QCD results from colliders

2007 Aspen Winter Conference

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U. Wisconsin - Madison

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Outline:

Parton Density Functions & Structure Functions

Jets & Measurements of α_S

Multijets, Inclusive Jets, W + Jets, Dijets

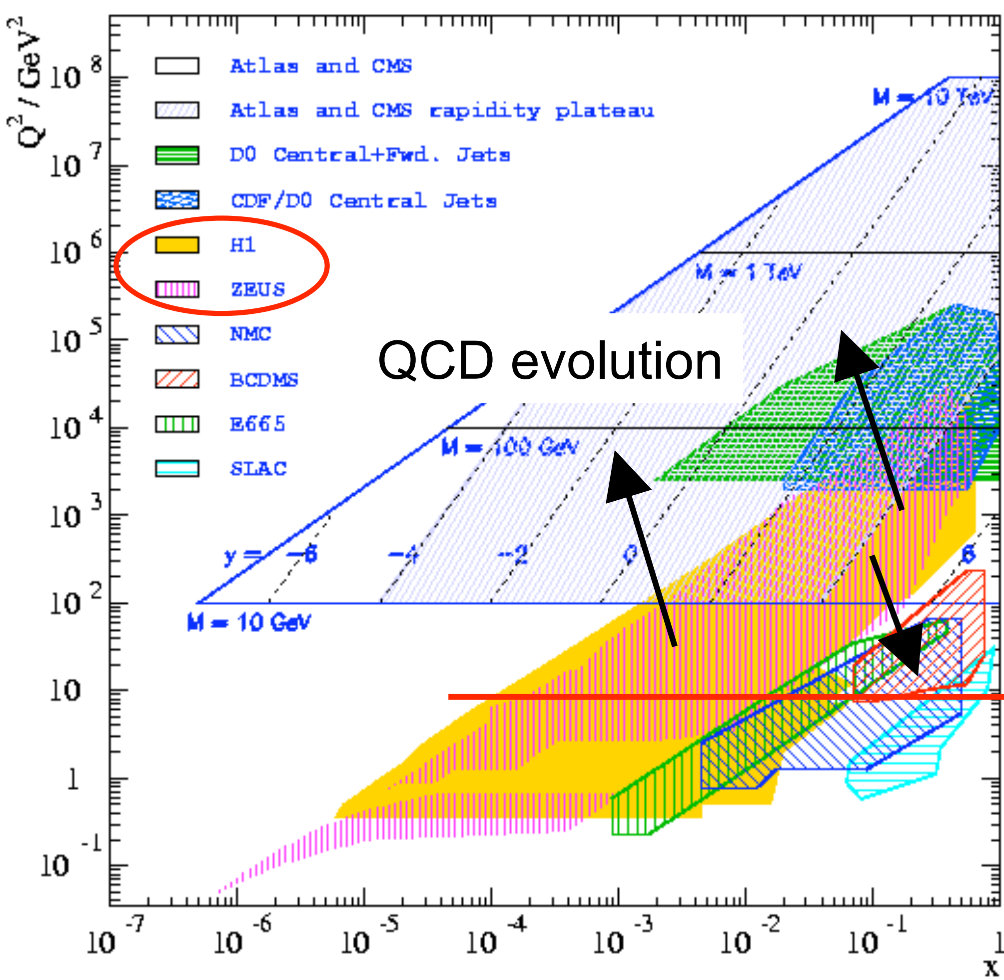
Prompt Photons

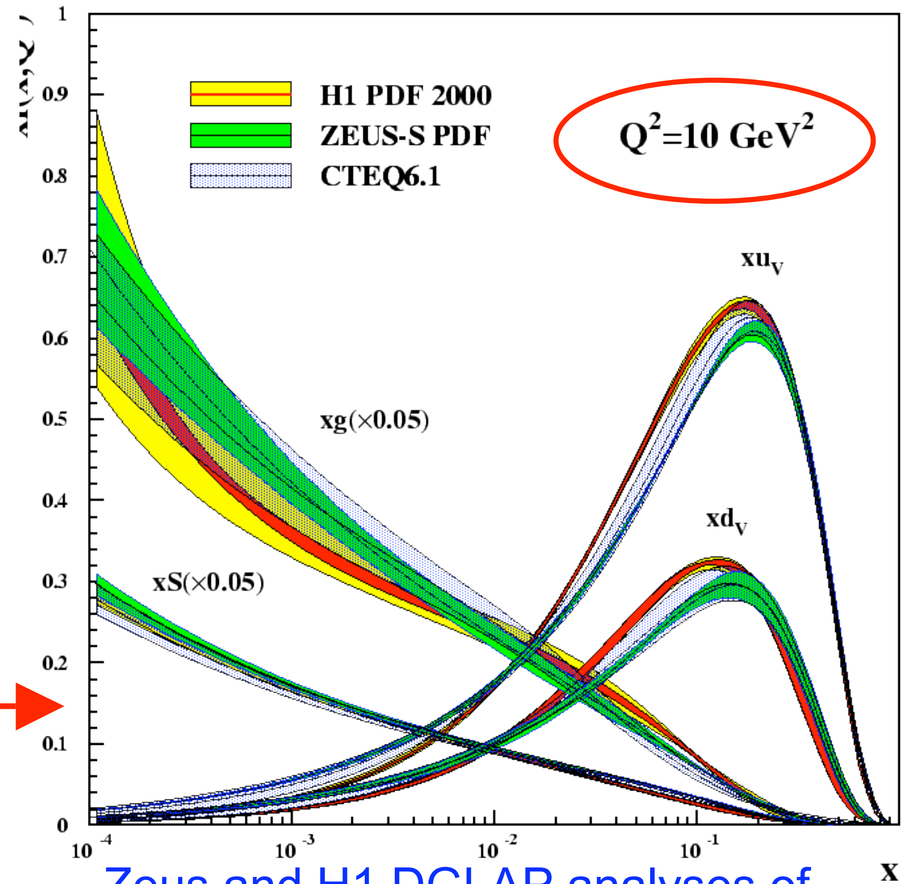
Diffraction

This talk is available on:

http://www.hep.wisc.edu/wsmith/files/exp_qcd_smith_aspen07.pdf

HERA Parton Densities





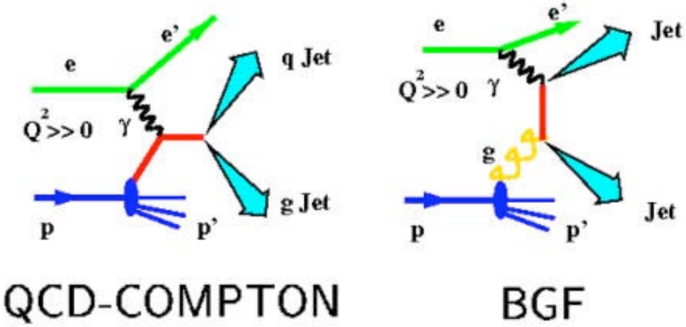
HERA PDFs essential for LHC

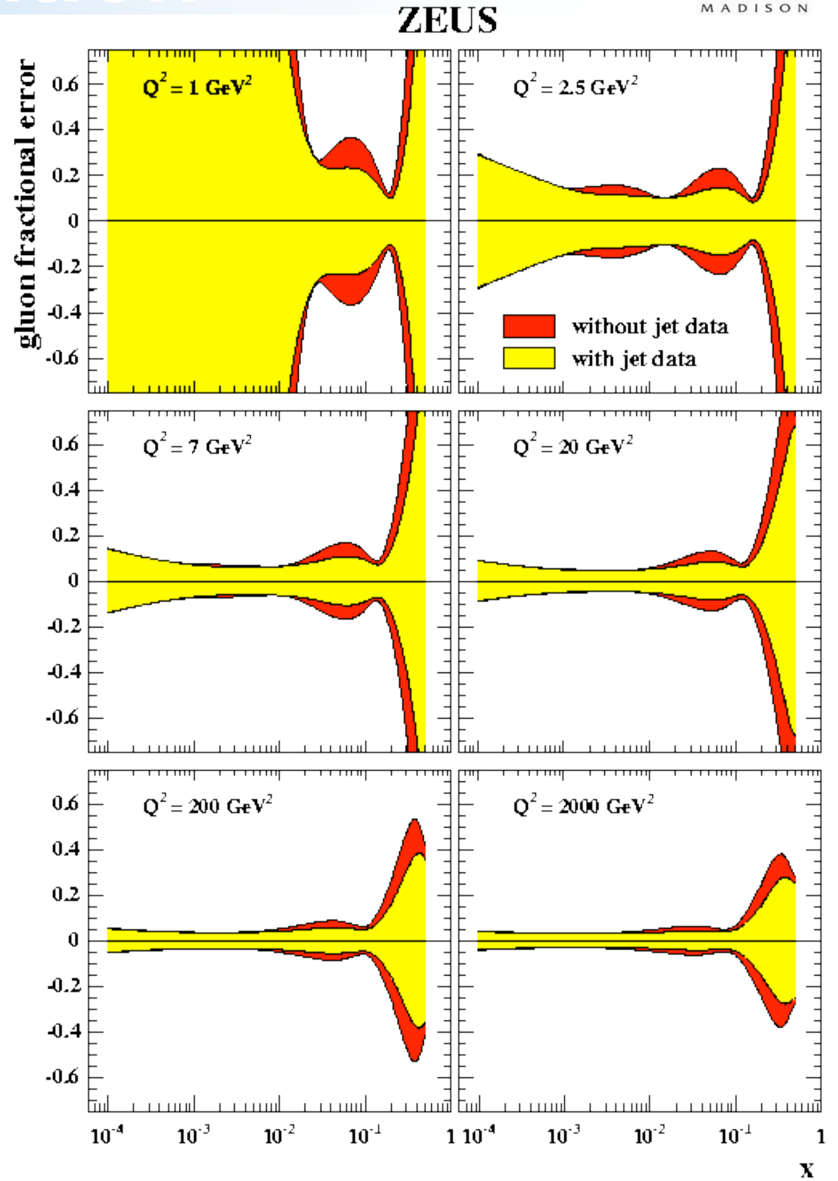
Zeus and H1 DGLAP analyses of HERA-I (130 pb^{-1}) and fixed target) data:

→ H1 2000 PDFs

→ ZEUS-S PDFs

Jets at HERA constrain gluon distribution





First fit using HERA incl and jets data

- HERA-I inclusive cross sects
- Inclusive jet cross sects in NC DIS
- Dijet cross sects in photo-production

Data from one Experiment only:

- Syst unc. well understood
- No fixed target unc.
- Valence quarks from high-Q^2 NC and CC cross sections

Jet data help to constrain the gluon and α_s:

- Reduction of gluon unc. by ~ factor 2 for $0.01 < x < 0.4$
- Precise determination of α_s

Measurement of F_L at HERA

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2(x,Q^2) - y^2 F_L(x,Q^2)\right]$$

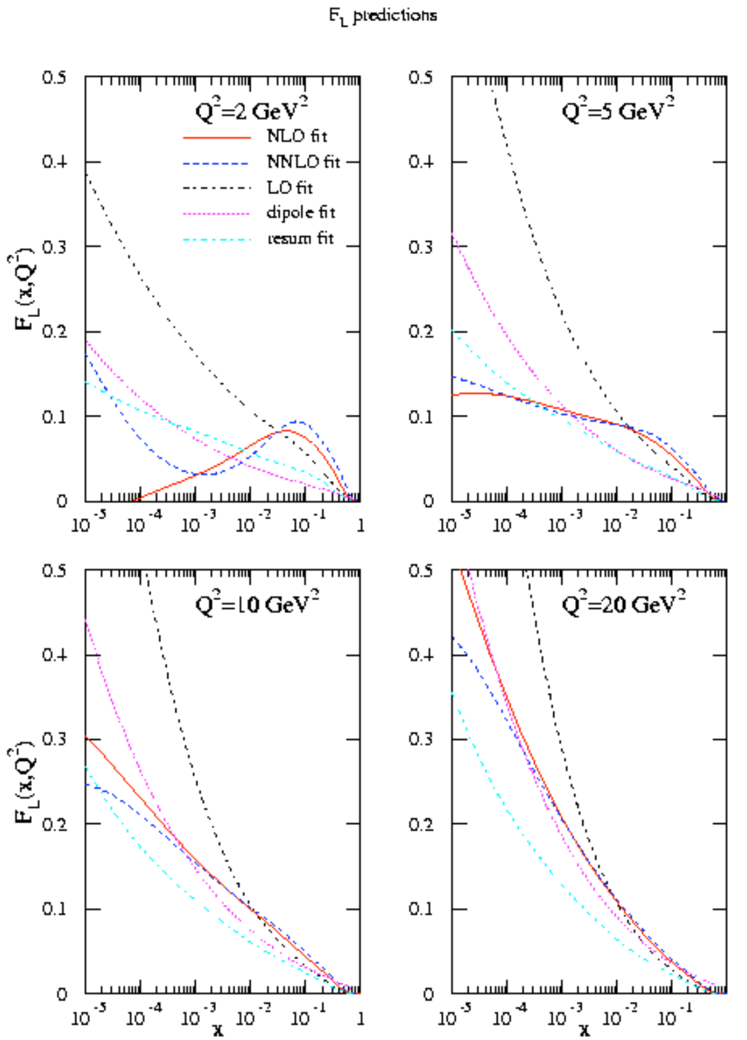
$$Y_+ = \left(1 + (1-y)^2\right)$$

$$F_L = \left(\frac{Q^2}{4\pi^2\alpha}\right)\sigma_L$$

Directly connected to the gluon distribution dominant at low-x
Predictions are still very uncertain

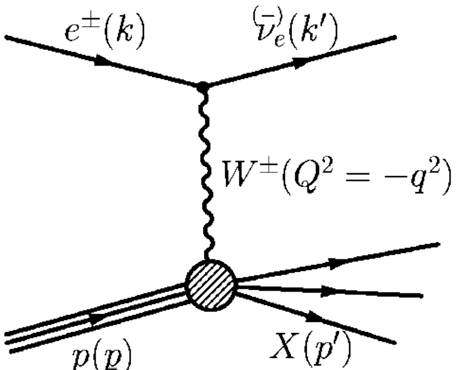
$$F_L = \frac{\alpha_S}{4\pi} x^2 \int_x^1 \frac{dz}{z^3}\left[\frac{16}{3}F_2 + 8\sum e_q^2 (1 - x/z) zg\right]$$

Martin,Stirling,Thorne



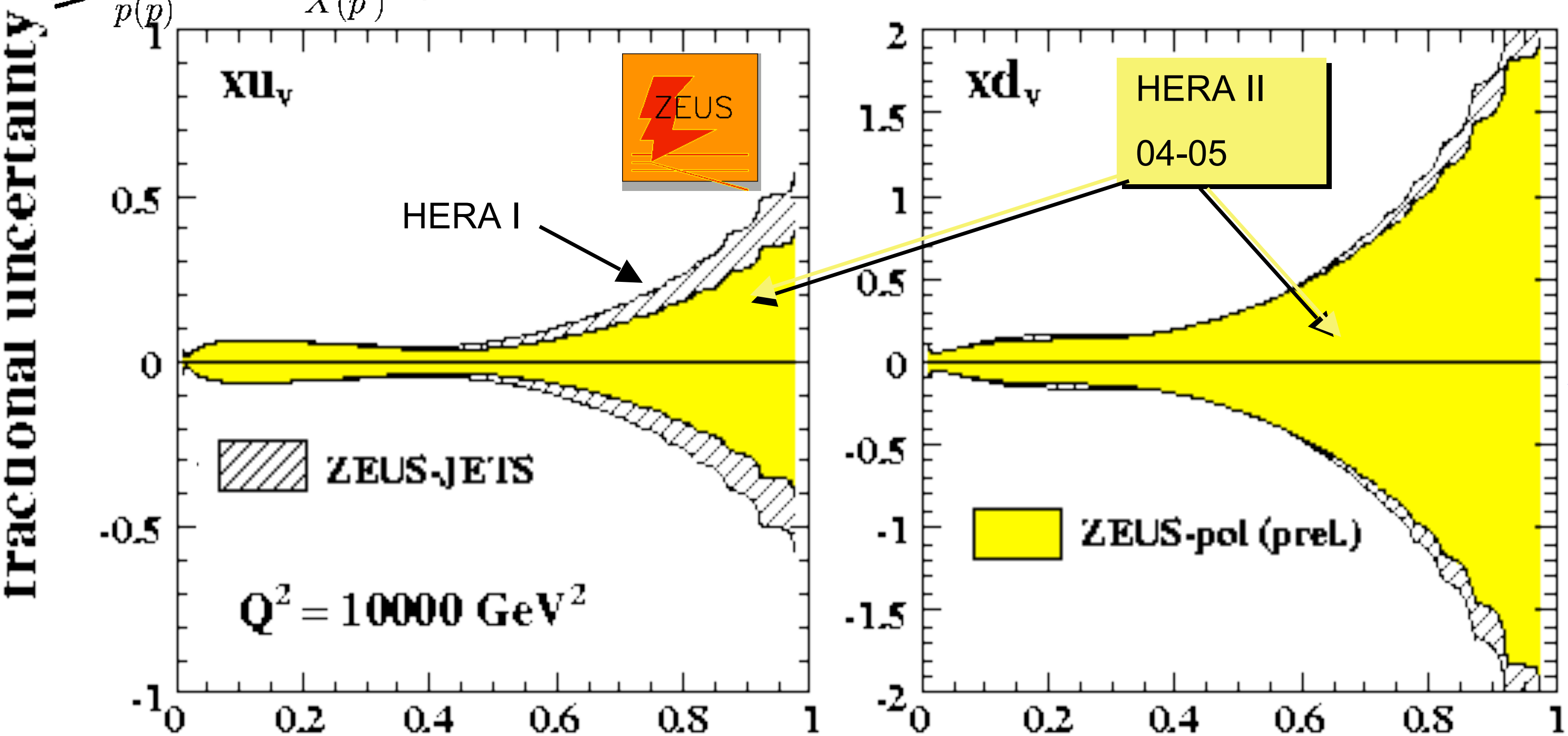
- Need to measure cross sections at same x, Q^2 and different y.
- To change $y=Q^2/xs$, HERA changes s by lowering E_p to 460 GeV
- The price in integrated luminosity is a factor of $4 \rightarrow 10\ \text{pb}^{-1}$ requires 3 months

HERA Charged Current Scattering: sensitive to u, d valence at high Q^2



$$\frac{d\sigma^{e^+p}_{unpolCC}}{dQ^2 dx} = \frac{G_F}{2\pi} \cdot \left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 \left[\bar{u}_i(Q^2,x) + (1-y)^2 d_i(Q^2,x)\right]$$

$$\frac{d\sigma^{e^-p}_{unpolCC}}{dQ^2 dx} = \frac{G_F}{2\pi} \cdot \left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 \left[u_i(Q^2,x) + (1-y)^2 \bar{d}_i(Q^2,x)\right]$$



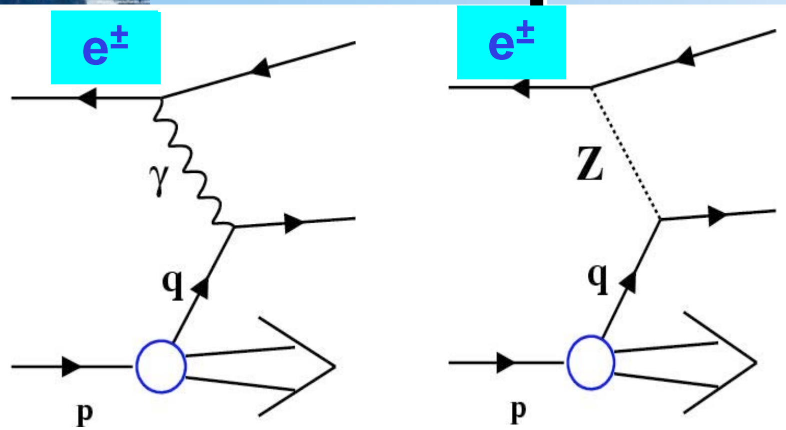
more e^- data: 16 pb^{-1} → 122 pb^{-1}

Central values unchanged

Uncertainty on u_V reduced

HERA-I: 130 pb^{-1}, HERA-II: 350 pb^{-1} with $e^{\pm}$ polarization so far -- stops June 30.

