Heavy flavour production at
hadron colliders
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# Inclusive heavy quark production at the LHC

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# The elephant in the room

# The elephant in the room

Most of what I will say about the theoretical framework is almost 20 years old. It will finally become obsolete (or, rather, will have to be updated) once the full, massive NNLO calculation for heavy quark hadroproduction will have been completed

Czakon and Mitov have published recently the NNLO qq and the gq channels (1207.0236 and 1210.6832). Work is ongoing for the (dominating) gg one.

Phenomenology of the newly available contributions (as well as of NNLL resummations for total cross section) has concentrated on top production

NNLO effects limited in size (e.g central value shifted by 8% at Tevatron, where qq dominates), but lead of course to smaller theoretical uncertainties

Nothing is yet available (to my knowledge) for charm and bottom

(qq and gq are however expected to contribute almost negligibly at the LHC)

# Outline

- I will describe precitions and measurements of inclusive production: identified mesons, leptons, quarkonia from B decays
    - The theory will provide normalisation and shapes for bare heavy quarks. Branching fractions, electroweak decays and non-perturbative information will be taken from data
- I will show data (total cross sections and single inclusive distributions) from RHIC, Tevatron and the LHC
    - What we will be testing are the predictions for the overall total rates (i.e. NLO calculations), and the consistency of the picture, meaning universality of branching fractions and of NP information extraction, from e+e- to hadronic collisions

# Heavy Quark production

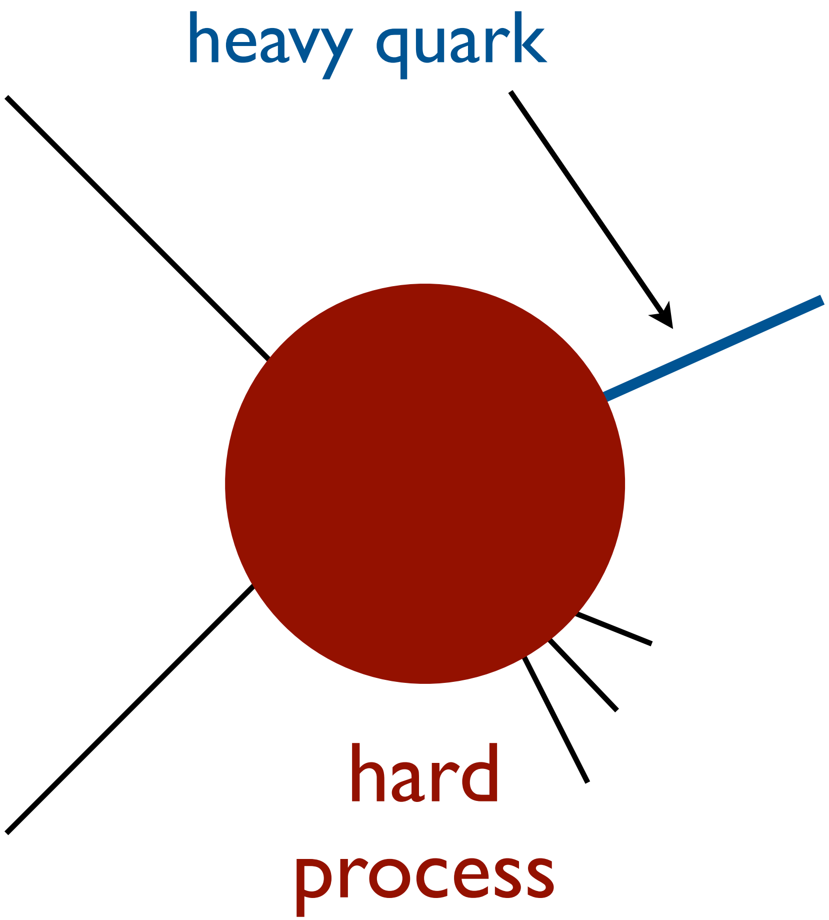
$$pp \stackrel{pQCD}{\longrightarrow} Q \stackrel{NP\,fragm.}{\longrightarrow} H_Q \stackrel{decay}{\longrightarrow} e$$

This part is QCD.
How accurately can we predict it?
What ingredients do we need?

A generic final state observable

Compare at this level, if possible.
A quark is not a physical object

# Sketch of inclusive production



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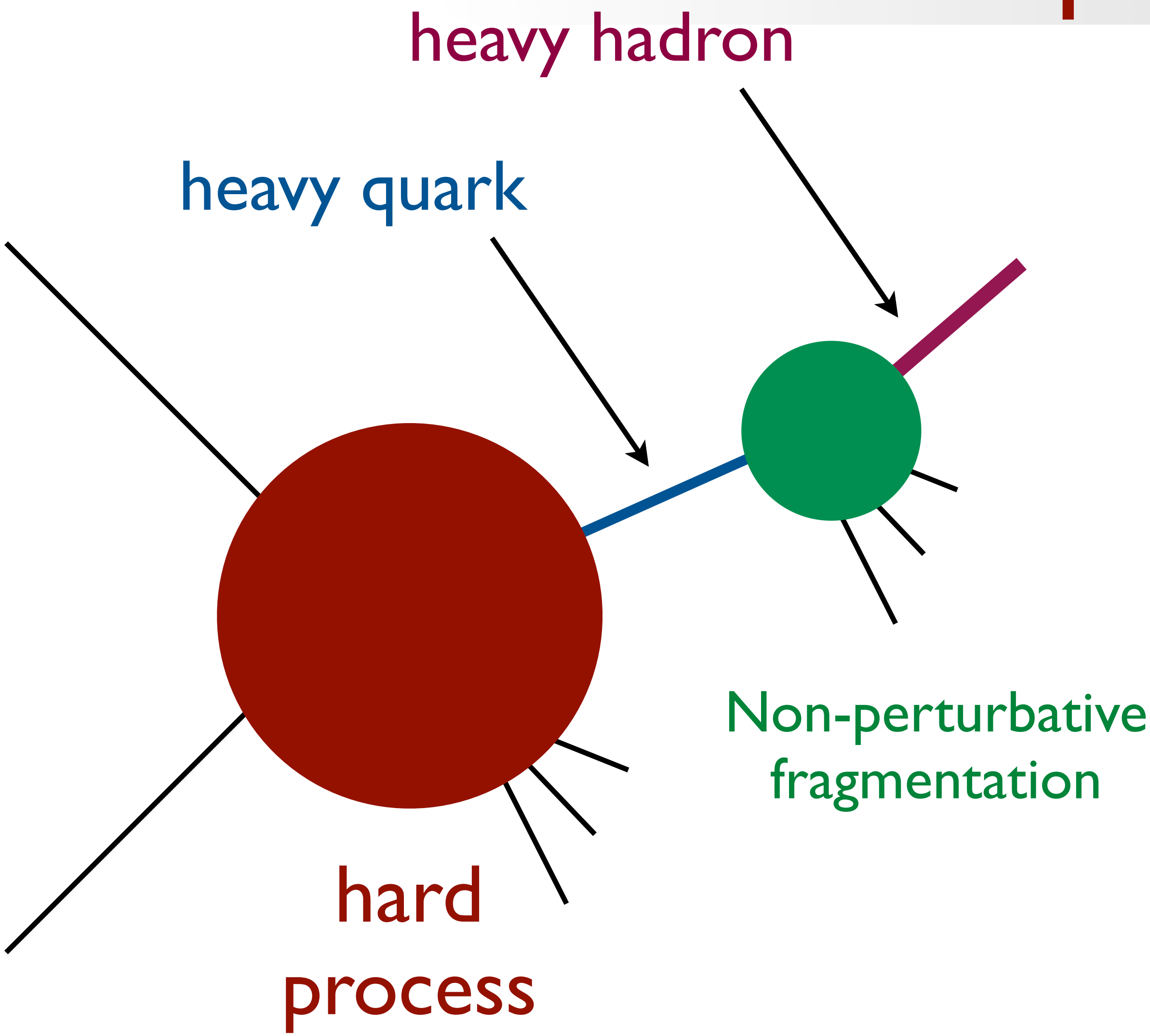

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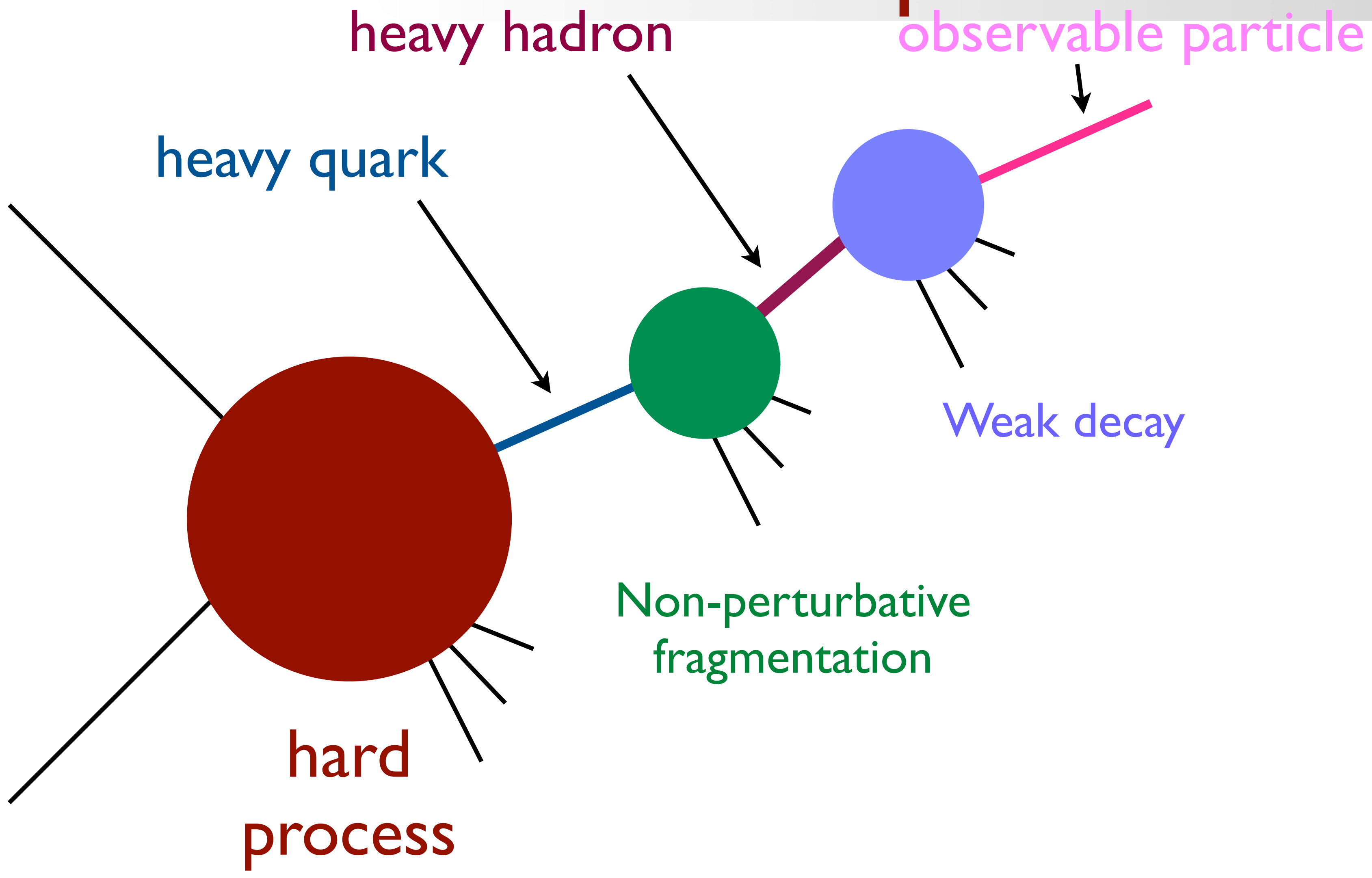
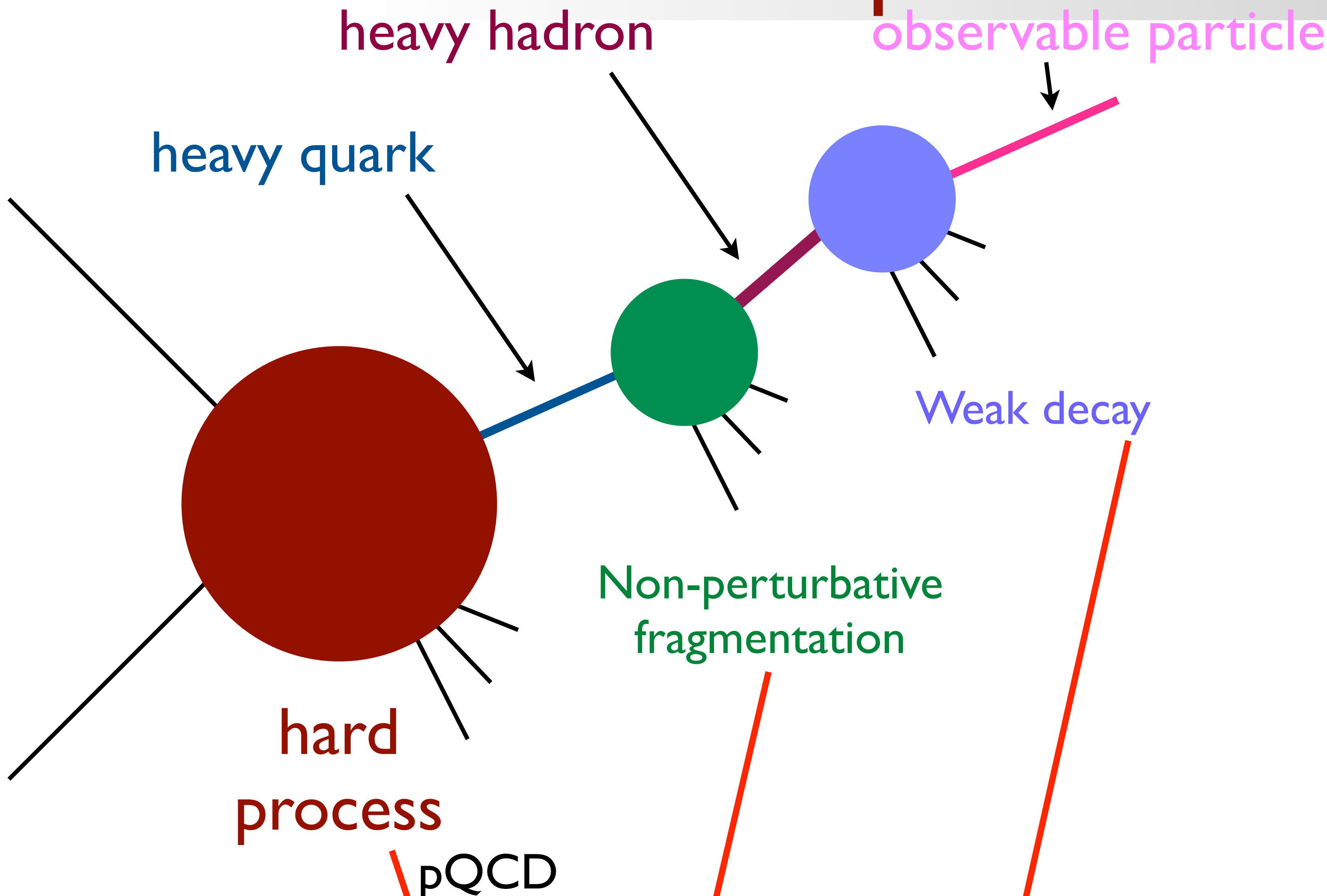
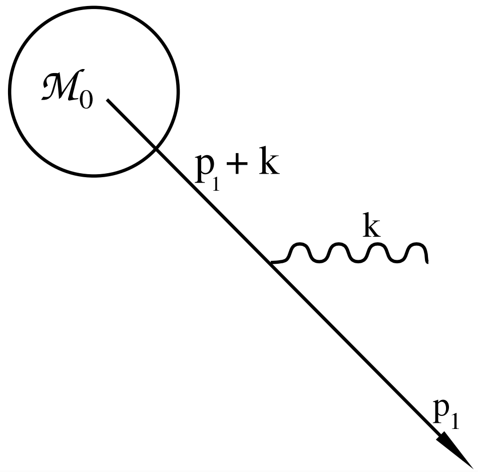


