On effects of multiple gluons in J/ψ hadroproduction

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Outline

- Goal: estimate magnitude of rescattering correction in heavy vector meson hadroproduction.

- Brief discussion of theory for VM hadroproduction: approaches, strong and week points.

- Motivation.

- Description of our approach.

- Results for J/ψ, interpretation and outlook.
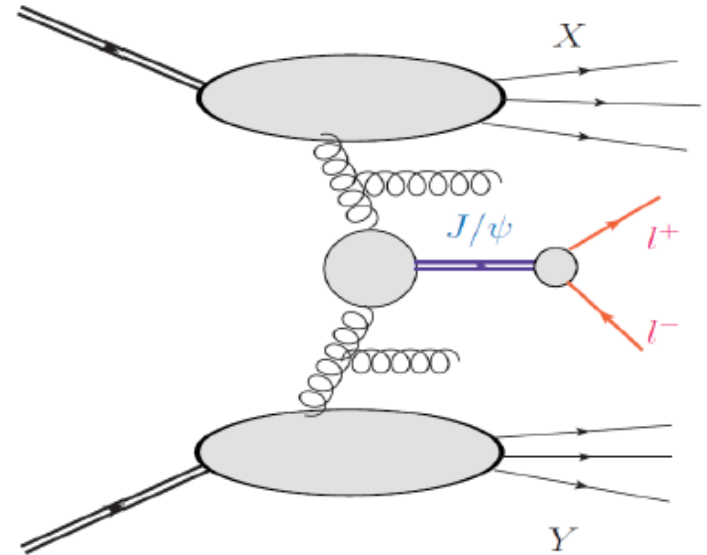
Work in progress, in collaboration with L. Motyka

Prompt quarkonia hadroproduction

Sources of J/ψ:
- direct production
- feed down from ψ', χ
- feed down from b-hadrons

Features:
- Perturbative
- abundant, clean signal
- pT and y dependence
- polarisation dependence

Data:
RHIC, Tevatron; **HERA;**
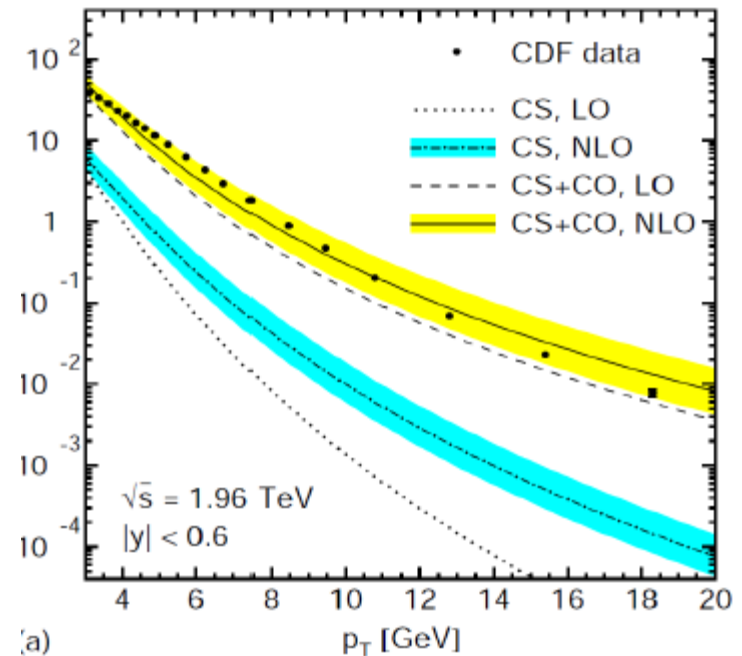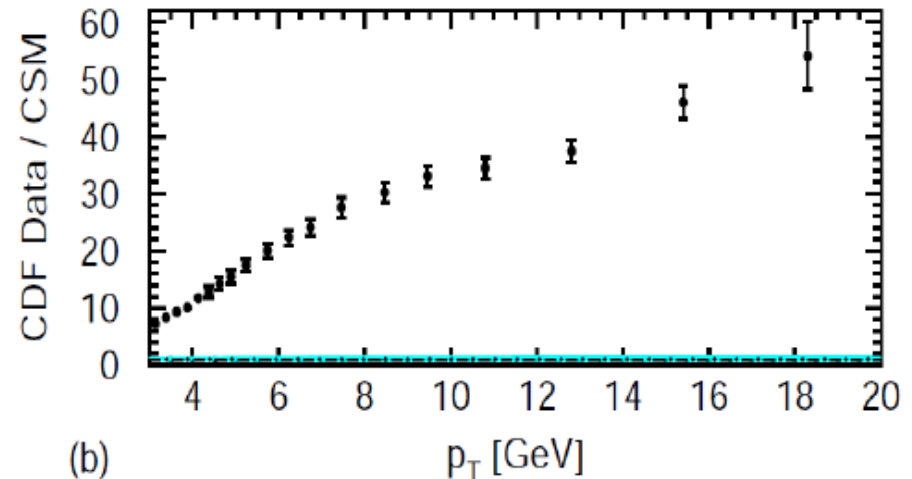**LHC**: ATLAS, CMS, LHCb
Collisions with nuclei: ALICE

Production mechanism

Heavy vector quarkonia:
need for 3 gluons in matrix element.
Spectacular failure of standard,
collinear LO QCD calculations,
especially at large pT

Ways out:
-color octet mechanism (NRQCD)
-kt-factorisation (+ COM)
-CGC+NRQCD
-higher orders color singlet
-rescattering
-color evaporation

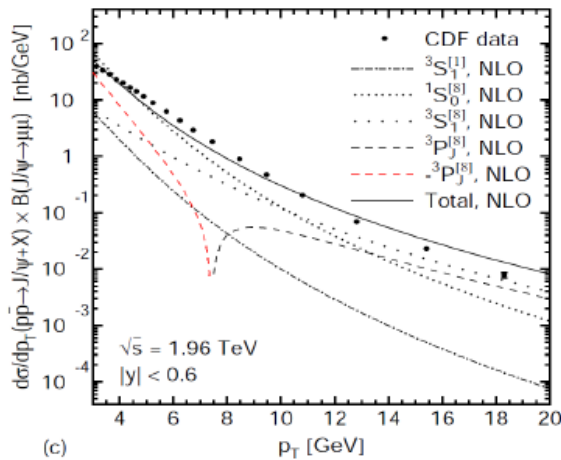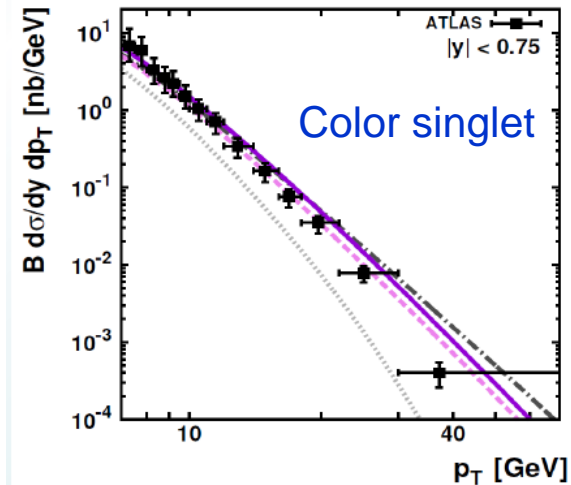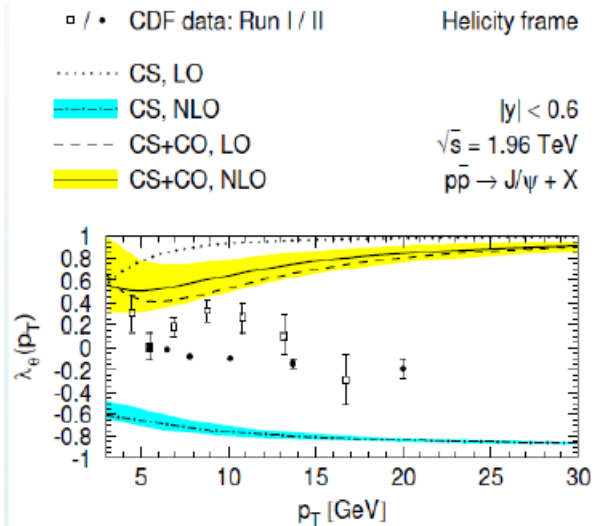# Color octet mechanism

