LPCC - Charm and bottom production
CERN
3/12/2010

Status of QCD predictions for heavy quark production

Matteo Cacciari
LPTHE - Paris 6,7 and CNRS

(+ paper in preparation with Frixione, Mangano, Nason, Ridolfi)

Heavy Quark production

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

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

The starting point is the 20+ years old NLO calculation

[Nason, Dawson, Ellis, '88
Beenakker et al., '91]

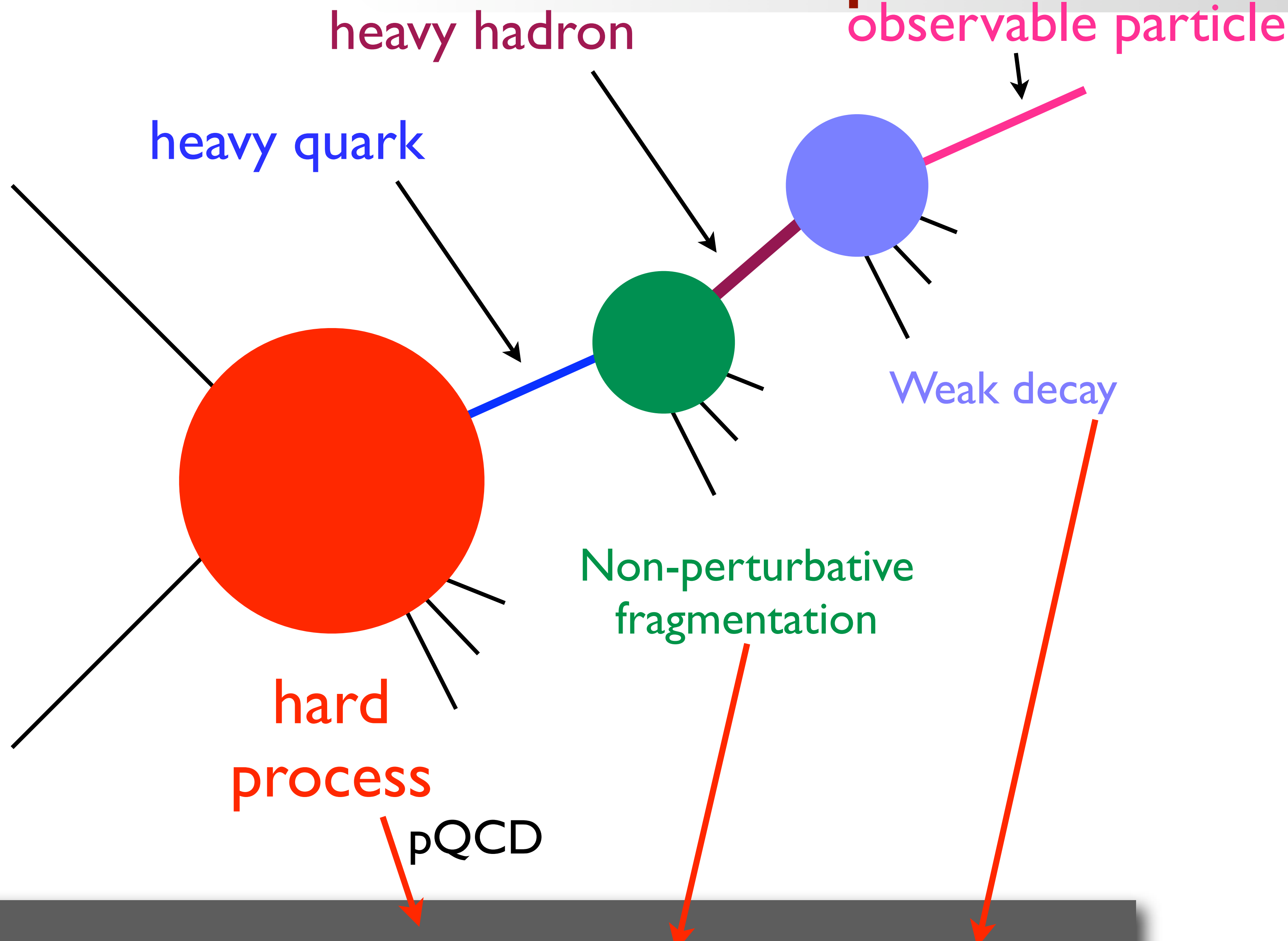
Due to the presence of a *parametrically large mass m*:

- It allows one to *predict the total cross section*
- For !(p_t >> m) differential distributions are also reliable (modulo the inclusion of a smallish non-perturbative contribution)

Any modern implementation/prediction should tend to the NLO result(*) in the small/moderate p_t limit or for total cross sections

(*) within the expected residual (i.e. NNLO) uncertainty

Sketch of inclusive production



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

How is it done?

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

- Fit remaining (small) non-perturbative contribution to data
  (usually e^+e^-, CLEO/BELLE, LEP,...)

- Set up code to calculate as realistic as possible cross sections
  (cuts, weak decays to observed particles -- **the latter typically taken from measured decay spectra**)

(Residual uncertainty usually dominated by perturbative one)

Perturbative corrections

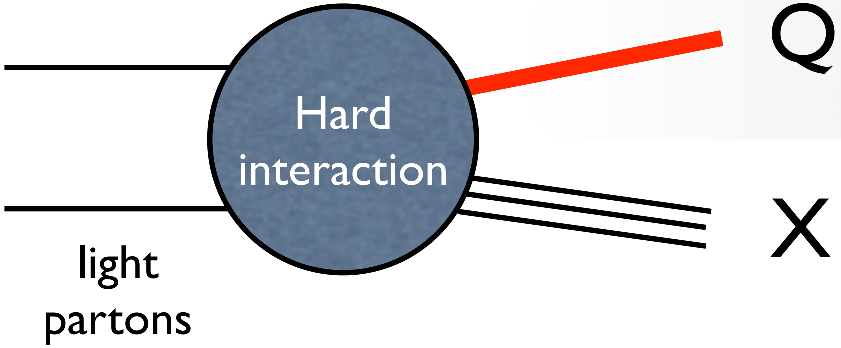
NLO + Logs (without double-counting)

- FONLL — MC, Greco '94, MC, Greco, Nason '98
  (An example of a GM-VFNS calculation. See Kniehl's talk for a different one)
- MC@NLO — Frixione, Webber '02
- POWHEG — Nason, '04

In all cases, matching between a NLO 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)

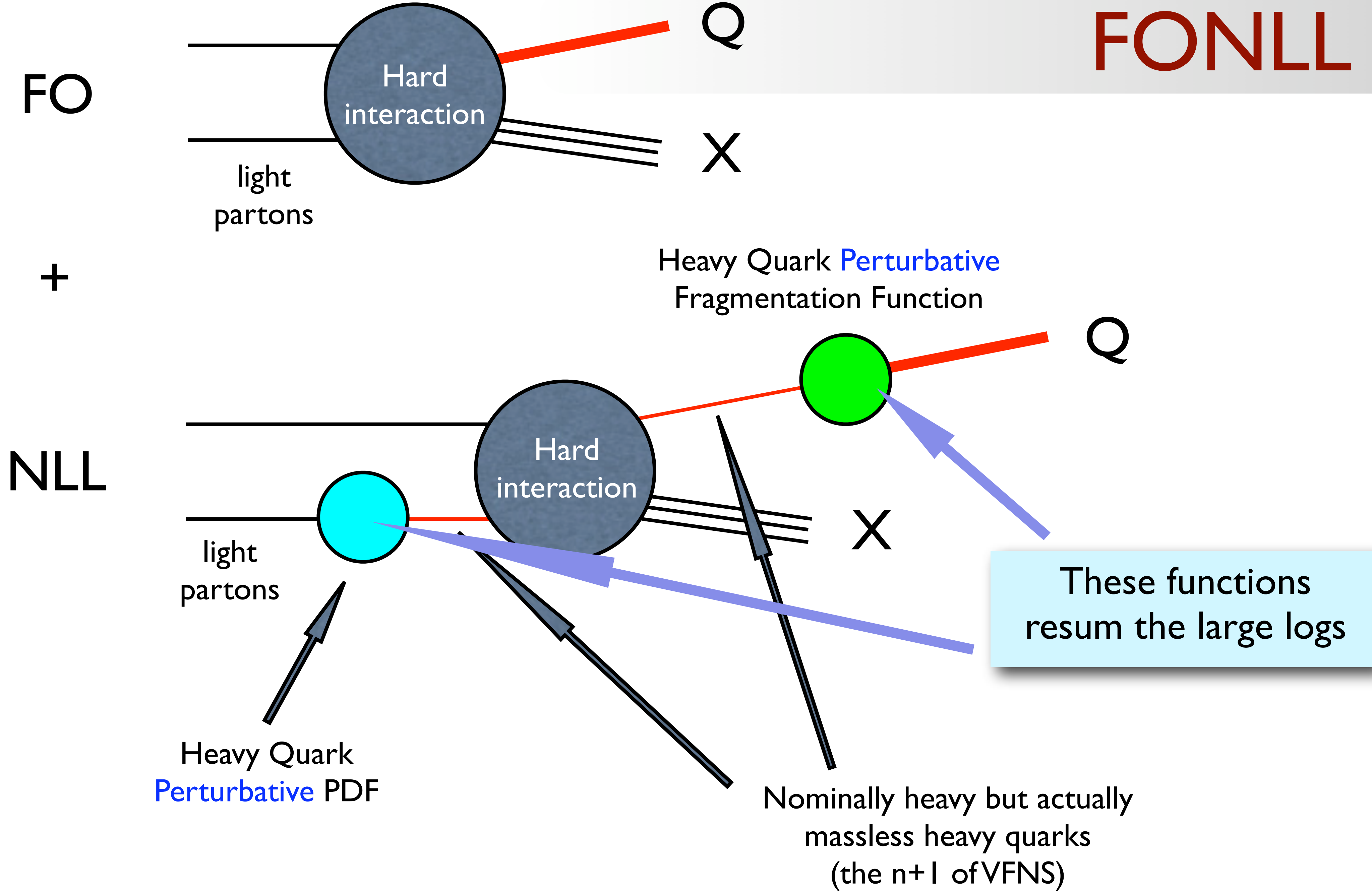
FONLL

FO



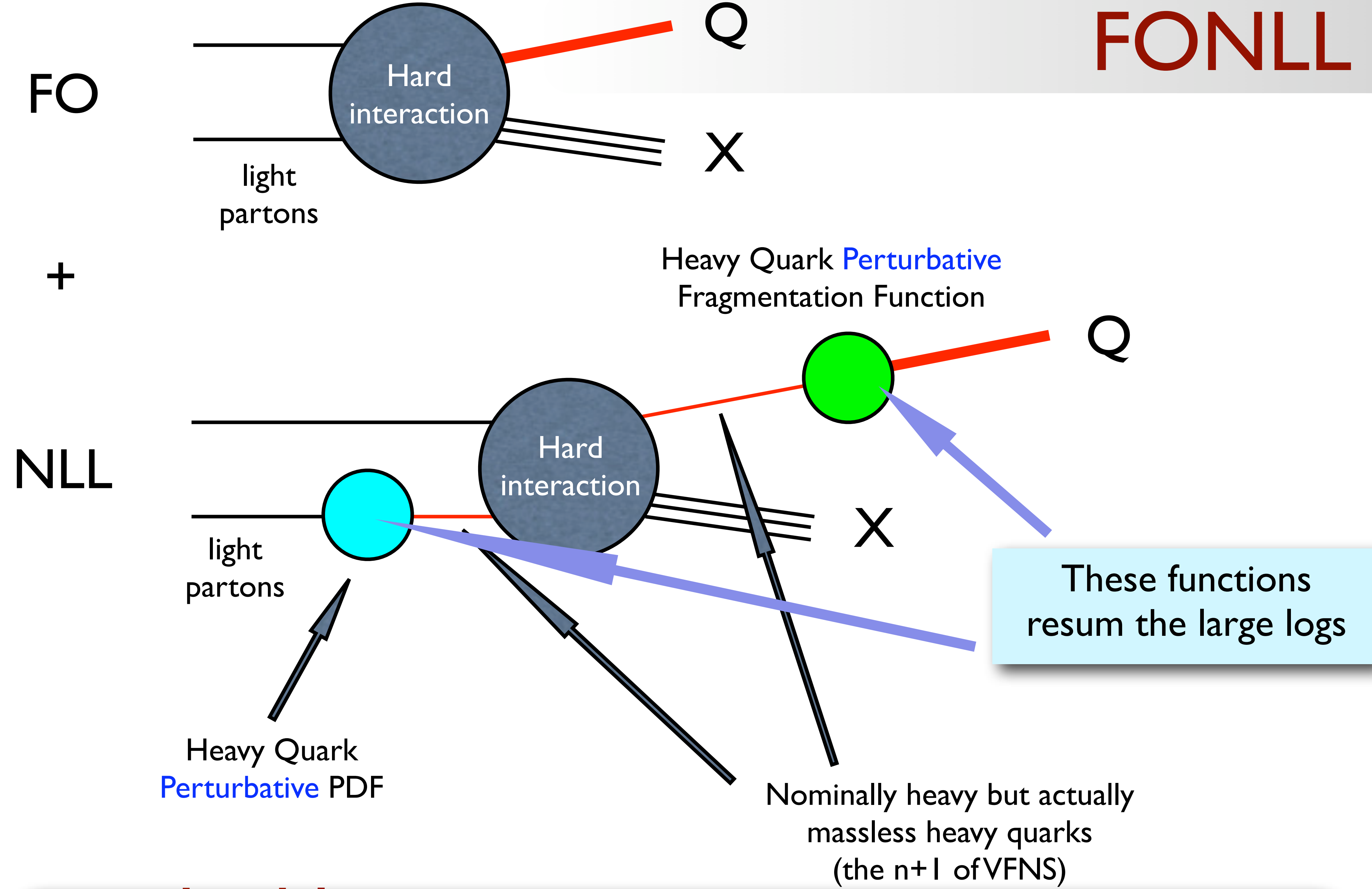
+

FONLL



FO
Hard interaction
Q
X
light partons
+
Heavy Quark Perturbative Fragmentation Function
Q
NLL
Hard interaction
X
light partons
These functions resum the large logs
Heavy Quark Perturbative PDF
Nominally heavy but actually massless heavy quarks (the n+1 of VFNS)

