On triple gluon effects in heavy vector quarkonia hadroproduction

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Outline

- Goal: to estimate rescattering correction in heavy vector meson hadroproduction and nuclear effects in perturbative production mechanism
- Sketch of the current status of theory for VM hadroproduction: approaches, strong and week points
- Motivation
- Description of our approach
- Results for J/ψ, Υ, interpretation and outlook

- Work done with M. Sadzikowski

Eur.Phys.J. C75 (2015) 5, 213
arXiv:1501.04915

Prompt quarkonia hadroproduction: what is measured

- The process at the LHC

  pp → XY J/ψ → XY leptons

- Sources of J/ψ:

  -direct production

  -feed down from ψ', χ

  -feed down from b-hadrons

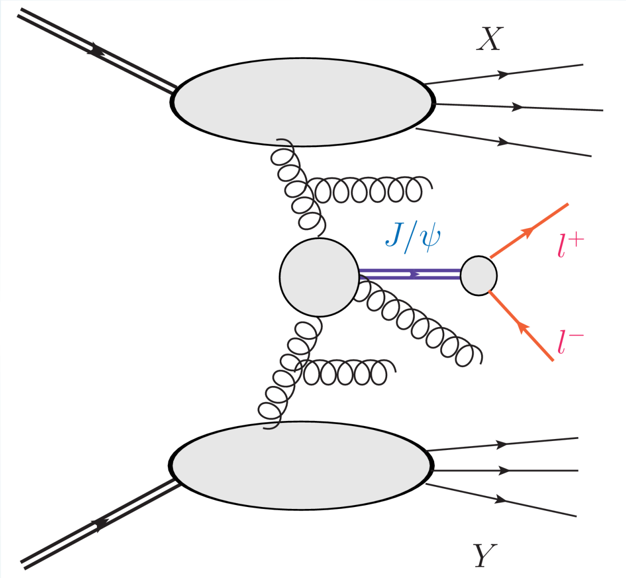
- Features:

  -abundant, clean signal

  -perturbative

  -pT and y dependence

  -polarisation dependence



Large and growing set of data:

RHIC, Tevatron;

LHC: ATLAS, CMS, LHCb

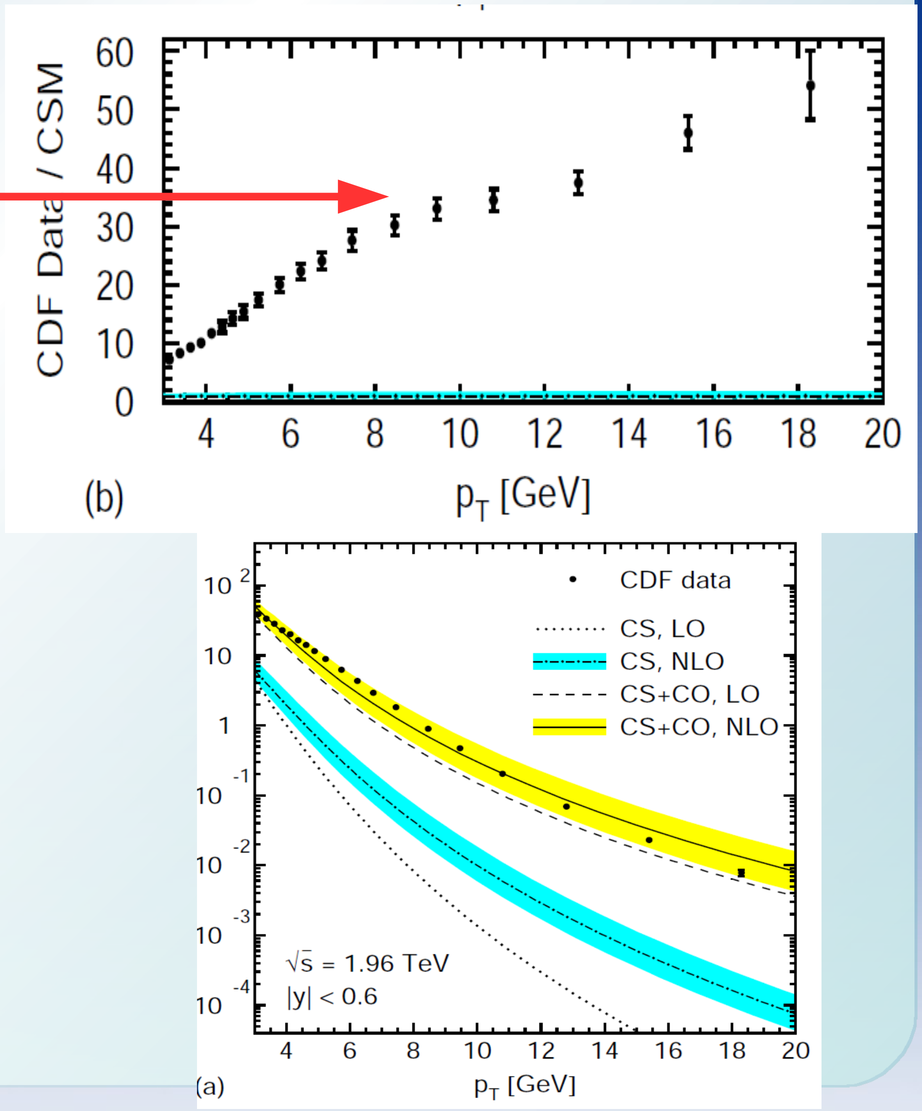
Collisions with nuclei: ALICE

Also psi', Upsilon (+ excited) quarkonia

Production mechanism: interesting physics

- Heavy vector quarkonia:
  C=-1 + color neutral → 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
  -higher orders color singlet
  -rescattering, comovers
  -color evaporation

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



Color octet mechanism

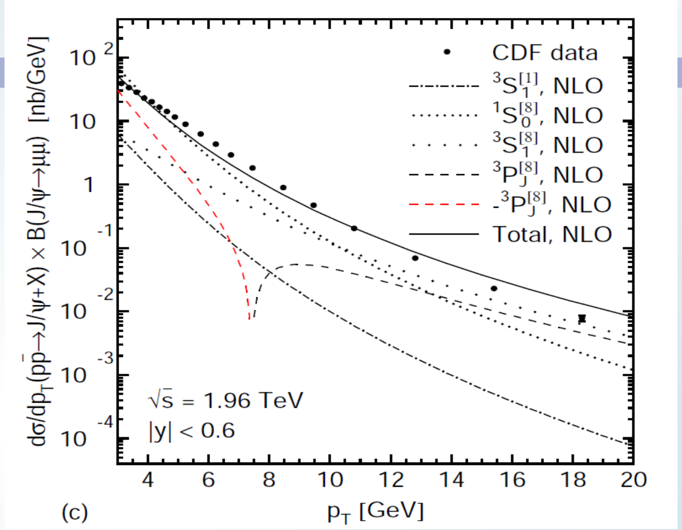
- Basis: NRQCD expansion of meson wave function– in powers of heavy quark velocity or 1/M
- (Q-anti Q gluon) Fock component in heavy meson: with (Q-anti Q) in color octet state and various NLO angular momentum sectors (like hydrogen atom spectroscopy)
- Scaling of such octet components O(v) ~ $O(\alpha_s)$
- Alternative picture: universal (environent-independent) fragmentation probability of octet Q-anti Q pair into vector meson
- Computed in collinear QCD at NLO, including polarisations

Success and problems of color octet mechanism

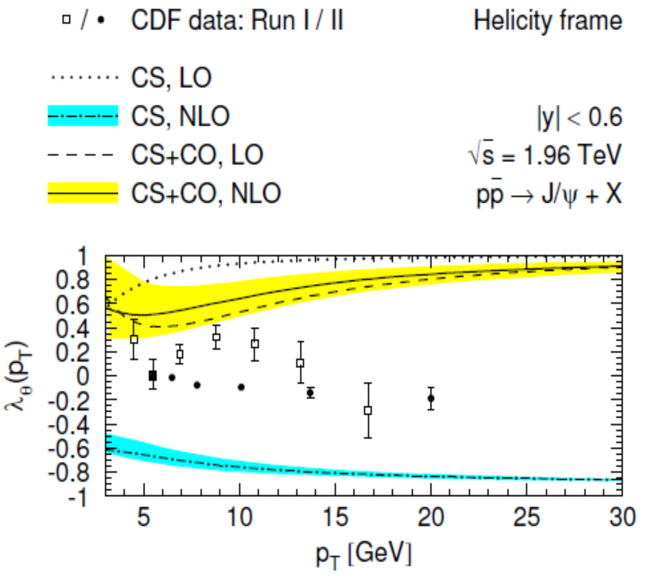
- A few partonic channels leading to components with different pT-shapes

