RELATIVE χ_c PRODUCTION AT LHCB

Deep Inelastic Scattering 2011
Newport News, VA

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INTRODUCTION

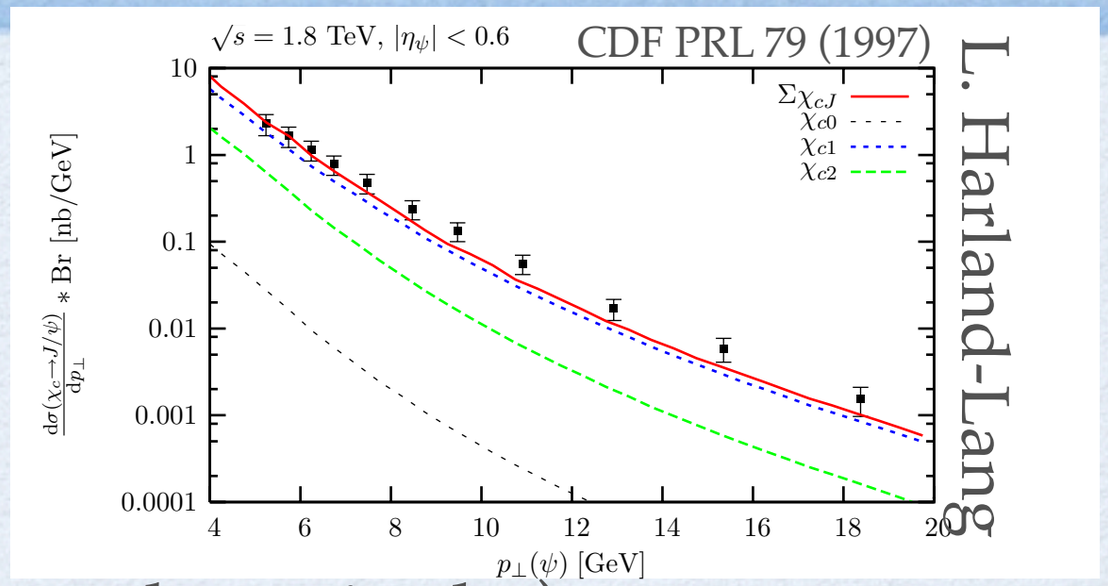
- Heavy Quarkonium production remains challenging problem for understanding QCD
- At LHC:
  - $c\bar{c}$ mainly produced via Leading-Order (LO) gluon-gluon interaction
    ➥ computed via perturbative QCD
- Formation of bound charmonium states described by non-perturbative models
  - Both colour singlet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

