Recent theoretical progress in quarkonium production:

going beyond NLO

Pierre Artoisenet (Ohio State) and Fabio Maltoni (CP3)

Production in hadronic collisions

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- What are the relevant parton processes?
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- How does the heavy quark pair bind to form quarkonium?
- Is the binding parametrizable with a few constants?
- Can they be calculated from first principles?

Production in hadronic collisions

Several Answers:

[Ellis, Einhorn, Quigg 1976;
Carlson and Suaya 1976;
Kuhn 1980; Degrand, Toussaint 1980;
Kuhn, Nussinov, Ruckl 1980;
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Color Singlet Model

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Color Singlet Model

- QQ is produced by parton collisions at zero relative momentum.
- Quantum numbers (spin and color) are the same as those of the physical final state.
- Probability of formation is related to $\psi(0)$, the same for each multiplet, determined from decays.
- Absolute predictions

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Berger, Jones 1981]

Color Evaporation Model

[Fritzsch 1977;
Halzen 1977]

- QQ is produced by parton collisions with invariant mass less than threshold.
- All possible states can evolve to a given quarkonium regardless of the color/spin.
- Probability of formation is universal and specific only to the quarkonium state. (Though, not related to decay).

Production in hadronic collisions

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Color Evaporation Model

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NRQCD

[Caswell and Lepage 1986
Bodwin, Braaten and Lepage 1995]

- QCD effective theory for heavy quark -antiquark pair.
- Theoretically consistent and systematically improvable.
- One setup for production and decays.
- Based on the factorization theorems
- Its applicability depends on the behaviour of the expansion in v.
- The factorization approach includes the CSM and CEM as special cases.

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

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

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

Production mechanisms

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

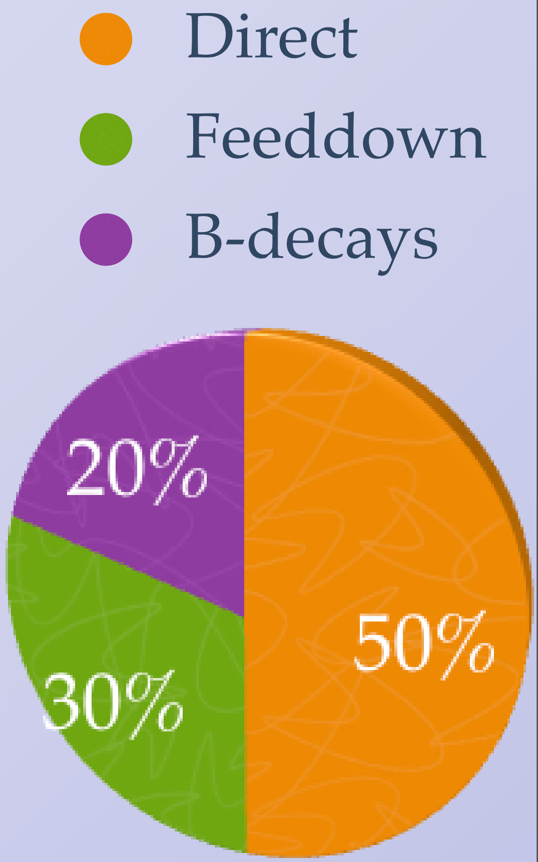
- In the case of J/ψ production at the Tevatron, contributing mechanisms include:

    - 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]

Prompt

    - 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]

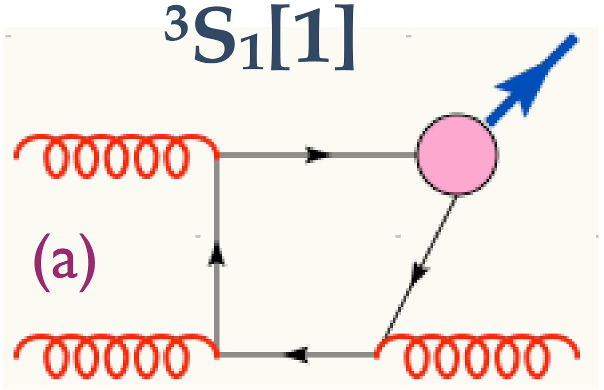
    - direct production....



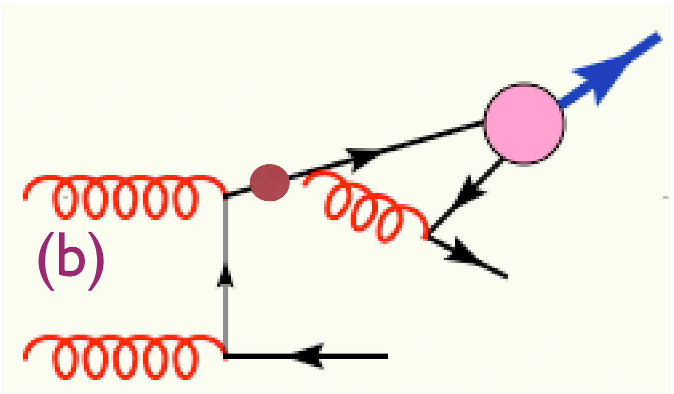
Scaling and dominant contributions

$^3S_1[1]$

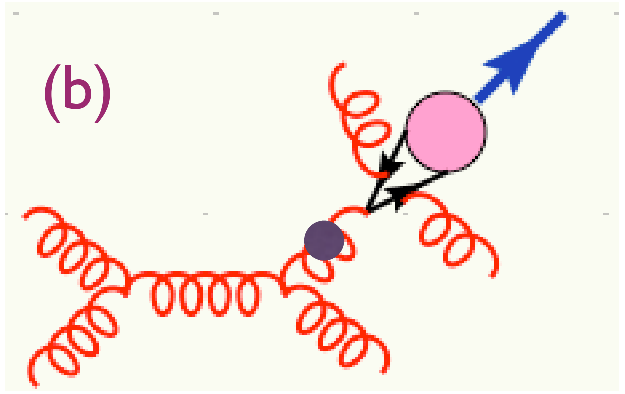
Starting with the singlet LO+frag contributions..



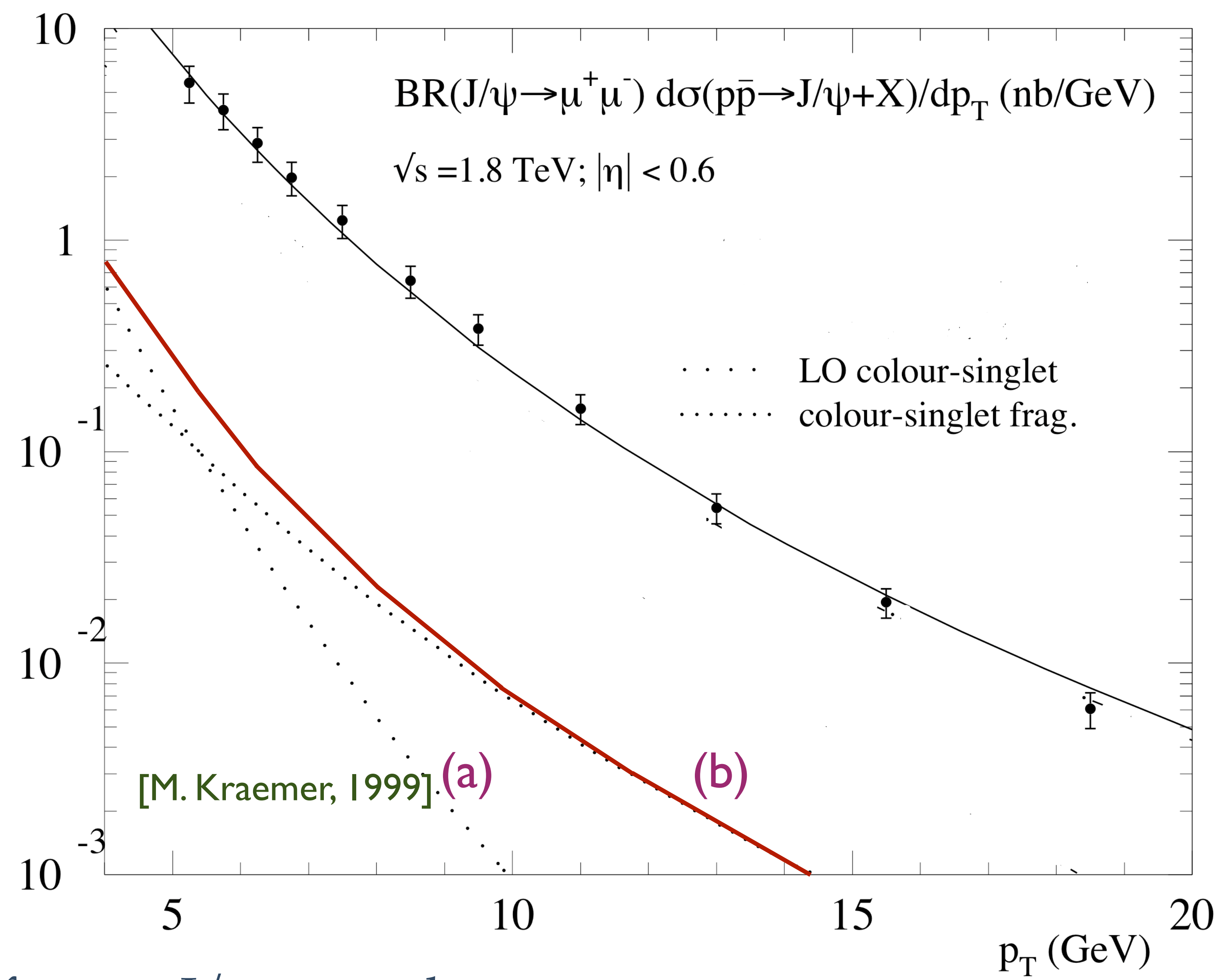
$$\alpha_S^3 \frac{(2m_c)^4}{p_T^8}$$



$$\alpha_S^4 \frac{1}{p_T^4}$$



$$\alpha_S^5 \frac{1}{p_T^4}$$

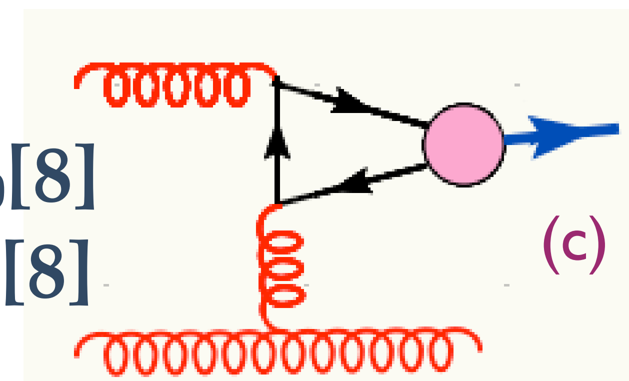


leads to the famous J/ψ anomaly...

Scaling and dominant contributions

Higher terms in v have a different scaling in p_T...

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



(c) $\alpha_S^3 \frac{(2m_c)^2 v^4}{p_T^6}$

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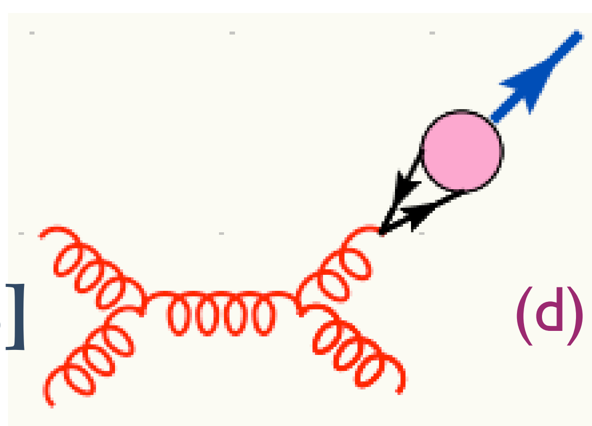

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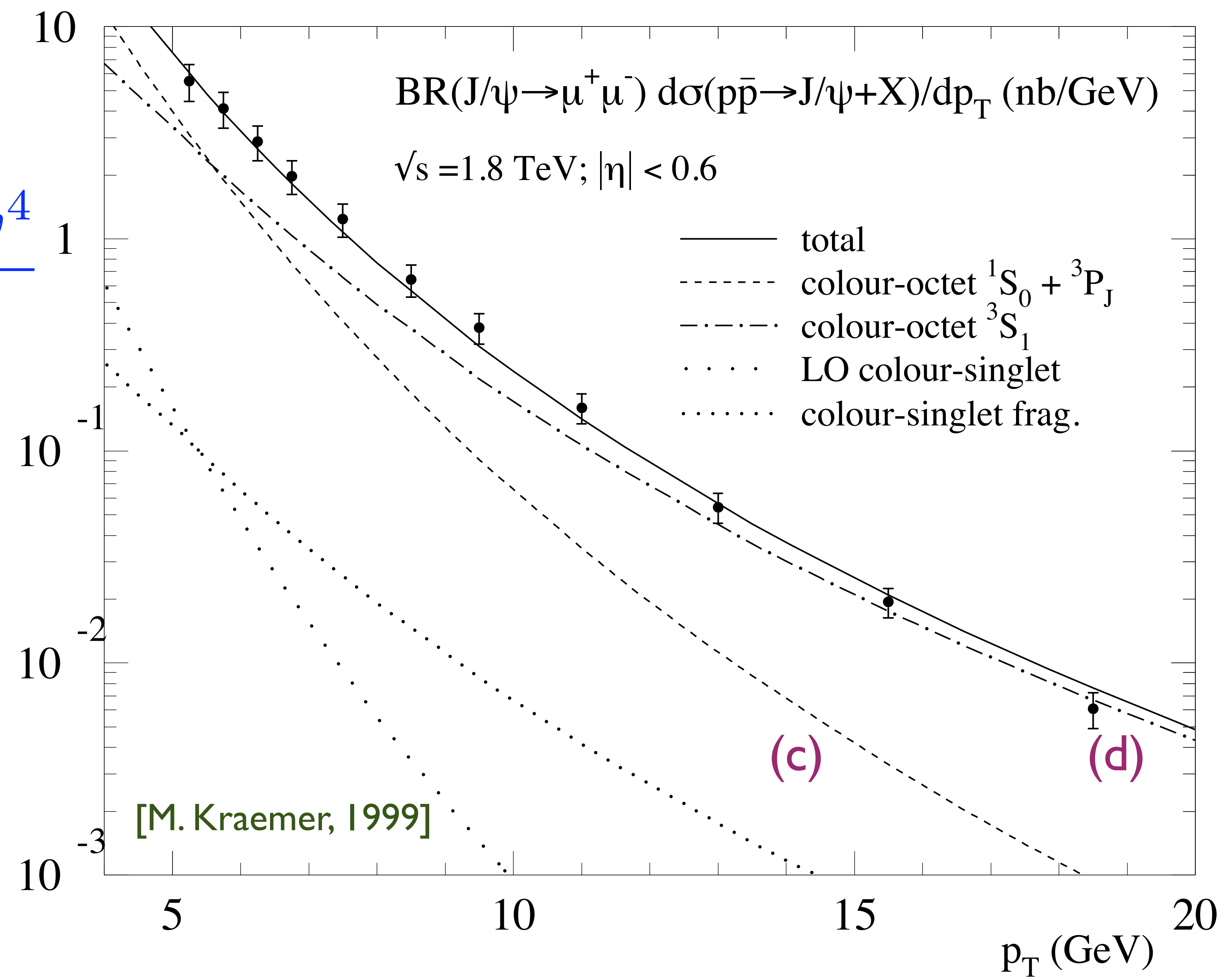

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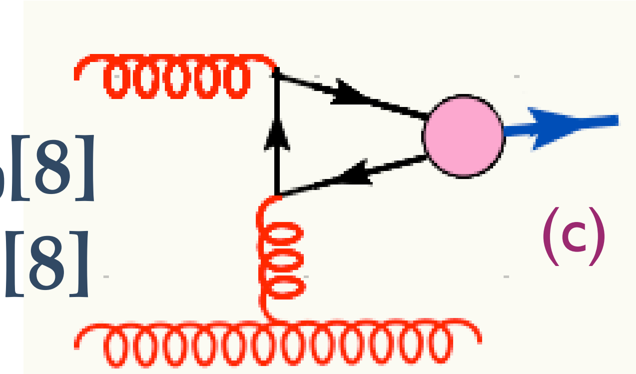

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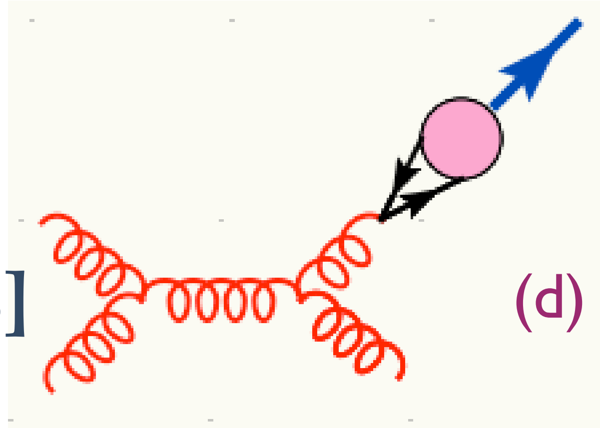

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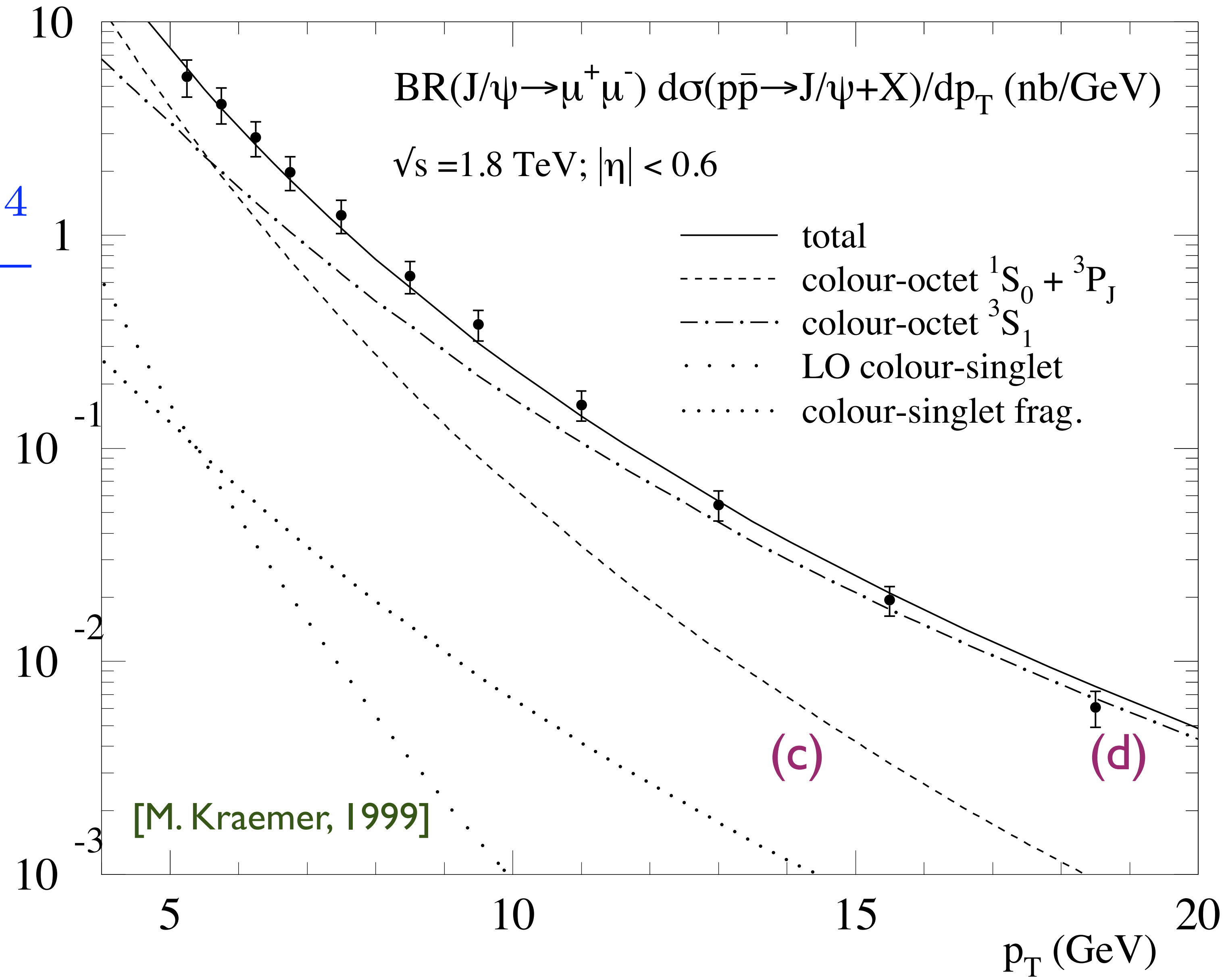
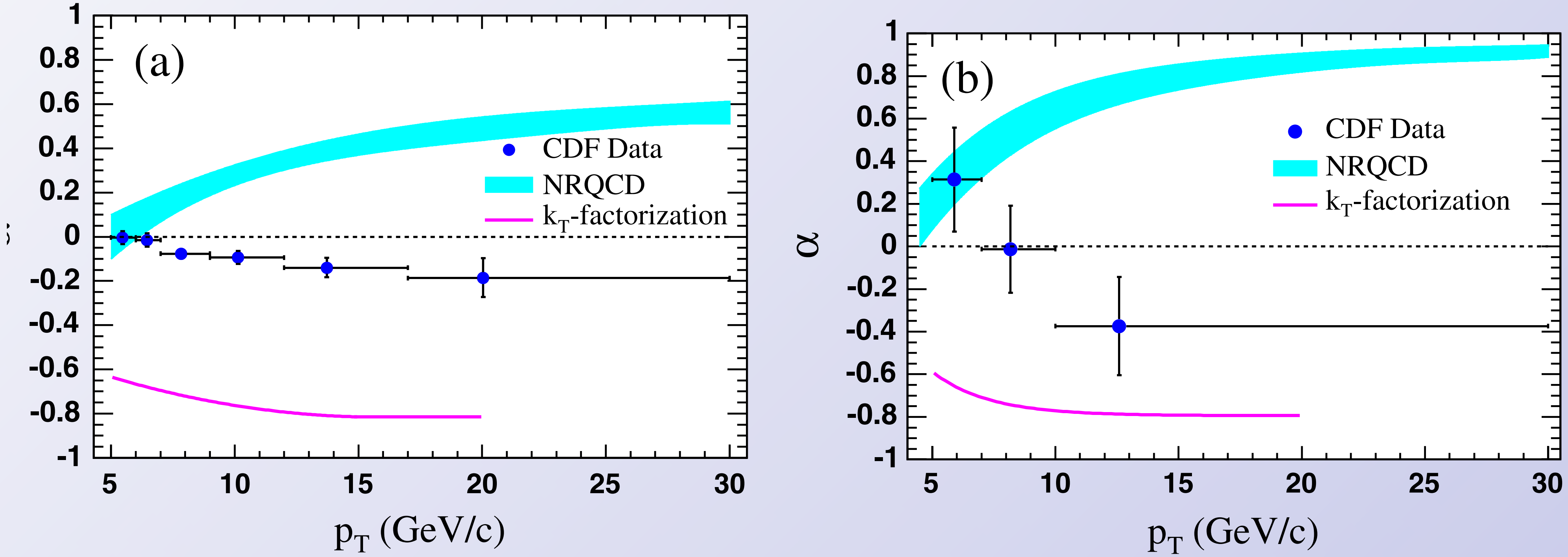


Are we done?

