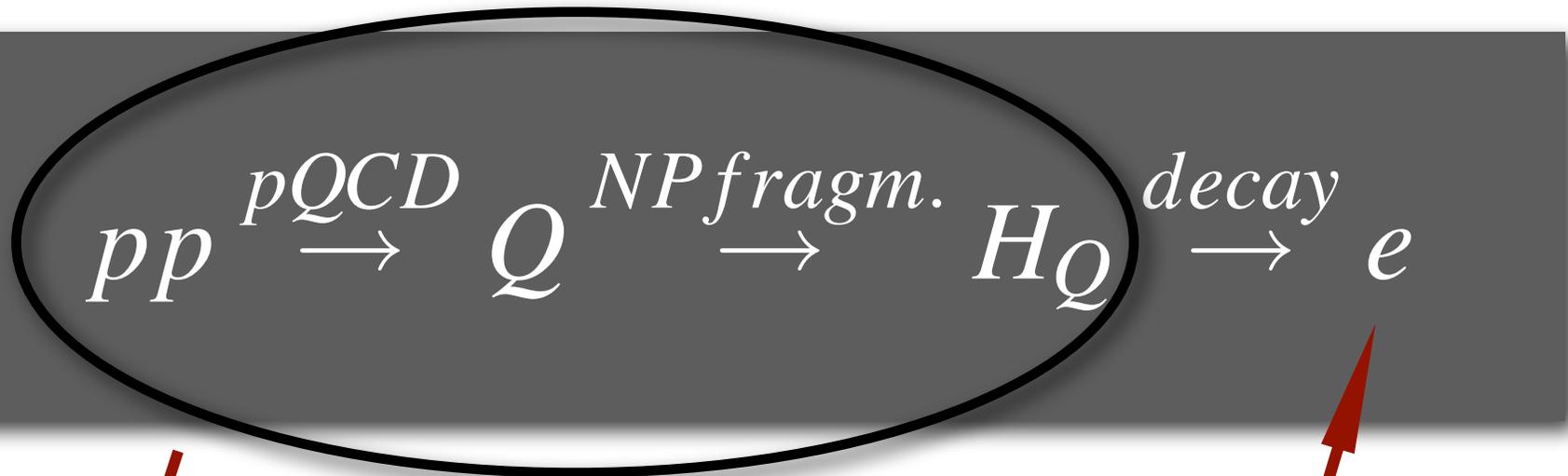


Predictions for heavy quarks in pp at the LHC

Matteo Cacciari

LPTHE - Paris 6,7 and CNRS

Heavy Quark production

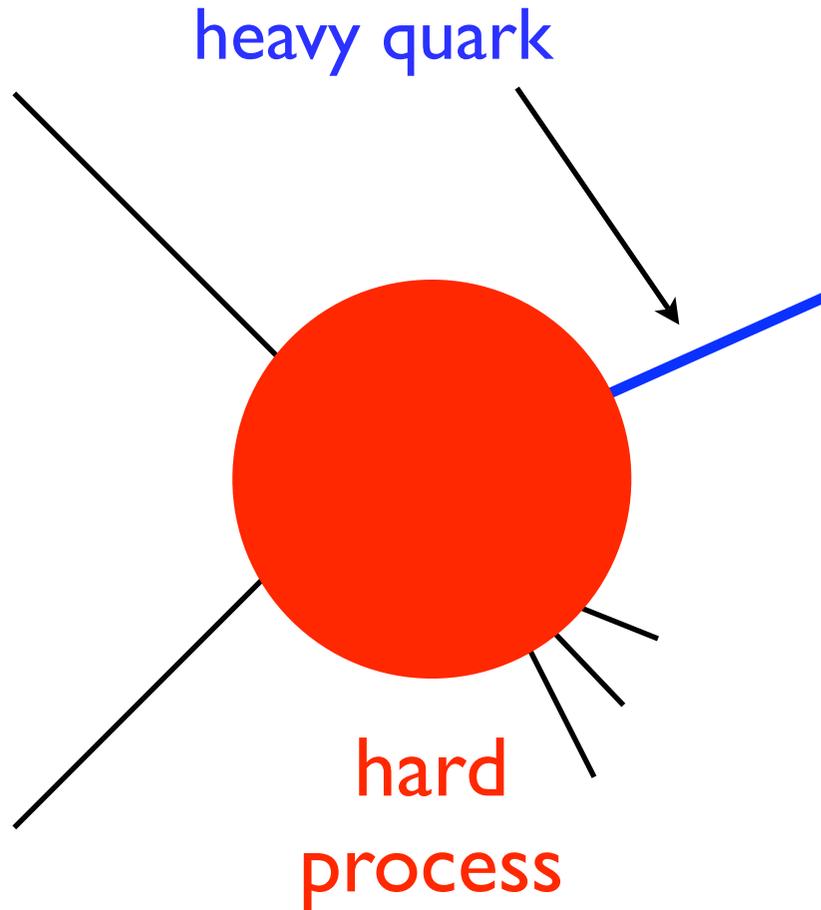


This part is QCD.
How accurately can we predict it?
What ingredients do we need?

