Prompt production of charmonium states at LHCb

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on behalf of *The LHCb Collaboration*

Charmonium Workshop at LHCb

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Non-relativistic QCD as a theoretical framework

Great improvements in the understanding of charmonium production in the last year.

Golden approach: Non-Relativistic QCD factorization.

Long Distance Matrix Elements (LDME)

- Non-Perturbarive part
- Depend on the charmonium state Q
- Should be the same for hadro-production, photoproduction, production from decays...

$$d\sigma_{pp\to\mathcal{Q}+X} = \sum_n d\hat{\sigma}_{pp\to Q\bar{Q}[n]+X}\langle\mathcal{O}^{\mathcal{Q}}(n)\rangle.$$

Production cross-section
(measured)

Short-Distance coefficients (SDC)

- Perturbative part
- Related to the c-cbar pair, rather than to the charmonium state
- Can be computed theoretically using pdf as input

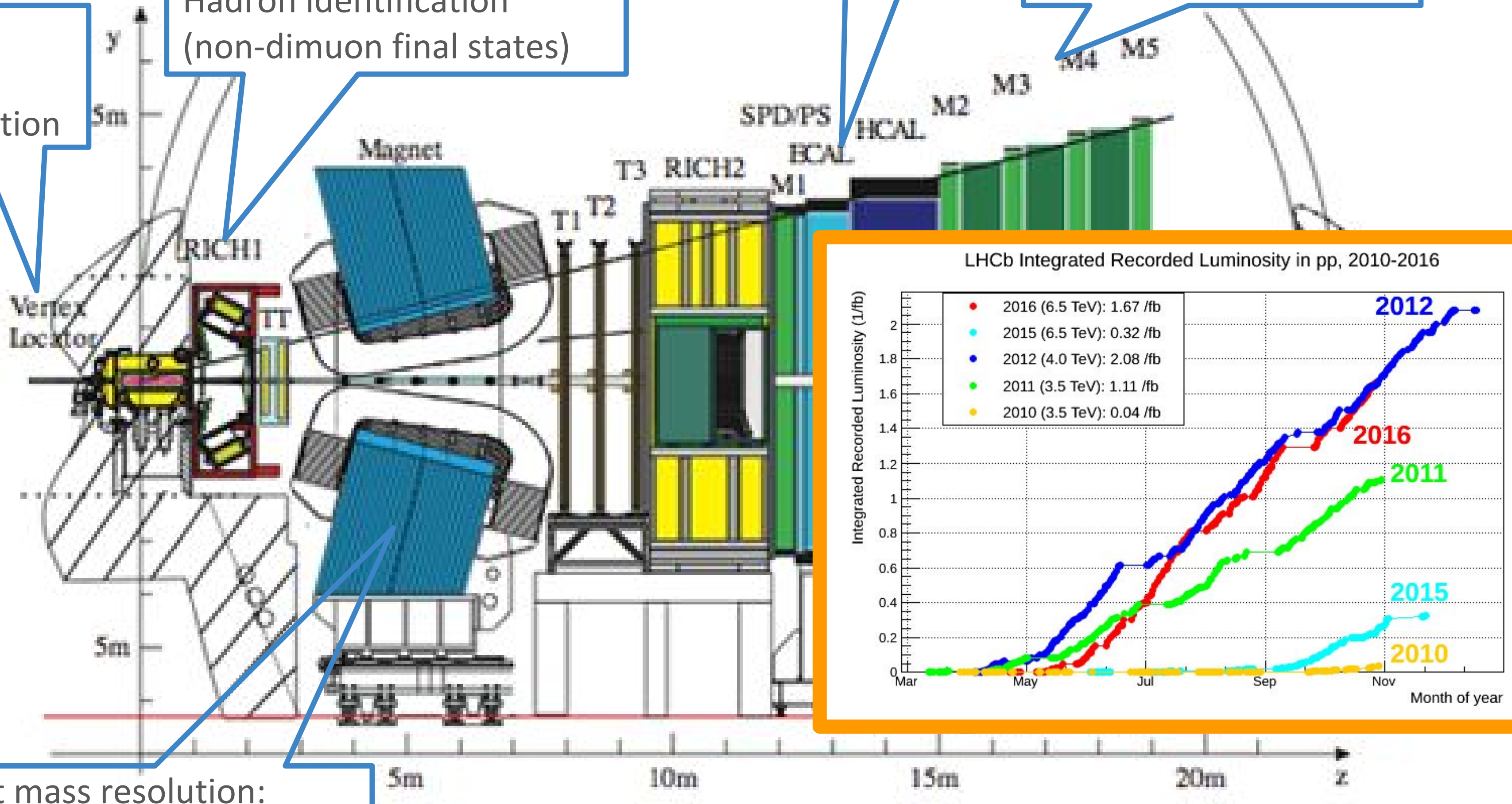
Predicts (or take as input in global fits):

- ➪ Charmonium Production in hadroproduction, photoproduction, e^+e^- annihilation...
- ➪ Charmonium polarization

The LHCb Detector

pp collisions at the LHC

A fully instrumented detector in the forward region



Prompt to detached discrimination

Hadron identification (non-dimuon final states)

Photon detection
Electron identification

Muon identification

Excellent mass resolution: better combinatorial rejection

The LHCb data processing

Trigger in three layers:

- ➪ Hardware (L0)
- ➪ Partially reconstructed (HLT1)
- ➪ Fully reconstructed (HLT2)

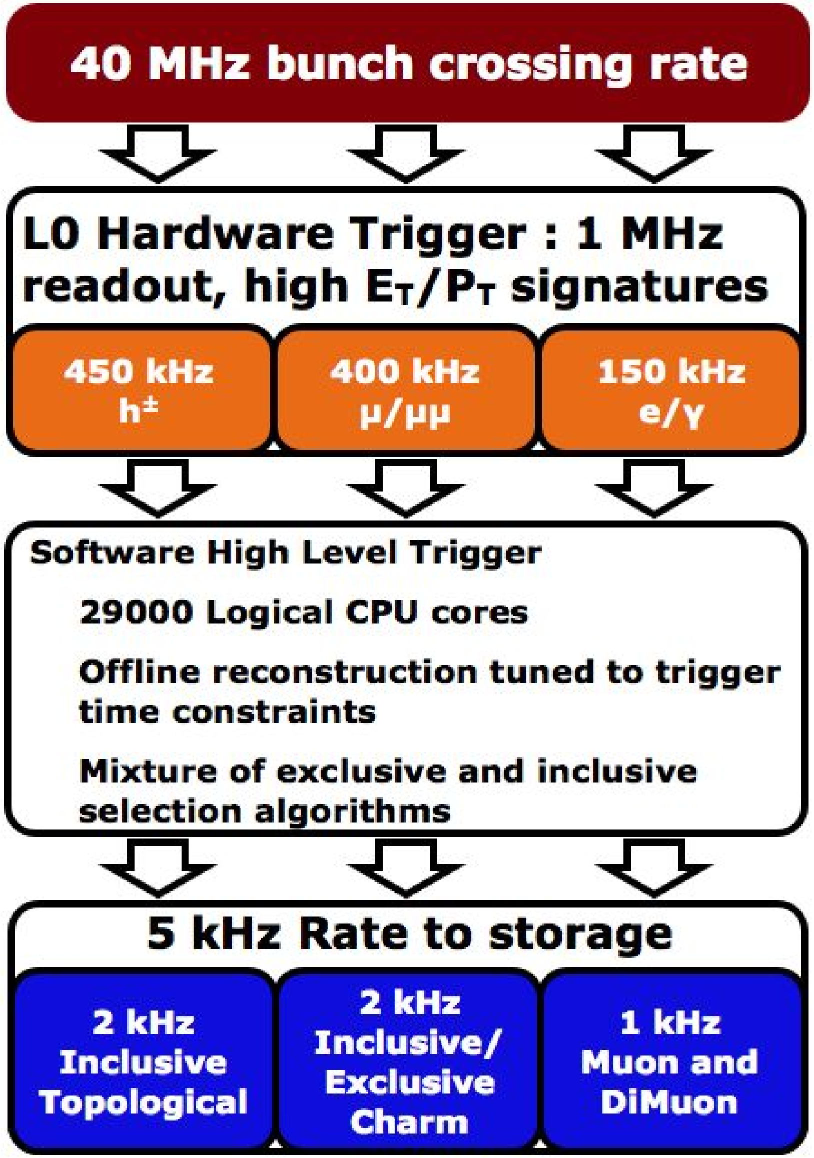
Dedicated dimuon lines at all layers.

Challenges of the hardware level.

Hadron trigger relies on HCAL.

Photon trigger, based on ECAL, works better for high-energy photons (less well for charmonium transitions).

Since Run2, tighter multiplicity cut at L0 to ease reconstruction in higher levels.



