Multi-jet cross sections in deep-inelastic *ep* scattering at HERA (H1) and determination of $\alpha_s(M_Z)$

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Neutral current deep-inelastic scattering (NC DIS)

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

- Center-of-mass energy

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

- Photon virtuality

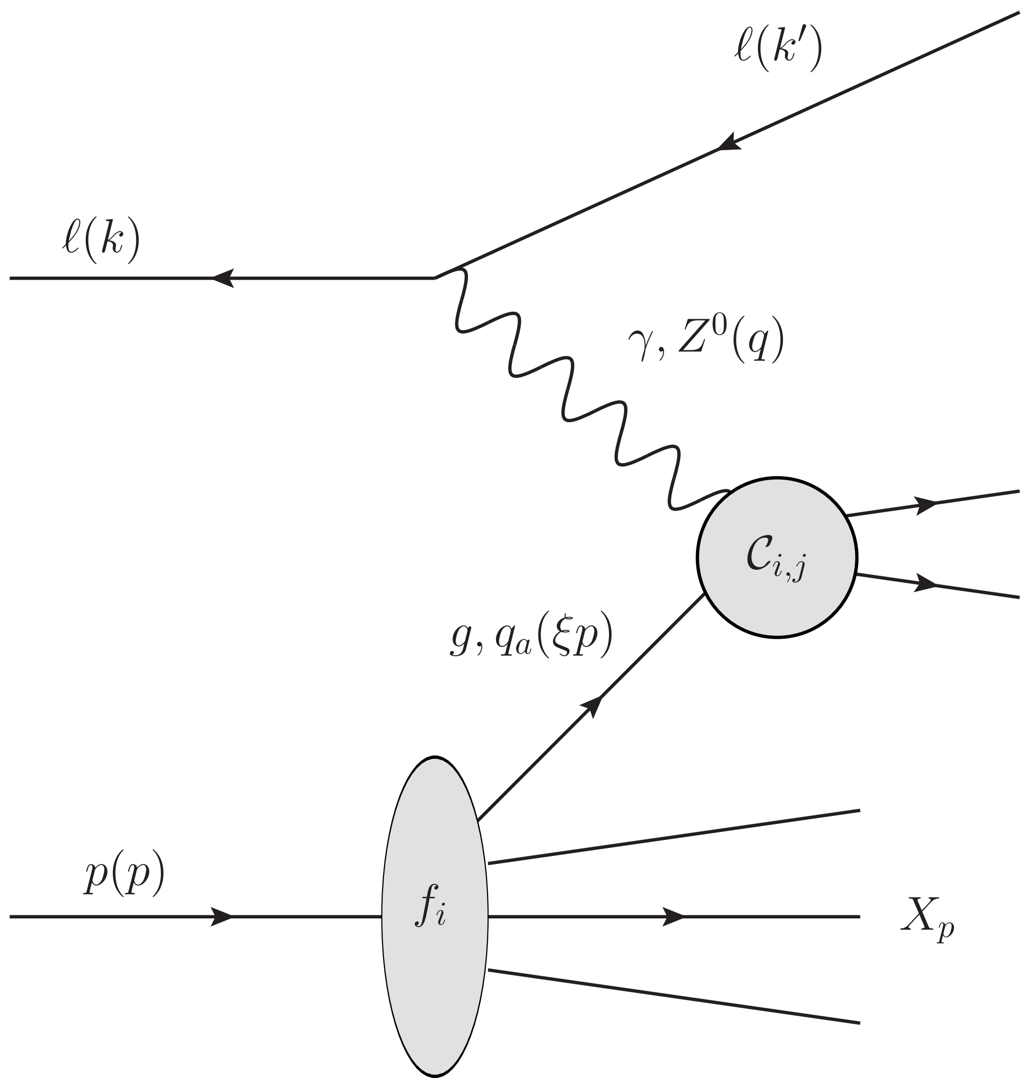
$$Q^2 = -q^2 = -(k-k')^2$$

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

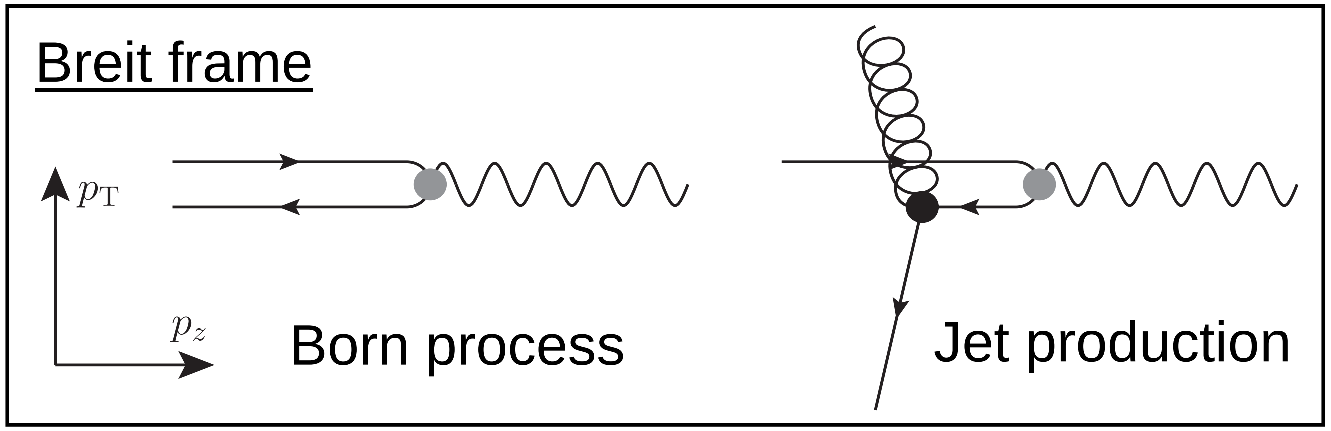
Unique method to study structure of proton and the strong force

