Normalized Multijet Cross Sections using Regularized Unfolding and Extraction of $\alpha_s(M_Z)$ in Deep-inelastic Scattering at high Q^2 at HERA

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on behalf of the H1 collaboration

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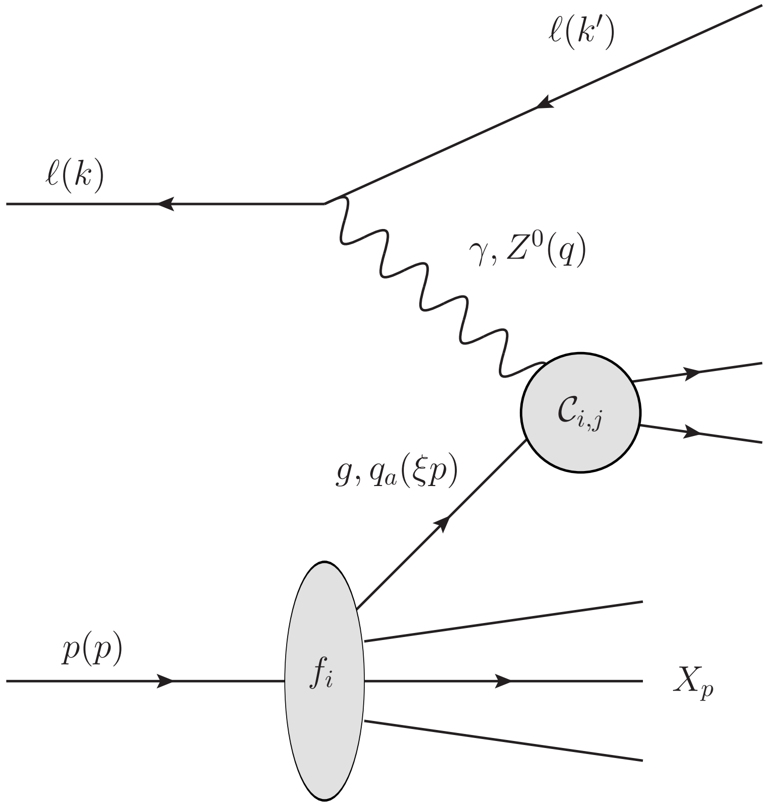
Jet production in *ep* scattering

Deep-inelastic *ep* scattering



Photon virtuality Q^2

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

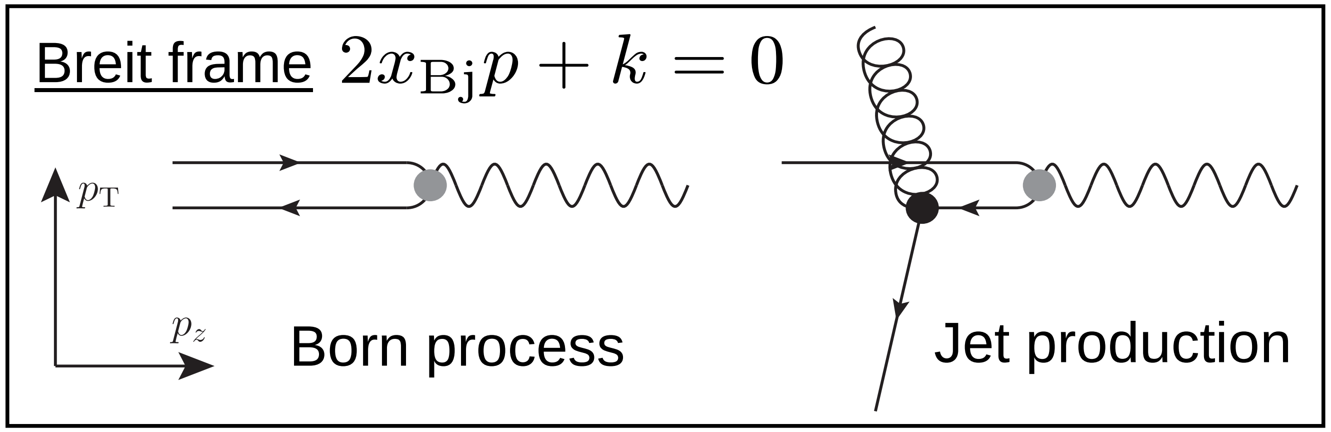
Inelasticity

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

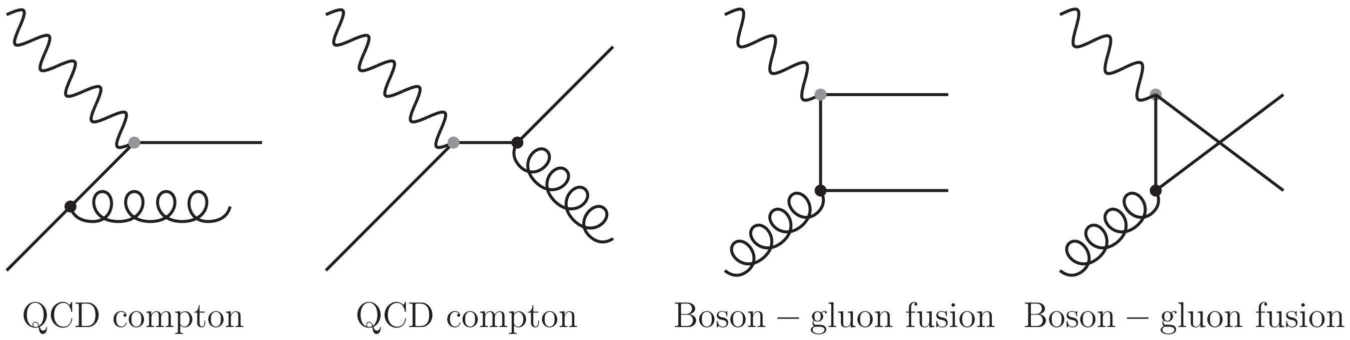
Bjorken variable

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

Jet measurements are performed in 'Breit frame'


