Surprises and Anomalies in Heavy Quarkonium Production

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Based on work done with Kang, Nayak, Sterman, and …

GGI workshop on "High-energy QCD after the start of the LHC"
Sept 5 – Oct 21, 2011, Florence, Italy

Outline of my talk

- Introduction
- Heavy quarkonium production models
- Surprises and anomalies
- Perturbative QCD factorization approach
- Connect pQCD factorization to NRQCD factorization
- Suppressions and puzzles in nuclear collisions
- Summary

The November revolution in 1974 (SM)

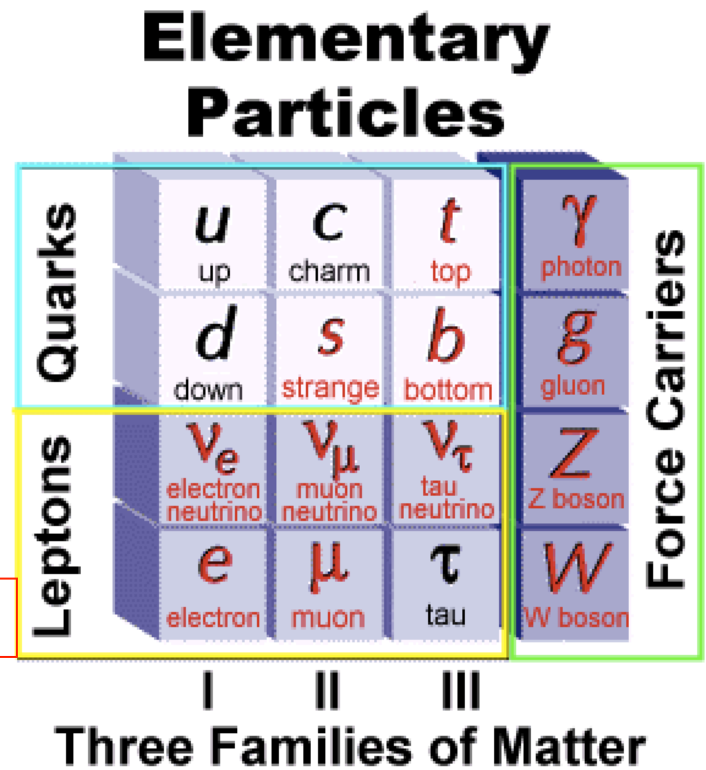
- New periodic table for elementary particles:

Flavor	Mass
u	1.5 – 4.5 MeV
d	5.0 – 8.5 MeV
s	80 – 155 MeV
c	1.0 – 1.4 GeV
b	4.0 – 4.5 GeV
t	174.3 ± 5.1 GeV

Light quarks

Λ_{QCD}

heavy quarks



- QCD can have bound states w/wo "localized" color charge!
- QCD could have "atom-like" bound systems – how about "molecule-like" systems in QCD: nuclei, X, Y, Z particles?

Hadrons with "localized" color charge(s)

- Heavy-light meson – "atom-like" system:
  - Charmed mesons: $D^+ = c\bar{d},\ D^0 = c\bar{u},\ \bar{D}^0 = \bar{c}u,\ D^- = \bar{c}d,\ \ldots$
  - Charmed, strange mesons: $D_s^+ = c\bar{s},\ D_s^- = \bar{c}s,\ \ldots$
  - Bottom mesons: $B^+ = u\bar{b},\ B^0 = d\bar{b},\ \bar{B}^0 = \bar{d}b,\ B^- = \bar{u}b,\ \ldots$

  Heavy quark symmetry $\Rightarrow$ HQET

- Heavy-heavy meson/quarkonium – "NR" system
  - Bottom, charmed mesons: $B_c^+ = c\bar{b},\ B_c^- = \bar{c}b,\ \ldots$
  - $c\bar{c}$ mesons: $J/\psi,\ \chi_c,\ \psi',\ \ldots$
  - $b\bar{b}$ mesons: $\Upsilon,\ \chi_b,\ \ldots$

  Heavy-heavy system: $\Rightarrow$ NRQCD, pNRQCD

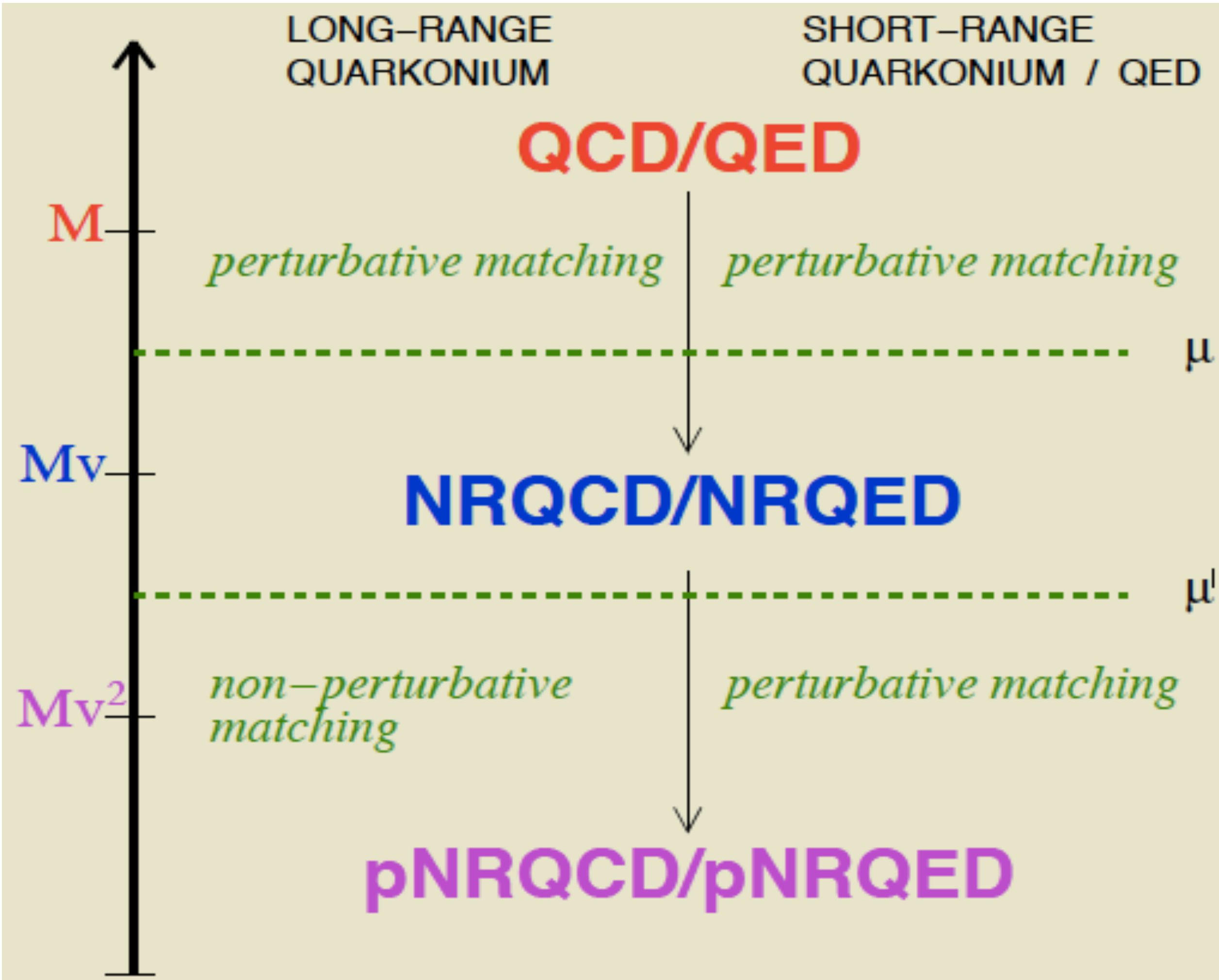
- Recent review:

  N. Brambilla et al. Eur. Phys. J. C71, 1534 (2011) [arXiv: 1010.5827]

Non-relativistic effective field theory

A. Vario, Hadron 2011

- Quarkonium scales:



Hard
(all scales > M)

Soft
(relative momentum)

Ultra Soft
(binding energy)

Another relevant scale in QCD: Λ_{QCD}

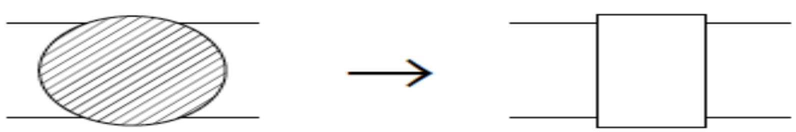
Non-relativistic QCD (NRQCD)

- ❑ **Perturbative expansion in the relative velocity:** $v \propto \dfrac{1}{m}$

$$
\begin{aligned}
\mathcal{L} = {} & \psi^\dagger \left(iD_0 + \frac{\mathbf{D}^2}{2m} + c_F \frac{\mathbf{S}\cdot g\mathbf{B}}{m} + c_D \frac{[\mathbf{D}\cdot, g\mathbf{E}]}{8m^2} + \ldots \right) \psi \\
& + \chi^\dagger \left(\qquad \ldots \qquad \right) \chi \\
& + \sum_K \frac{f}{m^2} \psi^\dagger \, K \, \chi \chi^\dagger \, K \, \psi + \cdots \\
& - \frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \sum^{n_f} \bar{q} \, i \not{D} \, q + \ldots
\end{aligned}
$$

Caswell, Lepage 86, Bodwin Braaten Lepage 95, Manohar 97

- ❑ **Integrate out the degrees of freedom that scales like "m":**



$\times$ c(μ/m)

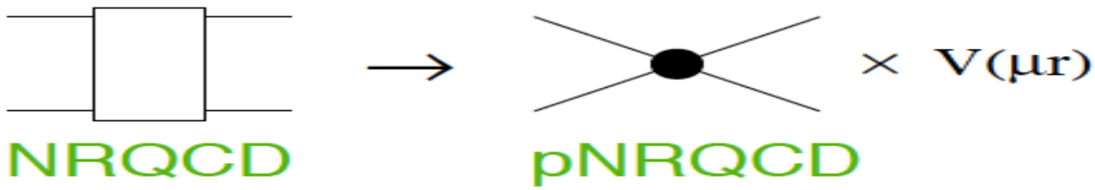
QCD NRQCD

- ❑ **Works very well for calculating the decay rate!**

Potential non-relativistic QCD (pNRQCD)

Pineda, Soto 98, Brambilla, Pineda, Soto, Vairo, 2000, review 2005

- Integrate out the degrees of freedom scales like “mv” ($>\Lambda_{QCD}$)



- Expansion in color states of heavy quark pairs and “r”

$$\mathcal{L} = -\frac{1}{4} F^{a}_{\mu\nu} F^{\mu\nu\, a} + \mathrm{Tr}\left\{ \mathrm{S}^\dagger \left(i\partial_0 - \frac{\mathbf{p}^2}{m} - V_s \right) \mathrm{S} + \mathrm{O}^\dagger \left(iD_0 - \frac{\mathbf{p}^2}{m} - V_o \right) \mathrm{O} \right\}$$

LO in “r”

$$\theta(T)\, e^{-iTH_s} \qquad \theta(T)\, e^{-iTH_o} \left(e^{-i\int dt\, A^{\mathrm{adj}}} \right)$$

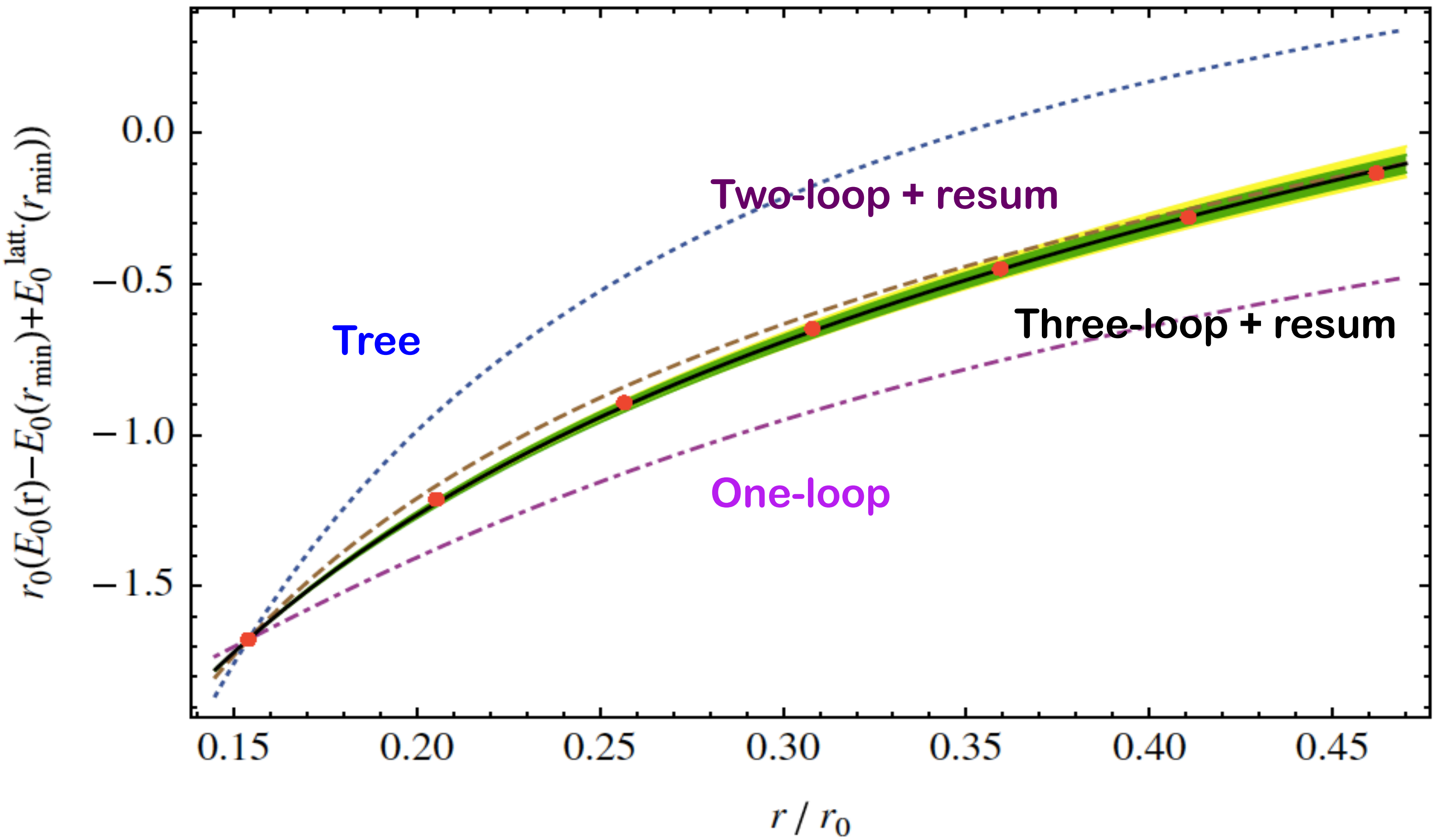
S: color singlet $Q\text{-}\bar{Q}$, O: color octet $Q\text{-}\bar{Q}$

- Systematic calculation of static potential when $r \ll r_0 \sim 0.5$ fm

$$V_s(r, \mu, \alpha_s(r))$$

Static potential energy vs lattice QCD

Brambilla, et al. PRL 2010



● Lattice QCD data points   Necco and Sommer, 2002

With a few parameters, potential models extended to a larger r have done a good job in fitting the quarkonia spectra!