Neutral Currents vs. lepton charge: xF_3

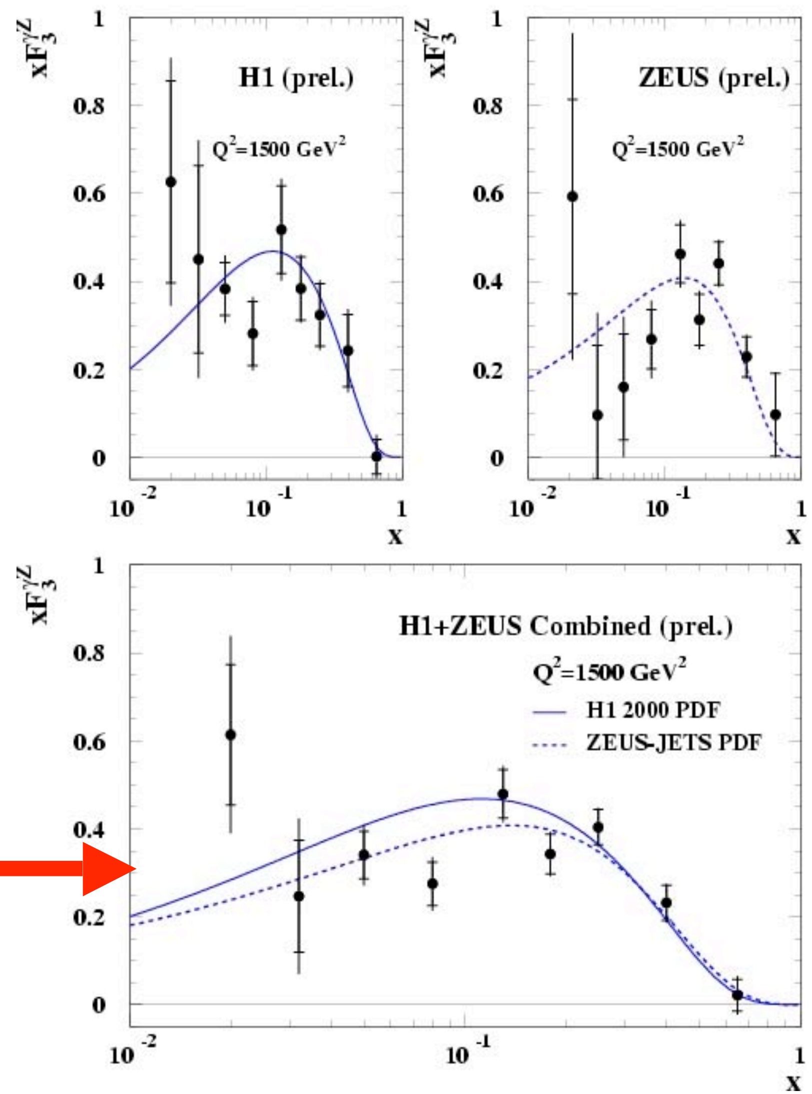


γ-Z interference flips sign when $e^+ \rightarrow e^-$

→ Add all e^+p (and e^-p) data, correct for residual pol. → σ^+, σ^-

$$xF_3^{\gamma Z} = \frac{Y_+}{2ka_eY_-} \cdot (\sigma^+ - \sigma^-) \simeq \frac{x}{3}[2u_v + d_v]$$

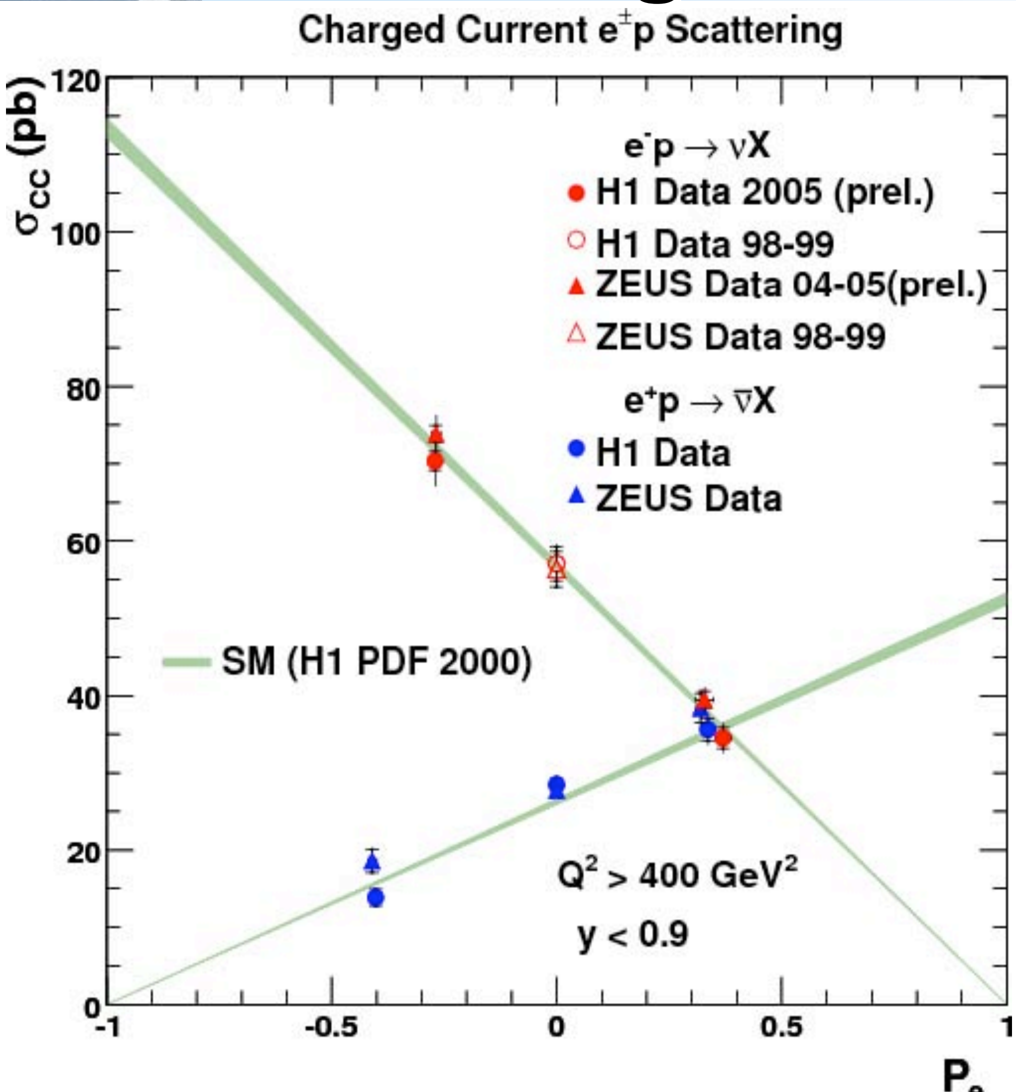
HERA I + II

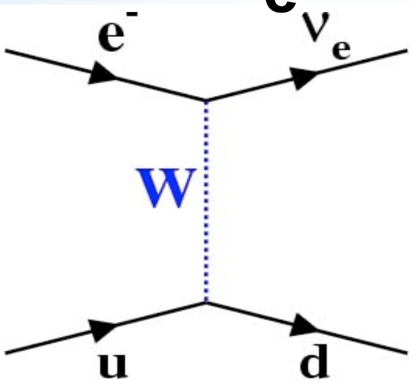


H1 & ZEUS combined data

→ Add to the knowledge of valence quarks at lower x

Electroweak tests: Charged current vs P_e





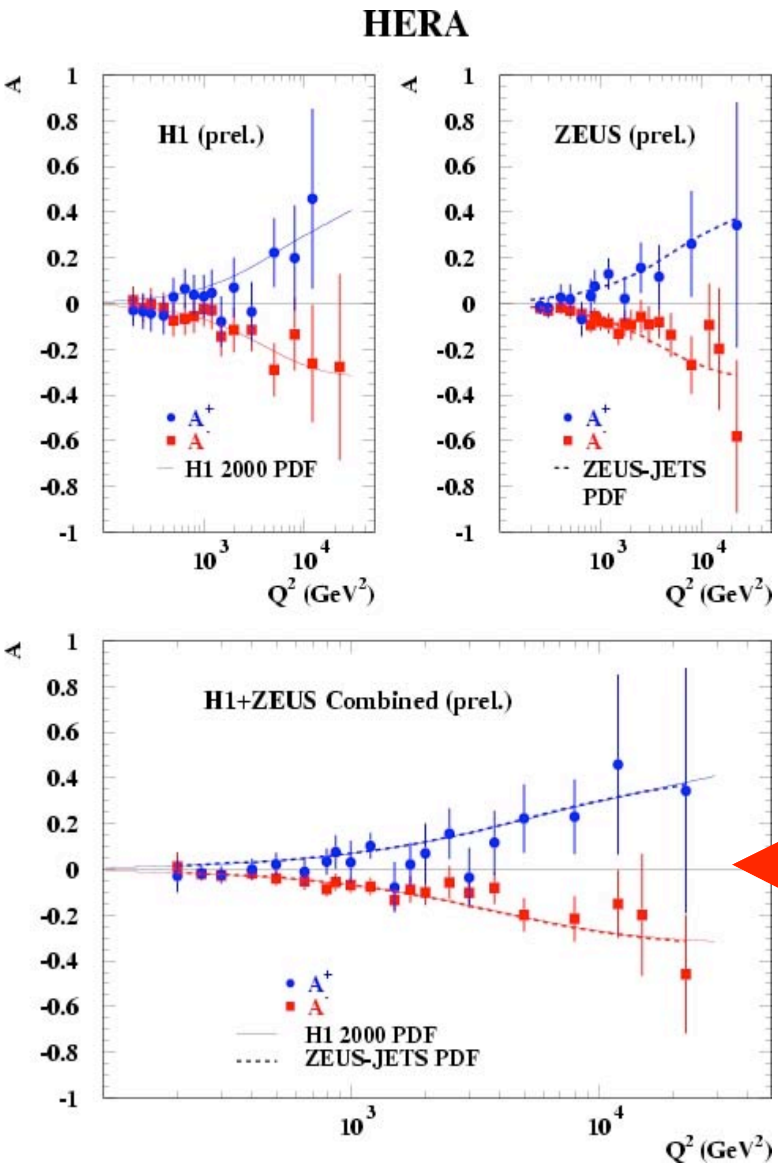
$$\sigma^{e^\pm p}_{\mathrm{polCC}}(Q^2,x) = \frac{1 \pm P_e}{2} \cdot \sigma^{e^\pm p}_{\mathrm{LHCC}}(Q^2,x)$$

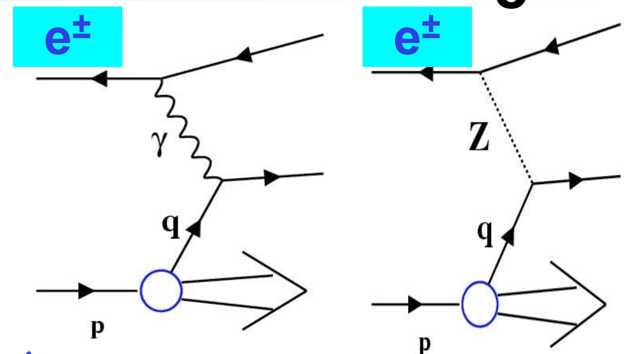
→ Demonstrates absence of RH charged currents

→ $M(W_R)$ > ~180-208 GeV with current precision

Polarized electron-proton scattering at HERA

Electroweak tests: Neutral currents vs P_e





→ **Use prelim. H1 and ZEUS $e^{\pm}p$ data from 2003-2005**

$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

~ Parity violating $a_e v_q$ terms

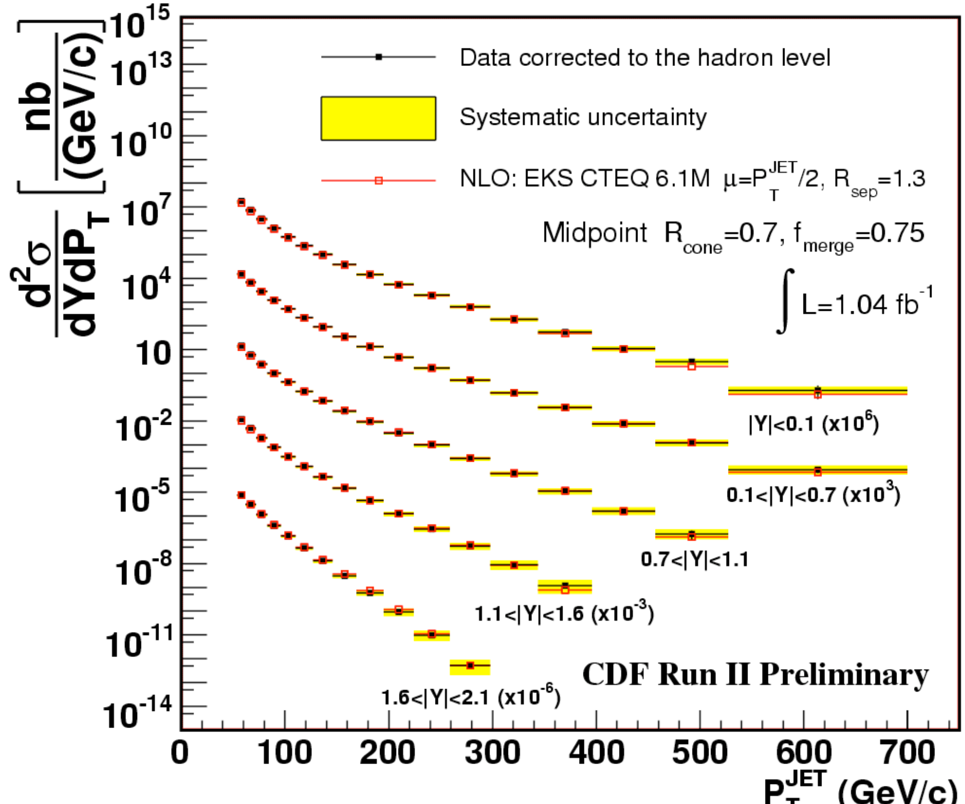
H1 & ZEUS combined data

→ **First observation of parity viol. in NC $e^{\pm}p$ data at $R < 10^{-18}$ m**

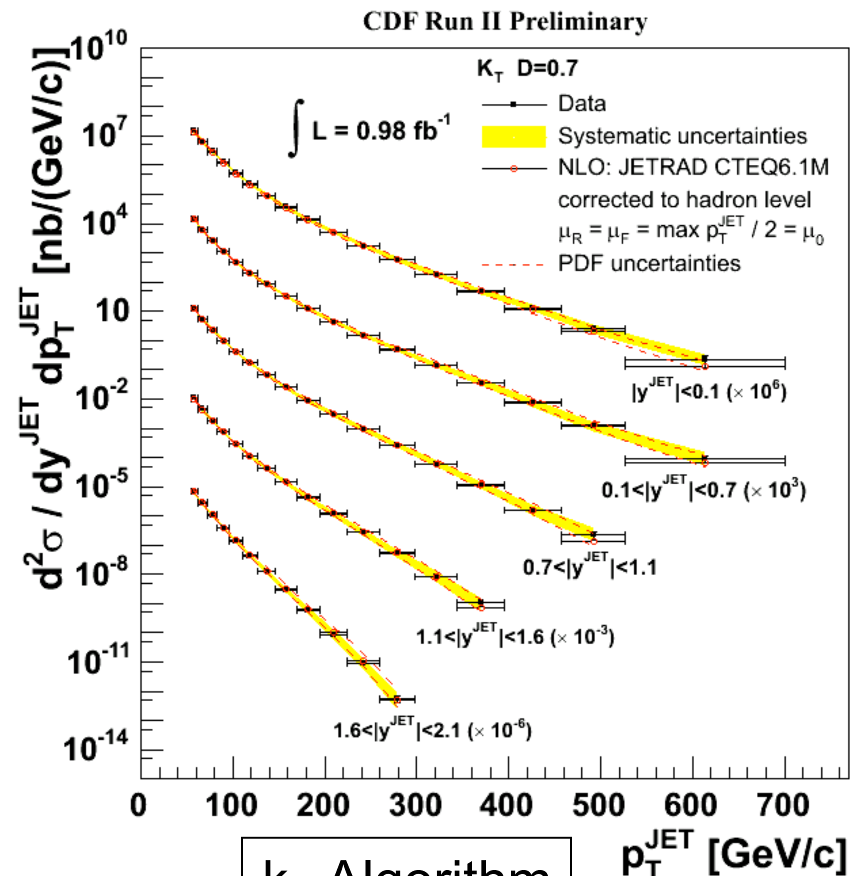
High p_T jets at the Tevatron

In 2005: CDF published both central cone and k_T jets with $400 pb^{-1}$

Now: new preliminary results with full rapidity coverage for $1 fb^{-1}$

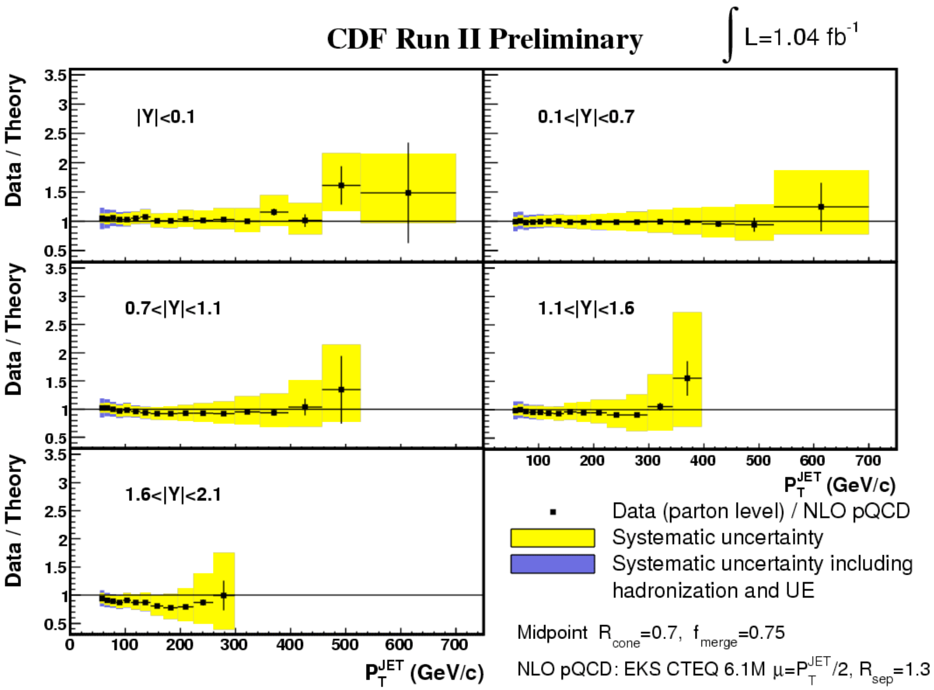


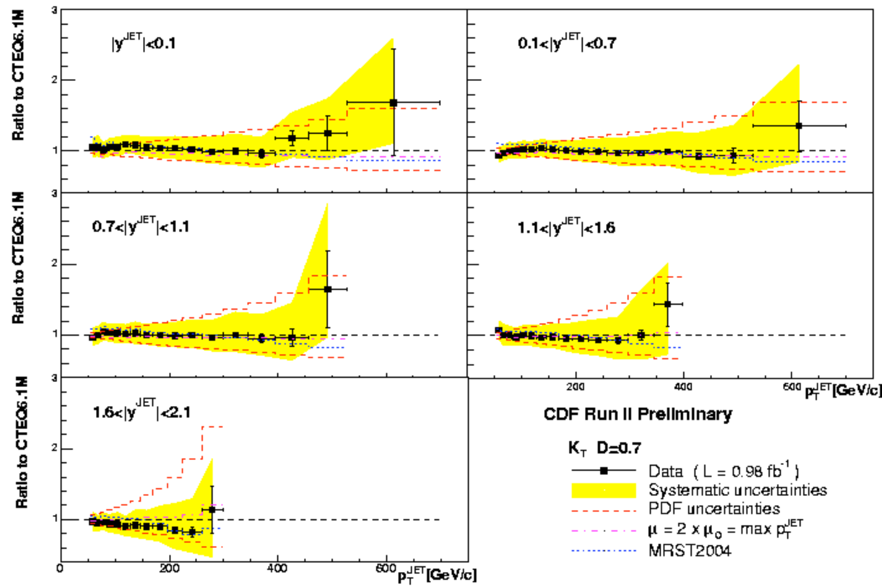
Midpoint Searchcone Algorithm



k_T Algorithm

Tevatron Inclusive Jets: cone & k_T





Midpoint Searchcone Algorithm

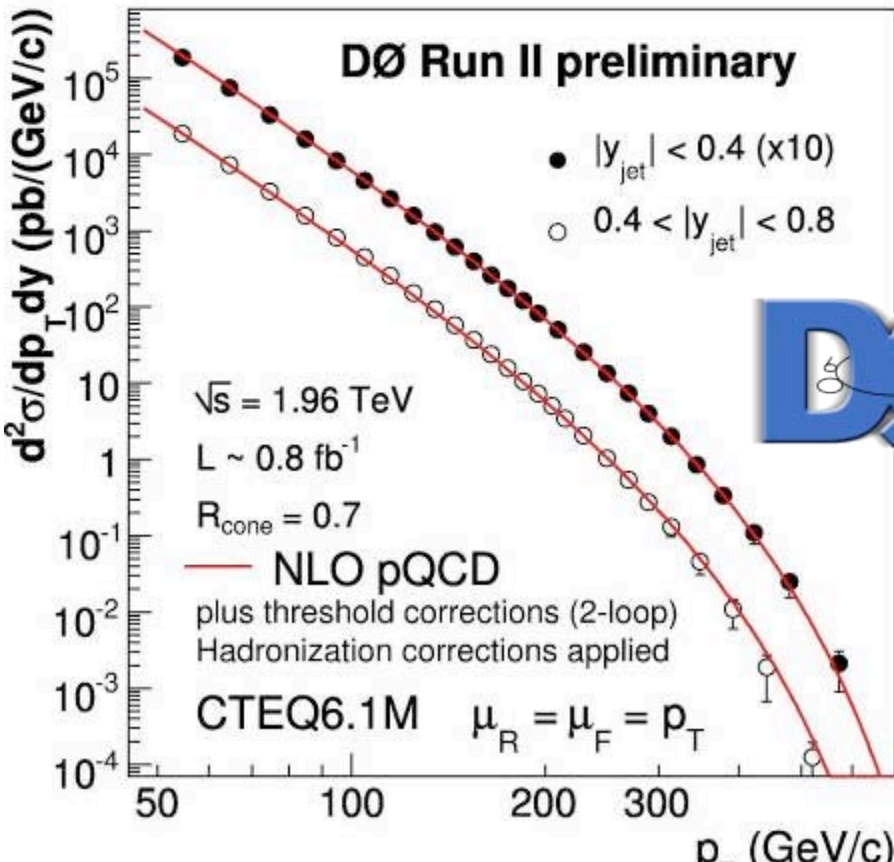
k_T Algorithm

Data are well-described by NLO pQCD

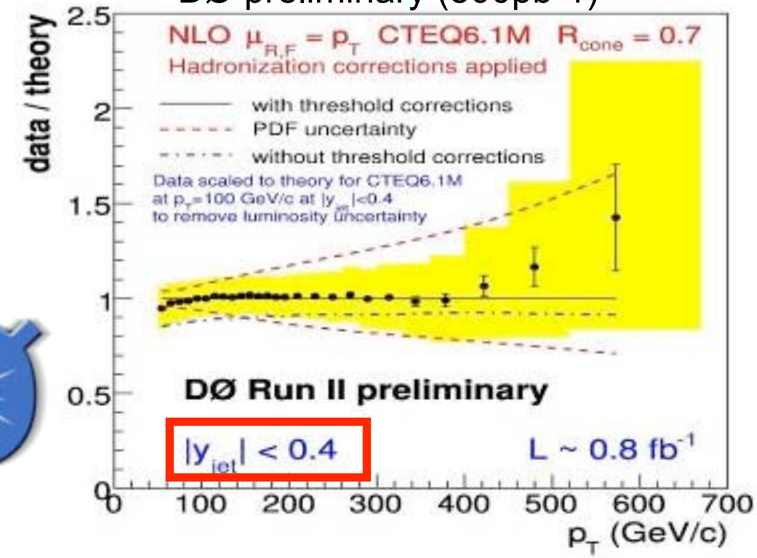
Experimental Uncertainties: Smaller than PDF Uncertainties!!

