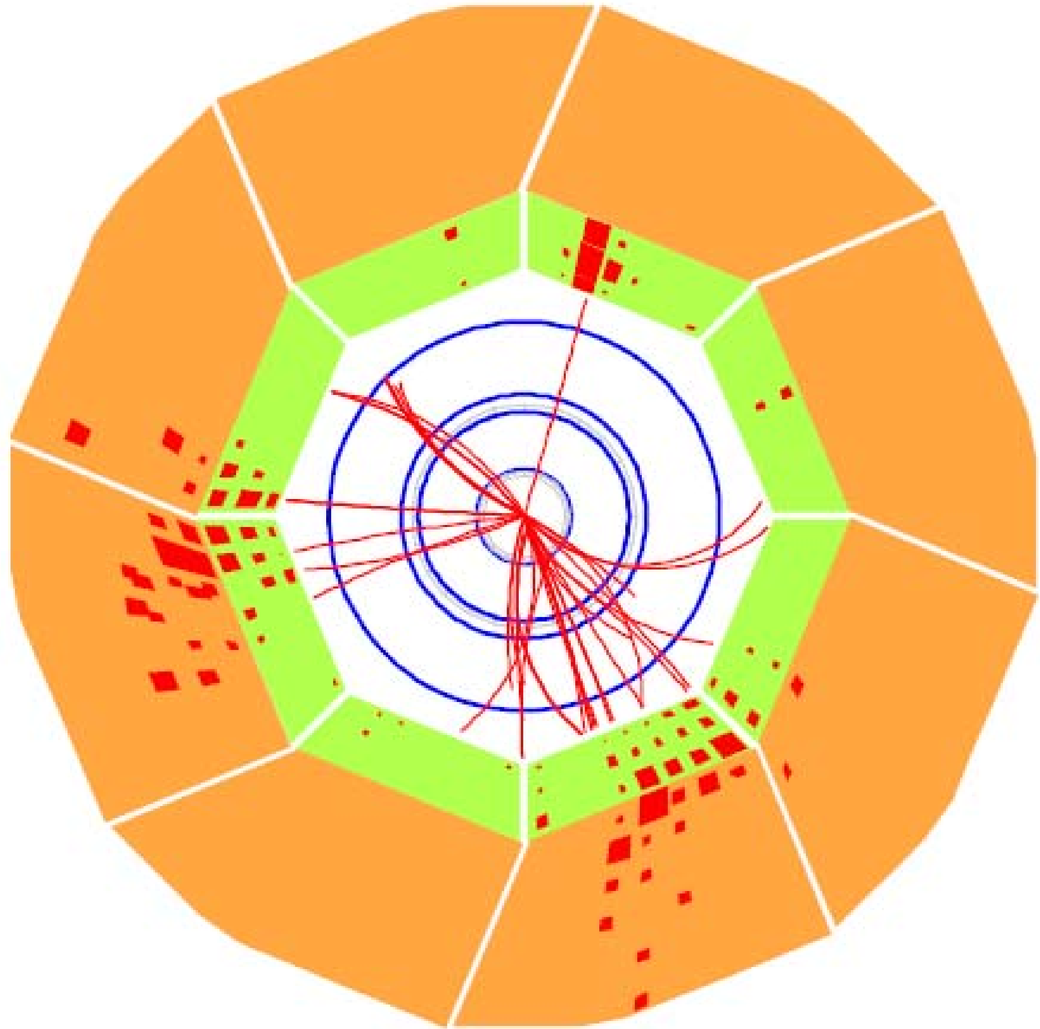
Tests of the QCD Sector of the Standard Model

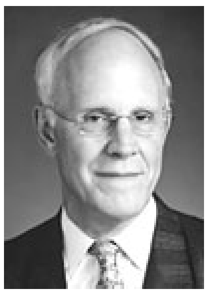
- Structure functions and α_s in DIS
- Spin physics
- Jets and α_s
- Event shapes
- Fragmentation
- Heavy flavours
- Summary



Tim Greenshaw, Liverpool University.

Introduction

- Progress on many fronts in QCD in last few years.
- Nobel prize in physics awarded to Gross, Politzer and Wilczek...

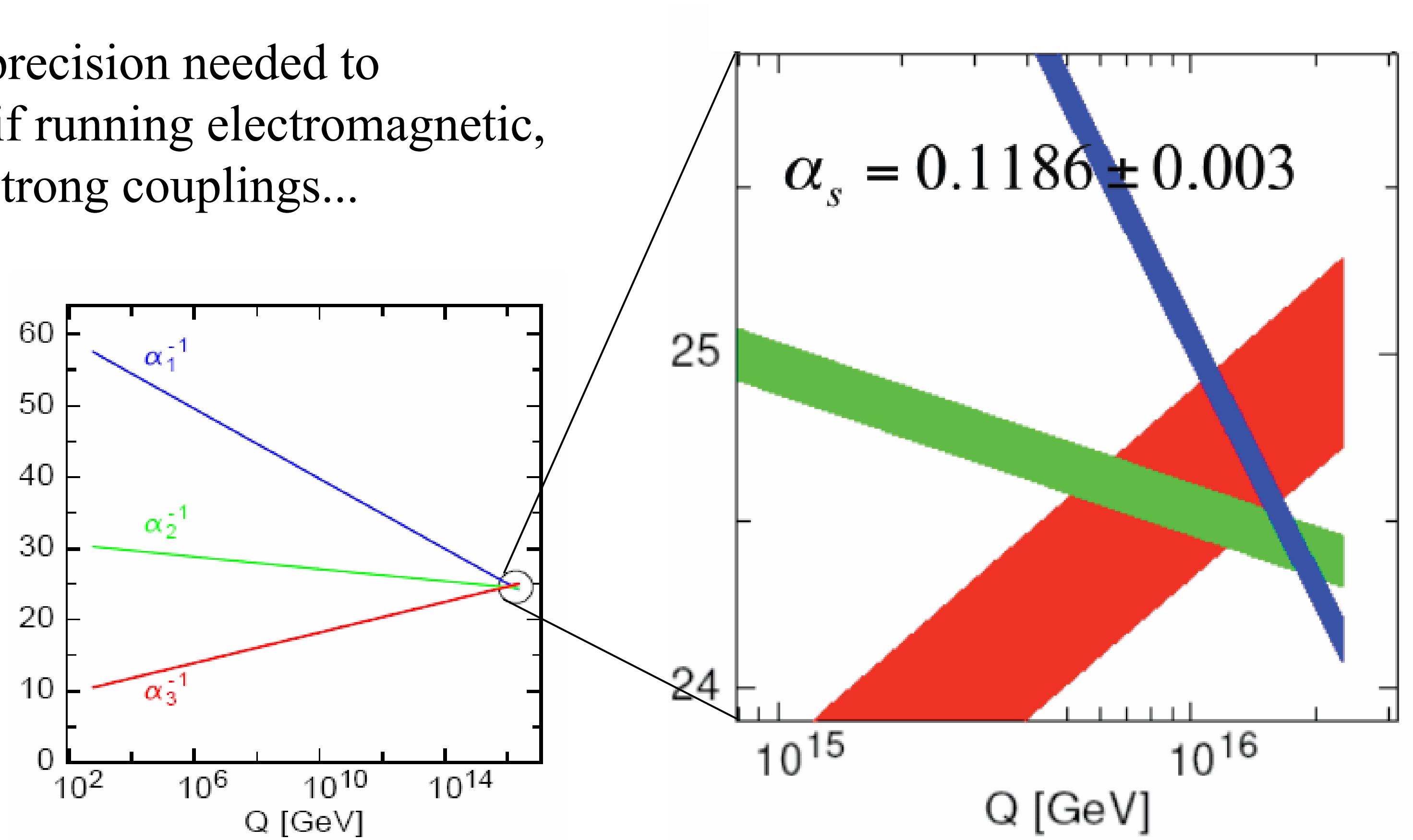


- "...for the discovery of asymptotic freedom in the theory of the strong interaction..."

- It is now official: QCD is the theory of the strong interactions!
- Why then "Tests of the QCD sector of the Standard Model"?
- Because we do not understand how partons are put together to make hadrons...
- ...or how those partons conspire to ensure the proton's spin is ½.
- Because we need to understand future high energy experiments at the LHC...

Introduction

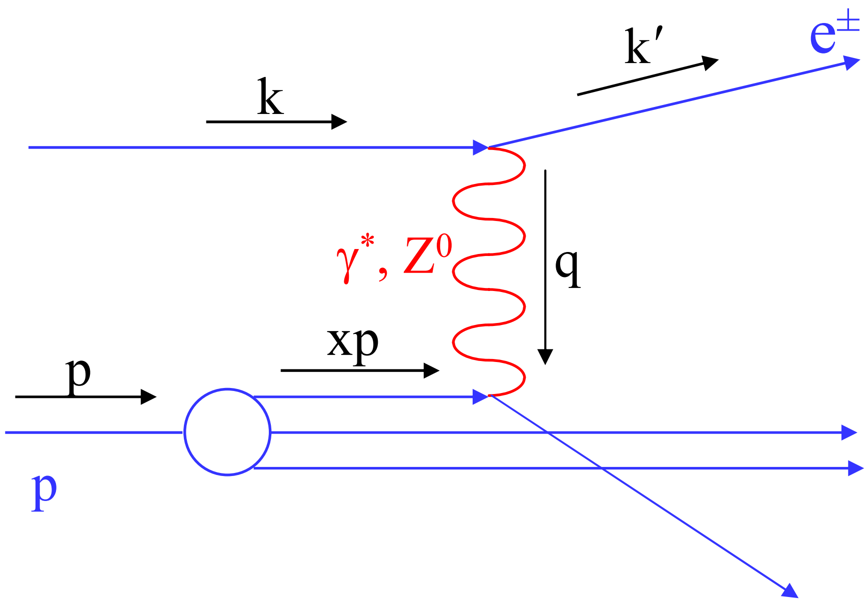
- ...and because α_s is the least well known of the fundamental constants of nature.
- Increased precision needed to determine if running electromagnetic, weak and strong couplings...
- ...unify at ~ 10^{16} GeV.



Allanach et al, hep-ph/0407067

Structure functions and α_s

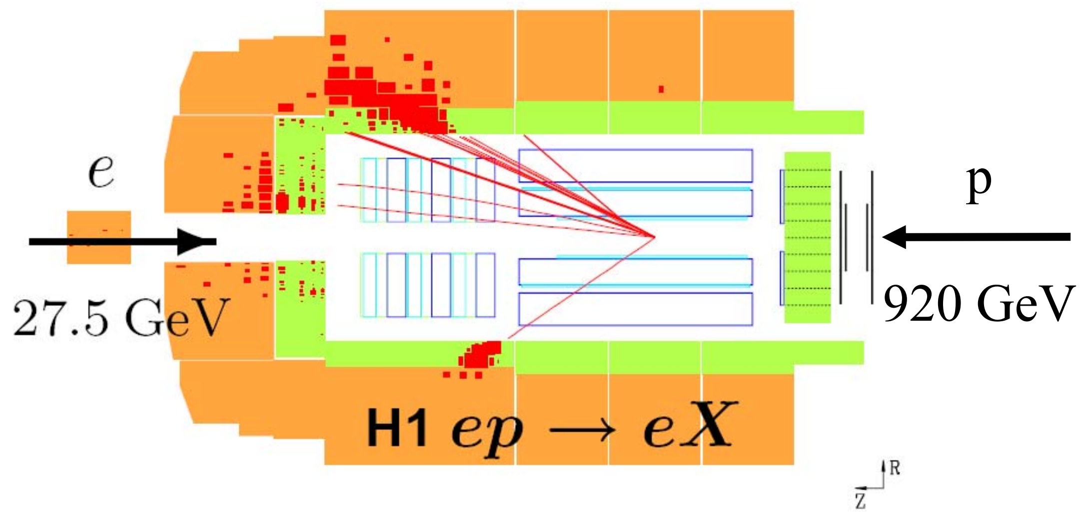
- Measure structure of hadrons in deep-inelastic lepton-nucleon scattering.
- Neutral current DIS:



- Describe in terms of:

$$Q^2 = -q^2, \quad x = \frac{Q^2}{2p \cdot q} \text{ and } y = \frac{p \cdot q}{p \cdot k}$$

- HERA is most important source of data on proton structure.



- $0 < Q^2 < 10^5$ GeV^2 i.e. sensitive to structure down to ~ 10^{-18} m.
- $10^{-6} < x < 1$.

Timescales in DIS

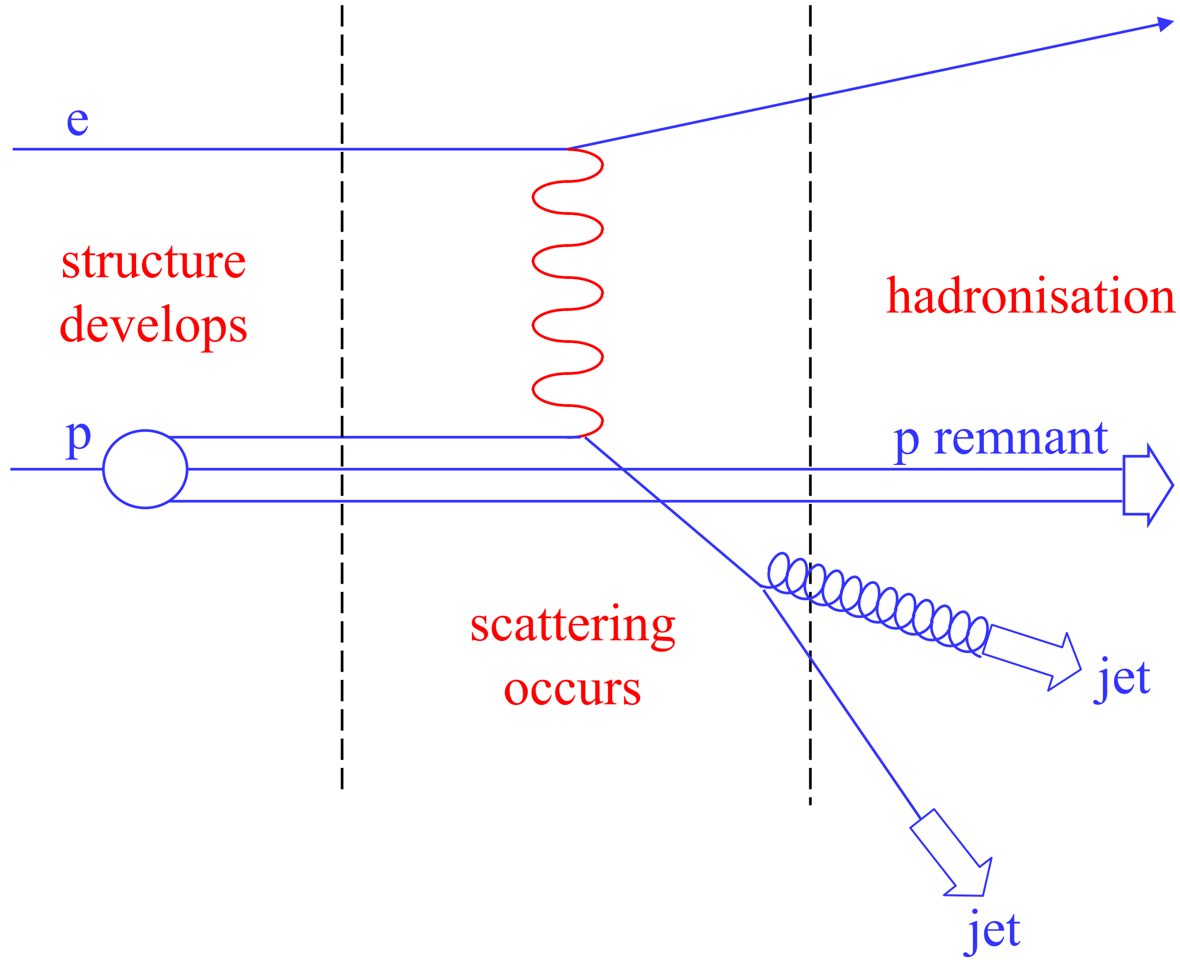
- Time scale for soft interactions

$$\Delta T_{SOFT} \approx \frac{E}{m}\frac{1}{\Lambda_{QCD}}$$

- For DIS

$$\Delta T_{DIS} \approx \frac{1}{\sqrt{Q^2}}$$

- $\Delta T_{SOFT} >> \Delta T_{DIS}$ so DIS takes snapshot of proton structure.



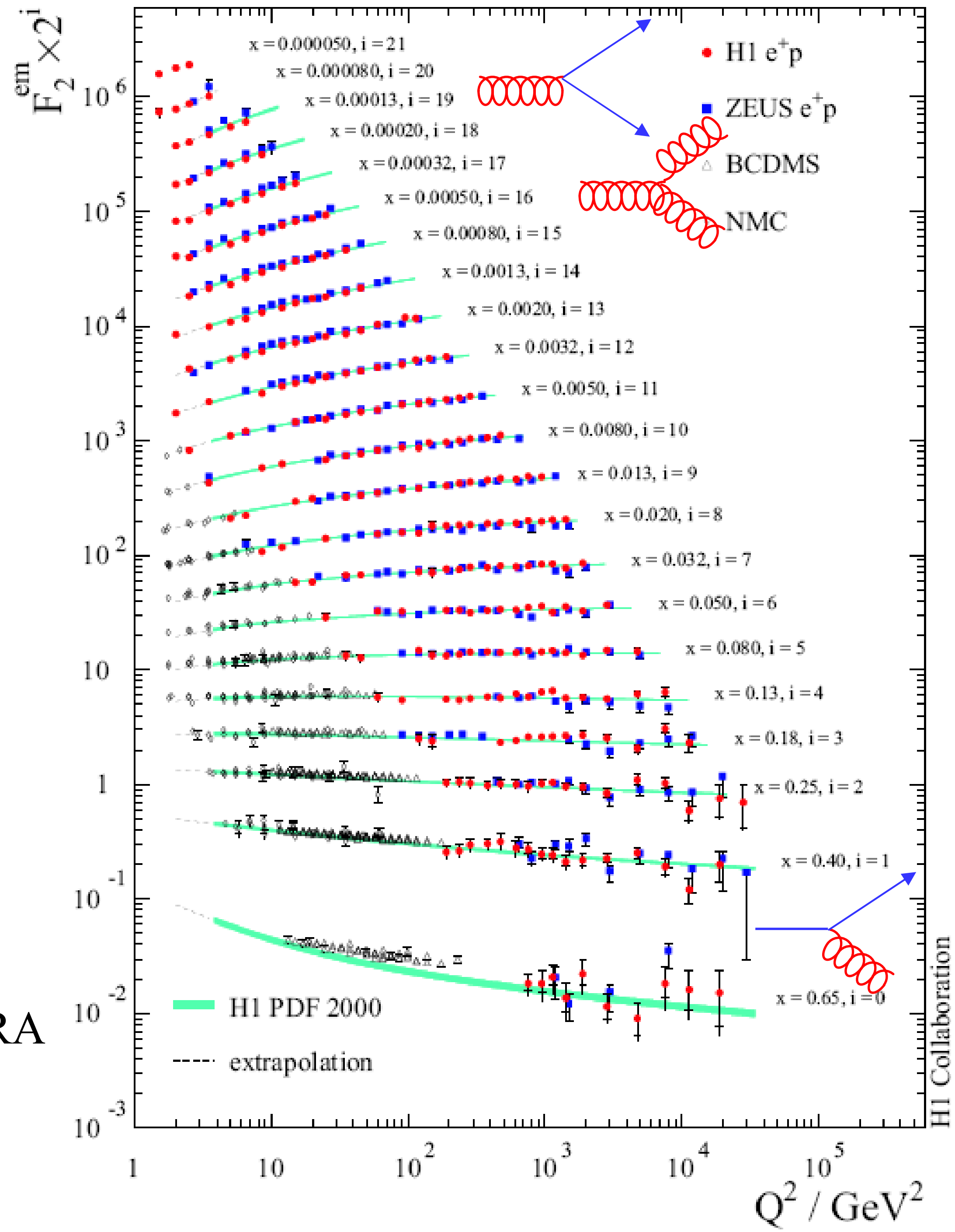
Neutral current cross section for DIS

- $$\frac{d^2\sigma_{NC}(e^{\pm})}{dx\,dQ^2} \sim Y_+F_2 \mp Y_- xF_3 + y^2F_L.$$
- $$Y_{\pm} = 1 \pm (1-y)^2.$$
- $$F_2 \sim \sum_q x\left(q(x,Q^2) + \bar{q}(x,Q^2)\right),$$

  $$xF_3 \sim \sum_q x\left(q(x,Q^2) - \bar{q}(x,Q^2)\right),$$

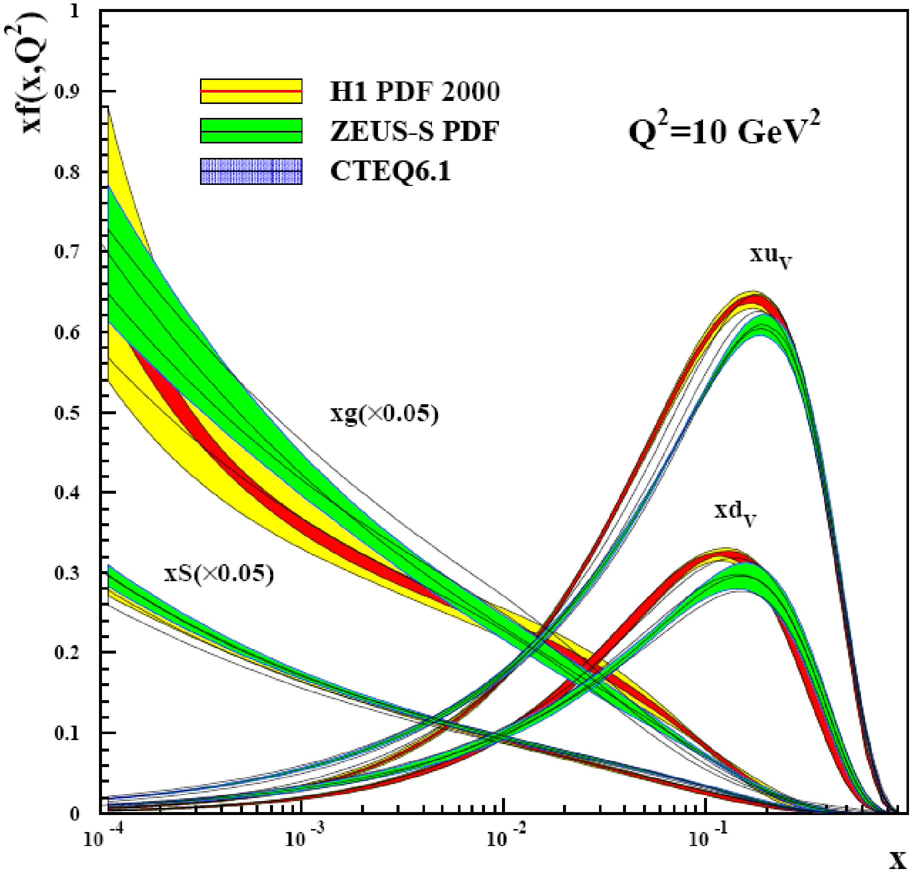
  $$F_L \sim \alpha_s(Q^2)\, x\, g(x,Q^2).$$

- F_2 dominant for $Q^2 < m_Z{}^2$.
- xF_3 measurements require large luminosities.
- Precise F_L measurement needs HERA running with lower proton beam energies.



