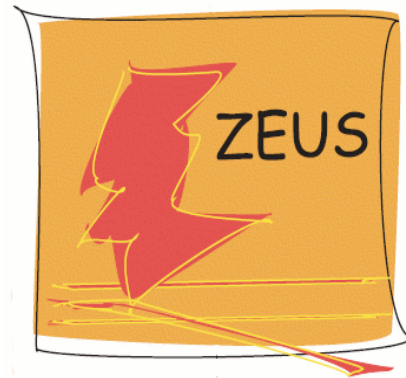


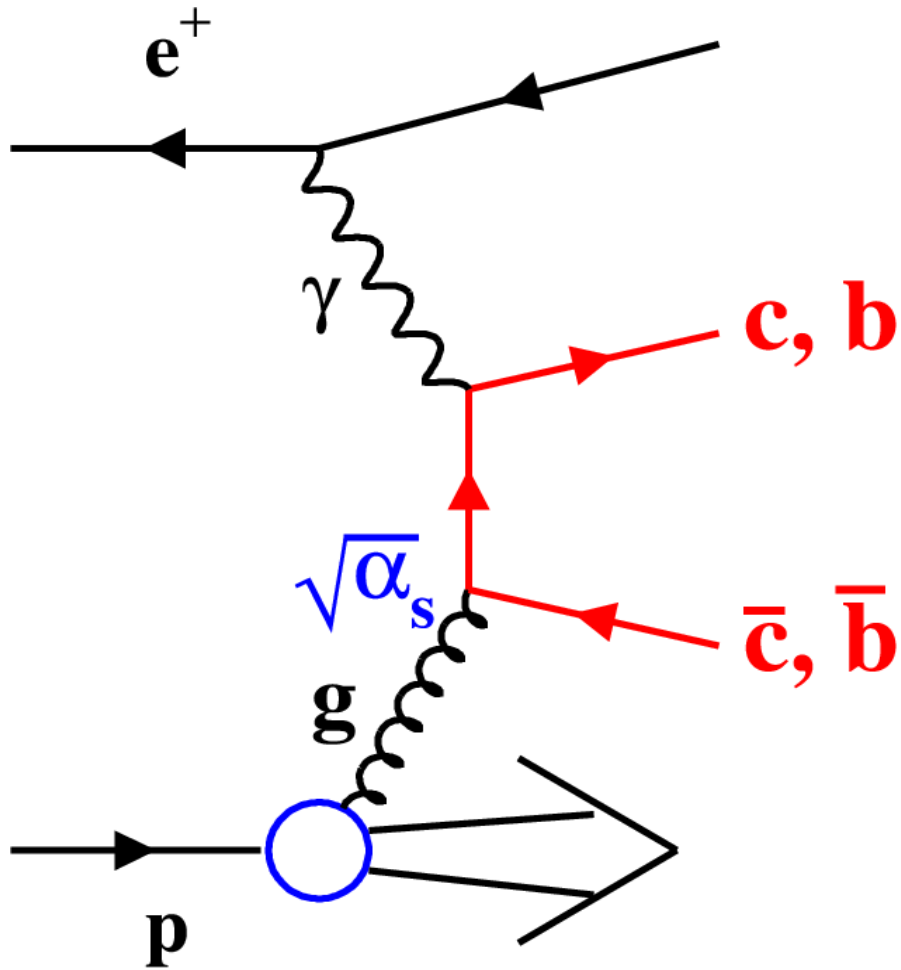
Charm and beauty production at HERA

New trends in HERA Physics,
Ringberg Castle, 27th sep 2011

Olaf Behnke (DESY)

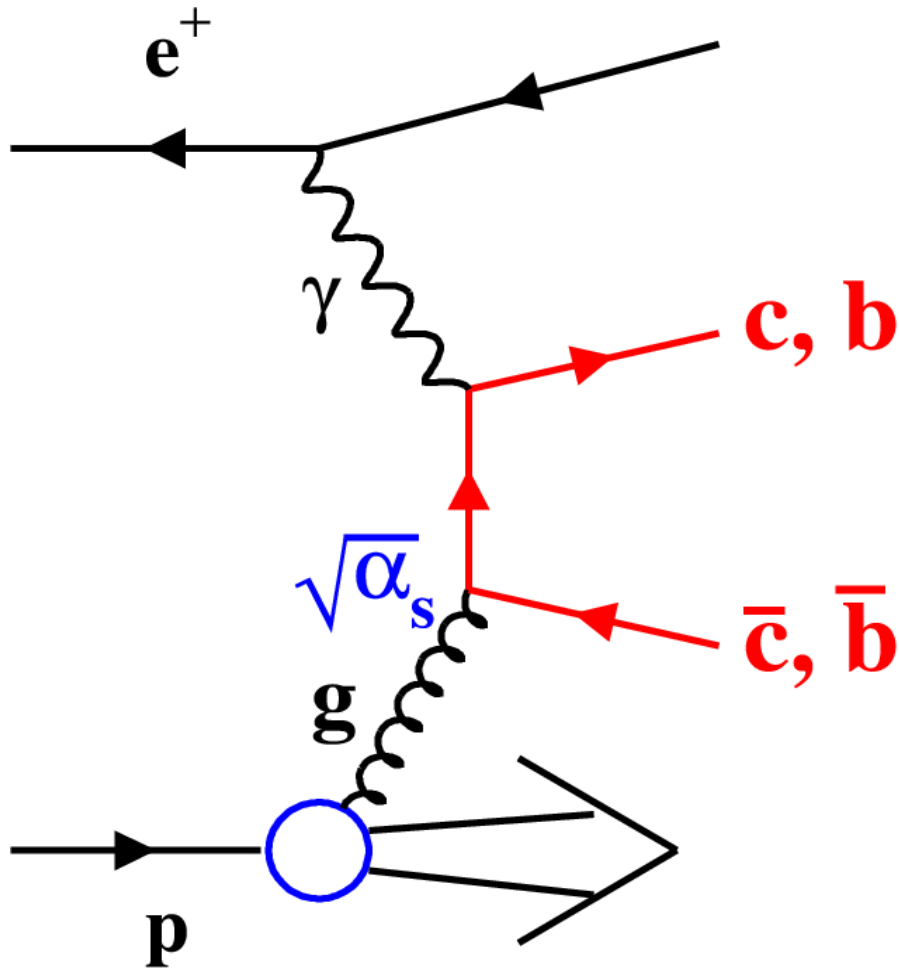


Charm and beauty production at HERA



- Sensitive to gluon density
- Significant contributions to total ep cross sections

Charm and beauty production at HERA

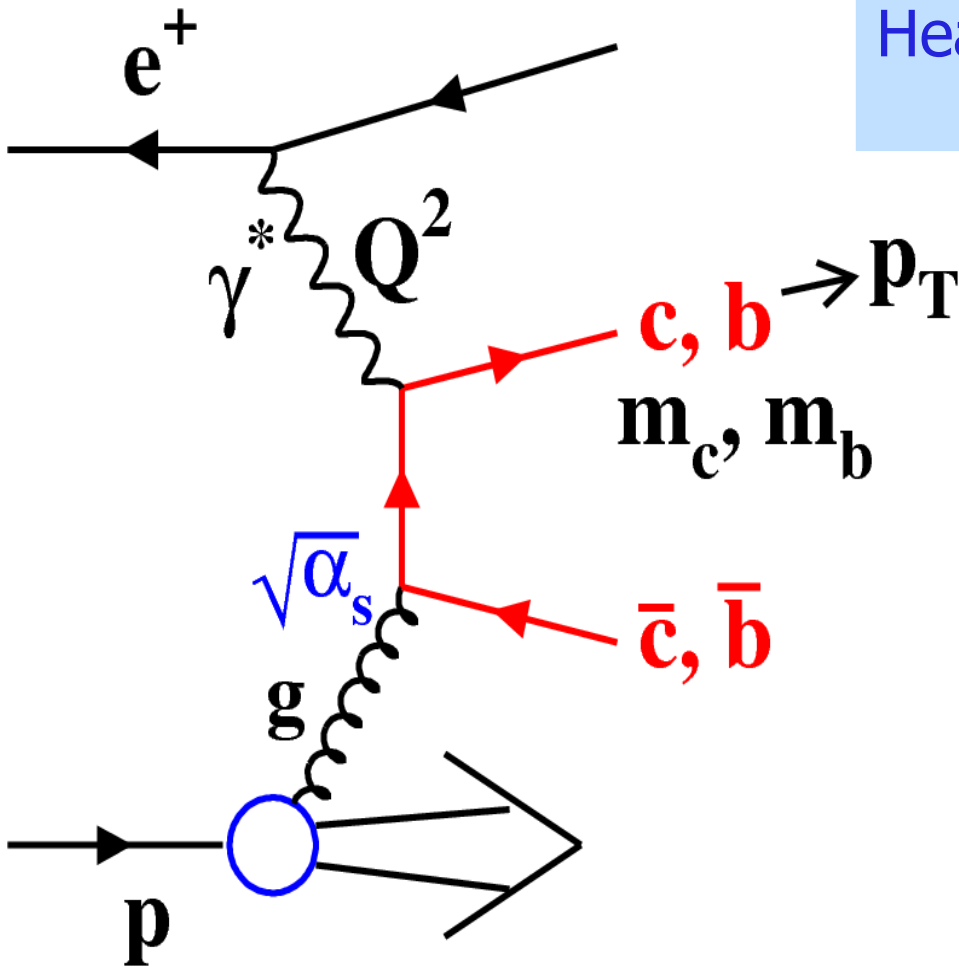


- Sensitive to gluon density
- Significant contributions to total ep cross sections

Identified “New trend in HERA physics”:
The HERA inclusive charm data in DIS allow to determine m_c -> very important for PDF fits and LHC predictions! See yesterday talk by K. Lipka

Theoretical challenges

Heavy quark masses introduce another hard scale \rightarrow complicates pQCD

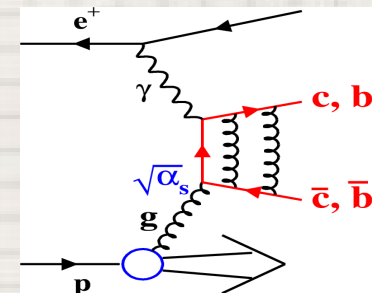


c, b Extra tasks/problems:

1. Threshold resummation
2. Collinear gluon radiations from heavy quarks create terms

$$[\alpha_s \ln(Q^2/m_c^2)]^n$$

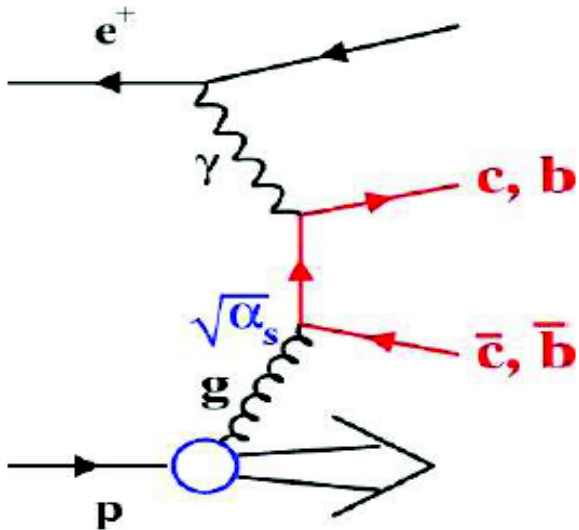
3. Two loop diagram with heavy quarks not yet calculated



QCD approximations

Massive scheme: FFNS

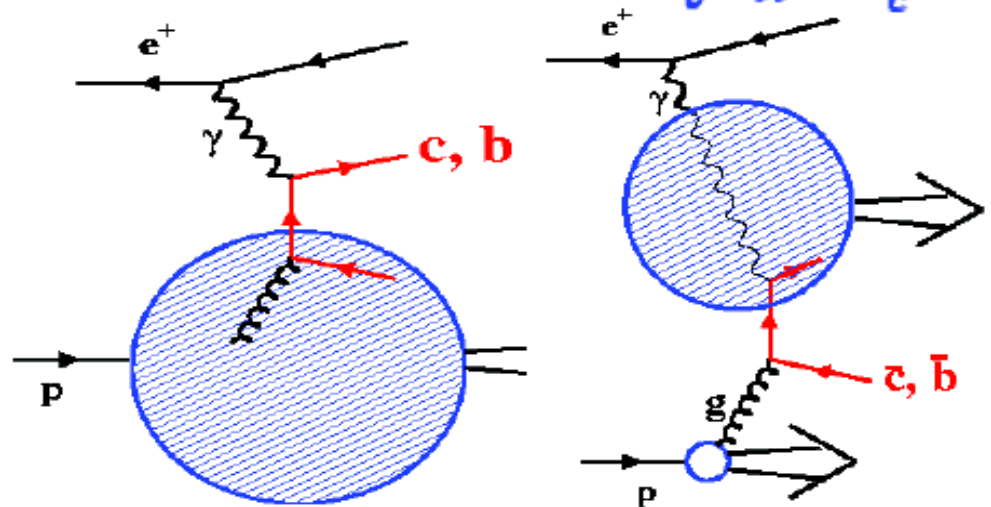
- ➔ Massive c, b
- ➔ Neglect $[\alpha_s \ln(Q^2/m_c^2)]^n$
- ➔ “Good” up to $Q^2 > m_c^2$



Only perturb. production!

Massless scheme: ZMVFNS

- ➔ Massless c, b
- ➔ Resum $[\alpha_s \ln(Q^2/m_c^2)]^n$
- ➔ “Good” for $Q^2 \gg m_c^2$



c, b also in proton and γ !!

Mixed schemes GMVFNS: make the best of both worlds


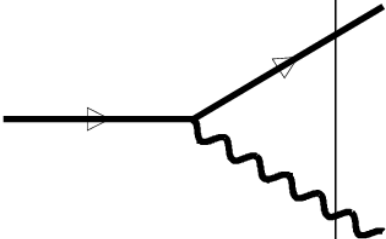
How well do the schemes work? Focus in this talk on massive scheme

Menu: walk through the scales

$Q^2 \rightarrow$

m_Q




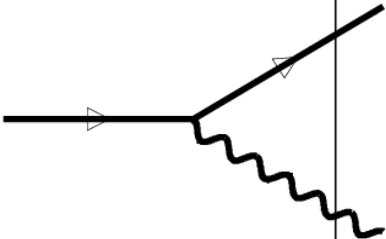
	Photoproduction $Q^2 \approx 0$	DIS $Q^2 \geq 1 \text{ GeV}^2$
c • 1.5 GeV		
b • 4.75 GeV	1.	3.
	2.	4.

Menu: walk through the scales

$Q^2 \rightarrow$

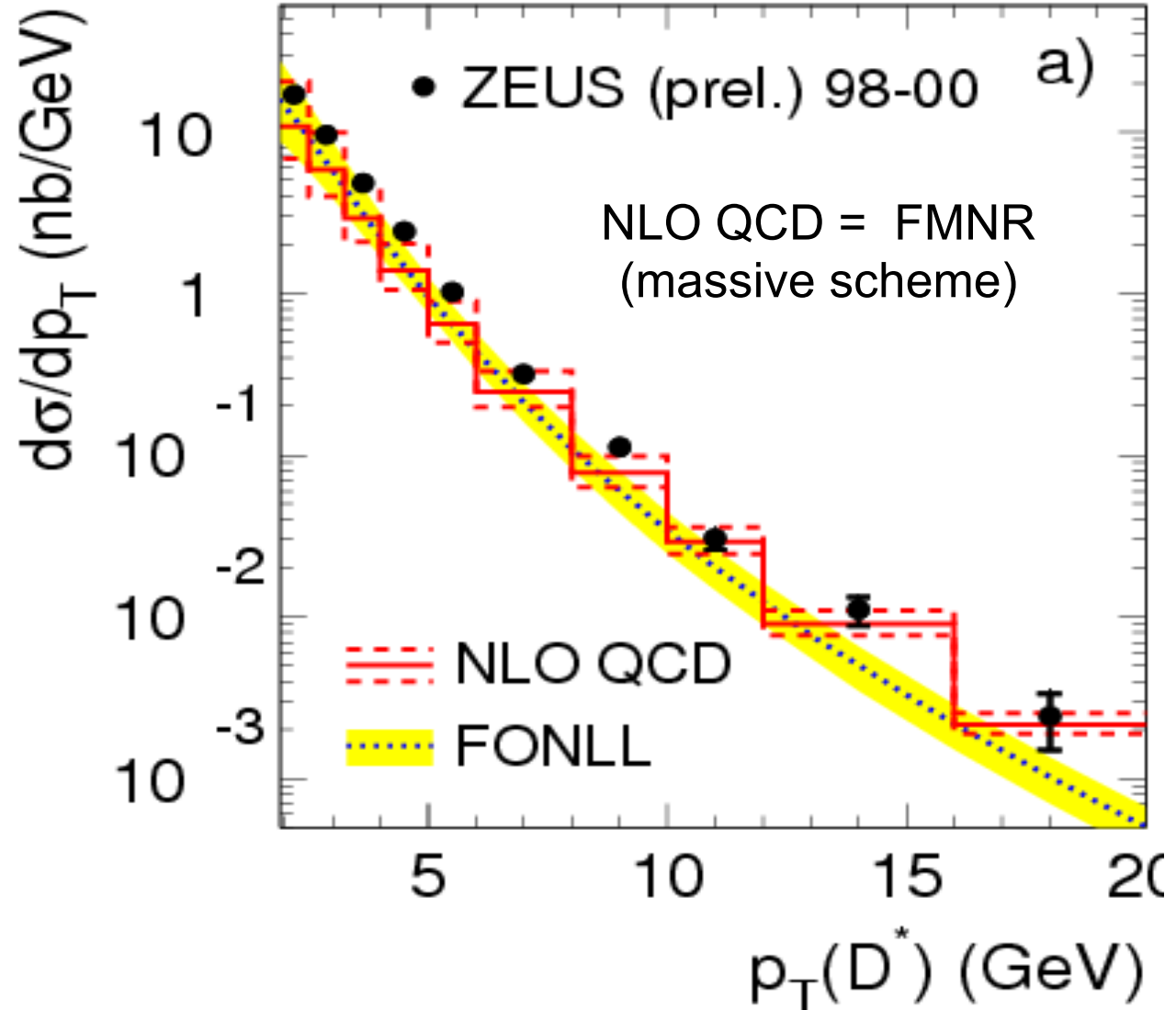
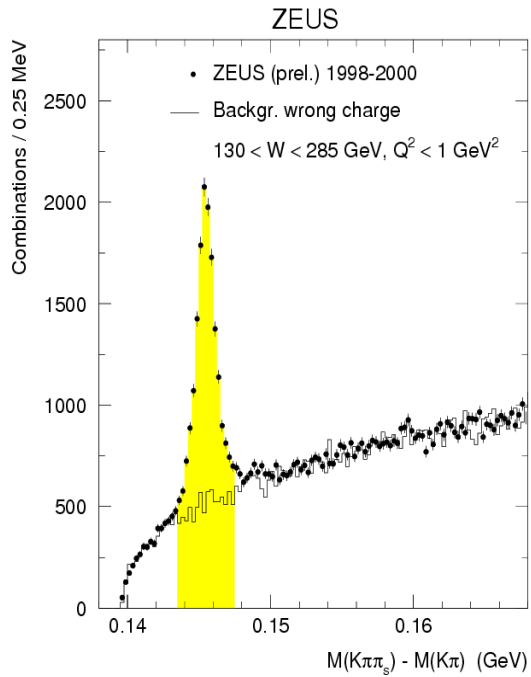
m_Q



	Photoproduction $Q^2 \approx 0$	DIS $Q^2 \geq 1 \text{ GeV}^2$
c • 1.5 GeV		
b • 4.75 GeV	2.	4.
	1.	3.

