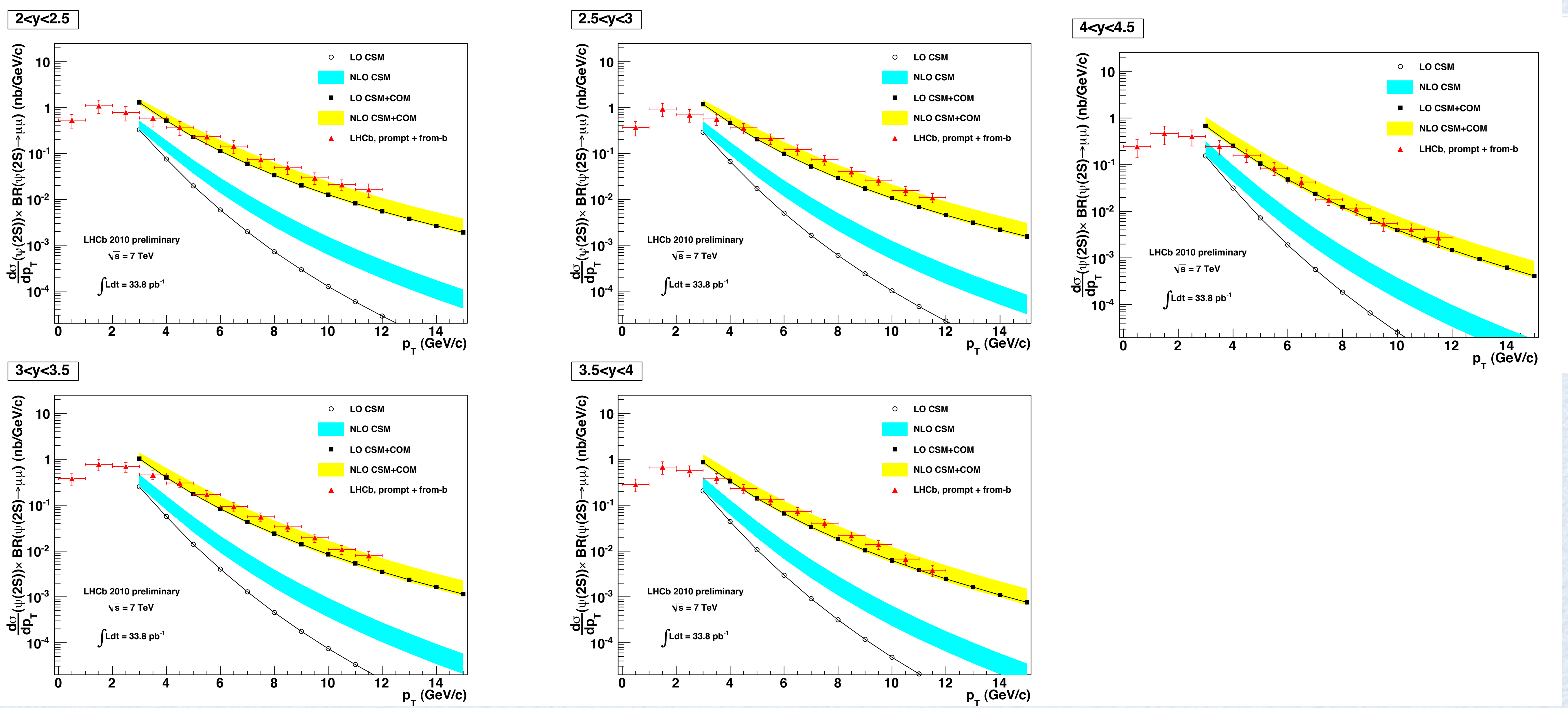




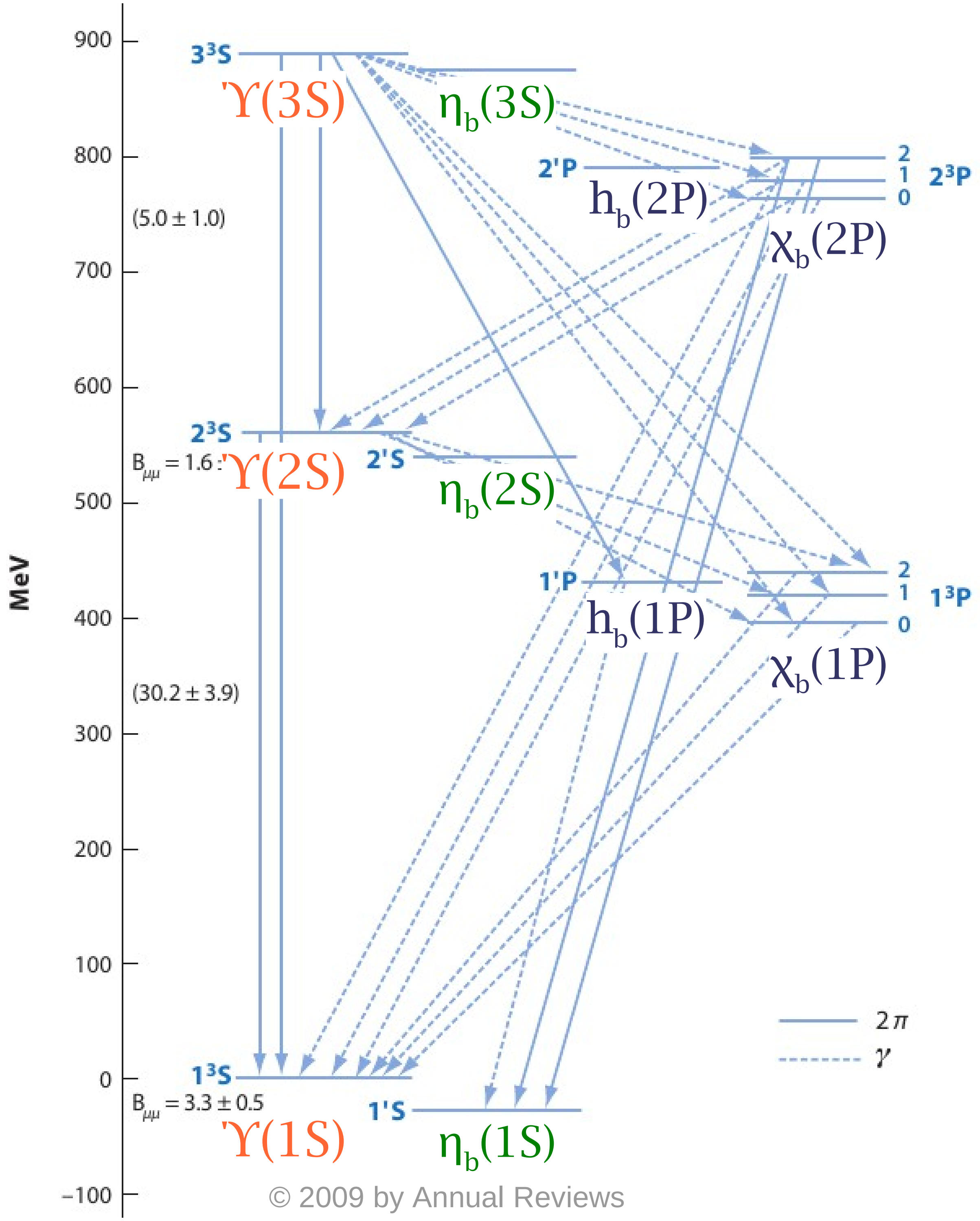
ψ (2S) Result

$\psi(2S) \rightarrow \mu^+\mu^-$:

Yellow: NLO CSM+COM, Blue: NLO CSM



Υ production



Bottomonium states

Two sources of Υ(1S)

- Direct production:

$$pp \to b\bar{b} + X$$
$$\to \Upsilon(1S) + X$$

- Feed-down from higher states

$$pp \to b\bar{b} + X$$
$$\to \chi_b$$
$$\to \Upsilon(1S) + \gamma$$

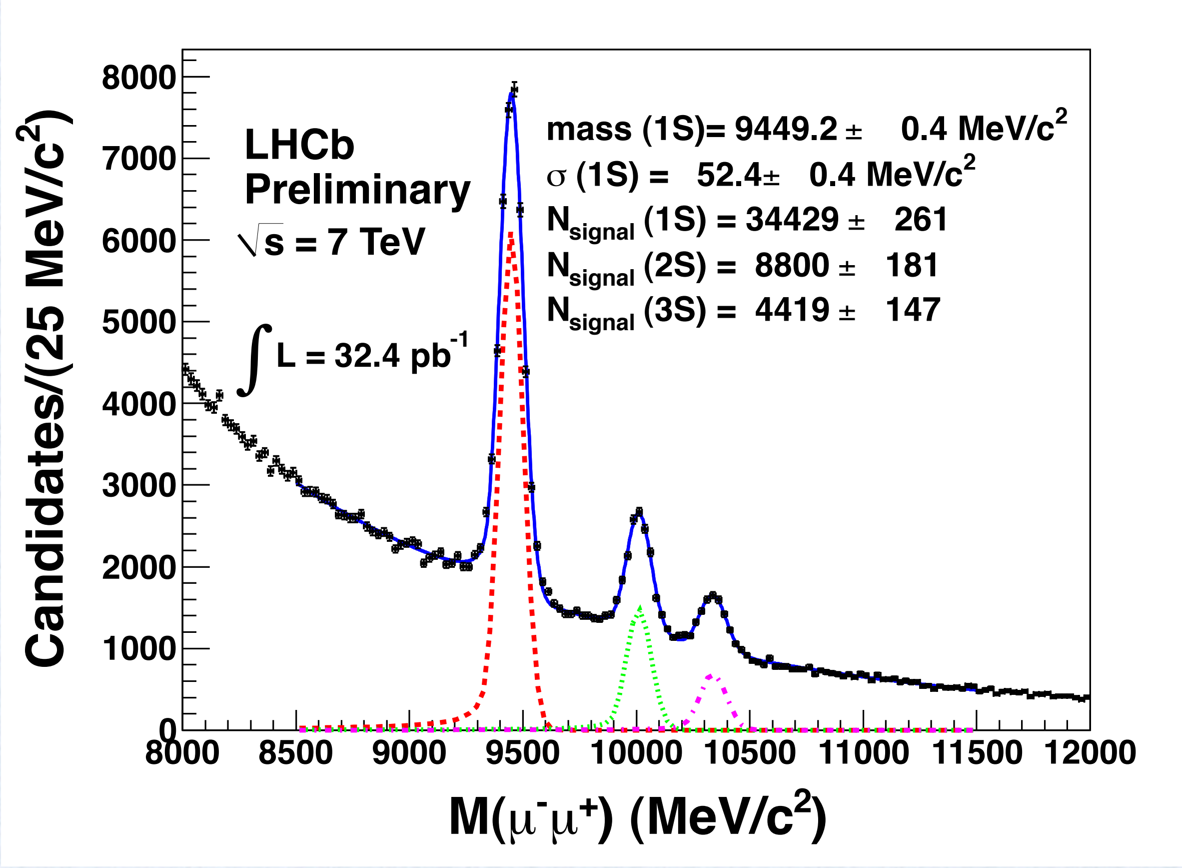
$$\to \Upsilon(nS)$$
$$\to \Upsilon(1S) + X$$

