Beauty Production at HERA

- Introduction
- Measurements using beauty tagging by
  - muons and jets, HERA I + new HERA II
  - lifetime information
  - double tags: muon + D* or muon + muon
- Comparisons and Summary

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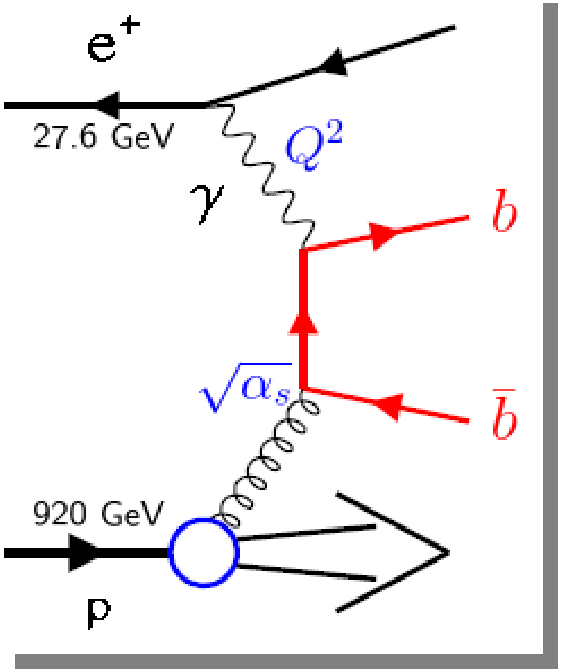
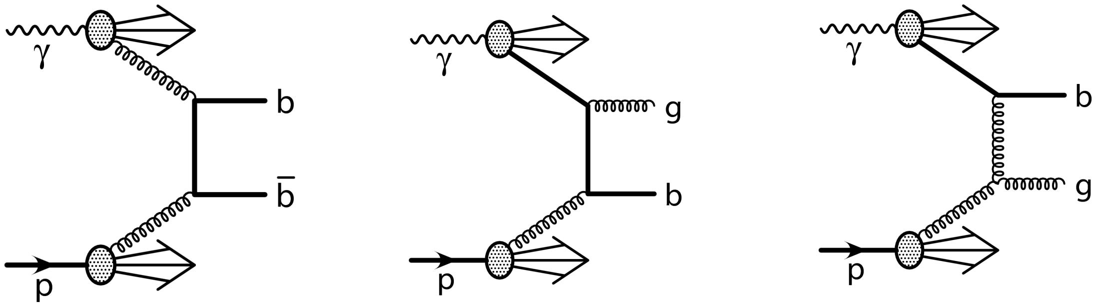
representing H1 and ZEUS

Beauty Production at HERA



- Heavy quarks are dominantly produced via direct photon-gluon fusion : $\gamma g \rightarrow bb$

+ resolved contributions ...



+ ...

"c/b-excitation"

Various scales involved:

$Q^2 < 1$ GeV^2 : Photoproduction (γP)

$Q^2 > 1$ GeV^2 : Deep Inelastic Scattering (DIS)

$M_b \sim 5$ GeV and $p_T^b \sim$ few GeV

- Powerful tool to test pQCD, measure g-density in proton and study hadronic components of photon.

QCD Calculations for Open Beauty

LO and PS programs:

- PYTHIA : direct and resolved (inc. flavour-excitation), DGLAP evolution
- RAPGAP : direct and resolved , CCFM-like evolution
- CASCADE: direct only, CCFM-like evolution

NLO calculations in pQCD used here:

- FO = fixed order in α_s, massive quarks scheme: valid for $p_t \sim m_Q$,
  uses fixed number of active flavours in p and γ (FFNS),
  - FMNR in photoproduction (direct +resolved), with CTEQ5M + GRV-G HO pdfs: Frixione, Mangano, Nason, Ridolfi
  - HVQDIS in DIS (direct), with CTEQ5F4 pdf : Harris+Smith

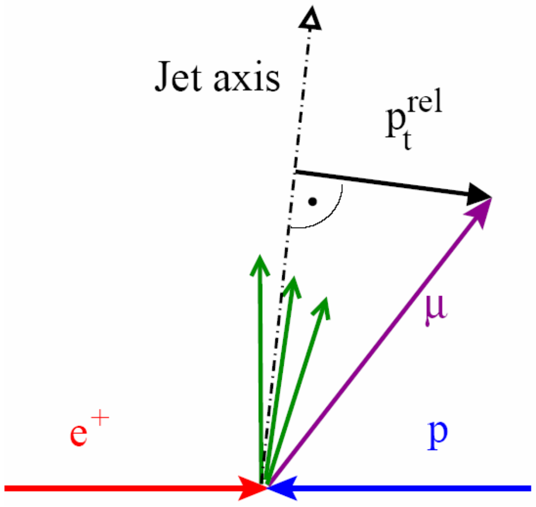
Jets for NLO: run jet algorithm on partons, then correct to hadron level with MC [O(5%)]

D*, μ –final states: fold Q with fragmentation function (e.g. Peterson) and add semileptonic decays for μ

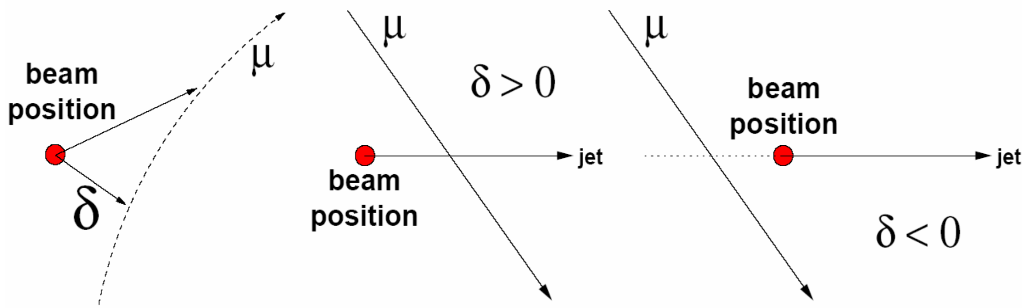
Beauty Tagging Techniques : jets, μ, D*, 2nd vertices

Exploit large B-mass and long B-lifetime

→ see SF-talk for more details



- $p_T^{rel} = p_T$ of μ w.r.t. jet axis: large for b due to b-mass
- δ = signed impact parameter of track (e.g. μ) w.r.t. primary vertex (using Si-vertex detectors); sign defined by jet-direction
- $S = \delta / \sigma(\delta)$: impact parameter significance
  - S1=highest S, S2=2nd highest S with same sign
  - positive tails for b and c due to lifetime
  - symmetric around zero for light-flavours

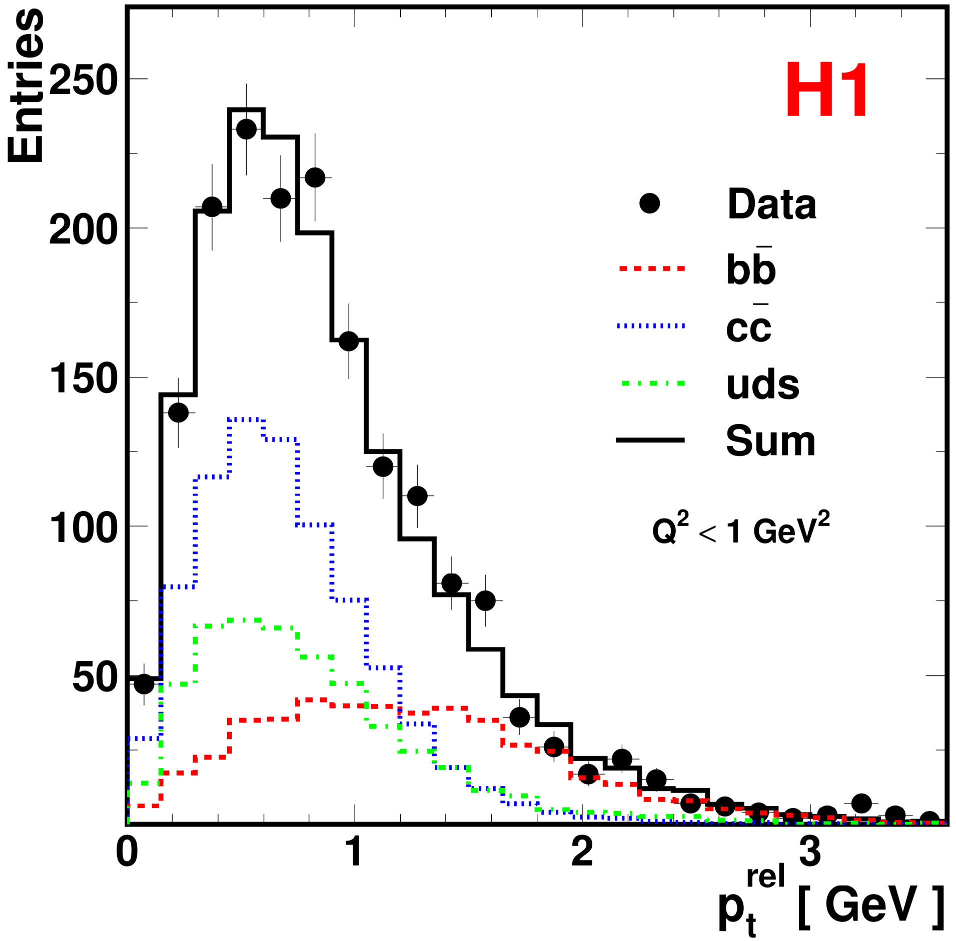


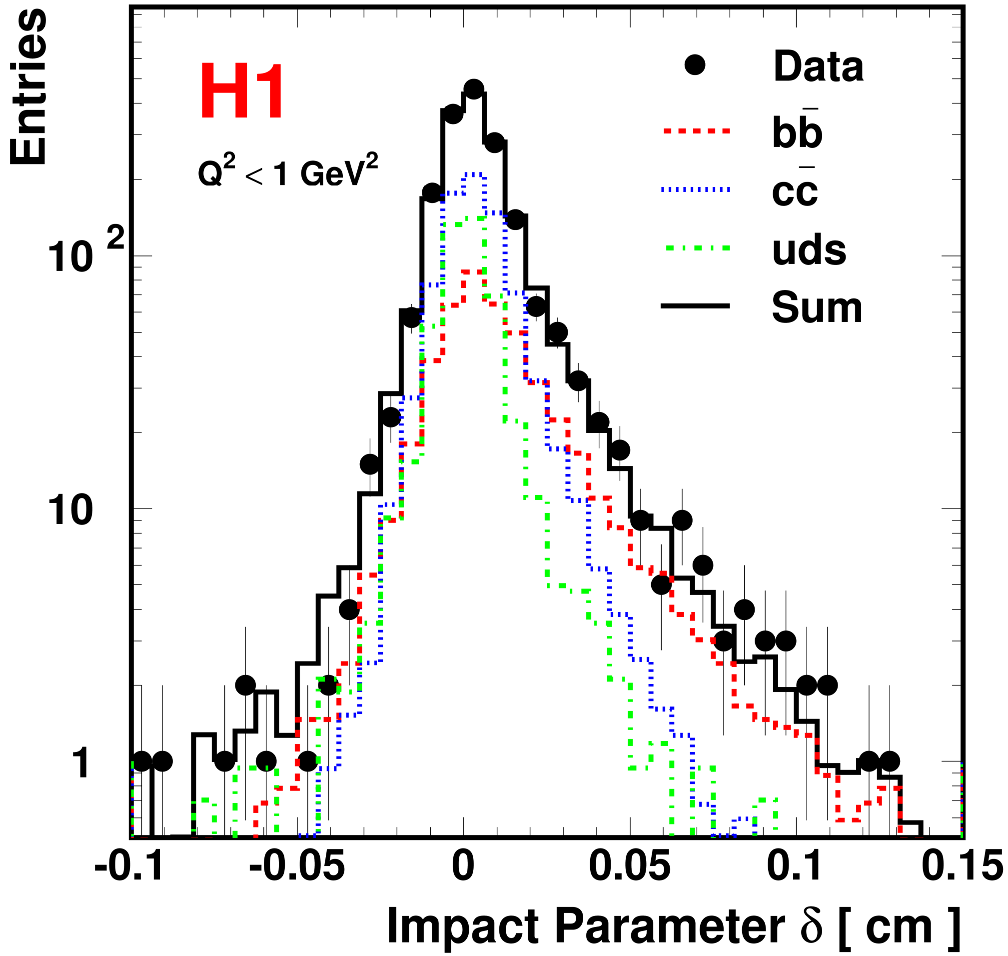
- **Determination of b-cross section:**
  - extract fractions of b-, c- and uds- by fitting distributions (p_T^{rel}, δ, Si) using MC templates for shape functions

