Experimental tests of QCD

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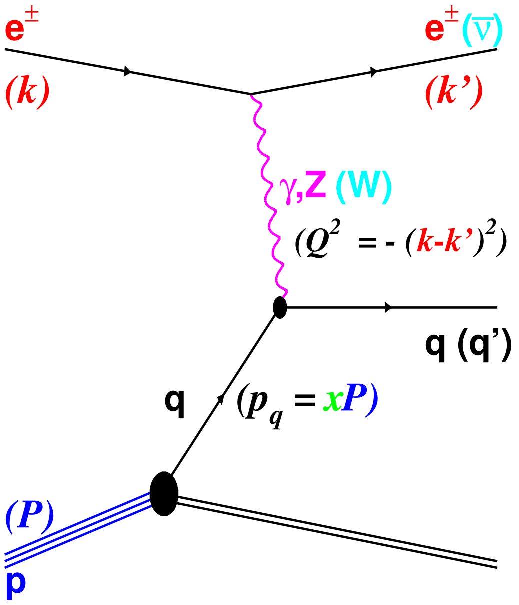
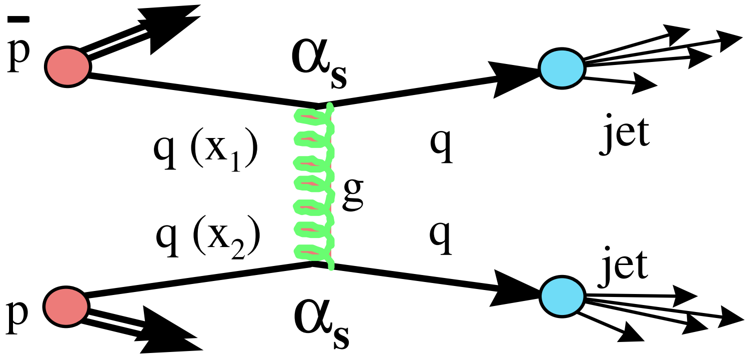
Contents:

- Proton structure function measurements at HERA
- Uncertainty on parton distributions in the proton
- High x gluon at the Tevatron
- α_S
- BFKL resummation effects and saturation
- Pentaquarks

ep and *pp* colliders

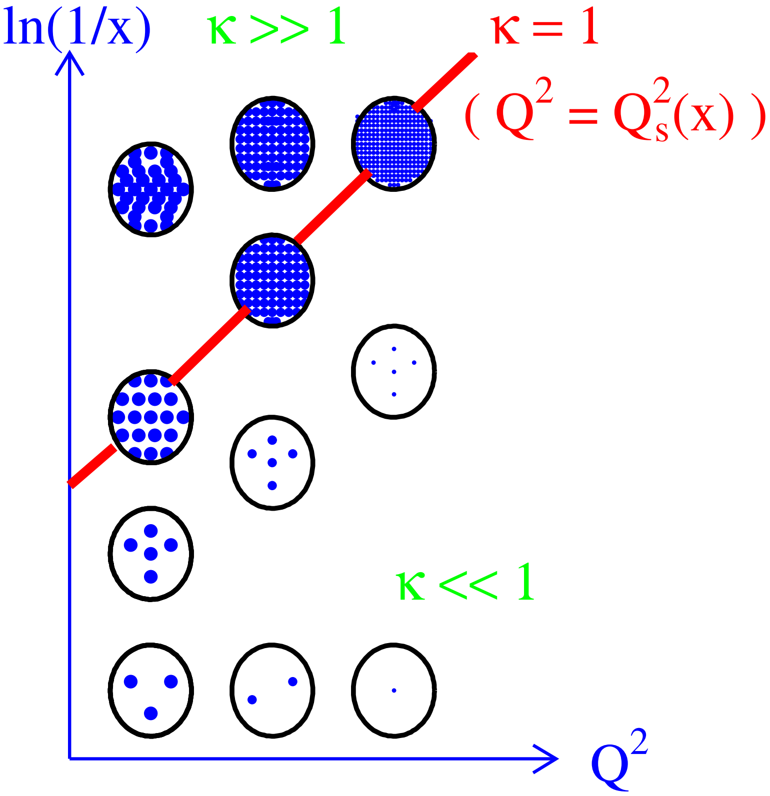




- ep/pp collider: allows to probe the proton structure in quark and gluon
- kinematical variables (HERA): $Q^2 = -(k-k')^2$, $x = Q^2/2P(k-k')$, can be determined using both the electron, jet
- Measurement of the proton structure function (HERA) $F_2 \sim x\Sigma_q e_q^2(q+\bar{q})$
- Hadronic colliders (Tev.): measurement of jet cross sections

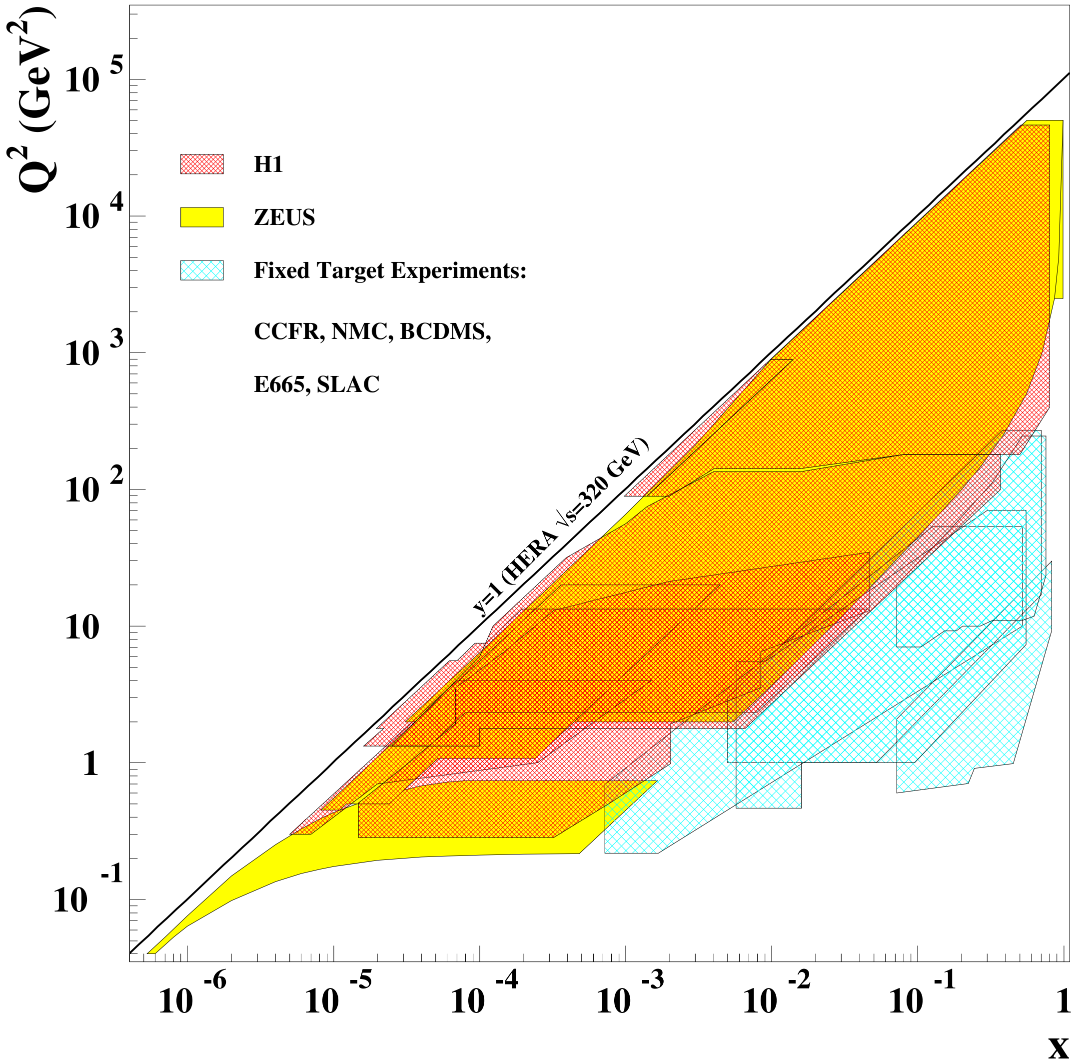
Test of QCD evolution equations

- Dokshitzer Gribov Lipatov Altarelli Parisi (DGLAP) resums all terms in $\alpha_S log Q^2$
- Baltiski Fadin Kuraev Lipatov (BFKL) resums all terms in $\alpha_S log 1/x$



HERA kinematical plane

Kinematical plane at HERA in (x, Q^2) compared to fixed target experiments



Proton structure functions and QCD fits

- Neutral current cross section:

$$\frac{d^2\sigma_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 - y^2F_L \mp Y_-xF_3\right]$$

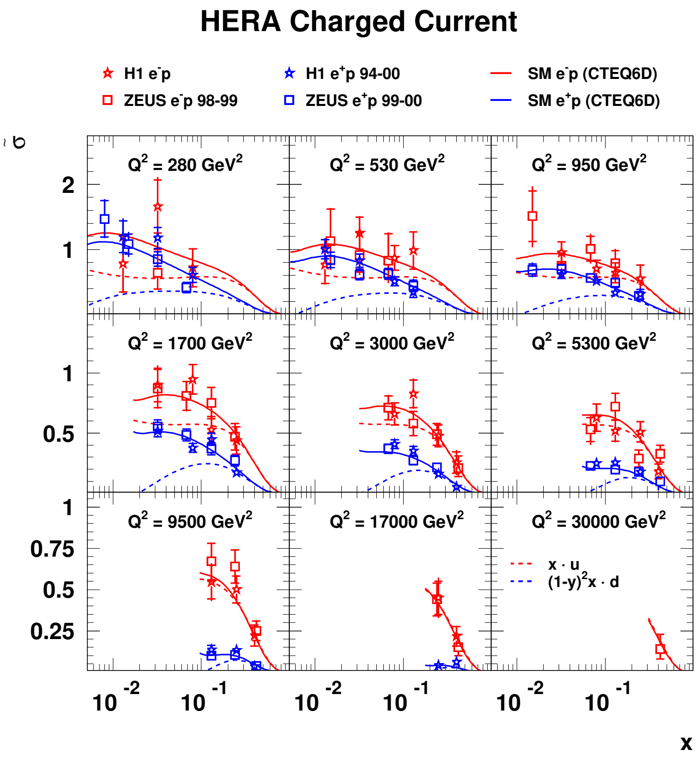
F_L, F_3 resp. large at high y, Q^2

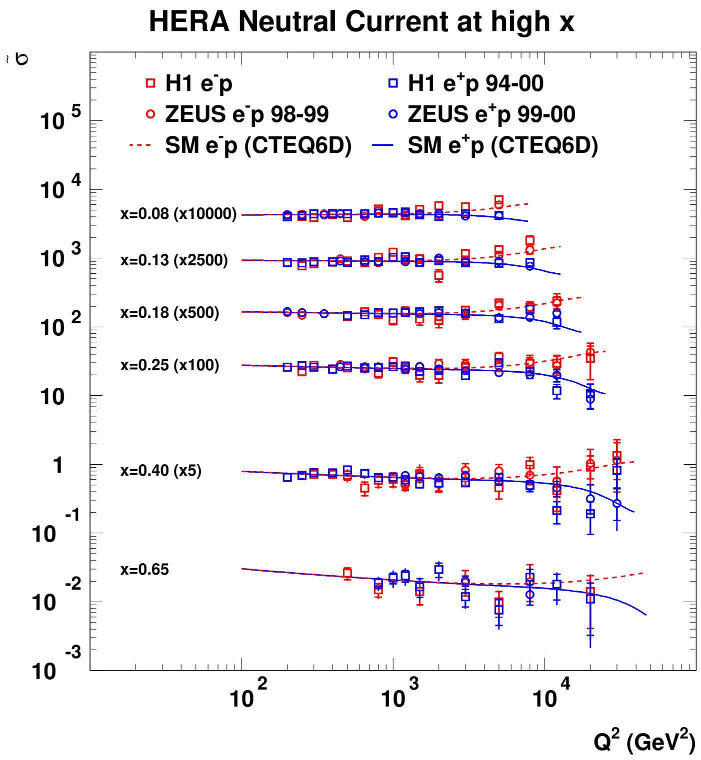
- Charged current cross section:

$$\frac{d^2\sigma_{CC}}{dxdQ^2} = \frac{G_F^2}{4\pi x}\left[\frac{M_W^2}{M_W^2+Q^2}\right]^2 \times \left[Y_+F_2^{CC} - y^2F_L^{CC} \mp Y_-xF_3^{CC}\right]$$