INTRODUCTION

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

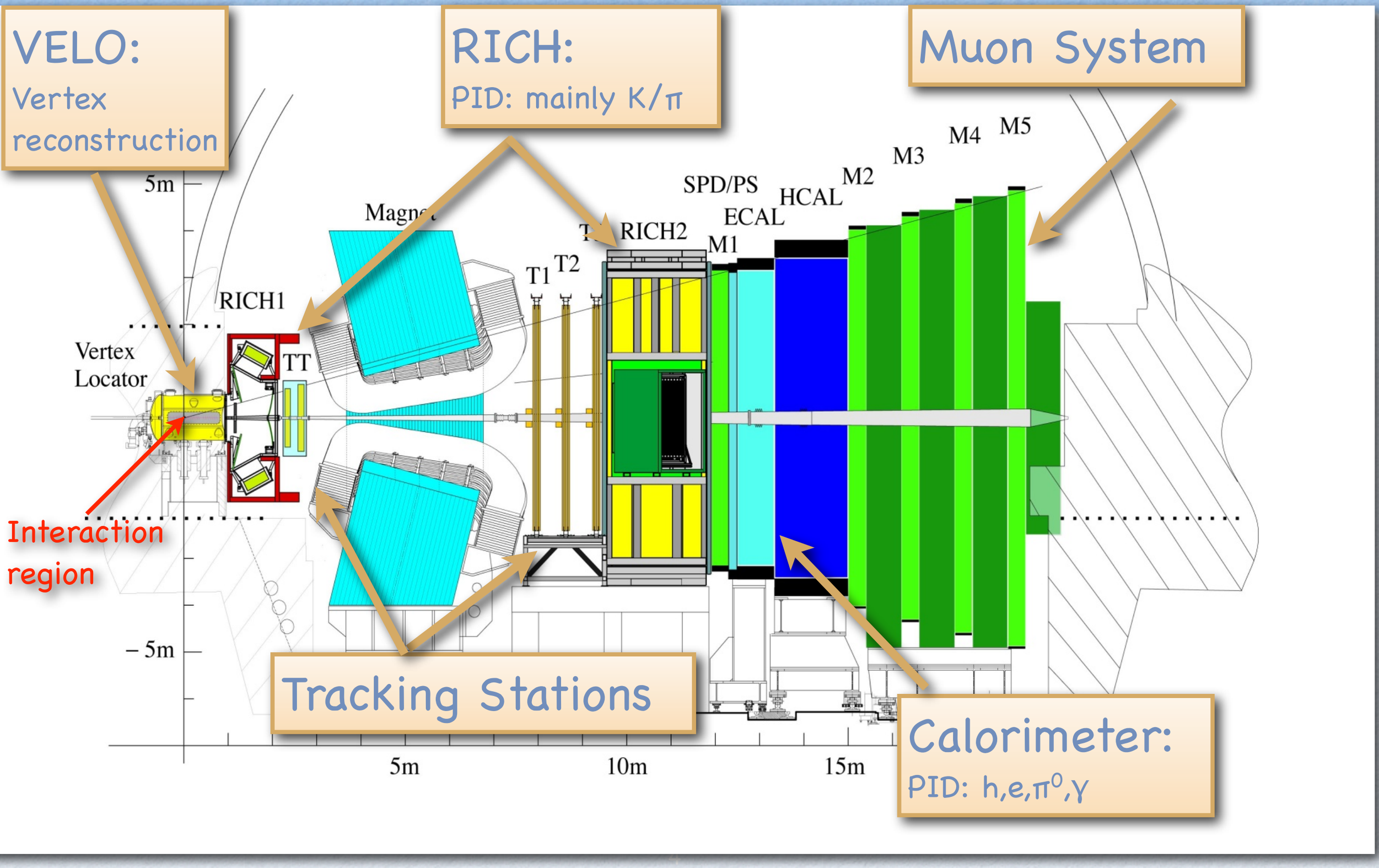
    ➥ contrary to observation

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



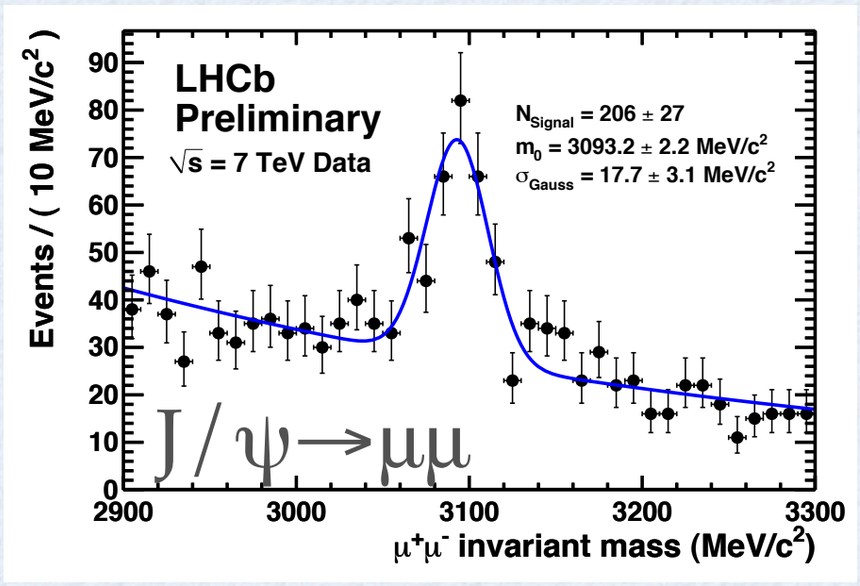
- However:
  - LO CS does not describe J/ψ production
  - Recent NLO corrections at high p_t for χ_c:
    - NLO corrections become large
    - Make CS contribution negative and comparable to CO
    - NLO scale as $1/p_t^4$ → NNLO probably small
- → Further charmonium studies needed