# Sketch of inclusive production



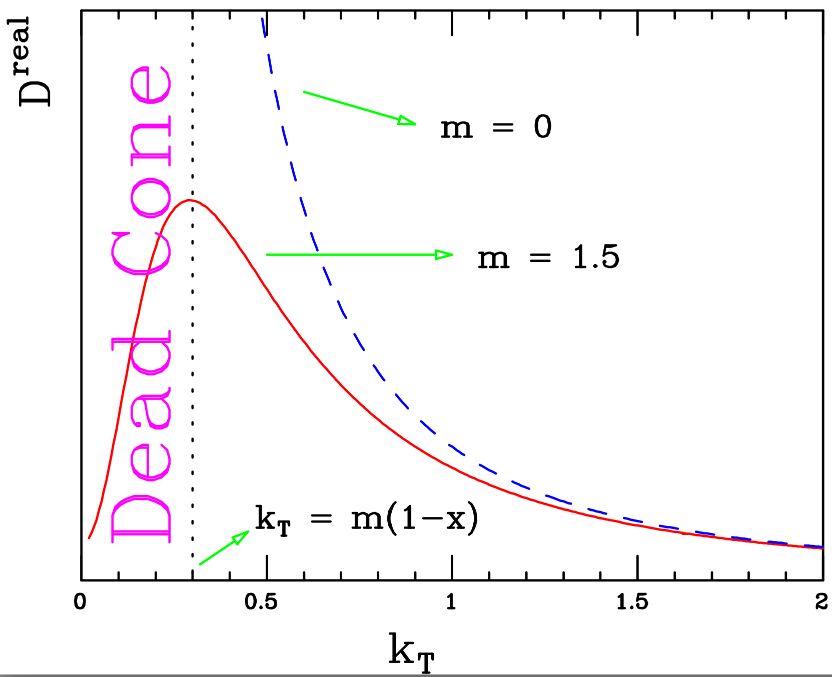

$$\frac{d\sigma(b \to B \to J/\psi)}{dp_T} = \frac{d\sigma(b)}{d\hat{p}_T} \otimes f(b \to B) \otimes g(B \to J/\psi)$$

# Heavy mass effects




## Gluon emission from a heavy quark

$$D^{\rm real}(x, k_T^2, m^2) = \frac{C_F \alpha_s}{2\pi} \left[ \frac{1+x^2}{1-x} \frac{1}{k_T^2 + (1-x)^2 m^2} - x(1-x) \frac{2m^2}{(k_T^2 + (1-x)^2 m^2)^2} \right]$$




Emission probability not divergent at small transvere momentum

**Calculability in pQCD**

# Factorization theorem

Collins, Soper, Sterman, Nucl. Phys. B263 (1986) 37

$$\sigma_Q(S,m^2) = \sum_{i,j\in L} \int dx_1 dx_2 \hat{\sigma}_{ij\to QX}(x_1 x_2 S, m^2; \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2) F_{i/A}(x_1,\mu_F) F_{j/B}(x_2,\mu_F) + O\left(\frac{\Lambda}{m}\right)^p$$

**Light** flavours only

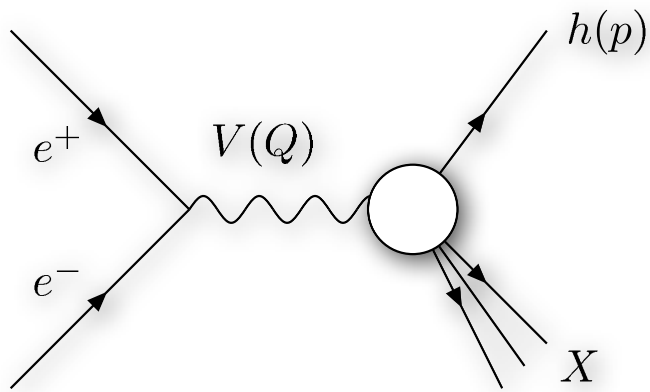
contribute most of the total cross section. The hard scattering function is perturbatively calculable in an expansion in powers of $\alpha_s(M)$: potential singularities in $H$ have been factorized into the parton distribution functions. Corrections to this formula are suppressed by powers of (hadron mass scale/$M$).

We have by no means proved this result in this paper, but we believe that the analysis given here should make the result plausible. We are arguing that heavy

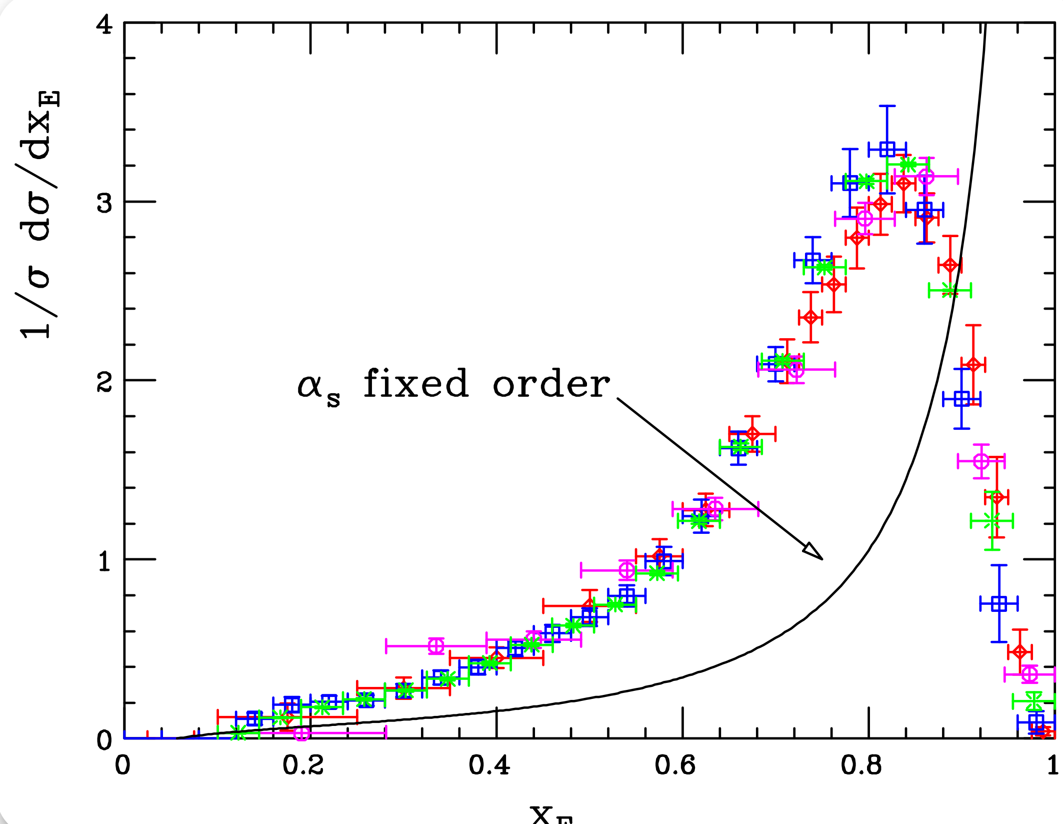
The upshot is that heavy quark rates are **calculable** in pQCD

# $e^+e^- \to B + X$

# Calculable ≠ accurate



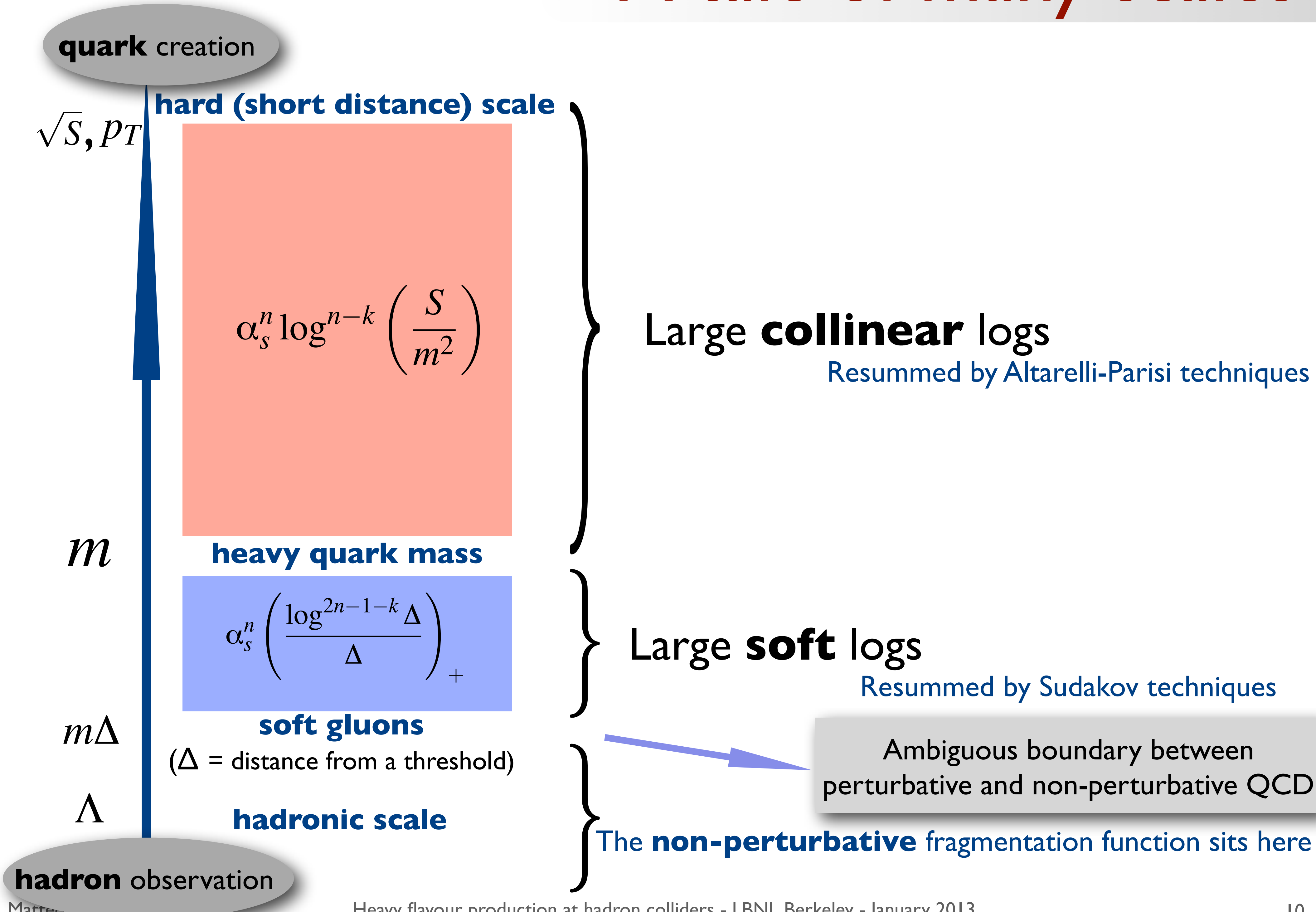

$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \delta(1-x)+\frac{\alpha_s(Q^2)}{2\pi}\left\{C_F+C_F\left[\ln\frac{Q^2}{m^2}\left(\frac{1+x^2}{1-x}\right)_+ \right.\right.$$
$$+ \quad 2\,\frac{1+x^2}{1-x}\log x-\left(\frac{\ln(1-x)}{1-x}\right)_+(1+x^2)+\frac{1}{2}\left(\frac{1}{1-x}\right)_+(x^2-6x-2)$$
$$\left.\left. + \quad \left(\frac{2}{3}\pi^2-\frac{5}{2}\right)\delta(1-x)\right]\right\} + \mathcal{O}\left(\frac{m}{Q}\right)$$




## What's missing?

Higher perturbative orders and non-perturbative effects

# A tale of many scales



# How to do it

1. Calculate **perturbative corrections** as well as you can (usually NLO + resummation of large logs)

2. Fit remaining (small) **non-perturbative contribution** to data (usually $e^+e^-$, CLEO/BELLE, LEP,…) within the same perturbative framework

3. Set up **code** to calculate as realistic as possible cross sections (cuts, weak decays to observed particles)

(Residual uncertainty usually dominated by perturbative one)

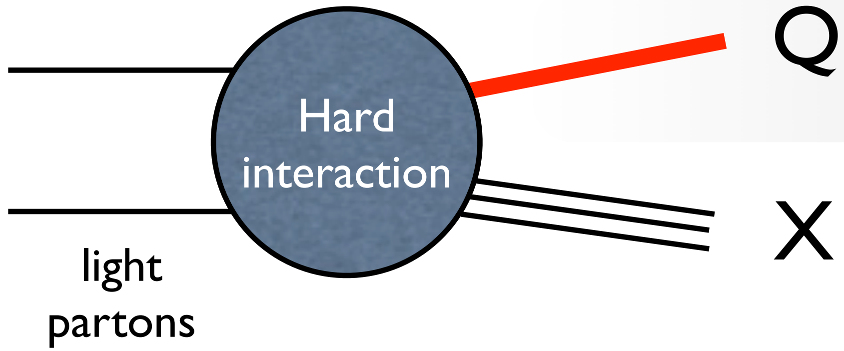
# (N)LO + Logs (without double-counting)

- PYTHIA
- HERWIG
- FONLL — MC, Greco '94, MC, Greco, Nason '98
- GM-VFN — Kniehl, Kramer, Schienbein, Spiesberger, '05
- MC@NLO — Frixione, Webber '02
- POWHEG — Nason, '04

In all cases, matching between a (N)LO fixed order calculation (Nason, Dawson, Ellis, '88) and the resummation of large logs, either semi-numerically (FONLL, NLL accuracy) or via a parton shower Montecarlo (LL accuracy)

# FONLL

FO

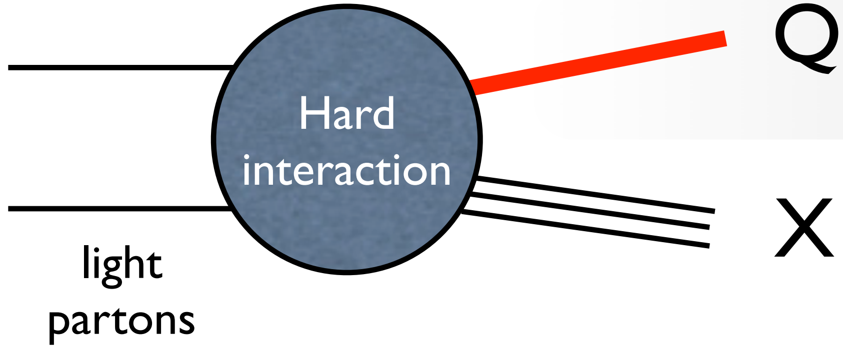



+

- double-counting (accurate at NLO+NLL)