- NLO DGLAP fits to F_2 data and extraction of parton densities

Neutral/Charged current cross section at high Q^2

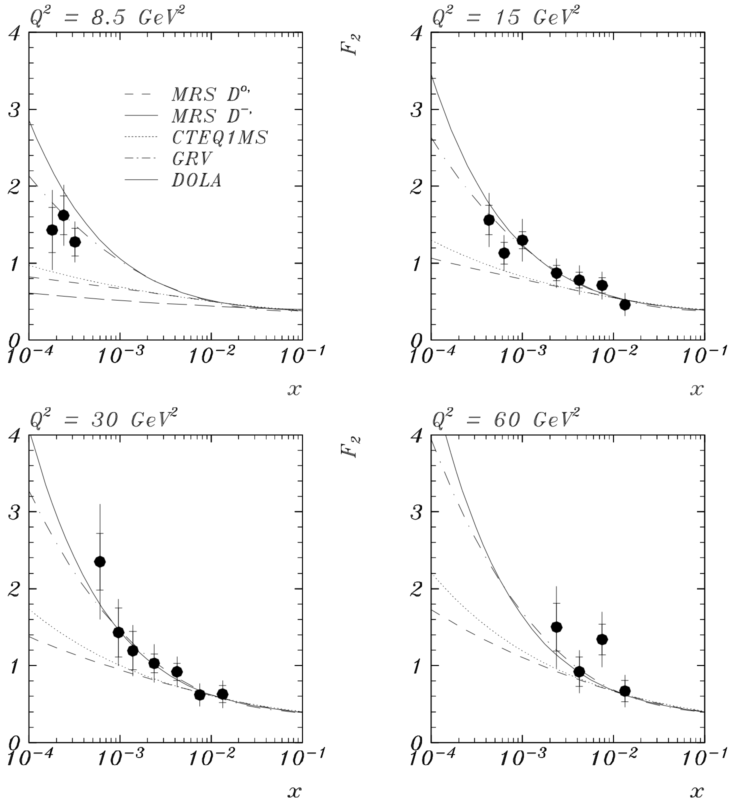

HERA Charged Current

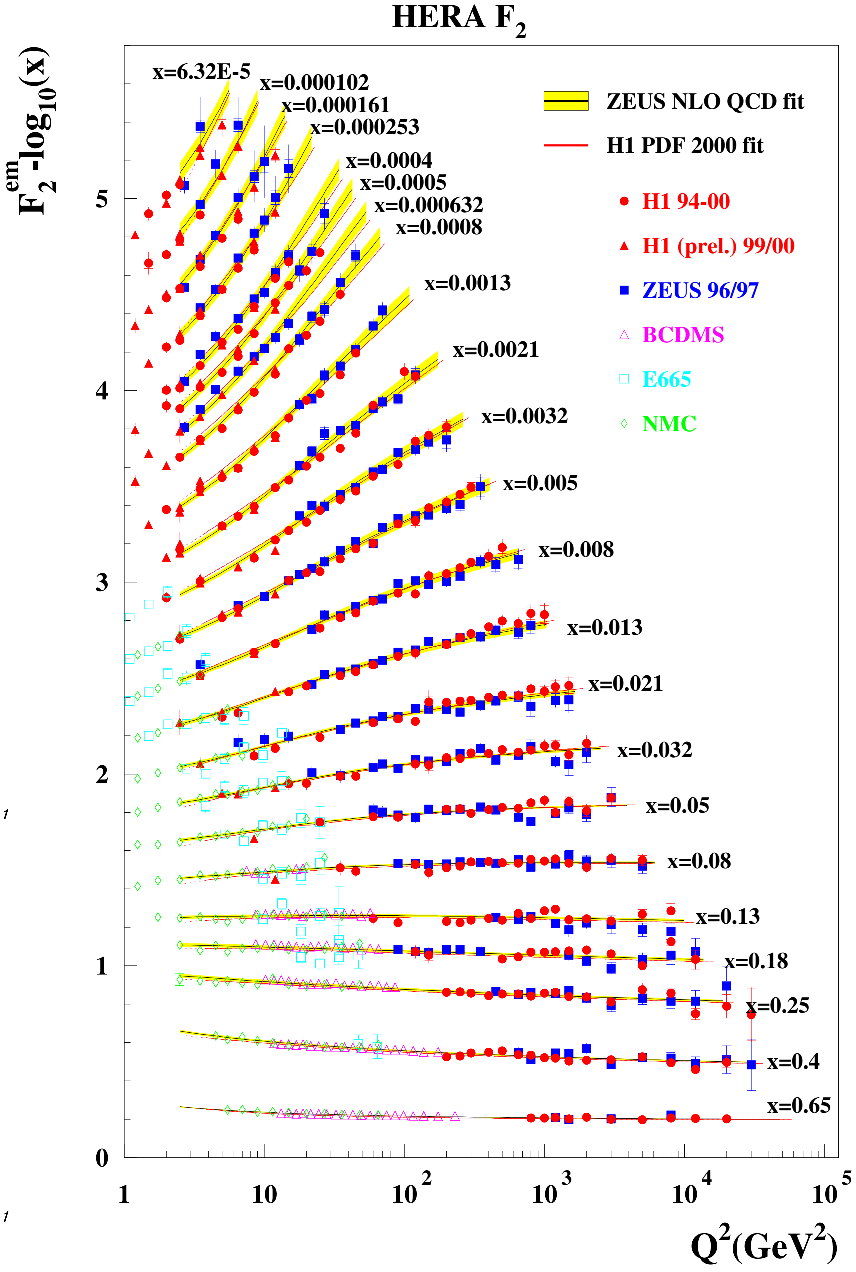

HERA Neutral Current at high x

- Differences between e^+p and e^-p at high Q^2: difference between up and down quark distribution
- CC at low Q^2: flat $(M_W^2/(M_W^2+Q^2)$ term)
- Precision will improve with higher statistics

Proton structure function F_2

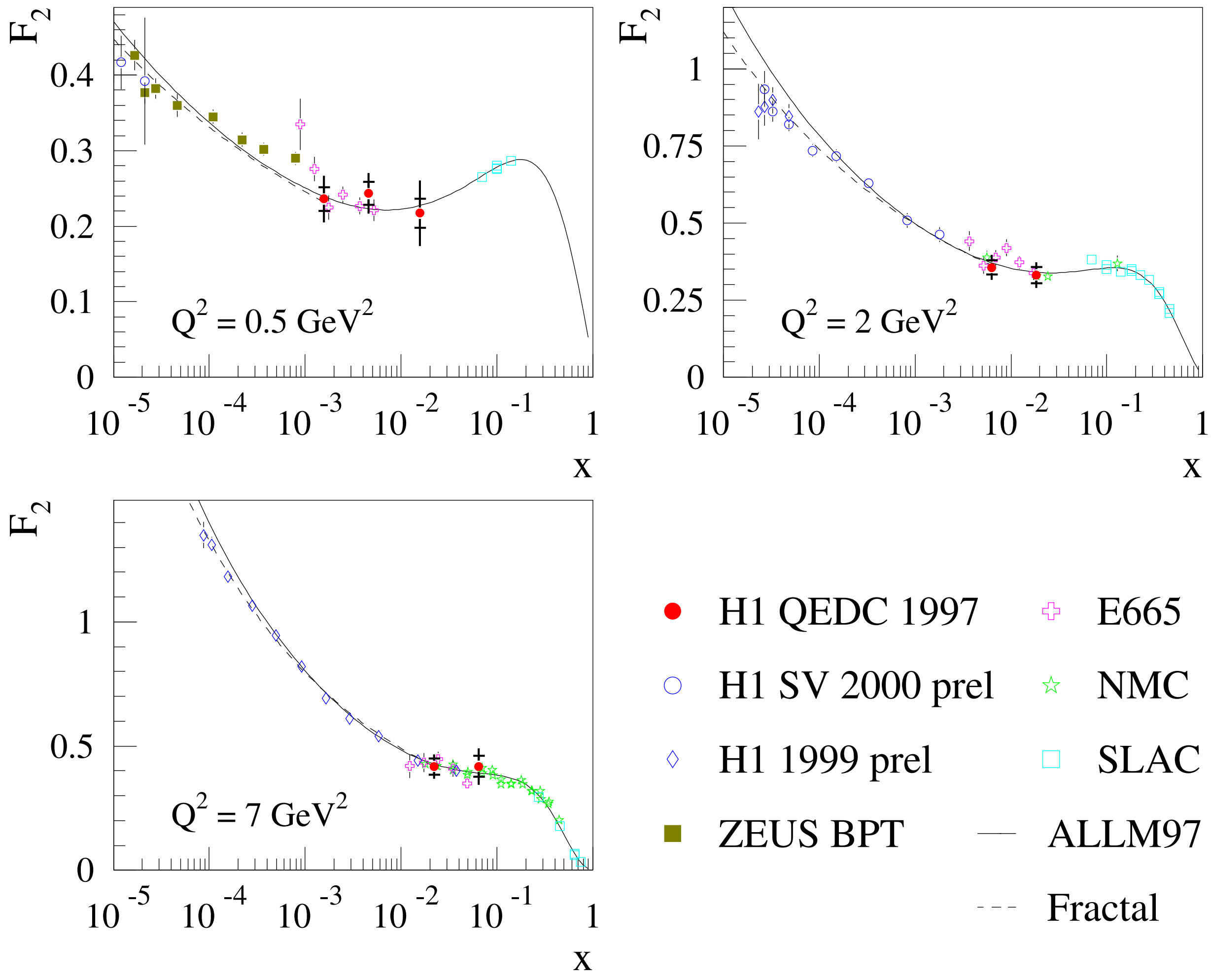
Measurement of F_2 over a wide range of (x, Q^2)
with a precision of ~ 1 % (similar to fixed target):
Great improvement since 1993!





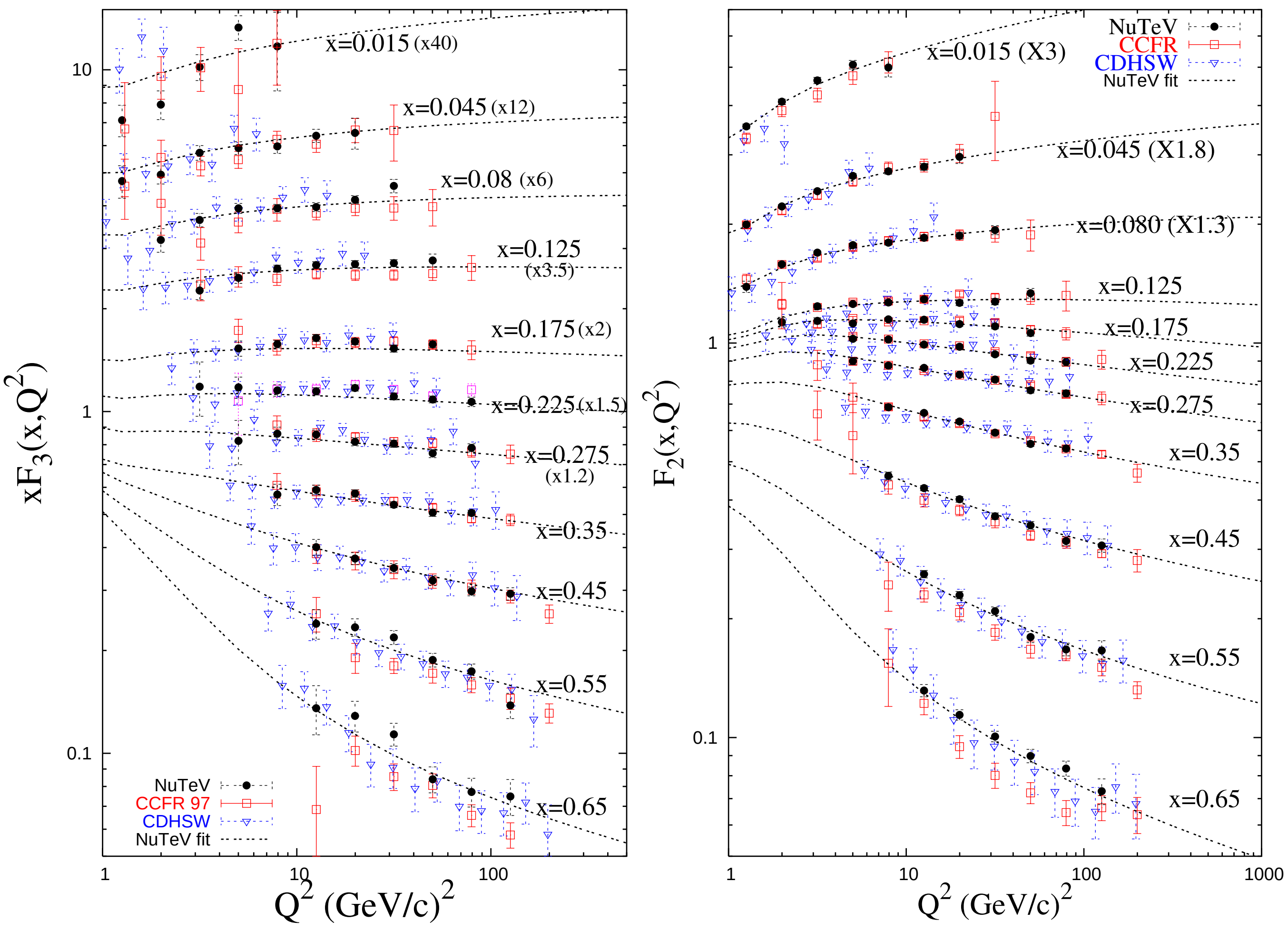
The corners of the phase space

- Low Q^2, high and low x: use dedicated data set (shifted vertex, Compton or radiative events)
- High Q^2, high x: Tevatron? Important for searches



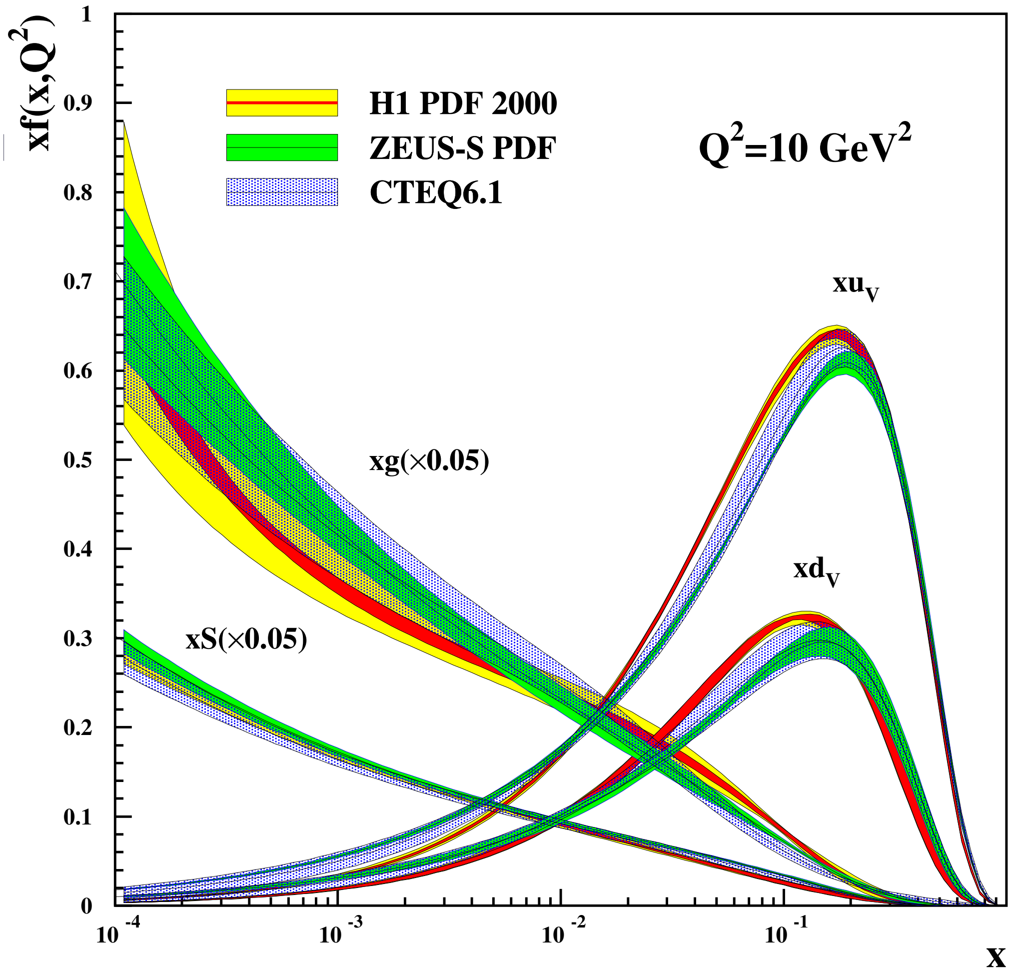
NuTeV results

NuTeV: measurement at low/moderate Q^2, high x



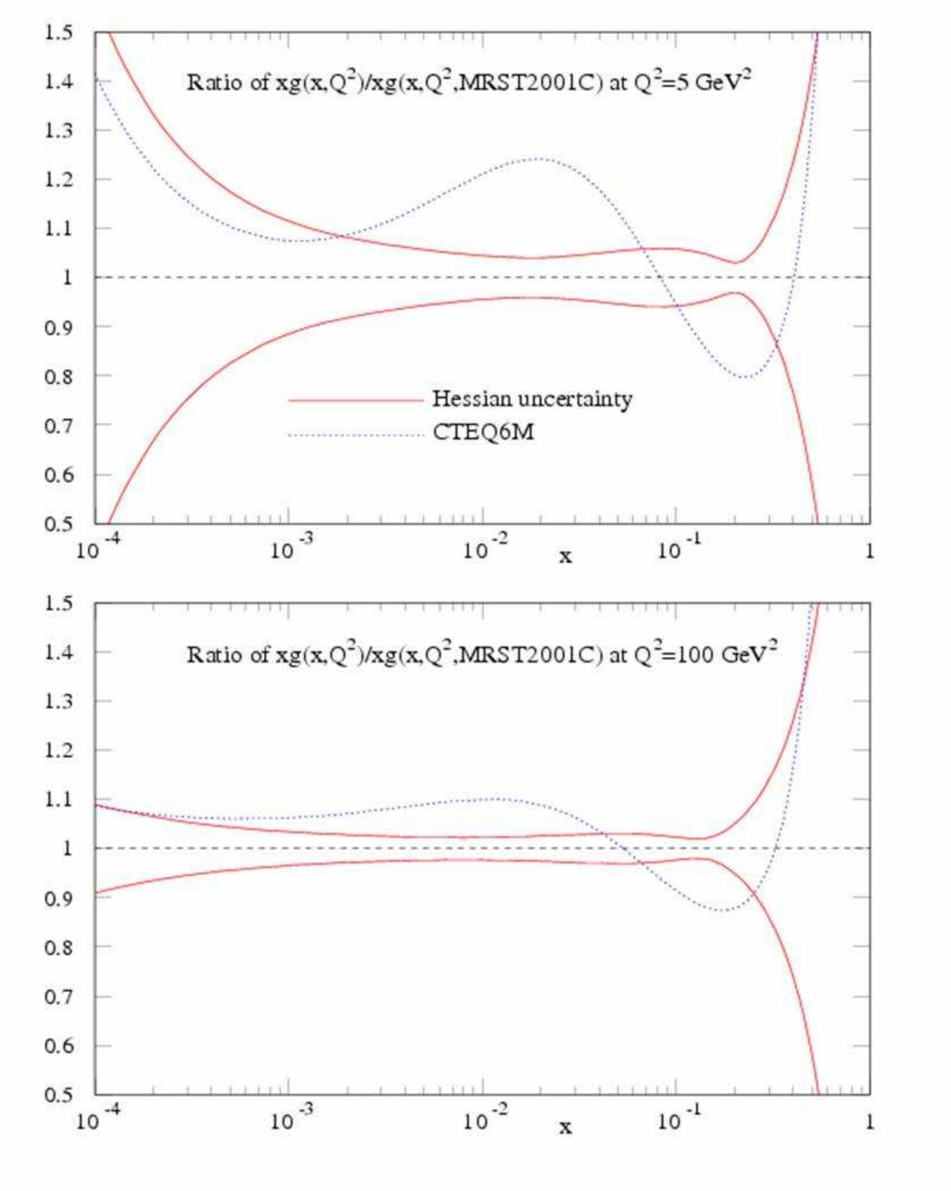
Quark and gluon densities

Extraction of the quark and gluon densities using NLO DGLAP evolution equation: parton distributions known with high precision for $10^{-3} < x < 0.1$



