J/ψ pair production at the LHC in the k_T-factorization approach

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PLAN OF THE TALK

1. Motivation
2. Theoretical framework and k_T-factorization
3. Comparisons with LHCb and CMS data
4. Conclusions

MOTIVATION

Production of J/ψ pairs provides a complex test
of our understanding of parton model (parton densities), perturbative QCD and bound state formation mechanisms.
An interesting an sensitive probe of both soft and hard physics involving short-distance and long-distance interactions

Disentangling the different theoretical scenarios:
–Color-singlet model versus color-octet model;
–Colinear factorization versus k_t-factorization;
–Single-parton versus double-parton interactions

Theoretical consideration is further encouraged by the recent LHCb and CMS measurements:

R. Aaij *et al.* (LHCb Collab.,) Phys.Lett.B 707, 52 (2012)
S. Chatrchyan *et al.* (CMS Collab.), JHEP 09, 094 (2014)

A long history

Leading-Order Color-Singlet Model

B.Humpert, P.Mèry, Z. Phys. C 20, 83 (1983); Phys.Lett.B 124, 265 (1983)
R.E.Ecclestone, D.M.Scott, Z. Phys. C 19, 29 (1983)

Onium-Onium Scattering

V.G.Kartvelishvili, A.K.Likhoded, Sov. J. Nucl. Phys. 40, 1273 (1984)
V.V.Kiselev, A.K.Likhoded, S.R. Slabospitsky, A.V.Tkabladze, Sov. J. Nucl. Phys. 49, 1041 (1989)

Effects of gluon polarization (LO color-singlet)

S.P.Baranov, H.Jung, Z. Phys. C 66, 647 (1995)

Leading-Order Color-Singlet + Color-Octet

F.Yuan, K.-T.Chao, Phys. Rev. D 63, 034006 (2001)

Next-to-Leading Order Singlet + Octet

Z.G.He, B.A.Kniehl, Phys. Rev. Lett. 115, 022002 (2015)

Double Parton Interactions

A.V.Berezhnoy, A.K.Likhoded, A.V.Luchinsky, A.A.Novoselov, Phys. Rev. D 84, 094023 (2011)
C.-H.Kom, A.Kulesza, W.J.Stirling, Phys. Rev. Lett. 107, 082002 (2011)
S.P.Baranov, A.M.Snigirev, N.P.Zotov, Phys.Lett.B 705, 116 (2011)
S.P.Baranov, A.M.Snigirev, N.P.Zotov, A.Szczurek, W.Schäfer (Phys. Rev. D 87, 034035 (2013))

THEORETICAL FRAMEWORK

Preface on k_t-factorization

QED

Weizsäcker-Williams approximation (collinear on-shell photons)

$$F_\gamma(x) = \frac{\alpha}{2\pi}\,[1+(1-x^2)]\log\frac{s}{4m^2}$$

Equivalent Photon approximation

$$F_\gamma(x,Q^2) = \frac{\alpha}{2\pi}\frac{1}{Q^2}\,[1+(1-x^2)]$$

$$Q^2 \approx k_t^2/(1-x)$$

Photon spin density matrix

$$L^{\mu\nu} \approx p^\mu p^\nu$$

use $k = xp + k_t$, then do gauge shift

$$\epsilon \longrightarrow \epsilon - k/x$$

QCD

Conventional Parton Model (collinear gluon density)

$$x\,G(x,\mu^2)$$

Unintegrated gluon density

$$\mathcal{F}(x,k_t^2,\mu^2)$$

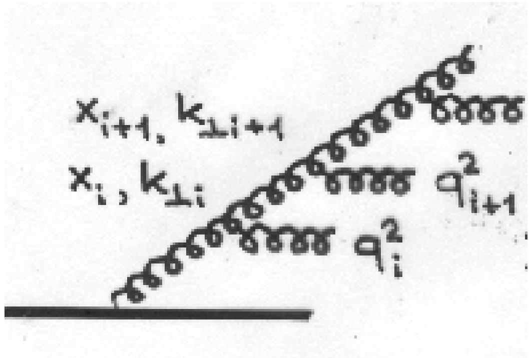
$$\int \mathcal{F}(x,k_t^2,\mu^2)dk_t^2 = x\,G(x,\mu^2)$$

Gluon spin density matrix

$$\epsilon^\mu\epsilon^{\nu *} = k_t^\mu k_t^\nu/|k_T|^2$$

so called nonsense polarization with longitudinal components

Initial State Radiation Cascade



Every elementary emission gives $\alpha_s \cdot 1/x \cdot 1/q^2$
x = longitudinal momentum fraction
q^2 = gluon virtuality

Integration over the phase space yields
$\alpha_s \cdot \ln x \cdot \ln q^2$

Random walk in the k_T-plane: ... $\langle k_{T\,i-1} \rangle < \langle k_{T\,i} \rangle < \langle k_{T\,i+1} \rangle$ ...

