J/ψ and double charmonium production with the LHCb detector

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Charmonium production at LHCb

- Measurements of production cross section and polarization of J/ψ (described in this talk). Physical motivations:
  - charmonium production mechanism is not well understood, many theoretical models have been proposed but they are not able to fit the polarization together with the cross section.
  - studies of B physics: charmonium is present in the final states of many interesting B decay channels.

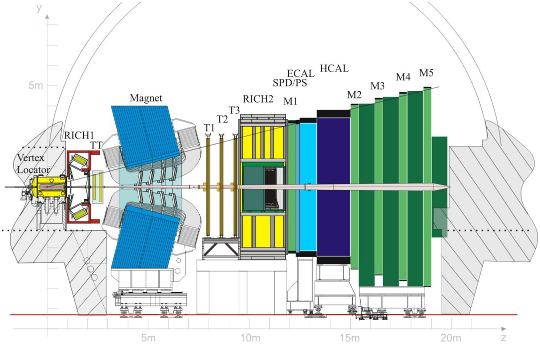
  Contributions at high energy to charmonium production are

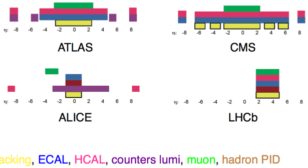
  1. Direct production in pp collisions prompt
  2. Feed down from excited states ($\psi(2S)$, χ_c ...) prompt
  3. Production from b-hadrons decays delayed

- Measurements of production cross section of double J/ψ (in this talk):
  - extremely rare process (as predicted by QCD);
  - at LHC energies the main contribution is expected from the gluon-gluon fusion.

The LHCb experiment

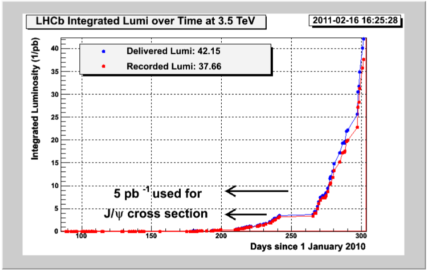
- Single-arm forward spectrometer. Angular coverage: 10-300 mrad (bending plane), 10-250 mrad (non-bending plane)
- Characteristics and performances:
  - Vertexing: proper time resolution 30-50 fs
  - MuonId: $\epsilon(\mu \to \mu) = 97\%$ $\epsilon(\pi \to \mu) = 2\%$
  - Charged tracks $\Delta p/p < 0.35\% - 0.55\%$

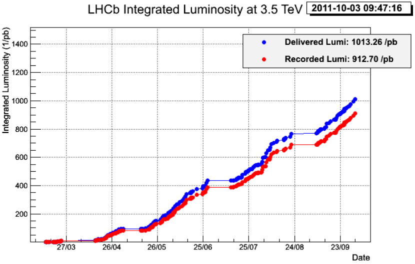




Possibility to explore a unique rapidity range

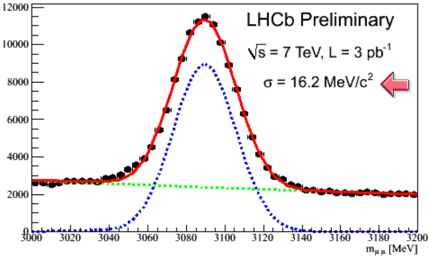
High efficiency 2010-2011 data taking



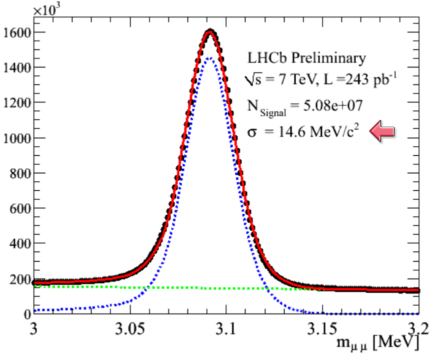


- 2010 data sample: 37 pb^{-1} recorded by LHCb at $\sqrt{s} = 7$ TeV.
  - 5 pb^{-1} used for J/ψ cross section measurement
  - 23 pb^{-1} used for J/ψ polarization measurement (homogeneous trigger conditions).
  - Full data sample used for double J/ψ production.
- 912 pb^{-1} recorded by LHCb so far. 1 fb^{-1} delivered last night!
- Working at instantaneous luminosity: $3.5 \cdot 10^{32}$ cm^{-2} s^{-1} (in 2010 reached $1.6 \cdot 10^{32}$ cm^{-2} s^{-1}).

