Double J/ψ production in diffractive processes at the LHC

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Outline

- Motivation
- Diffractive physics
- Double J/ψ production
  - color singlet and color octet models
- Diffractive production of double J/ψ considering the Resolved Pomeron Model
  - central diffractive processes (DPE)
- Present some estimates for $2J/\psi + X$ production in central diffractive processes @ LHC
- Comparison with recent LHCb data
- Conclusions

Introduction

- Quarkonium production at high energies probes the proton's gluon distribution due to dominance of subprocesses with two gluons in the initial state
- Still the quarkonium formation mechanism is a long standing puzzle, not fully understood, with interplay of perturbative and non-perturbative effects
- Diffractive processes $\Longrightarrow$ rapidity gaps in the hadronic final state
- Exchange of a Pomeron with vacuum quantum numbers
- $p I\!\!P$ and $I\!\!P I\!\!P$ interactions
- What is a Pomeron actually? Soft, hard, BFKL Pomeron...
- If Pomeron has substructure $\Longrightarrow$ DPDFs
- Diffractive distributions of quarks and gluons in the Pomeron
- Tested in several processes like dijets, dileptons, heavy quarks, quarkonium + photon...
- Other channels recently proposed: single and central diffractive $\gamma + \mathrm{jet}$, $\gamma + \gamma$ (*C.B.M., V.P. Goncalves, PRD 88 (2013)*)
- Since double quarkonium production is also dominated by gluon-gluon initiated subprocesses, this channel might be usefull to test the validity of Pomeron resolved model for diffractive interactions and pomeron structure

