QCD corrections to J/ψ and ϒ production at hadron colliders

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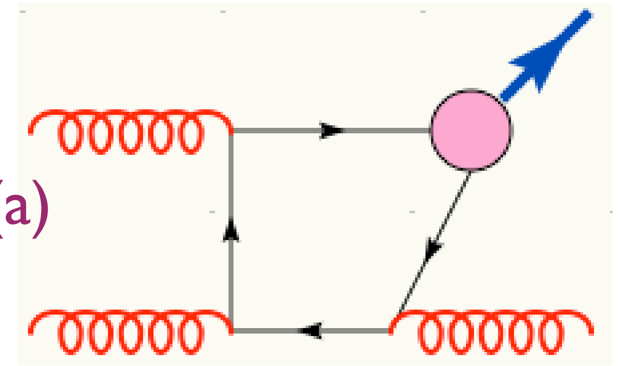
J. Campbell, F. M., F. Tramontano, PRL98:252002,2007
P. Artoisenet, J. Campbell, J.-P. Lansberg, F. M., F. Tramontano, in progress

Outline

- Motivations
- Calculation
- Phenomenology
- Conclusions & Outlook

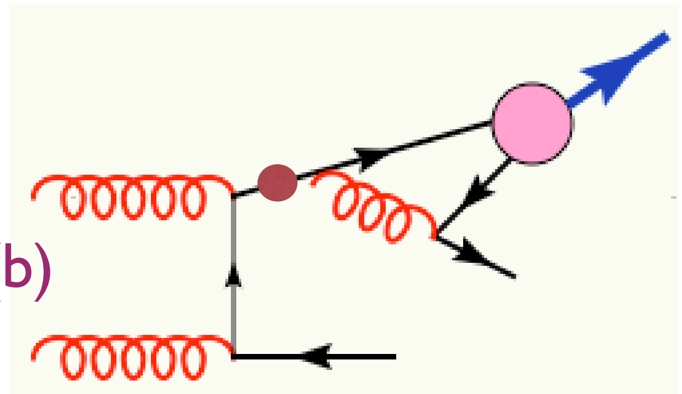
J/ψ at the Tevatron

(a)



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

(b)



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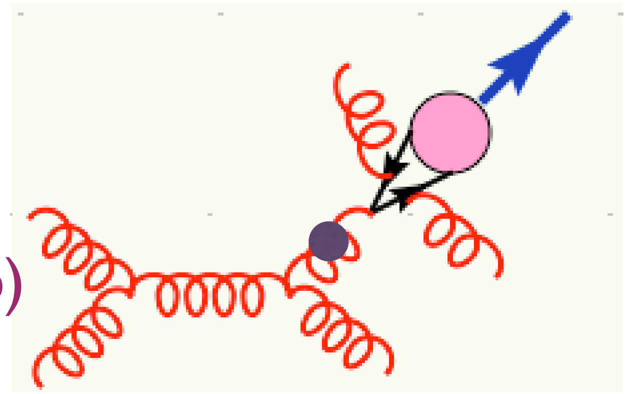
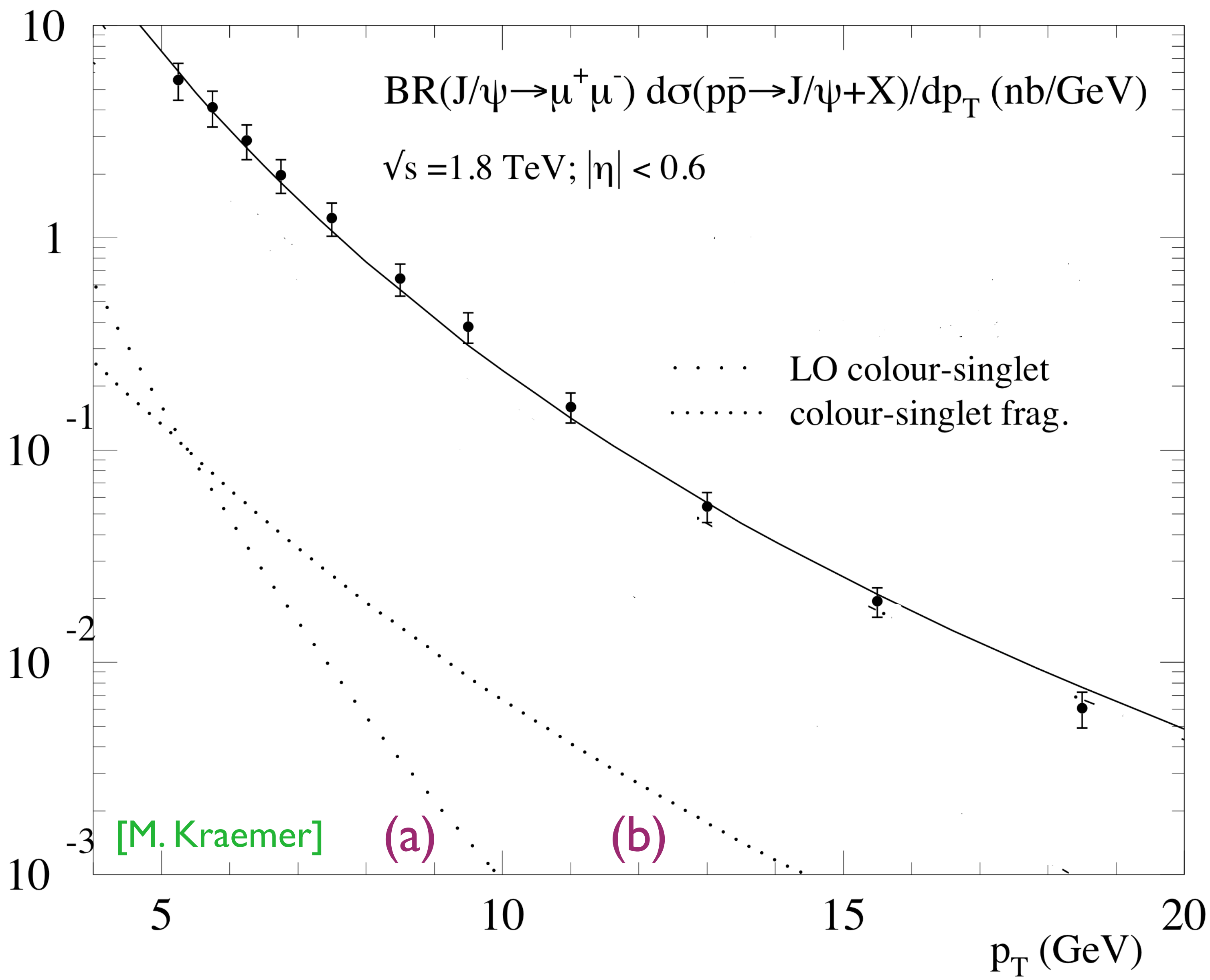


$$\alpha_S^5 \frac{1}{p_T^4}$$



The overall shape (a)+(b) is ok, but the normalization is off by a large factor!
Some higher order contributions included through the fragmentation approximation.

The NRQCD revolution

In 1995, Braaten, Bodwin and Lepage proposed NRQCD, where a quarkonium state can be written as an expansion in powers of v in a Fock space.

For a J/ψ

$$
\begin{aligned}
|J/\psi\rangle &= O(1)|Q\overline{Q}(^3S_1^{[1]})\rangle \\
&+ O(v)|Q\overline{Q}(^3P_J^{[8]})g\rangle \\
&+ O(v^2)|Q\overline{Q}(^1S_0^{[8]})g\rangle \\
&+ O(v^2)|Q\overline{Q}(^3S_1^{[8]})gg\rangle + O(v^4)
\end{aligned}
$$

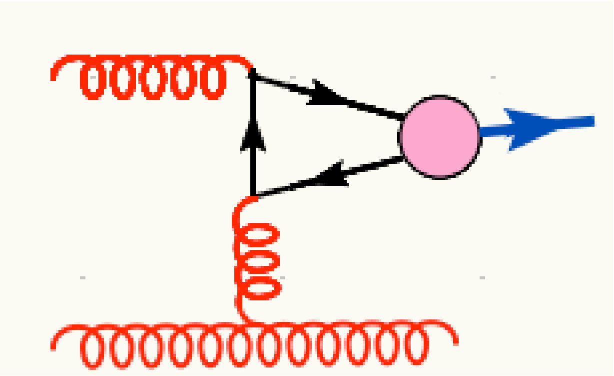
while for χ_J

$$|\chi_J\rangle = O(1)|Q\overline{Q}(^3P_J^{(1)})\rangle + O(v)|Q\overline{Q}(^3S_1^{(8)})g\rangle + O(v^2)$$

The final scaling of a process is obtained through a power counting in v (long distance) and α_S (short distance).

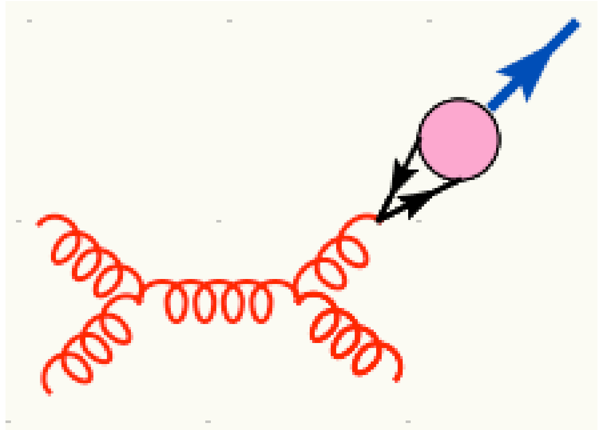
J/ψ at the Tevatron

(c)

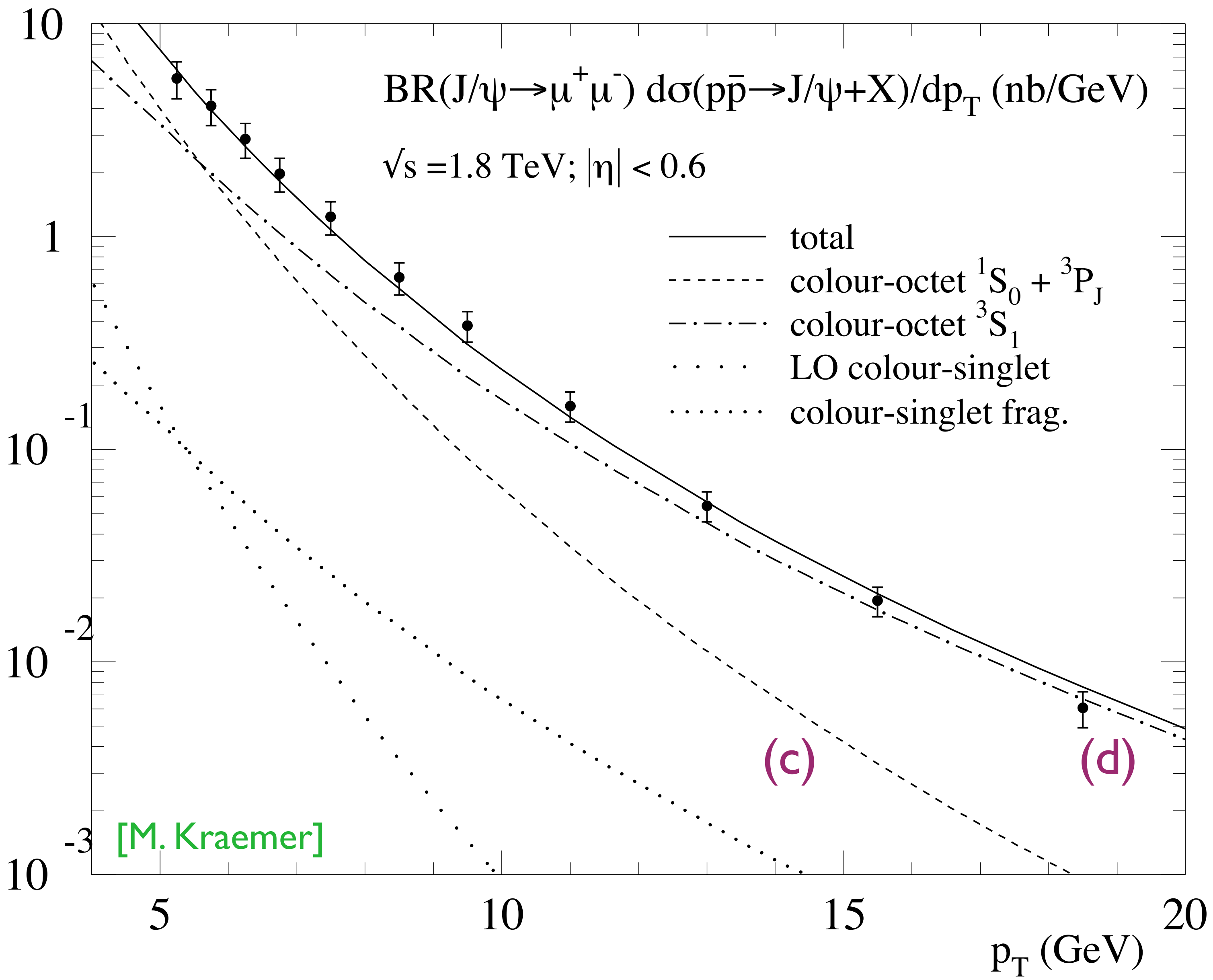


$$\alpha_S^3 \frac{(2m_c)^2 v^4}{p_T^6}$$

(d)