J/ψ collection at LHCb



First alignment with early 2010 data.



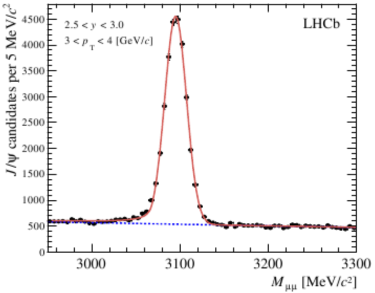
- $\sim 10^5$ reconstructed J/ψ per 1 pb^{-1}.
- More than 10^8 reconstructed J/ψ in the full data sample ($\sim 900\ \text{pb}^{-1}$).
- Improvement of the mass resolution: from 16.2 MeV/c^2 to 14.6 MeV/c^2.
- Close to MC expectation (resolution from MC $\sim$ 13 MeV/c^2).

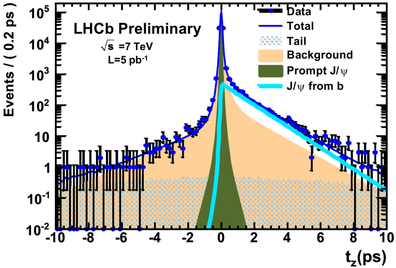
J/ψ cross section (Eur. Phys. J. C 71 (2011) 1645)

J/ψ production cross section: $$\frac{d^2\sigma}{dp_T dy} = \frac{N(J/\psi \to \mu^+\mu^-)}{L \times \varepsilon_{tot} \times Br(J/\psi \to \mu^+\mu^-)\Delta p_T \Delta y}$$

- Signal selection: good muon tracks and vertexing, muons $p_T > 700$ MeV/c.
- Efficiency ε_{tot}: from an unpolarized MC sample and cross-checked with data.
- Use J/ψ pseudo proper time to disentangle prompt J/ψ and J/ψ from b.

$$t_z = \frac{(z_{J/\psi} - z_{PV})m_{J/\psi}}{p_z}$$

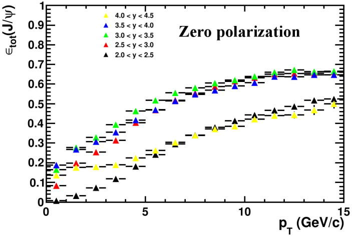


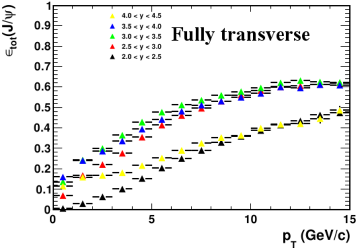


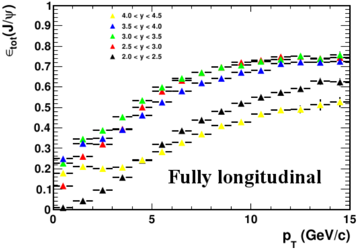
Efficiency

Total efficiency ε_{tot} includes detector acceptance, reconstruction, trigger.

- J/ψ **polarization** (acceptance and reconstruction efficiency): ε_{tot} built with non-zero polarization MC sample.

