Jet production and QCD measurements at HERA

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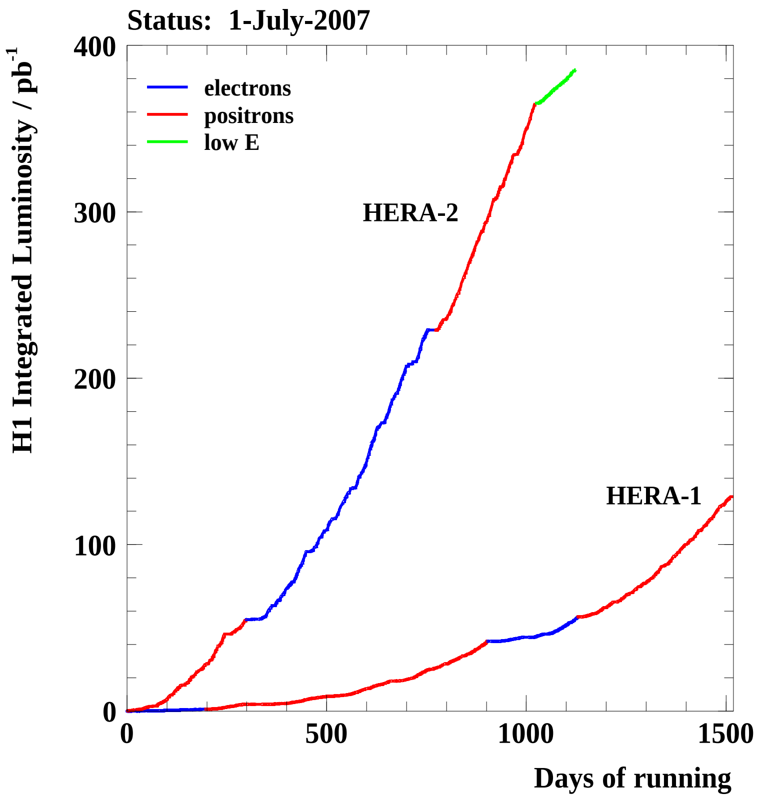
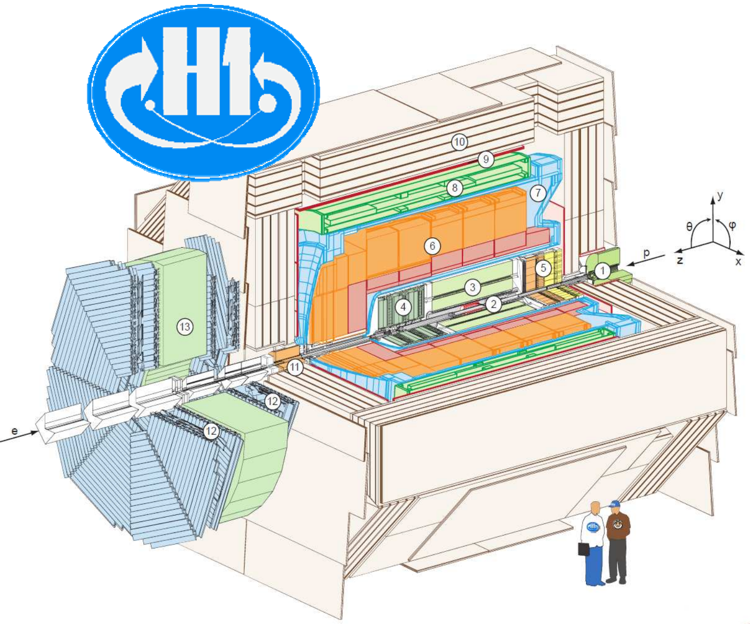
pikabu.ru

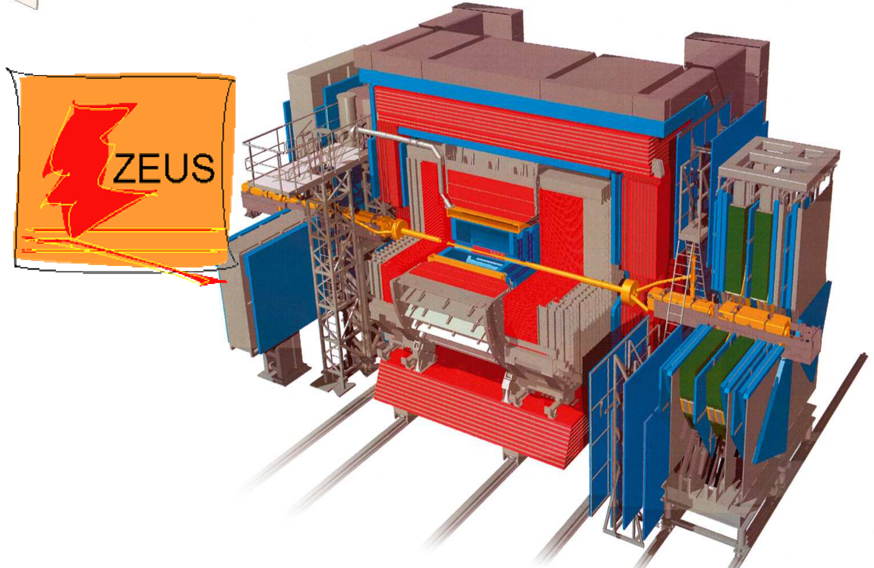
HERA with the H1 and ZEUS detectors

HERA $e^{\pm}p$ collider

- $\sqrt{s}$ = 319 GeV
  - E_e = 27.6 GeV
  - E_p = 920 GeV
- Operational until 2007







Two multi-purpose experiments: H1 and ZEUS

- Luminosity: ~0.5 fb^{-1} per experiment
- Excellent control over experimental uncertainties
  - Overconstrained system in DIS
  - Electron measurement: 0.5 – 1% scale uncertainty
  - Jet energy scale: 1%
  - Trigger and normalisation uncertainties: 1-2 %
  - Luminosity: 1.8 – 2.5%

Inclusive deep-inelastic *ep* scattering (DIS)

***ep* scattering:** $e^{\pm}p \rightarrow e^{\pm} + X$

- Center-of-mass energy

$$\sqrt{s} = \sqrt{(k+p)^2}$$

- Virtuality of exchanged boson

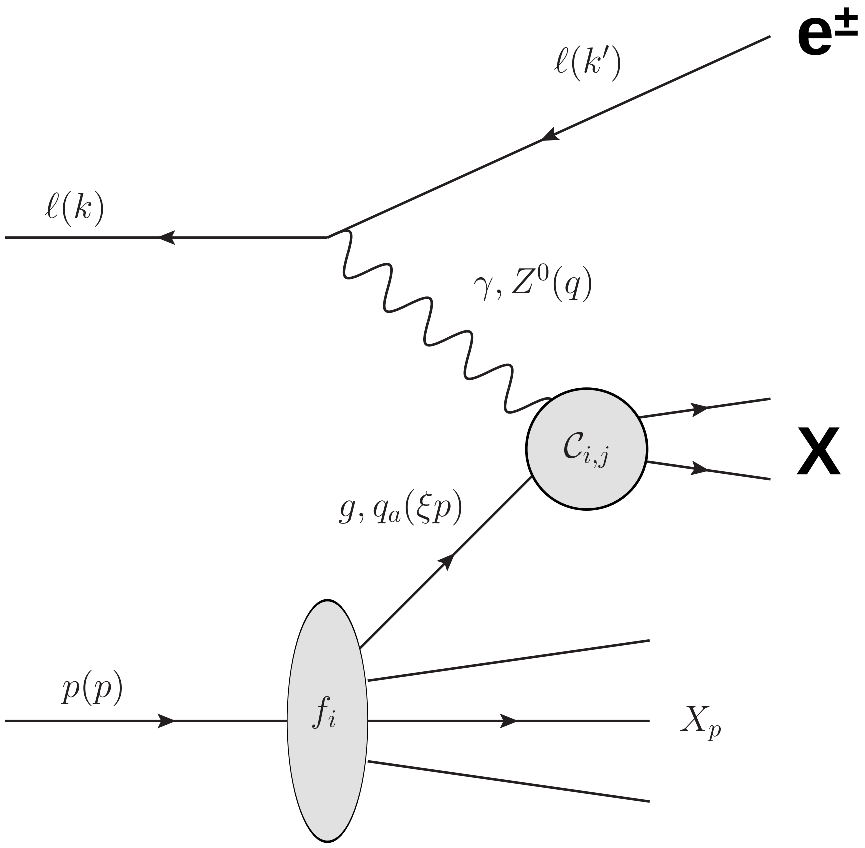
$$Q^2 = -q^2 = -(k-k')^2$$

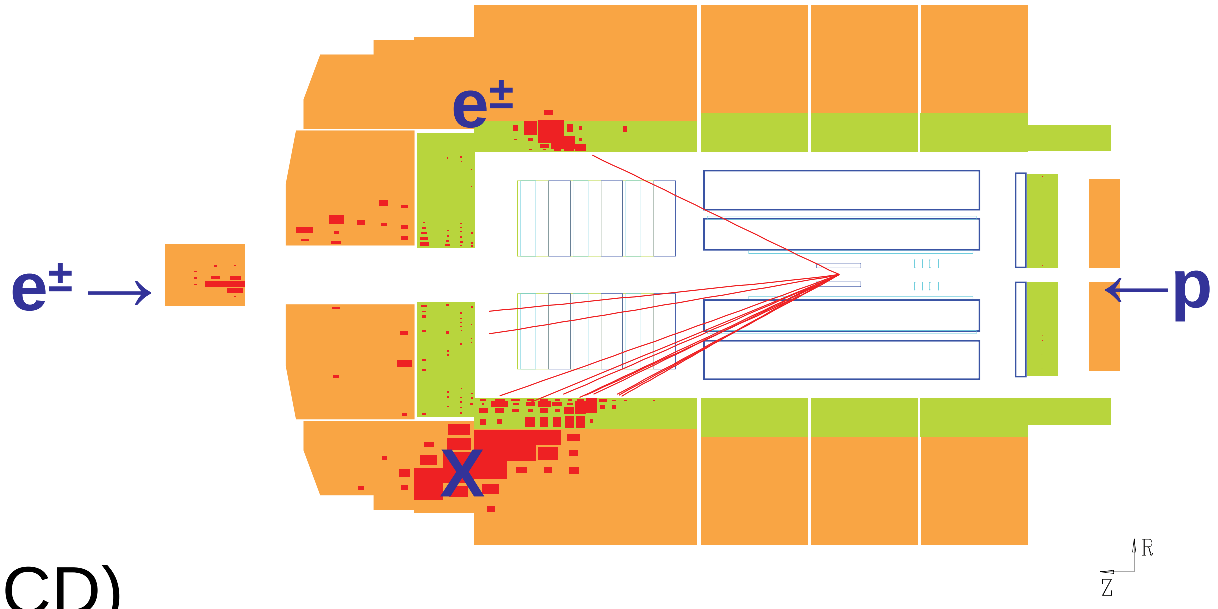
- Bjorken scaling variable

$$x_{\mathrm{Bj}} = \frac{Q^2}{2p \cdot q}$$

- Inelasticity

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



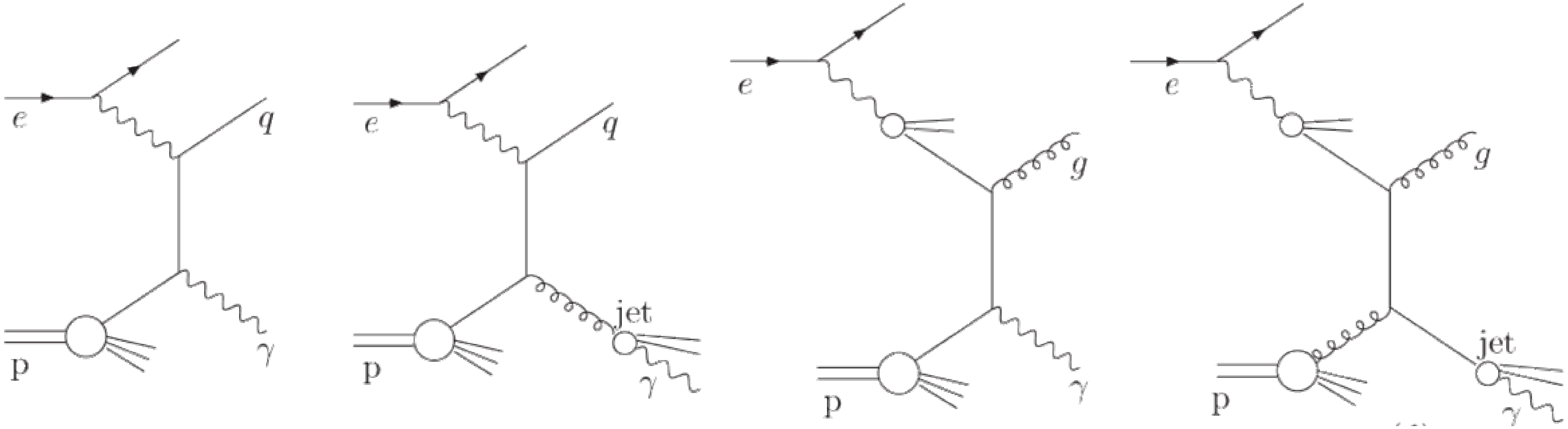


Cross section calculation

- Collinear factorisation
- Hard scattering calculable in QCD (pQCD)
- PDFs have to be determined from experiment

ZEUS Coll. Phys Lett B 730 (2014) 293

Prompt photons in γp: ep → γ+X (+j) [+e]



Prompt photons in photoproduction ($Q^2 \rightarrow 0$ GeV^2)

- Direct ($x_\gamma^{\text{meas}} \rightarrow 1$) and resolved ($x_\gamma^{\text{meas}} < 0.8$) processes
- Prompt radiation and fragmentation

Partonic momentum fraction of the photon:

$$x_\gamma^{\text{meas}} = \frac{E^\gamma + E^{\text{jet}} - p_Z^\gamma - p_Z^{\text{jet}}}{E^{\text{all}} - p_Z^{\text{all}}}$$

Measured *with* and *without* accompanying jet [ZEUS Coll. Phys Lett B 730 (2014) 293]

Measured separately for direct- and resolved-enhanced region [arXiv:1405.7127]

Theory

FGH: NLO with fragmentation functions ($O(\alpha^3\alpha_s^2)$)

