Heavy Flavour Production, QCD, and the Quark-Photon Coupling

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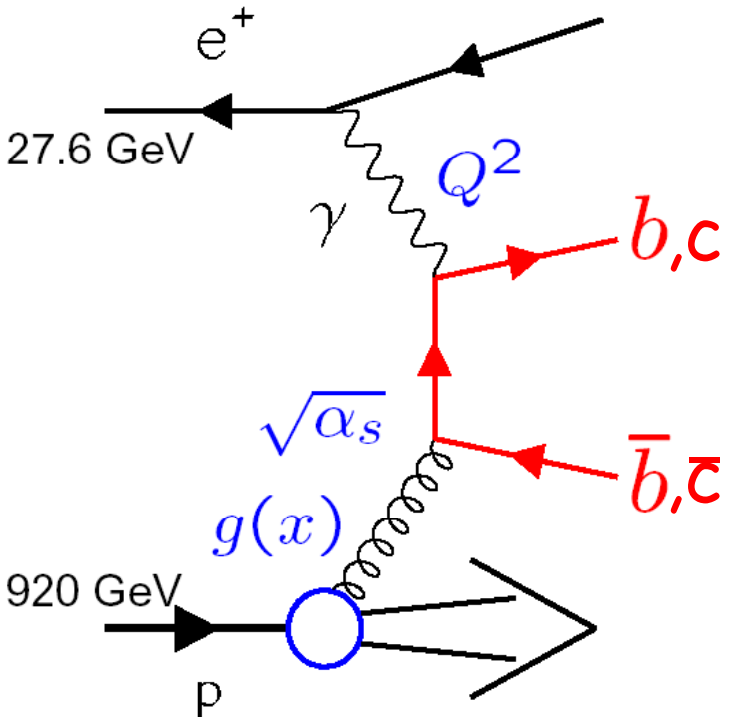
- Introduction: Heavy Quark photoproduction
- Choice of renormalization/factorization scales in QCD:
  Phenomenological considerations and cross checks with data
  Plea for a change of default QCD scale for NLO calculations
- Speculation on photon-quark coupling
- Conclusions

Photoproduction of Open Heavy Flavour

Dominant production process in ep-collisions: Boson-Gluon -Fusion



- Driven by gluons in the proton
- Relevant scales:

m_b $\sim$ 5 GeV, m_c ~ 1.5 GeV

Q^2 $\lesssim$ 1 GeV^2 $\rightarrow \gamma p$

$>$ 2 GeV^2 $\rightarrow$ DIS

$p_T^{b,c}$ Event selection: $p_t^{jet} > 6$ or 7 GeV

multiscale problem

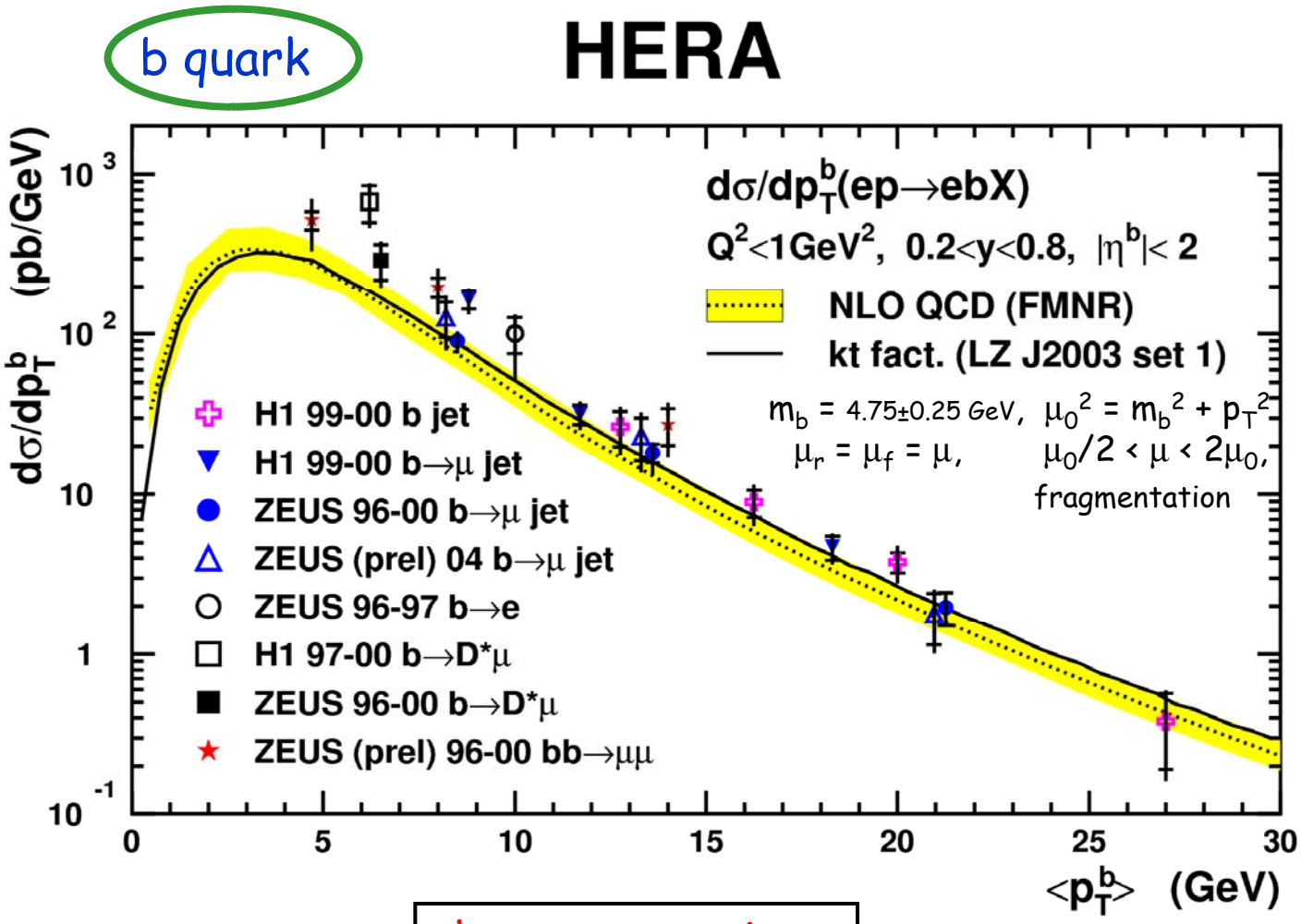
-> terms $[\alpha_s \ln (Q^2/m_Q^2)]^n$, $[\alpha_s \ln (p_T^2/m_Q^2)]^n$, etc.

in perturbative expansion -> potentially large th. errors

Beauty in photoproduction: summary

details->talk J. Loizides

b quark



data/QCD:

reasonable agreement, but tendency data > QCD at low p_T

theory uncertainty underestimated?

scale choice often dominant theoretical error

How well do we understand choice of QCD scales?

(issue also raised e.g. in talk G. Grindhammer)

remarks on QCD scale dependence

- Ideally (calculation to all orders) QCD predictions should not depend on the choice of **renormalization and factorization scales** μ_r, μ_f
  => **not physical parameters** => can not be determined from data

- In practice, finite order calculations **do** depend on choice of these scales
  = reference points for perturbative expansion (Taylor expansion)

- **Choice of scale is to large extent arbitrary**.
  Best solution is case by case evaluation of sensible scales, and detailed study of behaviour of cross section with respect to variation of these scales.

- In practice often replaced by **simple recipes**. Overinterpretation might lead to premature conclusions that data/QCD predictions do not agree.

- If recipes at all, at least try to use the "best"
  => try to evaluate performance

Common recipes for scale choice

Common sense criterion/try to minimize occurrence of large logs:

- => **1. choose "natural" scale of process involved** (m, Q^2, E_T, ...)
  but subscales (e.g. subdominant gluon radiation) often lower

nowadays often only criterion used

Two other textbook criteria from the late 80ies: **time for a revival?**

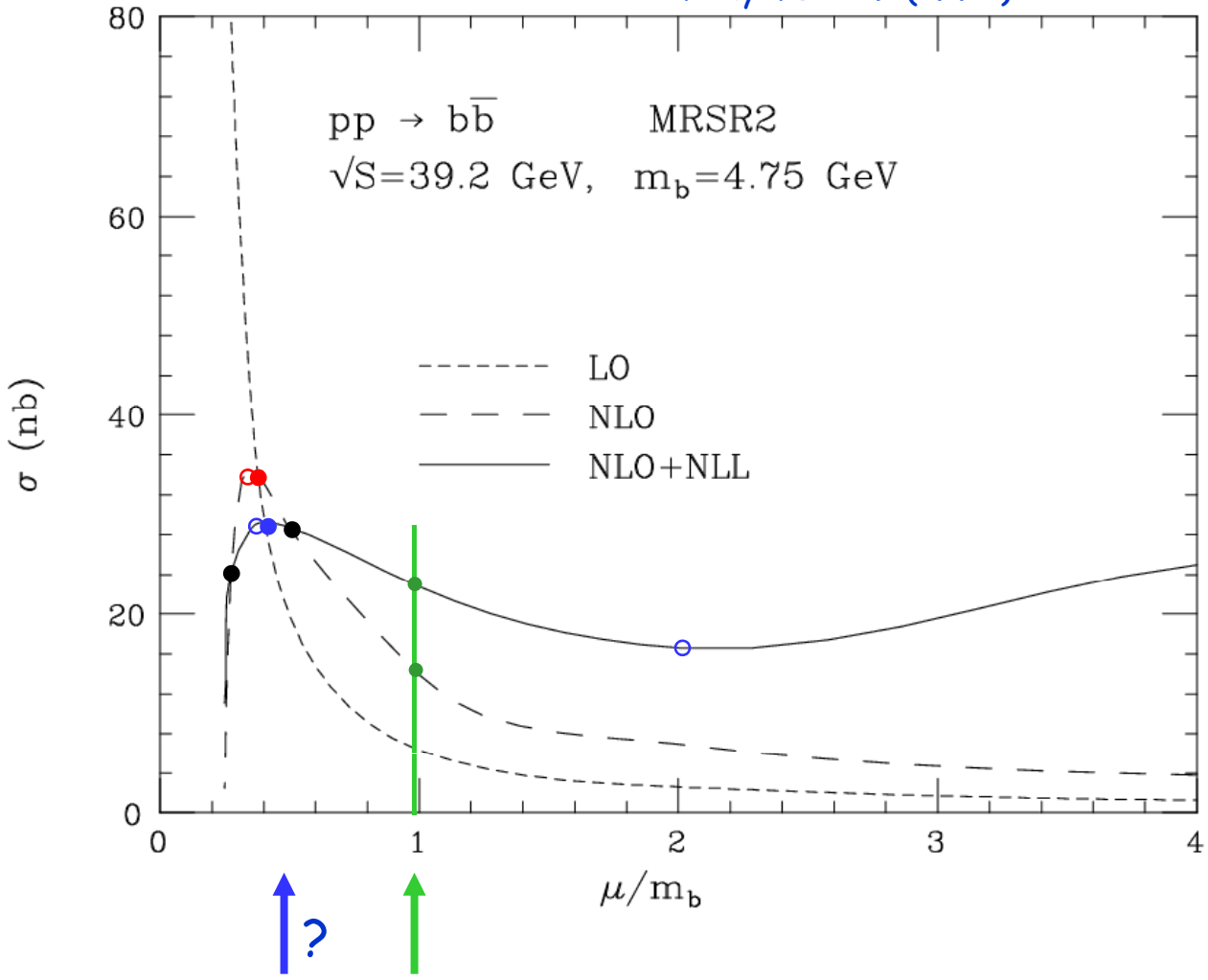
- principle of fastest apparent convergence: choice of scales such that, ideally, cross sections will not change when higher order corrections are included
  => **2. best bet: NLO = LO => hope: NNLO = NLO** **check!**
- principle of minimal sensitivity: minimize sensitivity to scale variations
  => **3. best bet: $d\sigma/d\mu = 0$ => hope: minimize NLO corrections**

- range of variation of scale is supposed to be a measure of theoretical error for uncalculated higher orders

- evaluate all three criteria to determine a "reasonable" choice

example: total b cross section at HERA-B

Bonciani, Catani, Mangano, Nason
Nucl. Phys. B 529 (1998) 424



NLO stability:

- NLO = LO
- $d\sigma_{NLO}/d\mu = 0$

NLO+NLL stability:

- NLO+NLL = LO
- NLO+NLL = NLO
- $d\sigma_{NLO+NLL}/d\mu = 0$

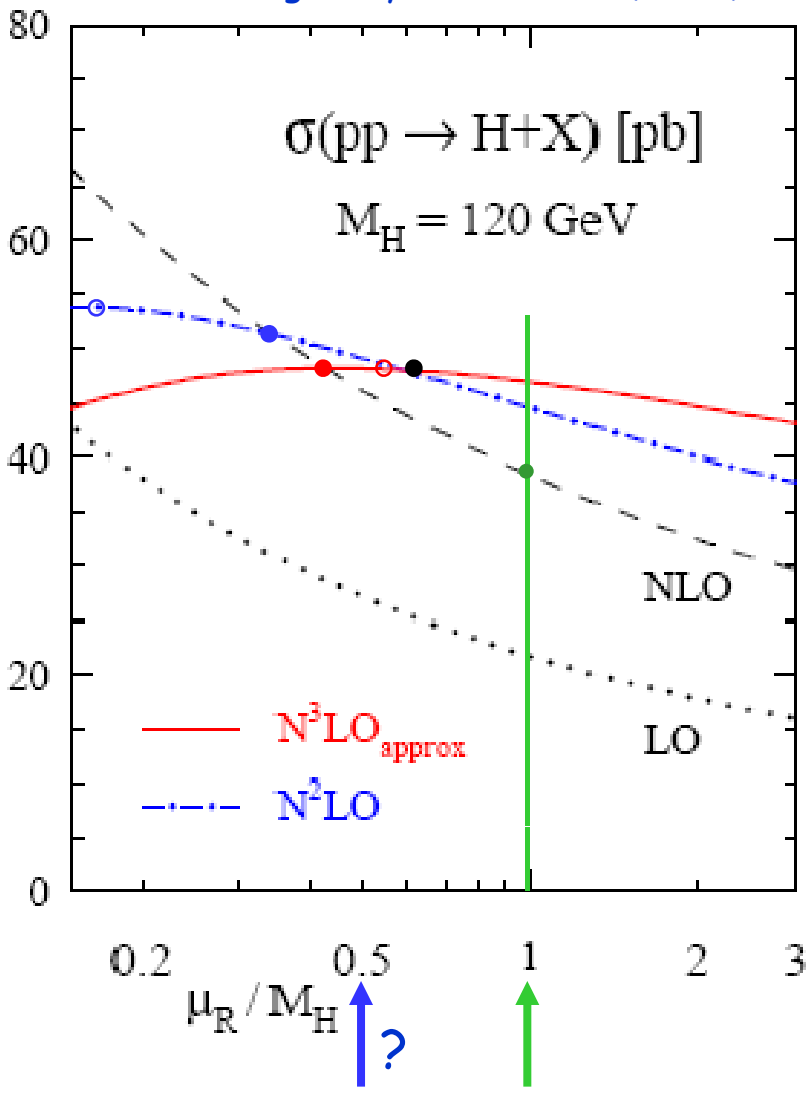
—— "natural" scale

in many cases, such solutions do not exist

=> consider those cases where they do

example: Higgs production at LHC

S. Moch, A. Vogt, Phys.Lett. B631 (2005) 48



NNLO stability:

- NNLO = NLO
  - $d\sigma_{NNLO}/d\mu = 0$

N³LO stability:

- N³LO = NLO
- N³LO = NNLO
  - $d\sigma_{NLO+NLL}/d\mu = 0$

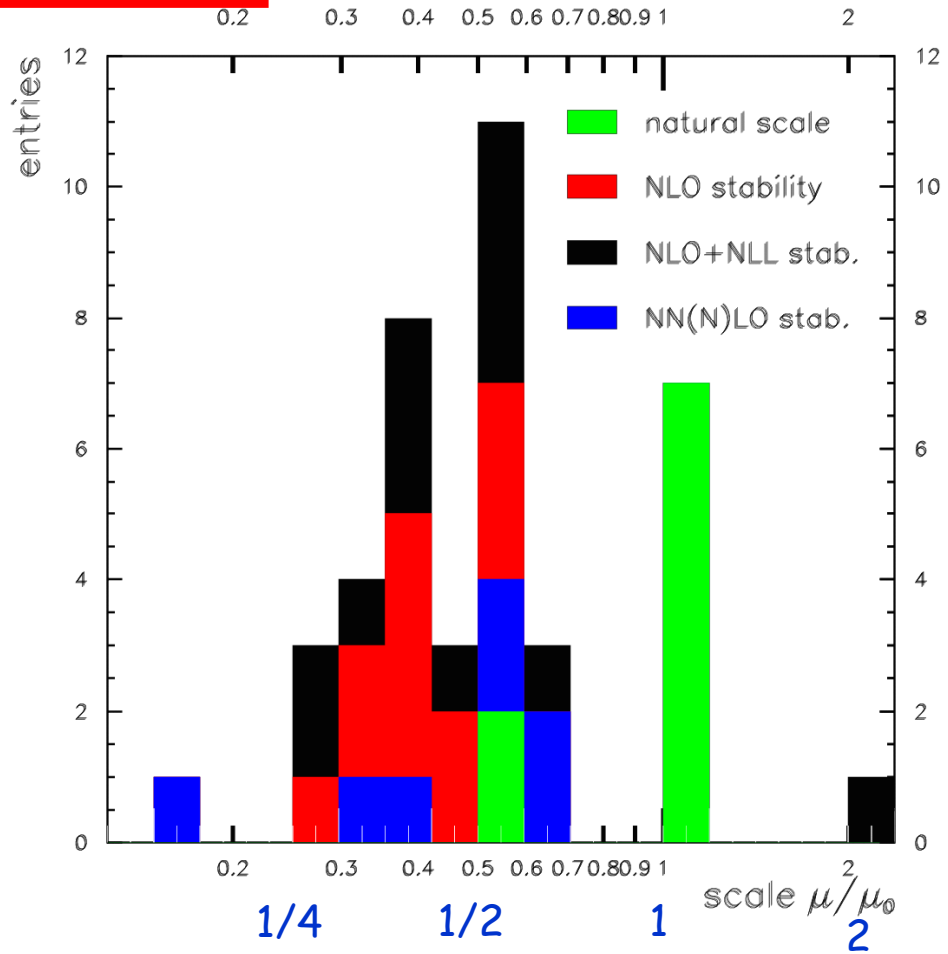
—— "natural" scale

NNLO/N3LO calculations, where available, support validity of scheme!

"optimal" ren./fact. scale from theory

$\mu_0/2 < \mu < 2\mu_0$ — "standard" scale range

$\mu_0/4 < \mu < \mu_0$ — **proposed new default**



NLO (NNLO) QCD survey of:

- beauty at Sp$\bar{p}$S, Tevatron, HERA-B
- top at Tevatron
- Z, H at LHC

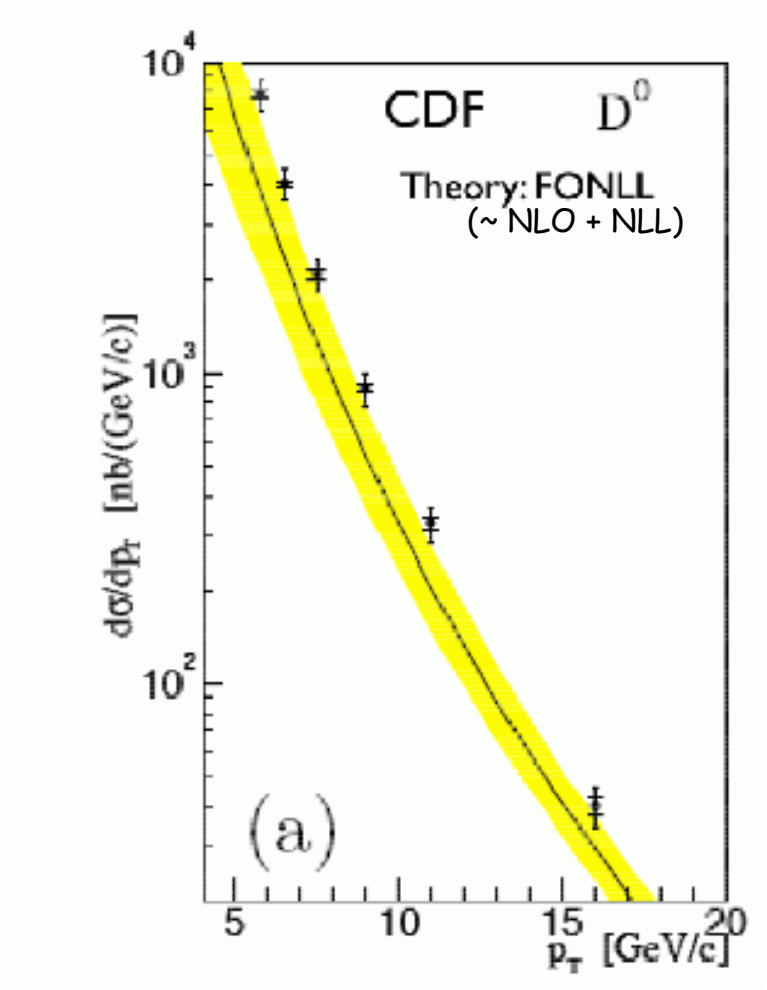
  $\mu_0^2 = m^2 (+ p_T^2)$

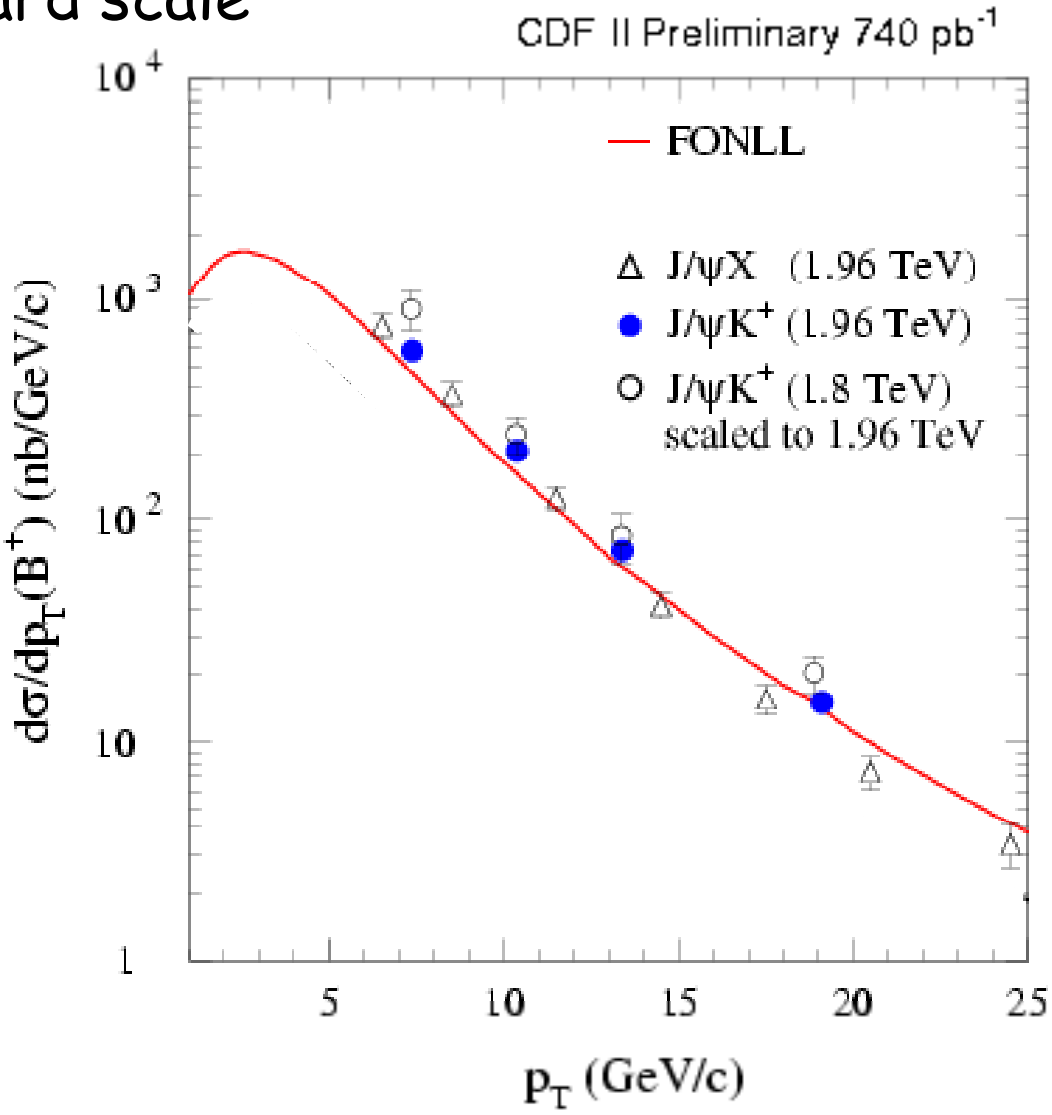
- jets in γp and at Tevatron

  $\mu_0^2 = E_T^2$

cross check with data: c and b at Tevatron

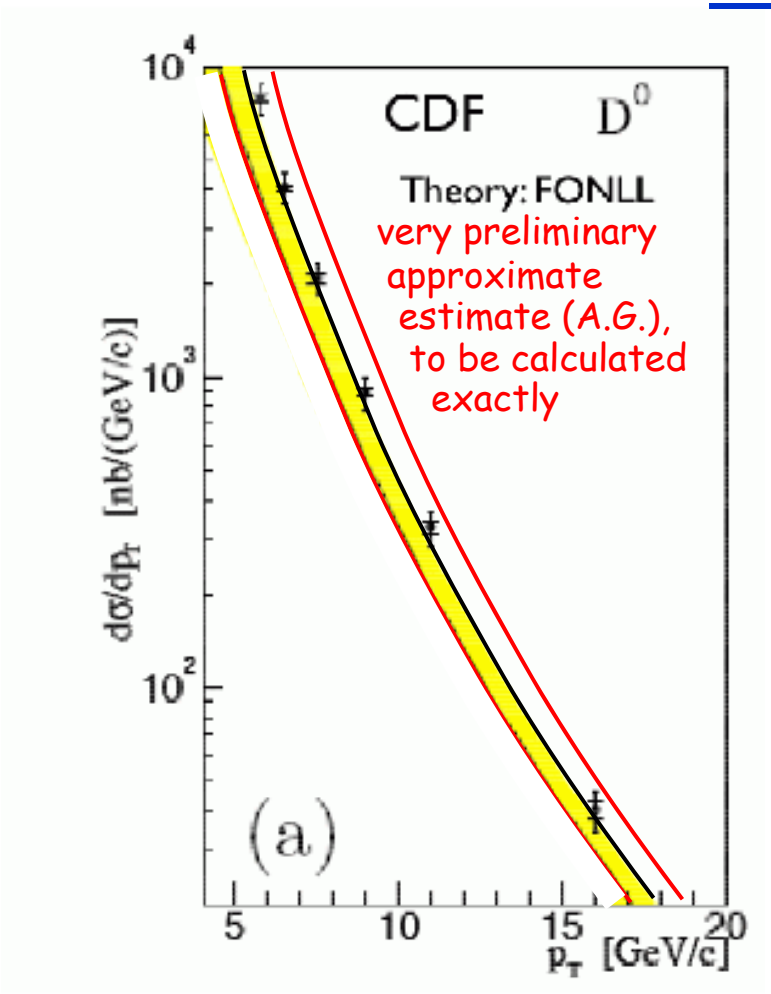
standard scale

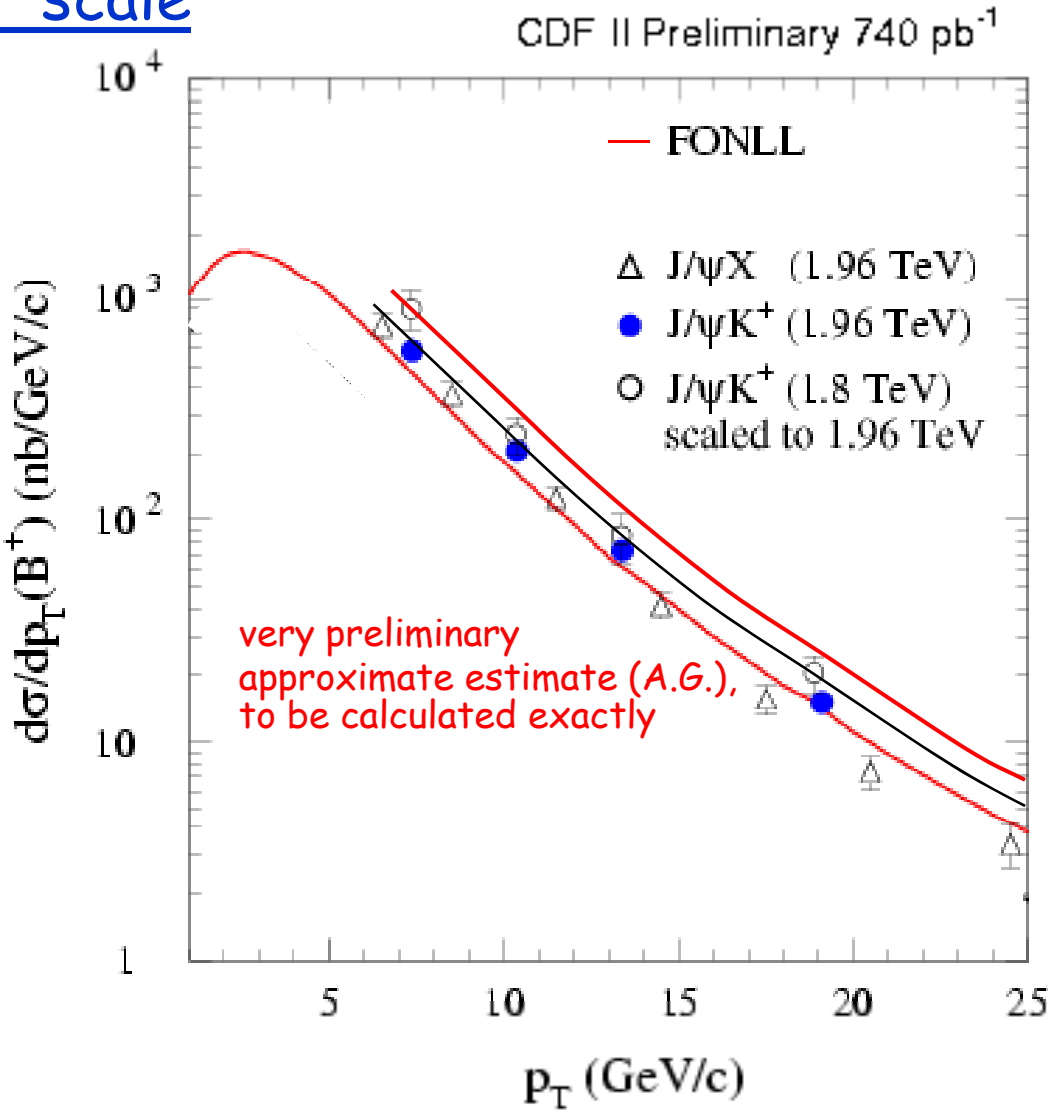




cross check with data: c and b at Tevatron

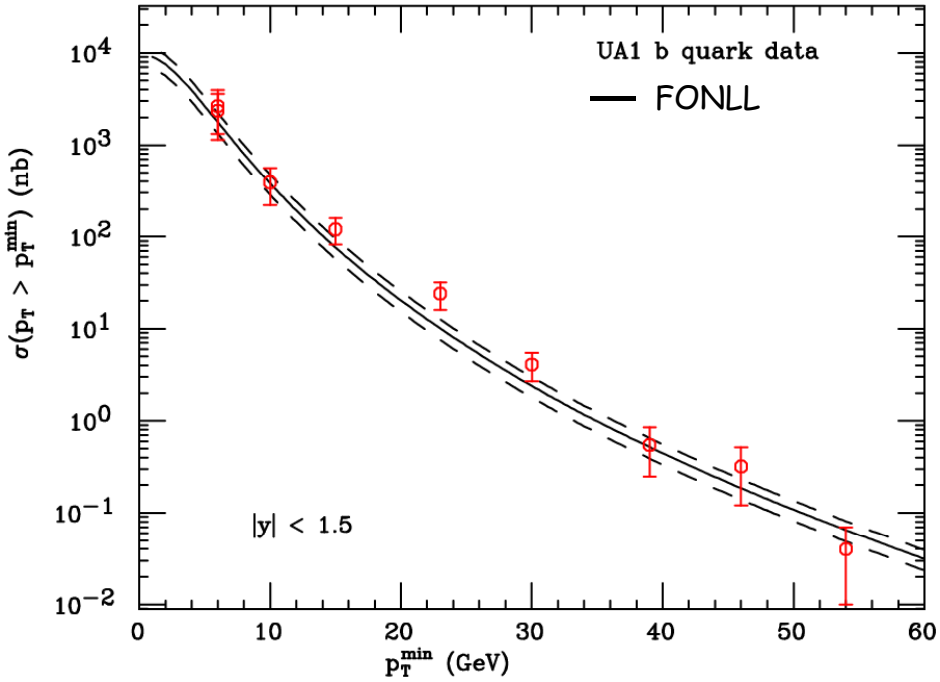
new scale

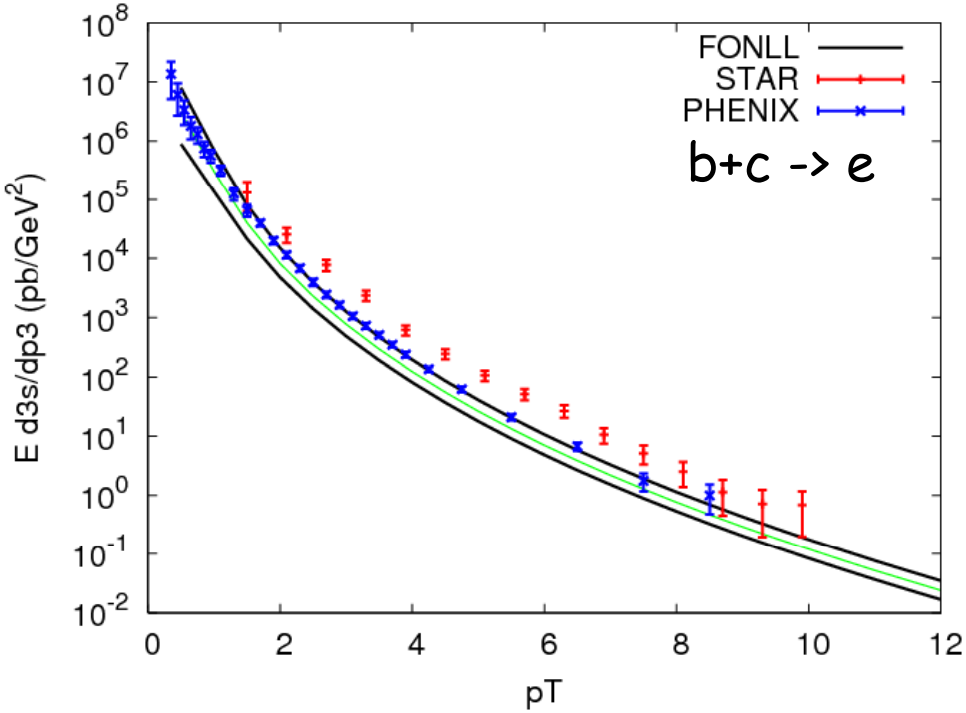




beauty at SpS̄, b+c at RHIC

standard scale





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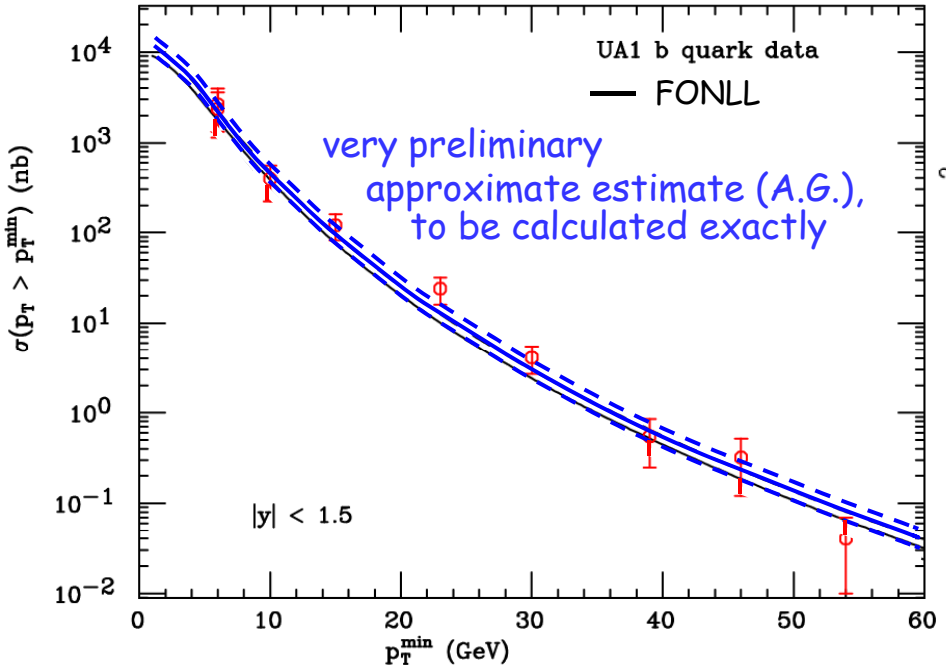
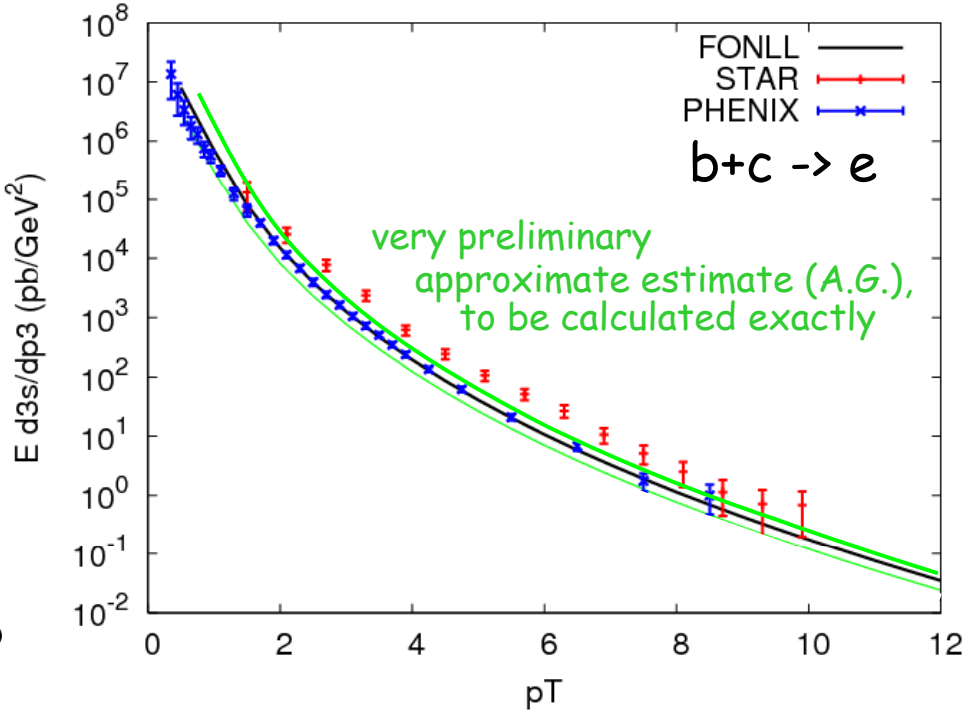
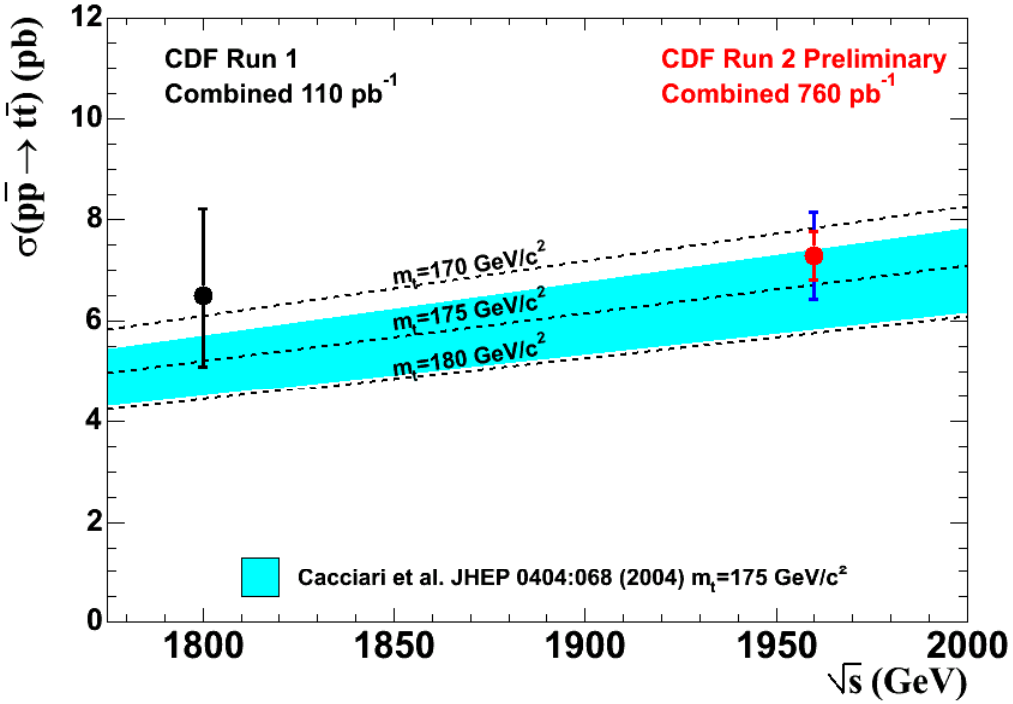
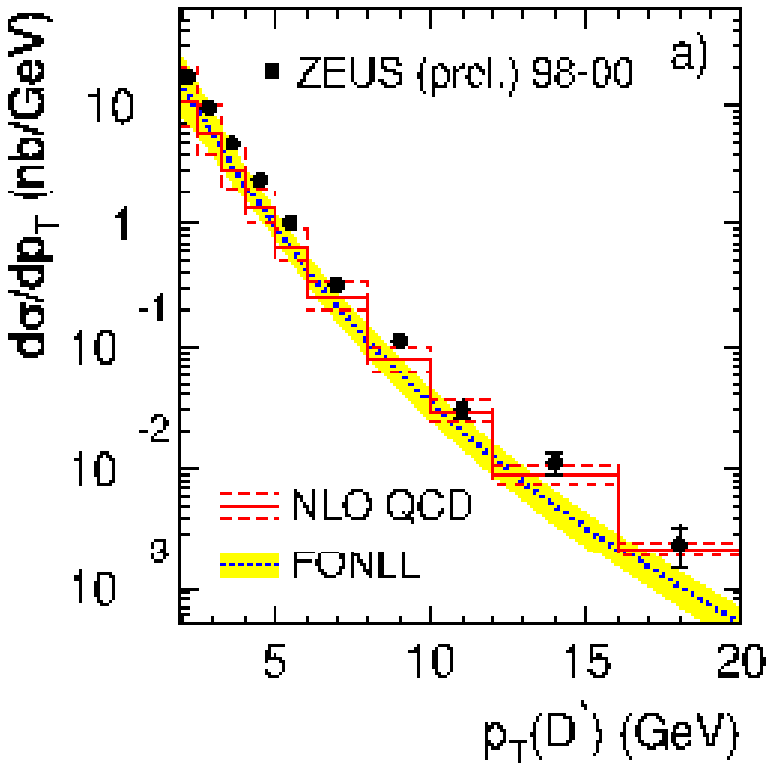