Jet production in *ep* scattering

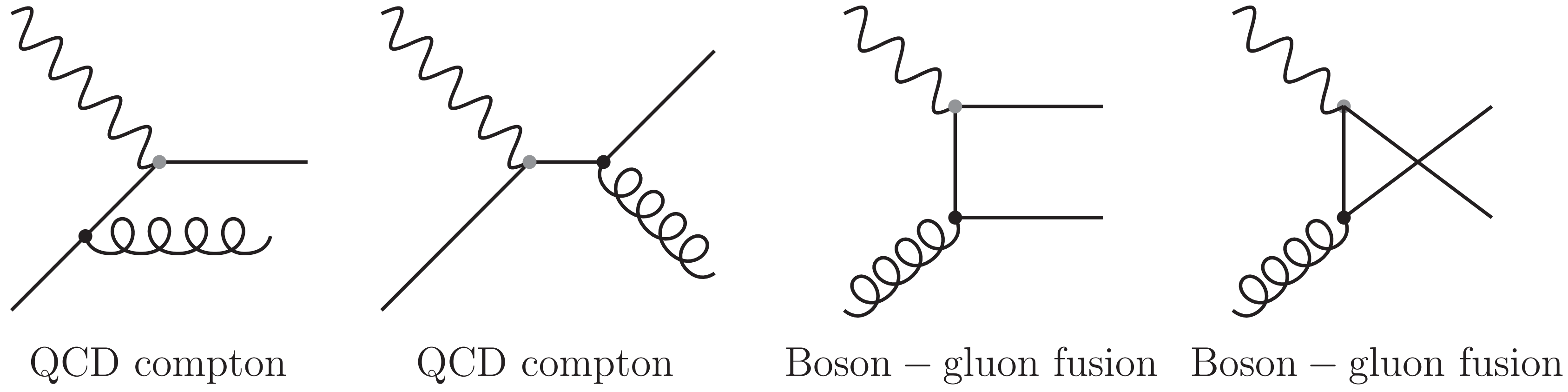
Breit frame of reference

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

- Only hard QCD processes generate considerable p_T in the Breit frame



Jet production in DIS in leading-order



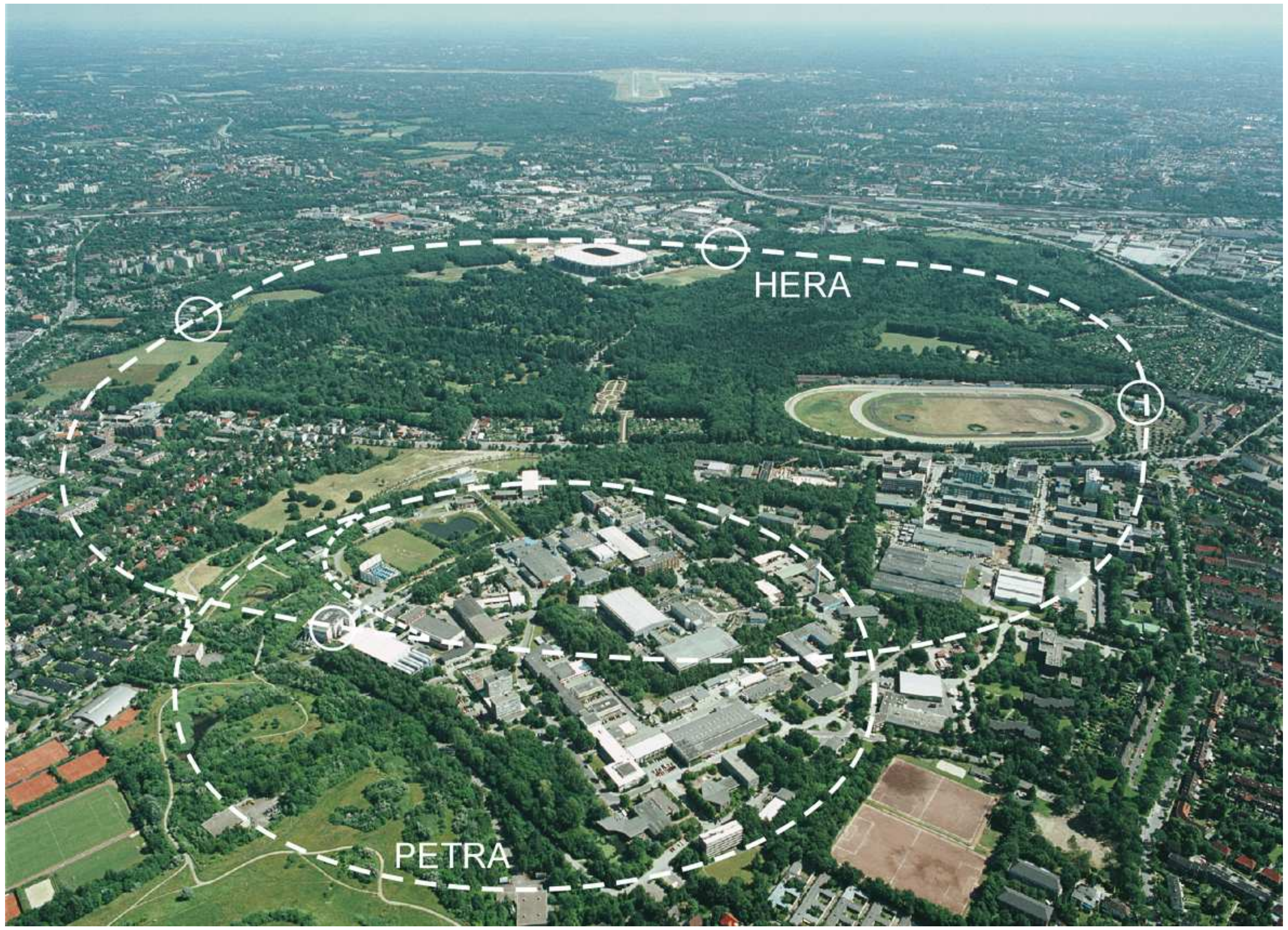
Jet cross section calculable in pQCD

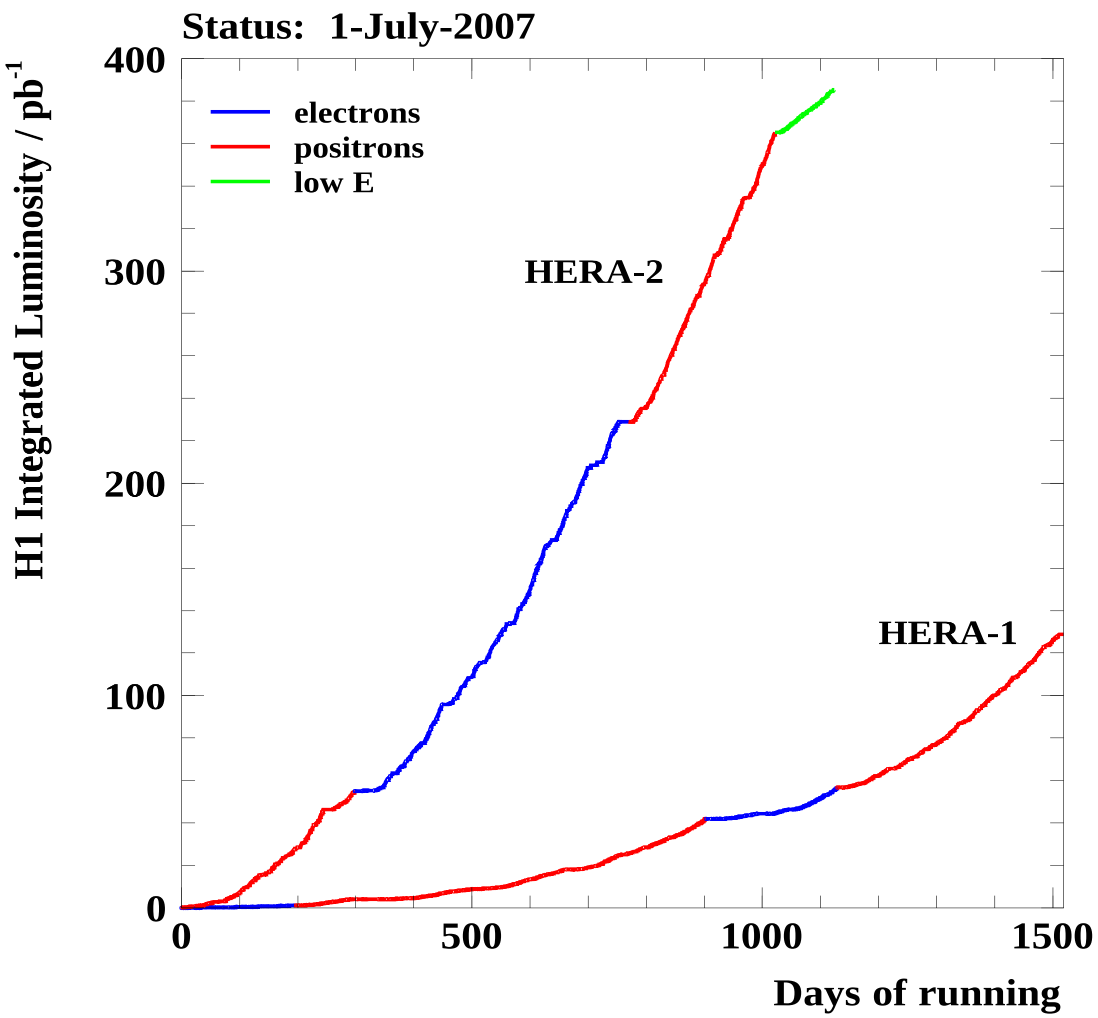
$$\sigma_{\mathrm{jet}} = \sum_{n} \sum_{a=q,\bar{q},g} \left[\sigma_{n,a} \otimes f_a\right] (1 + \delta_{\mathrm{had}})$$

- Expansion in orders of $\alpha_s(\mu_r)$ with $n \geq 1$
- Hadronization effects with correction factor
- Coefficients available up to next-to-leading order