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



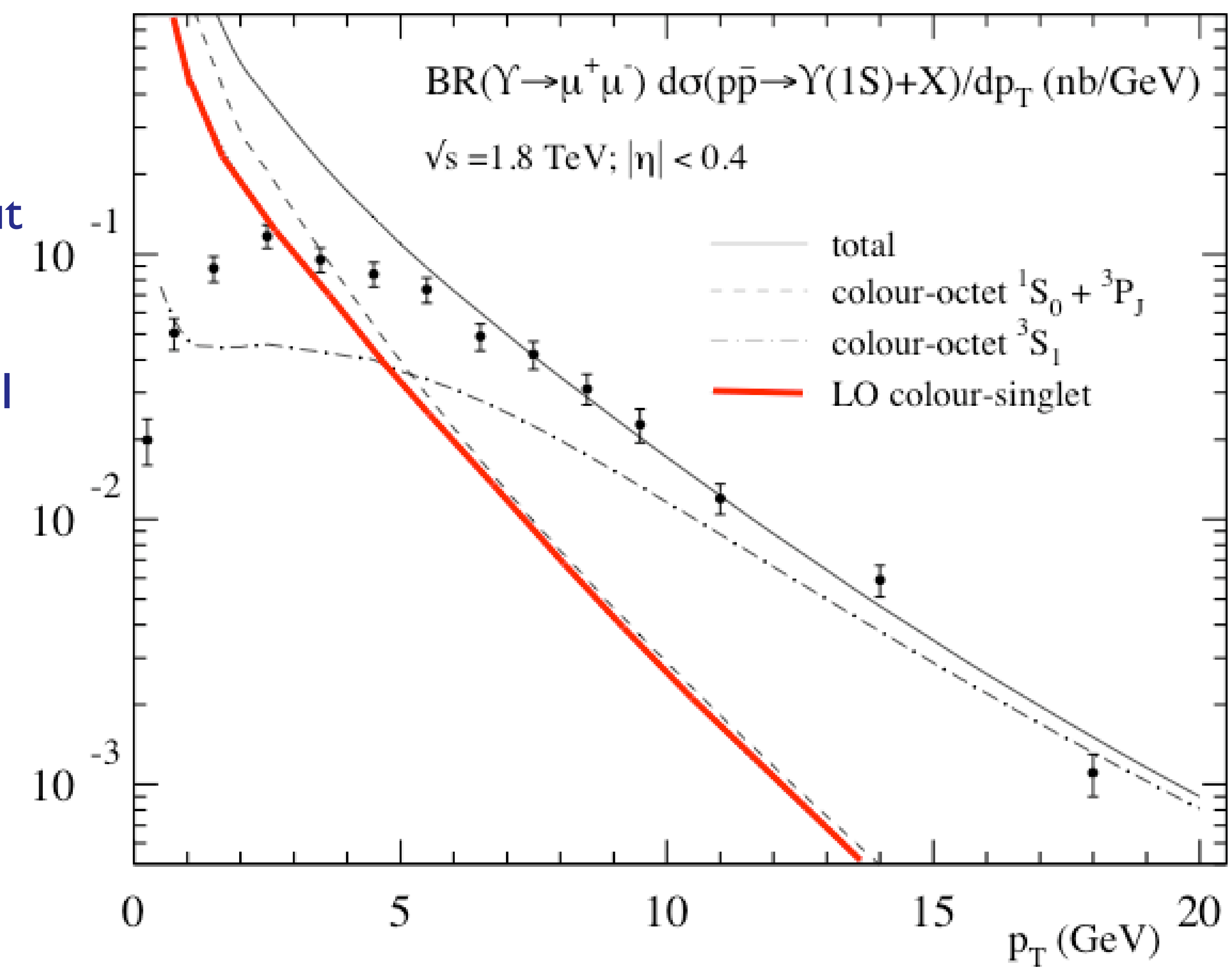
(c) & (d) are fitted to the data, but the resulting NP MEs are of the order predicted by the scaling rules of NRQCD.

Υ at the Tevatron

Situation is similar to the charmonium, but much less dramatic.

This is expected from the fact that $v^2 = 0.1$ and therefore color-octet contributions are more suppressed.

Actually, the total rate here is not too far from the LO singlet.



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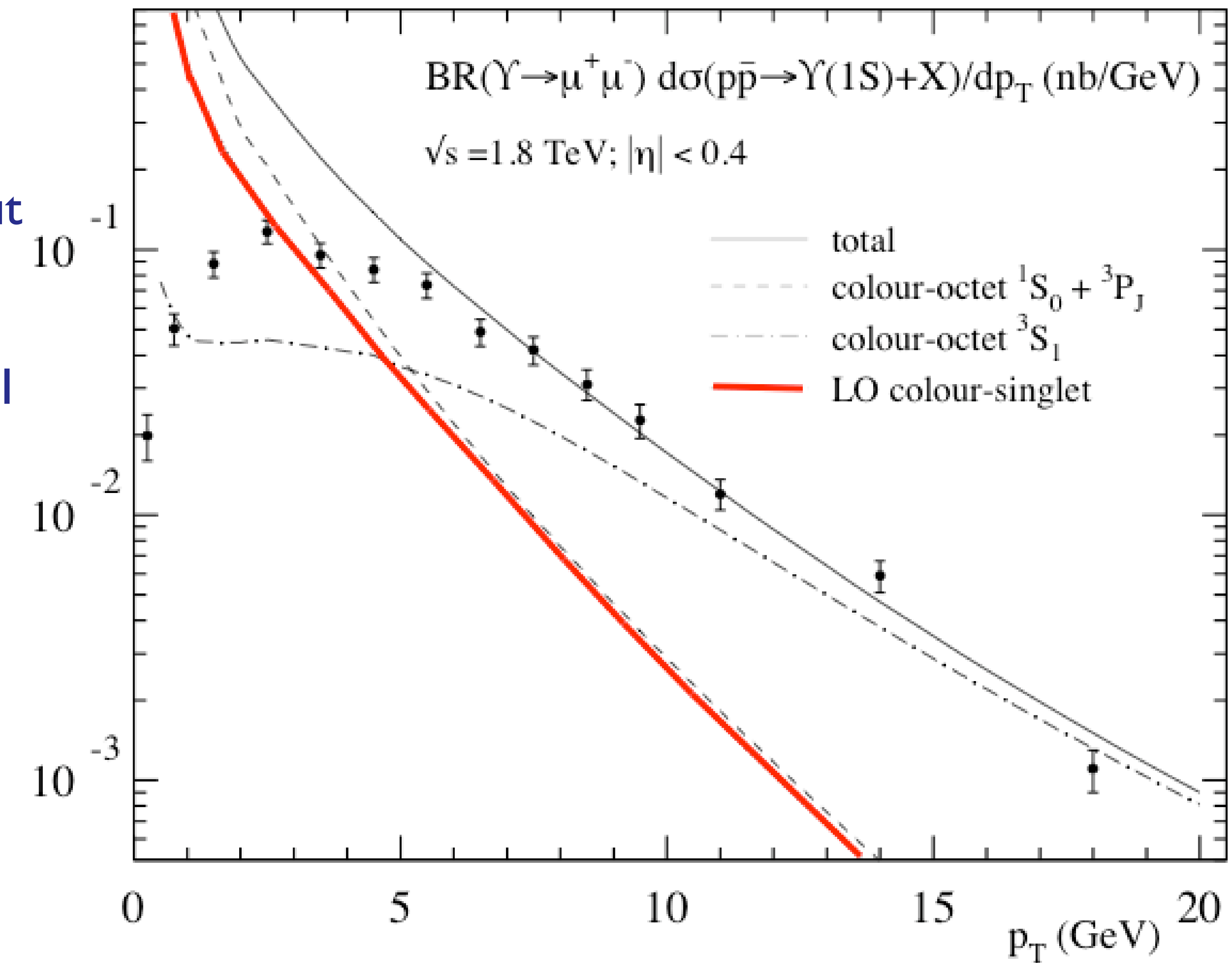

Are we done?

Open questions

- Universality of the NP matrix elements is not well established.
- Octets are important in pp at high-pt , probably in γγ, but not in e+e-, γp or fixed target experiments.
- The J/psi is unpolarized in pp at high-pt, contrary to expectations.

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A critical (re)-analysis of our TH predictions is needed!

Directions for TH improvements in quarkonium production

1. Improve predictions systematically:
   - Calculate higher order corrections in v and α_s.
   - Build better MC tools
2. Propose and test alternative approaches
3. Propose new and/or more exclusive measurements.

Example Talks:

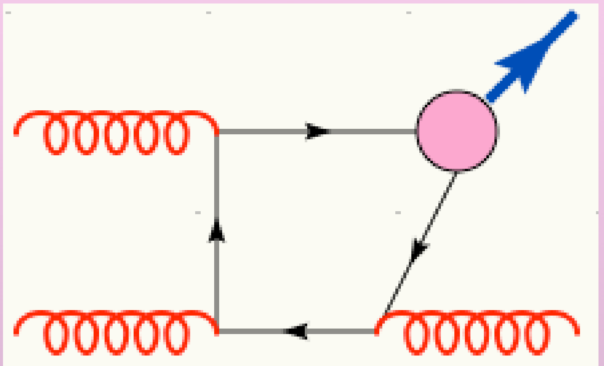
FM, J.-P. Lansberg, A. Leibovich, Y-J Zhang G. Bodwin

P. Artoisenet, A. Kraan

S. Baranov, V. Saleev, V. Braguta

TH/EXP Round Tables

Improving on pp → $^3S_1^{[1]}$ + X



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

LO

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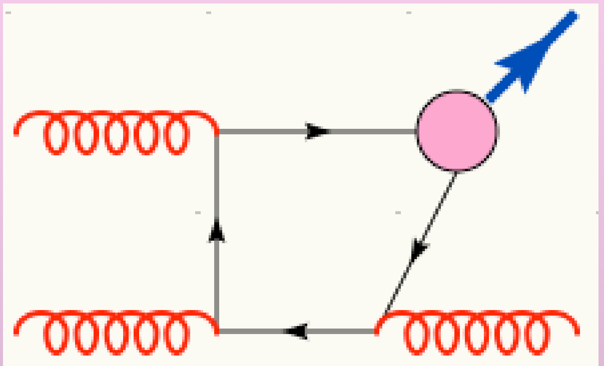