- With corresponding free fit parameters: pT-dependence of cross sections well reproduced

- However: polarisation description is not fully satisfactory: neither at LO nor at NLO [theoretical NLO description works better for LHC data]



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



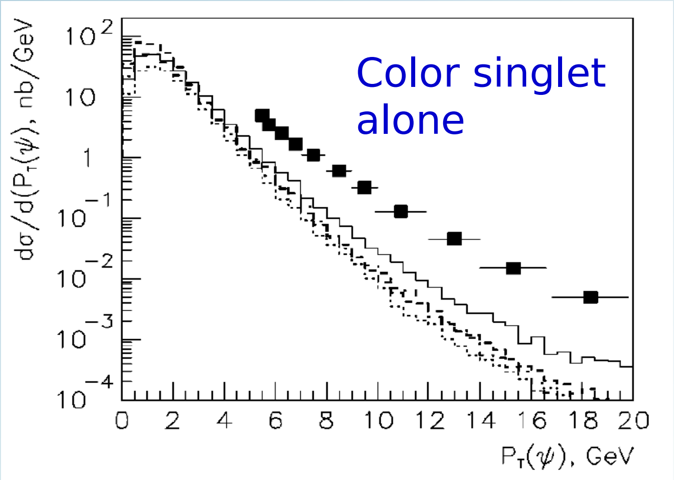
M. Butenschoen, B.Kniehl, Phys.Rev.Lett. 108 (2012) 172002

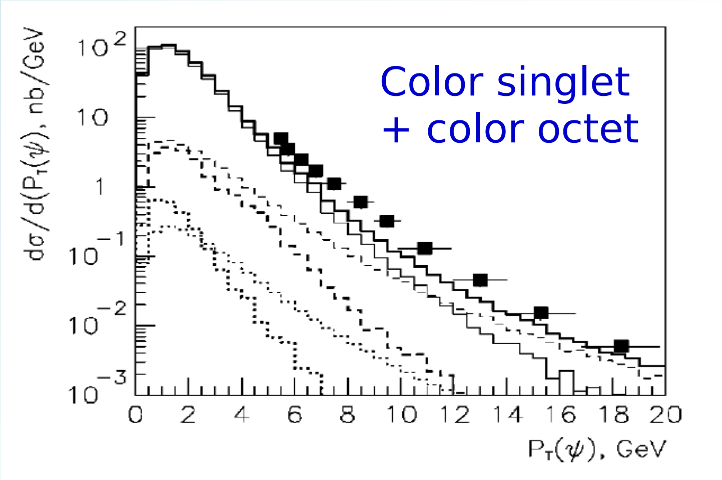
Kt - factorisation

- Meson pT-shapes – at LO highly sensitive to incoming parton kT
- kT-factorisation approach: based on unintegrated distributions of partons with non-zero kT and off-shell matrix elements from pQCD
- May be combined with NRQCD picture of meson wave function and color octet mechanism or rely upon the color singlet assumption
- Not fully clear picture: Tevatron data seem to require color octet, LHC data were described with color singlet alone

Kt-factorisation – glimpse of results

Tevatron, 2002





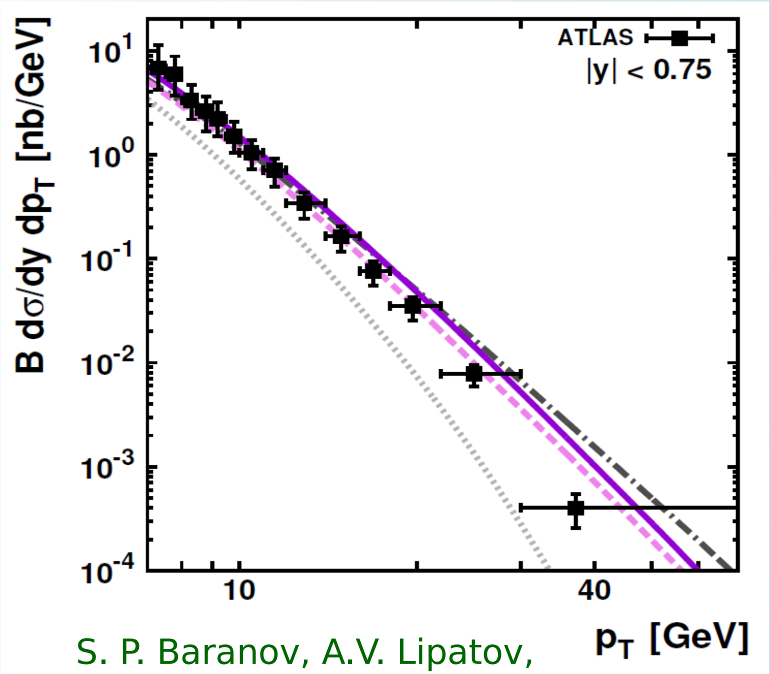
S. P. Baranov, PHYSICAL REVIEW D 66, 114003, 2002

LHC data are well described in kT factorisation with singlet alone (however some problems with chi to J/psi ratios)

Tevatron data required large octet contribution

In meantime: improvements of the unintegrated gluon density→ unclear picture

LHC, 2011



S. P. Baranov, A.V. Lipatov, N.P. Zotov, 2011

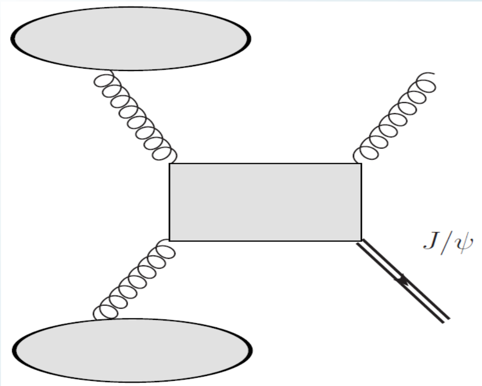
Potentially important color singlet rescattering

Importance of rescattering in VM hadroproduction stressed by Khoze, Martin, Ryskin and Stirling (2004)

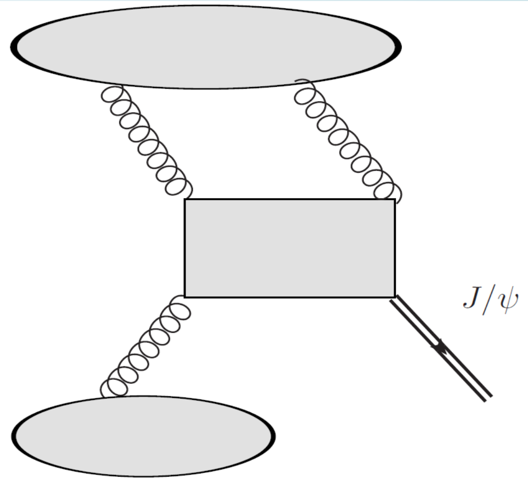
Motivation:

- Matrix elements at the same order of pQCD as the other contributions
- Large double gluon density involved
- Large hadron collision energy → small x of incoming gluons → double density / single density >> 1: enhancement
- However: double gluon density → twist 4 → power suppression with process scale (transverse mass)
- KMRS results: very encouraging, but leaving quite some space for detailed calculations
- **Recent calculation within CGC: Qing Ma, Venugopalan**

