Jet production and measurements of α_s at HERA

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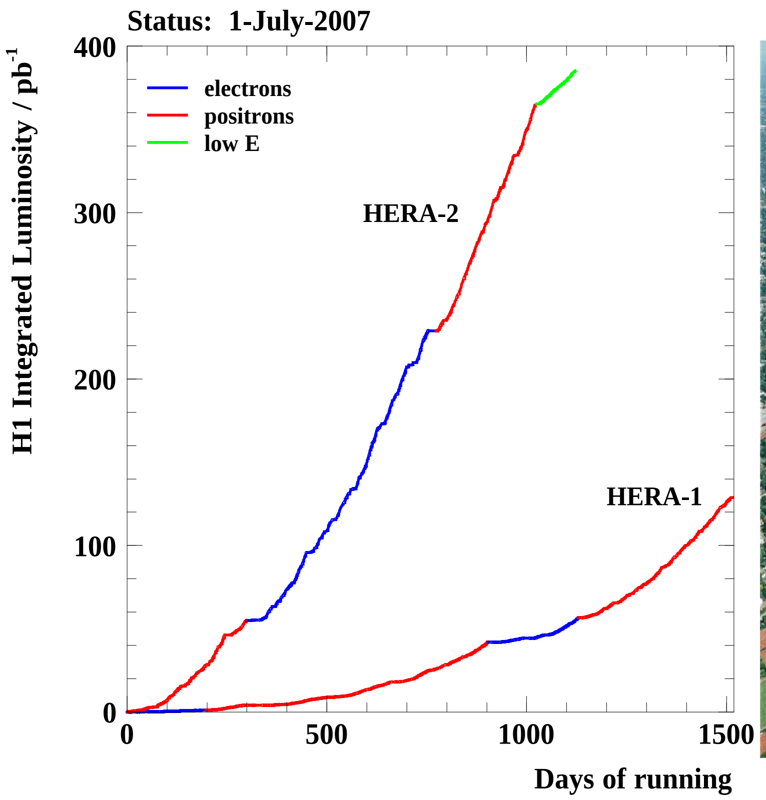
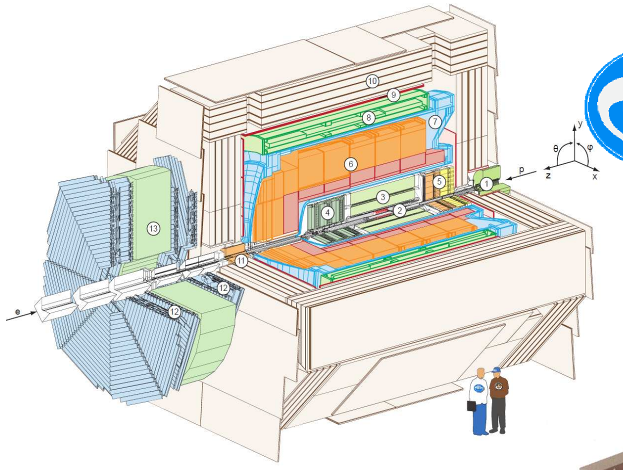
3rd International Conference on New Frontiers in Physics
ICNFP2014
August 6, 2014

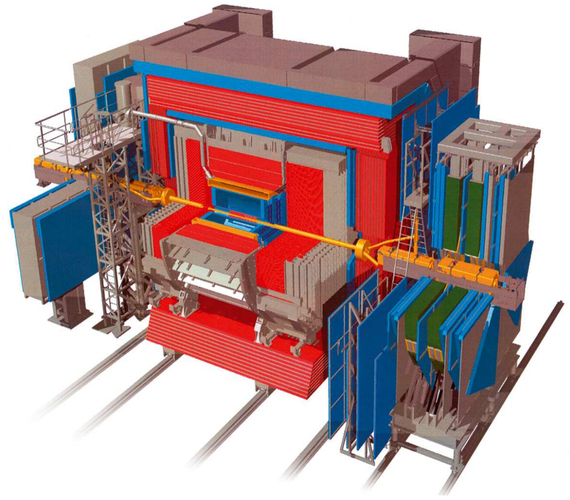
HERA with the H1 and ZEUS detectors

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 normalization uncertainties: 1-2 %
  - Luminosity: 1.8 – 2.5%

Inclusive deep-inelastic *ep* scattering (DIS)

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

- Center-of-mass energy

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

- Virtuality of exchanged boson

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

- Bjorken scaling variable

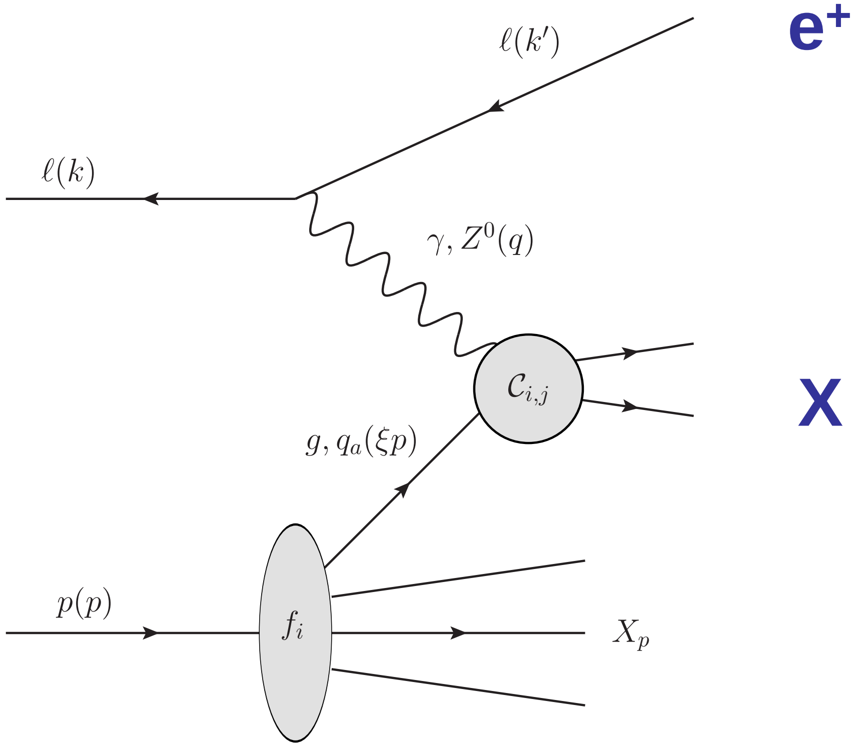
$$x_{\mathrm{Bj}} = \frac{Q^2}{2p\cdot q}$$

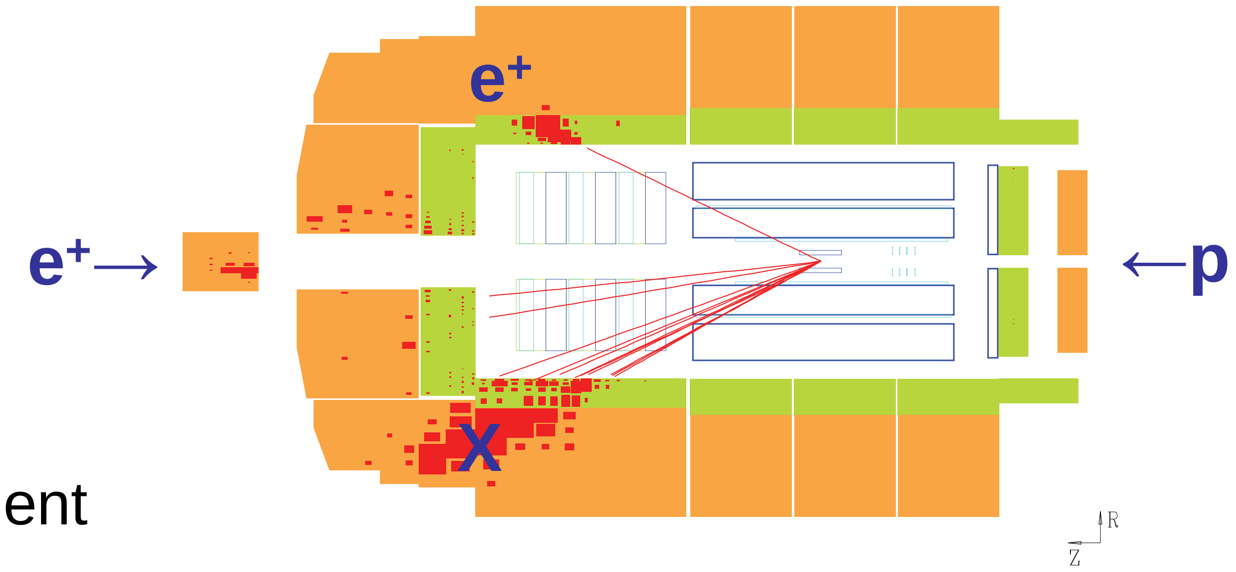
- Inealsticity

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

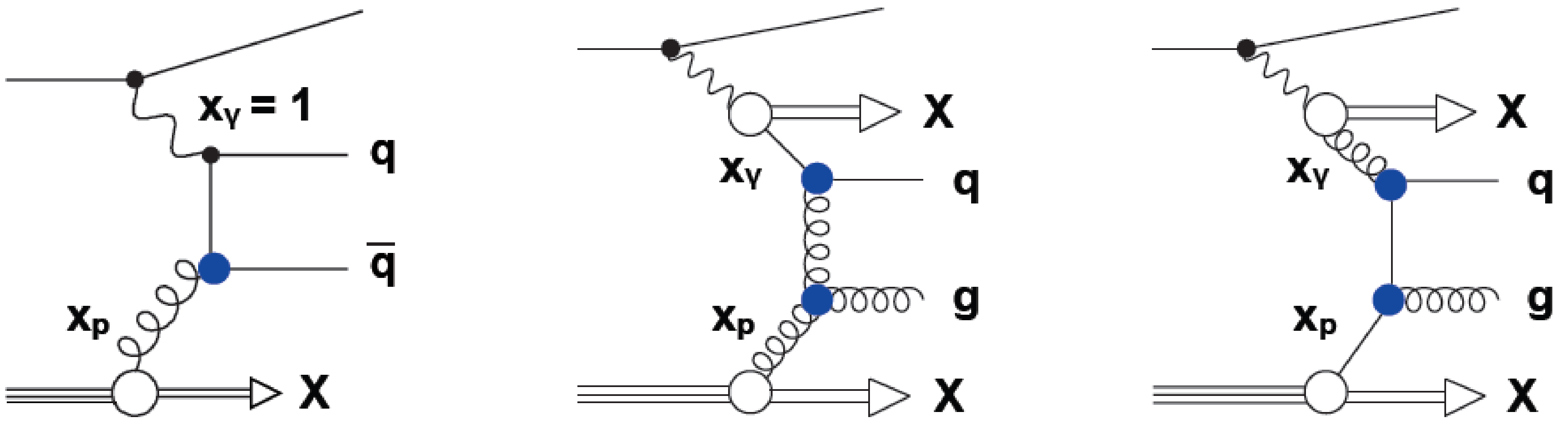
Cross section calculation

- Collinear factorization
- Hard scattering calculable in QCD (pQCD)
  - Calculable up to NNLO for inclusive NC DIS
- PDFs have to be determined from experiment





Jet production in photoproduction γp



direct photoproduction

resolved photoproduction

When $Q^2 \rightarrow 0$ GeV^2: Two processes contribute

Direct photoproduction $x_\gamma^{obs} \rightarrow 1$: 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