The polarization puzzle

[CDF collaboration, 07]

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



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. Overall we are comparing with a LO picture and one observable might not be enough...

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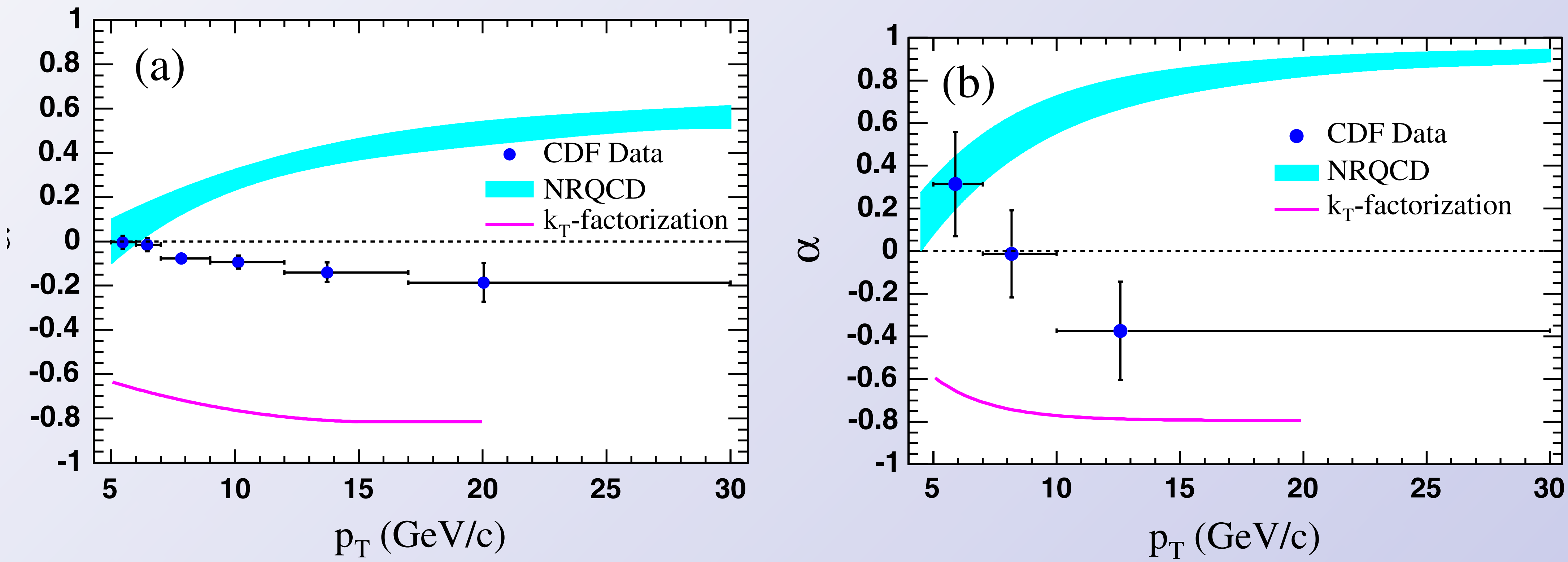

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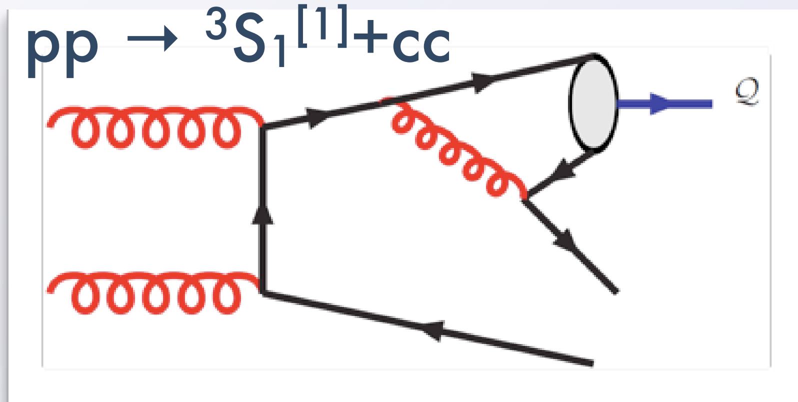
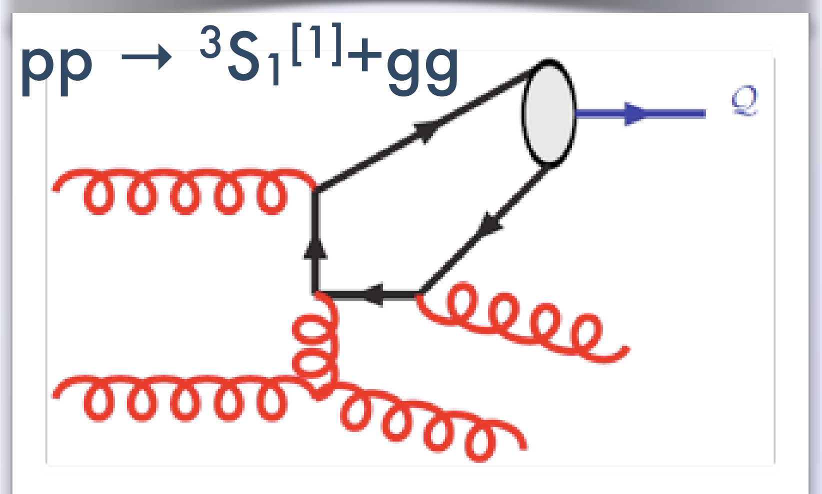
Let's start again from the singlet...

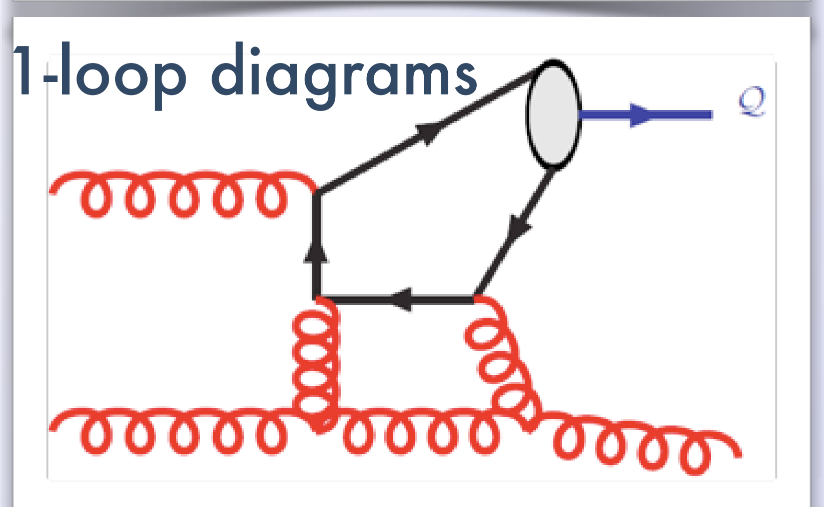
α_s correction to the color-singlet transition

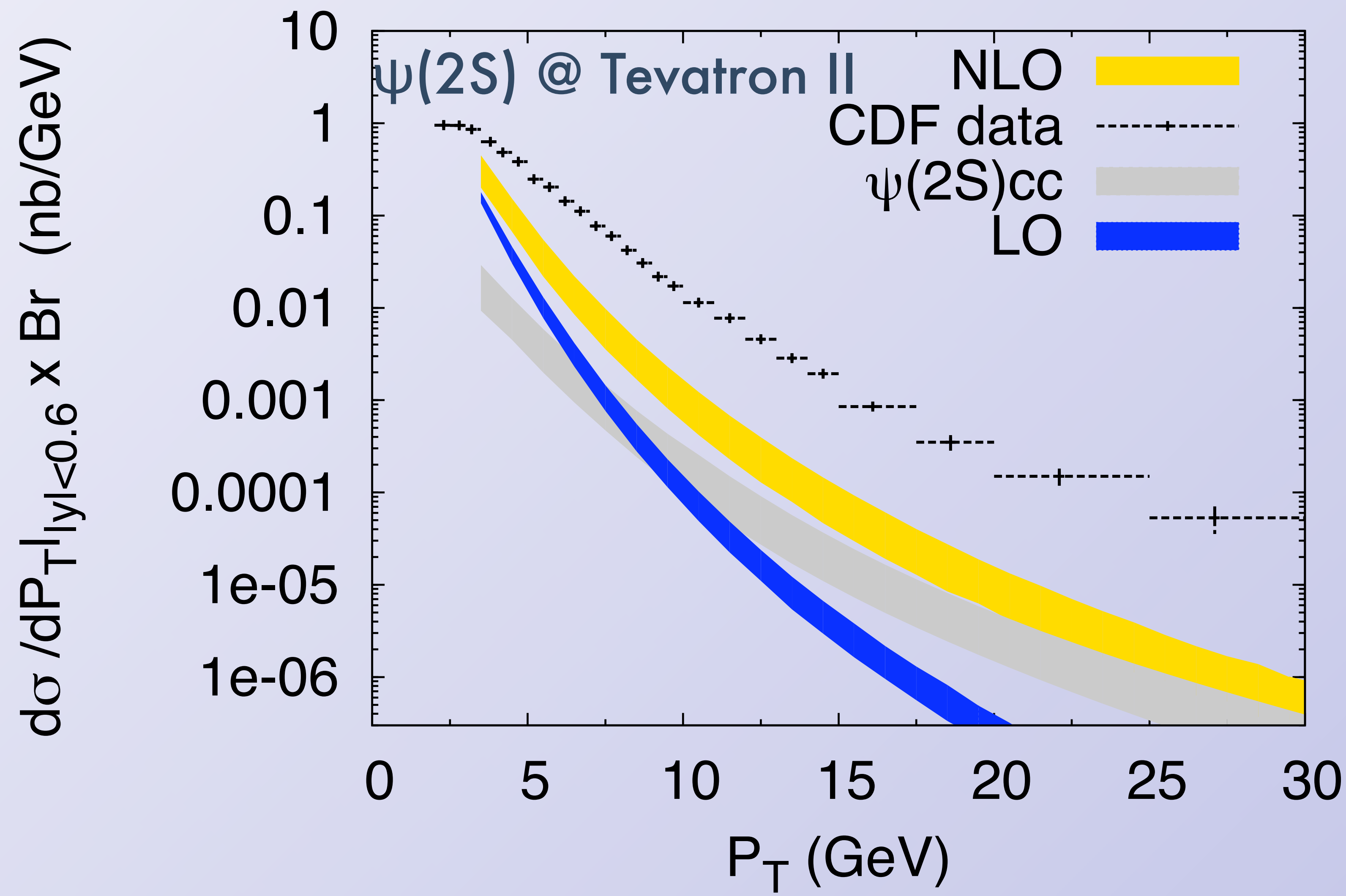
[Campbell, FM, Tramontano, 2007]

- New contributions at α_s^4









- 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

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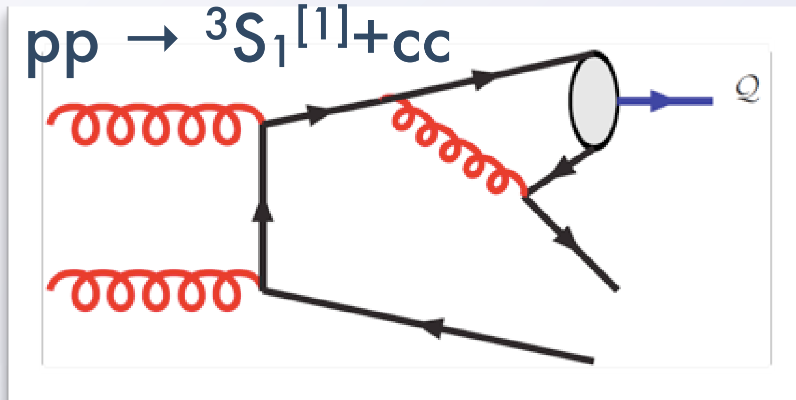
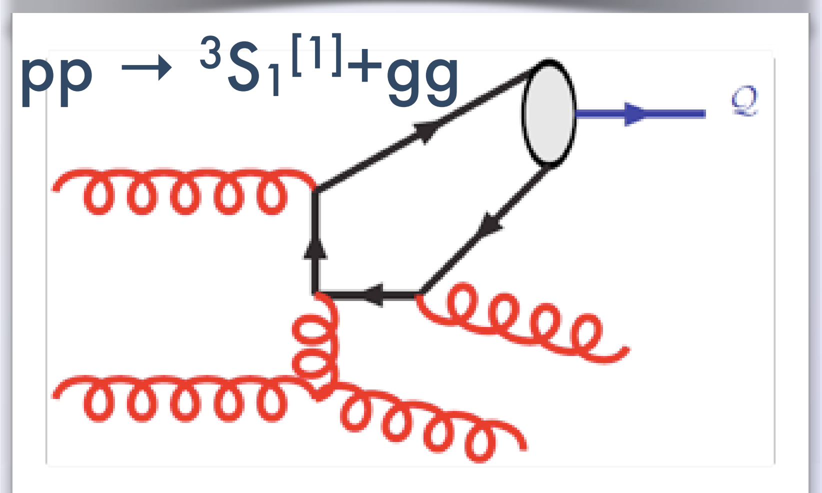
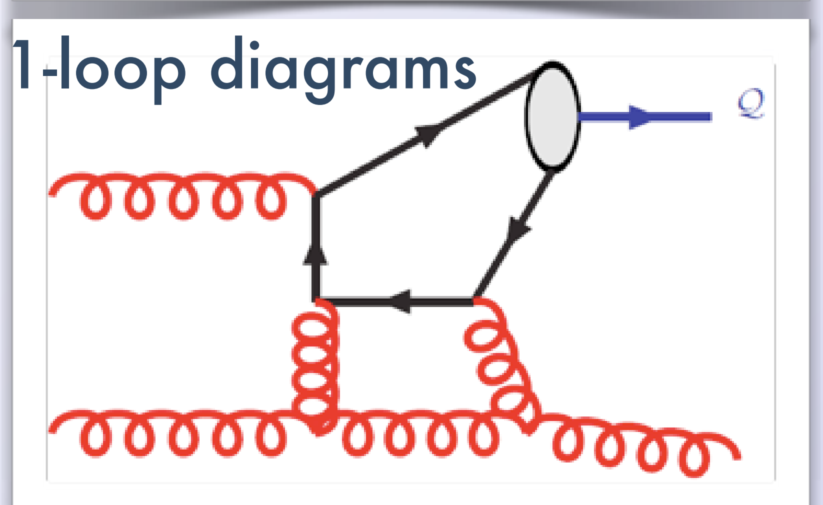
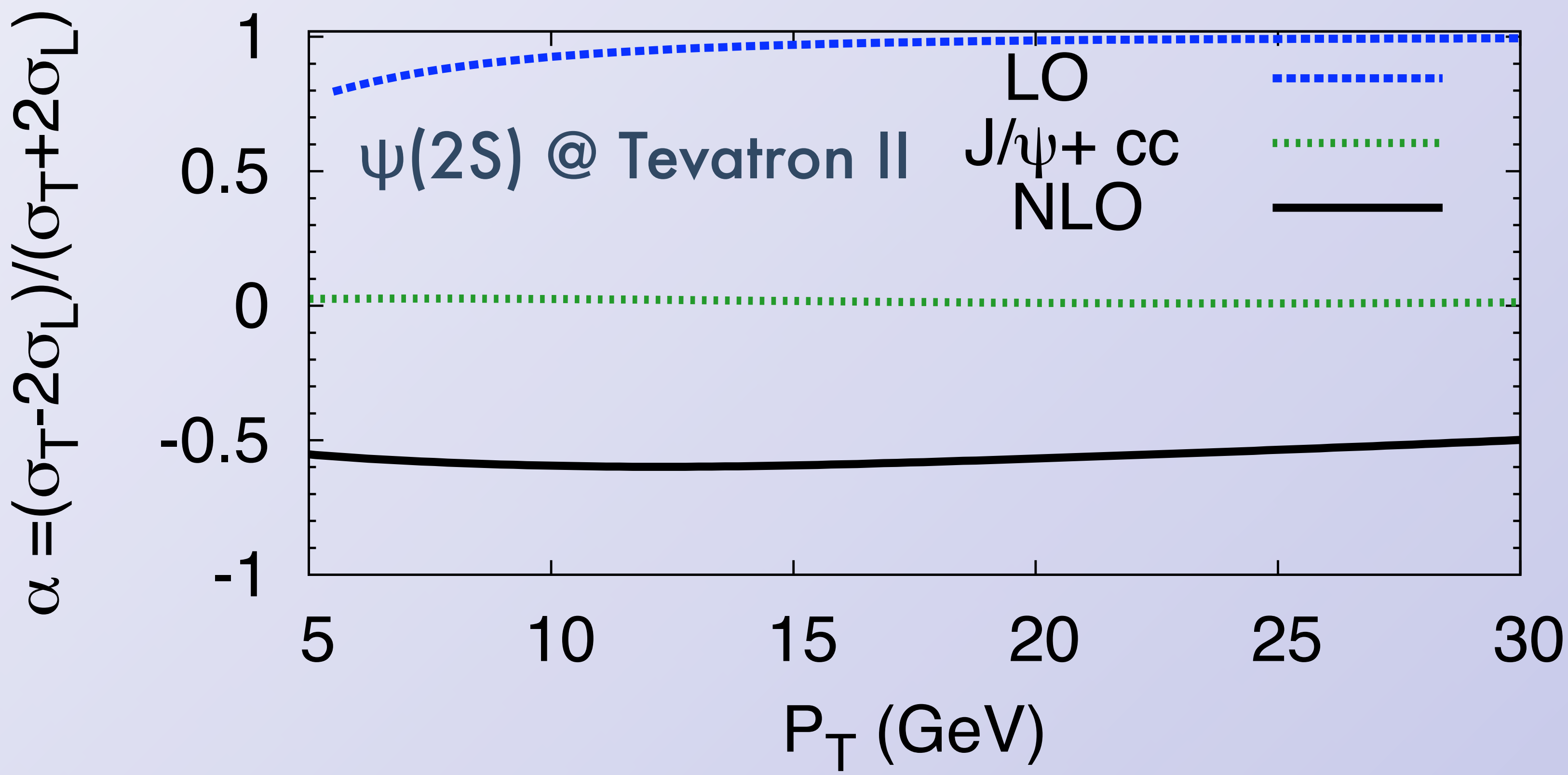