$$\sigma(ab \to H + X) = \sum_n \sigma(ab \to c\bar{c}[n] + X)\langle O^H[n]\rangle$$

M. Butenschoen, B.Kniehl, Phys.Rev.Lett. 106 (2011) 022003

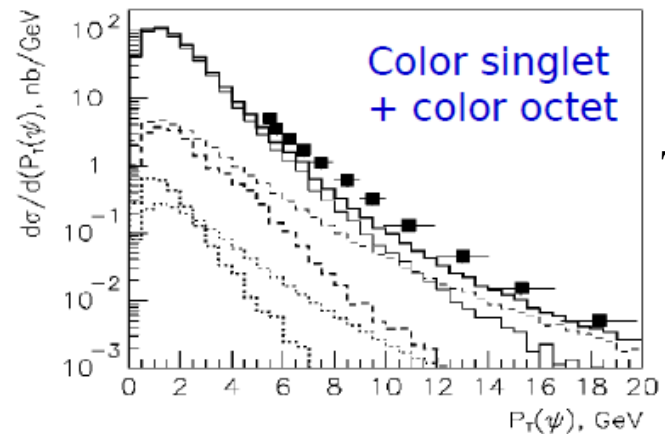S. P. Baranov, A.V. Lipatov, N.P. Zotov, Phys.Rev. D85 (2012) 014034

LHC

M. Butenschoen, B.Kniehl, Phys.Rev.Lett. 108 (2012) 172002

S. P. Baranov, Phys. Rev. D66 (2002) 114003

Tevatron

Color singlet rescattering

Importance of rescattering in VM hadroproduction stressed by Khoze, Martin, Ryskin and Stirling (2004) and recently by Kang, Ma and Venugopalan (2013).

Motivation:
•Matrix elements at the same order of pQCD as the other contributions.
•Double gluon density involved.
•Double gluon density → twist 4 → power suppression with process scale (transverse mass).
•However: large hadron collision energy → small x of incoming gluons → double density / single density >> 1: enhancement.
•KMRS results: very encouraging, but leaving quite some space for detailed calculations.
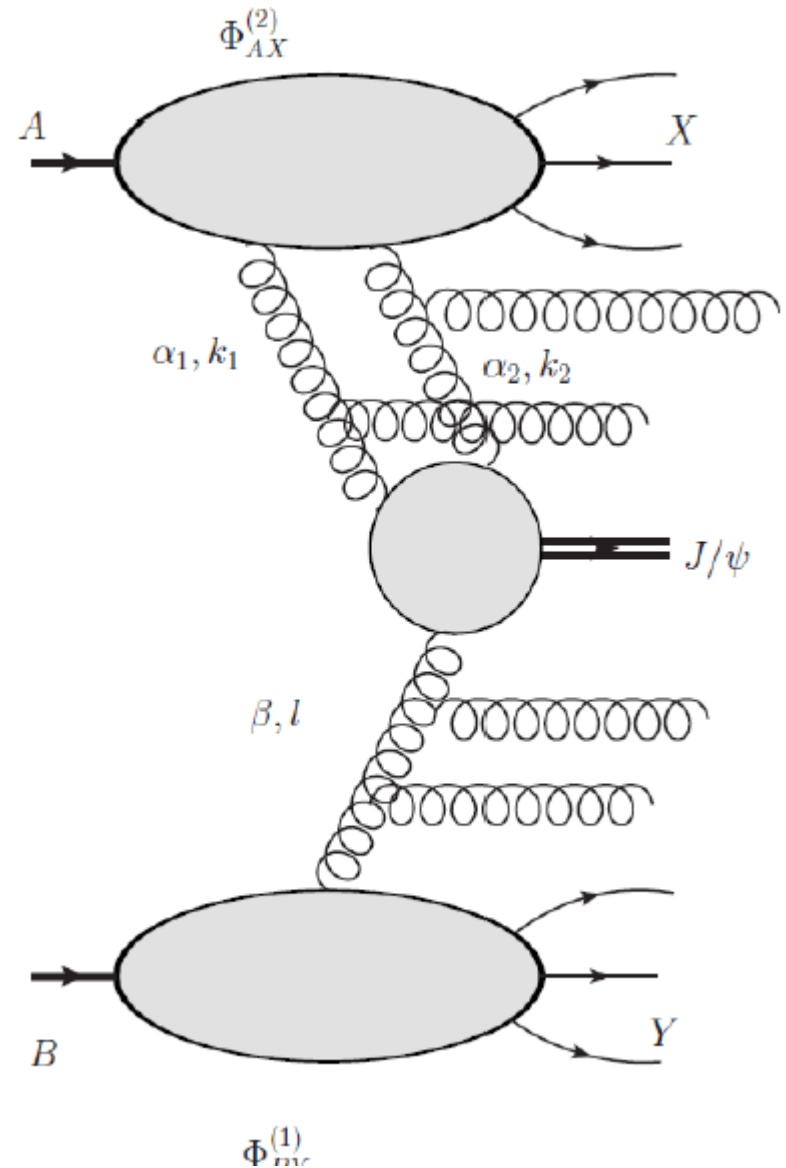
Standard color singlet: gluon emission
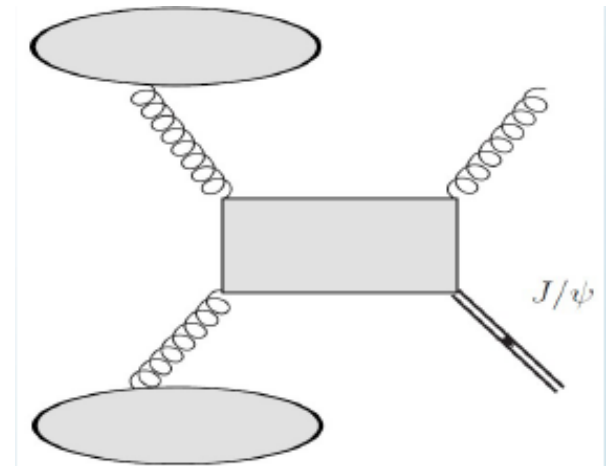
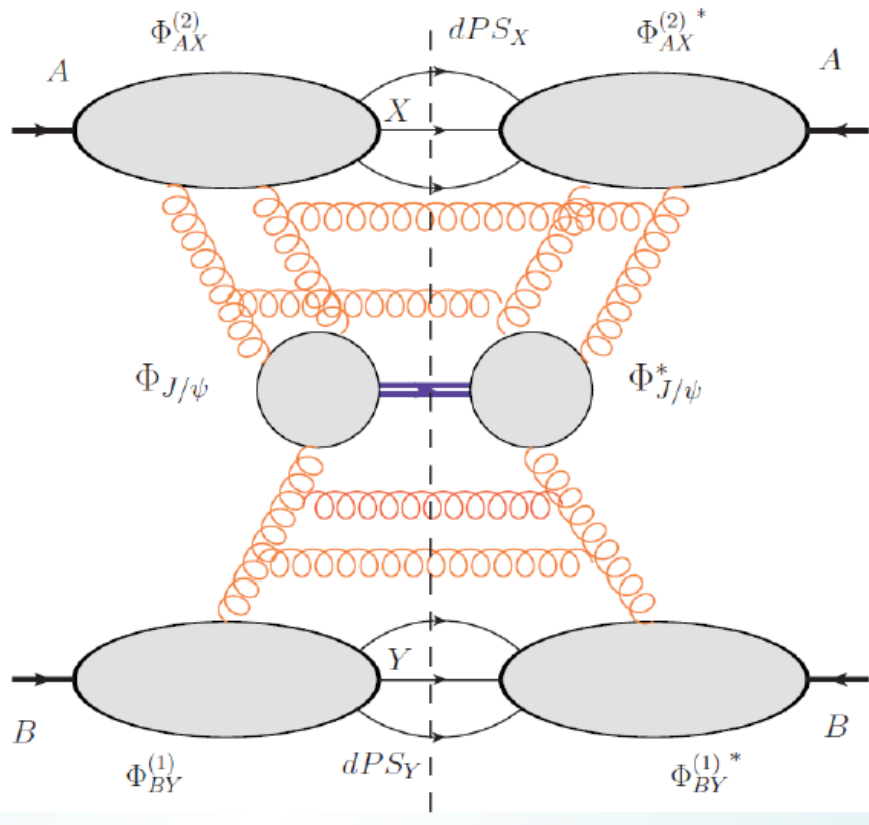Singlet rescattering: double gluon
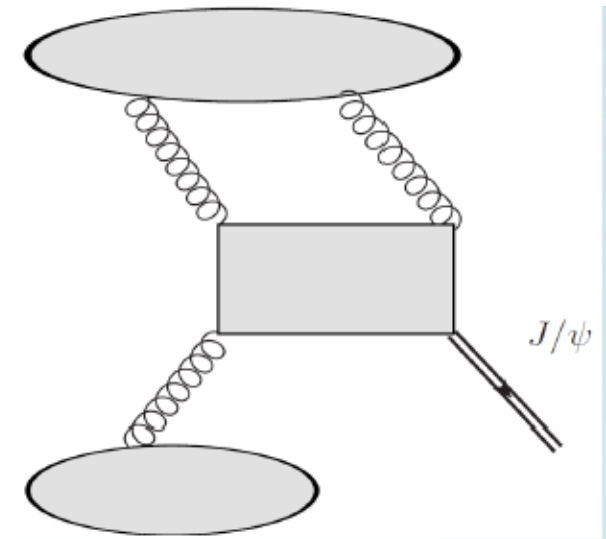
High energy amplitude: Ingredients