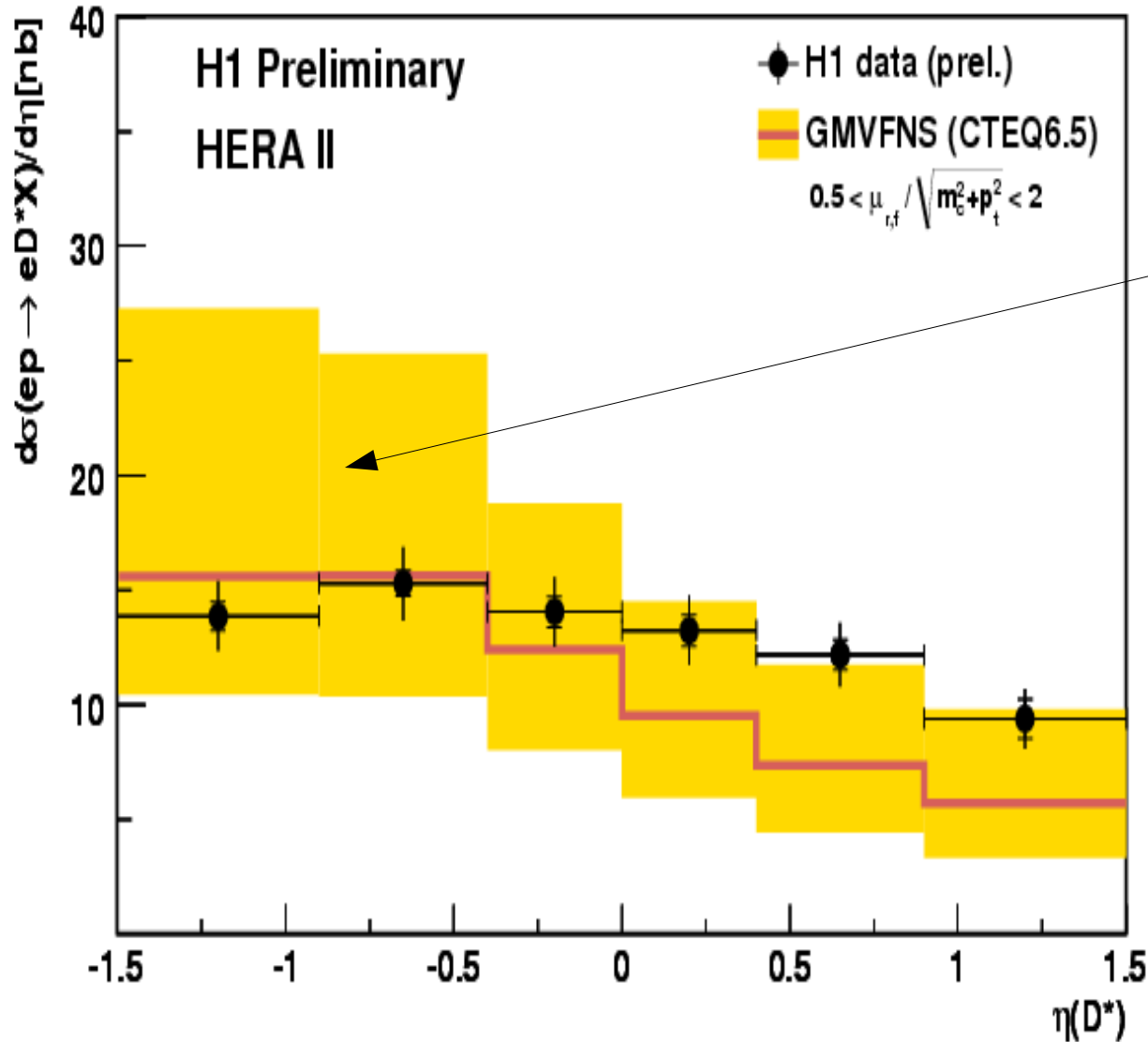
Charm in Photoproduction with D^*

Zeus-prel-02-00



Upper one-sigma level of the theory curves matches data

D^* in Photoproduction



Like reading tea leaves

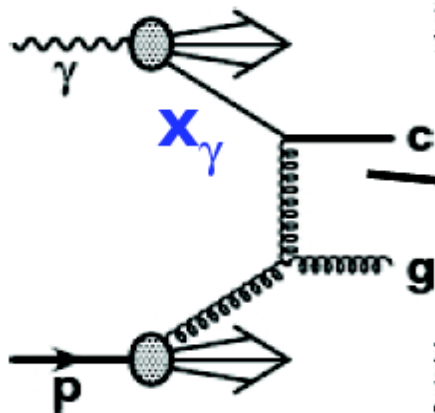


Large theory uncertainties!

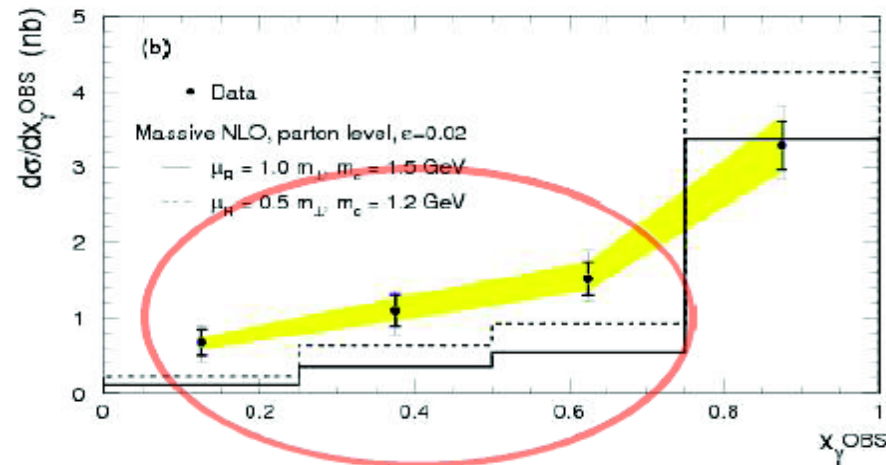
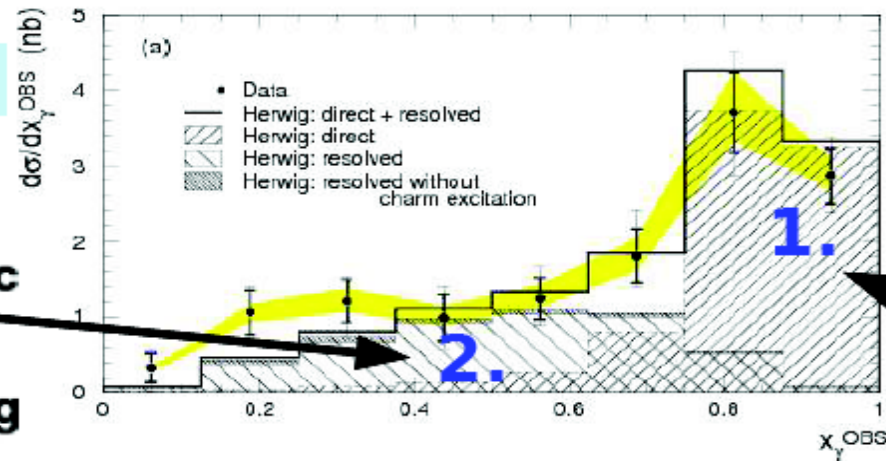
Charm in γp with D^{*+} +dijets

x_γ = Fraction of γ -energy used for dijets

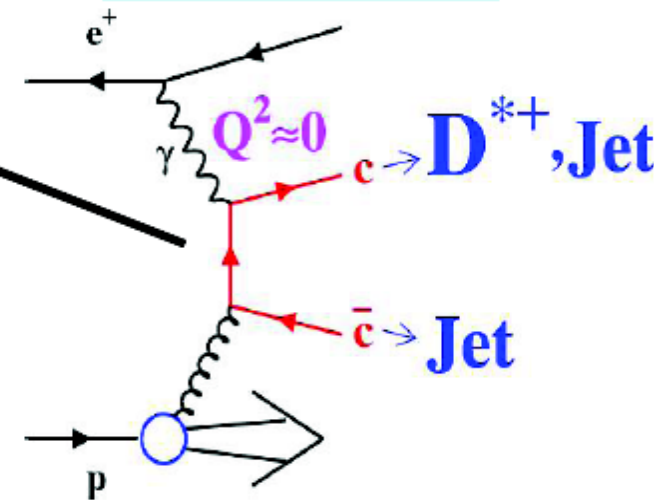
2. Charm in γ



ZEUS 1996+97



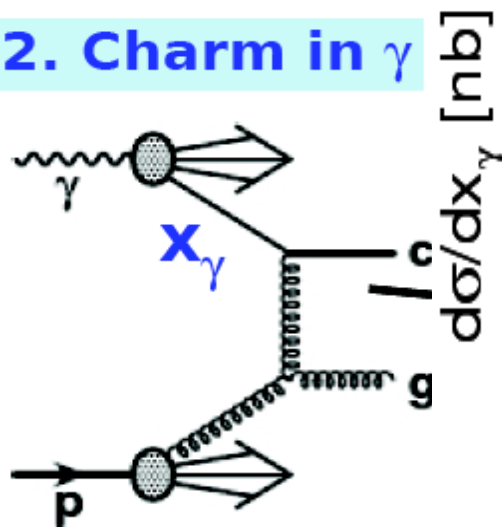
1. Direct γ



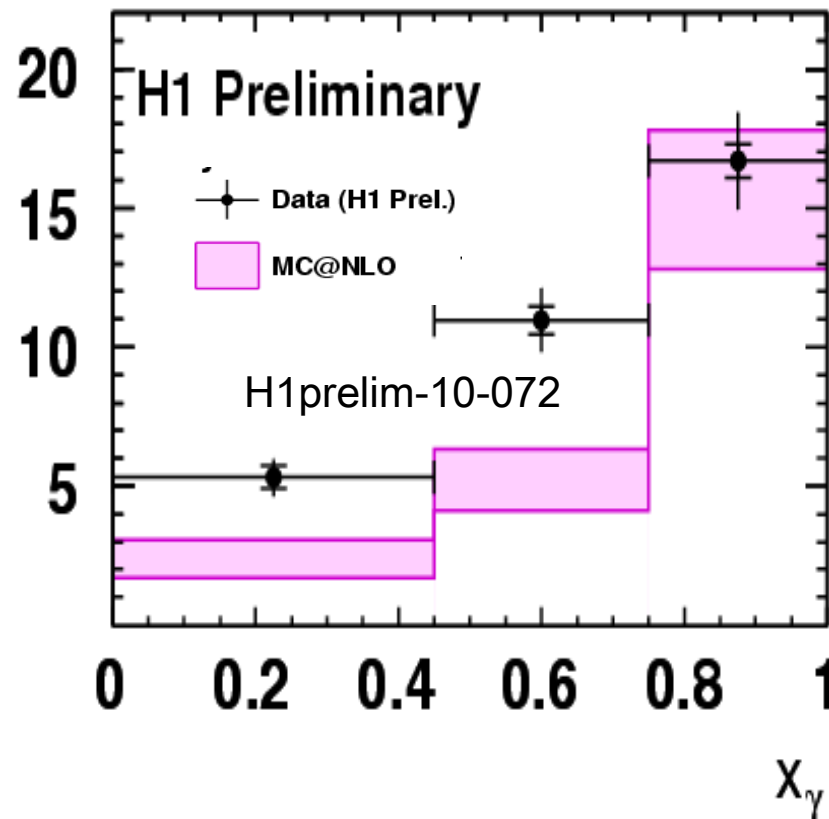
Charm in γp with $D^* + \text{dijets}$

x_γ = Fraction of γ -energy used for dijets

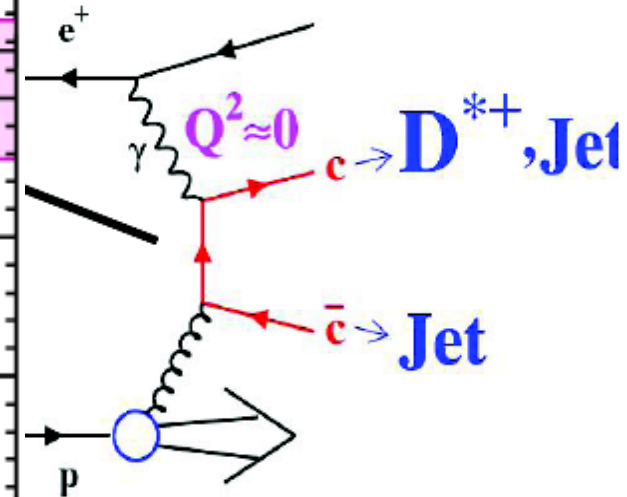
2. Charm in γ



$D^* + 2 \text{ jets in } \gamma p$

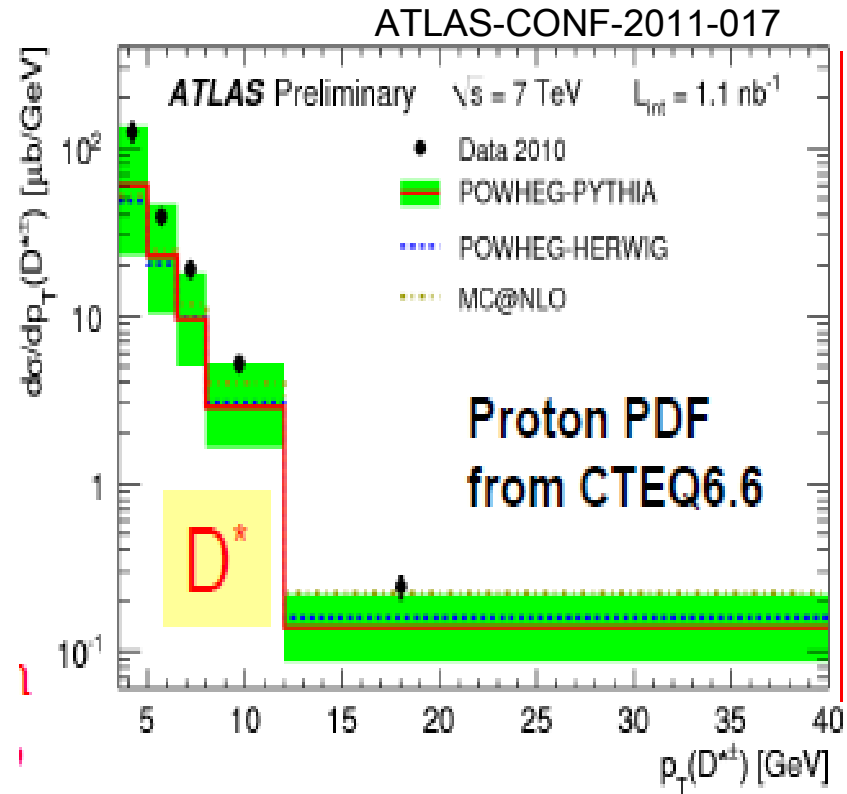
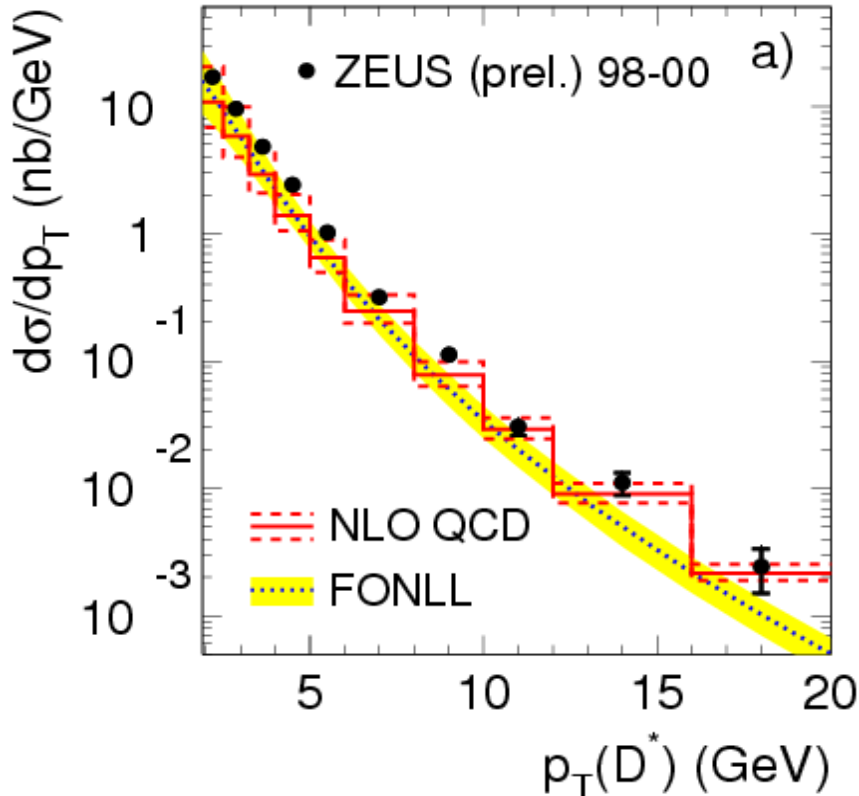
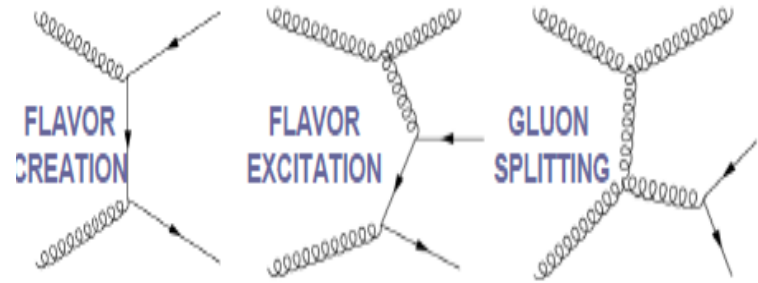
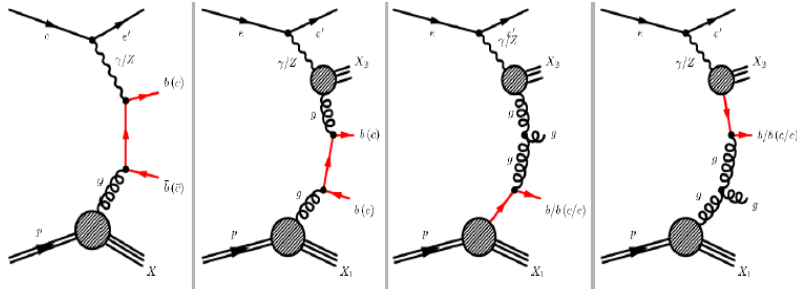