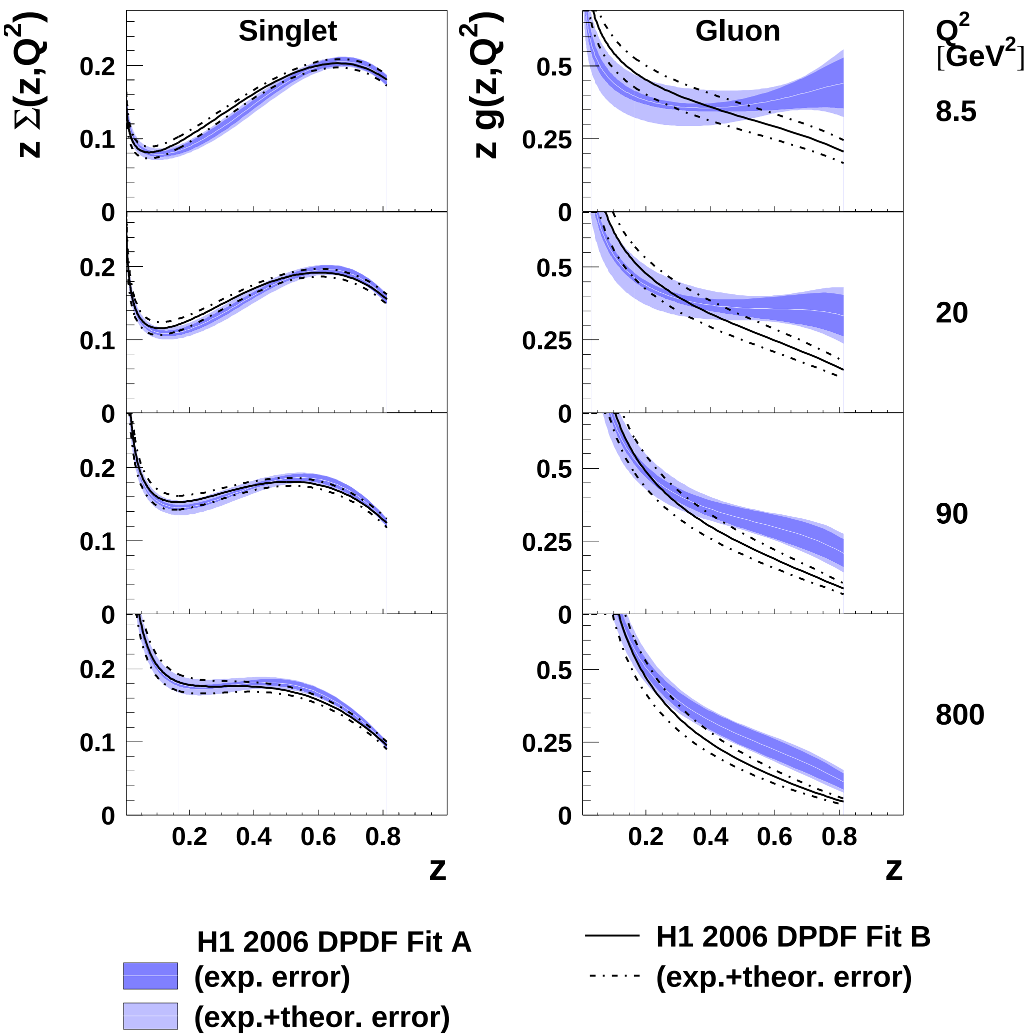
Diffractive parton distributions

- Resolved Pomeron Model
- Diffractive parton distributions in the proton: Convolution of
  - flux of Pomerons $\Rightarrow f_{I\!P}(x_{I\!P}) = \int_{t_{min}}^{t_{max}} dt f_{I\!P}(x_{I\!P}, t)$
    - $x_{I\!P}$: momentum fraction of the proton carried by the Pomeron
    - t_{min}, t_{max}: kinematic boundaries
    - H1 Collaboration: flux factor motivated by Regge theory $\Rightarrow$ $f_{I\!P/p}(x_{I\!P}, t) = A_{I\!P} \cdot \frac{e^{B_{I\!P} t}}{x_{I\!P}^{2\alpha_{I\!P}(t)-1}}$
    - Pomeron trajectory assumed linear: $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} t$
  - parton distributions in the Pomeron $\Rightarrow g_{I\!P}(\beta, \mu^2)$, $q_{I\!P}(\beta, \mu^2)$
    - β: momentum fraction carried by the parton inside the Pomeron
- Diffractive quark and gluon distributions:

$$q^D(x, \mu^2) = \int dx_{I\!P} d\beta \delta(x - x_{I\!P}\beta) f_{I\!P}(x_{I\!P}) q_{I\!P}(\beta, \mu^2) = \int_x^1 \frac{dx_{I\!P}}{x_{I\!P}} f_{I\!P}(x_{I\!P}) q_{I\!P}(\frac{x}{x_{I\!P}}, \mu^2)$$

$$g^D(x, \mu^2) = \int dx_{I\!P} d\beta \delta(x - x_{I\!P}\beta) f_{I\!P}(x_{I\!P}) g_{I\!P}(\beta, \mu^2) = \int_x^1 \frac{dx_{I\!P}}{x_{I\!P}} f_{I\!P}(x_{I\!P}) g_{I\!P}(\frac{x}{x_{I\!P}}, \mu^2)$$

Diffractive parton distributions from HERA fits



- Two H1 2006 fits [*EPJC 48, 715 (2006)*]
- $\neq$ parton densities at starting scale for QCD evolution
- $\neq$ effective pomeron intercept and other parameters...
  - fit A: $\alpha_{\mathbb{P}}(0) = 1.118 \pm 0.008$, ...
  - fit B: $\alpha_{\mathbb{P}}(0) = 1.111 \pm 0.007$, ...
- larger uncertainty for the gluon content of the Pomeron
- $\Rightarrow$ *fit B used in our first results*

Inclusive Quarkonium production

- Still not fully understood, with interplay of perturbative and non-perturbative effects
- Phenomenological models
  - **Color singlet model**: $Q\bar{Q}$ pairs are produced in a color singlet state already at perturbative level $\Rightarrow gg \to Q\bar{Q}_1(^3S_1) + X$
  - **Color octet model**: $Q\bar{Q}$ pair can be produced in a color octet state which evolves into a color singlet quarkonium state H via emission of soft gluons
    - based on NRQCD effective theory, with a factorization formula:

$$d\sigma(pp \to H + X) = \sum_{a,b,n} f_{a/p} f_{b/p} \otimes d\hat{\sigma}[ab \to Q\bar{Q}[n] + X]\langle O_n^H \rangle$$

    - power series in α_s and v (non-relativistic heavy-quark velocity v)
    - takes into account the complete structure of $Q\bar{Q}$ Fock space spanned by states $n = {}^{2S+1}L_J^{[a]}$, with $a = 1, 8$.
    - $\langle O_n^H \rangle$: NRQCD matrix elements obeying velocity-scaling rules, usually determined by fits to experiments
    - contains color singlet contributions $\to$ CSM in the $v = 0$ limit
  - other models like eg. color evaporation and soft color interaction models (not considered here)

Inclusive double J/ψ production

- Dominant contributions: gluon initiated subprocesses $gg \to c\bar{c}_1(^3S_1)c\bar{c}_1(^3S_1)$, $gg \to c\bar{c}_8(^3S_1)c\bar{c}_8(^3S_1)$
- Inclusive double J/ψ production cross section

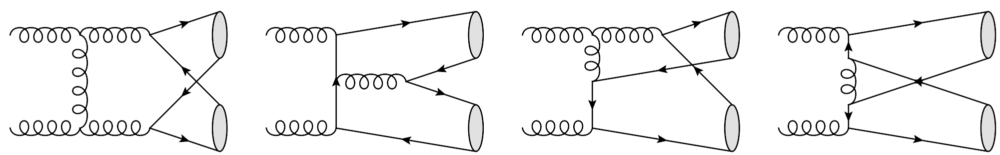
$$\frac{d\sigma}{dydp_T^2} = \int_{x_{a\,min}}^{1} dx_a f_a(x_a,\mu^2) f_b(x_b,\mu^2) \frac{x_a x_b}{2x_a - \bar{x}_T e^y} \sum_{i=1,8} \frac{d\hat{\sigma}}{d\hat{t}}(gg \to 2c\bar{c}_i(^3S_1)) \langle O_i^{J/\psi}(^3S_1)\rangle \langle O_i^{J/\psi}(^3S_1)\rangle$$

$$x_{a\,min} = \frac{\bar{x}_T e^y}{2 - \bar{x}_T e^{-y}} \;, x_b = \frac{x_a \bar{x}_T e^{-y}}{2x_a - \bar{x}_T e^y} \;, \bar{x}_T = \frac{2m_T}{\sqrt{s}} \;, m_T = \sqrt{M^2 + p_T^2}$$