FONLL

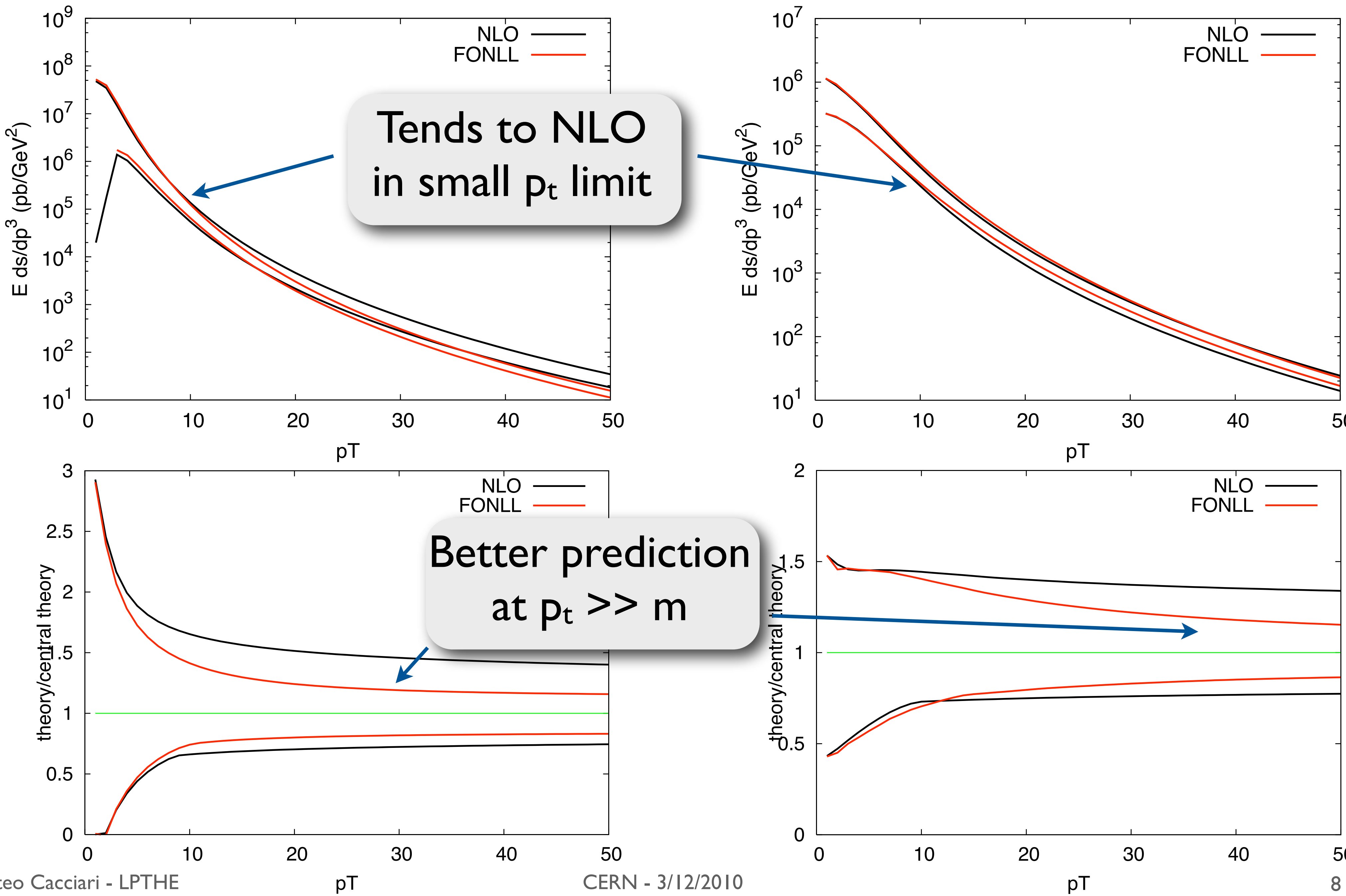


- double-counting, properly merged

(accurate at NLO+NLL)

Charm & bottom quarks @ LHC14

Charm | Bottom

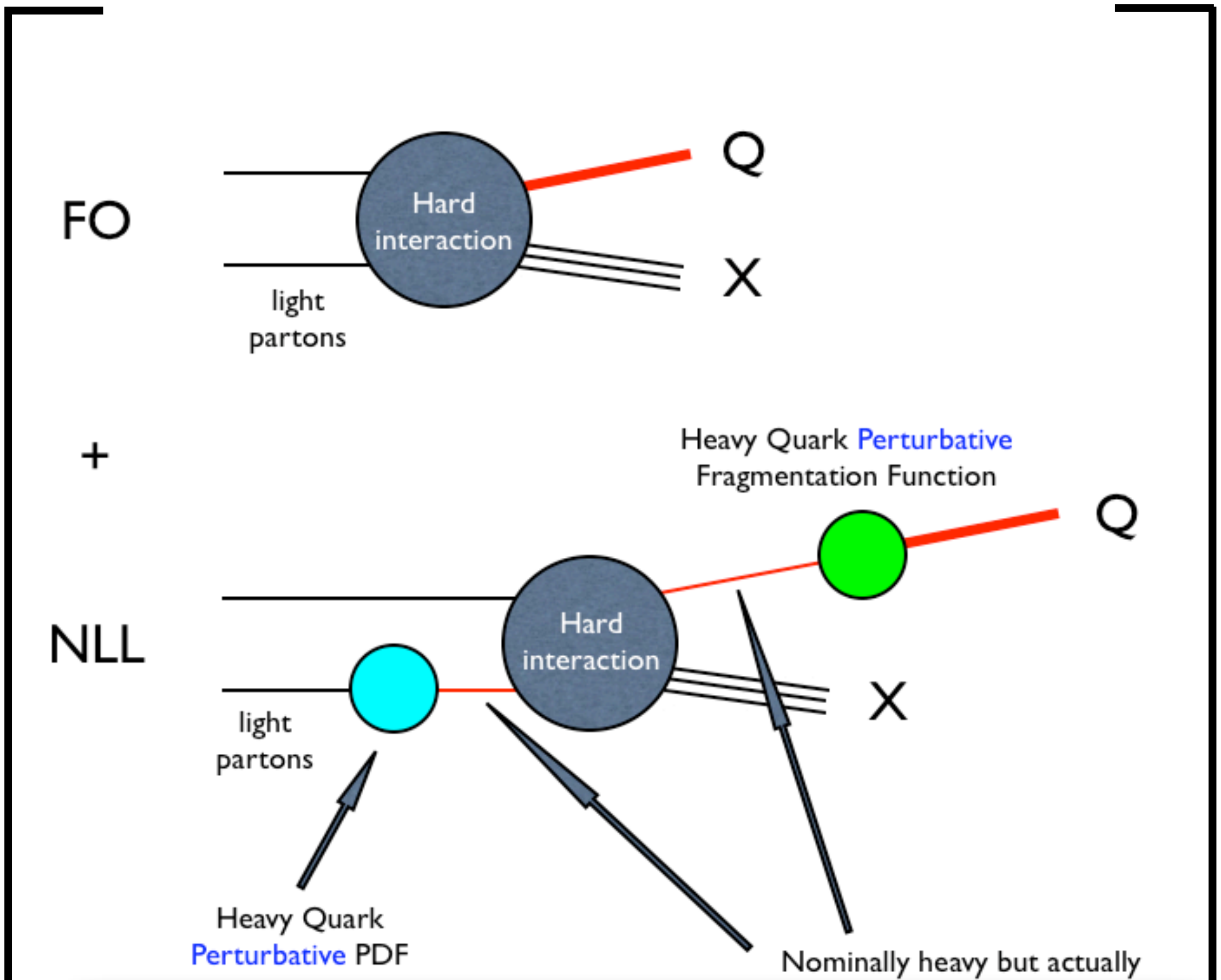


$$\frac{d\sigma_H}{dp_T} = \frac{d\sigma_Q}{dp_T} \otimes D^{np}$$

measured cross section

NLO (+NLL) calculation

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



- double-counting
(accurate at NLO+NLL)

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

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 object (factorisation theorem) which we must extract from data (e.g. pion fragmentation functions)

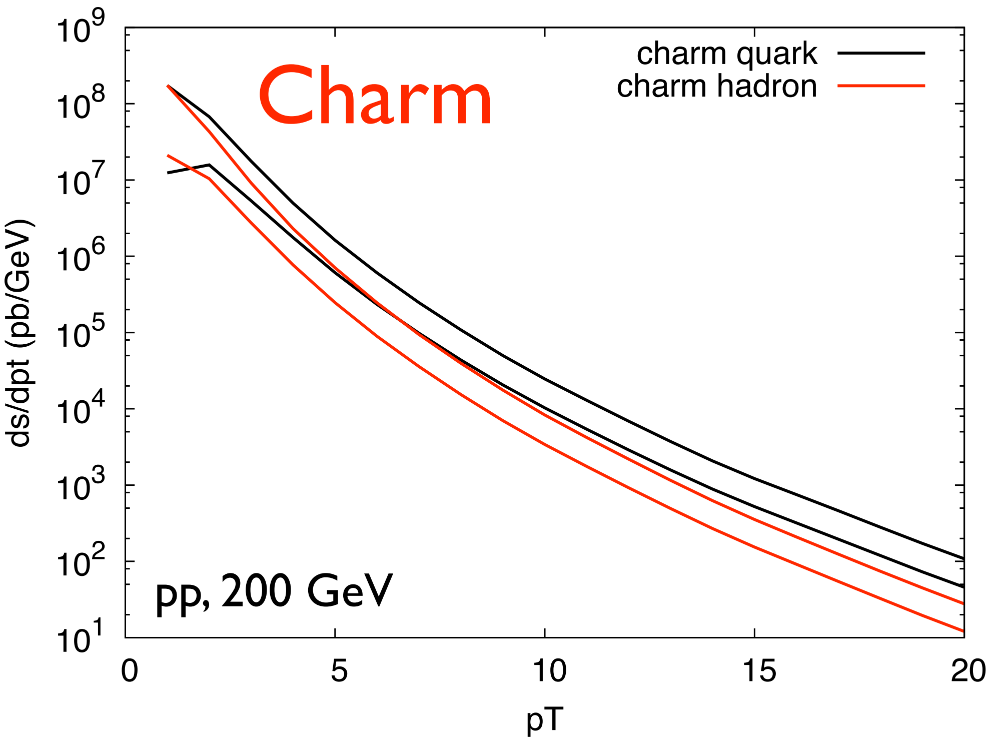
If the quark is heavy, its fragmentation function is still ambiguous, but we can tell something more about it:

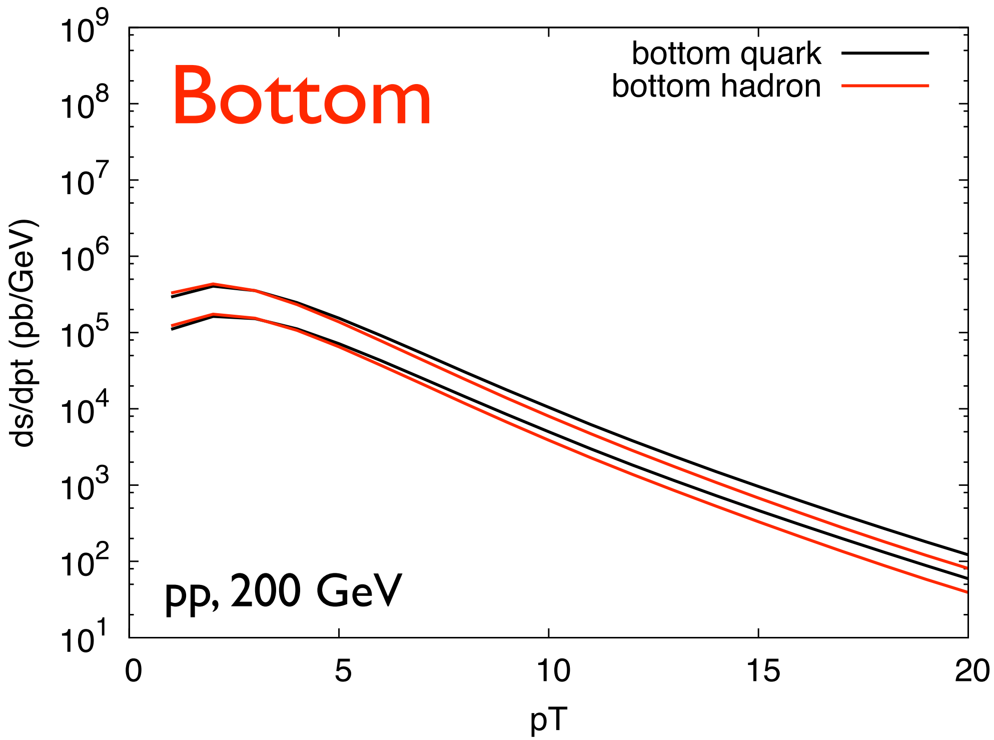
- we know it's a (parametrically) small effect, $O(\Lambda/m)$
- we can relate it to the hadronisation scale and to the heavy quark mass
- we can test this on D and B data

