Jets Physics at the LHeC

Building on HERA experience

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with input / material from
Jörg Behr, Thomas Gehrmann, Claudia Glasman, Juan Terron, Thomas Kluge

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Geneva, 12/13 November 2010

OVERVIEW

- Introduction
  - Motivation
  - Jet physics at HERA: Results
- Scenarios and selections
- Results: DIS jets at the LHeC
- Results: PHP jets at the LHeC
- Excursion: strong coupling
- Theory status
- Conclusions

MY WAY TO LHeC

MY WAY TO LHeC

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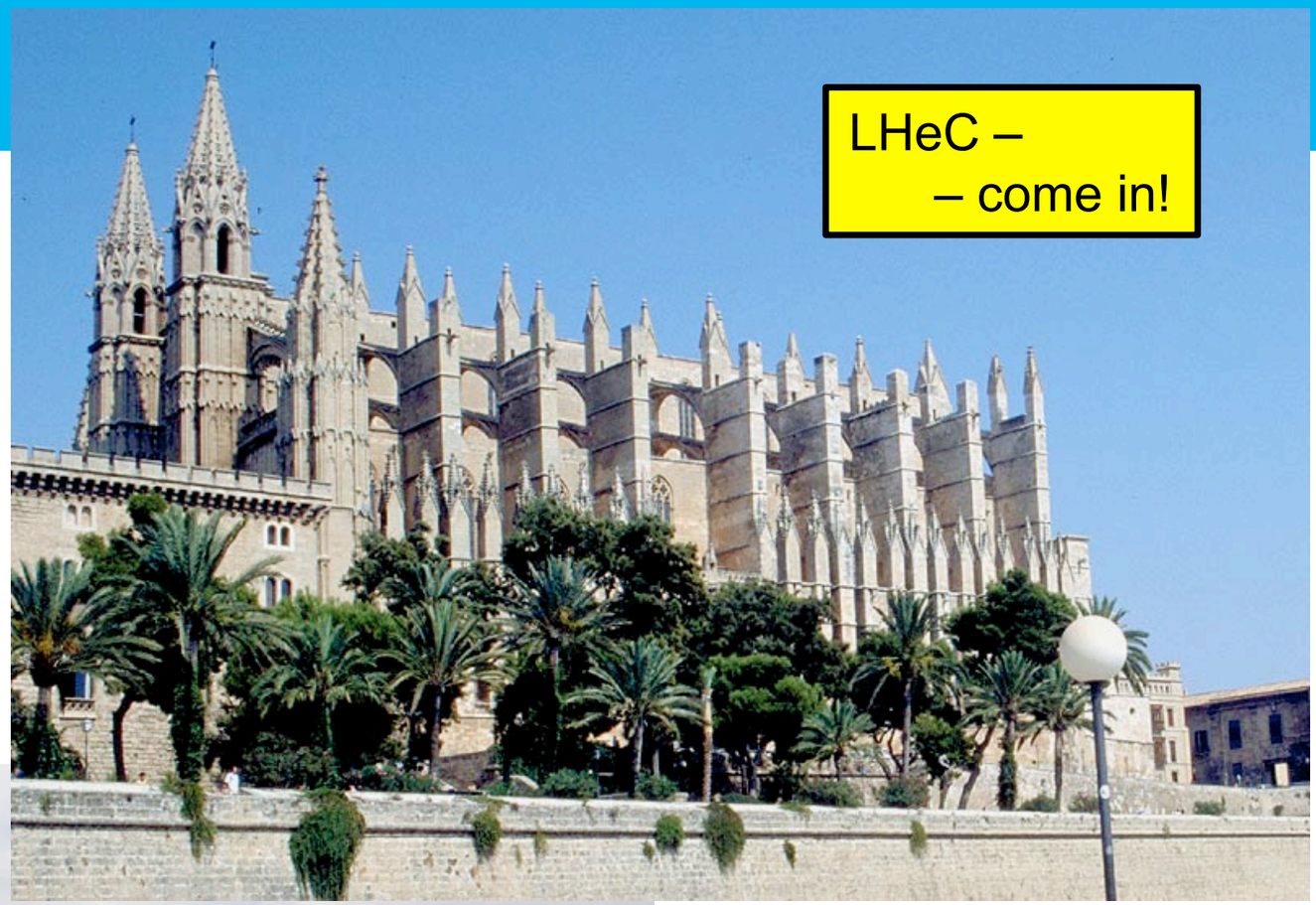
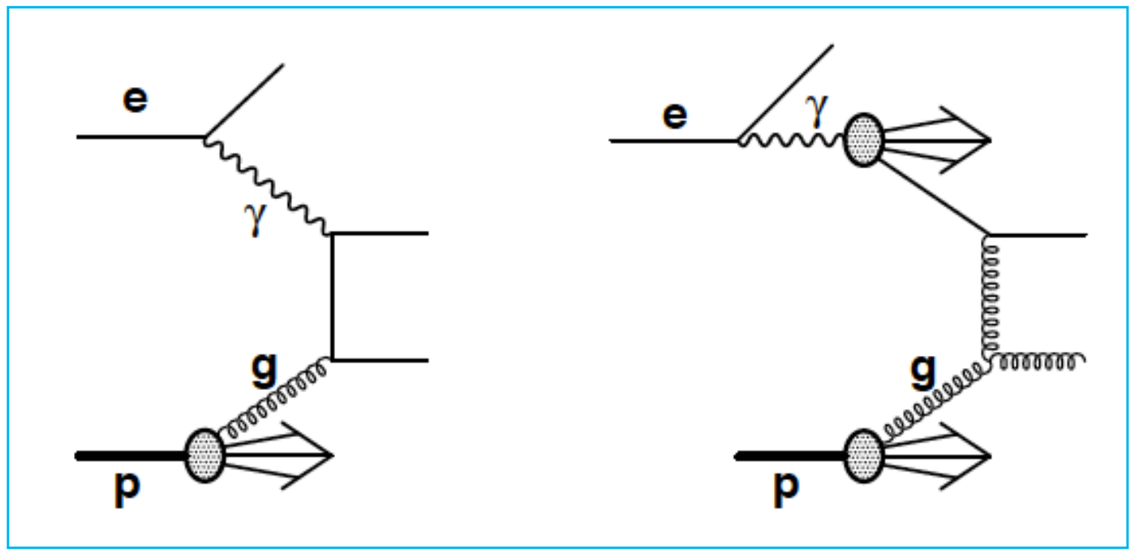
MY WAY TO LHeC



DIS results were obtained > 1 year ago!

INTRODUCTION

- Jet physics in DIS and photoproduction: tests of QCD!
- In leading order $O(\alpha\alpha_S)$:



Proton PDF | Photon PDF | PDF universality

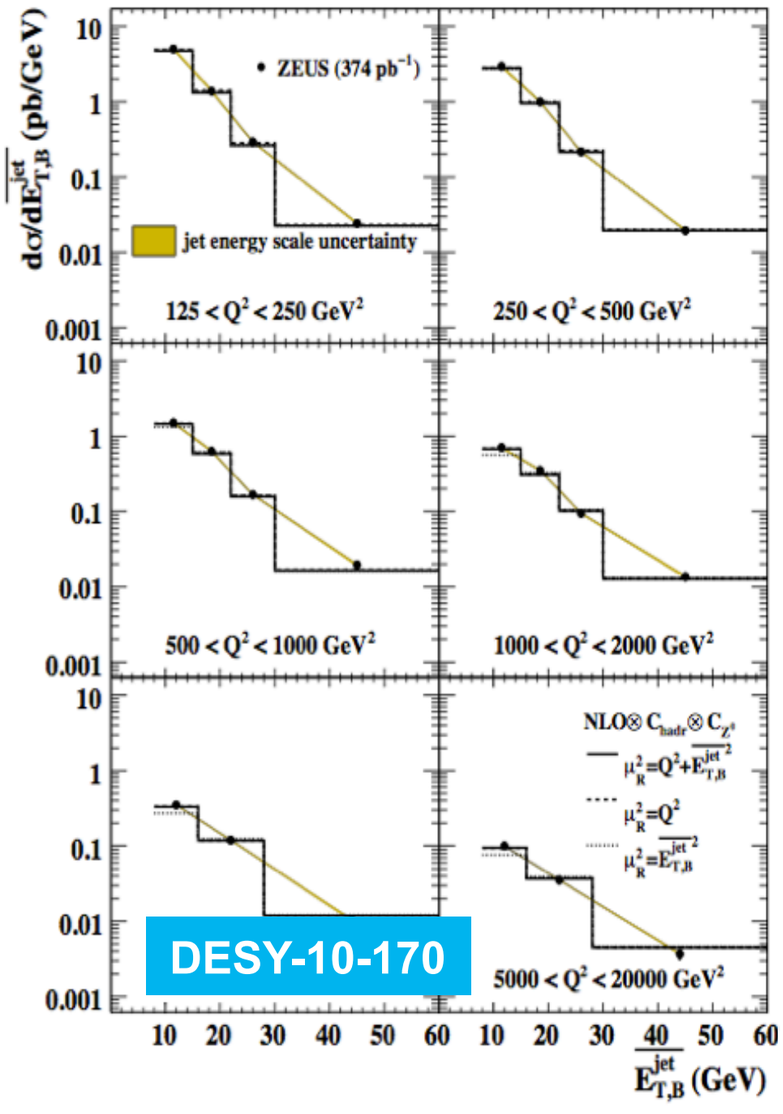
$$\sigma_{jet} = \sum_{n,a,b} \alpha_S^n \cdot f_{a/p} \otimes \hat{\sigma}_{n,a} \otimes f_{b/\gamma} \overset{DIS}{=} \sum_{n,a} \alpha_S^n \cdot f_{a/p} \otimes \hat{\sigma}_{n,a}$$

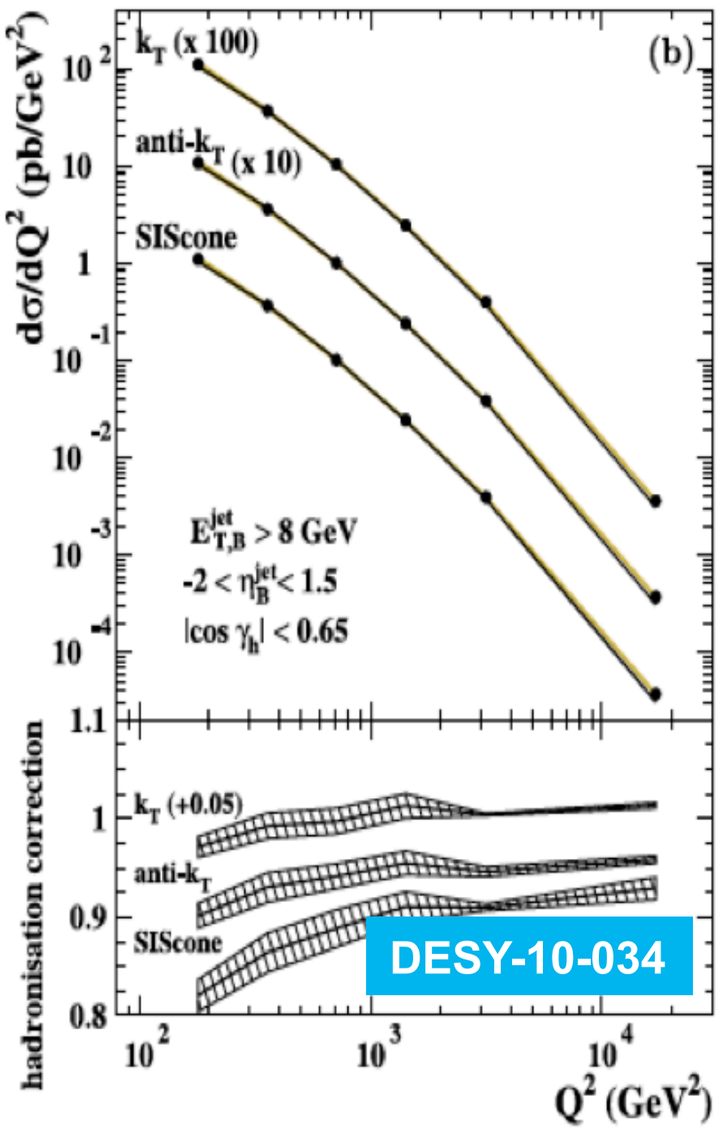
Pert. expansion | Strong coupling | Factorisation

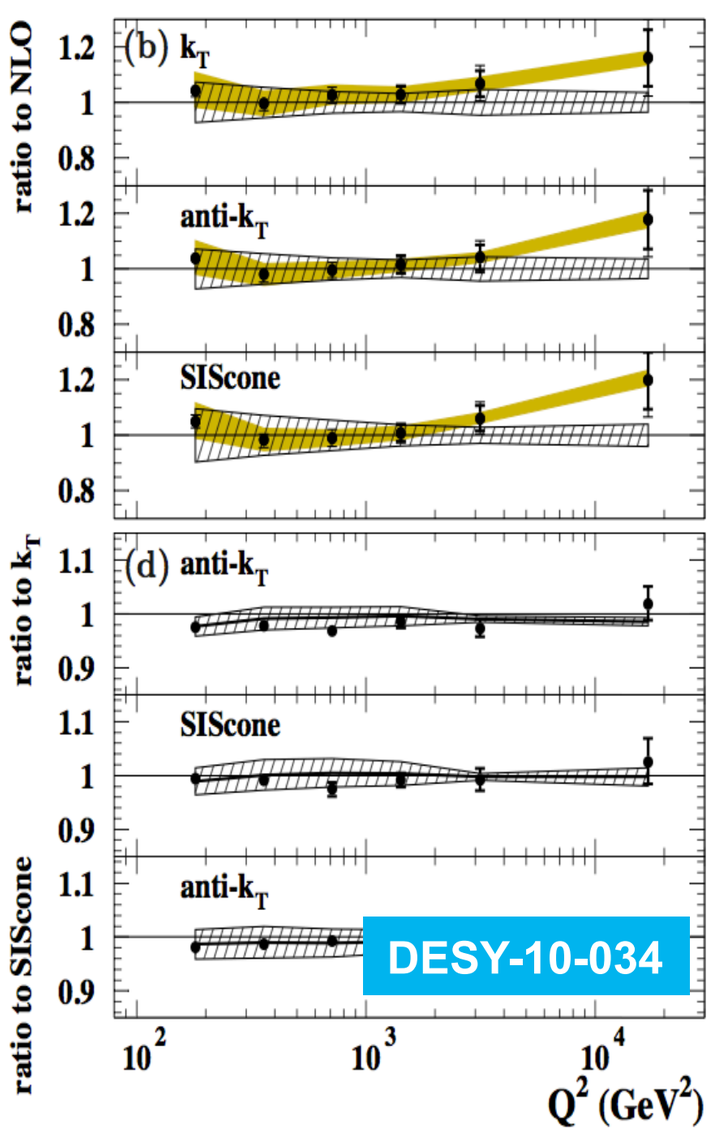
- Many measurements performed → next slide

MEASUREMENTS AT HERA (DIS)

- Numerous high-precision measurements performed in H1 and ZEUS.
  - Many measurements limited by theory (variation of renormalisation scale)!

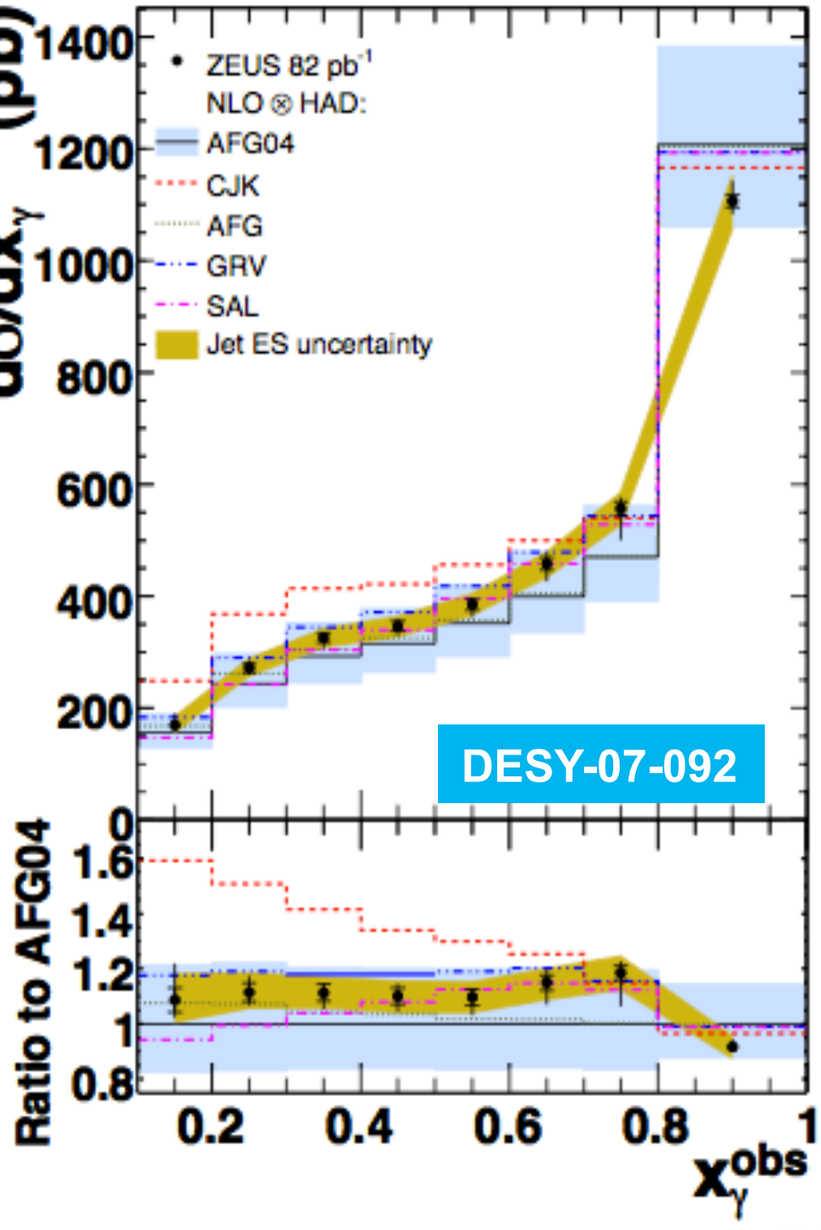






MEASUREMENTS AT HERA (PHP)

