Jet Physics (HERA, Tevatron, LHC)

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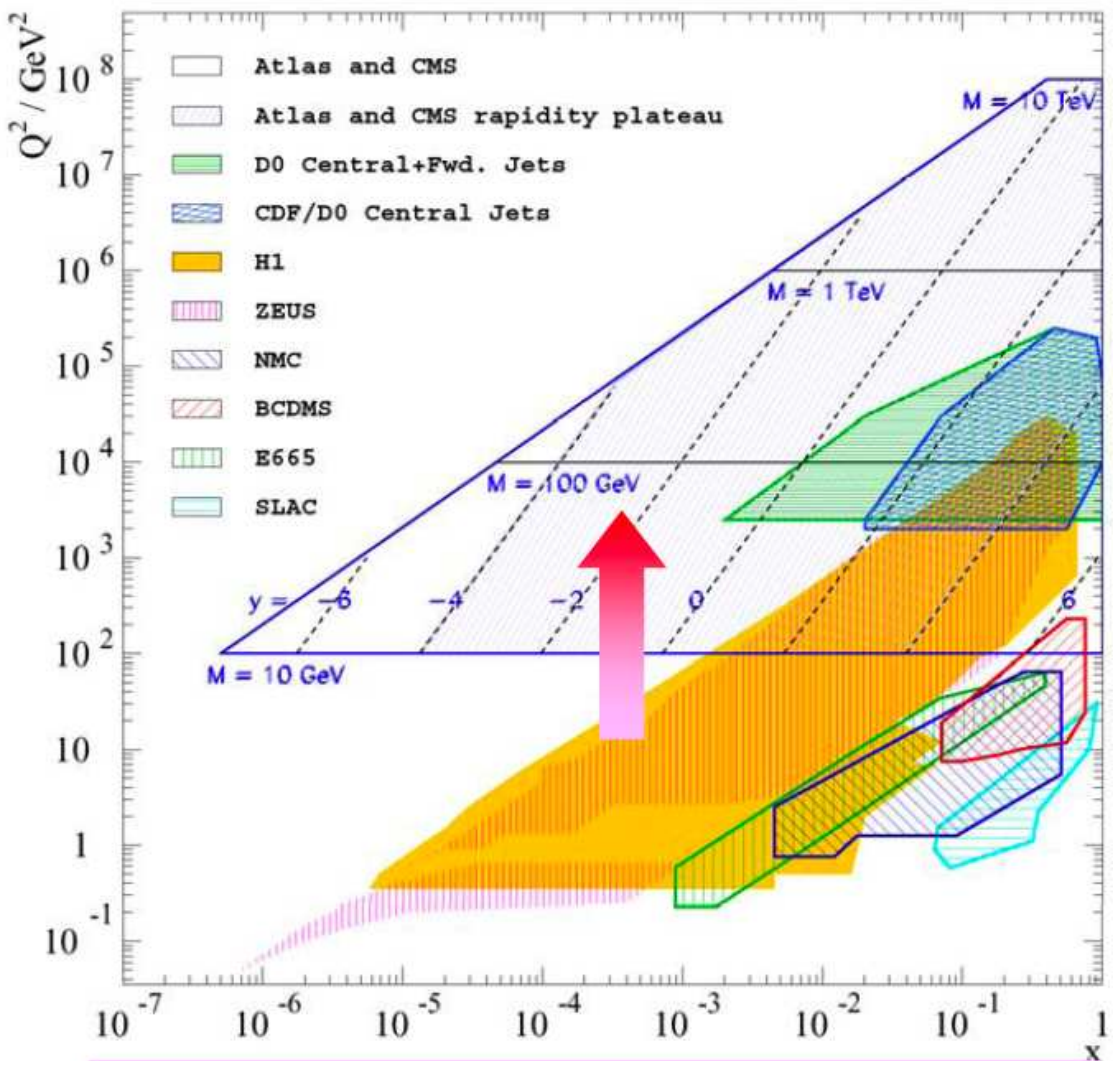
Contents:

- High Q^2, E_T dynamics: PDF constraints using inclusive jets at HERA and Tevatron
- Multijet cross sections
- W+b-jets, Z+b-jets...
- Low x dynamics: Forward jets at HERA and Mueller-Navelet jets at Tevatron/LHC

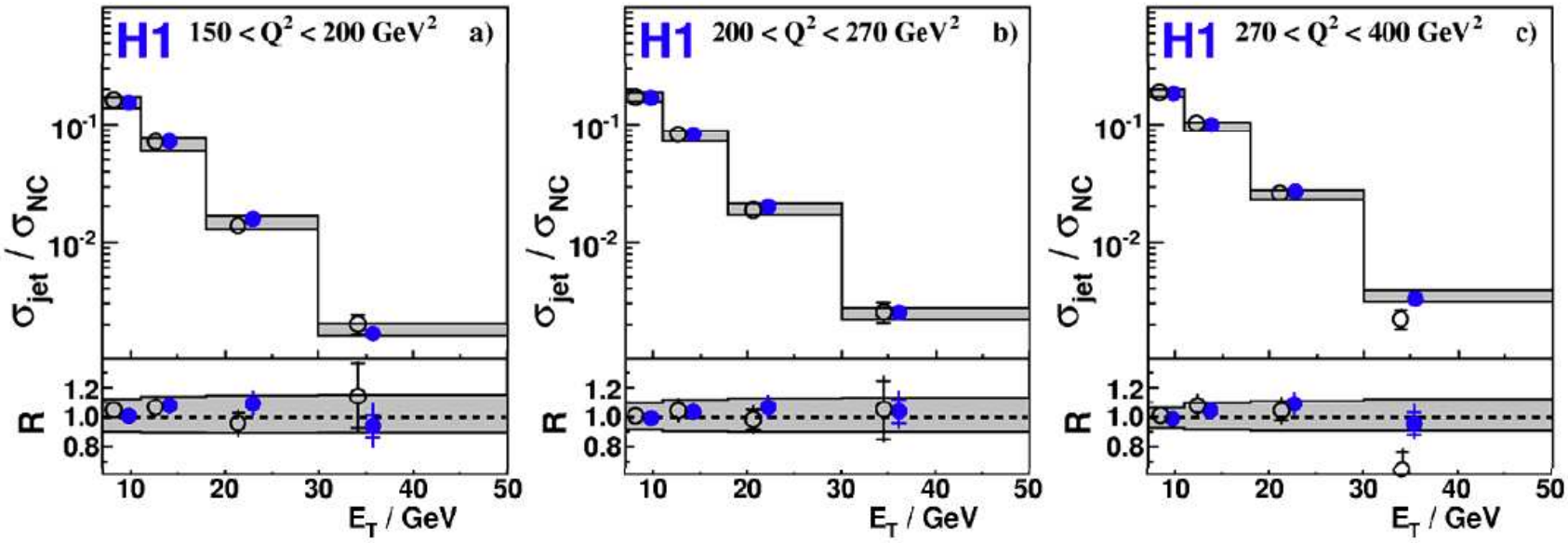
HERA, Tevatron and LHC kinematical planes

- Kinematical plane at HERA, Tevatron and LHC in (x, Q^2) compared to fixed target experiments
- Jets at HERA and Tevatron are complementary to constrain PDFs (NB: structure functions at HERA discussed in Achim's talk)



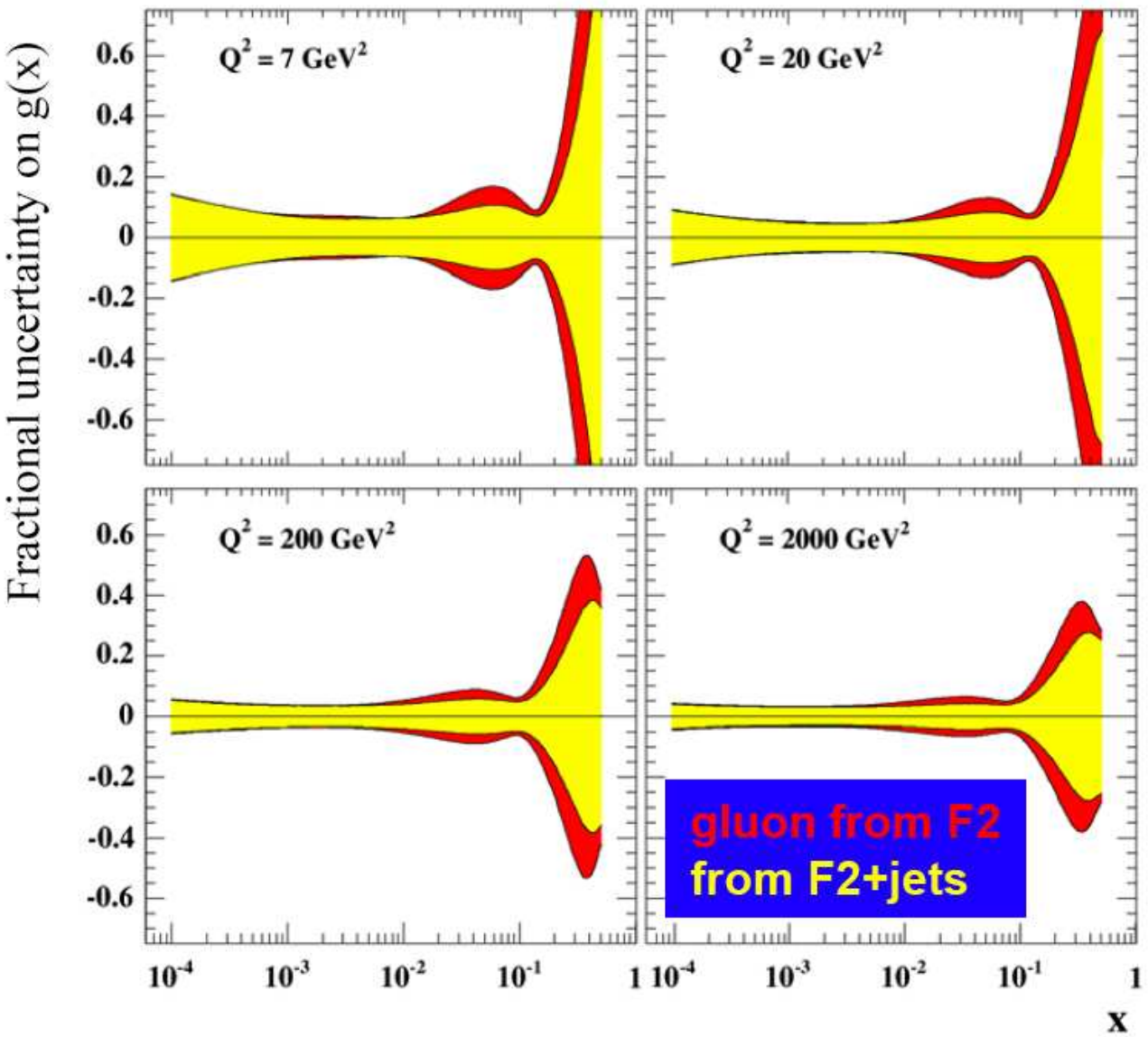
HERA jets at high Q^2

- Measurement of ratio of jet and neutral current cross sections at HERA: reduce systematics uncertainties
- Jets and heavy quark production at HERA: directly sensitive to gluon density in proton and QCD dynamics, complementary to parton densities using proton structure function and DGLAP NLO
- Tests of NLO QCD evolution
- High Q^2 ($Q^2 > 100$ GeV^2), NLO QCD (grey band) works well: use these data to constrain PDFs and α_S



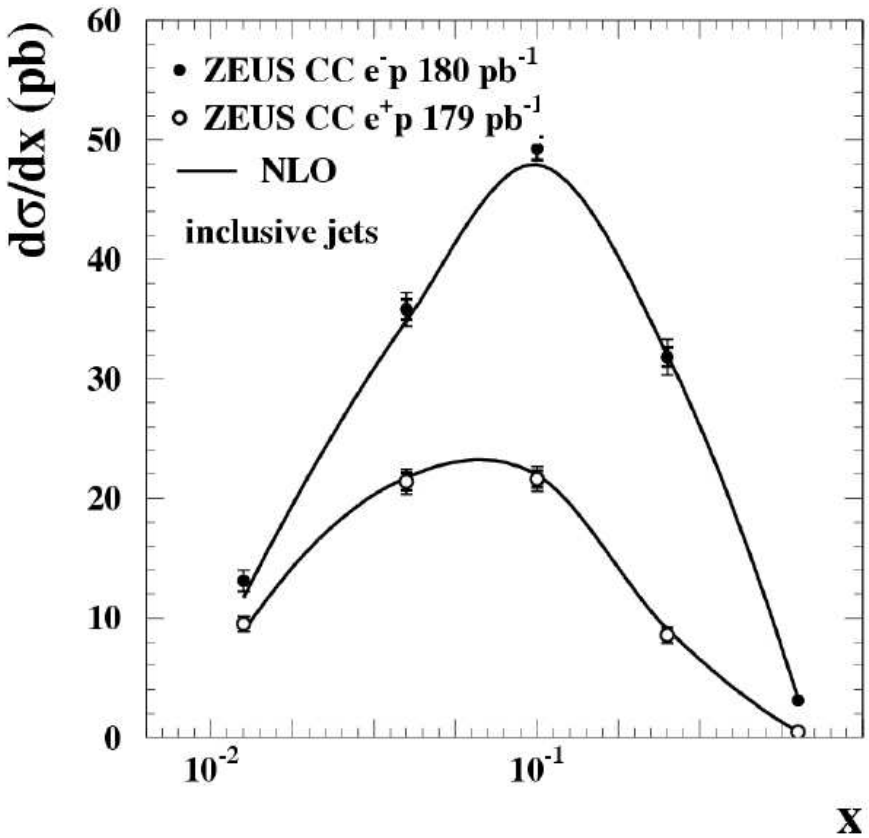
Gluon density from jets at HERA

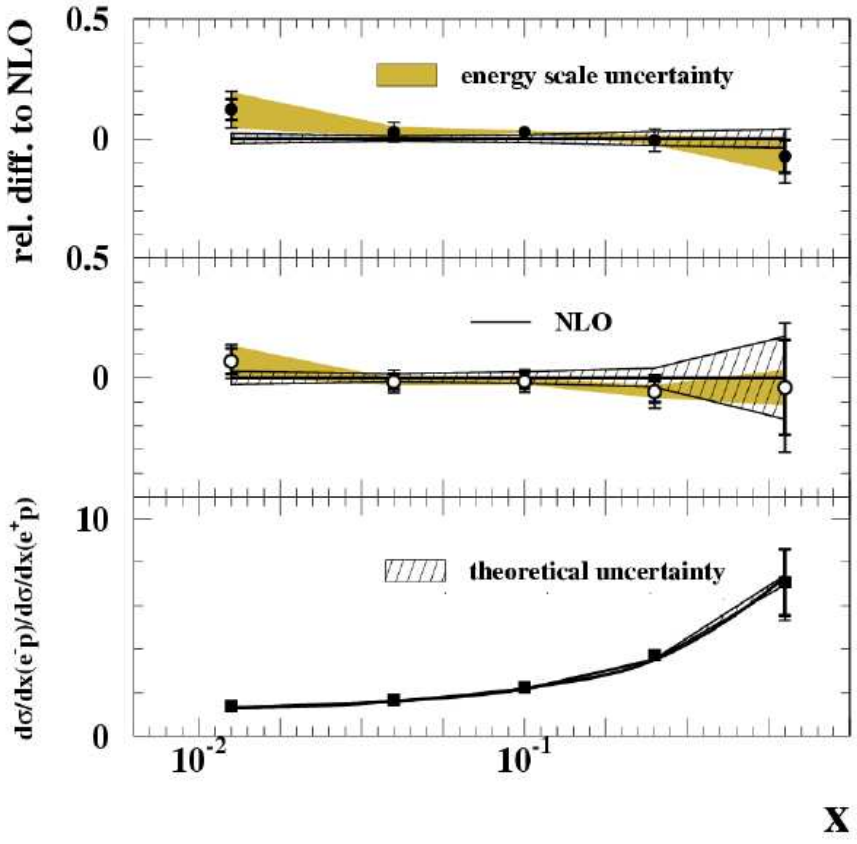
- Parton densities obtained using the combined F_2 measurement from H1/ZEUS
- Jet cross section measured at HERA allows to constrain further the gluon density at high x, still large uncertainties



Jets at high Q^2 in CC at HERA

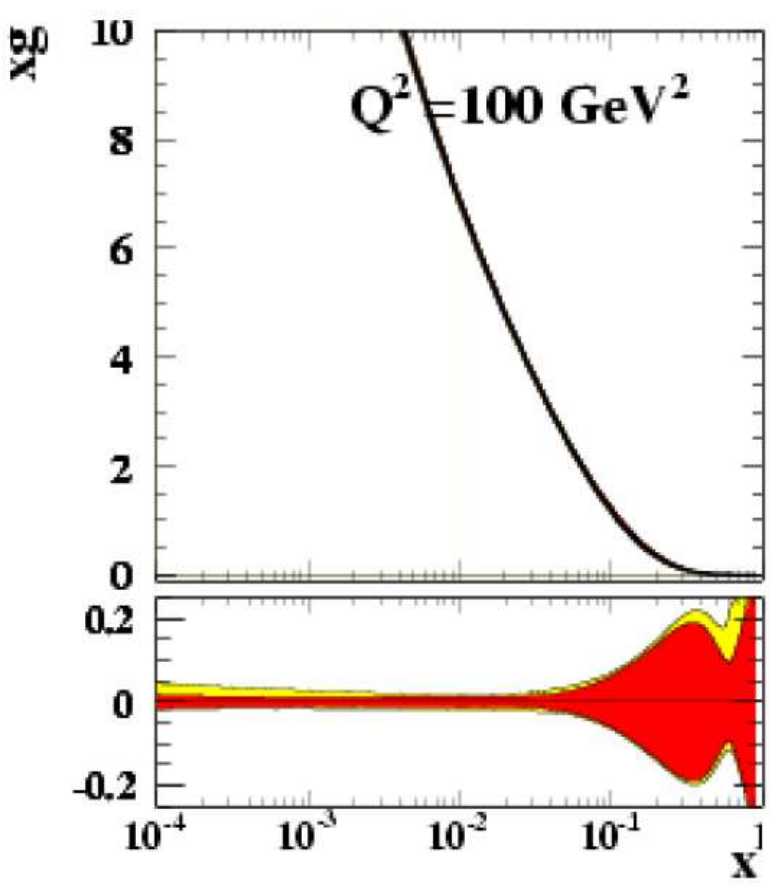
- Measurement of the charged current jet production at HERA for jets E_T greater than 100 GeV
- Good agreement with NLO calculation
- Large theoretical uncertainties at high x: in addition to PDF uncertainties, NNLO calculation needed