Effect of NP fragmentation

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**

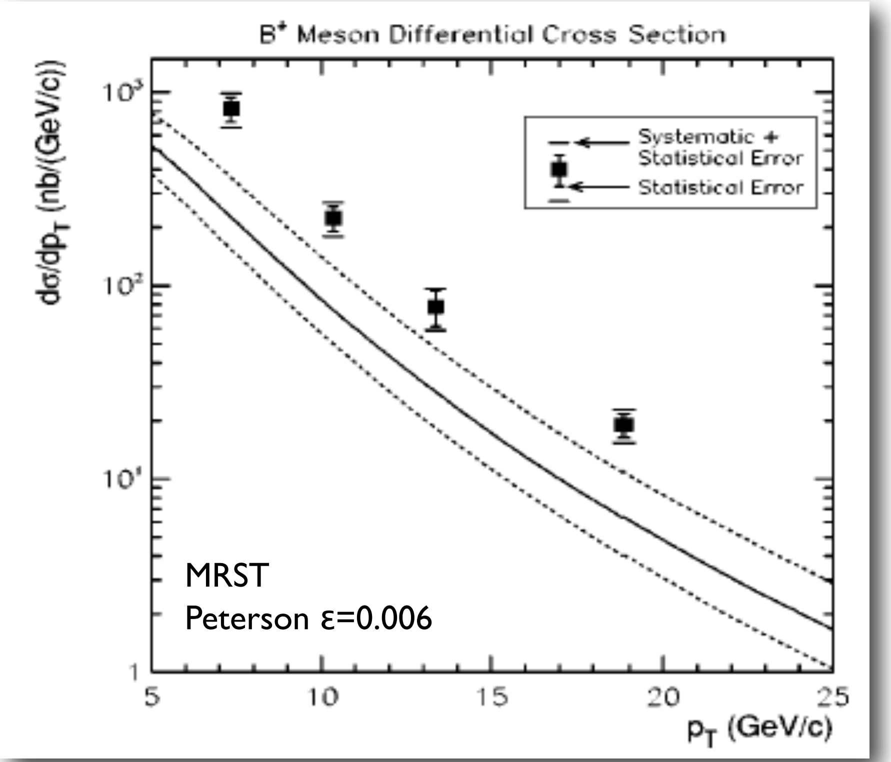


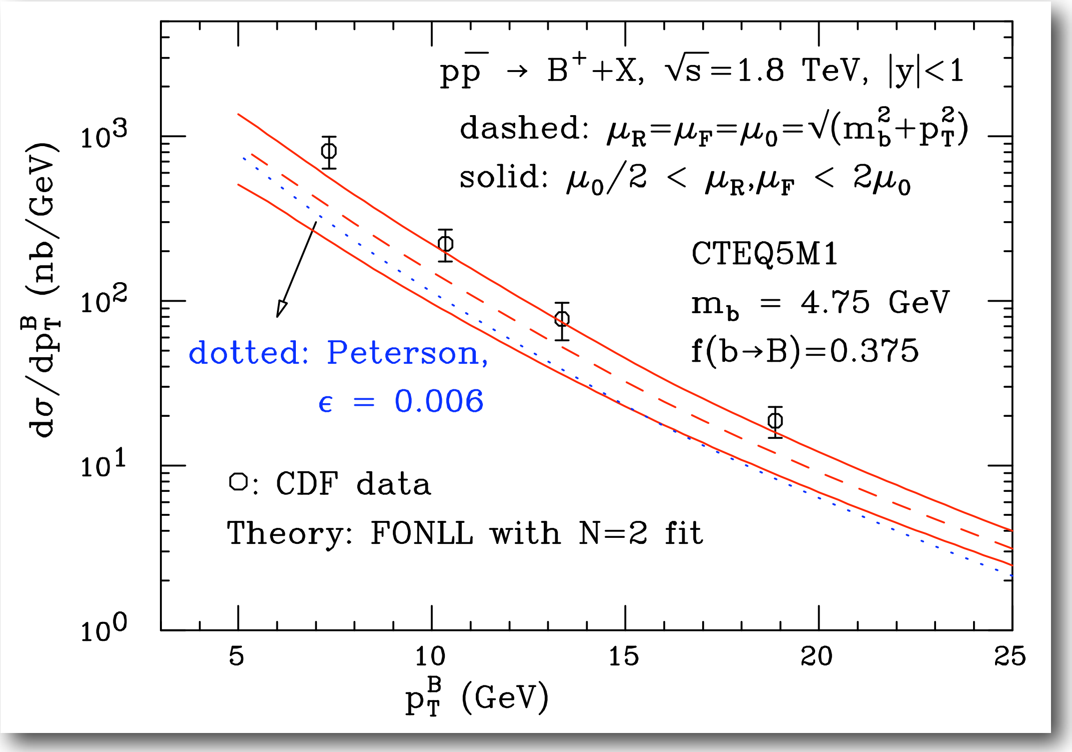


However, the non-perturbative correction is expected (and observed) to be **parametrically small, O(Λ/m)**

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

Lessons from Tevatron





Using proper inputs (PDFs, α_s) and correct fragmentation leads to an acceptable description of 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

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

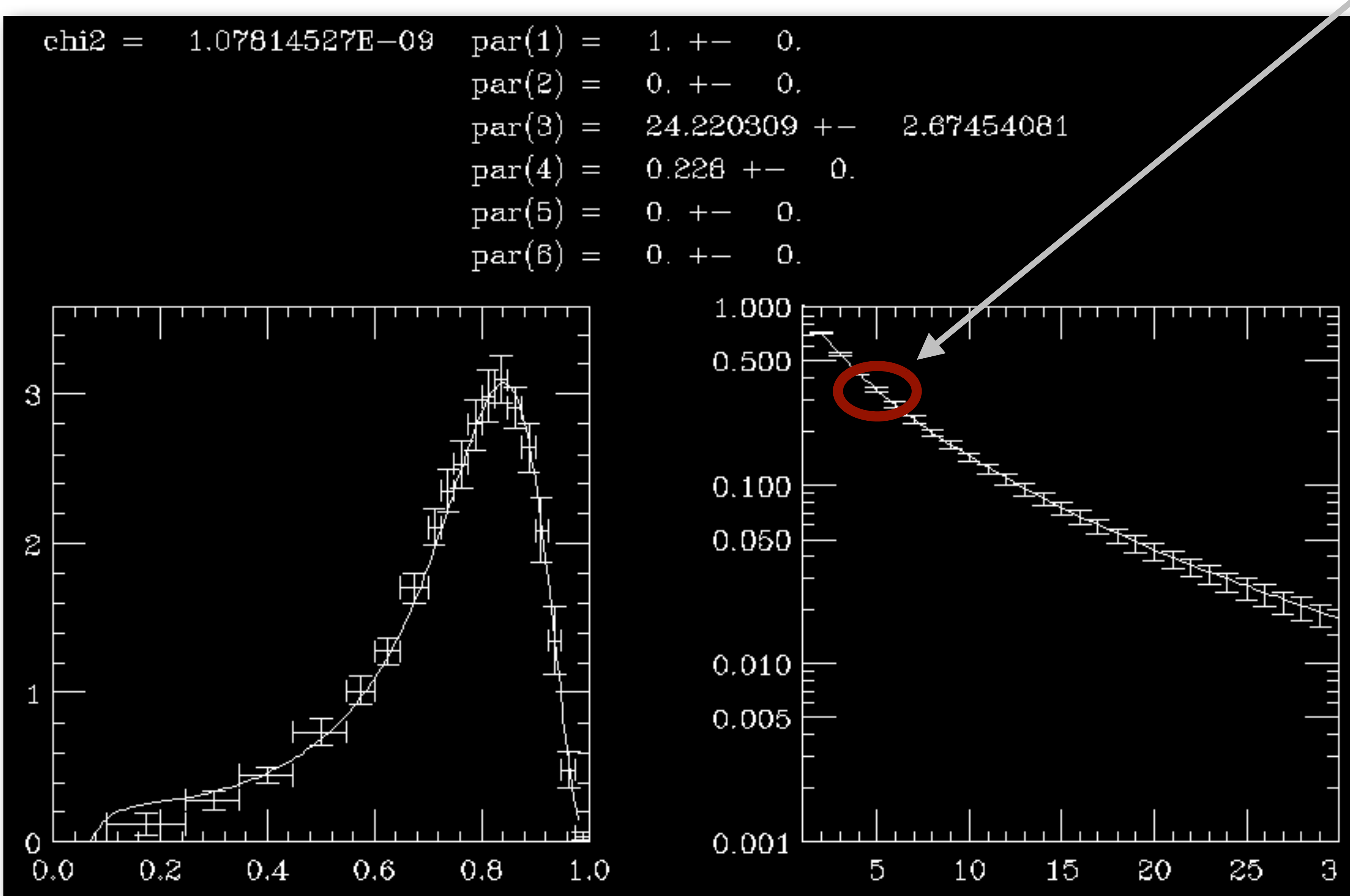
It's the ***n*th moment** of the non-perturbative fragmentation function that controls the effect of hadronisation at large transverse momentum