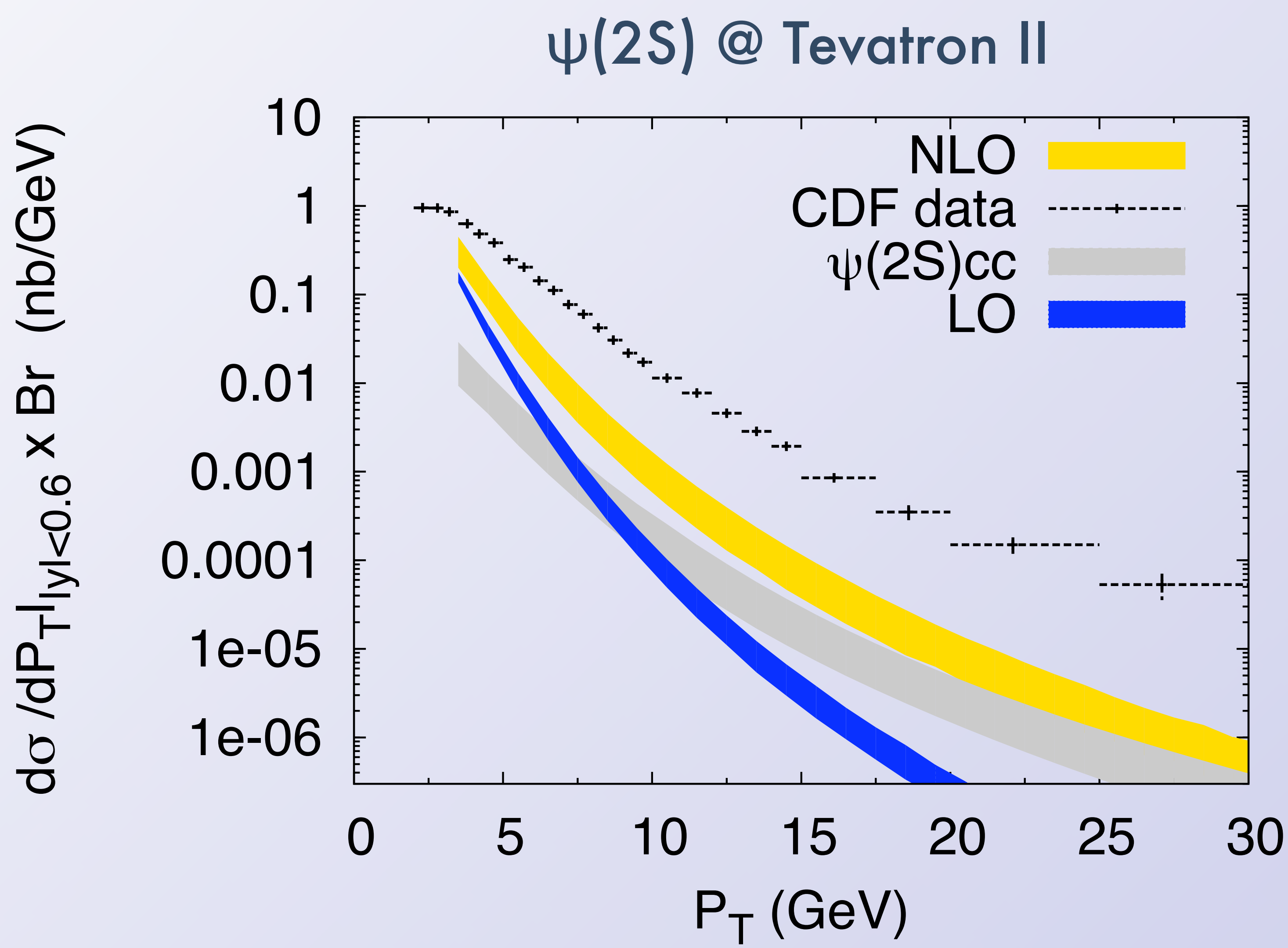




- New channels at α_s^4 strongly affect the polarization parameter α (polar asymmetry in the c.m. helicity frame)
- Polarization is longitudinal component at NLO
- Large correction may arise at order α_s^5 because new channels with a different p_T scaling open up at that order. One of them is the gluon fragmentation $g^* \rightarrow {}^3S_1^{[1]}$ ...

What now?

[Campbell, FM, Tramontano, 2007]



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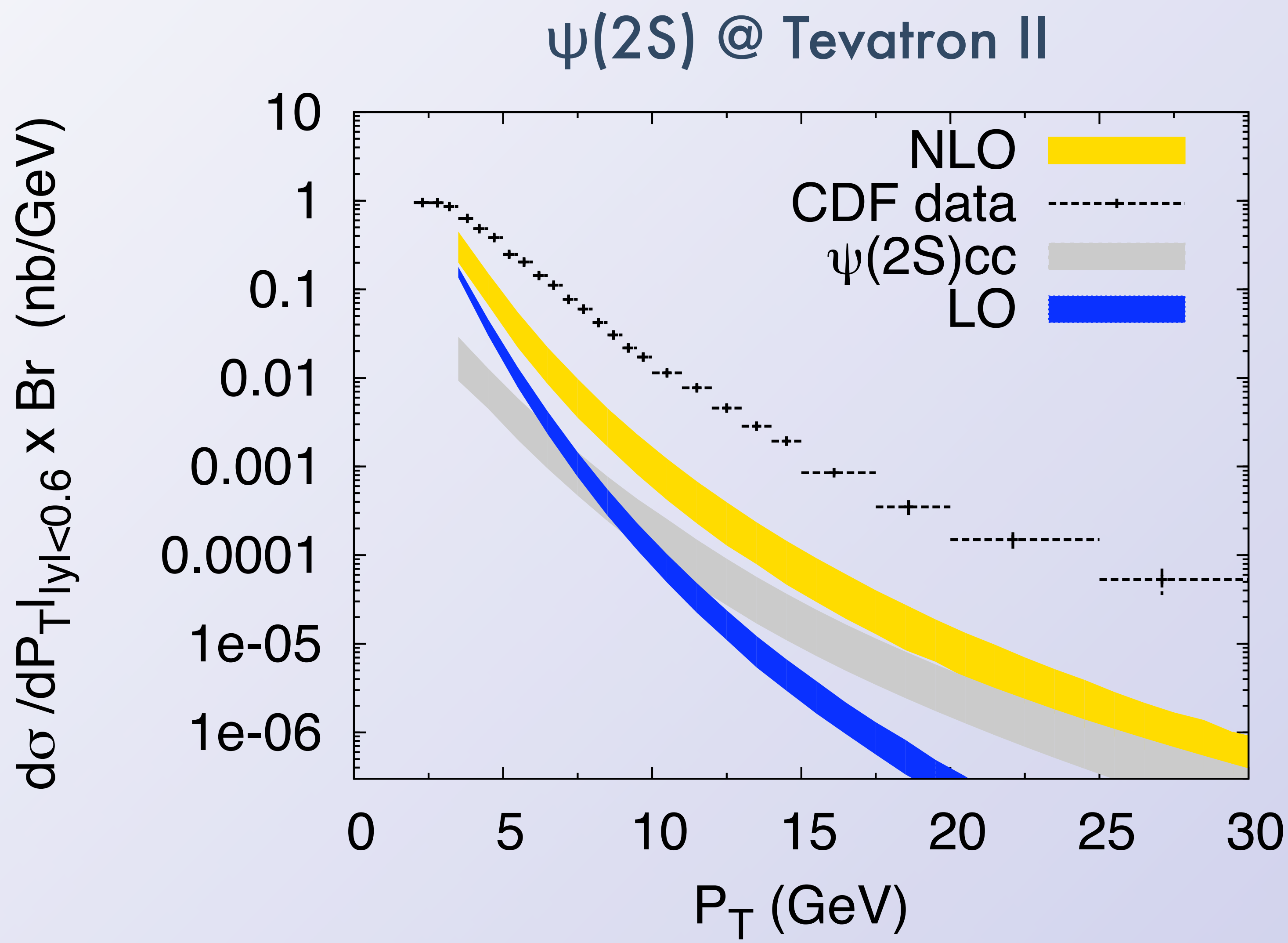

1. Add the octets, fitting them to the data.

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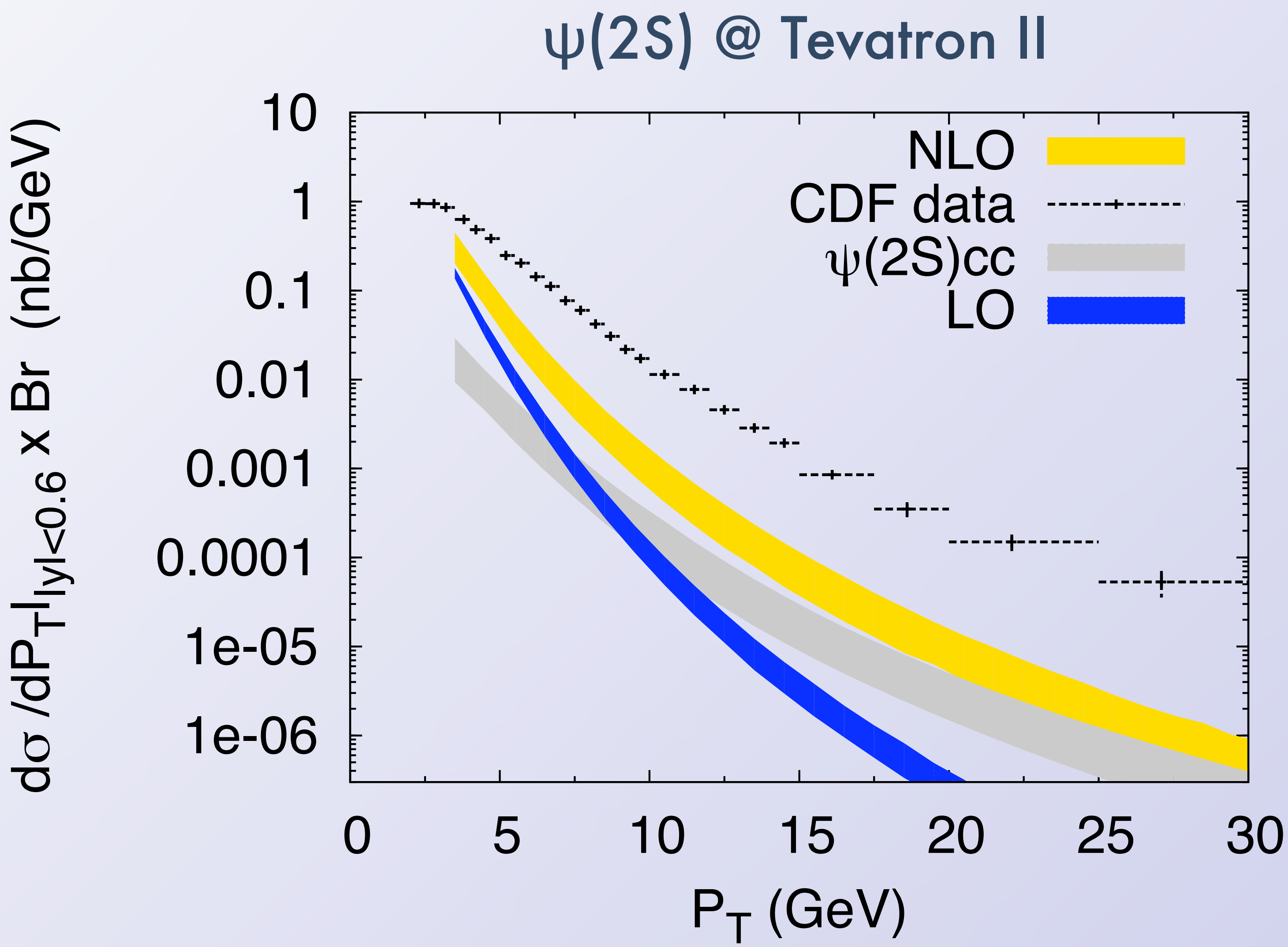

1. Add the octets, fitting them to the data.
2. Check higher order corrections...!!*

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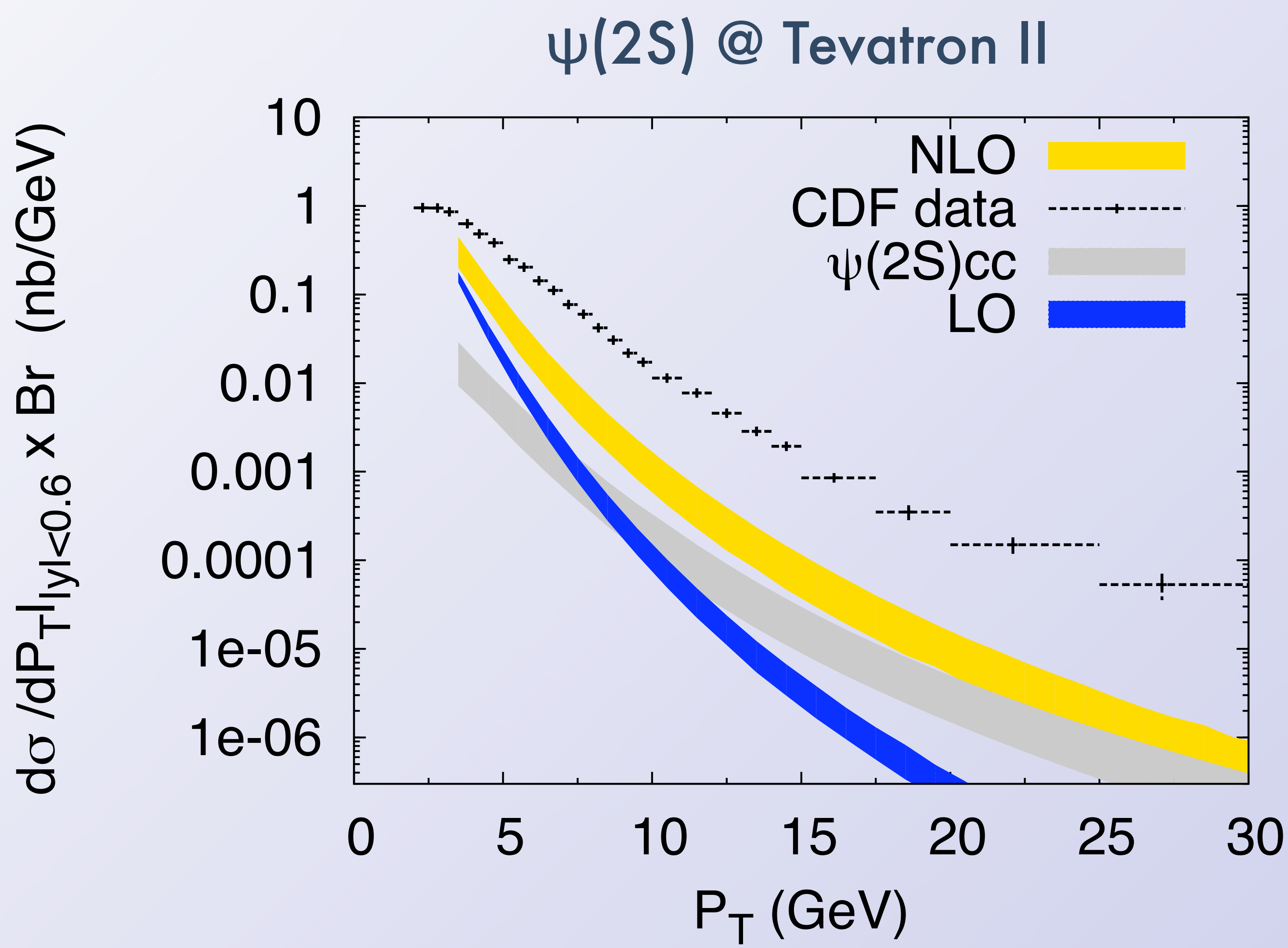

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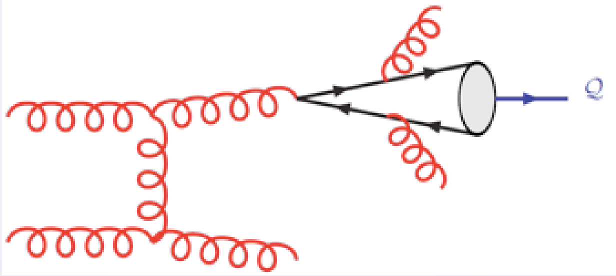
* a.k.a. "Color Singlet Model on steroids" ☺

Including NNLO dominant terms (α_s^5)

[Artoisenet, Campbell, Lansberg, FM, Tramontano, 2008]

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



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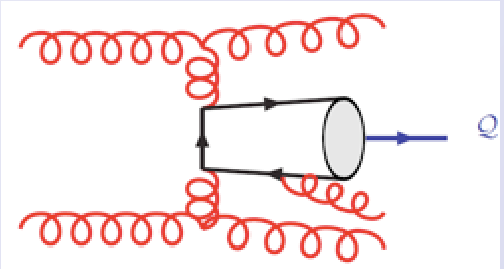
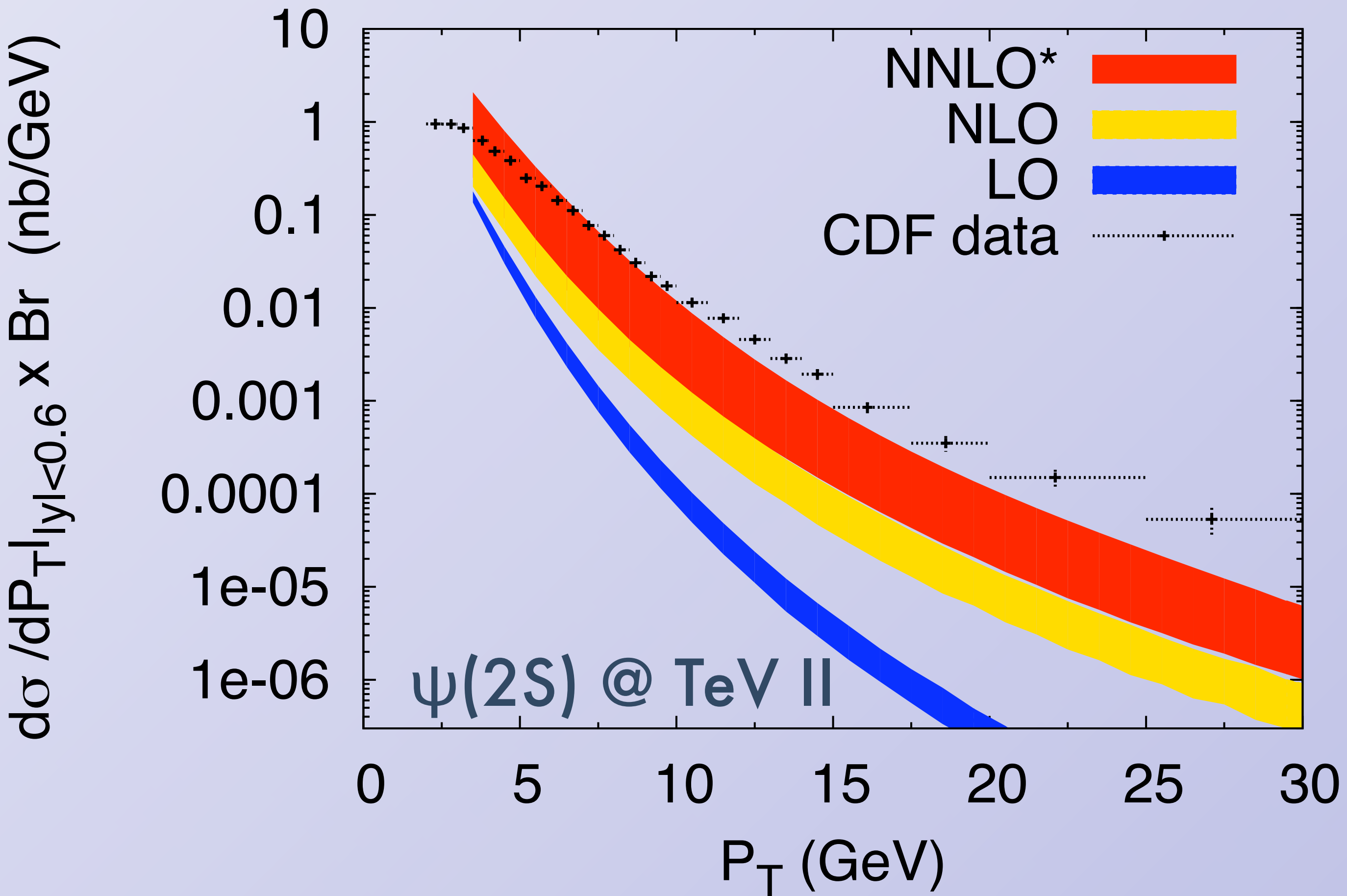