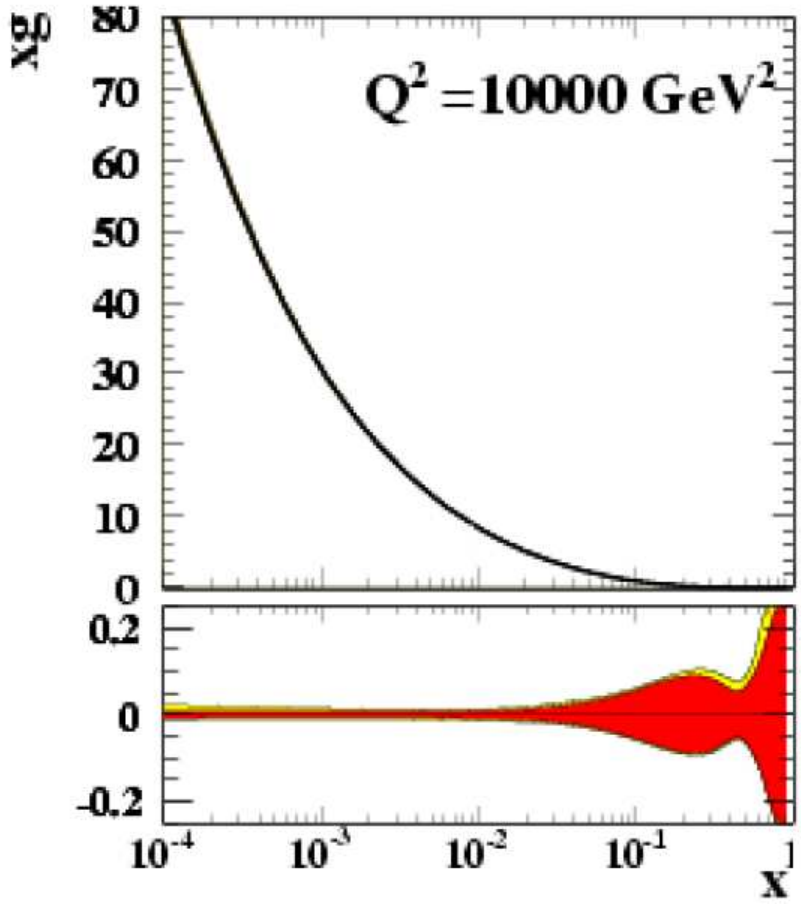




Uncertainty on gluon density

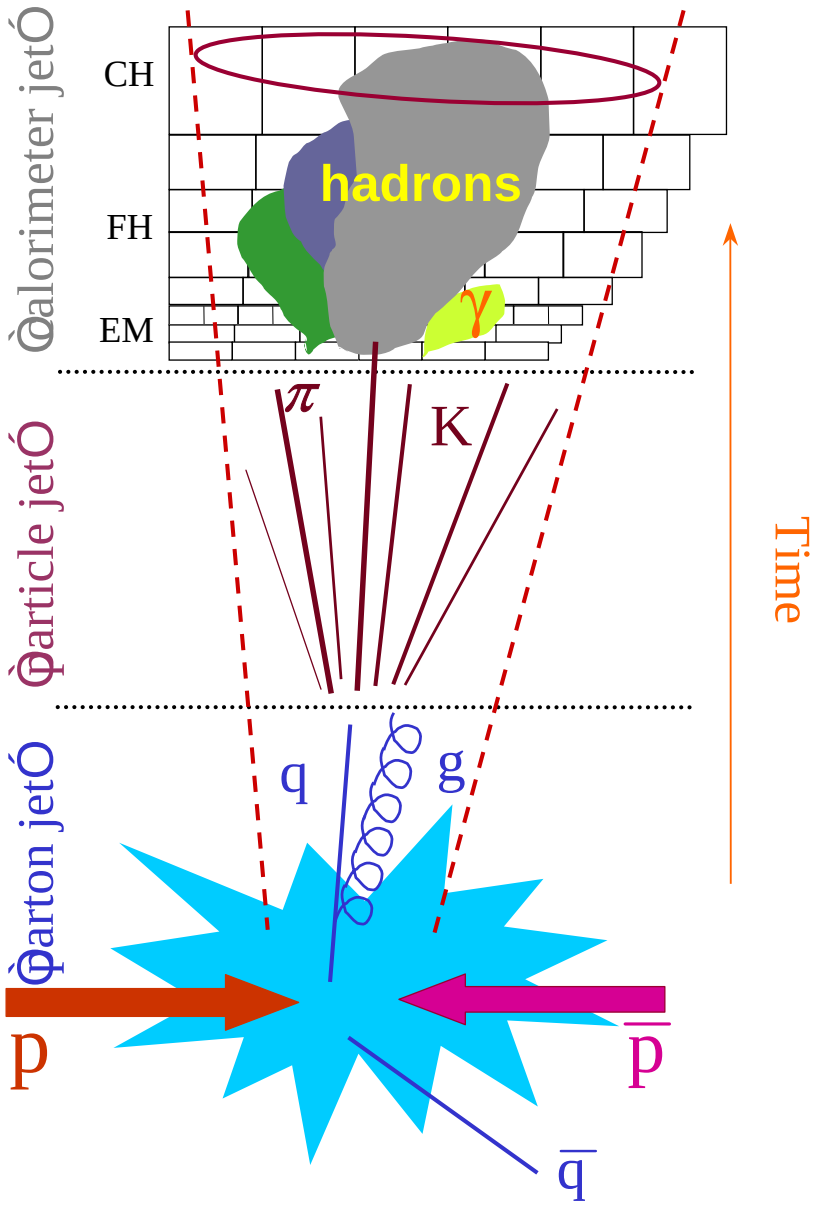
- Large uncertainties on the gluon density measured at HERA at high x: Important for searches at the LHC in jet channels
- Can Tevatron (and then LHC) constrain further the PDFs at high x?





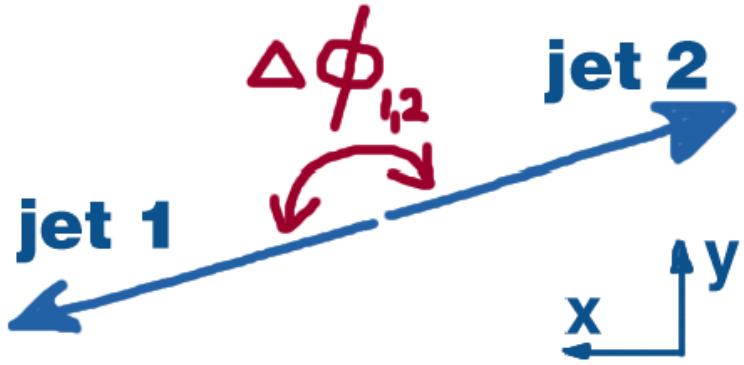
Jets at the Tevatron (and the LHC)

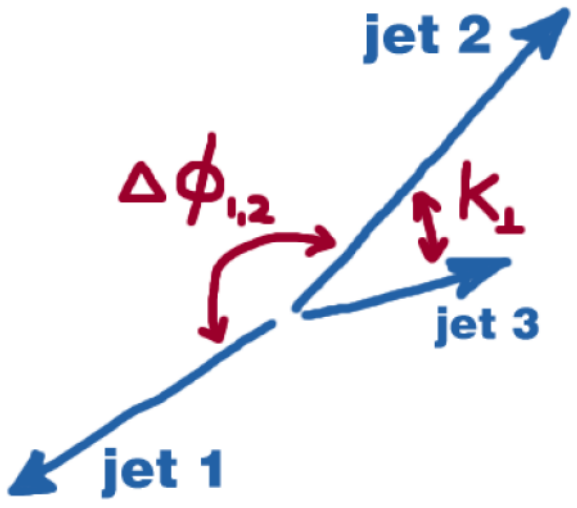
Dominant uncertainty: Determination of jet energy scale in calorimeter: use γ+jet at Tevatron, Z+jets at LHC



Tests of NLO QCD

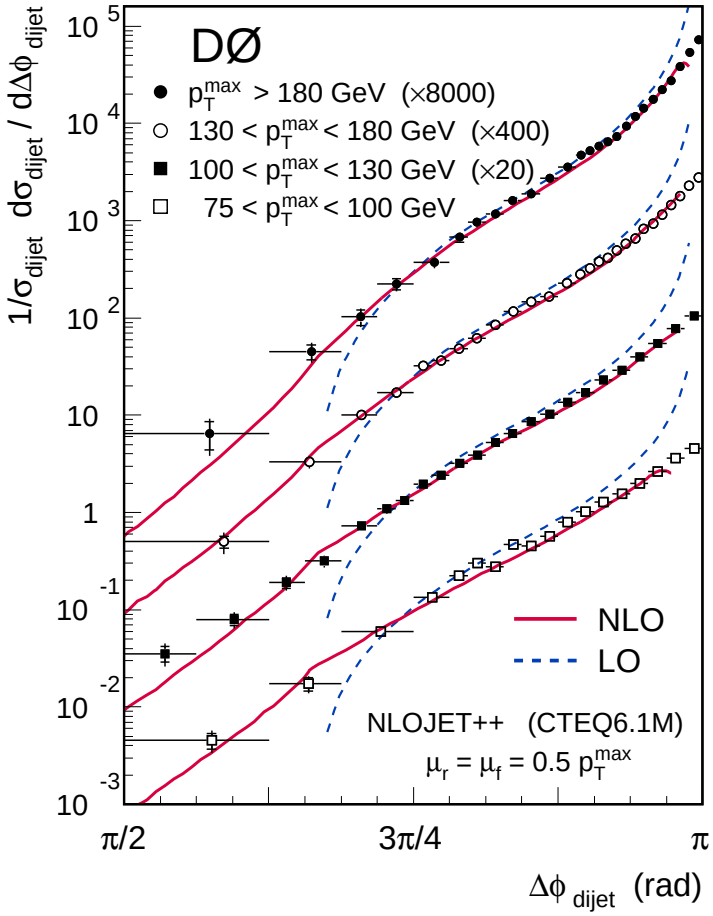
- Measurement of mutijet cross section also important for LHC ($t\bar{t}$ cross sections, search for Higgs bosons in association with $t\bar{t}$, search for R-parity violated SUSY (8-10 jets per event...))
- Measurement of the difference in azimuthal angle between two leading jets (D0), sensitive to multijets: no need of precise knowledge of jet energy scale

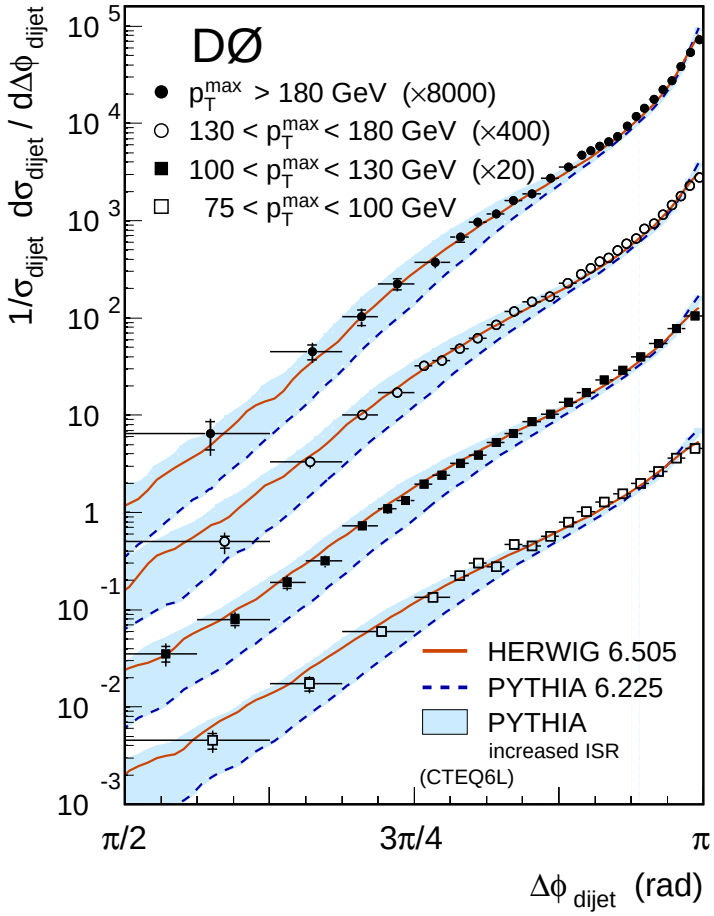




Tests of NLO QCD - MC tuning

- Measurement of the difference in azimuthal angle between 2 jets
- NLO calculation in good agreement with measurement (except at very high $\Delta\phi$: soft radiation)
- MC tuning: comparison with HERWIG, PYTHIA





Jet energy scale measurement

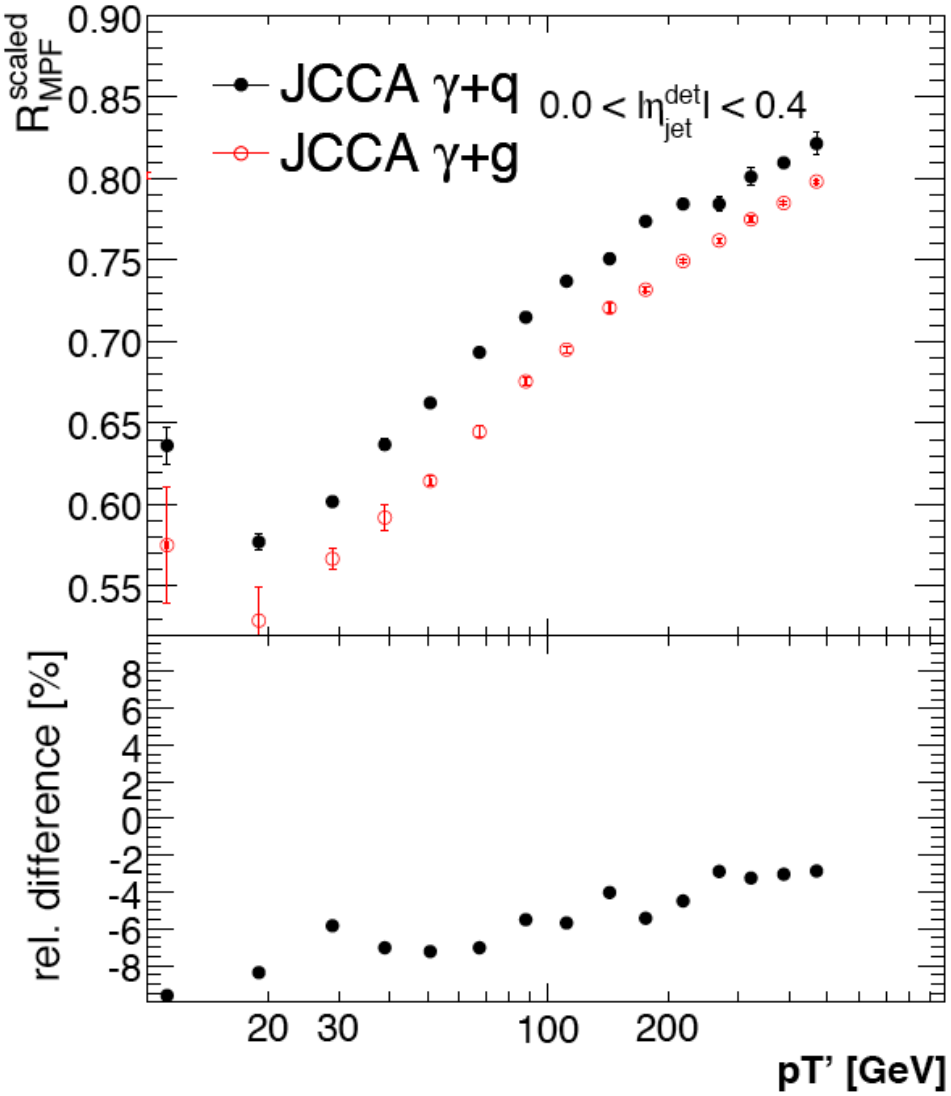
- Jet energy scale measurement (D0):

$$E_{jet}^{corr} = \frac{E_{jet}^{uncorr.} - Off}{Show \times Resp}$$

- Basic JES: use p_T balance in γ+jet events
- Off: offset corrections, related to uranium noise, pile-up..., Determined using zero-bias data
- Show: Showering corrections, takes into account the energy emitted outside of jet cone because of detector, dead material..., of course, does not take into account physics showering outside the jet cone, particles outside the cone
- Resp: Jet response
  - η dependent corrections: equalise calorimeter response
  - Jet response, obtained using p_T balance in $\gamma+$ jet events, cross check using $Z+$ jet event
  - Differences between quark and gluon jets
- CDF: JES obtained using tuned MC (beam tests, single pion response...)

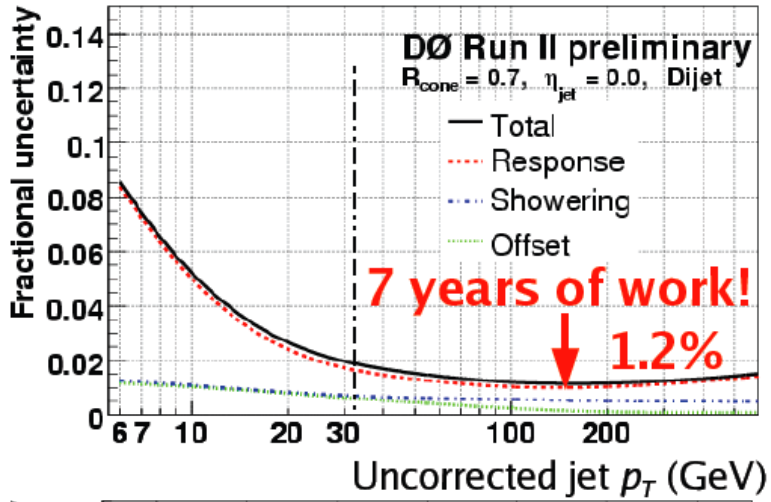
Differences between quark and gluon responses

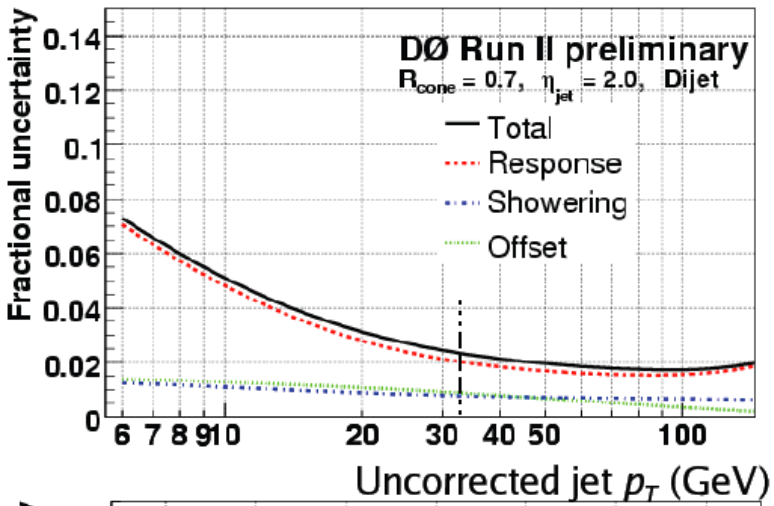
- Different quark and gluon jet responses (studied in response between quark and gluon using the γ+jet and inclusive jet samples)
- Means different corrections depending on physics: QCD jets (gluon dominated), $t\bar{t}$ events (quark dominated)...

