Precision Tests of QCD

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on behalf of the H1 and ZEUS collaborations

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Štrbské Pleso, Slovakia

QCD and Precision

QCD

$$\mathcal{L} = \sum_{f}^{n_f} \bar{q}_f (i\gamma^\mu \mathcal{D}_\mu - m_f) q_f - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

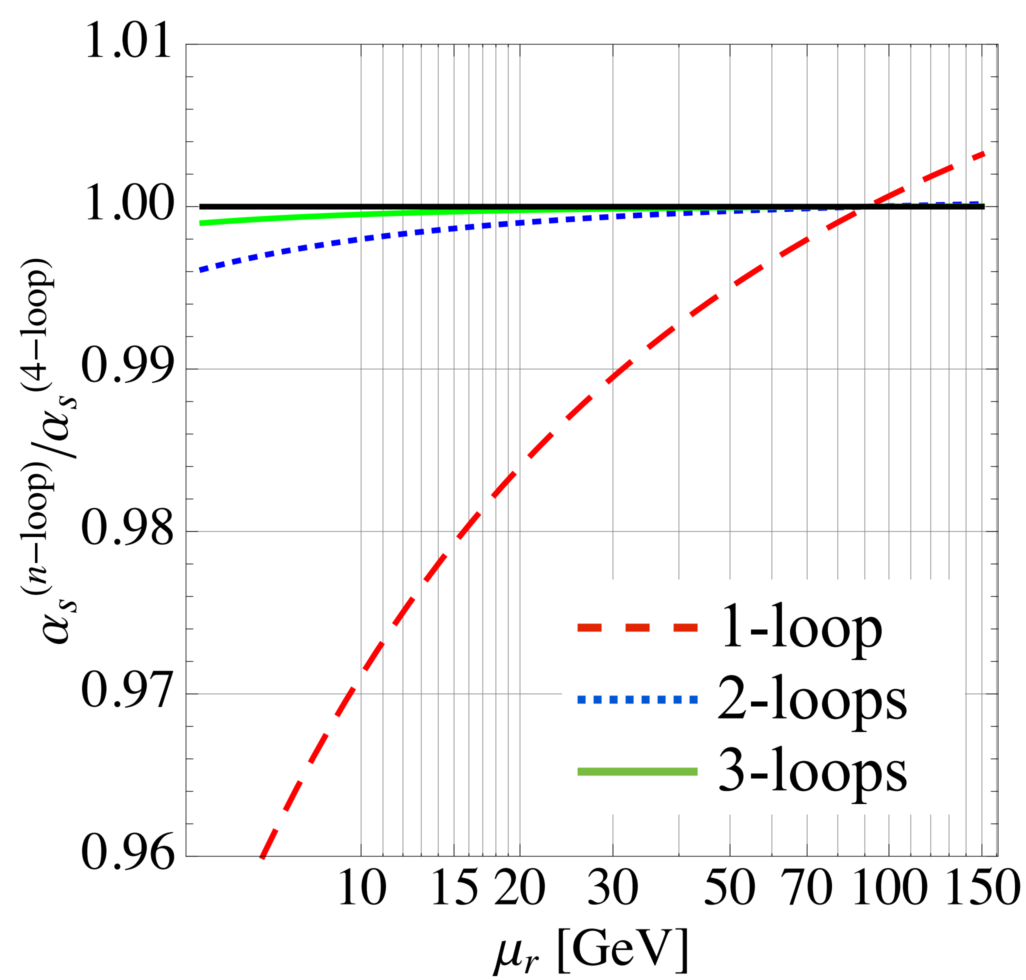
Beautiful theory, fully determined by the heavy quark masses m_f and α_s

The Strong Coupling α_s

Solution of the Renormalisation Group Equation (RGE) leads to the β-function

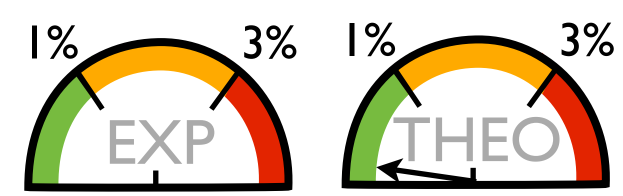
$$\beta(\alpha_s) = -\alpha_s \sum_{n=0}^{\infty} \beta_n \left(\frac{\alpha_s}{4\pi}\right)^{(n+1)}$$

with β_n known up to 4 loops (T. van Ritbergen *et al.*, Phys. Lett. B400, 379 (1997))



Computed with RunDec by Chetyrkin, K.G. et al., Comp. Phys. Comm. 133, 43(2000)

→ Test universality and energy behaviour of α_s



$\alpha_s(M_Z)$ from Z→hadrons

- Fit of electroweak precision observables
- Input mostly from LEP data from the Z-peak
- Determination of α_s: most sensitivity through total hadronic cross section at the Z-pole and the partial leptonic width

$$\sigma^0_{\mathrm{had}} \equiv \frac{12\pi}{m^2_{\mathrm{Z}}} \frac{\Gamma_{\mathrm{ee}}\Gamma_{\mathrm{had}}}{\Gamma^2_{\mathrm{Z}}} \qquad R^0_\ell \equiv \Gamma_{\mathrm{had}}/\Gamma_{\ell\ell}$$

obtained from the four LEP experiments, 17 million Z decays

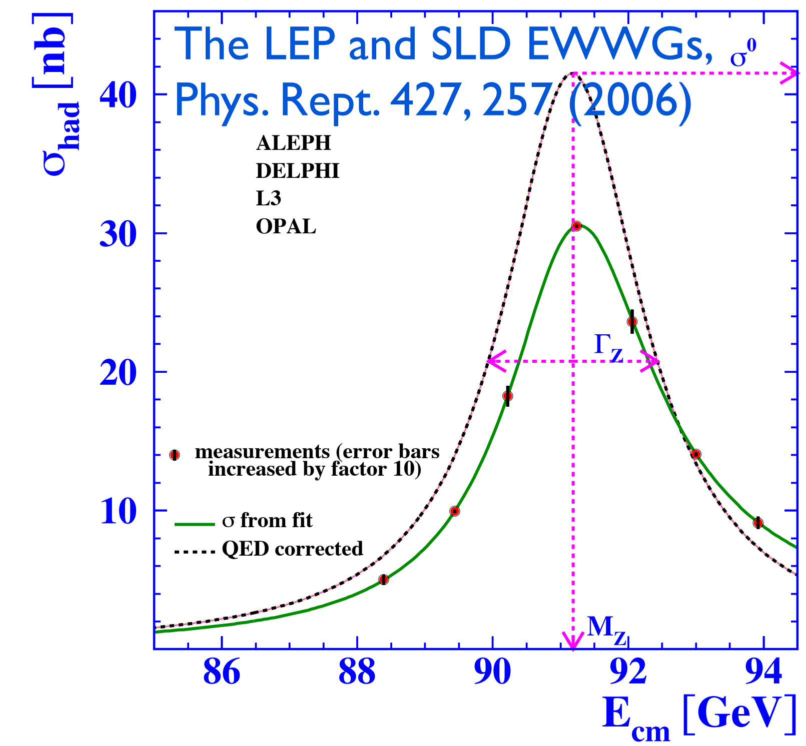
Complete $O(\alpha_s^4)$ calculation available:

P. Baikov et al., Phys. Rev. Lett. 108, 222003 (2012)

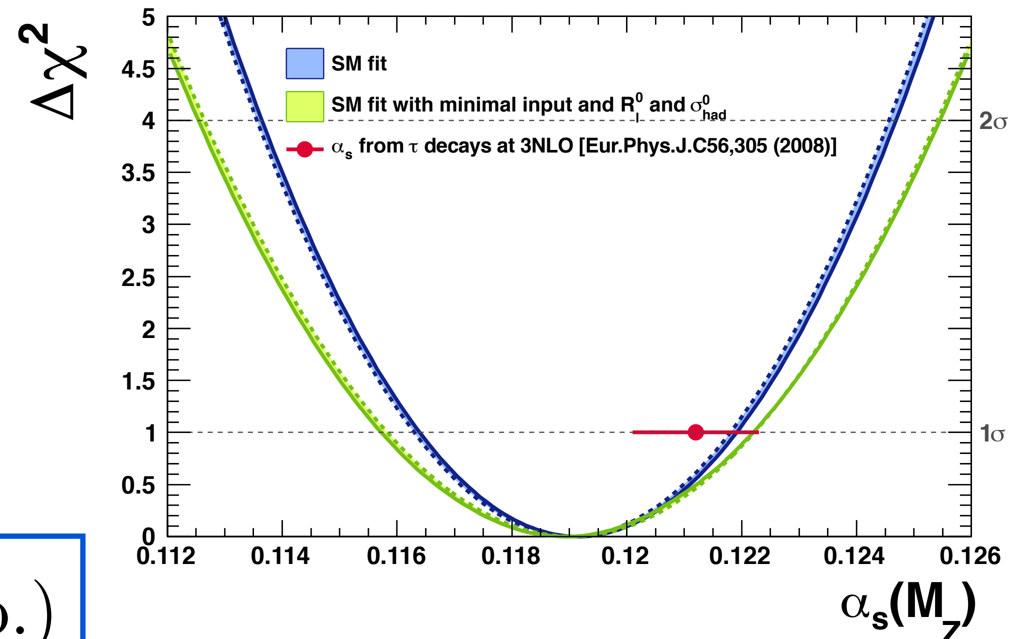
Gfitter:

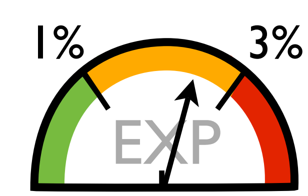
$$\alpha_s(M_Z) = 0.1191 \pm 0.0028\,(\mathrm{exp.}) \pm 0.0001\,(\mathrm{theo.})$$

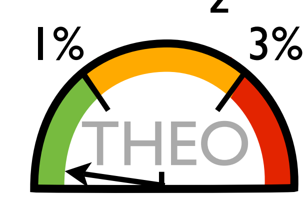
Improvement in precision only with ILC/GigaZ expected



Gfitter Group, EPJ C72, 2003 (2012)

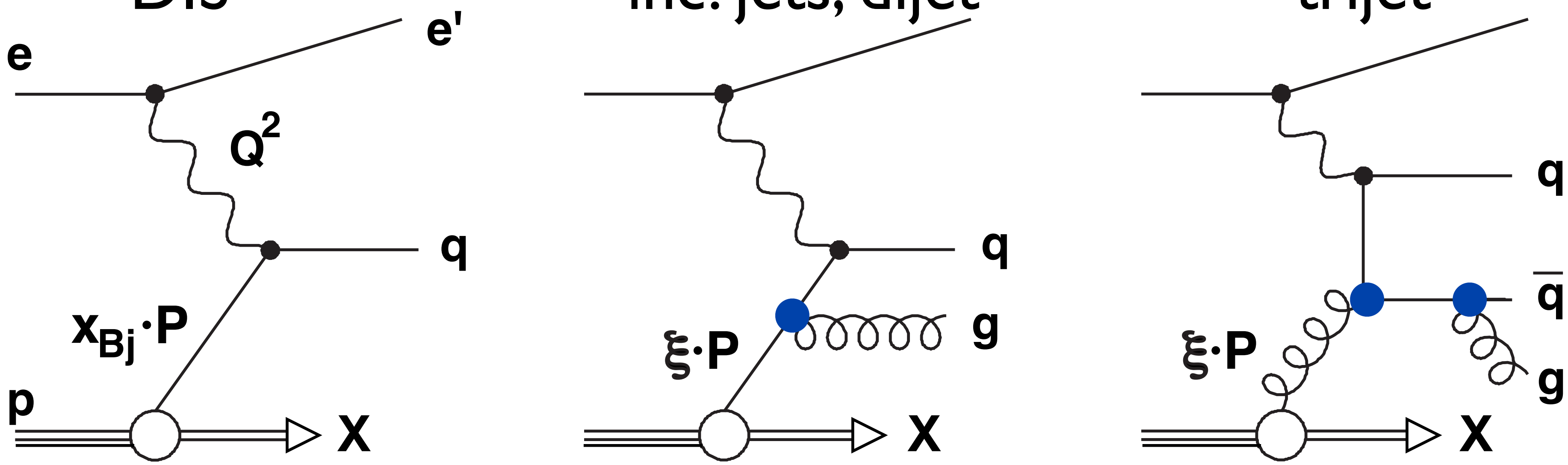




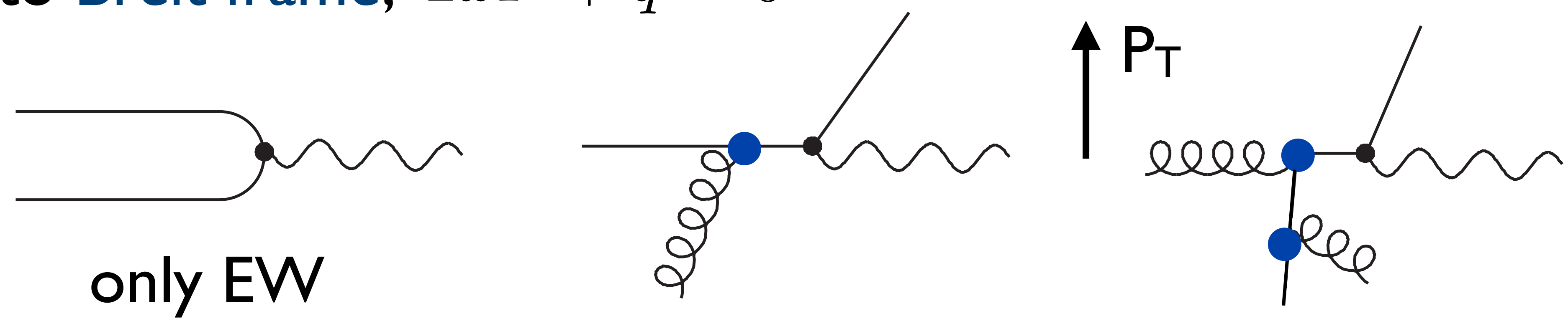


Jet Production in DIS

DIS | inc. jets, dijet | trijet



Boost to Breit frame, $2xP + q = 0$



only EW coupling | $\propto \alpha_s$ | $\propto \alpha_s^2$

Momentum fraction of struck parton (in LO): $\xi = x\left(1 + \frac{M_{12}^2}{Q^2}\right)$