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$

400 kHz $\mu/\mu\mu$

150 kHz e/γ

Software High Level Trigger

29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

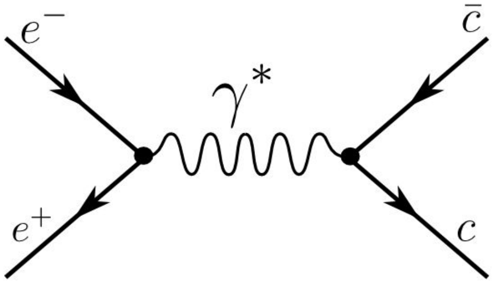
5 kHz Rate to storage

2 kHz Inclusive Topological

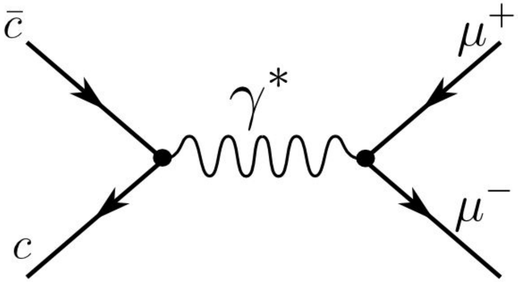
2 kHz Inclusive/ Exclusive Charm

1 kHz Muon and DiMuon

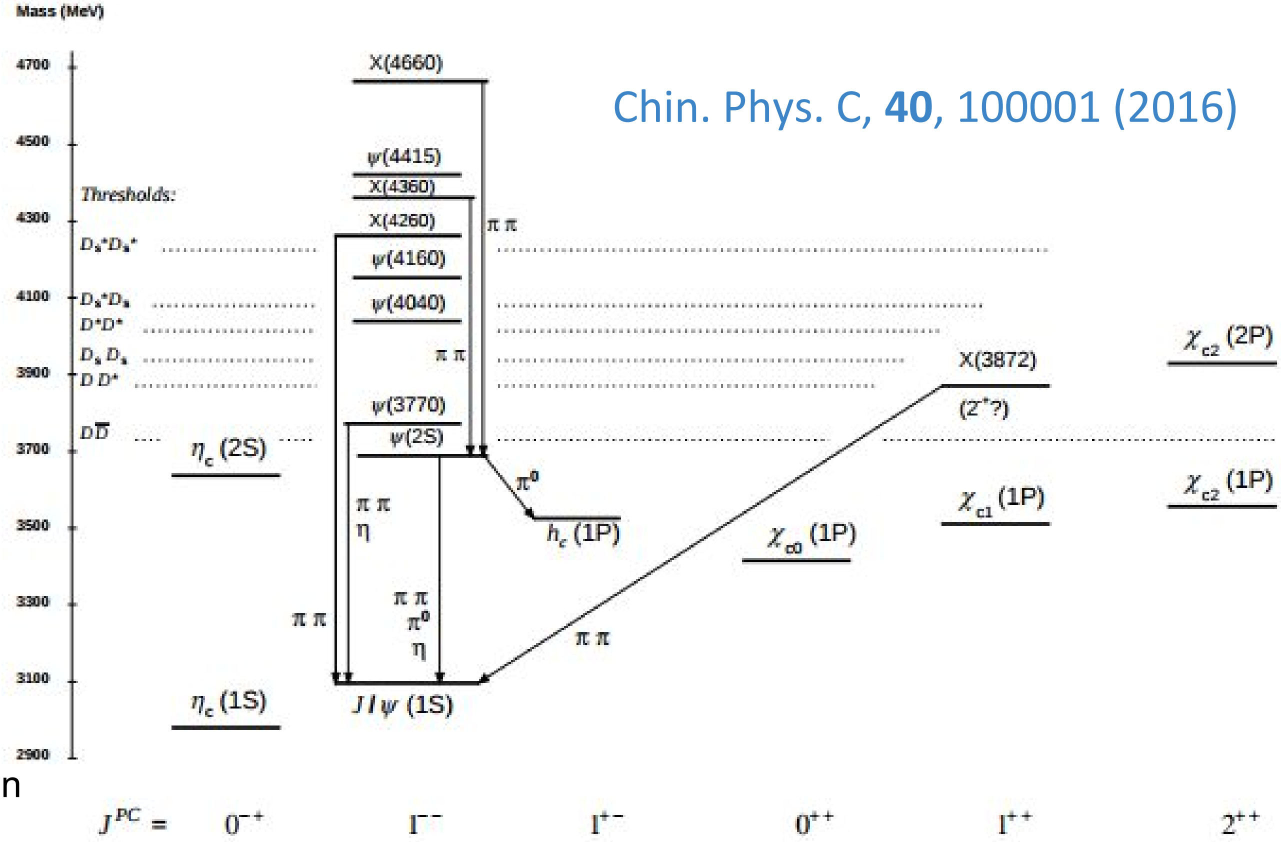
The 1^{--} states are "privileged" by photon interaction



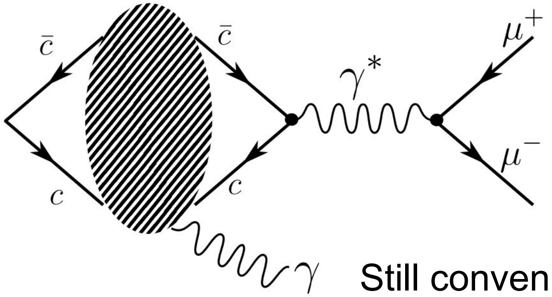
Historical privilege in production



Today, privilege for reconstruction



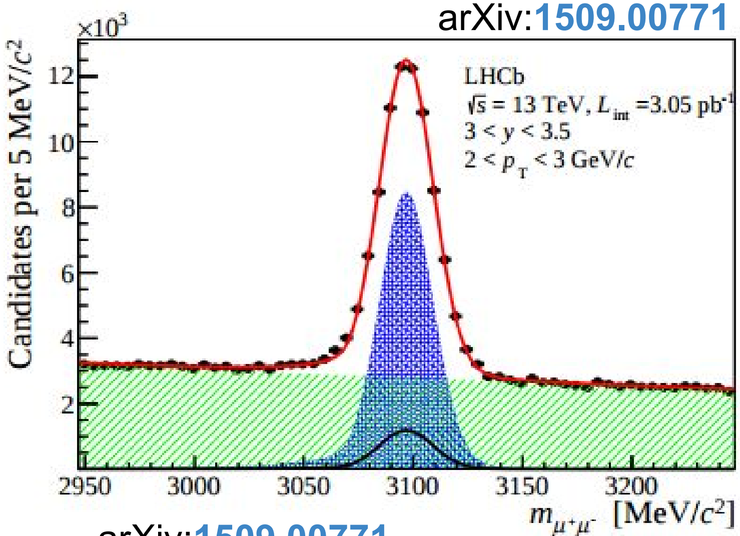
Chin. Phys. C, **40**, 100001 (2016)



Still convenient to reconstruct states decaying to 1^{--} states from radiative transitions

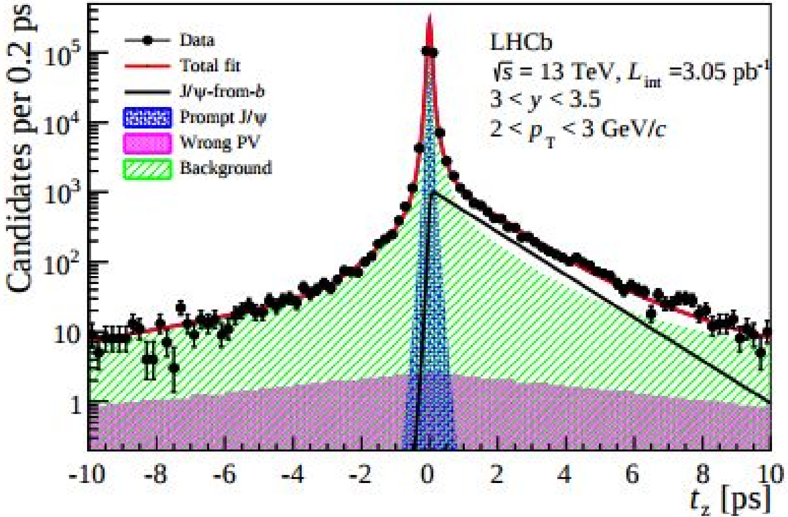
J/ψ double-differential production cross-section

arXiv:1509.00771

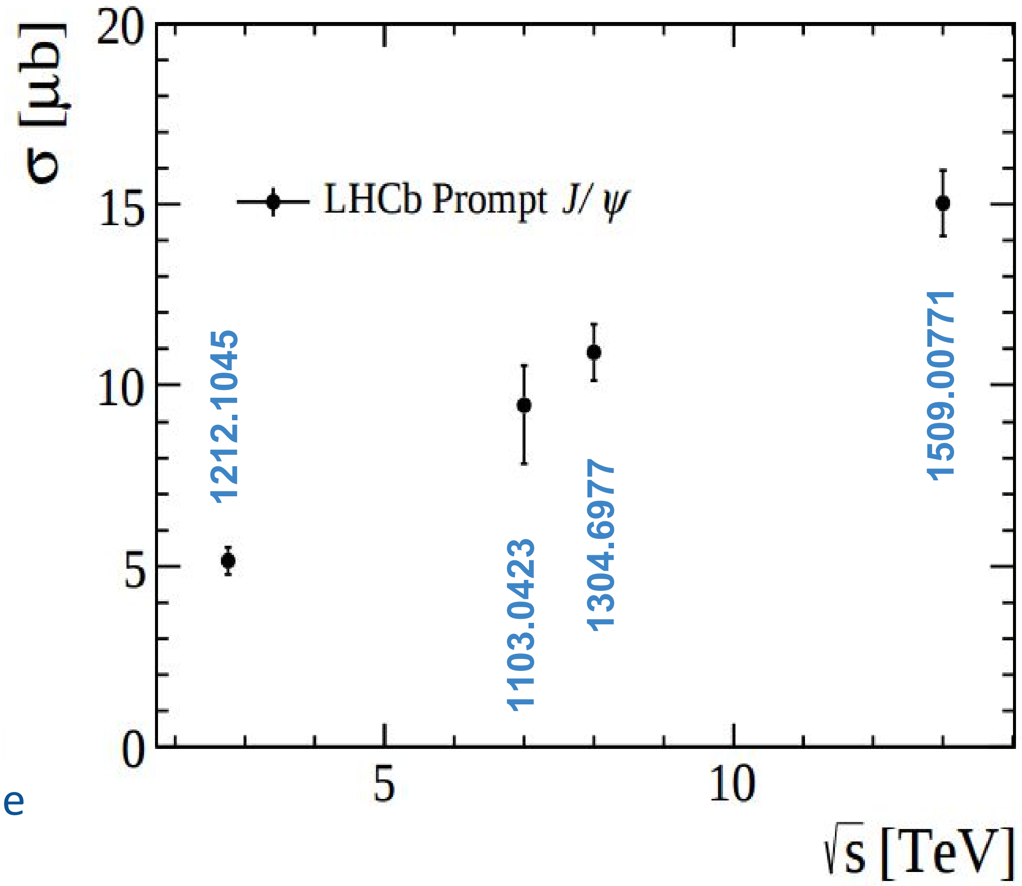


Excellent mass resolution:
rejection of combinatorial background

arXiv:1509.00771



Excellent vertex resolution: to disentangle prompt and from-*b* production.



