ICHEP08

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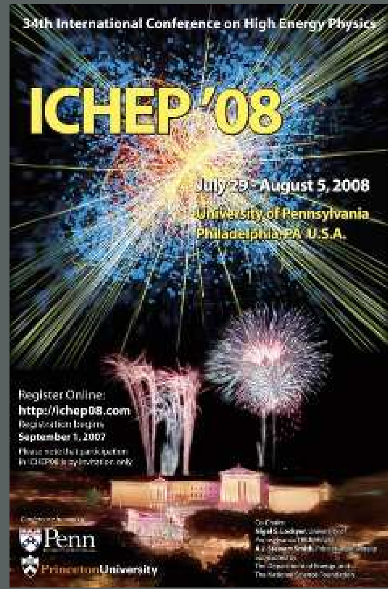

Precision tests of QCD with jets and vector bosons at HERA and TevaTron

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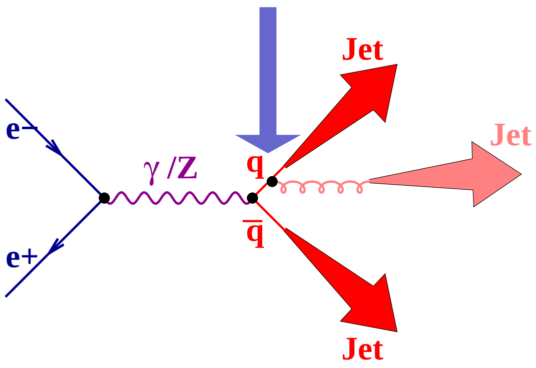
QCD

QCD processes are dominant at hadron colliders

$\longrightarrow$ **background to new physics**

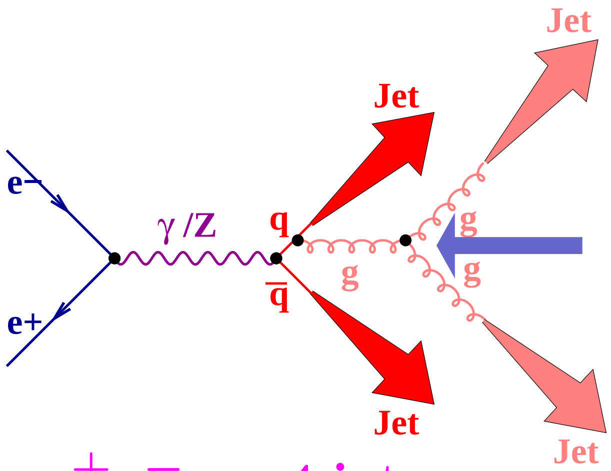
$\longrightarrow$ **need good understanding of QCD processes**

$\longrightarrow$ **At LEP (e^+e^-):**



$e^+e^- \longrightarrow 3$ jets

$\longrightarrow$ **measurements of α_s**



$e^+e^- \longrightarrow 4$ jets

$\longrightarrow$ **color dynamics (eg self-coupling of the gluon)**

QCD

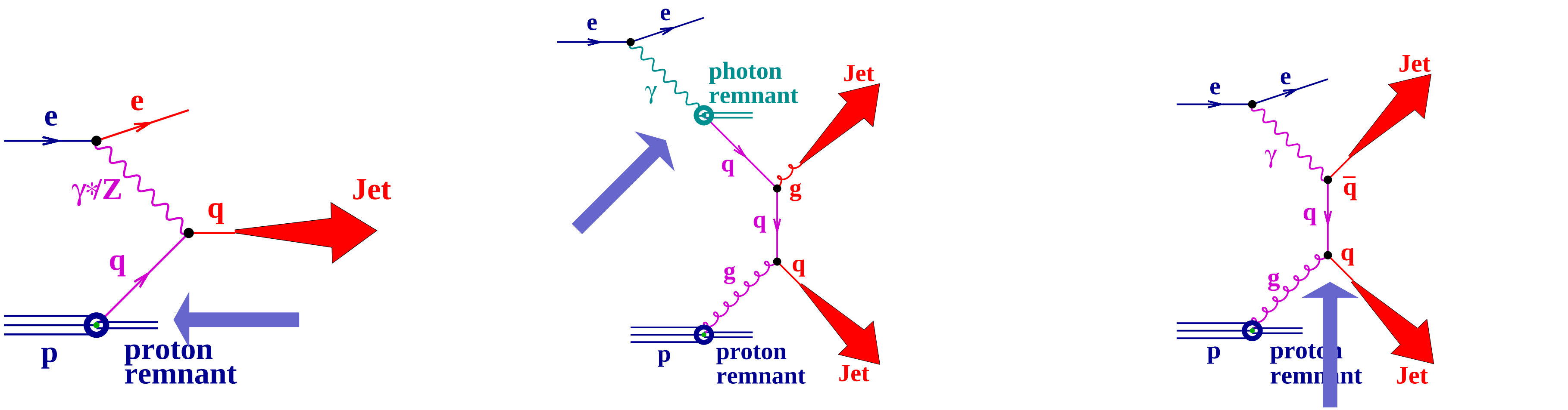
QCD processes are dominant at hadron colliders

$\longrightarrow$ background to new physics

$\longrightarrow$ need good understanding of QCD processes

$\longrightarrow$ LEP (e^+e^-)

$\longrightarrow$ At HERA (ep):



$ep \longrightarrow e + \text{jet} + \text{X}$ $\longrightarrow$ proton structure

$\gamma p \longrightarrow 2\ \text{jets} + \text{X}$ $\longrightarrow$ test of photon structure

$\gamma p \longrightarrow 2\ \text{jets} + \text{X}$ $\longrightarrow$ measurements of α_s

QCD

QCD processes are dominant at hadron colliders

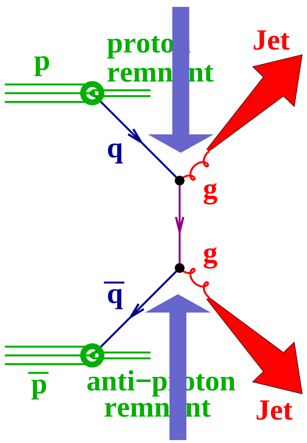
$\longrightarrow$ background to new physics

$\longrightarrow$ need good understanding of QCD processes

$\longrightarrow$ LEP (e^+e^-)

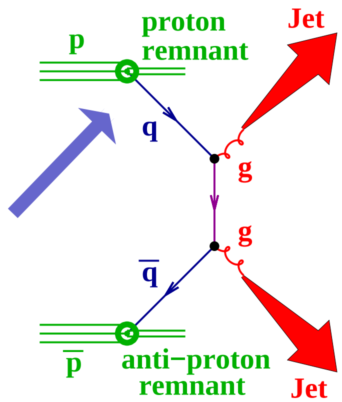
$\longrightarrow$ At TevaTron ($p\bar{p}$):

$\longrightarrow$ HERA (ep)



$p\bar{p} \longrightarrow \text{jets} + \text{X}$

$\longrightarrow$ tests of matrix elements



$p\bar{p} \longrightarrow 2\ \text{jets} + \text{X}$

$\longrightarrow$ tests of proton structure

QCD

QCD processes are dominant at hadron colliders

$\longrightarrow$ background to new physics

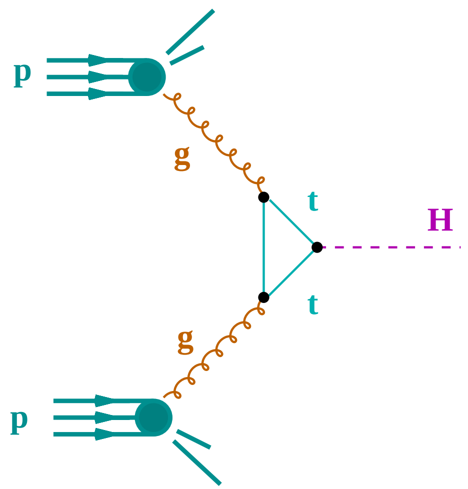
$\longrightarrow$ need good understanding of QCD processes: α_s, pPDFs, matrix elements

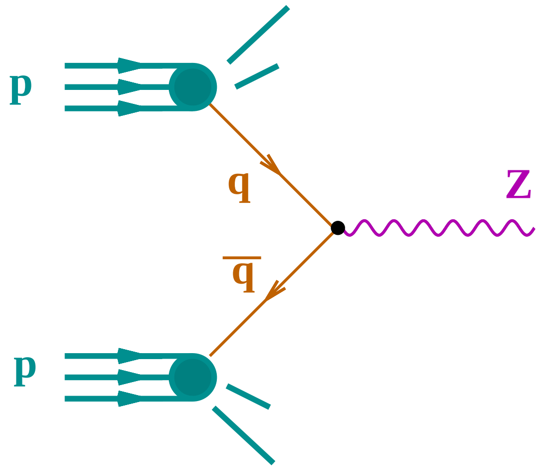
$\longrightarrow$ LEP (e^+e^-)

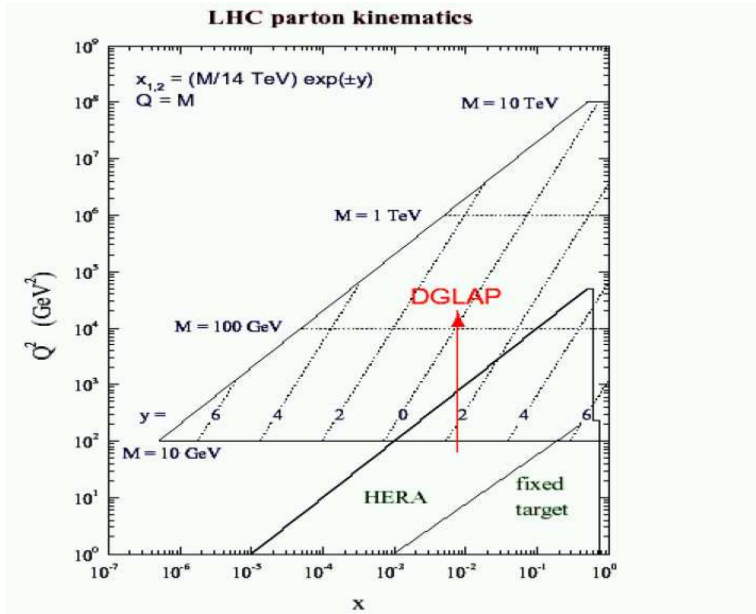
$\longrightarrow$ HERA (ep)

$\longrightarrow$ TevaTron ($p\bar{p}$) $\longrightarrow$ At LHC (pp):

$$\sigma_{pp\to H(W,Z,...)+X} = \sum \int dx_1\, f_{a/p}(x_1,\mu_F^2) \int dx_2\, f_{b/p}(x_2,\mu_F^2)\, \hat{\sigma}_{ab\to H(W,Z,...)}$$







How do we study QCD at HERA and TevaTron ?

- We measure:

structure functions	heavy quark production	jet production	particle production
↓	↓	↓	↓
F_2^p, F_2^{CC}, F_2^D, F_2^c, ...	charm beauty	**jet cross sections** jet substructure **forward jets**	hadrons **photons/W/Z** event shapes **underlying event**

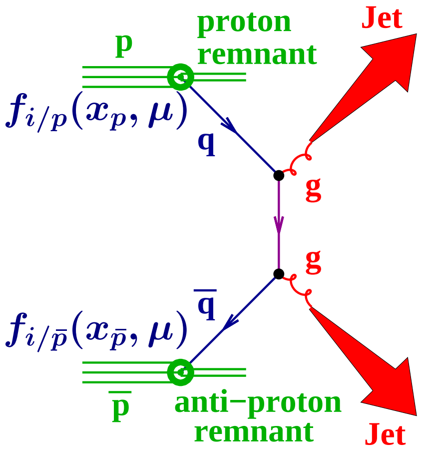
to obtain results on:

— proton, photon, pomeron structure: parton densities
— tests of pQCD: up to which extent does pQCD describe parton dynamics?
— parton dynamics at low x: breakdown of DGLAP?
— measurements of α_s: the fundamental parameter of the theory
— color dynamics: color factors, subprocesses
— non-perturbative effects: can they be described from first principles?

$\longrightarrow$ Do we have enough information on QCD to understand LHC physics?

Jets: e^+e^- vs $p\bar{p}$

- Jet search in e^+e^- annihilations is simple:
  - $\longrightarrow$ initial state: only leptons; final state: arising uniquely from short-distance interaction (all hadrons in final state associated with hard process)
  - $\longrightarrow$ best frame: centre-of-mass system = LAB
  - $\longrightarrow$ variables invariant under rotations: energies and angles
  - $\longrightarrow$ distance between hadrons: angular separation
- Jets in hadronic collisions are not as easily identified because jets carry only a fraction of the available energy and are accompanied by several soft hadrons not correlated with the hard interaction

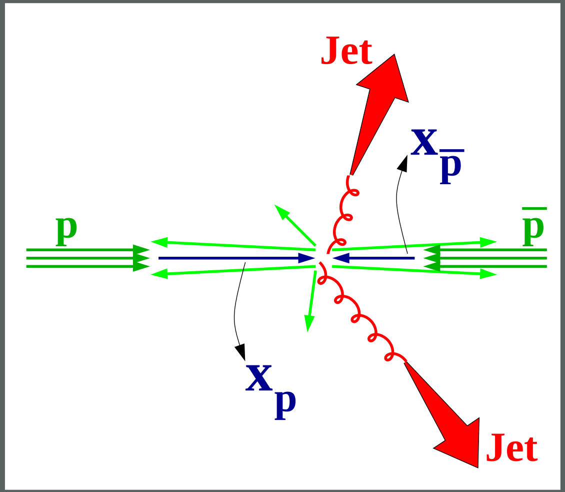


$p\bar{p} \longrightarrow \text{jet} + \text{jet} + \text{X}$

- Initial state: colored partons
- Initial partons carry only a fraction $x_p/x_{\bar{p}}$ of the parent hadron momentum
- Spectator partons:
  - $\longrightarrow$ remnant jets
  - $\longrightarrow$ "underlying event": soft/hard interaction between the partons in the remnants

Jets in $p\bar{p}$ collisions

- In hadronic colliders, collisions do not occur in CMS:
  $\longrightarrow$ initial-state parton-parton system not at rest
  $\longrightarrow$ final-state partonic system boosted along beam axis



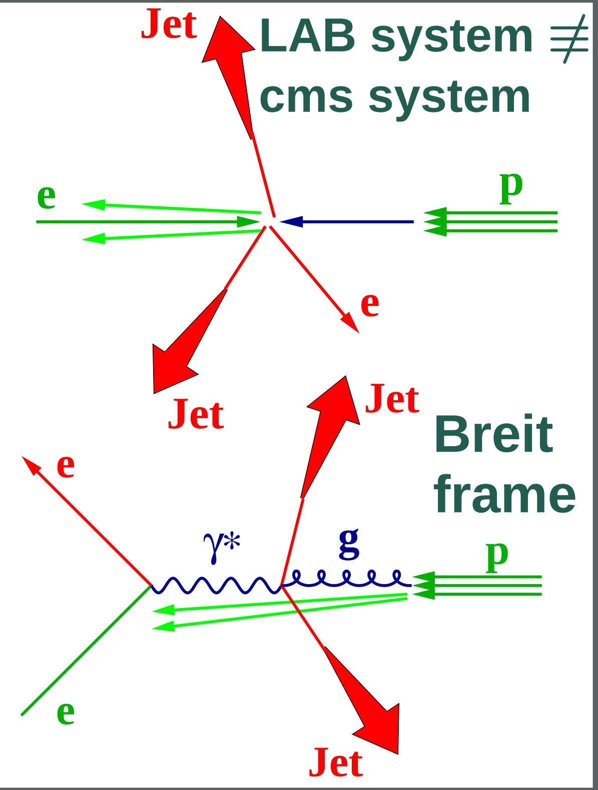
LAB system $\not\equiv$ centre-of-mass system

- To treat on equal footing all possible final-state hadronic systems $\longrightarrow$ use variables invariant under longitudinal boosts: $E_{T,i}$, $\Delta\eta_{ij}$ ($\eta = -\ln\tan\frac{\theta}{2}$) and φ_i

- Advantage of using transverse energies:
  $\longrightarrow$ large energy $\neq$ small distance (ie hard scattering)
  $\longrightarrow$ the beam remnant jets have huge energies, but they have not undergone a hard scattering
  $\longrightarrow$ large momentum transfer $\equiv$ small distance (hard scattering): large transverse energies $\equiv$ hard interaction
  $\longrightarrow$ the use of transverse energies helps to disentangle between the products of the hard interaction and the beam remnant jets (absent in e^+e^- annihilations)

Jets in ep collisions

- Photoproduction (ep for $Q^2 \approx 0$):
  $\longrightarrow$ hadronic-like collision (similar to $p\bar{p}$)
- Deep inelastic scattering (high Q^2):
  $\longrightarrow$ hadronic-like collision, but no UE
  $\longrightarrow$ initial-state γ^*-parton system boosted and rotated (γ^* carries p_T)
- Effect of p_T carried by γ^* removed by selecting frame in which γ^* collides head-on with proton, eg Breit frame
- k_T cluster algorithm in longitudinally inclusive mode:
  $\longrightarrow$ best algorithm to reconstruct jets at HERA
  $\longrightarrow$ in use since many years for making precision tests of pQCD $\longrightarrow$ now at TevaTron (also: mid-point cone algorithm)



- Advantages of k_T/mid-point algorithm in hadronic-type interactions:
  $\longrightarrow$ allows transparent translation of experimental setup to theoretical calculations (avoids ambiguities of overlapping and merging of jets (cone algorithm))
  $\longrightarrow$ calculations using k_T/mid-point are finite at all orders
  $\longrightarrow$ smallest hadronisation corrections (with k_T at HERA)

NLO calculations

- Ingredients of a pQCD calculation for (eg) jet production in $p\bar{p}$:

$$\sigma_{p\bar{p}\to\text{jets}} = \sum \int dx_p\, f_{a/p}(x_p, \mu_F) \int dx_{\bar{p}}\, f_{b/\bar{p}}(x_{\bar{p}}, \mu_F)\, \hat{\sigma}_{ab\to\text{jets}}(\mu_R, \alpha_s, x_p, x_{\bar{p}})$$

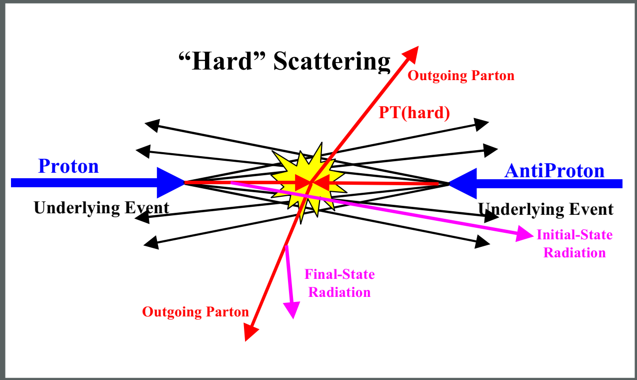
$\longrightarrow$ jet cross sections sensitive to pPDFs, provide determinations of α_s and test QCD matrix elements

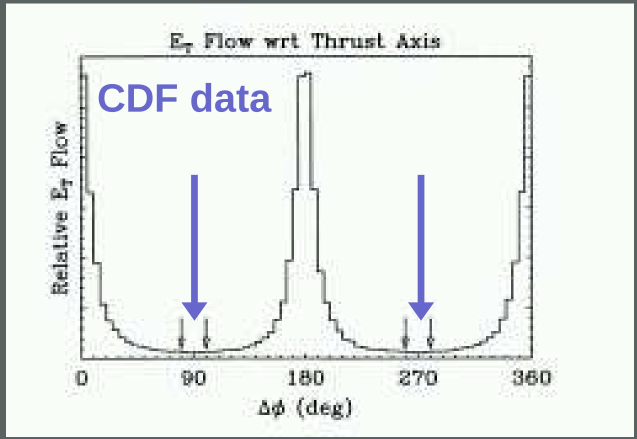
- need to assume a value of $\alpha_s(M_Z)$
- need to assume parametrisations for the pPDFs
- choice of hard scale (μ_R and μ_F: functions of E_T^{jet})
- calculations are for jets of partons and measurements are done at hadron level $\longrightarrow$ need to correct for hadronisation effects

- Theoretical uncertainties:
  - terms beyond NLO (usually estimated by varying μ_R by a factor of 2 up and down)
  - uncertainties on the parametrisations of the pPDFs (using PDF error analysis)
  - uncertainty coming from the hadronisation corrections
  - uncertainties on the value of $\alpha_s(M_Z)$
- Similar for other processes (vector boson production)

Experimental uncertainties of jet cross sections

- **Jet energy scale:**
  - $\longrightarrow$ Energy of jets known with a certain precision due to uncertainties in response of apparatus to hadrons
  - $\longrightarrow$ Since jet cross sections go like $1/(E_T^{\rm jet})^p$, any uncertainty on $E_T^{\rm jet}$ translates into a larger uncertainty on the cross section
- **The underlying event:**
  - $\longrightarrow$ Distribution of energy on top of the hard interaction coming from the soft interaction between the spectator partons or multiparton interactions
    - $\longrightarrow$ non-perturbative effects: not accounted for in pQCD calculations
    - $\longrightarrow$ more jets in data than in the predictions at a certain $E_T^{\rm jet}$
    - $\longrightarrow$ need to model UE well
      - $\longrightarrow$ UE at LHC?
- **Jet profiles:** energy density wrt jet axis as function of $\Delta\varphi$ $\longrightarrow$ Indication of presence of UE $\longrightarrow$

