Quarkonium production
A theoretical status

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Outline

- Introduction
- NRQCD factorization
- Phenomenology of quarkonium production
    - charmonium production at B factories
    - J/ψ production at HERA
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    - J/ψ, $\psi(2S)$ and $\Upsilon(nS)$ hadroproduction
- Conclusion

The different scales in quarkonium production

- creation of a perturbative heavy-quark pair over distances of order $1/m_Q$ or smaller
- typical size of the quarkonium is $1/vm_Q$
- as v is small, these two scales are well separated, the production of the perturbative heavy-quark pair is almost point-like compared to the size of the bound state

charmonium: $v^2 \sim 0.3$ **bottomonium**: $v^2 \sim 0.1$

NRQCD factorization

- Effective Field Theory that separates the high energy scales of order m_Q or higher from the low energy scales $\sim v m_Q$ or smaller, by mean of an expansion in v
- momentum modes below the factorization scale Λ are described by matrix elements of four-fermion operators
- momentum modes above the factorization scale Λ are encoded into short distance coefficients

$$\sigma(ij \to \mathcal{Q} + X) \sim \sum_n \hat{\sigma}_\Lambda(ij \to Q\bar{Q}(n) + X)\langle \mathcal{O}^{\mathcal{Q}}(n)\rangle_\Lambda$$

short distance coefficients

- perturbative expansion in α_s
- infrared safe
- process dependent

long distance matrix elements

- non perturbative effects
- hierarchy in v
- universal

Relation with other models

- Color Singlet Model
  keep only the leading-order color-singlet NRQCD matrix element

- Color Evaporation Model
  can be expressed as the NRQCD matrix elements having a hierarchy according to the orbital angular momentum Bodwin, Braaten, Lee, (2005)

Proof of the factorization

- factorization form conjectured by Bodwin, Braaten and Lepage (1995)
- a complete rigorous proof of factorization does not exist yet. It would involve to demonstrate that, at each order in α_s,
  - all soft singularities cancel or can be absorbed into NRQCD matrix elements,
  - all collinear singularities can be absorbed into parton distributions
- Nayak, Qiu, Sterman (2005, 2006): factorization holds in gluon fragmentation up to NNLO accuracy in α_s, provided that the color-octet NRQCD matrix elements are modified by the inclusion of eikonal lines that make them gauge invariant

Proof of the factorization

- Nayak, Qiu, Sterman (2007): in quarkonium production in association with heavy quarks, NRQCD factorization breaks down at NNLO in α_s due to configuration with color transfer between the active heavy quark and one co-moving passive heavy quark.
- Bodwin, Garcia i Tormo, Lee (2008): proof of the factorization for exclusive quarkonium production
  - factorization holds in B-meson decays to a charmonium plus a light meson up to correction of order m_c/m_b
  - factorization holds in e^+e^- annihilation to two charmonia up to corrections of order m_c^2/s

On a more phenomenological ground:

is the universality of the NRQCD matrix elements validated experimentally ?

Charmonium production at B factories

- exclusive double charmonium production: $e^+e^- \to J/\psi + \eta_c$

Experiment:

Belle: $\sigma[e^+e^- \to J/\psi + \eta_c] \times B_{>2} = 25.6 \pm 2.8 \pm 3.4$ fb.

BABAR: $\sigma[e^+e^- \to J/\psi + \eta_c] \times B_{>2} = 17.6 \pm 2.8^{+1.5}_{-2.1}$ fb.

NRQCD at LO in v and in α_s:

Braaten, Lee (2003): $\sigma[e^+e^- \to J/\psi + \eta_c] = 3.78 \pm 1.26$ fb.

Liu, He, Chao (2003): $\sigma[e^+e^- \to J/\psi + \eta_c] = 5.5$ fb.

- theoretical uncertainties from the values of m_c, α_s, and the NRQCD matrix elements.
- color-singlet transition, NRQCD matrix elements determined from $\eta_c \to \gamma\gamma$ and $J/\psi \to e^+e^-$

similar discrepancies are observed for $\sigma[e^+e^- \to J/\psi + \chi_{c0}]$
$\sigma[e^+e^- \to J/\psi + \eta_c(2S)]$.

Including relativistic and α_s corrections

- correction at NLO in α_s computed by Zhang, Gao, Chao (2005), confirmed by Gong, Wang (2007)
- v^2 correction to the short-distance coefficient computed by Braaten, Lee (2003)
- determination of matrix elements of higher order in v by making use of a potential model (Bodwin, Kang, Lee, 2006)
- Bodwin, Chung, Kang, Kim, Lee, Yu (2006): corrections at NLO in α_s plus relativistic corrections may bring theory into agreement with experiment, confirmed by He, Fan, Chao, (2007)
- new Calculation of $\sigma[e^+e^- \to J/\psi + \eta_c]$ including radiative correction + a resummed class of relativistic corrections + QED contribution, and giving a detailed error analysis (Bodwin, Chung, Kang, Lee, Yu, 2007)

- updated comparison for $e^+e^- \to J/\psi + \eta_c$
  (Bodwin, Chung, Kang, Lee, Yu, 2007)

Theory: $\sigma[e^+e^- \to J/\psi + \eta_c] = 17.6^{+8.1}_{-6.7}$ fb

Belle: $\sigma[e^+e^- \to J/\psi + \eta_c] \times B_{>2} = 25.6 \pm 2.8 \pm 3.4$ fb.

BABAR: $\sigma[e^+e^- \to J/\psi + \eta_c] \times B_{>2} = 17.6 \pm 2.8^{+1.5}_{-2.1}$ fb.

- calculation of the α_s correction to $\sigma[e^+e^- \to J/\psi + \chi_{c0}]$
  (Zhang, Ma, Chao, 2008) shows that large K factor may bring the theory in agreement with the data

- inclusive J/ψ production $e^+e^- \to J/\psi + X$

Experiment: (Belle Collaboration, 2009)

$$\sigma(e^+e^- \to J/\psi + c\bar{c}) = 0.74 \pm 0.08^{+0.09}_{-0.08}\ \text{pb}$$

$$\sigma(e^+e^- \to J/\psi + X_{\text{non-}c\bar{c}}) = 0.43 \pm 0.09 \pm 0.09\ \text{pb}$$

NRQCD prediction (LO in α_s)

$$\sigma(e^+e^- \to J/\psi + c\bar{c} + X)/\sigma(e^+e^- \to J/\psi + X) \approx 0.1$$

Corrections of higher order in α_s and v

- Zhang, Chao (2007): NLO calculation of $\sigma[J/\psi + c\bar{c}]$ leads to a large K factor

$$\sigma(e^+e^- \to J/\psi + c\bar{c} + X) = 0.53^{+0.59}_{-0.23}\ \text{pb.}\ (\mu = \sqrt{s}/2)$$

