Status of theory calculations
&
LHC predictions

Workshop on quarkonium production
CERN

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February 19, 2010

Direct production vs feed-down

- Quarkonium production can proceed directly through short-distance interactions of initial partons, or via the decay of heavier hadrons (feed-down)

- In the case of J/ψ production at the Tevatron, contributing mechanisms include

  - b-hadron decays: at Tevatron II, $b\to J/\psi+X$ accounts for 10% of the inclusive production rate at $p_T=1.5$ GeV (increasing to 45% at $p_T=20$ GeV) [CDF collaboration, 04]

  - feed-down from charmonium states: at Tevatron I, $\psi(2S)\to J/\psi\pi\pi$ and $\chi_c\to J/\psi\gamma$ accounts for 35% of the prompt production rate [CDF collaboration, 97]

➡ Charmonium production from b-hadron decays and quarkonium feed-down mechanisms cannot be neglected in hadron collisions

Outline

Let us review the current theoretical understanding by introducing the issues one by one:

- Feed-down from b-hadron decays

  Tevatron data, run II: $b \to J/\psi(2S)+X$, $b \to \psi(2S)+X$

- Feed-down from excited quarkonium states

  Tevatron data, run I: $\chi_c \to J/\psi\gamma$, $\chi_b \to \Upsilon(1S)\gamma$

- Direct production (CO/CS transitions)

  Tevatron data, run II: prompt $\psi(2S)$, $\Upsilon(3S)$
  Tevatron data, run I: J/ψ, $\Upsilon(1S)$ [p_T spectrum only]

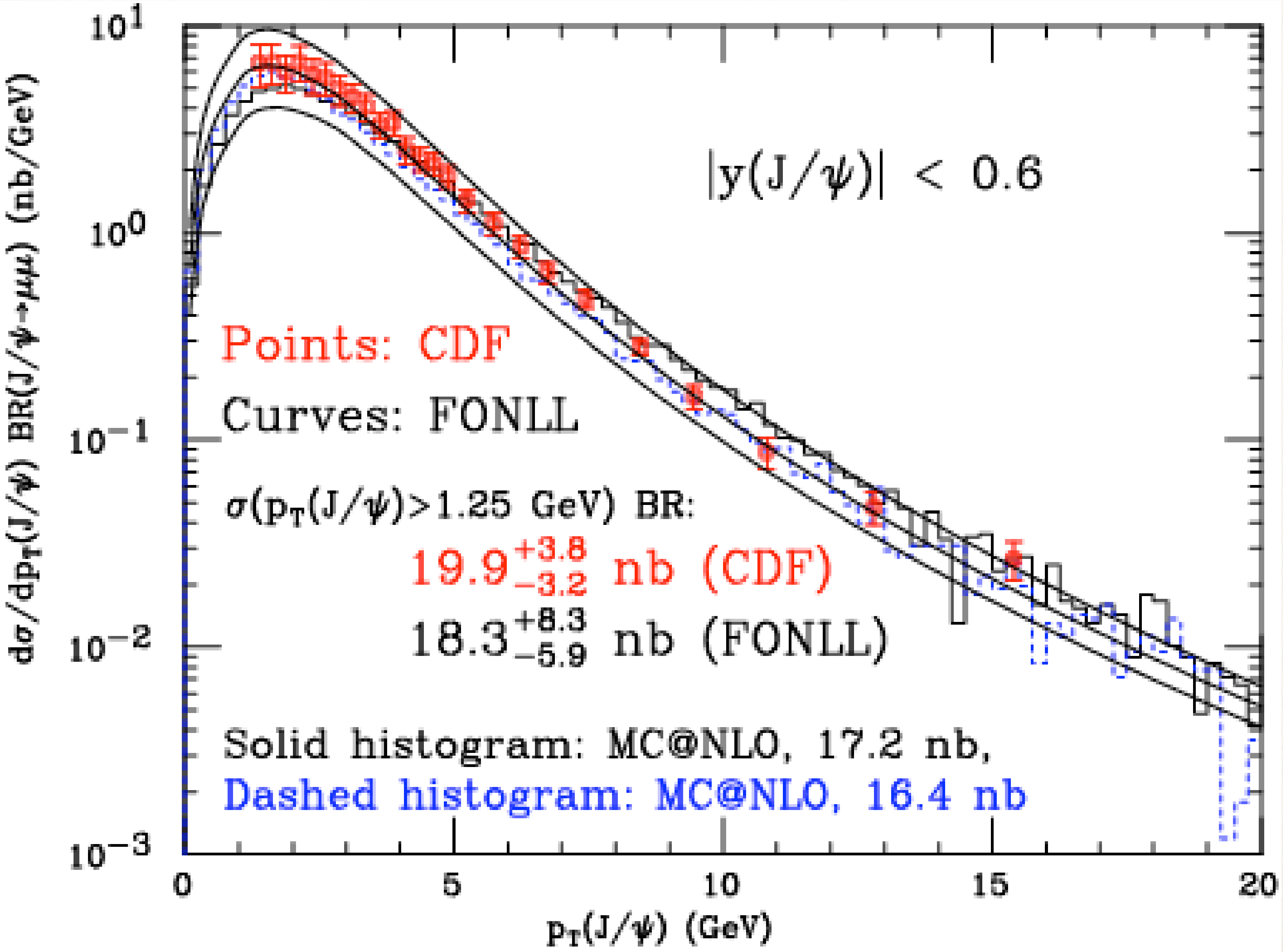
b-hadron decays

b-hadron decays into J/ψ

- FONLL scheme: [Cacciari, Greco, Nason]
  - resummation of logarithms of p_T/m_b, with next-to-leading logarithmic accuracy, particularly relevant at the LHC
  - matching with the fixed order, exact NLO calculation for massive quarks
- predictions based on non-perturbative inputs:
  - gluon and light quark PDFs
  - b quark to H_b fragmentation (fitted to LEP data)
  - H_b to J/psi branching ratio + decay spectrum

b-hadron decays into J/ψ (2)

- [Cacciari, Frixione, Mangano, Nason, Ridolfi]



- Good agreement with the data (no free parameter)
- Scale, mass and PDF uncertainties summed in quadrature

Prompt production

NRQCD factorization

The cross section for inclusive quarkonium production is expressed as a sum of products of short-distance coefficients and long-distance matrix elements

$$\boxed{\sigma[\mathcal{Q}] = \sum_n \hat{\sigma}_\Lambda[Q\bar{Q}(n)]\,\langle \mathcal{O}^{\mathcal{Q}}(n)\rangle_\Lambda}$$

SD coefficients
many recent works have been devoted to improving their accuracy, i.e. by computing higher-order corrections in α_s
→ **reviewed in this talk**

LD matrix elements
for the color-octet, no theoretical tool to constrain the LDME’s other than the power counting rules in v

→ **not much to say about recent progress** (contrary to decays)

Fragmentation processes [Braaten & Yuan, 93]

- At large p_T, quarkonium production is dominated by fragmentation.
- Calculations of cross sections simplify in the fragmentation approximation

$$d\sigma[\mathcal{Q}+X] = \int_0^1 d\hat{\sigma}[i(p/z)+X,\mu]D_{i\to\mathcal{Q}}(z,\mu) + \mathcal{O}(m_Q/p_T)$$

$$D_{i\to\mathcal{Q}}(z,\mu) = F^{\text{pert.}}_{i\to Q\bar{Q}(n)}(z,\mu,\Lambda)\langle\mathcal{O}^{\mathcal{Q}}(n)\rangle_\Lambda$$

- The DGLAP evolution equation can be used to resum the terms $(\alpha_s \log[p_T/m_Q])^n$

$$\mu\frac{\partial}{\partial\mu}D_{i\to\mathcal{Q}}(z,\mu) = \sum_j \int_z^1 \frac{dy}{y}P_{i\to j}(z/y,\mu)D_{j\to\mathcal{Q}}(y,\mu)$$

- Drawback: in some cases, the correction terms of order m_Q/p_T may be enhanced by large coefficients such that the fragmentation approximation is not accurate in the p_T region of interest

Let us consider first the feed-down from excited quarkonium states

Feed-down from ψ(2S):

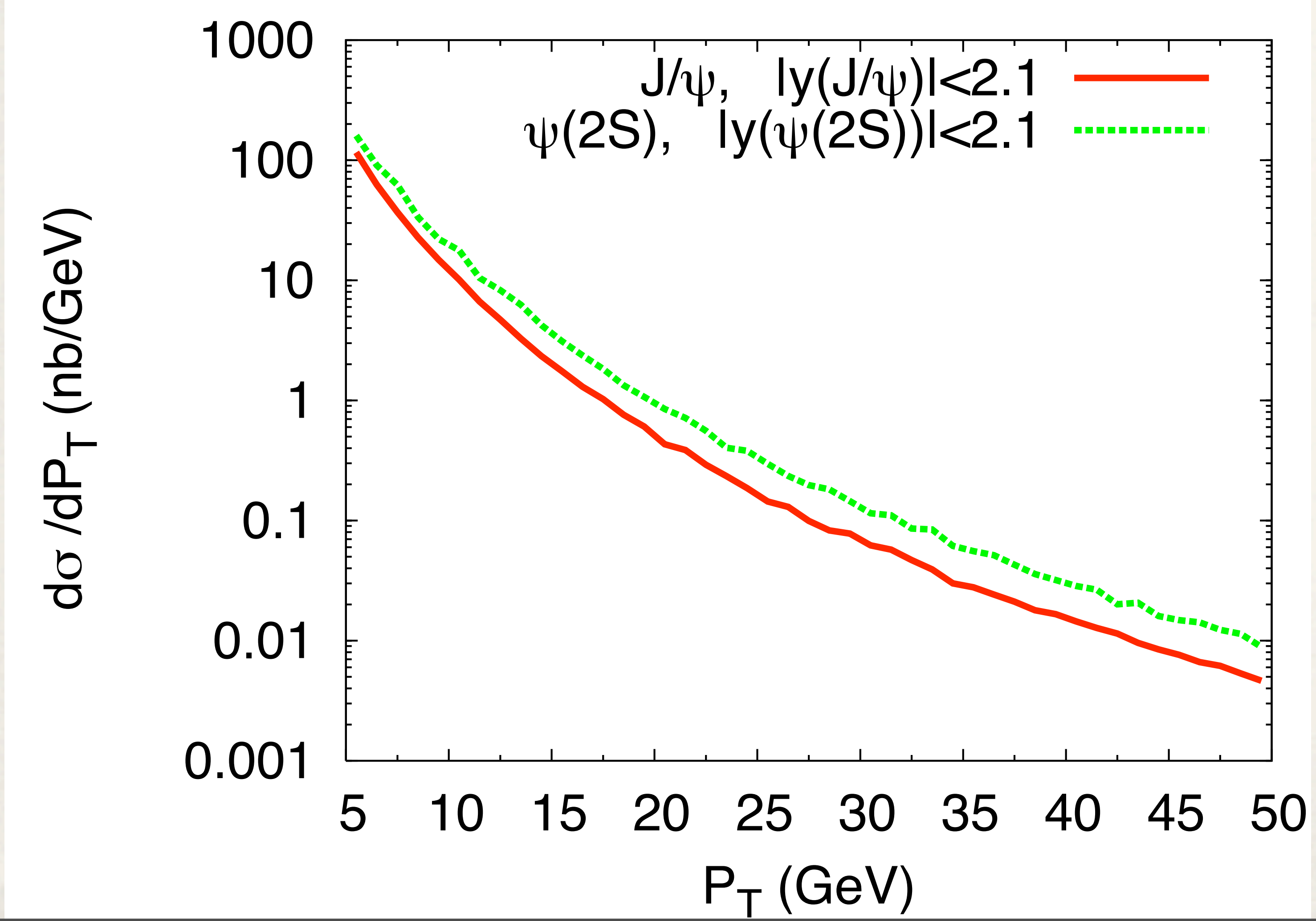
- At the Tevatron, the p_T spectrum for pp→X+[ψ(2S)→J/ψππ] can be deduced from the experimental spectrum for pp→X+[ψ(2S)→μμ] and from Monte-Carlo simulation for the decay ψ(2S)→J/ψππ
- The resulting J/ψ polarization is not well known, since the polarization of ψ(2S) has large uncertainties, both experimentally and theoretically
- In the past, the feed-down from ψ(2S) has been addressed by considering inclusive long-distance matrix elements, e.g.