+ ... (≈1k diagrams)

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

- IR cutoff logarithmic dependence expected to disappear at large p_T, but sizable at moderate p_T.
- Work extremely well at NLO.
- This gives a large uncertainty on the normalization, the shape is rather stable though.
- Opening gap as p_T increases



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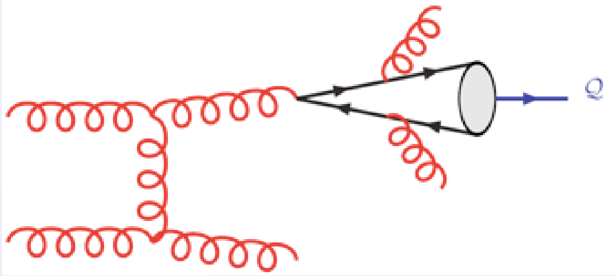

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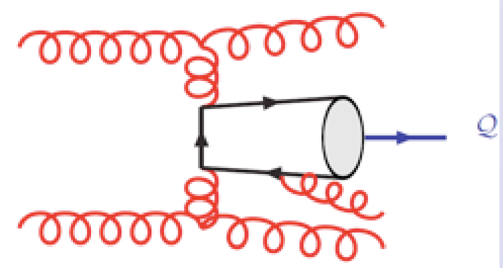

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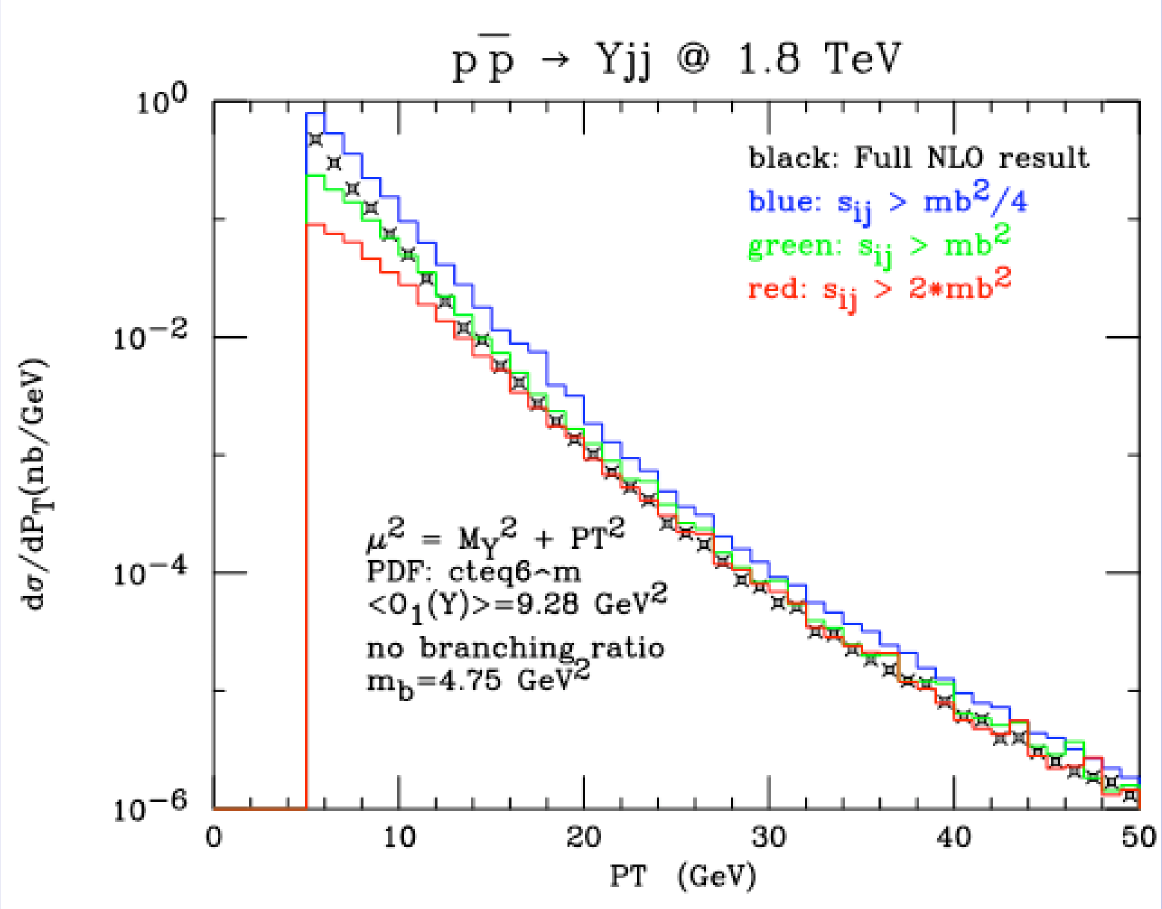

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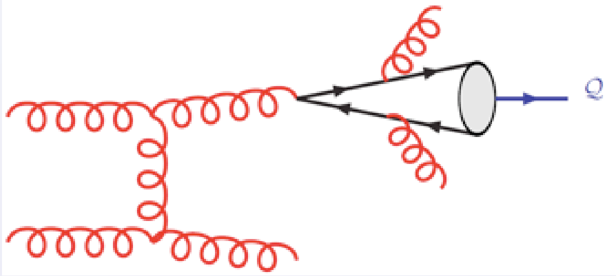

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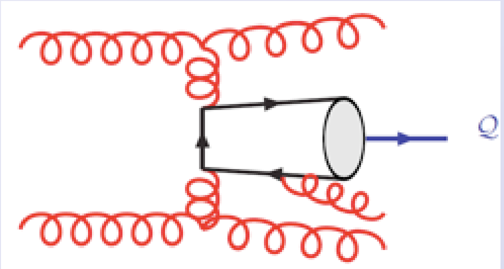

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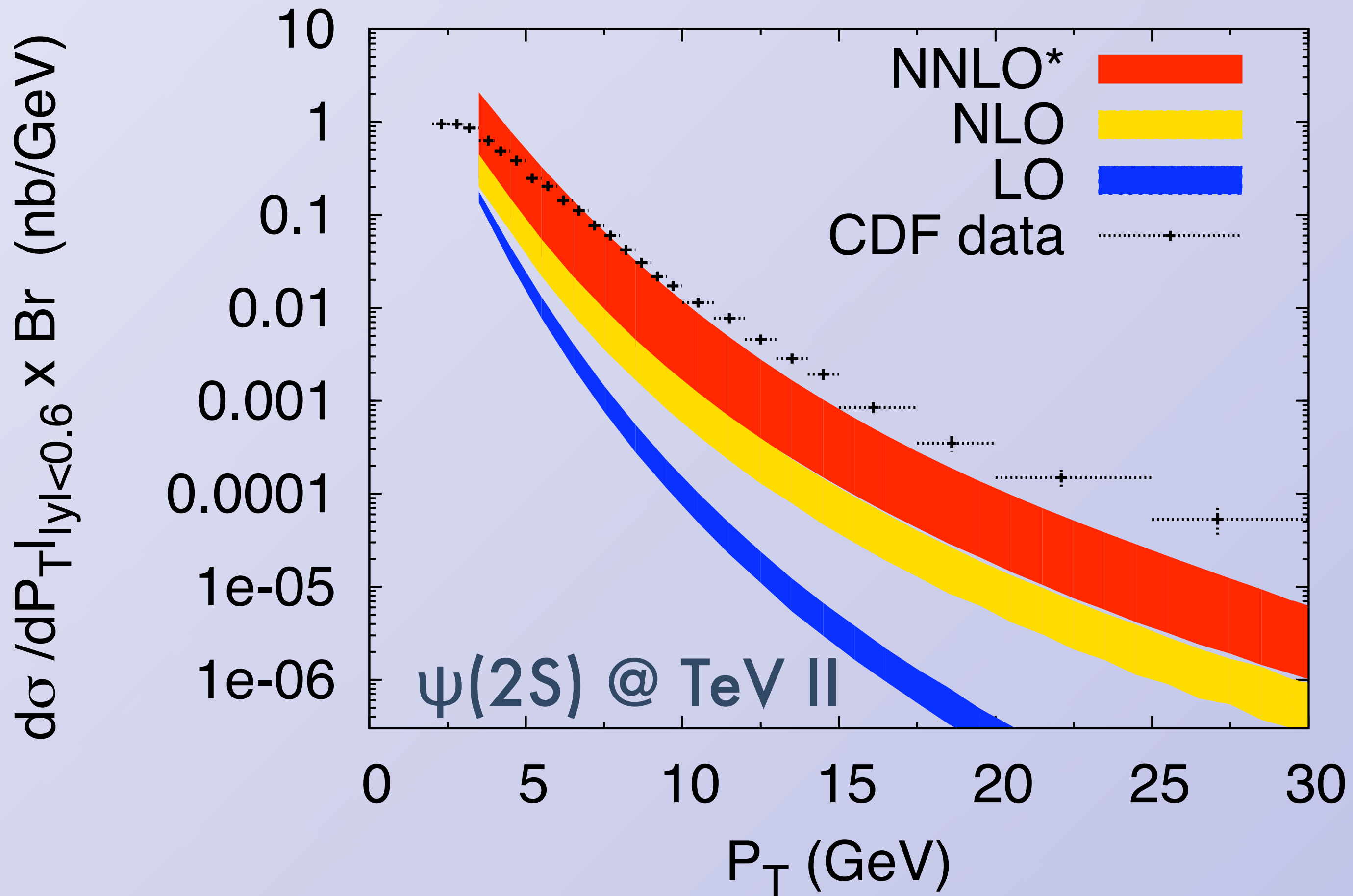
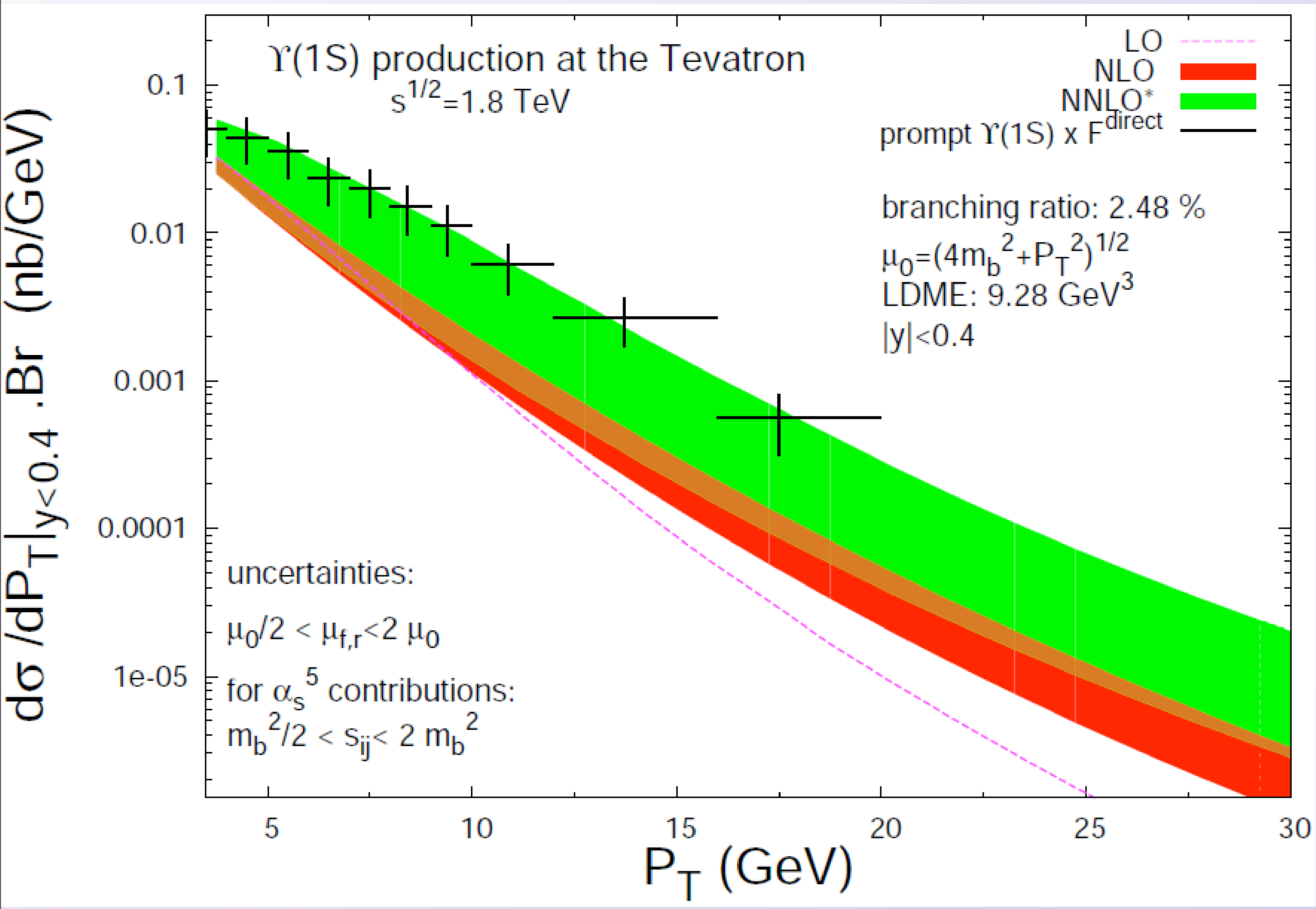


Υ production : Status TH vs EXP

[Artoisenet, Campbell, Lansberg, FM, Tramontano, 2008]

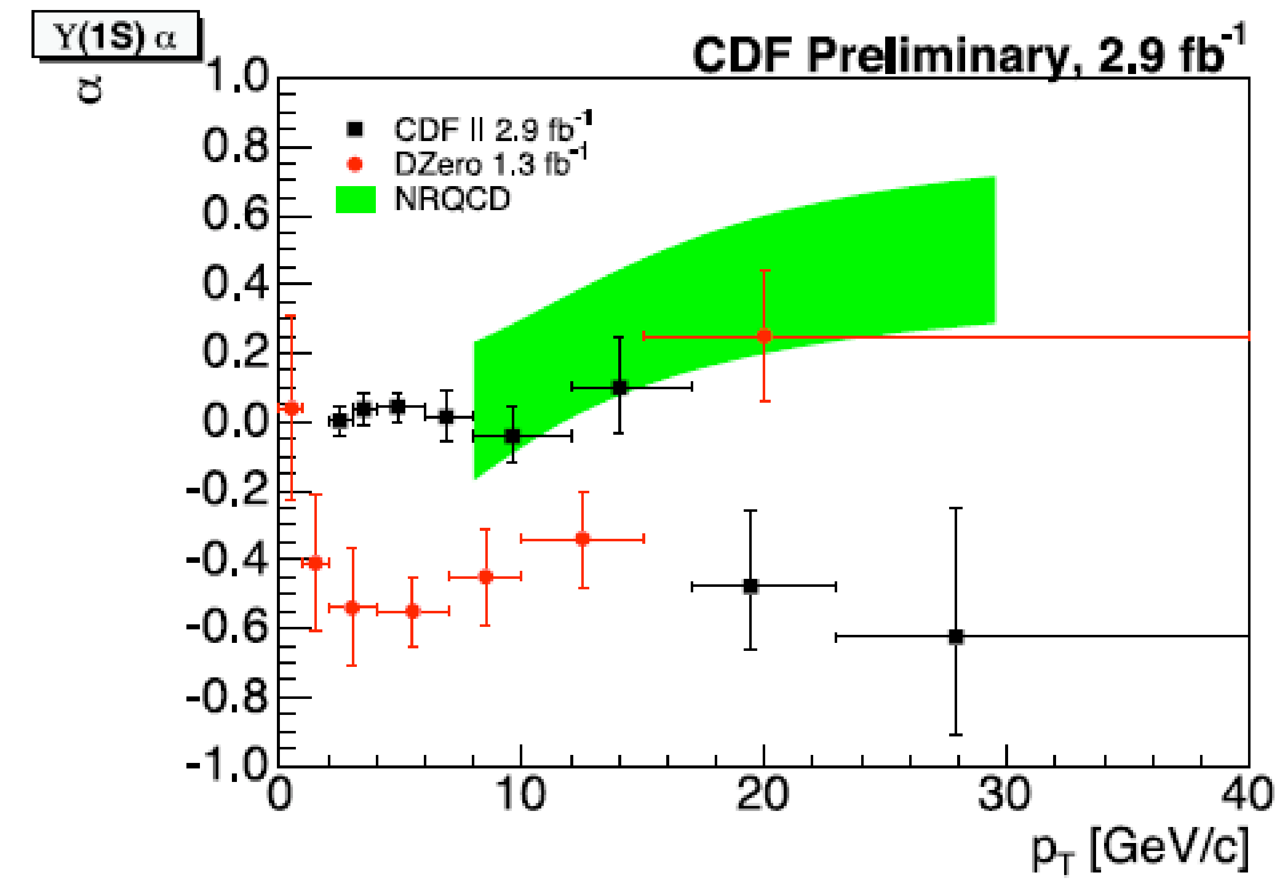
- p_T distribution

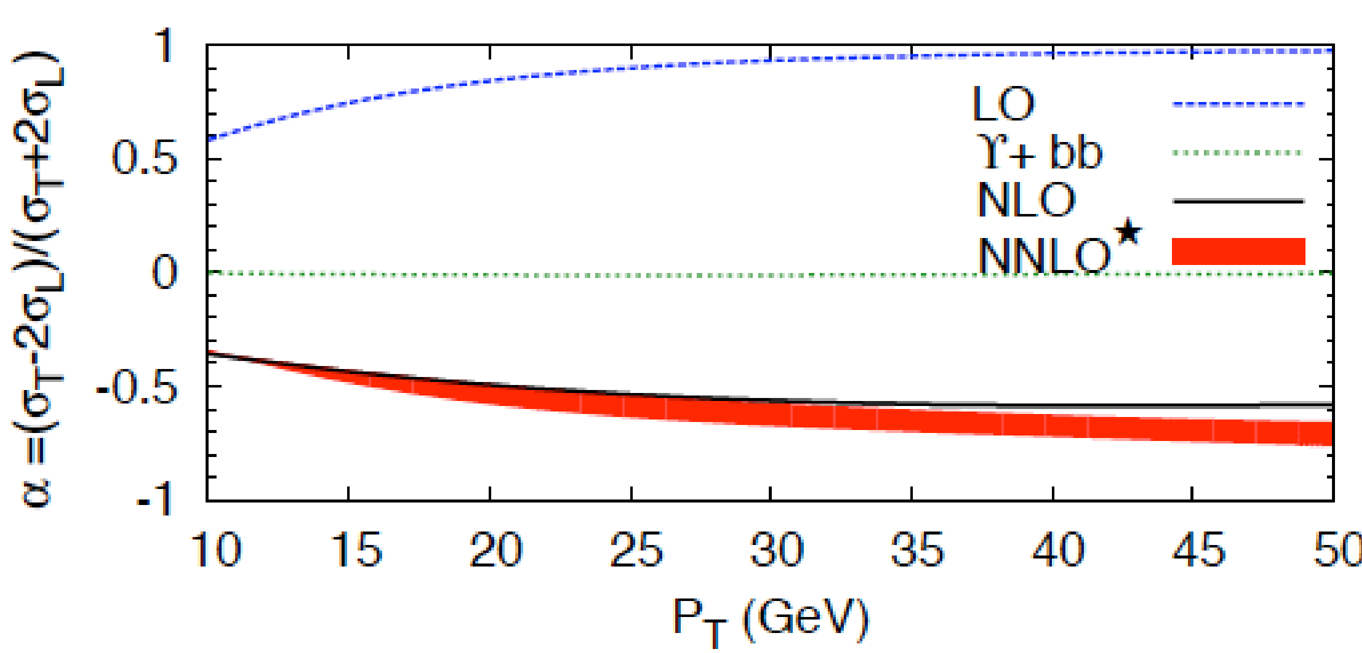


- smaller gap between CS at NLO and the data, a with p_T
- α_s^5 channels may provide the missing contribution: the shape is in good agreement with the data, but large uncertainties on the normalization.
- The $(1/p_T)^n$ re-organization could reduce the uncertainties further...