Jet production directly sensitive to α_s

HERA and H1





HERA collider in Hamburg, Germany

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

HERA-II period

2002 – 2007

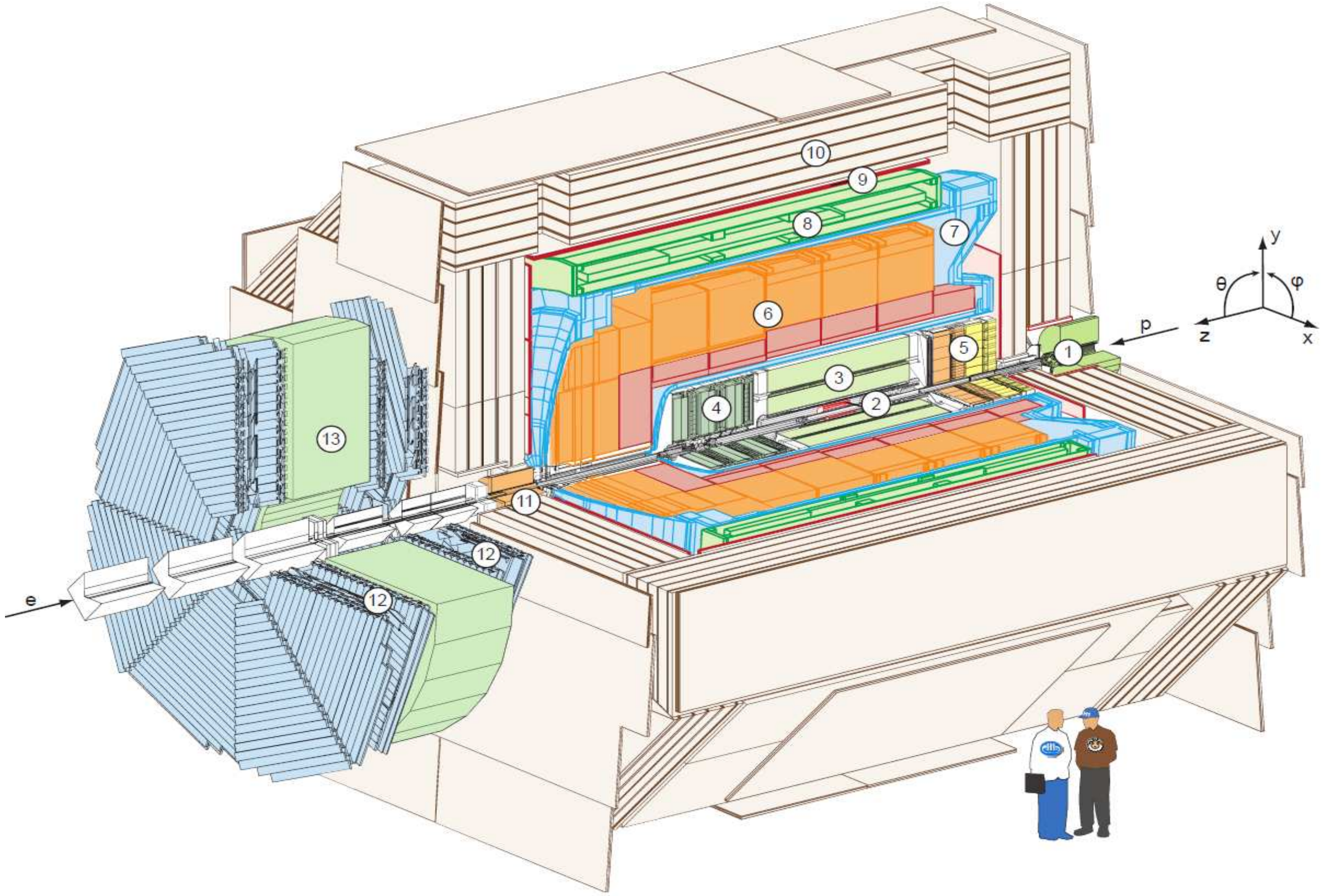
Electrons and positron runs

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

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



Multi-jet measurement at H1

Four measurements are performed

Neutral current phase space

150 < Q^2 < 15000 GeV^2

0.2 < y < 0.7

Jet acceptance

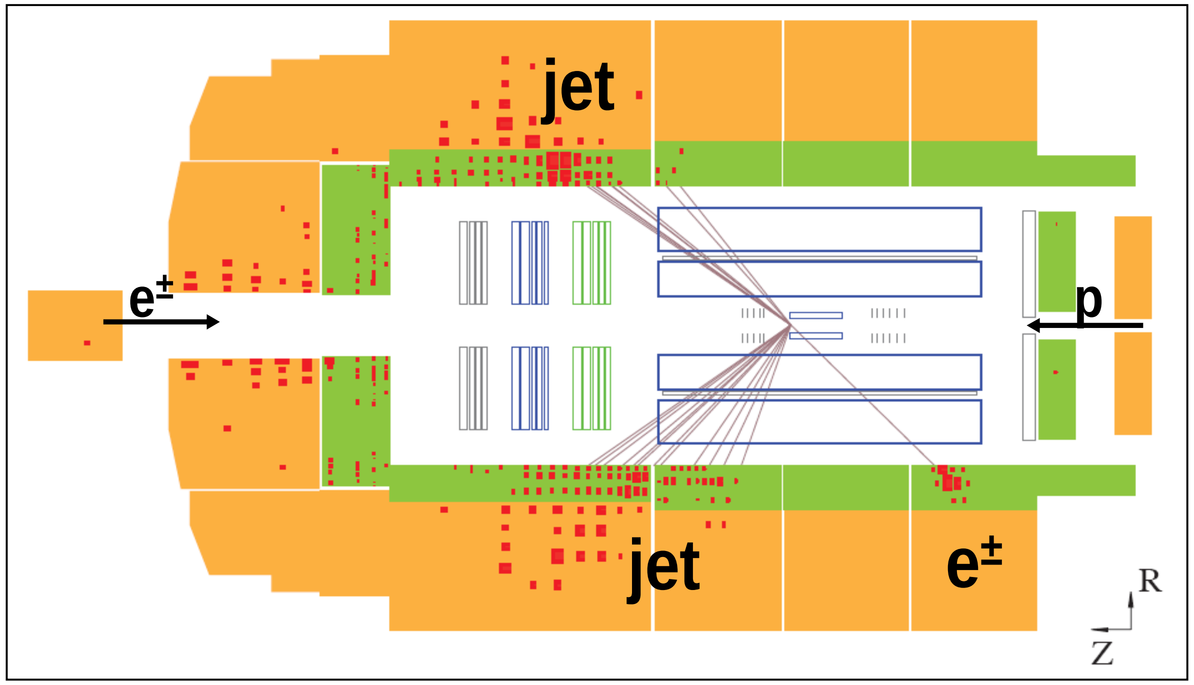
-1.0 < η_{lab} < 2.5

Inclusive Jet

7 < p_T^{jet} < 50 GeV

Dijet ($n_{jet} \geq 2$)	Trijet ($n_{jet} \geq 3$)