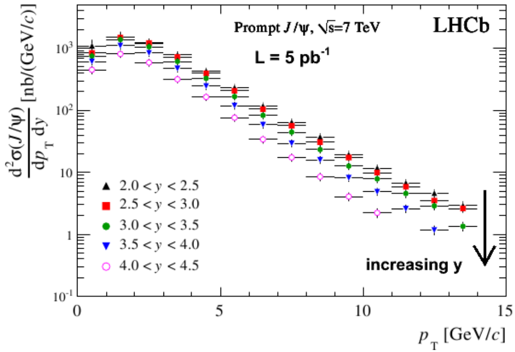






- Deviation from zero polarization gives the major systematic uncertainty ($\sim 20\%$). Polarization measurement is fundamental to reduce the uncertainty.

Results: prompt J/ψ



Total cross section is estimated summing over each analysis bin ($p_T < 14$ GeV/c and $2 < y < 4.5$).

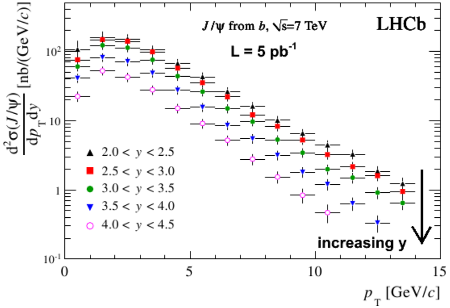
$$\sigma^{J/\psi}_{\text{prompt}} = (10.52 \pm 0.04|_{stat} \pm 1.40|_{syst}\ {}^{+1.64}_{-2.20}|_{pol})\,\mu\text{b}$$

- Main systematics from luminosity, tracking, trigger efficiency.

Results: J/ψ from b and $b\bar{b}$ cross section

Total cross section is estimated summing over each analysis bin ($p_T < 14$ GeV/c and $2 < y < 4.5$).

- $$\sigma^{J/\psi}_{\text{from } b} = [1.14 \pm 0.01|_{stat} \pm 0.16|_{syst}]\ \mu\text{b}$$
- Main systematics: same as in the prompt cross section.

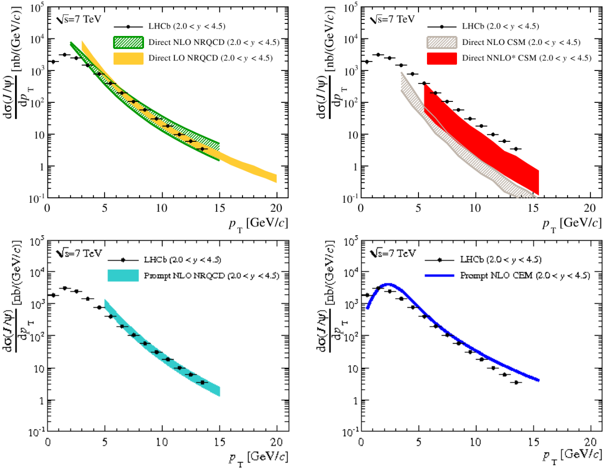


- $$\sigma(pp \to b\bar{b}X) = \alpha_{4\pi} \frac{\sigma_{J/\psi \text{ from } b}}{2\mathcal{B}(b \to J/\psi X)} = [288 \pm 4|_{stat} \pm 48|_{syst}]\ \mu\text{b}$$

  to be compared with $\sigma(pp \to b\bar{b}X) = (284 \pm 20 \pm 49)\ \mu\text{b}$ with 14 nb^{-1} obtained from $b \to D^0 \mu\nu X$ decays in LHCb (Phys. Lett. B694 (2010) 209).

