Low & High & Multiple Scales @ HERA

Günter Grindhammer
MPI für Physik, München

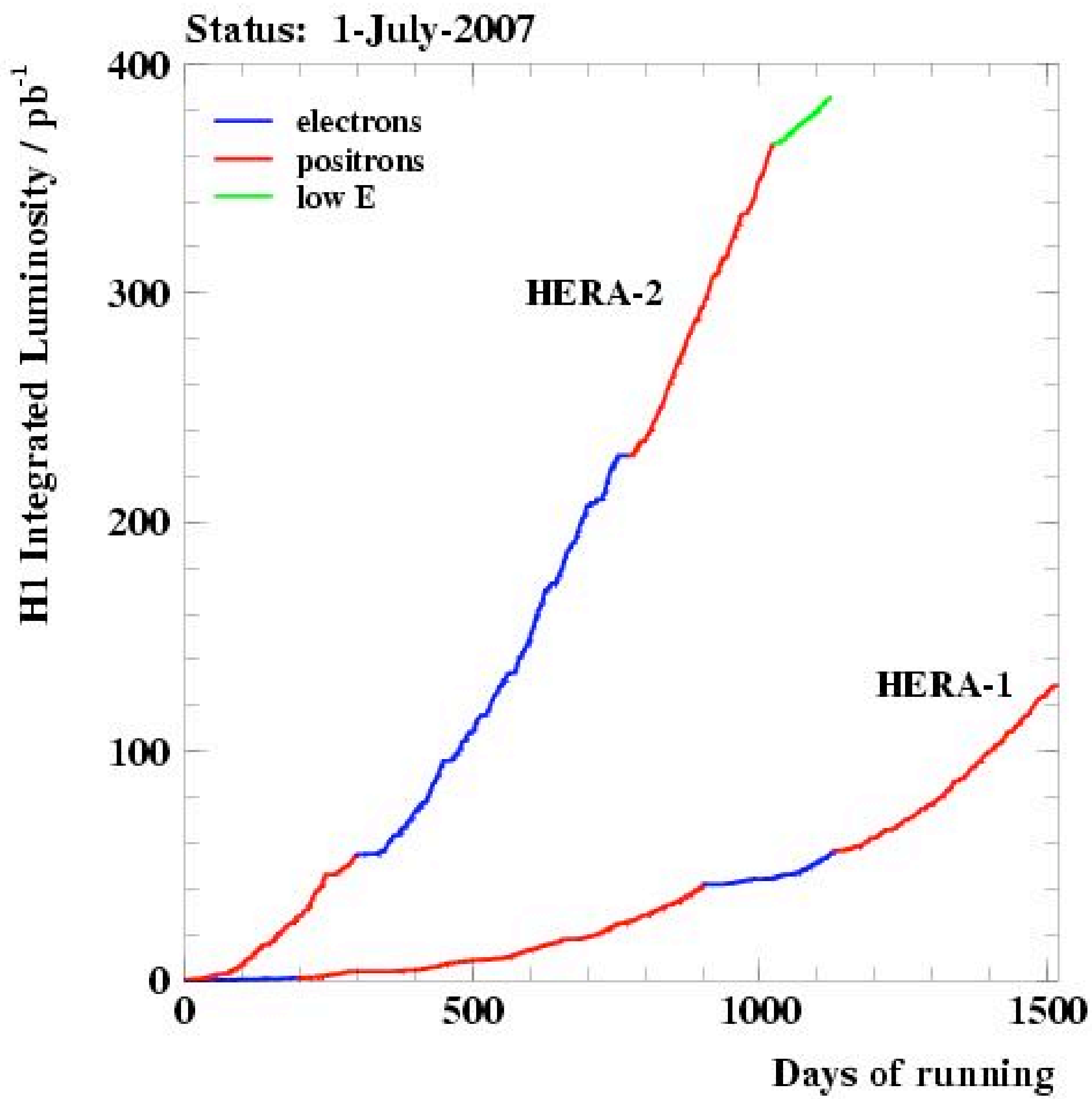
Photon 2009, Hamburg, May 11-14, 2009

on behalf of the H1 and ZEUS collaborations

Latest results on:

- underlying event in photoproduction
- most precise determinations of $\alpha_s(M_Z)$ from jets
- charm and beauty in deep-inelastic scattering

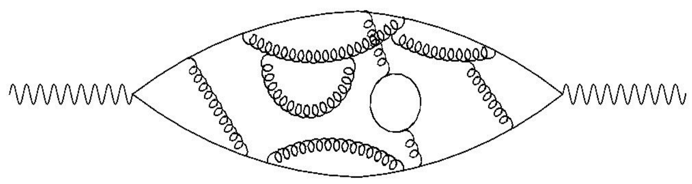
Available HERA Data



- 1992 - 2007
- 

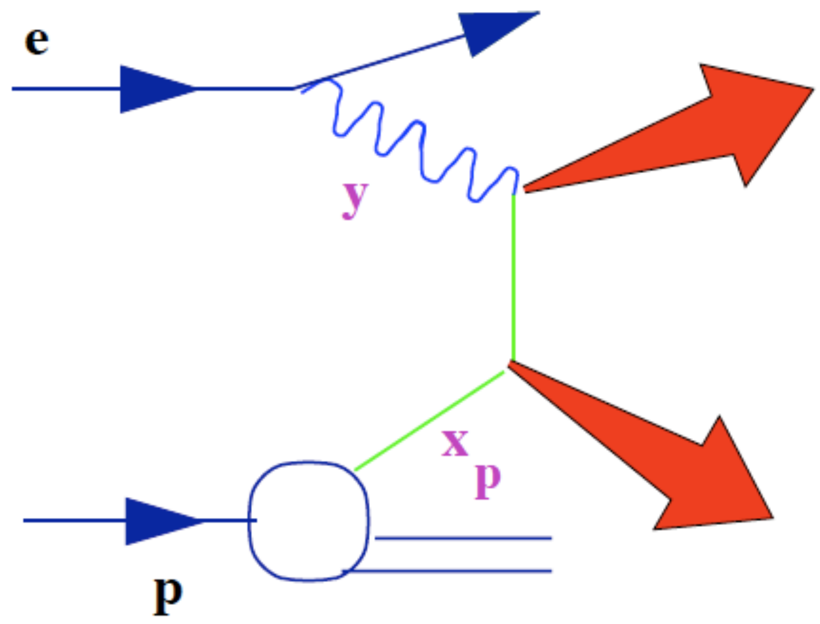
- 2001/2002 luminosity upgrade → HERA-2
- since HERA-2 both experiments are equipped with micro vertex detectors
- ~ 500 pb^{-1} of data collected per experiment

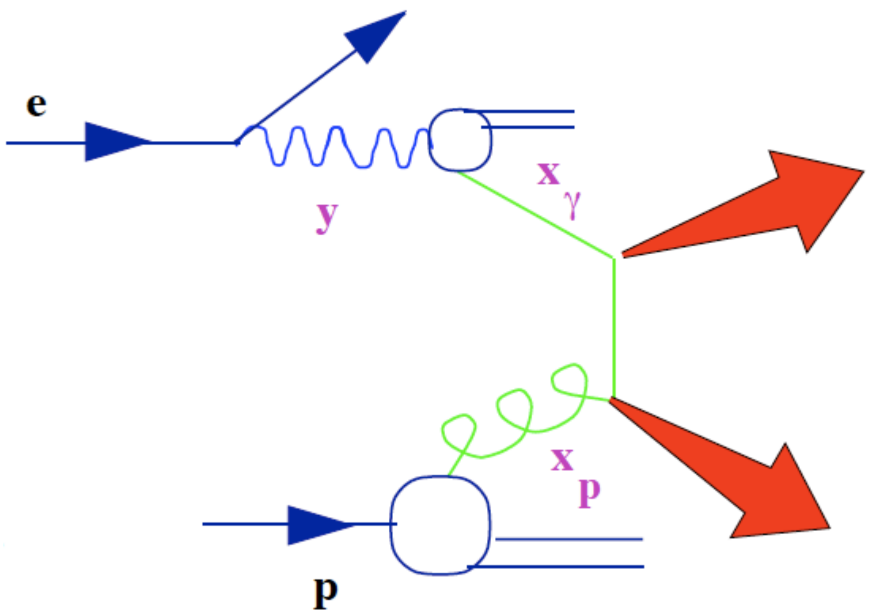
Resolved γ p & Underlying event



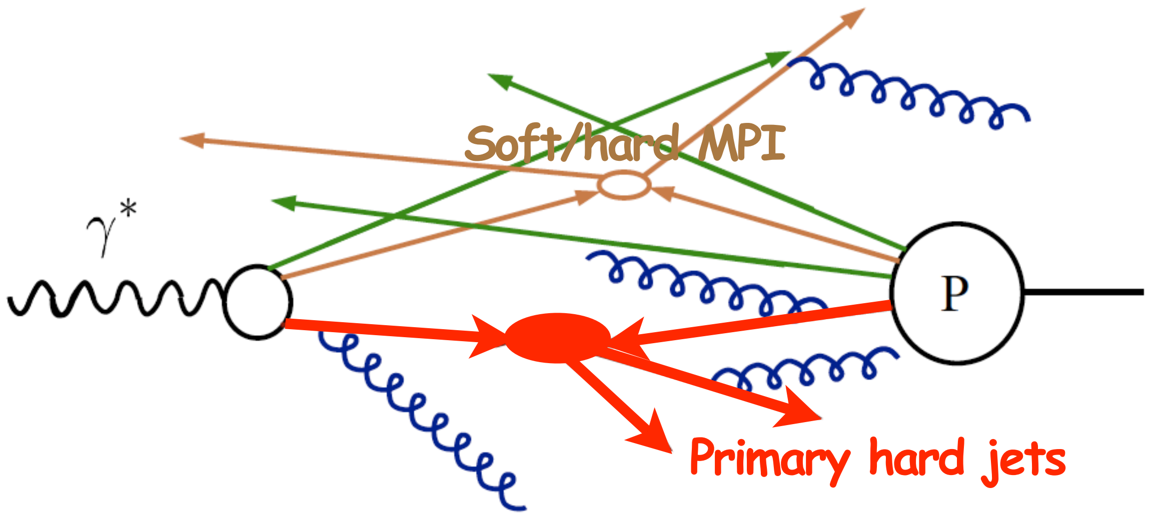
- the photon can fluctuate into partons
- thus, the photon has direct and resolved interactions with the proton (LO)
- the resolved photon allows remnant-remnant interactions
- at HERA, they can be switched "on" by studying events with x_γ < 0.7 or "off" for x_γ > 0.7

$$x_\gamma = \frac{E_{T,\mathrm{jet1}} \exp^{-\eta_{\mathrm{jet1}}} + E_{T,\mathrm{jet2}} \exp^{-\eta_{\mathrm{jet2}}}}{2yE_e}$$





Underlying event



it is a nuisance:

- jet energies are measured too large
- "resonance" peaks are shifted and smeared

it is of interest by itself:

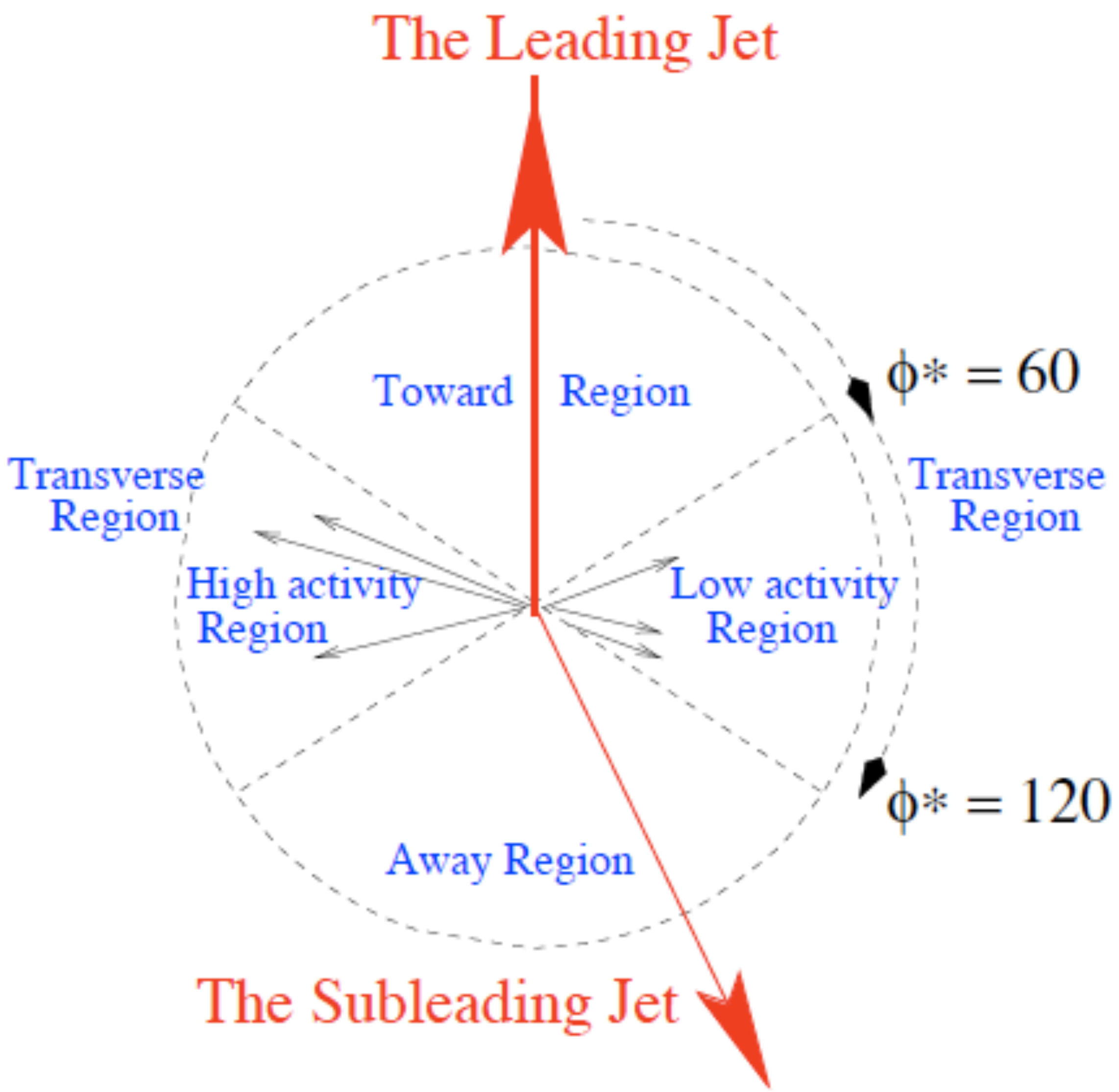
+ how can it be modeled?
+ understand beam remnants (color-connected to interacting partons)

- Primary hard parton-parton interaction ➜ hard dijets
- Underlying event (MPI)
  - additional "soft" interactions ➜ particle multiplicity
  - additional "hard" interactions ➜ jet multiplicity
- unfortunately, it also includes
  - higher order QCD corrections (e.g. parton showers)
  - effects of fragmentation
  - beam remnants

MPI study in PHP (H1)

H1-prelim-08-036

- a leading and a sub-leading jet with $P_T^{jet} > 5$ GeV and $|\eta^{jet}| < 1.5$
- charged particles with $P_T > 150$ MeV and $|\eta| < 1.5$
- two transverse regions:
  - high activity region with higher $P_T^{sum} = \sum_i P_{T,i}$ compared to the
  - low activity region



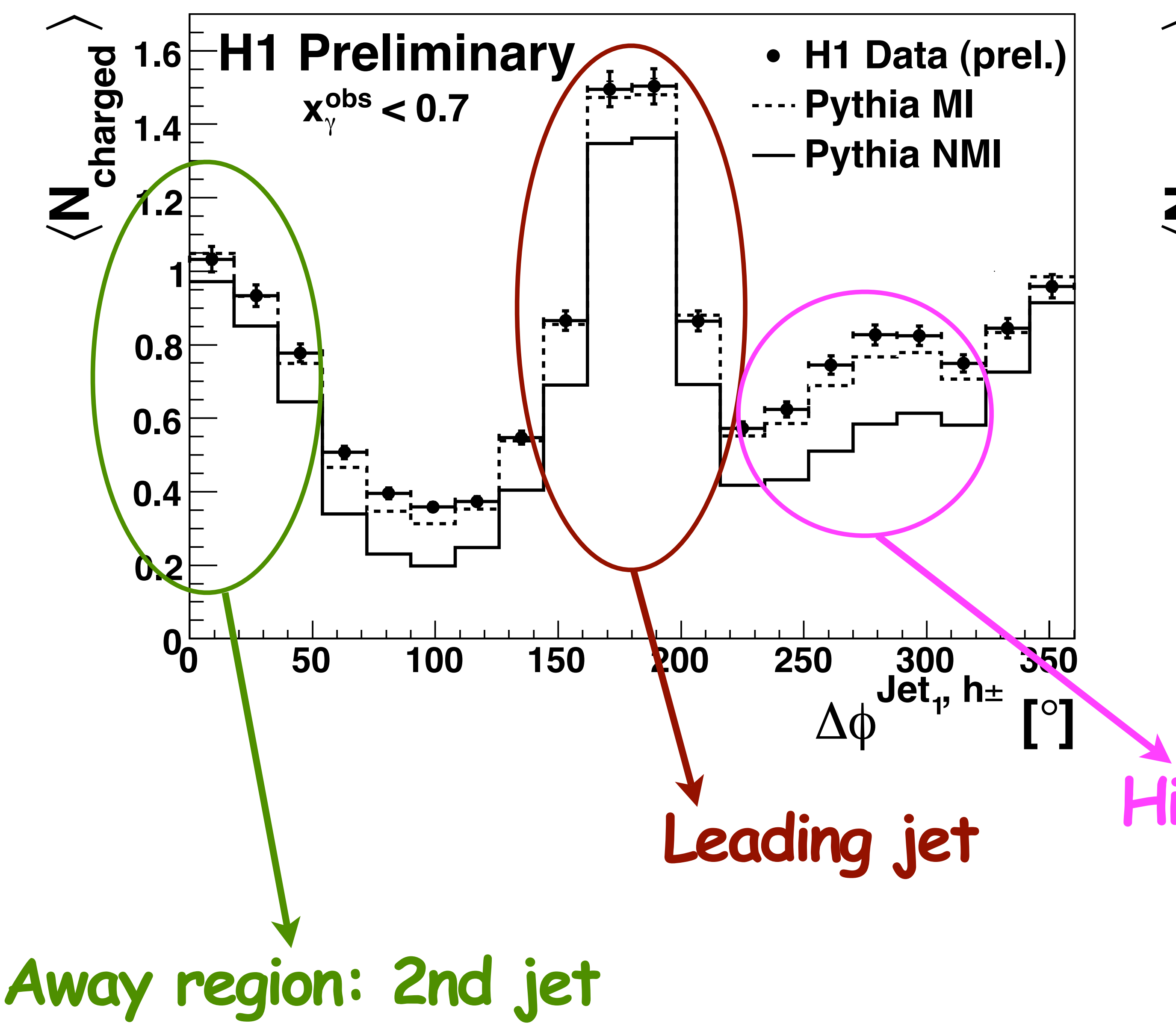
measure charged particle multiplicity in all regions
→ expect sensitivity to MPI in transverse regions