$$\langle\mathcal{O}[n]\rangle^{J/\psi}_{\rm inc} = \langle\mathcal{O}[n]\rangle^{J/\psi} + \sum_H B_{H\to J\psi}\langle\mathcal{O}[n]\rangle^{H}$$

but this does not take into account the kinematic effects associated to the decay ψ(2S)→J/ψππ

Feed-down from ψ(2S):

- Let us assume that $^3S_1^{[8]} \to \psi(2S)$ is the dominant transition at the LHC
- Let us decay the ψ(2S) into J/ψππ according to a uniform distribution in the ψ(2S) rest frame
- The curves $d\sigma/dp_T[J/\psi, |y(J/\psi)|<2.1]$ and $d\sigma/dp_T[\psi(2S), |y(\psi)|<2.1]$ deviate from each other at large p_T



$m_c=0.5M_{\psi(2S)}$

$\mu=M_T[\psi(2S)]$

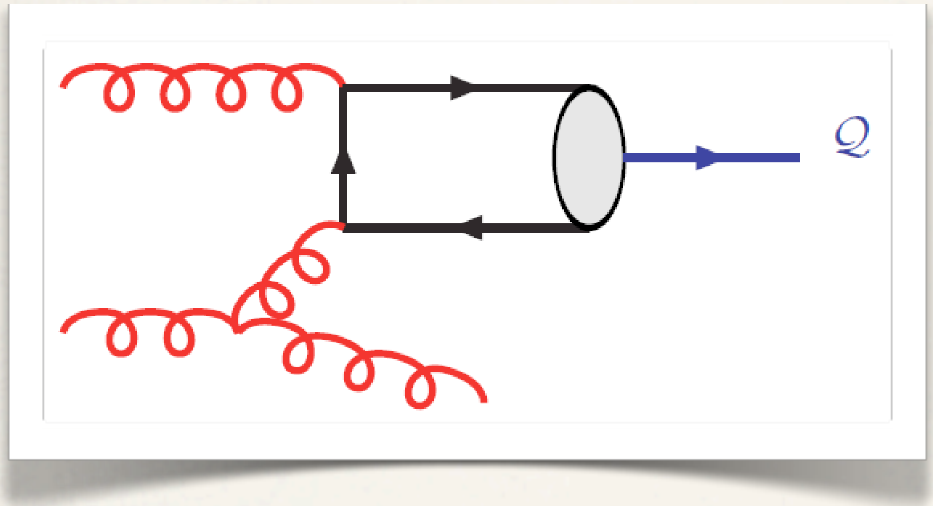
$\langle O(^3S_1^{[8]})\rangle=6\ 10^{-3}$ GeV

$Br[\psi(2S)\to J/\psi\pi\pi]=1$

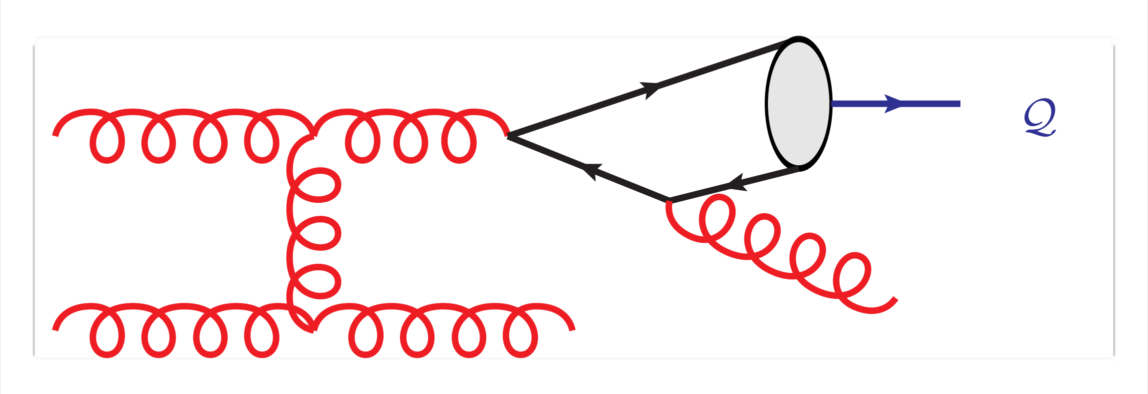
the kinematics of the decay ψ(2S)→J/ψππ must be taken into account properly

Feed-down from P-wave: $pp \to [\chi_{cJ} \to J/\psi\gamma] + X$

$^3P_J[1]$

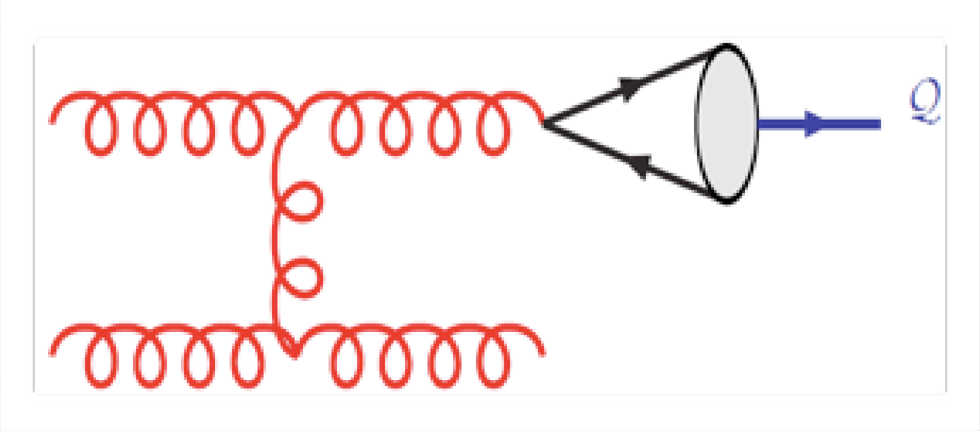


no fragmentation channel at α_s^3, you need to go to α_s^4 :



only known within the fragmentation approximation

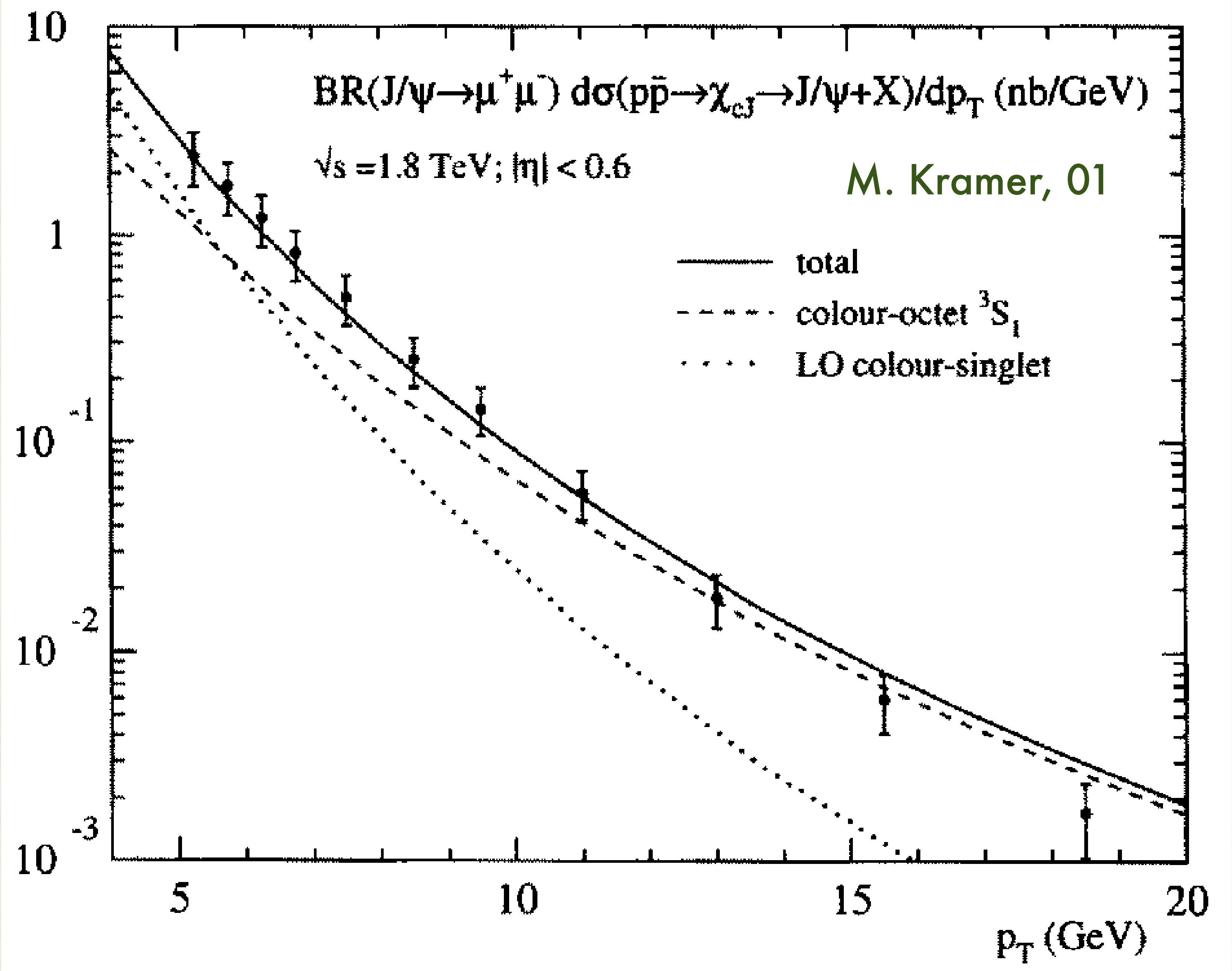
$^3S_1[8]$



gluon fragmentation channel already at α_s^3

What we call CS or CO contributions at α_s^4 depends on Λ_{NRQCD}
To a certain extend, α_s correction to the CS production can be reabsorbed into $<O(^3S_1[8])>$ by adjusting Λ_{NRQCD}

Comparison with Tevatron data



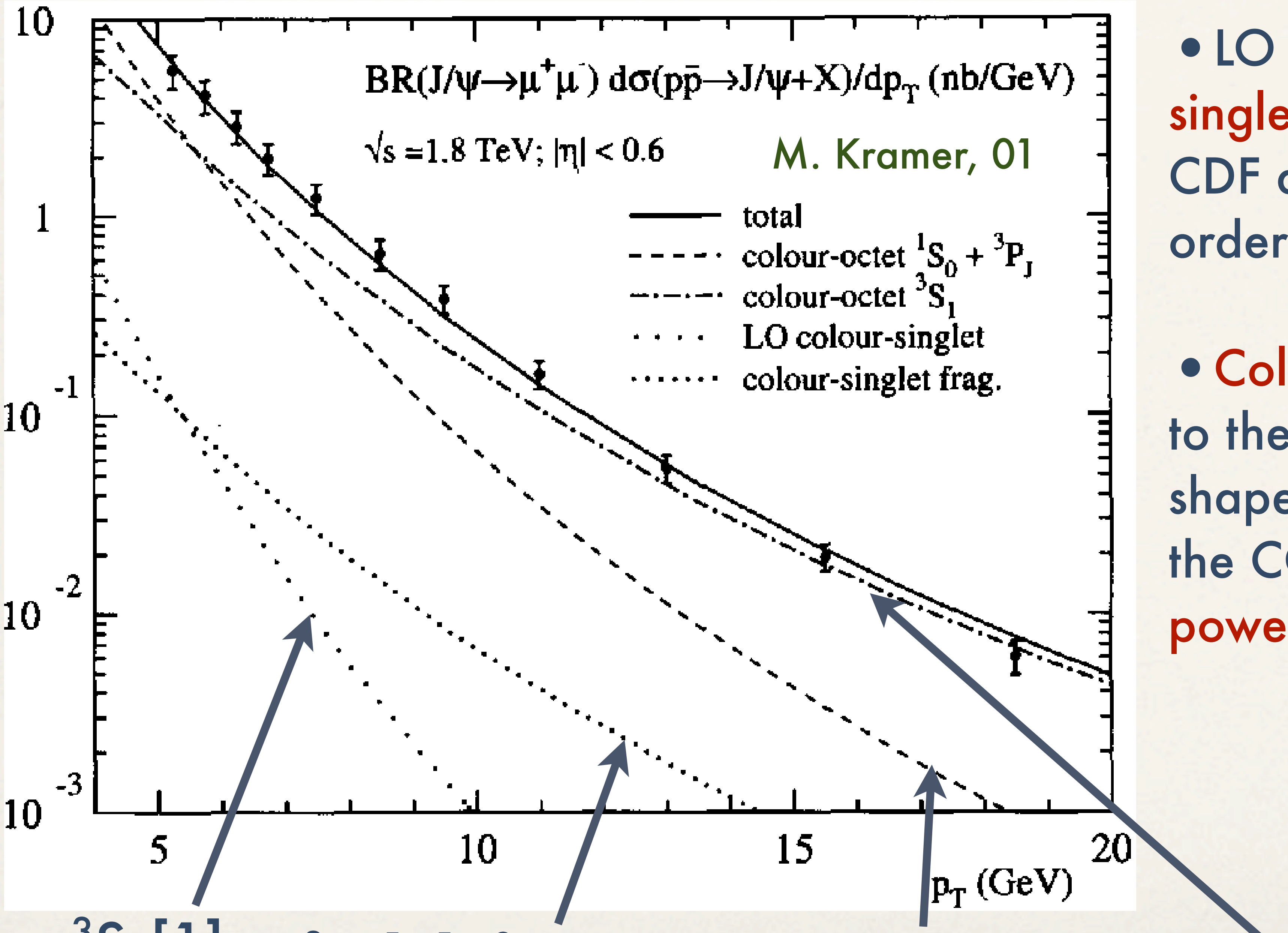
- Leading-order NRQCD prediction provides a good description of the Tevatron data (CO LDME is a free parameter)

