Latest results on hard QCD at HERA

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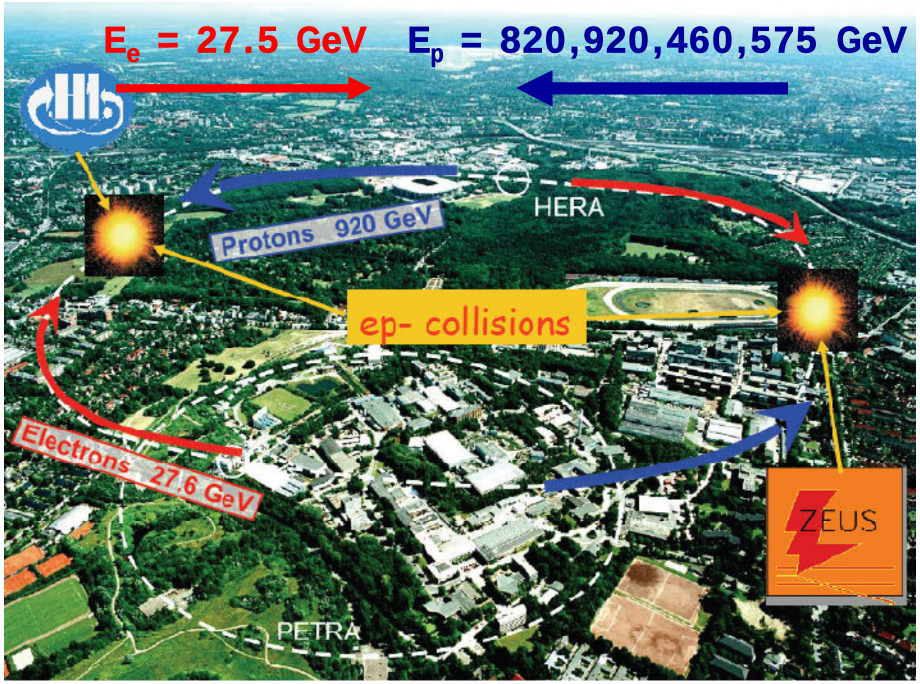
on behalf of the H1 and ZEUS Collaborations

Excited QCD 2018

Kopaonik, Serbia, March 11th – March 15th, 2018

HERA (DESY, Hamburg) was the only ep collider: 1992 - 2007



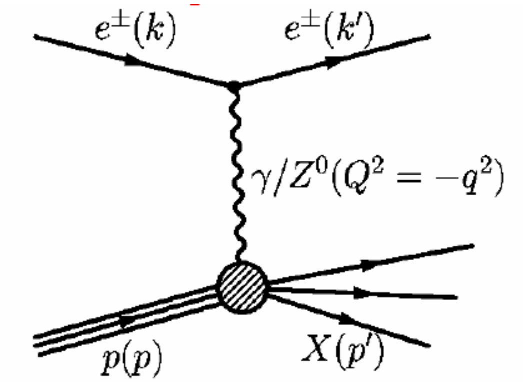
- Total lumi H1, ZEUS: 0.5 fb^{-1} each
  - HERA-I 1992-2000 ~120 pb^{-1}
  - HERA-II 2003-2007 ~380 pb^{-1}
- Beams and energies
  - $E_{e+/e-}$ = 27.6 GeV
  - E_p = 820, 920 GeV (HERA-I)
  - E_p = 920 GeV (HERA-II)
  - E_p = 460, 575 GeV (Since April 2007 until the end of June)

Outline

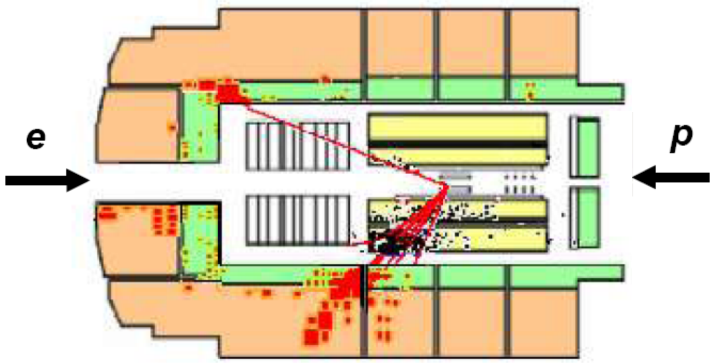
- **Final combination of charm and beauty data from H1 and ZEUS experiments**
  H1prelim-17-071 and ZEUS-prel-17-01
  H1prelim-18-071 and ZEUS-prel-18-01-extension
- **First determination of α_s from DIS jet data at NNLO – H1 collaboration**
  Eur.Phys.J.C77 (2017), 79 [arxiv:1709.07251]
- **Isolated photon production with a jet in DIS – ZEUS collaboration**
  JHEP 1801 (2018) 032 [arXiv:1712.04273]

Deep Inelastic Scattering (DIS)

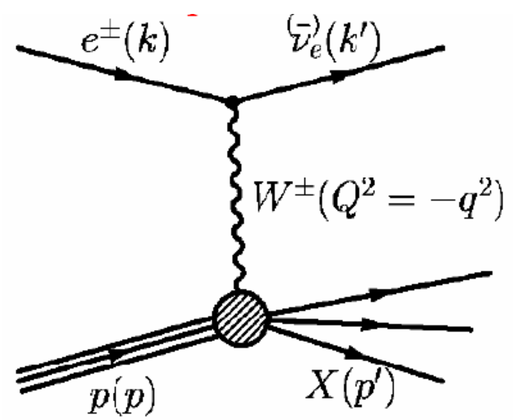
Neutral Current (NC)



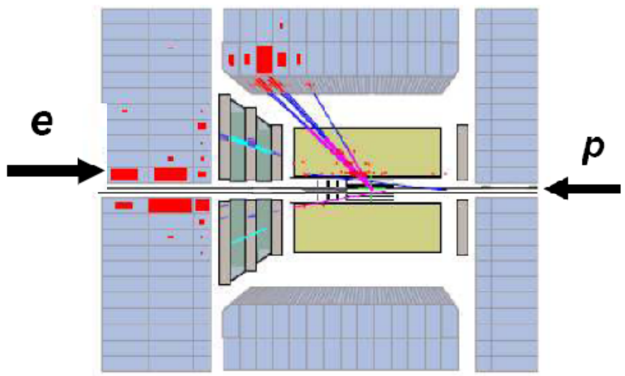
H1 NC event display



Charged Current (CC)



ZEUS CC event display



Virtuality of exchanged boson:

$$Q^2 = -q^2 = -(k-k')^2$$

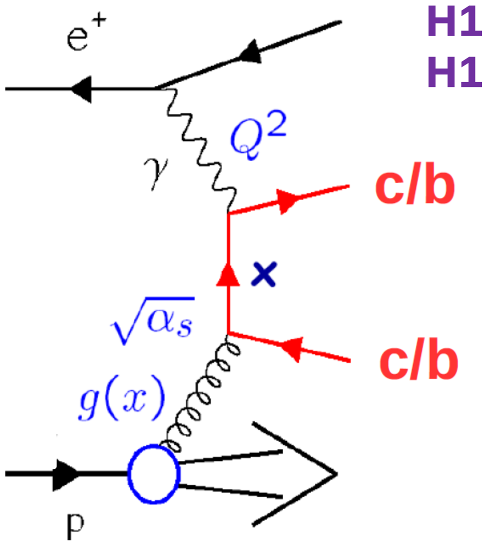
Fraction of proton momentum carried by struck quark