1. Direct γ



MC@NLO fails too,
indications for charm component in resolved photon,
also from further observables

D* production at HERA and at LHC




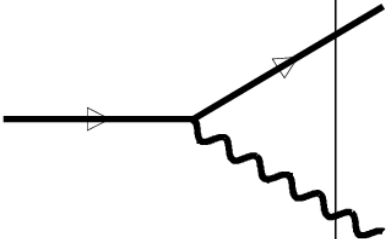
Intriguing similarities! Similar quality of description by NLO

Menu: walk through the scales

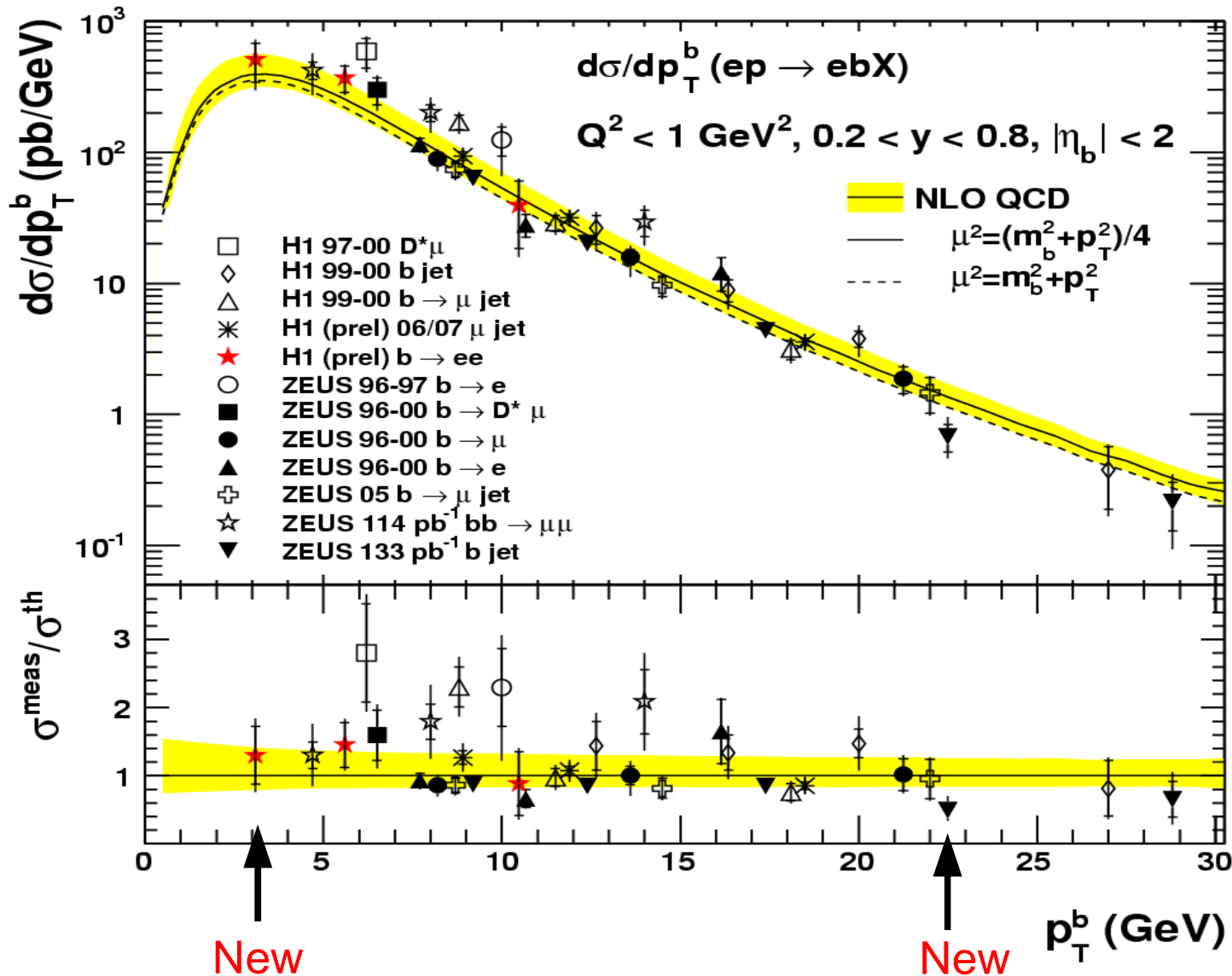
$Q^2 \rightarrow$

m_Q



	Photoproduction $Q^2 \approx 0$ 	DIS $Q^2 \geq 1 \text{ GeV}^2$ 
c • 1.5 GeV	Large theory uncertainties Evidence for charm in resolved photon	3.
b • 4.75 GeV	2.	4.

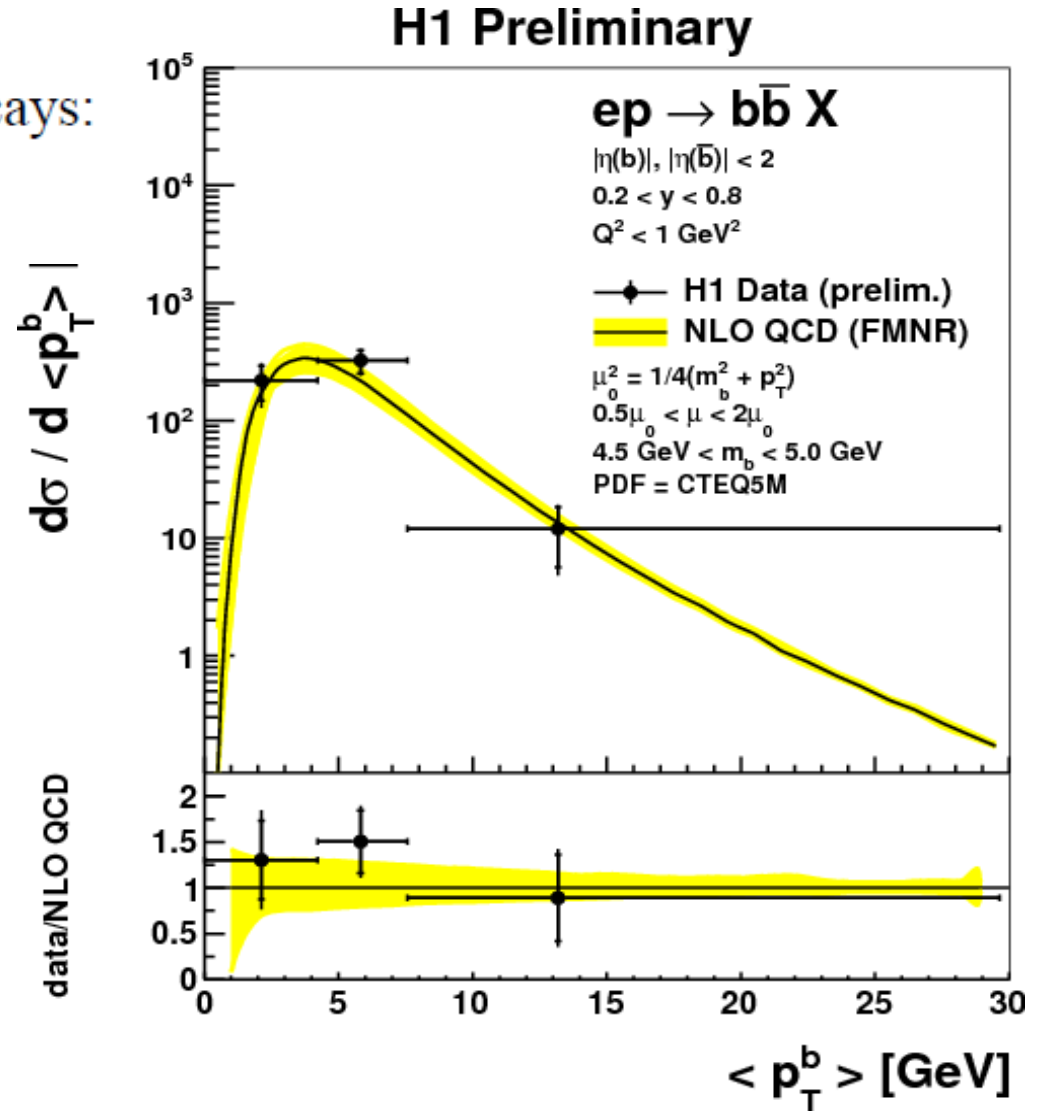
Beauty photoproduction at HERA vs $p_T(b)$



Reasonable description by massive NLO over whole p_T range

- Chosen beauty-tag:
 - 2 electrons from semileptonic decays:

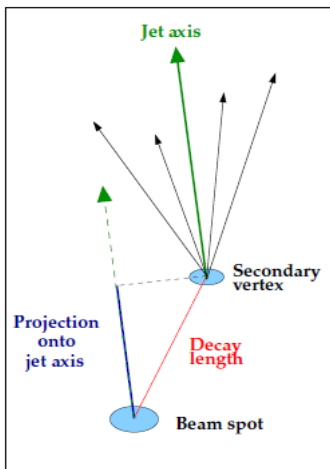
$$b\bar{b} \rightarrow eeX$$



Good description by massive NLO down to threshold

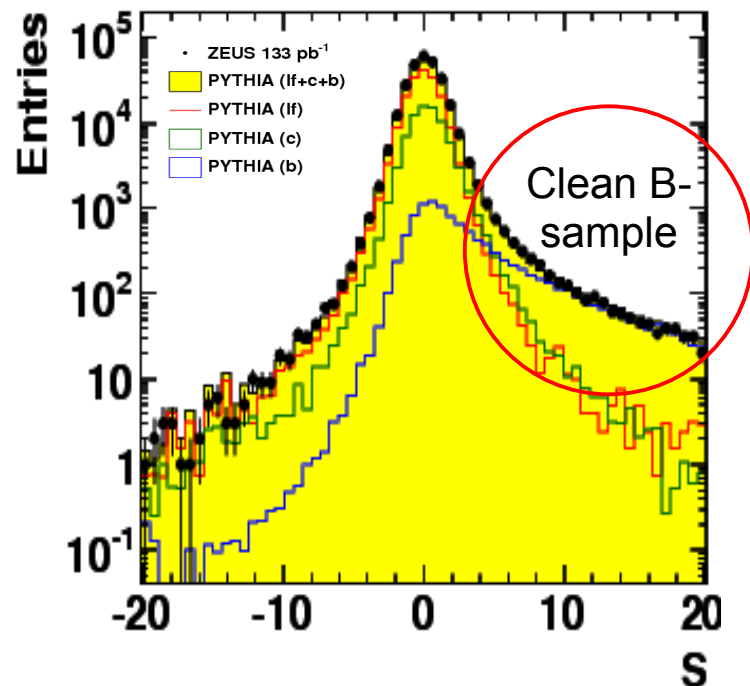
Beauty in PHP with dijets and inclusive secondary vertex