J/ψ double-differential production cross-section

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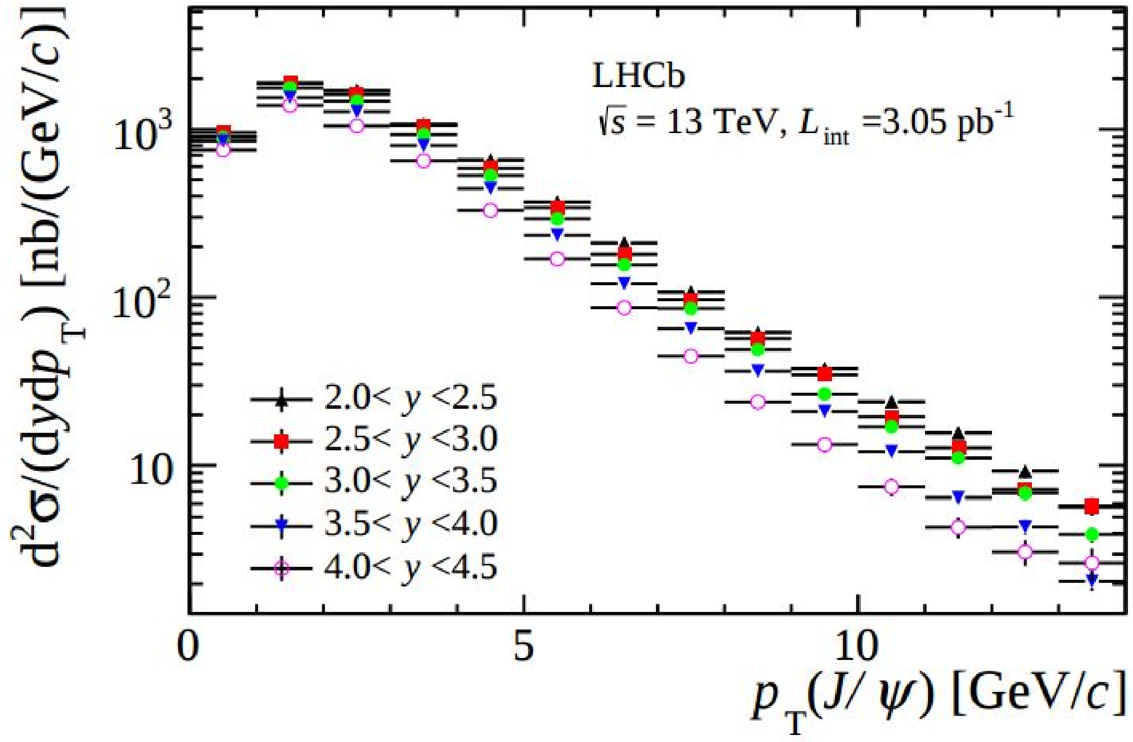
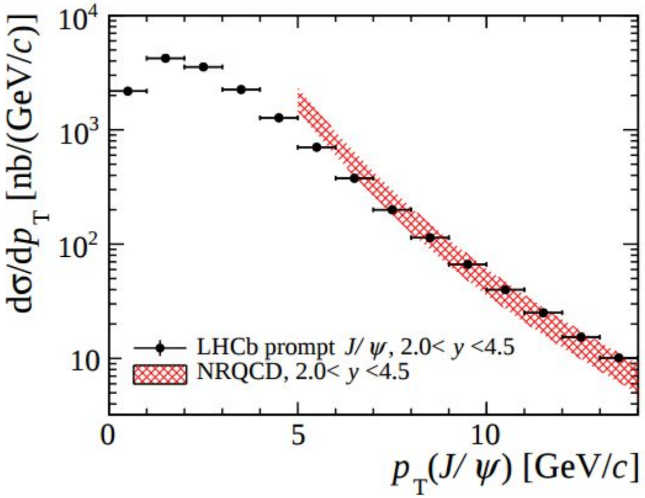
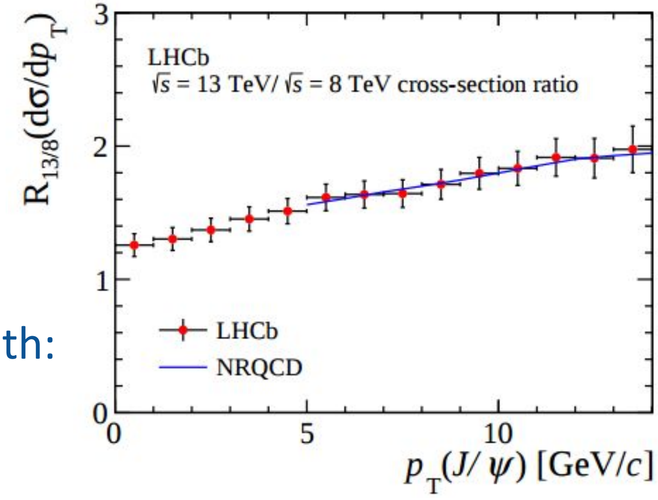


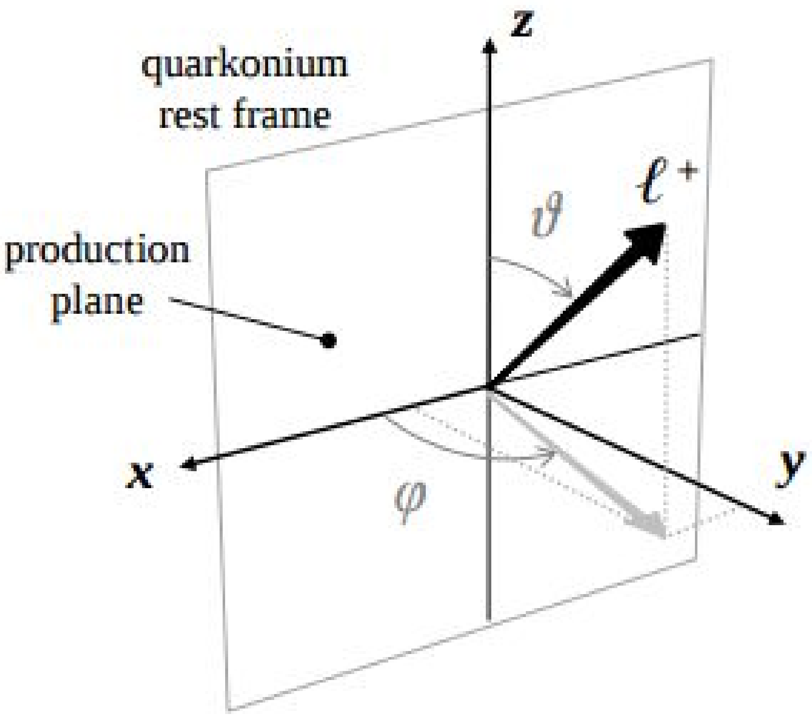




Non-relativistic QCD (arXiv:1411.3300) explains quite well both:

- the absolute scale of the cross-section
- the increase in cross-section due to the increase in √s

J/ψ polarization



Coordinate system:
Several choices are possible for the *z*-axis.

In the helicity frame, z is the direction of the boost between the quarkonium rest frame and the lab.

Azimuthal and Polar angles are defined.

The probability of a decay as a function of θ and ϕ is expressed as

$$\frac{d^2N}{d\cos\theta\, d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\phi} \sin 2\theta \cos\phi + \lambda_\phi \sin^2\theta \cos 2\phi,$$

Polarization parameters

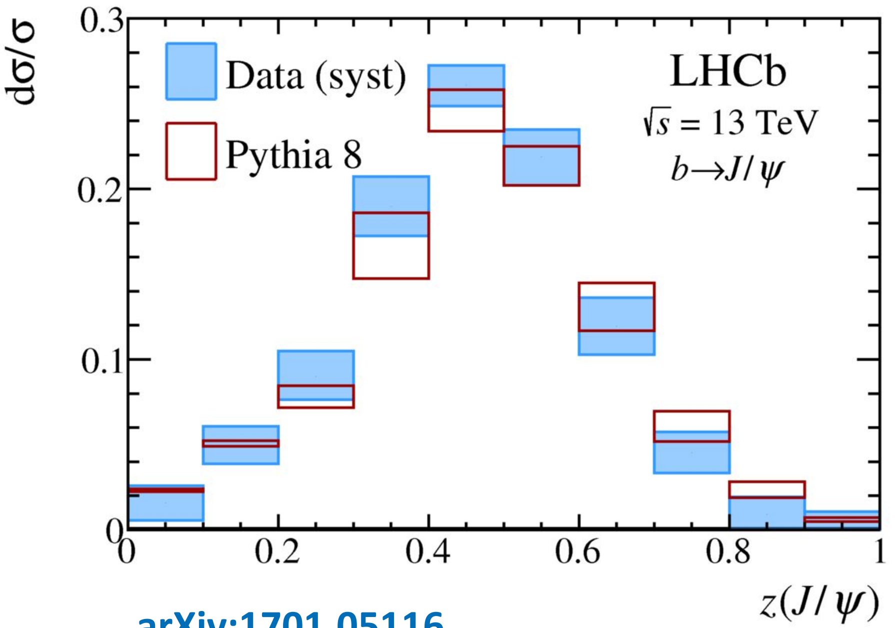
J/ψ production in jets

The fraction of the jet transverse momentum carried by the J/ψ meson,

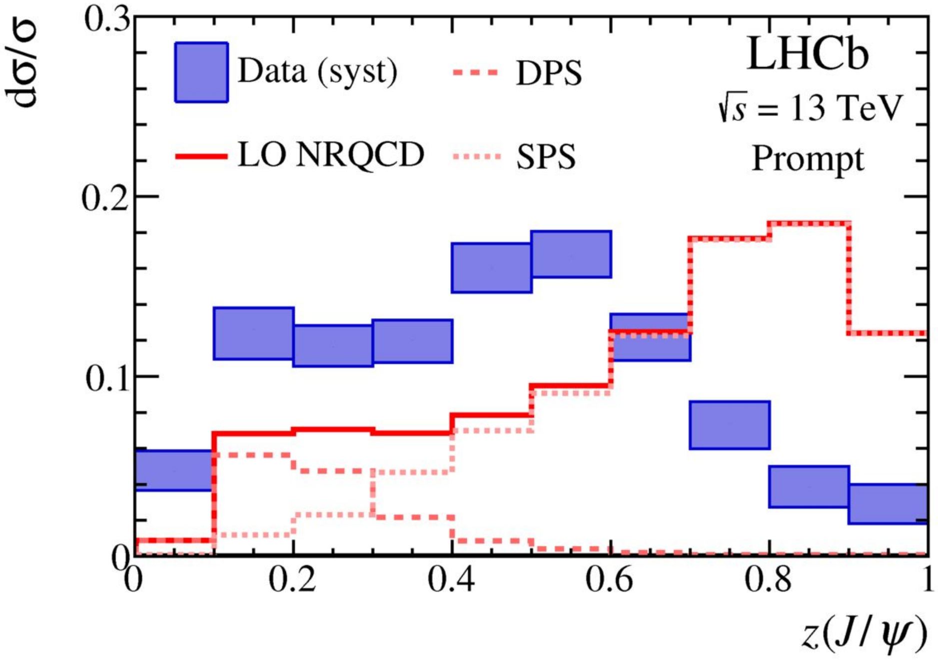
$$z \equiv p_T(J/\psi) \,/\, p_T(\text{jet}),$$