Technical method of $\alpha_s^n [\ln(1/x)]^n$ resummation: the integral equations,
BFKL E.A. Kuraev, L.N. Lipatov, V.S. Fadin, Sov. Phys. JETP 45, 199 (1977); Ya. Balitsky, L.N. Lipatov, Sov. J. Nucl. Phys. 28, 822 (1978);
or CCFM
S.Catani, F.Fiorani, G.Marchesini, Phys.Lett.B 234, 339 (1990); Nucl.Phys. B336, 18 (1990); G.Marchesini, Nucl.Phys. B445, 49 (1995); M.Ciafaloni, Nucl.Phys. B296, 49 (1998);

Solving the integro-differential evolution equations one arrives at a k_t-dependent (=unintegrated) gluon density $\mathcal{F}(x, k_t^2, \mu^2)$

In the collinear scheme, the evolution is only used to calculate the parton densities and has no effect on the hard interaction subprocess.

In the k_t-factorization, the parton evolution changes the character of the hard interaction: both the kinematics (due to the initial parton transverse momentum) and polarization properties (longitudinal component for the off-shell gluons).

The evolution cascade is part of the hard interaction. By means of the evolution equation we resum a subset of Feynman diagrams (up to infinitely high order) representing higher-order contributions: i.e., the ladder diagrams enhanced with $\alpha_s^n[\ln(1/x)]^n$.

THE BENEFIT:

With the LO matrix elements for the hard subprocess we get access to effects requiring complicated next-to-leading order calculations in the collinear scheme. Many important results have been obtained in the k_t-factorization much earlier than in the collinear case.

Subprocesses taken into consideration

on the SPS side:

Leading-Order direct production $\mathcal{O}(\alpha_s^4)$

Color singlet production	$g + g \to J/\psi + J/\psi$
Color octet production	$g + g \to g^* + g^* \to J/\psi + J/\psi$
Singlet+octet production	$g + g \to J/\psi + g^* \to J/\psi + J/\psi$

Onium-onium (pseudodiffractive) scattering $\mathcal{O}(\alpha_s^6)$

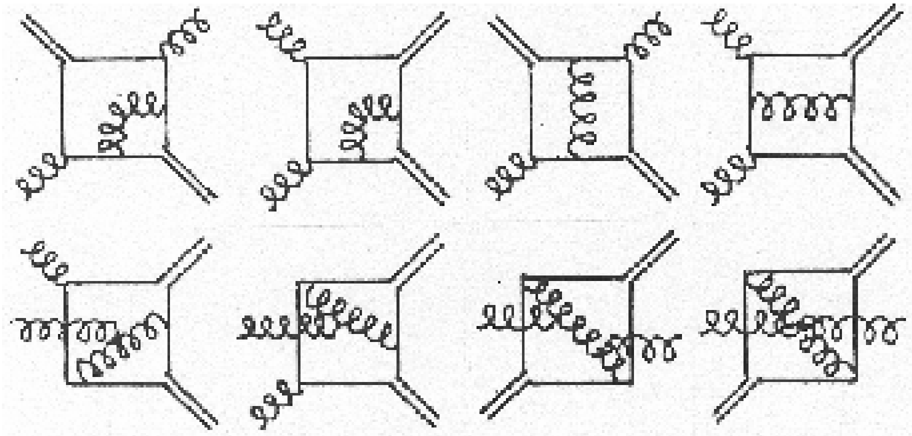
one-gluon exchange	$g + g \to J/\psi + J/\psi + g + g$
two-gluon exchange	$g + g \to J/\psi + J/\psi$

on the DPS side:

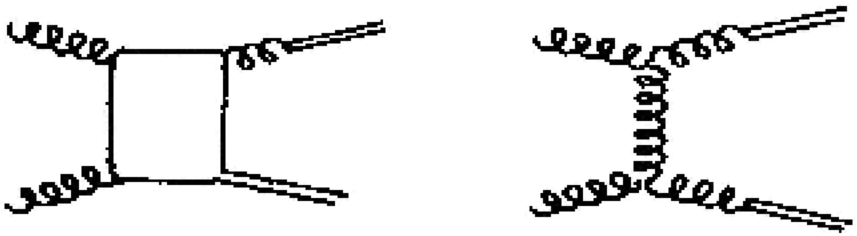
Inclisuve direct J/ψ production	$g + g \to J/\psi + g$
Inclisuve direct χ_c production	$g + g \to \chi_c \to \psi + \gamma$