DESY-11-067

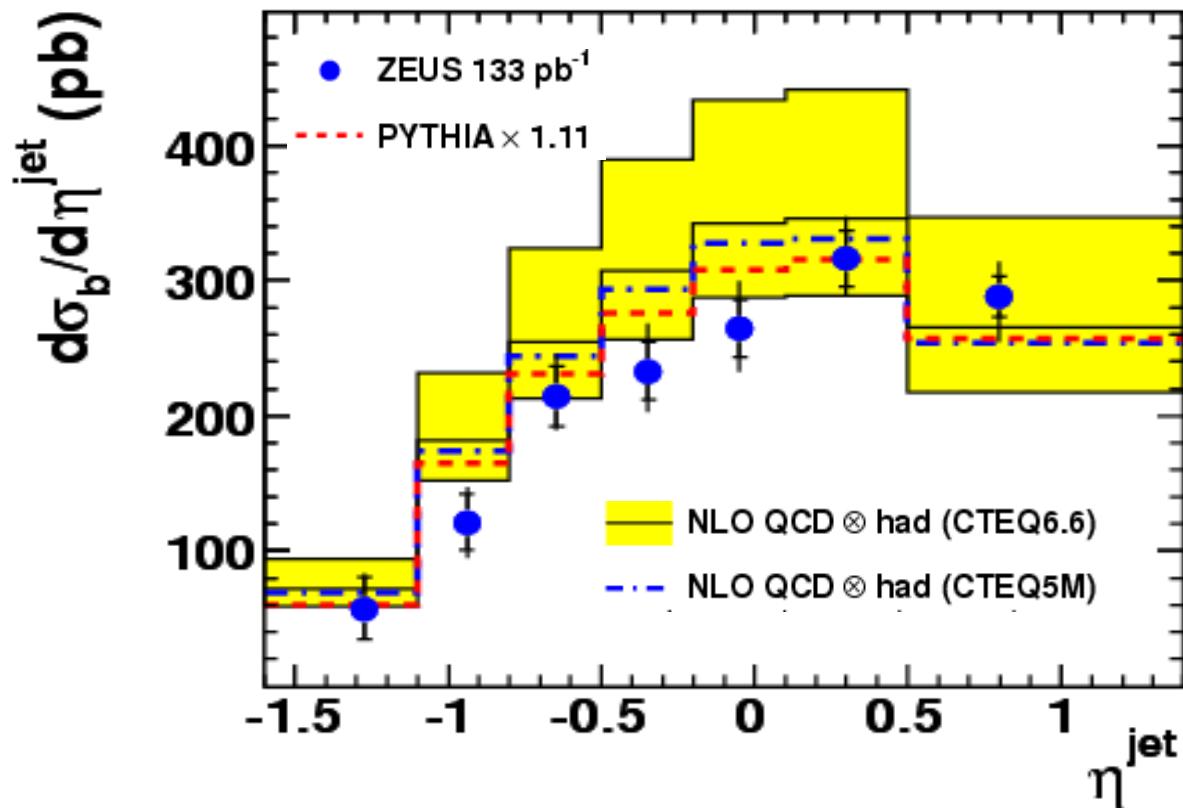


Use
significance S
of decay length

$$2 \leq m_{\text{vtx}} < 7.5 \text{ GeV}$$

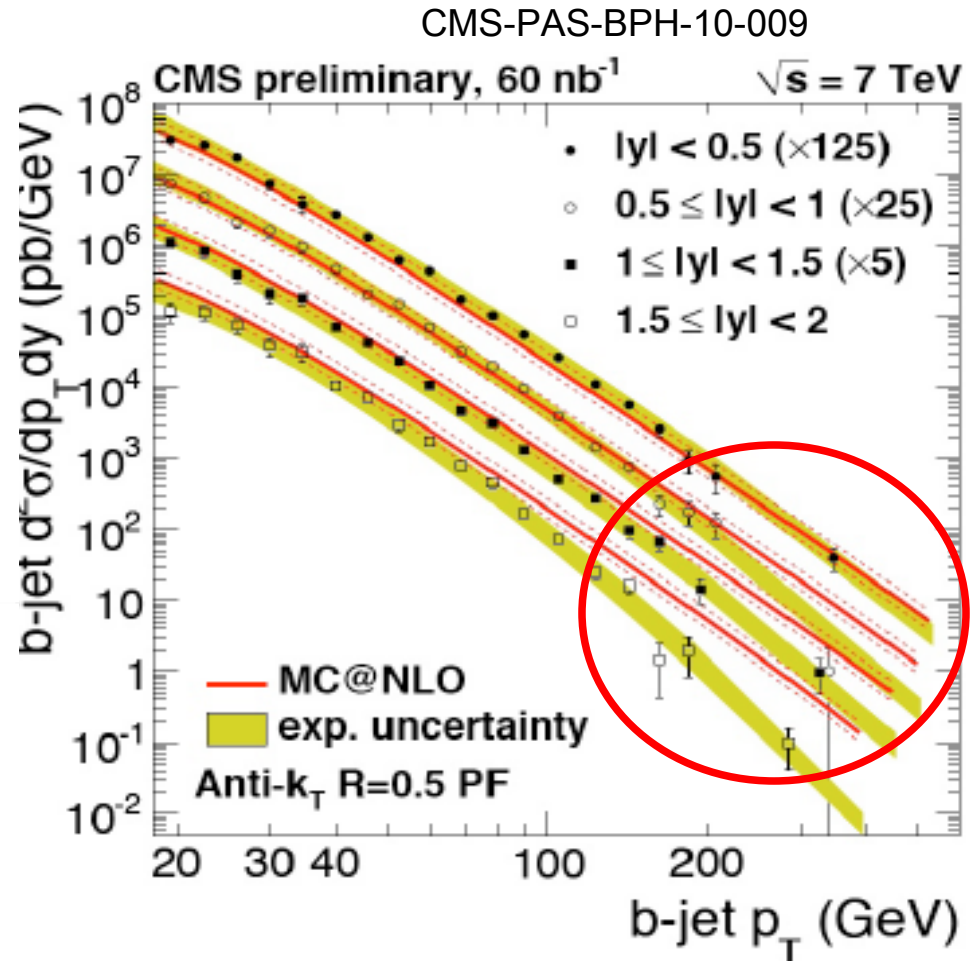
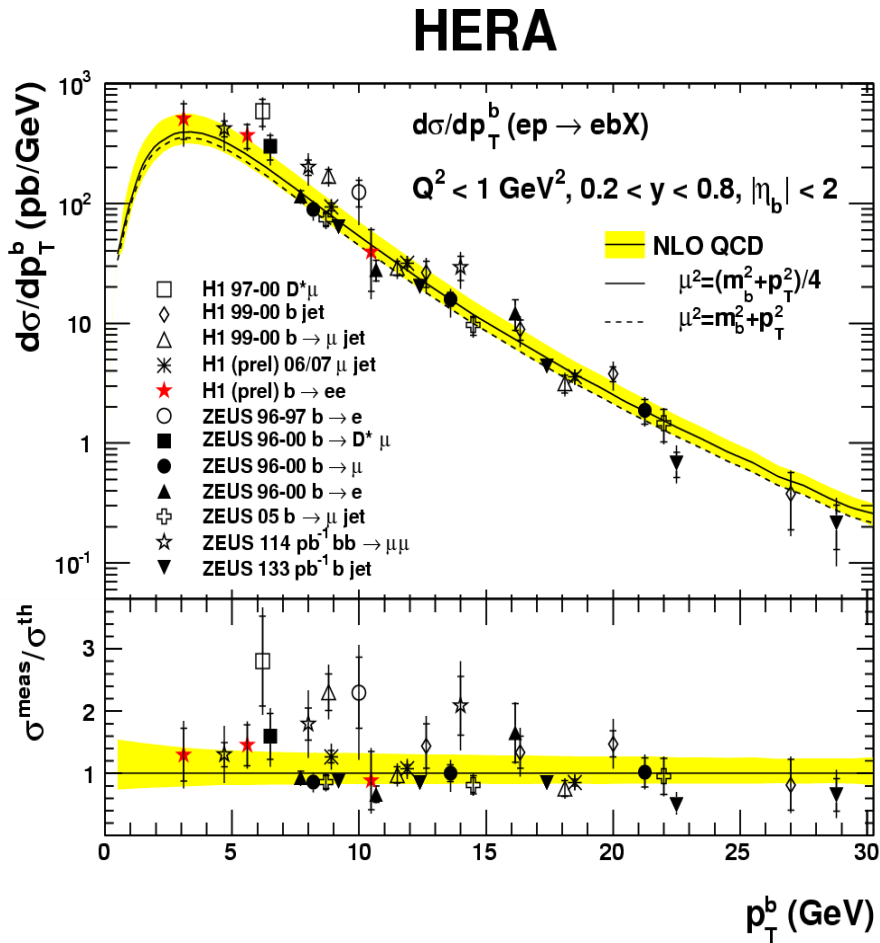


Beauty



Reasonable description

Beauty in HERA PHP and at LHC




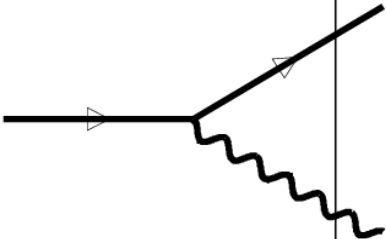
~for both reasonable description by massive NLO,
 MC@NLO Overshoots CMS data at high p_T

Menu: walk through the scales

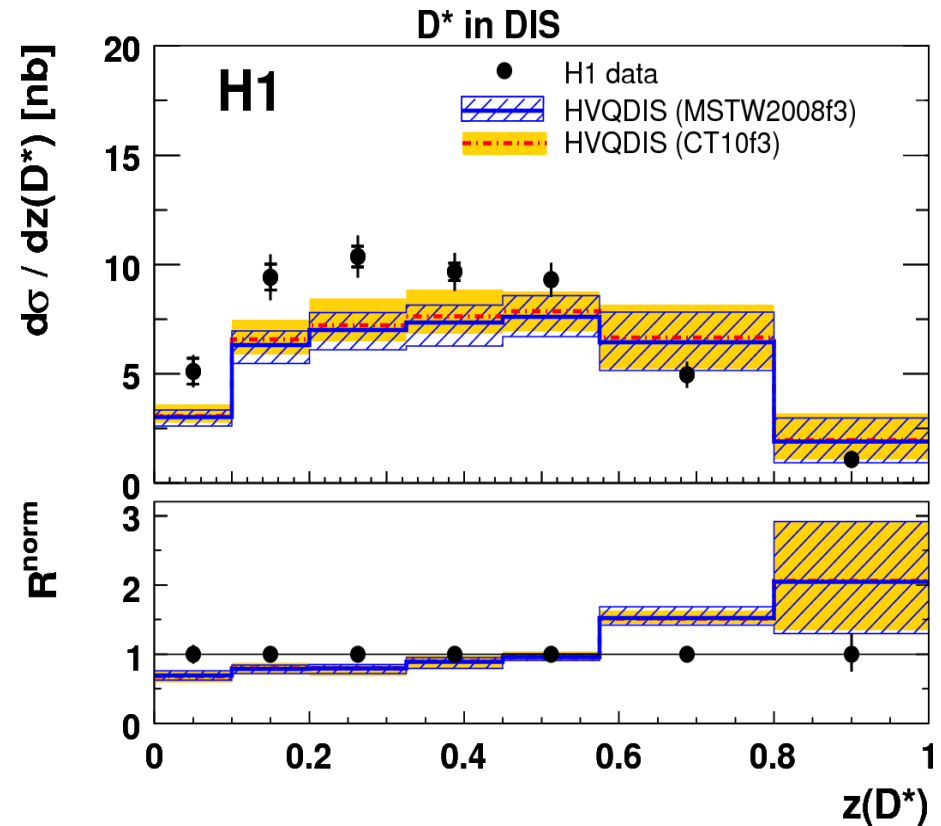
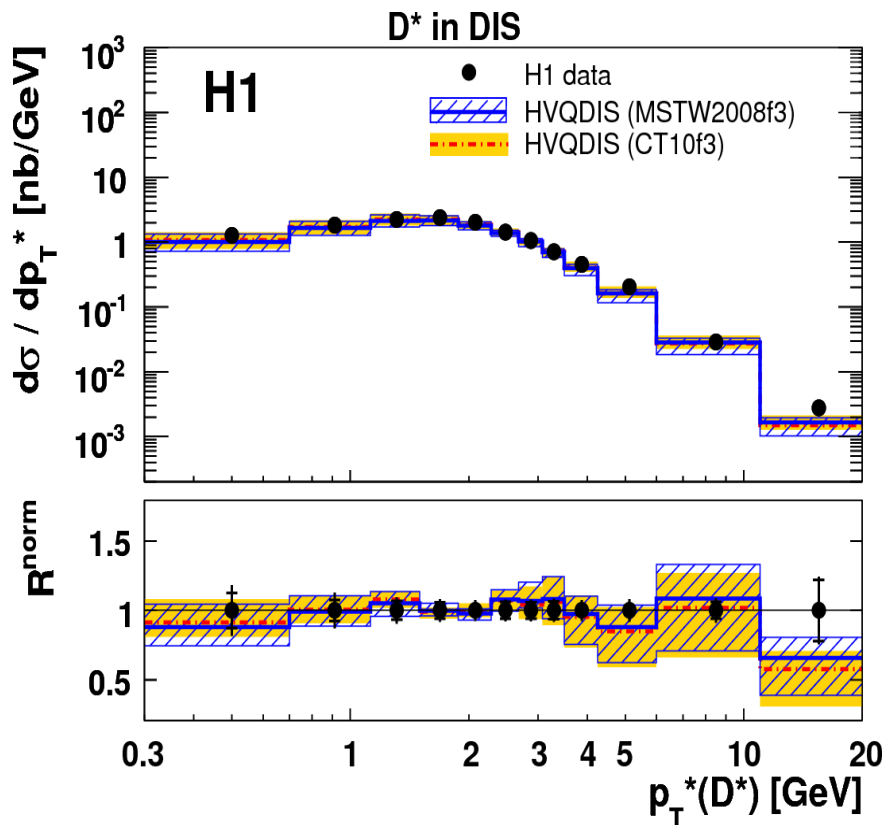
$Q^2 \rightarrow$

m_Q

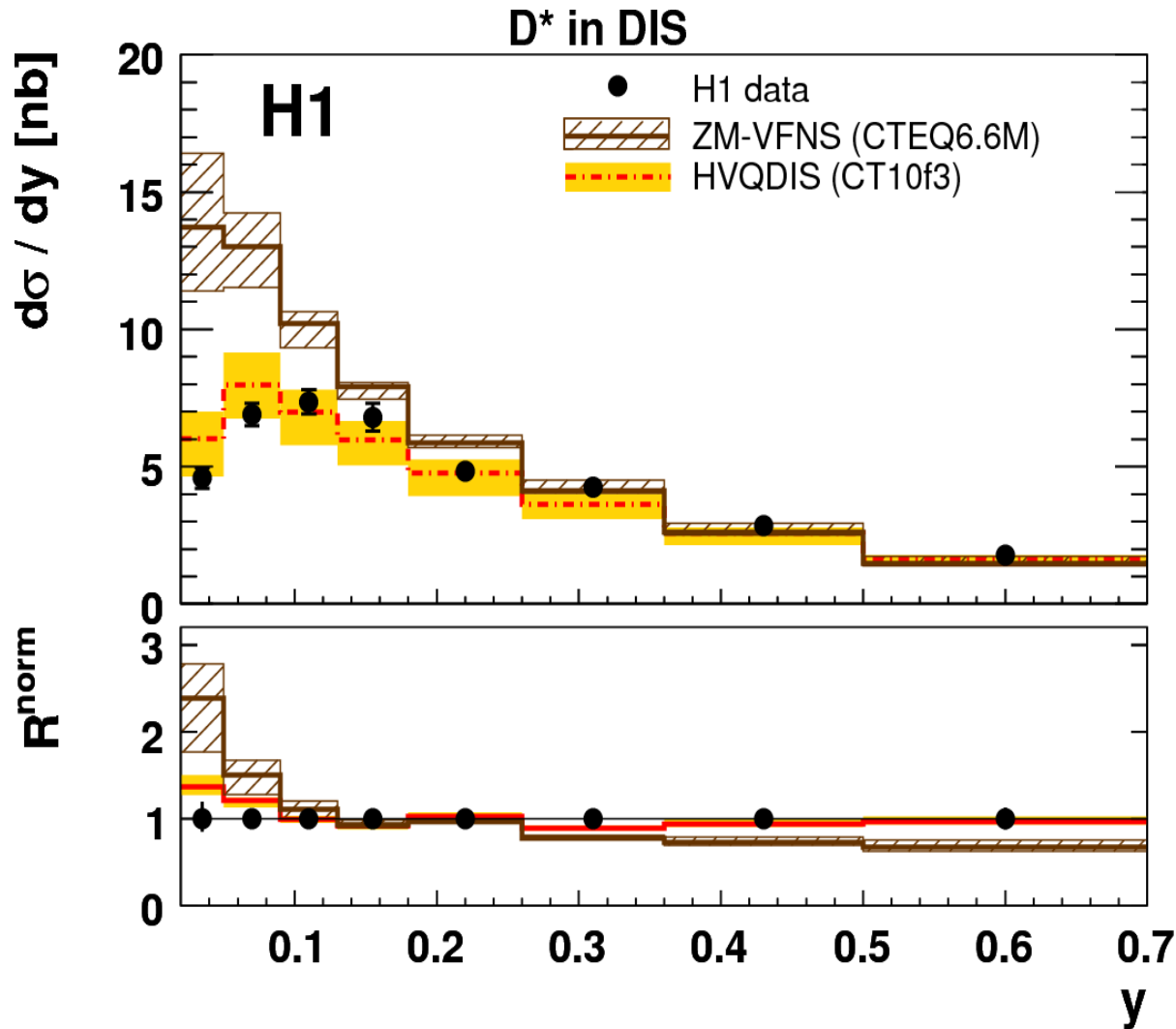


	Photoproduction $Q^2 \approx 0$ 	DIS $Q^2 \geq 1 \text{ GeV}^2$ 
c • 1.5 GeV	Large theory uncertainties Evidence for charm in resolved photon	3.
b • 4.75 GeV	Reasonable agreement with massive NLO using scale $\mu_r^2 = (p_t^2 + m_b^2)/4$	4.

$z(D^*) = \text{energy fraction of photon taken by } D^*$



Massive NLO generally
 \sim ok, but fails to describe $z(D^*)$

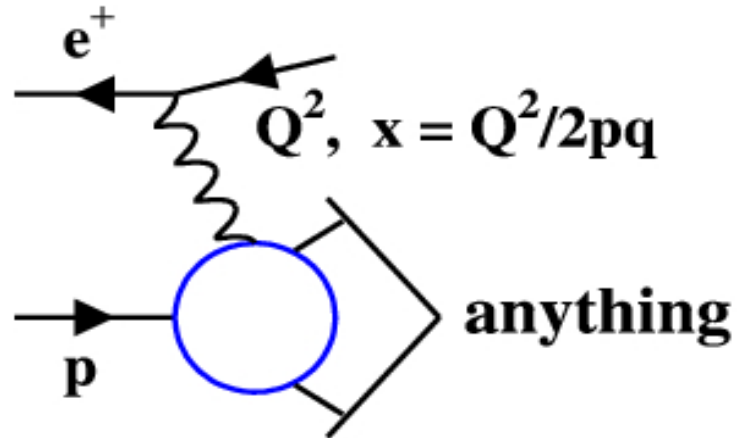


With additional cut on $pt^*(D^*) > 2$ GeV

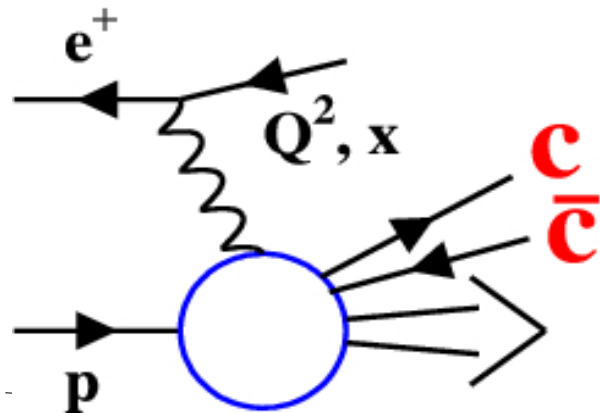


Massive NLO calculation better than massless

Charm contribution to DIS: F_2^{cc}



$$\frac{d^2\sigma^{ep}}{dQ^2 dx} \propto F_2(x, Q^2)$$



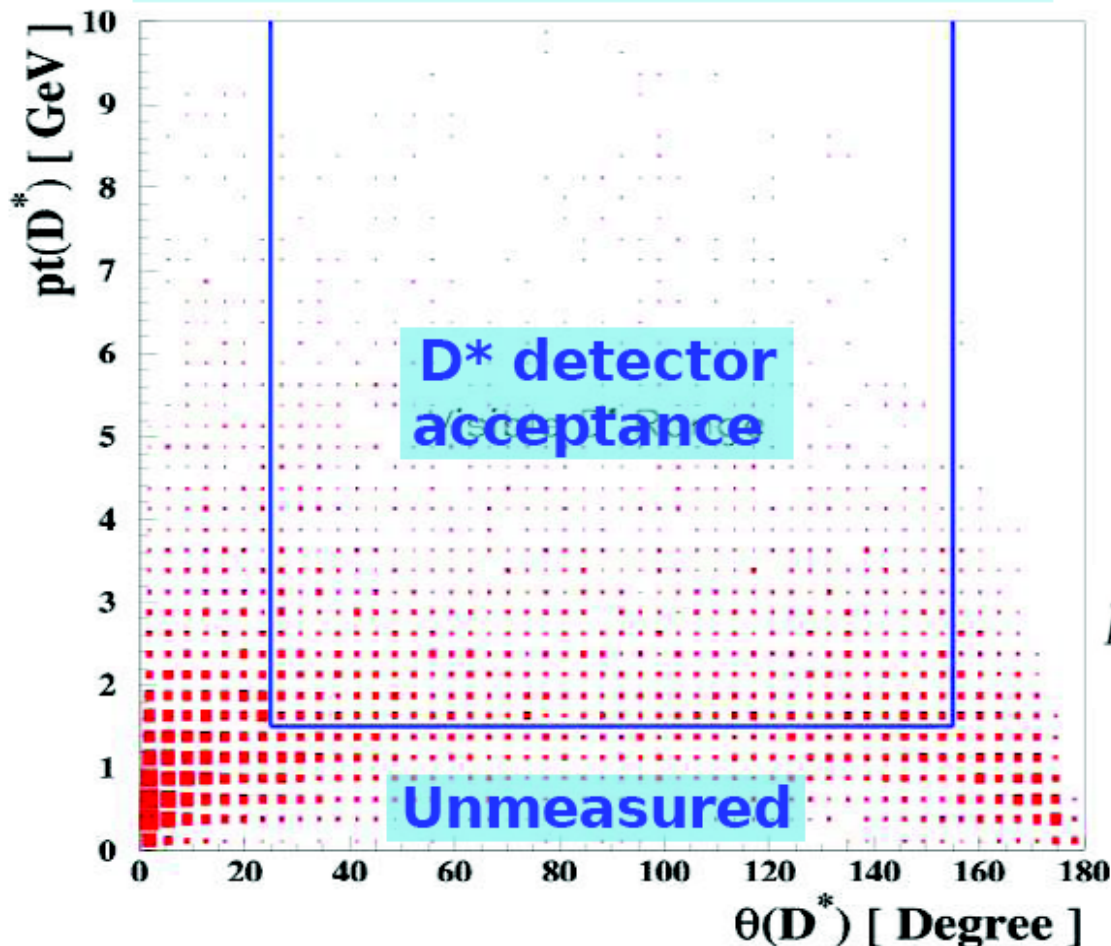
$$\frac{d^2\sigma^{ep \rightarrow c\bar{c}x}}{dQ^2 dx} \propto F_2^{c\bar{c}}(x, Q^2)$$

