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Charm and Bottom Production at RHIC

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LPTHE - Paris 6

Outline

- FONLL
- Motivations for heavy quark predictions at RHIC
- Results [MC, P. Nason and R. Vogt, hep-ph/0502203]
  [N. Armesto, MC, A. Dainese, C. Salgado and U. Wiedemann, hep-ph/0511257]

FONLL features

(MC, M. Greco, S. Frixione, P. Nason)
http://home.cern.ch/cacciari/FONLL

FONLL (Fixed Order plus Next-to-Leading Logarithms) is a code for calculating double-differential, **single inclusive** heavy quark production cross sections in pp(bar) and (electro)photoproduction

FONLL merges the **massive NLO calculation** with the **NLL resummation** of terms of collinear origin, $\alpha_S \log(p_T/m)$, which become large when $p_T >> m$

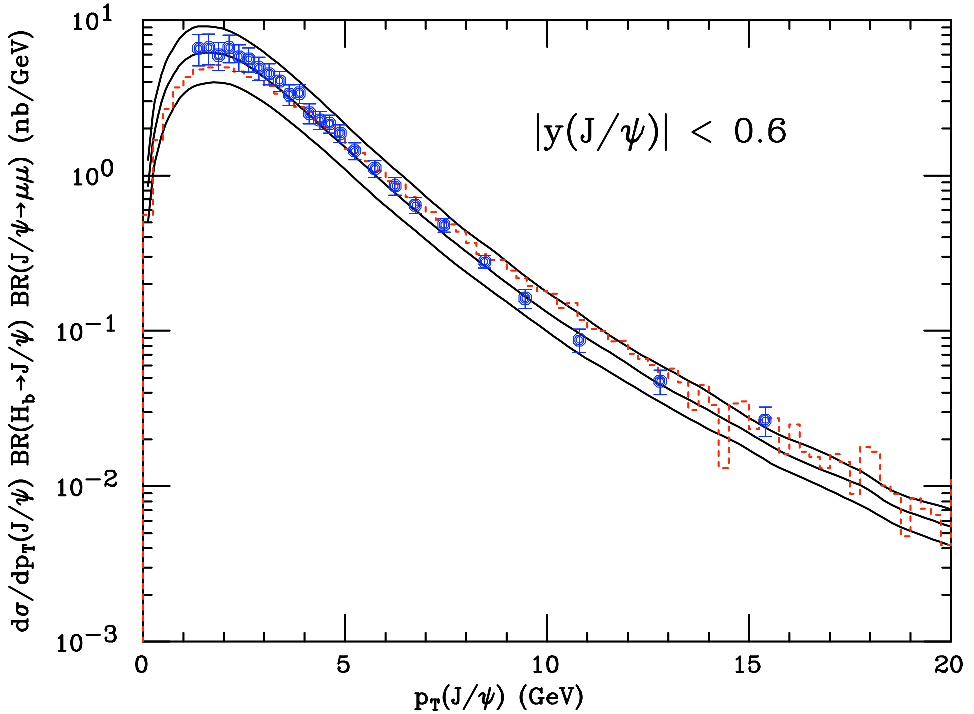
Advantages of the FONLL framework:

- The perturbative uncertainty does not increase when $p_T >> m$
- non-perturbative input describing the **quark-to-meson hadronization** can be extracted from e+e- data and included in predictions for hadronic collisions in a self-consistent way
- It predicts total heavy quark production rates according to NLO QCD. Not always the case with other approaches (e.g. GM-VFNS can predict the differential distributions for heavy hadrons, but needs to extract from e+e- data a normalization factor)