•High energy factorisation.

•Single and double unintegrated gluon distributions emerge

•Off-shell 3g → J/Ψ (3 → 1 particle) matrix element (not leading to partonic cross-section!)
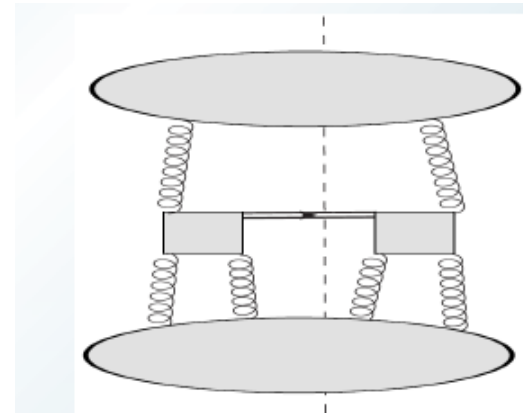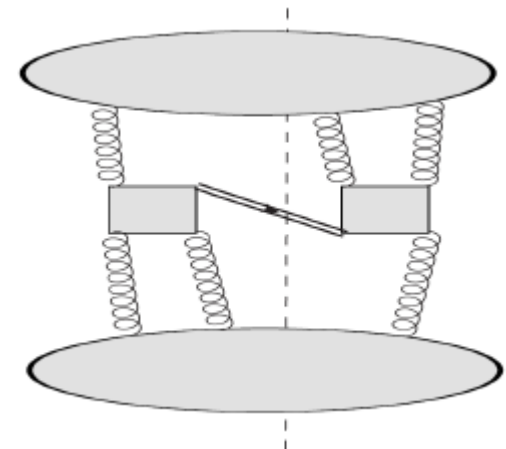
Cross section and interference

Leading contribution: 2 and 4
gluon t-channel states

Also leading: fliped diagram
- incoherrent sum

Interference term: subleading
3 gluon t-channel evolution,
may be neglected

3 gluon → J/ψ vertex
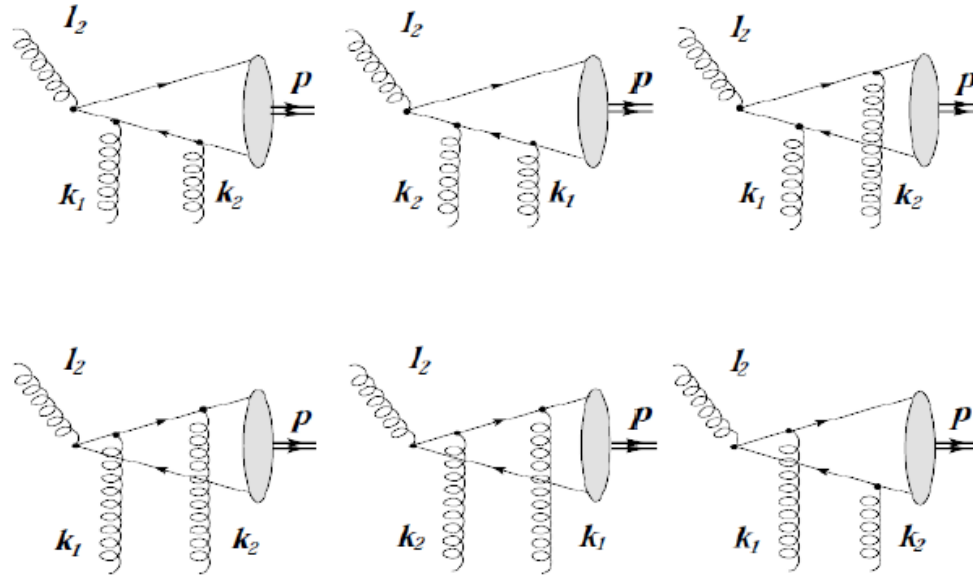
Bzdak, Cudell, Motyka, Szymanowski, Phys.Rev. **D75** (2007) 094023