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

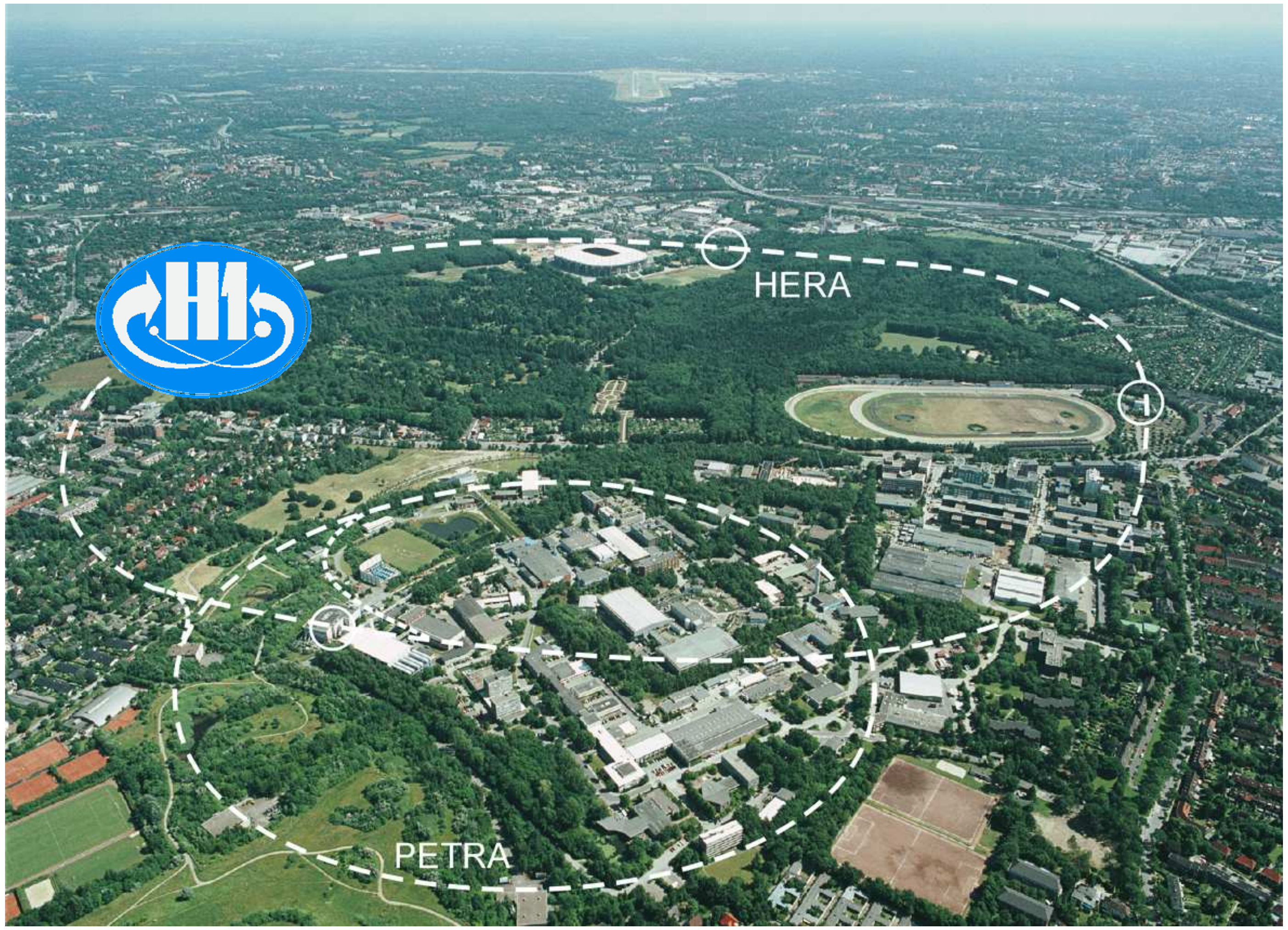
Jet production in leading-order pQCD


QCD compton
QCD compton
Boson – gluon fusion
Boson – gluon fusion

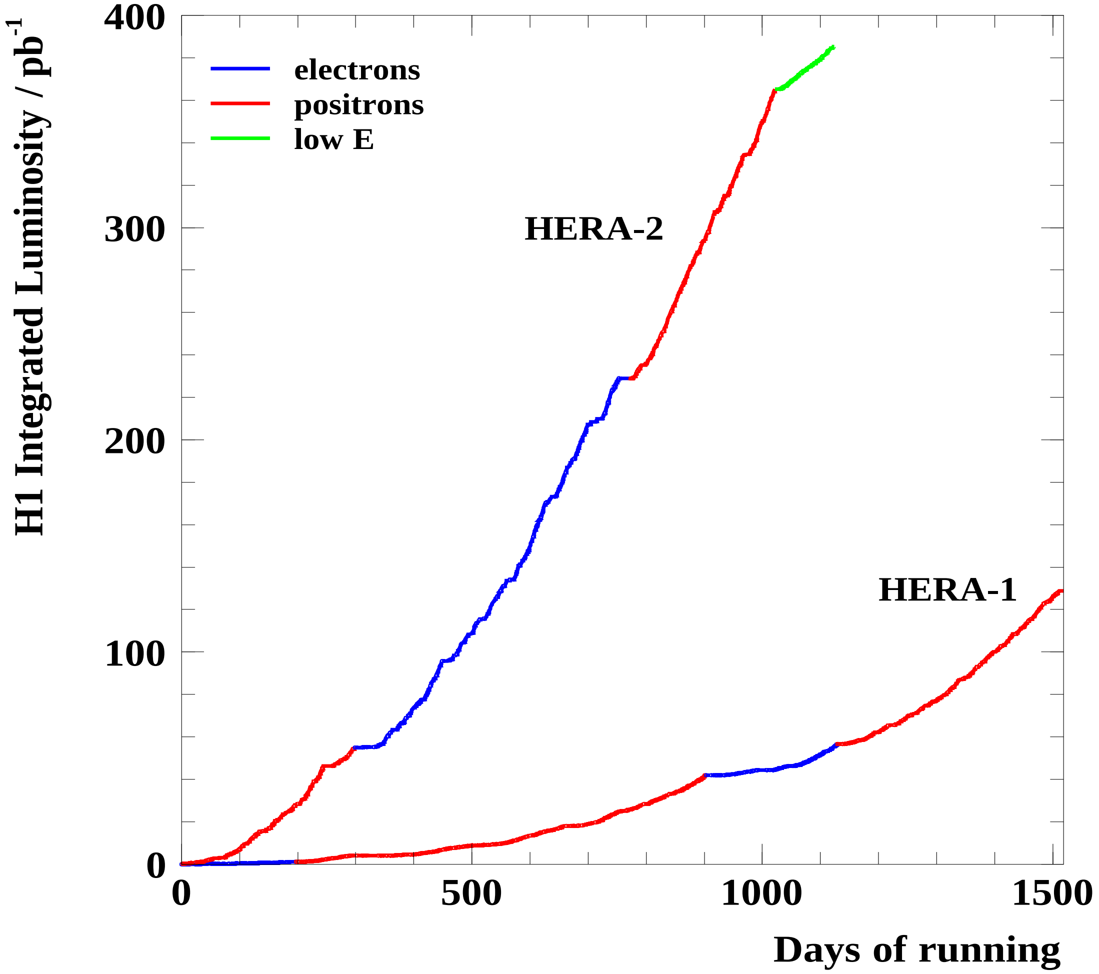
Jet production is directly sensitive to α_s

H1 detector at HERA

HERA *ep* collider



Integrated H1 Luminosity



HERA collider in Hamburg, Germany

- e$^{\pm}$p collider
- $\sqrt{s}$ = 319 GeV
  - E_e = 27.6 GeV
  - E_p = 920 GeV