similar for b: F_2^{bb}

Extrapolations

For F_2^{cc} : Need to measure $\sigma(ep \rightarrow cc)$ in x, Q^2 bin

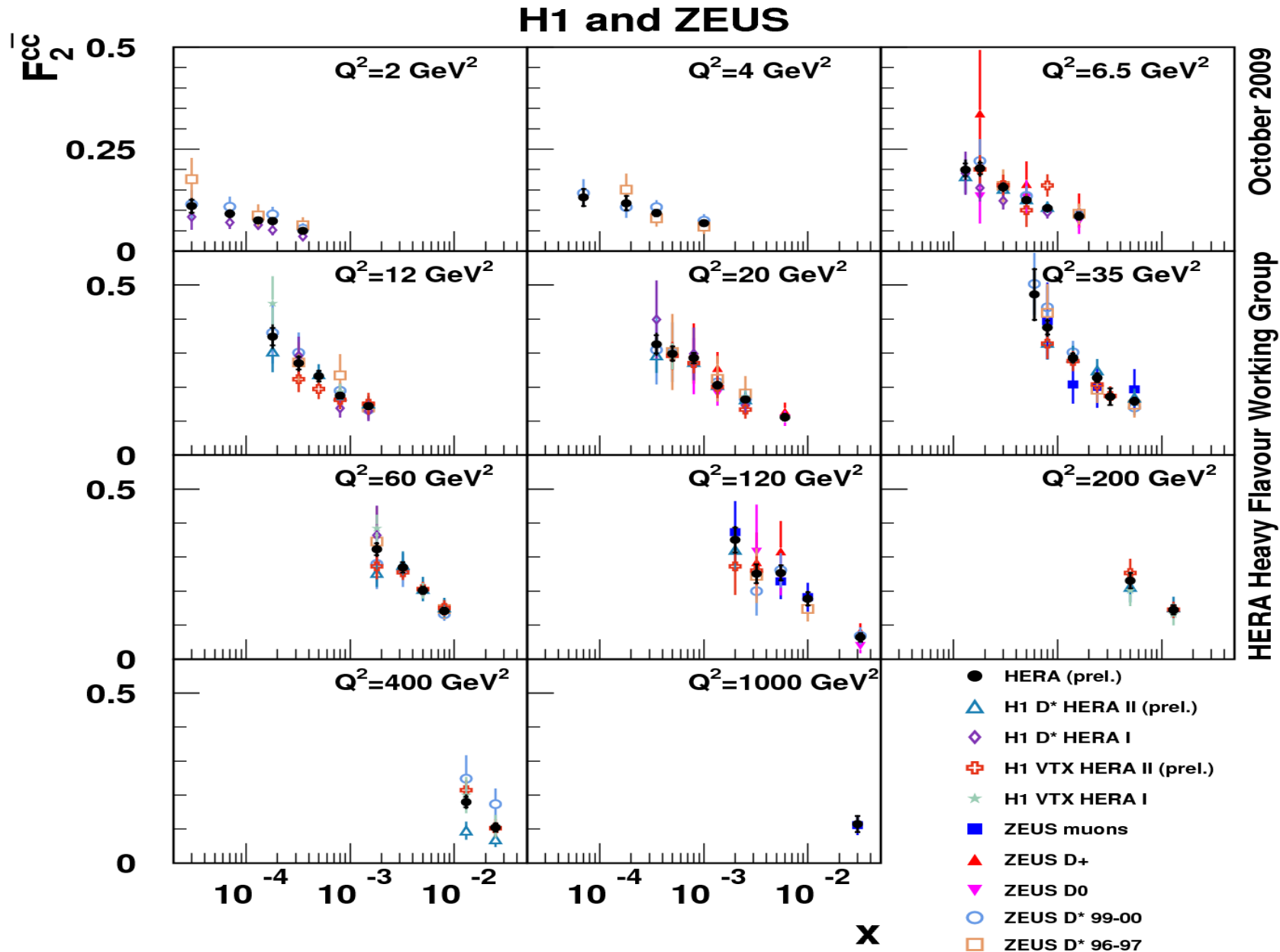
Simulation of D^* , $Q^2 > 1 \text{ GeV}^2$:



Extrapolation factors
vary from $\sim 1.5-10$

$$F_{2,\text{meas}}^{c\bar{c}}(x_i, Q_i^2) = \frac{\sigma_{i,\text{meas}}(ep \rightarrow D^* X)}{\sigma_{i,\text{theo}}(ep \rightarrow D^* X)} F_{2,\text{theo}}^{c\bar{c}}(x_i, Q_i^2)$$

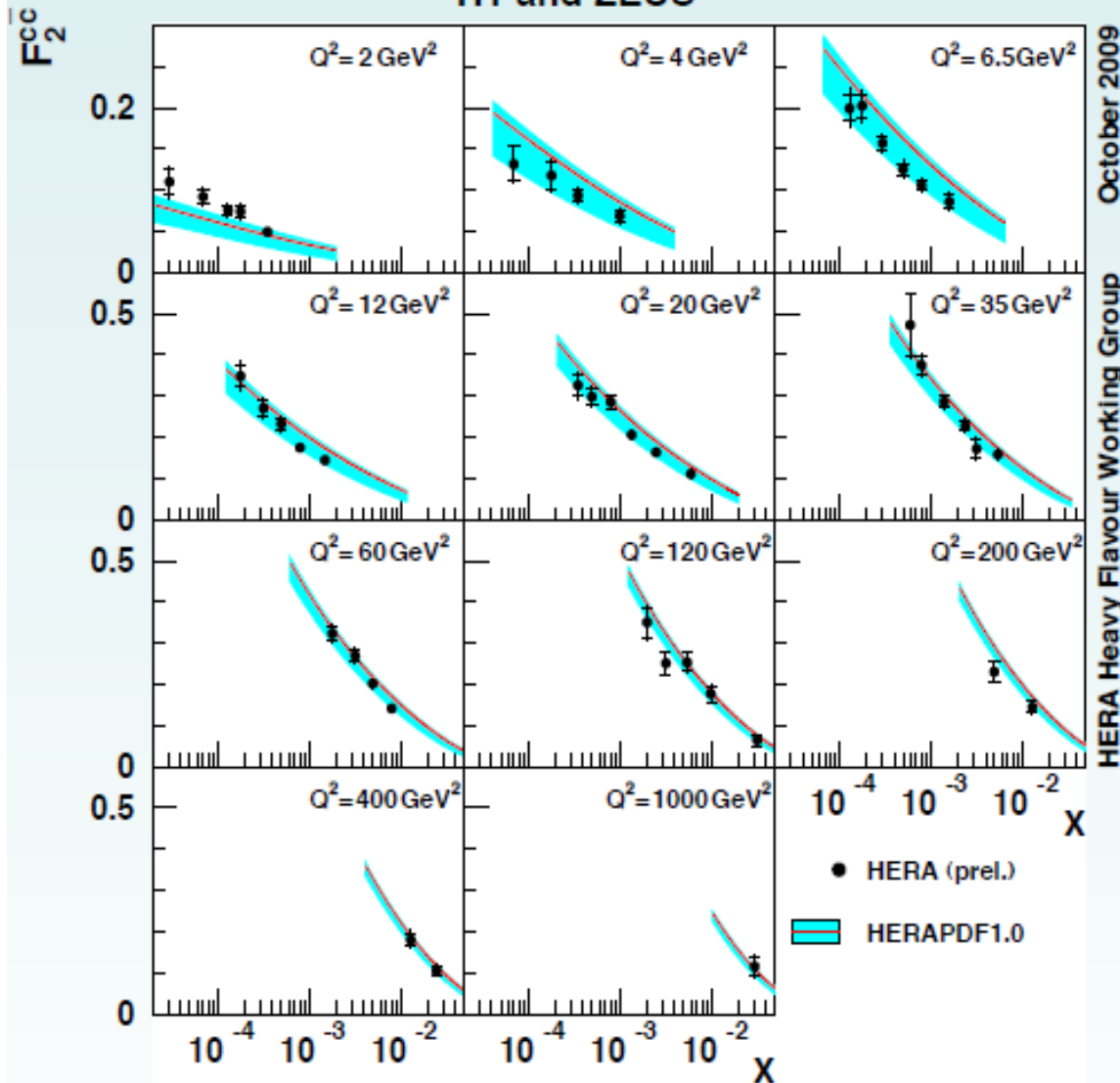
Combination of F_2^{cc} measurements



Charm at HERA: Test Choice of m_c in PDF

From K.Lipkas talk

H1 and ZEUS



$F_2^{c\bar{c}}$ not included in HERAPDF1.0

but is well described

charm quark mass value varied
in the PDF Fit:

— $m_c = 1.4 \text{ GeV}$

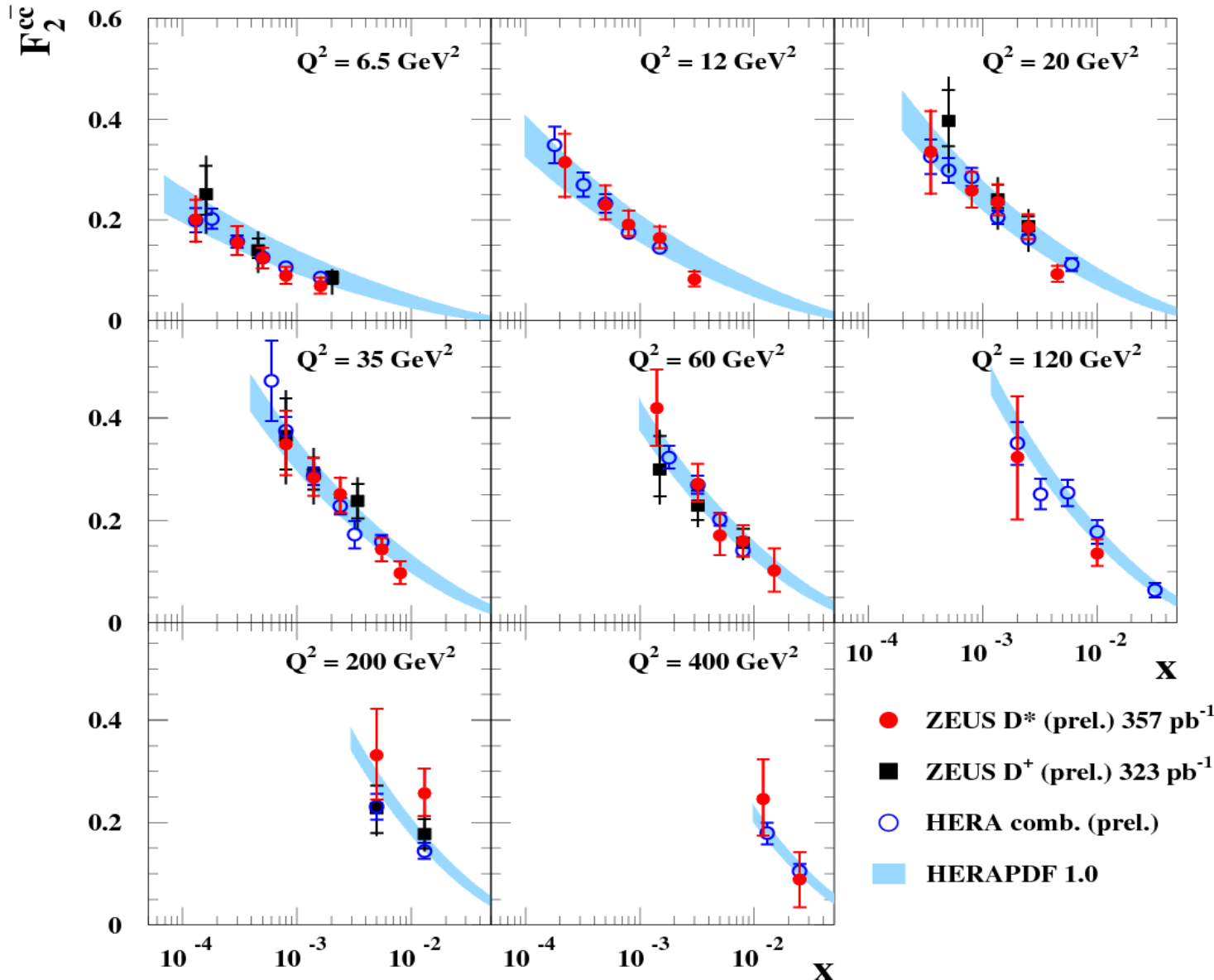
■ $m_c = 1.35 \text{ vs } 1.65 \text{ GeV}$

PDG pole mass

$F_2^{c\bar{c}}$ data can be used to
determine m_c and to test
HF schemes (for more see K.L.talk)

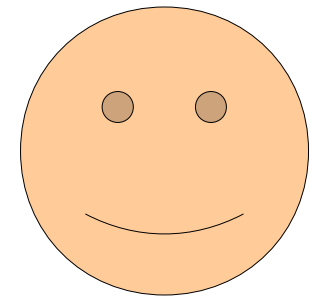
F_2^{cc} further brand new results (not yet used in combination)

ZEUS



ZEUS-prel-10-005

ZEUS-prel-11-012


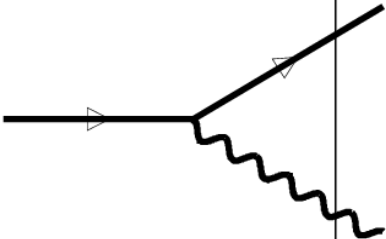


Menu: walk through the scales

$Q^2 \rightarrow$

m_Q

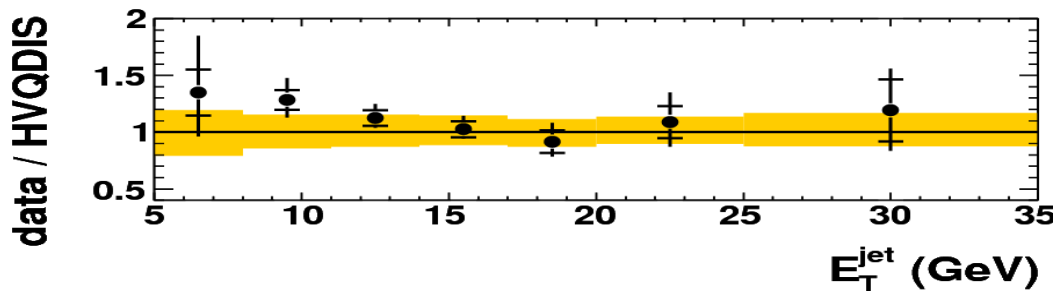
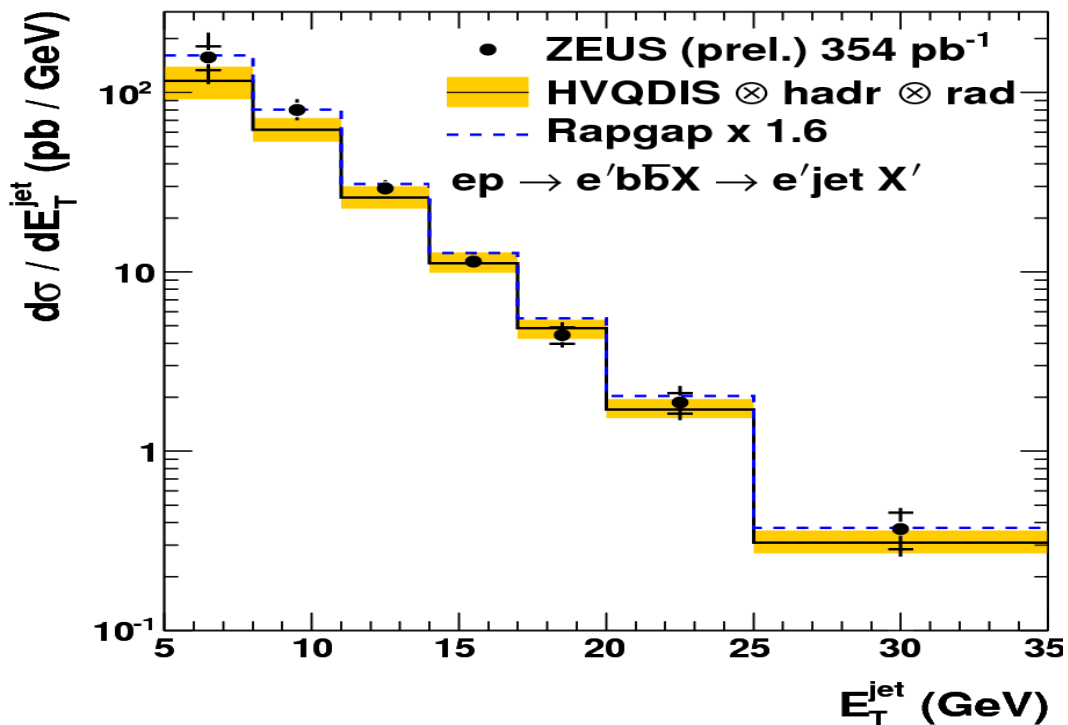