$$x = \frac{Q^2}{2p \cdot q}$$

Fraction of energy transferred from incoming lepton in proton rest frame

$$y = \frac{p \cdot q}{p \cdot k}$$

Production of heavy quarks in DIS



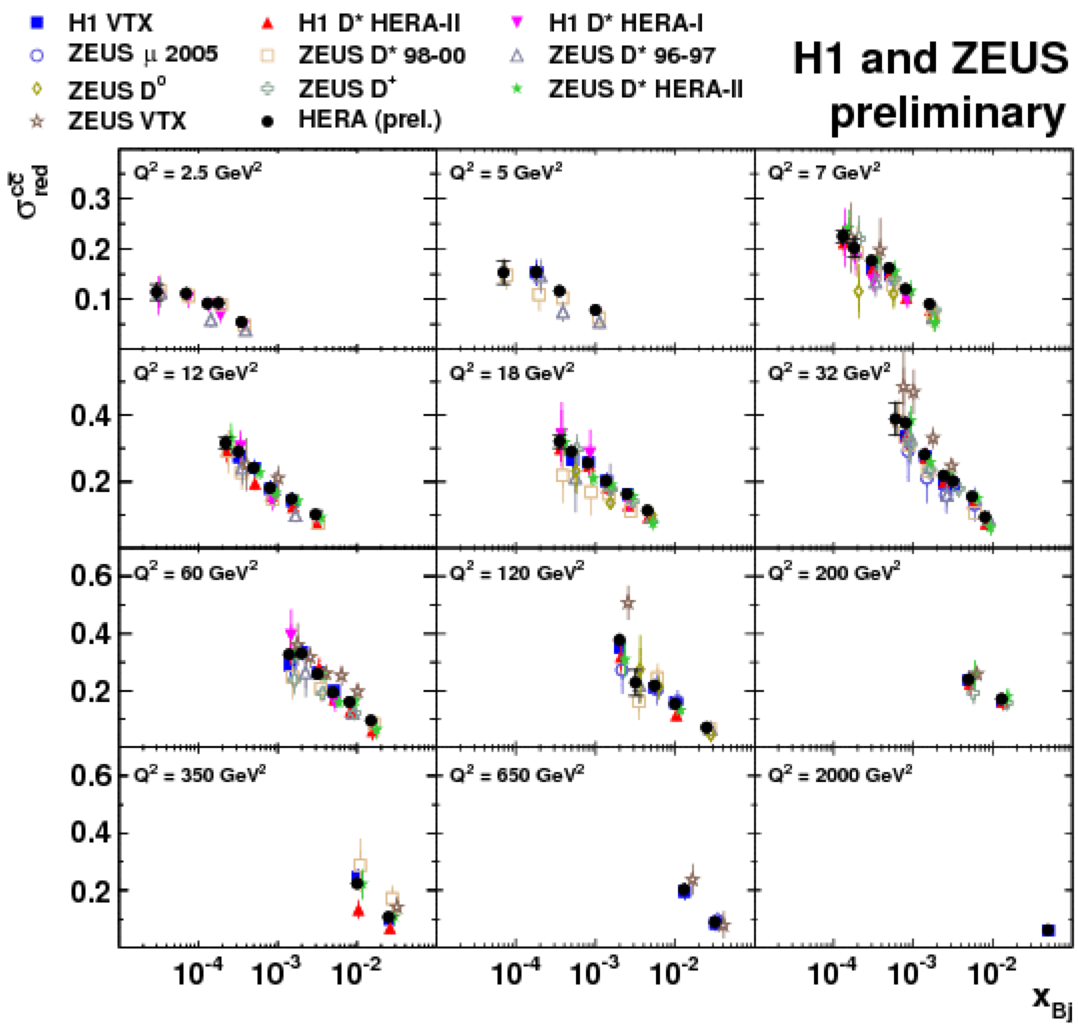
H1prelim-17-071 and ZEUS-prel-17-01
H1prelim-18-071 and ZEUS-prel-18-01-extension

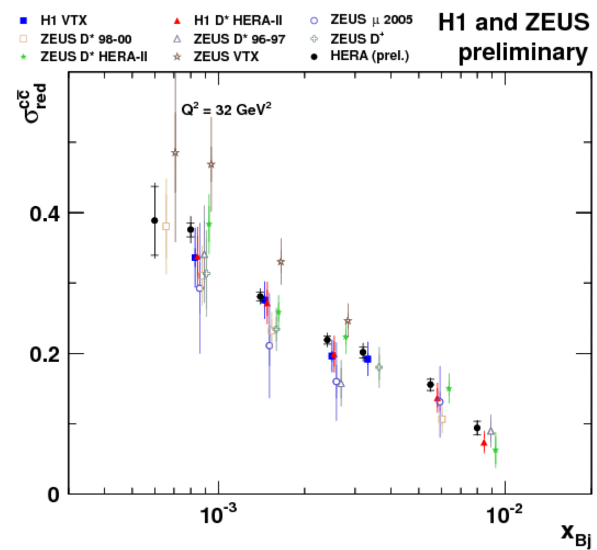
- Boson-gluon fusion - main source of heavy quarks
- Inclusive production – up to about 30 % is due to charm and up to 1 % due to beauty
- Reduced cross sections calculated as

$$\sigma_{\text{red}}^{Q\bar{Q}} = \frac{d^2\sigma^{Q\bar{Q}}}{dx_{\text{Bj}}dQ^2} \cdot \frac{xQ^4}{2\pi\alpha^2(1+(1-y)^2)}$$

- To improve precision, H1 and ZEUS combine their measurements based on different tagging techniques:
  - the reconstruction of particular decays of charmed mesons (8 data sets)
  - the inclusive analysis of tracks exploiting lifetime information (2 data sets)
  - reconstruction of leptons from heavy-flavour semi-leptonic decays (3 data sets)
- There are 8 new data sets (3 charm and 5 beauty data sets) compared to previous combination for charm cross sections (EPJ C73 (2013) 2311)

Combined charm cross section measurements

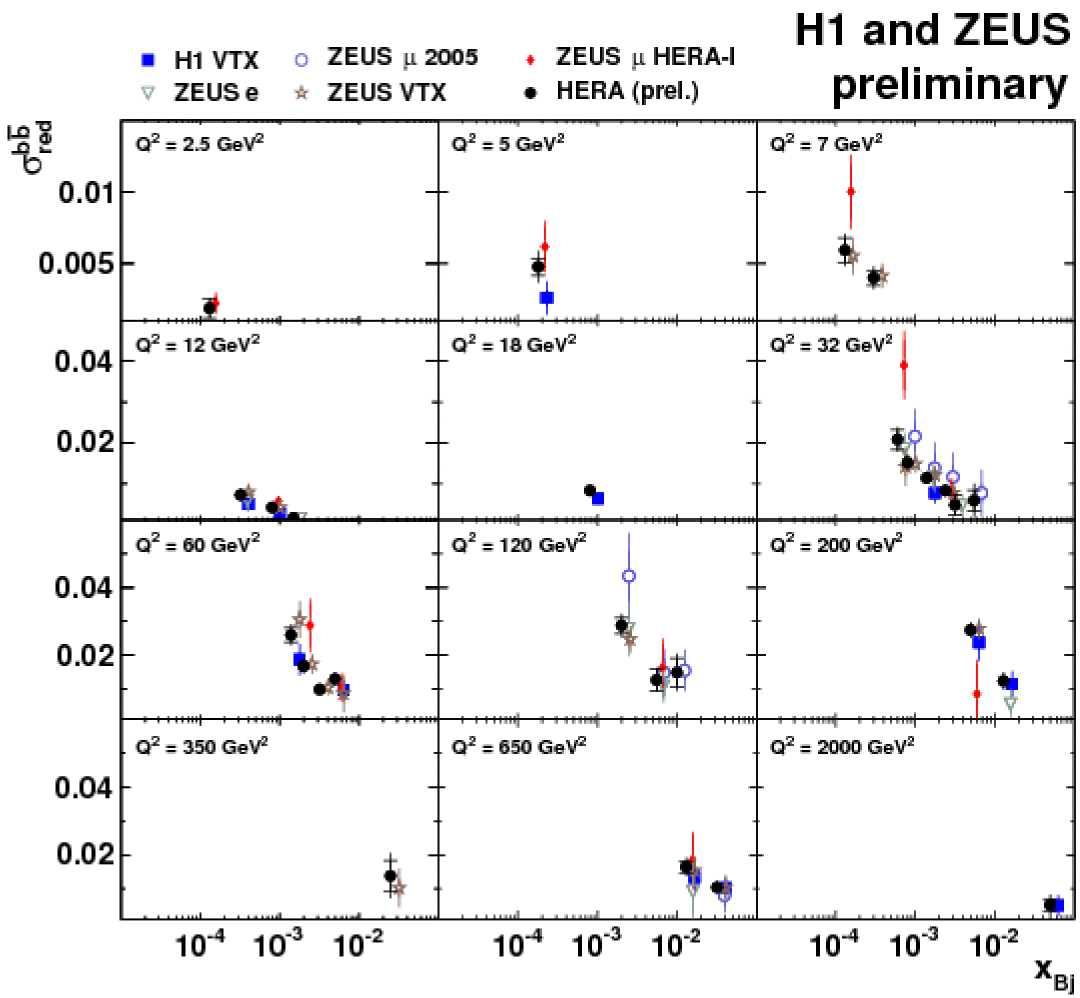


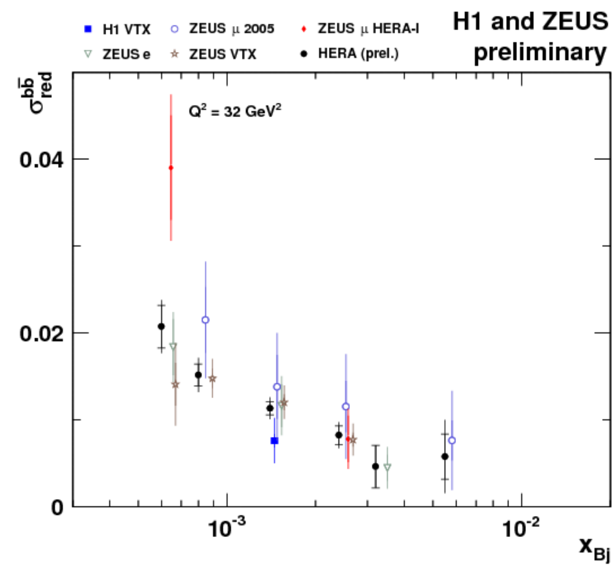


- ❑ 209 charm and 57 beauty data points combined simultneously to 52 reduced charm and 27 beauty cross sections