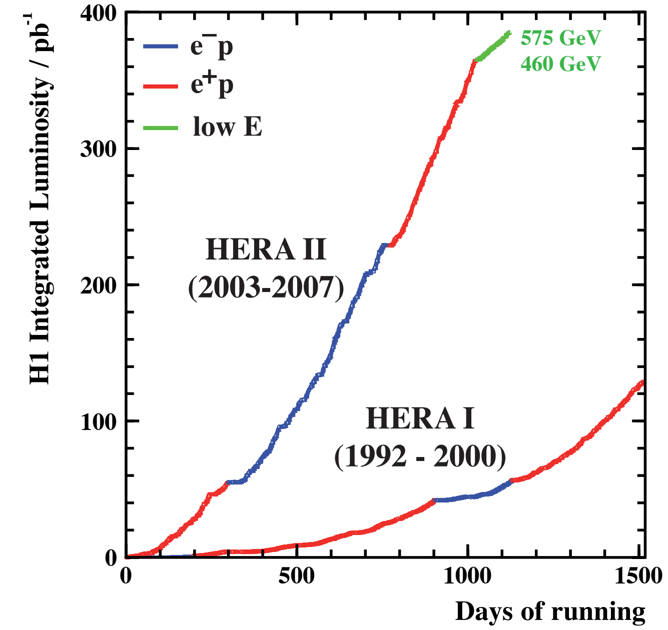
Direct sensitivity to α_s and gluon PDF

Precision Jet Measurements at HERA

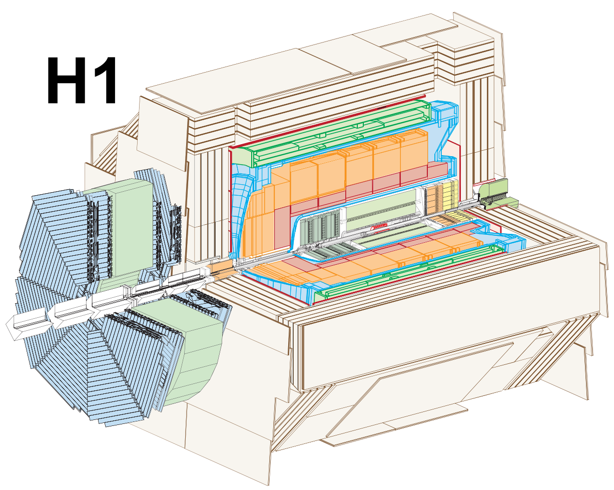
HERA-2 jet measurements

High statistics

L = 300-500 pb^{-1}: small statistical uncertainties, even at high Q^2 and high P_T



Excellent control over systematic uncertainties



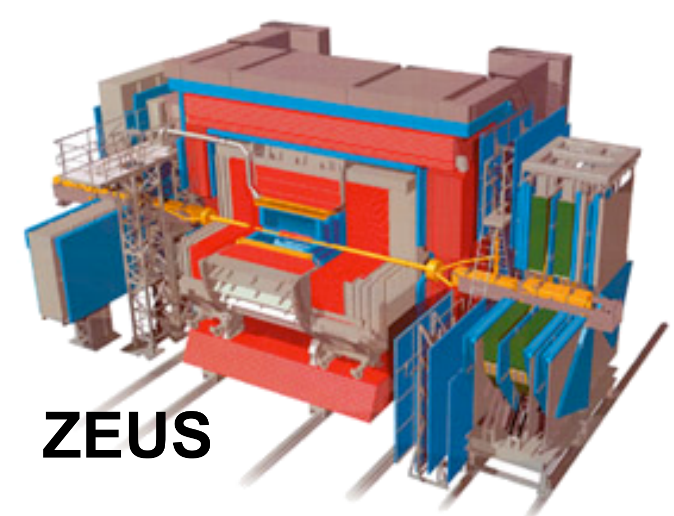
electron measurement: 0.5 – 1% scale uncertainty

jet energy scale: 1% uncertainty!
effect on jet cross sections: 3 – 10%

acceptance correction:
4 – 5% uncertainty

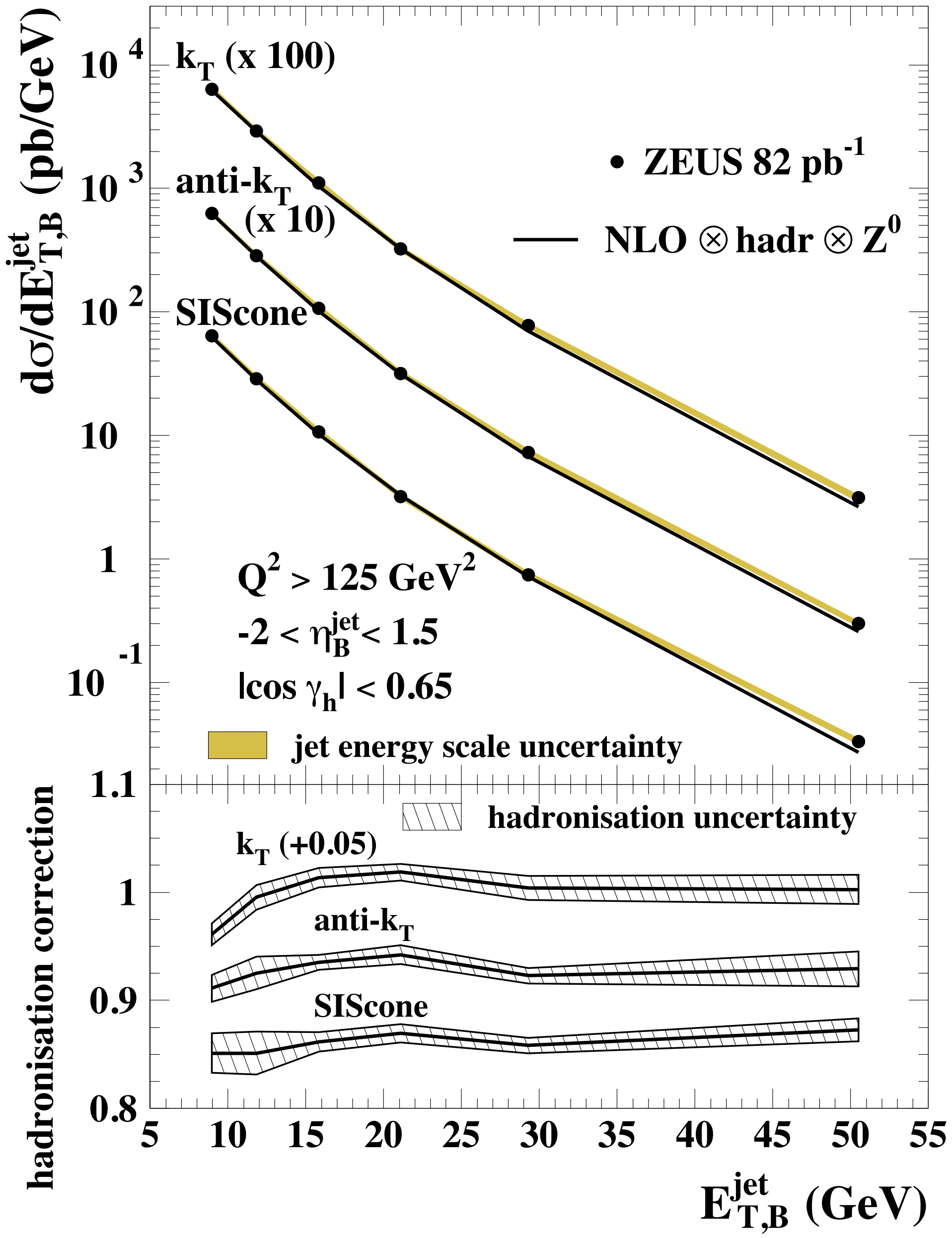
trigger: 1 – 2% normalisation uncertainty

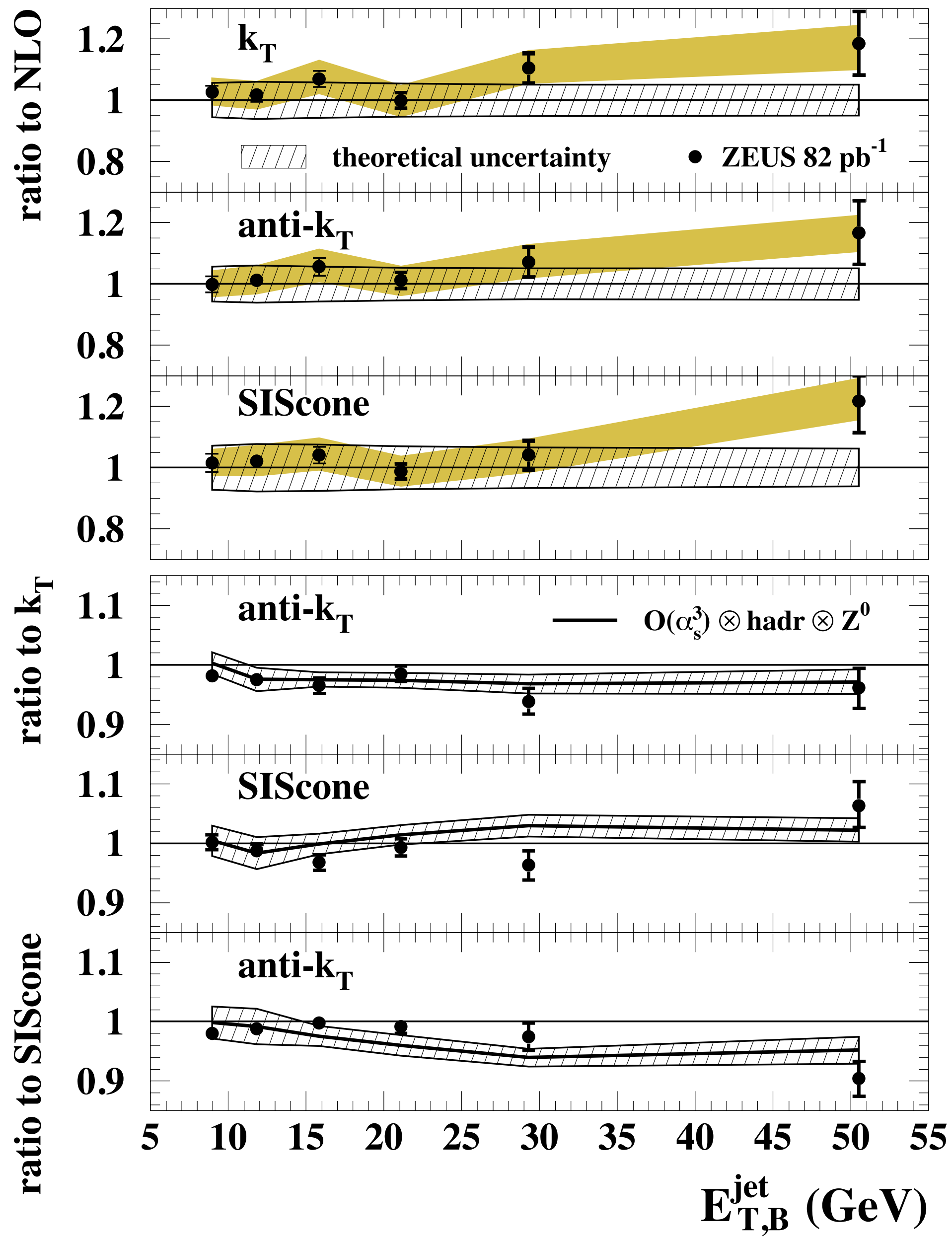
luminosity: 2 – 2.5% normalisation uncertainty



Jet Algorithms in DIS

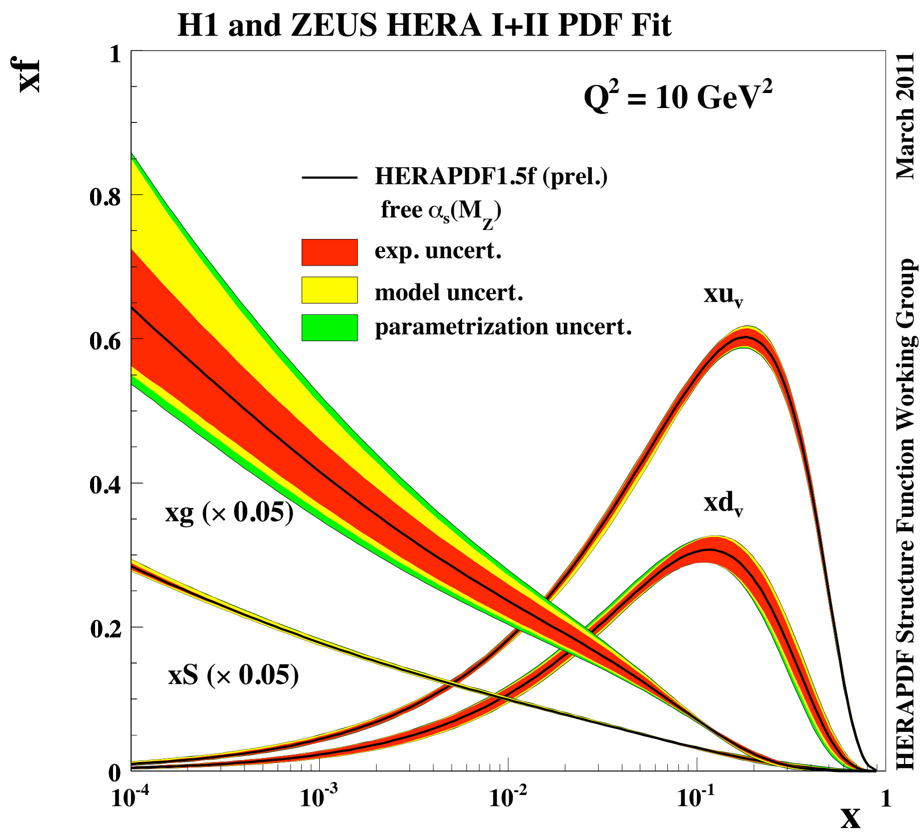
ZEUS, Phys. Lett. B691, 127 (2010)