- LHC data will allow to test the shape over a wider range in p_T

Direct production

J/ψ, ψ(2S) direct production

Th. status of direct J/ψ production at the Tevatron I: 9 years ago



M. Kramer, 01

$^3S_1[1]$ $^3S_1[1]$, frag approx $^1S_0[8]$+$^3P_J[8]$ $^3S_1[8]$

- LO + fragmentation color-singlet channels undershoots the CDF data by more than an order of magnitude.
- Color-octet contributions fitted to the data describe well the shape in p_T, and the values of the CO LDME's agree with the power counting rules in v.

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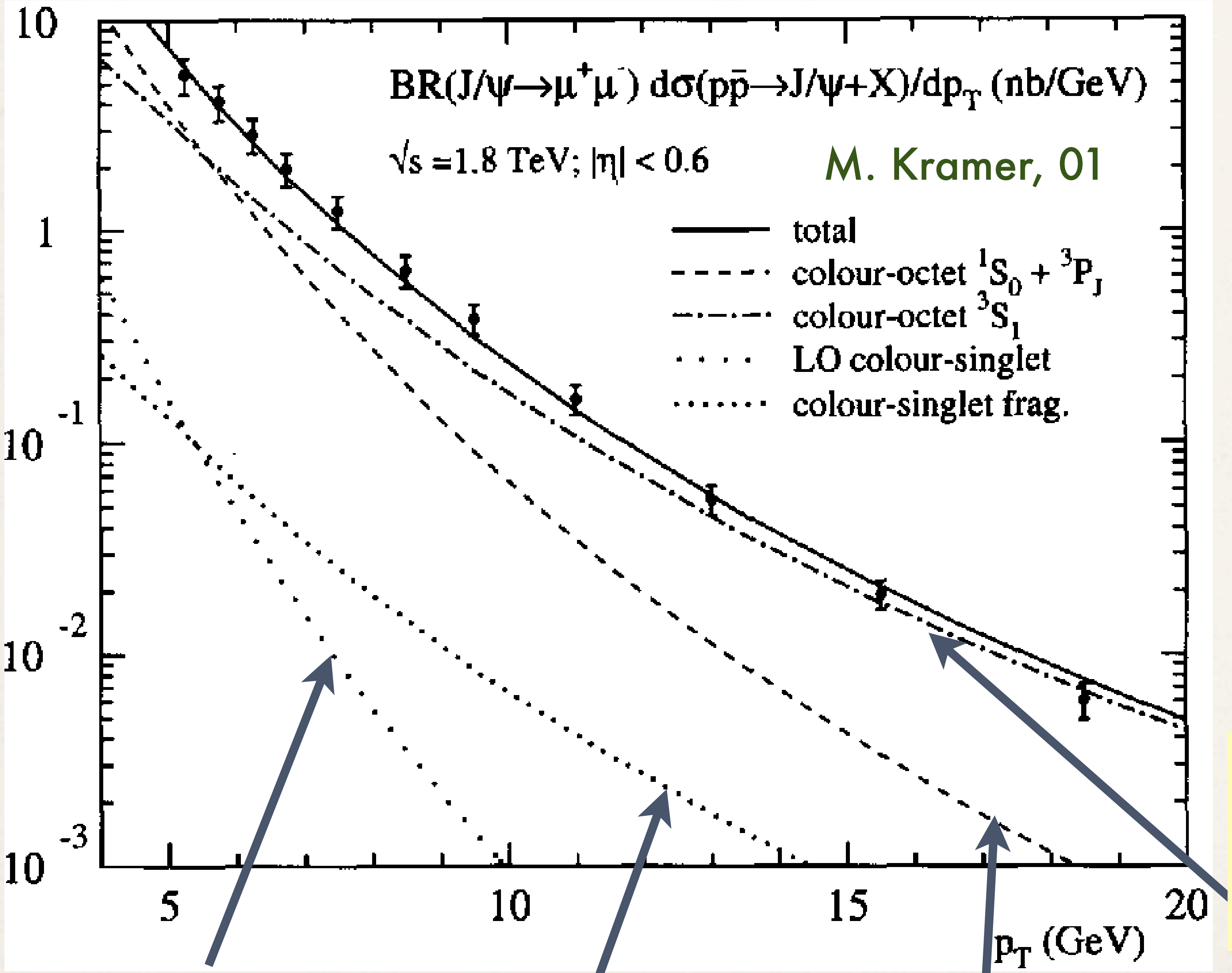

$^3S_1[1]$

$^3S_1[1]$, frag approx

$^1S_0[8]+^3P_J[8]$

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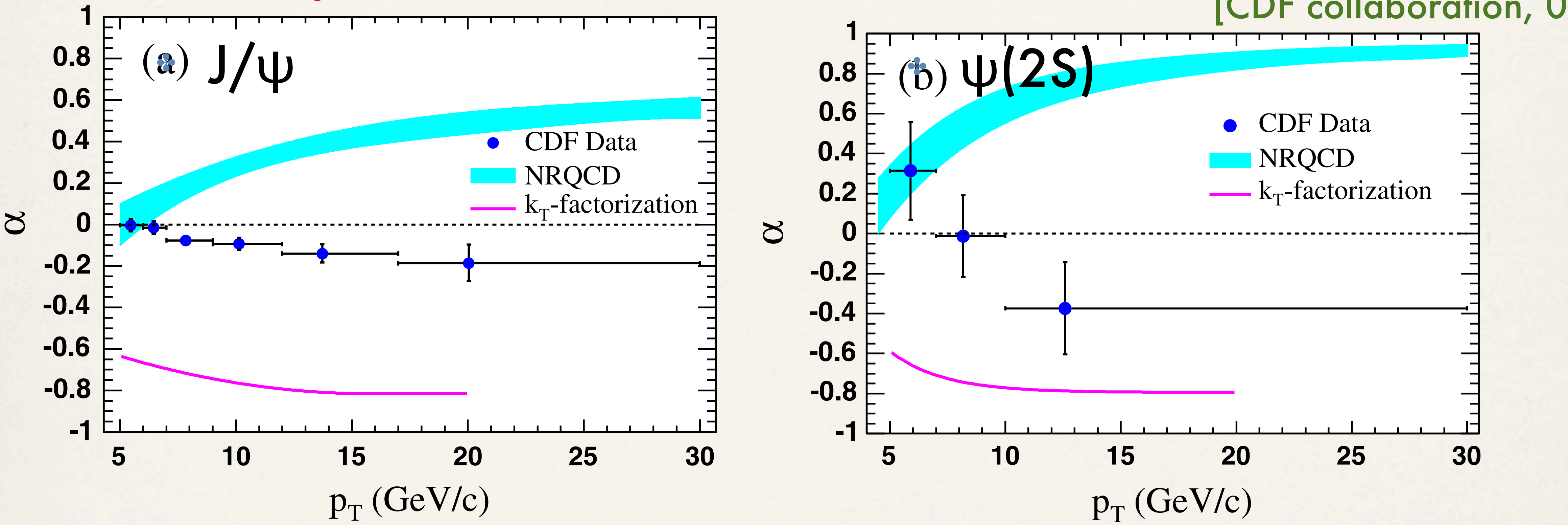
- Color-octet contributions fitted to the data describe well the shape in p_T, and the values of the CO LDME's agree with the power counting rules in v.

To be updated with recent progresses on α_s corrections to the SD coefficients

Open questions

- The leading-order NRQCD prediction for the polarization of ψ(2S) and J/ψ is in disagreement with CDF data

[CDF collaboration, 07]



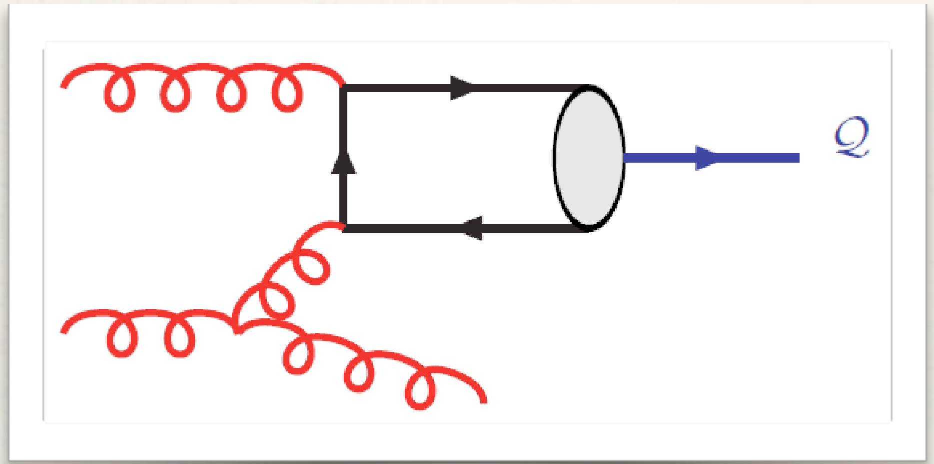
At large p_T, the production is dominated by $g^* \to {}^3S_1^{[8]}$, which leads to transverse polarization in the c.m. helicity frame. This prediction may be affected by perturbative and non-perturbative corrections

α_s correction is partially known (results reviewed in the next slides)

e.g: spin-symmetry breaking chromomagnetic interactions in the transition ${}^3S_1^{[8]} \to \psi$: only constrained by the counting rules in v

Color-octet channels (direct prod.)