  - $f_{a,b}$: CTEQ6 parton distributions
  - $\mu = m_T$
  - $\frac{d\hat{\sigma}}{d\hat{t}}$: LO α_s^4 partonic cross sections

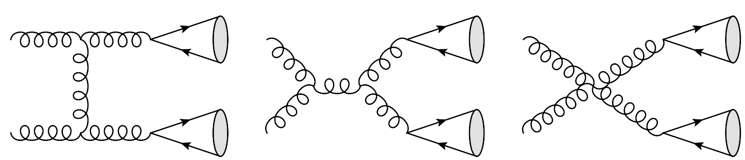
Inclusive double J/ψ: dominant processes

- Dominant contributions: gluon initiated subprocesses $gg \to c\bar{c}_1(^3S_1)c\bar{c}_1(^3S_1)$, $gg \to c\bar{c}_8(^3S_1)c\bar{c}_8(^3S_1)$
- Typical non-fragmentation contributions (both color singlet and color octet)



+ ...

- Typical gluon-fragmentation contributions (only color octet)



Inclusive double J/ψ production

LO α_s^4 partonic cross sections:

- Color singlet contributions (*Qiao, C., PRD 66 (2002) 057504*):

$$\frac{d\hat{\sigma}}{d\hat{t}}\langle O_1^{J/\psi}(^3S_1)\rangle\langle O_1^{J/\psi}(^3S_1)\rangle = \frac{16\pi\alpha_s^4|R(0)|^4}{81M^2s^8(M^2-t)^4(M^2-u)^4}\sum_{jkl} a_{jkl}M^j t^k u^l$$

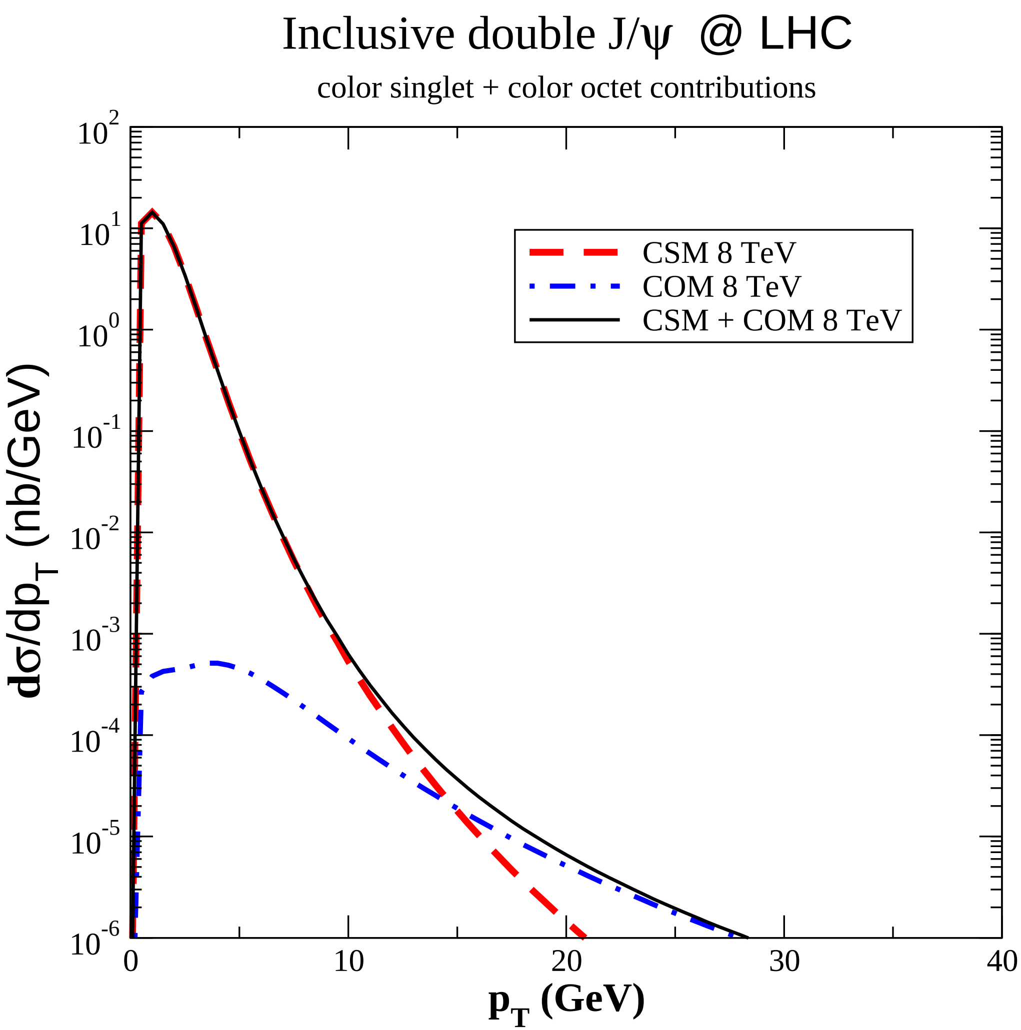
$|R(0)|^2 = 0.8GeV^3$, $M = 2m_c$, $m_c = 1.5GeV$