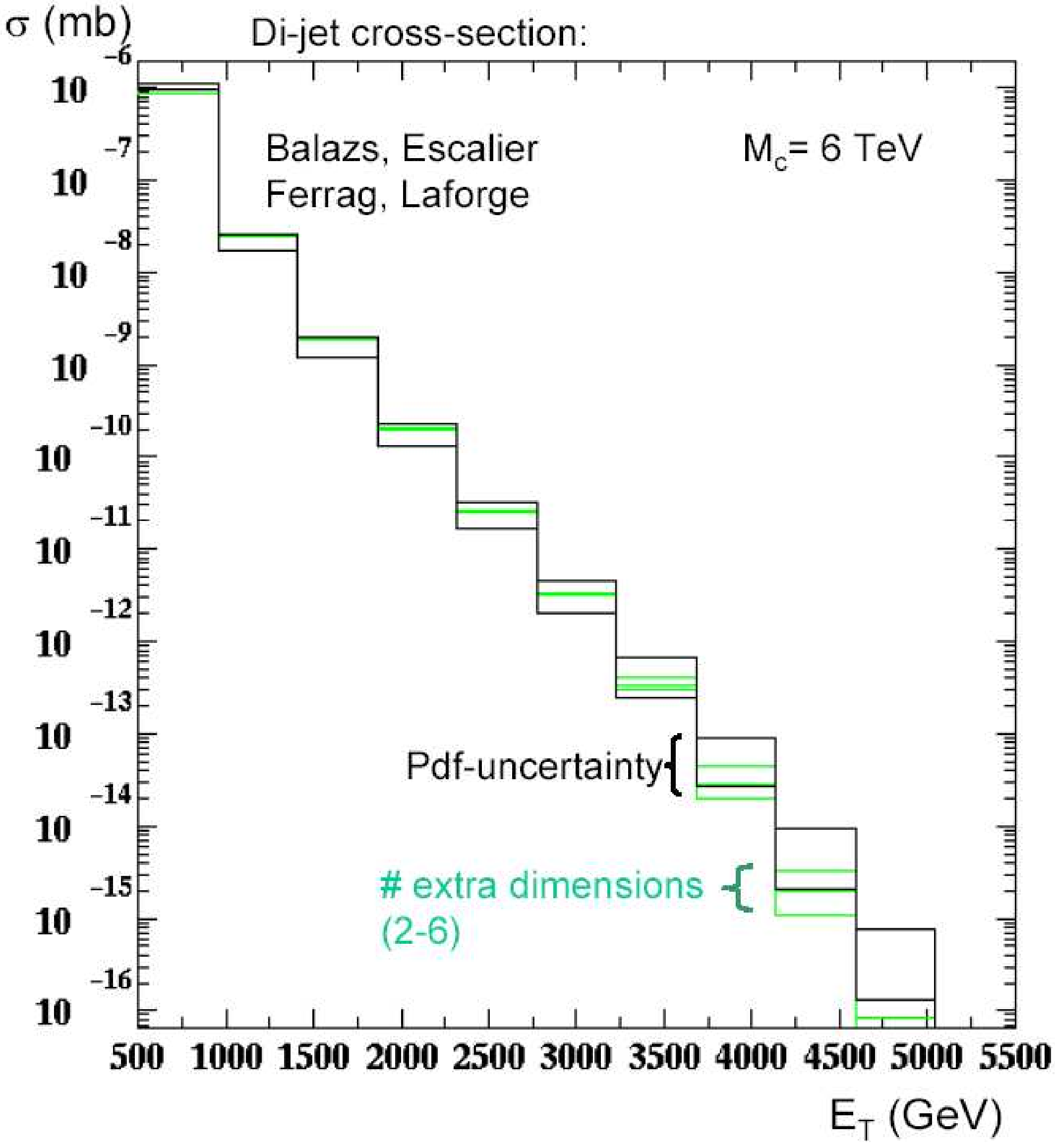
Uncertainty on gluon distribution

CTEQ gluon density (in blue) compared to MRST error band (in red): high uncertainty in the high x region



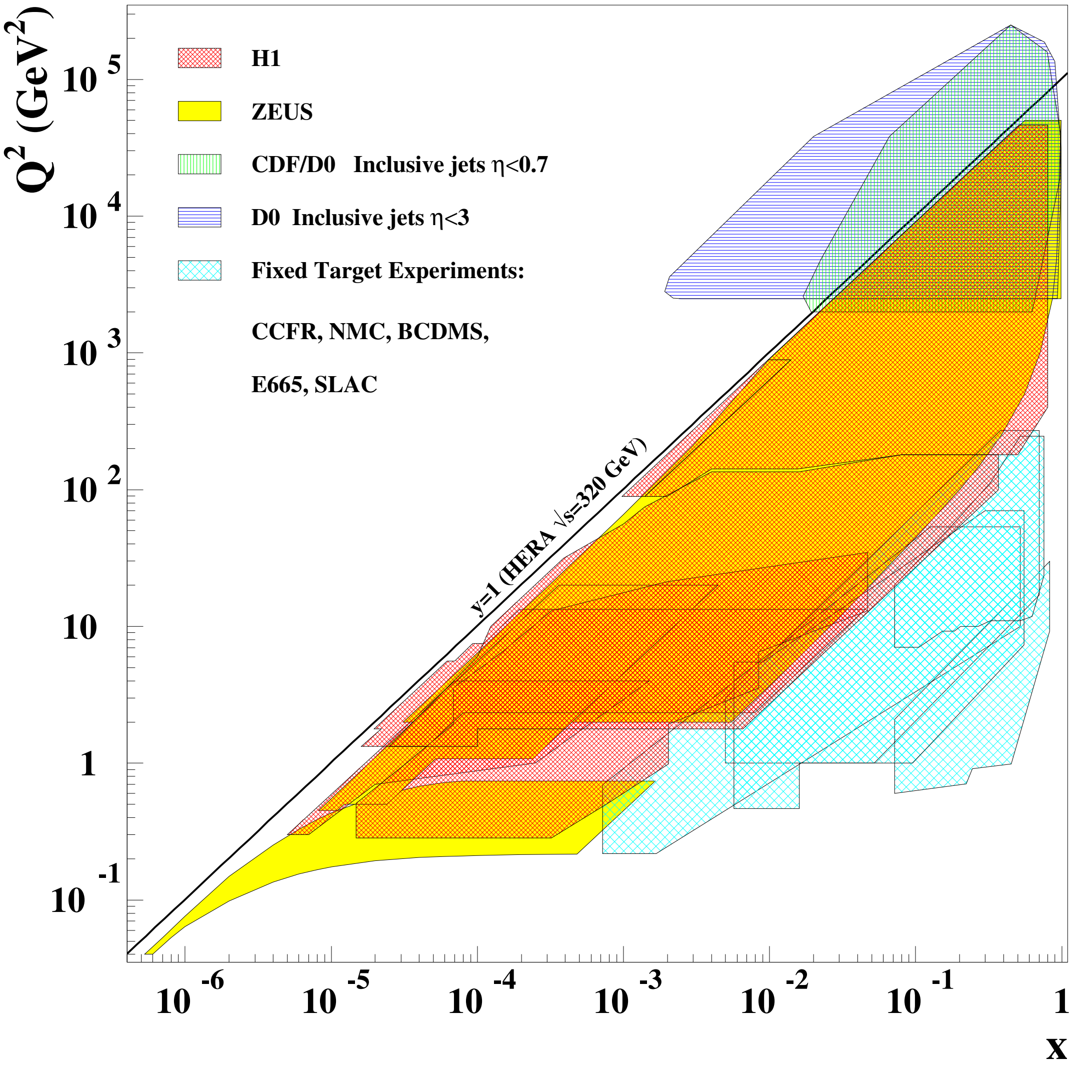
Importance for searches at the LHC

Uncertainty on parton distribution at high x compromises the search for extra dimensions at the LHC



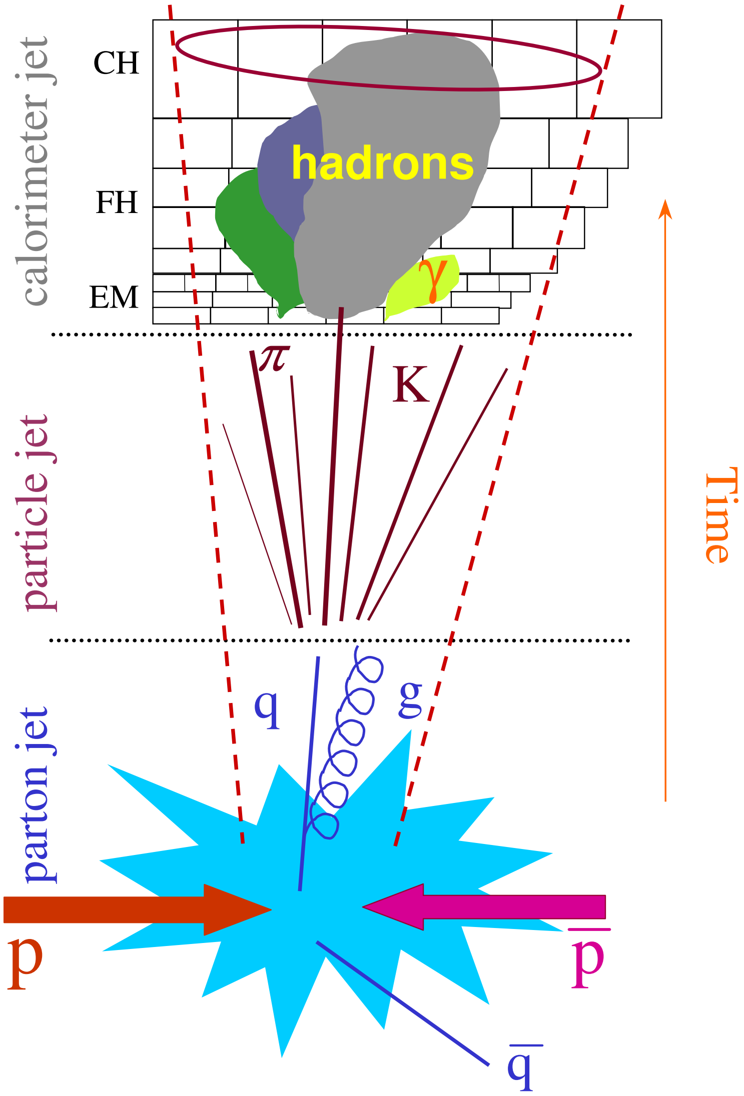
Tevatron and HERA kinematical domains

HERA and Tevatron kinematical domains are complementary



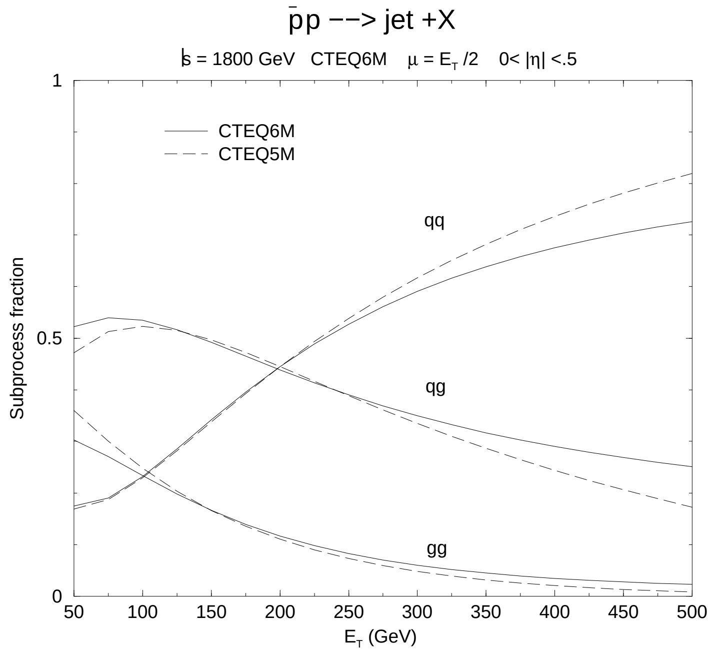
Jets at the Tevatron (and the LHC)

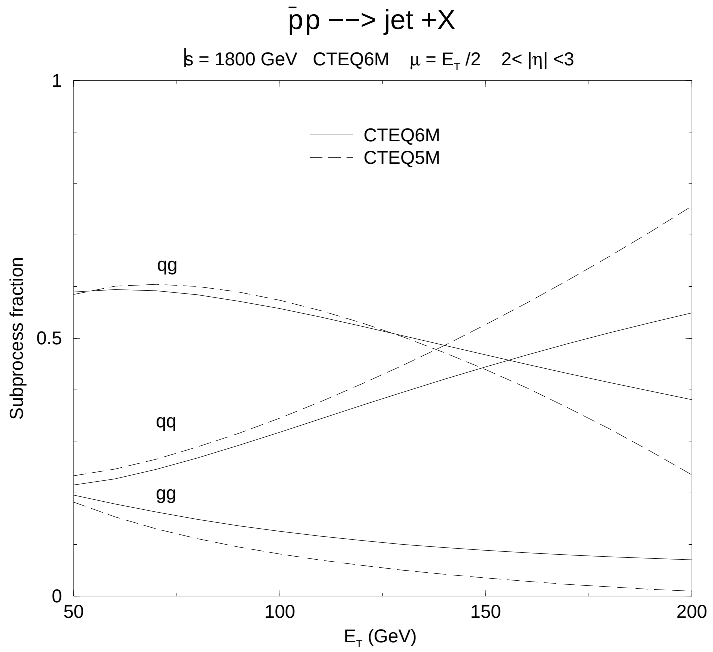
Dominant error: Determination of jet energy scale in calorimeter: use γ+jet at Tevatron, Z+jets at LHC