is measured using jets with

$p_T(\text{jet}) > 20$ and $2.5 < \eta(\text{jet}) < 4.0$.



arXiv:1701.05116



The result for $b \to J/\psi\, X$ decays agrees with pythia predictions.

The results for prompt J/ψ production do not agree with predictions based on fixed-order non-relativistic QCD.

J/ψ polarization

Polarization parameters are extracted through an unbinned maximum likelihood fit.

Likelihood maximised in the fit process

Polarization pdf

Efficiency

$$\log L \;=\; \sum_{i=1}^{N_{\rm tot}} w_i \times \log\left[\frac{P(\cos\theta_i,\phi_i|\lambda_\theta,\lambda_{\theta\phi},\lambda_\phi)\;\epsilon(\cos\theta_i,\phi_i)}{N(\lambda_\theta,\lambda_{\theta\phi},\lambda_\phi)}\right]$$

Background subtraction

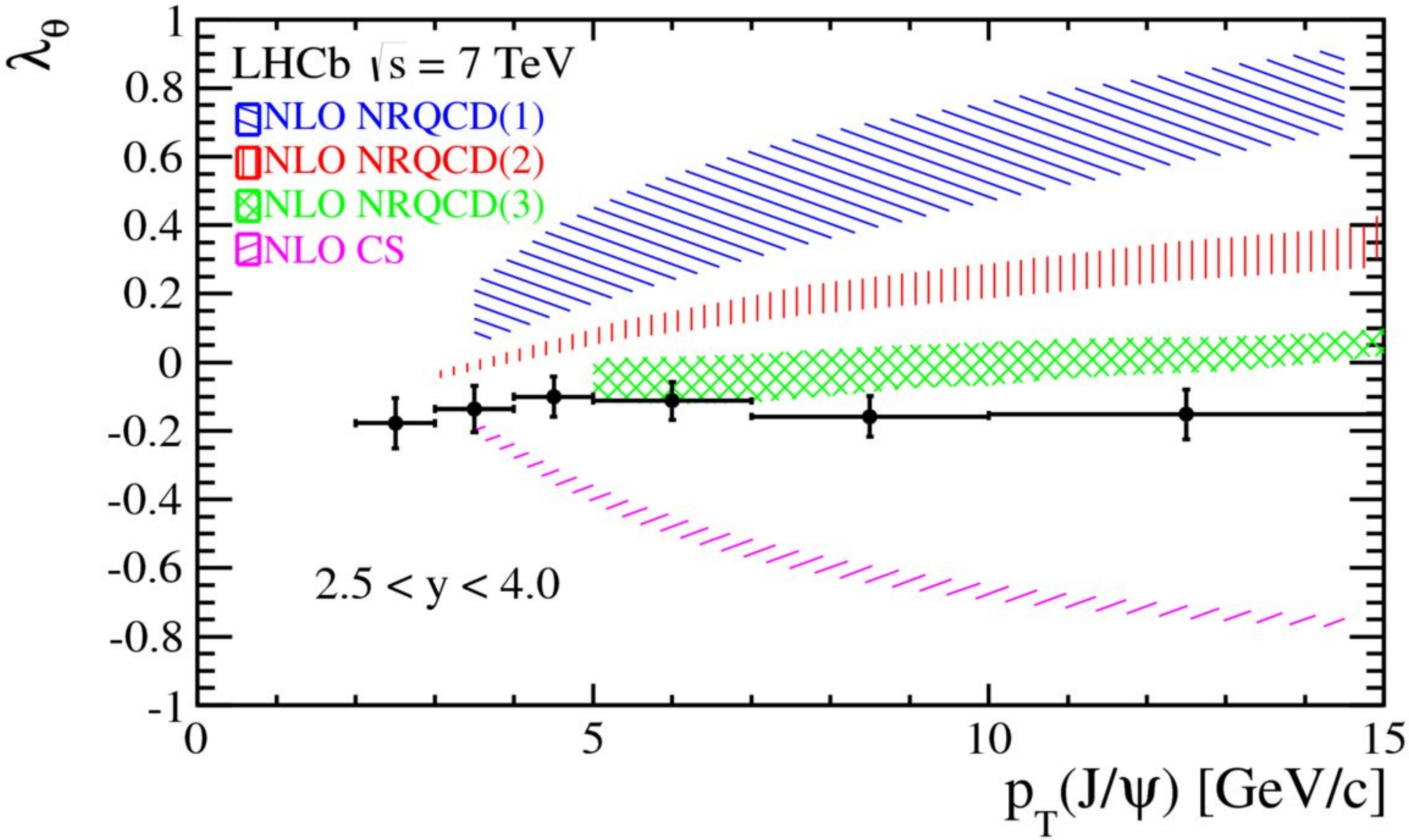
Normalization of P × ϵ

Large simulated samples are used to compute the efficiency and the normalization.

Decays of longitudinal-polarized J/ψ produced in $B^+ \to J/\psi\, K^+$ are used as cross-check.

J/ψ polarization

arXiv:1307.6379



For polarization, theoretical model seems more dependent on the underlying assumptions.

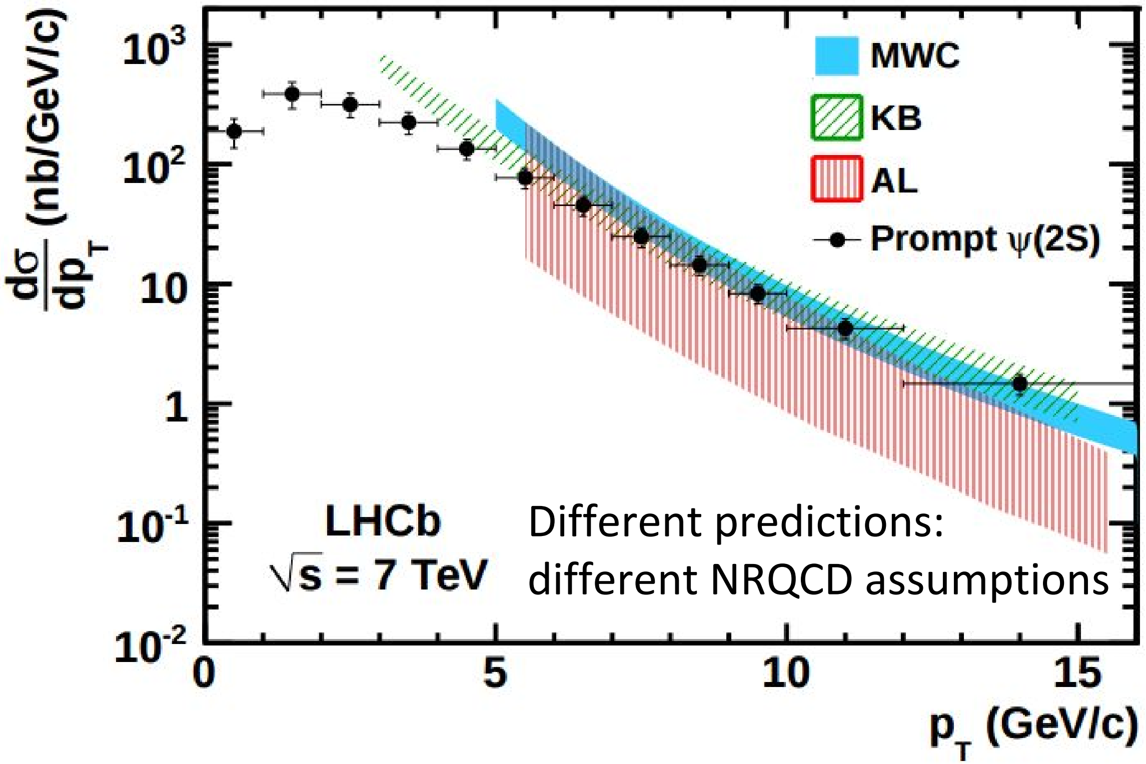
ψ(2S) production

Feed-down complicates the description of the production mechanism.
Production of excited states is important to pin down the theory.