LHCB


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

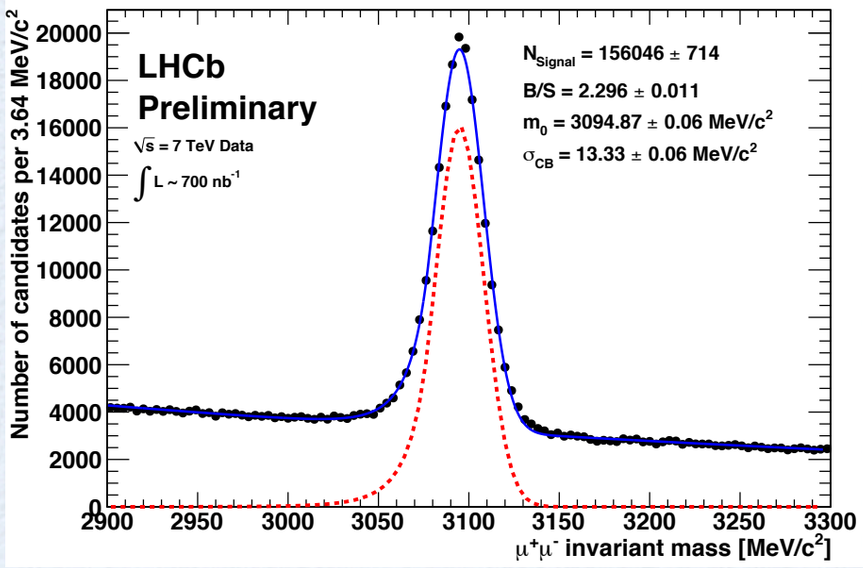
Muon detector and calorimeter

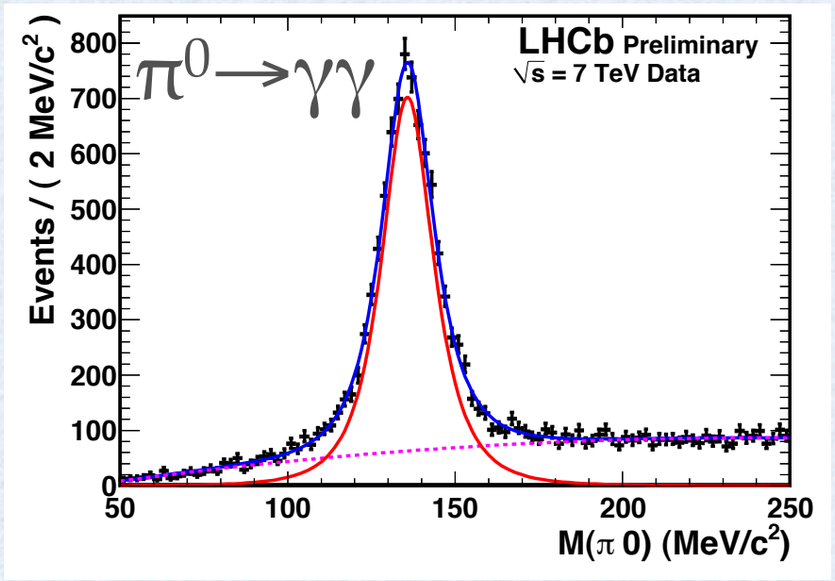
- Muon detector comprises of 5 dedicated sub-detectors
  - Alignment in 2010: close to expectation (12 MeV/c^2)



from 18 MeV/c^2

to 13 MeV/c^2

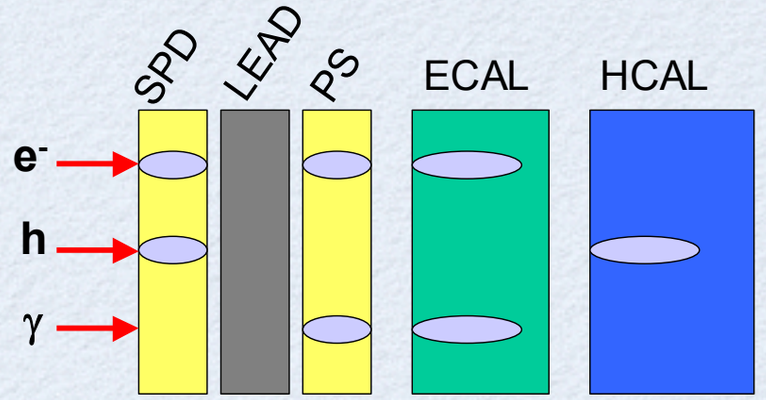




- Electro-magnetic calorimeter
  - $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$
  - Able to clearly resolve e.g. $\pi^0 \to \gamma\gamma$

PHOTON IDENTIFICATION

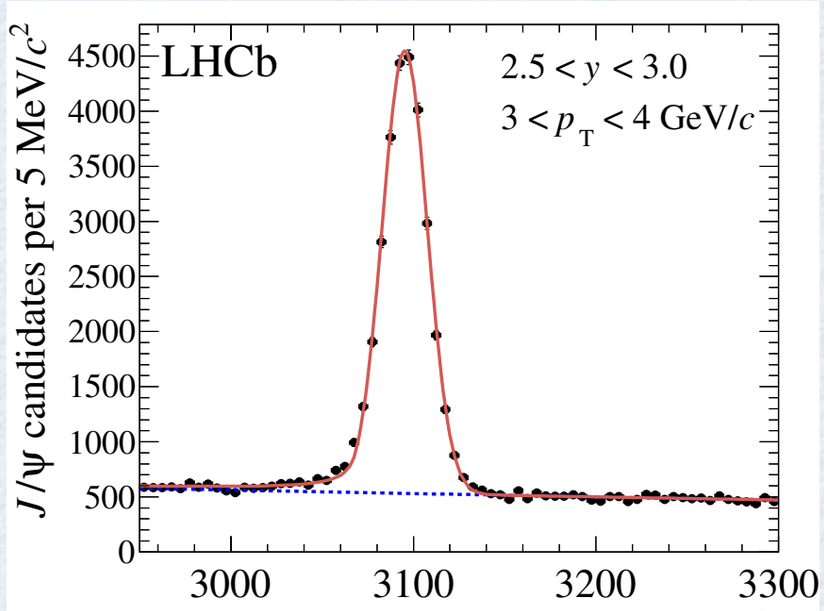
- Photons are reconstructed as
  - Unconverted photons
  - Converted photons ($\gamma \rightarrow e^+e^-$) after the magnet
  - The converted photons are identified by requiring a signal in the Scintillating Pad Detector (SPD)