LMZ: k_T factorisation with unintegrated parton densities

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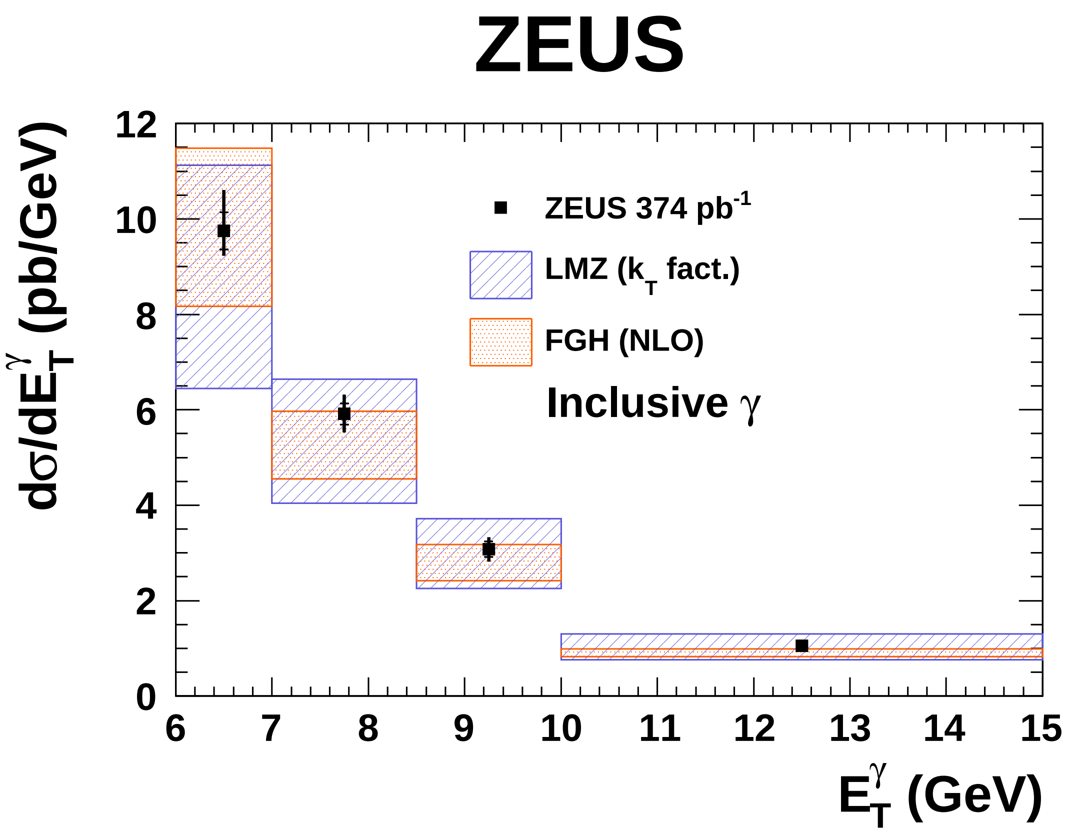
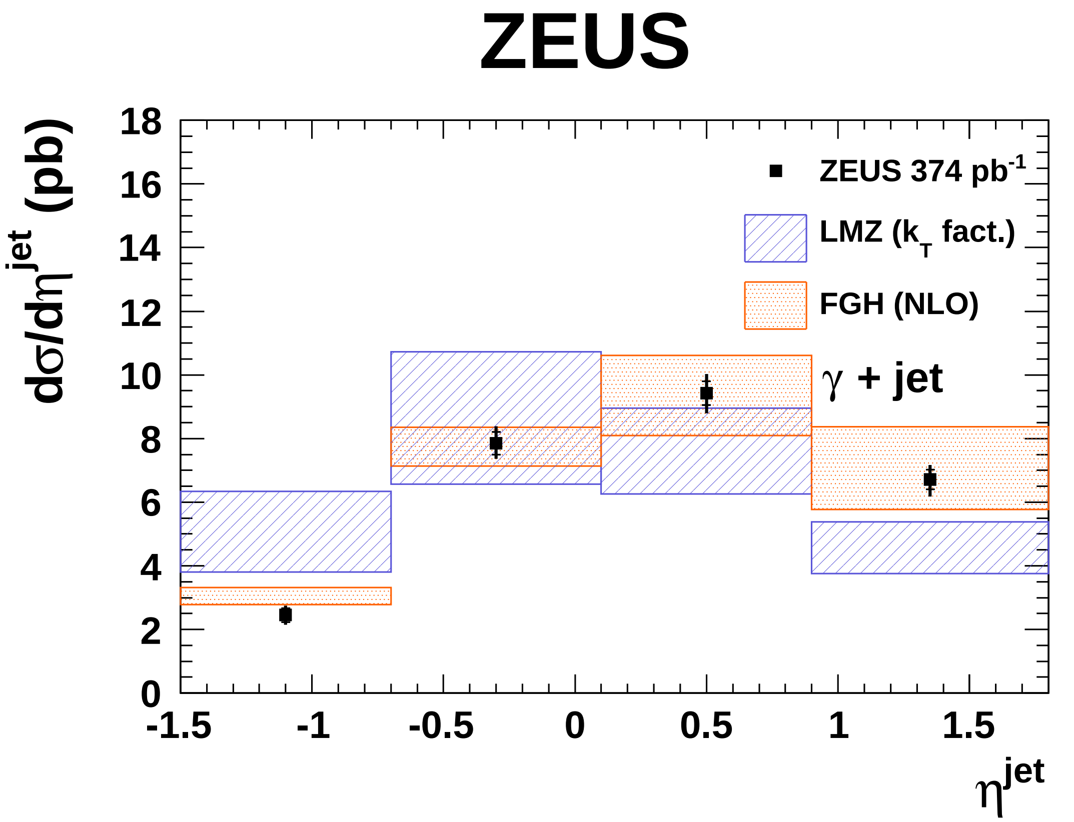
Prompt photons in γp: ep → γ+X (+jet) [+e]



Cross sections: Inclusive γ production

- NLO predictions give good description
- LMZ (k_t factorisation) give good description

- Experimental uncertainties are substantially smaller than theoretical ones

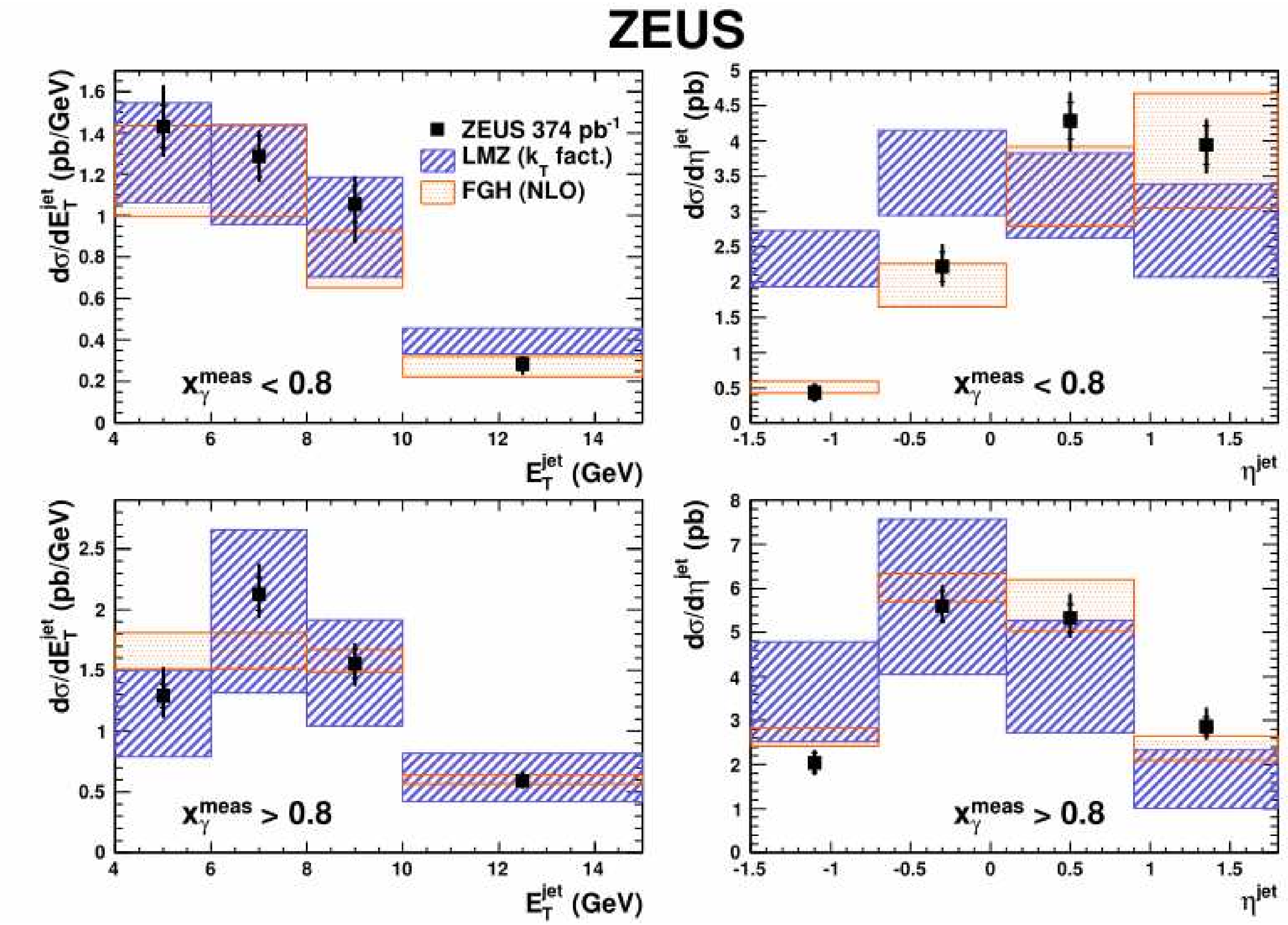


Cross sections: γ + jet

- In general both predictions agree well with data
  - Normalisation well described
  - Fixed order NLO give better description of η_{jet} shape

- Theoretical uncertainties are smaller compared to γ inclusive cross sections subm. to JHEP, arXiv:1405.7127

Further studies: ep → γ+jet+X [+e]



Cross section as function of jet variables in bins of x_γ^{meas}

- Both theories within large uncertainties agree well with the data
- Except LMZ in η^{jet} at $x_\gamma^{meas} < 0.8$

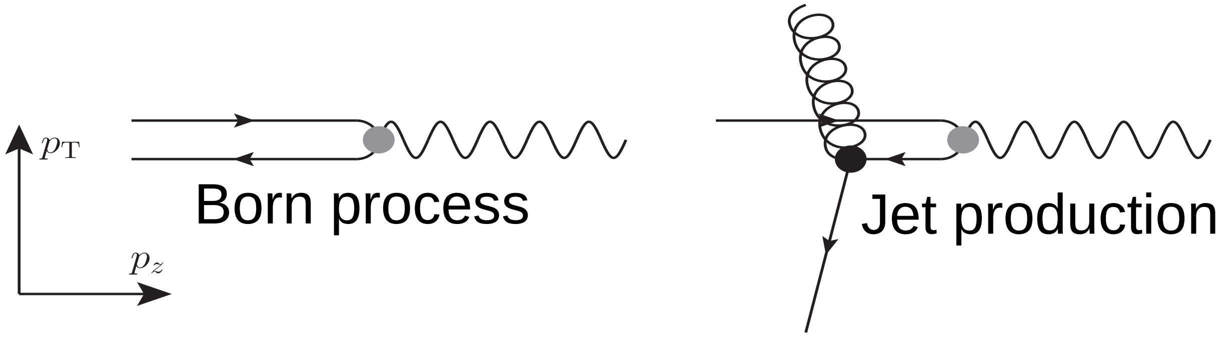
Further observables studied, like azimuthal difference, difference in pseudorapidity, …

See also talk by M. Nefedov on thursday

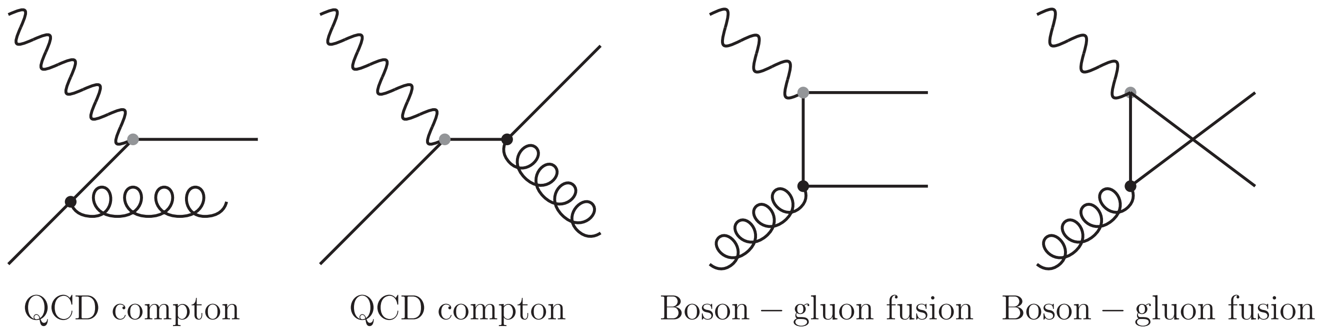
Jet production in neutral current DIS

Jet measurements performed in 'Breit frame'

Breit frame fullfils equation $2x_{\mathrm{Bj}}p + k = 0$

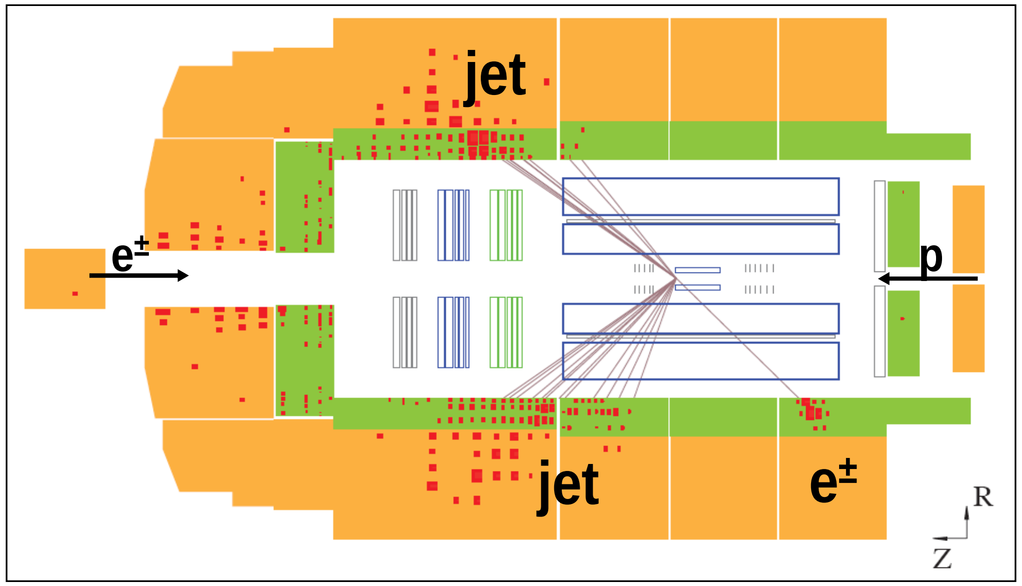


Jet production in leading-order pQCD



Jet production is directly sensitive to αs

Events show two-jet topology



Inclusive jet

Count every single jet

Measure transverse momentum

Dijet and trijet observable

Average momentum of two/three leading jets

$$\langle p_{\mathrm{T}}\rangle_2 = (p_{\mathrm{T}}^{\mathrm{jet1}} + p_{\mathrm{T}}^{\mathrm{jet2}})/2$$

