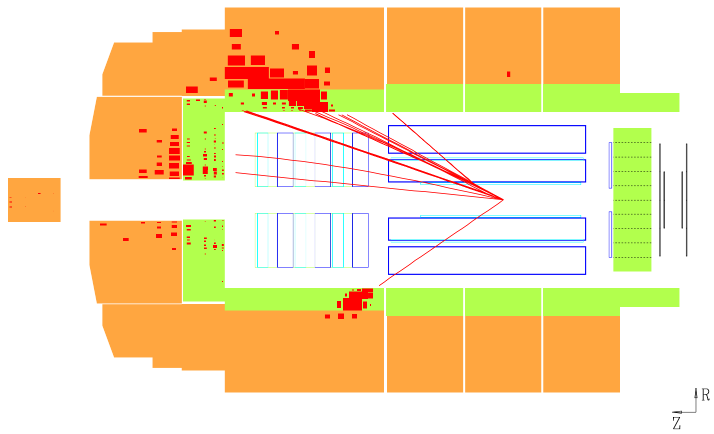
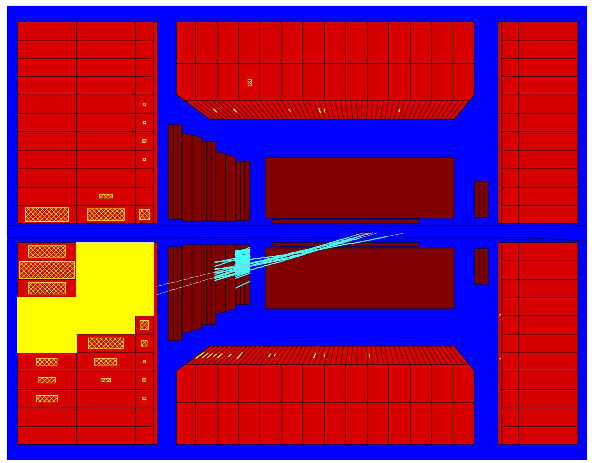
Hadronic Final States and QCD:

HERA as a preparation for LHC



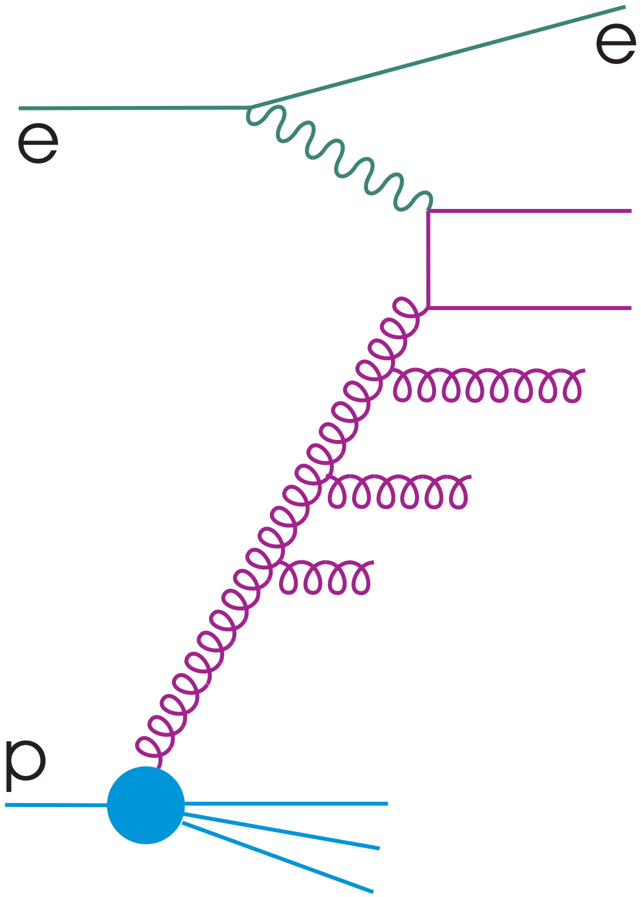
Paul Newman   Birmingham University

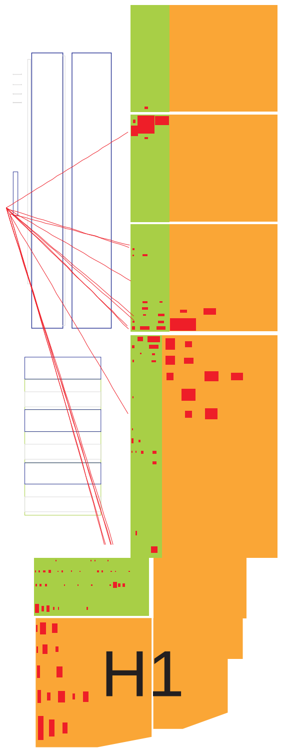


- **HERA-LHC Overview**
- **The Gluon Density**
- **Limits of applicability of DGLAP**

HERA: QCD from the established to the “speculative”

Precise electron and hadron reconstruction over wide rapidity range





Structure Functions $\longrightarrow$ Max Klein

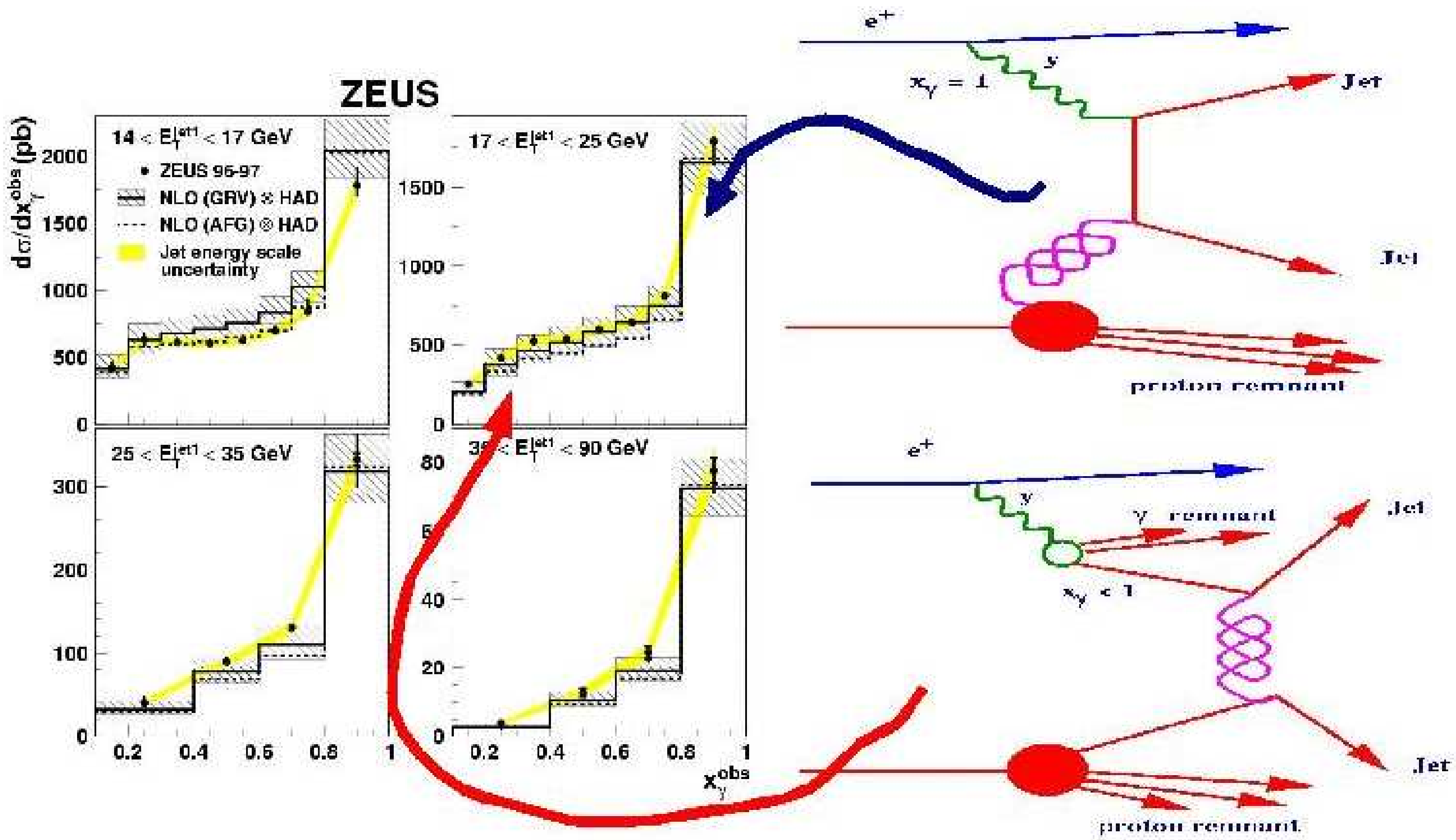
Precision QCD tests

Parton dynamics

Rapidity Gaps, Diffraction

Searches at highest $\sqrt{s}$ with intial state lepton

HERA as a Hadron-Hadron Collider



At large Q^2, photon behaves point-like

At $Q^2 \sim 0$, photon can behave point-like or hadron-like

By tuning Q^2 and x_γ choose whether to look at "simple" point-like processes

hadron-hadron processes or something in-between

Some Areas of Interest for LHC

HERA is *the* precision machine for PDFs and the QCD of Hadronic Interactions

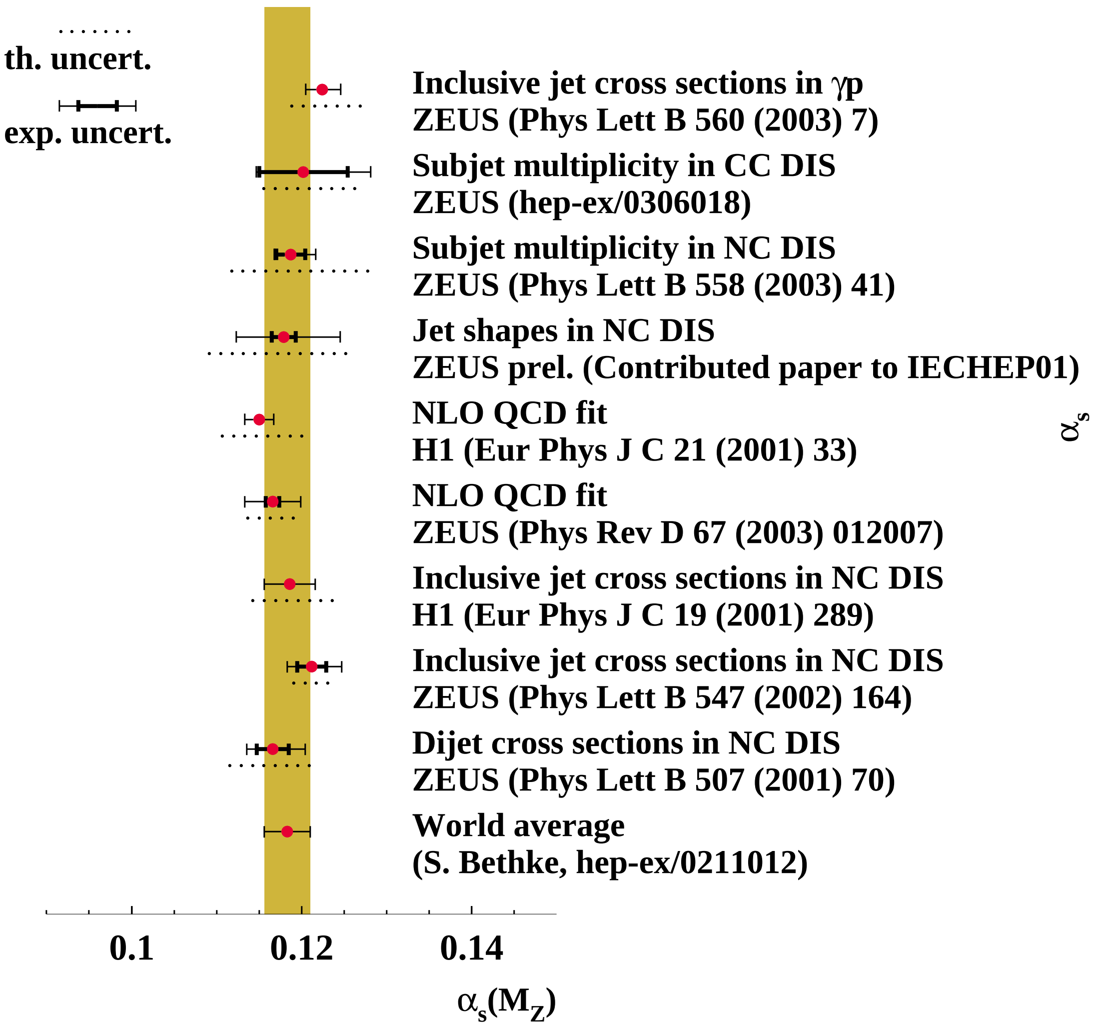
Many observables to test / tune theory for LHC (NNLO, NLO $\otimes$ PS, hadronisation . . .)