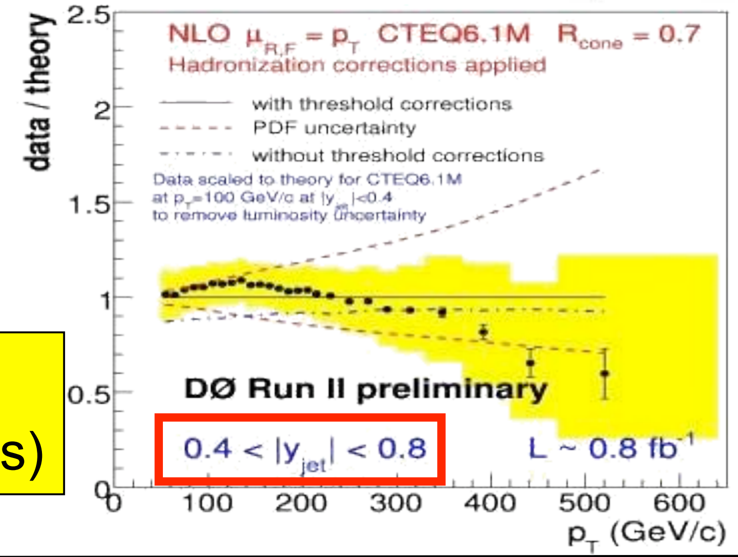
(only shown for kT Algorithm)

Inclusive Jet Cross Section



DØ preliminary (800pb-1)

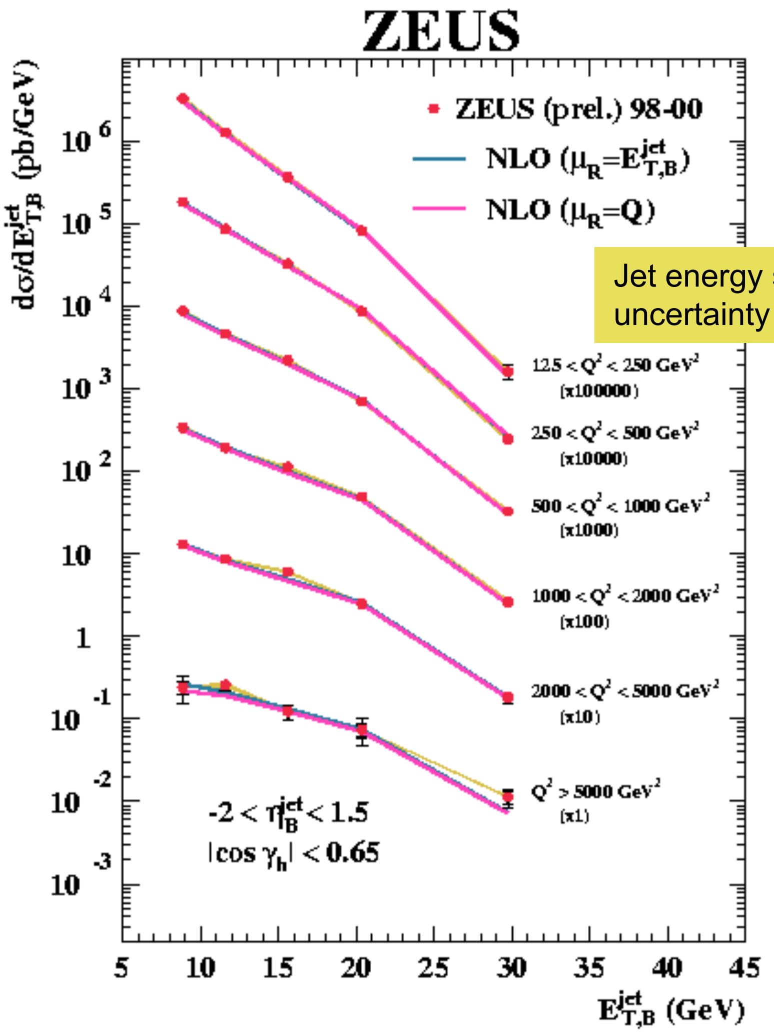




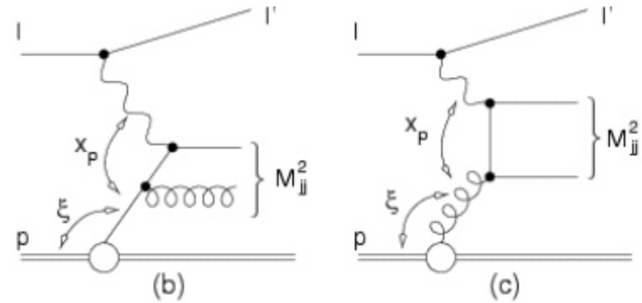
Compare to NLO pQCD + 2-loop Threshold Corrections (Kidonakis, Owens)

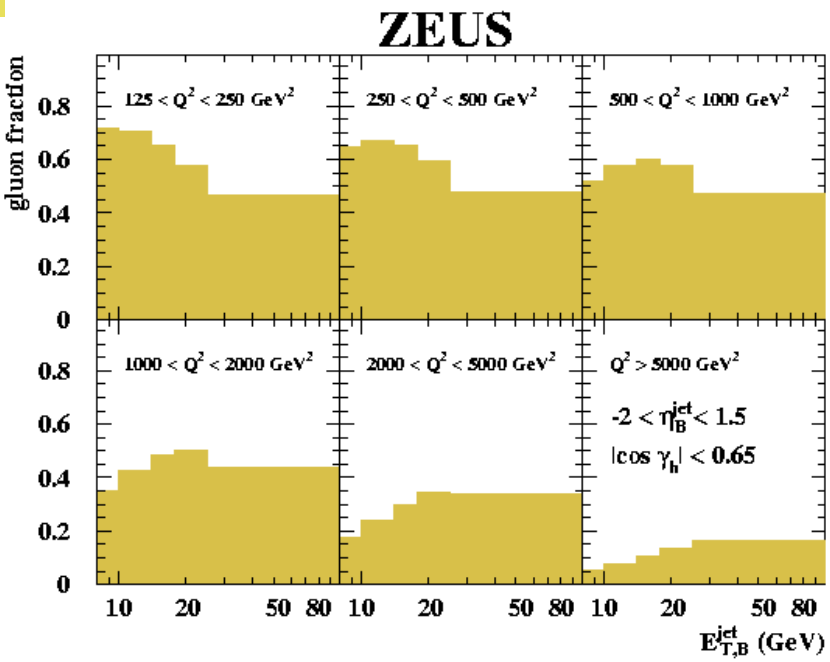
→ Sensitive to PDFs!! -- esp. Gluon!

New DIS Jet data: gluons & α_S



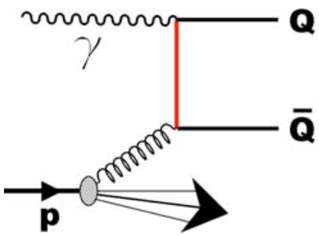
Jet energy scale uncertainty of 1%





These measurements will provide additional constraints for the gluon distribution at middle *x*; and give a measurement of α_S

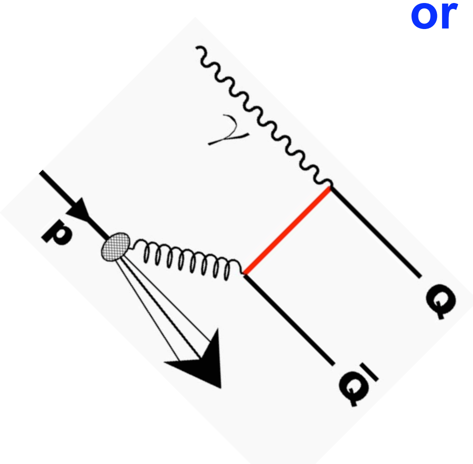
charm contribution to F_2



c massive

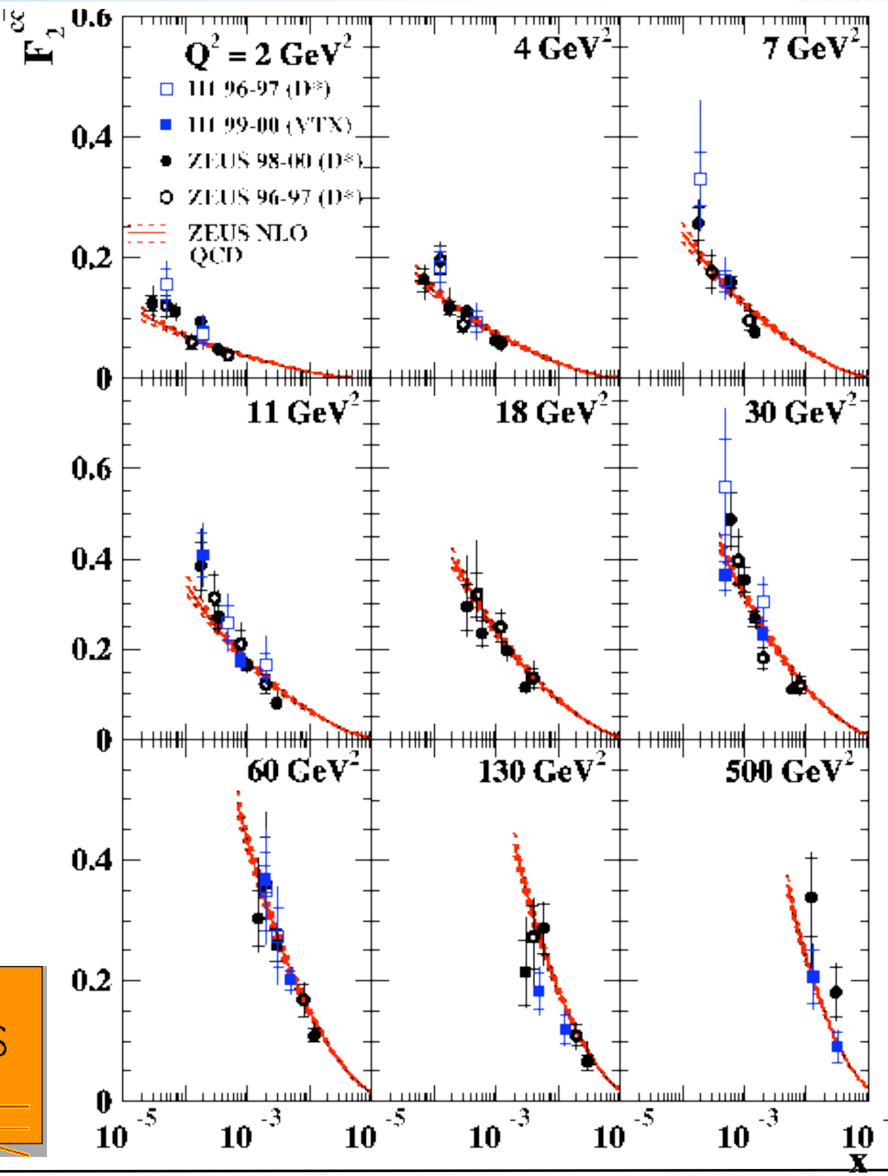
→ test/constrain gluon density

or

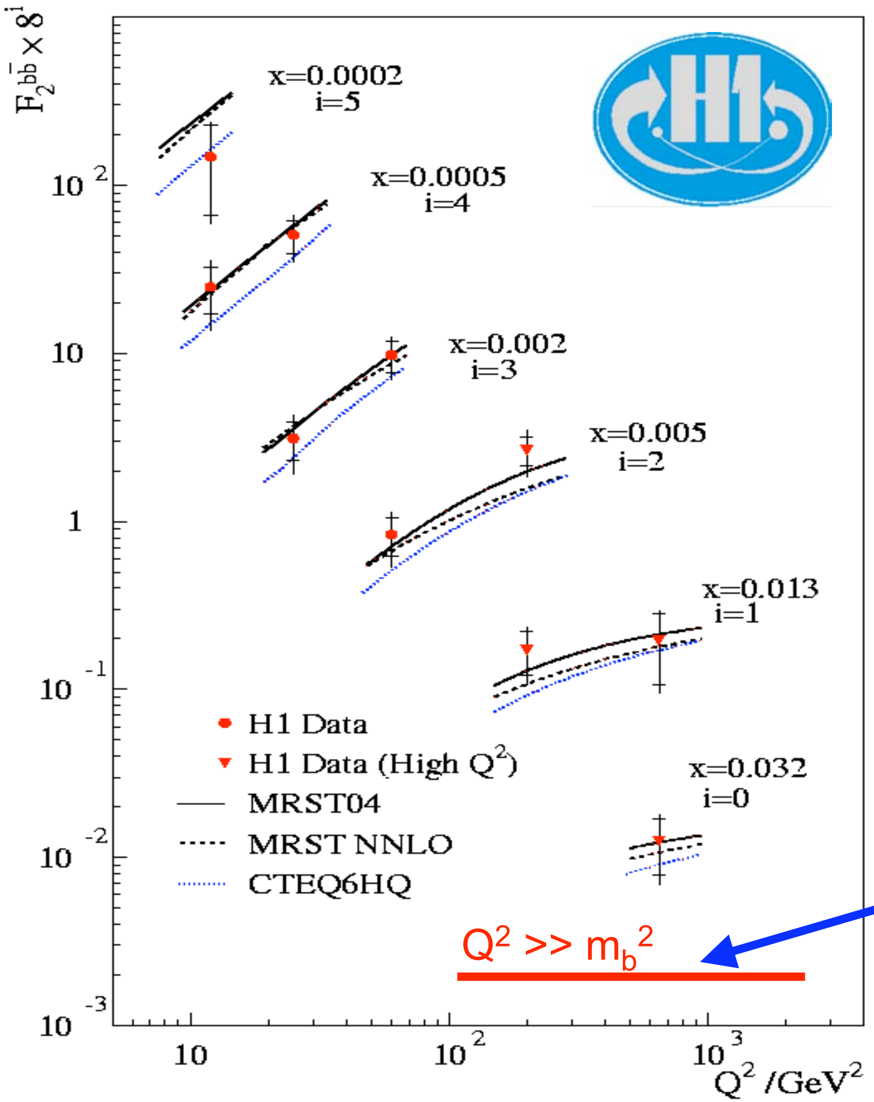


c massless
($Q^2 >> m_c^2$)

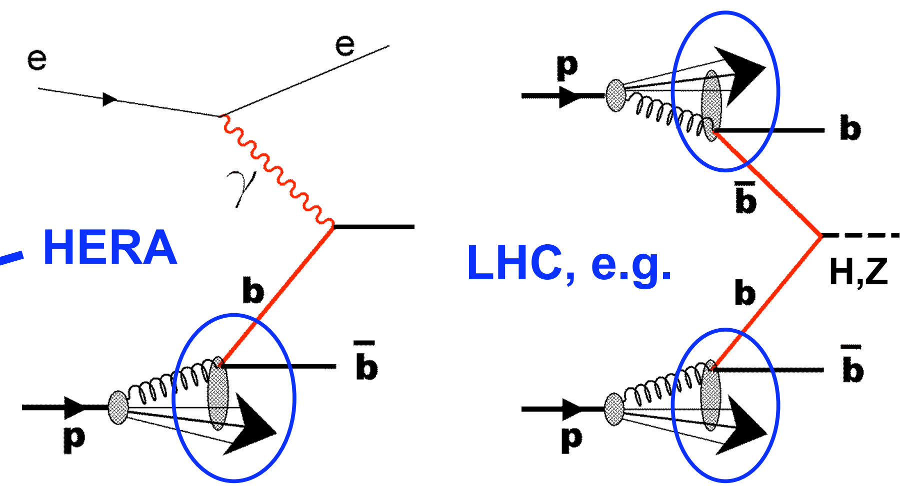
→ obtain virtual charm content
(charm PDF) of proton



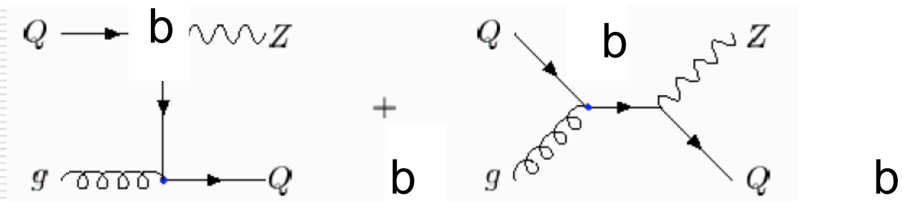
Beauty contribution to F_2

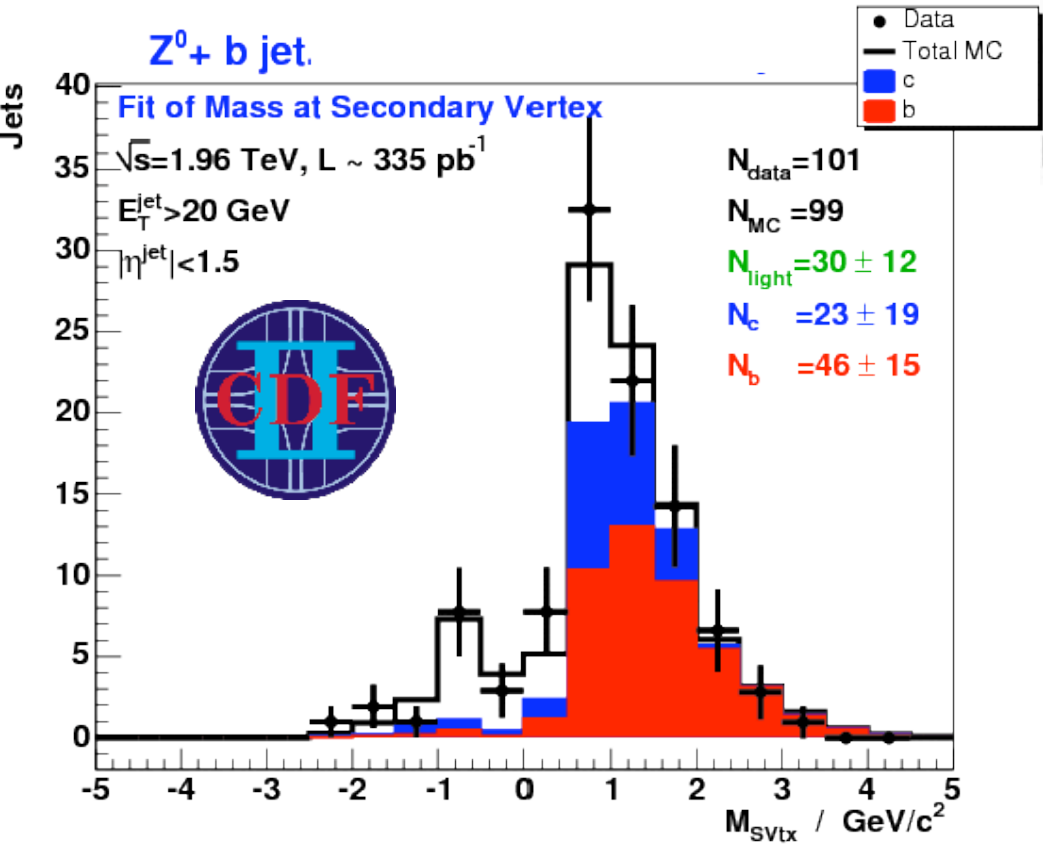


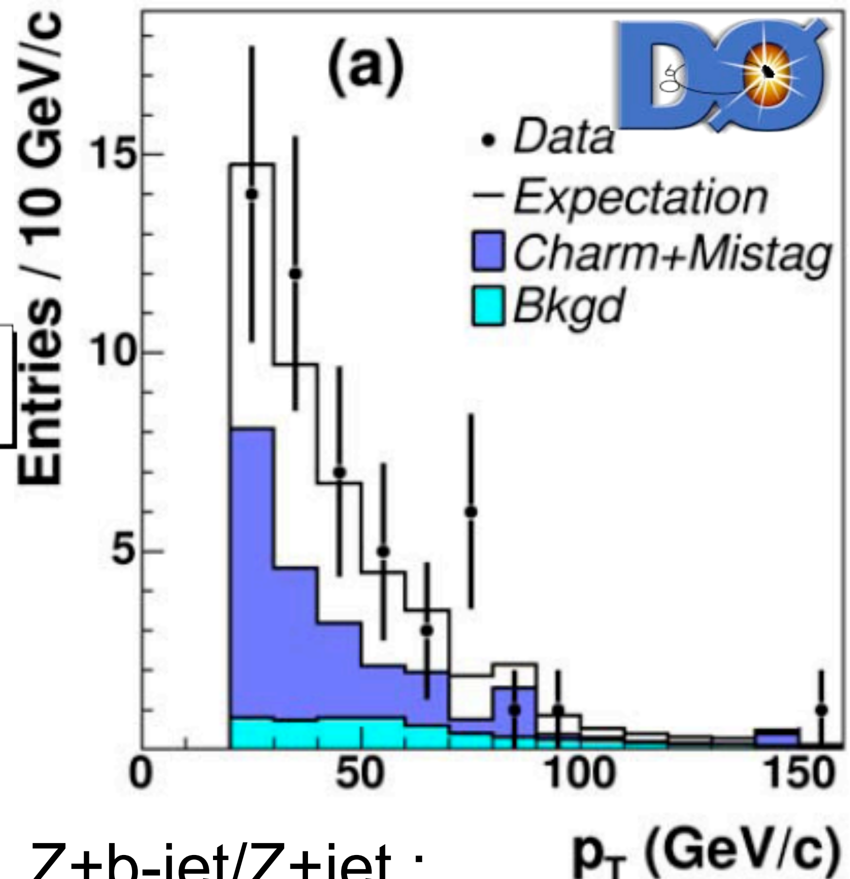
- first measurement of F_2^{bb}
- first NNLO calculation
- data in agreement with NLO and NNLO
- checks b PDF for LHC:



Probe b PDF with Z+b-jet at Tevatron







Z+b-jet/Z+jet :

CDF: 2.4+-0.7(stat) +-0.5(sys) %

D0: 2.1+-0.4(stat) +0.3-0.2(sys) %

NLO: 1.8+-0.4 % (CTEQ6)

OK✓

can Tevatron results be used for LHC?

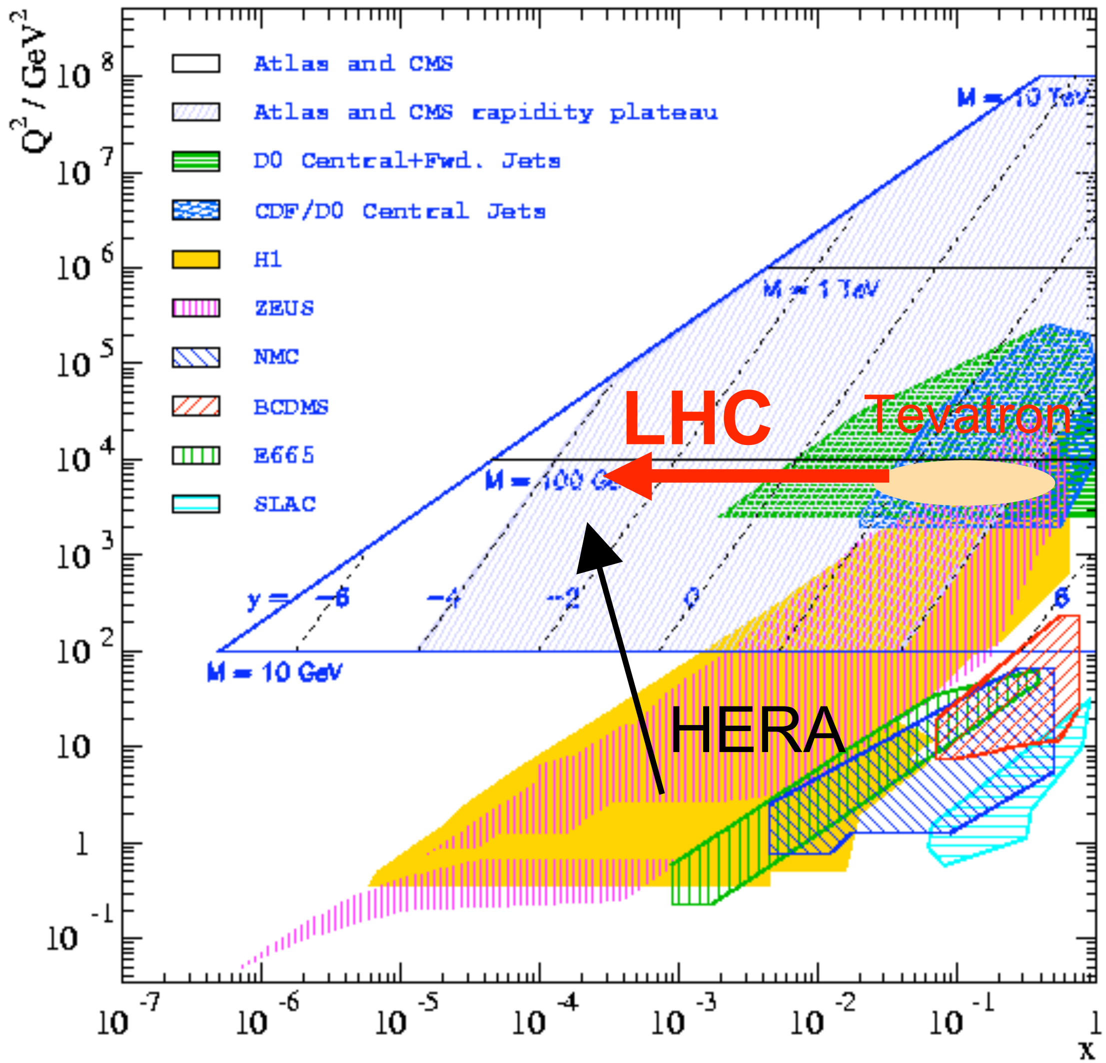
Are PDFs measured thus far applicable?

Does DGLAP QCD evolution work sufficiently to extrapolate?