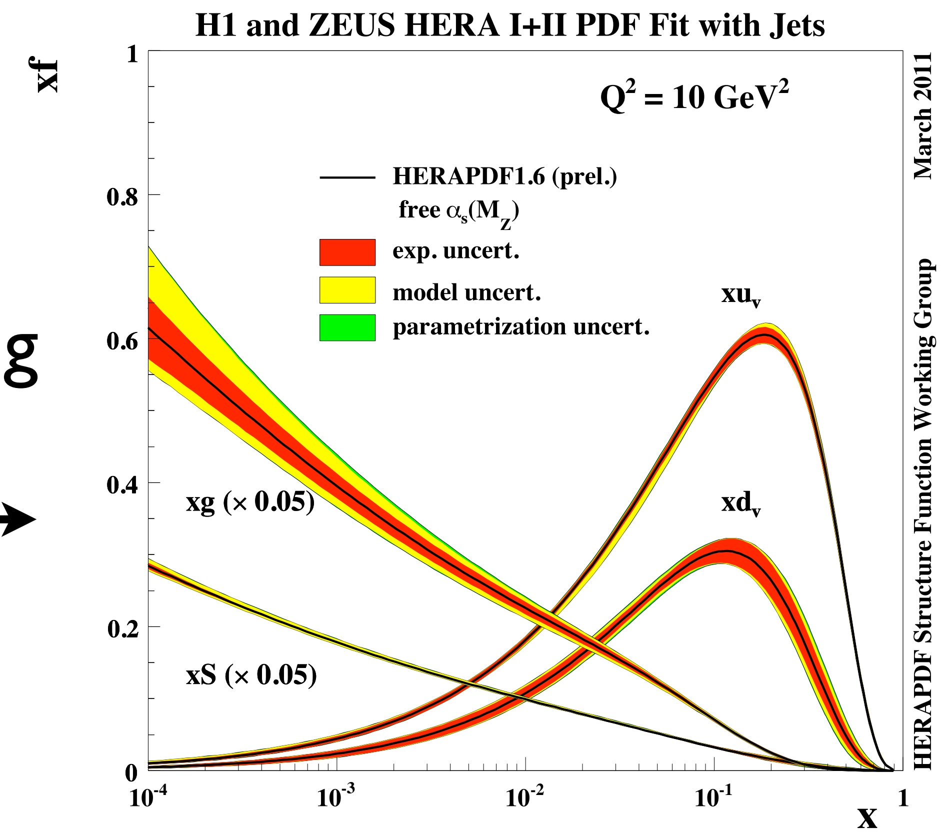


- No pile-up subtraction or corrections for the underlying event
- Differences very small, within uncertainties
- HERA provides a very clean environment to study QCD

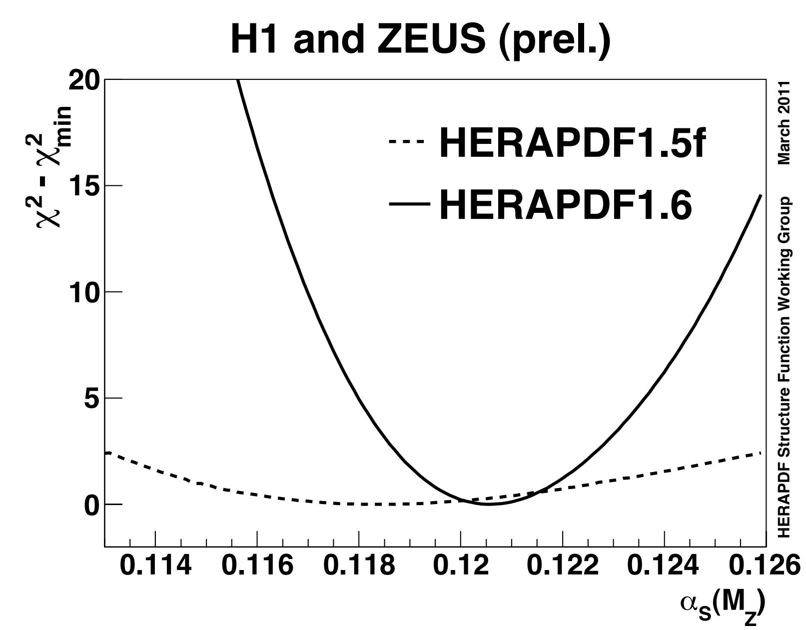
HERA Jet Data in PDF Fits



including jets



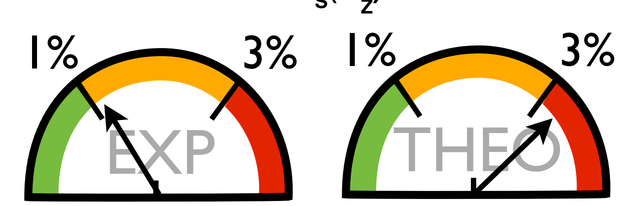
H1prelim-11-034, ZEUS-Prel-11-001



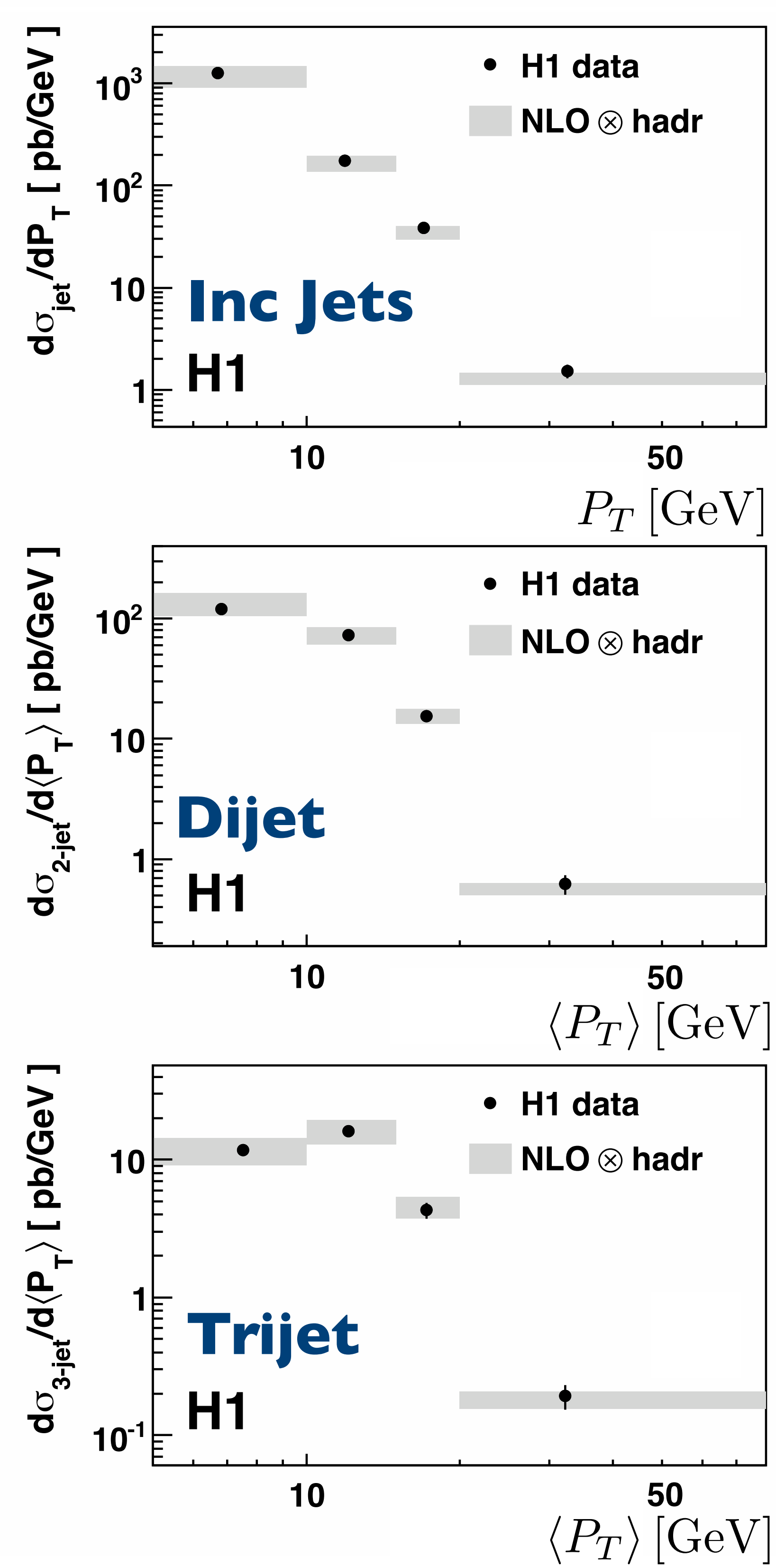
Only inclusive jet cross sections included in HERAPDF fits so far

Large potential shown: correlation between gluon PDF and $\alpha_s(M_Z)$ disentangled

$$\alpha_s(M_Z) = 0.1202 \pm 0.0013(\text{exp.}) \pm 0.0012(\text{had}) \pm 0.0045(\text{scale})$$



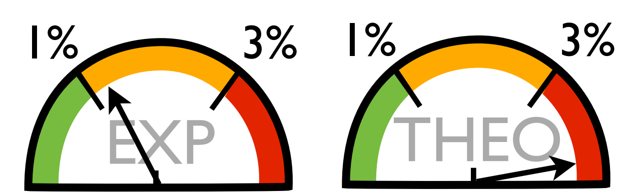
Multijet Cross Sections At Low Q²



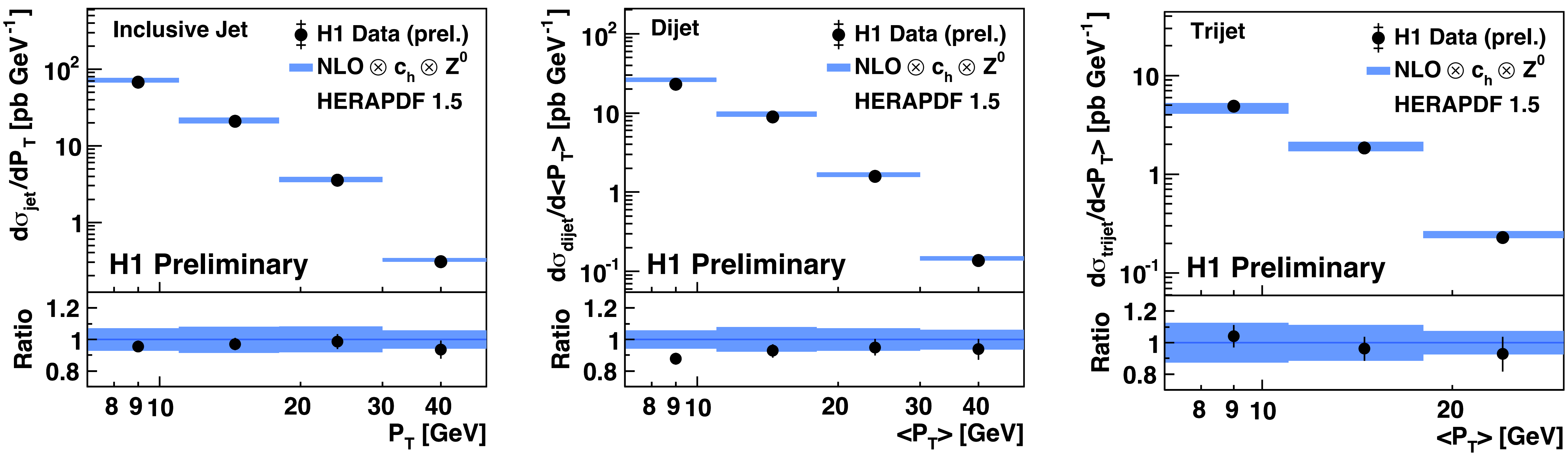
- Double-differential inclusive jet, dijet and trijet measurement, small experimental uncertainties of 6 – 10 %
- Data well described by NLO, $\mu_r = \sqrt{(Q^2 + P_T^2)/2}$ theoretical uncertainties dominated by missing higher orders:
  30% at low Q^2, P_T and 10% at high Q^2, P_T
- choice of $\mu_r = \langle P_T \rangle$ disfavoured by data
- Simultaneous $\alpha_s(M_Z)$ fit to 62 data points:

$$\alpha_s(M_Z) = 0.1160 \pm 0.0014(\text{exp.})^{+0.0093}_{-0.0077}(\text{th.}) \pm 0.0016(\text{pdf})$$

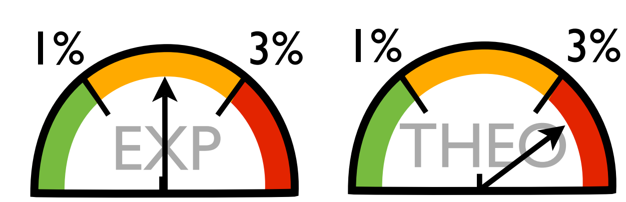
H1, EPJ C67, 1 (2010)



Multijet Cross Sections At High Q^2



- Double-differential inclusive jet, dijet and trijet measurement at $150 < Q^2 < 15000$ GeV^2
- Reduced scale dependence compared to low Q^2 measurement
- Data are well described by NLO calculations, $\mu_r = \sqrt{(Q^2 + P_T^2)/2}$ independent test of HERAPDF 1.5
- Determination of $\alpha_s(M_Z)$ from individual observables with ~2% experimental and ~3.5% theoretical uncertainty