Y production : Status TH vs EXP

- polarization. Left: prompt TH (LO) vs EXP . Right: direct TH (NNLO*)



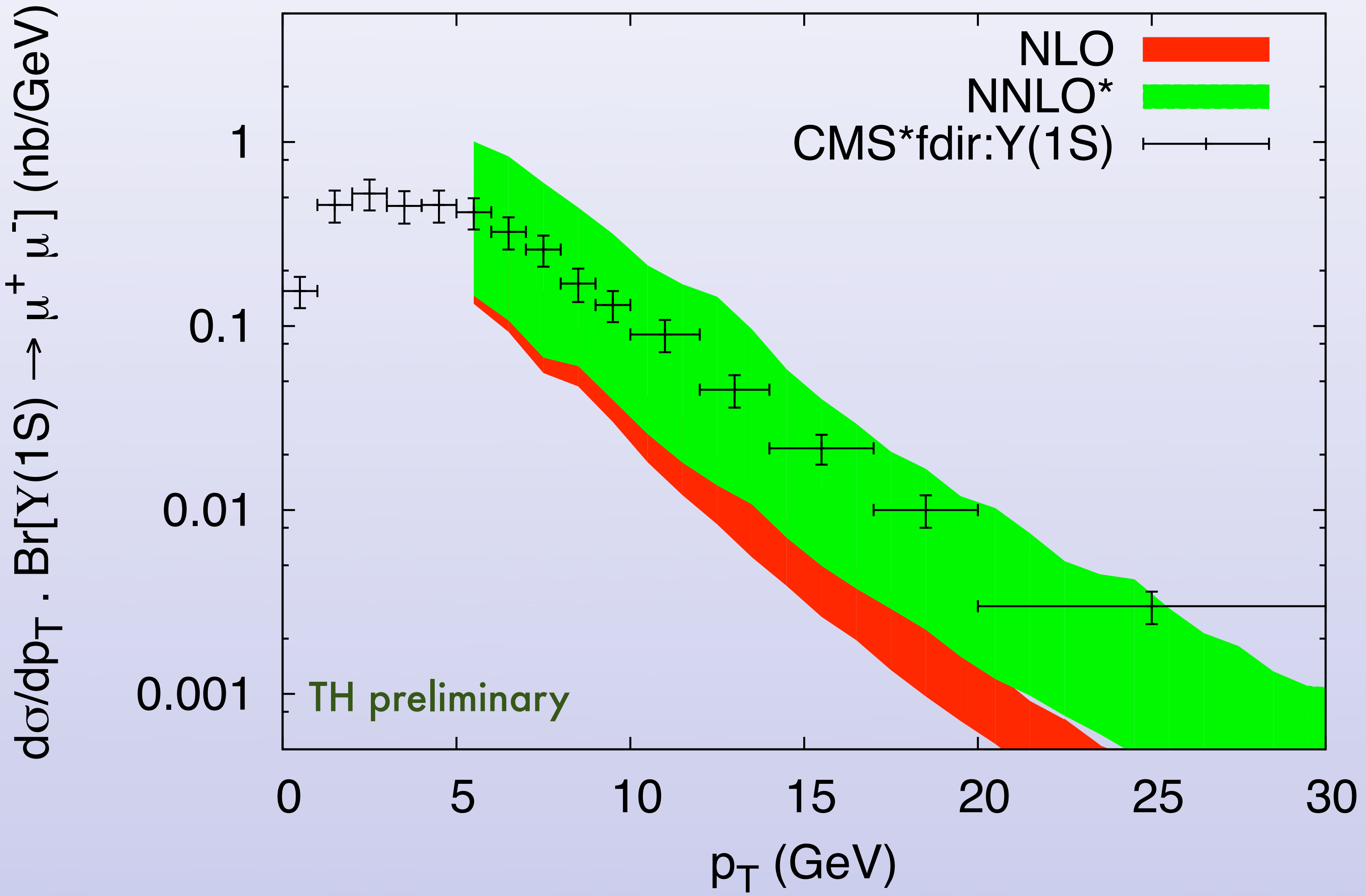


[Artoisenet, Campbell, Lansberg, FM, Tramontano, 2008]

Experimental issue at Tevatron? Looking forward to the LHC data to confirm or disprove the CS dominance in the Y case.

Y(1S) production : Status TH vs EXP

[using the calculation presented in Artoisenet, Campbell, Lansberg, FM, Tramontano,2008]



fdir=0.5

|y|<2

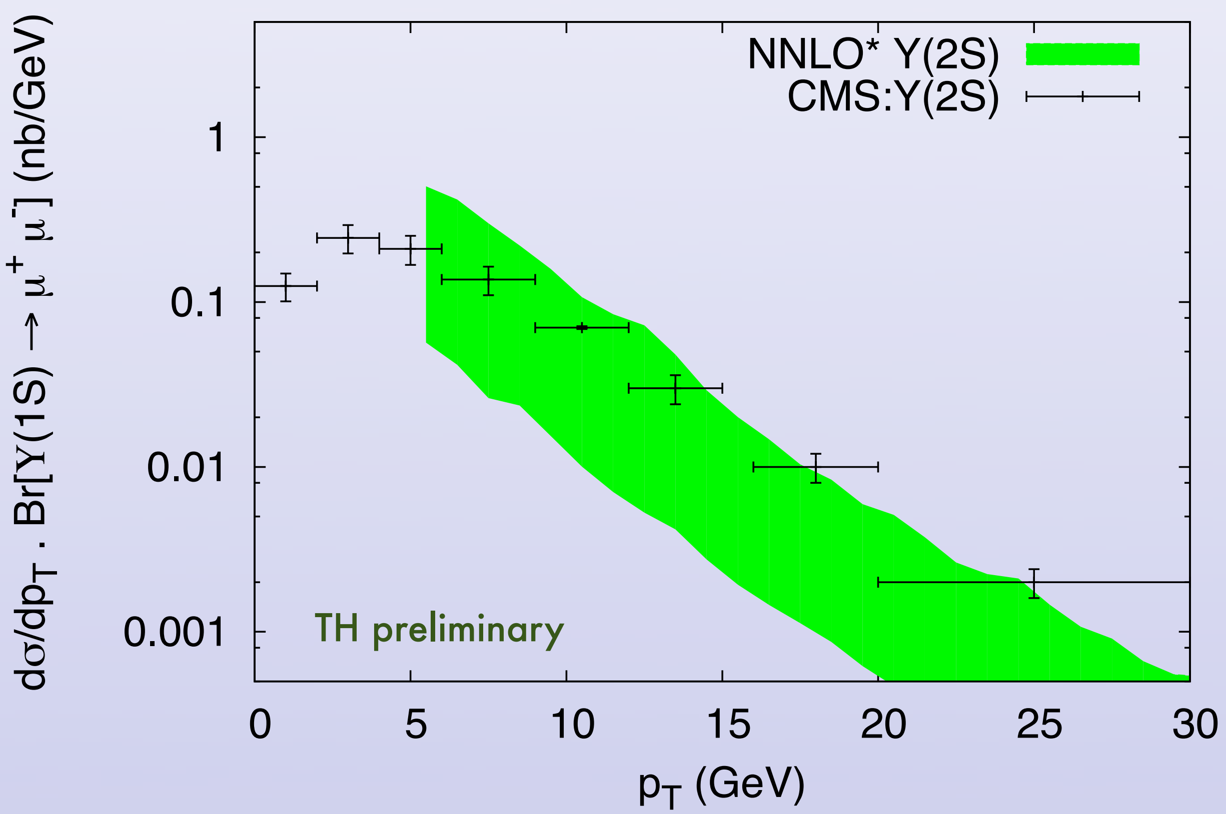
$\sqrt{s}$ = 7 TeV

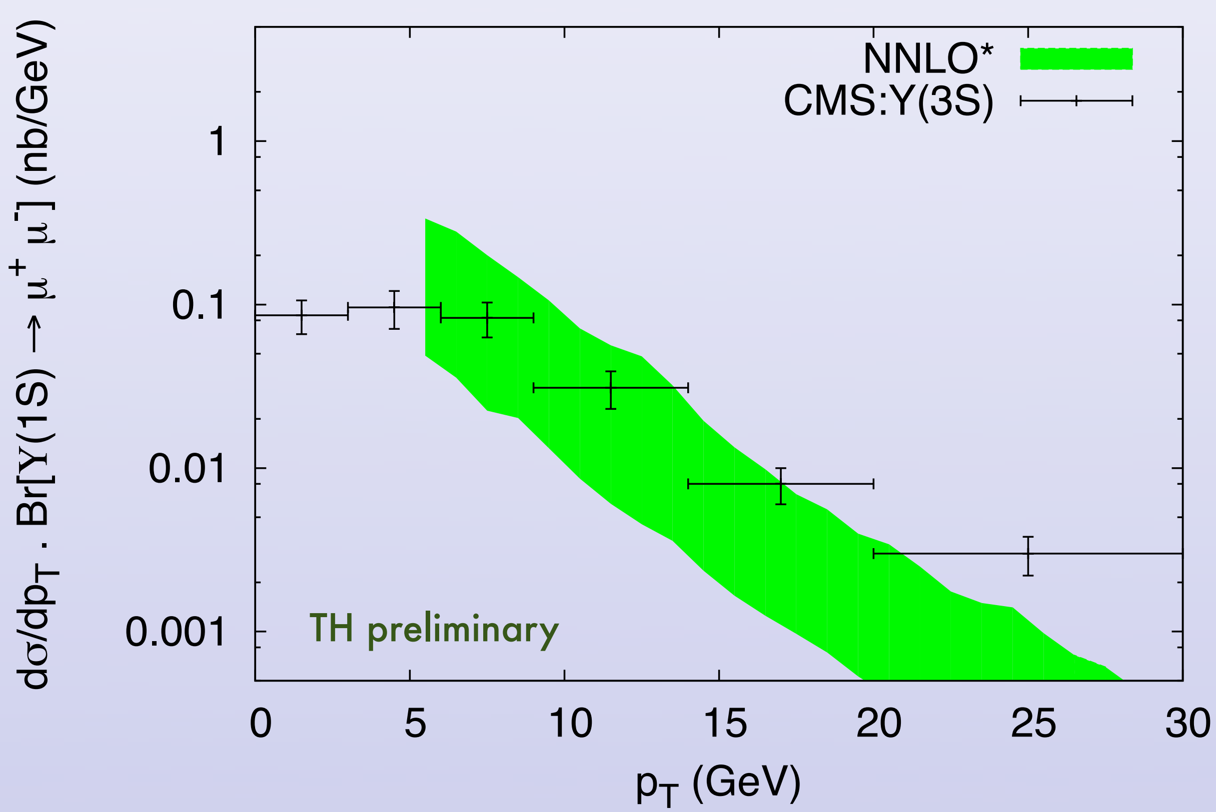
NO free parameters!

Data: CMS PAPER BPH-10-003

Y(2S) & Y(3S) production : Status TH vs EXP

[using the calculation presented in Artoisenet, Campbell, Lansberg, FM, Tramontano,2008]

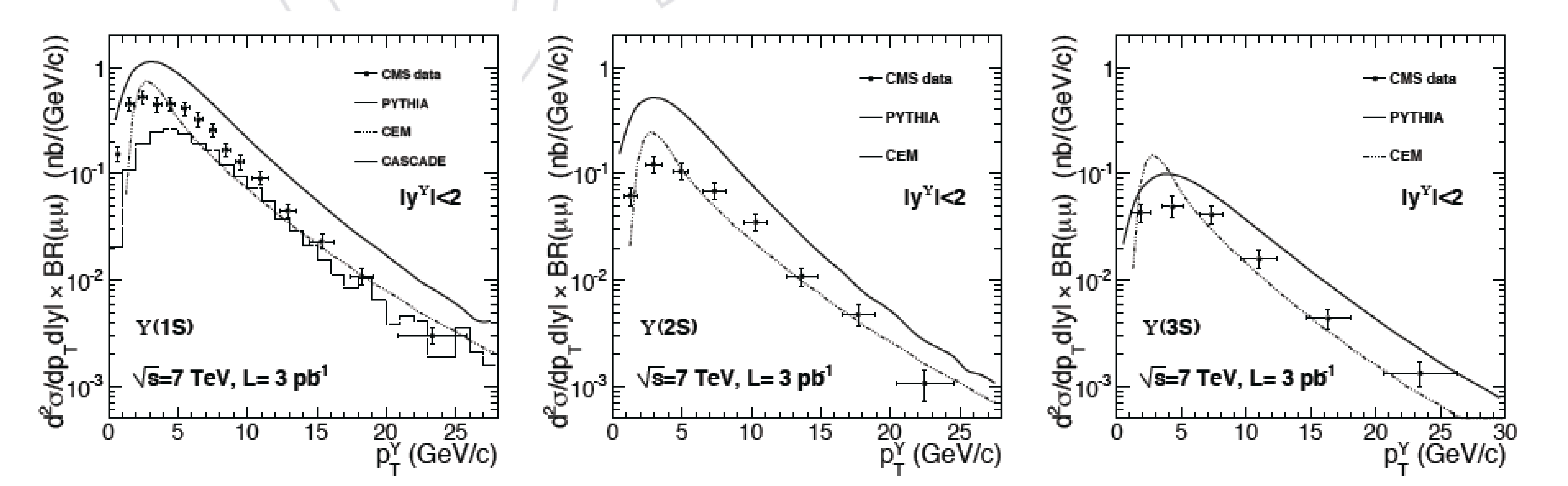




fdir=1 |y|<2 $\sqrt{s}$ = 7 TeV

Data: CMS PAPER BPH-10-003

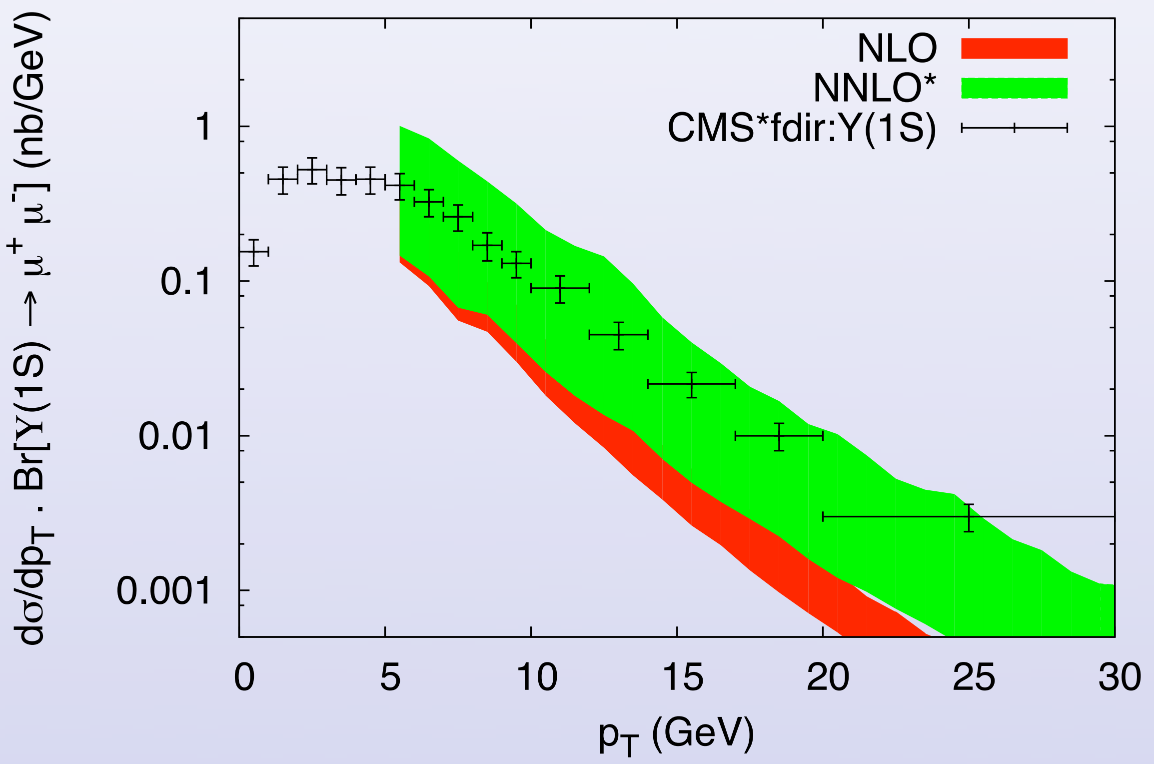
Υ production : Status TH vs EXP



The Tevatron tune of Pythia is also kind of overshooting the data.
(Even though no error is quoted here).

From: CMS PAPER BPH-10-003

How to improve our predictions?



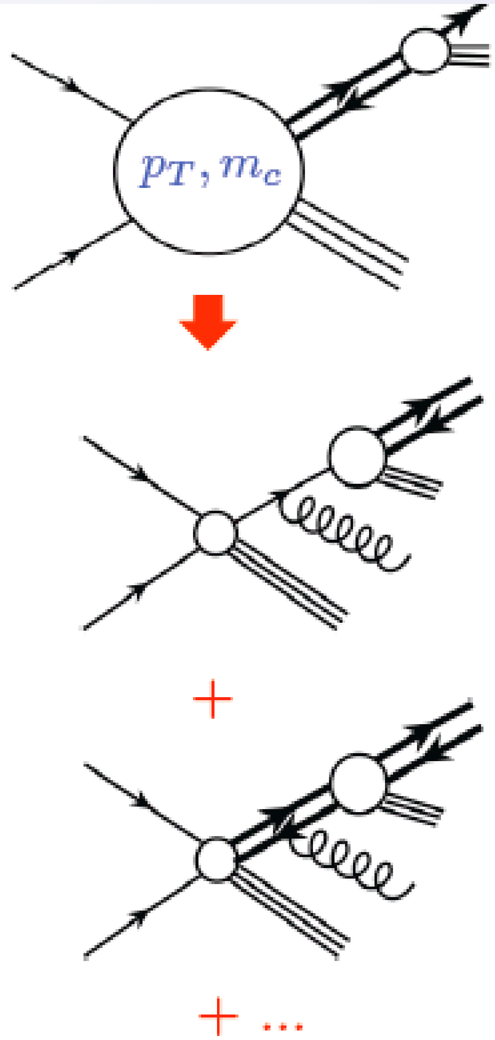
TH predictions for the singlet at NNLO* are affected by large TH uncertainties.

This is mostly due to our very rough approach and can certainly be improved:

1. Perform a suitable matching procedure to get rid of the log dependence (a la CKKW). [Artoisenet, FM]
2. Use the "Giant K-factor" method [Rubin, Salam,2010]
3. Reorganize the perturbative expansion [J. Qiu, G. Sterman]

Reorganize the expansion...

[Kang, J. Qiu, G. Sterman, 2010, in progress]



$$E\frac{d\sigma_{J/\psi}}{d^3P}:$$

High p_T: $\frac{1}{p_T^4}$ $\sigma^{\rm LP}_{ab\to f}(z,p_T,\alpha_s)\otimes D_{f\to J/\psi}(z,m_c)$

+

Medium p_T: $\frac{1}{p_T^6}$ $\sigma^{\rm NLP}_{ab\to[c\bar{c}(\kappa)]}(z,p_T,\alpha_s)\otimes D_{[c\bar{c}(\kappa)]\to J/\psi}(z,m_c)$

+

Low p_T: $\sigma^{\rm “Direct”}_{ab\to[c\bar{c}(\kappa)]}(p_T,m_c)\otimes\langle\mathcal{O}[c\bar{c}(\kappa)](0)\rangle$

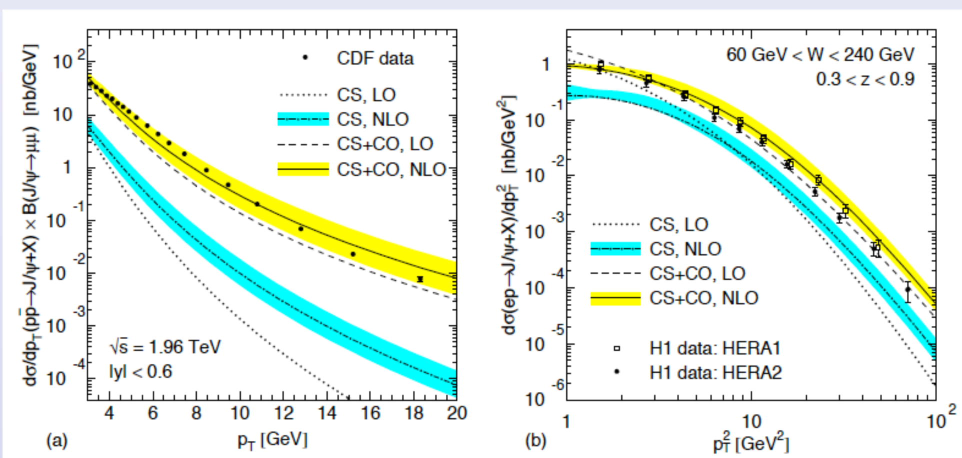
[J. Qiu's talk in QWG2010]

Reorganize the perturbative expansion order by order in $(1/pT)^n$!