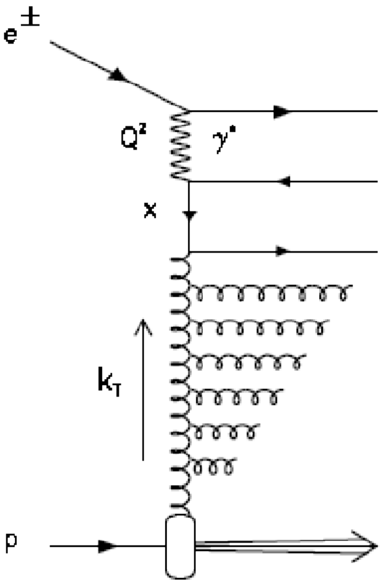
Need to take care of low-x effects:

- saturation
- multiple interactions

BFKL vs. DGLAP
→ study at HERA



Evolution & Resummation

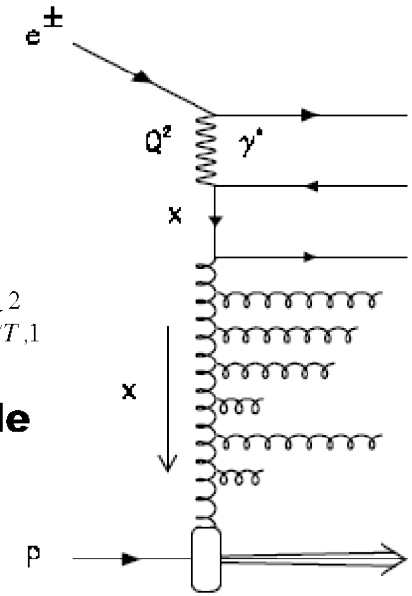


DGLAP

Evolution & resummation in powers of *lnQ2*

$$Q^2 >> k_{T,n}^2 >> ... >> k_{T,2}^2 >> k_{T,1}^2$$

The DGLAP gluon cascade is strongly ordered in k_T and ordered in x



BFKL

Evolution & resummation in powers of *ln(1/x)*

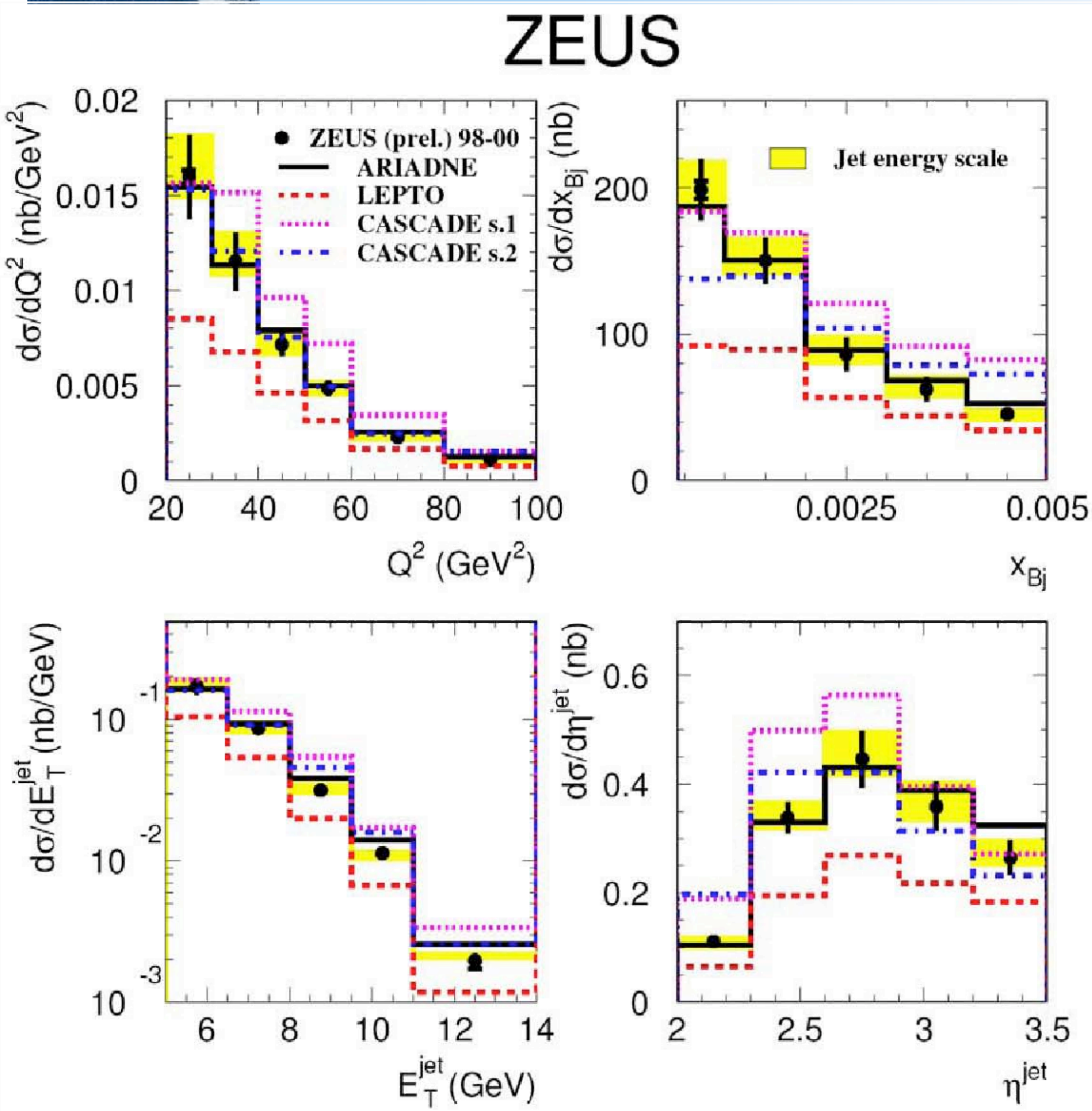
$$x_1 >> x_2 >> ... >> x_n >> x$$

The BFKL is only strongly ordered in x

←Expect more energetic jets in forward region

- **DGLAP** (**D**okshitzer-**G**ribov-**L**ipatov-**A**ltarelli-**P**arisi) is expected to break down at low *x* and Q^2 region (LEPTO, DISENT)
- **BFKL** (**B**alitsky-**F**adin-**K**uraev-**L**ipatov) can be applicable at low x (~ARIADNE)
- **CCFM** (**C**iafaloni-**C**atani-**F**iorani-**M**archesini) describes an evolution in both Q^2 and *x* and approches BFKL at low *x* and DGLAP at high Q^2; angular ordering (CASCADE)

ZEUS Forward Jets

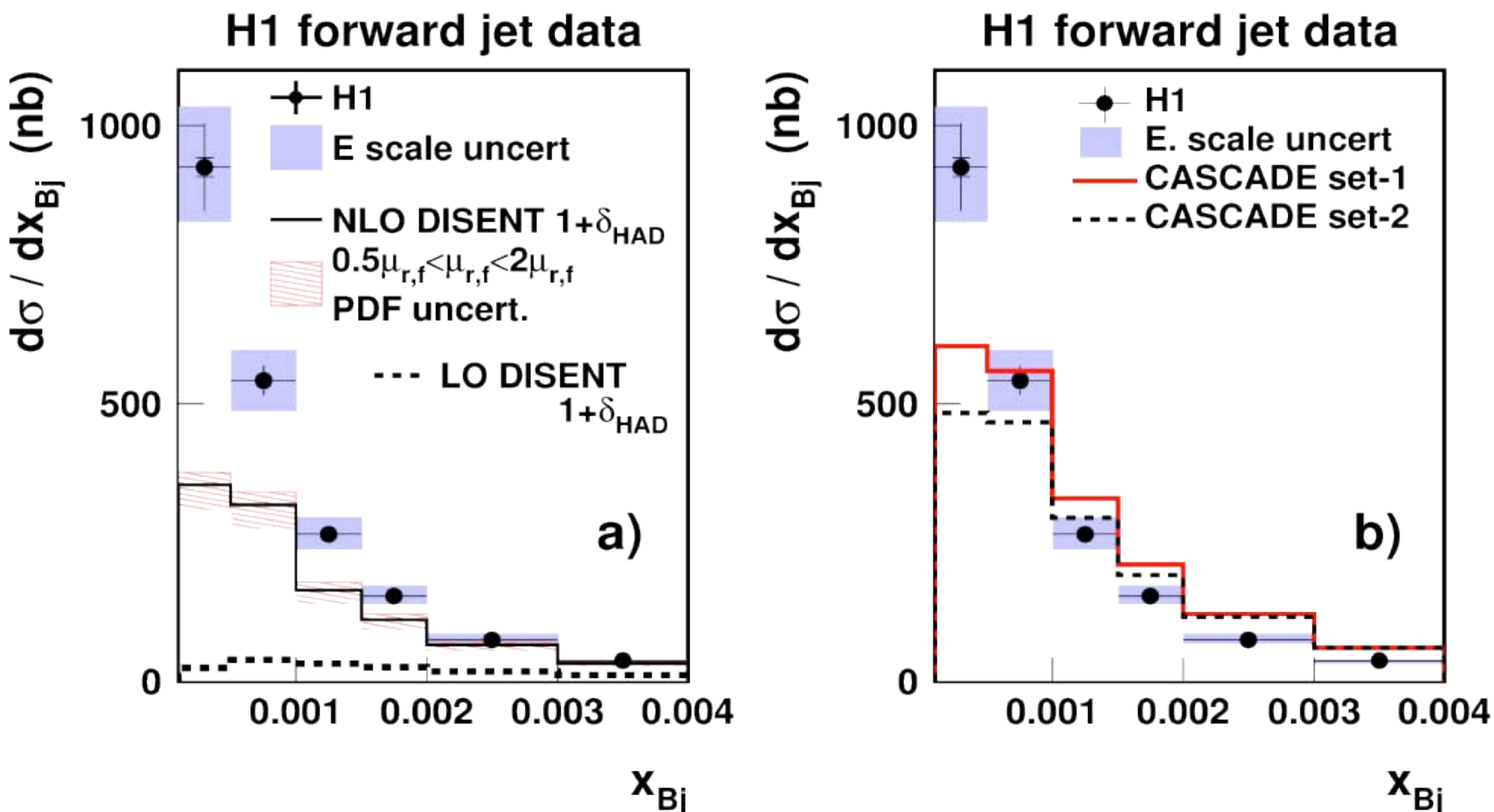


Measurement extended to $2<\eta^{jet}<3.5$

- CASCADE *set1* disagrees with all cross sections
- CASCADE *set2* (with non singular terms) is in a good agreement with data in Q^2 and E_T^{jet} but fails to reproduce the shapes of x_{Bj} and η^{jet}
- CDM (ARIADNE) gives a good description of data in all measured cross sections
- LEPTO underestimates data by a factor of 2

H1 forward jets

Forward JET: $\theta_{jet} < 20^{o}$ and $x_{jet} = E^{*}_{jet}/E_{p} > 0.035$

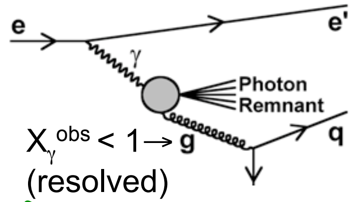


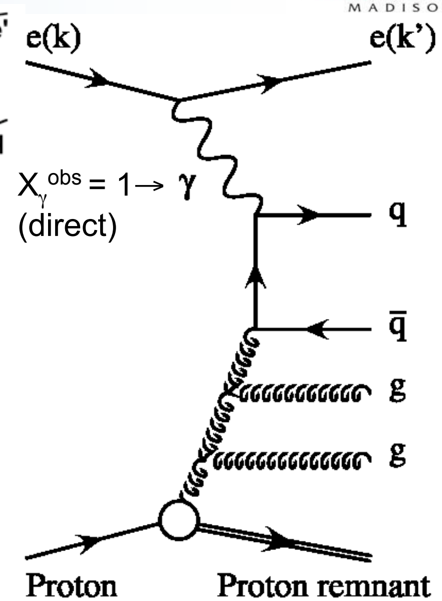
LO is suppressed by kinematics,

NLO is a factor of 2 too low, Cascade somewhat better

Multijets in photoproduction:
3-jet & 4-jet events from ZEUS

Test pQCD at higher order of α_s
- NLO calculations for $O(\alpha\alpha_s^2)$: 3 jets
- 4 jets measure $O(\alpha\alpha_s^3)$



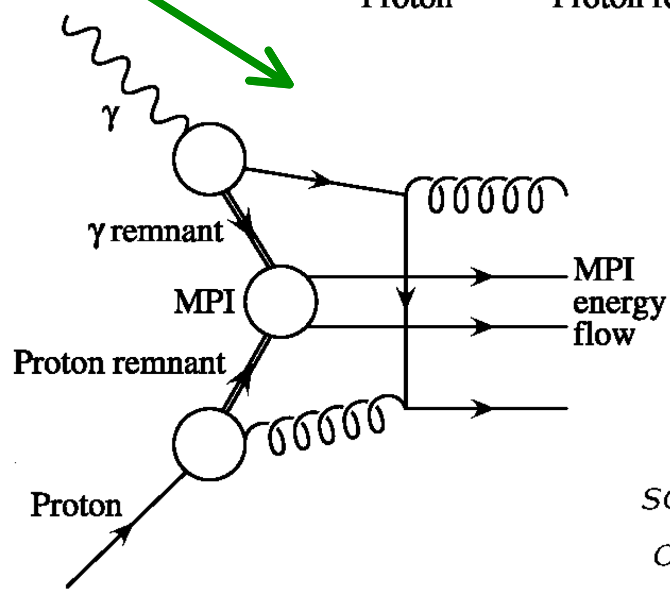


4-jet direct (tree-level)

Test of MC models (LO+PS) & Multiple Parton interactions
- MPIs and Multi-jet HFS will be abundant at the LHC

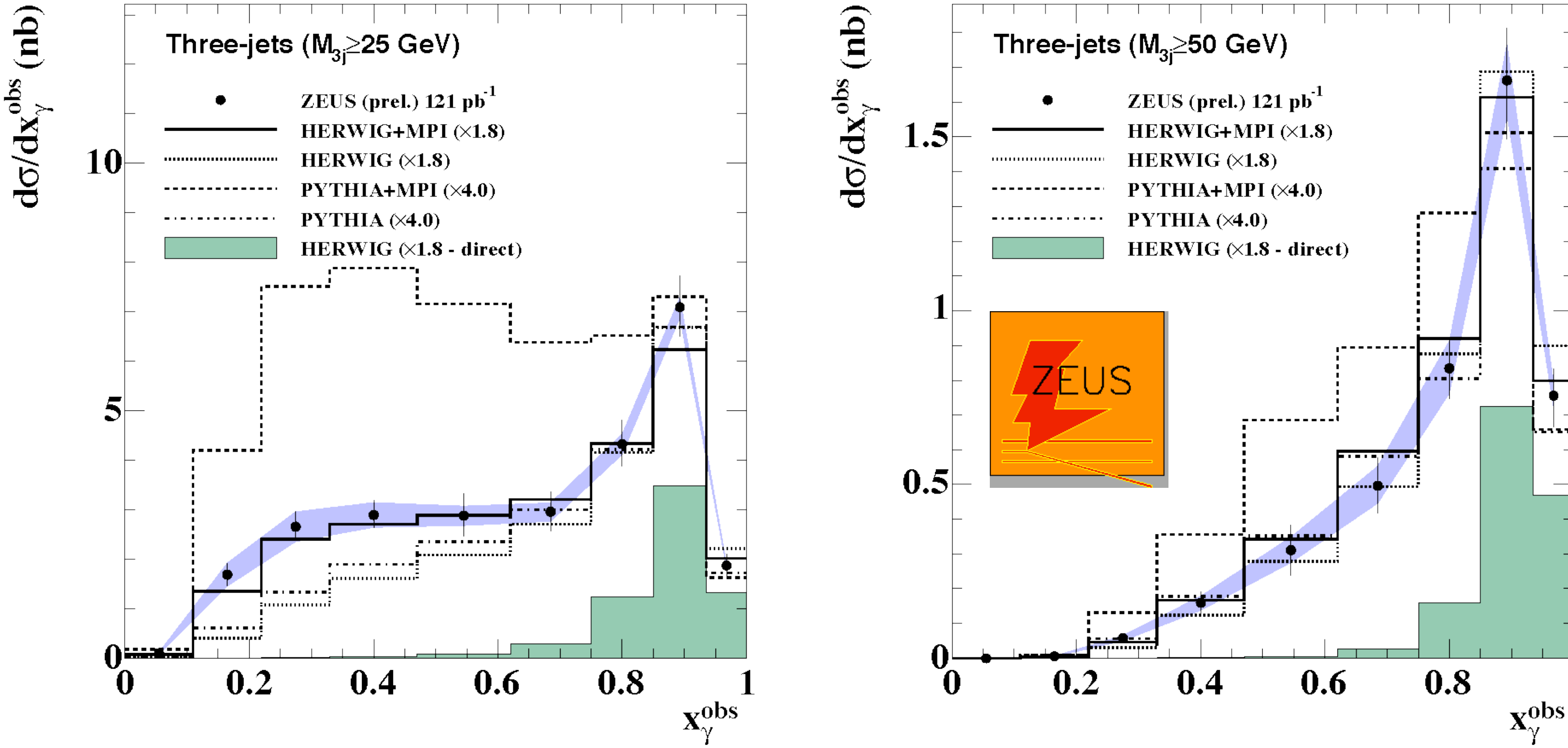
Test of parton showers (LLA) used to simulate multi-jet states in (LO ME+PS) Monte Carlos.

What's new:
- 7.5 × more lumi than existing 3-jet photoproduction results.
- 3-jets studied in more inclusive phase-space region.
- No published 4-jet photoproduction results by ZEUS or H1 yet.



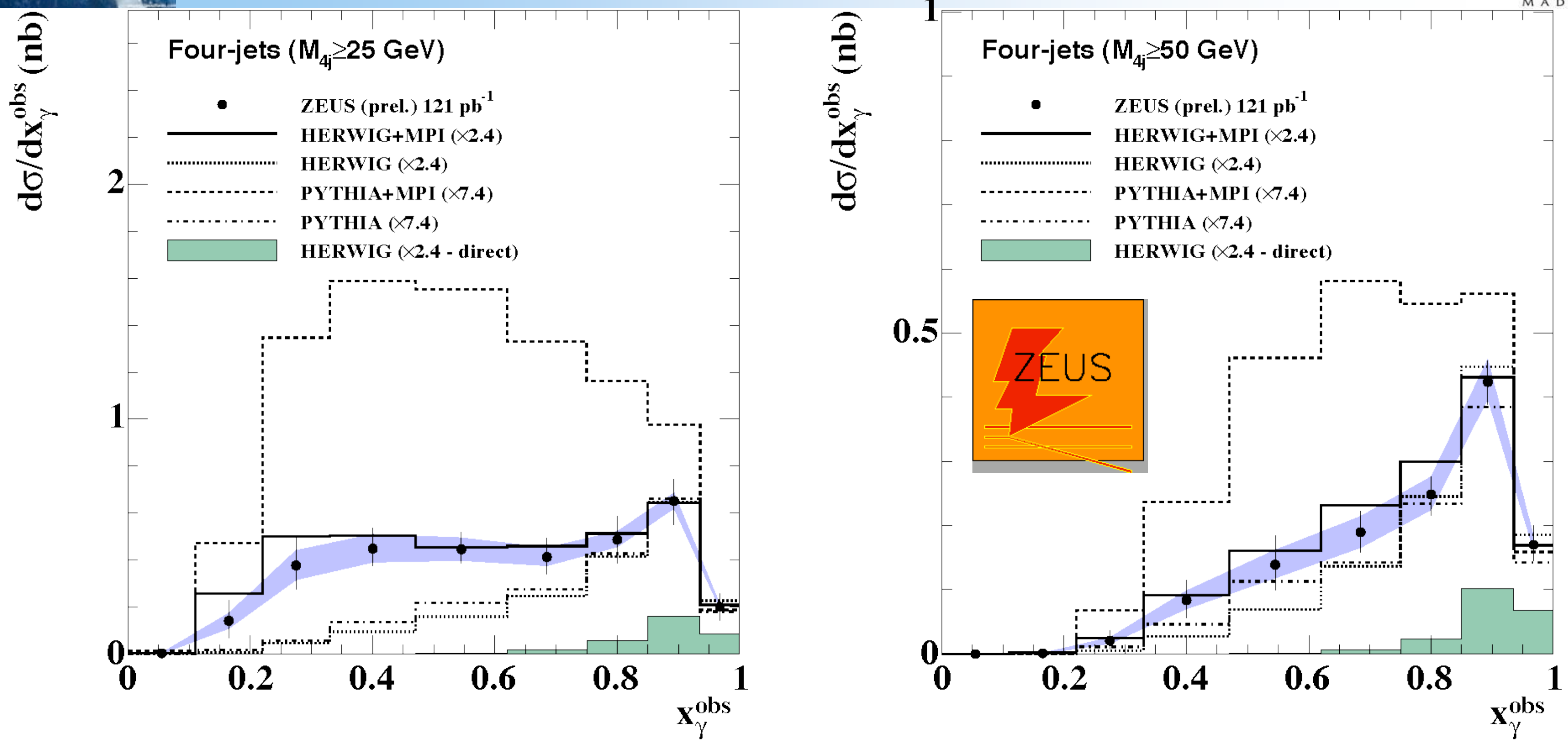
schematic of a MPI

ZEUS 3-jet photoproduction



- cross sections peak at $x_\gamma^{obs} \approx 0.9$, and are kinematically suppressed at low x_γ^{obs}.
- MC predicts peaks partly due to direct (LO definition) but significant resolved PHP contributions.
- MCs without MPIs fail to describe low x_γ^{obs} region at low M_{3j} - MC requires additional component.
- MC predicts MPIs augment low x_γ^{obs} but don't affect high x_γ^{obs} - are MPIs the missing component?
- PYTHIA MPI model predicts excessive contribution - HERWIG+MPI describes x_γ^{obs} very well.

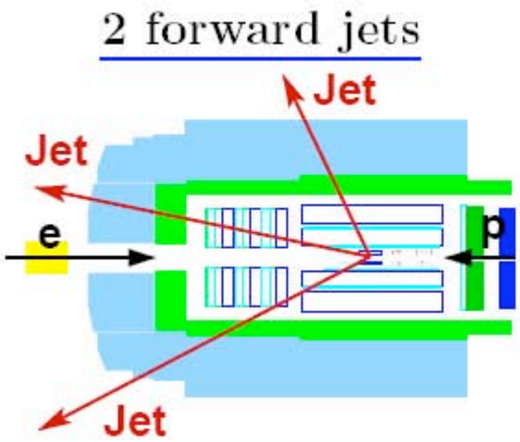
ZEUS 4-jet photoproduction

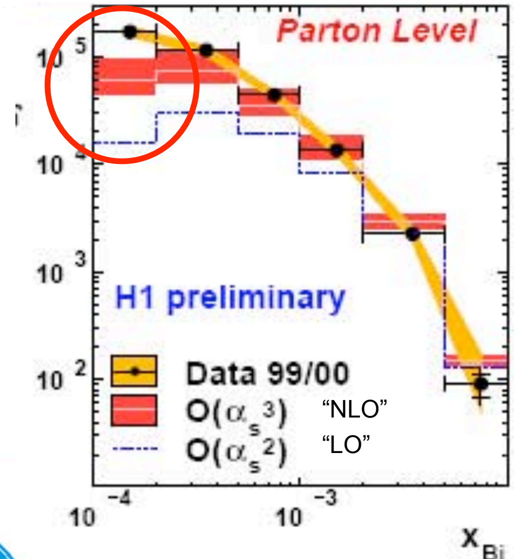


- again, cross sections peak at $x_\gamma^{obs} \approx 0.9$ and low x_γ^{obs} kinematically suppressed... BUT...
- ...smaller direct contribution and less suppression even though four-jet HFS more tightly constrained.
- MCs predict that differences at low x_γ^{obs} are due to larger missing component/more MPIs... BUT...
- ...high x_γ^{obs} region is insensitive to MPIs so not the sole reason for larger resolved contribution.
- resolved processes have more complex colour structure - generate multi-jet states more efficiently.