H1-Prelim-11-032

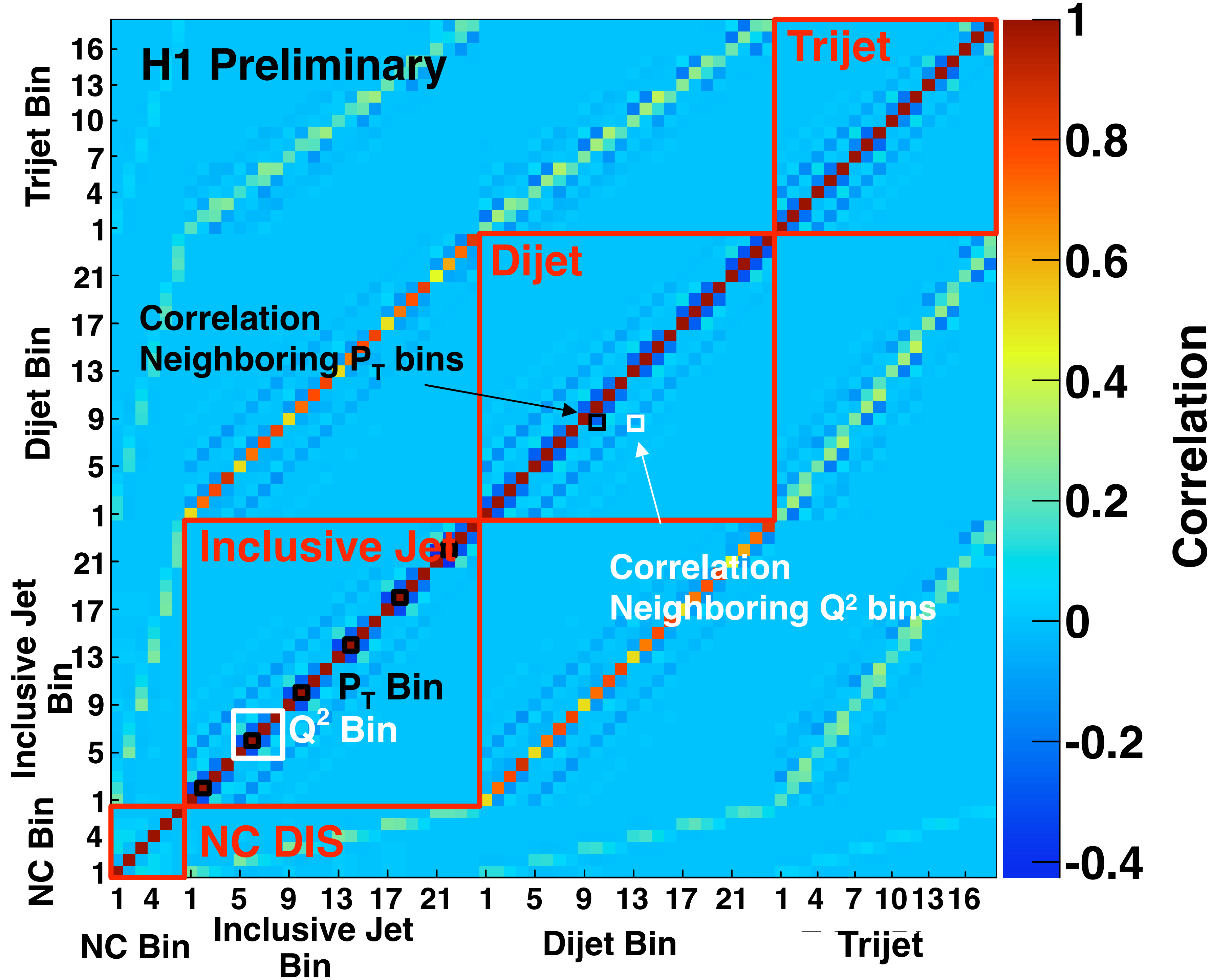
Unfolding of Multijet Cross Sections

Take correlations between observables into account

Full, partly anti-correlated, covariance matrix available after unfolding

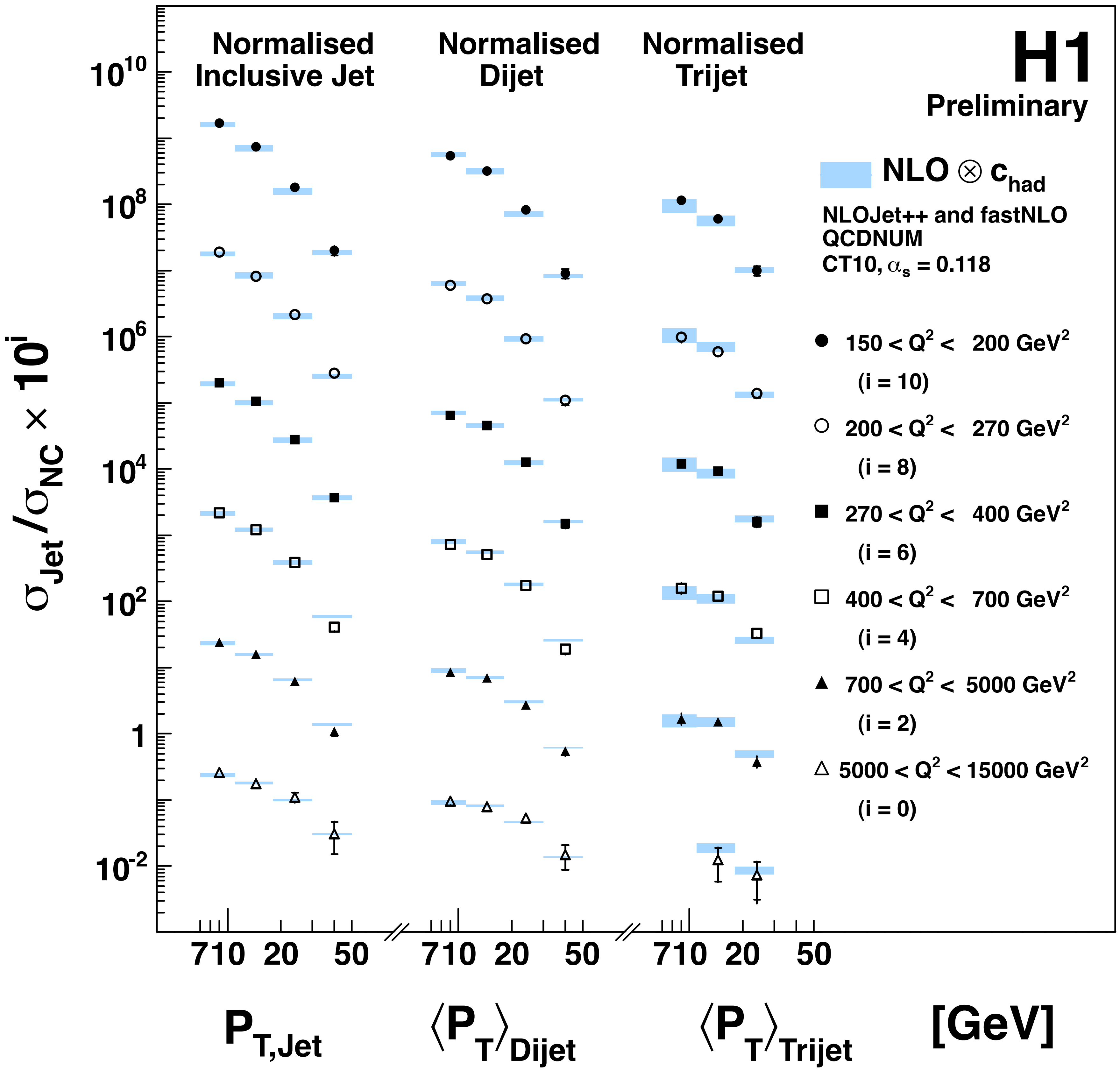
Normalisation of individual measurements possible using full error propagation

Valuable information for QCD fits



H1-Prelim-12-031

Normalised Multijet Cross Sections



NLO Calculation

NLOJet++ and QCDNUM corrected for hadronisation effects

Scale choice:

$$\mu_f^2 = Q^2$$

$$\mu_r^2 = \frac{1}{2}(Q^2 + P_T^2)$$

H1-Prelim-12-031

Determination of $\alpha_s(M_Z)$

Normalized Inclusive Jet

$$\alpha_s = 0.1197 \pm 0.0008\ (\text{exp}) \pm 0.0014\ (\text{PDF}) \pm 0.0011\ (\text{had}) \pm 0.0053\ (\text{theo})$$

$$\chi^2 / \text{ndf} = 28.7/23 = 1.24$$

Normalized Dijet

$$\alpha_s = 0.1142 \pm 0.0010\ (\text{exp}) \pm 0.0016\ (\text{PDF}) \pm 0.0009\ (\text{had}) \pm 0.0048\ (\text{theo})$$

$$\chi^2 / \text{ndf} = 27.0/23 = 1.17$$

Normalized Trijet

$$\alpha_s = 0.1185 \pm 0.0018\ (\text{exp}) \pm 0.0013\ (\text{PDF}) \pm 0.0016\ (\text{had}) \pm 0.0042\ (\text{theo})$$

$$\chi^2 / \text{ndf} = 12.0/16 = 0.75$$

Good χ^2/ndf for each individual observable

Tension between α_s from dijets and inclusive/trijets observed, but α_s values well within theoretical uncertainties

Combined Fit

$$\alpha_s = 0.1177 \text{ +/- } 0.0008\ (\text{exp})$$

$$\chi^2 / \text{ndf} = 104.608 / 64 = 1.634$$

Fit to all data points

Relatively large χ^2/ndf

H1-Prelim-12-031

Combined Fit

Largest benefit is from a combined fit

simultaneous fit to normalised inclusive jet, dijet and trijet cross sections

Sensitivity to higher orders

theoretical uncertainty estimated by variation of scale, use k-factor as indicator for higher order contributions

$k = \sigma_{\mathrm{NLO}} / \sigma_{\mathrm{LO}}$ range of k-factor: $1.05 < k < 1.45$

Restrict analysis to $k < 1.3$

faster convergence of perturbative series

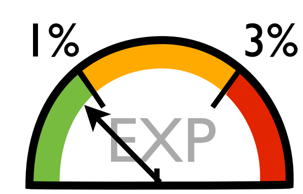
trade-off between number of data points and smaller theoretical uncertainty

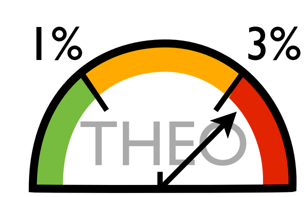
Normalised Multijets with $k < 1.3$

$$\alpha_s = 0.1163 \pm 0.0011\ (\mathrm{exp})\ \pm 0.0014\ (\mathrm{PDF})\ \pm 0.0008\ (\mathrm{had})\ \pm 0.0039\ (\mathrm{theo})$$

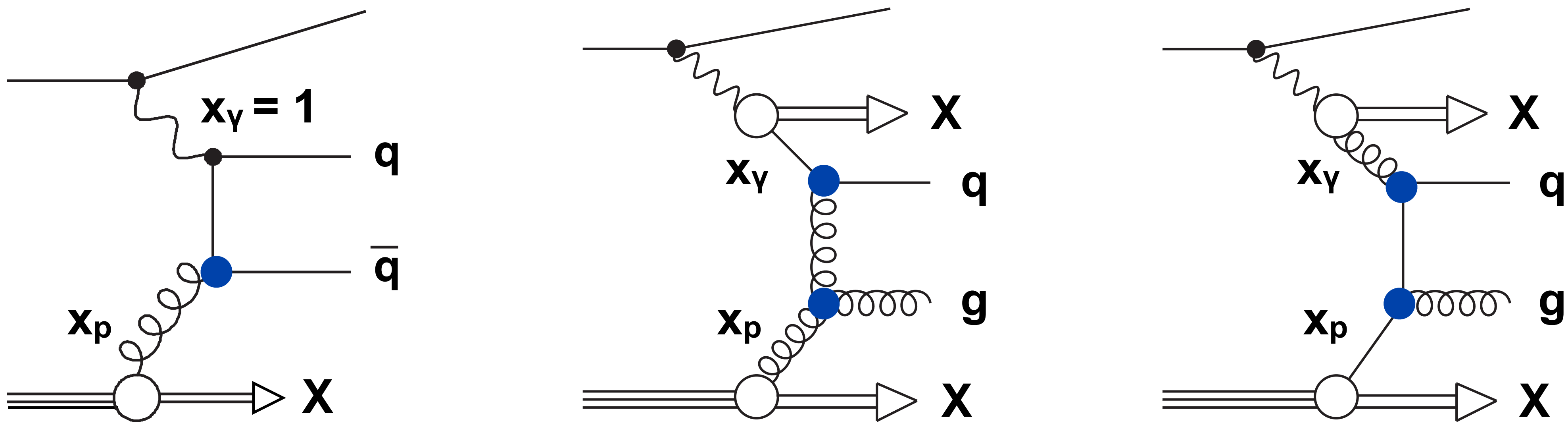
much better χ^2/ndf: 53.2 / 41 = 1.30

H1-Prelim-12-031





Jet Production in Photoproduction



direct photoproduction

resolved photoproduction

$$\sigma^{\gamma p}_{\mathrm{n-jet}} = \sum_m \alpha_s^m(\mu_r) \sum_{i,j=q,\bar{q},g} \int \mathrm{d}x_p \int \mathrm{d}x_\gamma$$

$$f_{i/p}(x_p,\mu_f) f_{j/\gamma}(x_\gamma,\mu_f) \cdot \hat{\sigma}^m_{ij}(x_p, x_\gamma, \mu_r, \mu_f)$$

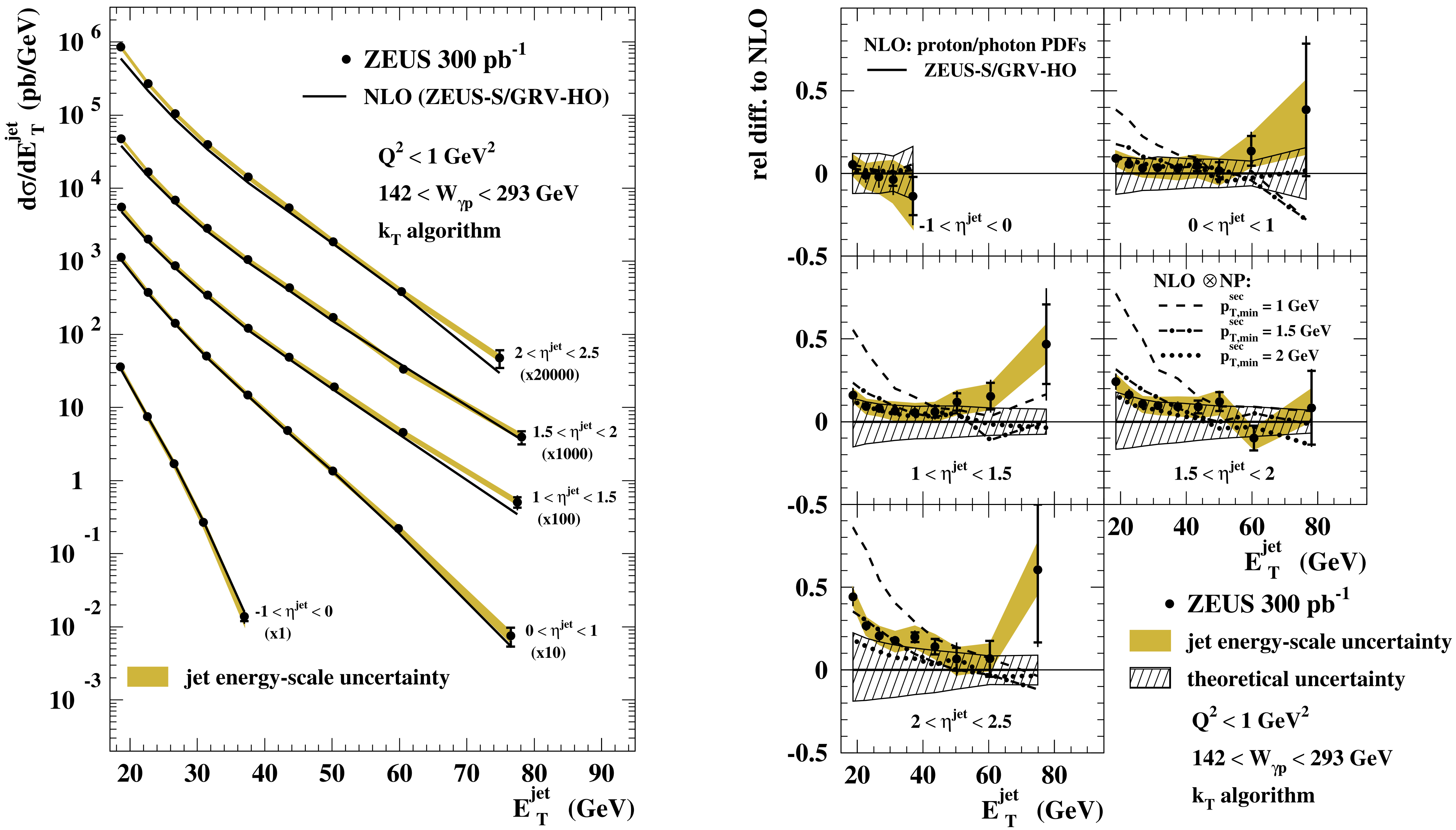
Photon flux: Weizsäcker-Williams approximation