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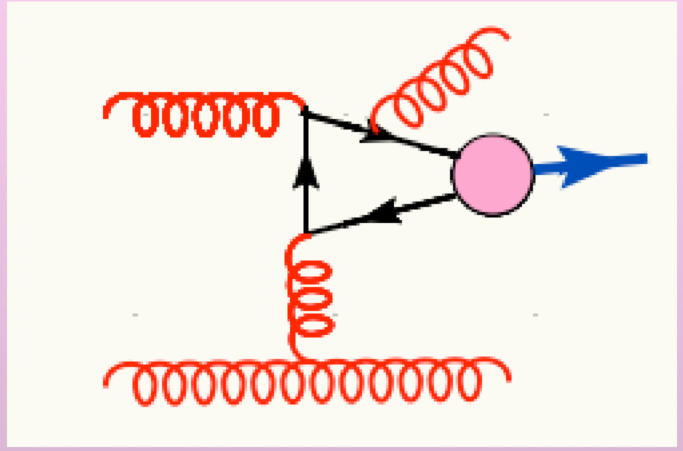
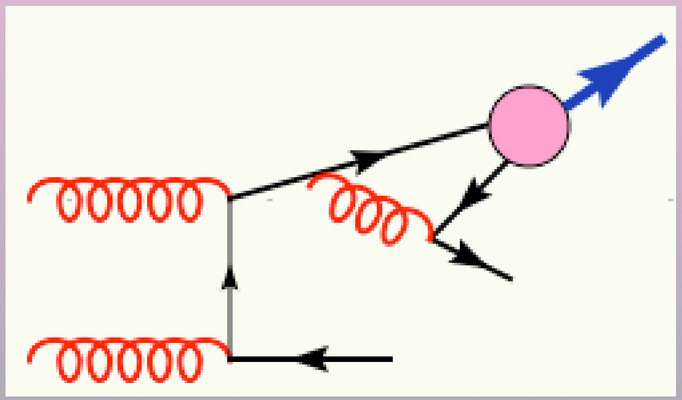


$$\alpha_S^4 \frac{(2m_c)^2}{p_T^6}$$

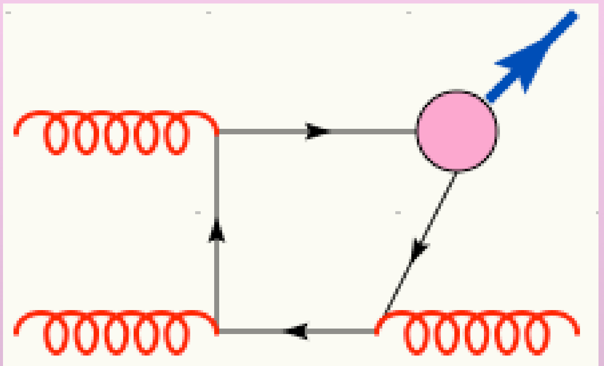


$$\alpha_S^4 \frac{1}{p_T^4}$$

NLO

* At NLO both p_T^{-6} and p_T^{-4} scalings appear, which compete with the octet contributions: α_s vs v^4
* Fragmentation approach might just be a bad approximation.
* Need for exact matrix element calculations.

Improving on pp → $^3S_1^{[1]}$ + X



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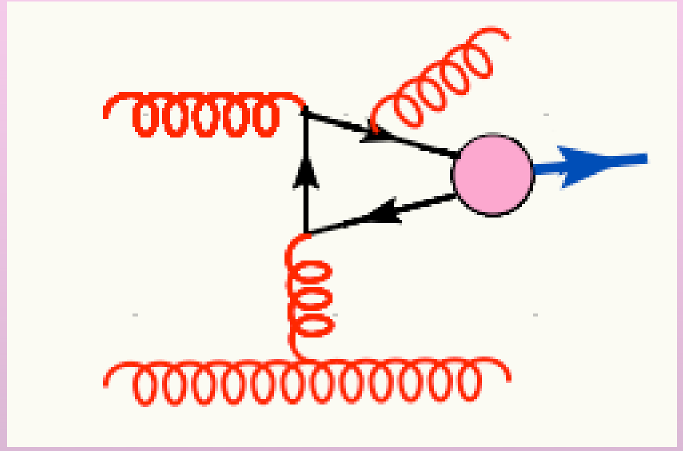

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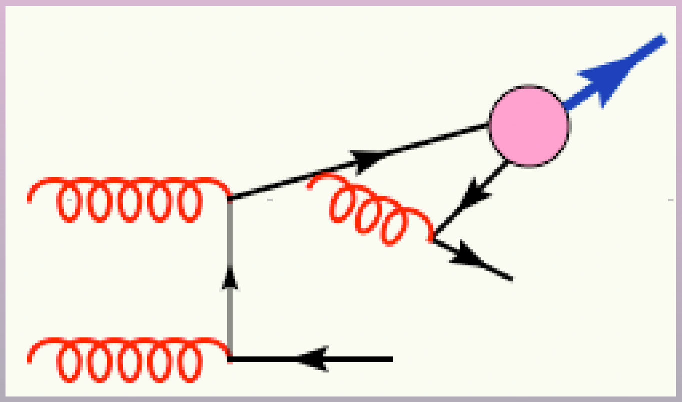

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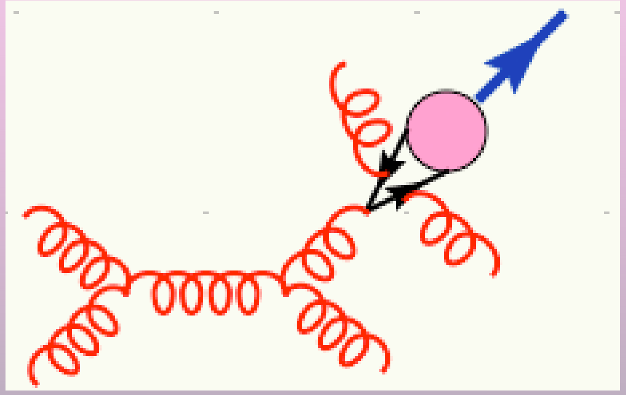

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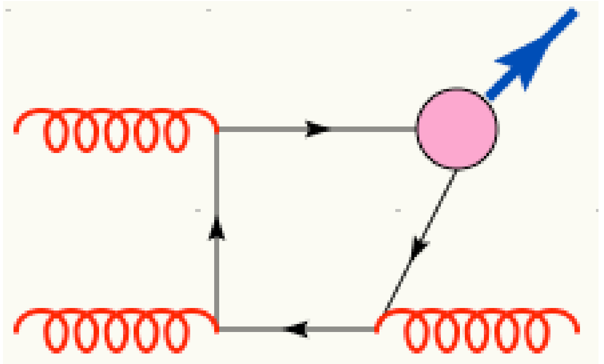
Leading order

$$\sigma(pp \to \mathcal{Q} + X) = \sum_{i,j,n} \int dx_1 dx_2 f_{i/p} f_{j/p}\, \hat\sigma[ij \to (Q\bar{Q})_n + x] \langle 0|\mathcal{O}_n^{\mathcal{Q}}|0\rangle$$



$$ggg \to {}^3S_1^{[1]} \to \ell\bar\ell$$

Calculation is involved
⇒ make use of modern NLO techniques:

1. Helicity amplitudes in 4 dimensions
2. Color decomposition (calculate dual amplitudes)
3. Decompose the $^3S_1^{[1]}$ momentum in two light-like momenta = include the decay.

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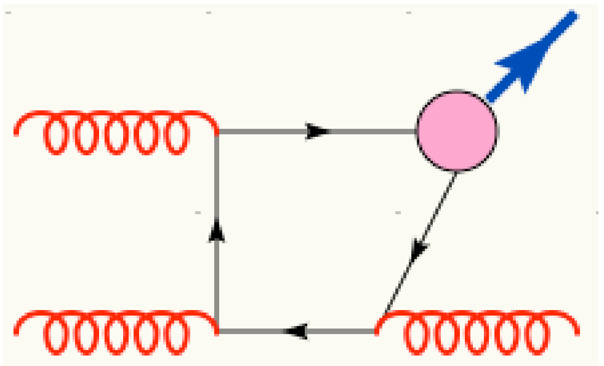

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1. Helicity amplitudes in 4 dimensions
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$$A(1^+,2^+,3^+;5_\ell^+,6_{\bar{\ell}}^-) = 0$$

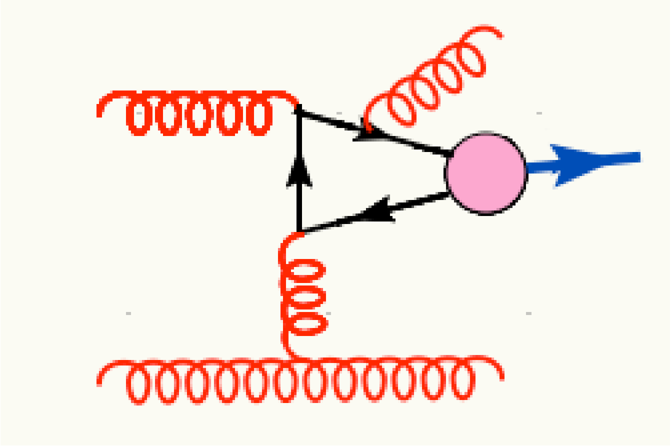
$$A(1^+,2^+,3^-;5_\ell^+,6_{\bar{\ell}}^-) = 8\sqrt{2} g_s^3 e^2 m_Q \frac{\langle 35\rangle^2 [12]^2 [56]}{(s_{12}+s_{13})(s_{13}+s_{23})(s_{12}+s_{23})}$$

$$\mathcal{A}(1,2,3) = \sum_{\sigma_{23}} \mathrm{Tr}(t^{a_1} t^{a_{\sigma_2}} t^{a_{\sigma_3}}) A(1,\sigma_2,\sigma_3)$$

$$\mathcal{A}^{LO} = g_s^3 \frac{d^{abc}}{\sqrt{N_c}} T(1,2,3)$$

Next-to-leading order: real contributions

$$\sigma^{NLO} = \int |\mathcal{A}^{\rm Real}|^2 d\Phi_3 + \int 2{\rm Re}(\mathcal{A}^{\rm Virt}\mathcal{A}^{\rm LO*})d\Phi_2$$



$$gggg, ggq\bar{q} \rightarrow {}^3S_1^{[1]} \rightarrow \ell\bar{\ell}$$

$$\mathcal{A}(1,2,3,4) = \sum_{\sigma_{234}} {\rm Tr}(t^{a_1}t^{a_{\sigma_2}}t^{a_{\sigma_3}}t^{a_{\sigma_4}})A(1,\sigma_2,\sigma_3,\sigma_4)$$

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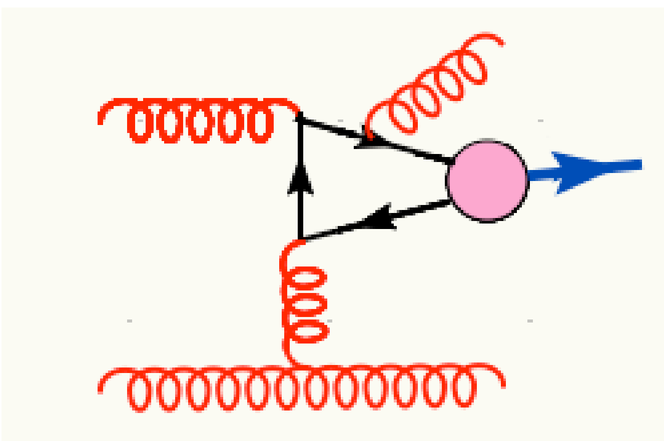

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$$|\mathcal{A}|^2 = C_2(F) N_c \sum_{\sigma_{234}} |A_\sigma|^2 \qquad C_2(F) = (d^{abc}/\sqrt{N_c})^2$$

$$\begin{array}{cccccc} C & A & A & A & A & B \\ A & C & A & B & A & A \\ A & A & C & A & B & A \\ A & B & A & C & A & A \\ A & A & B & A & C & A \\ B & A & A & A & A & C \end{array}$$

Impressive "color magic" simplification!