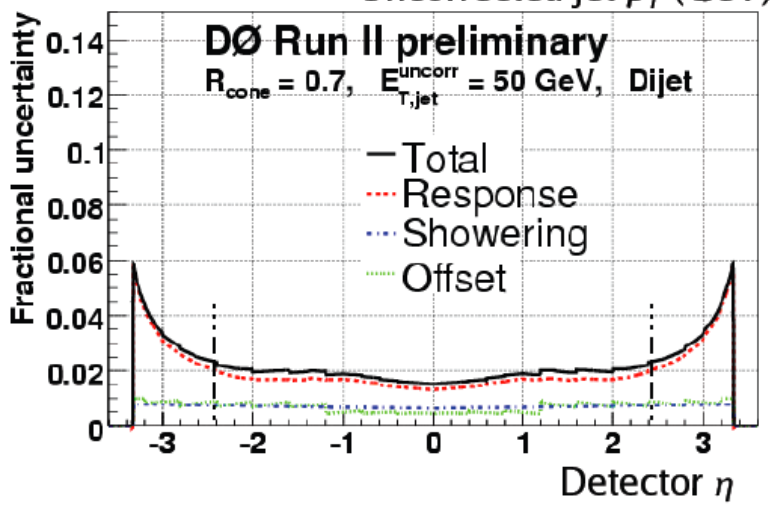


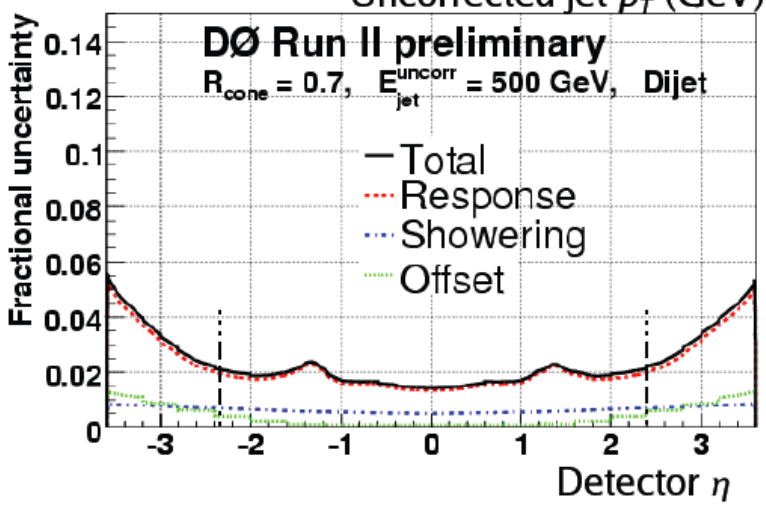
Jet Energy Scale in D0

- "Standard" JES determined using γ+jet
- Corrections for JES for QCD jets obtained using inclusive jet sample and p_T balance between dijets
- Uncertainties of the order of 1.2% for central jets and $p_T \sim 100$ GeV



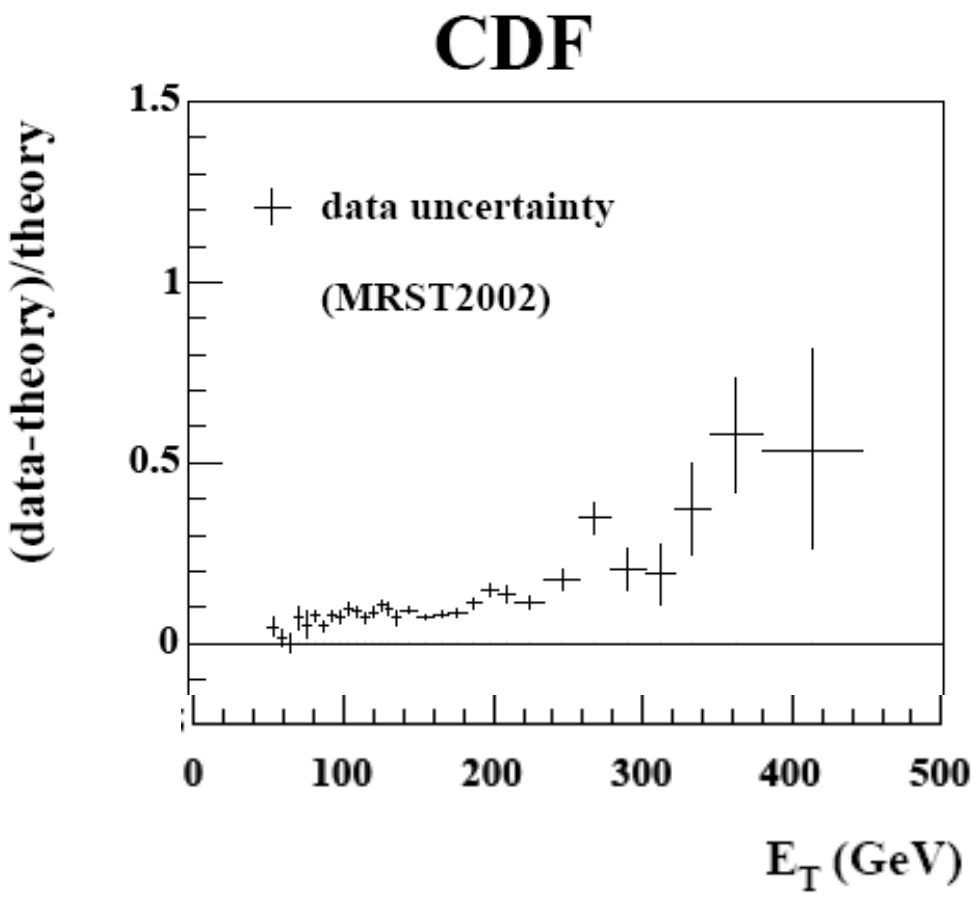






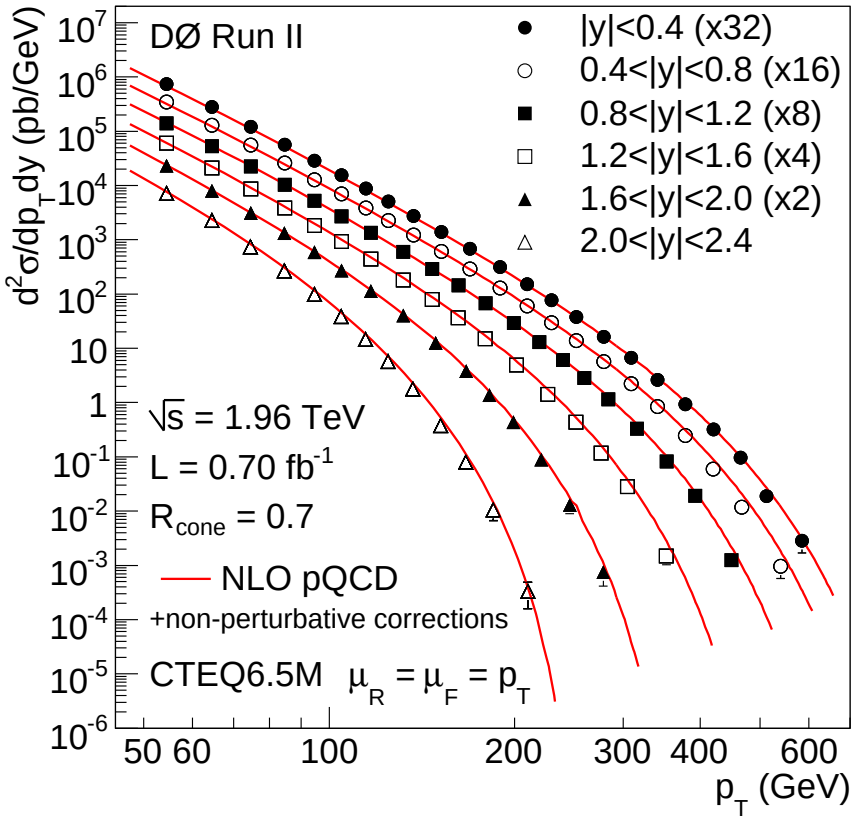
1995 CDF excess in the jet E_T spectrum

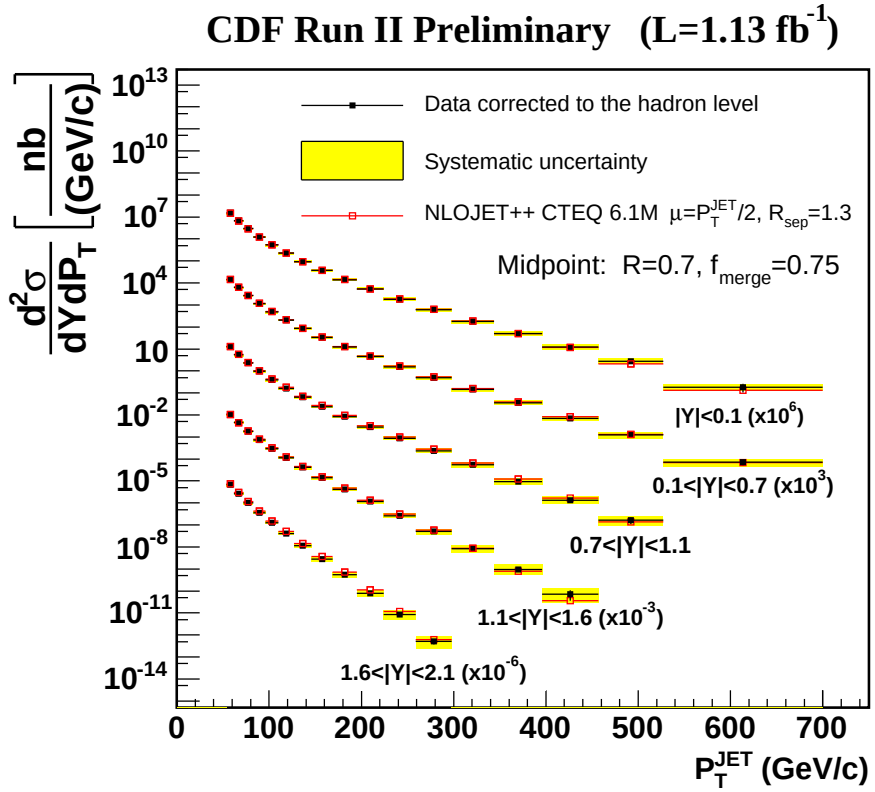
- CDF observed an excess compared to theory in the inclusive jet p_T cross section measurement
- Originally suspected to be a signal of quark substructure
- Increasing the gluon density at high x can accomodate these data
- Raises the question of PDF vs beyond standard model effects: same for the LHC, the limiting factor can come from PDF uncertainties



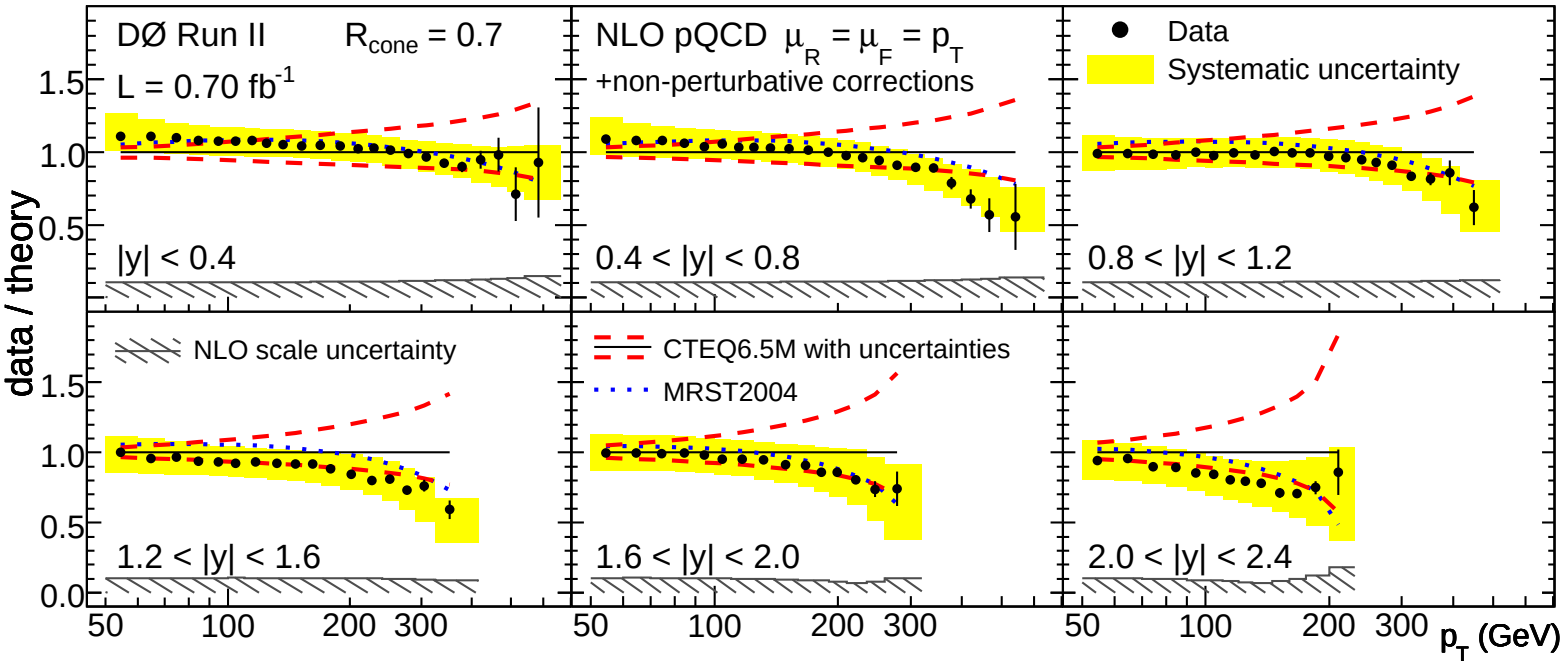
Jet inclusive p_T cross section (D0 and CDF)

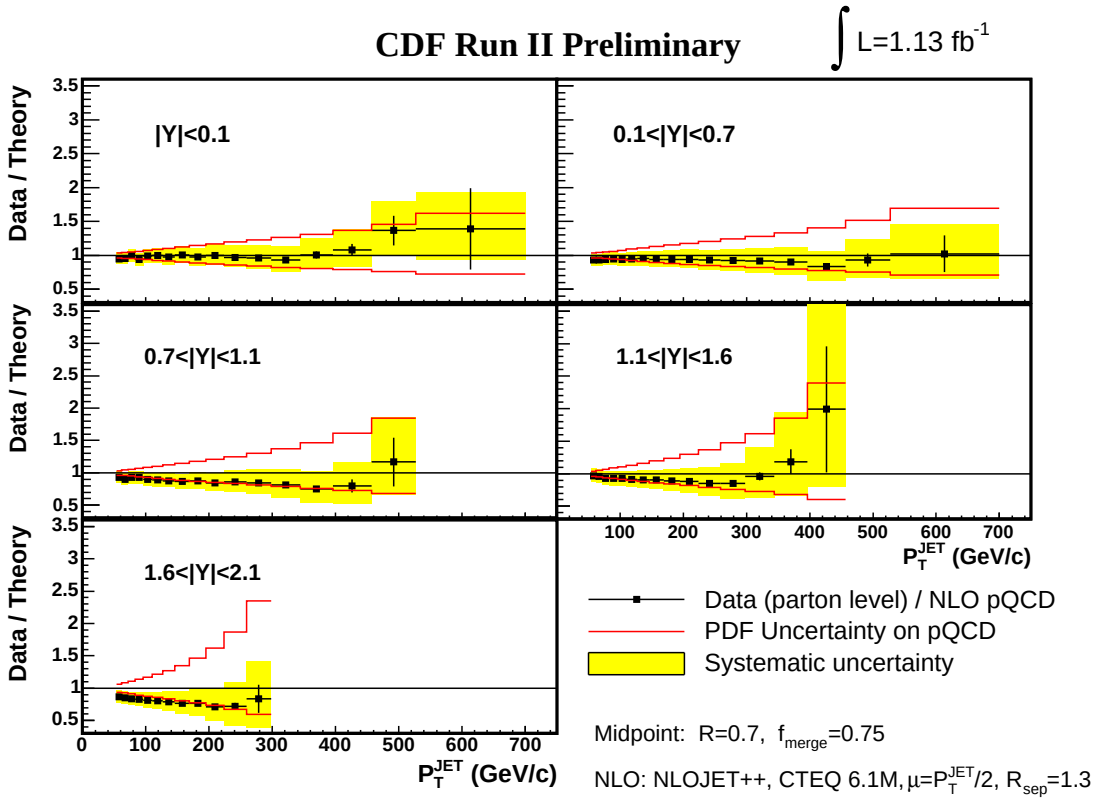
- Measurement of the inclusive jet cross section using 0.7 cone algorithm in a p_T range 50-700 GeV and a rapidity up to 2.4 (D0)
- Corrections up to hadron level (D0), parton level (CDF)
- Comparison with NLO QCD calculation (CTEQ6.5M for D0, CTEQ6.1 for CDF with uncertainties $\sim$ two times larger): Good agreement over six orders of magnitude
- Study data/theory: see how these data can be used to test NLO QCD and tune PDFs





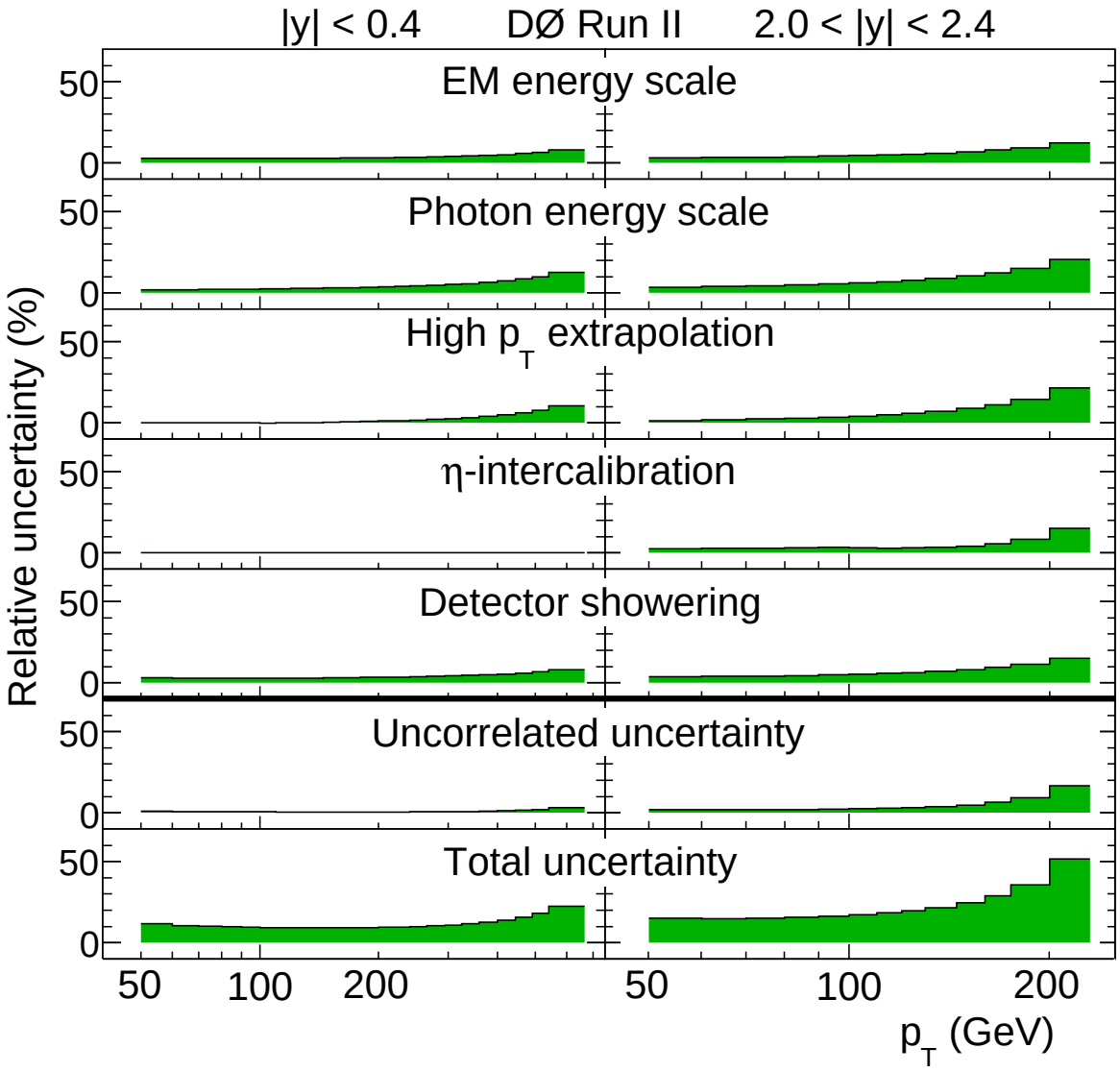
Data/Theory for inclusive jet cross section