Beauty Tagging with muon and jets

b-tag μ+2j: δ and p_t^{rel} in γp : H1

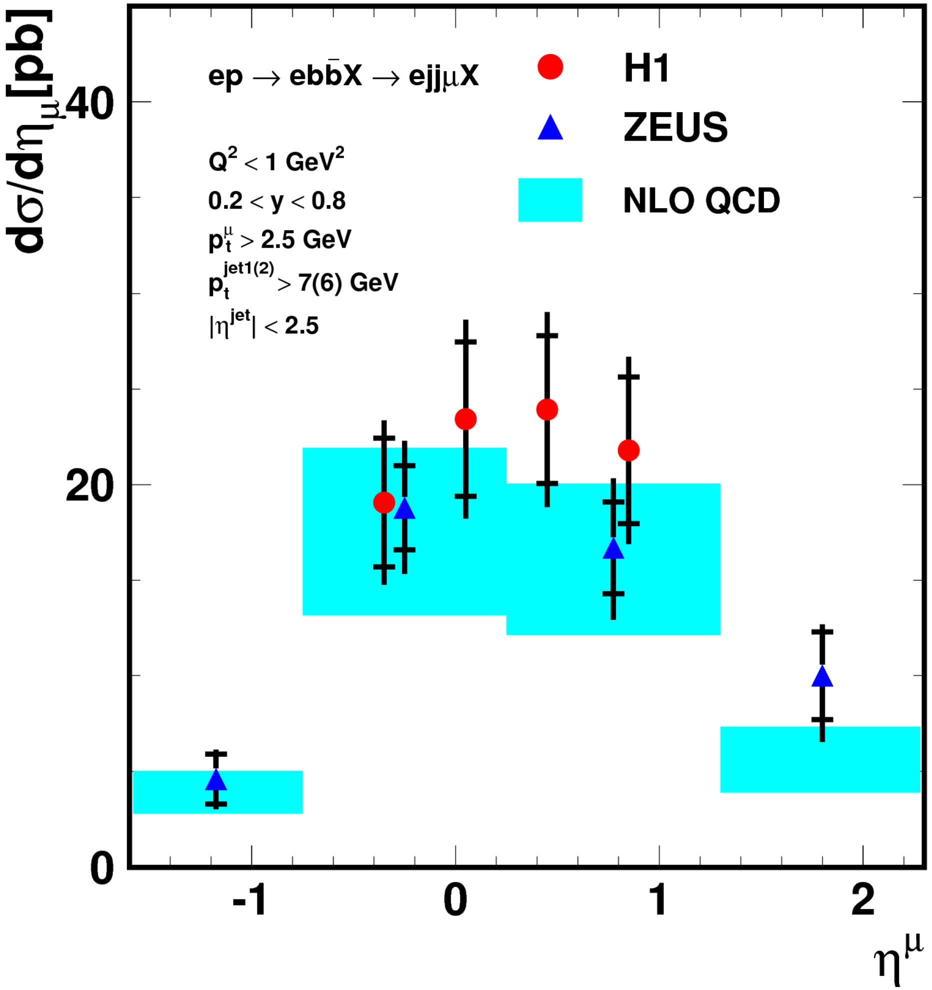
- Select events with muon and jet(s)
- likelihood fit to (p_t^{rel},δ) distributions; example below yields 30% b-fractions
- Sum is described

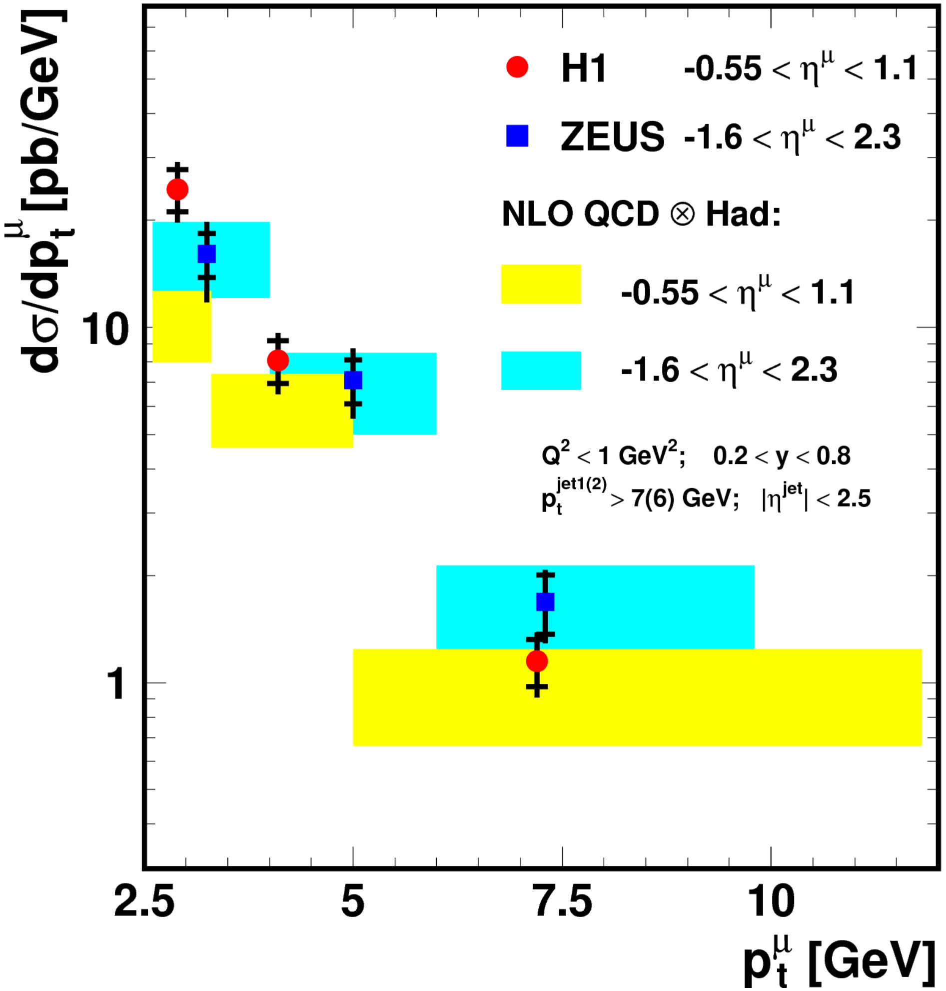




b-tag μ+2j: δ and p_t^{rel} in γp : H1 + ZEUS

H1 : 2D-fit to p_t^{rel} and δ (~ 50 pb^{-1}); ZEUS : fit to p_t^{rel} (~ 110 pb^{-1})





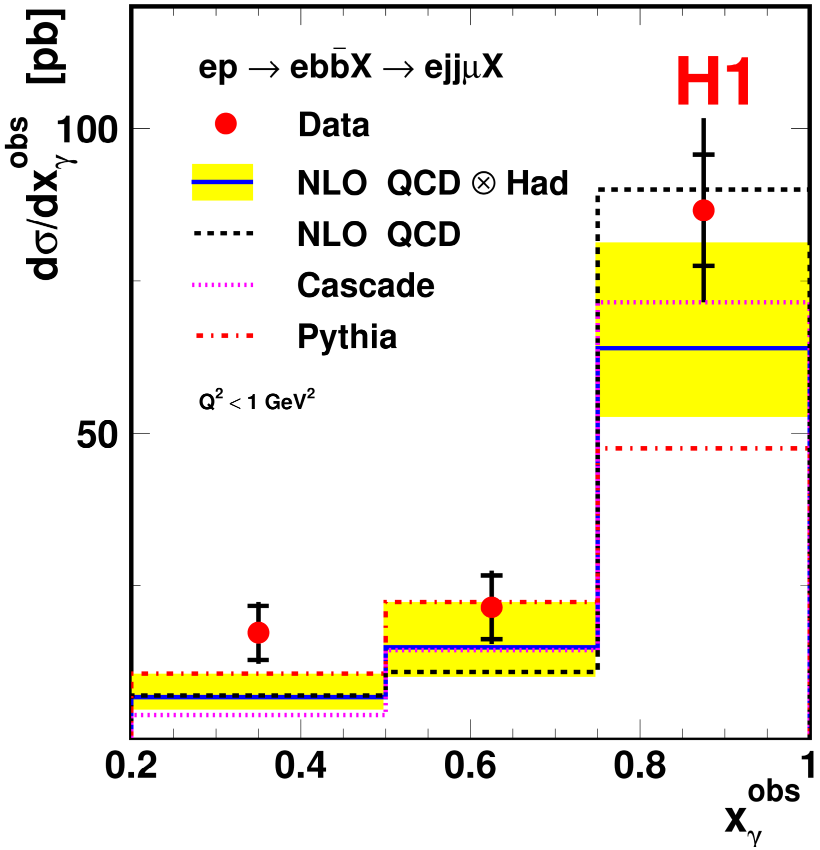
- General agreement between H1 and ZEUS
- NLO (FMNR): shape close, agreement within errors
- H1 excess at low p_t^{μ}

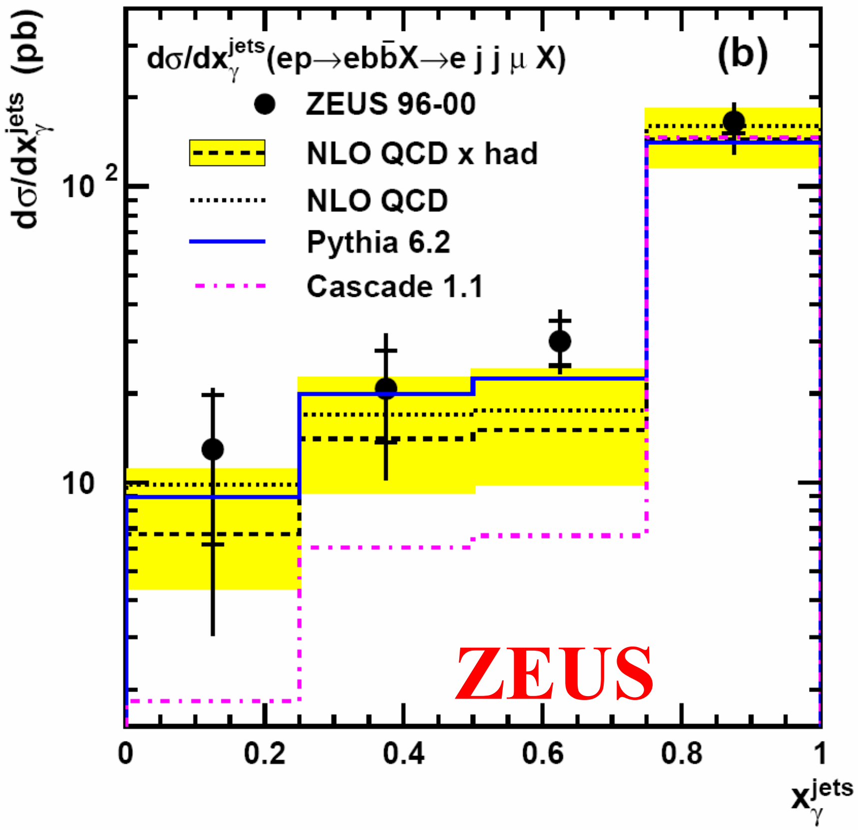
b-tag μ+2j: δ and p_t^{rel} in γp : H1 + ZEUS

H1 : $Q^2<1$ GeV^2, $0.2<y<0.8$; $p_t^{jet}>7(6)$ GeV, $|\eta_{jet}|<2.5$; $p_t^{\mu}>2.5$ GeV, $-0.55<\eta_{\mu}<1.2$;

ZEUS: $Q^2<1$ GeV^2, $0.2<y<0.8$; $p_t^{jet}>7(6)$ GeV, $|\eta_{jet}|<2.5$; $p_t^{\mu}>2.5$ GeV, $-1.6<\eta_{\mu}<1.3$;

$p_t^{\mu}>1.0$ GeV AND $p^{\mu}>4.0$ GeV in $1.48<\eta_{\mu}<2.3$



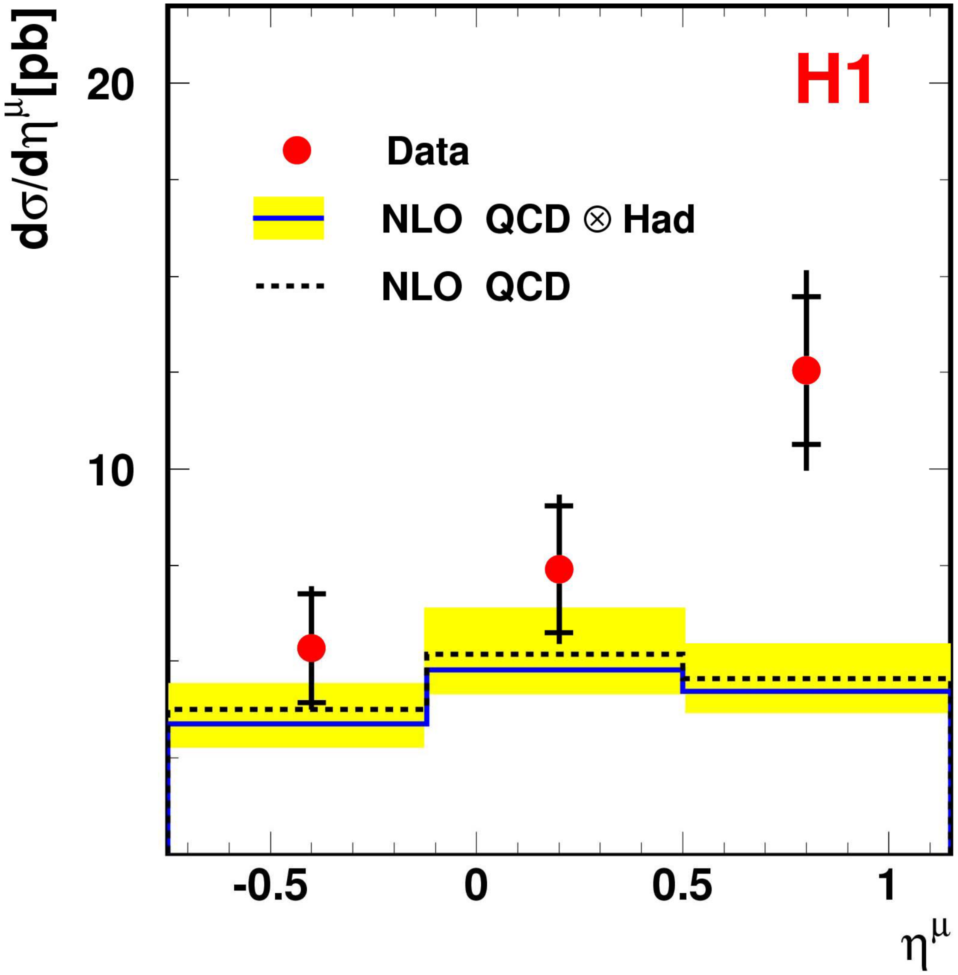


- LO: Pythia fails at $x_\gamma=1$ in H1, Cascade fails at low x_γ in ZEUS
- NLO: reasonable agreement (large uncertainties)