- Color octet contributions (*Ko, Lee, Yu, JHEP 01 (2011) 070*):

$$\frac{d\hat{\sigma}}{d\hat{t}}[gg \to 2c\bar{c}_8(^3S_1)] = \frac{\pi\alpha_s^4}{972M^6s^8(M^2-t)^4(M^2-u)^4}\sum_{j=0}^{14} a_j M^{2j}$$

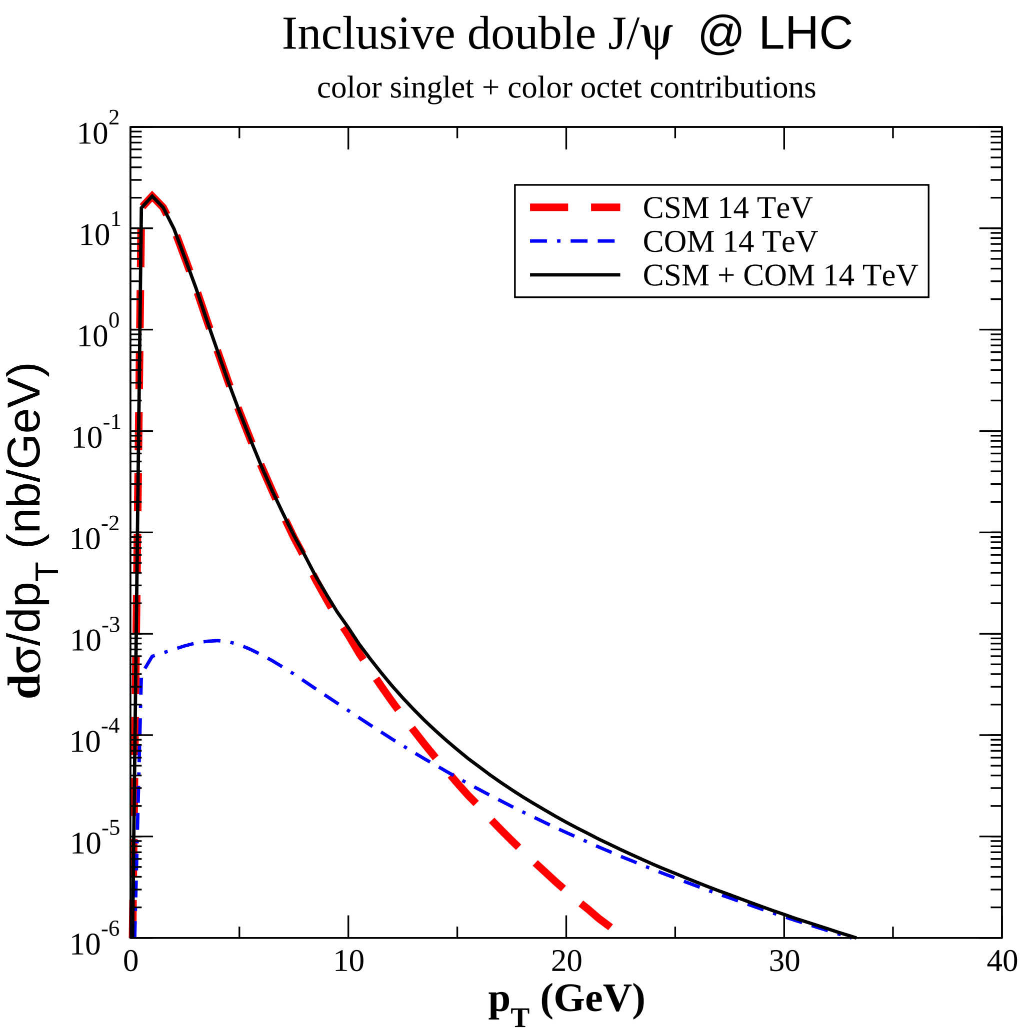
$$\langle O_8^{J/\psi}(^3S_1)\rangle = 3.9\times 10^{-3}GeV^3$$