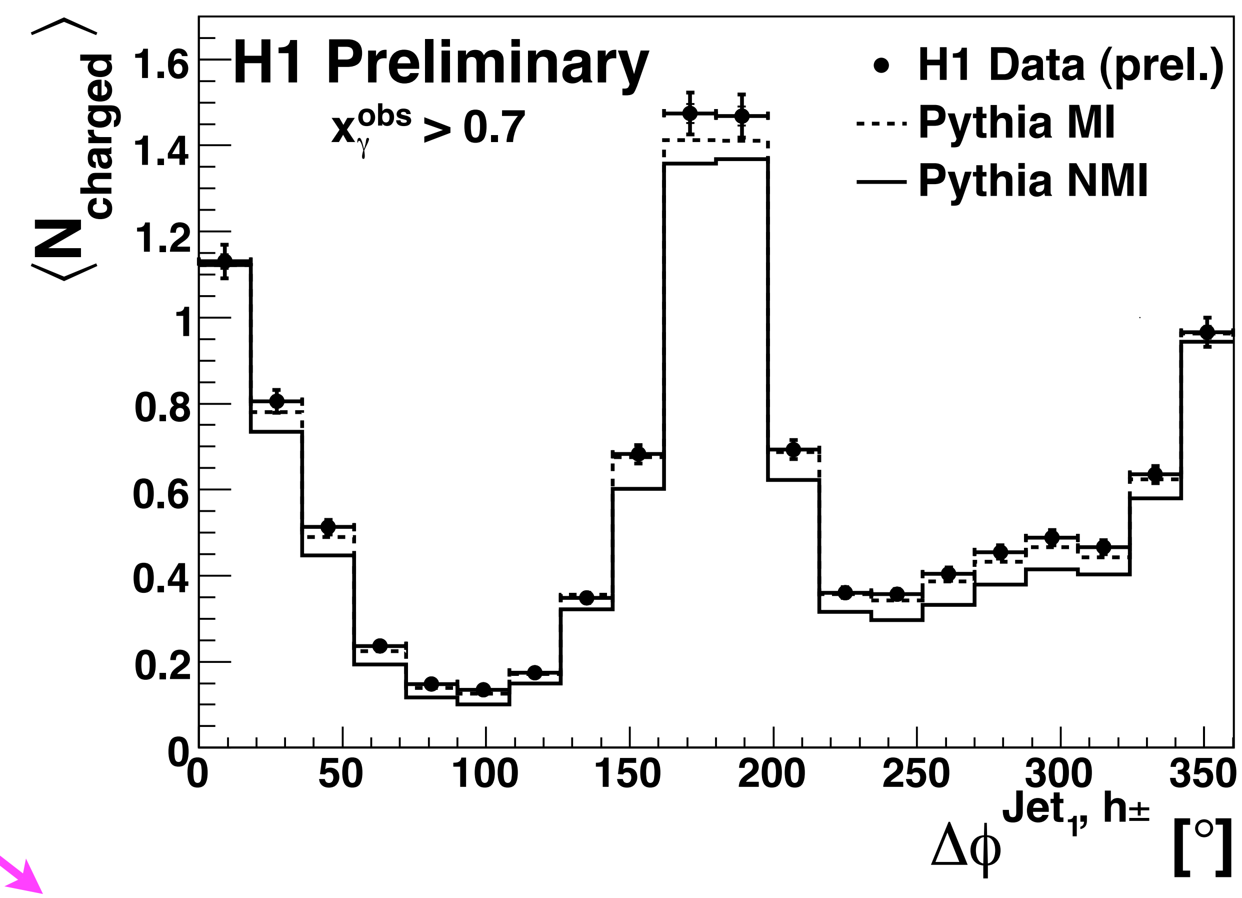
Charged particle multiplicity vs. $\Delta\Phi$

$\Delta\Phi$ ... angle between leading jet and charged particles

resolved photon enhanced

direct photon enhanced

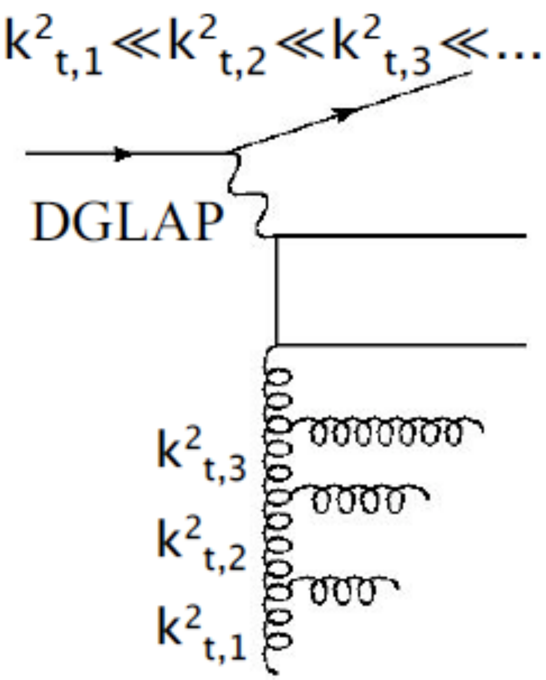




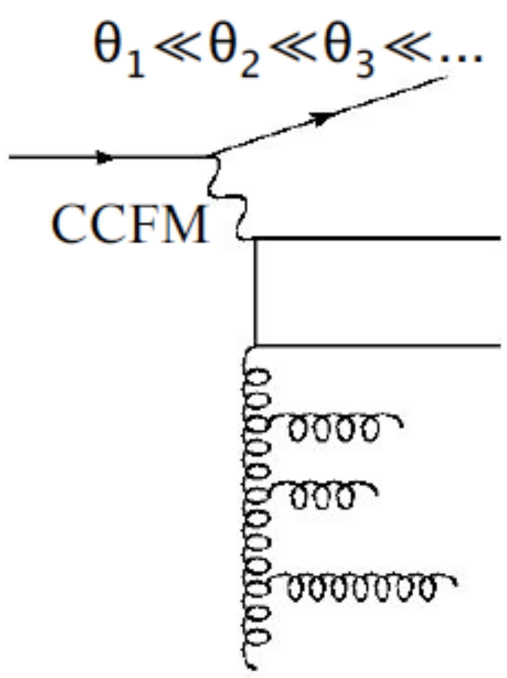
- Data described by Pythia only when MI included

QCD Models

- Pythia
  - direct+resolved processes in LO
  - matched DGLAP parton showers
  - with/without MPI (additional “semi-hard” interactions down to $P_{T,min}$ = 1.2 GeV)



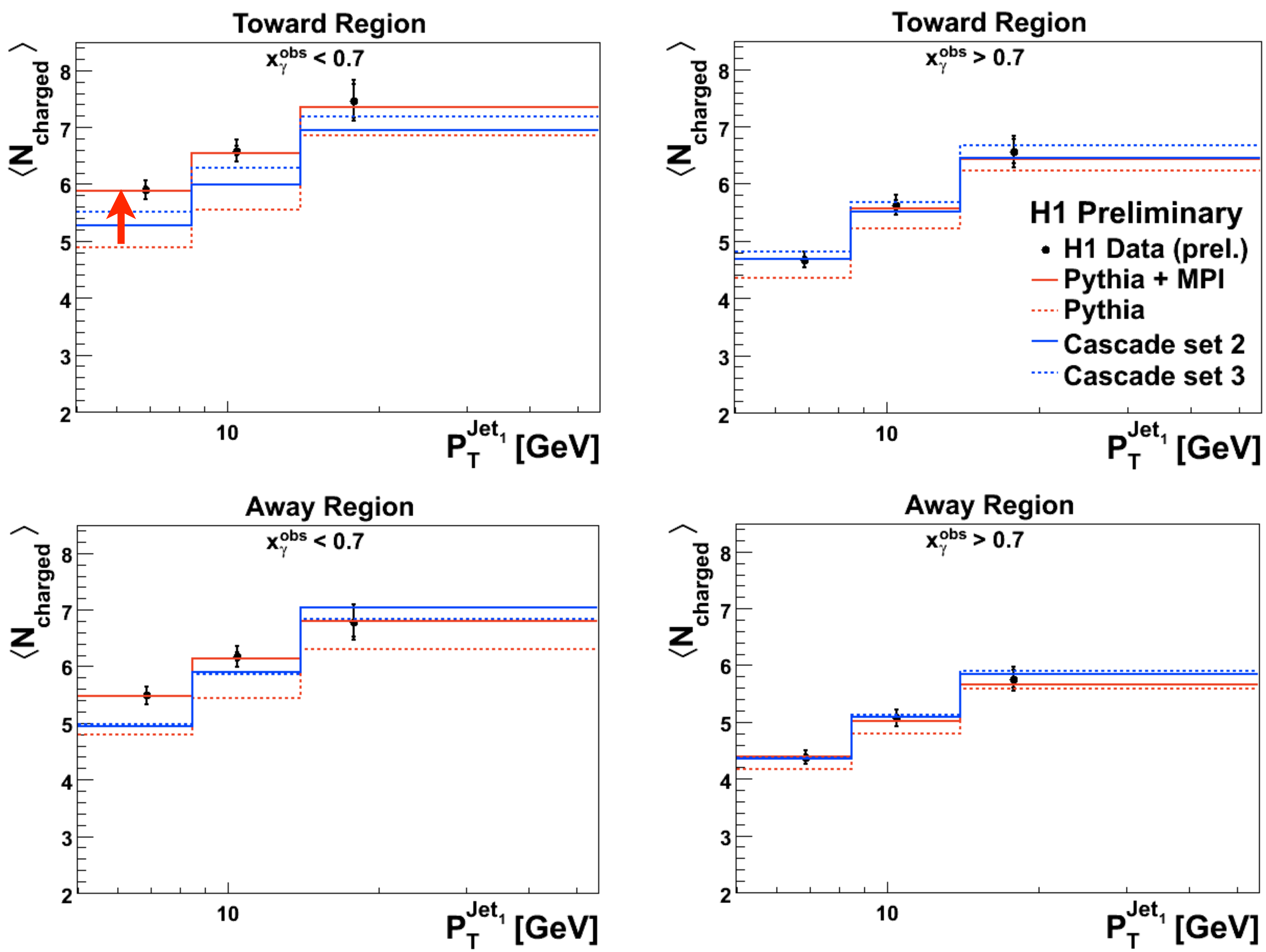
- Cascade
  - off-shell LO ME for direct processes
  - matched with CCFM parton showers
  - k_t un-integrated gluon densities (set1 & set2)
  - no resolved photon, no MPI



⟨$N_{charged}$⟩ in Toward and Away region

MPI in Pythia contribute more at low P_T^{jet1}

Cascade without MPI not too bad

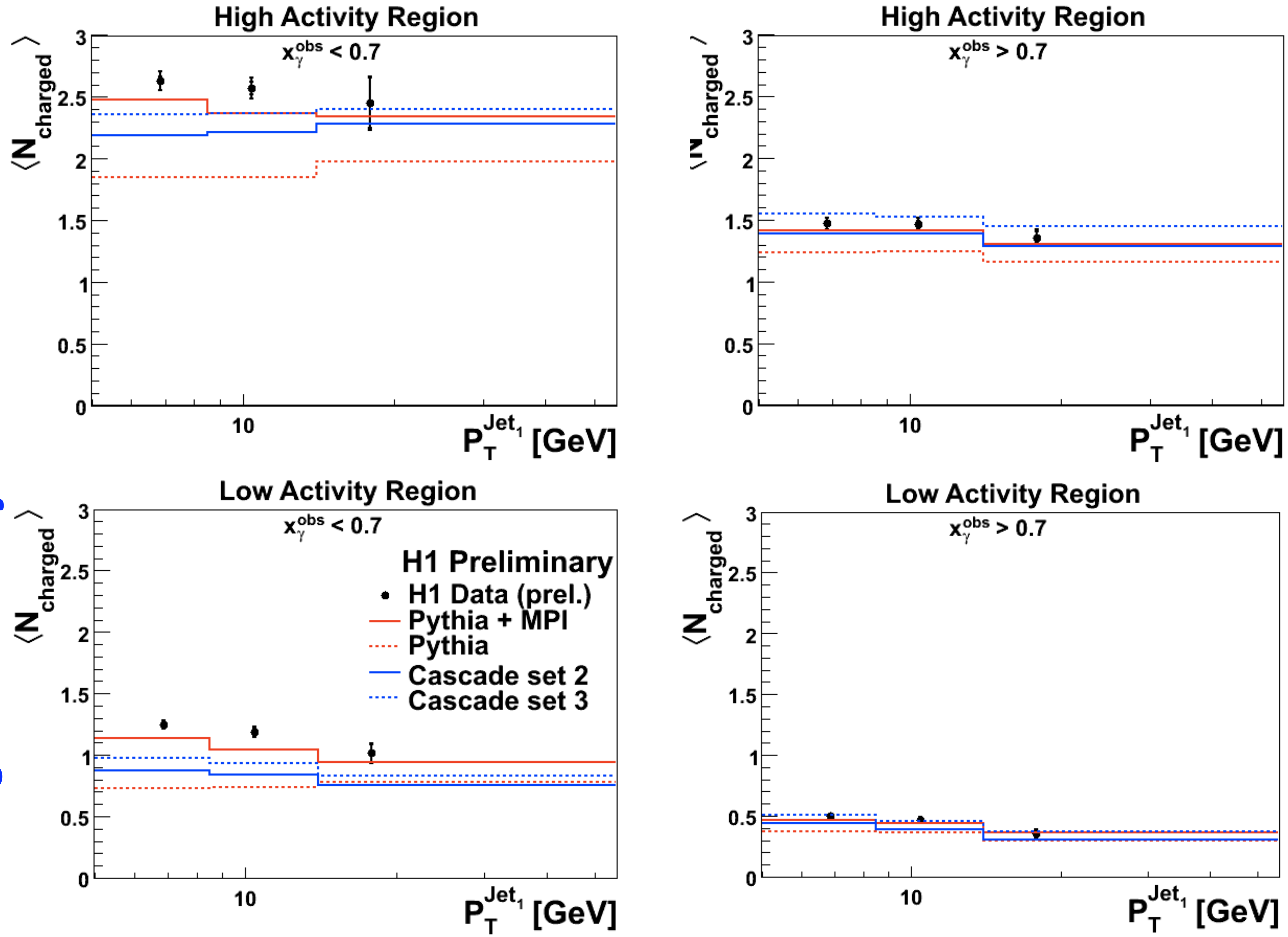


models are similar at high x_γ

⟨$N_{charged}$⟩ in transverse regions

Pythia + MPI provides reasonable description of the data

Cascade fails for resolved enhanced events, but is above Pythia w/o MPI



Pythia+MPI and Cascade are similar at high x_γ

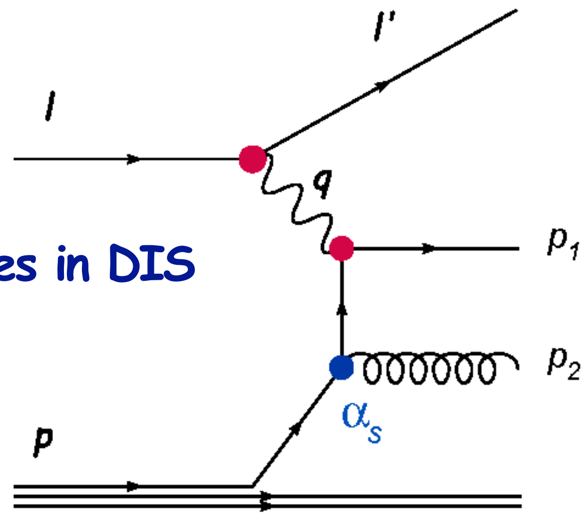
Underlying event in γ p

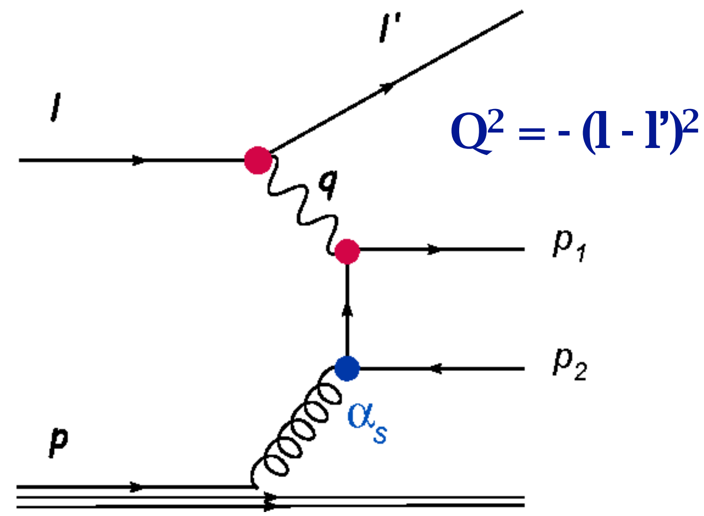
- for <charged particle multiplicities> Pythia + MPI provides a reasonable description of the data
- interestingly, Cascade (no MPI) is only somewhat worse in describing the data, signicantly better than Pythia w/o MPI.
- further studies are needed

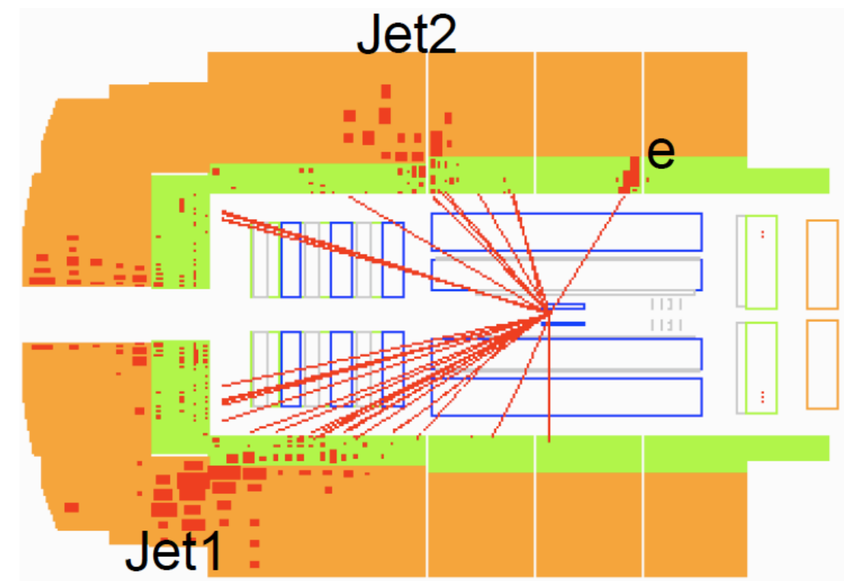
High scales: jet prod. in DIS & PHP

in DIS, 2 high scales: Q^2 & $(P_T^{jet})^2$ ➜ $(Q^2 + (P_T^{jet})^2)/2$ or $(P_T^{jet})^2$