FONLL predictions

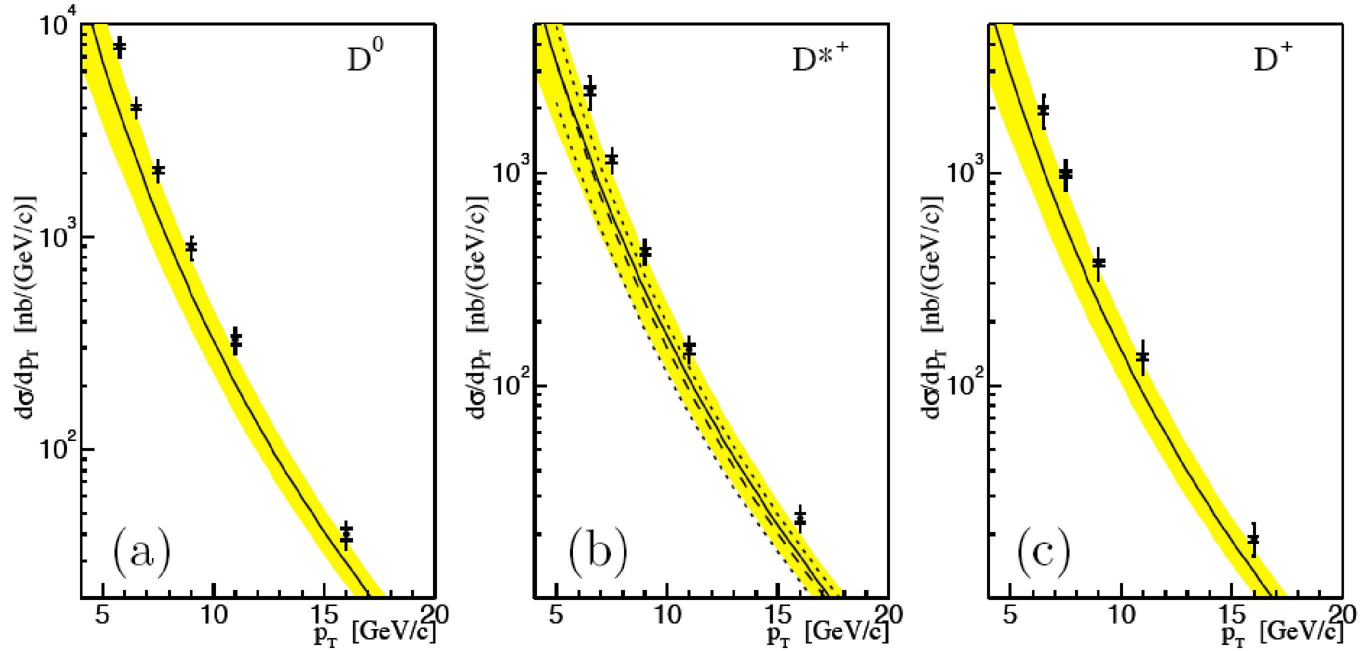
CDF Run II **b → B → J/ψ**

MC, Frixione, Mangano, Nason, Ridolfi, *JHEP* ***0407*** *(2004) 033*



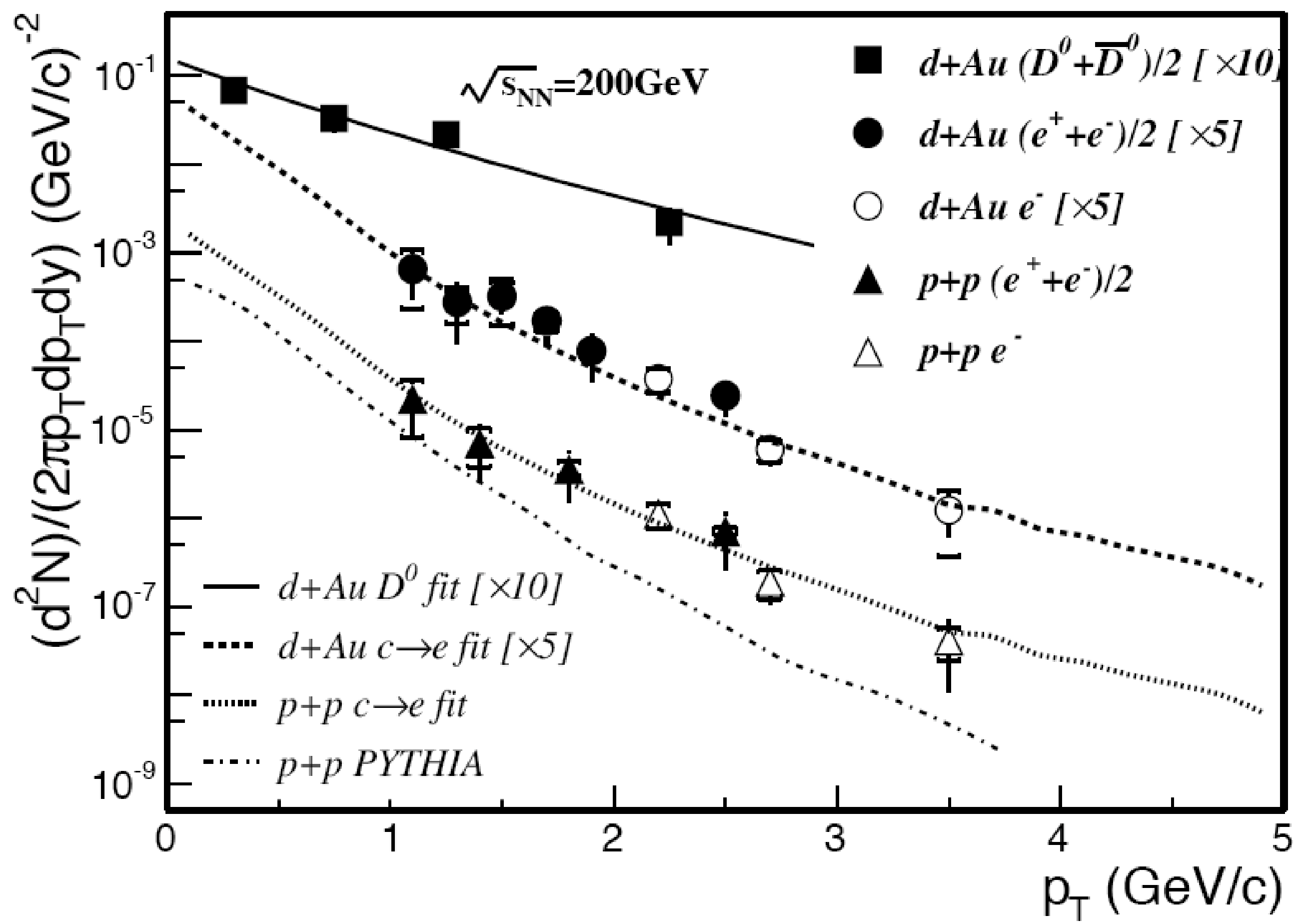
CDF Run II **c → D**

MC and P. Nason, *JHEP* ***0309*** *(2003) 006*



Motivations I: production yield

Recent data from RHIC have been analyzed by the PHENIX and STAR collaborations, yielding differential heavy quark production cross sections up to p_T ~ 5-10 GeV, often in the form of an **electron spectrum**



Most of the times, such data are only compared to empirical fits or to leading order Monte Carlo predictions, usually rescaled by some 'suitable' (and often large) fudge factor

Motivations I: production yield

The purpose of this work is:

1- to provide a **solid QCD benchmark** against which to compare **directly** the experimental data

2- to check if FONLL can describe these data as well as the Tevatron ones

We implement (Q = c **and** b):

$$pp \stackrel{pQCD}{\longrightarrow} Q \stackrel{NP fragm.}{\longrightarrow} H_Q \stackrel{decay}{\longrightarrow} e \quad \rightarrow \quad \frac{d\sigma(Q \to H_Q \to e)}{dp_T} = \frac{d\sigma(Q)}{d\hat{p}_T} \otimes f(Q \to H_Q) \otimes g(H_Q \to e)$$

The most up-to-date ingredients, both at the perturbative (HVQ production) and non-perturbative (HVQ hadronization) level, are employed.