Direct case: $f_{j/\gamma}(x_\gamma,\mu_f) = \delta(x_\gamma - 1)$

Direct sensitivity to α_s, gluon and photon PDFs

Jet Production in Photoproduction

ZEUS, Nucl. Phys. B, 864, 1 (2012)

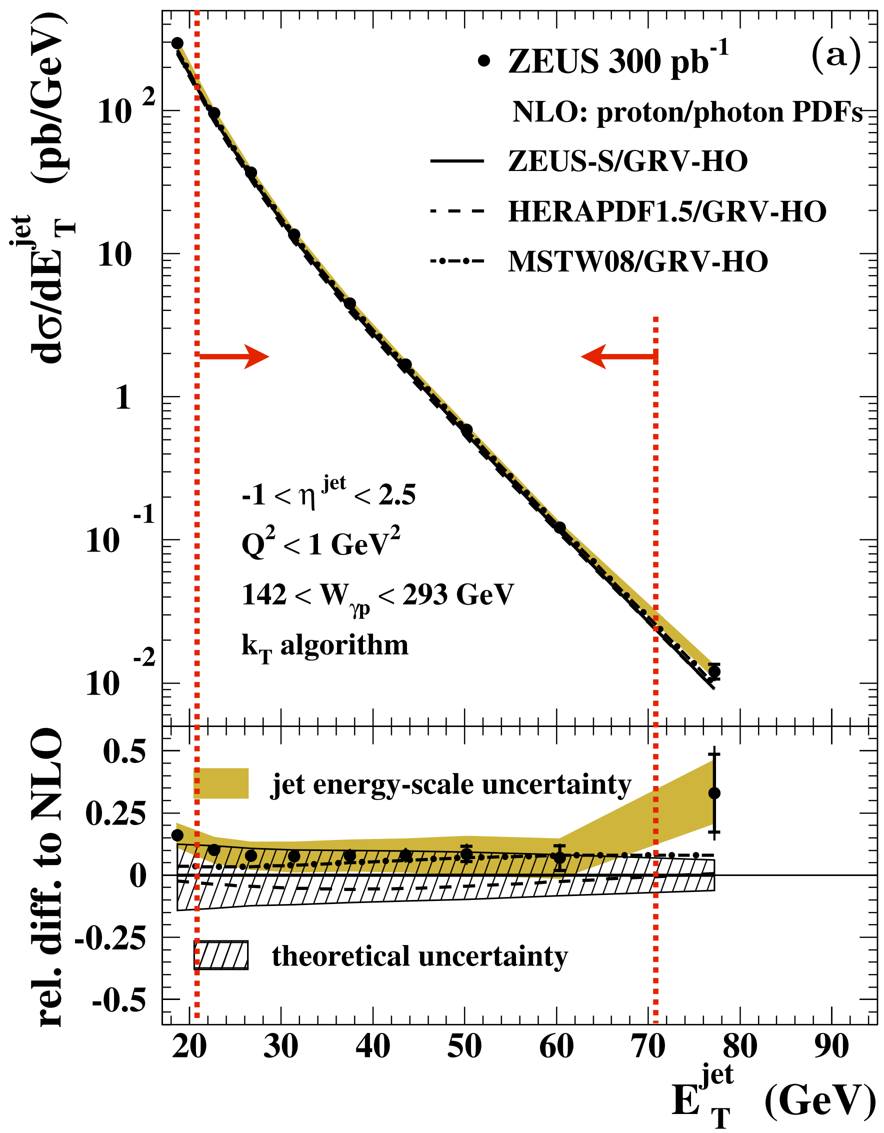


Double differential measurement in P_T and η

- Higher P_T reach than in the DIS case
- Differences between data and NLO at low PT/large η could be from photon PDFs or non-perturbative effects

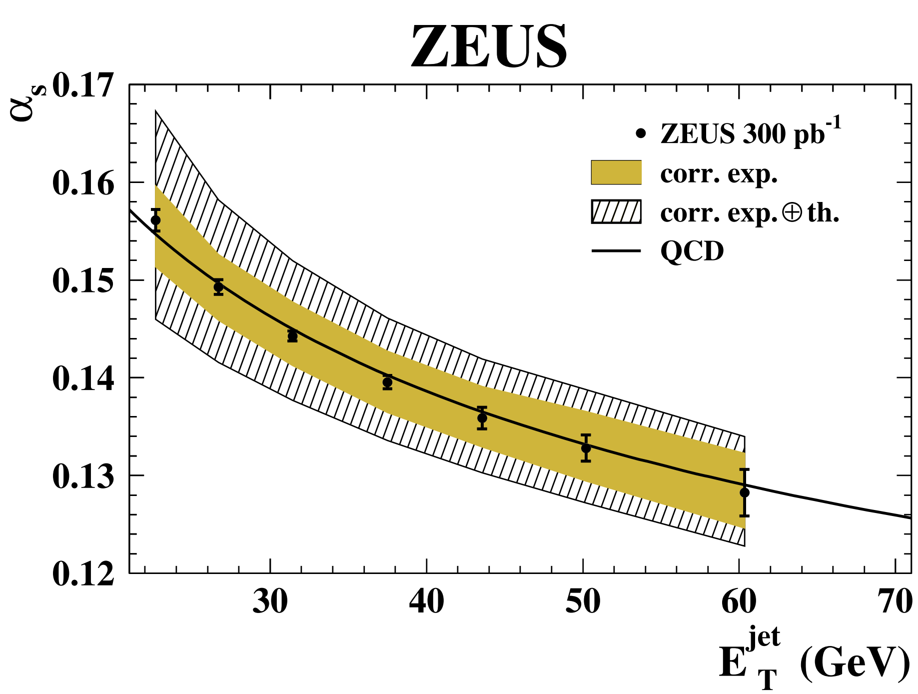
Jet Production in Photoproduction

ZEUS, Nucl. Phys. B, 864, 1 (2012)

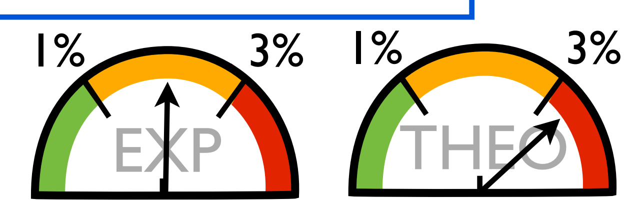


Determination of α_s

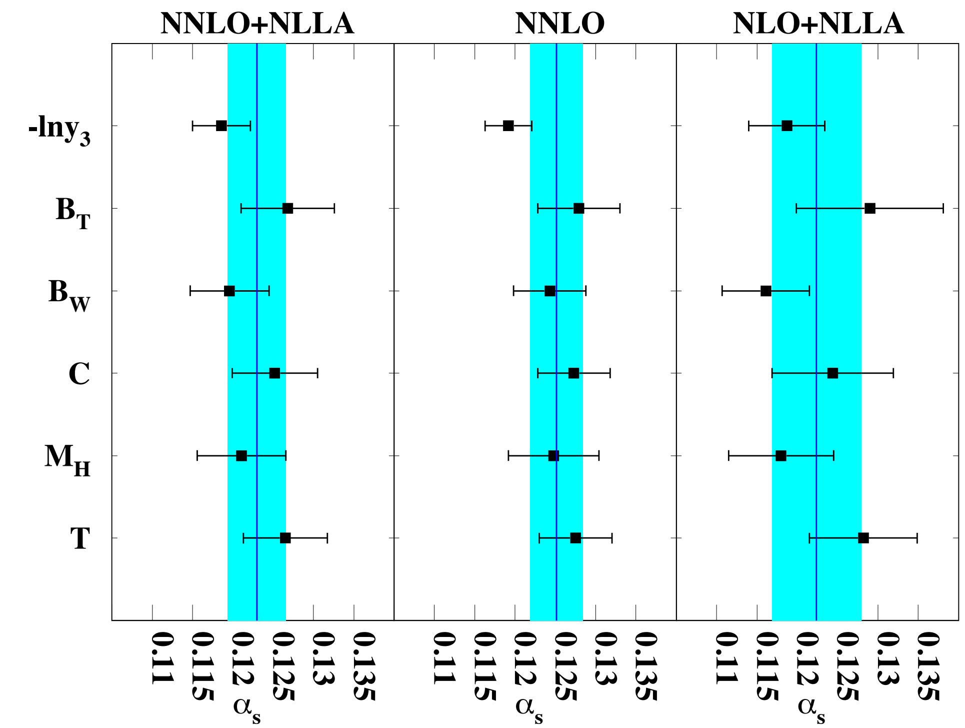
- restricted P_T region of $21 < P_T < 71$ GeV to reduce non-perturbative effects and dependence on proton PDF
- similar values obtained of k_T, anti-k_T and SISCone algorithms
- reduced uncertainty due to missing higher orders, but uncertainty due to photon PDFs non-negligible



$$\alpha_s(M_Z) = 0.1206\,^{+0.0023}_{-0.0022}\,(\text{exp.})\,^{+0.0042}_{-0.0035}\,(\text{th.})$$

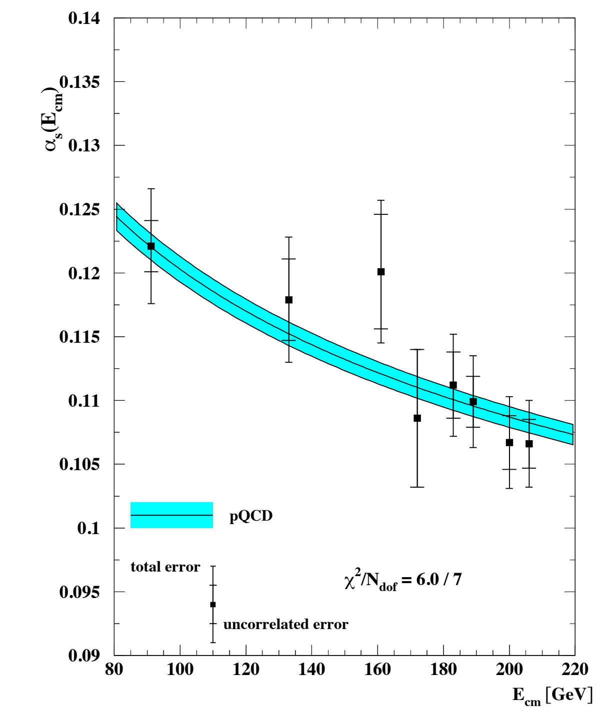


Extending the Reach: e^+e^-



Use event shapes at $\mu \neq M_Z$

- $-\ln(y_3)$, the two-to-three jet transition
- B_T and B_W, the total and wide jet broadening
- C, the C-parameter derived from the linearised momentum tensor
- M_H, the heavy jet mass
- T, thrust

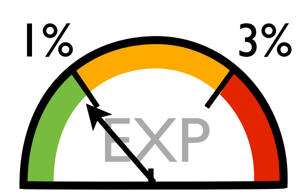


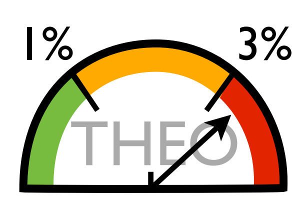
NNLO Calculations have been performed

- Resummation of leading logs due to soft gluon radiation essential
- Partial re-introduction of scale dependence
- Running of α_s probed up to μ = 204 GeV

$$\alpha_s(M_Z) = 0.1224 \pm 0.0009\,(\mathrm{stat}) \pm 0.0009\,(\mathrm{exp}) \pm 0.0012\,(\mathrm{had}) \pm 0.0035\,(\mathrm{theo})$$