Next-to-leading order: virtual contributions

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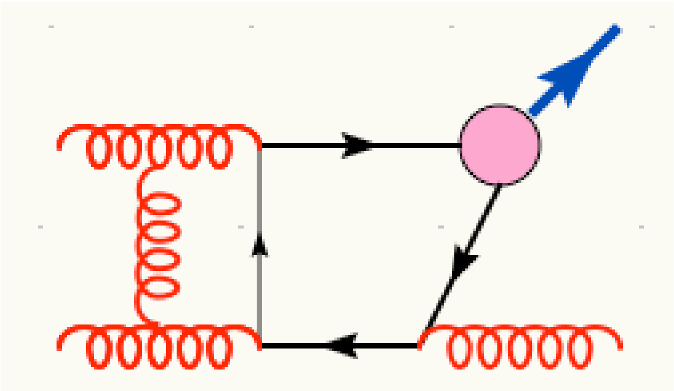

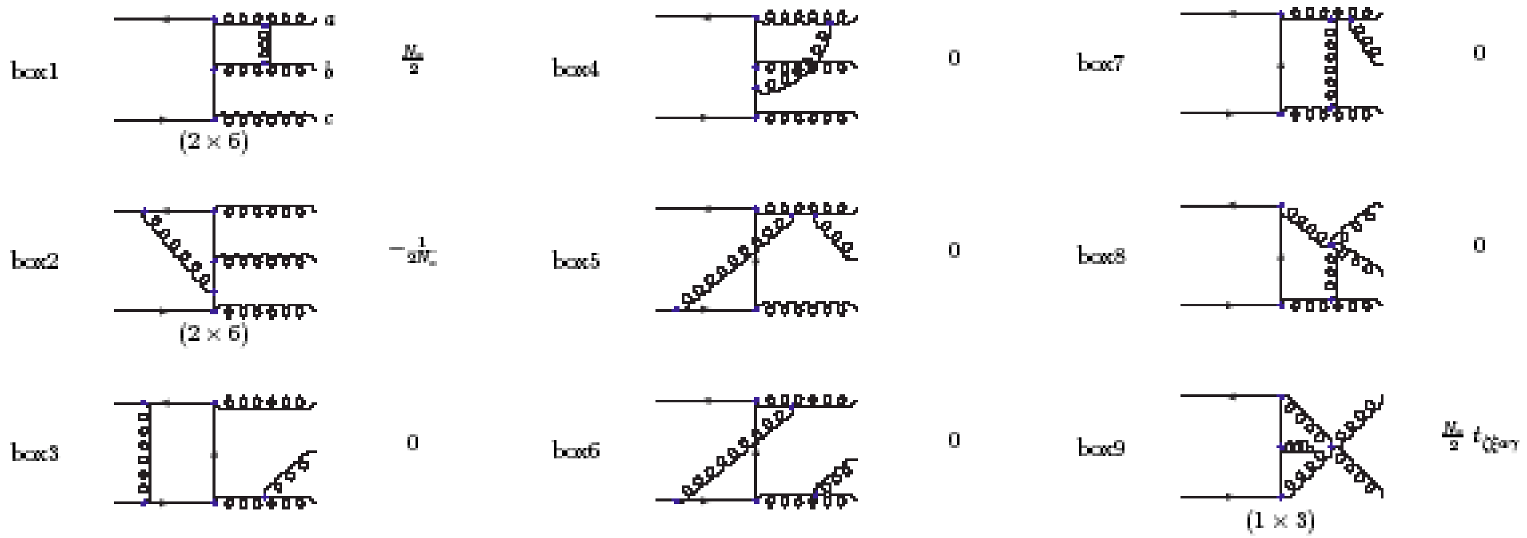

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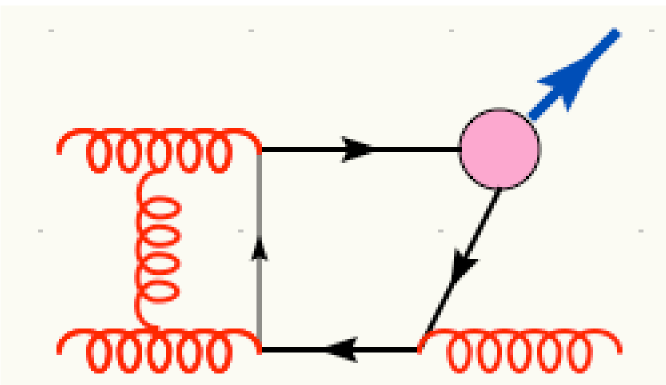
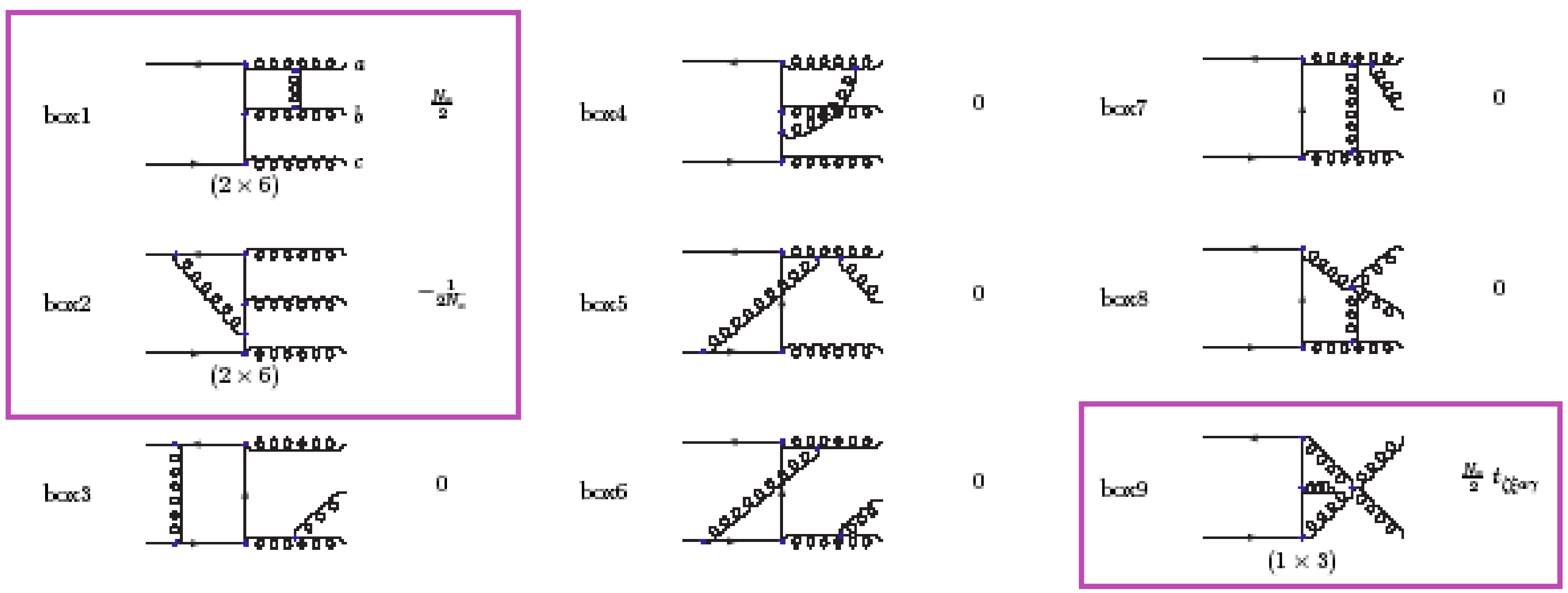




vtx 10 → 5

box 9 → 3

penta 4 → 3

* color plays entails again a huge simplification.

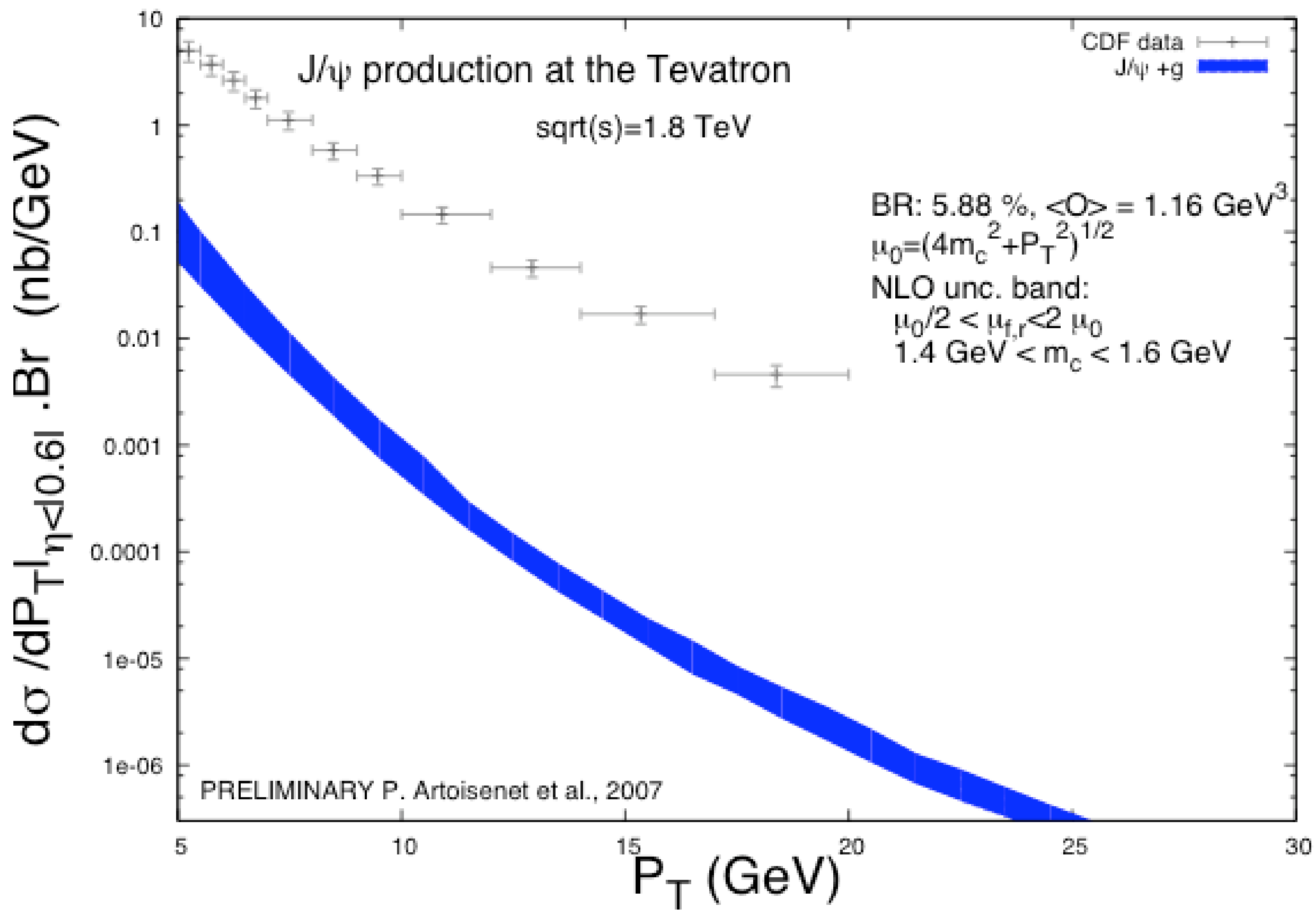
* only the same diagrams as $\gamma gg \to {}^3S_1^{[1]}$ at 1 loop survive. (but color prefactors are different).

$$\mathcal{A}^{\rm Virt} = g_s^5 \frac{d^{abc}}{\sqrt{N_c}} T^{\rm Virt}(1,2,3)$$

Checks

- Gauge invariance (reference vectors for the polarization)
- Real and virtual pole structure via the dipole subtraction scheme
- Positronium decay at NLO in em
- Υ decay into hadrons and into γ+hadrons