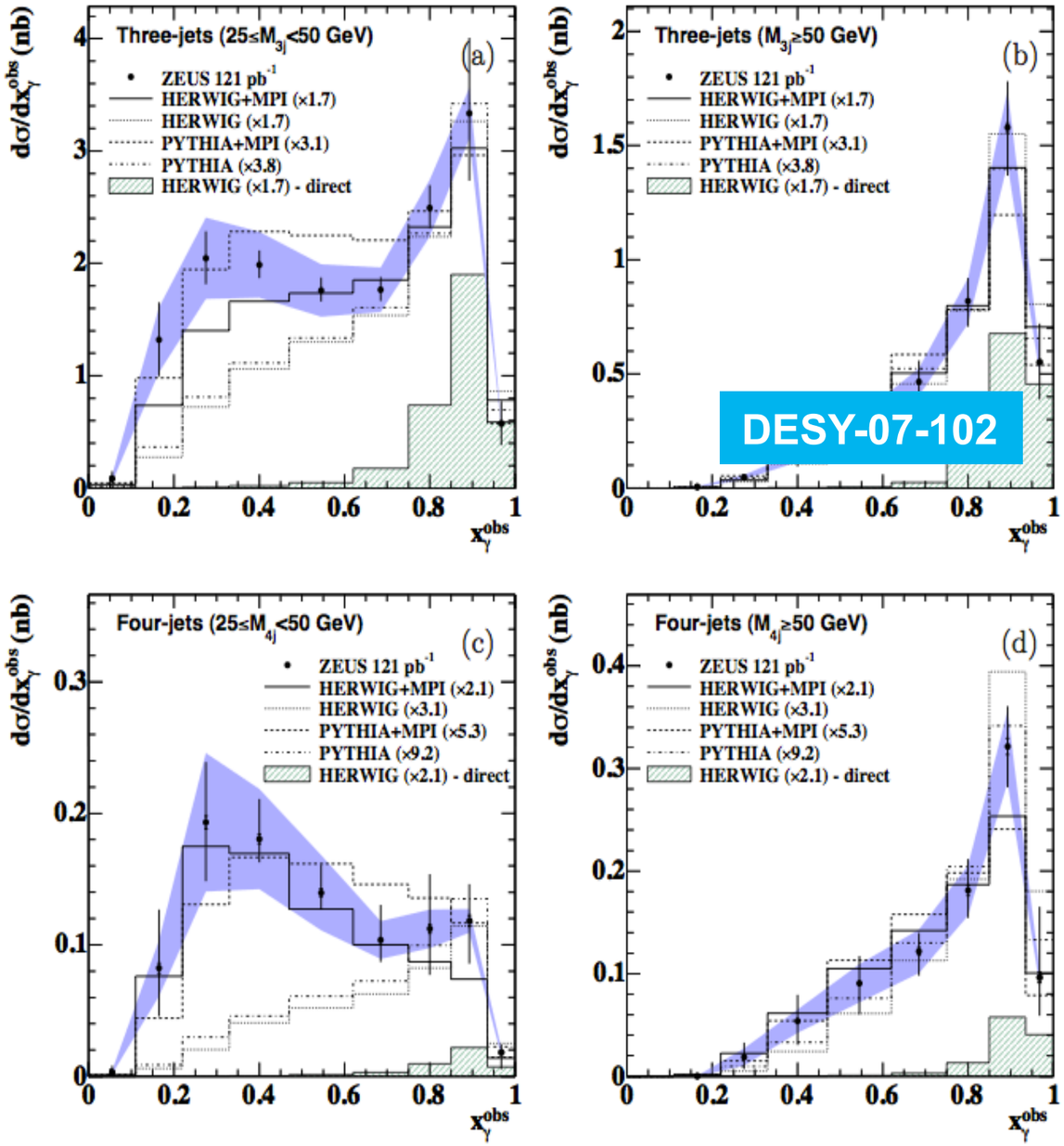
- In PHP, additional complications through photon PDF uncertainty and (at low x_γ) multi-parton interactions / underlying event activity.



- Dijets at high E_T in PHP: Sensitivity to photon PDF at low x_γ.
  - AFG, SAL, GRV differ by 25%, covered by uncertainties.
  - CJK off by up to 60%.
  - Room for improvement, but large potential to constrain photon PDF.

MEASUREMENTS AT HERA (PHP)

- In PHP, additional complications through photon PDF uncertainty and (at low x_γ) multi-parton interactions / underlying event activity.

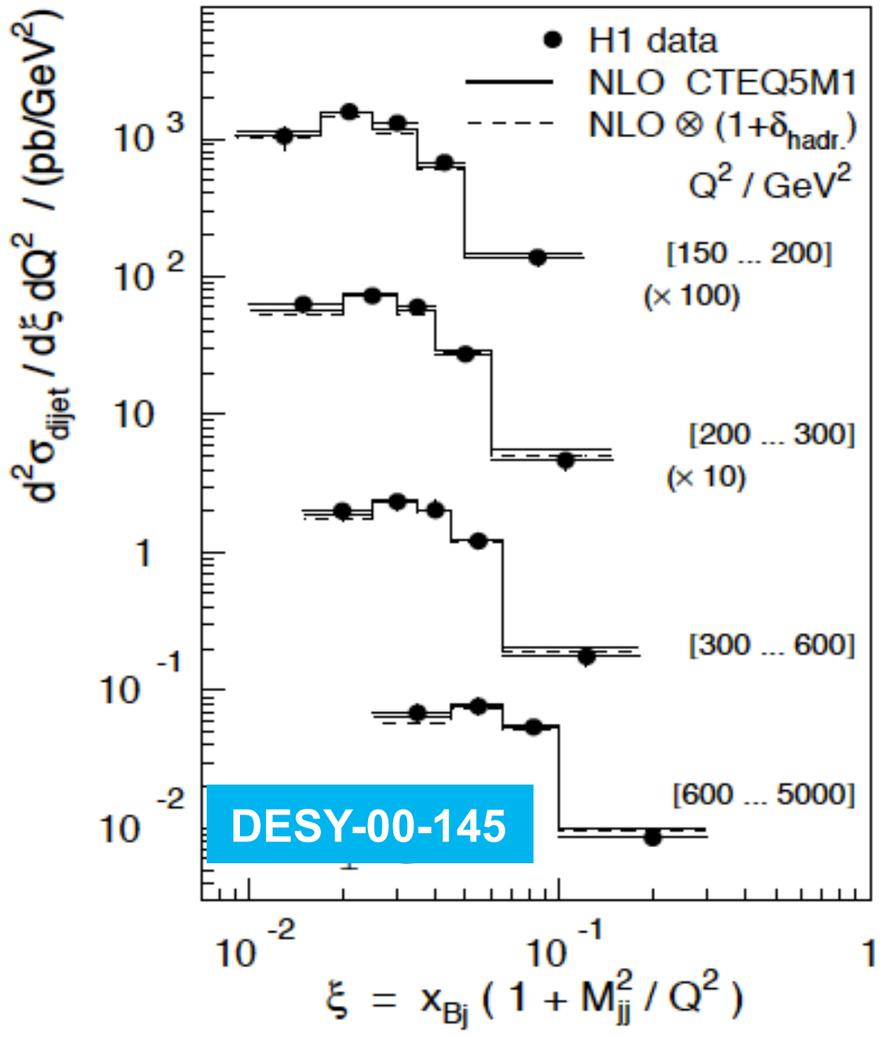


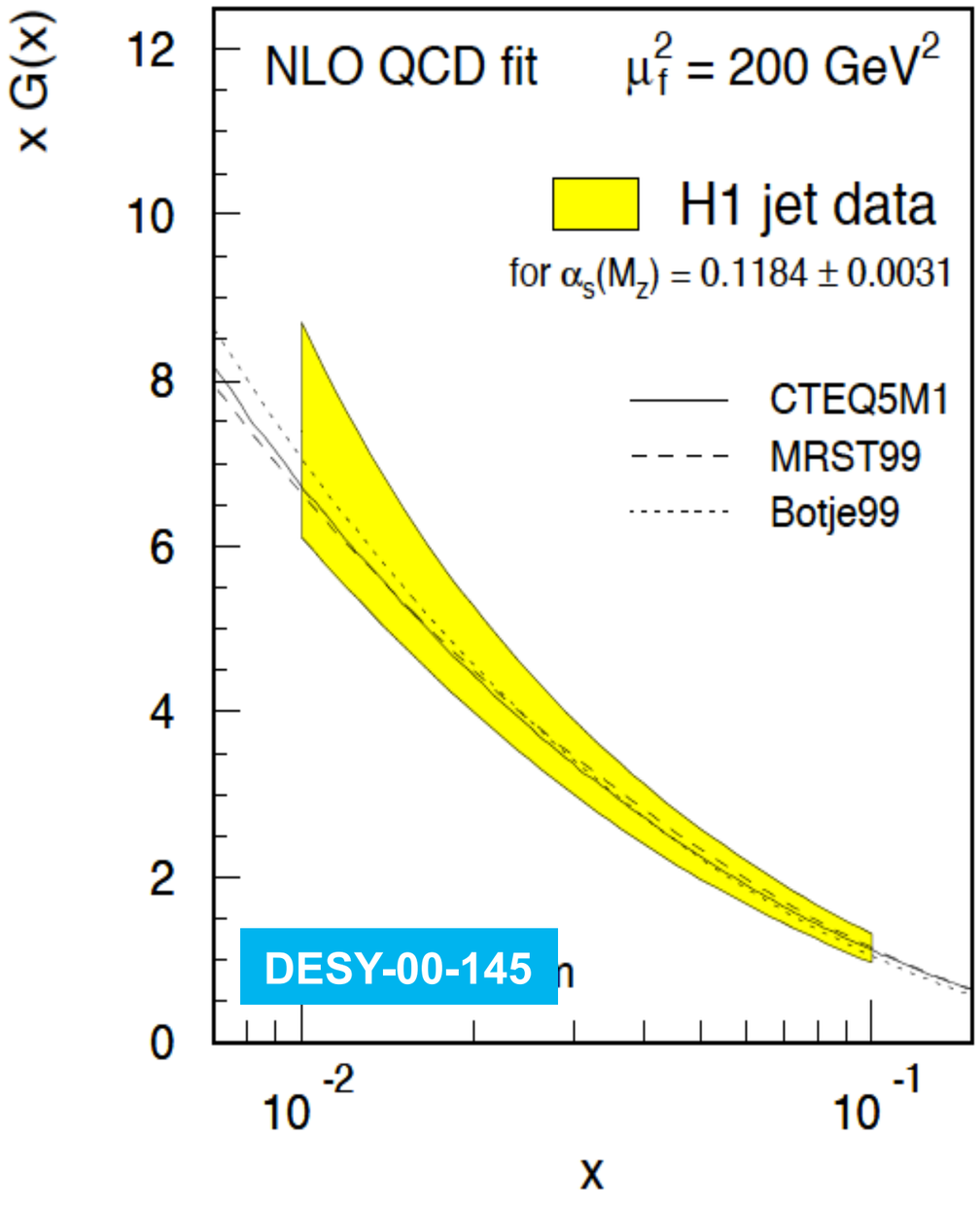
- 3- and 4-jets in PHP:
  - As expected from MPI / UE, large discrepancy between LO MEPS models and data!
  - Effect increased with more activity and with softer final state.
  - MPI/UE modelling situation currently not satisfactory
    ➔ need more input from other measurements.

INFLUENCE ON (PROTON) PDFs (1)

- First idea to improve PDFs using jet data: H1 (2000)

$$\sigma_{jet} = \sum_{n,a,b} \alpha_S^n \cdot f_{a/p} \otimes \hat{\sigma}_{n,a} \otimes f_{b/\gamma}$$





INFLUENCE ON (PROTON) PDFs (2)

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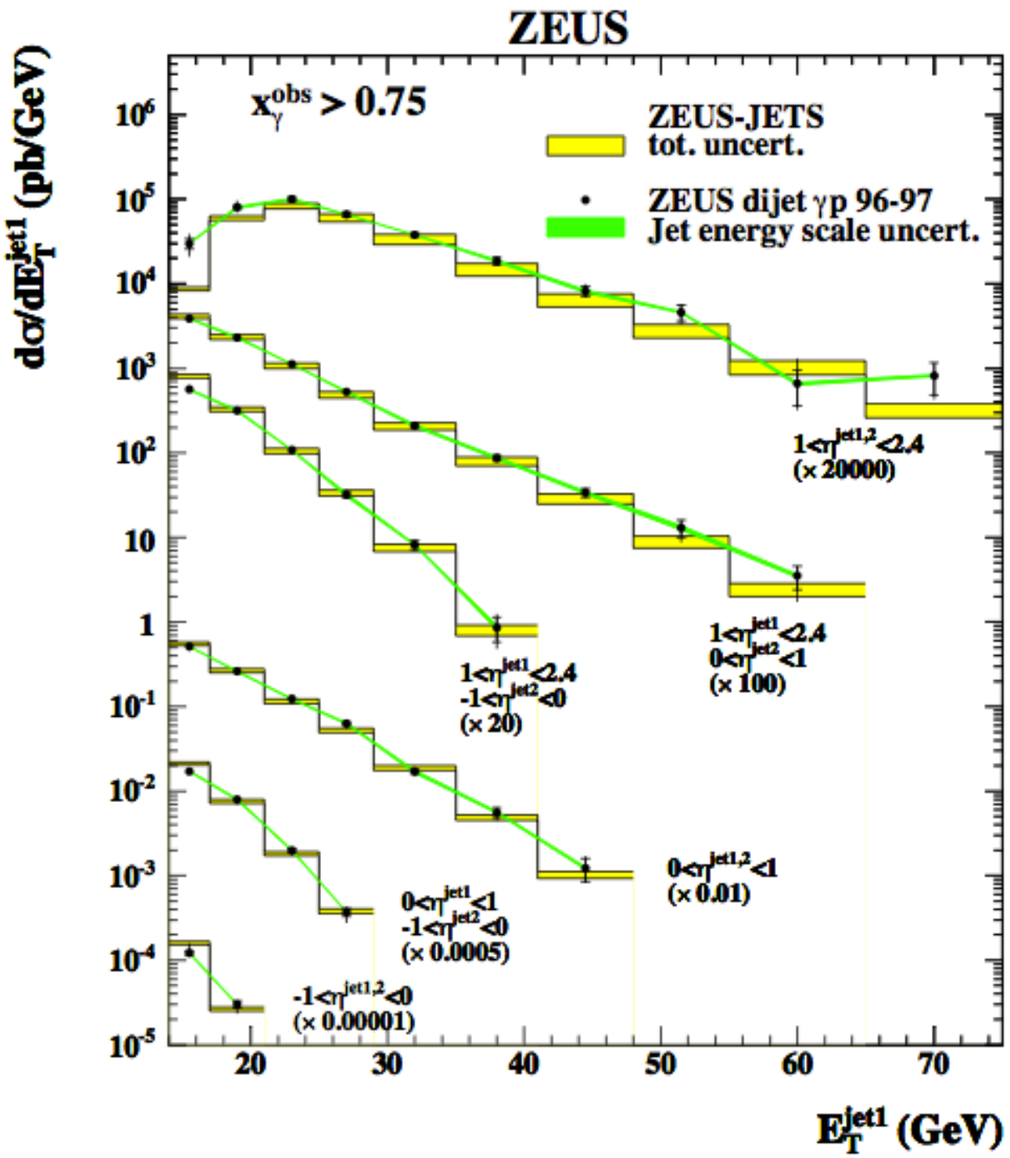
$$\sigma_{jet} = \sum_{n,a,b} \alpha_S^n \cdot f_{a/p} \otimes \hat{\sigma}_{n,a} \otimes f_{b/\gamma}$$

- ZEUS (2007): Use of PHP dijet and DIS inclusive-jet cross sections in ZEUS-S PDF fit.