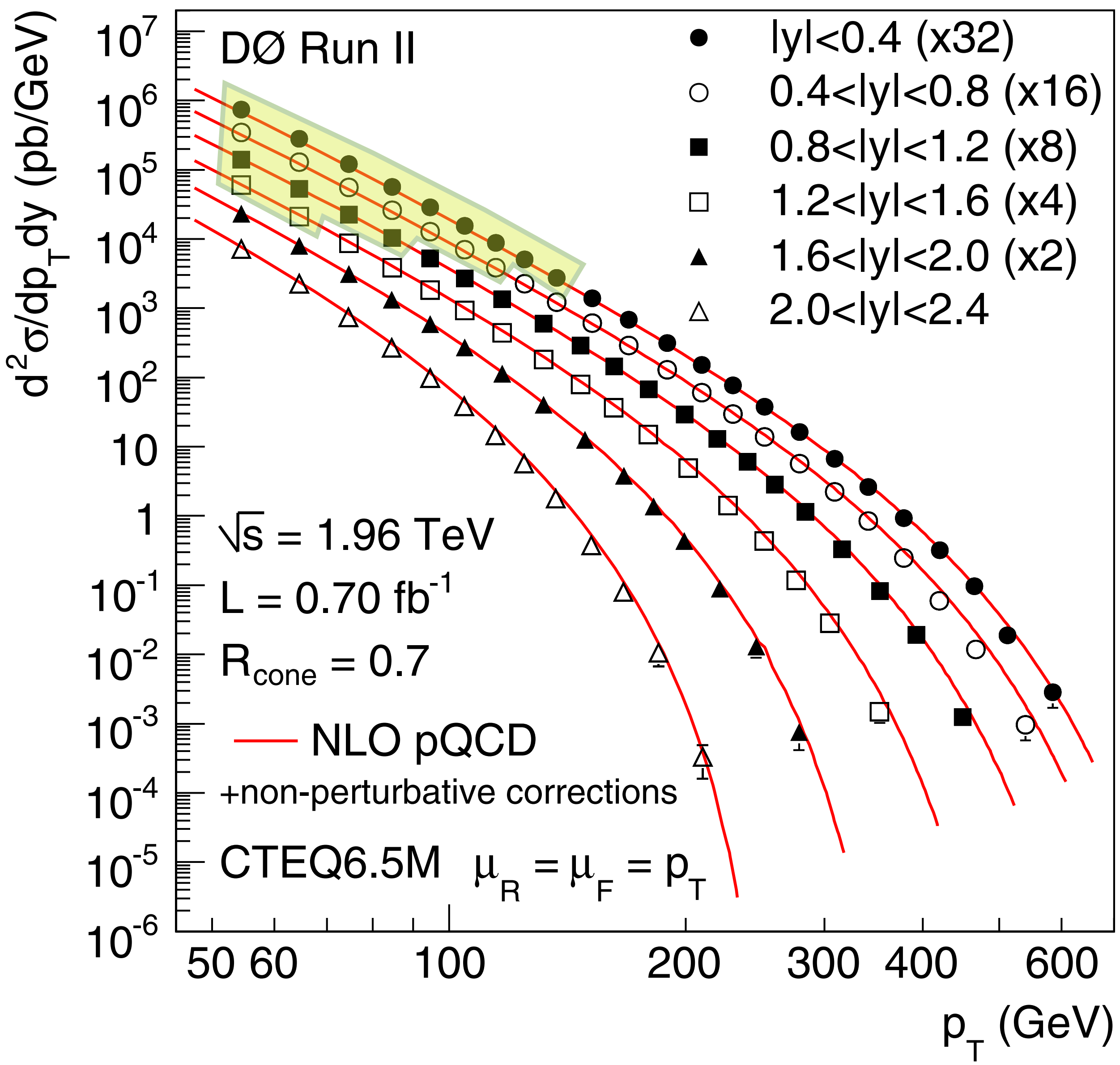
G. Dissertori et al., JHEP 08, 036 (2009)





Extending the Reach: $p\bar{p}$

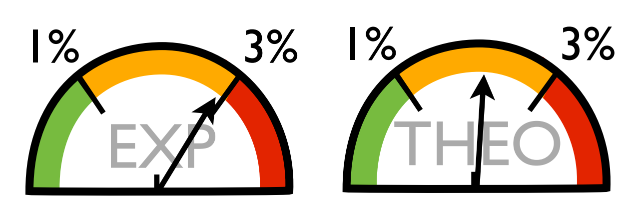
D0 measurement of inclusive jet production



- Jet P_T measured up to 600 GeV
- Good description over full η and P_T range by NLO calculations
- Potential bias: data are input for PDF fits and influence gluon density at x > 0.2
- Extraction of α_s restricted to $x_1, x_2 < 0.25$, only 22 bins left at relatively small P_T
- threshold corrections available: reduction of theoretical uncertainty

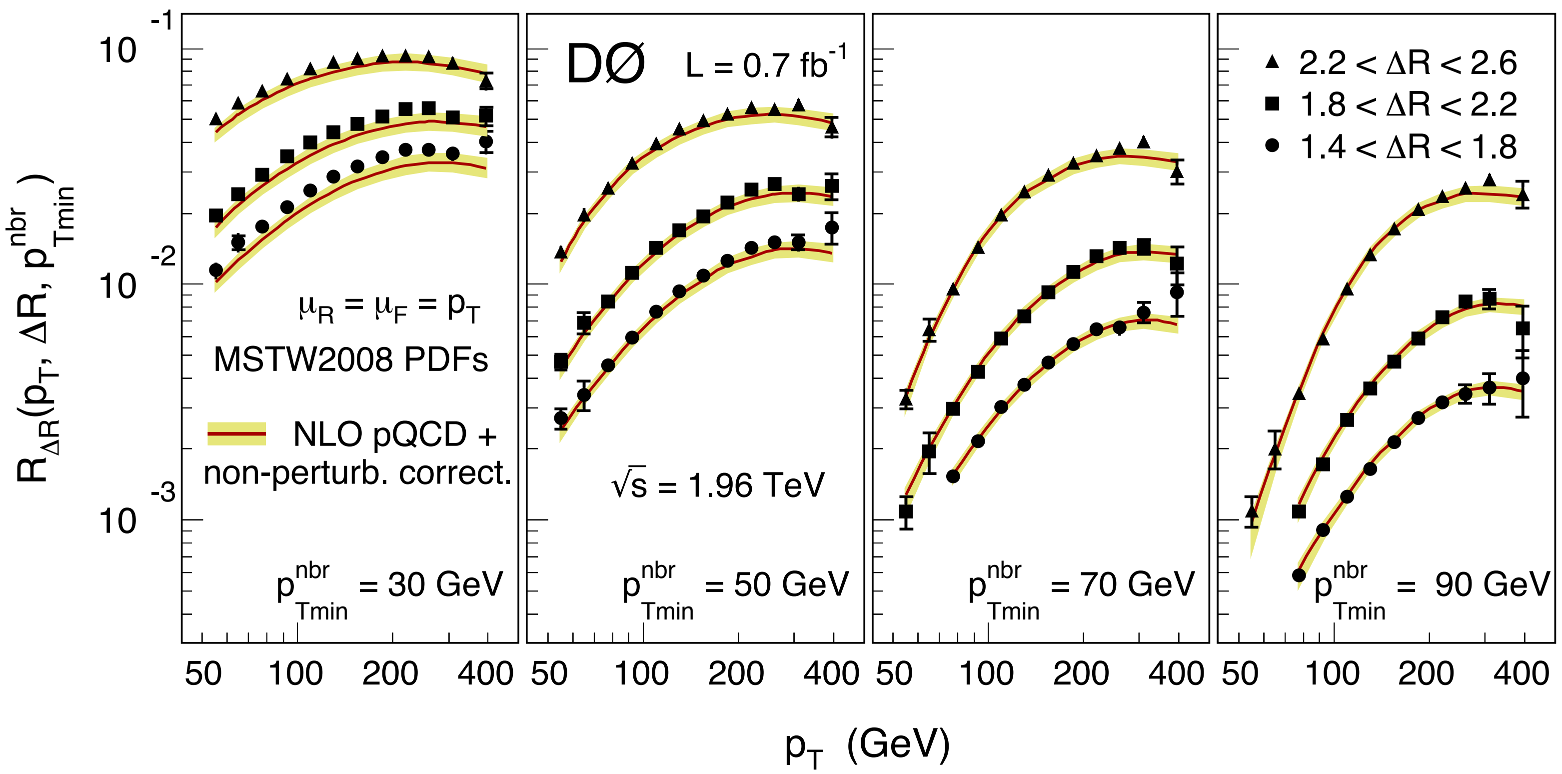
$$\alpha_s(M_Z) = 0.1161\,^{+0.0034}_{-0.0033}\,(\text{exp.})\,^{+0.0029}_{-0.0035}\,(\text{theo.})$$

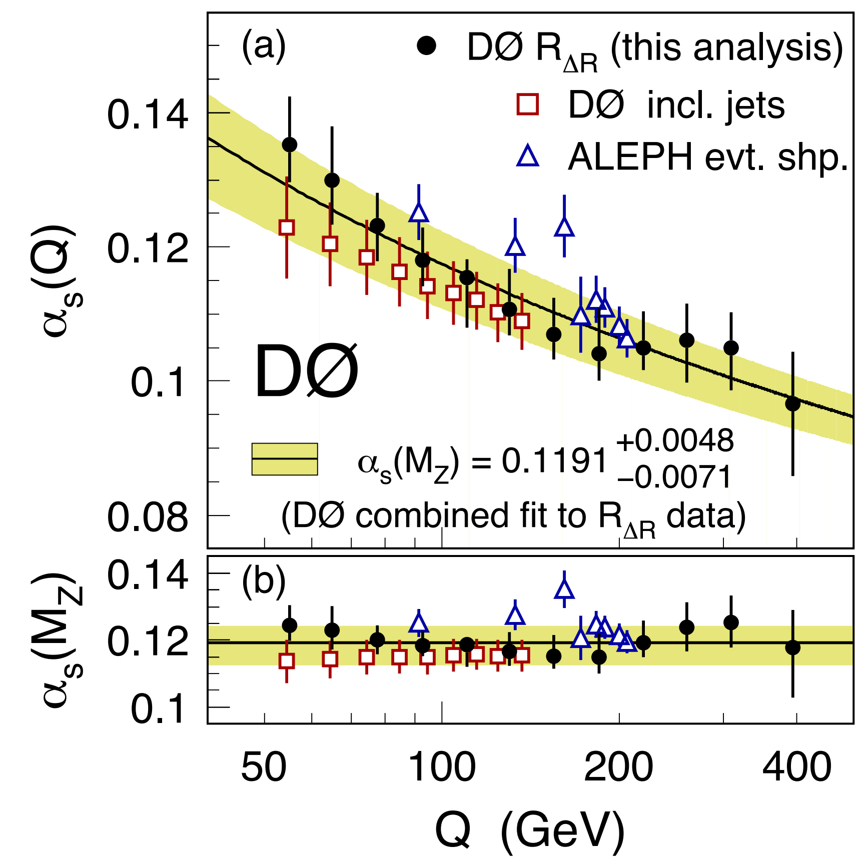
D0, Phys. Rev. D80, 111107 (2009)



Extending the Reach: $p\bar{p}$

Normalised jet cross sections at the Tevatron

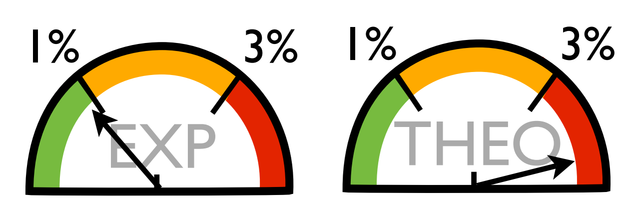




D0, arXiv:1207.4957

Measurement of $R_{\Delta R} = \dfrac{\sum_{i=1}^{N_{\rm jet}(p_T)} N_{\rm nbr}^{(i)}(\Delta R, p_{T\min}^{\rm nbr})}{N_{\rm jet}(p_T)}$

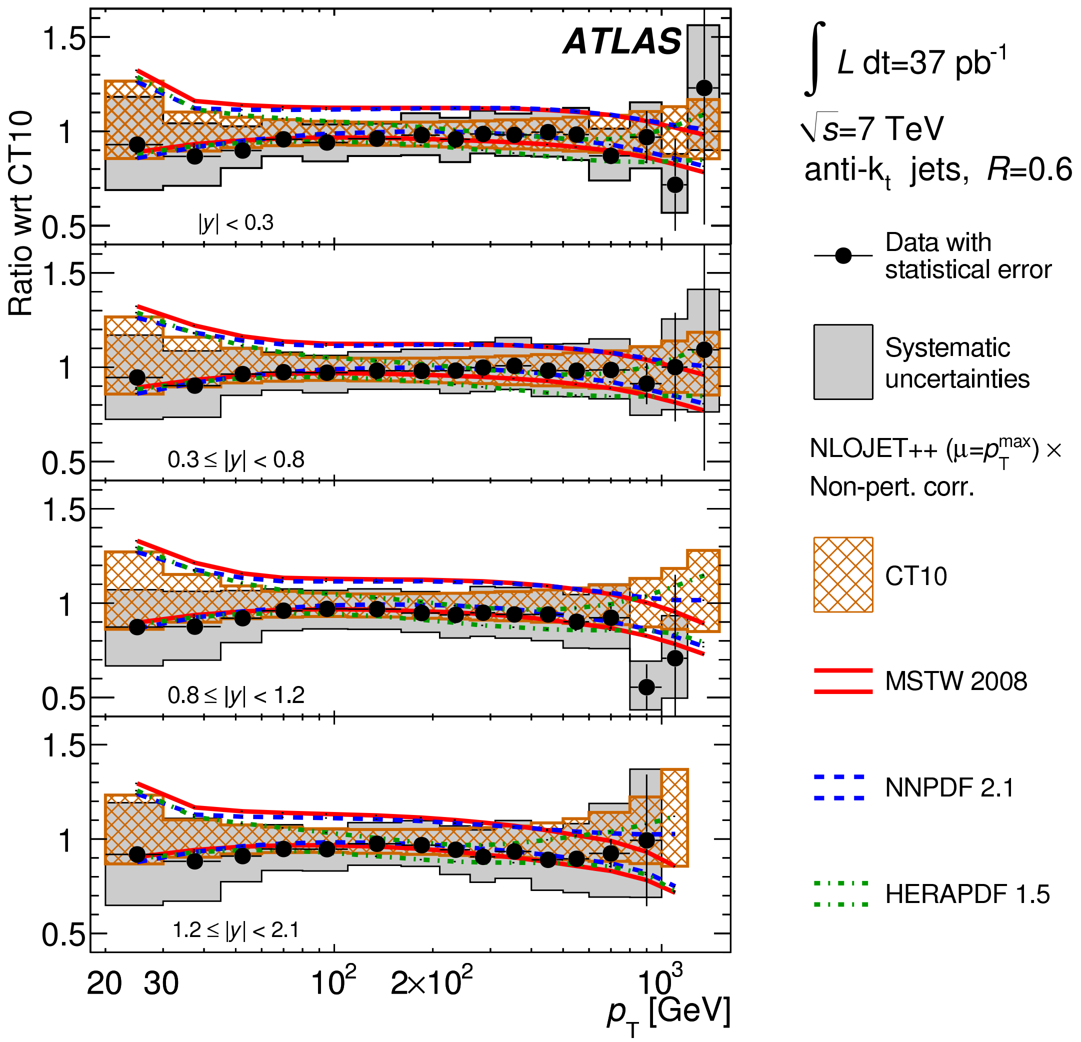
- Measure of hardness of neighbouring jets within ΔR
- Small sensitivity to proton PDFs
- Small experimental uncertainty due to partial cancellations
- Probing of scales up to 400 GeV, but large theoretical uncertainty (only NLO calculations available)



LHC

Jet measurements at the LHC are gaining in precision

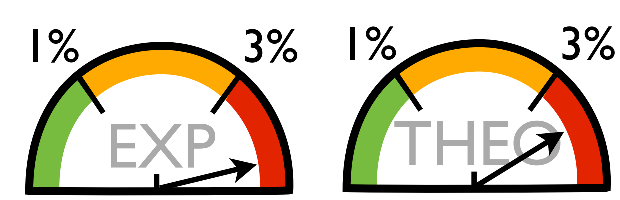
ATLAS, Phys. Rev. D86, 014022 (2012)