Inclusive double J/ψ @ LHC



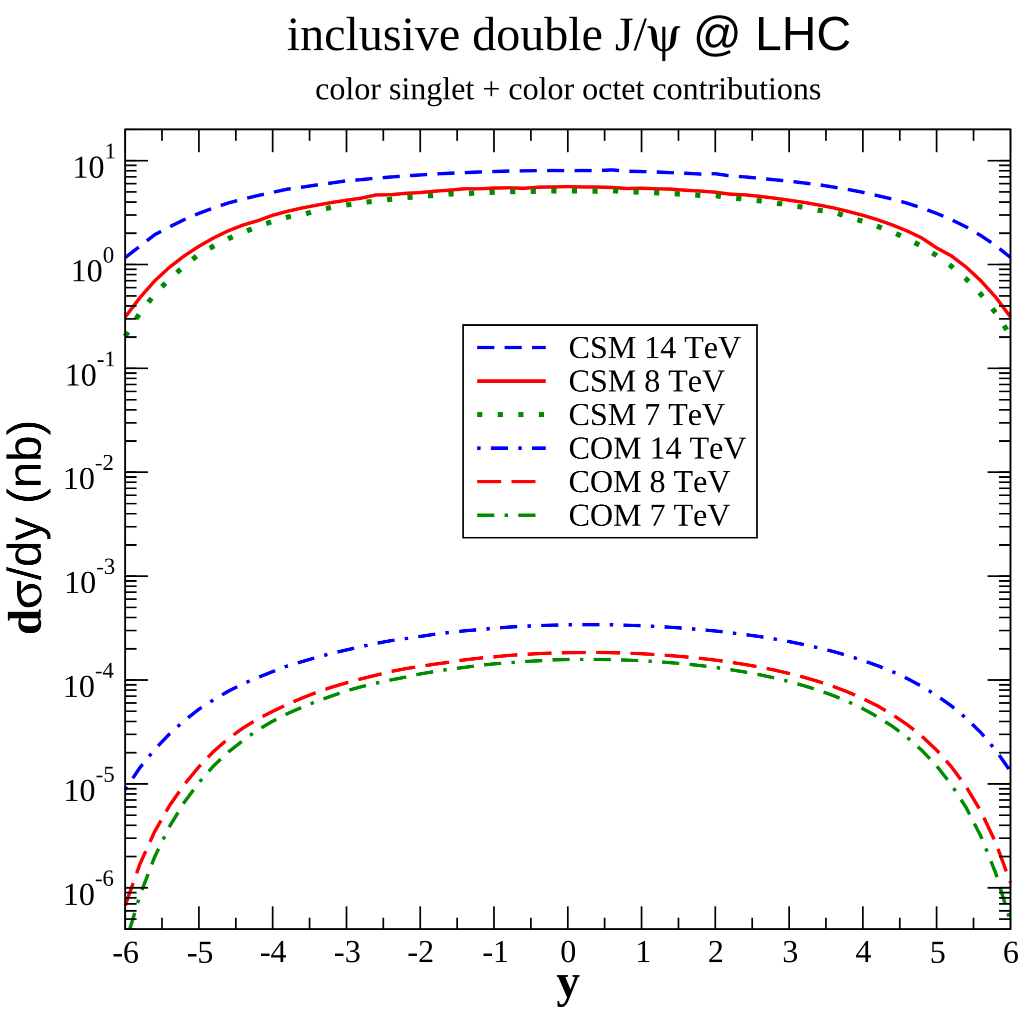
- p_T distribution of one J/ψ @ central region $|y| < 2.5$
- Inclusive color singlet and color octet contributions
- CSM: dominant except at large p_T region
- CSM X COM: cross-over around 15 GeV
- COM/CSM reduction of four orders of magnitude at low p_T peak

Inclusive double J/ψ @ LHC



- p_T distribution of one J/ψ @ central region $|y| < 2.5$
- Inclusive color singlet and color octet contributions
- CSM: dominant except at large p_T region
- CSM X COM: cross-over around 15 GeV
- COM/CSM: reduction of four orders of magnitude at low p_T peak
- Results in agreement with (*Ko, Lee, Yu, JHEP 01 (2011) 070*)
- This can be measured at the LHC

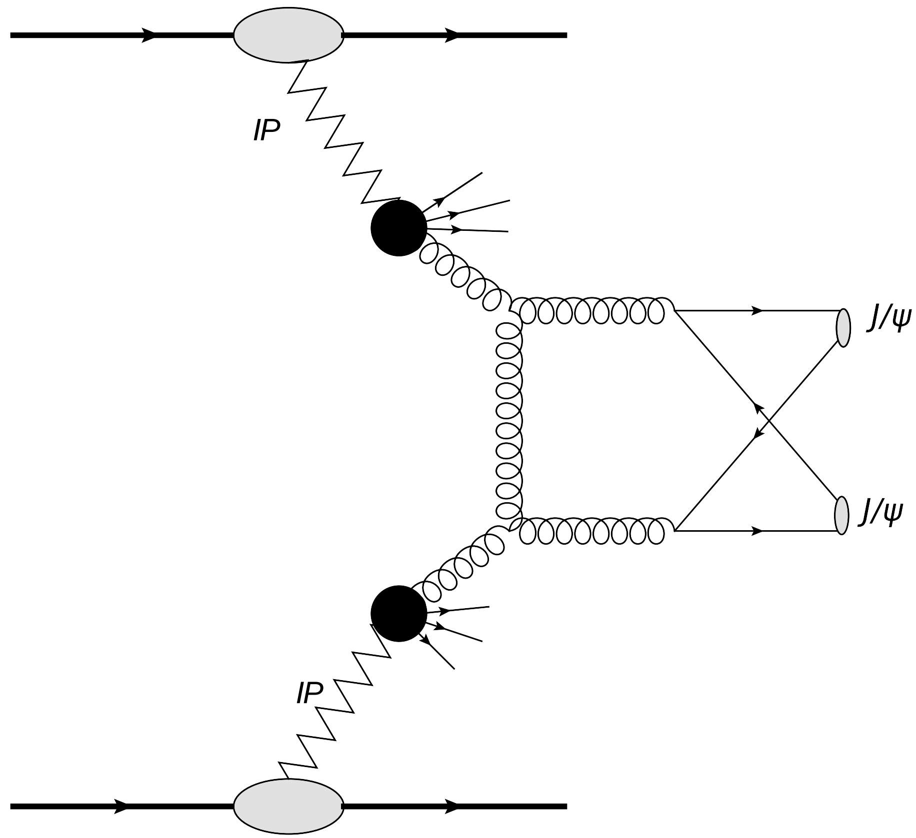
Inclusive double J/ψ @ LHC



- rapidity distribution of one of the produced J/ψs
- Inclusive color singlet and color octet contributions for the 7 TeV, 8 TeV and 14 TeV LHC runs
- CSM contributions dominate all regions for p_T integrated spectra
- COM contributions negligible in all regions for p_T integrated spectra
- COM/CSM: reduction of four orders of magnitude
- This could be measured at the LHC