To reduce the statistical uncertainty decay modes

- ➪ $\psi(2S) \rightarrow \mu\mu$
- ➪ $\psi(2S) \rightarrow J/\psi\, \pi\, \pi$
  - ➢ $J/\psi \rightarrow \mu\mu$

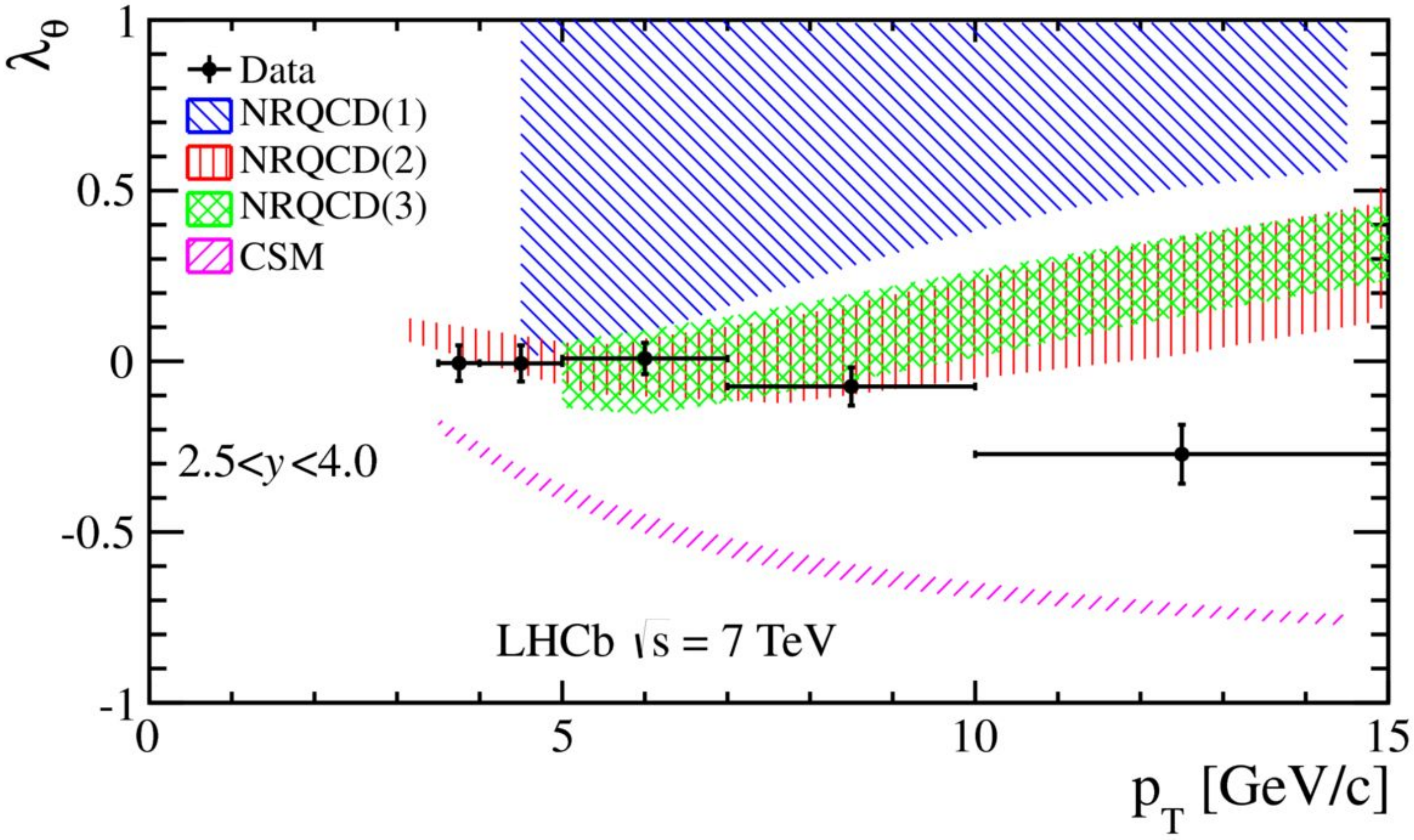
are combined.



Different predictions:
different NRQCD assumptions

ψ(2S) polarization

arXiv:1403.1339



Similar picture for the ψ (2S) as for the J/ψ polarization.

χ_c production

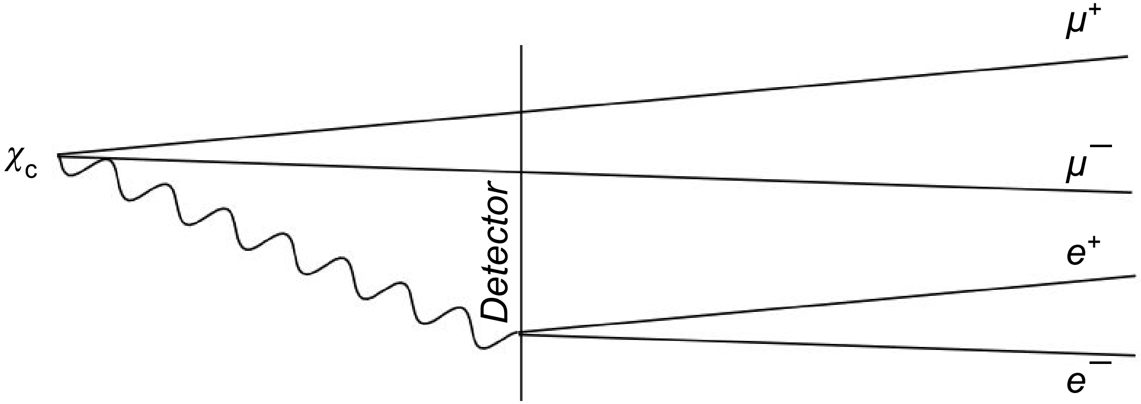
χ_c production is described by the same models (NRQCD) testing the same assumptions:

- factorization
- universality

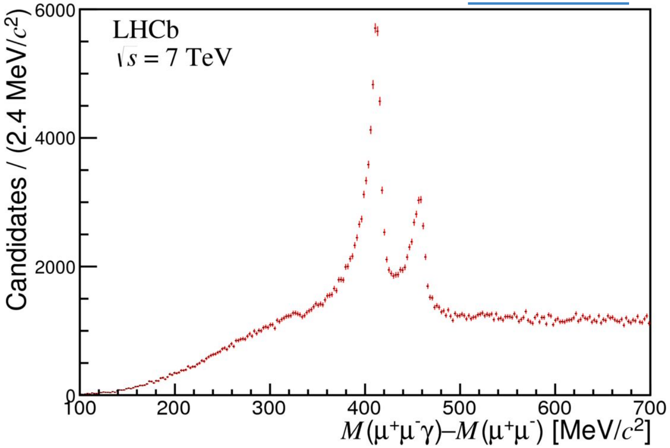
but it is much **cleaner**

- *less parameters to be extracted from experiment*
- *it's basically free from feed-down decays*

Using photons converted into electron pairs in the detector improves the mass resolution.



arXiv:1307.4285

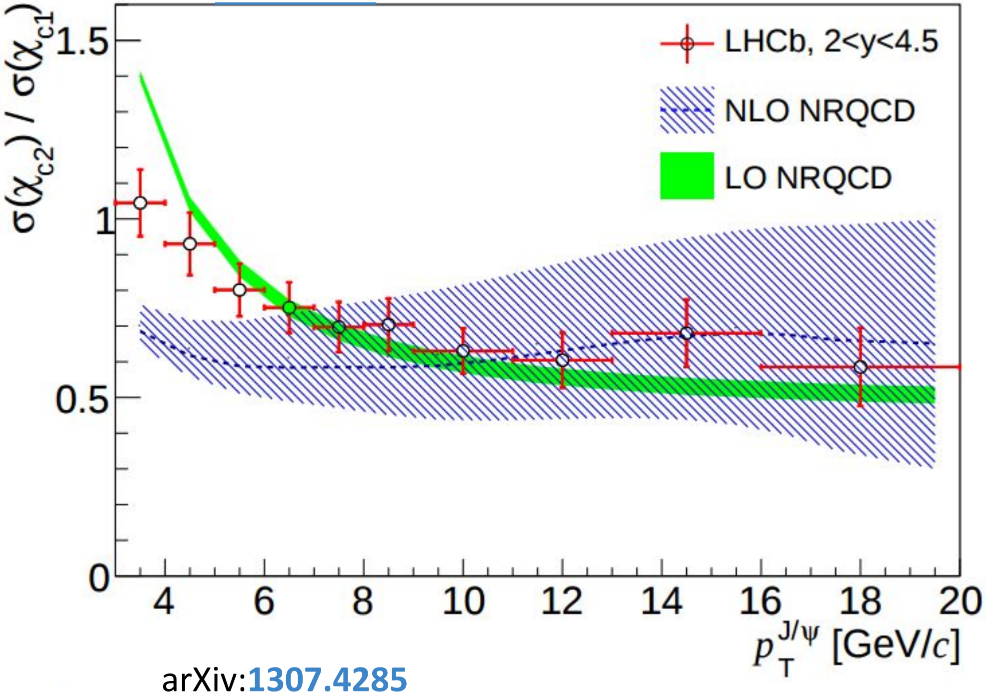


χ_c production

Results are consistent with NRQCD

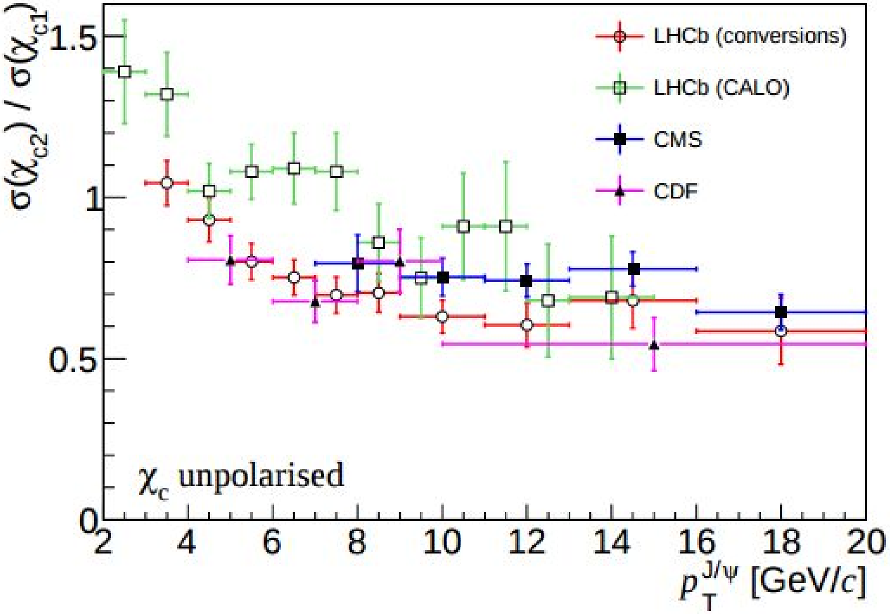
(lower p_T region is known to be more difficult)

arXiv:1307.4285



Results are consistent with other experiments at LHC and TeVatron.