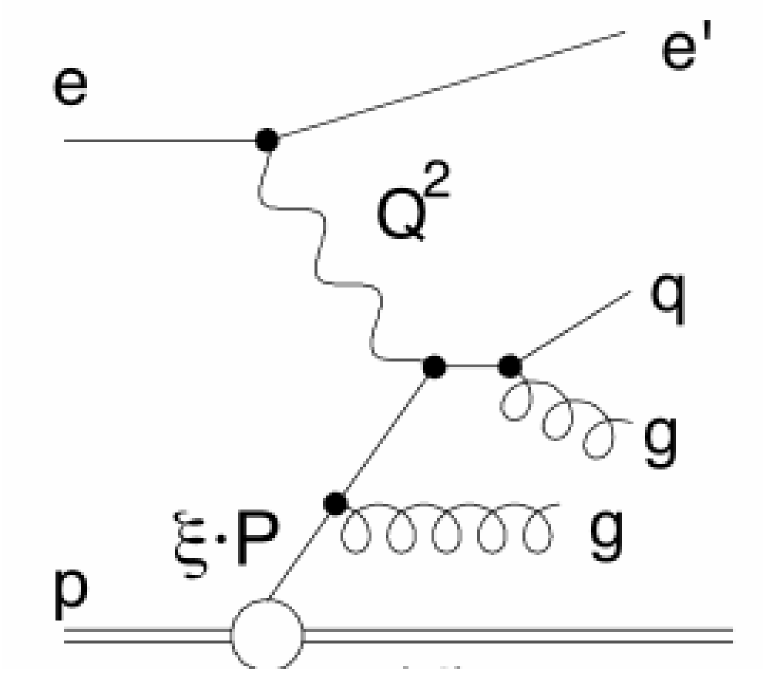
ZEUS-prel-14-008

Trijet measurement in DIS (ZEUS)

Trijet production in neutral current DIS has been measured

(ZEUS-prel-14-008) with:

- Photon virtuality $125 < Q^2 < 20000$ GeV^2
- Inelasticity: $0.2 < y < 0.6$
- Jet transverse momentum $E^{jet}_{T,B} > 8$ GeV



Statistics

- L =295pb^{-1}

A major source of systematic uncertainties:

jet energy scale ~1% (3%), for jets with $E^{jet}_{T,L}$ >10GeV (<10GeV)

NLO Calculation

NLOJet++ corrected for

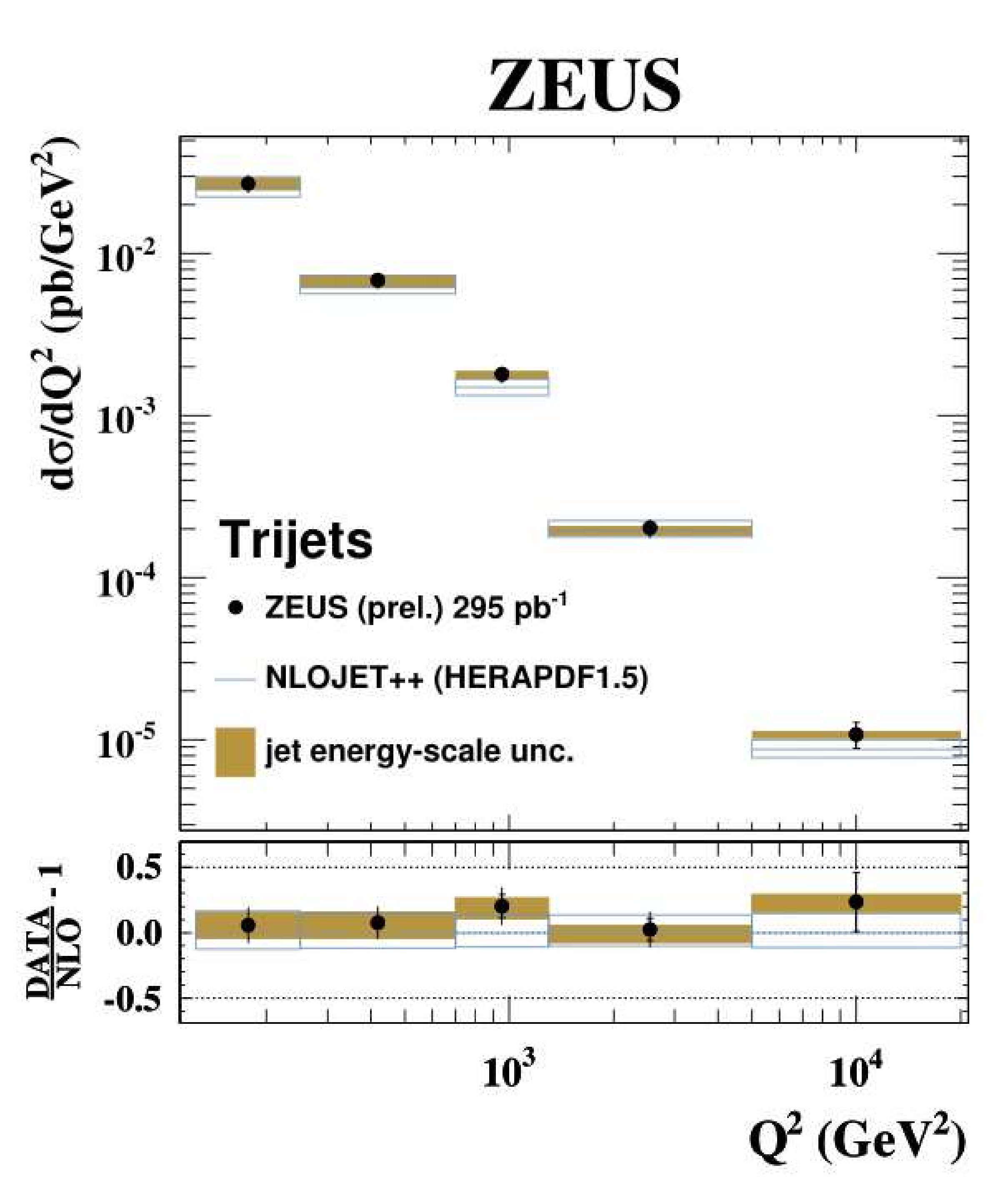
- hadronisation effects
- HERAPDF1.5

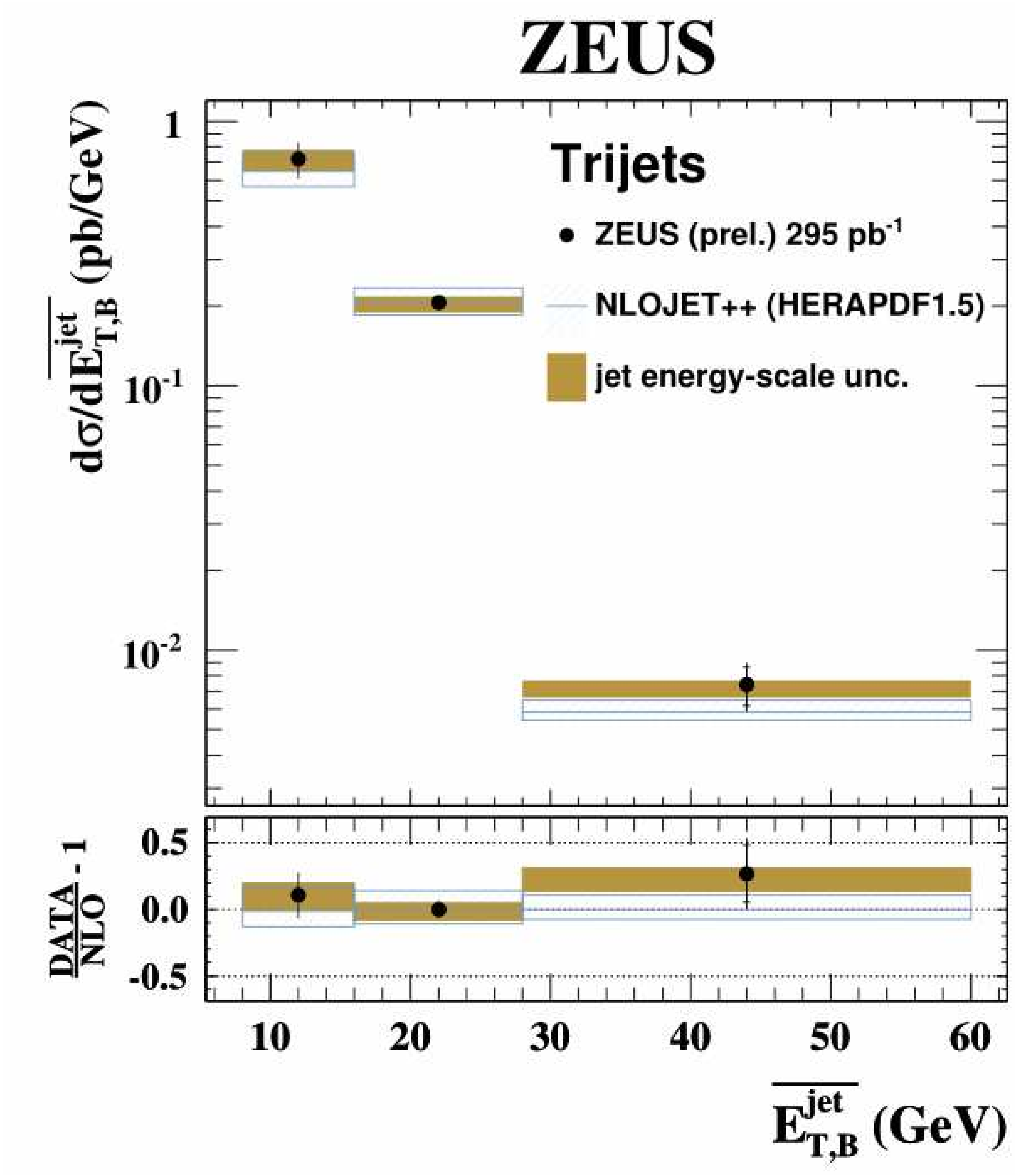
Scale Choice:

- $\mu_f^2 = Q^2$
- $\mu_r^2 = Q^2 + < E^{jet}_{T,B} >$

ZEUS-prel-14-008

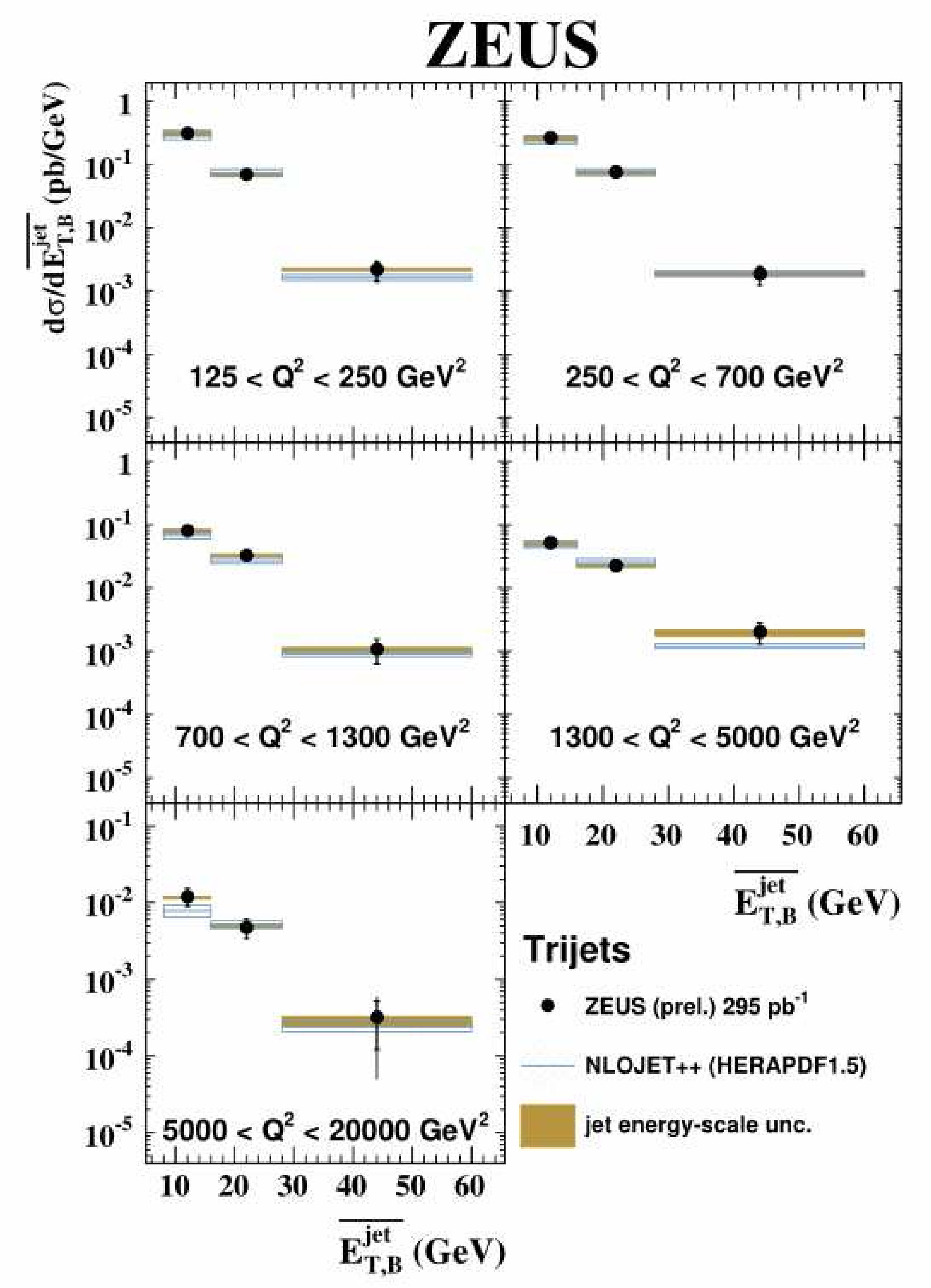
Single differential trijet cross sections