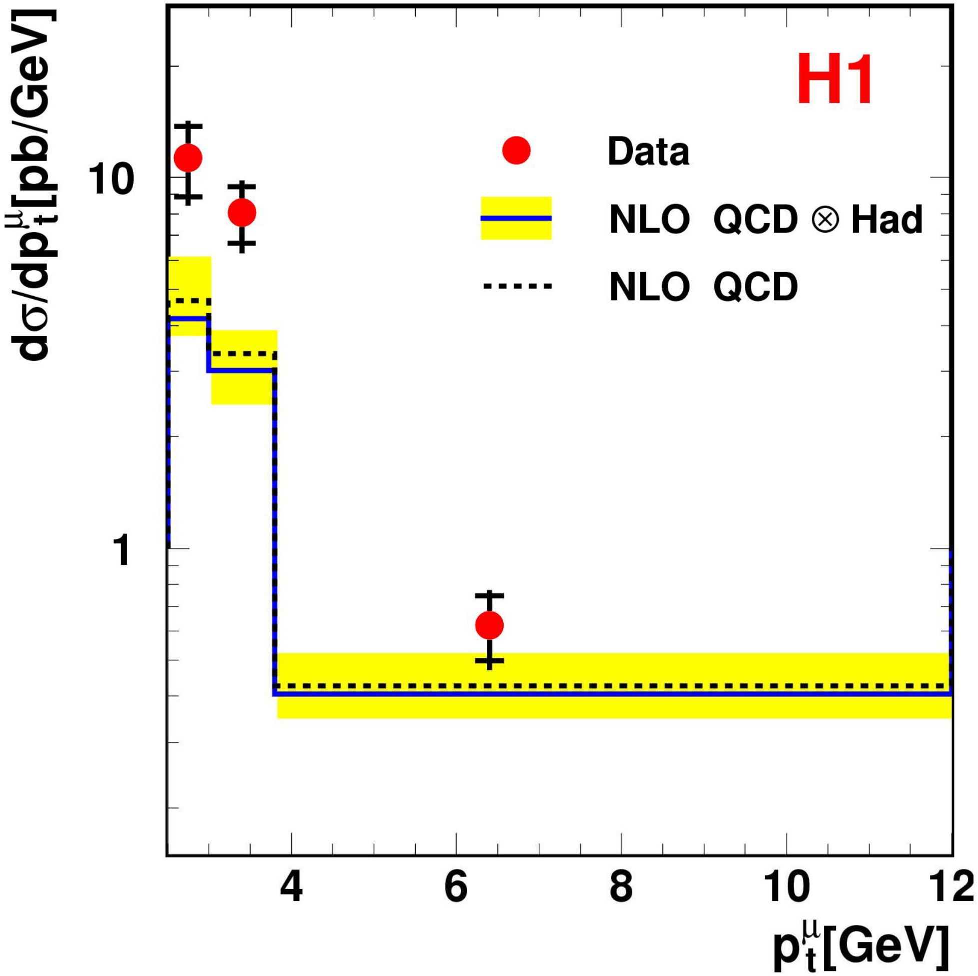
$$x_\gamma = \frac{\sum_{jet1,\,jet2}(E-P_z)}{\sum_{hadrons}(E-P_z)}$$

b-tag μ+j: δ and p_t^{rel} in DIS : H1

H1: $2<Q^2<100$ GeV^2, $0.1<y<0.8$; $p_t^{\mu}>2.5$ GeV, $-0.55<\eta_{\mu}<1.2$; $p_t^{jet}>6$ GeV, $|\eta_{jet}|<2.5$



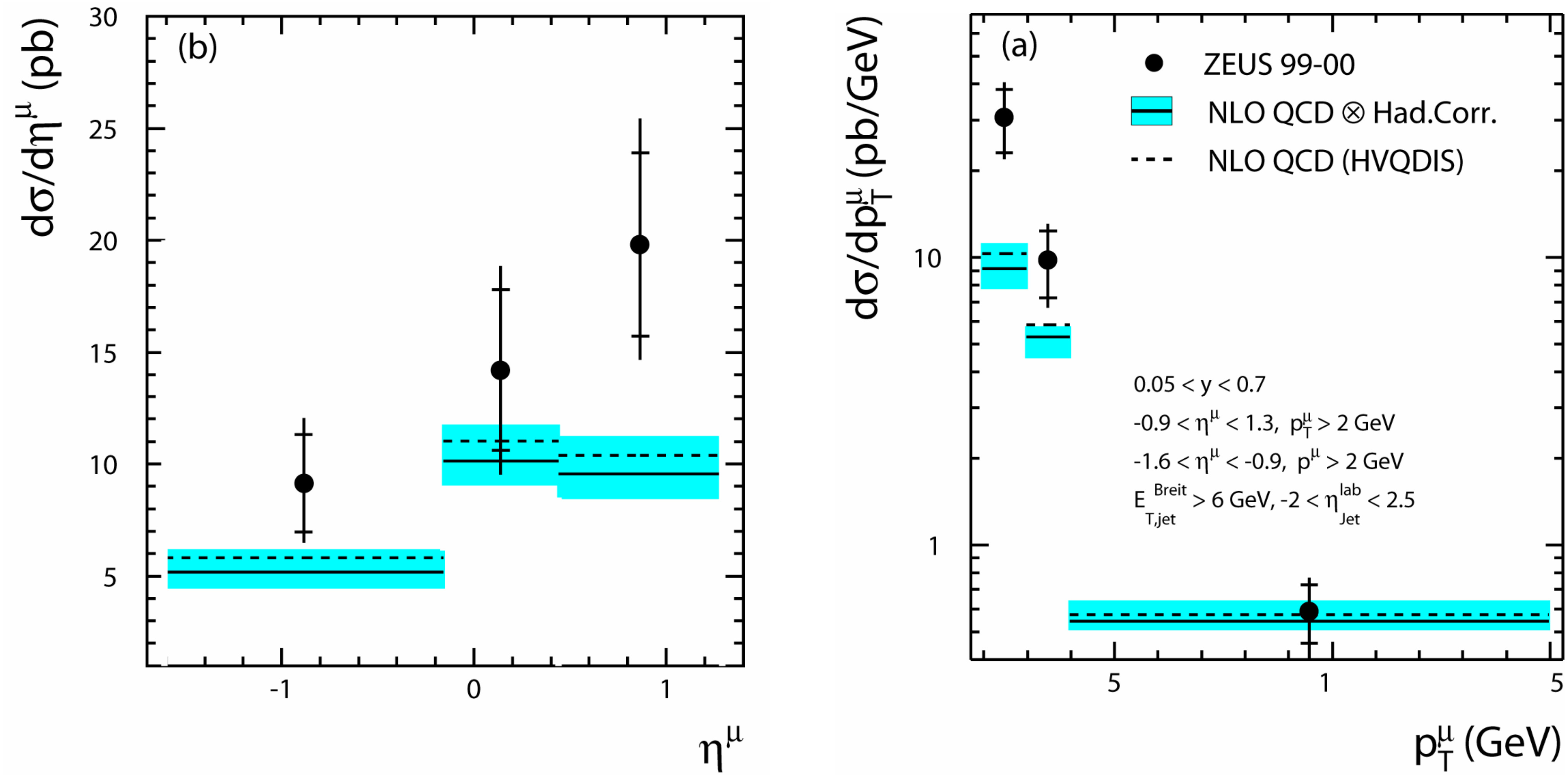
- NLO (HVQDIS): norm low, in particular in forward direction



- Data softer
- NLO (HVQDIS): norm low at low pt

b-tag μ+j: δ and p_t^{rel} in DIS : H1

ZEUS: $Q^2>2$ GeV^2, $0.05<y<0.7$; $p_t^{\mu}>2.0$ GeV for $-0.9<\eta_{\mu}<1.3$; AND $p^{\mu}>2.0$ GeV in $-1.6<\eta_{\mu}<-.9$;
$E_t^{jet}>6$ GeV, $-2>\eta_{jet}<2.5$



- Same general message …

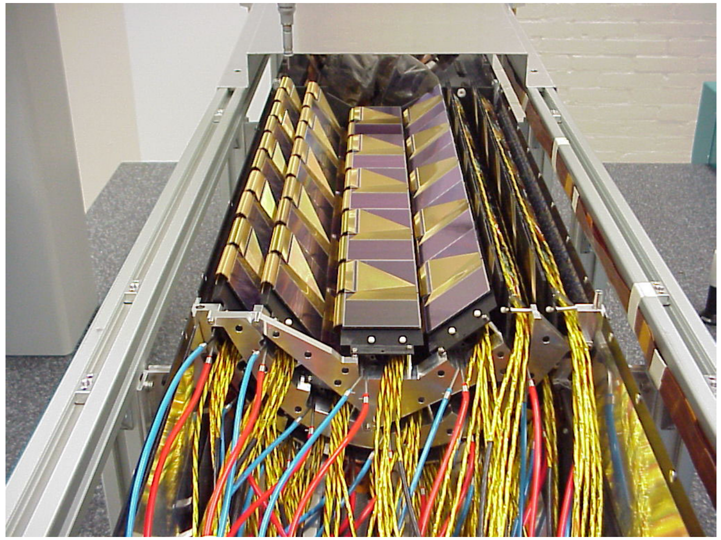
Beauty tagging with muon and jets

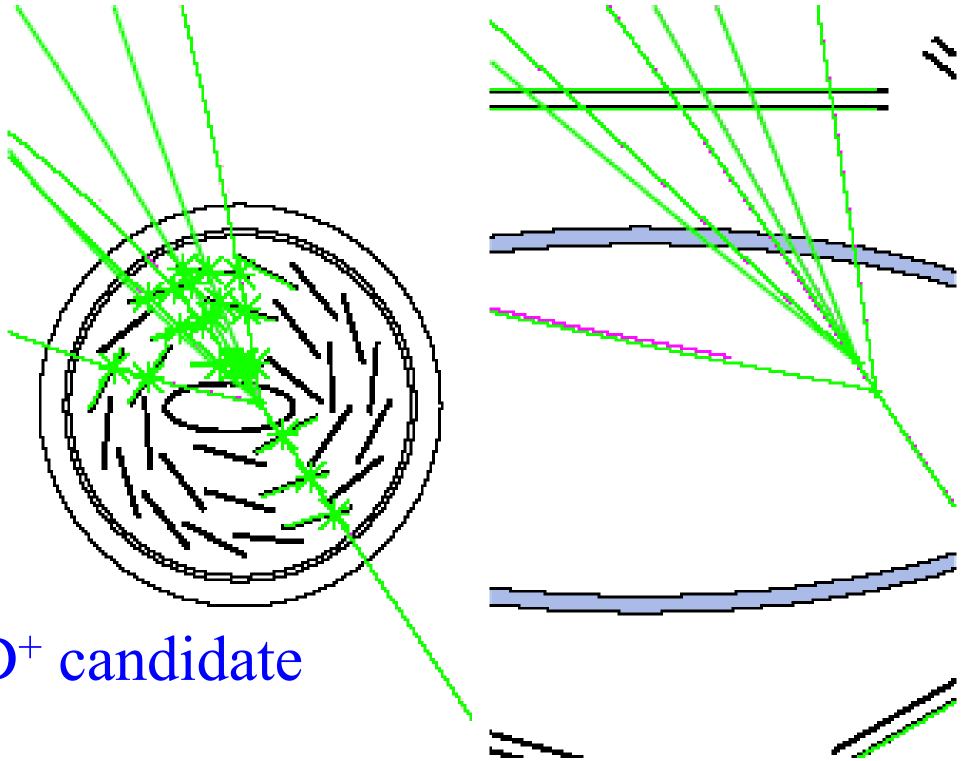
ZEUS with MVD in HERA-II data

ZEUS Microvertex Detector at HERA-II

Barrel: 3 layers, double sided strips,
65 cm length, covering 30 - 150^o

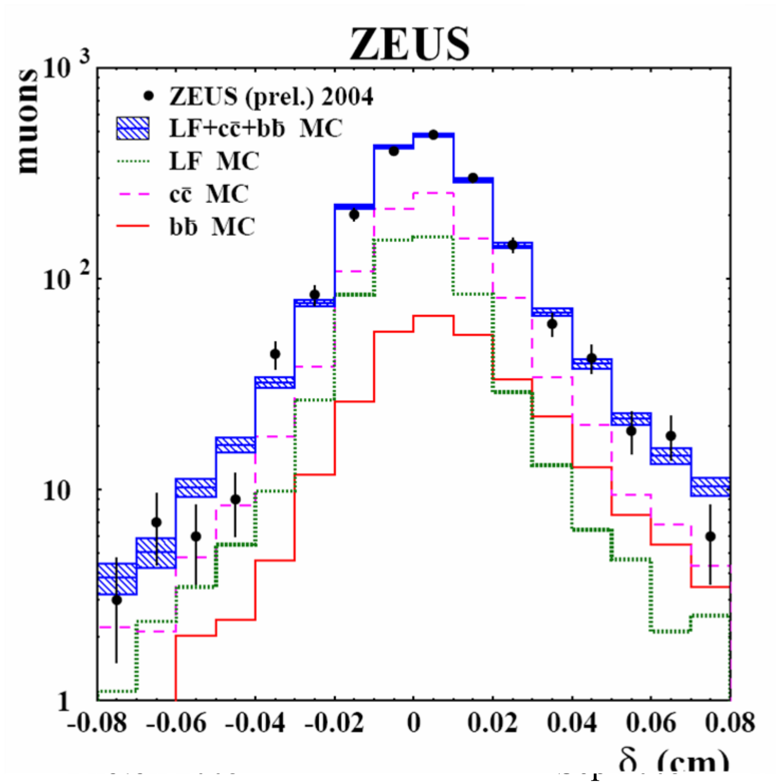
- Beam spot size : 110 x 30 μm^2 .