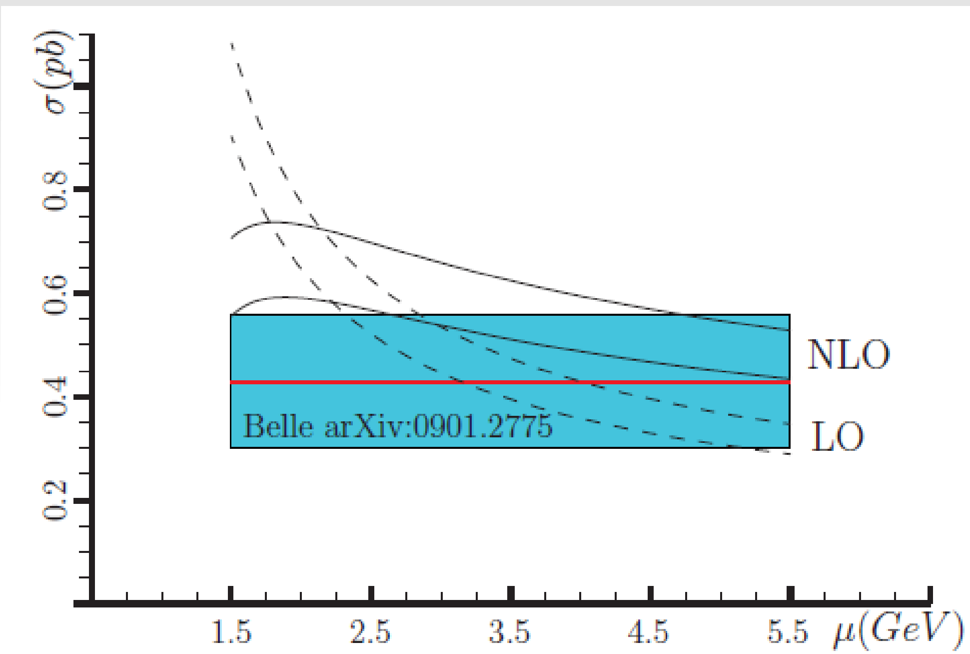
- He, Fan, Chao (2007): v^2 correction to $\sigma[J/\psi + c\bar{c}]$ is negligible

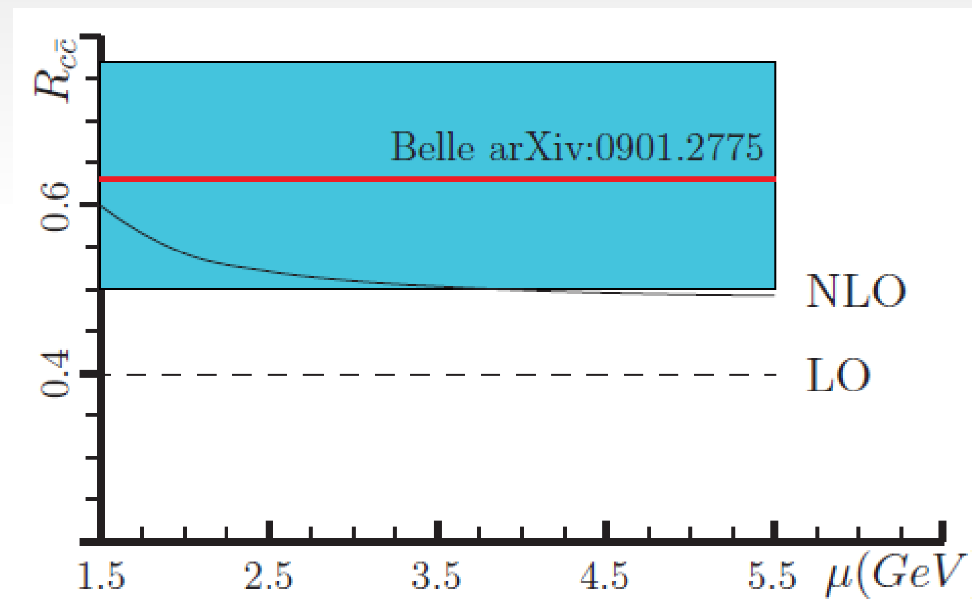
- Nayak, Qiu, Sterman (2007): at NNLO in α_s, color transfer between the active and a co-moving passive charm quark can lead to a non-perturbative enhancement

- Zhang, Ma, Chao (2008): color-octet contribution at NLO in α_s

$$\sigma(e^+e^- \to J/\psi^{(8)} + g) = 0.586\ \text{pb (LO,}\ \mu = 2m_c)$$
$$\sigma(e^+e^- \to J/\psi^{(8)} + g) = 1.19\ \text{pb (NLO,}\ \mu = 2m_c)$$

- Ma, Zhang, Chao (2009): NLO correction to the color-singlet process $e^+e^- \rightarrow J/\psi + gg$



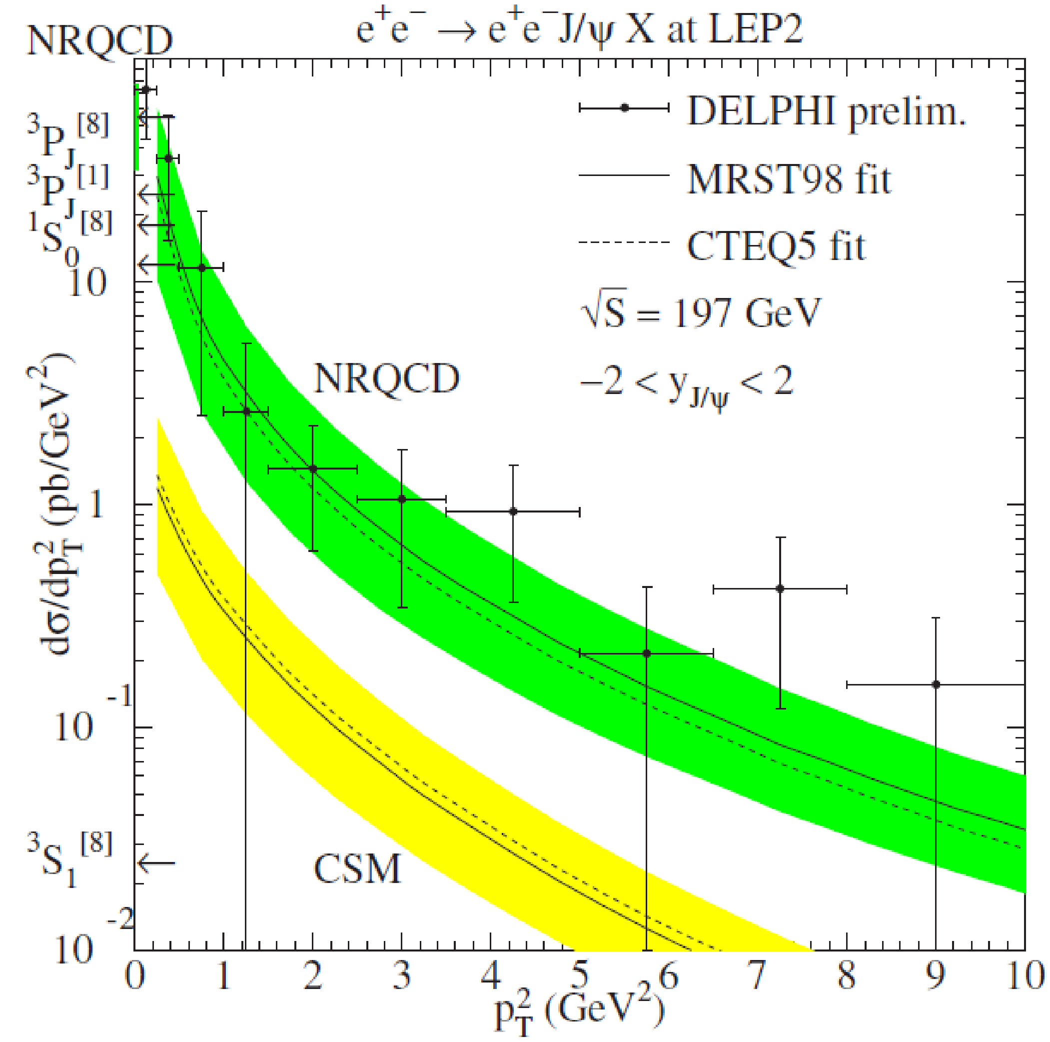


Under the assumption that color octet contribution can be ignored, the ratio

$$R_{c\bar{c}} = \sigma[J/\psi + c\bar{c}]/(\sigma[J/\psi + c\bar{c}] + \sigma[J/\psi + gg])$$