Jet cross section measurements at Tevatron

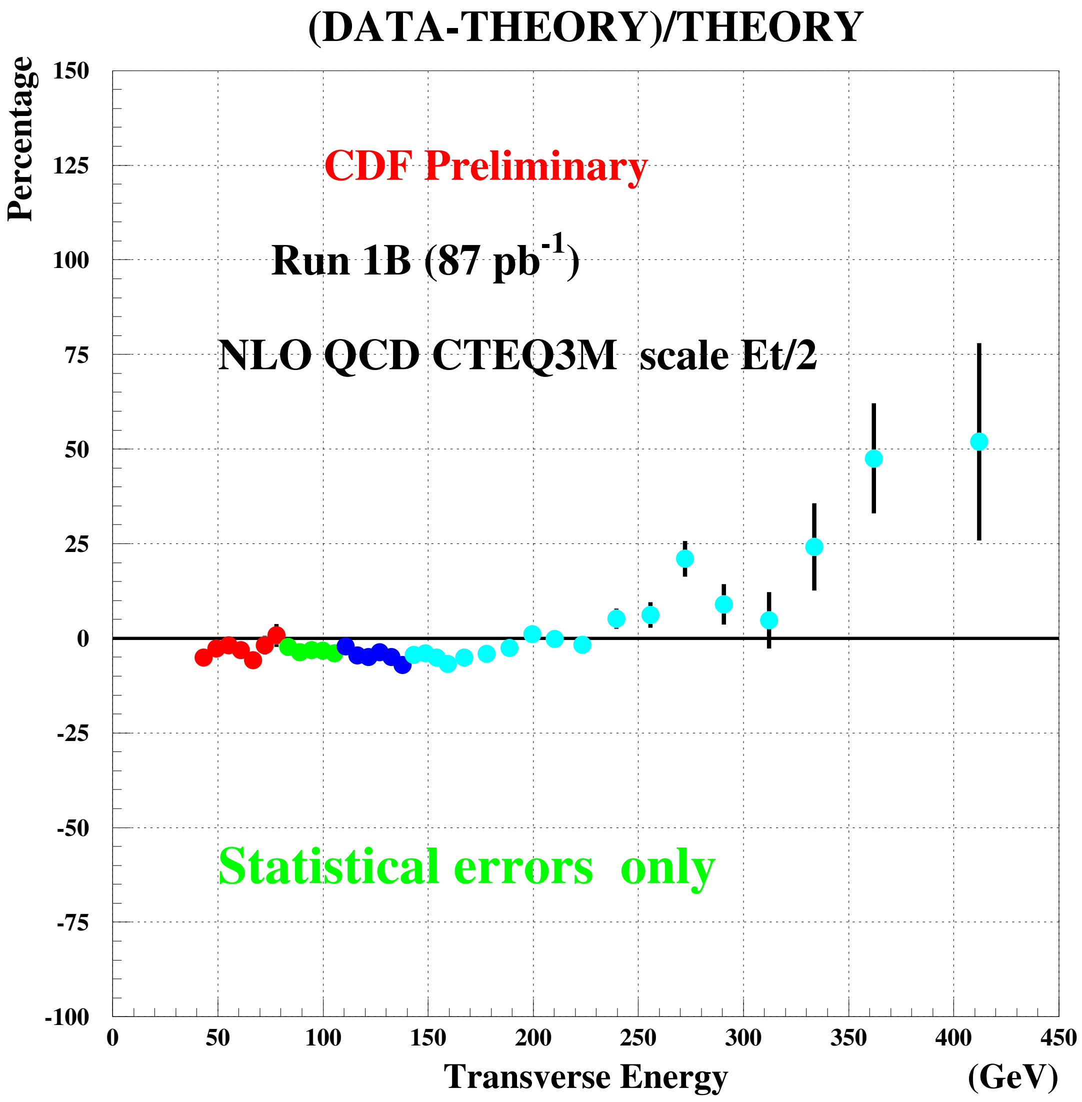
Sensitivity on high-x gluon of jet cross section measurement at the Tevatron





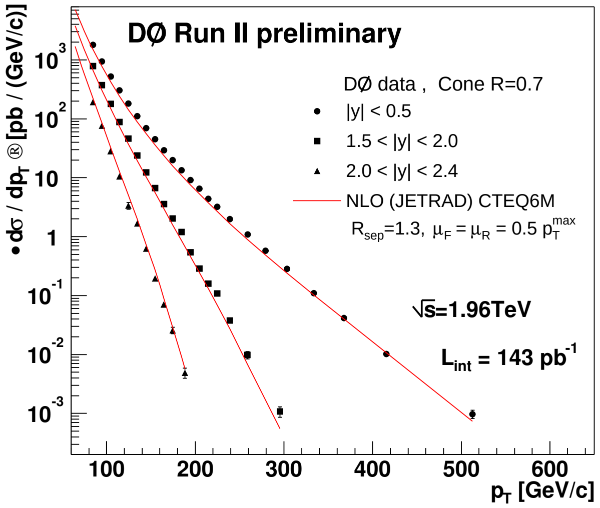
Jet cross section measurements at Tevatron

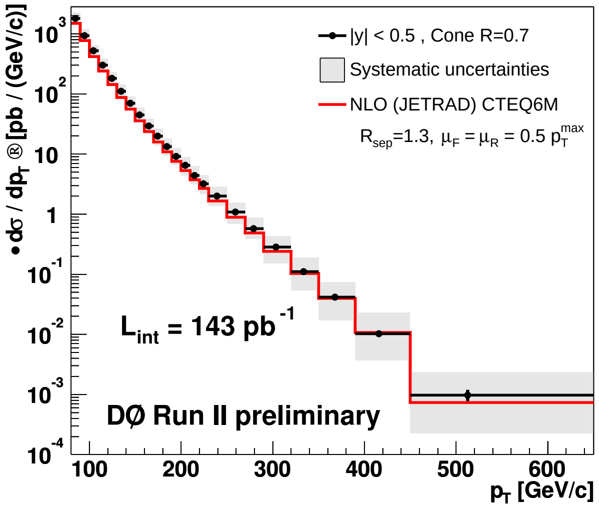
CDF run I: excess at high jet p_T $\rightarrow$ modification of high-x gluon

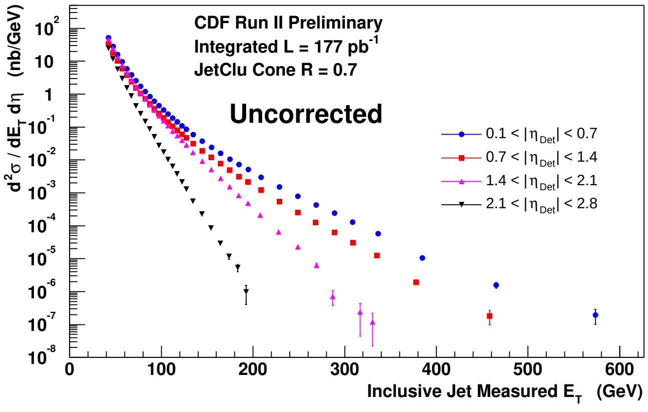


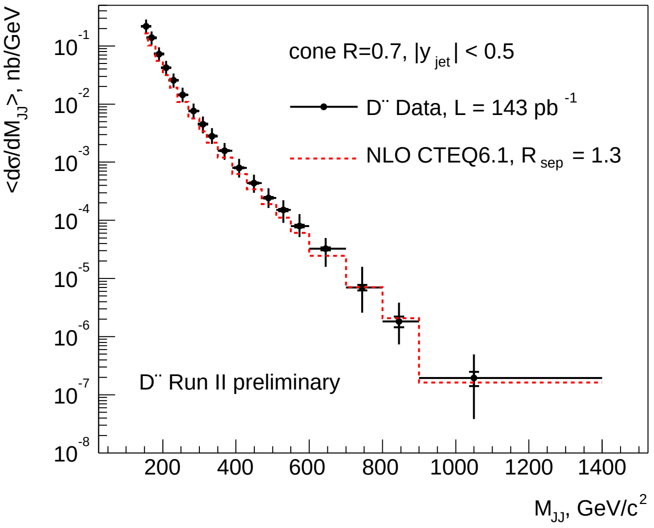
Jet cross section measurements at Tevatron

Run II: measurement of inclusive jet cross section as s function of p_T, dijet cross section as a function of dijet mass, sensitivity on high-x gluon





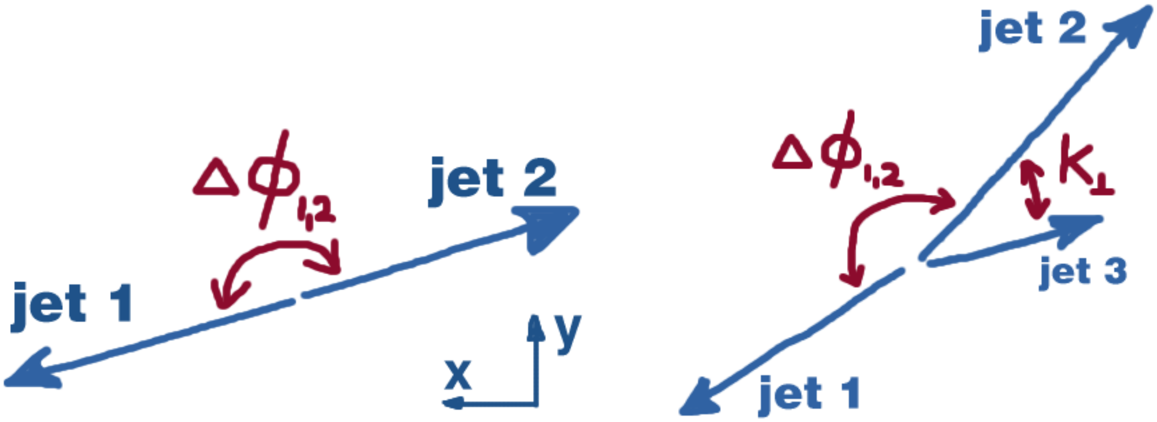




Test of NLO QCD

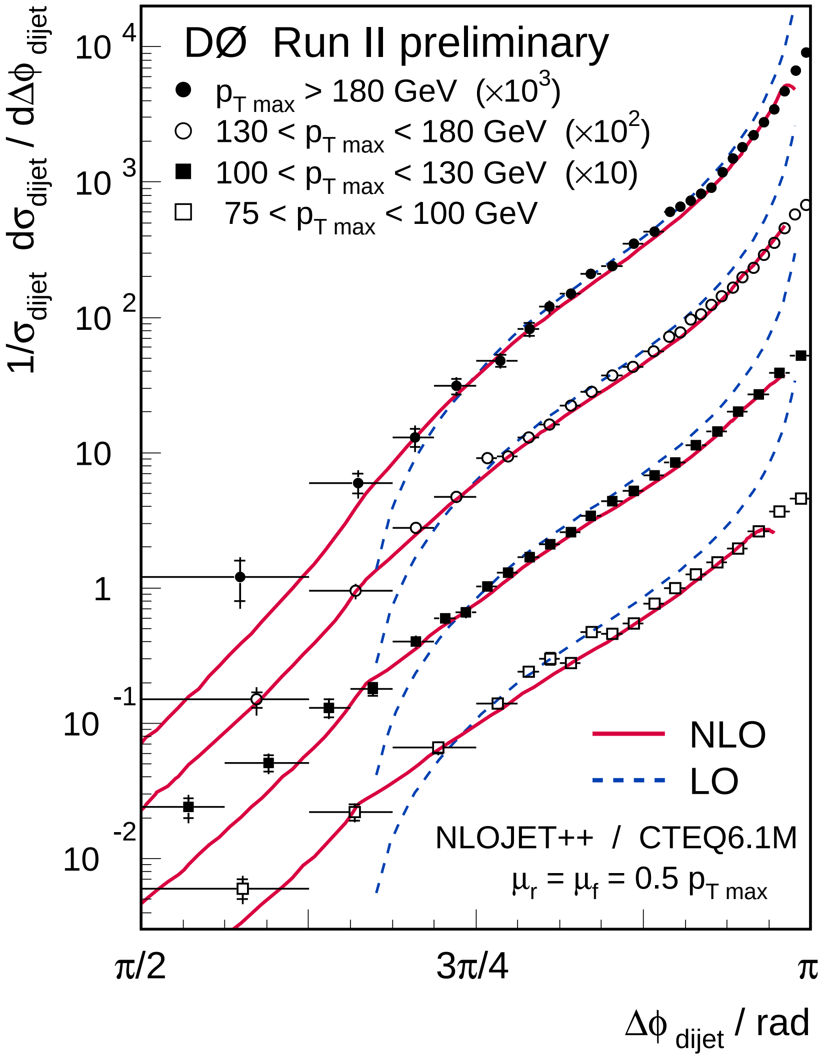
Need to get multijet production cross sections for the LHC ($t\bar{t}$ cross sections, search for Higgs bosons in association with $t\bar{t}$, $b\bar{b}$, search for R-parity violated SUSY (8-10 jets per event...))

Measurement of the difference of azimuthal angle in two jet events (DØ): sensitive to higher order effects ($\Delta\Phi < \pi$)



Test of NLO QCD

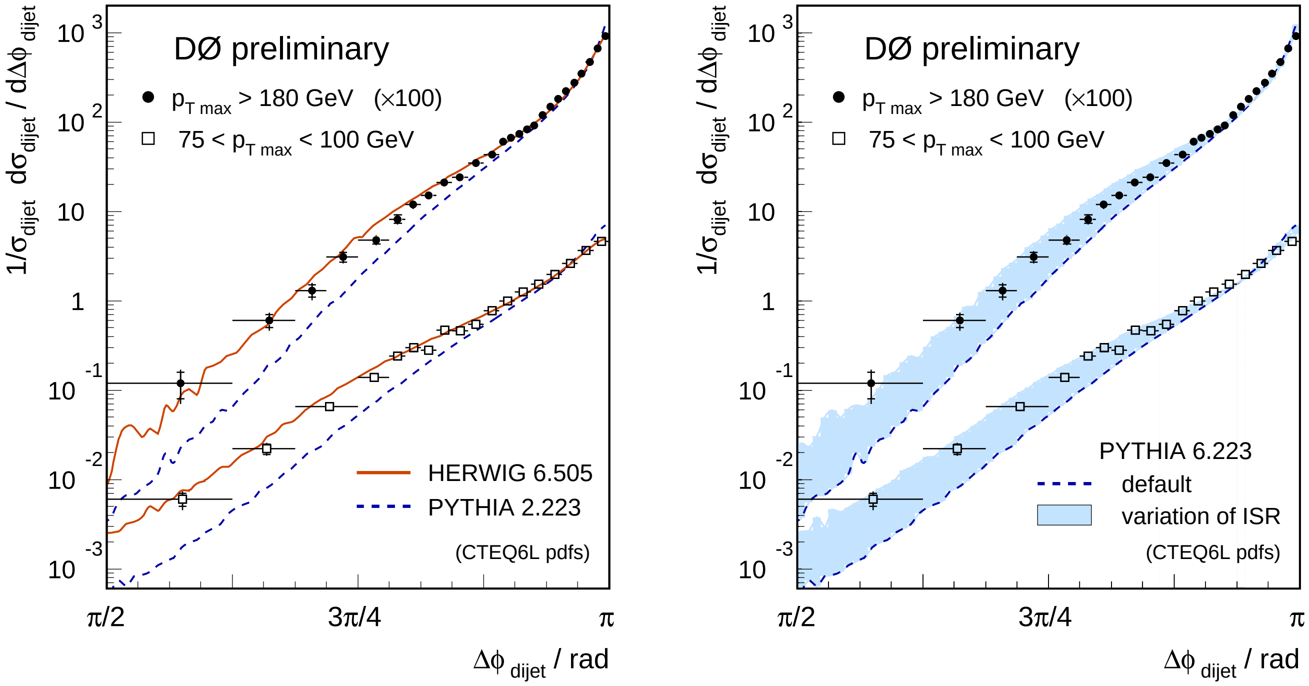
Measurement of the difference of azimuthal angle between 2 jets