ϒ(1S) cross-section

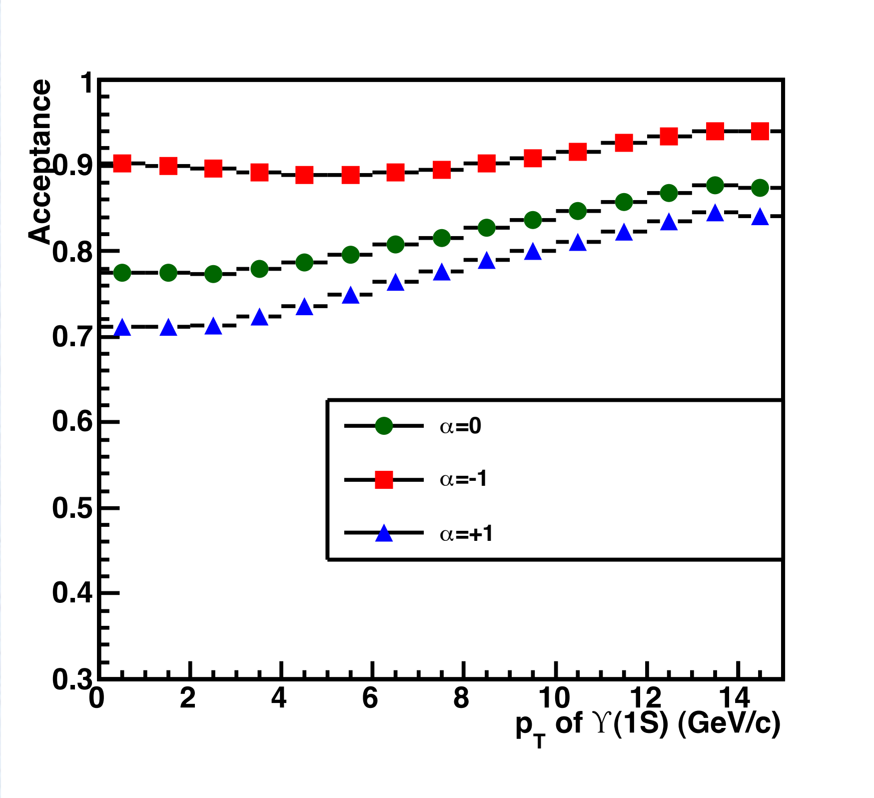
- Analysis strategy:
  - Measure double differential cross section in rapidity and p_t

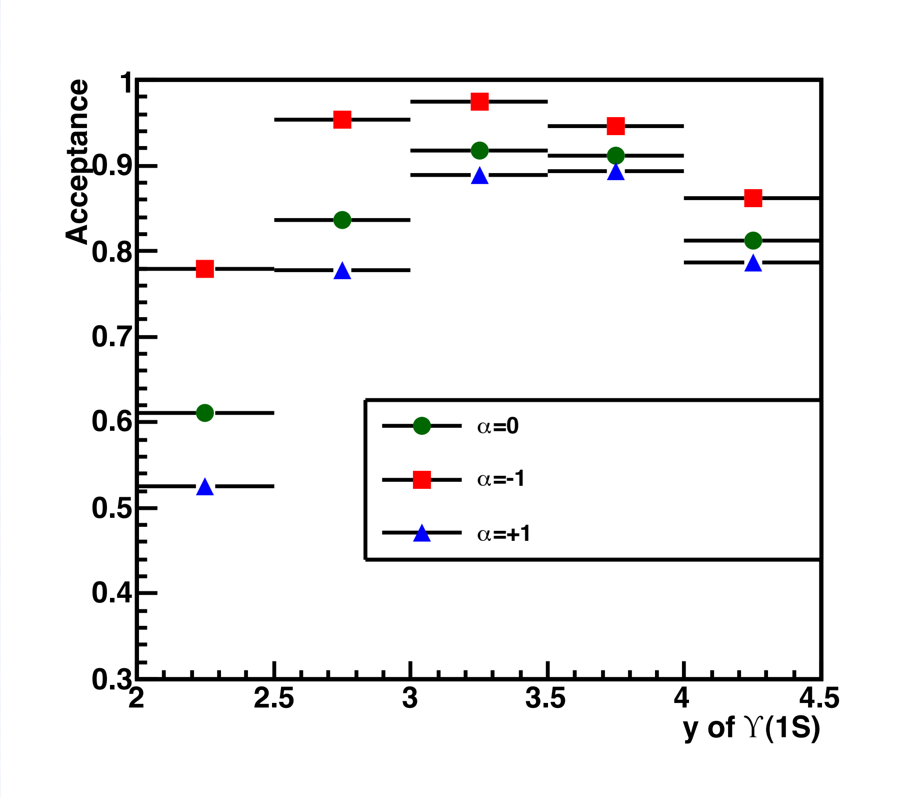
$$\frac{d^2\sigma}{dp_T dy} = \frac{N(\Upsilon(1S) \to \mu^+\mu^-)}{\mathcal{L} \times \varepsilon \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) \times \Delta y \times \Delta p_T},$$

- μμ final state
- $0 < p_t < 15$ GeV, $2 < y < 4.5$
- Data from April - Nov. 2010, integrated luminosity: 32.4 pb^{-1}
- Acceptance and reconstruction efficiencies estimated from simulation, trigger eff. from data



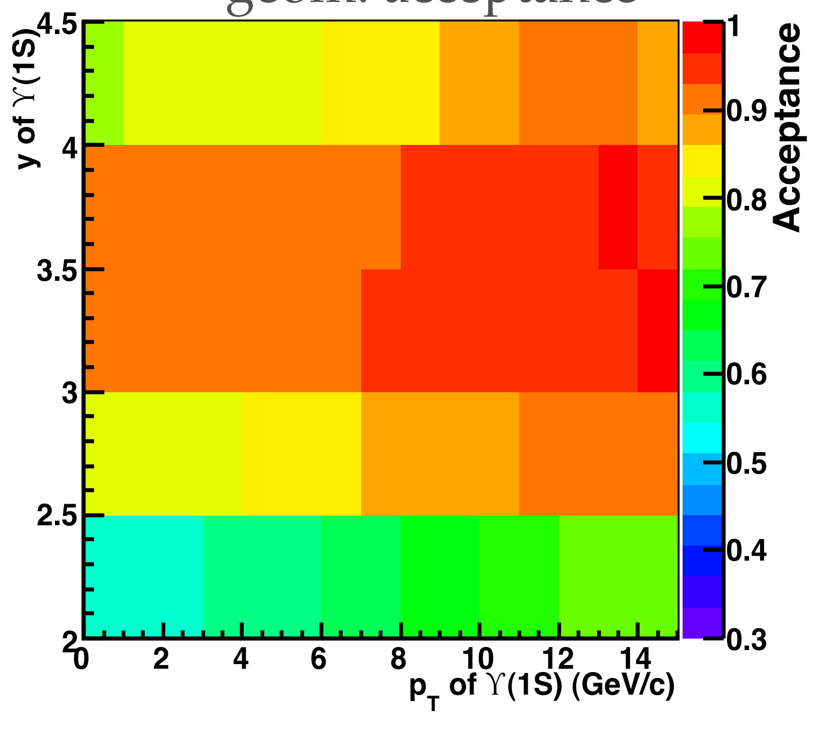
ϒ(1S) efficiencies



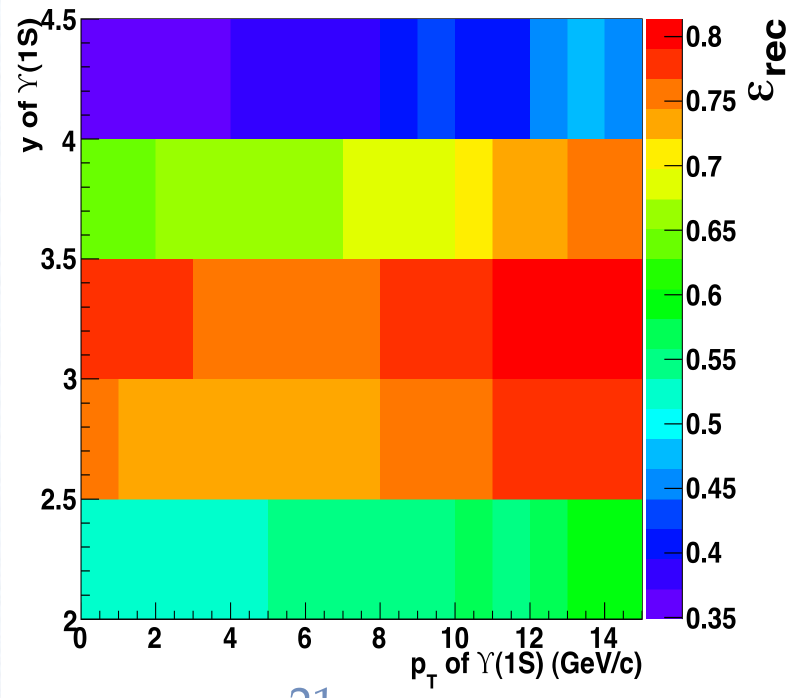


Effect of polarisation

geom. acceptance



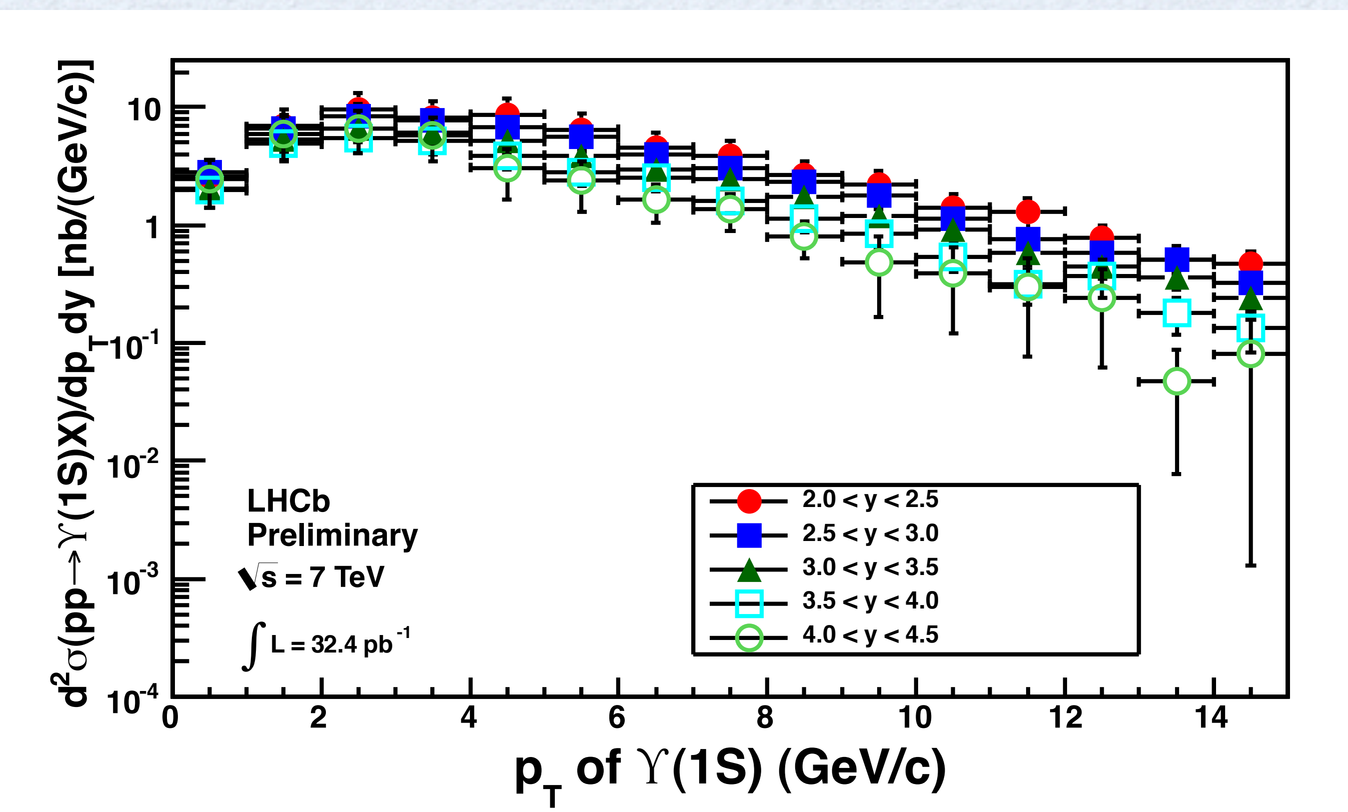
reconstruction eff.