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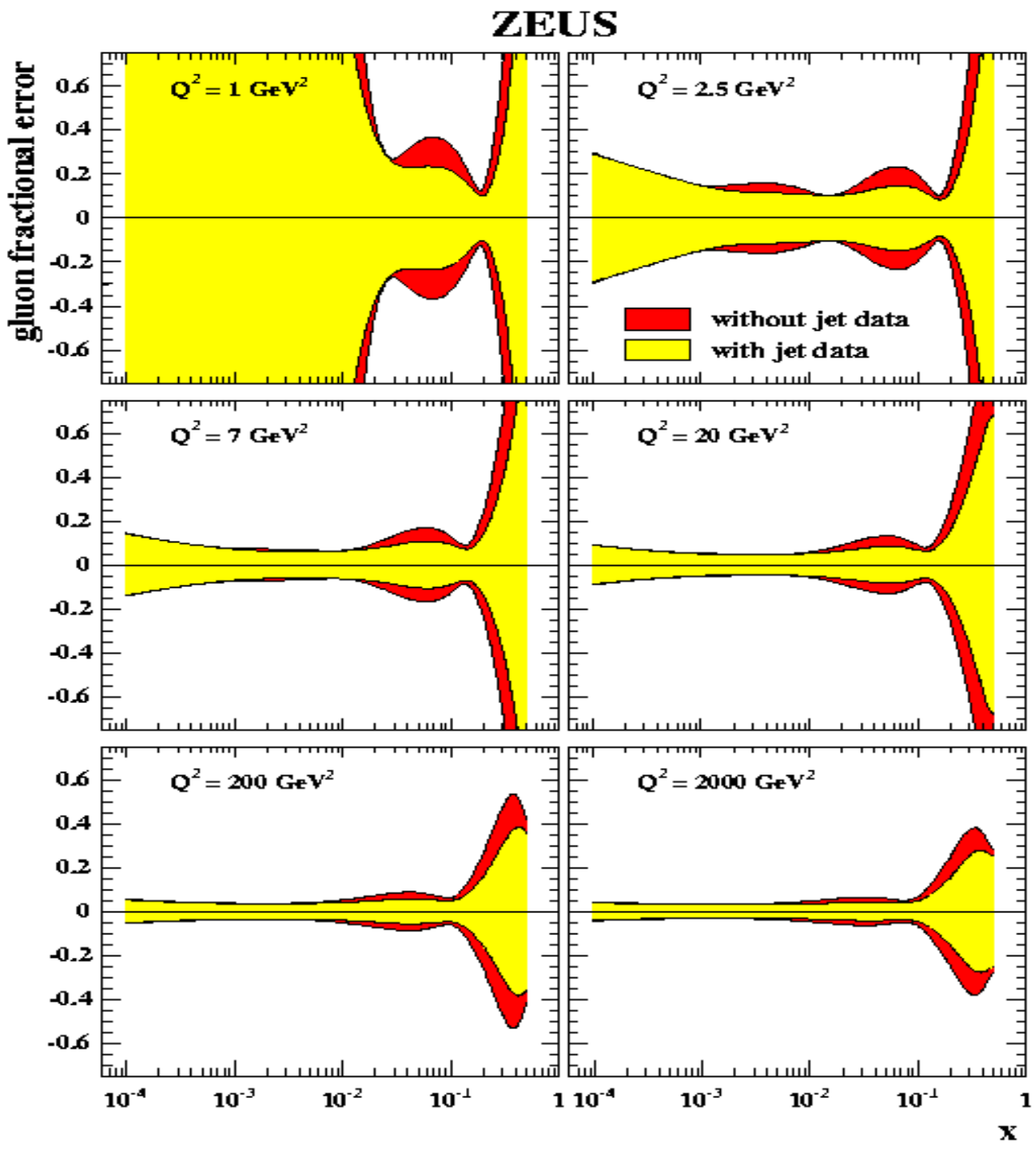
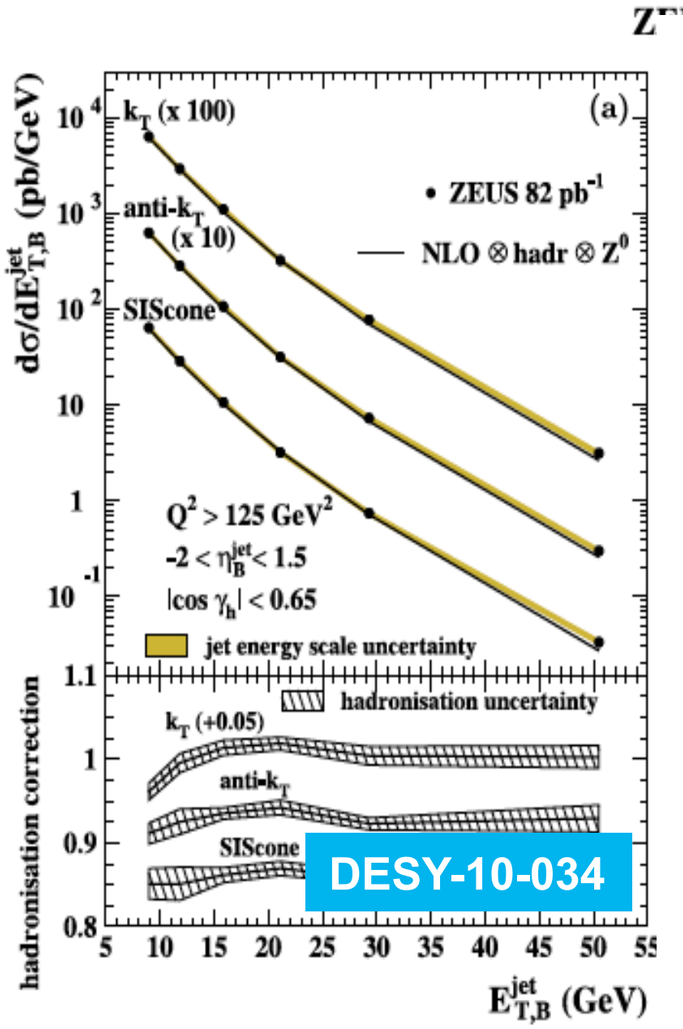
$$\sigma_{jet} = \sum_{n,a,b} \alpha_S^n \cdot f_{a/p} \otimes \hat{\sigma}_{n,a} \otimes f_{b/\gamma}$$

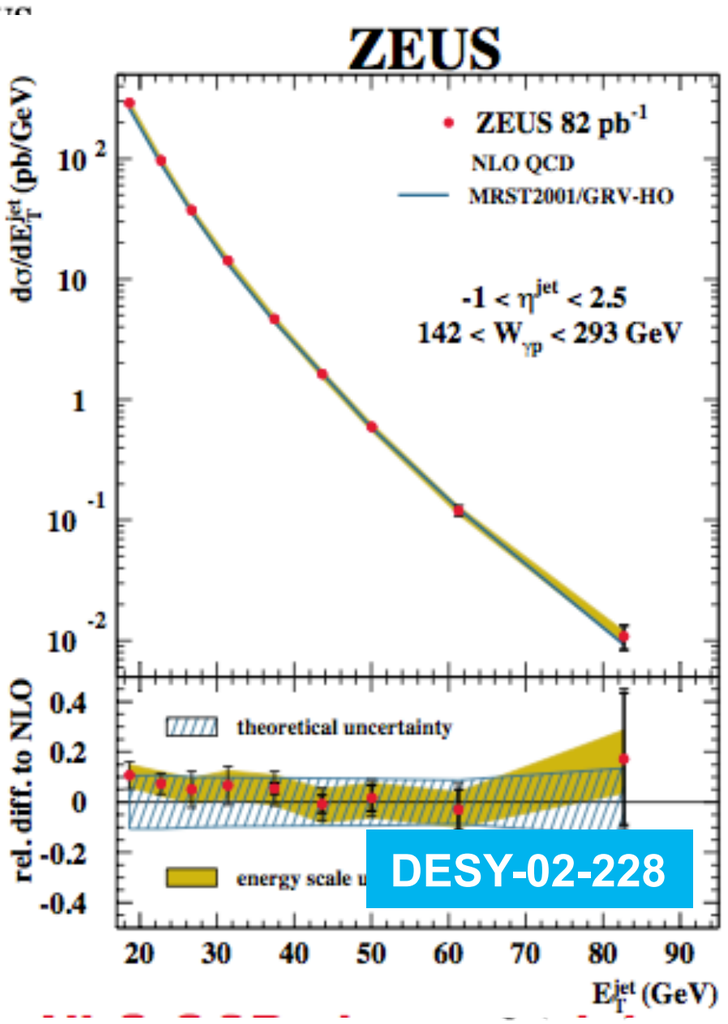
- ZEUS (2007): Use of PHP dijet and DIS inclusive-jet cross sections in ZEUS-S PDF fit.
- Significant improvement of gluon density uncertainty at medium and high x:
  - Reduction of uncertainty of up to 30% or so.
  - Playing around with additional HERA data sets to further improve uncertainties.



INFLUENCE ON STRONG COUPLING (1)

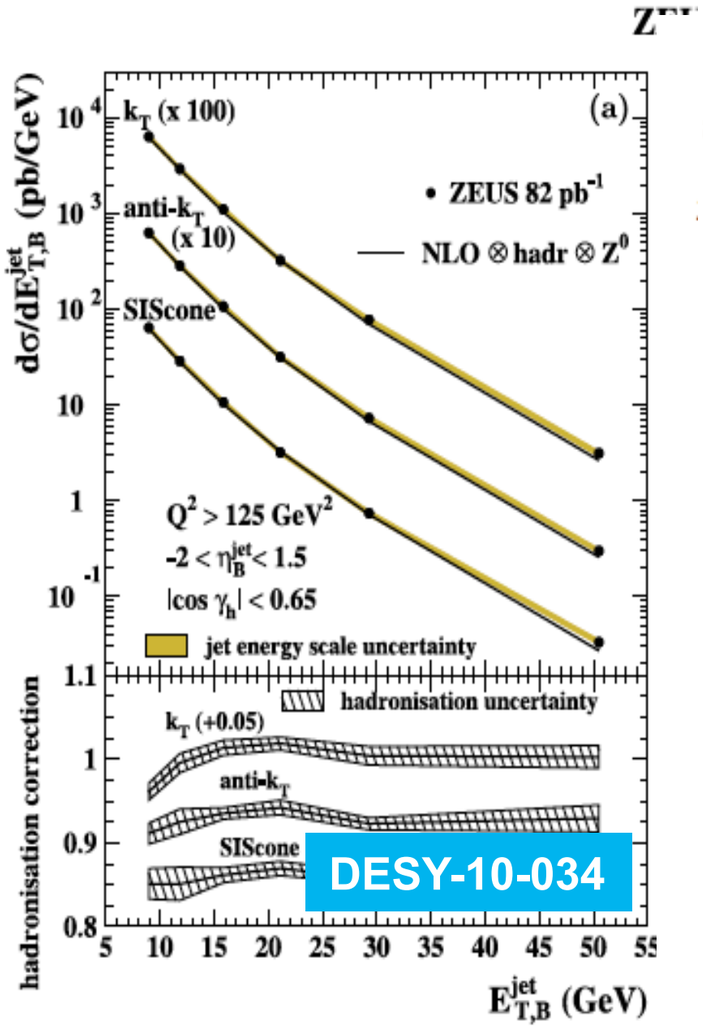
- Presently fixed-order calculations available up to NLO
  - For inclusive-jet, dijet ($O(\alpha_S^2)$) and trijets (in DIS, ($O(\alpha_S^3)$)).

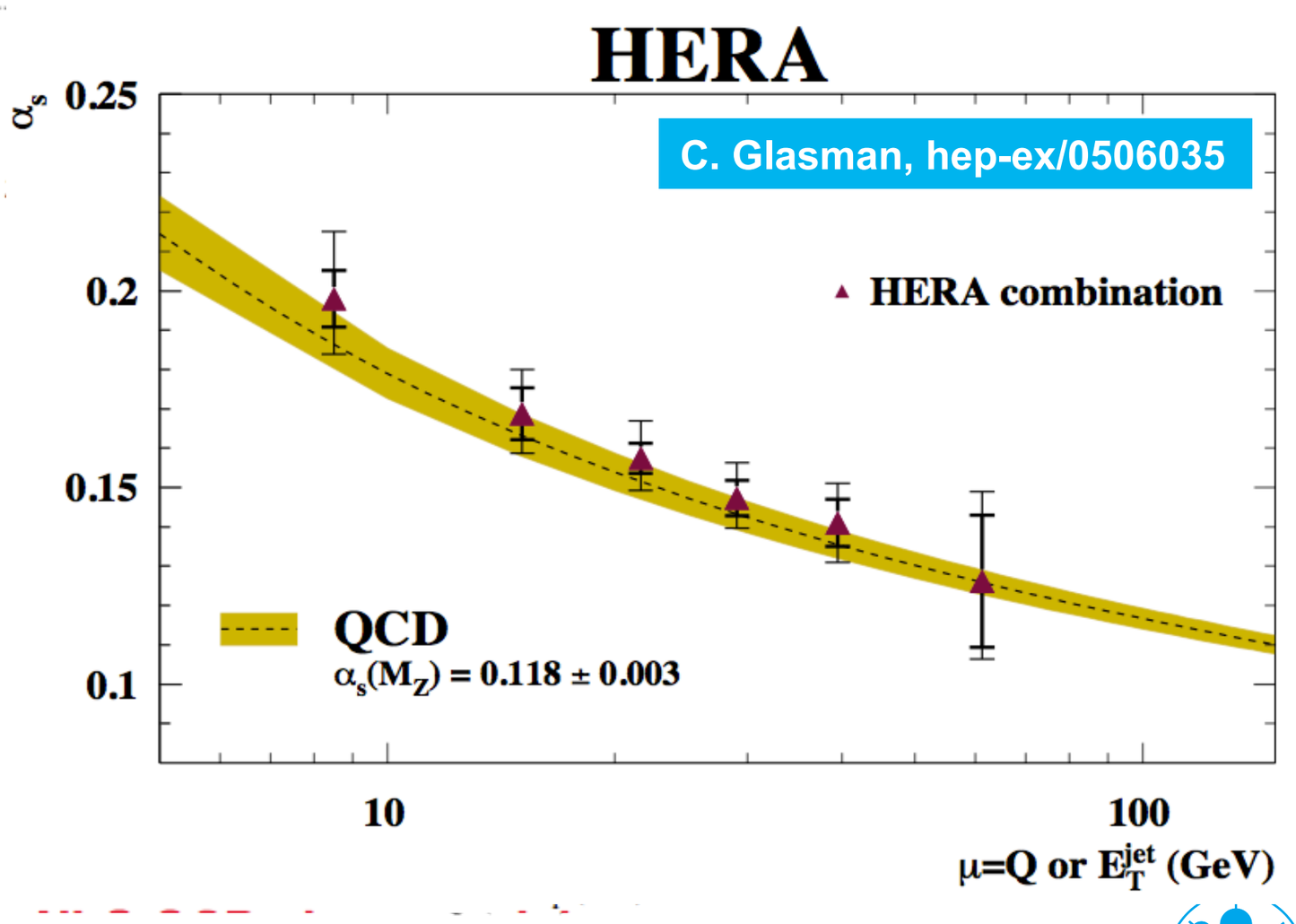




INFLUENCE ON STRONG COUPLING (2)

- Presently fixed-order calculations available up to NLO
  - For inclusive-jet, dijet ($O(\alpha_S^2)$) and trijets (in DIS, ($O(\alpha_S^3)$)).
- Allows high-precision extraction of strong coupling at HERA





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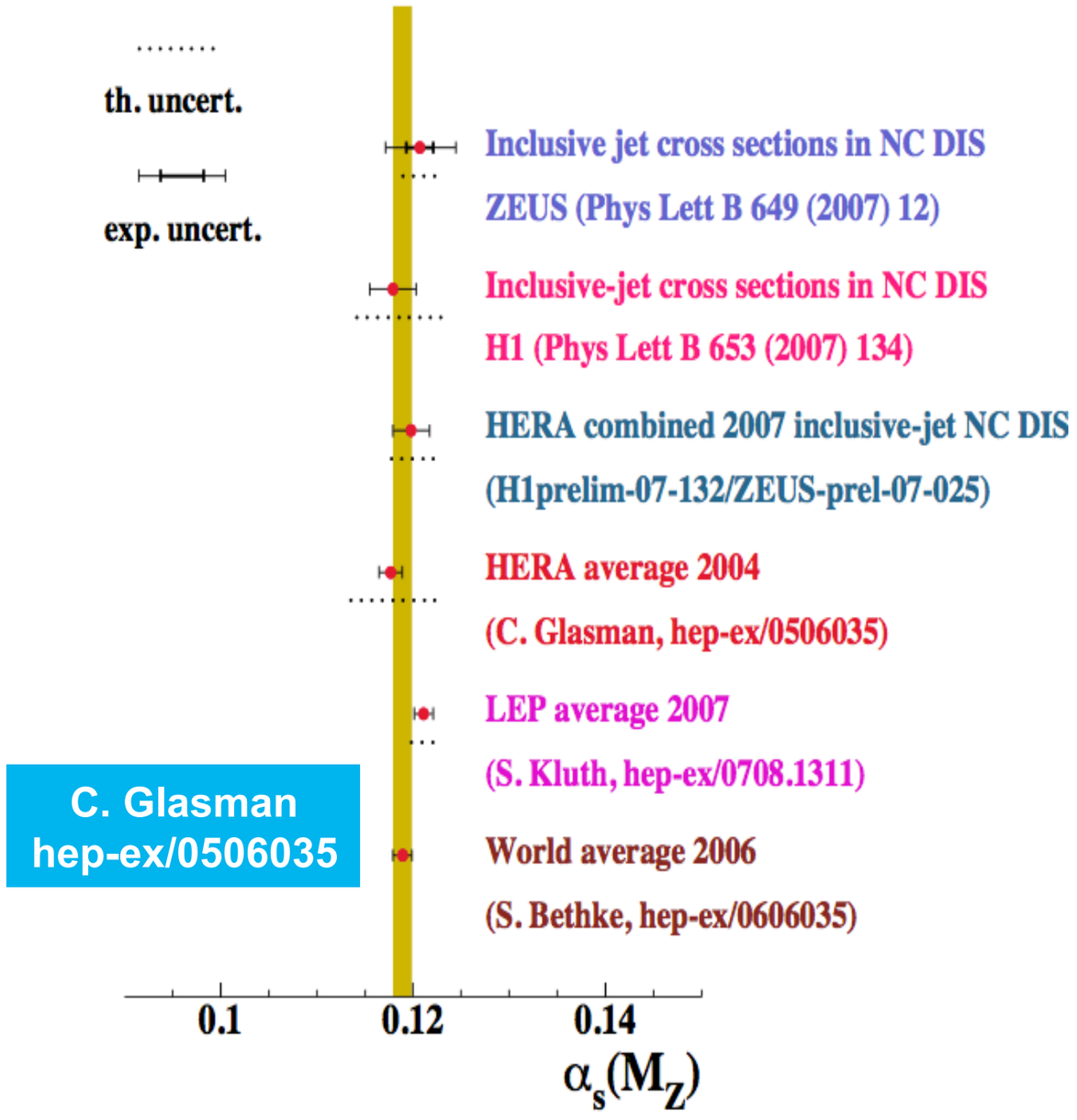
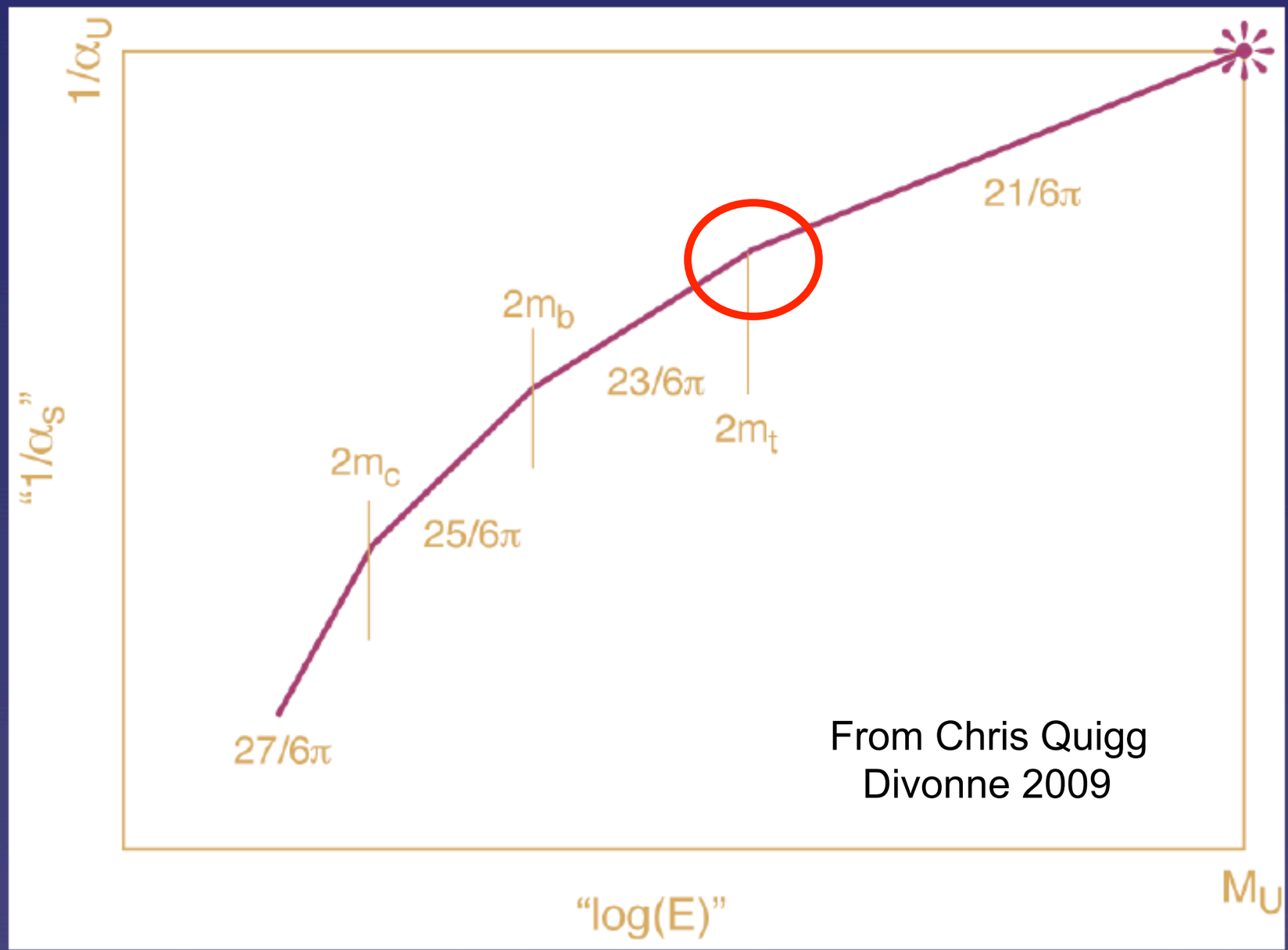