direct processes in DIS

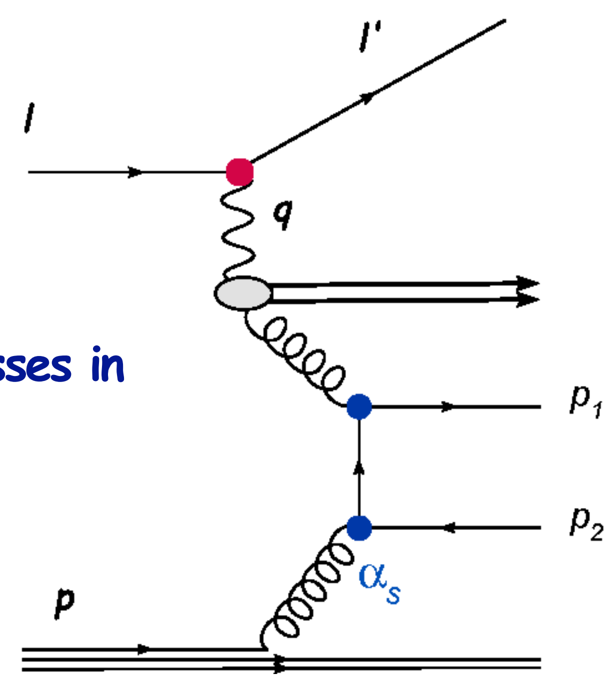


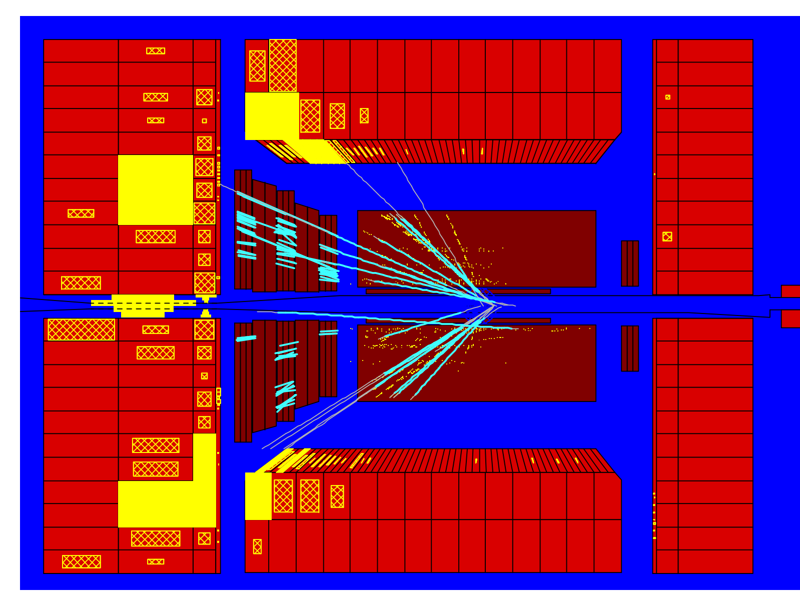




in PHP, 1 high scale: $(P_T^{jet})^2$

+ resolved processes in PHP





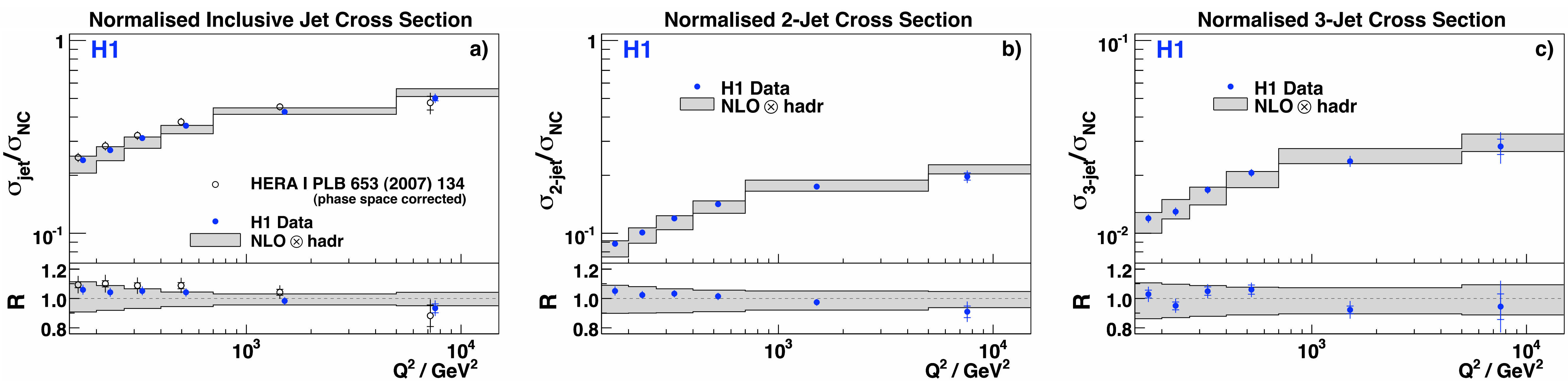
Jet multiplicities in DIS from H1

- data sample 1999-2007: 395 pb-1, $150 < Q^2 < 15000\ \mathrm{GeV}^2$
- exp. errors reduced by measuring jet multiplicties (N_{jets}/N_{NC})
- hadronic energy scale uncertainty ≤ 1.5% is dominant exp. uncertai

$P_T^{\mathrm{jet}} > 7\ \mathrm{GeV}$
$-0.8 < \eta_{\mathrm{jet}} < 2.0$

$P_T^{\mathrm{jet1,\,jet2}} > 5\ \mathrm{GeV} \quad M_{12} > 16\ \mathrm{GeV}$
$-0.8 < \eta_{\mathrm{jet}} < 2.0$

$P_T^{\mathrm{jet1,\,jet2,\,jet3}} > 5\ \mathrm{GeV} \quad M_{12} > 16\ \mathrm{GeV}$
$-0.8 < \eta_{\mathrm{jet}} < 2.0$



- data are well described by NLO QCD (NLOJET++) using CTEQ 6.5M &

$$\mu_r = \sqrt{(Q^2 + P_T^2)/2} \text{ and } \mu_f = Q$$

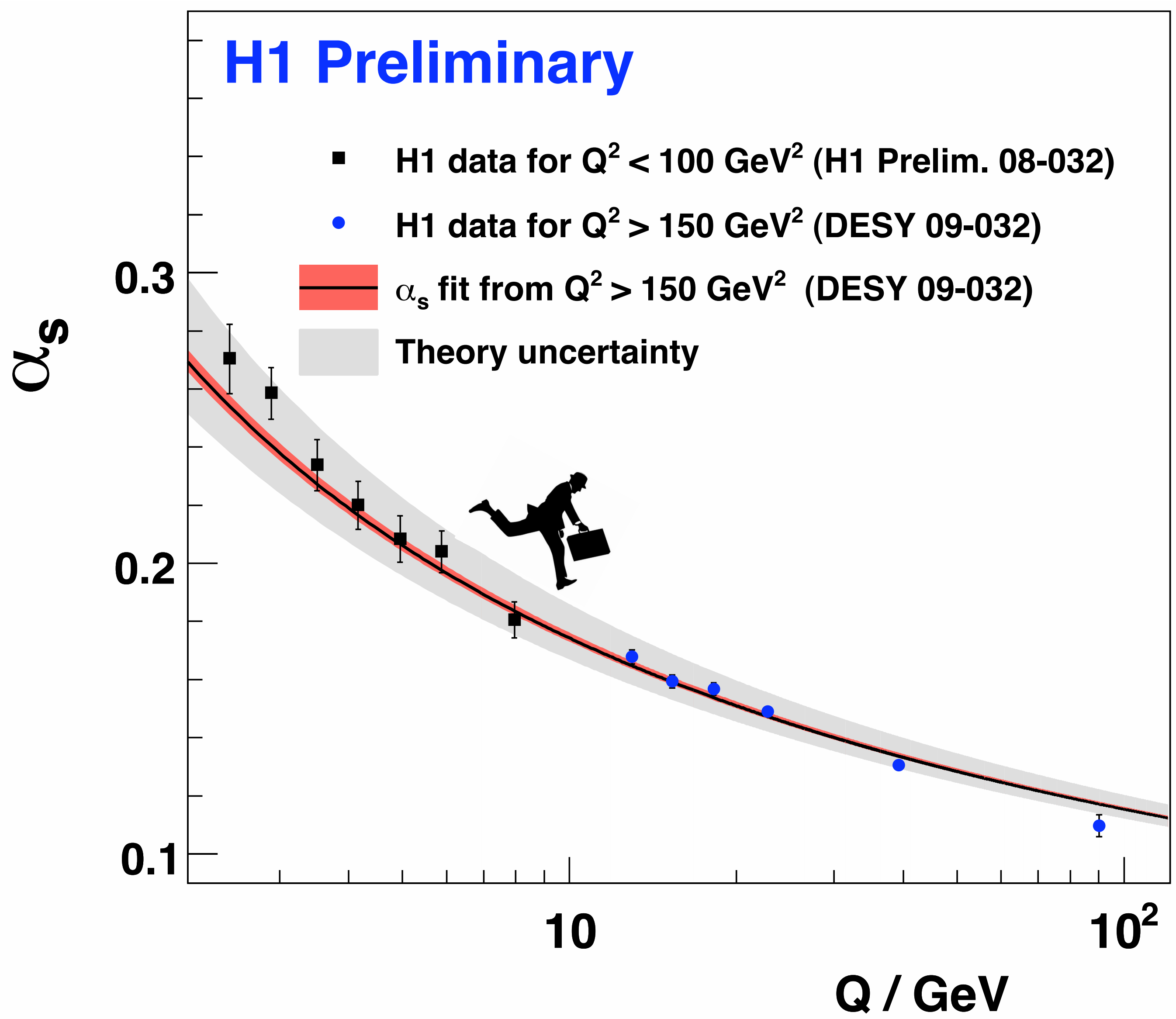
α_s from jets in DIS (H1)

- H1 has measured jet multiplicities for incl. and dijets as a function of Q^2 and $E_{T,jet}$ and as a function of Q^2 for trijets

DESY 09-032, arXiv:0904.3870

- Result of simultaneous fit: Q^2 > 150 GeV^2

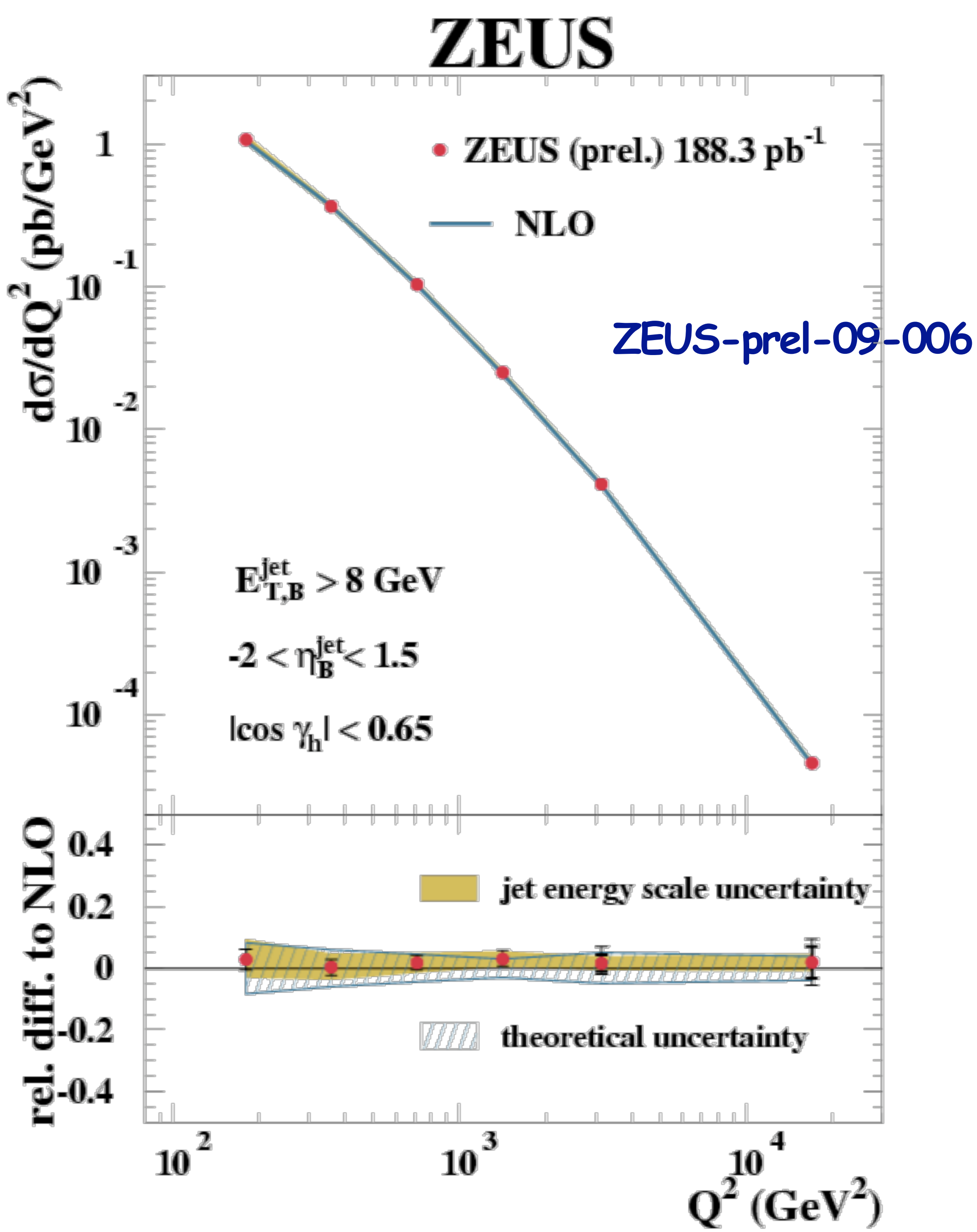
$$\alpha_s(M_Z) = 0.1168 \pm 0.0007(\text{exp})\,^{+0.0046}_{-0.0030}(\text{theory}) \pm 0.0016(\text{pdfs})$$



0.6% exp. and 3.6% total error

- the low Q^2 α_s values are consistent with the extrapolation of the fit to the high Q2 data
- they lie within the theory uncertainty of the high Q^2 fit

α_s from jets in DIS (ZEUS)



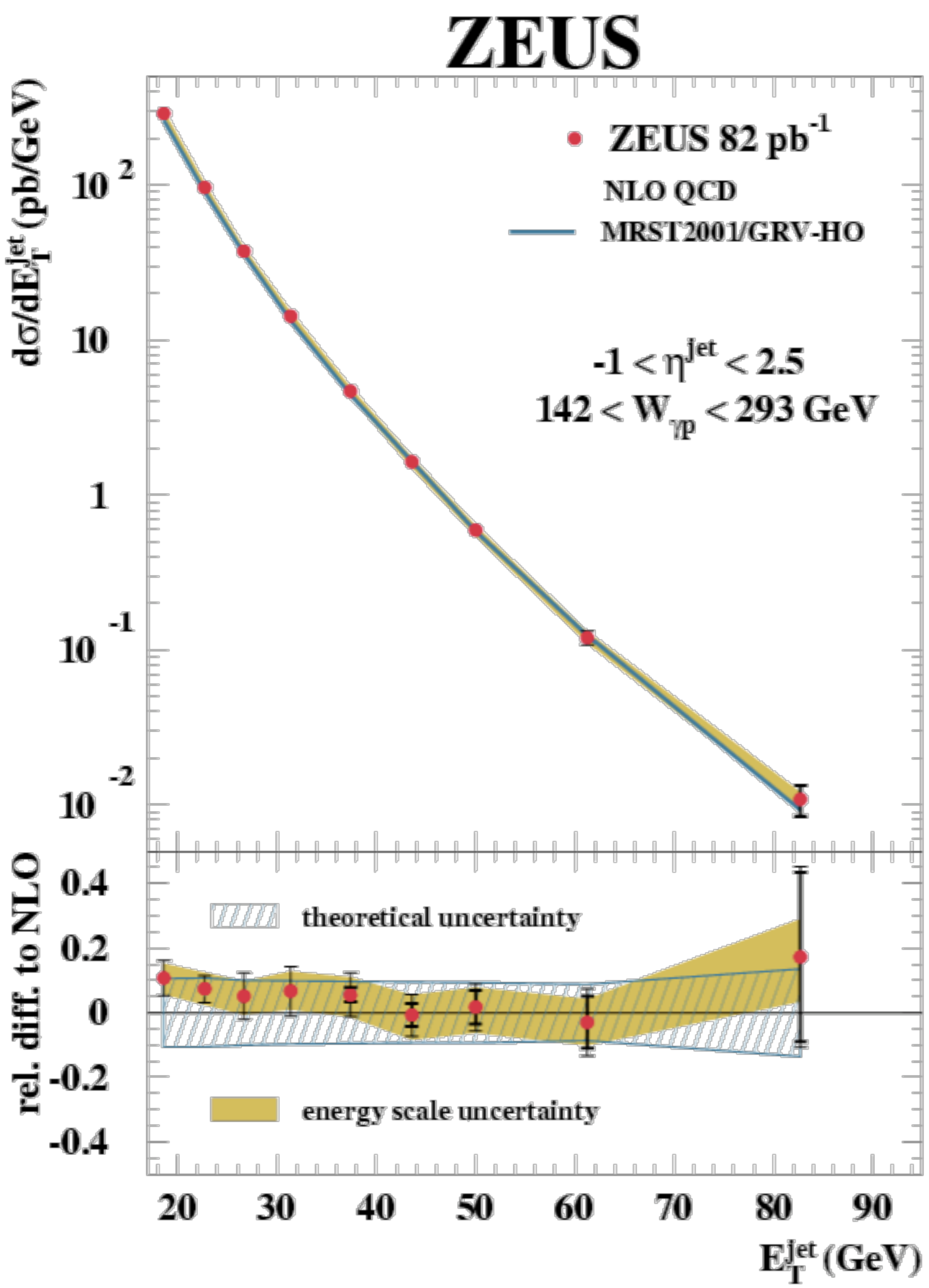
- new prel. measurement of the incl. jet cross section in NC DIS from HERA-2 (188 pb^{-1})
- hadronic energy scale uncertainty ≤ 1.9% is dominant exp. uncertainty
- data are well described by NLO QCD (DISENT) using ZEUS_S PDFs and $\mu_r = E_T^{Breit}$ and $\mu_f = Q$
- NLO uncertainty estimated using method by Jones et al.

smallest total uncertainty obtained by fitting data for $Q^2 > 500$ GeV^2

$$\alpha_s(M_Z) = 0.1192 \pm 0.0009(\text{stat})\,^{+0.0035}_{-0.0032}(\text{exp})\,^{+0.0020}_{-0.0021}(\text{th})$$

2.9% stat+exp and 3.5% total error

α_s from jets in PHP (ZEUS)



- α_s from reanalysis of incl. jets in PHP, HERA-1, 82 pb-1, Phys. Lett. B560 (2003) 7
- hadronic energy scale uncertainty ≤ 1.5% is dominant exp. uncertainty
- NLO QCD (KKK), PDFs: MRST01 & GRV-HO, $\mu_r = \mu_f = E_T^{jet}$
- had. corr. and PDF uncertainty reduced; now NLO uncertainty estimated using method by Jones et al.