5 < p_T^{jet} < 50 GeV	
M_{12} > 16 GeV	
7 < $\langle p_T \rangle_2$ < 50 GeV	7 < $\langle p_T \rangle_3$ < 30 GeV

NC DIS measurement used for normalized jet cross sections



Measurements are performed double-differentially

$$\langle p_T \rangle_2 = (p_T^{jet1} + p_T^{jet2})/2$$

Correction of detector effects using regularized unfolding

Detector effects

- Acceptance and efficiency effects
- Migrations and limited resolution
- 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

- 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

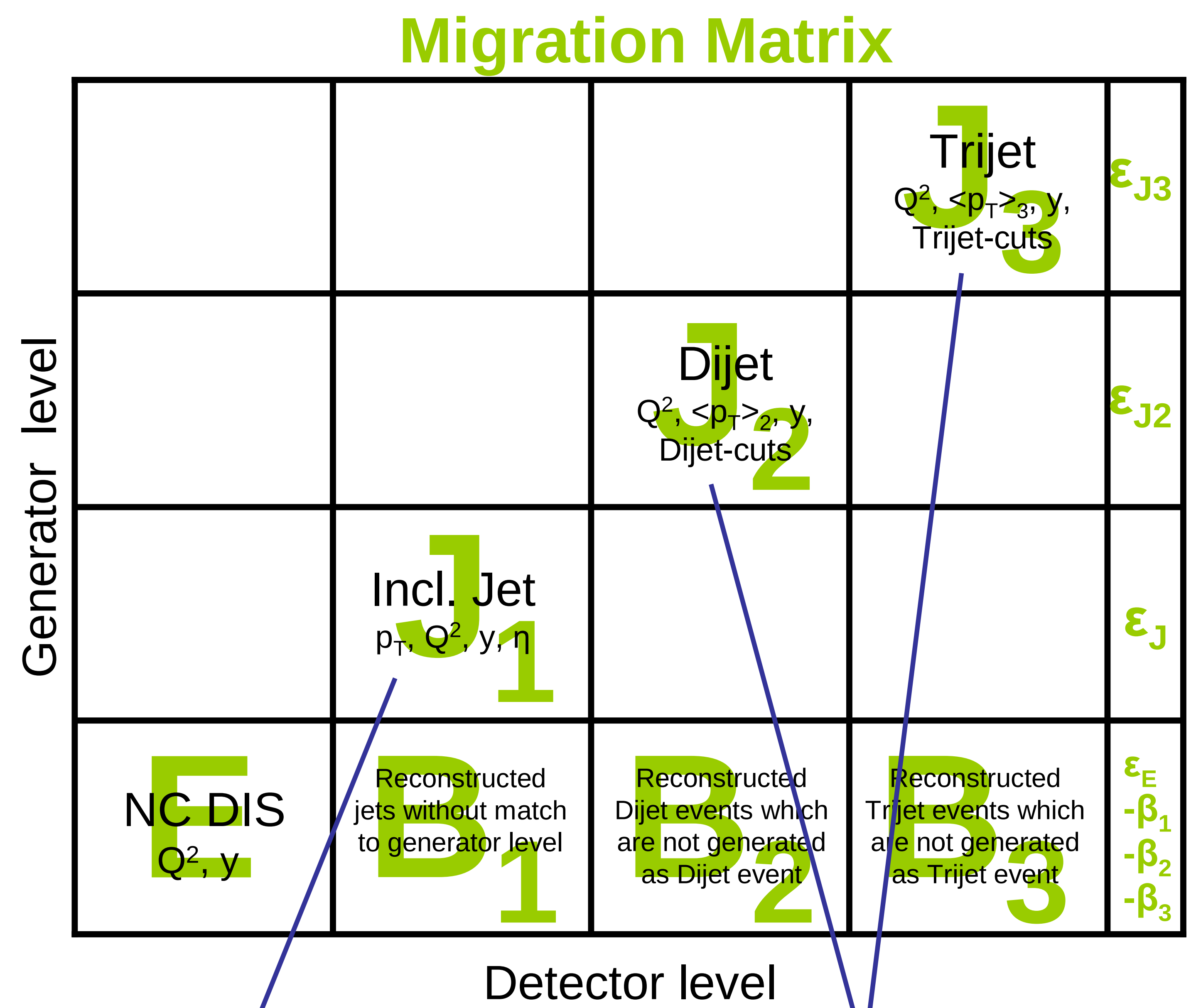
Constrain reconstructed but not generated contributions