Study parton dynamics with DIS multijets at HERA

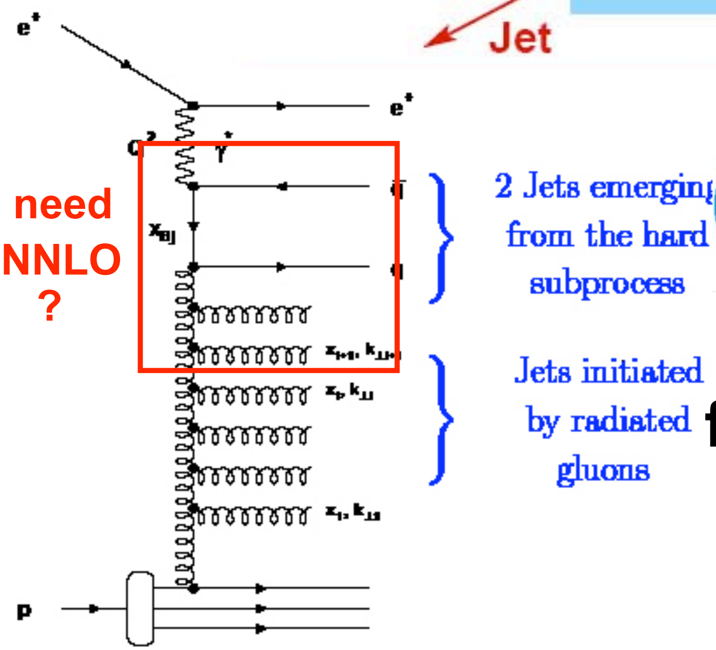
three jet events



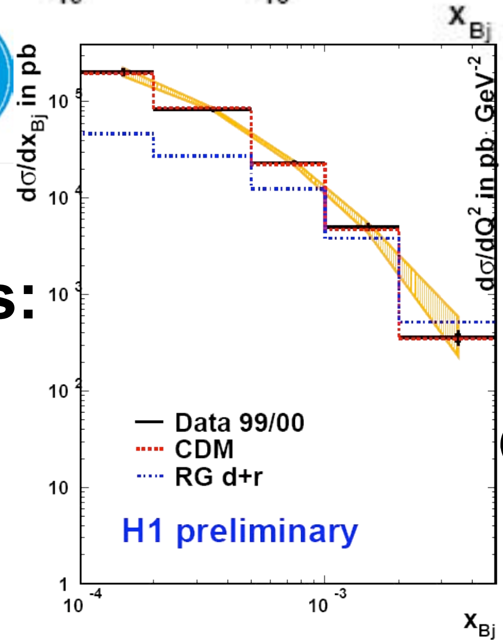


$O(\alpha_s^3)$ ("NLO")
much better than
$O(\alpha_s^2)$ ("LO")
but not perfect

need NNLO ?



four jets:



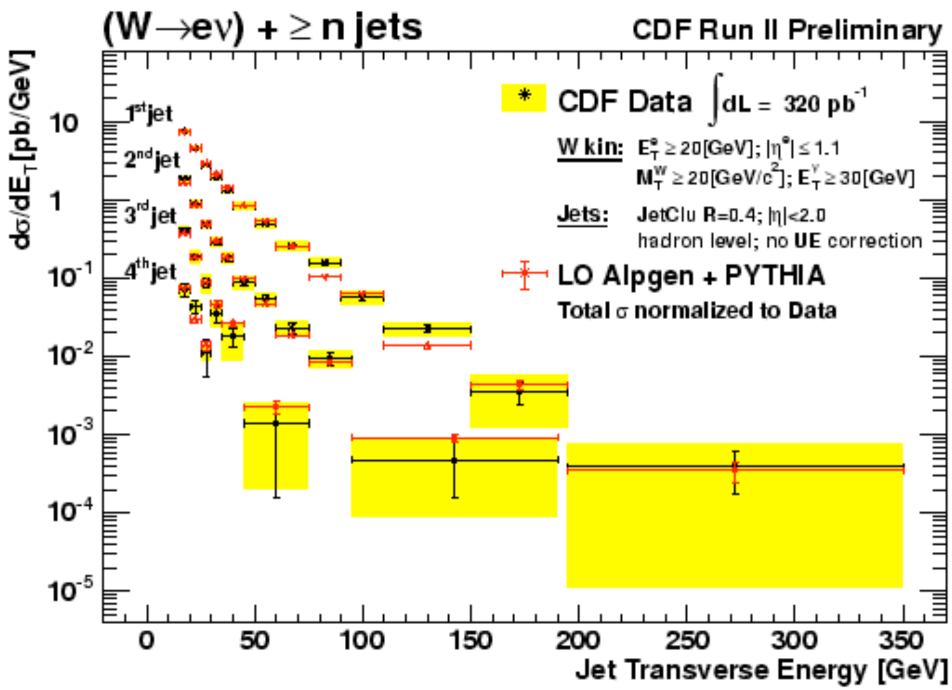
NLO: not available!
=> use LO+PS
Color Dipole Model OK
(DJANGOH: CDM: k_T unordered gluons)
DGLAP parton shower fails
(Rapgap: k_T ordered parton showers & resolved photon component)

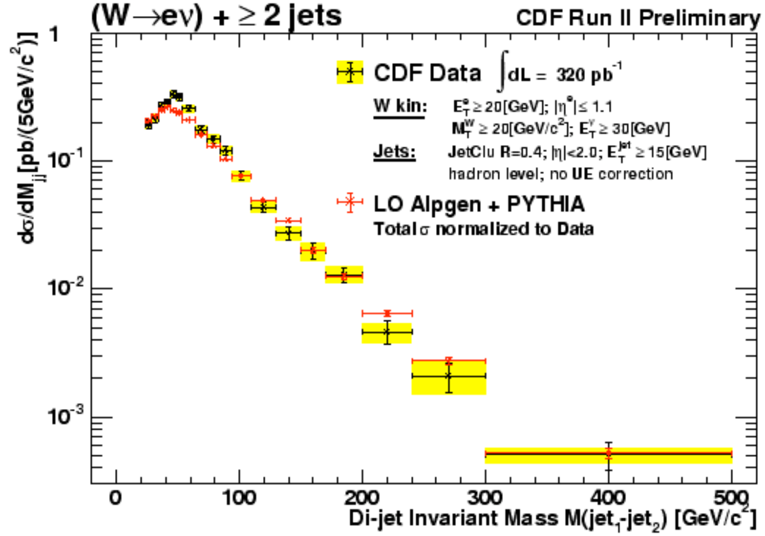
or need unordered gluon radiation?

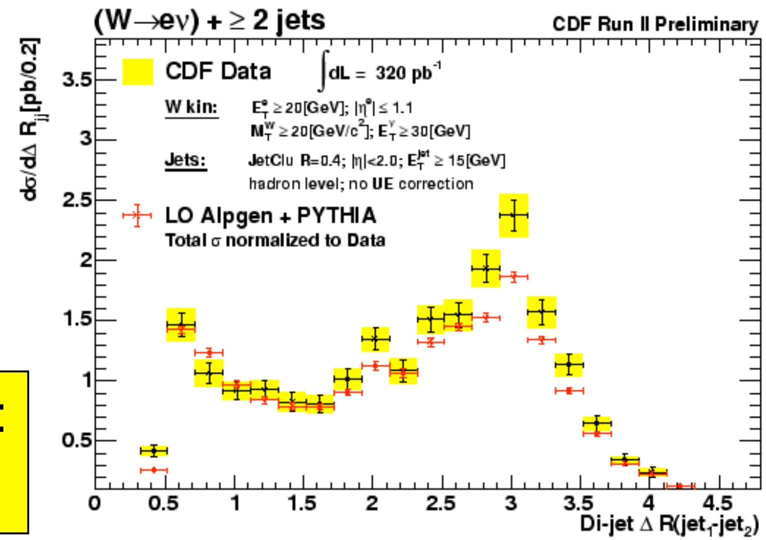
W+n Jets W+2 Jets

CDF preliminary (320pb-1)

Cross Section for Restricted W Phase Space
→ Avoid Model-Dependent Acceptance Corr.







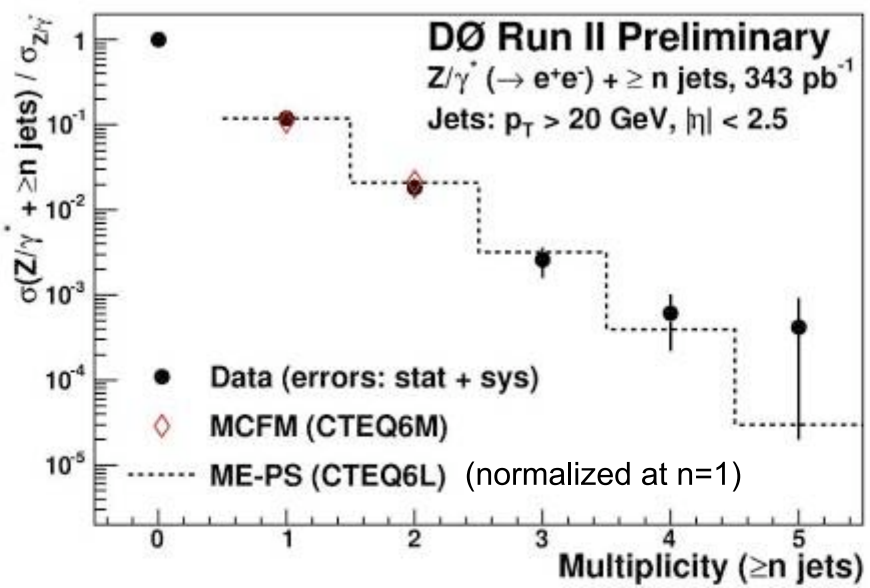
Shape-Comparison with LO Alpgen+PYTHIA: Reasonable Agreement!

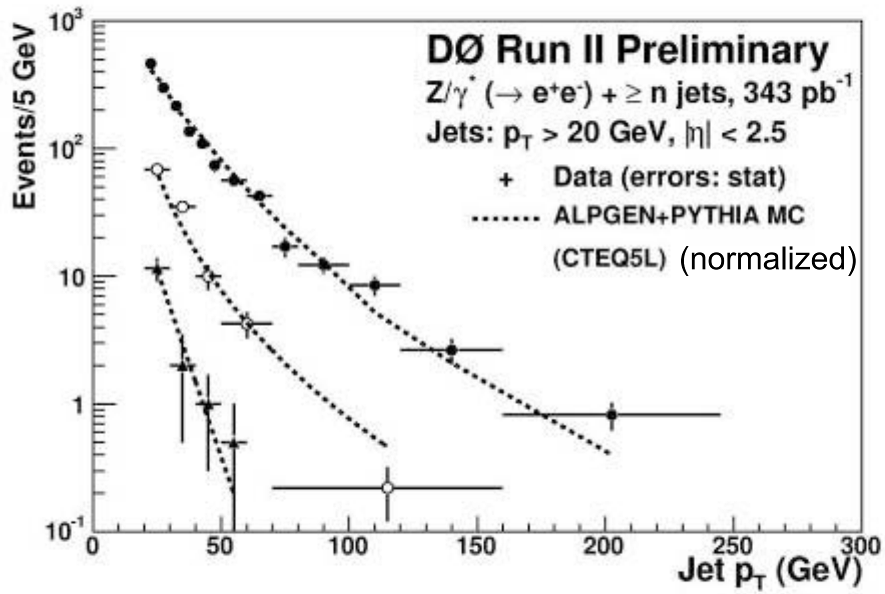
Z+n Jets

Smaller σ than (W+Jets) but cleaner exp. signature

Ratios to total inclusive Z→ee

D0 preliminary (340pb-1)





Data are described by:

MCFM: NLO for Z+jet, Z+2-jet

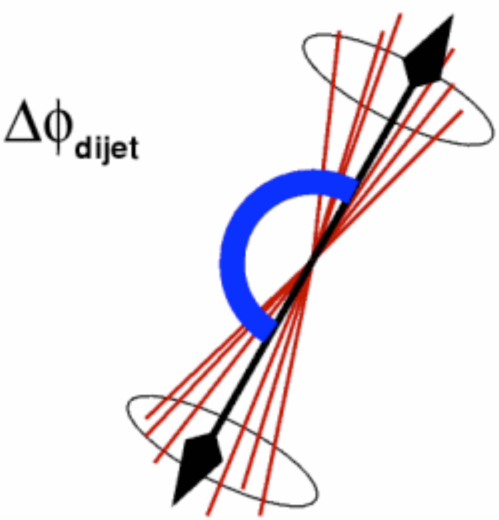
Madgraph: ME+PS (Z+ ≤ 3 parton) tree-level + PYTHIA parton shower

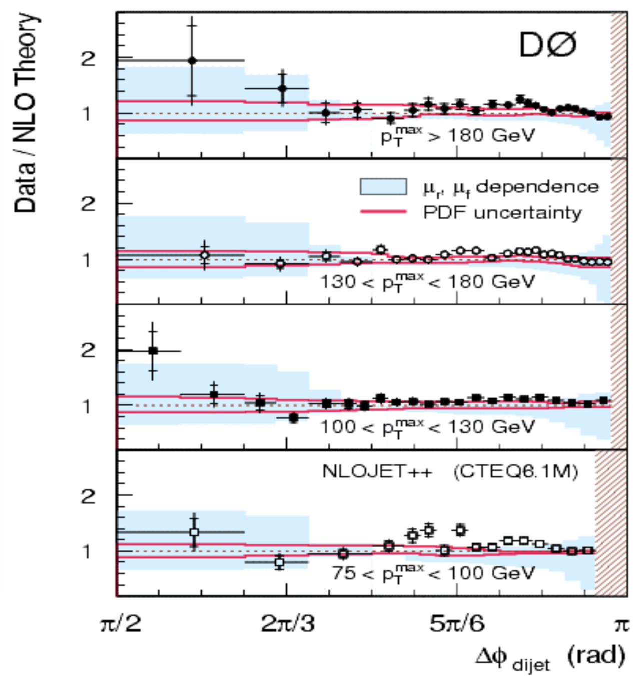
ALPGEN (LO ME) (p_T Dependence)

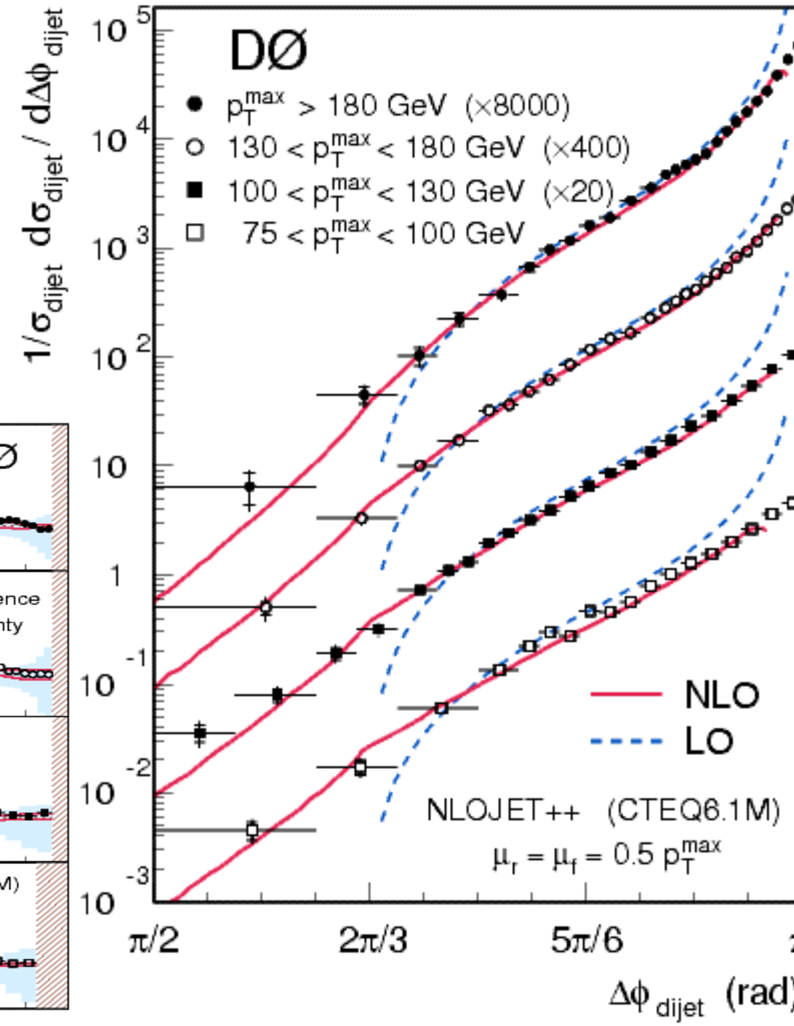
Dijet Azimuthal Decorrelation

Compare with theory:

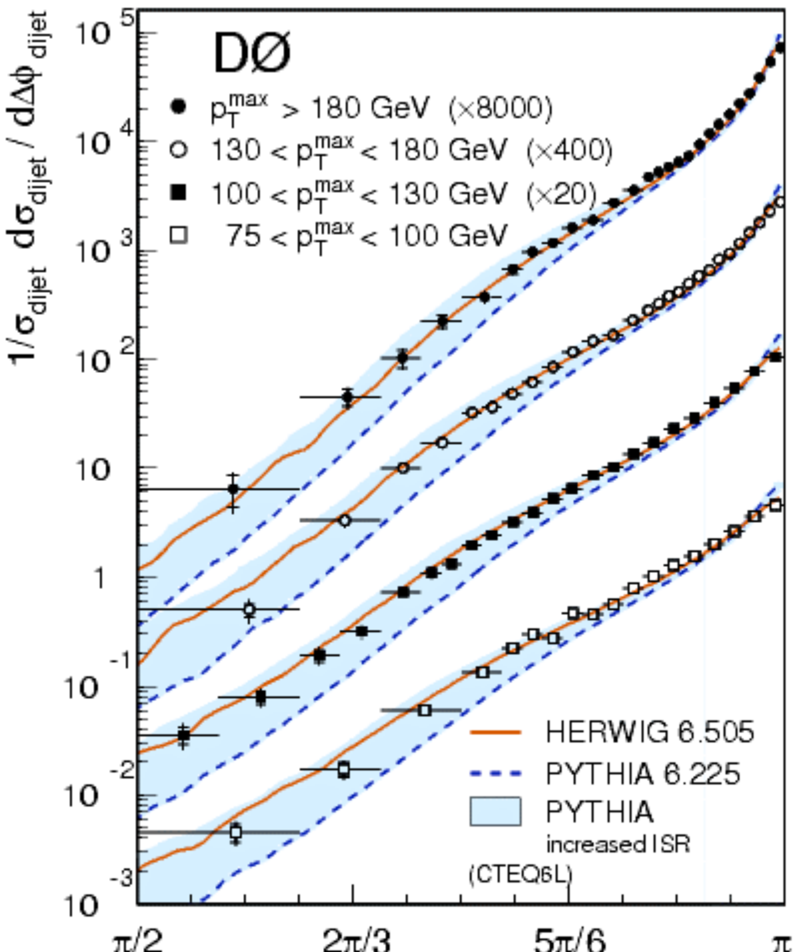
- LO has Limitation $>2\pi/3$
  & Divergence towards π
- NLO is very good – down to $\pi/2$
  & better towards π
  … still: resummation needed

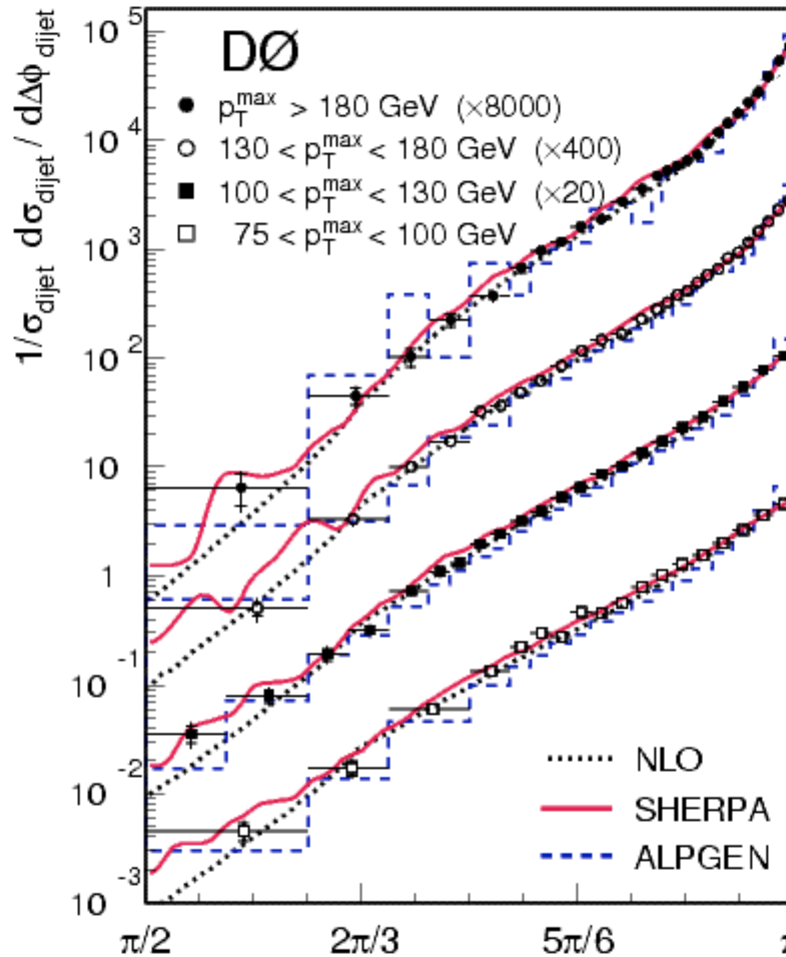






Dijet Azimuthal Decorrelation





Compare with theory:

- HERWIG is perfect “out-the-box”
- PYTHIA too low in tail but can tune

- SHERPA (ME+PS+CKKW match) good
- ALPGEN (LO ME) looks good – but low efficiency → large stat. flucts.