Straightforward calculations, all done in the k_t-factorization approach

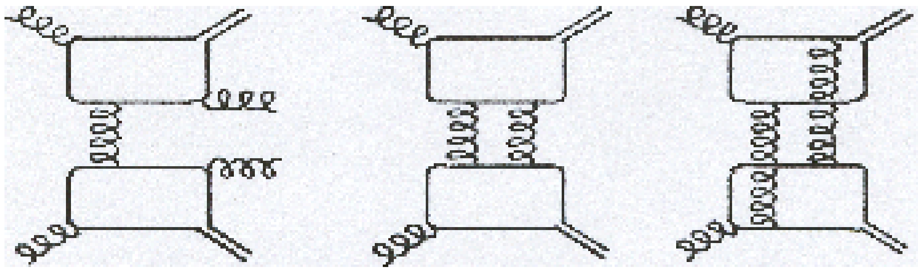
Examples of Feynman diagrams for SPS contributions



Direct gluon-gluon fusion,
color-singlet production
(Leading-Order)



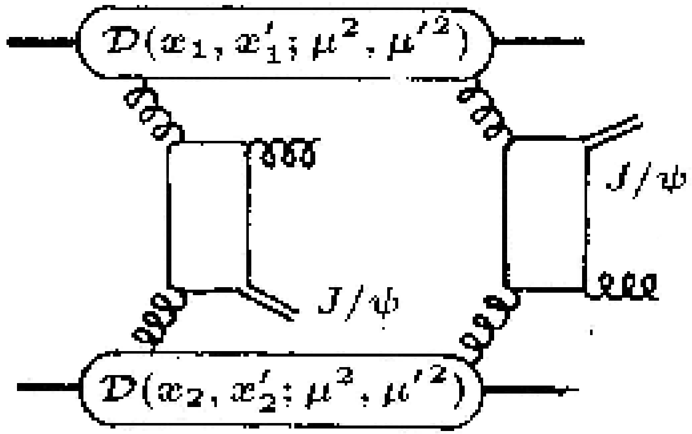
singlet+octet production
octet+octet production
(gluon fragmentation)

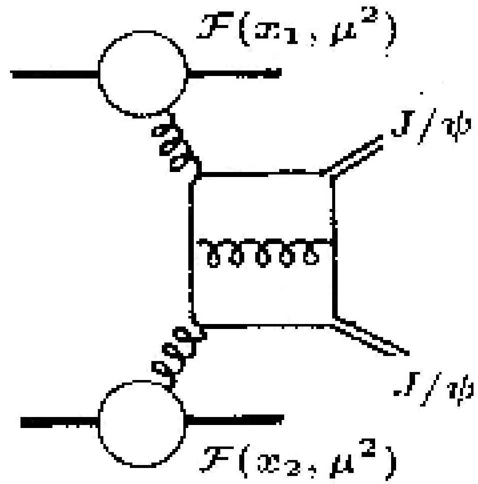


Onium-onium scattering:
one-gluon exchange
two-gluon exchange

Double-parton scattering

Two independent interactions $\hat{\sigma}^A$ and $\hat{\sigma}^B$ at a time.





Further assumptions:
Decoupling of longitudinal and transversal variables

$$\Gamma_{ij}(x, x'; \mathbf{b_1}, \mathbf{b_2}; Q^2, Q'^2) = \mathcal{D}_{ij}(x, x'; Q^2, Q'^2) f(\mathbf{b_1}) f(\mathbf{b_2})$$