Production

- **More momentum scales:**

  Momentum of quarkonium: $p_T >> M_{J/\psi}$

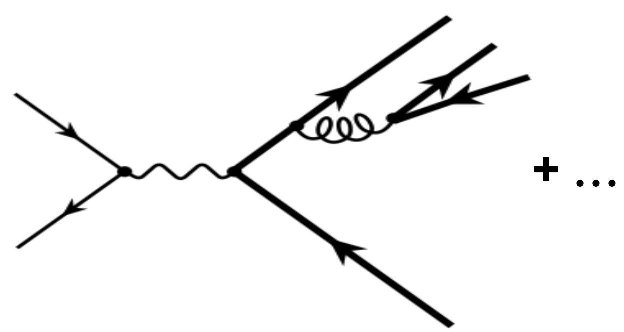
  Invariant mass of the pair: $M_{c\bar{c}} > M_{J/\psi}$

- **More than one-pair, more than one velocity, …**

  Potential Coulomb singularity:

  Current NRQCD is not consistent

  for this type of processes



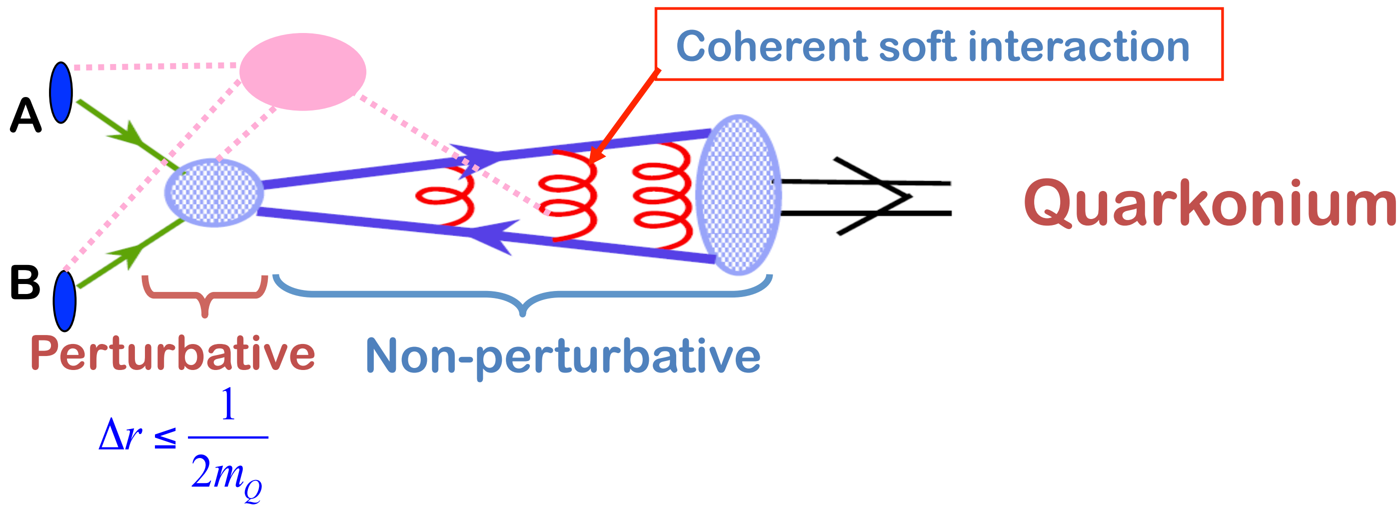
- **A physical quarkonium is unlikely formed when the heavy quark pair was produced**

$$\frac{1}{2m_Q} \ll \mathcal{O}(\mathrm{fm})$$

Brodsky, Mueller, 1988

Basic production mechanism

- Production of an off-shell heavy quark pair:



- Approximation: on-shell pair + hadronization

$$\sigma_{AB\to J/\psi} = \sum_{\text{states}} \int d\Gamma_{Q\bar{Q}} \left[\frac{d\hat{\sigma}(Q^2)}{d\Gamma_{Q\bar{Q}}}\right] F_{\text{states}(Q\bar{Q})\to J/\psi}(p_Q, p_{\bar{Q}}, P_{J/\psi})$$

✧ Different models ⇔ Different assumptions/treatments on how the heavy quark pair becomes a quarkonium?

✧ Factorization – No proof!

A long history for the production

- Discovery of J/ψ – November revolution – 1974
- Color singlet model: 1975 –

  Einhorn, Ellis (1975),
  Chang (1980),
  Berger and Jone (1981), …

  Only the pair with right quantum numbers

  Effectively No free parameter!

- Color evaporation model: 1977 –

  Fritsch (1977), Halzen (1977), …

  All pairs with mass less than open flavor heavy meson threshold

  One parameter per quarkonium state

- NRQCD model: 1986 –

  Caswell, Lapage (1986)
  Bodwin, Braaten, Lepage (1995)
  QWG review: 2004, 2010

  All pairs with various probabilities – NRQCD matrix elements

  Infinite parameters – organized in powers of v and α_s

- pQCD factorization approach: 2005 –

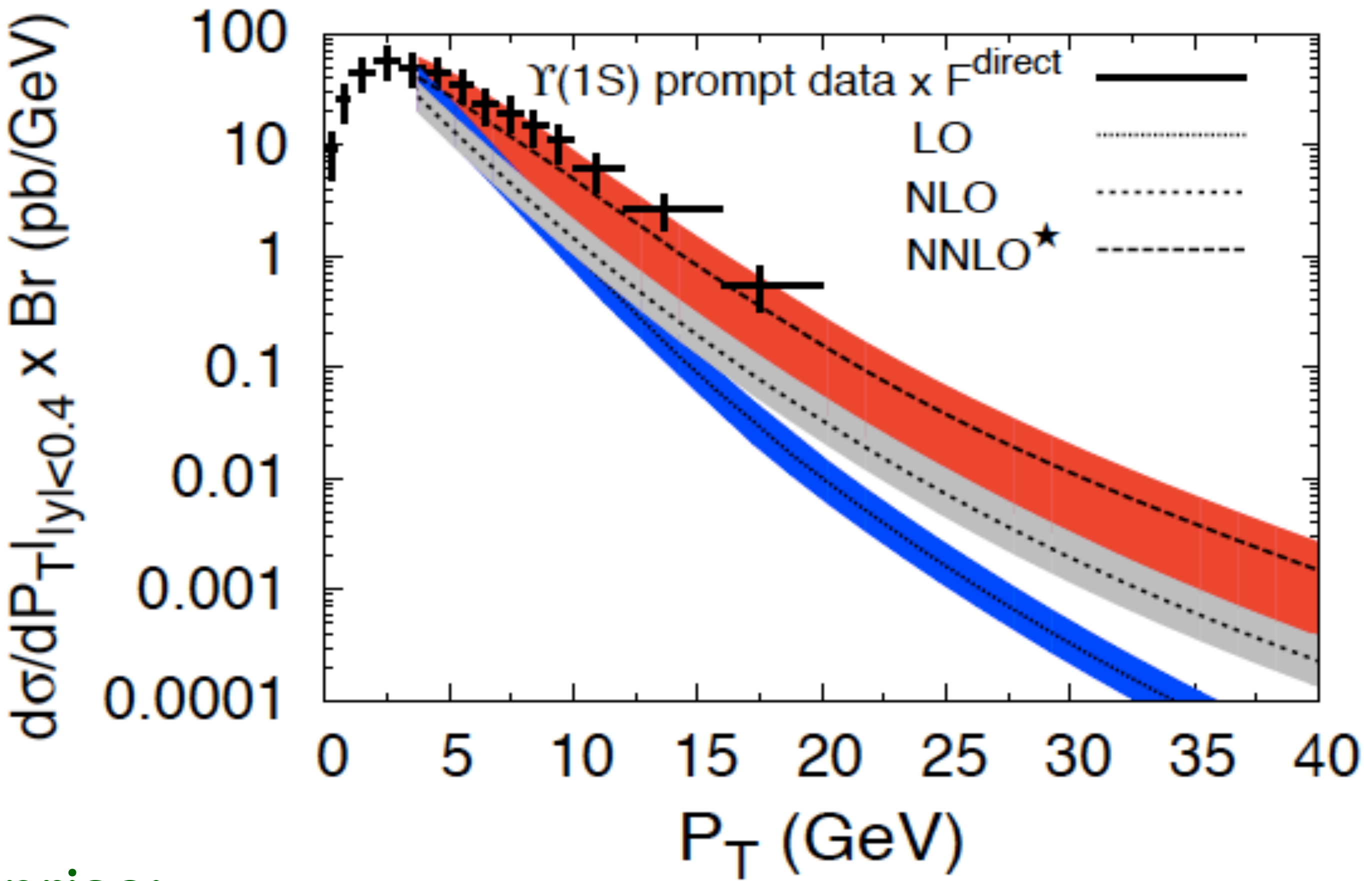
  Nayak, Qiu, Sterman (2005), …
  Kang, Qiu, Sterman (2010), …

  $P_T >> M_H$: M_H/P_T power expansion + α_s – expansion

  Universal fragmentation functions – evolution/resummation

Color singlet model – huge HO contribution

Campbell, Maltoni, Tramontano (2007), Artoisenet, Lansburg, Maltoni (2007)
Artoisenet, Campbell, Lansburg, Maltoni, Tramontano (2008)

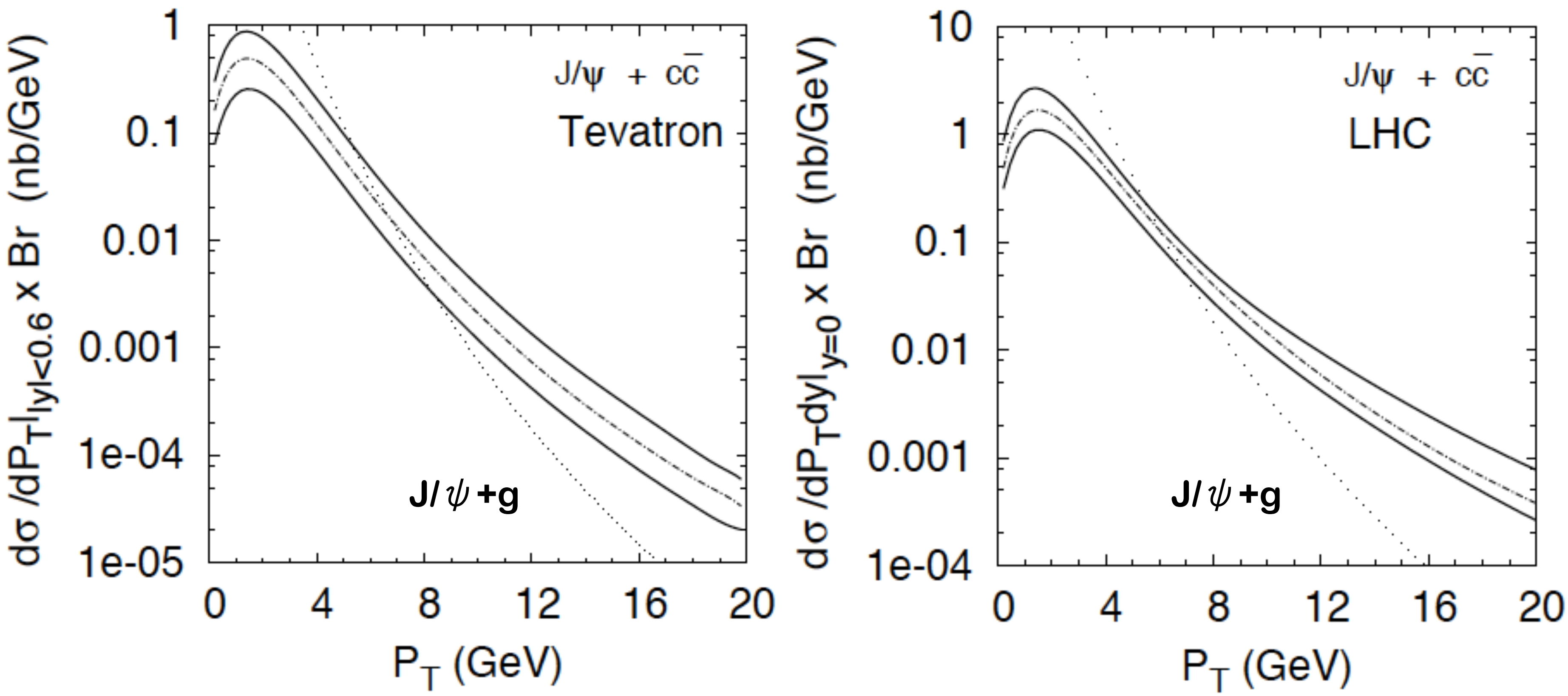


- ❑ **Surprise:**

Order of magnitude enhancement from high orders?

Color singlet model – huge associate production

Artoisenet, Lansburg, Maltoni (2007)

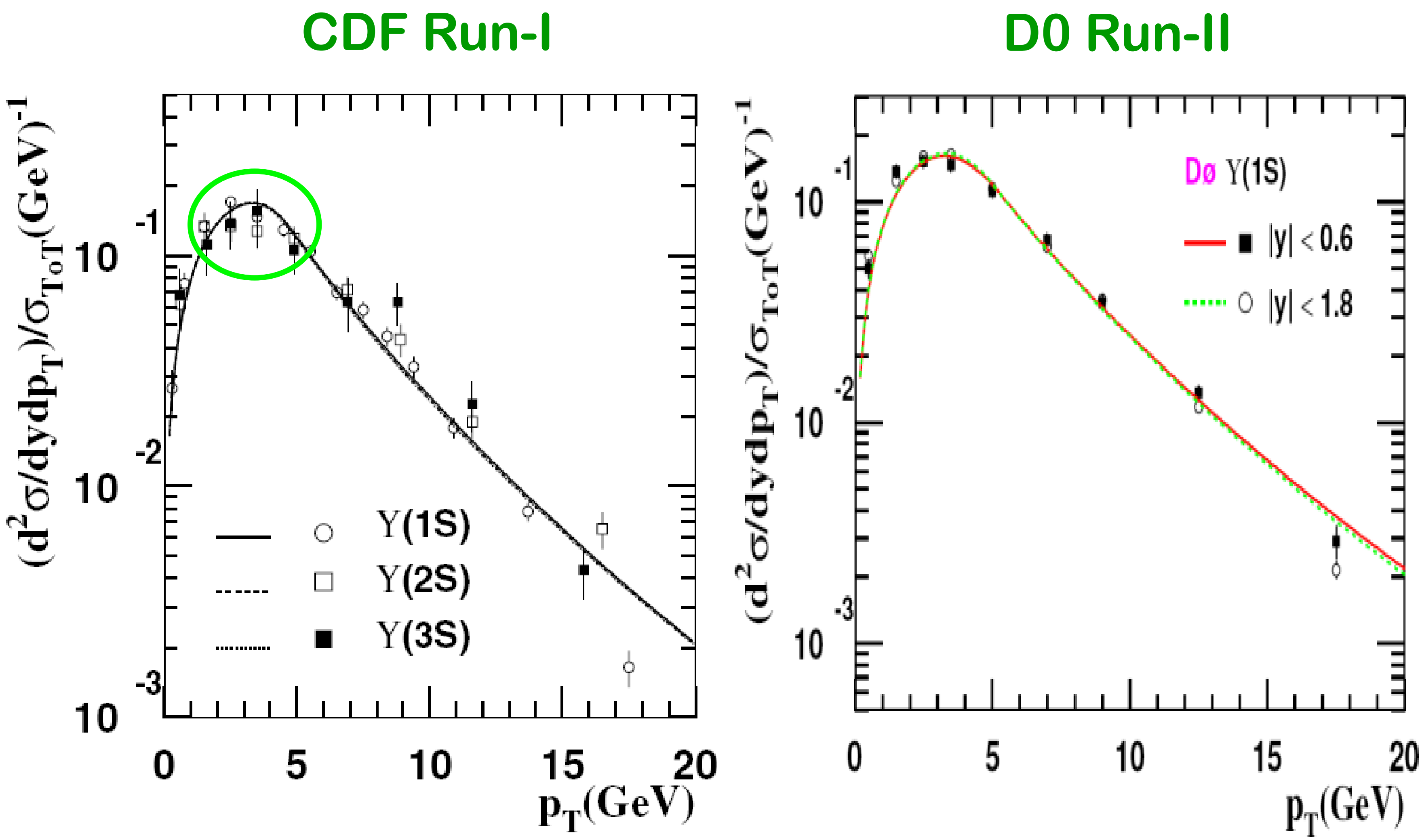


- **More surprises and question:**

  Wrong shape and strong collision energy dependence?