top at Tevatron, charm at HERA

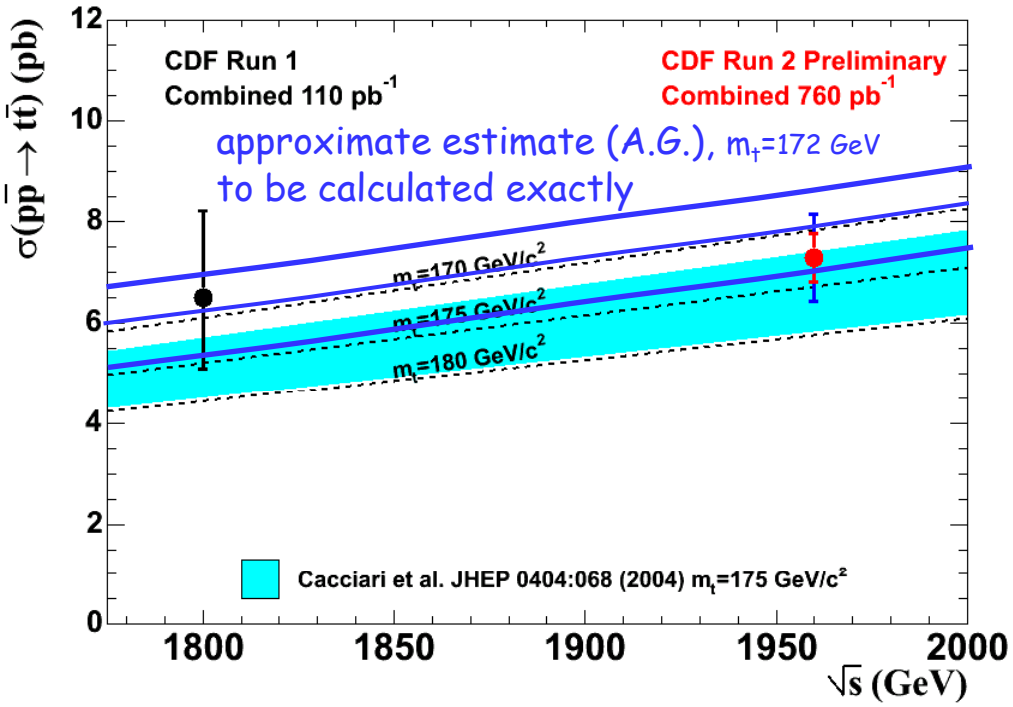
standard scale

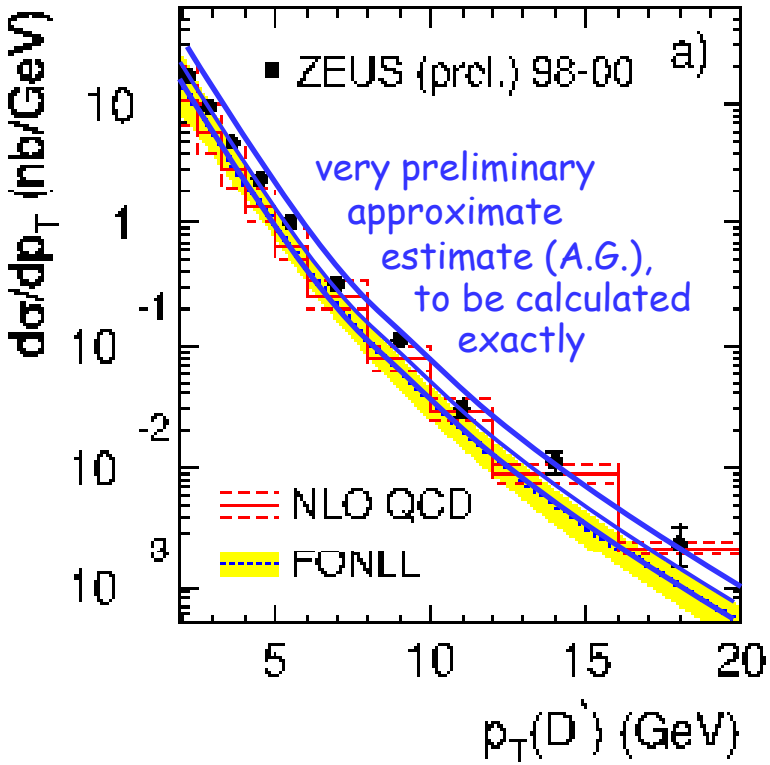




top at Tevatron, charm at HERA

new scale

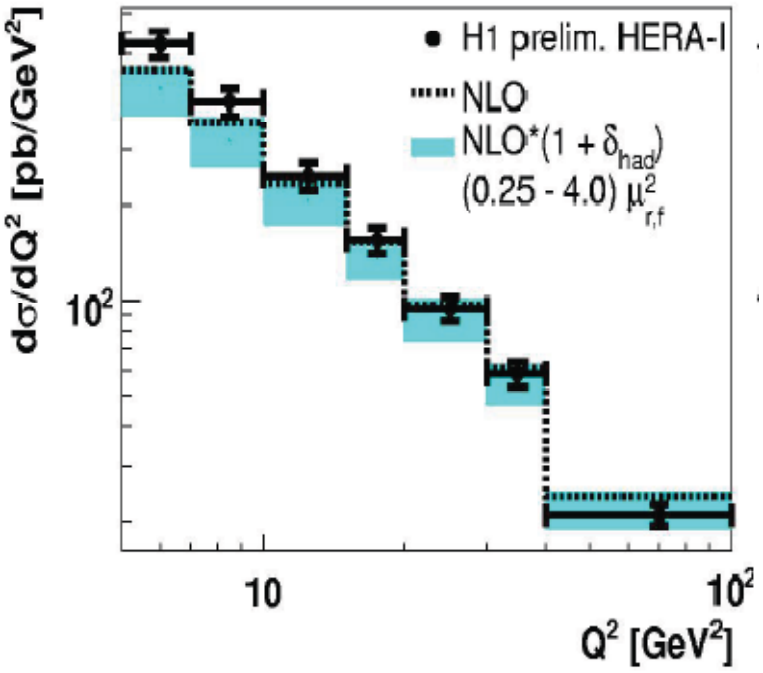


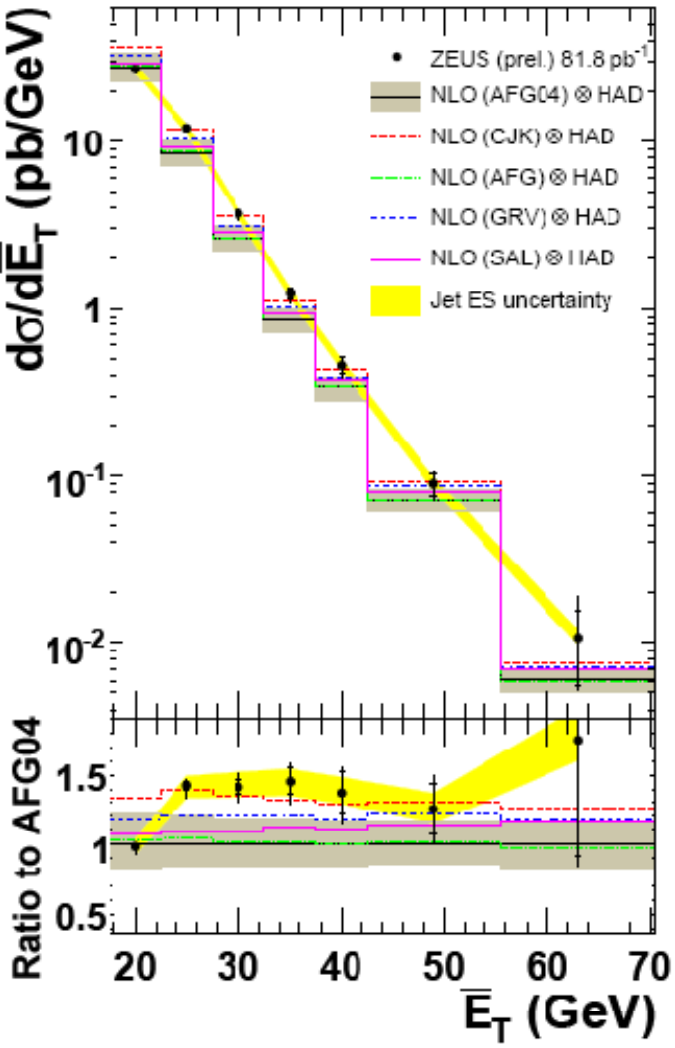


Incl. Jets at HERA PHP

standard scale

DIS

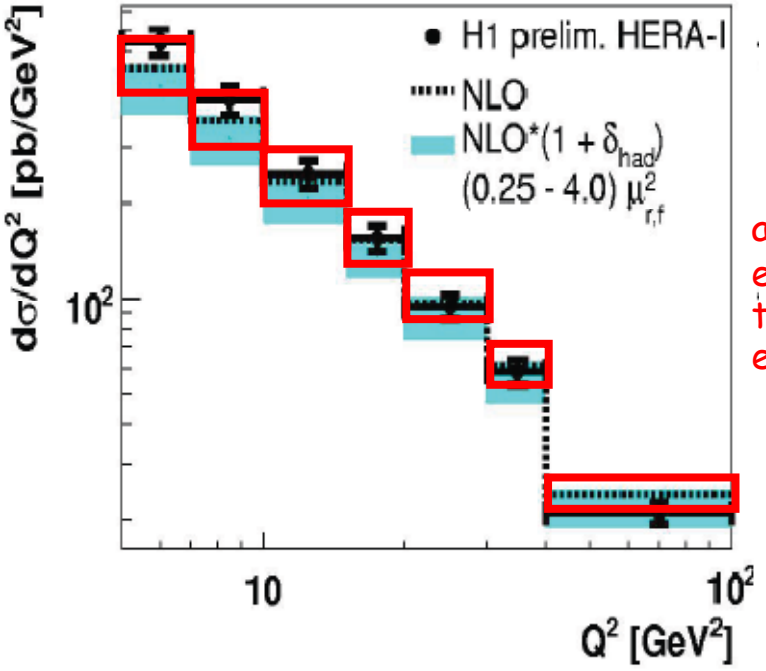




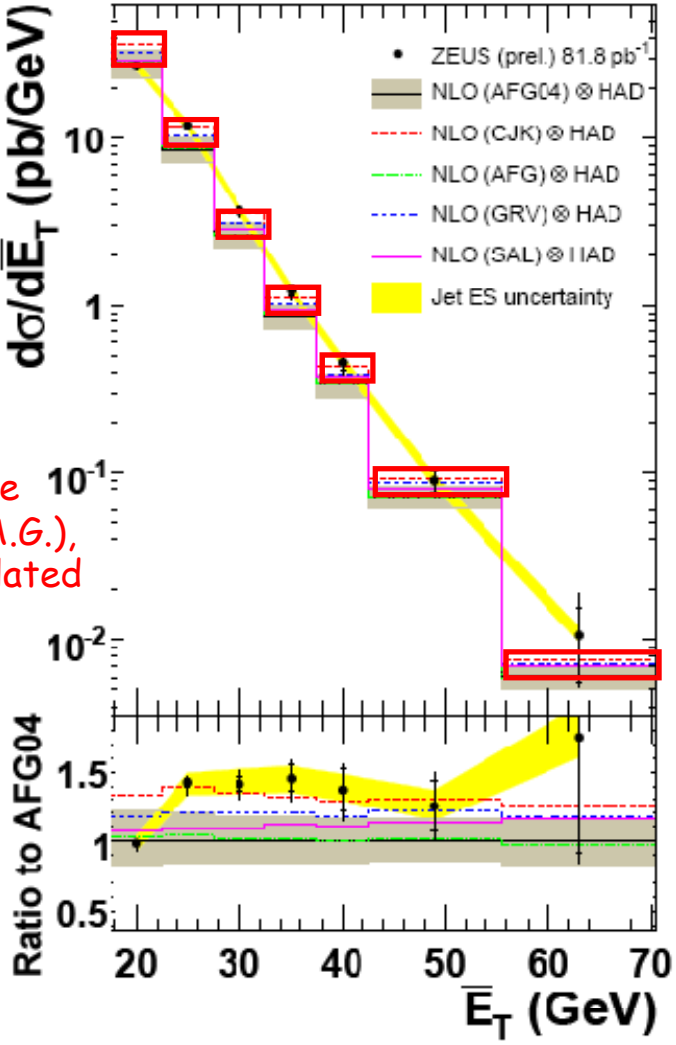
Incl. Jets at HERA PHP

new scale

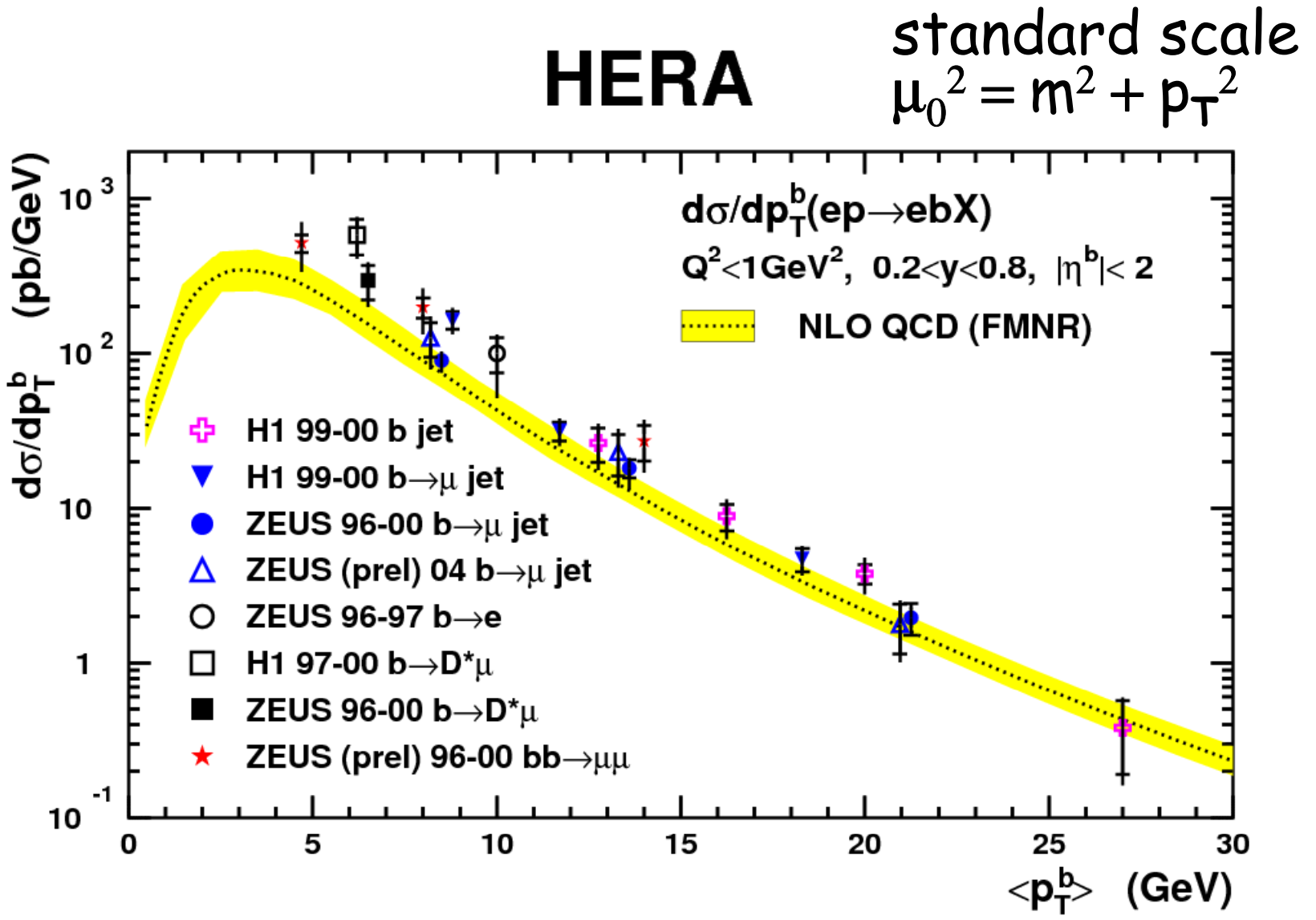
DIS



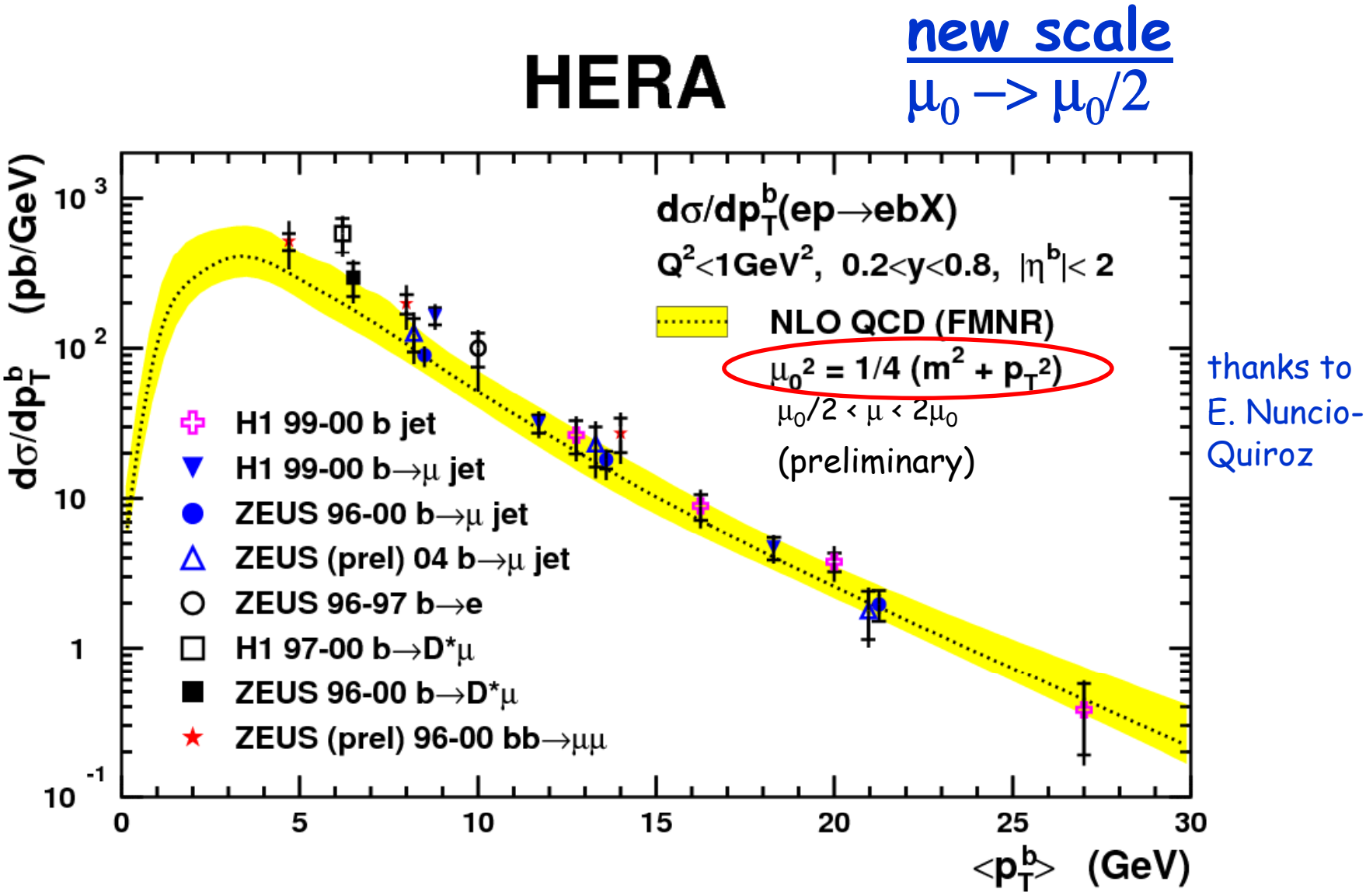
approximate estimate (A.G.), to be calculated exactly



Beauty in photoproduction: standard



Beauty in PHP: new reference scale

