Heavy Quark Studies at HERA

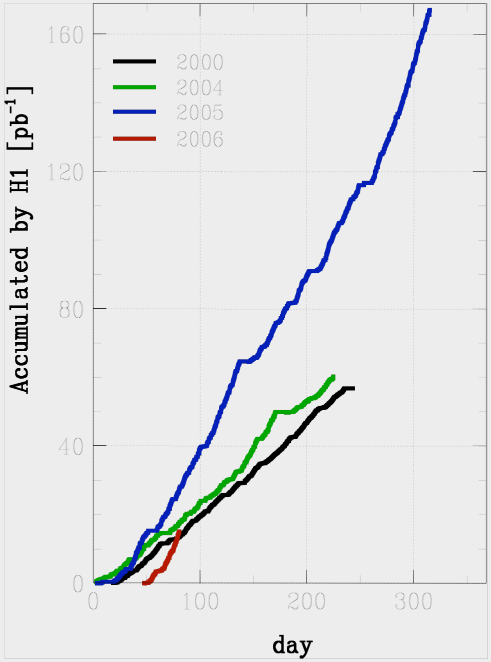
G. Leibenguth

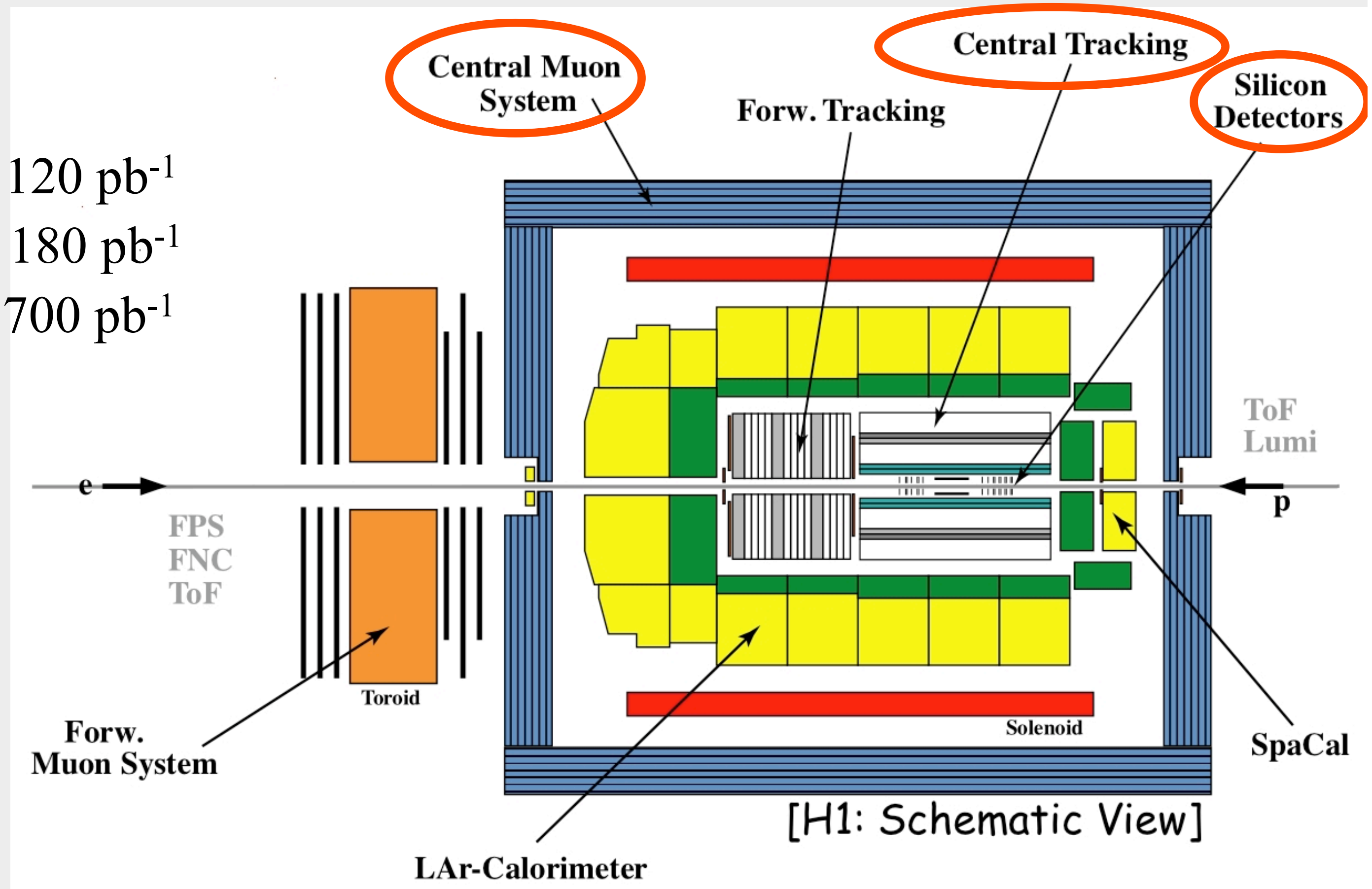
- o Introduction
- o Charm Production
- o Beauty Production
- o F_2 Contribution
- o Conclusion

The Experiments: H1 and Zeus

Integrated Lumi:

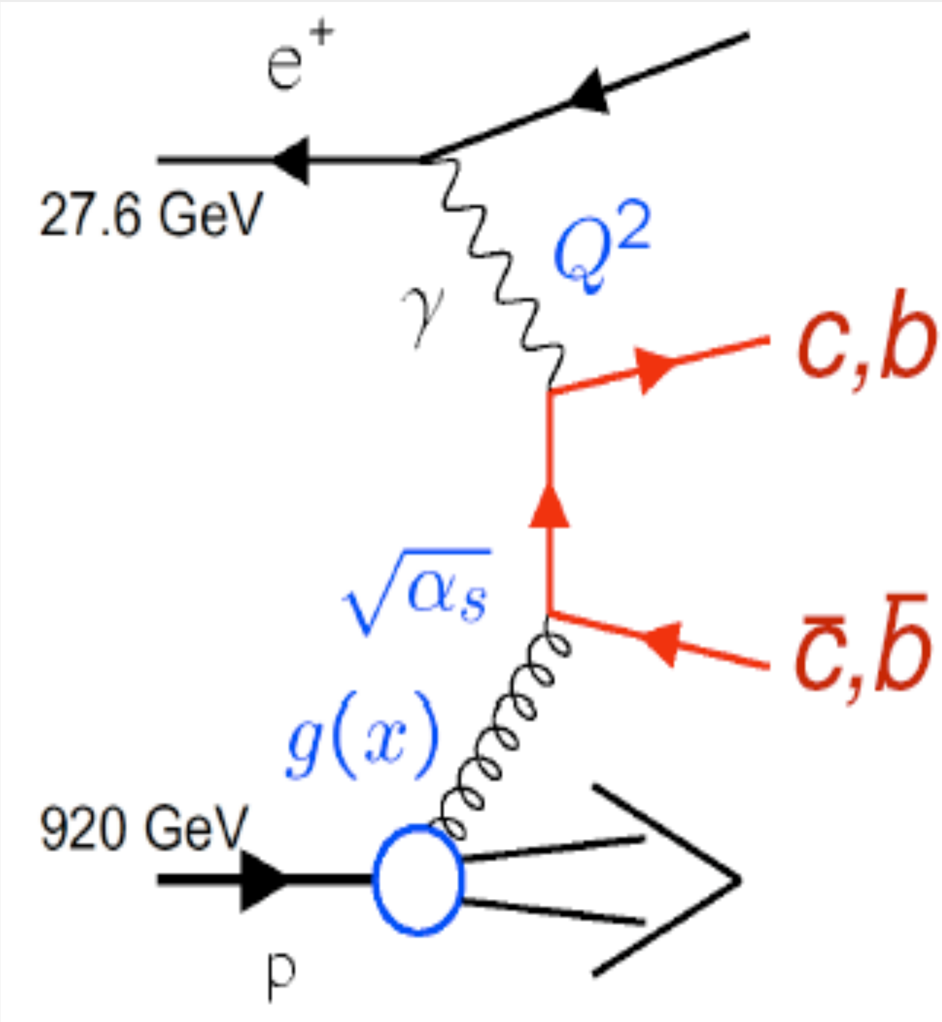
- Hera I (92-00): 120 pb^{-1}
- Hera II (03-05): 180 pb^{-1}
- By June 2007 : 700 pb^{-1}





Key detectors:
Muon chambers, tracking and vertex detectors

Heavy Flavor Production



Hard scale: m_b / m_c, Q^2,P^2_t

- ✓ pQCD applicable
- ✓ Multi hard scale problem
- ✓ $[\alpha_s \ln(Q^2/m_b^2)]^n$

⇒ Probe a large range of Q^2

⇒ Study interplay of scales

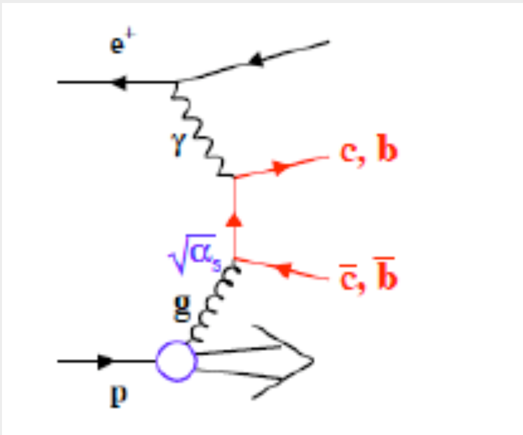
2 kinematics regimes:

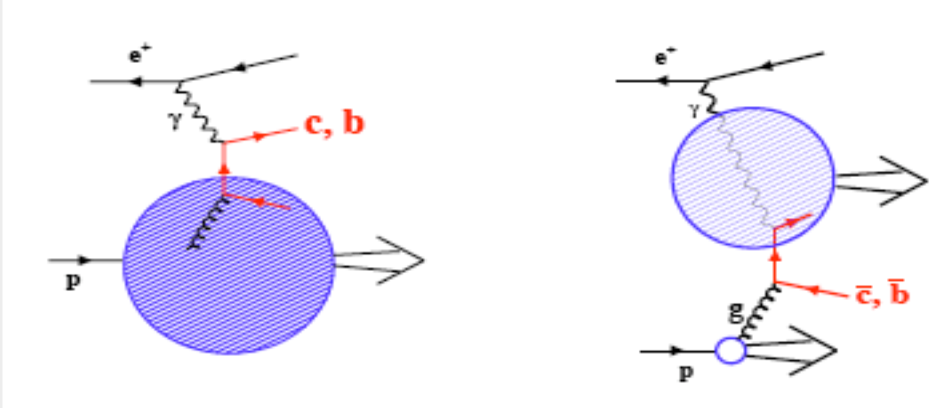
- ✓ Photoproduction (γp): $Q^2 < 1$ GeV^2
- ✓ Deep Inelastic Scattering (DIS): $Q^2 > 1$ GeV^2

pQCD approximation

Massive approach:

- ❖ Fixed order calculation in α_s, with $m_q \neq 0$
- ❖ HQ produced only dynamically





Massless approach

- ❖ Resums in α_s, with $m_q = 0$ (HQ is flavor active in structure function)
- ❖ Reliable at $p_t >> m_q$

Intermediate (or variable) scheme :
massive at low Q^2, massless at high Q^2

Experimental Conditions

Total production rate at HERA:

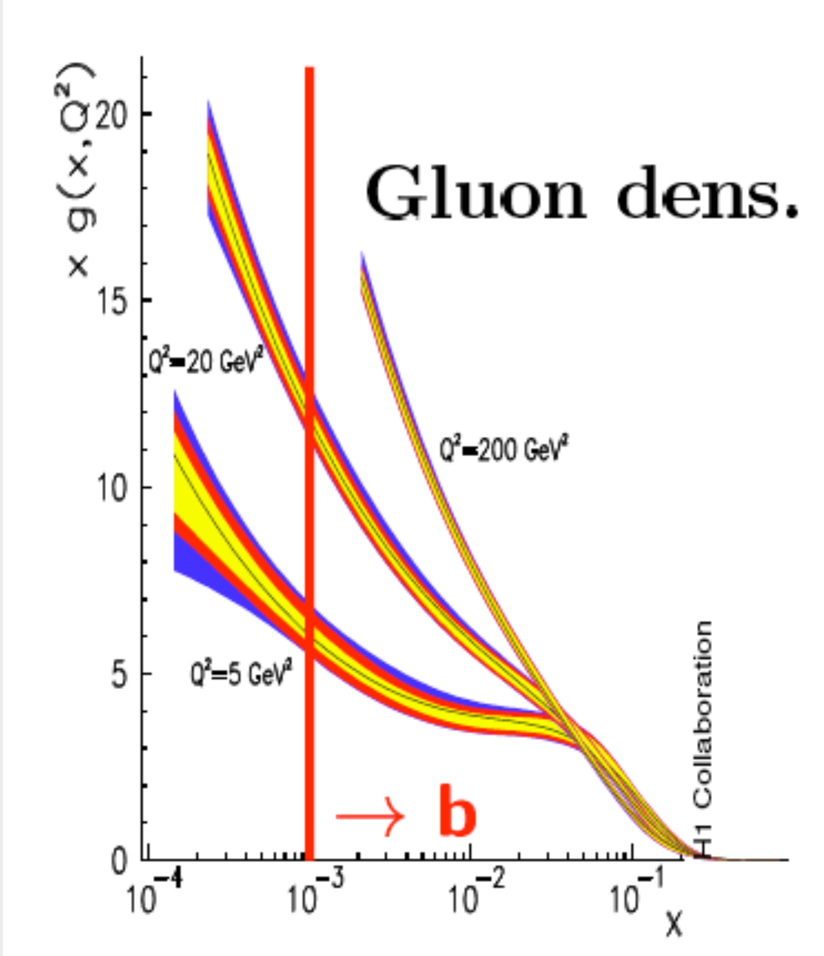
$\sigma_{uds} : \sigma_{charm} : \sigma_{beauty} \sim 2000 : 200 : 1$

Main reason for beauty suppression:

phase space,

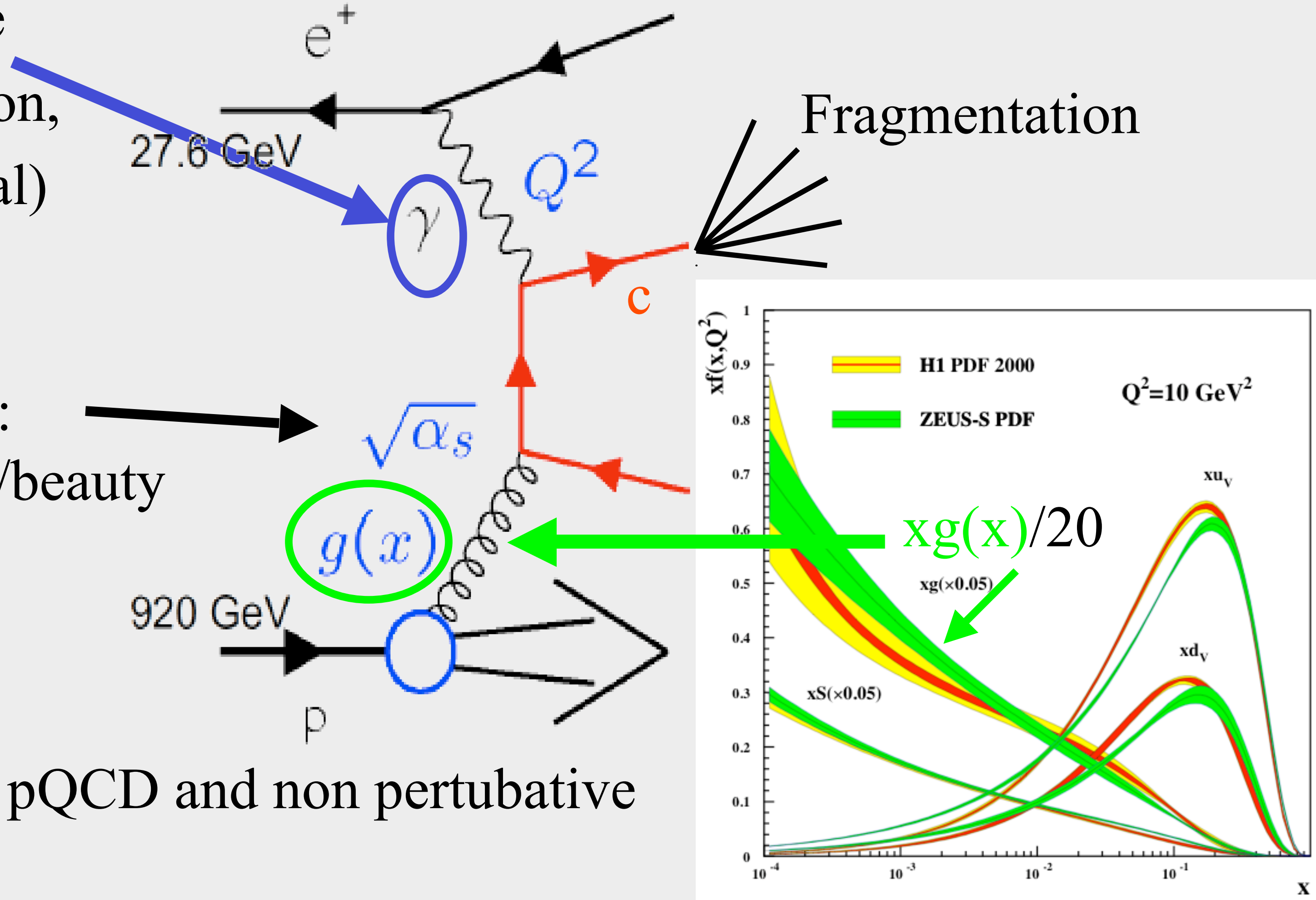
$$\mathbf{X}_g \geq \frac{m_Q^2}{E_\gamma \cdot 920\ \mathbf{GeV}}$$

…



Charm Overview

Photon structure
(photo-production,
photon quasi-real)



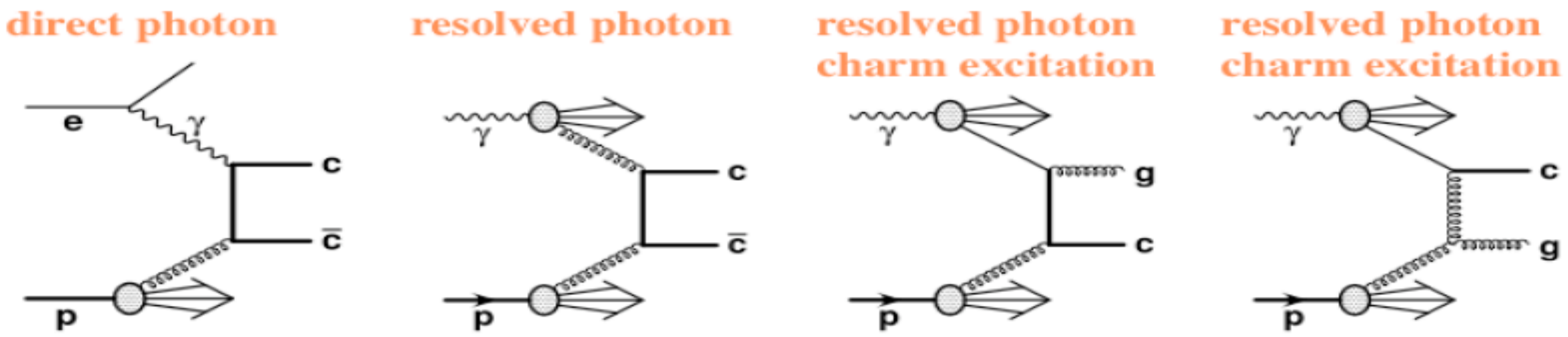
Strong coupling:
“small” (charm /beauty
masses)

Factorization of pQCD and non pertubative components

γg Charm Production at HERA

Boson Gluon Fusion Dominate (@LO) :

⇒ Direct process $\gamma g \rightarrow cc$ dominates, in γp resolved contribution plays a significant role



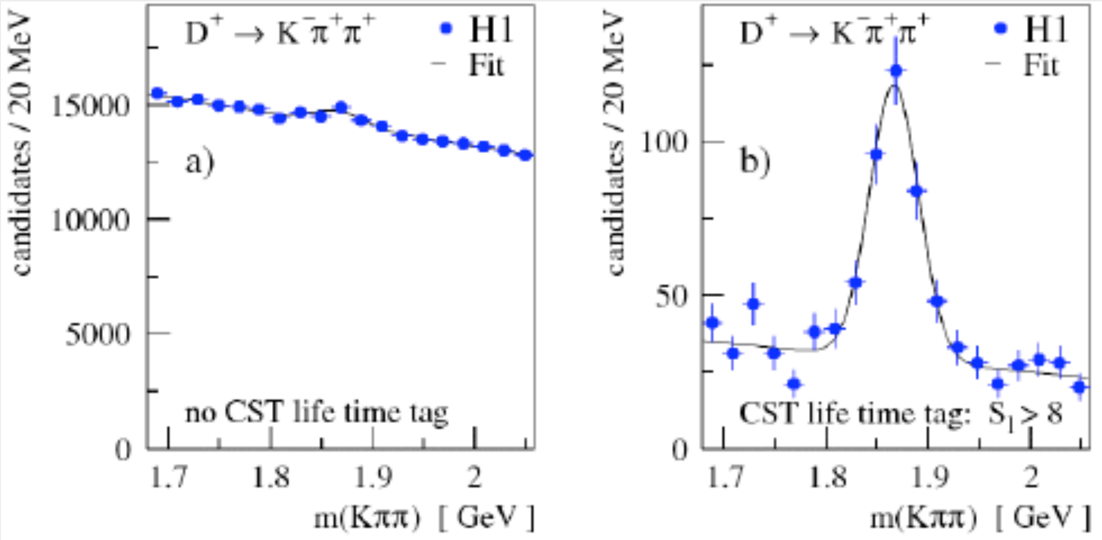
Factorisation:

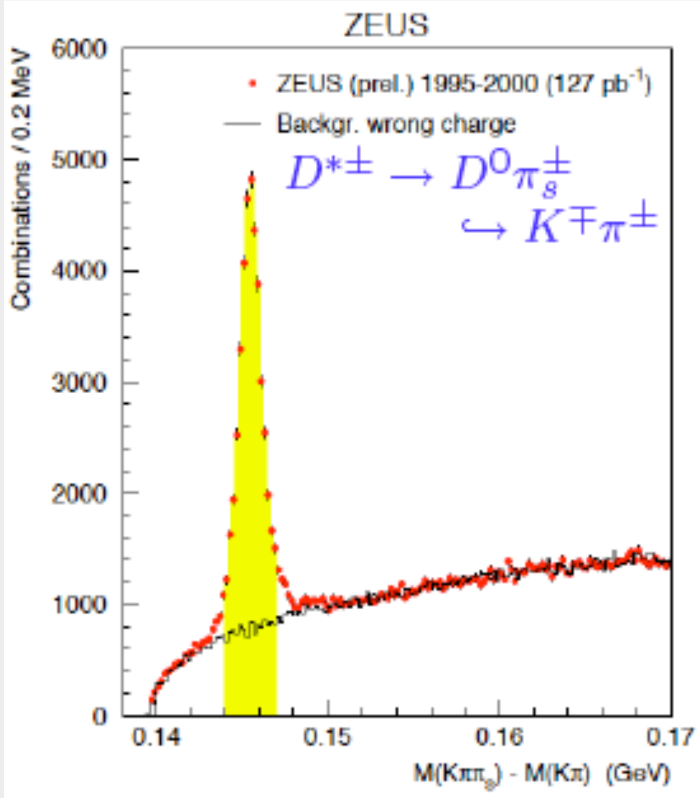
σ = proton PDF ⊗ $\sigma_{\gamma g \rightarrow qq}$ ⊗ photon PDF ⊗ fragmentation function

Charm Tagging

✓ Via D* resonance reconstruction : $D^* \rightarrow K^- \pi^+ \pi^+$, knowledge of kinematics, signal and background

✓ Via lifetime tagging (vertex detector)