$^1S_0[8]$, $^3P_J[8]$



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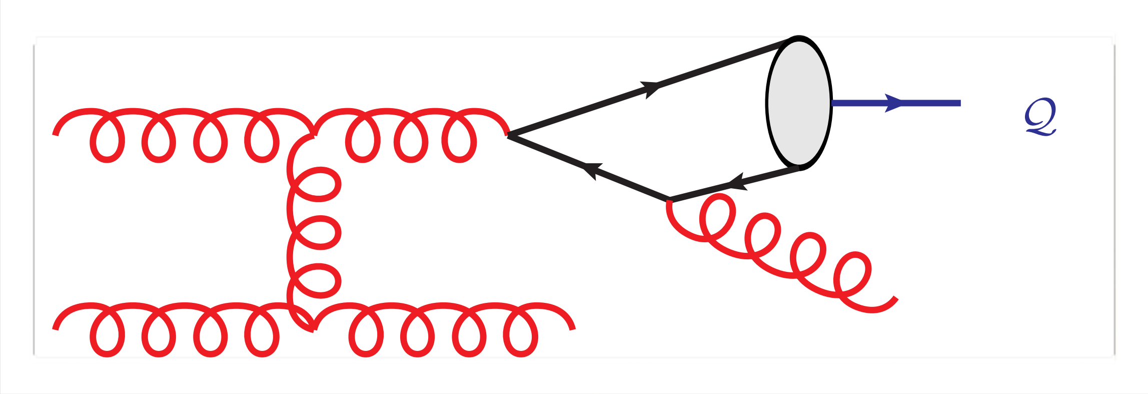
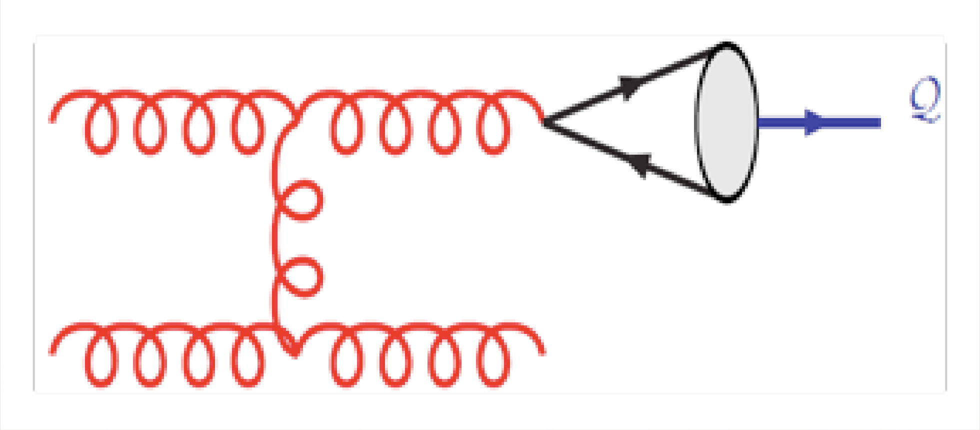


$^3S_1[8]$



gluon fragmentation channel already there at α_s^3

no new high-p_T enhanced channels at NLO, do not expect large corrections

new high-p_T enhanced channels open at at NLO → large corrections at high p_T

α_s correction to color-octet transitions

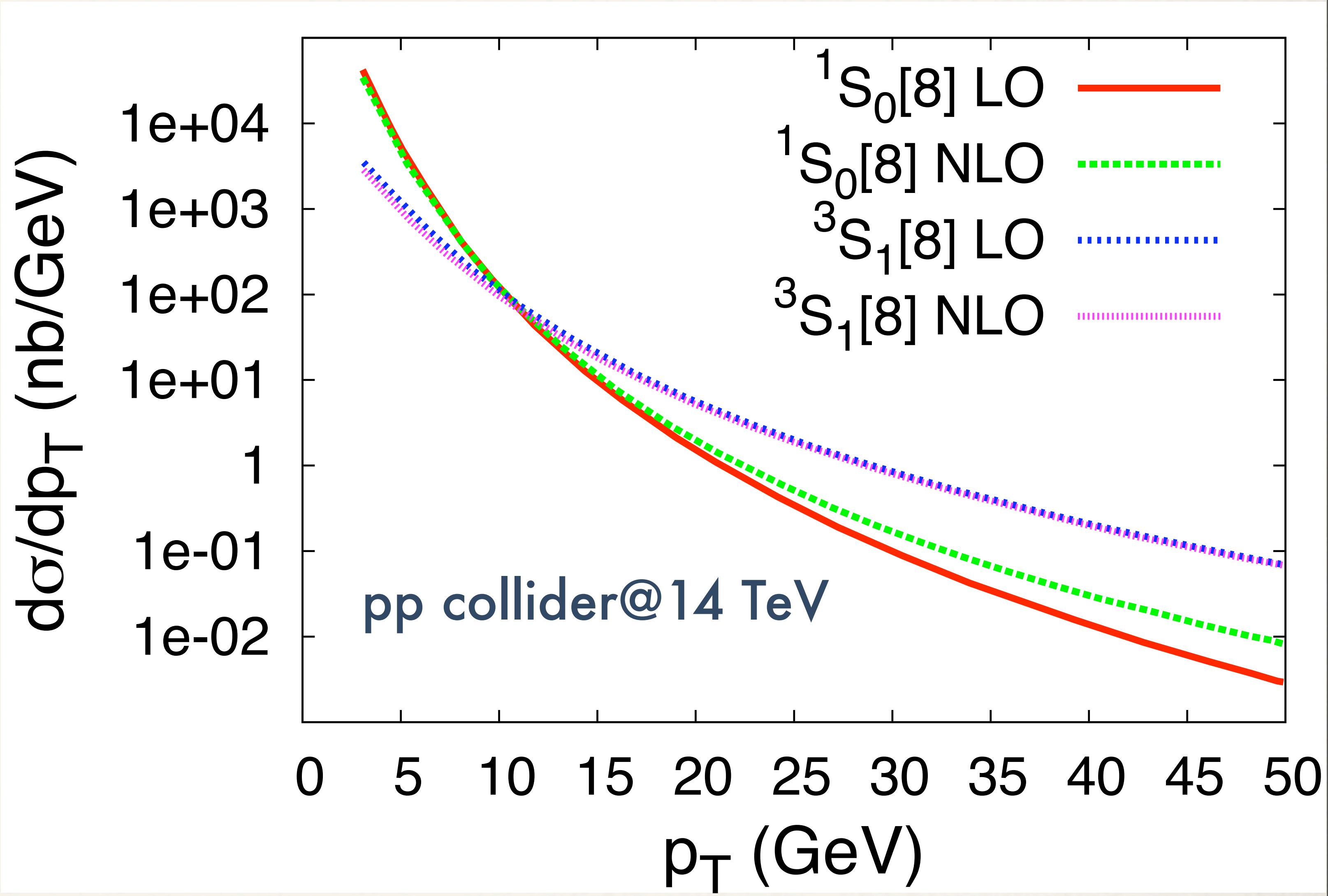
- $^3S_1{}^{[8]}$: [Gong, Li, Wang; 08]

  NLO correction is small in the entire p_T range, very small correction to the polarization [also investigated in the frag. approx: Ma 95, Beneke & Rothstein 96, Braaten & Lee, 00].

- $^1S_0{}^{[8]}$: [Gong, Li, Wang; 08]

  NLO correction is small at low pT, but increasingly important at large p_T, no correction to the polarization

- $^3P_J{}^{[8]}$: no complete calculation at NLO, unknown correction to the polarization



uncertainties at NLO: only the scale uncertainty on $\sigma[p_T>3$ GeV] has been analyzed (small variation)

α_s correction to color-octet transitions

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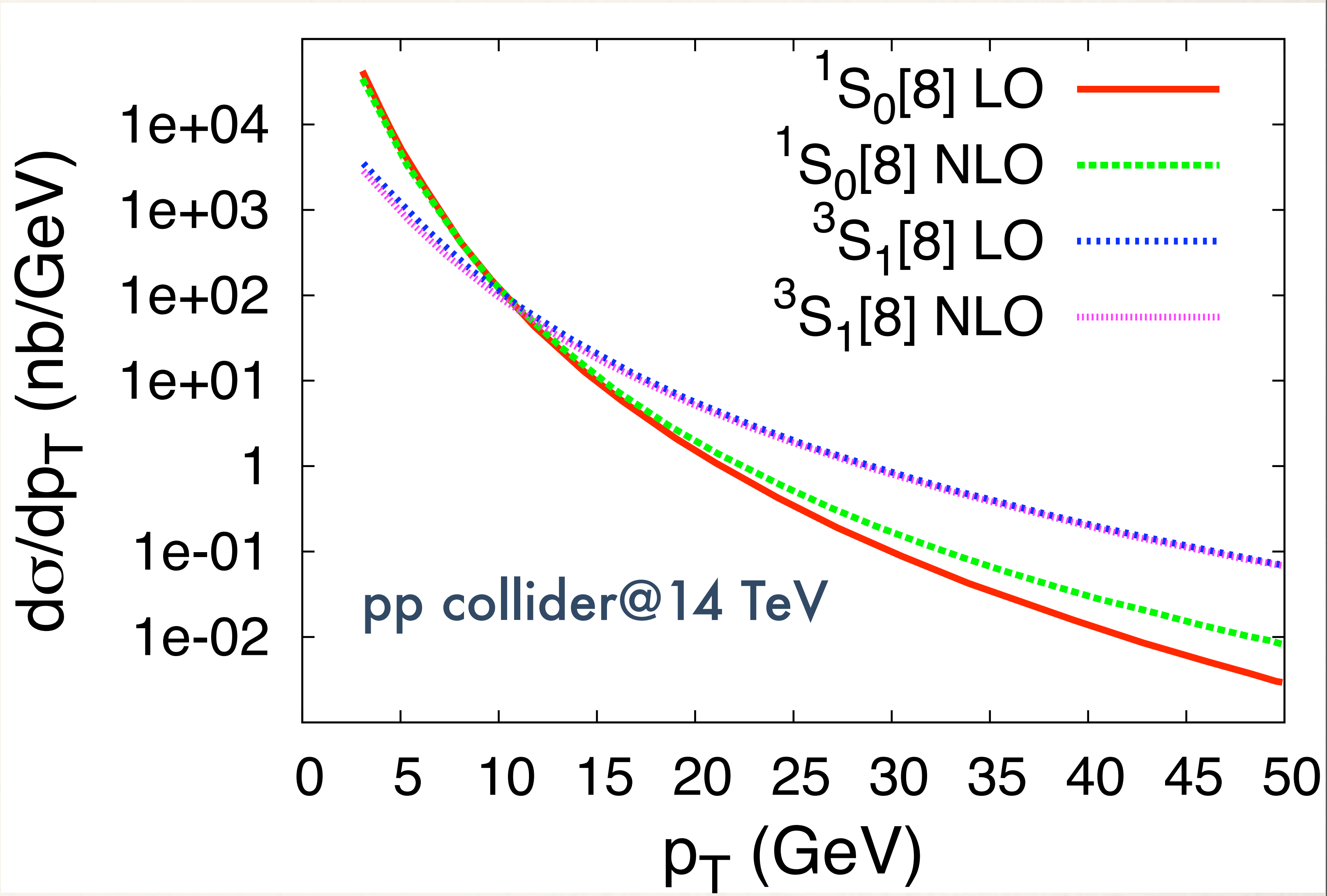


Observation for the $^3S_1{}^{[8]}$ case:

no effects of the large $\log(p_T/m_c)$ at high p_T ?

Fragmentation vs full FO calculation

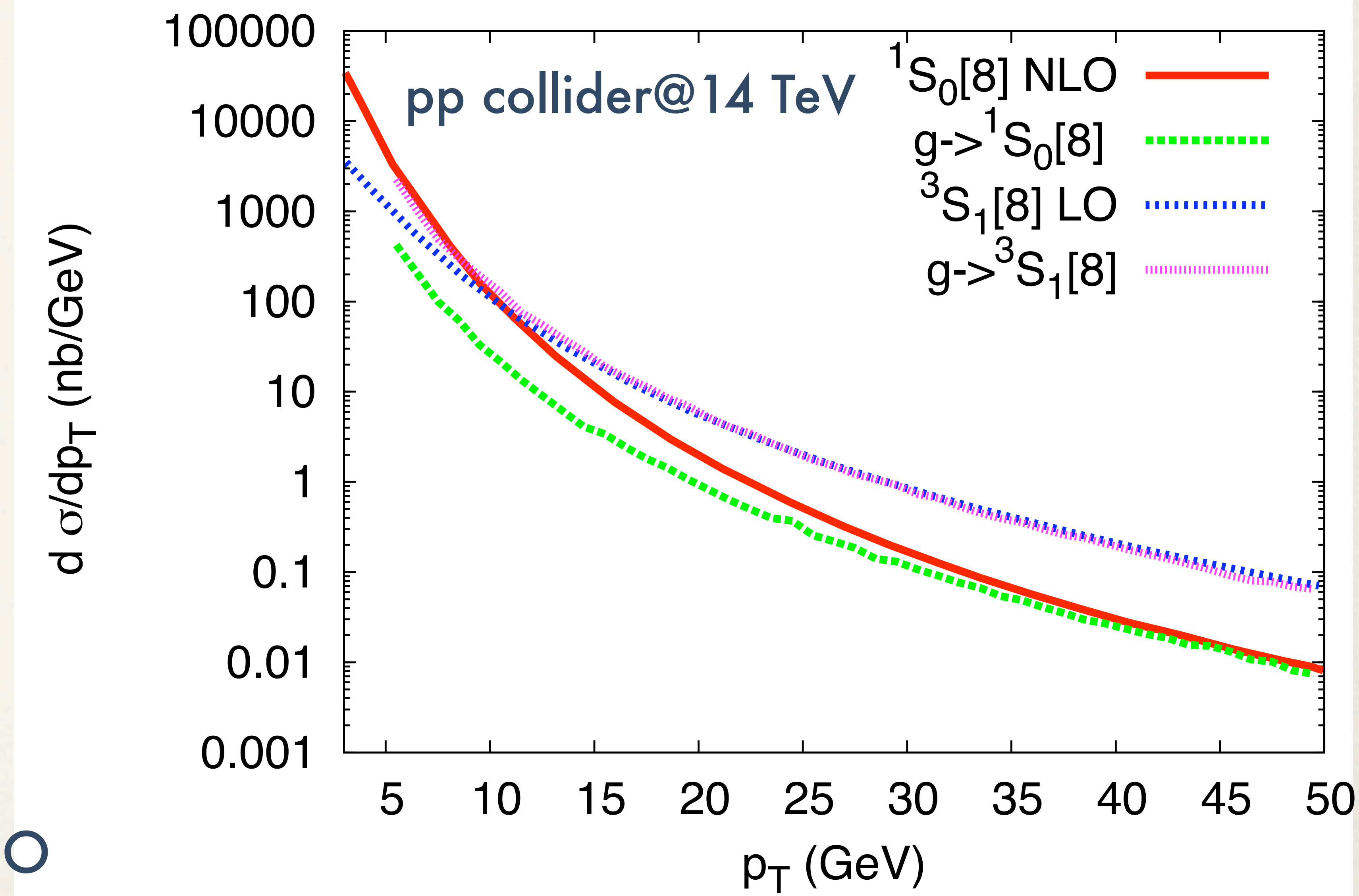
- Let us use exactly the same input parameters and compare the two calculations (frag. vs FO).