NLO calculations in good agreement with measurement (except at very high $\Delta\Phi$: soft radiation)

Tuning MC

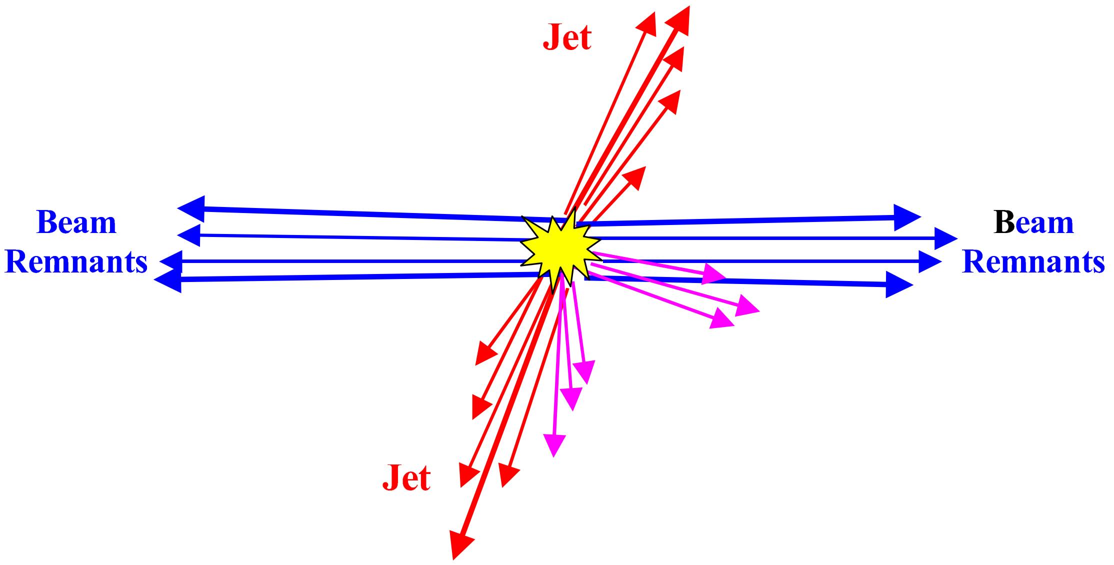
Tuning MC (PYTHIA/HERWIG...). Needs multiple jet cross section measurement at the Tevatron, HERA

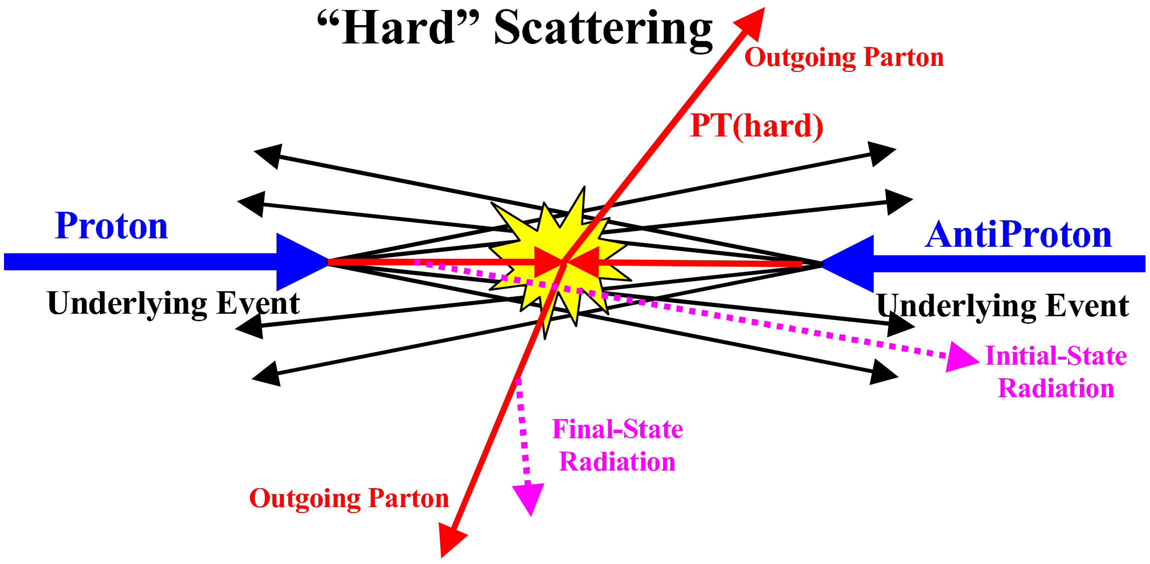


Fundamental for searches at the LHC!

A parenthesis: underlying events at Tev./LHC

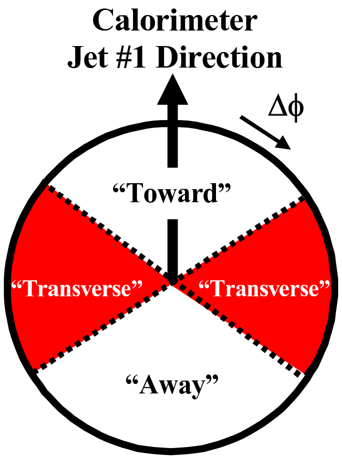
Study of underlying events at the Tevatron

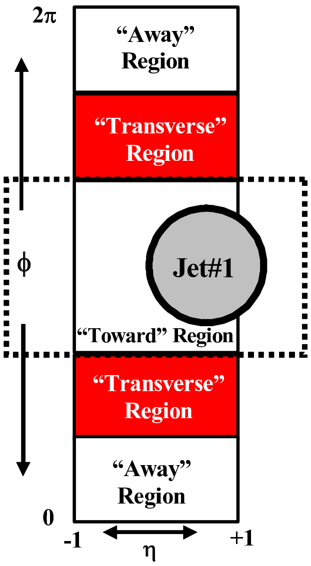


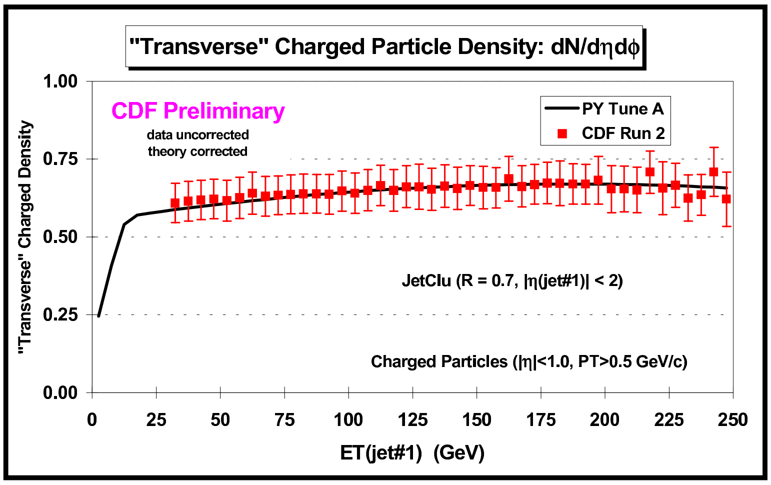


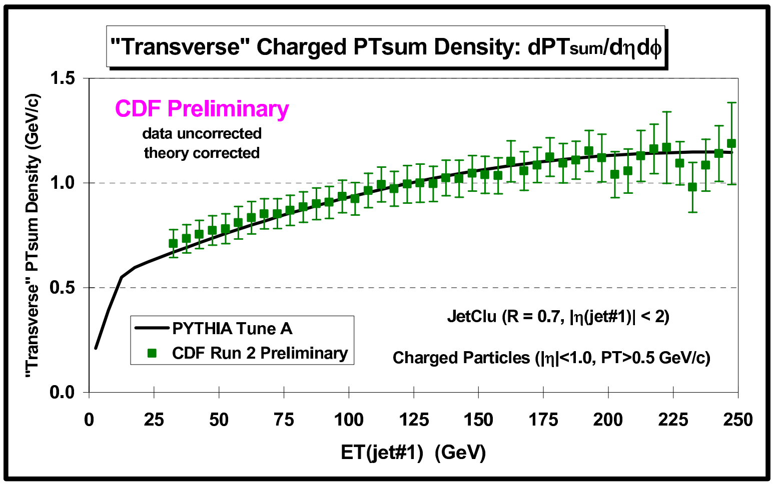
A parenthesis: underlying events at Tev./LHC

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



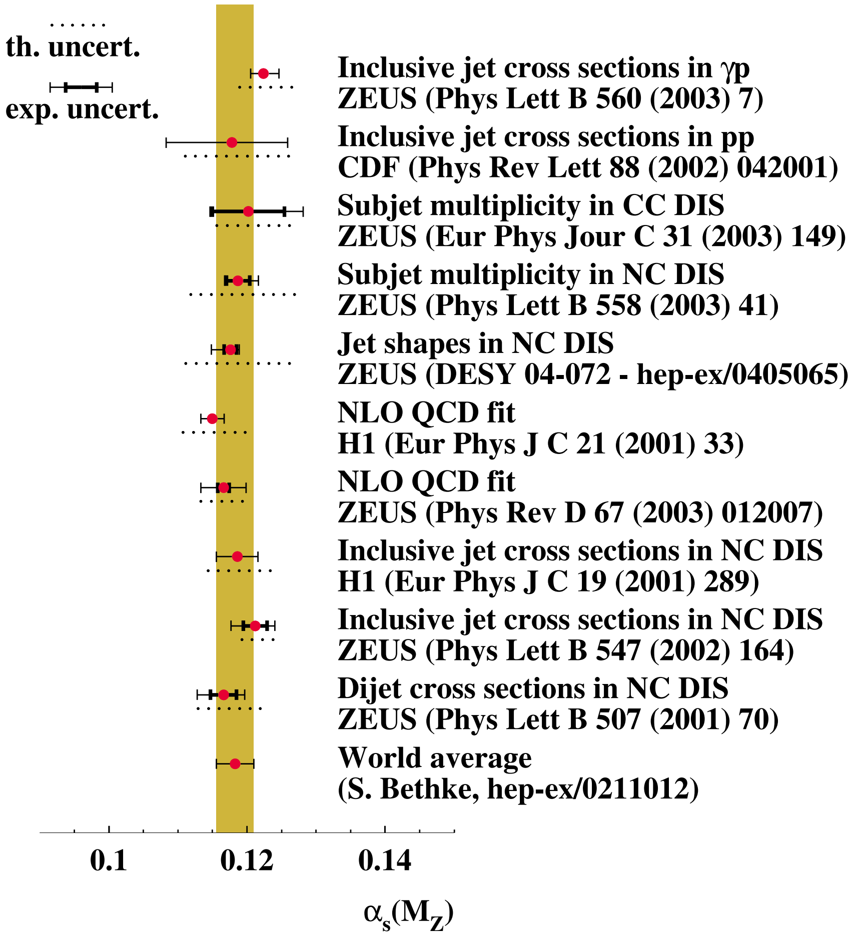


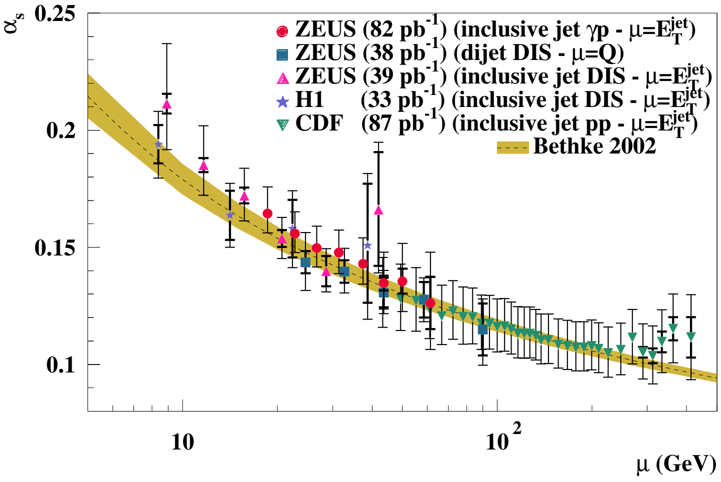




α_S measurements

Important test of QCD: measurement of α_S, can be performed at hadronic colliders using jet final states, DGLAP evolution equation

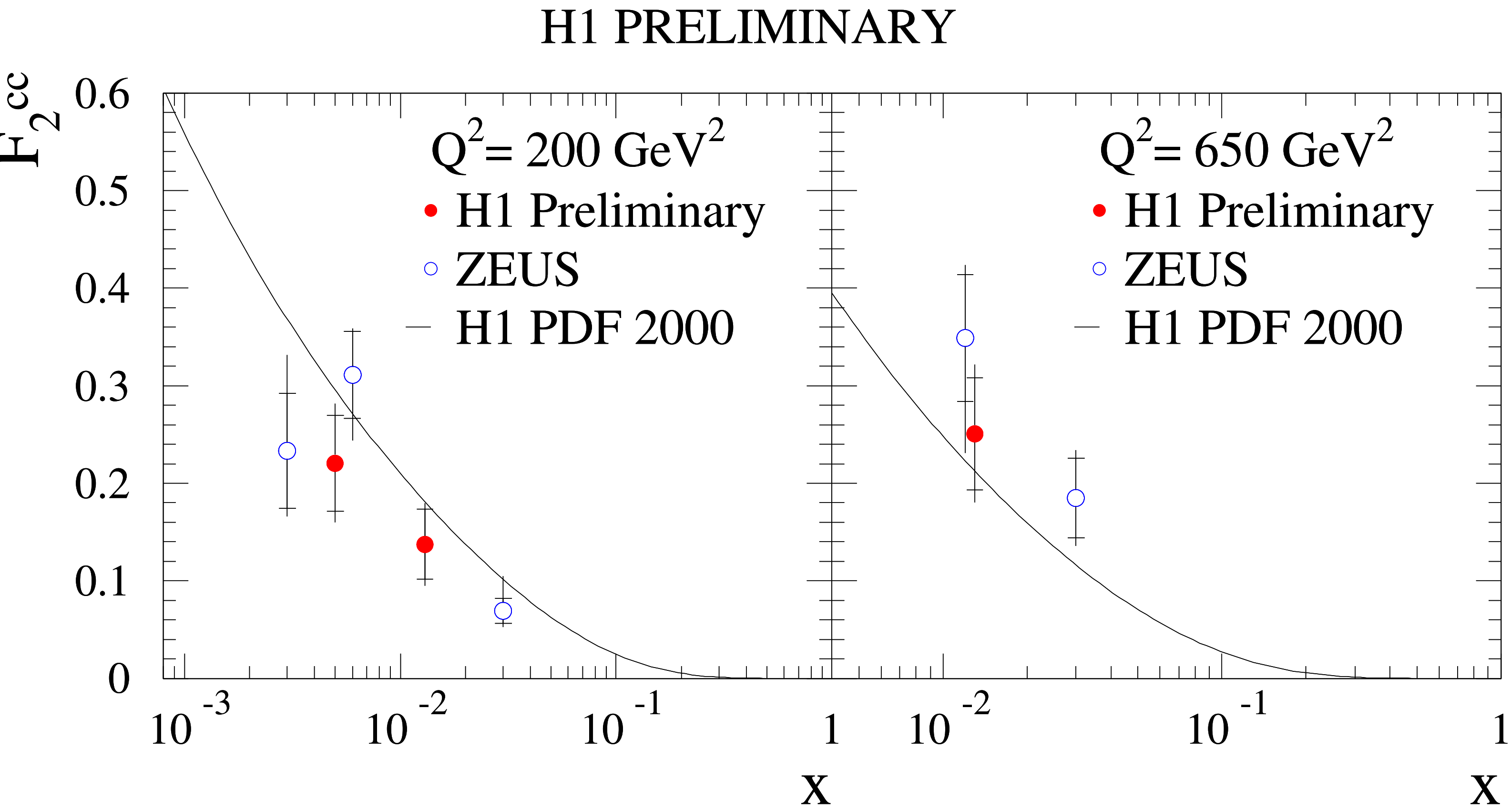




Experimental precision from hadronic experiments close to world average precision, theoretical uncertainties still large