Motivations II: relative charm/bottom yield

Heavy ion collisions show the phenomenon of **quenching**: the production of hadrons at large transverse momentum is suppressed due to their passage through the nuclear matter after production in the hard interaction

Observation/prediction of the quenching ratio

$$R_{AB}(p_T) = \frac{\left.\frac{\mathrm{d}N^{AB\to h}_{\mathrm{medium}}}{\mathrm{d}p_T\,\mathrm{d}y}\right|_{y=0}}{\langle N^{AB}_{\mathrm{coll}}\rangle \left.\frac{\mathrm{d}N^{pp\to h}_{\mathrm{vacuum}}}{\mathrm{d}p_T\,\mathrm{d}y}\right|_{y=0}}$$

represents one of the important issues in heavy ion physics

The calculation of the quenching ratio for electrons coming from heavy quarks depends critically on the relative charm/bottom yield. Hence the need for an accurate prediction of their respective production cross sections

More on this later on

Three Steps:

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

1. Perturbative QCD

Next-to-Leading Order + Next-to-Leading Log resummation: FONLL
Inputs: charm (1.5 ± 0.2 GeV) and bottom (4.75 ± 0.25 GeV) masses, strong coupling ($\alpha_s(M_Z) = 0.118$)

2. Non-Perturbative QCD

Proton Parton Distribution Functions (CTEQ6M)
Heavy Quark Fragmentation functions: extracted from LEP data.

NB. **NOT** Peterson

3. Weak Decay

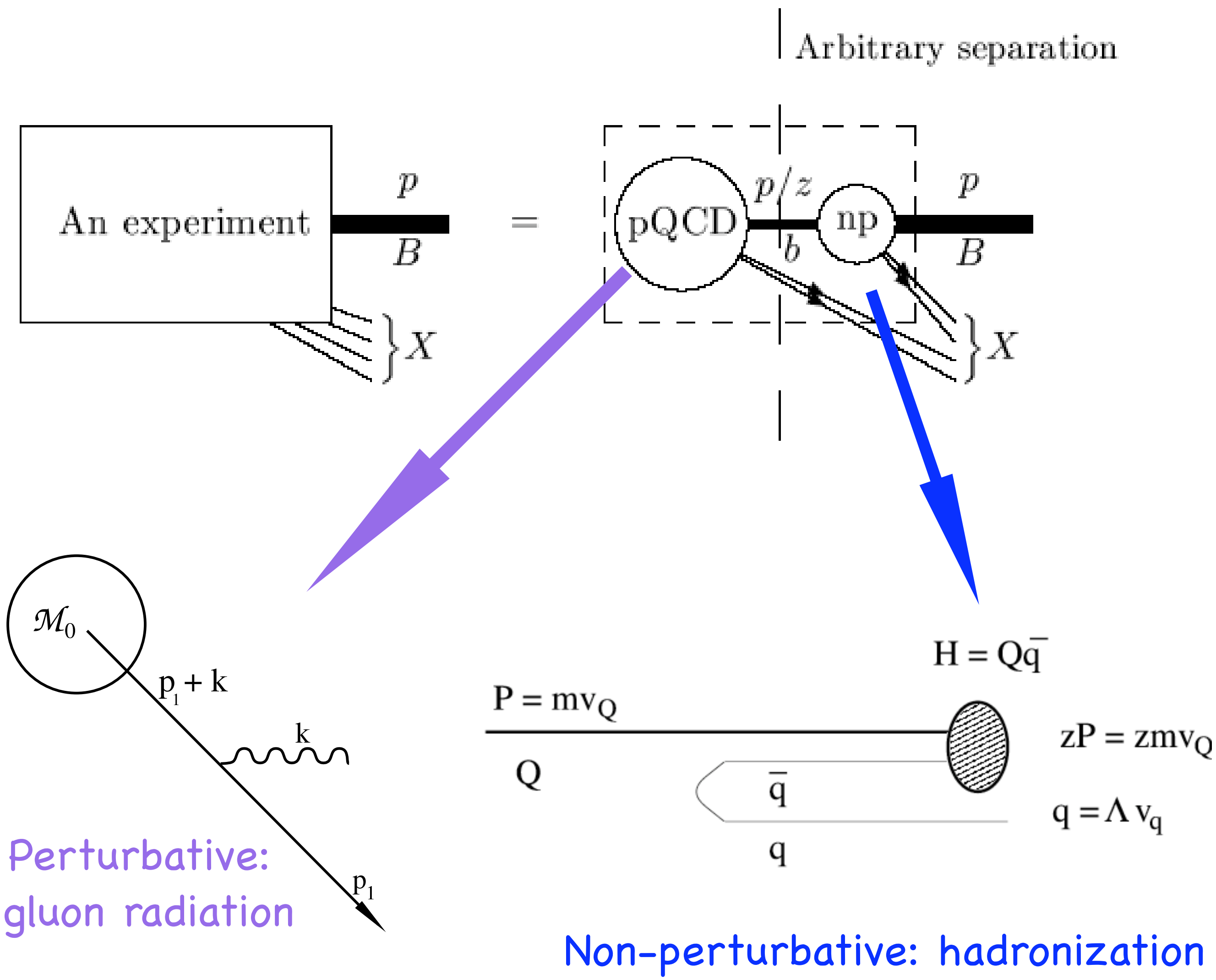
Decay spectra measured by CLEO and BaBar. Phenomenological fit used.
Branching fractions, heavy meson masses taken from PDG.

NB. Last but most important: we shall estimate **theoretical uncertainties**, so as to be able to compare to data and quantify likelihood of seeing an agreement or a disagreement. The predictions will be presented in the form of a **theoretical uncertainty band**

Non-perturbative fragmentation

Besides improving pQCD, FONLL (or, rather, collinear log resummation) allows to **consistently extract** from data non-perturbative information regarding the **heavy quark → heavy meson fragmentation**

In fact, there is an unavoidable interplay between the perturbative and the non-perturbative fragmentation processes:



Not being the c/b quark a physical particle, **the non-perturbative fragmentation function cannot be a physical observable**: its details depend on the perturbative calculation it is interfaced with.