$^3S_1[8]$

The frag. approx. does a good job already at p_T>7 GeV

$^1S_0[8]$

The frag. approx. is not accurate below p_T =30 GeV



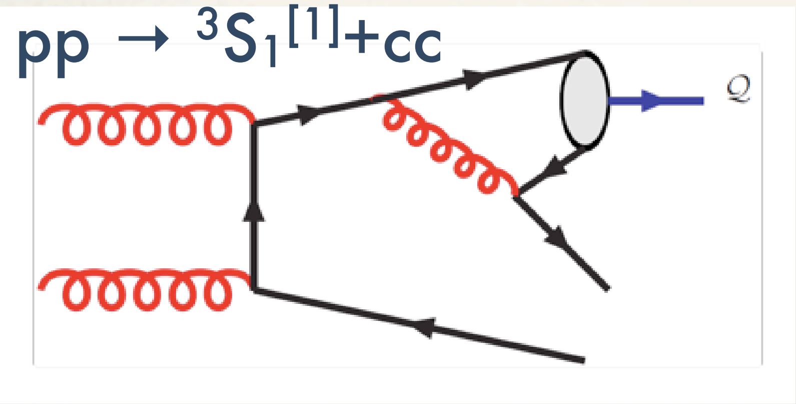
a more accurate calculation would require to match the FO calculation with the fragmentation approximation at NLO accuracy

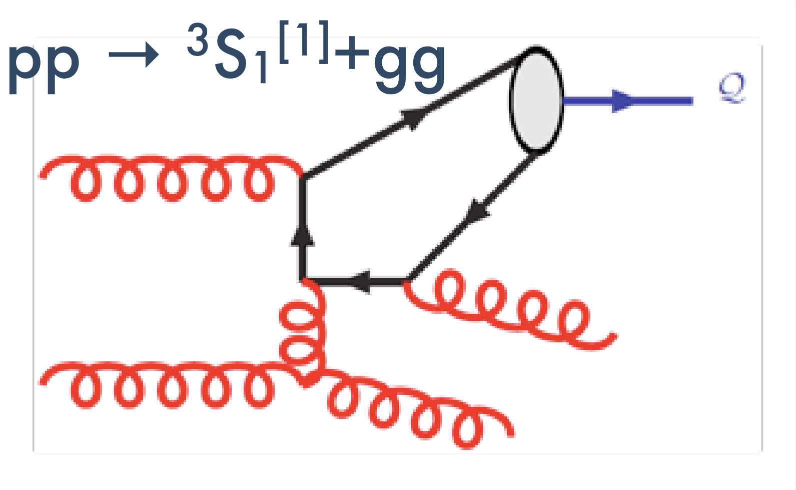
scale: $m_T(\psi(2S))$ (also in the frag. fct)
no DGLAP evolution

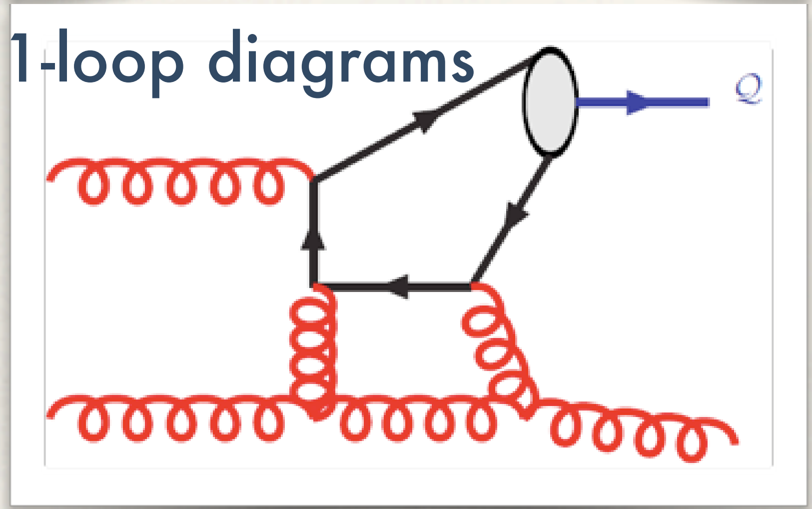
α_s correction to the color-singlet transition

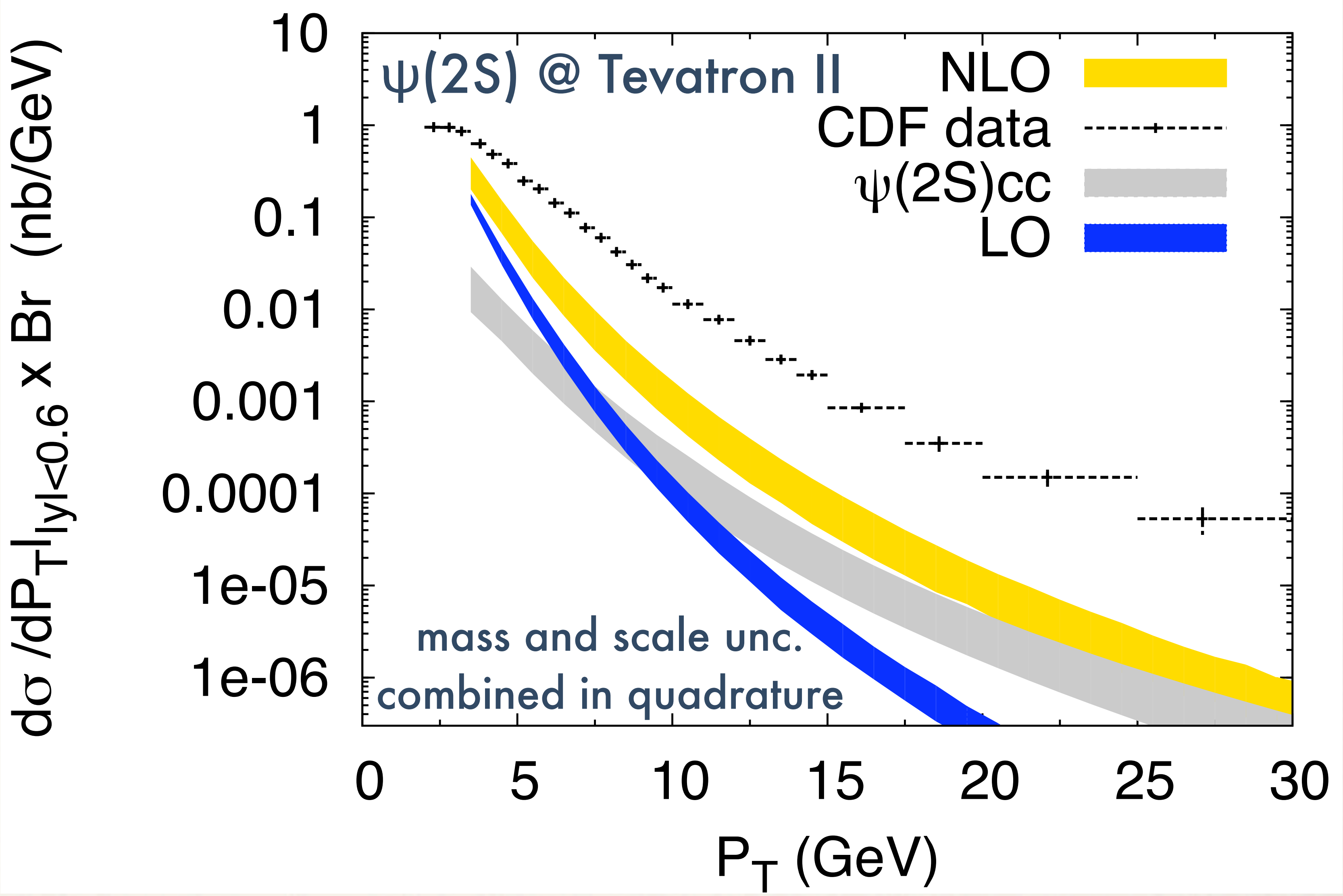
- New contribution at α_s^4

[Campbell, Maltoni, Tramontano, 2007]


pp → ${}^3S_1^{[1]}$+cc


pp → ${}^3S_1^{[1]}$+gg

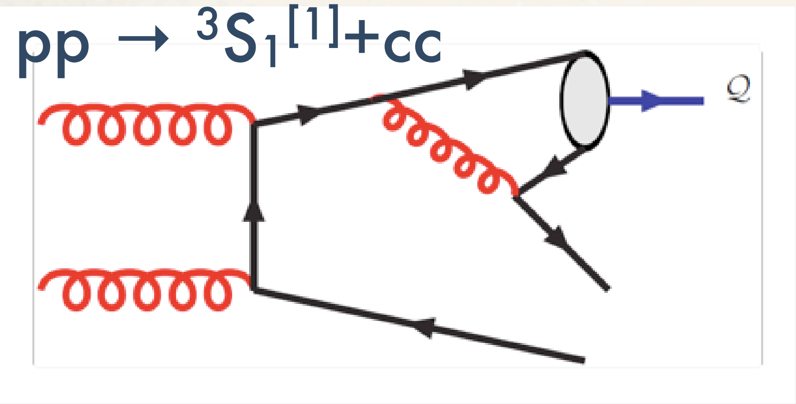

1-loop diagrams



- new channels at α_s^4 give rise to a huge enhancement at large p_T, overall the correction is small
- large th. unc., mainly from variations of the scales
- still a large opening gap with the data