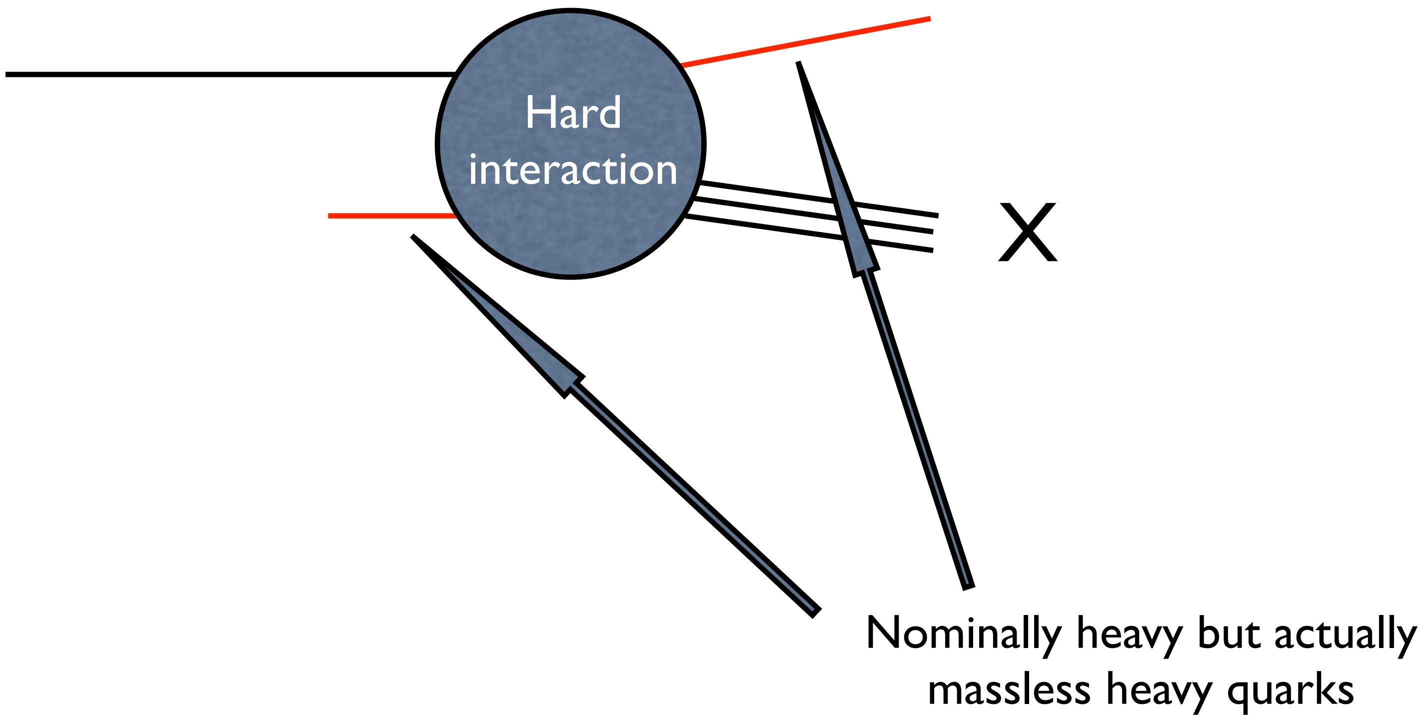
# FONLL

FO



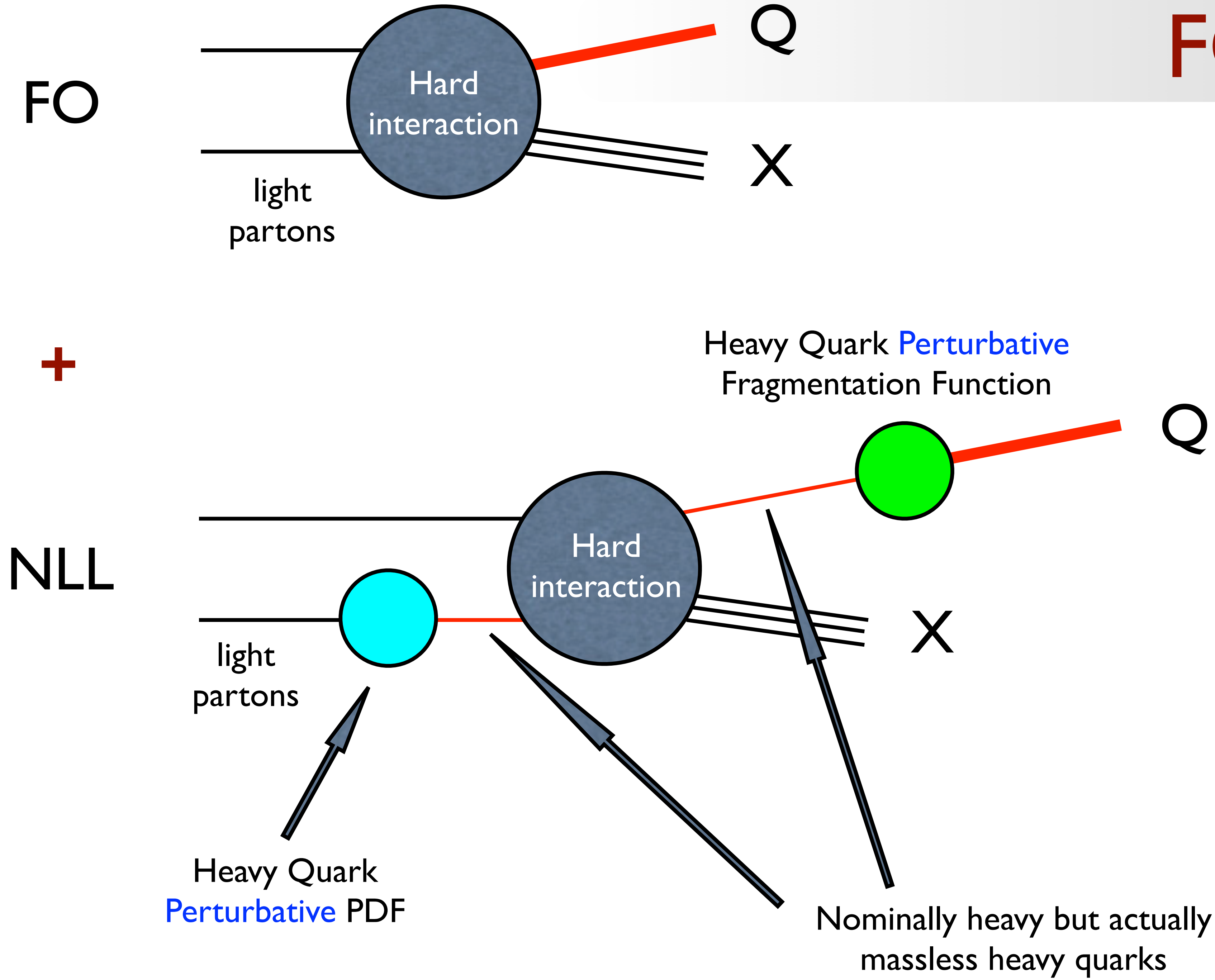

+

NLL



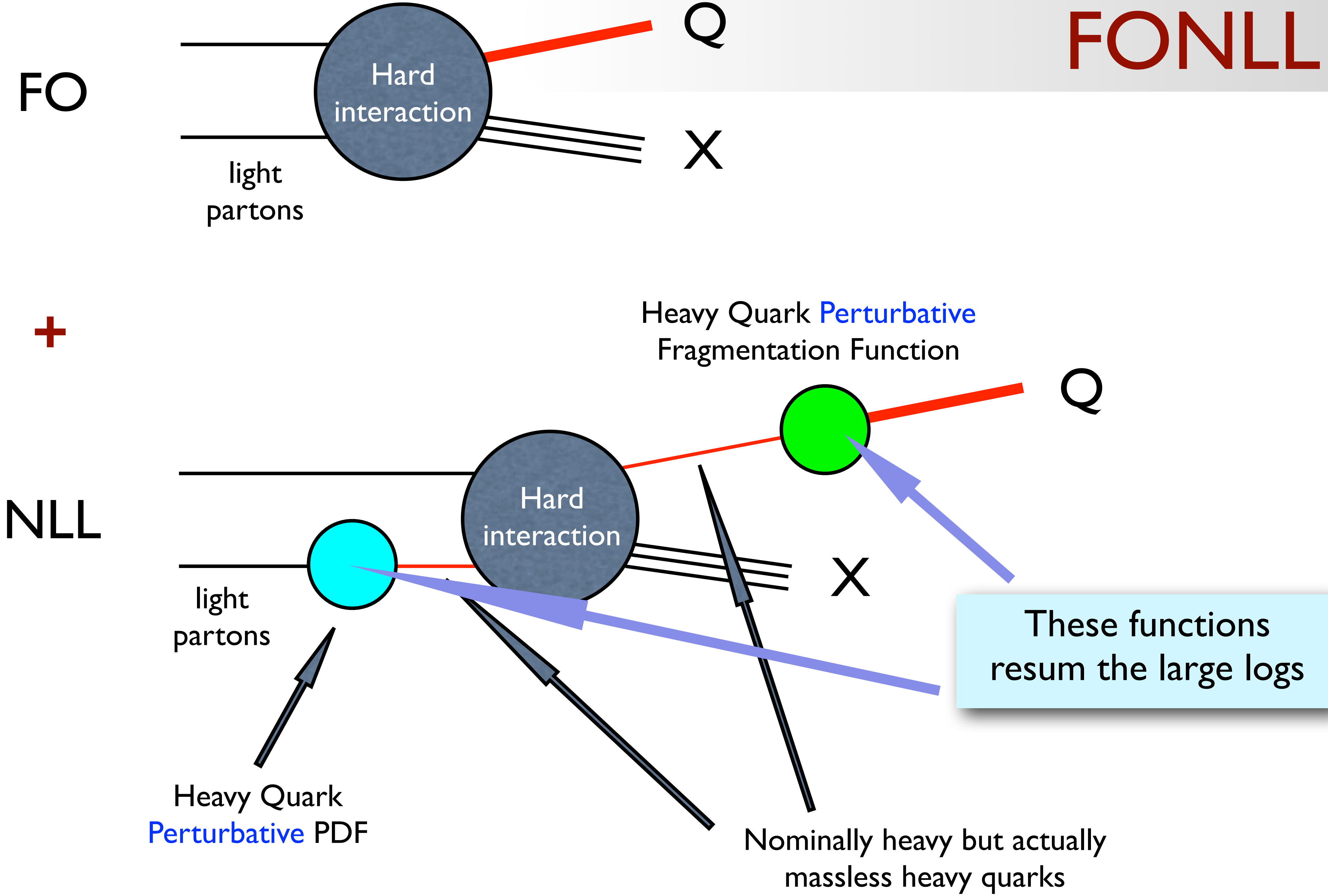

- double-counting (accurate at NLO+NLL)

# FONLL



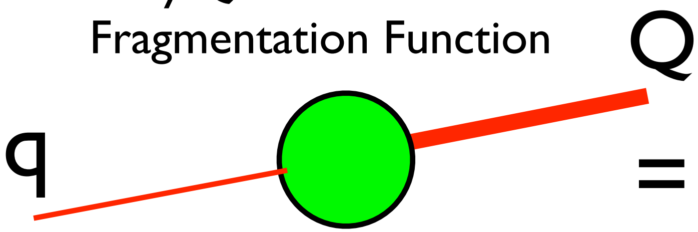

- double-counting (accurate at NLO+NLL)

# FONLL




## - double-counting (accurate at NLO+NLL)

Heavy Quark Perturbative Fragmentation Function




$$= E(\mu,\mu_0) \otimes \left[ D^{\mathrm{ini},S}(\mu_0,m) + D^{\mathrm{ini}}(\mu_0,m) - D^{\mathrm{ini}}(\mu_0,m)|_{\alpha_S} \right]$$

**Altarelli-Parisi evolution**
(resums collinear logs)

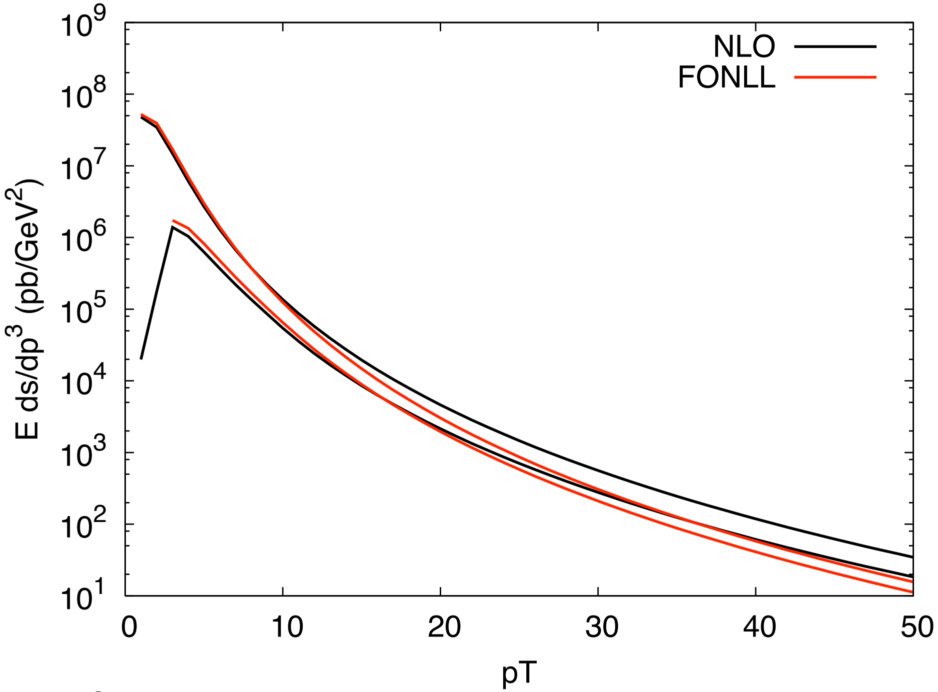
Subtraction of doubly counted terms (accurate to NLL)

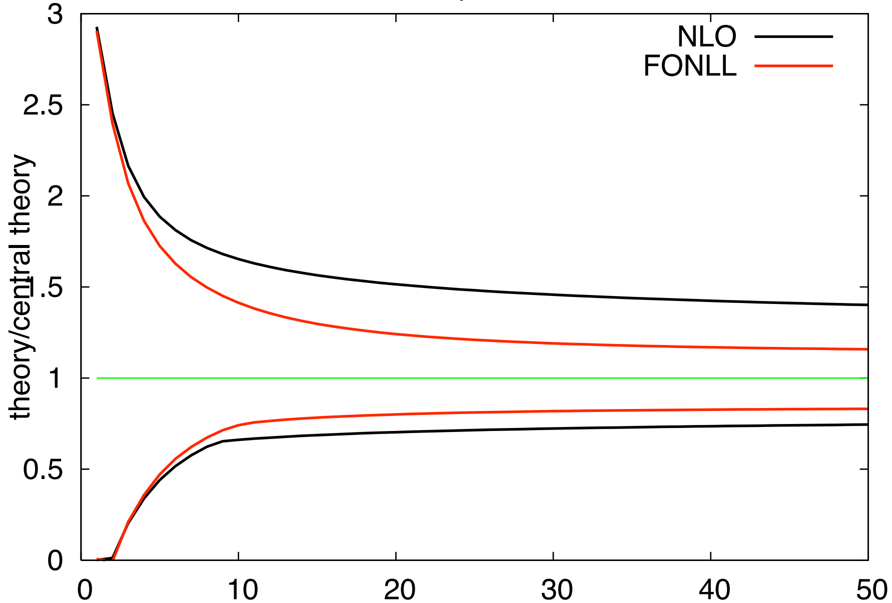
**Sudakov resummation**
(resums soft logs)