arXiv:1307.4285



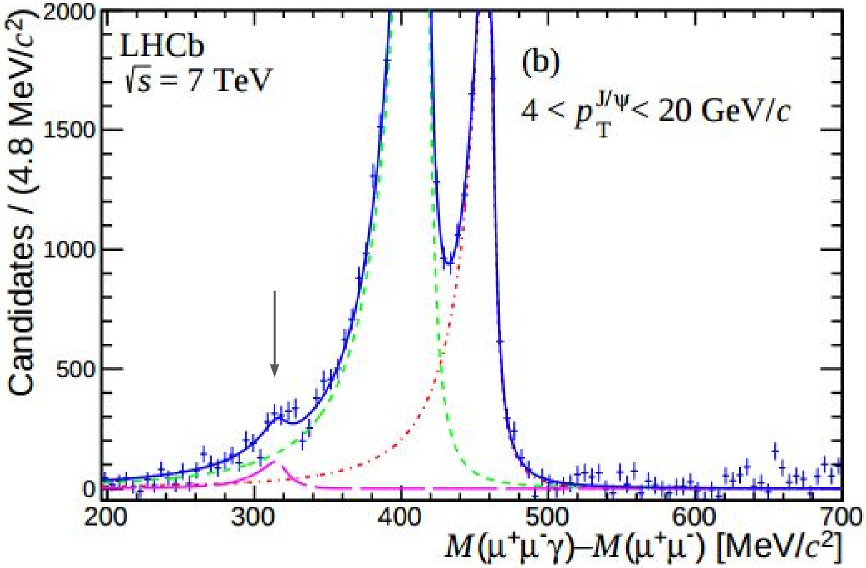
χ_{c0} production

In the same work, first evidence of χ_{c0} decays.

Statistics is only sufficient for integrated production measurement in range

$$4.0 < p_T(J/\psi) < 20\ \text{GeV}/c$$

arXiv:1307.4285



$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 1.19 \pm 0.27\,(\text{stat}) \pm 0.29\,(\text{syst}) \pm 0.16\,(\,p_{\rm T}\ \text{model}) \pm 0.09\,(\mathcal{B}),$$

The result is consistent with NRQCD:

$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 0.62 \pm 0.10$$ arXiv:1002.3987

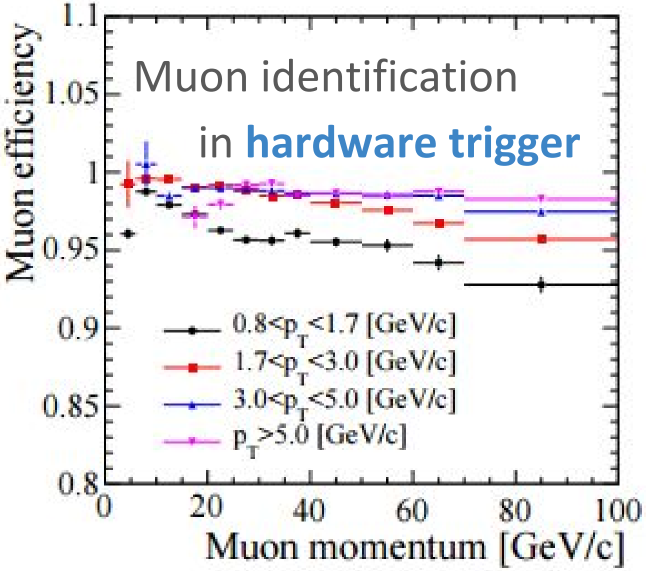
$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 0.53 \pm 0.02$$ arXiv:1305.2389

The challenge of non-dimuon final states

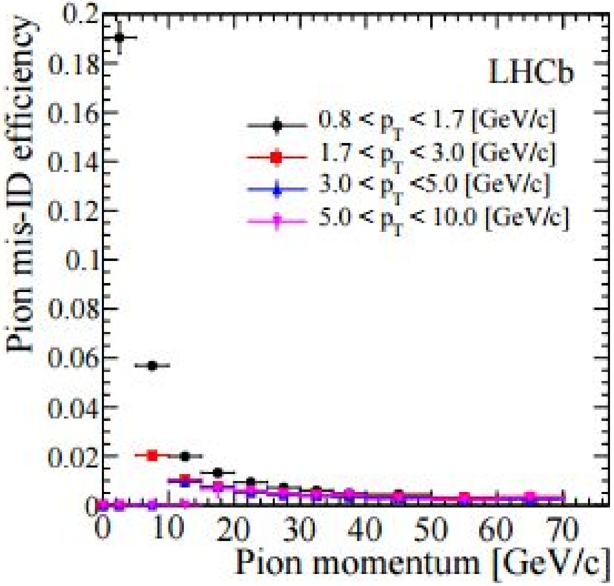
Given the overwhelming **pion background**, pure identification is crucial.

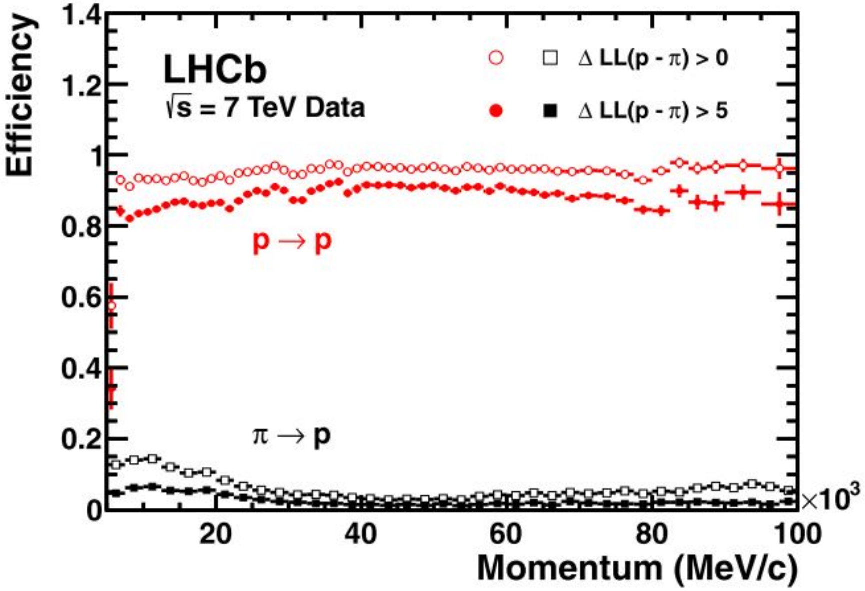
Detachment from the primary vertex can also reduce combinatorial background.

The **LHCb muon system** is built to be read in the hardware trigger stage, increasing selection efficiency.



Muon identification in **hardware trigger**





η_c production

Using dedicated Software-level trigger lines including experimental support to hadron identification.

The efficiency-corrected yield ratios are

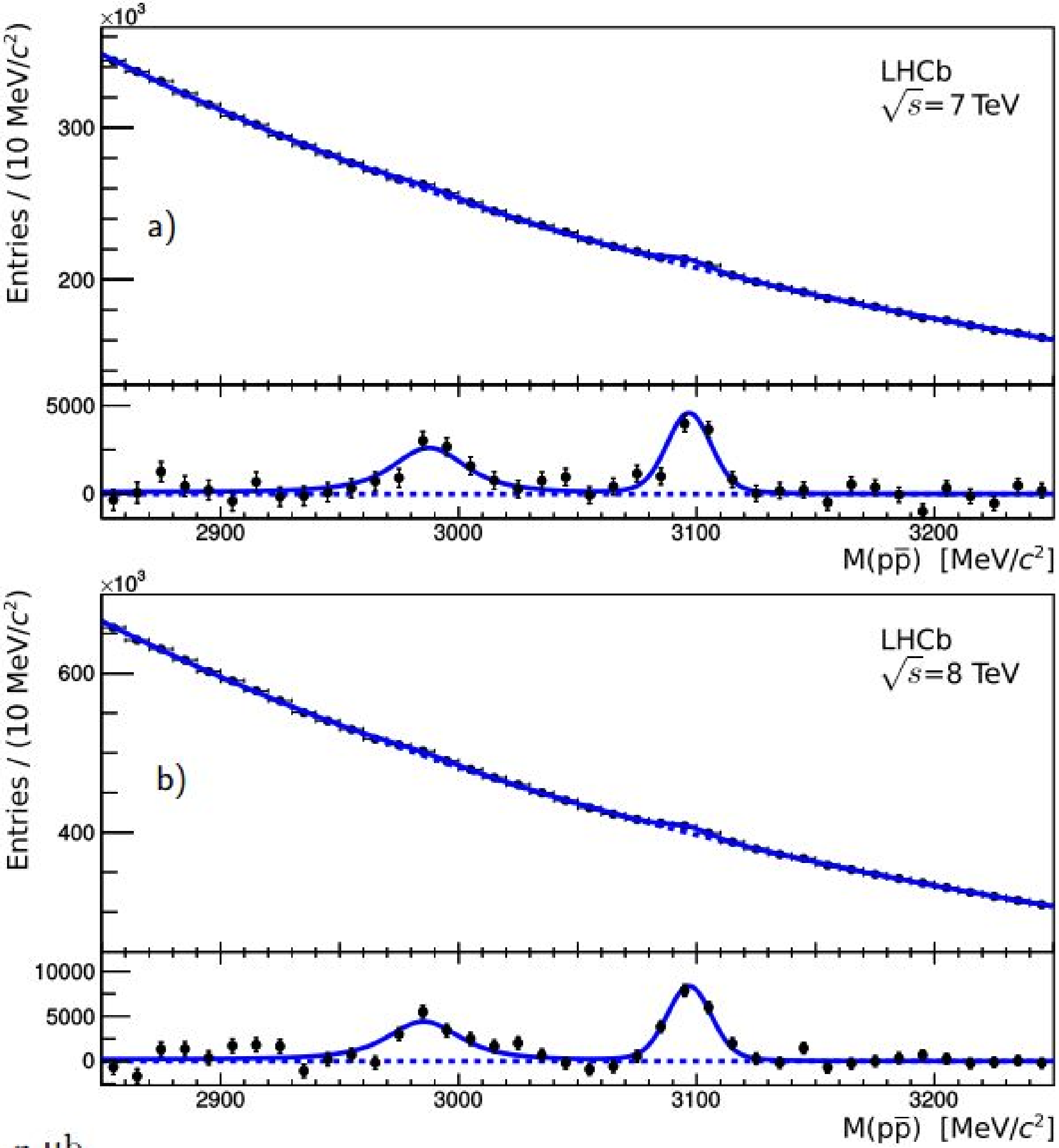
$$\left(\sigma_{\eta_c(1S)}/\sigma_{J/\psi}\right)_{\sqrt{s}=7\,\mathrm{TeV}} = 1.74 \pm 0.29 \pm 0.28 \pm 0.18_{\mathcal{B}},$$