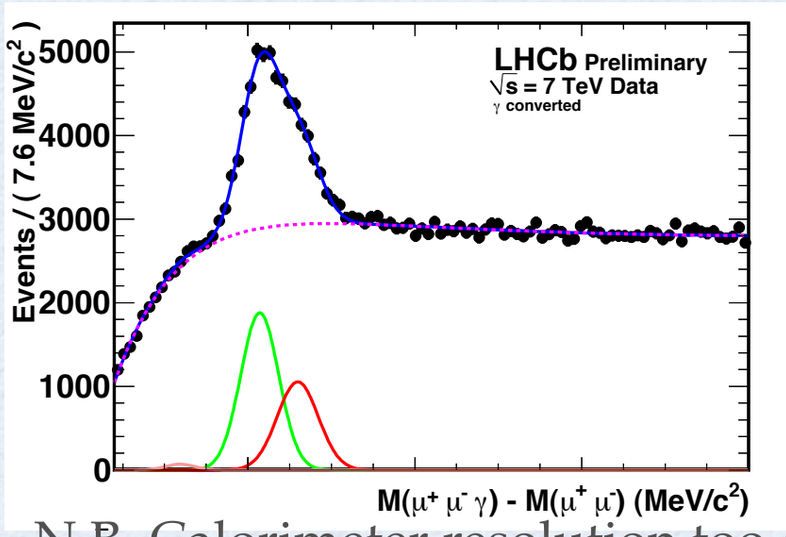
- Photons from χ_c are identified using a Confidence Likelihood:
  - Calorimeter information
  - Tracking information
  - Ratio of track seed energy to ECAL cluster energy
- Additional $e^{\pm}$ rejection: no match between any track and ECAL cluster

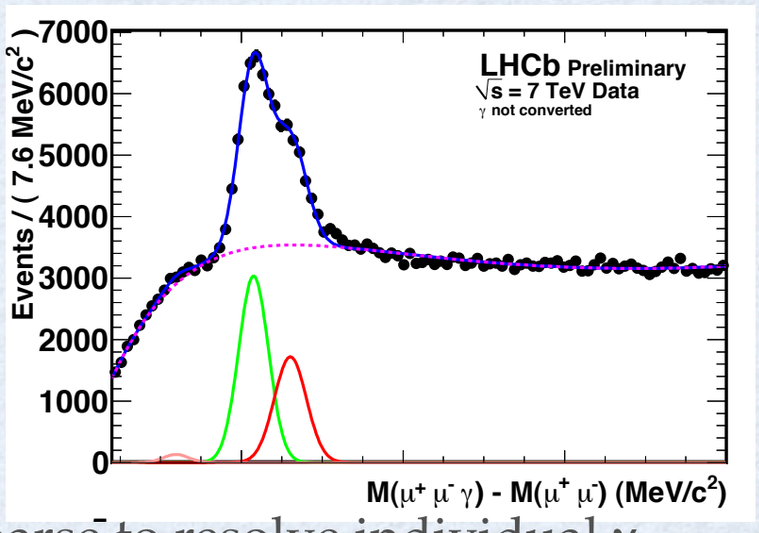
χ_c SELECTION

- J/ψ Selection:
  - p_t (J/ψ) > 2 GeV/c
  - vertex prob. > 0.5%
  - p_t (μ) > 0.7 GeV/c
  - tracks have hits in μ sub-det.
  - prompt component: $t_z < 0.1$ps



- Photon Selection:
  - γ CL > 0.5
  - p(γ) > 5 GeV/c
  - pt(γ) > 0.65 GeV/c





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

Fit model: Gaussian for signal, RooDstD0BG for background

Measurement outline

- Measure production cross section:

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

in bins of $p_t(J/\psi)$ in the range: $3 < p_t(J/\psi) < 15$ 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