C. Glasman hep-ex/0506035

- Consistent and competitive!
- Excellent confirmation of QCD expectations.
- Potential at HERA for further improvement:
  - Jet energy scale? (1/3%)
  - NNLO calculations!

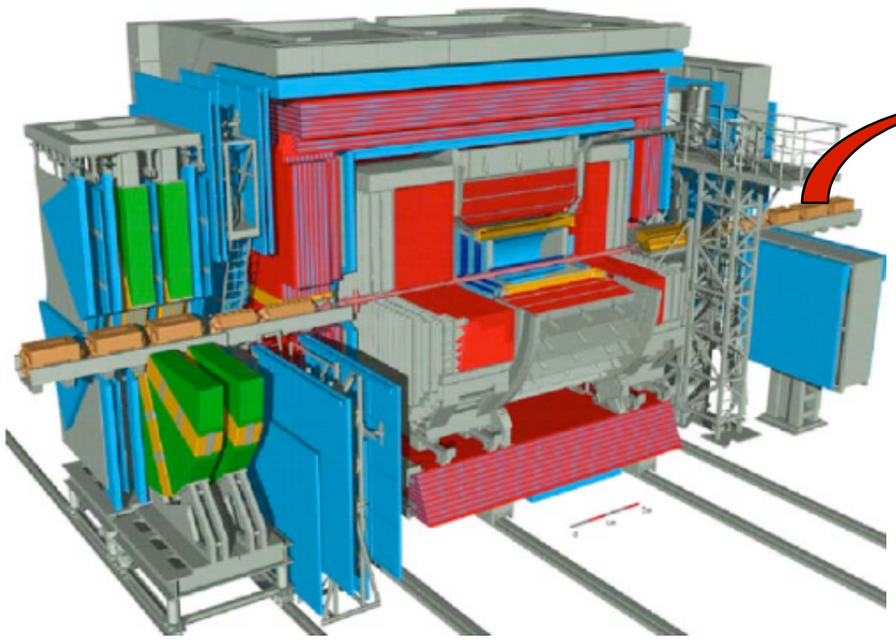
INTRODUCTION

Measure change in slope at top threshold?



From Chris Quigg
Divonne 2009

HERA AND LHeC SCENARIOS



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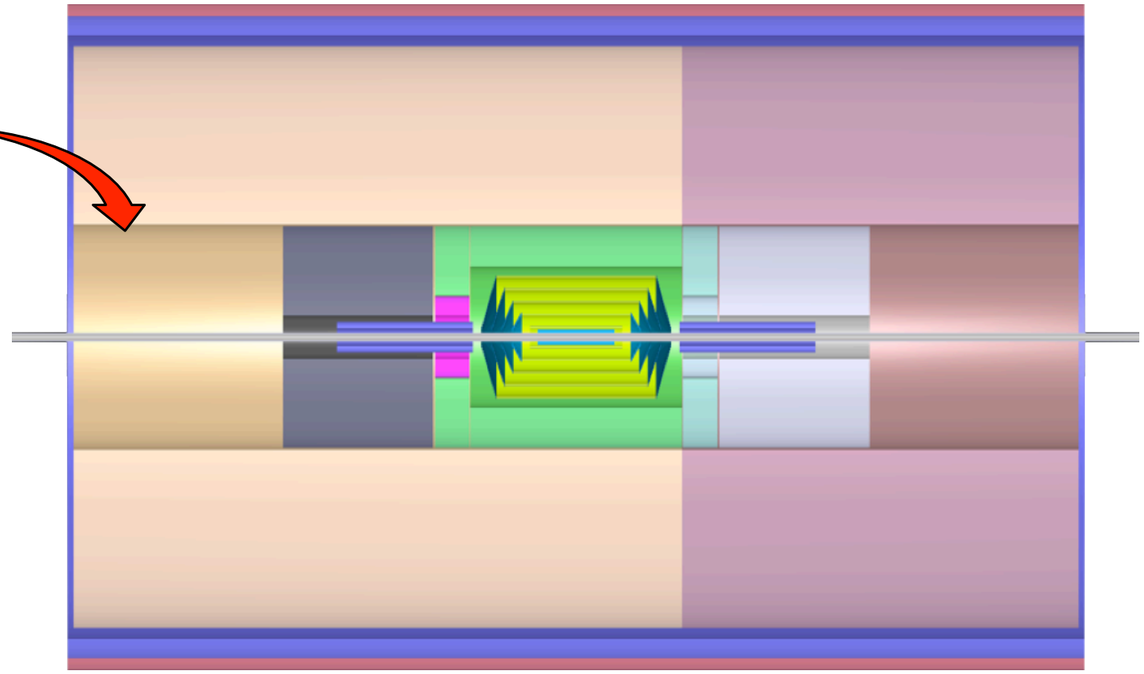
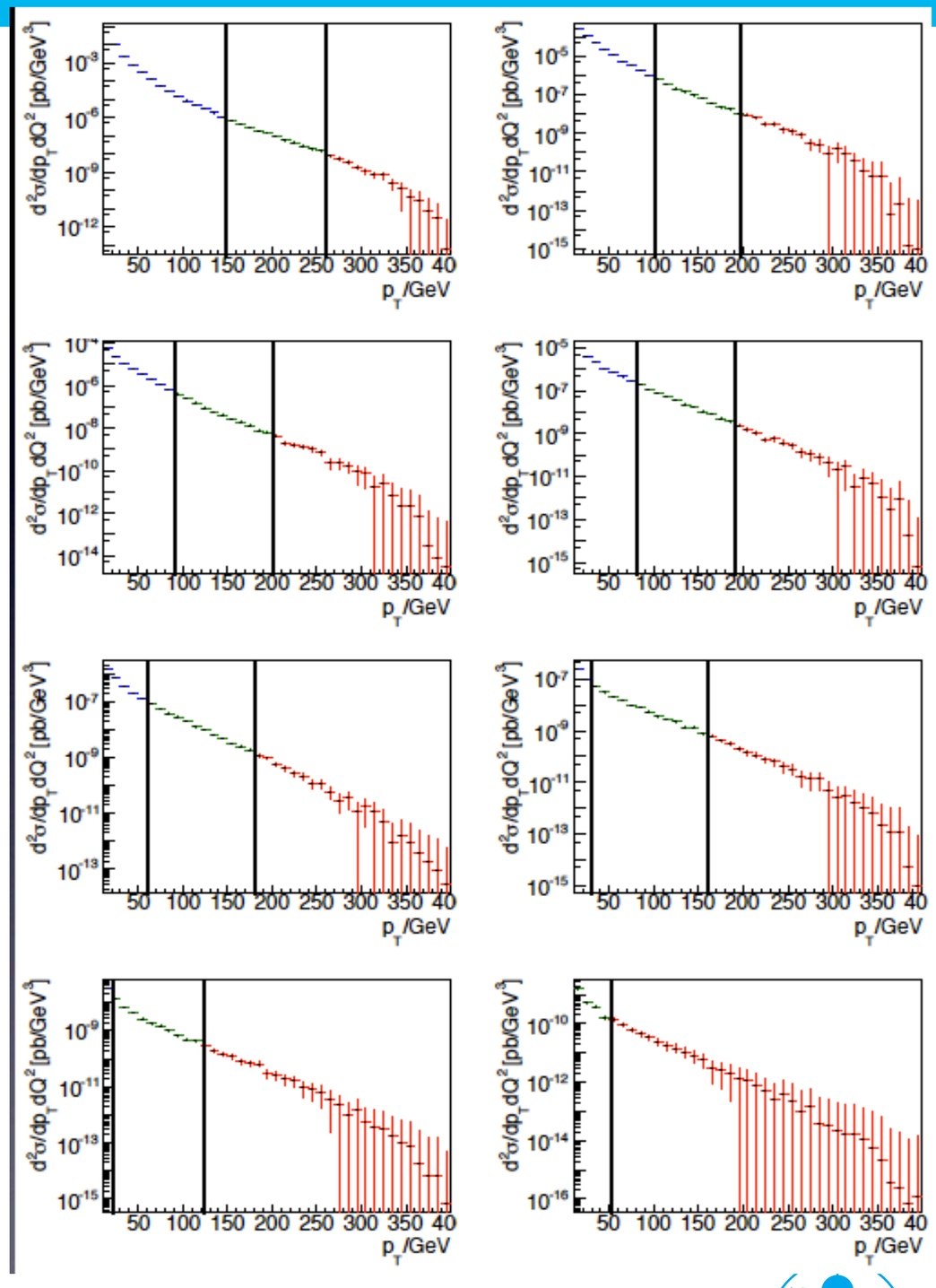


DIS	*PHP*
$\sqrt{s} = 318$ GeV	$\sqrt{s} = 318$ GeV
$Q^2 > 125$ GeV^2	$Q^2 \approx 0$
$E_{T,Breit} > 8$ GeV	$E_T > 14$ GeV
$-1 < \eta_{lab} < 2.5$	$-1 < \eta < 2.5$

DIS	PHP
$E_{p/e} = 7000/70(50)$ GeV	$E_{p/e} = 7000/50-150$ GeV
$\sqrt{s} = 1400$ GeV	$\sqrt{s} = 1183-2049$ GeV
$Q^2 > 100$ GeV^2	$Q^2 \approx 0$
$E_{T,Breit} > 20$ GeV	$E_T > 15$ GeV
$-2 < \eta_{lab} < 3$	$-3 < \eta_{lab} < 3$

DIS JET STUDIES (T. Kluge et al.)

- Study by T. Kluge et al.:
  - 0.001 experimental precision on α_S from inclusive data alone possible!
  - Challenge for theory!
  - Angular acceptance of detector crucial; also low E_p runs help!
- Study of influence of jet data
  - inclusive jets, 5 – 640000 GeV^2
  - 200 fb^{-1}, bins of 10 GeV
    blue: <1% stat. error
    green: 1-10% stat. error
    blue: >10% stat. error



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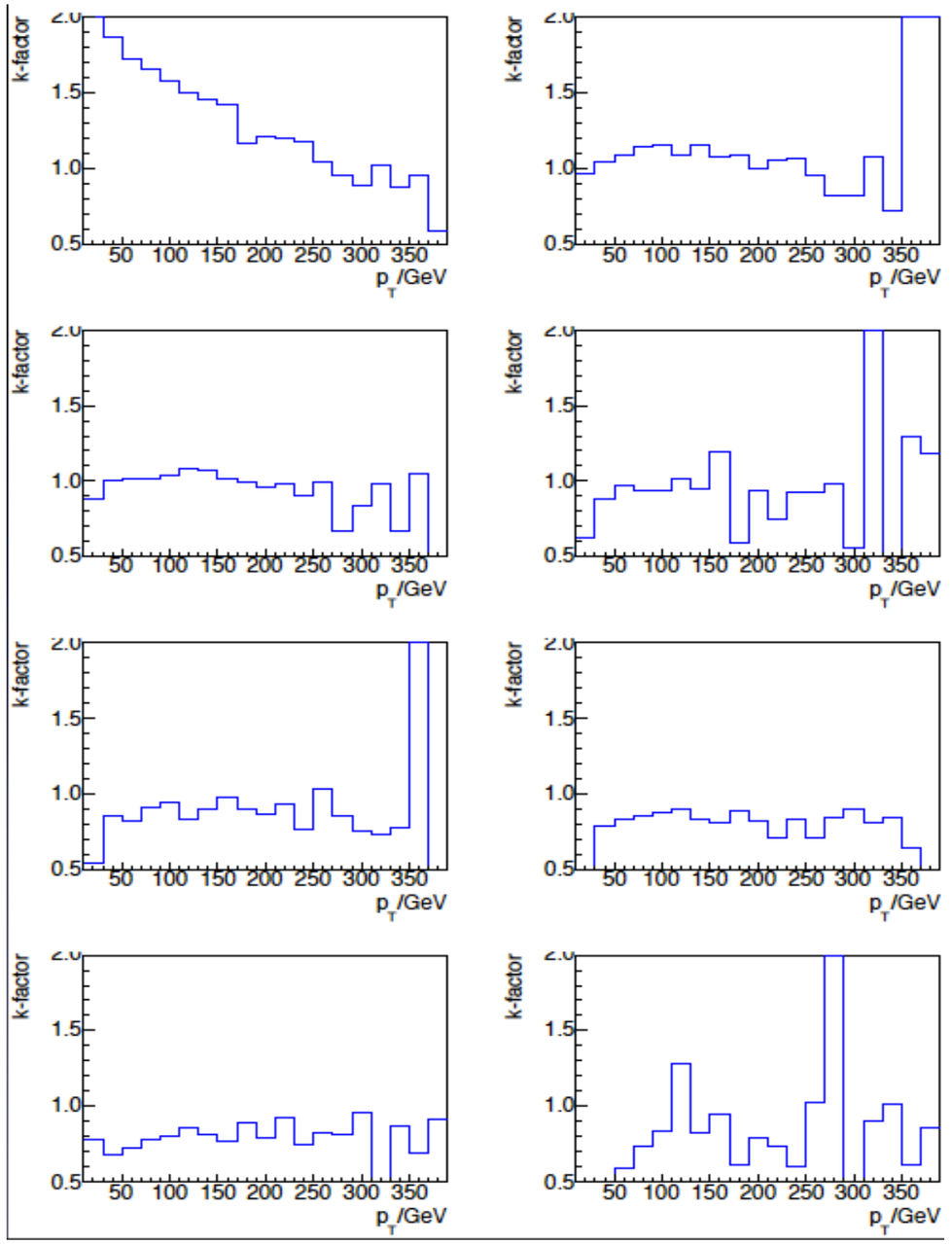
- K factors (NLO/LO) stable
  - Trust NLO calculations (NLOJET++)



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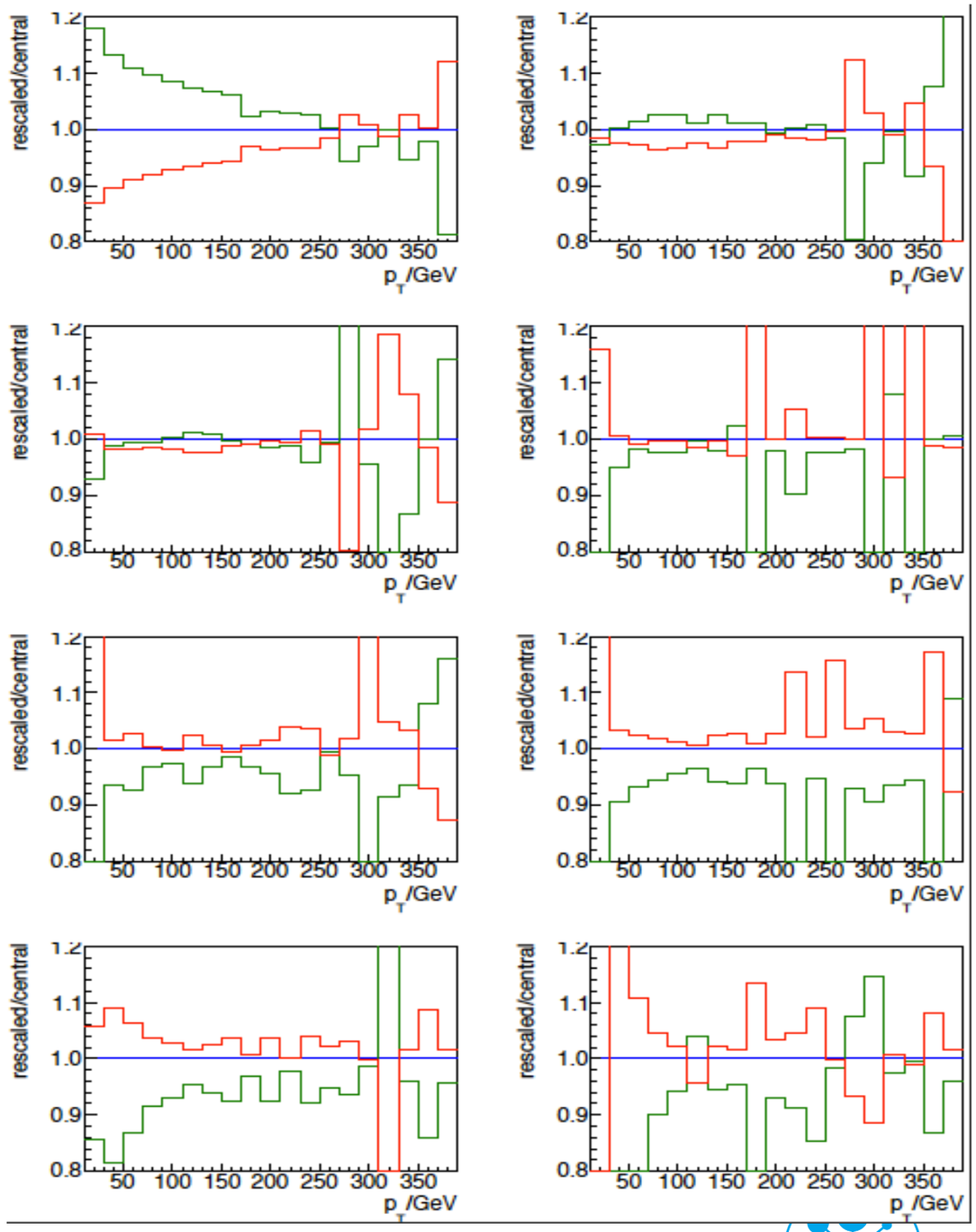
- K factors (NLO/LO) stable
  - Trust NLO calculations (NLOJET++)
- Scale uncertainty:
  - Consistent with TSS. NNLO???