Previous result:

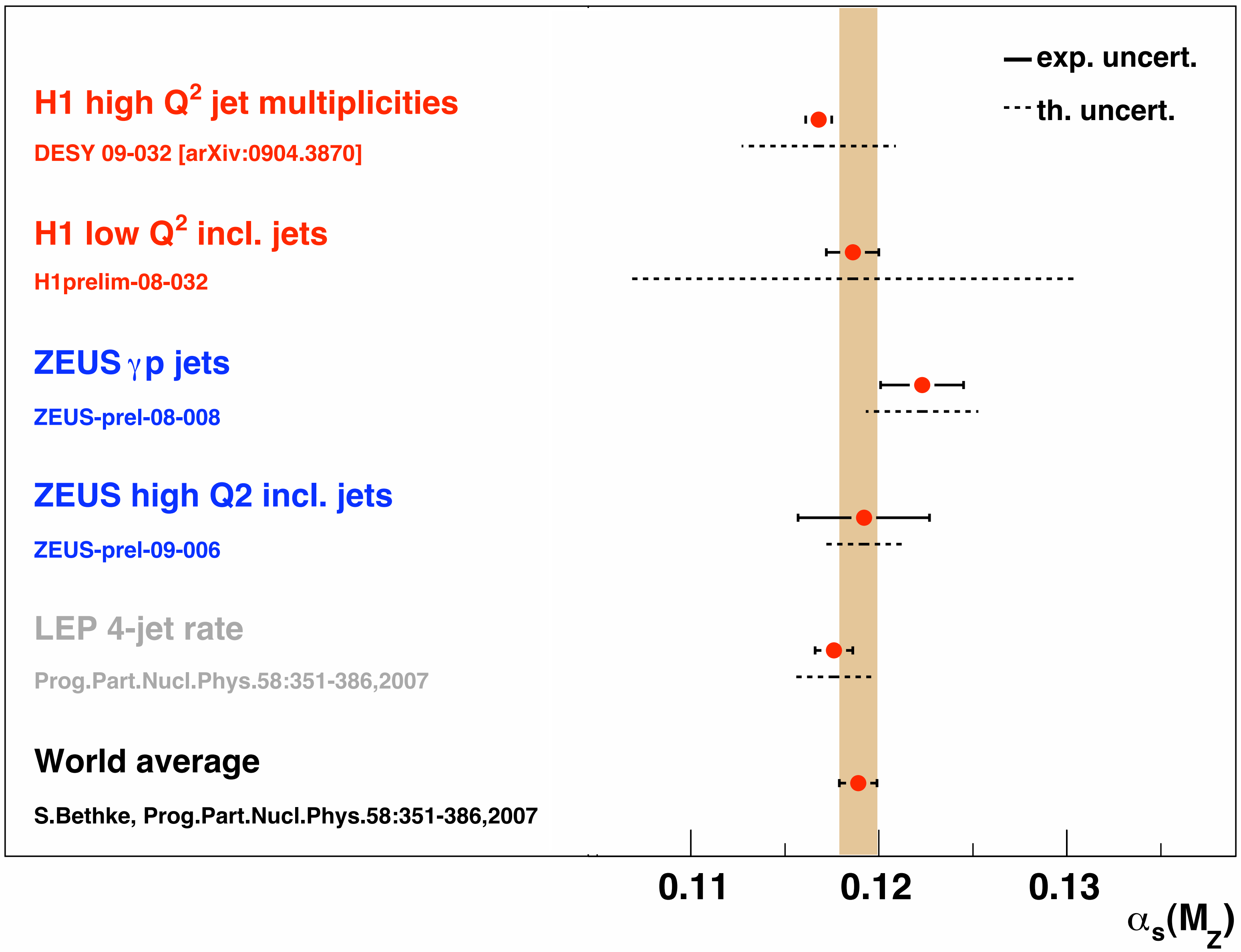
$$\alpha_s(M_Z) = 0.1224 \pm 0.0001(\text{stat})\,^{+0.0022}_{-0.0019}(\text{exp})\,^{+0.0054}_{-0.0042}(\text{th})$$

$$\alpha_s(M_Z) = 0.1223 \pm 0.0001(\text{stat})\,^{+0.0023}_{-0.0021}(\text{exp})\,^{+0.0029}_{-0.0030}(\text{th})$$

ZEUS-prel-08-008

1.8% exp and 3.1% total error

Summary of $\alpha_s(M_Z)$

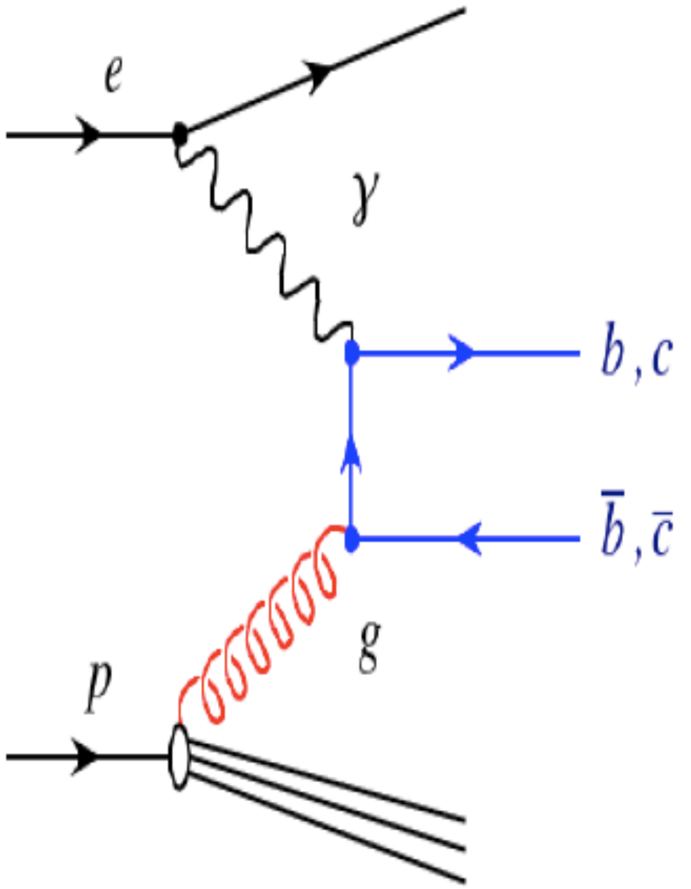


- new precise & consistent $\alpha_s(M_Z)$ extractions in γp and NC DIS
- compatible with LEP and the world average
- high exp. precision (0.6 to 3%)
- error dominated by NLO uncertainty

still further improvements expected: hadronic calibration, more data to be analyzed, final combinations of H1 & ZEUS data, and NNLO calculations

Multiple scales & Heavy flavors

- mainly produced via boson gluon fusion in DIS
- multiple scale problem in QCD
  - M^2, P_T^2, Q^2
- direct sensitivity to the gluon density
- fraction of charm in total NC DIS is large (up to ~30%)
- beauty fraction is small (up to ~1%)
- mass thresholds are visible



focus on beauty because of heavy mass (~4.5 GeV)

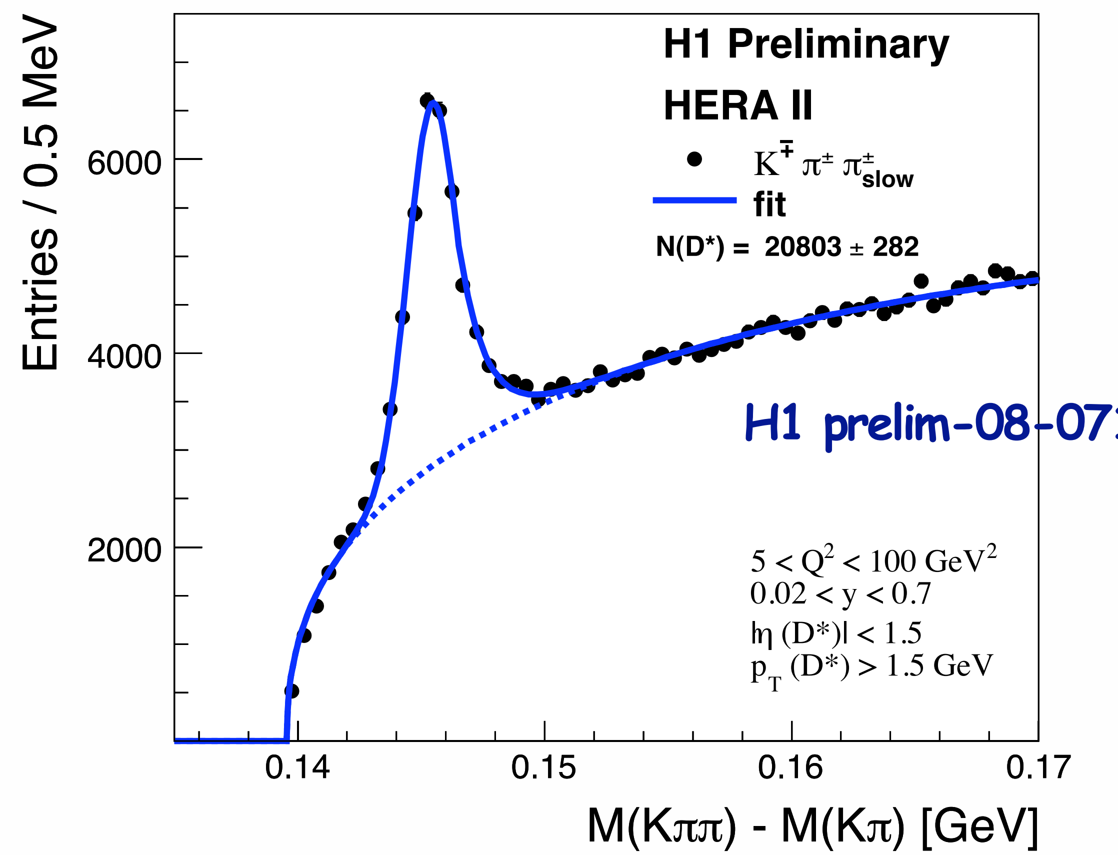
$b\bar{b} \longrightarrow$ Higgs !

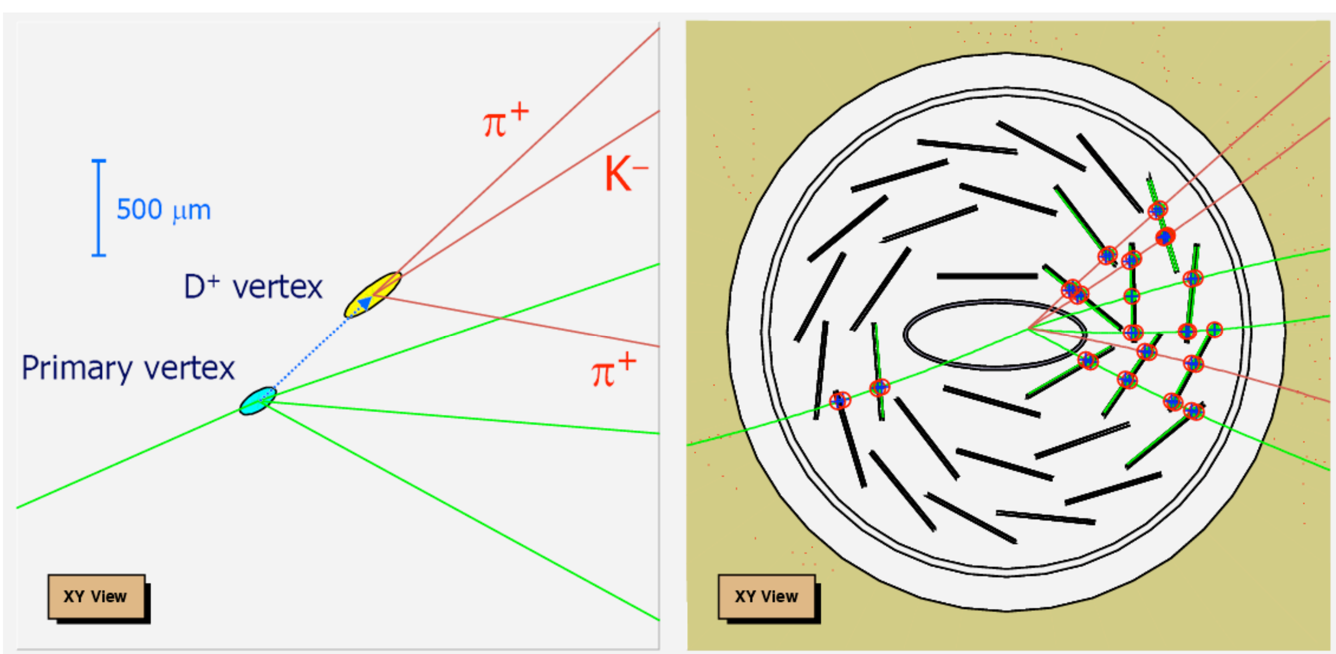
QCD calculations for HF production

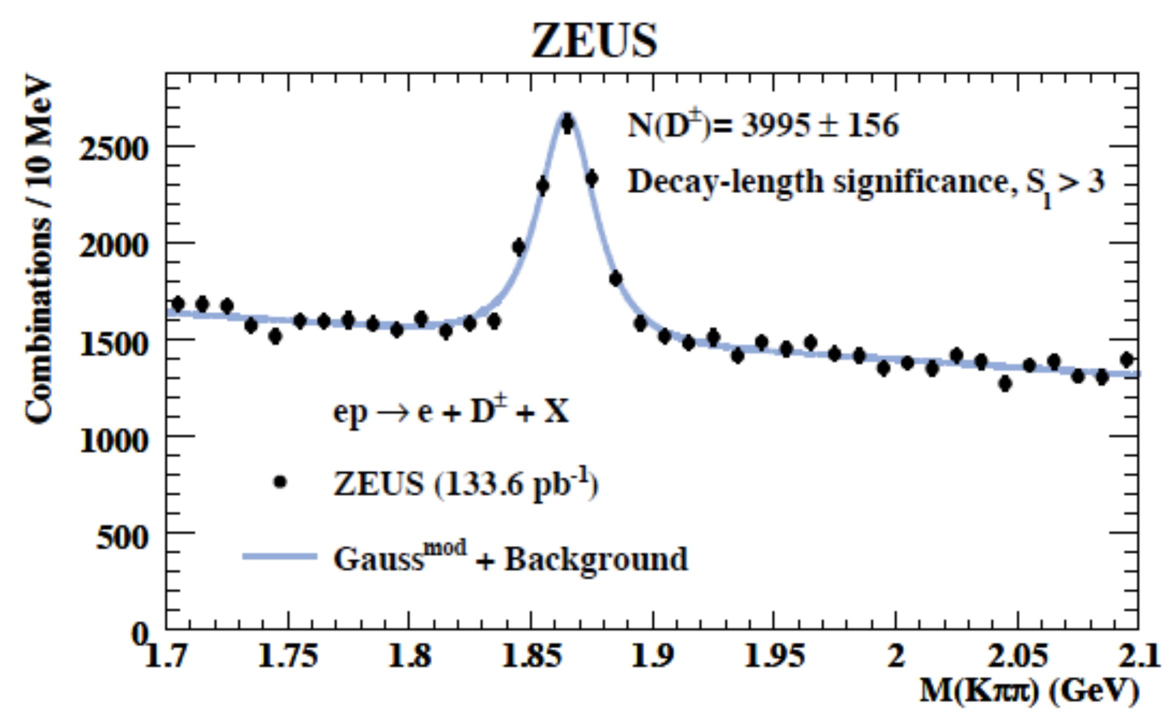
- Due to the multi-scale problem a number of approaches exist:
  - "massless" (ZM-VFNS) → $Q^2 >> M^2$, resums $\alpha_s \ln Q^2/M^2$, c and b exist in the proton
  - "massive" (FFNS) → $Q^2 \sim M^2$, neglects $\alpha_s \ln Q^2/M^2$, c and b are only produced dynamically; HVQDIS and FMNR NLO programs
  - GM-VFNS → combination of massless and massive schemes; it is used in the latest global PDF fits; CTEQ 6.6 NLO, MSTW08NLO, MSTW08NNLO,

Tagging heavy quarks (c)

- reconstructing charm mesons: D^*, D^+, D^0, …
- charm mesons and measuring decay length using micro vertex detectors





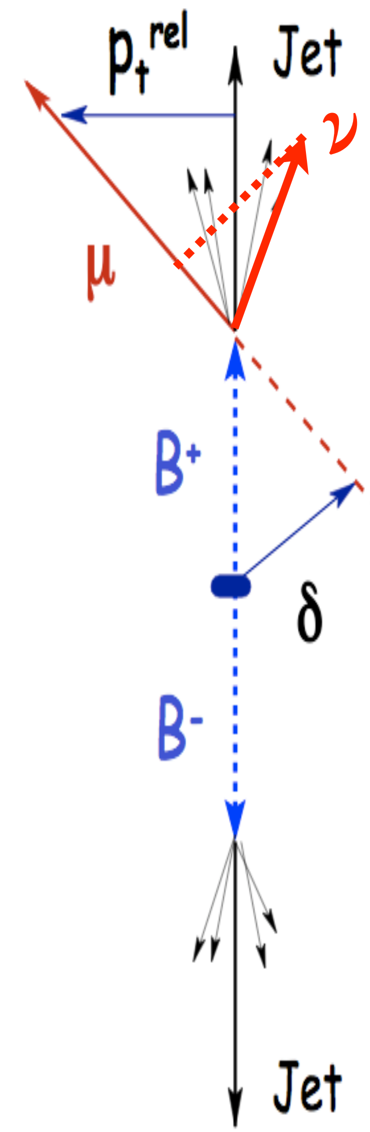


DESY 08-201, arXiv:0812.3775

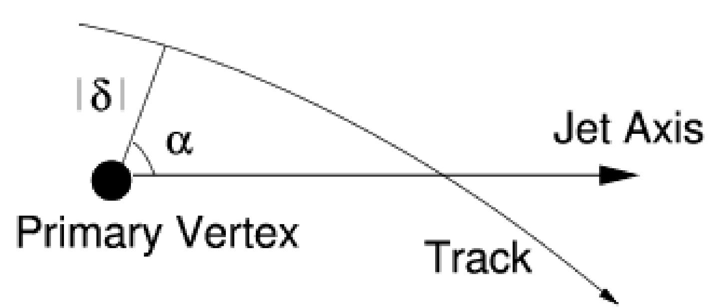
Tagging heavy quarks (b,c)

- use various properties of B-hadrons
  - semileptonic decays: μ, e
  - large mass: p_t^{rel} of μ w.r.t. jet axis
  - missing ν : $p_t^{miss} \parallel \mu$
  - long life-time:
    - reconstruct secondary vertex
    - impact parameter δ or

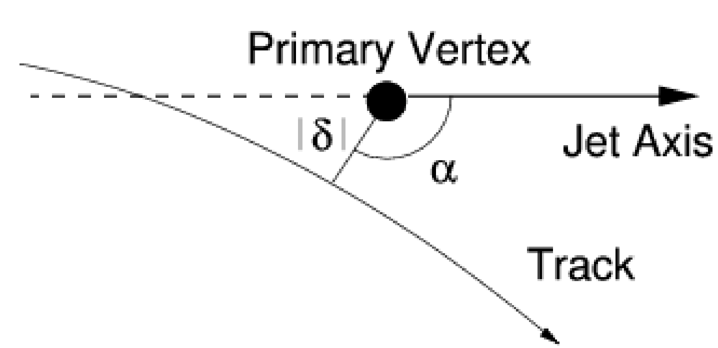
      significance $S = \delta / \sigma(\delta)$ of tracks



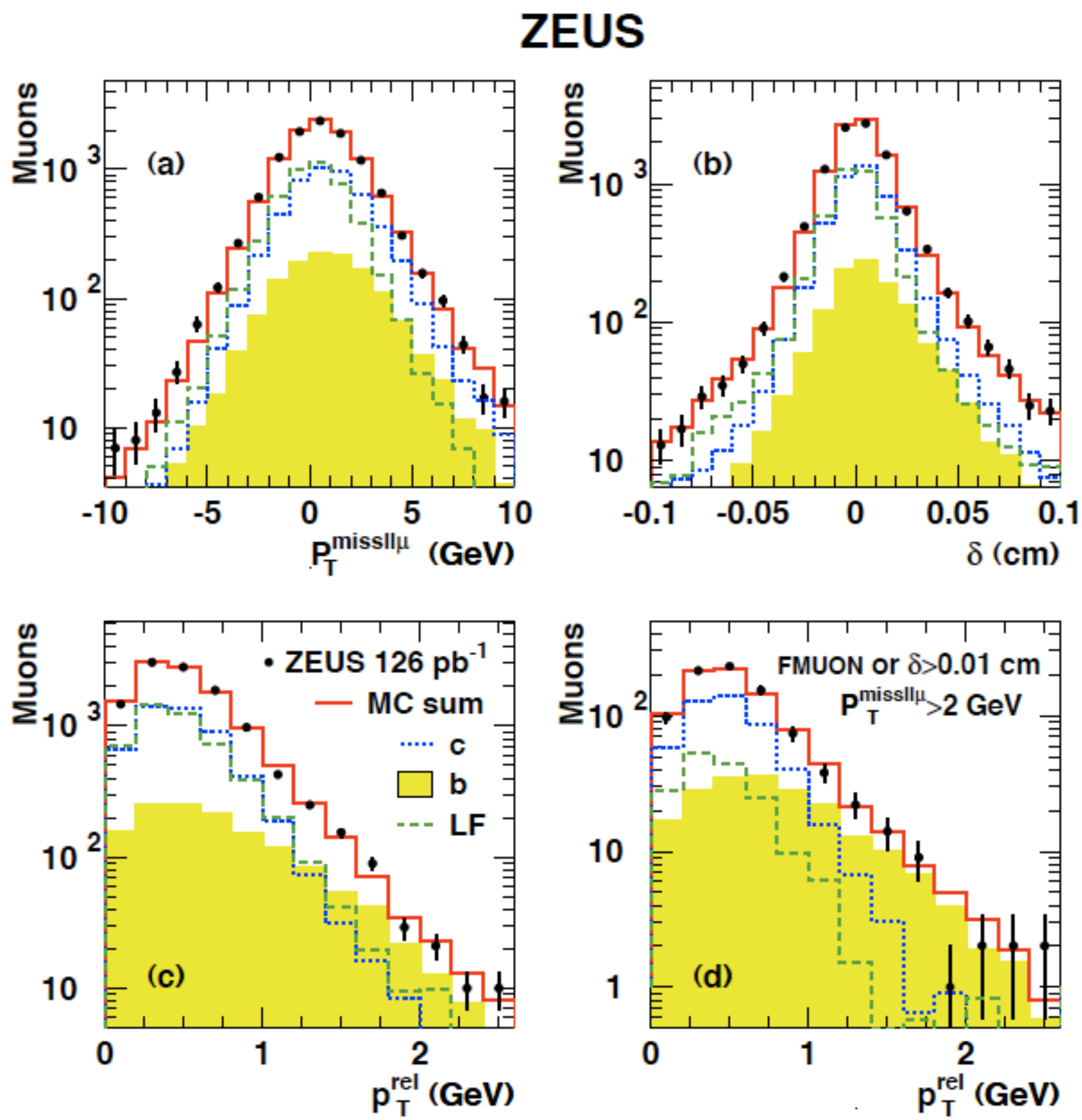
$\alpha < 90^\circ \rightarrow \delta = +|\delta|$