- ❑ The combination method accounts for the correlations of the statistical and systematic uncertainties among the different data sets

Combined beauty cross section measurements





- First combination of b cross sections

- χ^2/ndf = 149/187 – consistency of input data
- Significant improvement by data combination

Theory predictions

- NLO and NNLO predictions calculated with OPENQCDRAD interfaced in xFitter (www-zeuthen.desy.de/~alekhin/OPENQCDRAD and www.xfitter.org)

- Comparison of the data to theoretical predictions performed using input PDFs: HERAPDF2.0, ABKM09, ABMP16, NNPDF or fitted

  - in the FFNS NLO and approximate NNLO QCD
  - in the VFNS NLO and approximate NNLO QCD

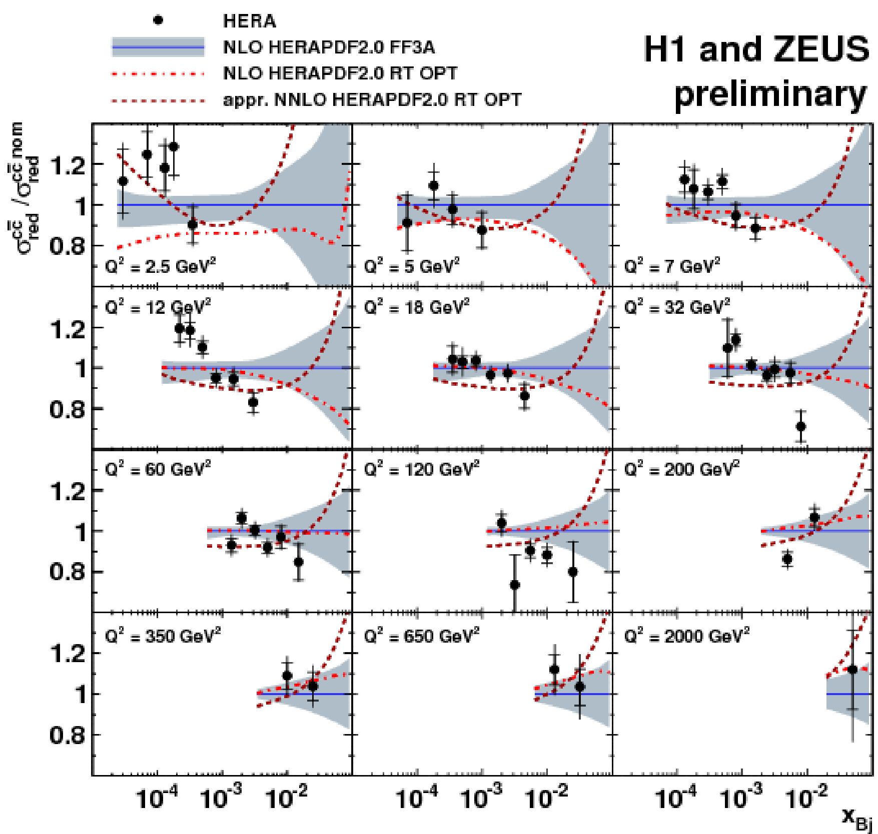
- $\mu_f = \mu_r = (Q^2 + 4m_Q^2)^{½}$ – dominant uncertainty (factor of 2 variations)

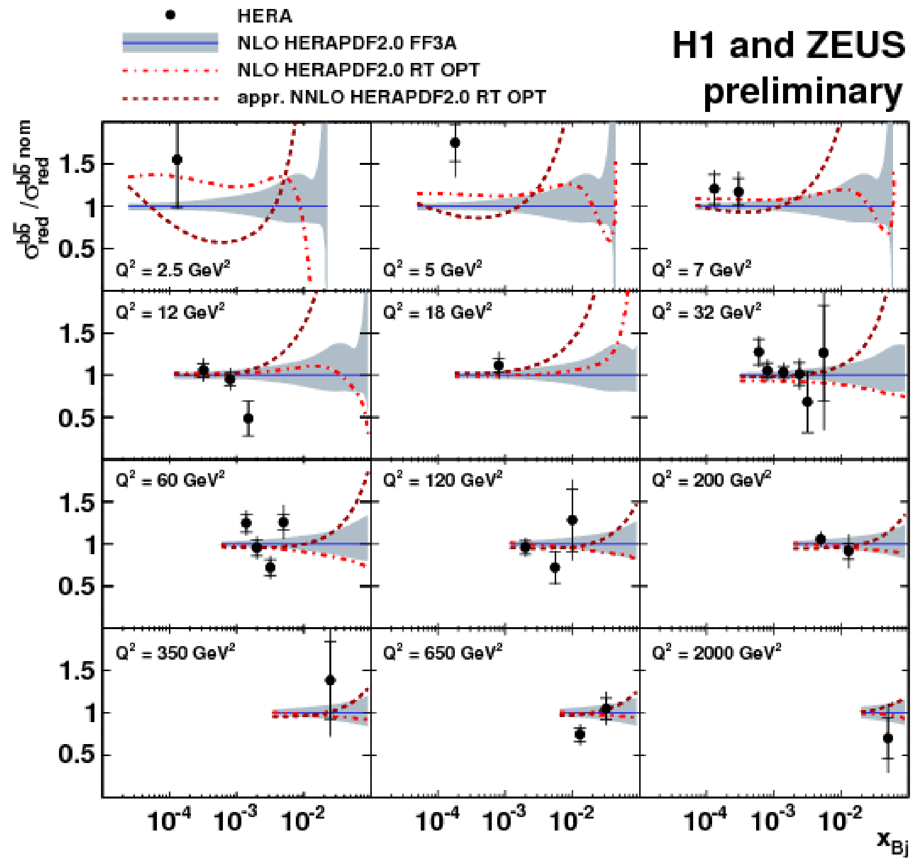
- $m_c(m_c) = 1270 \pm 30$ MeV, $m_b(m_b) = 4180 \pm 30$ MeV [PDG2016], or fitted

- Here, we show:

  - Comparison of the combined data and predictions obtained using HERAPDF2.0 at NLO using FFNS and at NLO and approximate NNLO using VFNS
  - QCD fit at NLO obtained from the combined data – HERAPDF-HQMASS
  - Results of determination of m_c and m_b

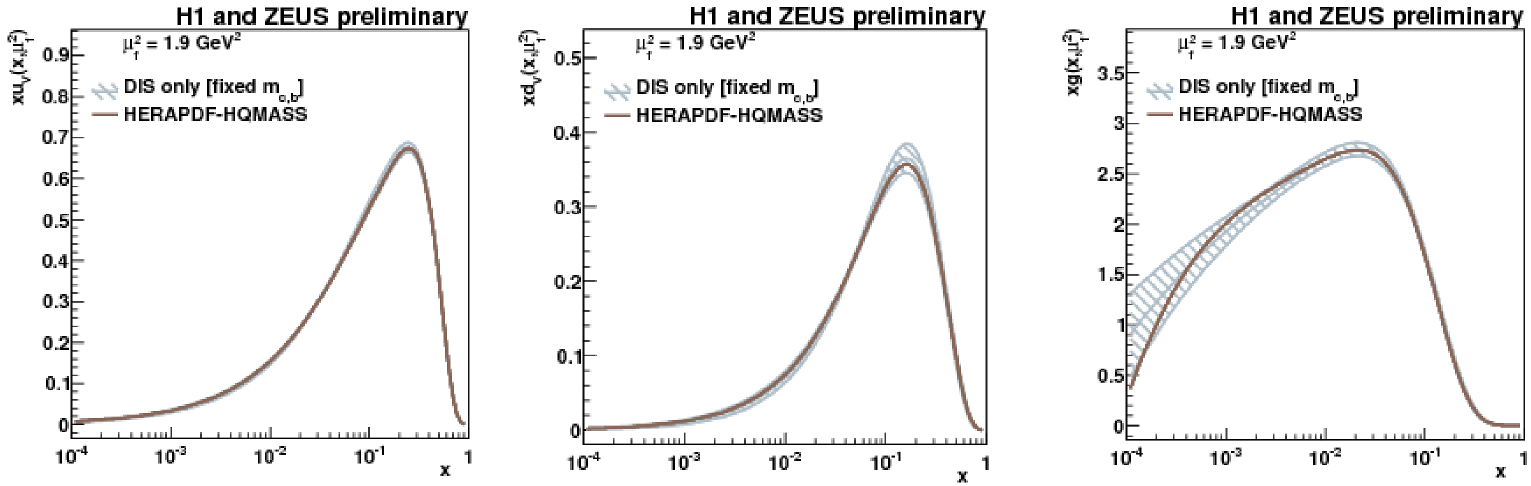
Combined data compared with theory predictions