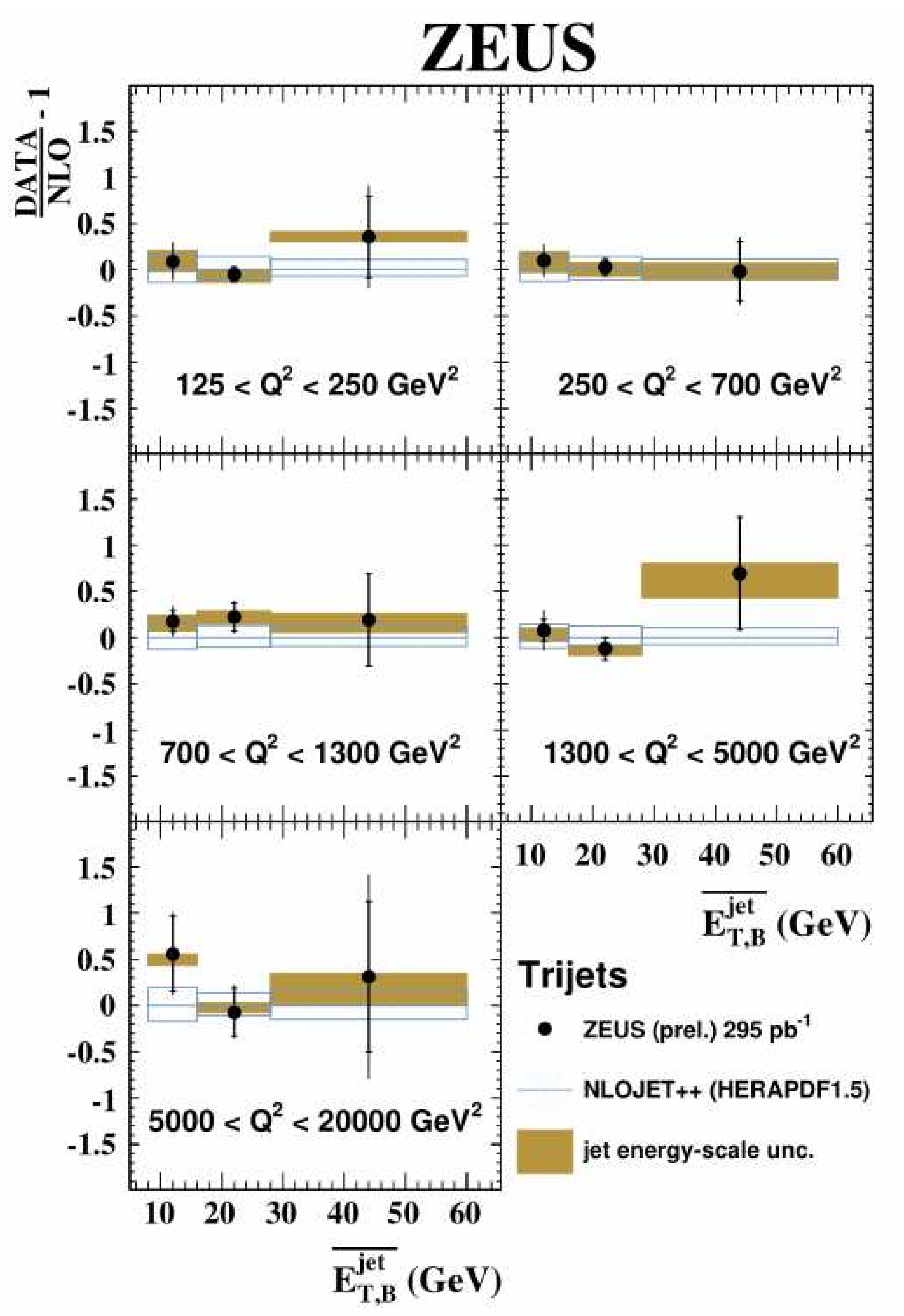




ZEUS-prel-14-008

Double differential trijet cross sections





Good agreement between data and NLO calculations

subm. to EPJ C, arXiv:1406.4709

Multijet at high Q^2 – Inclusive Jet, Dijet, Trijet (H1)

Simultaneous Measurement of

- inclusive jet, dijet and trijet cross sections

Also measured

- normalised inclusive jet, dijet and trijet cross sections
- Normalisation w.r.t. inclusive NC DIS
- (Partial) cancellation of exp. uncertainties

Neutral current phase space

$150 < Q^2 < 15000\ \mathrm{GeV}^2$
$0.2 < y < 0.7$

Jet acceptance

$-1.0 < \eta_{\mathrm{lab}} < 2.5$

Inclusive Jet

$7 < p_T^{\mathrm{jet}} < 50$ GeV

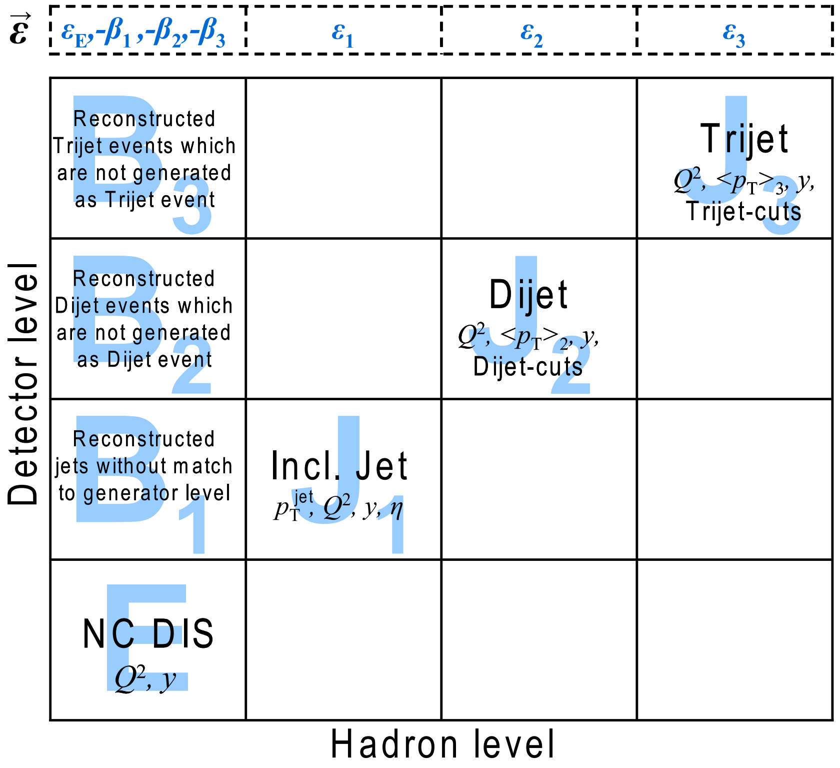
Dijet and Trijet

$5 < p_T^{\mathrm{jet}} < 50$ GeV
$M_{12} > 16$ GeV
$7 < \langle p_T \rangle < 50$ GeV

Multidimensional Regularised Unfolding

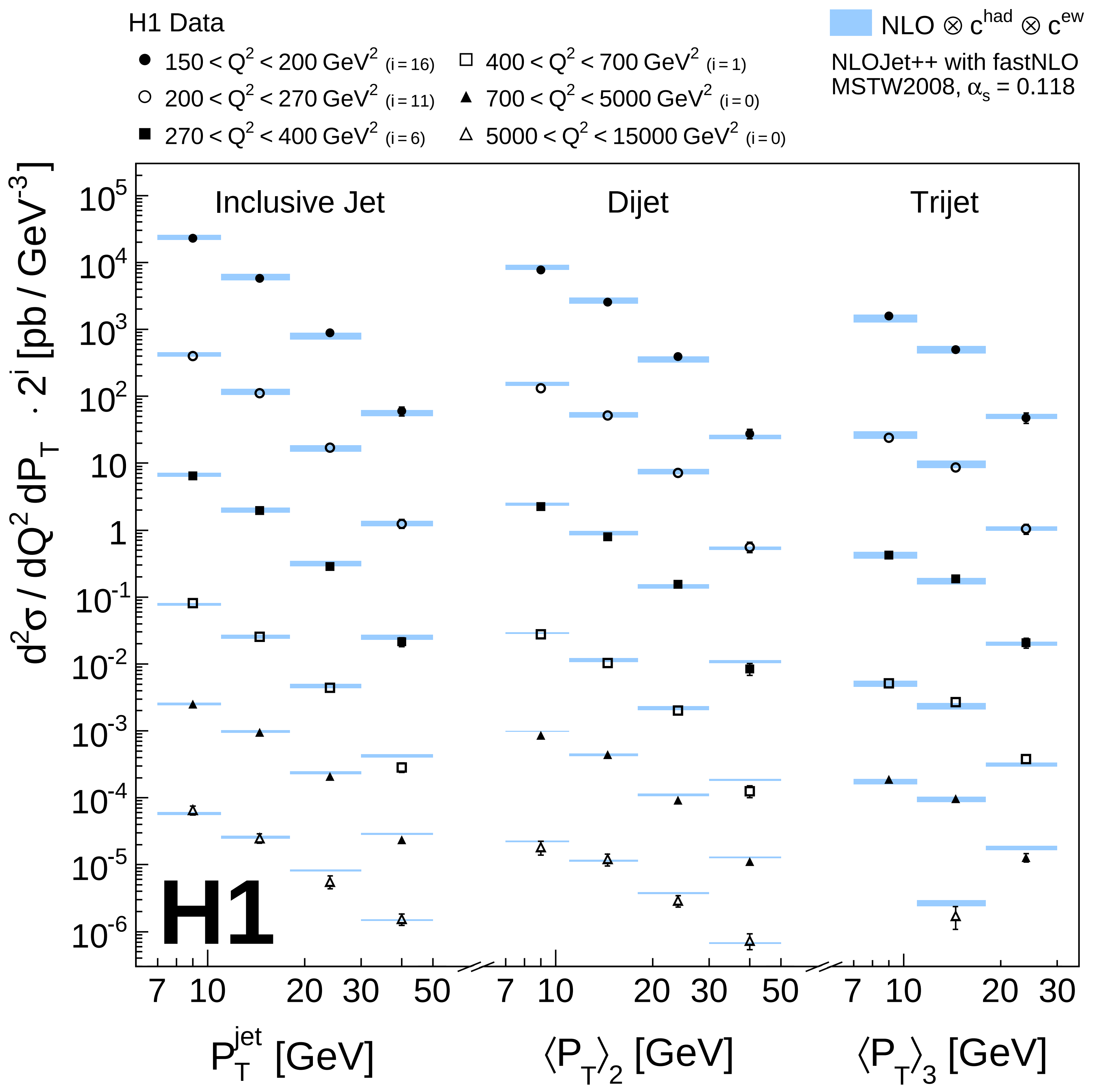
- 4 double-differential measurements are unfolded simultaneously
  - NC DIS, inclusive jet, dijet and trijet
- Using TUnfold tool
  - Statistical correlations considered
  - Enlarged phase space for migrations
  - Up to 7 observables are considered for migrations

Migration Matrix



subm. to EPJ C, arXiv:1406.4709

Multijet at high Q^2 – Inclusive Jet, Dijet, Trijet (H1)



NLO Calculations

NLOJet++ corrected for

- hadronisation effects

Scale Choice:

- $\mu_f^2 = Q^2$
- $\mu_r^2 = (Q^2 + P_T^2)/2$

Theory uncertainty

- Vary scales by factor 2

NLO QCD with MSTW2008 describes well inclusive jet, dijet and trijet differential cross sections

subm. to EPJ C, arXiv:1406.4709

Multijet at high Q^2 – Inclusive Jet, Dijet, Trijet (H1)

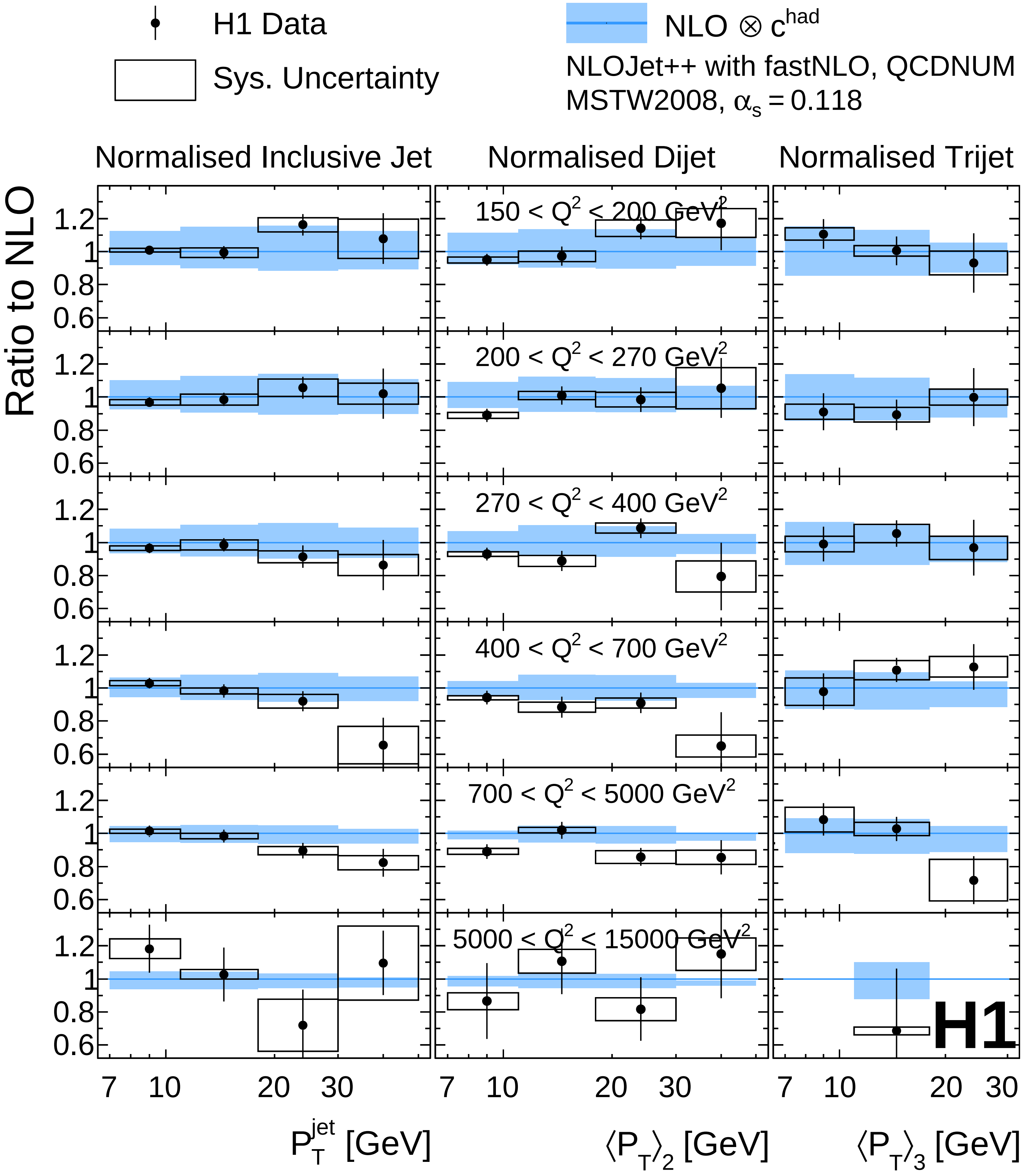
Ratio to NLO calculations

Normalised Multijets

- Cancellation of experimental uncertainties
  - Normalisation uncertainties cancel
  - Other exp. uncertainties cancel partially