  How reliable is the perturbative expansion?

CEM: with resummation of shower logs



- Question:

  Too hard p_T distribution – polarization?

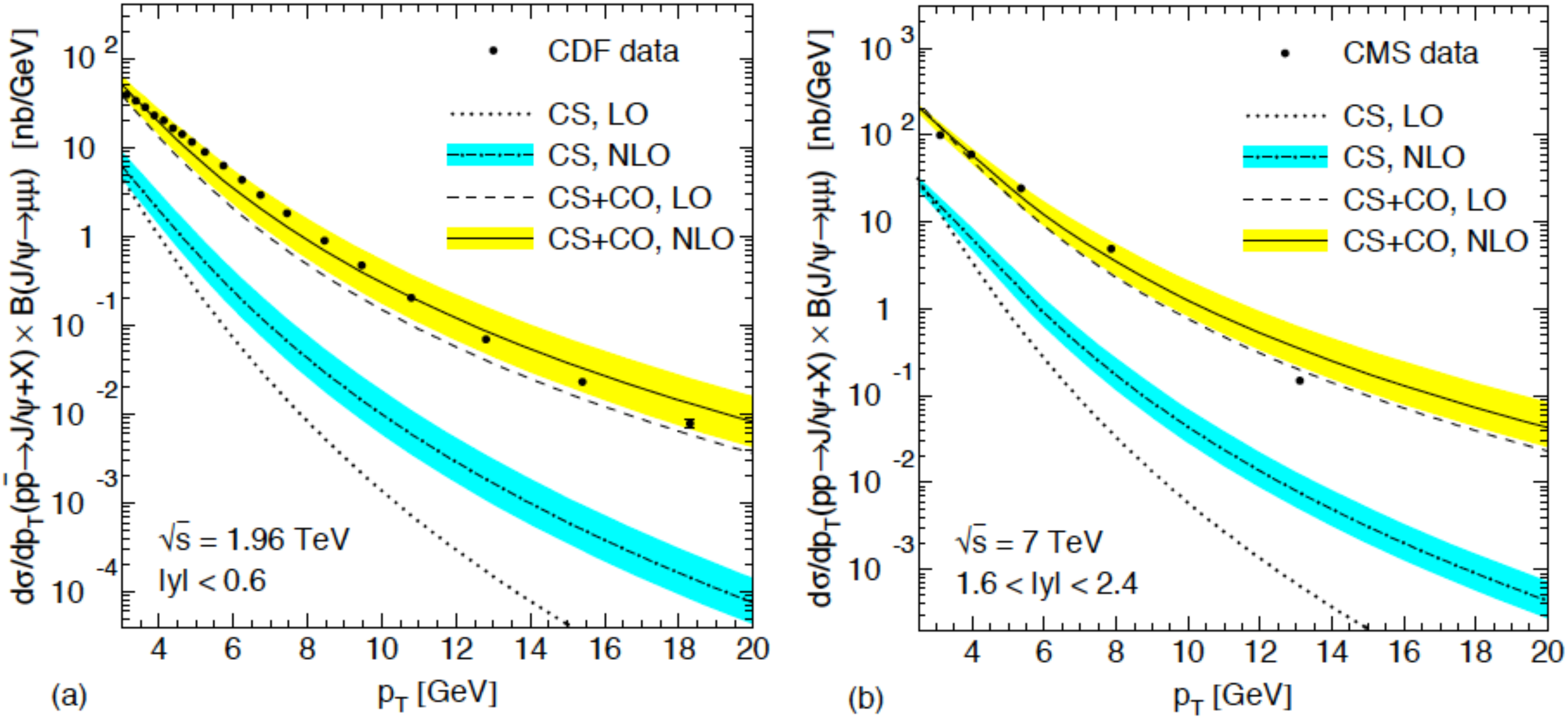
Berger, Qiu, Wang, 2005

NRQCD – most successful so far

- NLO color octet contributions – becoming available:

  Most hard calculations were done in China and Germany!

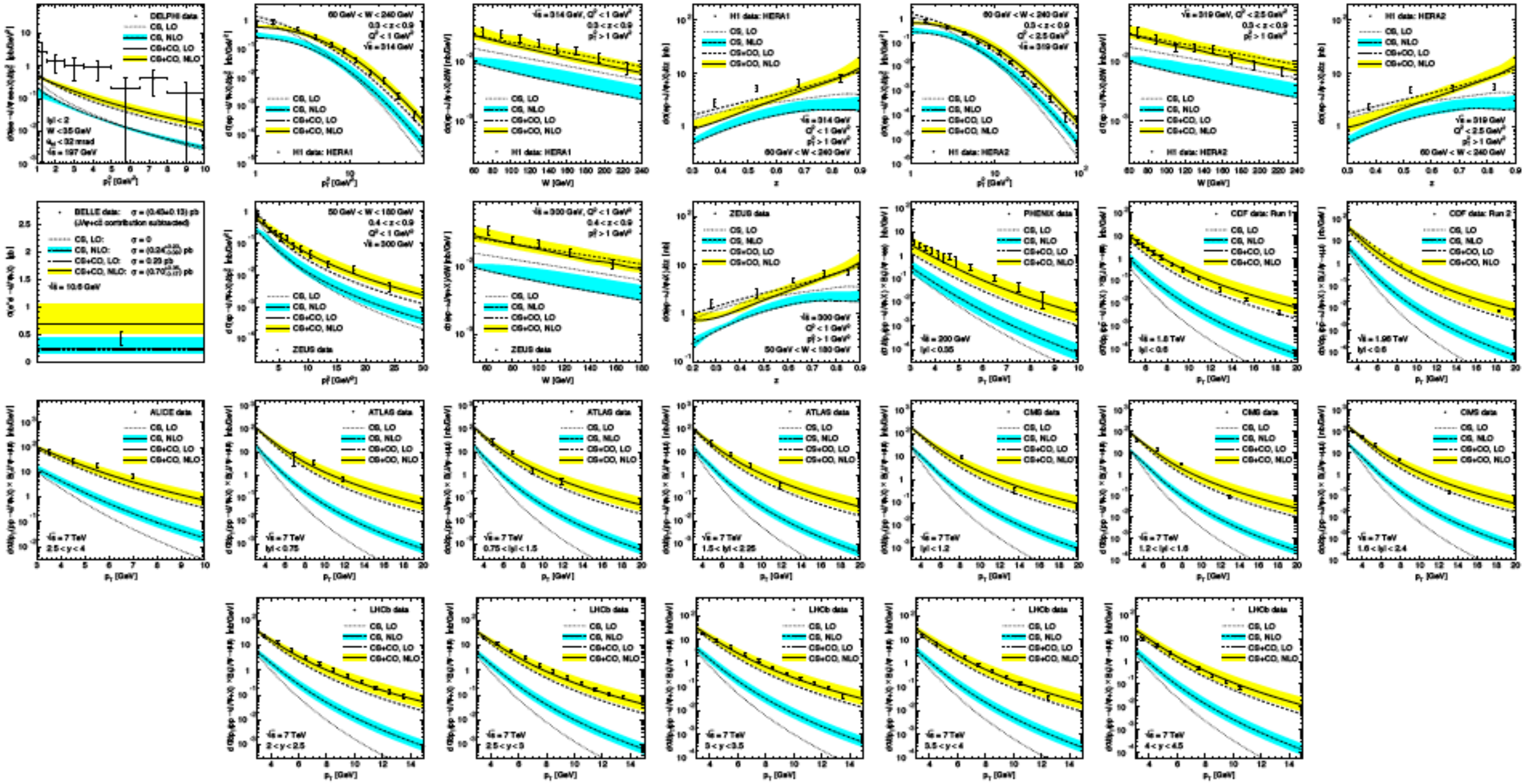
- Phenomenology:



- Fine details – shape – high at large p_T?

PRL 106, 022003 (2011)

NRQCD – global analysis



194 data points from 10 experiments, fix singlet $\langle O[^3S_1^{[1]}]\rangle = 1.32\ \mathrm{GeV}^3$

$\langle O[^1S_0^{[8]}]\rangle = (4.97 \pm 0.44)\cdot 10^{-2}\ \mathrm{GeV}^3$ $\langle O[^3S_1^{[8]}]\rangle = (2.24 \pm 0.59)\cdot 10^{-3}\ \mathrm{GeV}^3$

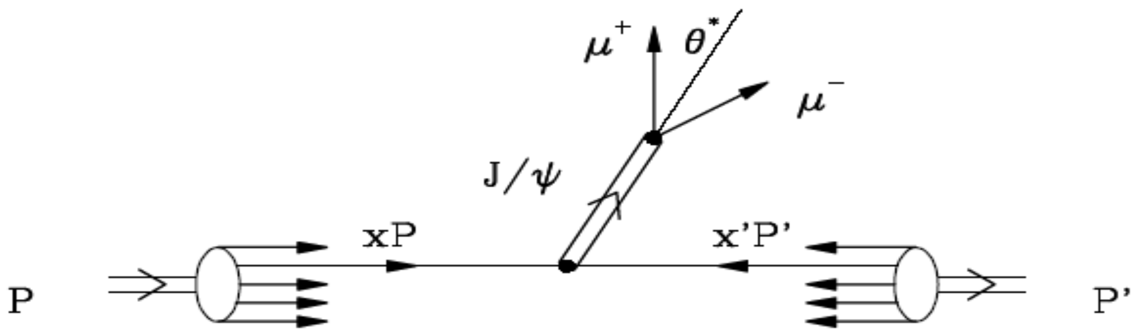
$\langle O[^3P_0^{[8]}]\rangle = (-1.61 \pm 0.20)\cdot 10^{-2}\ \mathrm{GeV}^5$

$\chi^2/d.o.f. = 857/194 = 4.42$

Butenschoen and Kniehl, arXiv: 1105.0820

Heavy quarkonium polarization

- Measure angular distribution of $\mu^+\mu^-$ in J/ψ decay



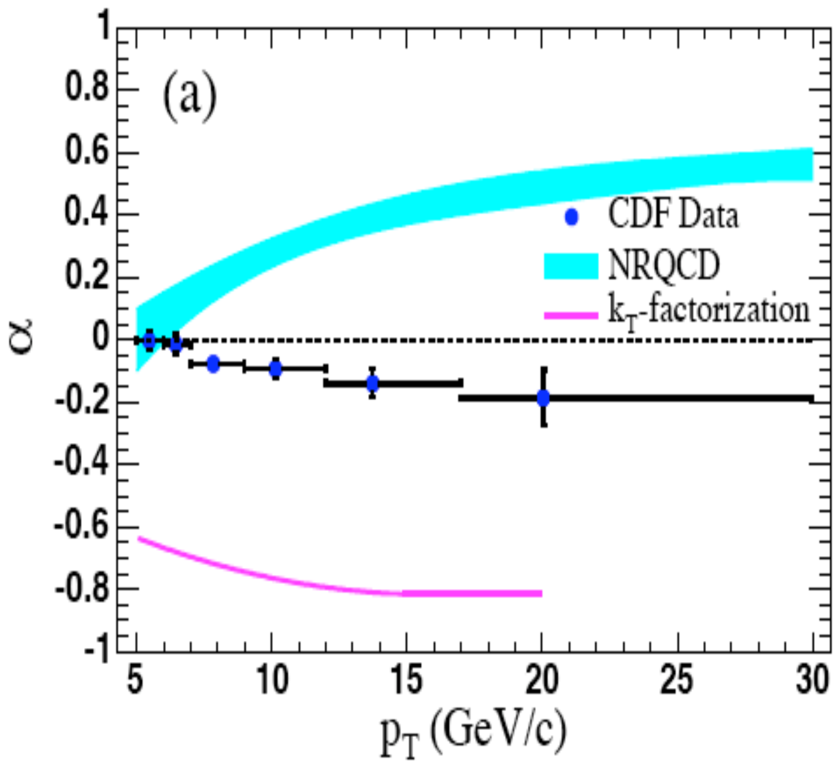
- Normalized distribution – integrate over φ:

$$I(\cos\theta^*) = \frac{3}{2(\alpha+3)}\left(1+\alpha\cos^2\theta^*\right)$$

$$\alpha = \begin{cases} +1 & \text{fully transverse} \\ 0 & \text{unpolarized} \\ -1 & \text{fully longitudinal} \end{cases}$$