computed at NLO in α_s is in agreement with the Belle measurement

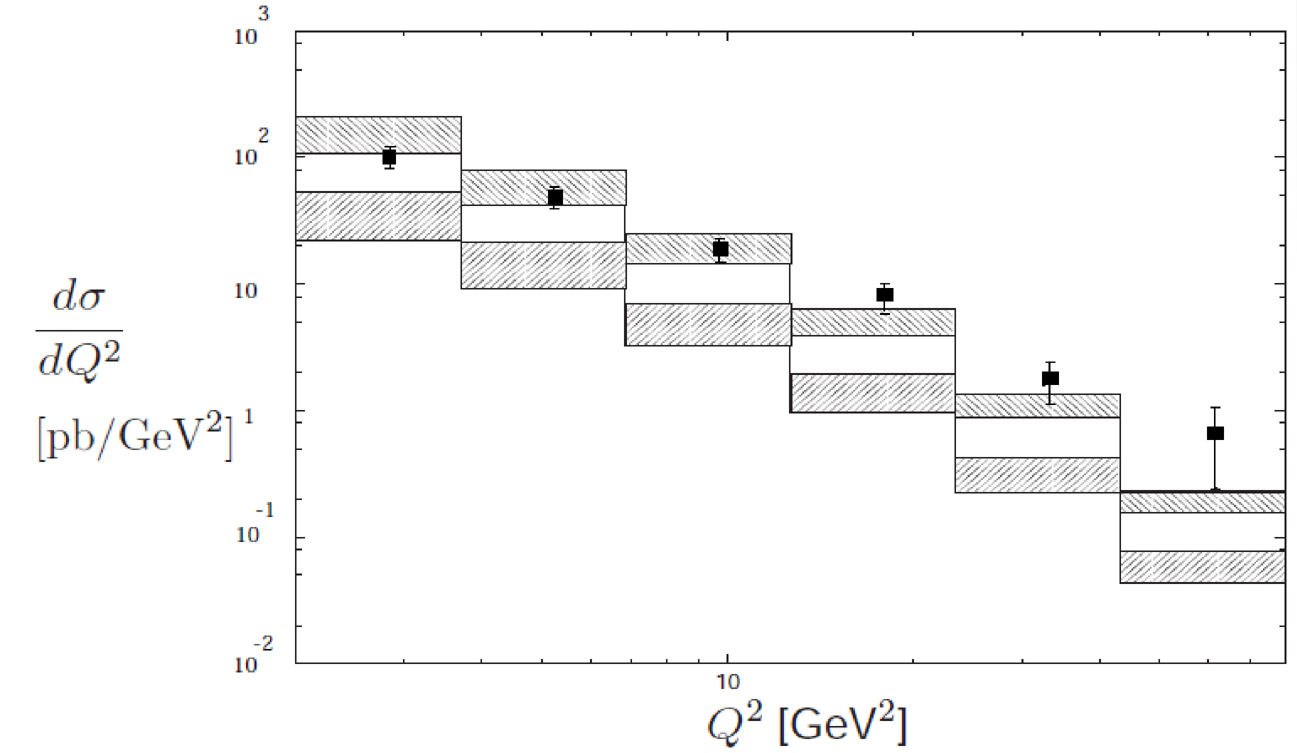
J/ψ photo-production at LEP



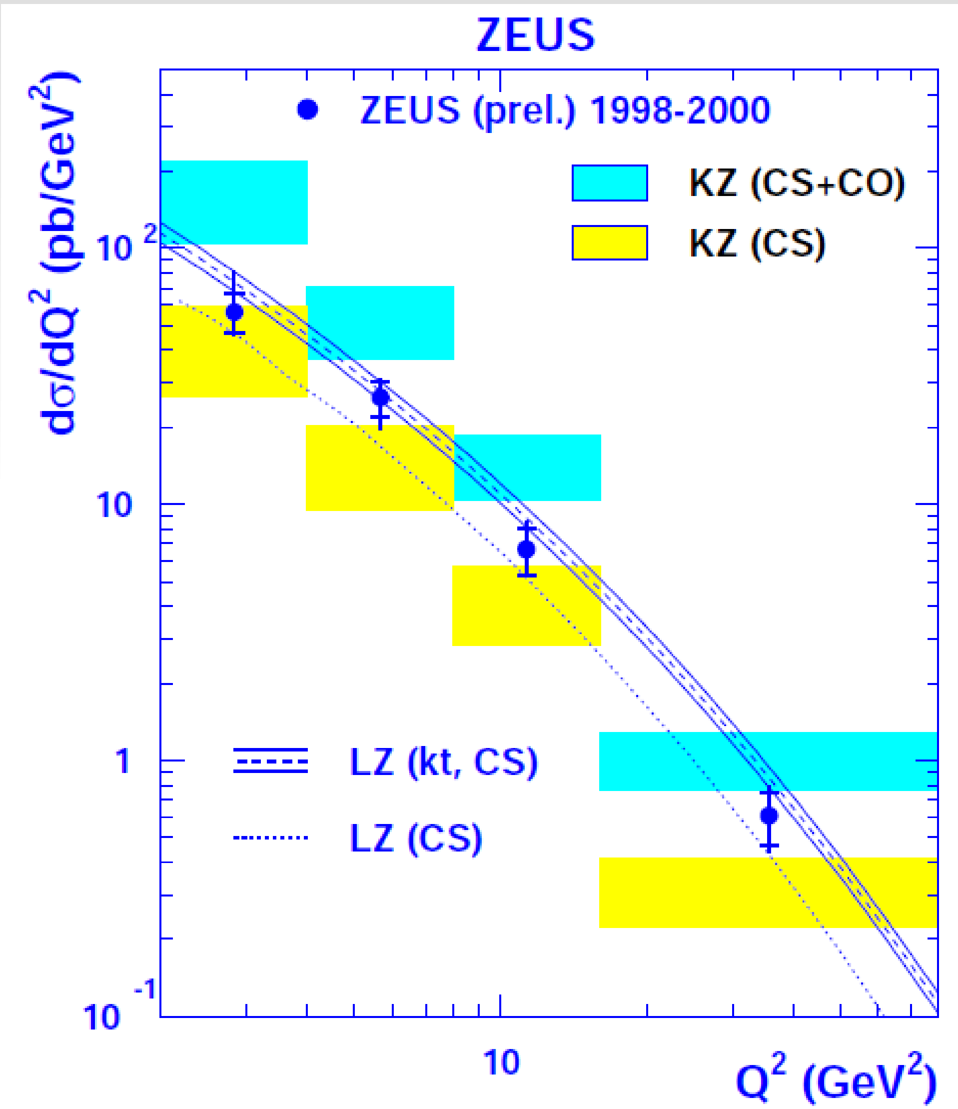
- color-octet matrix elements extracted from Tevatron data
- prediction at LO in α_s (!)
- Delphi data favors NRQCD over the Color Singlet Model (Klasen, Kniehl, Mihaila, Steinhauser, 2001)
- large uncertainties from the variation of the scales