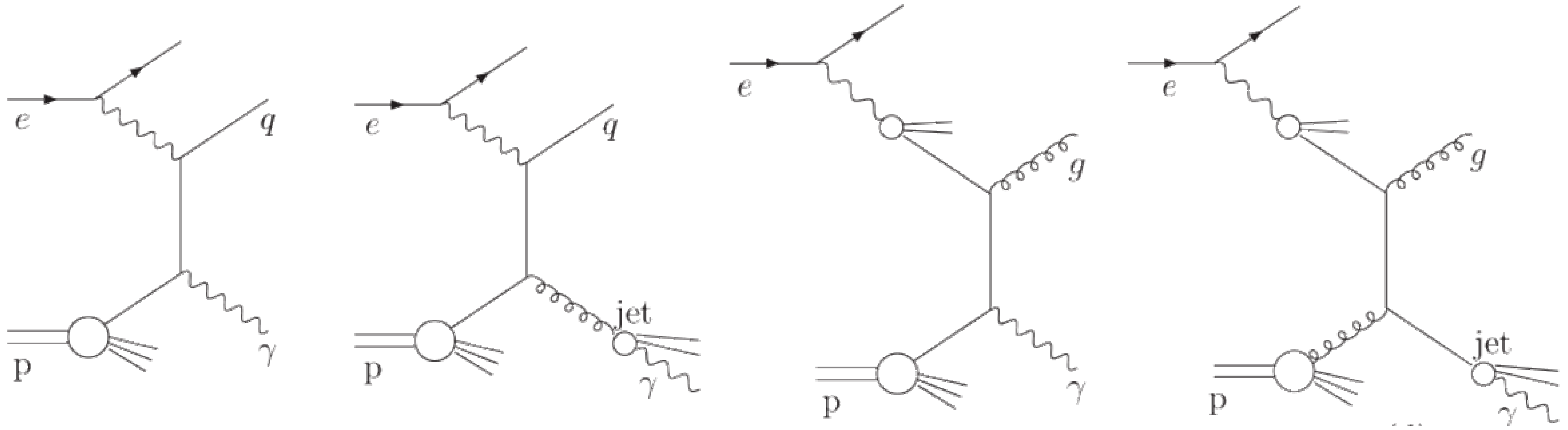
Partonic momentum fraction of the photon:

$$x_\gamma^{\mathrm{obs}} = \frac{E_T^{\mathrm{jet1}} e^{-\eta^{\mathrm{jet1}}} + E_T^{\mathrm{jet2}} e^{-\eta^{\mathrm{jet2}}}}{2yE_e}$$

Analysis performed in laboratory rest frame

ZEUS Coll. Phys Lett B 730C (2014) 293

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



Prompt photons in photoproduction $Q^2<1$ GeV^2

- Direct and resolved processes
- Prompt radiation and fragmentation

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

Measured separately for direct- and resolved-enhanced region [arXiv:1404.0201]

Theory

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

- Data well described within theory uncertainties

LMZ: k_T factorization with unintegrated parton densities

- Data well described within uncertainties
- Less good at low η^{jet} and low resolved region in γ+jet ($x_\gamma^{meas} \to 1$)

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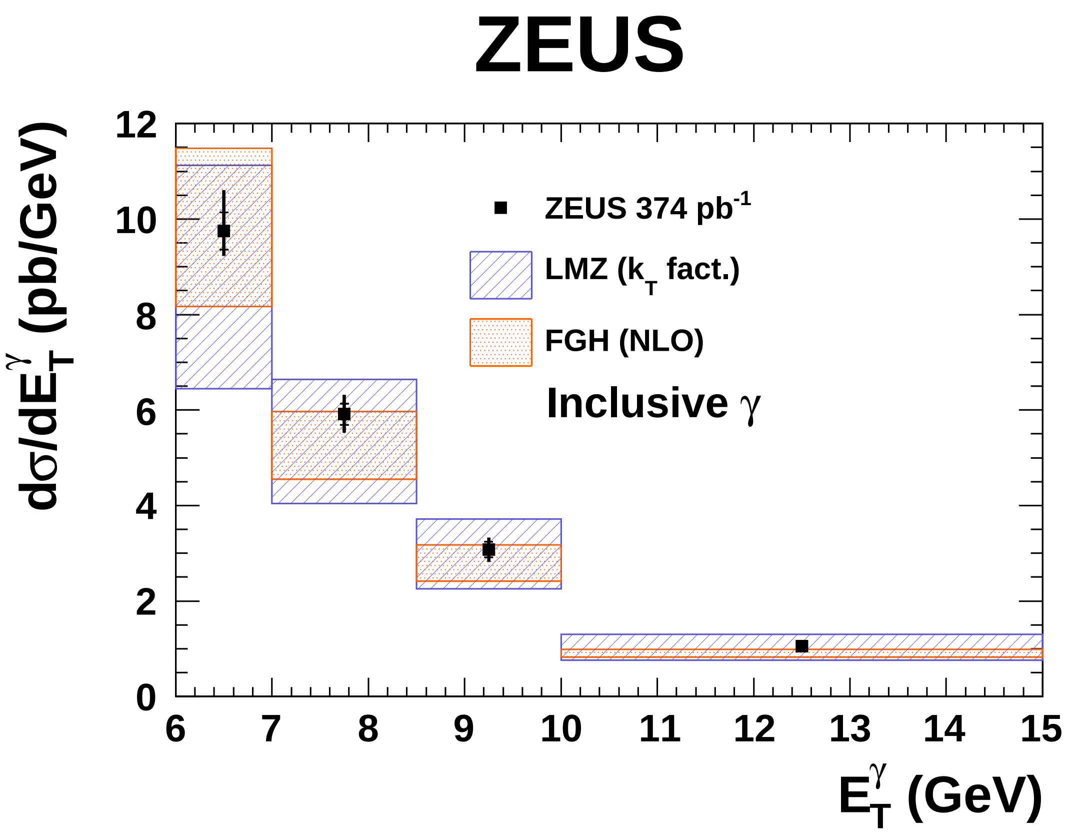
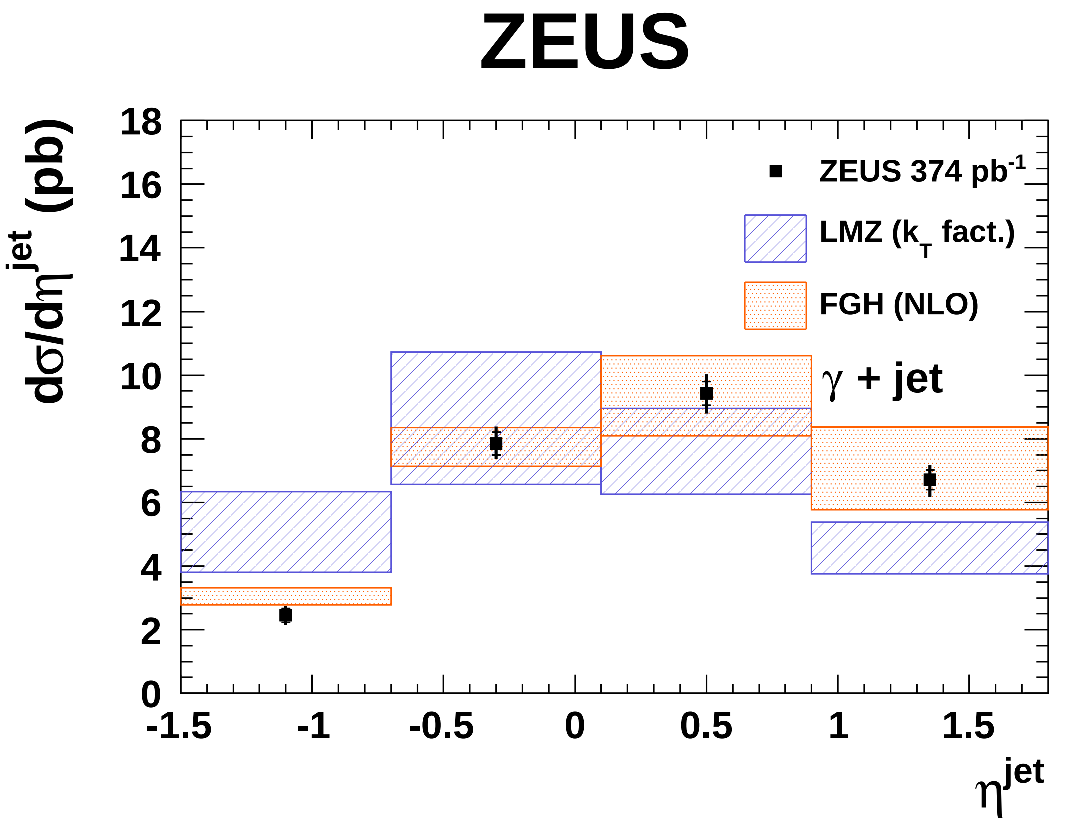
Prompt photons in γp: ep → γ+X (+j) [+e]



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

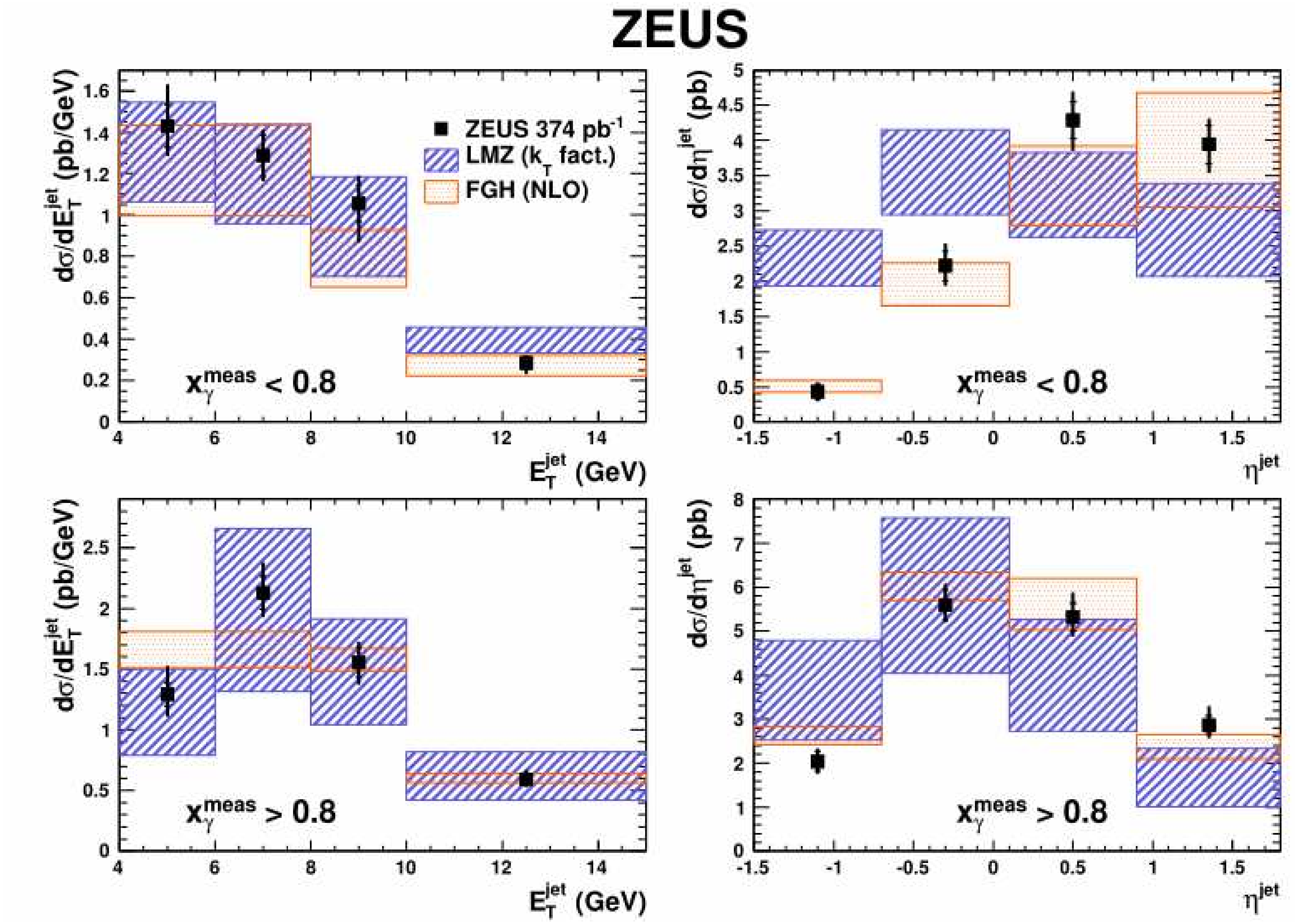


Cross sections: γ + jet

- 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 arXiv:1404.0201

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



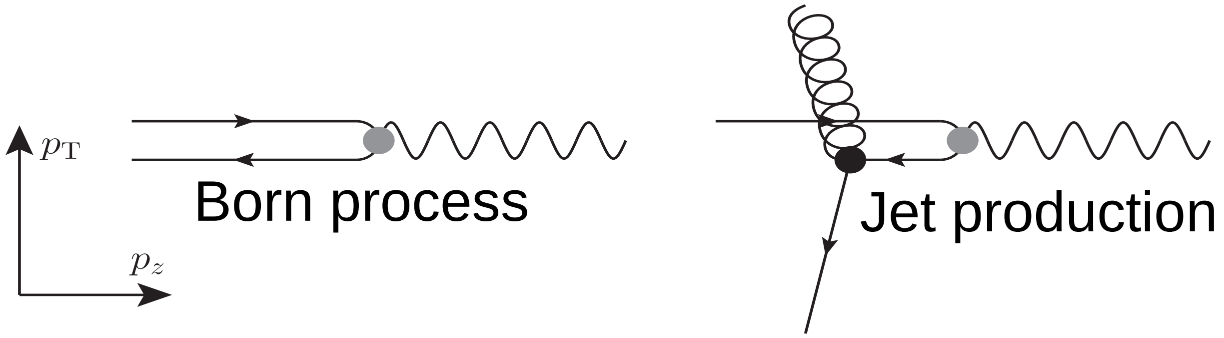
Cross section as function of jet variables in bins of x_γ^{meas}