Two MC generators

Django and Rapgap

Phase space is enlarged

in all variables where migrations are relevant



4-dimensional unfolding in p_T, Q^2, y, η

Up to 7 observables are considered to discribe migrations

Four measurements are unfolded simultaneously: Stat. correlations are considered

Results: Multi-jet cross sections in DIS

Data

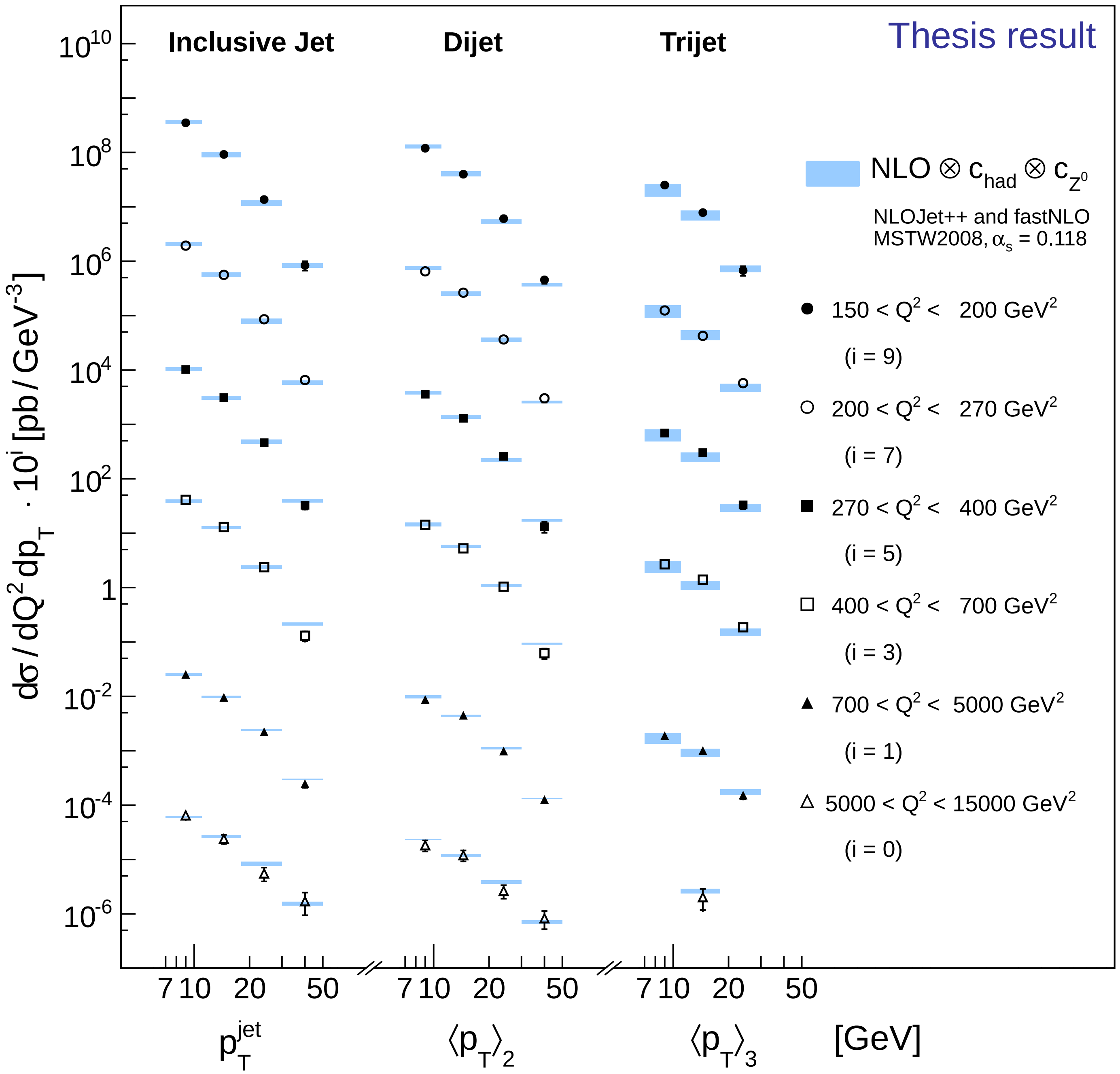
- Corrected for detector effects and QED radiation using regularized unfolding
- All data points are correlated

Final precision of H1 data

- Improved electron calibration
- Improved hadronic calibration
- Improved luminosity measurement