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

Quality of moment-space fits

ALEPH B hadrons

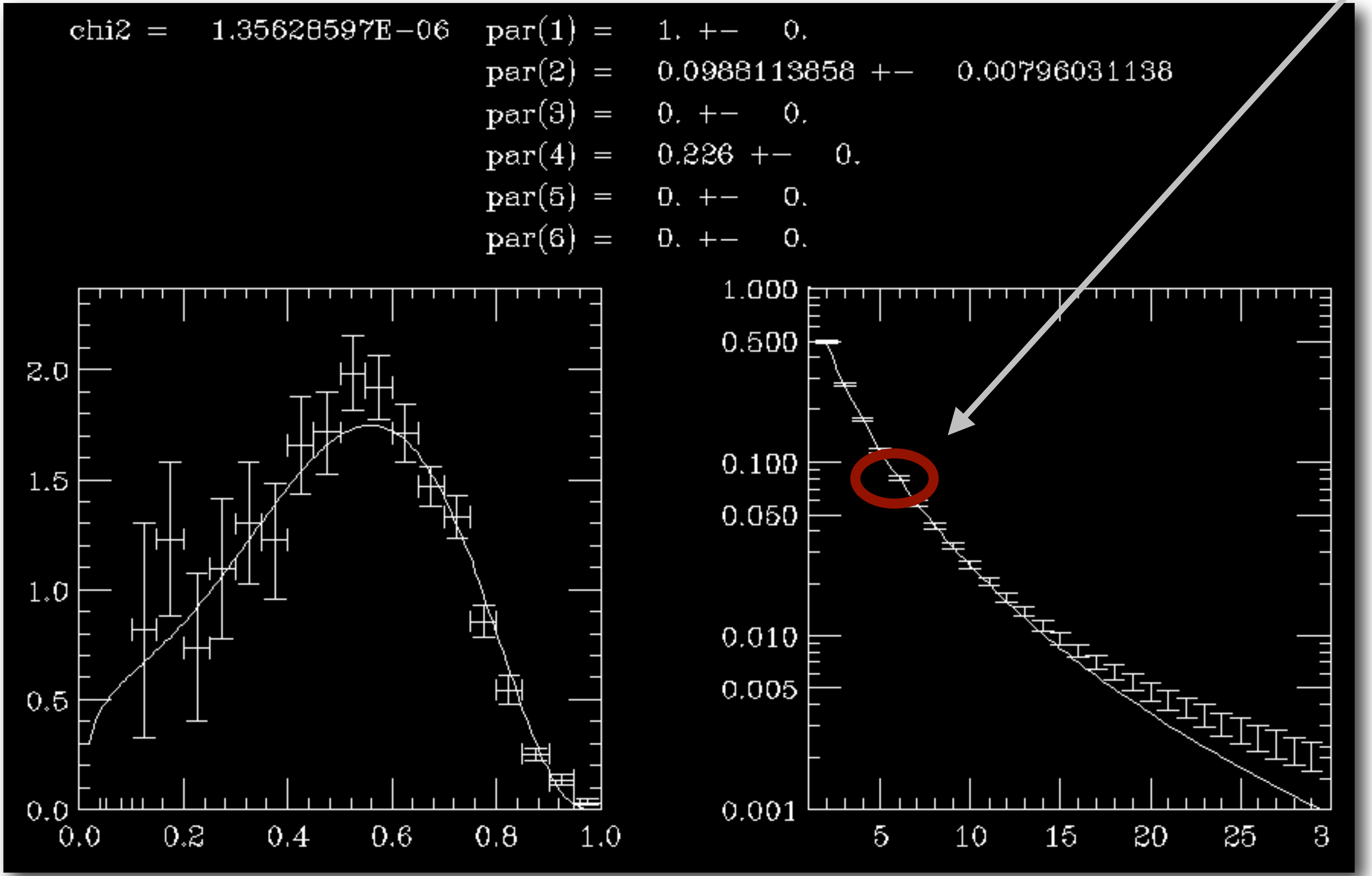
Fit to N=5



Quality of moment-space fits

ALEPH D^{*+} hadrons

Fit to N=5



Theoretical uncertainties

Scales, masses and PDFs

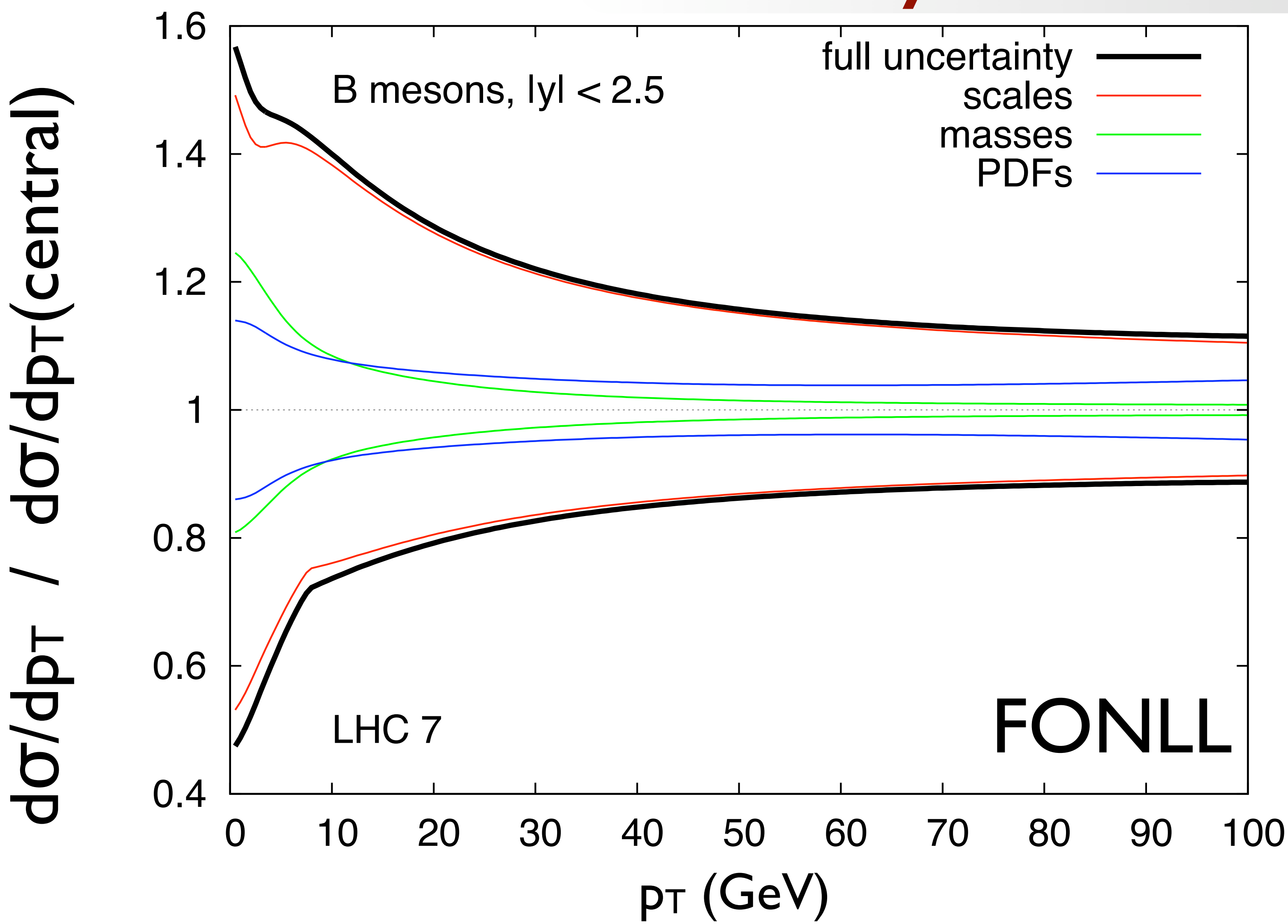
- Renormalisation and factorization scales varied ***independently*** in the range $1/2 < \mu/m_T < 2$, with the *additional constraint* $1/2 < \mu_R/\mu_F < 2$

- masses varied as (4.5, 4.75, 5) GeV for bottom, (1.3,1.5, 1.7) GeV for charm. Non perturbative parameters fitted accordingly.

- PDF uncertainties calculated from the usual N ‘plus’ and ‘minus’ eigenvectors of the PDF set (CTEQ6.6 in this case)

These three uncertainties summed in quadrature

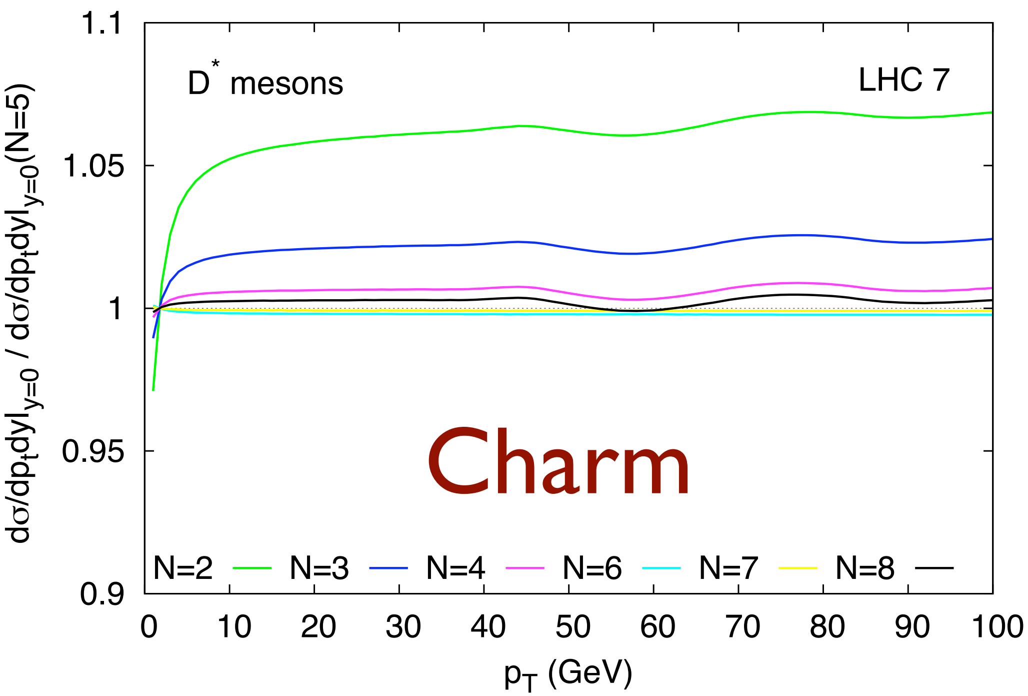
Anatomy of uncertainty

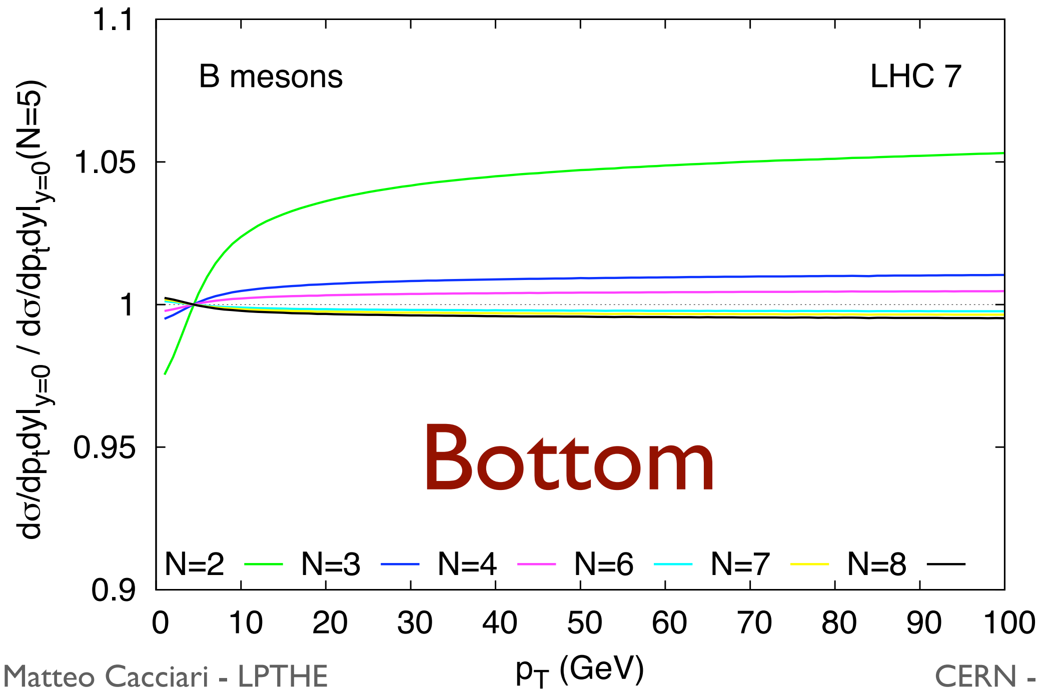


Typically dominated by scales uncertainty

What about the uncertainty from NP fragmentation?

Choice of non-perturbative parameter



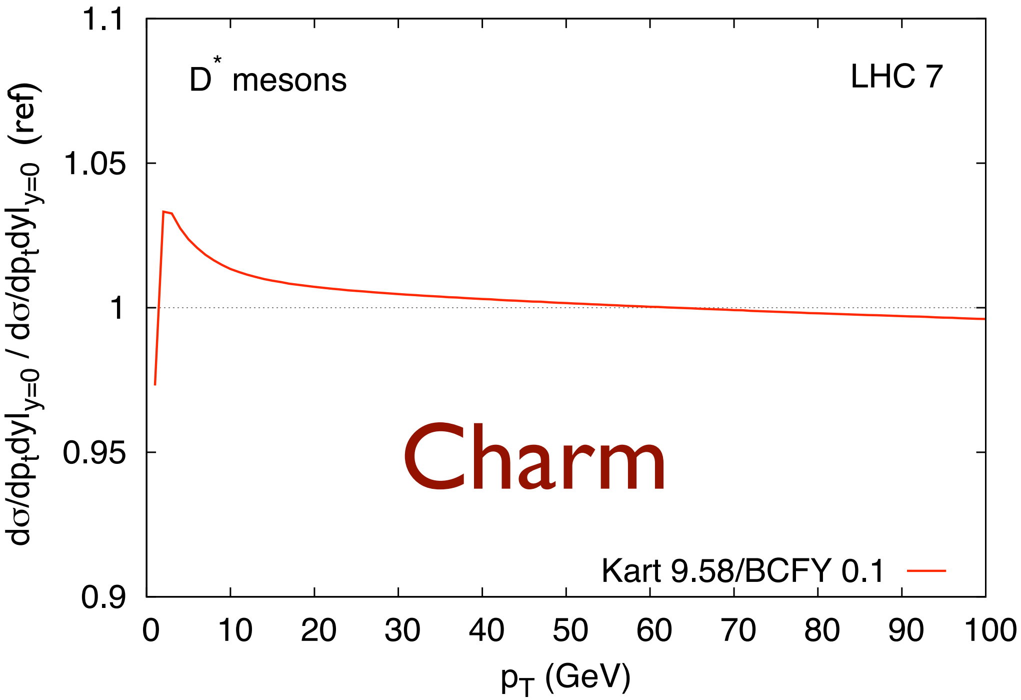


Using the **N=2** fit in place of the **N=5** one gives at most a **~5%** difference

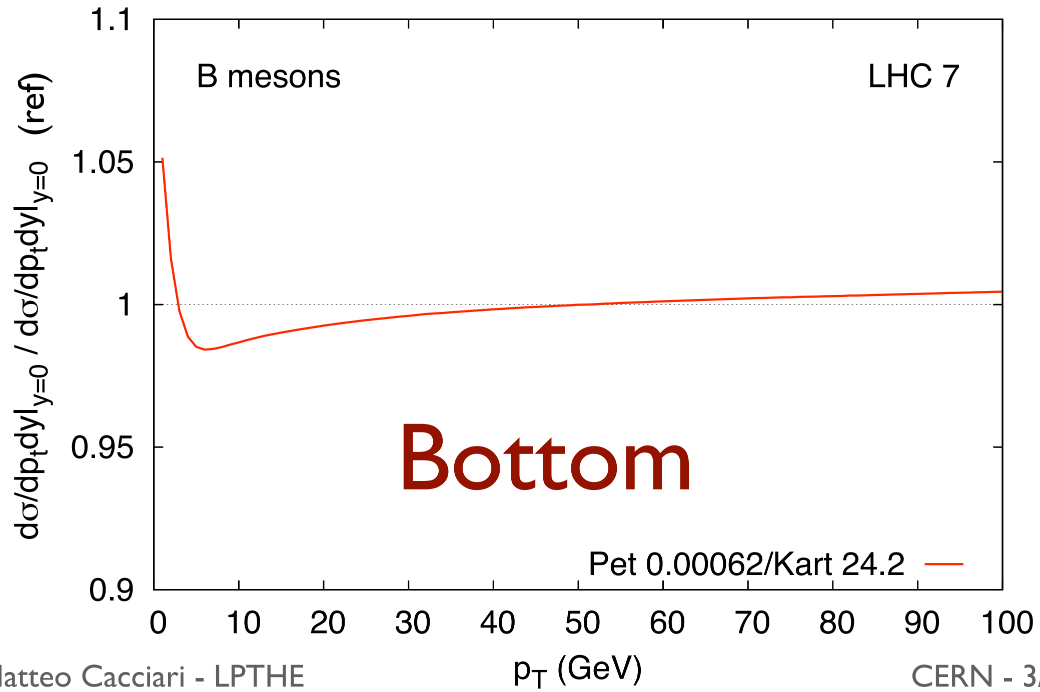
Other choices only result in O(1%) differences

The shape of the p_t distribution is largely unaffected by the choice

Choice of non-perturbative form



$$\frac{\text{Kartvelishvili } \alpha=9.58}{\text{BCFY } r=0.1}$$



$$\frac{\text{Peterson } \varepsilon=0.00062}{\text{Kartvelishvili } \alpha=24.2}$$

Did experimentalists and theorists converge?