Results

$$\sigma(\Upsilon(1S) \to \mu^+\mu^-) = 108.3 \pm 0.7 \, ^{+30.9}_{-25.8} \text{ nb}$$

- Sizeable contribution to uncertainties due to unknown Υ polarisation
  - (+18.8 nb, - 7.9 nb) contributes to syst. uncertainty

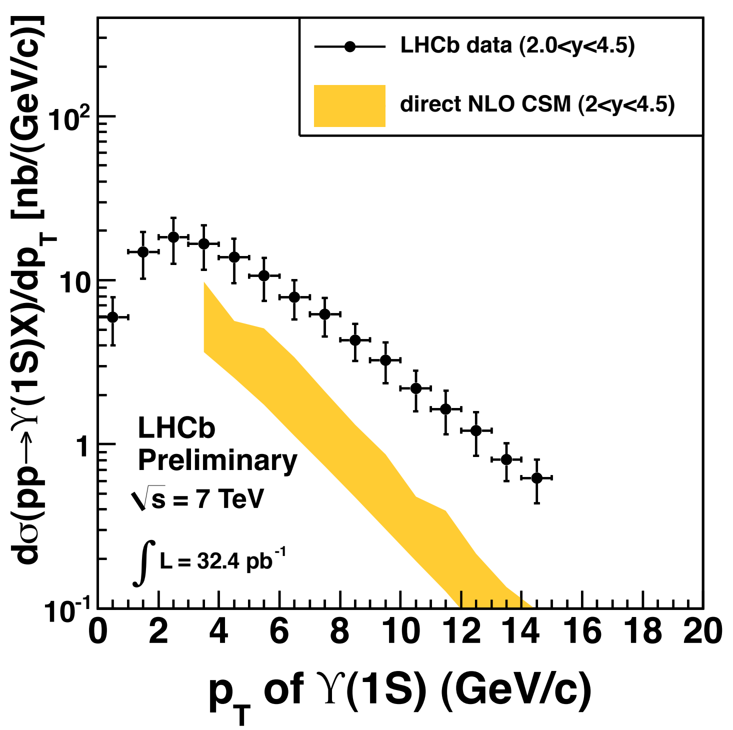


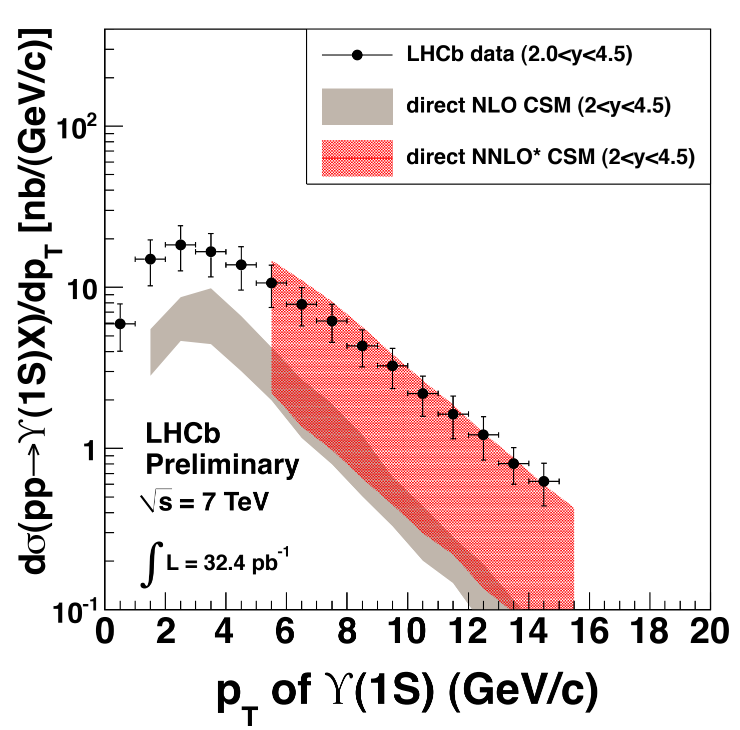
Source	Method	Value
Luminosity	Precision on beam current	10%
Trigger	Difference between J/ψ and Υ(nS) (simulation)	0-67%
Polarisation on acceptance	Extreme polarisation scenarios	0-33%
Polarisation on reconstruction	Extreme polarisation scenarios	0-21%
Choice of fit function	Test different functions	1%
Unknown pt spectrum	Estimate effect of 0.5% p_T resolution	1%
Global event cut (trigger)	Statistical uncertainty on data	2%
Track quality cut	Difference between data and simulation	0.5%/track
Track finding algorithm	Difference between data and simulation	4%/track
Vertexing	Difference between data and simulation	1%
Muon ID	Difference between data and simulation	1.1%