D$^+$ candidate

Lifetime effects → asymmetric δ →



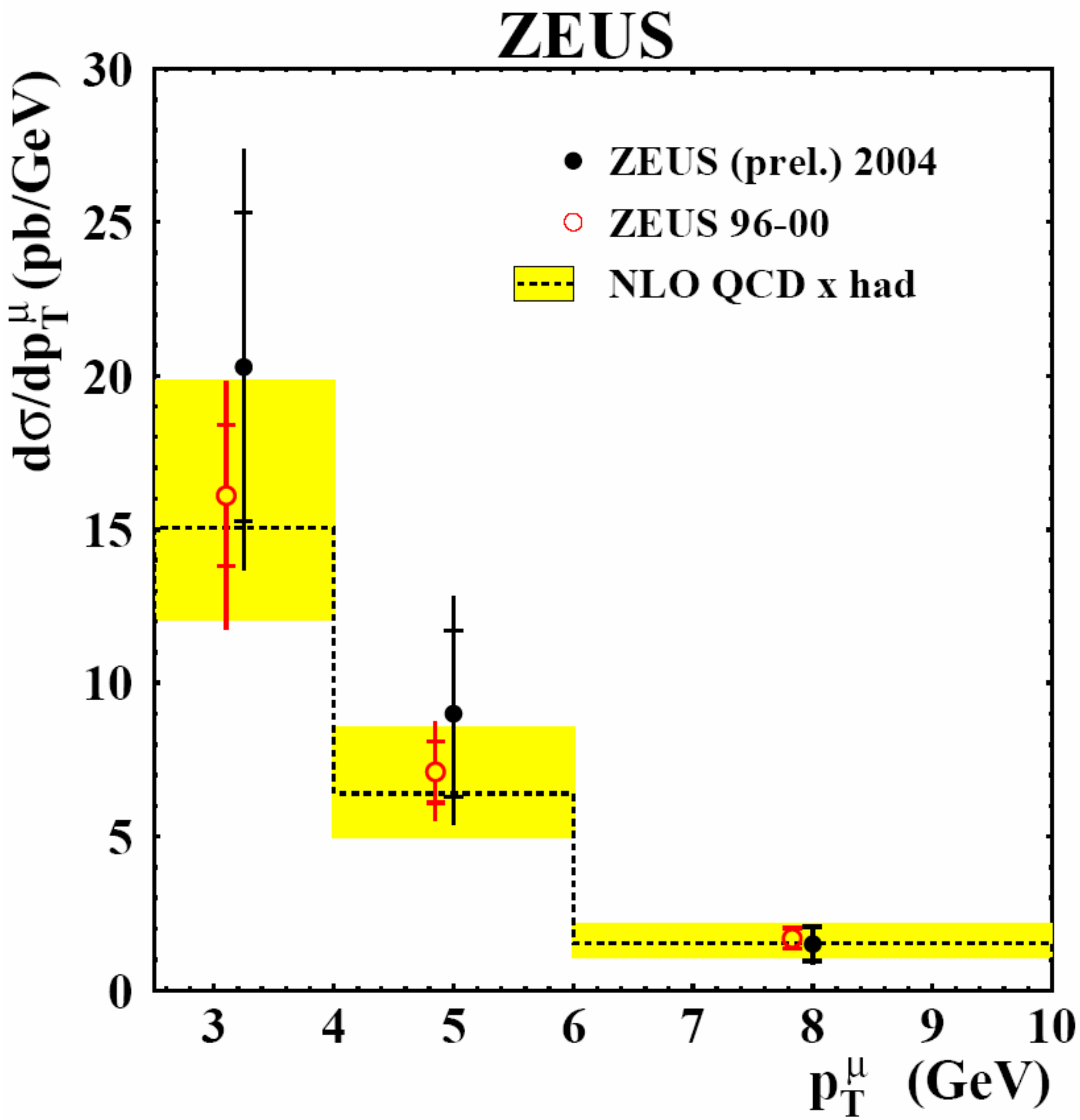
b-tag μ+2j: δ and p_t^{rel} in γp : ZEUS at HERA-II

ZEUS: $Q^2<1$ GeV^2, $0.2<y<0.8$; $p_t^{jet}>7{,}6$ GeV, $|\eta_{jet}|<2.5$; $p_t^{\mu}>2.5$ GeV, $-1.6<\eta_{\mu}<2.3$

- HERA-II results for 33 pb^{-1} from a 2-D fit (δ,p_t^{rel}) yield:

  $f_b=(16.7\pm2.6)\%$ $f_c=(52 \pm 10)\%$

- **no excess seen at low p_T^{μ}**
- agreement with previous measurements (used p_t^{rel})
- pQCD NLO (FMNR) including had. corrections describes data well

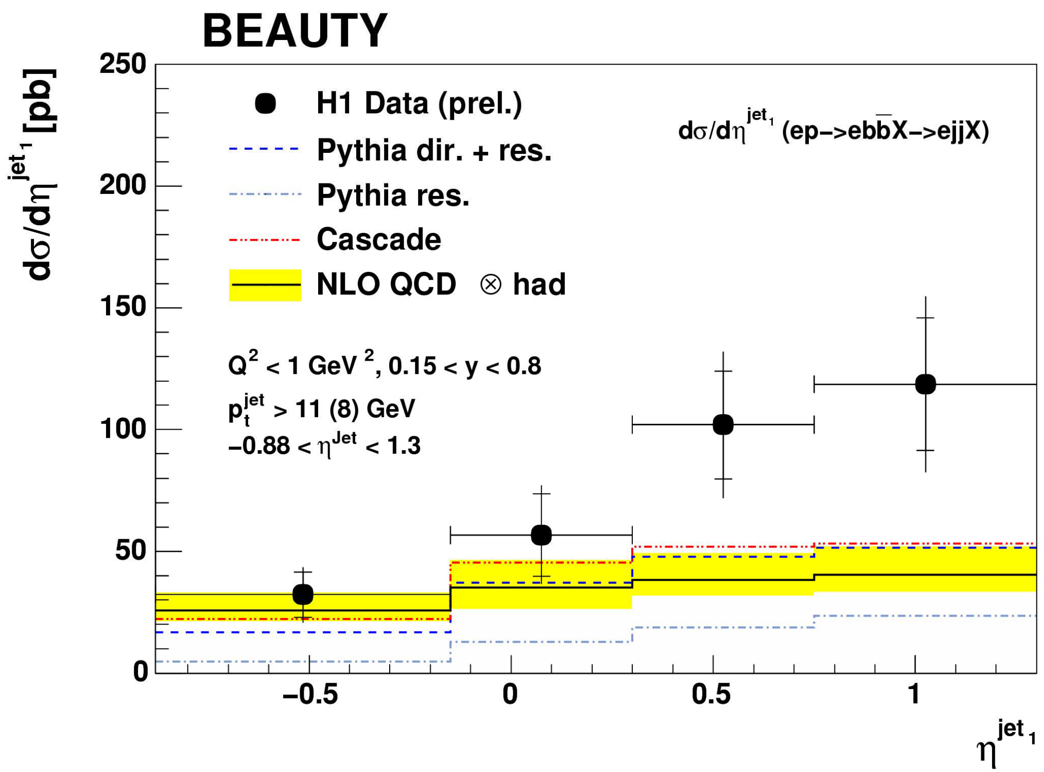


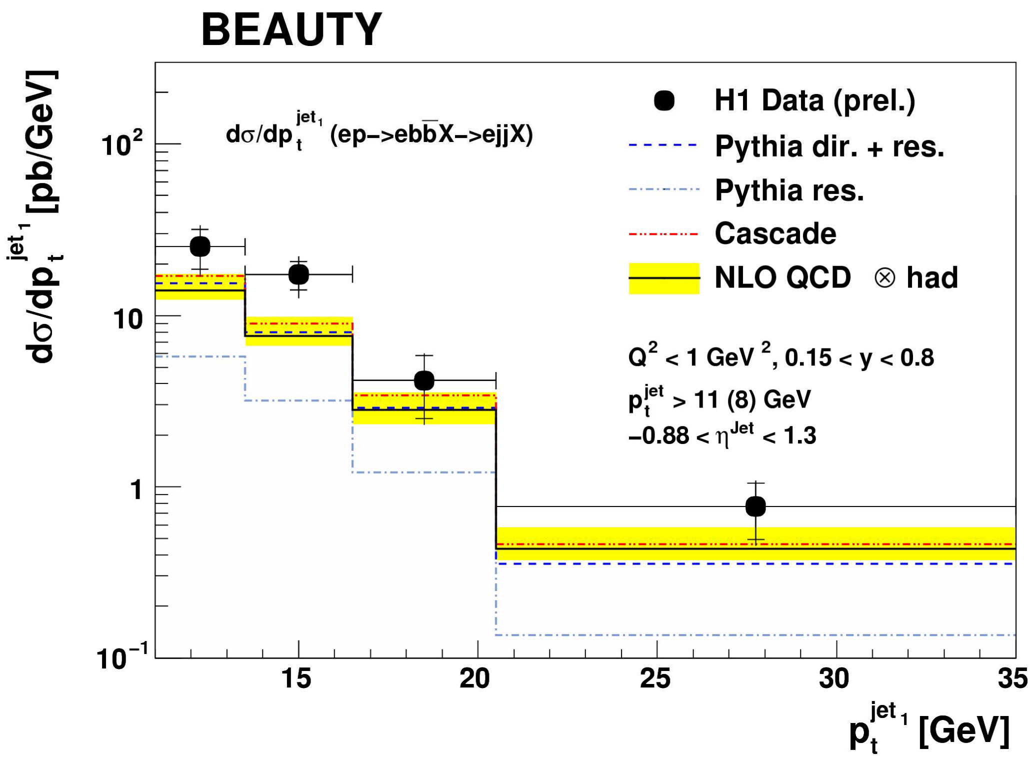
Beauty tagging using inclusive lifetime in γp 2 jets , no muon

b-tag: inclusive lifetime + 2 jets: in γp : H1

New measurement without muons: fit to subtracted S1, S2 distributions, using MC shape templates → See SF-talks for details on method

Q^2<1 GeV^2; 0.15<y<0.8; p_t(jet)> 11(8) GeV; -0.88< η(jet)< 1.3; from 57.7 pb^{-1}