A single fragmentation function cannot do for all calculations

Extraction of the non-perturbative component

Three issues are therefore important:

1. The perturbative description (and its parameters) used in extracting the FF must match the one used in calculating predictions using the FF

2. Try to extract as universal as possible non-perturbative FFs. Resumming the perturbative collinear logarithms via FONLL (large at LEP: log(√S/m)) helps doing precisely this

3. Because of the steep slope of transverse momentum distributions in hadron-hadron collisions, higher moments of the FF are actually more important than its x-space shape:

Assuming $\frac{d\sigma}{d\hat{p}_T} \sim \frac{1}{\hat{p}_T^N}$ we get $\frac{d\sigma}{dp_T} \sim \int \frac{dz}{z} (\frac{z}{\hat{p}_T})^N f(z) = f_N \frac{d\sigma}{d\hat{p}_T}$

Heavy **quark** spectrum, N typically ~ 4,5

Heavy **meson** spectrum

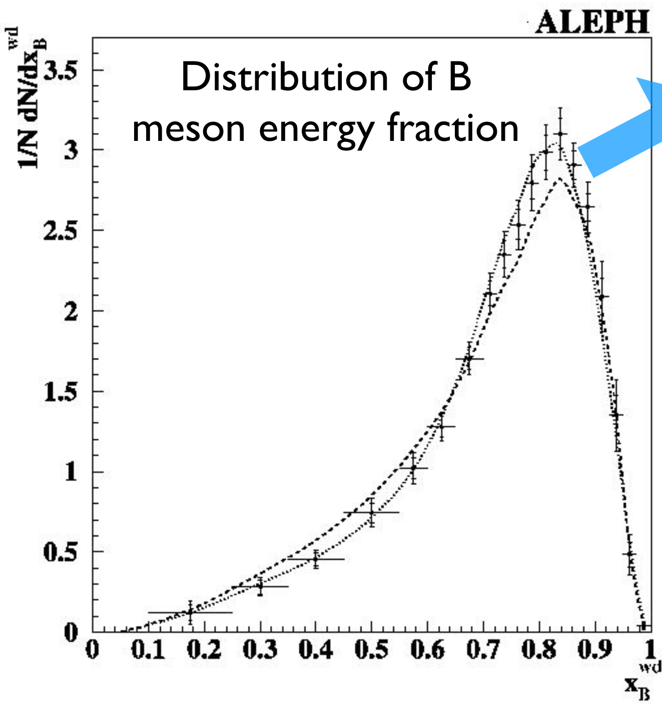
Mellin **moment** of the fragmentation function

Heavy **quark** spectrum

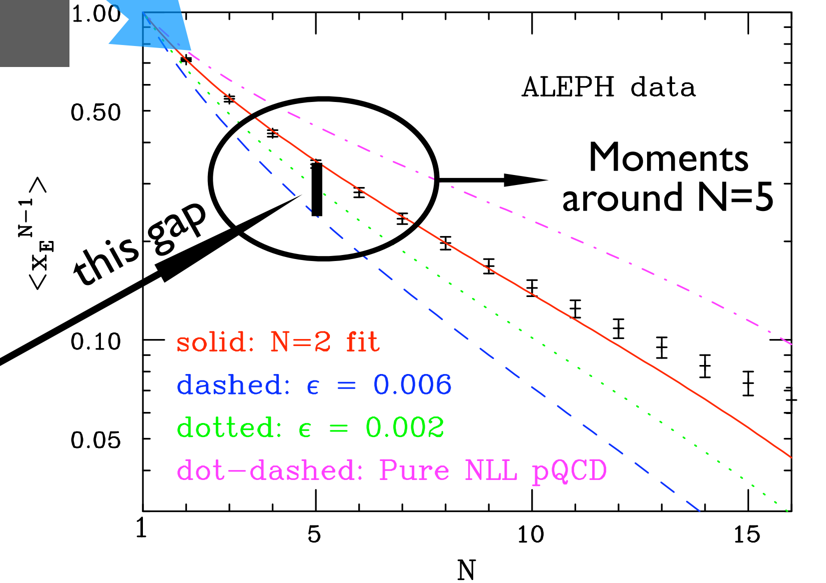
Fitting well the proper moments (N ~ 4-5) is therefore more important then describing the whole fragmentation spectrum in e+e- collisions, if the fragmentation function is then to be used for making predictions in hadronic collisions

Extraction of the non-perturbative component

Fit **moments** of LEP fragmentation data:



$$\langle x_E^{N-1}\rangle = \int_0^1 x_E^{N-1} f(x_E)\, dx_E$$



Note that Peterson with ϵ_b = 0.006 underestimates the moments around N=5. Its use will consequently underestimate the hadronic B cross section

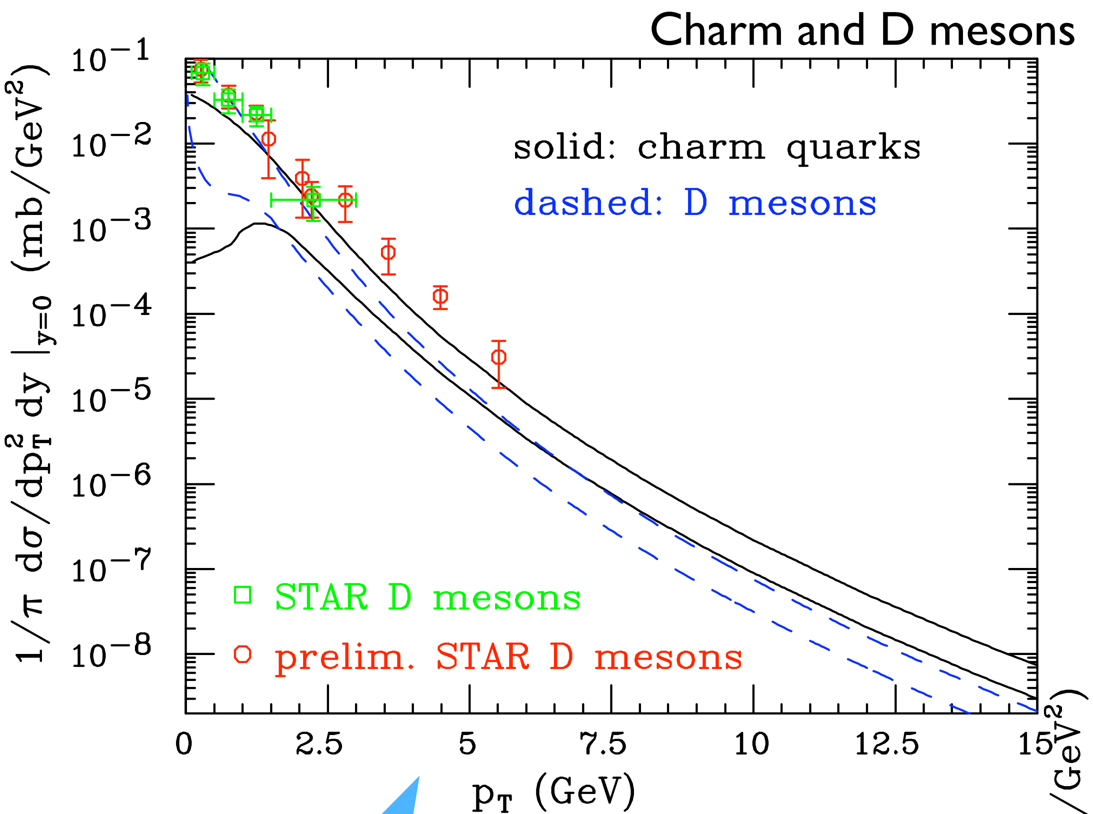
We don't fit this...... **...but rather this**