- Precision PDFs and α_s
- Limits of validity of DGLAP evolution
- Heavy flavour production mechanisms and evolution
- Multi-scale QCD (Q^2, p_T^2, m_q^2)
- Fragmentation parameters
- Underlying event (tune x_γ, Q^2 to switch on / off)
- Diffractive PDFs (factorisation, survival probabilities) . . . Understand *mechanisms*!)
- . . .

Tools exist for systematic tuning of model parameters (JETWEB, HZTOOL . . .)

Precision Measurements of α_s

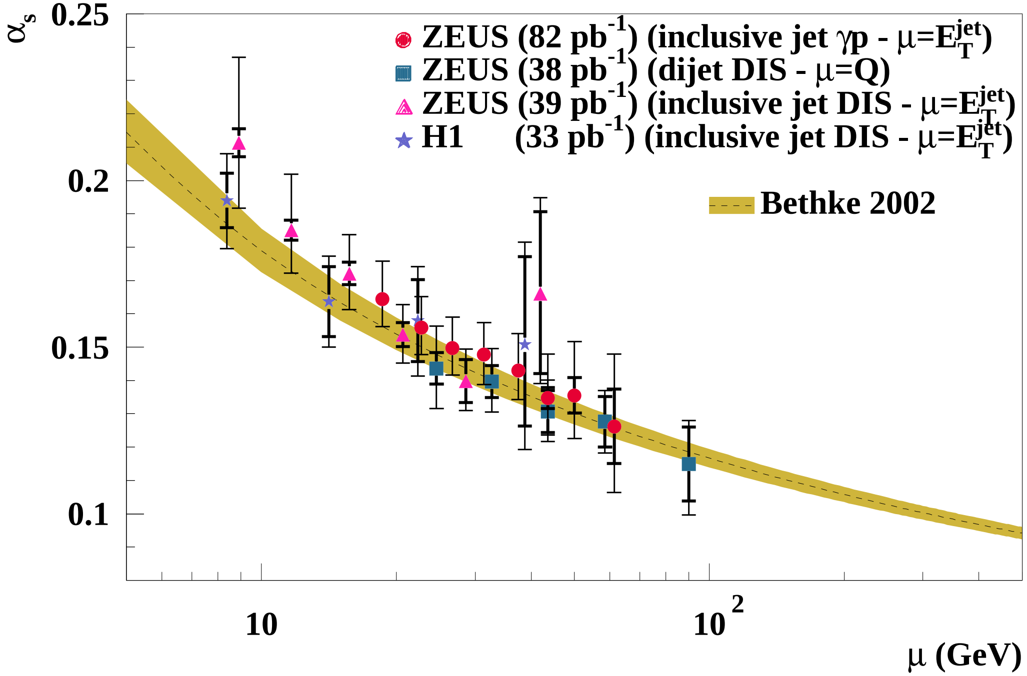
Jet measurements up to "large" $E_T \lesssim 80$ GeV with hadronic energy scale uncertainty $\rightarrow 1\%$



Many different observables

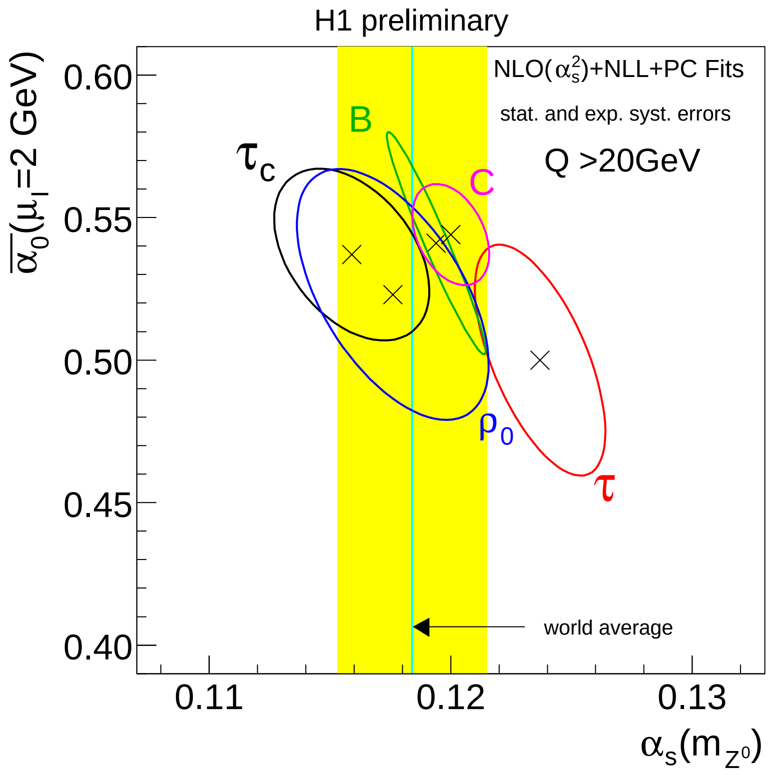
Power to add in both inclusive

and jet measurements $\rightarrow 1\%$?

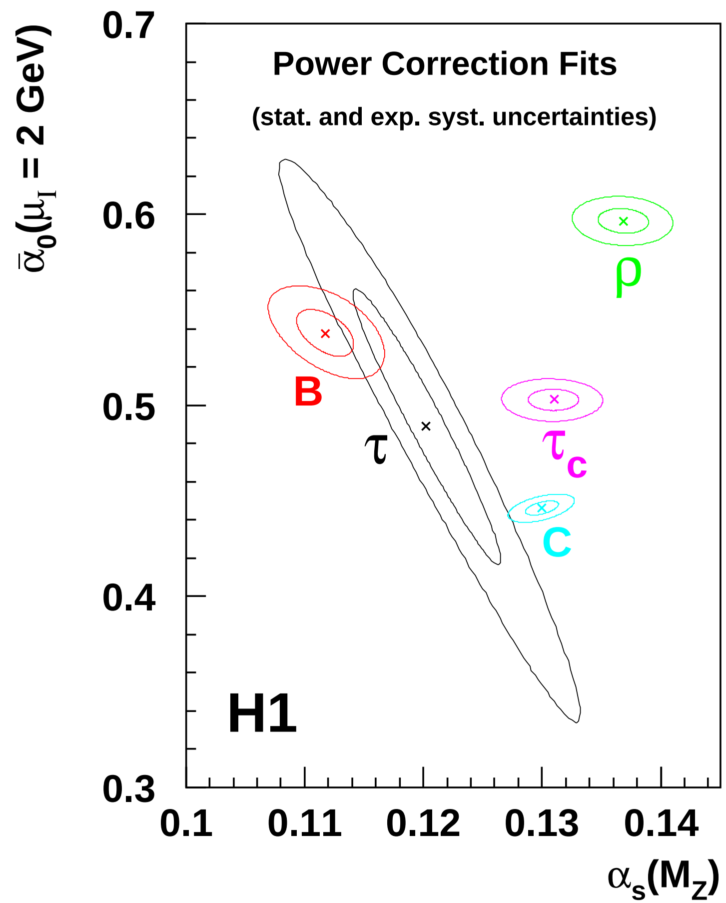


Event Shapes, α_s and Power Corrections

95-00 data, resummed, fit distributions



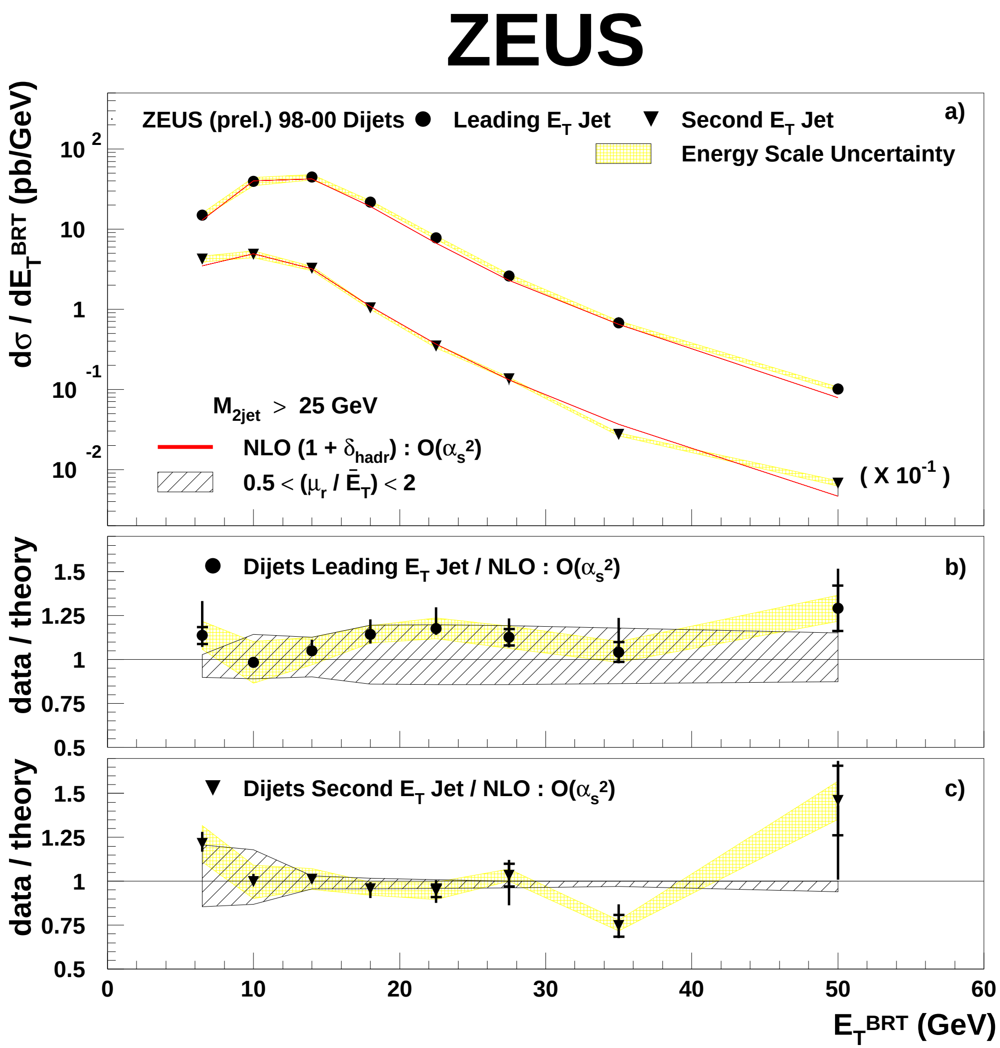
94-97 data, non-resummed, fit means



New techniques and theory . . .