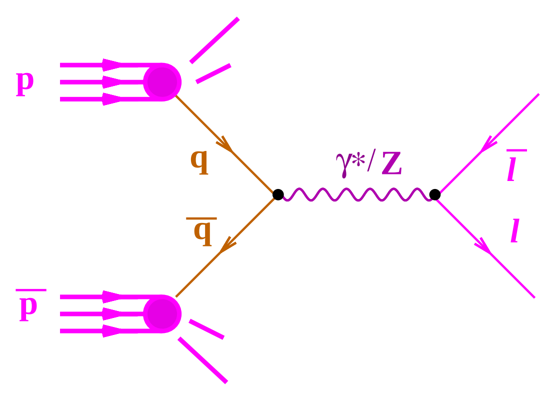




CDF, PRD 44 (1991) 601

Underlying event: Drell-Yan processes in $p\bar{p}$

- **Drell-Yan:** $p\bar{p} \to \gamma^*/Z^0 \to e^+e^-$ or $\mu^+\mu^-$

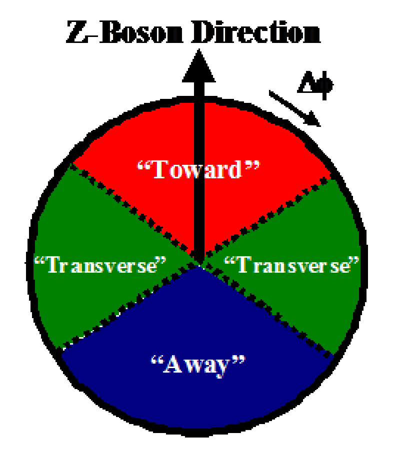


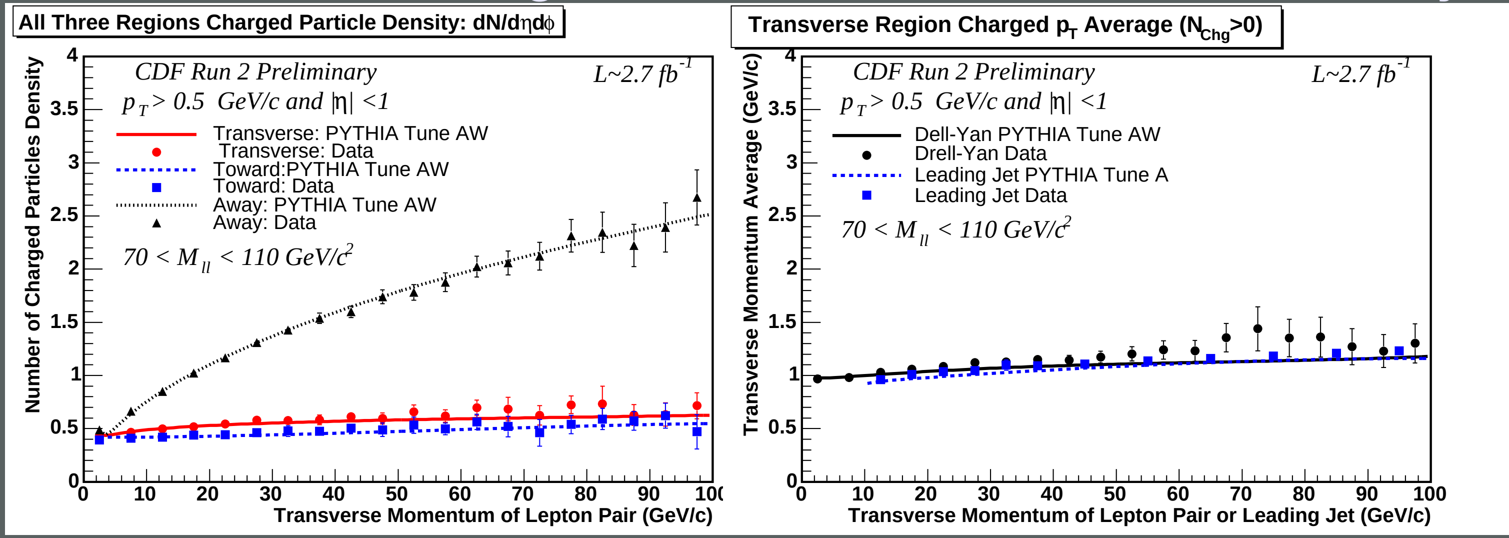
→ in this analysis, everything except $l\bar{l}$ (easy to remove) in final state is underlying event

→ Drell-Yan events very clean probe of underlying event

→ Study of UE observables for $70 < M_{l\bar{l}} < 110$ GeV in DY and comparison to leading-jet UE

→ "Transverse" region most sensitive to UE in DY and jets





→ UE observables constant with lepton-pair P_T in "Transverse" and "Toward"

→ UE observables increase with lepton-pair P_T in "Away" region

→ Adequate agreement between DY and leading-jet UE results

CDF, abstract 419, CDF/PUB/CDF/PUBLIC/9351

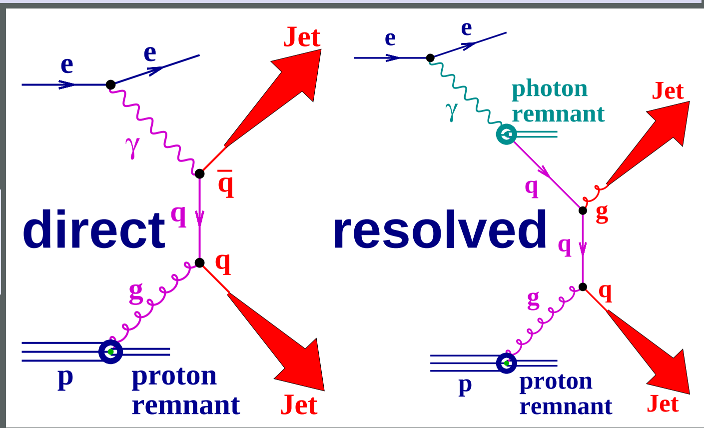
Underlying event: multijets in photoproduction

- Photoproduction at LO $\longrightarrow$

$$x_\gamma^{\rm obs} = \frac{1}{E_\gamma}(\sum_{\rm jets} E_T^{\rm jet} e^{-\eta^{\rm jet}})$$

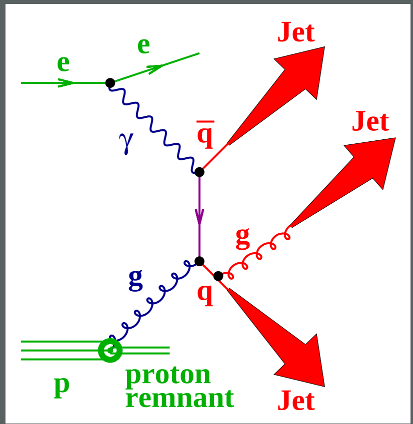
direct: $x_\gamma^{\rm obs} \sim 1$

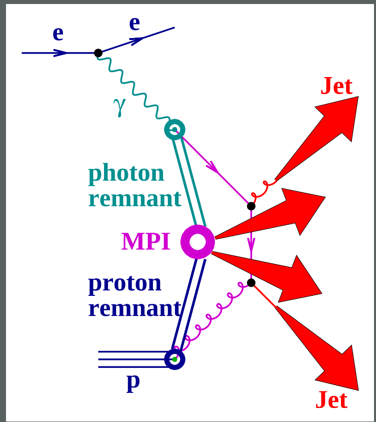
resolved: $x_\gamma^{\rm obs} < 1$

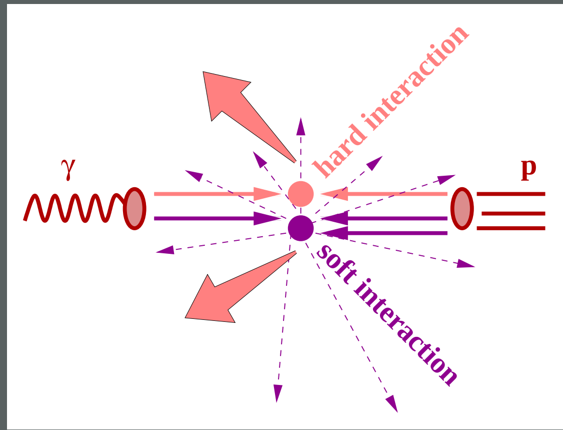


- Measurements of multijet cross sections in PHP allow tests of

multijet production — multiparton interactions — soft underlying event



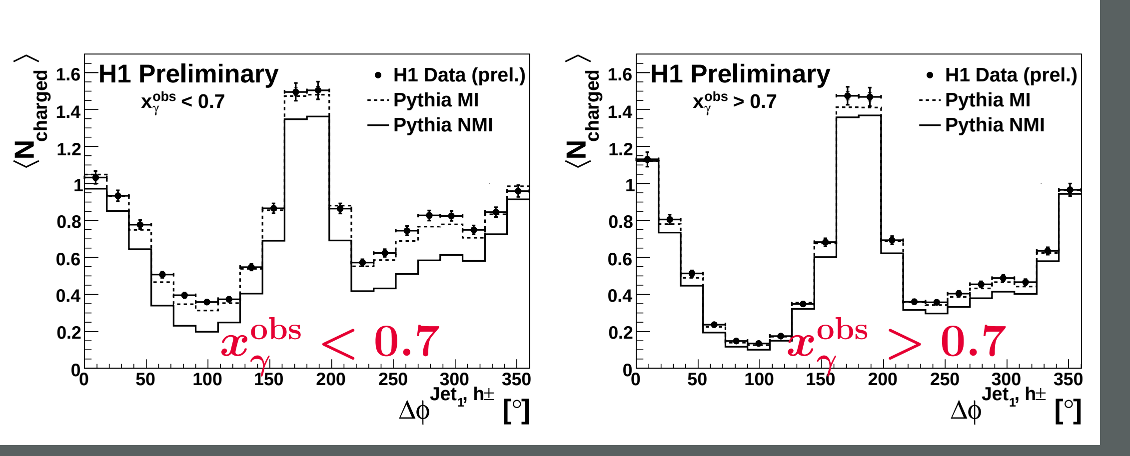




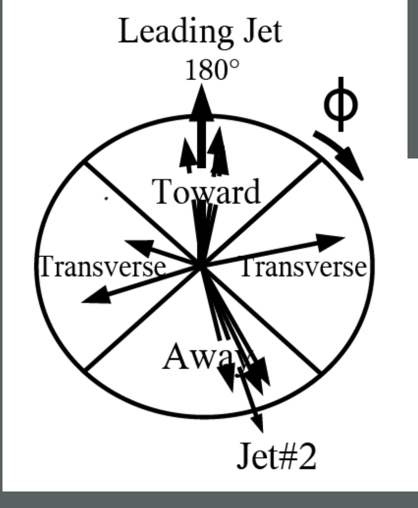
- Multijet production is directly sensitive to high orders: $\sigma_{\rm 3jet} \propto \alpha_s^2$
- Test of parton showers in Monte Carlo models
- Sensitivity to multiparton interactions/underlying event $\longrightarrow$ test/tune models

Underlying event: dijets in photoproduction

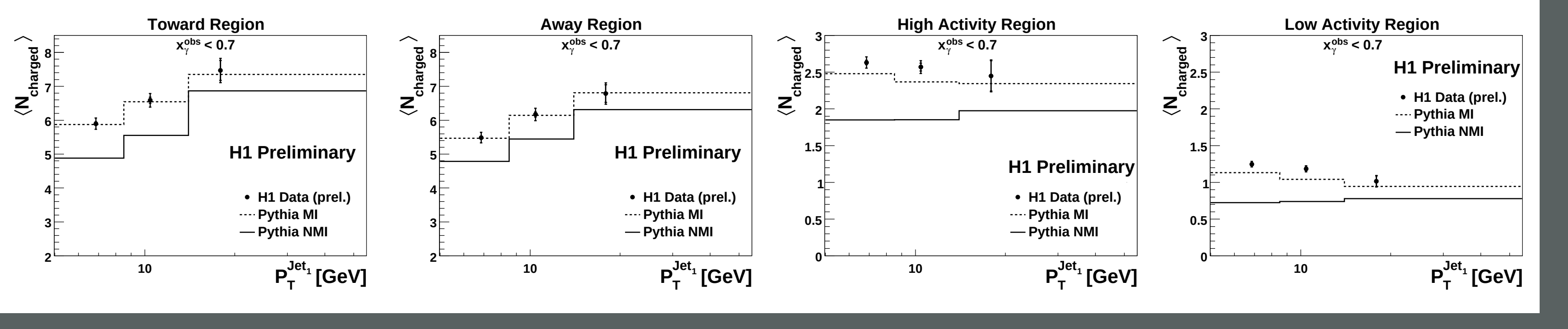
- In dijets in PHP, the UE (defined as everything except the two leading jets) can be studied similarly as at TevaTron



- **Jet profiles:** mean charge multiplicity as a function of $\Delta\phi$ wrt leading jet $\longrightarrow$ large UE contribution expected for $x_\gamma^{obs} < 0.7$ (hadronic-like)



- Mean charge multplicity vs leading E_T^{jet} for $x_\gamma^{obs} < 0.7$



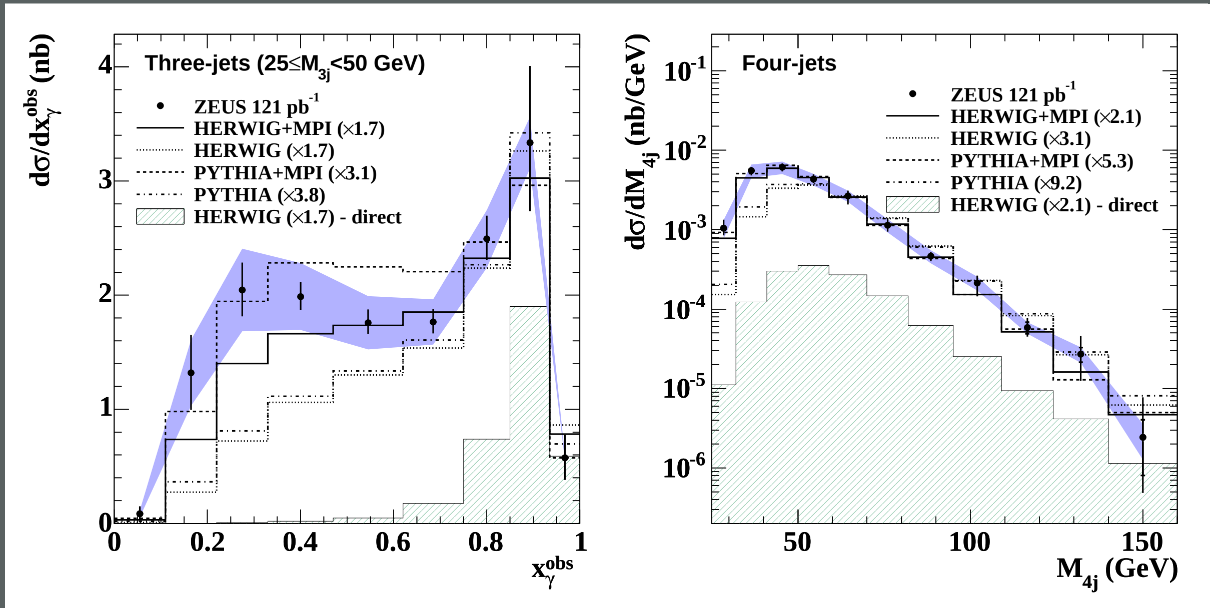
$\longrightarrow$ In "toward" and "away" regions $\langle N_{ch} \rangle$ increases with increasing leading E_T^{jet}

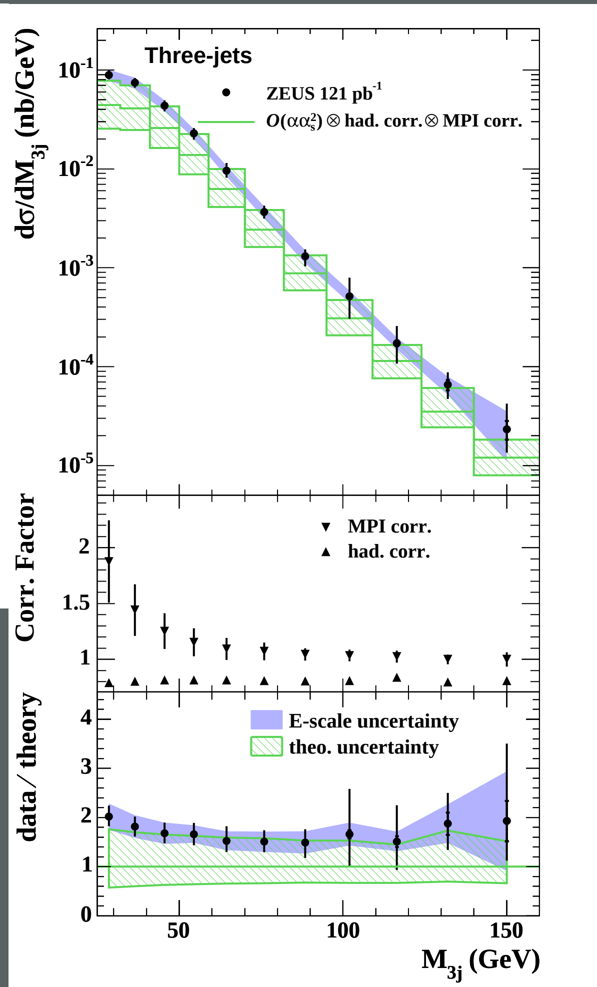
$\longrightarrow$ In "high"/"low" activity (highest/lowest-E_T density) regions, $\langle N_{ch} \rangle$ decreases

$\longrightarrow$ Inclusion of MPIs improves description of data in all regions for $x_\gamma^{obs} < 0.7$

H1, abstract 849, H1-prelim-08-036

Underlying event: multijets in photoproduction





PYTHIA MPI (simple model: $p_T^{\min(\mathrm{mpi})} = 4.5(1.9)$ GeV)

HERWIG MPI (JIMMY model $p_T^{\min(\mathrm{mpi})} = 4.0(2.2)$ GeV)

→ HERWIG tuned to x_γ^{obs} data

→ MC models without MPI describe data at high M_{nj} for all x_γ^{obs}, but fail at low M_{nj} and low x_γ^{obs} values

→ MC models with MPI describe data in full range

→ MPI corrections improve description of data by pQCD calculations (LO)

→ corrections increase as $M^{3\mathrm{j}}$ decreases

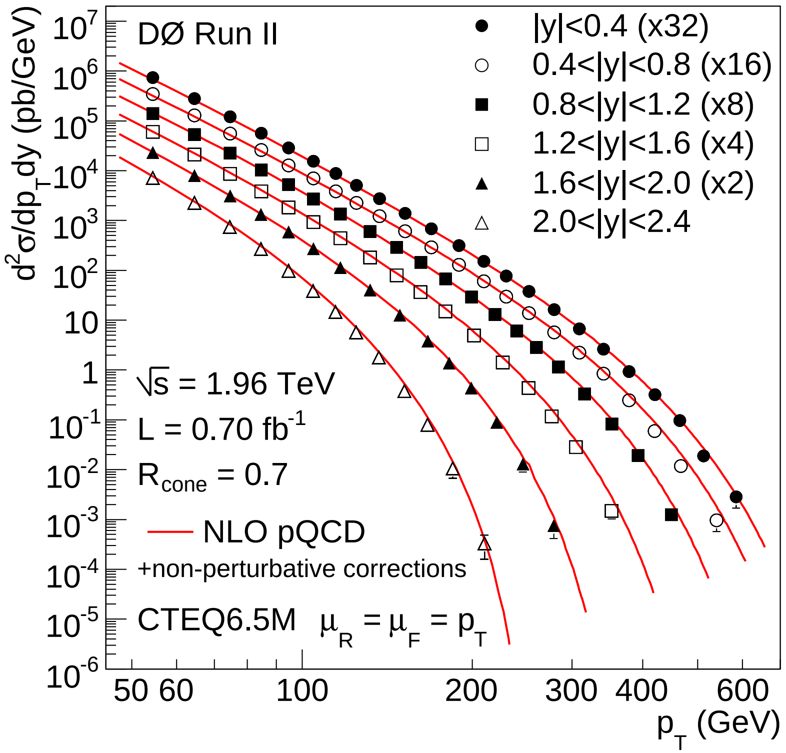
ZEUS, abstract 130, NPB 792 (2008) 1

Probing pQCD at the highest energies...

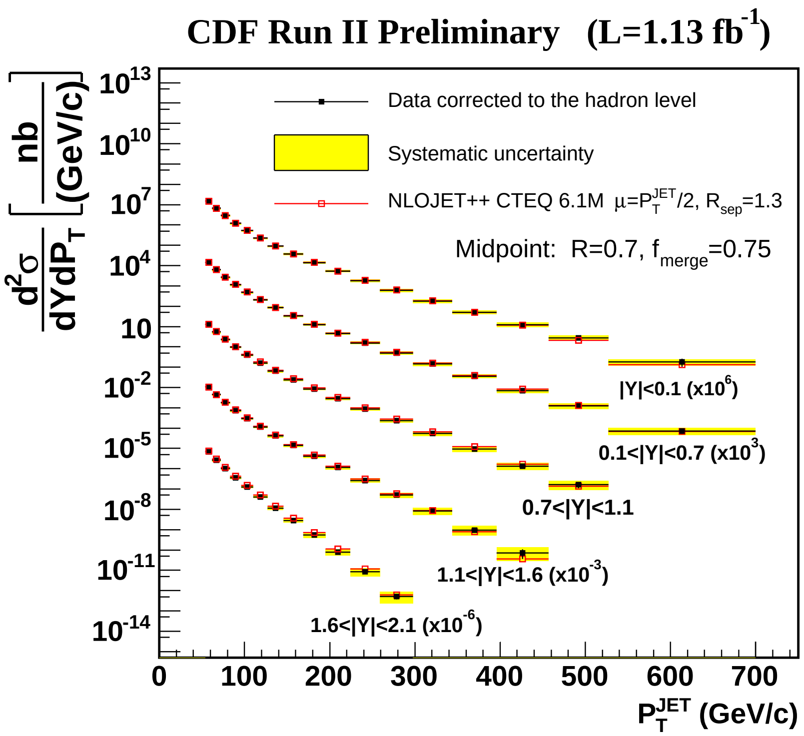
Jet cross sections at TevaTron

- Inclusive-jet cross sections in $p\bar{p}$ collisions: high precision measurements at high $E_T^{\rm jet}$, where new physics might show up (and sensitive to g PDF at high x)

DØ



CDF



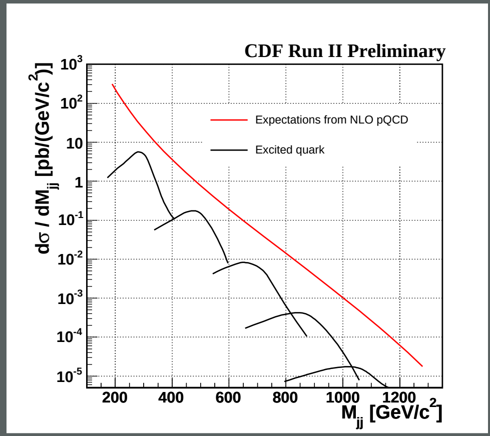
→ Good description of data by NLO QCD calculations

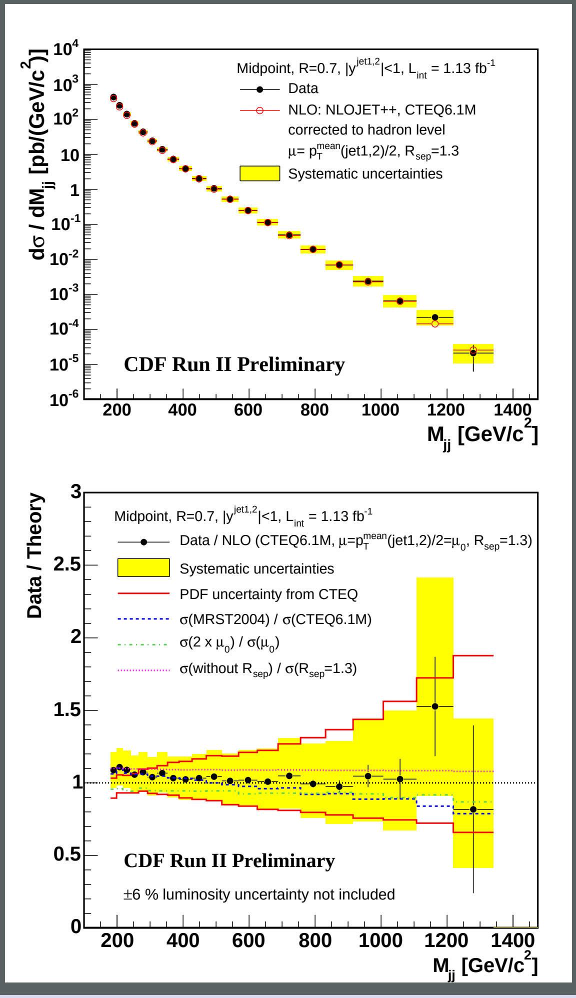
→ These measurements constitute the most stringent test of pQCD at highest available energies