Heavy quarks

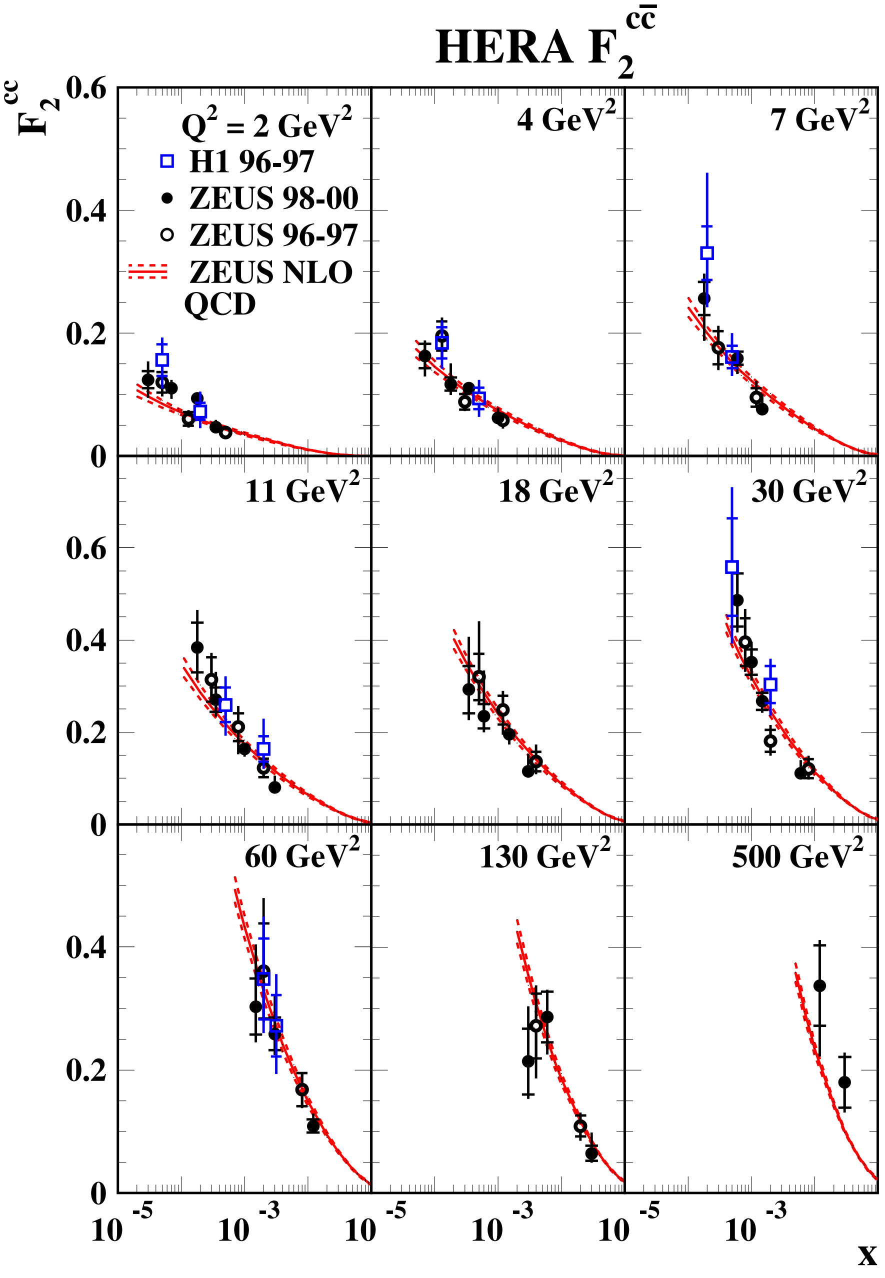
F_2^b structure function measurement at HERA: no discrepancy with improved NLO predictions



More precise measurements from HERA expected soon!

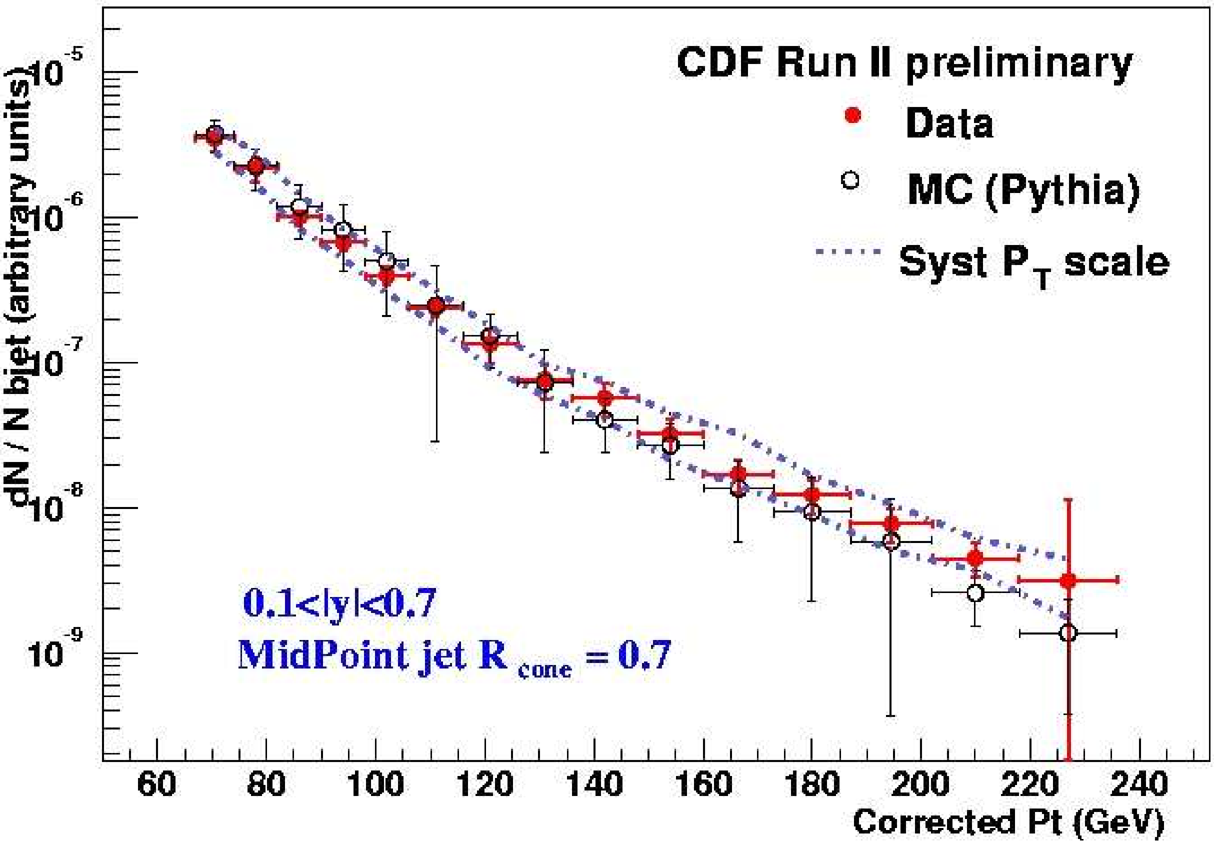
Heavy quarks

F_2^c structure function measurement at HERA:



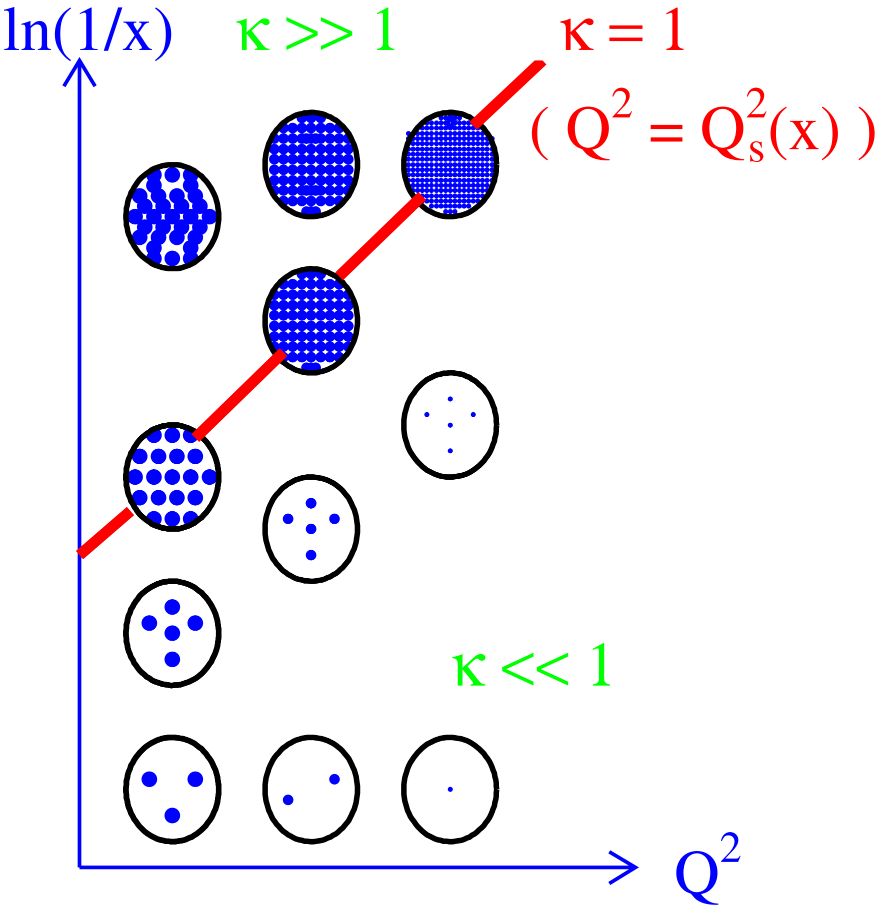
b jet cross section at the Tevatron

Measurement of the b jet cross section and comparison with PYTHIA LO.



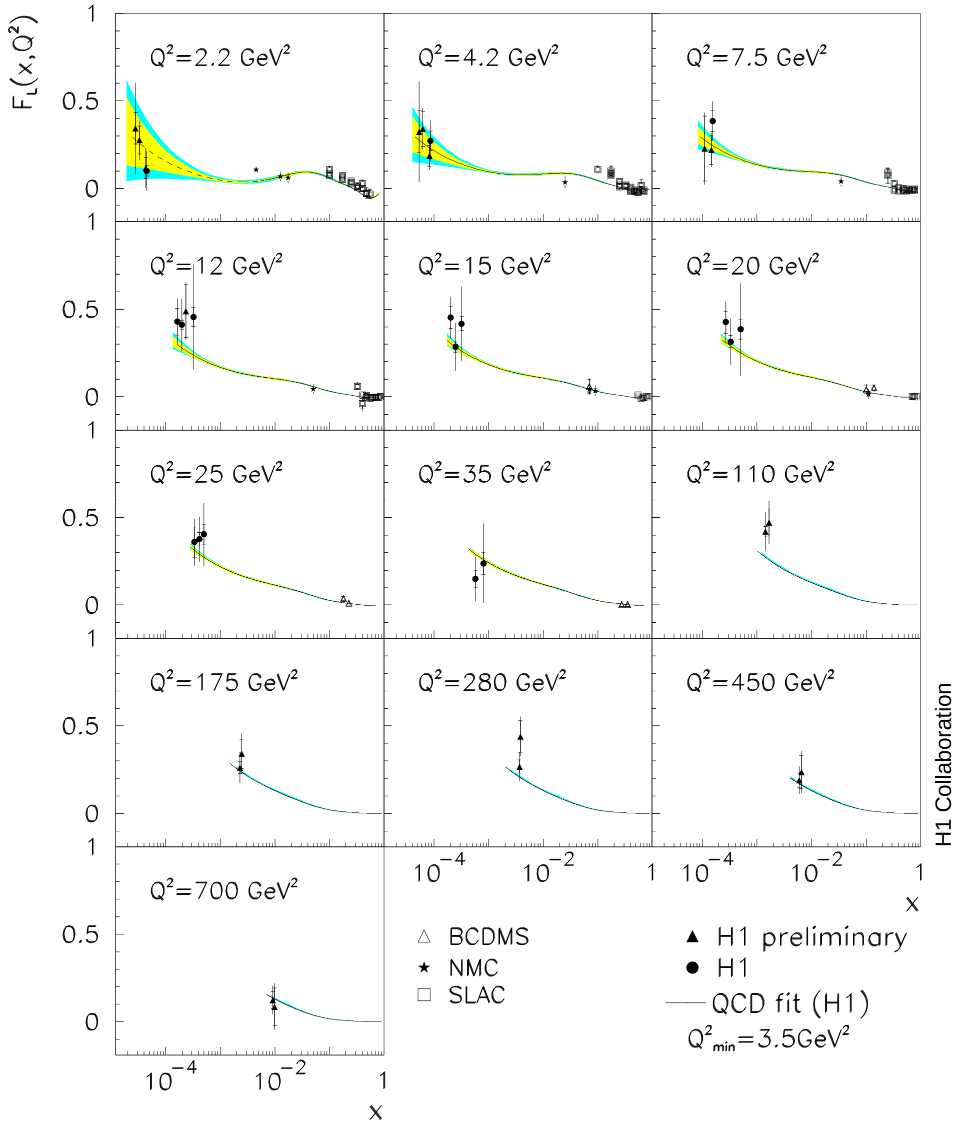
Phenomenology of saturation - BFKL equation

- BFKL effects: low x region, but DGLAP evolution describes nicely F_2, look for F_L!
- Saturation effects: low x, moderate Q^2, screening effects



F_L results

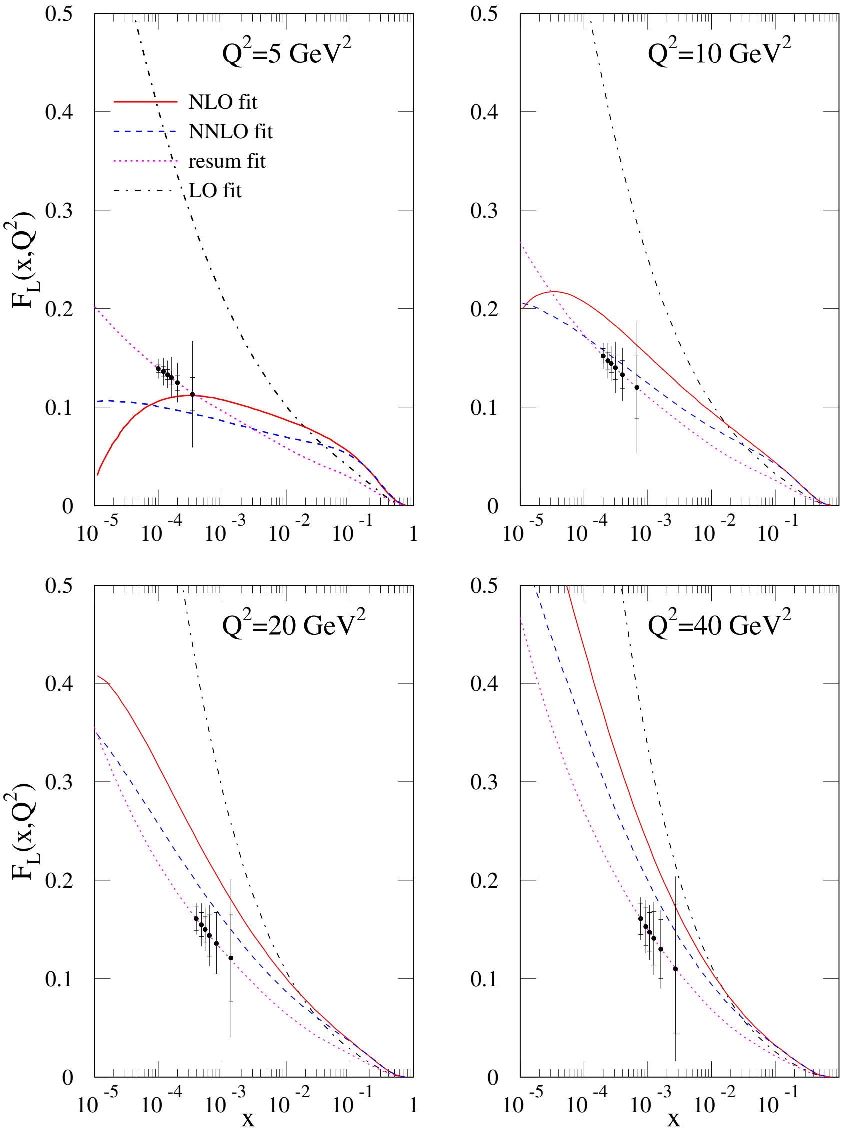
Indirect measurement of F_L using either the *ep* cross section measurement and the subtraction of the F_2 component after DGLAP evolution or radiative events