**Fully massive O($\alpha_S$) initial condition**
(ensures predictivity of heavy quark cross sections)

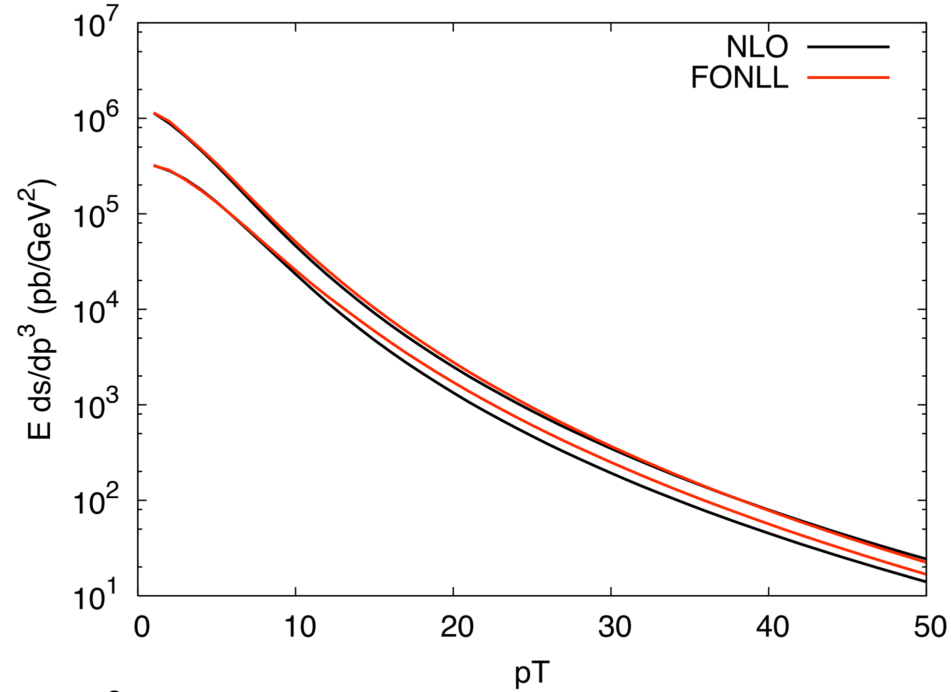
# Charm & bottom quarks @ LHC

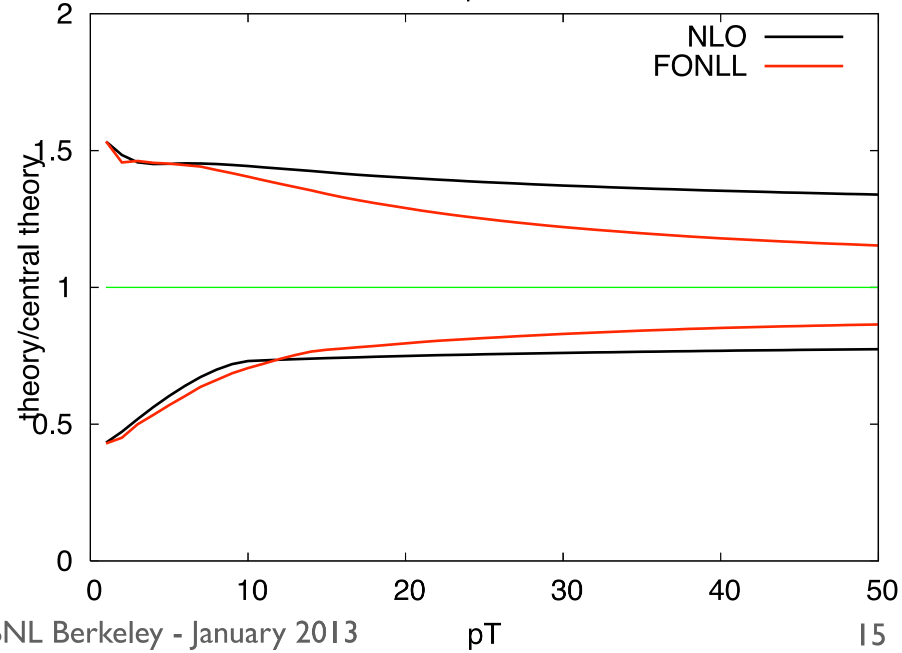
## Charm




## Bottom



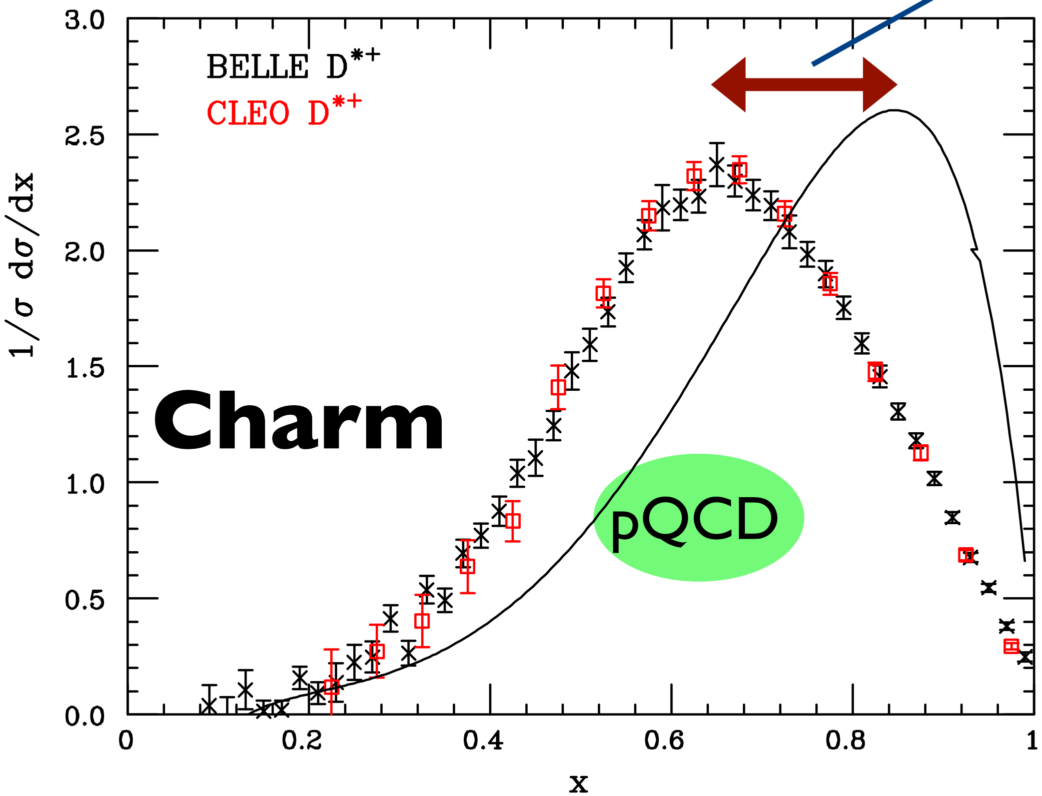



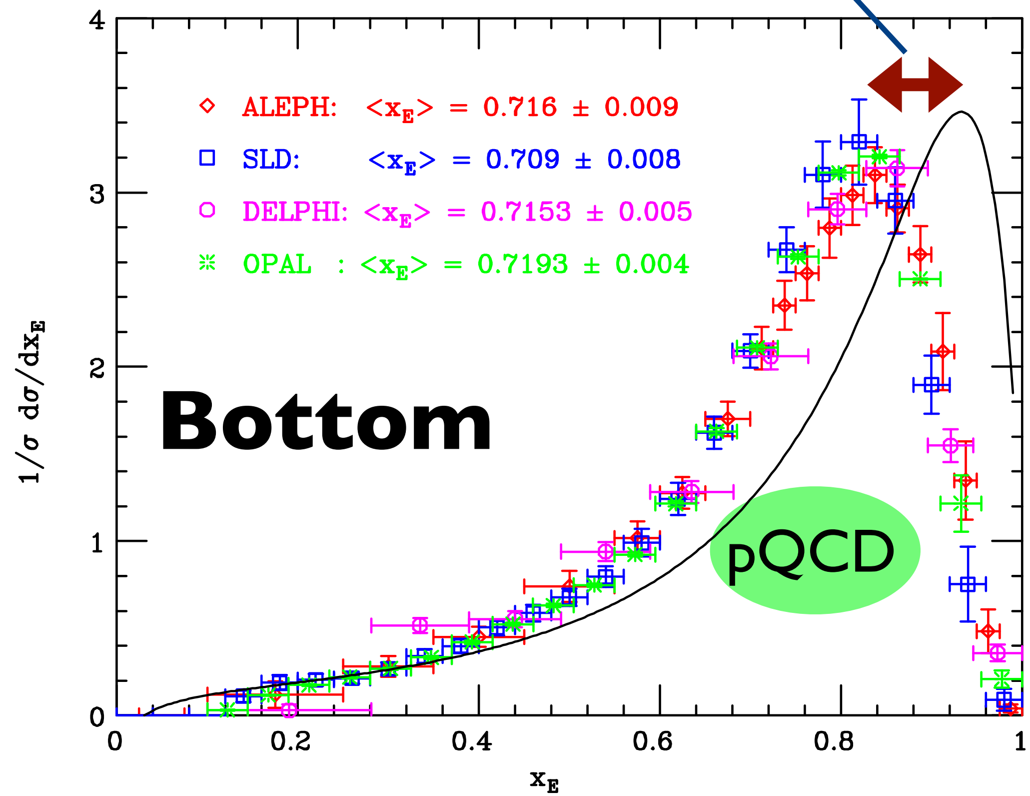
# Perturbative fragmentation v. data

$$e^+e^- \to QX \to H_Q X$$

non-perturbative contributions

$O(\Lambda/m_{charm})$ $O(\Lambda/m_{bottom})$




- non-perturbative contributions limited in size and compatible with expectations
- high-accuracy expt. data allow it to be precisely determined

# 2. Non-perturbative corrections

$$\frac{d\sigma_H}{dp_T} = \frac{d\sigma_Q}{dp_T} \otimes D^{np}$$

measured
cross section

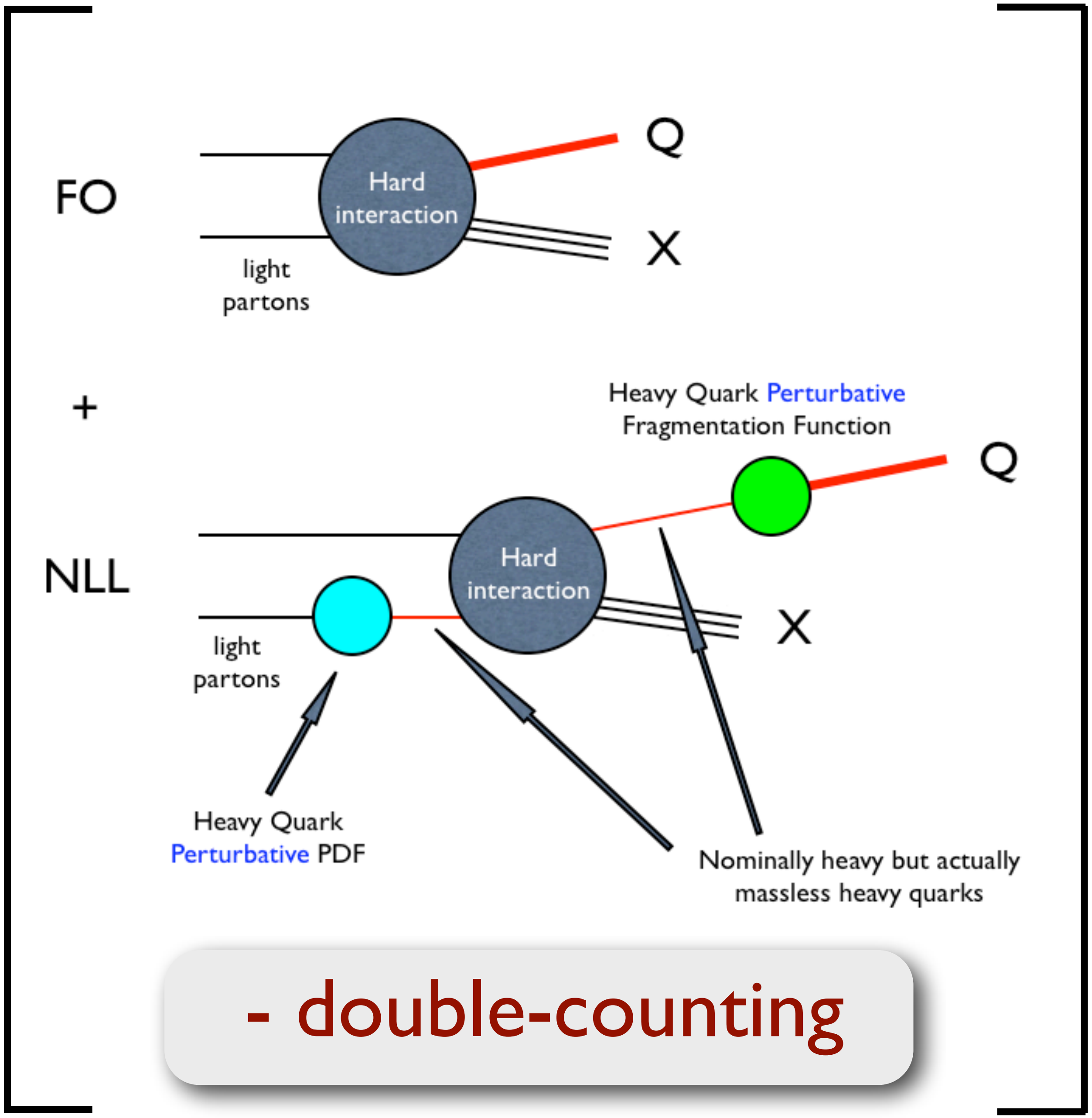
Perturbative
calculation

This could be at various
accuracies, LO, LO+LL,
NLO+NLL, with or without
collinear or soft resummation, etc)

non-perturbative
fragmentation
(usually extracted
from e+e- data)


Matteo Cacciari

# Non-perturbative corrections: FONLL




$$\otimes \quad D_{Q\to H}$$

Fitted to e+e- data
in the **same scheme**

# Non-perturbative fragmentation

## What do we know about it?

If the quark is light, not much. It's a process-independent artificial (i.e. non-physical) object (factorisation theorem) that we must extract from data (e.g. pion fragmentation functions)

If the quark is heavy, its fragmentation function is still artificial, but we can say something more about it:

- we know that it is a (parametrically) small effect
- we can relate it to the hadronisation scale and to the heavy quark mass
- we can test this on D and B data

# It's the moment that matters

$$\frac{d\sigma_Q}{dp_T} \sim \frac{A}{p_T^n}$$

heavy **quark** cross section

$$\Downarrow$$

heavy **hadron** cross section

$$\frac{d\sigma_H}{dp_T} = \frac{d\sigma_Q}{dp_T} \otimes D^{np} = \int \frac{d\sigma_Q}{dp_T}(p_T/z) D^{np}(z) \frac{dz}{z} = \int \frac{A}{(p_T/z)^n} D^{np}(z) \frac{dz}{z} = \frac{d\sigma_Q}{dp_T}(p_T) D_n^{np}$$

It's the ***n*^th^ moment** of the non-perturbative fragmentation function that controls the effect of hadronisation at large transverse momentum with a steeply falling cross section