HERA-2 period

Years 2003 – 2007

Electron and positron runs

$\mathcal{L} \simeq 356$ pb^{-1}

Normalized multijet measurement at H1

Four measurements are performed

Neutral current phase space

150 < Q^2 < 15000 GeV^2

0.2 < y < 0.7

Jet acceptance

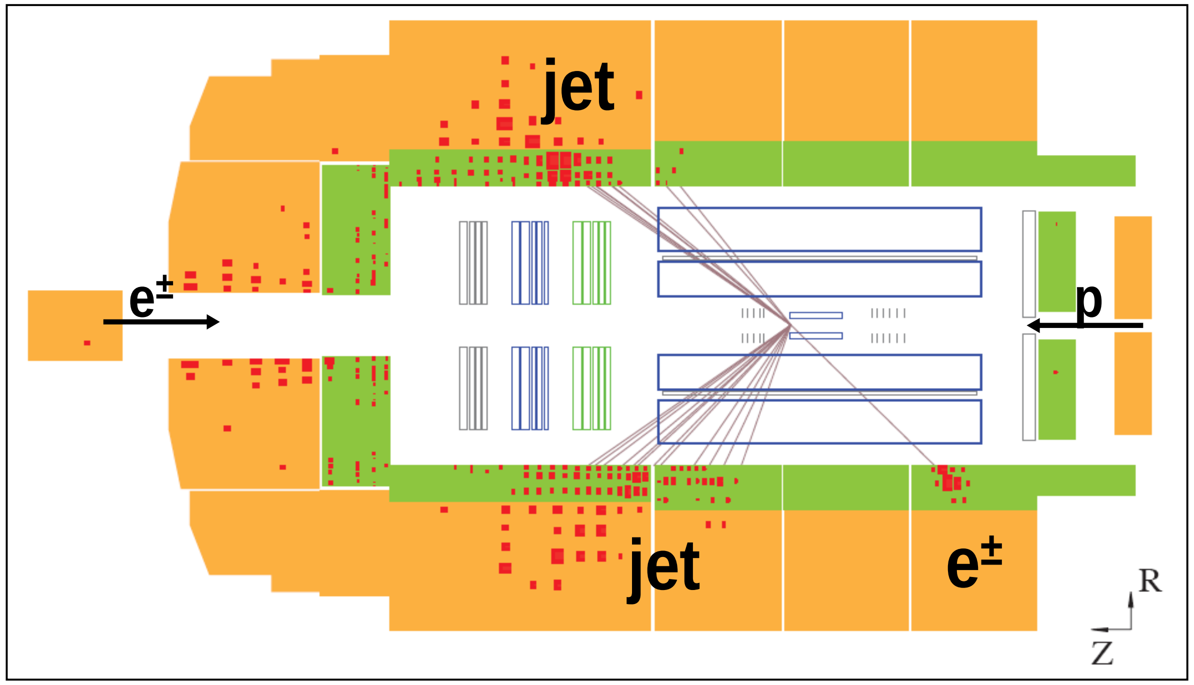
-1.0 < η_{lab} < 2.5

Inclusive Jet

7 < p_T^{jet} < 50 GeV

<table>
<tr><th>Dijet (n_{jet} ≥2)</th><th>Trijet (n_{jet} ≥ 3)</th></tr>
<tr><td colspan="2">5 < p_T^{jet} < 50 GeV
M_{12} > 16 GeV</td></tr>
<tr><td>7 < $\langle p_T \rangle_2$ < 50 GeV</td><td>7 < $\langle p_T \rangle_3$ < 30 GeV</td></tr>
</table>

NC DIS measurement used for normalized jet cross sections



Measurements are performed double-differentially

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

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 V_y

takes statistical correlations of observables into account

Individual unfolding schemes

- E, J_1, J_2, J_3 studied in detail
- Are optimized separately using MC

Matrices B_i

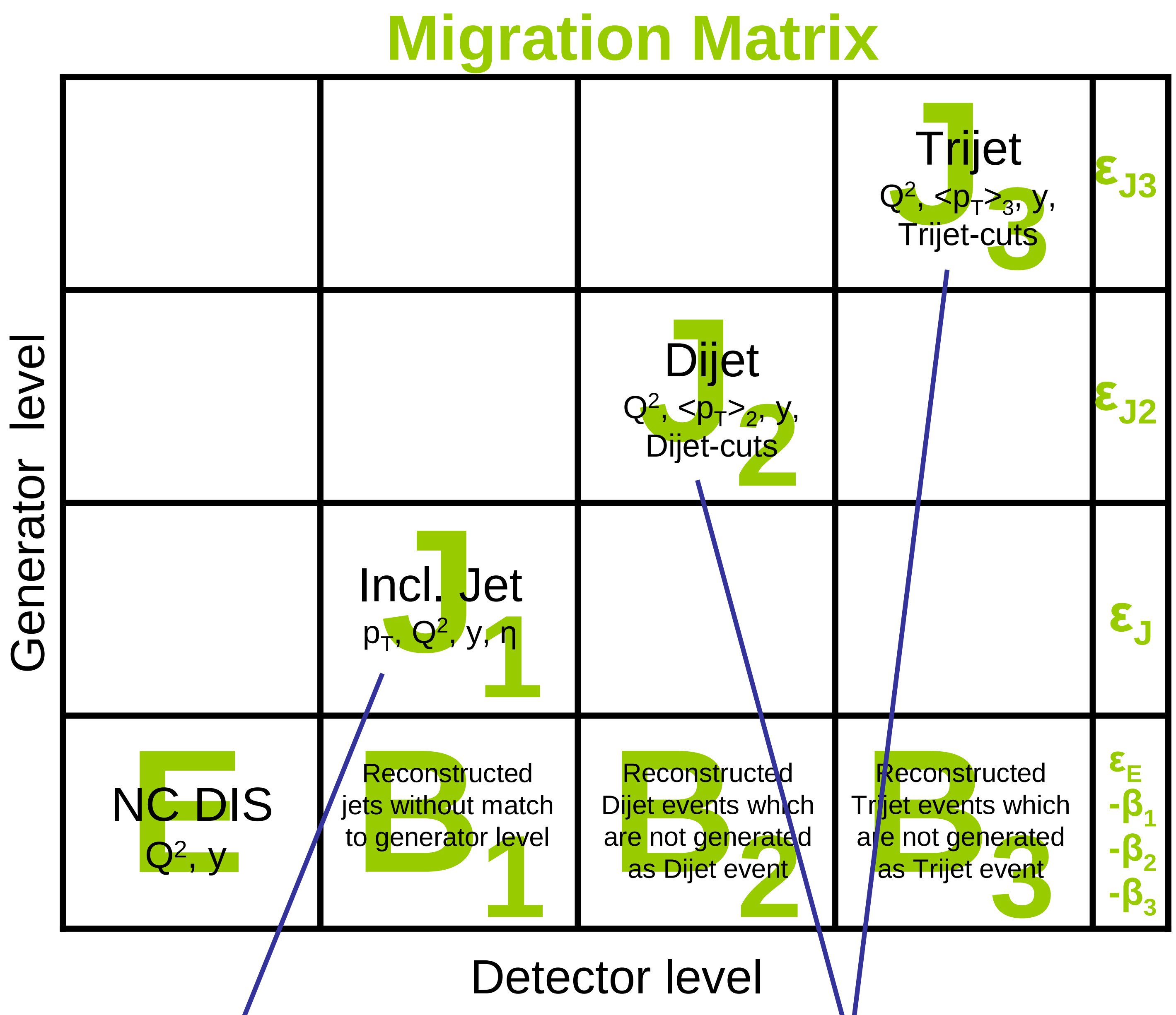
Constrain reconstructed but not generated contributions