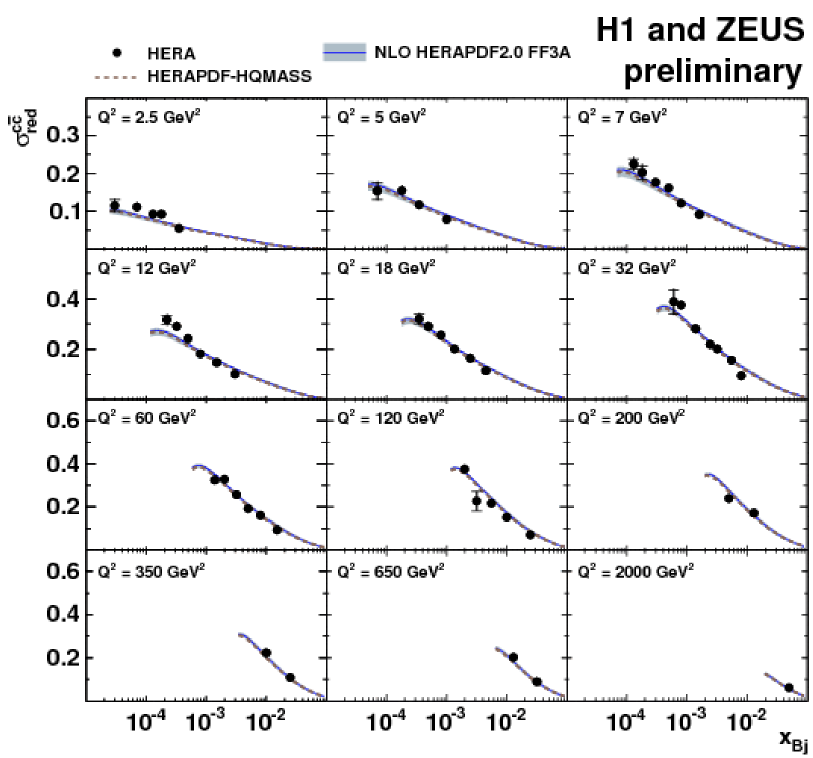




- Cross sections are normalized to NLO predictions using HERAPDF2.0 FF3A
- The uncertainties for VFNS predictions are of similar size to those presented for the FFNS calculation
- Overall reasonable description by NLO predictions
- Within the uncertainties the aNNLO provides fair description

HERAPDF-HQMASS and extracted m_c and m_b





- ❑ Only uncertainties for the fit to the inclusive data shown for better visibility
- ❑ Good agreement between the two fits
- ❑ With m_c and m_b as free parameters, QCD fit in NLO in FFNS (n_f = 3) performed using the combined heavy quark cross sections together with inclusive HERA data

$$m_c(m_c) = 1290^{+46}_{-41}(\text{fit})\,^{+62}_{-14}(\text{mod})\,^{+7}_{-31}(\text{par})\ \text{MeV}$$

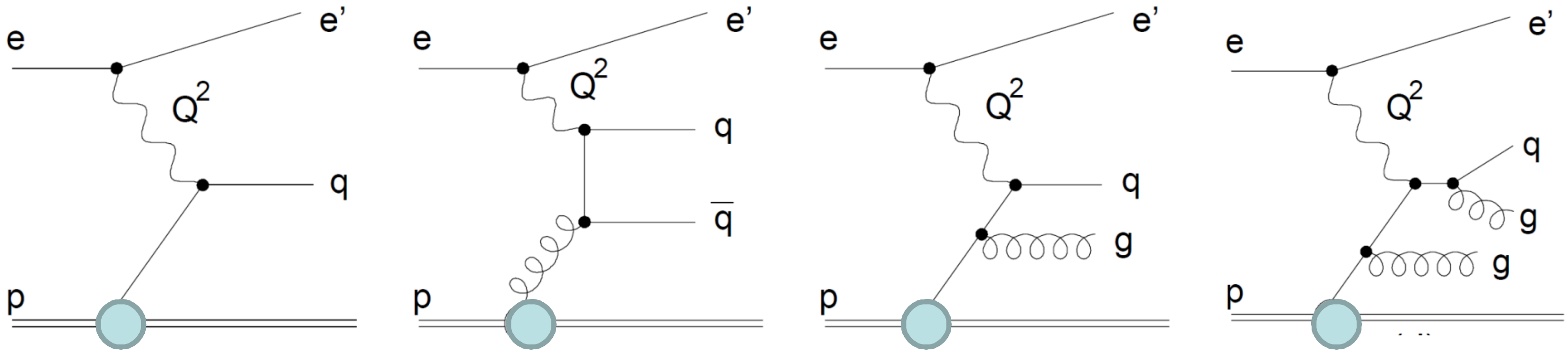
$$m_b(m_b) = 4049^{+104}_{-109}(\text{fit})\,^{+90}_{-32}(\text{mod})\,^{+1}_{-31}(\text{par})\ \text{MeV}$$

➢ Consistent with world average

$m_c(m_c)$ = 1270 ± 30 MeV, $m_c(m_b)$ = 4180 ± 30 MeV

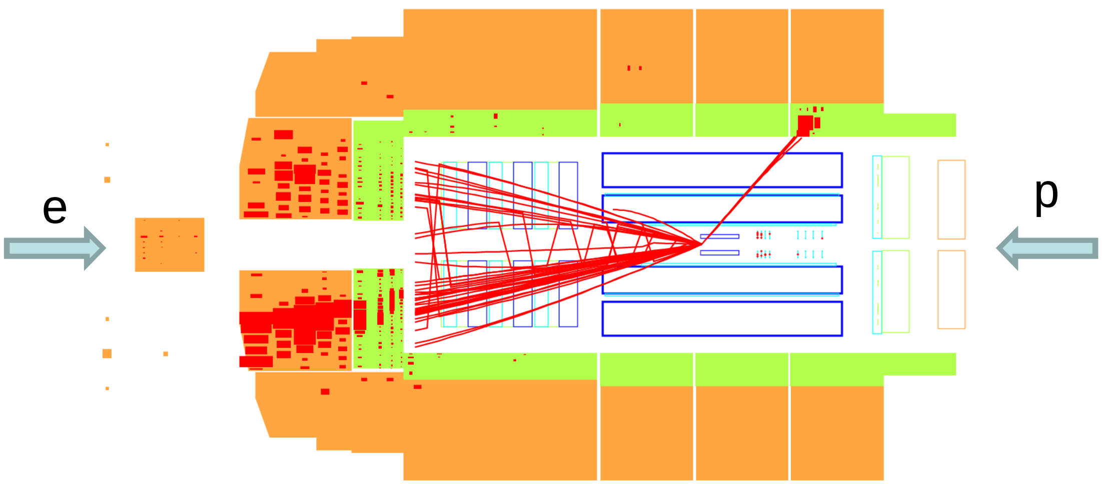
NNLO α_s fit of DIS jet data

Eur.Phys.J.C77 (2017), 79 [arxiv:1709.07251]



EW coupling | BG fusion ~ α_s | QCD Compton ~ α_s | ~ α_s^2

- Jet production directly sensitive to the strong coupling and has a clean experimental signature with sizable cross sections



Dijet production in NC DIS

NNLO α_s fit of DIS jet data

- Precise knowledge of α_s as one of the least known parameters of the SM crucial for:

➢ precision measurements

➢ consistency tests of the SM and

➢ searches for physics beyond the SM.