- Impact factor computed with the NR meson wave function
- Safe in the infra-red

Unintegrated gluon distribution

$$\int d\alpha_l \, \Phi_{2,p}^{b_1 b_2}(\alpha_l, \beta, \boldsymbol{l}) \sim f(\beta, \boldsymbol{l}^2)\delta^{b_1 b_2}$$

To relate impact factors with unintegrated gluon distribution we apply
Collins-Ellis trick: `nonsense gluon polarisations'

Four gluon amplitude in proton
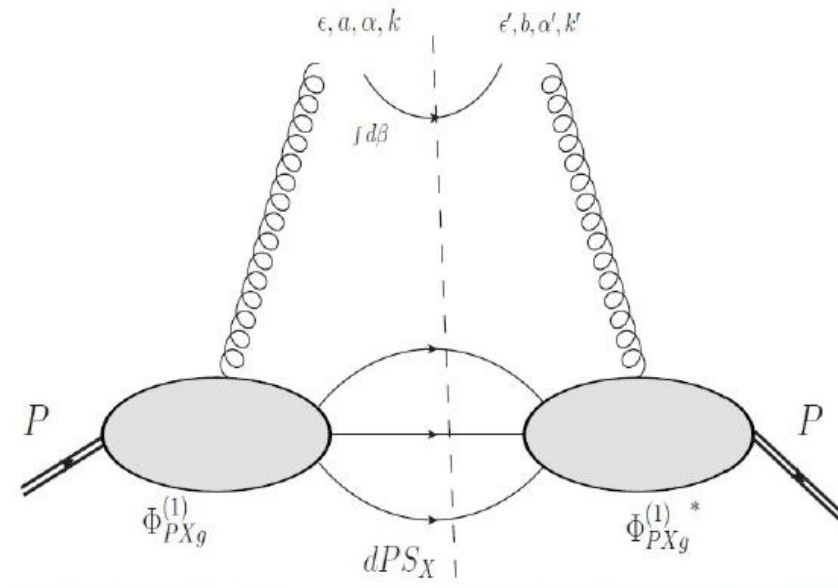
$$\int d[\alpha_i]\Phi_{4,p}^{a_1a_2a_3a_4}(\{\alpha_i\},\{\beta_i\},\{\mathbf{k}_i\}) \sim G_4^{a_1a_2a_3a_4}(\{\beta_i\},\{\mathbf{k}_i\})$$

• The phase-space integrated impact factor for four gluons related to four gluon amplitude in proton

• Dominant color-momentum structure: two (nonforward) ladders – double gluon distribution
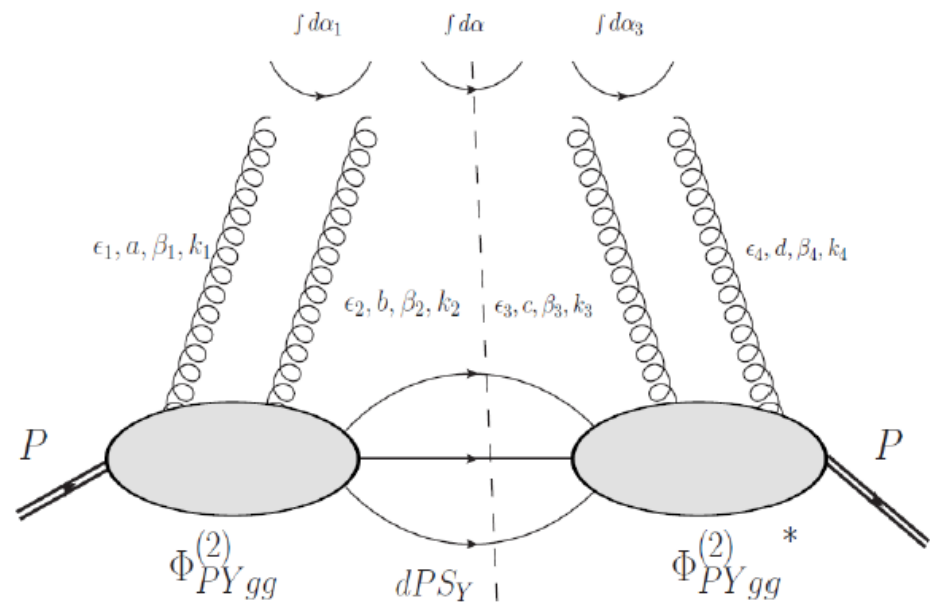
Double gluon distribution: factorized approximation

Factorized Ansatz + symmetries of the amplitudes (consistent with AGK) :

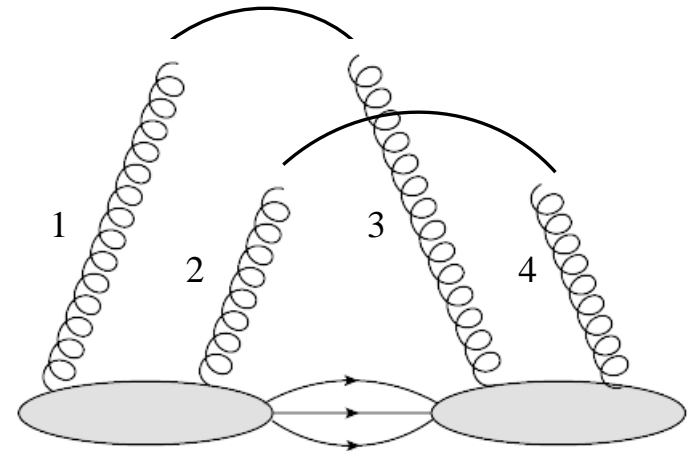$$G_4(\{\beta_i\}, \{\mathbf{k}_i\}) = \mathcal{N}\,[f(\beta_1, \beta_2, \mathbf{k}_1, \mathbf{k}_2)\delta^{a_1 a_2} f(\beta_3, \beta_4, \mathbf{k}_3, \mathbf{k}_4)\delta^{a_3 a_4}$$

$$+ f(\beta_1, \beta_3, \mathbf{k}_1, \mathbf{k}_3)\delta^{a_1 a_3} f(\beta_2, \beta_4, \mathbf{k}_2, \mathbf{k}_4)\delta^{a_2 a_4} +$$

$$+ f(\beta_1, \beta_4, \mathbf{k}_1, \mathbf{k}_4)\delta^{a_1 a_4} f(\beta_2, \beta_3, \mathbf{k}_2, \mathbf{k}_3)\delta^{a_2 a_3}]$$