Two MC generators

Django and Rapgap

Phase space is enlarged

in all variables where migrations are relevant



Migration Matrix

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

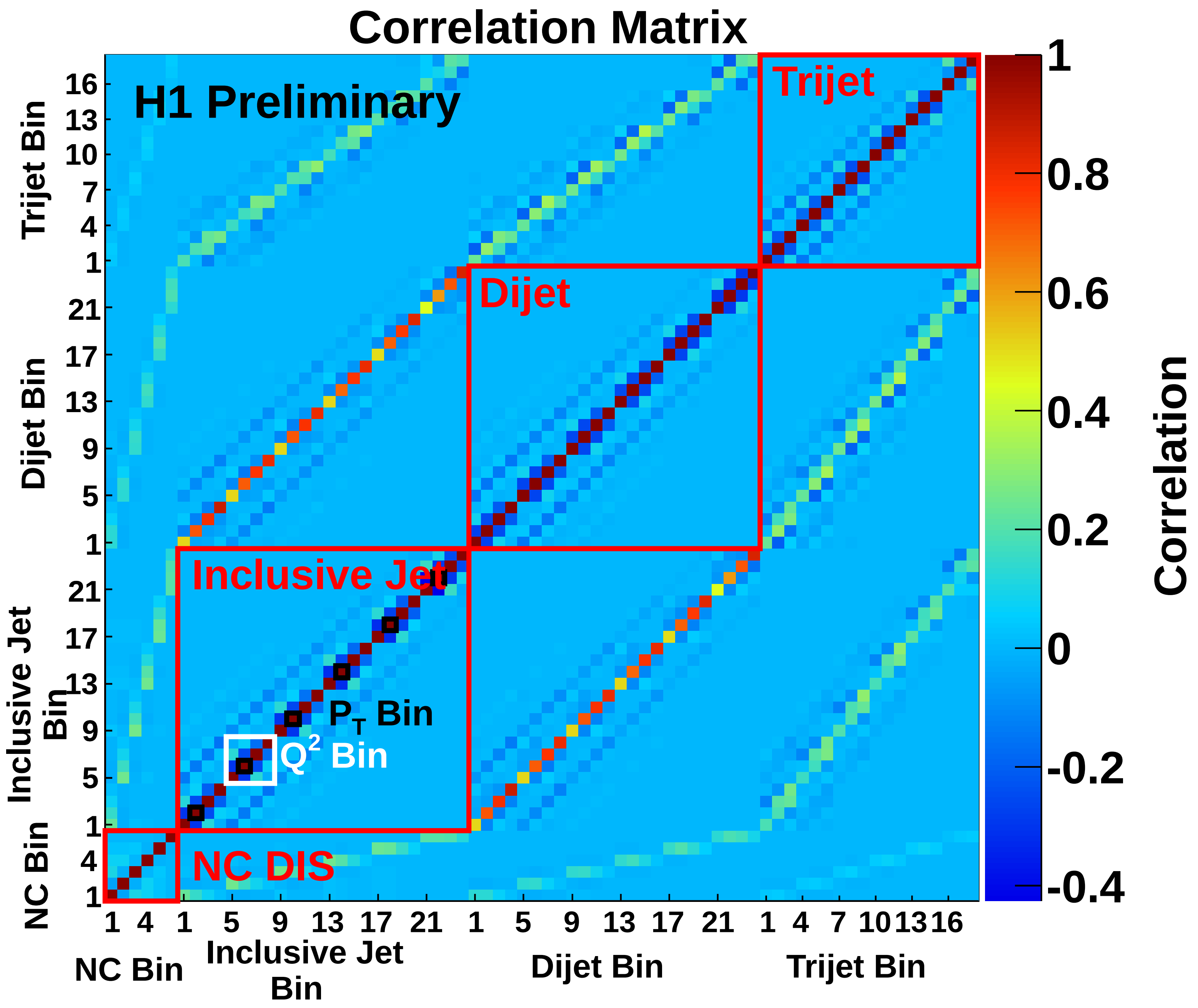
Obtained through linear error propagation of statistical uncertainties