DIS: CALCULATIONS AND SELECTION

- Calculations performed with DISENT using
  - CTEQ6.1 PDFs
  - $\mu_R = \mu_F = Q$.
- Corrections: Predictions were correct for Z^0 exchange and hadronisation (so plots at “hadron level”).
  - LEPTO LO ME+PS MC
- Inclusive Phase space:
  - $100 < Q^2 < 500.000\ \mathrm{GeV}^2$
  - $0.1 < y < 0.7$
- Jets: inclusive k_T algorithm in the Breit frame
  - $-2 < \eta_{lab} < 3$
  - Inclusive jets: $E_T > 20$ GeV
  - Dijets: slightly asymmetric cut: $E_{T1(2)} > 25(20)$ GeV; still some convergence problems at lot M_{jj} (NLO problem?)

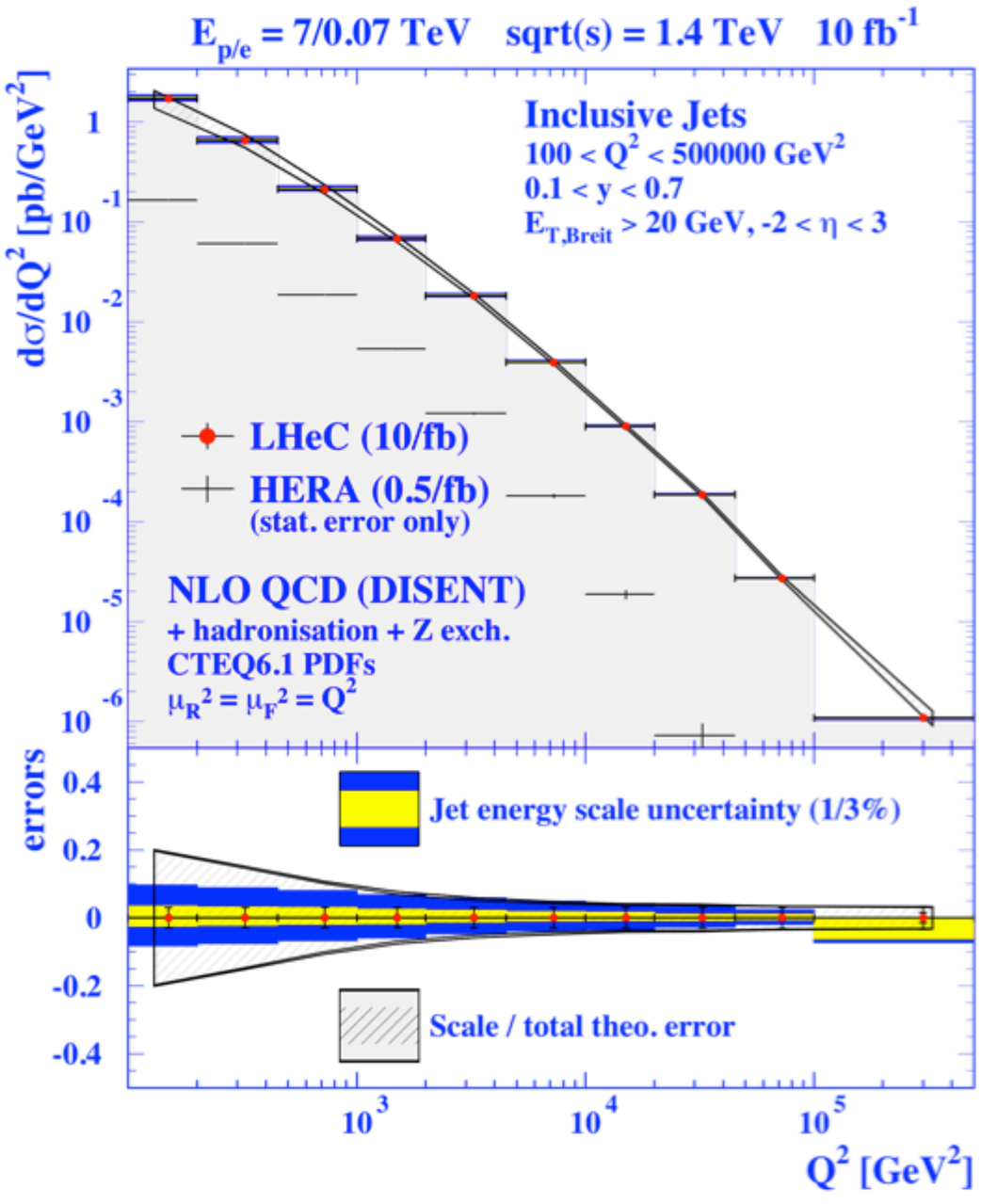
DIS: UNCERTAINTIES

- Scale uncertainty: μ_R varied by factor 2 up and down → dominant!
- PDF uncertainty: evaluated using 40 error sets from CTEQ6.1
- α_S: evaluated using CTEQ6AB and scaling to world average error (0.001 from Bethke).

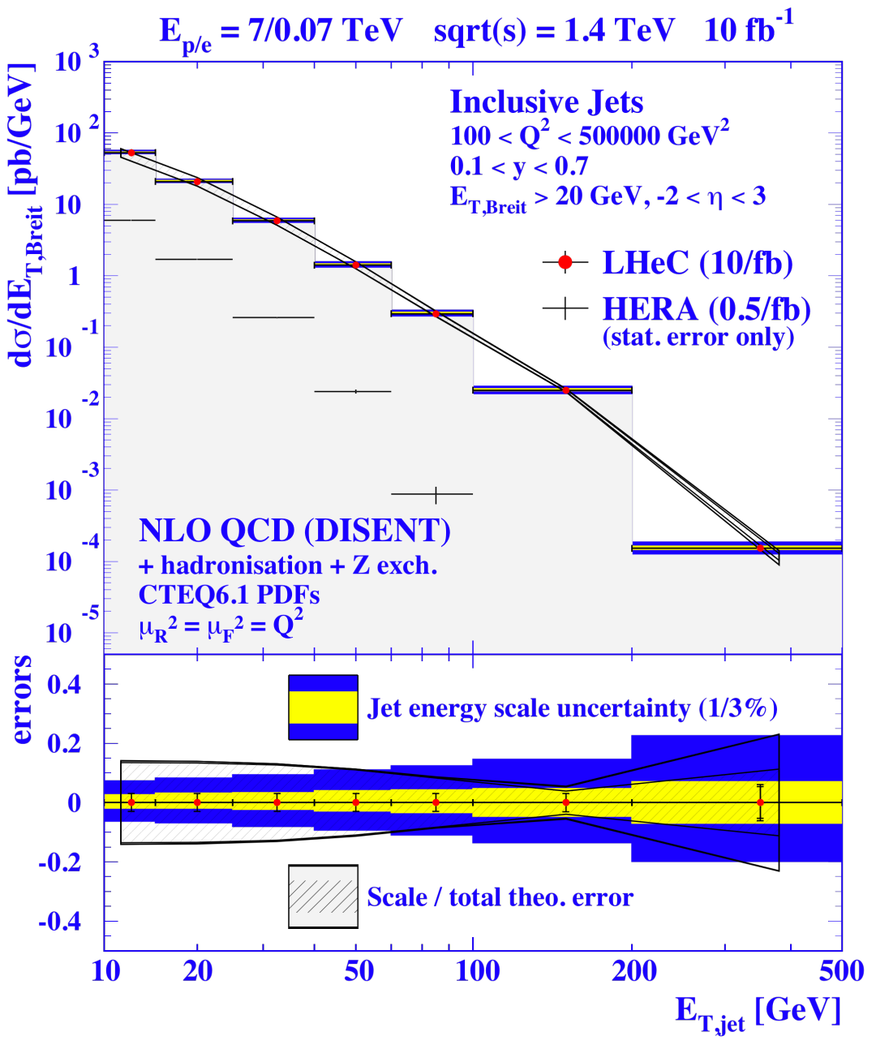
- Statistical uncertainty: assuming 10 fb^{-1}. Can mostly be neglected (maximally 10% at highest scales).
- Systematics:
  - Jet energy scale, indicated as coloured bands (plus/minus 1 and 3%) → dominant experimental uncertainty.
  - Model uncertainty: 3% throughout (→ not very realistic?).

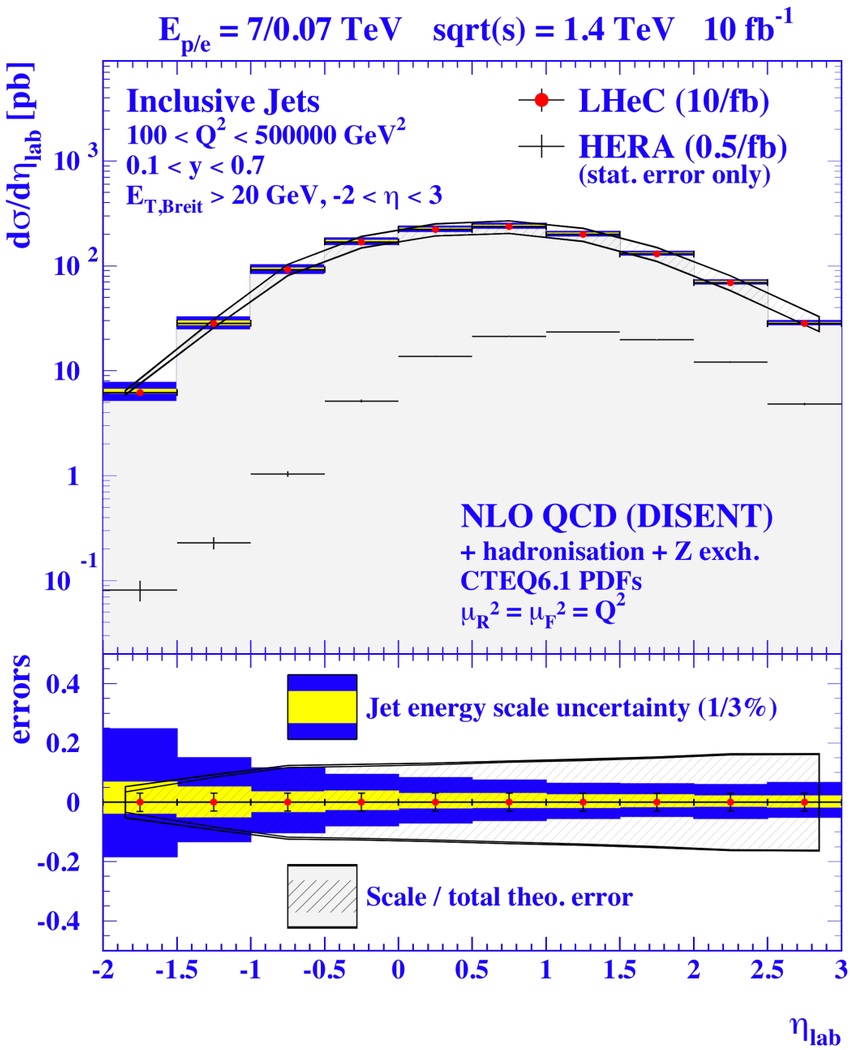
INCLUSIVE DIS JETS: Q^2

- Small Q^2 (and x):
  - Theory error dominates;
  - Total exp. uncertainty 10%.
- Cross section
  - 1-2 orders of magnitude larger than at HERA at same kinematic point.
- Theory error driven by scale uncertainty
  - Variation of renormalisation scale by traditional factor of 2 up/down. (see remarks on NNLO theory later!)
  - Potential for PDF constraints????



INCLUSIVE DIS JETS: $E_{T,Breit}$ AND η_{lab}

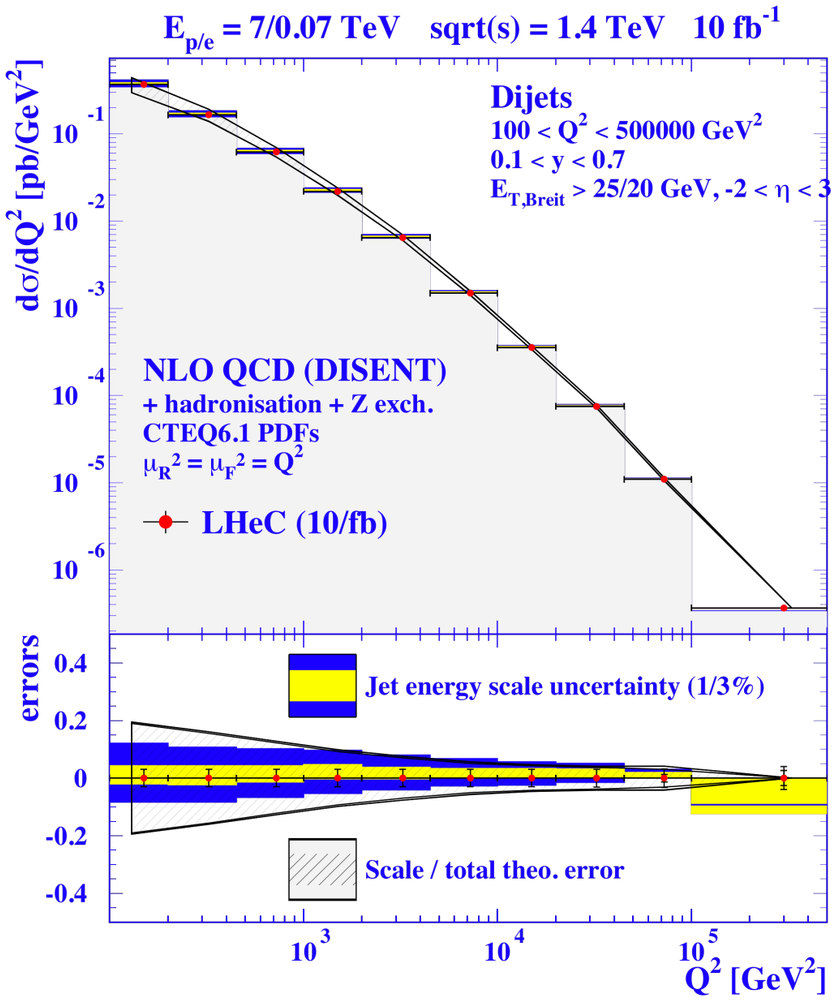


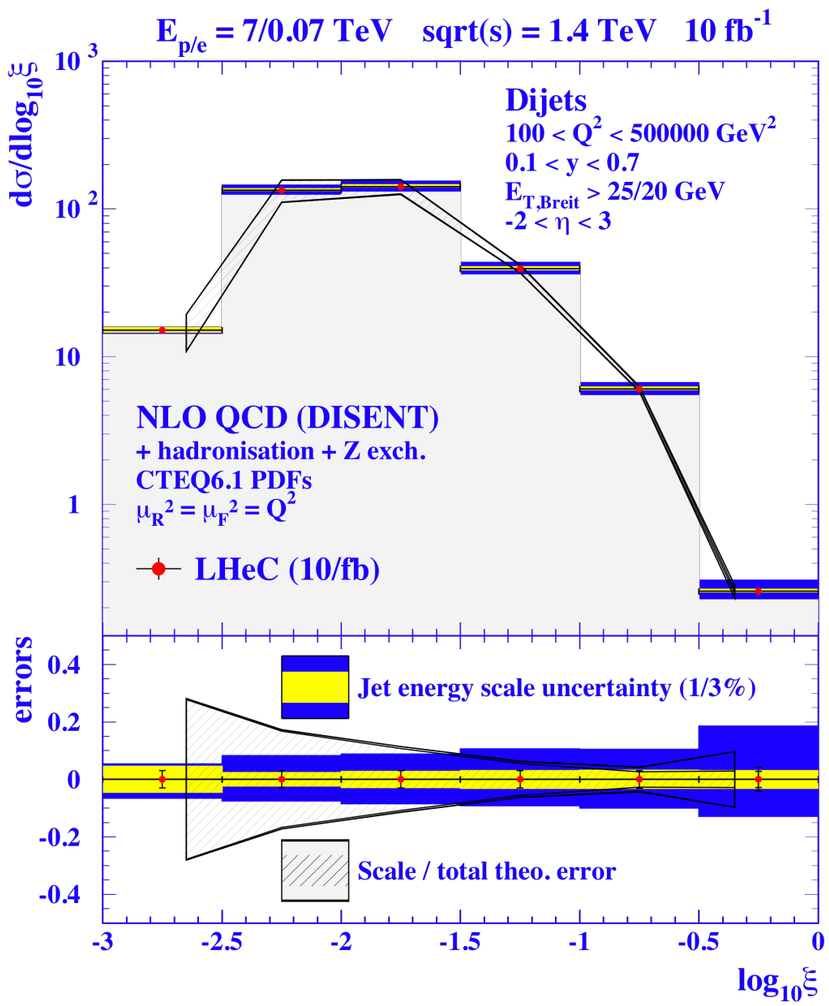


- Cross section much increased with respect to HERA.
- Can reach several hundred GeV in transverse energy (Breit frame).
- High scales: PDF uncertainty significant!