- Four gluon amplitude splits into two color singlets
- Intrinsic momentum in ladder > total momentum transfer
- Locality in impact parameter

$$G_4(\{\beta_i\}, \{\mathbf{k}_i\}) \to f(\beta_1, \beta_3, \mathbf{k}_1, \mathbf{k}_3)\delta^{a_1 a_3} f(\beta_2, \beta_4, \mathbf{k}_2, \mathbf{k}_4)\delta^{a_2 a_4}$$

$$\to f^{\mathrm{off}}(\beta, \mathbf{k}_1)\tilde{S}(\mathbf{q})\delta^{a_1 a_3} f^{\mathrm{off}}(\beta, \mathbf{k}_2)\tilde{S}(-\mathbf{q})\delta^{a_2 a_4}$$

$$\to f^{\mathrm{off}}(\beta, \mathbf{k}_1) S(\mathbf{b}_1 - \mathbf{b})\delta^{a_1 a_3} f^{\mathrm{off}}(\beta, \mathbf{k}_2) S(\mathbf{b}_2 - \mathbf{b})\delta^{a_2 a_4}$$

Normalization

Normalisation constant in relation of double gluon density and the 4 gluon proton impact factor obtained from analysis of double hard event using collinear expressions compared to full kT amplitudes.

$$d\sigma_d = g(\alpha_1, \mu^2) g(\beta_1, \mu^2) \, d\hat{\sigma}_1(\alpha_1, \beta_1) \, g(\alpha_2, \mu^2) g(\beta_2, \mu^2) \, d\hat{\sigma}_2(\alpha_2, \beta_2)$$

$$\times \int d^2 \boldsymbol{b} \, d^2 \boldsymbol{b}_1^A \, d^2 \boldsymbol{b}_2^A S(\boldsymbol{b}_1^A) S(\boldsymbol{b} - \boldsymbol{b}_1^A) S(\boldsymbol{b}_2^A) S(\boldsymbol{b} - \boldsymbol{b}_2^A)$$
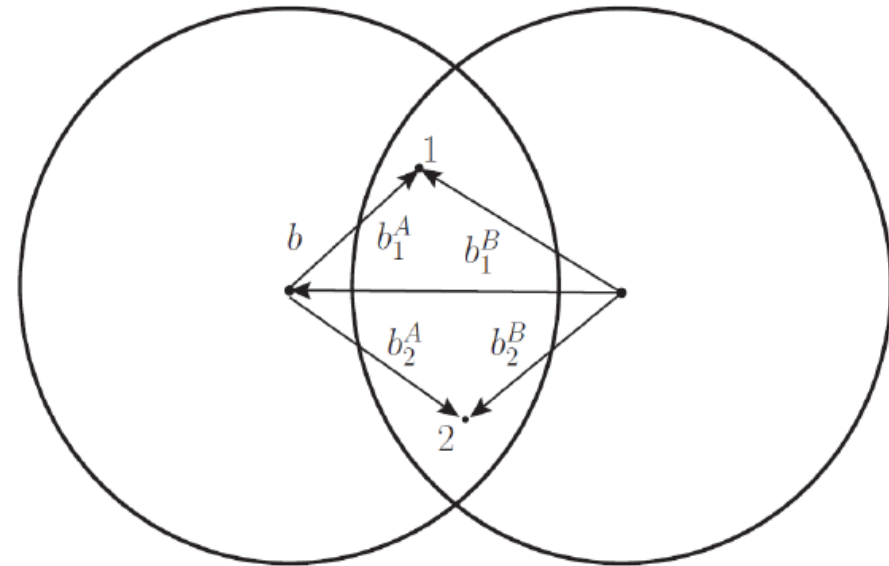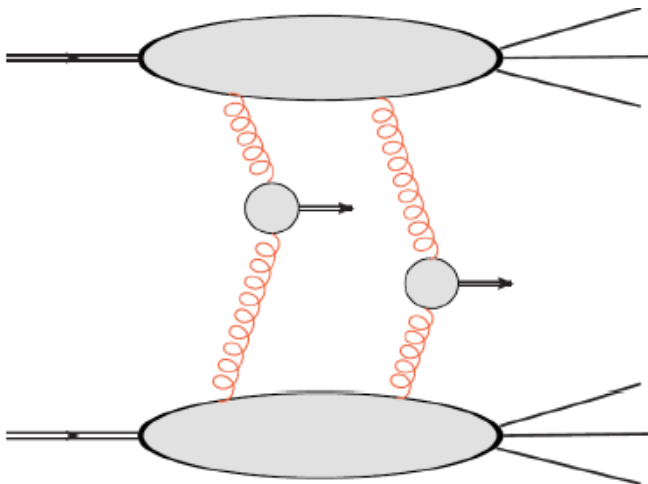
Final formula

$$\frac{d^2\sigma_{pp\to J/\psi X}}{dY\,dp_T^2} = \mathcal{N}\,\frac{R_{\text{sh}}^2}{\sigma_0}\int d^2k\,d^2l\,\frac{\alpha_s^3\,f(\beta,l^2,\mu)\,f(\alpha,k^2,\mu)\,f(\alpha,(\boldsymbol{p}-\boldsymbol{k}-\boldsymbol{l})^2,\mu)}{[k^2\,l^2\,(\boldsymbol{p}-\boldsymbol{k}-\boldsymbol{l})^2]^2}$$

$$\times\,\left|\Phi_{J/\psi}(\alpha,\beta;\boldsymbol{k},\boldsymbol{p}-\boldsymbol{k}-\boldsymbol{l},\boldsymbol{l};\varepsilon)\right|^2 + (\alpha\leftrightarrow\beta,\ p_A\leftrightarrow p_B)$$

• Leading order in strong coupling constant

• Proportional to square of gluon density

• Power supressed, subleading twist

• Unintegrated gluon: KMR procedure with CT10 (NLO) – used for plots and MSTW – similar results

• Off-diagonal gluon densities: inclusion of Shuvaev factor.

• $\alpha_s\,(M_c^2 + k^2)$ - running coupling scale evaluated "locally".

• Quark mass $M_c = M_\psi/2$.