- Standard color singlet: gluon emission

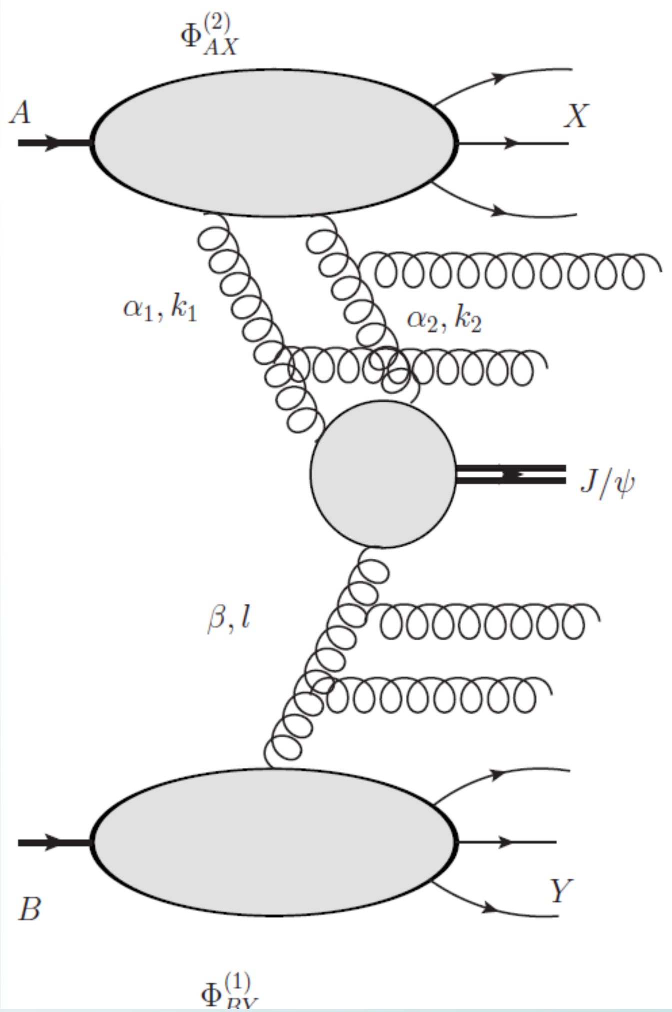


- Singlet rescattering: double gluon



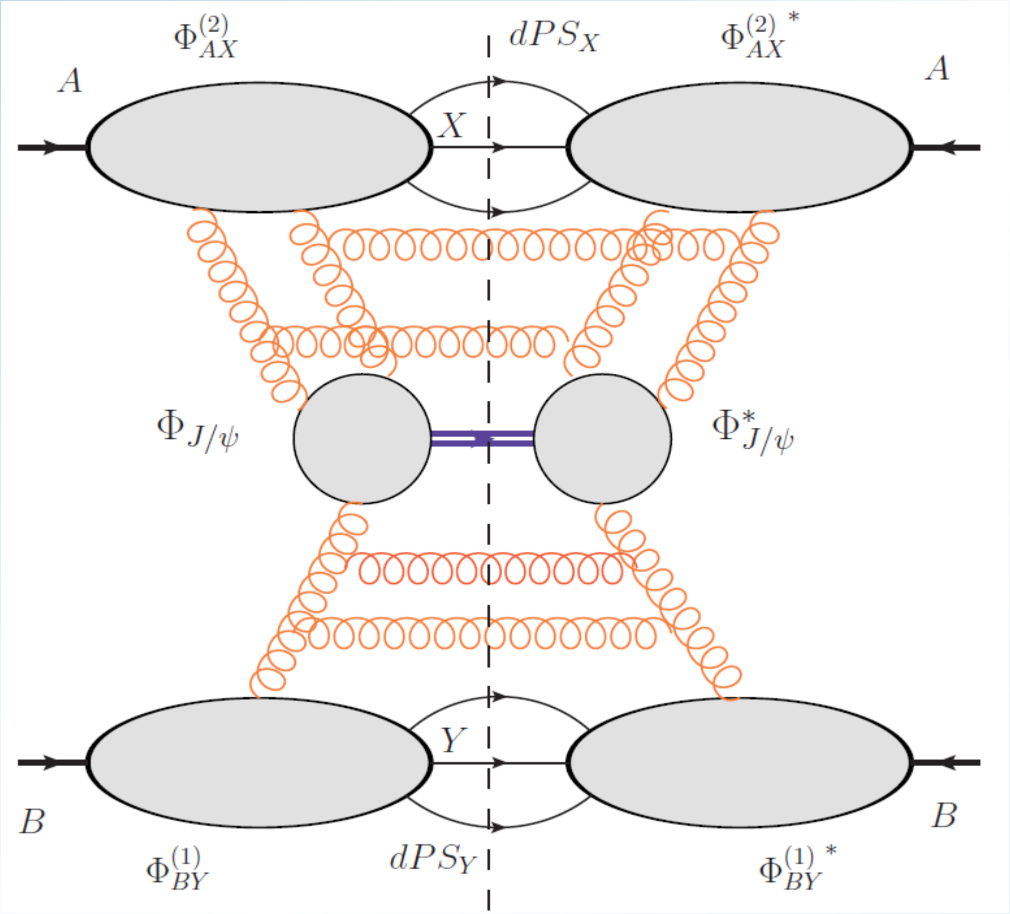
Our computation of high energy amplitude: Ingredients

- High energy factorisation
- Single and double unintegrated gluon distributions emerge
- Off-shell 3g → J/ψ (3 → 1 particle) matrix element (not leading to F partonic cross-section!)
- Impact parameter dependence in double gluon distribution is crucial

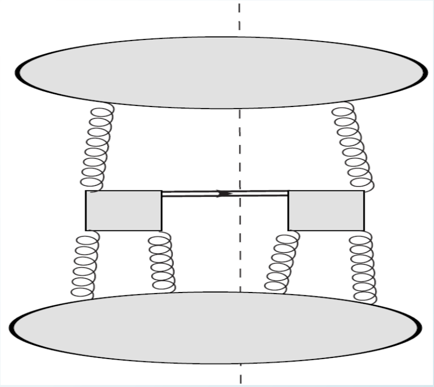


Cross-section and interference

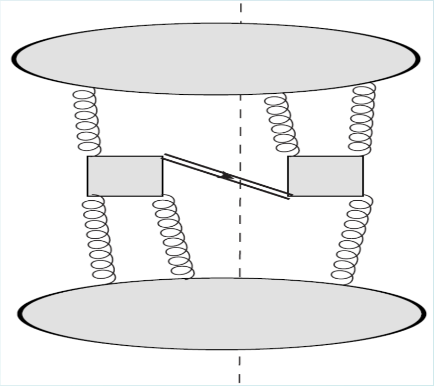
- Leading contribution: 2 and 4 gluon t-channel states



- Also leading: fliped diagram
  - incoherrent sum



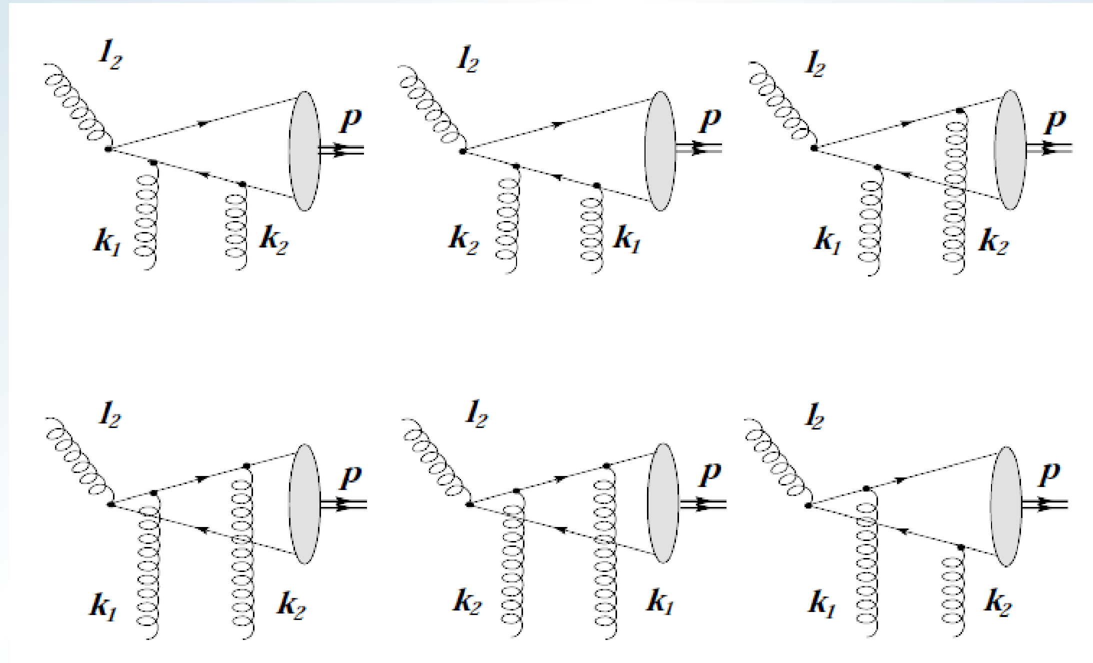
- Interference term: subleading 3 gluon t-channel evolution, may be neglected



3 gluon → J/ψ vertex

Impact factor:
already known

$$\int d\beta_{k_1} \mathcal{S}^{\lambda_2\kappa_1\kappa_2}_{\mu_2'\nu_1'\nu_2'}(J/\psi)\frac{p_A^{\mu_2'}p_B^{\nu_1'}p_B^{\nu_2'}}{s}$$