$\alpha > 90^\circ \rightarrow \delta = -|\delta|$



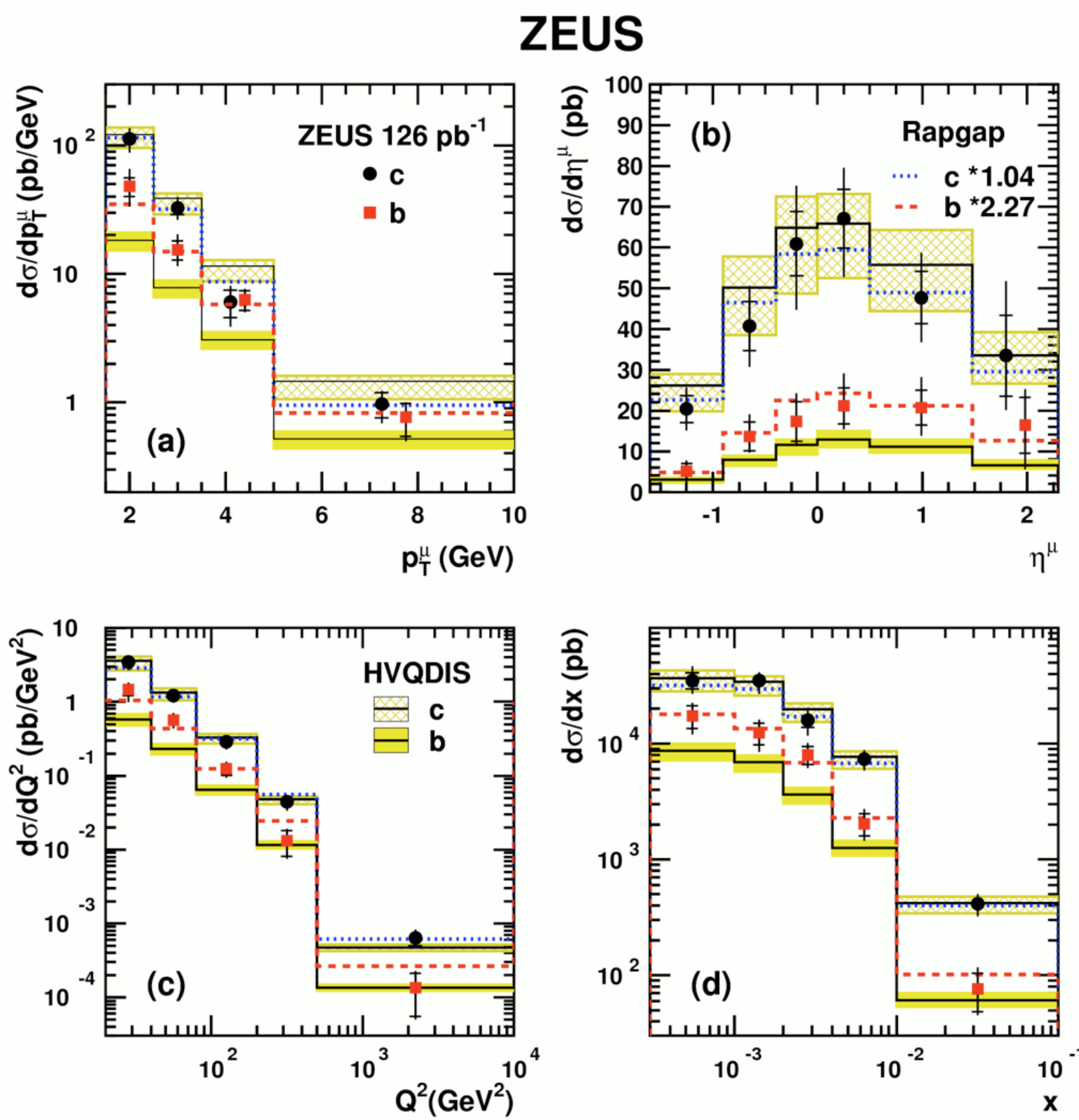
Charm & Beauty from muons (ZEUS)



- 3D-fits of MC templates to $p_t^{miss \parallel \mu}$, p_t^{rel} and δ to extract charm and beauty fractions

DESY 09-56, arXiv:0904.3487

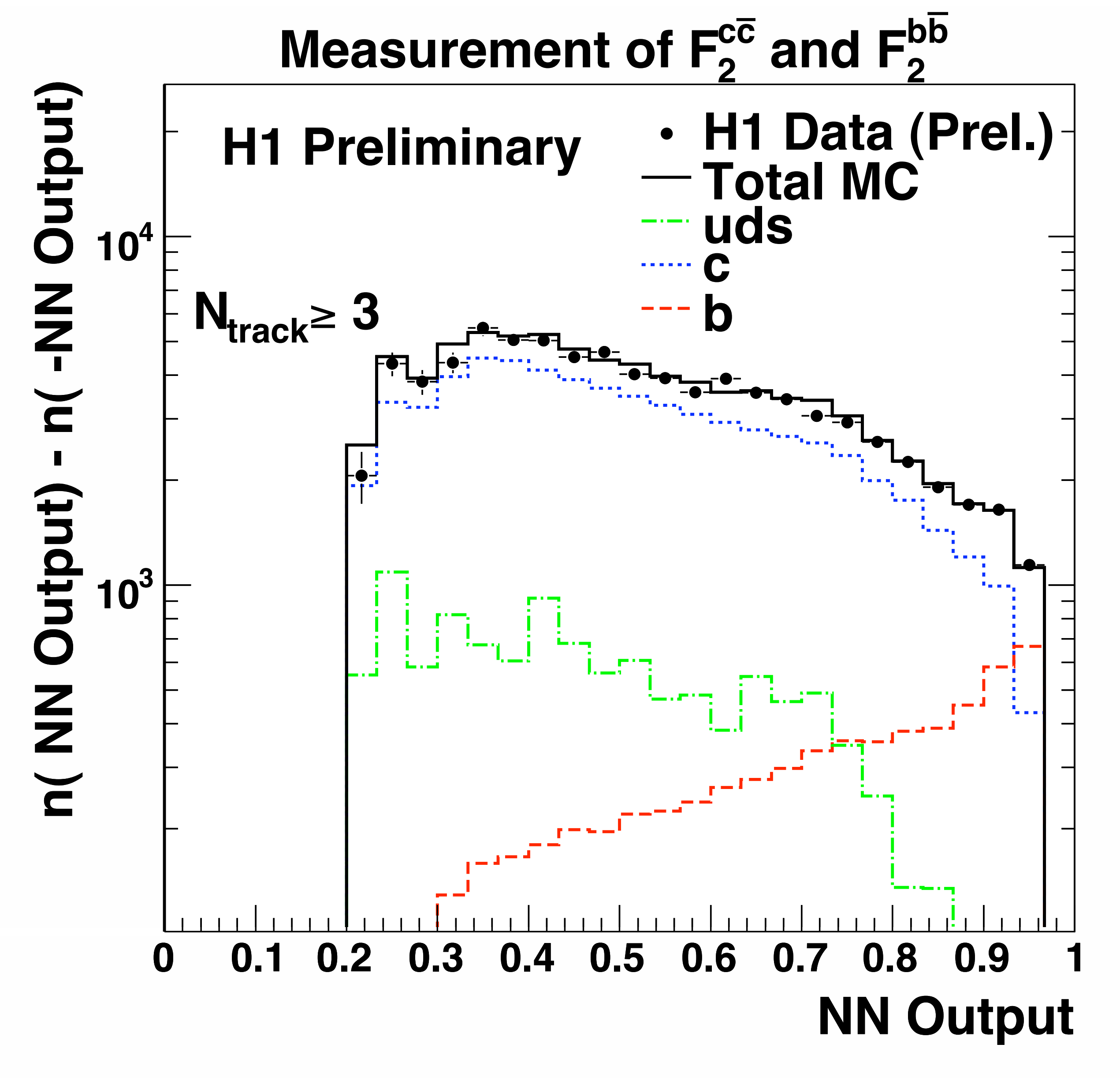
Charm & Beauty from muons (ZEUS)



- charm data are well described by HVQDIS
- beauty data lie above the HVQDIS prediction at low Q^2/low x
- data are used to obtain F_2^b

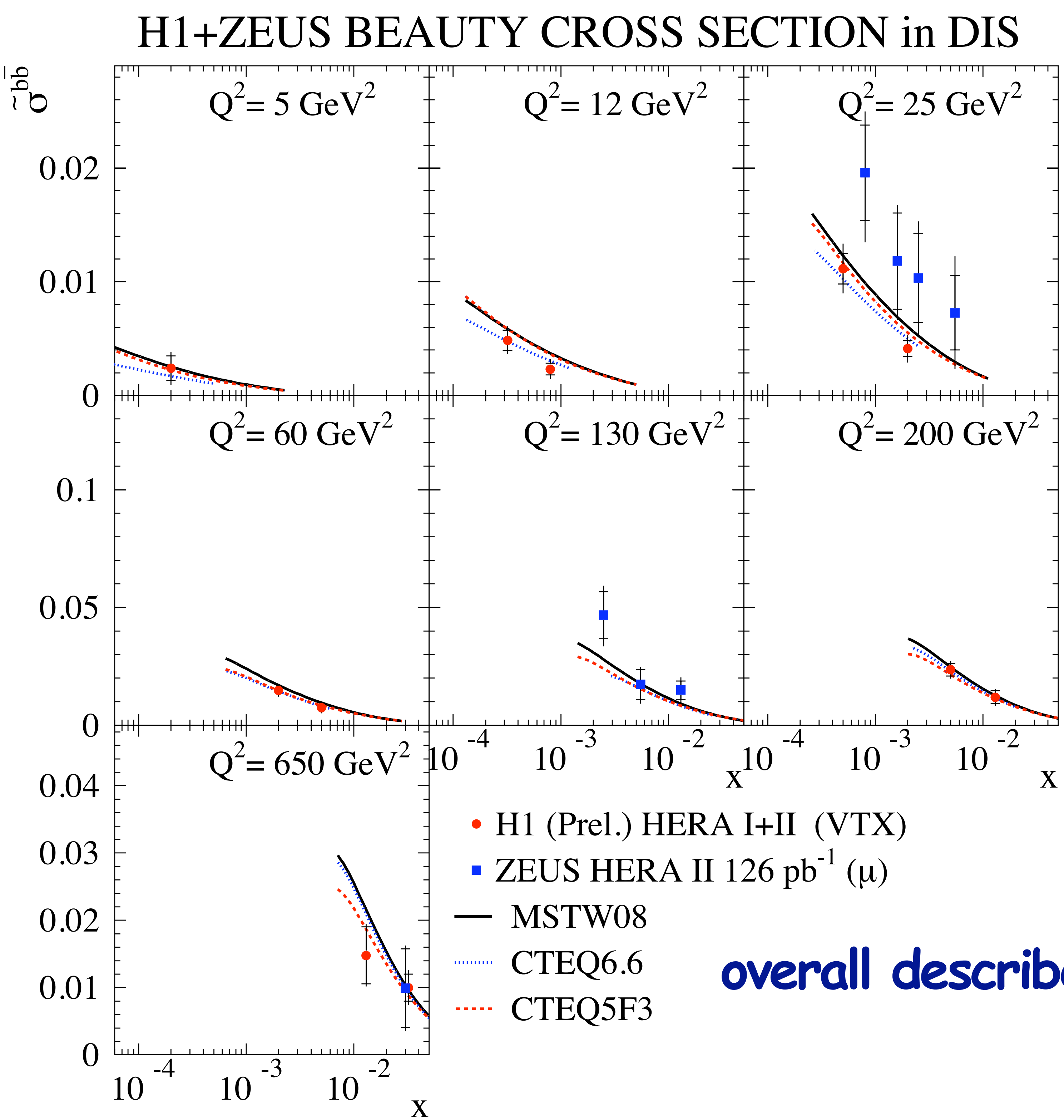
Charm & Beauty from tracks (H1)

- in this analysis all tracks with hits in the micro vtx detector are used
- different strategies depending on the number of tracks are used
- for events with ≥ 3 tracks a neural network (NN) is used



fit MC templates to various distributions (track impact parameters and NN) to obtain c and b fractions

Latest H1 & ZEUS b cross sections



- different methods lead to similar results; ZEUS data tend to be higher than H1 data
- inclusive measurement (H1) has higher statistics compared to the exclusive measurement (ZEUS)

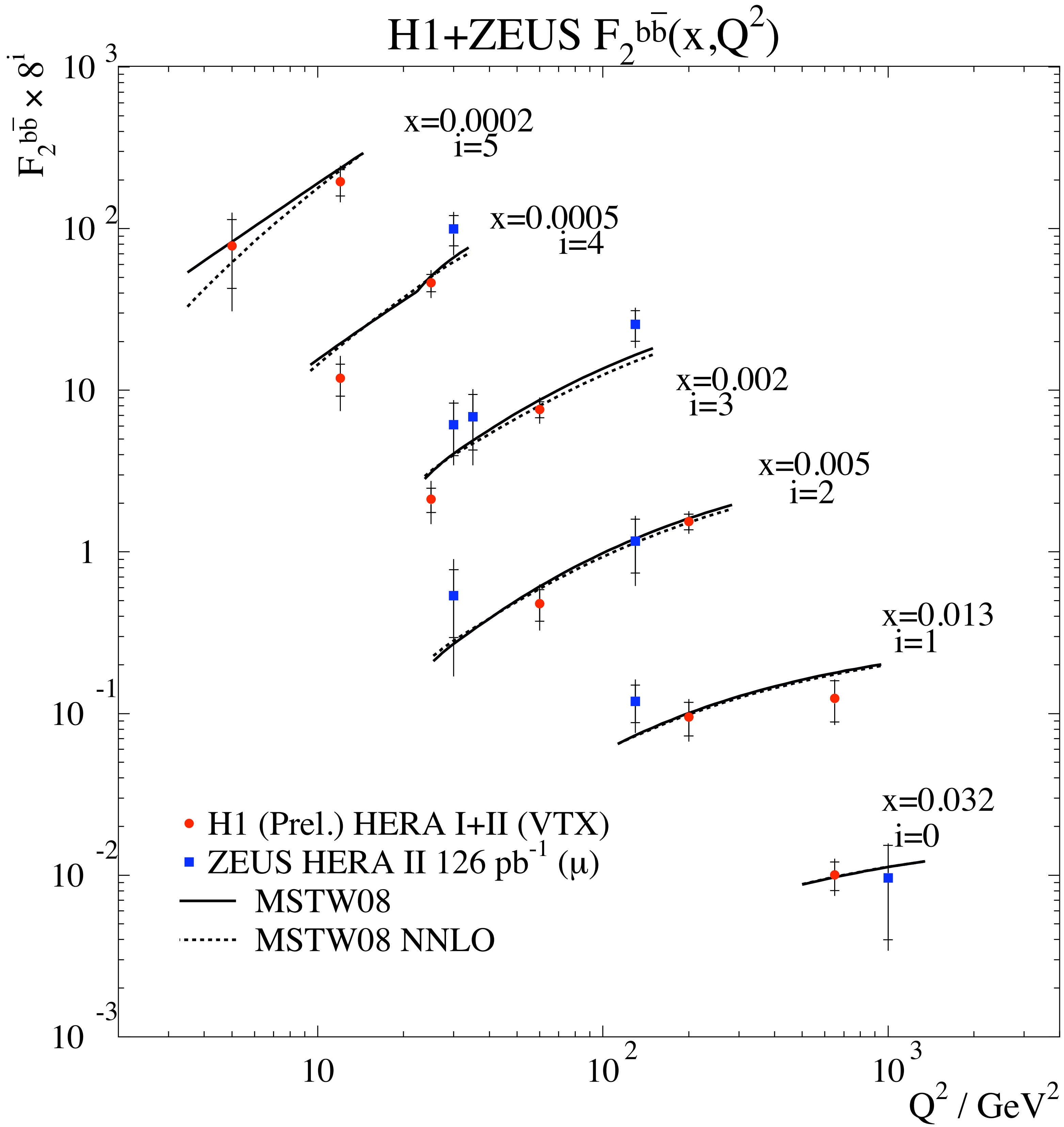
overall described by NLO QCD

The beauty structure function

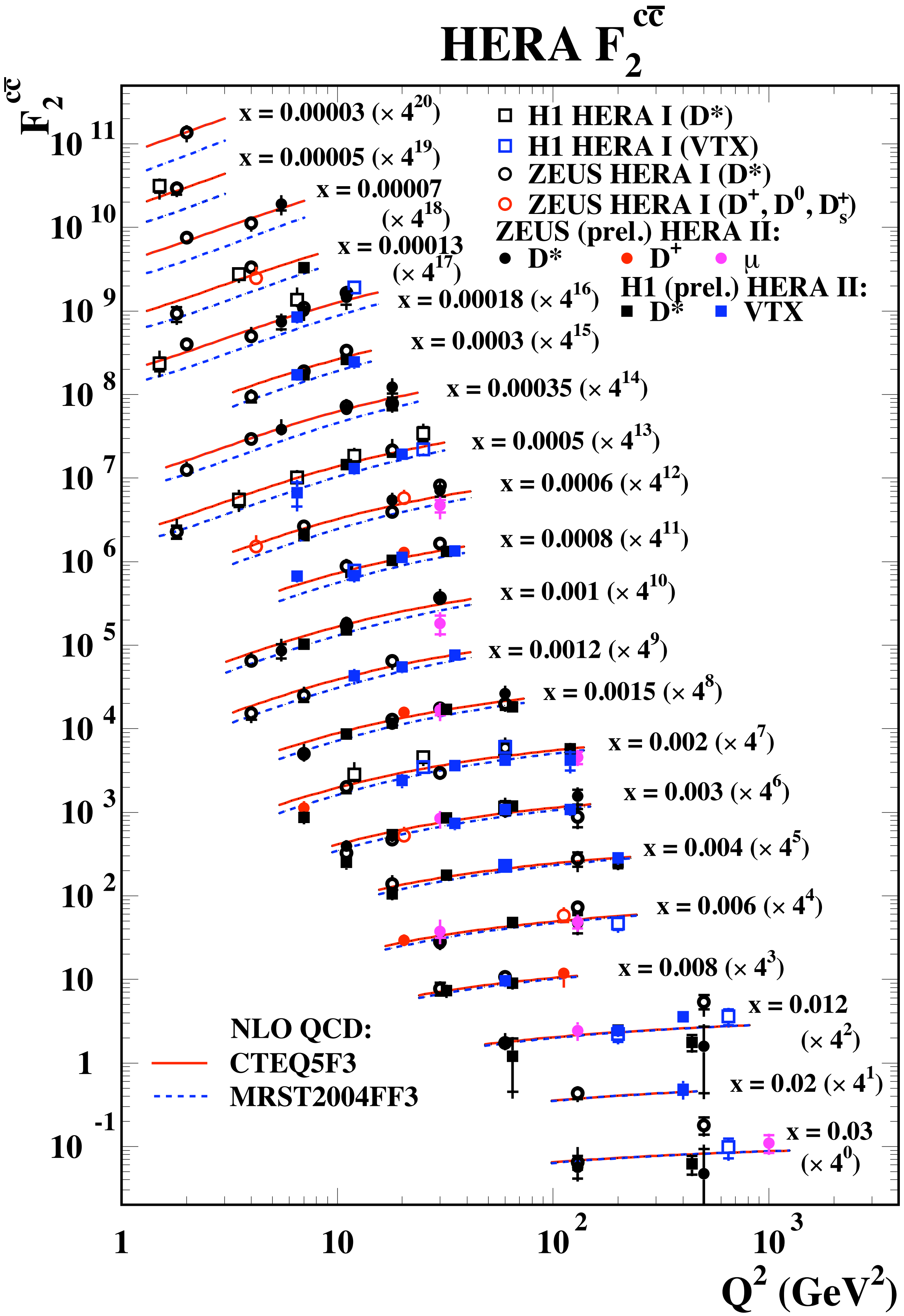
$$\frac{d^2\sigma^{b\bar{b}}}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4x} Y_+ [F_2^{b\bar{b}}(x,Q^2) - \frac{y^2}{Y_+} F_L^{b\bar{b}}(x,Q^2)]$$

$$F_{2,exp}^{b\bar{b}}(x_i,Q_i^2) = \frac{\sigma_{exp,i}^{vis}}{\sigma_{theo,i}^{vis}} F_{2,theo}^{b\bar{b}}(x_i,Q_i^2)$$