J/psi production at the Tevatron Run I



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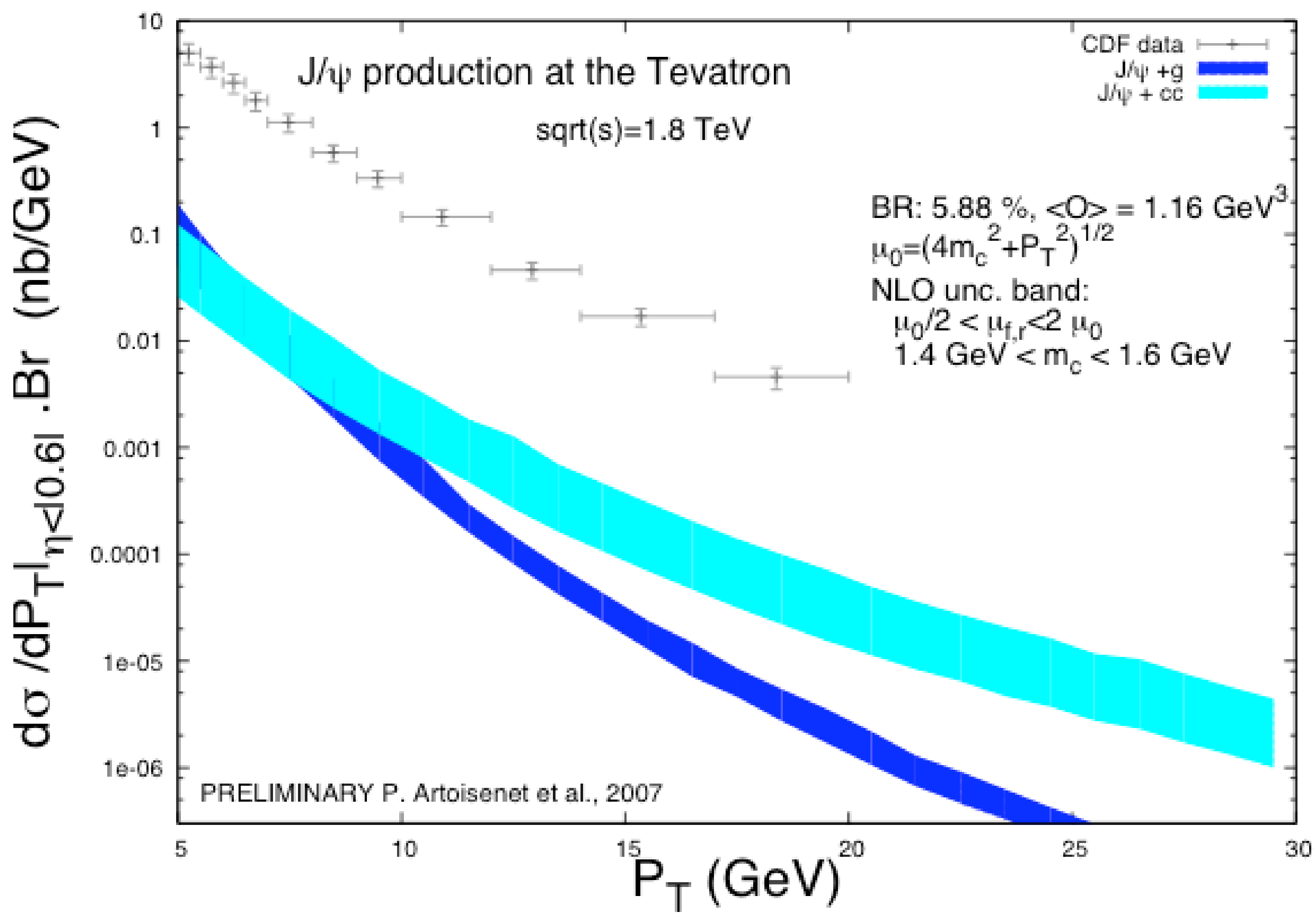

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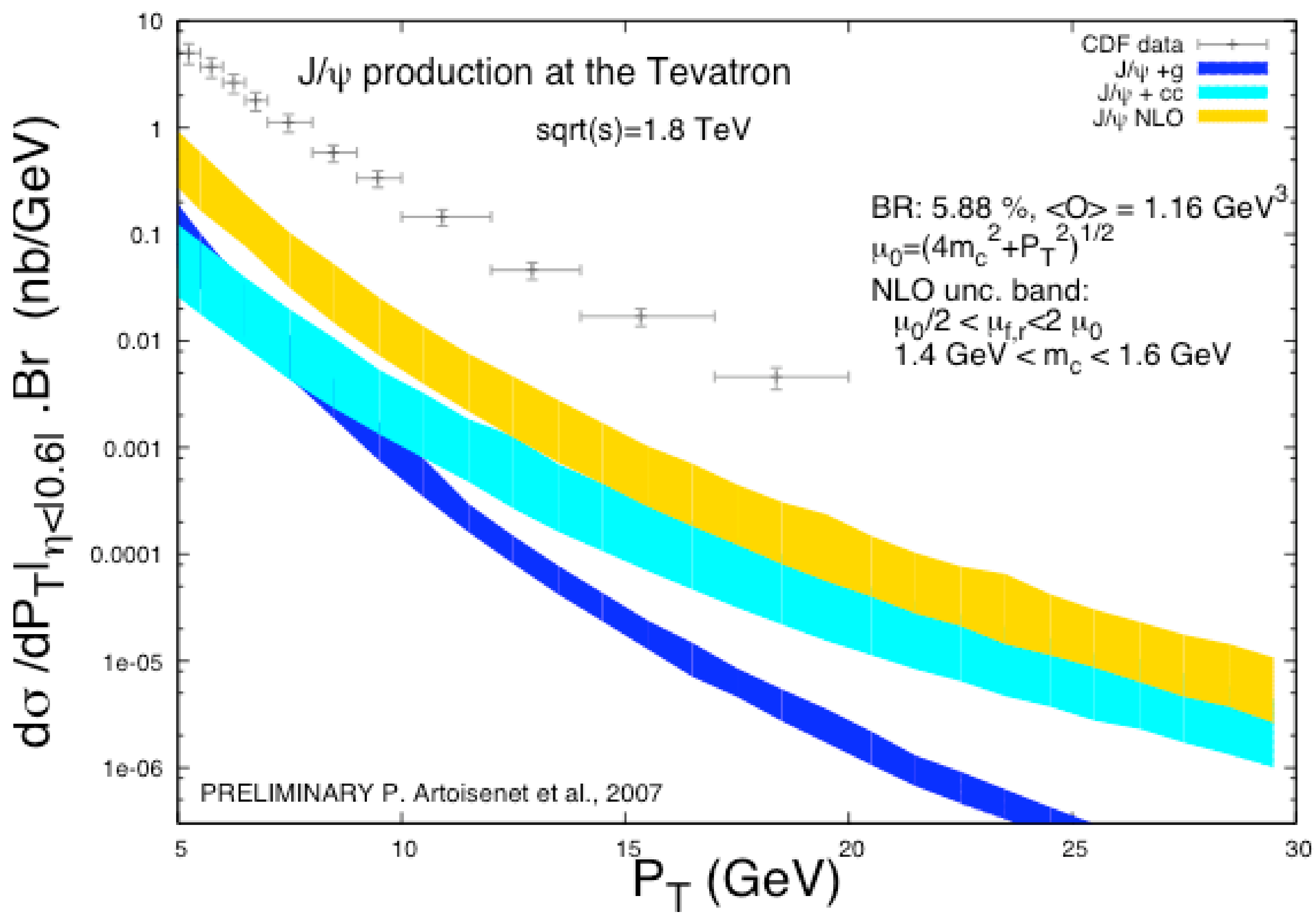
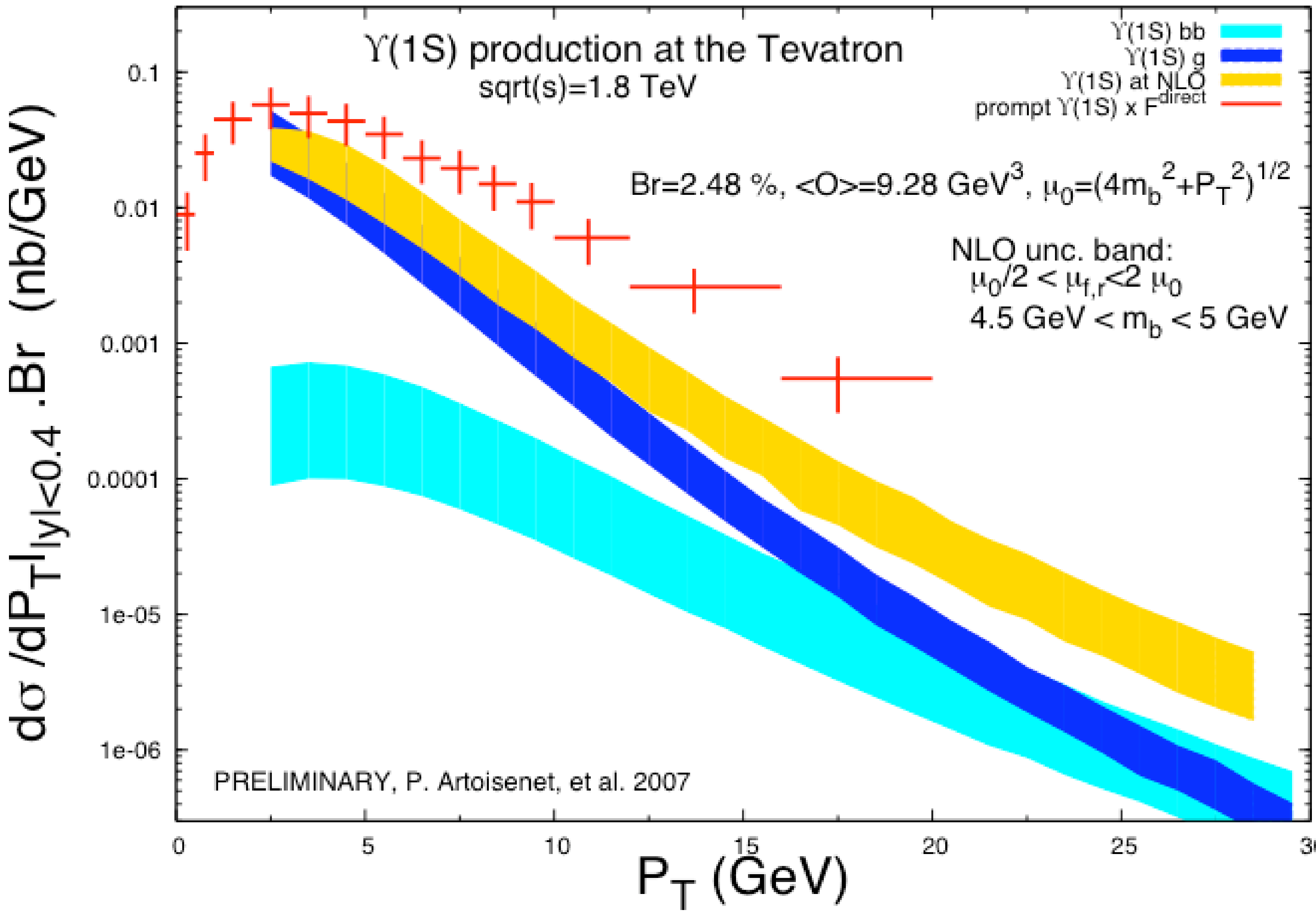


Dramatic improvement in shape and normalization but certainly not close enough to data.