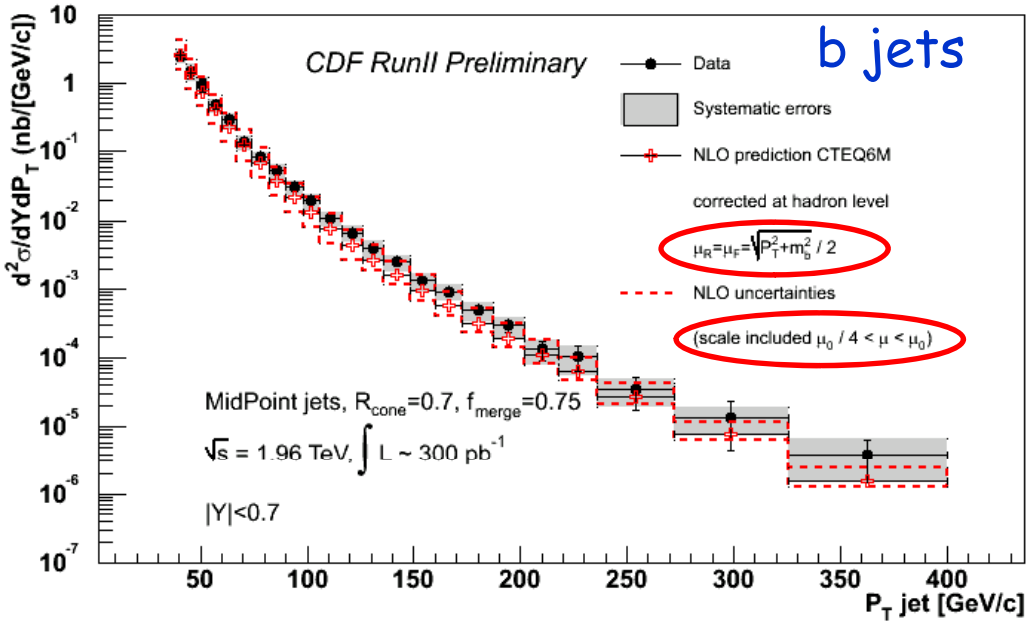


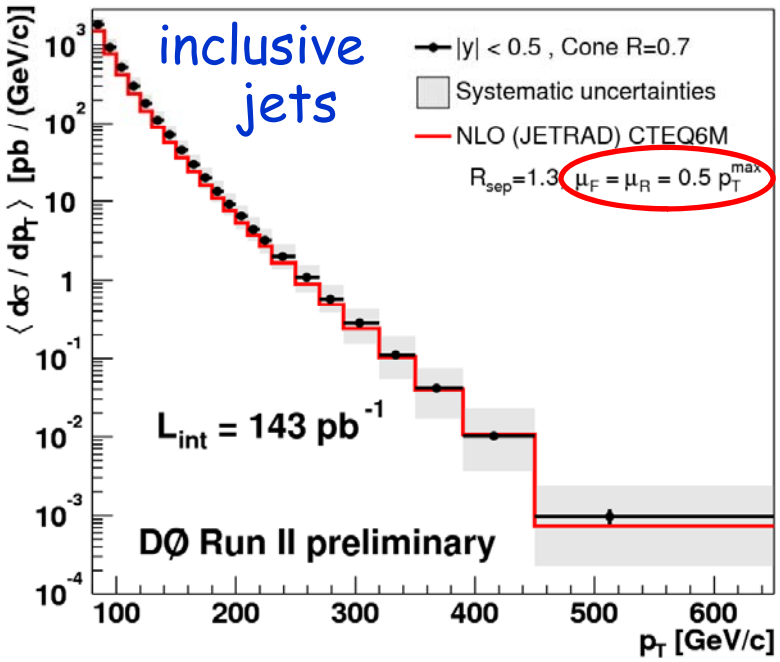
thanks to E. Nuncio-Quiroz

Conclusion/Plea: either dedicated study, or

- propose, from now on, to use default QCD scale $\mu_0/2$ for all heavy flavour (and other?) NLO cross section predictions at HERA and elsewhere, including LHC
- scale variation by factor 2 seems reasonable

some people are doing this already:

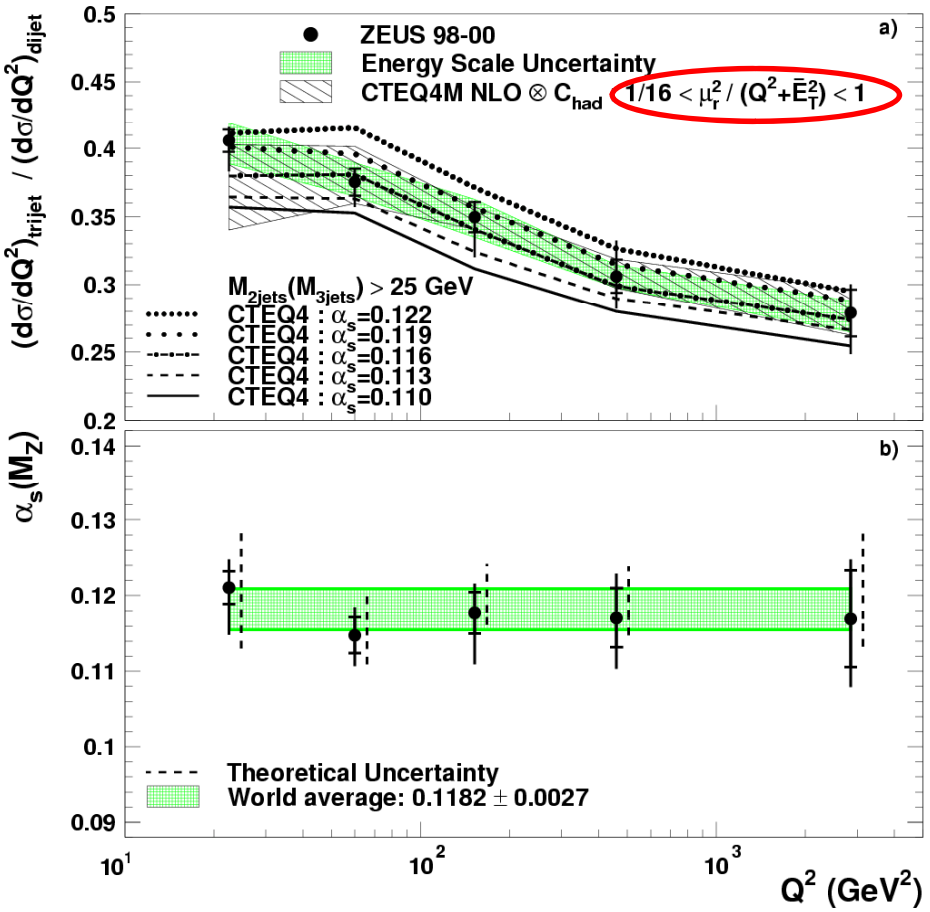




also at HERA

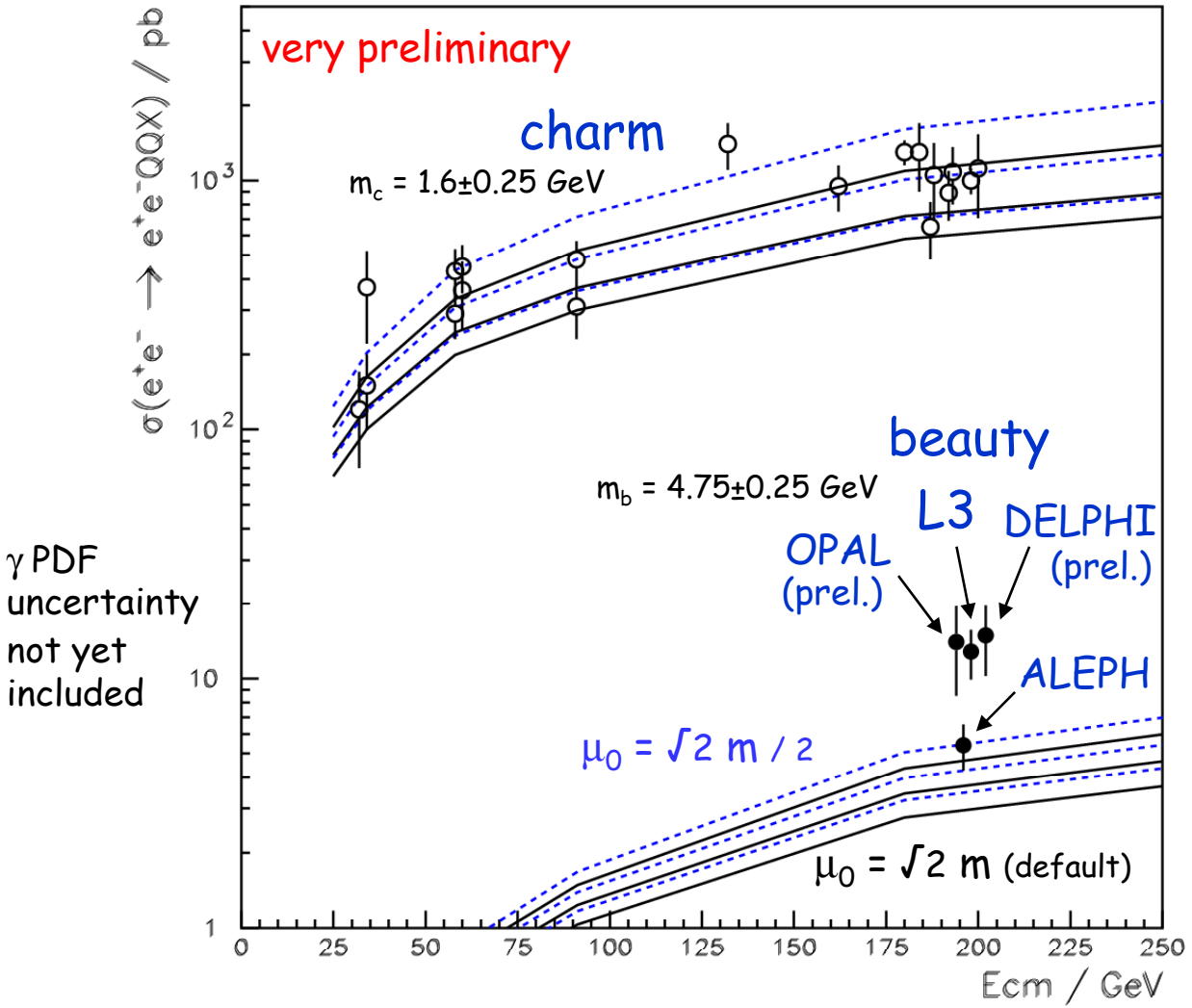
see also talk G. Grindhammer

EPJ C44 (2005) 183: Multijet-Production in DIS



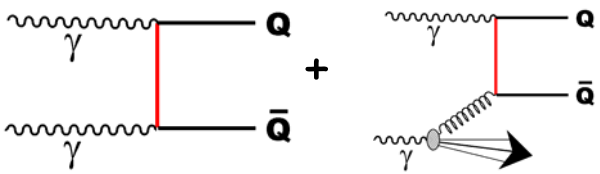
BUT: Heavy Flavours in γγ at LEP ?