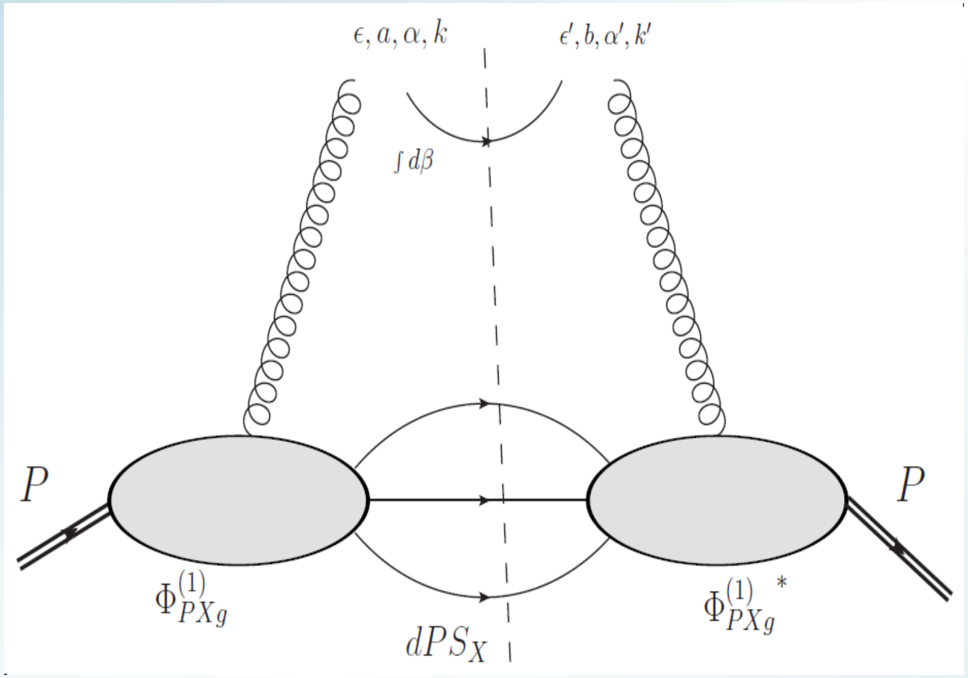


[Bzdak, Cudell, Motyka, Szymanowski]

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

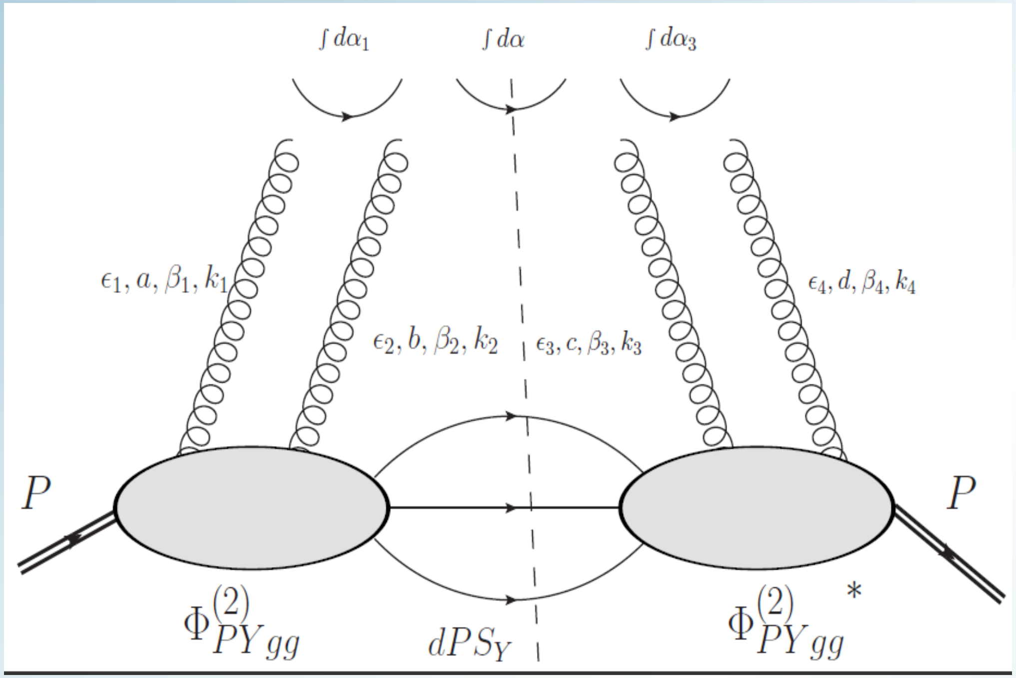
Unintegrated gluon distribution

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



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

Four gluon amplitude in proton



- 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

$$\int [d\alpha_i]\, \Phi^{a_1a_2a_3a_4}_{4,p}(\{\alpha_i\}, \{\beta_i\}, \{\boldsymbol{k}_i\}) \sim G_4(\beta; \beta_1, \beta_3; \boldsymbol{q}, \boldsymbol{k}_1, \boldsymbol{k}_3)$$

Double gluon distribution: factorized approximation

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

$$G_4(\{\beta_i\},\{k_i\}) \longrightarrow f(\beta_1,\beta-\beta_1;\boldsymbol{k}_1,\boldsymbol{q}-\boldsymbol{k}_1)\delta^{a_1a_3} f(\beta_2,-\beta-\beta_2;\boldsymbol{k}_2,-\boldsymbol{q}-\boldsymbol{k}_2)\delta^{a_2a_4}$$

$$\longrightarrow f^{\text{off}}(\beta_1,\beta;\boldsymbol{k}_1)\tilde{S}(\boldsymbol{q})\delta^{a_1a_3} f^{\text{off}}(\beta_2,-\beta;\boldsymbol{k}_2)\tilde{S}(\boldsymbol{-q})\delta^{a_2a_4}$$

$$\longrightarrow f^{\text{off}}(\beta_1,\beta;\boldsymbol{k}_1)S(\boldsymbol{b}_1-\boldsymbol{b})\delta^{a_1a_3} f^{\text{off}}(\beta_2,-\beta;\boldsymbol{k}_2)S(\boldsymbol{b}_2-\boldsymbol{b})\delta^{a_2a_4}$$

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

$$\int d\alpha_i \Phi_{4,p}^{a_1a_2a_3a_4}(\{\alpha_i\},\{\beta_i\},\{\boldsymbol{k}_i\}) = \mathcal{N}\Big[\delta^{a_1a_2}\delta^{a_3a_4} f(\beta_1,\beta_2;\boldsymbol{k}_1)\tilde{S}(\boldsymbol{k}_1-\boldsymbol{k}_2) f(\beta_2,\beta_4,\boldsymbol{k}_3)\tilde{S}(\boldsymbol{k}_3-\boldsymbol{k}_4)$$

$$+\delta^{a_1a_3}\delta^{a_2a_4} f(\beta_1,\beta_3;\boldsymbol{k}_1)\tilde{S}(\boldsymbol{k}_1-\boldsymbol{k}_3) f(\beta_2,\beta_4,\boldsymbol{k}_2)\tilde{S}(\boldsymbol{k}_2-\boldsymbol{k}_4)$$

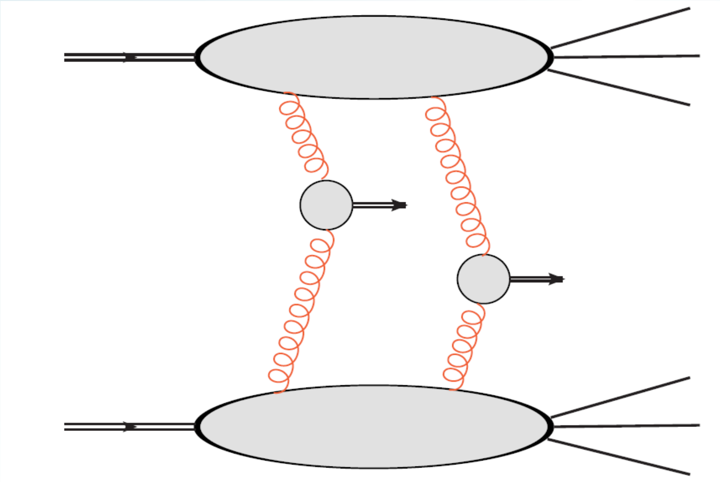
$$+\delta^{a_1a_4}\delta^{a_2a_3} f(\beta_1,\beta_4;\boldsymbol{k}_1)\tilde{S}(\boldsymbol{k}_1-\boldsymbol{k}_4) f(\beta_2,\beta_3,\boldsymbol{k}_2)\tilde{S}(\boldsymbol{k}_2-\boldsymbol{k}_3)$$