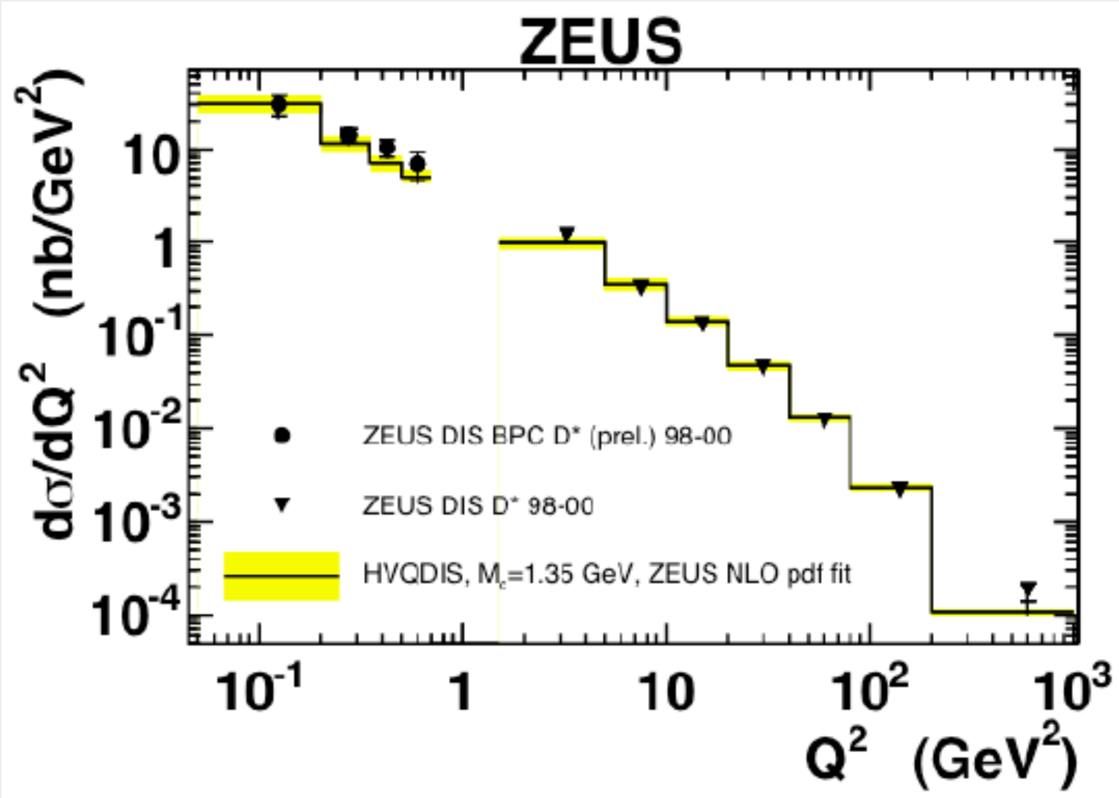




Large sample:
≈ 40000 D* (Hera I)

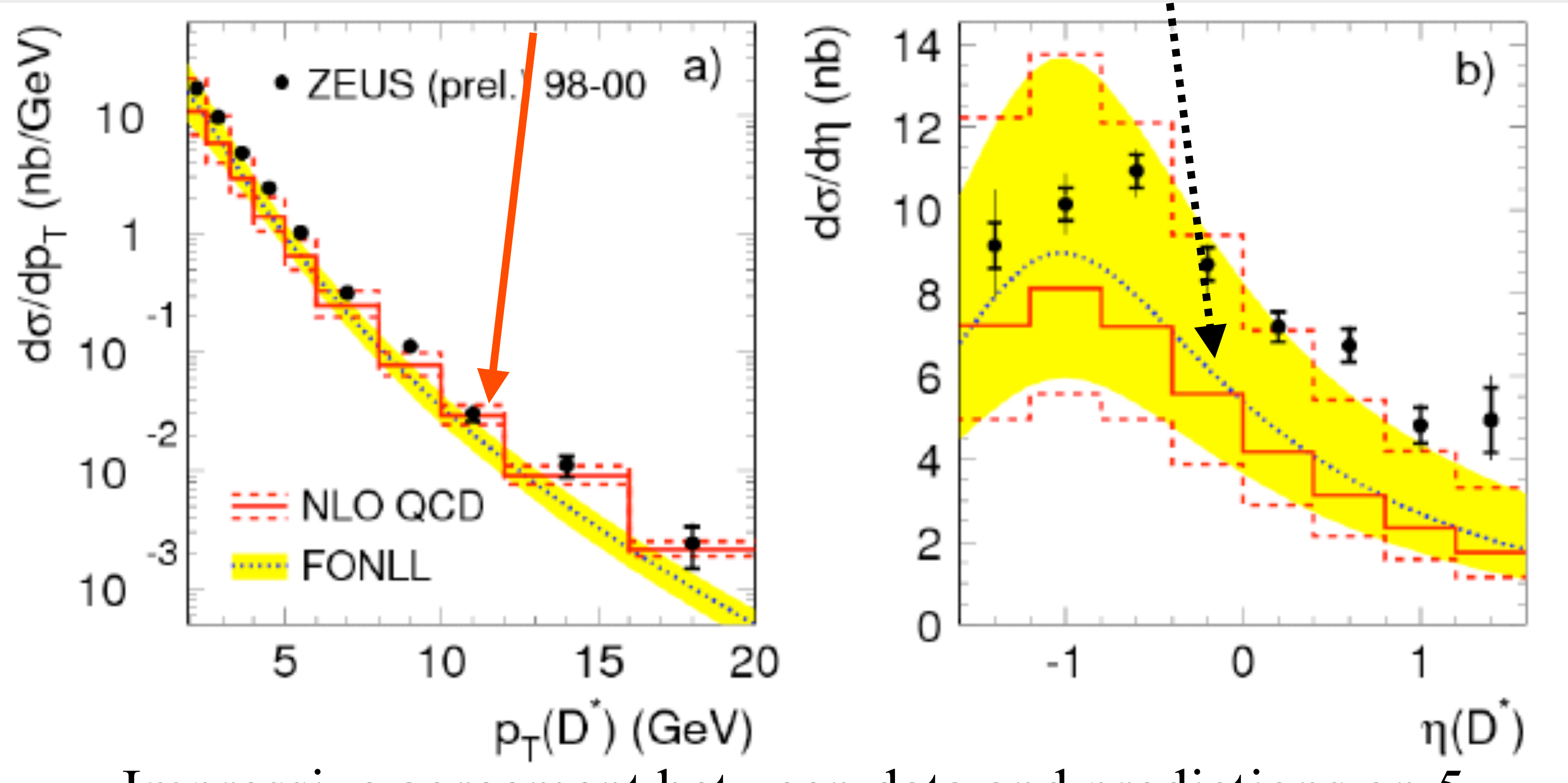
Charm spans over Q^2

✓ Q^2 evolution describes data over 4 orders of magnitude!



D* γp inclusive cross sections

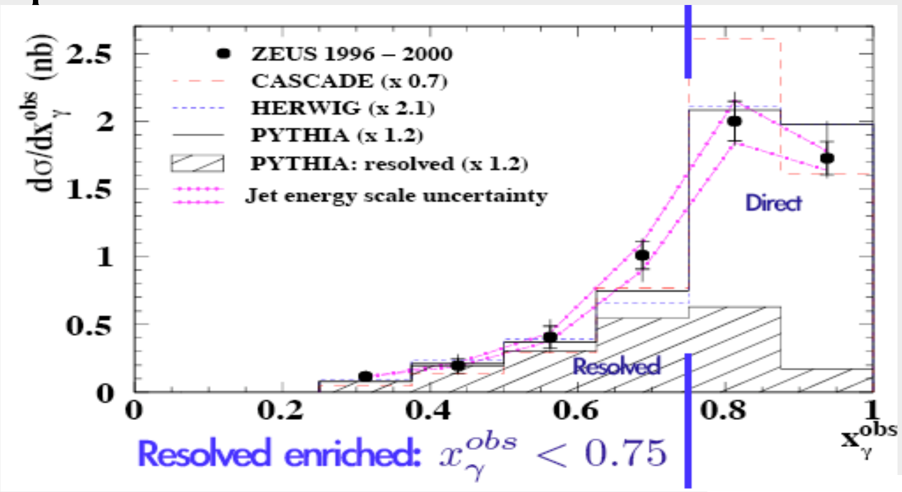
NLO “massive” and “variable scheme”

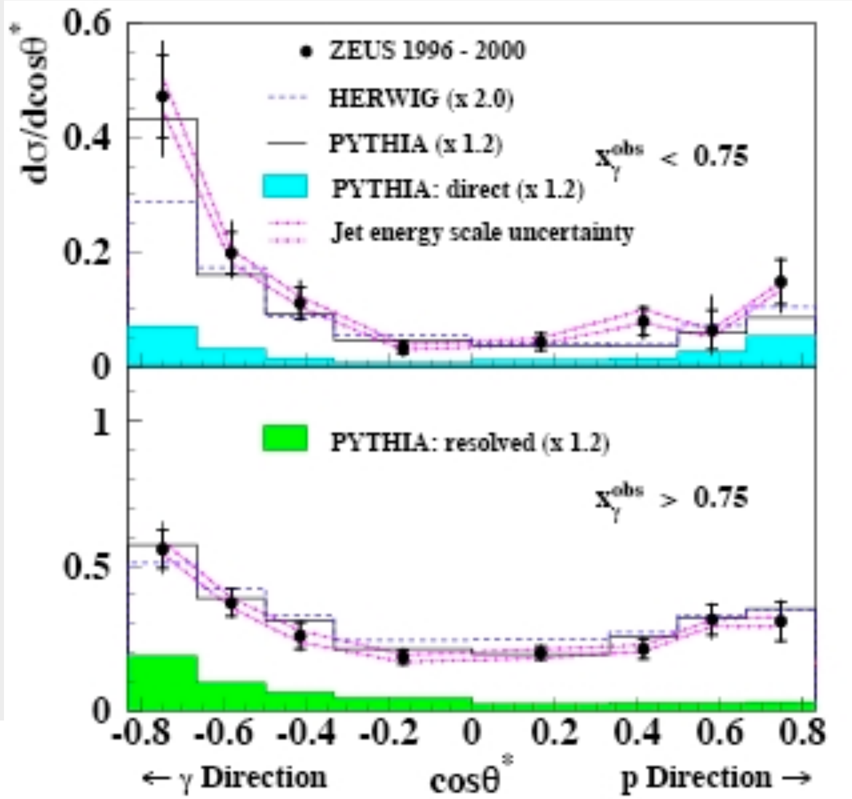


Impressive agreement between data and predictions on 5 orders of magnitude! Large theoretical uncertainty

Charm Dijets

In charm dijet event, reconstruct momentum fraction of parton from photon side

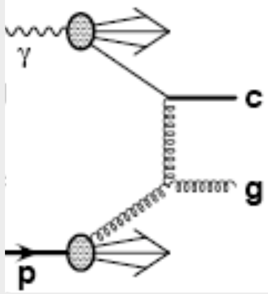




D* in photon direction:

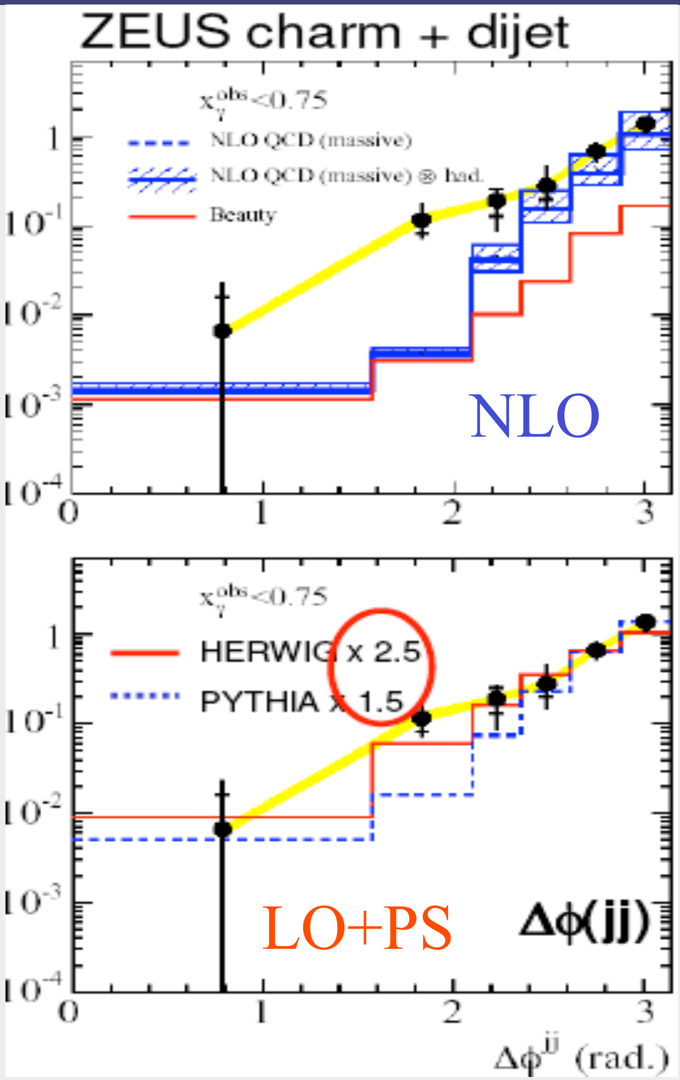
Increase in γ direction:

c-Excitations components



$$x_\gamma^{obs} = \frac{\sum_{j_1,j_2}(E_t^j e^{-\eta^j})}{2yE_e}$$

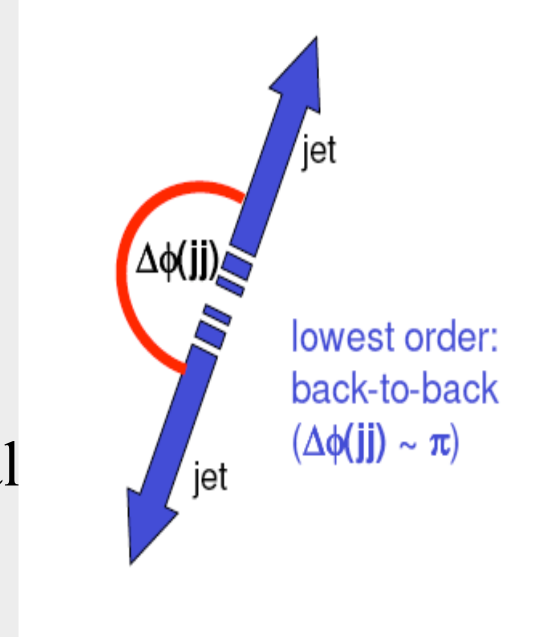
Charm Jet Production



D* and jet production (x_γ^{obs} <0.75):

- Tag second hard parton by a jet (k_t algorithm)

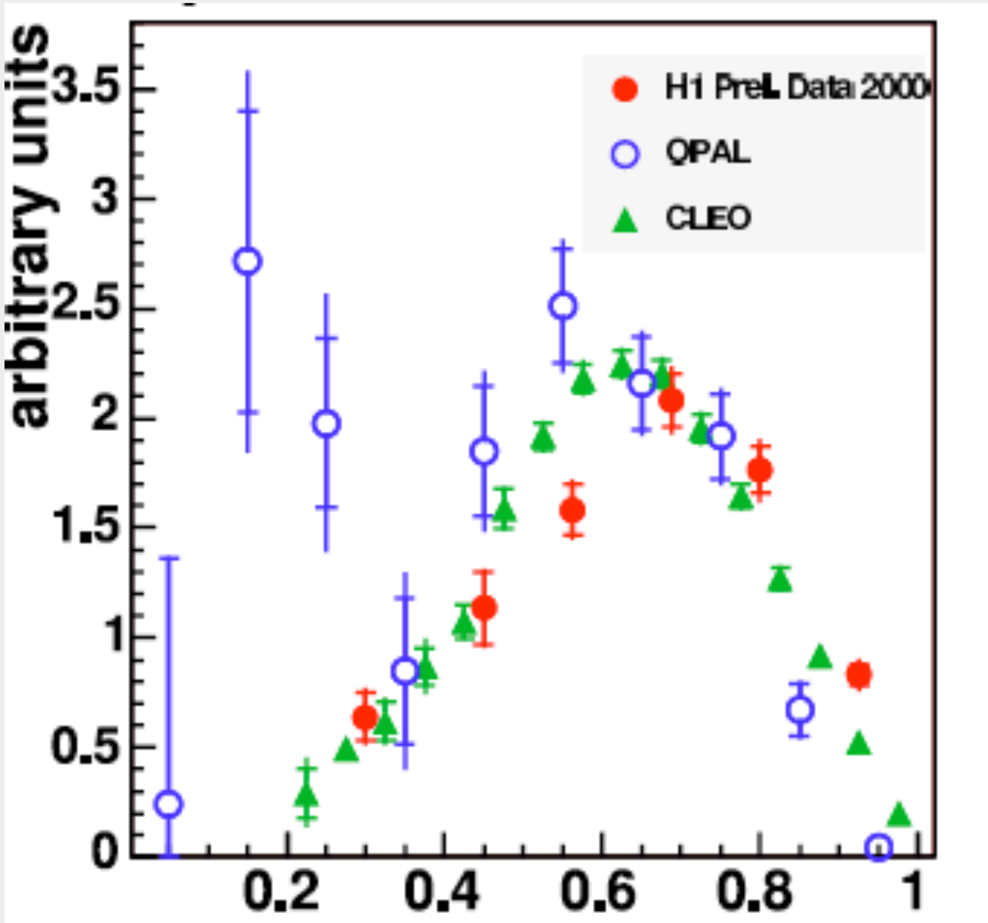
⇒ Provide an additional hard scale



NLO: shape wrong, normalization ok

LO + PS: shape ok, normalization off

Charm Fragmentation



Gluon splitting: OPAL @ low z

H1 hemisphere method:
$<\sqrt{(s)}> \approx 10$ GeV

$$z = \frac{(E+p_L)_{D^*}}{\sum_{hem}(E+p)}$$

OPAL $<\sqrt{(s)}> \approx 91.2$ GeV

$$z = 2E_{D^*}/\sqrt{s}$$

CLEO $<\sqrt{(s)}> \approx 10$ GeV

$$z = p_{D^*}/p_{max}$$

HERA data: competitive precision with e^+e^- data!

Fragmentation Functions

Fit theoretical prediction to the data, extract MC parameter

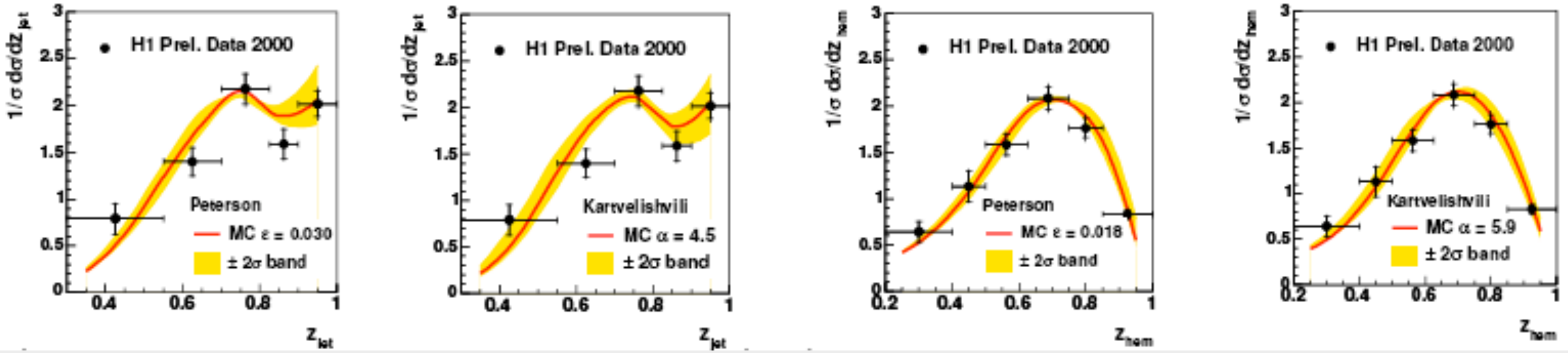
⇒ values of ε parameters (@ LO): *Peterson* : $f(z) \sim z^{-1}[1 - \frac{1}{z} - \frac{\varepsilon}{1-z}]^{-2}$

ZEUS: ε = 0.064 ± 0.006,

Zeus: photo-production data

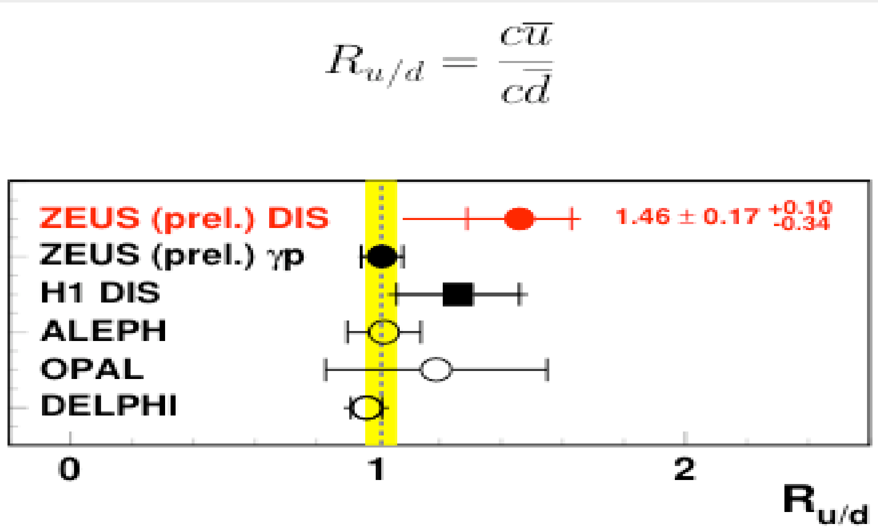
H1(HEM): ε = 0.018 ± 0.004

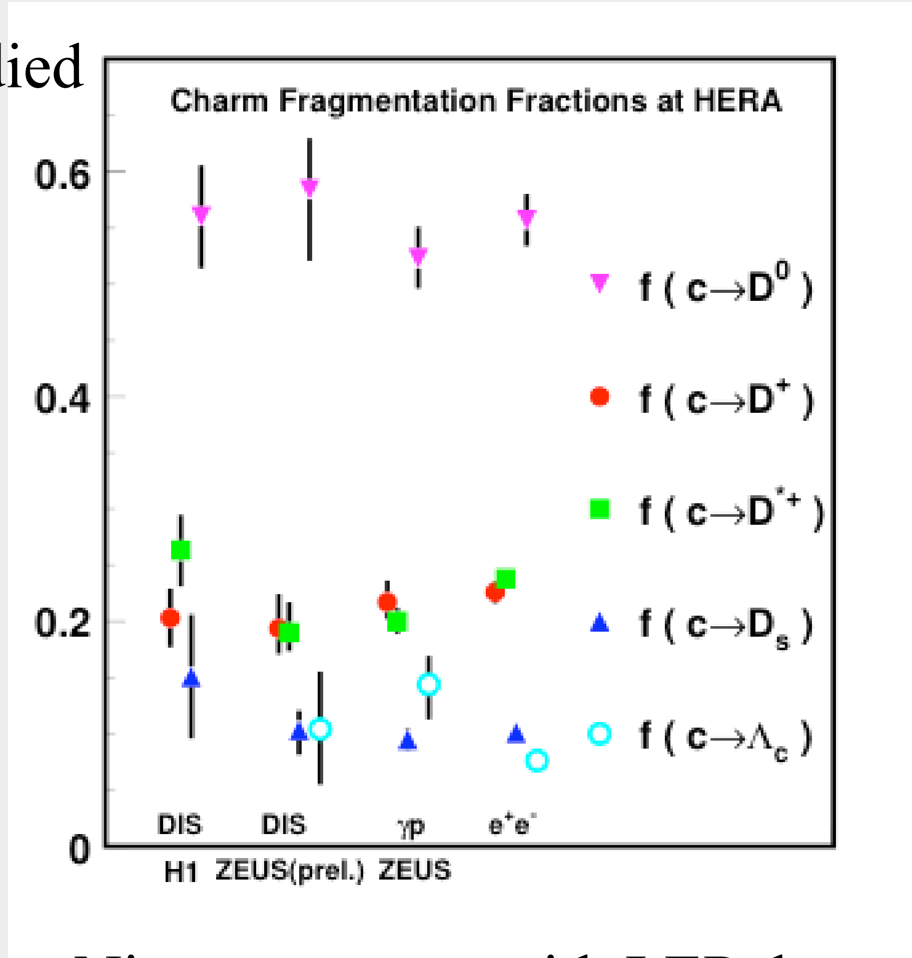
Hem method in DIS



Fragmentation Fractions

- All charm decay channels studied
- Universality of charm fragmentation observed
- Up and down quark produced equally => strong isospin invariance holds