DØ, abstract 506, hep-ex/0802.2400 CDF, abstract 452, CDF/DOC/JET/PUBLIC/8928

Jet cross sections at TevaTron

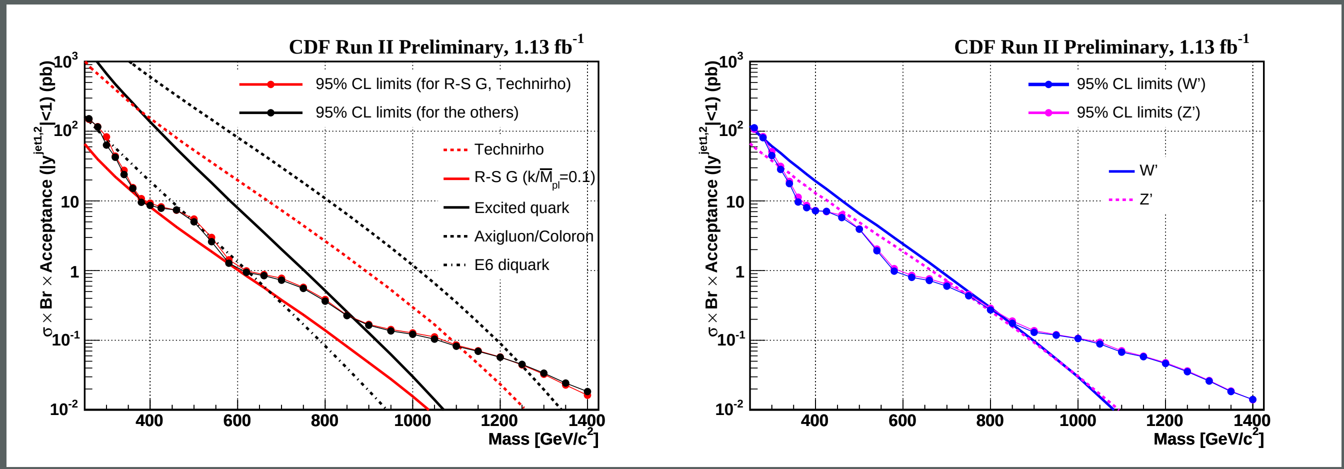
- **Jet production dominant at hadron colliders → highest reach in energy and probe of hard interactions at shortest distances**
  → dijet production ideal to test SM and search for new physics (narrow resonances in dijet mass spectrum)





→ **Good description of data by NLO QCD over whole $M^{\rm jj}$ range ($0.2 < M^{\rm jj} < 1.4$ TeV)**

→ **Set limits on new physics: excited quarks, W', Z' and gravitons**

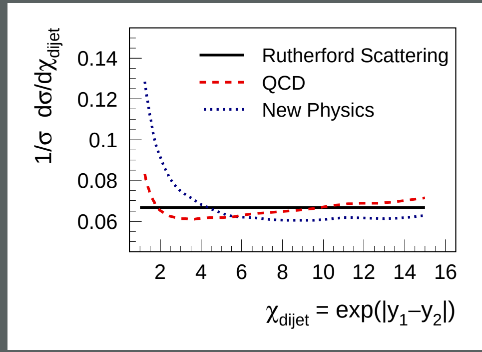


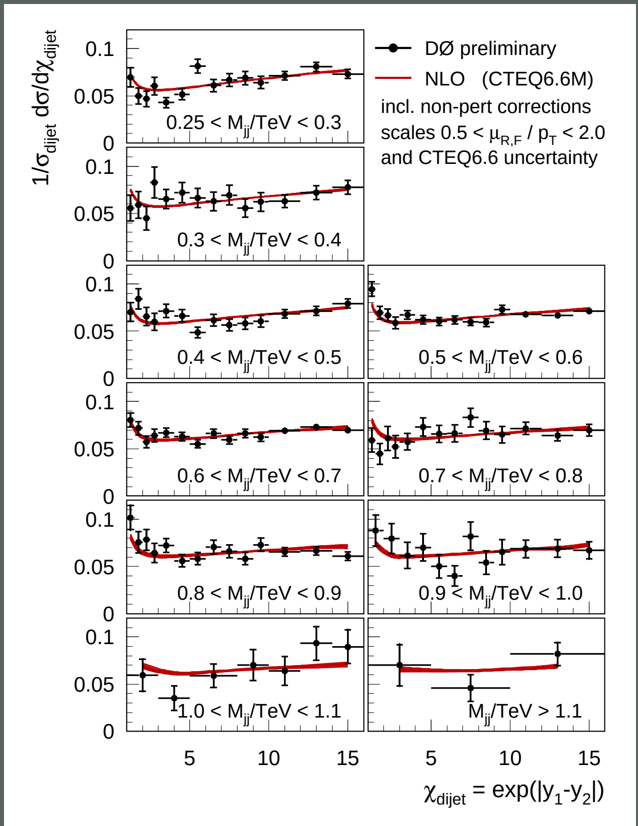
CDF, abstract 452, CDF/9246

Jet cross sections at TevaTron

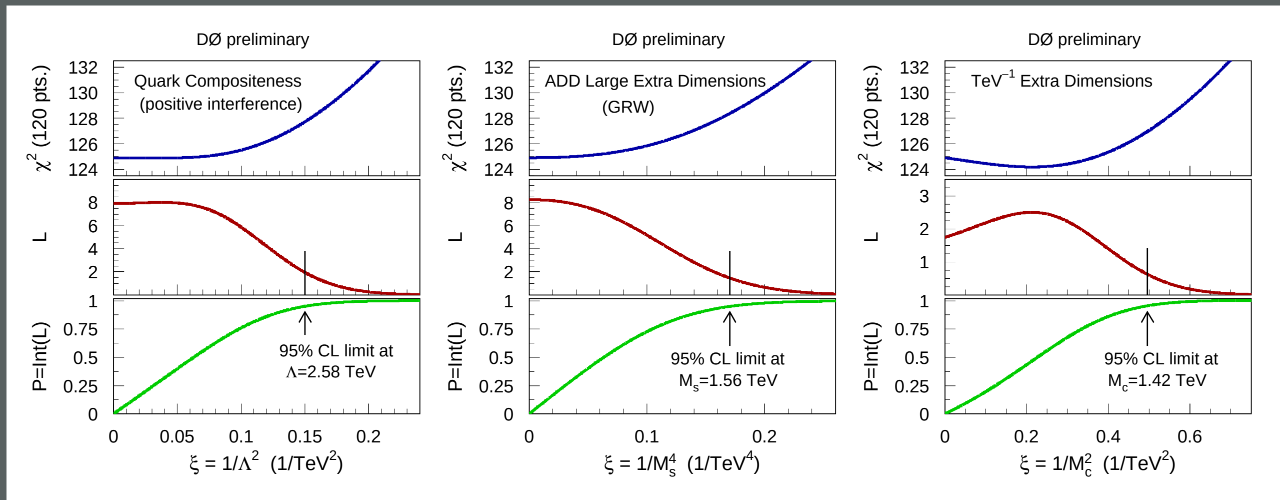
- Jet production dominant at hadron colliders ⟶ highest reach in energy and probe of hard interactions at shortest distances
  - ⟶ dijet production ideal to test SM and search for new physics
  - ⟶ angular correlations directly sensitive to underlying dynamics

$$\chi_{\rm dijets} = \exp(|y_1 - y_2|)$$





- ⟶ Good description of data by NLO QCD over whole M^{jj} range (from 0.25 to above 1.1 TeV) ($\chi^2 = 124.9/120$)
- ⟶ Set limits on new physics: quark compositeness and extra dimensions models



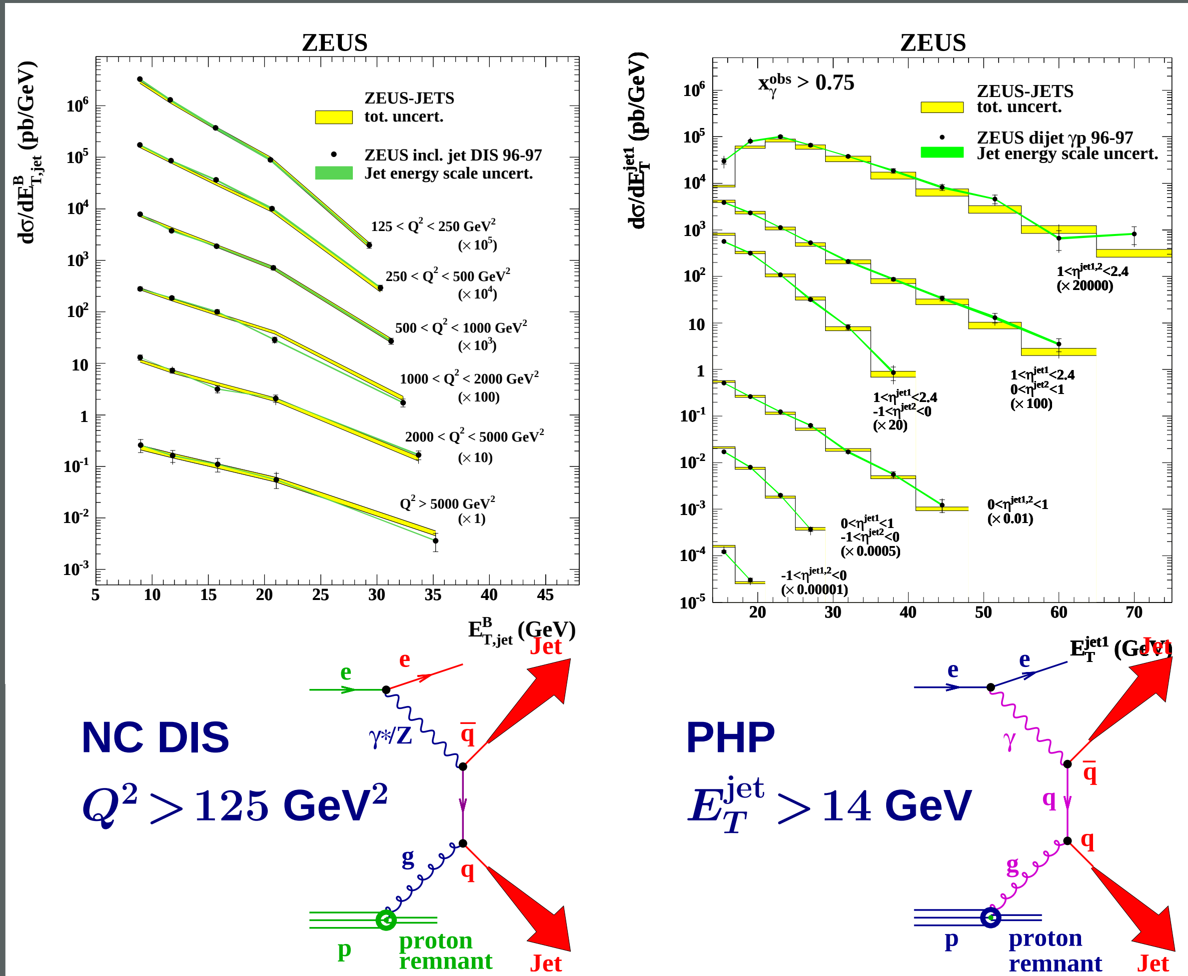
⟶ Most stringent limits from hadron colliders

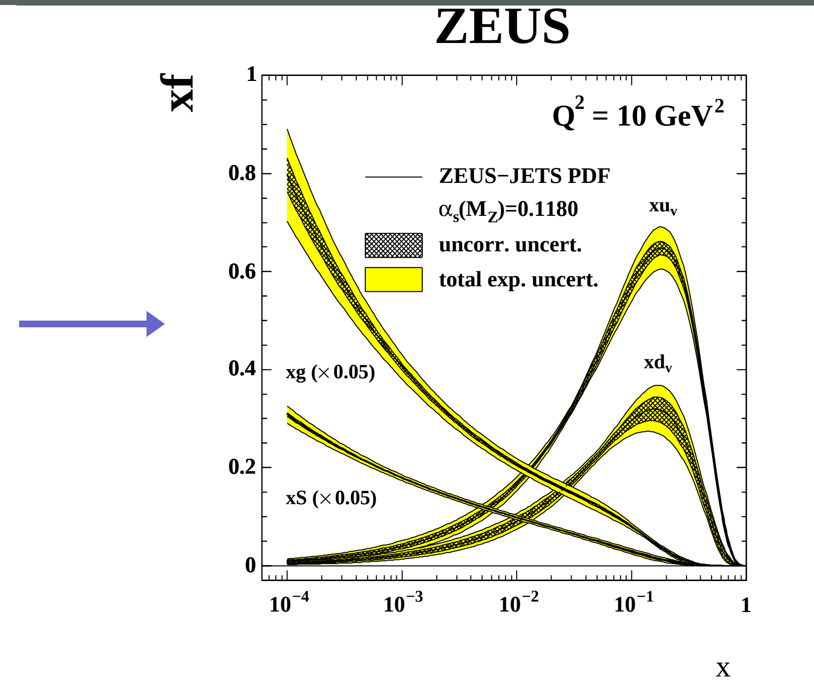
DØ, abstract 507

Precision measurements

Jets and pPDFs at HERA

- **Very precise jet cross sections in NC DIS and PHP (directly sensitive to gluon content of proton): useful to constrain gluon density, especially at mid- to high-x $\longrightarrow$ relevant at LHC energies**
- **Measurements incorporated in a QCD fit to determine PDFs parametrisations:**



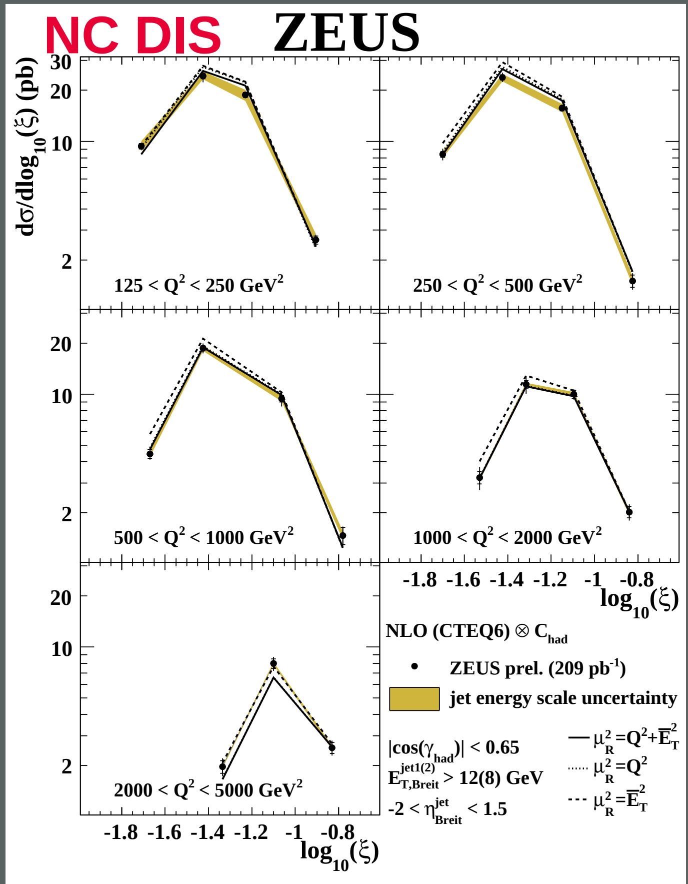


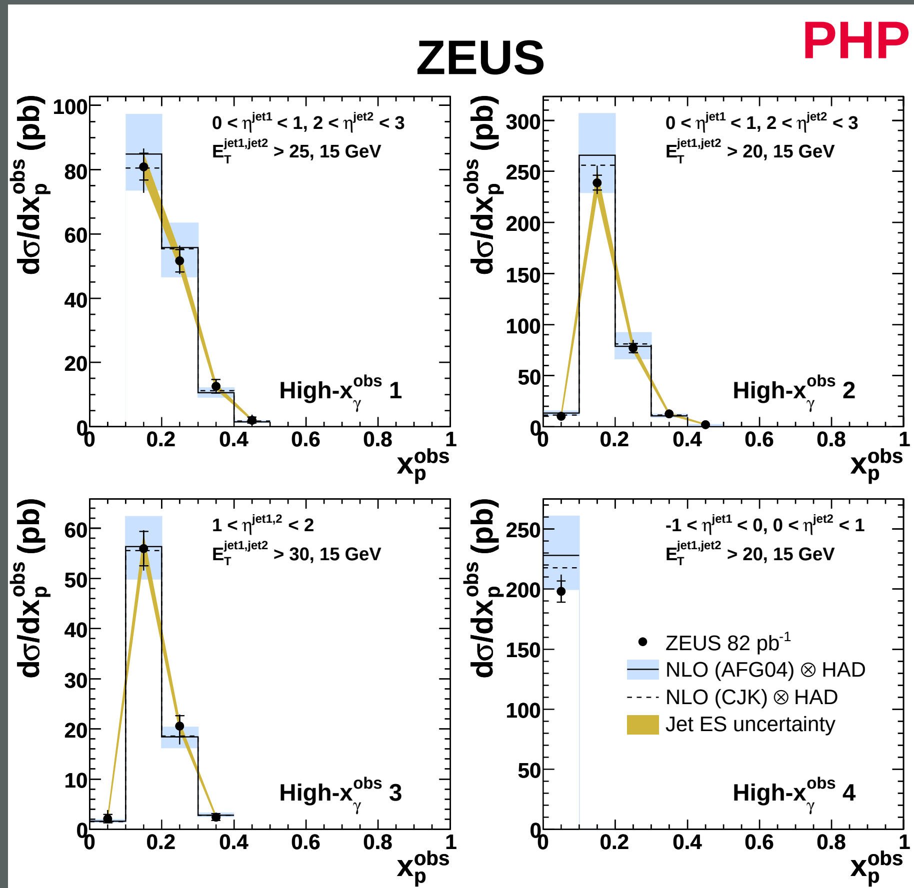
- **Improved determination of gluon density: uncertainty reduced by up to factor of 2 for mid- to high-x**

ZEUS, EPJ C 42 (2005) 1

Jet cross sections at HERA

- **Dijet cross sections in NC DIS and photoproduction as a function of ξ and x_p^{obs}, both estimators of the fractional momentum carried by the struck parton**





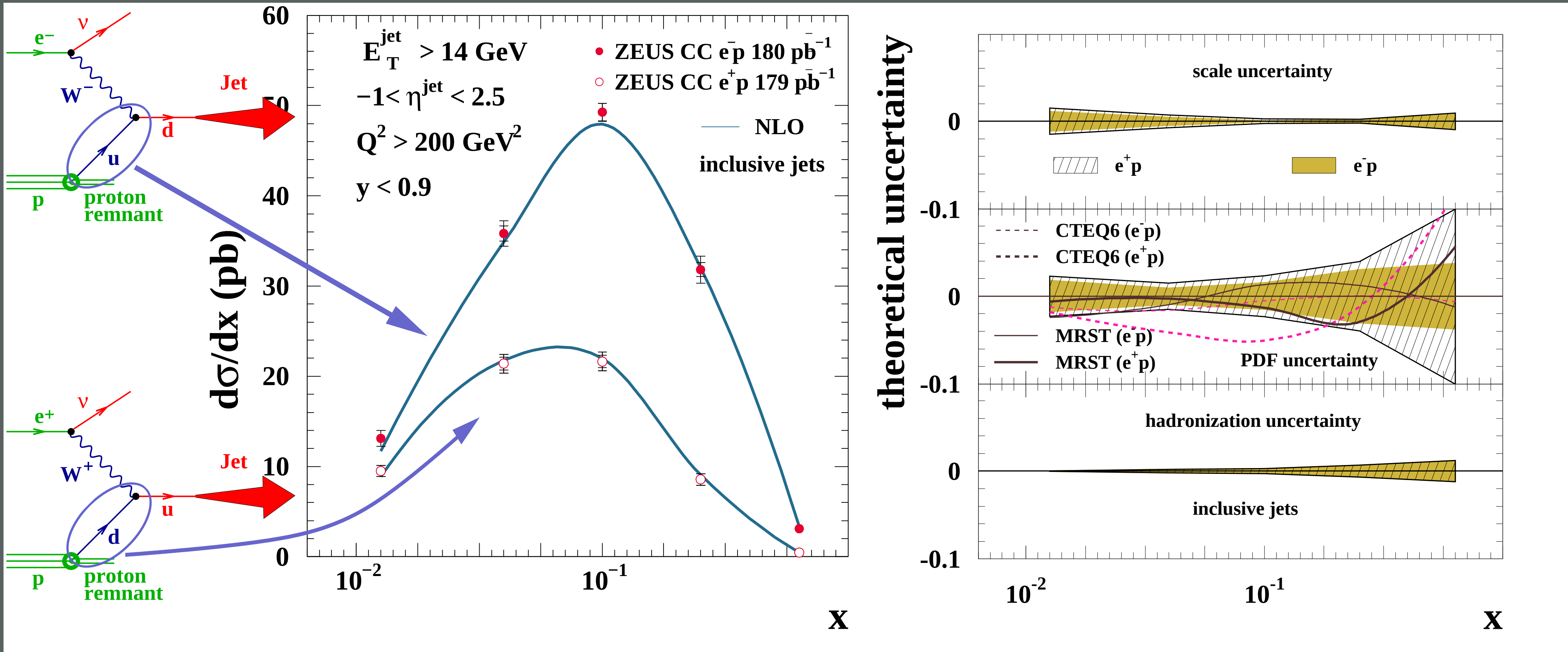
$\longrightarrow$ **Good description of data by NLO QCD calculations**

$\longrightarrow$ **Measurements optimised for best sensitivity to gluon density**

ZEUS, abstract 143, ZEUS-prel-07-005 ZEUS, abstract 125, PRD 76 (2007) 072011

Jet cross sections at HERA

- Inclusive-jet cross sections in charged-current deep inelastic $e^{\pm}p$ scattering:



→ Good description of data by NLO QCD calculations

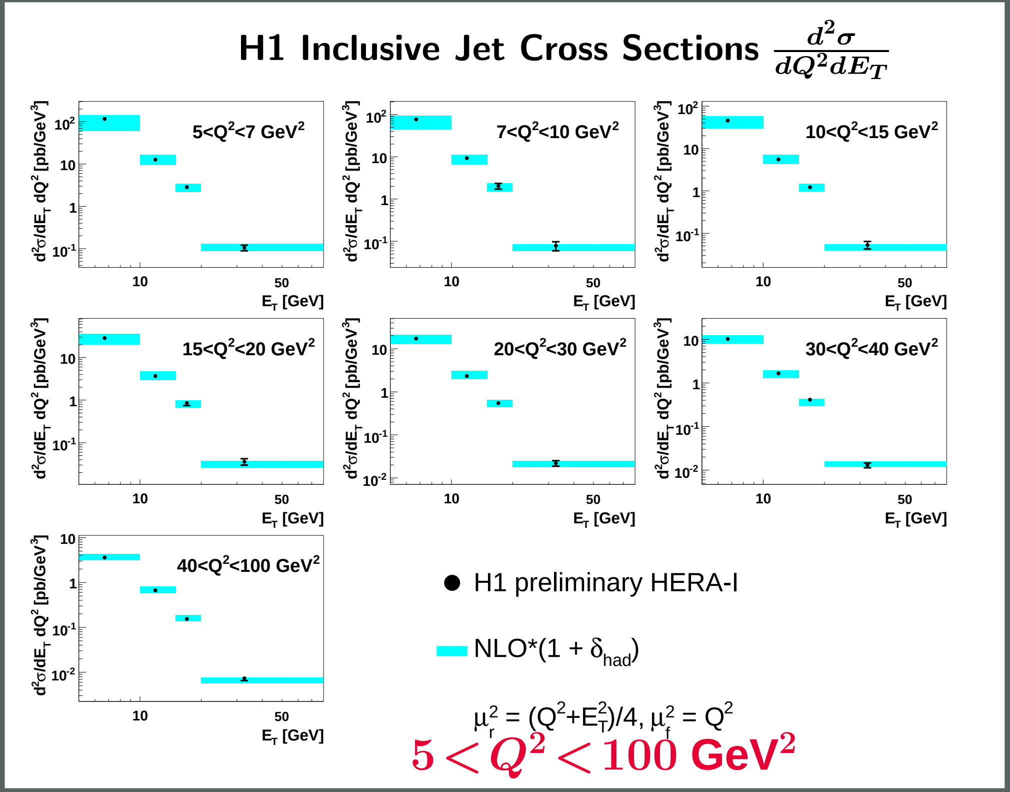
→ Theoretical uncertainties dominated by PDF uncertainty

→ measured cross sections can help to constrain further u and d PDFs

ZEUS, abstract 132, hep-ex/0802.3955

Jet cross sections at HERA

- **Double-differential inclusive-jet cross sections in NC DIS at low Q^2:**



→ Good description of data by NLO QCD calculations

→ theoretical uncertainty dominated by terms beyond NLO

→ μ_R and μ_F variation yields up to 30% uncertainty at lowest Q^2

→ need NNLO calculations!