Talk in BNL - 2005
Still actual today

Not much room to wiggle around:

The NLO calculation has been around for 15 years. With the addition of the NLL resummation, its perturbative uncertainty at large transverse momentum is not larger than a few 10% (+5)

The uncertainty from the PDFs should be fairly constrained. Say 10-15% — Probably quite smaller today

The non-perturbative fragmentation contribution is tightly constrained by e+e- data. It is definitely known to better than 10% — Make it a few %

So, at large transverse momenta, where the theoretical framework is better under control, the overall uncertainty of the theoretical prediction should be smaller than 40-50%. → Quite conservative. Make it less than 20%

==> No room for factors of three discrepancies

(BTW: the expt. accuracy is actually often better than the theoretical one!)

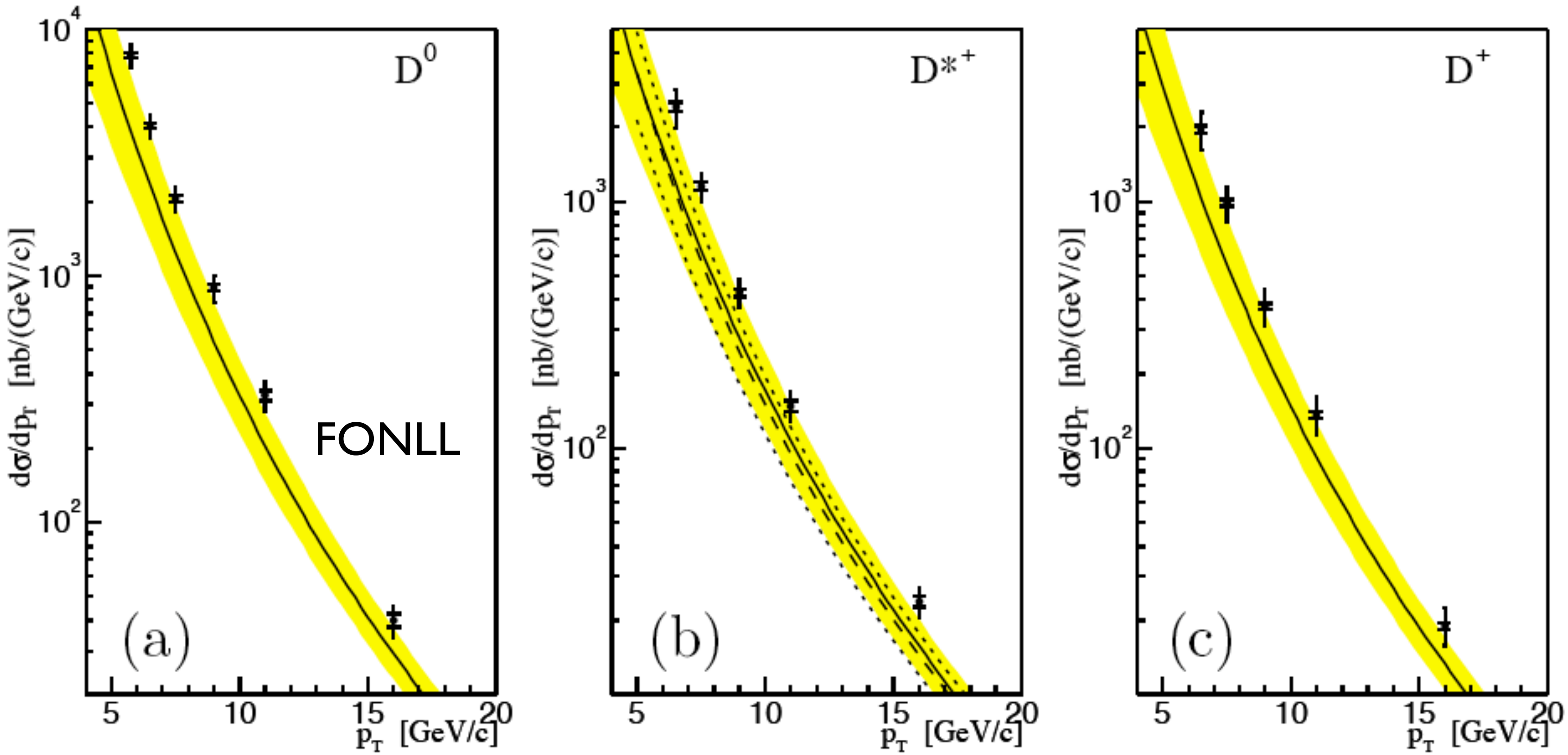
Results

Time stability

- The FONLL framework has not significantly changed since 1998:
  - Successful description of Tevatron bottom data in 2002
  - Most recent non-perturbative fits in 2005, consistent with what had been used before

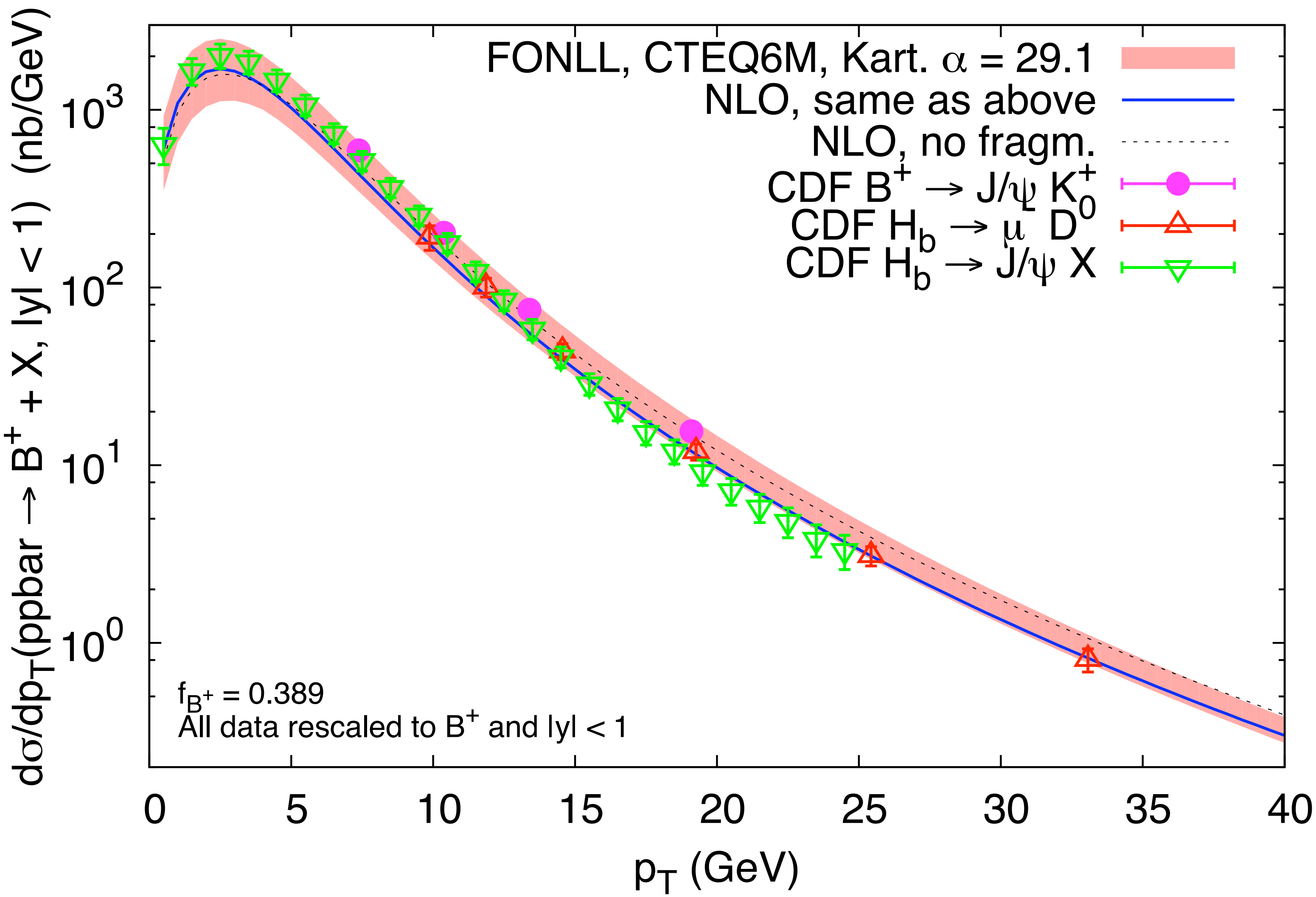
Everything still actual today:
will use framework unchanged at the LHC

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.

bottom @ Tevatron

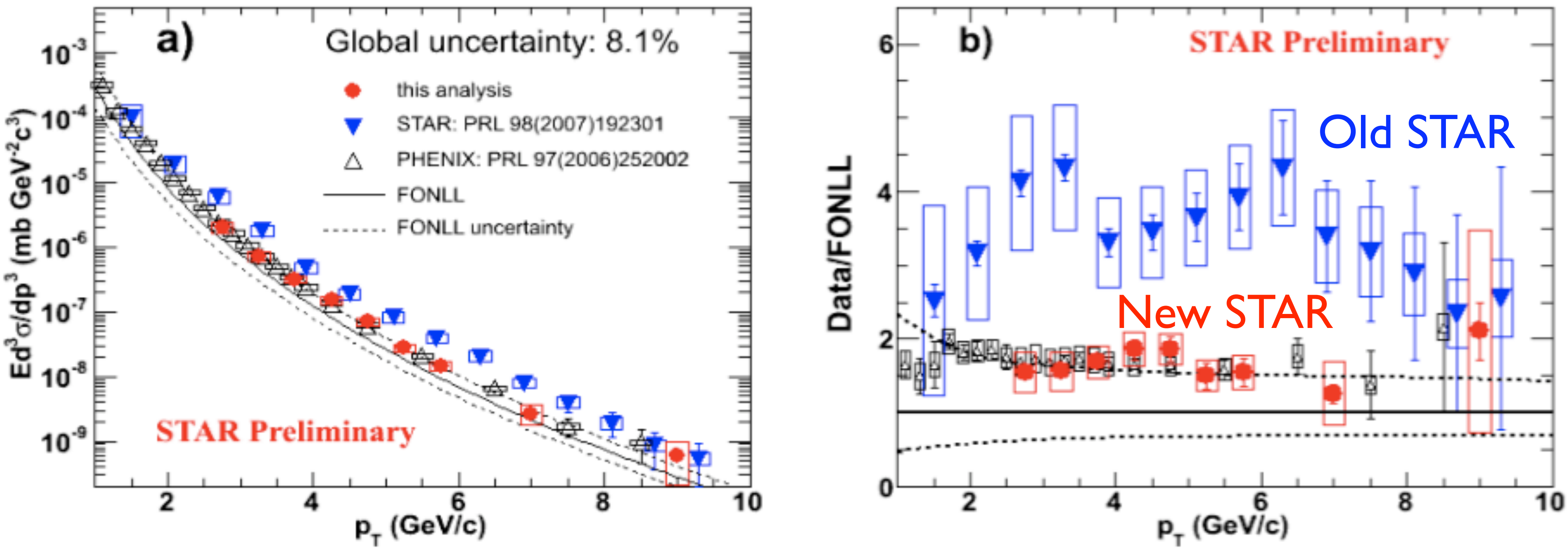


Good agreement, with minimal non-perturbative correction

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

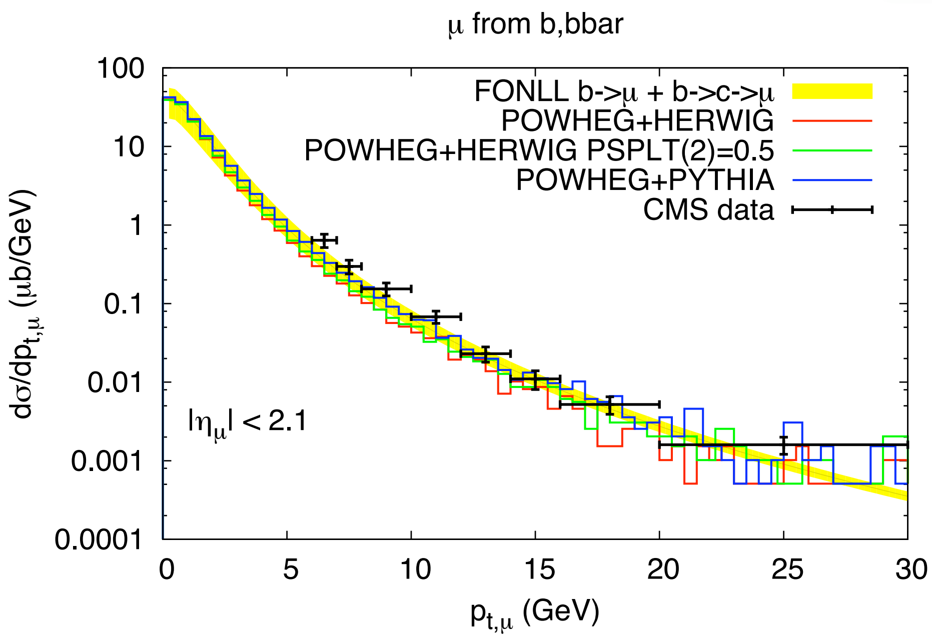
- NLO QCD predicts correctly the ‘total’ heavy quark bottom cross sections