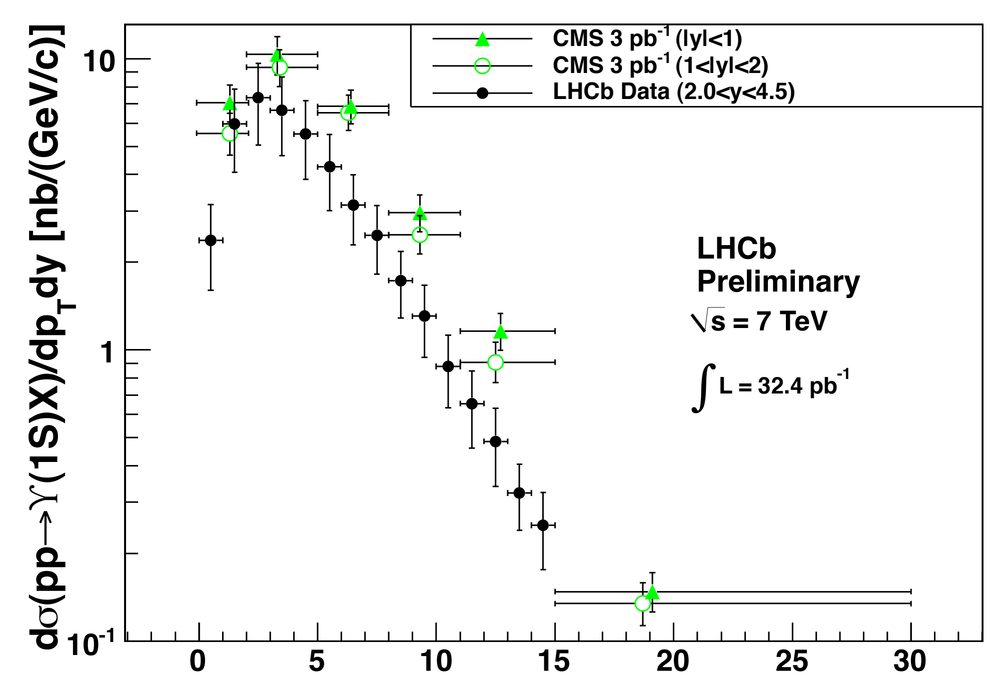
Effect from Luminosity will decrease

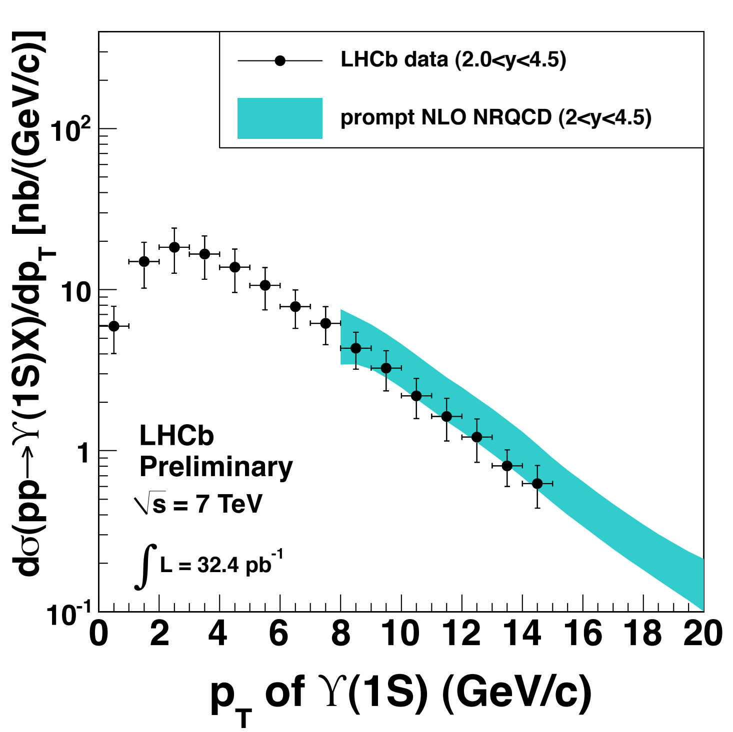
➥ more precise beam current measurement

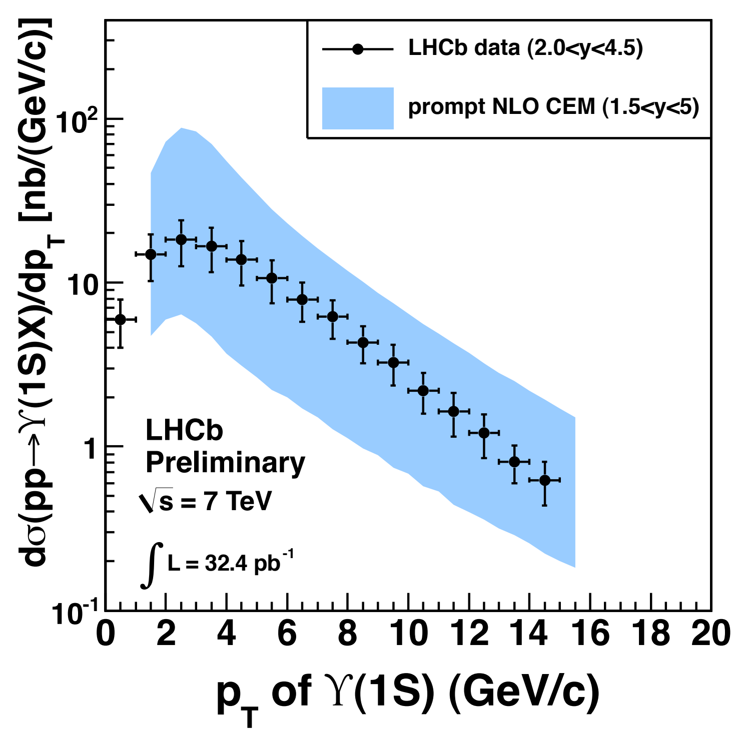
Comparison to Theory / CMS

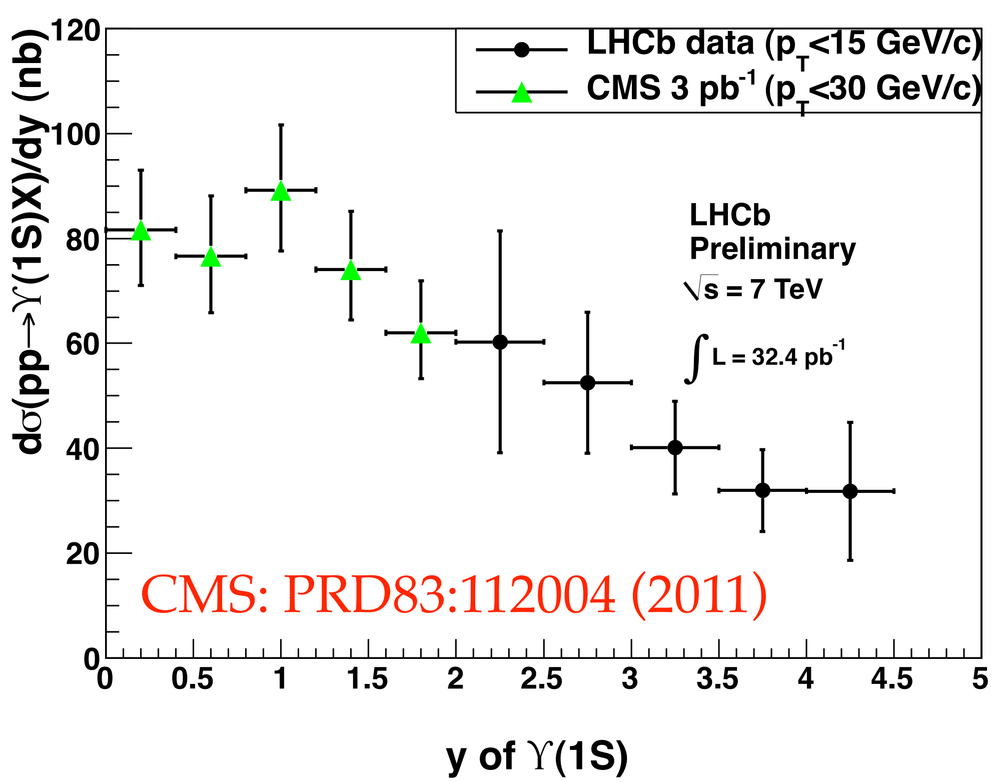












Summary

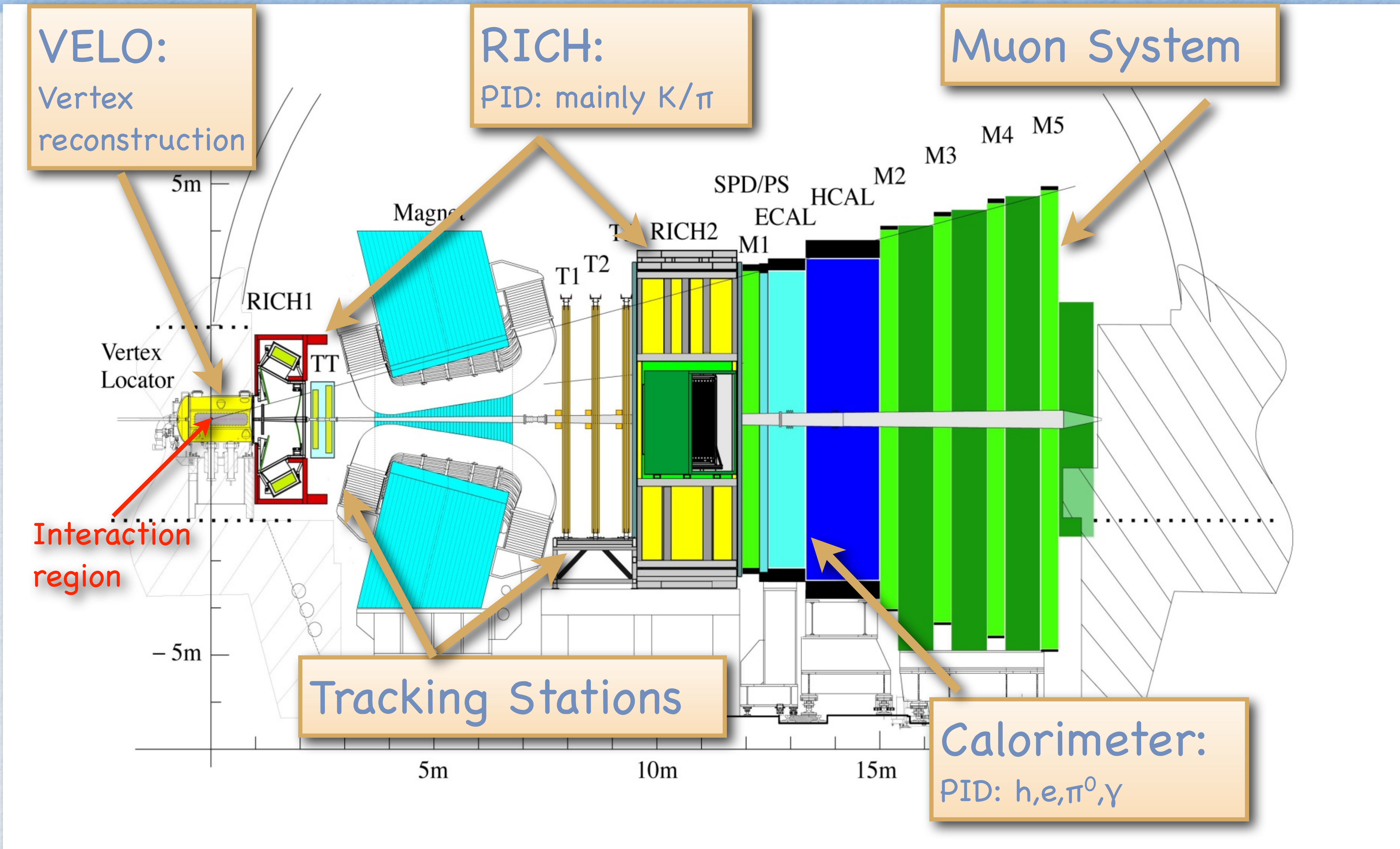
- Many measurements related to spectroscopy pursued in LHCb
- First measurement of the relative χc cross - section using data recorded in 2010 ($\sigma(\chi_{c2})/\sigma(\chi_{c1})$).
  - Comparison with dedicated event generator and NLO calculation show discrepancy esp. at low $p_t(J/\psi)$
  - Measurement of $\sigma(\chi_c)/\sigma(J/\psi)$ almost ready
- Branching fraction of (cc) mesons in exclusive production
- $\psi(2S)$ cross-section measurement in good agreement with NLO CSM +COM calculations
  - Theoretical predictions to low p_t?
- $\Upsilon(1S)$ cross-section measurement in good agreement with NLO
  - Theoretical predictions to low p_t?
  - Good agreement with measurement from CMS
- First analysis of χ_b state in LHCb in progress
  - Limited range of predictions available

BACKUP

INTRODUCTION

- Heavy Quarkonium production remains challenging problem for understanding QCD
- At LHC:
  - $c\bar{c}$ mainly produced via Leading-Order (LO) gluon-gluon interaction
    ➥ computed via perturbative QCD
- Formation of bound charmonium states described by non-perturbative models
  - Both colour singlet (CS) and colour octet (CO)
- Key ingredients to understand production mechanism
  - J/ψ and $\psi(2S)$ production cross-section and polarisation at large transverse momenta (p_t)
  - Ratio of production rates of χ_{c2} vs χ_{c1}

LHCB

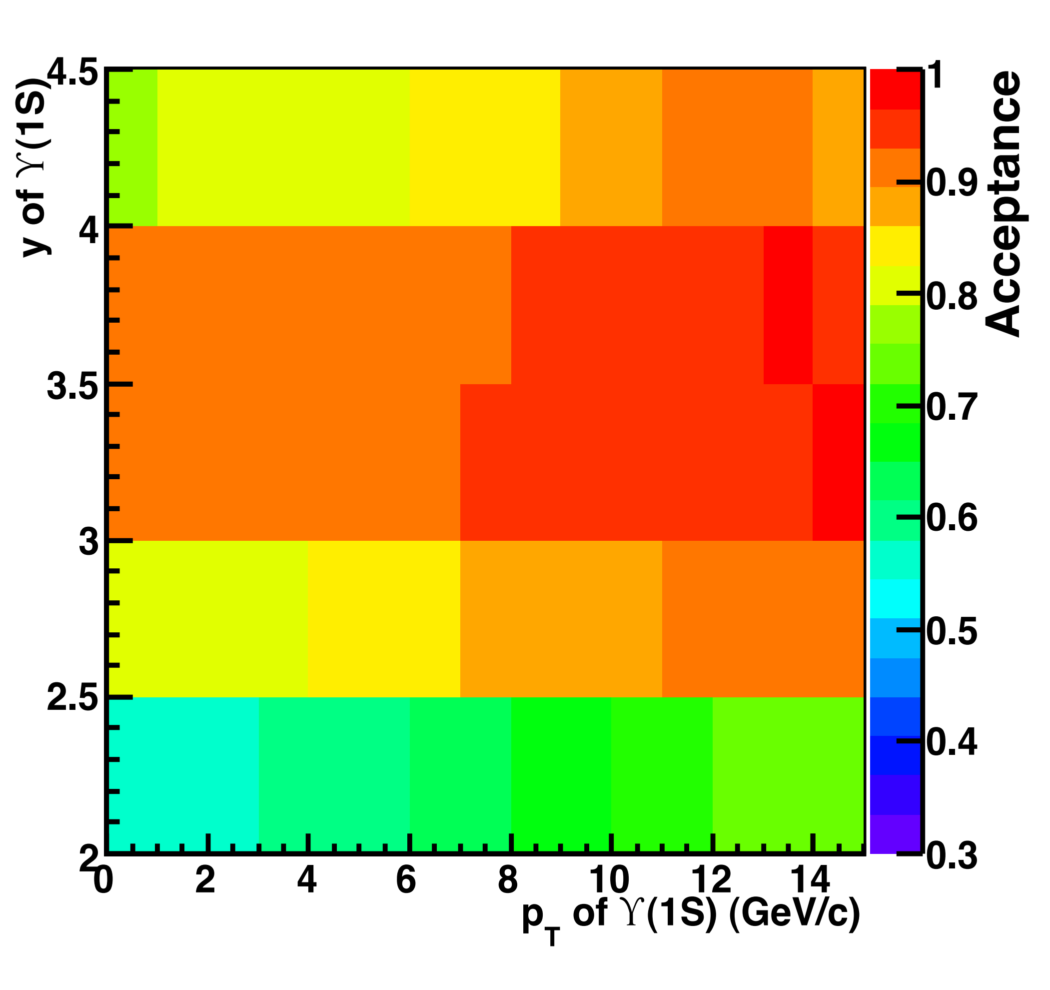

VELO:
Vertex reconstruction
RICH:
PID: mainly K/π
Muon System
Tracking Stations
Calorimeter:
PID: h,e,π⁰,γ
Interaction region
Vertex Locator
RICH1
TT
Magnet
T1
T2
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
− 5m
5m
10m
15m

Υ(1S) cross-section

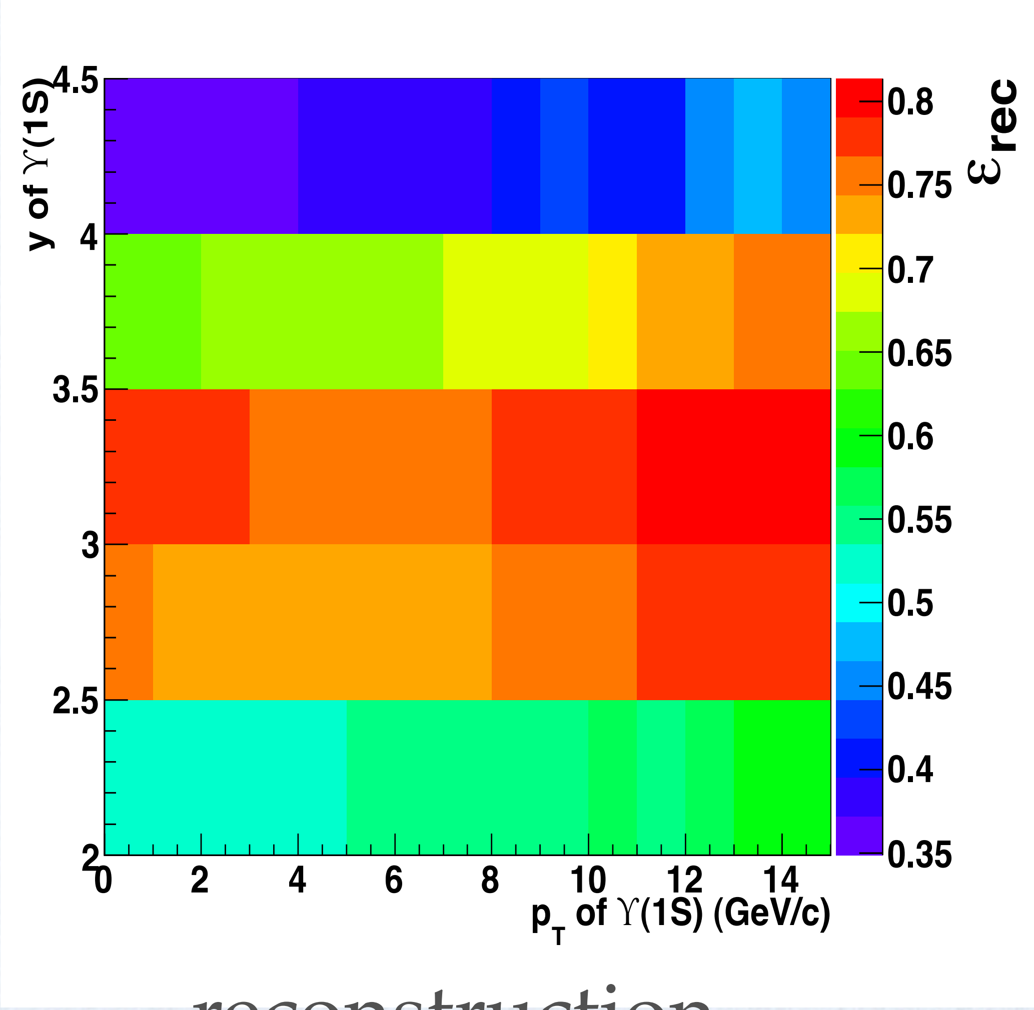
Table 3: $\Upsilon(1S)$ production cross-section results as a function of y and p_T, in nb. The first uncertainty is statistical, the second systematic.