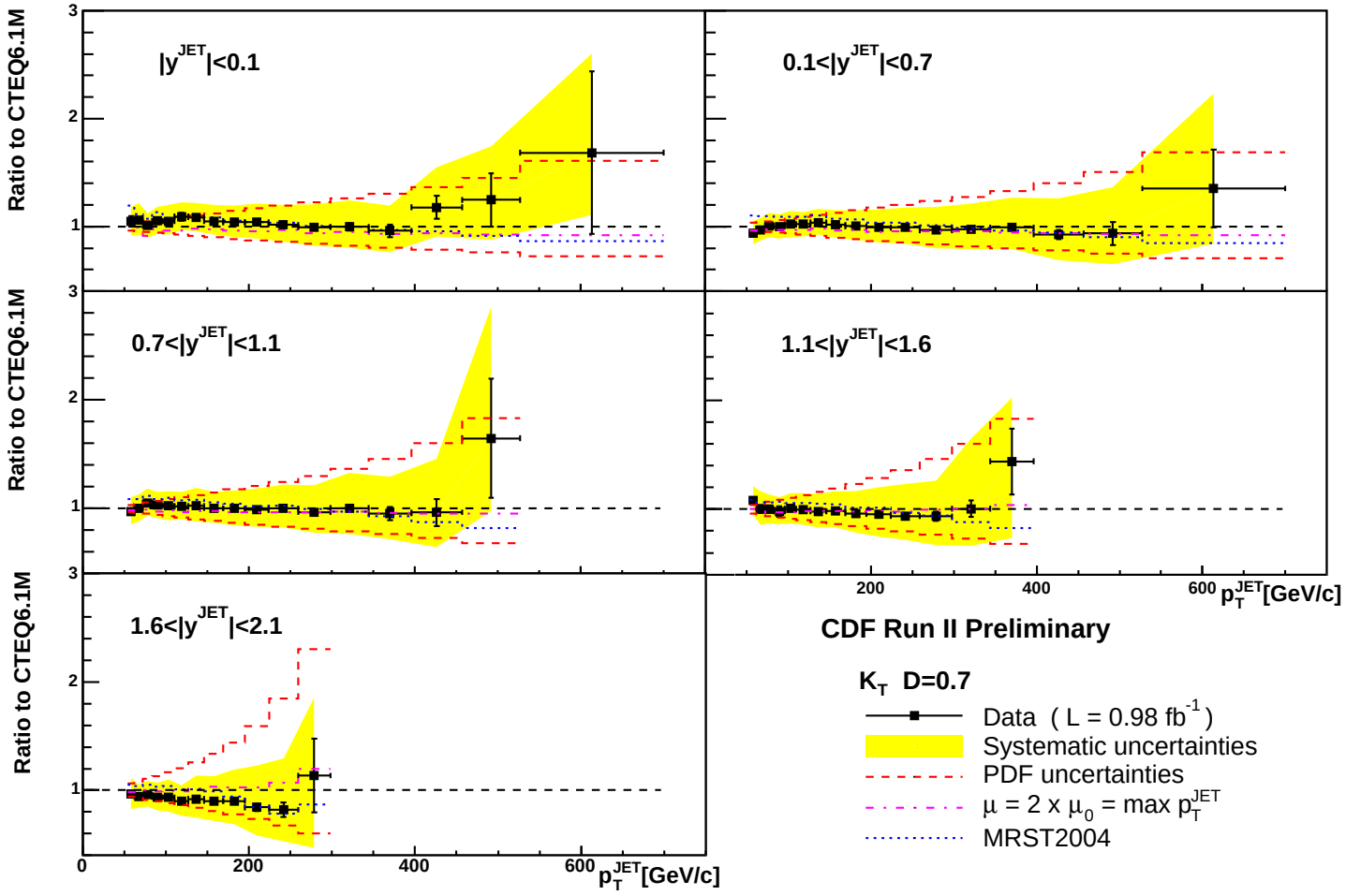
Correlation studies for jet inclusive p_T cross section (D0)

- Full correlation studies: give the effects of 24 sources of systematics in data
- Possibility to constrain further PDFs using correlation matrices



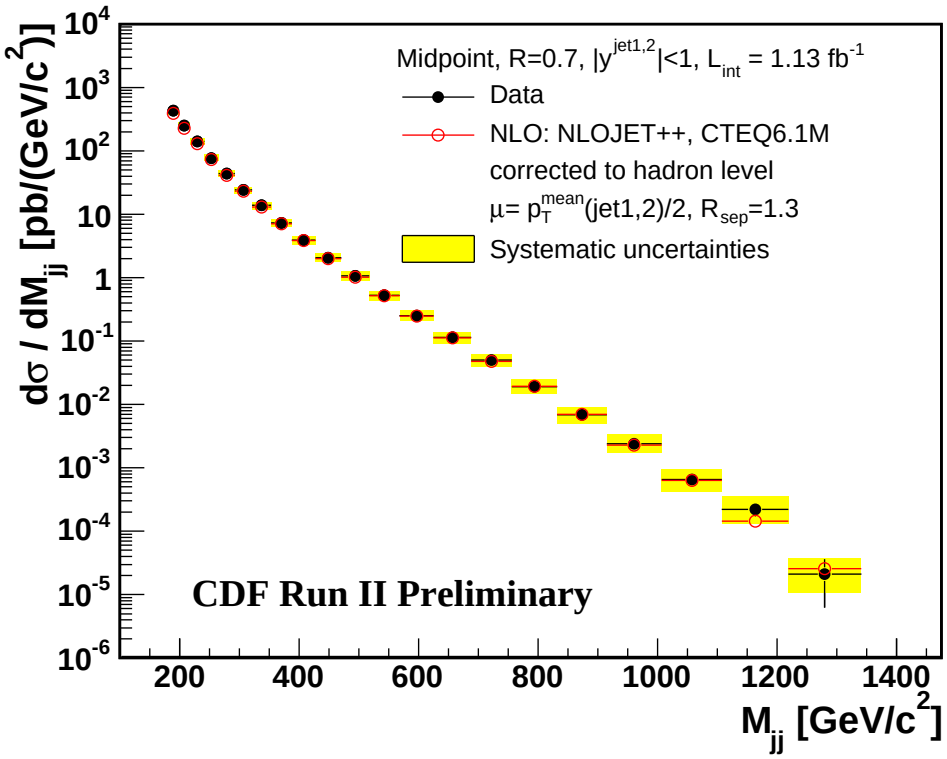
Jet inclusive p_T cross section using the k_T algorithm (CDF)

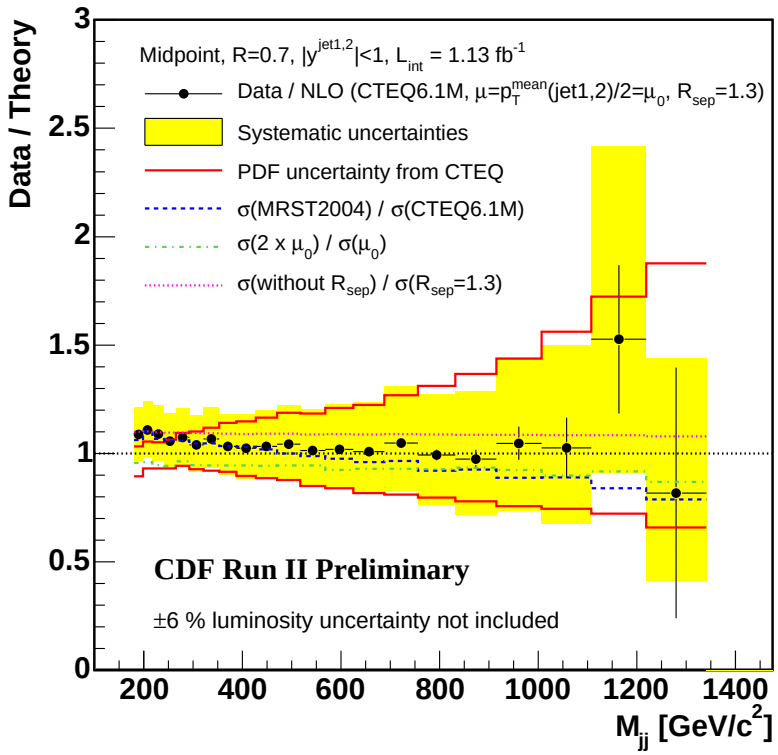
- Measurement in 5 rapidity bins
- Measurement performed at hadron level, NLO calculations (JETRAD) corrected for hadronisation and underlying events



Measurement of the dijet mass (CDF)

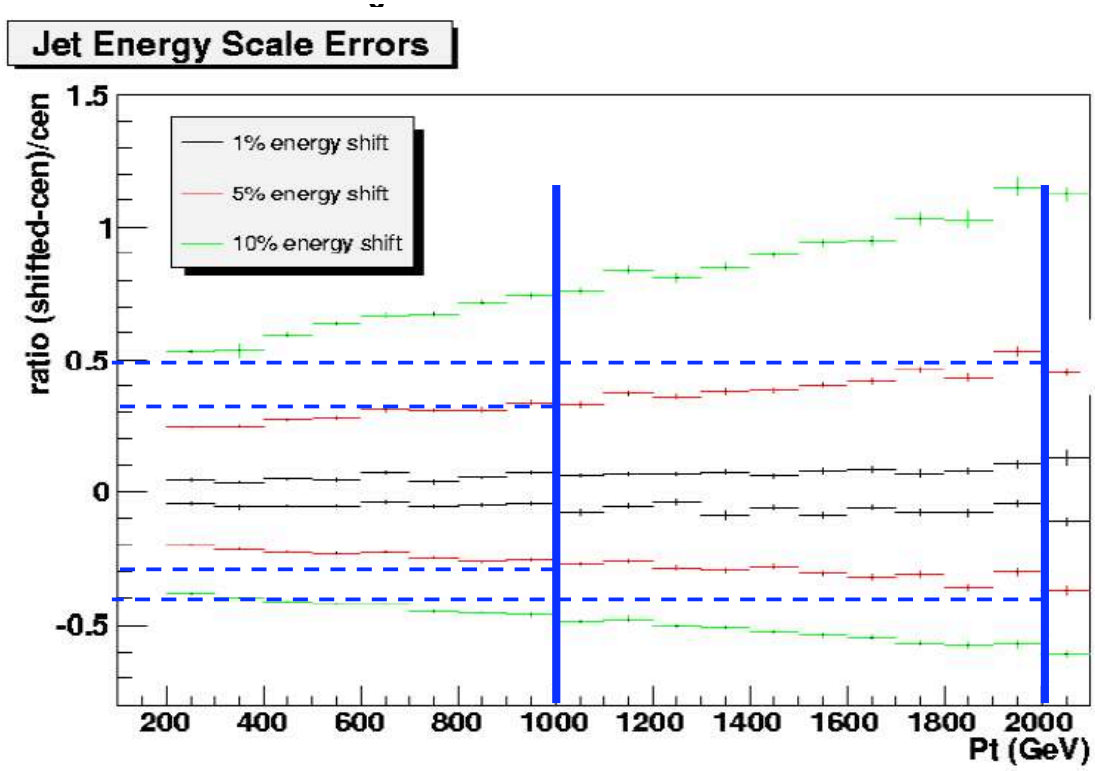
- Measurement of the dijet mass above 180 GeV up to 1.2 TeV: good agreement with NLO calculations
- Allows to exclude excited quarks below 870 GeV, and Z' (resp. W') below 740 (resp. 840) GeV, and technirho below 1.1 TeV (NB: stronger limits on Z' and W' come from lepton based searches)





Can PDF be further constrained at the LHC

- Can PDFs be further constrained using jet inclusive measurements at the LHC?
- PDF uncertainties of the order of 15% at 1 TeV, 25% at 2 TeV for $1 < |\eta_{jet}| < 2$ (without taking into account new Tevatron measurements)
- Need very good control of JES to improve knowledge of gluon at high x



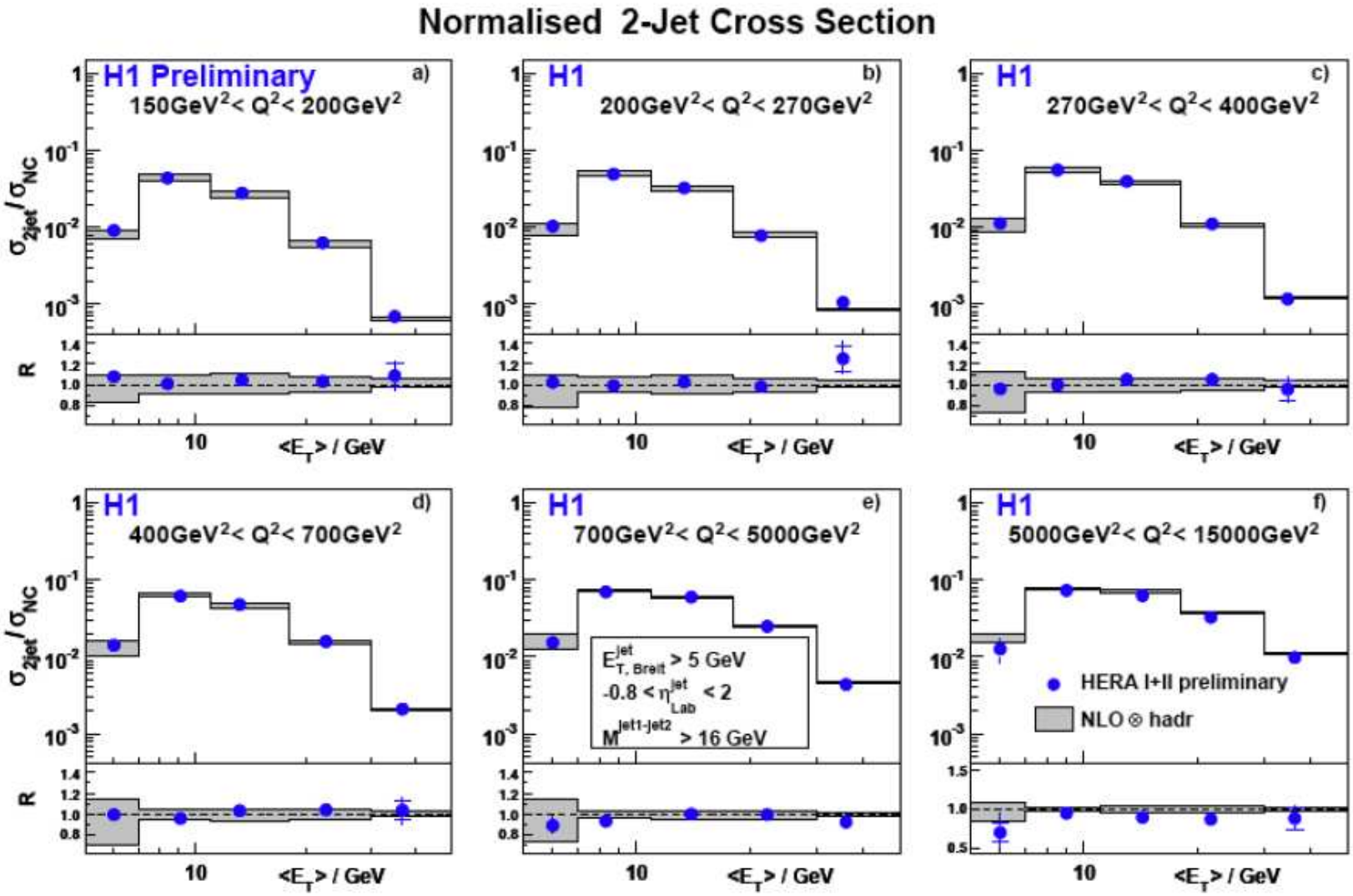
10% JES → 60% on σ

5% JES → 30% on σ

1% JES → 6% on σ

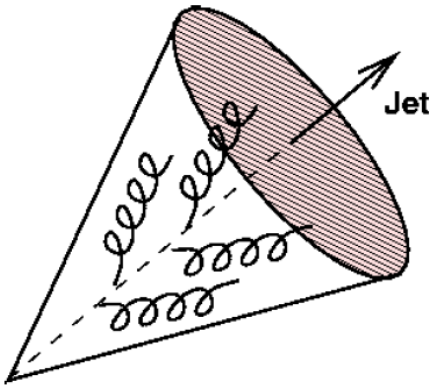
Measurement of multijet cross section (HERA)

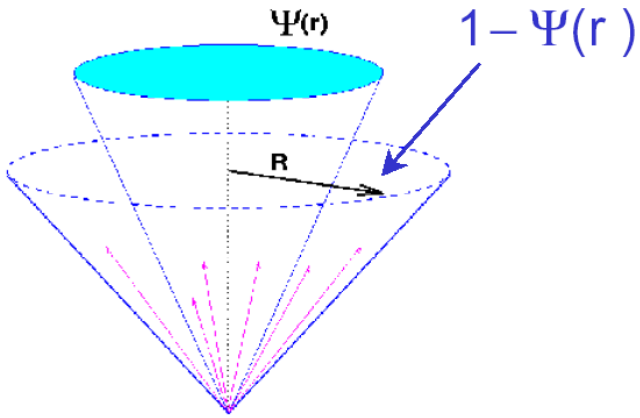
- Measurement of multijet cross section useful for LHC (top events, R-parity violated SUSY... where many jets are produced)
- Measurement of the 2 (or 3 jet) production cross section relatively to neutral current cross section: allows to reduce systematics
- Good agreement with NLO calculations



Jet shape measurements (CDF)

- Jet shape dictated by multi-gluon emission from primary partons
- Sensitivity to quark/gluon contents, PDFs, and running α_S
- Sensitivity to underlying events

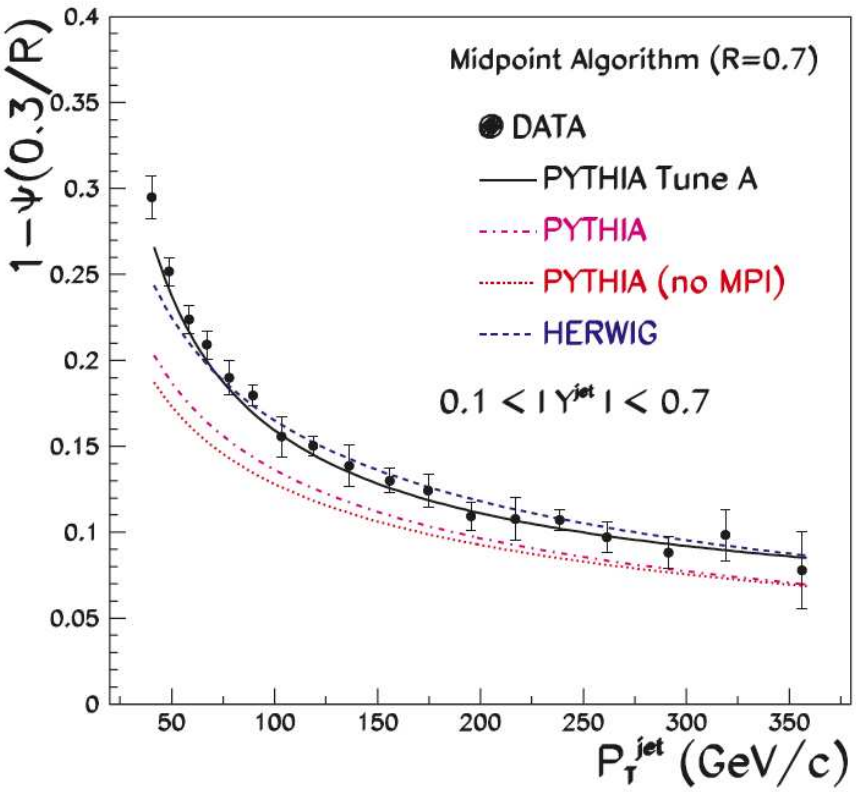


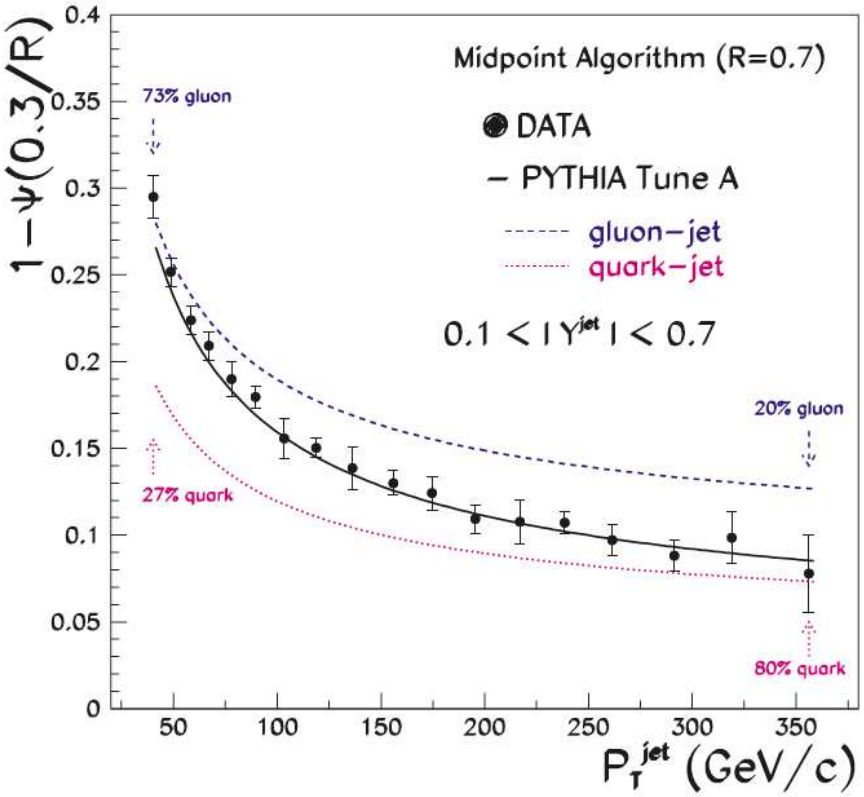


$$\Psi(r) = \frac{1}{N_{jets}} \Sigma_{jets} \frac{P_T(0,r)}{P_T^{jet}(0,R)}$$

Jet shape: Sensitivity to parton distributions (CDF)