- Both theories within large uncertainties agree well with the data
- Except LMZ in η^{jet} at $x_\gamma^{meas} < 0.8$
  - probably connected with setting the rapidity of the jet coming from the evolution cascade

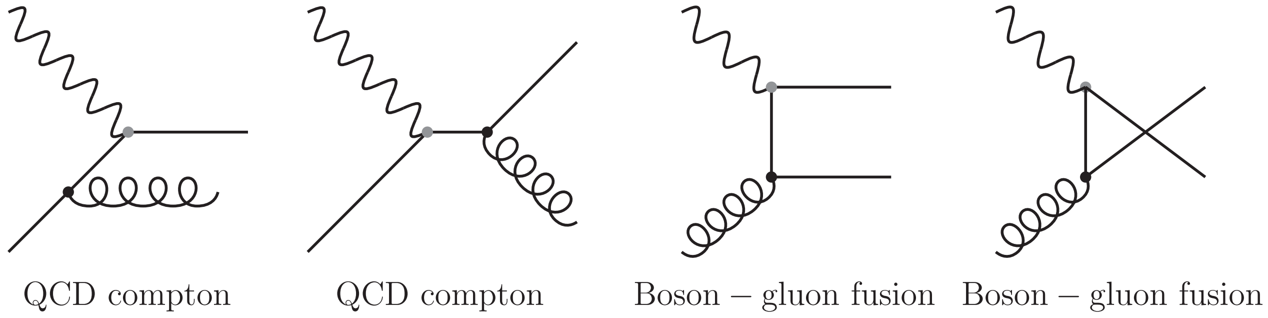
Jet production in neutral current DIS

Jet measurements performed in 'Breit frame'