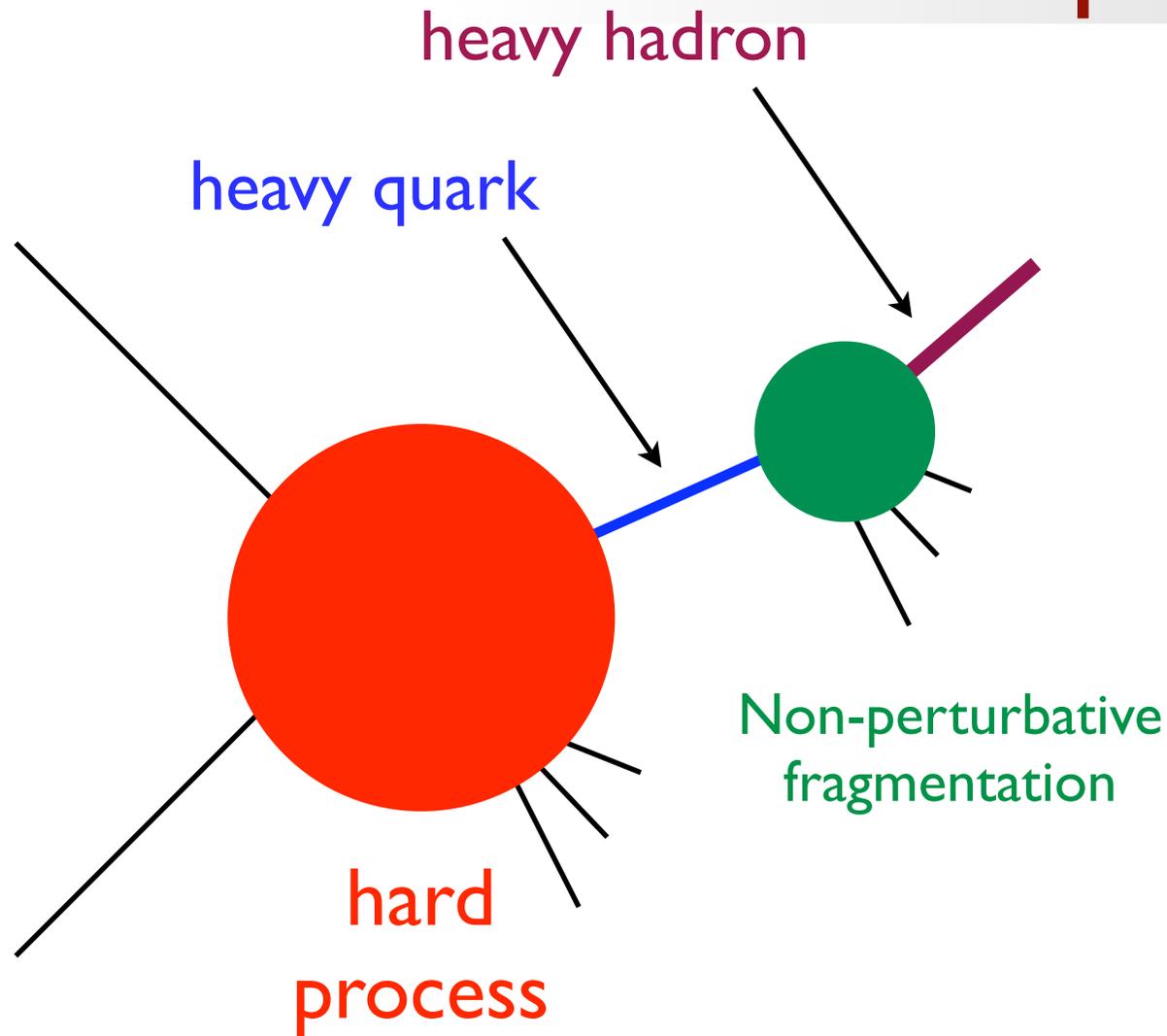
A generic final state
observable

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

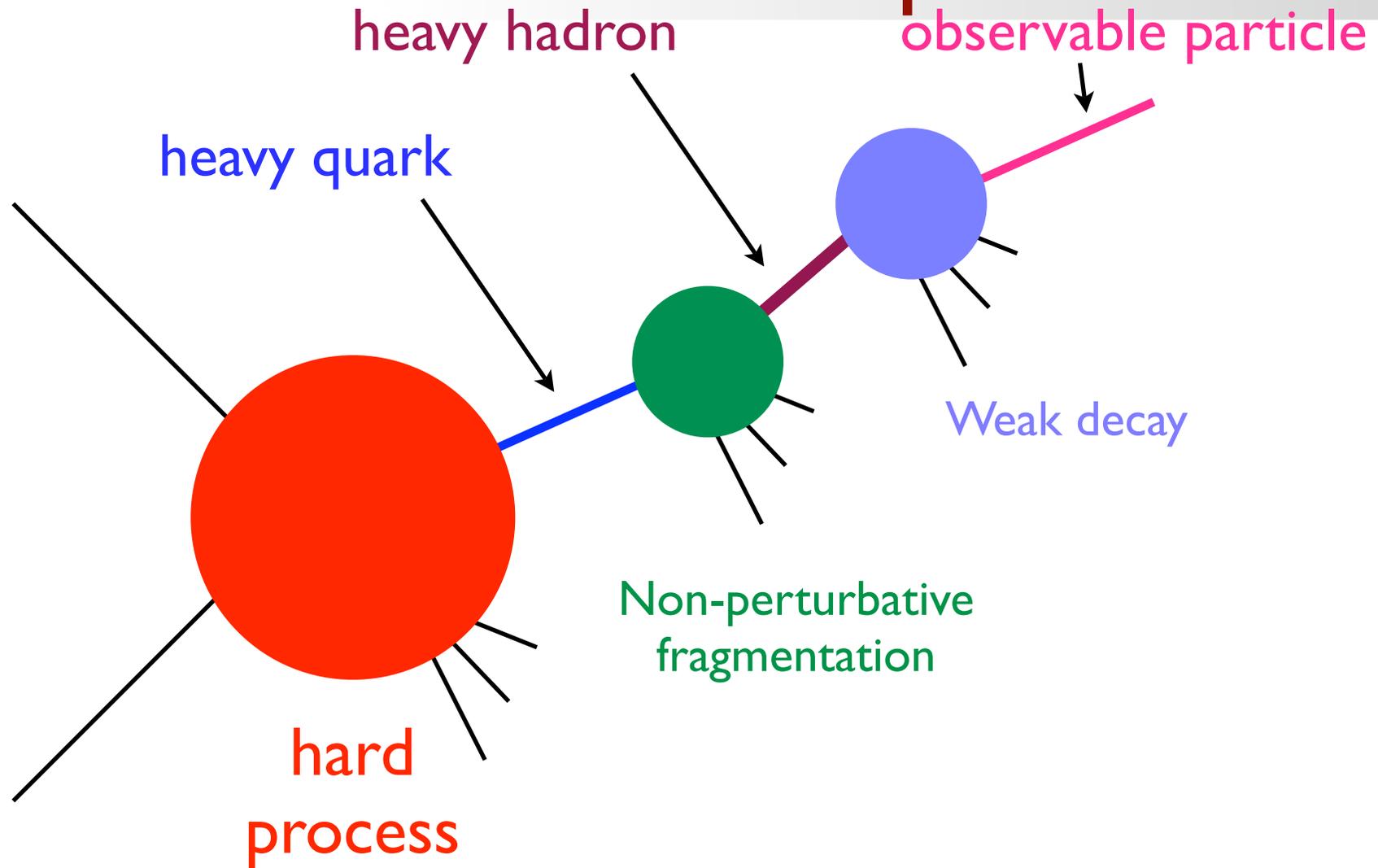
Sketch of inclusive production



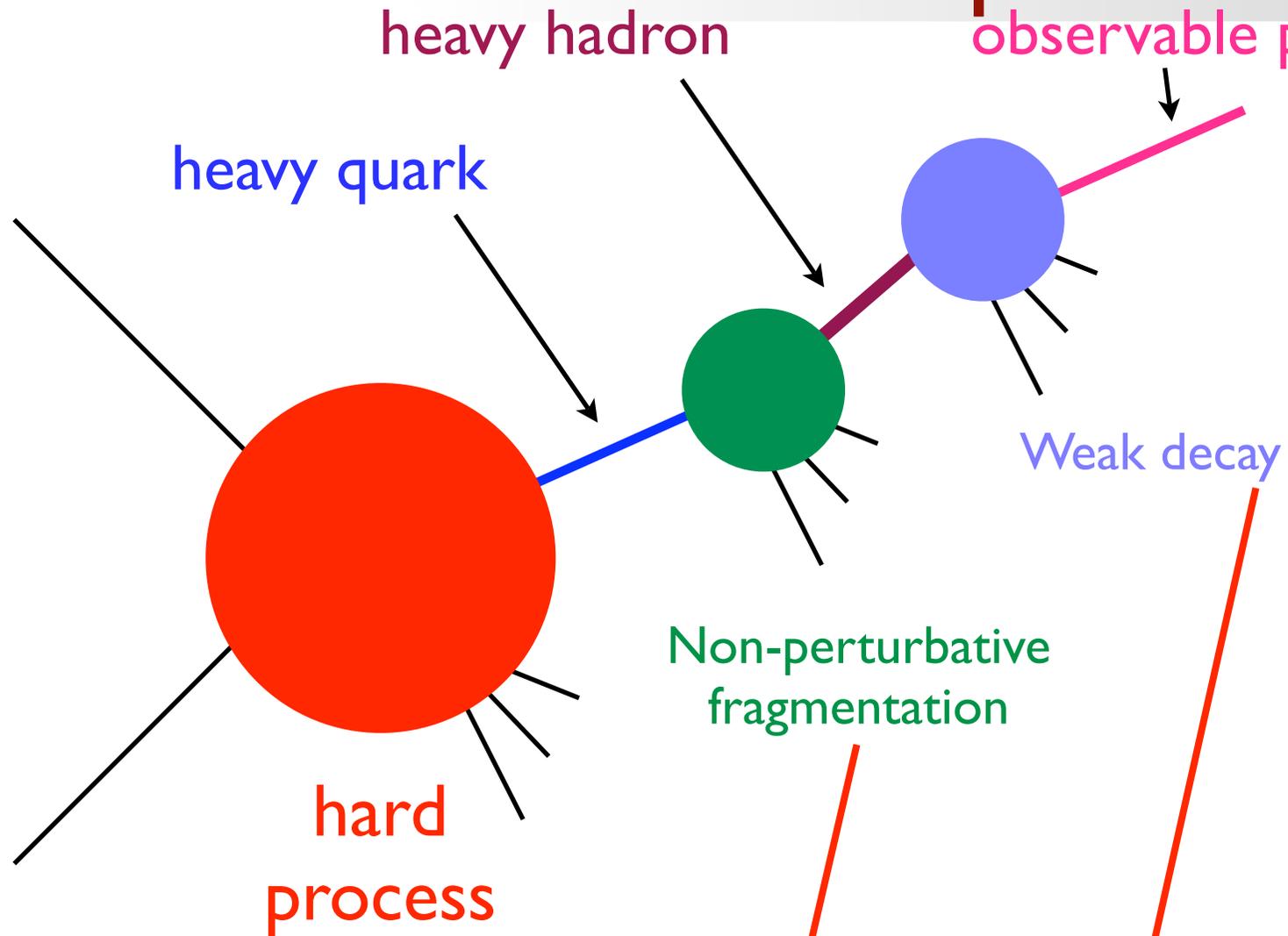
Sketch of inclusive production



Sketch of inclusive production

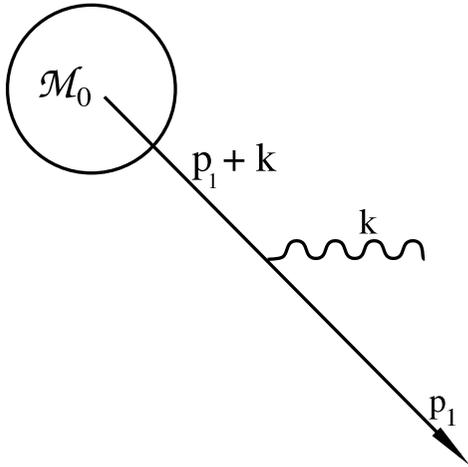


Sketch of inclusive production



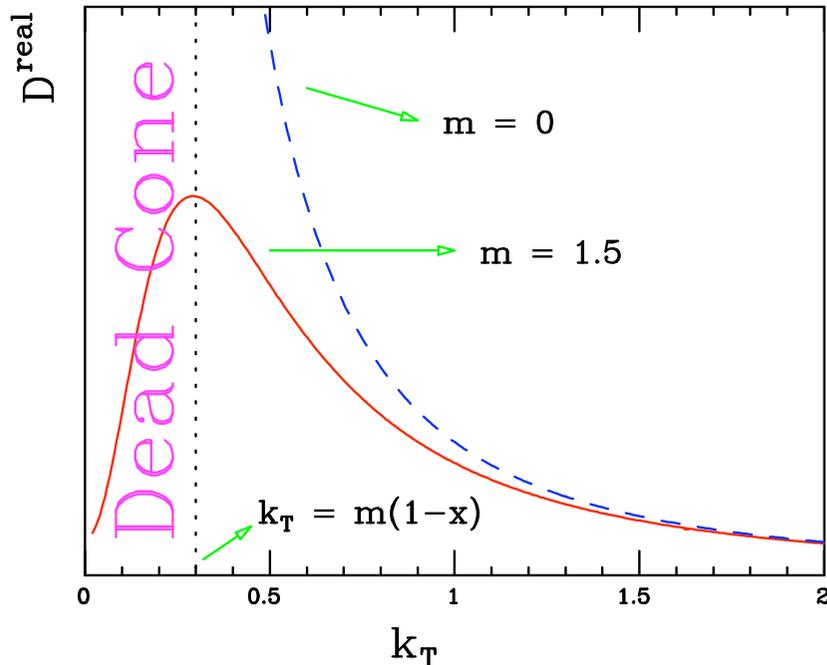
$$\frac{d\sigma(b \rightarrow B \rightarrow J/\psi)}{dp_T} = \frac{d\sigma(b)}{d\hat{p}_T} \otimes f(b \rightarrow B) \otimes g(B \rightarrow J/\psi)$$

Heavy mass effects



Gluon emission from a heavy quark

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



Emission probability not divergent at small transverse momentum



Calculability in pQCD

Factorization theorem

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

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

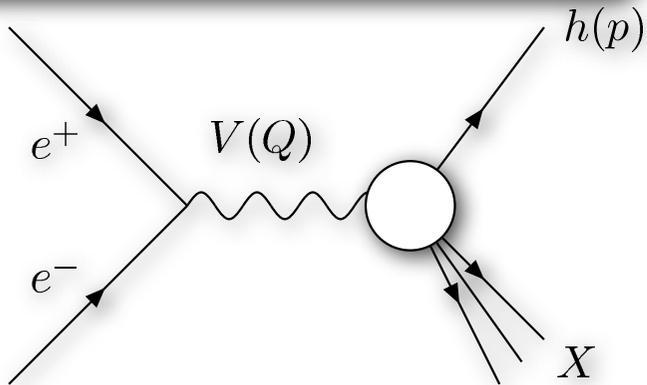
Light flavours only

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)**.

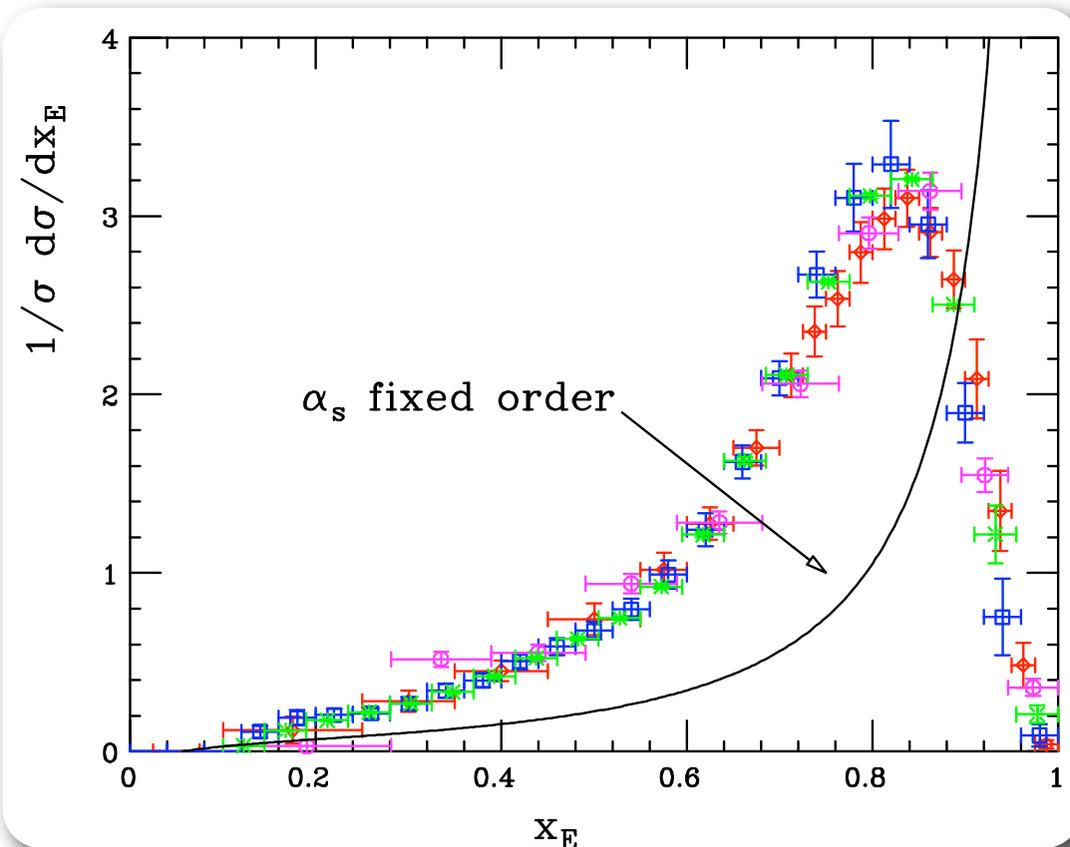
We have by no means proved this result in this paper, but we believe that the analysis given here should make the result plausible. We are arguing that heavy

Finite \neq accurate

$$e^+e^- \rightarrow B + X$$

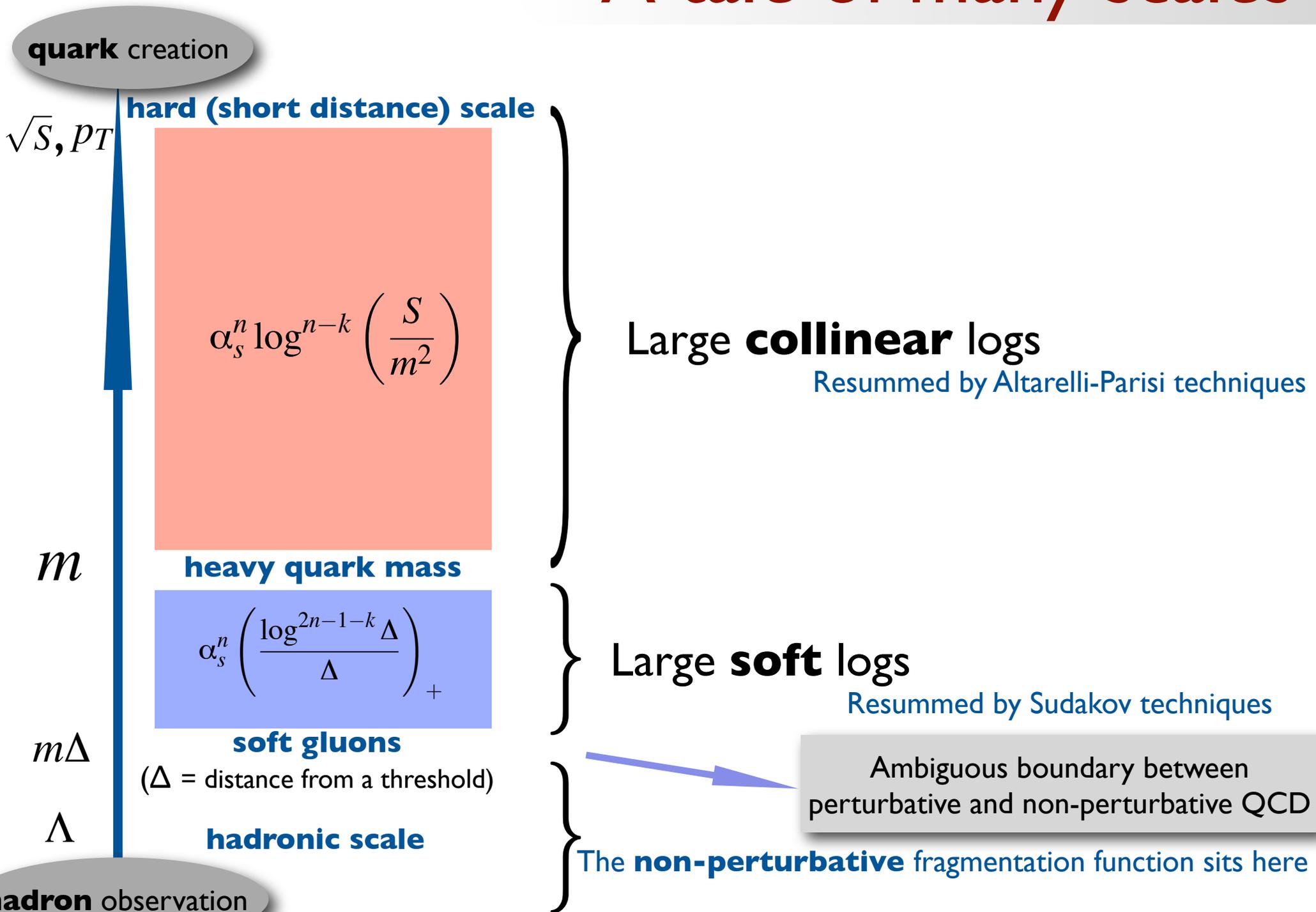


$$\begin{aligned} \frac{1}{\sigma} \frac{d\sigma}{dx} &= \delta(1-x) + \frac{\alpha_s(Q^2)}{2\pi} \left\{ C_F + C_F \left[\ln \frac{Q^2}{m^2} \left(\frac{1+x^2}{1-x} \right)_+ \right. \right. \\ &+ 2 \frac{1+x^2}{1-x} \log x - \left(\frac{\ln(1-x)}{1-x} \right)_+ (1+x^2) + \frac{1}{2} \left(\frac{1}{1-x}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



What's missing?
Higher perturbative orders and non-perturbative effects

A tale of many scales



How do we do it?