**In hadronic collisions, *n* is typically ~ 5**

# Non-perturbative fragmentation

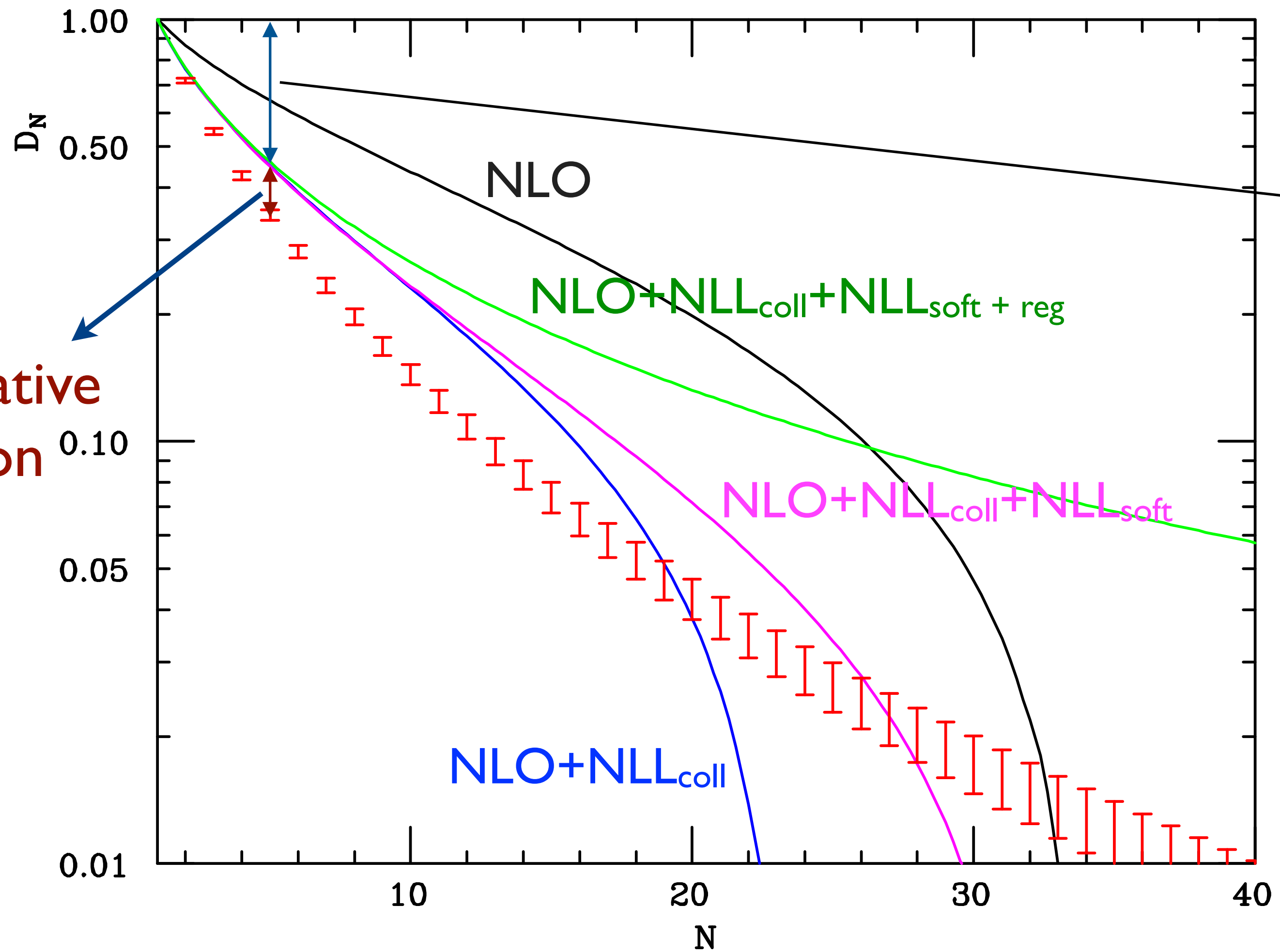
## LEP B meson data translated to Mellin space

$$f_N \equiv \int_0^1 x^{N-1} f(x)\, dx = \langle x^{N-1} \rangle$$

In this space
**convolutions become products**

$$\langle x \rangle_{expt} = \langle x \rangle_{pQCD} \langle x \rangle_{np}$$

This gap: non-perturbative contribution for N=5




resummed pQCD

Successive approximations improve the perturbative prediction and approach the data

# NP fragmentation: quantitative picture

N=2 moments (i.e. $\langle x \rangle$ )

| $N$ | 2 |
|---|---|
| | |
| $c$ @ 10.58 GeV | 0.7359 |
| $c$ @ 91.2 GeV (NS) | 0.5858 |
| $c$ @ 91.2 GeV (full) | 0.5954 |
| $b$ @ 91.2 GeV | 0.7634 |
| | |
| BELLE $D^{*+} \to D^0$ (ISR corr.) | $0.6418 \pm 0.0042$ |
| ALEPH $D^{*+}$ (ISR corr.) | $0.4920 \pm 0.0152$ |
| ALEPH $B$ | $0.7163 \pm 0.0085$ |
| | |
| CLEO $D^{*+}$ | $0.877^{+0.009}_{-0.010}$ |
| BELLE $D^{*+} \to D^0$ | $0.872^{+0.005}_{-0.006}$ |
| ALEPH $D^{*+}$ | $0.840^{+0.022}_{-0.031}$ |
| Tab. 2 and eq. (4.2) | 0.868 |
| ALEPH $B$ | $0.938^{+0.009}_{-0.014}$ |
| SLD $B$ | $0.931^{+0.016}_{-0.030}$ |

→ pQCD (NLL)

→ data (very precise!)

→ $D^{np} = \frac{\text{data}}{\text{pQCD}}$

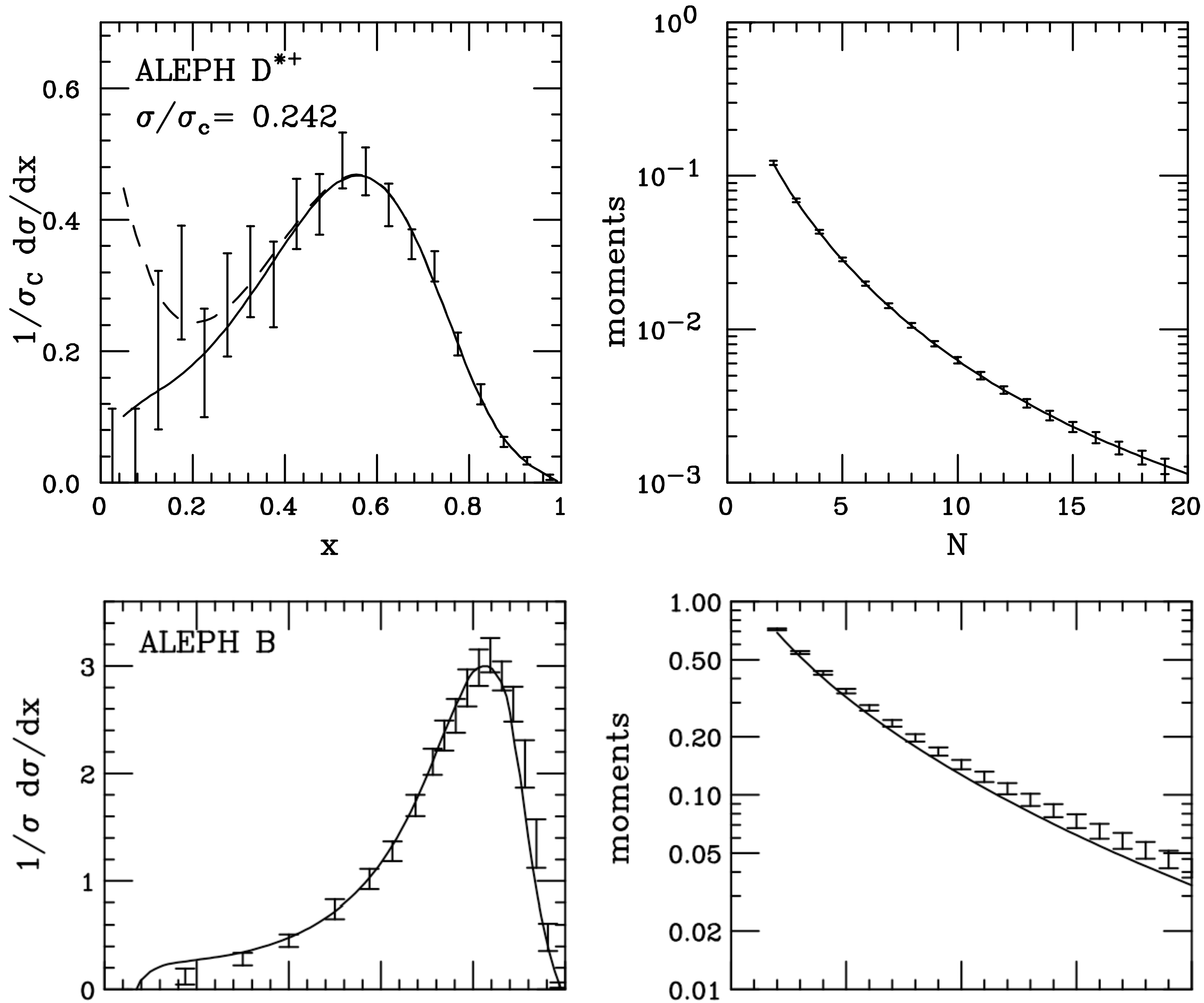
charm ~ 1 - 0.16
bottom ~ 1 - 0.06

Compatible with $D_N^{np} = 1 - \frac{(N-1)\Lambda}{m} + \cdots$ and $\Lambda \simeq 0.25$ GeV

# pQCD +NP: overall description of data

x space | N space

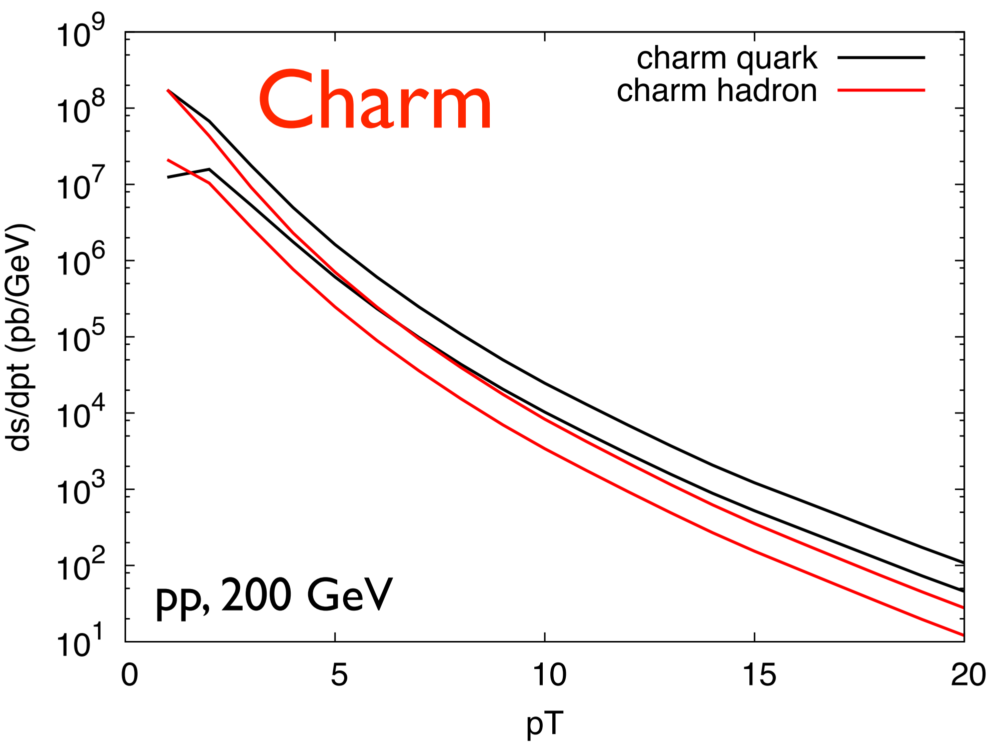
charm mesons | bottom mesons

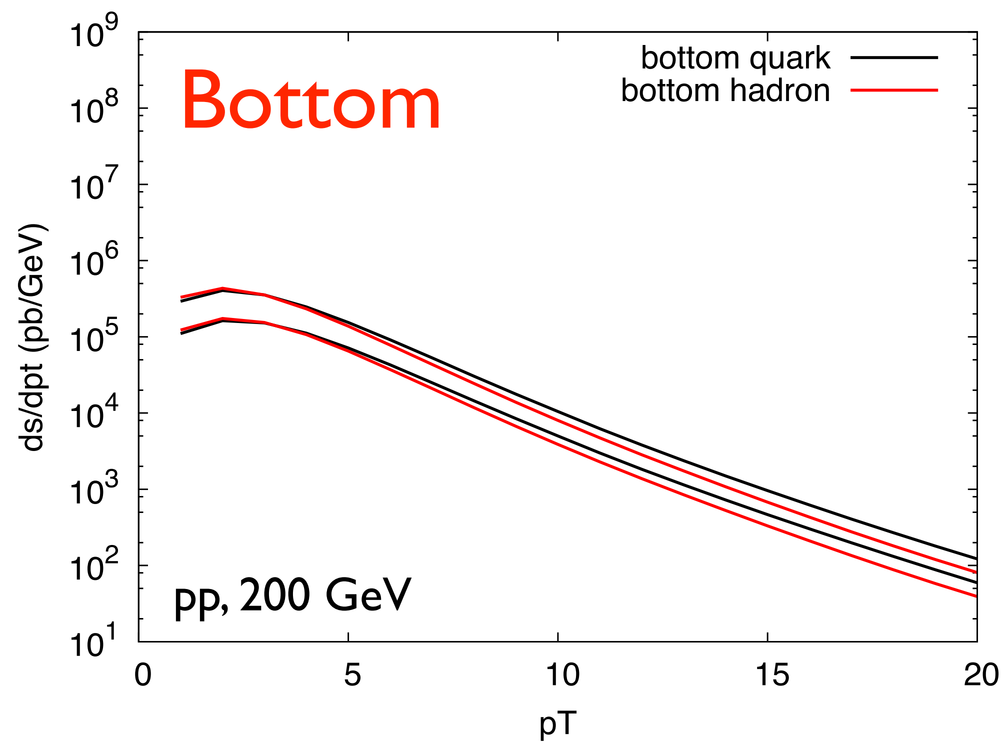


# Hadronic differential distributions

The **total number** (and of **heavy hadrons**) of heavy quarks is a **genuine prediction of pQCD**

At the **differential** level instead, **hadrons and quarks differ**



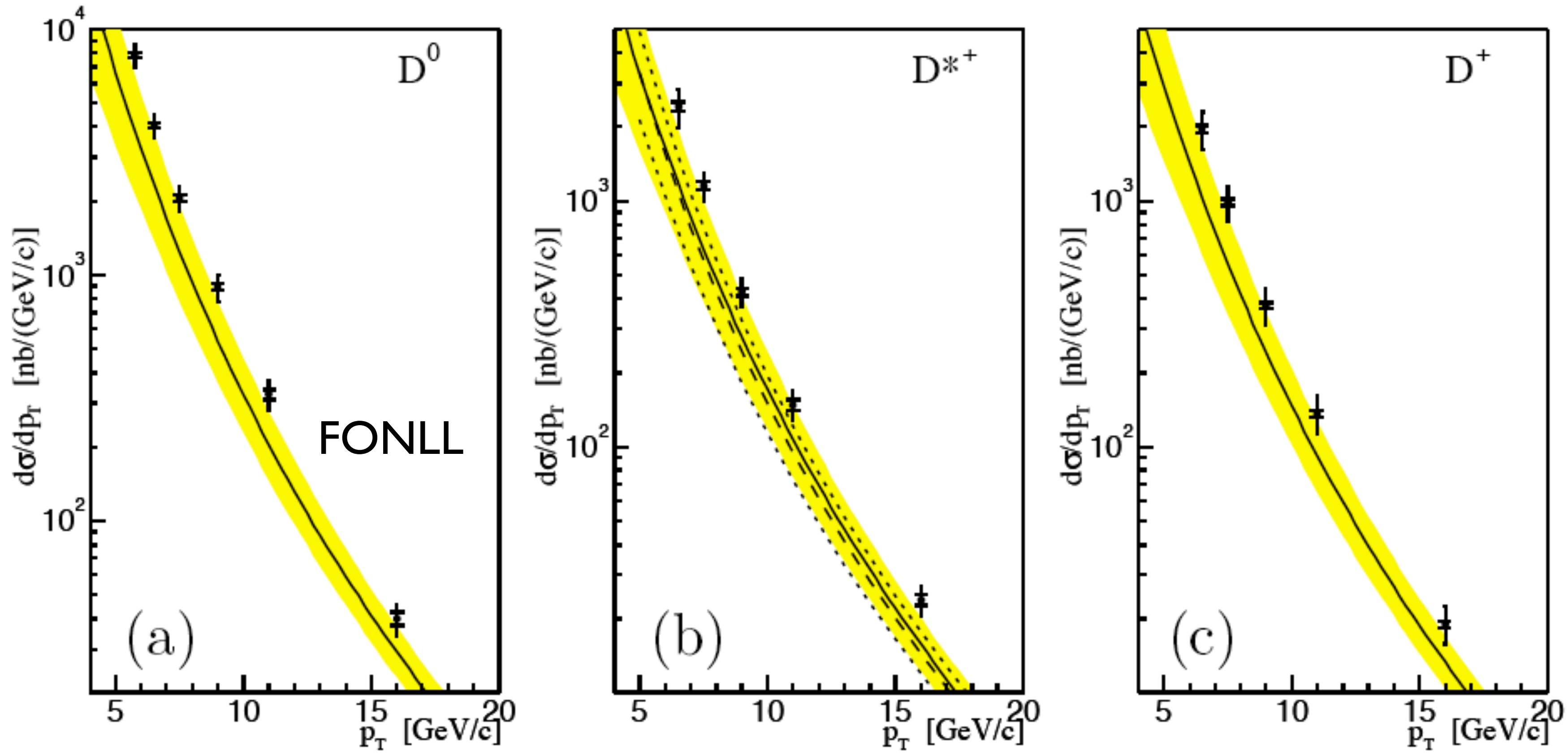




However, the non-perturbative correction is expected (and observed) to be **parametrically small,** $O(\Lambda/m)$