p_T (GeV/c)	$\sigma(2.0 < y < 2.5)$ (nb)	$\sigma(2.5 < y < 3.0)$ (nb)	$\sigma(3.0 < y < 3.5)$ (nb)	$\sigma(3.5 < y < 4.0)$ (nb)	$\sigma(4.0 < y < 4.5)$ (nb)
0 – 1	2.59 ± 0.18 ± 1.00	2.78 ± 0.12 ± 0.77	2.05 ± 0.10 ± 0.48	1.98 ± 0.11 ± 0.55	2.47 ± 0.25 ± 1.04
1 – 2	6.89 ± 0.29 ± 2.69	6.70 ± 0.19 ± 1.82	5.40 ± 0.16 ± 1.24	4.90 ± 0.17 ± 1.30	5.96 ± 0.38 ± 2.40
2 – 3	9.54 ± 0.33 ± 3.61	8.48 ± 0.22 ± 2.32	6.55 ± 0.18 ± 1.51	5.45 ± 0.18 ± 1.37	6.69 ± 0.40 ± 2.59
3 – 4	8.26 ± 0.30 ± 3.03	7.74 ± 0.21 ± 2.03	6.16 ± 0.17 ± 1.40	5.20 ± 0.18 ± 1.23	5.86 ± 0.36 ± 2.31
4 – 5	8.67 ± 0.30 ± 3.08	6.72 ± 0.19 ± 1.73	5.16 ± 0.16 ± 1.13	3.92 ± 0.15 ± 0.92	3.07 ± 0.23 ± 1.40
5 – 6	6.51 ± 0.26 ± 2.24	5.59 ± 0.17 ± 1.40	3.89 ± 0.14 ± 0.84	2.85 ± 0.13 ± 0.66	2.41 ± 0.19 ± 1.08
6 – 7	4.59 ± 0.21 ± 1.52	4.01 ± 0.15 ± 0.98	2.99 ± 0.12 ± 0.62	2.50 ± 0.12 ± 0.54	1.64 ± 0.15 ± 0.57
7 – 8	3.89 ± 0.19 ± 1.25	3.04 ± 0.13 ± 0.72	2.47 ± 0.11 ± 0.50	1.61 ± 0.09 ± 0.35	1.37 ± 0.14 ± 0.46
8 – 9	2.65 ± 0.16 ± 0.82	2.36 ± 0.11 ± 0.54	1.72 ± 0.09 ± 0.35	1.13 ± 0.08 ± 0.25	0.80 ± 0.10 ± 0.26
9 – 10	2.23 ± 0.14 ± 0.65	1.78 ± 0.09 ± 0.40	1.19 ± 0.07 ± 0.24	0.84 ± 0.07 ± 0.19	0.49 ± 0.08 ± 0.31
10 – 11	1.41 ± 0.11 ± 0.40	1.14 ± 0.07 ± 0.25	0.92 ± 0.06 ± 0.18	0.53 ± 0.05 ± 0.12	0.39 ± 0.07 ± 0.26
11 – 12	1.31 ± 0.10 ± 0.36	0.76 ± 0.06 ± 0.16	0.58 ± 0.05 ± 0.12	0.32 ± 0.04 ± 0.10	0.30 ± 0.07 ± 0.21
12 – 13	0.77 ± 0.08 ± 0.21	0.59 ± 0.05 ± 0.13	0.45 ± 0.04 ± 0.09	0.37 ± 0.04 ± 0.12	0.24 ± 0.06 ± 0.17
13 – 14	0.51 ± 0.06 ± 0.14	0.51 ± 0.05 ± 0.11	0.36 ± 0.04 ± 0.07	0.18 ± 0.03 ± 0.05	0.05 ± 0.02 ± 0.03
14 – 15	0.47 ± 0.06 ± 0.13	0.32 ± 0.04 ± 0.07	0.24 ± 0.03 ± 0.05	0.13 ± 0.03 ± 0.04	0.08 ± 0.03 ± 0.07

Υ(1S) efficiency



geometric acceptance



reconstruction efficiency

obtained from fully simulated events

ψ (2S) RESULT

$\psi(2S) \to \mu\mu$

p_T (GeV/c)	$2.0 < y \leq 2.5$	$2.5 < y \leq 3.0$	$3.0 < y \leq 3.5$
0-1	$138.71 \pm 18.24 \pm 18.62^{+25.41}_{-49.75}$	$95.82 \pm 6.28 \pm 15.44^{+19.16}_{-38.58}$	$98.76 \pm 5.29 \pm 13.19^{+17.92}_{-35.54}$
1-2	$285.28 \pm 22.93 \pm 38.08^{+53.86}_{-105.83}$	$243.34 \pm 10.04 \pm 38.86^{+45.71}_{-90.20}$	$202.73 \pm 7.28 \pm 28.43^{+33.34}_{-66.74}$
2-3	$205.32 \pm 15.48 \pm 33.58^{+41.46}_{-82.82}$	$181.06 \pm 8.03 \pm 26.76^{+31.88}_{-64.02}$	$179.58 \pm 6.48 \pm 23.87^{+25.07}_{-49.33}$
3-4	$153.72 \pm 10.34 \pm 25.50^{+31.64}_{-63.04}$	$146.32 \pm 5.25 \pm 19.96^{+23.12}_{-45.92}$	$118.84 \pm 4.20 \pm 17.18^{+13.19}_{-25.79}$
4-5	$96.89 \pm 5.03 \pm 12.96^{+19.69}_{-39.07}$	$93.71 \pm 3.17 \pm 12.92^{+13.88}_{-27.54}$	$79.14 \pm 2.58 \pm 11.32^{+8.18}_{-16.17}$
5-6	$60.34 \pm 3.11 \pm 8.05^{+11.92}_{-24.13}$	$55.21 \pm 1.85 \pm 7.81^{+7.94}_{-15.66}$	$44.44 \pm 1.55 \pm 6.16^{+4.43}_{-9.16}$
6-7	$37.70 \pm 1.84 \pm 5.07^{+7.25}_{-14.28}$	$31.97 \pm 1.14 \pm 4.30^{+4.45}_{-8.66}$	$24.30 \pm 0.94 \pm 3.24^{+2.51}_{-5.19}$
7-8	$19.05 \pm 1.14 \pm 2.57^{+3.50}_{-6.95}$	$19.04 \pm 0.78 \pm 2.55^{+2.39}_{-4.87}$	$14.42 \pm 0.67 \pm 1.93^{+1.54}_{-3.10}$
8-9	$13.02 \pm 0.82 \pm 1.76^{+2.24}_{-4.61}$	$10.38 \pm 0.54 \pm 1.44^{+1.21}_{-2.39}$	$8.81 \pm 0.49 \pm 1.18^{+0.91}_{-1.85}$
9-10	$7.67 \pm 0.60 \pm 1.04^{+1.19}_{-2.49}$	$6.85 \pm 0.42 \pm 0.93^{+0.77}_{-1.60}$	$5.06 \pm 0.36 \pm 0.68^{+0.46}_{-0.99}$
10-11	$5.44 \pm 0.44 \pm 0.76^{+0.77}_{-1.58}$	$4.10 \pm 0.32 \pm 0.55^{+0.47}_{-0.87}$	$2.81 \pm 0.27 \pm 0.38^{+0.27}_{-0.54}$
11-12	$4.23 \pm 0.39 \pm 0.61^{+0.74}_{-1.59}$	$2.84 \pm 0.26 \pm 0.39^{+0.29}_{-0.63}$	$2.05 \pm 0.22 \pm 0.28^{+0.22}_{-0.38}$

ψ(2S) result

$\psi(2S) \to \mu\mu$

p_T (GeV/c)	$3.5 < y \leq 4.0$	$4.0 < y \leq 4.5$
0-1	$73.30 \pm 3.82 \pm 11.59^{+12.35}_{-25.24}$	$62.84 \pm 3.28 \pm 19.57^{+11.45}_{-22.59}$
1-2	$175.70 \pm 6.11 \pm 32.66^{+27.84}_{-55.87}$	$121.42 \pm 5.15 \pm 42.43^{+19.82}_{-39.31}$
2-3	$147.19 \pm 5.45 \pm 25.91^{+19.94}_{-40.96}$	$104.53 \pm 4.86 \pm 30.55^{+16.19}_{-32.40}$
3-4	$100.86 \pm 3.80 \pm 19.03^{+10.84}_{-21.81}$	$63.77 \pm 3.27 \pm 17.70^{+8.41}_{-16.31}$
4-5	$60.38 \pm 2.19 \pm 9.45^{+5.80}_{-11.87}$	$41.31 \pm 2.42 \pm 10.24^{+4.30}_{-8.80}$
5-6	$33.98 \pm 1.30 \pm 5.41^{+3.12}_{-6.17}$	$21.94 \pm 1.43 \pm 5.72^{+2.19}_{-4.57}$
6-7	$19.11 \pm 0.85 \pm 2.71^{+1.81}_{-3.69}$	$11.00 \pm 0.88 \pm 2.08^{+0.84}_{-1.78}$
7-8	$10.48 \pm 0.58 \pm 1.40^{+1.01}_{-2.07}$	$4.60 \pm 0.53 \pm 0.83^{+0.36}_{-0.74}$
8-9	$5.61 \pm 0.38 \pm 0.75^{+0.52}_{-1.05}$	$2.93 \pm 0.46 \pm 0.55^{+0.22}_{-0.41}$
9-10	$3.60 \pm 0.33 \pm 0.49^{+0.31}_{-0.64}$	$1.40 \pm 0.25 \pm 0.31^{+0.10}_{-0.24}$
10-11	$1.74 \pm 0.20 \pm 0.24^{+0.15}_{-0.33}$	$1.06 \pm 0.19 \pm 0.24^{+0.08}_{-0.13}$
11-12	$0.99 \pm 0.17 \pm 0.18^{+0.09}_{-0.19}$	$0.71 \pm 0.19 \pm 0.19^{+0.03}_{-0.08}$