	Photoproduction $Q^2 \approx 0$ 	DIS $Q^2 \geq 1 \text{ GeV}^2$ 
c • 1.5 GeV	Large theory uncertainties Evidence for charm in resolved photon	Massive NLO ok with exceptions (low z), F_2^{cc} data separate HF schemes/ m_c
b • 4.75 GeV	Reasonable agreement with massive NLO using scale $\mu_r^2 = (p_t^2 + m_b^2)/4$	<div style="background-color: #92d050; text-align: center; padding: 20px; font-size: 2em; font-weight: bold;">4.</div>

Beauty in DIS with inclusive secondary vertex

ZEUS-prel-10-004

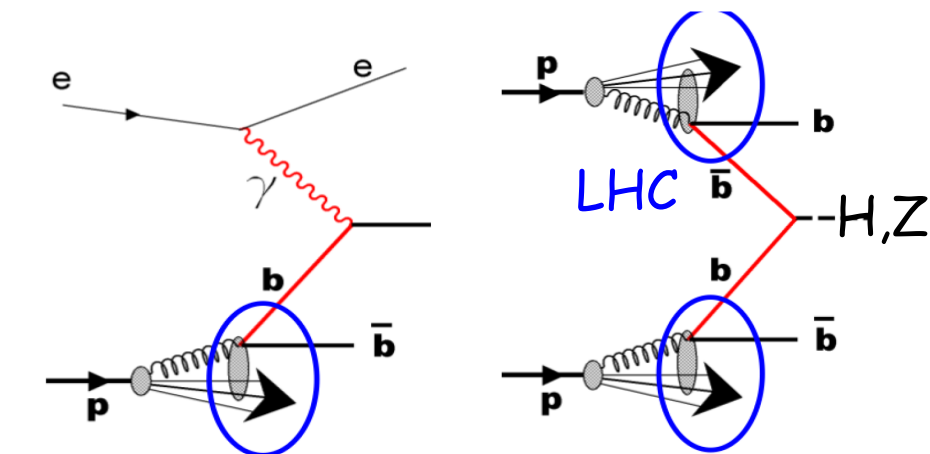
ZEUS



Most precise b in DIS results so far

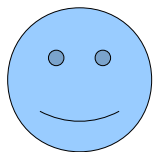
Beauty of the proton: F_2^{bb}

$b(x)$ from HERA "goes to" LHC

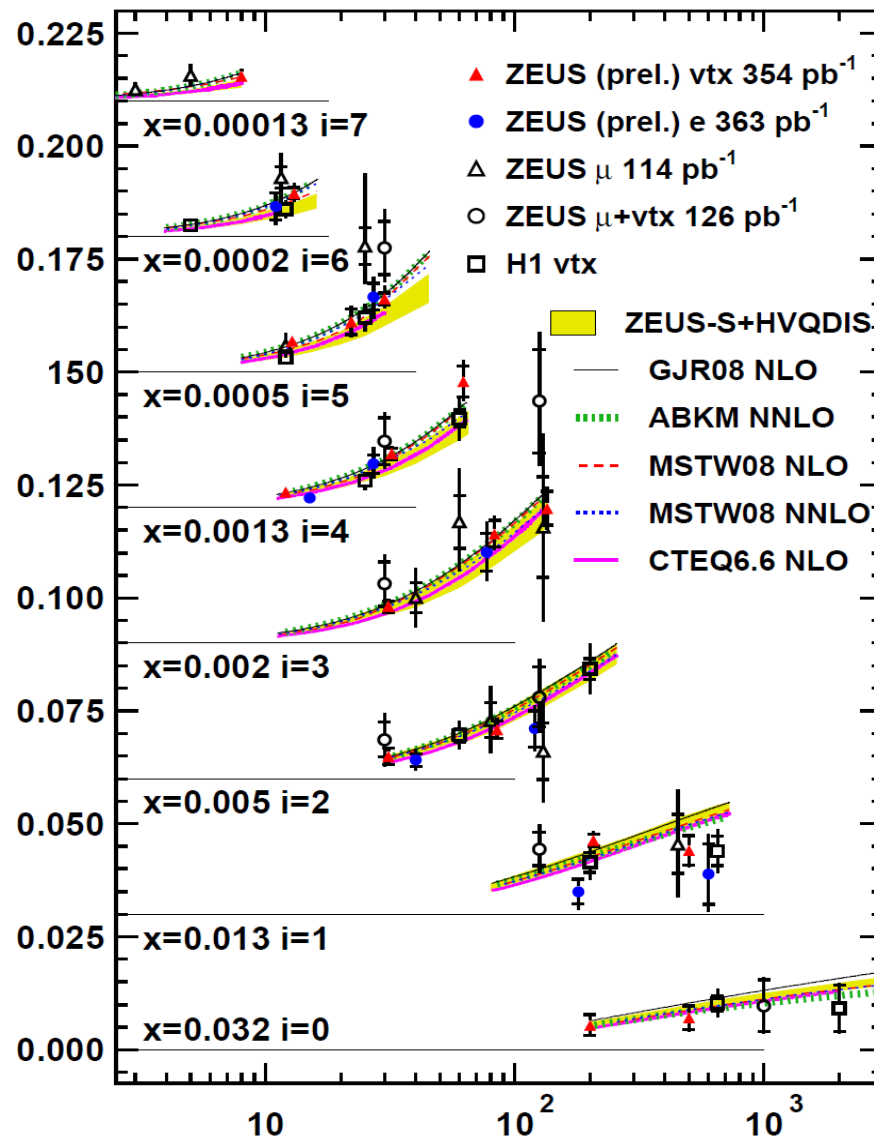


$=\frac{b\bar{b}}{2} + 0.03 i$

- New precise results
- Various HF schemes

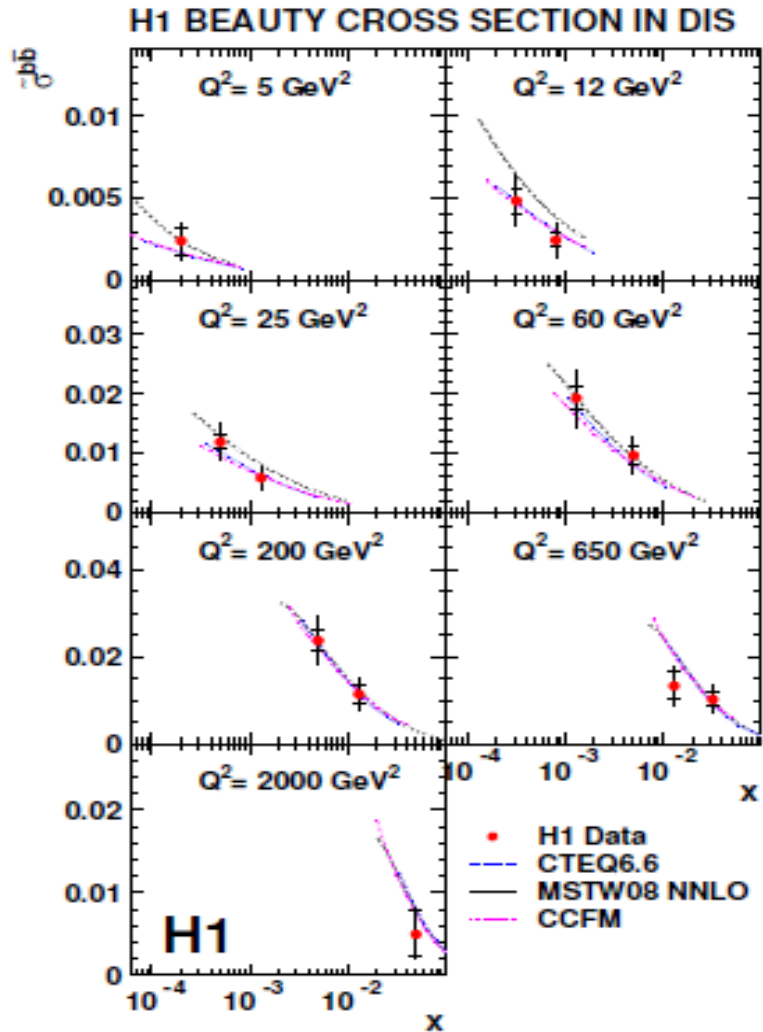


ZEUS

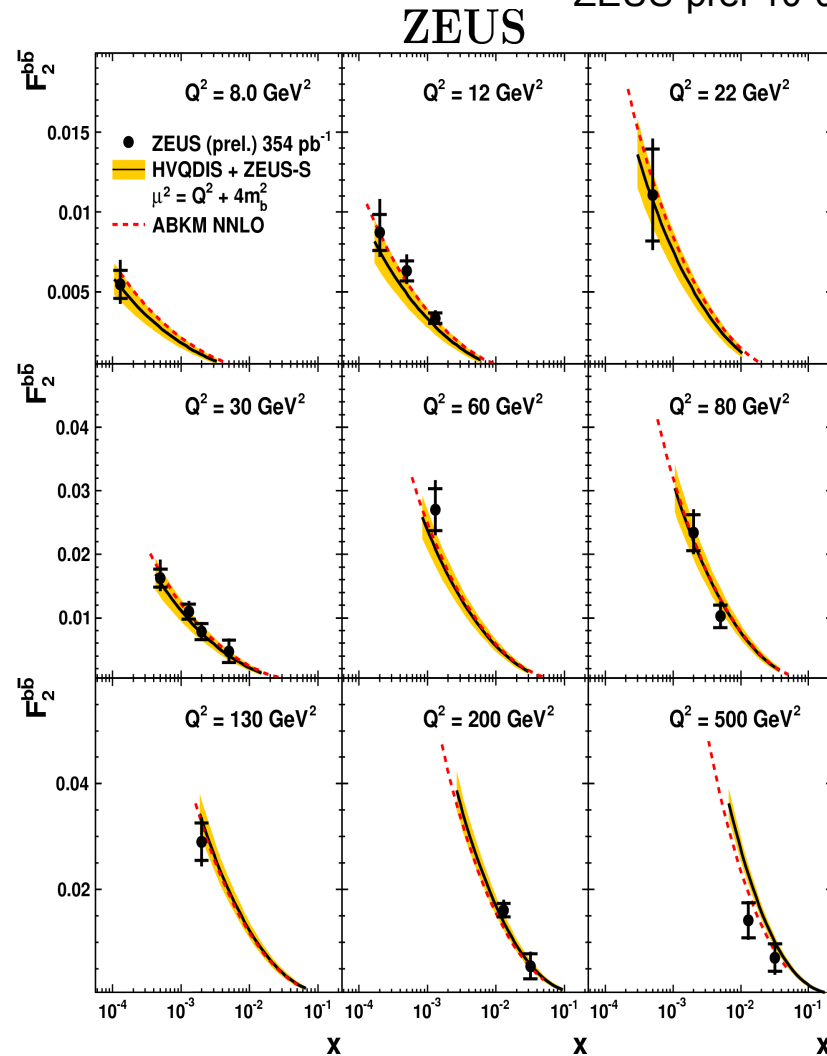


F_2^{bb} from the secondary vertex analyses alone

DESY-09-096



ZEUS-prel-10-004




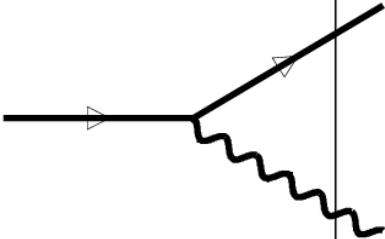
Data combination will further improve precision

Menu: walk through the scales

$Q^2 \rightarrow$

m_Q




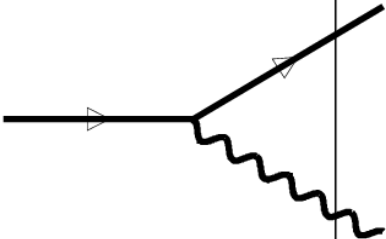
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b • 4.75 GeV	Reasonable agreement with massive NLO using scale $\mu_r^2 = (p_t^2 + m_b^2)/4$	F_2^{bb} described well by different schemes

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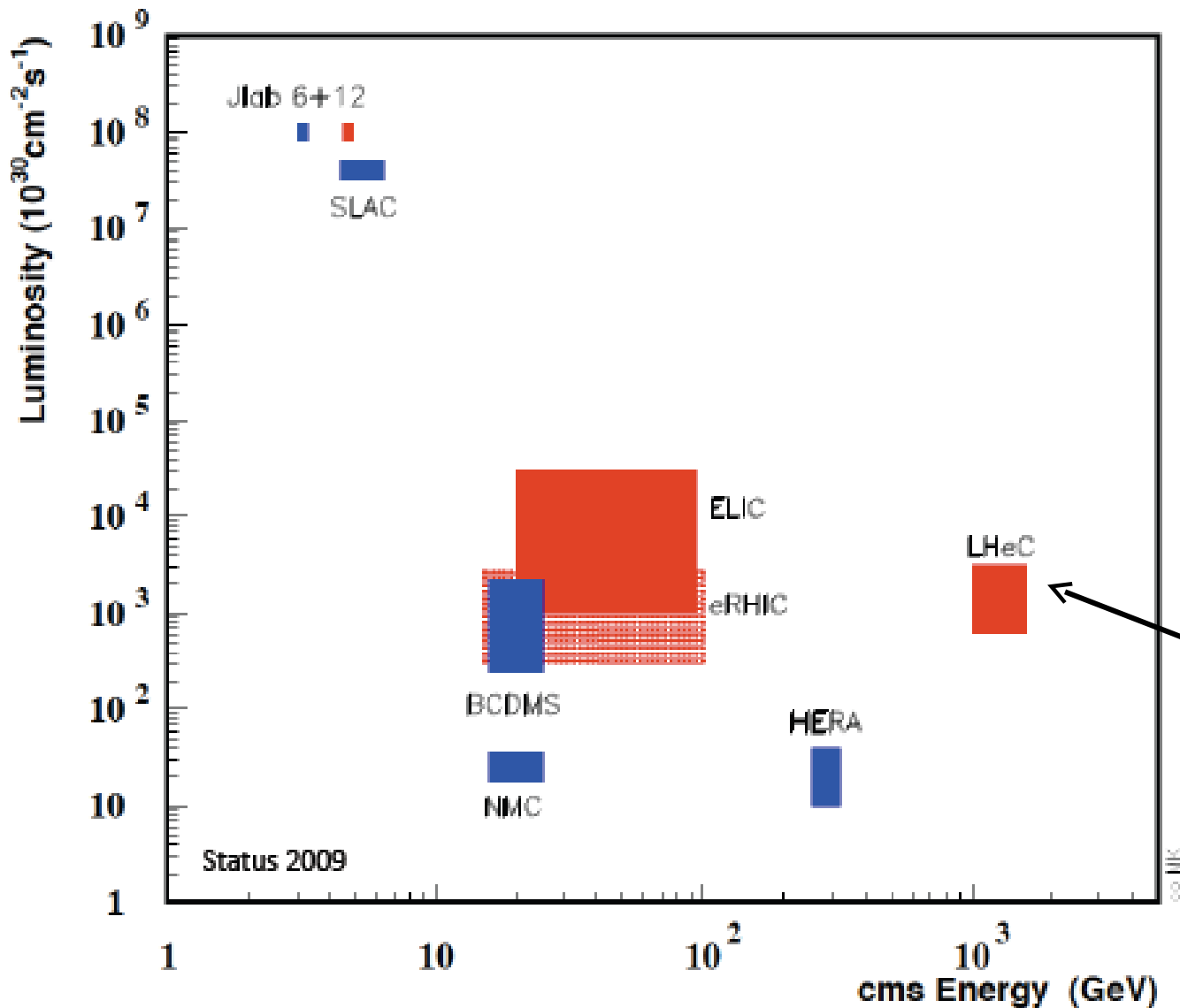


Before final conclusion:



HERA ended in 2007,
what about the
future of ep colliders?