Experimental precision higher than theory uncertainty from scale variations

Overall good description of data by theory in NLO



subm. to EPJ C, arXiv:1406.4709

Extraction of strong coupling constant α_s

Extraction of strong coupling constant $\alpha_s(M_Z)$

Iterative χ^2 minimisation

- Fit theory (t) to data (m) taking stat. correlations into account ($\boldsymbol{V}$)
- $\alpha_s(M_Z)$ and ε are free parameters in the fit

$$\chi^2 = \vec{p}^{\mathrm{T}} \boldsymbol{V}^{-1} \vec{p} + \sum_k^{N_{\mathrm{sys}}} \varepsilon_k^2$$

$$p_i = \log m_i - \log t_i - \sum_k^{N_{\mathrm{sys}}} E_{i,k}$$

$$E_{i,k} = \sqrt{f_k^{\mathrm{C}}} \left(\frac{\delta_{m,i}^{k,+} - \delta_{m,i}^{k,-}}{2} \varepsilon_k + \frac{\delta_{m,i}^{k,+} + \delta_{m,i}^{k,-}}{2} \varepsilon_k^2 \right)$$

- Consistent treatment of all uncertainties δ (stat., uncorr., corr.) -> uncertainties are considered as *log-normal* distributed and as '*relative*' uncertainties

subm. to EPJ C, arXiv:1406.4709

Extraction of strong coupling constant α_s

Extraction of strong coupling constant $\alpha_s(M_Z)$

- Jet cross sections directly sensitive to $\alpha_s(M_Z)$
- Simultaneous χ^2-fit to normalised inclusive jet, dijet and trijet cross sections

$$\begin{aligned}\alpha_s(M_Z)|_{k_\mathrm{T}} &= 0.1165\ (8)_\mathrm{exp}\ (5)_\mathrm{PDF}\ (7)_\mathrm{PDFset}\ (3)_{\mathrm{PDF}(\alpha_s)}\ (8)_\mathrm{had}\ (36)_{\mu_r}\ (5)_{\mu_f}\\ &= 0.1165\ (8)_\mathrm{exp}\ (38)_\mathrm{pdf,theo}\ .\end{aligned}$$

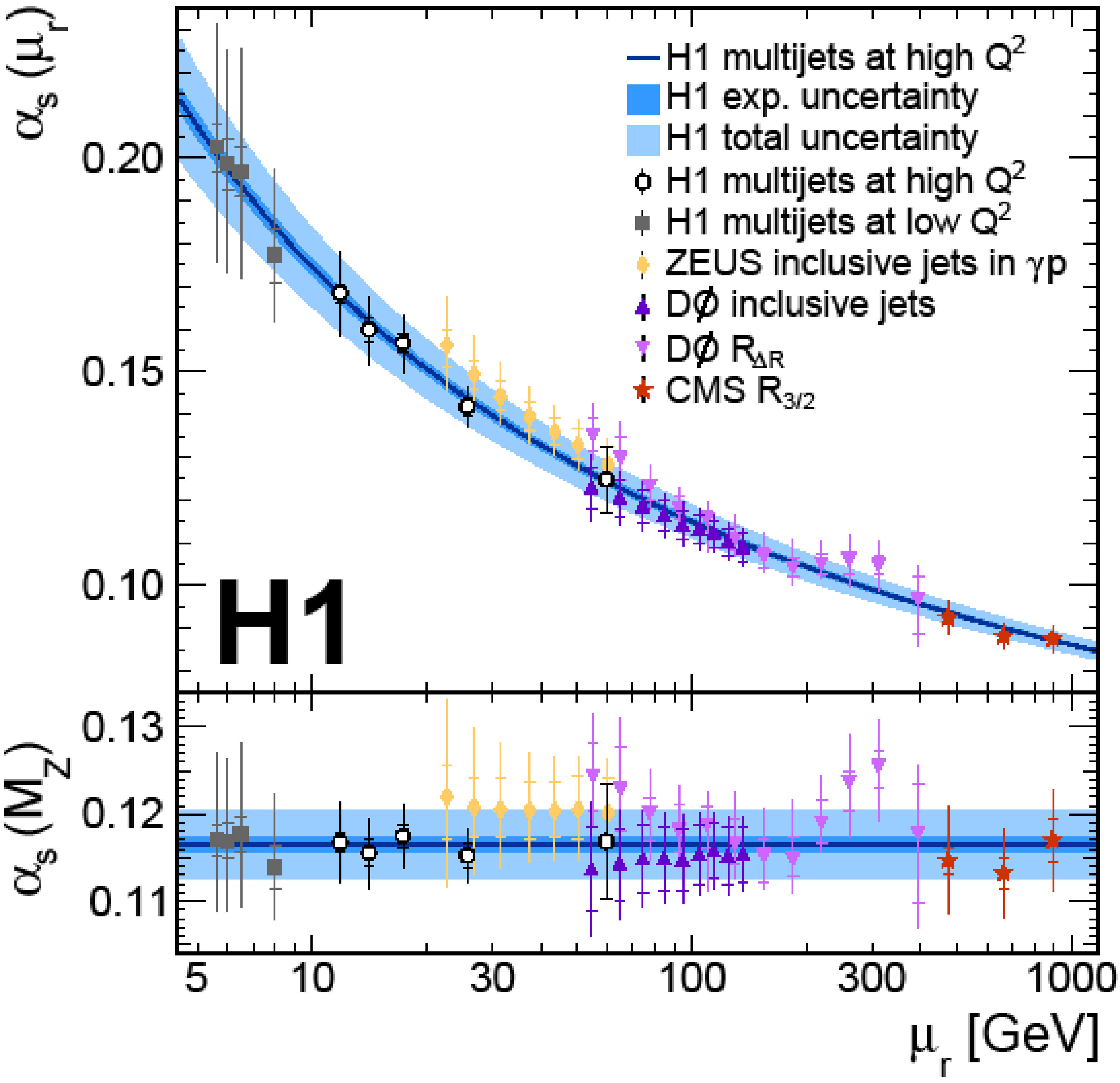
- Experimental uncertainty significantly smaller than theoretical one
- Higher order calculations mandatory
- Value consistent with value extracted using anti-k_t jets

Most precise value of $\alpha_s(M_Z)$ from jet cross sections

Normalised jet cross sections can be used in PDF fit together with inclusive data

subm. to EPJ C, arXiv:1406.4709

Extraction of strong coupling constant α_s



Determination of $\alpha_s(M_Z)$ at various scales

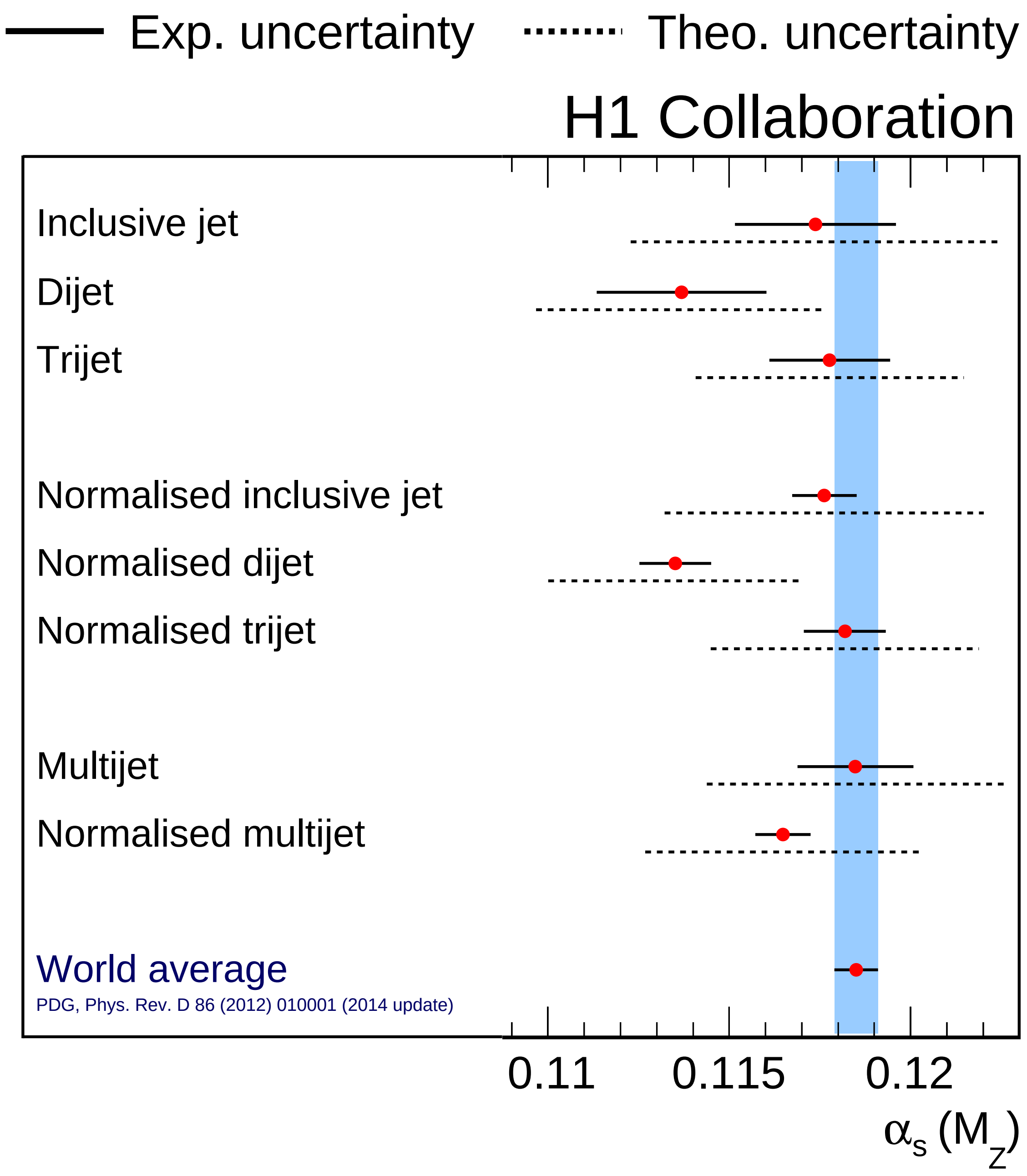
- H1 Multijet cross sections with superior precision
- Consistency with other jet data
- Confirmation of prediction by SU(3) over more than two orders of magnitude
- Recent ZEUS trijet data will also be used for α_s extraction in future

subm. to EPJ C, arXiv:1406.4709

Extraction of strong coupling constant α_s

Extraction separately for absolute and normalised

- Inclusive jet
- Dijet
- Trijet



Values consistent within total uncertainties

Value of $\alpha_s(M_Z)$ from dijet cross sections smaller than from inclusive jet or trijets

- Seen in all previous H1 and ZEUS studies
- Most likely attributed to higher order contributions in phase space regions which are different in the dijet and the inclusive jet measurement

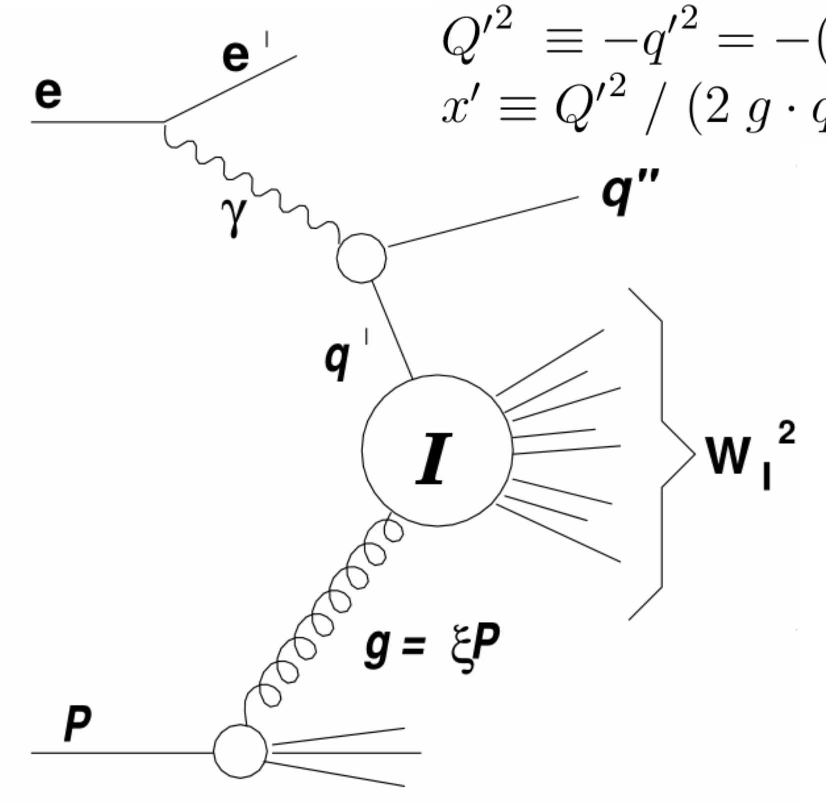
H1-prelim-14-031

QCD Instantons

Variables of I-subprocess:

$$Q'^2 \equiv -q'^2 = -(\gamma - q'')^2$$

$$x' \equiv Q'^2 \;/\; (2\, g \cdot q')$$



QCD Instantons

- Solution to Yang-Mills equation of motion
- Physical interpretations:

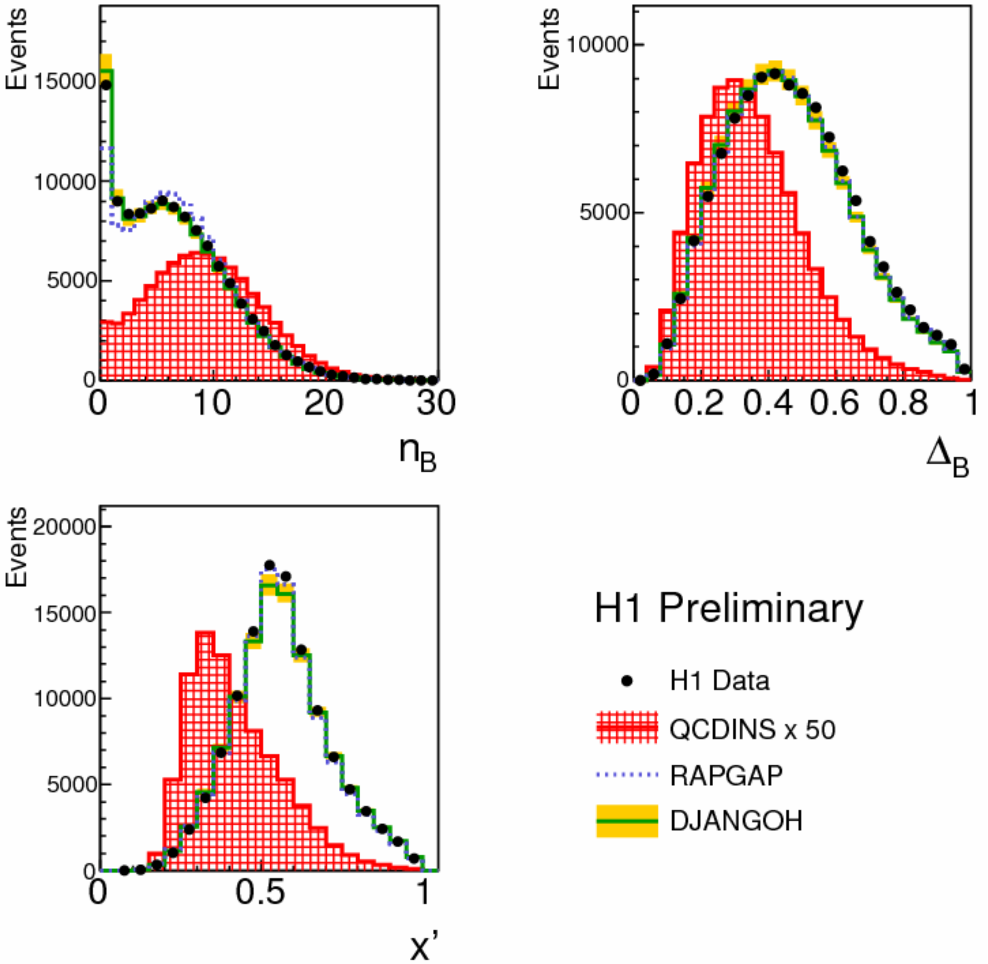
  Pseudo-particle or tunneling process between topologicaly different vacuum states

Signatures

- One hard jet (not originating from instanton)
- Densily populated narrow band, flat in φ
- Large particle multiplicities

Strategy

- Find jets in hadronic center of mass frame
  - Remove hardest jet from HFS
- Boost to instanton rest frame and define variables
  - Topological: Sphericity, Fox-Wolfram moments, azimuthal isotropy (Δ_B)…
  - Number of charged particles in band (n_B)
  - Energy of band ($E_{Inst.}$), …
- Variables are input to MVA



QCD Instantons

Multivariate analysis

Probability density estimator with range search (PDERS)

Training

- Rapgap, Django
- QCDINS (Ringwald, Schremp)

Good description of discriminator in background region

Signal region

D > 0.86

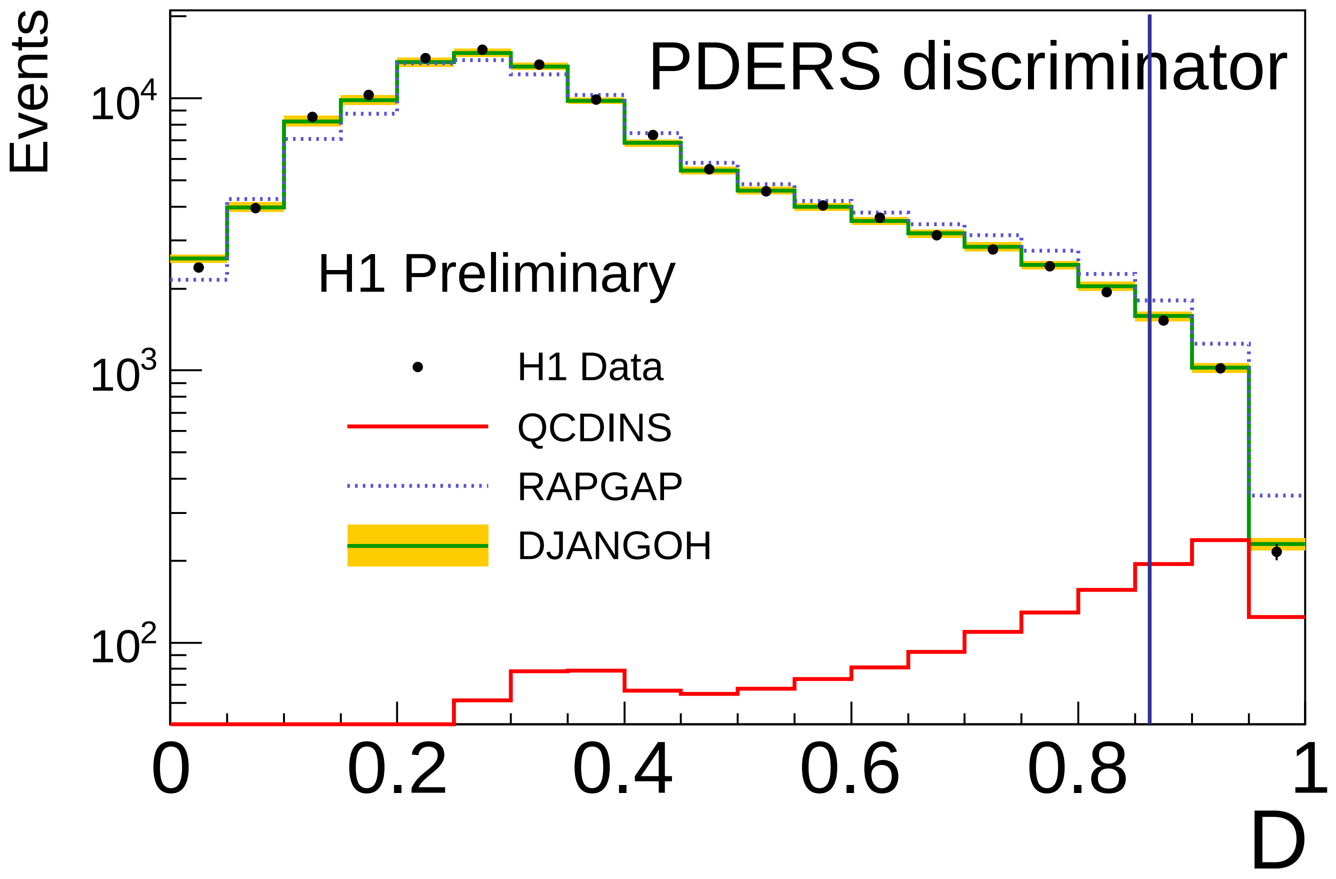
Input for limit calculation

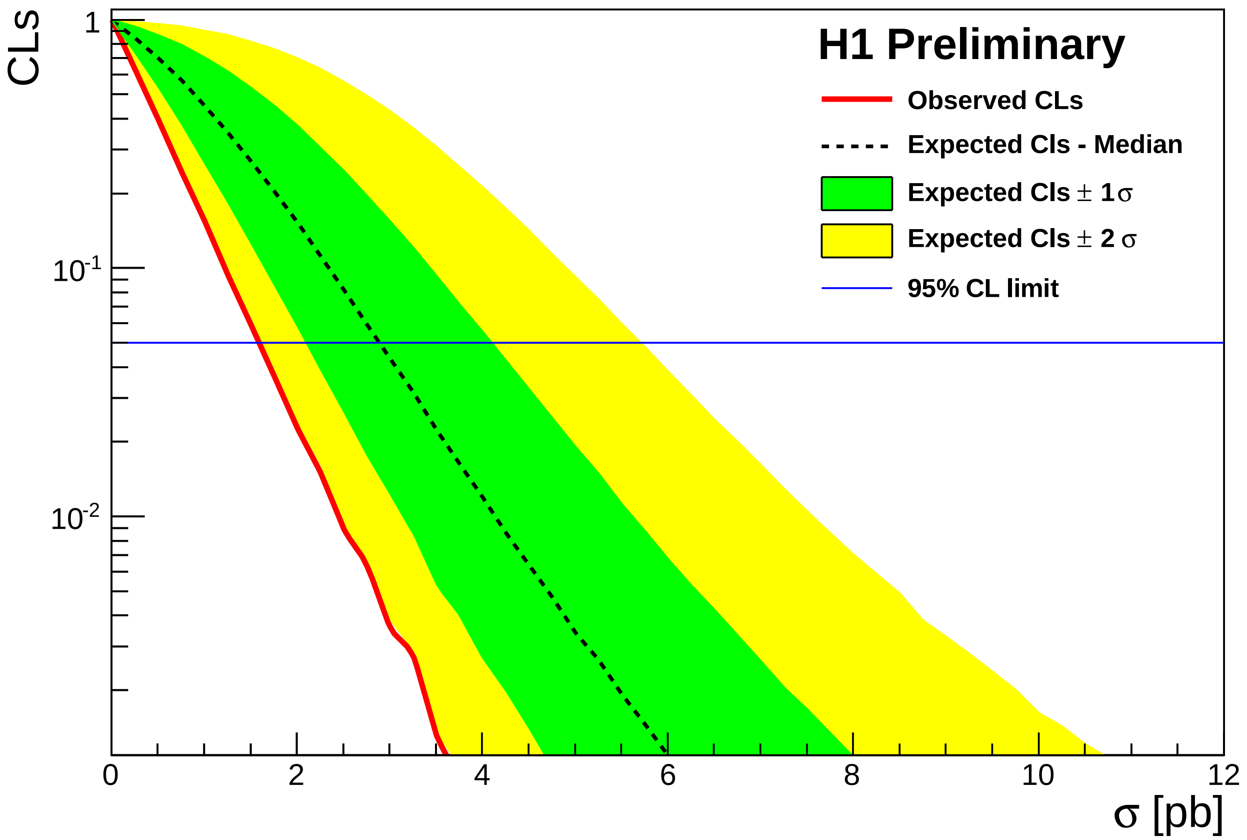
QCD Instanton cross section: 10 ± 2 pb

Uncertainties: Systematic and model

Upper limit for 95% CL: 1.6pb

- Data are consistent with background
- No evidence for QCD Instantons
- Upper limit suggests exclusion of the Ringwald-Schremmpp‘s predictions for HERA QCD instantons.





Summary

New QCD results from HERA experiments with final data precision

Photons in photoproduction → NLO and k_t-factorisation give good description

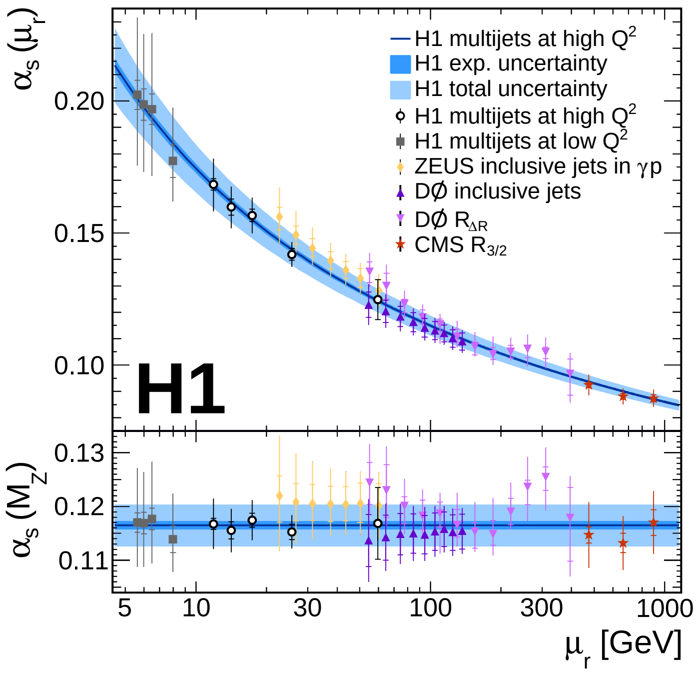
QCD Instanton → Ringwald-Schrempp’s solution appears to be excluded

Trijet cross sections in DIS → Cross sections well described by theory

Multijet cross sections in DIS → Data well described by NLO QCD

Determination of strong coupling α_s

- Multijet cross sections with high sensitivity and small experimental uncertainties
- Value consistent with world average value
- Most precise value from jet cross sections



The H1 and ZEUS experiments are finalizing their QCD physics program

Backup

subm. to EPJ C, arXiv:1406.4709

Extraction of strong coupling constant α_s

Extraction of strong coupling constant $\alpha_s(M_Z)$

- Jet cross sections directly sensitive to $\alpha_s(M_Z)$
- Simultaneous χ^2-fit to inclusive jet, dijet and trijet cross sections

$$\begin{aligned}\alpha_s(M_Z)|_{k_\mathrm{T}} &= 0.1165\ (8)_\mathrm{exp}\ (5)_\mathrm{PDF}\ (7)_\mathrm{PDFset}\ (3)_{\mathrm{PDF}(\alpha_s)}\ (8)_\mathrm{had}\ (36)_{\mu_r}\ (5)_{\mu_f}\\ &= 0.1165\ (8)_\mathrm{exp}\ (38)_\mathrm{pdf,theo}\ .\end{aligned}$$

Comparison to current CMS inclusive jet value:

CMS-PAS-SMP-12-028
CMS-PAS-SMP-12-027

$$\alpha_s(M_Z) = 0.1185 \pm 0.0019(\exp) \pm 0.0028(PDF) \pm 0.0004(NP) \pm^{0.0055}_{0.0022} (scale)$$

- 2.5 times higher experimental precision
- 3.3 times smaller PDF uncertainty

CMS-PAS-SMP-12-028 CMS-PAS-SMP-12-027 arXiv 1406:470

α_s measurement

Slide from Chiara Roda from ICHEP 14 QCD summary

World average (2014)

$\alpha_s(M_Z)$= 0.1185 ± 0.0006 (0.5%)

CMS Most recent: inclusive jet (5%)

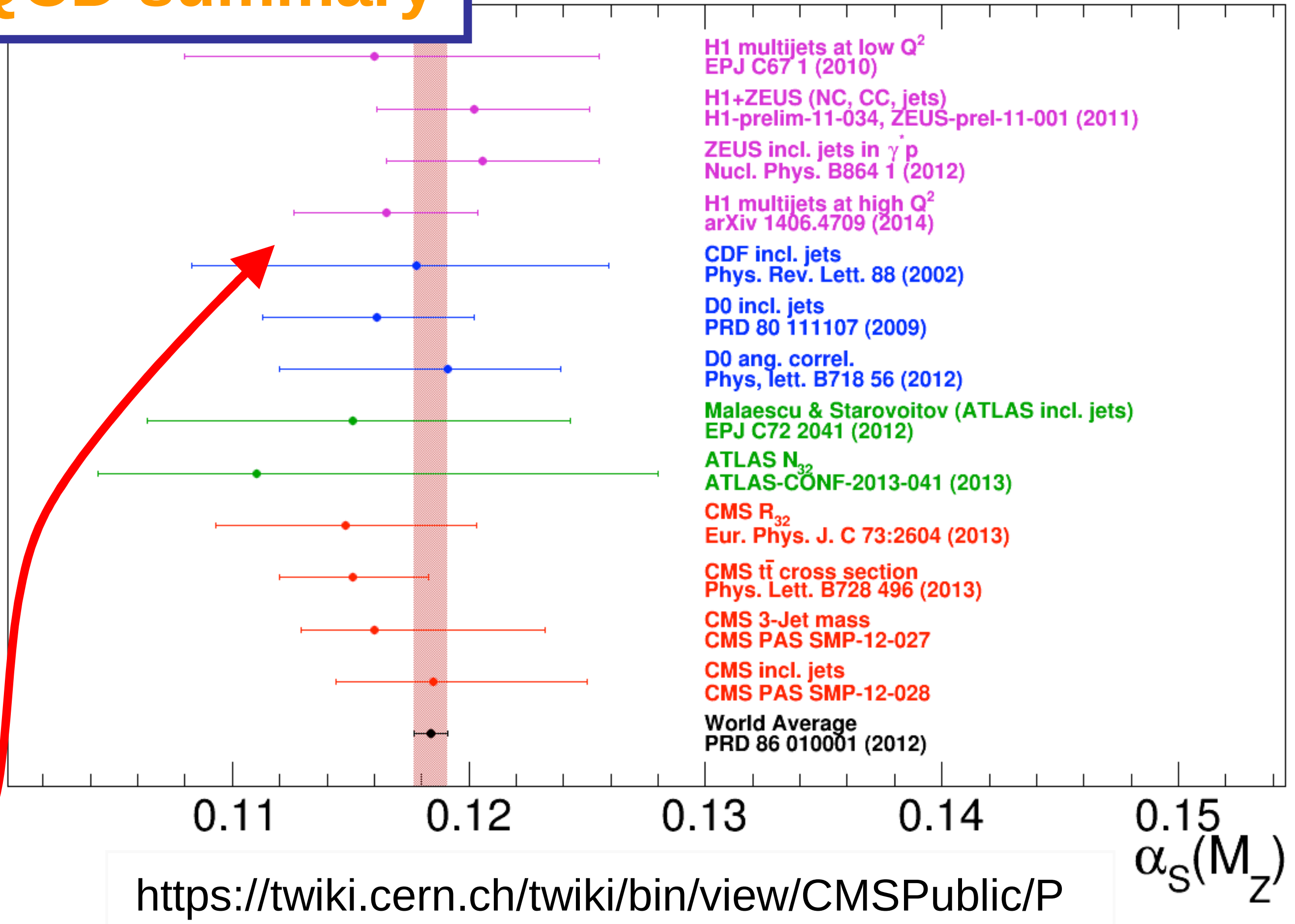
$$\alpha_s(M_Z) = 0.1185 \pm 0.0019(\exp) \pm 0.0028(PDF)$$
$$\pm 0.0004(NP) \pm^{0.0055}_{0.0022} (scale)$$

H1 most recent α_s extraction from inclusive and multjet cross-section. Best precision is reached from fit to normalised multijet cross sections:

$$\alpha_s = 0.1165 \pm 0.0008(\exp) \pm 0.0038(PDF, theo)$$

0.0036 (scale)

exp. unc.0.7%



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

Correction of detector effects using regularised unfolding

Detector effects

- Acceptance and efficiency
- Migrations due to limited resolution

Aim

- Cross section on hadron level
- Direct matrix inversion of A often not possible

Detector response

$$y = A \cdot x$$

- Measured vector y
- Hadron level vector x
- Detector response matrix A
- Covariance matrix V_y

Regularised unfolding using Tunfold (JINST 7 (2012) T10003**)**

- Find hadron level x by analytic minimisation of

$$\chi^2(x,\tau) = \underbrace{(y - Ax)^T V_y^{-1} (y - Ax)}_{\text{Matrix inversion: } \chi^2} + \underbrace{\tau^2 (x - x_0)^T (L^T L)(x - x_0)}_{\text{Regularisation: } \chi^2}$$

- Find stationary point by solving analytically as function of x
- ‘True’ hadron level can be determined directly

$$x = (A^T V_y^{-1} A + \tau^2 L^2)^{-1} A^T V_y^{-1} y =: By$$

- *x* (and *L*) are free parameters

Correlation matrix of all data points

Covariance matrix

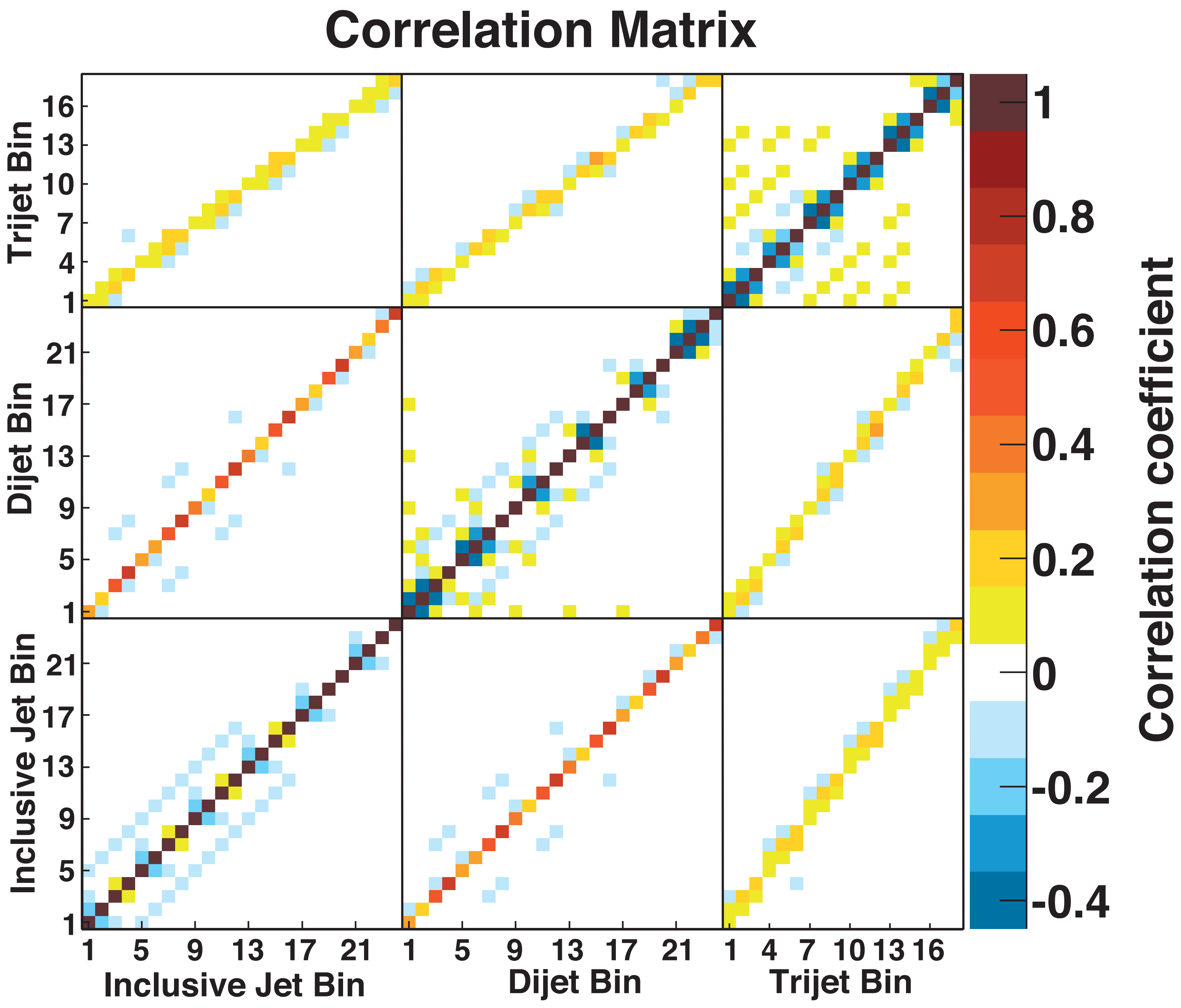
Obtained through linear error propagation of statistical uncertainties

Correlations

- Resulting from unfolding
- Physical correlations
  - Between measurements
  - Within inclusive jet