Parton distribution functions

- NLO QCD fits to F_2, xF_3, and CC data allow extraction of the PDFs.



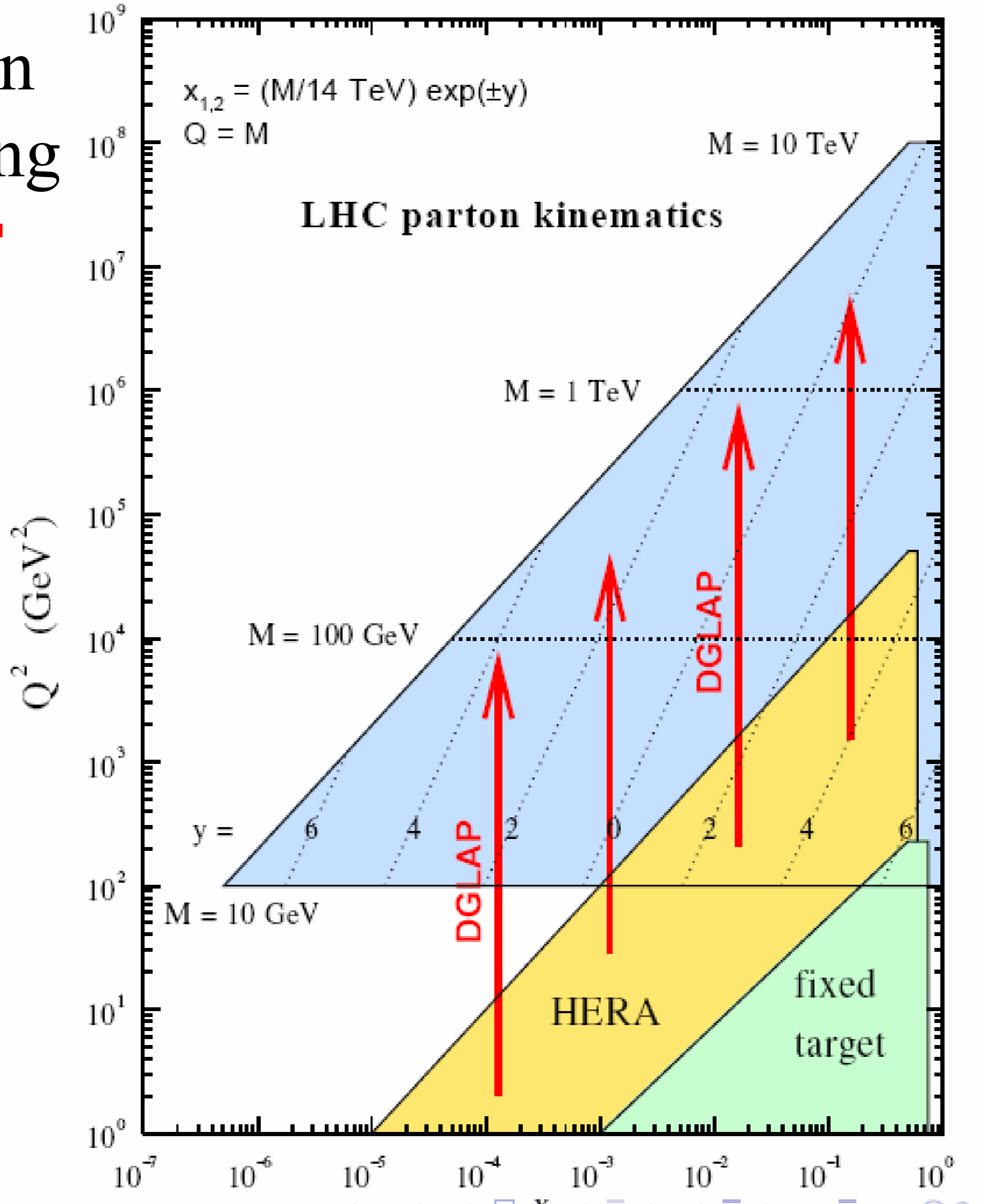
- ...and of α_s.
- E.g. for ZEUS fit:

$$\alpha_s(m_Z) = 0.1166 \pm 0.0008(\text{unc}) \pm 0.0032(\text{corr}) \pm 0.0036(\text{norm}) \pm 0.0018(\text{mod})$$

- Gluon distribution determined from evolution with Q^2: uncertainties large and gluon distribution correlated with $\alpha_s(Q^2)$.

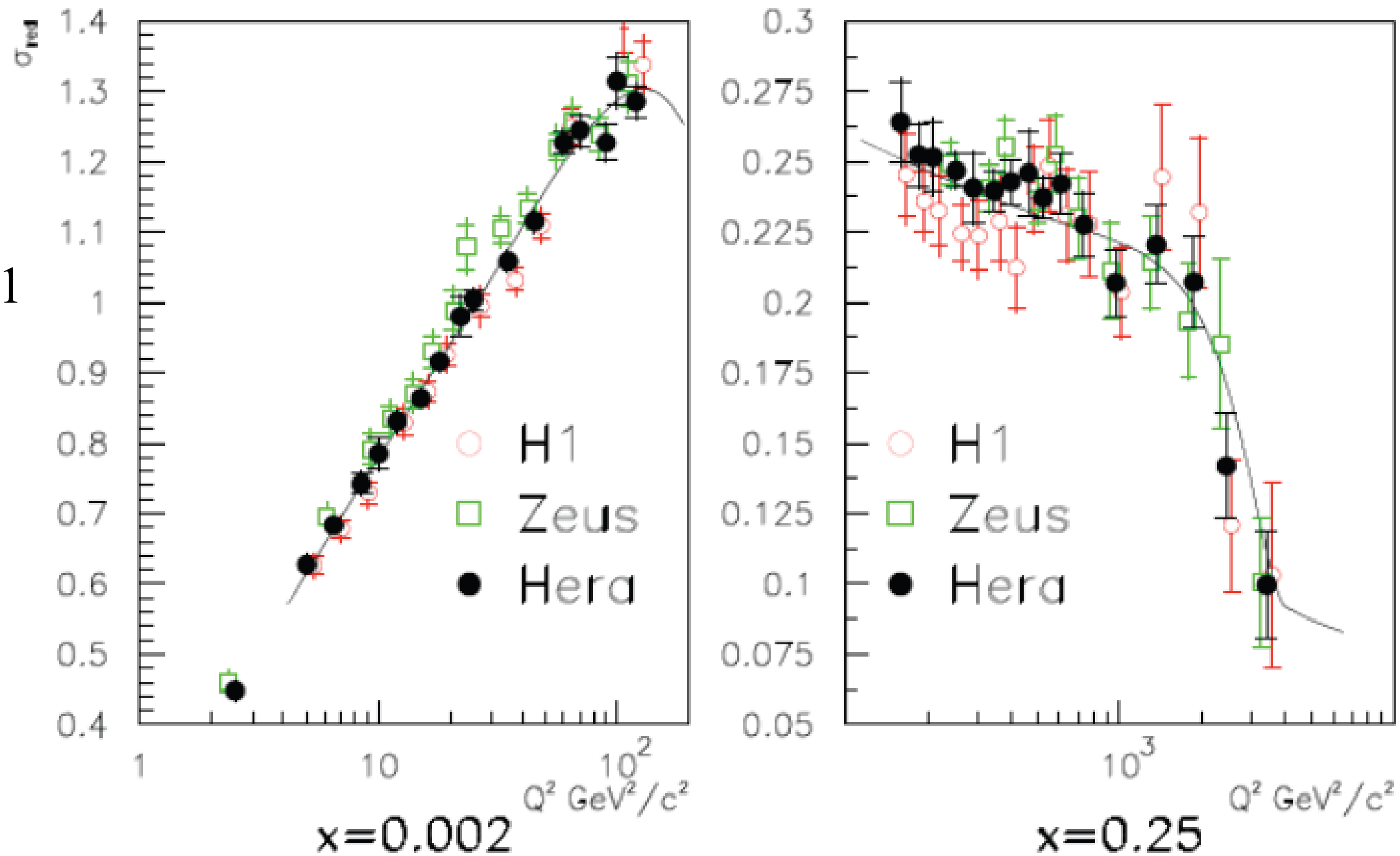
Recent improvements in theoretical understanding

- NNLO DGLAP splitting functions and DIS coefficient functions recently calculated (Moch, Vermaseren, Vogt).
- Will lead to improved precision of PDFs and α_s – progress shown by Guffanti (Blümlein, Böttcher) and by Alekhin on incorporating DIS and E605 DY data.
- Splitting functions also crucial to extrapolation of PDFs from HERA to TeVatron and the LHC.
- DGLAP appropriate at low x?
- NLO MC developments also underway.



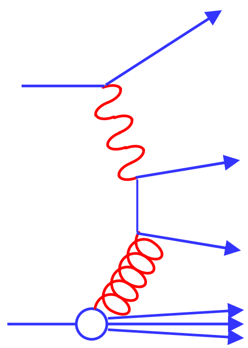
Experimental progress

- Data taking at high luminosity ongoing (HERA II)
- Techniques for combination of H1 and ZEUS data being studied (HERA-LHC workshop), cross calibration will lead to reduced systematic errors.

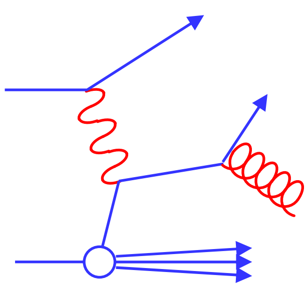


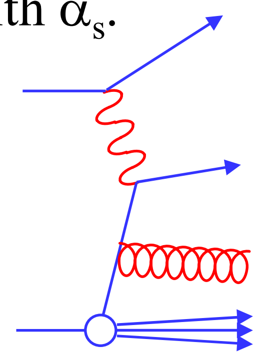
Add jet data to PDF determinations

- ZEUS exploit additional constraints provided by DIS and γp jet data.
- Boson gluon fusion sensitive to gluon distribution.

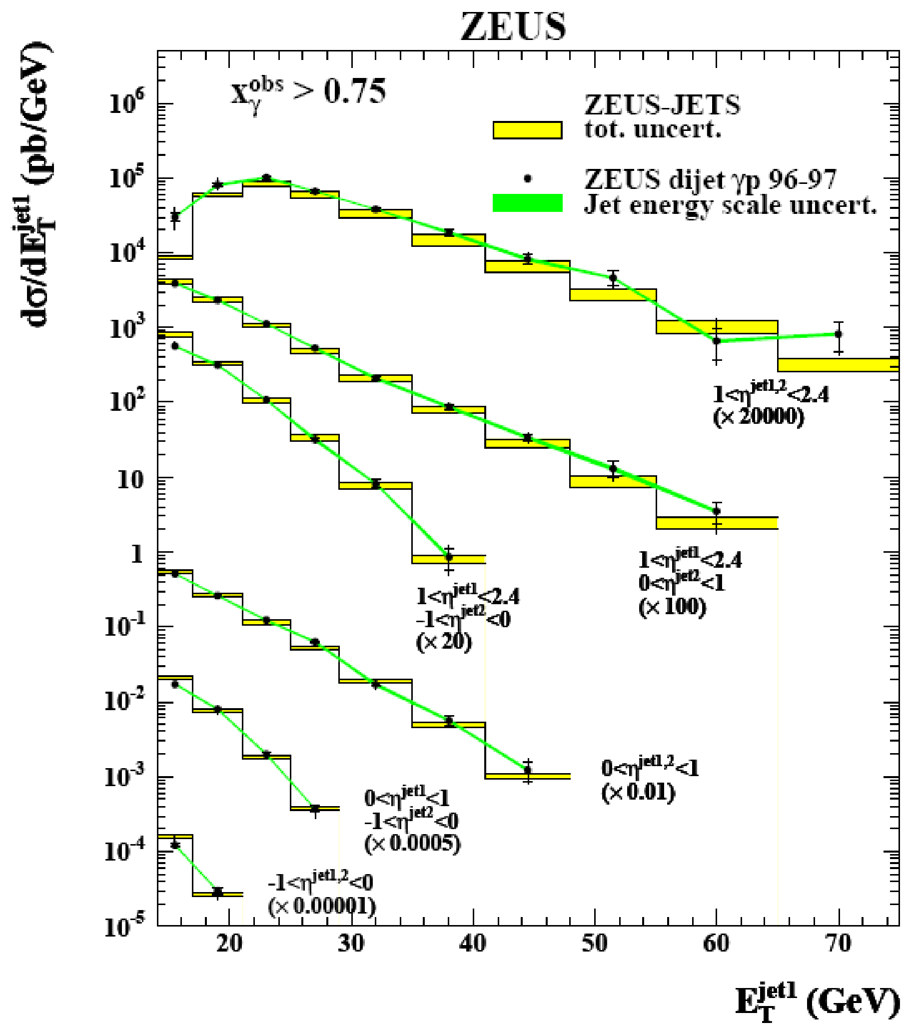


- Contributions from other diagrams break correlations with α_s.



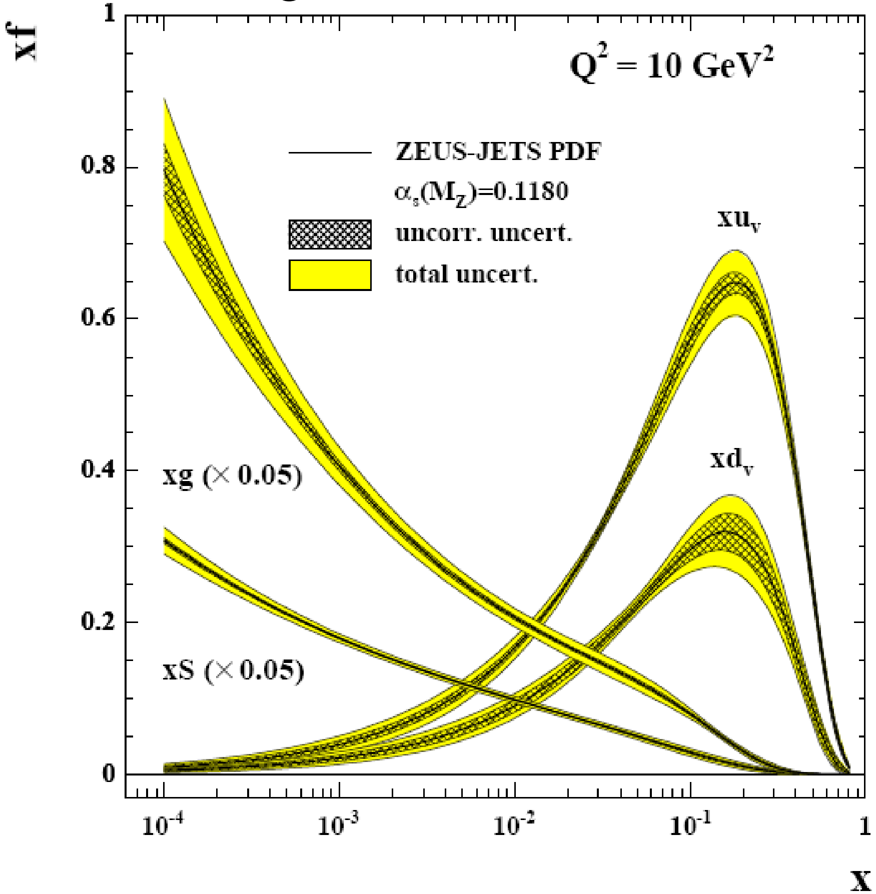


- Dijet cross section, photoproduction:

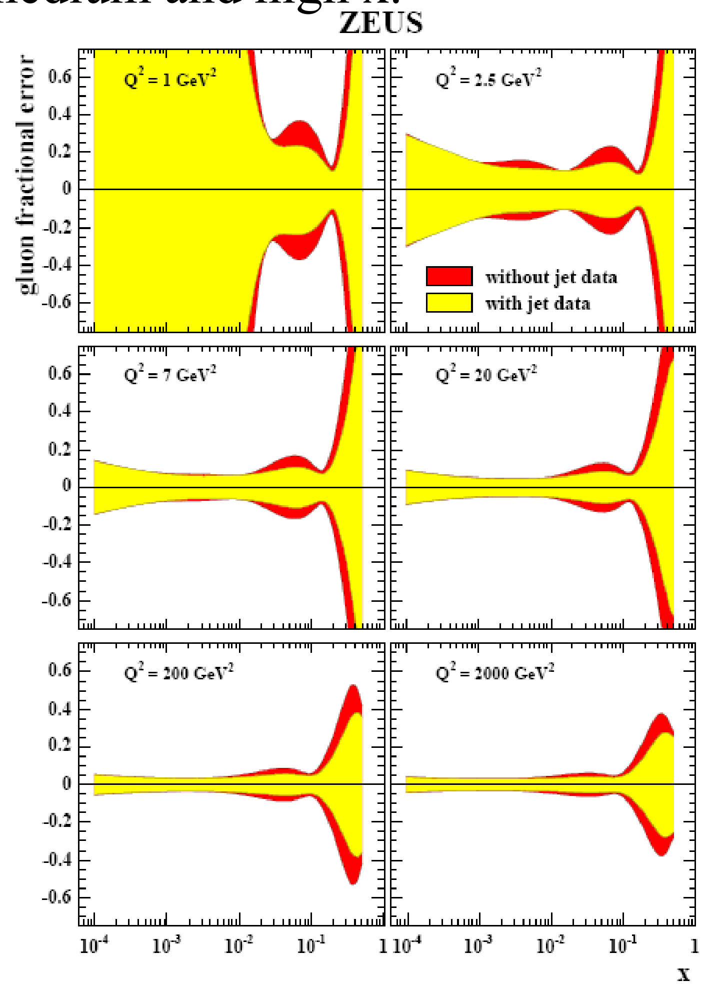


Using jet data in PDF determinations

- $\alpha_s(m_Z) = 0.1183 \pm 0.0028$ (exp.) ± 0.0008 (mod.) ± 0.005 (scale).
- Resulting PDFs:

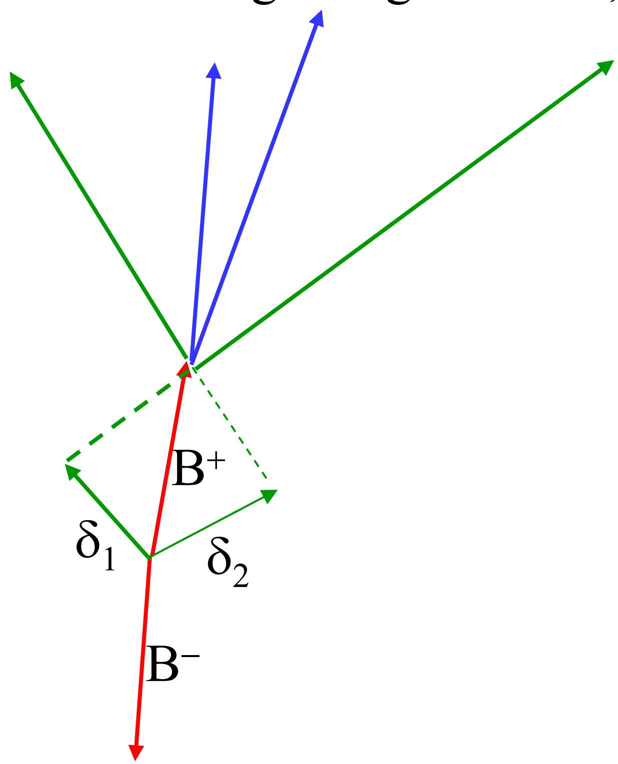


- Improved precision for gluon at medium and high x.