J/ψ production in DIS at HERA

- α_s LO predictions, based on the color-octet matrix elements extracted at the Tevatron (Kniehl, Zwirner, 2001)

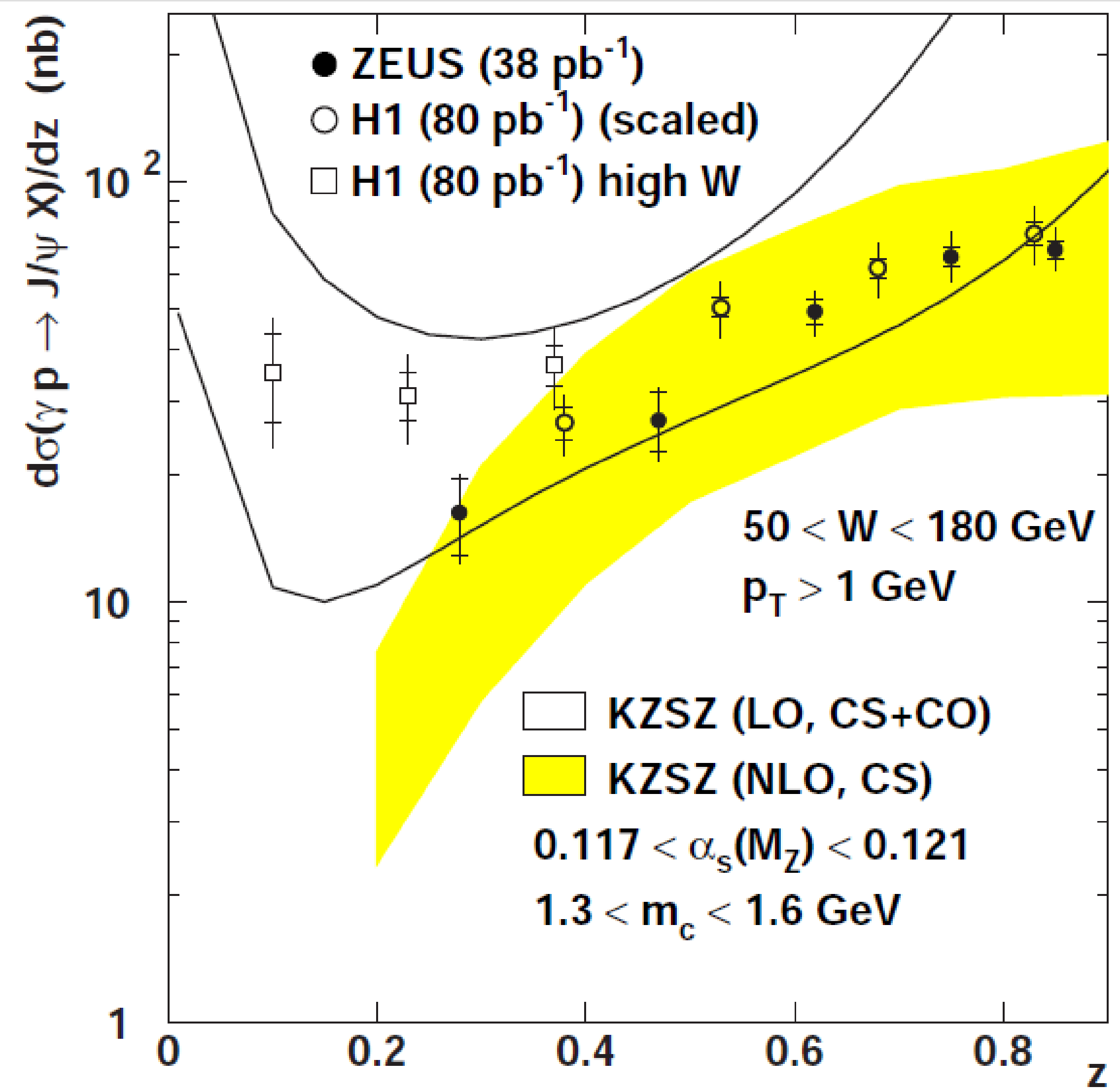


H1 data as a function of Q^2 favor NRQCD prediction (upper) over the Color Singlet prediction (lower)



- the comparison with the ZEUS data shows a less good agreement
- the color-singlet yield in the kt factorization approach (Baranov, Zotov) is in good agreement with the data

J/ψ photoproduction at HERA



- LO NRQCD calculations by Cacciari, Krämer (1996); Amundson, Fleming, Maksymyk (1996); Ko, Lee, Song (1996); Kniehl, Krämer (1997)
- The LO color-octet contrib. is strongly peaked at $z = 1$ (resummation is required Beneke, Rothstein, Wise, 97)
- CS at NLO (Krämer, 1996) in agreement with the data, if we set $\mu_{r,f}=m_c/\sqrt{2}$

J/ψ photoproduction at HERA

- the computation of the color-singlet cross section at NLO has been cross-checked by P.A., Campbell, Maltoni, Tramontano (2009) and by Chang, Li, Wang (2009)
- In addition, the **polarization of the color-singlet yield at NLO** accuracy is presented in these works