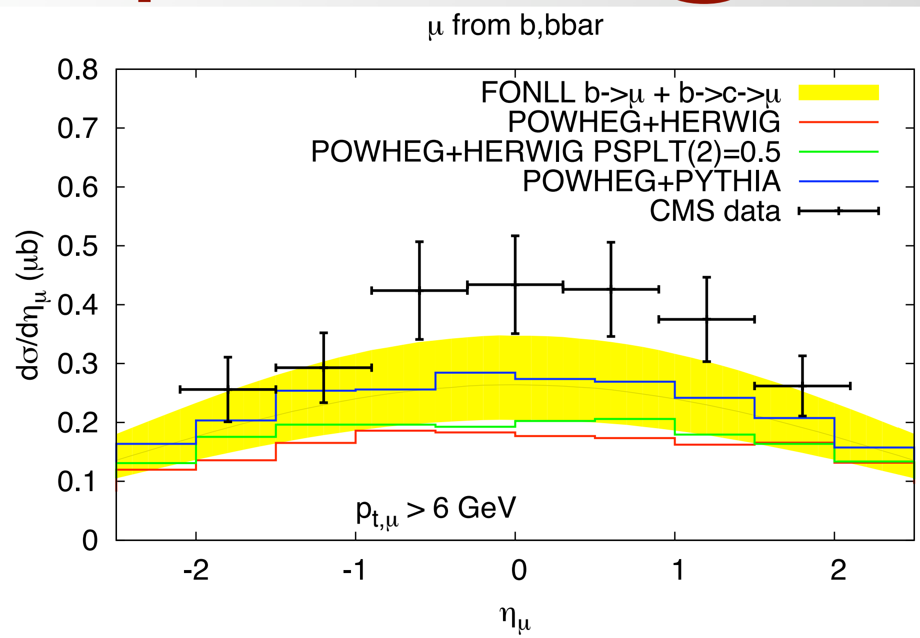
- FONLL with non-perturbative fragmentation extracted from CLEO/BELLE and LEP describes correctly the differential distributions

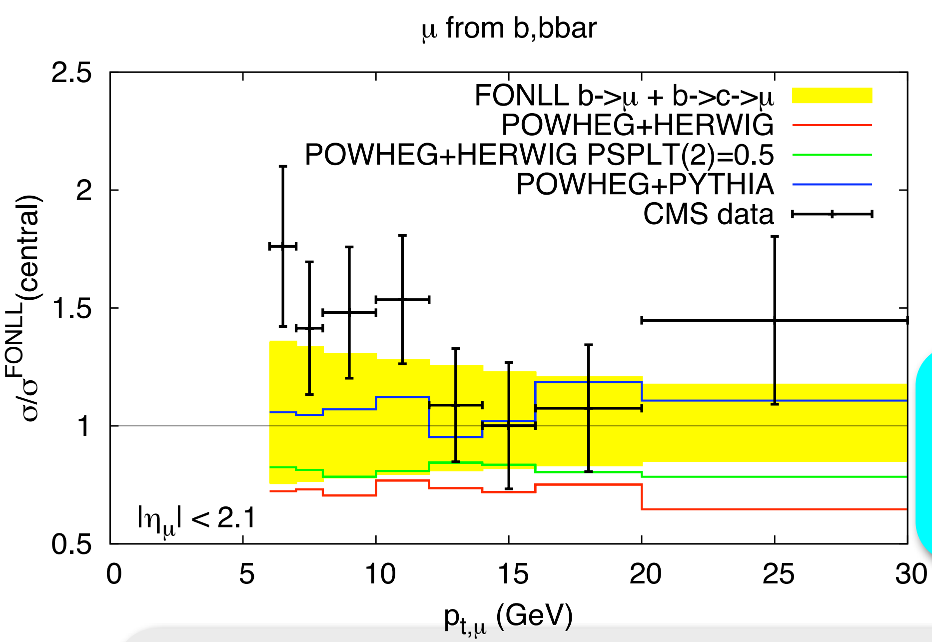
First results from LHC

μ from B @ CMS

CMS PAS BPH-10-007







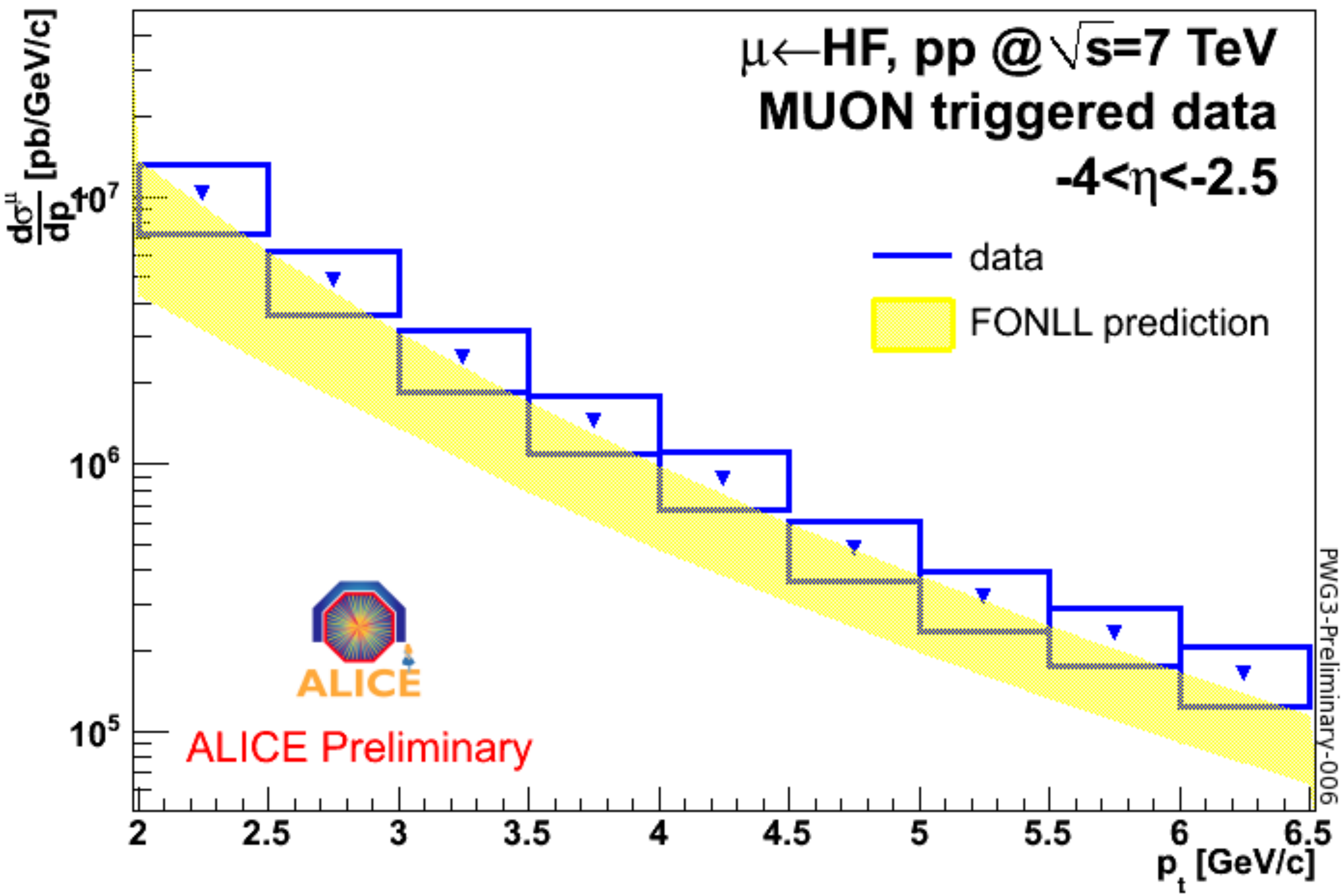
- FONLL and POWHEG+PYTHIA perfectly compatible
- CMS slightly high, but compatible within uncertainties

FONLL

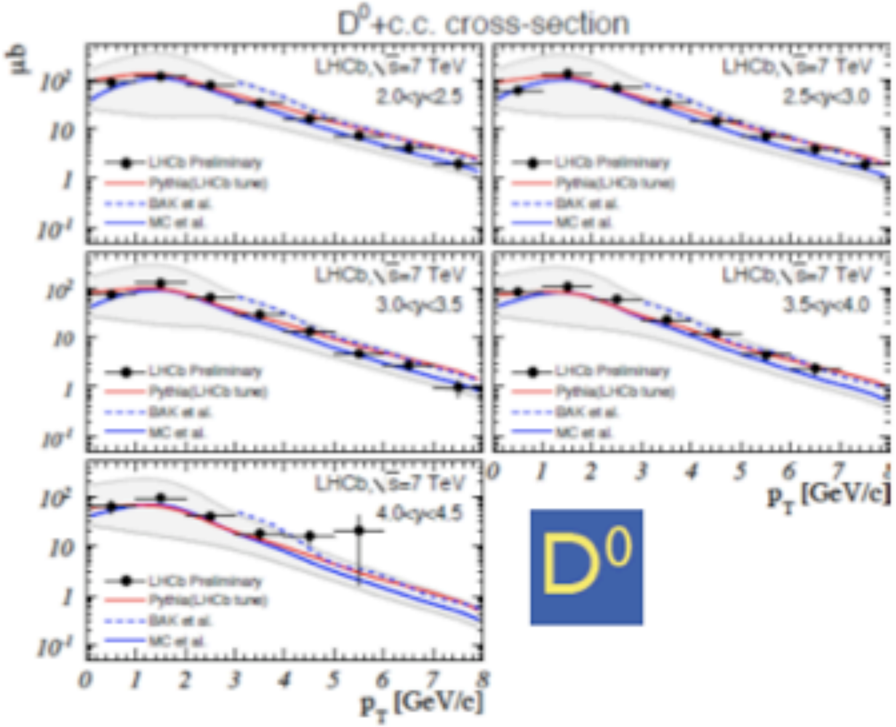
$0.97\ ^{+0.31}_{-0.22}$ (scales/masses) $\pm$ 0.06 (PDFs) μb

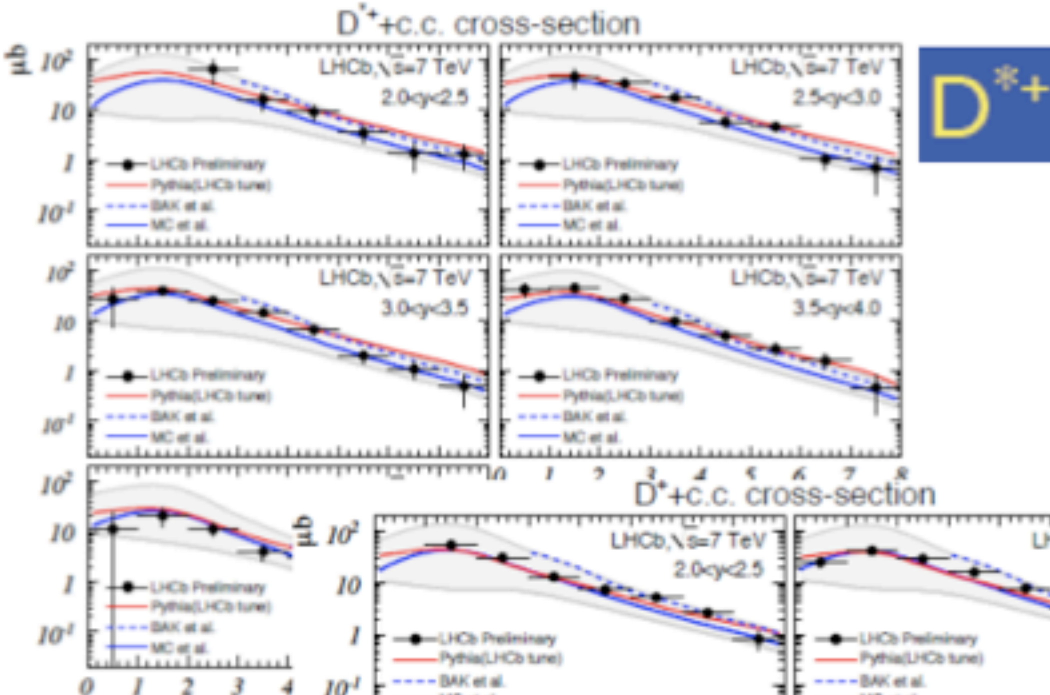
$$\sigma(pp \to b + X \to \mu + X', p_\perp^\mu > 6\,\mathrm{GeV}, |\eta^\mu| < 2.1) = (1.48 \pm 0.04_{\mathrm{stat}} \pm 0.22_{\mathrm{syst}} \pm 0.16_{\mathrm{lumi}})\ \mu\mathrm{b}.$$