DIS DIJETS: Q^2 AND $\log_{10}\xi$

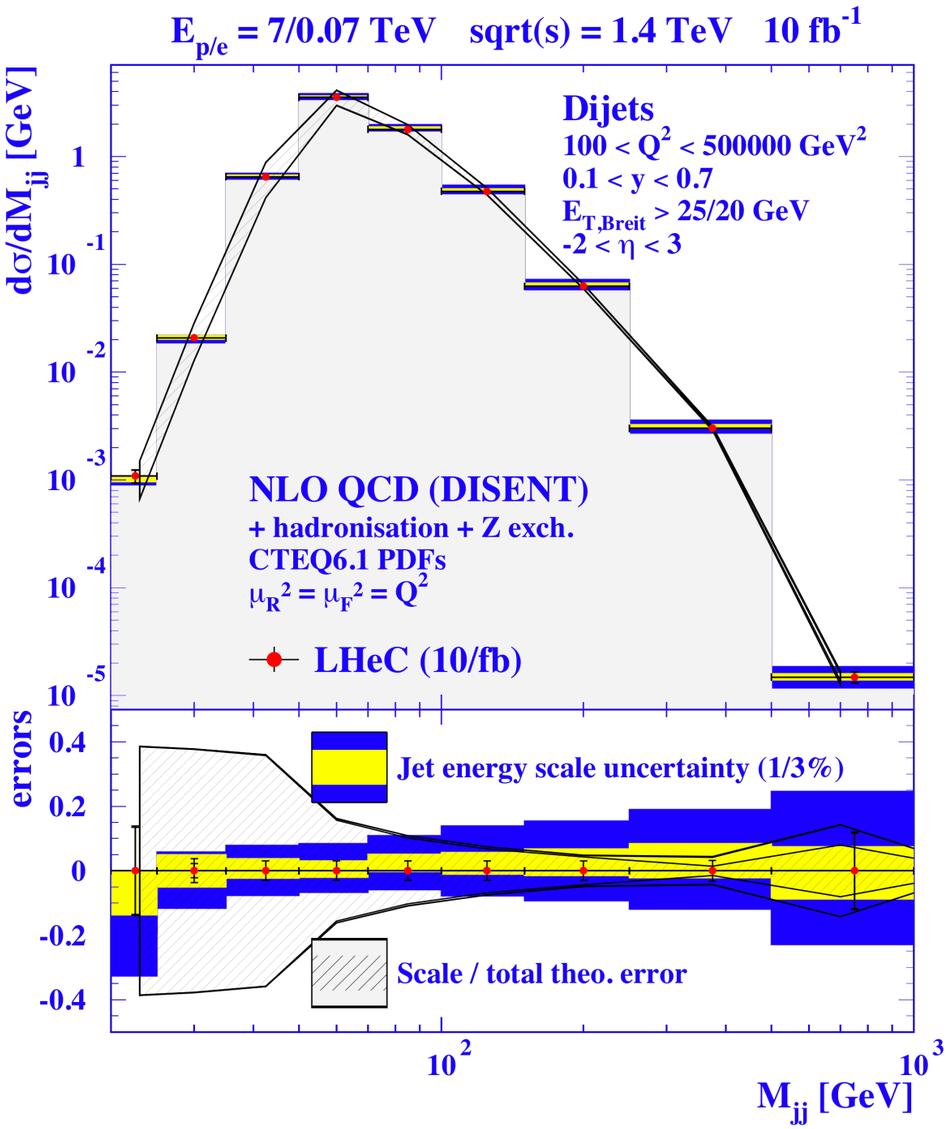
- Note: $\xi = x_{Bj}(1+M_{jj}^2/Q^2)$, directly related to x in PDF.

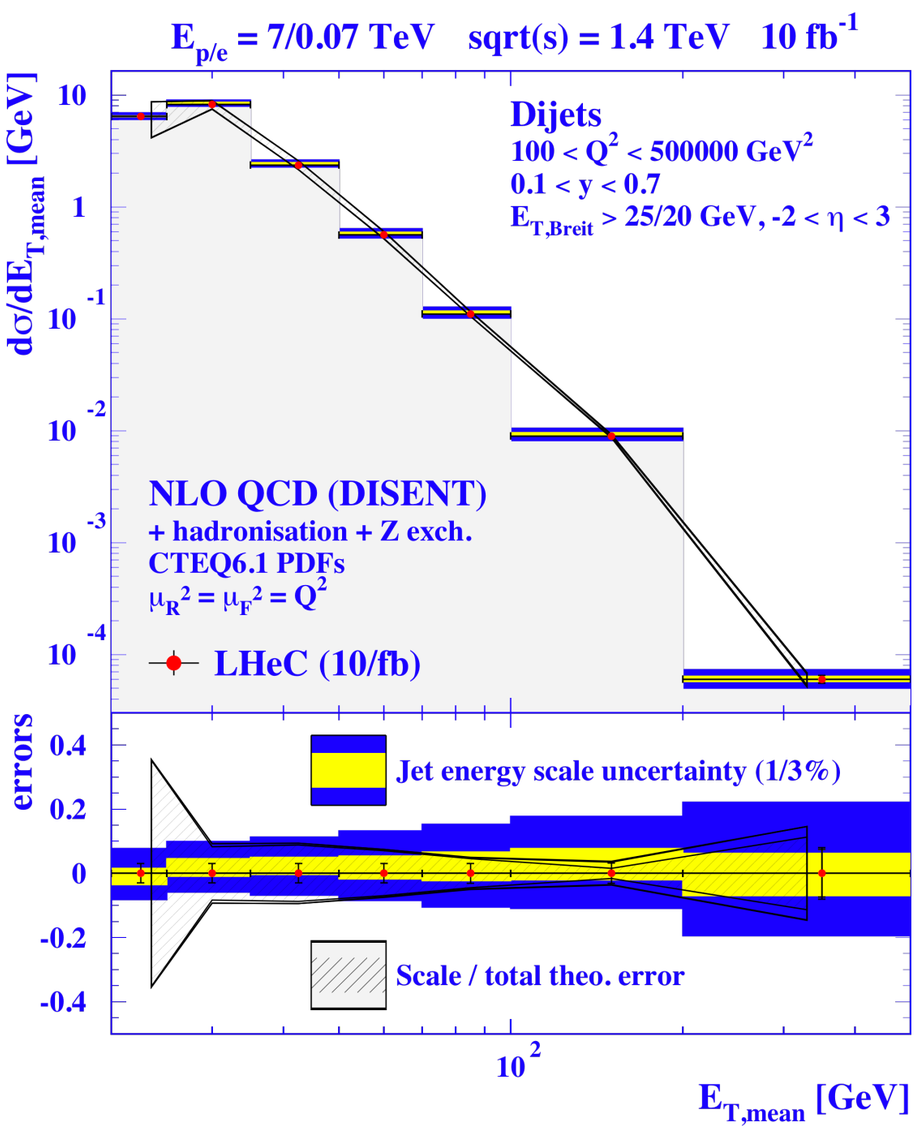




- Overall high precision even at highest Q^2 of several 10^5 GeV^2.
- Sensitivity to PDFs at high values of $\log_{10}\xi$!

DIS DIJETS: M_{jj} AND MEAN $E_{T,Breit}$

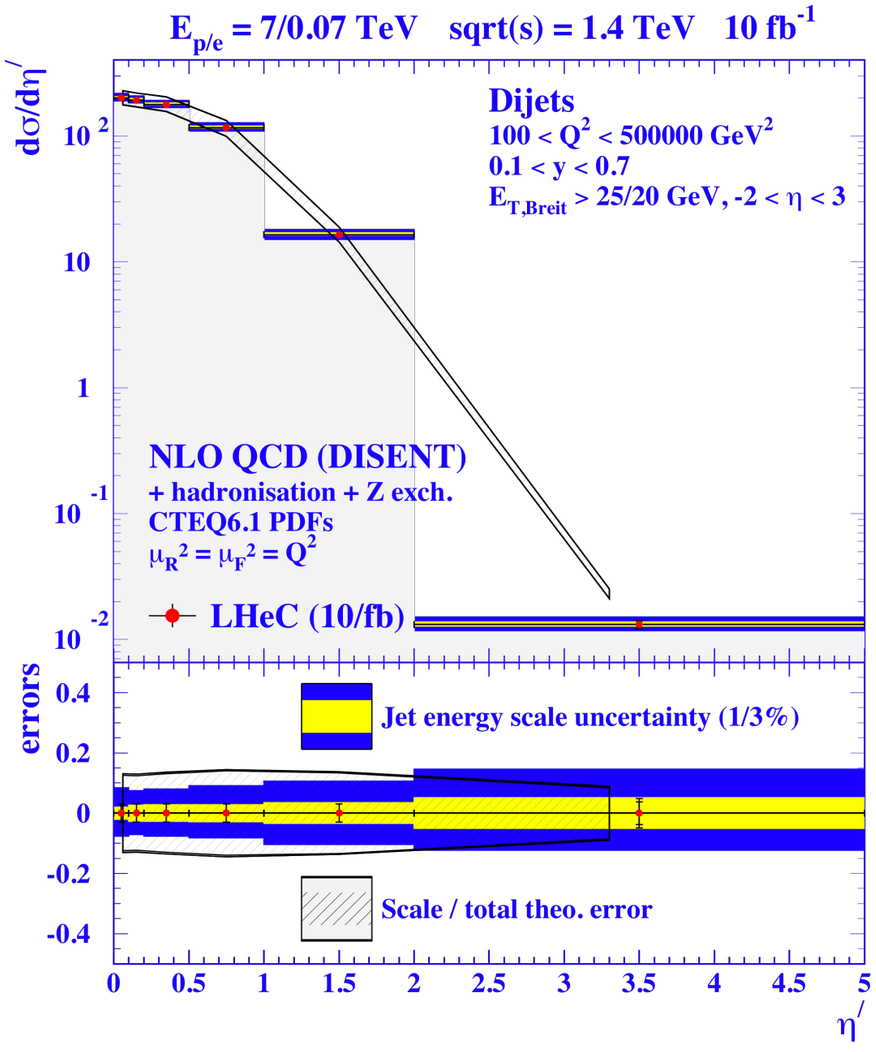




- Some NLO statistics limitations in predictions at high scales!
- Instabilities at lowest invariant dijet masses.

DIS DIJETS: $\eta' = 1/2 * |\eta_1 - \eta_2|$

- Sensitivity to QCD matrix element



- Relatively constant uncertainties.
- As at HERA, NLO problems for large η‘.

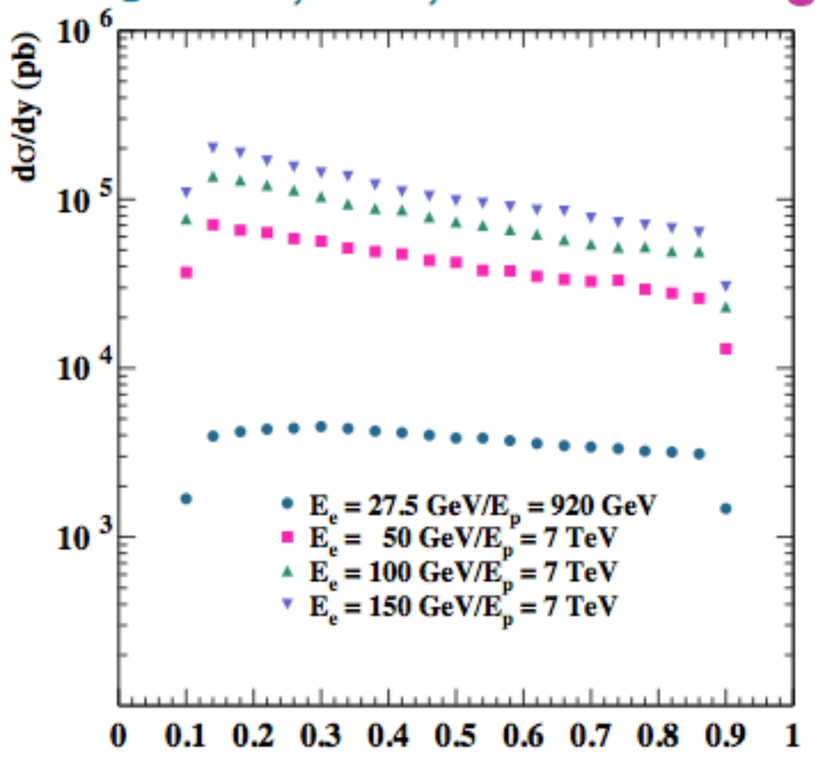
PHP JETS AT THE LHC (GLASMAN / TERRON)

Photoproduction studies at LHeC energies

- Three E_e scenarios were studied for $E_p = 7$ GeV: $E_e = 50,\ 100, 150$ GeV using PYTHIA MC (resolved and direct processes)

$$ep \to e + \text{jet} + \text{X}$$

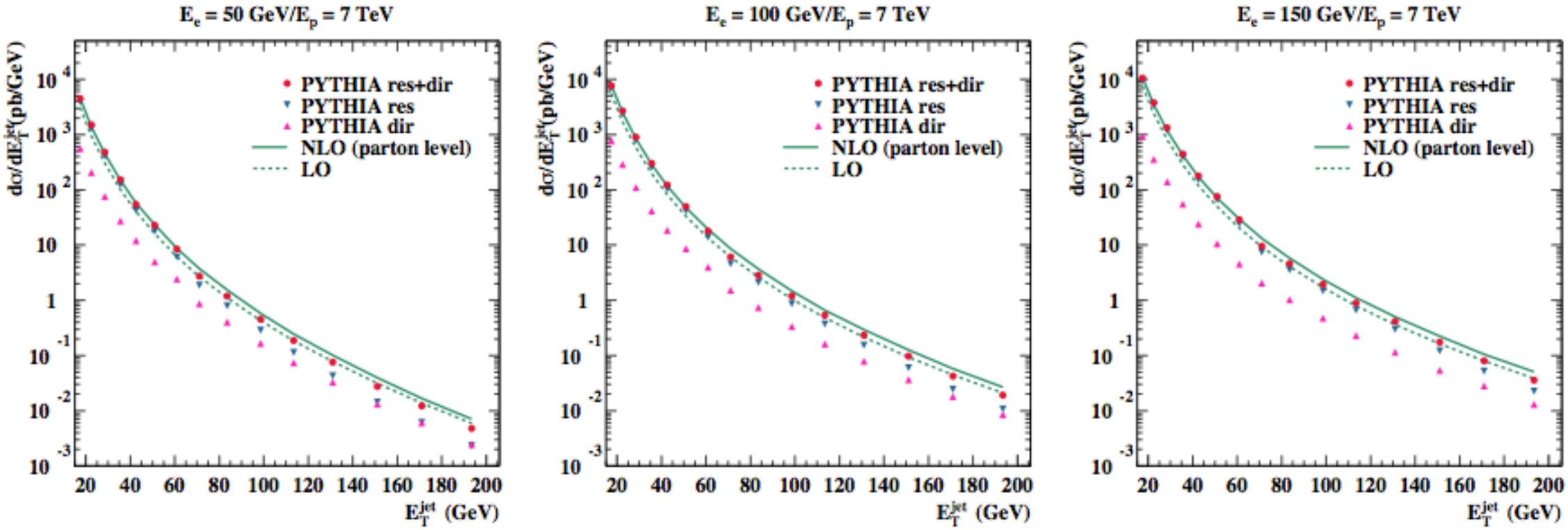
- Jets searched using the k_T cluster algorithm
- Kinematic region: $0.1 < y < 0.9$ and $Q^2 \leq 1$ GeV^2
- At least one jet of $E_T^{\text{jet}} > 15$ GeV and $-3 < \eta^{\text{jet}} < 3$



- Fixed-order QCD calculations:
  → differential cross sections were calculated at $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$ using Klasen et al. program with:
  - pPDFs: CTEQ6.1 sets
  - γPDFs: GRV-HO set
  - α_s was calculated at two loops with $\alpha_s(M_Z) = 0.119$ as default input
  - renormalisation and factorisation scales $\mu_R = \mu_F = E_T^{\text{jet}}$ of each jet

PHP JETS: LO MC vs NLO

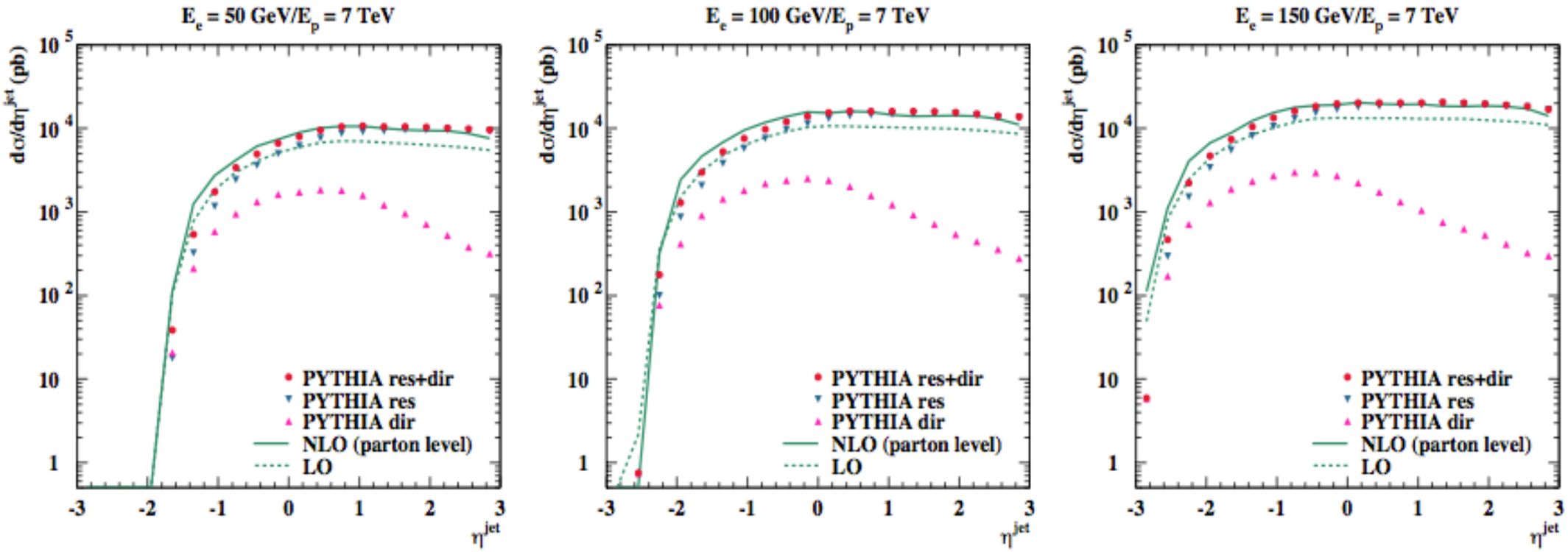
- Cross section $d\sigma/dE_T$ at parton level