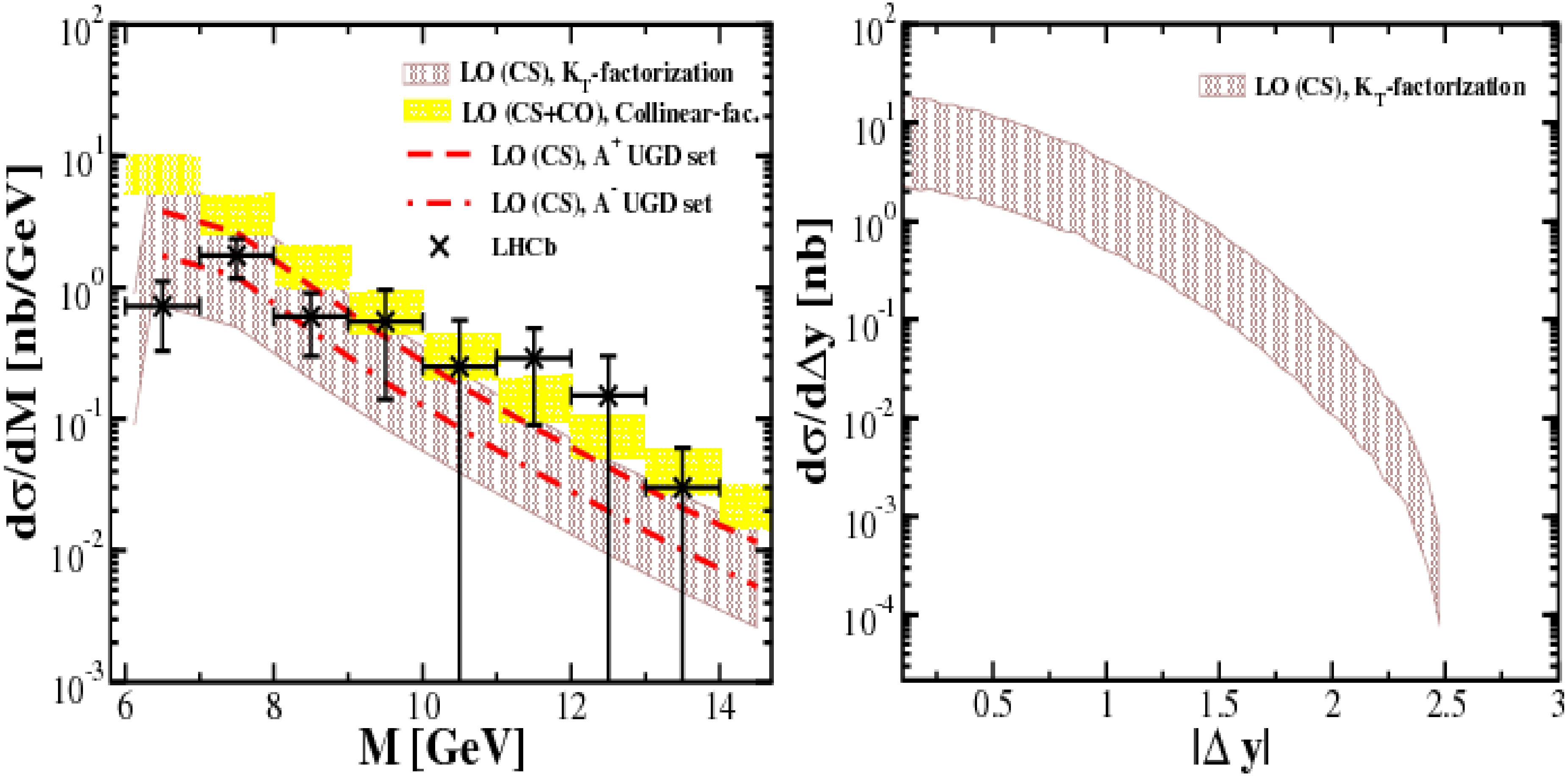
Factorization of parton distributions

$$\mathcal{D}_{ij}(x, x'; Q^2, Q'^2) = \mathcal{F}_i(x, Q^2)\mathcal{F}_j(x', Q'^2)$$

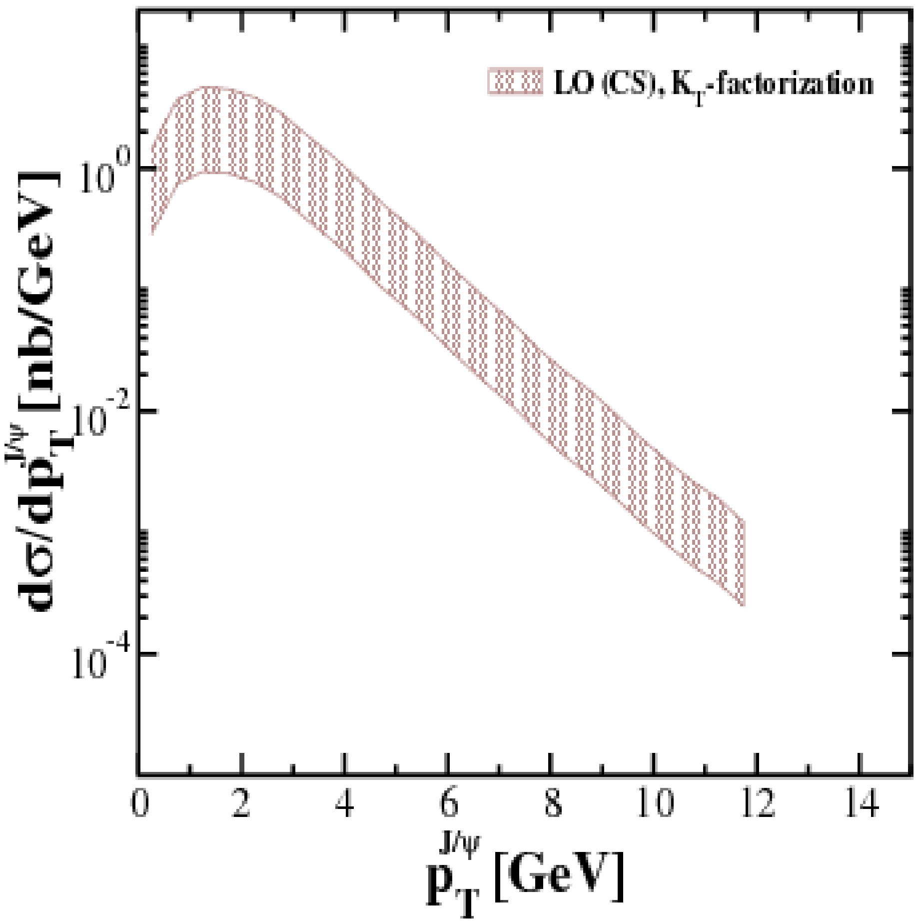
Result in $\sigma^{\rm AB}_{\rm DPS} = \frac{1}{2}\frac{\sigma^A_{\rm SPS}\sigma^B_{\rm SPS}}{\sigma_{\rm eff}}$ with $\sigma_{\rm eff} = 14.5\ mb$