DIS Event Shapes

Use power corrections to correct for non-perturbative effects in infrared and collinear safe event shape variable, F:

Used to determine the hadronization corrections

$$\langle F \rangle = \langle F \rangle_{perturbative} + \langle F \rangle_{power\ correction}$$

$$\langle F \rangle_{pow} = a_V \frac{3MA_1(\alpha_s, \bar{\alpha}_0)}{\pi Q}$$

$\tau = 1 - T_\gamma$ with $T_\gamma = \frac{\sum_h |\vec{p}_{z,h}|}{\sum_h |\vec{p}_h|}$

$\tau_C = 1 - T_C$ - thrust along the axis maximising T (like in e^+e^-)

$B = \frac{\sum_h |\vec{p}_{t,h}|}{2\sum_h |\vec{p}_h|}$ – Jet Broadening

$\rho = \frac{(\sum_h E_h)^2 - (\sum_h \vec{p}_h)^2}{(2\sum_h |\vec{p}_h|)^2}$ – Jet inv. mass

$C = \frac{3}{2}\frac{\sum_{h,h'} |\vec{p}_h||\vec{p}_{h'}| \sin^2\theta_{h,h'}}{(\sum_h |\vec{p}_h|)^2}$ - Collinear & infrared safe combination of sphericity eigenvalues

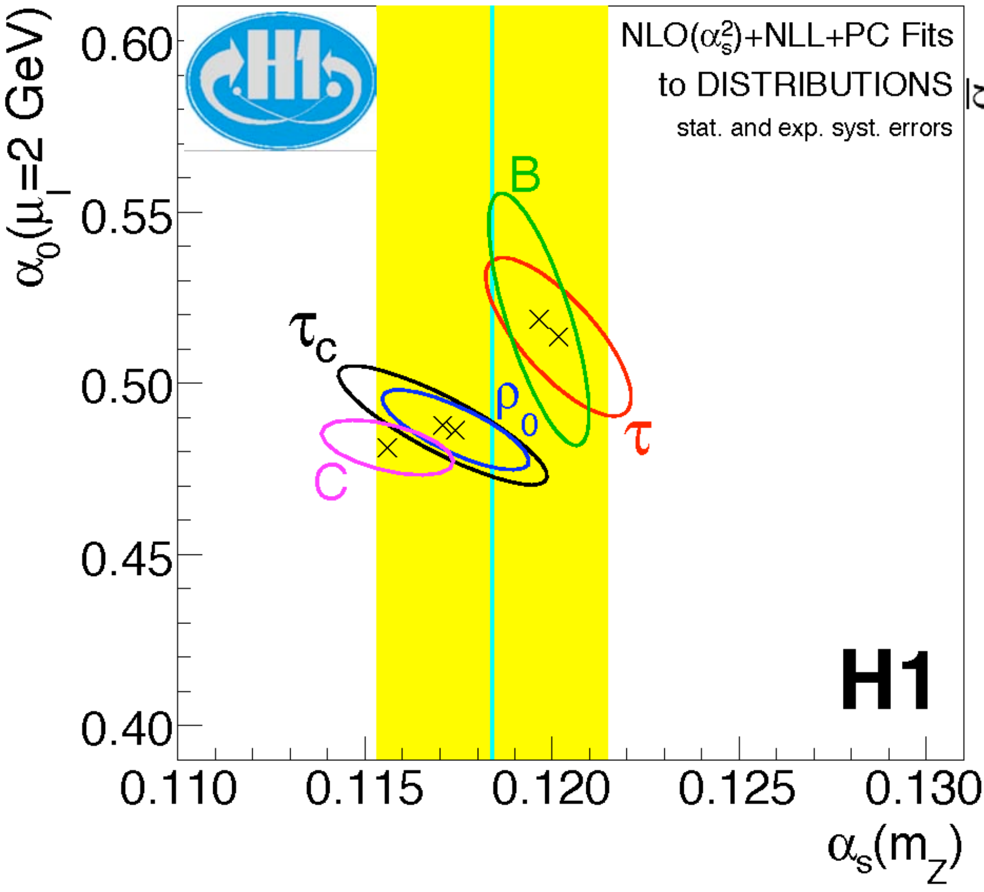
Valid for event shape means and differential distributions

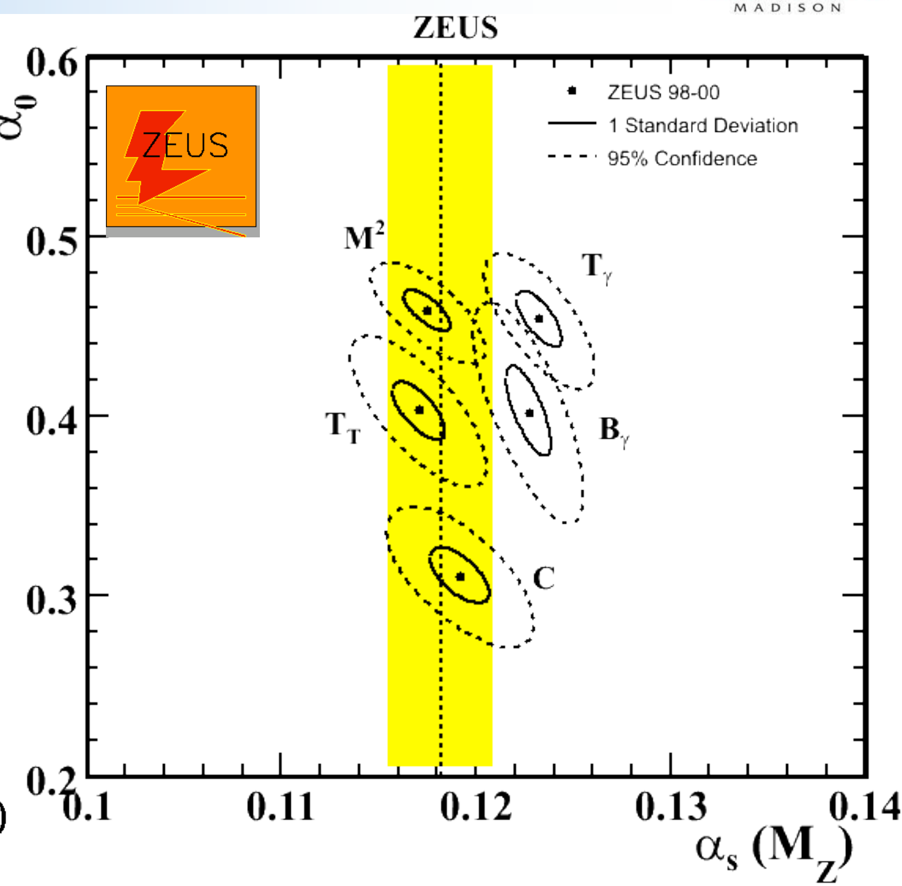
Power correction:

- **Independent of any fragmentation assumptions**

$\overline{\alpha_0} =$ **Universal "non-perturbative parameter"**
*** – (Dokshitzer, Webber, phys. Lett. B 352(1995)451)**

α_s & α_0 from DIS event shapes



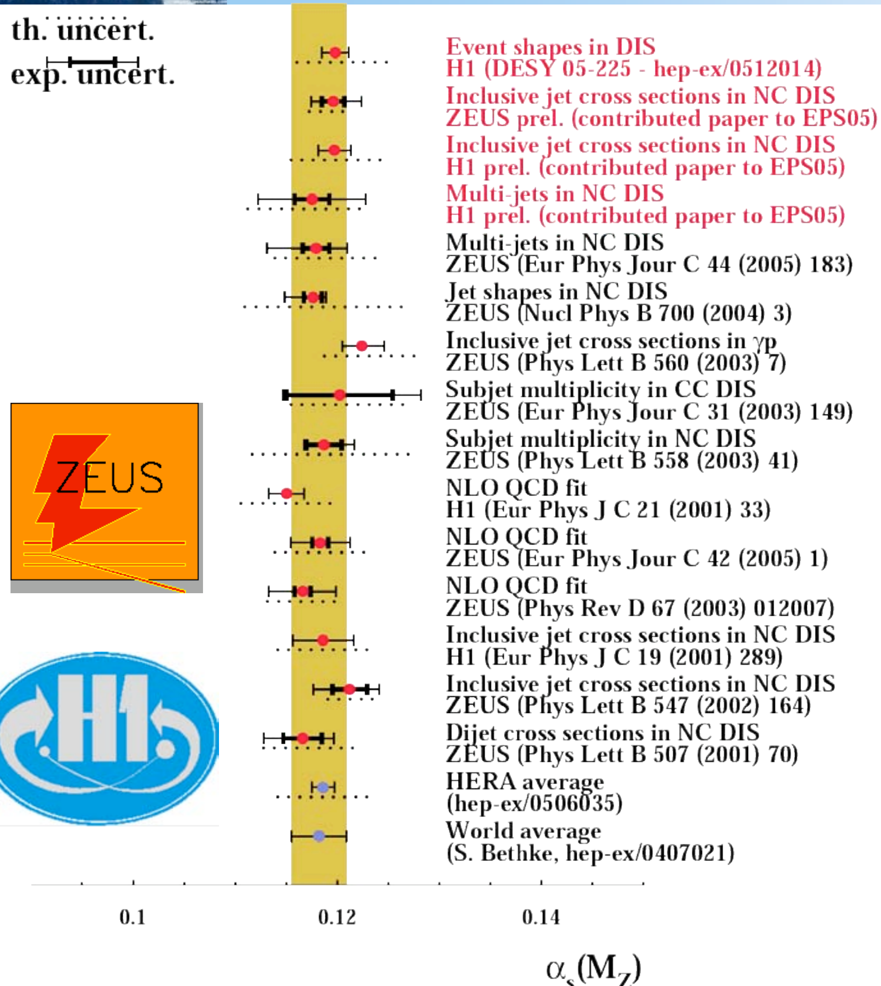


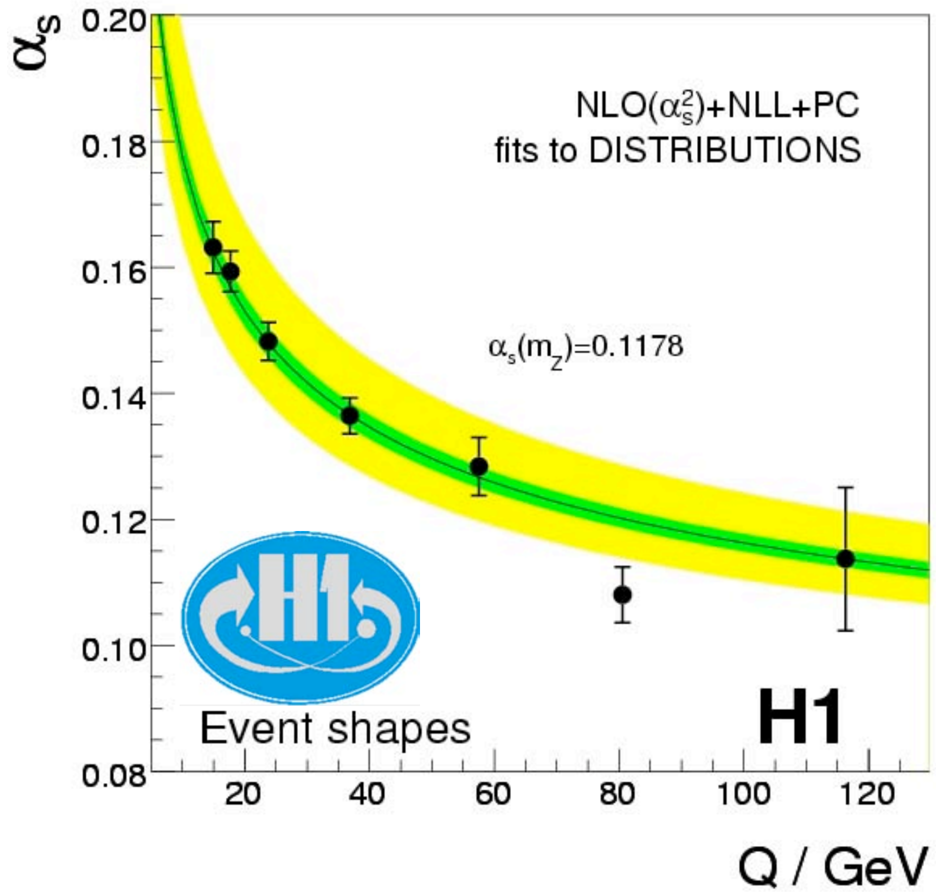
$$\alpha_s(M_Z) = 0.1198 \pm 0.0013(\text{exp})^{+0.0056}_{-0.0043}(\text{th})$$

$$a_0 = 0.476 \pm 0.008(\text{exp})^{+0.018}_{-0.059}(\text{th})$$

Extracted values of α_S are in good agreement with world average(shown as yellow band)

DIS Jets, Event Shapes & α_s





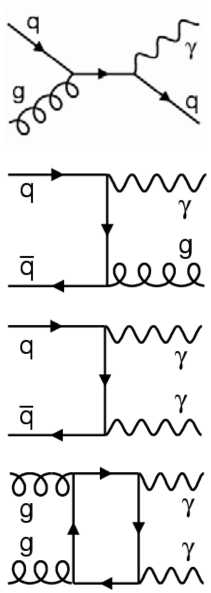
Precise measurement of α_s at HERA, error dominated by theory

Running measured from jets and event shapes in a single experiment

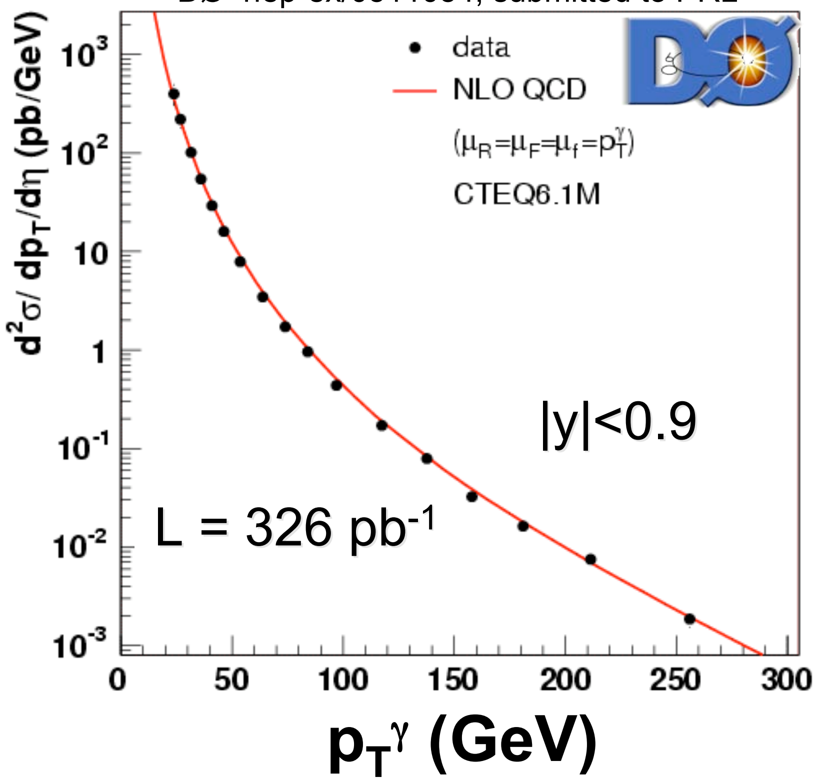
New world measurement incl. HERA Jets: $\alpha_s = 0.1189 \pm 0.0010$ (hep-ex/0606035)

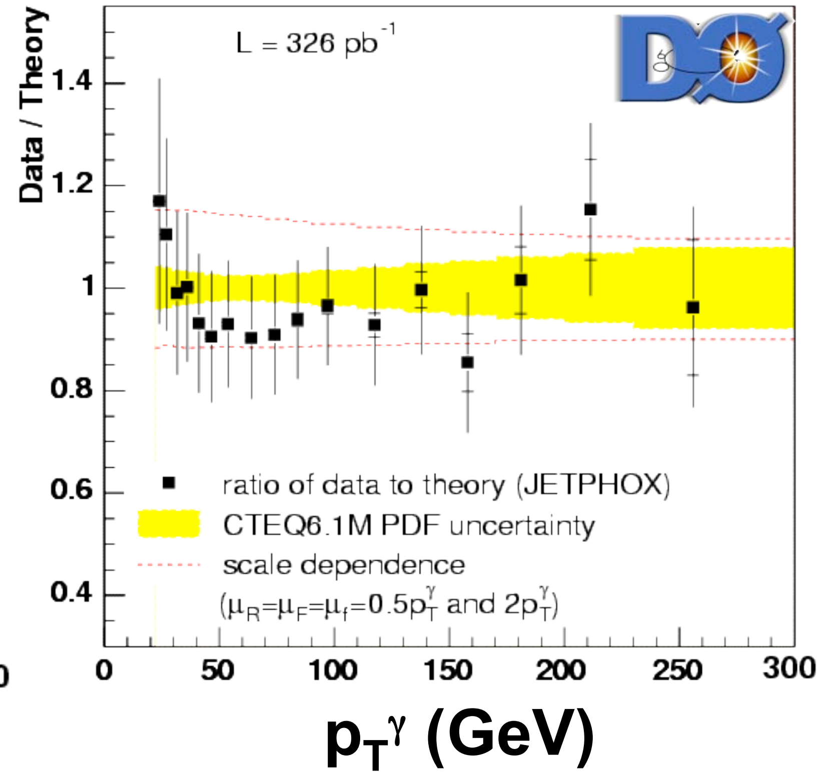
Isolated Photon Cross Sect.

Direct photons directly probe hard scattering dynamics:



DØ hep-ex/0511054, submitted to PRL





data/theory (NLO: JETPHOX): good agreement over $23<p_T<300$GeV

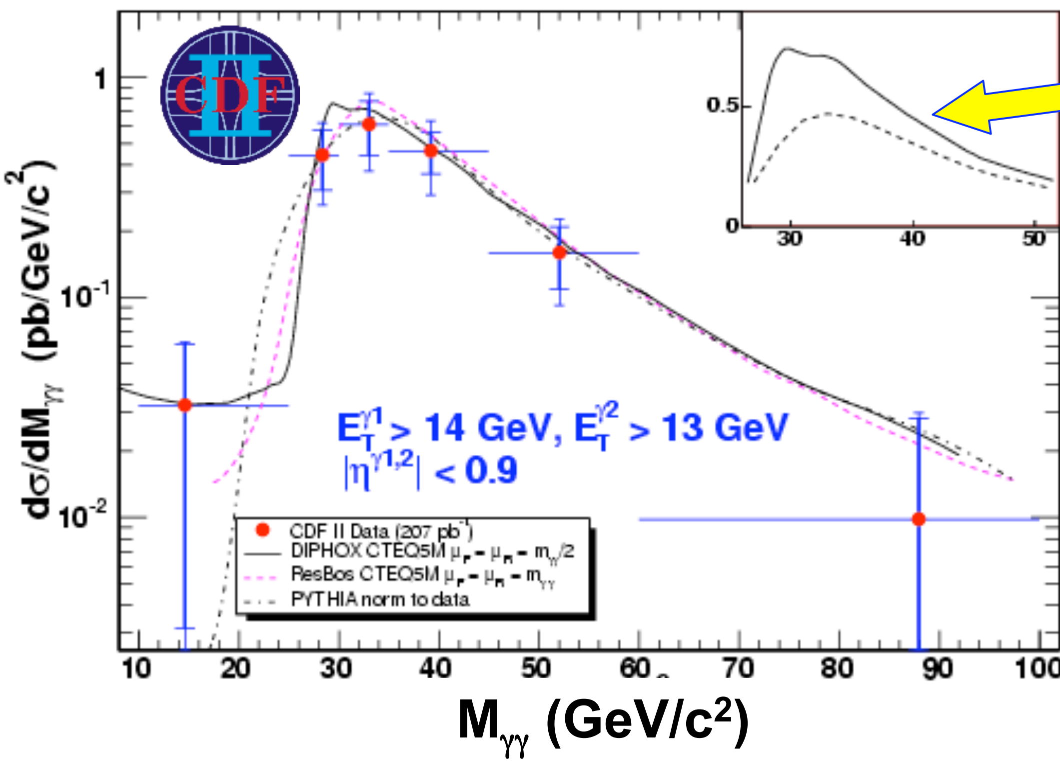
→ PDF sensitivity requires:

- Reduced exp. uncertainties – dominated by purity uncertainty
- Improved theory (resummation / NNLO)

Di-Photon Cross Section

CDF Collab., Phys. Rev. Lett. 95, 022003, 2005. (207pb-1)

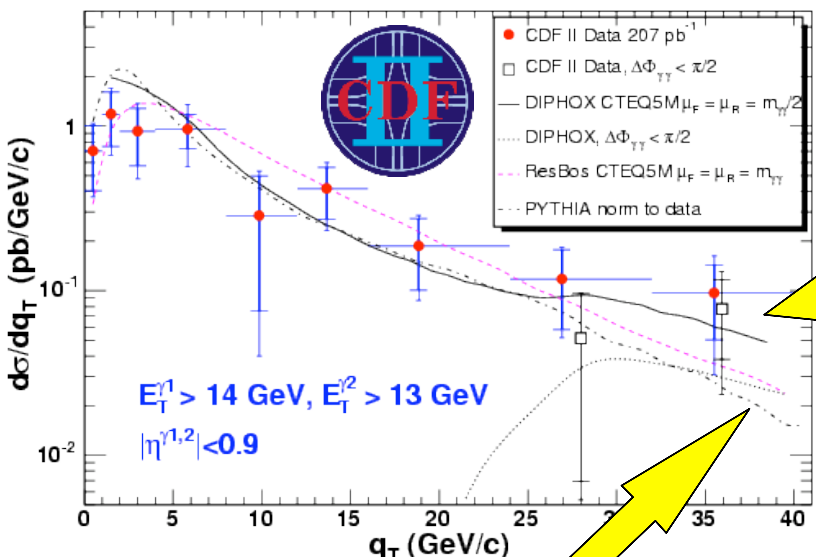
- Pseudorapidity < 0.9
- Photon p_T> 13 & 14 GeV



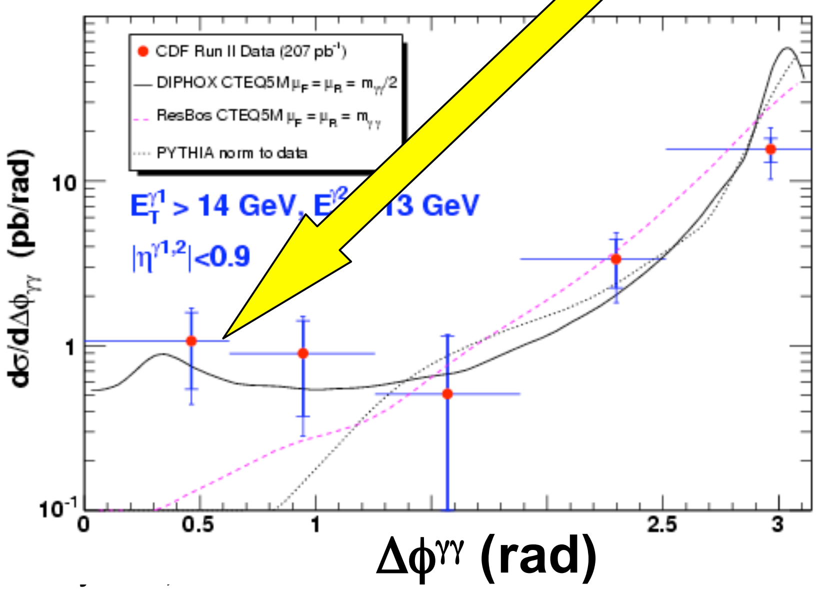
DIPHOX: with and w/o NNLO gg-diagram

- **DIPHOX**:
  - NLO prompt di-photons
  - NLO fragmentation (1 or 2 γ)
  - NNLO gg→$\gamma\gamma$ diagram
- **ResBos**:
  - NLO prompt di-photons
  - LO fragmentation contribution
  - Resummed initial state gluon radiation (important for q_T)
- **PYTHIA** (increased by factor 2)

Di-Photon Cross Section



Additional measurement for $\Delta\phi$ (gamma-gamma) < $\pi/2$ (open markers) compared to DIPHOX



NLO fragmentation contribution

- only in DIPHOX

→ at high q_T, low $\Delta\phi$, low mass

Resummed initial-state gluon radiation – only in ResBos → at low q_T

<u>Important:</u>

Combined Calculation with

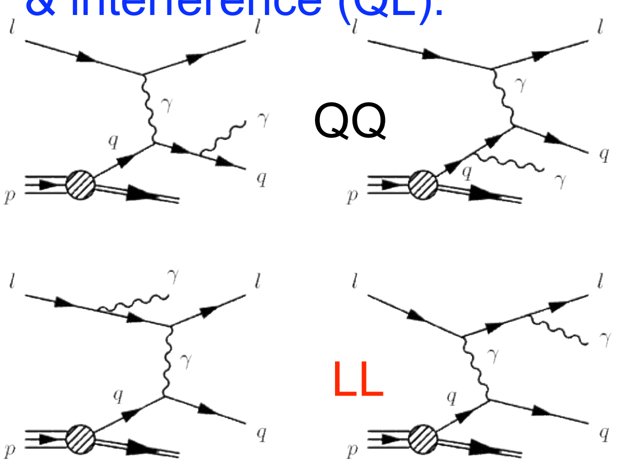
NLO Fragmentation

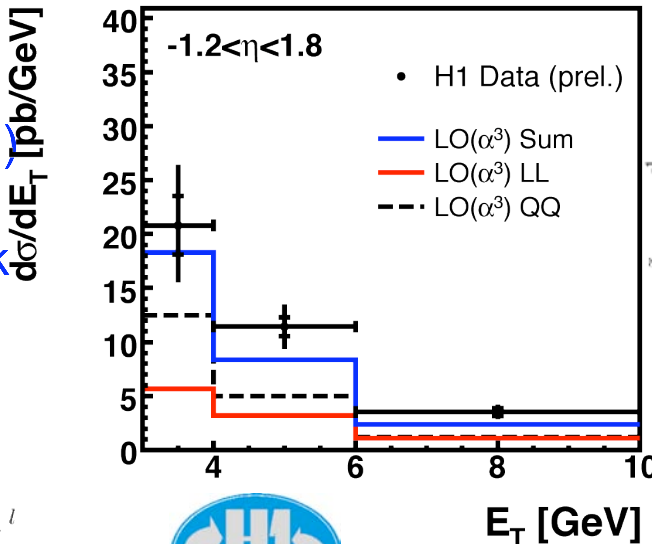
& Initial State Resummation

Statistical fluctuations: much larger data set soon - 1 fb^{-1}

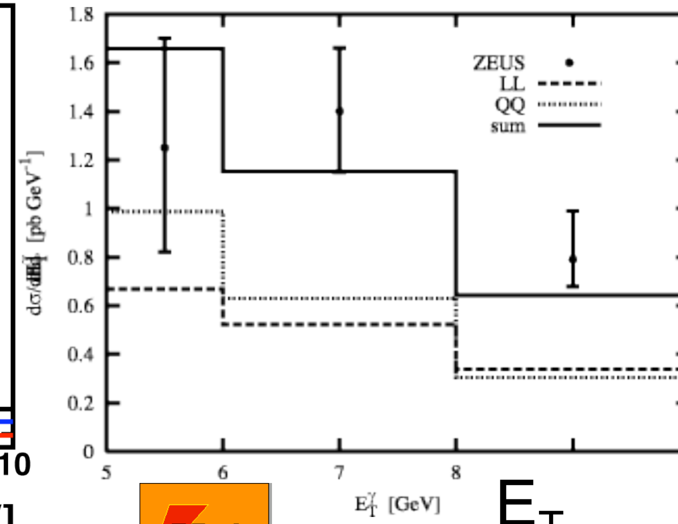
Inclusive Prompt γ at HERA:
effective quark to photon fragmentation fn.