Central Diffractive double J/ψ production

- Central diffractive: $I\!\!P I\!\!P$ interactions



- events with two rapidity gaps and $J/\psi + J/\psi$ at central region (it's not an exclusive process)
- amplified sensitivity to test the DPDF's (compared with single diffractive case)

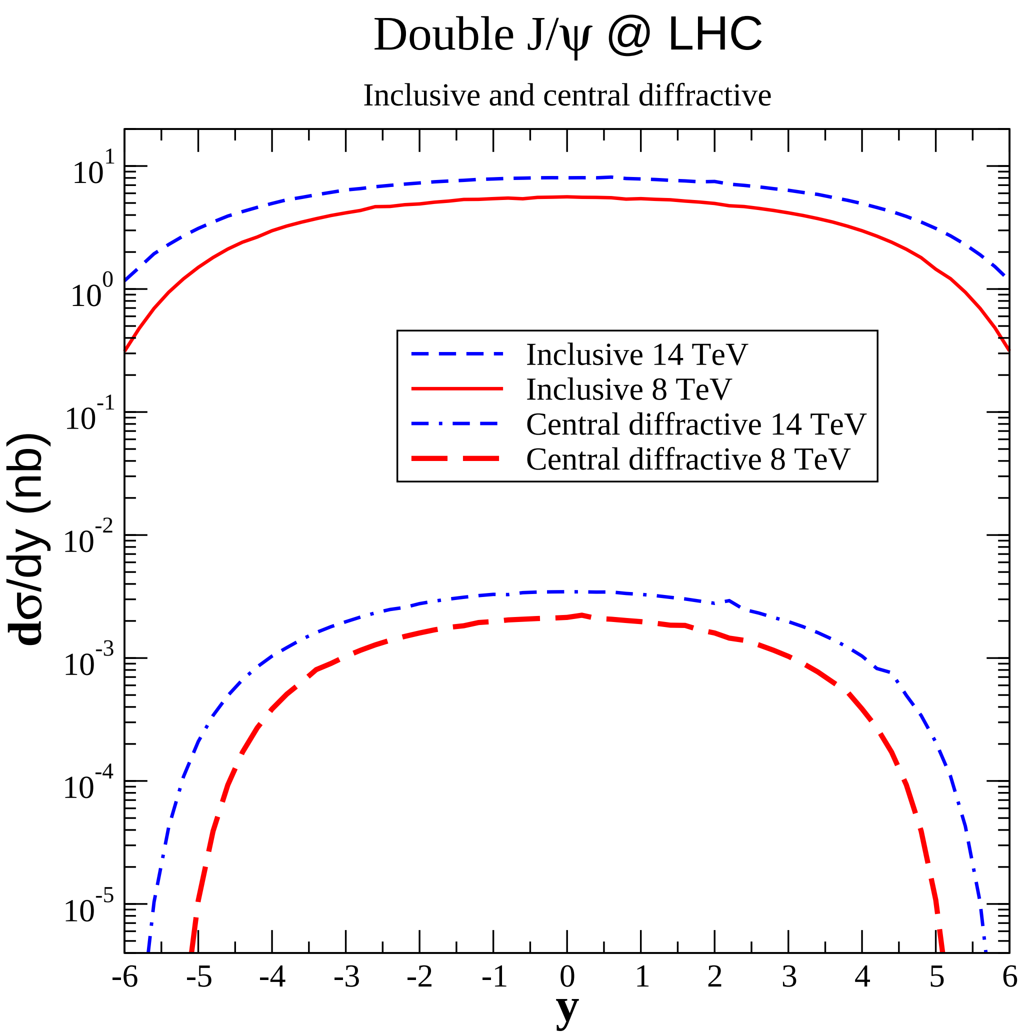
Central Diffractive double J/ψ production

- Contributing LO diagrams: the same as in the inclusive case
- only considering the dominant gluon initiated diagrams
- Central diffractive double J/ψ production cross section

$$\frac{d\sigma}{dy dp_T^2} = \int dx_a f_a^D(x_a,\mu^2) f_b^D(x_b,\mu^2) \frac{x_a x_b}{2x_a - \overline{x}_T e^y} \sum_{i=1,8} \frac{d\hat{\sigma}}{d\hat{t}}(gg \to 2c\bar{c}_i(^3S_1)) \langle O_i^{J/\psi}(^3S_1)\rangle^2$$