More consistent picture for α_s and power corrections

Precision Jet Measurements



Very precise data on 1, 2 jet final states over wide range in E_T, Q^2

Real and virtual photons

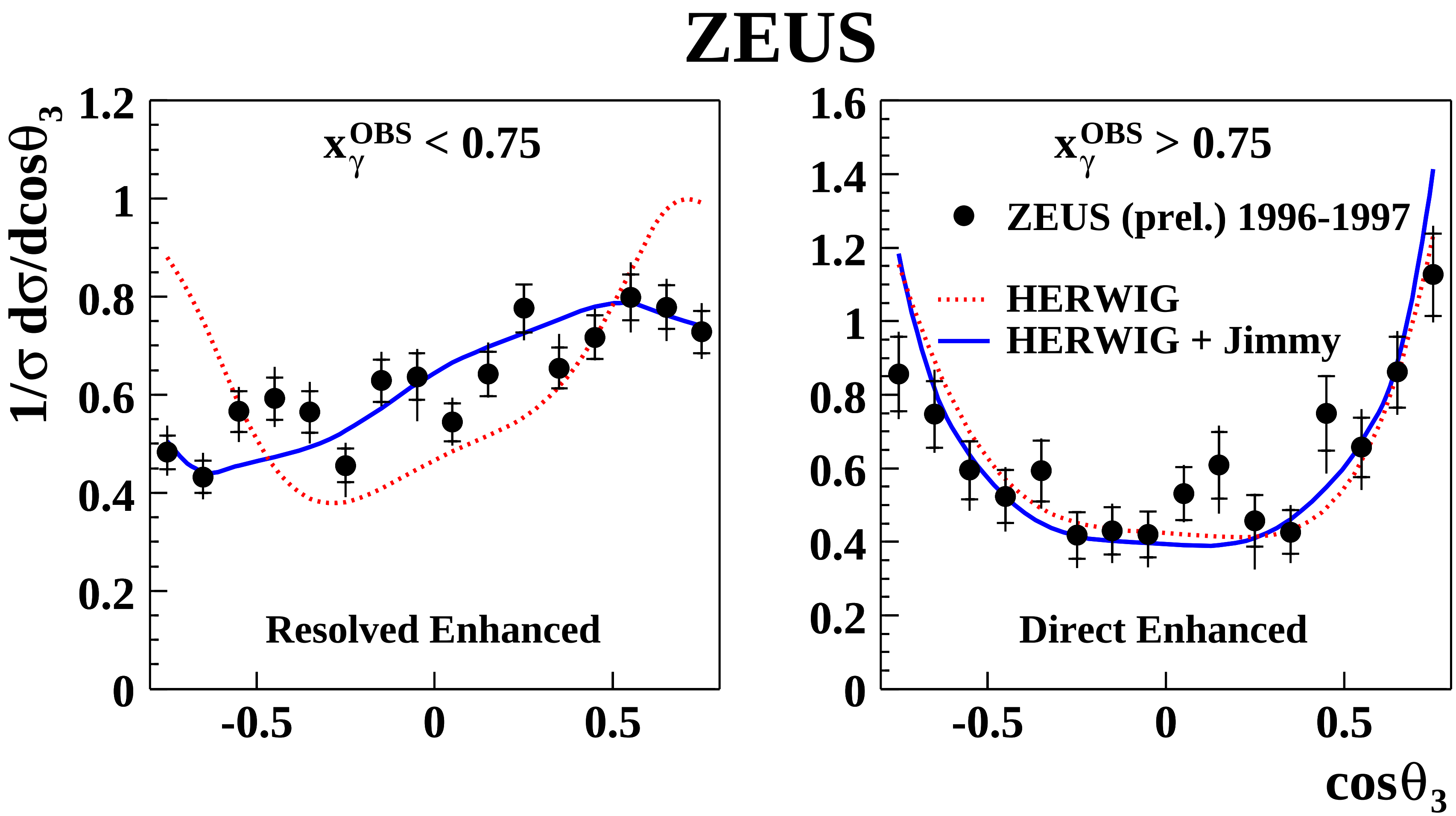
Detailed results on leading and sub-leading jets in different η ranges . . .

tests of pQCD, PDFs, hadronisation models . . .

Beautiful description by NLO QCD

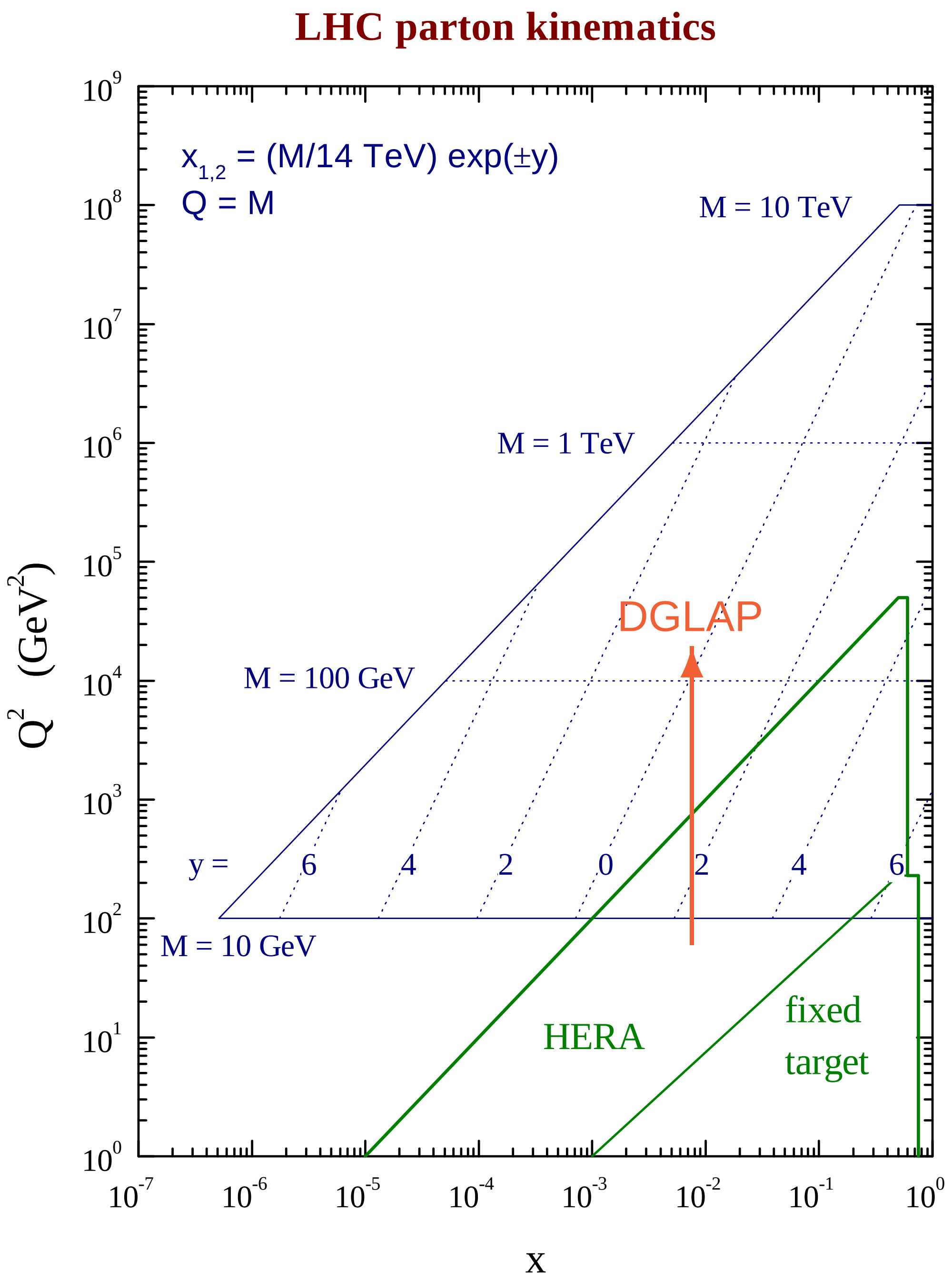
Hadronisation corrections typically $\sim 5 - 10\%$, larger at small E_T

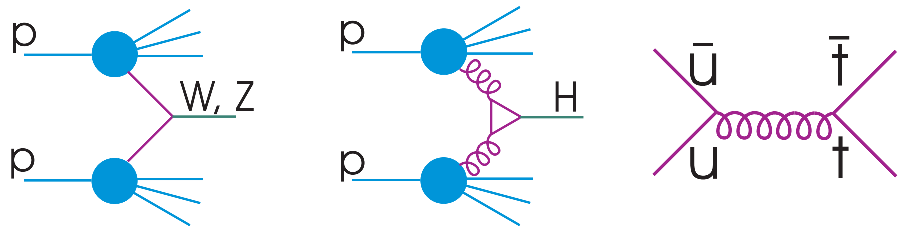
Multi-Jet Final States



Measurements of final states with up to 4 jets

PDFs and Tevatron/LHC



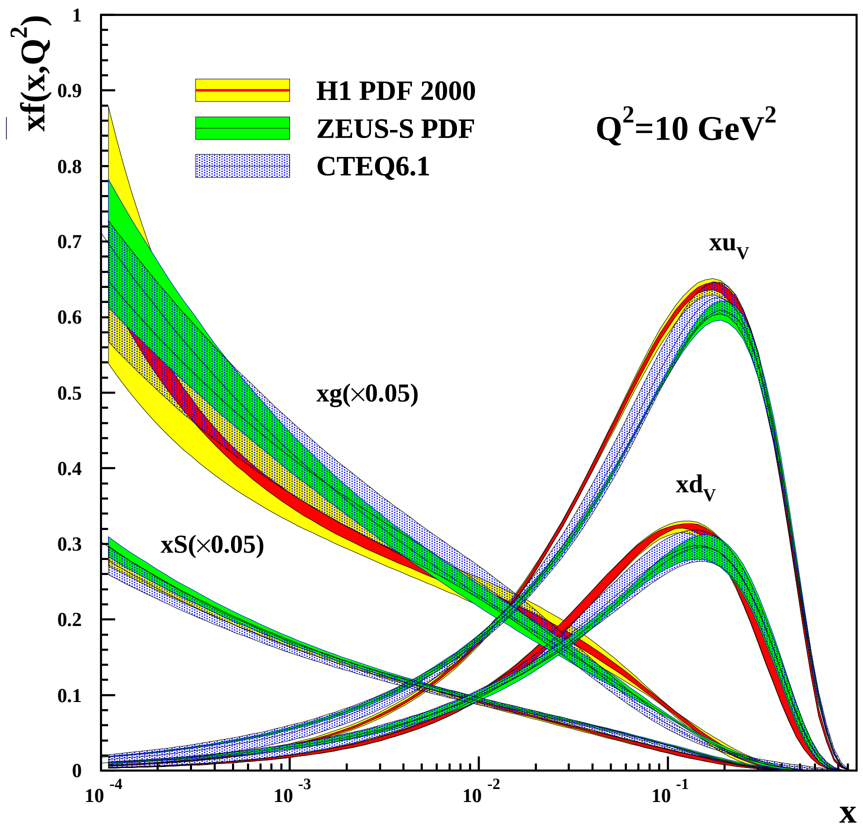


e.g. Production at central rapidity . . .

M (GeV)	x_{Tevatron}	x_{LHC}
100	0.05	0.007
350	0.2	0.025
1000	0.5	0.07

To understand signal and background at Tevatron and LHC, need precise quark and gluon at all x

Final States and the Gluon



Inclusive data indirectly sensitive to $xg(x)$ ...

$$\frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s x g(x)$$

From DGLAP fits, experimental uncertainty $\sim 3\%$ at $Q^2 = 10\ \mathrm{GeV}^2$, $10^{-4} < x < 10^{-1}$

High x $\longrightarrow$ poorly constrained

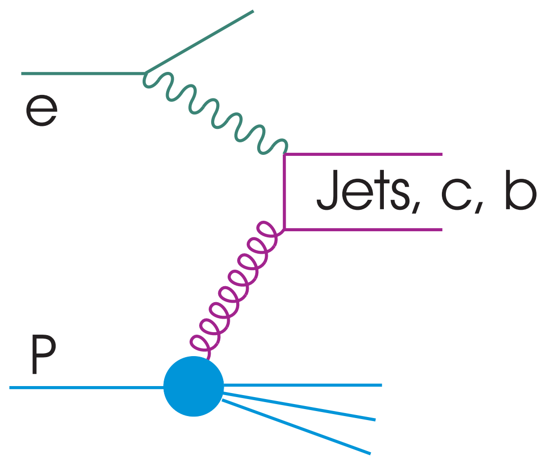
Low x $\longrightarrow$ gluon very large . . . DGLAP sufficient?