Correlations

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

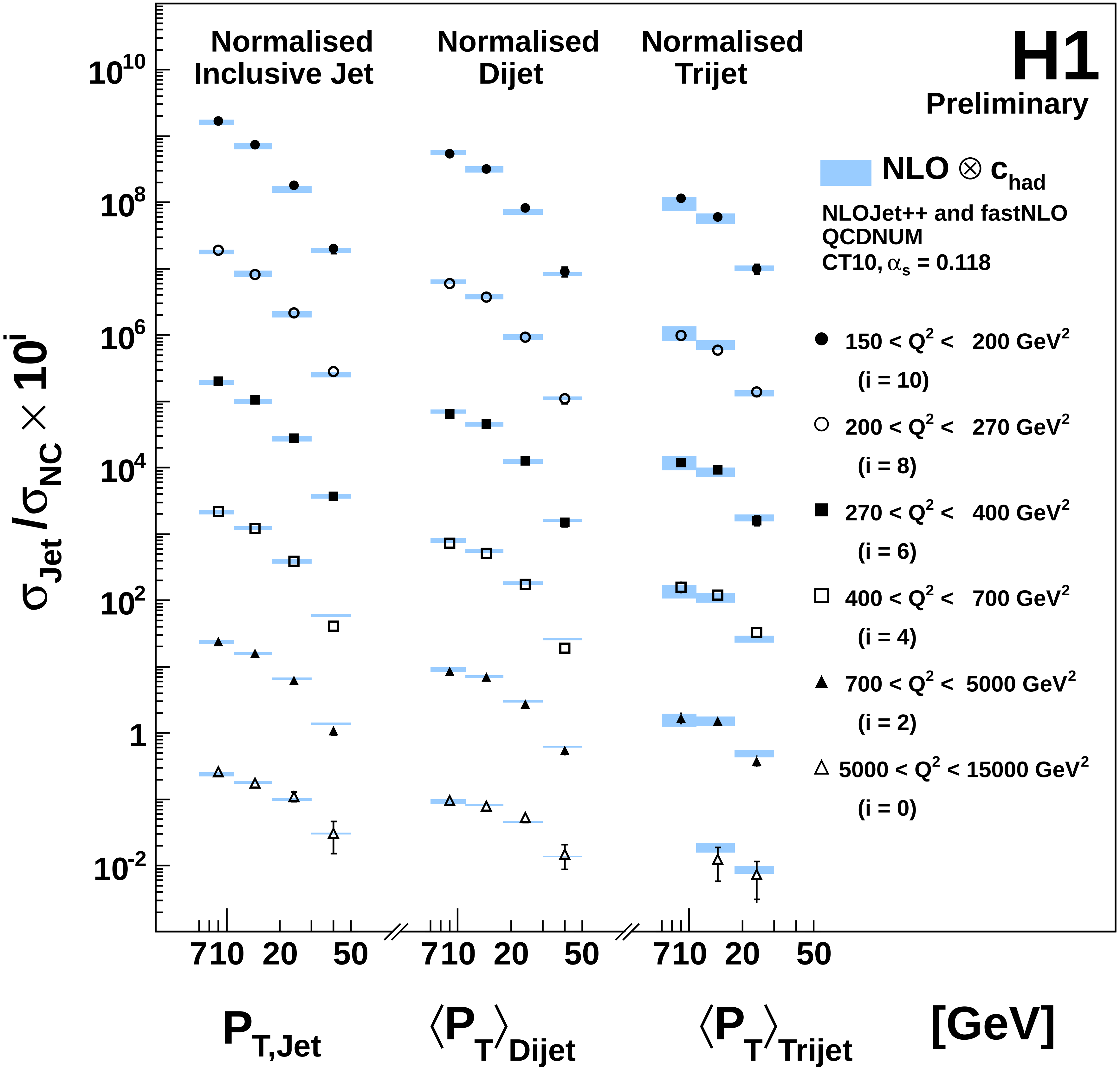
Useful for

- Cross section ratios
- Combined fits
- Normalized cross sections



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

Normalized multijet cross sections



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Data are employed for extraction of $\alpha_s(M_Z)$

Experimental input m_i

- Normalized incl. jet, dijet and trijet data

Experimental uncertainties $\delta_k m_i$

- Taken into account in fit
- Covariance matrix V takes correlations into account
- Experimental uncertainties k are respected with nuisance parameters

Theoretical input t_i

- NLO predictions from
  - NLOJET++ and fastNLO
  - QCDNUM
- Hadronization corrections
- PDF: CT10
- Scale choices
  - $\mu_r^2 = (Q^2 + E_T^2)/2$
  - $\mu_f^2 = Q^2$

- FastNLO provides fast repeated calculation of cross section predictions

Iterative χ^2 minimization using TMinuit with $\alpha_s(M_Z)$ and ε_k are free parameters

$$\chi 2(\alpha_s(M_Z), \varepsilon_k) = pV^{-1}p + \sum_k^{N_{sys}} \varepsilon_k^2$$

$$p_i = d_i - t_i\left(1 - \sum_k^{N_{sys}} \delta_{i,k}\varepsilon_k\right)$$

α_s fits to individual measurements

Normalized inclusive jet

$\alpha_s(M_Z) = 0.1197 \pm 0.0008\,(\mathrm{exp}) \pm 0.0014\,(\mathrm{PDF}) \pm 0.0012\,(\mathrm{had}) \pm 0.0054\,(\mathrm{theo})$

χ^2 / ndf = 28.7/23 = 1.25

Normalized dijet

$\alpha_s(M_Z) = 0.1142 \pm 0.0010\,(\mathrm{exp}) \pm 0.0017\,(\mathrm{PDF}) \pm 0.0009\,(\mathrm{had}) \pm 0.0048\,(\mathrm{theo})$

χ^2 / ndf = 27.0/23 = 1.18

Normalized trijet

$\alpha_s(M_Z) = 0.1185 \pm 0.0018\,(\mathrm{exp}) \pm 0.0013\,(\mathrm{PDF}) \pm 0.0016\,(\mathrm{had}) \pm 0.0043\,(\mathrm{theo})$

χ^2 / ndf = 12.0/16 = 0.75

Results

- High experimental precision
- Reasonable χ^2/ndf for each fit

Tension between inclusive jet and dijet

Visible also in previous H1 and ZEUS analyses

Theory uncertainties using offset method

- PDF

  Obtained from PDF eigenvectors (90%CL)

- Hadronization (had)

  Half-difference between ‘Lund string’ and ‘cluster’ fragmentation

- Missing higher orders (theo)

  Scale variations: μ_r and μ_f between 0.5 and 2

α_s fit to normalized multijet cross sections

Simultaneous fit to

- Normalized inclusive jet
- Normalized dijet
- Normalized trijet

Taking statistical correlations between observables into account

Demanding NLO corrections < 30%: k<1.3

Normalized Multijet (k < 1.3)

$\alpha_s(M_Z) = 0.1163 \pm 0.0011(\text{exp}) \pm 0.0014\ (\text{PDF}) \pm 0.0008\ (\text{had}) \pm 0.0040\ (\text{theo})$

$\chi^2 / \text{ndf} = 53.3 / 41 = 1.30$

$\alpha_s(M_Z)$ from H1 multijet cross section

Value consistent with world average (**Phys. Rev. D 86 (2012) 010001**)