→ constrain on gluon PDF at low Q^2 when higher-order calculations available

H1, abstract 845, H1-prelim-08-032

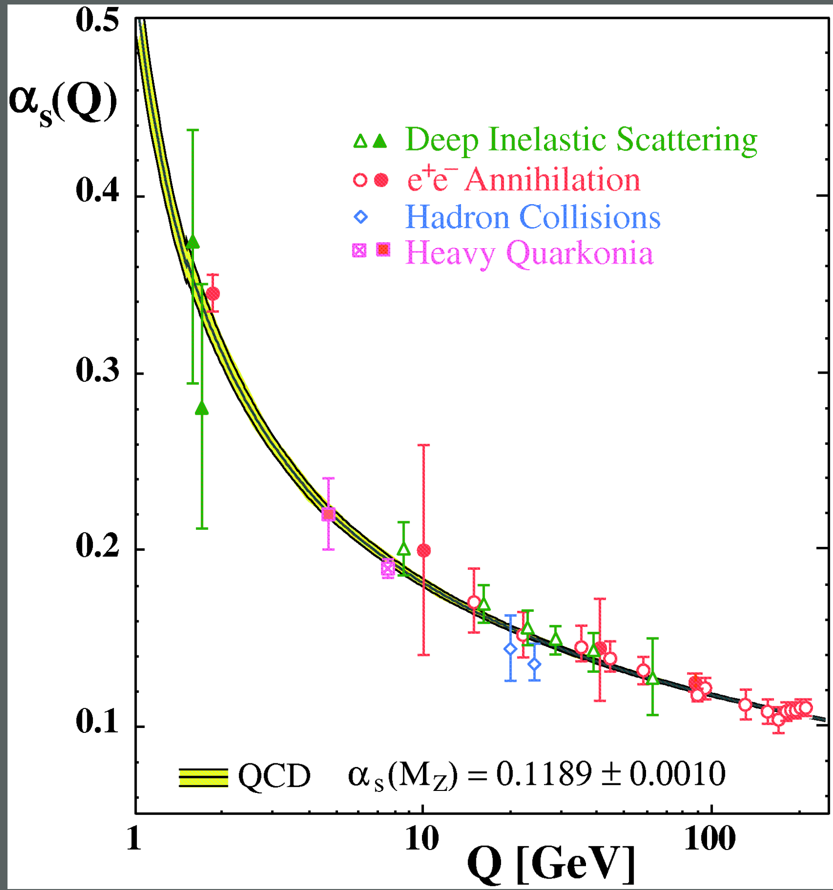
The strong coupling constant α_s

- The strong coupling constant, α_s, is one of the fundamental parameters of QCD
- However, its value is not predicted by the theory and must be determined from experiment
- The success of pQCD lies on precise and consistent determinations of α_s from diverse phenomena:
  structure functions, τ decay, Z line shape, lattice, jets,...

- **Current world average:**

$$0.1189 \pm 0.0010$$

S Bethke, hep-ex/0606035



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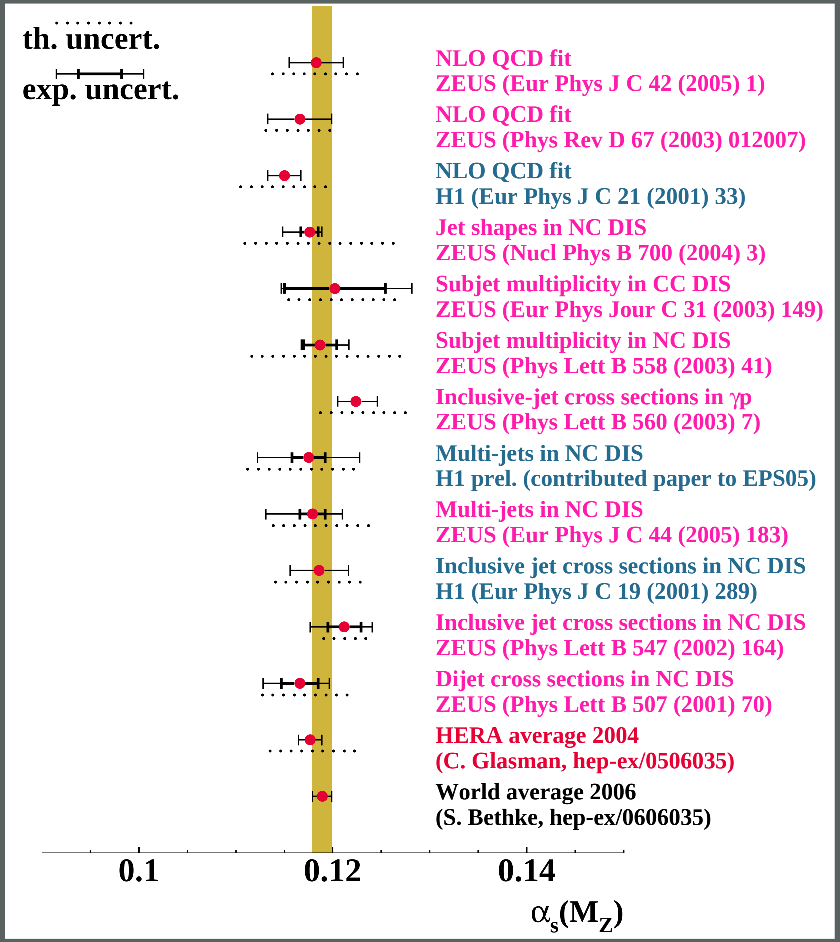
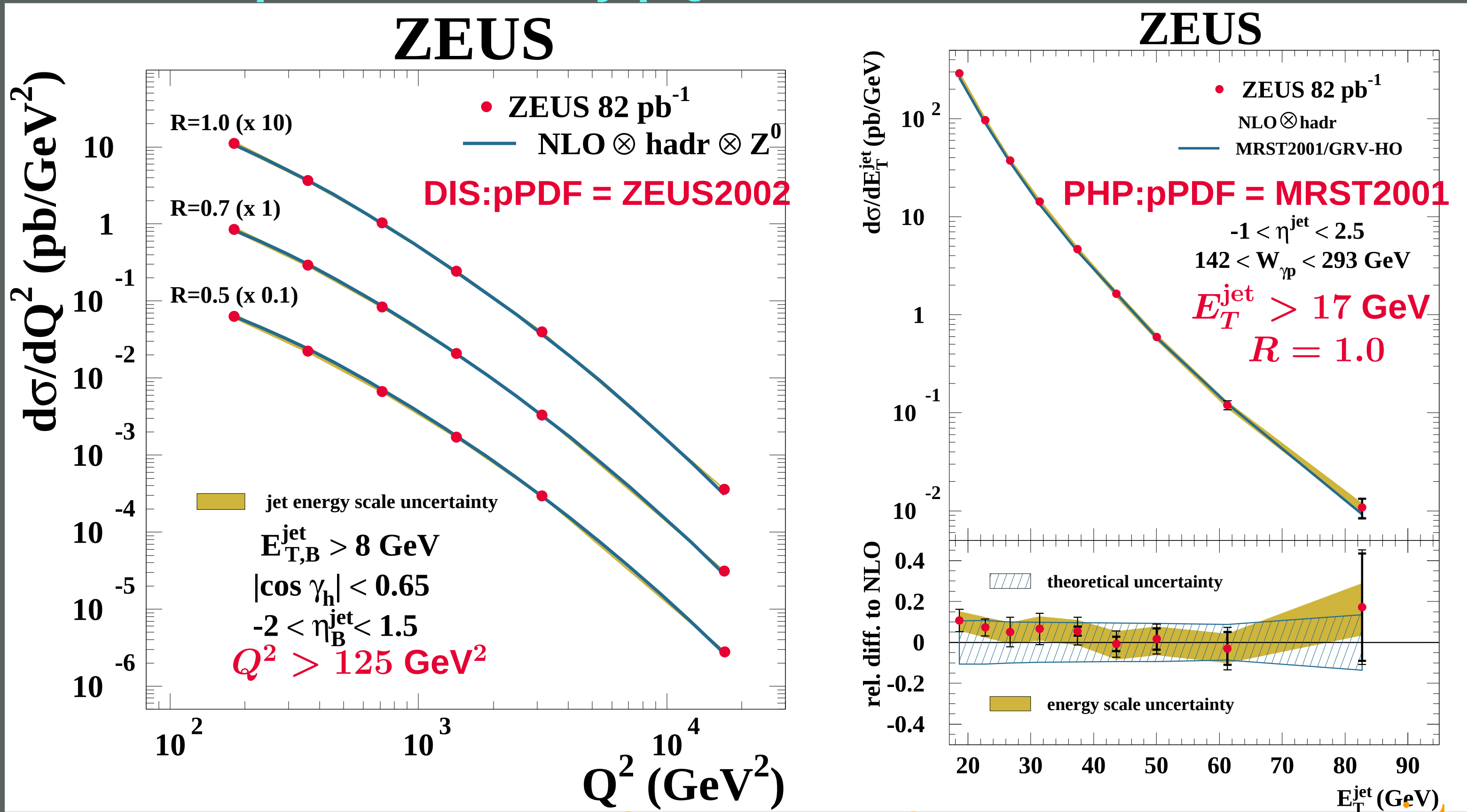


- Observables resulting from jets at HERA lead now to determinations of α_s as precise as those from more inclusive measurements

Jet cross sections at HERA

- Inclusive-jet cross sections in NC DIS and photoproduction (k_T algorithm)
  $\rightarrow$ good description of data by pQCD for $R=0.5-1.0$ with similar accuracy



- From the measured NC DIS ($Q^2>500$ GeV^2, $R=1$) and PHP ($E_T^{jet}>17$ GeV) cross sections precise values of α_s have been extracted:

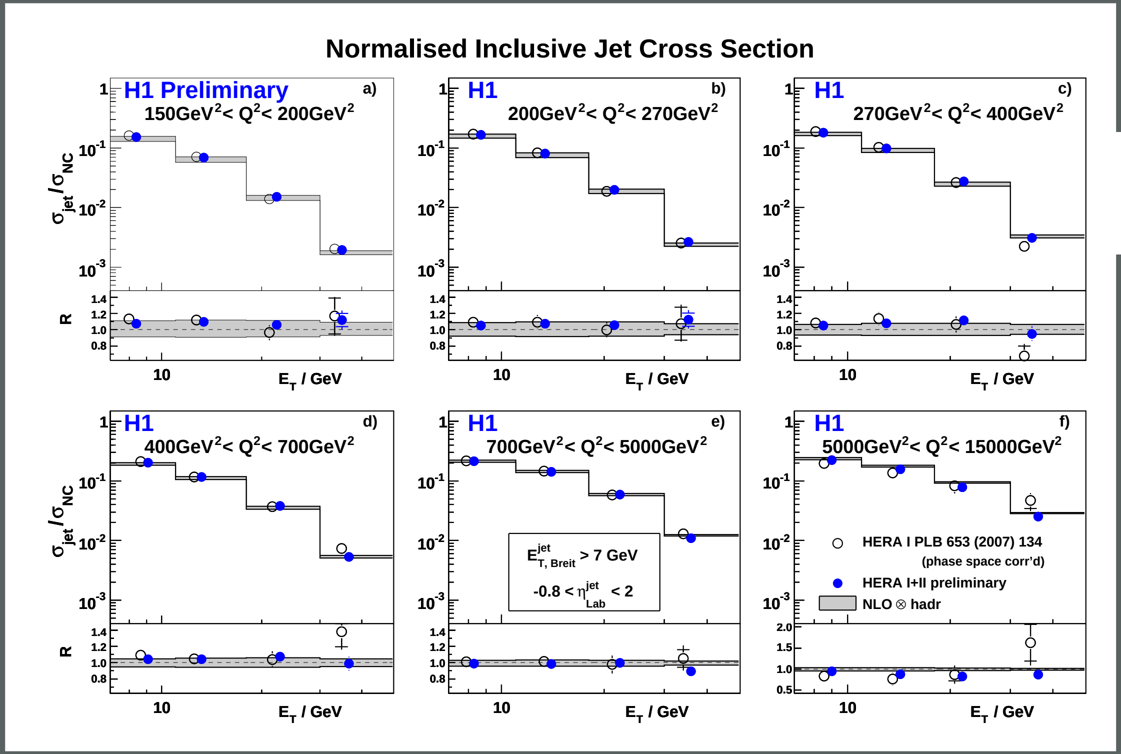
$$\alpha_s(M_Z)=0.1207\pm0.0037(\text{exp})\pm0.0022(\text{th}) \qquad \alpha_s(M_Z)=0.1223\pm0.0022(\text{exp})\pm0.0030(\text{th})$$

$\rightarrow$ total uncertainty: $\pm3.6(3.1)\%$; theoretical uncertainty: $\pm1.9(2.5)\%$

ZEUS, abstract 121, PLB 649 (2007) 12 ZEUS, abstract 152, ZEUS-prel-08-008

Jet cross sections at HERA

- Normalised inclusive-jet cross sections in NC DIS in different regions of Q^2
  $\longrightarrow$ cancellation of correlated uncertainties; good description of data by pQCD



pPDF = CTEQ6.5M

$150 < Q^2 < 15000$ GeV^2

- From the measured NC DIS ($5 < Q^2 < 100$ GeV^2 and $150 < Q^2 < 15000$ GeV^2) cross sections values of α_s have been extracted:

$\alpha_s(M_Z) = 0.1186 \pm 0.0014(\text{exp}) \pm 0.0134(\text{th})$ $\quad$ $\alpha_s(M_Z) = 0.1196 \pm 0.0010(\text{exp}) \pm 0.0053(\text{th})$

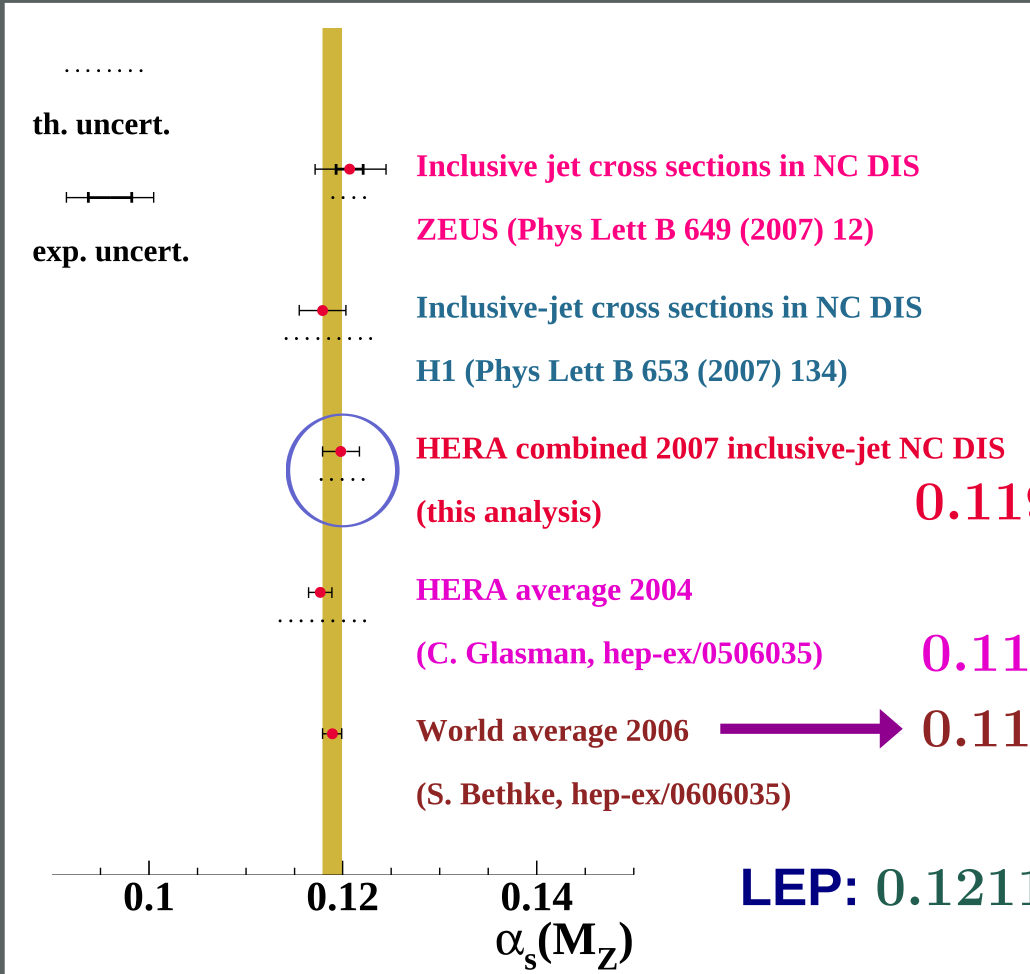
$\longrightarrow$ total uncertainty: $\pm 11.4(4.5)\%$; experimental uncertainty: $\pm 1.2(0.8)\%$

H1, abstract 845, H1-prelim-08-032 H1, abstract 844, H1-prelim-08-031

HERA α_s combination

- **HERA combined 2007 $\alpha_s(M_Z)$ value:**
  - simultaneous fit to ZEUS and H1 inclusive-jet cross sections in NC DIS

$$\alpha_s(M_Z) = 0.1198 \pm 0.0019\ (\text{exp.}) \pm 0.0026\ (\text{th.})$$



Measurements consistent with each other and the world average

HERA combined 2007: $0.1198 \pm 0.0019(\text{exp}) \pm 0.0026(\text{th})$ (2.7%)

HERA average 2004: $0.1186 \pm 0.0011(\text{exp}) \pm 0.0050(\text{th})$ (4.3%)

World average 2006: 0.1189 ± 0.0010 (0.8%)

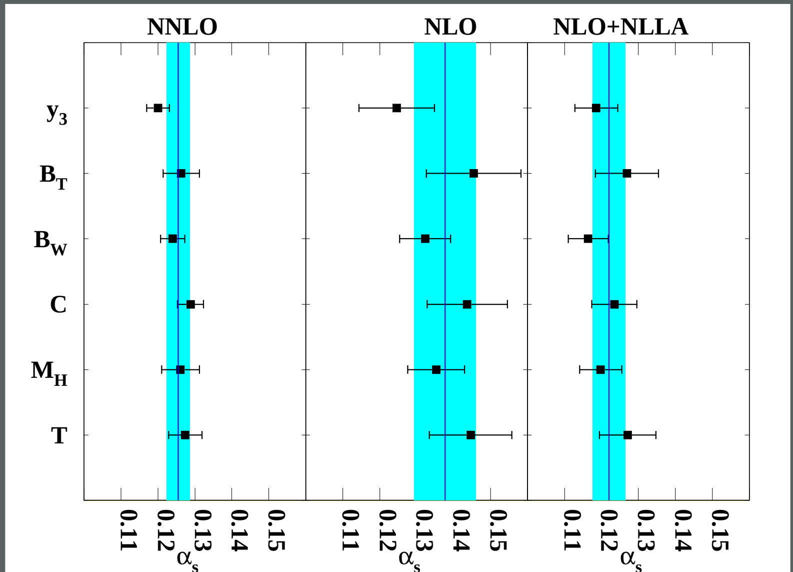
LEP: $0.1211 \pm 0.0010(\text{exp}) \pm 0.0018(\text{th})$ (1.7%)

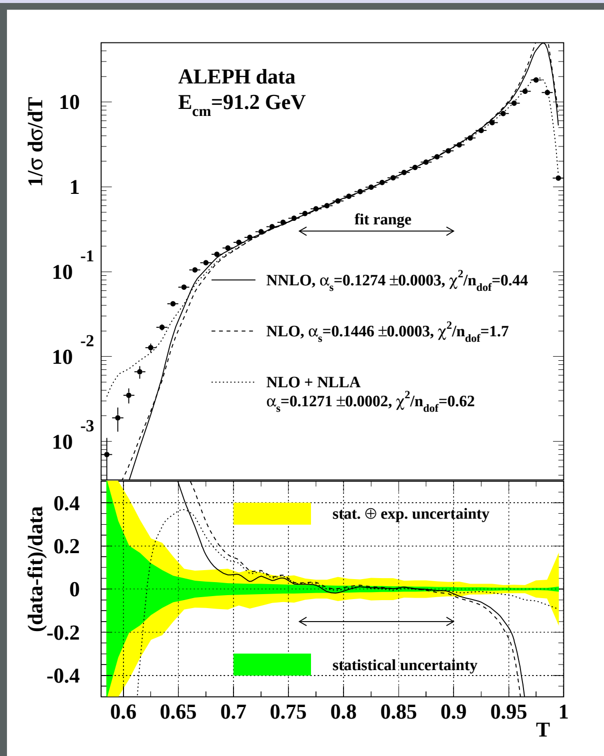
HERA α_s Working Group

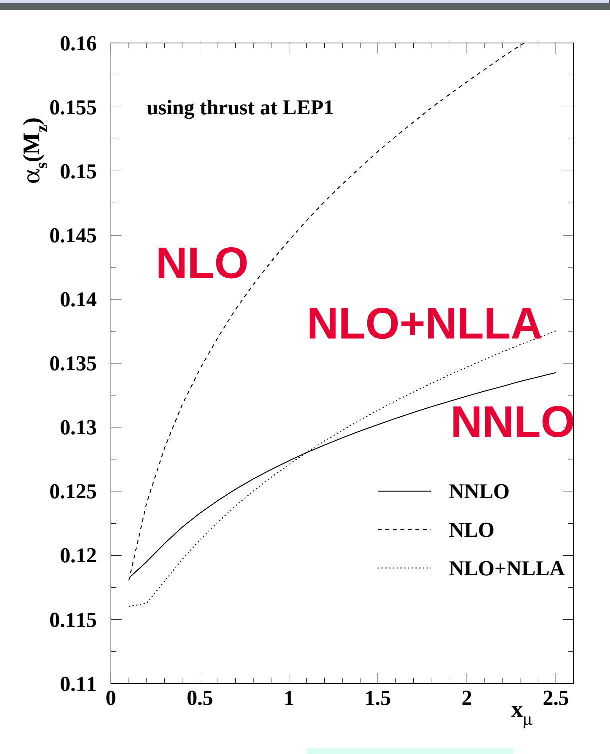
H1 and ZEUS, abstract 628, H1-prelim-07-132 and ZEUS-prel-07-025