Experimental uncertainties

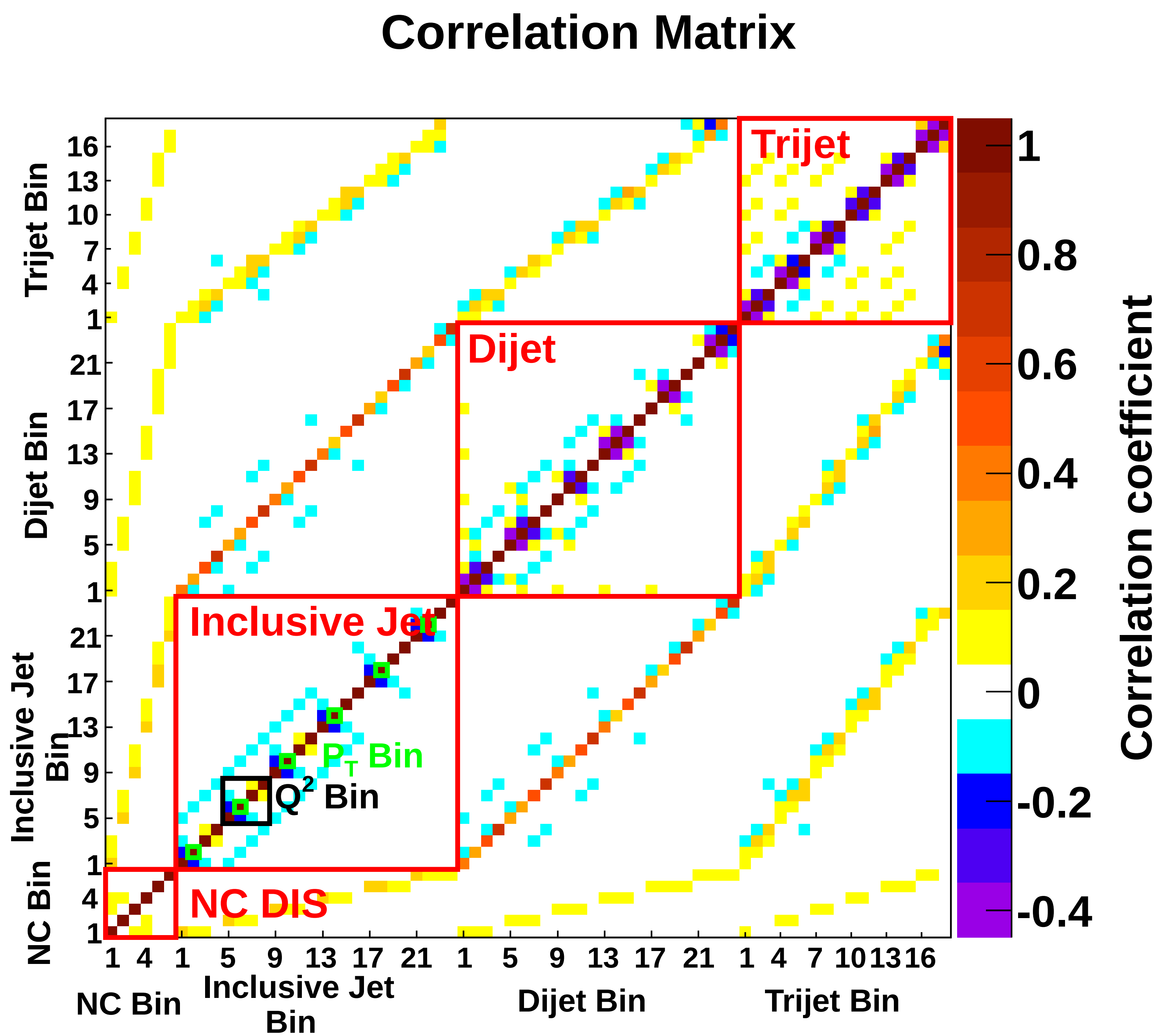
Luminosity, trigger, vertex:	2.9%
HFS reconstruction:	2-7%
Electron reconstruction:	1-2%
Model uncertainty:	2-7%
Statistical precision:	> 3%



Correlation matrix

Correlations

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



Useful for

- Normalized cross sections
- Cross section ratios
- Combined fits to all jet data

Normalized multijet cross sections

Normalized jet cross sections

- Measure ratio $\sigma_{jet} / \sigma_{NC}$
- Interpretable as event rate

Uncertainties

- Partial cancellation of experimental uncertainties
- Normalization uncertainties cancel
- Statistical uncertainties determined by error propagation using the correlations