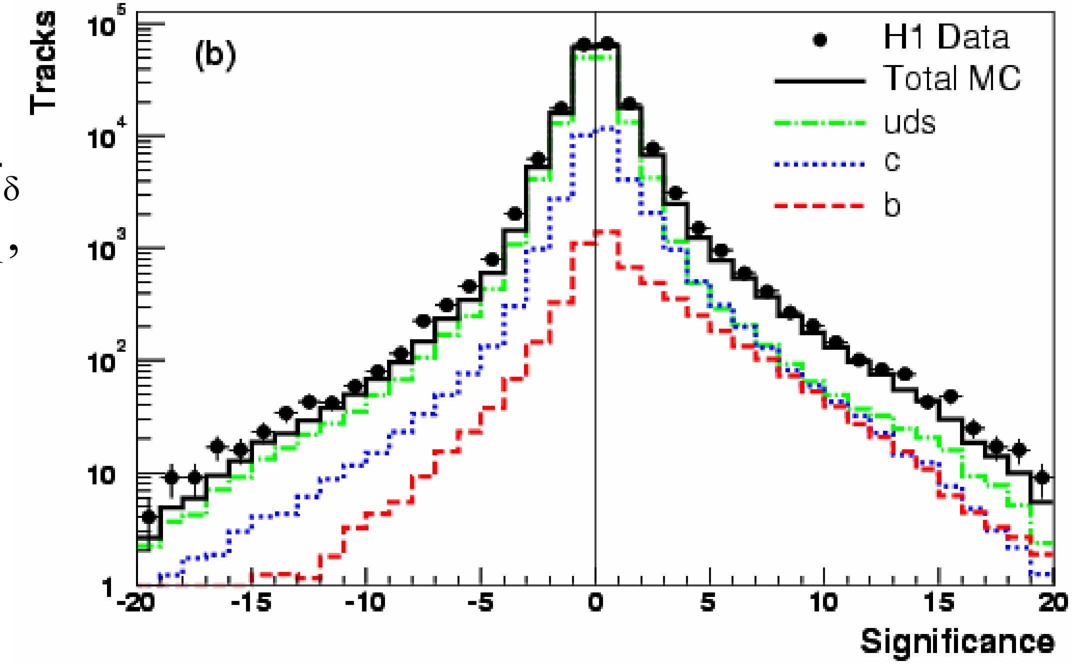


Charm and beauty in the proton

- Charm and beauty identified using H1 central silicon tracker to measure impact parameter δ and its error σ_δ.
- Flavour discrimination using $S = \delta/\sigma_\delta$ of tracks with largest significance, S_1, S_2...

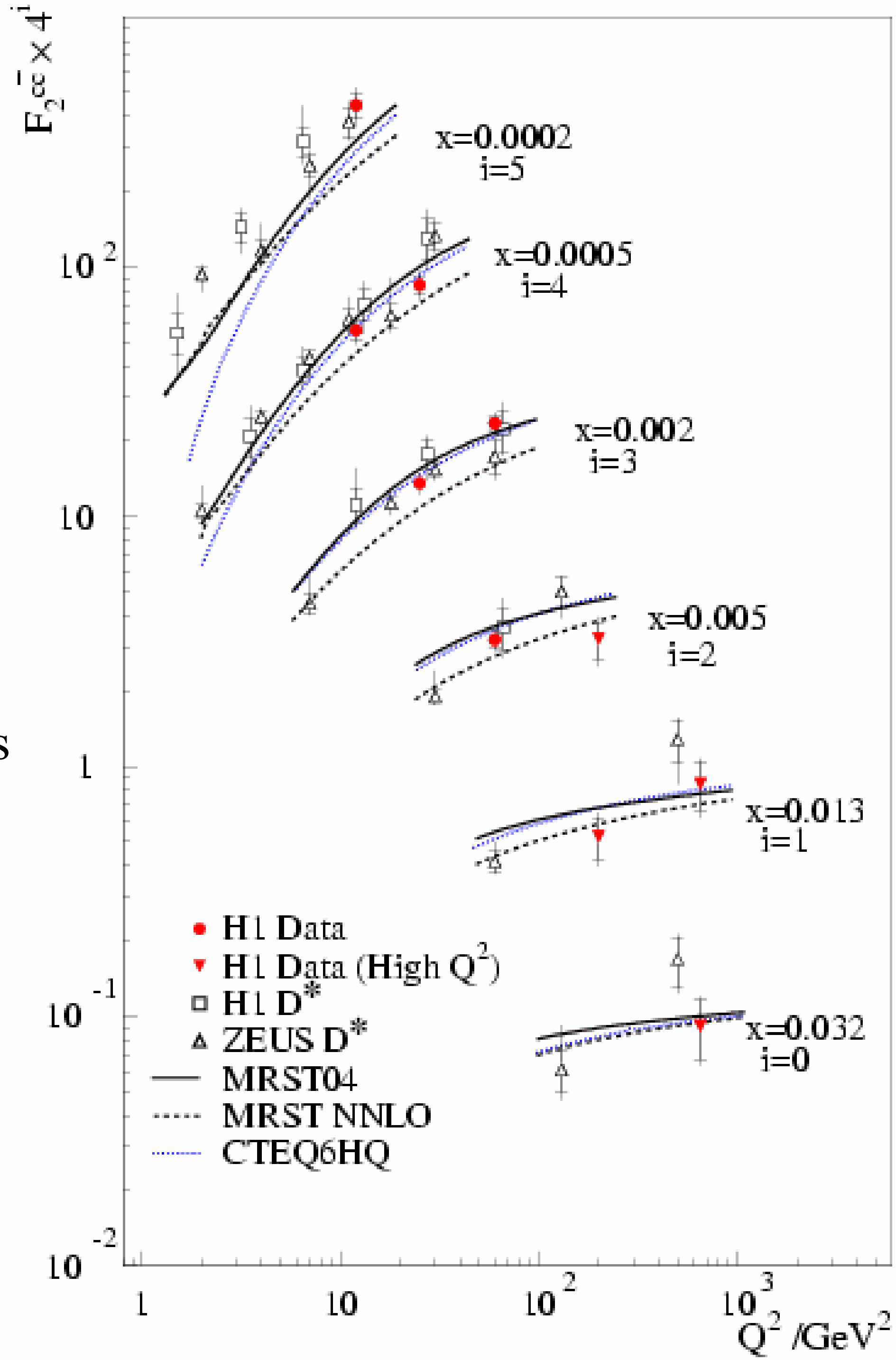


- Significance S_1.



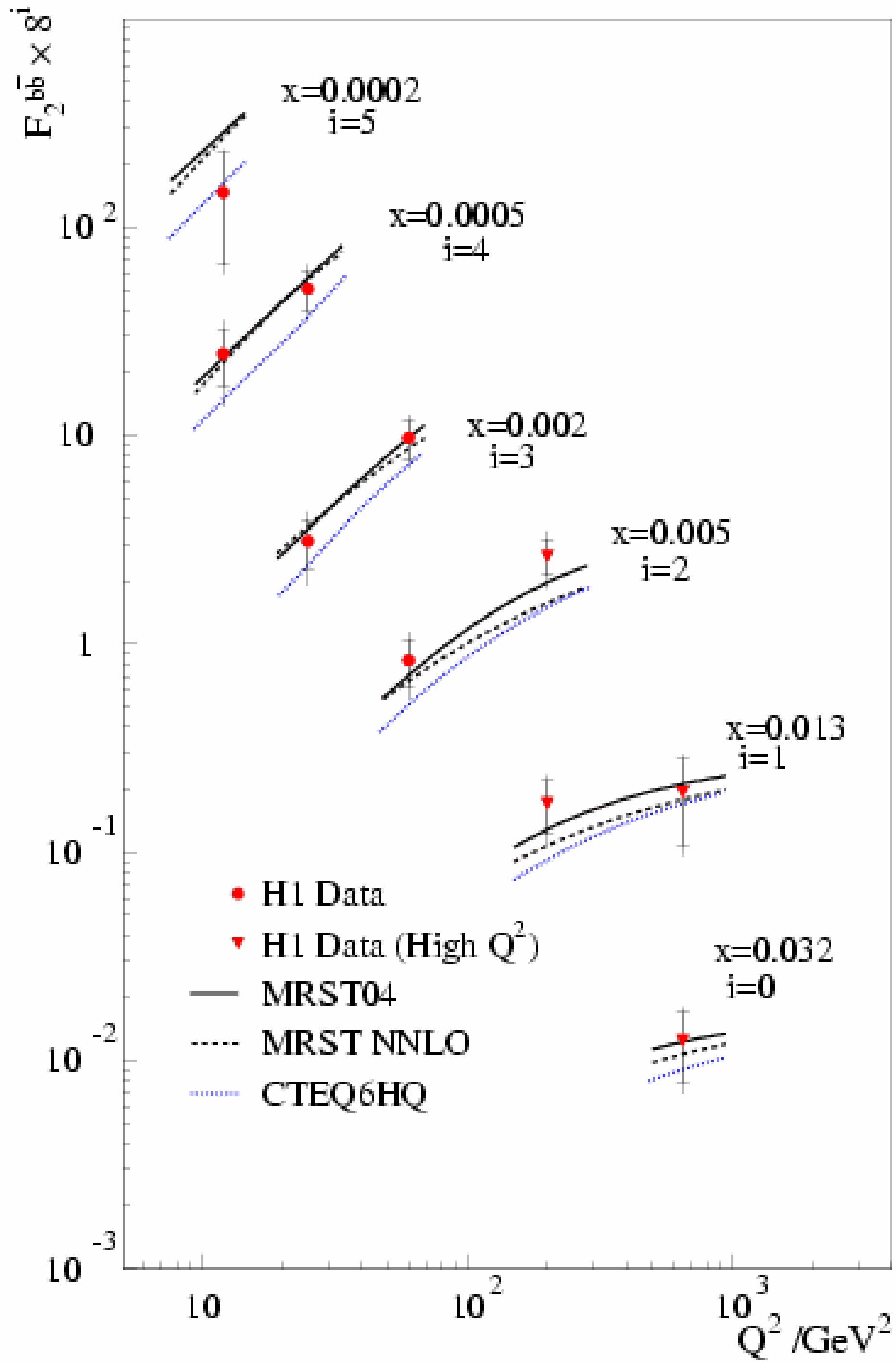
Charm in proton

- Proportion of c events determined as function of x and Q^2, ~ 24% decreasing slightly with x.
- Hence extract $F_2^{c\bar{c}}$.
- Good agreement between “lifetime” and “D* based” measurements.
- Positive scaling violations increase as x decreases.
- Well described by higher order QCD calculations.



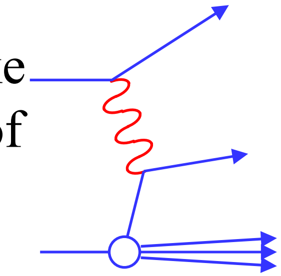
Beauty in proton

- Proportion of b events found to be 0.3 to 3%, inc. with Q^2.
- Hence obtain first ever measurements of $F_2^{b\bar{b}}$.
- Well described by higher order QCD calculations.
- Of interest to LHC, e.g. $b\bar{b} \to H$.
- $b\bar{b}$ contributes ~ 5% to $pp \to ZX$.
- Need better than 20% accuracy on b distribution for 1% Z cross sections at the LHC.

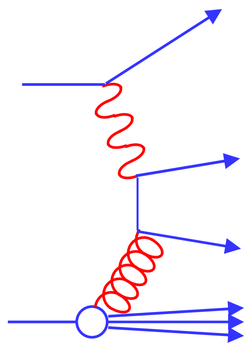


Two scale problems in QCD and b production

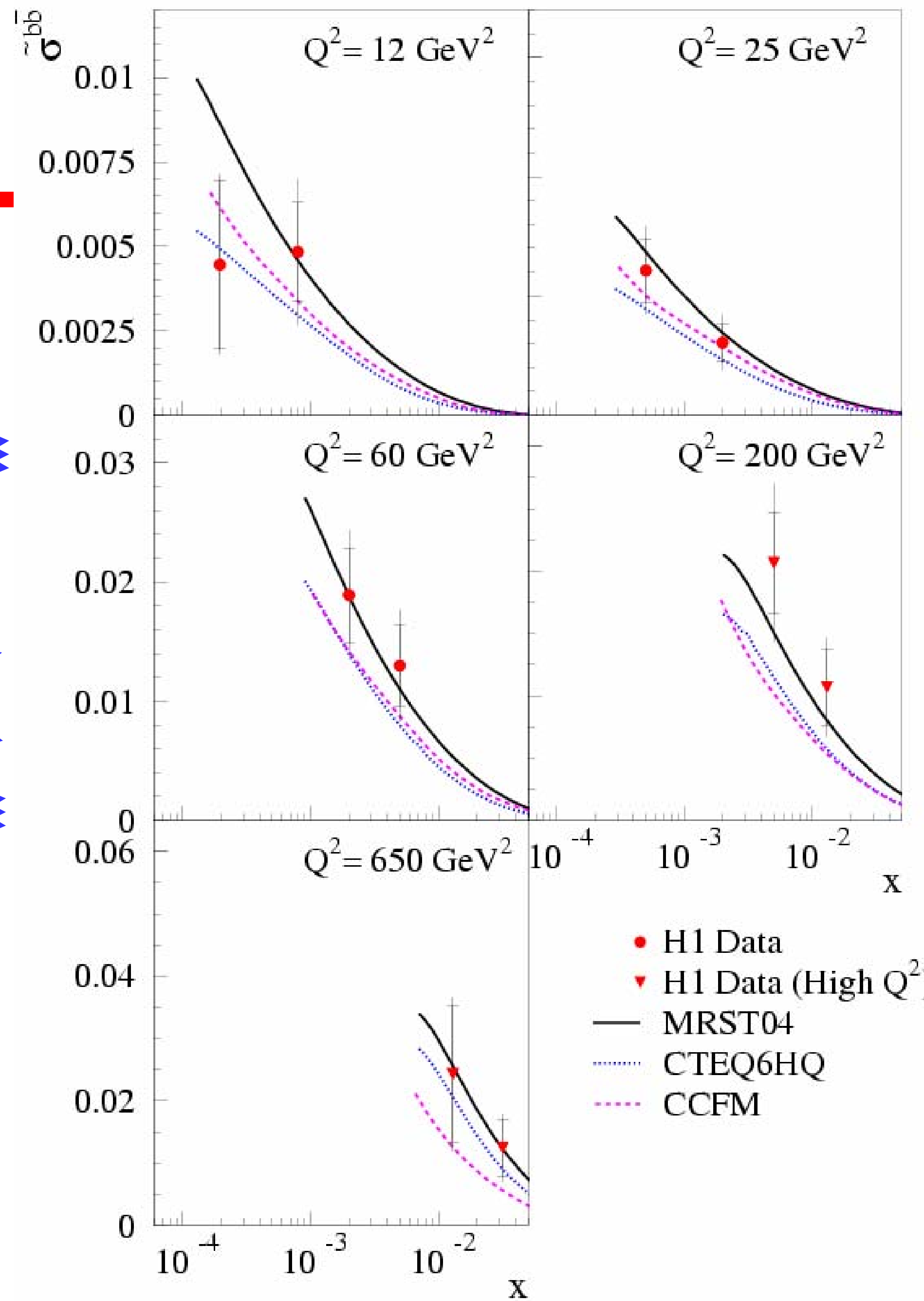
- For $Q^2 >> m_Q^2$, treat Q like uds, i.e. part of structure of proton.



- If $Q^2 \sim m_Q^2$, to LO Q produced via boson gluon fusion.

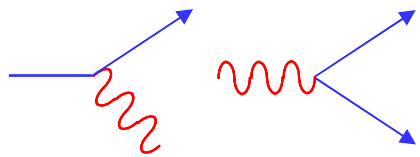


- Careful matching needed to cover entire Q^2 range, "variable flavour number scheme" (ACOT, MRST).
- MRST04 and CTEQ6HQ VFNS, CCFM "massive" calculation.
- More HERA data needed here!



Contribution of photon to proton structure

- Include photons in evolution.



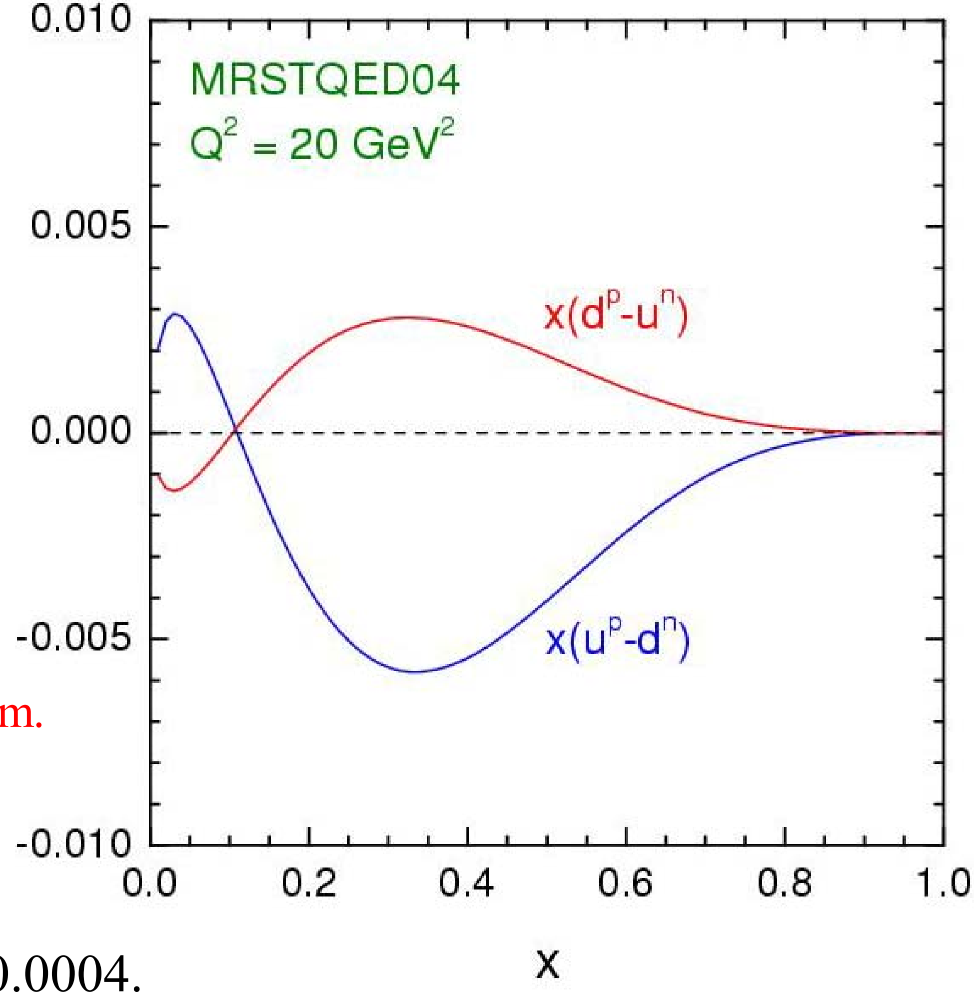
- u quarks radiate more than d, so fewer u quarks in proton at high x than d quarks in neutron.
- Isospin asymmetry: $d^p \neq u^n$, $u^p \neq d^n$.
- Effect is small, but influences NuTeV determination of $\sin^2\theta_W$:

$$\frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \frac{1}{2} - \sin^2\theta_W + \text{isospin viol. term.}$$

- $\sin^2\theta_W = 0.2277 \pm 0.0013 \pm 0.0009$

  ~ -0.002

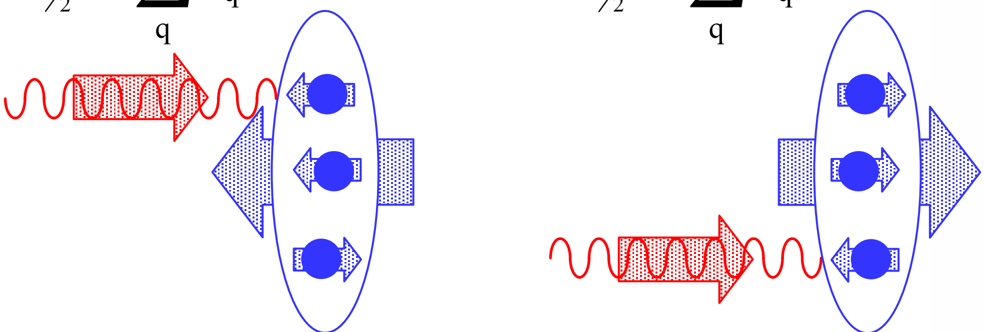
- C.f. world average $\sin^2\theta_W = 0.2227 \pm 0.0004$.