Nice agreement with LEP data

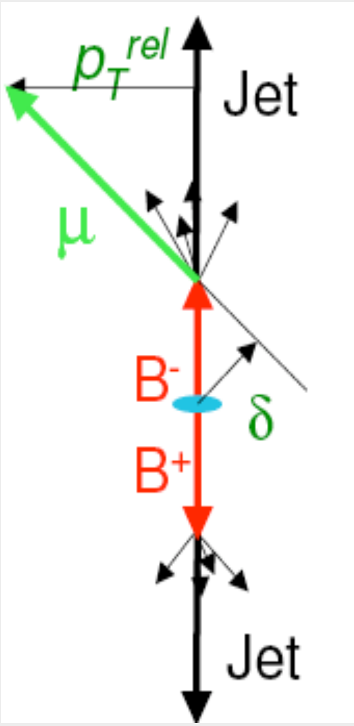
Beauty Measurements

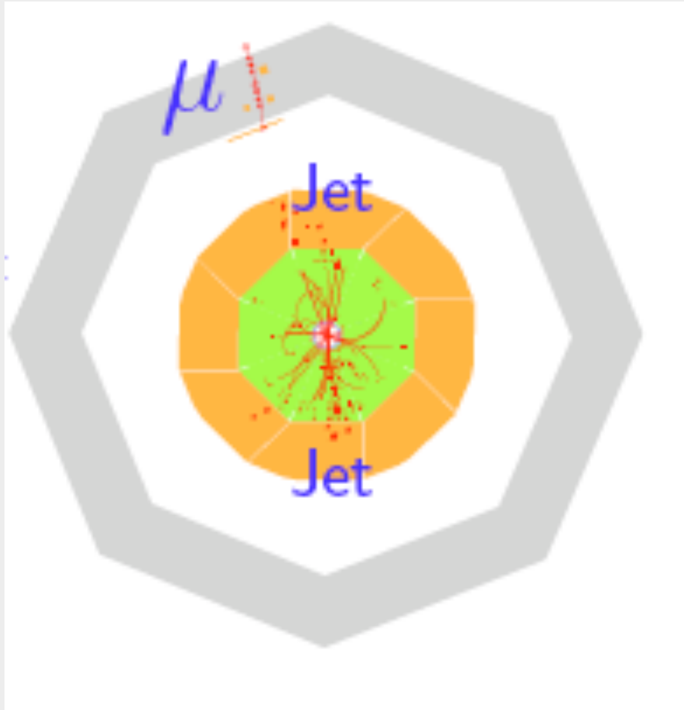
	Photo-production	DIS $Q^2>1GeV^2$	DIS $Q^2>150\ GeV^2$
$P_t > 0$ GeV	μμ D*μ	Inclusive lifetime	Inclusive lifetime
$P_t > 6$ GeV	μ+jets	μ+jets	μ+jets
$P_t > 11$ GeV	Jet-jet Incl. lifetime		

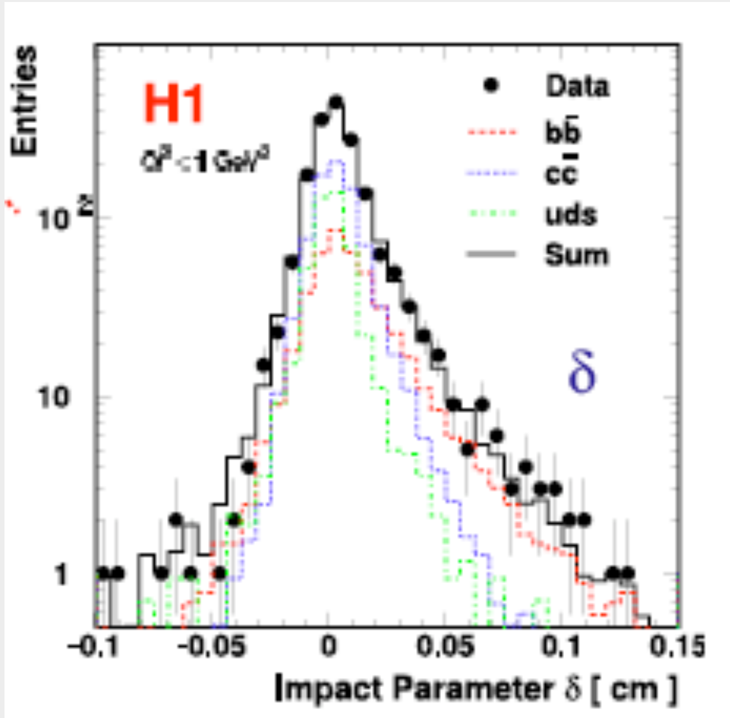
Beauty Tag, Muon and Jets

μ from semileptonic b decays, separation power from:

- ✓ B mass: P_t^{rel} (p_t of μ w.r.t jet axis)
- ✓ Large b lifetime: impact parameter δ





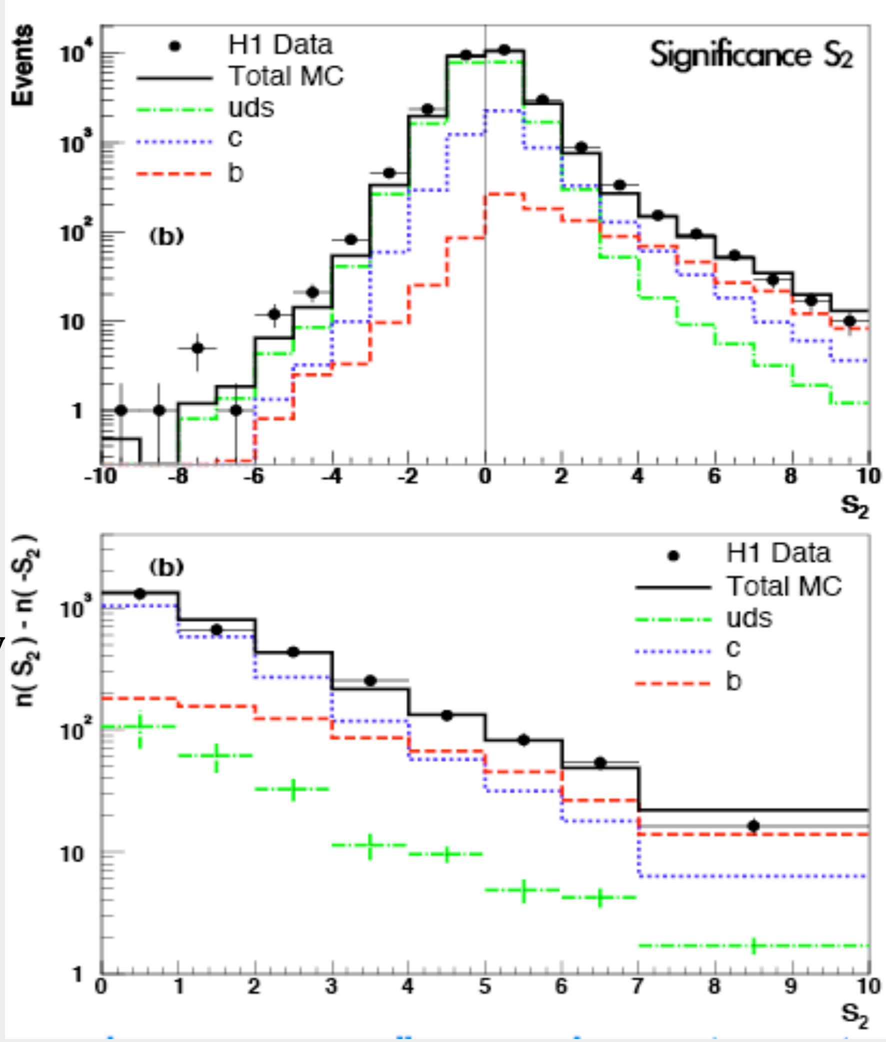


Inclusive Lifetime Analysis

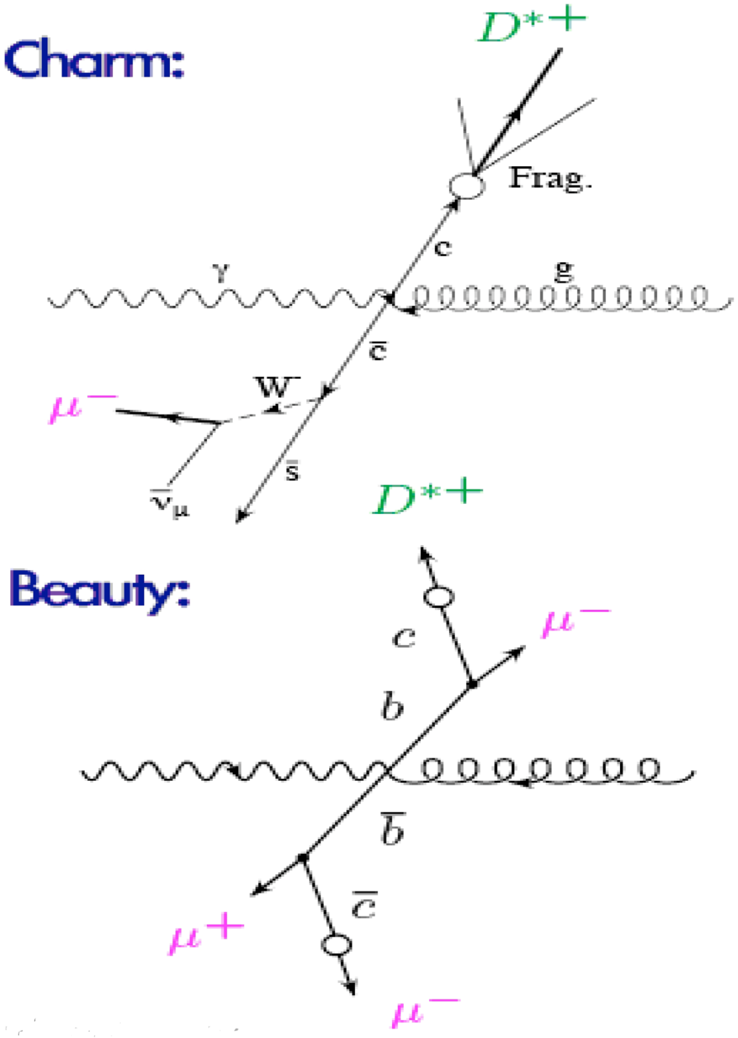
- Use all tracks (p_t> 0.5 GeV) with silicon information
- Significance of signed impact parameter:

$$S = \frac{\delta}{\sigma(\delta)}$$

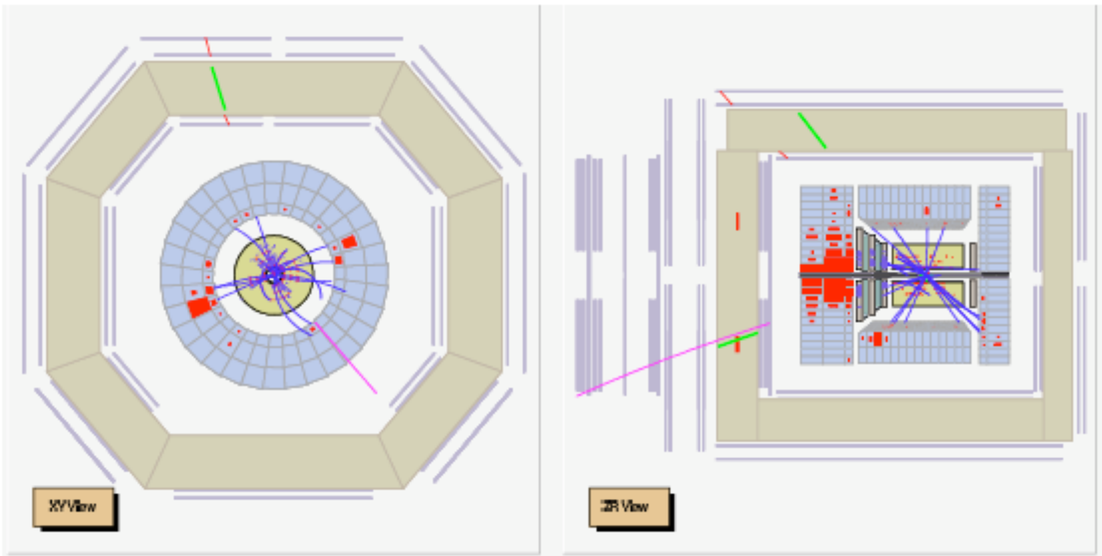
- Subtract negative side from positive, enhance charm and beauty
- Example: tracks with 2nd highest significance