The fragmentation functions that we extract are specific to our FONLL framework.
For a comparison, they **roughly** correspond to Peterson et al. FF's with $\epsilon_c \approx$ **0.005** and $\epsilon_b \approx$ **0.0005**

⇒ quite harder than 'usual' values $\epsilon_c \approx 0.06$ and $\epsilon_b \approx 0.006$

⇒ hadronic cross sections will be larger (cfr. Ramona Vogt's observation that bare quark distributions for charm - i.e. delta function-like FF - seem to agree better with RHIC data)

How these tools fare at RHIC

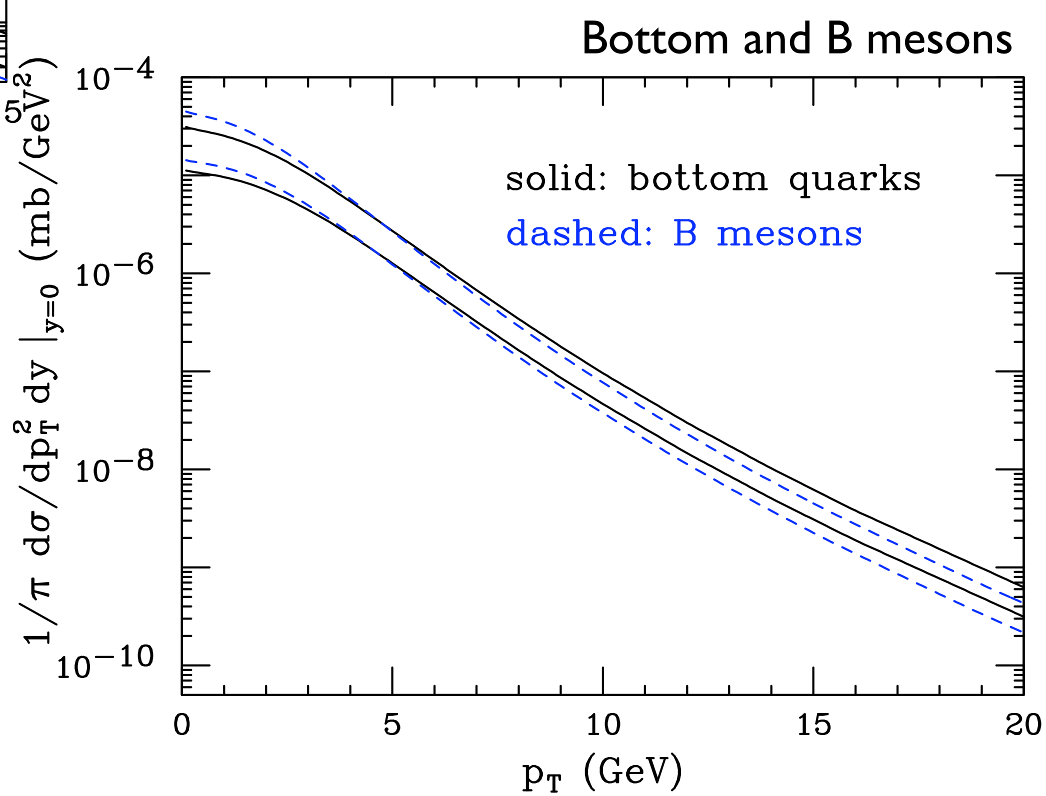


Charm and bottom @ RHIC

[MC, P. Nason, R. Vogt, hep-ph/0502203]

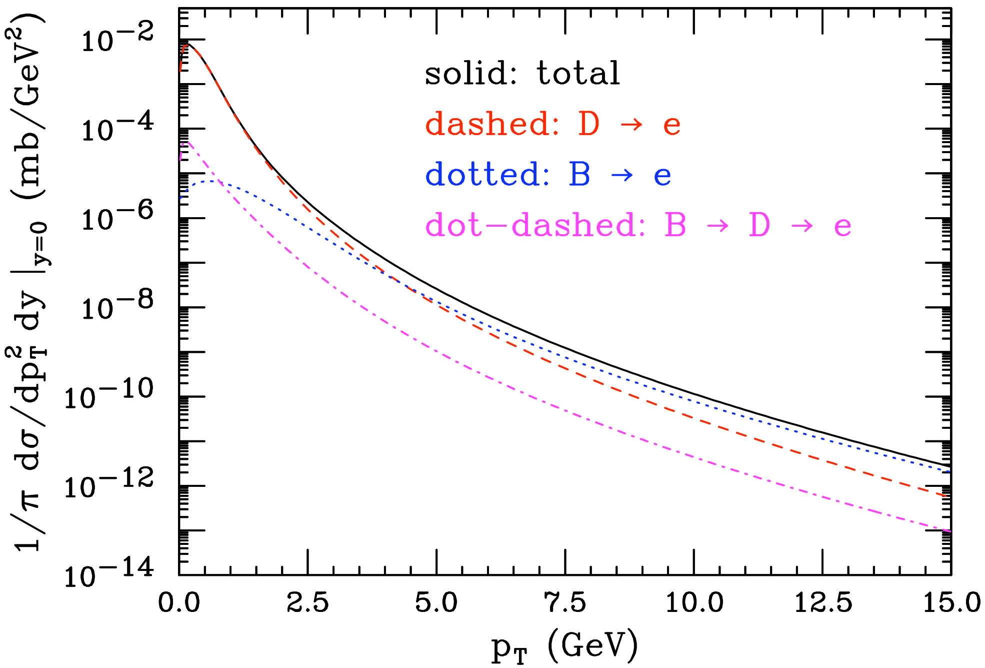
NB. No nuclear effects in these predictions.
Just a `perturbative QCD' benchmark