- With PYTHIA 6.4 $\alpha_{4\pi} = \dfrac{J/\psi \text{ from } b \text{ events in full range}}{J/\psi \text{ from } b \text{ events in } 2 < y < 4.5} = 5.88$

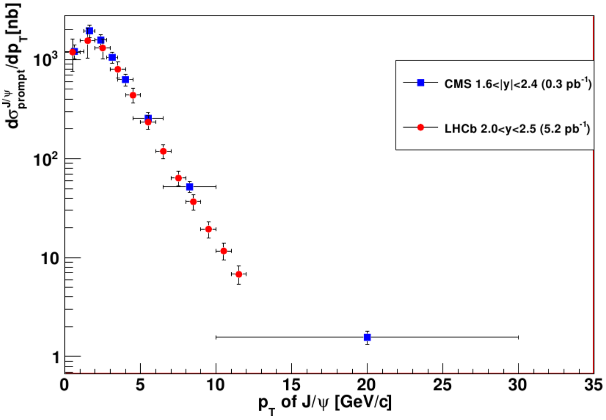
Comparison with theory: prompt J/ψ



- direct J/ψ production with COM and CSM (arXiv:1009.5662v3, arXiv:0811.4005v1);
- direct J/ψ production + contribution from χ_c decay with COM and CEM (arXiv:1009.3655v2, arXiv:0806.1013v2).

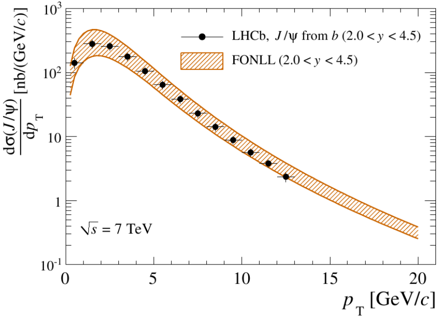
- Good agreement with NRQCD models.

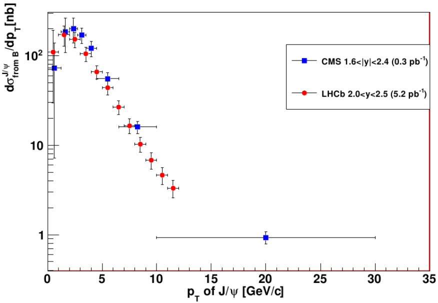
Comparison with CMS results: prompt J/ψ



- Good agreement with CMS results (arXiv:1011.4193).

Comparison with theory and CMS results: J/ψ from b





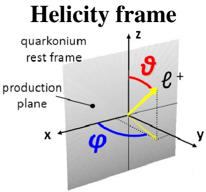
- Comparison with FONLL model (arXiv:hep-ph/0102134v1).
- Very good agreement with the prediction and CMS results.

Polarization measurement of prompt J/ψ

- Prompt J/ψ polarization in the **helicity frame**

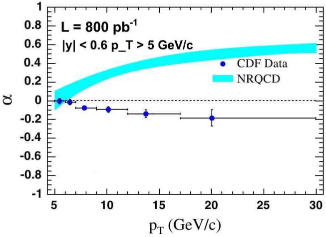
$$\frac{dN}{d(\cos\theta)d\phi} \propto 1+\lambda_\theta \cos^2\theta+\lambda_\phi \sin^2\theta \cos 2\phi+\lambda_{\theta\phi} \sin 2\theta \cos\phi$$

  - θ: polar angle between μ^+ in J/ψ rest frame and J/ψ flight direction.
  - ϕ: azimuthal angle between J/ψ production plane (beam axis and J/ψ momentum) and the μ^+ plane (beam axis and μ^+ momentum).



- Investigated also other frames (orthogonal to Collin-Soper)

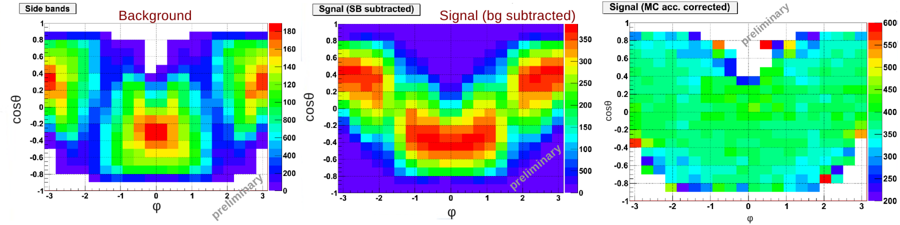
- Polarization measurement needed together with the cross section to better understand the production mechanism. COM failed to predict polarization (CDF data, Phys. Rev. Lett. 99, 132001 (2007))
- Reduce the systematic uncertainty on the cross section.