- ▶ 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)

(Residual uncertainty usually dominated by perturbative one)

Perturbative corrections

NLO + Logs (without double-counting)

▶ FONLL

MC, Greco '94, MC, Greco, Nason '98

▶ MC@NLO

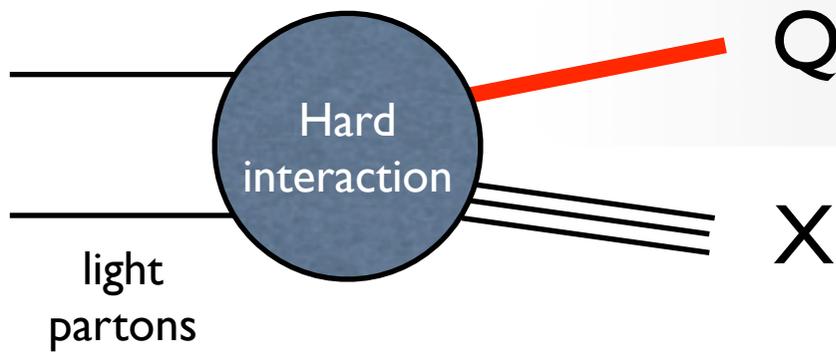
Frixione, Webber '02

▶ POWHEG

Nason, '04

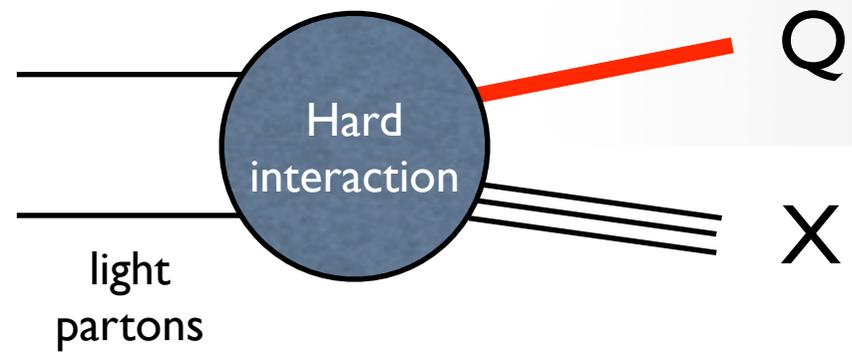
In all cases, matching between a NLO fixed order calculation (Nason, Dawson, Ellis, '88) and the resummation of large logs, either semi-numerically (FONLL, NLL accuracy) or via a parton shower Montecarlo (LL accuracy)