α_s at NNLO in e^+e^-

- First extractions of $\alpha_s(M_Z)$ using NNLO calculations on event-shape observables







ALEPH

$$\alpha_s(M_Z) = 0.1240 \pm 0.0008(\text{stat}) \pm 0.0010(\text{exp}) \pm 0.0011(\text{had}) \pm 0.0029(\text{th})$$

→ Central value 10% lower wrt NLO

→ Dominant theoretical uncertainty reduced by a factor of 2 wrt NLO

→ Scatter among $\alpha_s(M_Z)$ values from different variables reduced substantially

→ Further development: using NNLO+NLLA

JADE

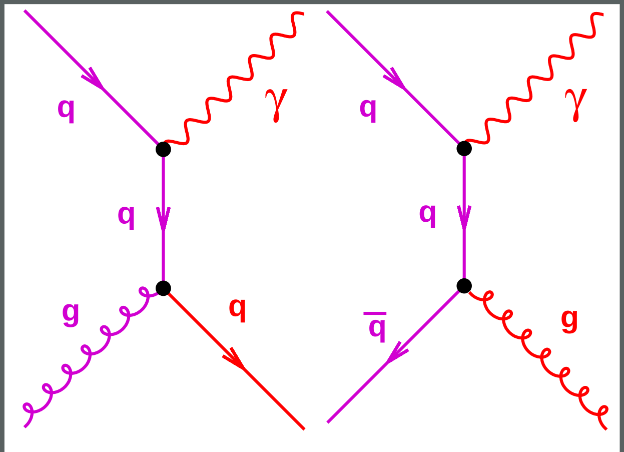
$$\alpha_s(M_Z) = 0.1172 \pm 0.0006(\text{stat}) \pm 0.0020(\text{exp}) \pm 0.0035(\text{had}) \pm 0.0030(\text{th})$$

S Bethke et al.(JADE), abstract 353 G Dissertori et al.(ALEPH), abstract 328, JHEP 0802 (2008) 040

Vector bosons: γ, W, Z (+ jets)

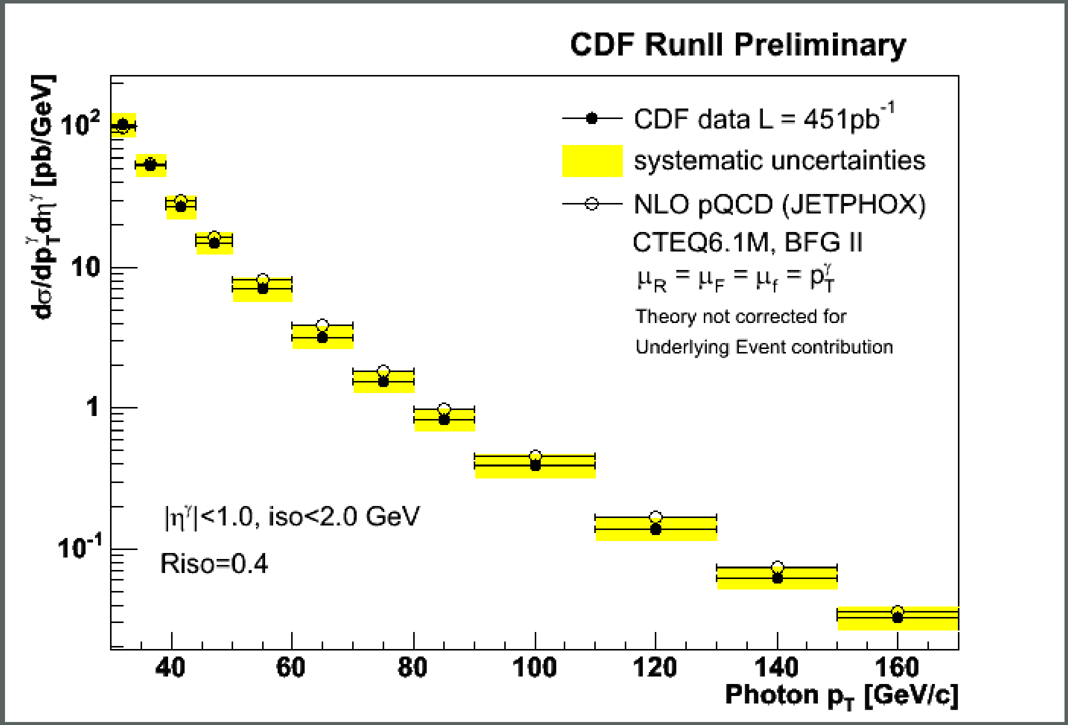
Inclusive prompt photons at TevaTron

- **Production of isolated photons:** $p\bar{p} \longrightarrow \gamma + X$



$\longrightarrow$ probe QCD dynamics with photons coming directly from hard interaction

$\longrightarrow$ largely independent of hadronisation corrections



- Understanding crucial for search of new particles decaying into photons

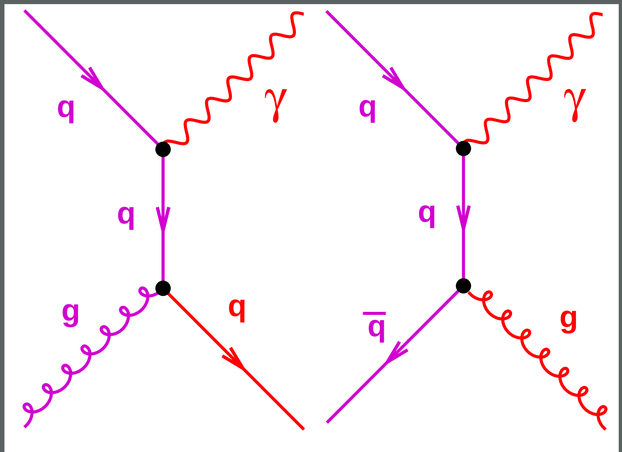
- Measurements as a function of p_T^γ integrated over η^γ $\longrightarrow$

$\longrightarrow$ NLO predictions for isolated photons describe the data within the uncertainties

CDF, abstract 411

Prompt photons + jets at TevaTron

- **Production of isolated photons in association with jets:** $p\bar{p} \rightarrow \gamma + \text{jet} + X$

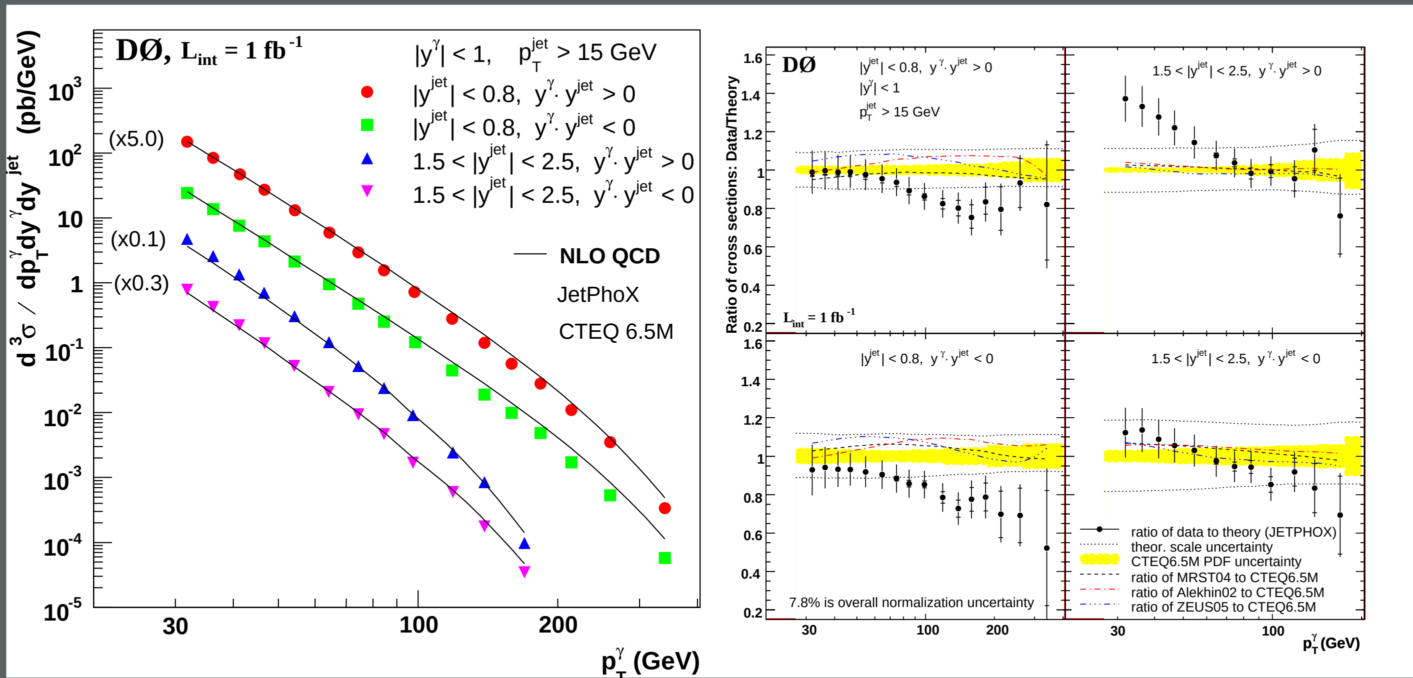


$\rightarrow$ **probe of dynamics of hard QCD interactions**

— **different angular configurations test different x and Q^2 regions $\rightarrow$ constrain on PDFs**

$0.007 \lesssim x \lesssim 0.8,\ 900 \leq Q^2 \equiv (p_T^\gamma)^2 \leq 1.6 \cdot 10^5$ **GeV**^{2}

- **Measurements as a function of p_T^γ for different photon and jet rapidities $\longrightarrow$**



$\rightarrow$ **NLO predictions with various PDF sets do not describe shape of cross section over entire measured range simultaneously**

$\rightarrow$ **an improved theoretical description of $\gamma + \text{jet}$ production is needed**

DØ, abstract 509, hep-ex/0804.1107

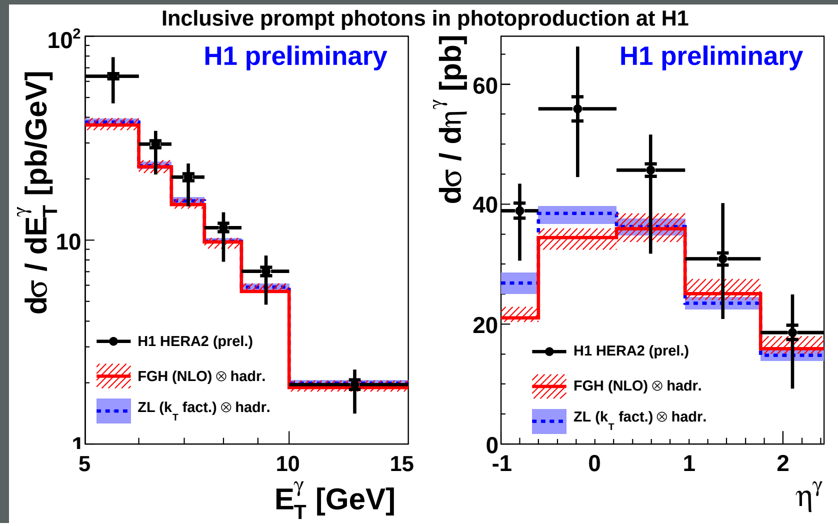
Prompt photons at HERA

- **Inclusive (exclusive) prompt photon photoproduction:** $ep \to \gamma\ (+\text{jet}) + X$

$\to$ probe of dynamics of hard QCD interactions

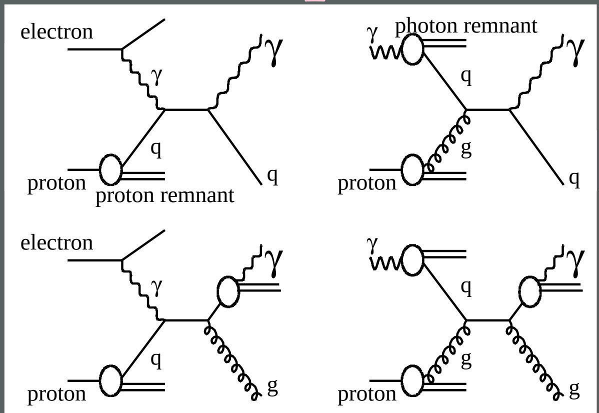
$\to$ complementary information to that from jets with smaller hadronisation corrections

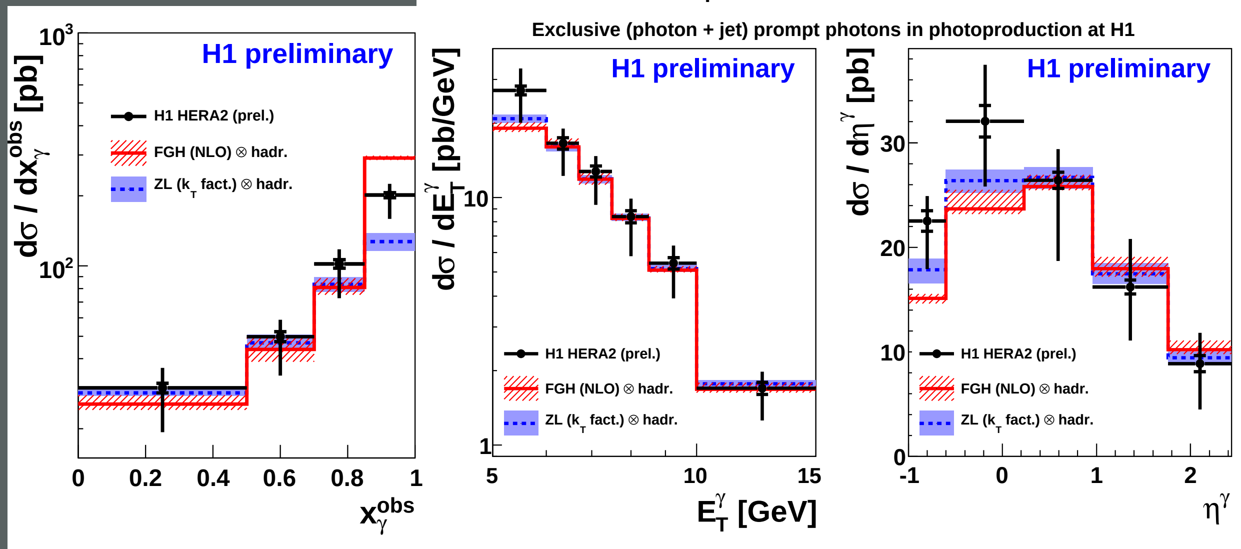
$\to$ sensitive to PDFs of both proton and photon



$\to$ **Inclusive prompt photon production:** $\longrightarrow$

$\to$ NLO calculations below data, especially at low E_T^γ and low η^γ





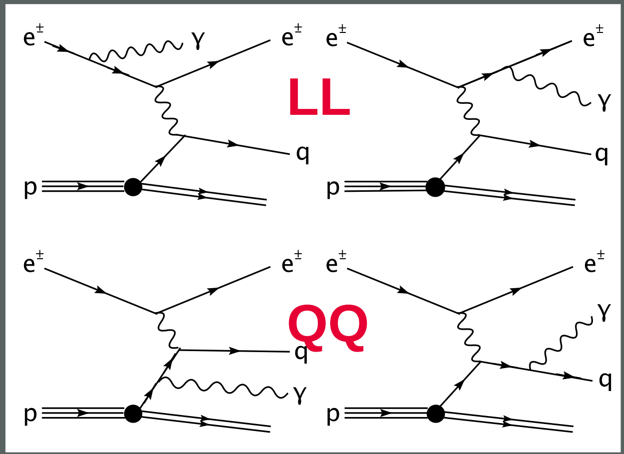
$\to$ **Exclusive prompt photon production ($\gamma + \text{jet}$):** $\longrightarrow$

$\to$ better description of data, except at high x_γ^{obs}

H1, abstract 846, H1-prelim-08-033

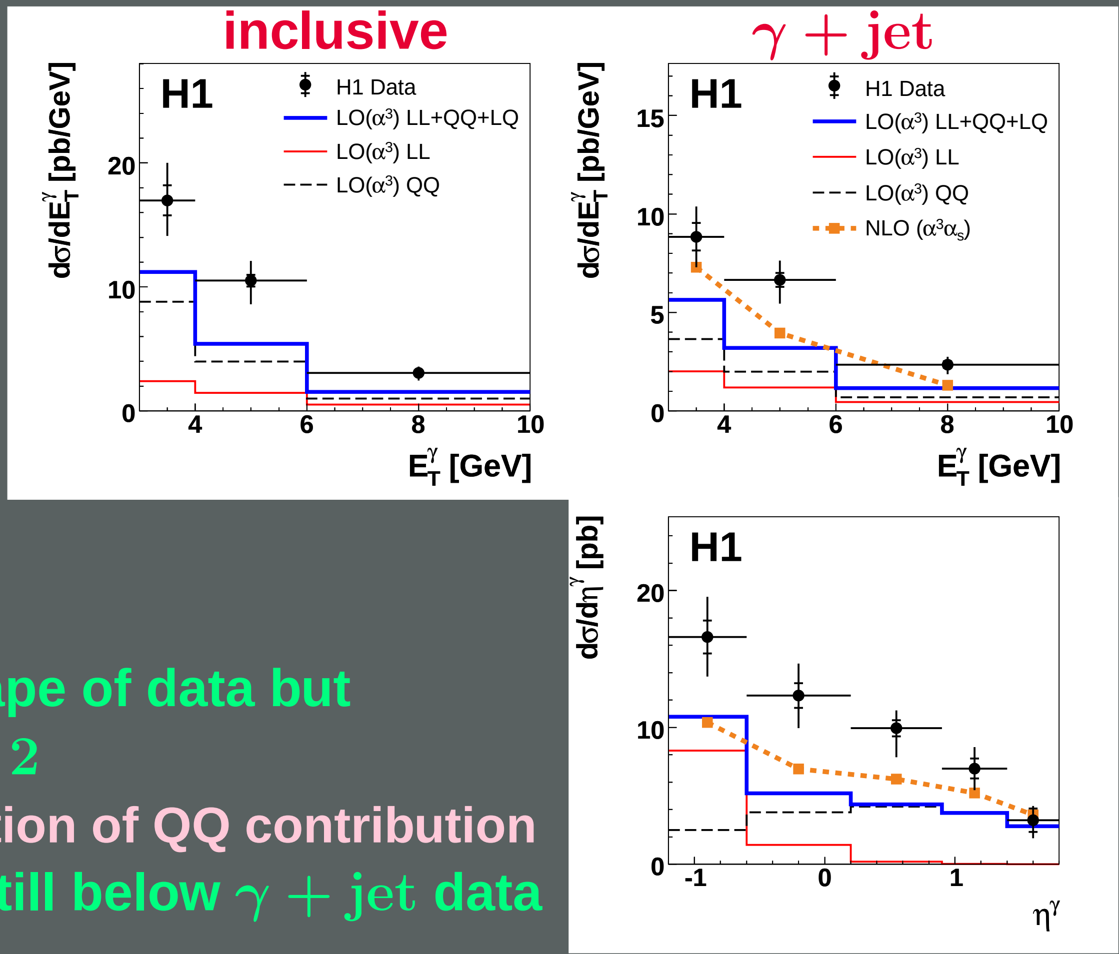
Prompt photons at HERA

- **Inclusive (exclusive) prompt photon in NC DIS:** $ep \to e\gamma\ (+\text{jet}) + X$



$\longrightarrow$ probe of dynamics of hard QCD interactions

$\longrightarrow$ photons from hard interactions largely insensitive to effects of hadronisation



- interference (LQ) small
- e and γ well separarated: low-angle QED radiation suppressed
- q to γ fragmentation suppressed by isolation requirement

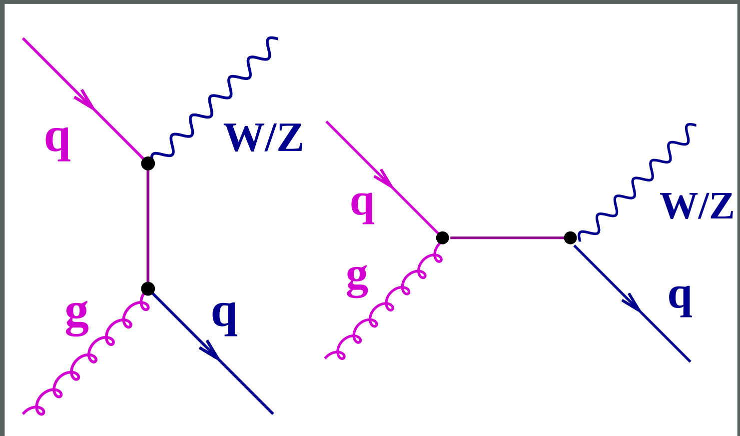
$\rightarrow$ $\mathcal{O}(\alpha^3\alpha_s^0)$ predictions describe shape of data but underestimate normalisation by ≈ 2

$\rightarrow$ can be attributed to underestimation of QQ contribution

$\rightarrow$ $\mathcal{O}(\alpha^3\alpha_s^1)$ predictions higher, but still below $\gamma + \text{jet}$ data