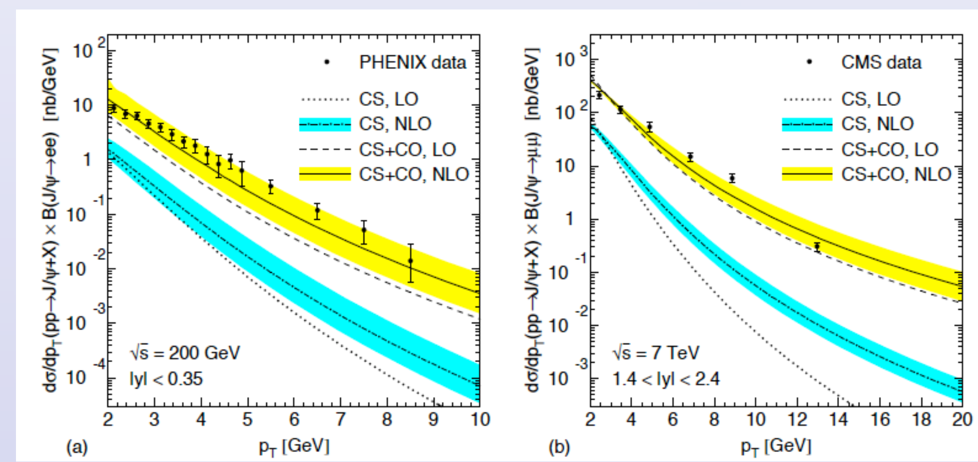
Very promising applications around the corner...!

Discussion: two strategies

- There are two possible strategies to make predictions for quarkonium at the LHC:
  - A maximally predictive one. Example J/ψ:



⇒



☺ Maximal use of other experiment information

☺ Best predictions for the LHC

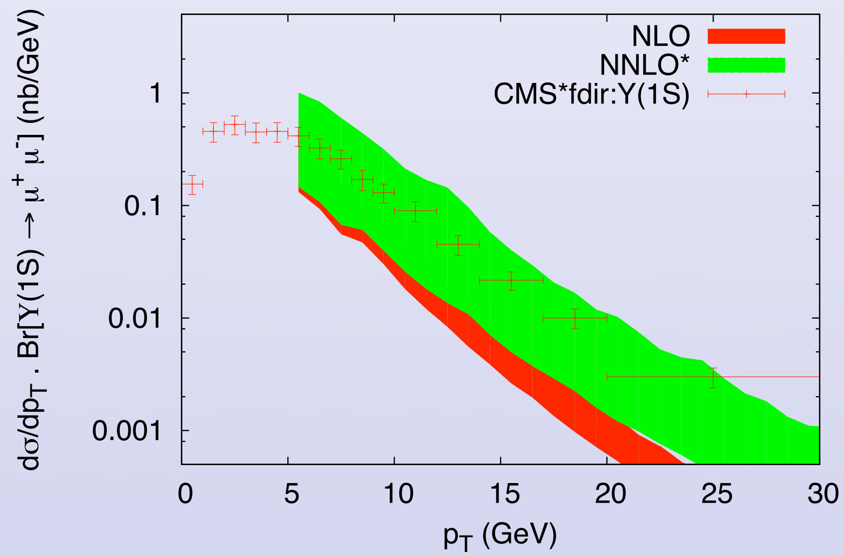
☹/ ☺ At the end marginally sensitive to NLO corrections...

☹ Several "free" parameters for J/psi ⇒ easy to fit

☹ Still to be improved (inclusion of feeddown, complete polarization information),...

Discussion: two strategies

- There are two possible strategies to make predictions for quarkonium at the LHC:
  - A first principles only: Example Υ:



☺ Singlet dominance: no free parameters!
☺ Approximated calculation of higher order effects needed.
☹ Large theoretical uncertainties in the predictions.
☹ Needs improvements for feeddowns.
☺ We can hope to learn how Υ is actually produced

Conclusions

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- Predictions and MC tools for the LHC are constantly improved and we are looking forward to detailed new studies...!

Many backup slides

New generation of MC tools

The evolution of our current understanding and calculations in quarkonium production is mirrored by a development of a new generation of tools that can make:

- Pythia : inclusive quarkonium production singlet and octets.
- MadOnia (MadGraph) + Pythia : any (user-defined) process in NRQCD upon user request at LO + interface to the shower.
- CASCADE + Pythia hadronization: k_T factorization MC for inclusive production in the CSM.
- BCVEGPY + Pythia : dedicated to B_c.
- MC@NLO : B meson production.

Υ vs ψ direct production

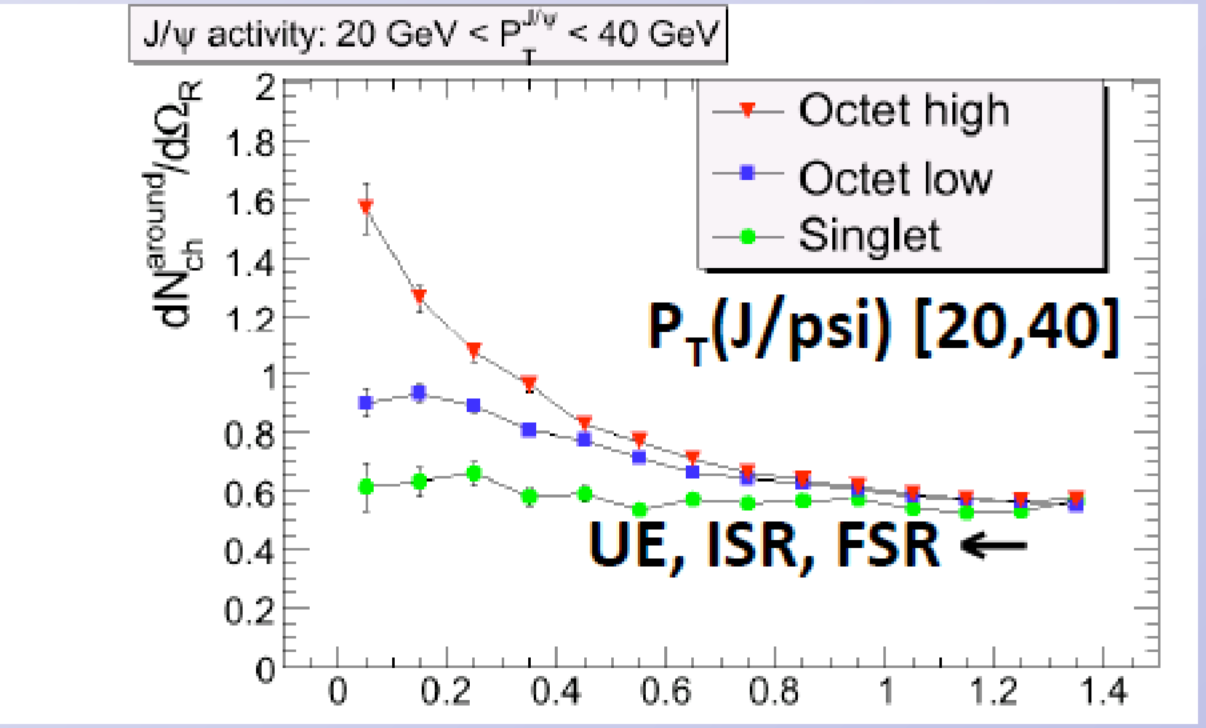
- For the Υ direct production, the color-octet contributions are not *required* to describe the data. Predictions at NNLO* for √s=7 TeV can be made available and should be compared to data.

- For J/ψ, ψ(2S) direct production, current data support the evidence for color-octet contributions to be relevant. However, new observables may help to understand the production mechanisms.

- One example is the study of extra radiation around the directions of the J/ψ:

[A. Kraan, 2010]

- First results: very challenging! Contamination from non-prompt J/psi increases with p_T. Muons are much closer in space, isolation cuts more difficult....



J/ψ production : ideas for new channels

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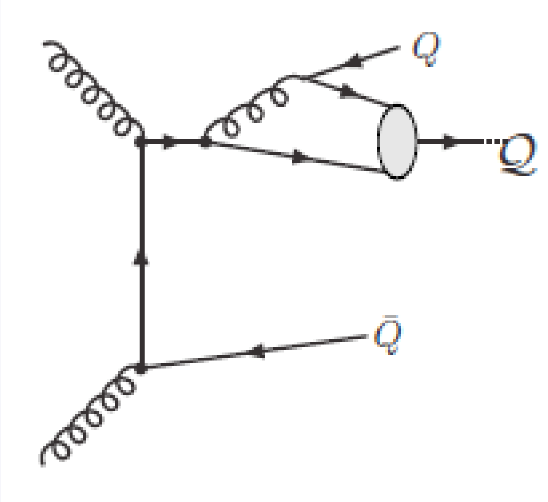
$$pp \longrightarrow J/\psi + c\bar{c}$$

[Artoisenet, Lansberg, FM, 2008]



Subdominant part of the NLO corrections to inclusive J/ψ, it is dominated by color singlet contributions. It could also give information on the charm fragmentation.

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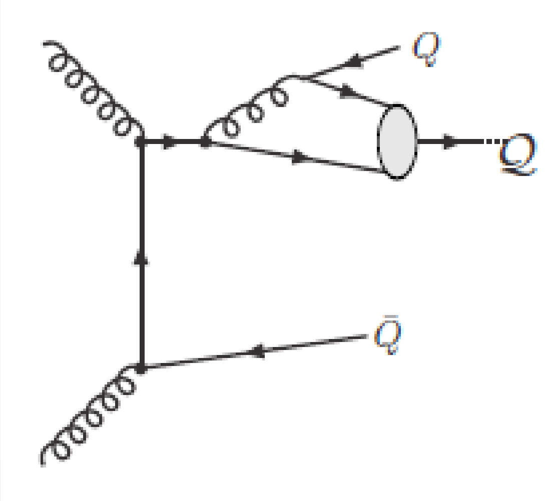

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$$pp \rightarrow J/\psi + \gamma$$

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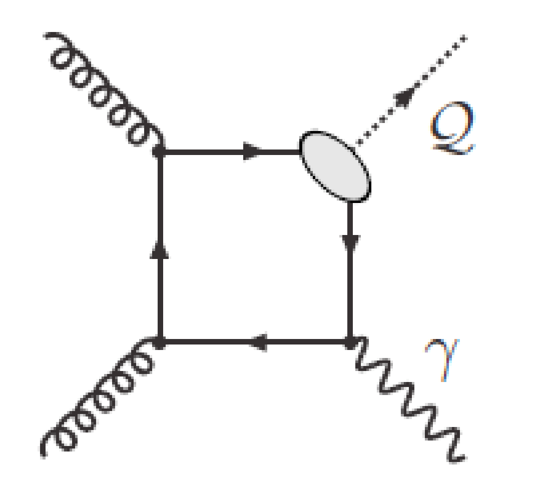

Extremely clean signature. Crossing of the leading production process at HERA which shares the same features (color singlet dominance).

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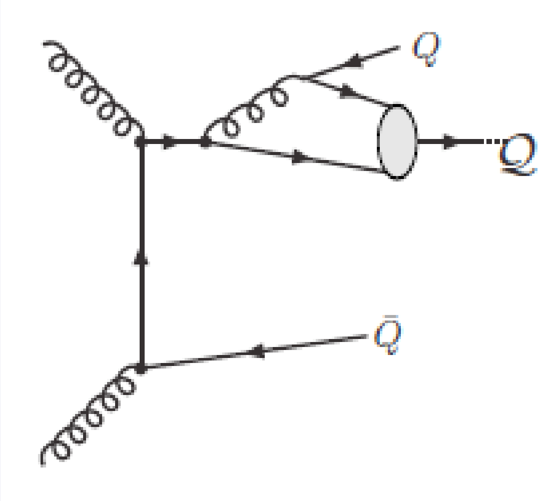

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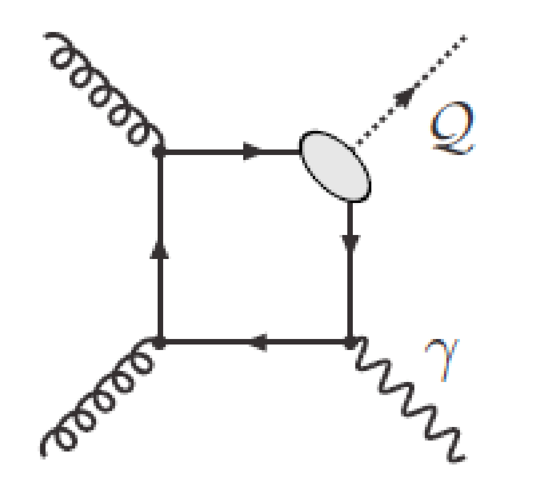

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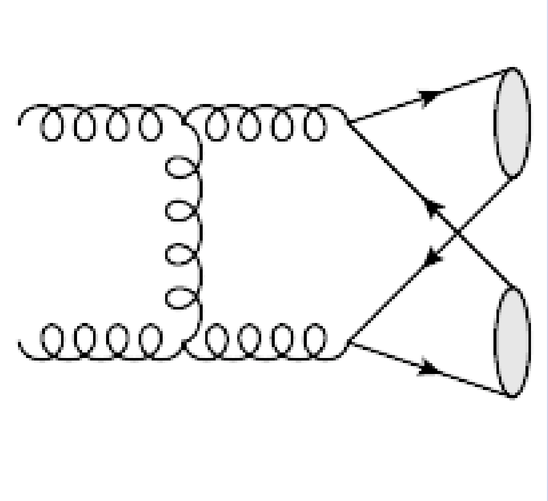
[Ko,Yu, Lee, 2010]



J/ψ+ J/ψ is dominated by the singlet while J/ψ + Υ is dominated by the octet. Small cross section but very clean signature at the LHC.

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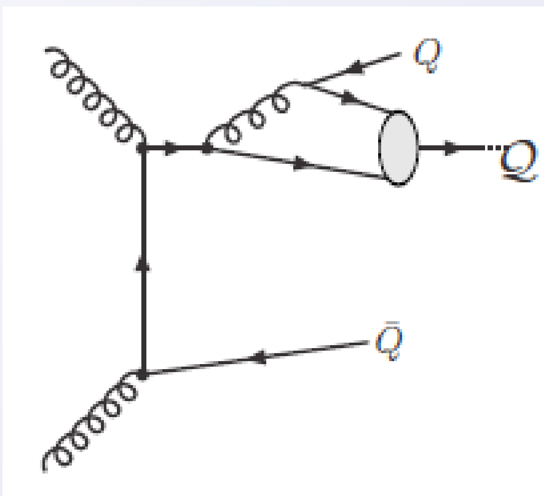

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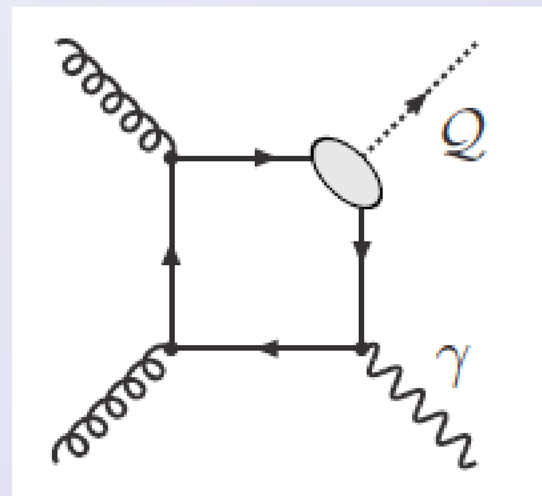

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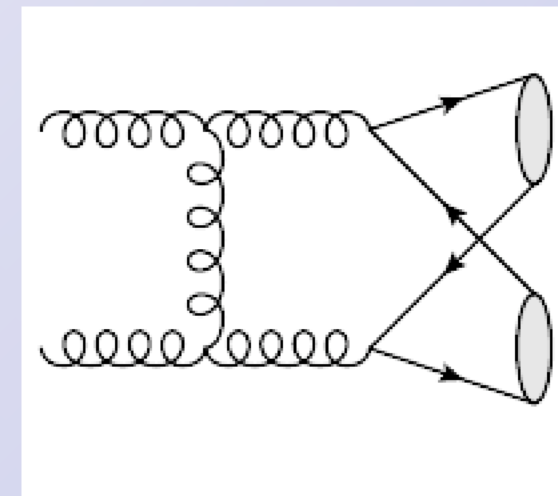

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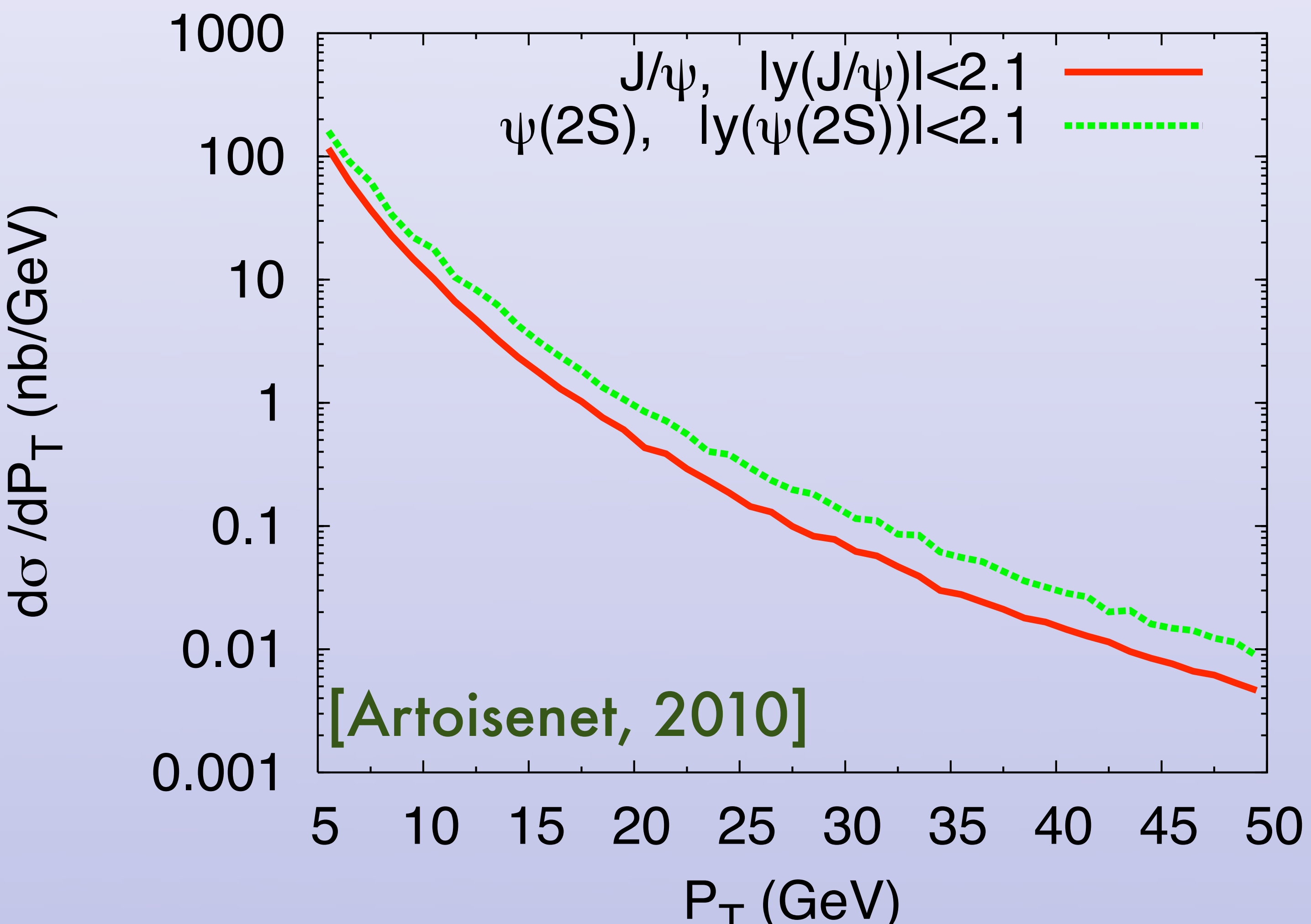
significant work and luminosity needed...!

Feed-down from $\psi(2S)$:

- Let us assume that $^3S_1^{[8]} \to \psi(2S)$ is the dominant transition at the LHC
- Let us decay the $\psi(2S)$ into $J/\psi\pi\pi$ according to a uniform distribution in the $\psi(2S)$ 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



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

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

$\langle O(^3S_1^{[8]})\rangle = 6\cdot10^{-3}$ GeV

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

Upshot:
the kinematics of the decay $\psi(2S)\to J/\psi\pi\pi$ must be taken into account properly.