- $\alpha_s(M_Z) = 0.1184 \pm 0.0007$

High experimental precision

Precision limited by theory predictions

Summary

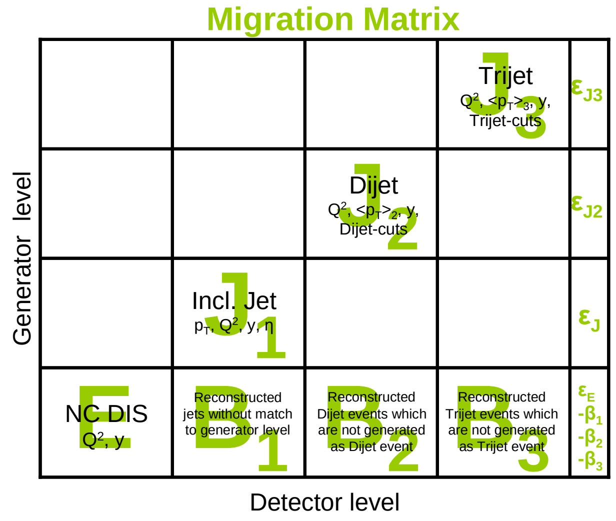
Regularized unfolding

Simultaneous unfolding of four measurements

Unfolding of NC DIS, inclusive jet, dijet and trijet data

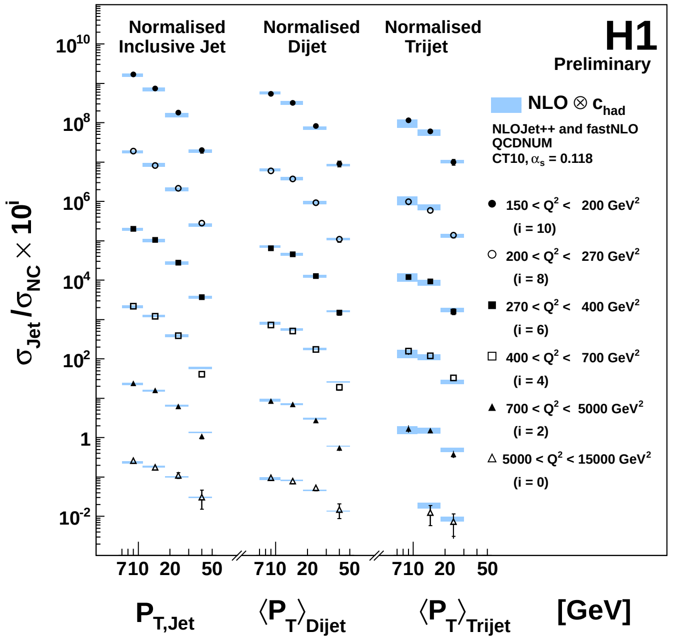
Migrations in up to 6 observables

Normalized cross sections can be obtained



Normalized Multijet Measurement at high Q^2

- Normalized Inclusive Jet
- Normalized Dijet
- Normalized Trijet



Extraction of $\alpha_s(M_Z)$

α_s fit using unfolded data to NLO QCD

Covariance matrix is considered

Also correlations between observables

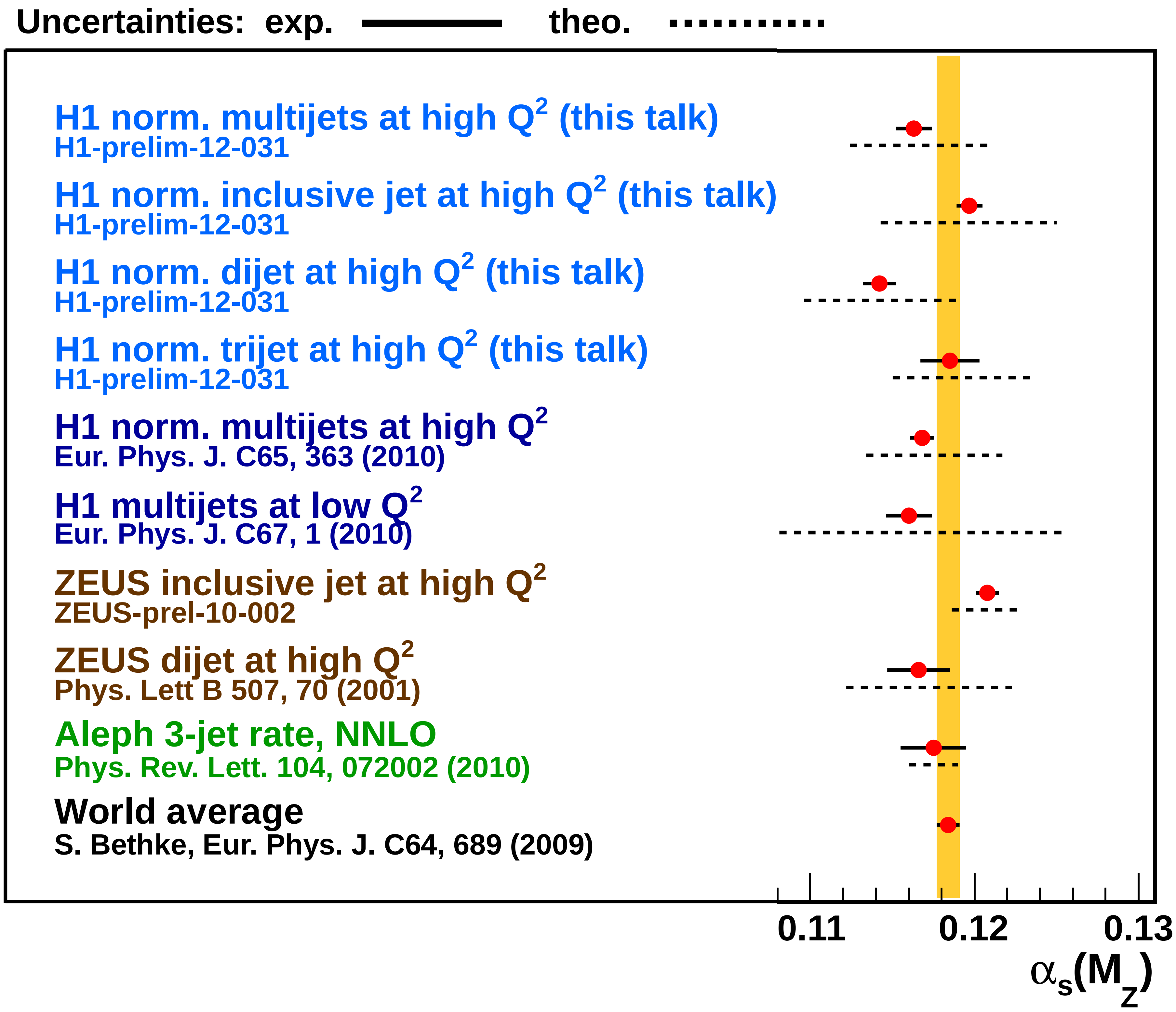
Experimental error 1%

Theoretical errors dominate with 3.4%

0.1163
± 0.0011 (exp)
± 0.0043 (th)