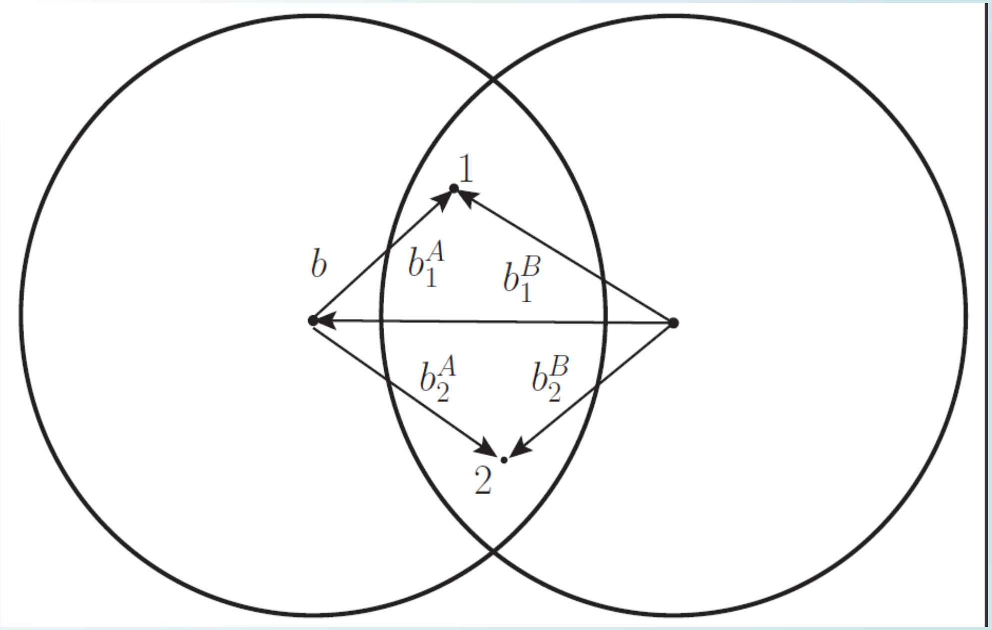
Determining the normalisation

- 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

$$d\sigma_d = g(\alpha_1,\mu^2)g(\beta_1,\mu^2)\,d\hat{\sigma}_1(\alpha_1,\beta_1)\;g(\alpha_2,\mu^2)g(\beta_2,\mu^2)\,d\hat{\sigma}_2(\alpha_2,\beta_2)$$
$$\times\int d^2\boldsymbol{b}\,d^2\boldsymbol{b}_1^A\,d^2\boldsymbol{b}_2^A\,S(\boldsymbol{b}_1^A)S(\boldsymbol{b}-\boldsymbol{b}_1^A)S(\boldsymbol{b}_2^A)S(\boldsymbol{b}-\boldsymbol{b}_2^A)$$

$$d\sigma_d = \frac{d\sigma_1 d\sigma_2}{\sigma_{\rm eff}}$$





Final formula

$$\frac{d^2\sigma_{pp\to J/\psi X}}{dY\,dp_\perp^2} = \mathcal{N}\alpha_s^3 R_{\mathrm{sh}}^2 \int d^2\boldsymbol{k}\,d^2\boldsymbol{k}_1 \frac{f(\beta,\boldsymbol{p}-\boldsymbol{k})f(\alpha,\boldsymbol{k}_1)f(\alpha,\boldsymbol{k}-\boldsymbol{k}_1)}{\left[(\boldsymbol{p}-\boldsymbol{k})^2\boldsymbol{k}_1^2(\boldsymbol{k}-\boldsymbol{k}_1)^2\right]^2}$$

$$\times \left|V_{J/\psi}(\alpha,\beta;\boldsymbol{k}_1,\boldsymbol{k}-\boldsymbol{k}_1,\boldsymbol{p}-\boldsymbol{k};\varepsilon)\right|^2 \int d^2\boldsymbol{q}\,\tilde{S}^2(\boldsymbol{q}) + (\alpha\leftrightarrow\beta, p_A\leftrightarrow p_B)$$

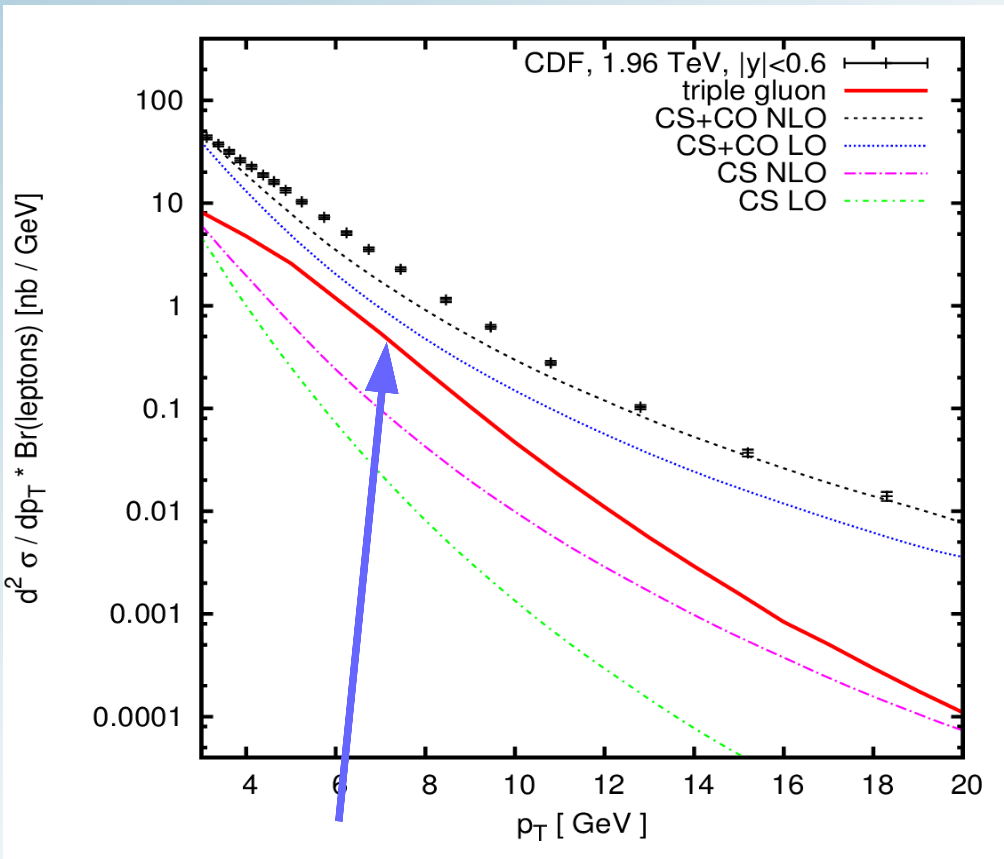
- Leading order in strong coupling constant
- Proportional do square of gluon density
- Power supressed, subleading twist

Calculation details

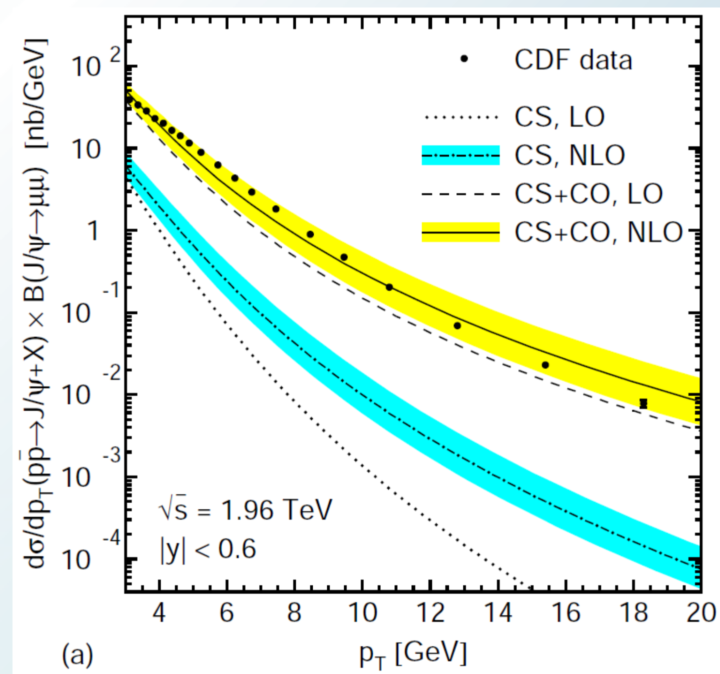
- Unintegrated gluon: KMR procedure with CT10 (NLO) – used for plots and MSTW – similar results
- Off-diagonal gluon densities: inclusion of Shuvaev factors
- $\alpha_s (M_c^2 + k^2)$ - running coupling scale evaluated “locally”
- Quark mass $M_c = M_\psi / 2$
- Impact parameter size for double parton density
  $R \sim 1.7$ / GeV → $\sigma_{eff} = 15$ mb

Results for J/ψ: Tevatron

Rescattering contribution: (new)