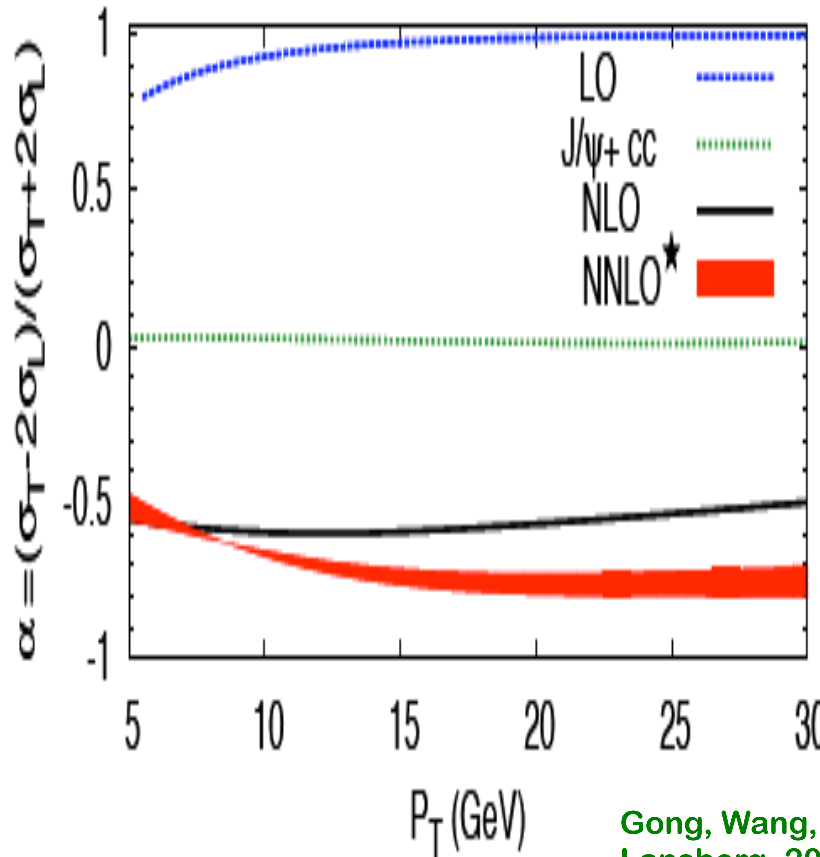
Anomalies from J/ψ polarization

NRQCD



Cho & Wise, Beneke & Rothstein, 1995, …

CSM

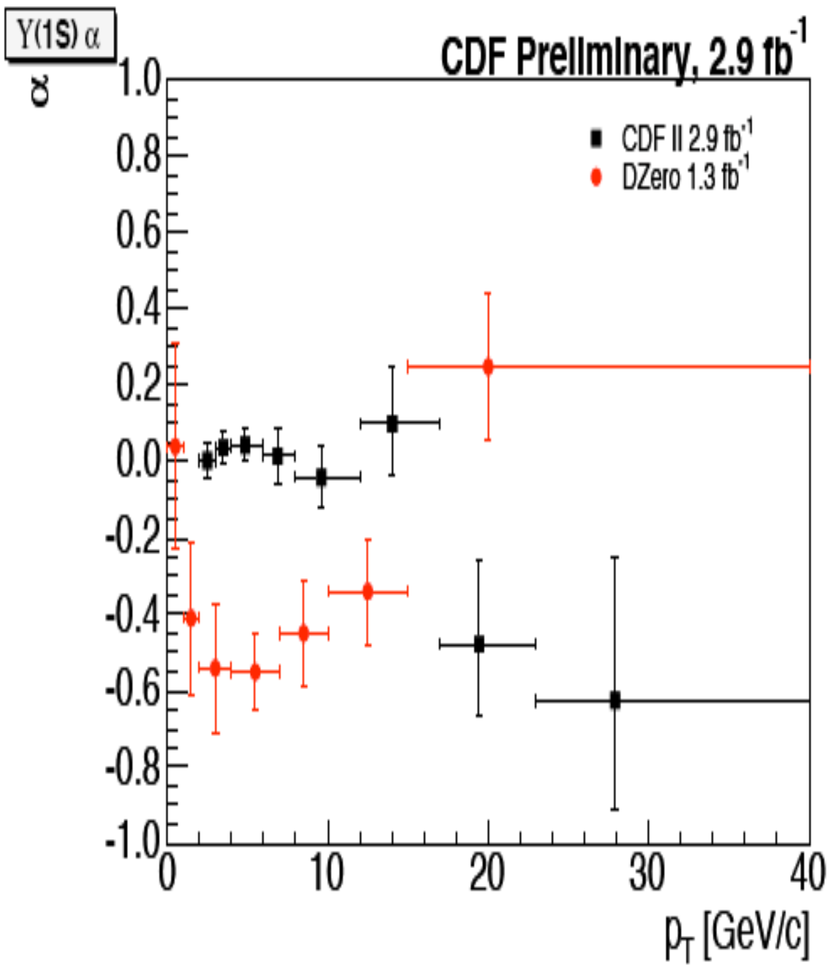


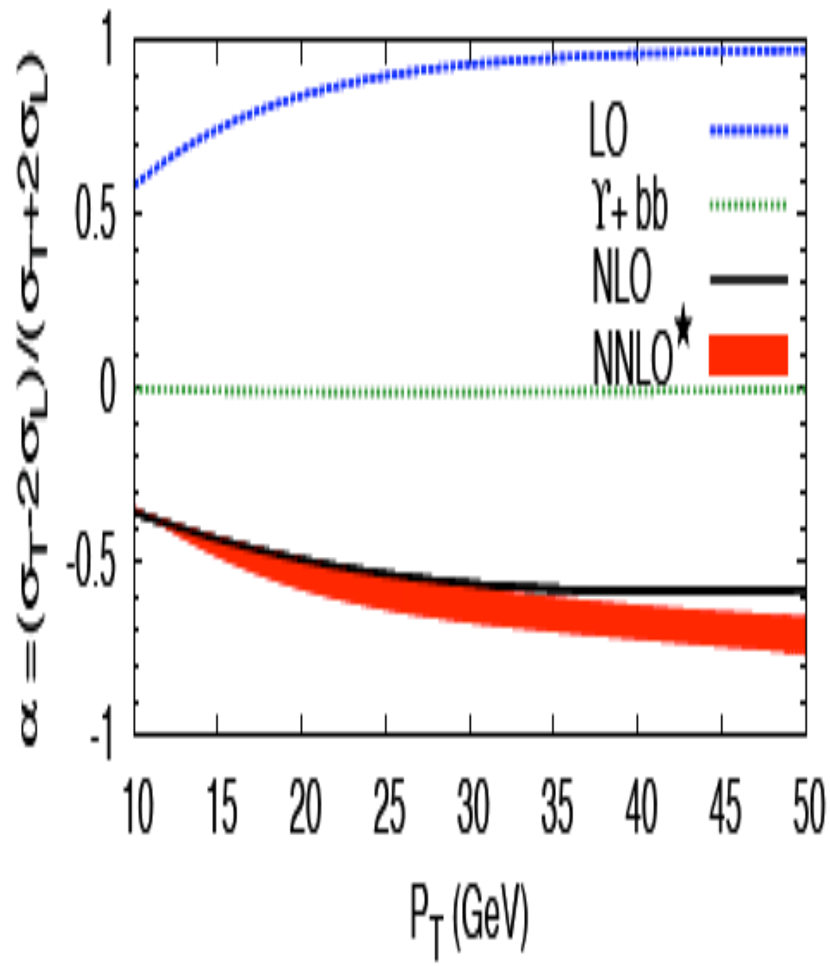
Gong, Wang, 2008
Lansberg, 2009

✧ **NRQCD:** Dominated by color octet – NLO is not a huge effect

✧ **CSM:** Huge NLO – change of polarization?

Confusions from Upsilon polarization





Resolution between CDF and D0?

Gong, Wang, 2008

Artoisenet, et al. 2008

Lansberg, 2009

Heavy quarkonium associate production

- **Inclusive J/ψ + charm production:**

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

Belle: $(0.87^{+0.21}_{-0.19} \pm 0.17)$ pb

NRQCD-LO: $:$ 0.07 pb

Kiselev, et al 1994,
Cho, Leibovich, 1996
Yuan, Qiao, Chao, 1997
…
Zhang, Chao, 2007 (NLO)

- **Ratio to light flavors:**

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

Belle: $0.59^{+0.15}_{-0.13} \pm 0.12$

- **Message:**

Production rate of $e^+e^- \to J/\psi c\bar{c}$ is larger than

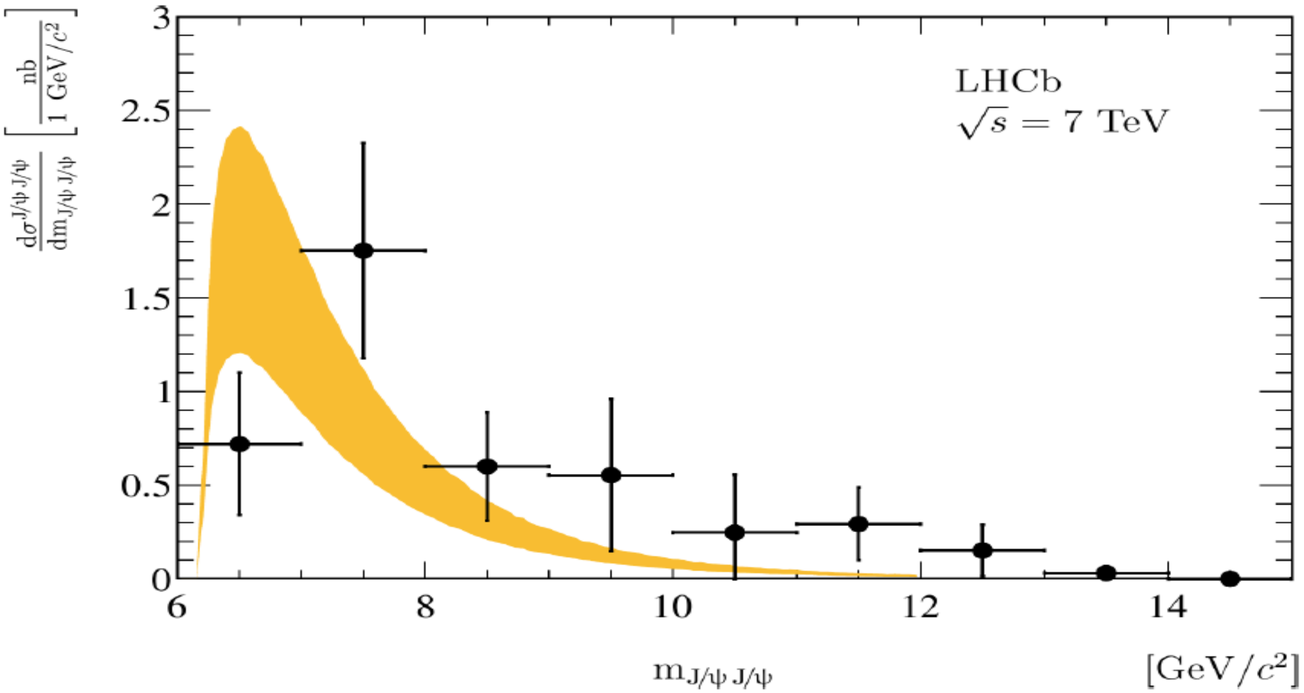
all these channels: $e^+e^- \to J/\psi gg$, $e^+e^- \to J/\psi q\bar{q}$, ...

combined ?

Double J/ψ production at LHC

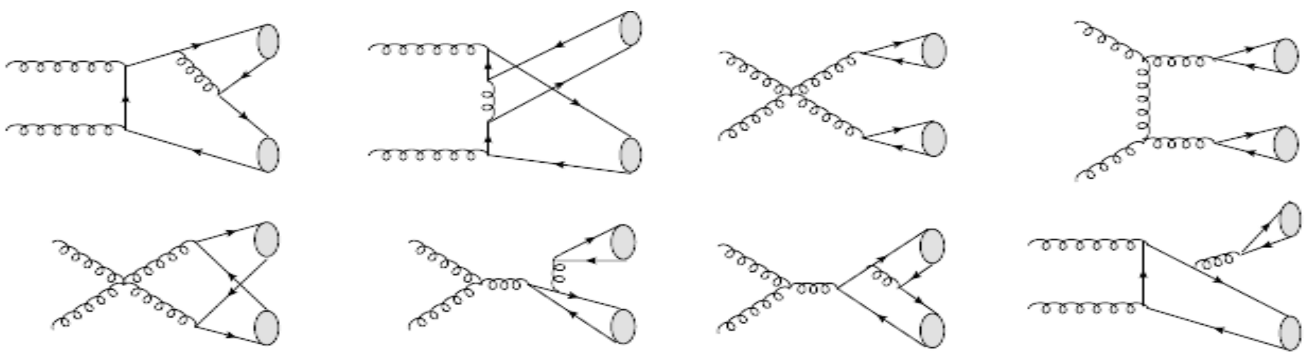
M. Frosini, QWG2011

- LHC data:



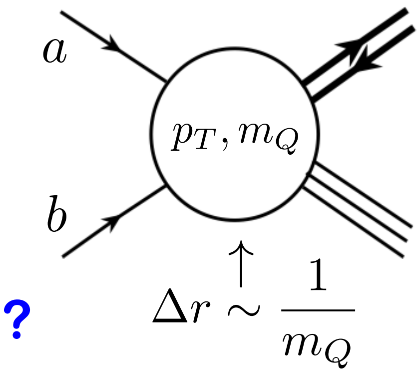
- Theory:

A.V. Berezhnoy, et al, 2011
C.F. Qiao, 2009, 2010



What can we learn from these surprises?

- What these calculations have in common?
  - ✧ Perturbative production of at least one heavy quark pair
  - ✧ Feynman diagram expansion in powers of α_s
- What is the key difference between these calculations?
  - ✧ The color and spin states of the heavy quark pair



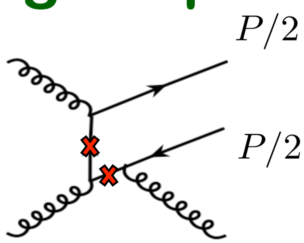
- What is missing in these calculations?
  - ✧ Where was the high p_T heavy quark pair produced?
- The active heavy quark pair (transforms into quarkonium) can be produced at $1/p_T$, $1/m_Q$, or somewhere between
  - ✧ The p_T-dependence of the production rate is sensitive to where the pair was produced!

Why high orders in CSM are so large?

Kang, Qiu and Sterman, 2011

- LO in α_s but higher power in $1/p_T$:

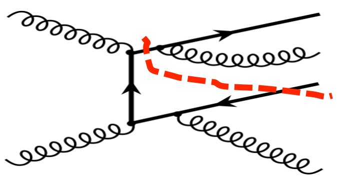
LO in α_s:

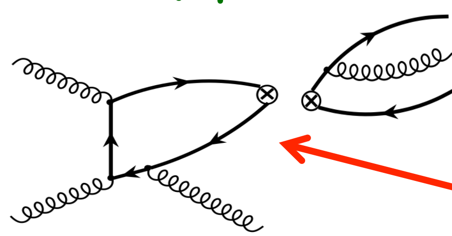


$$\hat{\sigma}^{\rm LO} \propto \frac{\alpha_s^3(p_T)}{p_T^8}$$

CSM and NRQCD Projection NNLP in $1/p_T$!

- NLO in α_s but lower power in $1/p_T$:



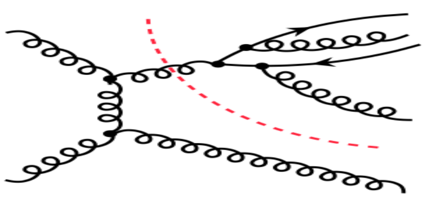


Relativistic projection to all "spin states"

$$\hat{\sigma}^{\rm NLO} \to \frac{\alpha_s^3(p_T)}{p_T^6} \otimes \alpha_s(\mu) \log(\mu^2/\mu_0^2)$$

$$\mu_0 \gtrsim 2m_Q$$

- NNLO in α_s but leading power in $1/p_T$:



$$\hat{\sigma}^{\rm NNLP} \to \frac{\alpha_s^2(p_T)}{p_T^4} \otimes \alpha_s^3(\mu) \log^m(\mu^2/\mu_0^2)$$

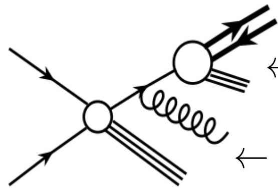
Leading order in α_s-expansion =\= leading power in $1/p_T$-expansion!