Lepton proton scattering experiments



*LHeC =
highest
energy and
high lumi*

LHeC Accelerator options

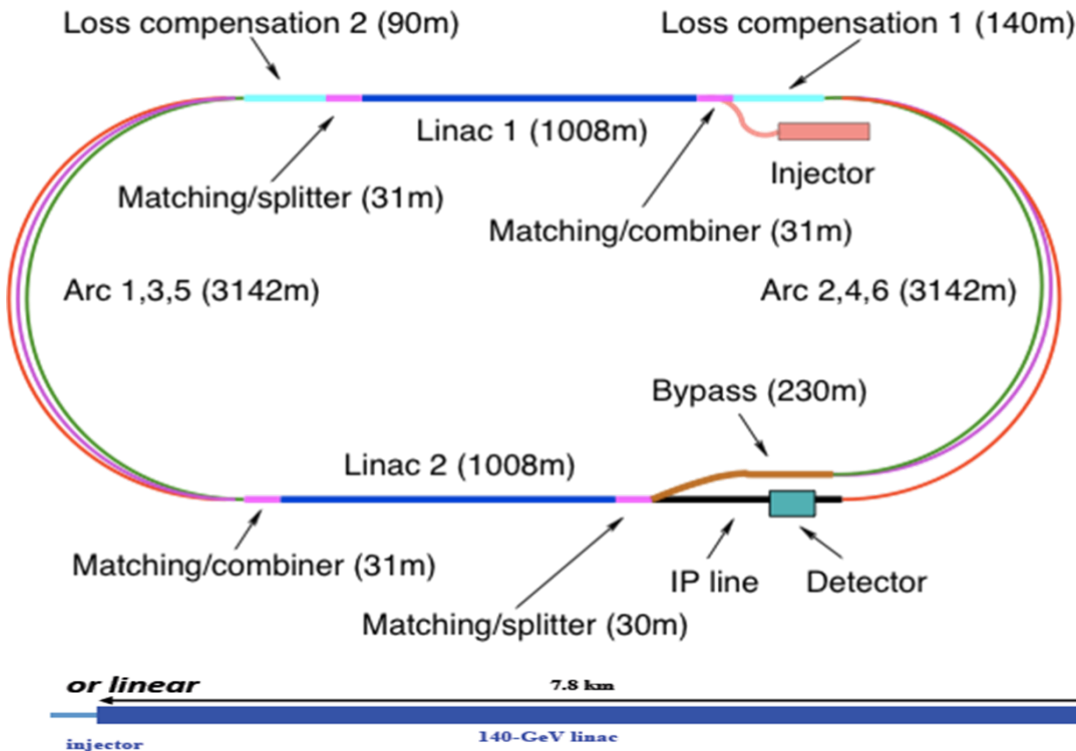


$$L = \frac{1}{4\pi} \cdot \frac{N_p}{\epsilon_p} \cdot \frac{1}{\beta^*} \cdot \gamma \cdot \frac{I_e}{e}$$

$$N_p = 1.7 \cdot 10^{11}, \epsilon_p = 3.8 \mu\text{m}, \beta^* = 0.2 \text{ m}, \gamma = 7000 / 0.94$$

$$L = 8 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{0.2}{\beta^* / \text{m}} \cdot \frac{I_e / \text{mA}}{1}$$

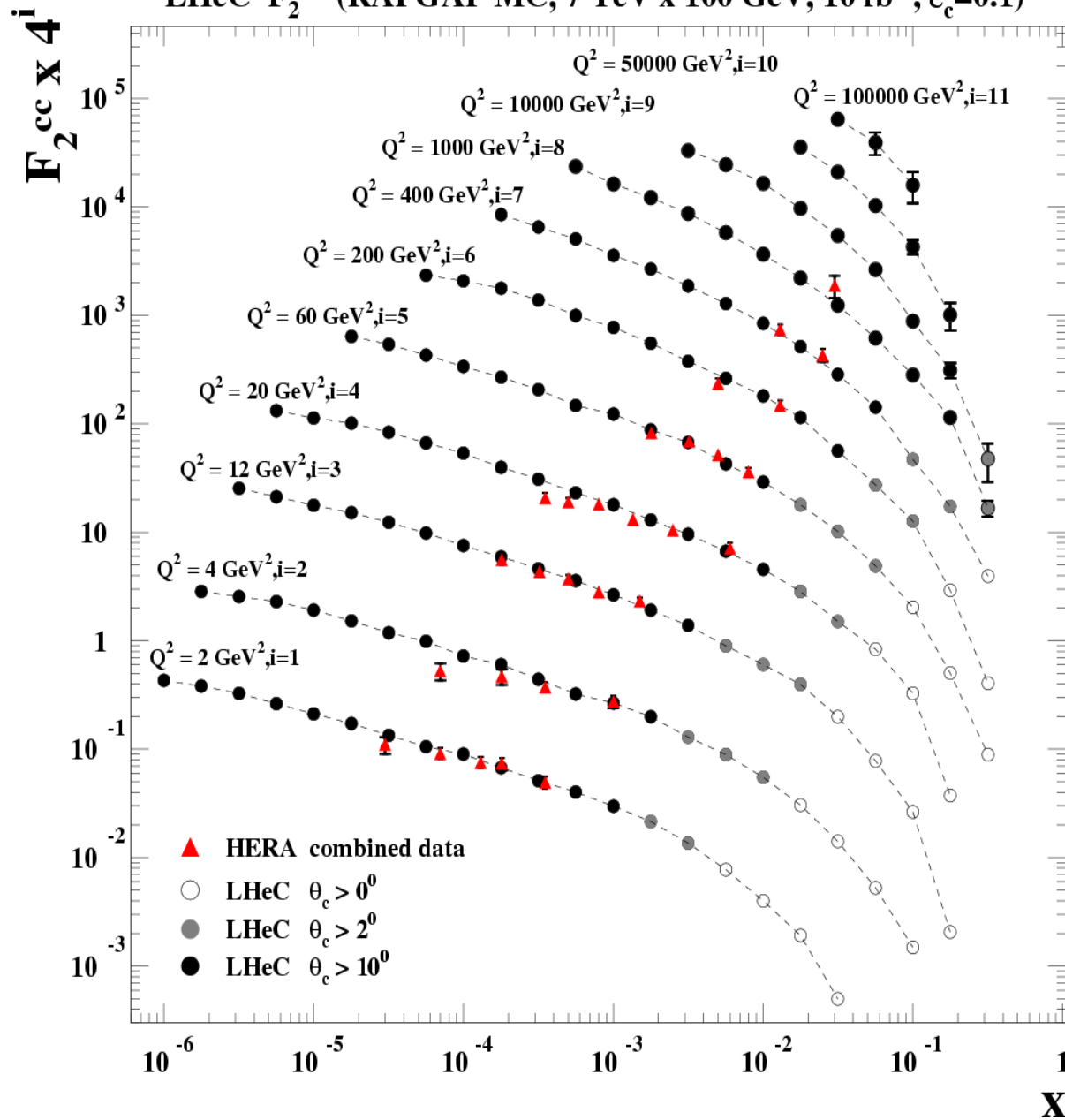
$$I_e = \text{mA} \frac{P / \text{MW}}{E_e / \text{GeV}}$$



A 60 GeV Energy Recovery "LINAC"

A 140 GeV pulsed LINAC

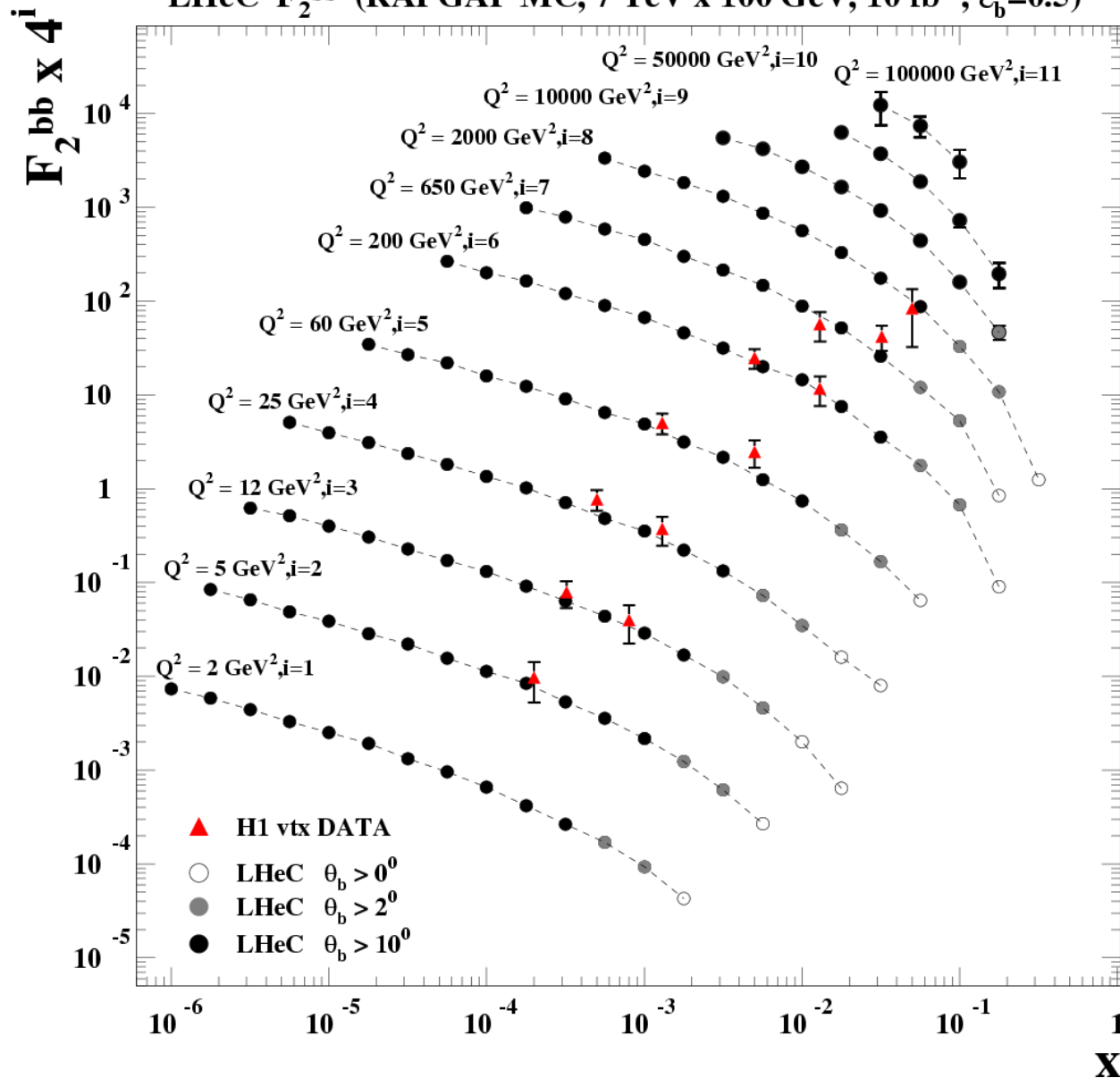
LHeC F_2^{cc} (RAPGAP MC, 7 TeV x 100 GeV, 10 fb^{-1} , $\epsilon_c=0.1$)



F_2^{cc} at
LHeC

Nice extensions!

LHeC F_2^{bb} (RAPGAP MC, 7 TeV x 100 GeV, 10 fb^{-1} , $\varepsilon_b=0.5$)

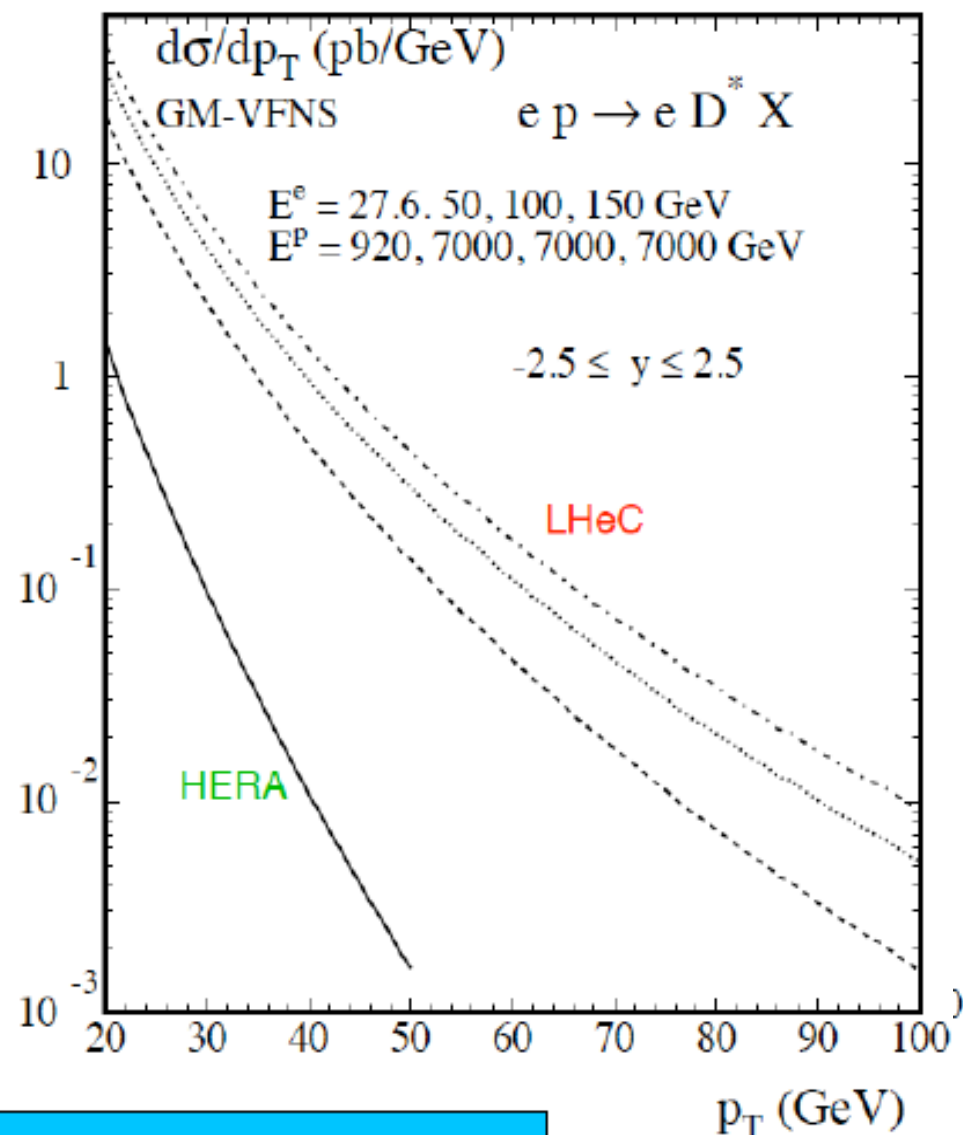
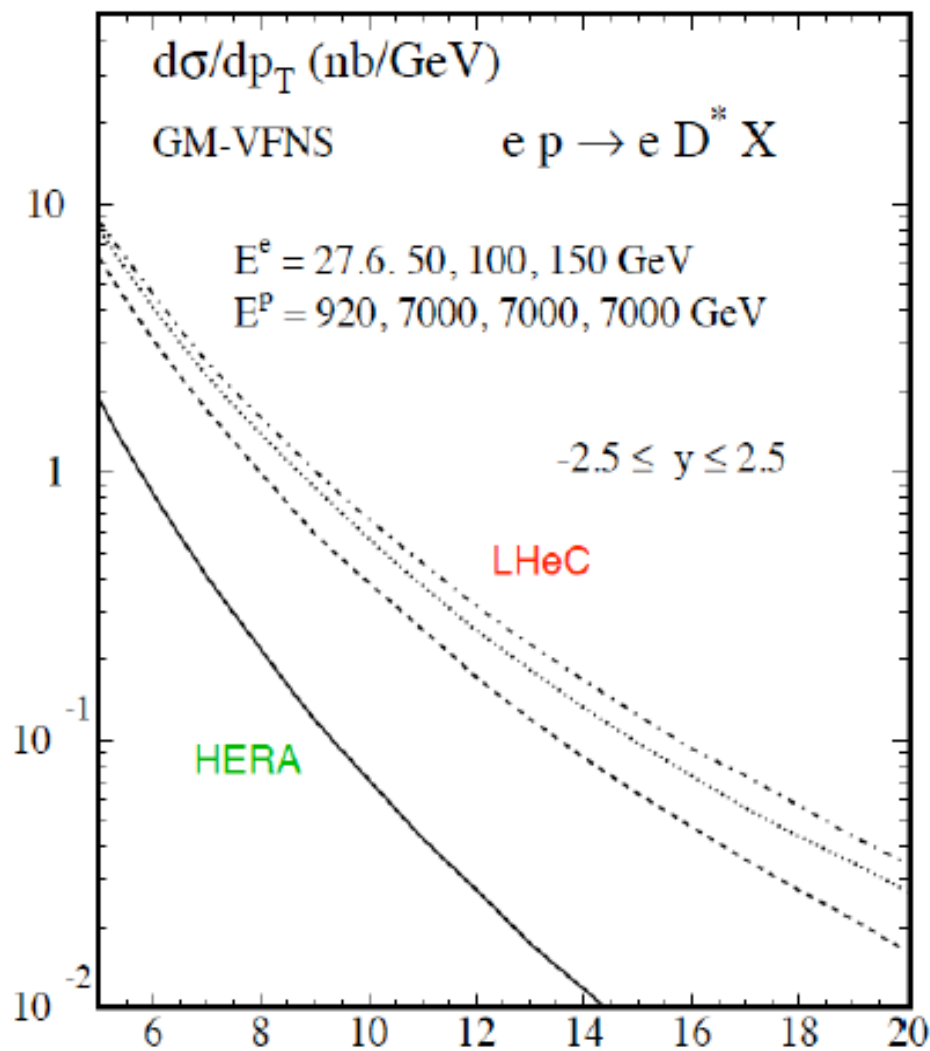


F_2^{bb} at
LHeC

Nice extensions!