NLO predictions $\otimes$ c_{had}

NLOJET++ and fastNLO for σ_{jet}

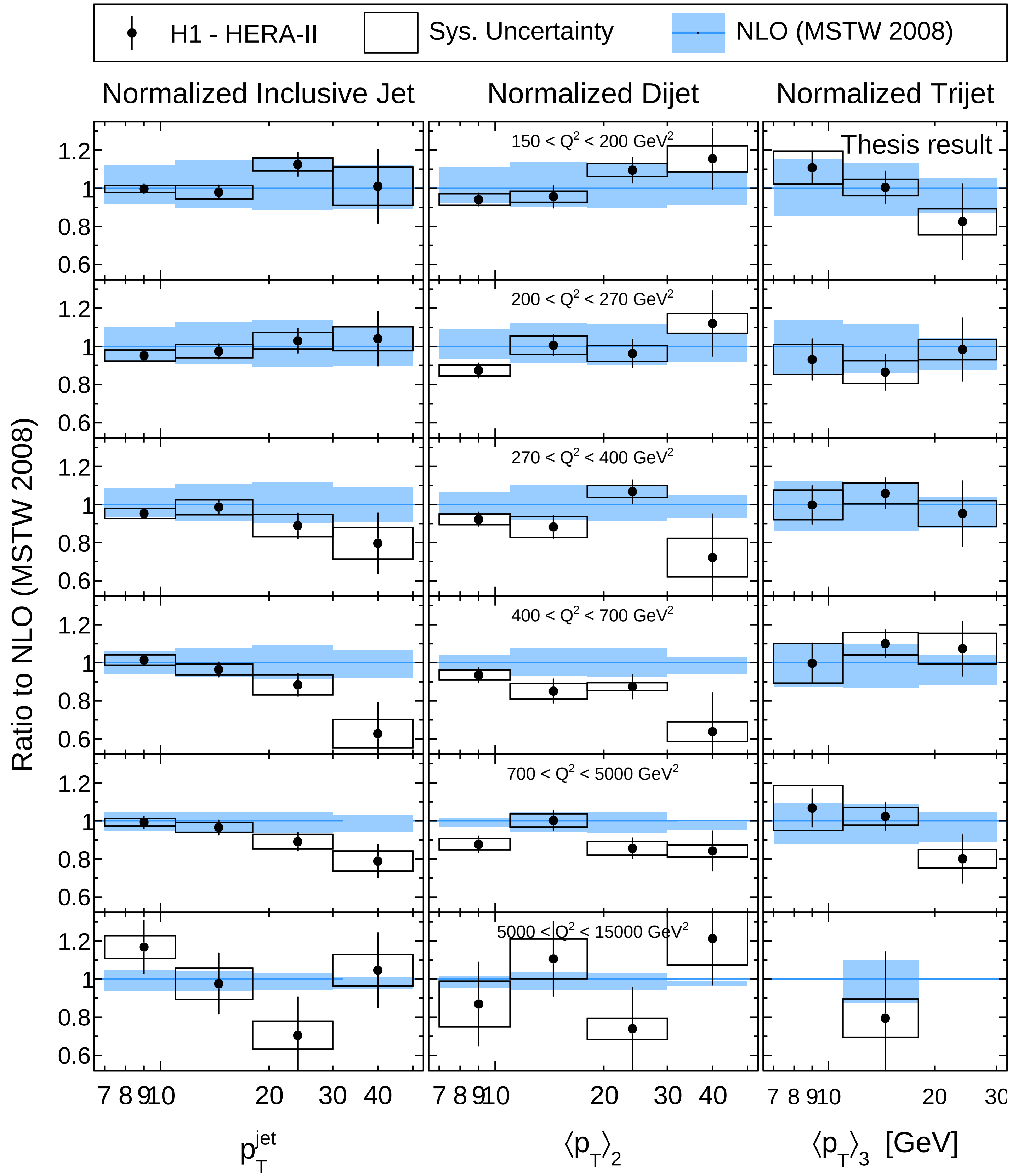
QCDNUM for σ_{NC}

Data-theory comparison

Data well described by theory

Theory uncertainty dominates

Blue error band from scale variations



$\alpha_s(M_Z)$ from multijet cross sections

$\alpha_s(M_Z)$ from a simultaneous χ^2-fit of

- NLO predictions (α_s as free parameter)

to

- Inclusive jet, dijet, trijet cross sections

Statistical correlations

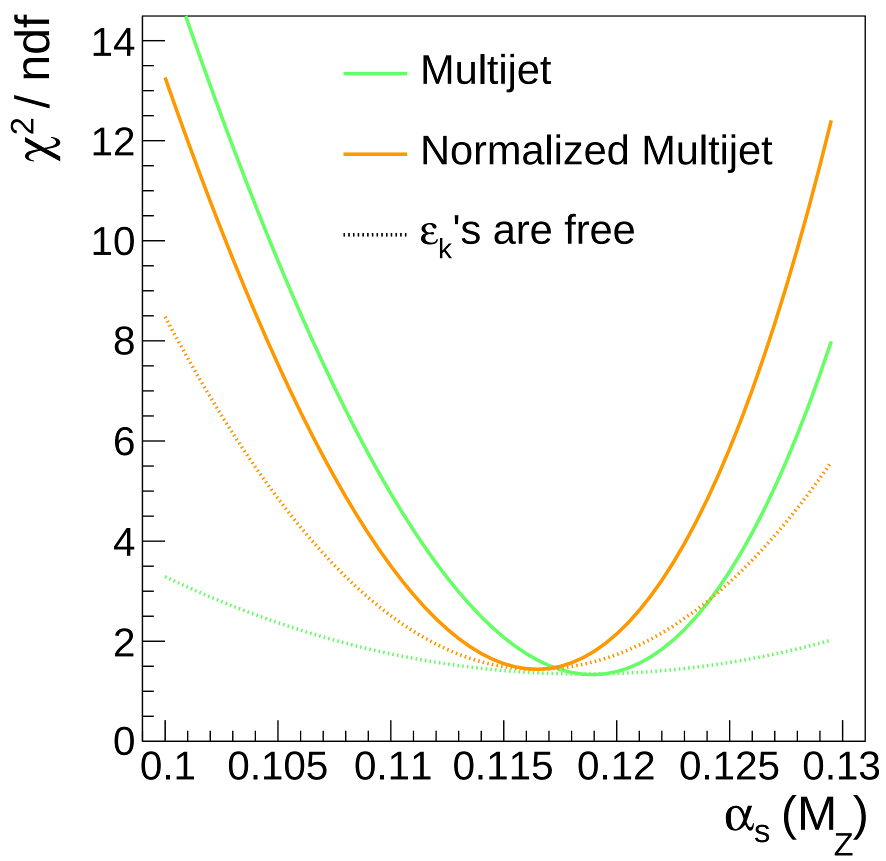
considered through covariance matrix

Benefit

- Large statistical precision of inclusive jet
- Increased sensitivity of trijet observable

Fit quality

$\chi^2/n_{dof} = 1.3$



Multijet: $\alpha_s(M_Z) = 0.1185\,(17)_{exp} \pm (6)_{PDFset} \pm (4)_{PDF} \pm (13)_{had} \pm (44)_{\mu_r} \pm (4)_{\mu_f}$

Thesis result

Normalized multijet

- Normalization uncertainties cancel
- Highest experimental precision
- $\chi^2/n_{dof} = 1.4$