H1, abstract 797, EPJ C54 (2008) 371

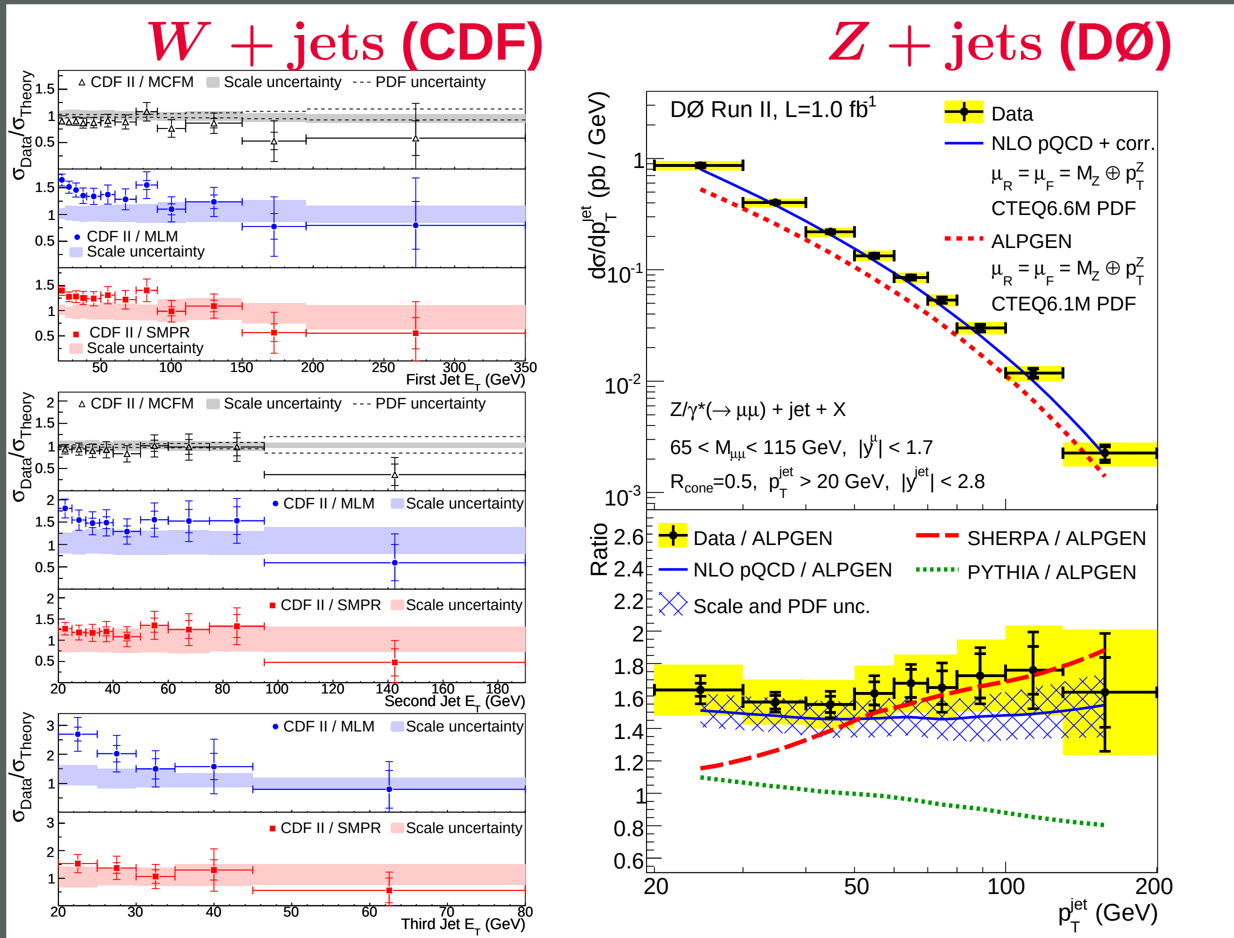
$W/Z + \text{jets}$ at TevaTron



- **Production of W/Z in association with jets**
  - $\longrightarrow$ **key signal channel for top production in SM**
  - $\longrightarrow$ **search for Higgs and new physics**
  - $\longrightarrow$ **production via QCD: stringent test of theory**

- **Irreducible background to searches**
  - $\longrightarrow$ **need precise understanding**

- **Comparison of data with NLO calculations (MCFM, up to two jets)**
  - $\longrightarrow$ **good description of the $W/Z + \text{jets}$ total and differential cross sections**

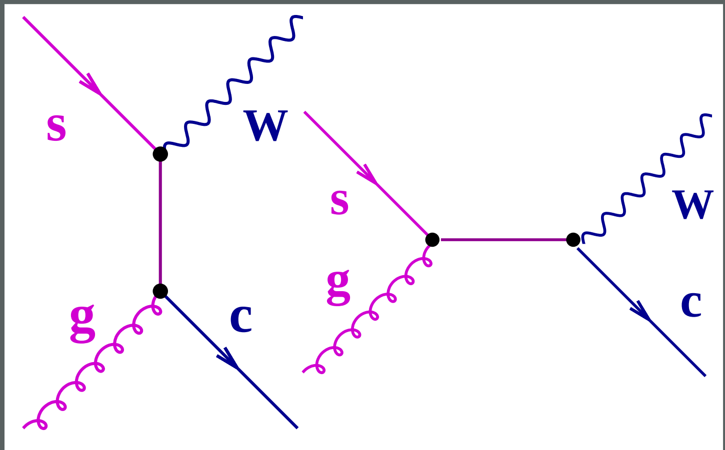


DØ, abstract 604

CDF, abstract 416, PRD 77 (2008) 011108 and PRL 100 (2008) 102001

$W + c - $ jets at TevaTron

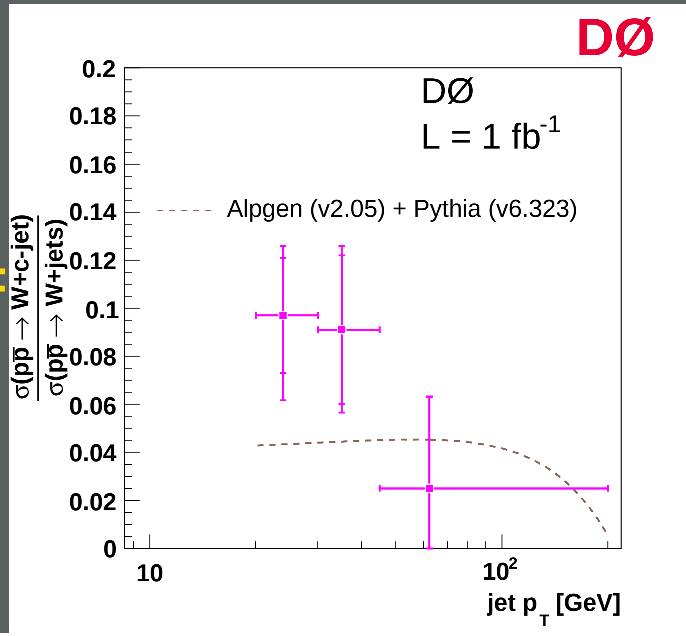
- $W + c$—jet production: dominated by $s - g$ fusion $\longrightarrow$ sensitive to V_{cs}



$\longrightarrow$ sensitive to g and s pPDFs at $\mu_R = M_W$:

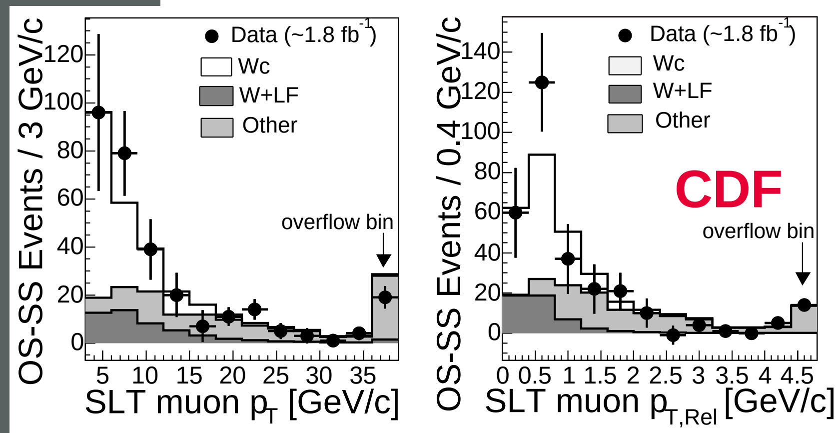
$\longrightarrow$ measurements at TevaTron test universality of sPDF and its evolution

$\longrightarrow$ background to top, Higgs, stop production and to new physics in hadron colliders



DØ: $F\left(\frac{W + c - \text{jet}}{W + \text{jets}}\right) = 0.074 \pm 0.019(\text{stat})^{+0.012}_{-0.014}(\text{syst})$

CDF: $\sigma_{Wc} \times Br(W \to l\nu) = 9.8 \pm 3.2(\text{exp})$ pb



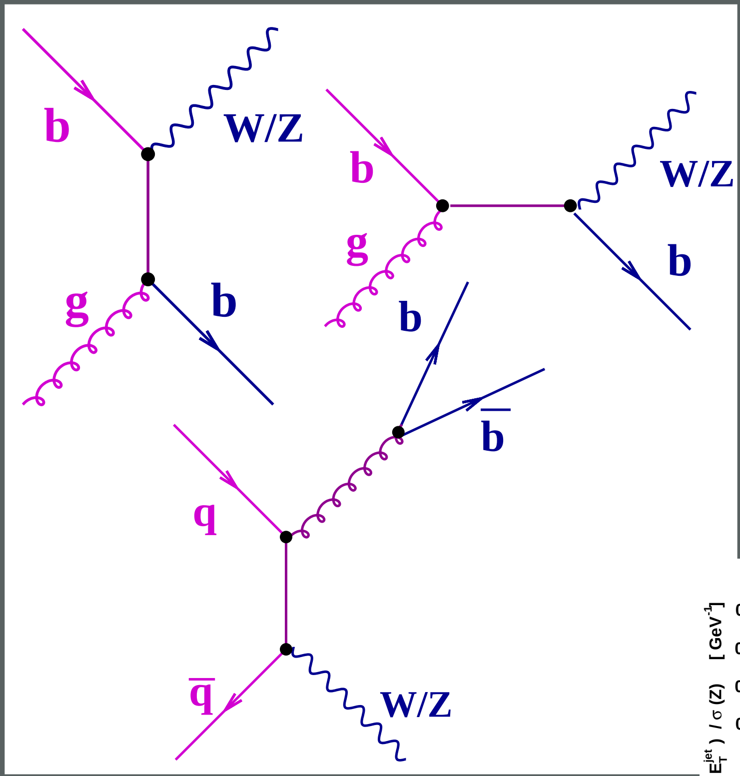
$\longrightarrow$ in agreement with predictions

$\longrightarrow$ Measurements provide direct experimental evidence of $sg \longrightarrow Wc$ process

$\longrightarrow$ Experimental validation of Wc theoretical cross section for use in searches

DØ, abstract 605, hep-ex/0803.2259 CDF, abstract 967, PRL 100 (2008) 091803

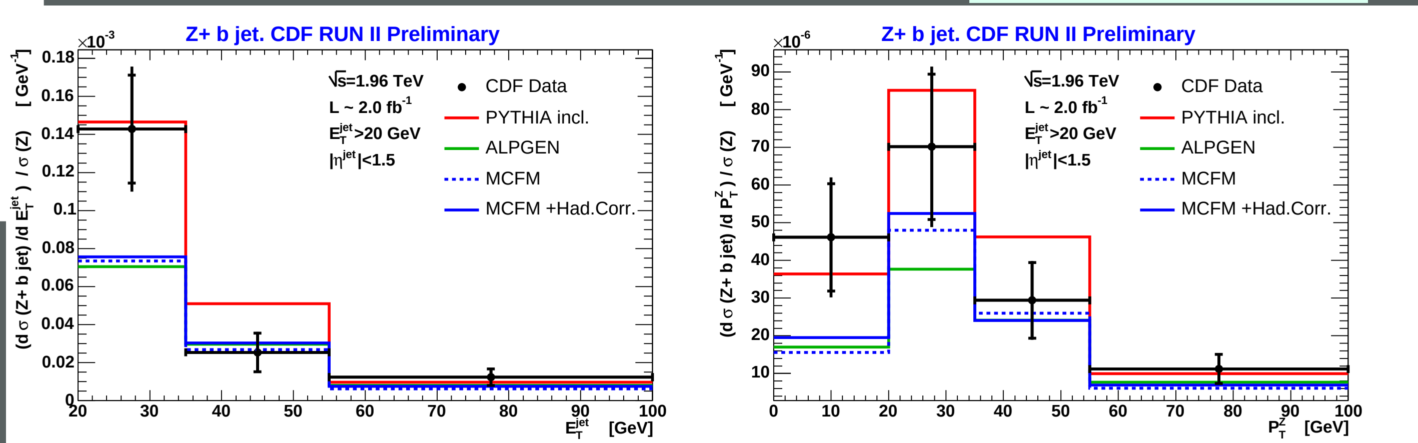
$W/Z + \mathrm{b-jets}$ at TevaTron



- Production of W/Z in association with b-jets
  $\longrightarrow$ test of pQCD; important background to eg Higgs
  $\longrightarrow$ sensitive to b parton density in proton: needed to predict the production of particles which couple to b (Higgs, SUSY, top, new physics)

$\sigma(Z+b\mathrm{jet}) = 0.86 \pm 0.14 \pm 0.12$ pb (NLO: 0.53 pb)

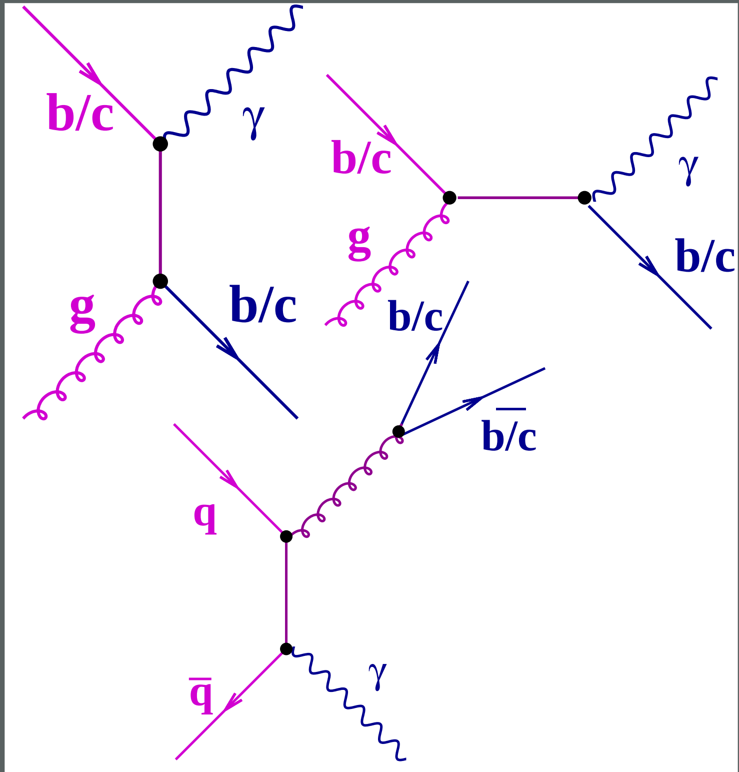
$\sigma(W+b\mathrm{jet}) \times BR(W \to l\nu) = 2.74 \pm 0.27 \pm 0.42$ pb (ALPGEN: 0.78 pb)



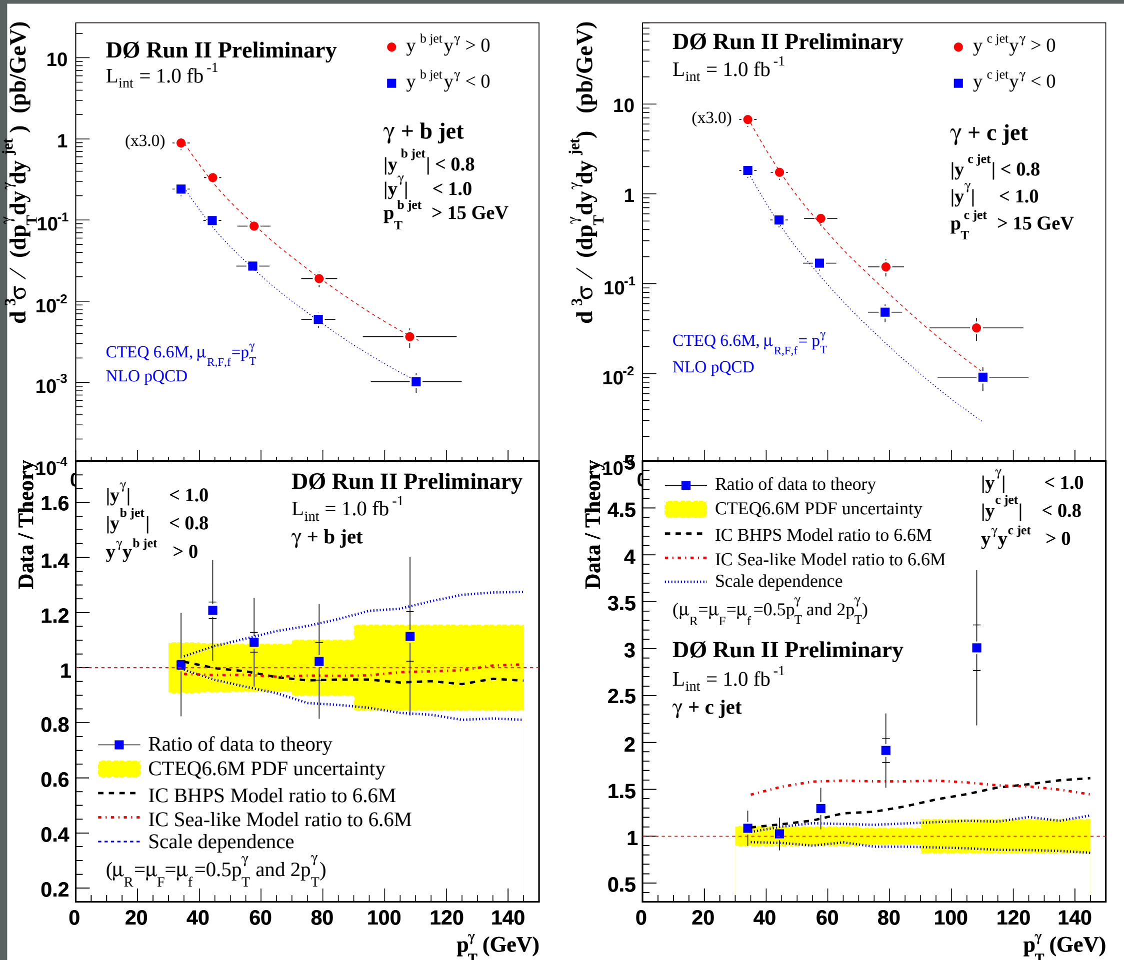
- Comparison of $W/Z + b$ data with predictions:
  $\longrightarrow$ MCFM and ALPGEN describe the $Z + b$ data at high E_T^{jet} and high p_T^Z
  $\longrightarrow$ ALPGEN prediction is ~ 3.5 times lower than the $W + b$ data
  $\longrightarrow$ 30-40% theory uncertainty; 18% data uncertainty $\longrightarrow$ constrain on theory

CDF, abstract 415

$\gamma + b/c - $ jets at TevaTron



- Production of γ in association with b/c-jets
  - $\longrightarrow$ tests of pQCD
  - $\longrightarrow$ sensitive to b/c pPDFs
  - $\longrightarrow$ background to Higgs and new physics



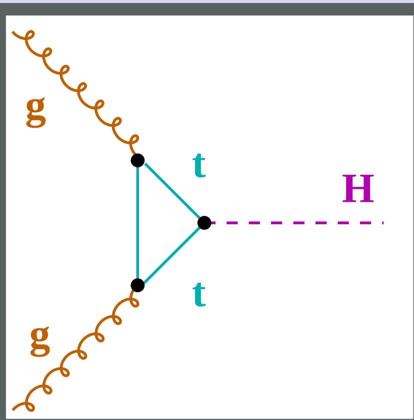
- Comparison with NLO predictions:
  - $\longrightarrow$ good agreement for $\gamma + b(c)$ in all p_T^γ ($p_T^\gamma < 50$ GeV)
  - $\longrightarrow$ difference for $\gamma + c$ grows with increasing $p_T^\gamma \longrightarrow$ can be attributed to intrinsic charm, uncertainties in $g \rightarrow Q\bar{Q}$, ...