Backup

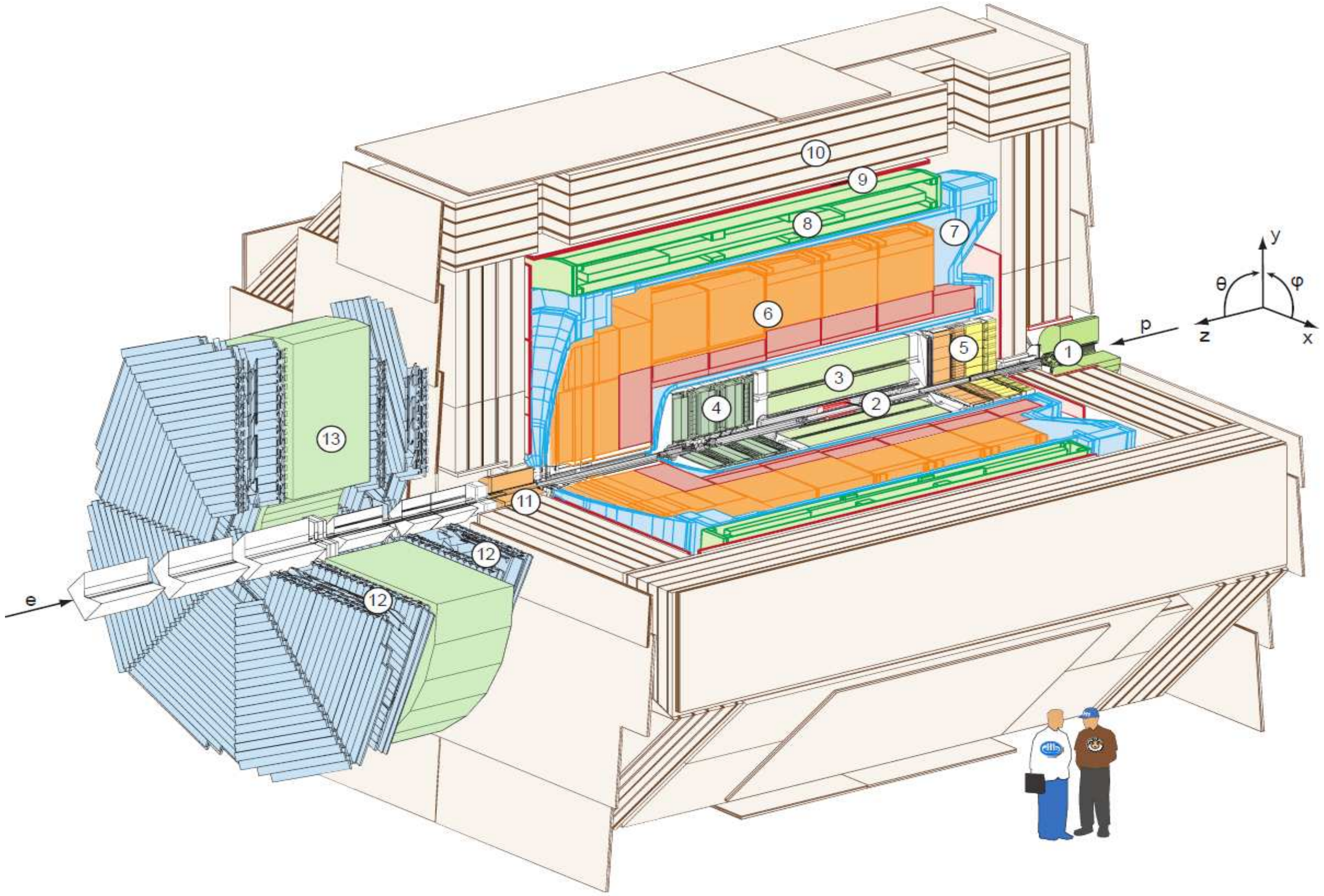
Comparision of α_s values



HERA and H1

H1 detector

- Multi-purpose detector
- Asymmetric design
- Trackers
  - Silicon tracker
  - Jet chambers
  - Proportional chambers
- Calorimeters
  - Liquid Argon sampling calorimeter
  - Scintillating fiber calorimeter
- Muon detectors
- Superconducting solenoid
  - 1.15T axial-symmetric magnetic field



Comparing unfolding with bin-by-bin method: Monte Carlo

Compare with Monte Carlo pseudo-data

- Bin-by-bin correctoin
  Bin-wise correction factors
- Regularized unfolding

Pull distributions

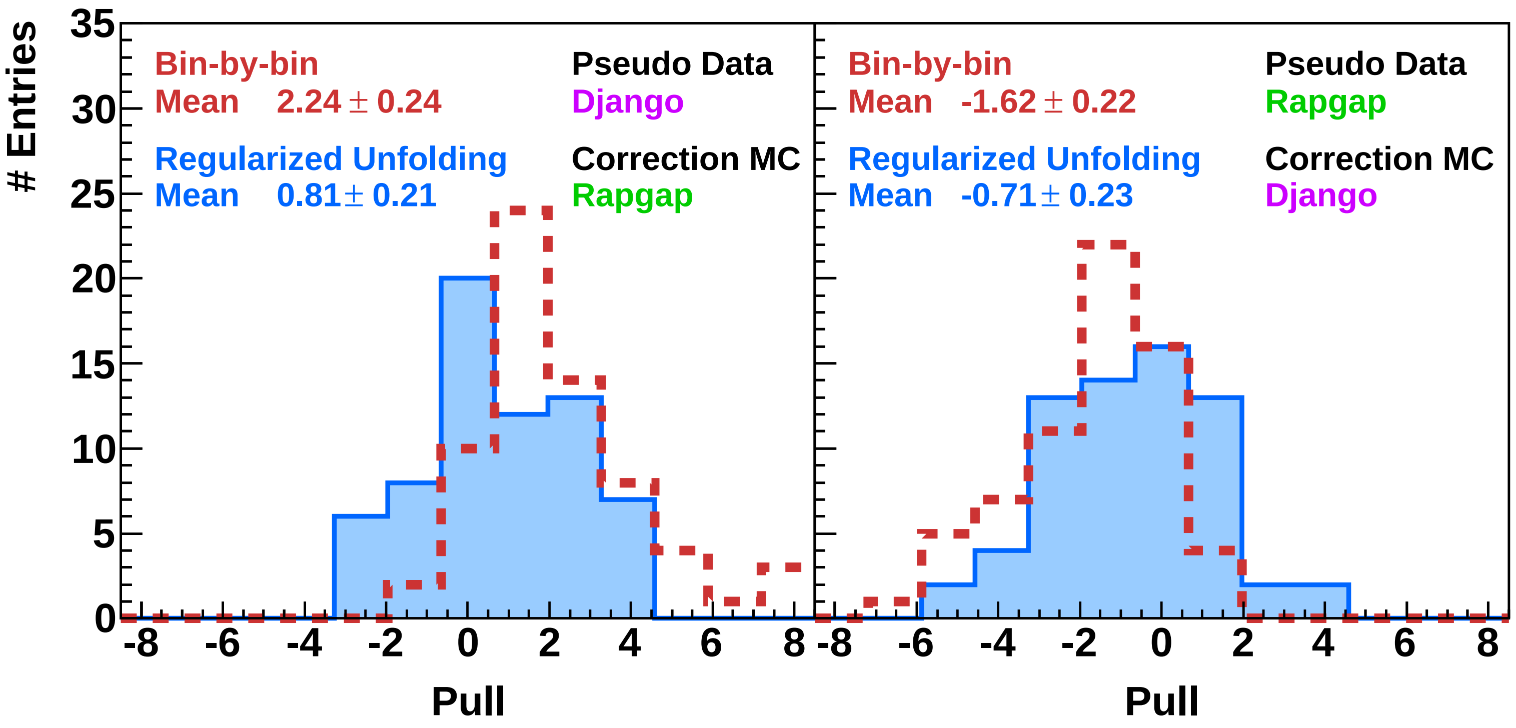
Corrected vs. true distribution

$$p_i = \frac{x_i^{\mathrm{unfold}} - x_i^{\mathrm{true}}}{\Delta x_i}$$

Two Incl. DIS Models

- Rapgap (MEPS)
- Django (CDM)