PQCD power counting

Kang, Qiu and Sterman, 2011

- IF $p_T \gg m_Q$, the pair produced

✧ at $1/m_Q$:



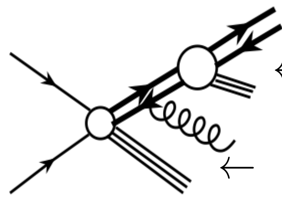
$\leftarrow \frac{1}{m_Q}$

$\leftarrow \Delta r \sim \frac{1}{p_T}$

$$\frac{1}{p_T^4}\sum_n \left[\log(\frac{p_T^2}{\mu_0^2})\right]^n$$

Only final-state fragmentation

✧ at $1/P_T$:



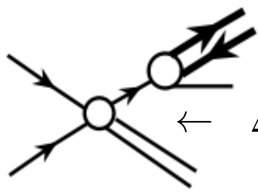
$\leftarrow \frac{1}{m_Q}$

$\leftarrow \Delta r \sim \frac{1}{p_T}$

$$\frac{1}{p_T^6}\sum_n \left[\log(\frac{p_T^2}{\mu_0^2})\right]^n$$

Short-distance Production

✧ between: $[1/m_Q, 1/P_T]$



$\leftarrow \Delta r \sim \frac{1}{p_T}$

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

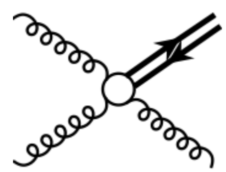
Modified evolution + pair production

- Role of color and spin projection:

✧ Color can be perturbatively resolved between m_Q and P_T

✧ Factorize into a singlet or octet pair

✧ Relativity affects p_T-dependence

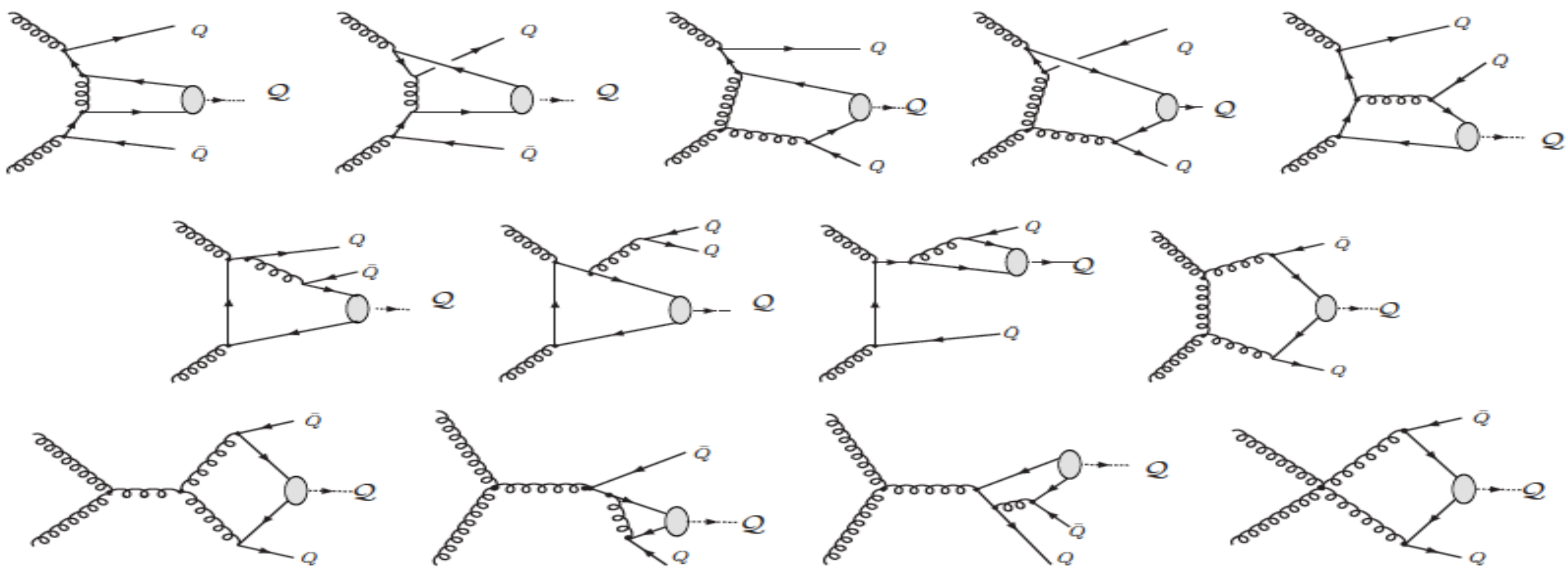


$$\left\{ \begin{array}{ll} \frac{1}{p_T^8} & \text{Non-relativistic projection} \\ \frac{1}{p_T^6} & \text{Relativistic projection} \end{array} \right.$$

Associate production as an example

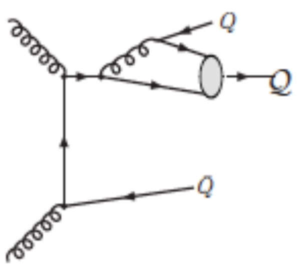
- Complete set of diagrams:

Artoisenet, Lansburg, Maltoni (2007)

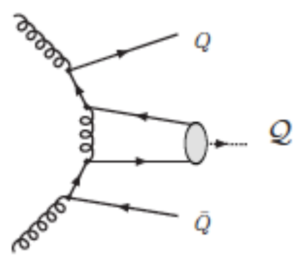


- Contribution to inclusive J/ψ is NOT perturbatively stable!

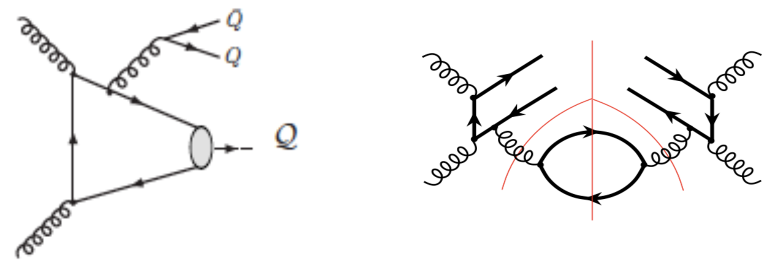
when $p_T >> m_Q$



Q-fragmentation



Logs in PDF



Need interference (virtual) diagrams

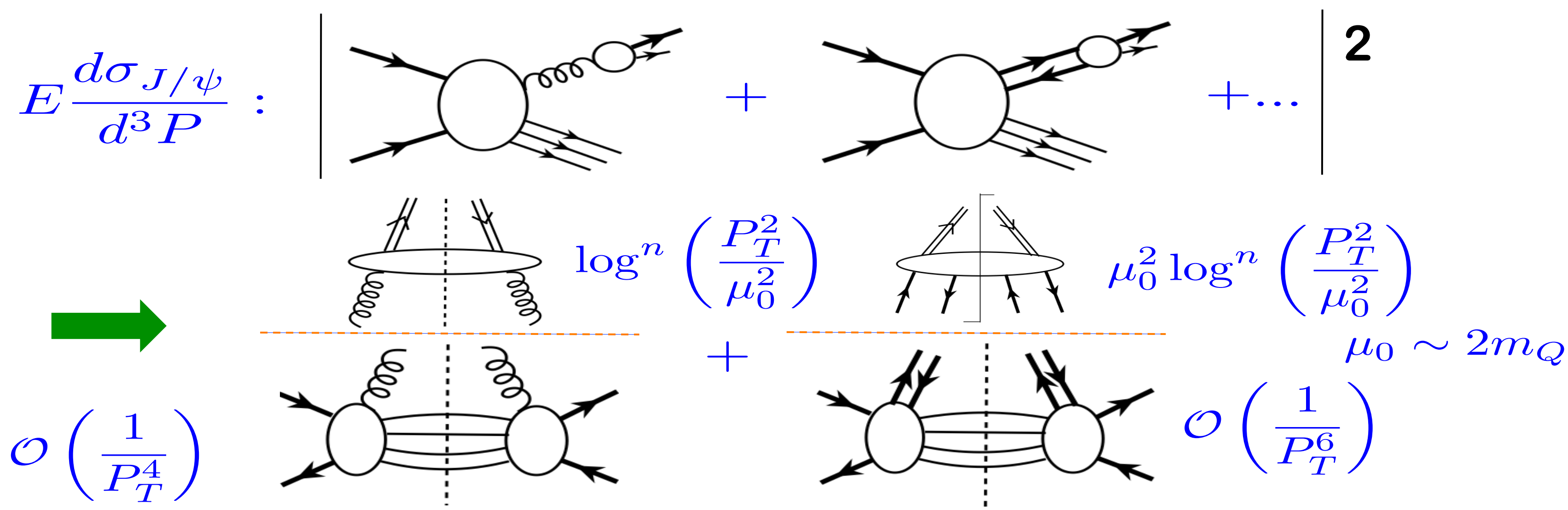
Perturbative factorization approach

Nayak, Qiu, and Sterman, 2005
Kang, Qiu and Sterman, 2010

❑ Ideas:

- ✧ Expand cross section in powers of μ_0^2/p_T^2 with $\mu_0 \gtrsim 2m_Q$
- ✧ Resum logarithmic contribution into "fragmentation functions"
- ✧ Apply NRQCD to input fragmentation functions at $\mu_0 \sim 2m_Q$

❑ Factorization – all orders in α_s:

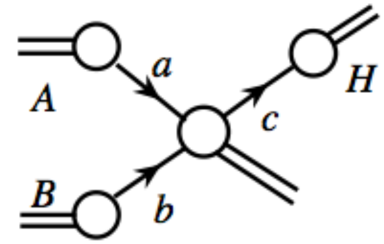


Power series in α_s without large logarithms

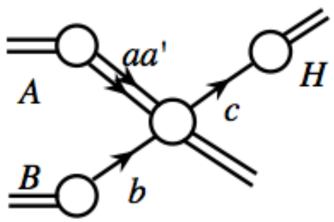
Why such power correction important?

- ❑ **Leading power in hadronic collisions:**

$$d\sigma_{AB\to H} = \sum_{a,b,c} \phi_{a/A} \otimes \phi_{b/B} \otimes d\hat{\sigma}_{ab\to cX} \otimes D_{c\to H}$$



- ❑ **1st power corrections in hadronic collisions:**



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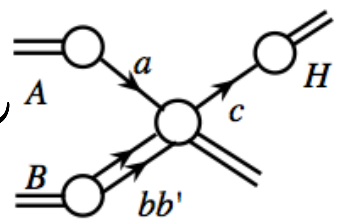

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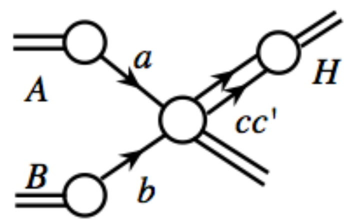
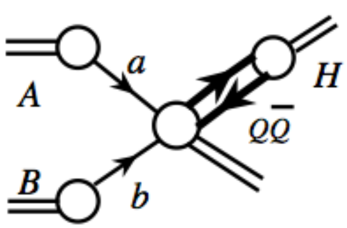


$$\sim \mathcal{O}\left(\frac{\Lambda^2_{\rm QCD}}{P_T^2}\right) \otimes D_{c\to H}$$

or $\mathcal{O}\left(\frac{\Lambda^2_{\rm QCD}}{P_T^2}\right) \otimes \mathcal{D}_{[ff]\to H}$

- ❑ **Dominated 1st power corrections:**



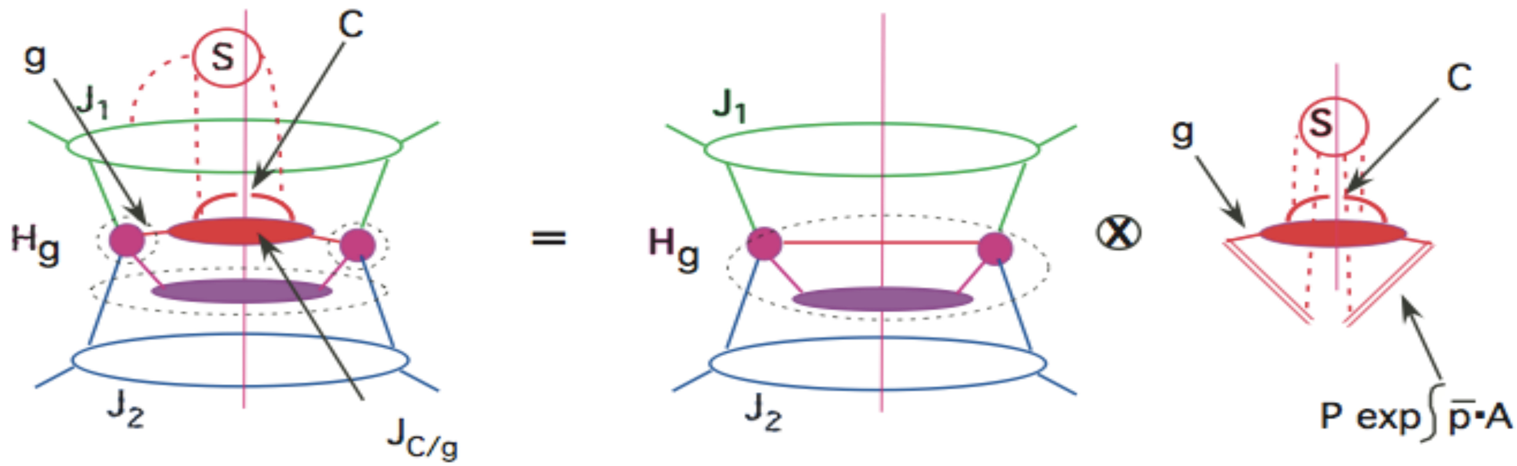
$$\sim \mathcal{O}\left(\frac{(2m_Q)^2}{P_T^2}\right) \otimes D^{(2)}_{[Q\bar{Q}]\to H}$$