• Impact parameter size for double parton density $R \sim 1.7\,/\,\text{GeV} \to \sigma_0 = 15$ mb
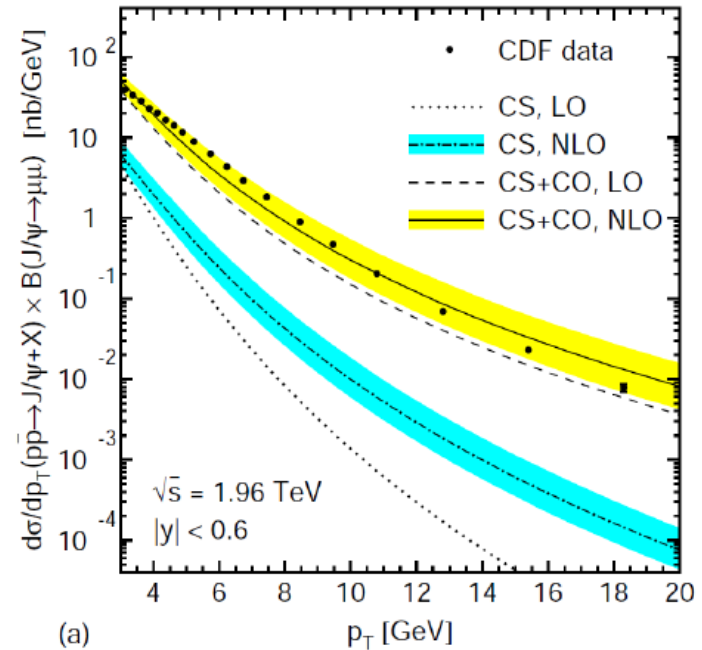
Results: Tevatron

Rescattering contribution: (new)
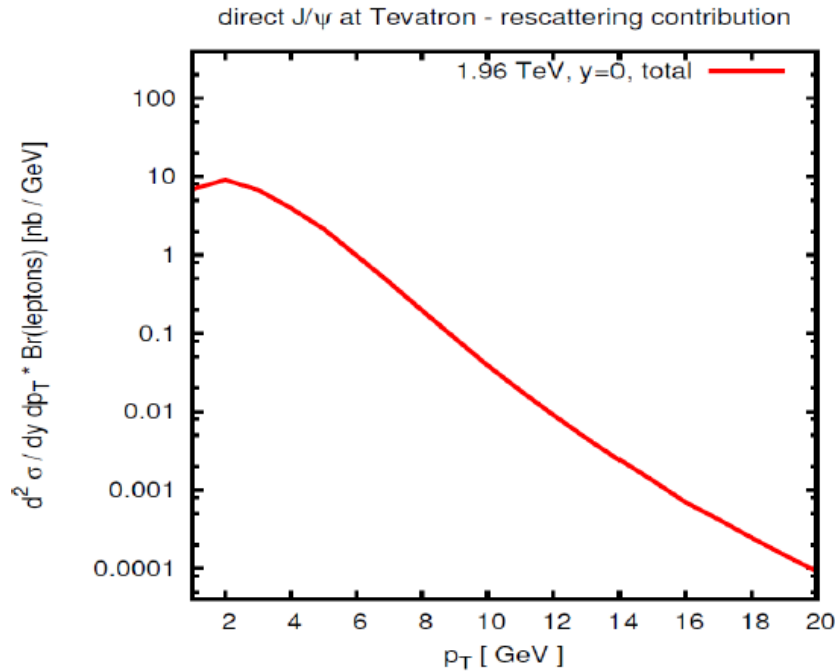
Reference: data and COM at NLO

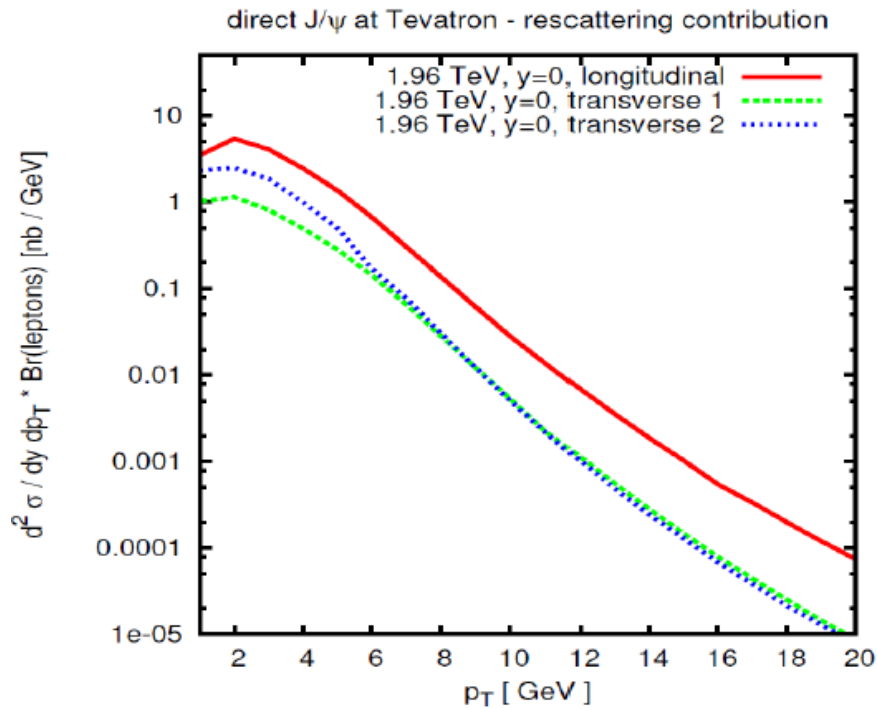M. Butenschoen and B. Kniehl, Phys. Rev. D84 (2011) 051501

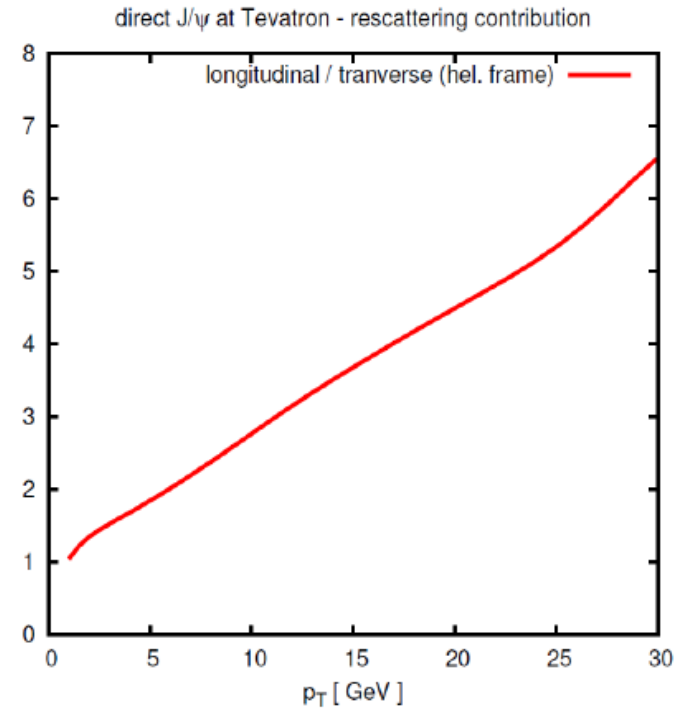Color singlet rescattering may make up to 25% of the total cross section at moderate pT (like CSM at NLO)

Shape: steep, power suppression manifest, significantly steeper than Khoze-Martin-Ryskin-Stirling estimates, total cross-sect. < KMRS