$$\left(\sigma_{\eta_c(1S)}/\sigma_{J/\psi}\right)_{\sqrt{s}=8\,\mathrm{TeV}} = 1.60 \pm 0.29 \pm 0.25 \pm 0.17_{\mathcal{B}},$$

and converted to cross-sections using the LHCb measurements with J/$\psi \longrightarrow \mu\mu$ decays read:

$$\left(\sigma_{\eta_c(1S)}\right)_{\sqrt{s}=7\,\mathrm{TeV}} = 0.52 \pm 0.09 \pm 0.08 \pm 0.06_{\sigma_{J/\psi},\mathcal{B}}\ \mu\mathrm{b},$$

$$\left(\sigma_{\eta_c(1S)}\right)_{\sqrt{s}=8\,\mathrm{TeV}} = 0.59 \pm 0.11 \pm 0.09 \pm 0.08_{\sigma_{J/\psi},\mathcal{B}}\ \mu\mathrm{b},$$



η_c production *comparison with theory (NRQCD)*

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η_c production at the LHC challenges nonrelativistic-QCD factorization

Mathias Butenschoen, Zhi-Guo He, and Bernd A. Kniehl
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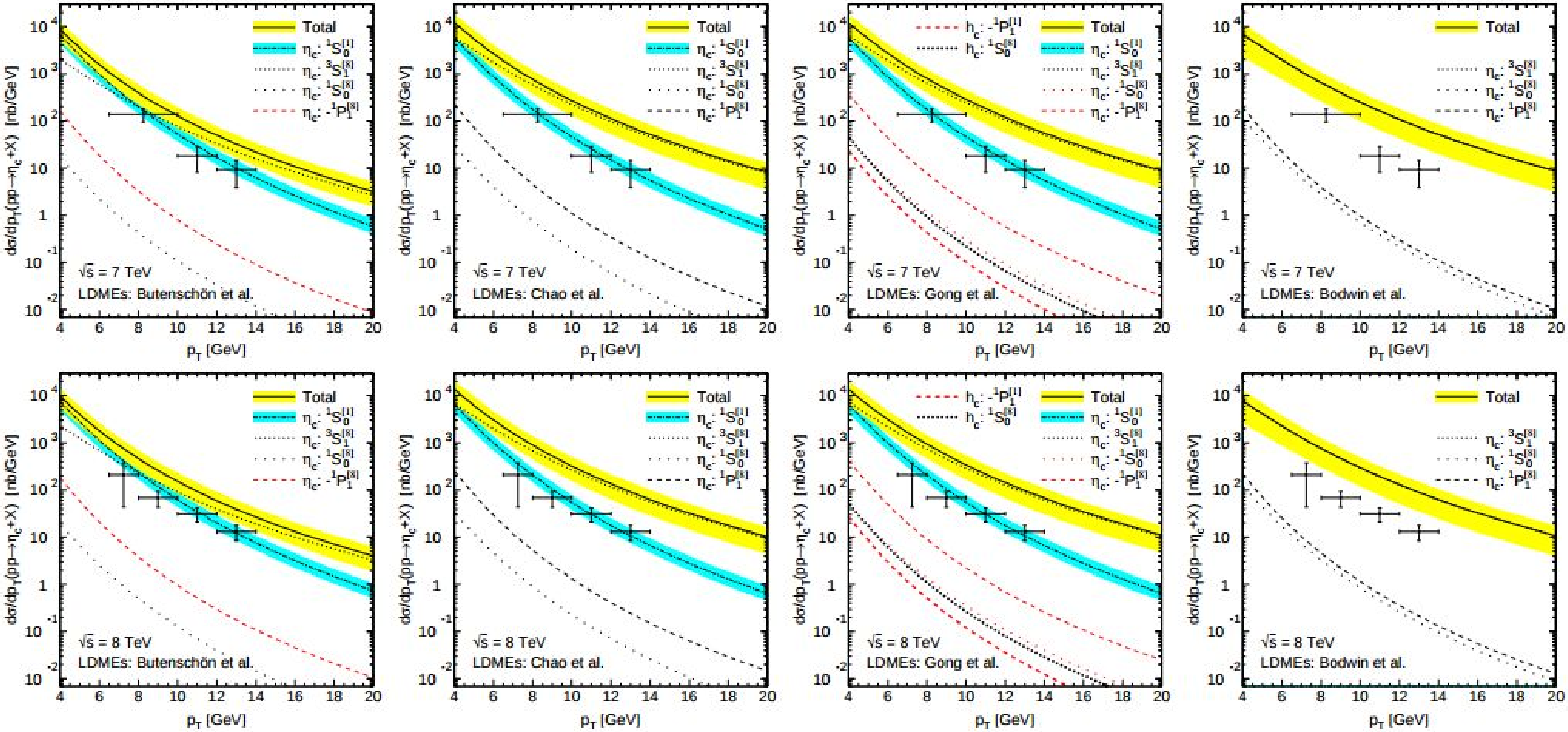
Luruper Chaussee 149, 22761 Hamburg, Germany



η_c production at LHC and implications for the understanding of J/ψ production

Hao Han[a], Yan-Qing Ma[b,c], Ce Meng[a], Hua-Sheng Shao[a,d], Kuang-Ta Chao[a,c,e]
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(d) Physics Department, Theory Unit, CERN, CH-1211 Geneva 23, Switzerland
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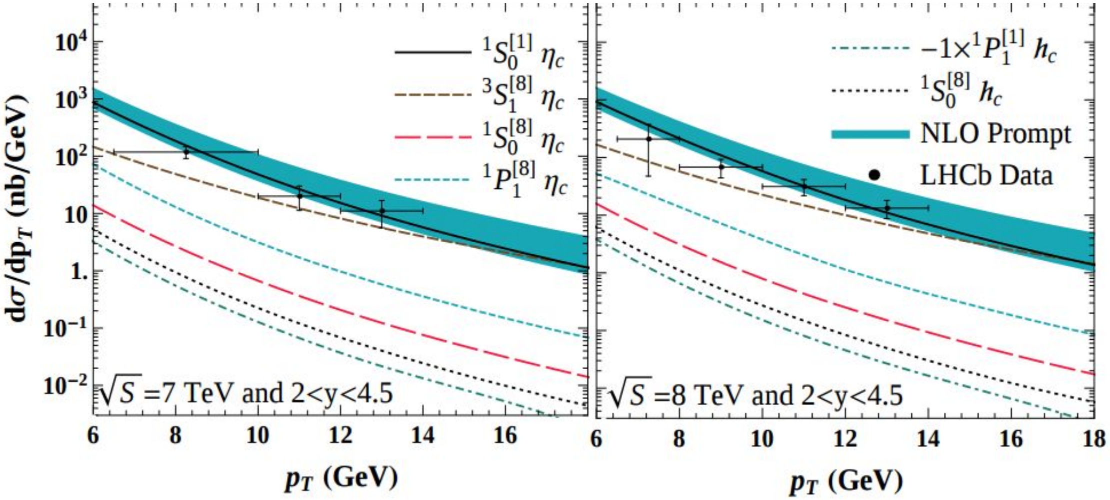
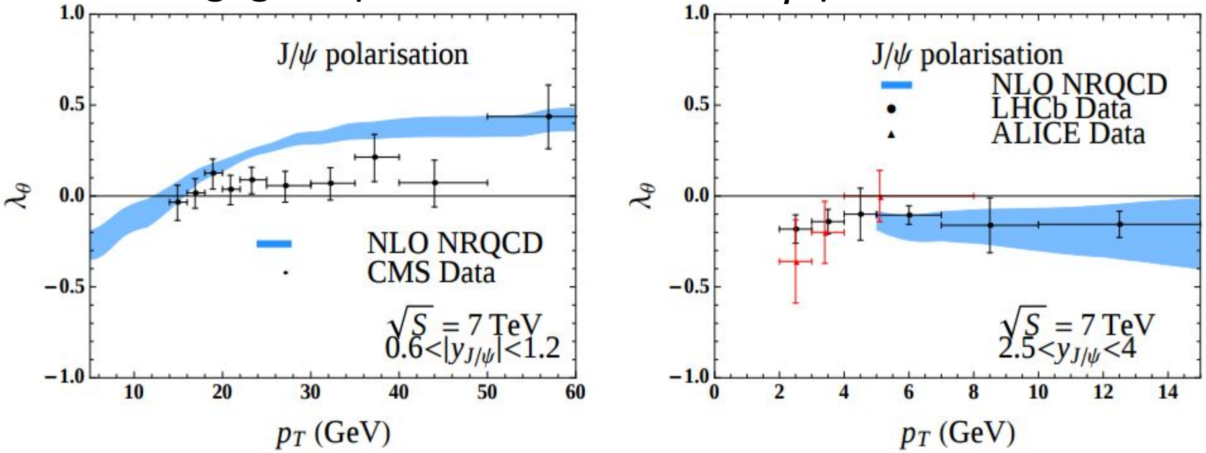