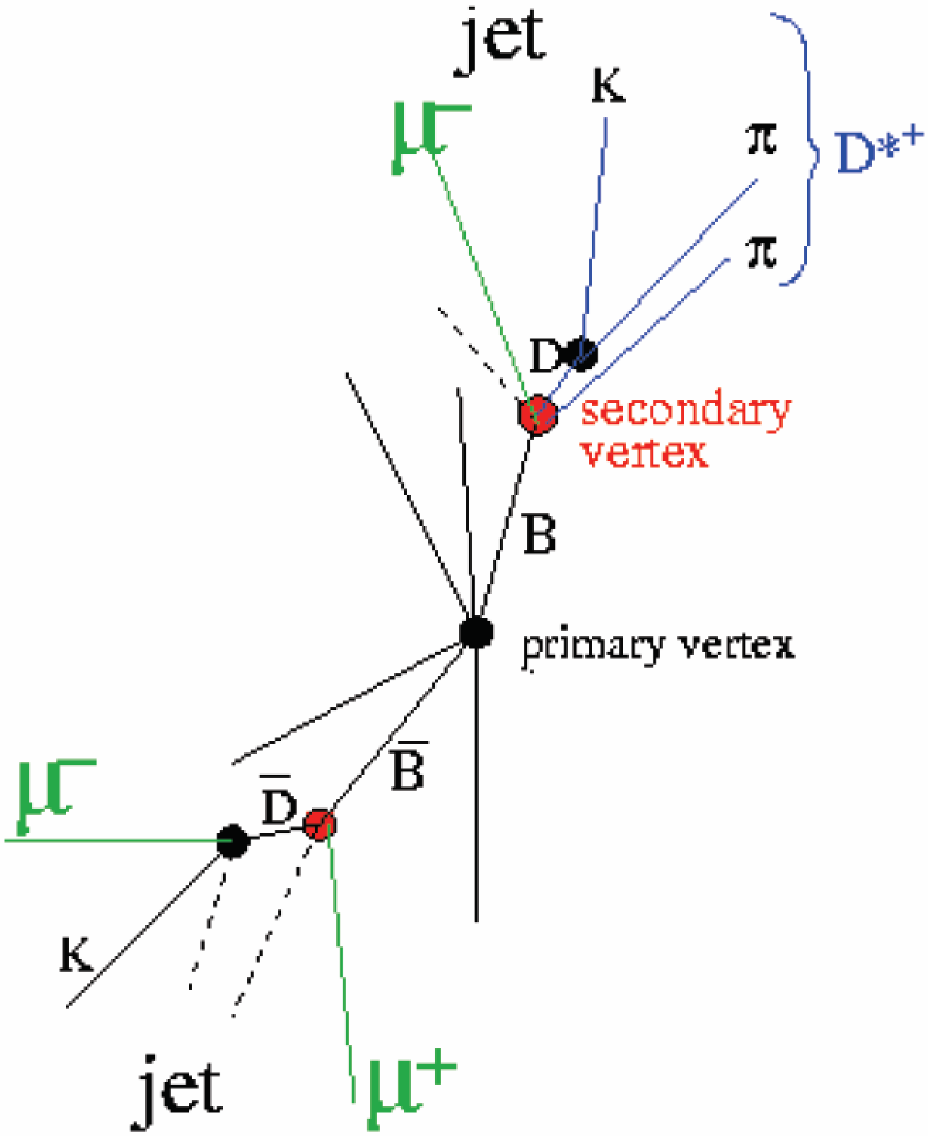




- General message from μ+2j confirmed: LO/NLO low (forward η and low pt)

Double tagging using D^*-muon correlations

Double Tagging



Tag BOTH b quarks by either a

- $D^* \rightarrow (K\pi)\,\pi$ and/or muon from semileptonic decay

A) $D^*\,\mu$: H1, ZEUS : Correlate charges and azimuthal angular separation $\Delta\phi(D^*\text{-}\mu)$

B) $\mu\mu$: ZEUS (prel) : Correlate charges and $M_{inv}\,(\mu\mu)$

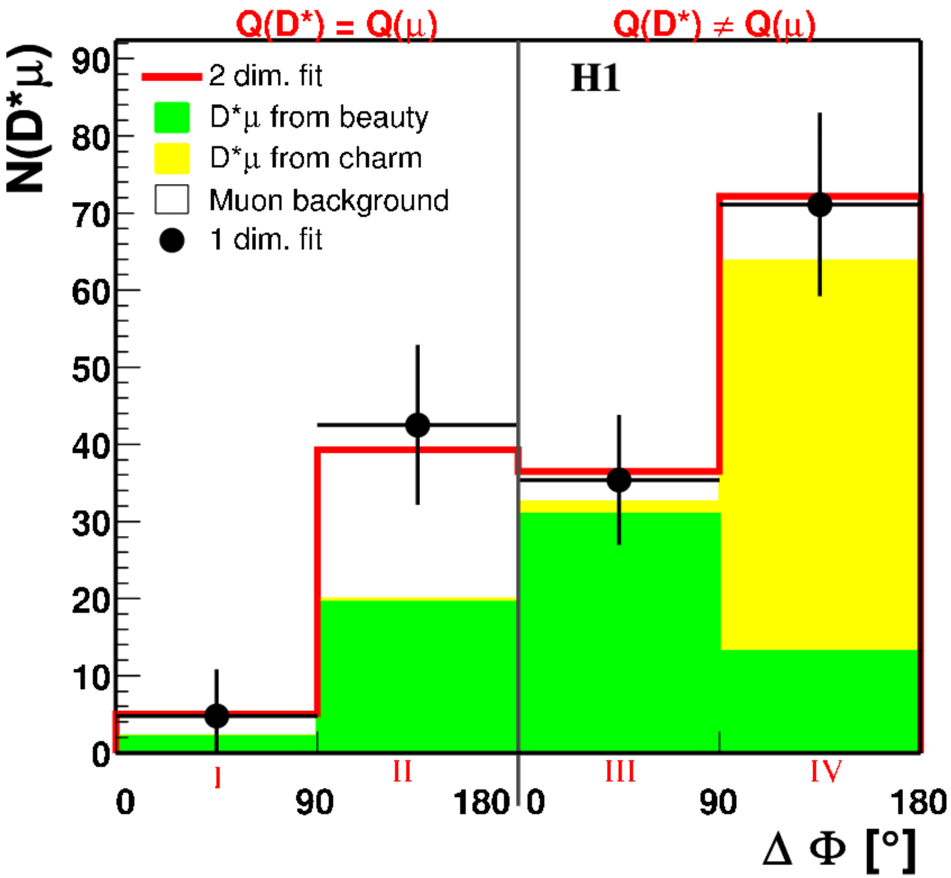
→ Obtain σ by fitting b,c,LF- fractions in 4 correlation regions

☺ Large phase-space for b:

- No jets required: reach lower $p_t(b)$
- large μ-acceptance in η of ZEUS

D*μ correlations in γp : H1

Population of 4 corr. regions well described



$Q^2 < 1$ GeV, $0.05<y<0.75$;

$p_t^{\mu}>2$ GeV, $|\eta_\mu|<1.735$;

$p_t(D^*)>1.5$ GeV, $|\eta(D^*)|<1.5$

beauty:

$\sigma_b^{vis}(ep \to e\ D^*\ \mu\ X)=206\pm53\pm35$ pb

(NLO: 52^{+14}_{-9} pb)

charm:

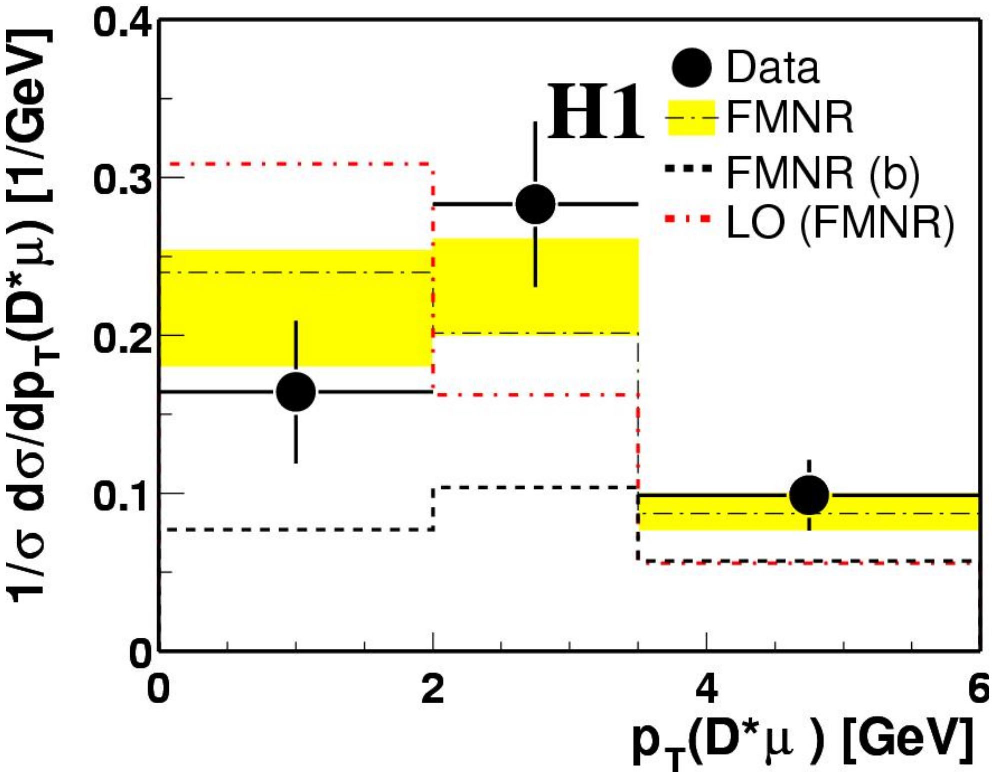
$\sigma_c^{vis}(ep \to e\ D^*\ \mu\ X)=250\pm57\pm40$ pb

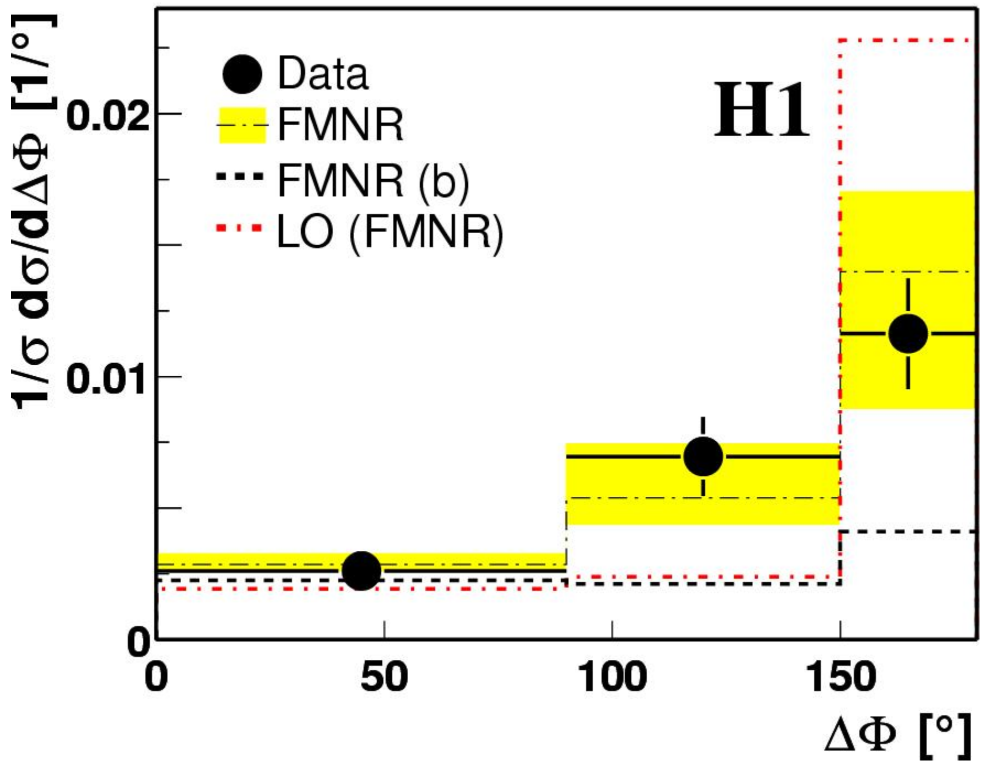
(NLO: 286^{+159}_{-59} pb)

Charm: good agreement
Beauty: NLO too low

D*μ correlations in γp : H1

normalized cross sections !!





Effects of higher orders (LO vs NLO) expected:

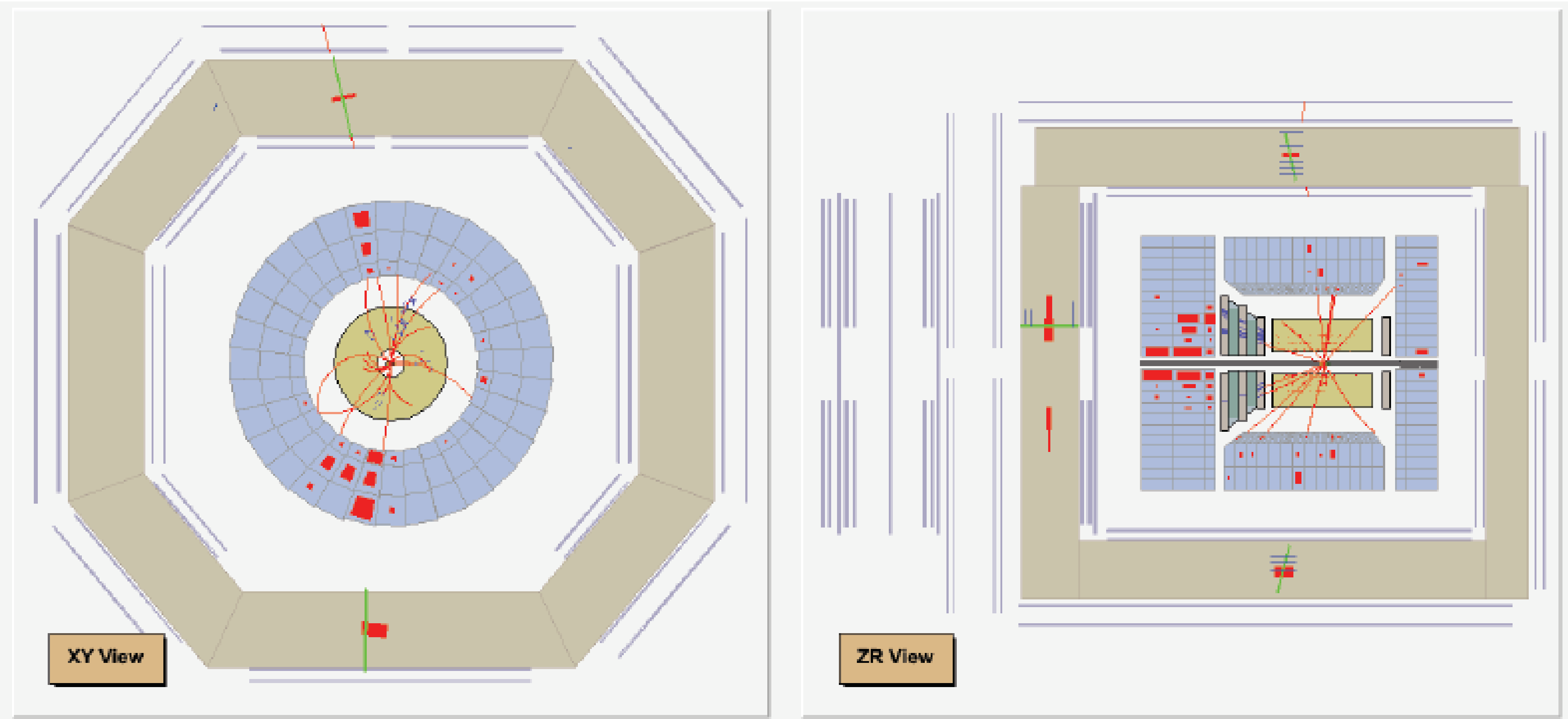
- $p_t(D^*\mu)$: flatter
- $\Delta\phi(D^*\mu)$: more spread out at 180°