D mesons predictions compared to STAR data

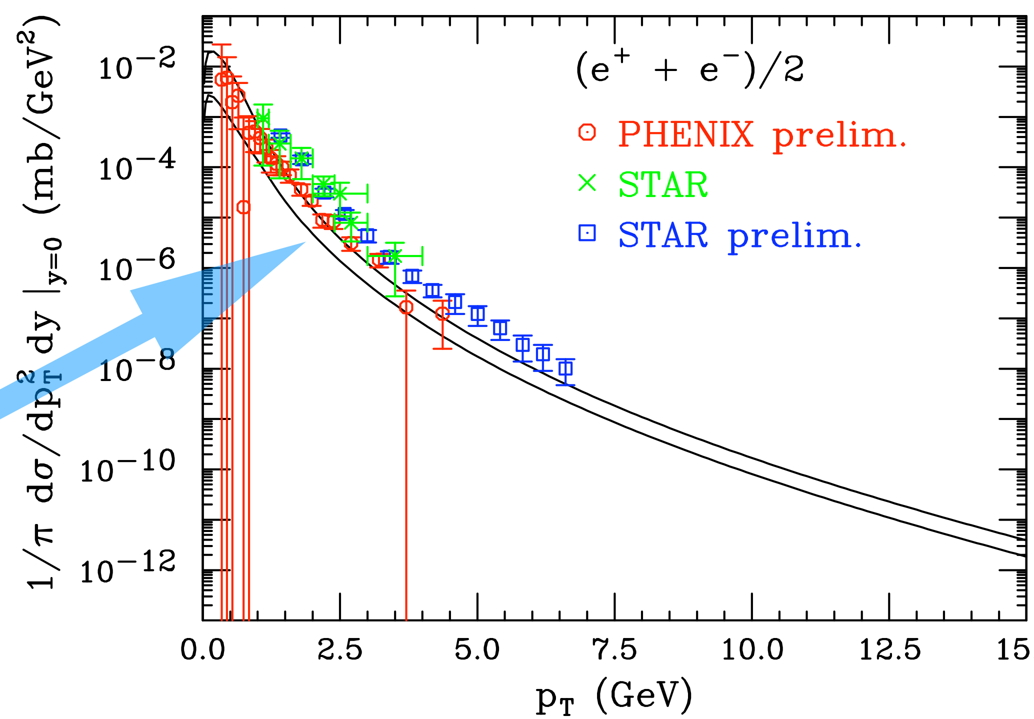


Electrons from Heavy Quarks @ RHIC

[MC, P. Nason, R. Vogt, hep-ph/0502203]



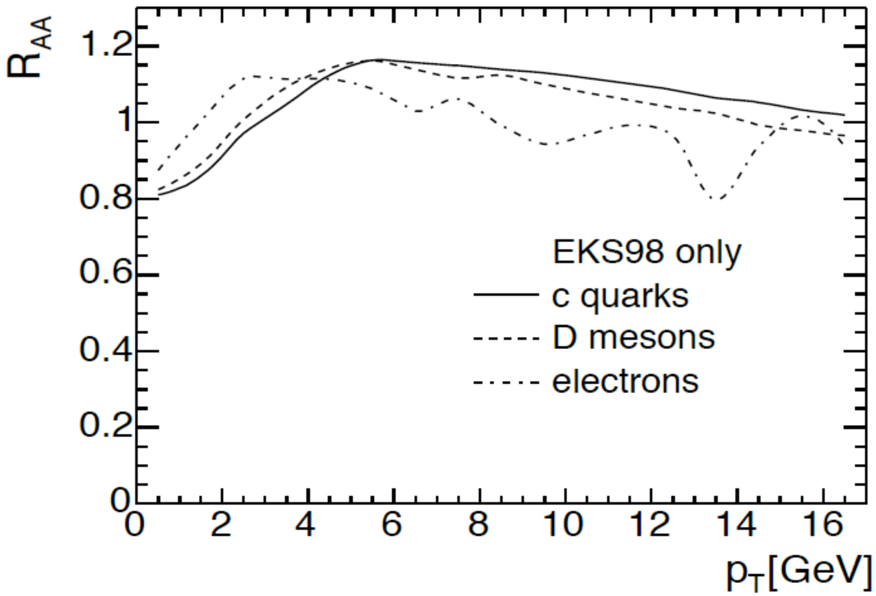
$$pp \xrightarrow{pQCD} Q \xrightarrow{NP\,fragm.} H_Q \xrightarrow{decay} e$$



Experimental results compared at the electron level: no deconvolutions needed, no LO Monte Carlo used, normalization is absolute (to NLO QCD accuracy)