FO



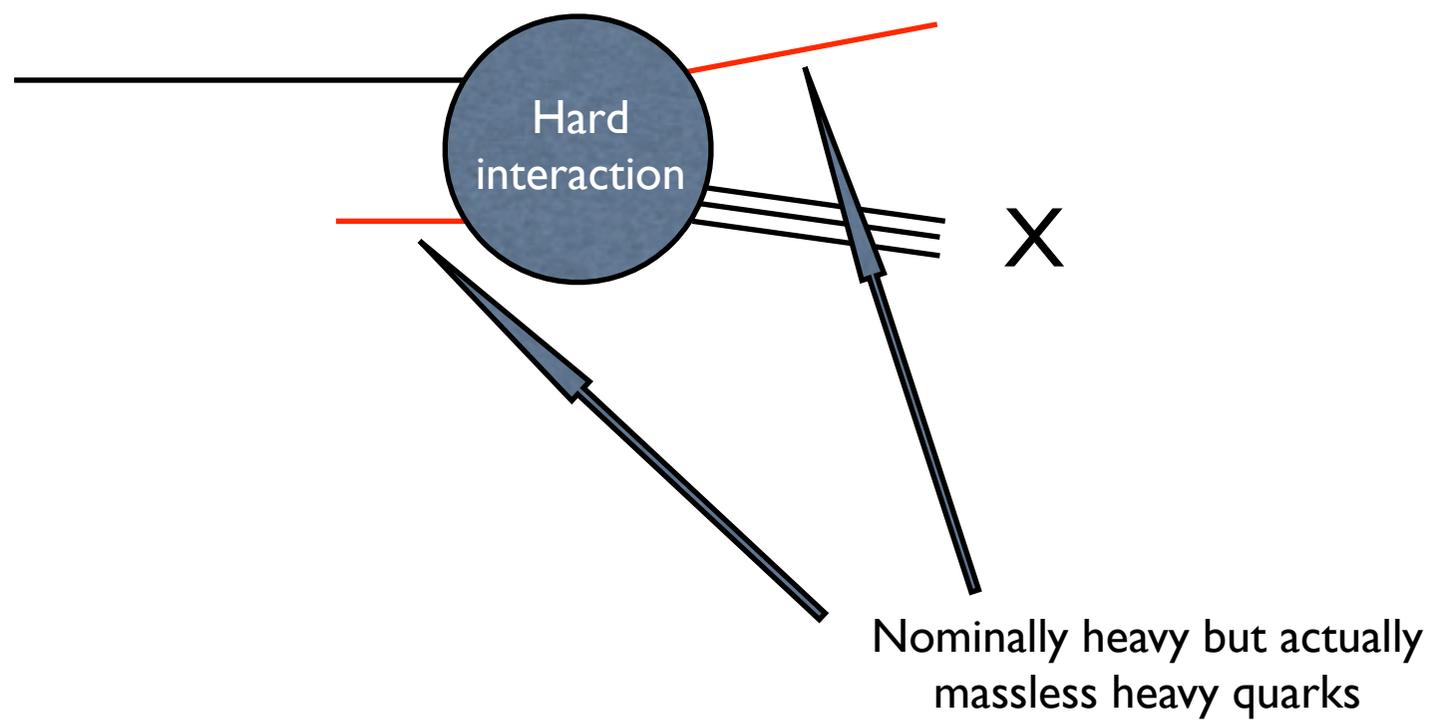
+

FO

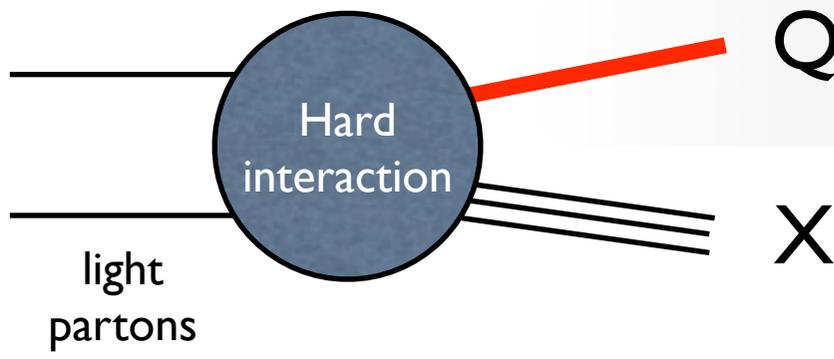


+

NLL

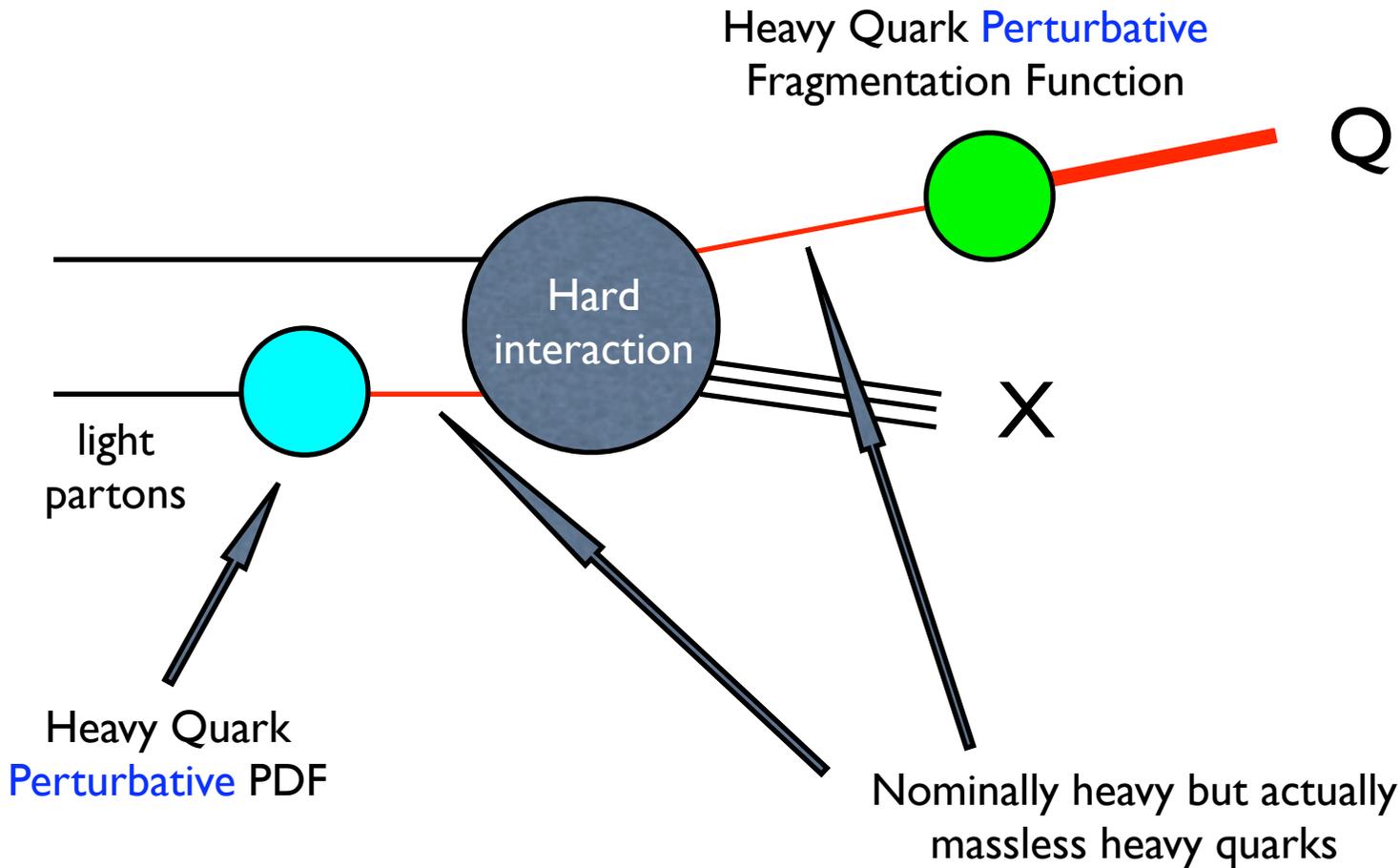


FO

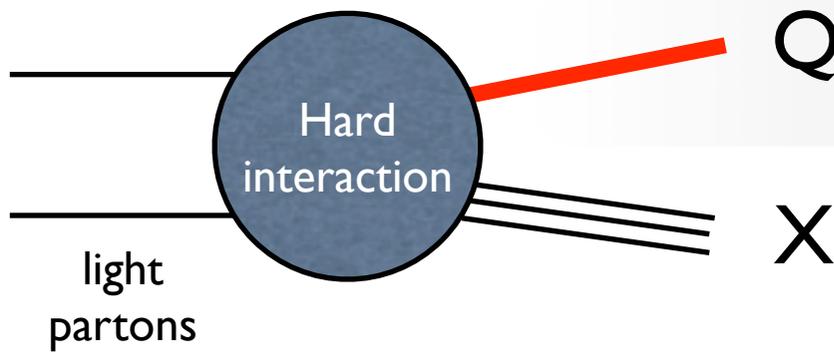


+

NLL

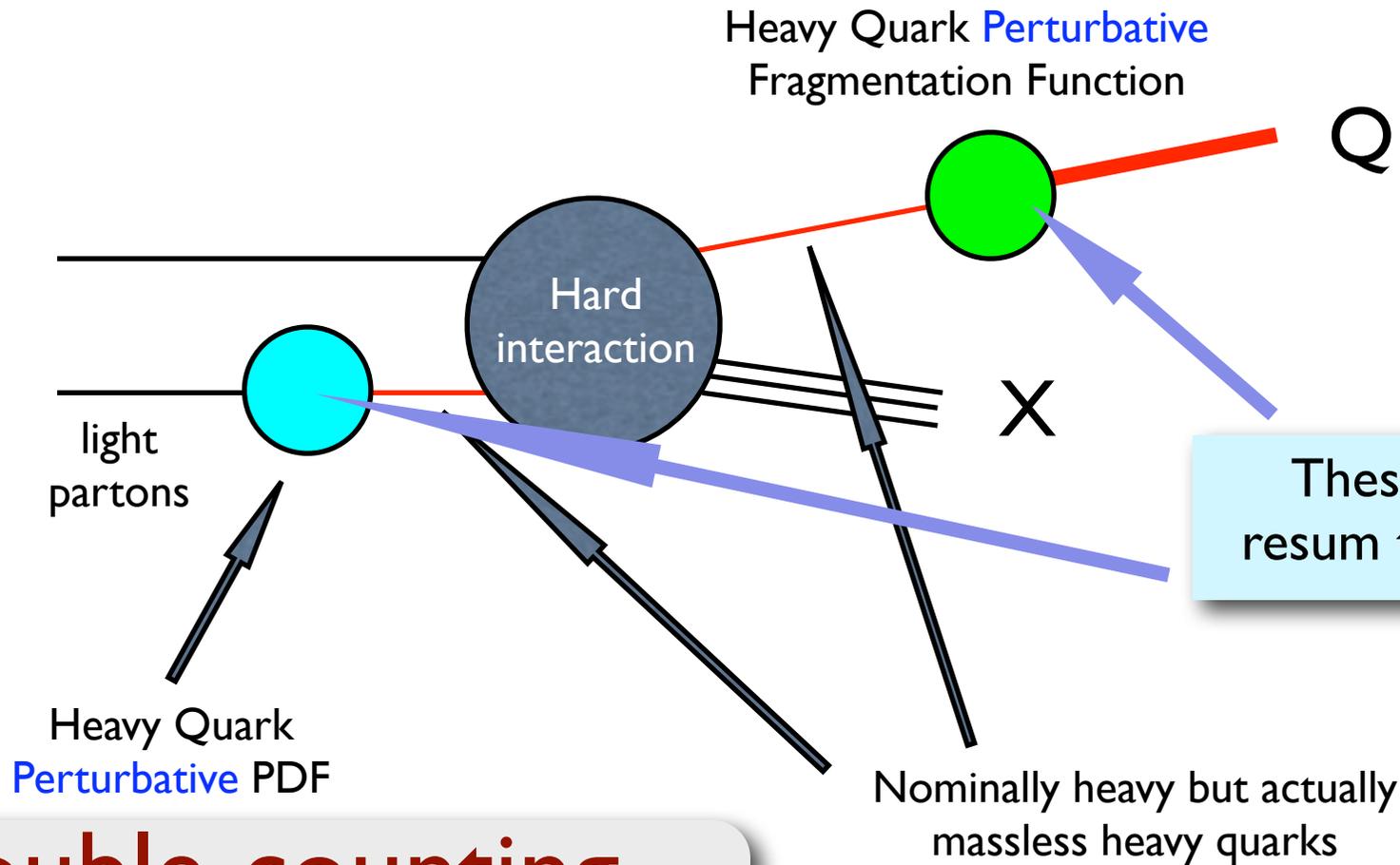


FO



+

NLL

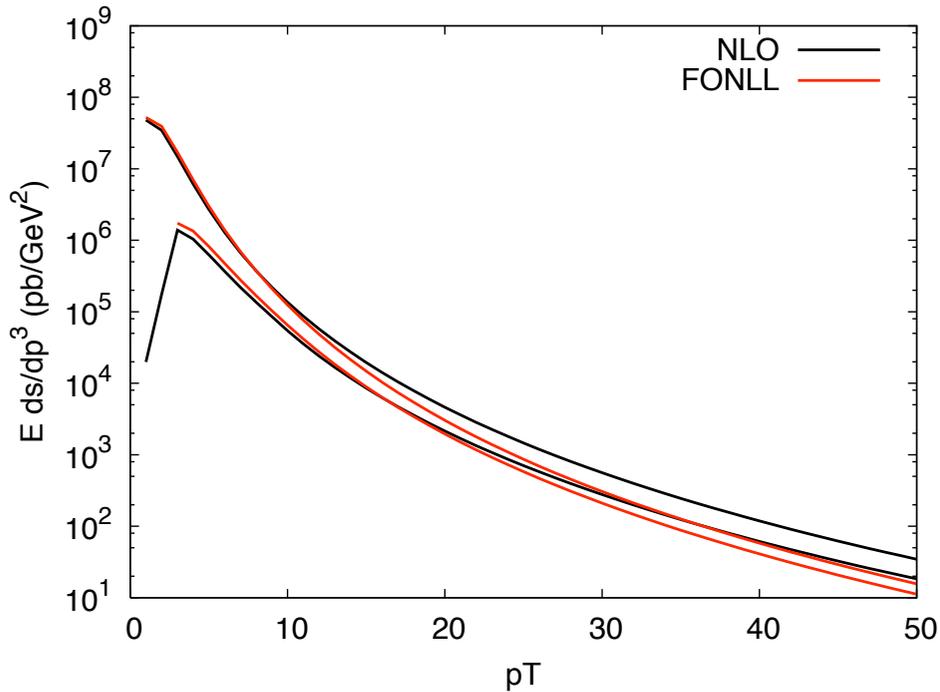


These functions resum the large logs

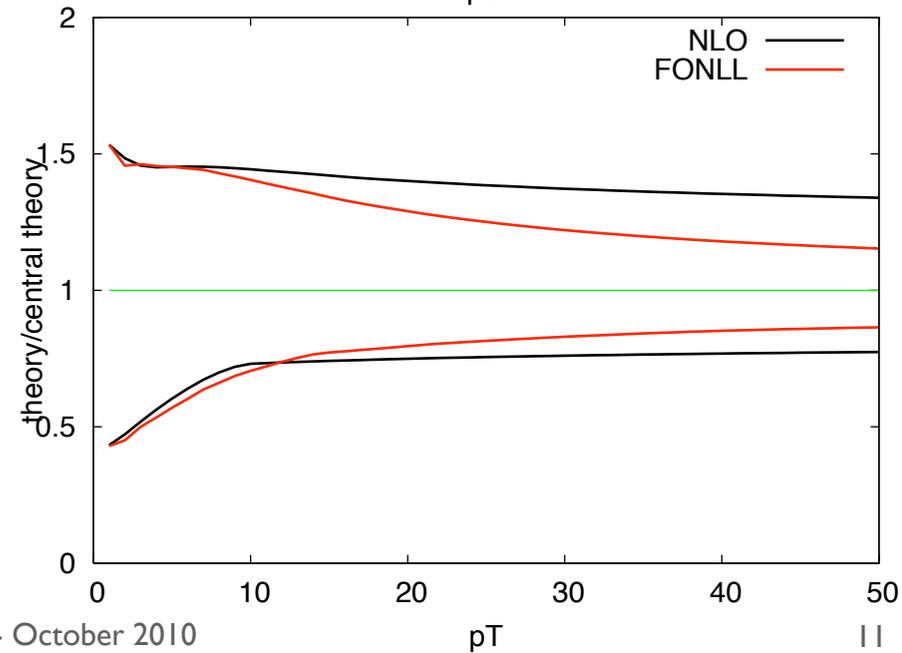
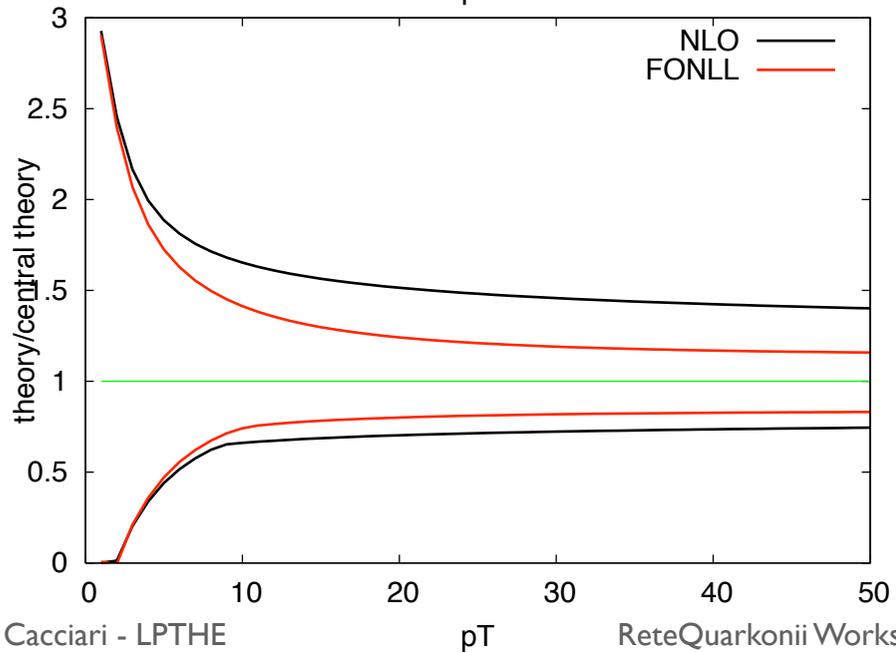
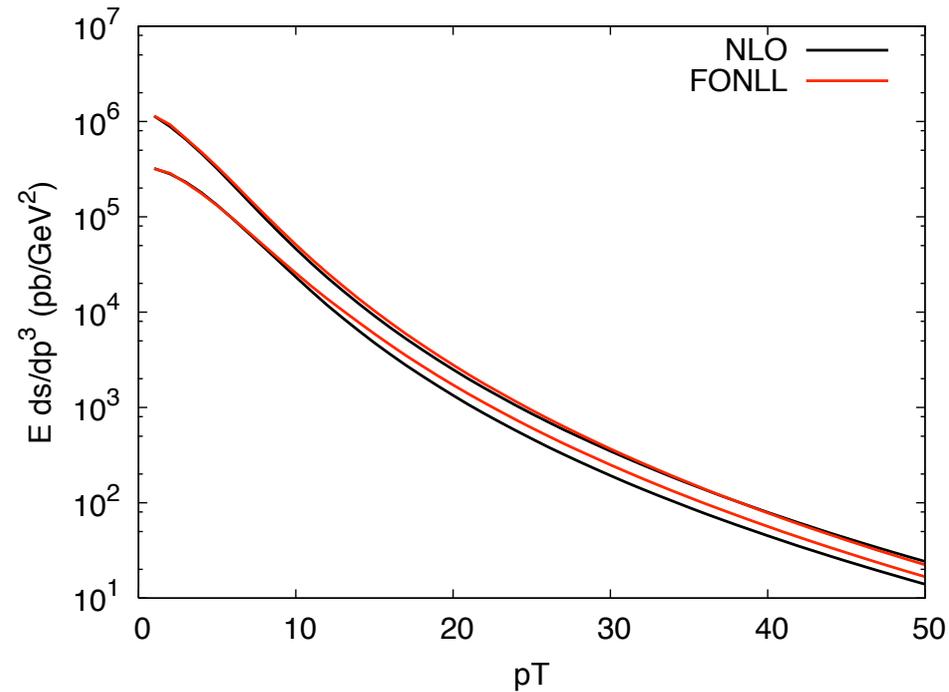
- double-counting
(accurate at NLO+NLL)

Charm & bottom quarks @ LHC

Charm



Bottom

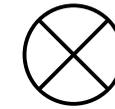
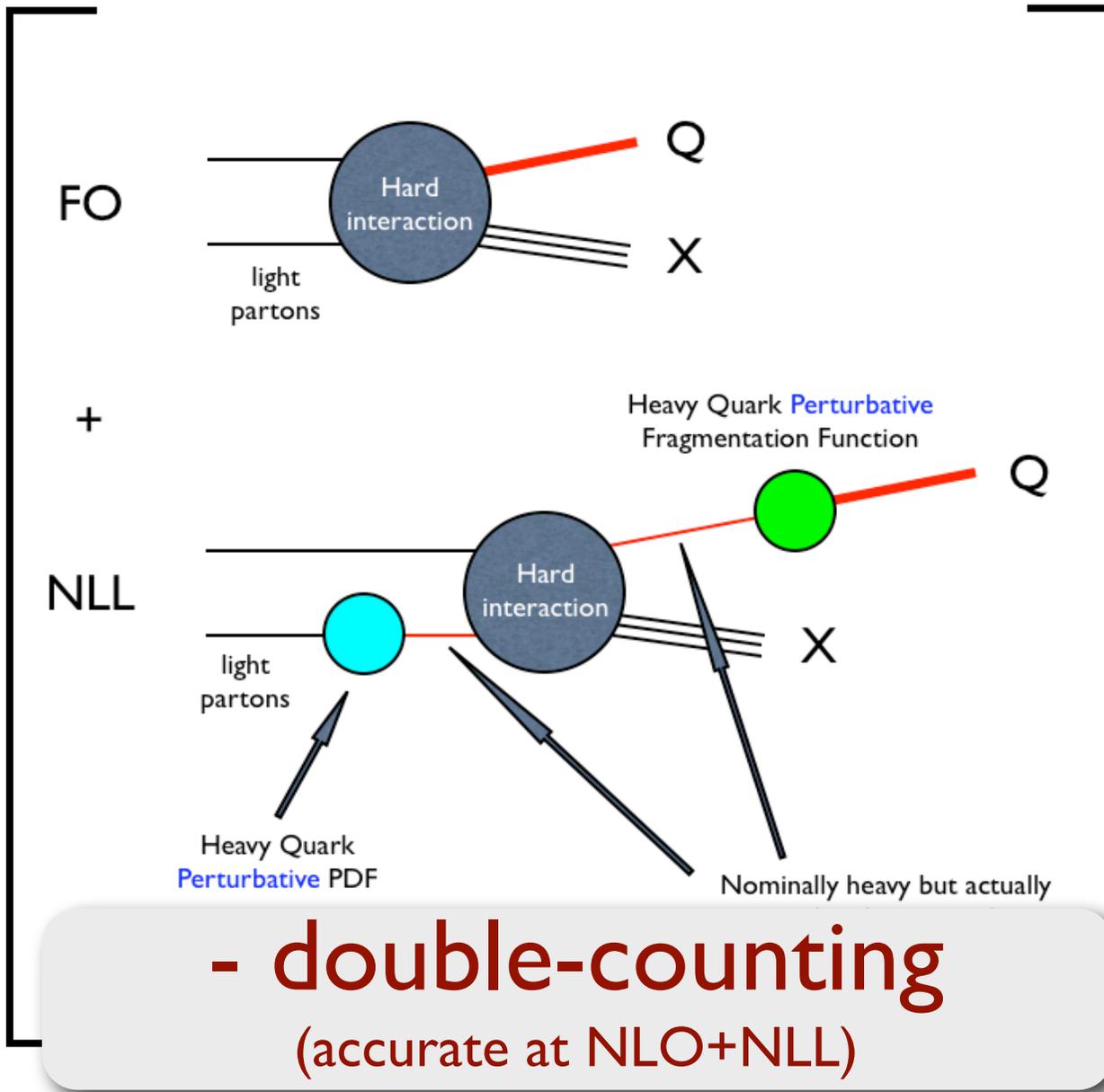


$$\frac{d\sigma_H}{dp_T} = \frac{d\sigma_Q}{dp_T} \otimes D^{np}$$

measured
cross section

NLO (+NLL)
calculation

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



$$D_{Q \rightarrow H}$$

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

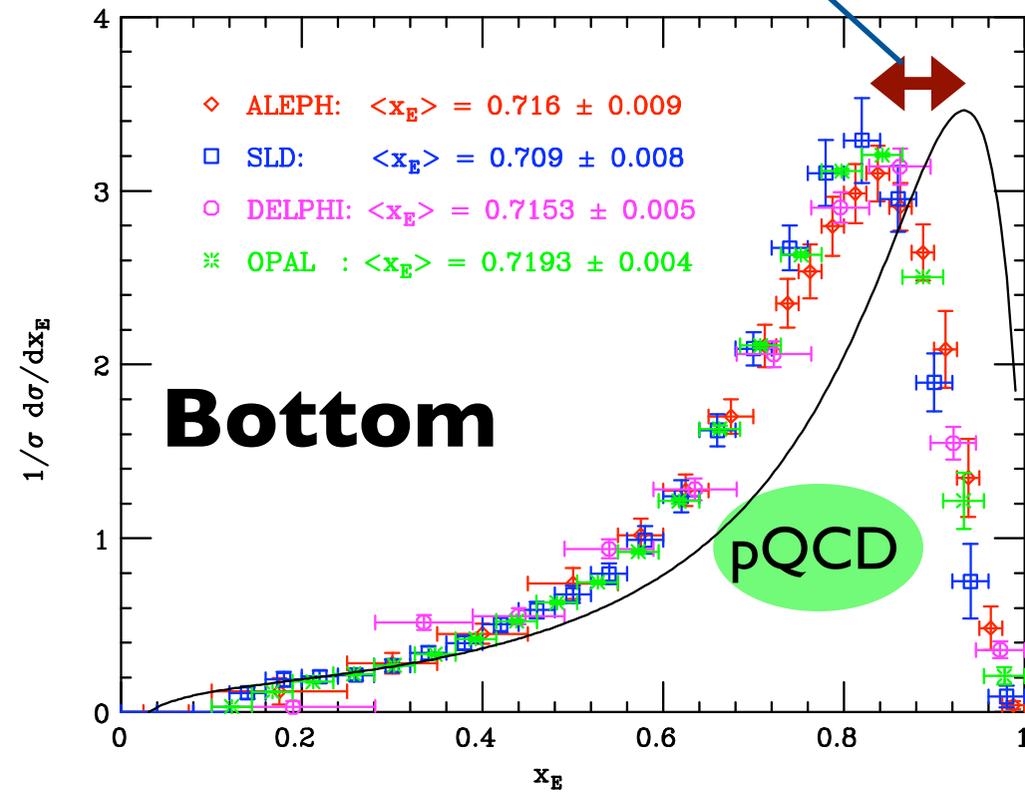
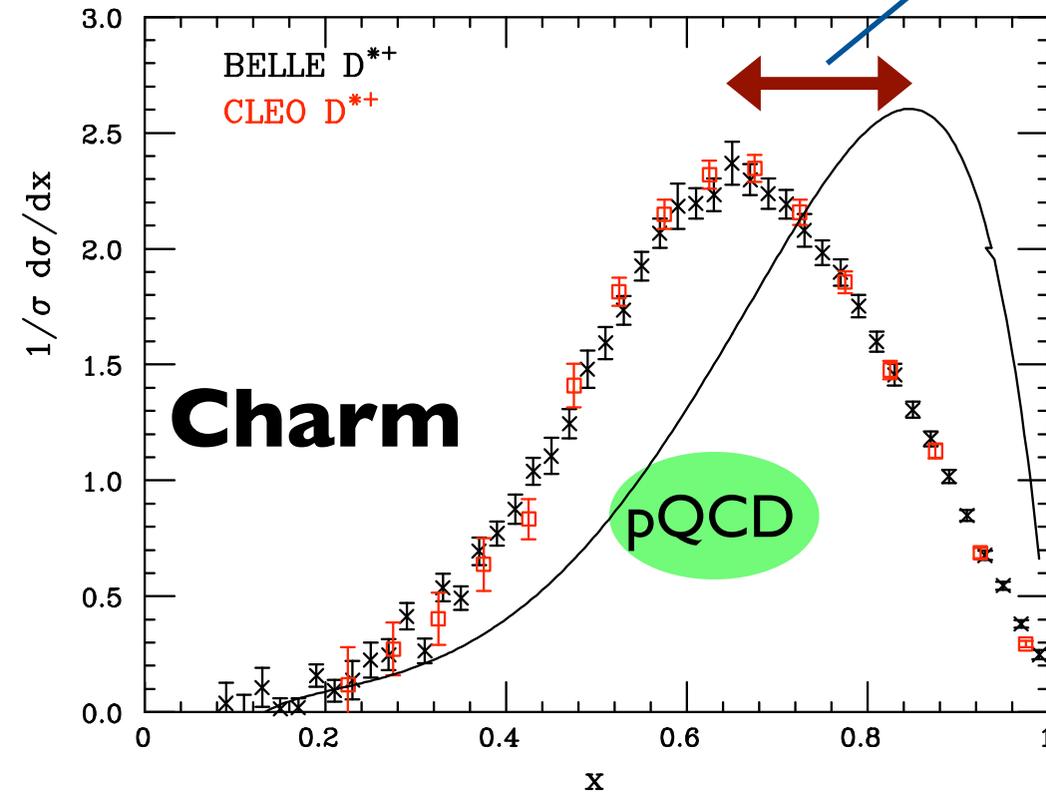
Non perturbative fragmentation