Key: competition between $P_T^2 \gg (2m_Q)^2$ **and** $D^{(2)}_{[Q\bar{Q}]\to H} \gg D_{c\to H}$

pQCD Factorization

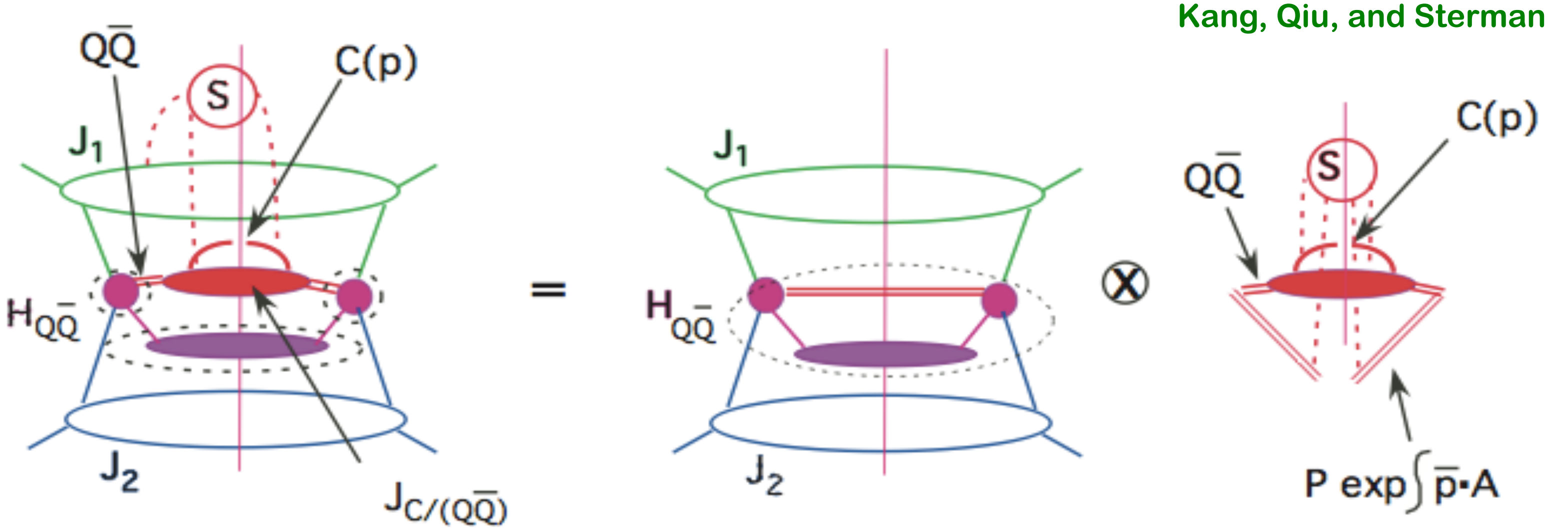
Nayak, Qiu, and Sterman, 2005

❑ Leading power – single hadron production



❑ Next-to-leading power – $Q\bar{Q}$ channel:

Qiu, Sterman, 1991
Kang, Qiu, and Sterman, 2010



Formalism and production of the pairs

- **Factorization formalism:**

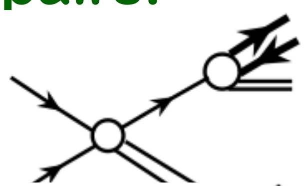
Kang, Qiu and Sterman, 2010

$$
\begin{aligned}
d\sigma_{A+B\to H+X}(p_T) = & \sum_f d\hat{\sigma}_{A+B\to f+X}(p_f = p/z) \otimes D_{H/f}(z, m_Q) \\
& + \sum_{[Q\bar{Q}(\kappa)]} d\hat{\sigma}_{A+B\to[Q\bar{Q}(\kappa)]+X}(p(1\pm\zeta)/2z, p(1\pm\zeta')/2z) \\
& \qquad \otimes \mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z, \zeta, \zeta', m_Q) \\
& + \mathcal{O}(m_Q^4/p_T^4)
\end{aligned}
$$

$$
\hat{p}_Q = \frac{1+\zeta}{2z}\,\hat{p}\,, \quad \hat{p}_{\bar{Q}} = \frac{1-\zeta}{2z}\,\hat{p}
$$

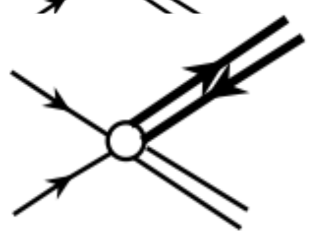
- **Production of the pairs:**

✧ at $1/m_Q$:



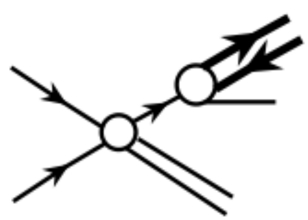
$$D_{i\to H}(z, m_Q, \mu_0)$$

✧ at $1/P_T$:



$$d\hat{\sigma}_{A+B\to[Q\bar{Q}(\kappa)]+X}(P_{[Q\bar{Q}]}(\kappa), \mu)$$

✧ between: $[\,1/m_Q\,,\ 1/P_T\,]$

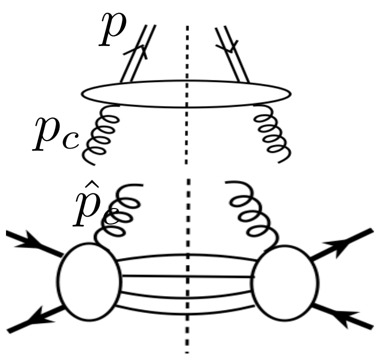


$$
\frac{d}{d\ln(\mu)} D_{i\to H}(z, m_Q, \mu) = \ldots
$$

$$
+ \frac{m_Q^2}{\mu^2}\,\Gamma(z) \otimes D_{[Q\bar{Q}(\kappa)\to H}(\{z_i\}, m_Q, \mu)
$$

Cut vertices and projection operators

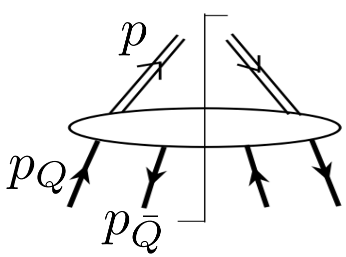
- **Leading power:**



$$\widetilde{\mathcal{P}}_{\mu\nu}(p) = \frac{1}{2}\left[-g_{\mu\nu} + \frac{p_\mu n_\nu + n_\mu p_\nu}{p\cdot n} - \frac{p^2}{(p\cdot n)^2} n_\mu n_\nu\right]$$

$$\mathcal{P}_{\mu\nu}(p) = -g_{\mu\nu} + \bar{n}_\mu n_\nu + n_\mu \bar{n}_\nu \equiv d_{\mu\nu}$$

- **Next-to-leading power – mass dependence:**



$$\widetilde{\mathcal{P}}_v^L(p) = \frac{1}{4p\cdot n}\gamma\cdot n$$

$$\widetilde{\mathcal{P}}_a^L(p) = \frac{1}{4p\cdot n}\gamma\cdot n\gamma^5$$

$$\widetilde{\mathcal{P}}_t^L(p) = \frac{1}{4p\cdot n}\gamma\cdot n\gamma_\perp^\alpha$$

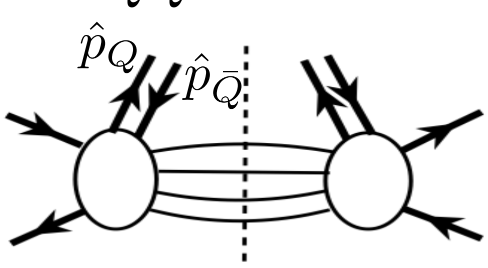
PQCD – relativistic:

Upper components

NRQCD – nonrelativistic:

Lower components

For a $Q\bar{Q}$ pair:



$$\mathcal{P}_v^L(\hat{p}_Q, \hat{p}_{\bar{Q}}) = \gamma\cdot\hat{p} = \gamma\cdot(\hat{p}_Q + \hat{p}_{\bar{Q}})$$

$$\mathcal{P}_a^L(\hat{p}_Q, \hat{p}_{\bar{Q}}) = \gamma_5\gamma\cdot\hat{p} = \gamma_5\gamma\cdot(\hat{p}_Q + \hat{p}_{\bar{Q}})$$

$$\mathcal{P}_t^L(\hat{p}_Q, \hat{p}_{\bar{Q}}) = \gamma\cdot\hat{p}\gamma_\perp^\alpha = \gamma\cdot(\hat{p}_Q + \hat{p}_{\bar{Q}})\gamma_\perp^\alpha$$

Hard part is insensitive to the difference in quarkonium states!

Short-distance hard parts

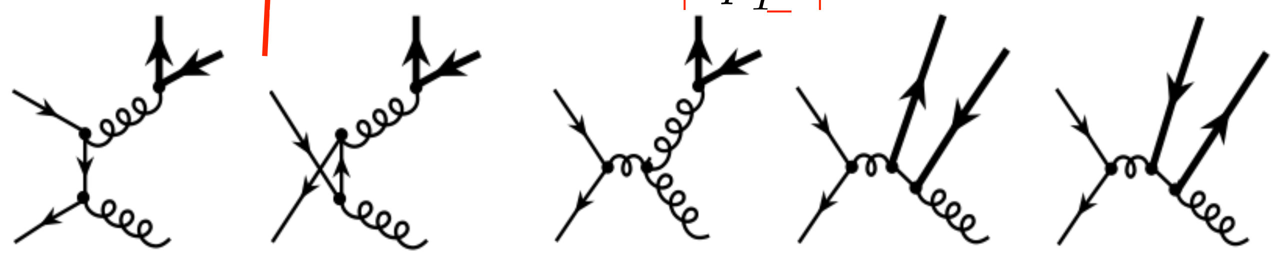
❑ Even tree-level needs subtraction:

$$\sigma^{(3)}_{q\bar{q}\to[Q\bar{Q}(c)]g} = \hat{\sigma}^{(3)}_{q\bar{q}\to[Q\bar{Q}(\kappa)]g} \otimes D^{(0)}_{[Q\bar{Q}(\kappa)]\to[Q\bar{Q}(c)]} + \hat{\sigma}^{(2)}_{q\bar{q}\to gg} \otimes D^{(1)}_{g\to[Q\bar{Q}(c)]}$$

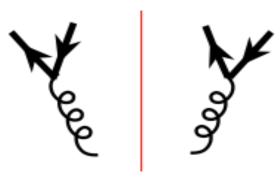
$$\Rightarrow \quad \hat{\sigma}^{(3)}_{q\bar{q}\to[Q\bar{Q}]g} = \sigma^{(3)}_{q\bar{q}\to[Q\bar{Q}]g} - \sigma^{(2)}_{q\bar{q}\to g} \otimes D^{(1)}_{g\to[Q\bar{Q}]}$$

$$\boxed{\frac{\alpha_s^3(\mu)}{p_T^6}} \qquad \boxed{\frac{\alpha_s^2(\mu)}{p_T^4}} \qquad \boxed{\frac{\alpha_s(2m_Q)}{(2m_Q)^2}}$$

$$\sigma^{(3)}_{q\bar{q}\to[Q\bar{Q}(c)]g} :$$



$$D^{(1)}_{g\to[Q\bar{Q}]} :$$



$$\widetilde{\mathcal{P}}_{\mu\nu}(p) = \frac{1}{2}\left[-g_{\mu\nu} + \frac{p_\mu n_\nu + n_\mu p_\nu}{p\cdot n} - \frac{p^2}{(p\cdot n)^2} n_\mu n_\nu\right]$$

$$H^{(3)}_{q\bar{q}\to[Q\bar{Q}(a8)]g} = \frac{8\pi\alpha_s}{\hat{s}} \frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2} \frac{1}{(1-\zeta^2)(1-\zeta'^2)} \frac{N^2-1}{N}\left[1+\zeta\zeta' - \frac{4}{N^2}\right]$$

Normalized to 2 → 2 amplitude square

Evolution of fragmentation functions

- **Independence of the factorization scale:**

Kang, Qiu and Sterman, 2011

$$\frac{d}{d\ln(\mu)}\sigma_{A+B\to HX}(P_T)=0$$

- ✧ at Leading power in $1/P_T$:

DGALP evolution

$$\frac{d}{d\ln\mu^2}D_{H/f}(z,m_Q,\mu)=\sum_j\frac{\alpha_s}{2\pi}\gamma_{f\to j}(z)\otimes D_{H/j}(z,m_Q,\mu)$$

- ✧ next-to-leading power in $1/P_T$:

$$\frac{d}{d\ln\mu^2}D_{H/f}(z,m_Q,\mu)=\sum_j\frac{\alpha_s}{2\pi}\gamma_{f\to j}(z)\otimes D_{H/j}(z,m_Q,\mu)$$
$$+\frac{1}{\mu^2}\sum_{[Q\bar{Q}(\kappa)]}\frac{\alpha_s^2}{(2\pi)^2}\Gamma_{f\to[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta')\otimes\mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q,\mu)$$

$$\frac{d}{d\ln\mu^2}\mathcal{D}_{H/[Q\bar{Q}(c)]}(z,\zeta,\zeta',m_Q,\mu)=\sum_{[Q\bar{Q}(\kappa)]}\frac{\alpha_s}{2\pi}K_{[Q\bar{Q}(c)]\to[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta')$$
$$\otimes\mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q,\mu)$$

- **Evolution kernels are perturbative:**

- ✧ Set mass: $m_Q\to 0$ with a caution

Predictive power

- Calculation of short-distance hard parts in pQCD:

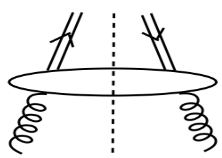
  Power series in α_s, without large logarithms

- Calculation of evolution kernels in pQCD:

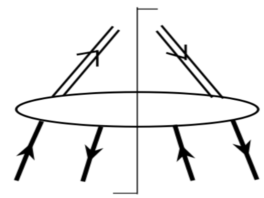
  Power series in α_s, scheme in choosing factorization scale μ

  Could affect the term with mixing powers

- Universality of input fragmentation functions at μ_0:



$D_{H/f}(z, m_Q, \mu_0)$



$\mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z, \zeta, \zeta', m_Q, \mu_0)$

- Physics of $\mu_0 \sim 2m_Q$ – a parameter:

  Evolution stops when $\log\left[\frac{\mu_0^2}{(4m_Q^2)}\right] \sim \left[\frac{4m_Q^2}{\mu_0^2}\right]$

  Different quarkonium states require different input distributions!

NRQCD for input distributions

- **Input distributions are universal, non-perturbative:**

  Should, in principle, be extracted from experimental data

- **NRQCD – single parton distributions – valid to 2-loop:**

$$D_{g\to J/\psi}(z,\mu_0,m_Q) \to \sum_{[Q\bar{Q}(c)]} \hat{d}_{g\to[Q\bar{Q}(c)]}(z,\mu_0,m_Q)\langle\mathcal{O}_{[Q\bar{Q}(c)]}(0)\rangle|_{\mathrm{NRQCD}}$$

Nayak, Qiu and Sterman, 2005

Dominated by transverse polarization

- **NRQCD – heavy quark pair:**

$$\mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q,\mu) \to \sum_c d_{[Q\bar{Q}(\kappa)]\to[Q\bar{Q}(c)]}(z,\zeta,\zeta',m_Q,\mu)\langle O^H_{[Q\bar{Q}(c)]}\rangle$$

Kang, Qiu and Sterman, 2011

Dominated by longitudinal polarization

- **No proof of such factorization yet!**

  Single parton case was verified to two-loops (with gauge links)!