→ Very important for LHC physics

- Complete predictions at NNLO for jet production in DIS are now available- about 25 years after NLO calculations for jet production cross sections in DIS have been available for the first time
  - for inclusive jet and dijet production in DIS
    J. Currie, T. Gehrmann and J. Niehues, Phys. Rev. Lett. 117 (2016) 042001, arXiv:1606.03991.
    J. Currie, T. Gehrmann, A. Huss and J. Niehues, JHEP 1707 (2017) 018,

- Jets are defined in the Breit frame (the virtual boson and the proton collide head on) using the k_t clustering algorithm with a resolution parameter R = 1

- Common to all used jet data sets is requirement on the pseudorapidity of the jets, $-1 < \eta_{lab}^{jet} < 2.5$

NNLO calculations

- $\alpha_s(m_Z)$ is determined from inclusive jet and dijet cross sections in NC DIS measured by the H1 collaboration and using NNLO QCD predictions.

$$\underbrace{\sigma_i}_{\text{Cross sect. for i-th interval of a given phase space}} = \sum_{k=g,q,\bar{q}} \int dx \underbrace{f_k(x,\mu_F)}_{\text{PDFs}} \underbrace{\hat{\sigma}_{i,k}(x,\mu_R,\mu_F)}_{\text{Perturbatively calculated partonic cross sections Matrix Elements (ME)}} \cdot \underbrace{c_{\mathrm{had},i}}_{\text{Accounts for non-pert. effects (hadronisation corrections)}}$$

Cross sect. for i-th interval of a given phase space

PDFs

Perturbatively calculated partonic cross sections Matrix Elements (ME)

Accounts for non-pert. effects (hadronisation corrections)

both parts α_s dependent

- The jet cross section calculations are performed using the program NNLOJET which is interfaced to fastNLO to provide efficient, repeated calculations with different values of α_s, different scale choices and different PDF sets.

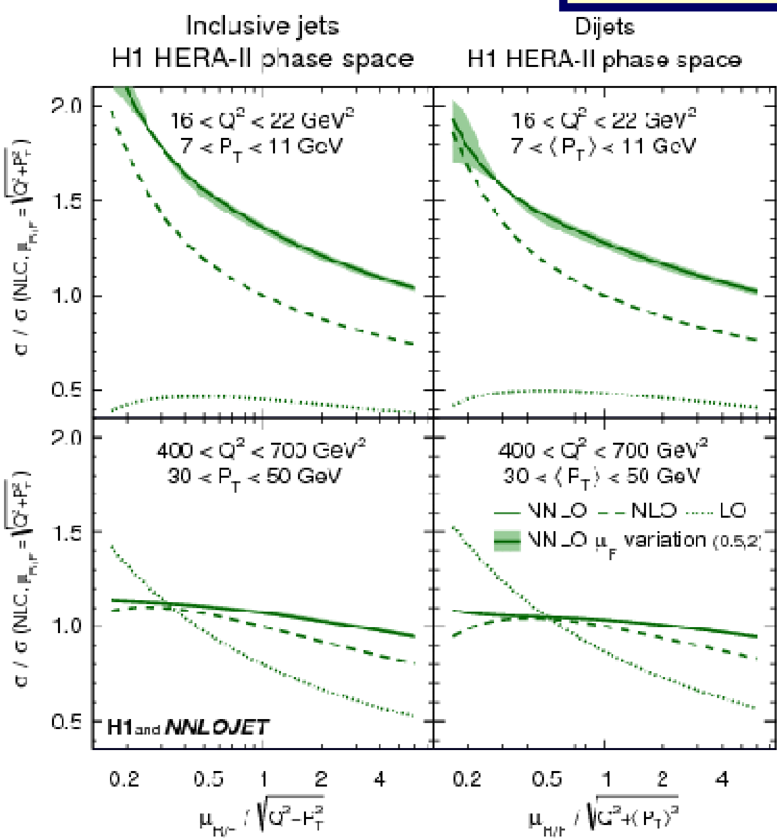
- Two approaches:

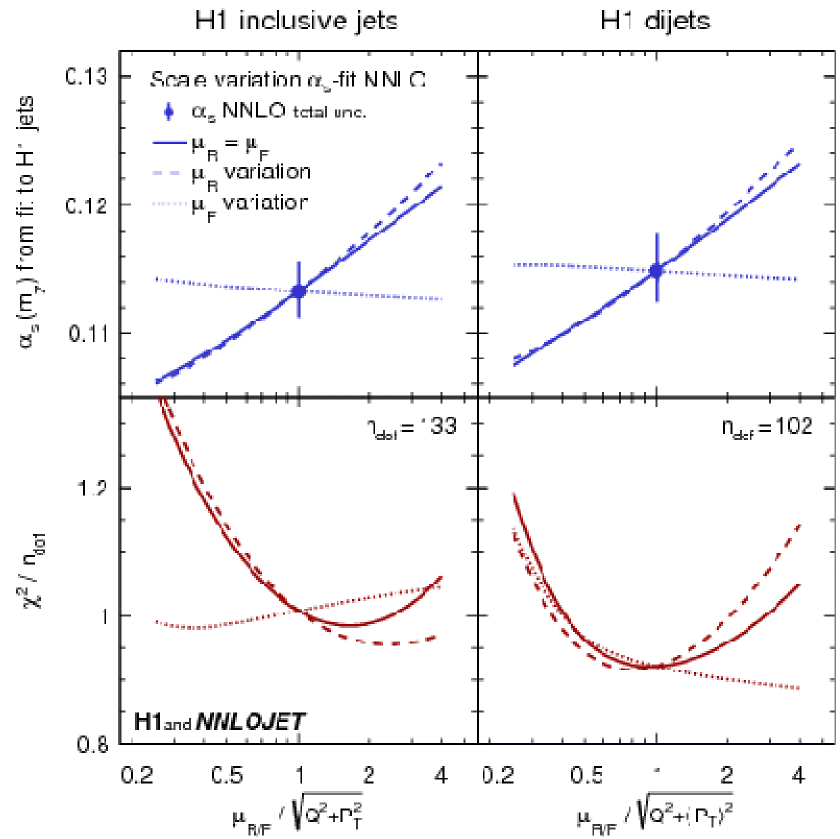
➢ The value of α_s determined in NNLO from inclusive and dijet data using pre-determined PDFs as input. The evolution starting scale μ_0 = 20 GeV.

➢ The value of α_s determined together with the PDFs from inclusive DIS data and jet data.

- The scales are chosen to be: $\mu_R^2 = \mu_F^2 = Q^2 + P_T^2$.

Scale dependence

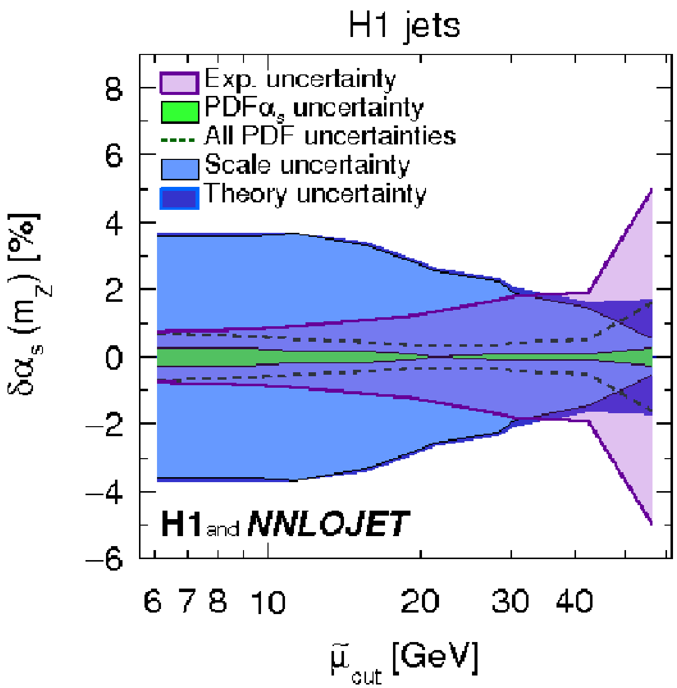




- The strongest dependence on the scale factor at lower values of μ_R (lower Q^2 and P_T)
- NNLO predictions less dependent on the scale factor than the NLO predictions

- Variations of μ_R have a larger impact on the result than those of μ_F
- The scale choice yields reasonable value of χ^2/ndf