Direct constraints from final state data . . .

$\sigma(\mathrm{jets}), \sigma(\mathrm{charm}), \sigma(\mathrm{beauty}) \sim \alpha_s\, xg(x)$ (LO QCD)

HERA jet data sensitive up to $x \sim 0.6$

Fast improving charm and beauty data . . .



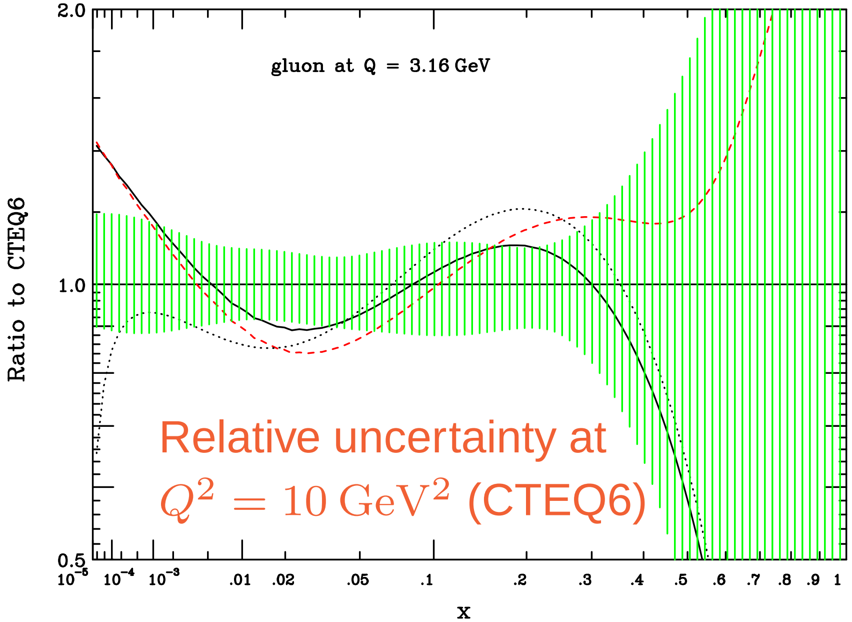
The Gluon Density at High x

Huge uncertainty for $x \gtrsim 0.25$

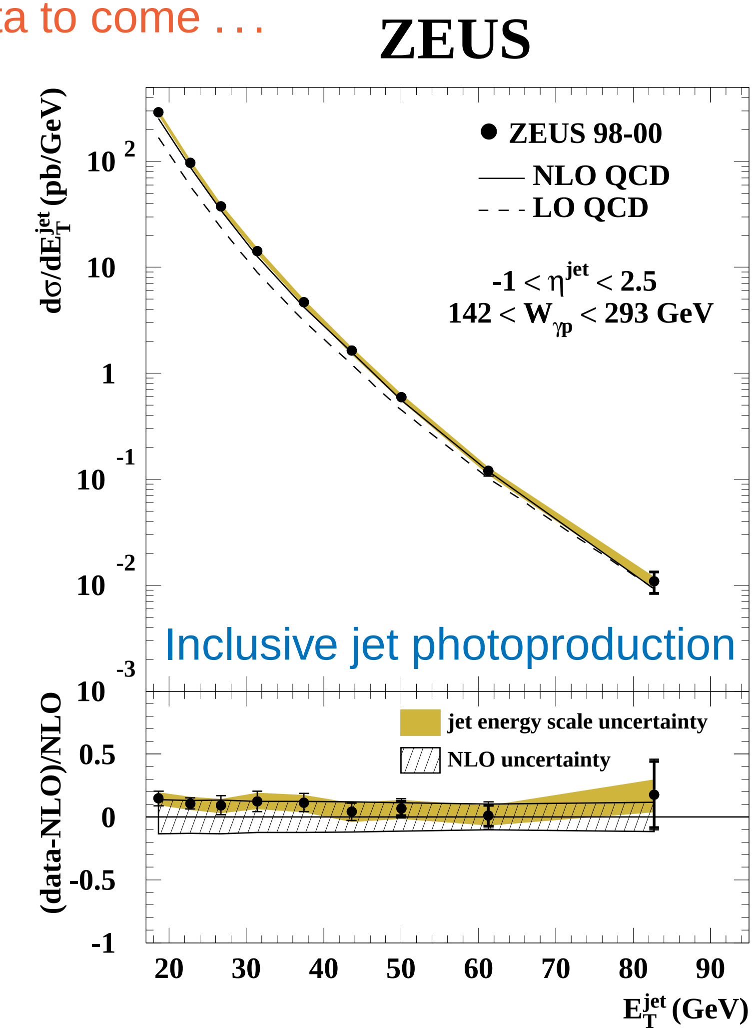
Can be addressed with HERA jet data

$x \sim 2E_T/W_{\gamma p} \sim 0.8$ for $E_T = 80\ \mathrm{GeV}, W = 200\ \mathrm{GeV}$

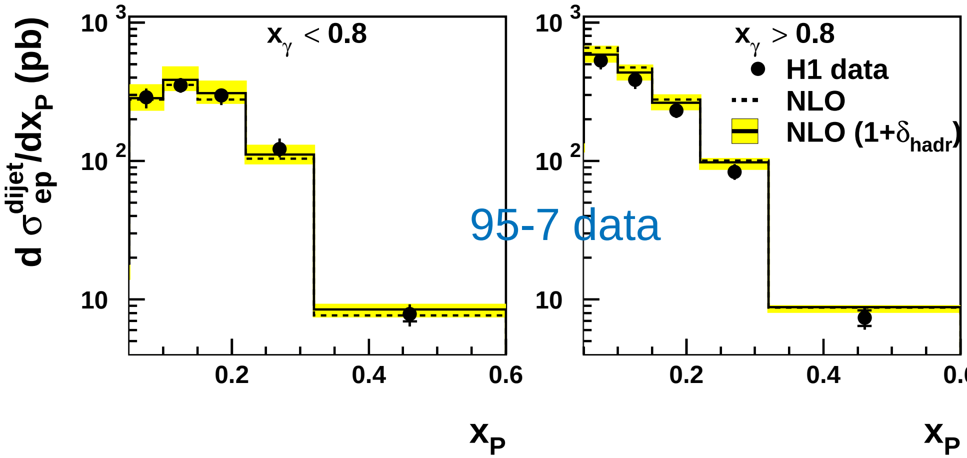
Improved data to come . . .



Relative uncertainty at $Q^2 = 10\ \mathrm{GeV}^2$ (CTEQ6)



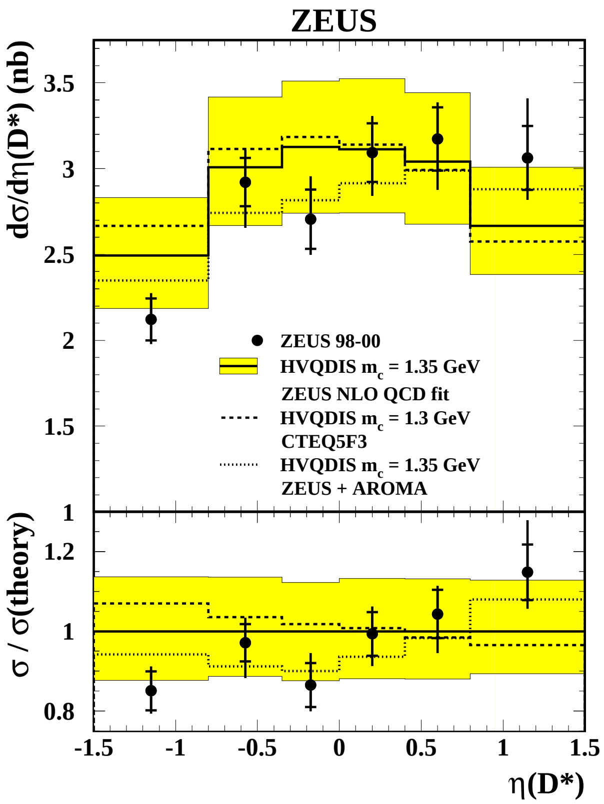
Inclusive jet photoproduction



95-7 data

Dijet Photoproduction

Charm and the Gluon



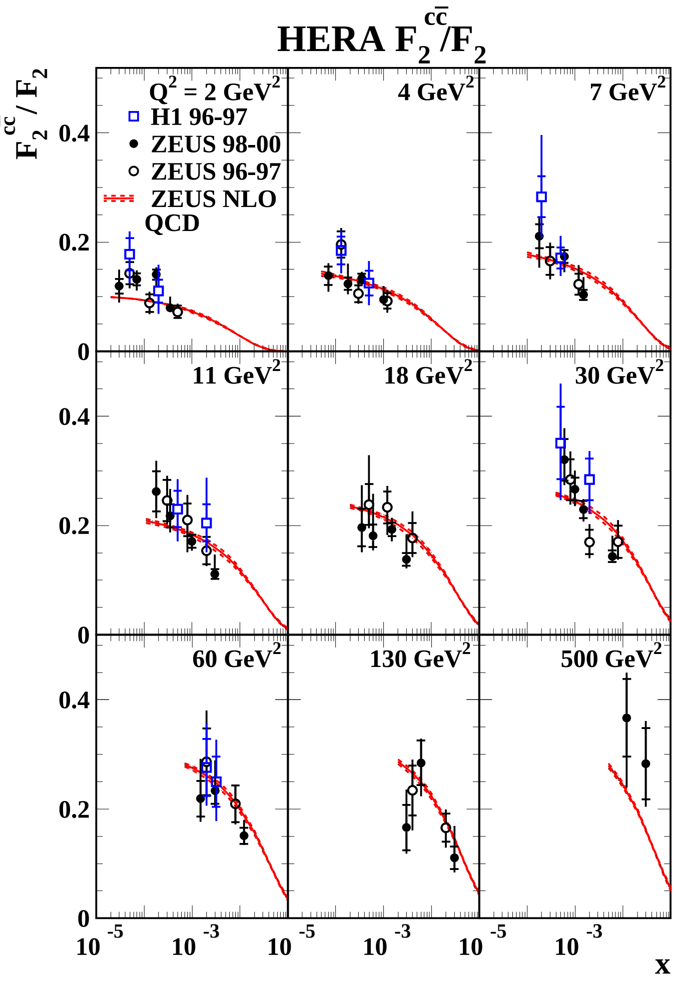
Charm from $\sigma(D^*)$

v NLO QCD $\otimes\, xg(x)$

Beautiful confirmation of gluon from scaling violations at 10% level

Sensitive to differences between fitted gluons

Theoretical uncertainties dominate $\longrightarrow\; m_c, \mu_r, \mu_f$ ϵ_c, HF scheme

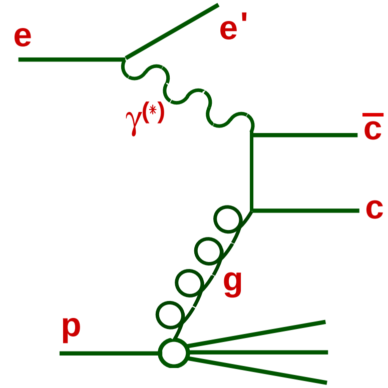


$F_2^{c\bar{c}}$ obtained with extrapolation in η, p_t (NLO HVQDIS)

Well above threshold, for massless charm, $\frac{F_2^{c\bar{c}}}{F_2} \longrightarrow \frac{e_c^2}{e_u^2+e_d^2+e_s^2+e_c^2} = \frac{4}{10}$