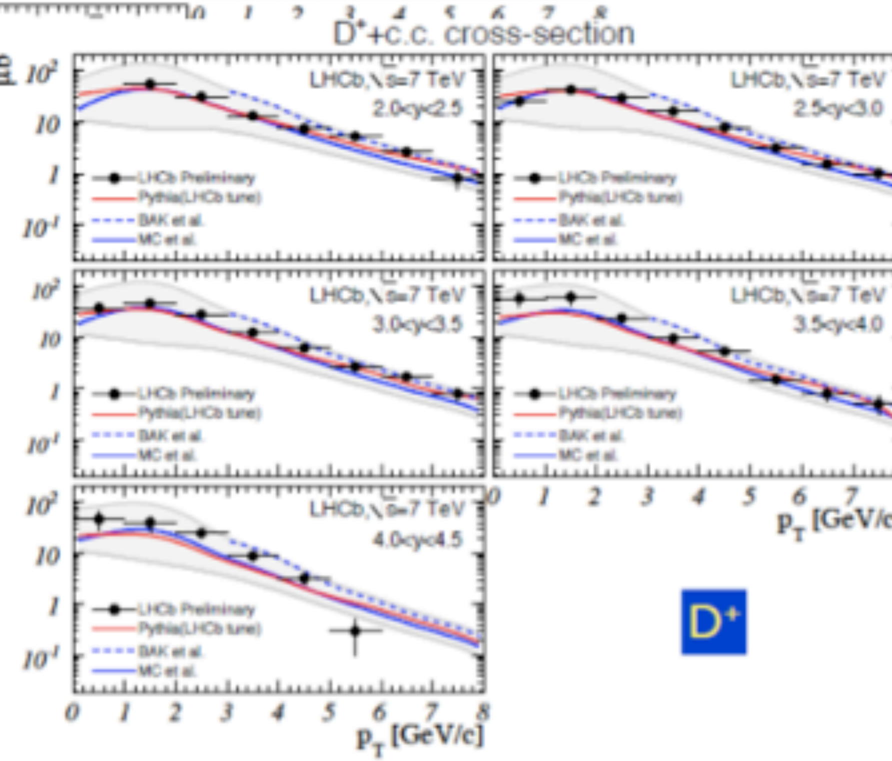
μ from HF @ ALICE



Open charm cross-sections





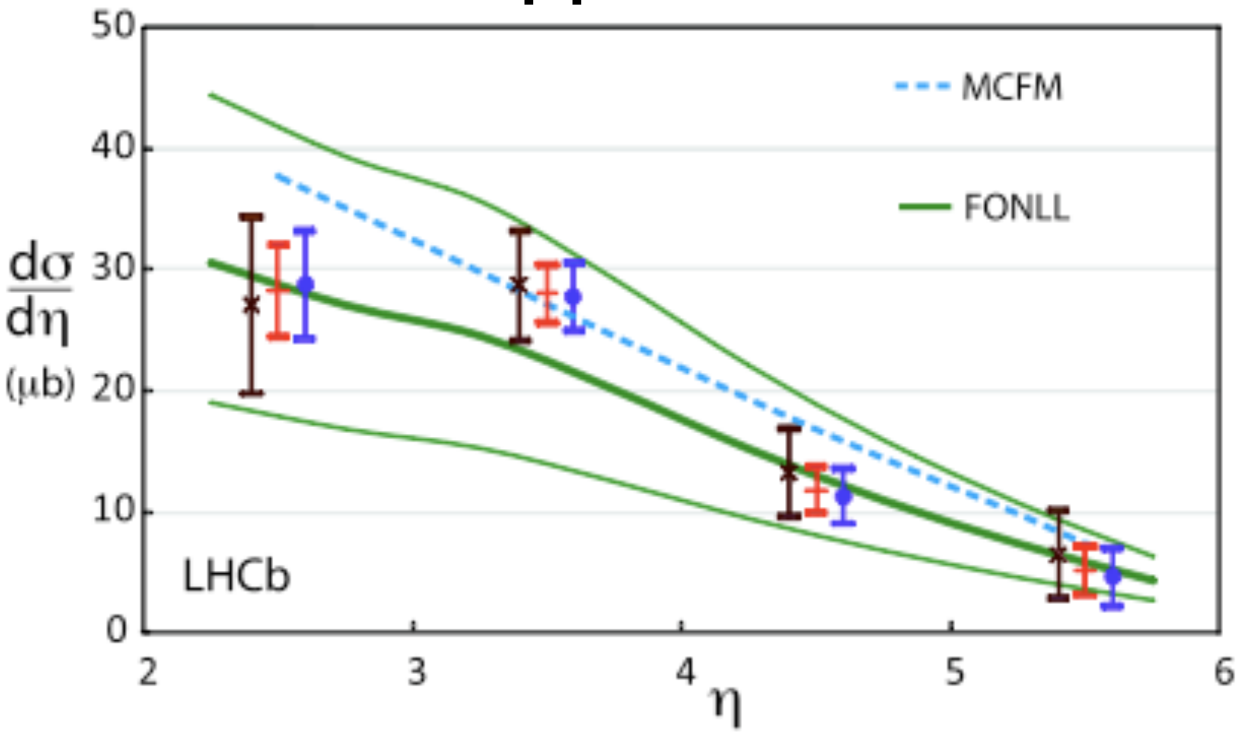


Extrapolating to all p_T and 4 can also confirm the expectation on ratio at $\sqrt{s}$=7TeV

$(pp \rightarrow c\bar{c}X) \approx 20 \times (pp \rightarrow b\bar{b}X)$

→ Good news for LHCb charm program

$pp \rightarrow H_b X$



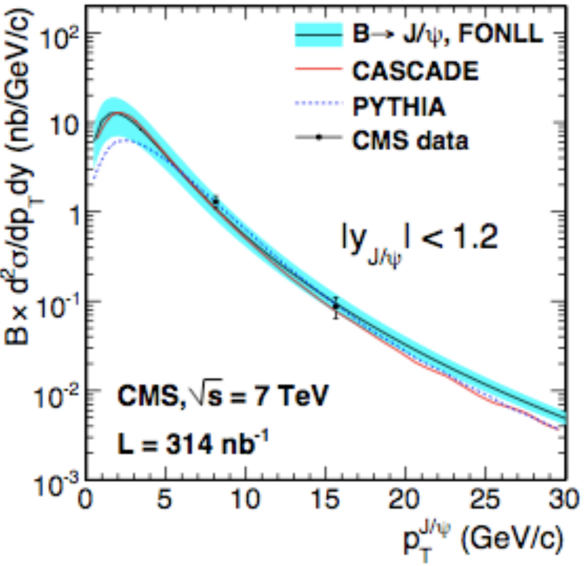
LHCb Collab. arXiv:1009.2731

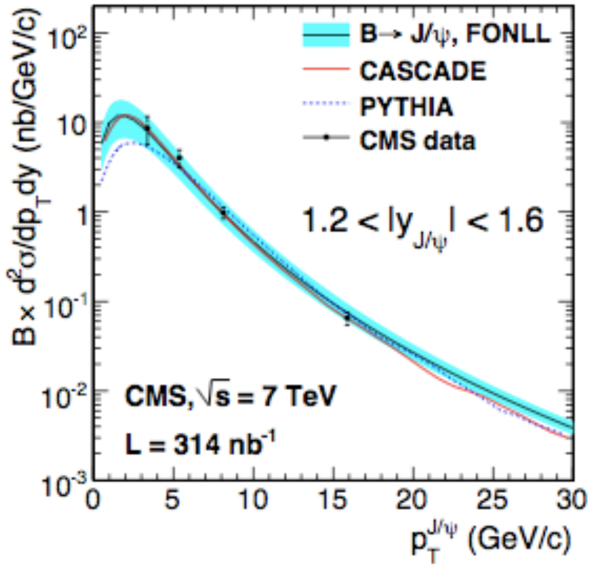
$$\sigma(pp \to H_b X) = (75.3 \pm 5.4 \pm 13.0)\ \mu b$$

[2 < η < 6]

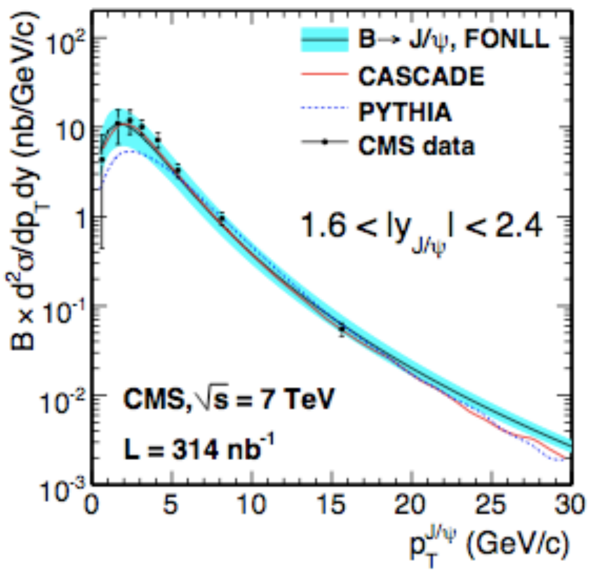
FONLL: $71\ ^{+33}_{-26}$ (scales) $^{+10}_{-12}$ (mass) $\pm$ 7 (PDFs) μb

J/ψ from B @ CMS





CMS Collab. arXiv:1011.4193



FONLL

$23.5\ ^{+8.3}_{-5.7}$ (scales/masses) ± 1.7 (PDFs) nb

$$\sigma(\mathrm{pp} \to bX \to \mathrm{J}/\psi X) \cdot \mathrm{BR}(\mathrm{J}/\psi \to \mu^+\mu^-) = 26.0 \pm 1.4\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst}) \pm 2.9\,(\mathrm{luminosity})\ \mathrm{nb}$$

First lessons from LHC

- Picture successful at Tevatron and RHIC still working very well

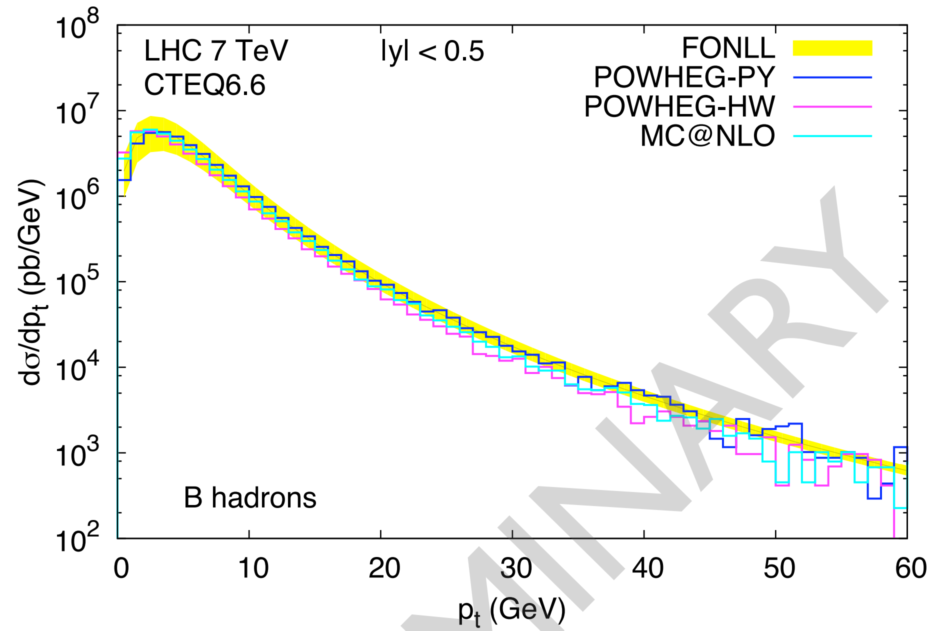
- No critical threshold apparently crossed going from Tevatron to LHC (no large small-x effects visible so far)

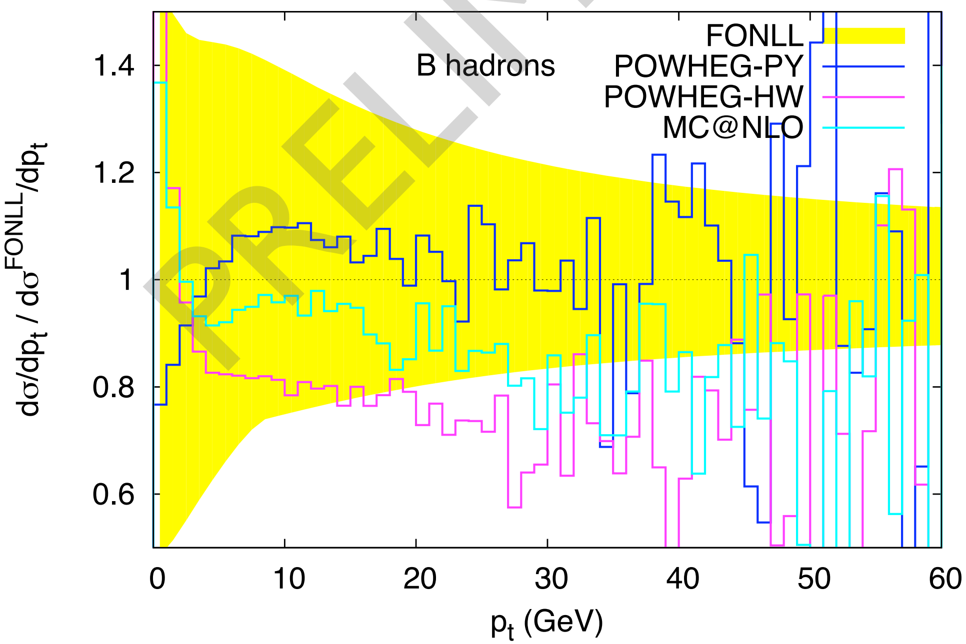
FONLL, MC@NLO, POWHEG

- Detailed comparisons of predictions of FONLL, MC@NLO and POWHEG is in progress

- A paper (MC, Frixione, Mangano, Nason, Ridolfi) presenting this work, and specific predictions for the four LHC experiments, is expected do appear (soon?)