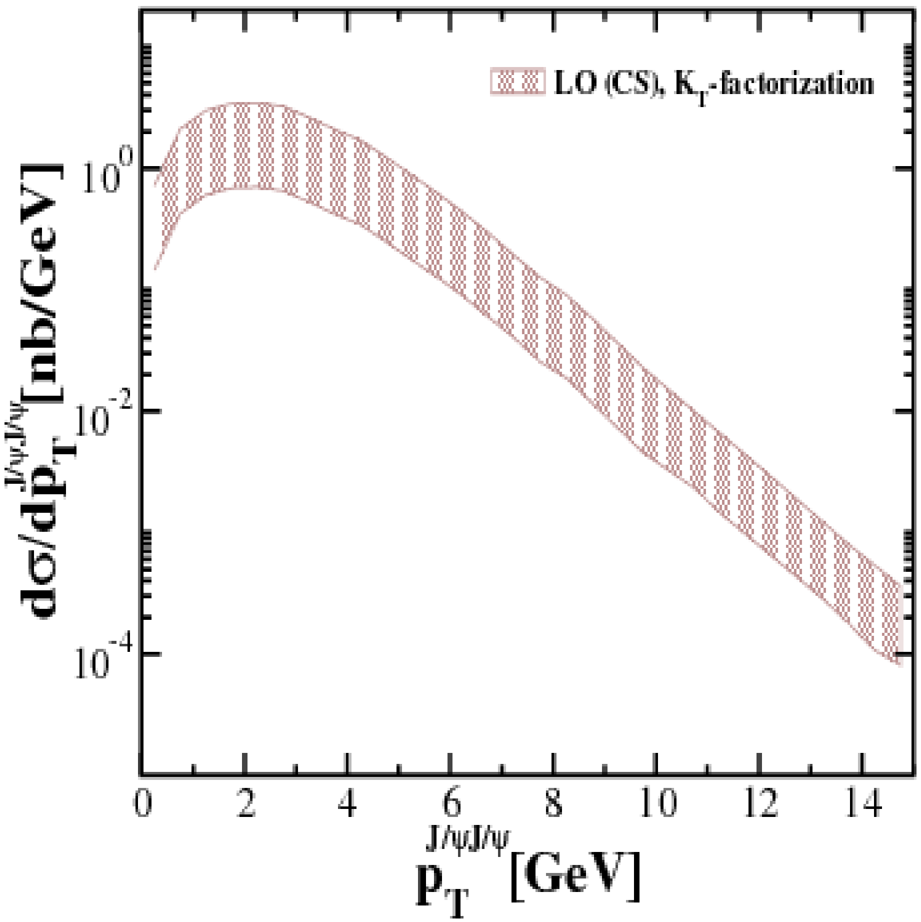
NUMERICAL RESULTS

Comparisons with LHCb data

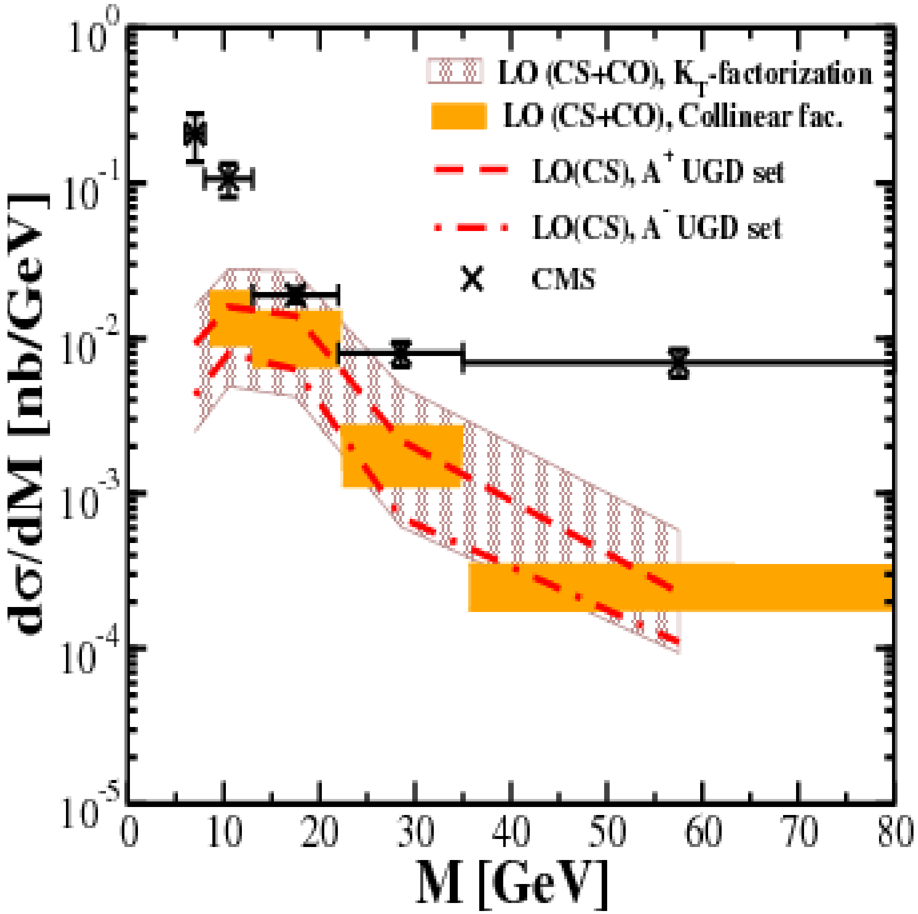


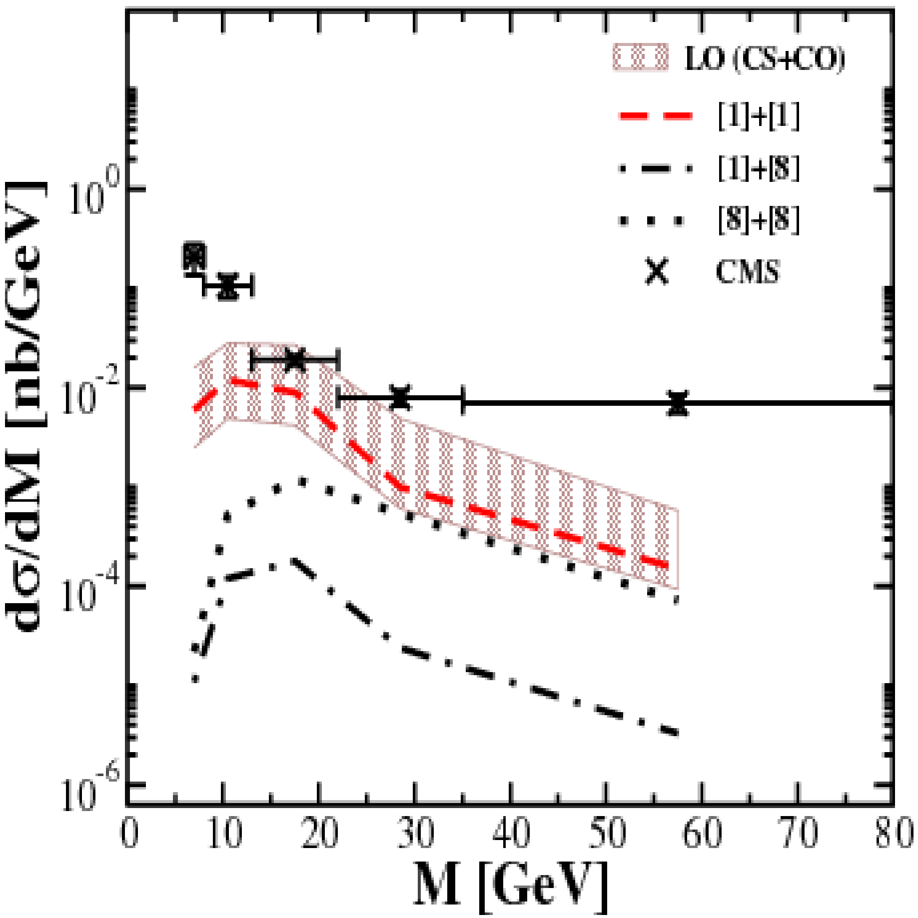
Further predictions for LHCb



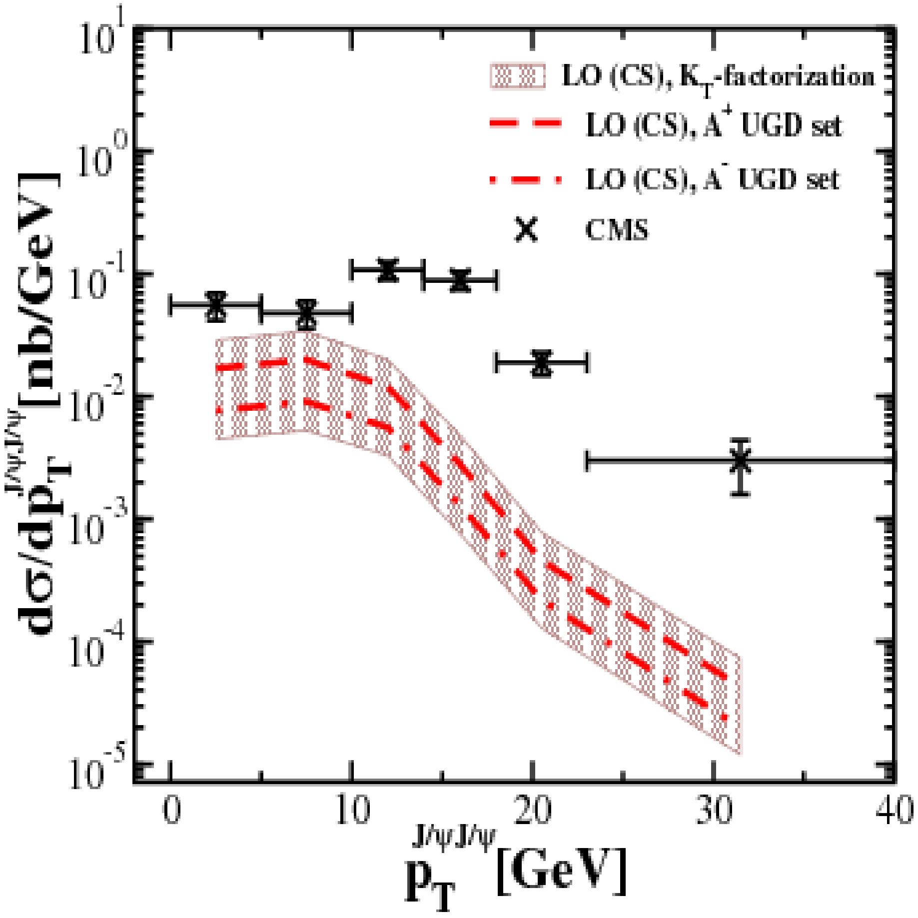


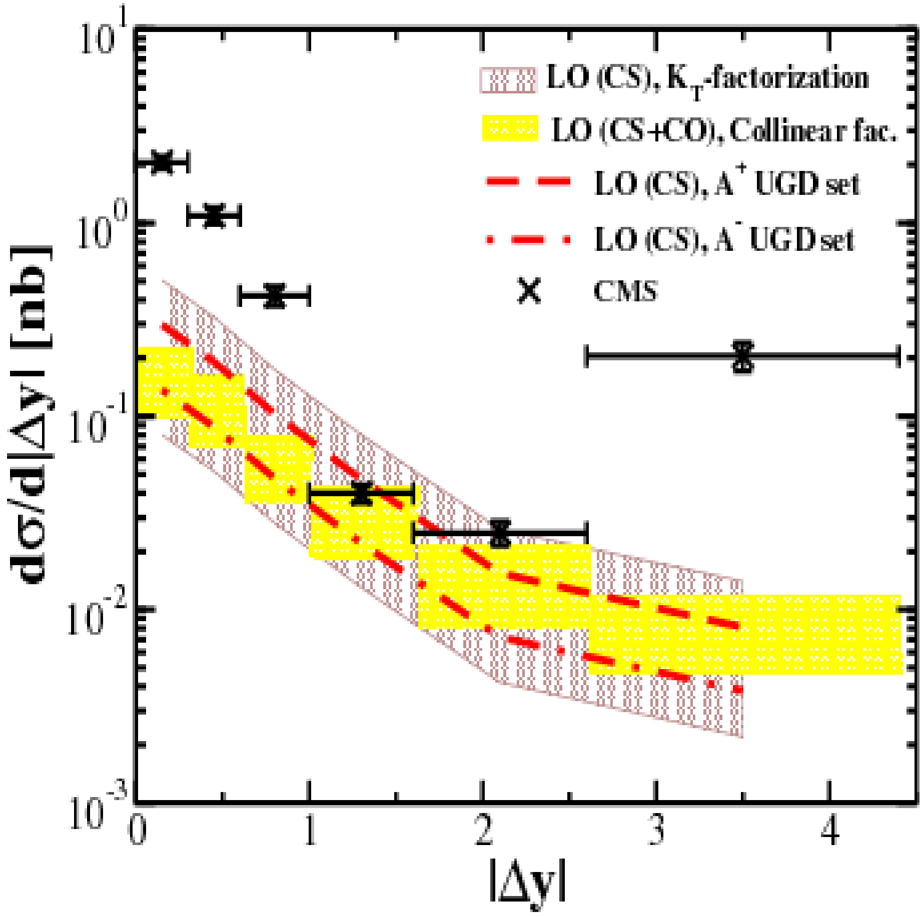
Comparisons with CMS data



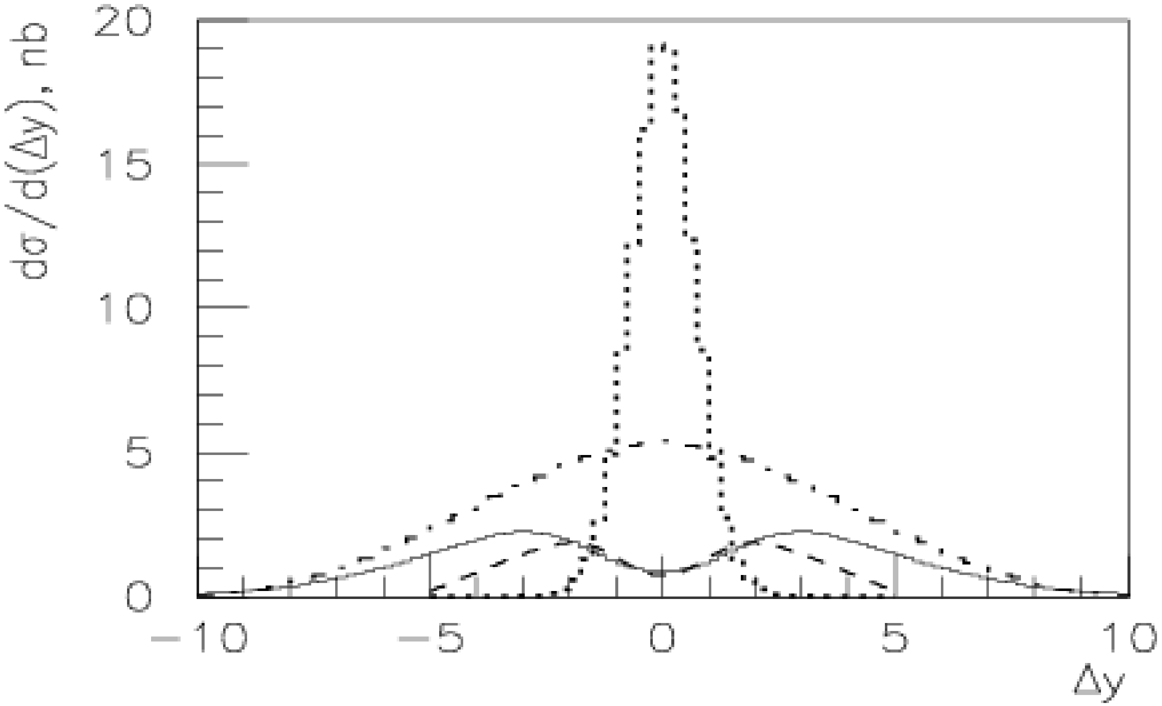


Comparisons with CMS data