Strategy for the measurement

- Analysis window: J/ψ rapidity $2 < y < 4.5$ and transverse momentum 2 GeV/c < p_T < 15 GeV/c.
- Results will be given in J/ψ p_T and y bins.
- Data: 23 pb^{-1} (70% of the full 2010 data sample), corresponding to $2.5 \cdot 10^6$ J/ψ.
- Polarization measured by extracting λ_θ, λ_ϕ, $\lambda_{\theta\phi}$ parameters extracted with an unbinned maximum likelihood analysis.
- λ invariant parameter measured as well:

$$\lambda = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$



Challenges

- Polarization measurements with full angular analysis, in p_T and y bins ongoing. Statistical sensitivity expected: from 0.01 to 0.16 for λ_θ and from 0.004 to 0.06 for λ_ϕ and $\lambda_{\theta\phi}$.
- Main systematics under evaluation: signal selection, separation of prompt component from delayed one, background subtraction, Monte Carlo reliability for the acceptance correction.

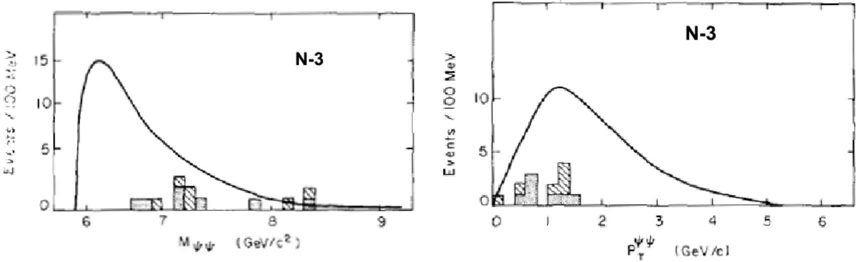
Cross checks with independent methods

- binned full angular analysis in $\cos\theta - \phi$
- single angular analysis in $\cos\theta$, ϕ and a combination of the two variables.

Results out soon.

Double J/ψ production

Double J/ψ events observed in $p-\pi$ collisions at 150 GeV/c and 280 GeV/c by N-3 (Phys. Lett. B 114, 457 (1982), Phys Lett B 158, 85 (1985)).



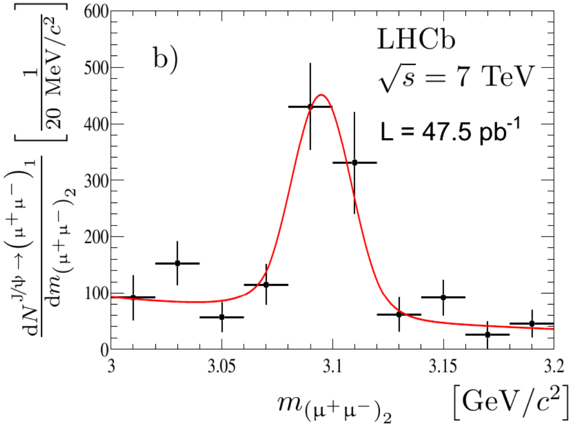
- Test COM vs CSM.
- Test production mechanisms such as DPS (Double Parton scattering) vs SPS (Single Parton scattering).
- Look for charmed tetraquark.

At LHCb (arXiv:1109.0963 , submitted to Phys. Lett. B, I. Belyaev, V. Egorychev):

- Measurement of J/ψ-J/ψ production cross section with both J/ψ $2 < y < 4.5$ and $p_T < 10$ GeV/c.
- Similar selection as for the J/ψ cross section measurement.

Invariant mass distribution

- Yield of first muon pairs in bins of second muon pairs.
- Double Crystal Ball function for signal, exponential for background.