(Still, at large $p_T$ the effect can be large)

# Comparisons with data

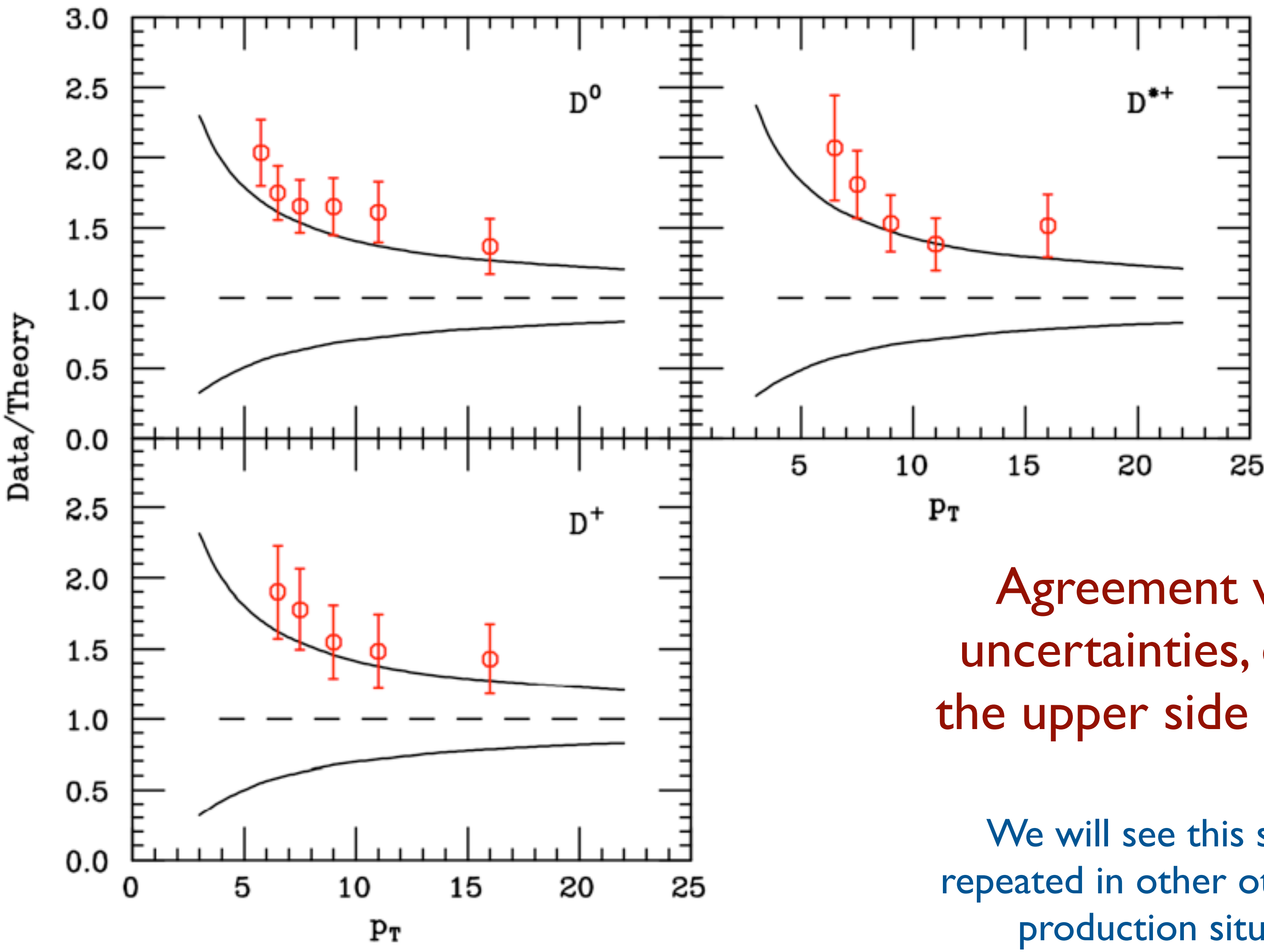
CDF Run II c → D data [PRL 91:241804,2003]




Non-perturbative charm fragmentation needed to describe the c → D hadronization extracted from moments of ALEPH data at LEP.

# Charm @ Tevatron

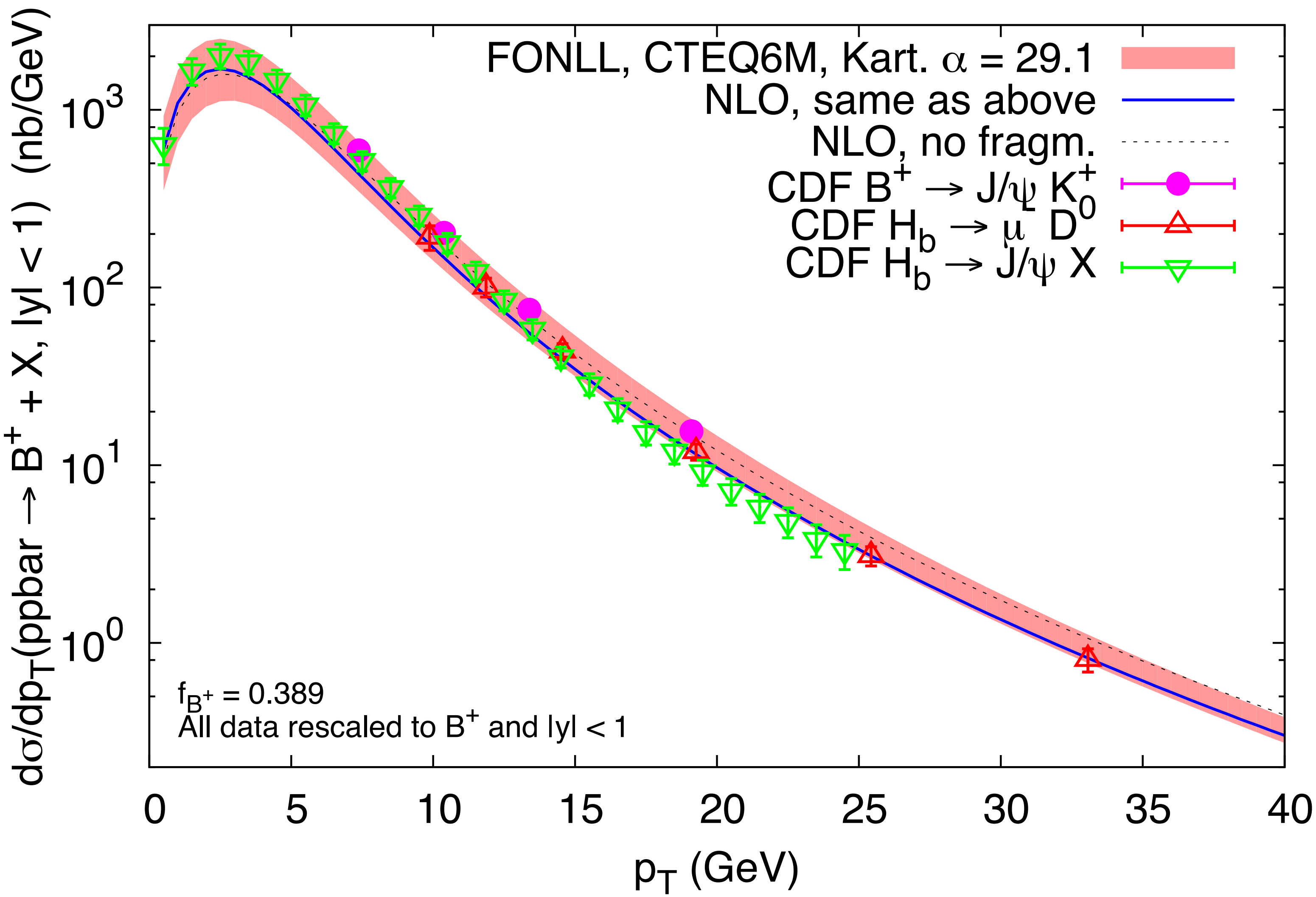
## Data/theory ratios




Agreement within uncertainties, data on the upper side of bands

We will see this situation repeated in other other charm production situations

# Bottom @ Tevatron

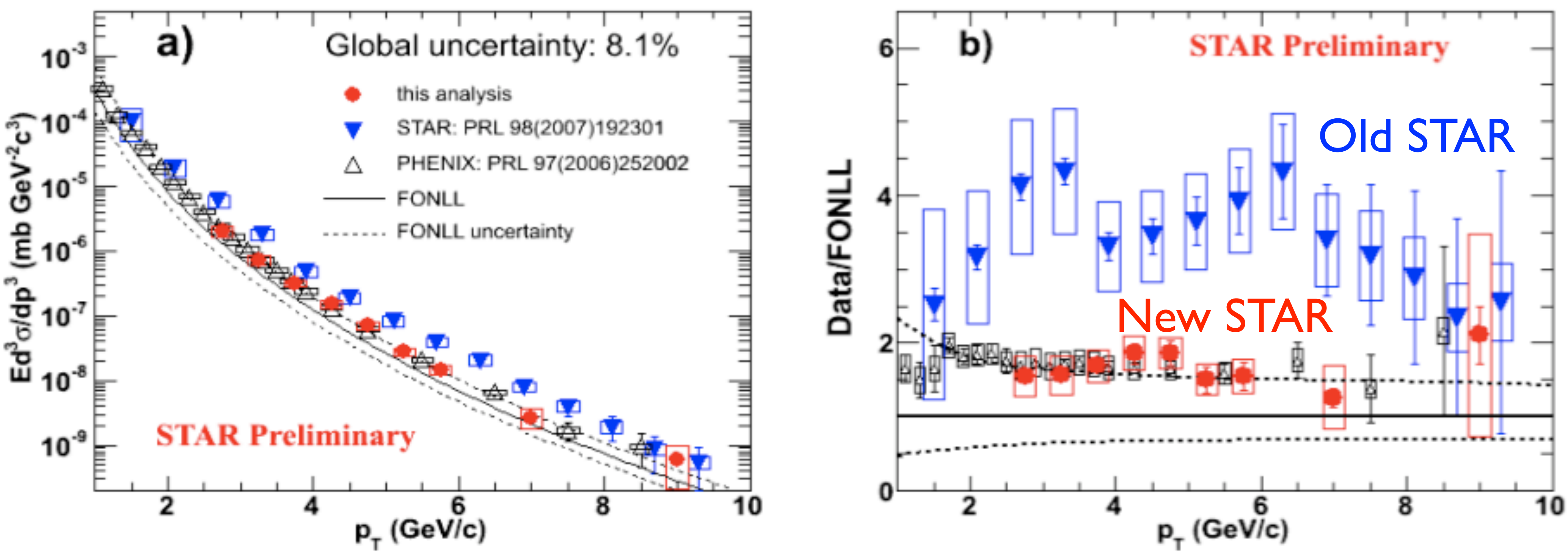



Good agreement, with minimal non-perturbative correction

NLO is sufficient for correct total rate prediction

# Charm and bottom @ RHIC

## ‘non-photonic’ electrons: pp → c,b → e




Theory holding firm,
STAR data initially showing an excess have come down

# Lessons from Tevatron and RHIC

- NLO QCD predicts correctly the ‘total’ heavy quark bottom cross sections

- Non-perturbative fragmentation extracted from CLEO/BELLE and LEP predict correctly heavy hadrons differential distributions in hadroproduction

- The effect of NLL resummation in hadroproduction has not yet really been probed (but is necessary for the extraction of the NP contribution from e+e- data)

# Moving on to the LHC

## A number of different observables can be measured

- (Almost) total cross sections

make sure that no new large logs (e.g. small-x) appear to spoil convergence of pQCD

- Differential distributions
  - Heavy mesons and hadrons
  - Leptons from heavy hadrons
  - J/ψ from b-hadrons

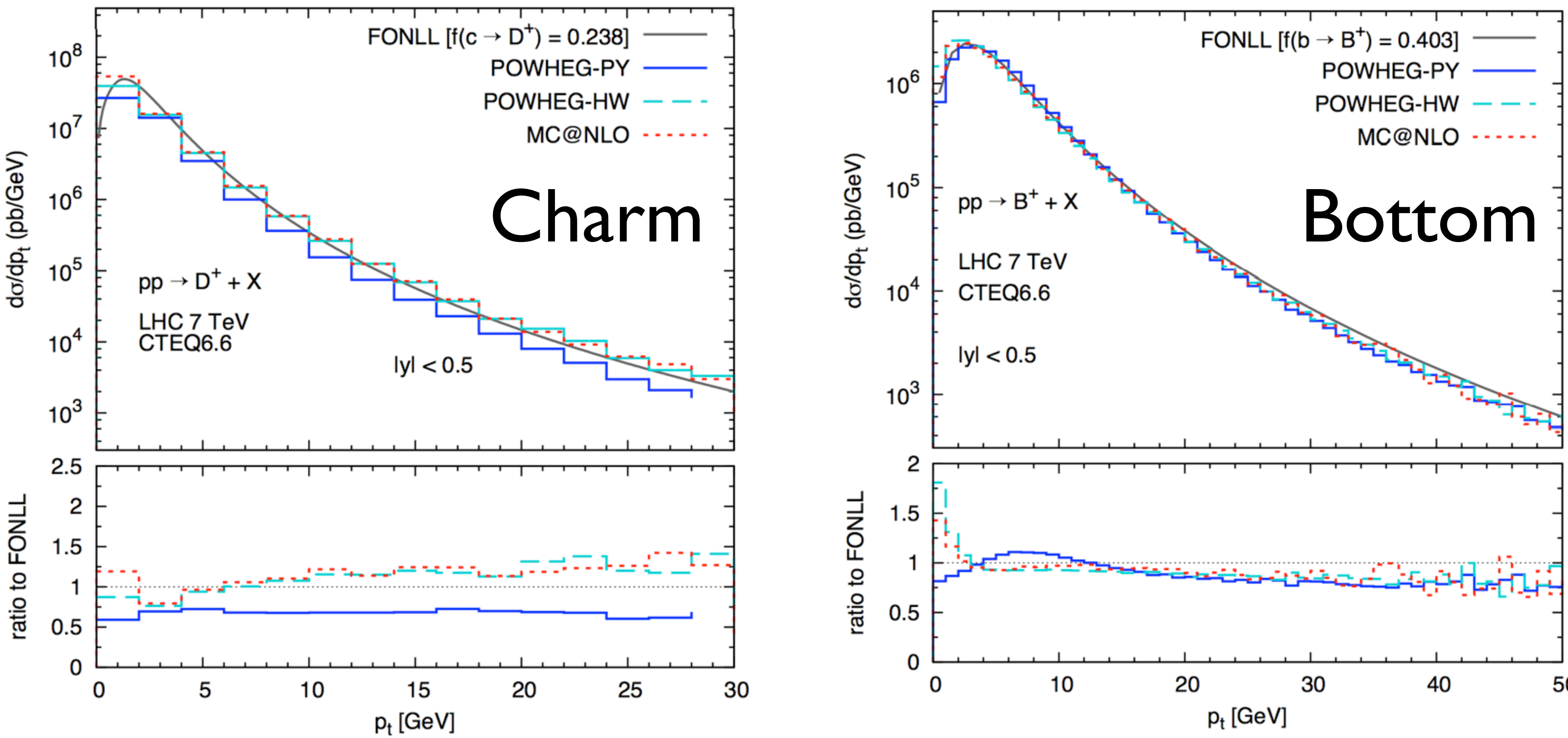
Check universality of non-perturbative fragmentation functions and decay functions fitted to data