- F_2^b vs. Q^2 for fixed x
- Comparison to MSTW08 in NLO and NNLO
- Differences between NLO and NNLO are small, except for $Q^2 < M_b^2$



The charm structure function



- substantially higher statistics, therefore large coverage in Q2 and x
- acceptance of different methods varies between 20% and 70%
- the different methods agree well
- to improve precision, combination of different methods within an experiment and within H1 & ZEUS is ongoing

Summary

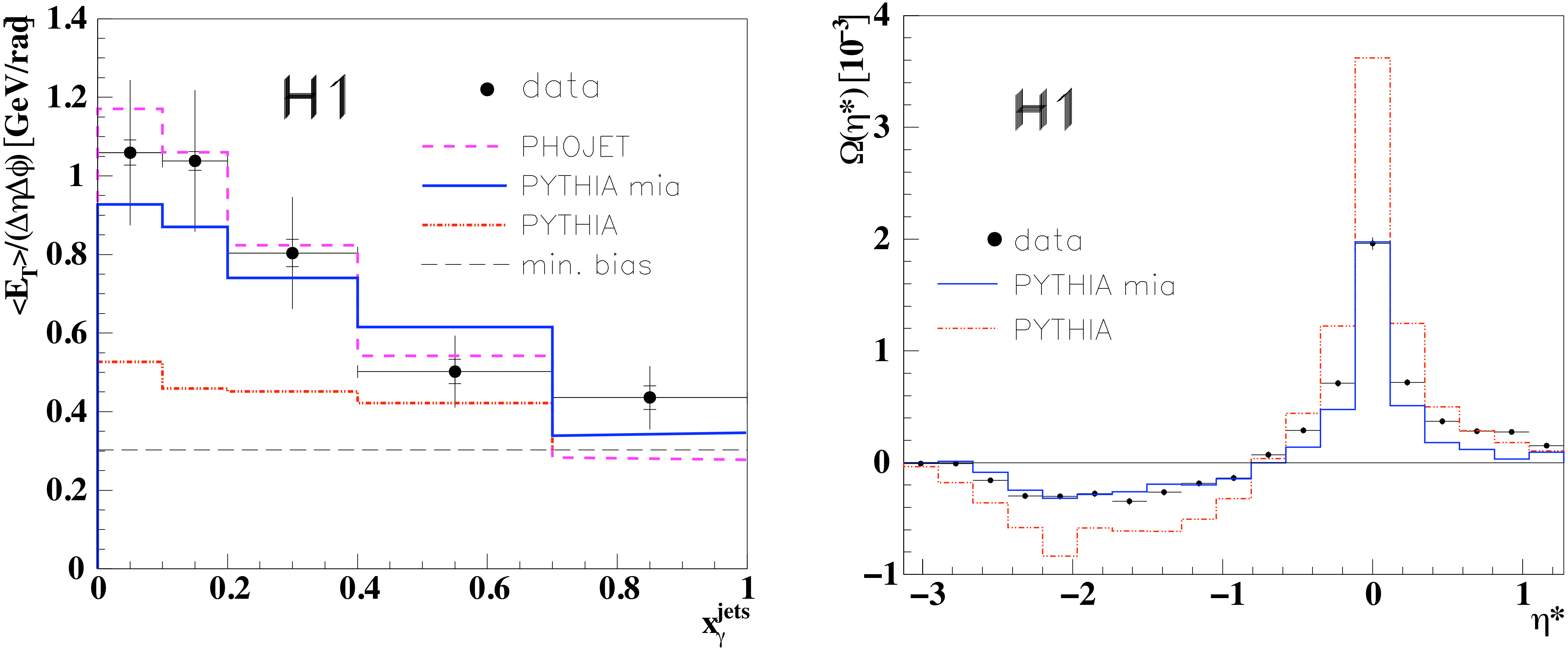
- low & high scales
  - description of <charged particle multiplicity> in resolved photon events with 2 hard jets requires MPI (at least when using Pythia)
- high scales
  - jets in γp and DIS are well described by NLO QCD
  - allows for precise extraction of αs(MZ), competitive and compatible with LEP results
  - exp. errors << theory errors ➜ expect significant increase in precision from NNLO
- multiple scales
  - measurements of charm & beauty across wide range in scales are overall well understood and described by NLO (NNLO)
- stay tuned to improved (statistics & precision) final HERA analyses !

Back-up

MPI in photoproduction

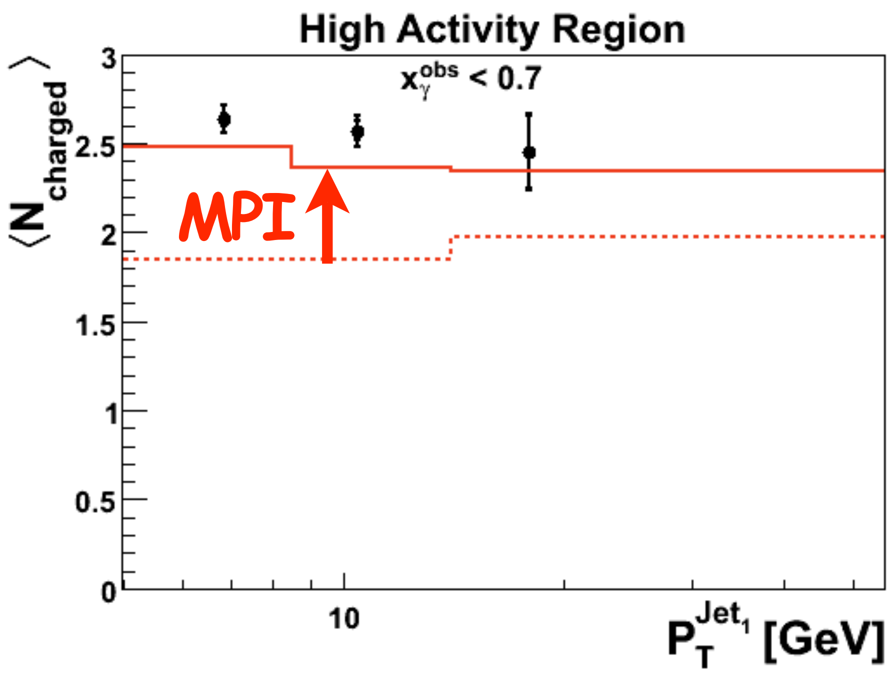
<Transverse energy flow>

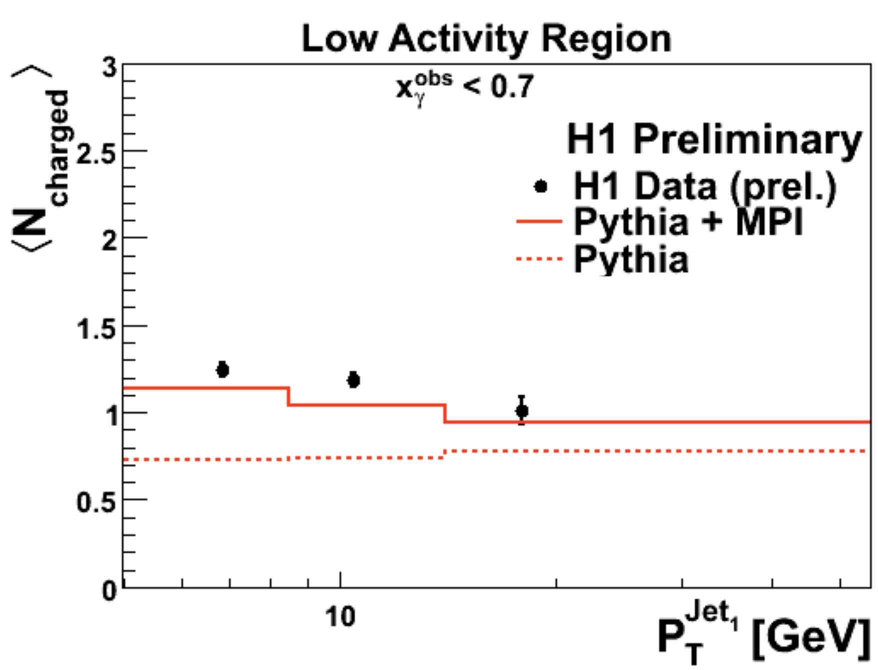
$$\Omega = \frac{1}{N_{ev}} \sum_{i=1}^{N_{ev}} \frac{(\langle E_{T,\eta=0}\rangle - E^{i}_{T,\eta=0})(\langle E_{T,\eta}\rangle - E^{i}_{T,\eta})}{(E_T^2)_i}$$



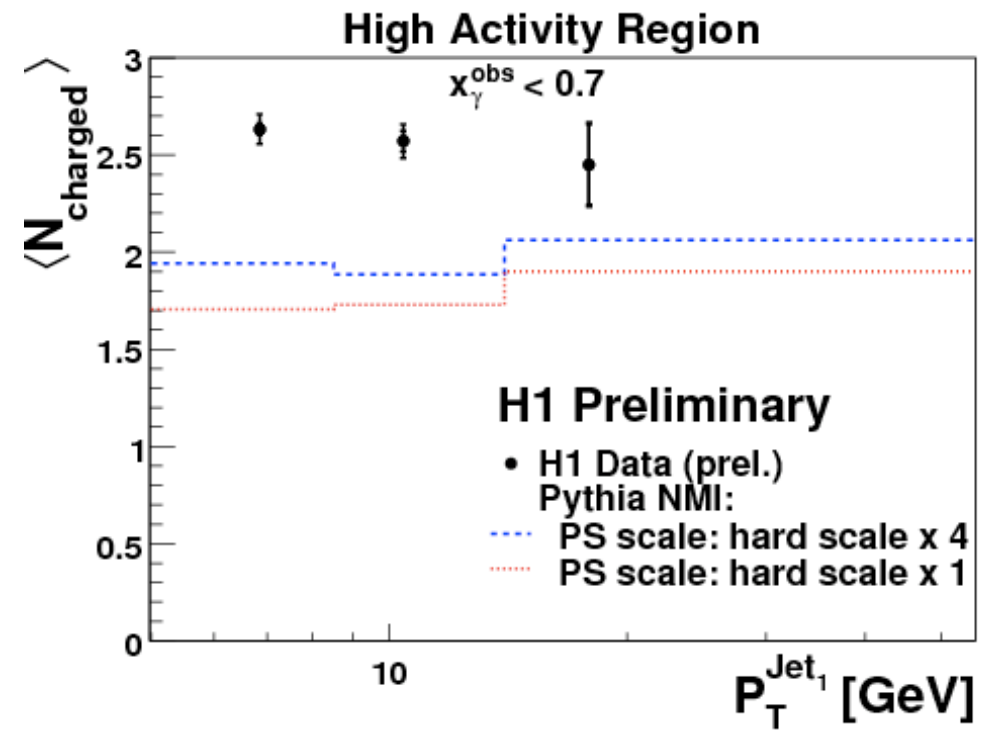
- **MPI provide a good description of energy flows and correlations**

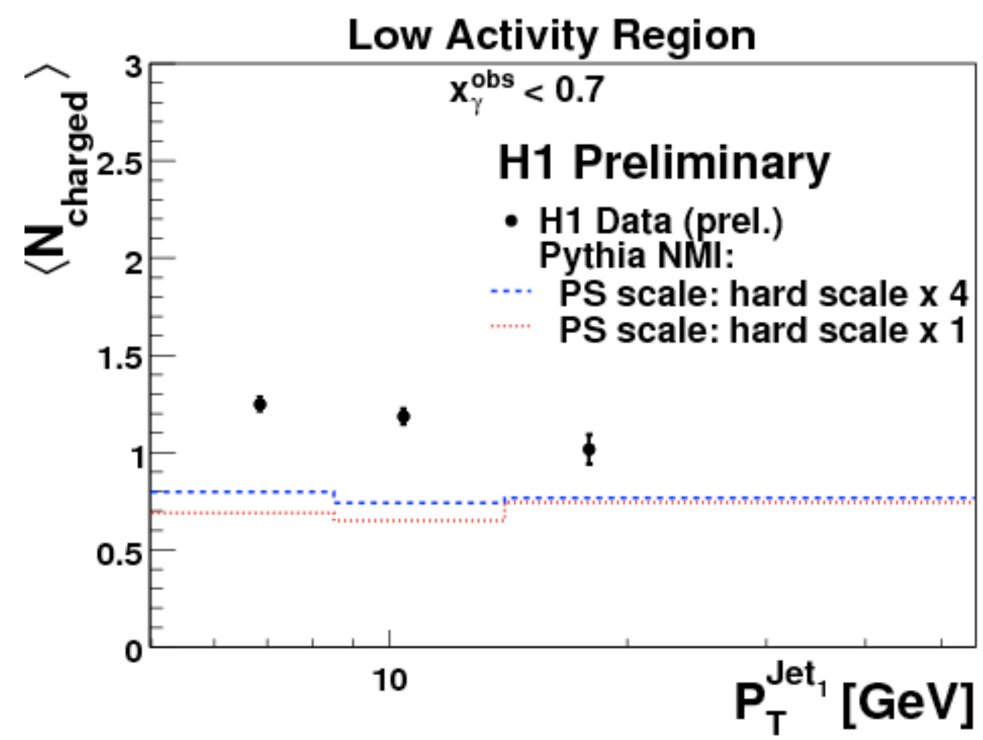
$\langle N_{charged} \rangle$ in transverse regions



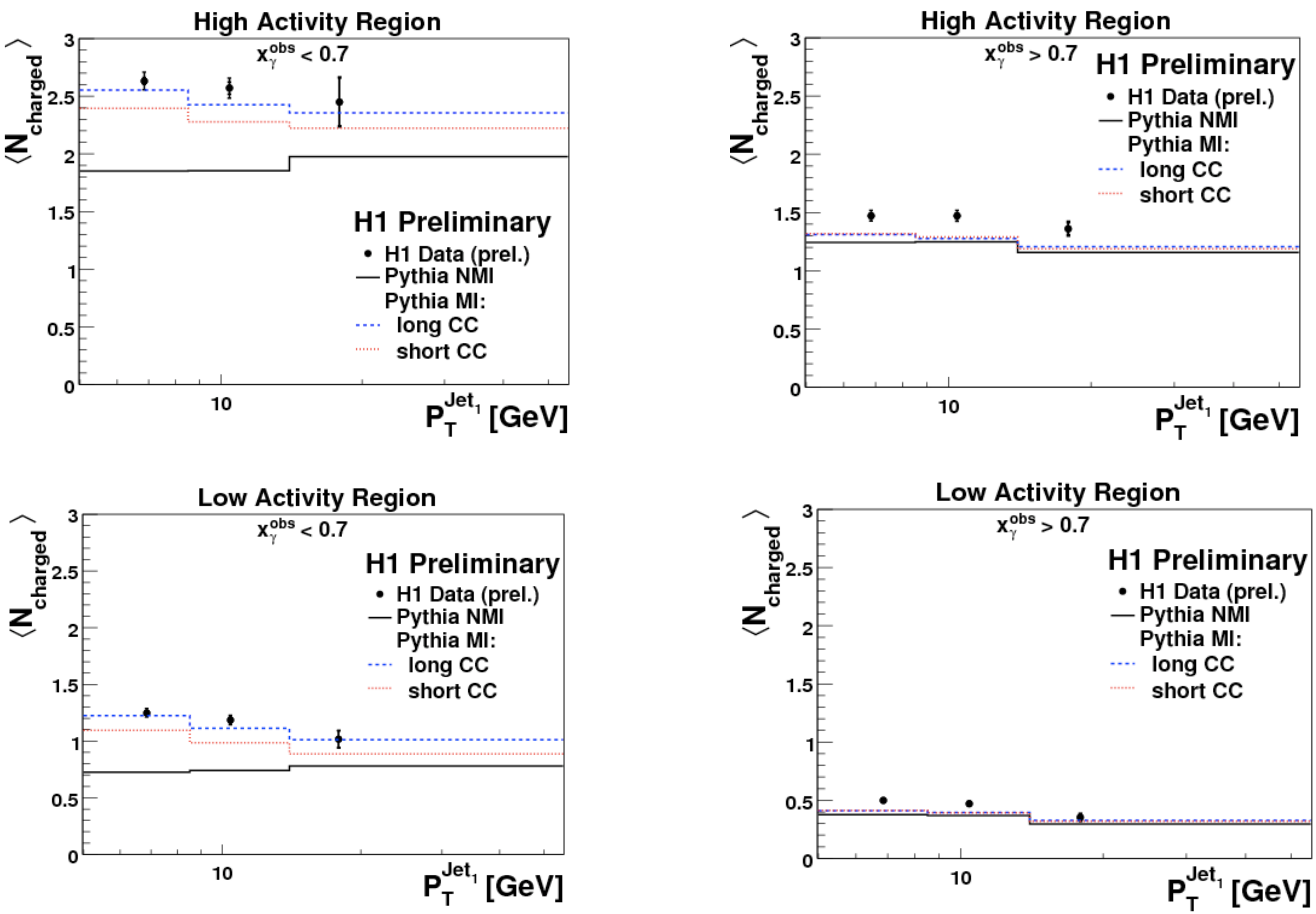


can Pythia
w/o MPI, but
inceased
parton shower
describe
data?