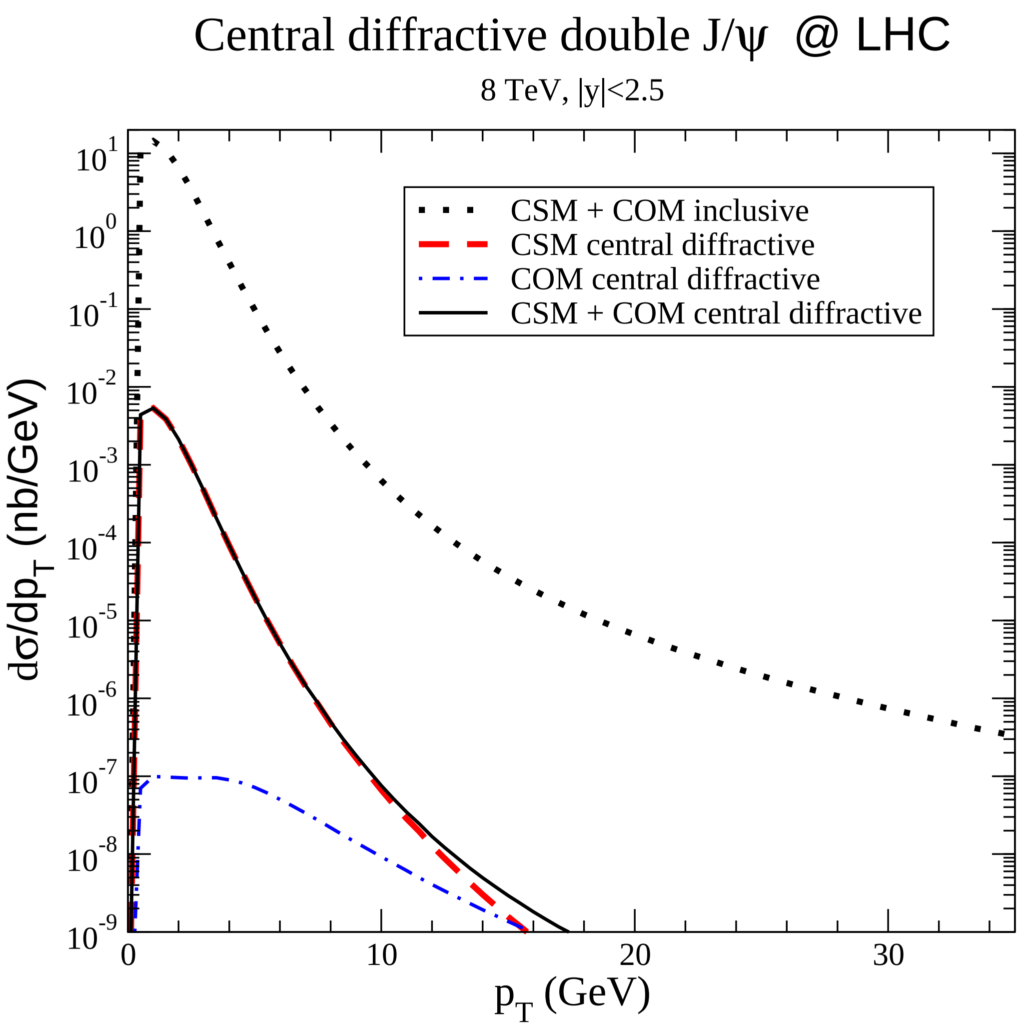
- $I\!P I\!P$ interactions
- $f_a^D(x_a,\mu^2)$, $f_b^D(x_b,\mu^2)$: diffractive PDF's in both protons
- In fact, the factorization above is violated in pp interactions
- soft interactions might destroy the rapidity gaps
- Absoption effects can be parametrized in terms of a rapidity gap survival probability $|S|^2 \to$ probability that scattered proton do not dissociate due to secondary interactions
- Multiply the cross section by the average probability $s_G = \langle |S|^2 \rangle$, given by KMR model (*Khoze, Martin, Ryskin, EPJC 18 (2000) 167*)