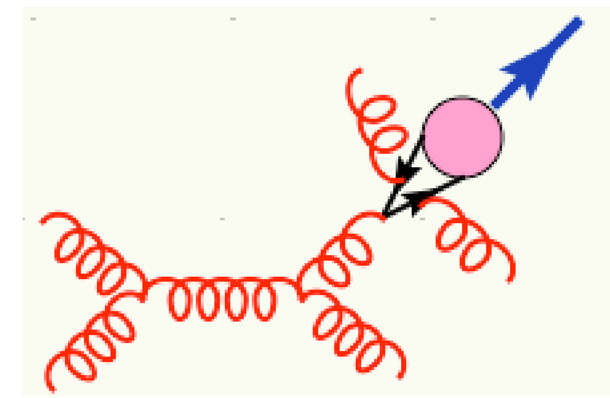
Υ(1S) production at the Tevatron Run I

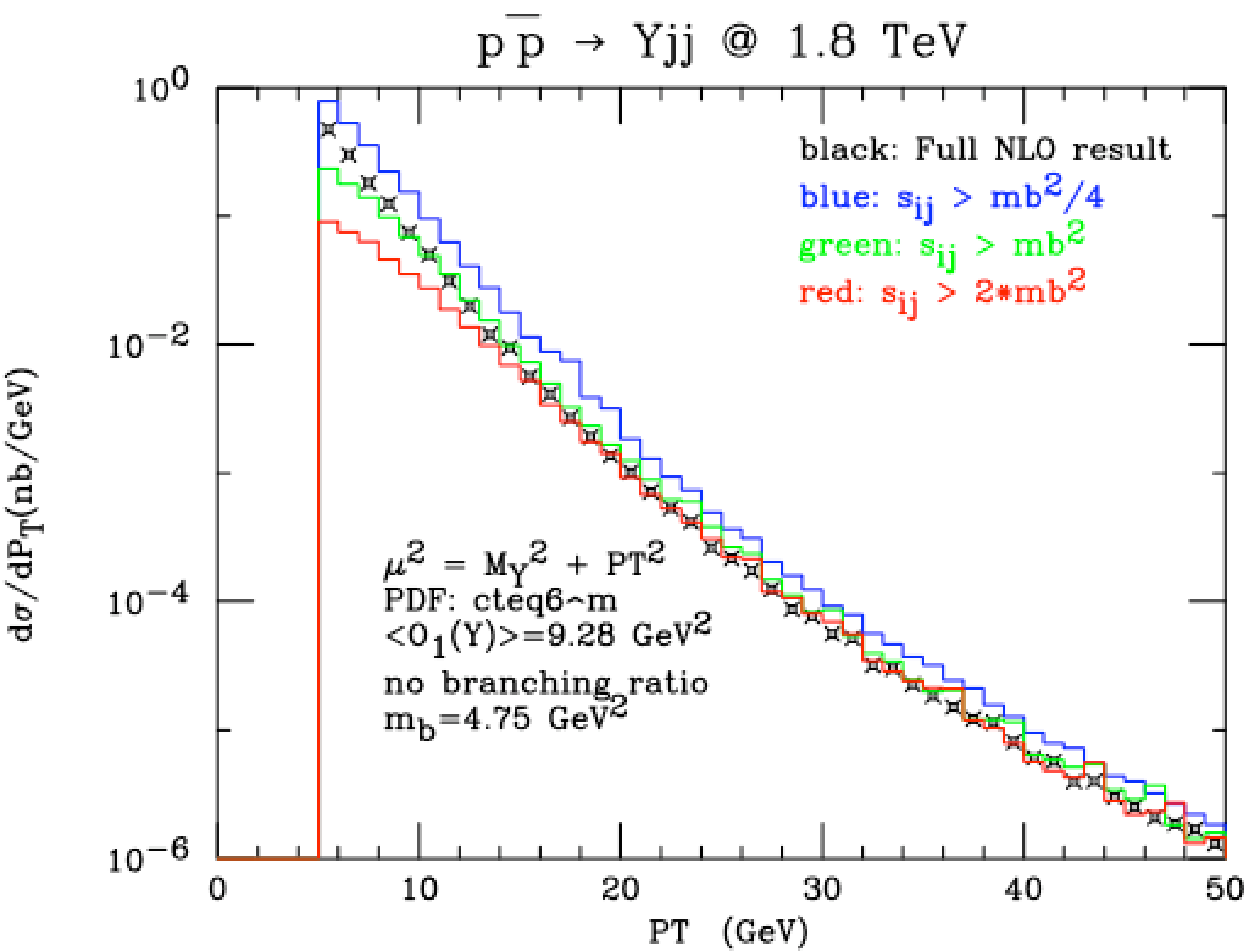


Improvement in shape and normalization. p_T is harder, but not too far....

Estimating the impact of NNLO contributions

Can we improve our description and include the α_S^5 / p_T^4 terms,
E.g., $gg \to {}^3S_1^{[1]}ggg$, not using the fragmentation approximation?
[see Lansberg's talk]
Technically challenging (~deca subprocesses, ~kilo diagrams) but now feasible! [see Artoisenet's talk]





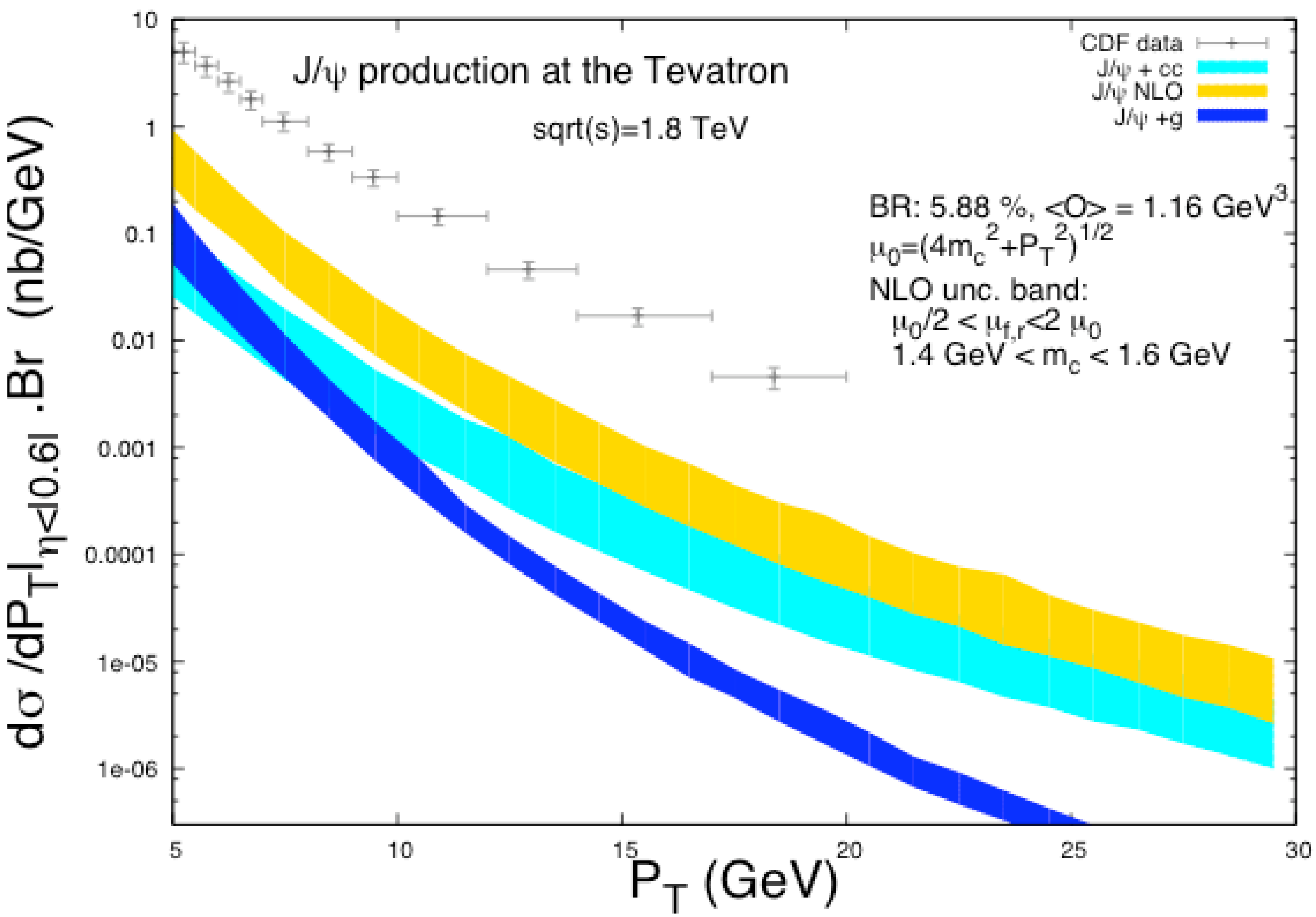
Strategy:

The real corrections with a democratic cut on $mb^2/4 < s_{ij} < 2\ mb^2$ approximate the NLO result very well.

As a first approximation we use the NLO result to find a reasonable interval of s_{ij} and give a rough estimate the NNLO contributions.

A more solid approach is based on the matching prescription a la CKKW...

Estimating the impact of NNLO contributions



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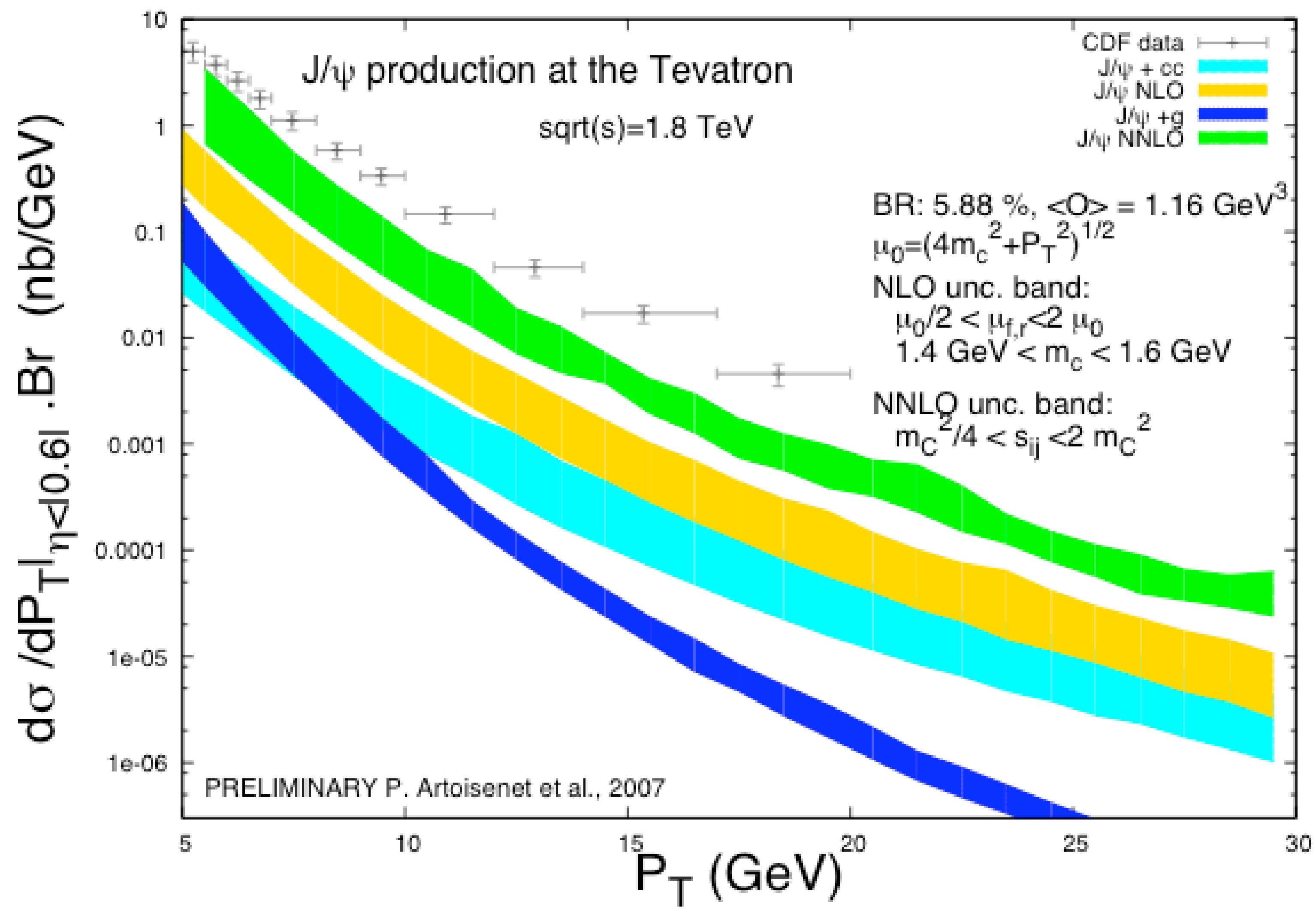