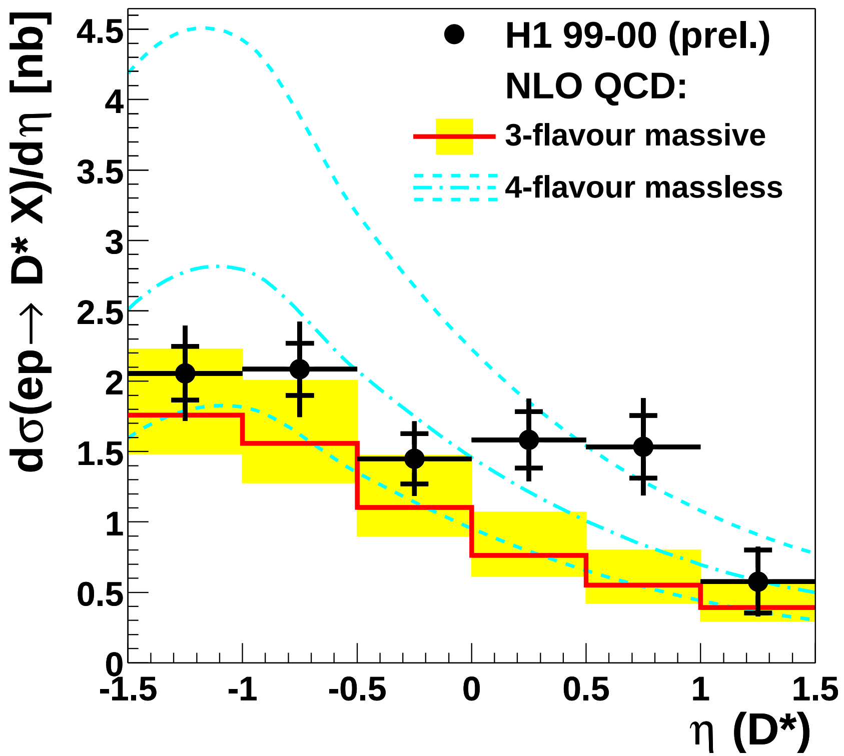
Upgraded Silicon detectors, triggers $\longrightarrow$ big charm future at HERA-II

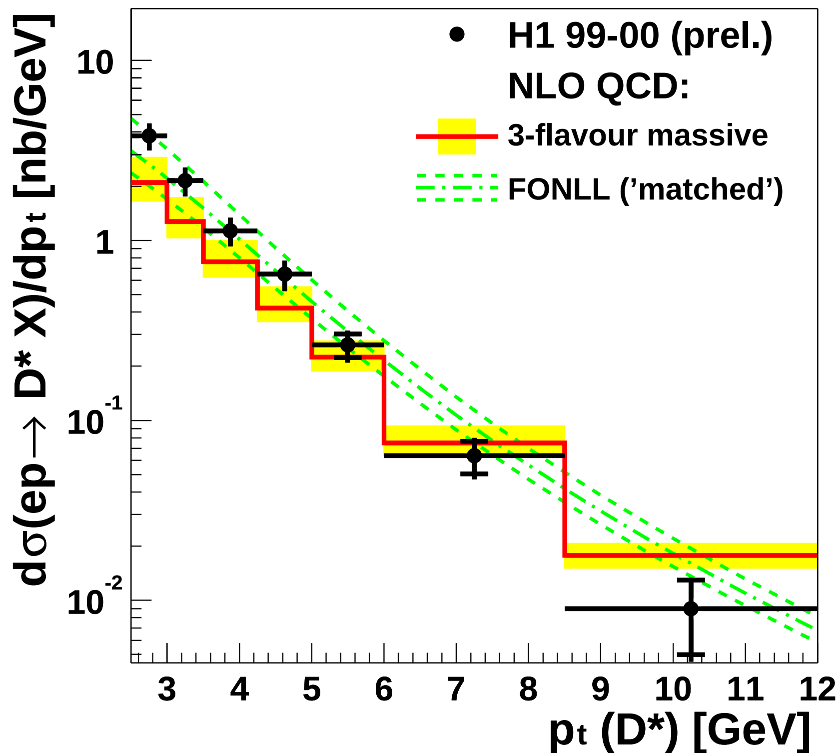
D^* Photoproduction



D^* data in tagged γp . . .

Testing MC models and NLO theory



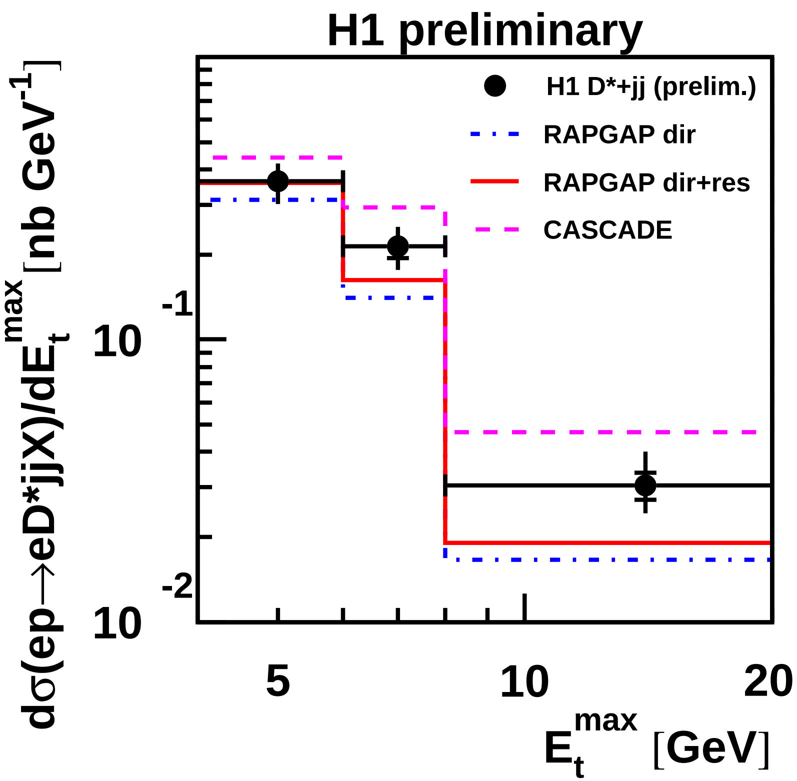


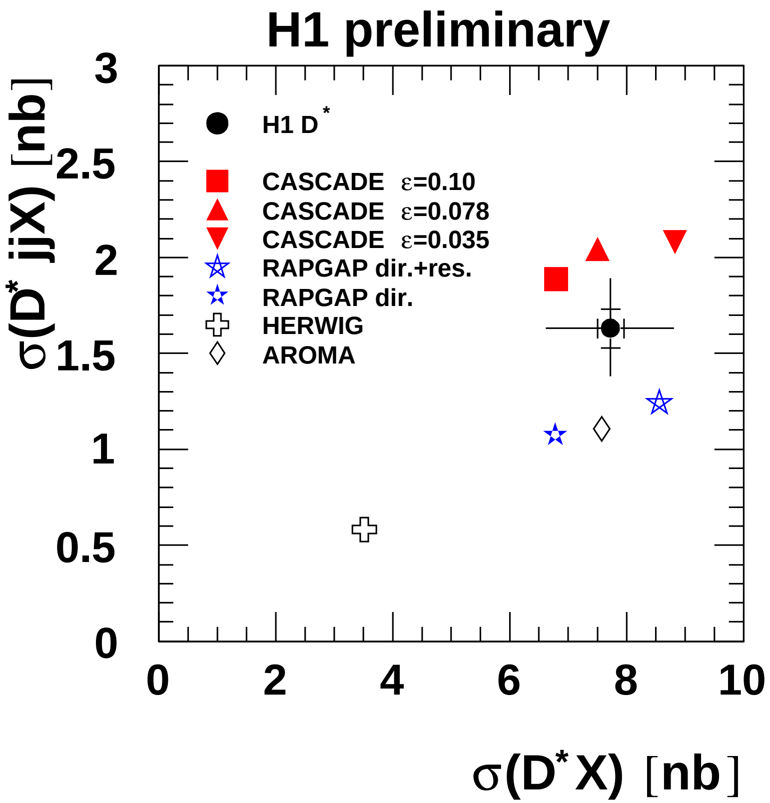
Not fully described by MC models or “massive” theory

Massless, Matched FONLL better?

Important data to constrain large theory uncertainties

$D^* +$ Dijets in DIS



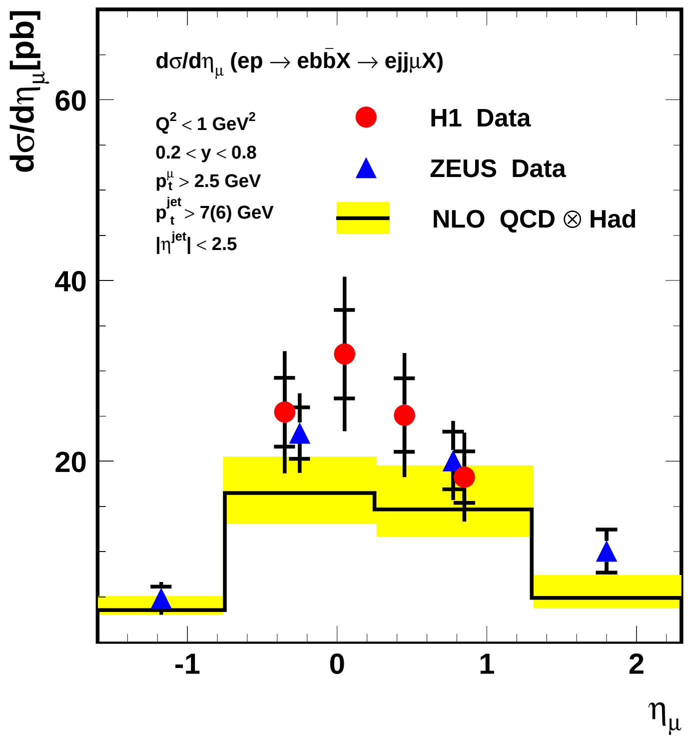


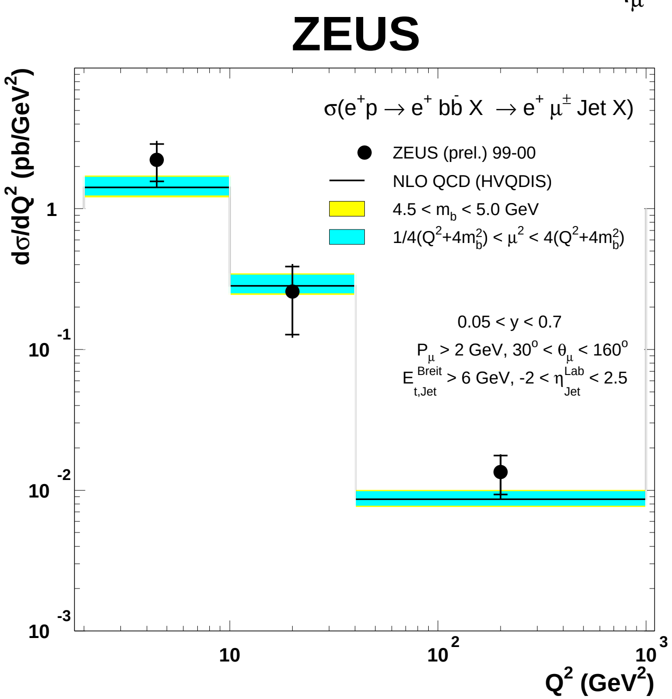
DIS Results for Inclusive D^* and $D^* +$ dijets

New insights with jet requirements

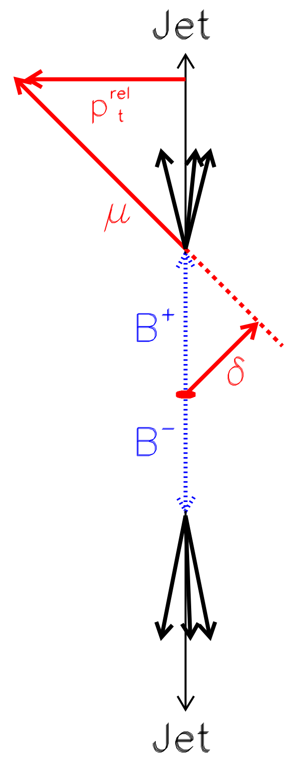
LO MC models describe inclusive data well, but dijets bring sensitivity to extra effects

Beauty Production





$\sigma(b)\ :\ \sigma(c)\ \sim\ 1\ :\ 200$



- Understanding parton dynamics and multi-scale QCD

- Previously reported HERA, Tevatron beauty "anomalies" . . .