Double Tagging: D*μ and μμ

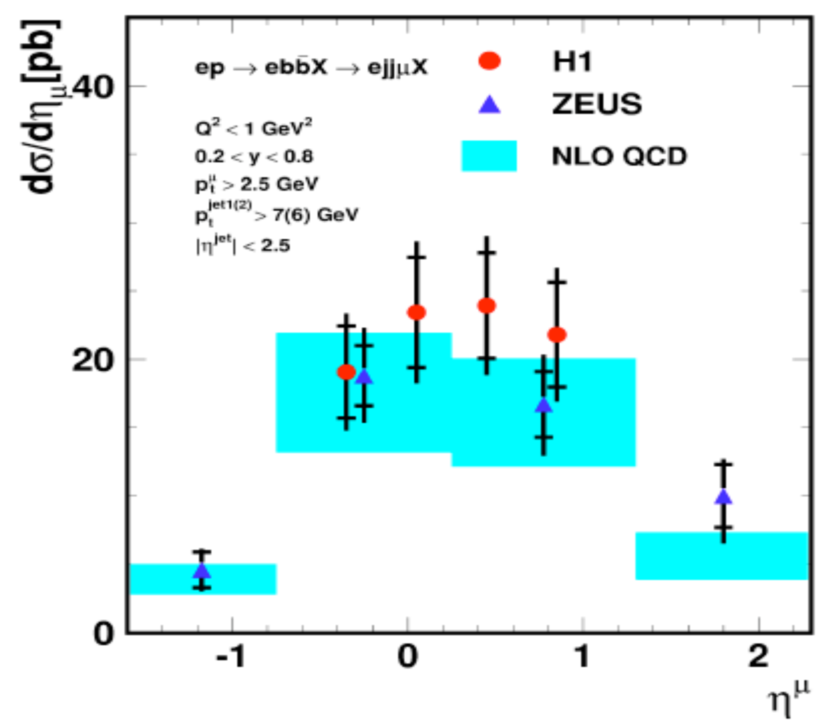


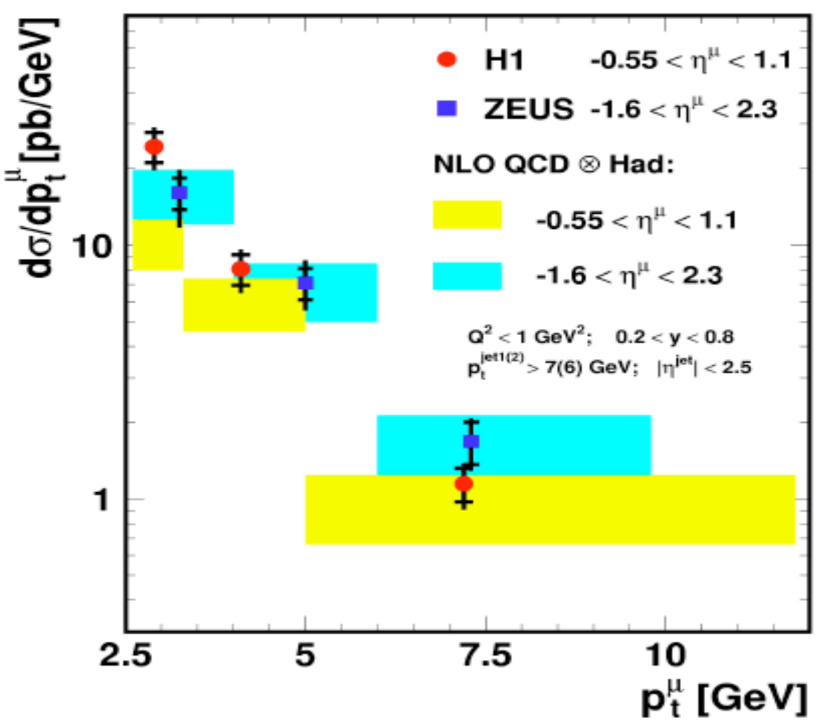
- D*μ: Separate charm and beauty with charge and/or angular correlations
- μμ: b-contribution from excess of unlike sign muon pairs



μ+Jets: Beauty in γp

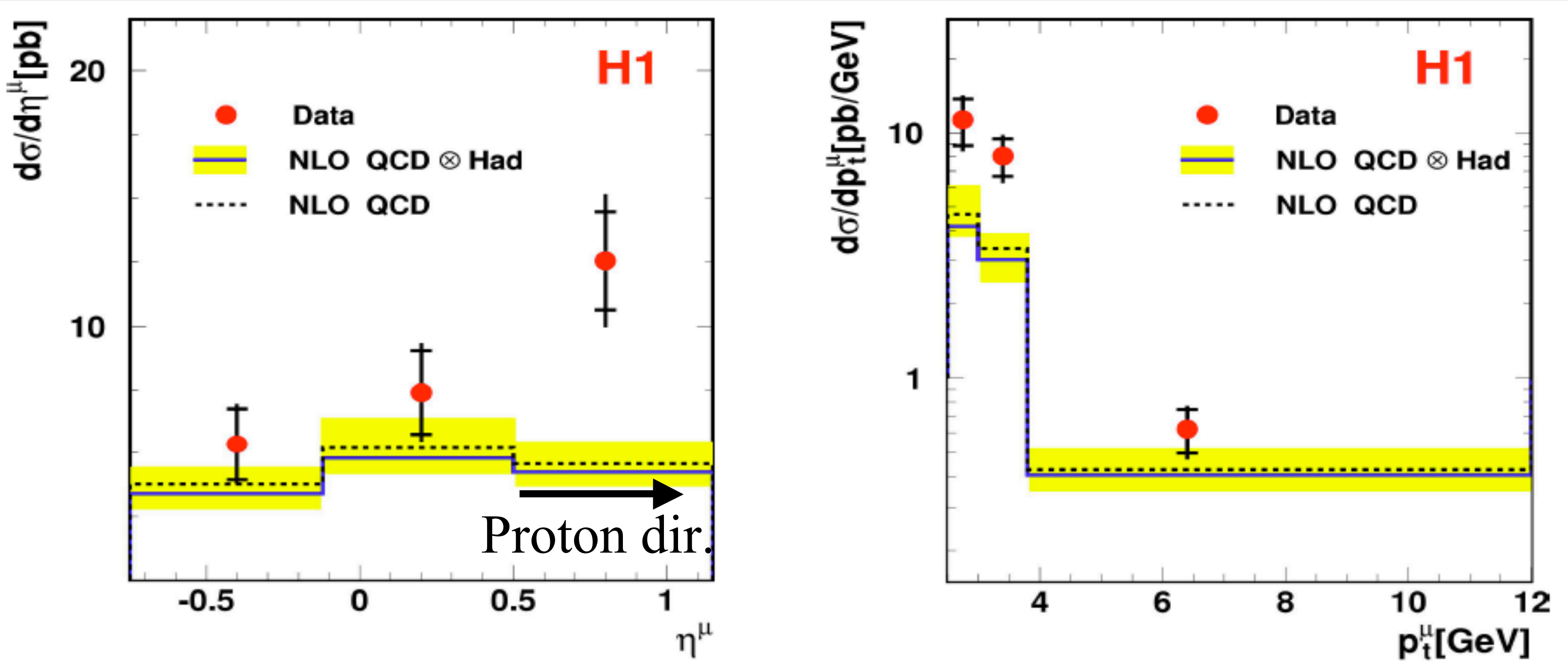
H1 (●): 2D-fit to p_t^{rel} and δ Zeus (■): 1D-fit to p_t^{rel}





NLO (FNMR): shape close, agreement within errors
(H1 excess at low P_t^{μ}, to compare with yellow band)

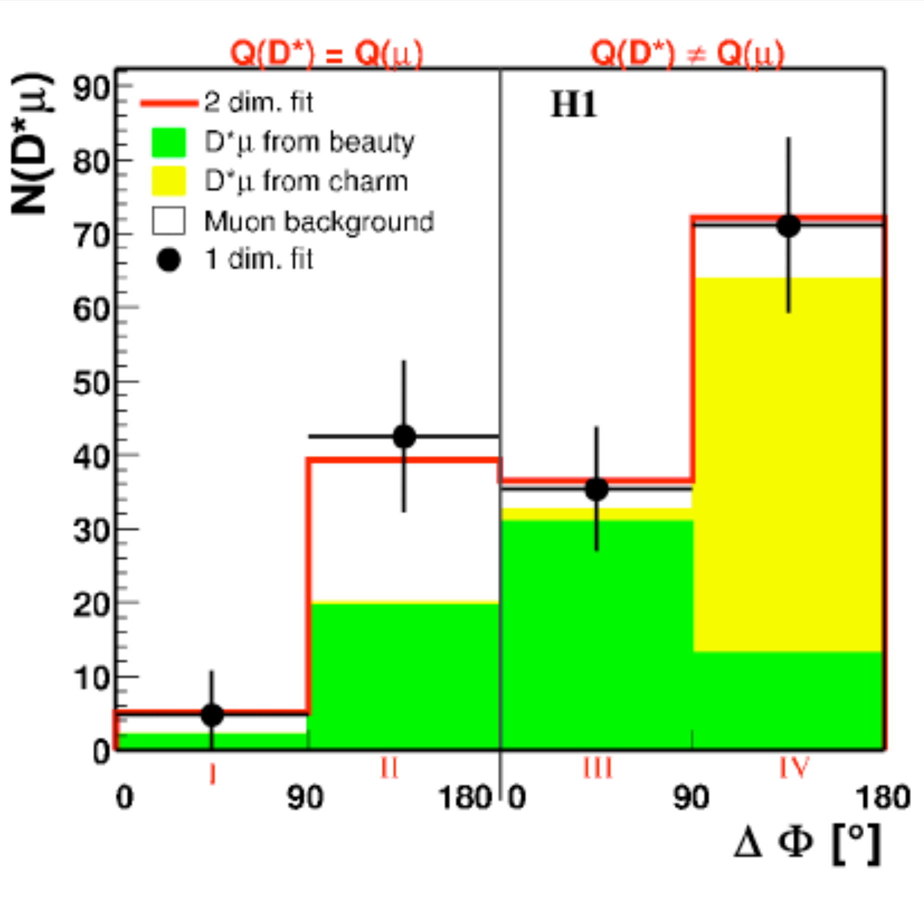
μ+Jets: Beauty in DIS



✓NLO (HVQDIS): norm low

✓Data softer

D*μ correlations @ H1



Beauty:

$\sigma_b^{vis}(ep \rightarrow eD^*\mu X) =$

$206 \pm 53 \pm 35$ pb

(NLO: 53^{+14}_{-9} pb)

Charm:

$\sigma_c^{vis}(ep \rightarrow eD^*\mu X) =$

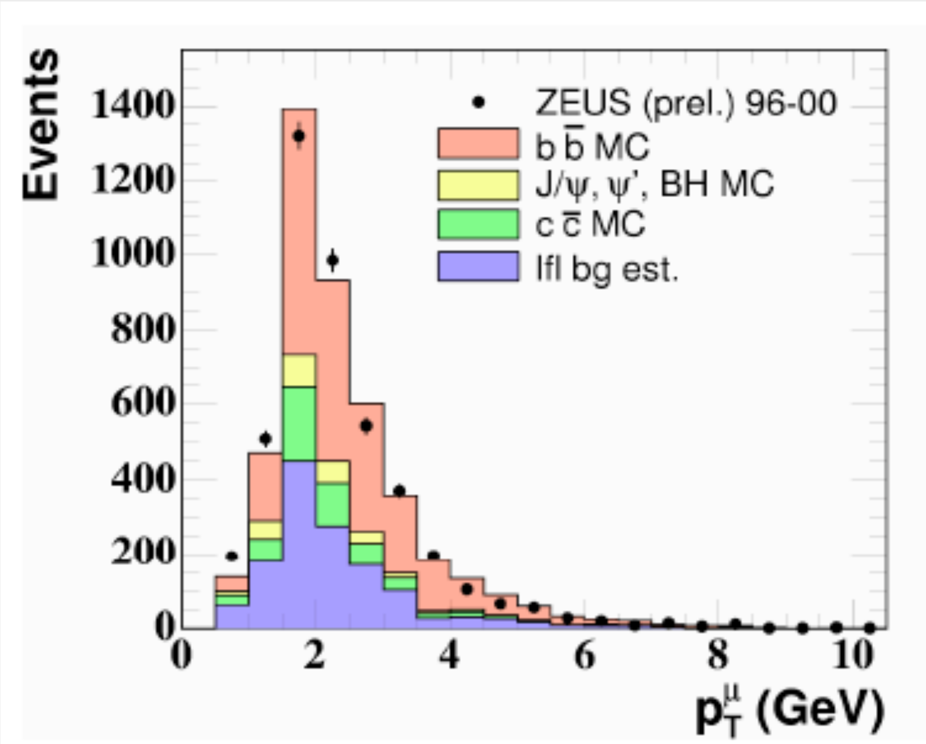
$250 \pm 57 \pm 40$ pb

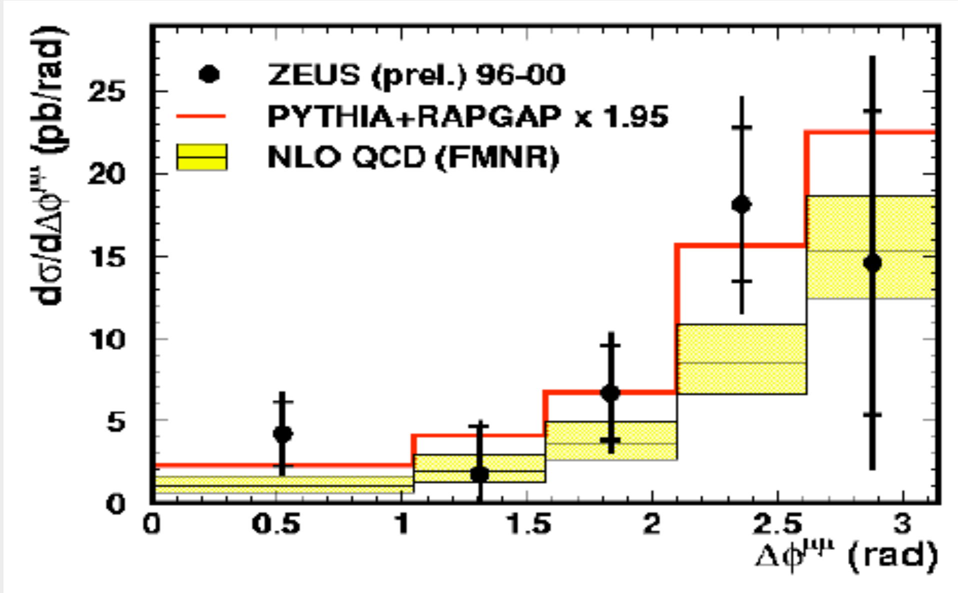
(NLO: 286^{+159}_{-59} pb)

Charm: good agreement, beauty: predictions too low

μμ correlations @ Zeus

Exploit data for background determination / subtraction





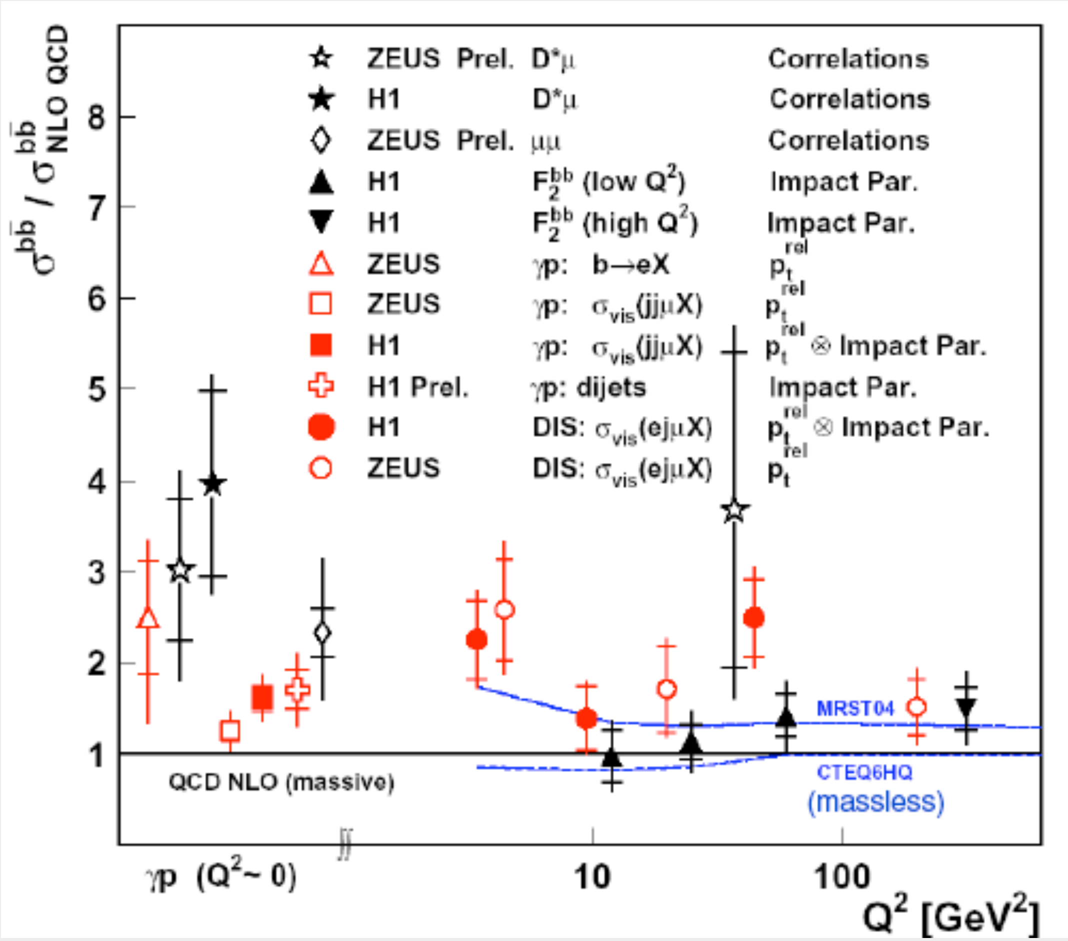
$M_{\mu\mu}$> 3.25 GeV => 2 μ from different b's

LO: shape ok, norm too low

NLO: agrees within errors

Beauty Production Summary

- General trend: slight overshoot of data versus massive NLO
- difference between QCD calculations
- need Hera II data for improved precision



Charm Contribution to e-p XSect

Define charm contribution to proton structure function :

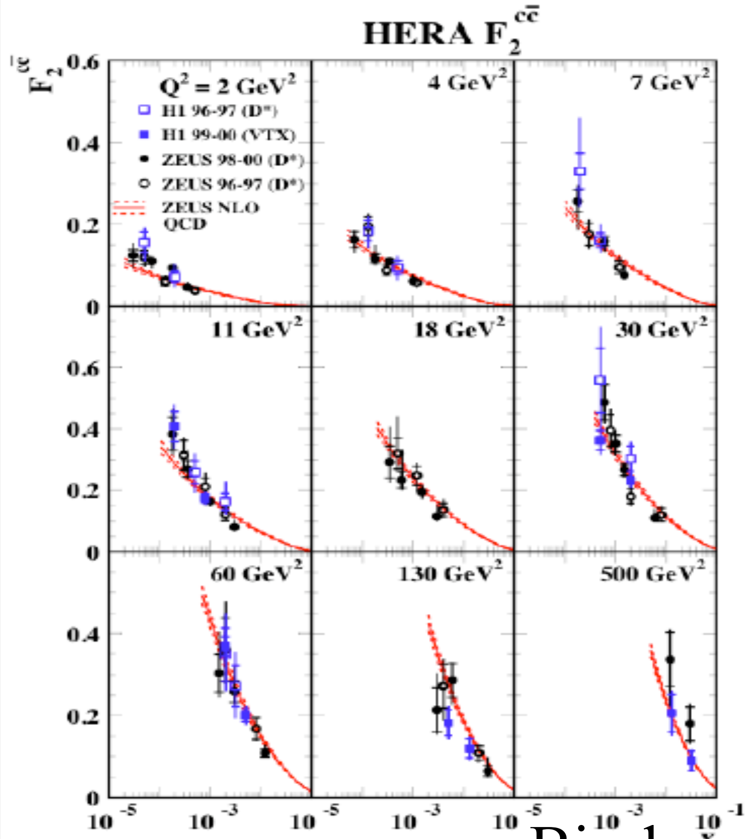
$$\frac{d^2\sigma^{ep\rightarrow c\bar{c}X}}{dxdQ^2} \propto F_2^{c\bar{c}}(x,Q^2)$$

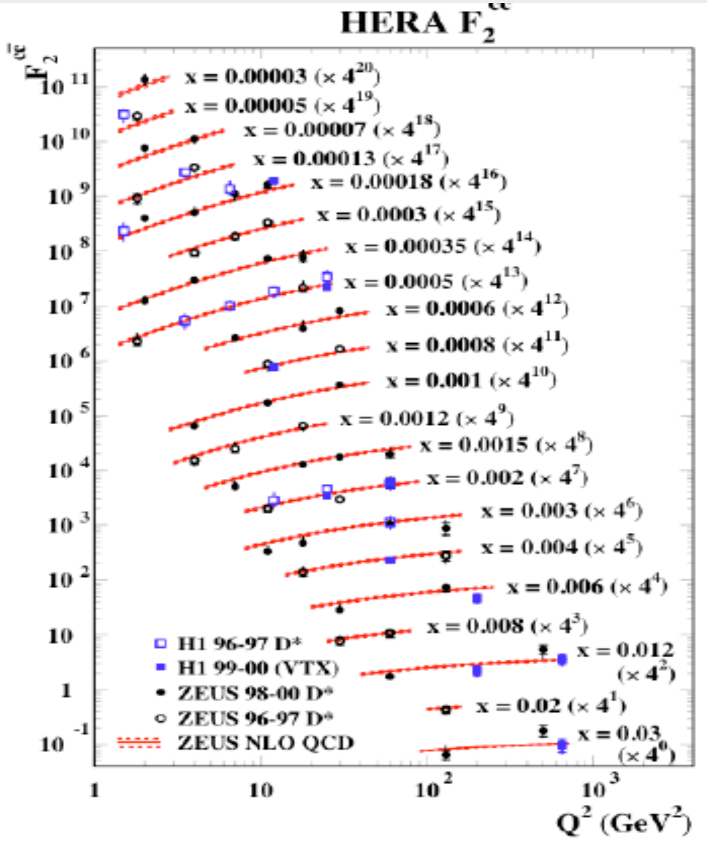
In analogy to inclusive structure function:

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

Recent measurement performed via lifetime tagging
(before, done by extrapolation of D* cross section)