DØ, abstract 526

Parton dynamics at low x

Parton dynamics at low x

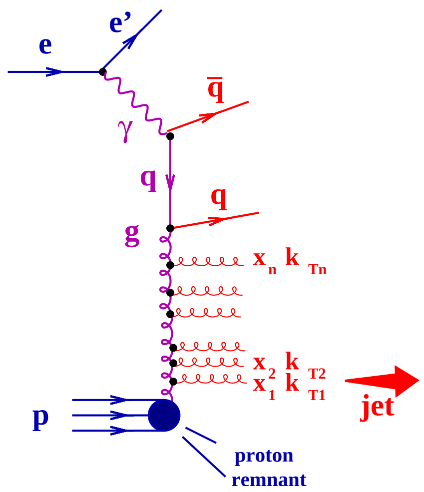
- One of the main channels of Higgs production at LHC is expected to be $gg \longrightarrow H$



- Predictions for these processes need information on
  - $\longrightarrow$ parton evolution at low x
  - $\longrightarrow$ unintegrated proton PDFs

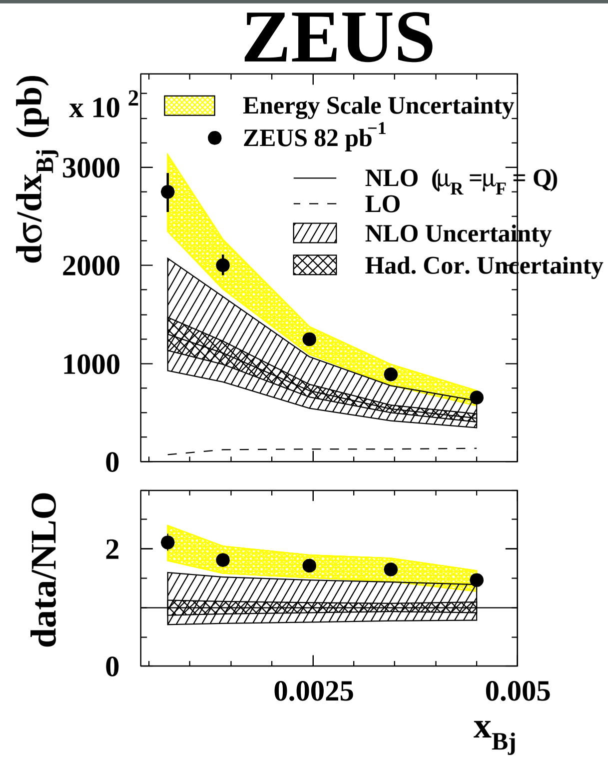
  } $\longrightarrow$ low-x jet data at HERA

- At high scales (Q, $E_T^{\rm jet}$), calculations using the DGLAP evolution equations give a good description of the data at NLO

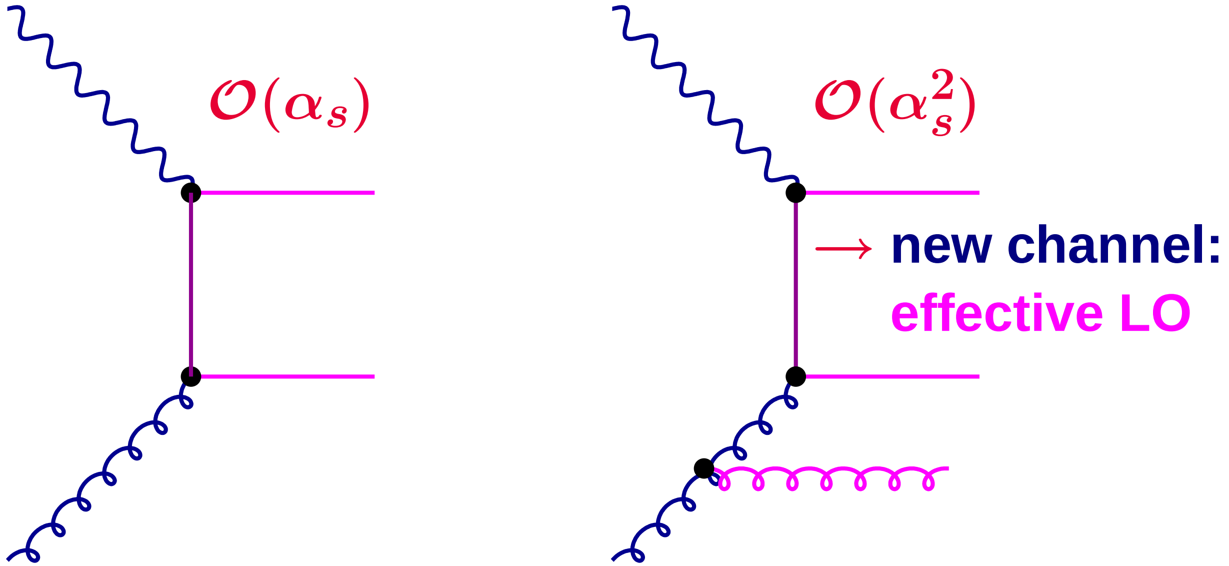


- DGLAP evolution equivalent to exchange of a parton cascade with exchanged partons strongly ordered in virtuality k_T
- But, DGLAP approximation expected to break down at low x:
  - — only leading logs in Q^2 are resummed
  - — contributions from $\log 1/x$ neglected (important for $\log Q^2 \ll \log 1/x$)
- Other approaches to low x parton dynamics:
  - — BFKL: resummation of $\log 1/x$ to all orders (low x)
  - — CCFM: angular-ordered parton emission (low and larger x)

Parton dynamics at low x



- **Inclusive-jet cross section at low x: forward jets**



→ **Forward-jet cross section rises with decreasing x**

→ **Comparison to predictions:**

– $\mathcal{O}(\alpha_s)$ **pQCD fails to describe the data**

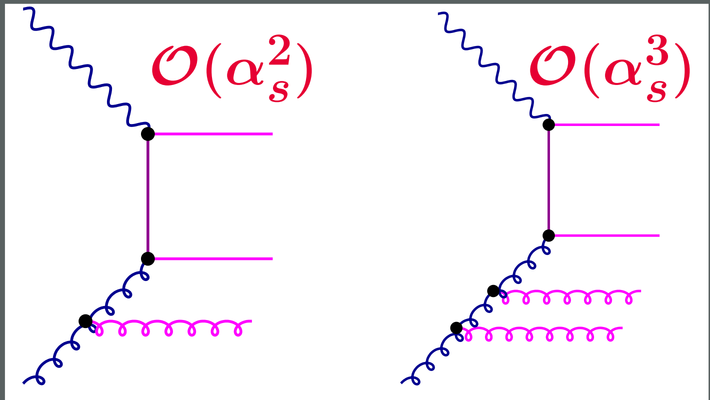
– $\mathcal{O}(\alpha_s^2)$ **pQCD closer to data**

→ **big jump from $\mathcal{O}(\alpha_s)$ to $\mathcal{O}(\alpha_s^2)$**
→ $\mathcal{O}(\alpha_s^2)$ **uncertainties large**
} → **higher orders very important**

ZEUS, abstract 126, EPJ C52 (2007) 515

Parton dynamics at low x

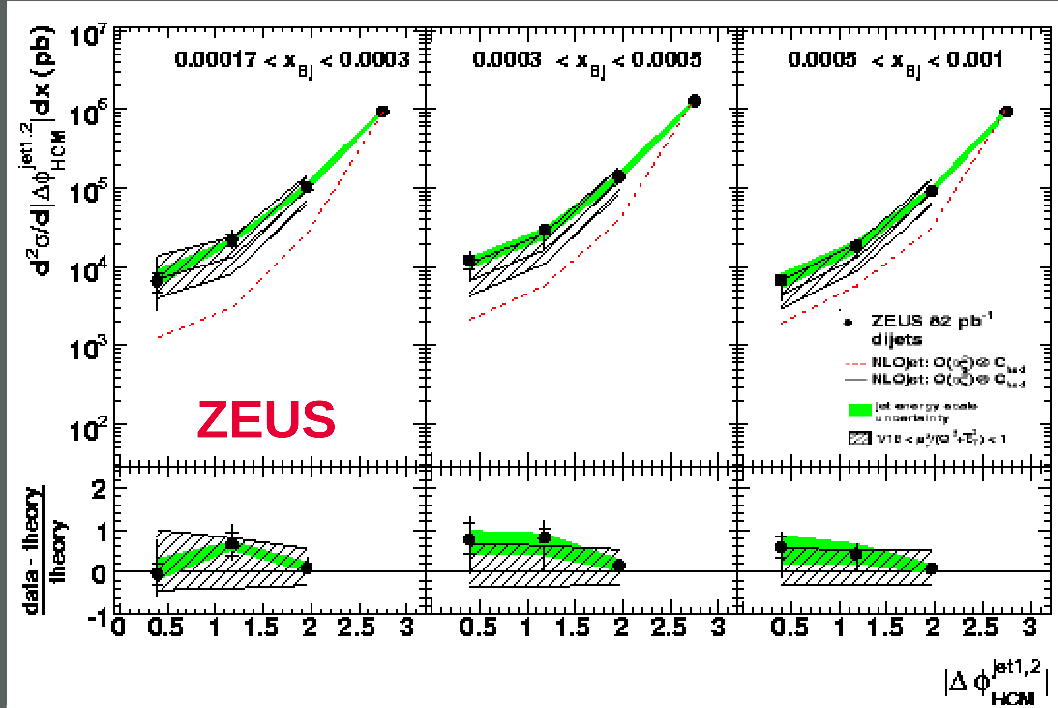
- **Multi-jet production in NC DIS**
  - → ideal environment for studying parton dynamics at low x directly beyond NLO

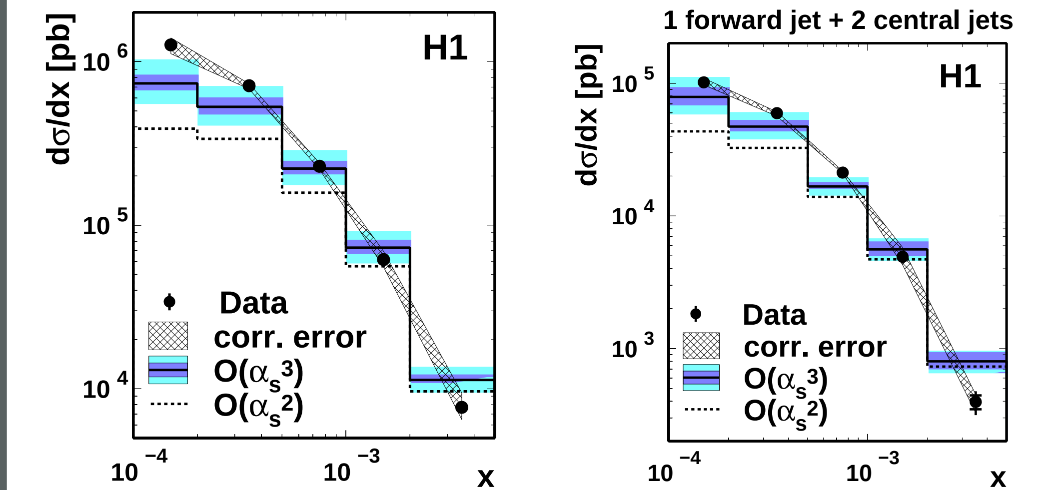


  - → angular correlations sensitive to effects beyond DGLAP dynamics

→ $\mathcal{O}(\alpha_s^2)$ predictions are one order of magnitude below the data

→ $\mathcal{O}(\alpha_s^3)$ predictions describe the data much better → importance of higher orders at low x (in particular gluon exchange in t-channel)



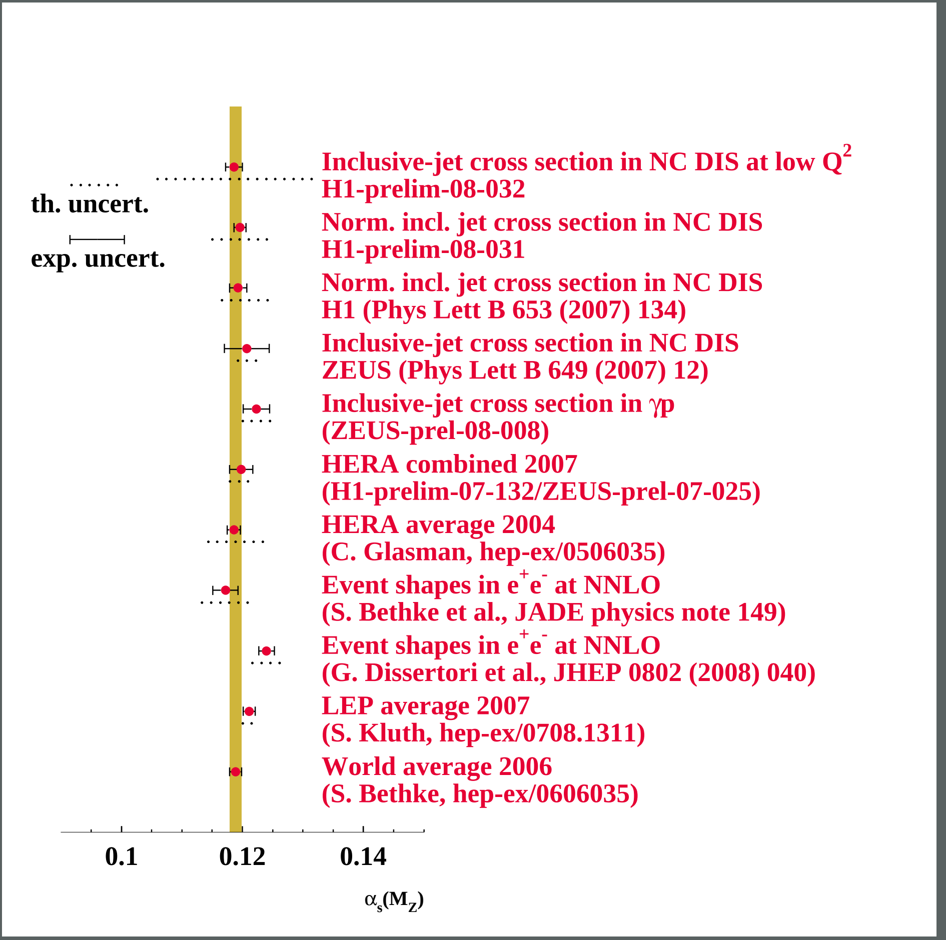


H1, abstract 798, EPJ C54 (2008) 389

ZEUS, abstract 122, NPB 786 (2007) 152

Summary

- **Wealth of new measurements from HERA and TevaTron which test QCD with high precision**
  - ⟶ well in the way towards new level of understanding underlying hard processes needed for LHC physics
  - ⟶ underlying event being tested in all possible environments
  - ⟶ new high precision data to help to constrain further the pPDFs
  - ⟶ more and more precise determinations of the strong coupling
  - ⟶ successful tests of colour dynamics at highest the available energies
  - ⟶ NNLO corrections needed for further progress



Thanks to: C Diaconu, G Dissertori, K Hatakeyama, G Hesketh, A Juste, S Kluth, C Pahl, S Soldner-Rembold, A Specka, J Terrón, M Wobisch

Back up slides

Theoretical calculations

- Very well tested programs of process- and observable-independent algorithms that allow complete analytical cancellation of soft and collinear singularities encountered in calculations of cross sections at NLO (ep and $p\bar{p}$)
  $\longrightarrow$ NNLO calculations for next generation of experiments?

- Programs for computing infrared- and collinear-safe observables at NLO:

photoproduction

$\longrightarrow$ S Frixione & G Ridolfi
$\longrightarrow$ M Klasen, T Kleinwort & G Kramer
$\longrightarrow$ BW Harris & JF Owens
$\longrightarrow$ P Aurenche, M Fontannaz & JP Guillet

DIS

$\longrightarrow$ DISENT (S Catani & MH Seymour)
$\longrightarrow$ MEPJET (E Mirkes & D Zeppenfeld)
$\longrightarrow$ DISASTER++ (D Graudenz)
$\longrightarrow$ NLOJET++ (Z Nagy & Z Trocsanyi)

$p\bar{p}$

$\longrightarrow$ SD Ellis, Z Kunszt and DE Soper
$\longrightarrow$ W Giele, EWN Glover and DA Kosower
$\longrightarrow$ F Aversa, M Greco, P Chiappetta and JP Guillet
$\longrightarrow$ NLOJET++ (Z Nagy & Z Trocsanyi)

W, Z and γ

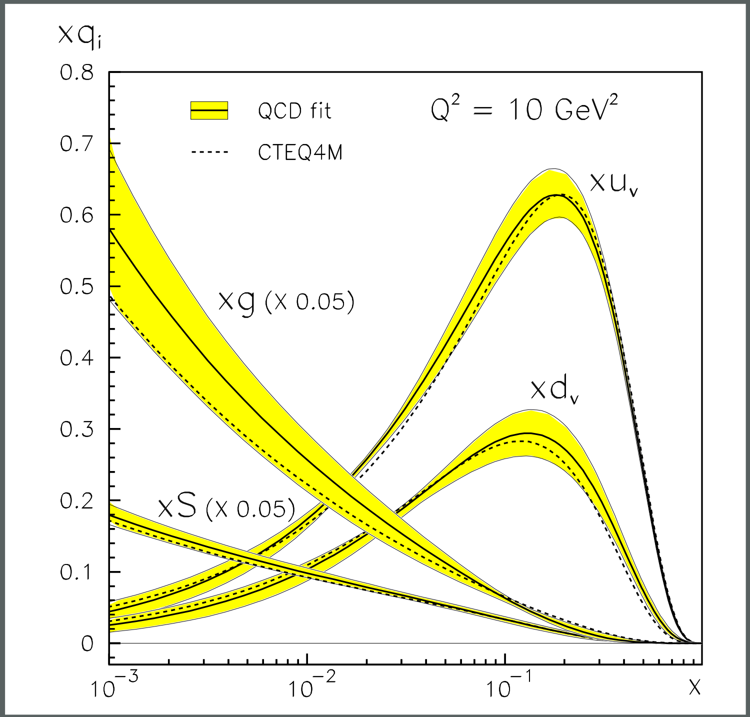
$\longrightarrow$ MCFM (J Campbell et al.)
$\longrightarrow$ JETPHOX (P Aurenche et al.)

Recent development in e^+e^-

$\longrightarrow$ NNLO calculations (Glover et al.)

Uncertainty of NLO calculations due to the PDFs

- Comparison of calculations based on different PDF sets does not give a reliable estimation of PDF uncertainty
- For the pPDFs, several groups (Botje, CTEQ, MRST, ZEUS) have developed methods to account properly for the statistical and correlated systematic uncertainties of each data used in the fits and the theoretical uncertainties affecting the extraction of the PDFs
  $\longrightarrow$ This allows the evaluation of the uncertainty on any function of the proton PDFs (eg $\sigma_{\rm jets}$)



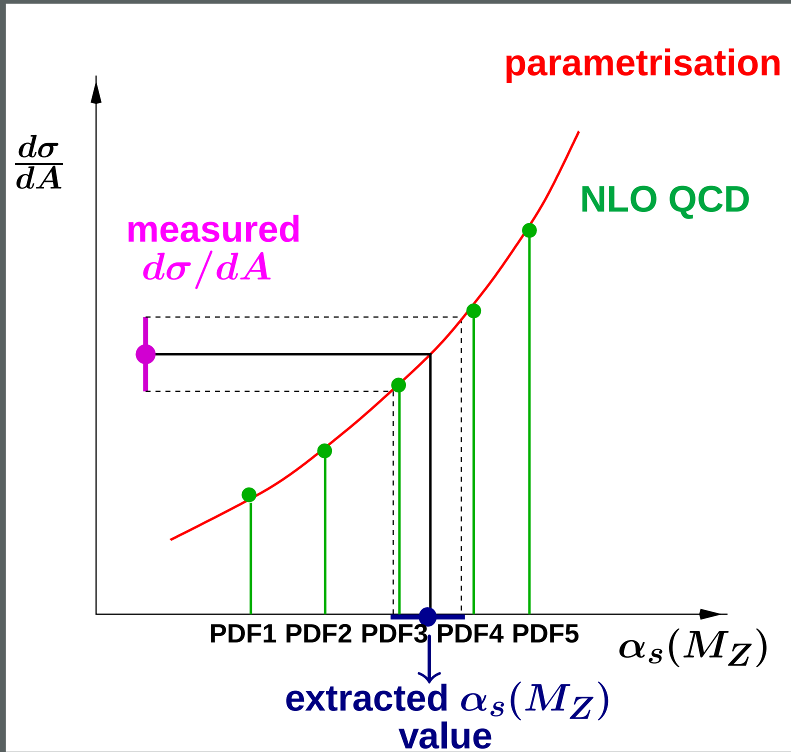
M Botje, Eur Phys J C14 (2000) 285

A method to determine α_s from jets in hadron colliders

- Cross sections in pQCD are a convolution of the PDFs and the matrix elements
- The procedure to determine α_s from jet observables used by ZEUS is based on the α_s dependence of the pQCD calculations and the correlation with the pPDFs:
  - perform NLO calculations using different sets of pPDFs
  - use as input in each calculation the value of $\alpha_s(M_Z)$ assumed in each PDF set
  - parametrise α_s dependence of prediction:

$$d\sigma/dA(\alpha_s(M_Z)) = C_1\,\alpha_s(M_Z) + C_2\,\alpha_s^2(M_Z)$$

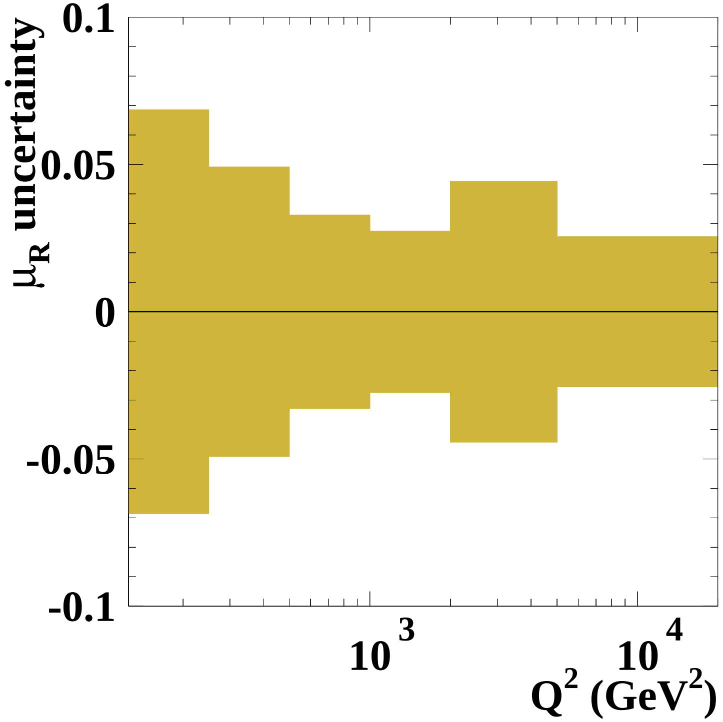
  - determine $\alpha_s(M_Z)$ from the measured value using the NLO parametrisation



- This procedure handles correctly the complete α_s-dependence of the NLO calculations (explicit dependence in the partonic cross section and implicit dependence from the PDFs) in the fit, while preserving the correlation between α_s and the PDFs

ZEUS, PLB 507 (2001) 70

Theoretical uncertainties on $\alpha_s(M_Z)$



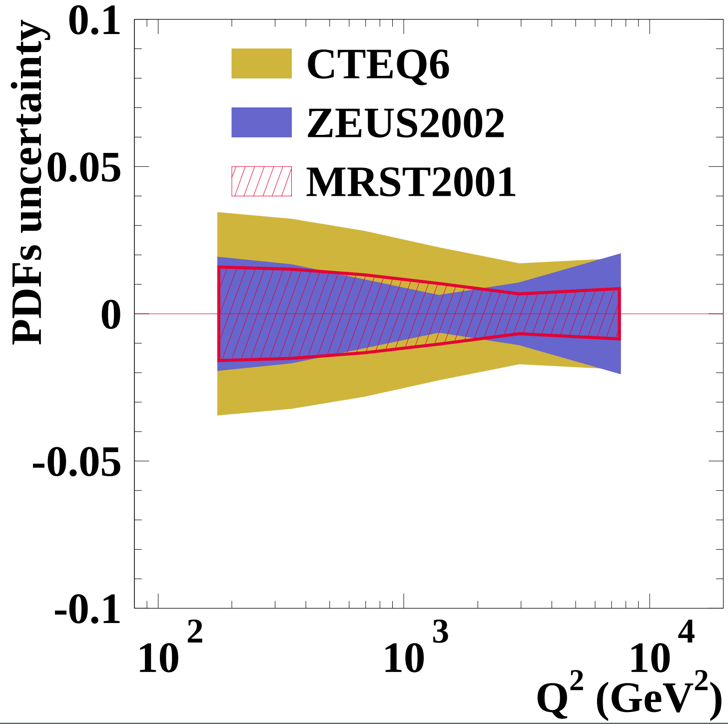
$\longrightarrow$ Uncertainty of inclusive-jet cross section from terms beyond NLO as a function of Q^2 estimated by varying μ_R by factors 2 and 0.5

- PDF uncertainty of inclusive-jet cross section as a function of Q^2 for various PDF sets $\longrightarrow$
- PDF uncertainty on $\alpha_s(M_Z)$:

  ZEUS2002-RT $\longrightarrow \pm 0.7\%$

  MRST-2001 $\longrightarrow \pm 0.7\%$

  CTEQ6 $\longrightarrow \pm 1.6\%$



$\alpha_s(M_Z)$ from jet cross sections

- $\alpha_s(M_Z)$ from the measured $d^2\sigma_{\rm jets}/dE_{T,\rm B}^{\rm jet}dQ^2$ for $150 < Q^2 < 15000$ GeV^2:

$$\alpha_s(M_Z) = 0.1179 \pm 0.0024\,(\rm exp.)^{+0.0052}_{-0.0032}\,(\rm th.) \pm 0.0028\,(\rm pdf)$$