Spin structure measurements

- $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$
- Meas. with pol. target and pol. beam.

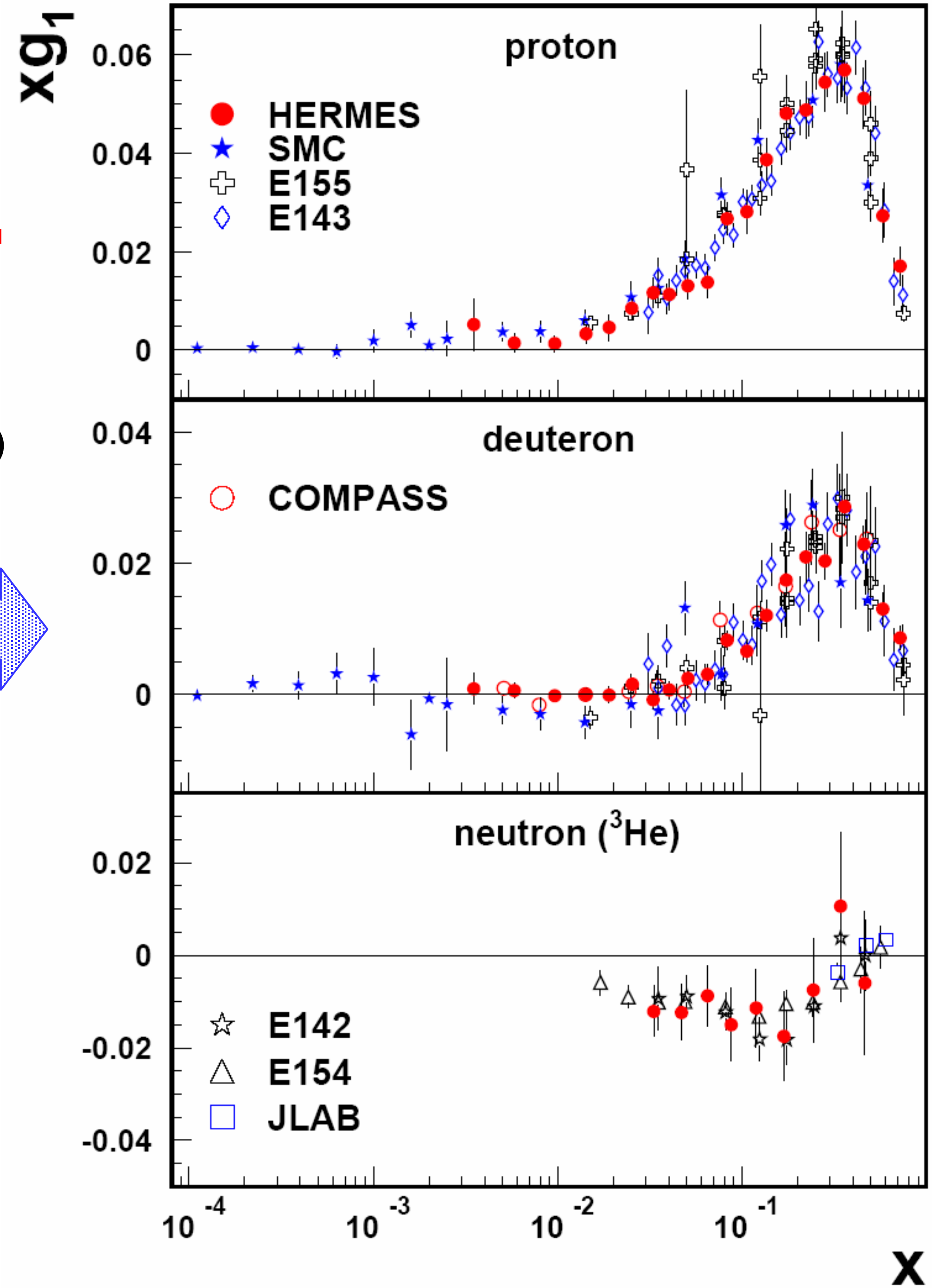
$$\sigma_{1/2} \sim \sum_q e_q^{\,2} q^{+}(x) \qquad \sigma_{3/2} \sim \sum_q e_q^{\,2} q^{-}(x)$$



- $A = \left(\sigma_{1/2} - \sigma_{3/2}\right) / \left(\sigma_{1/2} + \sigma_{3/2}\right)$

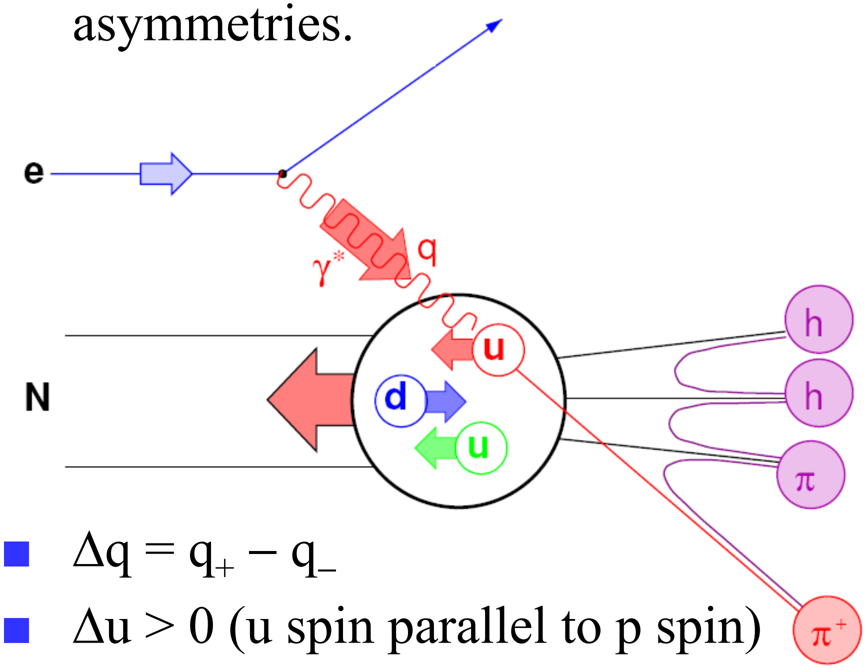
$$\sim \frac{\sum e_q^{\,2}(q_+ - q_-)}{\sum e_q^{\,2}(q_+ + q_-)} \sim \frac{g_1(x)}{F_1(x)}$$

- New data from COMPASS.
- $\Delta\Sigma = 0.202^{+0.042}_{-0.077} \rightarrow 0.237^{+0.024}_{-0.029}$

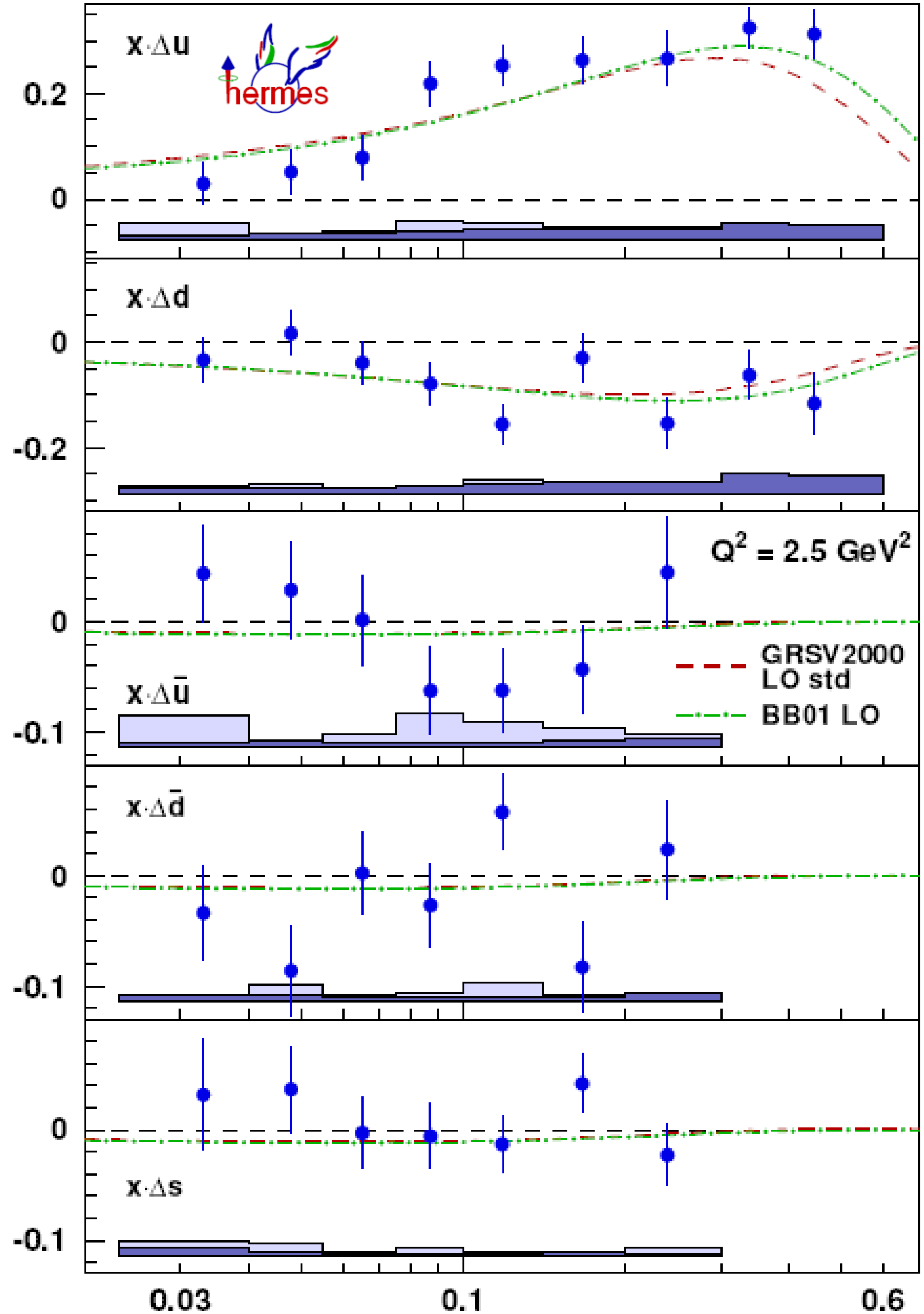


Spin structure measurements

- Extract contributions of different flavours by measuring semi-inclusive asymmetries.

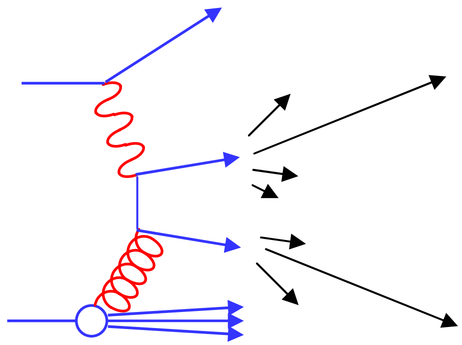


- $\Delta q = q_+ - q_-$
- $\Delta u > 0$ (u spin parallel to p spin)
- $\Delta d < 0$ (d spin anti-parallel to p spin)
- $\Delta\bar{u}$, $\Delta\bar{d}$ and $\Delta\bar{s}$ all ~ 0.

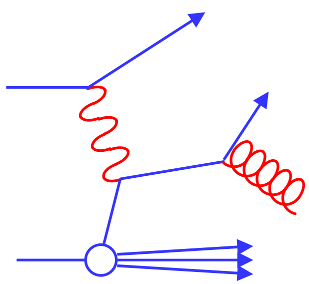


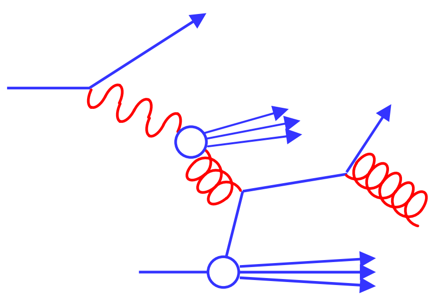
Spin structure measurements

- Probe gluon spin using photon gluon fusion

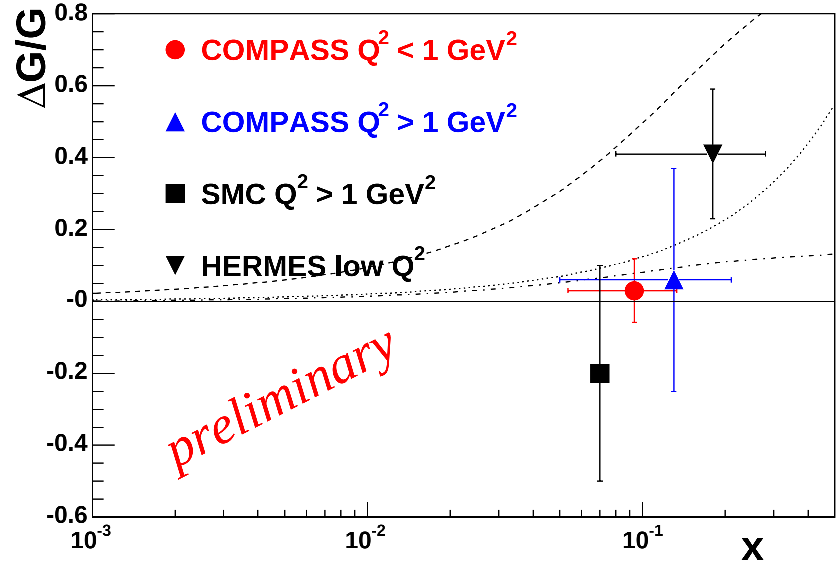


- Demand two high p_T hadrons in final state.
- Background from QCDC and resolved photon events (at low Q^2).





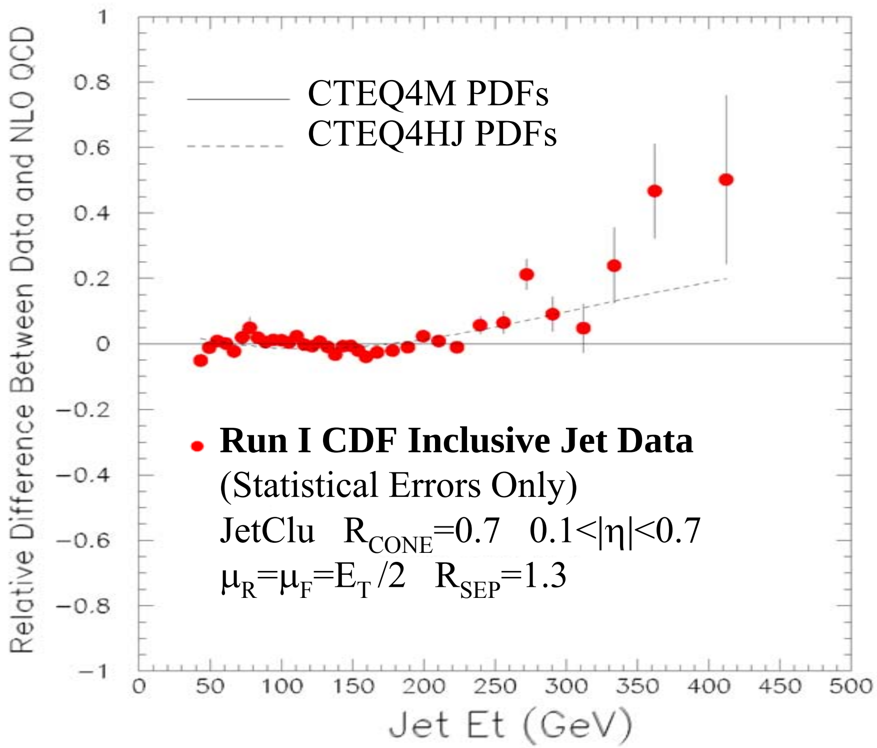
- $A - A_{BG} \sim \Delta G/G$
- Resulting measurements



- $$\frac{\Delta G}{G} = 0.024 \pm 0.089 \pm 0.057$$
- $\Delta G = \int \Delta G(x)\,dx = 0.2,\ 0.6,\ 2.5$ using GRSV min. standard and max. curves.

Jets at the TeVatron

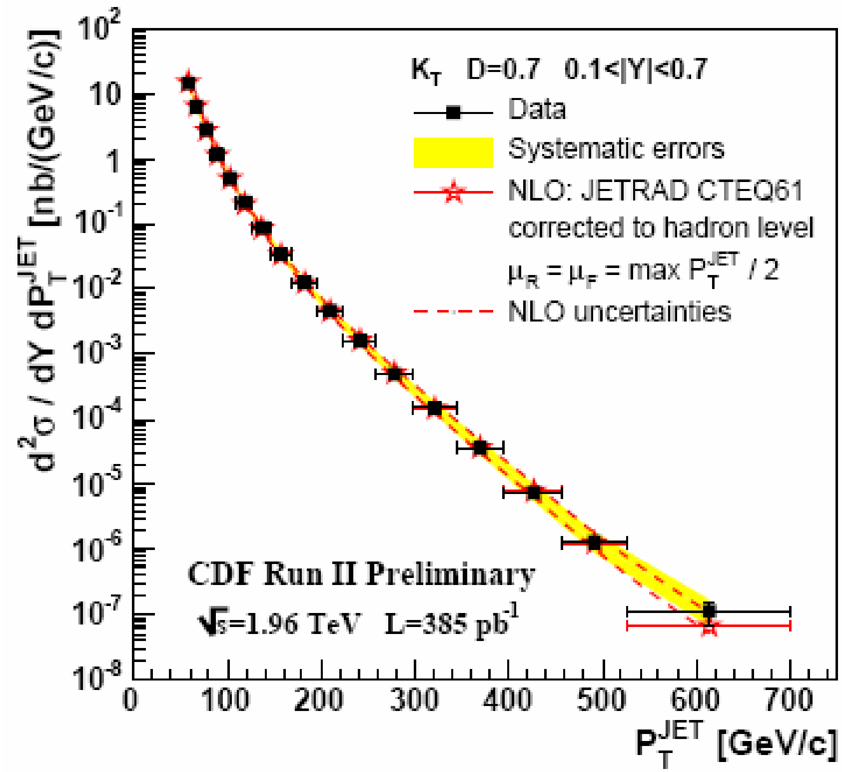
- TeVatron jets test of pQCD over ~ 8 orders of magnitude in E_T.
- Probe distances down to ~ 10^{-19} m.
- Excitement when excess observed in Run I jet data.

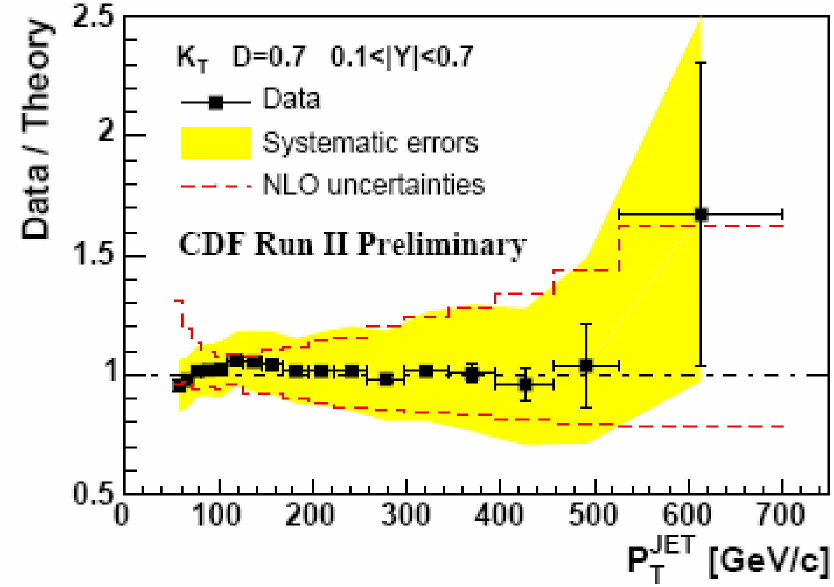


- Can be explained by increasing gluon distribution at large x.
- Various problems addressed in Run II jet analyses:
  - JetClu algorithm not IR or collinear safe.
  - "Fudge factor" R_{sep} introduced to mimic effects of jet algorithm in calculations.
- Move to using "safe" inclusive k_T and midpoint algorithms.