Central Diffractive double J/ψ @ LHC



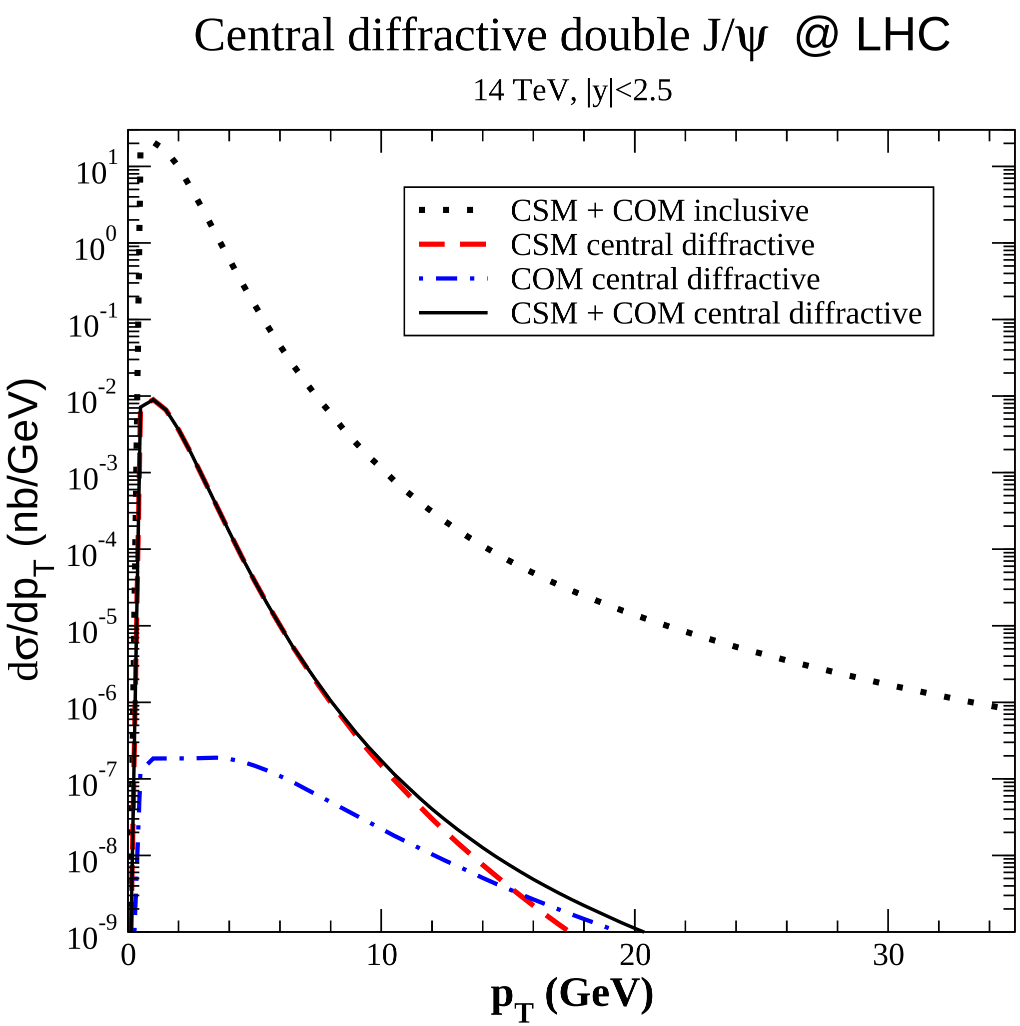
- rapidity distribution of J/ψs
- Inclusive and central diffractive channels
- Gap survival factors included (*KMR*)
  - $S_G(CD) = 0.02$
- reduction of four orders of magnitude
  - inclusive to central diffractive

Central Diffractive double J/ψ @ LHC



- p_T distribution of one of the J/ψs
- Inclusive and central diffractive channels
- Gap survival factors included (*KMR*)
  - $S_G(CD) = 0.02$
- reduction of four orders of magnitude
  - inclusive to central diffractive
- too low cross section for color octet contributions at higher p_T tail

Central Diffractive double J/ψ @ LHC



- p_T distribution of one of the J/ψs
- Inclusive and central diffractive channels
- Gap survival factors included (*KMR*)
  - $S_G(CD) = 0.02$
- reduction of four orders of magnitude
  - inclusive to central diffractive
- too low cross section for color octet contributions at higher p_T tail

Estimates for the total cross section

- including gap survival probabilities

y range	CM energy	inclusive	central diffractive	CEP*
$\|y\| < 2.5$	8 TeV	27203 pb	9.51 pb	10 pb
$\|y\| < 2.5$	14 TeV	39690 pb	16.02 pb	17 pb
$2 < y < 4.5$	8 TeV	9709 pb	2.16 pb	2.5 pb
$2 < y < 4.5$	14 TeV	15220 pb	4.43 pb	4.7 pb

- Recent LHCb data ($2.0 < y < 4.5$) for central exclusive double J/ψ production at 8 TeV: $\sigma = 24 \pm 9$ pb
- * Similar values compared with H-LKR approach applied to exclusive $J/\psi J/\psi$ production (Born level $gg \to J/\psi J/\psi$ amplitudes in non-relativistic quarkonium approximation) within the Durham perturbative model and CTEQ6L PDF (*Harland-Land et al, arXiv:1409.4785[hep-ph]*): $\sigma = 1.9 - 6.7$ pb
- Uncertainties in the gap survival probabilities
- Diffractive PDF's and resolved pomeron model can be further tested @ LHC

Conclusions and discussion

- Central diffractive processes probe $I\!\!P I\!\!P$ interactions
- We have computed the central diffractive double J/ψ production in the framework of the Pomeron resolved model, including survival gap probabilities
- Resolved Pomeron model based on the diffractive factorization formalism: Pomeron with partonic substructure (describes HERA data very well)
- Dominant color singlet and color octet contributions included for both inclusive and central diffractive double J/ψ production
  - For the p_T integrated rapidity distribution, only CSM is important
  - For the p_T distributions, CSM dominate in the more important low p_T region, whereas COM dominates the higher p_T tail.
  - Only CSM is important for the considered central diffractive process
- Predictions for central diffractive double J/ψ production at the LHC
  - Results are very similar to a recent CEP calculation and below recent LHCb data
  - Remains to be studied the sensitivity with the factorization scale and with the gap survival probabilities
- To further test the underlying model for the Pomeron and diffractive parton distributions
- Next steps: consider the single diffractive channel ($I\!\!P p$) and other quarkonium states