  - Key ingredient: Determination of the various efficiencies

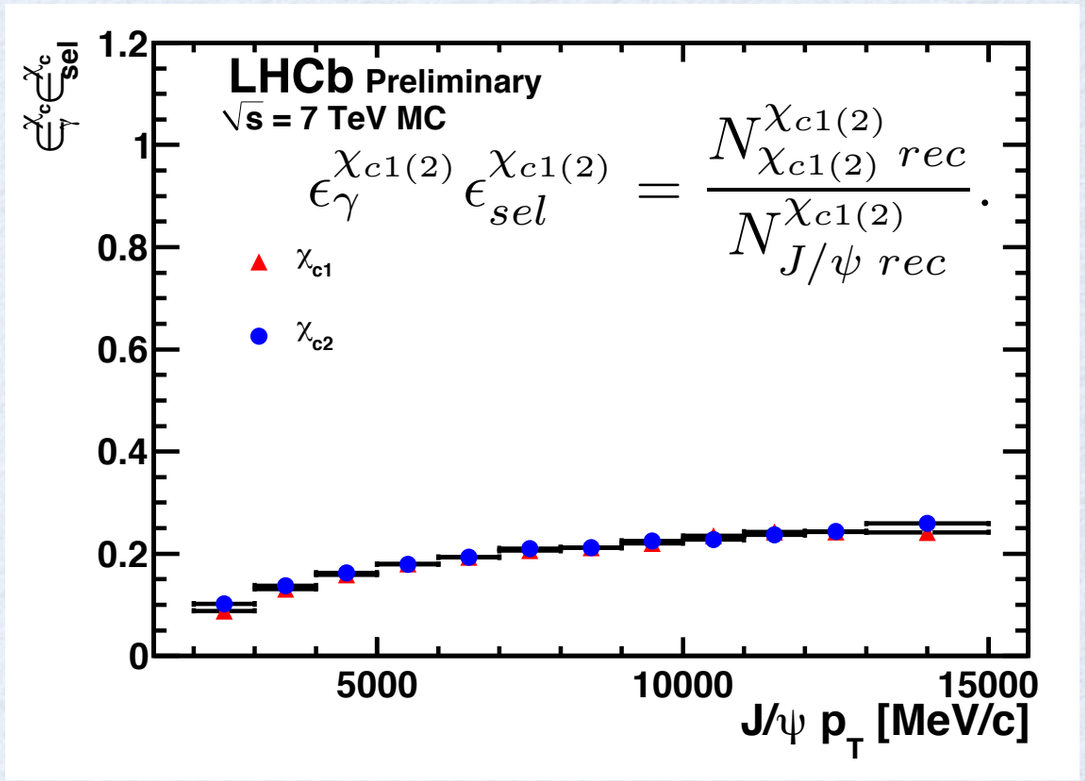
EFFICIENCIES

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

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

- Efficiencies are determined using fully simulated events
- Two components:
  - J/ψ reconstruction:
    ➥ consistent with 1 for all $p_t(J/\psi)$
  - χ_c reconstruction:
    - N(χ_c): generated χ_c
      → reconstructed and selected
    - N(J/ψ): #J/ψ from a χ_{cn} state
      - Very similar (but not identical)
      - Cut $p_t(\gamma)$ introduces edge in first bin

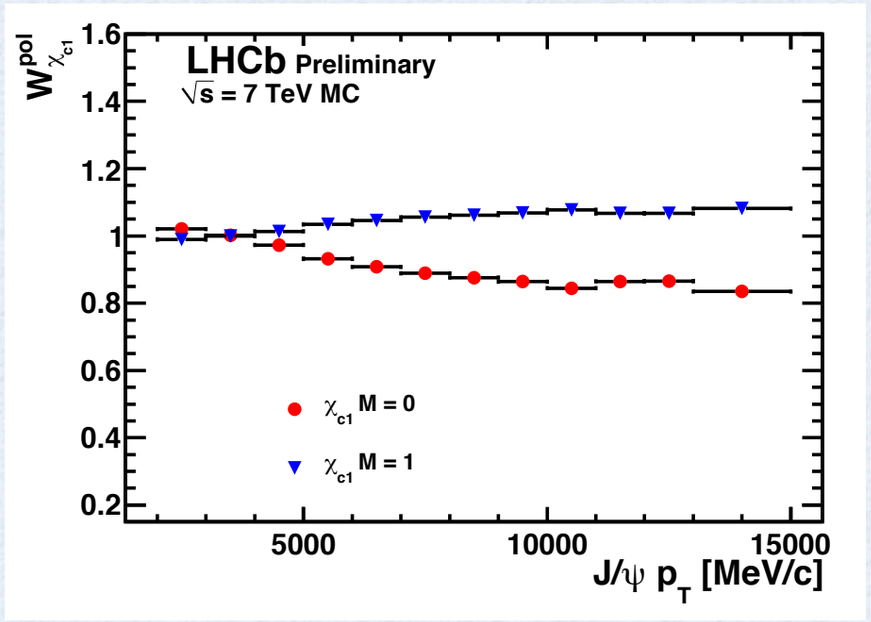
$$\frac{\epsilon_{J/\psi}^{\chi_{c2}}}{\epsilon_{J/\psi}^{\chi_{c1}}} = \frac{N_{J/\psi\ rec}^{\chi_{c2}}}{N_{J/\psi\ rec}^{\chi_{c1}}} \cdot \frac{N_{J/\psi\ gen}^{\chi_{c1}}}{N_{J/\psi\ gen}^{\chi_{c2}}}.$$