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

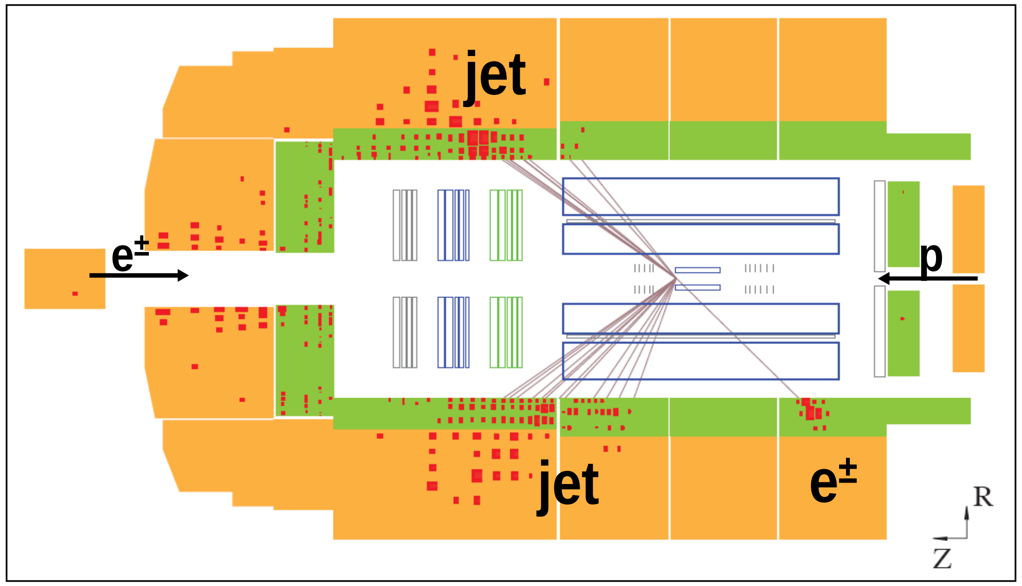


Jet production in leading-order pQCD



Jet production is directly sensitive to α_s

Events show two-jet topology



Inclusive jet

Count every single jet with transverse momentum

Dijet and trijet observable

Average of two/three leading jets

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

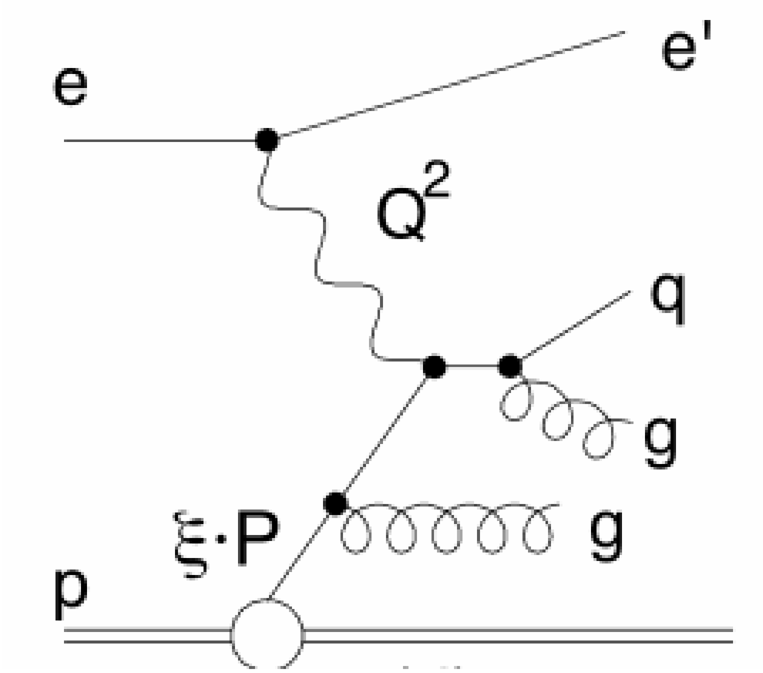
ZEUS-prel-14-008

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

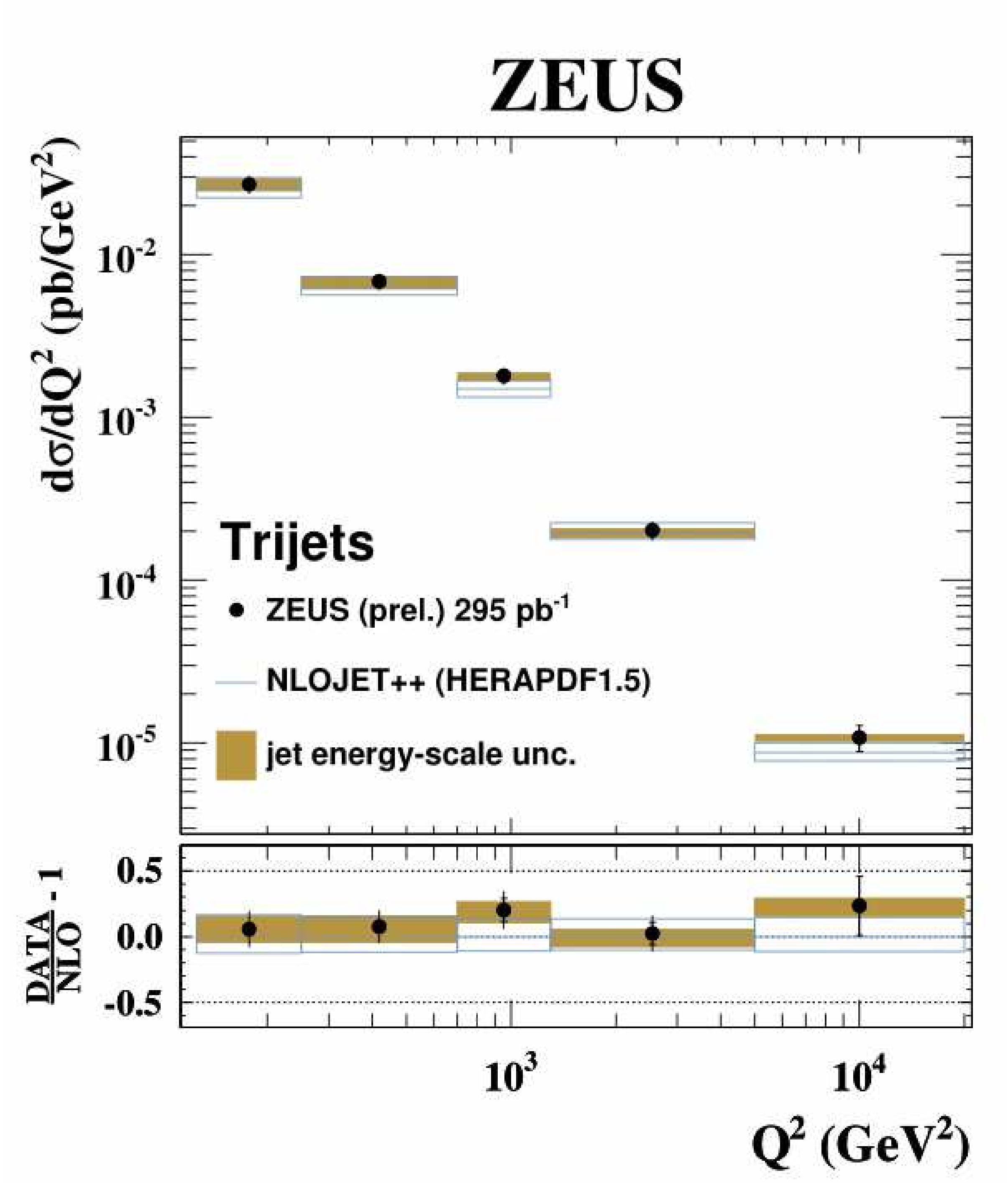
- hadronisation effects
- HERAPDF1.5

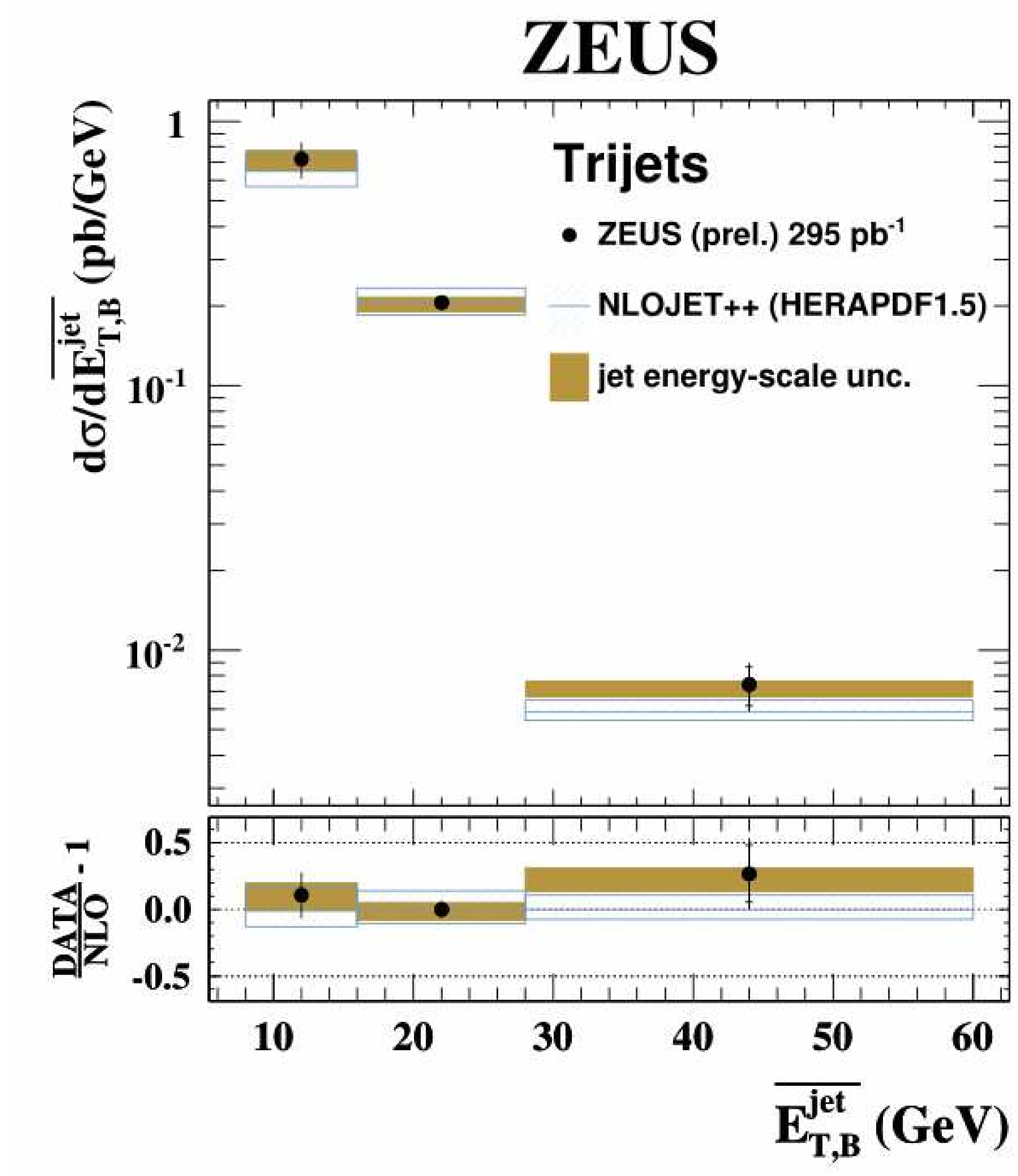
Scale Choice:

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

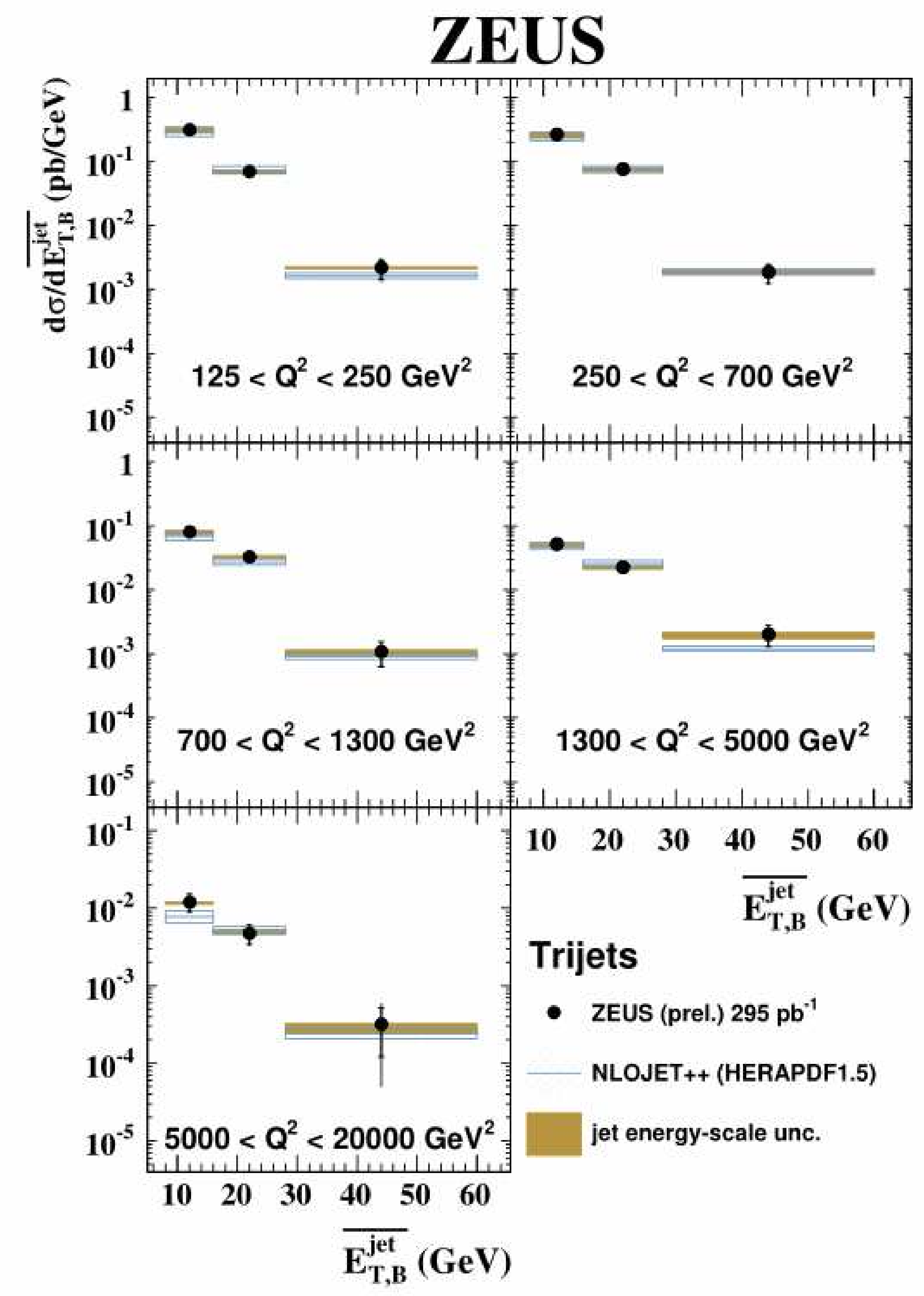
ZEUS-prel-14-008

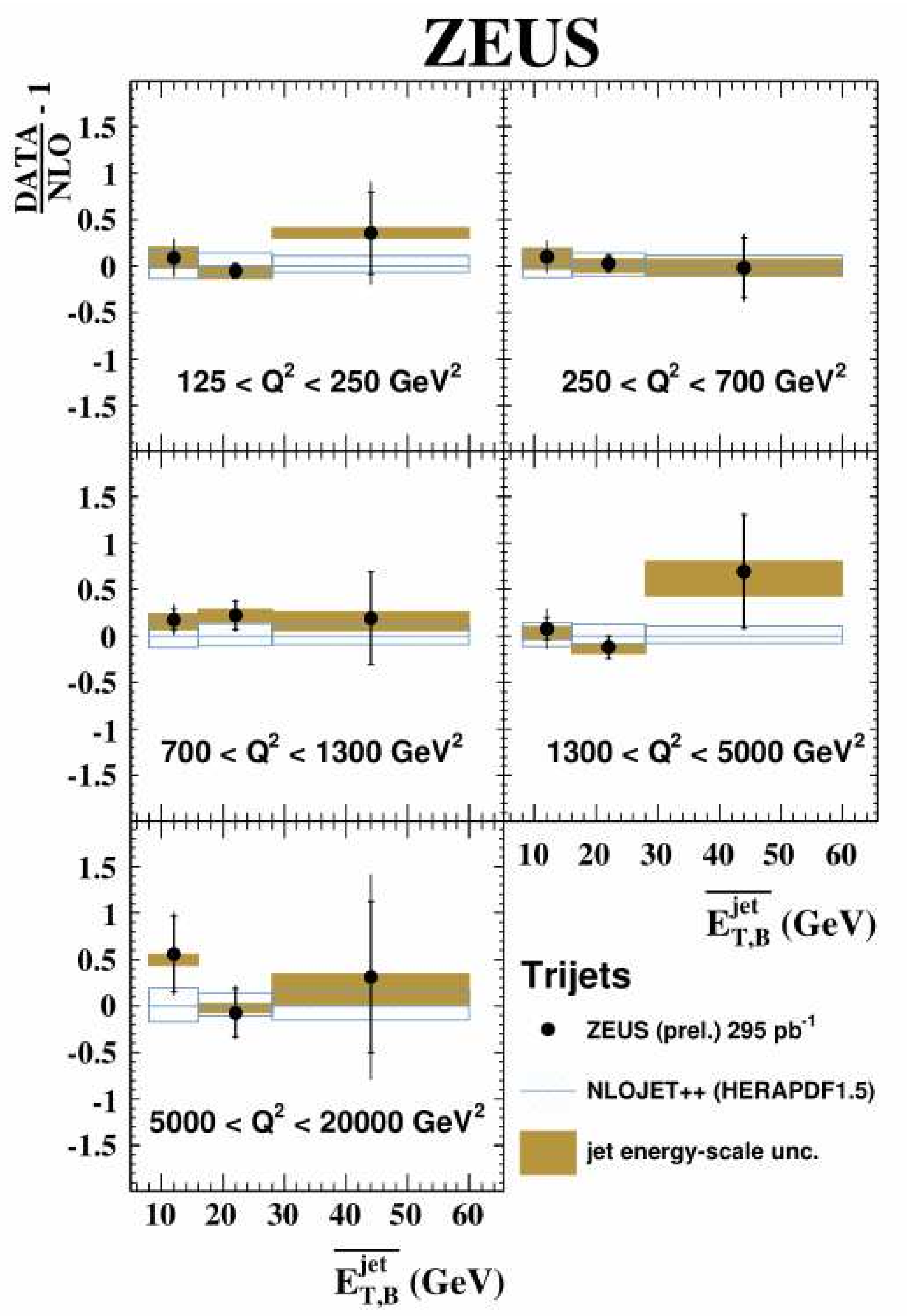
Single differential trijet cross sections





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)