F_L prospects

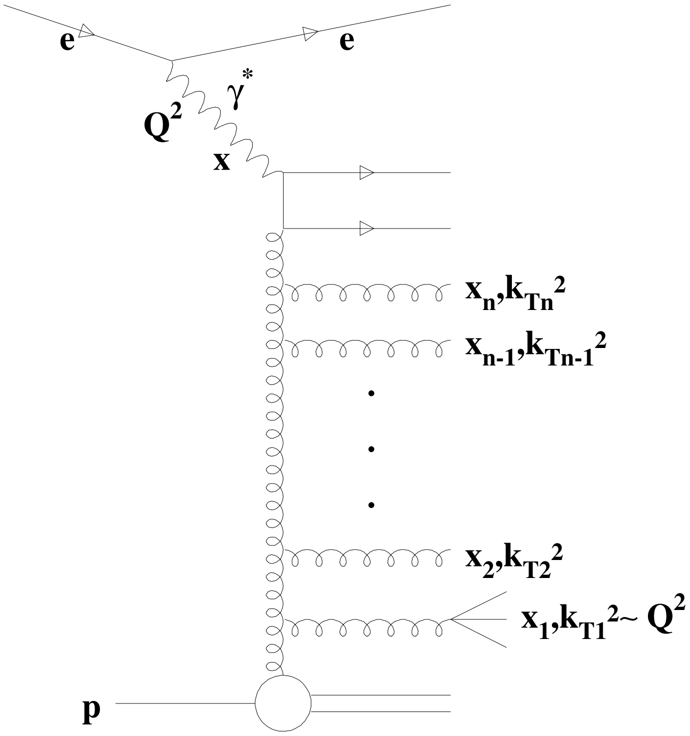
Measurement of F_L using reduced beam energies at HERA (same x and Q^2 but different y values): allows better tests of QCD!

F_L LO , NLO, NNLO and resummed - Simulation of Low E_p H1 Data



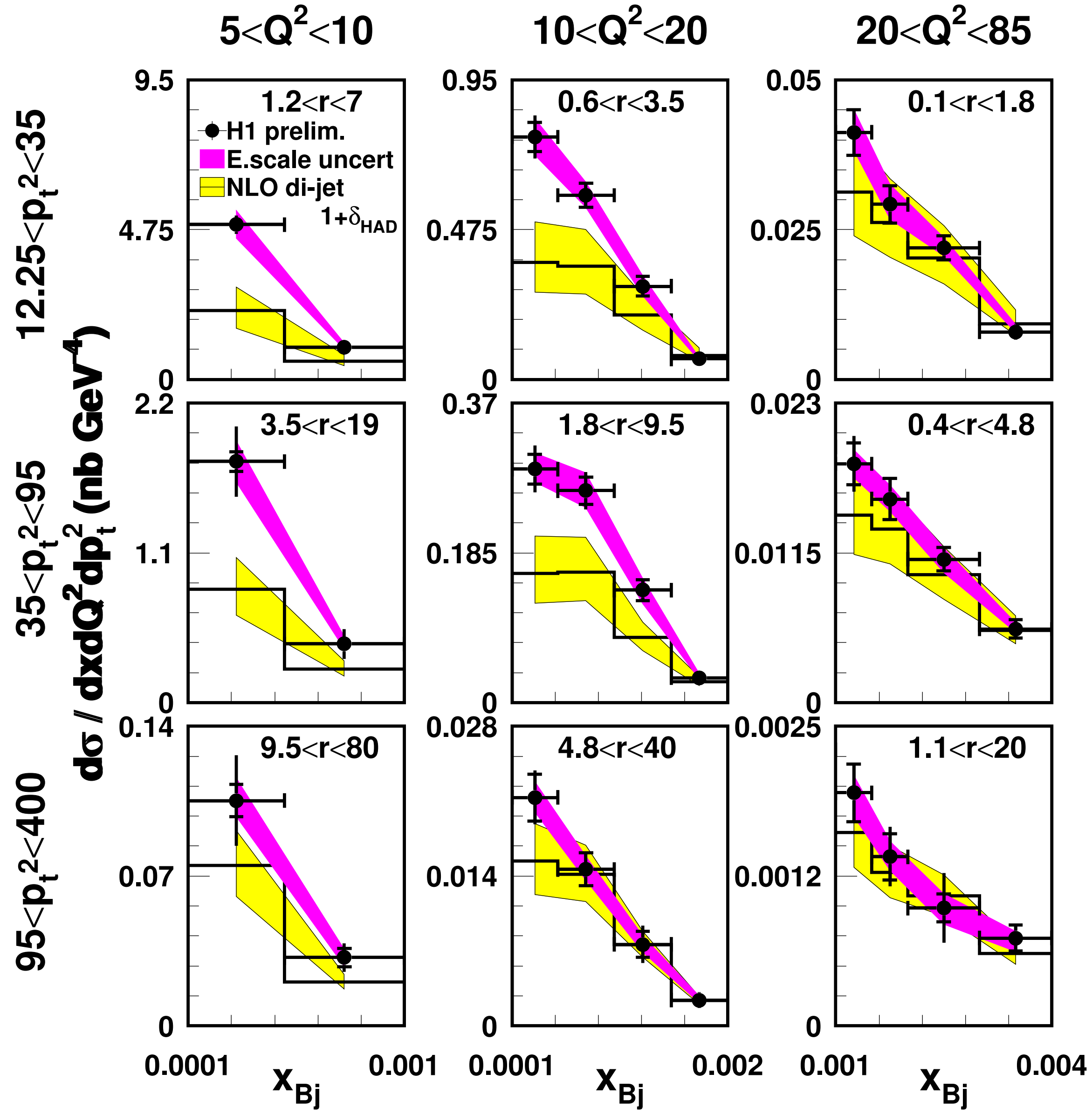
BFKL: look for forward jets at HERA

- No obvious observation of BFKL resummation or saturation effects in $F_2 \rightarrow$ look in final state...
- Very simple idea: look for jets with $k_T^2 \sim Q^2(\gamma)$ to favour BFKL equation, and look for saturation as a function of rapidity: the increase of cross section will be slower than for the linear one



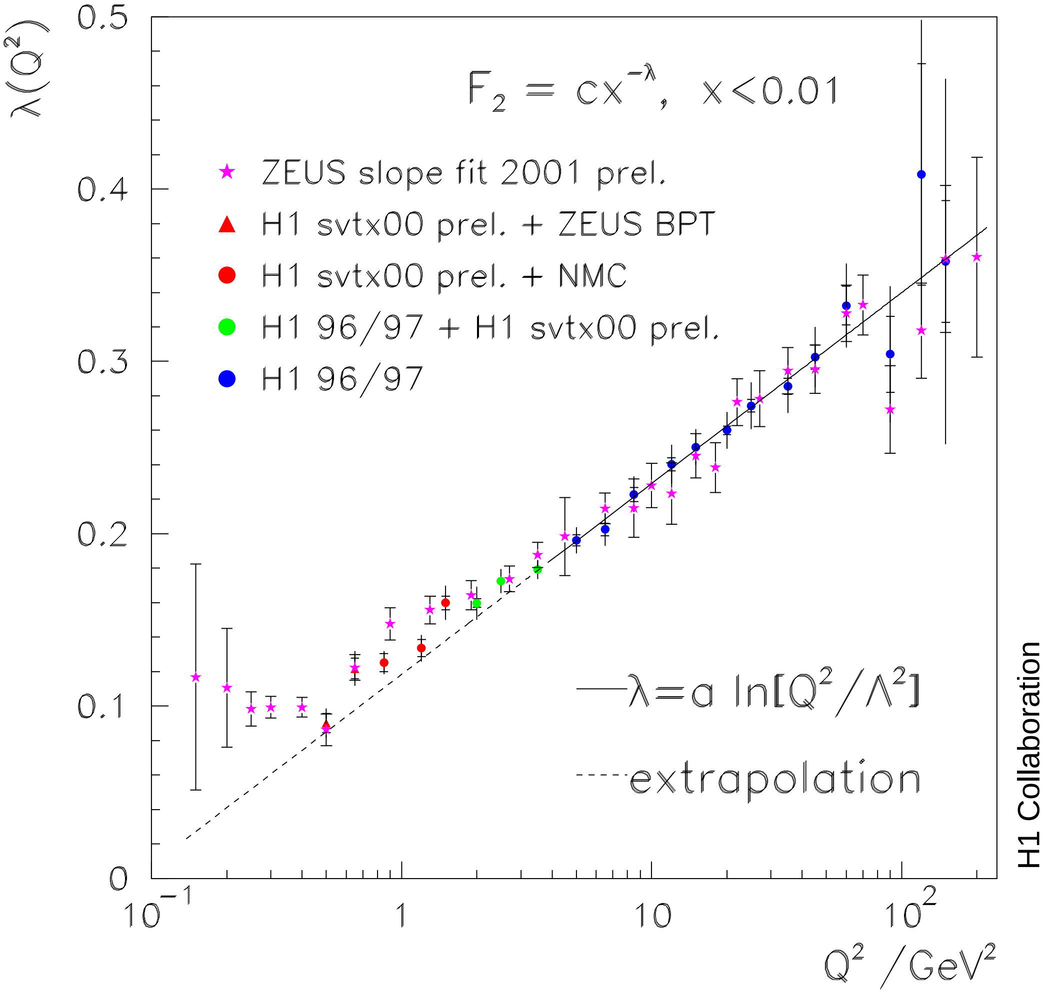
BFKL: look for forward jets at HERA

Measurement in different bins of x, Q^2, $r = p_T^2/Q^2$: measurement higher than NLO DGLAP prediction!



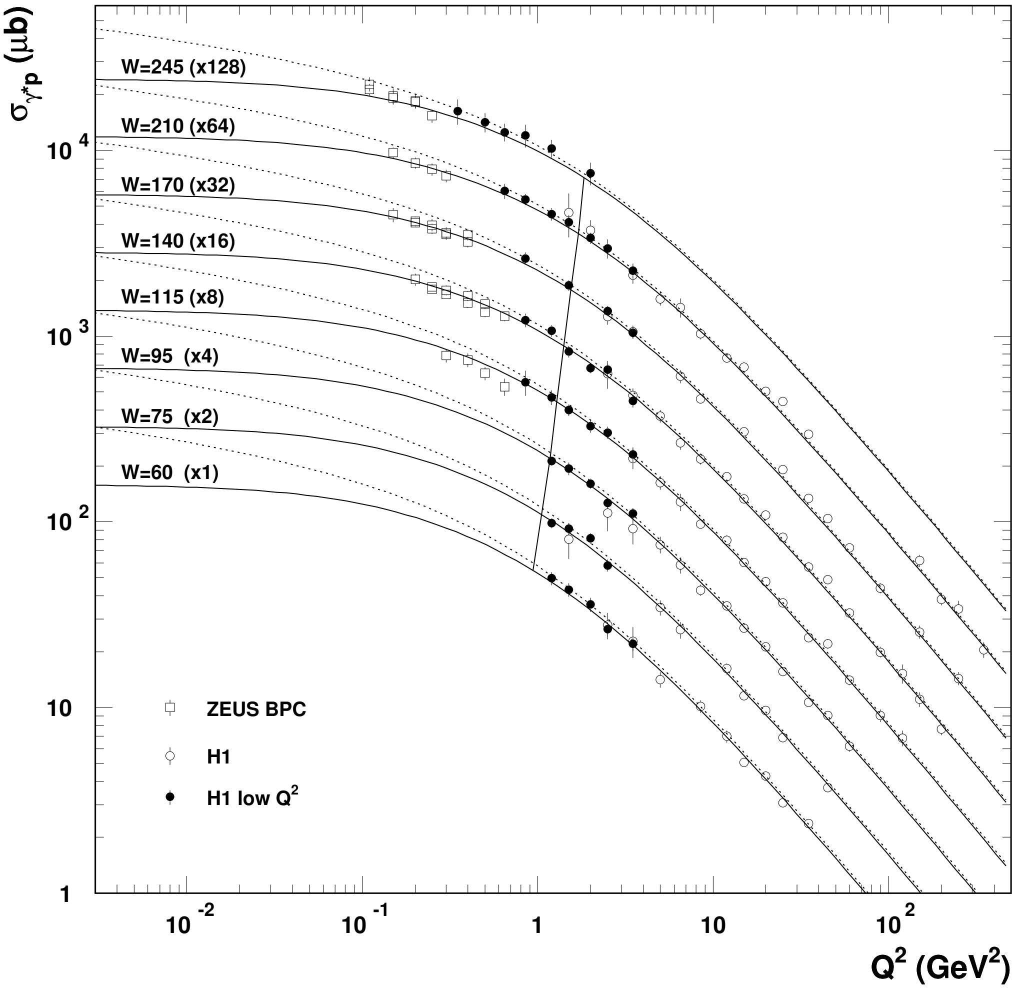
Saturation: what to learn from HERA?

Measurement of the slope of F_2 ($\frac{dlogF_2}{dlog1/x}$) as a function of Q^2: change of slope at very low Q^2, saturation? or outside the domain of perturbative QCD?



Saturation: what to learn from HERA?