Prediction for prompt γ in ep DIS: Gehrmann et al. (hep-ph/0601073,0604030) LO(α^3) calculation with lepton radiation (LL), quark radiation (QQ - incl. non-perturb. frag. function based on ALEPH data) & interference (QL):

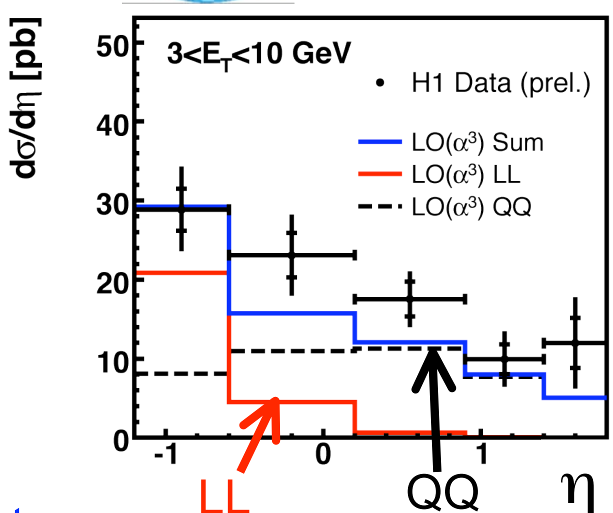


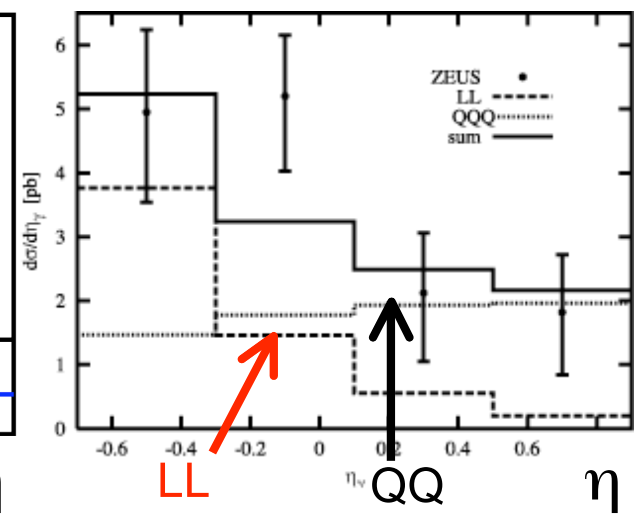


$Q^2 > 4$ GeV^2



$Q^2 > 30$ GeV^2



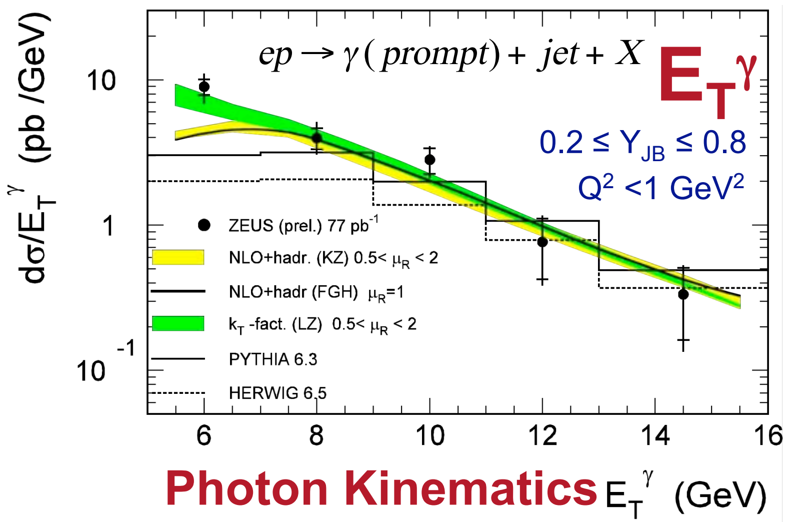


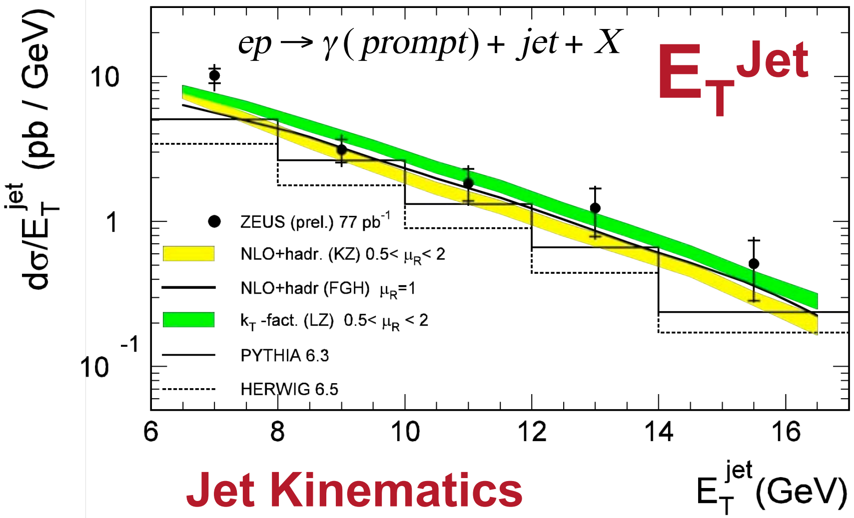
LL dominates at small η

QQ dominates at large η

Reasonable description of data

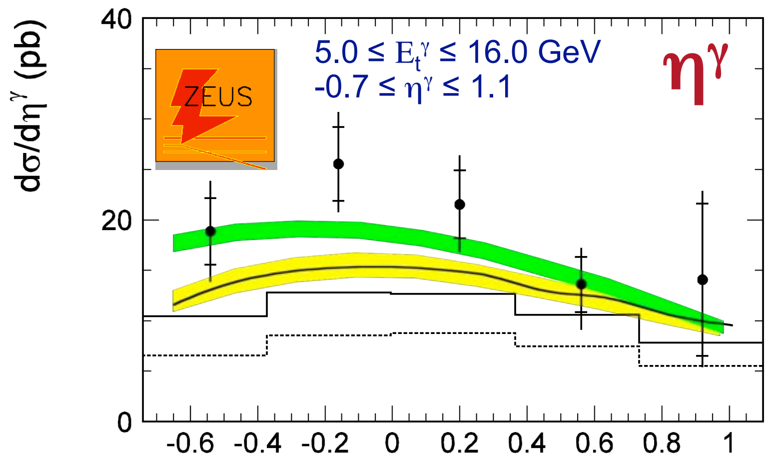
Photoproduced Prompt γ + Jet

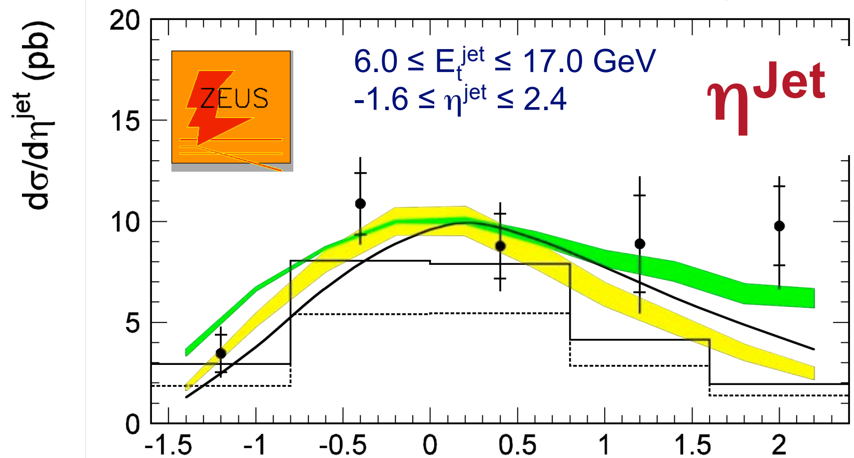




Photon Kinematics

Jet Kinematics





Sensitive to k_t unintegrated parton densities in the proton, resolved γ

KZ: GRV p & γ SFs

FGH: MRST01 p & AFG02 γ SFs

Both below data for Low E_t^{jet} & deviate from data at low E_t^{γ}

LZ: K_t-factorization & unintegrated q/g densities

Better in forward jet region & for E_t^{γ} &low η^{γ}

also seen by H1: hep-ex/0407018

$$\sigma(e^{\pm}p \rightarrow e^{\pm} + \text{prompt}\ \gamma + \text{jet} + X) = 33.1 \pm 3.0\ (\text{stat.})\ ^{+4.6}_{-4.2}\ (\text{syst.})\ \text{pb}$$

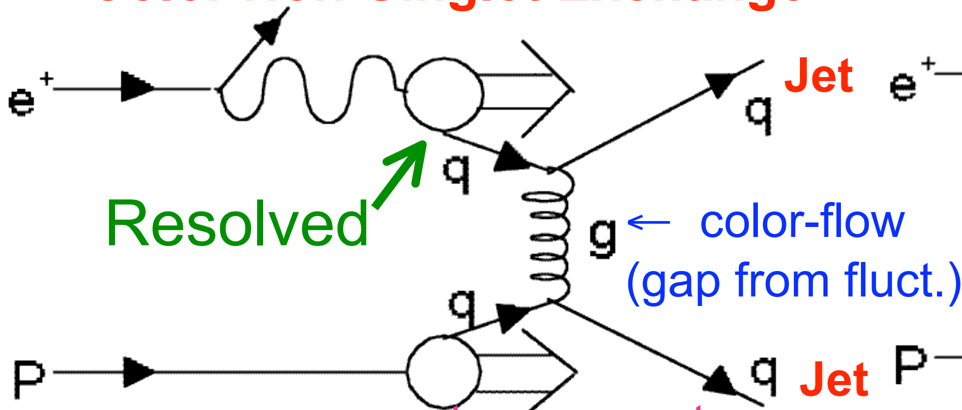
Underestimate data:

PYTHIA	19.98 pb
HERWIG	13.54 pb

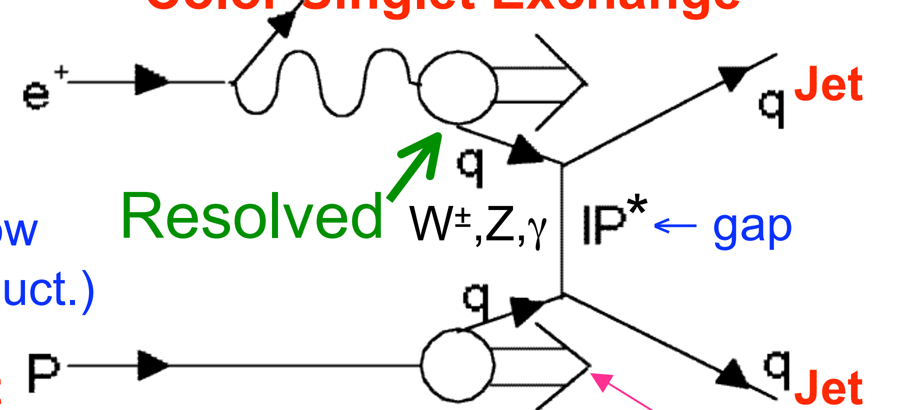
KZ	23.31 pb
FGH	23.52 pb
LZ	30.73 pb

Color Non-Singlet and Singlet Exchange in Photoproduction

Color Non-Singlet Exchange



Color Singlet Exchange

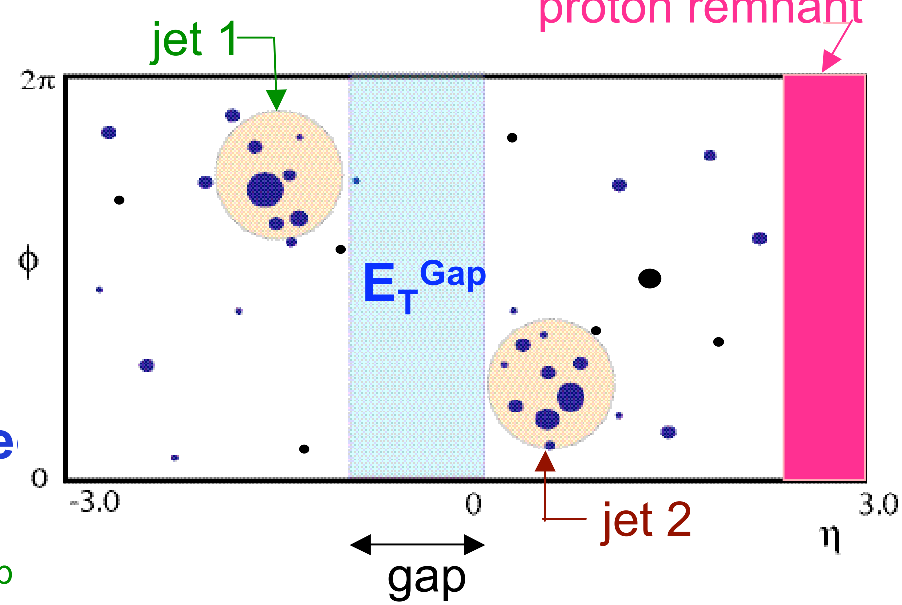


Color Non-Singlet Exchange:

- Final state partons color connected
- Space between final state partons filled with final state particles
  - No Gap between jets

Color Singlet Exchange:

- Final state partons not color connecte
- Space btw final state partons empty
  - Rapidity Gap between jets--measure E_T^{Gap}

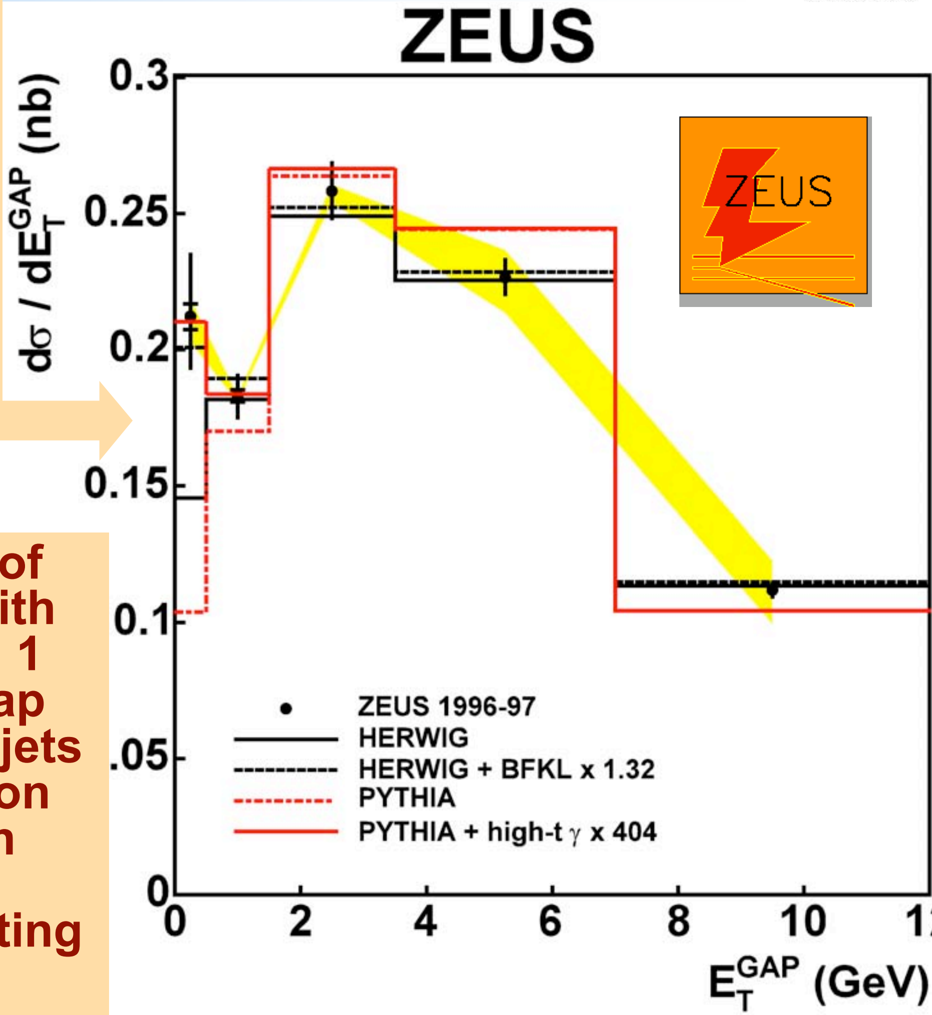


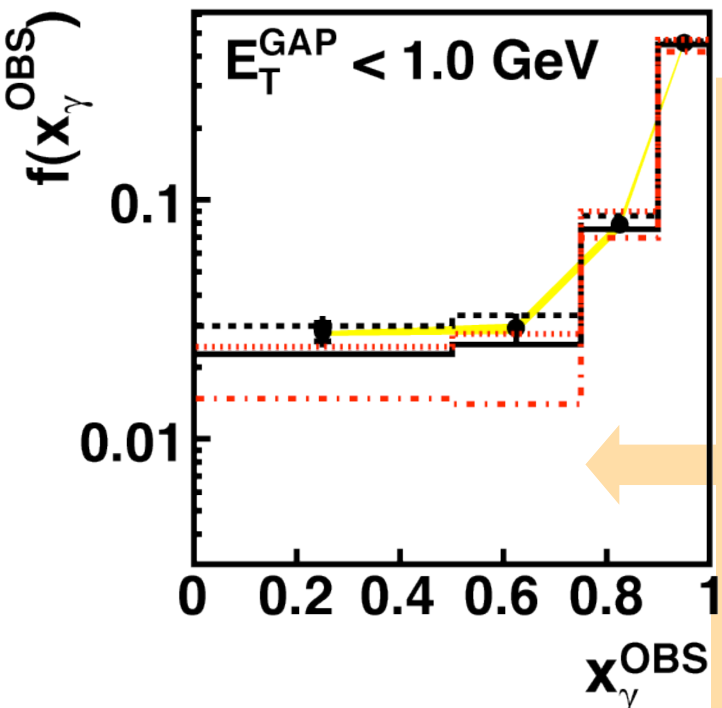
Evidence for Color Singlet

Inclusive dijet gap cross section vs. E_T^{Gap} for Herwig (x 3.3) & Pythia (x 1.8) with & w/o color- singlet exchange.

MCs w/o color-singlet do not describe data in two lowest E_T^{Gap} bins.

Color-singlet needed for best fit to data is ~3-4% of total inclusive dijet gap cross section for E_T^{Gap} from 0 - 12 GeV





Fraction of events with less than 1 GeV in gap between jets vs. fraction of photon energy participating in hard scatter.

Indicates variation in gap probability (i.e. survival) from Tevatron-like low x_γ to pointlike DIS at x_γ = 1.