Jets at the TeVatron

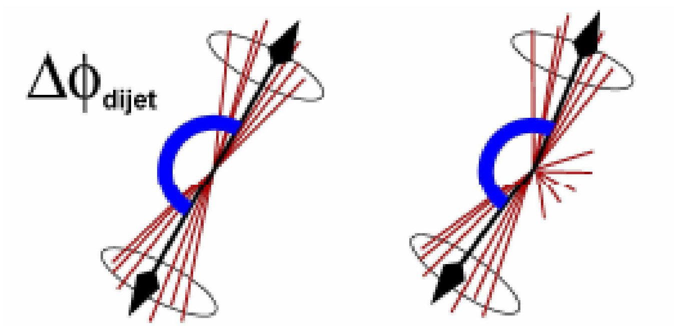
- At Run II, reach in p_T extended by ~ 150 GeV compared to Run I.
- Experimental uncertainty dominated by energy scale (luminosity uncertainty of 6% not shown on plots).
- NLO QCD corrected to hadron level using Pythia tune A (~ 20% decreasing to ~ 0% with p_T).
- Theoretical error dominated by uncertainty in gluon at large x.
- Caution: Moretti, Nolton and Ross recently determined weak corrections to the theory: ~ – 30% at the highest jet E_T and ~ –12% at p_T = 450 GeV, consequences not yet fully explored.





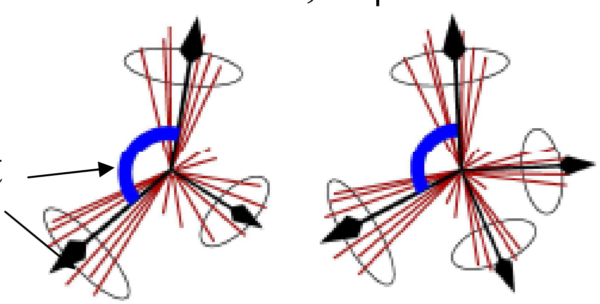
Dijet azimuthal separation at the TeVatron

- Two jets back to back in ϕ if only little additional soft radiation.

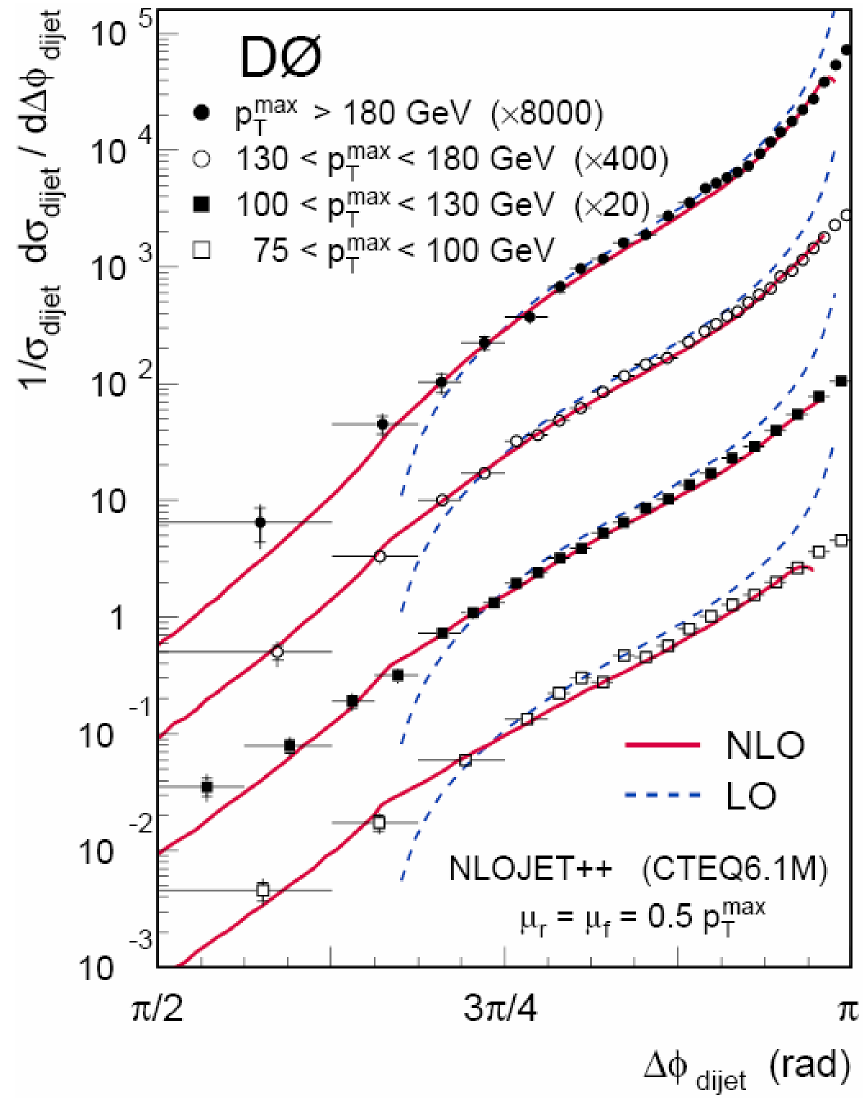


- If hard radiation, $\Delta\phi$ can be large.

Highest E_T jets



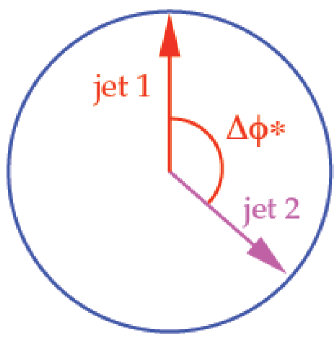
- $\Delta\phi < 2\pi/3$, four jet region.
- Small and large $\Delta\phi$ regions poorly described by LO calc, NLO better.



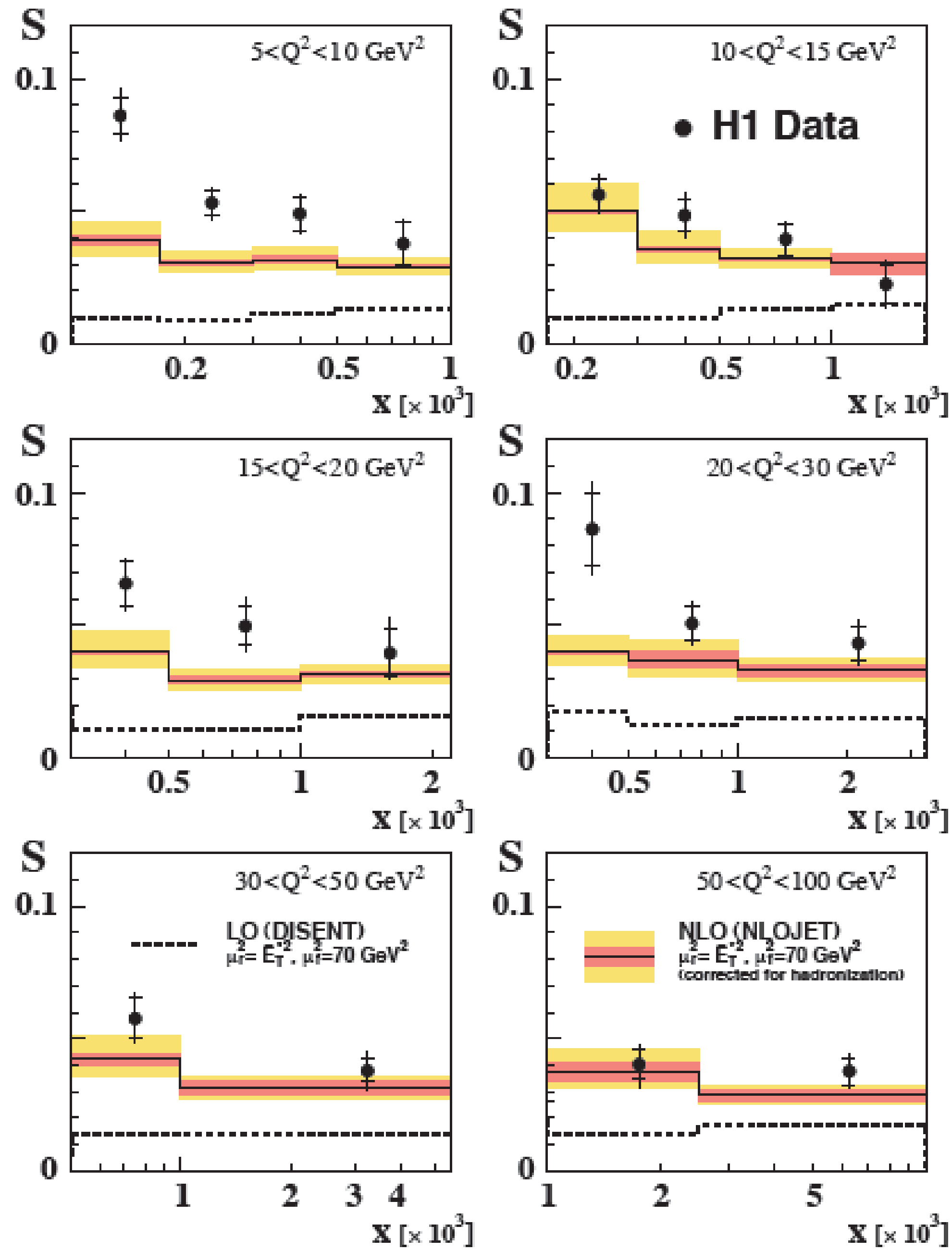
Dijet azimuthal separation at HERA

- Study frac. of dijets with $\Delta\phi^* < 2\pi/3$.

$$S = \frac{\int_0^{2\pi/3} N_{\mathrm{dijet}}(\Delta\phi^*)\, d\Delta\phi^*}{\int_0^{\pi} N_{\mathrm{dijet}}(\Delta\phi^*)\, d\Delta\phi^*}$$

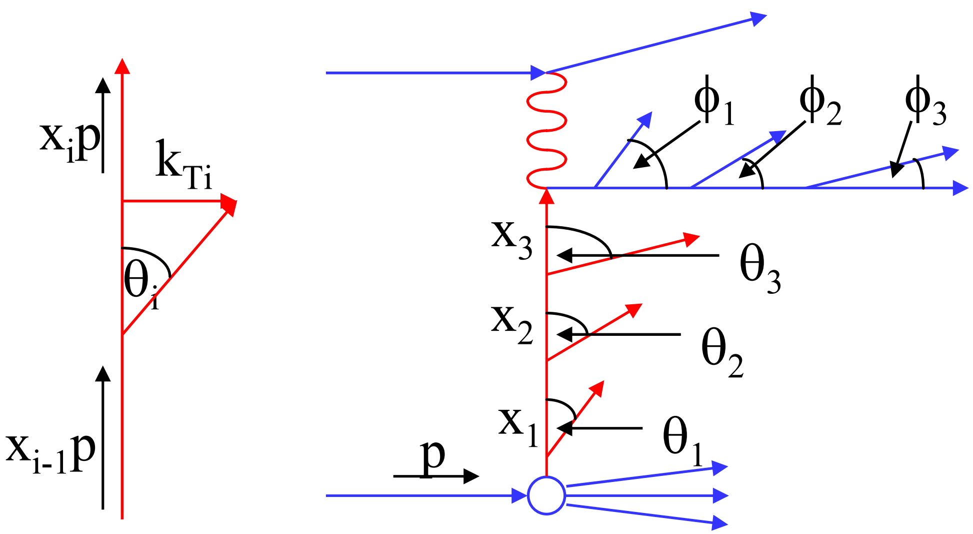


- LO calc [$O(\alpha_s)$], at most 2 jets, fails to describe data.
- NLO calc [$O(\alpha_s^3)$], up to 4 jets, OK at high x, Q^2, but fails at low x and Q^2!



Evolution schemes

- Look again at multiple parton emissions in evolution of p structure.



- QCD interference effects give rise to angular ordering of partons.
- DGLAP approximation, large Q^2: $\theta_1 < \theta_2 < \theta_3 \cdots$

$$\rightarrow k_{T1} < k_{T2} < k_{T3} \cdots$$

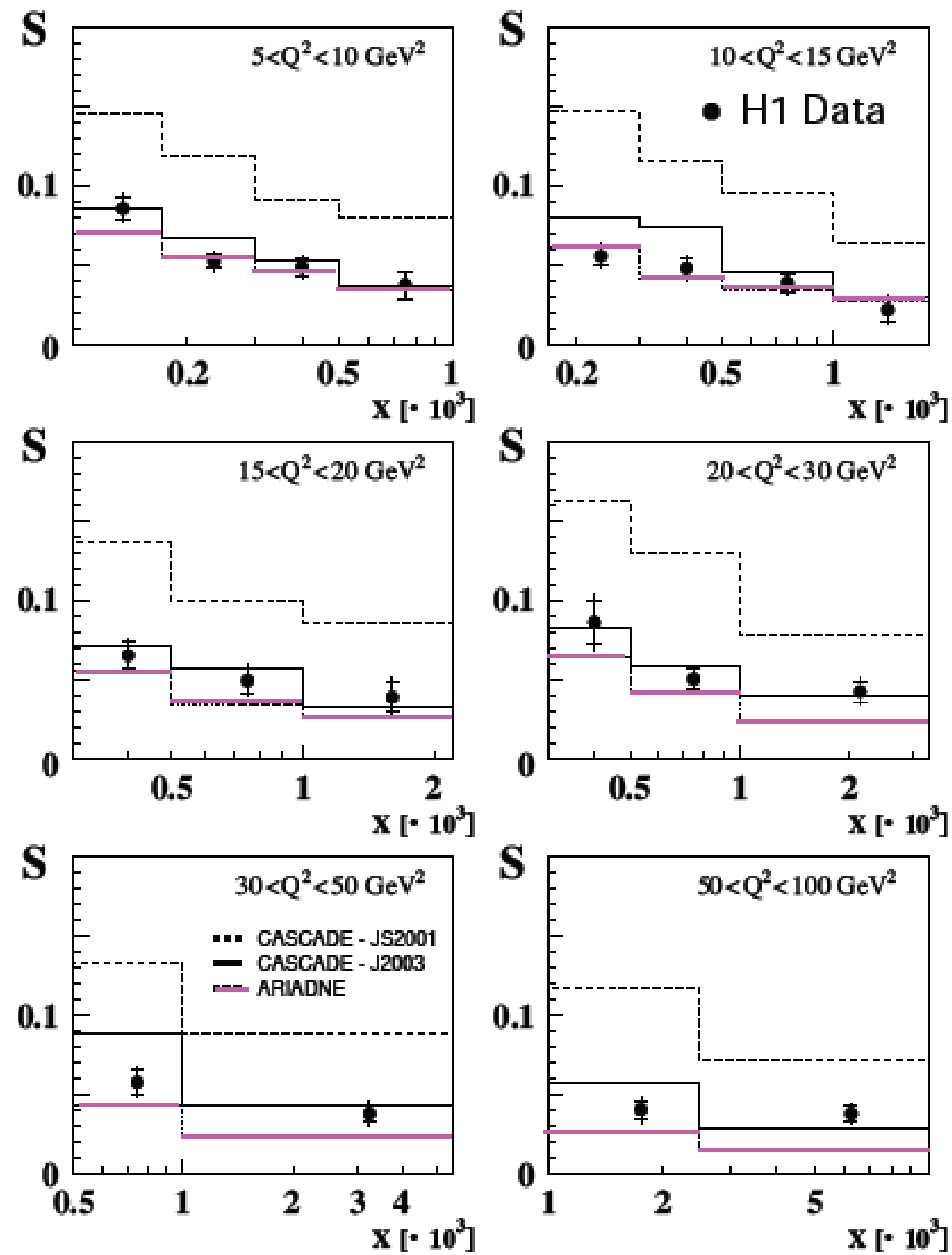
- In small x regime inappropriate: ignores terms ~ ln(1/x).
- BFKL evolution equation, small x: $\theta_1 < \theta_2 < \theta_3 \cdots$

$$\rightarrow x_1 > x_2 > x_3 \cdots$$

k_T not ordered, sums ln(1/x) terms.
- CCFM equation implements angular ordering, applicable at all x and Q^2.
- Do multiple emissions give measured separation at low x and Q^2?
- Check using CASCADE Monte Carlo, based on CCFM equations.

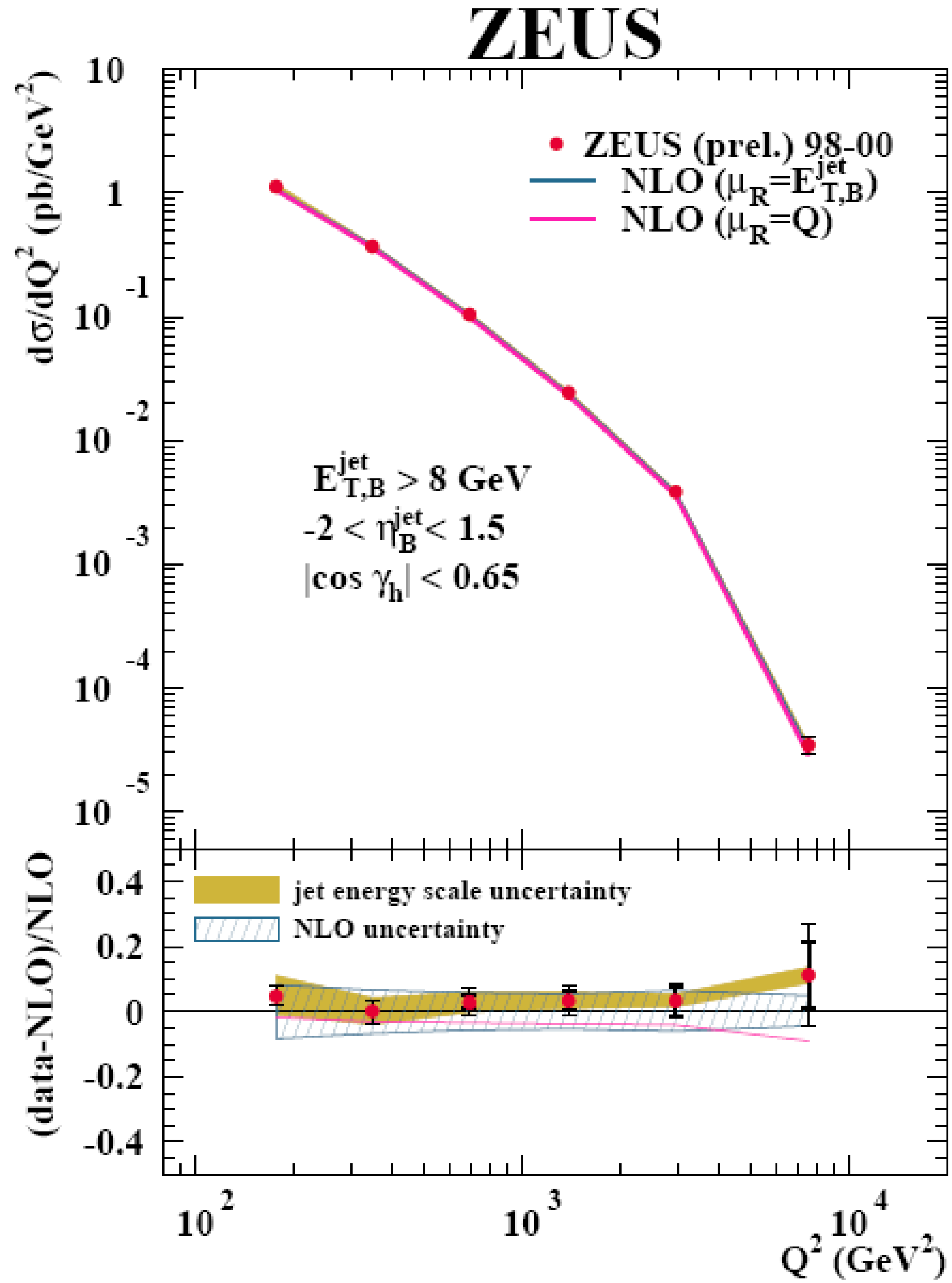
Jet separation and CCFM evolution

- CASCADE describes data well, using unintegrated PDF.
- J2003 inc. full splitting function much better than JS2001 (singular terms only).
- ARIADNE (k_T not ordered) also describes data in low x and Q^2 regime, but fails at high x and Q^2.