Measure using $b \longrightarrow c\nu\mu$

Unfold from charm, uds using δ (Si) and $p_T^{\mathrm{rel}}(\mu - jet)$

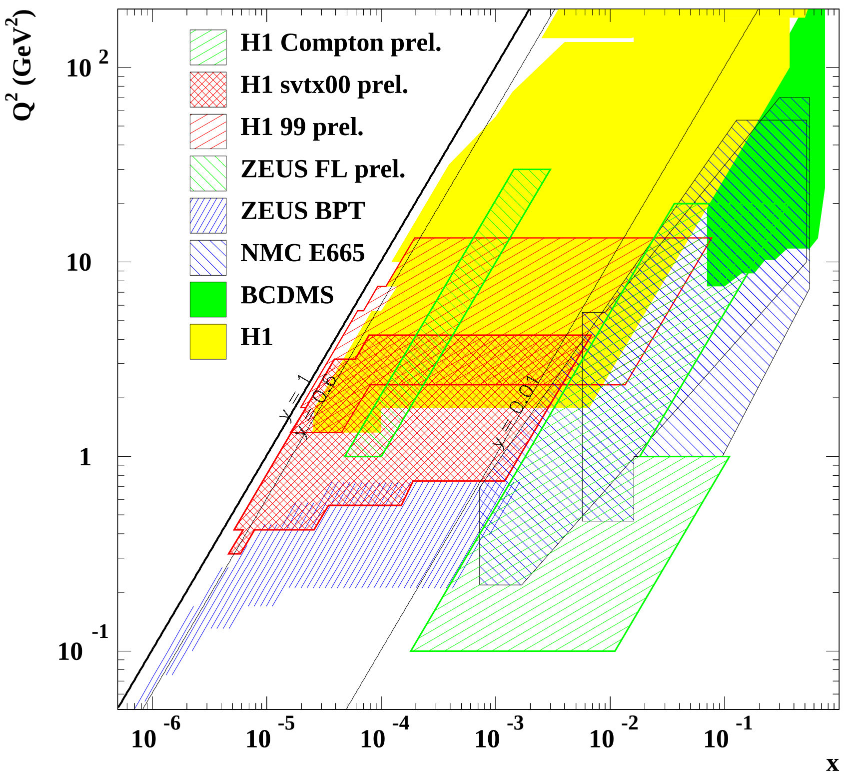
Compare with NLO QCD directly in measured range

Good agreement at large Q^2, p_T

Data $>$ theory at $Q^2 = 0\ \ (1.5\sigma)$

Larger statistics and more Si in future $\longrightarrow F_2^{b\bar{b}}$

The Limits of DGLAP Evolution



Precitions for LHC assume validity of DGLAP evolution

DGLAP Must Ultimately break down at low x

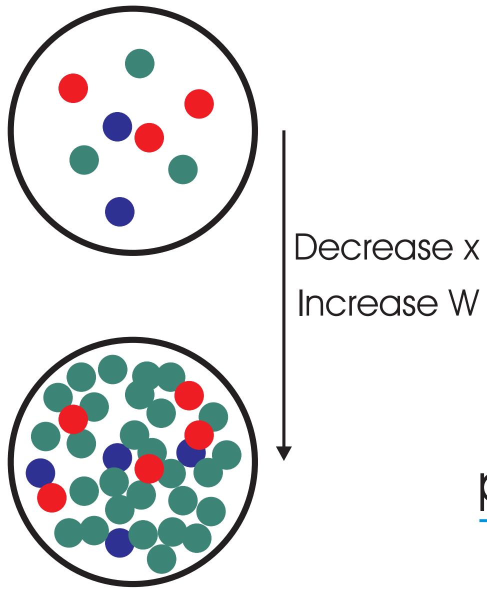
Important to test low x gluon directly

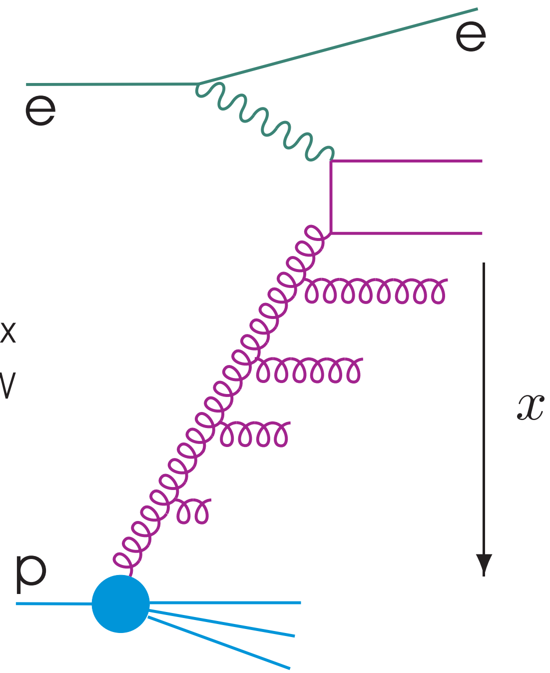
Low x, low Q^2 kinematically correlated

- **Low x . . .**

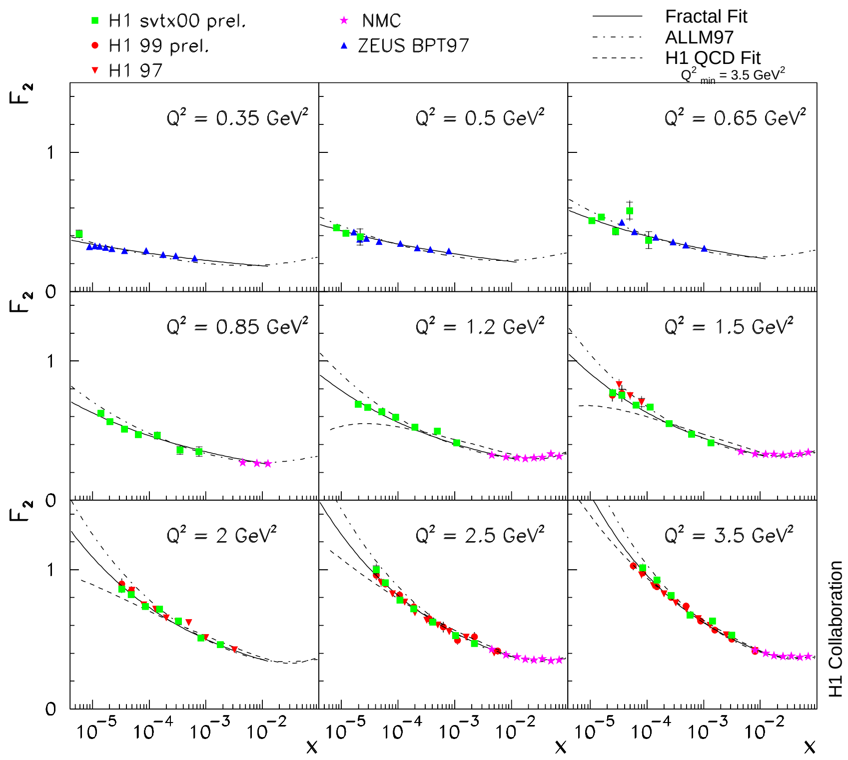
High parton densities $\longrightarrow$ unitarity limit, gluon recombination?

Long parton cascades $\longrightarrow$ Breakdown of DGLAP approximation? ($\log 1/x$ evolution?) (BFKL, CCFM?)





F_2 at low Q^2

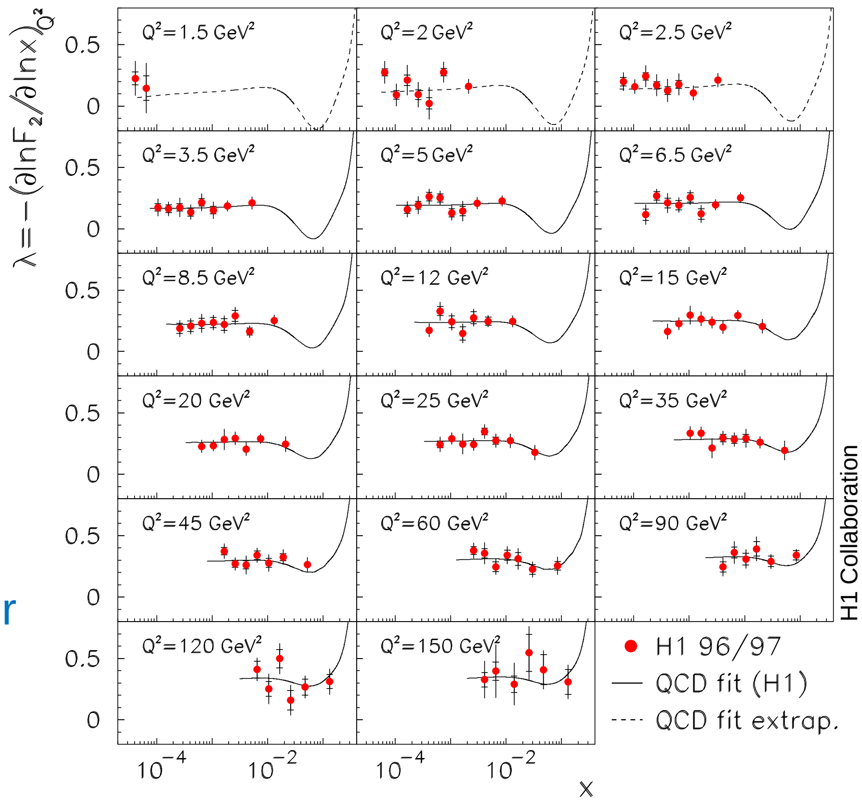


F_2 measurements at low $Q^2 \sim 1\ \mathrm{GeV}^2$

($y < 0.6$ to avoid F_L effects)

$Q^2 = 3.5\ \mathrm{GeV}^2 \rightarrow$ fast rise with decreasing x ...

$Q^2 = 0.35\ \mathrm{GeV}^2 \rightarrow$ soft rise with decreasing x

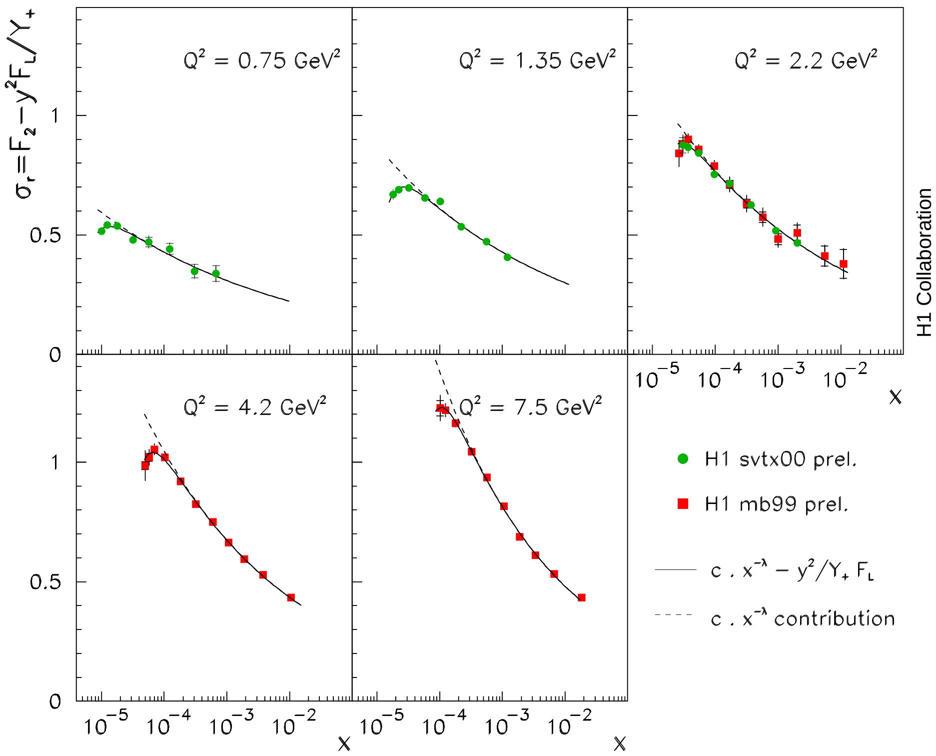


If unitarisation effects present, expect taming of rise of $xg(x)$ and hence F_2 at low x