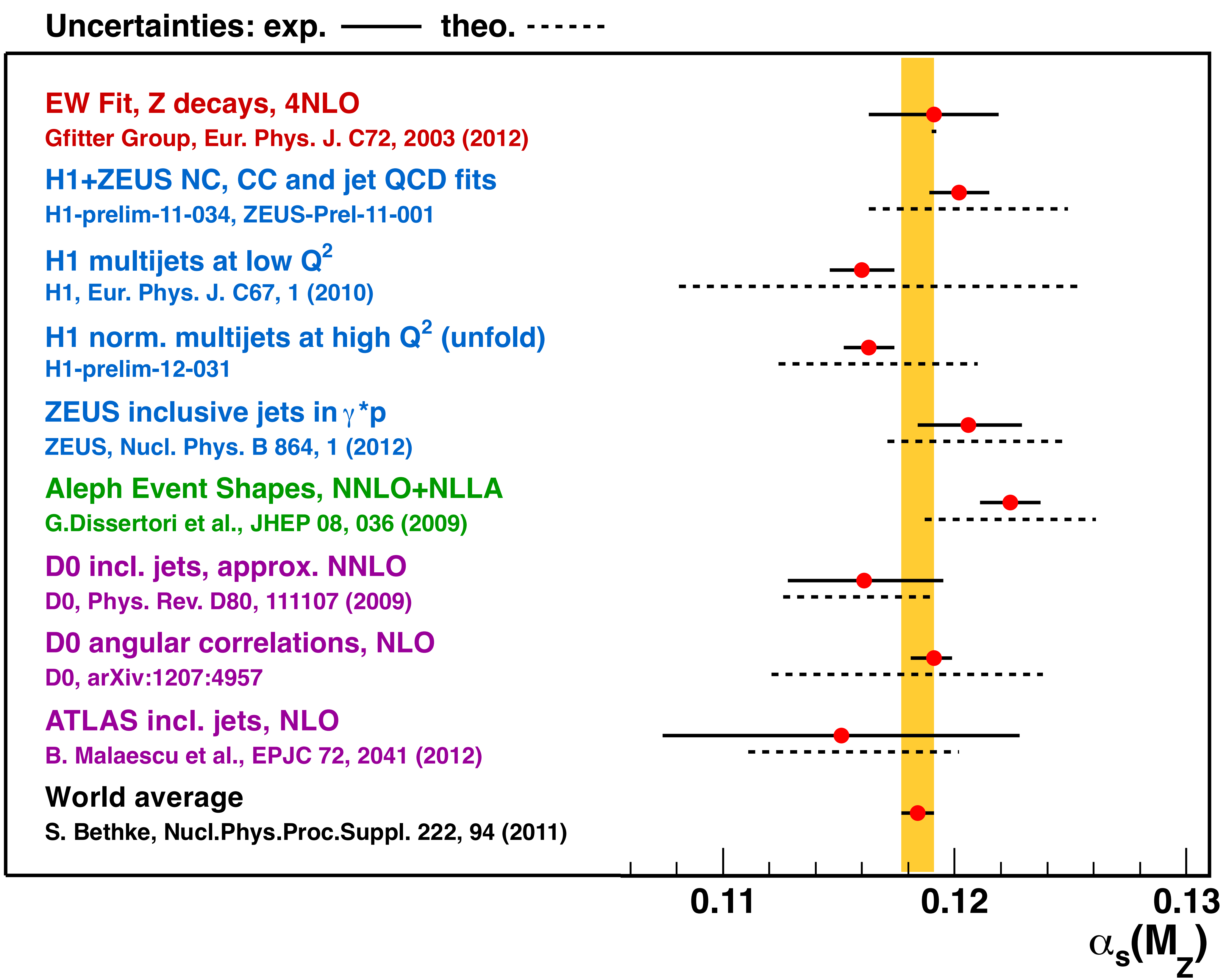
- Jet data available with scales up to 1-2 TeV
- Full unfolding of experimental effects of ATLAS inclusive jet data
- Experimental uncertainties of 10-20%
- Non-negligible non-perturbative corrections
- First determination of α_s at scales up to 600 GeV
- Large uncertainty due to disagreement between R=0.4 and R=0.6

$$\alpha_s(M_Z) = 0.1151 \pm 0.0077\,(\text{exp.})\,^{+0.0051}_{-0.0040}\,(\text{theo.})$$

B. Malaescu, P Starovoitov, EPJC 72, 2041 (2012)



Comparison of $\alpha_s(M_Z)$ Values



Summary

The Strong Coupling α_s

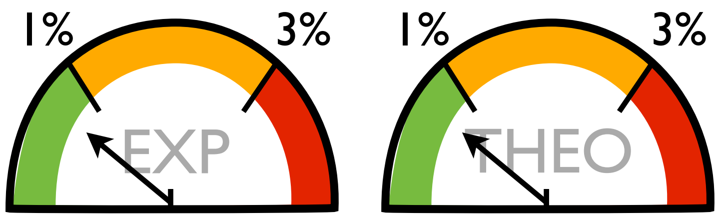
- Allows for stringent tests of QCD
- Universality impressively demonstrated by determination from very different processes at very different scales
- Deviations from the RGE could hint at new physics - precision needed!

Experimental Data

- HERA jet data among the most precise data for precision tests of QCD
- New normalised Tevatron jet measurement with exp. uncertainty ~1%
- Probe highest scales with LHC jet data

Theory

- Missing higher orders often the dominating source of uncertainty



We are not there yet!

Additional Material

Jet Observables

Inclusive Jets

each jet above a given P_T requirement contributes to the cross section: large statistics, calculation needs contributions from higher-order configurations

Dijets

events with at least two jets above a certain P_T contribute: reduced statistics but NLO calculations have smaller scale dependence

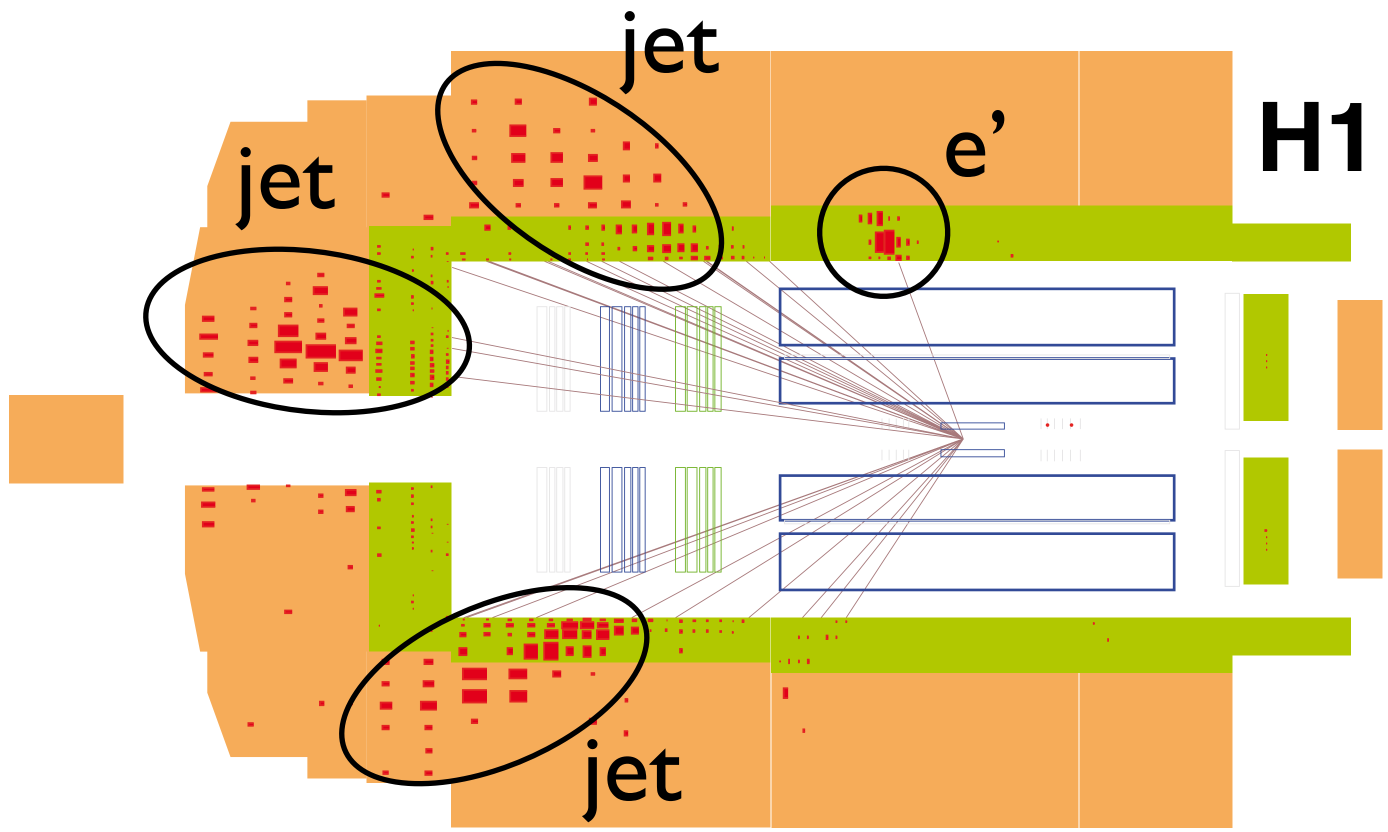
Trijets

events with at least three jets above a certain P_T contribute: smaller statistics and slightly larger experimental uncertainties but high sensitivity to α_s ($O(\alpha_s^2)$ at LO)

Normalised Jet Cross Sections

benefit from partial cancellations of experimental and theoretical uncertainties by measurement of σ_{jet}/σ_{NC}

Multijet Measurement in DIS



Physical correlations

individual jet measurements are correlated: correlations between individual jets in the inclusive jet sample, dijet events are a subsample of inclusive jets, trijet and dijet events...

Experimental effects

correlations may change due to the detector resolution: introduces migrations between different jet samples

Regularised Unfolding

Migration matrix $\mathbf{A}$ describes the detector response

$$\mathbf{m} = \mathbf{A} \cdot \mathbf{x}$$

$\mathbf{m}$: measured distribution (detector level)
$\mathbf{x}$: true distribution (particle level)

Perform unfolding by analytic minimisation of

$$\chi^{\mathbf{2}} = \frac{\mathbf{1}}{\mathbf{2}}(\mathbf{m} - \mathbf{A}\mathbf{x})^{\mathbf{T}}\mathbf{V}^{-\mathbf{1}}(\mathbf{m} - \mathbf{A}\mathbf{x})^{\mathbf{T}} + \tau^{\mathbf{2}} \cdot \mathbf{L}$$

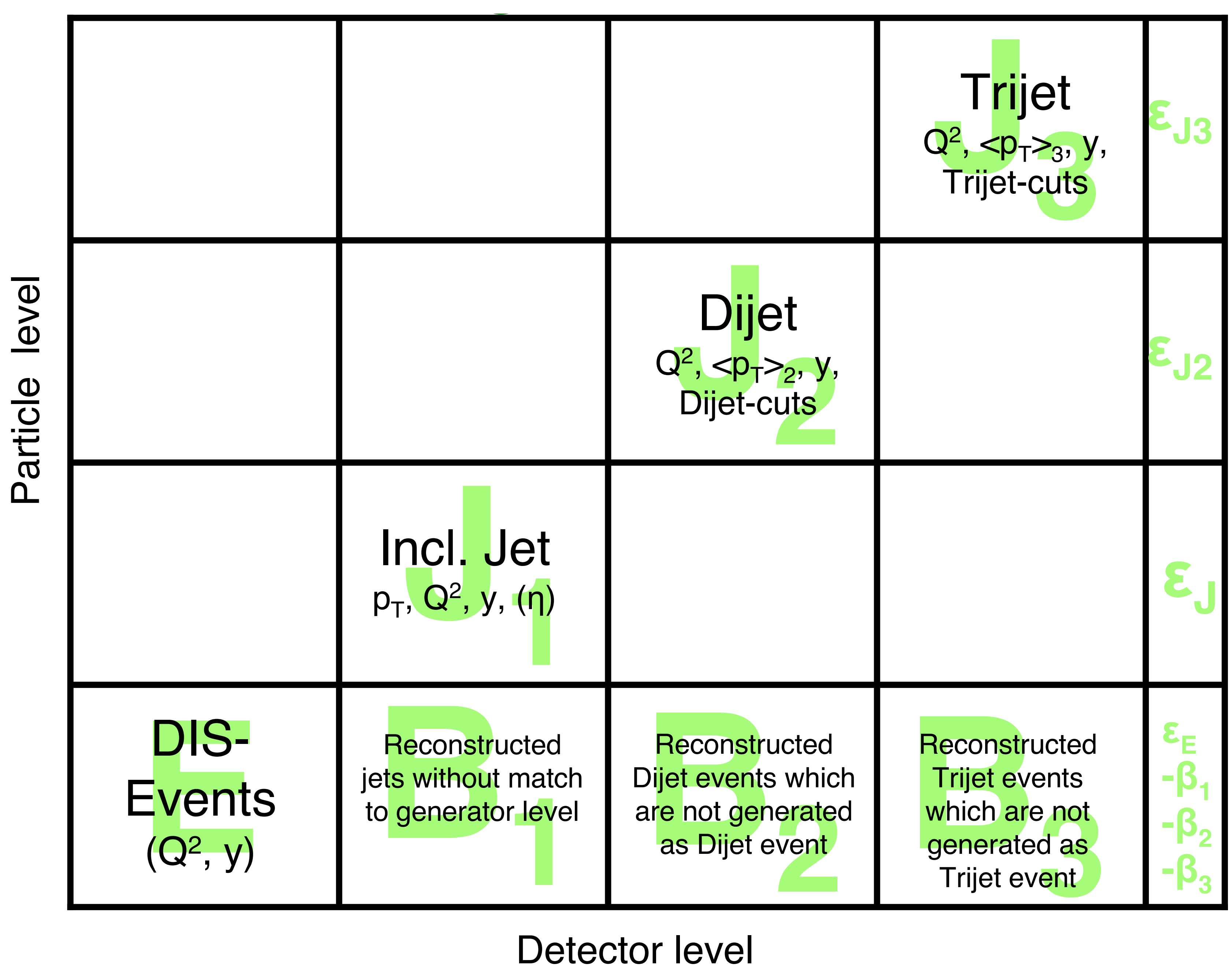
TUnfold (S. Schmitt), arXiv:1205.6201

Regularisation parameter $\boldsymbol{\tau}$ suppresses large fluctuations

Correlation of datasets contained in covariance matrix $\mathbf{V}$

Possibility to unfold four measurements at once:
NC DIS, inclusive jet, dijet and trijet cross sections