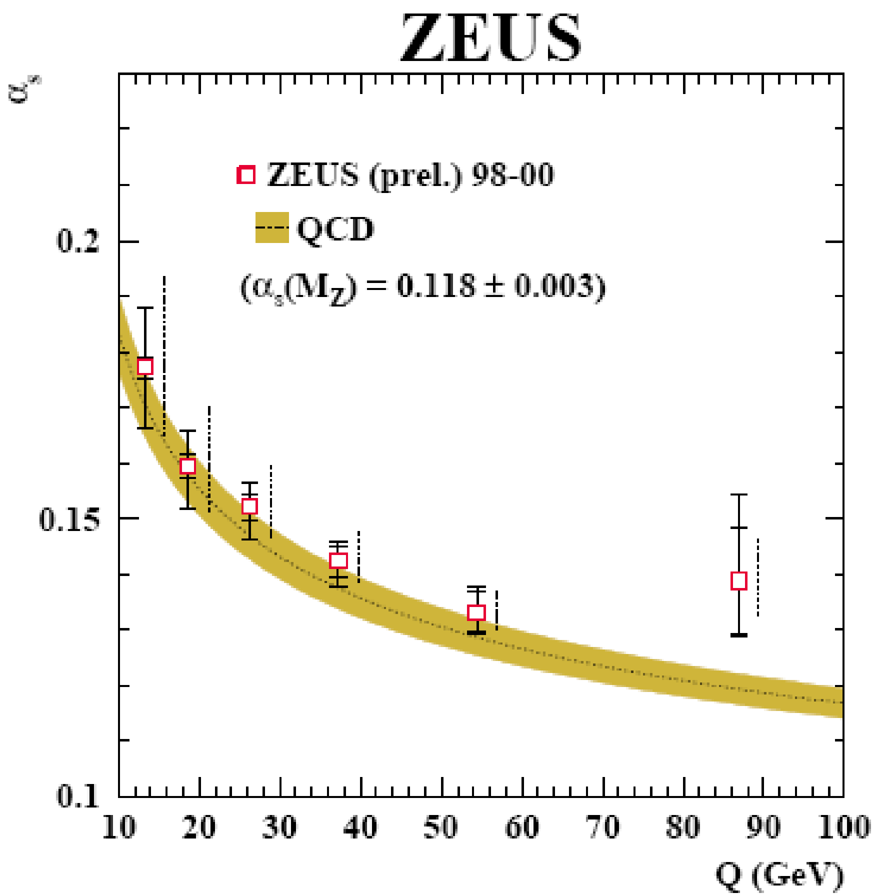
Jet production and α_s measurements

- Complementary measurements of α_s to inclusive fits possible using jets.
- Use longitudinally invariant k_T jet algorithm in the Breit Frame:
  - Iterative clustering
    $$d_{i,j} = \min(E_{T,i}{}^2, E_{T,j}{}^2) \times \left((\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \right)$$
  - Gives n jets with $d_{i,j} > R_0 = 1$.
  - Collinear and IR safe.
- Comparison with DISENT.



Jet production and α_s measurements

- α_s from inclusive jet cross section.



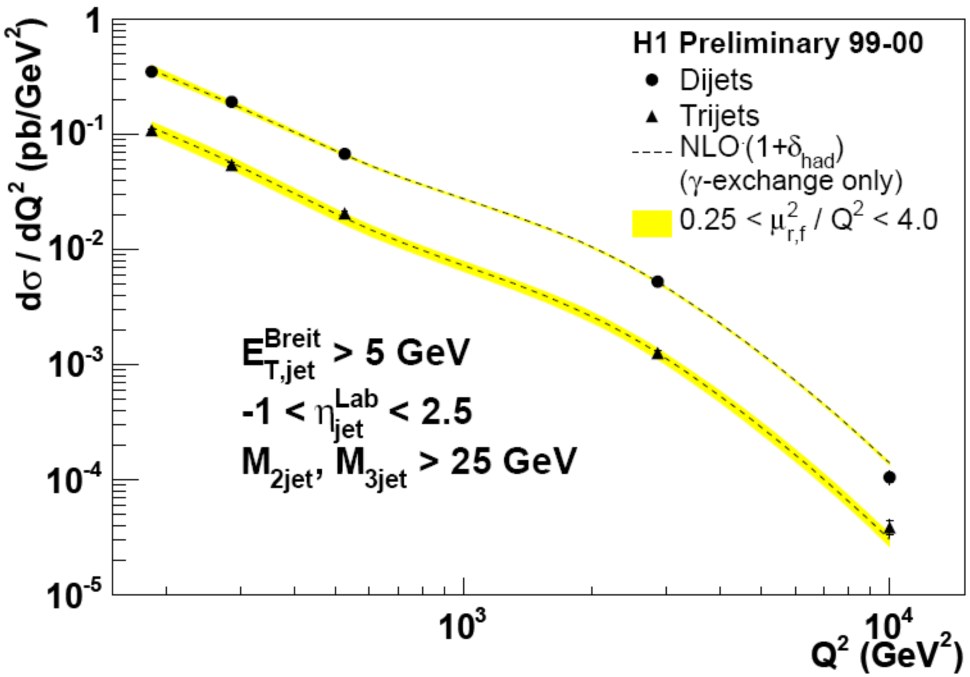
- $\alpha_s(m_Z) = 0.1196 \pm 0.0011(\text{stat})$

$$^{+0.0019}_{-0.0025}(\text{exp})\,^{+0.0029}_{-0.0017}(\text{theory})$$

- Dominant experimental systematic error hadronic energy scale.
- Theory error largely due to renormalisation and factorisation scale uncertainties.

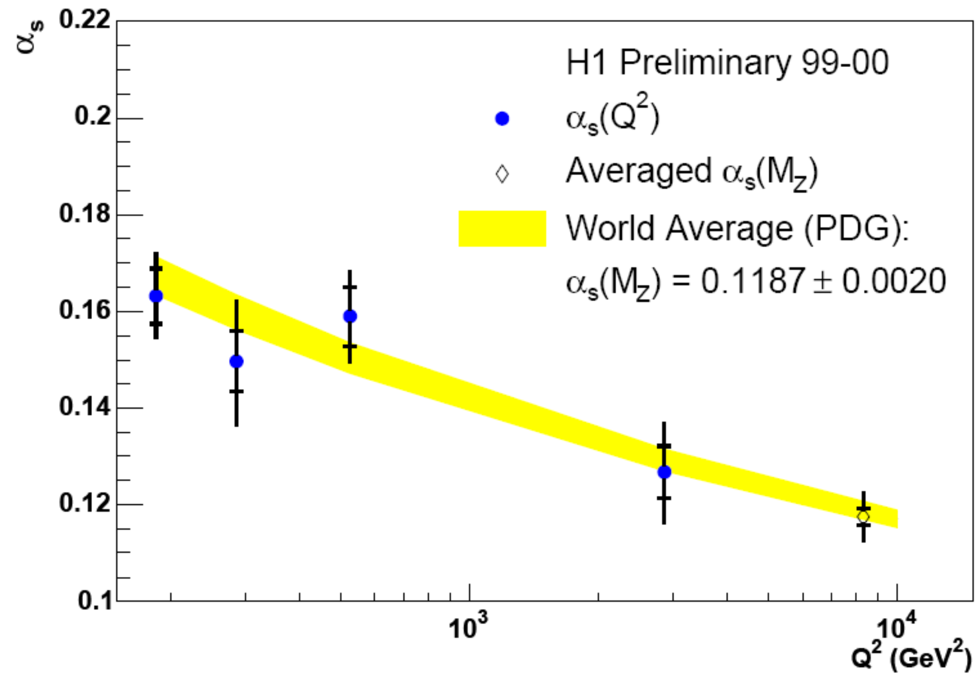
Jet production and α_s measurements

- Ratio of cross sections for 2 and 3 jet production also sensitive to α_s.



- Good agreement with NLOJET calculations (γ exchange) except where EW effects significant.

- Resulting α_s measurement:



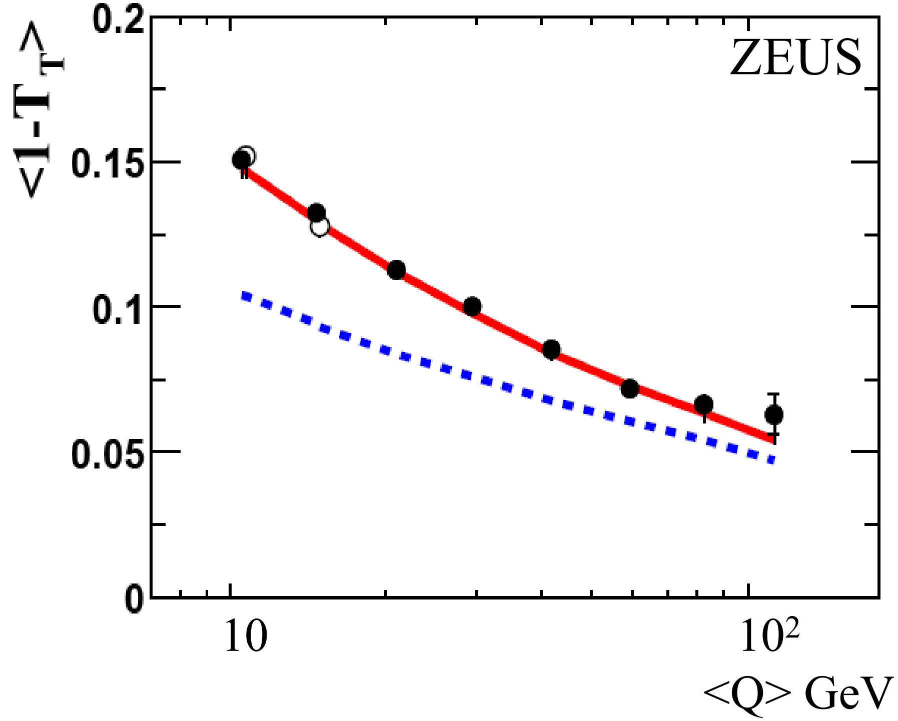
- $\alpha_s(m_Z) = 0.1175 \pm 0.0017(\text{stat.})$

$$\pm 0.0050(\text{exp.})\,{}^{+0.0054}_{-0.0068}(\text{th.})$$

Event shapes

- Study of event shapes allows tests of pQCD and ideas beyond pQCD.
- E.g. thrust, $T_T = \max_{\hat{n}} \left(\frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|} \right)$.
- Describe $\langle 1 - T_T \rangle$ using pQCD plus "power corrections" (Dokshitzer, Webber...) which decrease with 1/Q
  $\langle 1 - T_T \rangle = \langle 1 - T_T \rangle_{PC} + \langle 1 - T_T \rangle_{pQCD}$
- Introduces universal parameter $\bar{\alpha}_0$.
- Fit also T distributions; "pQCD" then re-summed NLL calculations matched to NLO (Dasgupta, Salam) as convergence of pert. series poor for small T.

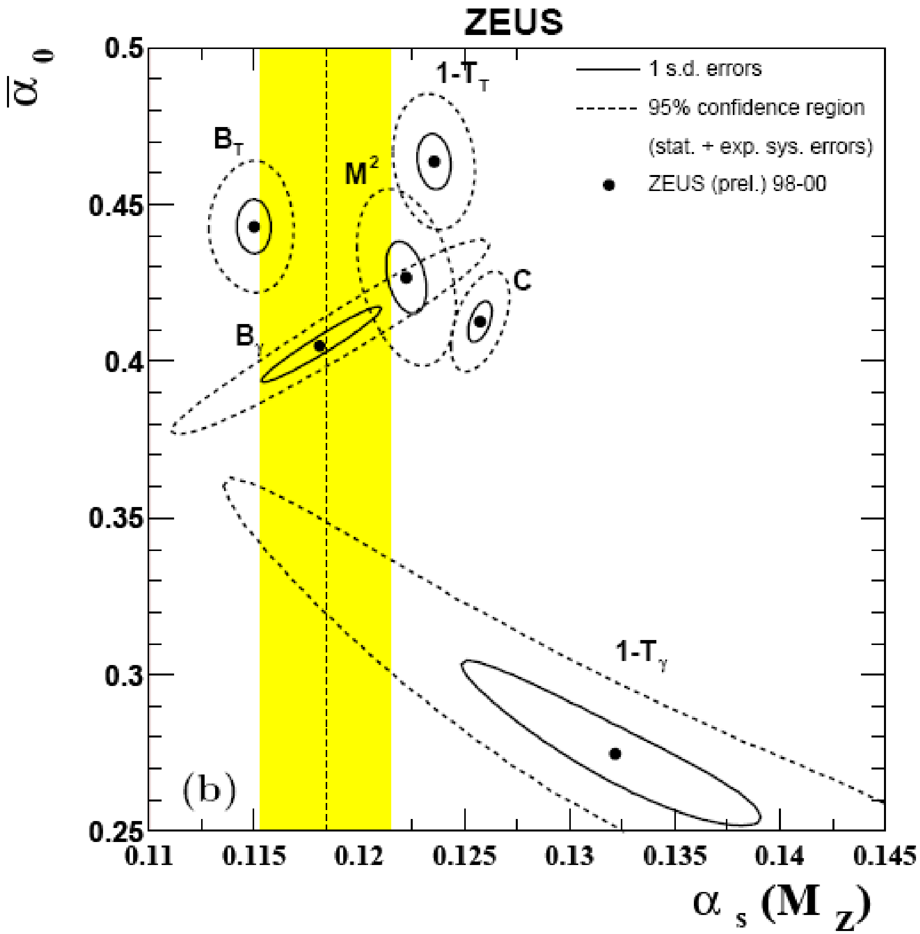
- Measurements in Breit Frame.



- Obtain values of $\bar{\alpha}_0$ and $\alpha_s(M_Z)$. from event shape means and distributions.

Event shapes

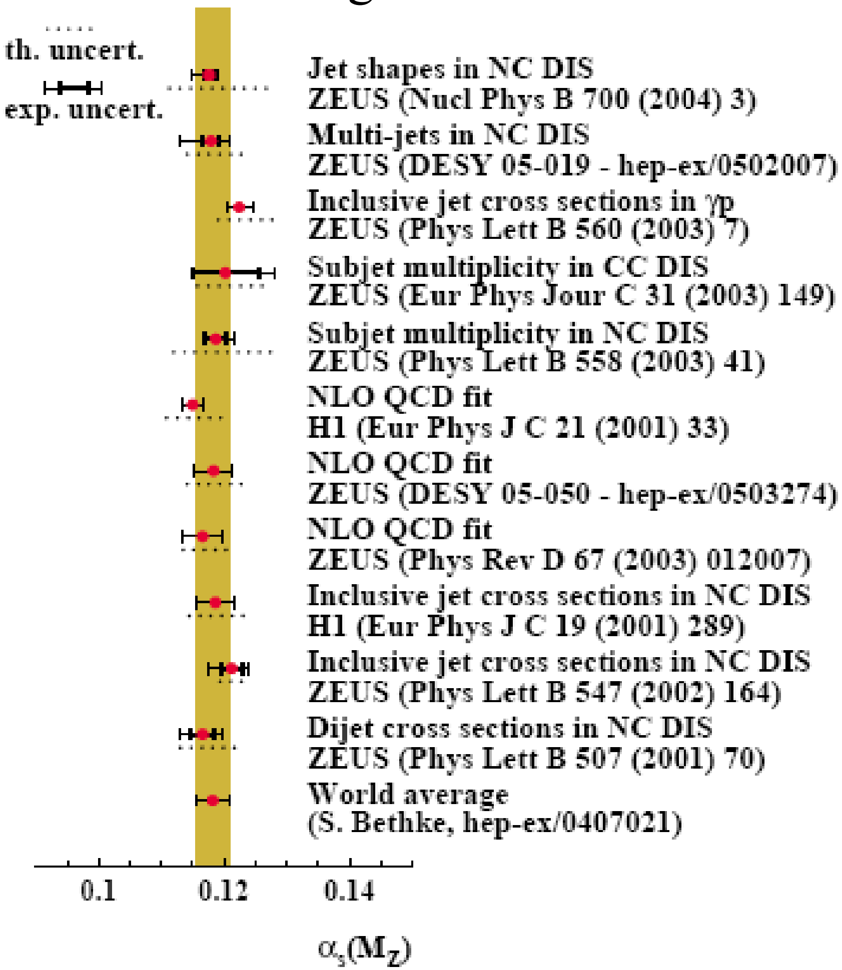
- From means:



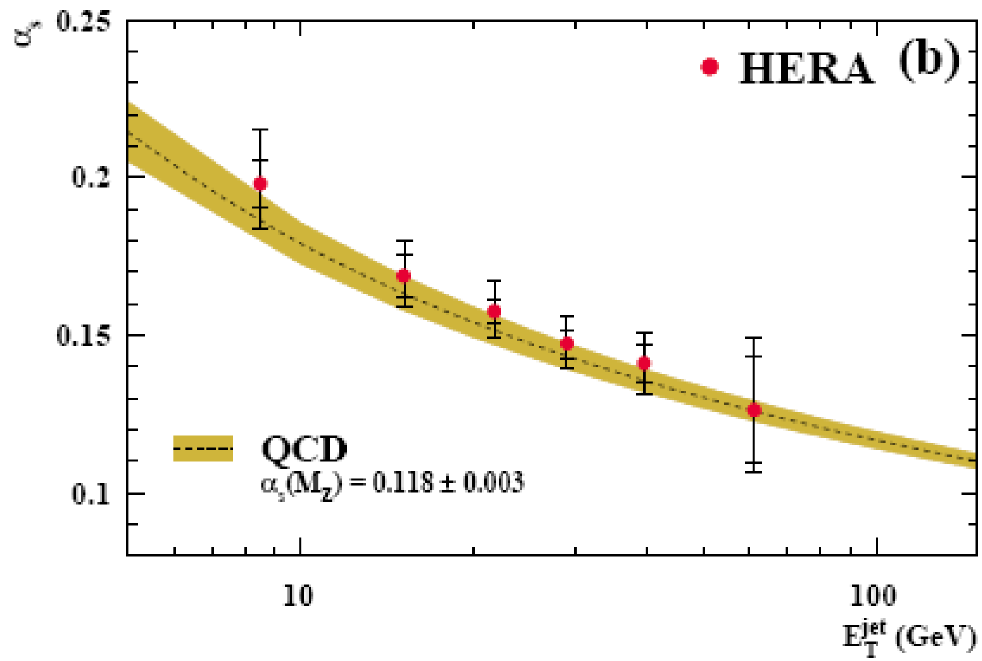
- Results from distributions qualitatively similar.
- $\bar{\alpha}_0 = 0.45 \pm 10\%$ for all variables except T_g and C.
- Values of $\alpha_s(m_Z)$ extracted from means consistent within 5%.
- $\alpha_s(m_Z)$ from distributions consistent with world average.
- Dispersion of $(\alpha_s(m_Z), \bar{\alpha}_0)$ values indicative of need for higher order calculations?

HERA α_s summary

- C.f. HERA α_s measurements and world average:



- α_s measurements from jets.