Signal events

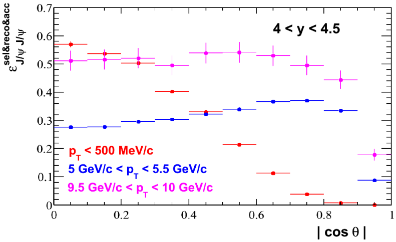
- With both J/ψ in the signal window: $p_T < 10$ GeV/c and $y \in [2; 4.5]$ $N_{J/\psi J/\psi} = 139 \pm 18$

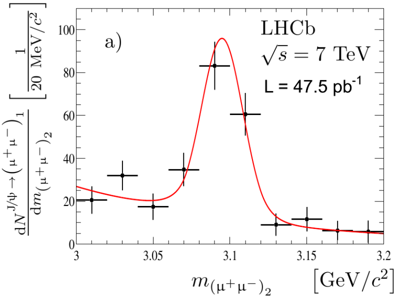
Efficiency correction

Total efficiency calculated event per event

$$\varepsilon^{tot}_{J/\psi J/\psi} = \varepsilon^{sel\&reco\&acc}_{J/\psi J/\psi} \times \varepsilon^{\mu ID}_{J/\psi J/\psi} \times \varepsilon^{trg}_{J/\psi J/\psi}$$

- Factorization of the three efficiency terms in single J/ψ efficiency.





- Efficiency correction: weight each event with $\omega = \left(\varepsilon^{tot}_{J/\psi J/\psi}\right)^{-1}$
- $J/\psi \to (\mu^+\mu^-)_1$ events efficiency corrected distribution in bins of $(\mu^+\mu^-)_2$ pair.

Signal events $N^{corr}_{J/\psi J/\psi} = 672 \pm 129$

Cross section determination

With $\mathcal{L} = 37.5 \pm 1.3\ \mathrm{pb}^{-1}$

$$\sigma_{J/\psi J/\psi} = \frac{N^{corr}_{J/\psi J/\psi}}{\mathcal{L}\,\mathcal{B}^2_{\mu^+\mu^-}} = (5.6 \pm 1.0|_{stat} \pm 1.1|_{syst})\ \mathrm{nb}$$

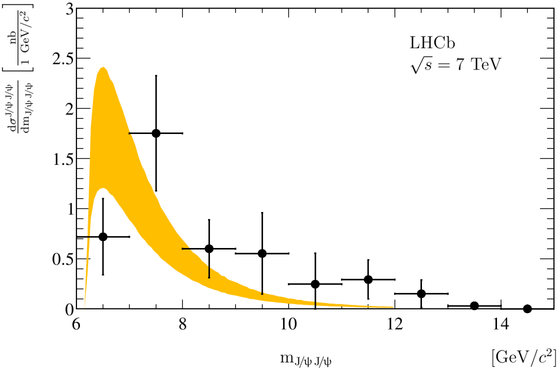
- Main systematics: tracking, trigger efficiency, J/ψ polarization.

Theoretical expectation (arXiv:1101.5881, arXiv:1106.2184):

- CSM at LO with Single Parton Scattering in LHCb acceptance: 4.15 nb with $\sim 30\%$ error;
- contribution from Double Parton Scattering in LHCb acceptance: 2 nb with $\sim 50\%$ error;
- sum of the two contributions is in agreement with experimental value.

Cross section determination

Double J/ψ cross section as function of J/ψ pair invariant mass



- Shaded area: theoretical expectation including direct production and feed down from $\psi(2S)$ (arXiv:1101.5881).
- With more statistics charmed tetraquarks could be seen at low energies.
- χ_b decays into two J/ψ with more statistics can appear at around 9 GeV/c^2.

Conclusion

- Precise tests of various production models and good agreement with theory prediction.
- J/ψ production cross section has been measured with 5 pb^{-1} for prompt and J/ψ from b decays.
- Production cross section for $b\bar{b}$ has been extrapolated to the 4π angle. Result is consistent with independent analysis published by the collaboration.
- J/ψ polarization is being measured with the 2010 dataset.
- Production cross section of double J/ψ has been measured with the full 2010 data sample.