Unfolding of Jet Multiplicities



Migration Matrix

Multidimensional unfolding in Q^2, P_T and y

Full treatment of migrations between jet observables

Normalisation preserved with inclusive NC DIS events

Detector response obtained from simulation

Dimension:
about 600 x 2200 bins

MC Test

Performance test:
Test unfolded result w.r.t. MC truth

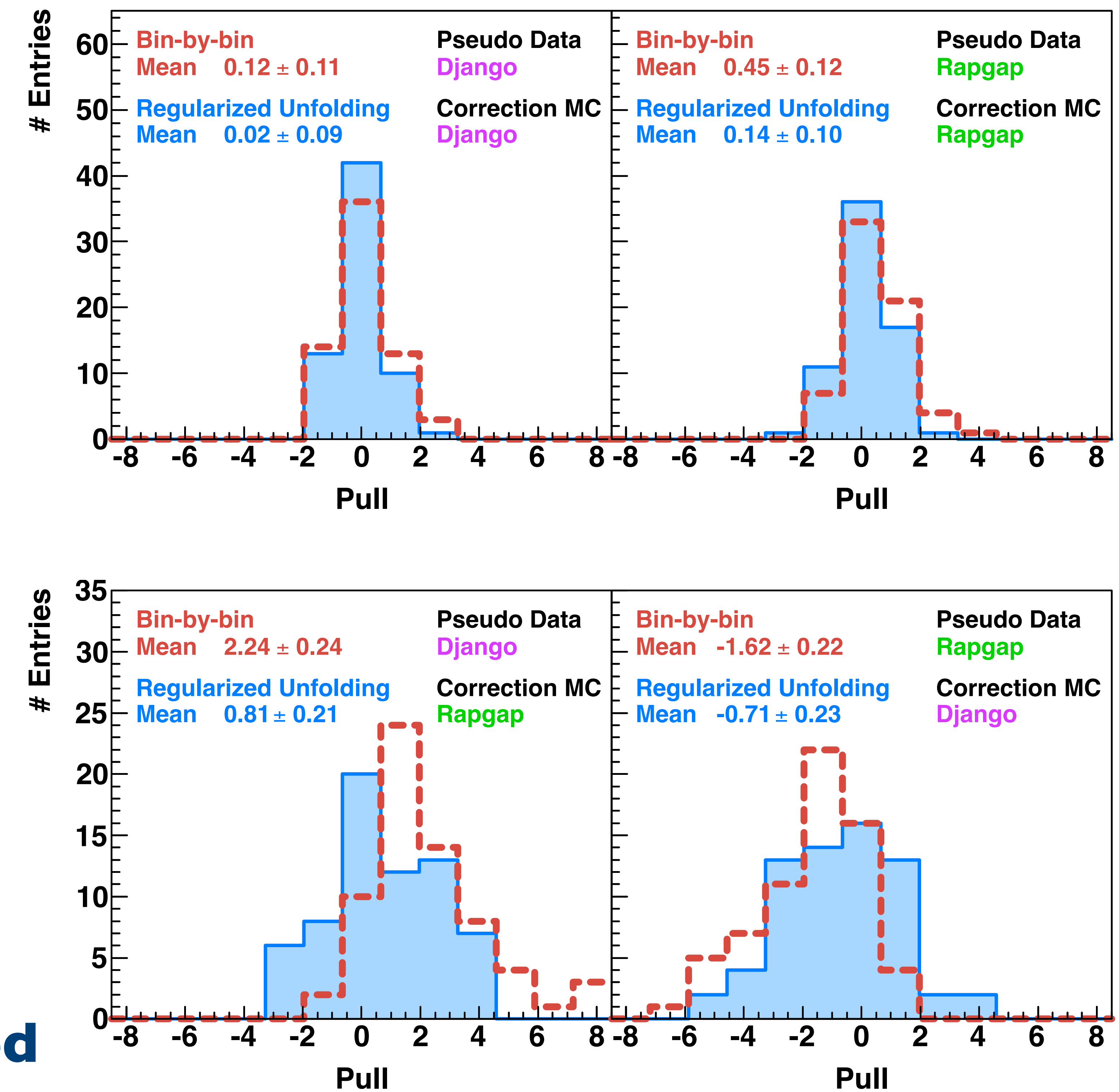
Pull distribution:

$$P_i = \frac{x_i^{\mathrm{unfold}} - x_i^{\mathrm{true}}}{\delta_i^{\mathrm{unfold}}}$$

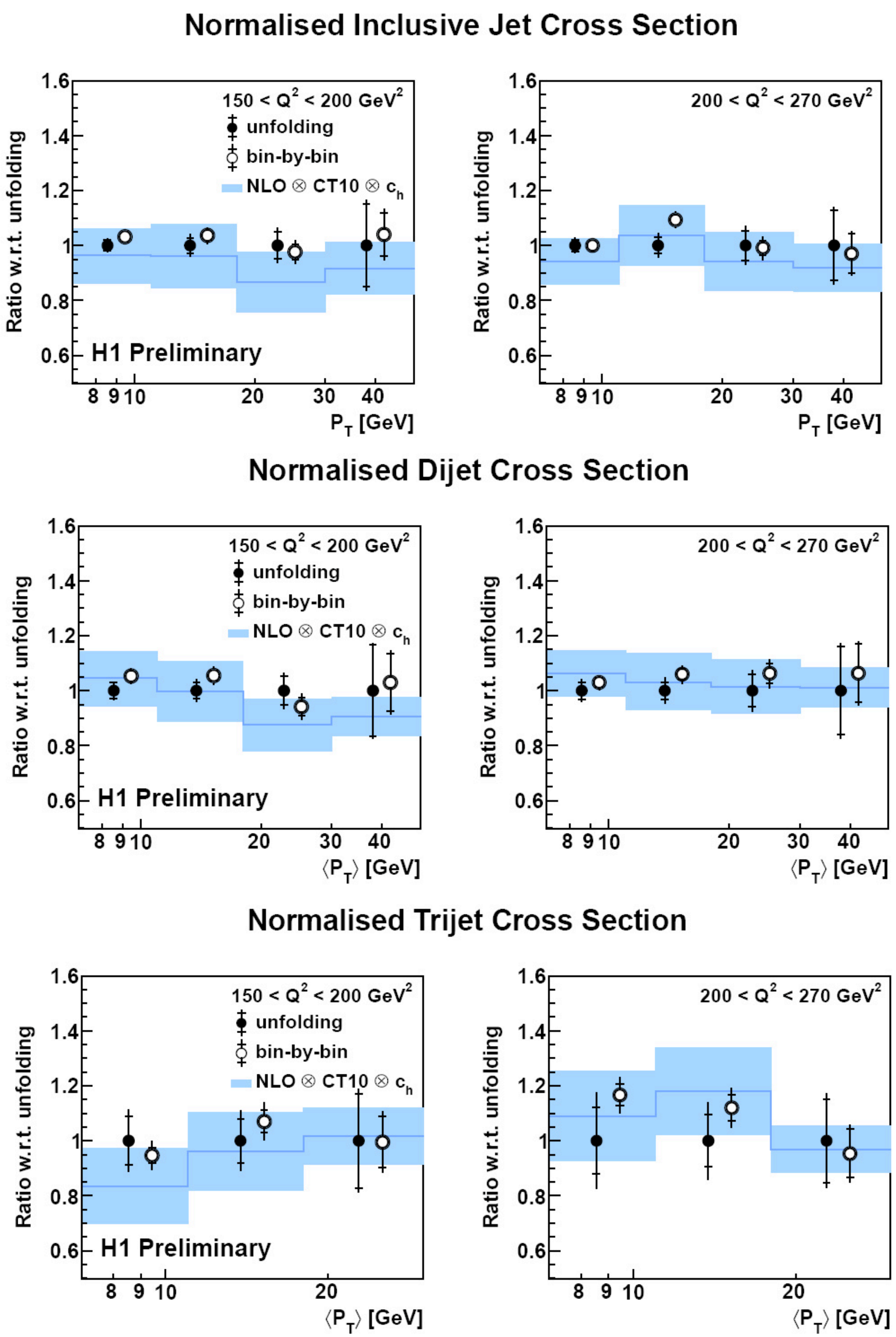
Two theo. models:
Djangoh (CDM)
Rapgap (MEPS)

Comparison:
Unfolded results with results obtained bin-wise derived correction factors

⇒ Unfolding less biased

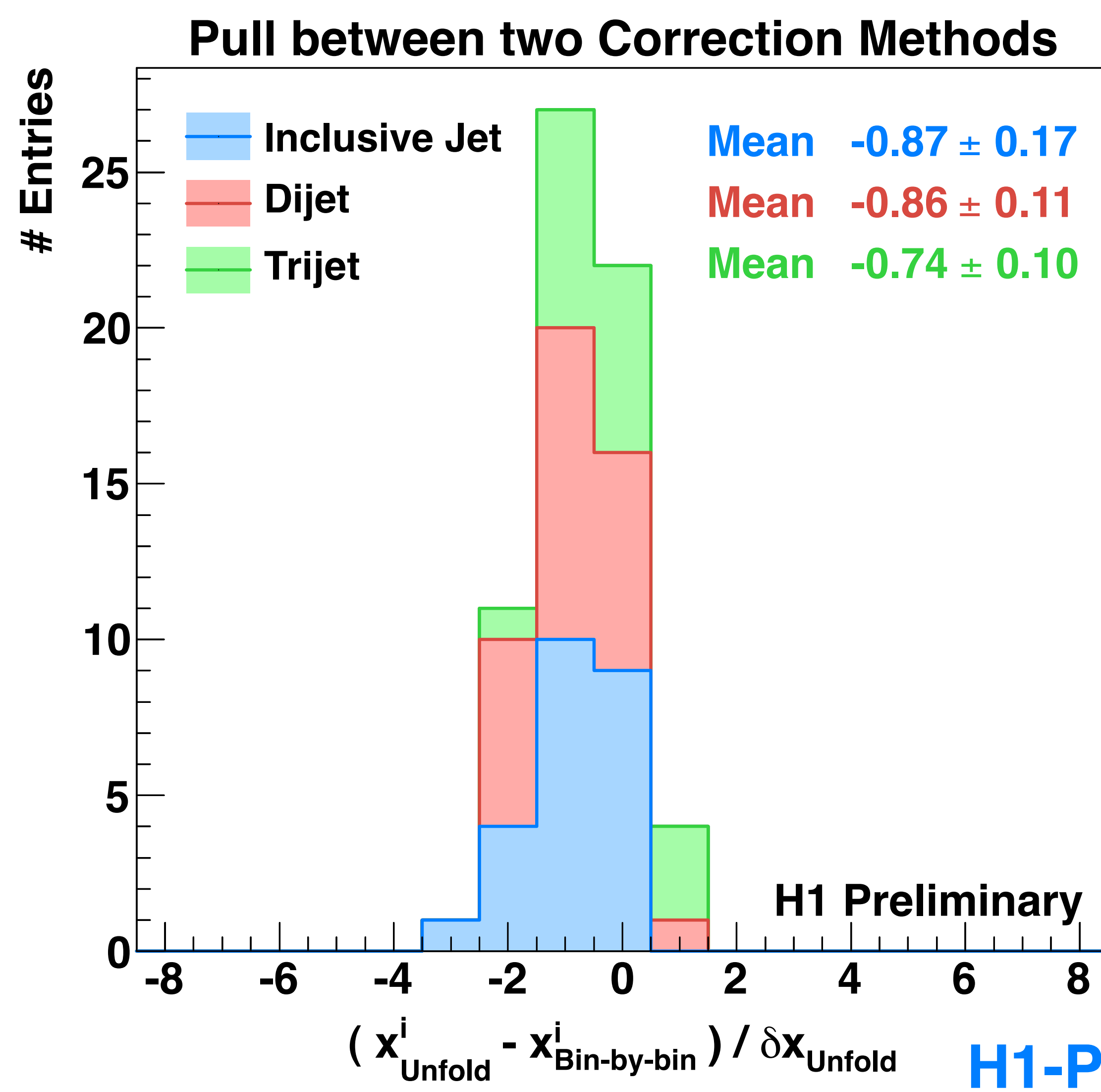


Comparison to “bin-by-bin”



Performance on data

- bin-by-bin result gives slightly higher cross section (~0.8σ)
- larger stat. error - but full covariance matrix available

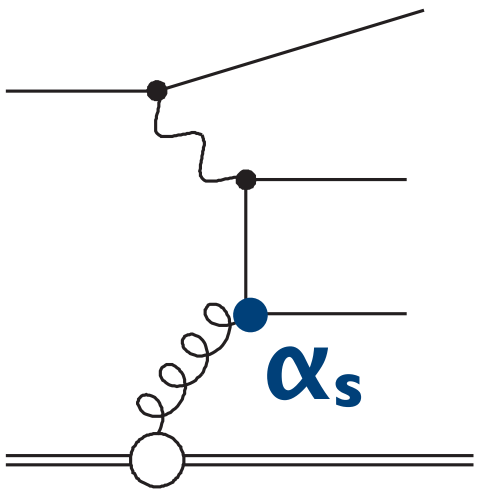


H1-Prel-12-031

Determination of $\alpha_s(M_Z)$

NLO calculation depends on PDF and $\alpha_s(M_Z)$

⇒ Keep PDF fixed and fit $\alpha_s(M_Z)$



Hessian method: Minimise $\chi^2(\alpha_s)$

$$\chi^2(\alpha_s) = \boldsymbol{u}^T \boldsymbol{V}^{-1} \boldsymbol{u} + \sum_k \epsilon_k^2$$

$$u_i = \sigma_i^{\text{exp}} - \sigma_i^{\text{theo}}(\alpha_s, \text{pdf}) \left(1 - \sum_{\text{k}} \Delta_{\text{ik}} \epsilon_{\text{k}}\right)$$

- Experimental uncertainty obtained by $\chi^2 = \chi^2_{\text{min}} + 1$
- Theoretical uncertainty obtained by offset method:
  - Repeat fit for μ_r and μ_f varied by a factor of 1/2 and 2
- PDF uncertainty calculated with PDF eigenvalues
- Consistency with PDF sets with varied $\alpha_s(M_Z)$ checked