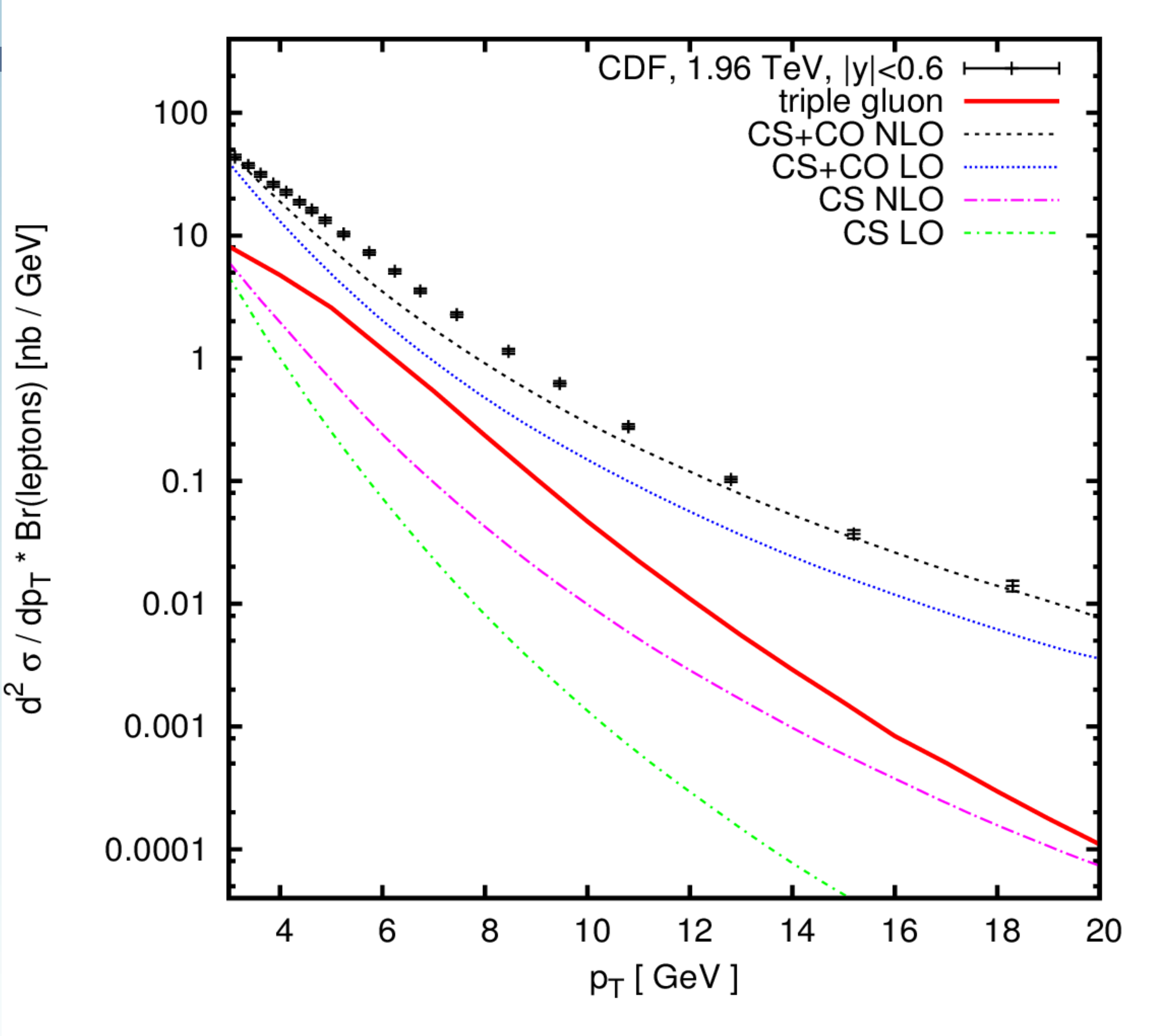


Reference: for COM at NLO
M. Butenschoen and B. Kniehl,
Phys. Rev. D84 (2011) 051501



- **Color singlet rescattering may make up to 25%** of the 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

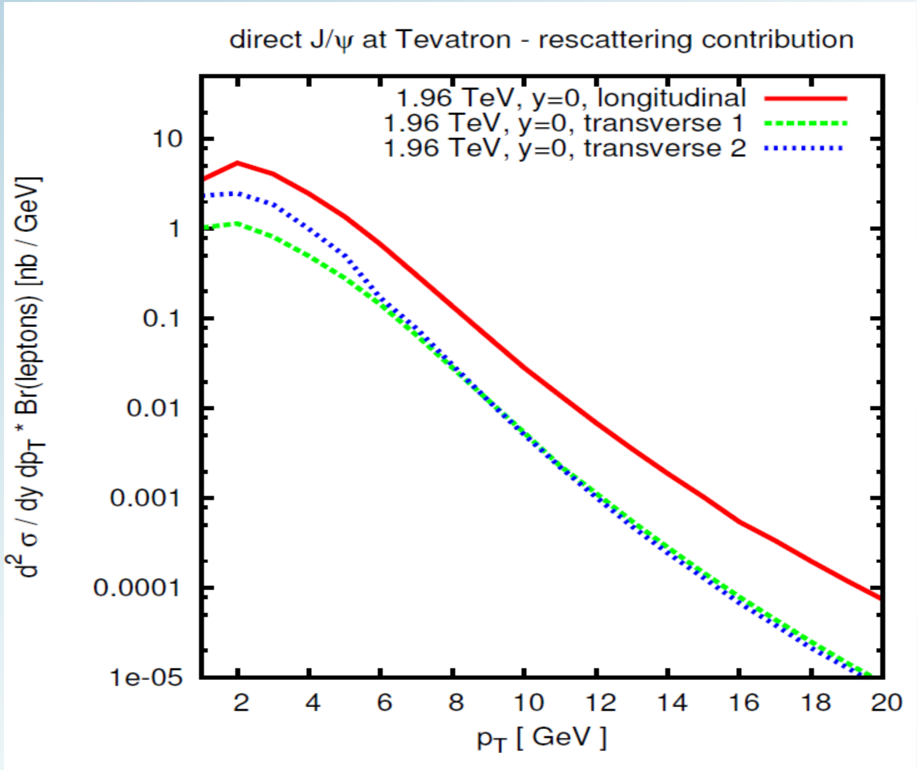
Results for J/ψ: Tevatron (zoom)

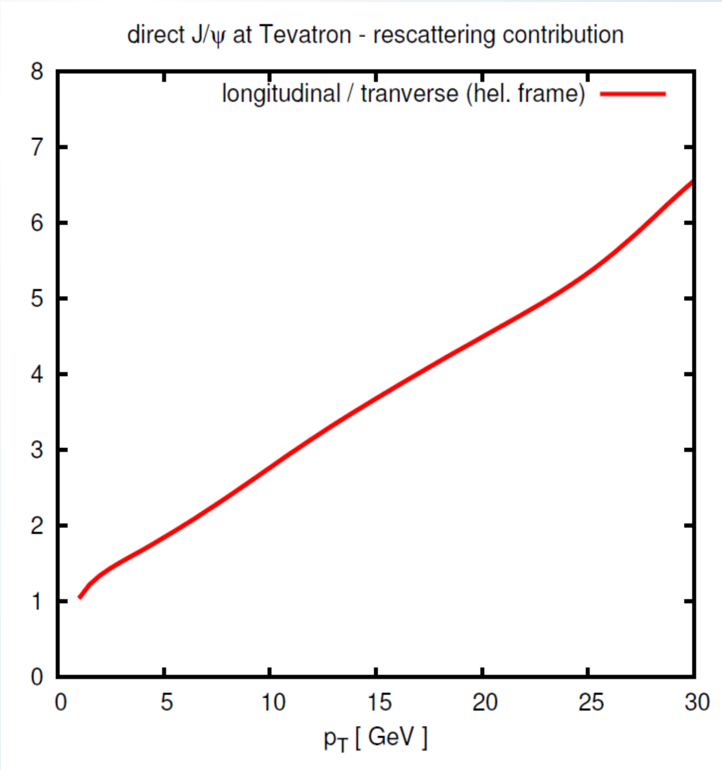


Results: polarisation at Tevatron (helicity frame)