FONLL, MC@NLO, POWHEG





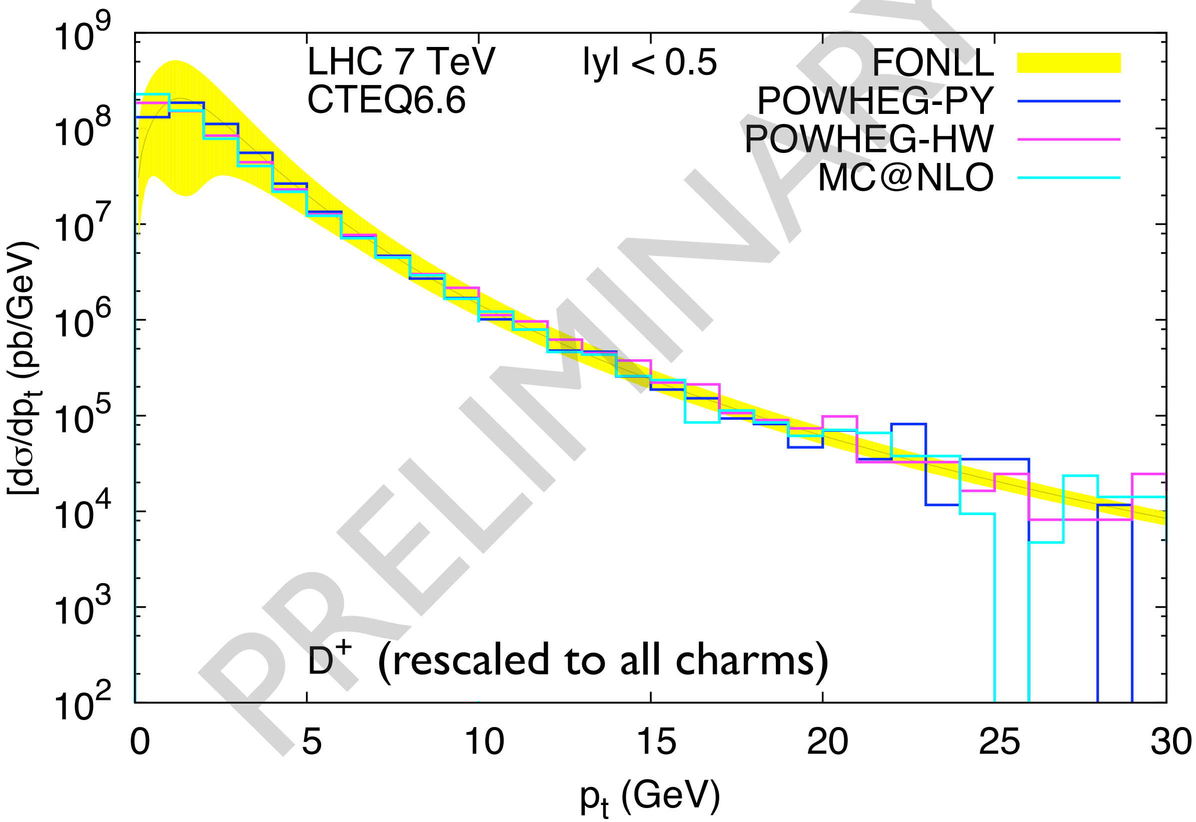
- POWHEG and MC@NLO in good agreement with FONLL
- POWHEG+PYTHIA in *excellent* agreement

(Similar results hold at non-central rapidities)

Not that fragmentation in the Montecarlos has NOT been tuned to data as precisely as in FONLL. This may hold the key to the residual differences

FONLL, MC@NLO, POWHEG

Situation for charmed hadrons production largely similar



Agreement within O(10-20%)

Conclusions

Conclusions

- NLO and resummations successfully matched in various frameworks: normalization is a genuine prediction.

Conclusions

- NLO and resummations successfully matched in various frameworks: normalization is a genuine prediction.
- Non-perturbative contributions under control. Residual uncertainties mainly of perturbative origin.

Conclusions

- NLO and resummations successfully matched in various frameworks: normalization is a genuine prediction.
- Non-perturbative contributions under control. Residual uncertainties mainly of perturbative origin.
- Predictions successful in early data. POWHEG/MC@NLO appear reliable, but NP fragmentation tuning in Montecarlo may need more work

Conclusions

- NLO and resummations successfully matched in various frameworks: normalization is a genuine prediction.
- Non-perturbative contributions under control. Residual uncertainties mainly of perturbative origin.
- Predictions successful in early data. POWHEG/MC@NLO appear reliable, but NP fragmentation tuning in Montecarlo may need more work
- Phenomenological inputs and theory quite constraining: All predictions (these and others) should probably agree within residual uncertainties (i.e. very few 10%s at $p_t >> m$)

Backup

Non-perturbative forms

Bottom: B

$$D_{\rm NP}(x) = (\alpha+1)(\alpha+2)x^\alpha(1-x)$$

Kartvelishvili et al., PLB78 (1978)

Charm: D*

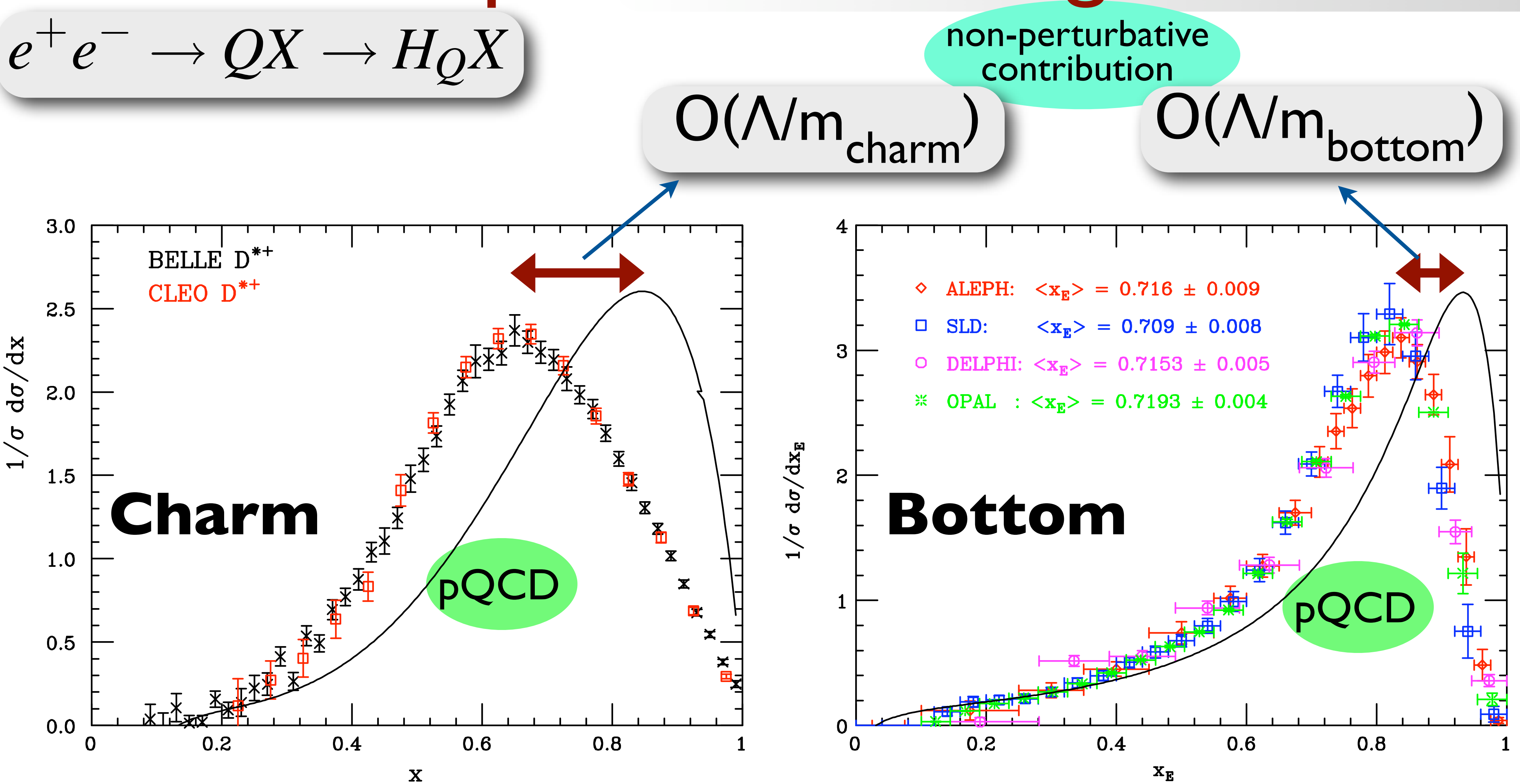
$$D_{Q\to V}(z) \;=\; 3N\,\frac{rz(1-z)^2}{(1-(1-r)z)^6}\Big[2-2(3-2r)z+3(3-2r+4r^2)z^2$$
$$-2(1-r)(4-r+2r^2)z^3+(1-r)^2(3-2r+2r^2)z^4\Big]\;.$$

Braaten et al, hep-ph/9409316

Other functional forms are possible.
No significant differences in predictions if fitted properly

Non perturbative fragmentation

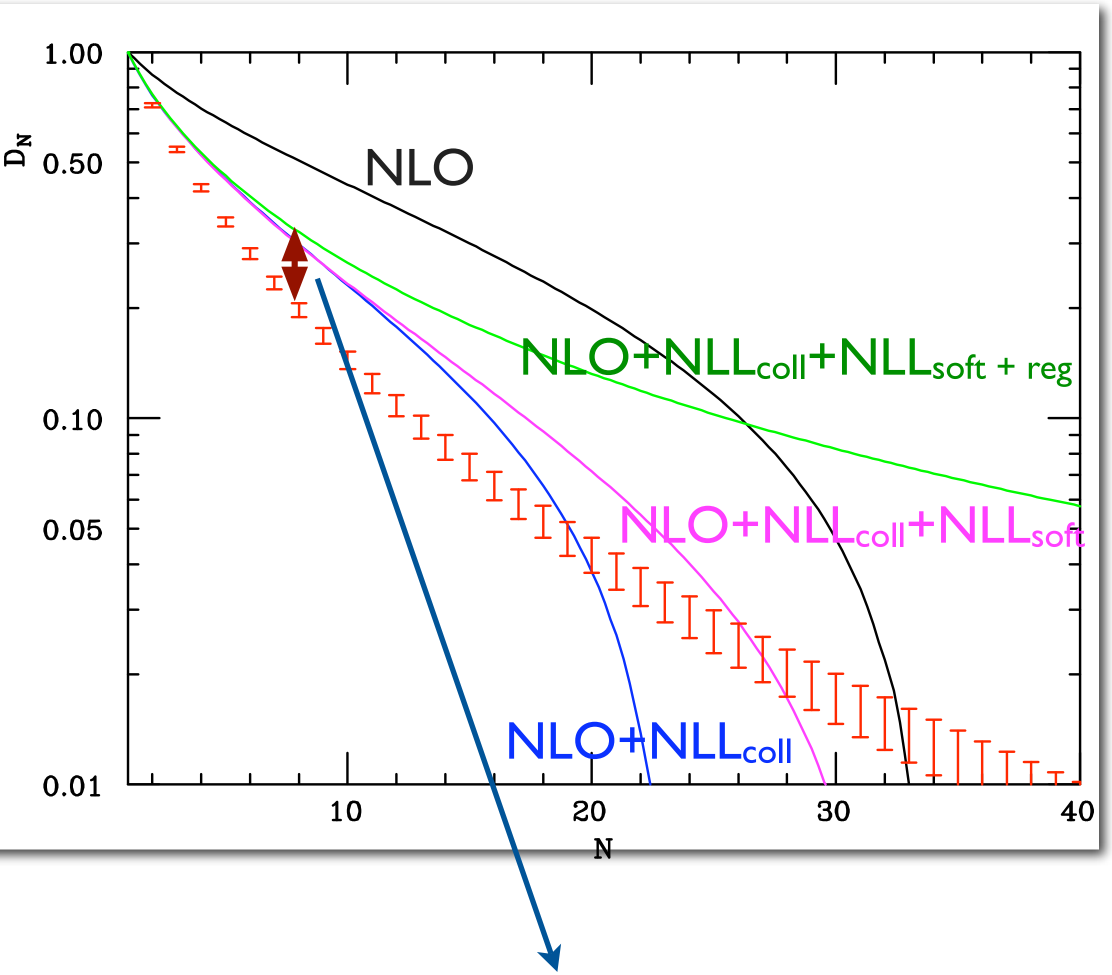
$$e^+e^- \to QX \to H_Q X$$



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

Non perturbative fragmentation

LEP B meson data translated to Mellin space:



This gap:
non-perturbative QCD

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

In this space
convolutions become products

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

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 ± 0.0042
ALEPH D^{*+} (ISR corr.)	0.4920 ± 0.0152
ALEPH B	0.7163 ± 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!)

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

charm ~ 1 - 0.16
bottom ~ 1 - 0.06

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