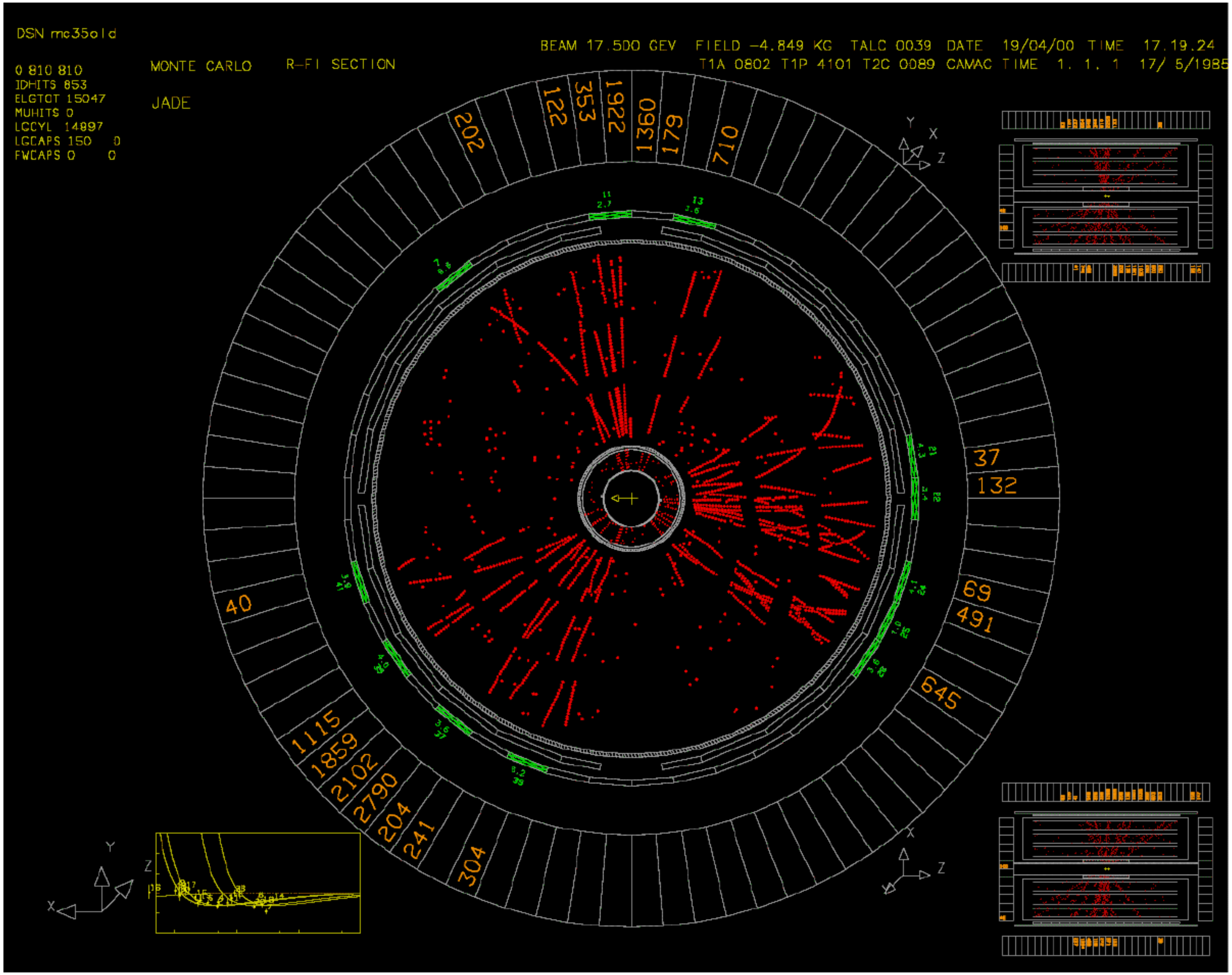


Glasman

- Preliminary HERA average:

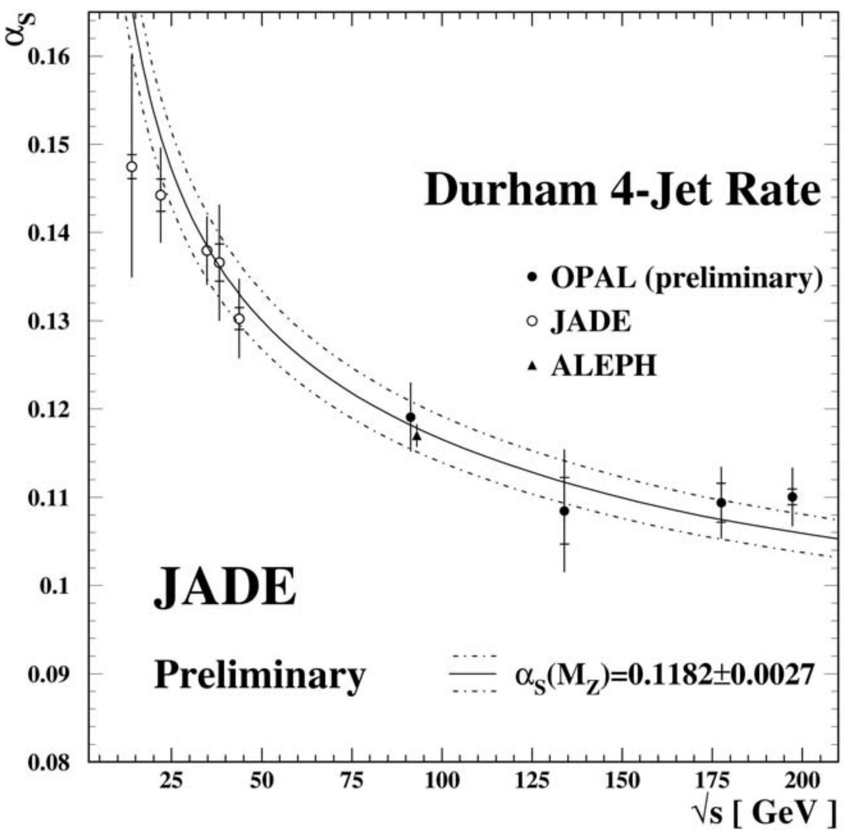
$$\alpha_s(m_Z^2) = 0.1186 \pm 0.0011(\text{exp.})$$
$$\pm 0.0050(\text{th.})$$

Back to PETRA where the gluon was discovered

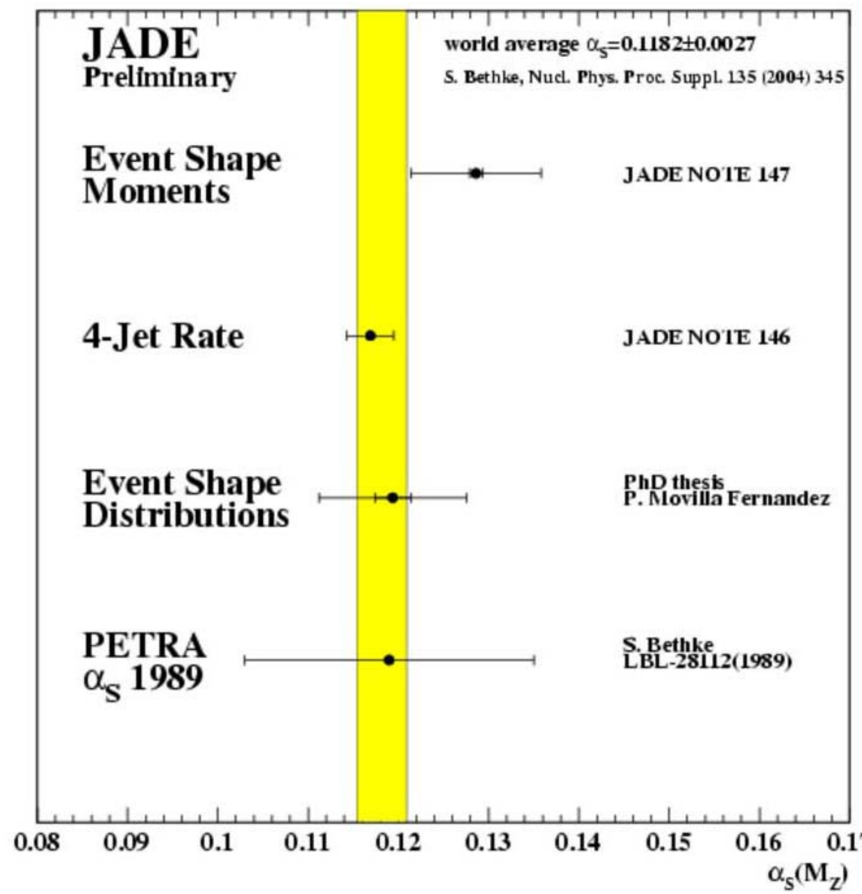


Reanalysis of JADE data

- Study 4 jet rate using modern Monte Carlos to make hadronisation and detector corrections, c.f. NLO + NLL calculations.

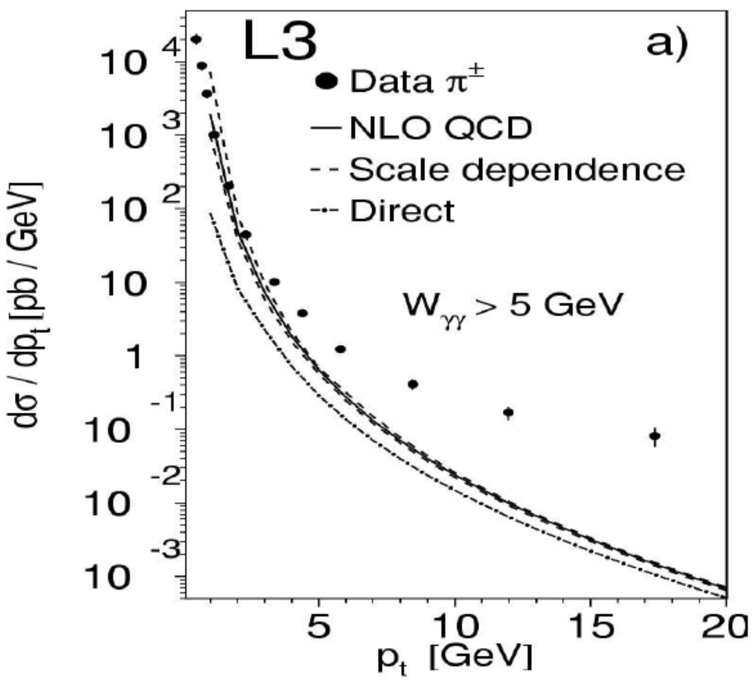


- Significant progress in determination of $\alpha_s(m_Z)$ in last ~15 years!

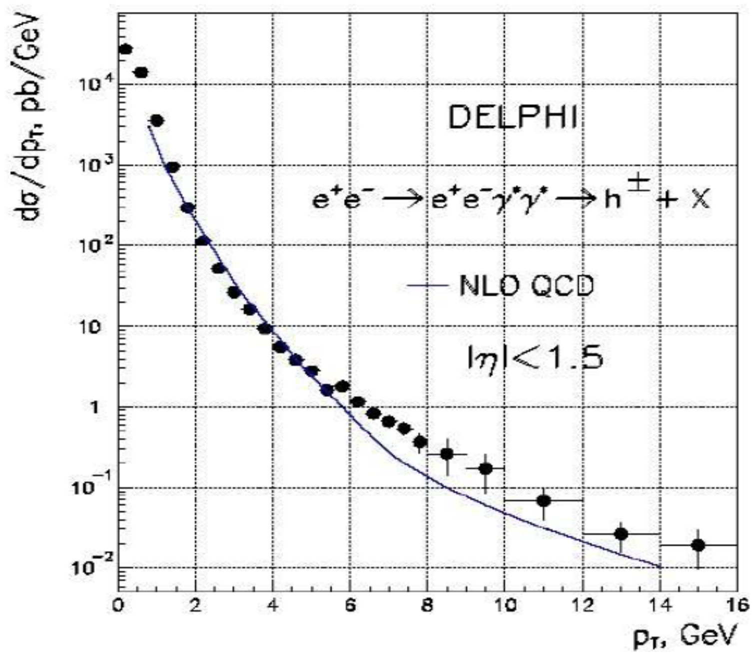


Hadron production in γγ collisions

- Large disagreement with NLO QCD observed by L3 in $\gamma^*\gamma^* \to hX$



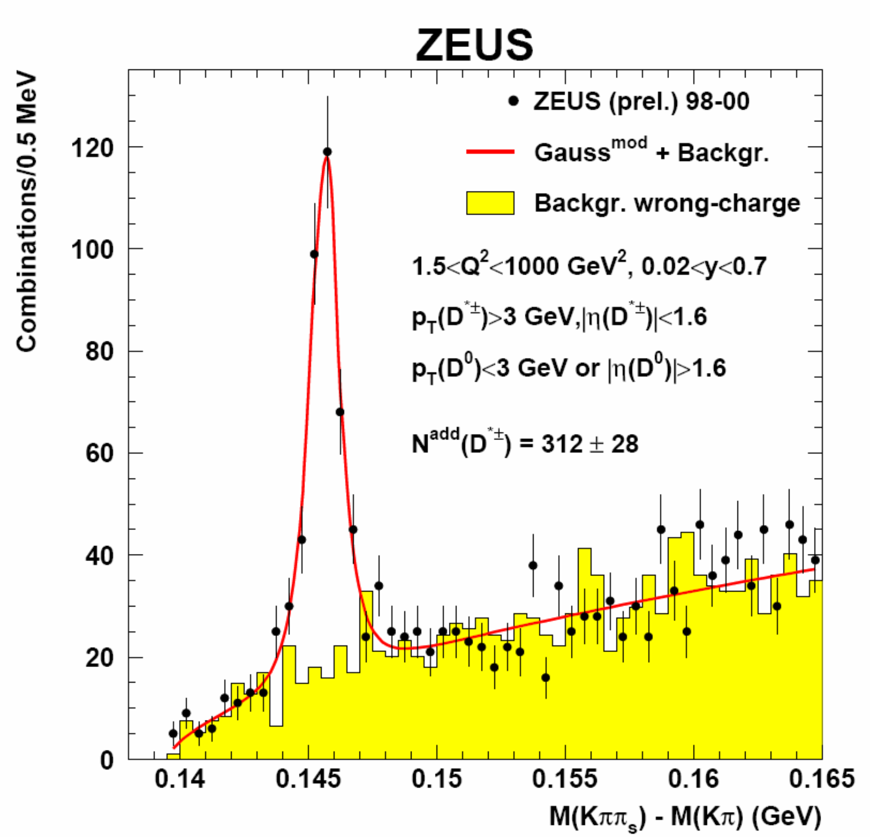
- New measurements by DELPHI show significantly better agreement.



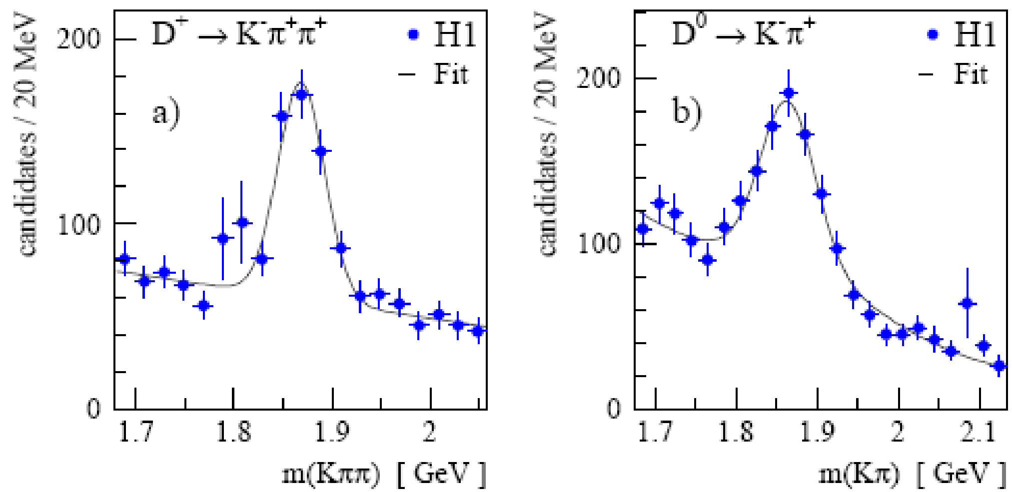
- DELPHI report using L3 cuts allows $e^+e^- \to q\bar{q}$ background into event sample at large p_T.

Charm fragmentation

- Inclusive cross sections for D*...



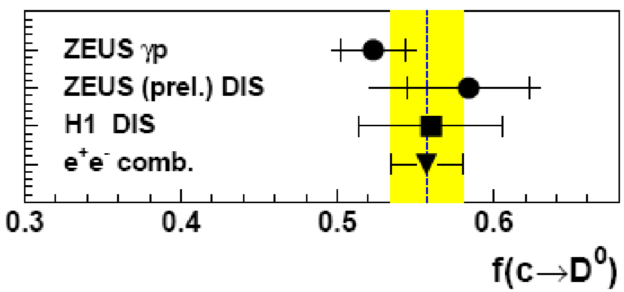
- ... D^+, D^0...

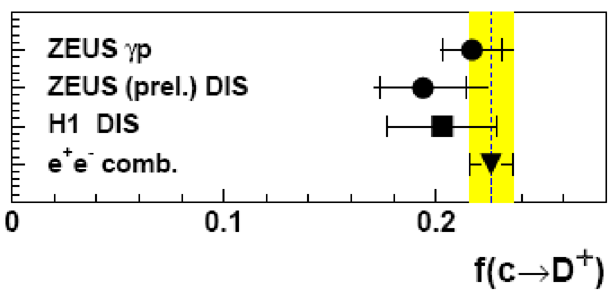


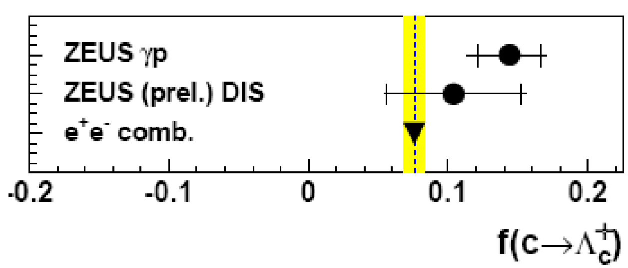
- ...D_s^+ and Λ_c measured by HERA experiments.

Charm fragmentation

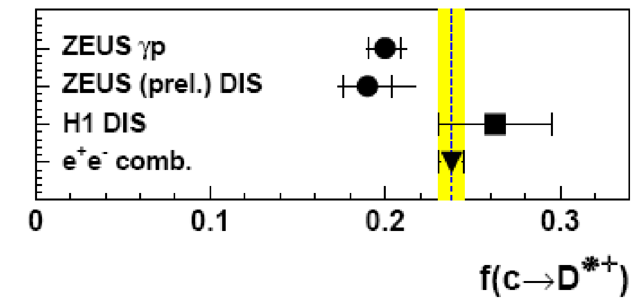
- Hence fragmentation fractions determined:

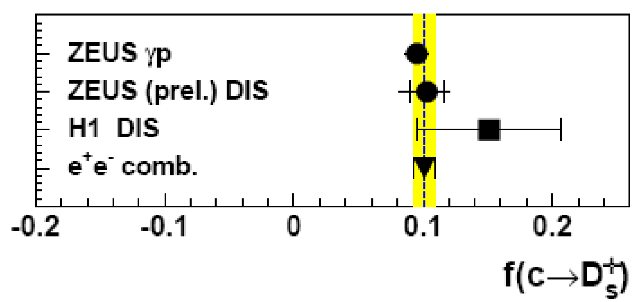






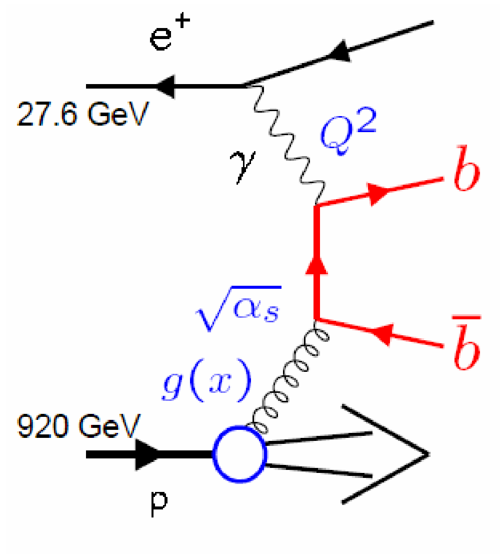
- All fragmentation fractions are consistent with world average and support assumption of universality.

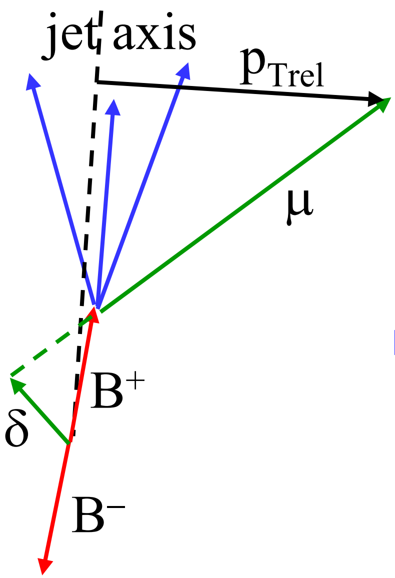




Beauty in DIS events

- Main production mechanism in DIS

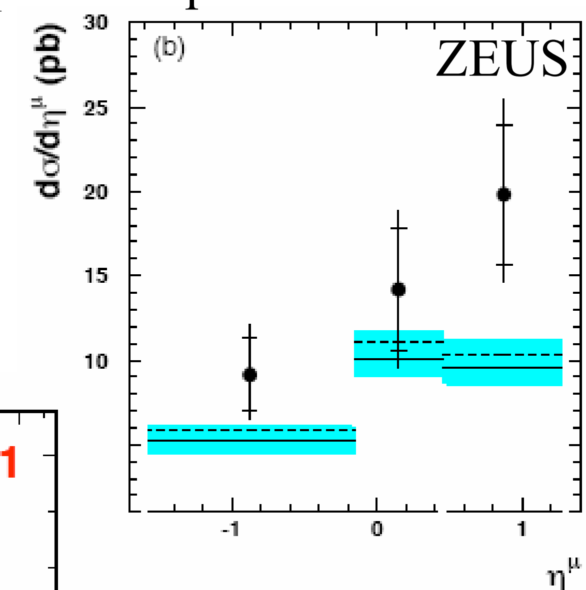


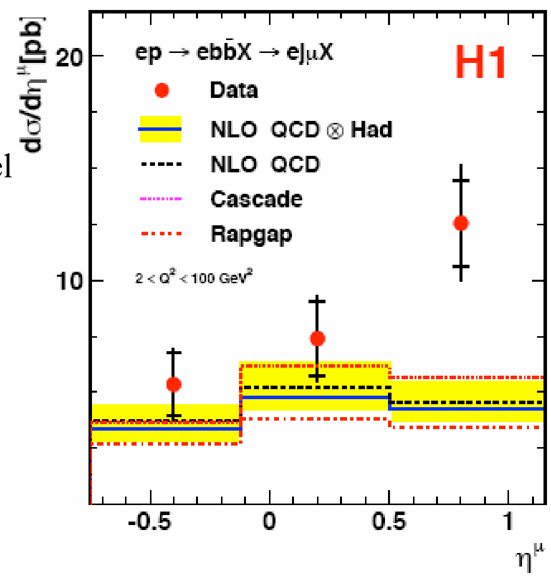


- Identify semi-muonic beauty decays via p_{Trel} and impact parameter δ of muon (H1) or δ (ZEUS).