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

non-perturbative contribution

$$\mathcal{O}(\Lambda/m_{\text{charm}})$$

$$\mathcal{O}(\Lambda/m_{\text{bottom}})$$



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

It's the moment that matters

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

heavy **quark**
cross section



heavy **hadron** cross section

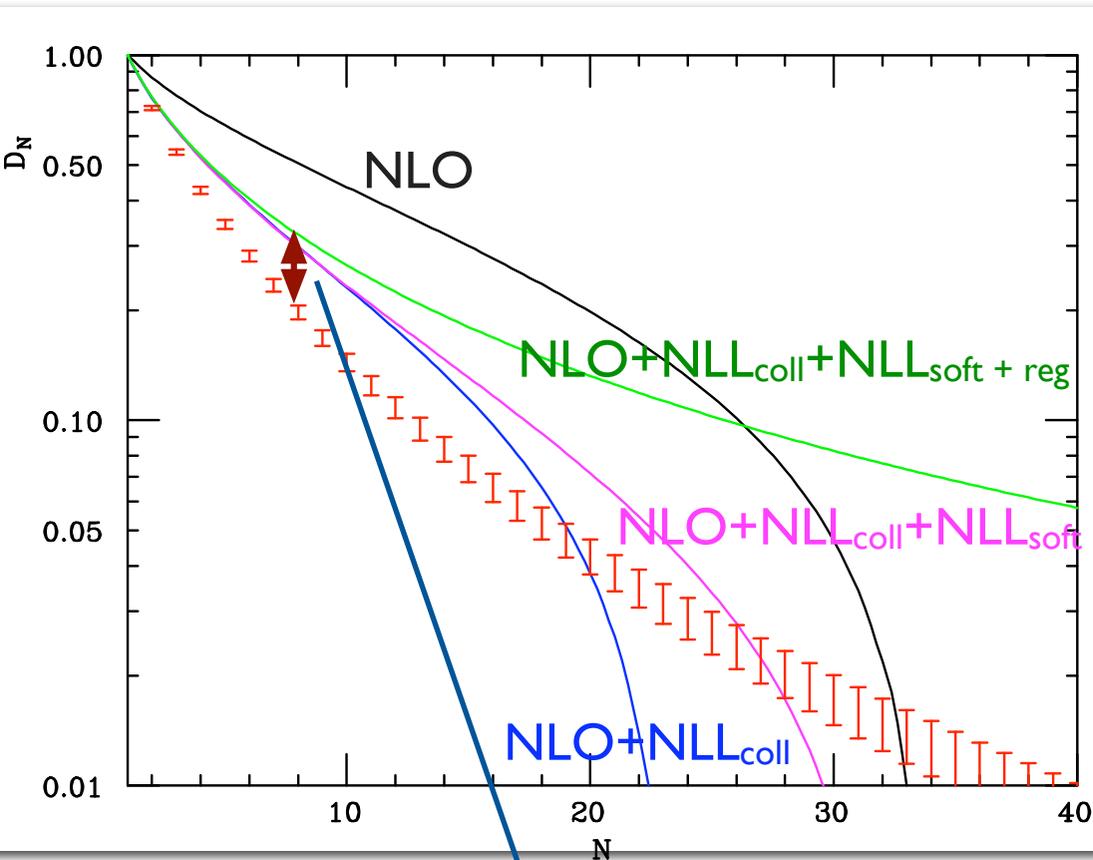
$$\frac{d\sigma_H}{dp_T} = \frac{d\sigma_Q}{dp_T} \otimes D^{np} = \int \frac{d\sigma_Q}{dp_T}(p_T/z) D^{np}(z) \frac{dz}{z} = \int \frac{A}{(p_T/z)^n} D^{np}(z) \frac{dz}{z} = \frac{d\sigma_Q}{dp_T}(p_T) D_n^{np}$$

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

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 $D^{*+} \rightarrow D^0$ (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 $D^{*+} \rightarrow D^0$	$0.872^{+0.005}_{-0.006}$
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!)

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

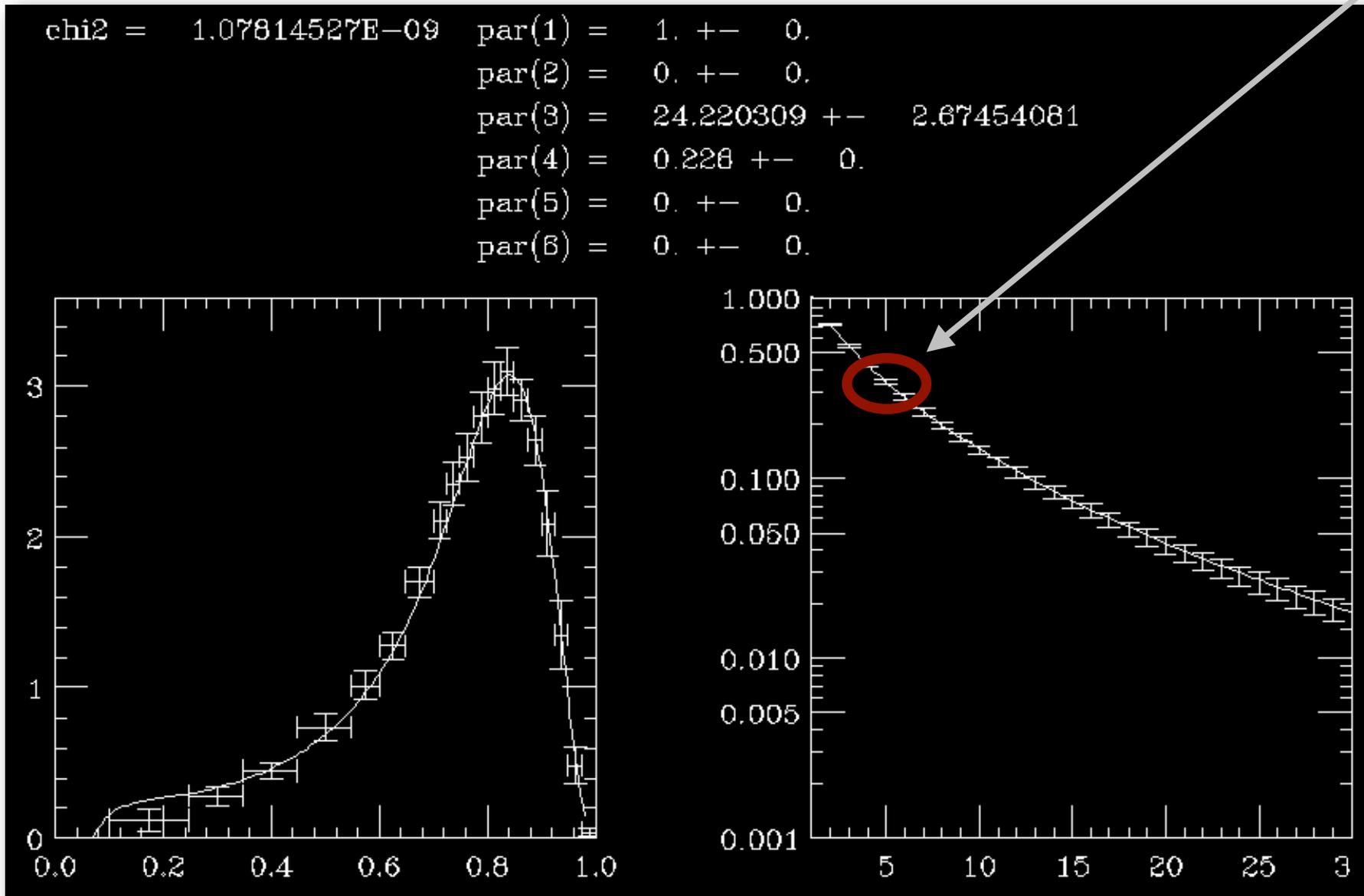
charm $\sim 1 - 0.16$
bottom $\sim 1 - 0.06$

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

Quality of moment-space fits

ALEPH B hadrons

Fit to N=5



Theoretical uncertainties

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%

The uncertainty from the PDFs should be fairly constrained. Say 10-15%

The non-perturbative fragmentation contribution is tightly constrained by e^+e^- data. It is definitely known to better than 10%

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 20%

==> No room for factors of three discrepancies

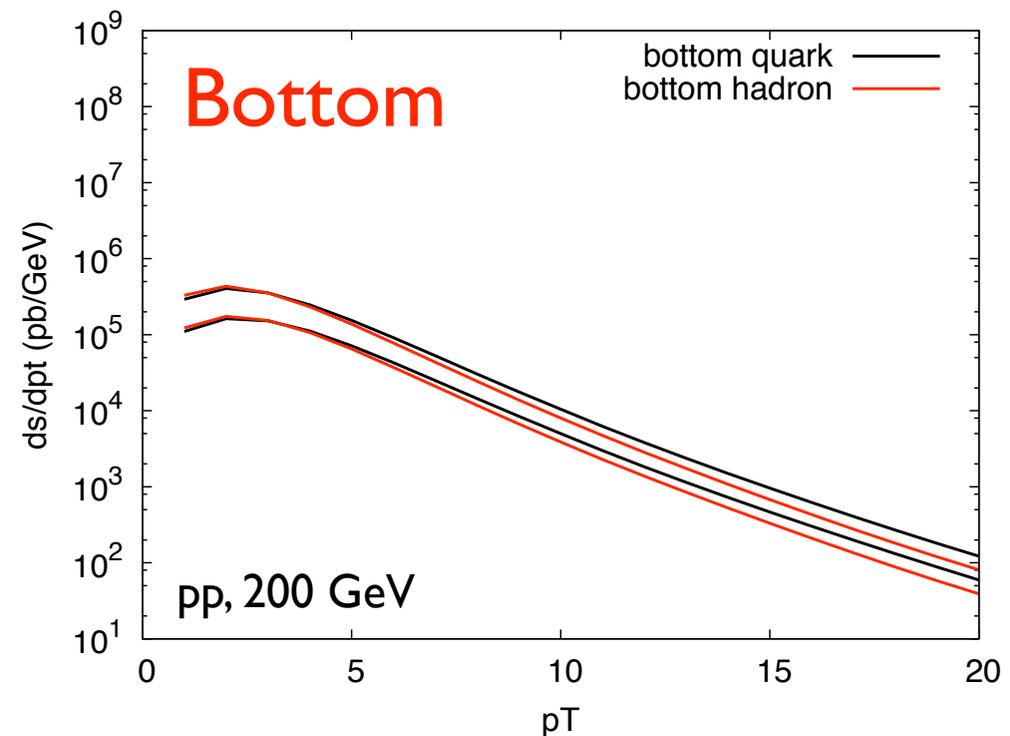
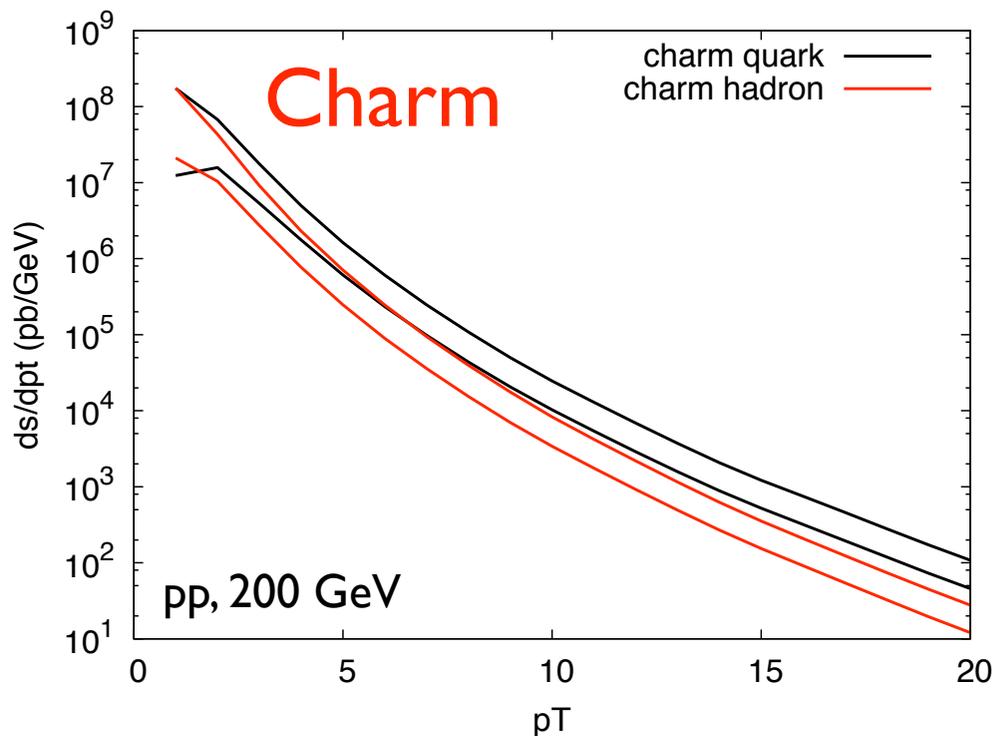
(BTW: the expt. accuracy is actually often better than the theoretical one!)