Feed-down from ψ(2S)

- At the Tevatron, the p_T spectrum for $pp \to X + [\psi(2S) \to J/\psi\pi\pi]$ can be deduced from the experimental spectrum for $pp \to X + [\psi(2S) \to \mu\mu]$ and from Monte-Carlo simulation for the decay $\psi(2S) \to J/\psi\pi\pi$

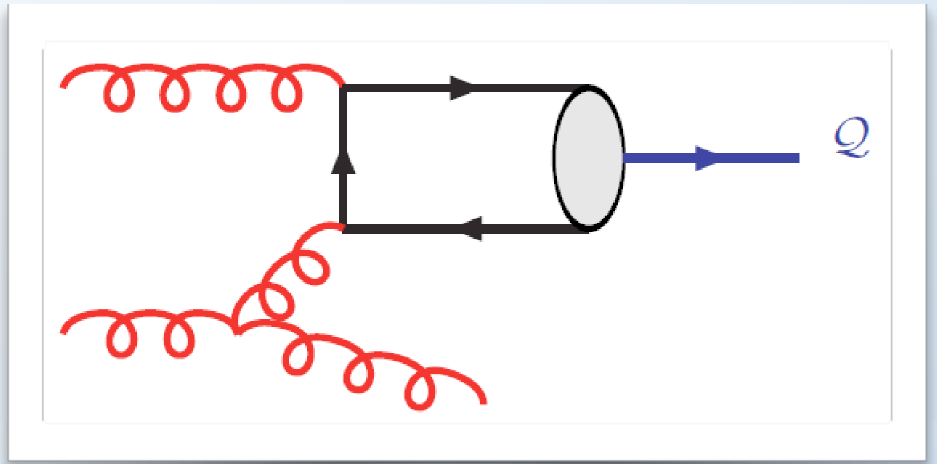
- The resulting J/ψ polarization is not well known, since the polarization of ψ(2S) has large uncertainties, both experimentally and theoretically.

- In the past, the feed-down from ψ(2S) has been addressed by considering inclusive long-distance matrix elements, e.g.

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

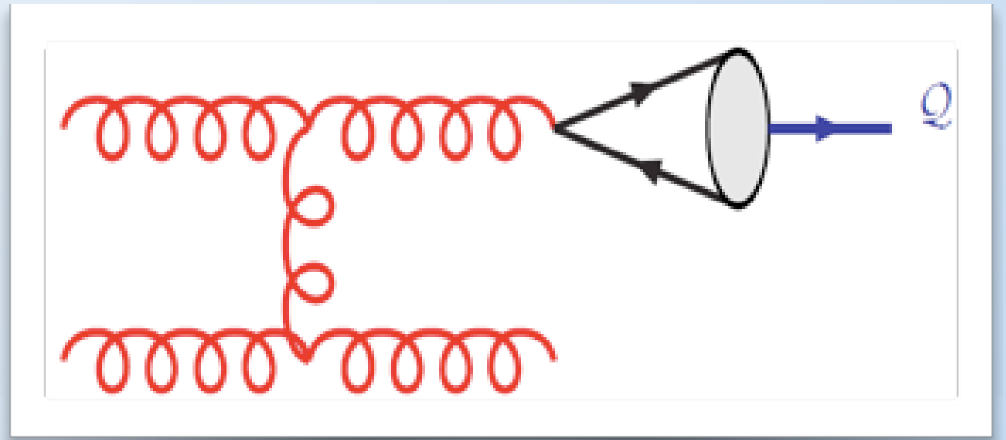
but this does not take into account the kinematic effects associated to the decay $\psi(2S) \to J/\psi\pi\pi$.

Feed-down from χ_{cJ}



$^3P_J^{[1]}$

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



$^3S_1^{[8]}$

gluon fragmentation channel already at α_s^3

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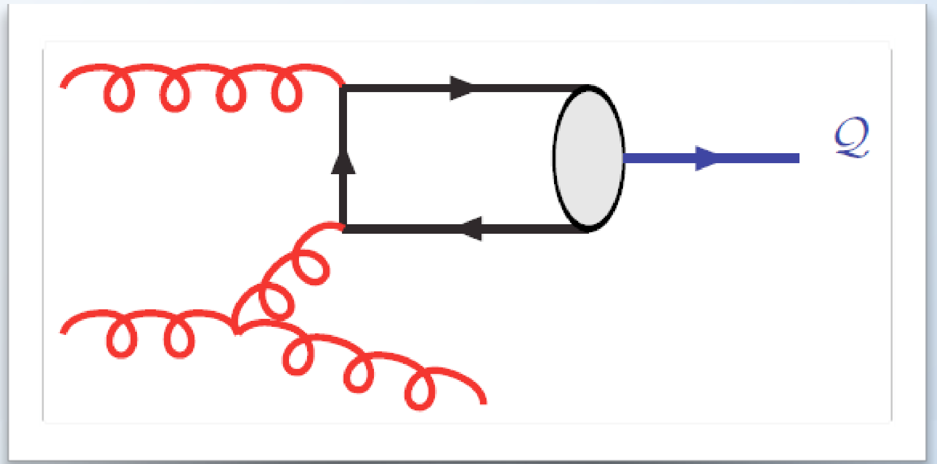

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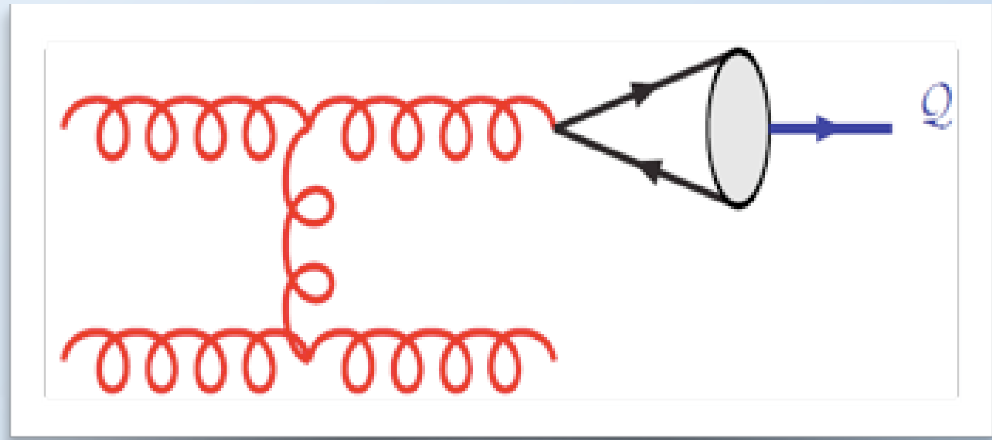

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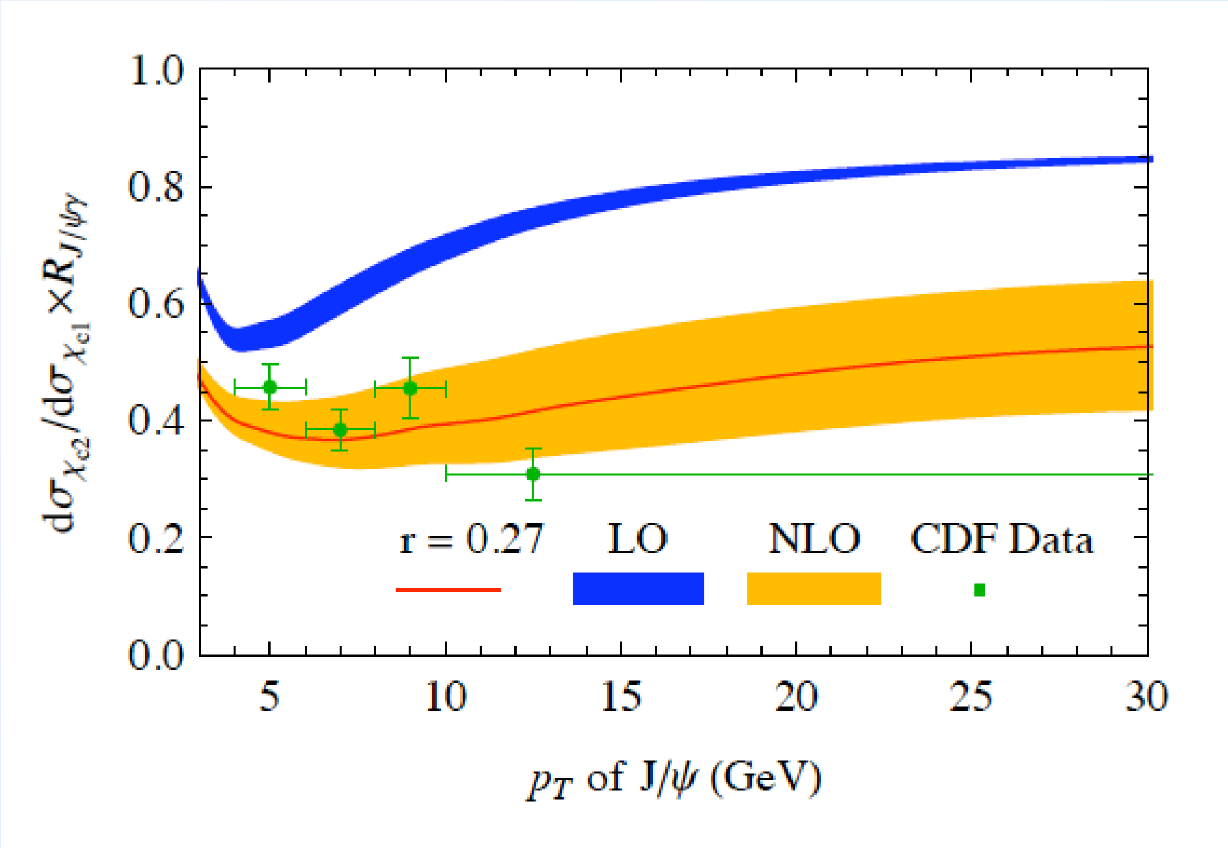


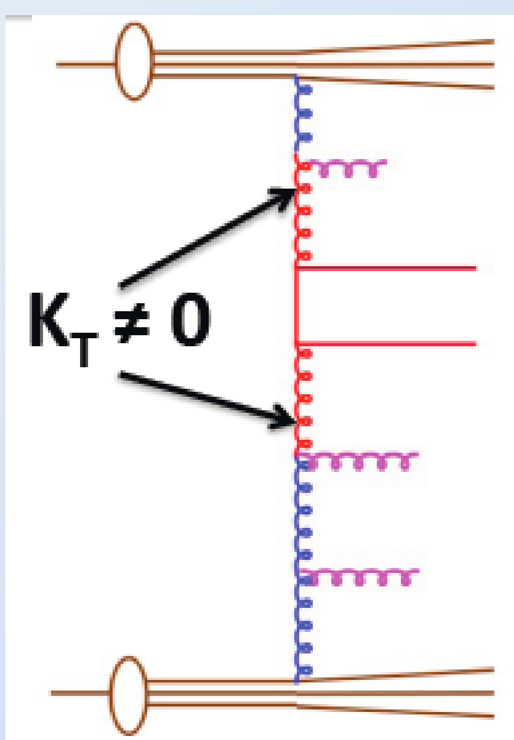
[Ma, Wang, Chao, 2010]

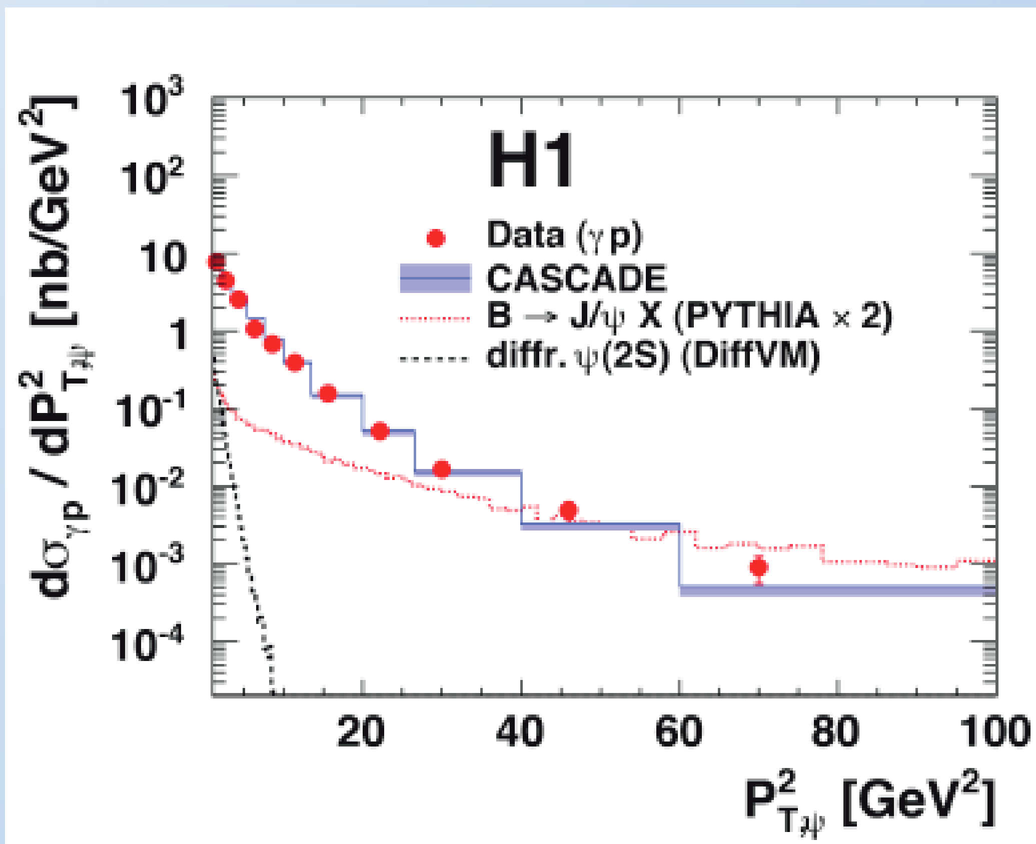
Data and NLO calculations agree reasonably well.

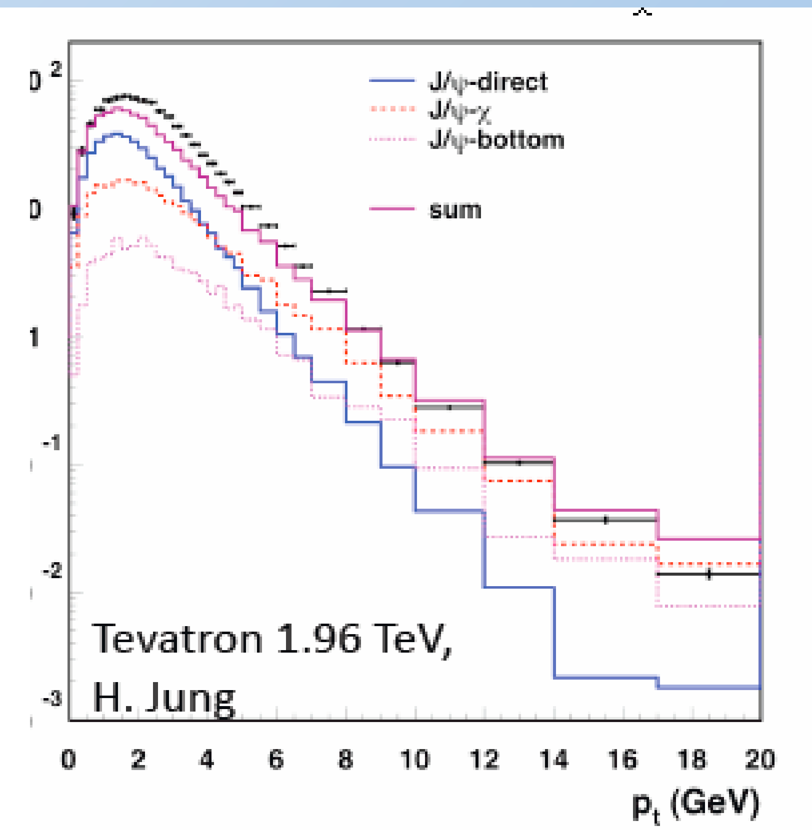
Connection with the k_T factorization approach

[Baranov, 2002; Jung 2009]

- The importance of the α_s^5 is also the starting point of the unintegrated PDF approach, which uses a rapidity ordered evolution.
- 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.).
- Sizable uncertainties associated with the unintegrated PDF (factor 2-3)
- Longitudinal polarization obtained.







Fragmentation processes

[Braaten & Yuan, 1993]

- 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

Fragmentation vs full FO calculation

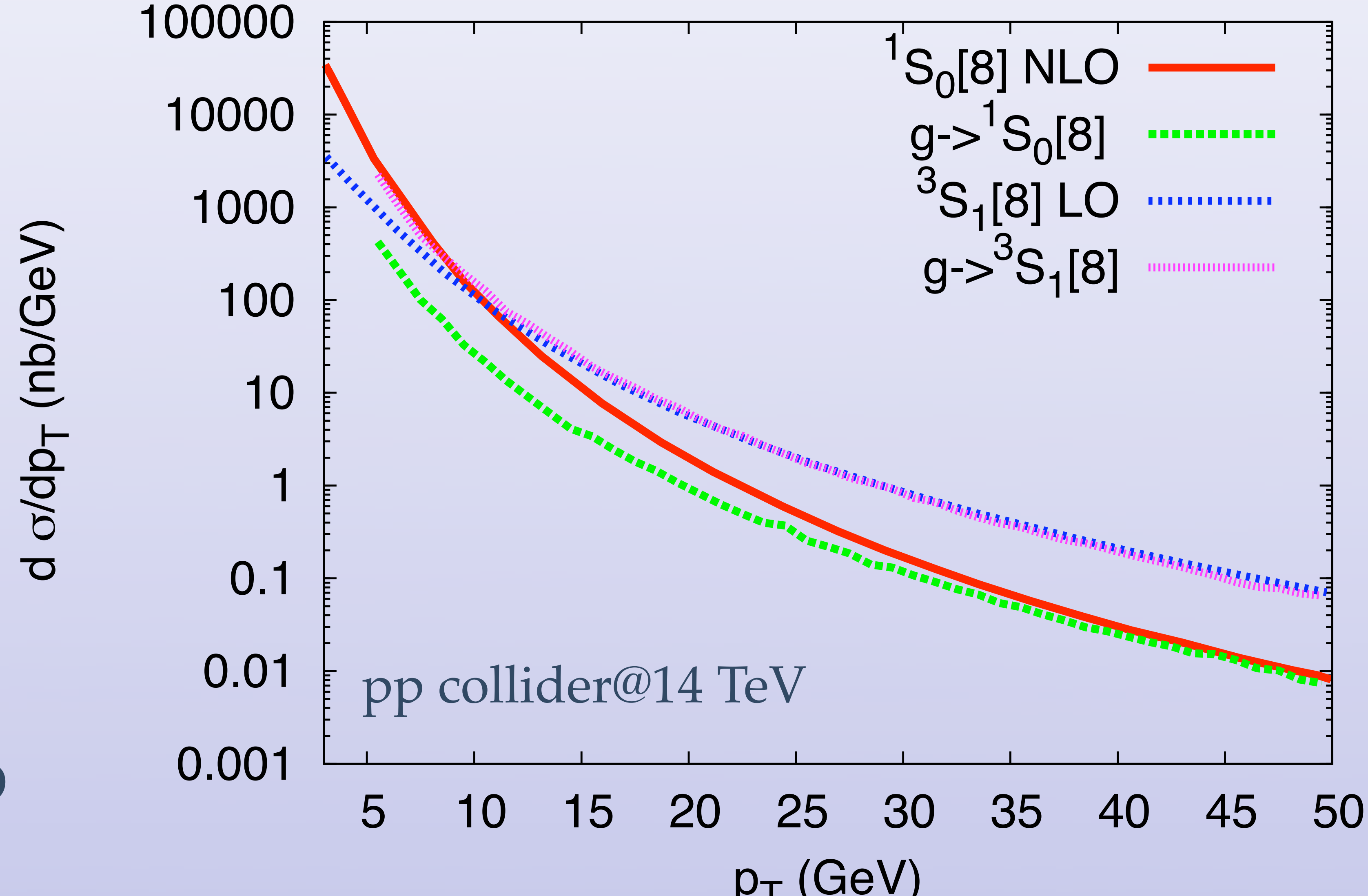
[Artoisenet, 2010]