The same fit predicts negligible polarization for the J/ψ produced at LHCb



arXiv:1412.0508

Impact of η_c hadroproduction data on charmonium production and polarization within NRQCD framework

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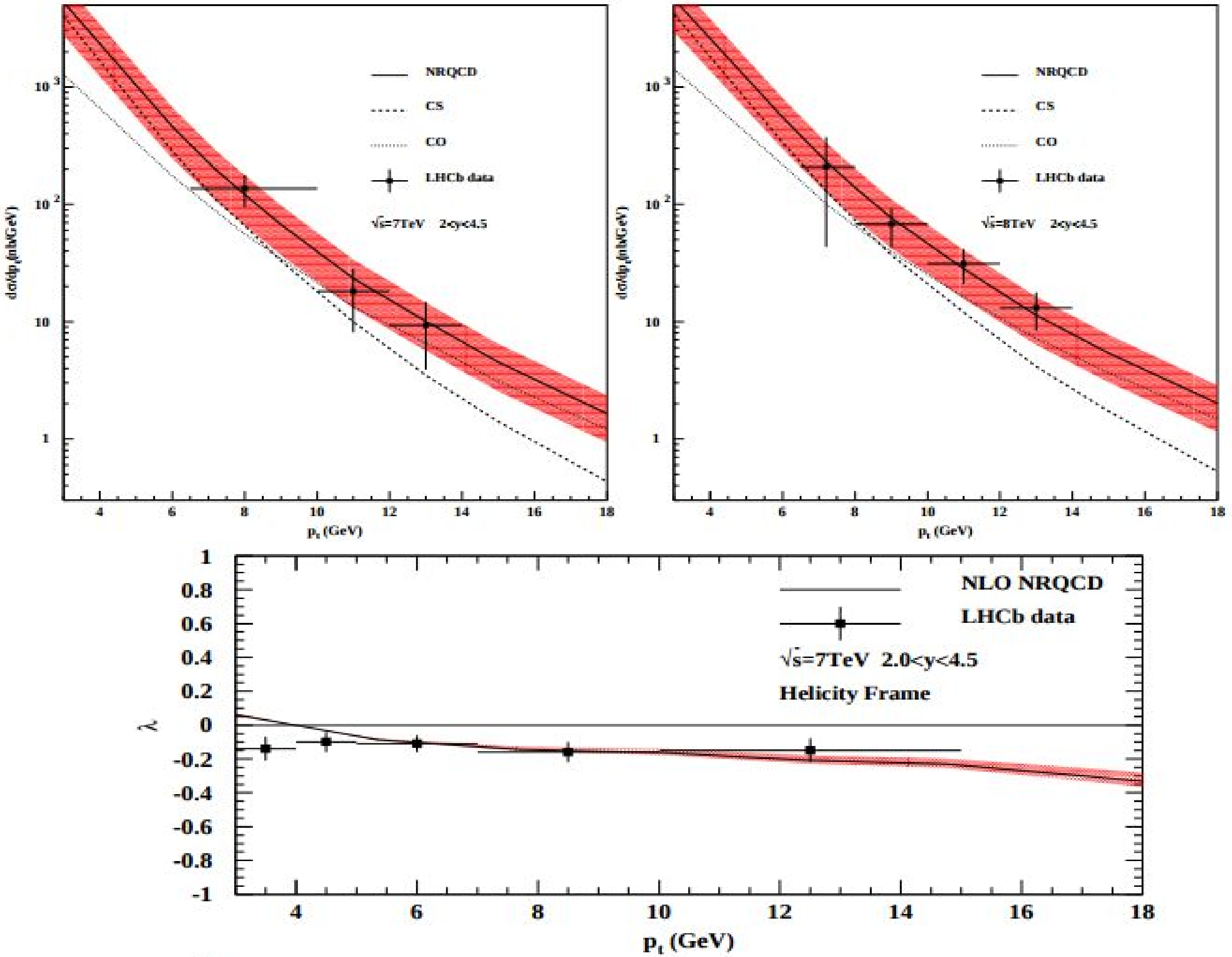
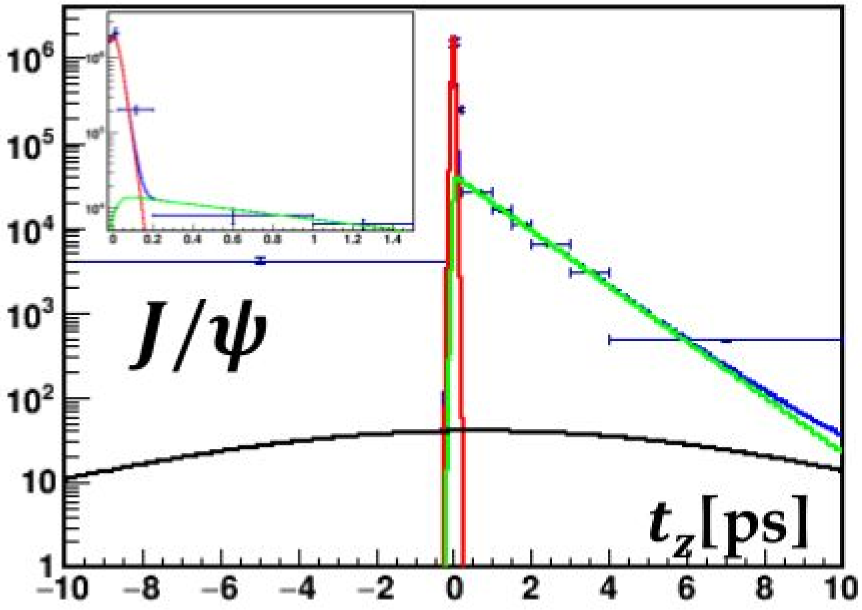
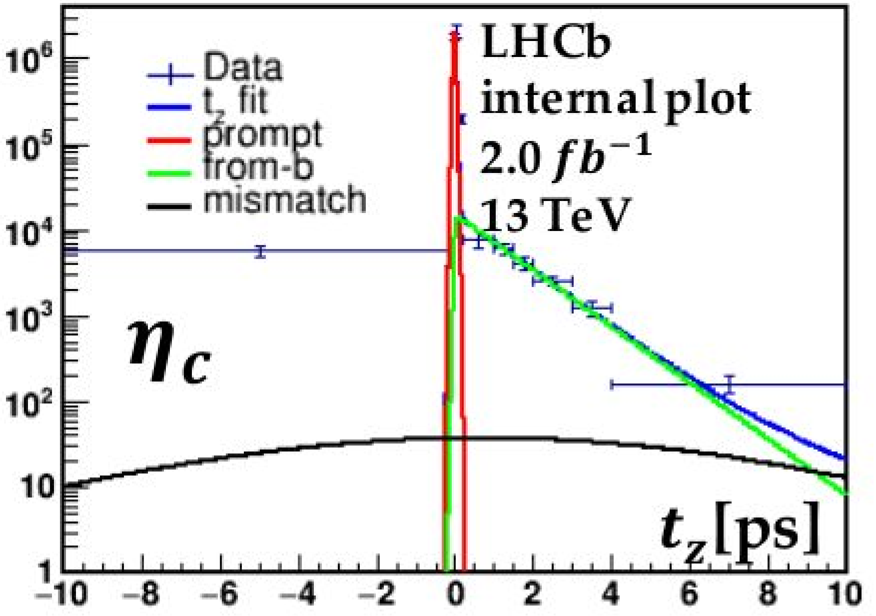


Towards an η_c production measurement at $\sqrt{s}$ = 13 TeV

Renewed Strategy

Use cleaner “from-b” decays to determine masses and resolution. → Perform invariant mass fit in bins of t_z → Fit t_z distribution to disentangle prompt and from-*b* components



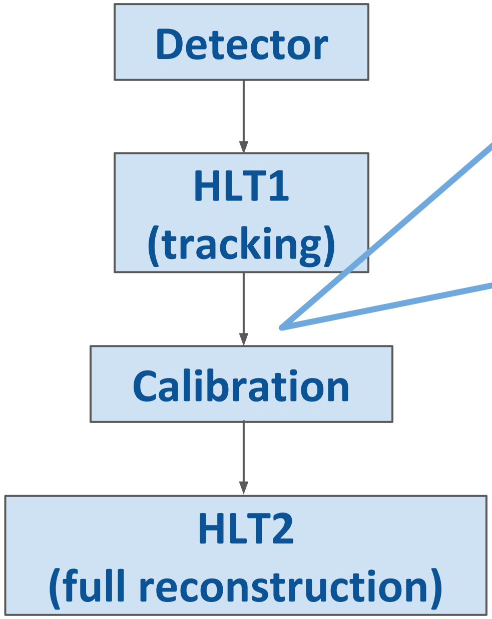


Future possible improvements

The LHCb trigger has evolved in Run-2:

- Online Offline-quality reconstruction allows exploitation of the RICH in the trigger.
- Refined DiProton Line to increase the selection efficiency

Current trigger scheme:



Detector

HLT1 (tracking)

Calibration

HLT2 (full reconstruction)

An important limitation comes here:

two prompt tracks with an invariant mass of 3 GeV is a too loose requirement.

- only J/ψ and η_c can be selected.

Investigation on selecting $\phi\phi$ final states.

Fast RICH reconstruction algorithms, originally developed for the upgrade,
can be used here “already” as further improvement.

Conclusive remarks and outlook

After several years of “confusion” around quarkonium production,
a **huge improvement was made with theoretical predictions**,

- ⇨ improving the description of the non-perturbative contributions
- ⇨ exploring heavy quark spin symmetry and velocity scaling rules

More to be done experimentally especially in the fields of

- ⇨ **Polarizations**
- ⇨ **Associative production (covered later)**
- ⇨ **Higher states, much cleaner theoretically**

Close interaction with theory community is obviously crucial in this field!
We (as experimentalists) are very happy of your indications on priorities!