} **visible and in agreement with NLO**

Beauty tagging with muon-muon correlations

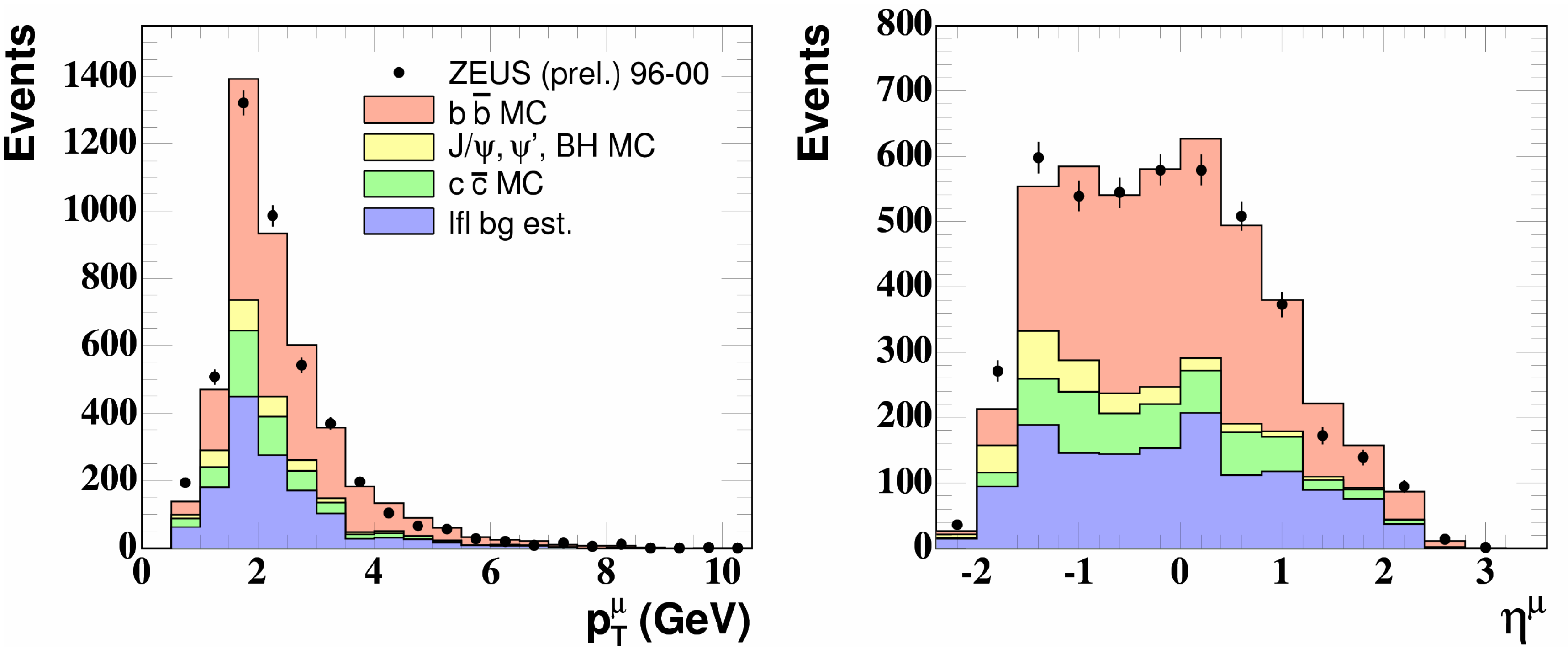
μμ correlations : ZEUS event

Two muon event measured with ZEUS detector



μμ correlations : ZEUS signal

- Take all μμ invariant masses, fit the (unlike-sign – like-sign –BG) data
- Exploit data for background determination/suppression:
  - use non-isolated muon pairs to reduce J/ψ, ψ', Bethe-Heitler μμ-pair background
  - remove fake μ-background by taking difference between unlike-sign and like-sign samples (light flavour cancels, if assumed equal in ++ and +-)
  - charm contribution (to unlike-sign only) estimated from $D^*\mu$ sample (no charm in like-sign high-mass) and fixed in fit

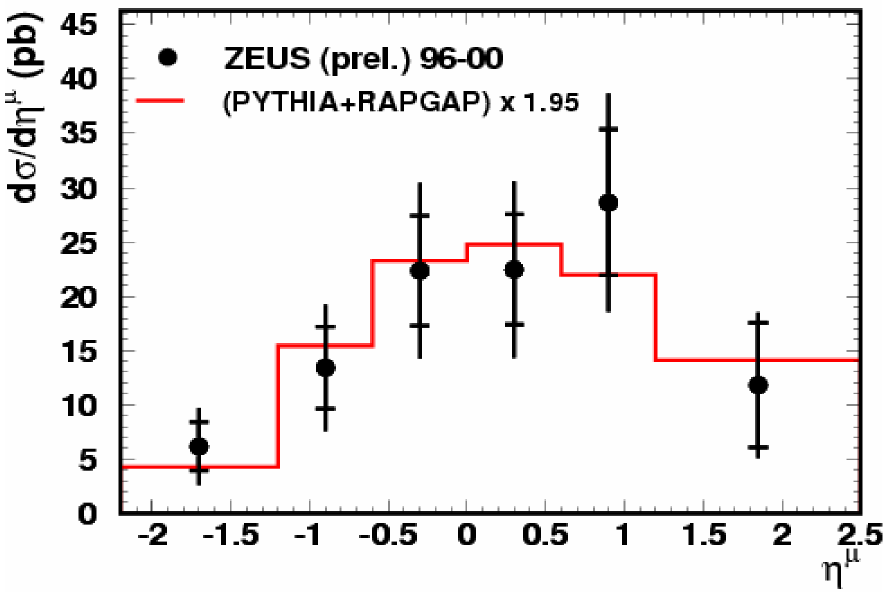


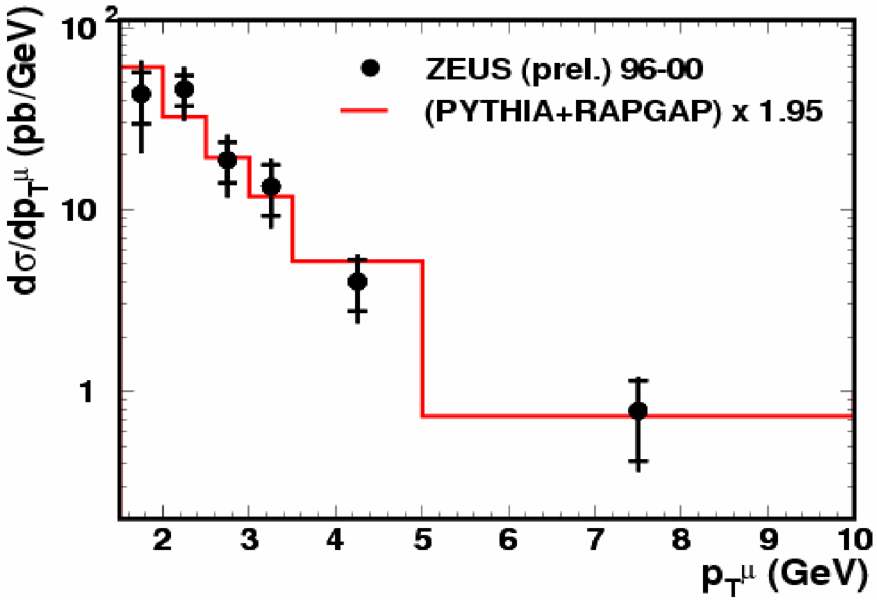
μ pairs: unlike-sign (non-isolated), all masses (low+high)

breakdown: MC agrees

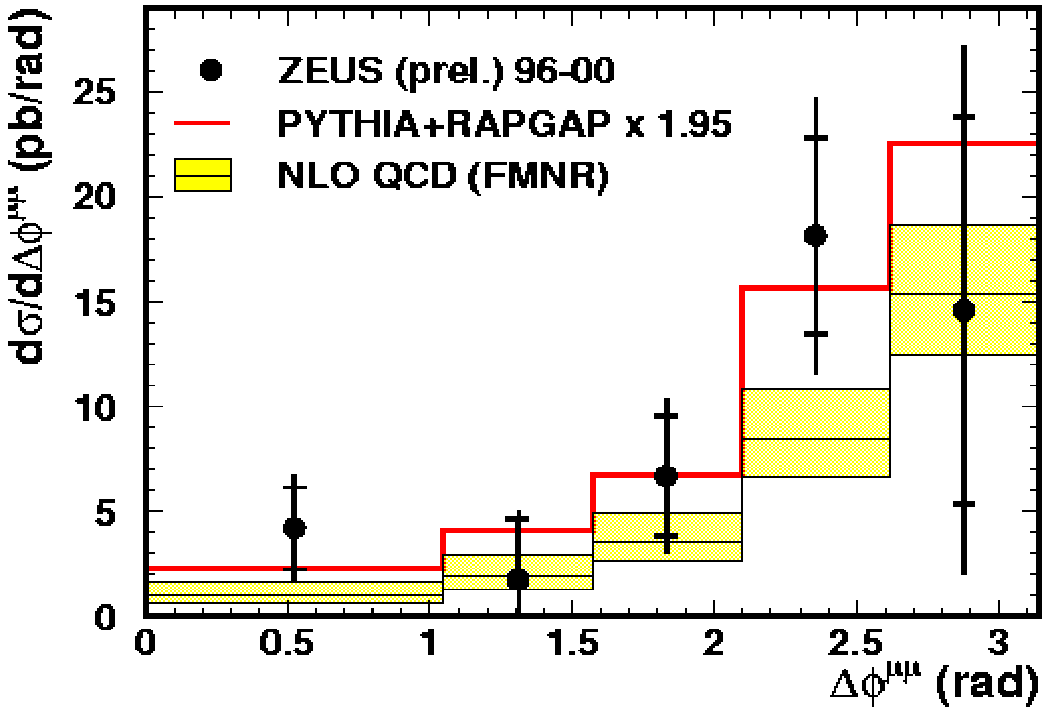
$\mu\mu$ correlations in γp + DIS : ZEUS

(For differential dσ: cuts on μ: $p_T>(\mu)>1.5$ GeV, $-2.2<\eta(\mu)<2.5$)





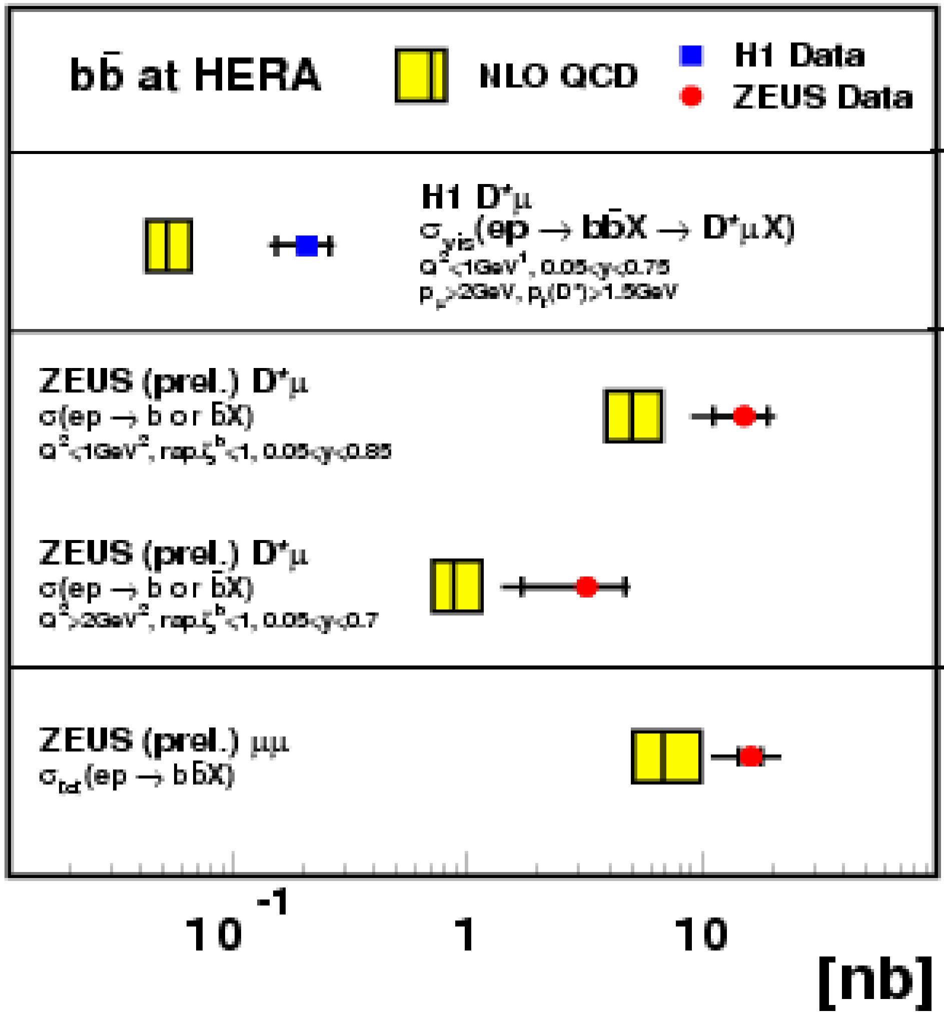
$M_{\mu\mu}$ >3.25 GeV leaves two μ's from different b's