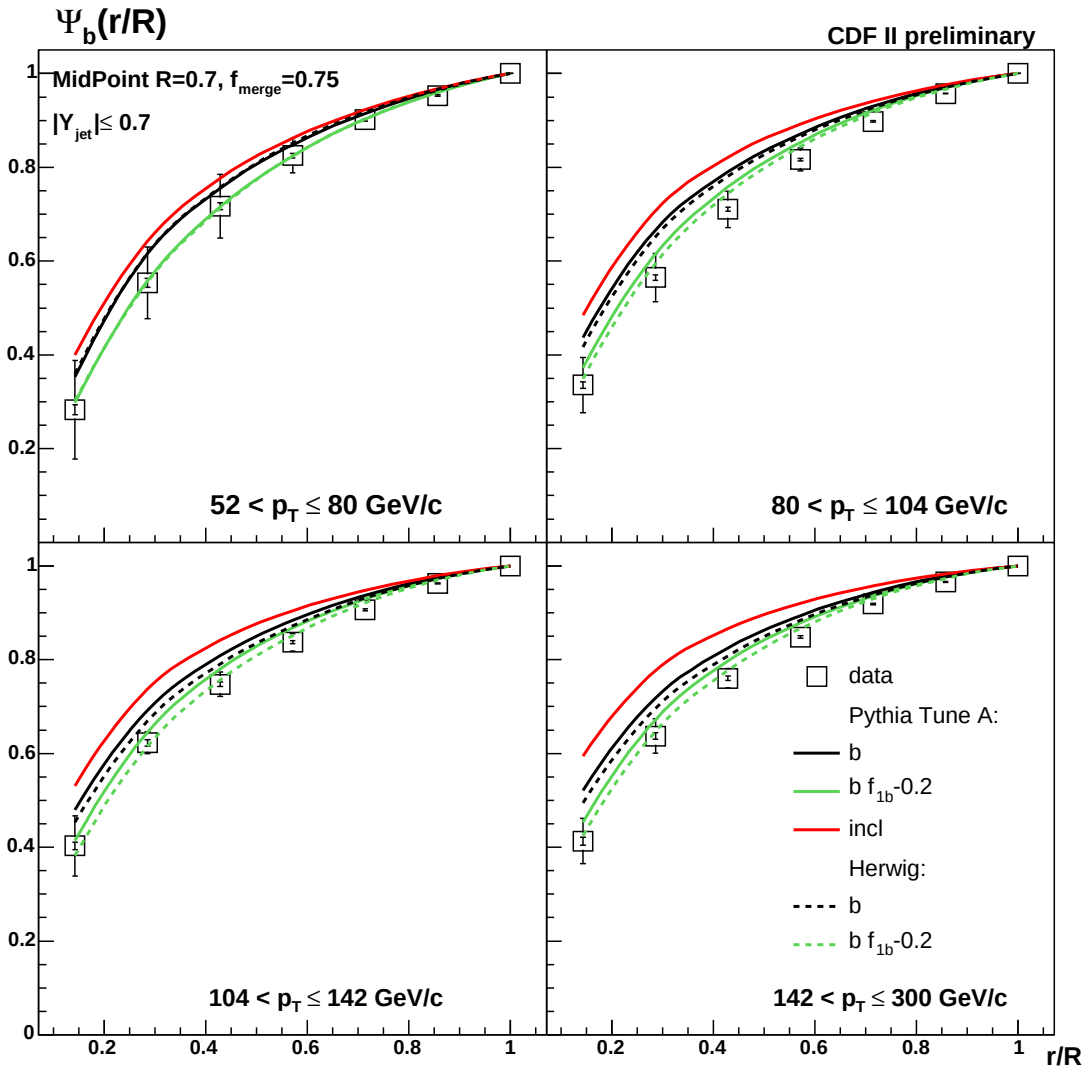
- allows to tune generators
- allows to distinguish between quark and gluon jets





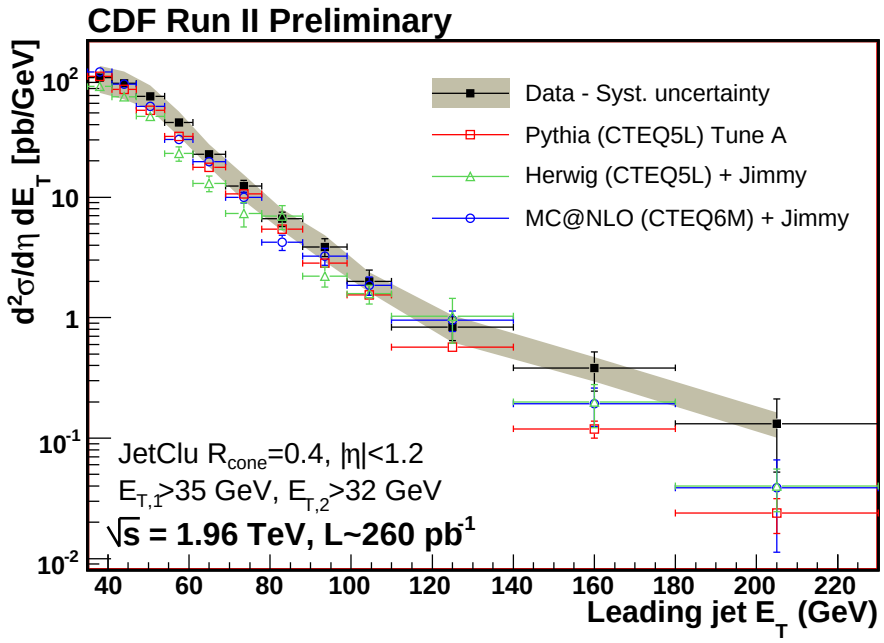
Jet shapes for b-jets (CDF)

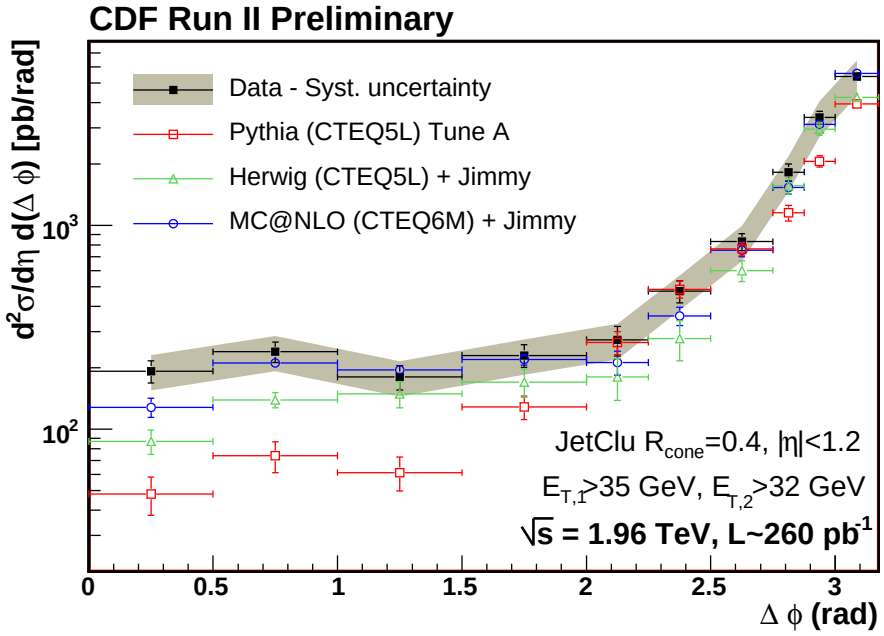
- Default PYTHIA and HERWIG cannot describe b-jet shape
- Single b-quark fraction reduced by 0.2 leads to a better description of data: the fraction of b-jets that originate from flavour creation (a single b-quark is expected in the same jet cone) over those that originate from gluon splitting (two b-quarks are expected to be in the same jet cone) is different in MC and data



$b\bar{b}$ dijets (CDF)

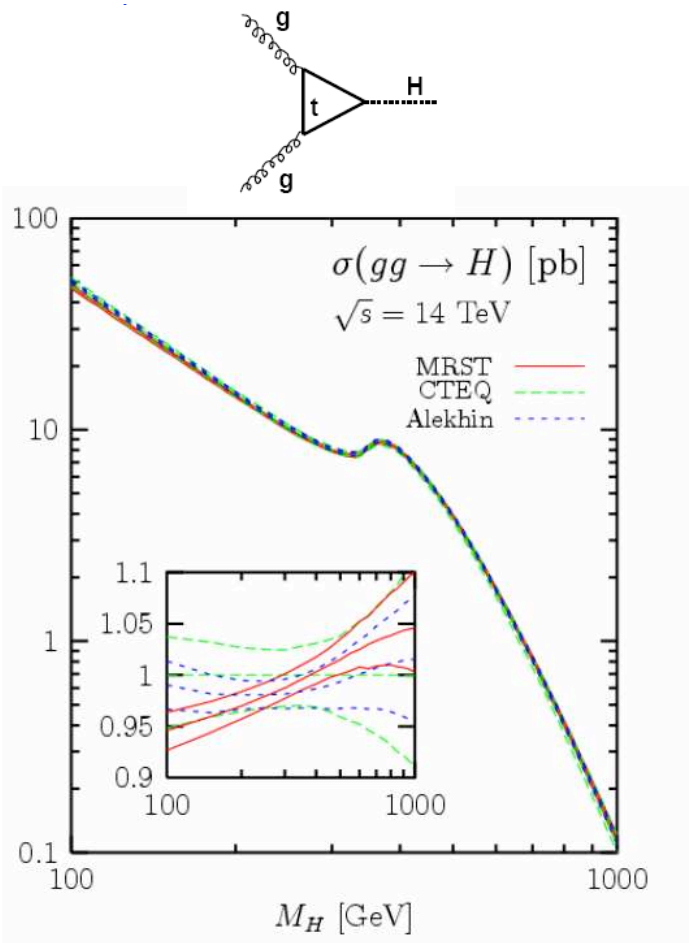
- Measurement of the $b\bar{b}$ dijet cross section as a function of leading jet p_T and the distance in azimuthal angle
- Pythia and Herwig underestimates the gluon splitting mechanism

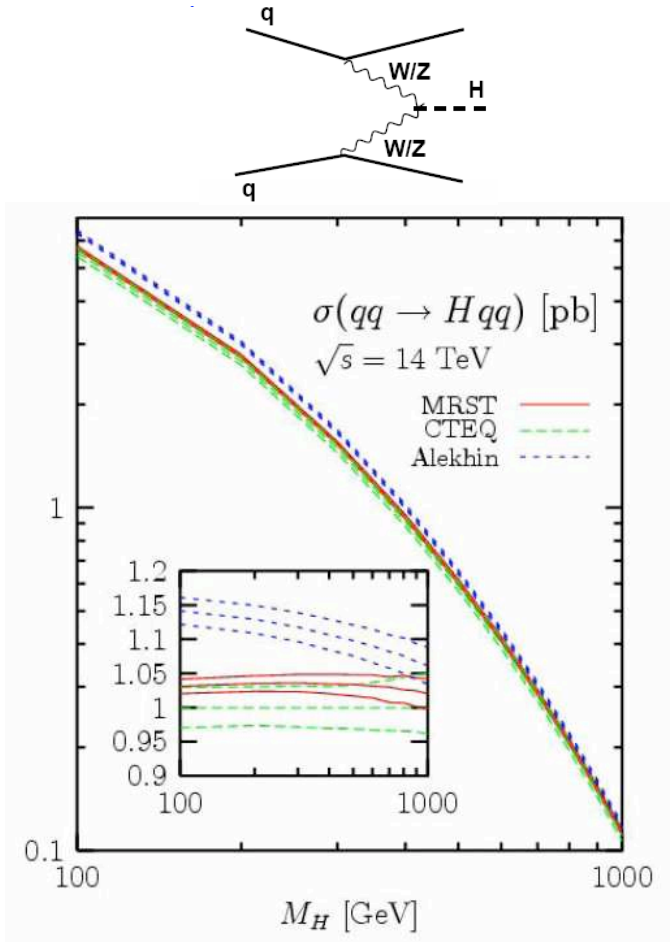




How do PDF uncertainties affect LHC potential?

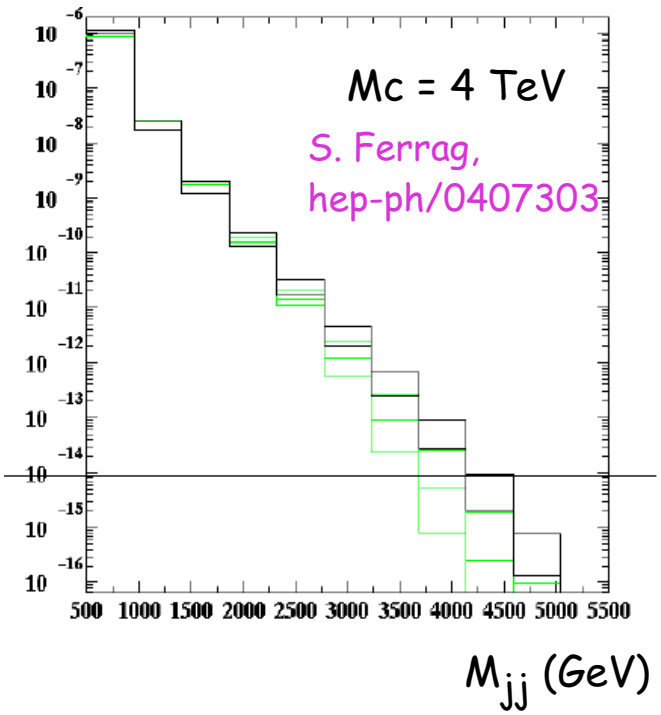
- How do PDF uncertainties affect LHC discovery potential on Higgs boson as an example?
- Cross sections (signal and background) are known within 10%, no strong impact on cross section calculation to produce heavy object (Higgs)
- Higher uncertainties due to NLO calculation: for example, for Higgs events at 120 GeV, NNLO effects are of the order of 9% (for Z^0, 4%)

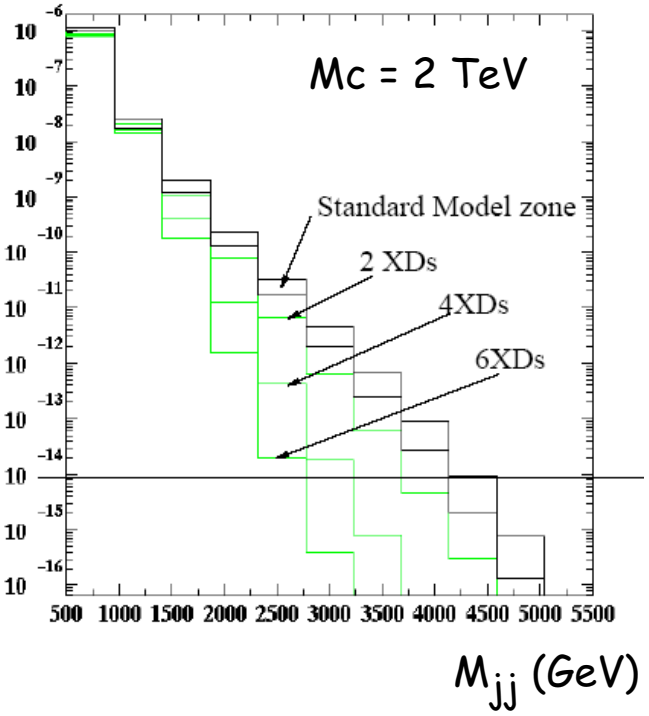




How do PDF uncertainties affect LHC potential?