Results: polarization at Tevatron (helicity frame)
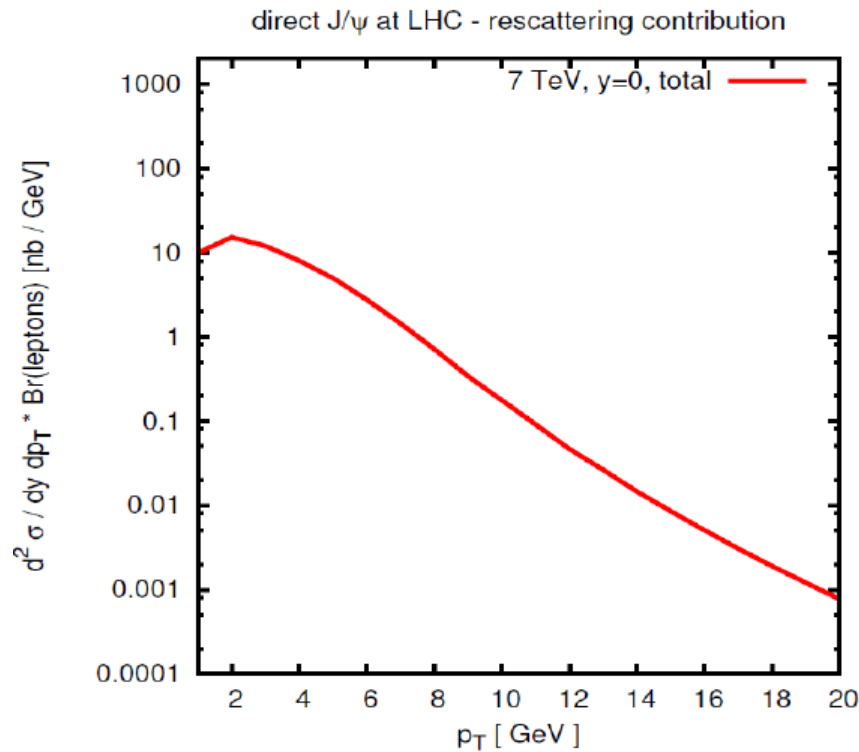
Polarised components

Longitudinal / Transverse
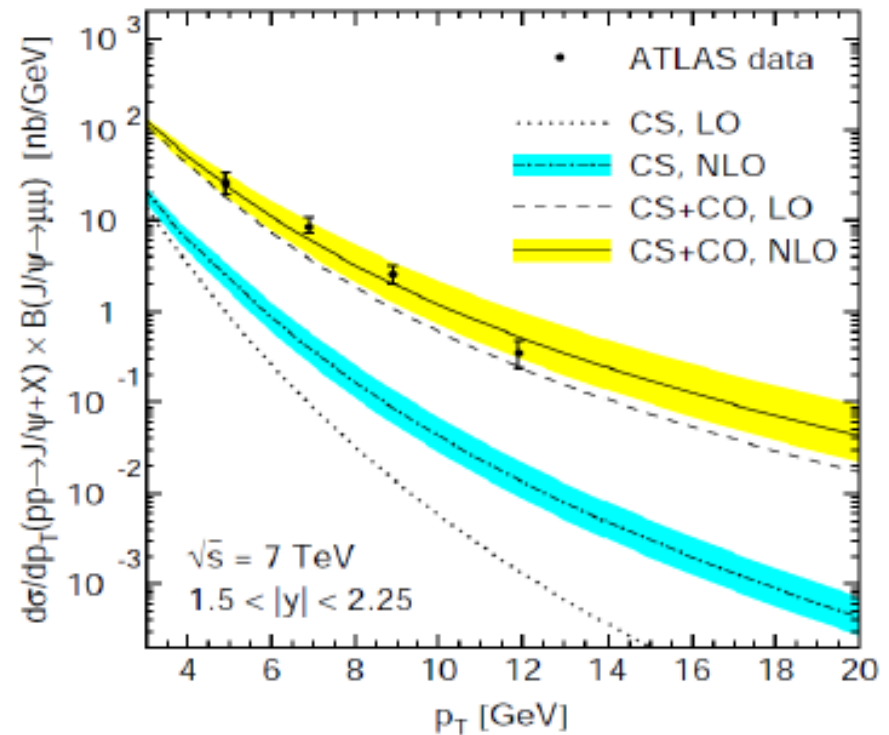

Dominance of longitudinal component grows with pT

Results: LHC

Rescattering contribution: (new)
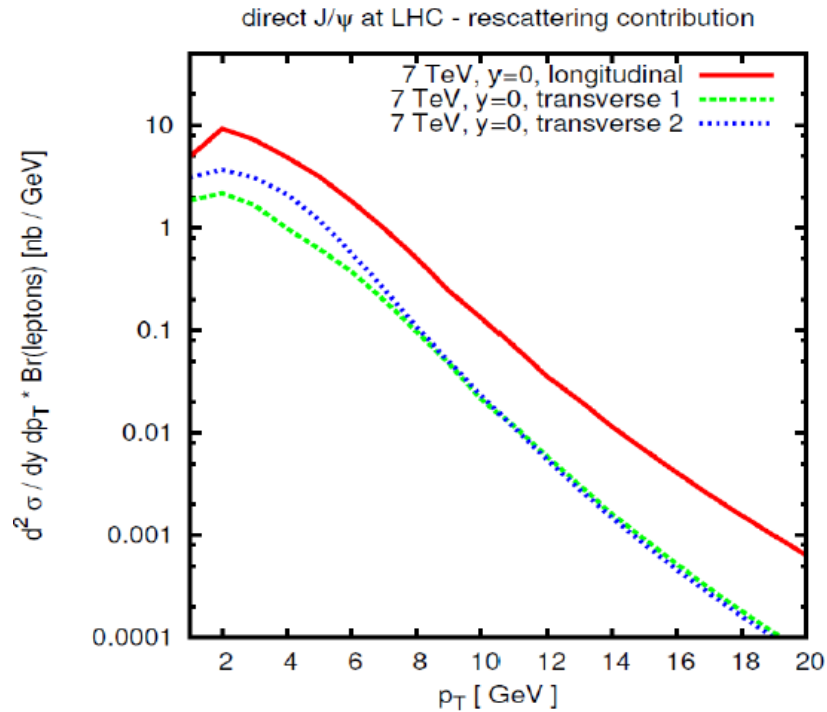
Reference: data and COM at NLO
M. Butenschoen and B. Kniehl, Phys. Rev. D84 (2011) 051501