Results

Hadronic differential distributions

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

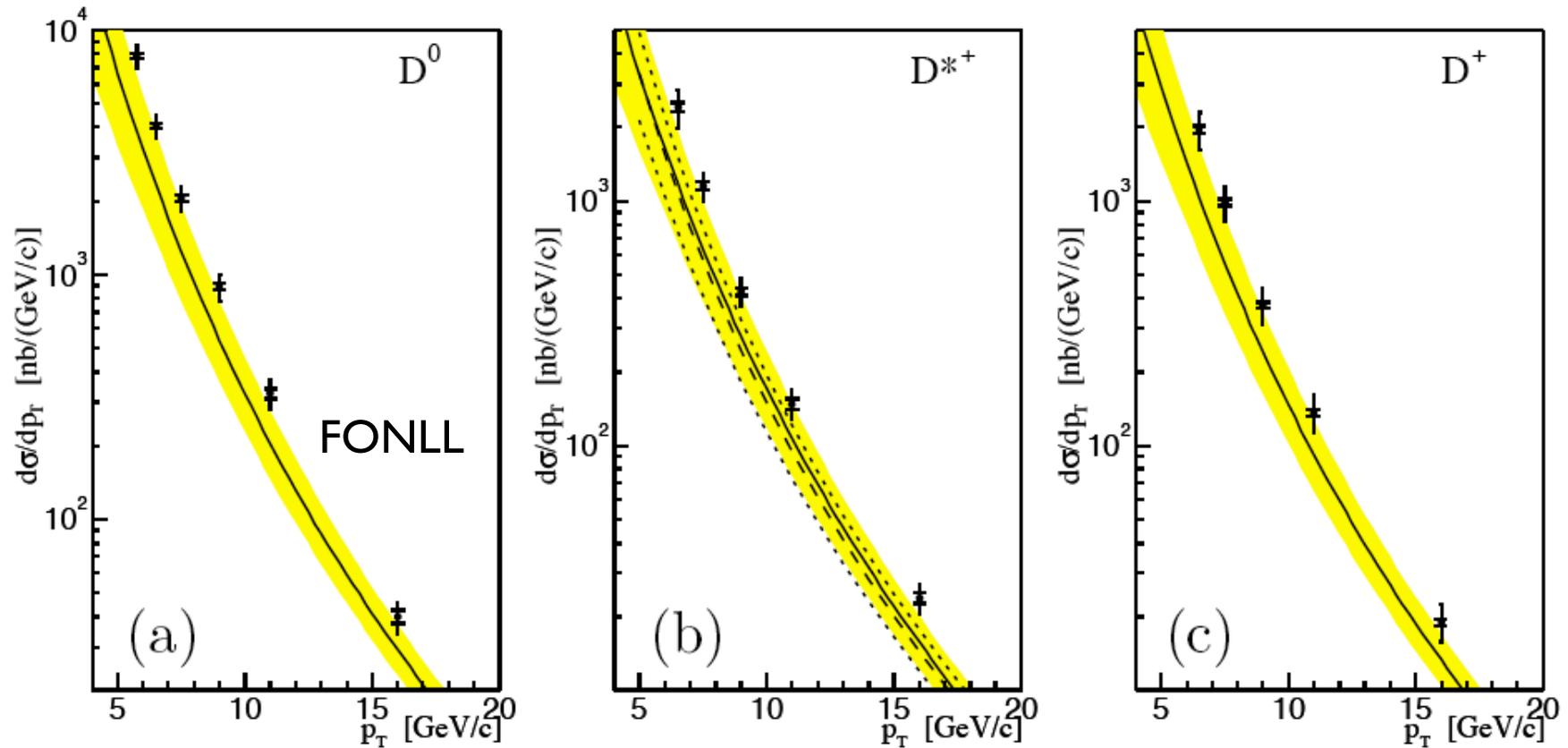
At the **differential** level instead, hadrons and quarks differ



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

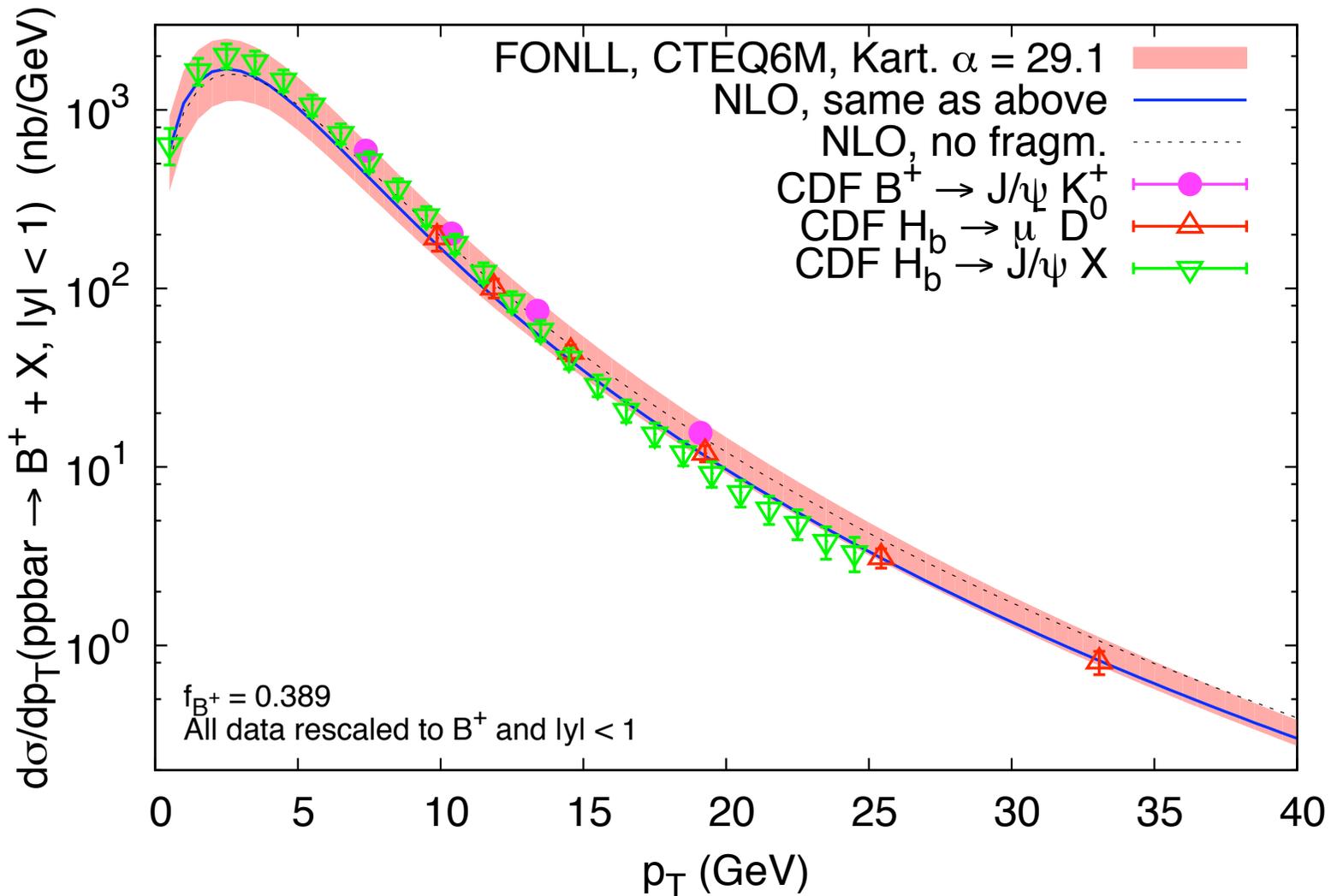
(Still, at large p_T the effect can be large)

CDF Run II $c \rightarrow D$ data [PRL 91:241804,2003]



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

bottom @ Tevatron

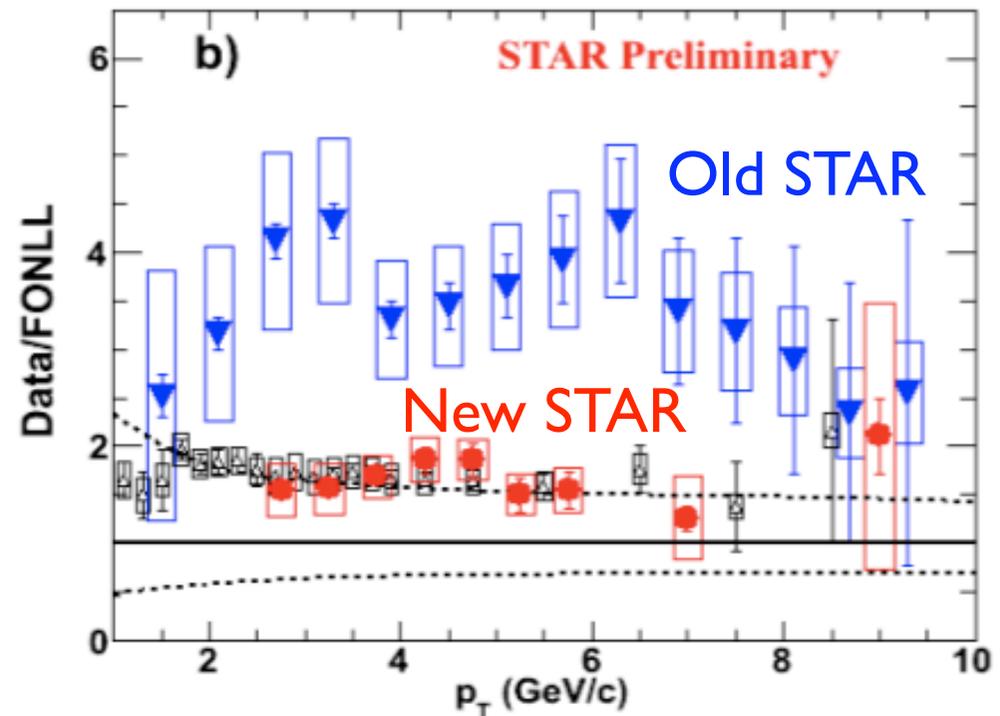
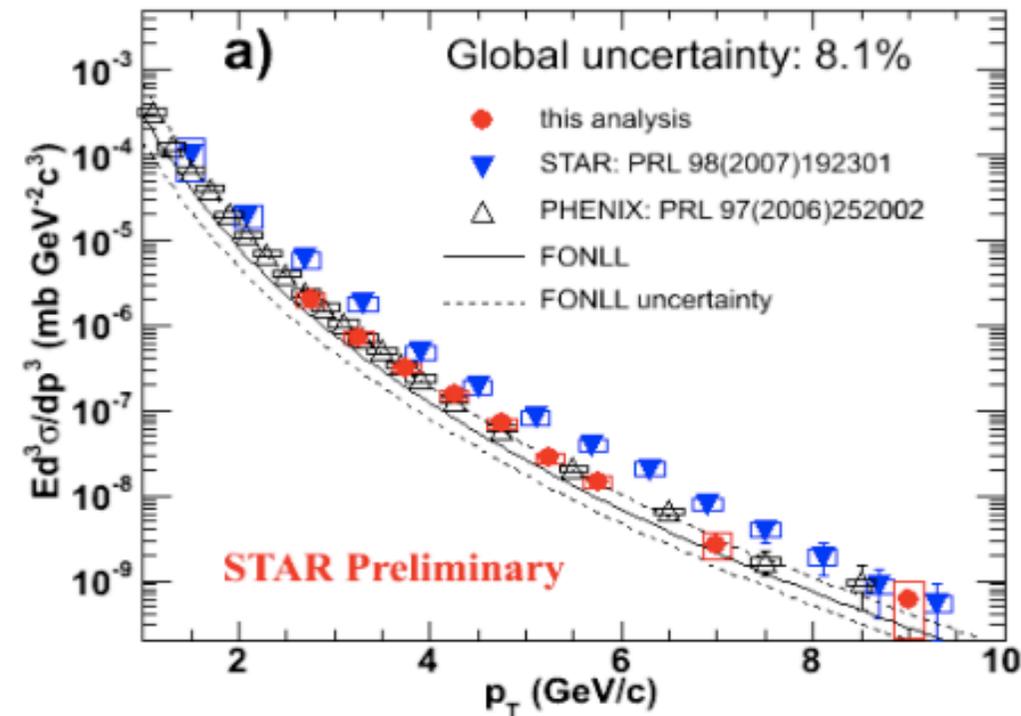