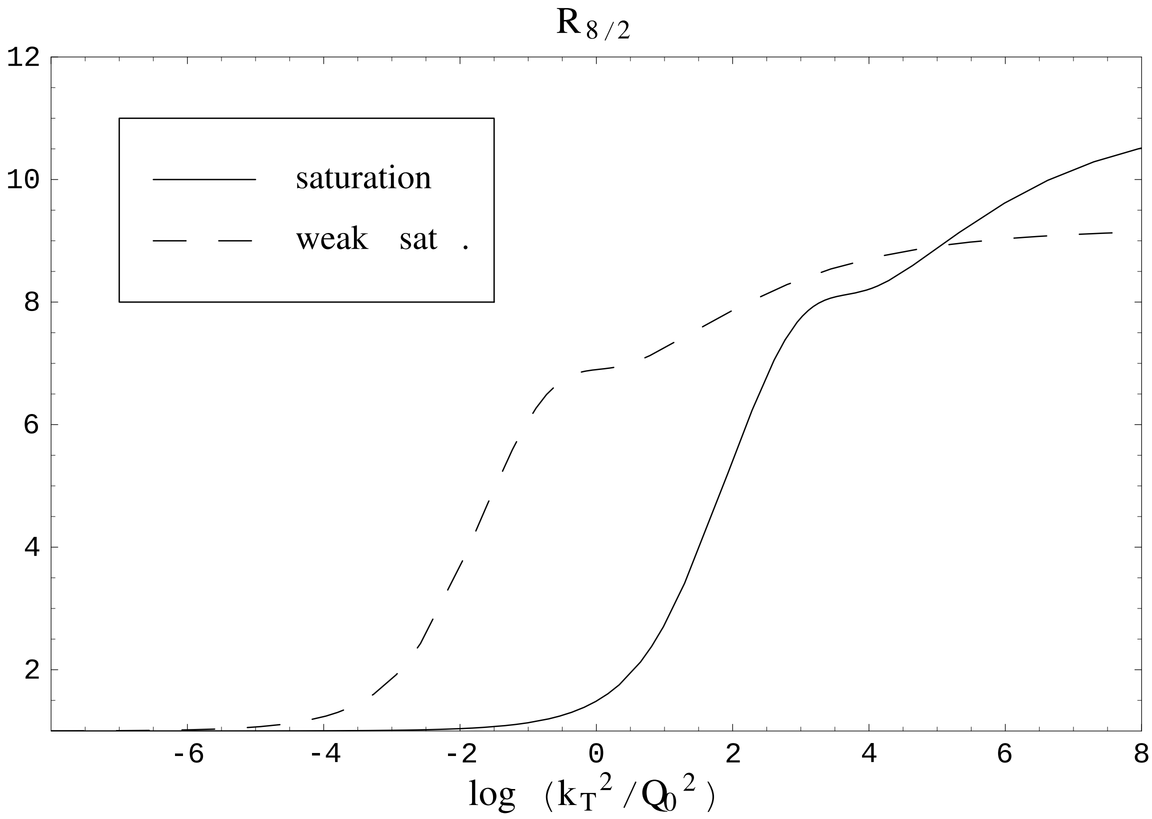
Look at HERA: do we see saturation effects, for instance in structure function measurements? (Golec-Biernat, Wuesthoff)



Transition occurs at the limit of the non perturbative regime: difficult to see at HERA

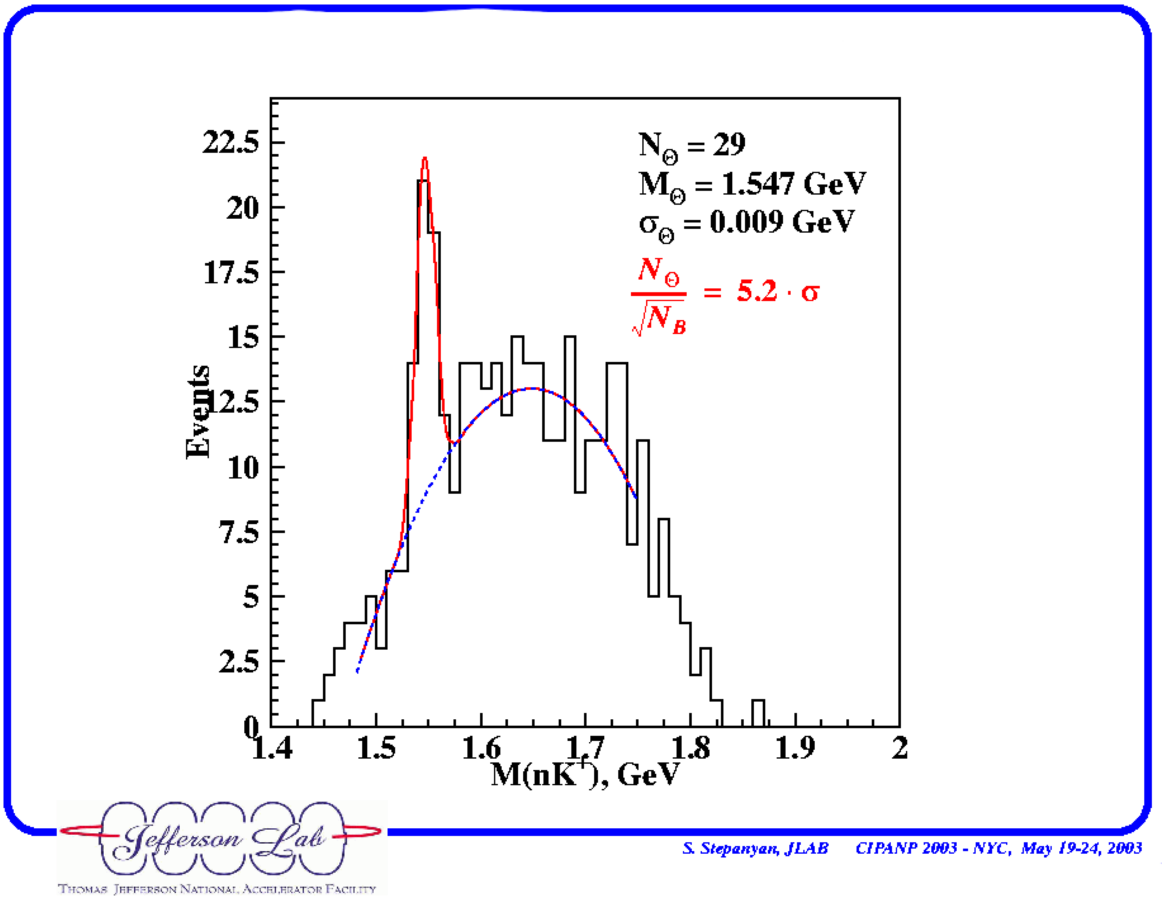
Saturation at the LHC?

Cross-section ratios $\mathcal{R}_{i/j}$ between two intervals in rapidities (2 and 8 for the LHC), for two different saturation models , without saturation: flat (Marquet, Peschanski, Royon)



Pentaquarks: JLAB/CLAS results

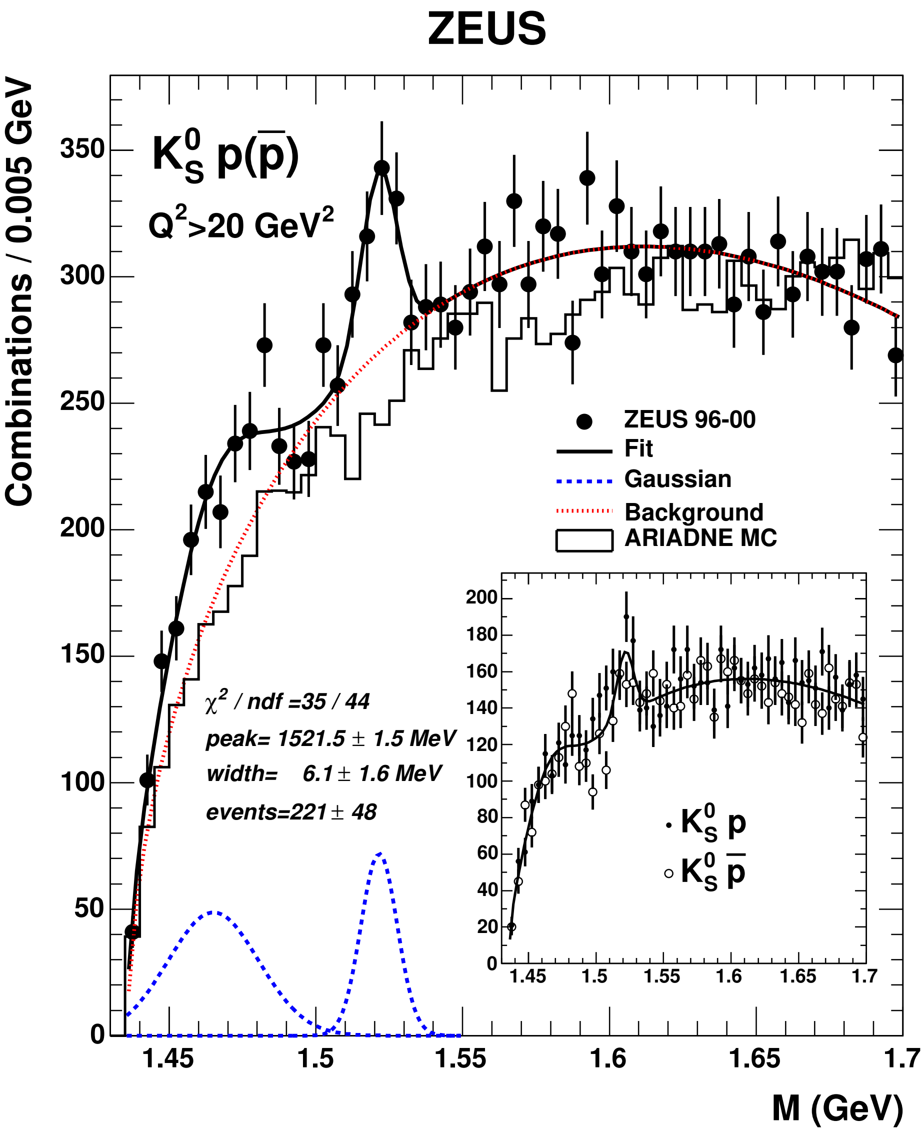
Original observation: resonance due to an exotic baryon of $S = +1$ in reaction $\gamma d \rightarrow K^+K^-pn$ $(udud\bar{s})$



Pentaquarks: ZEUS results

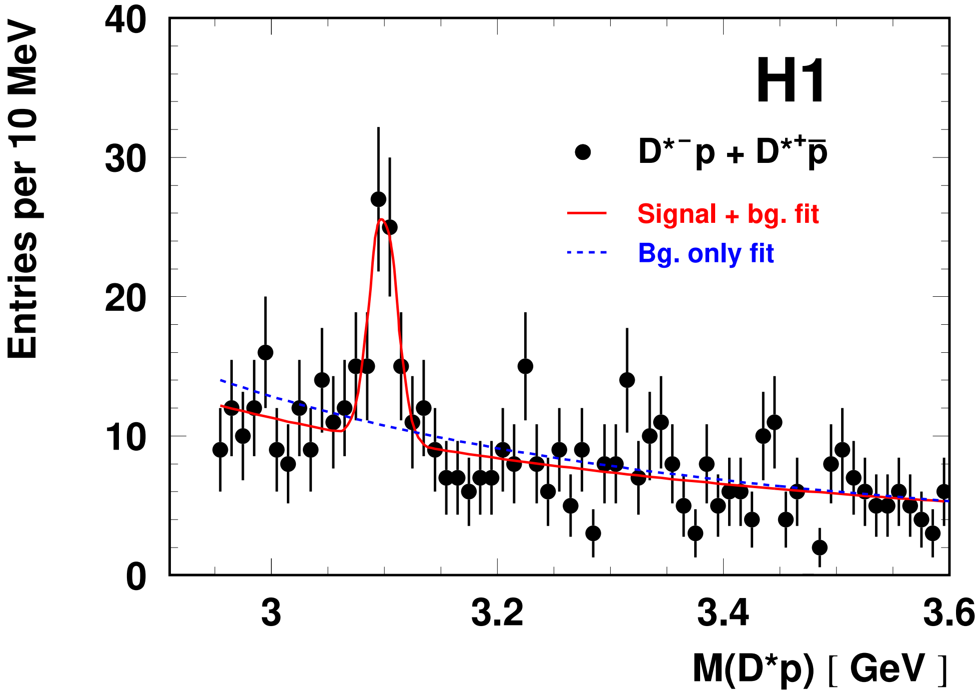
Search for a resonance in $K^0_S p$ and $K^0_S \bar{p}$ invariant mass spectrum: confirm results of fixed target experiment ($udud\bar{s}$)

M=1521.5 ± 1.5 MeV



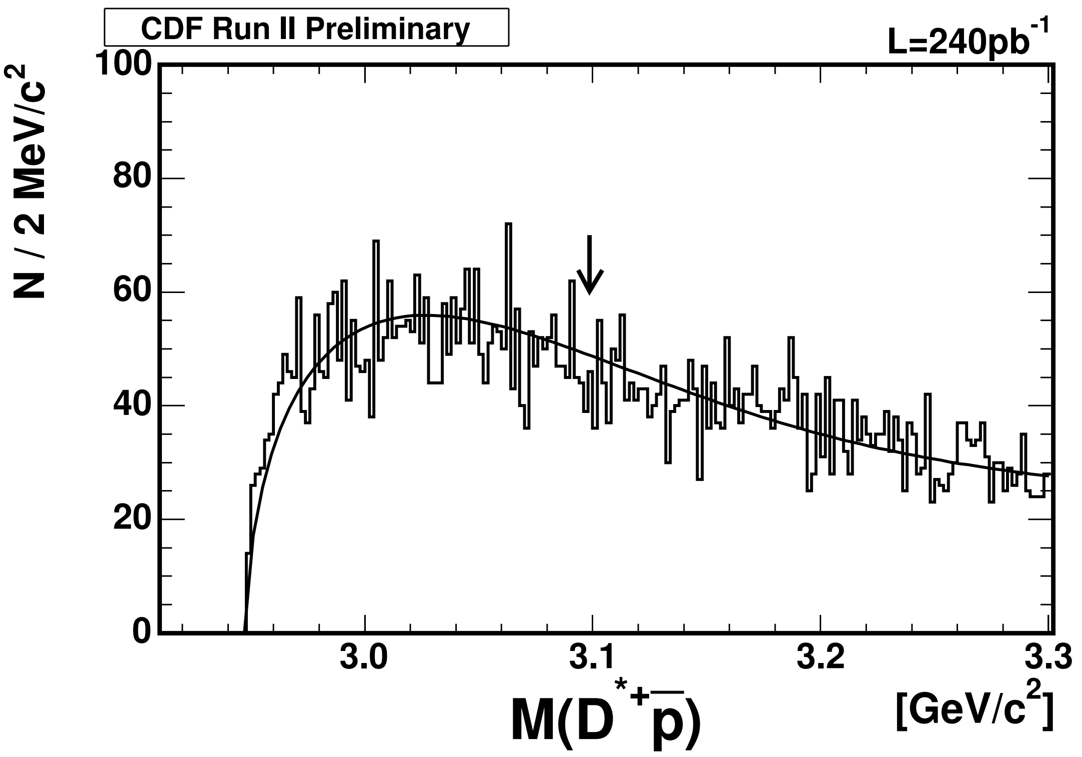
Pentaquarks: H1 results

- Observation of a narrow resonance in $D^{*-}p$ and $D^{*+}\bar{p}$ invariant mass combinations ($udud\bar{c}$), not observed by ZEUS/CDF
- $M(D^{*+}\bar{p}) - M(D^{*+})$ at $M(D^{*+}\bar{p}) = 3099 \pm 3 \pm 5$ MeV
- no $udud\bar{s}$ resonance observed



Pentaquarks: CDF results

- Look for $\Xi_{3/2} \rightarrow \Xi\pi$ $(qsqs\bar{q})$: no signal in a sample 18 times larger than the one of NA49 (NA49 results, M=1.862 ± 0.002 GeV)
- Search for $\theta^+ \rightarrow pK_S^0$ $(udud\bar{s})$ (seen by CLAS, ZEUS...): no signal found
- Search for θ_C decaying in $D^{*+}\bar{p}$ $(udud\bar{c})$ (seen by H1): no signal found



Looking for Θ^+ $(udud\bar{s})$

Exp	Prod.	Decay	Mass	σ
LEP	$\gamma n \longrightarrow K^-\Theta^+$	K^+n	1540	4.6
DIANA	$K^+X_e \longrightarrow N\Theta^+$	K^0_Sp	1539	4.4
CLAS	$\gamma d \longrightarrow pK^-\Theta^+$	K^+n	1542	5.2±0.6
SAPHIR	$\gamma p \longrightarrow K^0_S\Theta^+$	K^+n	1540	4.8
CLAS	$\gamma p \longrightarrow pK^-\Theta^+$	K^+n	1555	7.8 ± 1.0
HERMES				