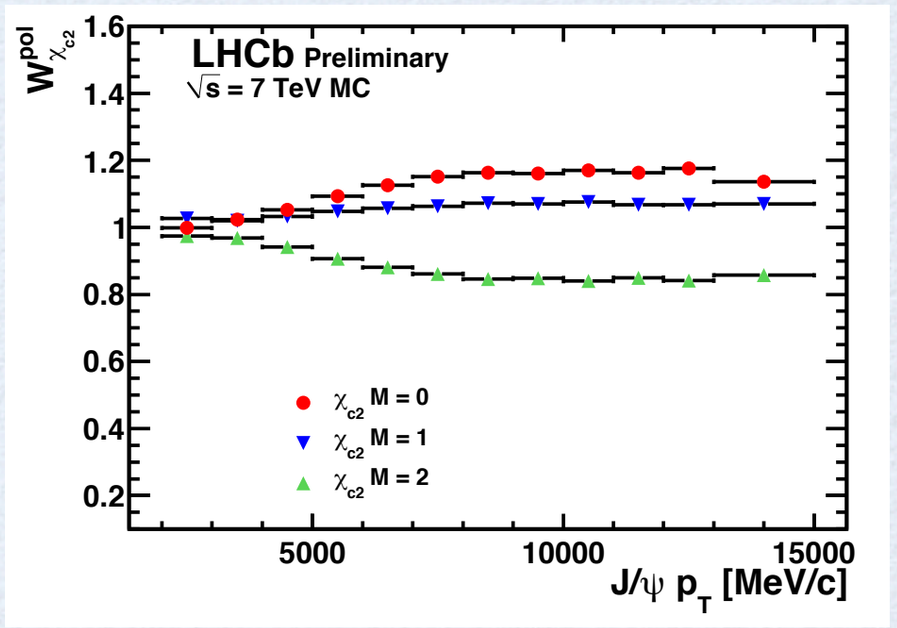


J/ψ AND χ_c POLARISATION

- 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: $M = 0 \ldots J$

Polarisation Weights

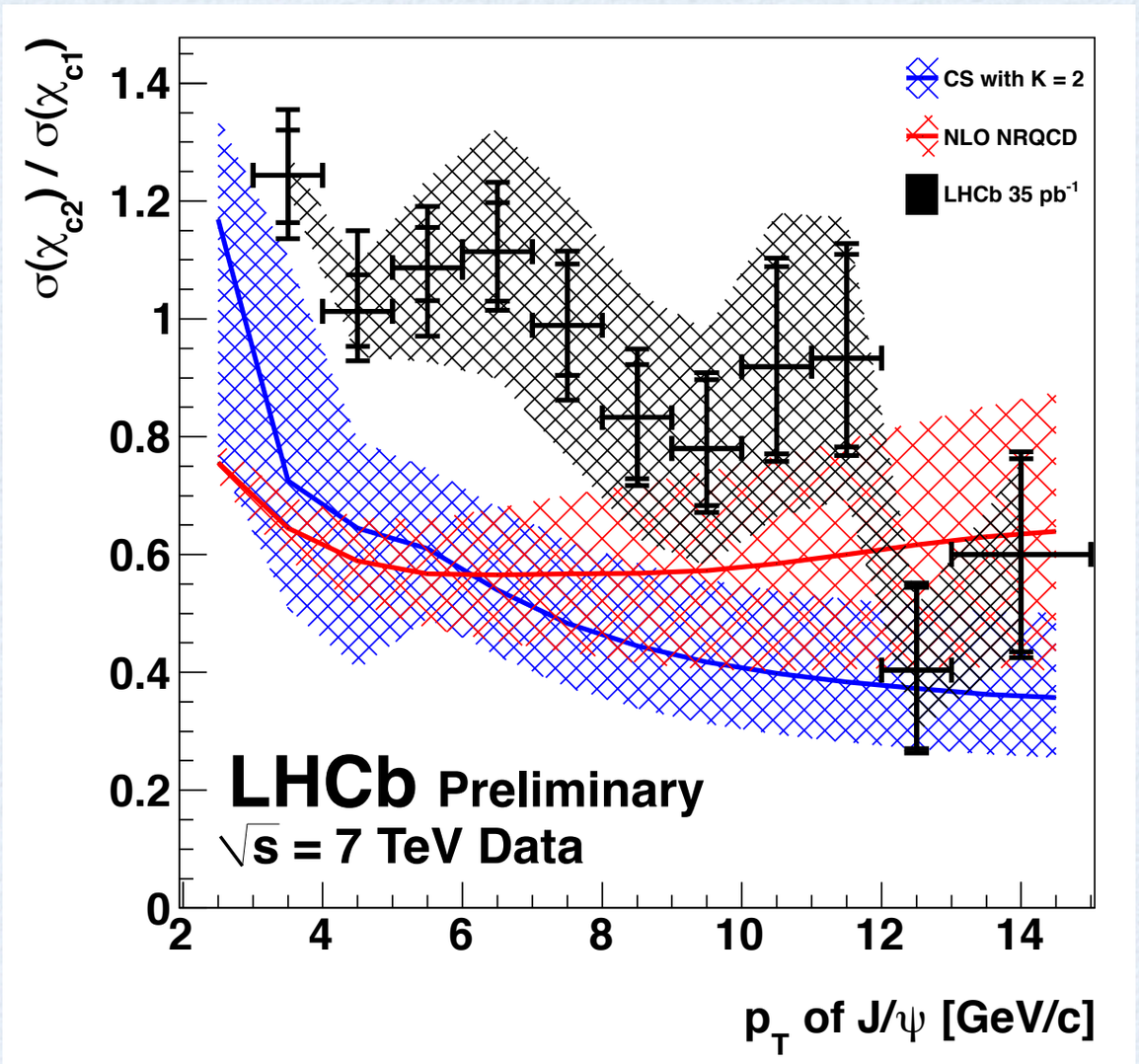




SYSTEMATICS

- 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 $\chi_c \to J/\psi\gamma$
    - Affects obtaining ratio of branching fractions $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ from ratio of yields
    - $\sigma(\chi_{c1}) \to J/\psi\gamma$: 36% , $\sigma(\chi_{c2}) \to J/\psi\gamma$: 20%

RESULTS



$p_T^{J/\psi}$ (GeV/c)	$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})}$	Polarization
$3-4$	$1.244^{+0.077\,+0.018\,+0.079}_{-0.081\,-0.018\,-0.070}$	$^{+0.039}_{-0.026}$
$4-5$	$1.013^{+0.062\,+0.105\,+0.061}_{-0.060\,-0.026\,-0.053}$	$^{+0.078}_{-0.077}$
$5-6$	$1.087^{+0.068\,+0.035\,+0.070}_{-0.056\,-0.088\,-0.053}$	$^{+0.153}_{-0.160}$
$6-7$	$1.114^{+0.083\,+0.026\,+0.079}_{-0.084\,-0.009\,-0.053}$	$^{+0.209}_{-0.216}$
$7-8$	$0.989^{+0.104\,+0.035\,+0.061}_{-0.085\,-0.079\,-0.053}$	$^{+0.223}_{-0.225}$
$8-9$	$0.833^{+0.090\,+0.053\,+0.053}_{-0.104\,-0.026\,-0.044}$	$^{+0.213}_{-0.206}$