Good agreement, with minimal non-perturbative correction

NLO is sufficient for correct total rate prediction

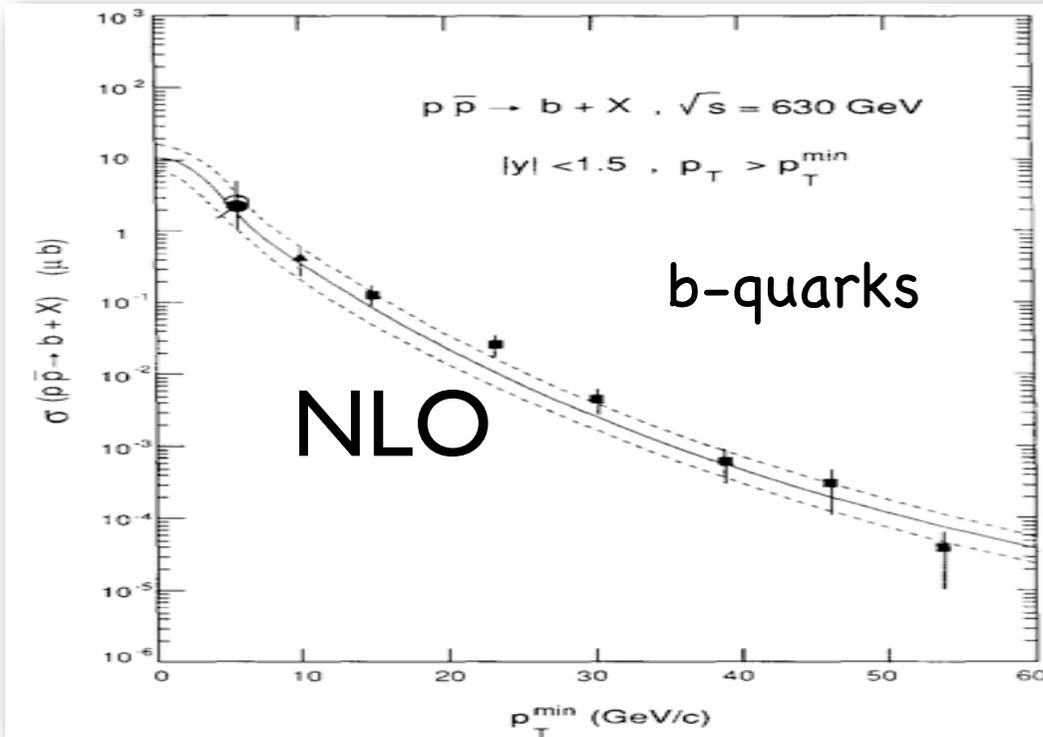
charm and bottom @ RHIC

‘non-photonic’ electrons: $pp \rightarrow c,b \rightarrow e$

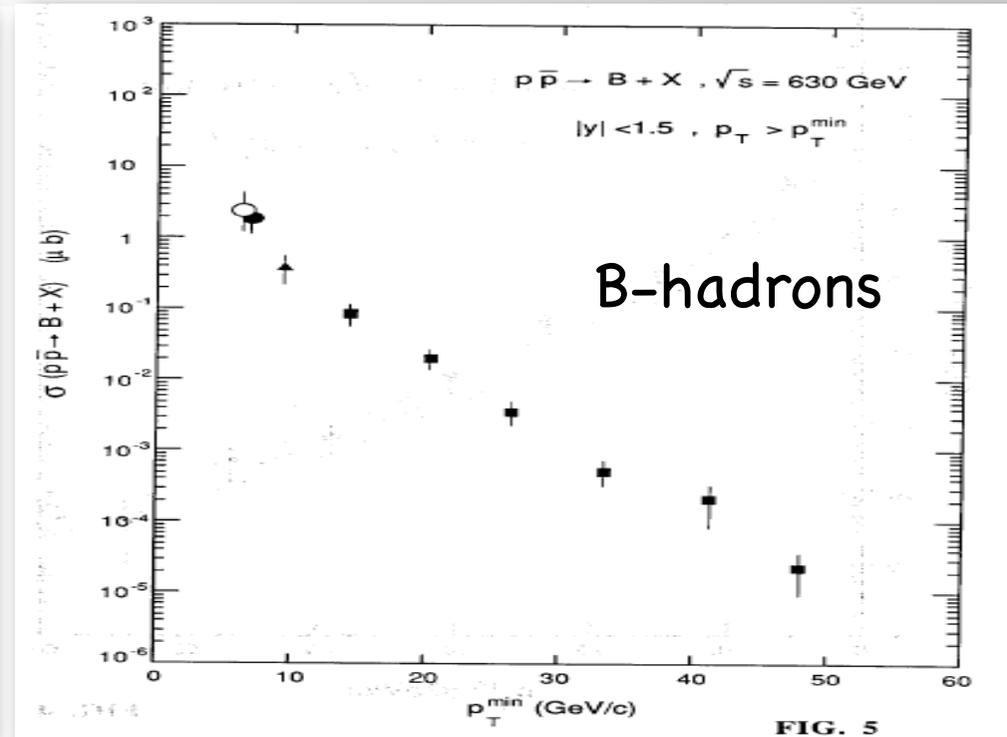


Theory holding firm,
STAR data initially showing an excess have come down

Back to the future: bottom @ UAI

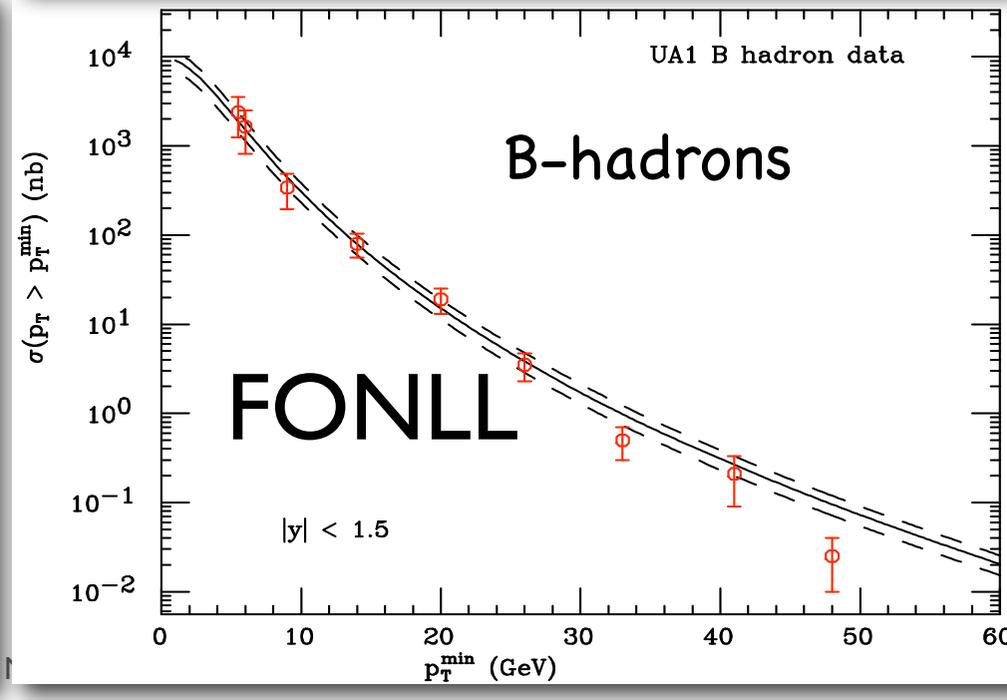
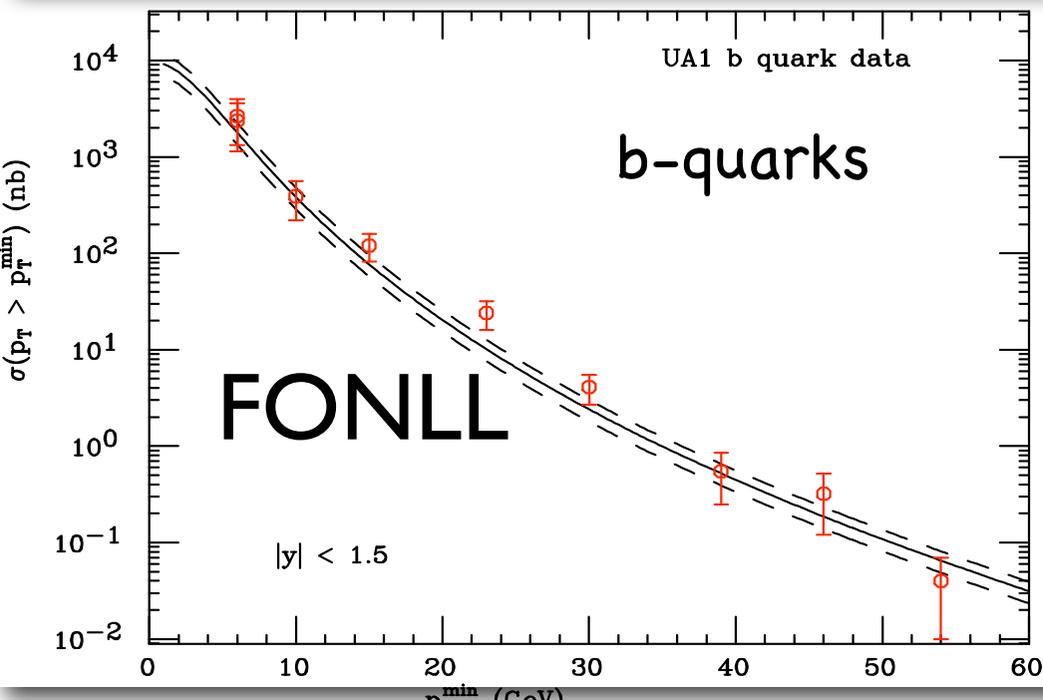
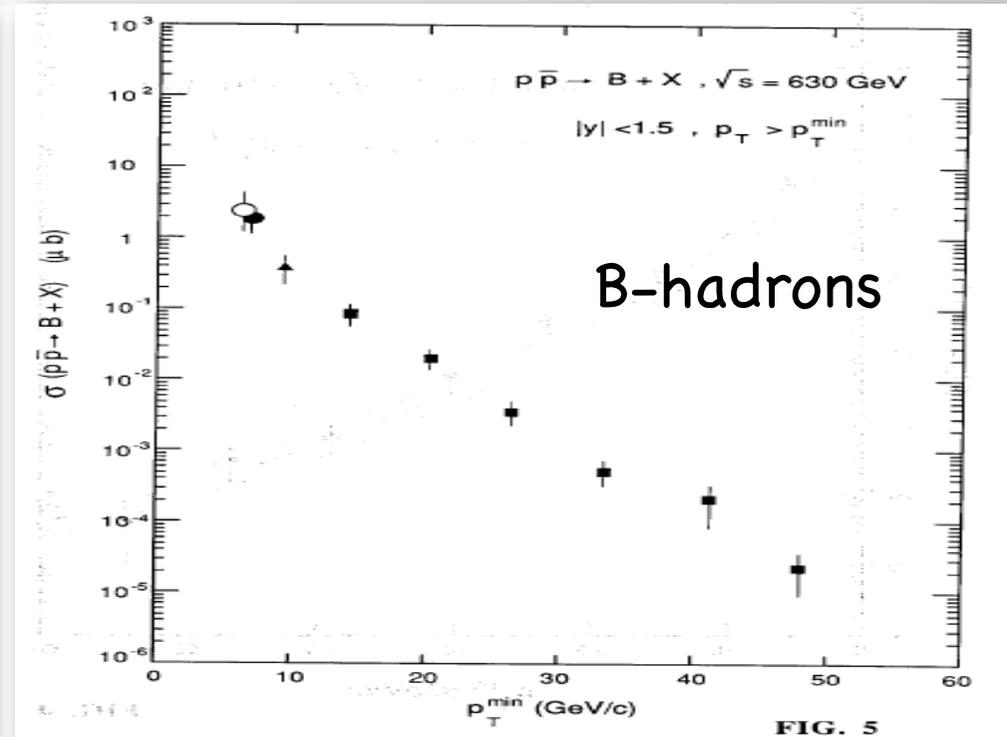
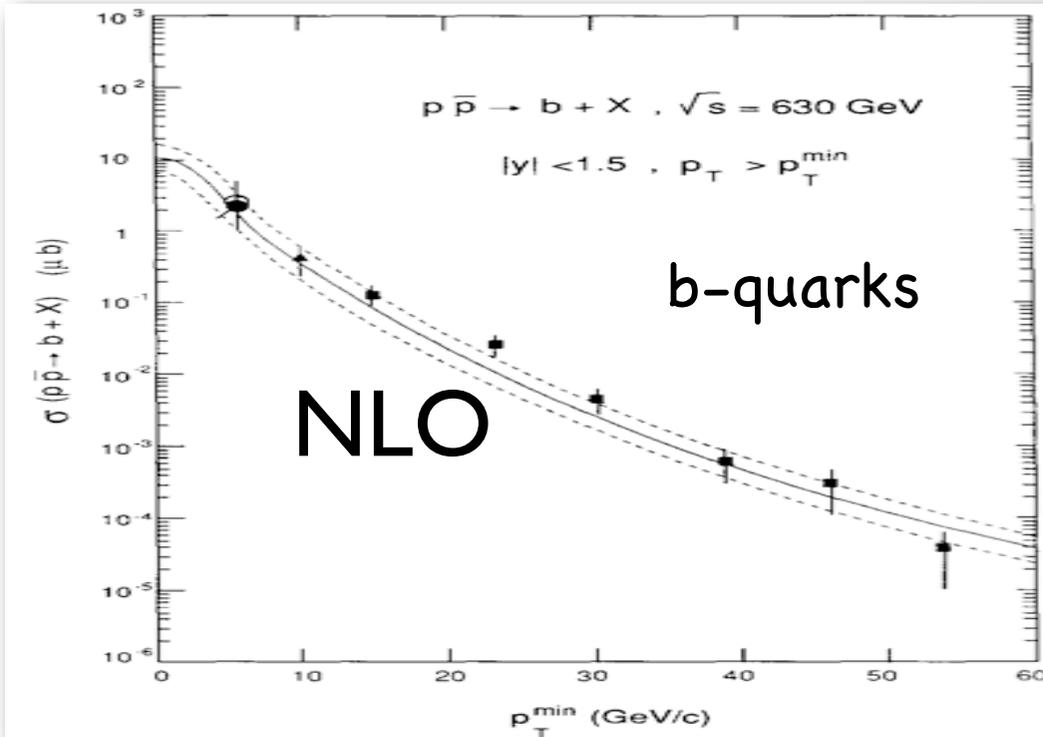


FONLL



FONLL

Back to the future: bottom @ UA1



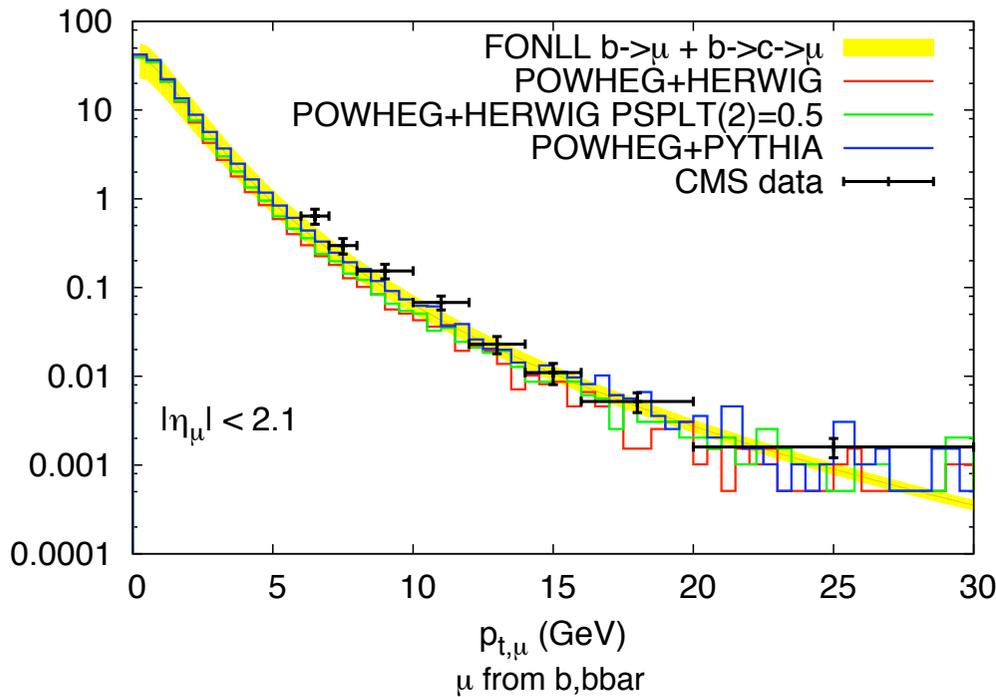
Lessons from Tevatron and RHIC

- ▶ NLO QCD predicts correctly the 'total' heavy quark bottom cross sections
- ▶ Non-perturbative fragmentation extracted from CLEO/BELLE and LEP predicts correctly the differential distributions