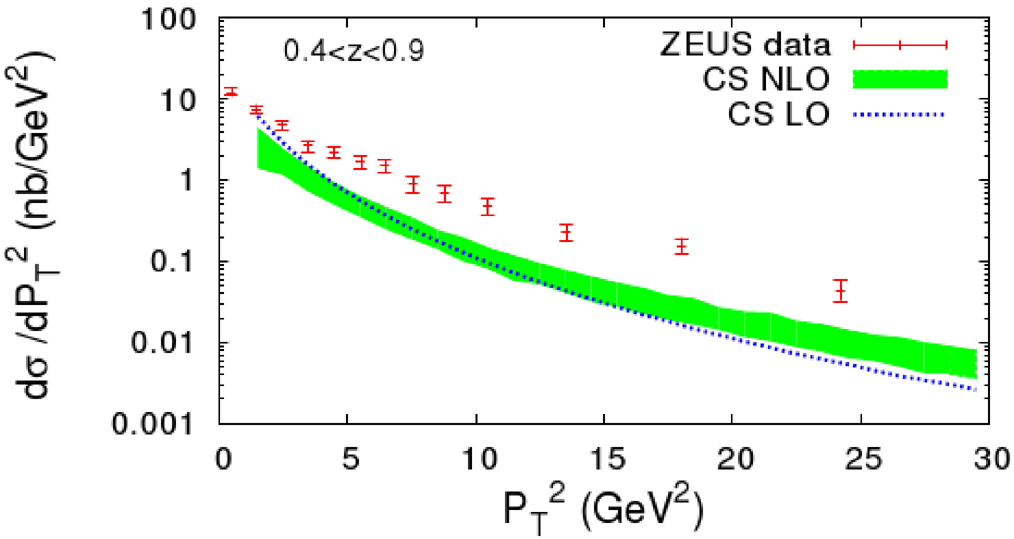
New comparison with data

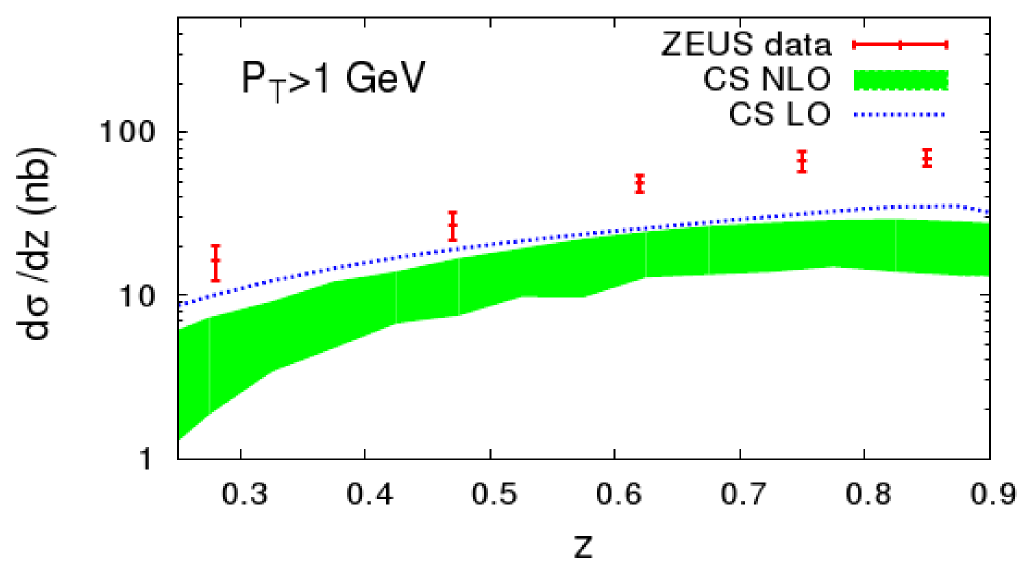
- color-singlet yield at NLO undershoots the data

  mass uncertainty: $1.4\ \mathrm{GeV} < m_c < 1.6\ \mathrm{GeV}$

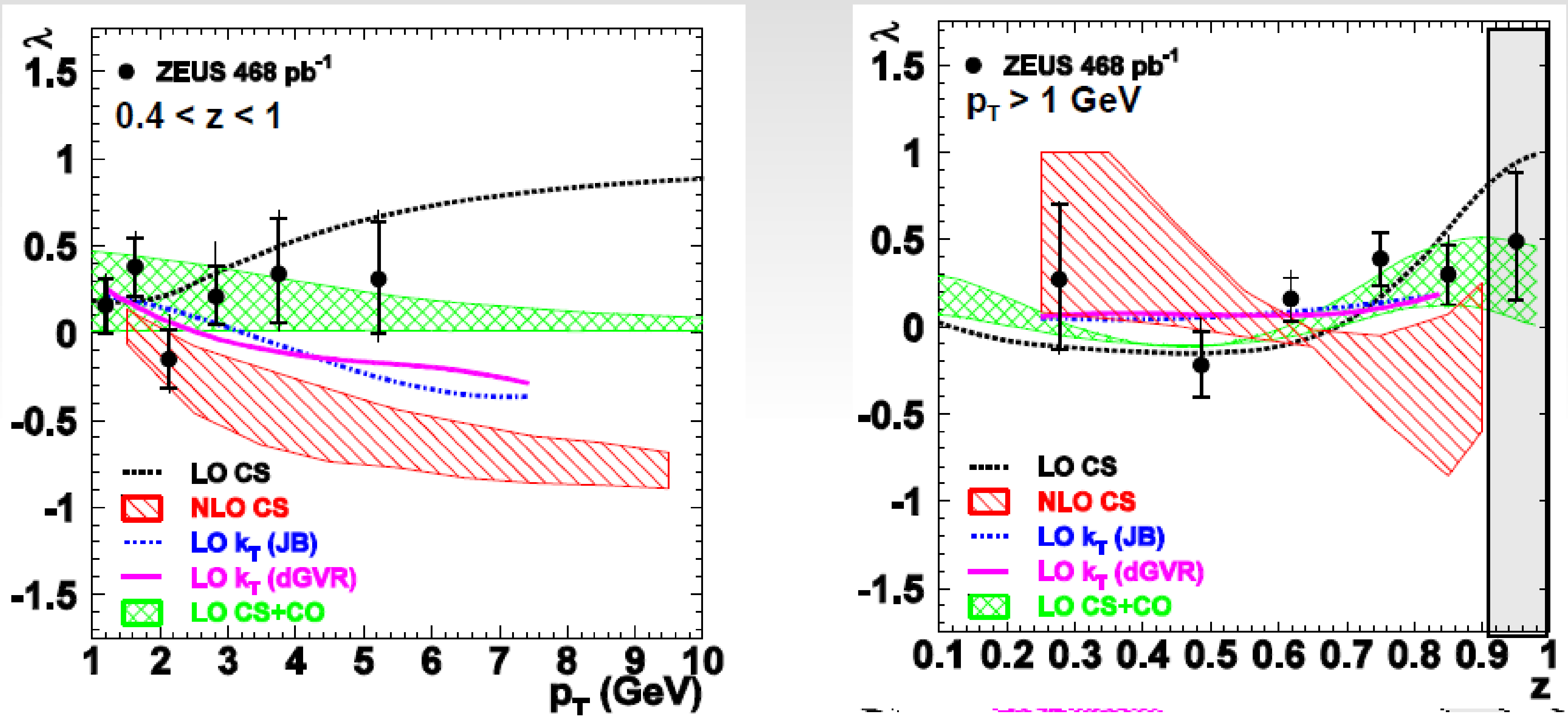
  scale uncertainty:

$$\mu_0 = 4m_c, \quad 0.5\mu_0 < \mu_r, \mu_f < 2\mu_0, \quad 0.5 < \frac{\mu_r}{\mu_f} < 2$$