Prospects with 2011 dataset

- Update of J/ψ cross section ongoing: include polarization effect (recalculate efficiency values), update luminosity value.
- Double J/ψ production: expected roughly 4000 events with 1 fb^{-1}. Investigating properties in details: mass, polarization, p_T, search for tetraquarks.
- $J/\psi D$ where D is D^0, D^+, D_s^+, Λ_c^+ with dedicated trigger. With gluon fusion expected $\sigma \sim 10$ nb in $2 < y < 4.5$ and D $p_T > 2$ GeV/c.
- Looking at $J/\psi J/\psi$, $J/\psi\psi(2S)$, $J/\psi\Upsilon$ to investigate DPS vs SPS.
- possibility of studying J/ψ + high p_T photons.

Back up slides

Luminosity measurements

1. Van der Meer scan method.
2. Beam profile method: beam overlap integral term of luminosity is determined studying each beam shape. The position, angle and size of bunches are measured from the collisions between the beam and the residual gas in the interaction region. Ref: NIM A 553 (2005) 388, arXiv:1008.3105v2 [hep-ex]

Results consistent within the 10 % error.

Theoretical models

1. **Colour Singlet Model (CSM)**
   - production of $c\bar{c}$ on-shell pair.
   - binding the $c\bar{c}$ pair to form the meson, assuming colour and spin don't change. Since the physical state is colourless $c\bar{c}$ pair must be produced in colour singlet state.
2. **Colour Octet Model (COM)**: NRQCD approach. Charmonium production is possible also through colour octet states.

Prompt J/ψ:

- Direct J/ψ production with Color Octet Model: arXiv:1009.5662v3 [hep-ph]
- Direct J/ψ production with Color Singlet Model: arXiv:0811.4005v1 [hep-ph]
- Prompt J/ψ production with Color Octet Model: arXiv:1009.3655v2 [hep-ph]
- Prompt J/ψ production with Color Evaporation Model: arXiv:0806.1013v2 [nucl-ex]

J/ψ from b:

- FONLL Fixed Order plus Next Leading Logarithm: arXiv:hep-ph/9803400v1, arXiv:hep-ph/0102134v1

Efficiency correction

Total efficiency calculated event per event

$$\varepsilon^{tot}_{J/\psi J/\psi} = \varepsilon^{sel\&reco\&acc}_{J/\psi J/\psi} \times \varepsilon^{\mu ID}_{J/\psi J/\psi} \times \varepsilon^{trg}_{J/\psi J/\psi}$$

- $\varepsilon^{sel\&reco\&acc}_{J/\psi J/\psi} = \varepsilon^{sel\&reco\&acc}_{J/\psi} \times \varepsilon^{sel\&reco\&acc}_{J/\psi}$ selection, reconstruction, acceptance efficiency estimated from MC.
- $\varepsilon^{\mu ID}_{J/\psi J/\psi} = \left(\varepsilon^{\mu ID}_{1\mu}\right)^4 = (91.0 \pm 0.1)\,\%$ muon identification efficiency, from data.
- $\varepsilon^{trg}_{J/\psi J/\psi} = 1 - \left(1 - \varepsilon^{trg/TOS}_{J/\psi 1}\right)\left(1 - \varepsilon^{trg/TOS}_{J/\psi 2}\right)$ trigger efficiency, from data.

Double J/ψ systematics

Table: Relative systematic uncertainties on the cross-section measurement, the total uncertainty is calculated as the quadratic sum of the individual components.

Source	Systematic uncertainty [%]
Track finding efficiency	4×4
Trigger efficiency	8
Per-event efficiency	3
J/ψ polarization	2×5
Data/simulation difference for χ^2_{DTF}	3
Global event cuts	2
Muon identification	2×1.1
Luminosity	3.5
$J/\psi \to \mu^+\mu^-$ branching ratio	2×1
Total	21