$\longrightarrow$ experimental, theoretical and PDFs uncertainties go up

$\alpha_s(M_Z)$ from the normalised $1/\sigma_{\rm NC}\, d^2\sigma_{\rm jets}/dE_{T,\rm B}^{\rm jet}dQ^2$ for $150 < Q^2 < 15000$ GeV^2:

$$\alpha_s(M_Z) = 0.1193 \pm 0.0014\,(\rm exp.)^{+0.0047}_{-0.0030}\,(\rm th.) \pm 0.0016\,(\rm pdf)$$

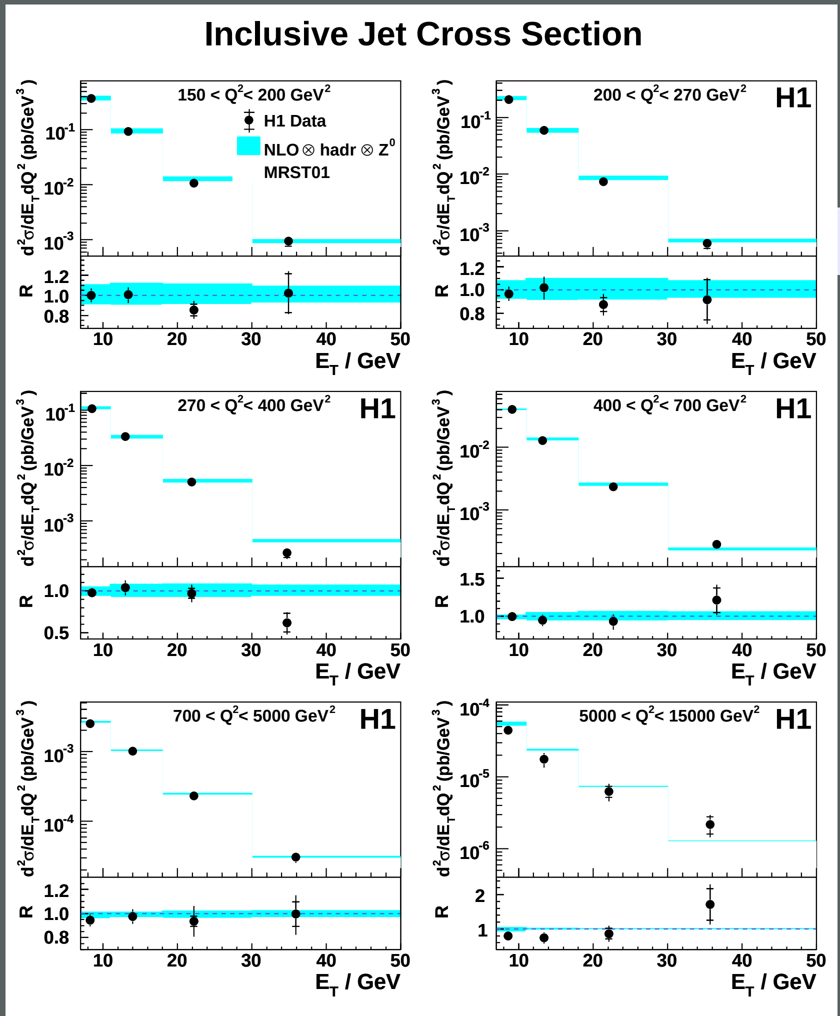
- $\alpha_s(M_Z)$ from the measured normalised $1/\sigma_{\rm NC}\, d^2\sigma_{\rm jets}/dE_{T,\rm B}^{\rm jet}dQ^2$ for $700 < Q^2 < 5000$ GeV^2:

$$\alpha_s(M_Z) = 0.1171 \pm 0.0023\,(\rm exp.)^{+0.0032}_{-0.0010}\,(\rm th.) \pm 0.0010\,(\rm pdf)$$

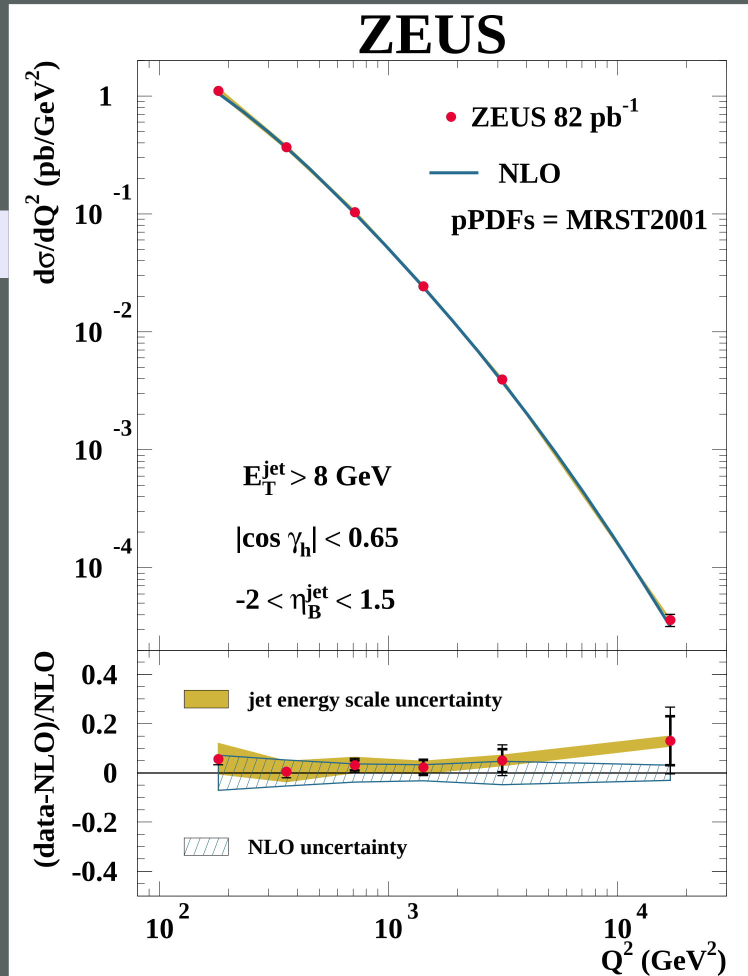
$\longrightarrow$ experimental uncertainty goes up, theoretical and PDFs uncertainties go down

HERA α_s combination

- $\alpha_s(M_Z)$ combination from inclusive-jet cross sections in NC DIS
  - simultaneous fit to ZEUS and H1 data sets which yield the most precise $\alpha_s(M_Z)$ values



MRST2001



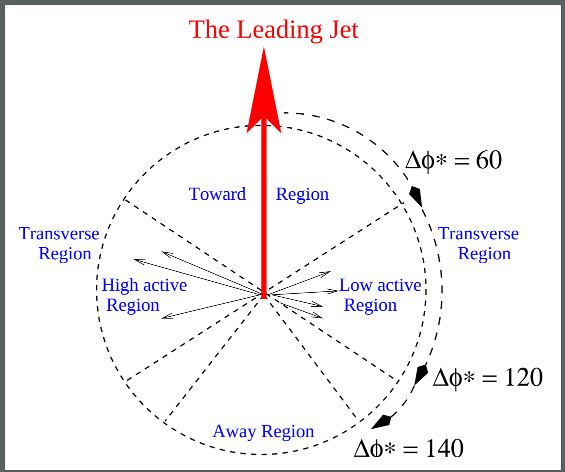
H1 and ZEUS, abstract 628, H1-prelim-07-132 and ZEUS-prel-07-025

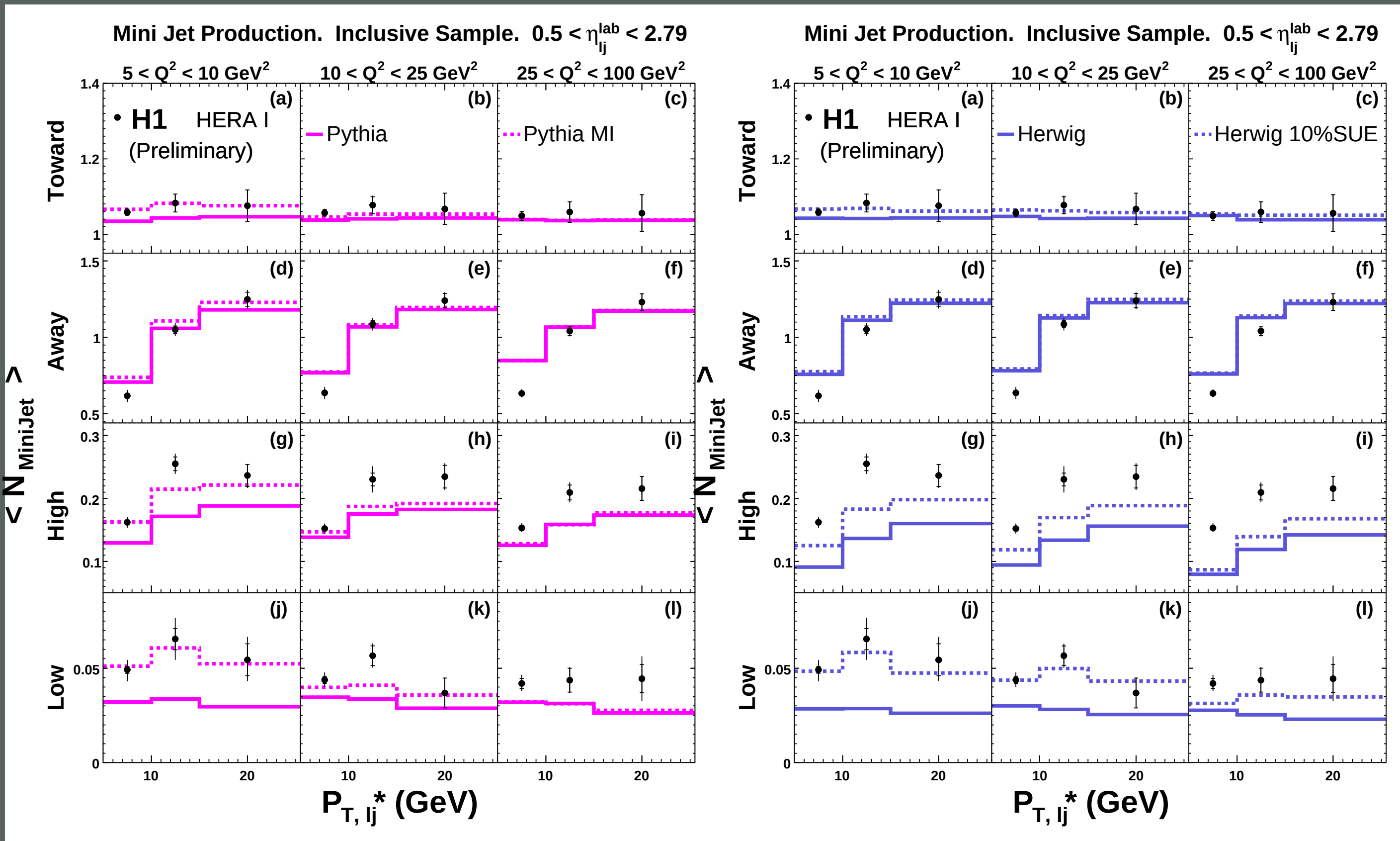
New HERA $\alpha_s(M_Z)$ combination

- **Fit to 30 measurements of inclusive-jet cross sections in NC DIS:**
  - $\longrightarrow$ 24 H1 data points from double-differential cross section ($150 < Q^2 < 15000$ GeV^2)
  - $\longrightarrow$ 6 ZEUS data points from single-differential Q^2 cross section ($125 < Q^2 < 10^5$ GeV^2)
- **NLO QCD calculations:**
  - $\longrightarrow$ differential cross sections were calculated at NLO ($\mathcal{O}(\alpha_s^2)$) with:
    - – pPDFs: MRST2001 sets
    - – renormalisation scale: $\mu_R = E_{T,\mathrm{B}}^{\mathrm{jet}}$ of each jet
    - – factorisation scale: $\mu_F = Q$
- **Experimental uncertainties on combined $\alpha_s(M_Z)$:**
  - $\longrightarrow$ 0.0019 (obtained using Hessian method; fit sources of systematic uncertainties, eg energy scale, luminosity, model dependence)
- **Theoretical uncertainties on combined $\alpha_s(M_Z)$:**
  - $\longrightarrow$ terms beyond NLO: 0.0021 (using Jones et al method, JHEP 122003007)
  - $\longrightarrow$ factorisation scale: 0.0010 (obtained by varying μ_F by factors 2 and 0.5 in the calculations)
  - $\longrightarrow$ pPDFs: 0.0010 (obtained by using 30 sets of MRST2001)
  - $\longrightarrow$ hadronisation: 0.0004 (obtained from different parton-shower models)

Underlying event using minijets in NC DIS

- If $(E_T^{\mathrm{jet}})^2 \gg Q^2$, virtual photon behaves like hadronic object
  $\longrightarrow$ study UE/MPI using low-p_T jets (minijets) in addition to the leading jet





$\longrightarrow$ In "toward" and "away" regions all models describe data in all Q^2 regions

$\longrightarrow$ In "high activity" (highest-E_T density) region no model describes data

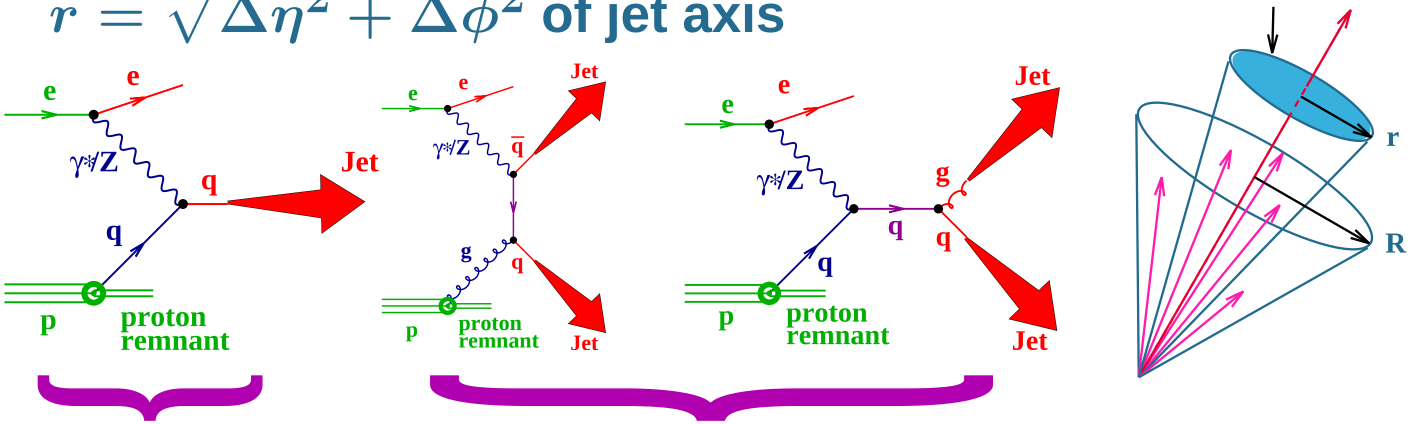
$\longrightarrow$ In "low activity" (lowest-E_T density) region HERWIG+10% SUE describes data

H1, abstract 808, H1-prelim-07-032

Jet substructure in NC DIS

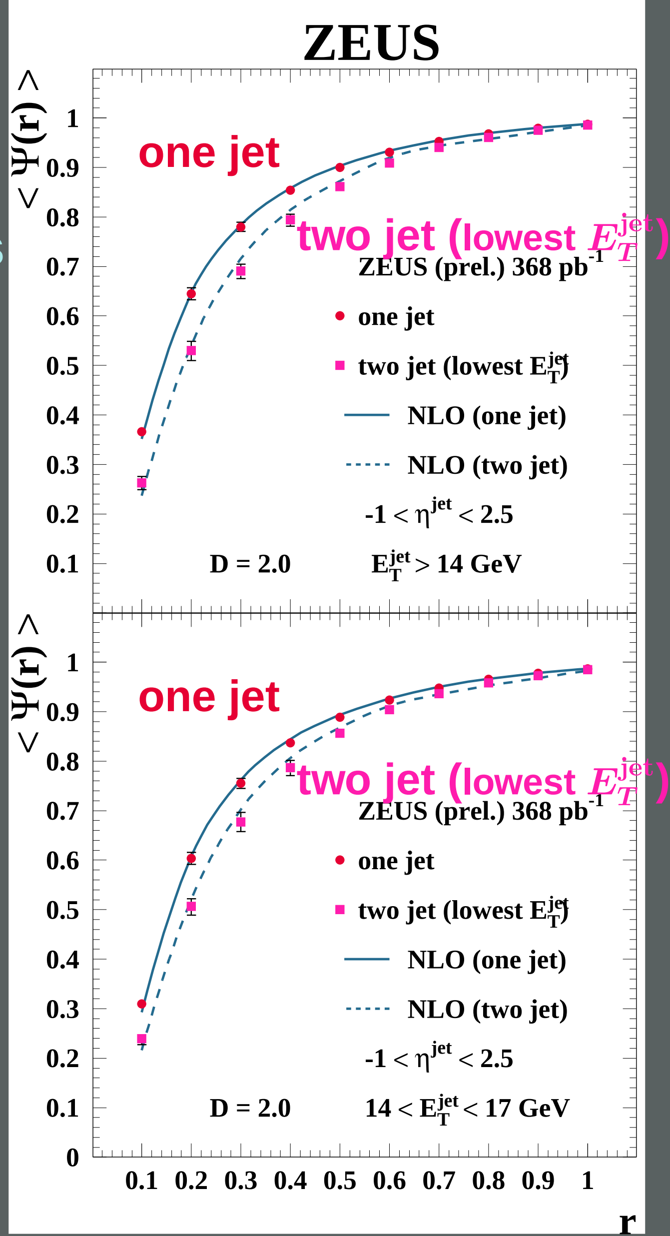
- Jet substructure:
  - — stringent tests of pQCD
  - — differences between quark and gluon jets
    - $\longrightarrow$ gluon jets expected to be broader than quark jets

- Integrated jet shape: average fraction of $E_T^{\rm jet}$ within $r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ of jet axis



one-jet events enriched in quark jets

two-jet events higher content of gluon jets



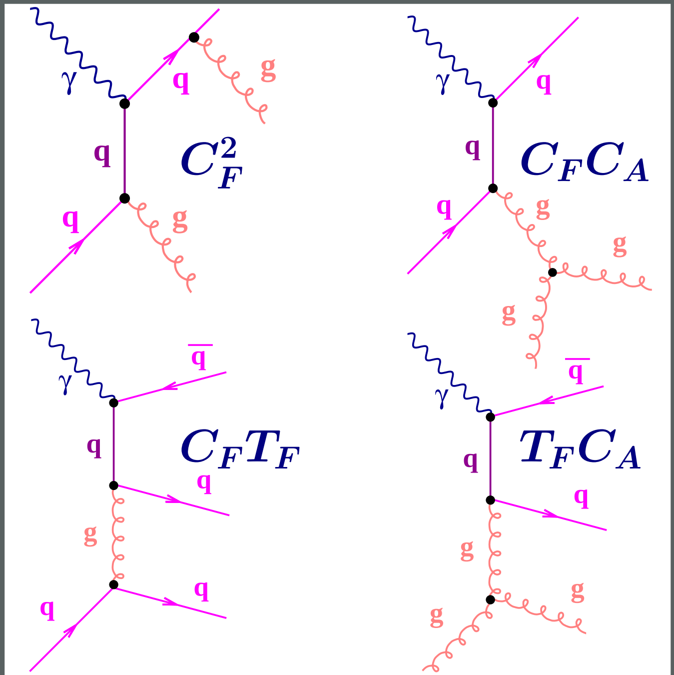
$\longrightarrow$ The lowest-$E_T^{\rm jet}$ jet in the two-jet sample is broader than the one-jet sample: consistent with a higher gluon content in dijet events, as predicted by pQCD

ZEUS, abstract 145, ZEUS-prel-07-013

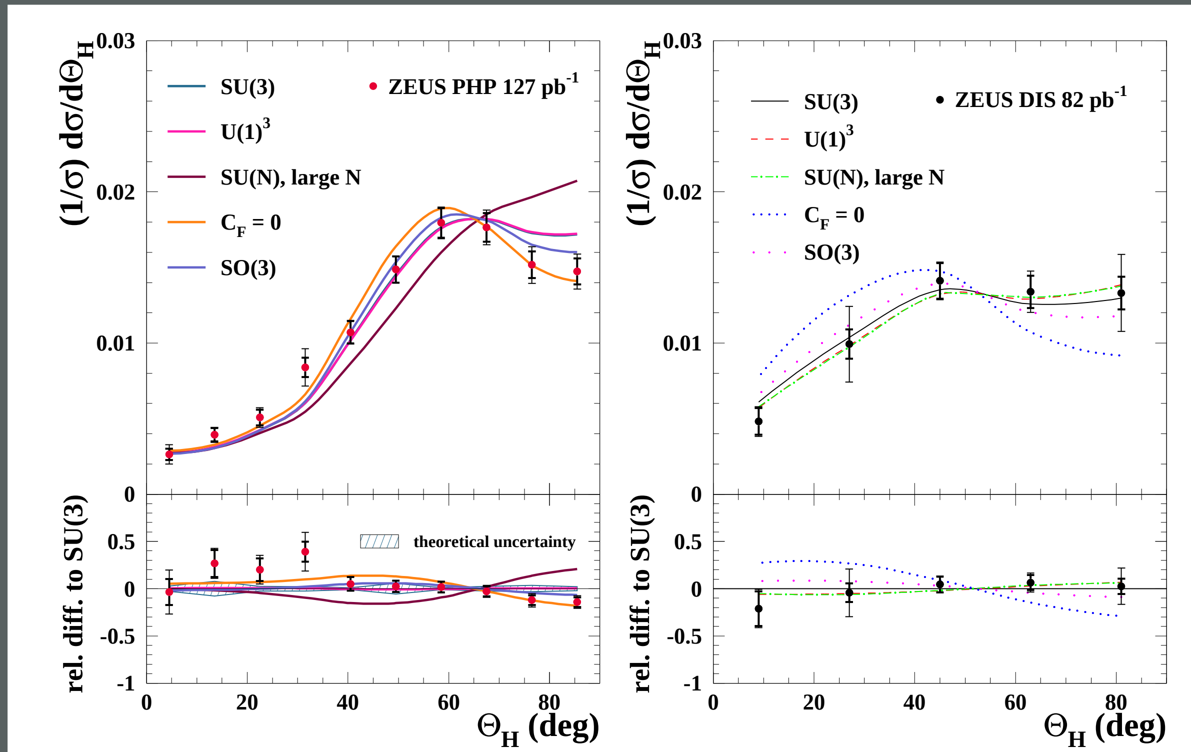
Multijet events in ep collisions

- $\mathcal{O}(\alpha\alpha_s^2)$ calculations of three-jet cross sections for direct-photon and NC DIS processes in terms of the colour factors C_A, C_F and T_F:

$$\sigma_{ep\to 3\text{jets}} = C_F^2 \cdot \sigma_A + C_F C_A \cdot \sigma_B + C_F T_F \cdot \sigma_C + T_F C_A \cdot \sigma_D$$



→ angular correlations in three-jet events sensitive to underlying gauge group symmetry



→ Stringent test of pQCD

→ data consistent with SU(3) and exclude other groups

→ potential to extract the colour factors

ZEUS, abstract 137, DESY-08-100