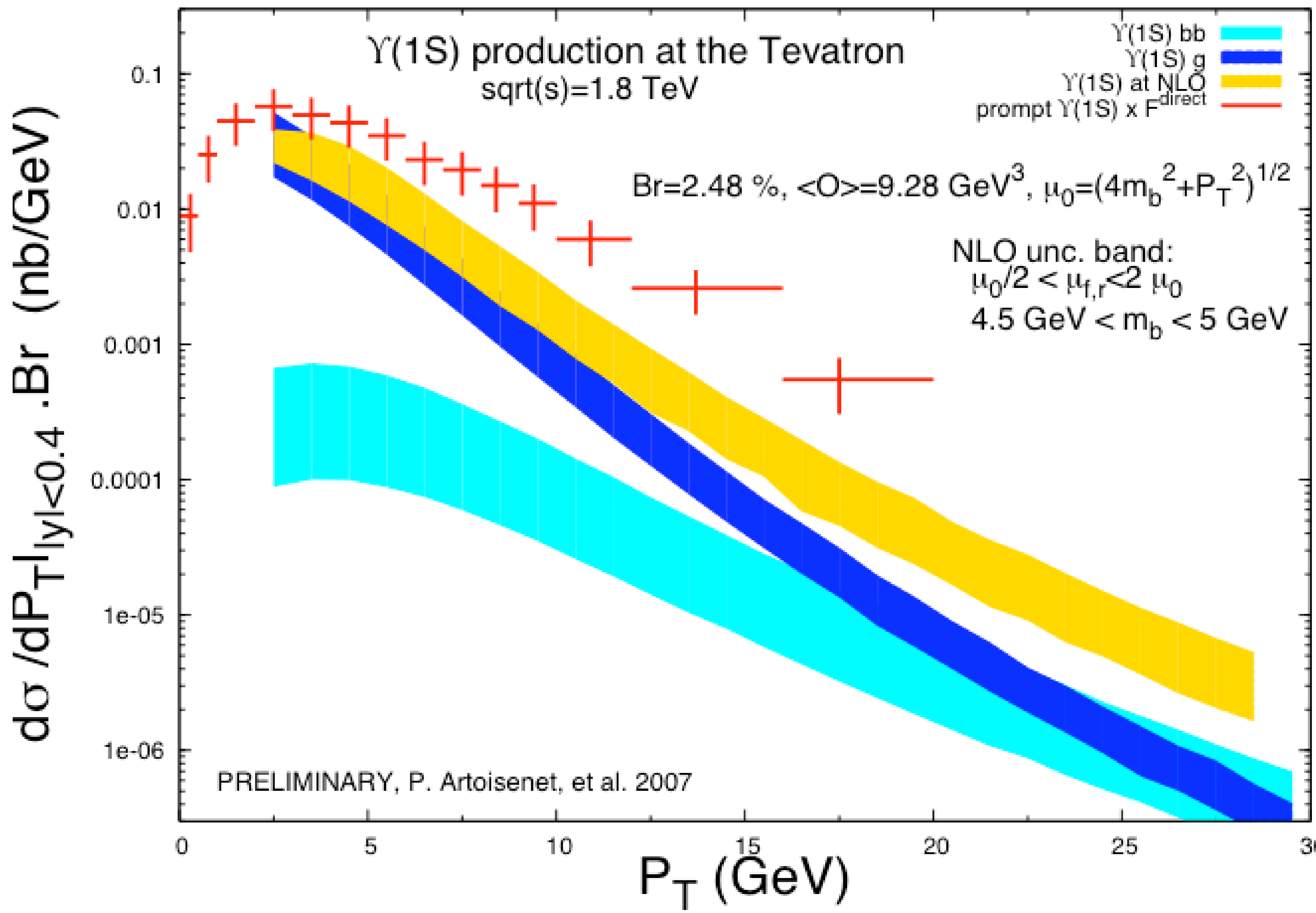
NNLO contribution is a very large effect.

*Predictions much closer to the data in shape and normalization.

*Singlet alone not able to describe the data alone but situation much less dramatic!

*More study on the TH systematics is needed (comparison with the fragmentation approach, smaller band at very high p_T,...)

Estimating the impact of NNLO contributions



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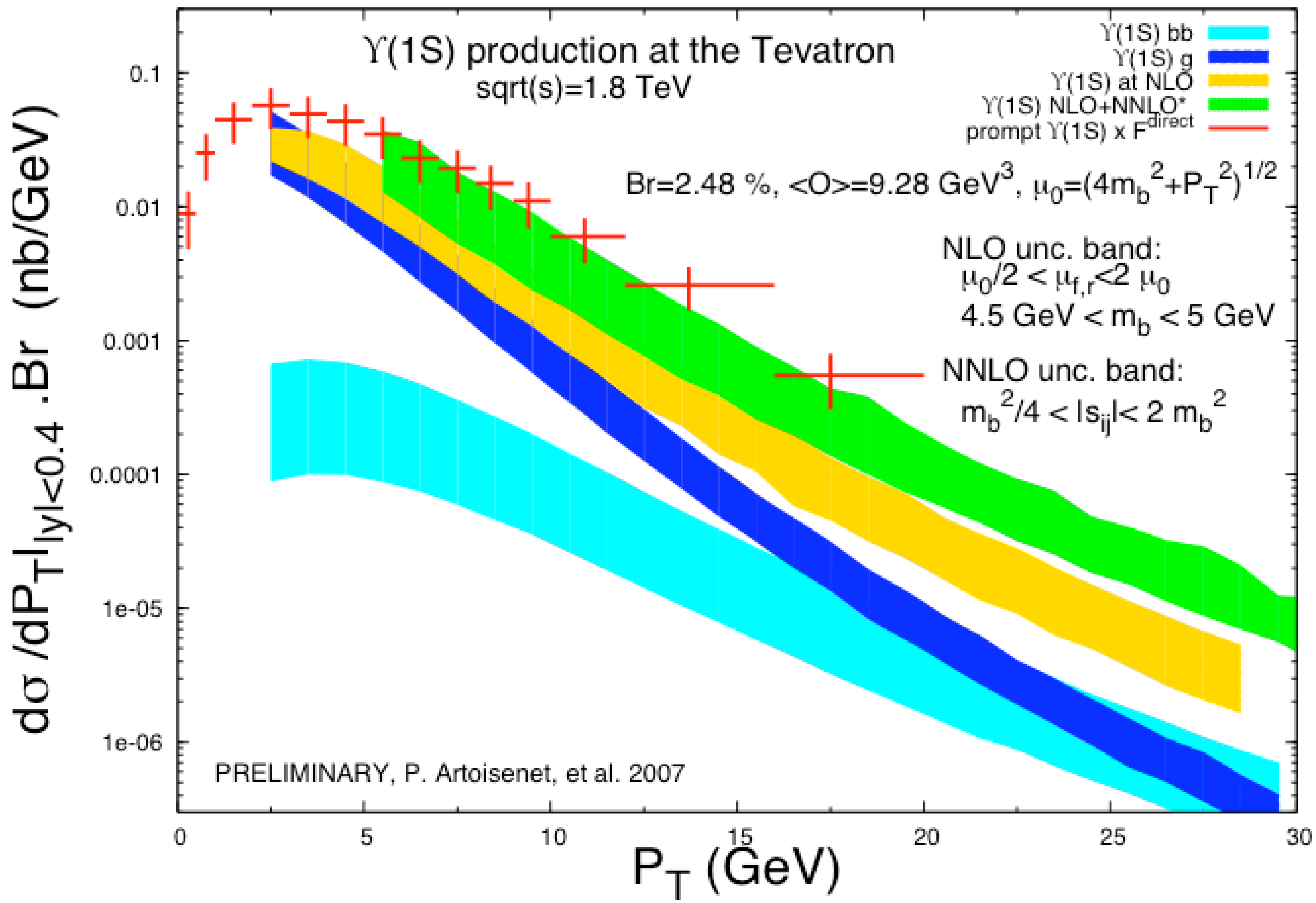


Mild effect, but exactly what is needed in terms of normalization and shape.

Inclusion of NNLO real contribution, i.e. of p_T^{-4} terms, allows a pretty good description of the data in terms of color singlet only.

More work on the systematics needed but looks promising!

Possible improvement:
do this with a better matching!

Outlook

On-going and future applications:

* Predictions for the polarization at Tevatron.
* Complete fixed target data analysis at NLO in NRQCD.
* RHIC

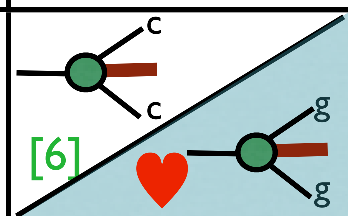
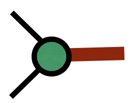
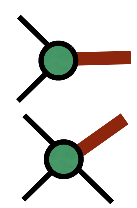
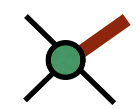
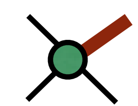
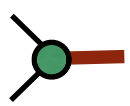
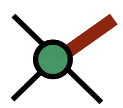
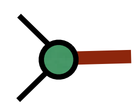
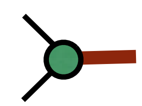
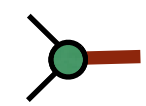
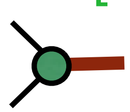
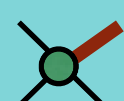
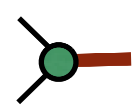
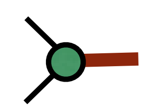
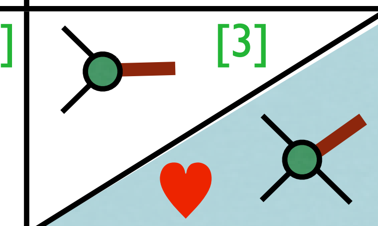
* $\gamma p \rightarrow {}^3S_1^{[1]} + X$ with polarization info and single resolved contributions [comparison with M. Kraemer's calculation (1995)]
* $\gamma\gamma \rightarrow {}^3S_1^{[1]} + X$ with polarization info + single and double resolved contributions + direct color singlet contribution
* $\gamma\gamma \rightarrow {}^3S_1^{[8]} + X$ with polarization info and single resolved contributions [comparison with Klasen et al. calculation (2005)]

Conclusions

- Quarkonium production phenomenology is very challenging.
- NLO strong corrections are now available for the color singlet production of J/psi and Y at hadron colliders.
- Preliminary comparison with Tevatron data shows that the color singlet at NLO :
  - is well below the J/psi data.
  - is just below the Y data.
- Evidence that NNLO corrections play an important role
- Further TH and EXP work needed!