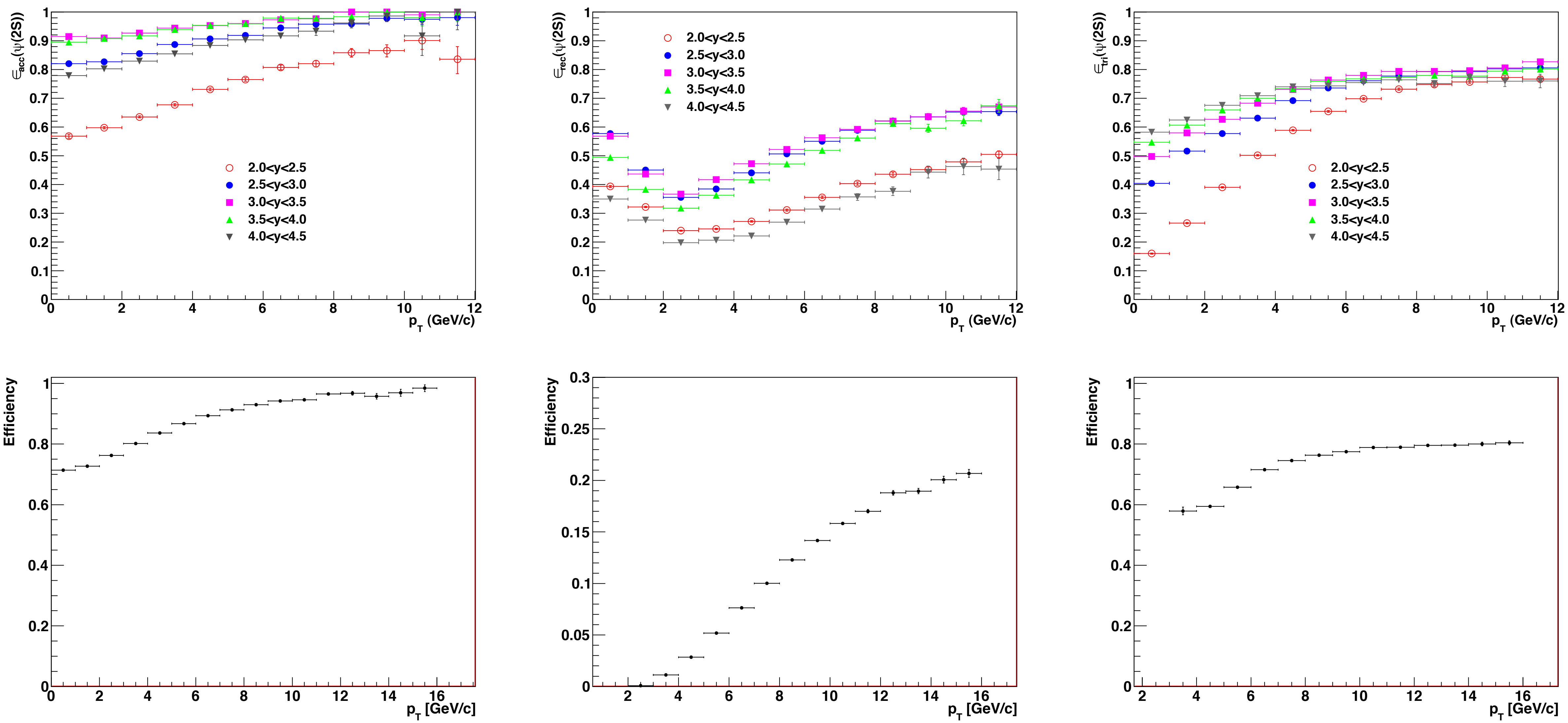
ψ (2S) Result

$\psi(2S) \rightarrow J/\psi\ \pi^+\pi^-$

p_T (GeV/c)	$d\sigma/dp_T$ (nb/GeV/c)
3-4	$241.2 \pm 21.0 \pm 46.3\ ^{+29.0}_{-57.1}$
4-5	$156.0 \pm 7.7 \pm 30.1\ ^{+17.8}_{-35.2}$
5-6	$90.5 \pm 3.5 \pm 17.4\ ^{+10.3}_{-20.6}$
6-7	$55.4 \pm 1.9 \pm 10.6\ ^{+6.3}_{-12.6}$
7-8	$31.5 \pm 1.1 \pm 6.0\ ^{+3.6}_{-7.1}$
8-9	$18.1 \pm 0.7 \pm 3.5\ ^{+2.0}_{-3.9}$
9-10	$10.8 \pm 0.5 \pm 2.1\ ^{+1.1}_{-2.3}$
10-11	$6.7 \pm 0.4 \pm 1.3\ ^{+0.7}_{-1.3}$
11-12	$4.4 \pm 0.3 \pm 0.9\ ^{+0.5}_{-1.0}$
12-13	$3.3 \pm 0.2 \pm 0.6\ ^{+0.4}_{-0.7}$
13-14	$2.3 \pm 0.2 \pm 0.5\ ^{+0.3}_{-0.5}$
14-15	$1.5 \pm 0.1 \pm 0.3\ ^{+0.2}_{-0.3}$
15-16	$1.1 \pm 0.1 \pm 0.2\ ^{+0.1}_{-0.2}$

ψ(2S) EFFICIENCIES

top: $\psi(2S) \rightarrow \mu^+\mu^-$, bottom: $\psi(2S) \rightarrow J/\psi\, \pi^+\pi^-$



acceptance reconstruction trigger

ψ(2S) selection

$\psi(2S) \rightarrow \mu^+\mu^-$

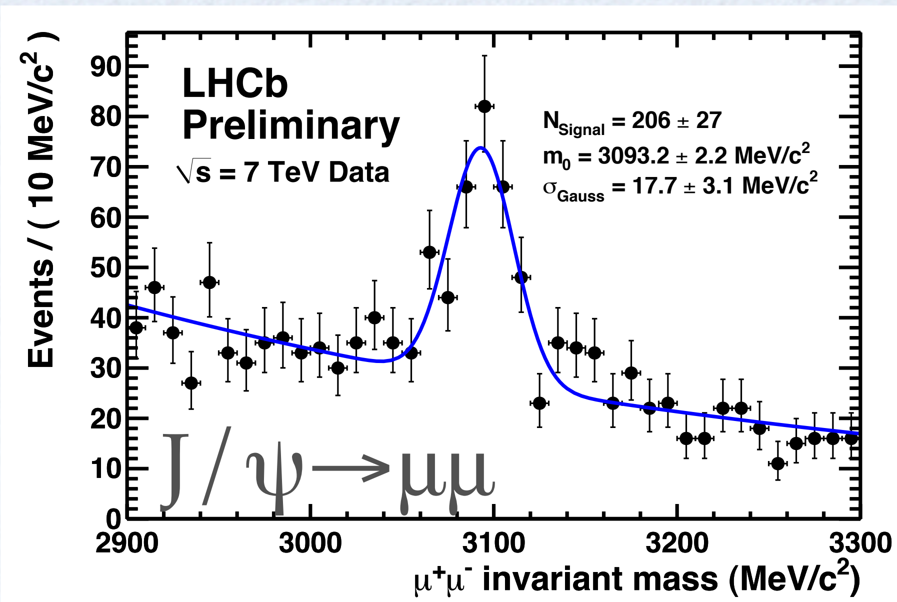
μ: long track with muon detector hits (IsMuon)
μ: $p_T > 1.2$ GeV/c
μ: track χ^2/ndof < 4
μ: $\mathrm{DLL}_{\mu\pi} > -1$
$\psi(2S)$: vertex $P(\chi^2) > 0.5\%$
$\psi(2S)$: $\cos(\theta_{\mu_1^\pm,\mu_2^\pm}) > 0.9999$ (clones removal)

$\psi(2S) \rightarrow J/\psi\, \pi^+\pi^-$

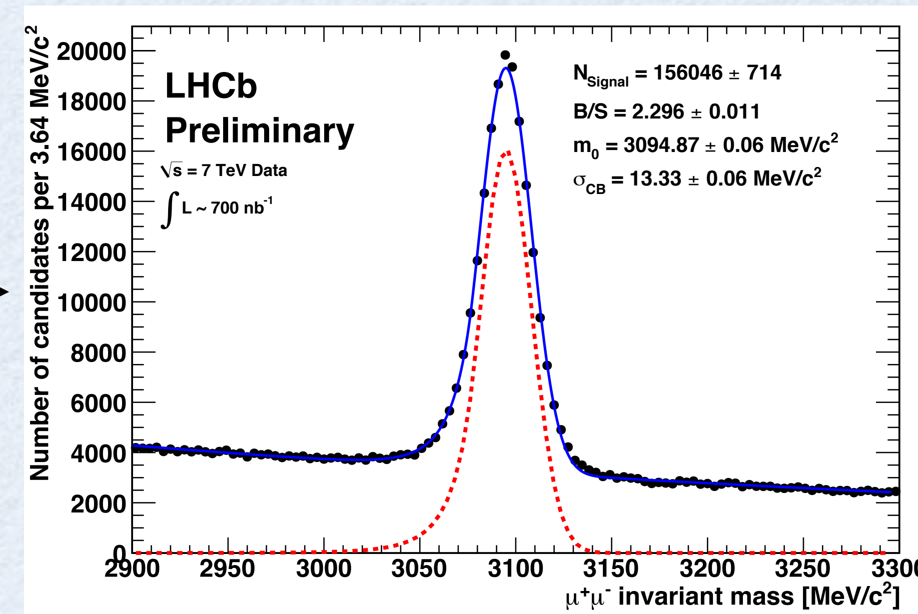
μ: Long track with muon detector hits	π: $p_\mathrm{T}(\pi^+) + p_\mathrm{T}(\pi^-) > 800$ MeV/c
μ: $\mathrm{DLL}_{\mu\pi} > -1$	π: DLL K-π > 5
μ: $p_\mathrm{T} > 700$ MeV/c	π: $p_\mathrm{T} > 300$ MeV/c
μ: p > 8 GeV/c and < 500 GeV/c	π: p < 500 GeV/c
μ: track χ^2/ndof < 4	π: track χ^2/ndof < 4
J/ψ: vertex χ^2/ndof < 20	$\psi(2S)$: vertex χ^2/ndof < 4
J/ψ: Mass > 3040 and < 3140 MeV/c^2	$\psi(2S)$: Mass > 3600 and < 3800 MeV/c^2
J/ψ: $p_\mathrm{T} > 2$ GeV/c	$\psi(2S)$: $p_\mathrm{T} > 2$ GeV/c
$Q = M(J/\psi\,\pi\pi) - M(\pi\pi) - M(\mu\mu) \geq 0$ and ≤ 200 MeV/c^2	

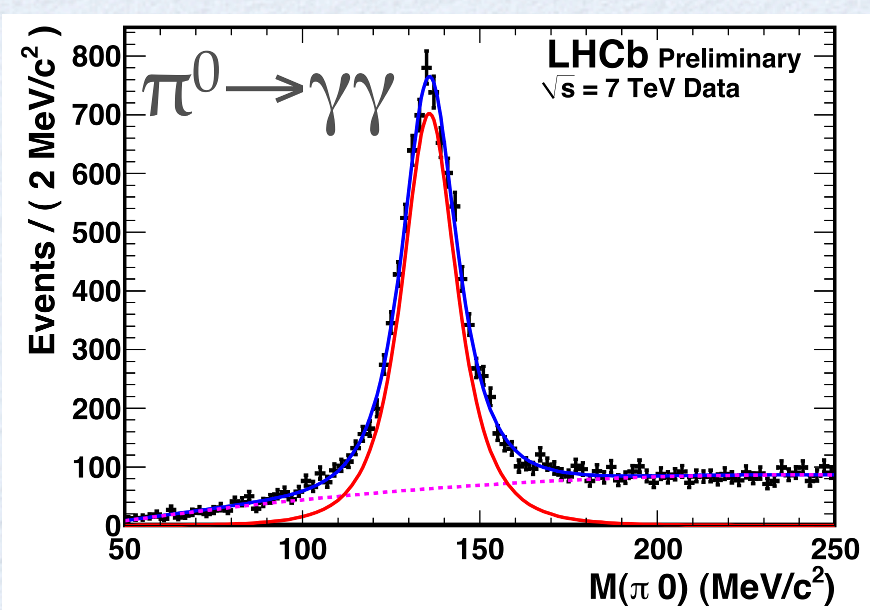
Muon detector and calorimeter

- Muon detector comprises of 5 dedicated sub-detectors
  - Alignment in 2010: close to expectation (12 MeV/c^2)



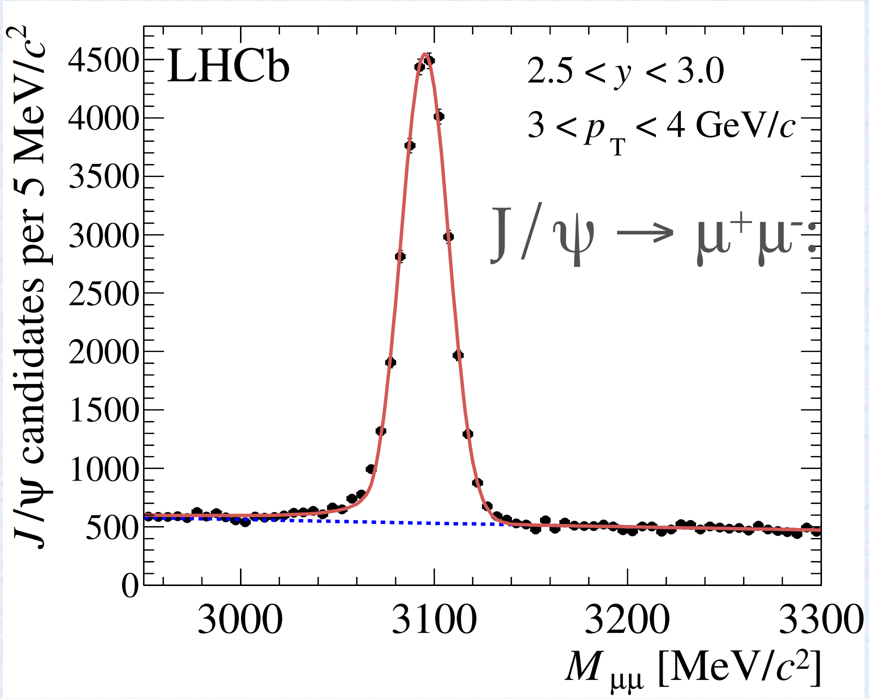
from 18 MeV/c^2 → to 13 MeV/c^2





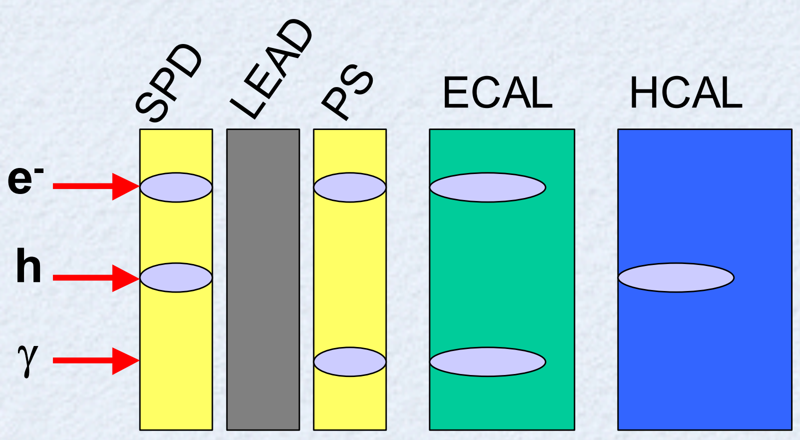
- Electro-magnetic calorimeter
  - $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$
  - Able to clearly resolve e.g. $\pi^0 \rightarrow \gamma\gamma$