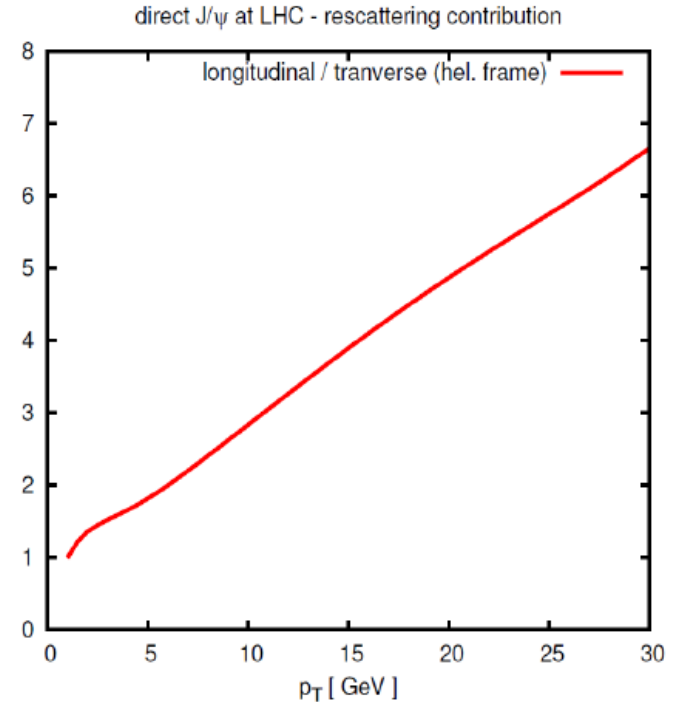direct J/ψ at LHC - rescattering contribution

Similar pattern to one found for Tevatron, O(20%) rescattering correction, steeply decreasing

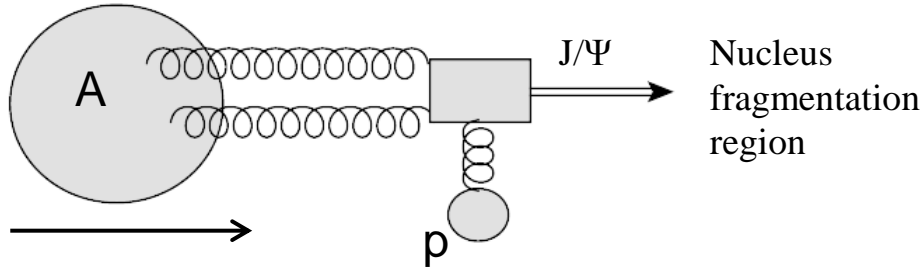# Results: polarization at LHC (helicity frame)

Polarised components

Longitudinal / Transverse

Dominance of longitudinal component grows with pT

Estimation of anti-shadowing in pA collisions

Proton rest frame:
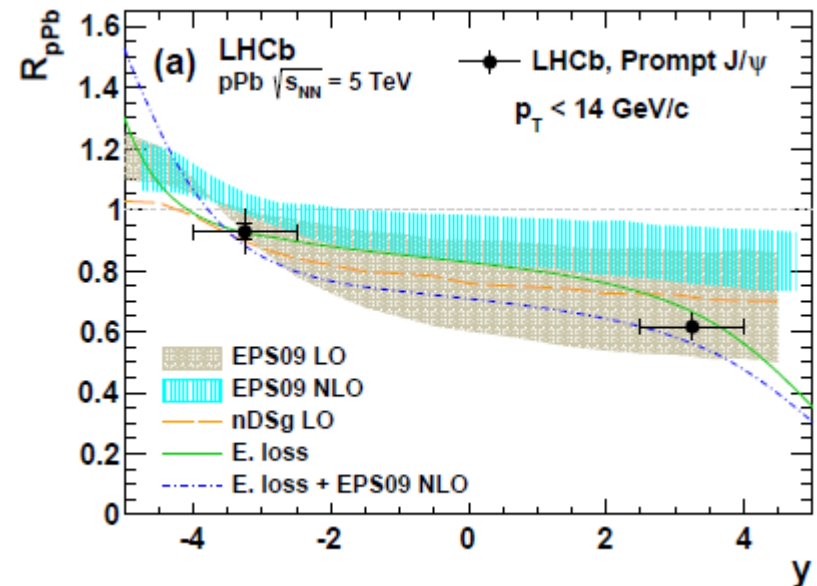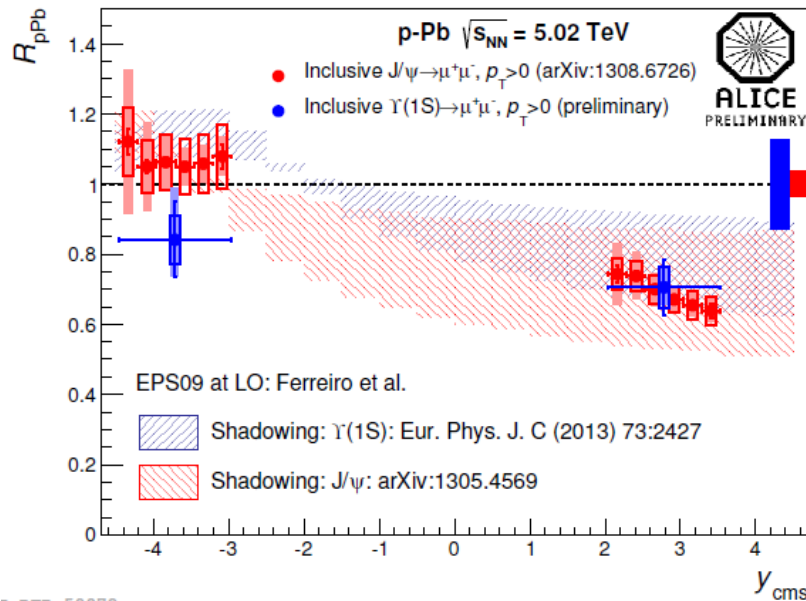

Compare with CGC approach: Kang, Ma and Venugopalan, 2013

Conventional mechanisms

Multiple scattering

$$\frac{\sigma_{pA \to J/\Psi X}}{A\sigma_{pp \to J/\Psi X}} = 1 + \frac{xg(x,\mu^2)}{\bar{x}g(\bar{x},\mu^2)} \frac{\bar{\sigma}}{2} A^{1/3}$$

For typical values: E=7 TeV, μ^2=10 GeV^2, Y=0 (pp) and Y = 3 (pA), correction is of order 10-15 % for p+ Pb collisions.

Conclusions

•Effects of color singlet rescattering in heavy vector quarkonia hadroproduction were studied in kT-factorisation approach.

•The effects are power-supressed but leading in perturbative expansion and enhanced by large gluon densities.

•Color singlet rescattering corrections are sizeable: at Tevatron and LHC: larger than standard color singlet contributions and may make up to 25% of direct J/ψ cross section at moderate pT.

•Large dependence of polarisation composition on pT was at moderate pT

•Enviroment dependent process (ee, ep, pp, pA). It may influence fits of color octet matrix elements depending on sets of data.

•Anti-shadowing in pA collisions in nucleus fragmentation region.

Outlook

•Heavy quarkonia hadroproduction receives a lot of experimental attention, high quality data are being provided by ATLAS, CMS, LHCb, ALICE

•Production mechanism is complex: the naive leading CS contribution fails badly to describe data, `subleading' effects (color octet, gluon offshellness, rescattering) may be all necessary to describe the data accurately.

•The color singlet rescattering component turns out to be sizeable at moderate pT and introduces strong polarisation effects, so it may affect the COM polarized fits to Tevatron and LHC data.

•Other non-standard processes are still to be evaluated.

•Interesting to address rescattering in processes with nuclei $\rightarrow$ parton level enhancement expected