CS polarization at NLO

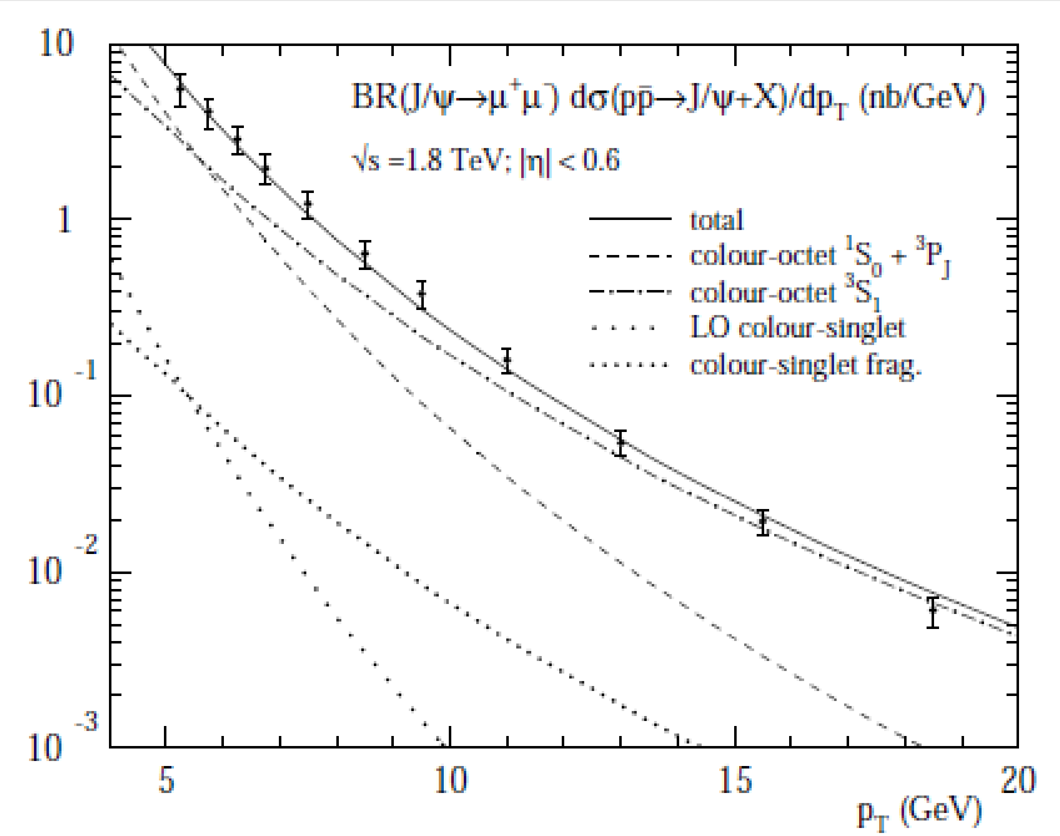


- Uncertainty band resulting from the variation of the scales:

$$\mu_0 = 4m_c, \quad 0.5\mu_0 < \mu_r, \mu_f < 2\mu_0, \quad 0.5 < \frac{\mu_r}{\mu_f} < 2$$

- large theoretical uncertainties in the region close to $P_T = 1$ GeV
- NLO color-singlet prediction for λ is not supported by the ZEUS prel. data

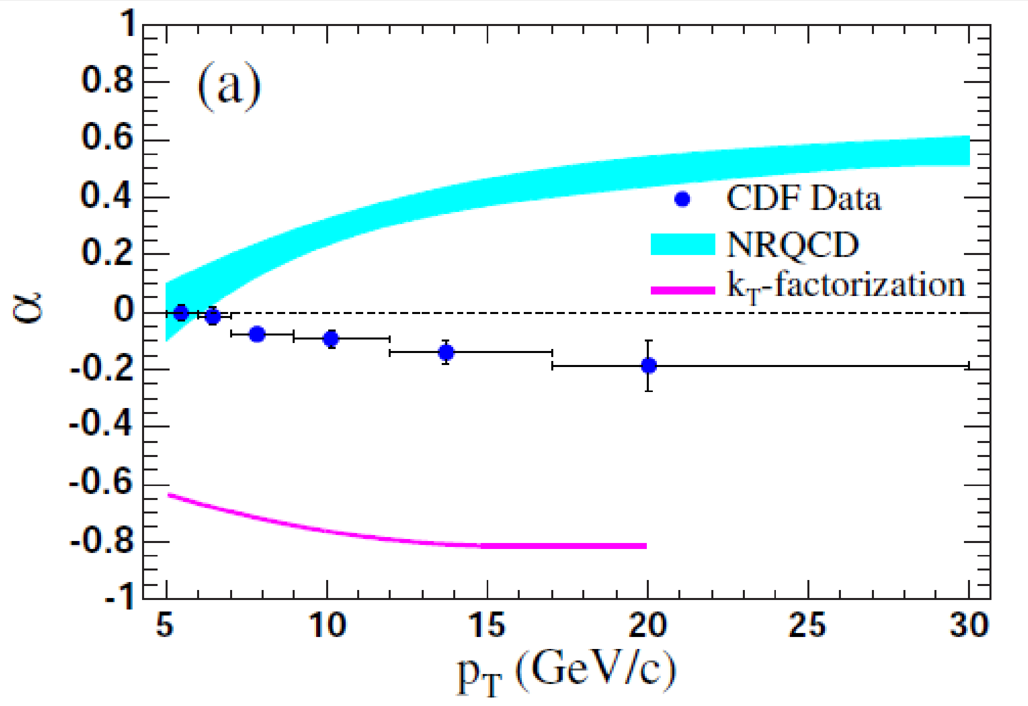
J/ψ production at the Tevatron



Kramer, 2001

- Color-singlet yield at LO in α_s undershoots the data by two orders of magnitude
- Color-singlet fragmentation channels improve the PT shape, but the normalization is still wrong
- Color-octet channels seem needed to explain the observed spectrum.

J/ψ polarization



CDF collaboration (2007)
NRQCD curve: Braaten, Kniehl (2000)
kt factorization curve: Baranov (2002)

At large PT:

- gluon fragmentation via a color-octet $^3S_1$ transition dominates
- the gluon is nearly real, and hence has a transverse helicity
- the gluon polarization is transfered to the J/ψ up to v^2 correction → expect a transverse helicity for the J/ψ (Cho, Wise, 1994)
- not seen in the CDF data

$\psi(nS)$, $\Upsilon(nS)$ hadroproduction

- **corrections of higher order in α_s**

• color-singlet $pp \to J/\psi + X$ at NLO
Campbell, Maltoni, Tramontano (2007), PA, Maltoni, Lansberg (2007), Gong, Wang (2008)

• color-octet $pp \to J/\psi + X$ at NLO (S-wave only)
Gong, Wang (2009) no substantial enhancement