Backup slides

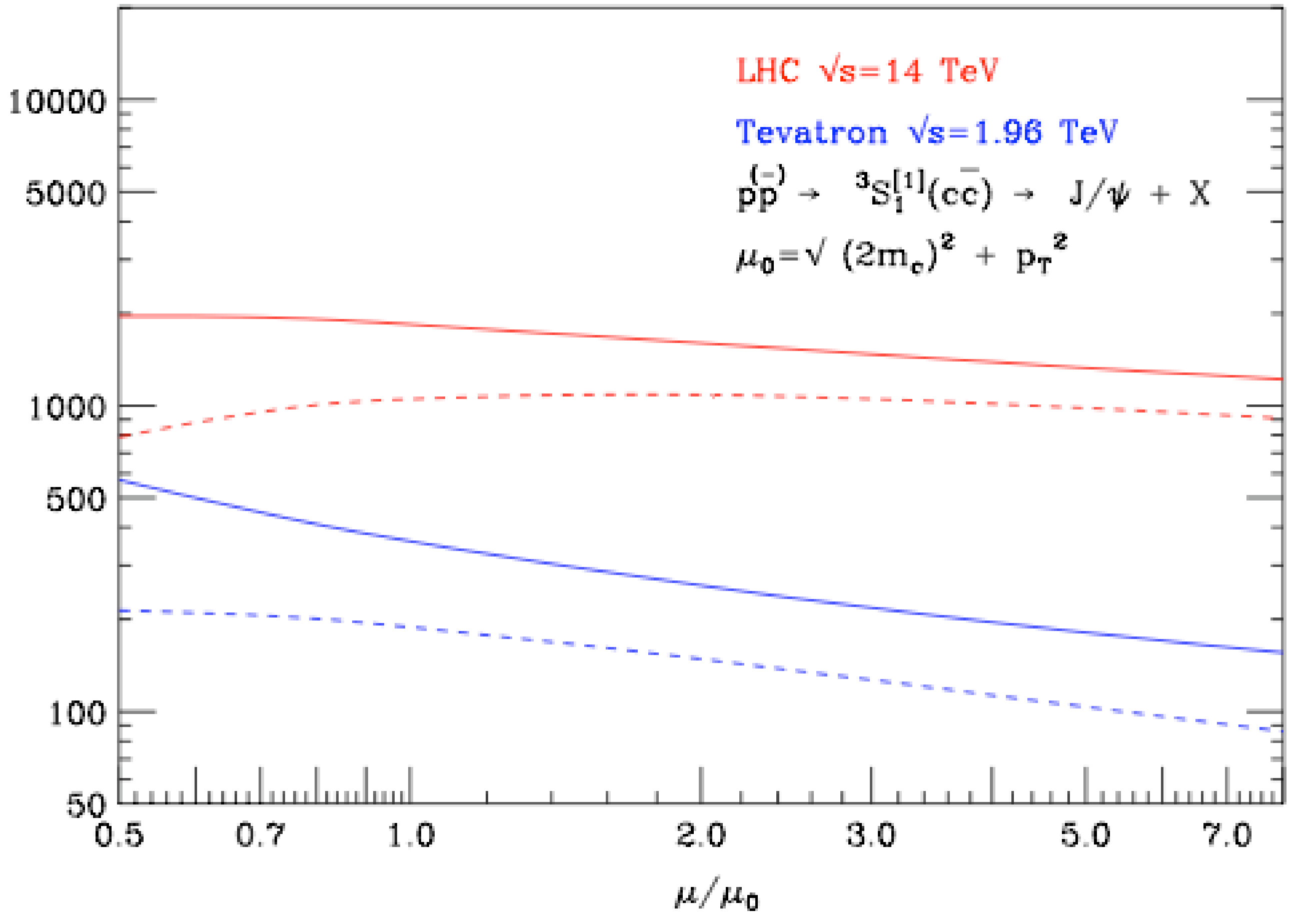
Quarkonium inclusive NLO cross sections

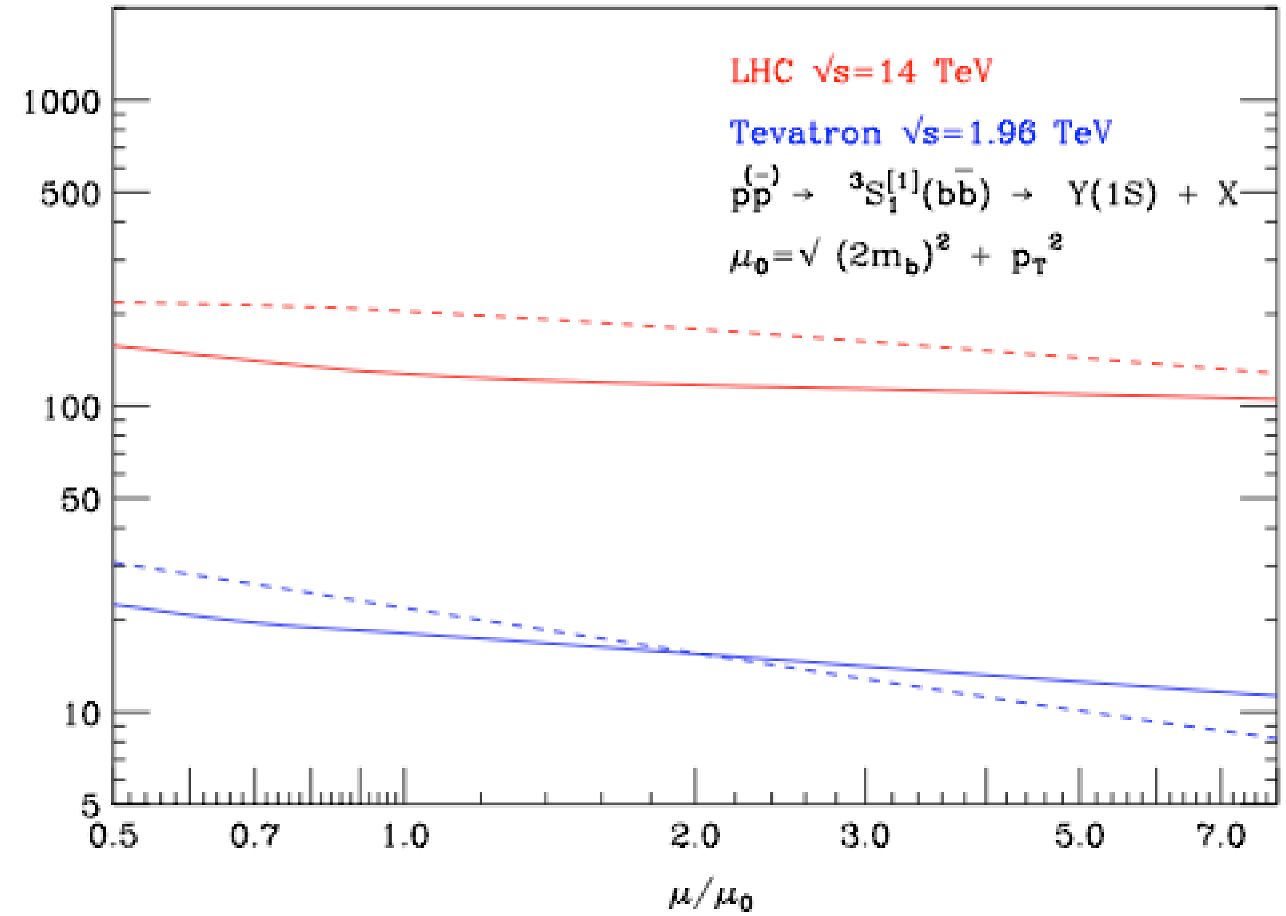
	$^1S_0^{[1]}$	$^3S_1^{[1]}$	$^3P_J^{[1]}$	$^1P_1^{[1]}$	$^1S_0^{[8]}$ $^3P_J^{[8]}$ $^1P_1^{[8]}$	$^3S_1^{[8]}$
e^+e^-		 [6] ♥				
$\gamma\gamma$	[4] 		[4] [5] 		[5] 	[5] 
γp	[4] 	[2] 	[4] 		[4] 	[4] 
pp	[1,3] 	[7] ♥ 	[3] 		[3] 	[3] ♥ 

[1] Kuhn and Mirkes, 1993;
[2] Kraemer, 1995
[3] Petrelli et al., 1998
[4] FM, Mangano Petrelli et al., 1999
[5] Klasen et al., 2005
[6] Y.-J. Zhang and K.-T. Chao, 2007
[7] Campbell, FM, Tramontano, 2007

♥ = desiderata

Results

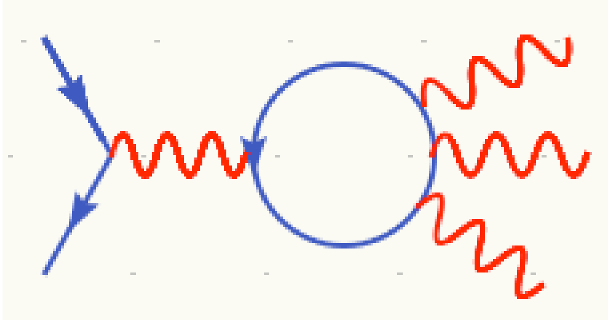




* p_T > 3 GeV, |y|<3
* "Total" K-factors are mild.
* Scale dependence slightly improved.

Checks

Orthopositronium decay:
* abelian subset of diagrams + new diagram



$$\Gamma^{\rm NLO}({\rm Orthopositronium} \to 3\gamma) = \Gamma^{\rm LO}\left[1 - 10.28665\frac{\alpha_{EM}}{\pi}\right],$$ [Adkins,et al. , 2000]

Y inclusive decay:

$$\Gamma^{\rm NLO}(\Upsilon \to LH) = \Gamma^{\rm LO}\left[1 + \frac{\alpha_S(\mu)}{\pi}\left(-9.471\ C_F + 4.106\ C_A - 1.150\ n_f + \frac{3}{2}\beta_0 \log\frac{\mu}{m_b}\right)\right],$$

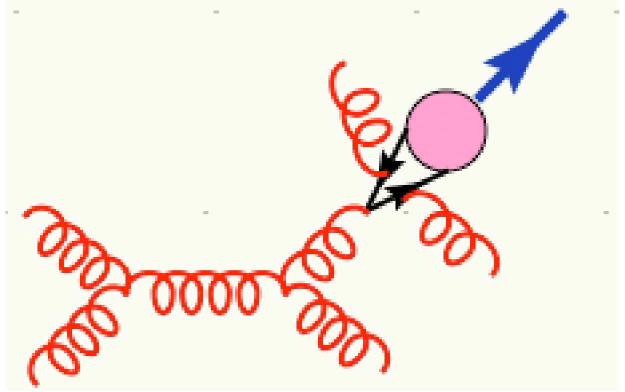
[Mackenzie & Lepage, 1981] $\left[1\ +\ (-9.46(2)C_F\ +\ 4.13(17)C_A\ -\ 1.161(2)n_f)\,\frac{\alpha_s}{\pi}\right]$

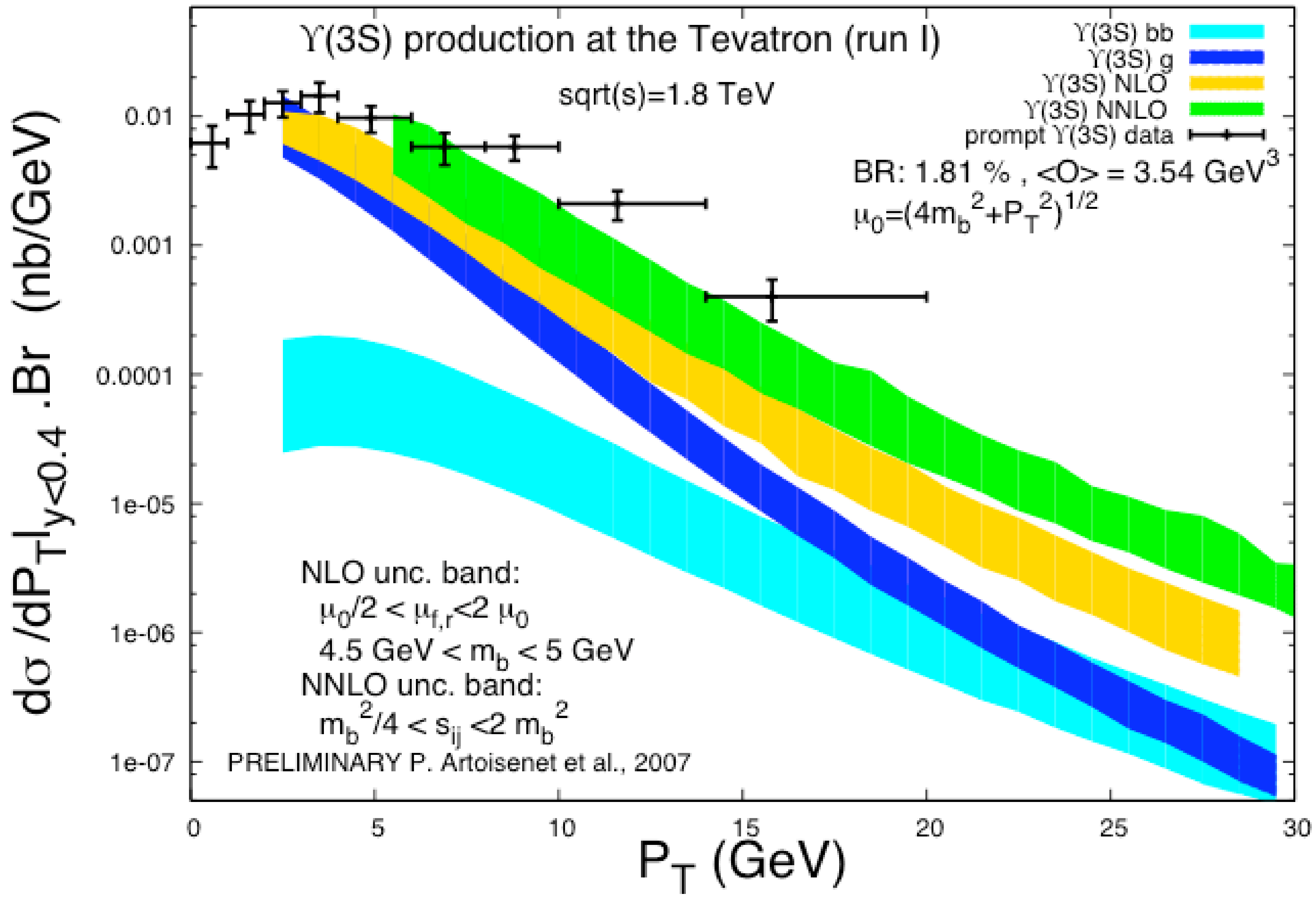
Y photon inclusive decay:

$$\Gamma^{\rm NLO}(\Upsilon \to \gamma{+}LH) = \Gamma^{\rm LO}\left[1 + \frac{\alpha_S(\mu)}{\pi}\left(-9.471\ C_F + \frac{2}{3}(4.106\ C_A - 1.150\ n_f + \frac{3}{2}\beta_0 \log\frac{\mu}{m_b})\right)\right],$$

[Mackenzie & Lepage, 1981; M. Kraemer 1998] $\left[1 + (-9.46(2)C_F + 2.75(11)C_A - 0.774(1)n_f)\,\frac{\alpha_s}{\pi}\right]$

Estimating the impact of NNLO contributions





A similar study can be also performed on the Υ(3S) data which don't have feeddown contributions but are only direct.