F_2^{cc}



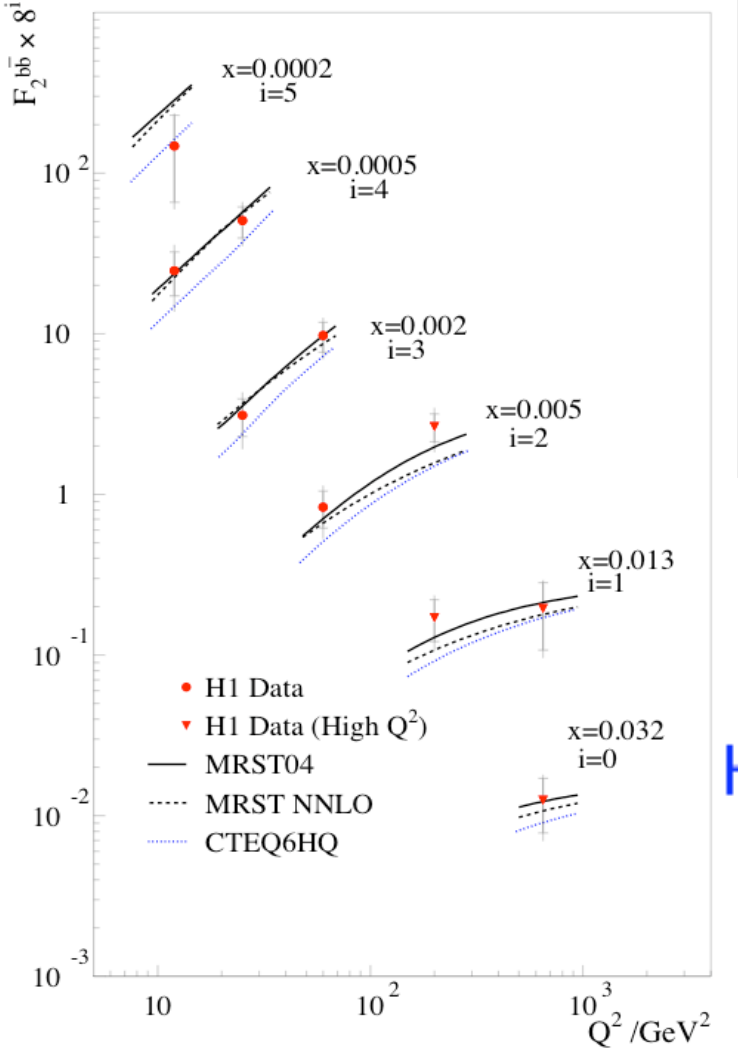


Bjorken X

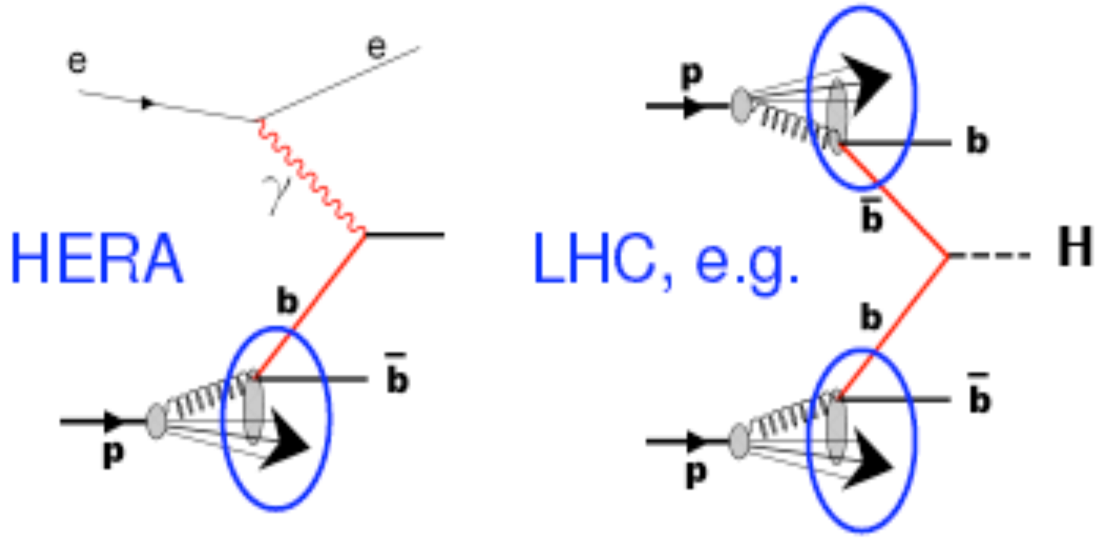
Good agreement with predictions using scaling violations

At low Q^2, charm starting to constrain gluon density

Beauty Contribution to F_2



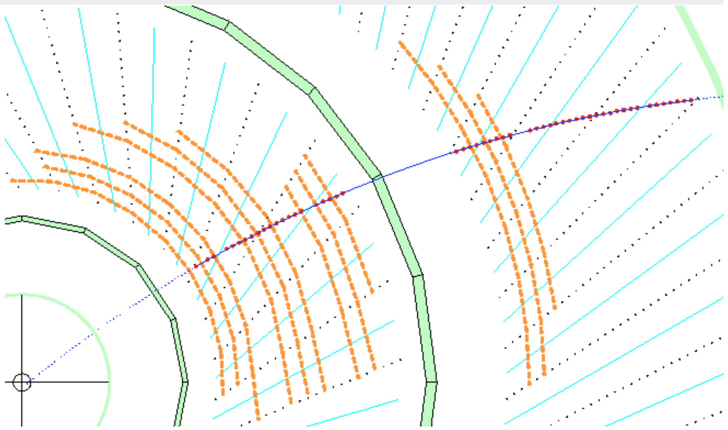
- First measurement
- Rise with g(x) (smaller x and larger Q^2)
- First NNLO calculation (R. Thorne) agree with HERA data, lower than NLO (~ 40%)

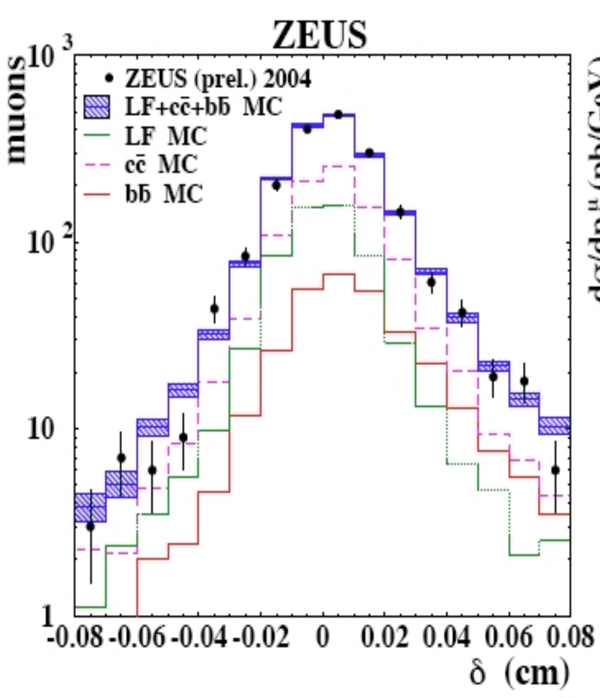


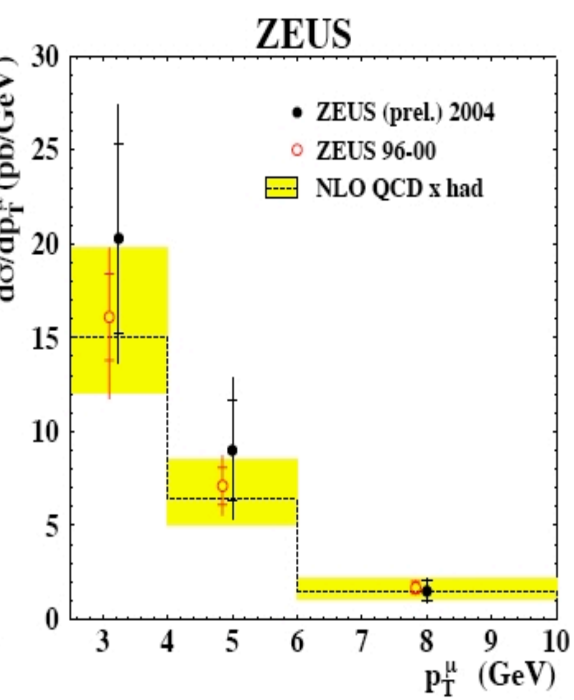
Detector Upgrade for HERA II

Most relevant upgrade for heavy flavor production:

- H1 Fast Track Trigger
- ZEUS Micro Vertex Detector







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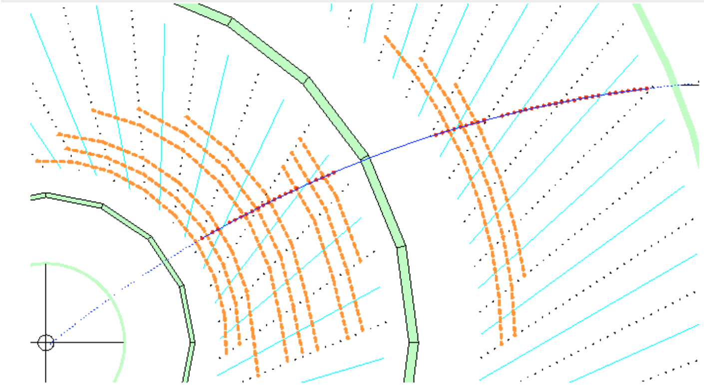

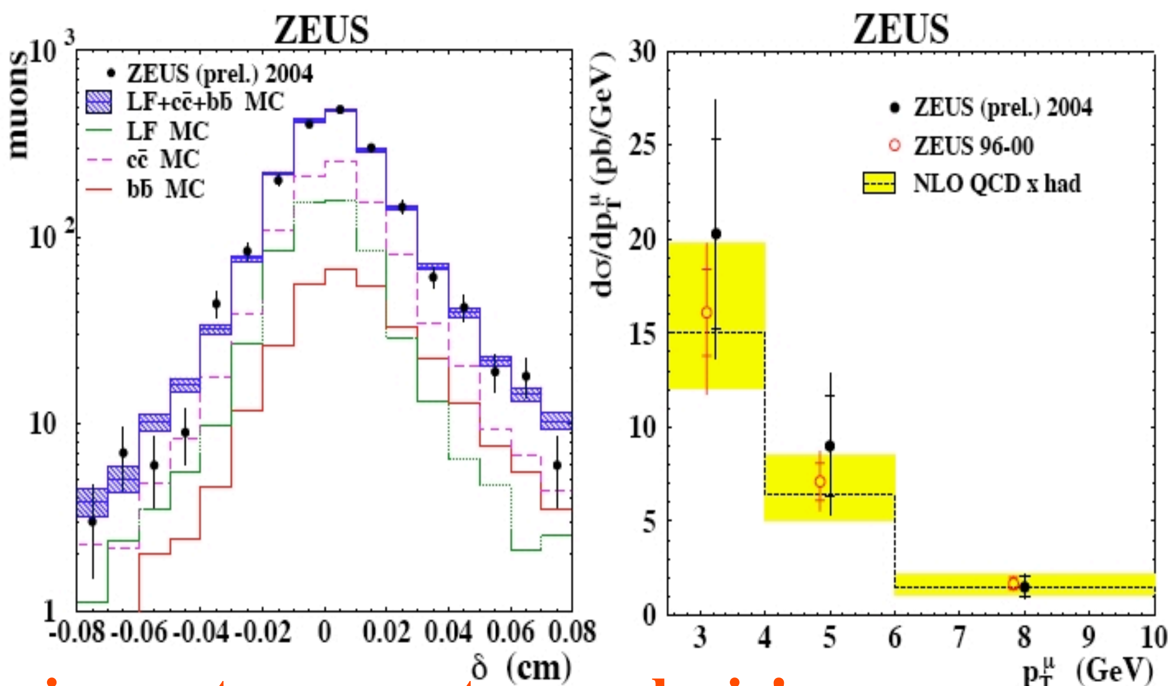

First Zeus impact parameter analysis!

Summary

- Heavy Flavor production: test of pQCD
- Charm production:
  - ✓ High precision data described by NLO
  - ✓ NNLO or NLO+PS needed at least in some phase space region
- Beauty description:
  - ✓ Reasonable agreement at high Pt, getting somewhat worse at lower pt
  - ✓ Data tend to be larger than NLO predictions
- First measurement of F_2^{bb} Structure Functions
- Hera II now on track, most data are still coming => higher precision in view