$9-10$	$0.780^{+0.116\,+0.018\,+0.053}_{-0.097\,-0.035\,-0.035}$	$^{+0.201}_{-0.200}$
$10-11$	$0.919^{+0.170\,+0.035\,+0.061}_{-0.149\,-0.044\,-0.044}$	$^{+0.260}_{-0.255}$
$11-12$	$0.933^{+0.177\,+0.061\,+0.053}_{-0.151\,-0.044\,-0.053}$	$^{+0.239}_{-0.240}$
$12-13$	$0.404^{+0.141\,+0.026\,+0.035}_{-0.133\,-0.044\,-0.009}$	$^{+0.108}_{-0.107}$
$13-15$	$0.600^{+0.163\,+0.053\,+0.035}_{-0.165\,-0.044\,-0.035}$	$^{+0.157}_{-0.159}$

- 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

SUMMARY

- First measurement of the relative cross - section $\sigma(\chi_{c_2})/\sigma(\chi_{c_1})$ using data recorded in 2010 ($\mathcal{L} \approx 37 pb^{-1}$) at $\sqrt{s} = 7$ TeV
  - Comparison with dedicated event generator and NLO calculation show discrepancy esp. at low $p_t(J/\psi)$
- Charmonium production remains a challenging topic for QCD
- Next steps:
  - Include converted photons based on tracks
    - ➥ improved resolution w.r.t calorimeter
    - ➥ able to fully resolve all χ_c states
  - Evaluate ratio $\sigma(\chi_c)/\sigma(J/\psi)$
- Please also see talk on exclusive χ_c production