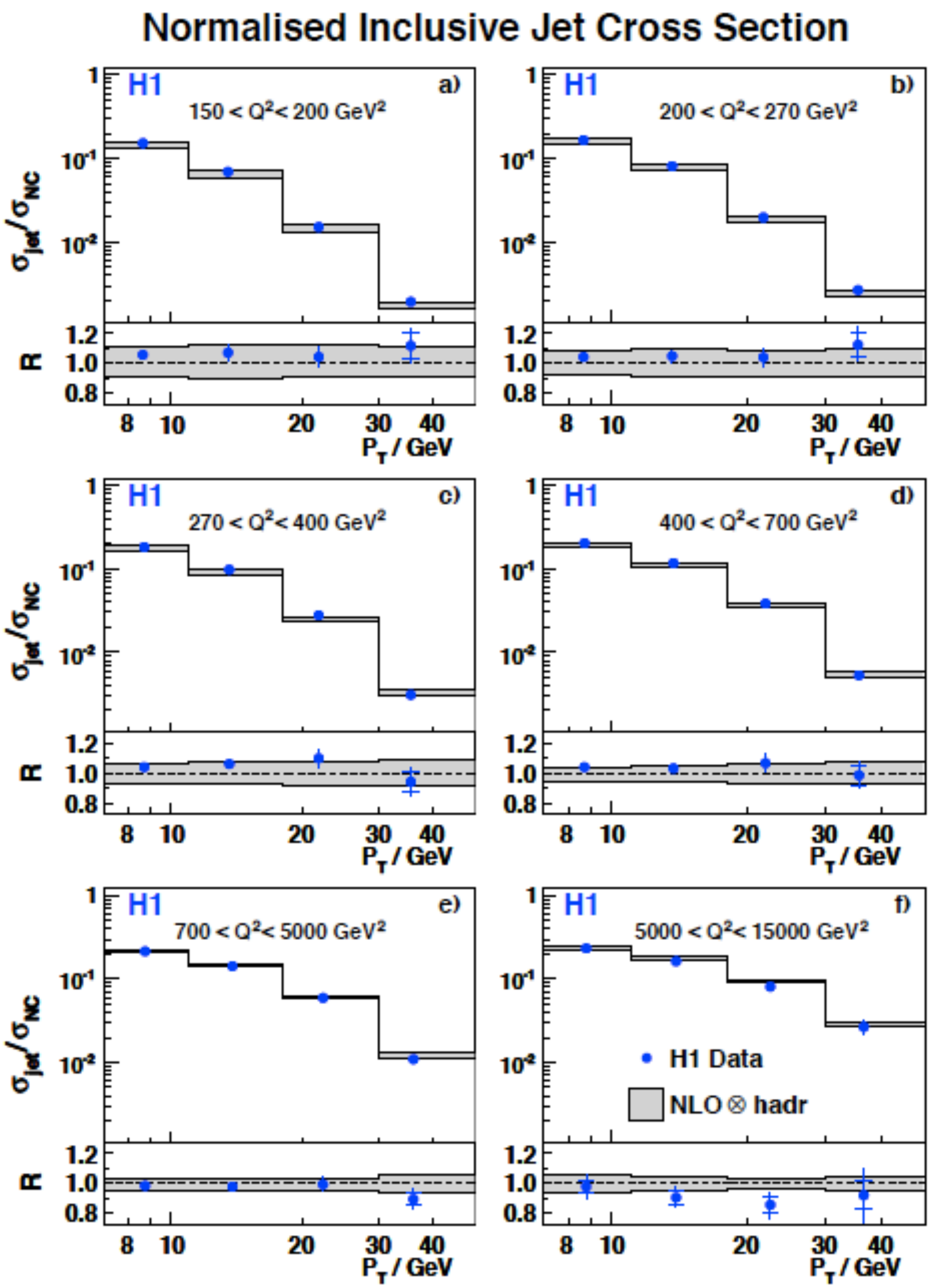


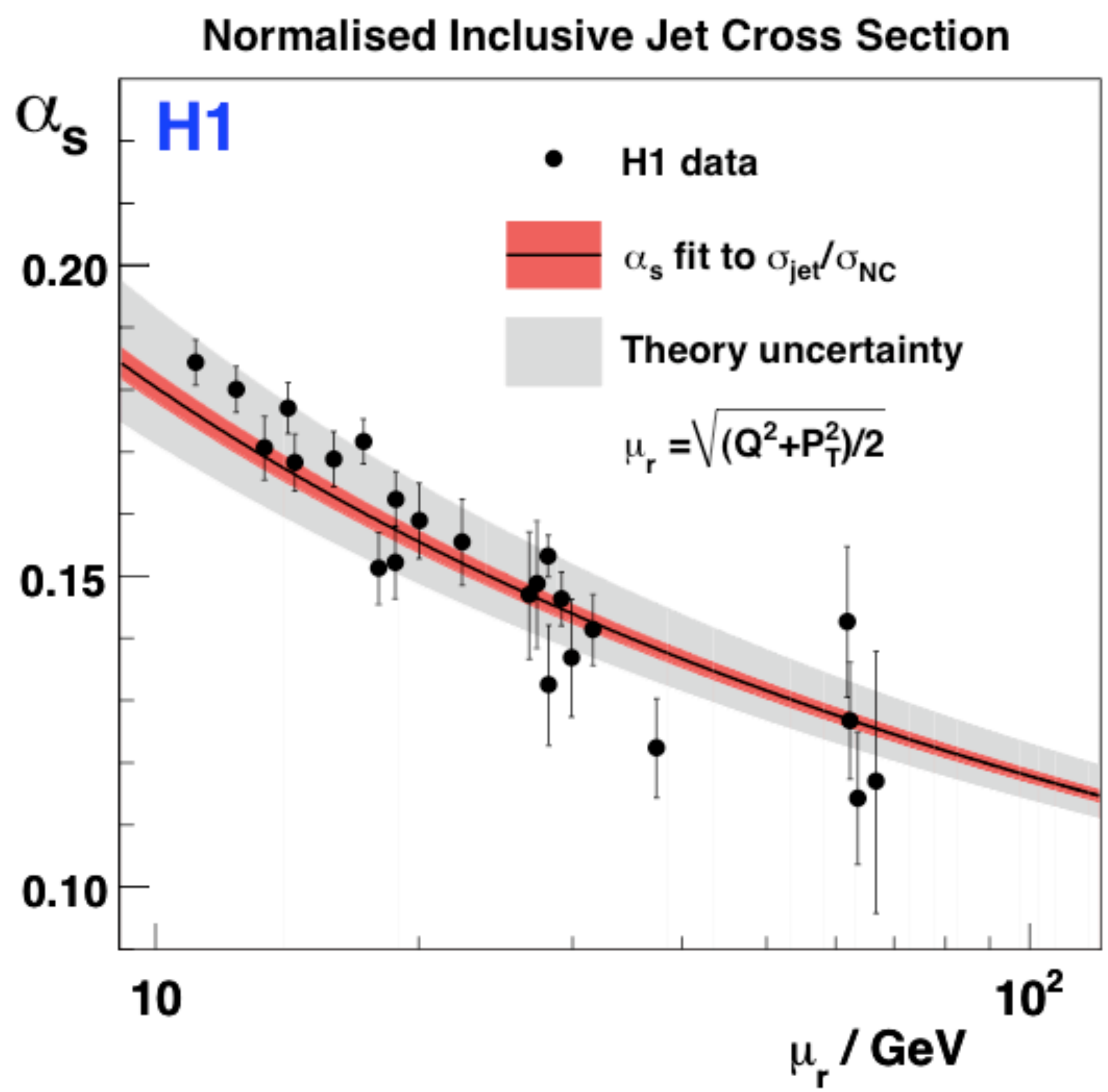
MPI & long/short color chains (CC)



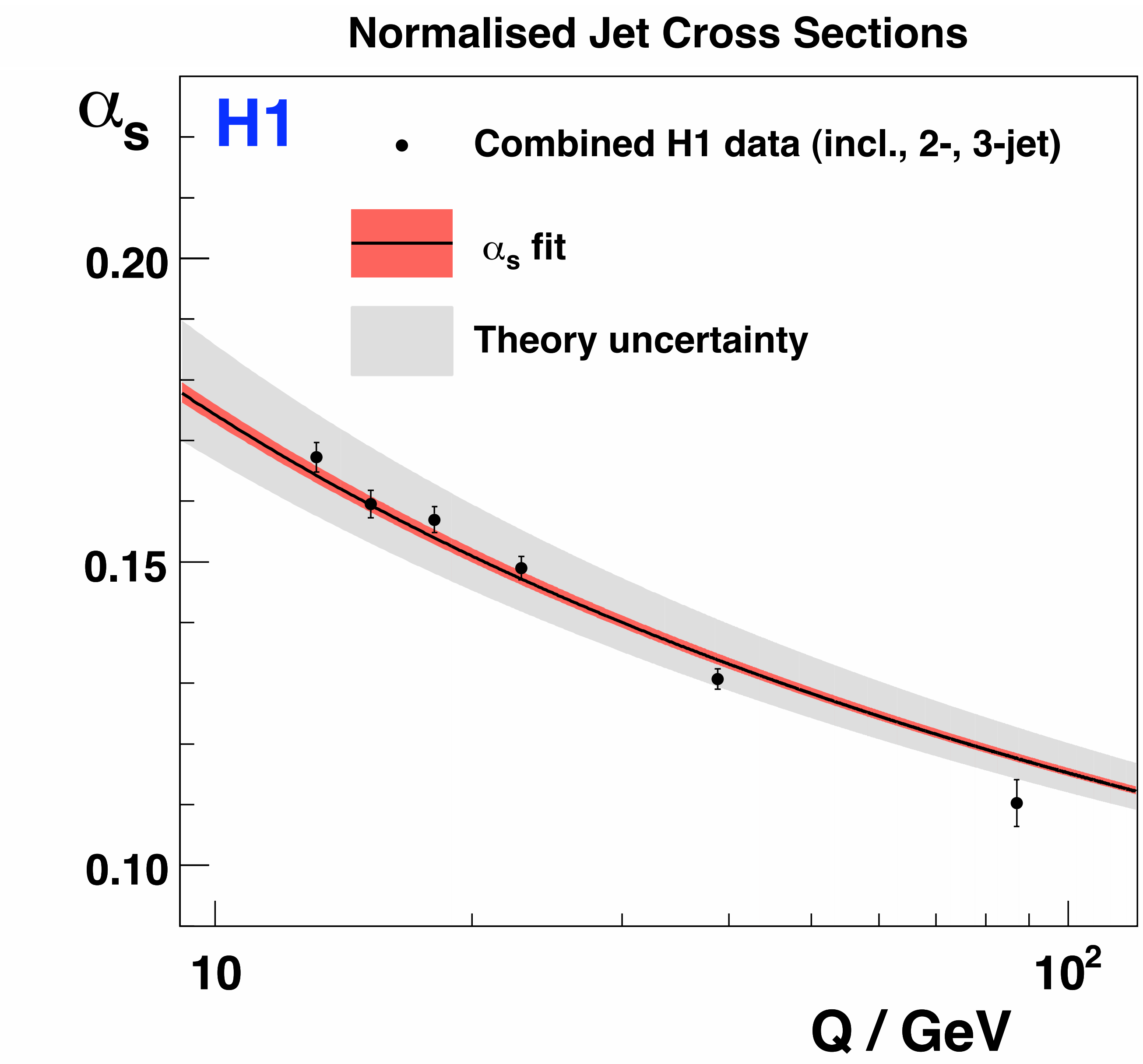
- Pythia for γp at HERA shows slight preference for long CC

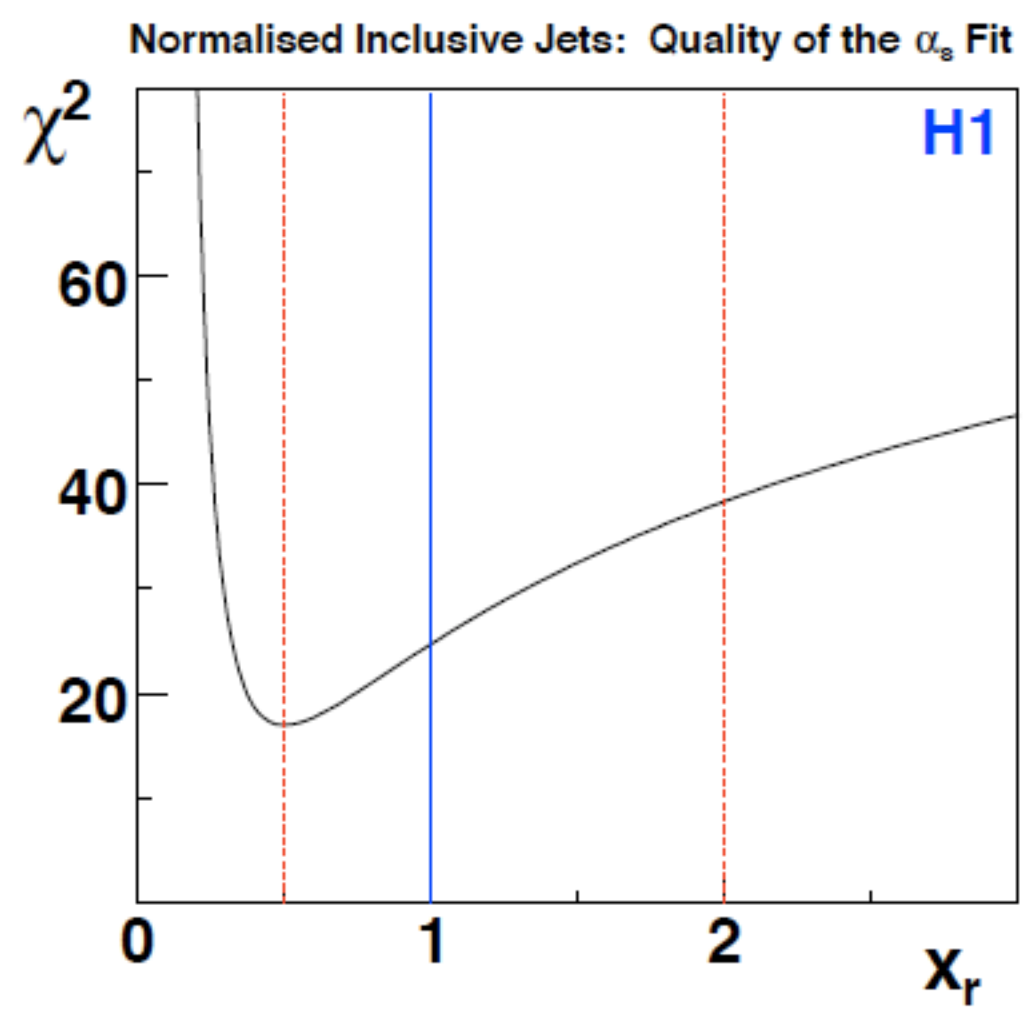
Jet multiplicity & Running α_s





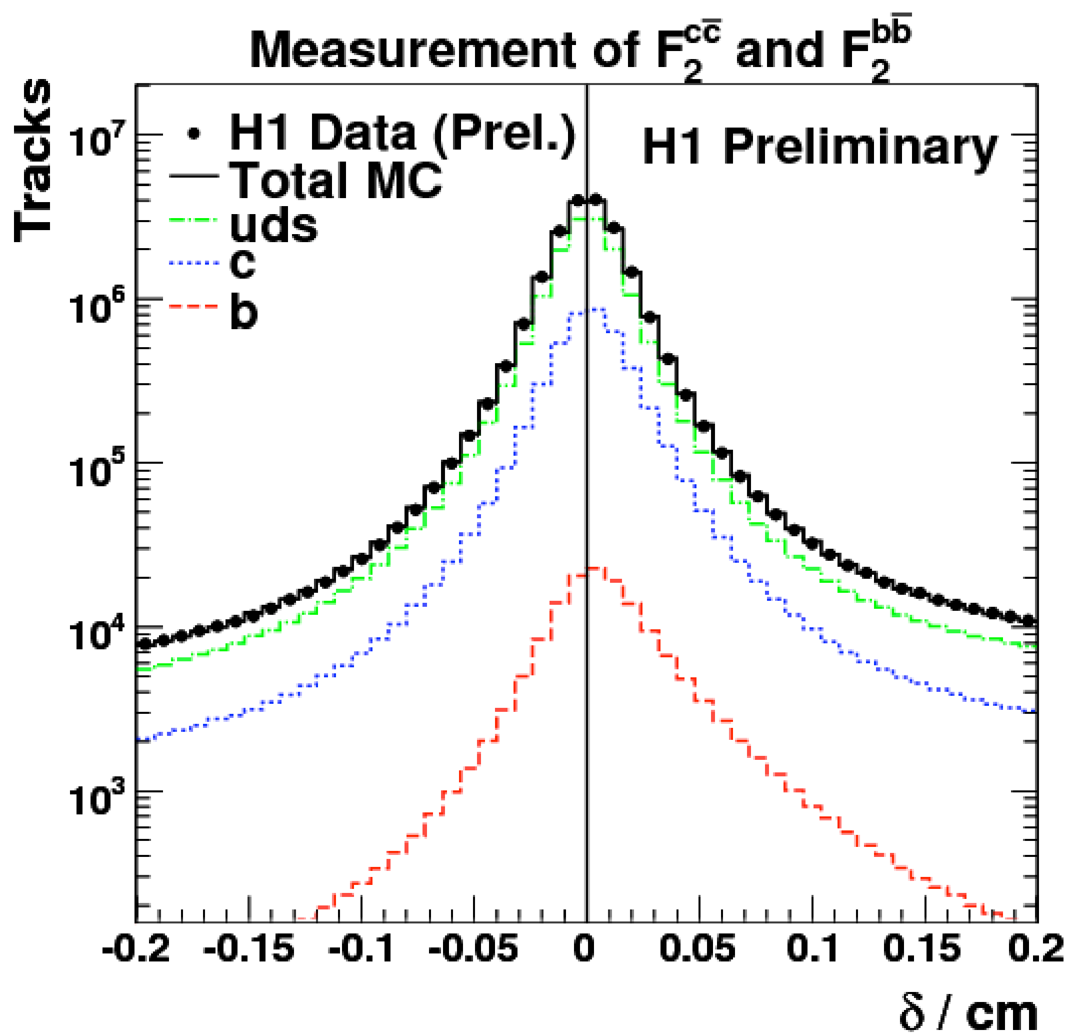
$\alpha_s(M_Z)$ fit and variation of scale



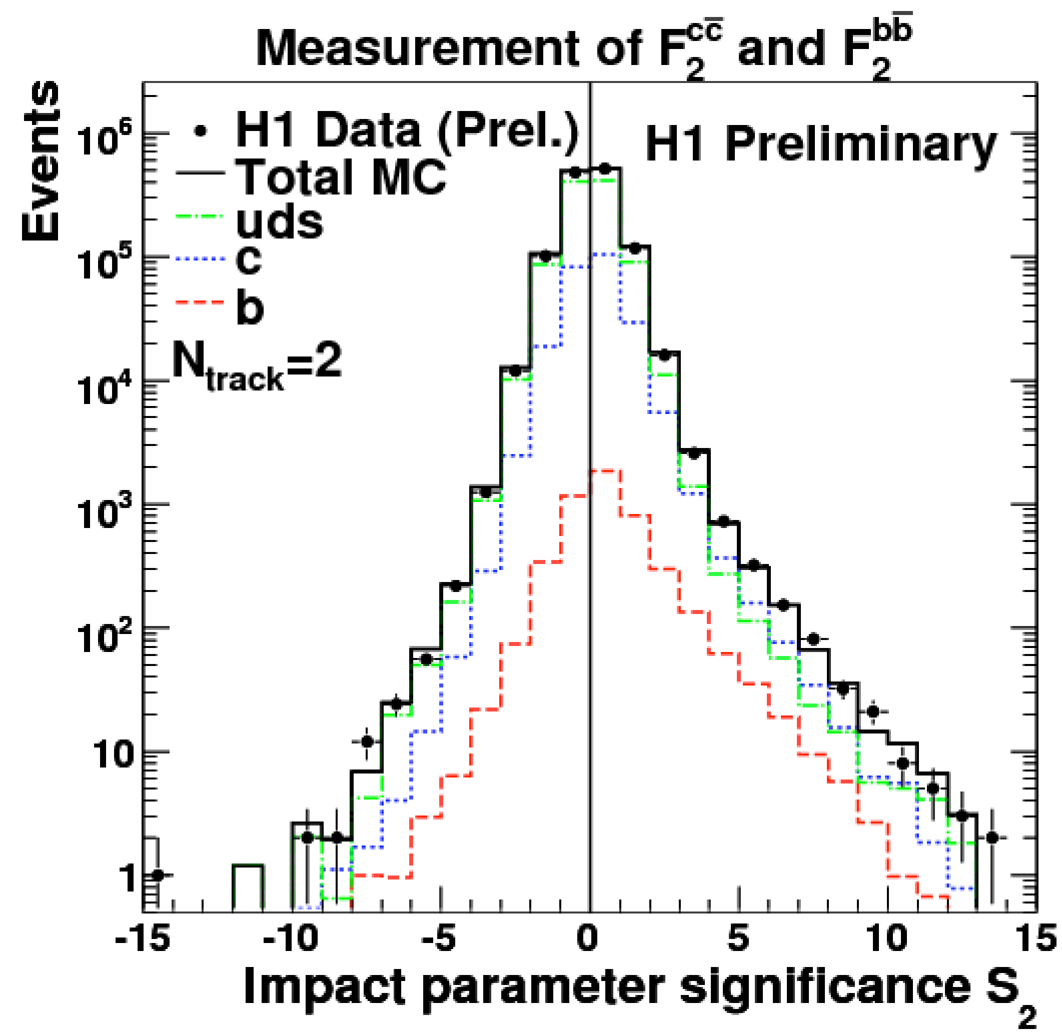


Charm & Beauty from tracks (H1)