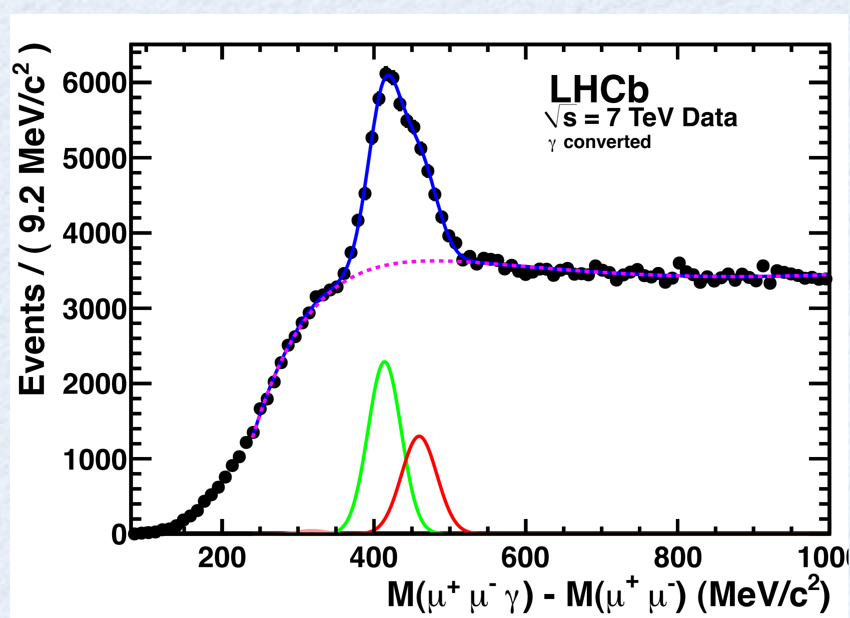
χ_c Reconstruction

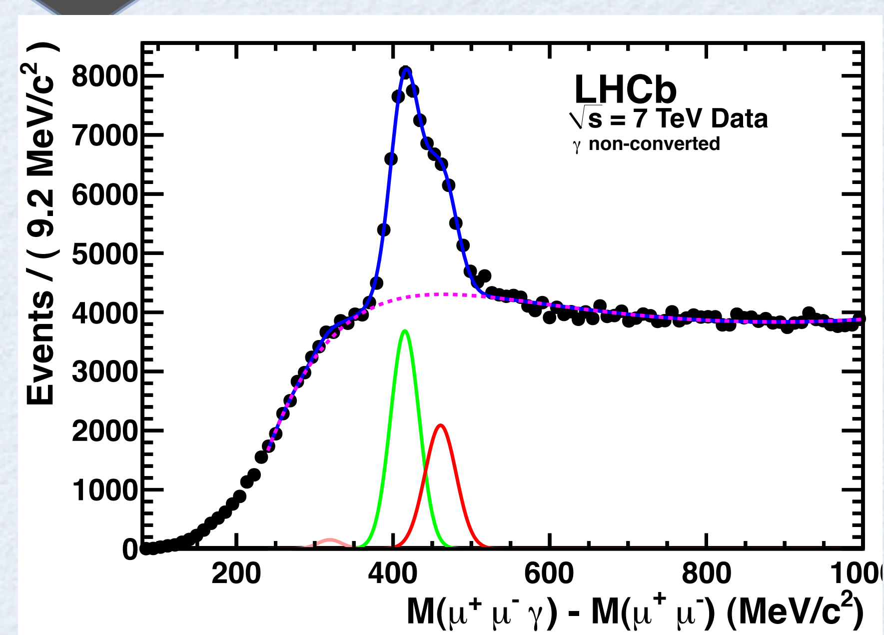


+

- **Photons** are reconstructed using the Calorimeter
  - Unconverted photons
  - Converted photons ($\gamma \rightarrow e^+e^-$) after the magnet
  - The converted photons are identified by requiring a signal in the Scintillating Pad Detector (SPD)







N.B. Calorimeter resolution too coarse to resolve individual χ_c states

Fit model: Gaussian for signal, RooDstD0BG for background

χ c relative cross section

- Fit model

  in bins of $p_t(J/\psi)$ in the range: $2 < p_t(J/\psi) < 15$ GeV/c

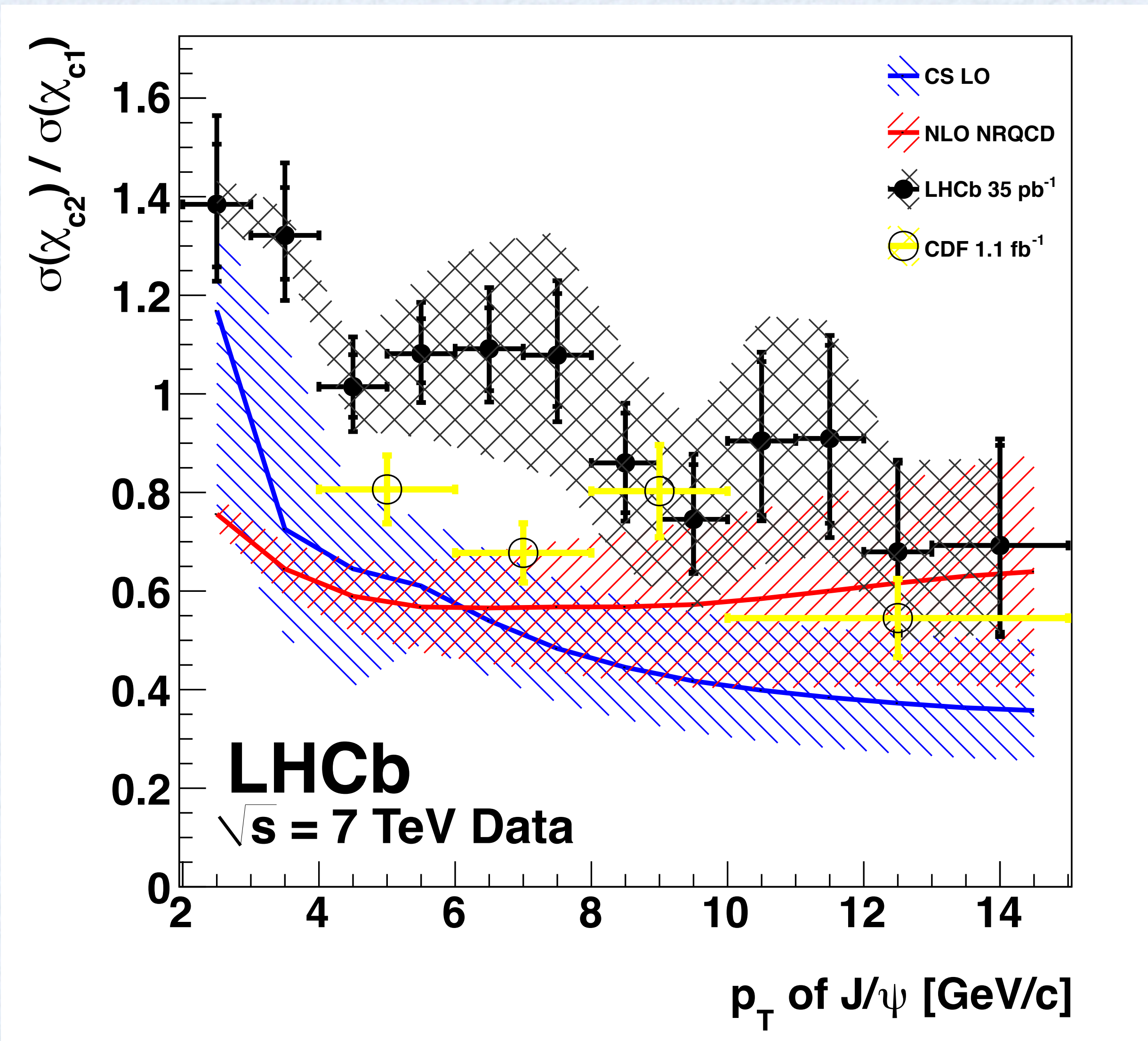
- Simultaneous fit to extract χ_{c0}, χ_{c1}, χ_{c2} yield + BG
  - Mass difference fixed to PDG for $\Delta m(\chi_{c0} - \chi_{c1})$ and $\Delta m(\chi_{c2} - \chi_{c1})$
  - Ratio of Gaussian resolution $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ fixed to fit on full sample
  - Gaussian resolution $\sigma(\chi_{c1})$ fixed to fit on full sample
  - Ratio of Gaussian resolution $\sigma(\chi_{c0})/\sigma(\chi_{c1})$ taken from simulation

  - Assume unpolarised states and investigate effect of polarisation

  -

LHCb-CONF-2011-020

χ_c Results



$p_T^{J/\psi}$ (GeV/c)	$\sigma(\chi_{c2})\,/\,\sigma(\chi_{c1})$	Pol.
2 – 3	$1.385^{+0.12\ +0.074\ +0.087}_{-0.13\ -0.068\ -0.079}$	$^{+0.061}_{-0.046}$
3 – 4	$1.321^{+0.097\ +0.067\ +0.086}_{-0.089\ -0.063\ -0.072}$	$^{+0.056}_{-0.046}$
4 – 5	$1.015^{+0.065\ +0.042\ +0.062}_{-0.062\ -0.040\ -0.059}$	$^{+0.088}_{-0.089}$
5 – 6	$1.082^{+0.071\ +0.045\ +0.066}_{-0.059\ -0.044\ -0.064}$	$^{+0.16}_{-0.17}$
6 – 7	$1.092^{+0.083\ +0.049\ +0.066}_{-0.085\ -0.046\ -0.064}$	$^{+0.22}_{-0.22}$
7 – 8	$1.079^{+0.12\ +0.058\ +0.067}_{-0.10\ -0.054\ -0.062}$	$^{+0.25}_{-0.25}$
8 – 9	$0.860^{+0.10\ +0.041\ +0.053}_{-0.10\ -0.046\ -0.049}$	$^{+0.22}_{-0.21}$
9 – 10	$0.746^{+0.11\ +0.040\ +0.047}_{-0.11\ -0.041\ -0.042}$	$^{+0.20}_{-0.19}$
10 – 11	$0.905^{+0.16\ +0.051\ +0.057}_{-0.15\ -0.052\ -0.052}$	$^{+0.25}_{-0.25}$
11 – 12	$0.910^{+0.19\ +0.092\ +0.064}_{-0.17\ -0.098\ -0.062}$	$^{+0.24}_{-0.24}$
12 – 13	$0.679^{+0.18\ +0.056\ +0.041}_{-0.16\ -0.048\ -0.041}$	$^{+0.19}_{-0.18}$
13 – 15	$0.692^{+0.20\ +0.067\ +0.042}_{-0.18\ -0.067\ -0.036}$	$^{+0.18}_{-0.18}$

- Cross-section ratio in bins of $p_t(J/\psi)$, stat. + syst. + BR(χ_c) errors
  - Black band corresponds to effect of χ_c polarisation
- Blue: Prediction from ChiGen event simulation
- Red : NLO NRQCD calculation