BACKUP

SYSTEMATICS

- Systematic uncertainties due to χ_c branching ratios

$p_T^{J/\psi}$ (GeV/c)	$2-3$	$3-4$	$4-5$
$Br(\chi_c \to J/\psi\gamma)$	–	$^{+0.070}_{-0.070}$	$^{+0.070}_{-0.053}$
Efficiencies	–	$^{+0.012}_{-0.011}$	$^{+0.015}_{-0.011}$
Systematics from fit	–	$^{+0.040}_{-0.040}$	$^{+0.029}_{-0.033}$
$p_T^{J/\psi}$ (GeV/c)	$5-6$	$6-7$	$7-8$
$Br(\chi_c \to J/\psi\gamma)$	$^{+0.070}_{-0.061}$	$^{+0.079}_{-0.061}$	$^{+0.061}_{-0.053}$
Efficiencies	$^{+0.015}_{-0.013}$	$^{+0.021}_{-0.019}$	$^{+0.021}_{-0.020}$
Systematics from fit	$^{+0.029}_{-0.033}$	$^{+0.043}_{-0.036}$	$^{+0.029}_{-0.033}$
$p_T^{J/\psi}$ (GeV/c)	$8-9$	$9-10$	$10-11$
$Br(\chi_c \to J/\psi\gamma)$	$^{+0.061}_{-0.044}$	$^{+0.061}_{-0.044}$	$^{+0.070}_{-0.061}$
Efficiencies	$^{+0.025}_{-0.024}$	$^{+0.034}_{-0.032}$	$^{+0.058}_{-0.053}$
Systematics from fit	$^{+0.027}_{-0.024}$	$^{+0.024}_{-0.029}$	$^{+0.027}_{-0.036}$
$p_T^{J/\psi}$ (GeV/c)	$11-12$	$12-13$	$13-15$
$Br(\chi_c \to J/\psi\gamma)$	$^{+0.061}_{-0.035}$	$^{+0.017}_{-0.018}$	$^{+0.044}_{-0.035}$
Efficiencies	$^{+0.053}_{-0.046}$	$^{+0.026}_{-0.023}$	$^{+0.055}_{-0.052}$
Systematics from fit	$^{+0.020}_{-0.020}$	$^{+0.022}_{-0.013}$	$^{+0.022}_{-0.043}$

not converted photons

$p_T^{J/\psi}$ (GeV/c)	$2-3$	$3-4$	$4-5$
$Br(\chi_c \to J/\psi\gamma)$	–	$^{+0.105}_{-0.079}$	$^{+0.061}_{-0.044}$
Efficiencies	–	$^{+0.024}_{-0.022}$	$^{+0.018}_{-0.013}$
Systematics from fit	–	$^{+0.066}_{-0.089}$	$^{+0.045}_{-0.045}$
$p_T^{J/\psi}$ (GeV/c)	$5-6$	$6-7$	$7-8$
$Br(\chi_c \to J/\psi\gamma)$	$^{+0.061}_{-0.053}$	$^{+0.053}_{-0.053}$	$^{+0.070}_{-0.053}$
Efficiencies	$^{+0.018}_{-0.019}$	$^{+0.021}_{-0.018}$	$^{+0.032}_{-0.031}$
Systematics from fit	$^{+0.045}_{-0.038}$	$^{+0.036}_{-0.040}$	$^{+0.052}_{-0.087}$
$p_T^{J/\psi}$ (GeV/c)	$8-9$	$9-10$	$10-11$
$Br(\chi_c \to J/\psi\gamma)$	$^{+0.044}_{-0.035}$	$^{+0.044}_{-0.017}$	$^{+0.035}_{-0.026}$
Efficiencies	$^{+0.028}_{-0.028}$	$^{+0.029}_{-0.025}$	$^{+0.040}_{-0.036}$
Systematics from fit	$^{+0.047}_{-0.052}$	$^{+0.040}_{-0.047}$	$^{+0.029}_{-0.036}$
$p_T^{J/\psi}$ (GeV/c)	$11-12$	$12-13$	$13-15$
$Br(\chi_c \to J/\psi\gamma)$	$^{+0.087}_{-0.061}$	$^{+0.053}_{-0.035}$	$^{+0.026}_{-0.026}$
Efficiencies	$^{+0.125}_{-0.098}$	$^{+0.091}_{-0.078}$	$^{+0.055}_{-0.050}$
Systematics from fit	$^{+0.158}_{-0.045}$	$^{+0.029}_{-0.024}$	$^{+0.038}_{-0.070}$

converted photons