α_s correction to the color-singlet transition

- New contribution at α_s^4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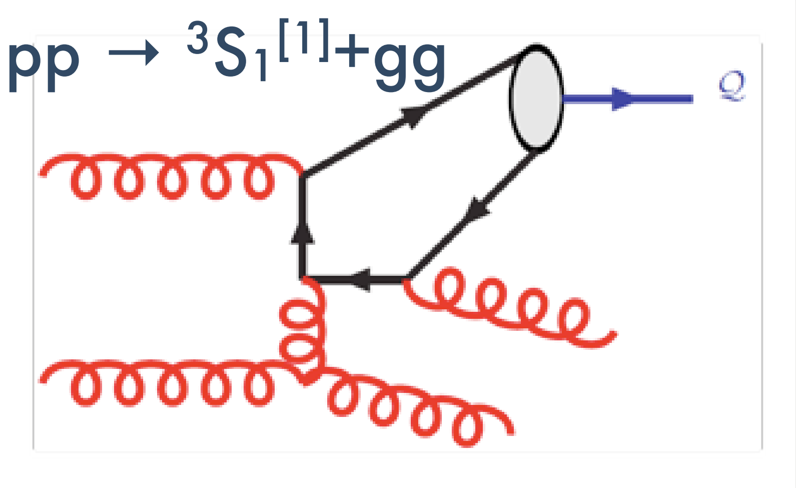
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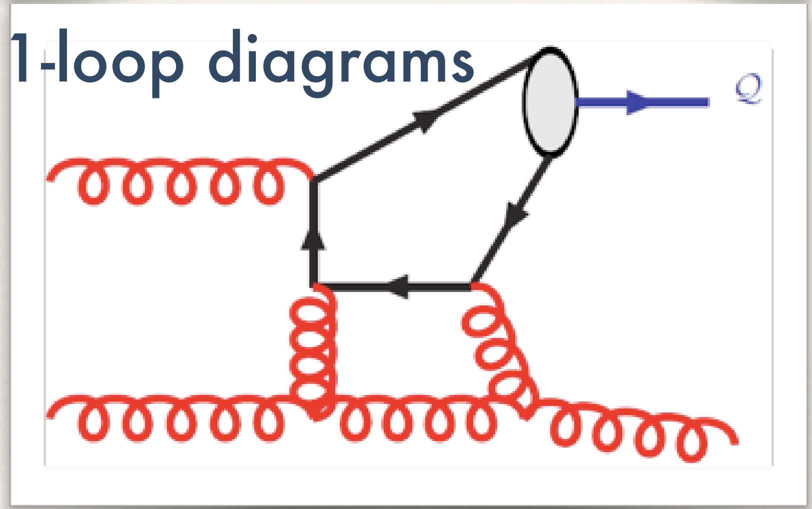
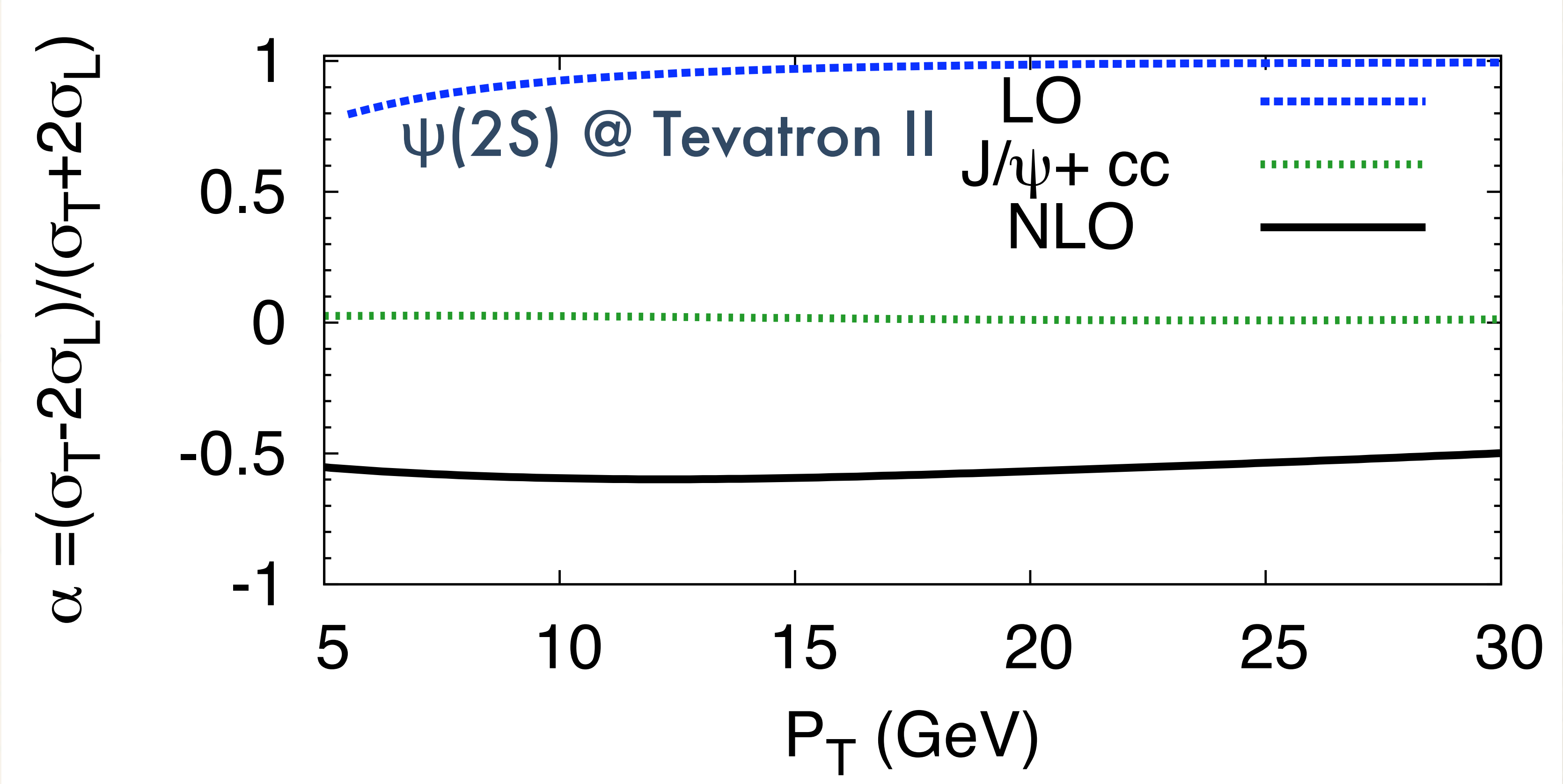

1-loop diagrams

[Gong, Wang; 07]



- new channels at α_s^4 strongly affect the polarization parameter α (polar asymmetry in the c.m. helicity frame)
- prediction of a large longitudinal component at NLO

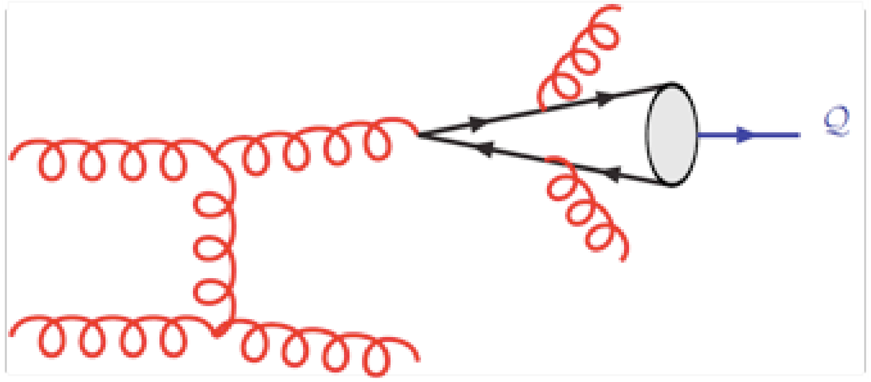
α_s correction to the color-singlet transition (2)

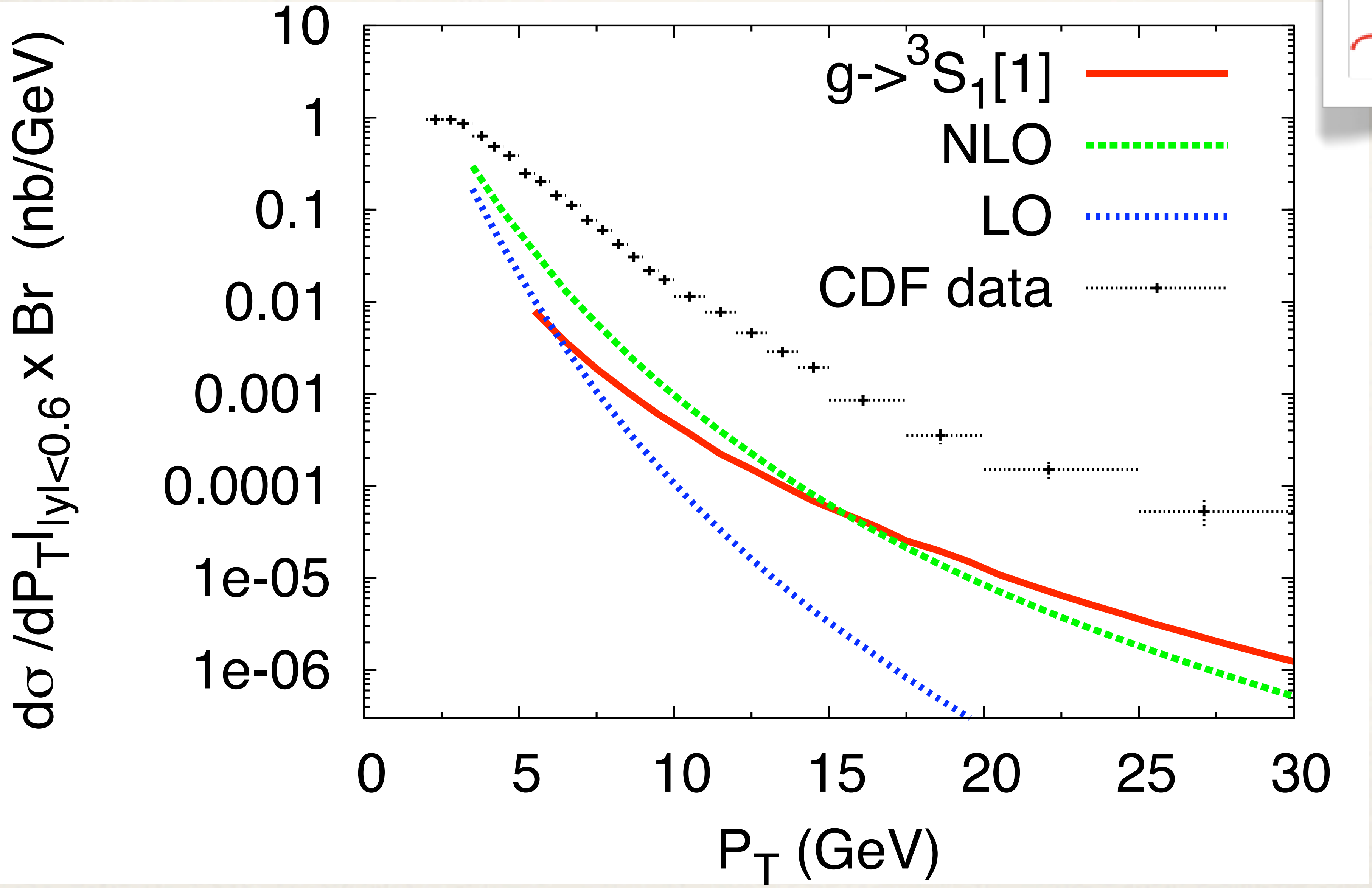
- The CS yield at next-to-leading order in α_s is still decreasing too fast in p_T ($d\sigma/dp_T^2 \sim 1/p_T^6$) in comparison with the $\psi(2S)$ data
- The associated channel $\psi(2S)+c\bar{c}$ has the correct shape ($1/p_T^4$), but the overall normalization is small
- Large correction may arise at order α_s^5 because new channels with a different p_T scaling open up at that order. One of them is the gluon fragmentation $g^* \rightarrow {}^3S_1^{[1]}$

Gluon fragmentation into $^3S_1[1]$

- The contribution from the channel $g^* \to {}^3S_1^{[1]}$ is known in the fragmentation approximation

[Braaten & Yuan; 93]