$\alpha_s(M_Z)$ uncertainties and alternatives for scales

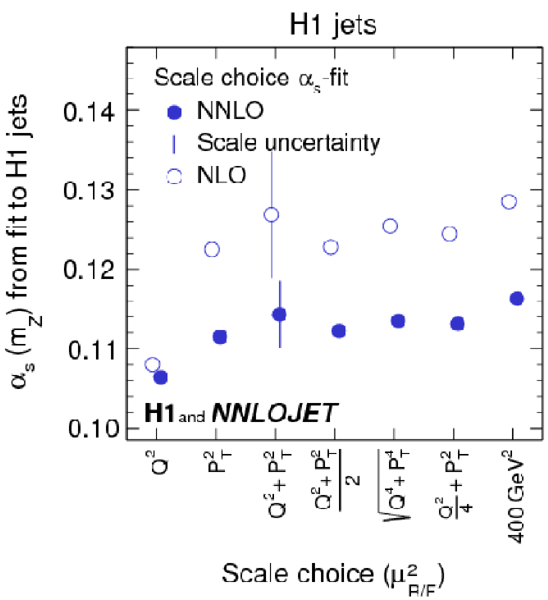


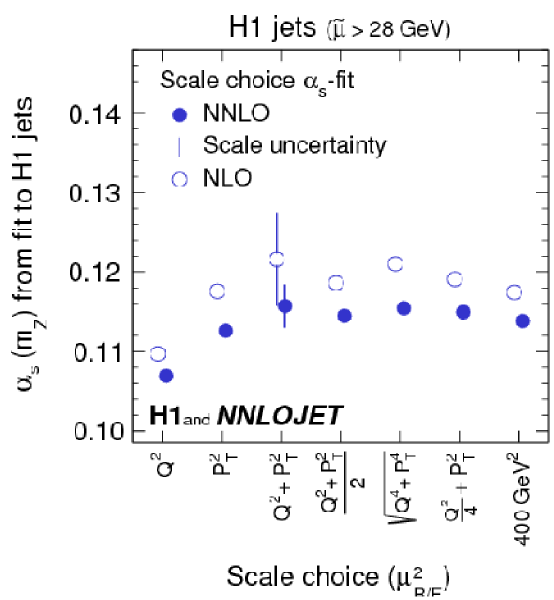
- Obtained for $\bar{\mu} > \mu_{cut}$
- Scale uncertainty increases at smaller scales
- Exp. uncertainty increases at larger scales
- Compromise: Only data with $\bar{\mu} > 28$ GeV used in the fit

➢ $\alpha_s(M_Z)$ value obtained from H1 jet data

$$\alpha_s(m_Z) = 0.1157\ (20)_{exp}(6)_{had}(3)_{PDF}(2)_{PDF\alpha s}(3)_{PDFset}(27)_{scale}$$

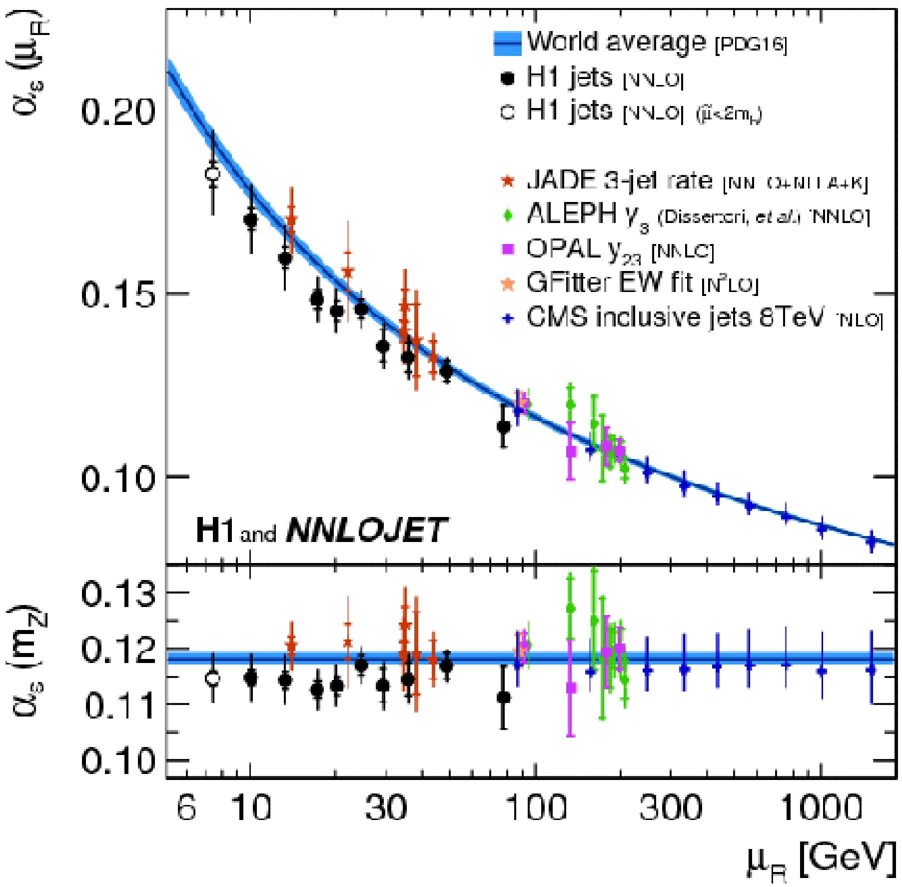
NNPDF3.1

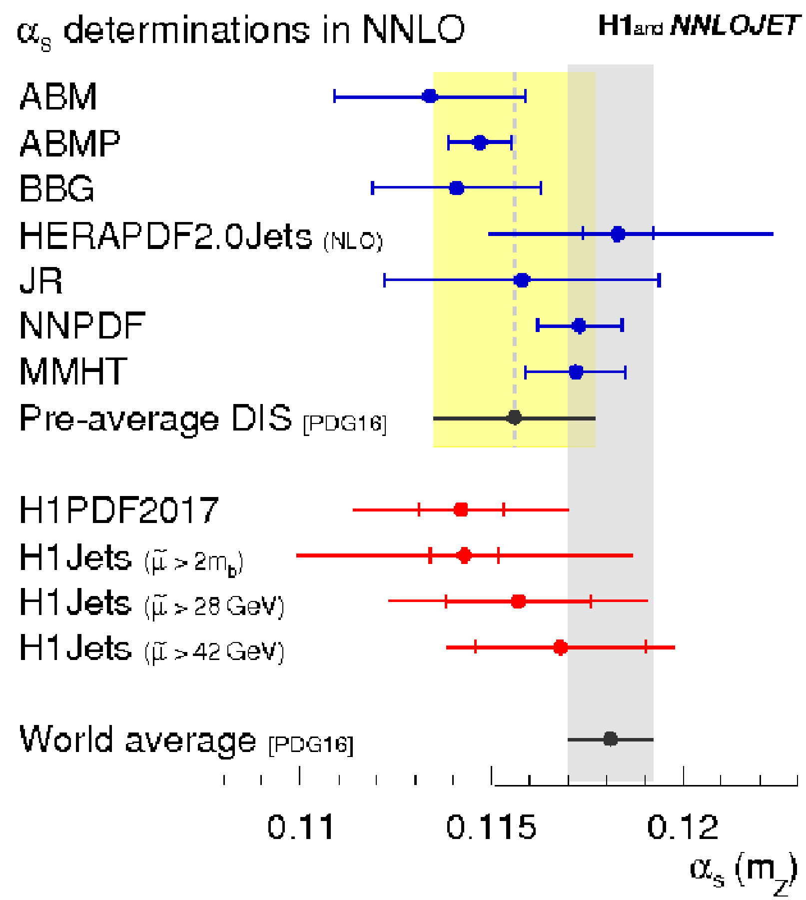




- Values of obtained for various definitions of μ_R and μ_F
- Not shown but measured that χ^2/nodf is almost two times worse for $\mu_R = \mu_F = Q^2$ than for other choices