- Significant rate up to 200 GeV transverse energy.
- At low transverse energies, resolved events dominate.
- Good agreement (in shape) between LO MC and NLO calculations.
- Hadronisation corrections small (<5%)

PHP JETS: LO MC vs NLO

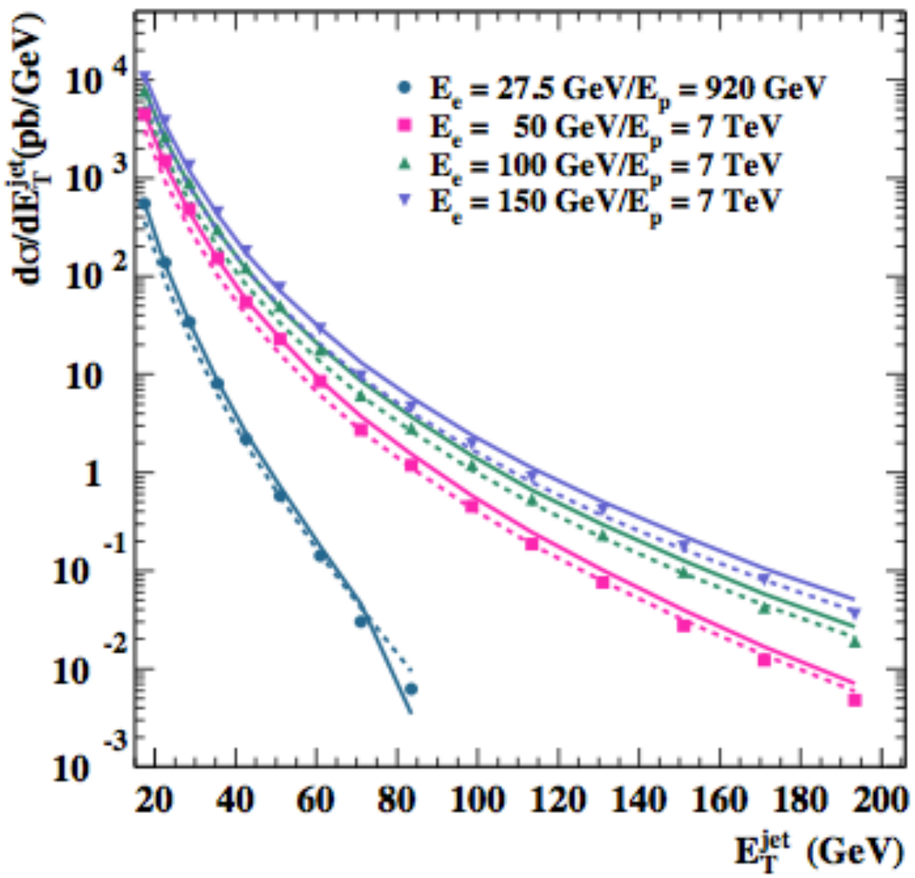
- Cross section dσ/dη at parton level

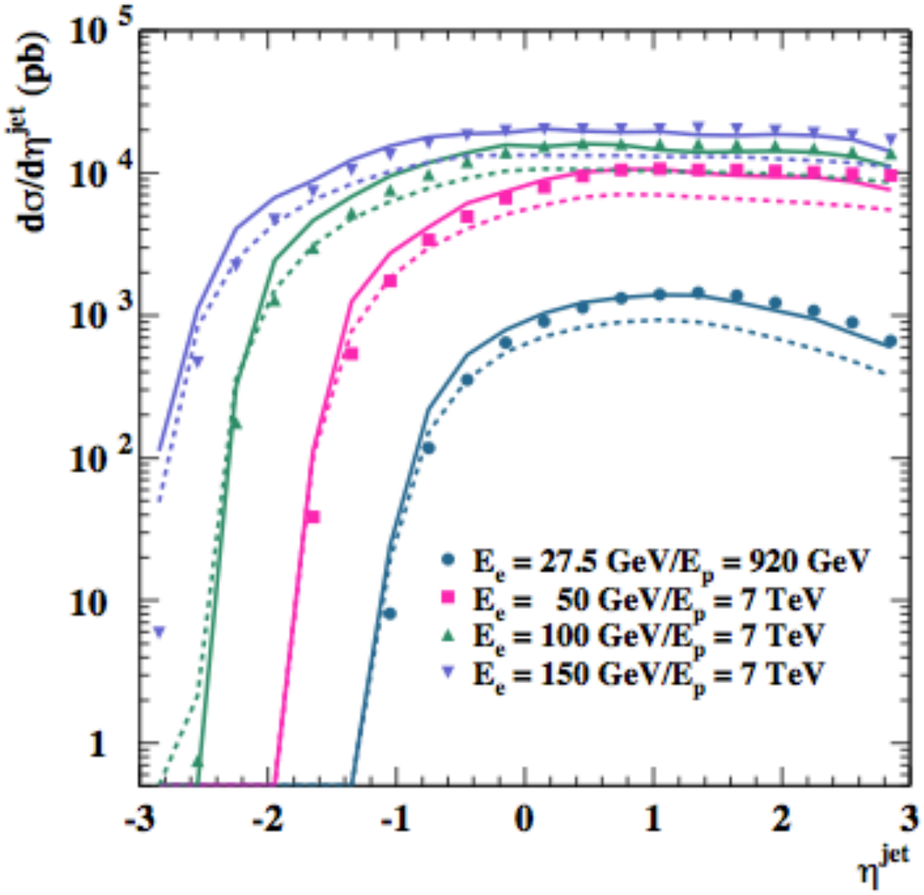


- Significant rate in forward region; dominated by resolved events.
- Good agreement (in shape) between LO MC and NLO calculations.
- Hadronisation corrections small (<5%)

PHP JETS: LO MC vs NLO

- Cross sections for different CMS energies (parton level):

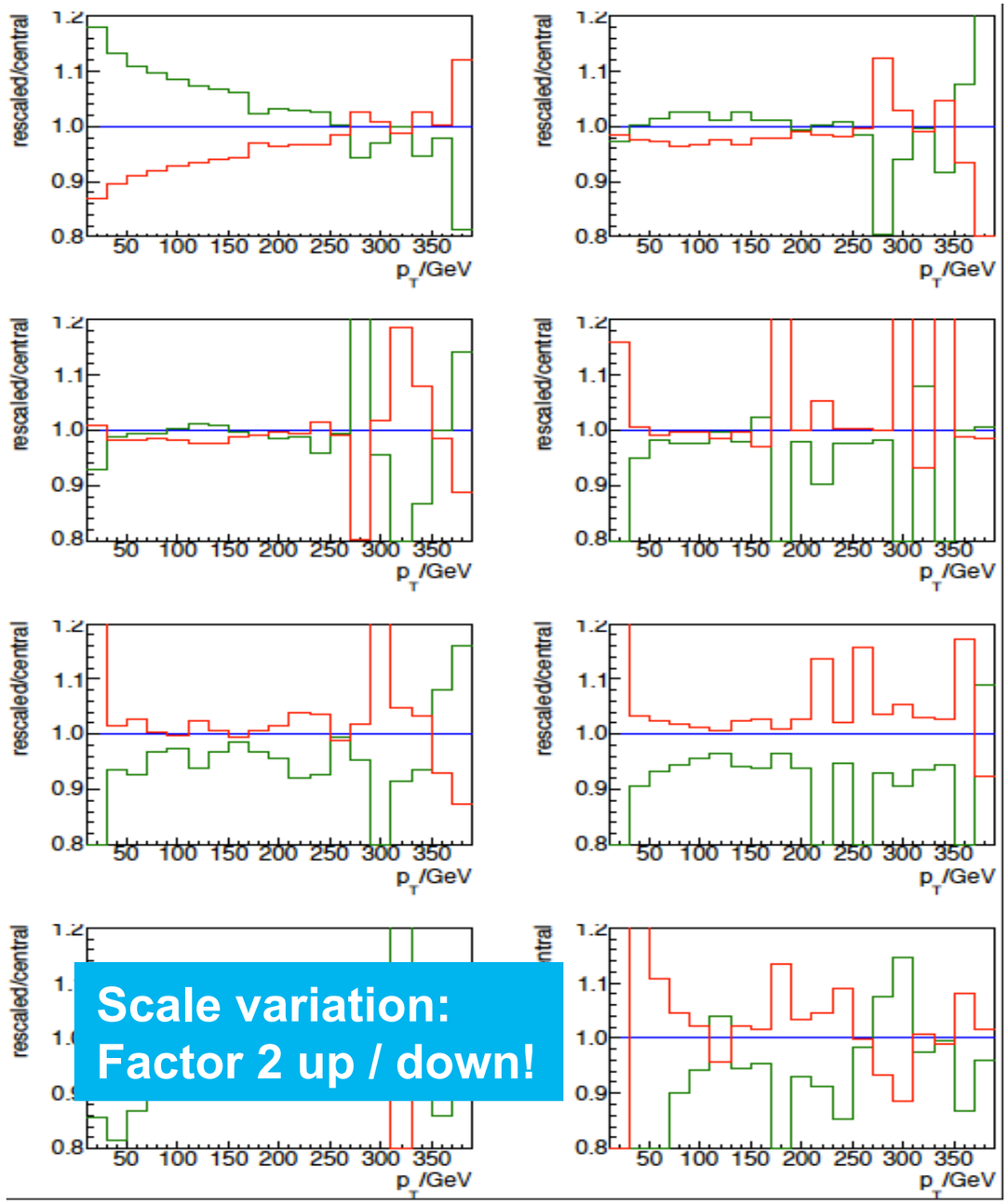




- Significant increase of cross sections with CMS energy
- Jets tend more backwards with higher CMS energy.
- Much increased reach wrt HERA!

STRONG COUPLING (T. Kluge et al.)

- Study by T. Kluge et al.: Scale uncertainty versus coupling sensitivity



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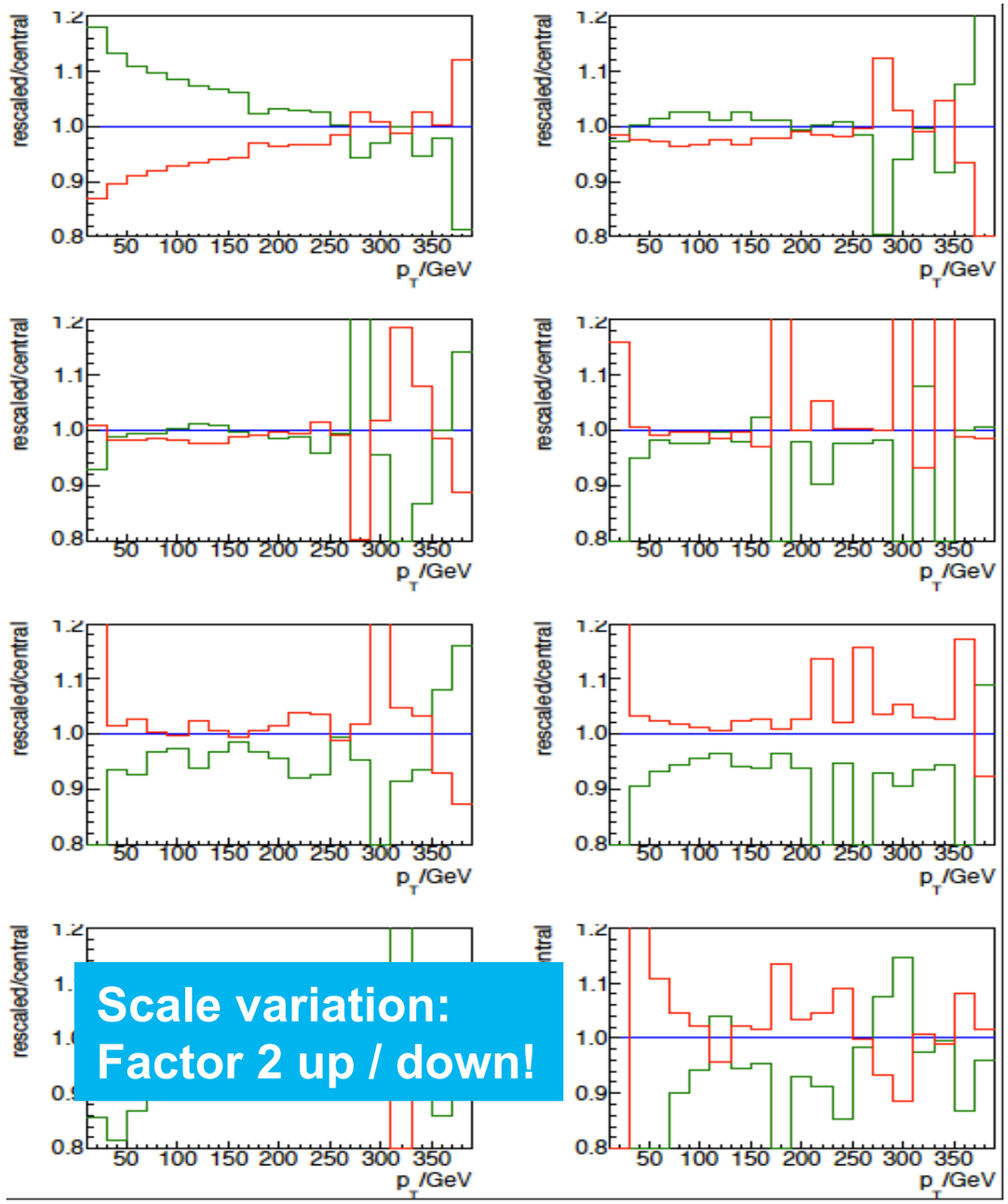
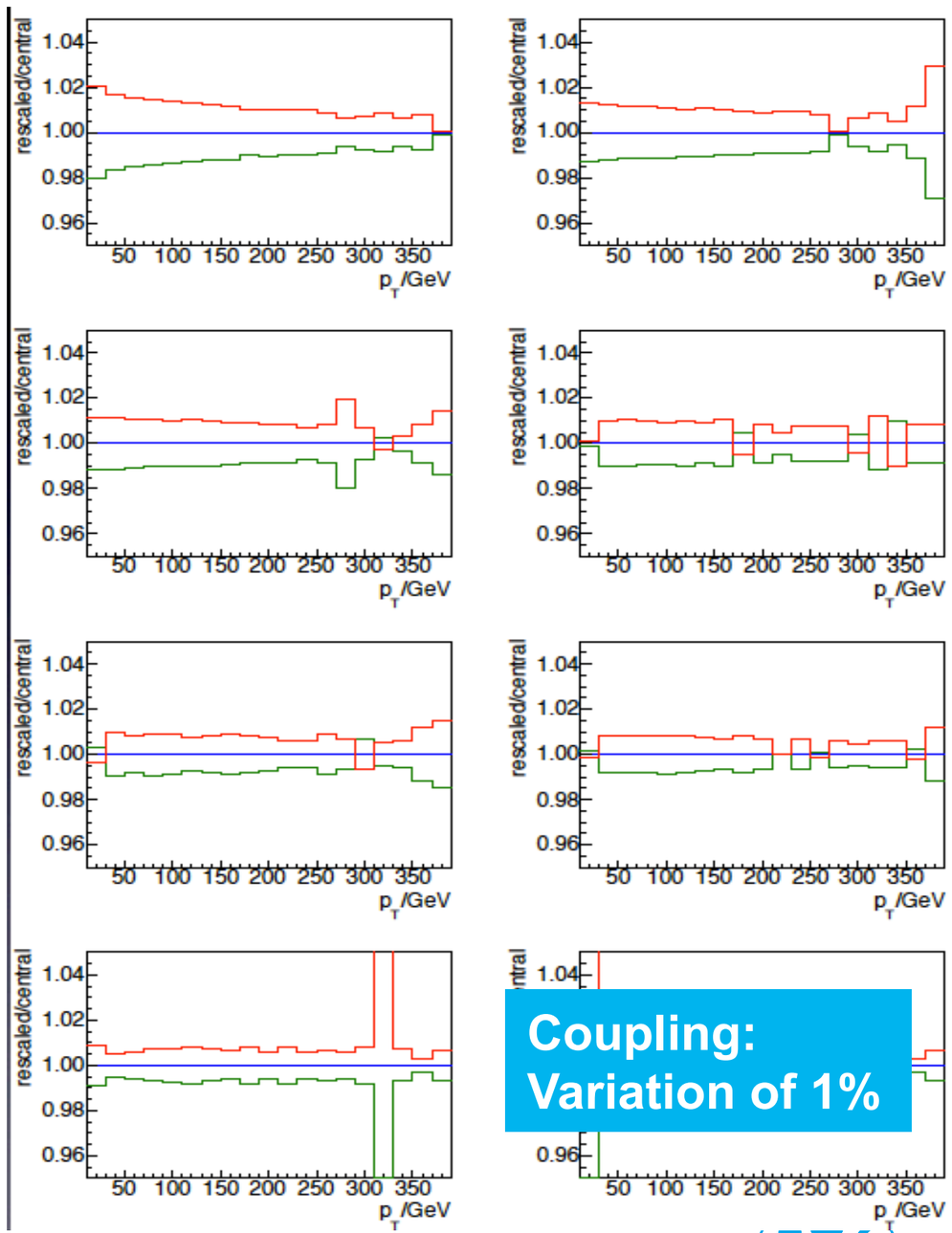