Polarised components

Longitudinal / Transverse

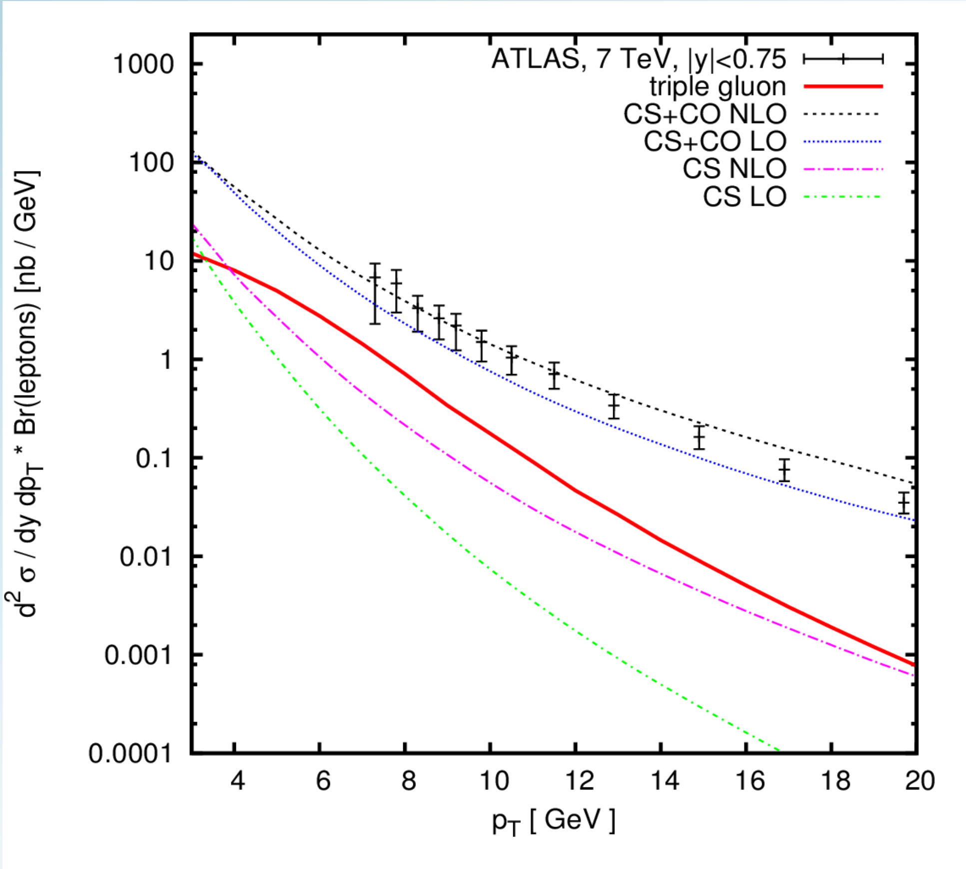




Dominance of longitudinal component grows with pT

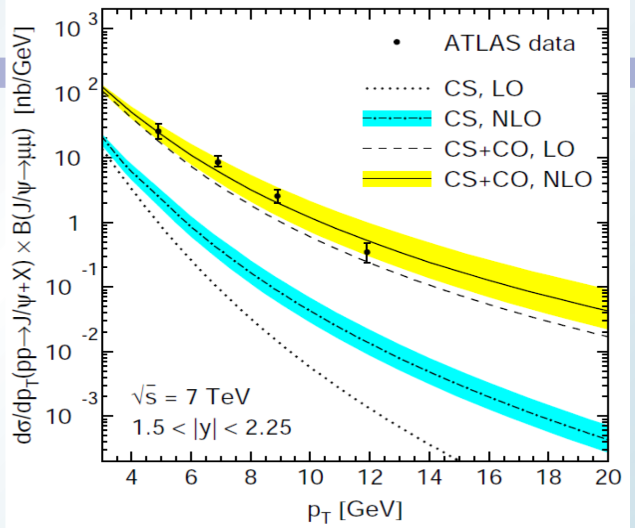
Results for J/ψ: LHC run 1

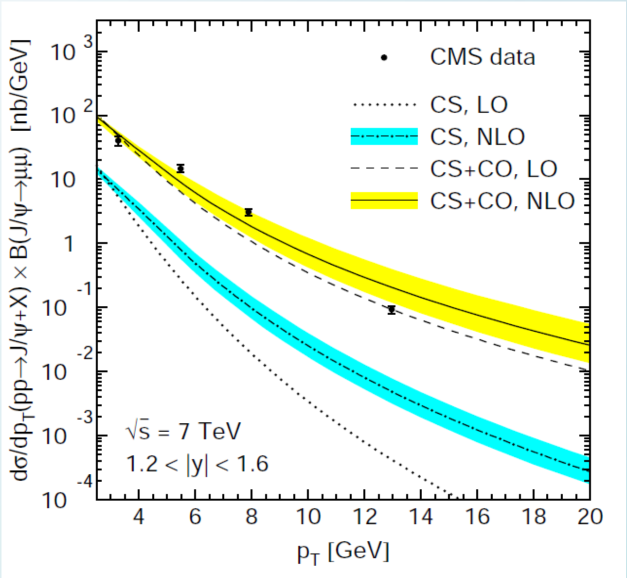
Color singlet rescattering comtribution (new)