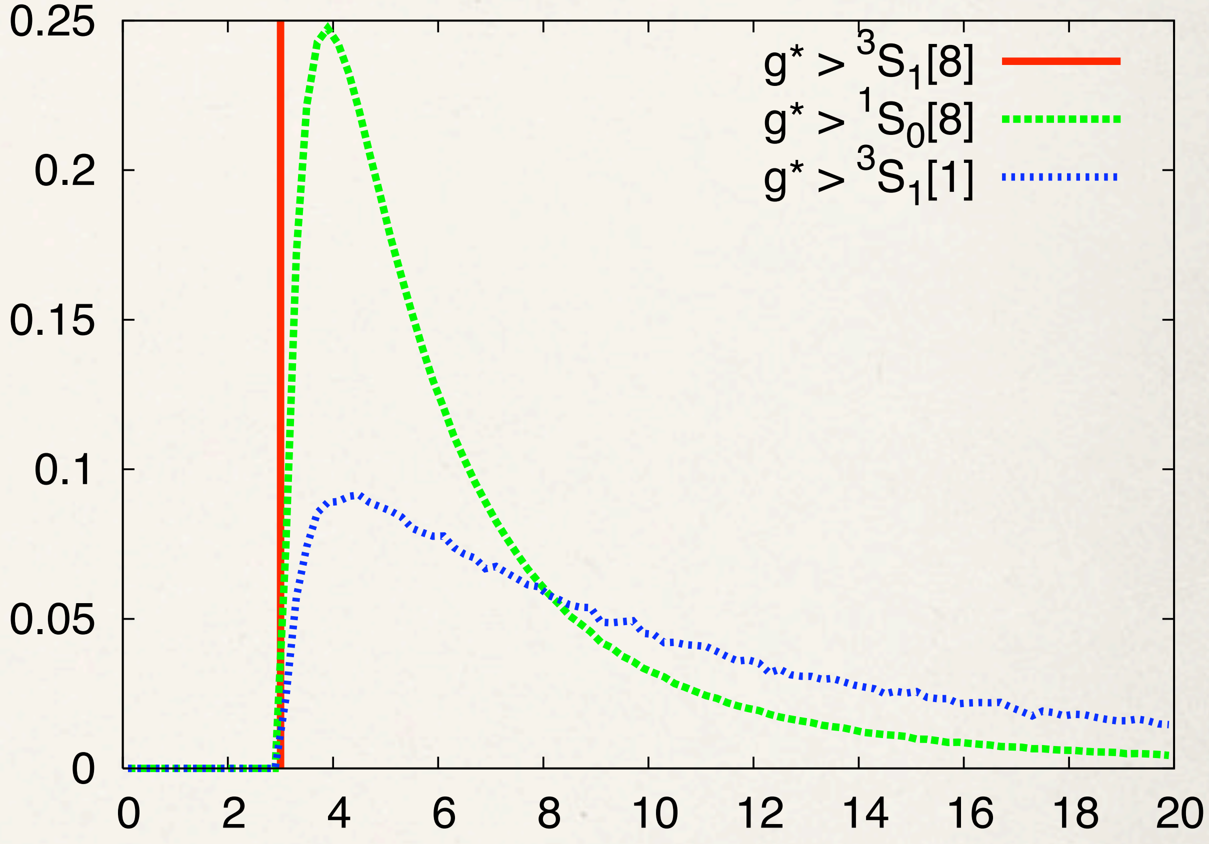


- large contribution compared to the NLO yield at large p_T
- small contribution compare to the data but ...

Gluon fragmentation into $^3S_1[1]$ (2)

- … we need to be critical of the fragmentation approximation

gluon frag. channel	QCD order	region of accuracy
$g^* \to {}^3S_1^{[8]}$	α_s	$p_T > 7$ GeV
$g^* \to {}^1S_0^{[8]}$	α_s^2	$p_T > 30$ GeV
$g^* \to {}^3S_1^{[1]}$	α_s^3	$p_T >$?? GeV



invariant mass of the fragmentation products at $p_T \to \infty$ (in GeV)

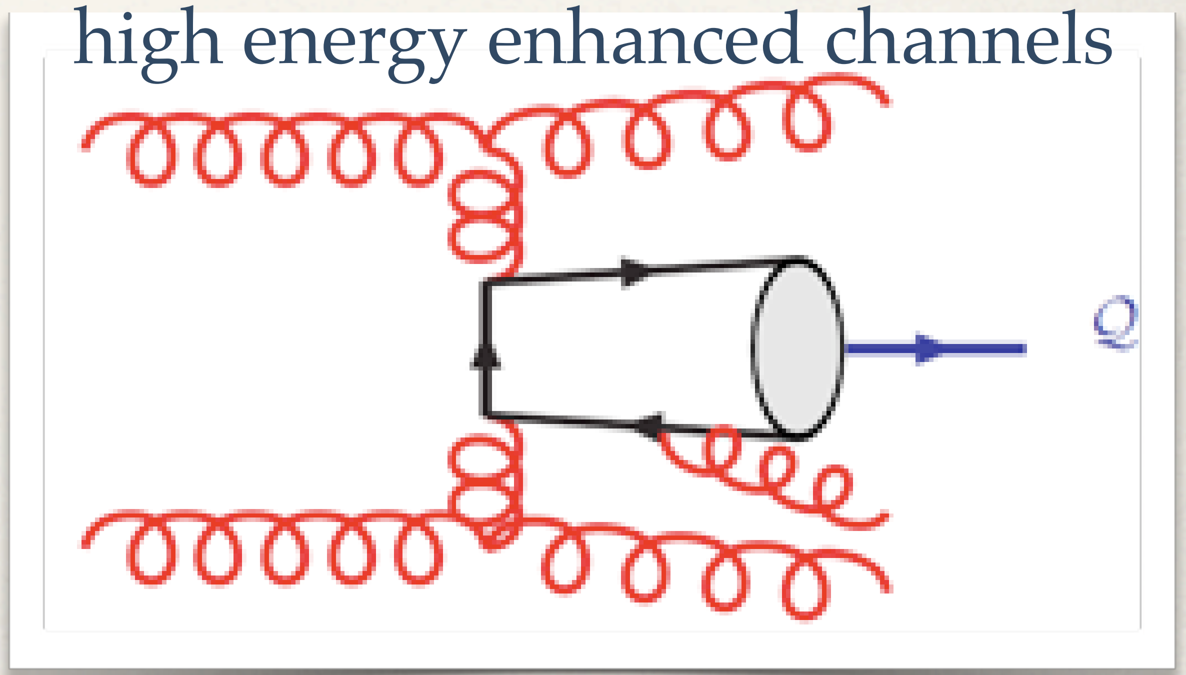
In the case of $g^* \to {}^3S_1^{[1]} gg$, the rather large invariant mass of the fragmentation products may lead to substantial corrections to the fragmentation approximation at finite p_T. Also channels that contribute at α_s^5 other than fragmentation topologies may give a large contribution at finite p_T.

Other important channels at α_s^5 ?

- In the region $s \gg \hat{s}$, the perturbative expansion in α_s may contain large logarithms $\ln[1/x]$.

- The resummation of these logs results in the so-called noncollinear or unintegrated parton distributions $F_i[x, k_T^2, \mu^2]$ that give probability of finding a parton of type i carrying the longitudinal momentum fraction x and transverse momentum k_T at the probing scale μ^2 [k_T factorization]

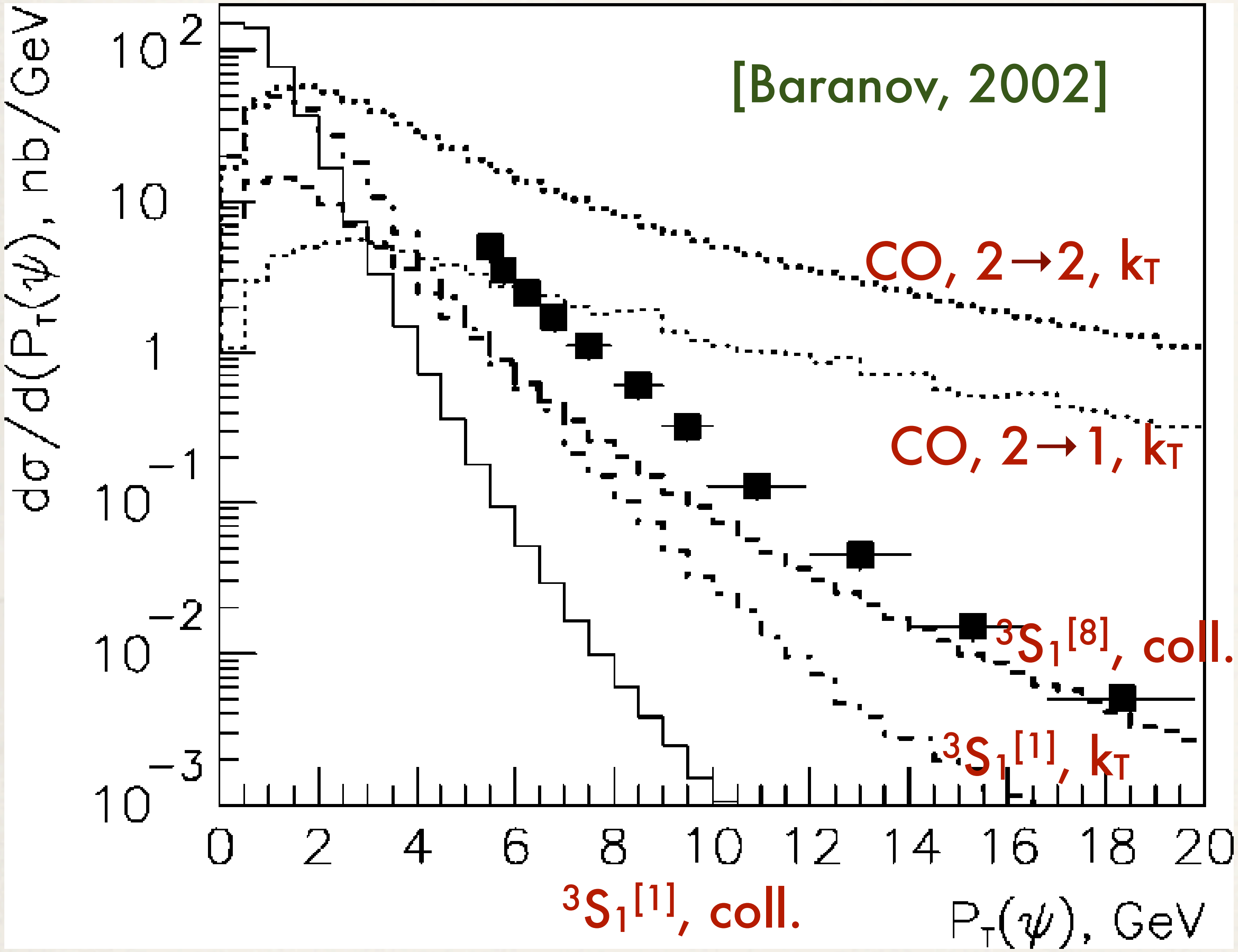
- With the k_T factorization, the leading-order prediction for production of ${}^3S_1^{[1]}$ accounts for topologies that appear at order α_s^5 in the collinear factorization [Baranov, Zotov]



high energy enhanced channels

Prediction in the k_T factorization approach

- J/ψ production at the Tevatron, run I

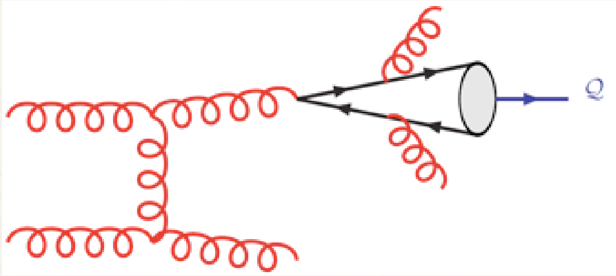


- With the k_T factorization, the $^3S_1^{[1]}$ p_T spectrum at LO is in better agreement with the data (compared to LO $^3S_1^{[1]}$ prediction in the coll. fact.) but a large gap remains
- Large uncertainties associated with the unintegrated PDF (factor 2-3)
- In the c.m. helicity frame, the polar asymmetry parameter is predicted to be negative (longitudinal polarization)

A new approach to evaluate channels at α_s^5

[PA, Campbell, Lansberg, Maltoni, Tramontano, 2008]

- Take the whole set of tree-level diagrams for ${}^3S_1^{[1]}$ + 3 jets. This set includes both gluon fragmentation and high-energy enhanced topologies