$J/\psi - J/\psi$ rapidity difference, $\sqrt{s} = 8$ TeV, no cuts



Dotted line = direct LO gluon-gluon fusion (SPS mode)
Dash-dotted = Double Parton Scattering
Dashed line = one-gluon exchange (multiplied by 1000)
Solid line = two-gluon exchange (multiplied by 25)

CONCLUSIONS

LHCb: the theory reasonably fits the data

– LO color-singlet alone is enough, all other contributions are small)

CMS: the theory is deficient by a factor of 10

– Onium-onium scattering is negligible (about 1%)
– Double parton scattering contributes at the level of 10%
only helps at large Δy, but still insufficiently
– Color-octet contributions dominate at very high p_t,
though do not help with the total yield.

A problem with understanding high-p_t behavior?

Thank you!

Reasons for pseudo-diffractive processes to be small

– **Two extra powers of** α_s

– **Larger average invariant mass** $M(\psi\psi)$

– **Color: Direct** $g + g \to J/\psi + J/\psi$

$$|tr\{T^a T^c T^c T^b\}|^2 = |[(N_c^2 - 1)/(4N_c)]\delta^{ab}|^2 = [\tfrac{2}{3}\delta^{ab}]^2 = 32/9$$

compared to Pseudodiffractive one- and two-gluon exchange

$$[\tfrac{1}{4}d^{ace}\tfrac{1}{4}d^{bde}]^2 = \frac{(N_c^2-1)(N_c^2-4)^2}{256\ N_c^2} = \frac{1}{256}\frac{200}{9} \simeq 0.1$$