From pp to AA

Initial state: nuclear modification of parton distribution functions

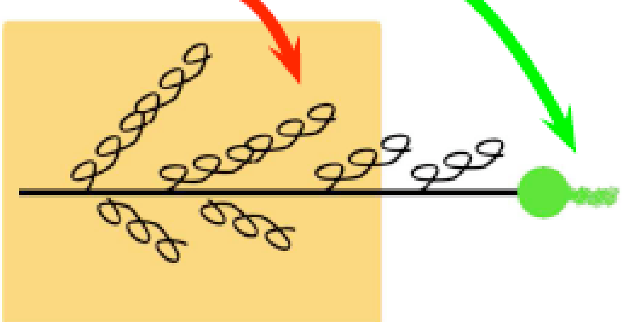


O(10-20%) effect max. Often negligible with respect to other matter effects

EKS98 available in FONLL as of version 1.2

Final state: energy loss enhanced by interaction with matter

$$d\sigma^{AA\to h+X}_{(\mathrm{med})} = \sum_f d\sigma^{AA\to f+X}_{(\mathrm{vac})} \otimes \boxed{P_f(\Delta E, L, \hat{q})} \otimes D^{(\mathrm{vac})}_{f\to h}(z, \mu_F^2)\,.$$



Quenching weights

[Armesto, Dainese, Salgado, Wiedemann, hep-ph/0501225]

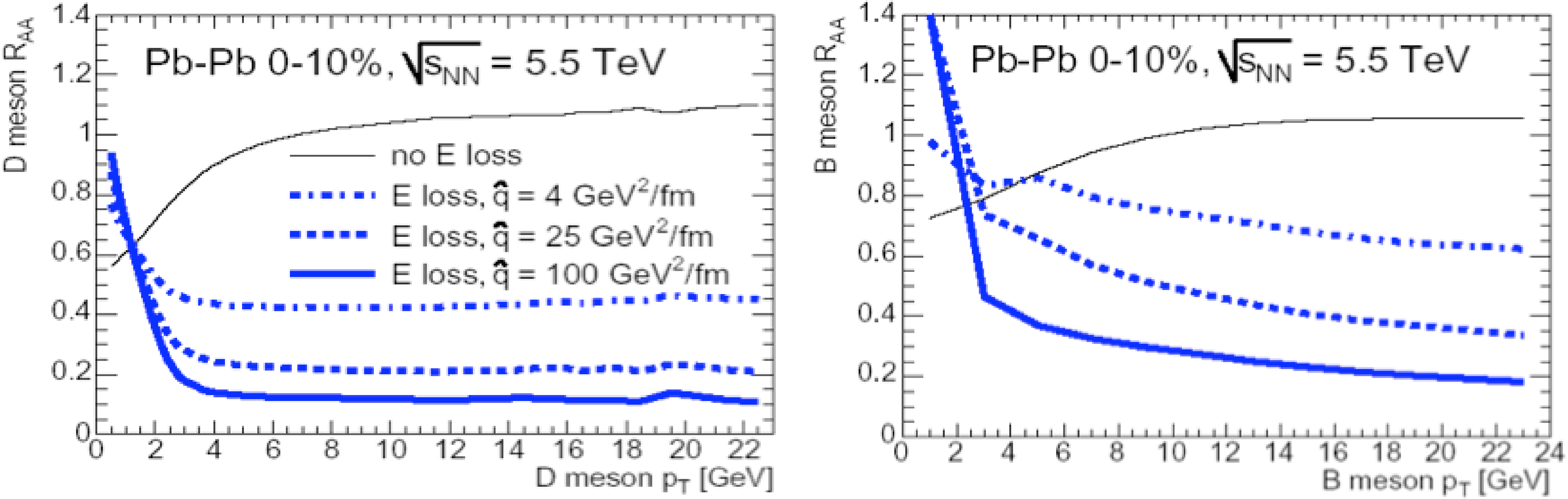
Quenching in Pb-Pb collisions @ LHC

$$R_{AB}(p_T) = \frac{\left.\frac{\mathrm{d}N^{AB\to h}_{\mathrm{medium}}}{\mathrm{d}p_T\,\mathrm{d}y}\right|_{y=0}}{\langle N^{AB}_{\mathrm{coll}}\rangle \left.\frac{\mathrm{d}N^{pp\to h}_{\mathrm{vacuum}}}{\mathrm{d}p_T\,\mathrm{d}y}\right|_{y=0}}$$