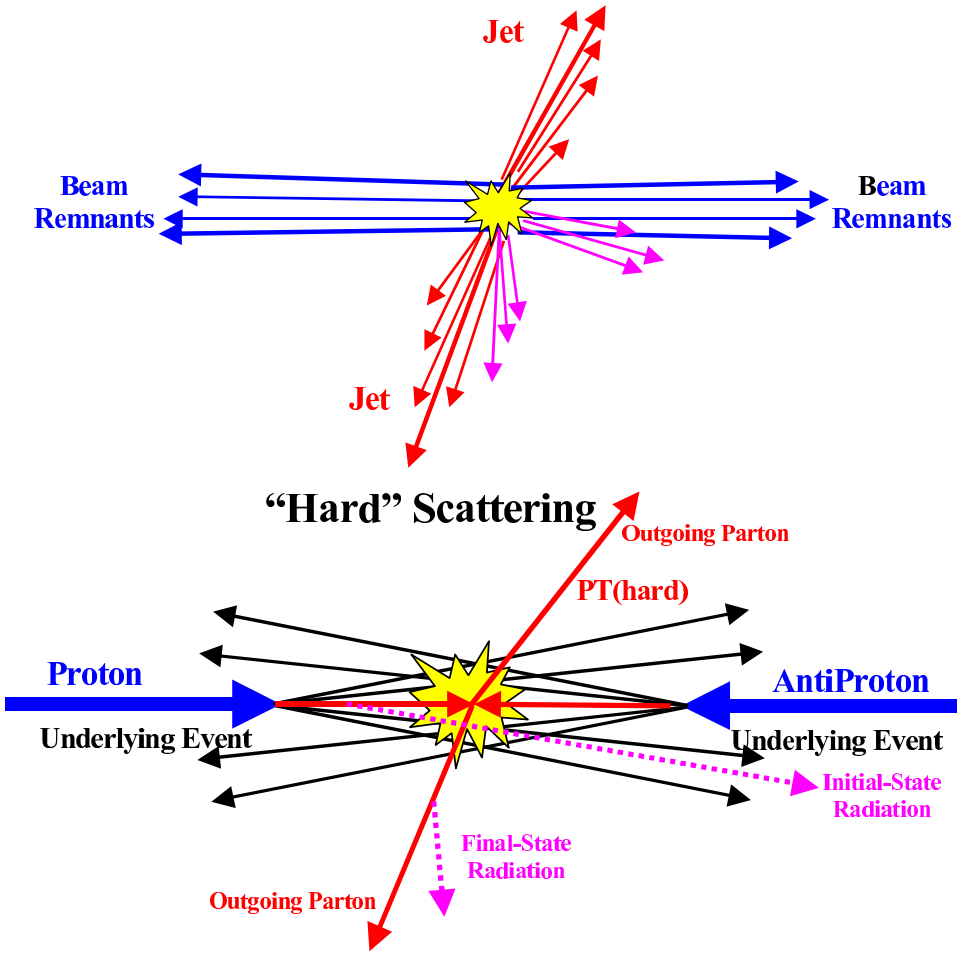
- PDF uncertainties have an impact on searches (higher dimensions. SUSY...), single top searches because of the background uncertainty
- An example: $qqqq$ contact interactions for two compactification scales: Look for excess in dijet mass spectrum
- Warning: No JES uncertainty considered in this study





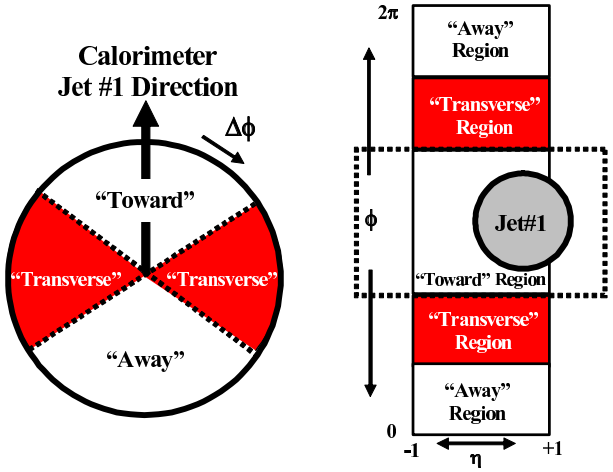
A parenthesis: underlying events at Tev./LHC

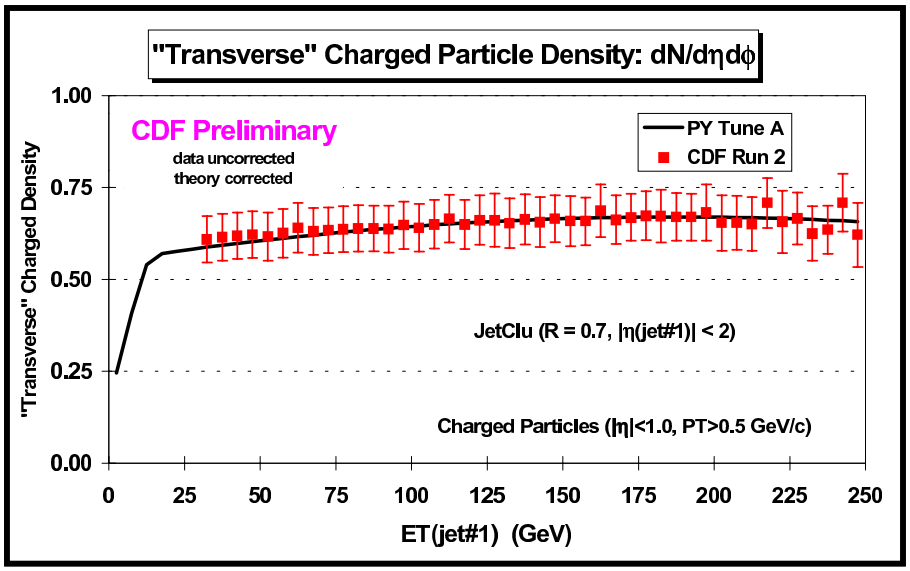
Study of underlying events at the Tevatron

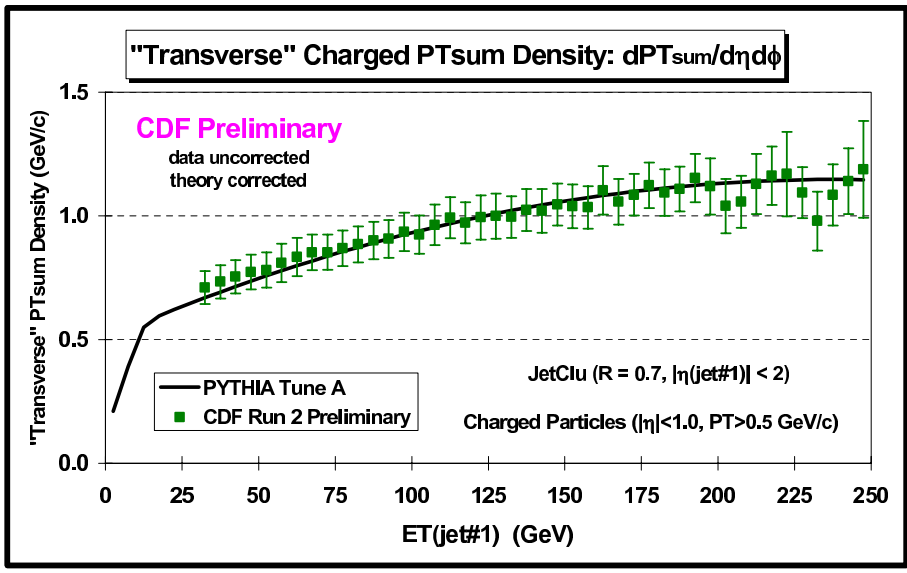


A parenthesis: underlying events at Tev./LHC

Idea: study the energy in the transverse region ($60 < \Delta\Phi < 120$ degrees)

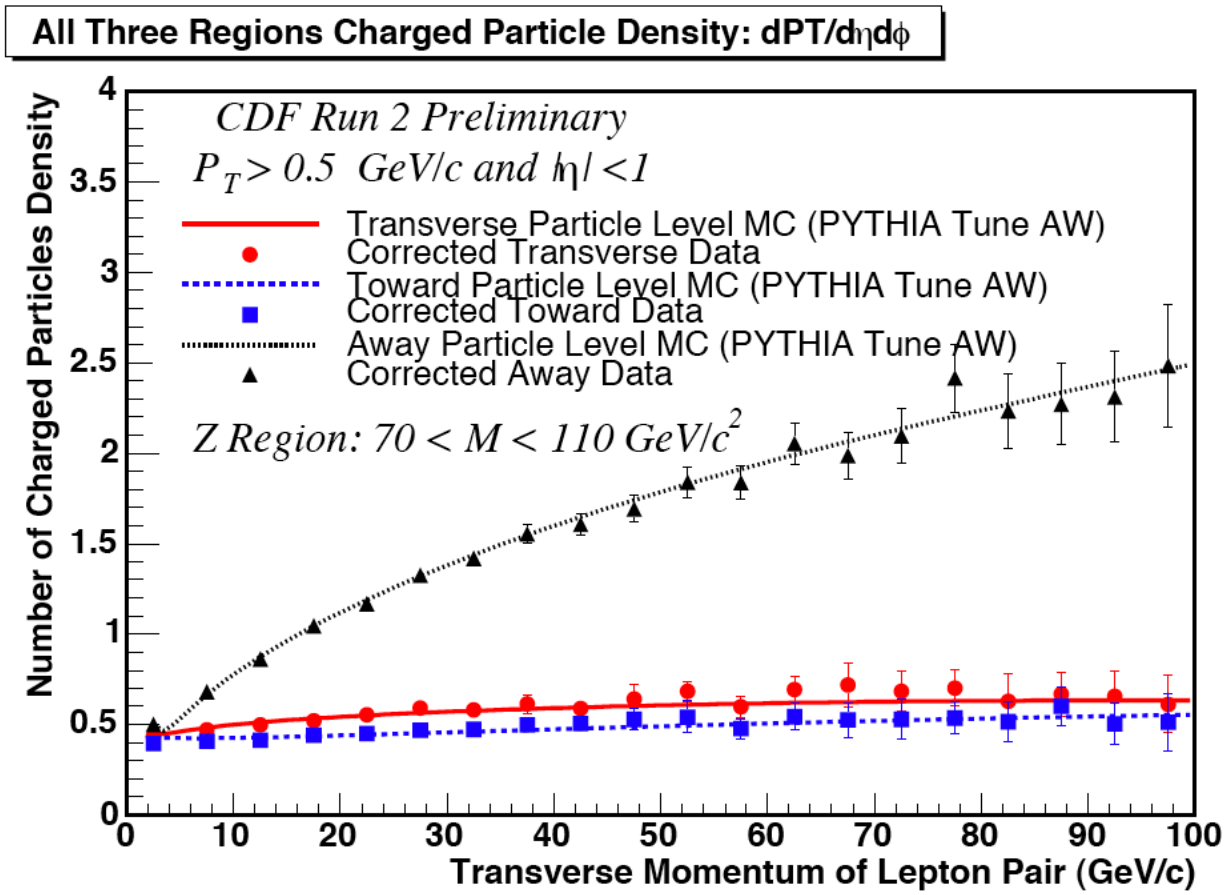






A parenthesis: underlying events at Tev./LHC

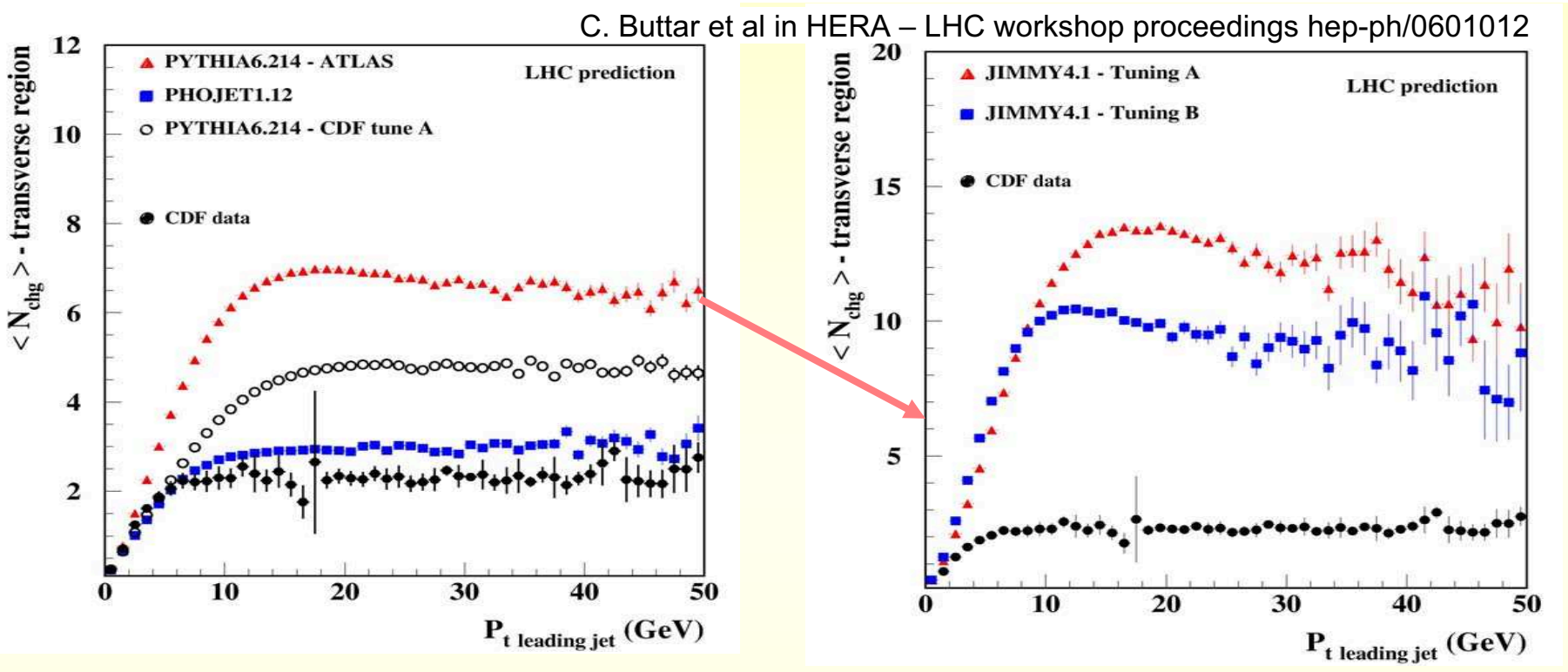
Study underlying events in clean Drell-Yan production: use the lepton pair to define the "toward" region, the "away" region opposite to it and the "transverse" region



A parenthesis: underlying events at LHC

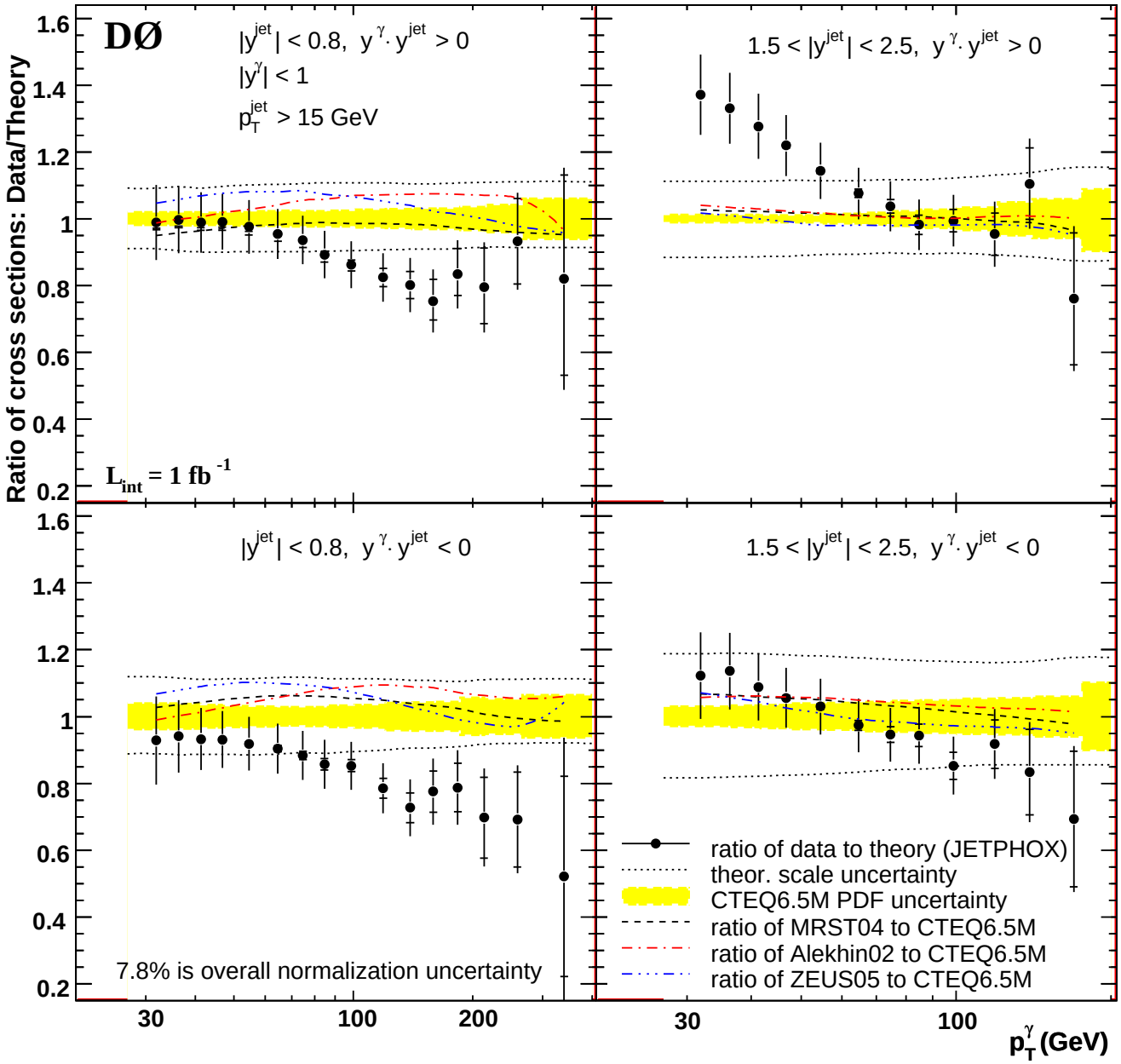
Large differences between different models at the LHC: measurement crucial at the beginning

C. Buttar et al in HERA – LHC workshop proceedings hep-ph/0601012



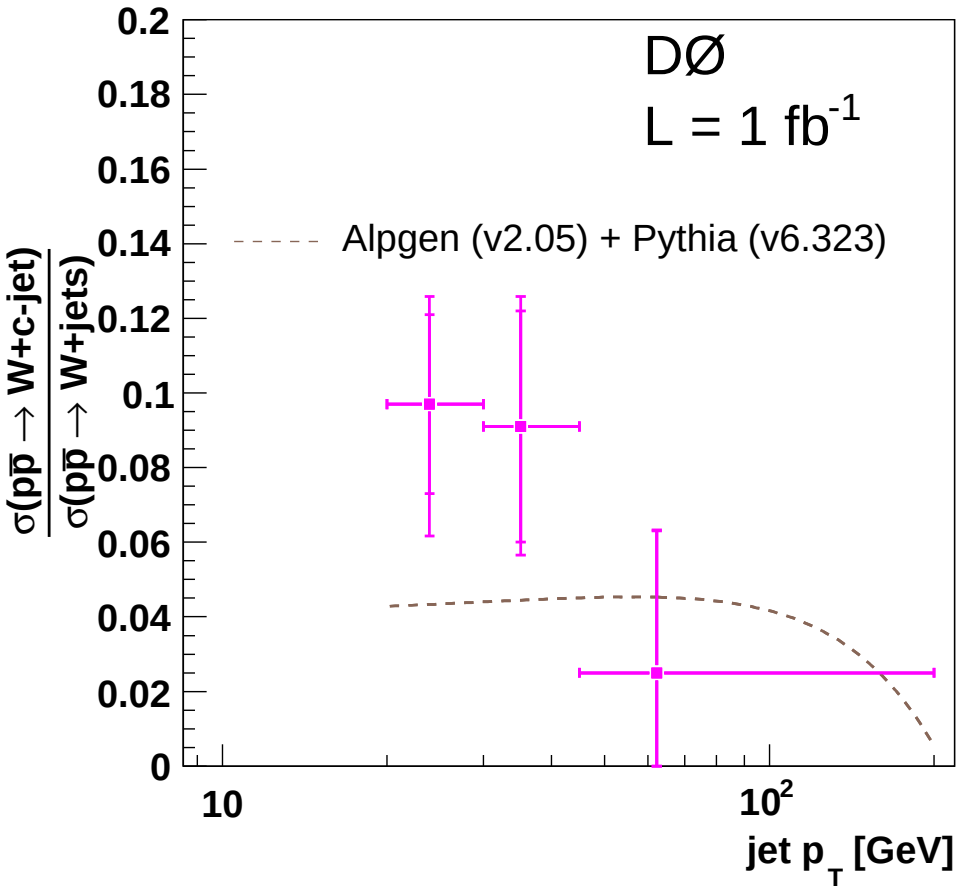
Measurement of photon + jet cross section (DO)

- Measurement of inclusive production cross section of isolated photons + jet in different detector regions (central photon, central or forward jets)
- Cross section in disagreement with NLO QCD at high p_T both in shape and normalisation