Simulataneous Measurement of

- inclusive jet, dijet and trijet cross sections

and

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

Neutral current phase space

$150 < Q^2 < 15000$ GeV^2
$0.2 < y < 0.7$

Jet acceptance

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

Inclusive Jet

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

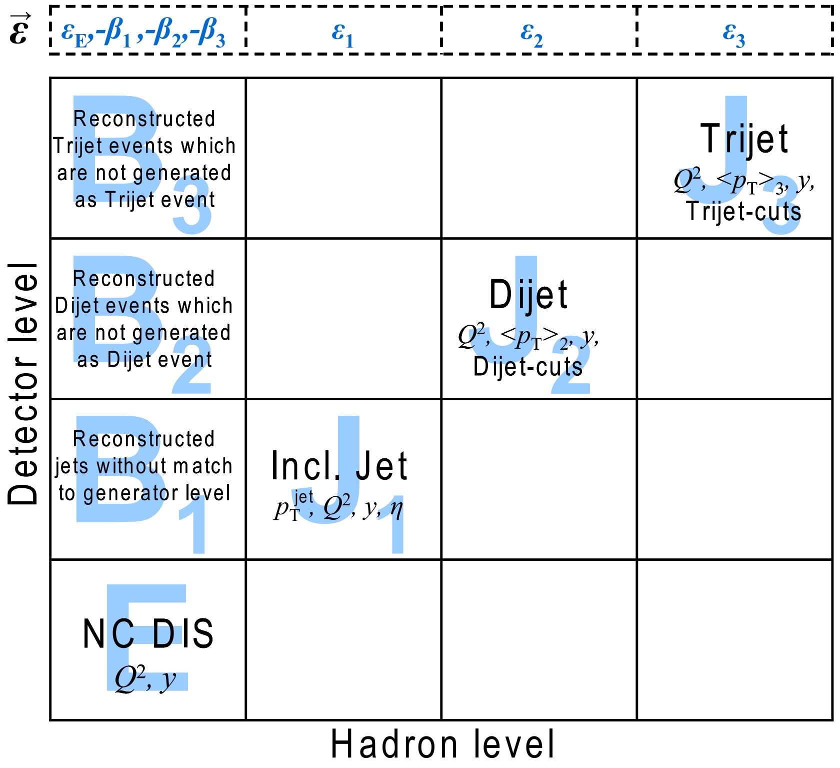
Dijet and Trijet

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

Multidimensional Regularized Unfolding

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

Migration Matrix



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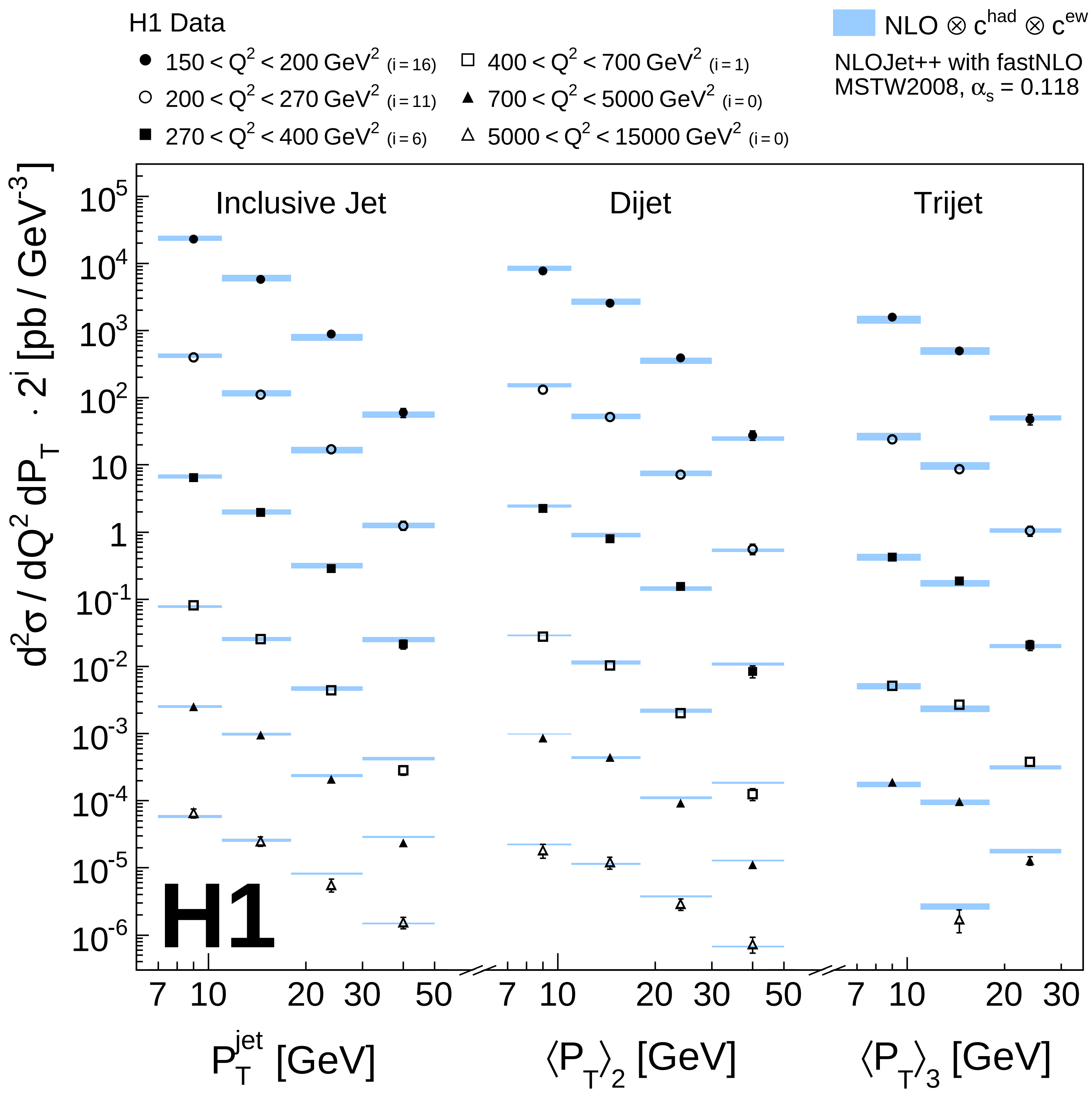
Multijet at high Q^2 – Inclusive Jet, Dijet, Trijet (H1)



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

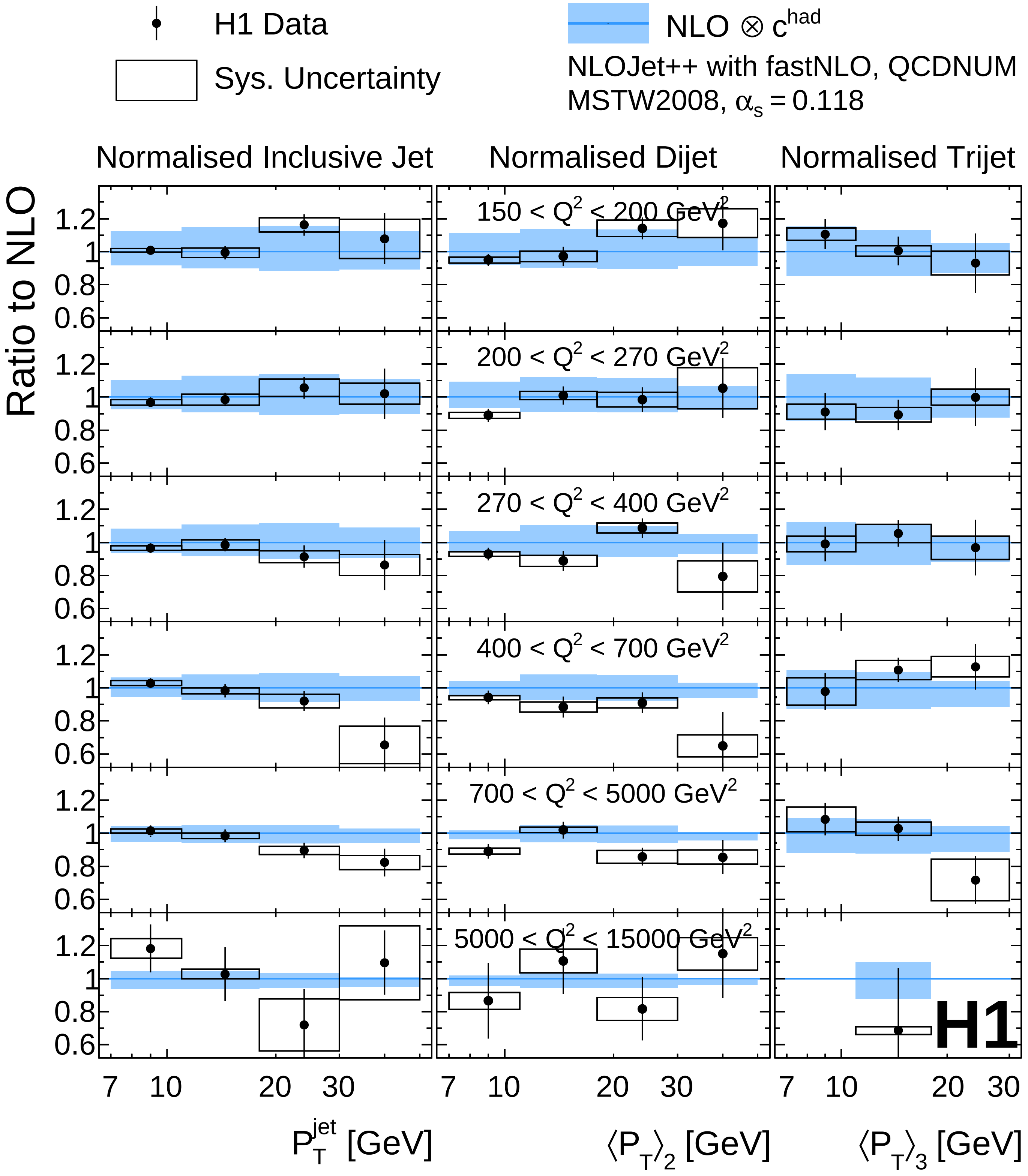
Multijet at high Q^2 – Inclusive Jet, Dijet, Trijet (H1)

Normalised Multijets

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

Experimental precision higher than theory uncertainty from scale variations

Overall good 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 $\alpha_s(M_Z)$

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

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

- Most precise value of $\alpha_s(M_Z)$ from jet cross sections
- Experimental uncertainty significantly smaller than theoretical one
- Higher order calculations mandatory

subm. to EPJ C, arXiv:1406.4709

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Compare to recent CMS inclusive jet value:

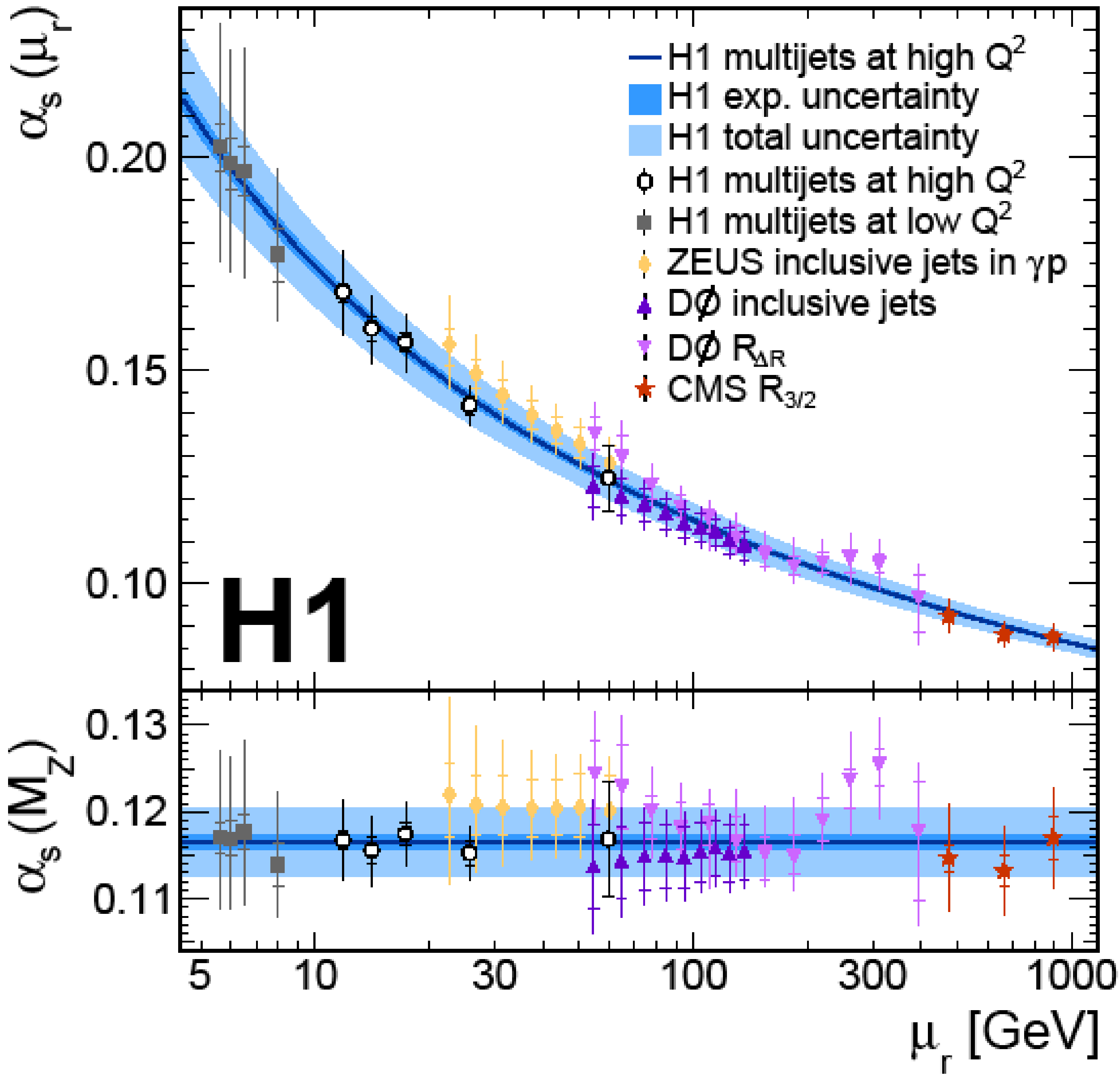
CMS-PAS-SMP-12-028
CMS-PAS-SMP-12-027

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

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

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

QCD Instantons

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

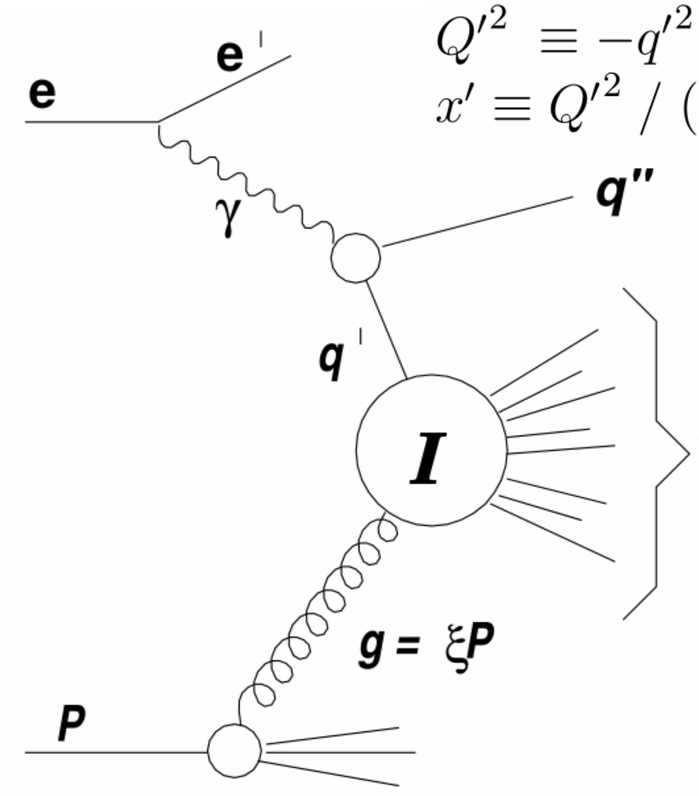
Strategy I

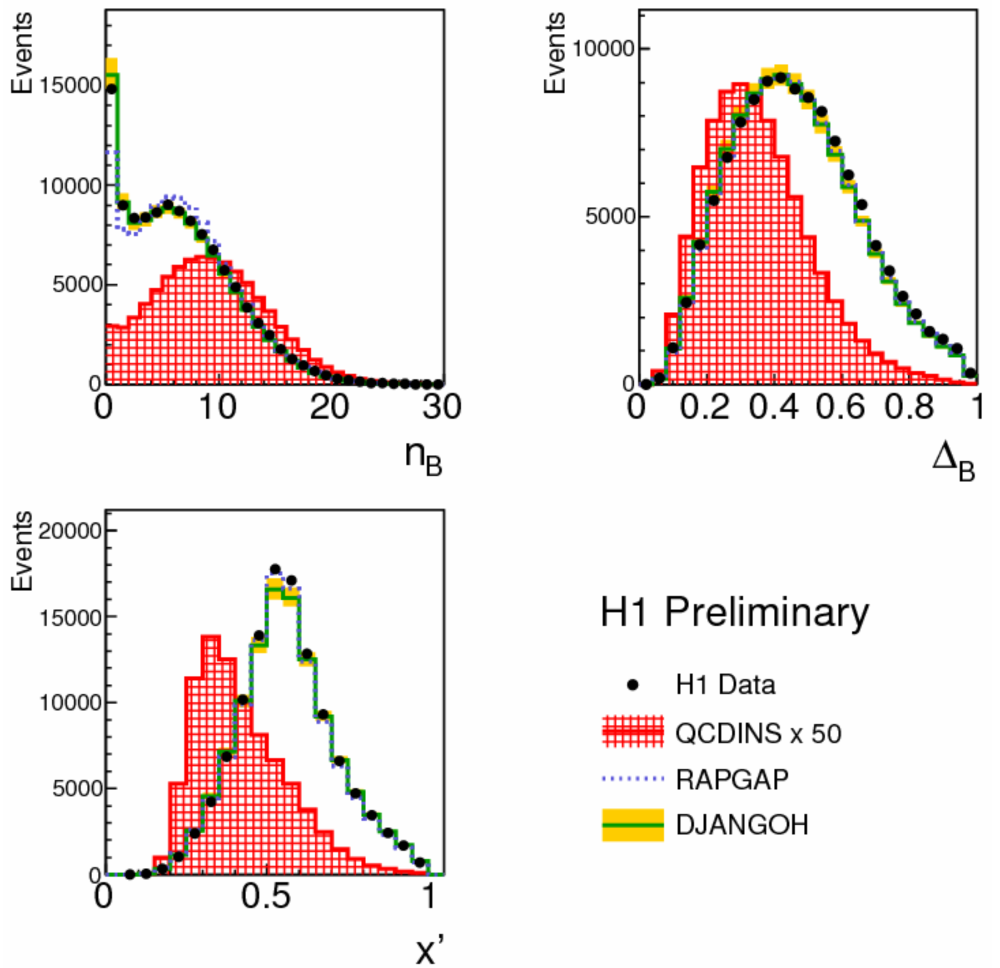
- Find jets in hadronic center of mass frame
  - Remove hardest jets from HFS
- Boost to instanton rest frame and define variables
  - Topological: Sphericity, Fox-Wolfram moments, azimuthal isotropy (Δ_B)…
  - Number of charged particles in band (n_B)
  - Energy of band ($E_{Inst.}$), …
- Variables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

Variables of I-subprocess:

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

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





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

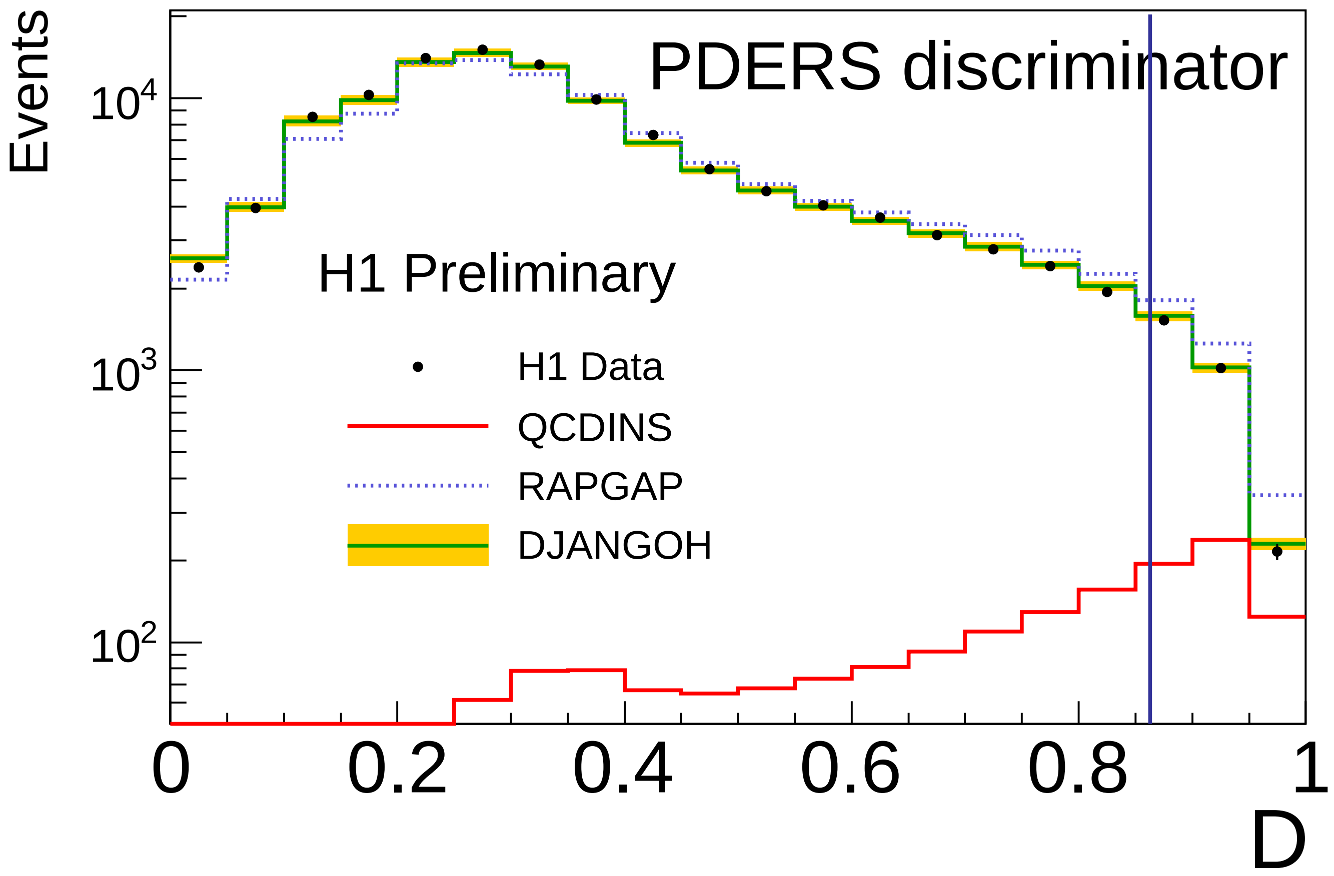
Input for limit calculation

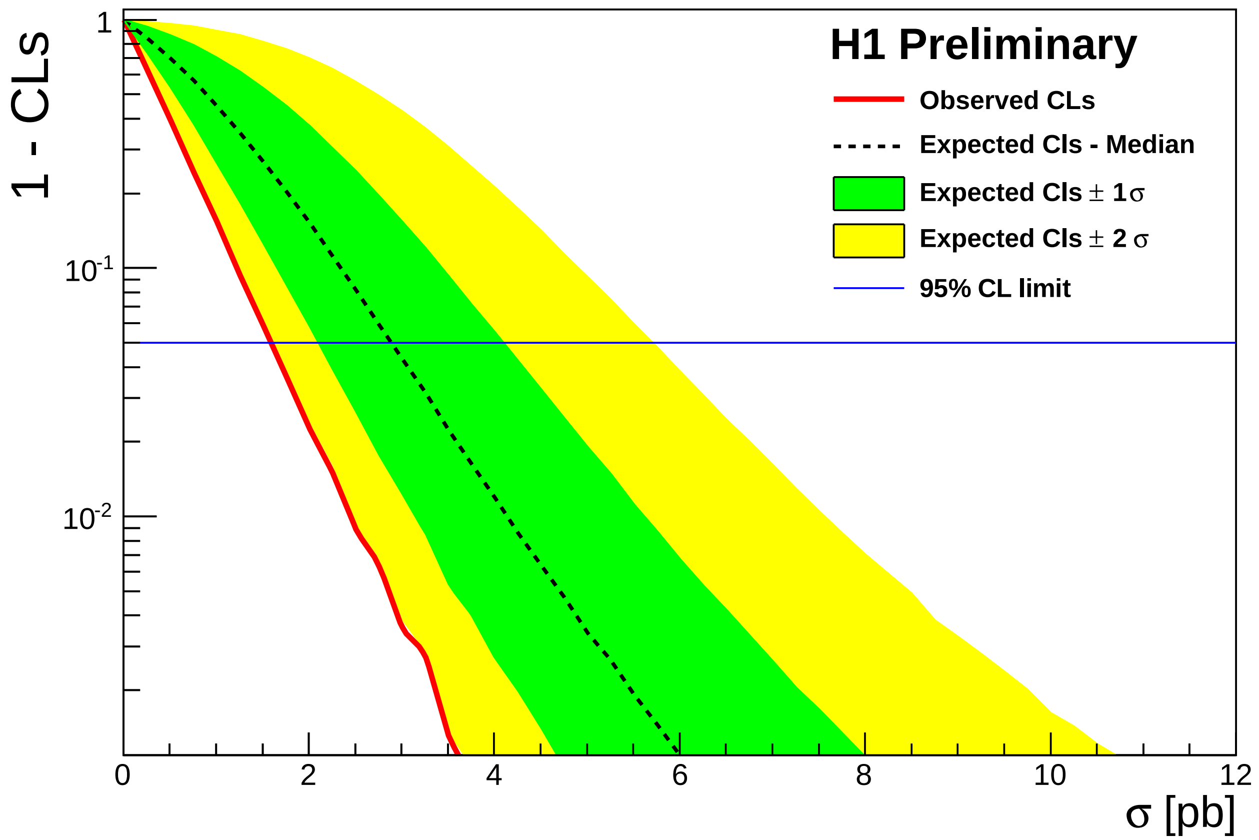
QCD Instanton cross section: 10 ± 2 pb

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-Schremmps‘ predictions for HERA QCD instantons.