- Measure cross section for $e\,p \rightarrow e\,b\,\bar{b}\,Y \rightarrow e\,\text{jet}\,\mu\,X$

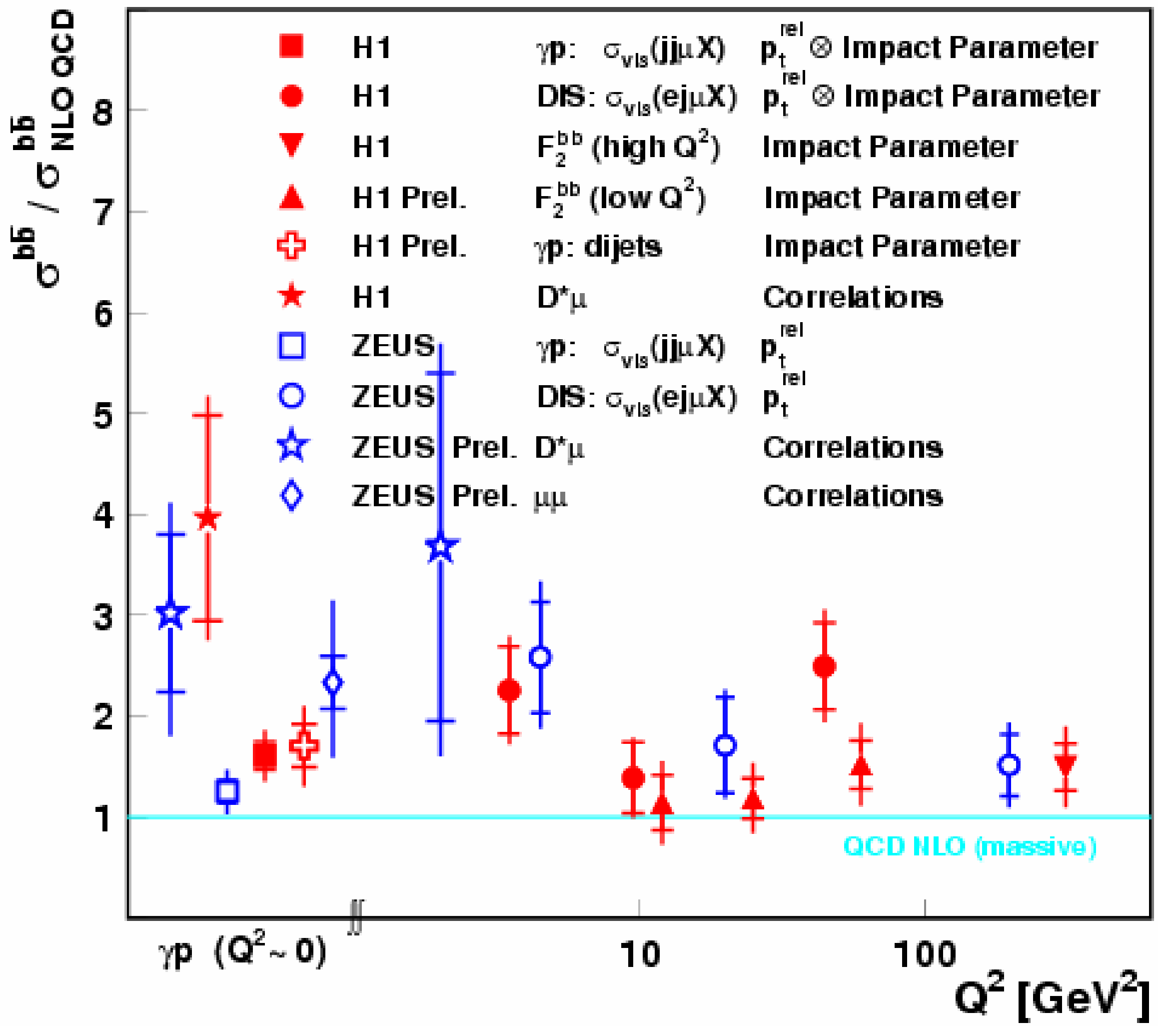
- NLO QCD below both H1 and ZEUS data at small p_T^{μ} and in p direction.





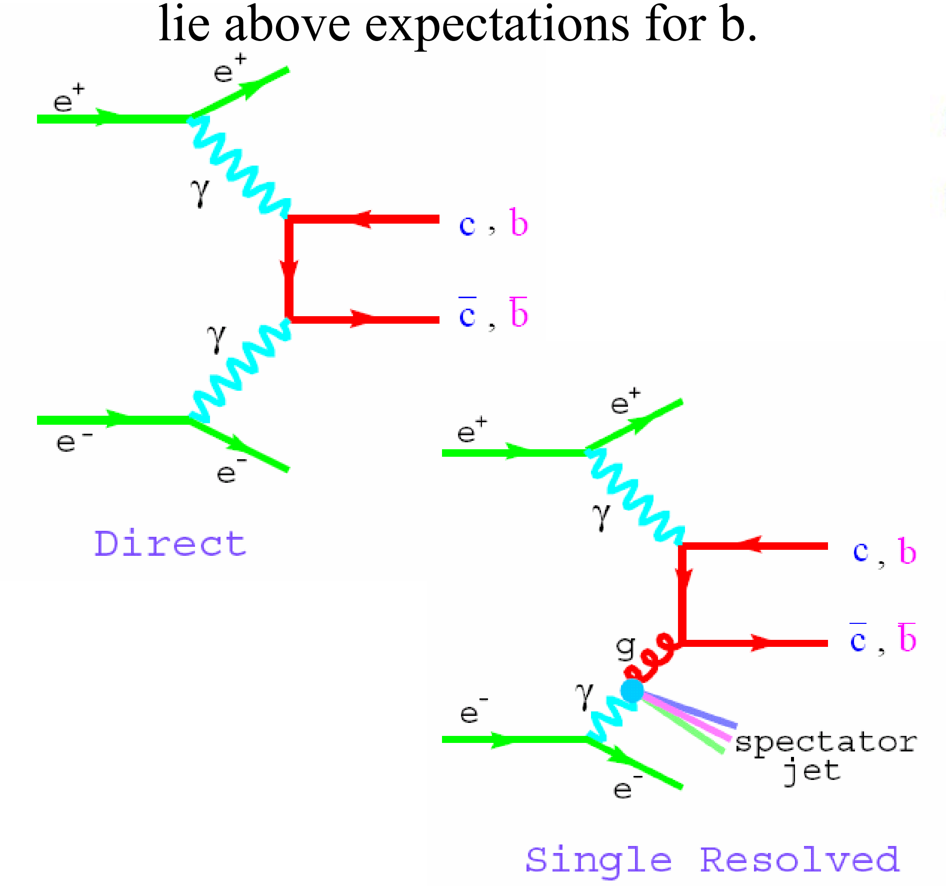
Summary of beauty measurements at HERA.

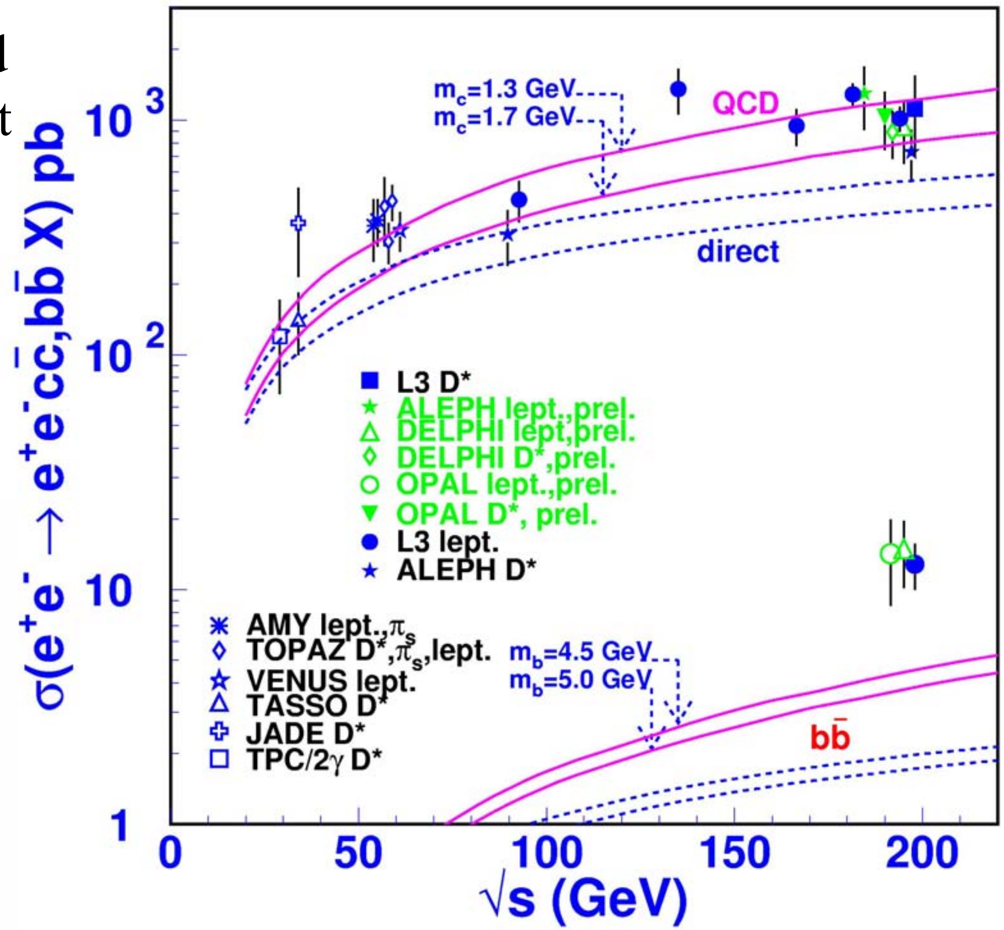
- Many measurements of beauty production now available.
- "Massive" NLO calcs tend to lie somewhat below the data (FMNR in photoproduction, HVQDIS for higher Q^2).
- Evidence that shapes of distributions poorly described in some places (e.g. in ejμX at low muon p_T and in proton direction).
- "Double tag" analyses with no jet requirement started, aim is to study production of $b\bar{b}$ with low p_T.



Heavy flavours in γγ scattering

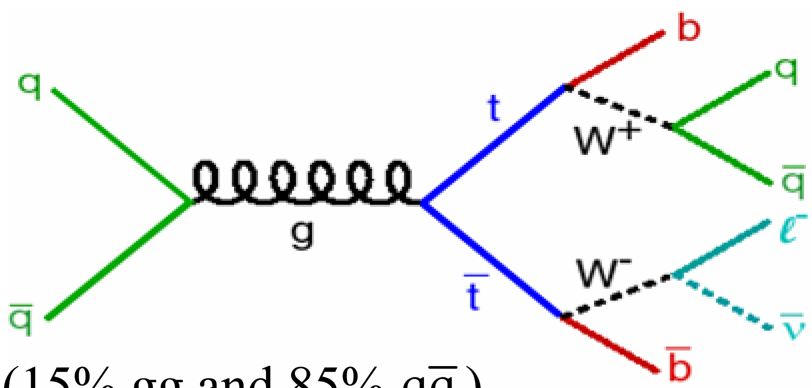
- Recent measurements of heavy flavour production by L3 show good agreement with NLO QCD for c, but lie above expectations for b.





Top quark production at the TeVatron

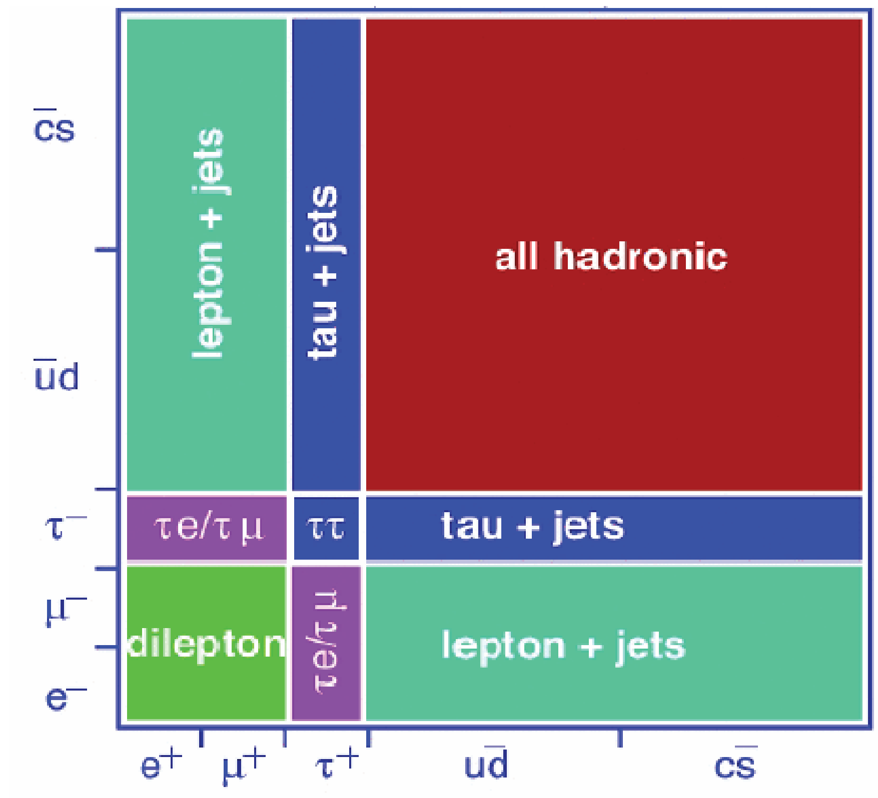
- Production mechanism:



(15% gg and 85% $q\bar{q}$)

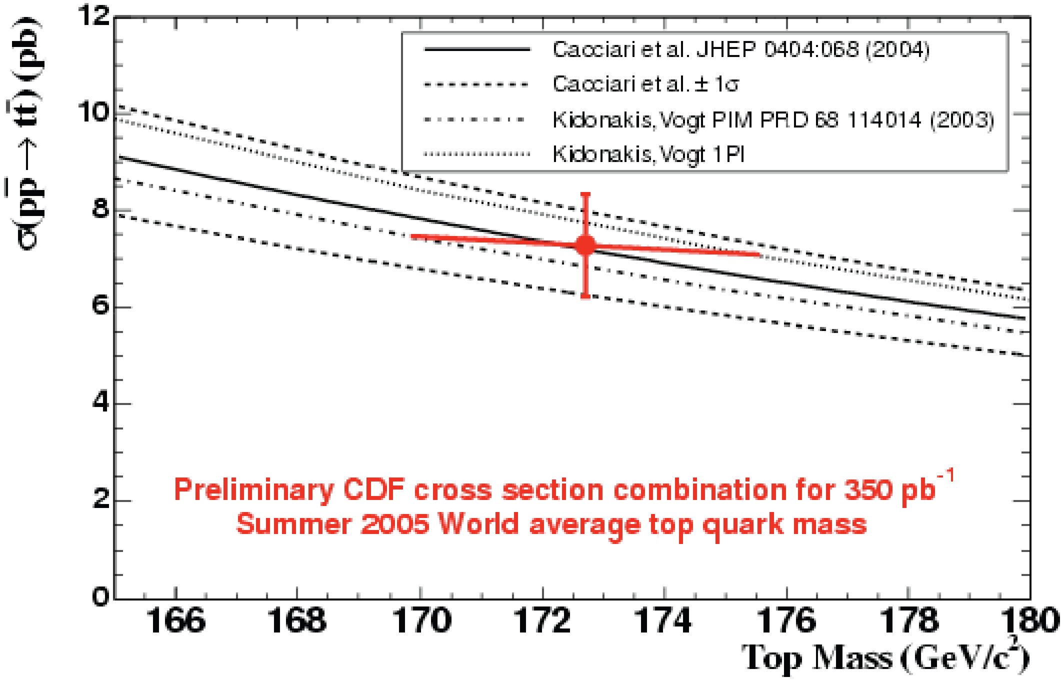
- Dominant theory errors are renormalisation and factorisation scale dependence (5%) and PDFs (7%).
- Study all hadronic, lepton + jets, tau + jets (CDF) and dilepton decay modes of Ws.

- Decays of Ws in top pair events, BR ~ area:

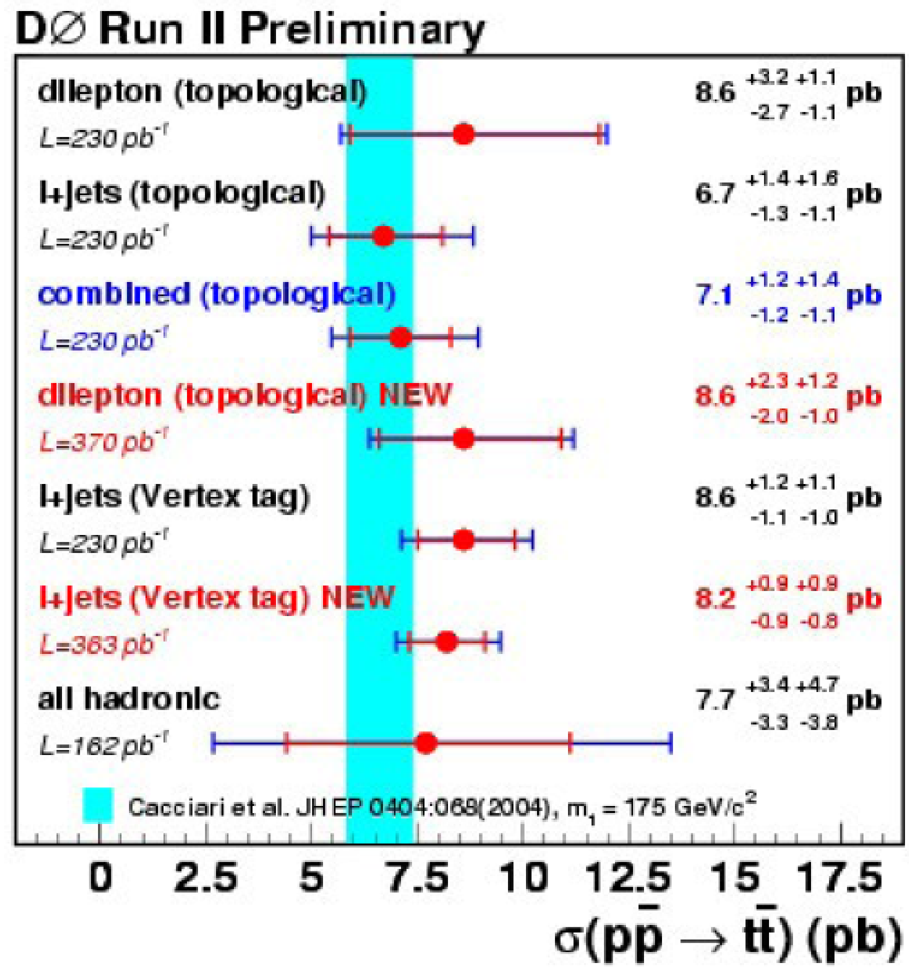


Top quark production at the TeVatron

- Combined CDF measurement.



- Summary of D0 results.



- So far ~ 300 pb^{-1} analysed. experiments have ~ 1 fb^{-1} on tape.
- No evidence yet for single top production.

Summary

Thanks to all the speakers in the Hard QCD session, and apologies to those whose work could not be mentioned in this summary!

- QCD is the theory of strong interactions, but developing a complete understanding of its implications remains a challenge.
- Theoretical progress is being made, e.g. in the area of NNLO calculations and in the development of NLO Monte Carlo programs.
- Experiments are increasing the precision and range of data used in structure function and α_s determinations.
- Further increasing the precision of nucleon PDFs requires more data, new data, and good ideas; some of which are available, or will be soon.
- Surprises continue to appear, such as the effect of the photonic component of proton structure and the size of weak corrections at the TeVatron.
- New and improved jet results coming from the TeVatron and a new round of jet measurements from HERA., studying both jet structure and jet rates.
- Some areas where need for more than DGLAP apparent.
- Inclusive heavy flavour production measurements well described, but still some areas where specific cross sections poorly described.