α_s results





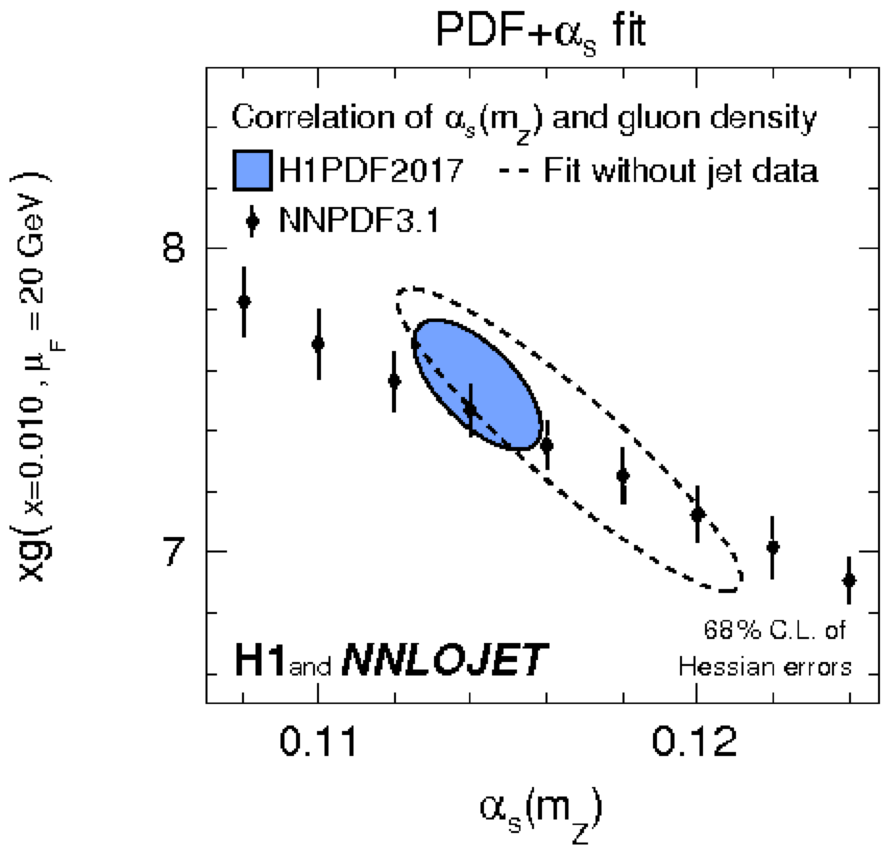
- The fitted values of $\alpha_s(M_Z)$ are translated to $\alpha_s(\mu_R)$ using the solution of the QCD renolmasation group equation
- **H1PDF2017** [NNLO] – PDF+α_s fit from inclusive and jet data

$$\alpha_s(m_Z) = 0.1142\ (11)_{exp,had,PDF}(2)_{mod}(2)_{par}(26)_{scale}$$

- Scale uncertainty reduced about two times in NNLO
- The theoretical scale uncertainty still dominates

Gluon density and α_s

- Error ellipse of 68 % confidence level of α_s and the gluon density as a result of two different fits



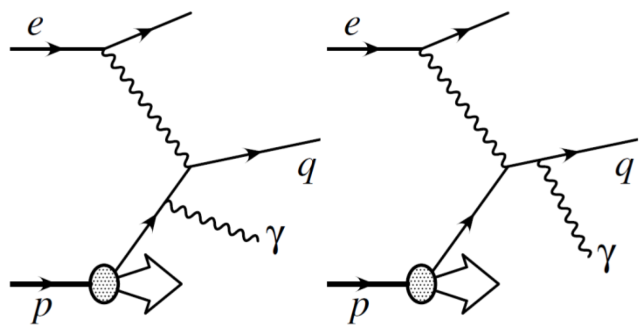
- The inclusion of jet data significantly reduces α_s and xg uncertainties

- All H1 jet data together with all inclusive H1 data provide simultaneous determination of xg and with xg with precision comparable to global PDF fits obtained at fixed value of α_s

Prompt photon accompanied by jet in DIS

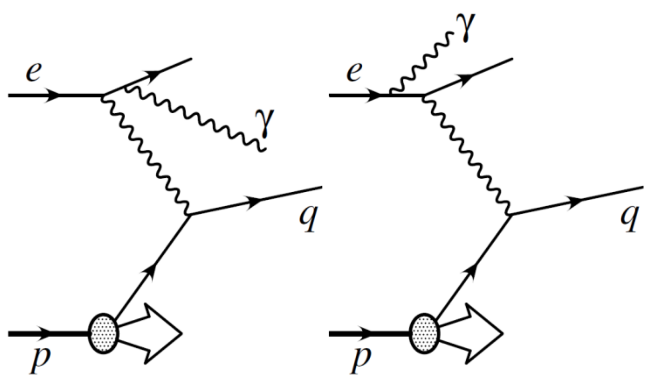
JHEP 1801 (2018) 032 [arXiv:1712.04273]

- Photons are emitted from incoming or outgoing quark (QQ-photons) or lepton (LL-photons)



QQ – photons

- γ is emitted from quark as part of hard process similar to multi-jets



LL - photons

- γ is radiated from incoming or outgoing lepton (theoretically very well determined)

- Prompt photons unaffected by parton hadronisation

→ Provide information on the structure of the proton and give a probe of underlying partonic process

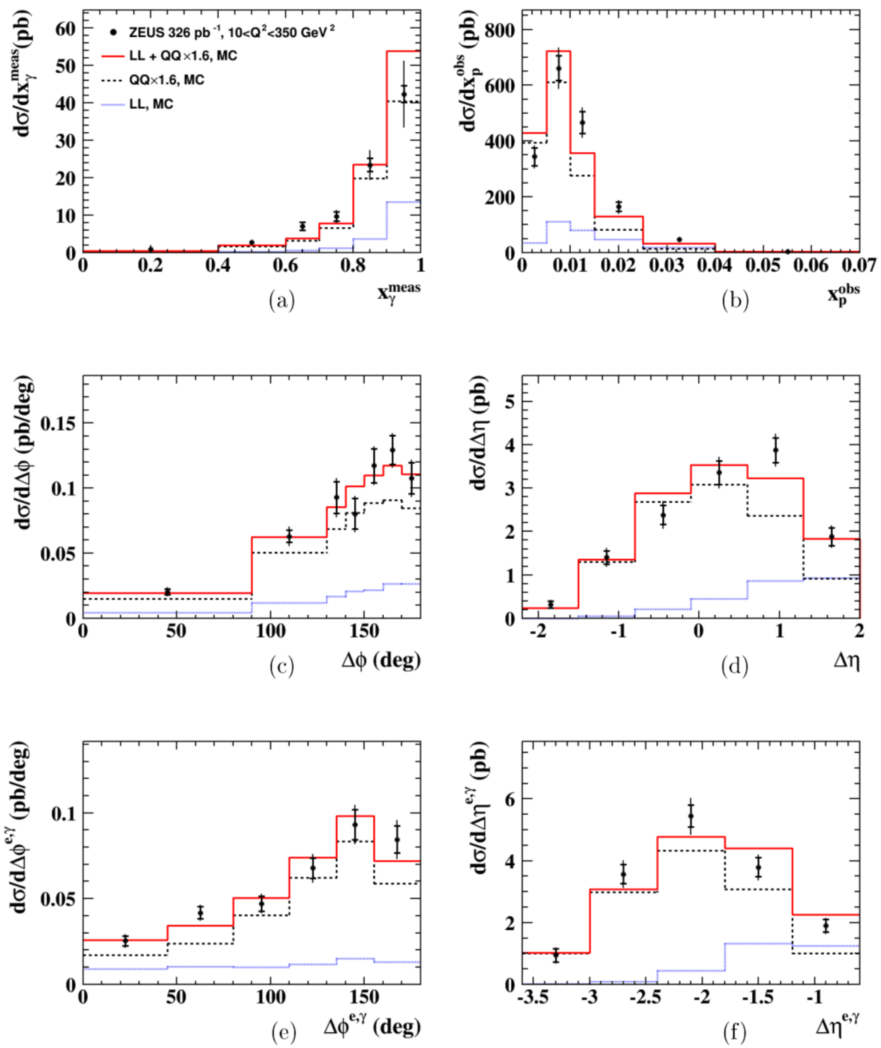
→ Complements previous result (Phys. Lett. B 715 (2012) 88)

Prompt photon accompanied by jet in DIS

ZEUS-prel-16-001

- $x_\gamma^{meas}, x_p^{obs}$ – fraction of the exchanged photon (proton) energy taken by γ+jet

$\Delta\phi, \Delta\eta$ ($\Delta\phi_{e,\gamma}$, $\Delta\eta_{e,\gamma}$) - separations of photon and jet (scattered electron)