Summary

New QCD results from HERA experiments with final data precision

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

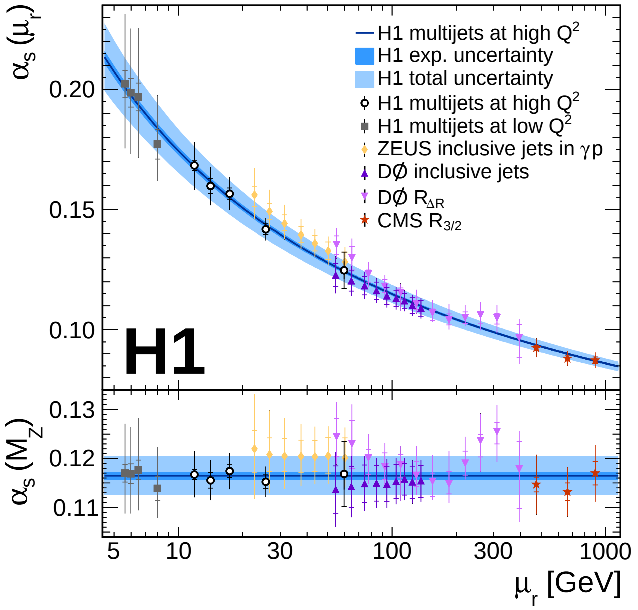
QCD Instanton → Ringwald-Schrempp' solution appears to be excluded

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

Multijet cross sections in DIS → Data well described by theory

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 physics program

Backup

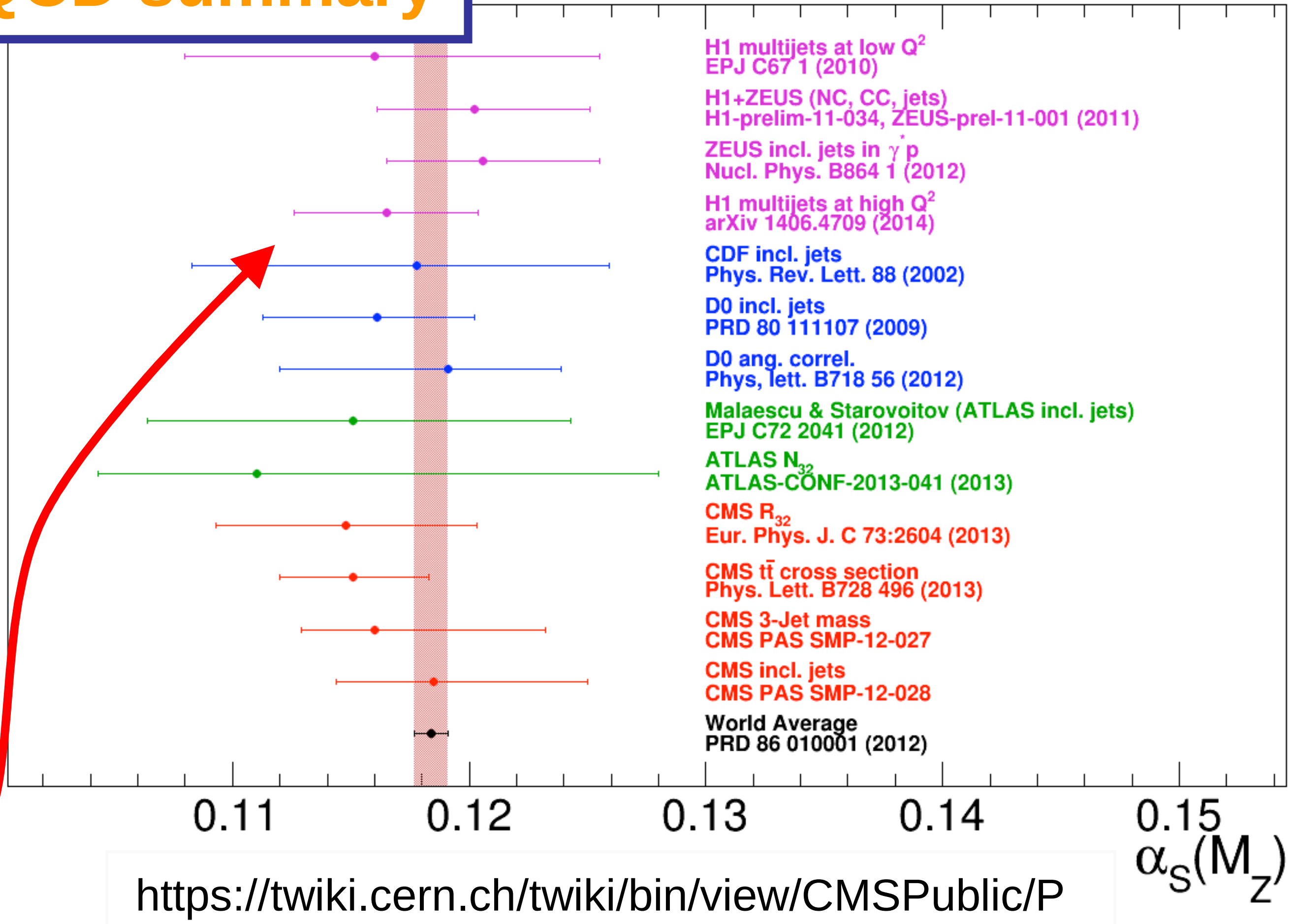
CMS-PAS-SMP-12-028 CMS-PAS-SMP-12-027 arXiv 1406:470

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%)



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

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%

Correction of detector effects using regularized 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

Regularized unfolding using Tunfold (JINST 7 (2012) T10003)

- Find hadron level x by analytic minimization of χ^2

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

- Find stationary point ($\partial\chi^2/\partial x = 0$) by solving analytically as function of x
- 'True' hadron level can be determined directly

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

- τ (and *L*) are free parameters

Schematic definition of migration matrix

Simultaneous unfolding

NC DIS, inclusive jet, dijet and trijet

Covariance matrix Vy

takes statistical correlations of observables into account

Individual unfolding schemes

- **E**, **J1**, **J2**, **J3** studied in detail
- Are optimized separately using MC

Matrices Bi

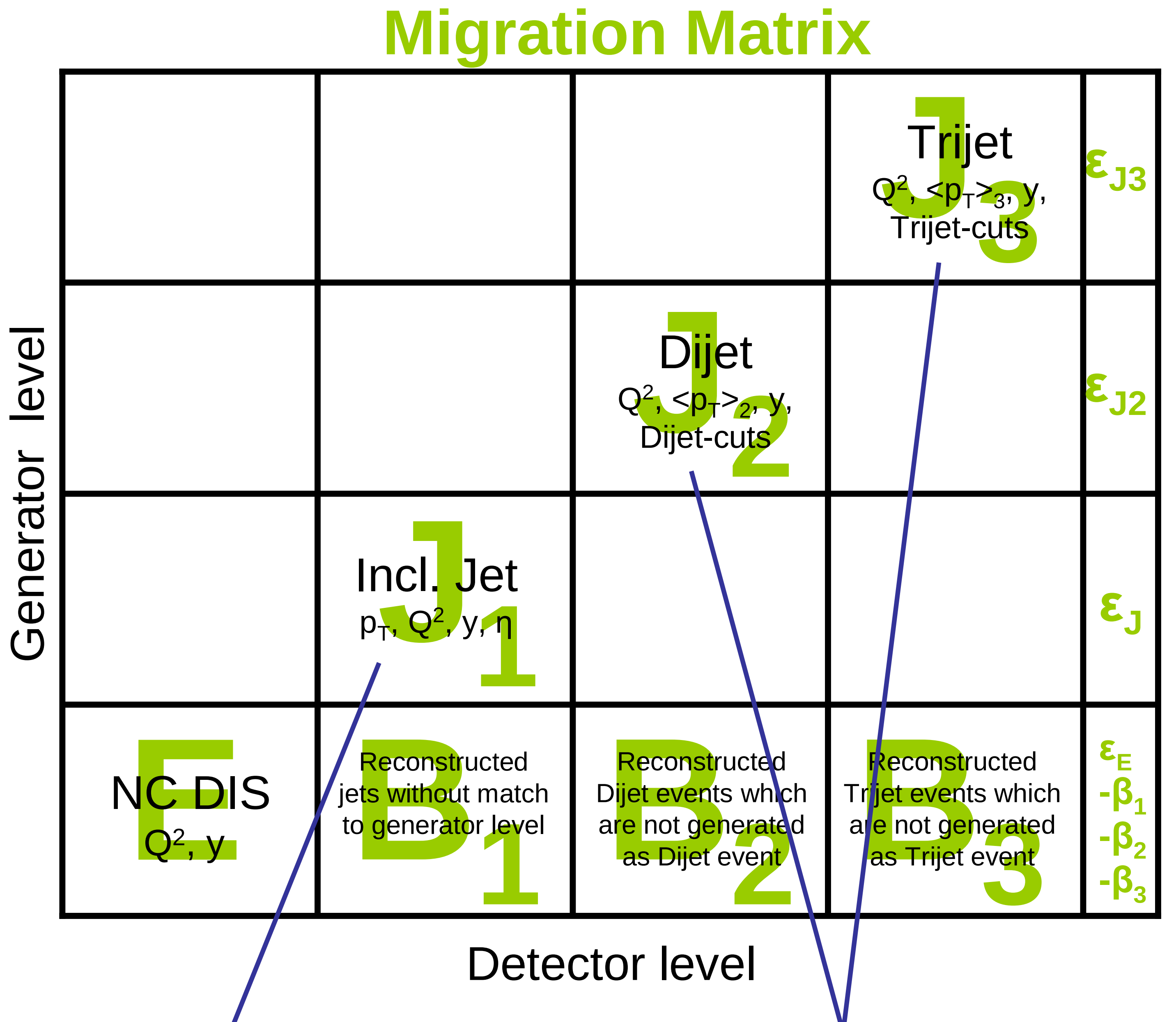
Constrain reconstructed but not generated contributions

Two MC generators

Django and Rapgap

Phase space is enlarged

in all variables where migrations are relevant



Migration Matrix

			Trijet Q^2, $\langle p_T\rangle_3$, y, Trijet-cuts J_3	ε_{J3}
		Dijet Q^2, $\langle p_T\rangle_2$, y, Dijet-cuts J_2		ε_{J2}
	Incl. Jet p_T, Q^2, y, η J_1			ε_J
NC DIS Q^2, y E	Reconstructed jets without match to generator level B_1	Reconstructed Dijet events which are not generated as Dijet event B_2	Reconstructed Trijet events which are not generated as Trijet event B_3	ε_E $-\beta_1$ $-\beta_2$ $-\beta_3$