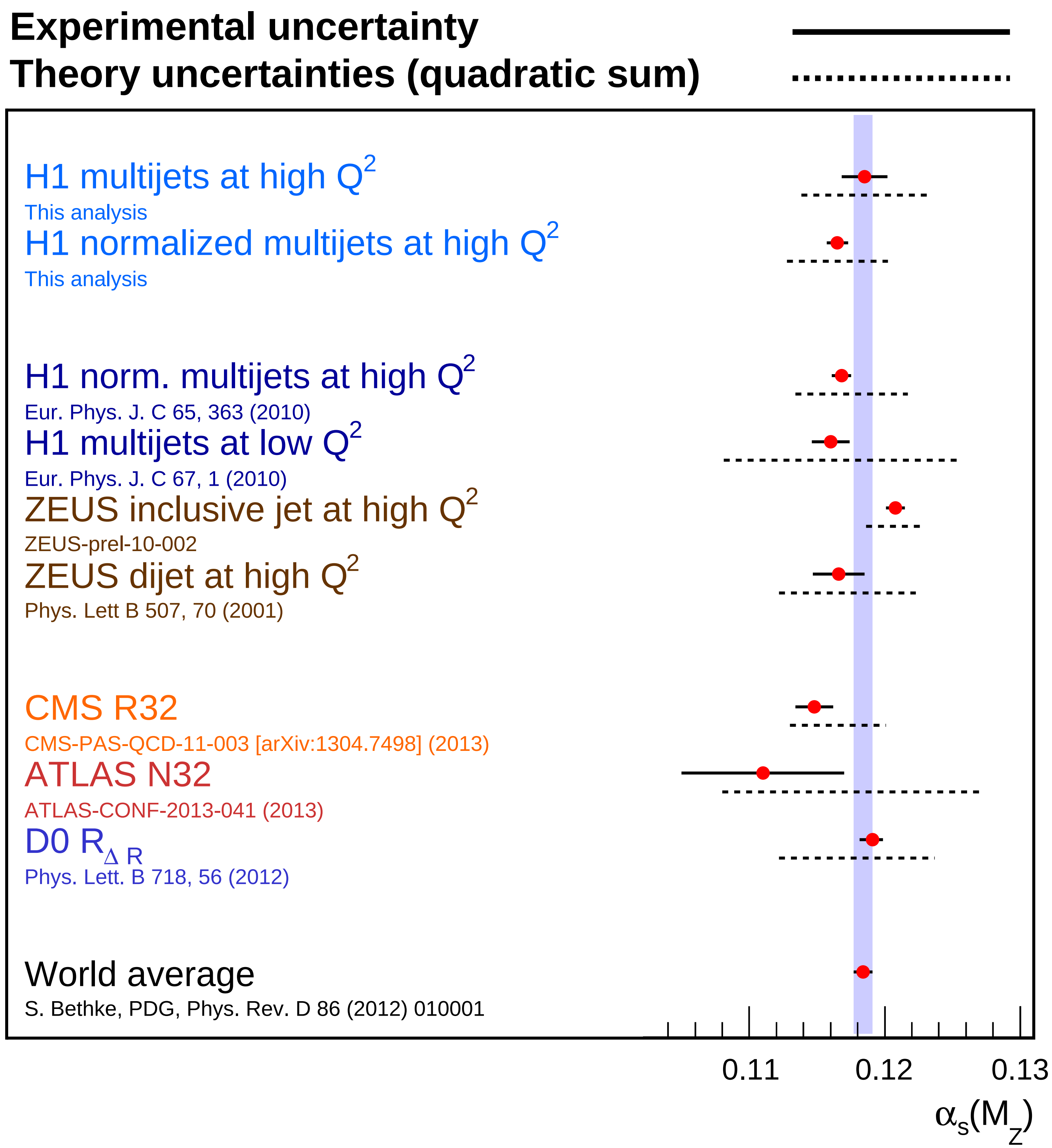
Theoretical uncertainties

Determined by linear error propagation

Normalized multijet: $\alpha_s(M_Z) = 0.1165\,(8)_{exp} \pm (4)_{PDF} \pm (8)_{PDFset} \pm (8)_{had} \pm (34\,)_{\mu_r} \pm (5\,)_{\mu_f}$

Thesis result

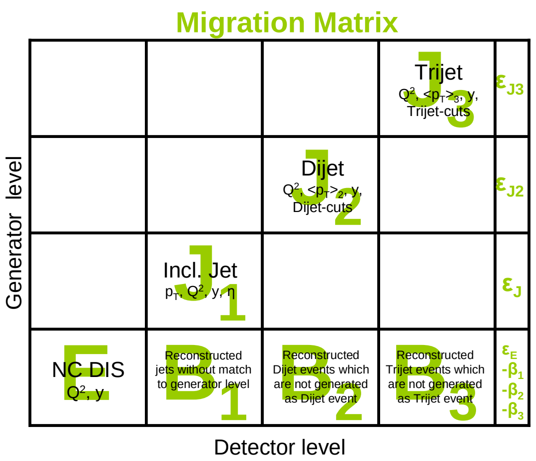
Comparison to other $\alpha_s(M_Z)$ values



Experimental precision compatible with world average value of $\alpha_s = 0.1184 \pm 0.0007$

H1-Prel-11-032
H1-Prel-12-031
PhD thesis D.B.
Publ. in prep.

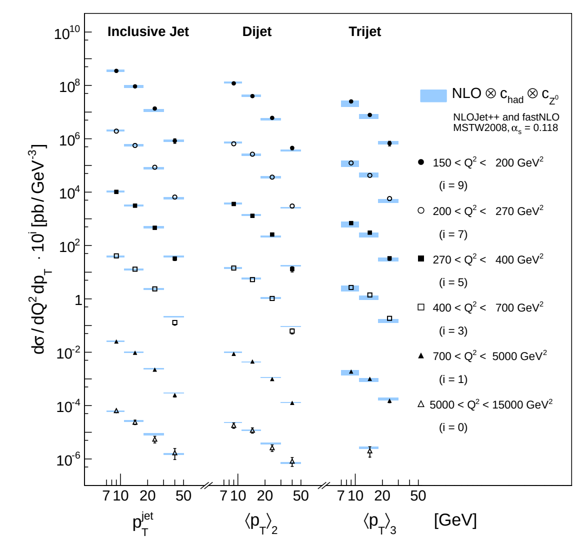
Summary



Data analyis

Very sophisticated unfolding procedure

Data with final H1 precision



Jet production cross sections

Cross sections for inclusive jet, dijet and trijet production

Normalized jet cross sections with reduced exp. uncertainties

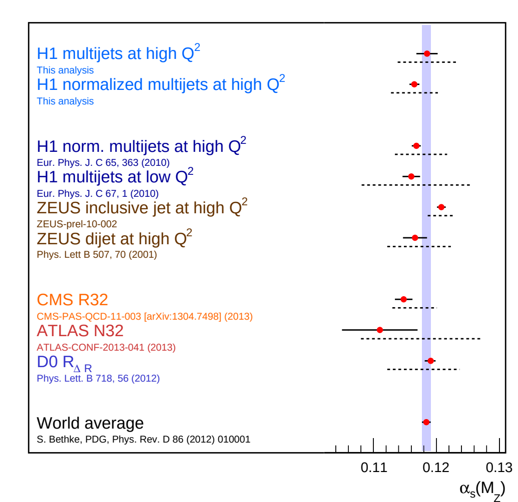
Stringent test of pQCD

Most precise jet data in given phase space for the next decades

Strong coupling constant $\alpha_s(M_Z)$

High experimental precision of 0.7%

Theory uncertainties account for 3-4% uncertainty



Prospects for the LHC

Data will help to constrain proton PDFs, espc. gluon density

Knowledge of PDFs and $\alpha_s(M_Z)$ is mandatory for BSM searches

Backup

Extraction of $\alpha_s(M_Z)$

Experimental input m_i
- Inclusive jet, dijet and trijet measurement
- 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
- Treatment of experimental uncertainties k in fit is crucial
  - Correlated: Nuisance parameter ε_k
  - Uncorrelated: Add to V_{ii}

Theoretical input t_i
- NLO coefficients
- Factorization
  - MSTW 2008
- Hadronization corrections
- FastNLO provides fast repeated calculation of cross section predictions

Uncertainties on theory
- Determined separately by linear error propagation

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

$$\chi^2\left(\alpha_s(M_Z), \varepsilon_k\right) = \vec{p}^T V^{-1} \vec{p} + \sum_k^{N_{\rm sys}} \varepsilon_k^2$$

$$p_i \simeq m_i - t_i \prod_k^{N_{\rm sys}} e^{-\delta_k m_i \cdot \varepsilon_k}$$