Couldn't find plot for RHIC, apologies. Same qualitative behaviour

Charm

Bottom

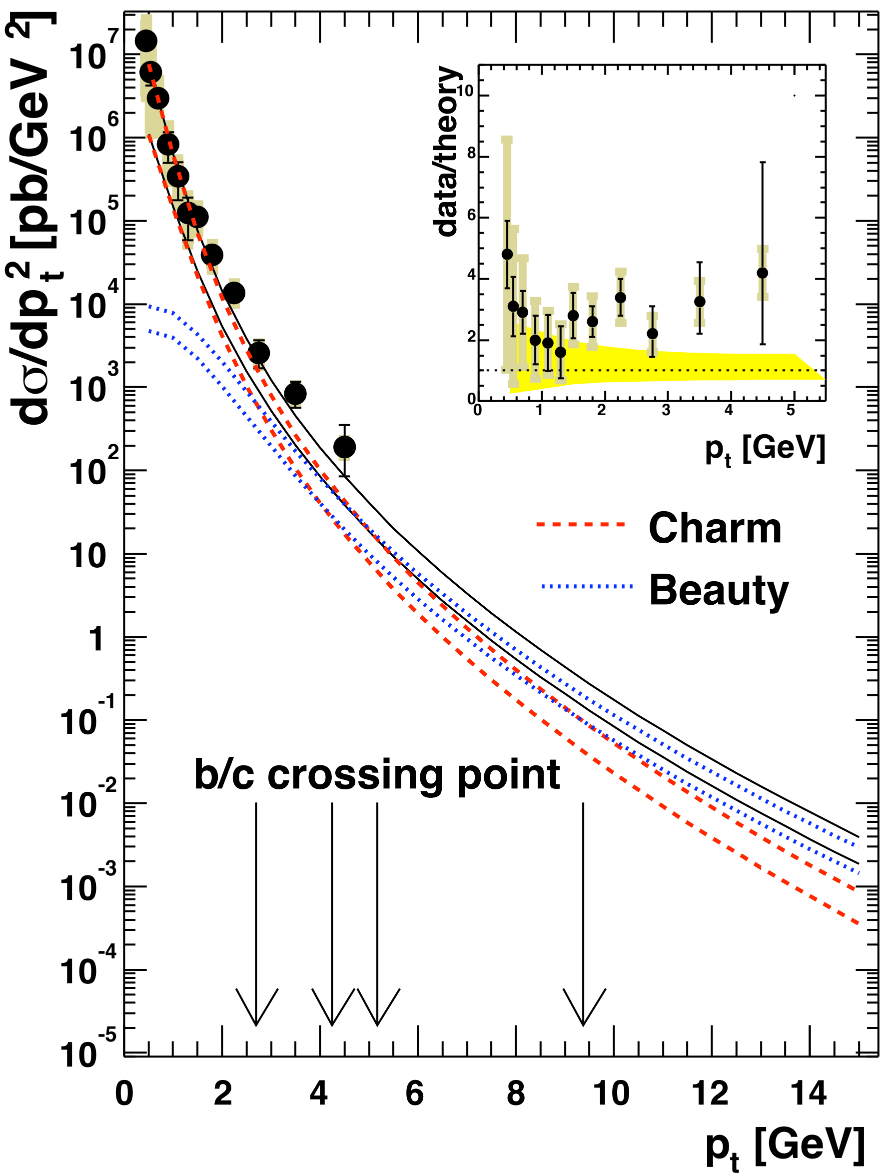


Bottom is less suppressed than charm, due to its larger mass

N.B. size of effect, up to 80%

Charm and bottom production @ RHIC

How well can be predict the relative contribution of charm and bottom to the electron yield?

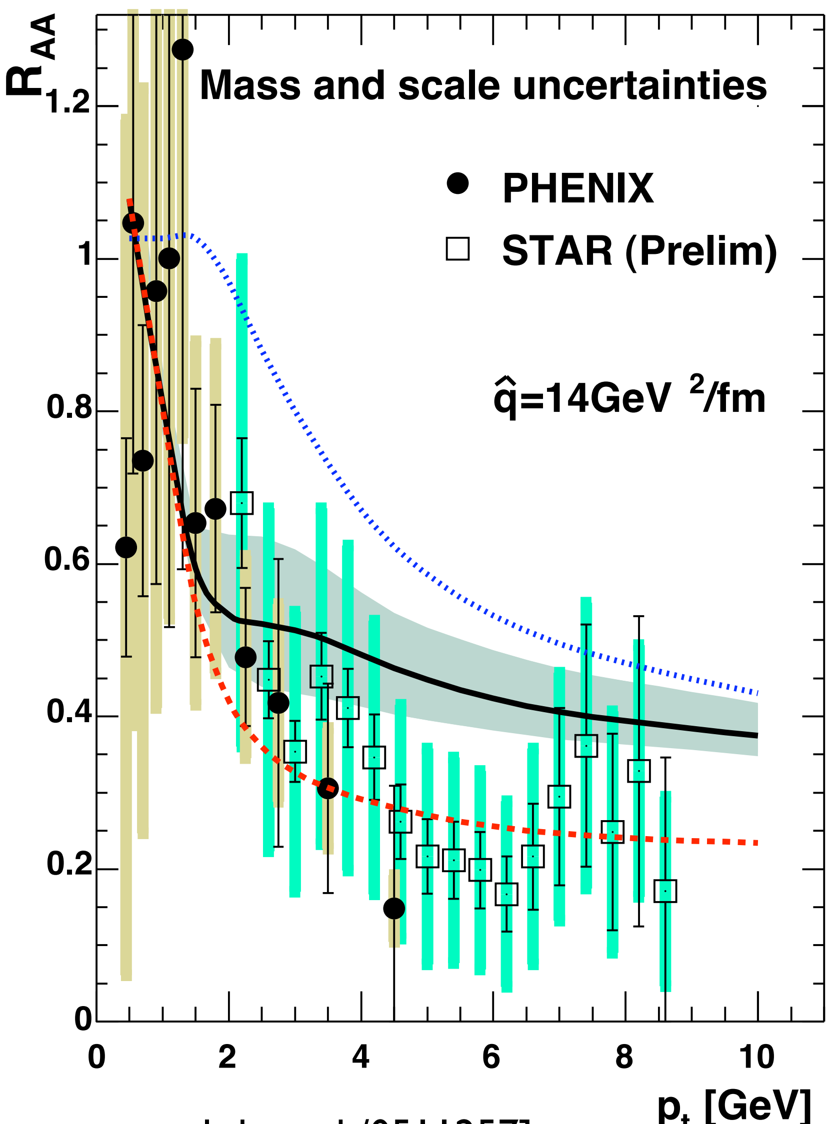


The slope of the charm and bottom contribution is fairly similar: the crossing point easily moves, though the relative contributions are less affected by uncertainties

NB. Especially for bottom the transverse momentum is small: the use of the standard factorization picture will yield an additional uncertainty beyond the ‘perturbative’ ones

R_{AA} for charm and bottom @ RHIC

The charm and bottom spectra easily translate into R_{AA} via the application of quenching weights



[Armesto et al., hep-ph/0511257]

The uncertainty on the charm and bottom relative contribution reflects on an uncertainty of order 0.1-0.2 on R_{AA}

R_{AA} looks too high. However, remember the very large perturbative uncertainty on charm: the NNLO prediction could be quite larger.

Observation: if you normalize charm to the data R_{AA} comes out about right

Conclusions

- We have calculated QCD predictions for charm and bottom production at RHIC, also including fragmentation to D and B mesons and their decay to electrons
- These predictions, which still neglect matter effects, include all the available knowledge for calculating heavy quark production in QCD, as implemented in the FONLL framework. They are not `just another model', and they also provide an estimate of the theoretical uncertainties
- FONLL predictions seem to agree well with Tevatron data for charm and bottom production. For Heavy Ion collisions they provide a **solid benchmark** against which to compare in the search for nuclear effects. Agreement with pp and dAu RHIC data is fair
- Matter effects can be added via modified PDF's and quenching weights. Energy loss as seen at RHIC in Au-Au collisions roughly reproduced, but pQCD control of charm/bottom relative contributions still limited
- Final note: given the size of intrinsic pQCD uncertainty, it is very unlikely that effects of the order of a few (tens of) percent will ever be visible just by comparing to the absolute value of the cross sections