3-dimensional unfolding in p_T, Q^2, y

Up to 6 observables are considered to discribe migrations

Four measurements are unfolded simultaneously: stat. correlations are considered

Correlation matrix of all data points

Covariance matrix

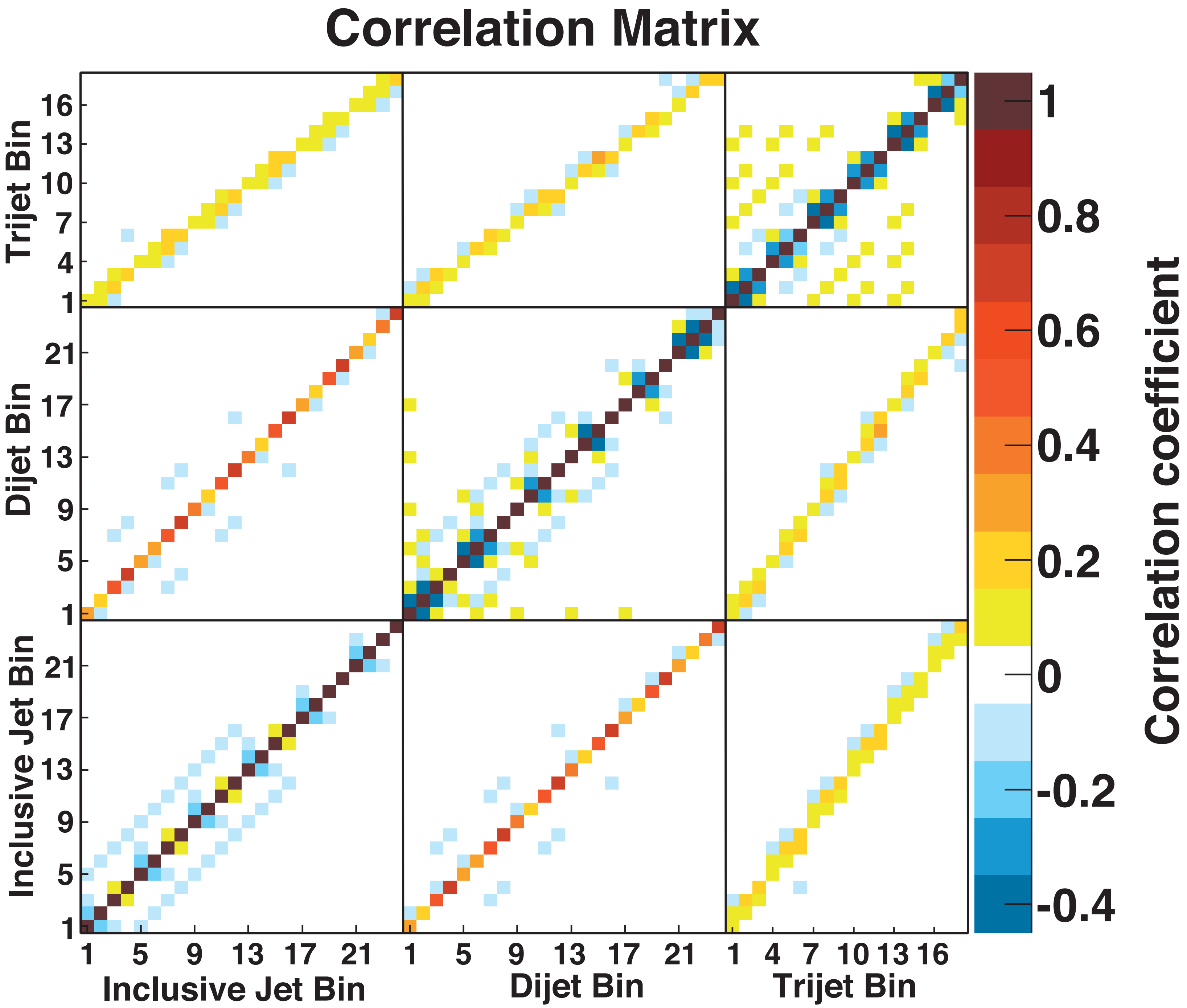
Obtained through linear error propagation of statistical uncertainties

Correlations

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

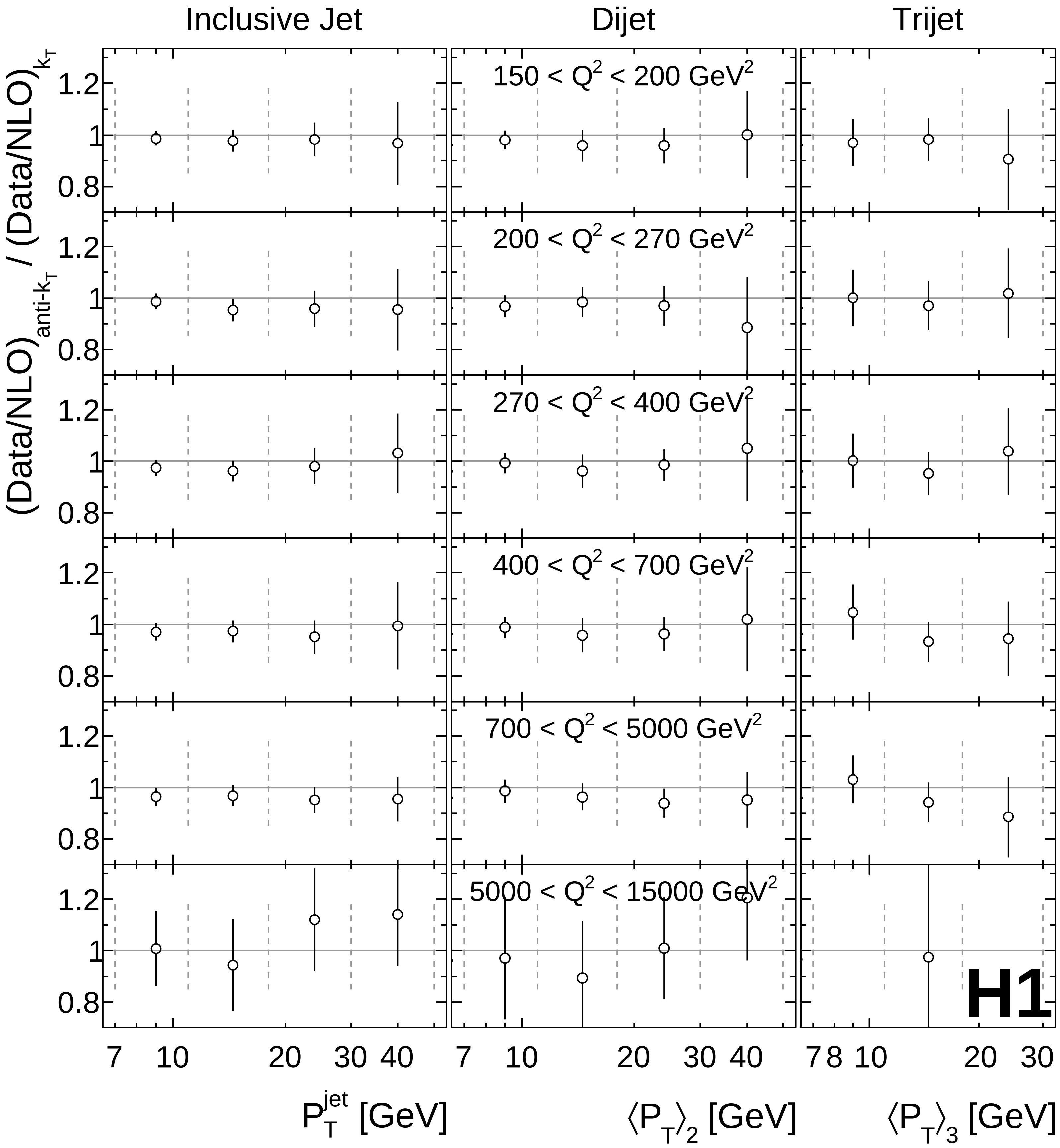
Useful for

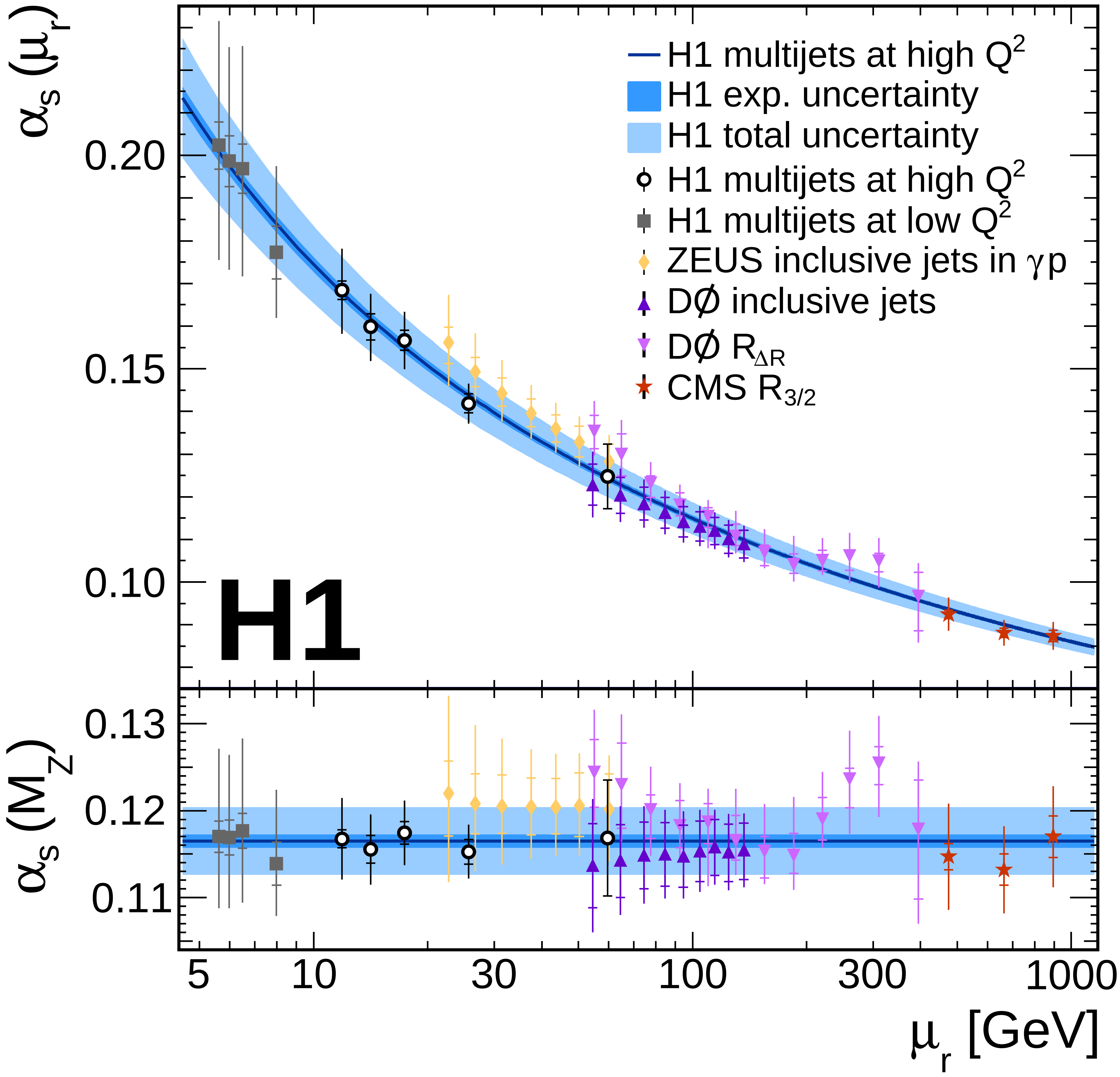
- Cross section ratios
- Combined fits
- Normalized cross sections



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

Multijet Cross Sections at High Q^2




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 $R_{3/2}$
H1
$\alpha_s(\mu_r)$
0.20
0.15
0.10
$\alpha_s(M_Z)$
0.13
0.12
0.11
5
10
30
100
300
1000
μ_r [GeV]