**Eventually, measuring heavy hadrons at very large $p_T$ ($\gg 20\times m$) will test the perturbative NLL resummation**

Since resummation of logarithms does not matter much, one would expect Monte Carlos and semi-analytical tools to broadly agree

In practice, non-negligible differences can be seen

arXiv:1205.6344

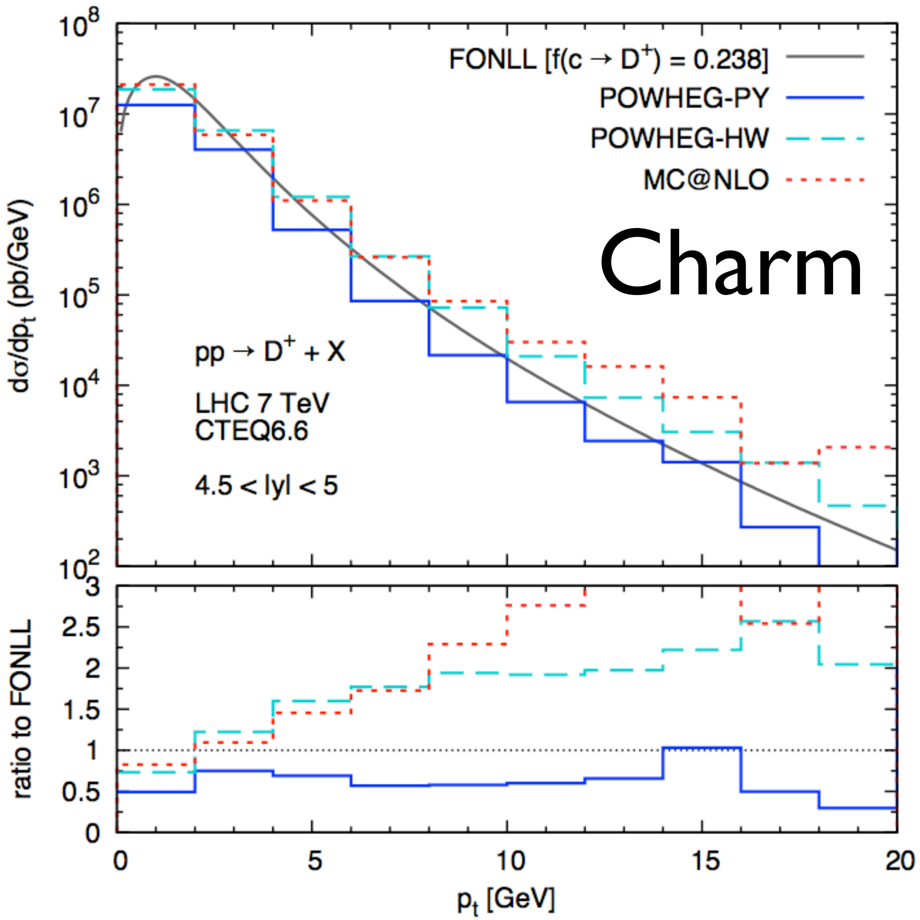


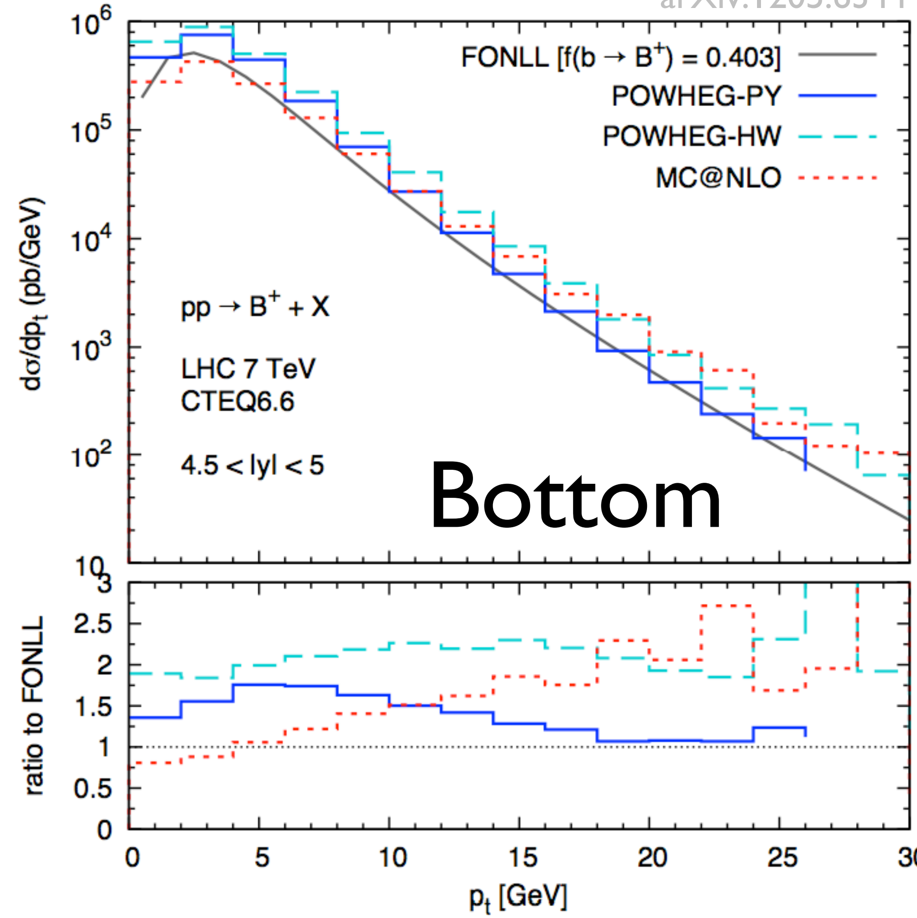

Since the perturbative content should be similar, the differences can probably be attributed to **non-perturbative physics**

# Comparison of tools

The differences can become significantly larger at large rapidity

arXiv:1205.6344

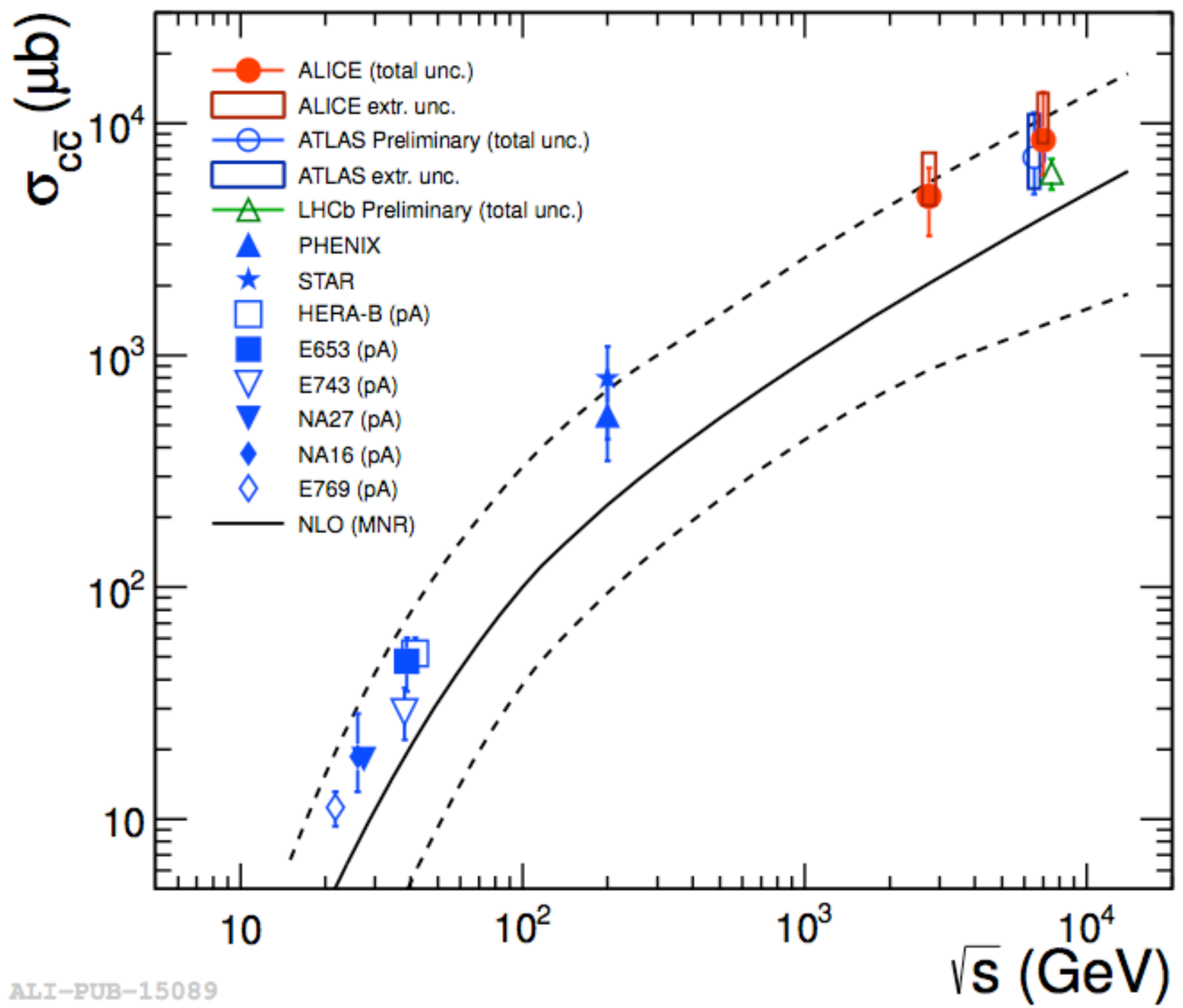



Data will have potential for discrimination

# Experimental results from LHC

# Total charm cross section

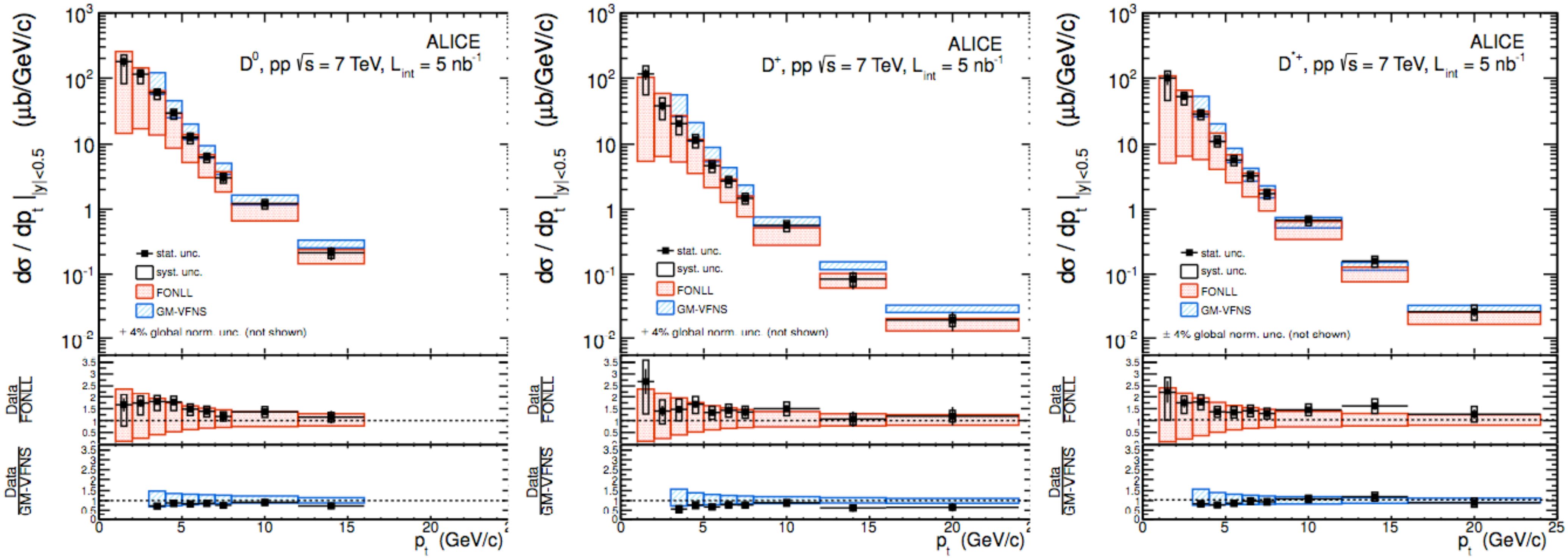



Agreement, but huge theoretical uncertainty

Charm total cross section is more an opinion than a prediction

(also, measurements usually include non-negligible extrapolation factors based on theory)

# Charm mesons



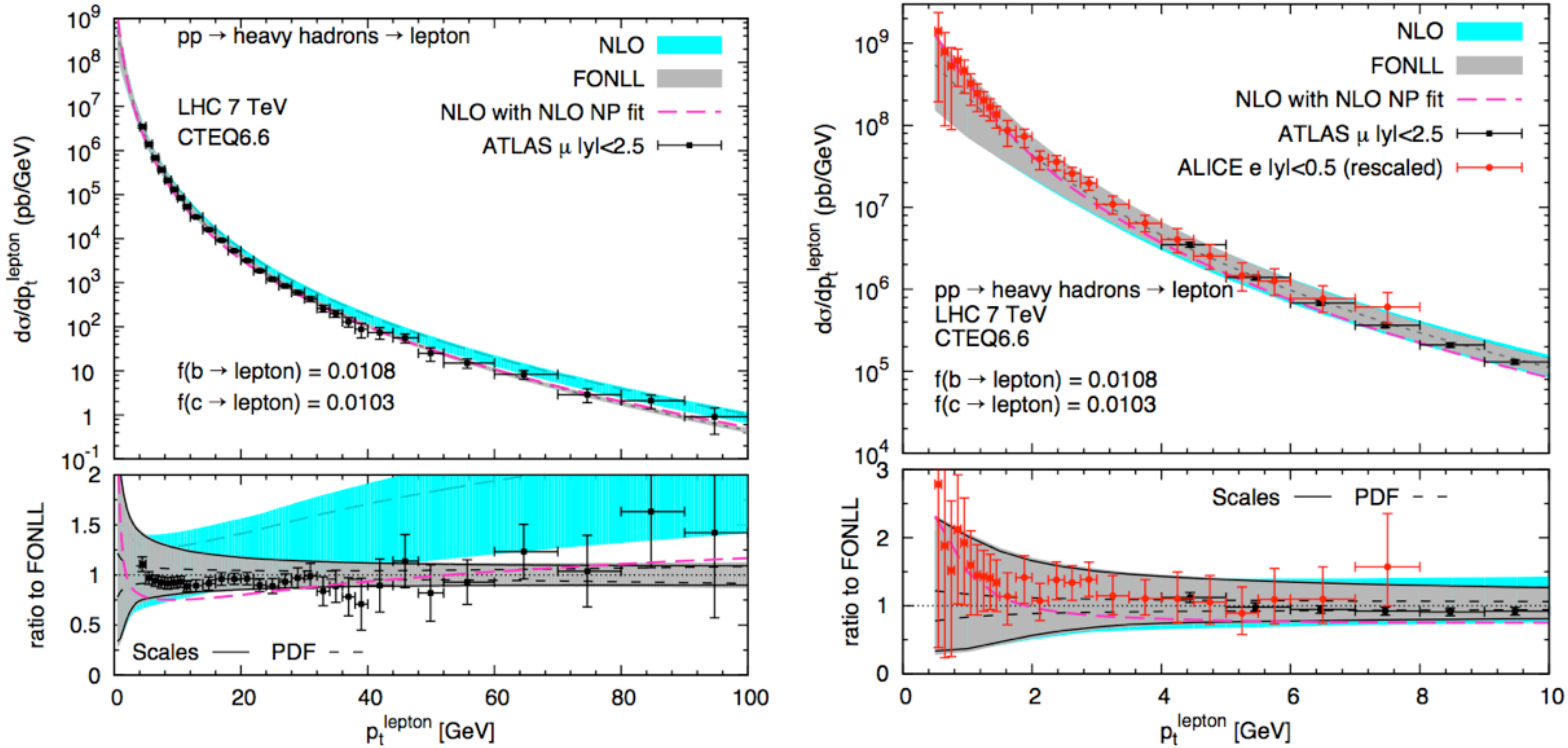

Situation similar to Tevatron:

agreement with upper side of theoretical bands

Worth noting: measurement down to very low $p_T \approx 1$ GeV

# Leptons from heavy flavours

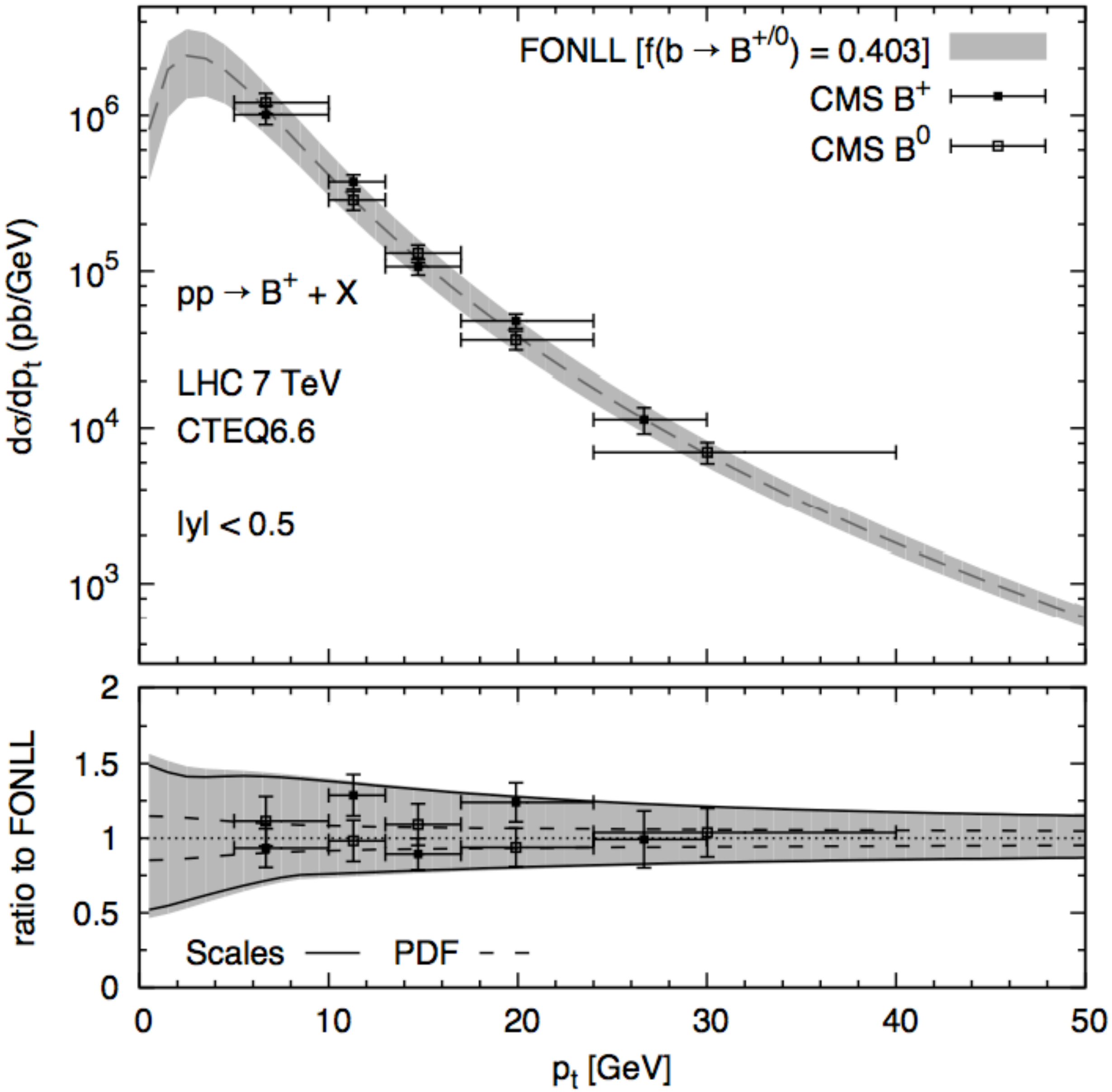
arXiv:1205.6344




- ATLAS and ALICE fully compatible
- Fair agreement with theory from 1 to 100 GeV
- Starts probing quasi-collinear NLL resummation at large $p_T$ (but not quite there yet)

# Bottom mesons

arXiv:1205.6344

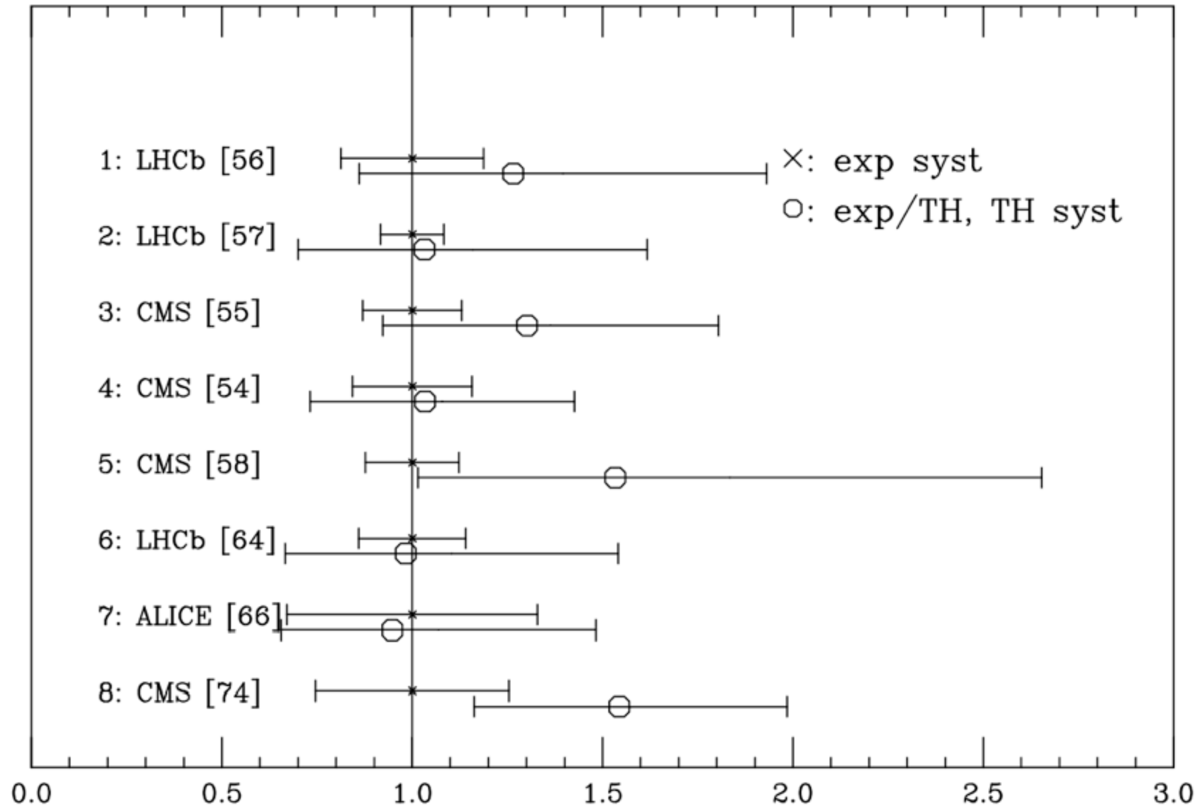



Quality of agreement same as at the Tevatron

# Compilation of bottom cross sections

| Expt | Observable ($p_T$ in GeV) | $\sigma^{exp}$ | $\sigma^{FONLL}$ | Comments |
|---|---|---|---|---|
| 1: LHCb [54] | $\sigma(H_b, 2 \le \eta \le 6)$ | $89.6 \pm 16.8$ $\mu$b | $70.8\ ^{+33.3}_{-24.4}$ $\mu$b | average $b + \bar{b}$ |
| 2: LHCb [55] | $\sigma(B^{\pm}, p_T < 40, 2 < y < 4.5)$ | $41.4 \pm 3.4$ $\mu$b | $40.1\ ^{+19.0}_{-14.5}$ $\mu$b | $f(b \to B^-) = 0.403$ |
| 3: CMS [53] | $\sigma(B^0,\ p_T^B > 5,\ \lvert y^B\rvert < 2.2)$ | $33.2 \pm 4.3$ $\mu$b | $25.5\ ^{+10.5}_{-7.1}$ $\mu$b | $f(b \to B^0) = 0.403$ |
| 4: CMS [52] | $\sigma(B^+,\ p_T^B > 5,\ \lvert y^B\rvert < 2.4)$ | $28.1 \pm 4.4$ $\mu$b | $27.2\ ^{+11.2}_{-7.5}$ $\mu$b | $f(b \to B^-) = 0.403$ |
| 5: CMS [56] | $\sigma(B_s^0,\ 8 < p_T^B < 50,\ \lvert y^B\rvert < 2.4)$ $\times \mathrm{BR}(B_s^0 \to J/\psi\,\phi)$ | $6.9 \pm 0.8$ nb | $4.5\ ^{+2.3}_{-1.9}$ nb (includes BR uncertainty) | $f(b \to B_s^0) = 0.11$ $\mathrm{BR}(B_s^0 \to J/\psi\,\phi) = (1.4 \pm 0.5) \times 10^{-3}$ |
| 6: LHCb [62] | $\sigma(H_b \to J/\psi, p_T^{\psi} < 14, 2 < y_{\psi} < 4.5)$ | $1.14 \pm 0.16$ $\mu$b | $1.16\ ^{+0.55}_{-0.42}$ $\mu$b | $\mathrm{BR}(b \to J/\psi) = 0.0116$ |
| 7: ALICE [64] | $\sigma(H_b \to J/\psi, p_T^{\psi} > 1.3, \lvert y_{\psi}\rvert < 0.9)$ | $1.26 \pm 0.16$ $\mu$b | $1.33\ ^{+0.59}_{-0.48}$ $\mu$b | $\mathrm{BR}(b \to J/\psi) = 0.0116$ |
| 8: CMS [72] | $\sigma(H_b \to \mu,\ p_T^{\mu} > 6,\ \lvert y^{\mu}\rvert < 2.1)$ | $1.32 \pm 0.34$ $\mu$b | $0.855\ ^{+0.28}_{-0.19}$ $\mu$b | $\mathrm{BR}(b \to \ell) = 0.0108$ $\mathrm{BR}(b \to c \to \ell) = 0.096$ |

arXiv:1205.6344

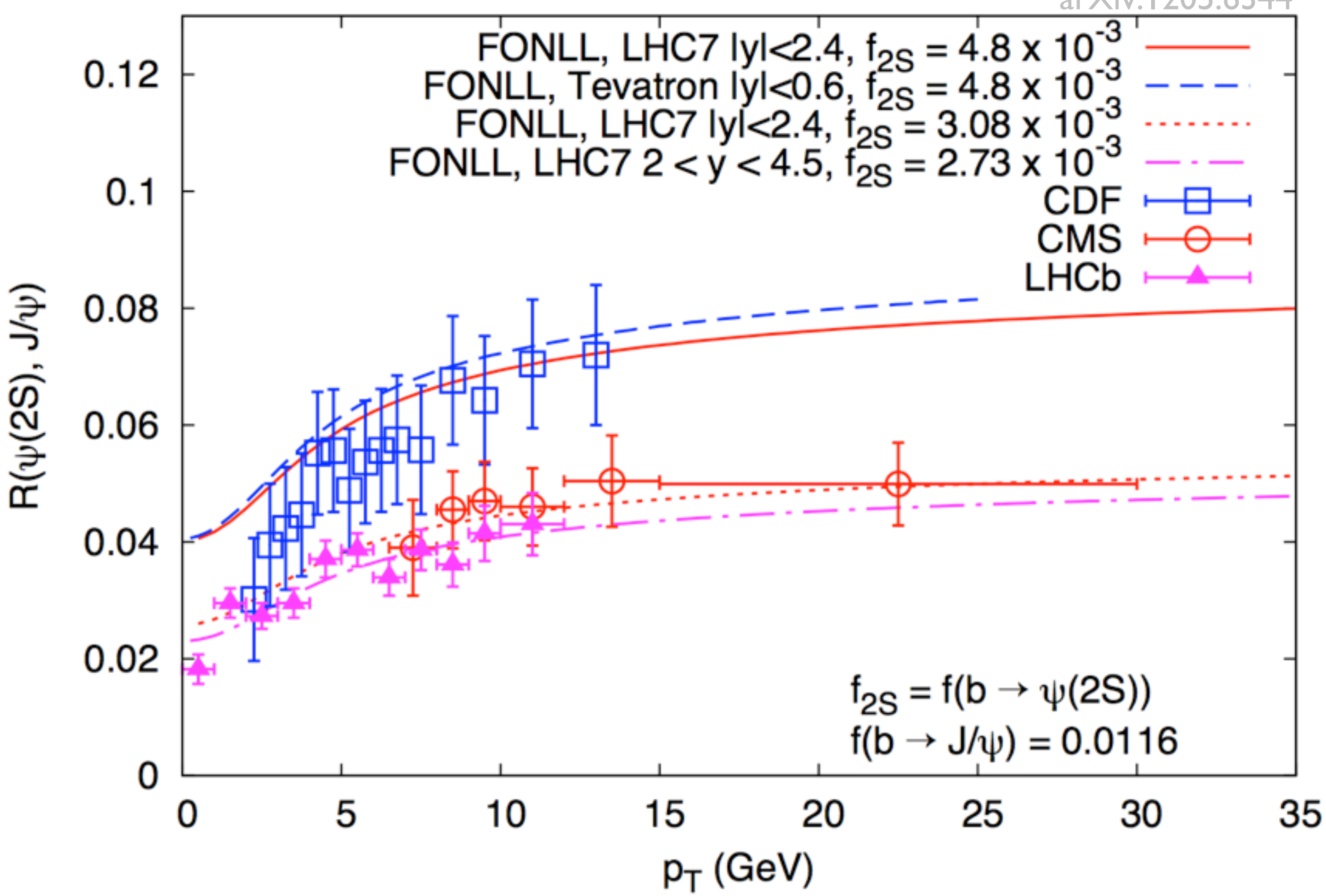



## Data/theory ratios

General good agreement within uncertainties

# Charmonium from b: J/ψ / ψ(2S) ratio

arXiv:1205.6344




CMS and LHCb in good agreement, new b→ψ(2S) ratios agree within themselves and with old one from PDG within its large error (4.8 ± 2.4)

Instead, CDF data only marginally consistent, while theory predicts no significant difference

# First lessons from LHC

- Picture successful at Tevatron and RHIC still working well

- No critical threshold apparently crossed going from Tevatron to LHC (no large small-x effects visible so far)

# Conclusions

- NLO and resummations successfully matched in various frameworks

- Predictions successful in first data. POWHEG/MC@NLO appear reliable, but NP fragmentation tuning in MCs may need more work

- These first data can only test the NLO calculation plus some rough matching with NP physics. More refined tests will need data at larger transverse momentum.