Extract $\lambda = \frac{\partial F_2}{\partial \ln x}$ at fixed Q^2 locally from precise data

Derivative independent of x for $x < 10^{-2}$: no evidence for saturation in perturbative part of HERA kinematic range

F_L at Low Q^2



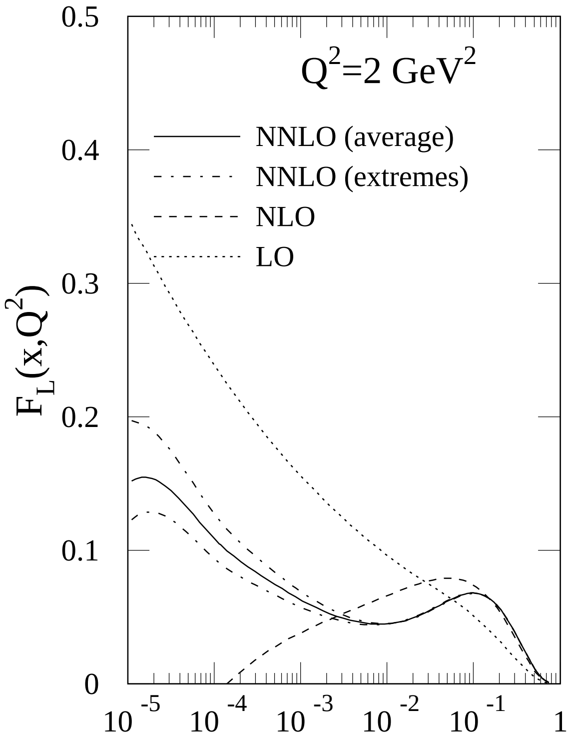
$xg(x)$ poorly known in low Q^2 region where DGLAP questionable

Beyond x reach of jet, charm data.

F_L is ideal observable for the gluon in this region

$\neq 0$ at $\mathcal{O}(\alpha_s^1)$ due to gluon radiation

Experimental data needed to constrain theory



Sensitivity at highest $y \to 0.9 \quad (E'_e > 3\,\mathrm{GeV})$

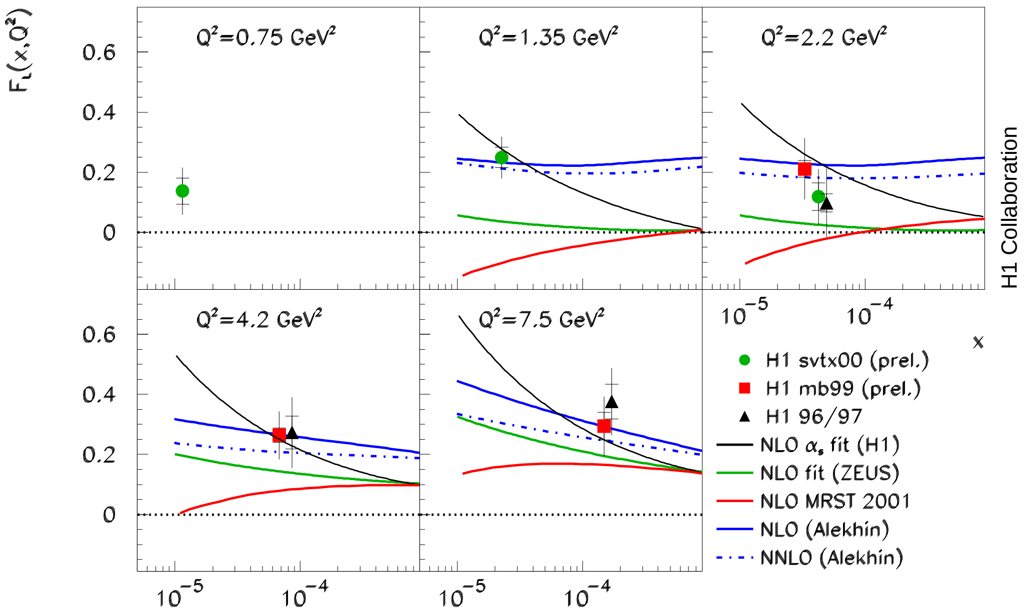
$$\boldsymbol{\sigma_r = F_2 - (y^2/Y_+)\, F_L}$$

Requires model for F_2 at high y ...

New method: fit at fixed Q^2: $\sigma_r = c \cdot x^{-\lambda} - (y^2/Y_+)\, F_L$

F_L determination in crucial region $Q^2 \sim 1$

F_L at Low Q^2



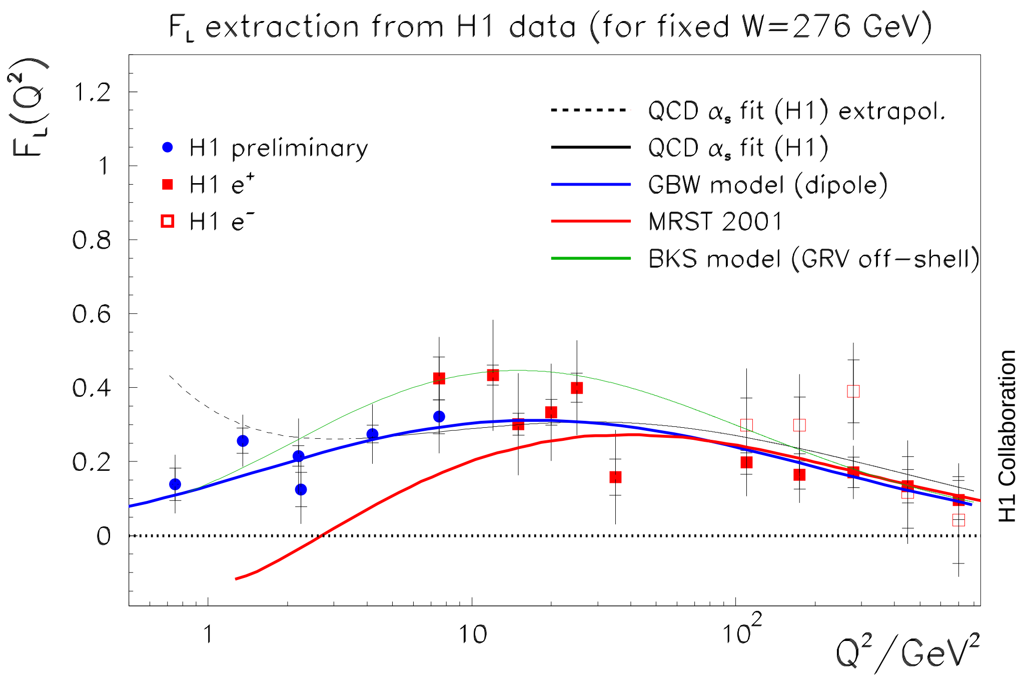
First data at $Q^2 \sim 1\ \mathrm{GeV}^2$

Distinguishes between DGLAP fits & other approaches at low Q^2

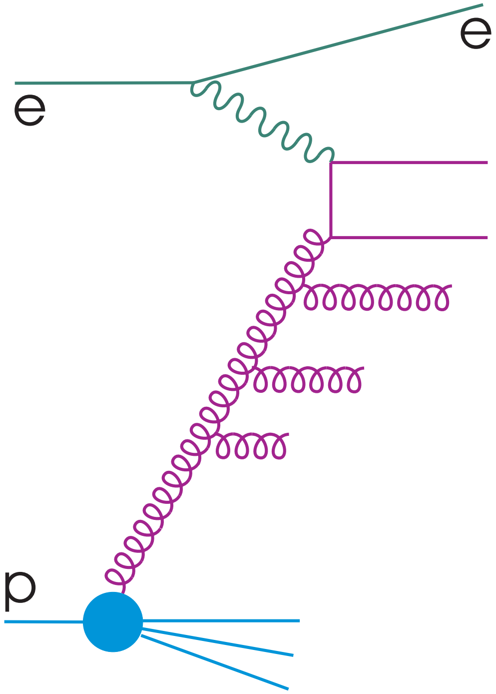
F_L determination now spans 3 orders of magnitude in Q^2

...but measurements of x dependence still required to see the full picture

Reduced E_p running required for x dependence and to avoid assumptions on F_2



Final States and Low x Physics



Final states offer complementary means of searching for novel parton dynamics

DGLAP approximation $\longrightarrow$ p_T ordered parton cascade

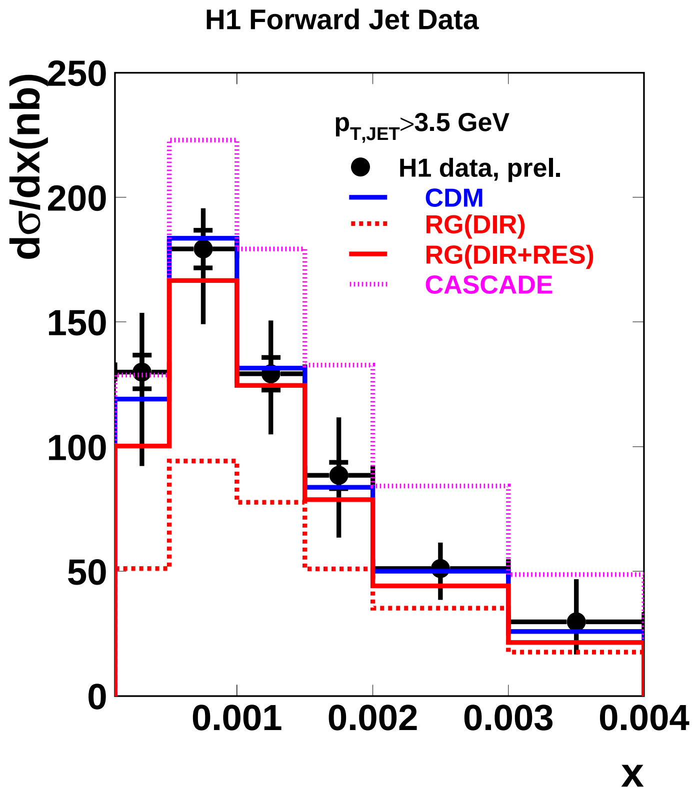
Search for parton emissions with $p_T^2 \sim Q^2$ low down ladder