- 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



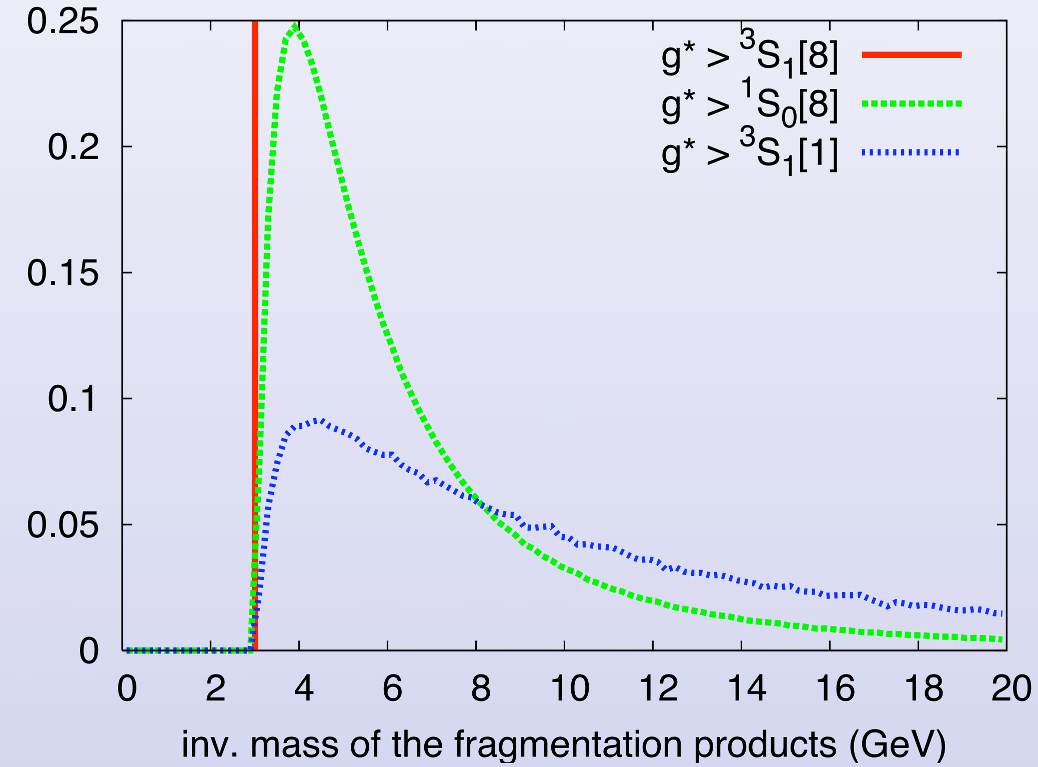
scale: $m_T(\psi(2S))$ (also in the frag. fct)
no DGLAP evolution

Gluon fragmentation into $^3S_1^{[1]}$

[Artoisenet, 2010]

- ... 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)

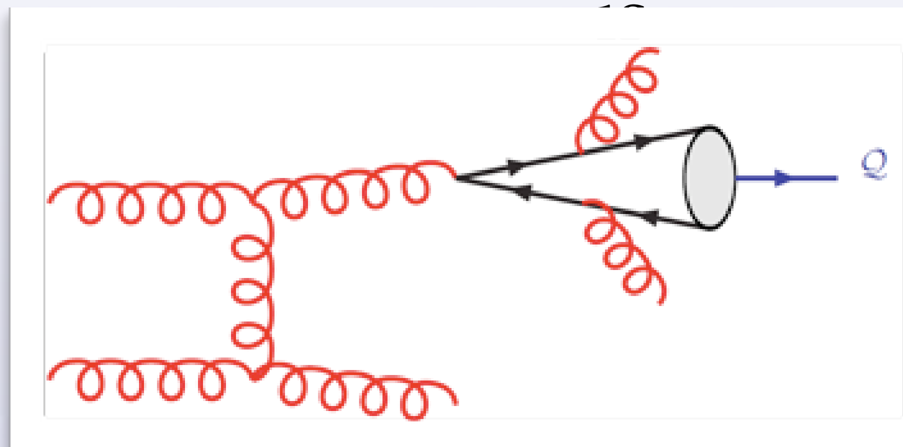
In the case of $g^* \to {}^3S_1^{[1]} gg$, the rather large invariant mass of the fragmentation products may lead to substantial corrections to the fragmentation approximation at finite p_T. Also channels that contribute at α_s^5 other than fragmentation topologies may give a large contribution at finite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

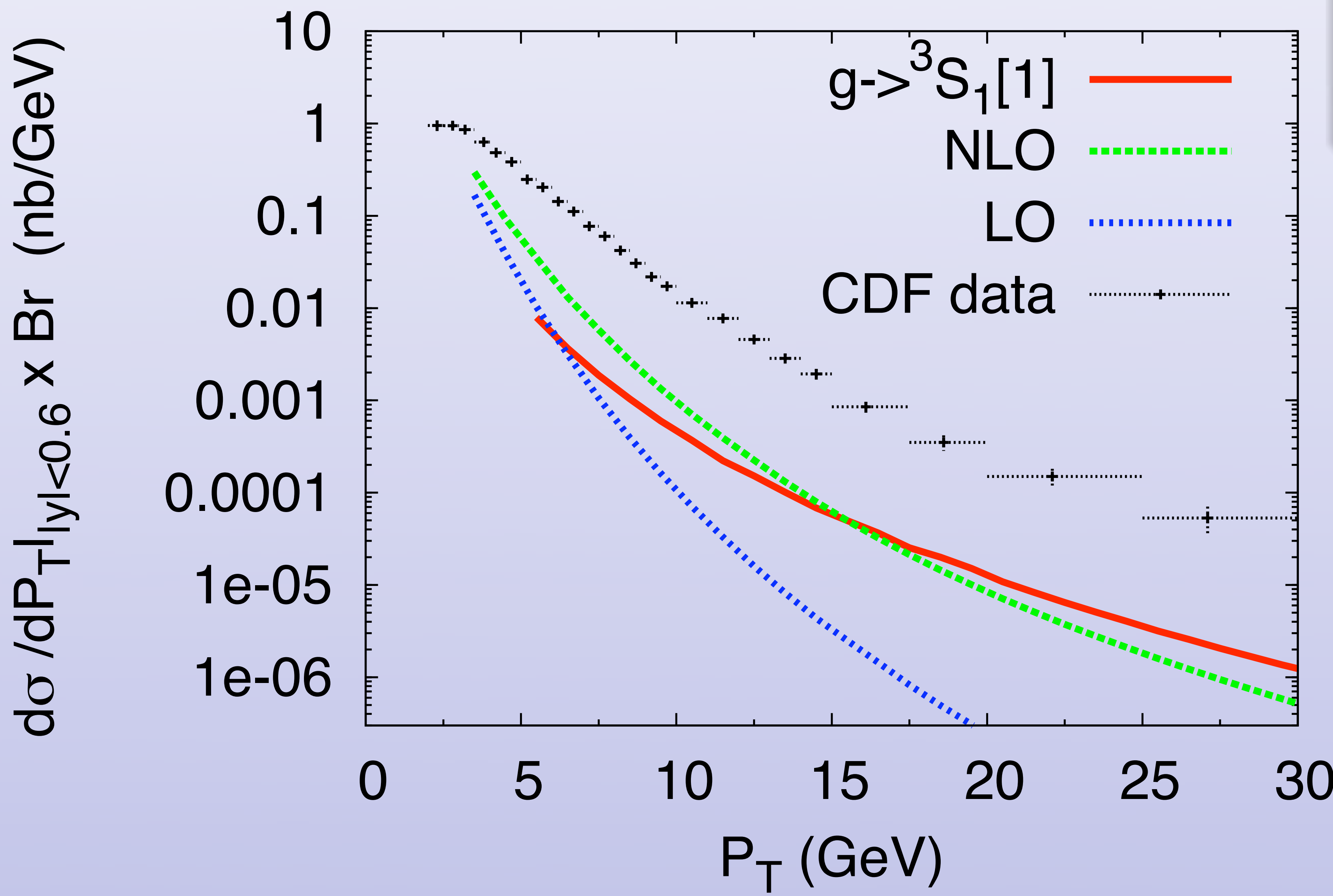
Gluon fragmentation into $^3S_1^{[1]}$

[Artoisenet, 2010]

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

[Braaten & Yuan; 93]



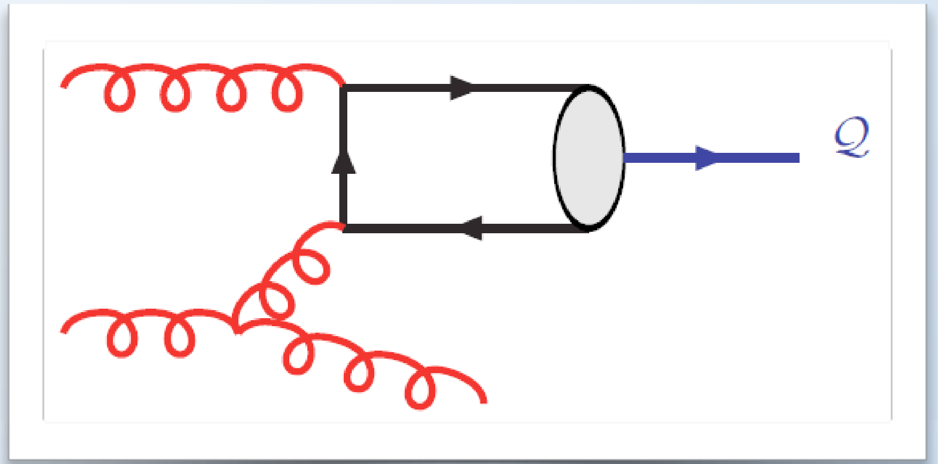


- large contribution compared to the NLO yield at large p_T

- small contribution compare to the data however...

α_s correction to color-octet transitions

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



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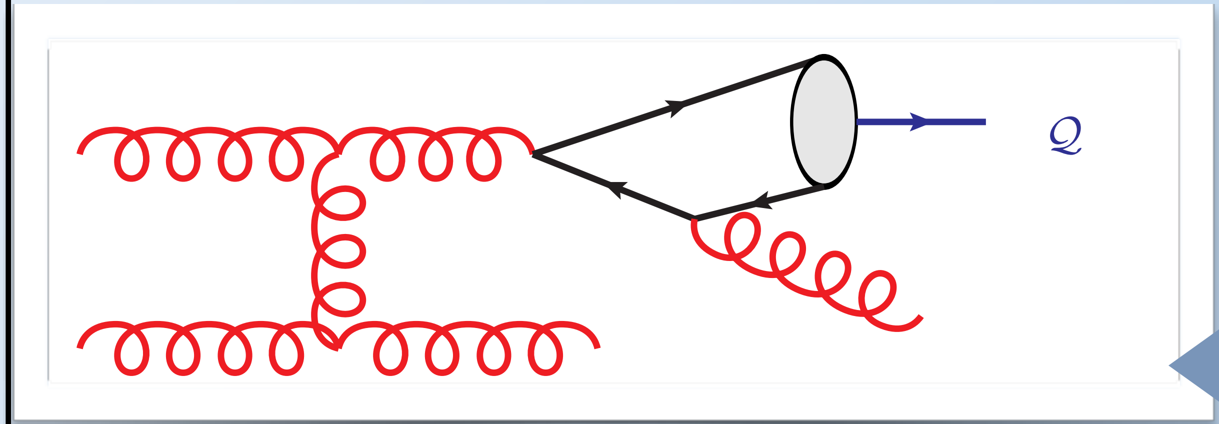
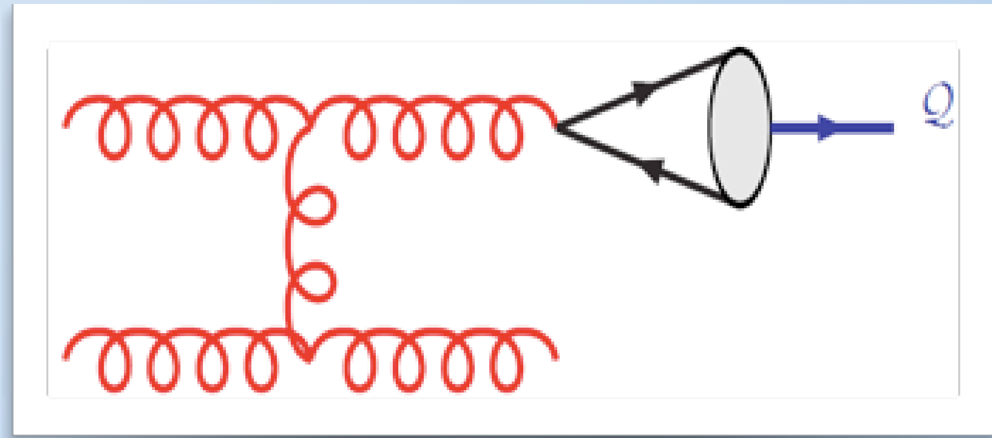


$^3S_1[8]$



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 $\rightarrow$ large corrections at high p_T

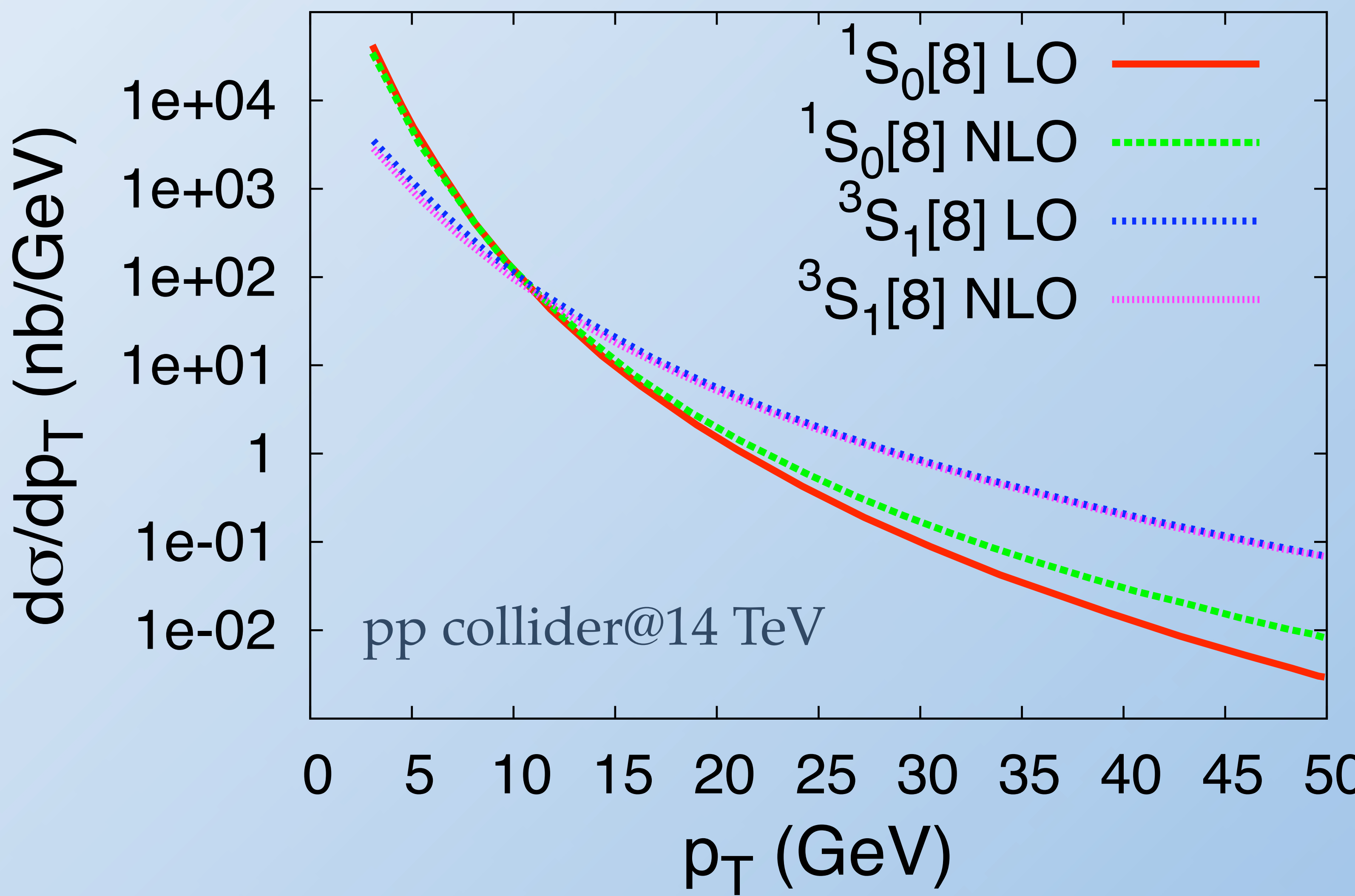
α_s correction to color-octet transitions

- $^3S_1^{[8]}$: [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



Interesting to note: no sign of large $\log(p_T/m)$ in the $^3S_1^{[8]}$ NLO results.

α_s correction to color-octet transitions

* $^3P_J^{[8]}$: [Ma, Wang, Chao 2010] [Butenschon, Kniehl 2010]

Very recently, two independent computations of the color octet short distance coefficients at NLO. Results on the short distance coefficients agree. $^3P_J^{[8]}$ is found negative.

UPSHOT : FULL fit @ NLO w/ Singlet + Octets is now possible!

However, different strategies (Tevatron vs Global fit)/assumptions (p_T shape of the feed-down) in the fitting lead to different values for non-perturbative matrix elements.

Let's see an example...

Production mechanisms

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

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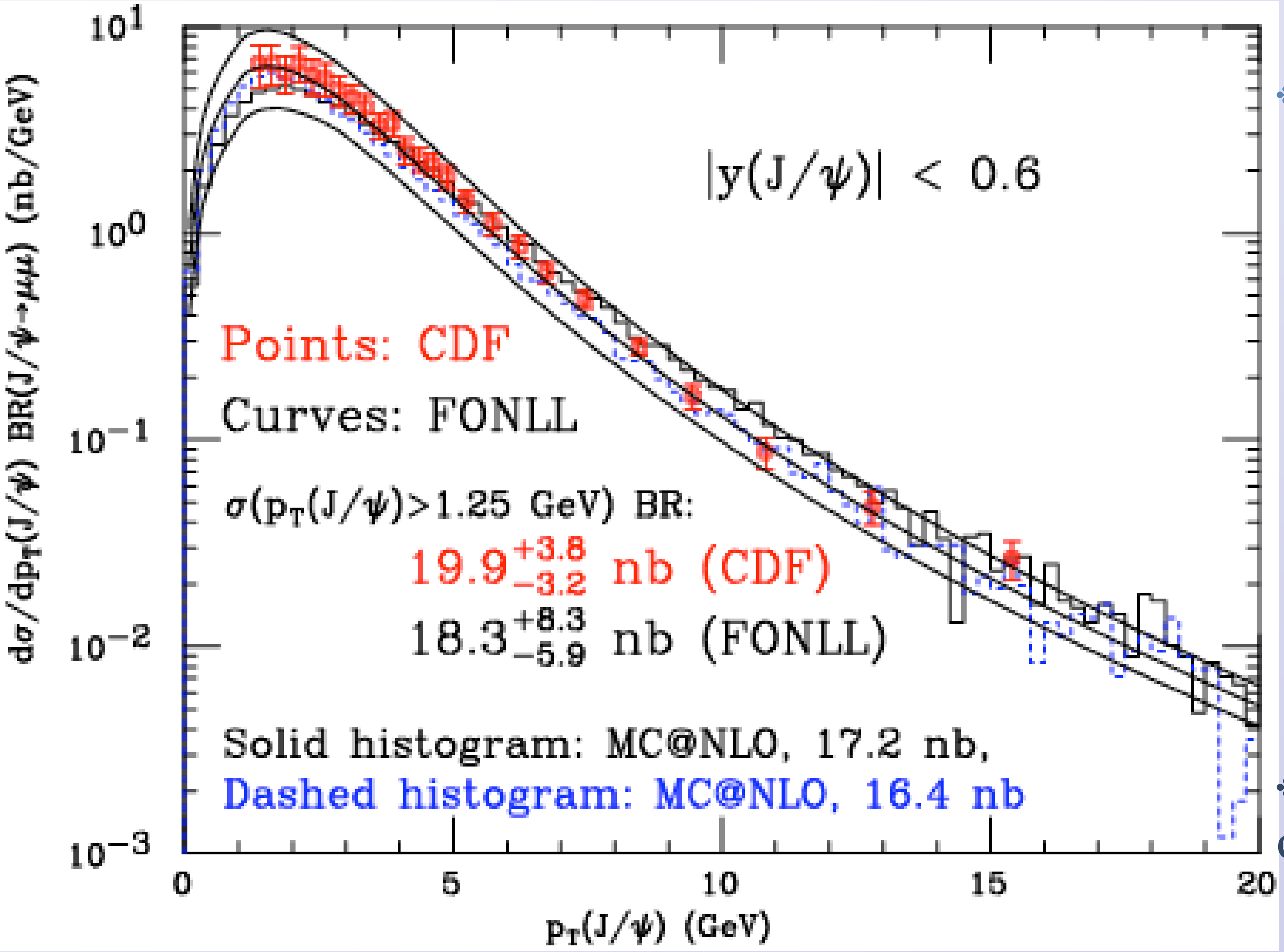
  - b-hadron decays: at Tevatron II, $b \to J/\psi + X$ accounts for 10% of the inclusive production rate at p_T=1.5 GeV (increasing to 45% at p_T=20 GeV) [CDF collaboration, 04]

B-hadron decays into J/ψ

- FONLL [Cacciari, Frixione, Mangano, Nason, Ridolfi, 2004]
- MC@NLO [Frixione, Webber, Nason, 2005]



- 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 (fitted to Belle &Babar data).
- Excellent agreement with the data (no free parameter)

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