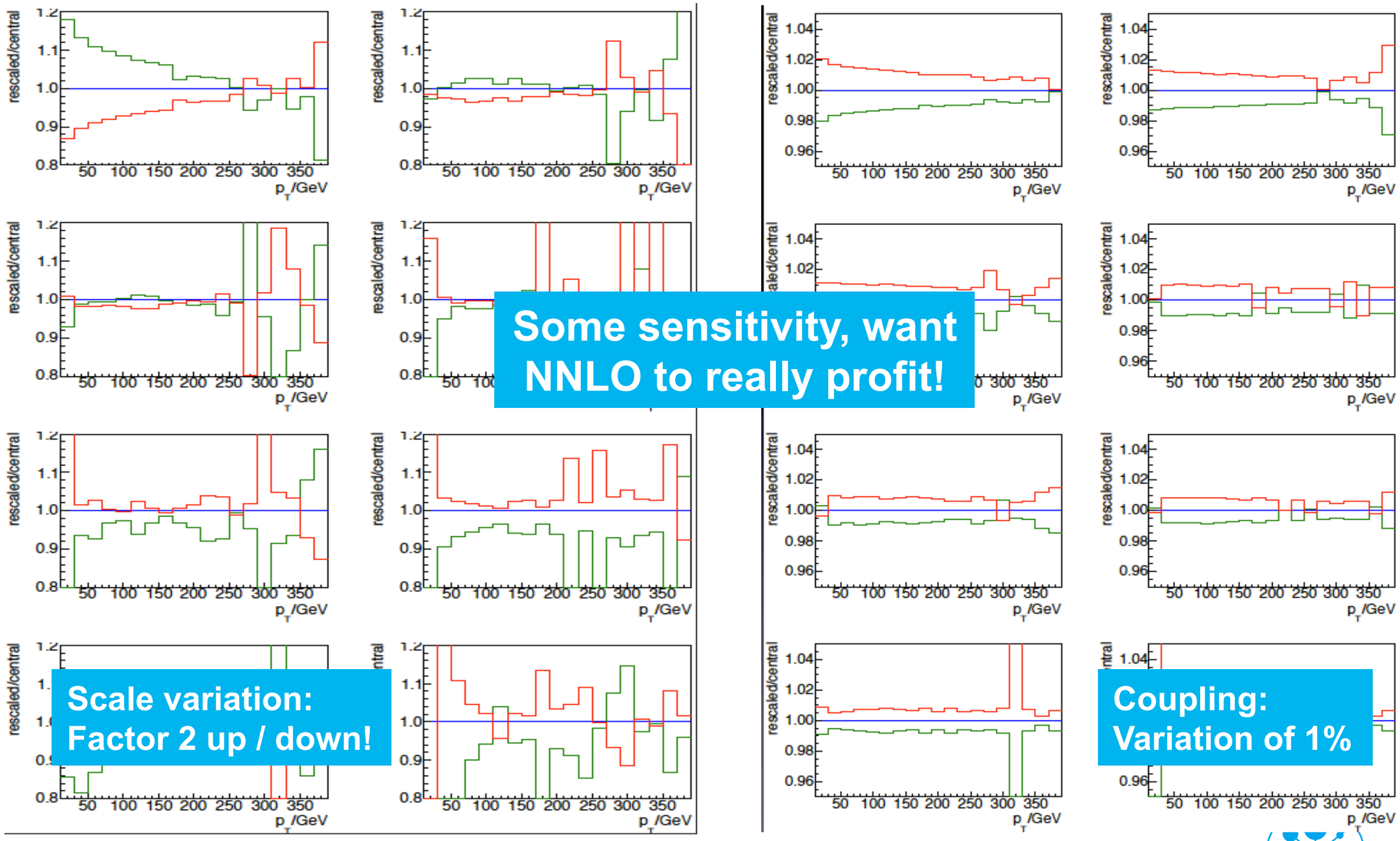
Scale variation: Factor 2 up / down!



Coupling: Variation of 1%

STRONG COUPLING (T. Kluge et al.)

- Study by T. Kluge et al.: Scale uncertainty versus coupling sensitivity



NNLO THEORY (T. Gehrmann et al.)

- NNLO calculations are ongoing. Matrix elements are either
  - already derived (NLO corrections to 3-jet production in DIS, Z. Nagy, NLOJET++) or
  - Contained in work by Gehrmann/Glover (for the two-loop 2-parton final state).

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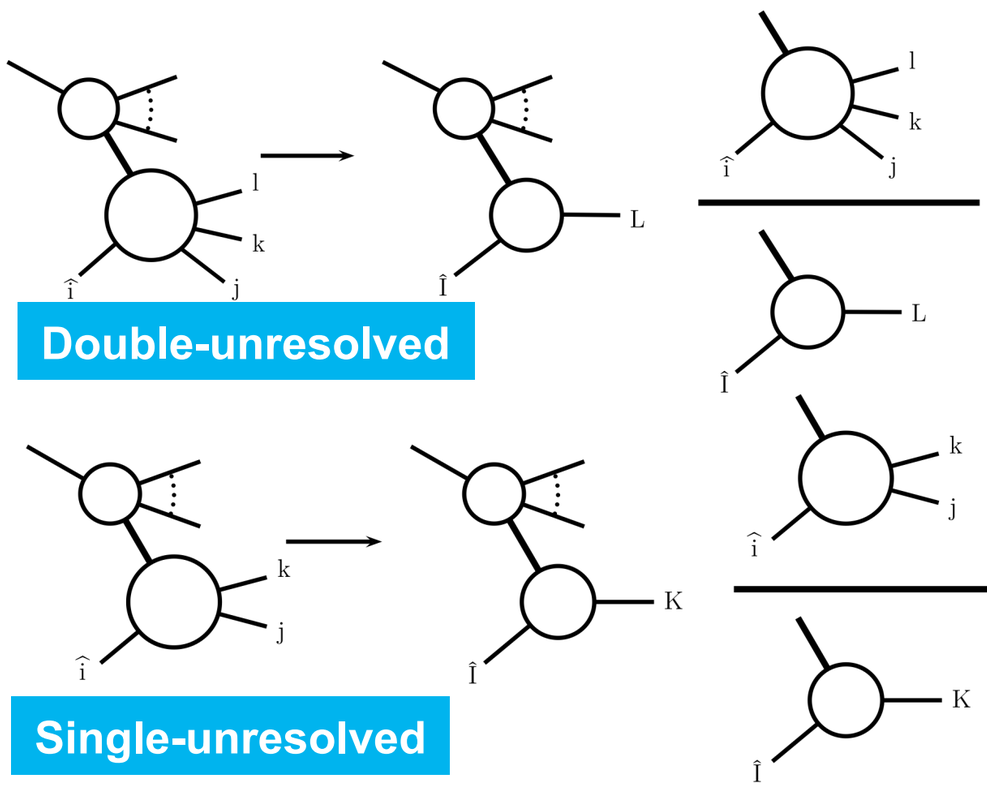
- Required: subtraction method!
  - Gehrmann et al.: antenna subtraction method (for DIS).

JHEP0704*2007)016
JEHP1001(2010)118



- Currently implementing method into program for DIS jet production.

SUMMARY AND OUTLOOK (1)

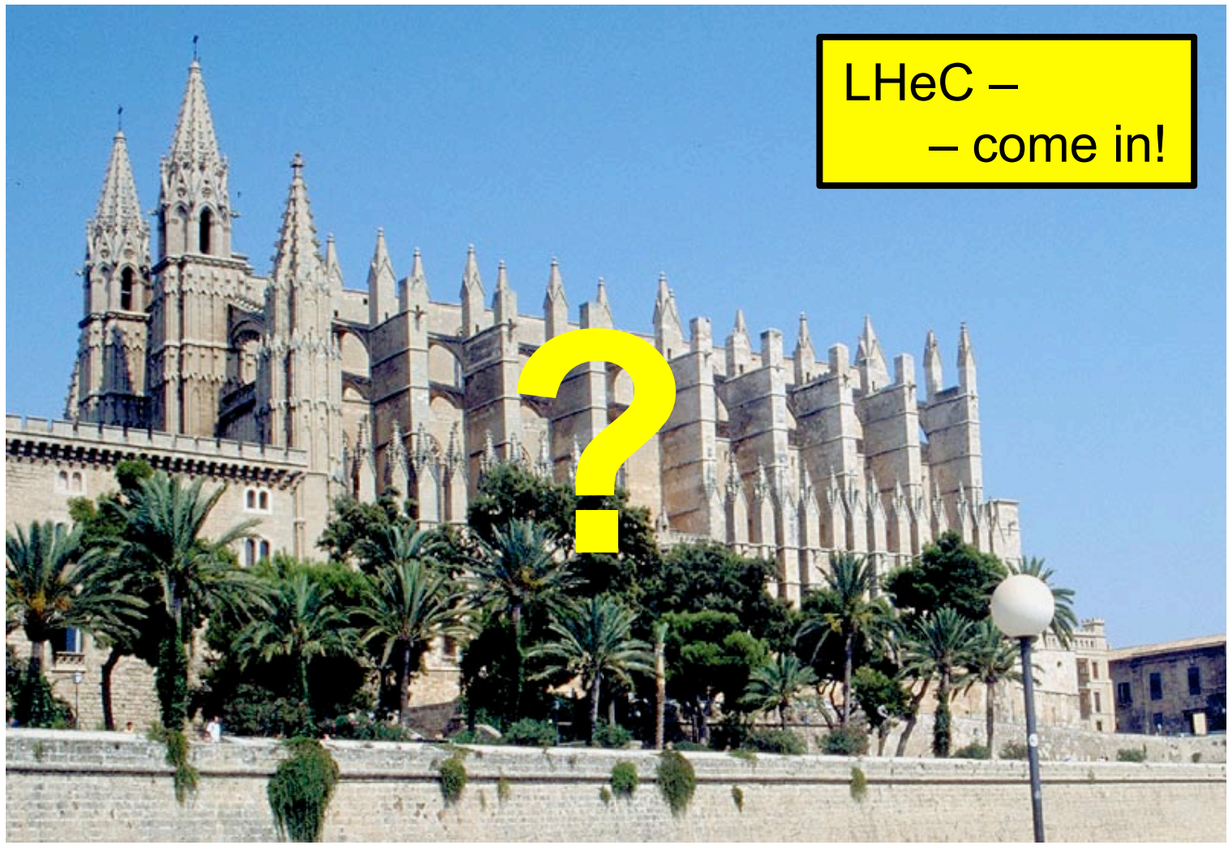
- DIS and PHP jets at the LHeC were studied for different scenarios (varying E_e beam energy, 50-150 GeV).
- PHP: Inclusive cross sections
  - Strong increase of Xsections with CMS energy!
  - Sizable rate predicted up to transverse energies of 200 GeV.
  - Reach much extended wrt HERA.
  - TODO: theory errors, MPI/UE effects, …
- DIS: inclusive-jet and dijet distributions
  - Significant extension of phase space and statistics with respect to HERA
  - In many regions theoretically dominated by scale uncertainty → need NNLO!
  - Large potential for precise QCD tests at high scales (up to 500 GeV in E_T!)
  - Some regions with large sensitivity to PDFs.
  - Necessity of NNLO calculations!
  - TODO: double-diff cross sections, cross checks (also with MC programs), more realistic scenarios, PDF potential, low Q^2, parton dynamics, …

SUMMARY AND OUTLOOK

- Investigations of strong coupling:
  - Studies of sensitivity for inclusive jets in broad Q^2 range (5 – 640000 GeV^2).
  - Some sensitivity visible, depending very much on boson virtuality.
  - Clear evidence for necessity of NNLO calculations!
- PDFs:
  - Sensitivity for proton and photon PDFs to be studied.
  - Large expectations for large momentum fractions.
- Theory status:
  - NNLO for ep DIS being worked on.
  - All bits and pieces around – implementing!

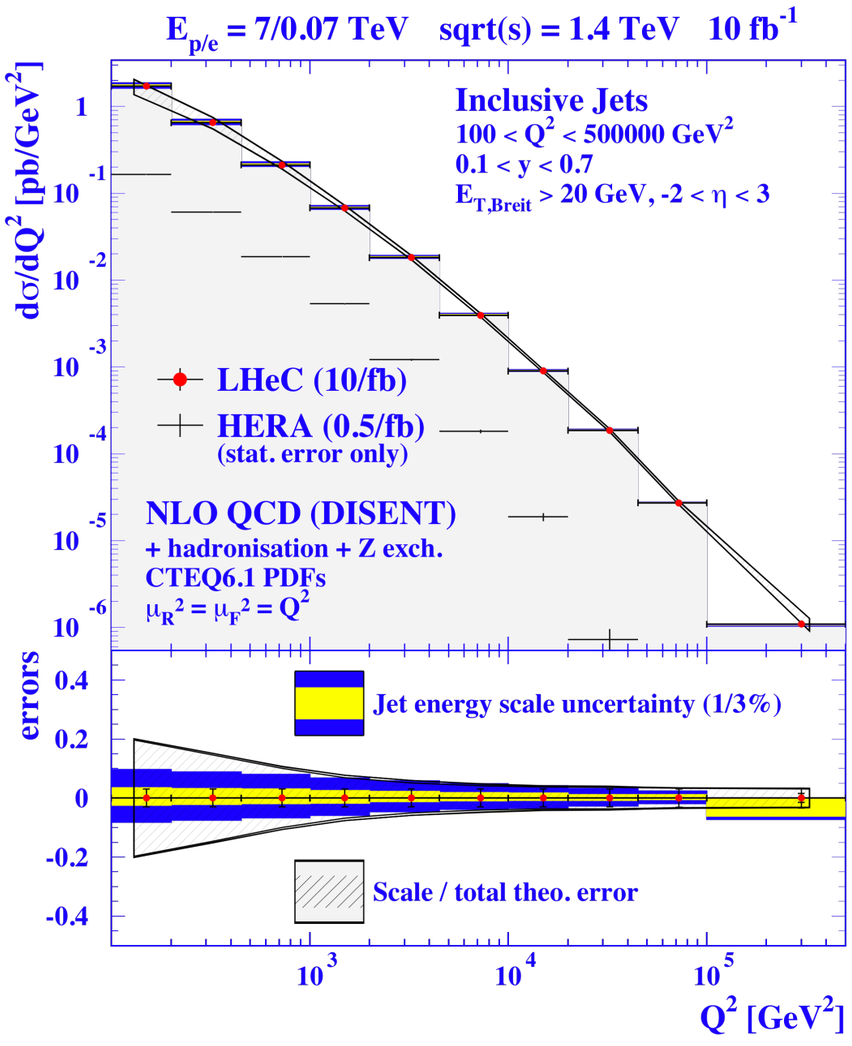
SUMMARY AND OUTLOOK

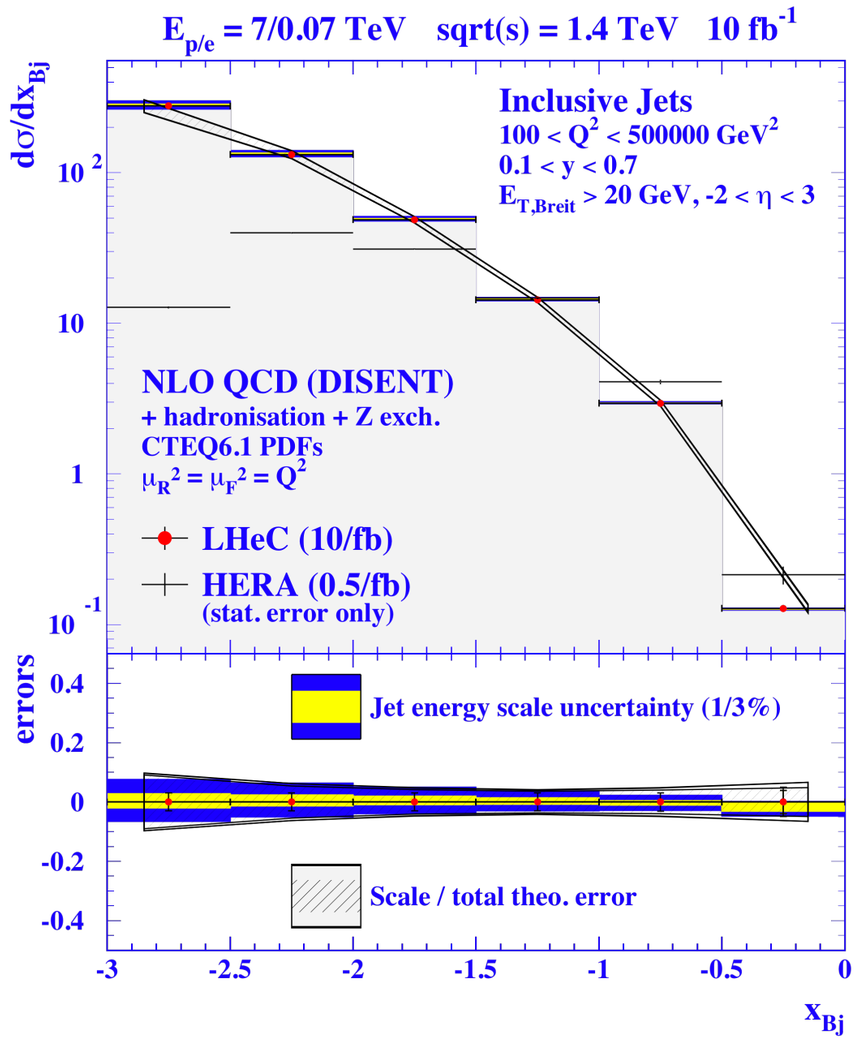
- Investigations of strong coupling:
  - Studies of sensitivity for inclusive jets in broad Q^2 range (5 – 640000 GeV^2).
  - Some sensitivity visible, depending very much on boson virtuality.
  - Clear evidence for necessity of NNLO calculations!
- PDFs:
  - Sensitivity for proton and photon PDFs to be studied.
  - Large expectations for large momentum fractions.
- All in all: … looks exciting …



BACKUP

INCLUSIVE DIS JETS: Q^2 AND x_{Bj}





- Small Q^2 and x: scale error dominates; total exp. uncertainty 10%.
- Cross section 1-2 orders of magnitude larger than at HERA at same kinematic point.