LO: shapes agree, norm 2x too low

NLO: (FMNR) agrees within errors

Double tag : D*μ and μμ vs NLO : H1&ZEUS



D*μ H1 PHP (visible)

D*μ ZEUS PHP [η(b)<1, y]

D*μ ZEUS DIS [η(b)<1, y]

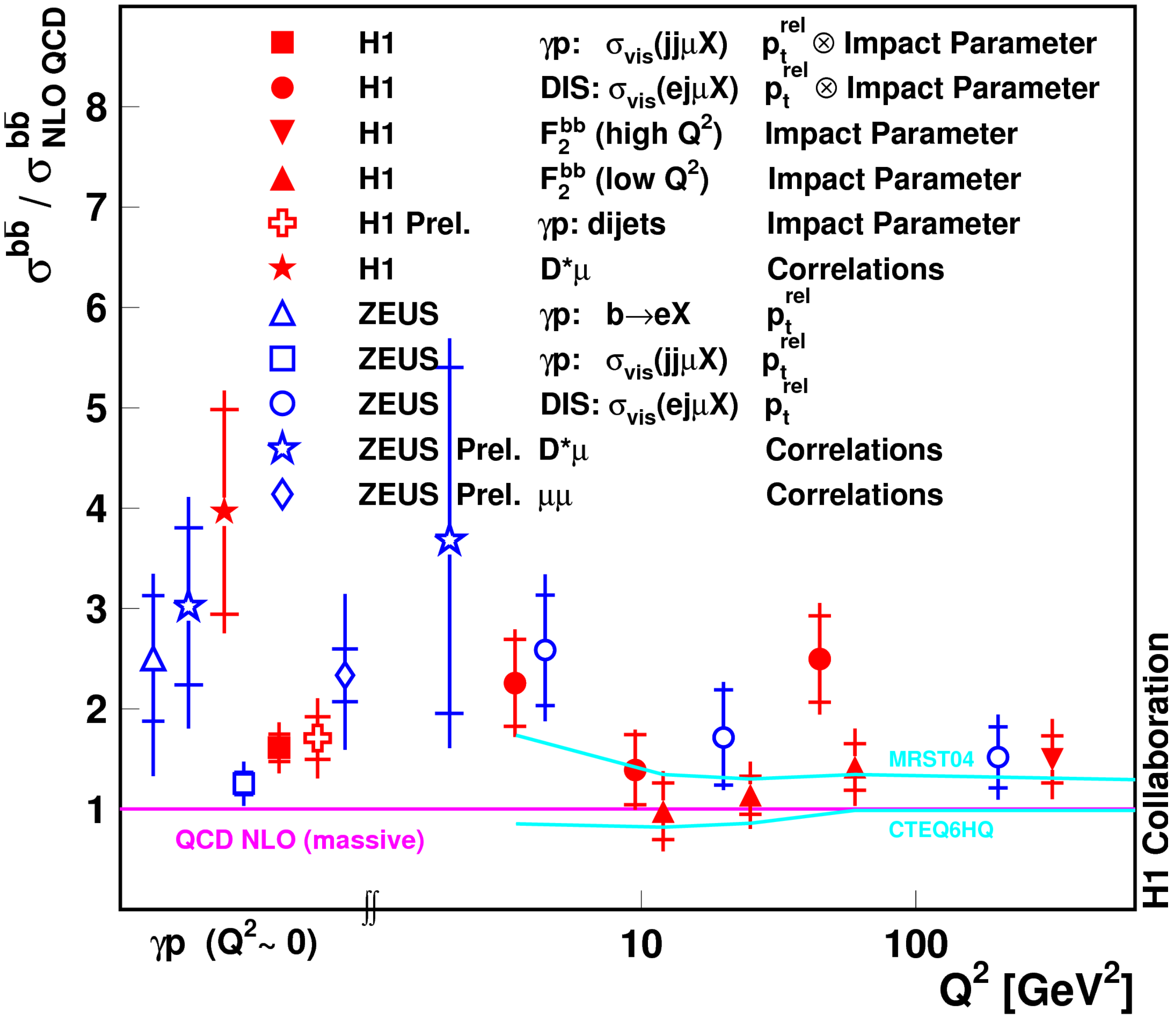
μμ ZEUS all Q^2 :
total inclusive [large b-phase space down to $p_t(b)\approx 0$]

NLO: normalisation still below data in ALL cases !

Comparison of various results with theory

B Production Cross Section Ratio: Data / NLO

- Comparison with pQCD NLO: **FMNR(γp) + HVQDIS (DIS)**



➔ **NLO predictions** are still below data…

… both in γp and DIS

To be settled in NLO:

- improve description of hadronisation
- resolved part is incomplete (no excitation graphs…)
- Possibly MC@NLO will help … ?

Summary

- Beauty with jets and muons : discrepancies dwindle away…
  - New measurements do not confirm the large excess seen earlier, BUT NLO predictions lie still below data, both in γp and DIS
  - Differential shapes deviate only in a few regions (low pt, forward η, low x_γ), seen in different measurements.

- Measurements with double tags D* -μ and μ-μ correlations :
  - statistically still limited
  - allow access to lower p_t and lower E_{cms}
  - exhibit effects of higher orders in shapes

- HERA-II : impressive first measurements …

With new HERA-II statistics, we hope to reach similar precision in b as we have in charm … ☺

Optional Slides

μ + jets : H1 selection + errors (opt)

- Select ≥1 muon with 2 CST-hits, with p_t>2.5 GeV, -0.55< η <1.1
- Select jets, using incl. k_T-algorithm
- Photoproduction: $Q^2 < 1$ GeV; $0.2 < y < 0.8$
  - ≥ 2 jets (in lab-frame) : p_t(jet)>7(6) GeV, | η |< 2.5
  - FMNR: m_b=4.75; CTEQ5M + GRVG-HO; eps=0.0033
    - variation: $\Delta\sigma$ (m_b+scale) = 25%; $\Delta\sigma$ (eps+-25%) < 3%; $\Delta\sigma$ (PDF) < 8%;
    - hadronisation corrections: -30% to +5%
- DIS: 2 < Q2 < 100 GeV ; 0.1 < y < 0.8 (e-Σ-method)
  - ≥ 1 jet (in Breit-frame) : p_t (jet)>6 GeV, | η |< 2.5
  - HVQDIS:
    - m_b=4.75; CTEQ5F4; eps=0.0033
    - variations: $\Delta\sigma$ (m_b+scale) = 15-20%;
- major sys.error: track/δ resolution = 7%; fragmentation uncertainty (Lund/Peter)=7%

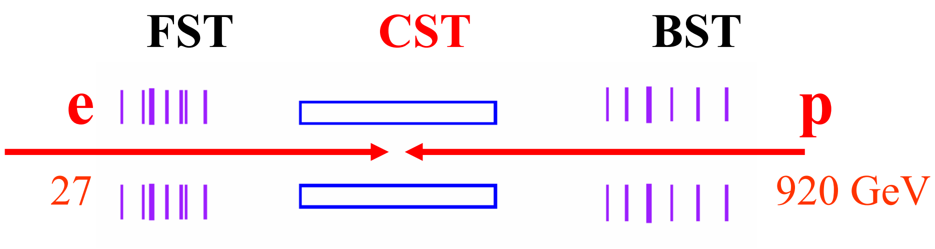
μ + jets : ZEUS selection + errors (opt)

- Select $\geq$1 muon with $p_t^{\mu}>2.5$ GeV in $-1.6<\eta_{\mu}<1.3$;

  $p_t^{\mu}>1.0$ GeV AND $p^{\mu}>4.0$ GeV in $1.48<\eta_{\mu}<2.3$

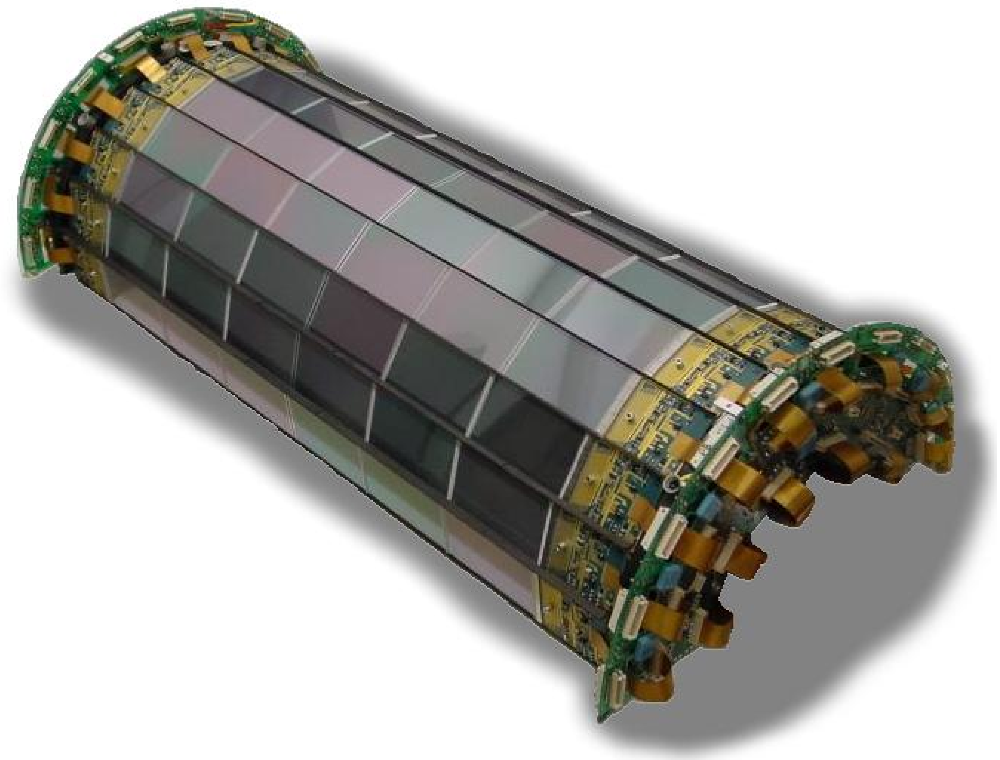
- Photoproduction: $Q^2 < 1$ GeV; $0.2 < y < 0.8$
  - $\geq$ 2 jets (in lab-frame) : p_t(jet)>7(6) GeV, $|\eta| < 2.5$
  - FMNR:
    - m_b=4.75; CTEQ5M + GRVG-HO; eps=0.0035
    - variation $\Delta\sigma$ (m_b+scale) = +34%/-22%; $\Delta\sigma$ (eps) < 3%; $\Delta\sigma$ (PDF) < 4%;
    - hadronisation corrections: -20% in rear-30% to -3% in fwd

H1 Vertex detector (opt)



Forward, Central and Backward Silicon Trackers

CST is used in this analysis:



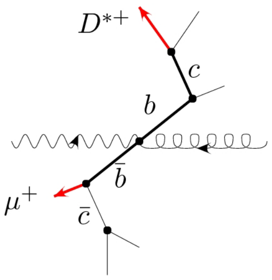
- Two layers, cylindrical (Hera-I) at 5.7 and 9.7 cm radii; double sided strips
- $30 < \theta < 150^o$ polar angles
- Hit resolution: 12 (25) μm in r-phi (z)
- Efficiency to link 2 CST-hits: 72%
- Tracks with 2 CST-hits:
- DCA-resolution= 33 +90/p_t [μm /GeV]
- Beamspot: 145 x 25 μm^2 measured with 5 μm accuracy

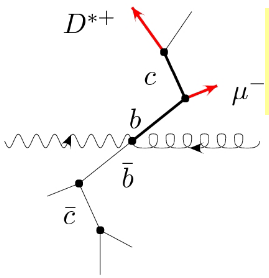
$D^*\mu$ correlations regions : (opt)