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

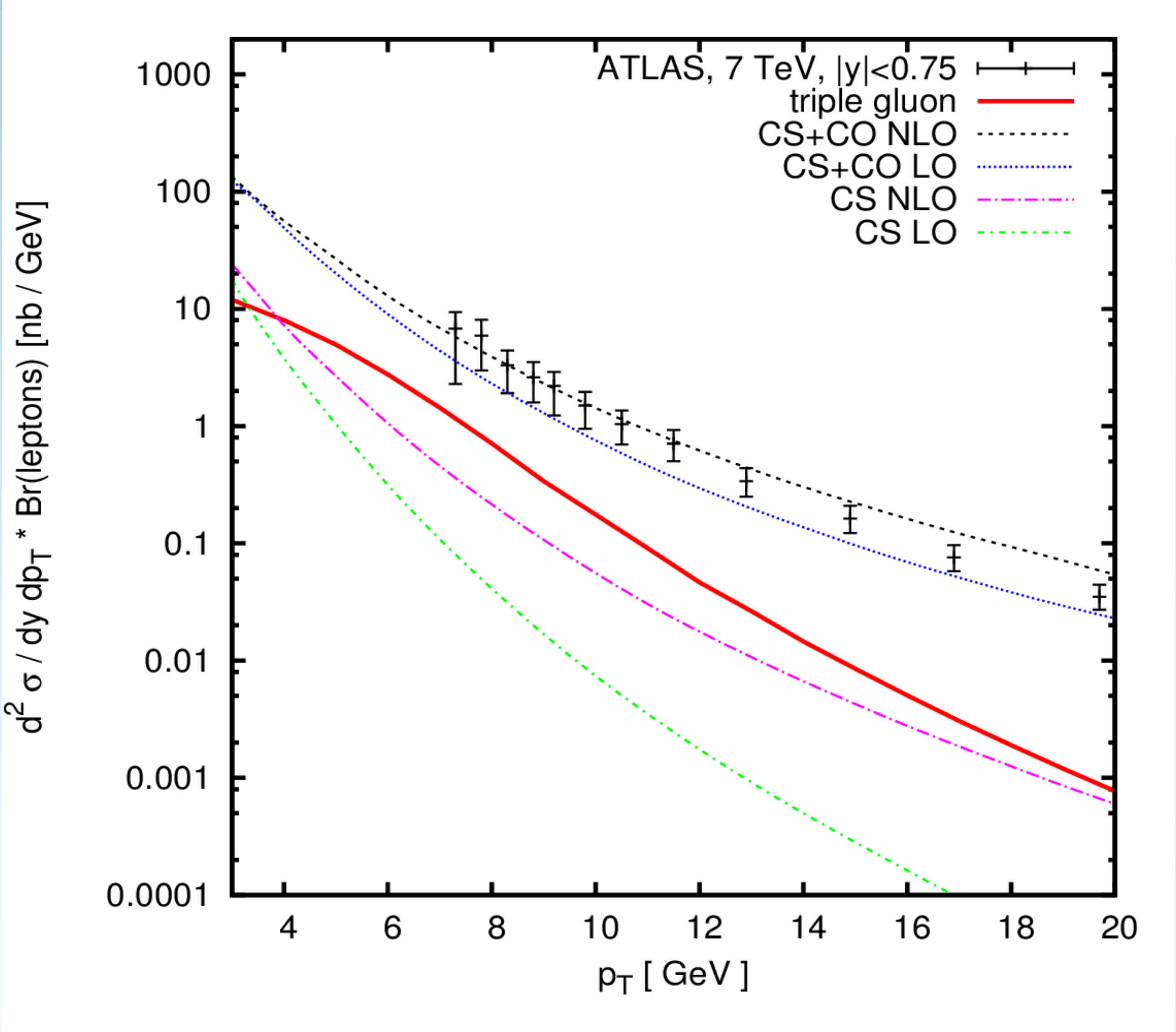
NLO COM Reference





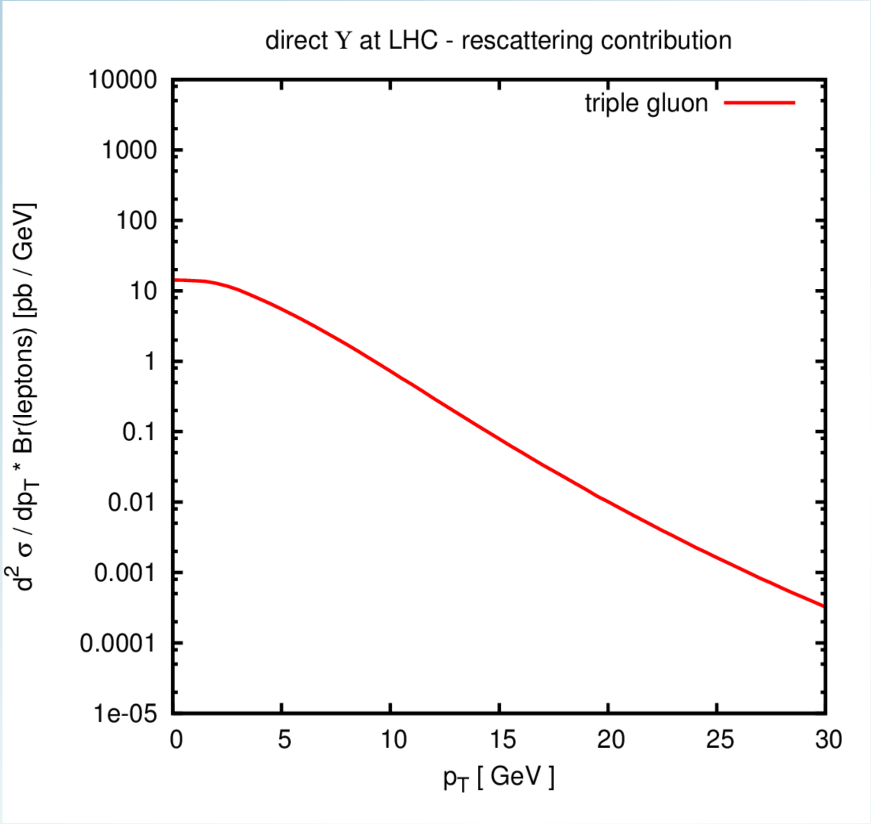
M. Butenschoen and B. Kniehl, Phys. Rev. D84 (2011) 051501

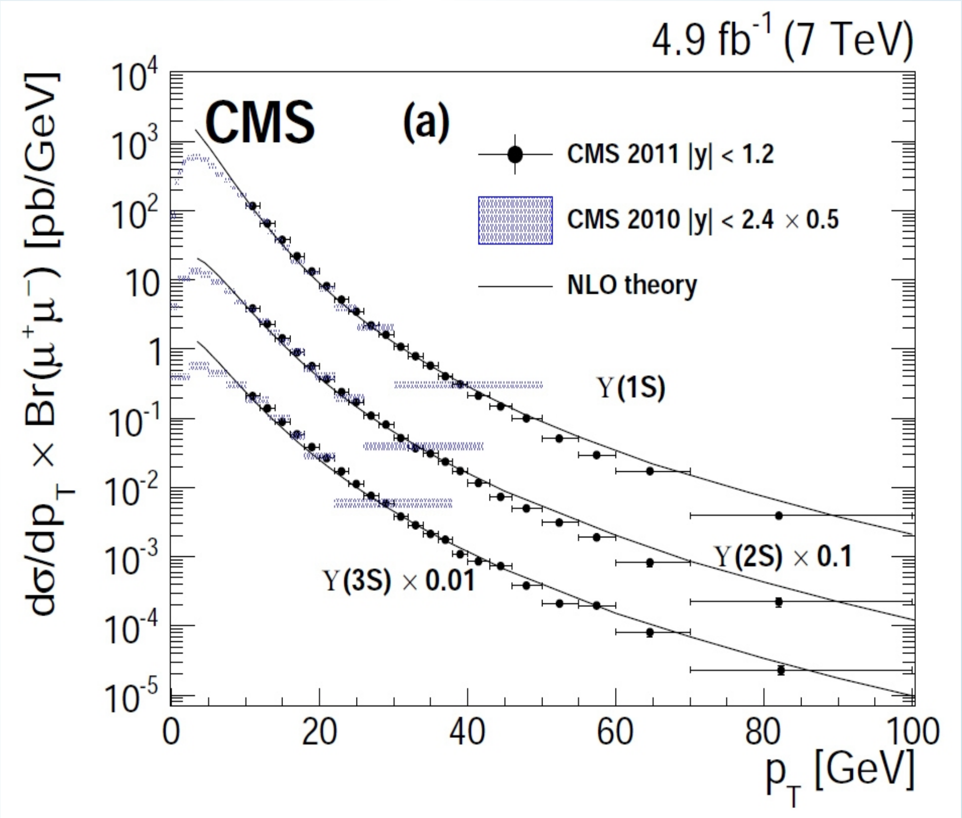
Results for J/ψ: LHC run 1 (zoom)



Results for Υ: LHC run 1

Color singlet rescattering comtribution (new)





- For Upsilon(1S) – neglibigle effects of rescattering at the LHC – O(2%) correction – consistent with power suppression of rescattering and larger values of parton x

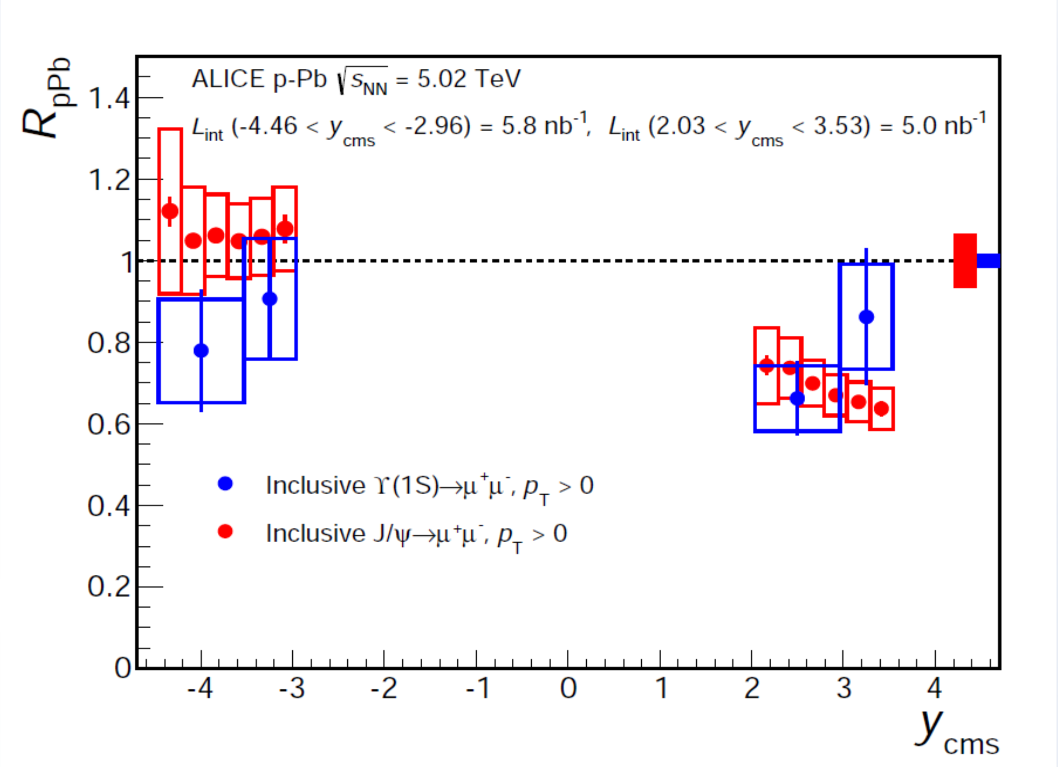
Effects in proton-nucleus collisions for J/ψ and Υ

- Recent ALICE results on quarkonia production:

  (proton – Pb)

  ―――――――――――――

  A * (proton – proton)



- We predict ~10% enhancement in nucleus fragmentation region for J/ψ, no visible effects for Υ →
- Effective anti-shadowing effect in nucleus fragmentation region
- Large ~1 correction in proton fragmentation region → calculation not applicable

Conclusions

- Effects of color singlet rescattering in heavy vector quarkonia hadroproduction were studied in kT-factorisation approach
- The effect is 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

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 naïve leading CS contribution fails badly to describe data, `subleading' effects (color octet, gluon offshellness, rescattering) may be all necessary to describe the data accurately
- 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 → parton level enhancement expected


Thank you!