Statistically independent samples



Checking

- Pseudo-data from ‘one’ model
- Unfolding matrix from 'other' model

Unfolding is less biased by Model predictions

Comparing unfolding with bin-by-bin method: Data

Using H1 Data

Average of two MCs for migration matrix

$$A = \frac{A_{\mathrm{Dj}} + A_{\mathrm{Rg}}}{2}$$

Compare pull values between

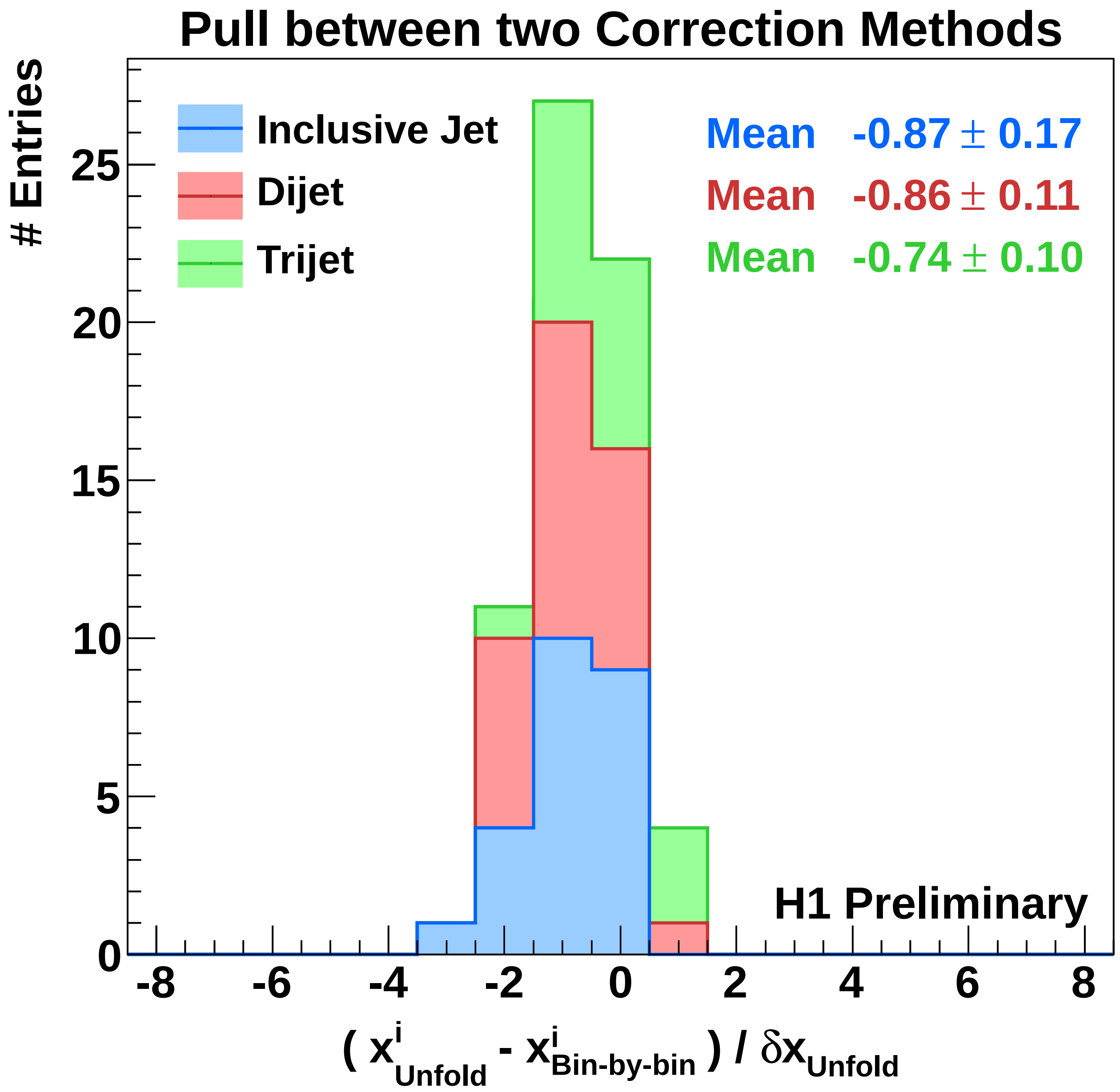
- Unfolded data points
- Bin-by-bin corrected data points

Bin-by-bin bias also in data

Statistical uncertainties of unfolding are larger

-> But correlations are known !

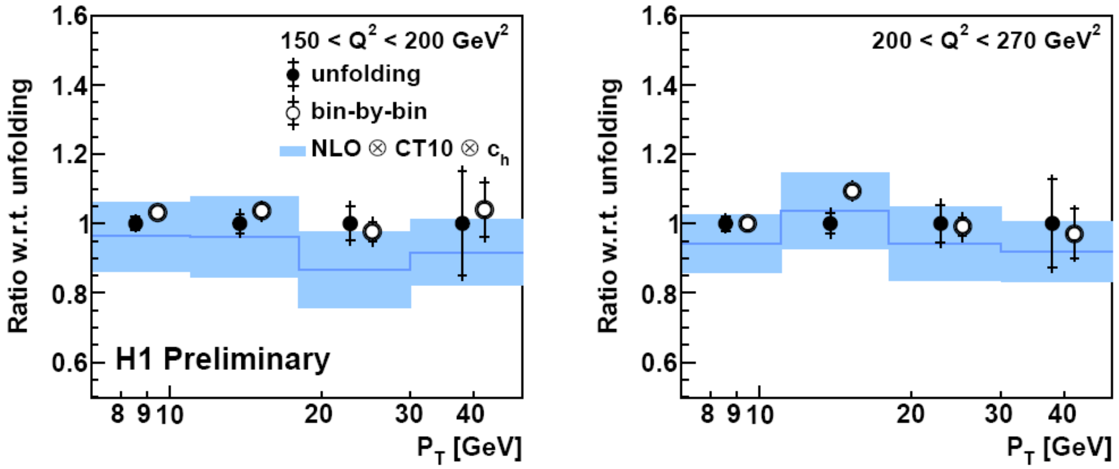
Unfolding features a full linear error propagation of (statistical) uncertainties



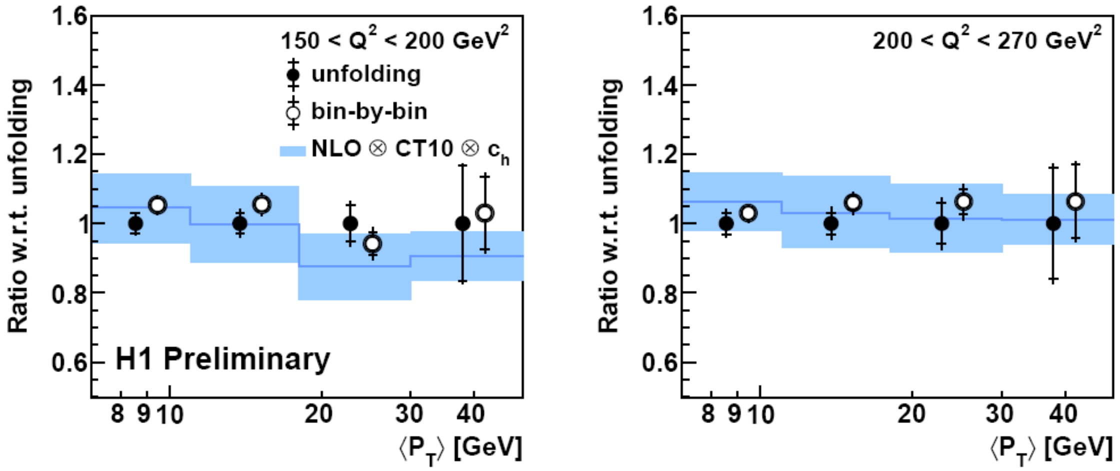
Unfolding has small, but visible effect on cross sections

Comparing unfolding with bin-by-bin method: Data

Normalised Inclusive Jet Cross Section



Normalised Dijet Cross Section



Normalised Trijet Cross Section