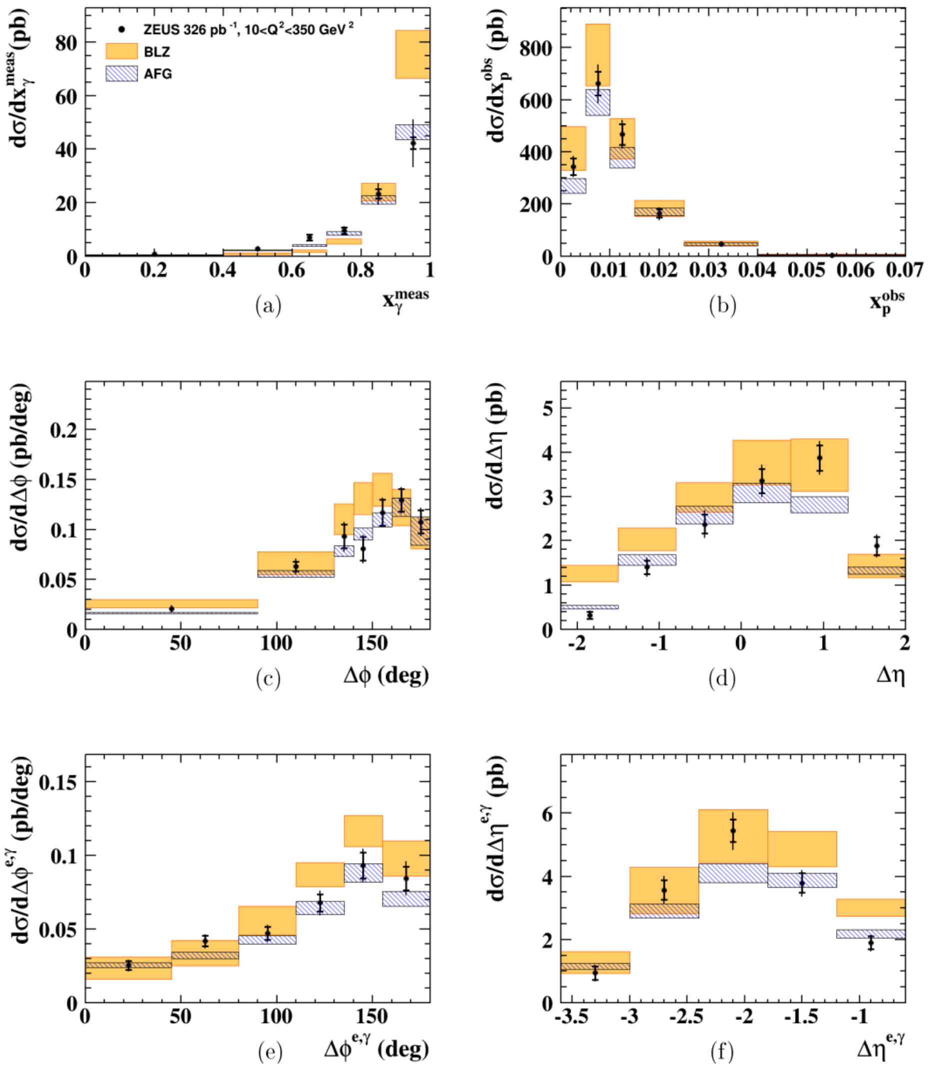


- ❑ Djangoh (LL contribution) and Pythia (QQ contribution)
- ➢ Reweighting of Pythia by 1.6 provides good description

Prompt photon accompanied by jet in DIS

- x_γ^{meas},x_p^{obs} – fraction of the exchanged photon (proton) energy taken by γ+jet

$\Delta\phi$,$\Delta\eta$ ($\Delta\phi_{e,\gamma}$, $\Delta\eta_{e,\gamma}$) - separations of photon and jet (scattered electron)



- ❑ BLZ (Baranov, Lipatov, Zotov) model (**PR D 81 (2010) 094034)**
  - ➢ x_γ^{obs} and $\Delta\eta$ distribution not described by k_T-factorisation
- ❑ AFG (Aurenche, Fontannaz, Guillet) model **(EPJ C 75 (2015) 64)**
  - ➢ Collinear factorisation in NLO provides reasonable description of the data

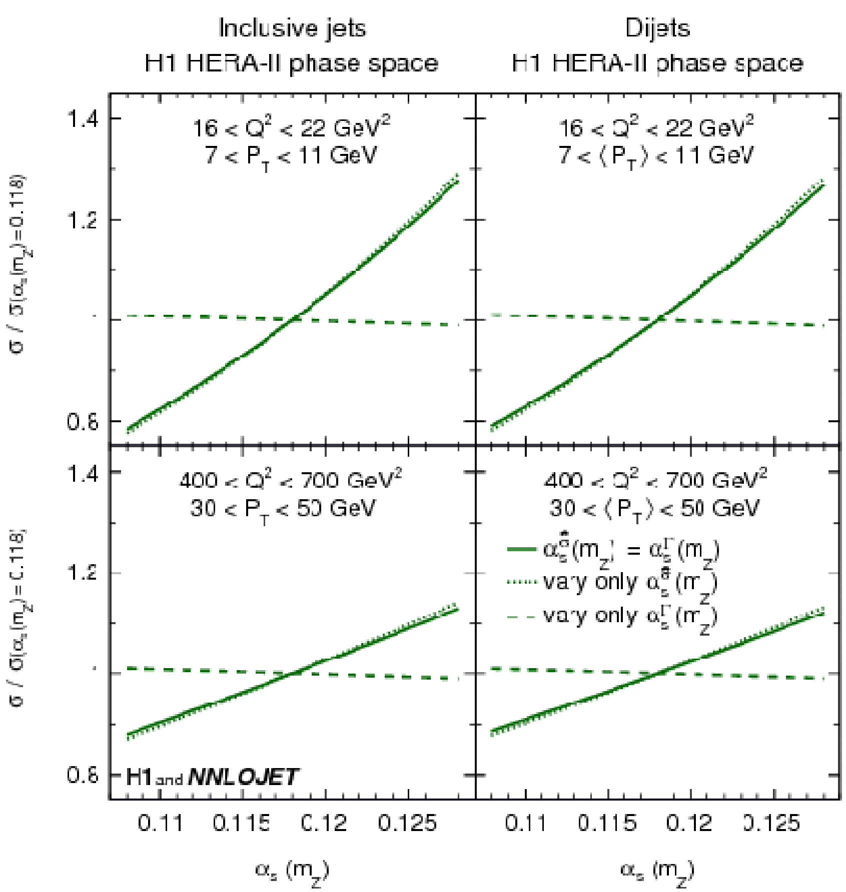
Summary

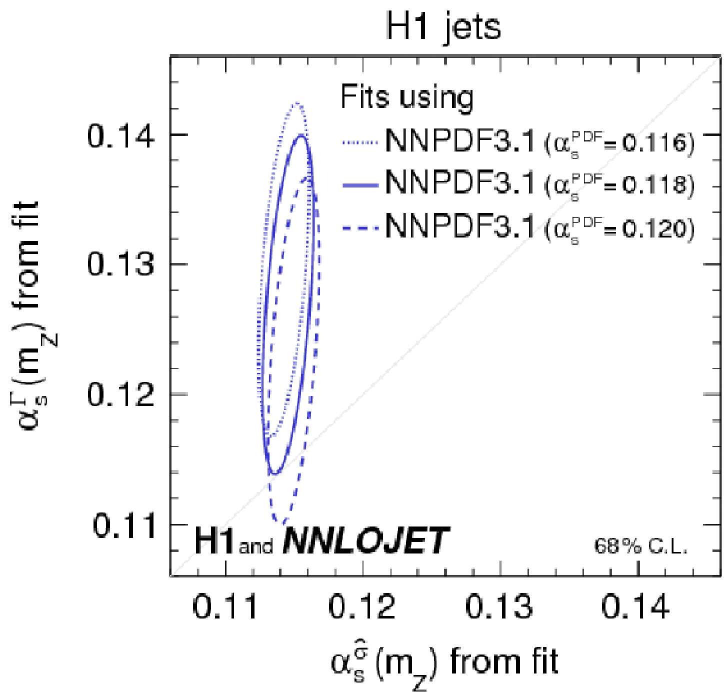
- **Combined results on charm and beauty cross sections in DIS by H1 & ZEUS**
  - significant improvement in precision
  - FFNS and VFNS (RT OPT) in NLO and aNNLO provide fear description of data
  - PDF fit of charm and beauty cross sections together with inclusive data from HERA alone yields values for running quark masses consistent with PDG

- **First determination of α_s from DIS jet data at NNLO**
  - The obtained value consistent with world average and competitive with LHC and LEP measurements
  - The NNLO calculations reduce the dominating scale uncertainty in comparison to previous NLO calculations
  - The first precision extraction of $\alpha_s(m_Z)$ from jet data at NNLO involving a hadron in the initial state

- **New ZEUS results on prompt photons acompained by jets in DIS**
  - good agreement with Djangoh and Pythia after rescaling QQ contribution in Pythia
  - reasonably described with collinear factorisation NLO (AFG)
  - not good description with k_T factorisation (BLZ)

$\alpha_s(M_Z)$ in PDF and in ME





- ❑ PDFs well constrained at scale μ_0 = 30 GeV by large amount of data and are not so sensitive to α_s

- ❑ Consistency of α_s from PDF and ME

➢More sensitivity to α_s comes from MEs

Ratio of jet cross sections to NNLO predictions

- Obtained with α_s from the fit of inclusive jet and dijet data

$$\alpha_s(m_Z) = 0.1157\ (20)_{exp}\ (6)_{had}\ (3)_{PDF}\ (2)_{PDF\alpha s}\ (3)_{PDFset}\ (27)_{scale}$$