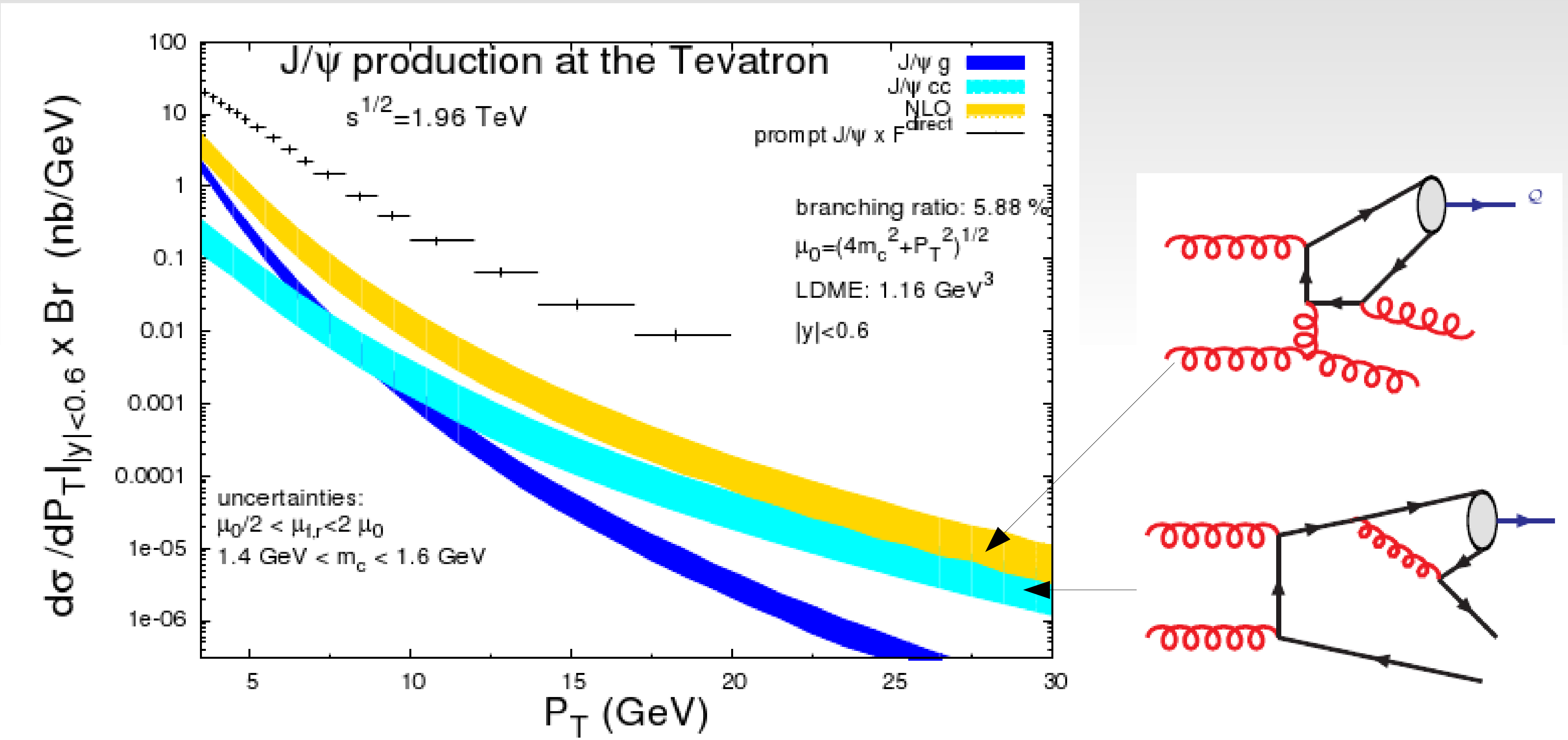
• prediction in the kt factorization approach Baranov, Zotov

• s-channel cut contribution Lansberg, Cudell, Kalinovsky (2005)

- **relativistic corrections**

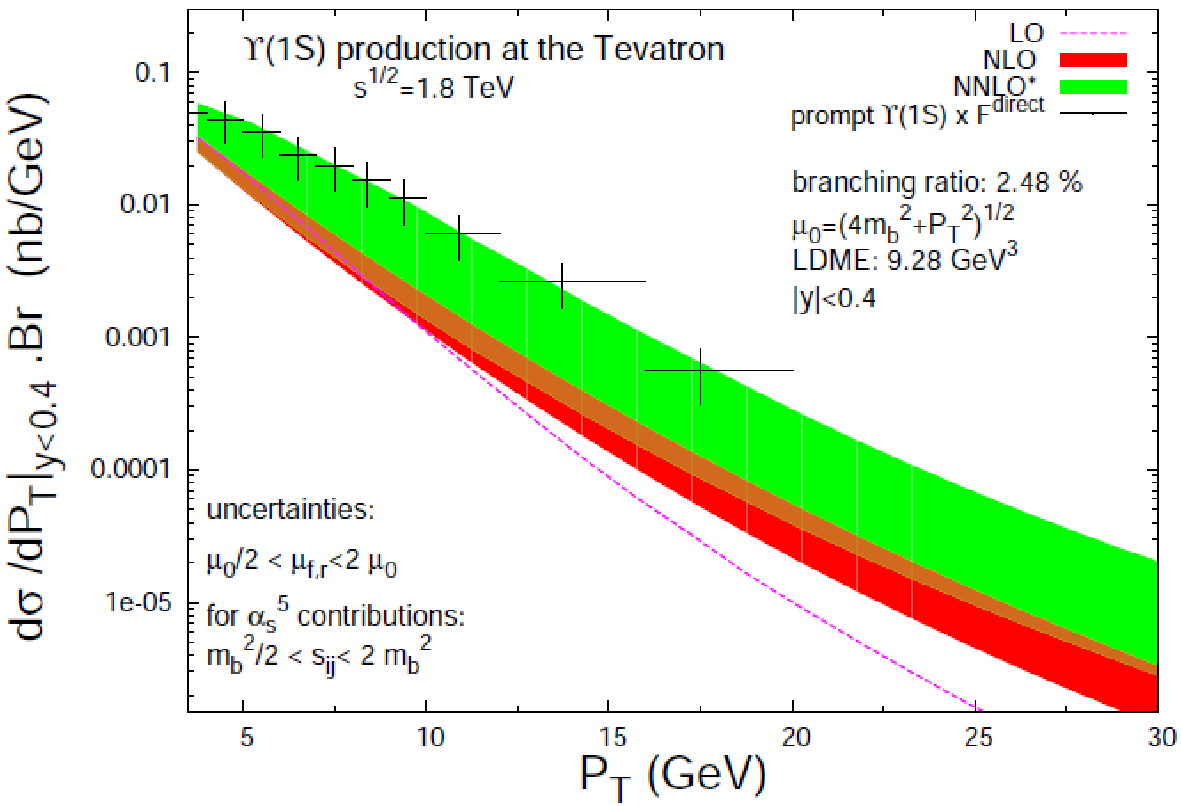
• v^2 correction to the color-singlet yield at LO in α_s

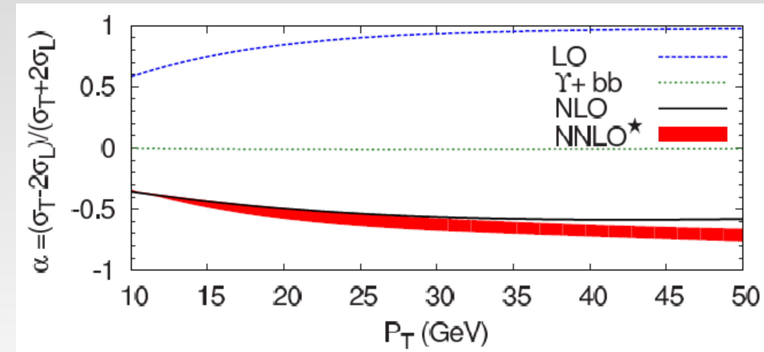
Color-singlet at NLO in α_s

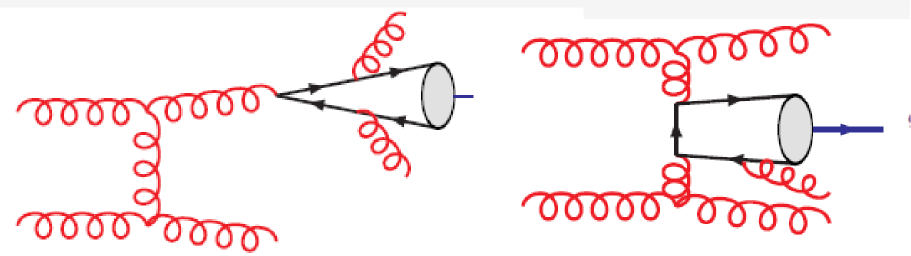


- very large enhancement at high PT due to the appearance of new channels P.A. et al (2008) see also Gong, Wang (2008)

Color-singlet at NNLO ?