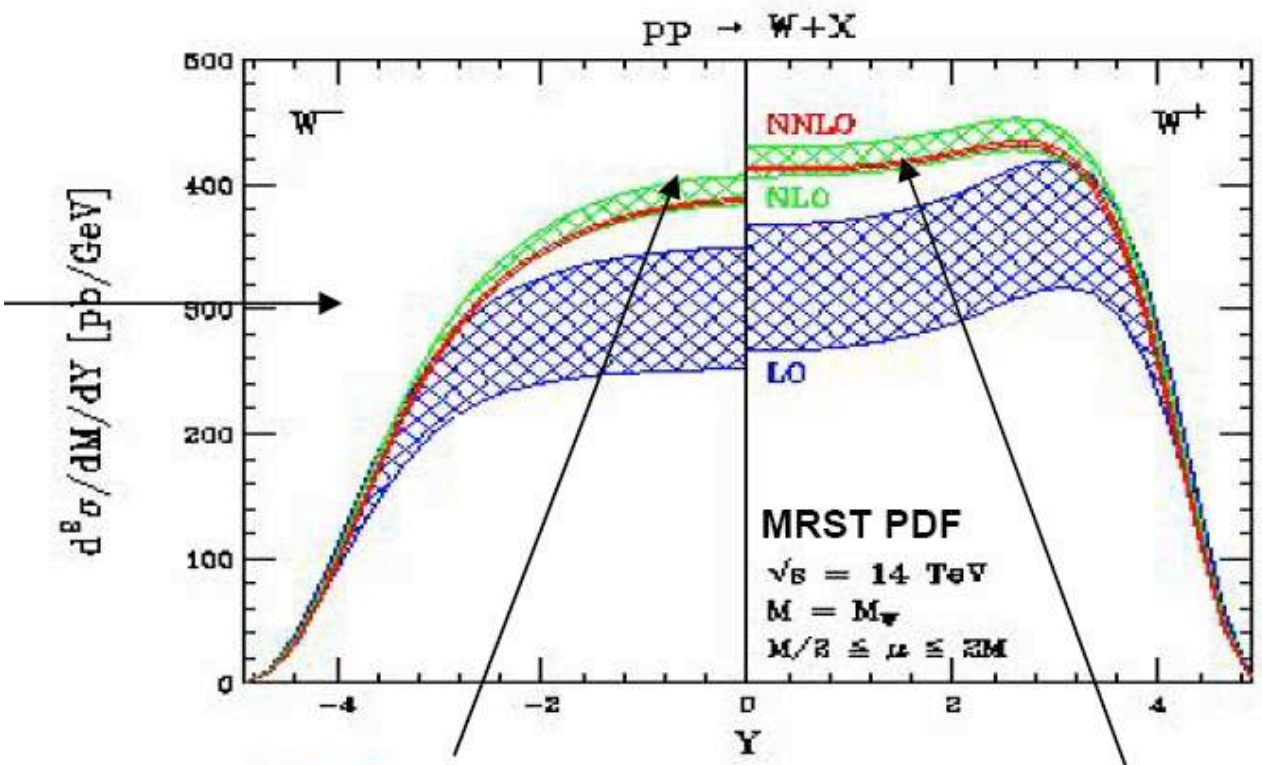
Measurement of W+c cross section (D0)

- Measurement of the ratio of the $W + c$ to the inclusive W cross section: 0.074 ± 0.019 (stat.) $\pm^{0.012}_{0.014}$ (syst.) in agreement with NLO calculation
- Sensitivity to s-quark PDF



W+X cross section at the LHC

- W+X production at the LHC: considered as "standard" candles
- Small theoretical uncertainties
- But PDFs not so well known: $< x > \sim 7.10^{-3}$ (between 5.10^{-4} and 5.10^{-2}), not in valence region, not in the region where quarks are best known
- Uncertainty quoted by many groups $\sim 5\%$, and differences between groups of the order of 8% $\rightarrow$ Not precise enough to be used as a lumi monitor



NNLO corrections small ~ few%

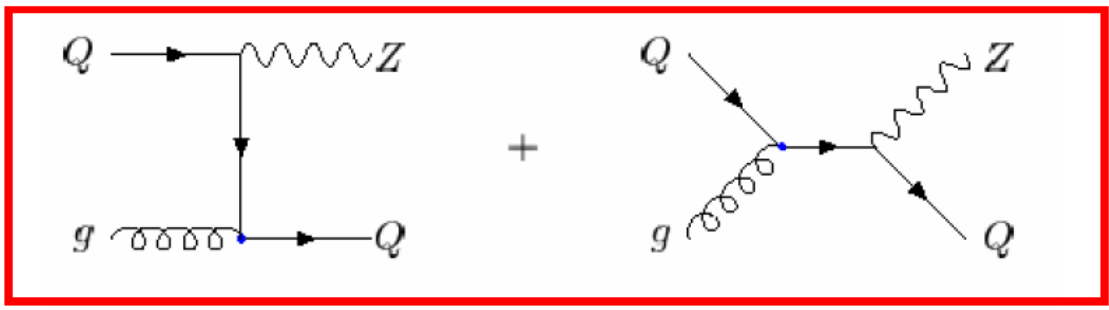
NNLO residual scale dependence < 1%

Z+b jet cross section: motivation

Motivation to measure Z+b jet events: QCD and background for Higgs

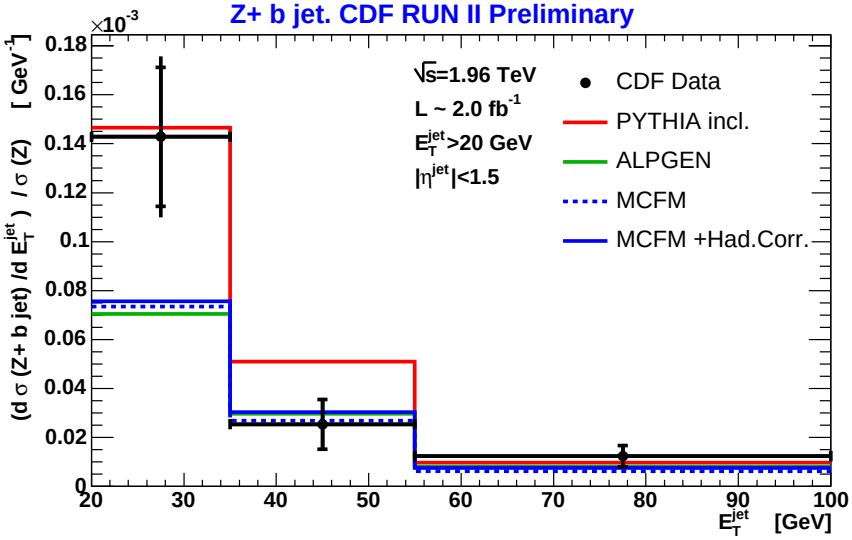
Background processes to Higgs

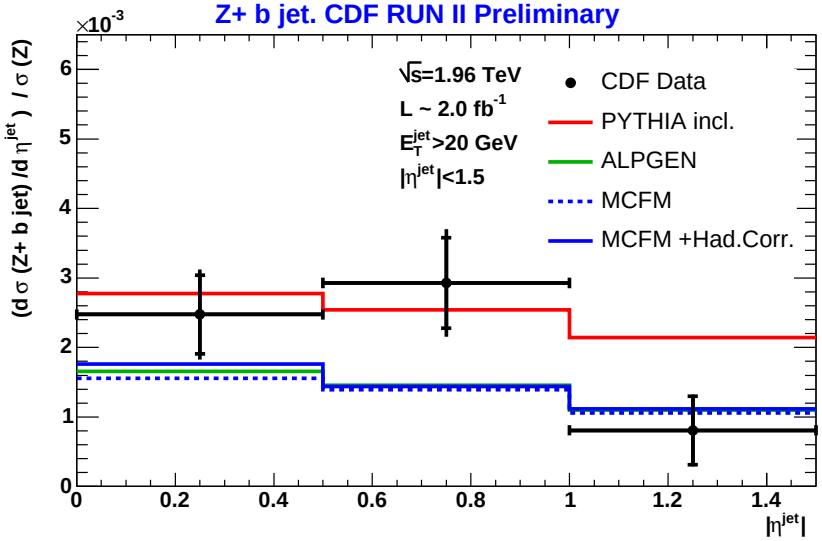
Probe b content of proton



$W/Z+$ b-jet cross section (CDF)

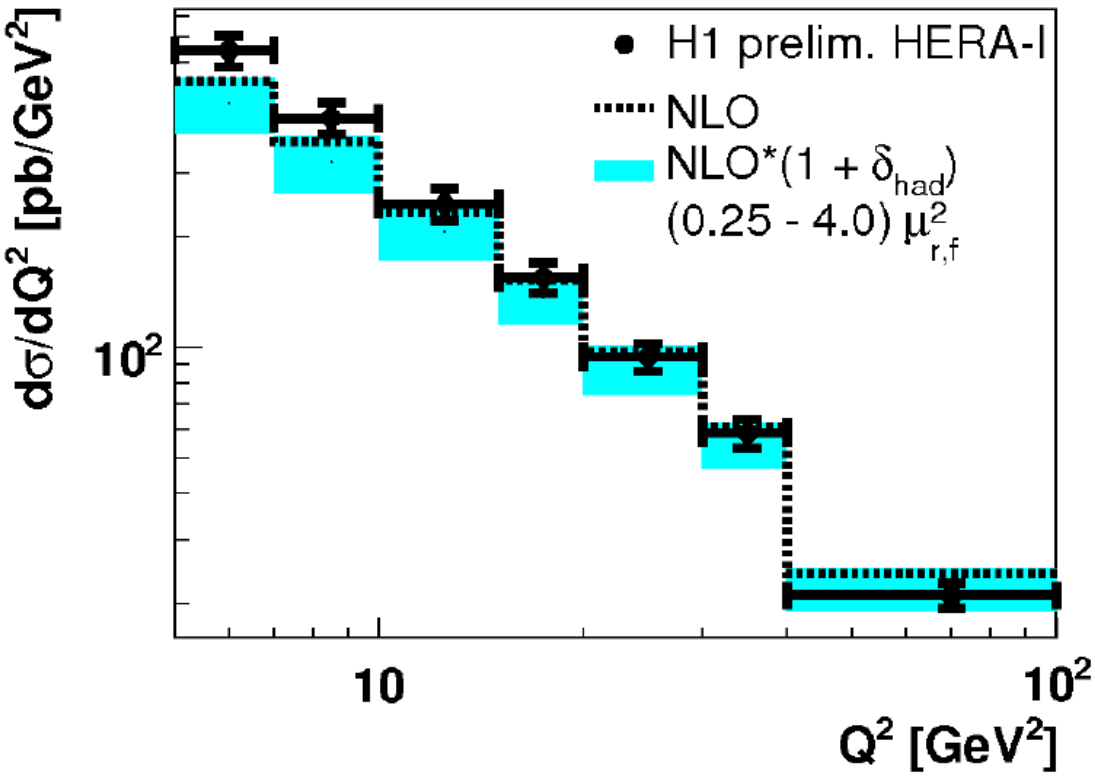
- Measurement of the $Z+$ b-jet cross section with jet $p_T > 20$ GeV and $|\eta| < 1.5$
- Good agreement with PYTHIA predictions
- $\sigma(Z + b\ jets)$ =0.86 $\pm$ 0.14 $\pm$ 0.12 pb ($\sigma_{NLO} = 0.53$ pb)
- $\sigma(W + b - jets) \times BR(W \to l\nu) = 2.74 \pm 0.27(stat.) \pm 0.42(sys.)$ pb (Alpgen: 0.78 pb)
- Fundamental for background to Higgs searches and single top production





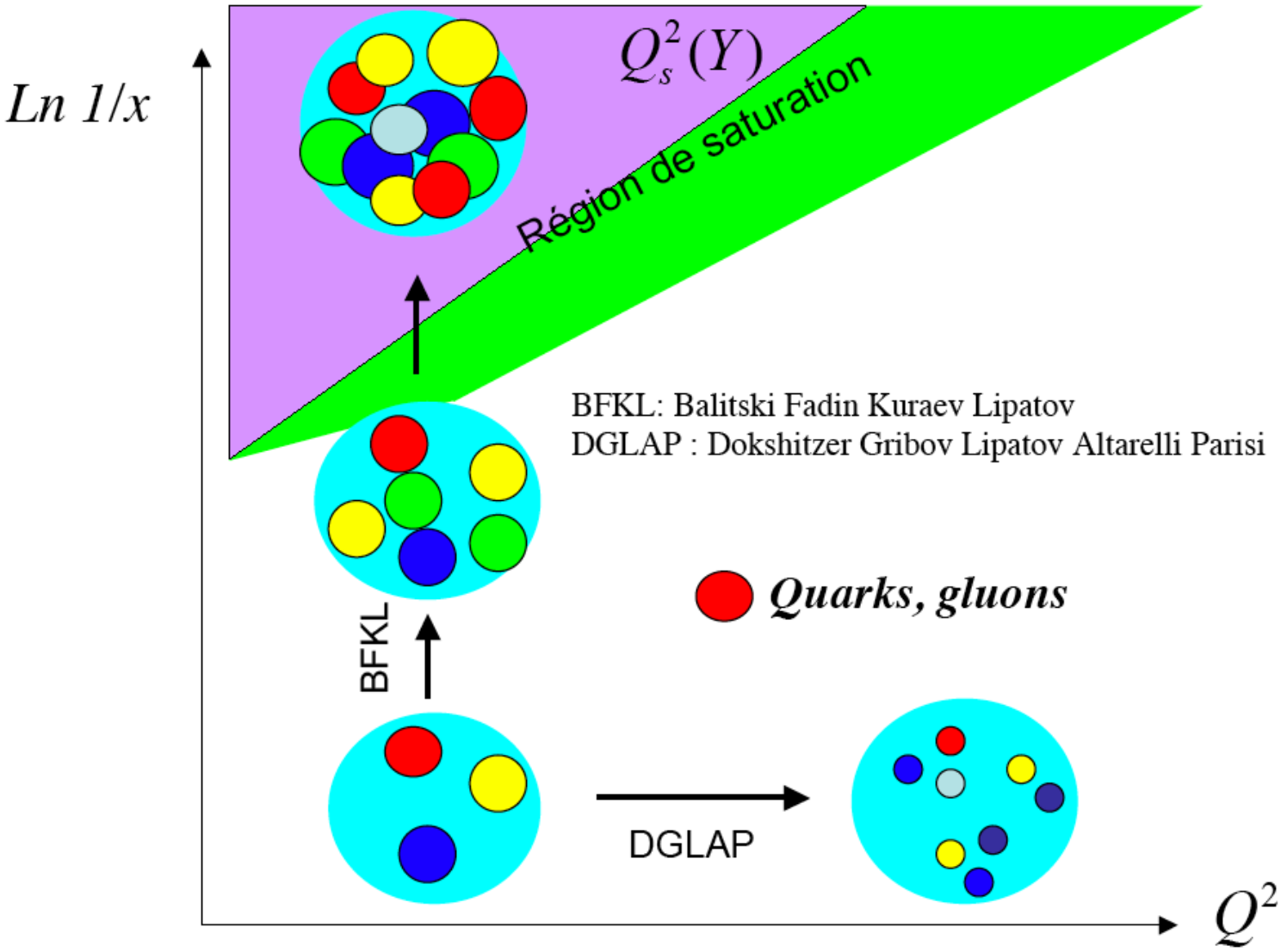
Jets at low Q^2 at HERA

- Inclusive jets at low Q^2: how low in Q^2 and E_T is pQCD at NLO reliable? Some new effects expected? What about BFKL resummation effects?
- Kinematic region: $5 < Q^2 < 100$ GeV^2, $E_T > 5$ GeV, discrepancy towards low Q^2
- Interpretation? Higher order QCD calculations (NNLO)? Missing low x resummation terms (BFKL)?

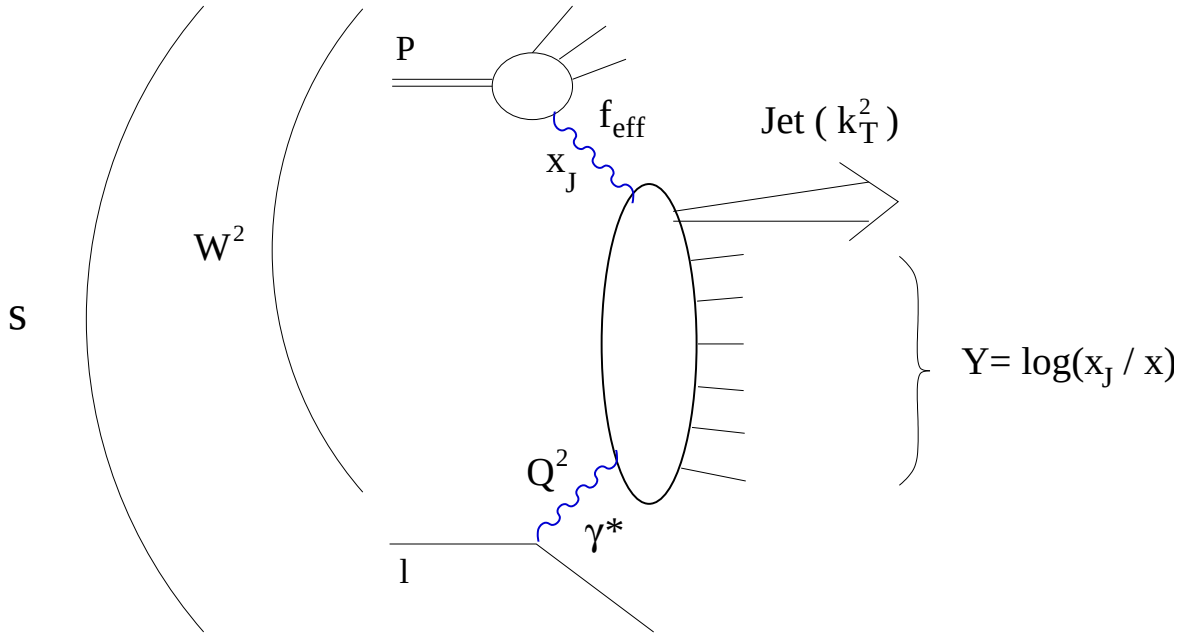


Looking for BFKL/saturation effects

At low x, looking for BFKL effects (x-resummation)



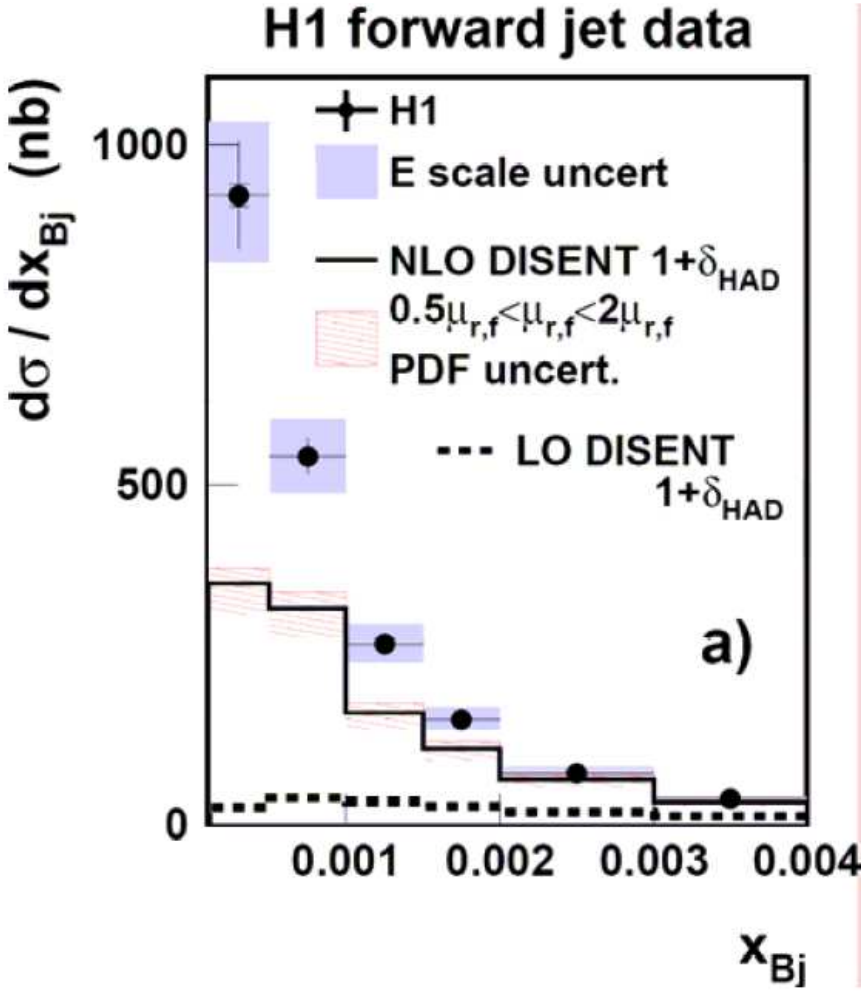
Forward jet measurement at HERA

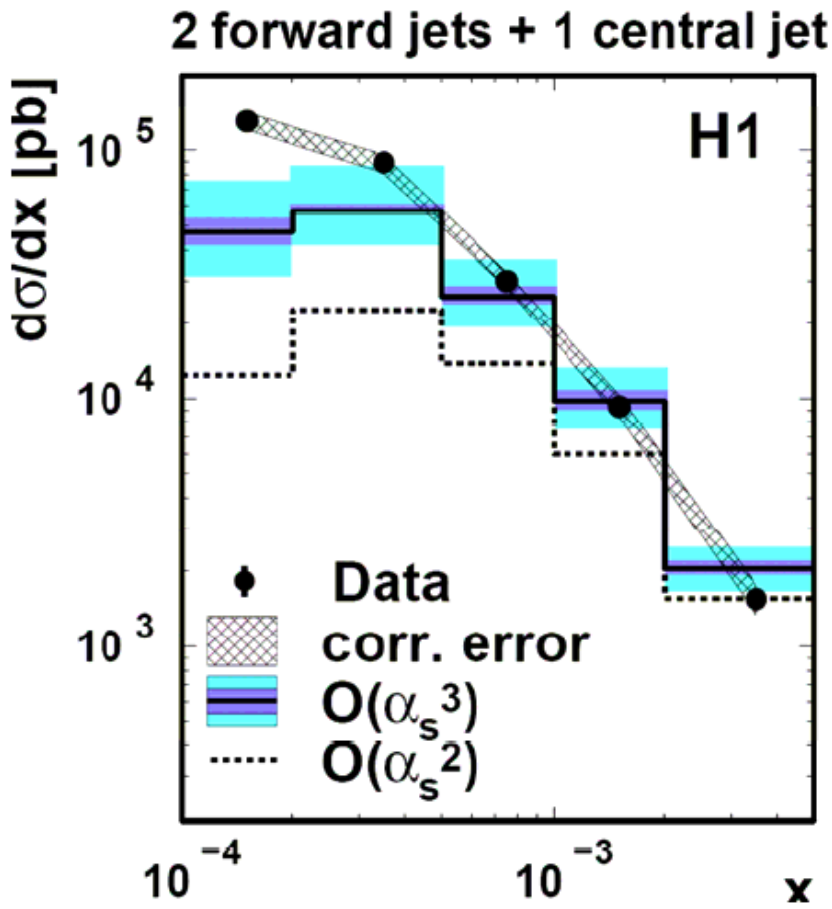


- Typical kinematical domain where BFKL effects are supposed to appear with respect to DGLAP: $k_T^2 \sim Q^2$, and Q^2 not too large
- Comparison with DGLAP NLO and NLL BFKL cross section calculations