- in this analysis all tracks with hits in the micro vtx detector are used
- sign of δ determined w.r.t. the highest P_T jet direction in the event

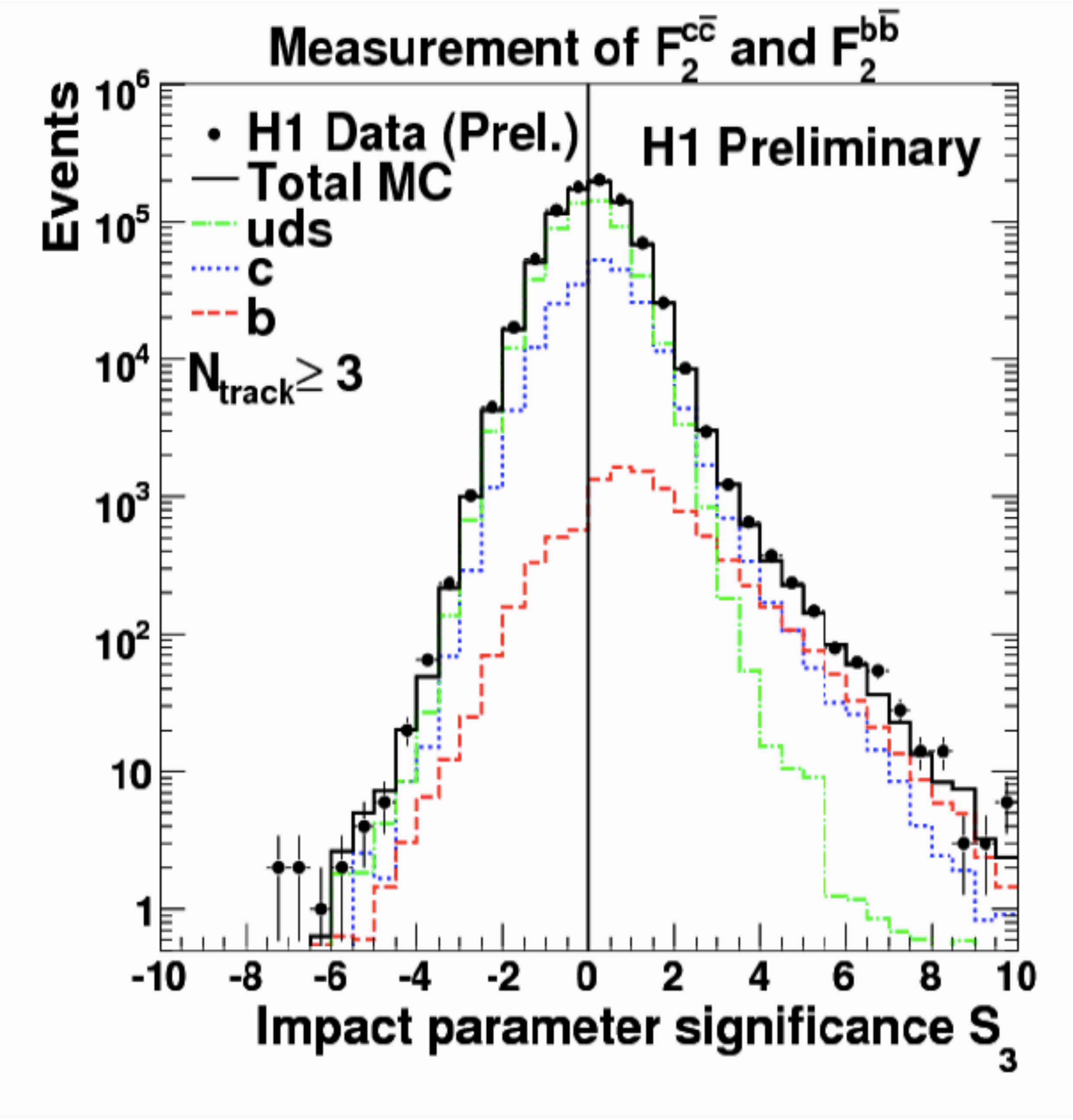


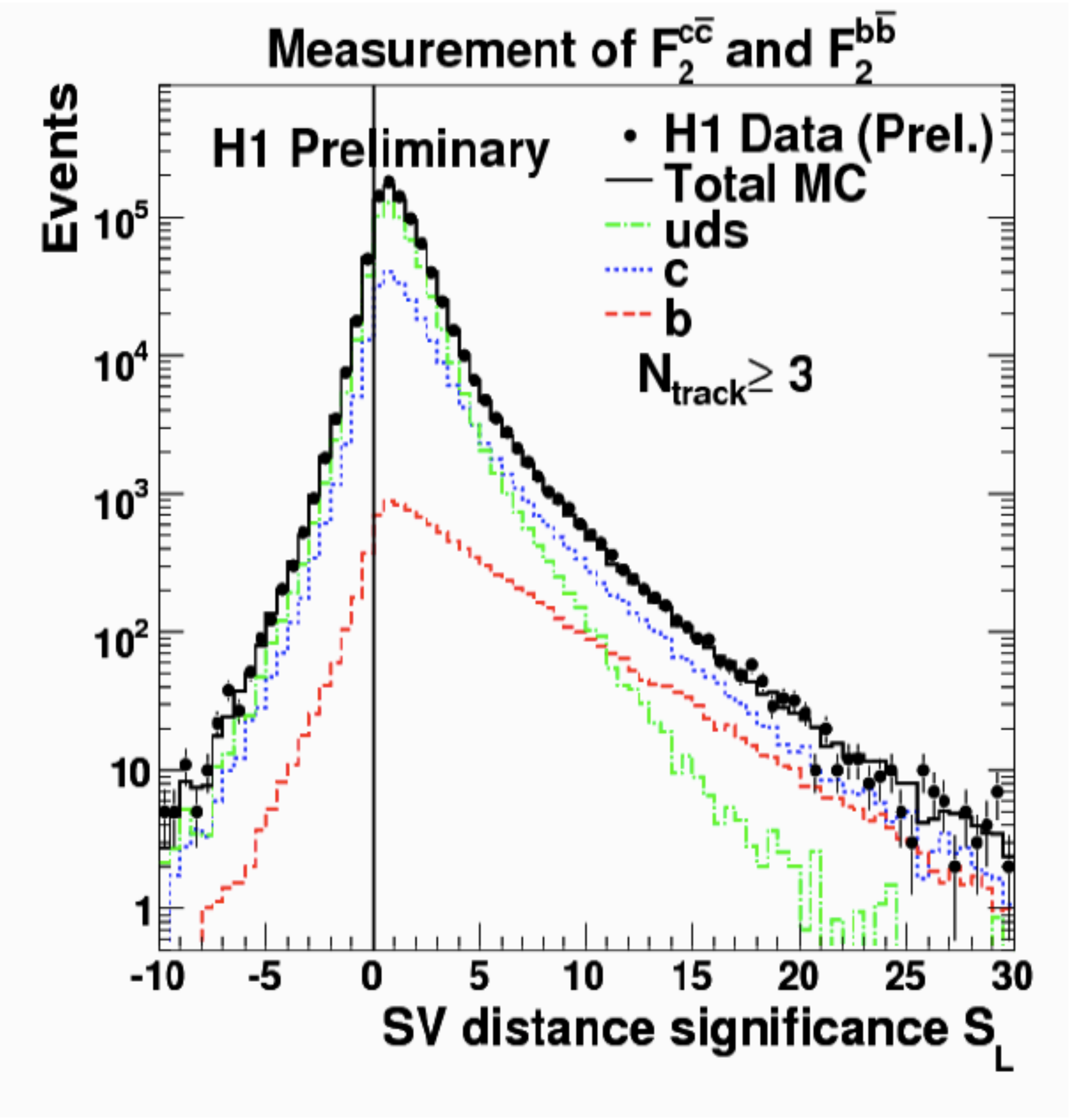
uds fairly symmetric, c & b asymmetric due to life-time



H1 prelim-08-132

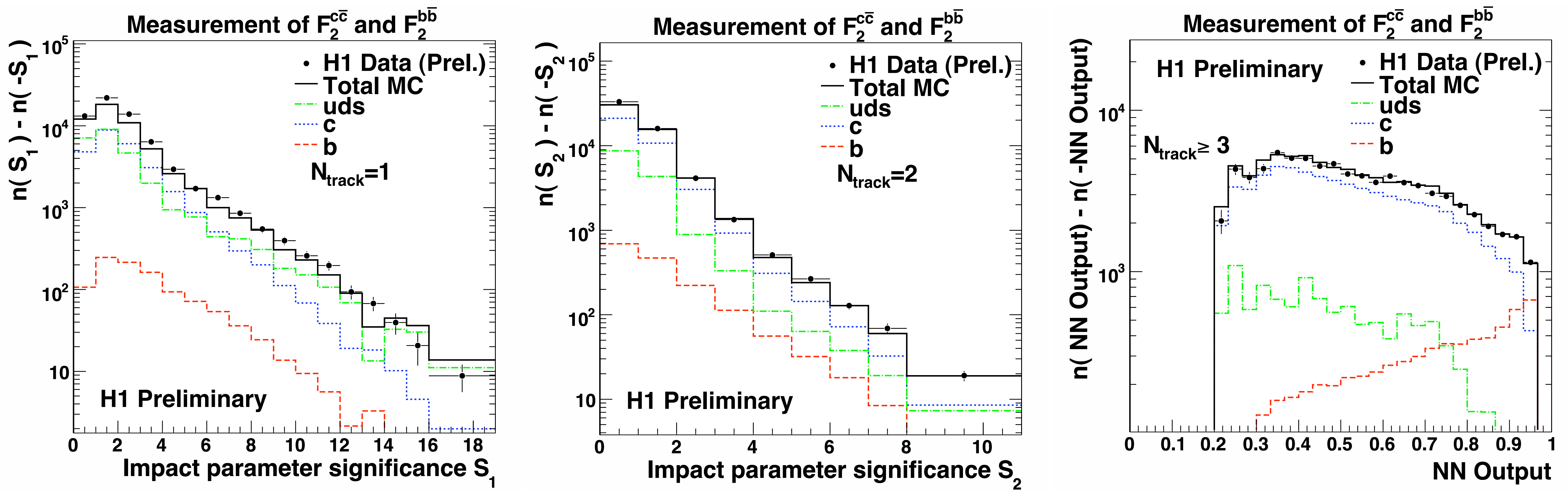
Charm & Beauty from tracks (H1)





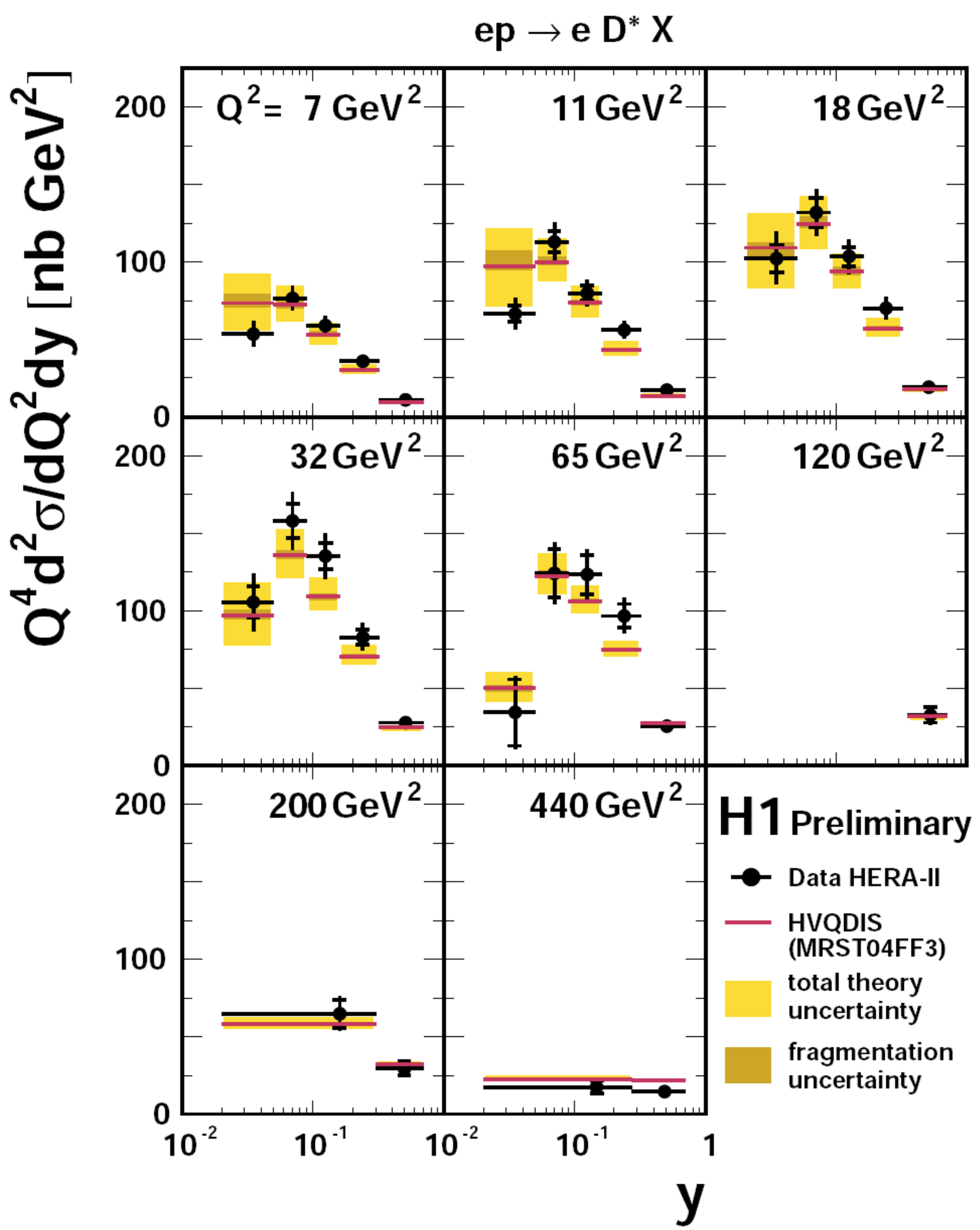
Charm & Beauty from tracks (H1)

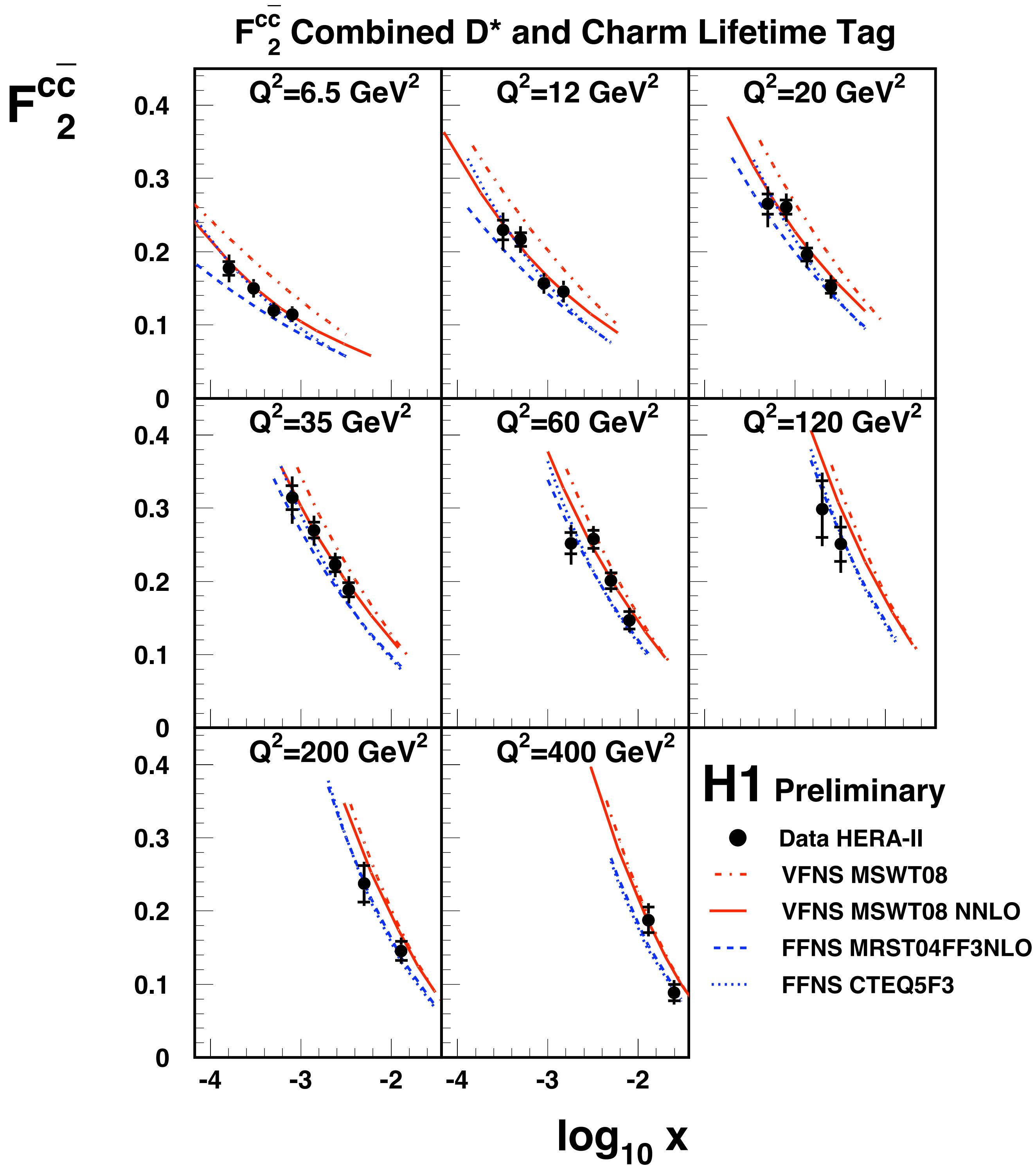
- NN input: S_1, S_2, S_3, S_L, track p_T, number of SV fitted tracks



- Fit S_1, S_2 and NN to obtain c and b fractions

D* cross section & F_2^c (D* & lifetime)





well described by HVQDIS

NNLO differs from NLO at low Q^2