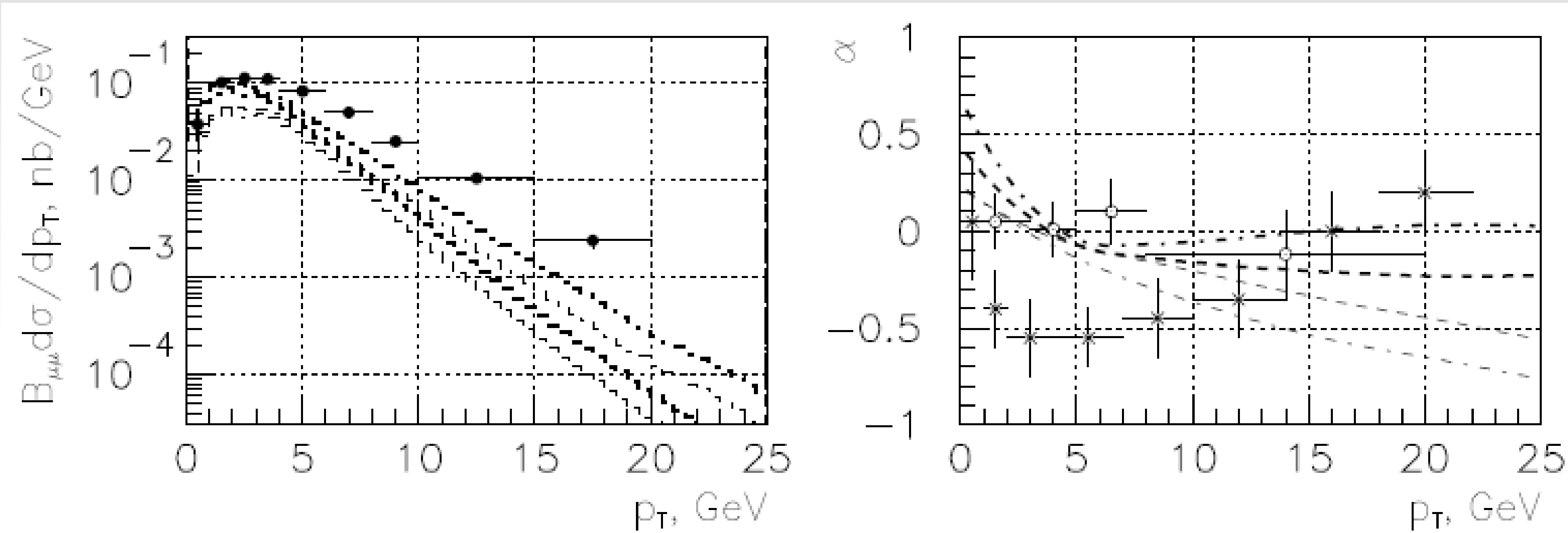


PA, Campbell, Lansberg, Maltoni, Tramontano (2008)

- new topologies arise at α_s^5, such as the CS gluon fragmentation channel or the two t-channel gluon initiated process -also evaluated in the **kt factorization** (Baranov, Zotov)-, can give a substantial enhancement at large PT

- reduce the role of CO transitions in Y production

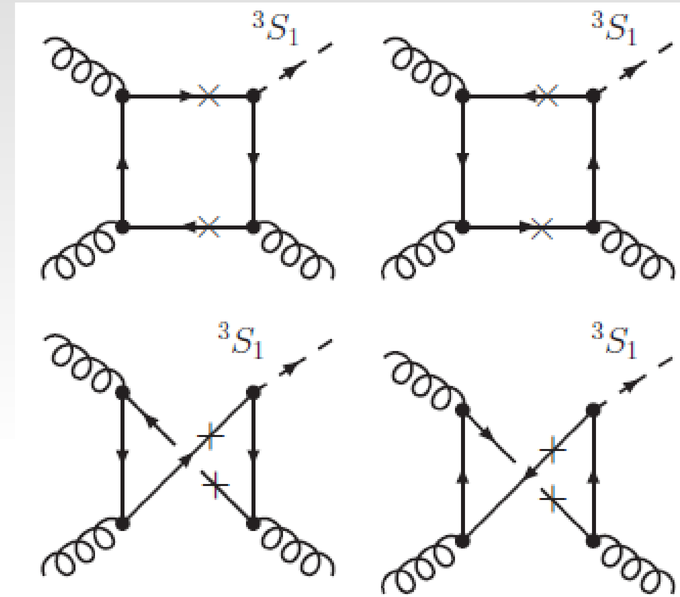
kt factorization: update for Υ



- estimation of the high-energy enhanced production mechanism initiated by two off-shell gluon
- predicts a polarization in qualitative agreement with the measurement Baranov, Zotov (2008)

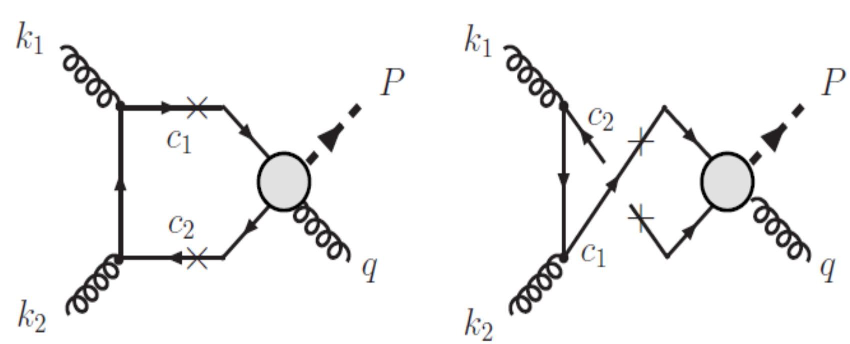
S-channel cut contribution

- suggested by Lansberg, Cudell, Kalinovsky (2005), in the frame of a phenomenological model (vertex function)



- new free parameters are introduced in the parametrization of the three-point and four-point vertex functions

- s-channel cut contributions first arise at order α_s^5 in NRQCD (no new parameters). They correspond to the rescattering a charm quark pair (PA, Braaten, under work)



Production at the LHC

- the calculations for quarkonium production at the Tevatron have direct implication for quarkonium production at the LHC
- new mechanisms are relevant at large PT
  CS fragmentation from a photon He, Li, Wang (2009)
- the higher rate of production and the extended range in PT opens the door to new -more exclusive- studies
  - double charmonium production Li, Zhang, Chao (2009)
  - J/ψ production in association with charm mesons Baranov, Zotov (2007), PA, Lansberg, Maltoni (2007)
  - J/ψ production in association with a photon
    NLO calculation by Li, Wang, 2008
    NNLO contributions by Lansberg, 2009
  - hadronic activity around the J/ψ Kraan, 2007

Conclusion

- Many new results in quarkonium production !
- Recent calculations for charmonium production at B factories have reduced previous discrepancies between NRQCD predictions and the experimental data
- Quarkonium production at HERA and at the Tevatron is still subject to debate
- LHC data will open the door to new analyses

Back-up

S-channel cut contribution

- application to J/ψ hadroproduction at the Tevatron energy