Nayak, Qiu and Sterman, 2005

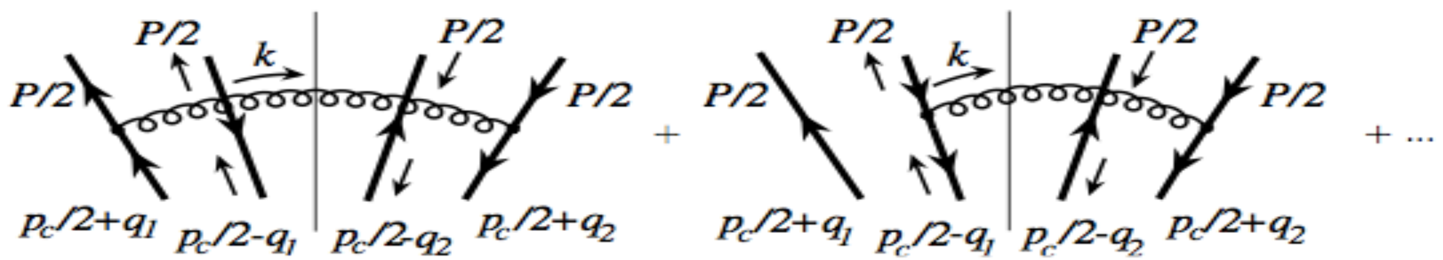
Polarization of heavy quarkonium

Kang, Qiu and Sterman, 2011

- Fragmentation functions determine the polarization

  Short-distance dynamics at r ~ 1/p_T is insensitive to the details taken place at the scale of hadron wave function ~ 1 fm

- Heavy quark pair fragmentation functions at LO:



NRQCD to a singlet pair:
$$\mathcal{D}_{[Q\bar{Q}(\kappa)]\to J/\psi} = 2\,\mathcal{D}^T_{[Q\bar{Q}(\kappa)]\to J/\psi} + \mathcal{D}^L_{[Q\bar{Q}(\kappa)]\to J/\psi}$$

$$\mathcal{D}^L_{[Q\bar{Q}(a8)]\to J/\psi}(z,\zeta,\zeta',m_Q,\mu) = \frac{1}{2N^2}\frac{\langle O^{J/\psi}_{1(^3S_1)}\rangle}{3m_c}\Delta(\zeta,\zeta')\;\frac{\alpha_s}{2\pi}z(1-z)\left[\ln\left(r(z)+1\right)-\left(1-\frac{1}{1+r(z)}\right)\right]$$

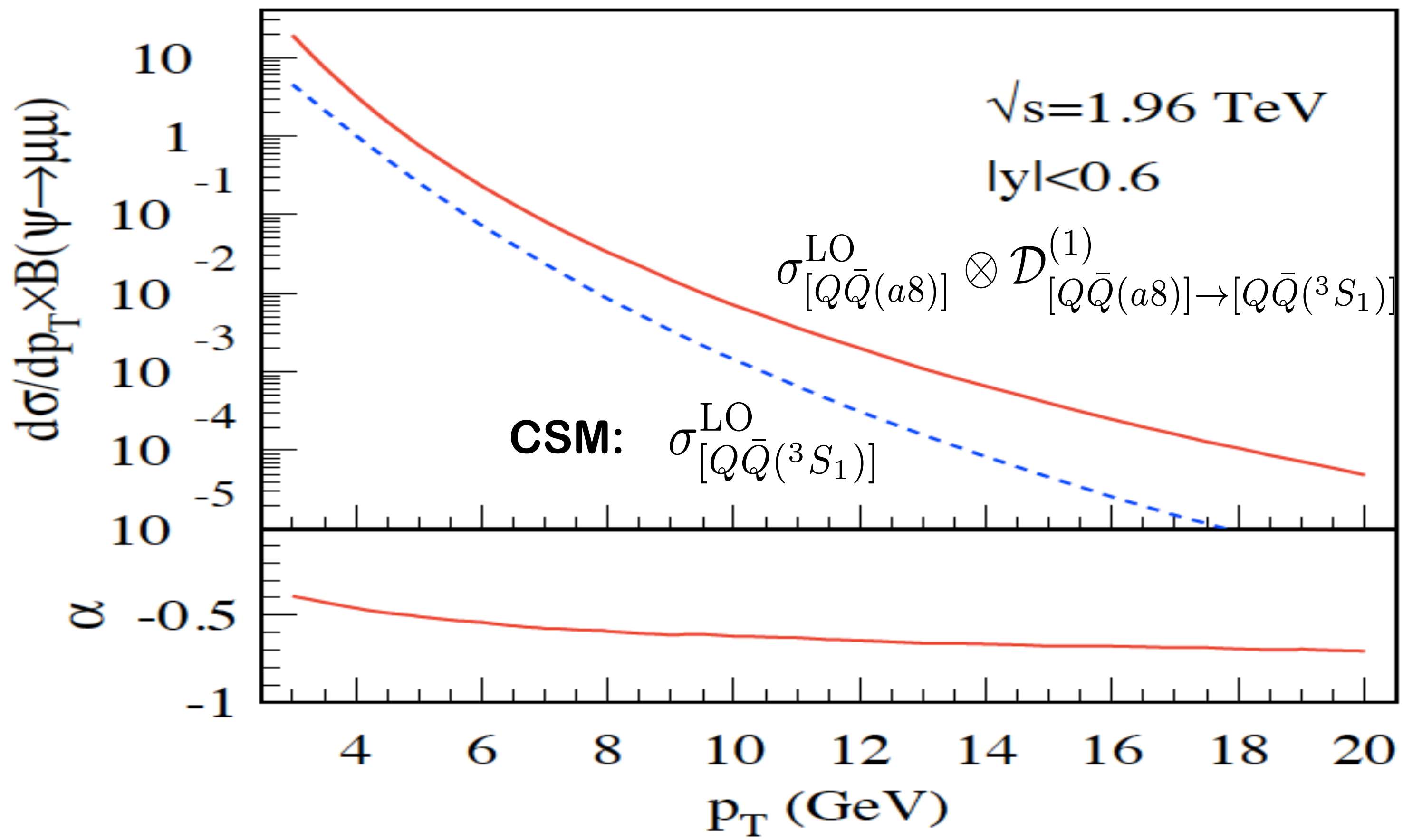
$$\mathcal{D}^T_{[Q\bar{Q}(a8)]\to J/\psi}(z,\zeta,\zeta',m_Q,\mu) = \frac{1}{2N^2}\frac{\langle O^{J/\psi}_{1(^3S_1)}\rangle}{3m_c}\Delta(\zeta,\zeta')\,\frac{\alpha_s}{2\pi}z(1-z)\left[1-\frac{1}{1+r(z)}\right]$$

where
$$\Delta(\zeta,\zeta') = \frac{1}{4}\sum_{a,b}\delta(\zeta-a(1-z))\delta(\zeta'-b(1-z)), \qquad r(z)\equiv\frac{z^2\mu^2}{4m_c^2(1-z)^2}$$

Production rate and polarization

Kang, Qiu and Sterman, 2011

- LO hard parts + LO fragmentation contributions:

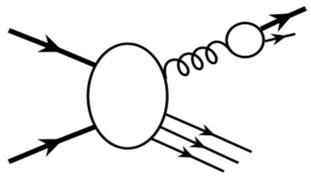


LO heavy quark pair fragmentation contribution reproduces the bulk of NLO color singlet contribution, and the polarization!

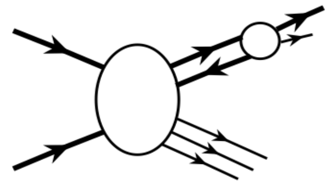
Polarization from different powers

- **Competition between LP and NLP:**

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



$+$



$+\ldots$

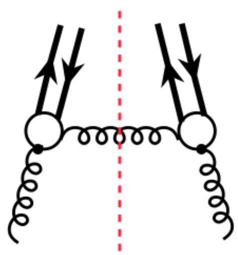
Transverse polarization

Longitudinal polarization

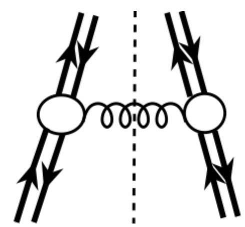
$$\frac{\langle\mathcal{O}_{\rm octet}\rangle}{p_T^4} \text{ vs. } \frac{\langle\mathcal{O}_{\rm singlet}\rangle}{p_T^6}$$

- **Contribution of high spin states – Fragmentation functions**

$$\frac{d^n}{dq^{\alpha_1}\ldots dq^{\alpha_n}}$$



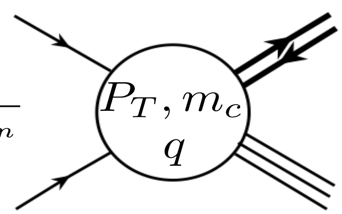
$$\frac{d^n}{dq^{\alpha_1}\ldots dq^{\alpha_n}}$$



$$P_c = P/2 + q$$
$$P_{\bar{c}} = P/2 - q$$

instead of,

$$\frac{d^n}{dq^{\alpha_1}\ldots dq^{\alpha_n}}$$



$$P_c = P/2 + q$$
$$P_{\bar{c}} = P/2 - q$$

Universal and process independent, if NRQCD factorization is valid

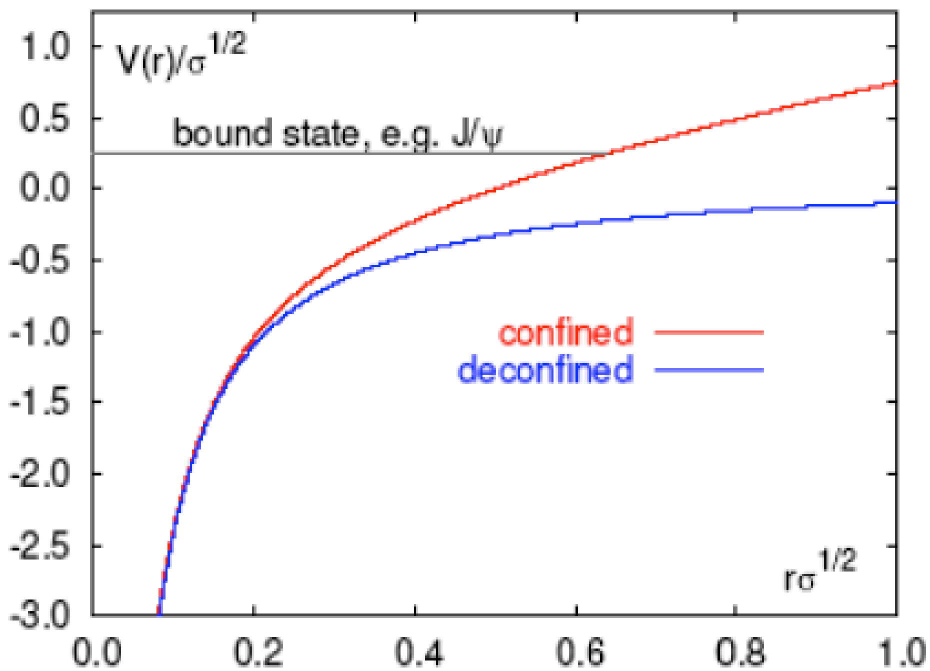
Quarkonium production at a finite T

❑ **Quark-antiquark color-screened potential:**

$$V_{Q\bar{Q}}(r,T) = -\frac{\alpha_{\rm eff}}{r}\,e^{-r/r_D(T)} + \sigma r_D(T)\left[1-e^{-r/r_D(T)}\right]$$

Screening radius/length: $r_D(T) \to 0$ as $T \to \infty$

❑ **No heavy quarkonium in a deconfined medium:**

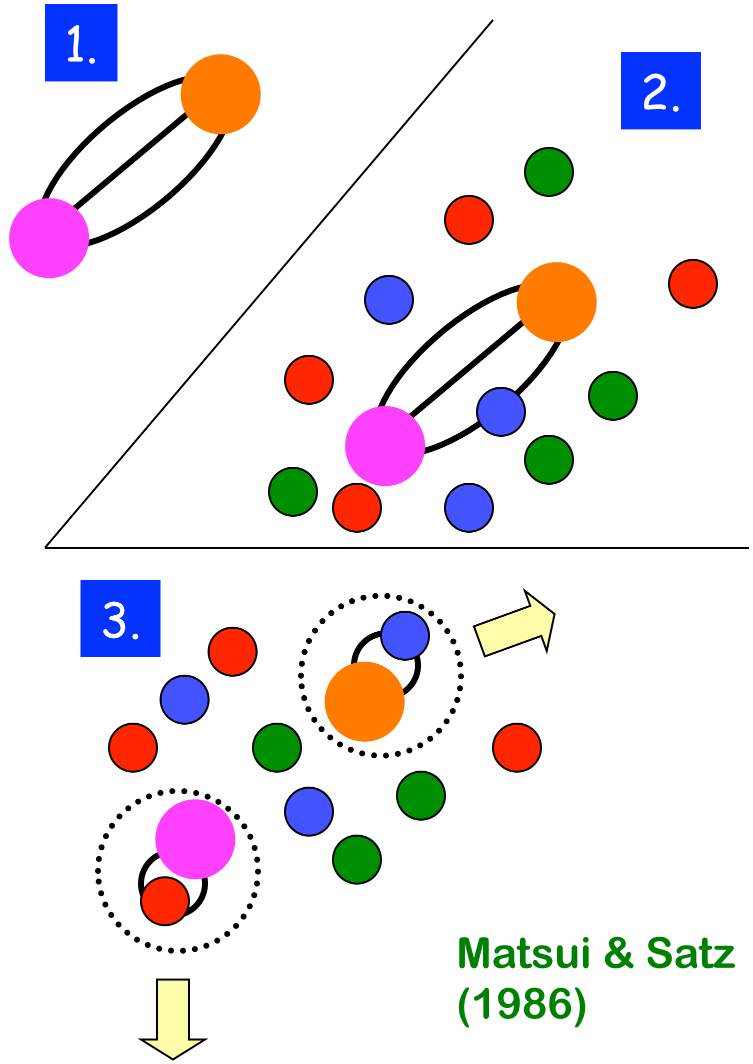


Matsui-Satz argument: (1986)

- ✧ **Deconfined QGP**
- ✧ **Color screen**
- ✧ **No quarkonium in QGP**

Melting a quarkonium in QGP

- Start with a J/ψ
  - ✧ This works with other charmonium states as well
  - ✧ The J/ψ is easiest to observe
- Put it in a sea of color charges
- The color lines attach themselves to other quarks
  - – This forms a pair of charmed mesons
- These charmed mesons "wander off" from each other
- When the system cools, the charmed particles are too far apart to recombine
  - – Essentially, the J/ψ has melted