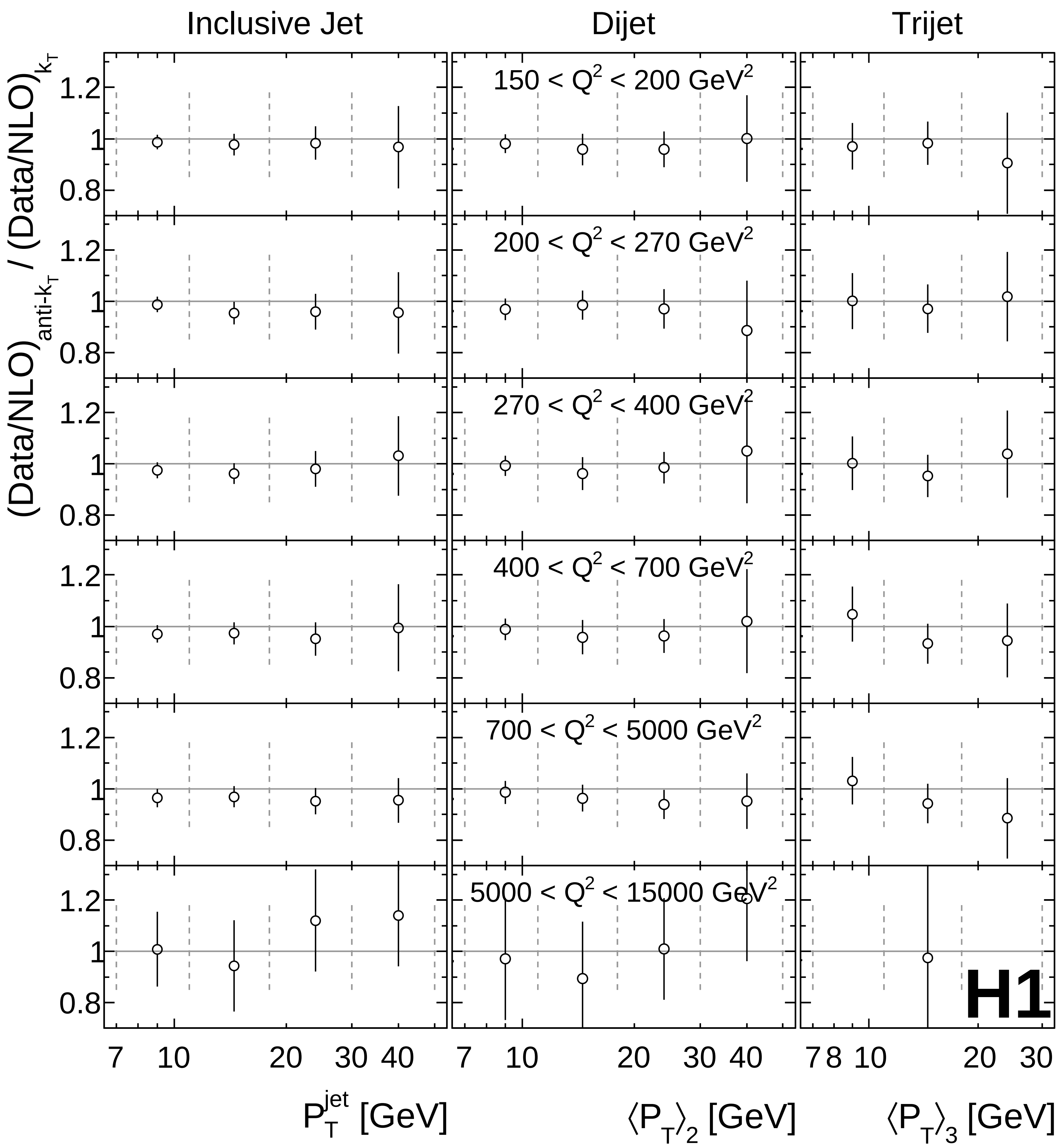
Useful for

- Cross section ratios
- Combined fits
- Normalised cross sections

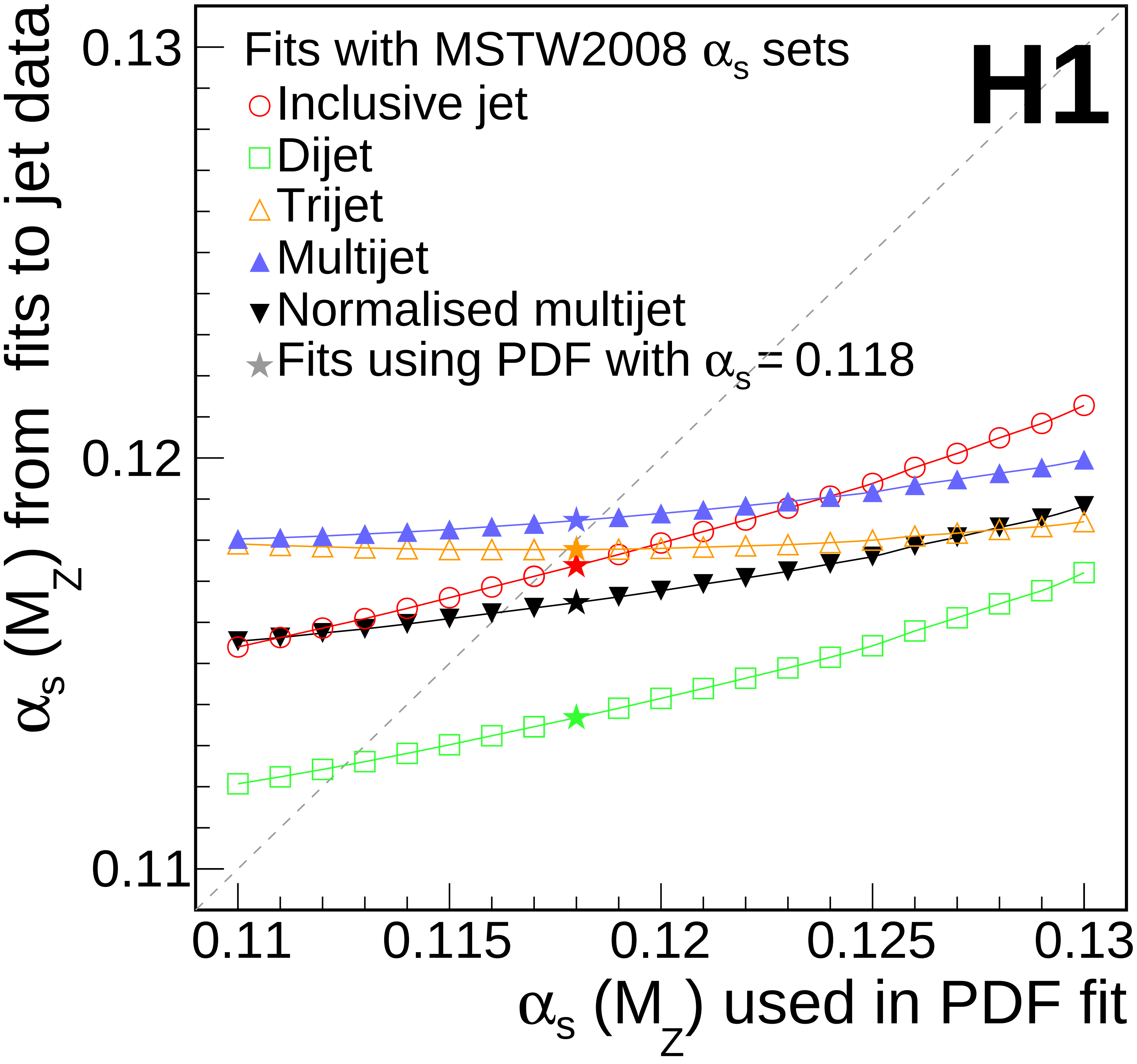


Correlation matrix is employed for correct error propagation for norm. cross sections

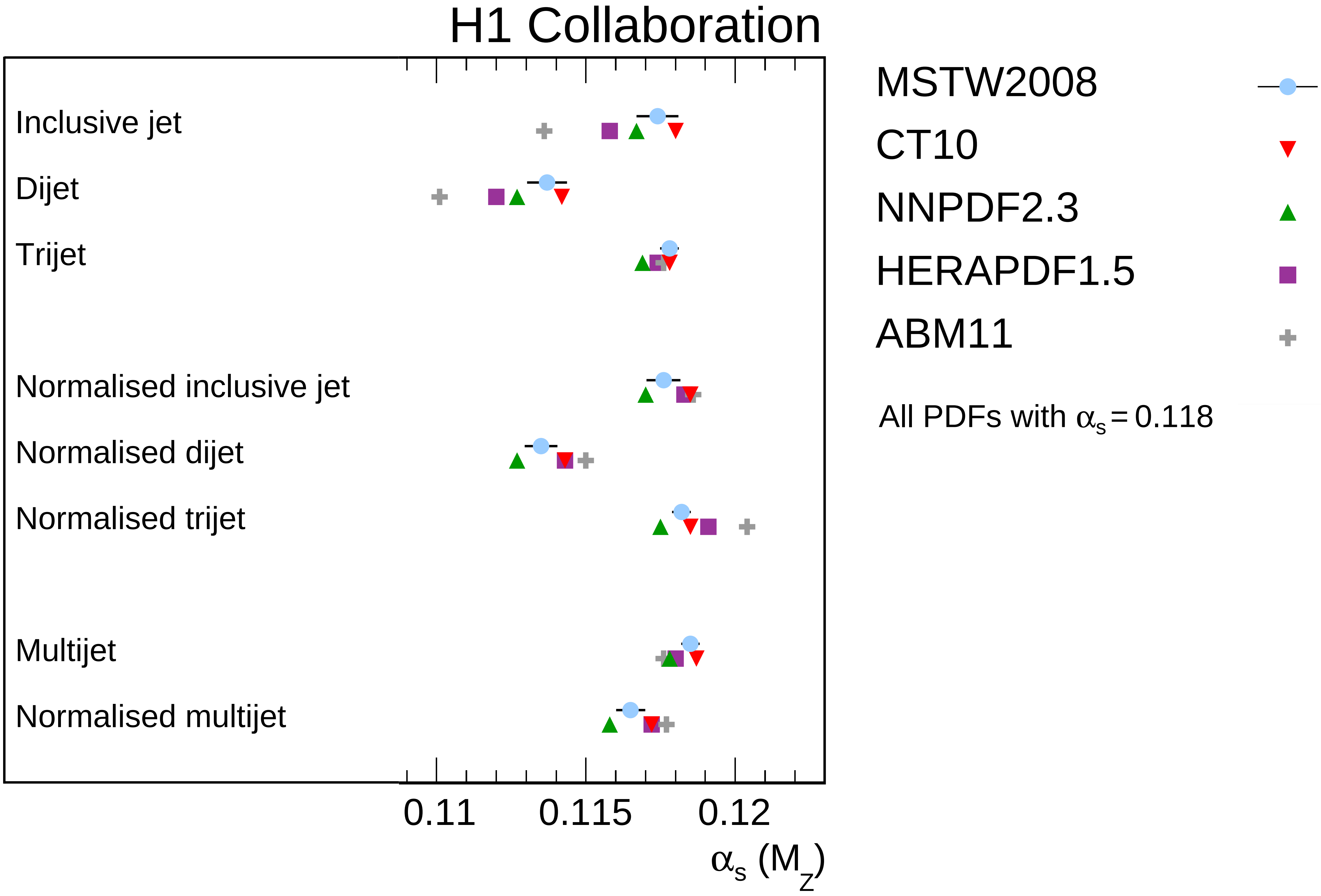
Multijet Cross Sections at High Q^2



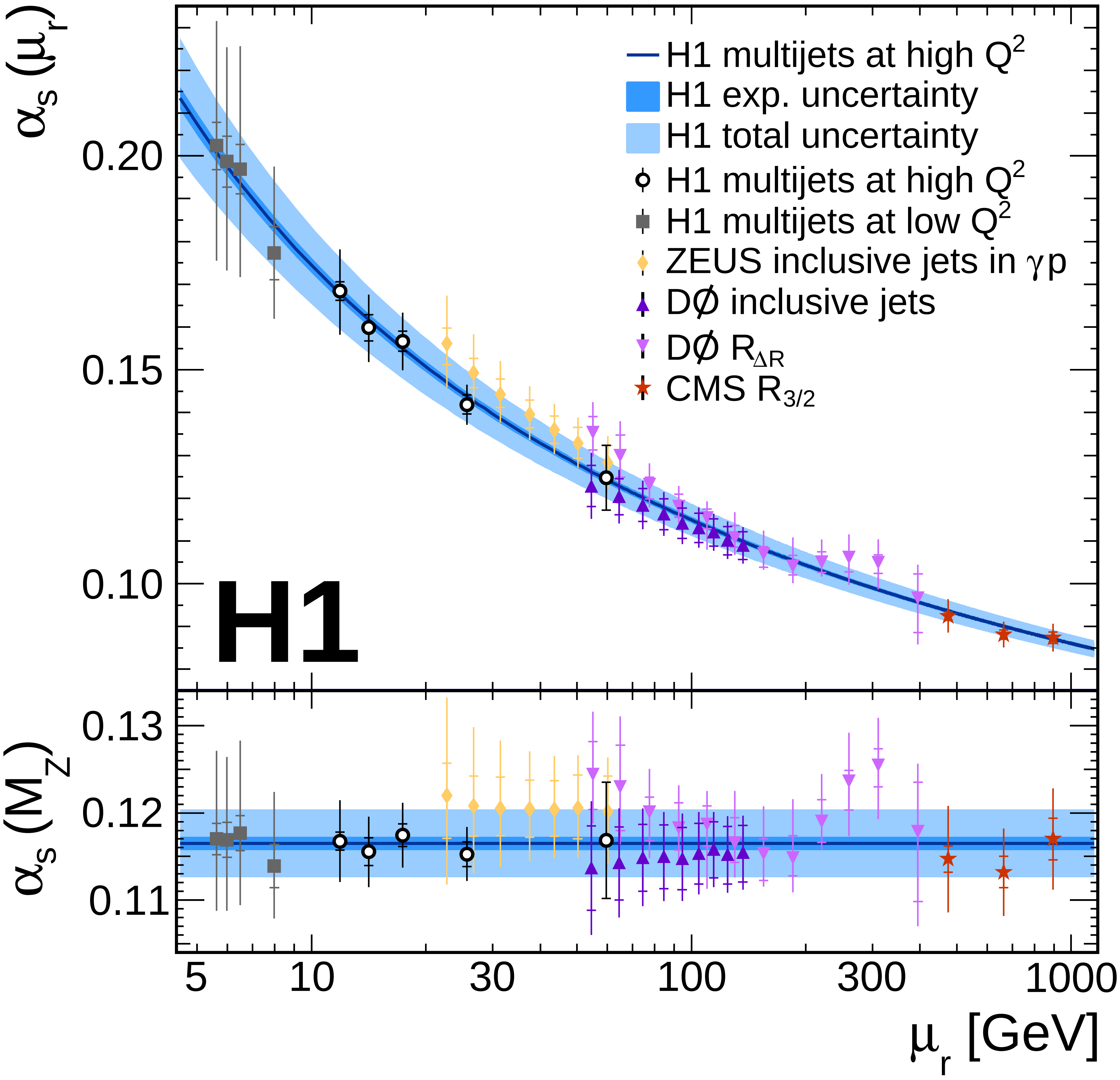
Dependence of $\alpha_s(M_Z)$ on input $\alpha_s(M_Z)$ to PDF fit



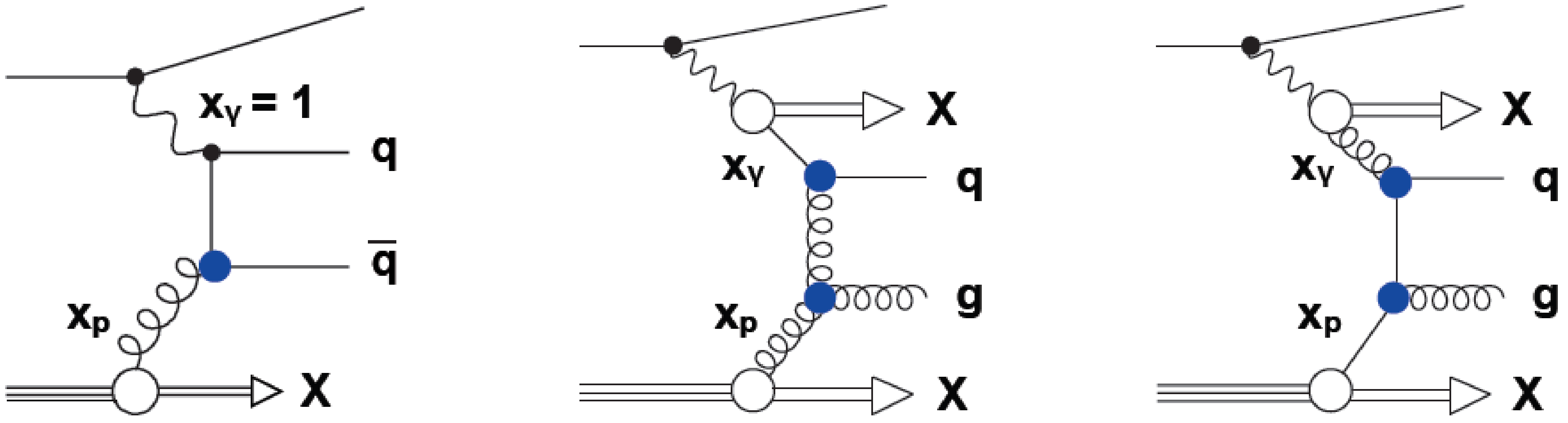
$\alpha_s(M_Z)$ extraced using different PDF sets



All PDFs with $\alpha_s = 0.118$


$\alpha_s(\mu_r)$
0.20
0.15
0.10
H1
H1 multijets at high Q^2
H1 exp. uncertainty
H1 total uncertainty
H1 multijets at high Q^2
H1 multijets at low Q^2
ZEUS inclusive jets in γp
DØ inclusive jets
DØ $R_{\Delta R}$
CMS $R_{3/2}$
$\alpha_s(M_Z)$
0.13
0.12
0.11
5
10
30
100
300
1000
μ_r [GeV]

Jet production in photoproduction γp



direct photoproduction

resolved photoproduction

When $Q^2 \to 0$ GeV²: Two processes contribute

Direct photoproduction $x_\gamma^{obs} \to 1$: order of α_s

Resolved photoproduction: $x_\gamma^{obs} < \sim 0.8$

- Leading order of $O(\alpha_s^2)$
- Two hadrons are involved
  -> sensitive to multi-parton interactions

Expect ≥ 2 jets in the final state

Partonic momentum fraction of the photon:

$$x_\gamma^{\mathrm{meas}} = \frac{E^\gamma + E^{\mathrm{jet}} - p_Z^\gamma - p_Z^{\mathrm{jet}}}{E^{\mathrm{all}} - p_Z^{\mathrm{all}}}$$

Analysis performed in laboratory rest frame