χ_c Systematics

- Systematic uncertainties are from the following categories
  - Fit modelling
    - Background model sensitive to region just below χ_{c1}
    - Background model parameters correlated to signal parameters
    - Modelling of χ_{c0} component
  - Finite statistics of simulated events
    - Affects extraction of efficiencies
  - Branching ratio of $\chi_c \rightarrow J/\psi\gamma$
    - Affects obtaining ratio of branching fractions $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ from ratio of yields
    - $\sigma(\chi_{c1}) \rightarrow J/\psi\gamma$: 36% , $\sigma(\chi_{c2}) \rightarrow J/\psi\gamma$: 20%

χ_c: Systematics

- Systematic uncertainties due to χ_c branching ratios

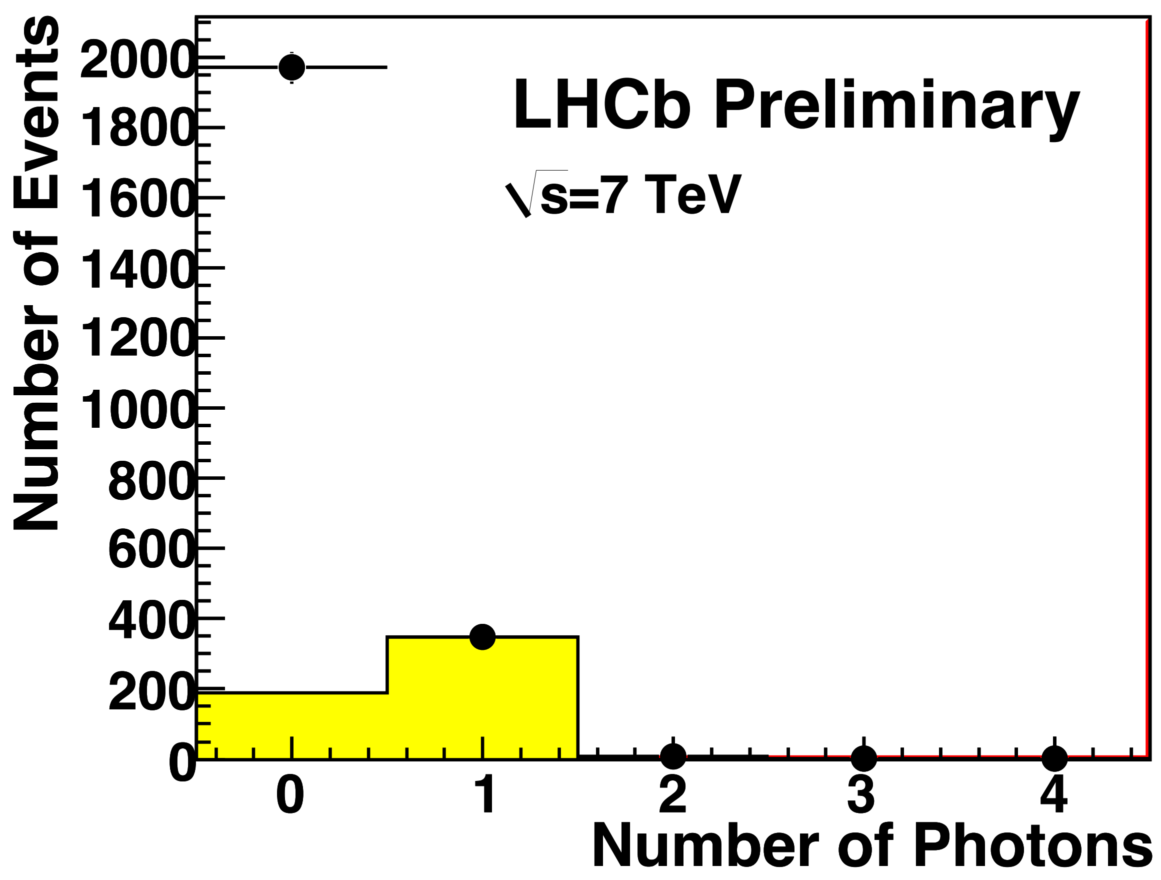
$p_T^{J/\psi}$ (GeV/c)	$2-3$	$3-4$	$4-5$	$5-6$	$6-7$	$7-8$
Branching ratios	$^{+0.087}_{-0.079}$	$^{+0.086}_{-0.072}$	$^{+0.062}_{-0.059}$	$^{+0.066}_{-0.064}$	$^{+0.066}_{-0.064}$	$^{+0.067}_{-0.062}$
Monte Carlo statistics	$^{+0.010}_{-0.010}$	$^{+0.010}_{-0.008}$	$^{+0.009}_{-0.007}$	$^{+0.011}_{-0.010}$	$^{+0.015}_{-0.013}$	$^{+0.020}_{-0.017}$
Systematics from fit	$^{+0.040}_{-0.051}$	$^{+0.045}_{-0.040}$	$^{+0.026}_{-0.034}$	$^{+0.026}_{-0.031}$	$^{+0.029}_{-0.037}$	$^{+0.051}_{-0.040}$
$p_T^{J/\psi}$ (GeV/c)	$8-9$	$9-10$	$10-11$	$11-12$	$12-13$	$13-15$
Branching ratios	$^{+0.053}_{-0.049}$	$^{+0.047}_{-0.042}$	$^{+0.057}_{-0.052}$	$^{+0.064}_{-0.062}$	$^{+0.041}_{-0.041}$	$^{+0.042}_{-0.036}$
Monte Carlo statistics	$^{+0.021}_{-0.019}$	$^{+0.024}_{-0.023}$	$^{+0.040}_{-0.037}$	$^{+0.060}_{-0.055}$	$^{+0.051}_{-0.046}$	$^{+0.049}_{-0.045}$
Systematics from fit	$^{+0.034}_{-0.040}$	$^{+0.034}_{-0.031}$	$^{+0.034}_{-0.026}$	$^{+0.020}_{-0.133}$	$^{+0.023}_{-0.018}$	$^{+0.075}_{-0.031}$

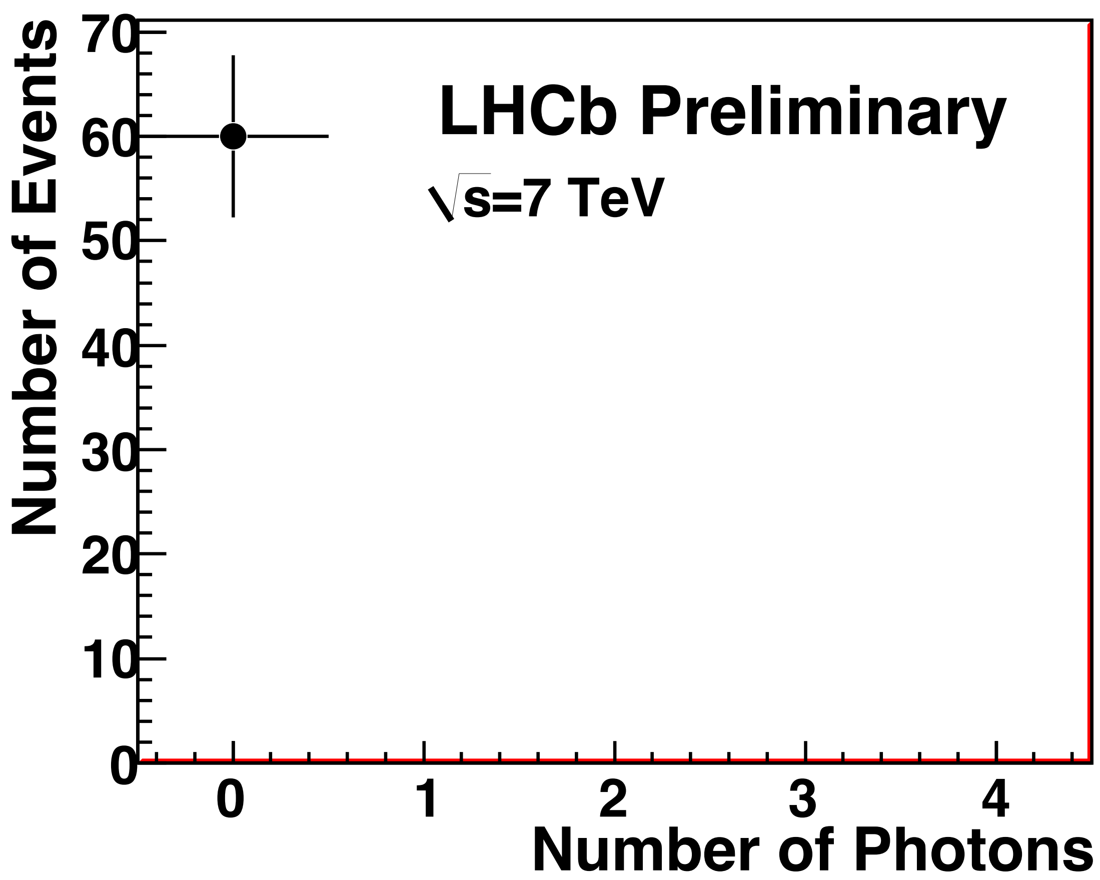
Central Exclusive Production

	J/ψ	$\psi(2S)$	χ_{c0}	χ_{c1}	χ_{c2}	diphoton
ϵ_{track}	0.97 ± 0.04	0.97 ± 0.04	0.97 ± 0.04	0.97 ± 0.04	0.97 ± 0.04	0.96 ± 0.04
$\epsilon_{\mu id}$	0.89 ± 0.03	0.89 ± 0.03	0.89 ± 0.03	0.89 ± 0.03	0.89 ± 0.03	0.89 ± 0.03
ϵ_{γ}			0.61 ± 0.08	0.75 ± 0.05	0.78 ± 0.04	
ϵ_{sel}	0.95	0.95	0.76	0.76	0.76	0.35
Efficiency	0.71 ± 0.07	0.71 ± 0.07	0.34 ± 0.06	0.43 ± 0.05	0.44 ± 0.04	0.25 ± 0.03
# Events	1468 ± 38	40 ± 6	25 ± 6	56 ± 18	99 ± 29	40 ± 6
Purity	0.71 ± 0.03	0.67 ± 0.03	0.39 ± 0.13	0.39 ± 0.13	0.39 ± 0.13	0.97 ± 0.01
L_{eff} (pb^{-1})	3.1 ± 0.6	3.1 ± 0.6	3.1 ± 0.6	3.1 ± 0.6	3.1 ± 0.6	2.3 ± 0.5
Cross-section $\times BR$ (pb)	474 ± 12 $\pm 51 \pm 92$	12.2 ± 1.8 $\pm 1.3 \pm 2.4$	9.3 ± 2.2 $\pm 3.5 \pm 1.8$	16.4 ± 5.3 $\pm 5.8 \pm 3.2$	28.0 ± 5.4 $\pm 9.7 \pm 5.4$	67 ± 10 $\pm 7 \pm 15$

Central Exclusive Production

- Events with no backward tracks, 2 forward tracks
  - $\mu^+\mu^-$ mass consistent with J/ψ or $\psi(2S)$
  - #photons for J/ψ cand. (left) or $\psi(2S)$ cand. (right)





Central Exclusive Production

- $J/\psi \rightarrow \mu^+\mu^-$ ($2 < \eta < 4.5$) : $\underline{\sigma = 474 \pm 12 \pm 51 \pm 92}$ pb
  - StarLight : *292 pb*
  - SuperChiC: *330 pb*
  - Motyka, Watt (PRD 014023 (2008)): 960 pb
    - Taking muon acceptance into account (Pythia) : 410 pb
    - Rescattering correction : *330 pb* (± 10-15%)
    - Uncertainty from Hera → LHC extrapolation ~10%
  - Schäfer, Szczurek (Diff2010, Heidelberg): 1670 pb
    - Taking muon acceptance into account (Pythia) : *710 pb*
  - Bzdak (PRD 75 094023 (2007)): *70 - 800 pb*

Central Exclusive Production

- $\psi(2S) \rightarrow \mu^{+}\mu^{-}$ ($2 < \eta < 4.5$) : $\sigma = 12.2 \pm 1.8 \pm 1.3 \pm 2.4$ pb
  - StarLight : 6.1 pb
  - Schäfer, Szczurek : 17 pb