“Forward” jet data prefer models which do not impose p_T ordering

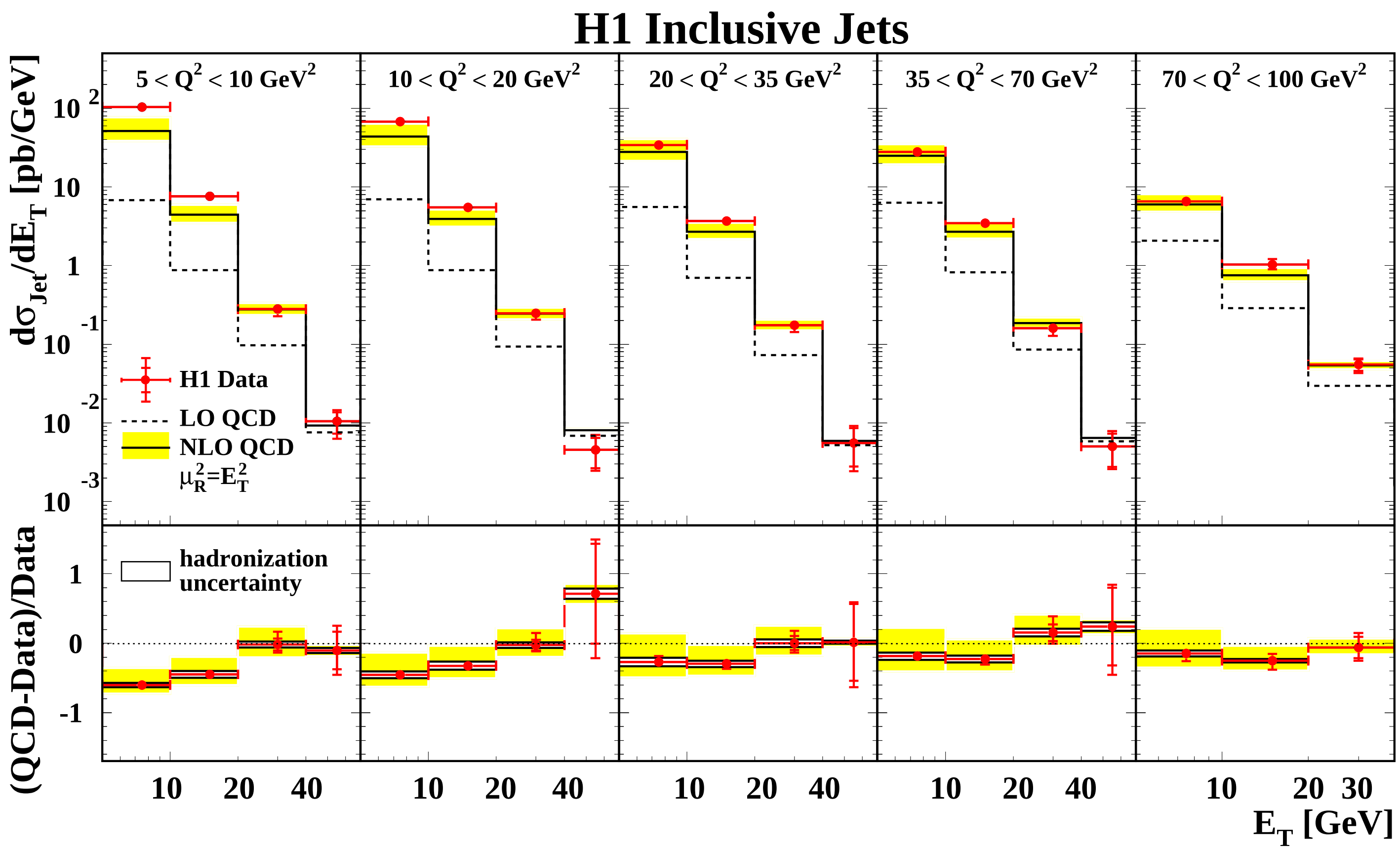
Not fully described by LO or NLO-QCD

$\longrightarrow$ BFKL-type model better (x-ordering)

$\longrightarrow$ CCFM-type model better (angular-ordering)



Inclusive jet cross sections for $1.5 < \eta_{\rm lab} < 2.8$

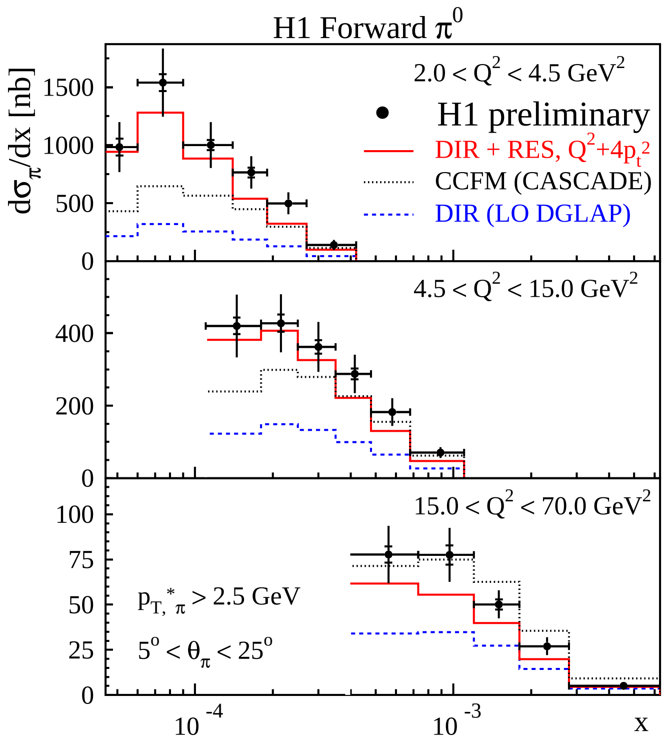


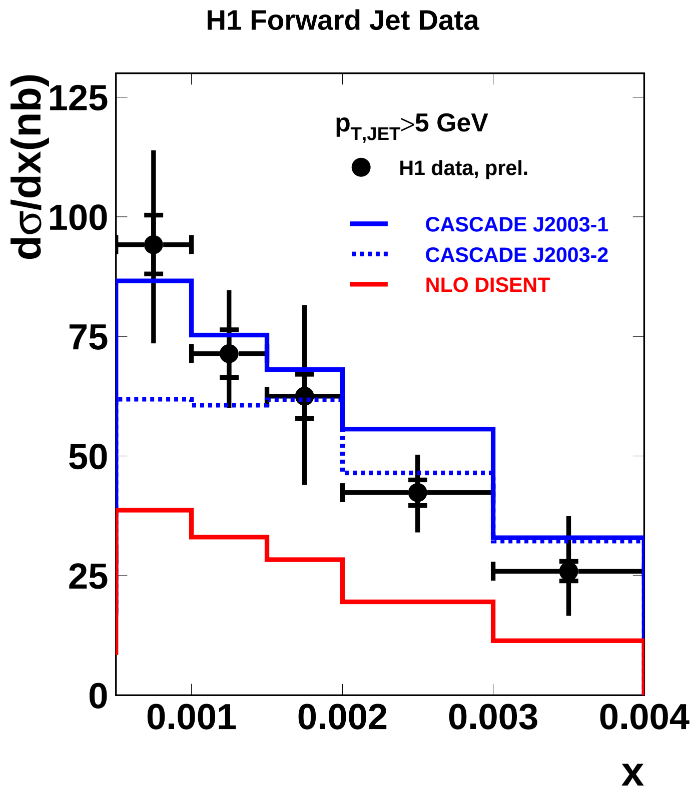
NLO DGLAP $\otimes$ hadronis'n corrections broadly successful.

Discrepancies only at low E_T, low Q^2, where NLO / LO corrections are largest

Is NNLO DGLAP the solution to all HERA data?

Forward Jet and π^0 Production



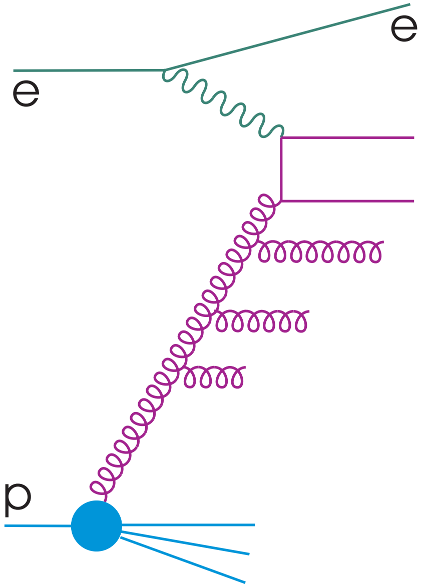


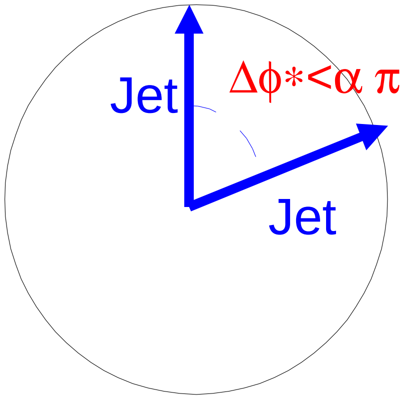
LO and NLO DGLAP fail to describe data

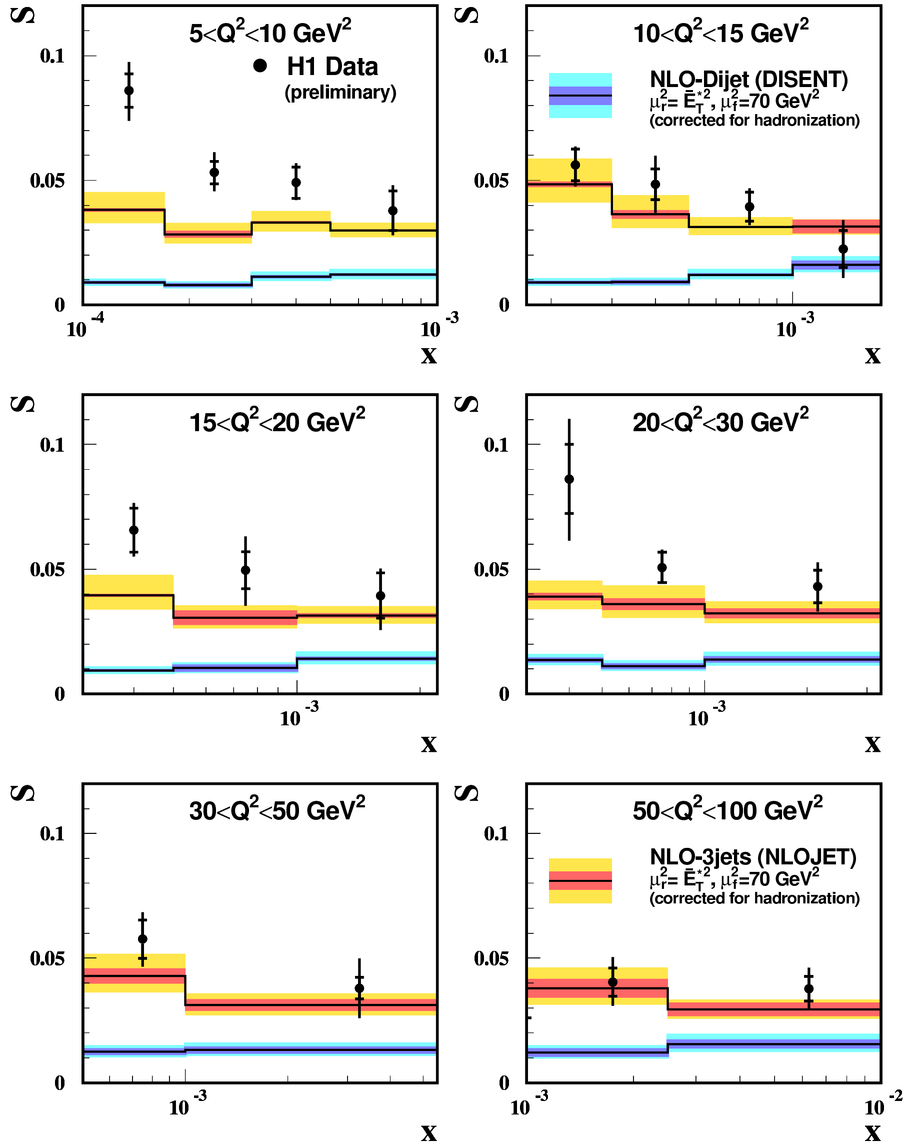
Resolved γ^* works, approximation to higher orders / non k_T ordering

CCFM can desceibe the data with appropriate choice of unintegrated gluon density

Azimuthal decorrelation of Dijets







Azimuthal decorrelation between jets in $\gamma^* p$ CMS

sensitive to higher order effects or incoming p_T

Measure S = Pr (2 leading jets have $\Delta\phi^\star < 120°$)

Mostly well described by NLO 3-jet theory

Still missing contributions at lowest $x, Q^2 \ldots$

Status and Prospects

HERA data are an indispensible tool to learn what to expect in QCD processes at LHC and to test improved theoretical models

HERA-I analysis ongoing ($\sim 100\,\mathrm{pb}^{-1}/\mathrm{expt.}$)

HERA-II just starting ($\rightarrow\sim 1\,\mathrm{fb}^{-1}/\mathrm{expt.}$, polarised leptons.
Upgrades to Si, forward trackers, triggers $\rightarrow$ heavy flavours, high x . . .)

Theoretical errors already limiting precision in many areas *(HELP!)*

Need to focus effort on most important measurements for LHC preparations *(HELP!)*