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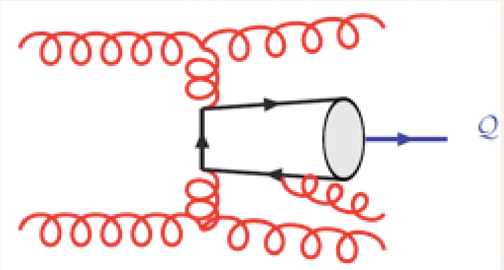
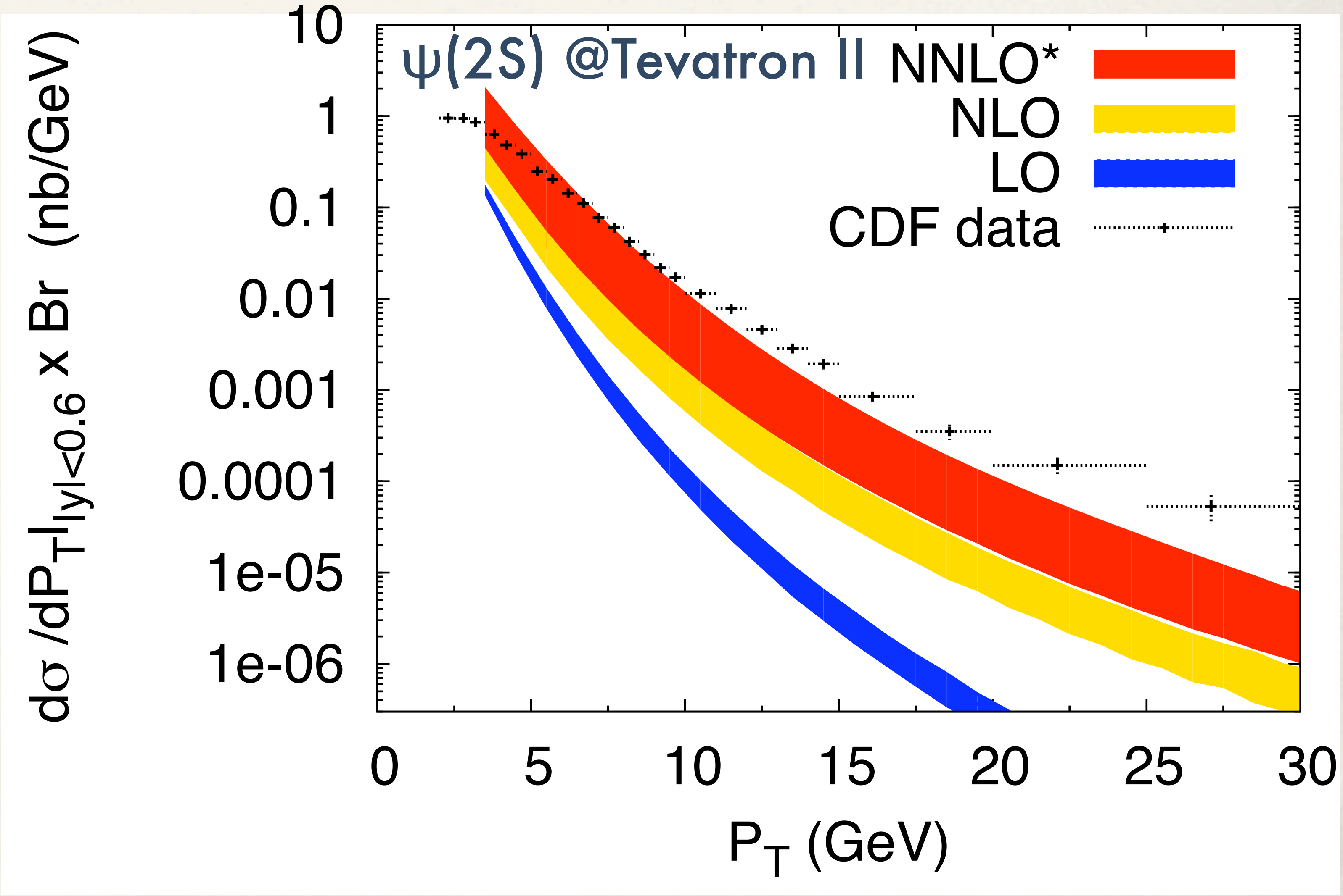


+ … (≈1k diagrams)

Integrate them with an IR cutoff to get a finite result (labeled as NNLO*)

- IR cutoff dependence, expected to disappear at large p_T
- no resummation of $\log[m_c/p_T]$ or $\log[1/x]$
- large uncertainty on the normalization, the shape is rather stable
- opening gap as p_T increases



J/ψ, ψ(2S) direct production: appraisal

- Differential cross section in NRQCD are expanded in v, but in the case of J/ψ, ψ(2S), v is not that small … Different scenarios are *a priori* possible:

1. Truncation of $\sigma[\psi]$ to order v^3 is a good approximation

In this case, there is no substantial contribution from color-octet transitions. This scenario is not excluded yet, since the large QCD corrections to the p_T spectrum associated with the color-singlet transition lead to very large theoretical uncertainties on $\sigma_1[{}^3S_1]$. More work is required to reduce these uncertainties.

J/ψ, ψ(2S) direct production: appraisal

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II. v^3 contribution to $\sigma[\psi]$ is small (due to SD coefficient suppression), the series truncated at order v^7 is accurate.

In this case, the main contribution come from the color-octet transitions. The prediction of the polarization at this accuracy in v disagrees with the CDF data.

J/ψ, ψ(2S) direct production: appraisal

- Differential cross section in NRQCD are expanded in v, but in the case of J/ψ, ψ(2S), v is not that small ... Different scenarios are *a priori* possible:

III. There are large contributions to σ[ψ] beyond v^7

In this case, heavy-quark spin-symmetry breaking interactions makes the prediction of the polarization more intricate, and lead to (at least a partial) depolarization of the charmonium state. The cross section differential in p_T may still be described by the production of ${}^3S_1{}^{[8]}$ state at large p_T, as the corresponding short-distance coefficient is dominant.

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- Differential cross section in NRQCD are expanded in v, but in the case of J/ψ, ψ(2S), v is not that small ... Different scenarios are *a priori* possible:

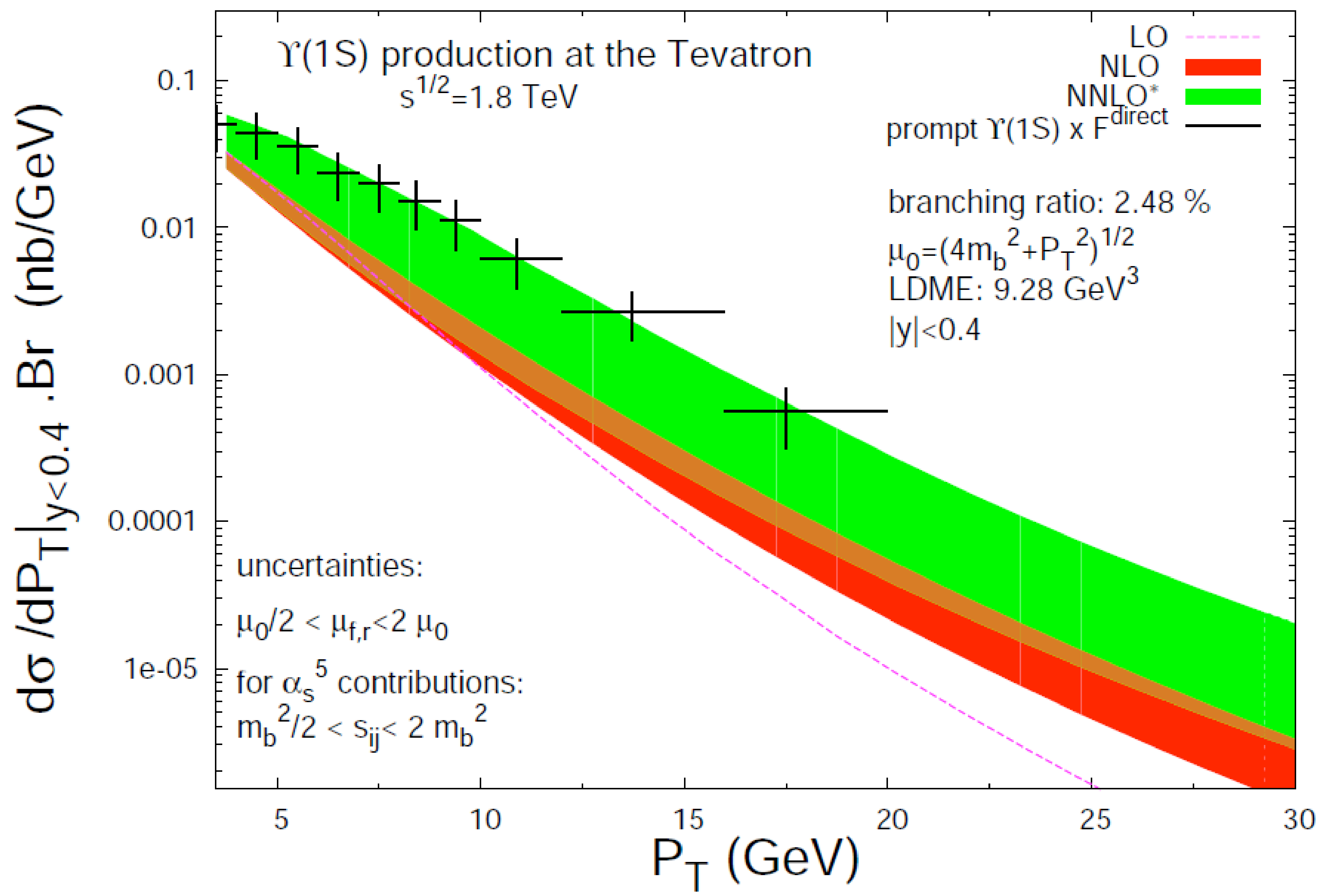
III. There are large contributions to σ[ψ] beyond v^7

In this case, heavy-quark spin-symmetry breaking interactions makes the prediction of the polarization more intricate, and lead to (at least a partial) depolarization of the charmonium state. The cross section differential in p_T may still be described by the production of $^3S_1{}^{[8]}$ state at large p_T, as the corresponding short-distance coefficient is dominant.

what happens if we consider the production of ϒ states ?
(expect a better behavior of the expansion in v)

Situation for Upsilon production (direct)

- $\Upsilon(1S)$ direct production



- smaller gap between CS at NLO and the data, increasing with p_T
- α_s^5 channels may provide the missing contribution: the shape is in good agreement with the data, but large uncertainties on the normalization

[PA, Campbell, Lansberg, Maltoni, Tramontano, 2008]

Υ vs ψ direct production

- For the ϒ direct production, the color-octet contributions are not *needed* to understand the cross section differential in p_T. Predictions at $\sqrt{s}=7$ TeV are ongoing.

- For J/ψ, ψ(2S) direct production, it is unclear what is the dominant transition in view of the current experimental data. New observables may help to understand the production mechanisms. Suggestions include both
  - more exclusive signatures: $pp \to J/\psi + c\bar{c}$

    $$pp \to J/\psi + \gamma$$

    $$pp \to J/\psi + J/\psi$$

    See talks by Fabio, Aafke, Jean-Philippe
  - inclusive observables for which the theoretical and/or experimental uncertainties partly cancel (see next slide)

[From G. Bodwin]

Ratios of Cross Sections at Different Values of $\sqrt{s}$

- We may be able to disentangle the color-singlet and color-octet contributions by taking ratios of cross sections at different values of $\sqrt{s}$.
  - The largest theoretical uncertainties cancel.
  - In a given experiment, some systematic uncertainties may tend to cancel as well.
- R is the ratio of the direct production rate at $\sqrt{s} = 10$ TeV to the direct production rate at $\sqrt{s} = 1.96$ TeV.
  - R_1 is the color-singlet ratio of rates.
  - R_8 is the color-octet ratio of rates.
  - R^{Exp} is the experimental ratio of cross sections.
  - r^X is the ratio of the color-octet contribution to the color-singlet contribution at experiment X.
- If R_1 and R_8 are well separated, then we can use R^{Exp} to determine r^X.

$$R^{\text{Exp}} = \frac{\sigma_1^{\text{LHC}} + \sigma_8^{\text{LHC}}}{\sigma_1^{\text{Tev}} + \sigma_8^{\text{Tev}}} = \frac{R_1 + r^{\text{Tev}} R_8}{1 + r^{\text{Tev}}}, \qquad \text{where} \qquad r^{\text{Tev}} = \frac{\sigma_8^{\text{Tev}}}{\sigma_1^{\text{Tev}}} = \frac{R_1}{R_8} r^{\text{LHC}}.$$

- Then $r^{\text{Tev}} = (R^{\text{Exp}} - R_1)/(R_8 - R^{\text{Exp}})$ can be used to make predictions for the polarization.

Conclusion

- The different mechanisms for quarkonium production are not all understood with the same level of accuracy:
  - Charmonium feed-down from b-hadron decays seems well understood both at the perturbative and non-perturbative levels, and the predictions describe the data well without any free parameters.
  - NRQCD leading-order predictions for production of χ_c states are in reasonable agreement with the Tevatron data, but need further experimental tests
  - The direct production of ψ and Υ states suffers from large uncertainties, both at the perturbative and non-perturbative level. In particular, it is not clear what transition dominates the production.