Inclusive photoproduction of D^* mesons at LHeC

Gustav Kramer,
Hubert Spiesberger



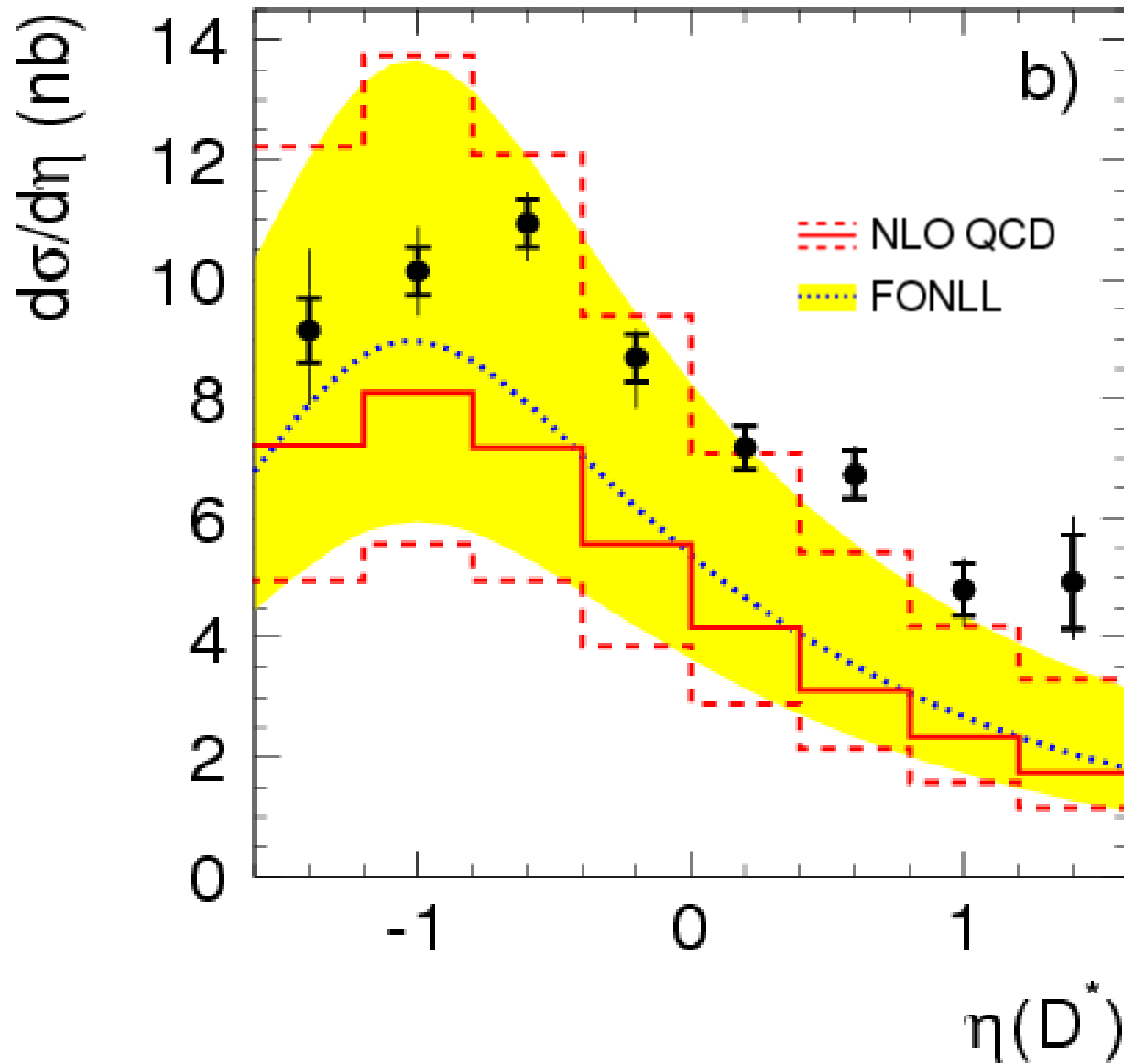
Can be studied at LHeC over very large p_T range

Conclusions

- HERA charm and beauty production data:
 - in general reasonably well described by Massive NLO calculations, up to highest p_T and Q^2
 - Deviations from massive NLO in certain phase space corners: evidence for charm component in resolved photons in Photoproduction (**the only massless scheme triumph?**), excess at low z for charm in DIS
- Charm and beauty related structure functions F_2^{cc} and F_2^{bb} : *extremely important for understanding of the whole proton structure and sensitive to the c and b masses*
- This is not the end: Further HERA II measurements of c and b production to come, and also the first H1ZEUS F_2^{bb} combination

Appendix, don't worry, it will be short

Charm in Photoproduction with D^*

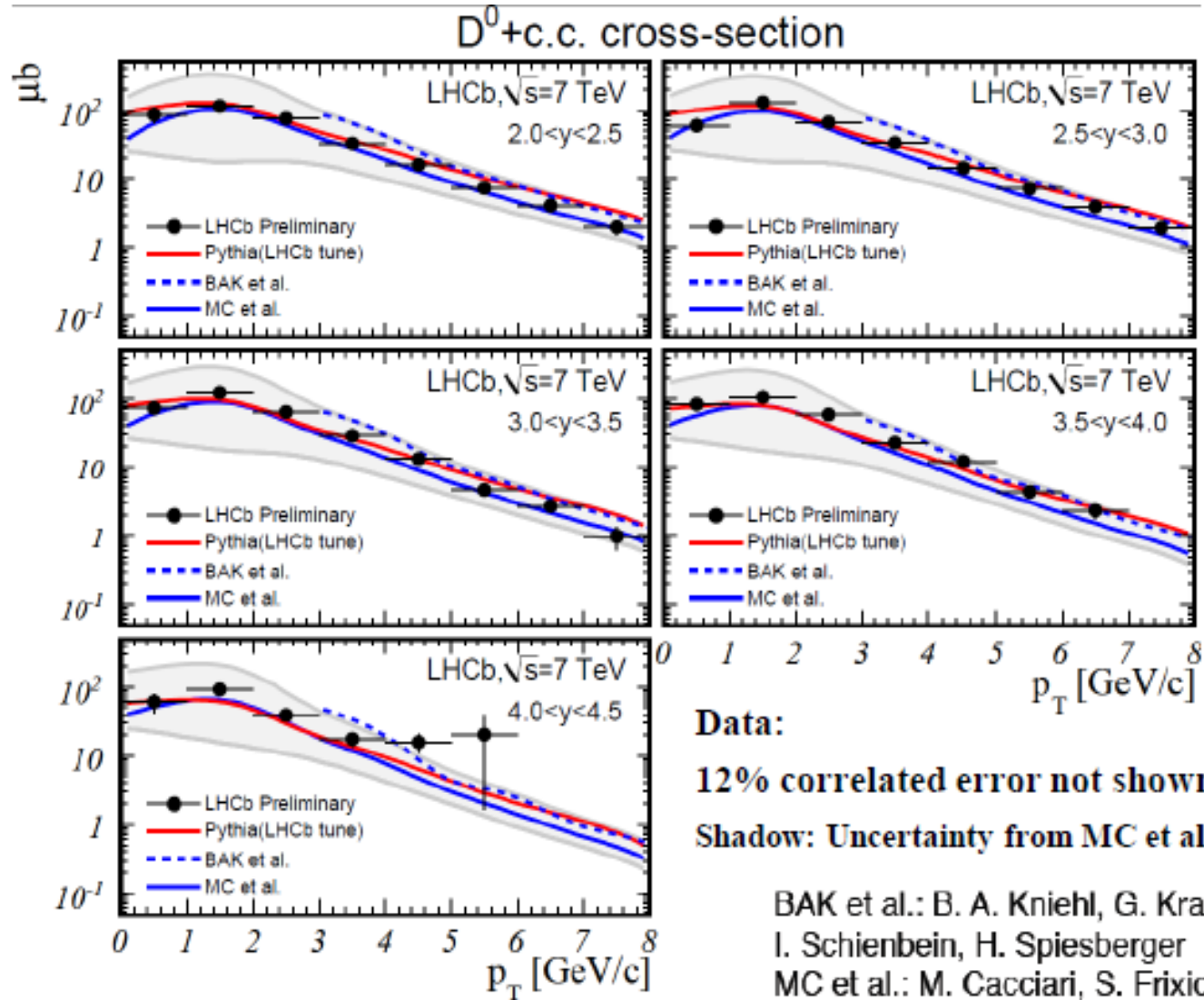


Large theory uncertainties!

D⁰ cross sections at LHCb

Liming Zhang

Covering
forward
rapidities
 $2 < y < 5$

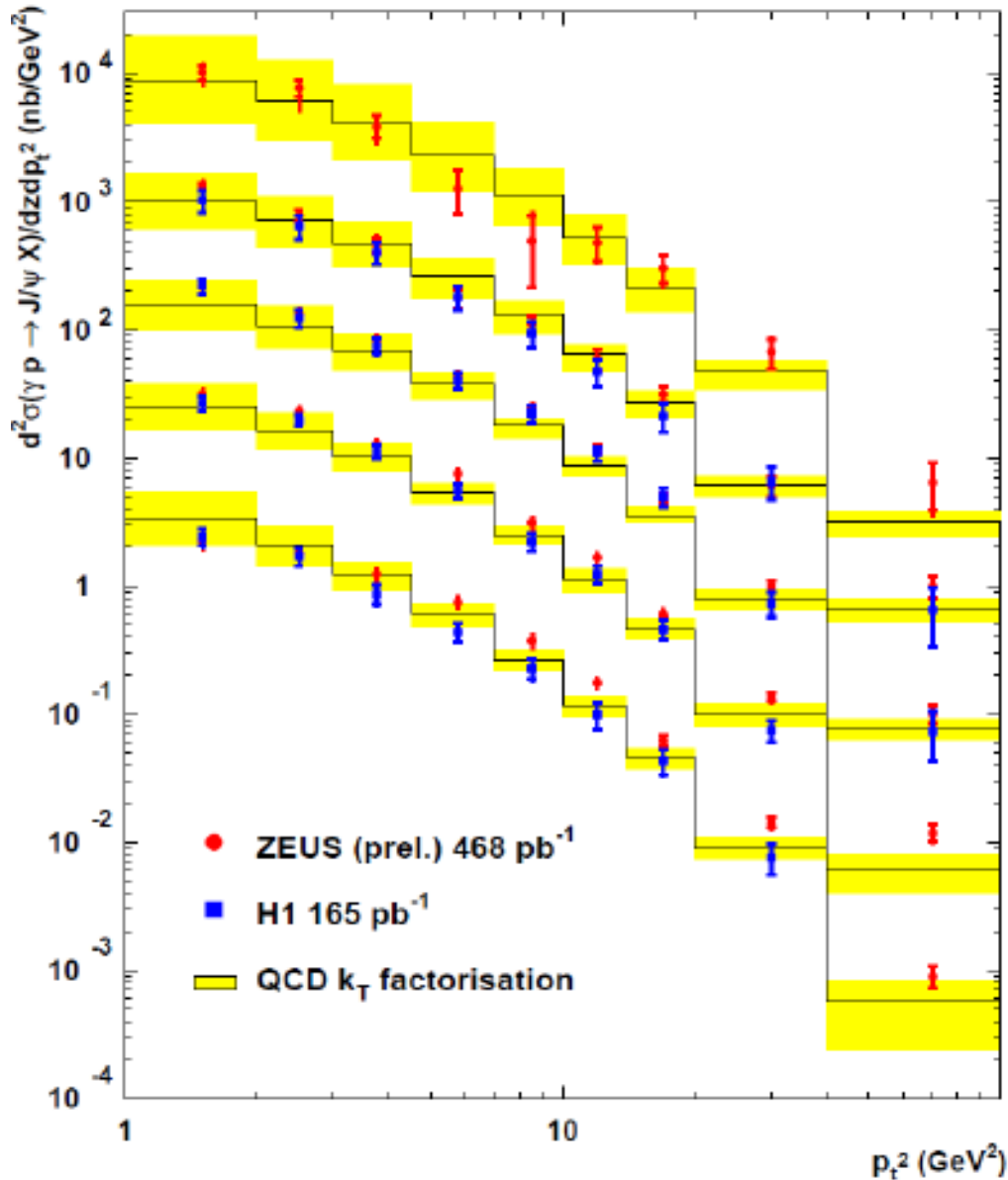


Good/reasonable description by the various calculations

J/psi photoproduction cross sections at HERA

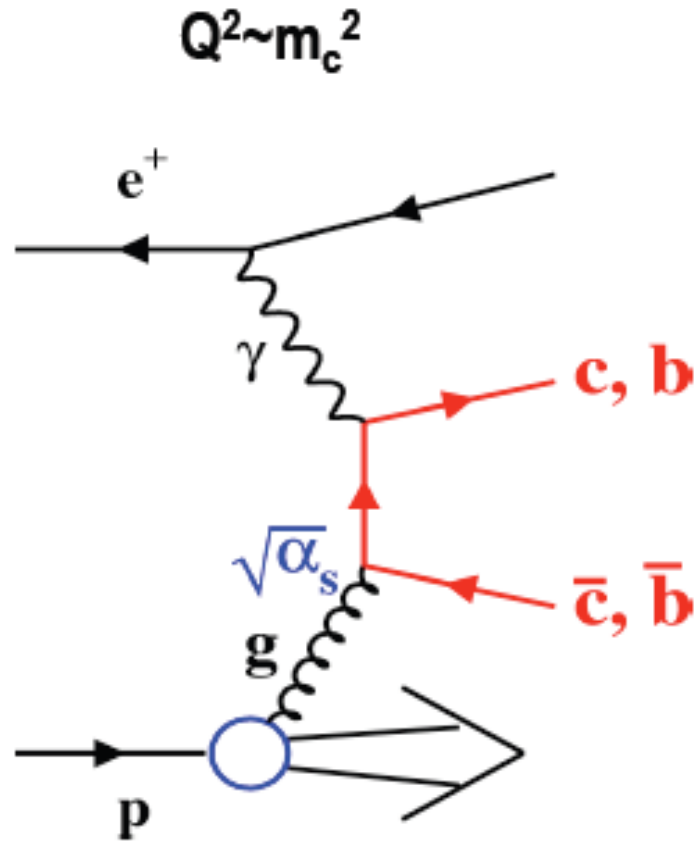
ZEUS

A. Bertolin

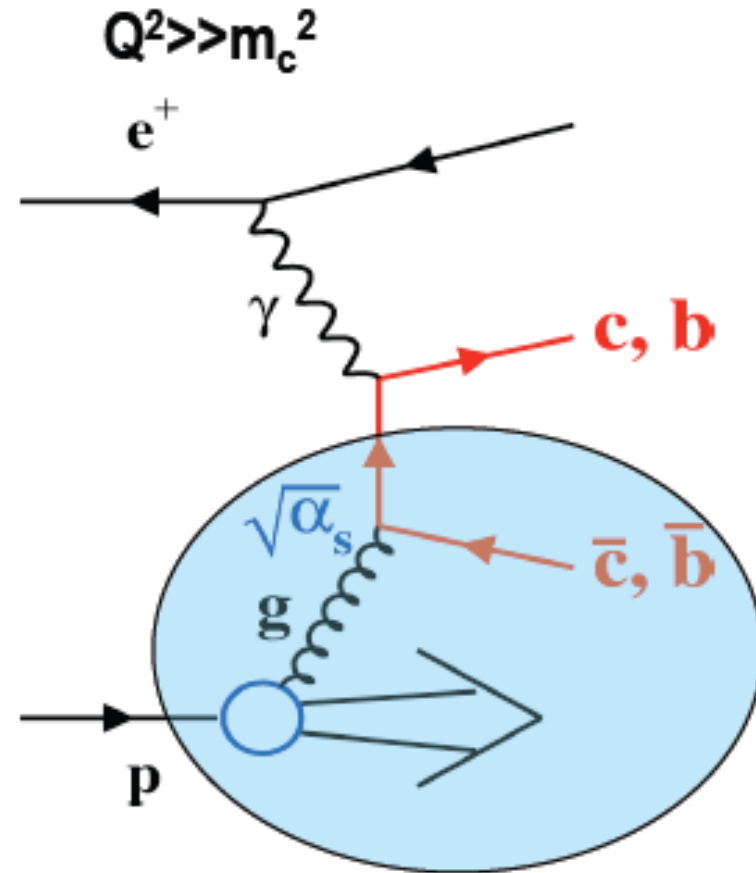


Awaiting comparisons with Theory (NRQCD, kT)

Subtle topic: correct treatment of heavy flavour masses in pQCD



Massive HQ

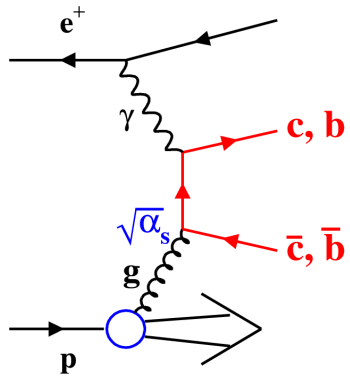


Massless Sea quark like c, b

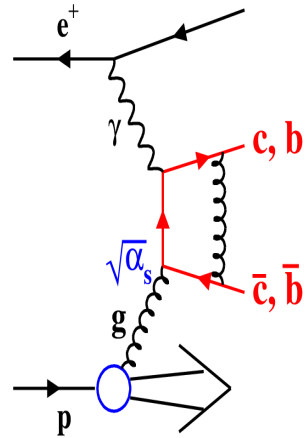
How to make properly the transition from left to right picture is a longstanding problem

QCD perturbation series

LO

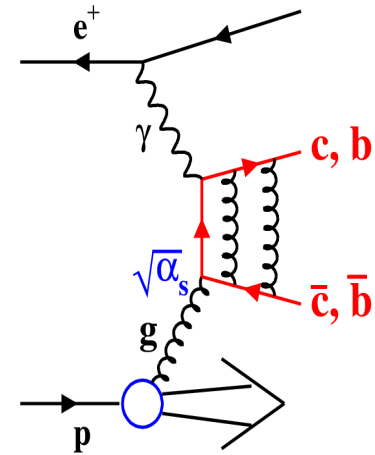


NLO



+ more

NNLO



+ many more