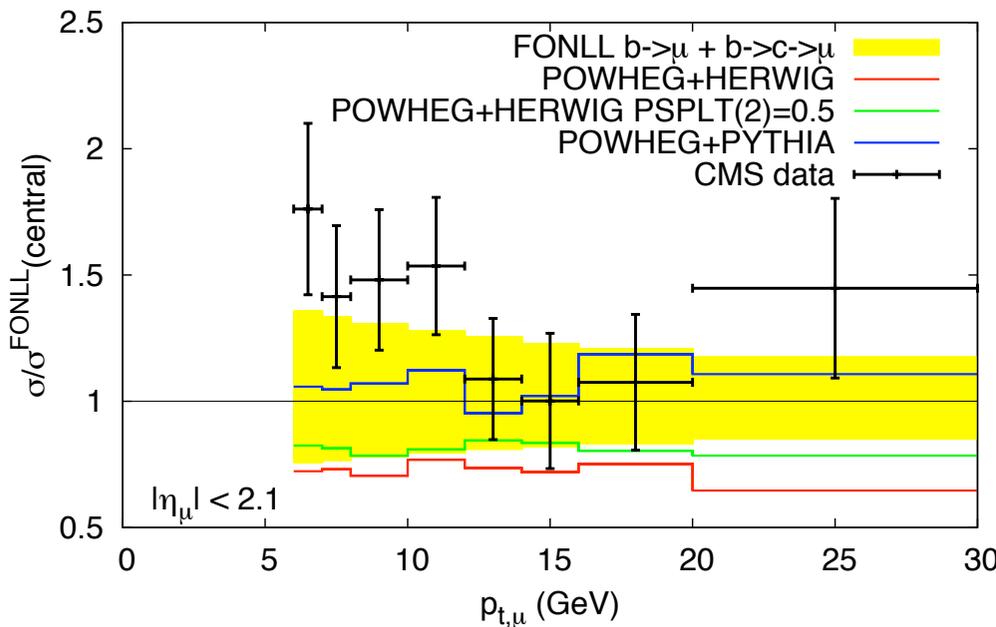
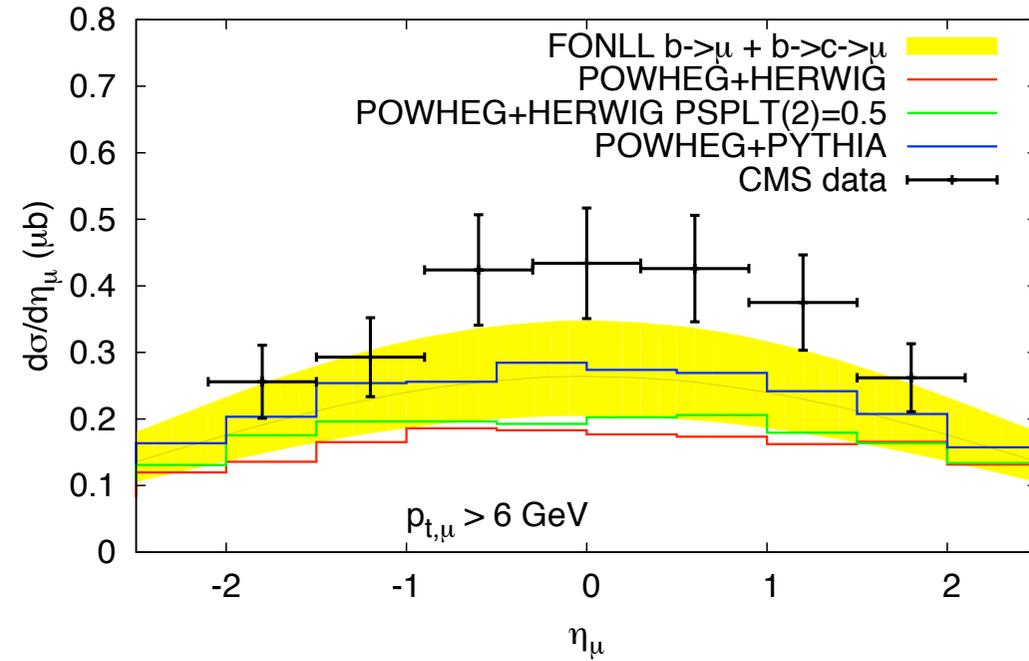
First results from LHC

bottom @ CMS

μ from b,bbar



μ from b,bbar



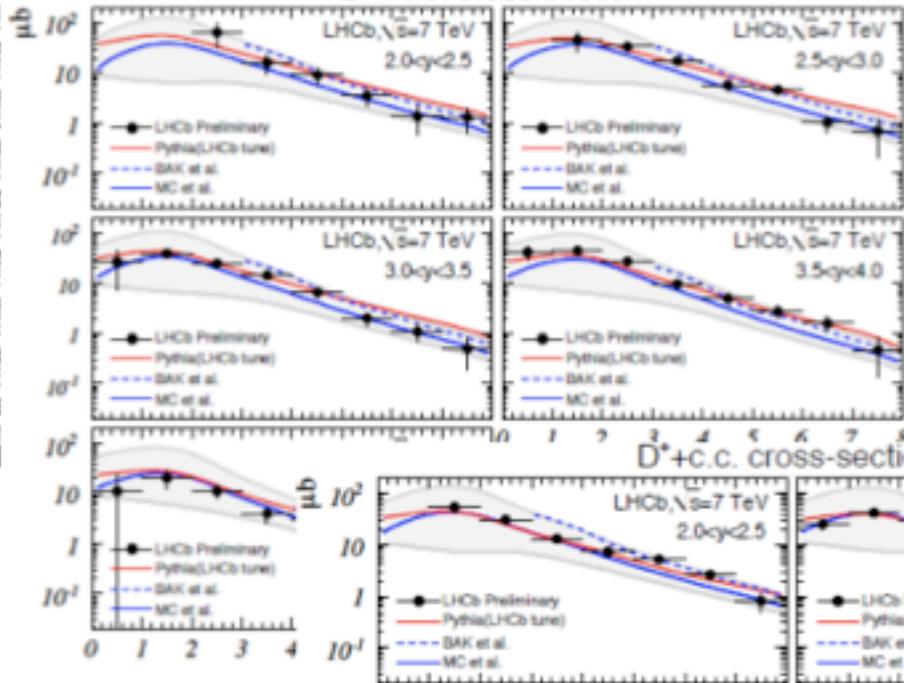
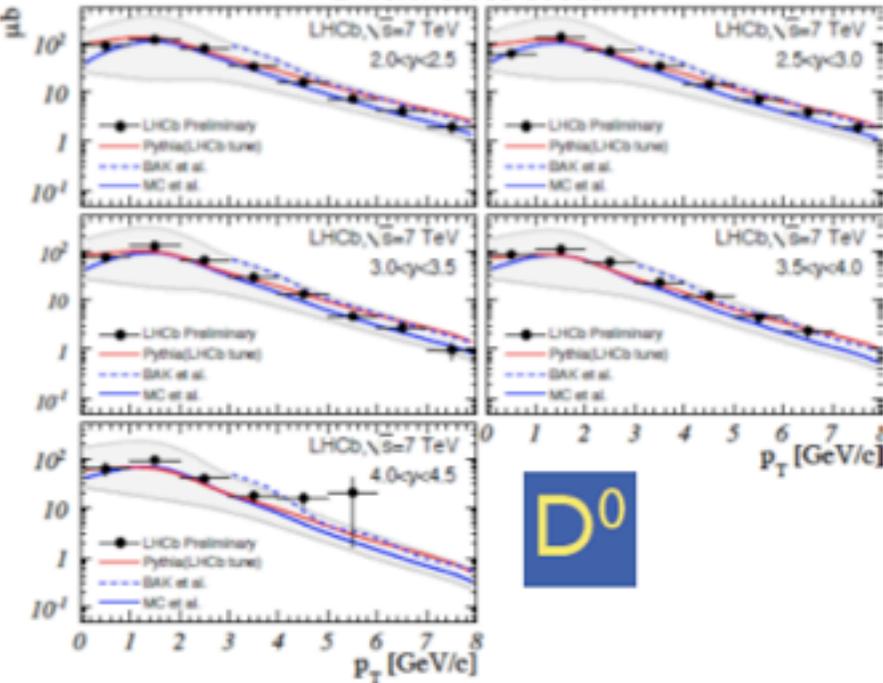
- ▶ FONLL and POWHEG+PYTHIA perfectly compatible
- ▶ CMS slightly high, but compatible within uncertainties

Open charm cross-sections

D^{*+}

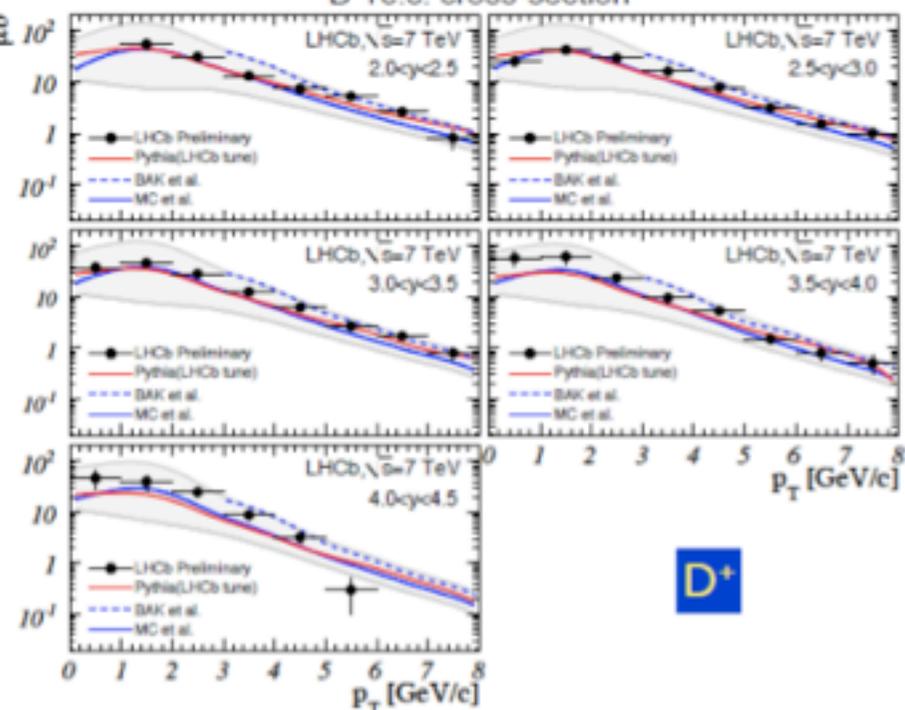
$D^0+c.c.$ cross-section

$D^{*+}+c.c.$ cross-section



Extrapolating to all p_T and 4 can also confirm the expectation on ratio at $\sqrt{s}=7\text{TeV}$
 $(pp \rightarrow c\bar{c}X) \approx 20 \times (pp \rightarrow b\bar{b}X)$

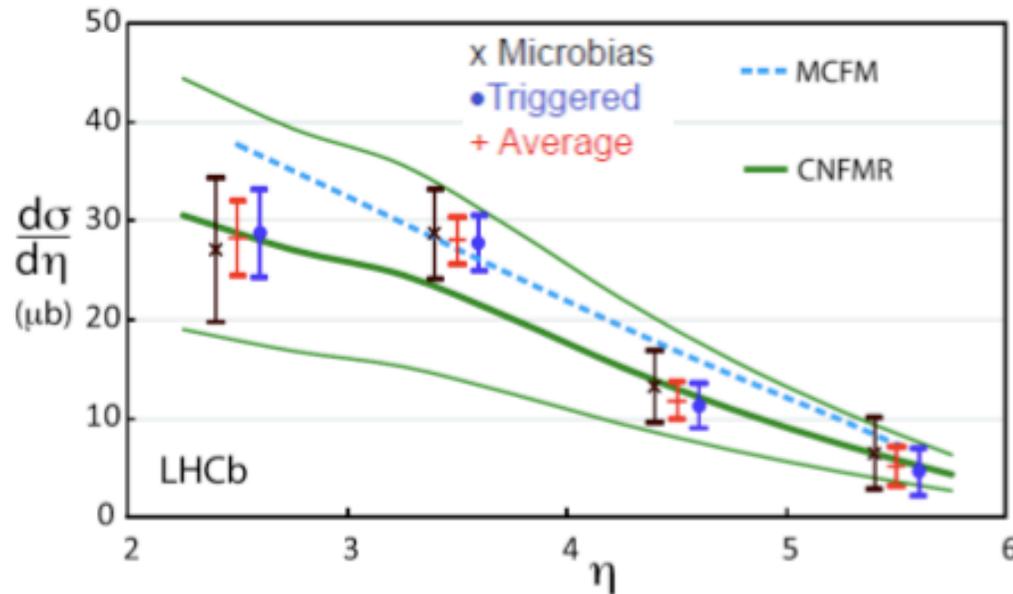
→ Good news for LHCb charm program



Beauty cross-section with $B \rightarrow D^0 X$



Cross section in four η bins, open trigger ($\sim 3 \text{ nb}^{-1}$) and muon trigger sample ($\sim 12 \text{ nb}^{-1}$) submitted to PLB (arXiv:1009.2731)



Shapes and scales agree well with expectation. Validates QCD predictions at LHC energies

$$\langle \sigma(pp \rightarrow H_b X) \rangle = 75.3 \pm 5.4 \pm 13.0 \mu\text{b} \quad \text{for } 2 < \eta < 6, \text{ any } p_T, \sqrt{s} = 7 \text{ TeV}$$

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

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: normalization is a genuine prediction (not necessarily the case in PYTHIA)

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- ▶ Non-perturbative contributions under control. Residual uncertainties mainly of perturbative origin

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- ▶ 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 may need more work