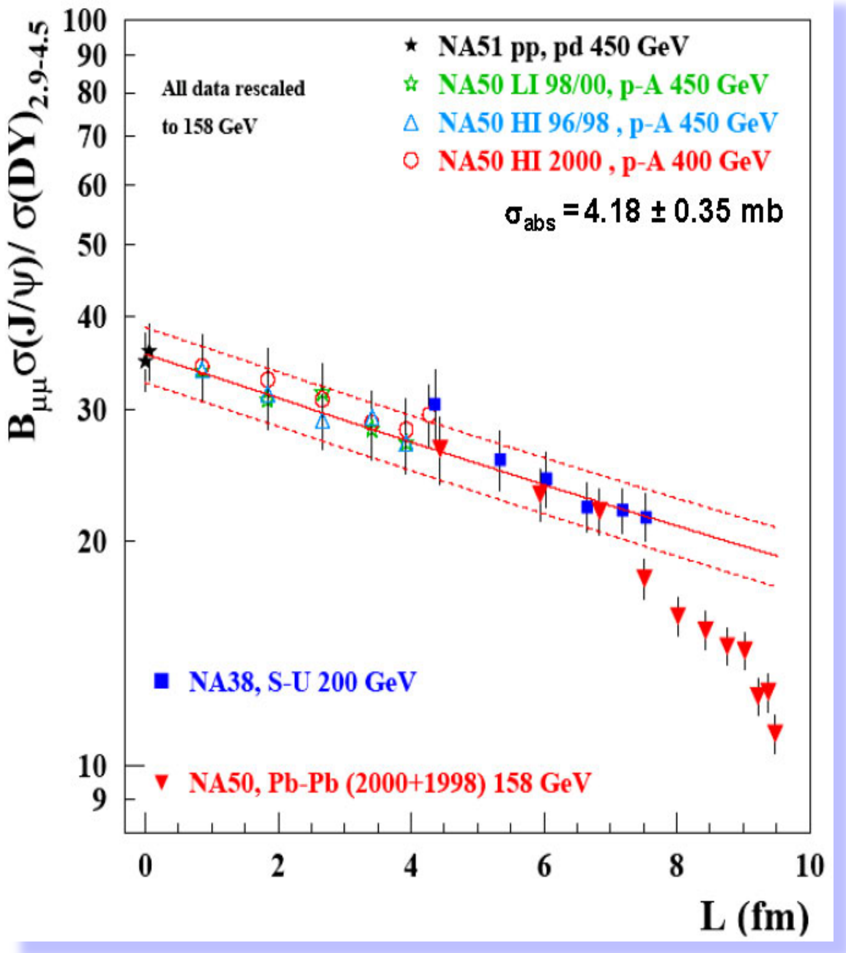


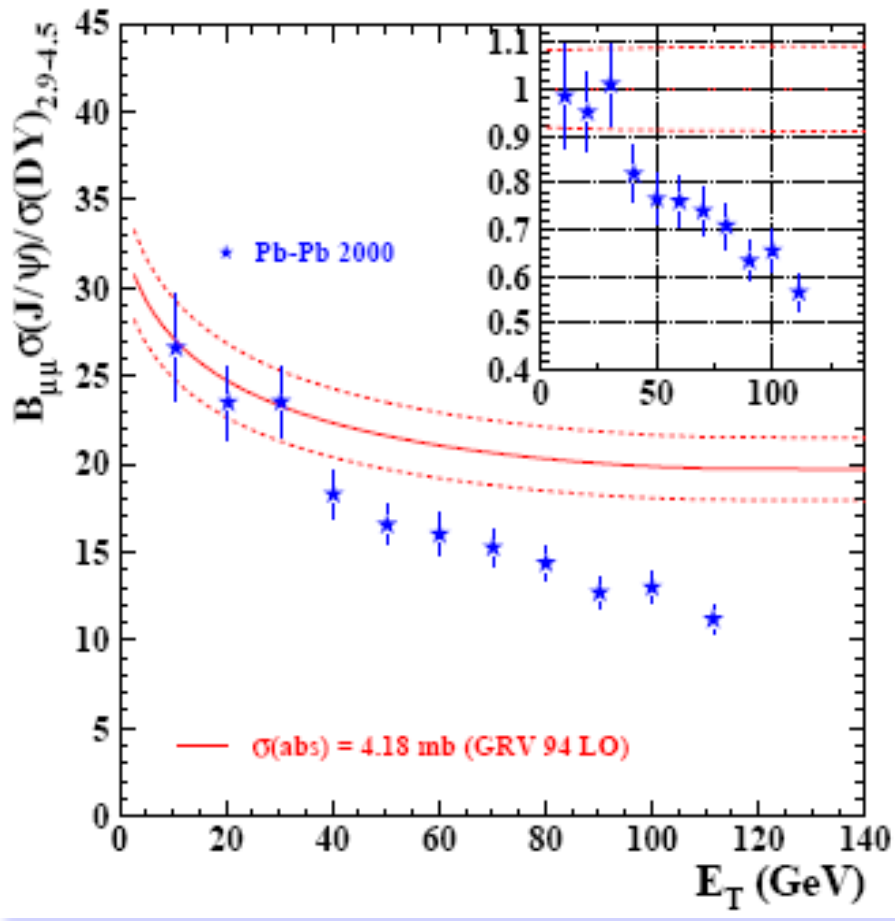
Matsui & Satz (1986)

Anomalous suppression in pA

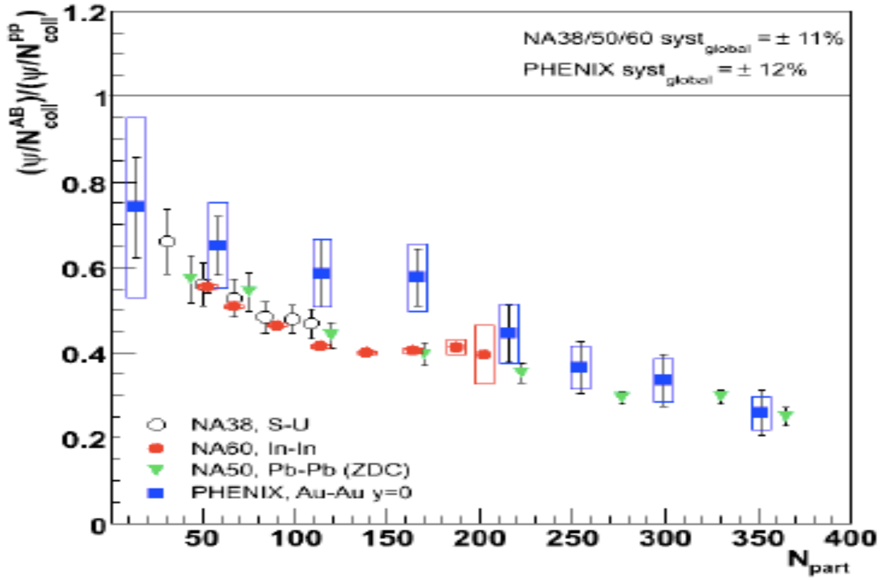
❑ Anomalous suppression:

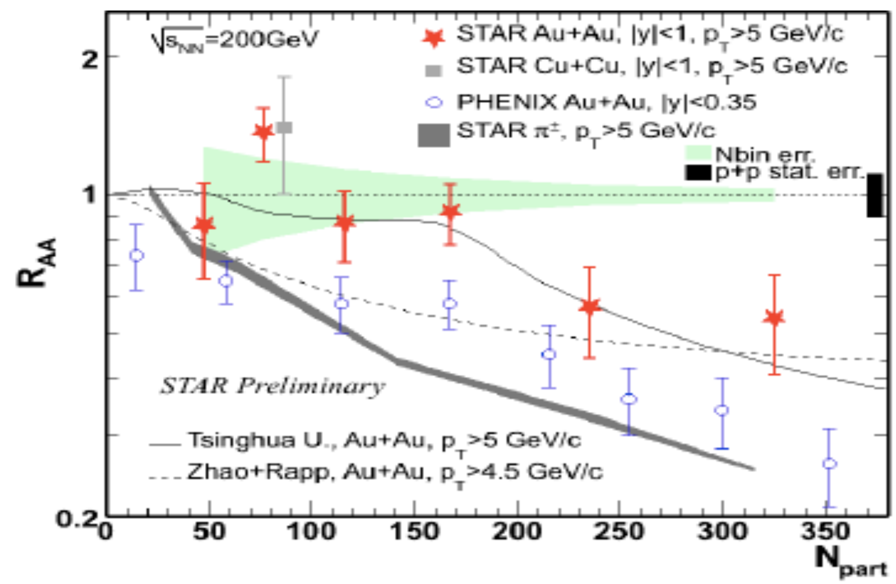
Not a straight line on the semi-log plots – additional suppression!

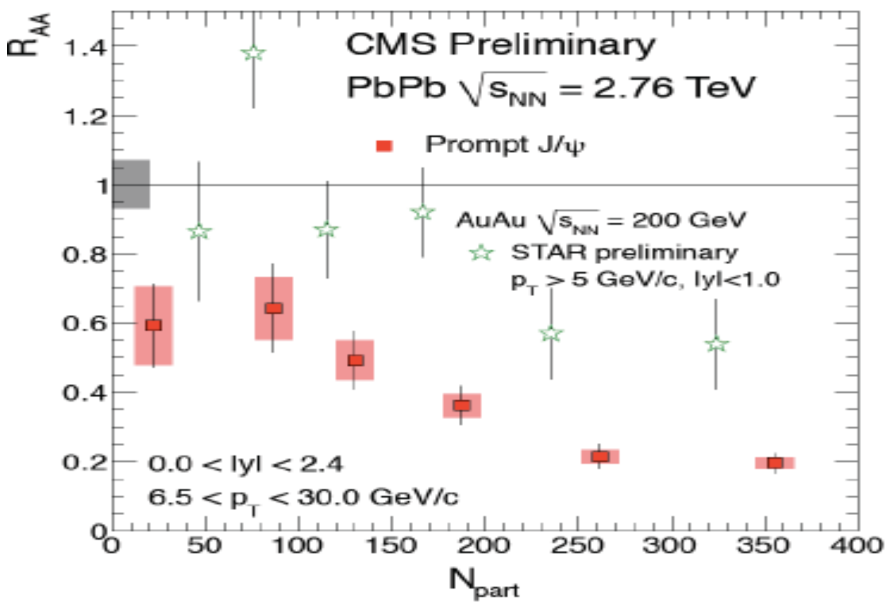


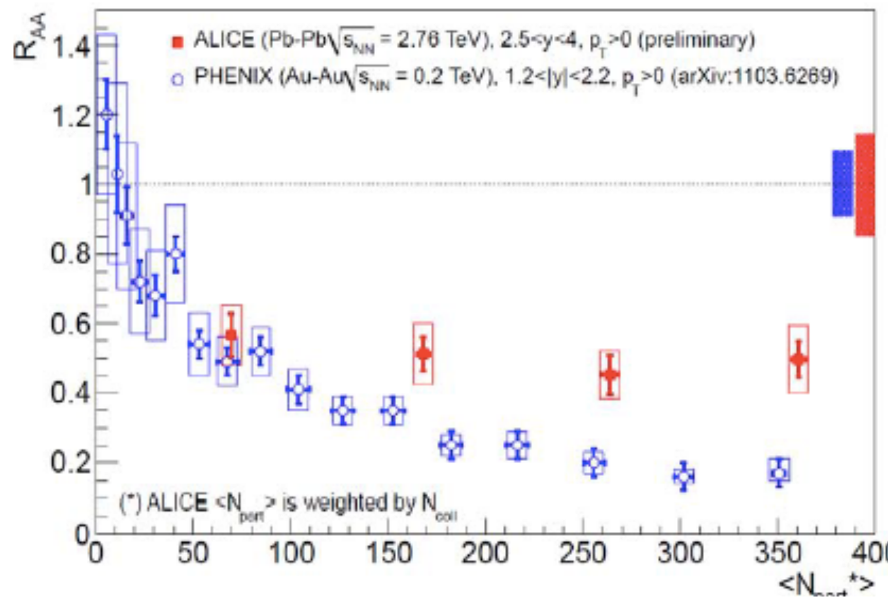


Confusion from data on AA









Summary

- ❑ When $p_T >> m_Q$ at collider energies, all existing models for calculating the production rate of heavy quarkonia are not perturbatively stable
  - ✧ LO in α_s-expansion may not be the LP term in $1/p_T$-expansion
  - ✧ Heavy flavor scattering channels are important when $p_T >> m_Q$

    (Resummation of initial-state logarithms)

- ❑ When $p_T >> m_Q$, $1/p_T$-power expansion before α_s-expansion

  Fragmentation approach takes care of both $1/p_T$-expansion and resummation of the large logarithms

- ❑ RHIC/LHC are offering excellent opportunities to learn and exam the formation of heavy flavor QCD bound states

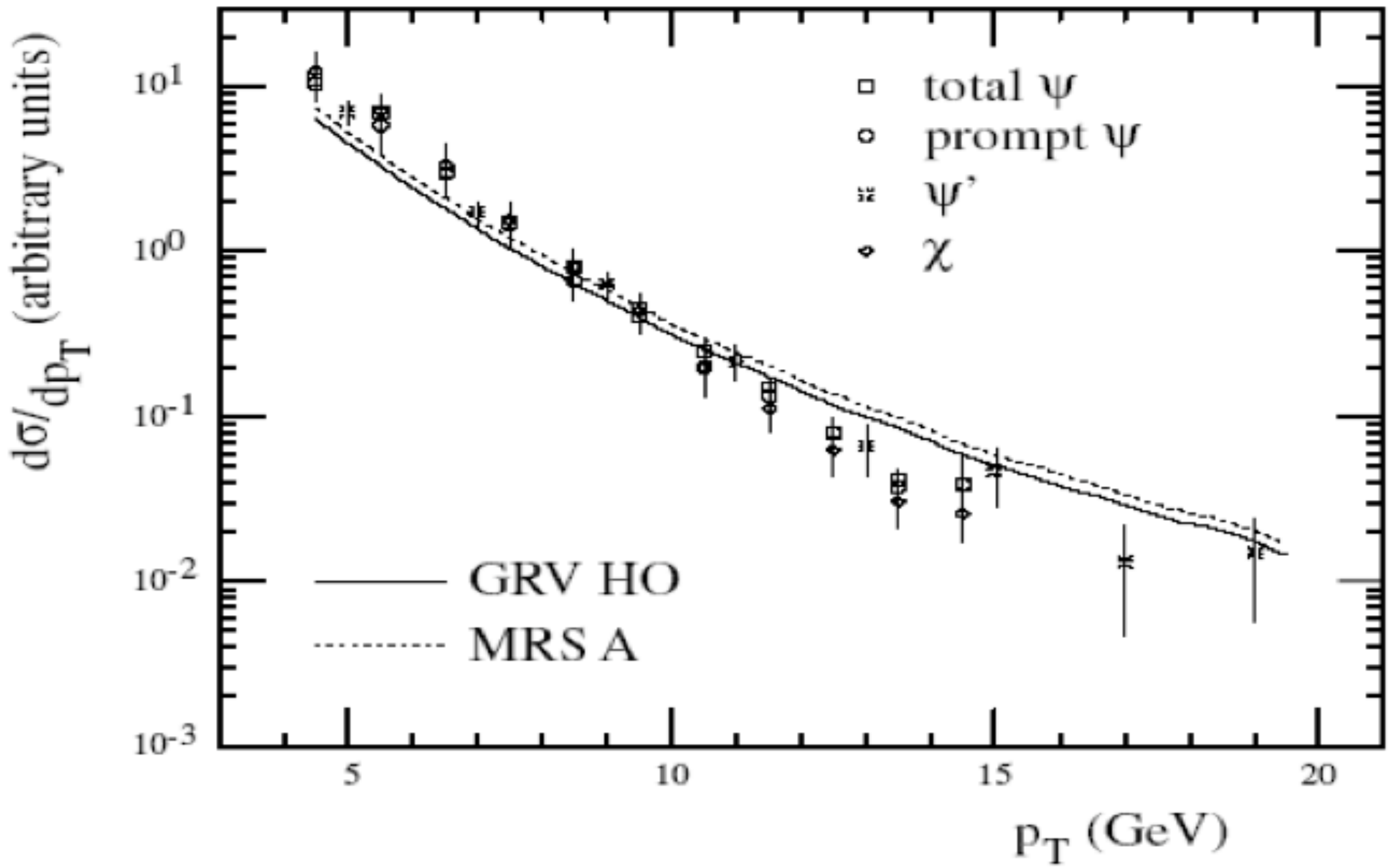
  – in a vacuum, as well as at a finite temperature

Thank you!

Backup slices

Color evaporation model

- Good for total cross section, ok for p_T distribution:



Amundson et al, PLB 1997

- Question:

Better p_T distribution – the shape?