Forward jets

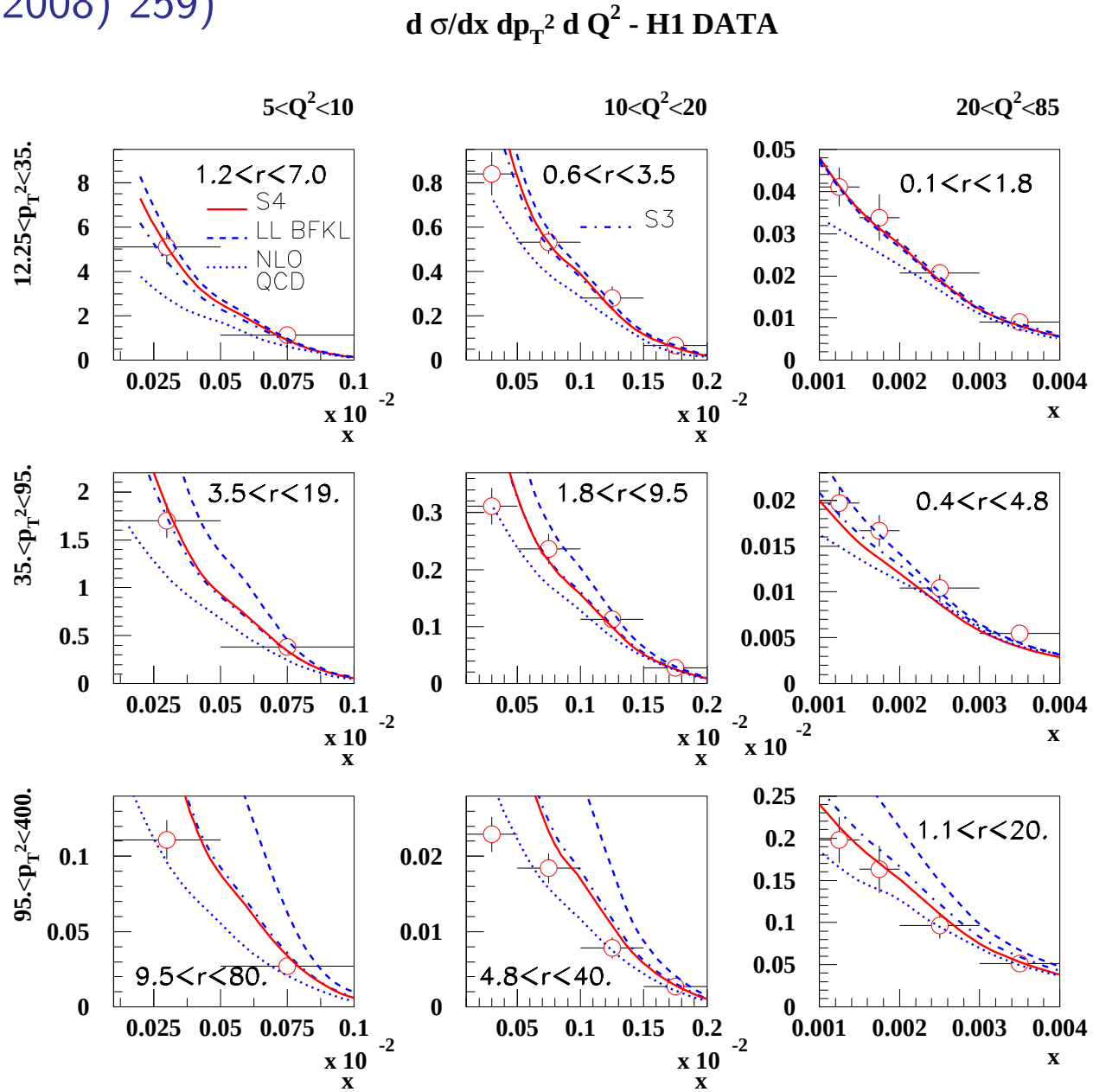
- Strategy 1: look for jets in forward region and compare with DGLAP expectation
- kinematics: $10^{-4} < x < 4.10^{-3}$, $p_T(jet) > 3,5$ GeV, $7 < \theta_{jet} < 20$ degrees, $0.5 < p_T^2/Q^2 < 5$
- Strategy 2: Look at 2 forward jets and 1 central jet (NNLO calculation would be needed to have a good comparison (4 jet events))





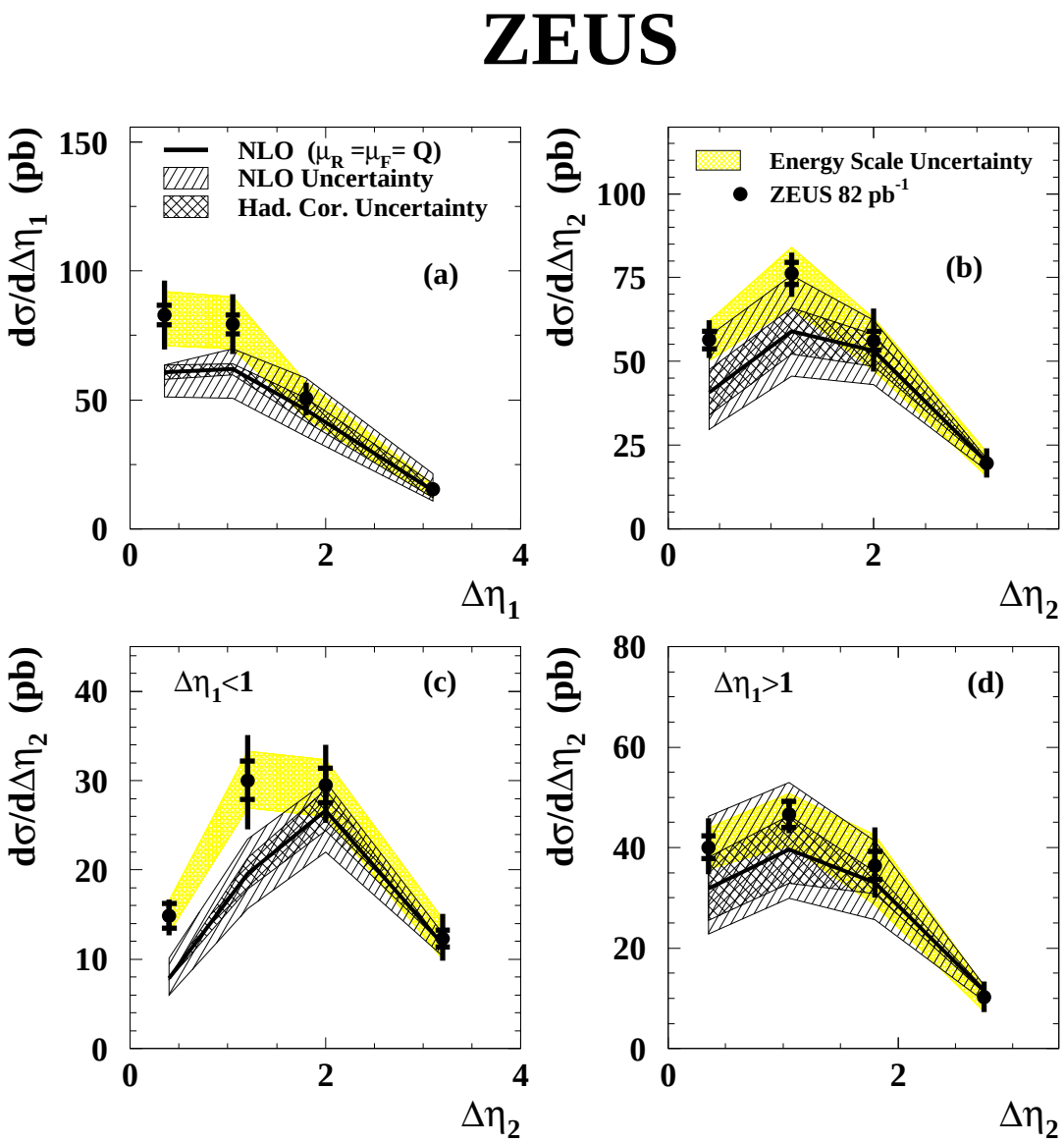
H1 triple differential data: BFKL calculation

- Triple differential cross section: Keep the normalisation from the fit to $d\sigma/dx$ and predict the triple differential cross section
- Good description over the full range (see: O. Kepka, C. Marquet, R. Peschanski, C. Royon, Phys. Lett. B 655 (2007) 236, Eur. Phys. J. C55 (2008) 259)



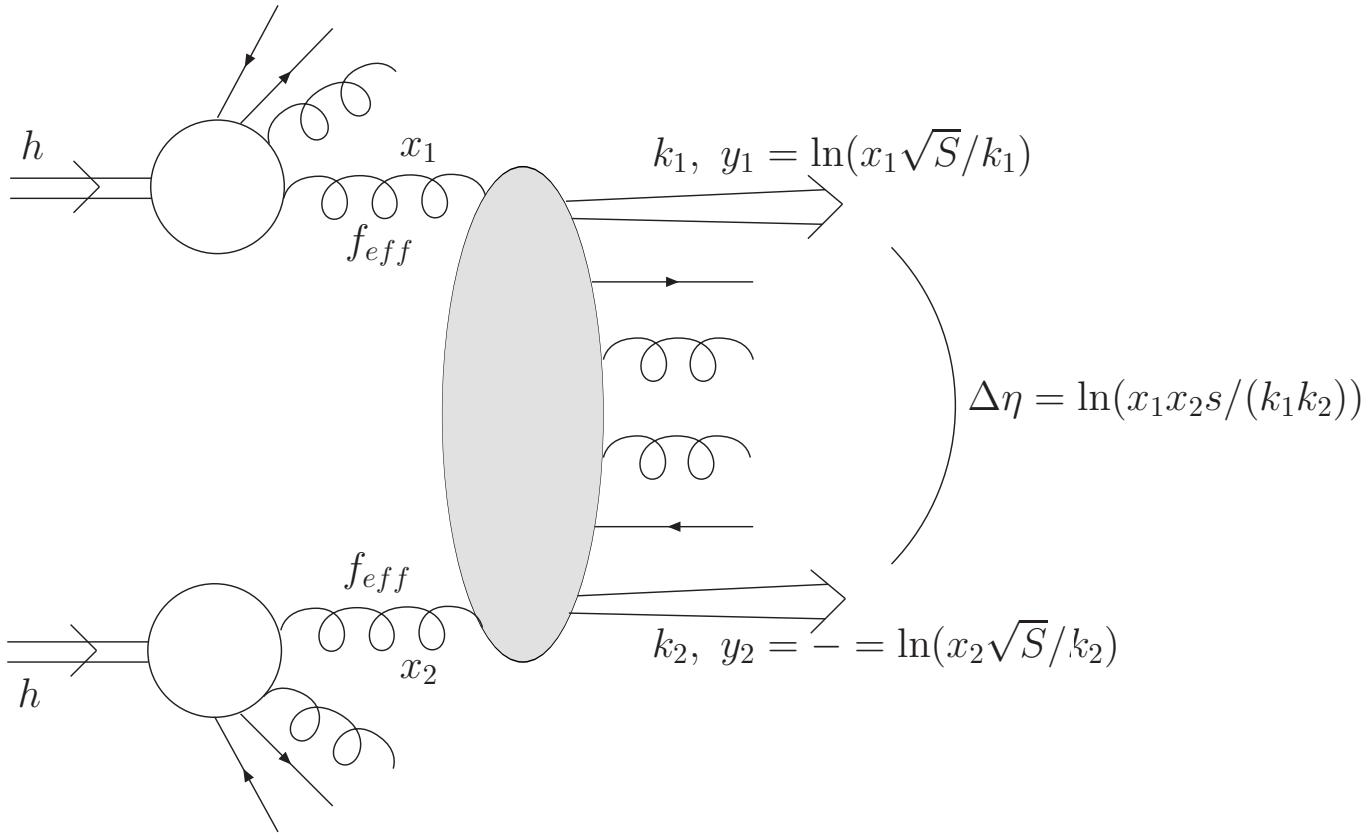
Forward jets cross section

- 3 jet cross section: $\eta^{jet1} < \eta^{jet2} < \eta^{jetf}$
- Disagreement when two jets in forward region: $\Delta\eta_1 = |\eta^{jet2} - \eta^{jet1}|$ and $\Delta\eta_2 = |\eta^{jetf} - \eta^{jet2}|$ small



Mueller Navelet jets

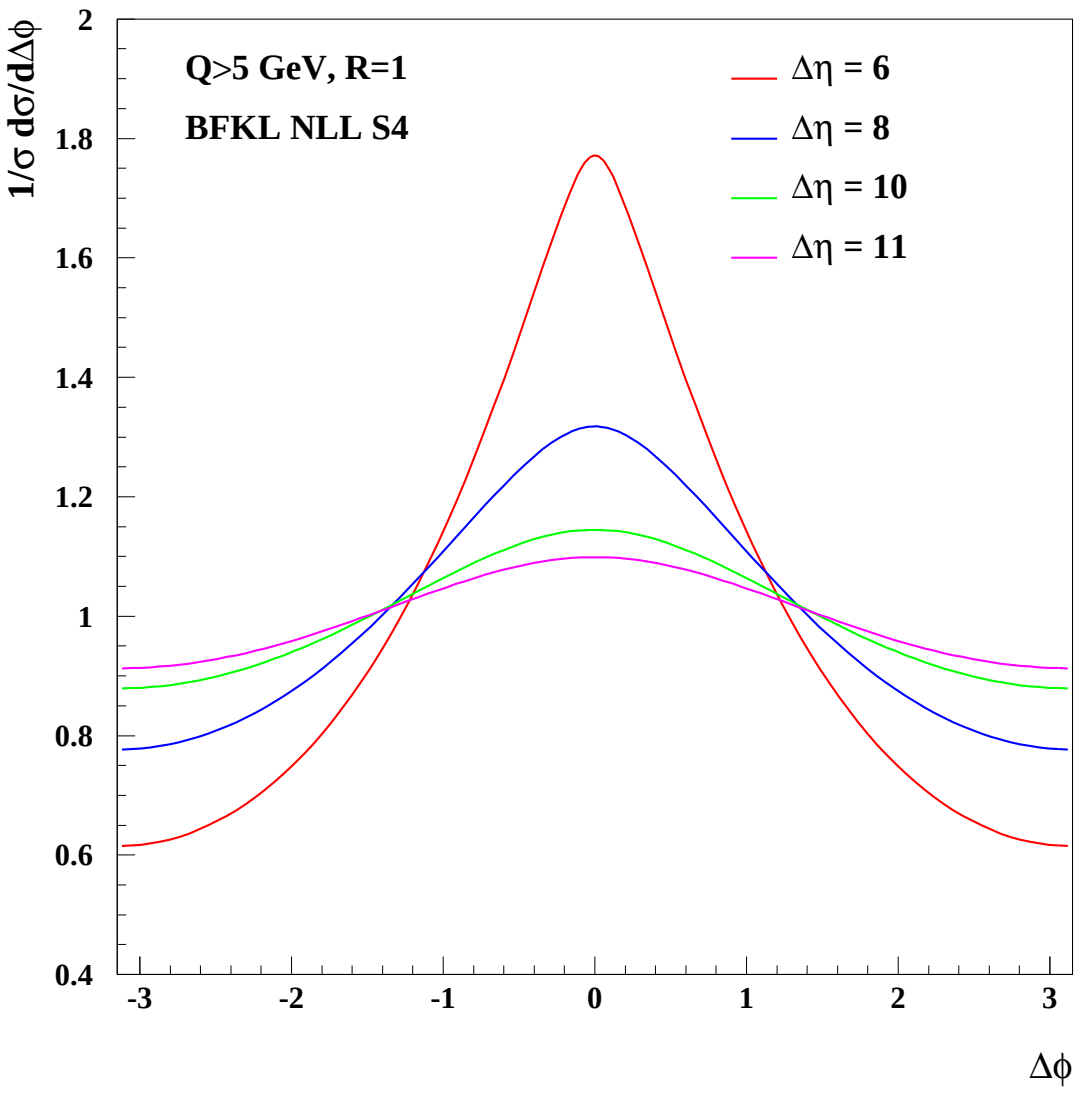
Same kind of processes at the Tevatron and the LHC



- Same kind of processes at the Tevatron and the LHC: Mueller Navelet jets
- Study the $\Delta\Phi$ between jets dependence of the cross section:
- For more information, see: C. Marquet, C. Royon, arXiv:0704.3409

Mueller Navelet jets in CDF

Possibility to measure $\Delta\Phi$ distribution in CDF for large $\Delta\eta$ and low jet p_T ($p_T > 5$ GeV) using the CDF miniPLUG calorimeter



Conclusion

- Inclusive jet cross sections at HERA and Tevatron: complementary to test NLO QCD and constrain gluon at high $x \longrightarrow$ Fundamental for searches at the LHC in the jet channel
- Recent measurements on jet cross sections with small JES uncertainties at the Tevatron will be useful to constrain PDFs
- Multijet cross section measurements: Agreement with NLO calculations
- $\gamma+$ jet cross sections: discrepancy with NLO calculation when one looks in different hemispheres between γ and jet
- $W+$jet, $Z+$jet: In general cross sections in agreement with NLO calculations, uncertainties still large
- Low Q^2 physics, forward jets, Mueller-Navelet jets: interesting to look for new regimes of QCD, would benefit also from NNLO calculations