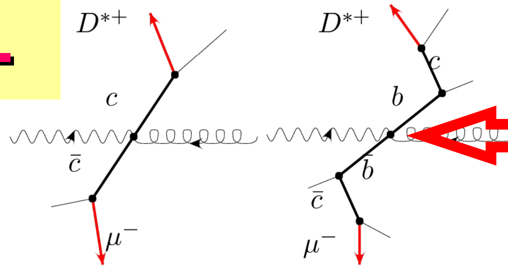
Exploit correlations: charges $Q(D^*,\mu)$ and azimuthal separation $\Delta\phi(D^*,\mu)$

u,d,s : dominate I
$\Delta\phi \approx 0^o$; $Q(D^*) = Q(\mu)$

	$\Delta\Phi < 90^\circ$	$\Delta\Phi > 90^\circ$
$Q(D^*) = Q(\mu)$	I ++ / --	II
	charm (%) 0.1 beauty (%) 3.8	0.1 20.4
$Q(D^*) \neq Q(\mu)$	III +-	IV
	charm (%) 6.0 beauty (%) 50.0	93.8 25.9







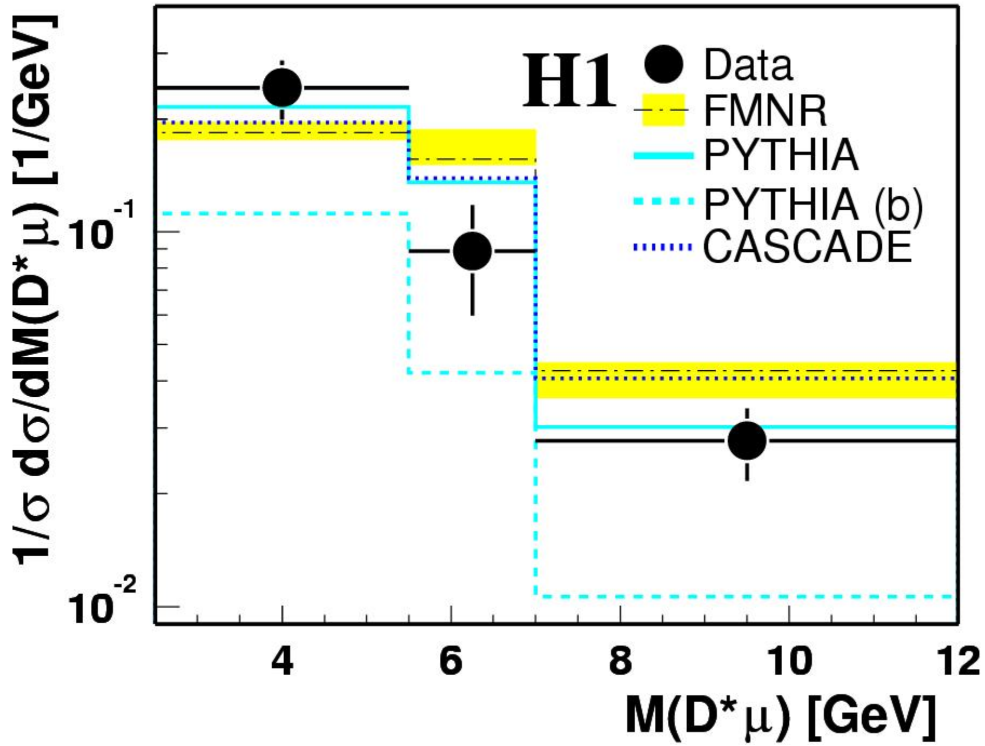
Beauty in regions II, II, IV :

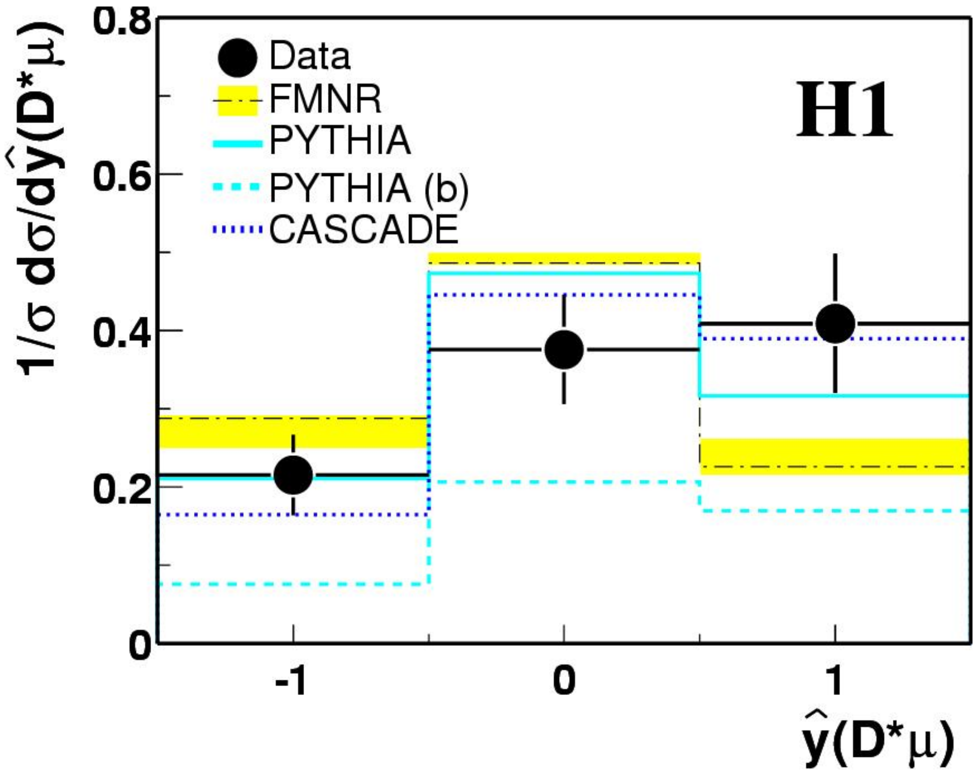
$\Delta\phi \approx 180^o$; $Q(D^*) = - Q(\mu)$ (IV)
$\Delta\phi \approx 180^o$; $Q(D^*) = + Q(\mu)$ (II)
$\Delta\phi \approx 0^o$; $Q(D^*) = - Q(\mu)$ (III)

Charm in region IV (mostly):

$\Delta\phi \approx 180^o$; $Q(D^*) = - Q(\mu)$
no c in like-sign regions

$D^*\mu$ correlations in γp : $\sigma_{c,b}^{vis}$ (opt)



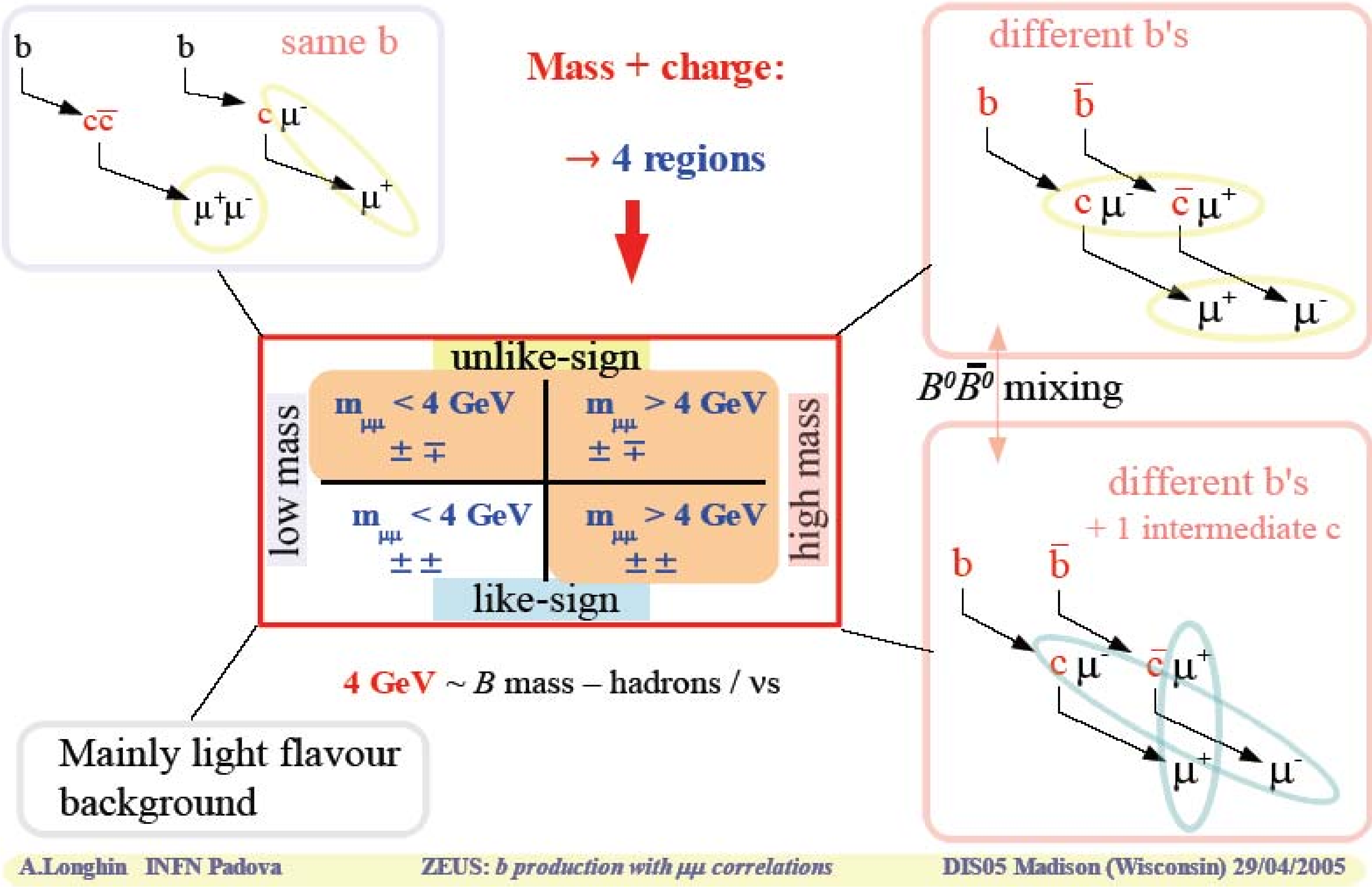


Cross sections in $D^*\mu$ variables :

- $M(D^*\mu)$: reflects E_{cm}(quark-pair)
- $y(D^*\mu)$: reflects E-ratio of quark-pair (from p or photon)

QCD : Reasonable description by both LO and NLO

μ–μ Correlations (opt)



$\mu\mu$ correlations : ZEUS selections (opt)

Selection to enhance beauty: in HERA-I data of L = 121 pb-1;

- E_T(all>10.deg - elec) > 8 GeV
- Muon: pt> 0.75/1.5 GeV in -2.2 < eta < 2.5
- Isolation cut: mu from b accompanied by hadrons are NOT isolated

  reduces J/psi, psi', Bethe-heitler di-muon production

Background reduction, (yields 40-50% b-purity):

- Open charm : MC-sample normalised to D*-μ data sample
- Light-flavour LF-BG:
  - Assume LF-BG is same in like-sign and unlike-sign data
  - like-sign high-mass has NO charm --> LF-BG = data – b-MC

Normalisation of signal: beauty

- Fix contributions of (charm+BH+J/psi+psi') and extract b-contributions from fit of unlike-sign data

Mu-Mu Correlations : ZEUS σ_{tot} numbers (opt)

Visible range: 1st μ: $p_t^\mu > 1.5$ GeV, $-2.2 < \eta_\mu < 2.5$
2nd μ: $p_t^\mu > 0.75$ GeV, $-2.2 < \eta_\mu < 2.5$ AND
$p^\mu > 1.8$ for $\eta_\mu < 0.6$ or $p^\mu > 1.8$ for $\eta_\mu > 0.6$

Prelim. visible cross section: $\sigma_{vis} = (44 \pm 5\ ^{+14.1}_{-12.3})$ pb
extrapolate (by 300x) to full p_t, η range of μ, all Q^2

Data ZEUS : $\sigma_{tot}(ep \rightarrow bbX) = (16.1 \pm 1.8\ ^{+5.3}_{-4.8})$ nb

- LO MC (Pythia 6.89 [$Q^2<1$] + Rapgap 0.92) = 7.81 nb
- NLO (FMNR 5.8 + HVQDIS 1.0) = (6.8 +3. -1.7) nb

→ LO and NLO well below data !

Main systematics of (+33% -30%): μ -efficiency, bg-subtraction, variation of pt-shape

References for new results (opt)

Region	Method	Collab	Reference	Published
Php + DIS	Incl. lifetime tag	H1	Prel. 04-173	
Php + DIS	D* - mu correlation	H1	DESY 05-040	
Php + DIS	Mu + jets	H1	DESY 05-004	
	Dijet, inclus.vtx	H1		
DIS	Impact param, F_2bb	H1	DESY 04-209	E.J.Phys. C40 (05) 349
Low Q2	Impact param, F_2bb	H1	DESY 05-110	
PHP	Mu + jets	ZEUS	DESY 03-212	
	Mu + jets; Hera-II MVTX	ZEUS	Prel- CHEP04	
	D* - mu correlation	ZEUS	Prel- EPS-03	
Php + DIS	Mu + mu correlation	ZEUS	Prel; Cont. DIS05	
DIS	Mu + jets; Q>2	ZEUS	DESY 04-070	PL B599 (04) 174