details on data: talk Finch



γ PDF uncertainty not yet included

mainly



predictions adapted from
Drees et al., PLB 306 (1993) 371

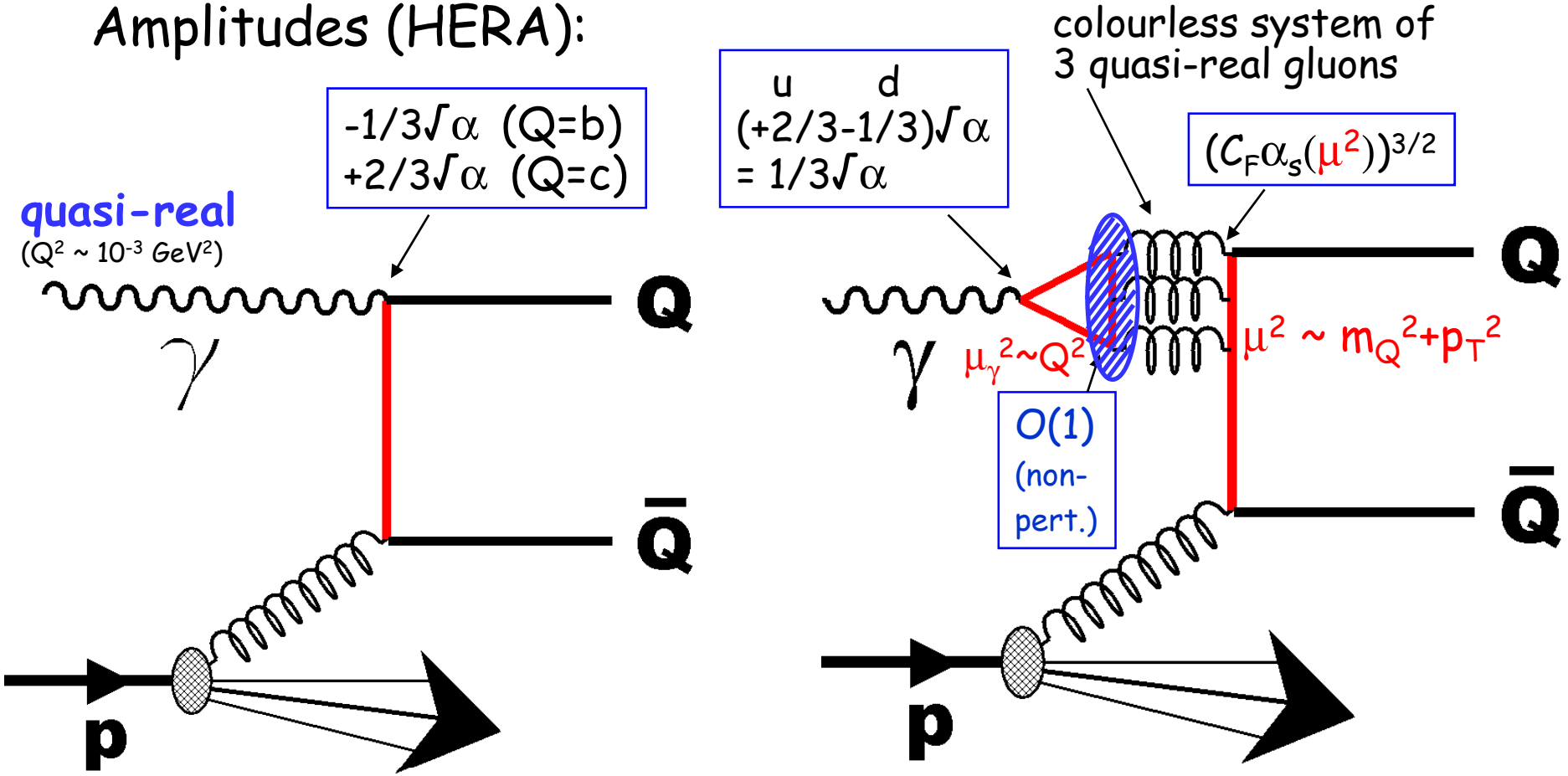
changing scale $\mu_0 \to \mu_0/2$ helps, but not much (LO process is pure QED)

How well do we understand the quark/photon coupling?

investigate very tentative idea:

Interference of QED with nonperturbative QCD??

Amplitudes (HERA):



Interference of QED with nonperturbative QCD?

amplitudes for effective photon coupling:

$$b \sim -1/3\,(1 + \kappa\,\underbrace{(C_F\,\alpha_s(\mu^2))^{3/2}}_{\sim 0.14})$$

$\mu^2 \sim m_Q^2 + p_T^2 \sim 2m_Q^2$

$\alpha_s(2m_b^2) \approx 0.20$

cancellation

$$c \sim 2/3\,(1 - \tfrac{1}{2}\kappa\,\underbrace{(C_F\,\alpha_s(\mu^2))^{3/2}}_{\sim 0.22\ (\sim 0.15 \text{ for } p_{Tc} \sim m_b)})$$

$\alpha_s(2m_c^2) \approx 0.27$

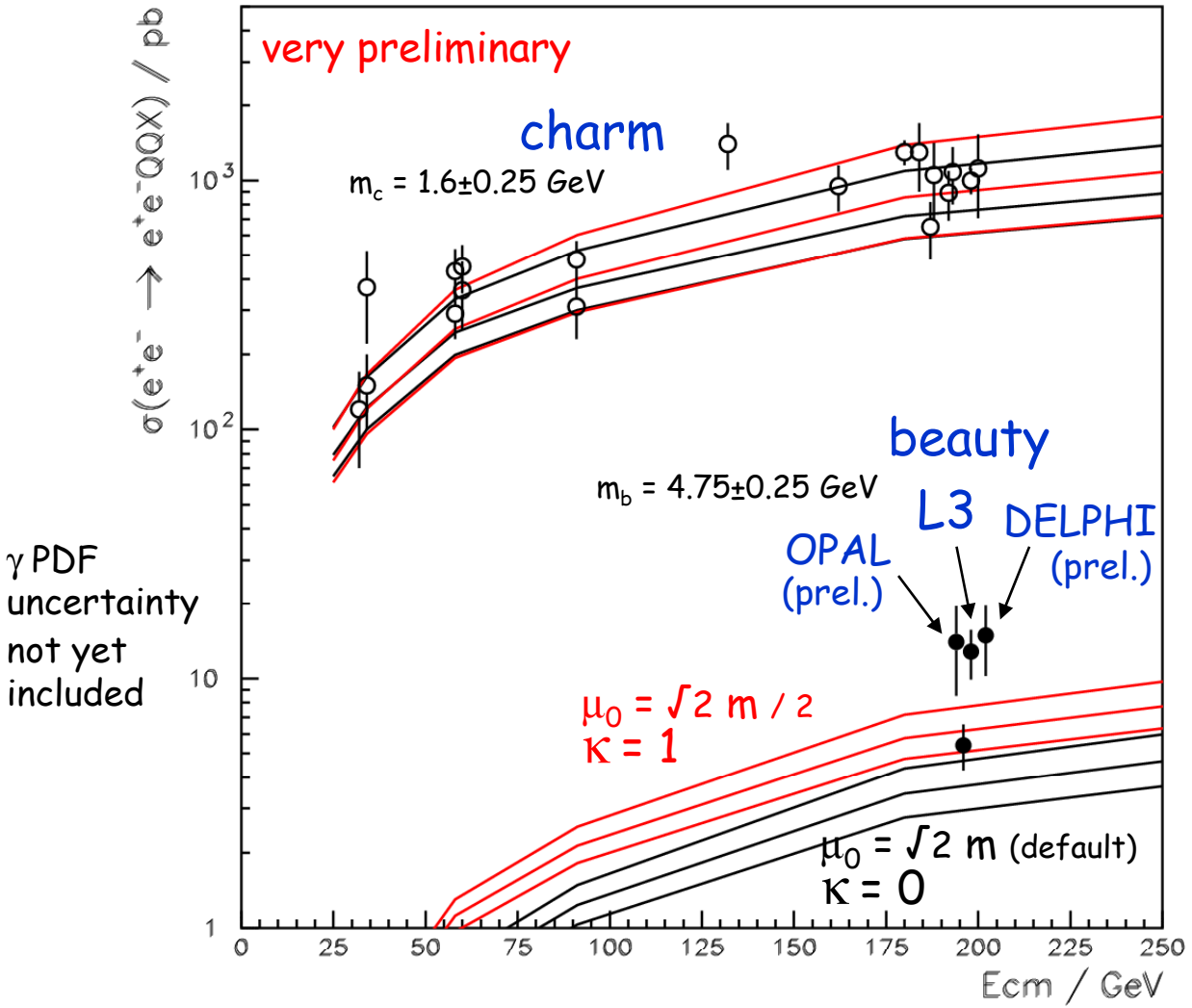
where κ = unknown complex factor of non-perturbative origin (of order 1)

example: arbitrarily **assume $\kappa \approx 1$** (real)

$\Rightarrow$ effective γb coupling enhanced by factor $(1+0.14)^2 = \mathbf{1.30}$

$\Rightarrow$ effective γc coupling reduced by factor $(1-\frac{1}{2}\times 0.22)^2 = \mathbf{0.79}$

Heavy Flavours in $\gamma\gamma$ at LEP, revisited



γ PDF uncertainty not yet included

scale ↑ and coupling ↓ changes cancel

standard predictions (κ=0) from Drees et al., PLB 306 (1993) 371

scale ↑ and coupling ↑ changes add

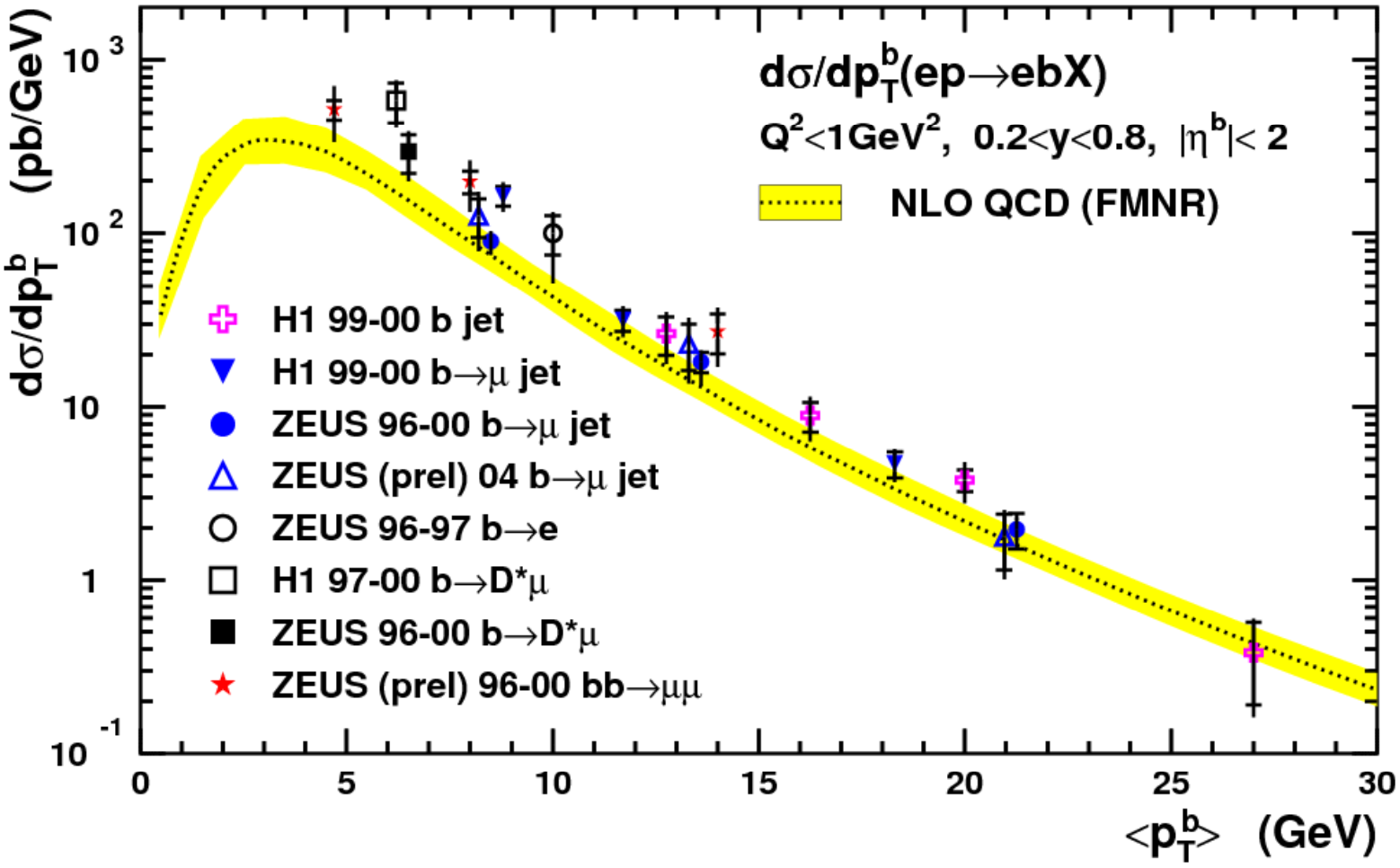
Beauty in photoproduction: standard

reminder:

HERA

$\mu_0^2 = m^2 + p_T^2$

standard photon coupling



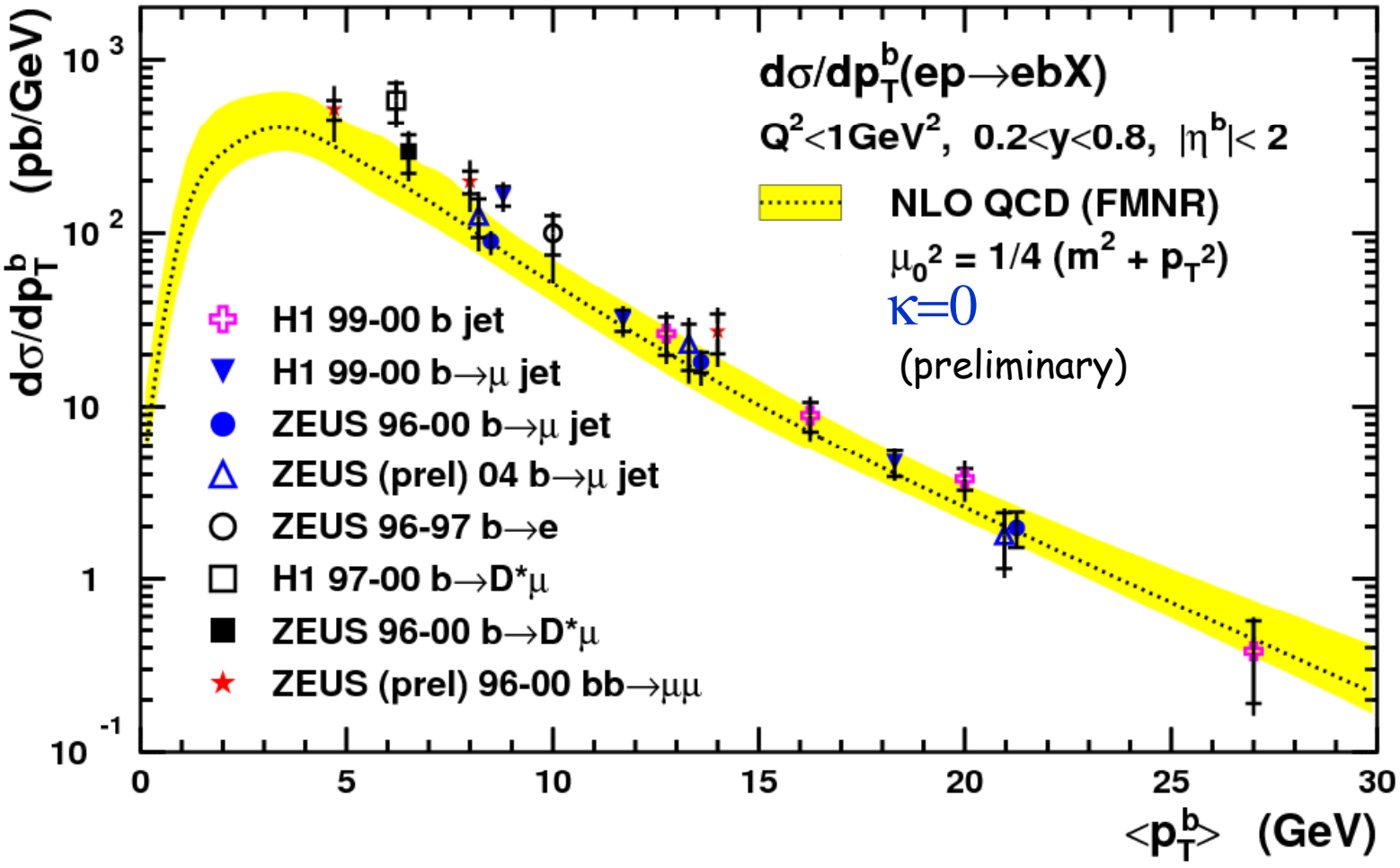
Beauty in photoproduction: new scale

reminder:

HERA

$\mu_0 \rightarrow \mu_0/2$

standard photon coupling

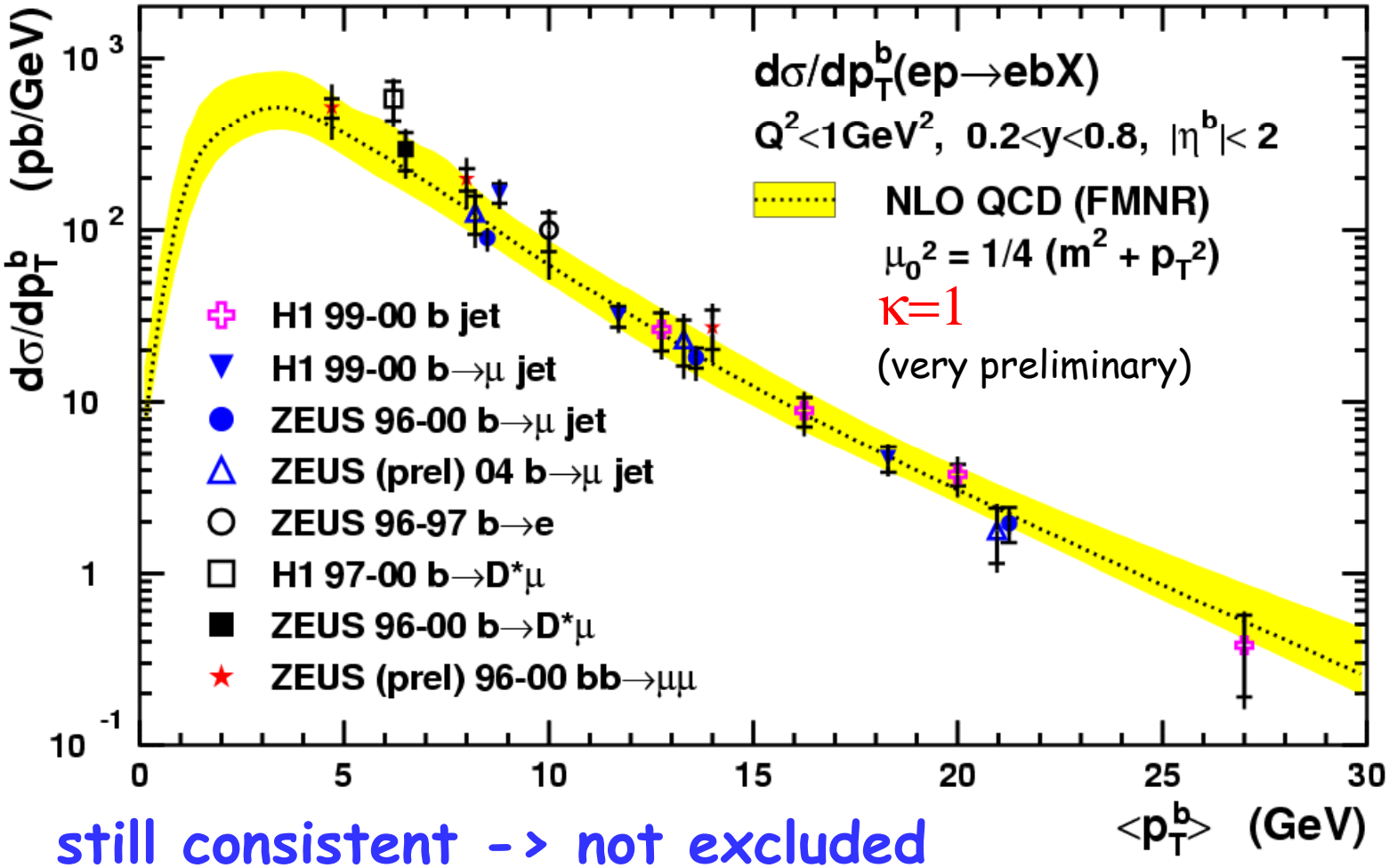


Beauty in photoproduction: non-standard

HERA

$\mu_0 \rightarrow \mu_0/2$

non-standard photon coupling



still consistent -> not excluded

compatibility with other measurements?

- purely hadronic processes (Tevatron, LHC) unaffected
- purely weak processes (W/Z at Tevatron, CC at HERA) unaffected

- change of coupling only relevant for (quasi-)real photons
  ($Q^2 > 1\ GeV^2$-> perturbative -> $\kappa << 1$ -> very small/negligible)
  $\Rightarrow$ no significant change for DIS at HERA, e^+e^- -> $q\bar{q}X$

- reduction of charm photoproduction at HERA, qualitatively
  compensated by increase due to μ -> $\mu/2$ (to be checked quantitatively)

- for hard scale $\mu >> m_q$, modifications for up and down quark contributions cancel exactly in leading order => u,d; s,c cancel
  $\Rightarrow$ no net effect for 2,4,6 final state flavours (e.g. N_F=4 γp fixed target)
  $\Rightarrow$ some increase (~2%) in PHP high E_T jet production at HERA, high E_T single photon production at Tevatron (5=3-2 flavours, b only) !

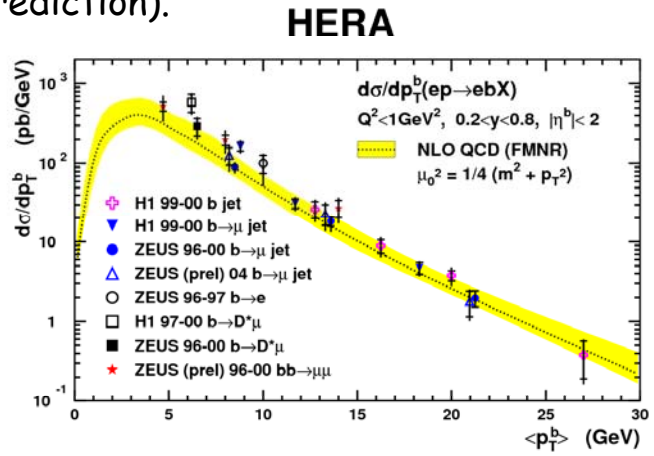
- should affect e.m. branching ratios, e.g. D*->Dγ (but not electroweak ones like b->sγ, since Wγ coupling unaffected) !

- other processes ?

Summary and conclusions

- Beauty cross sections at HERA and elsewhere in reasonable agreement with perturbative QCD predictions (but often above "central" prediction).

- Phenomenological arguments (independent of data) suggest shift in choice of "optimal" renormalization/factorization scales to ~half their "standard" values
  ⇒ good agreement with many different data sets



- Plea to make this the new default, whenever a dedicated study is absent, in particular before claiming disagreement between data and NLO QCD.
  up/down scale variation by factor 2 looks OK.
  (theorists who do not like this: please provide NNLO calculations!)

- b "excess" of $\gamma\gamma$ at LEP? => investigate modification of photon-quark coupling from interference with non-perturbative QCD? => compatible with HERA beauty data.
  Compatibility with other measurements and theoretical constraints to be checked
  Important e.g. for α_s from PHP jets at HERA -> hopefully exclude (confirm??) soon.

Backup slides

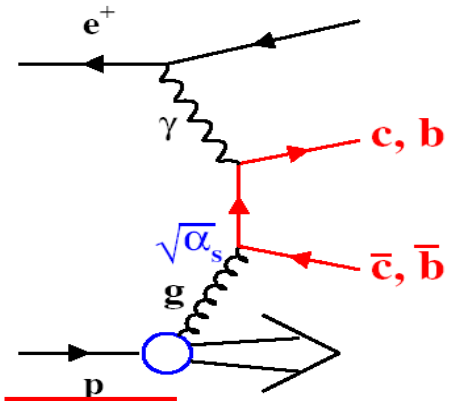
pQCD approximations

assume one dominant hard scale:

Massive scheme: $\rightarrow m_b$

- **b massive** p_T^2
- **neglects** $[\alpha_s \ln(Q^2/m_b^2)]^n$

$\rightarrow$ **Perturbative production:**

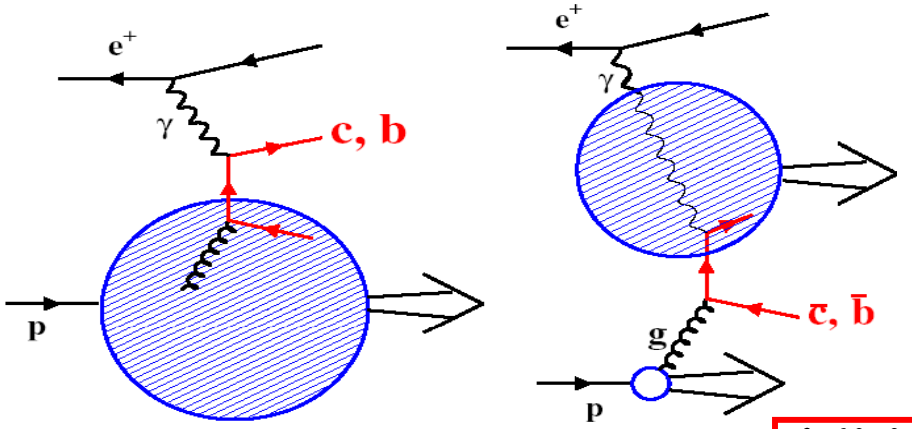


NLO

Massless scheme: $\rightarrow p_T, Q^2$

- **b massless!** p_T^2
- **Resums** $[\alpha_s \ln(Q^2/m_b^2)]^n$

$\rightarrow$ **b also in Proton and Photon!**



NLL

Variable schemes (VFNS): p_T

$\rightarrow$ **at small** Q^2 **massive, at large** Q^2 **massless**

=FFNS

p_T FONLL

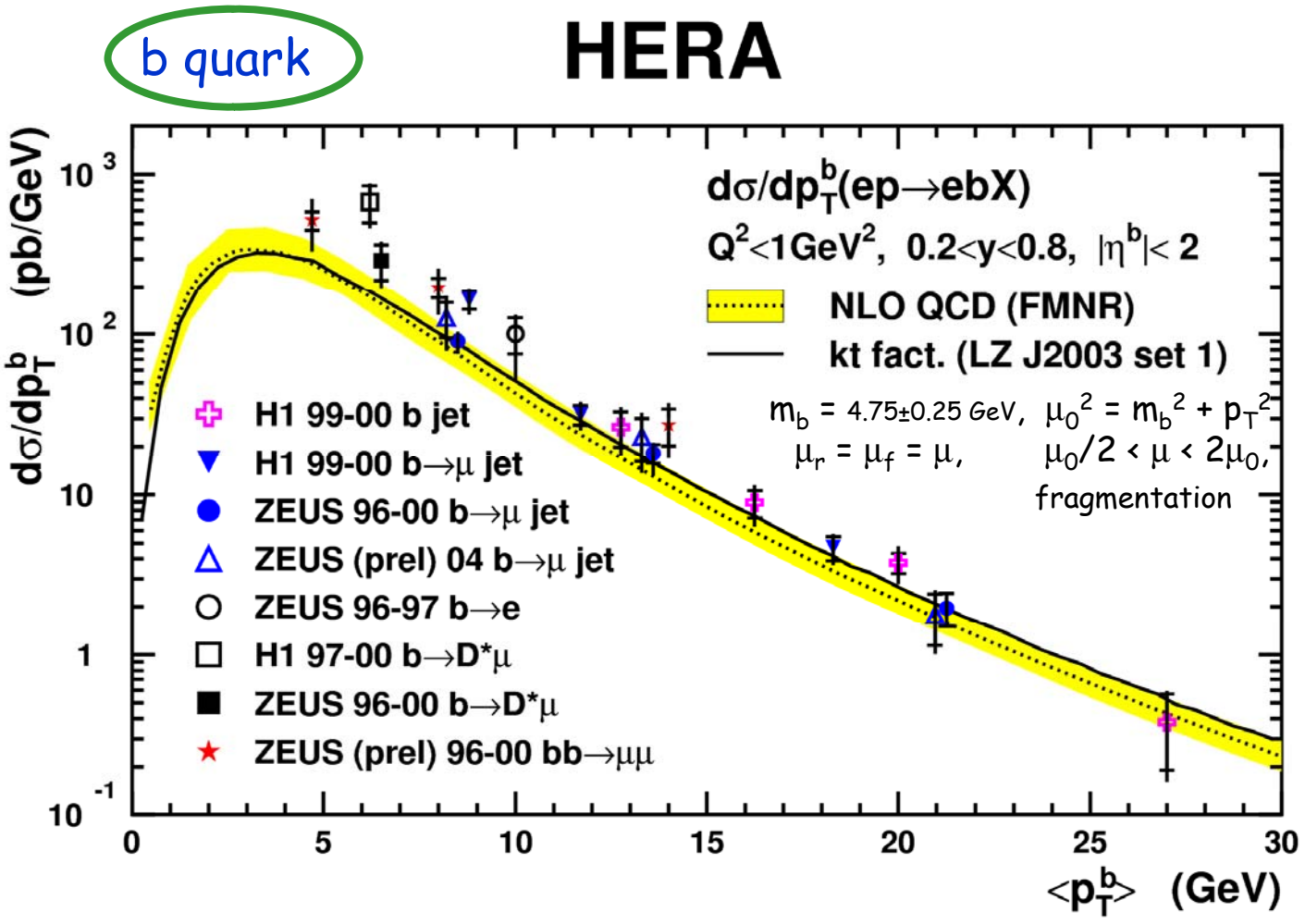
=ZM-VFNS

(GM)-VFNS

alternative: kt-factorization

Beauty in photoproduction: summary

b quark



data/QCD:

reasonable agreement, but tendency data > QCD at low p_T

k_T factoriz. and NLO predictions agree

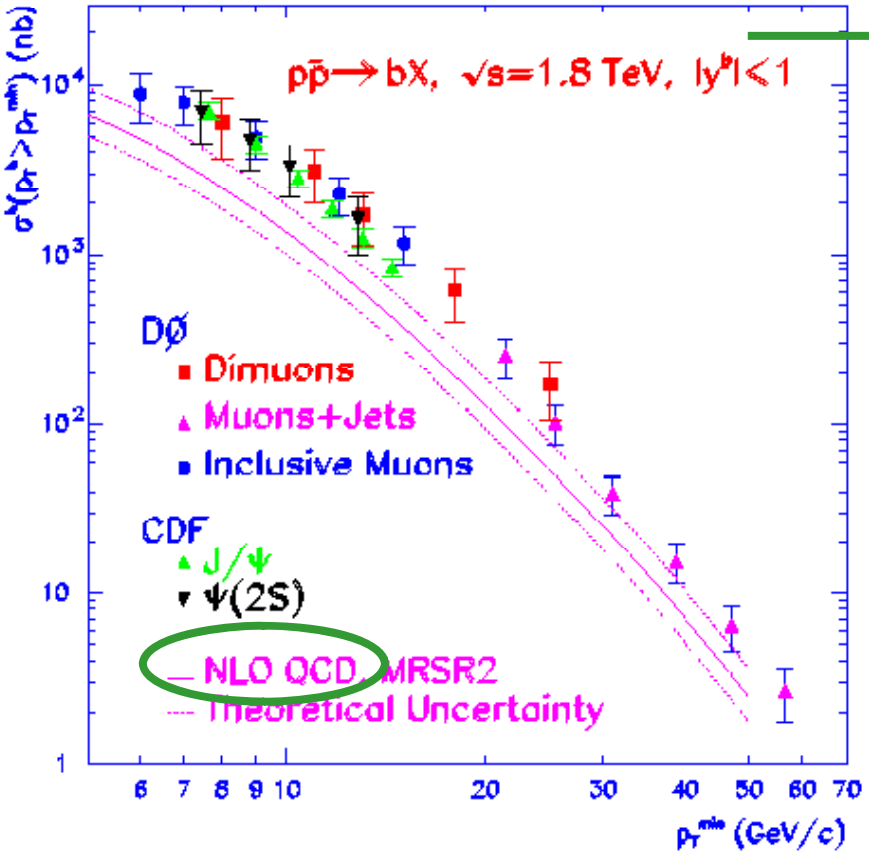
theory uncert. underestimated?

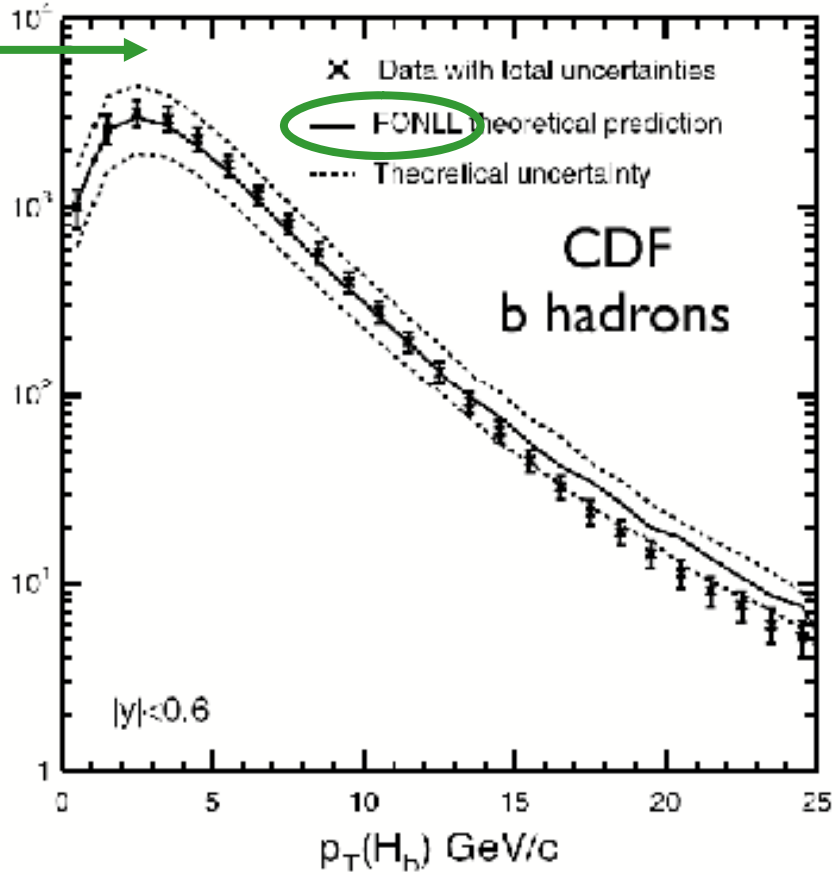
FONLL (VFNS) prediction not yet available, **should it help?**

famous b cross sections at the Tevatron

(a bit of history)

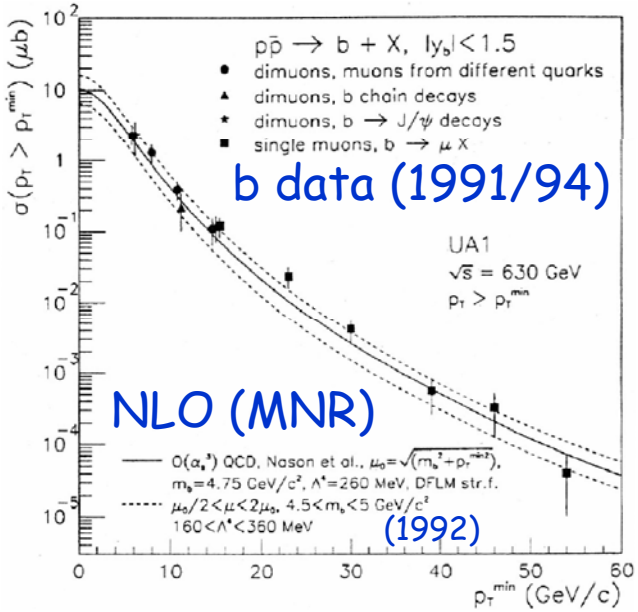
combination of appropriate fragmentation, NLL corrections, + many smaller experimental and theoretical issues (Cacciari et al.)





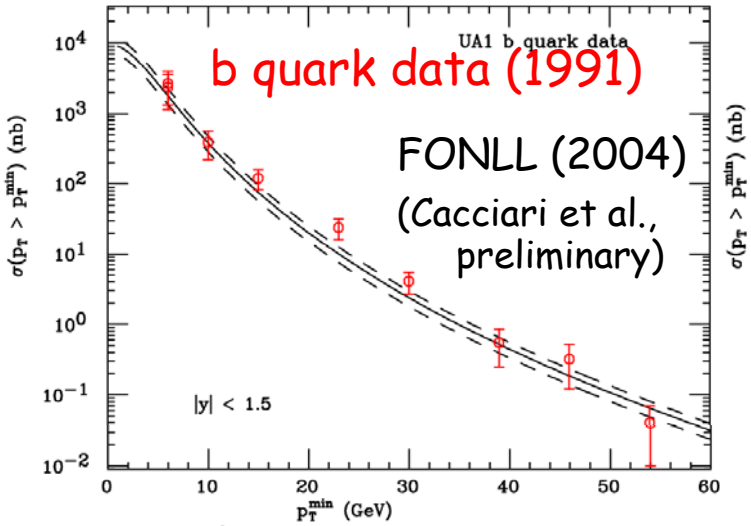
problem also for HERA? could one have done better?

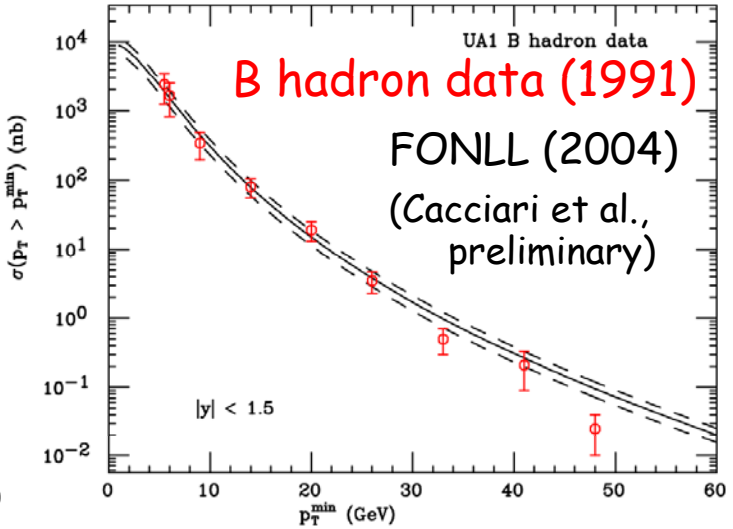
b cross sections at UA1 (630 GeV $p\bar{p}$)



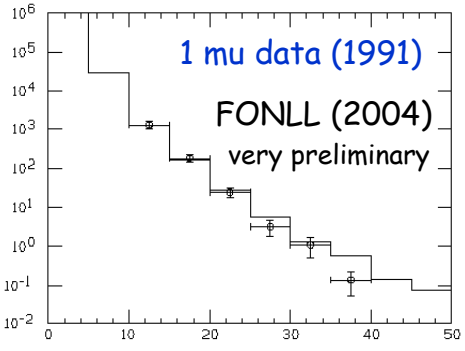
NLO (1992) and FONLL (2004) agree with each other and with data (1991/94)
(fragm. and decay spectra, br. ratios, ...
were all consistently tuned in MC to measured data)

FONLL (2004) agrees with data (1991) at b quark, B hadron, and muon level

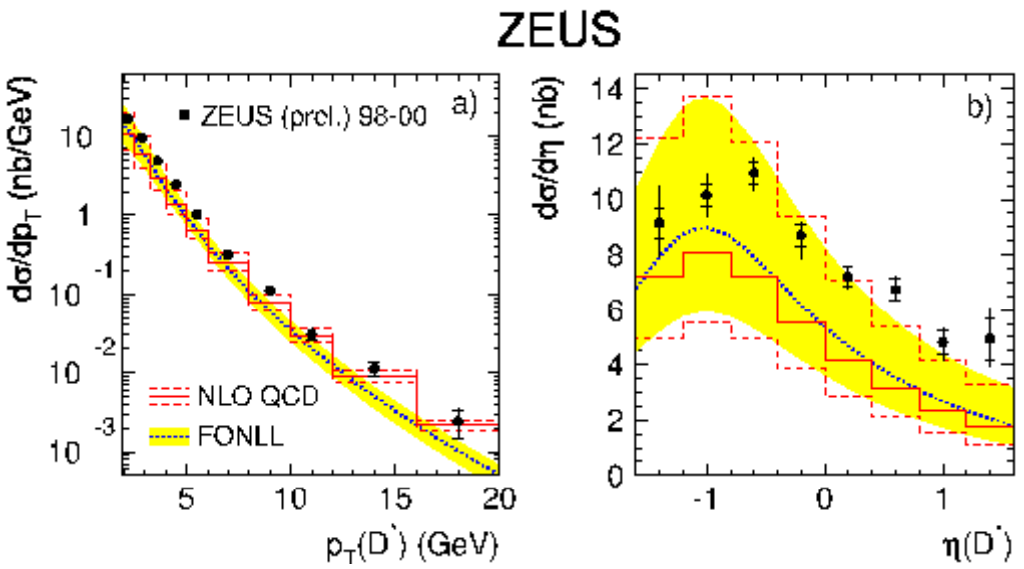




UA1, PLB 256 (1991) 112
UA1, Z.Phys.C 61 (1994) 41
MNR, Nucl.Phys.B 373 (1992) 295
Cacciari et al., JHEP 0407 (2004) 33



Charm in photoproduction at HERA



=> Do not expect major change for b at HERA from

NLO (no resummation)

-> FONLL (with resummation)

but would be nice to have

QCD calculations using

CTEQ5M1 + AFG structure functions

m_c = 1.5 +- 0.2 GeV, $\mu_0^2 = m_c^2 + p_T^2$,

$\mu_r = \mu_f = \mu$, $\mu_0/2 < \mu < 2\mu_0$

f(c->D*) = 0.235

update?

$\epsilon_{Peterson}$ = 0.035 (FO NLO), 0.02 (FONLL)

NLO (FMNR)

reasonable agreement

some differences at forward η

FONNL (Cacciari et al.)

similar, not better at large p_T