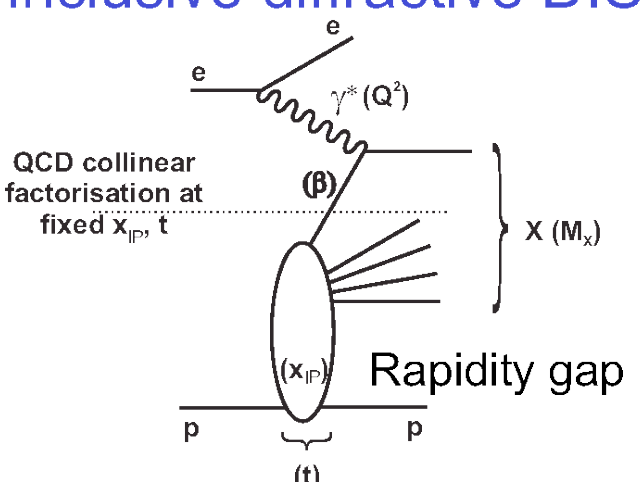
Diffractive DIS & Factorization

$$\sigma^D(\gamma^* p \rightarrow Xp) = \sum_{parton\_i} f_i^D(x, Q^2, x_{IP}, t) \cdot \sigma^{\gamma^* i}(x, Q^2)$$

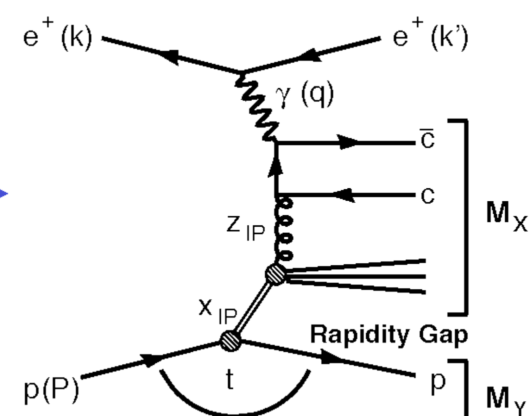
$\sigma^{\gamma^* i}$ - universal hard scattering cross section (same as in inclusive DIS)

f_i^D - Diffractive Parton Distribution Function ➔ obey DGLAP, universal for diffractive *ep* DIS (inclusive, Dijets, Charm)

❑ Extract DPDFs from QCD fit to inclusive diffractive DIS



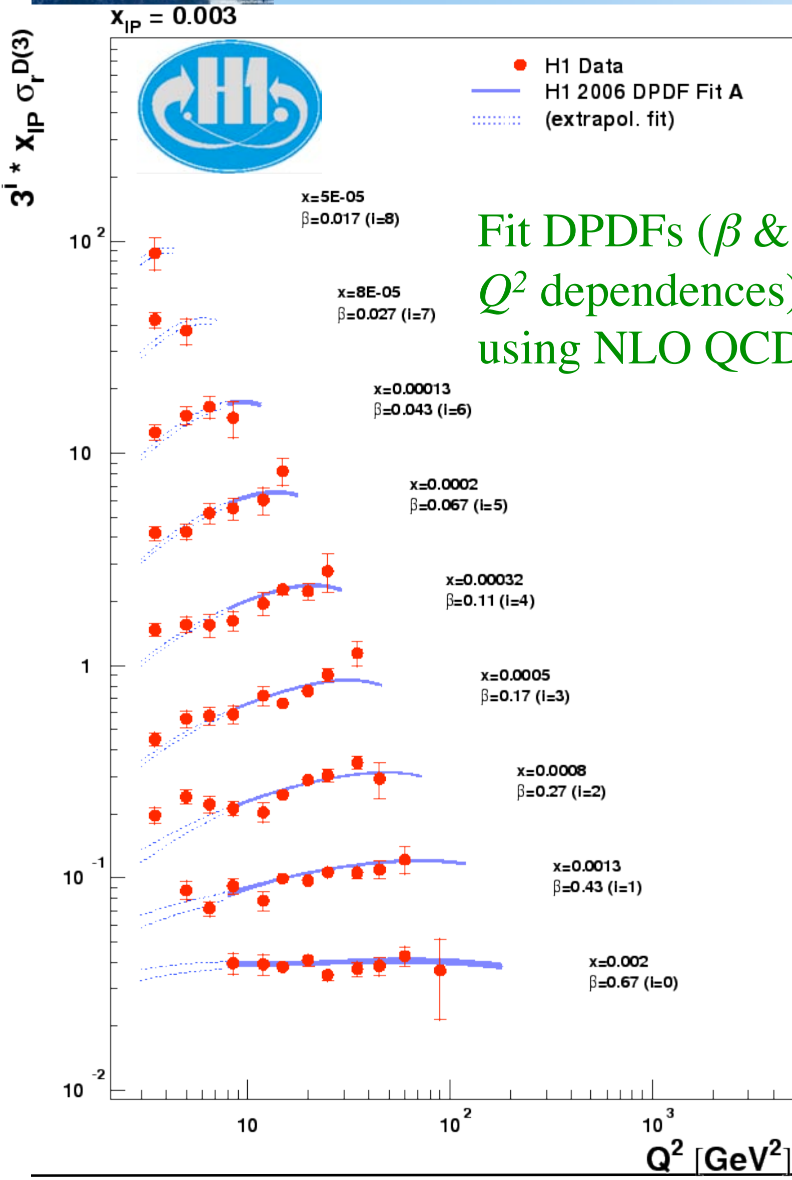
❑ Test DPDFs in diffractive Final States (Boson Gluon Fusion)



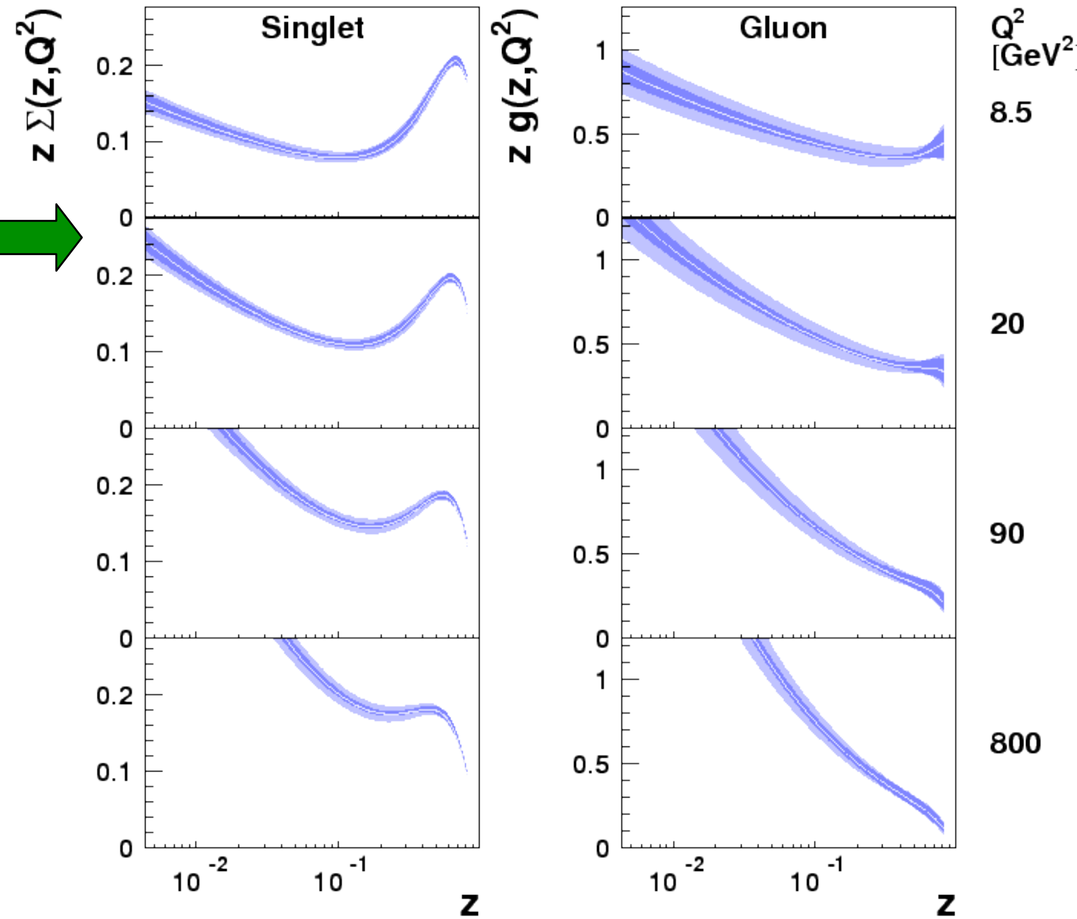
Assumption: proton vertex factorization: shape of diffractive PDFs independent of x_{IP} and t (needed?)

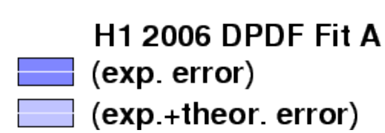
x_{IP} - momentum fraction of proton carried by color singlet exchange
z_{IP} - momentum fraction of color singlet carried by parton entering hard sub-process
β - momentum fraction of color singlet carried by struck quark

DPDFs from Inclusive Diff DIS



Fit DPDFs (β & Q^2 dependences) using NLO QCD.





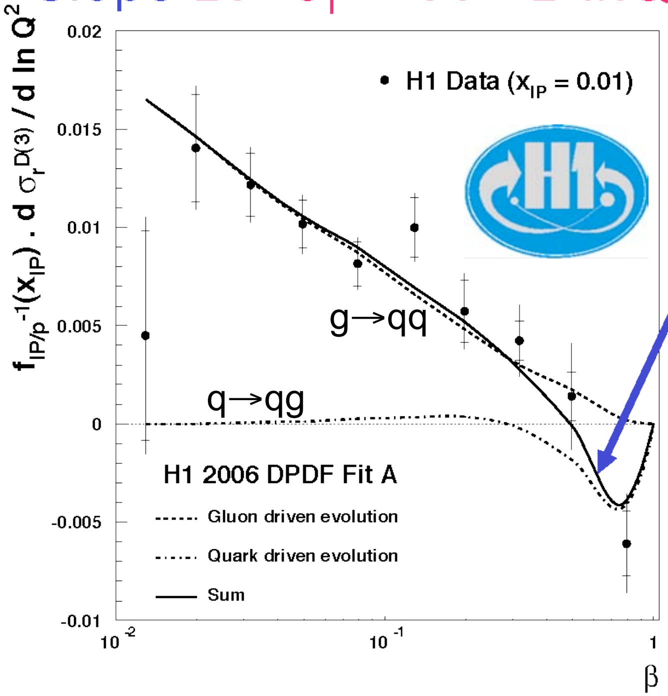
~70% gluons

Integrated over *z*

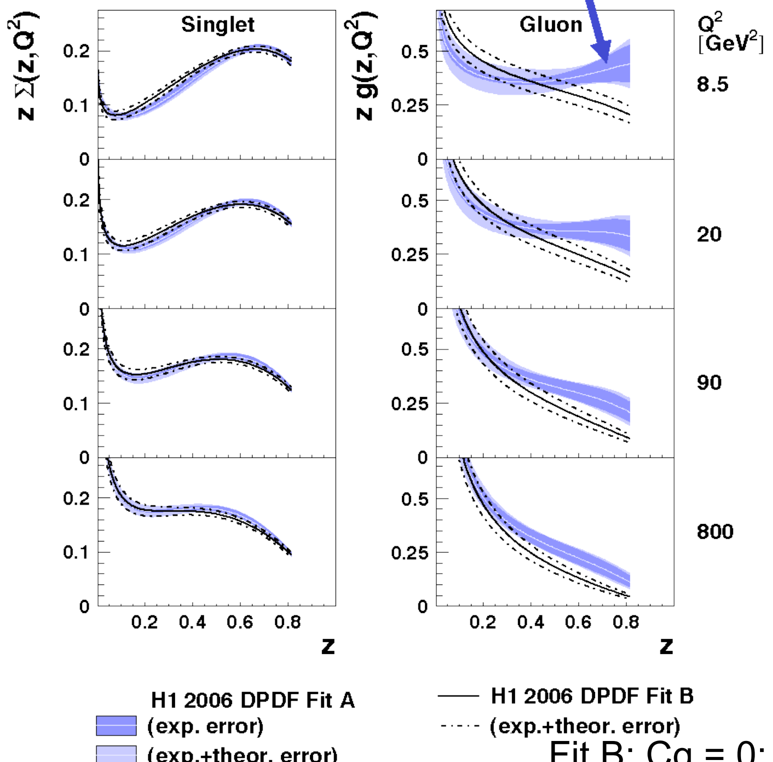
Inclusive DPDFs at high z

- Gluon DPDF ➔ from positive scaling violations ➔ larger uncertainty

Slope *B*: $\sigma_r^D = A + B \ln Q^2$



- At high momentum fraction QCD evolution is driven by quark radiation ➔ no sensitivity to gluon DPDF



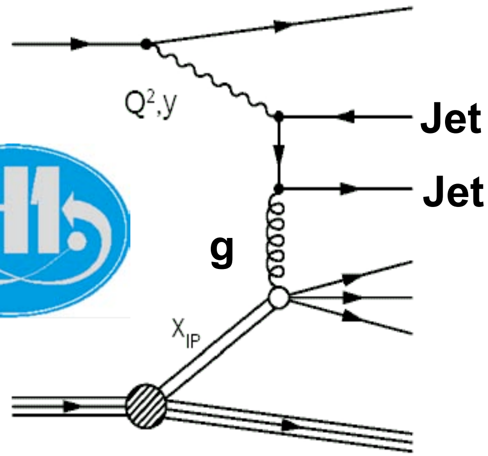
- Fit constrains quark singlet DPDF and gluon DPDF at low z

$$z\Sigma(z, Q_0^2) = A_q z^{B_q}(1-z)^{C_q}$$

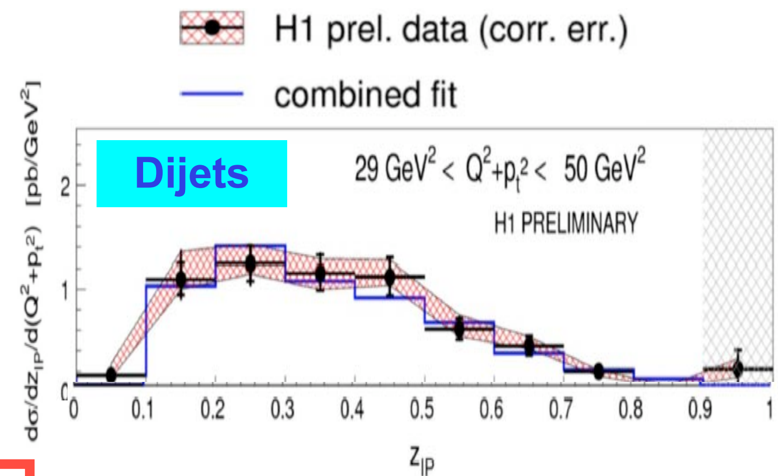
$$zg(z, Q_0^2) = A_g(1-z)^{C_g}$$

Fit B: Cg = 0: Gluon constant at Q_0^2

Add Diff. Dijets to DPDF fit

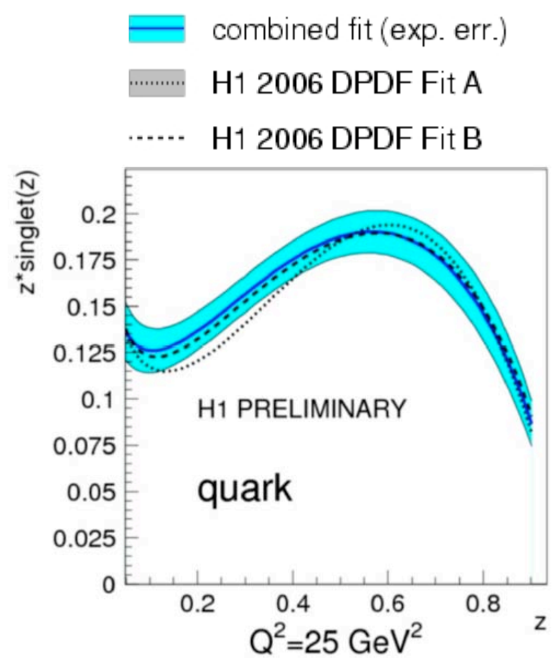


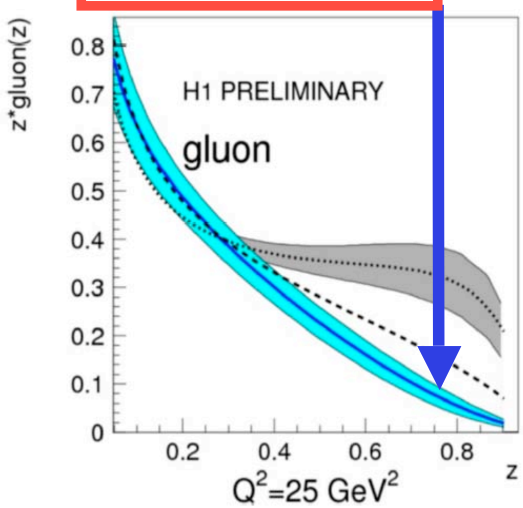
Combined fit of F_2^D and dijet data



Obtain better constraint on high z gluon

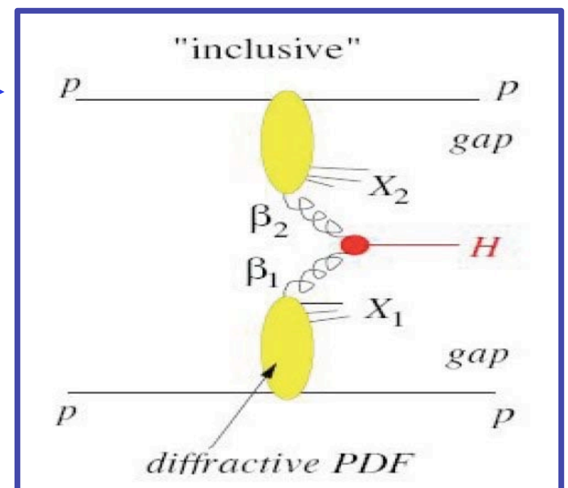
→ Both datasets well described by combined fit



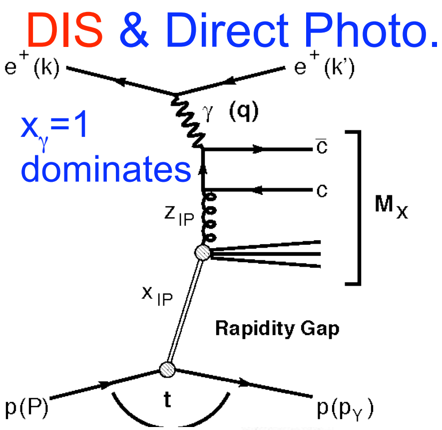


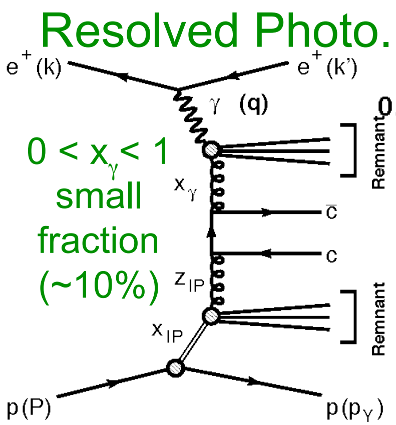
LHC

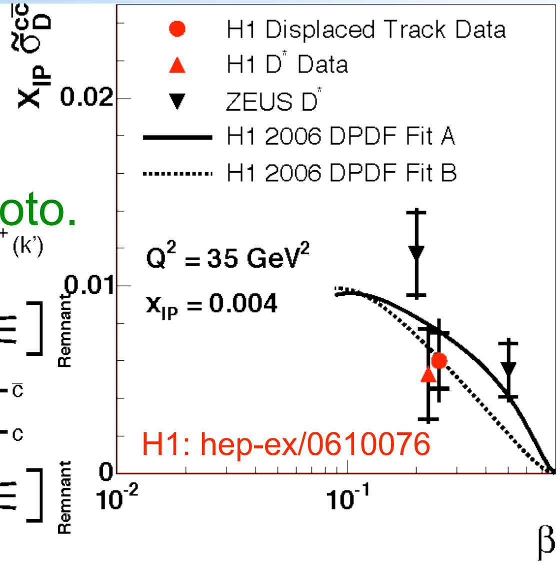
Caveat: Gap survival (reinter-actions)

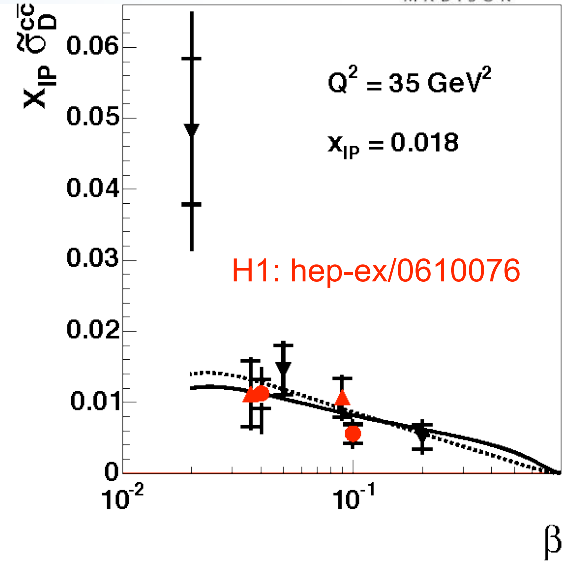


Test factorization: diffr. charm

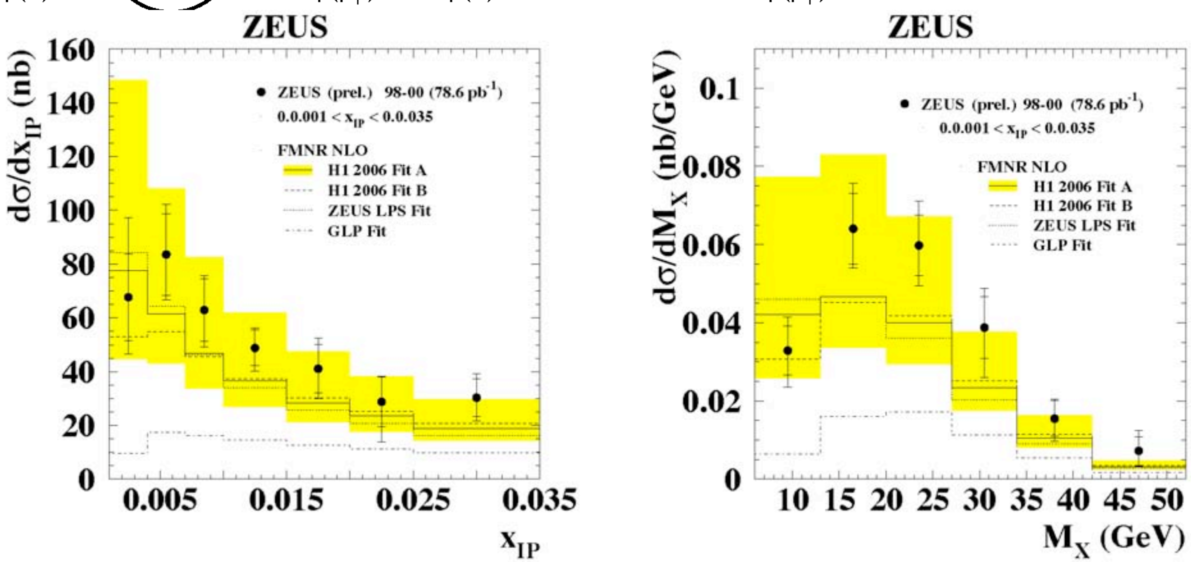






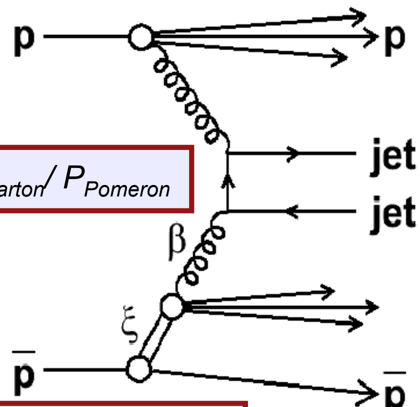


↑ **DIS: D* & H1 Lifetime method data consistent with NLO QCD**



← **Photoprod: D* data consistent with NLO QCD within scale error**

Inclusive Diffraction at CDF



$\beta = P_{parton} / P_{Pomeron}$

$\xi = P_{pomeron} / P_{proton}$

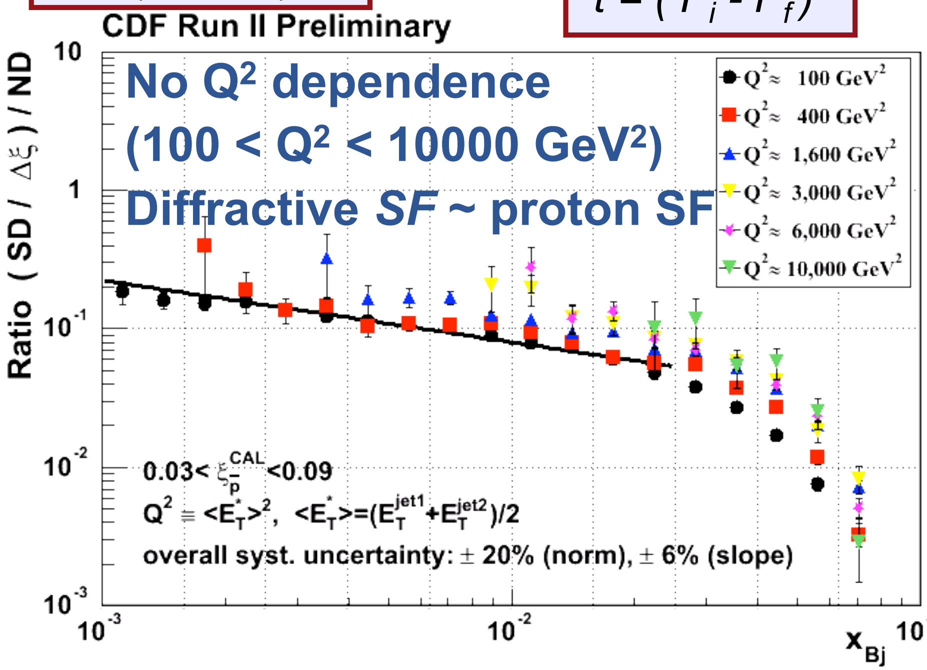
Use high p_T jets to measure *Diffractive Structure Function, F_{jj}^D*

$t = (P_i - P_f)^2$

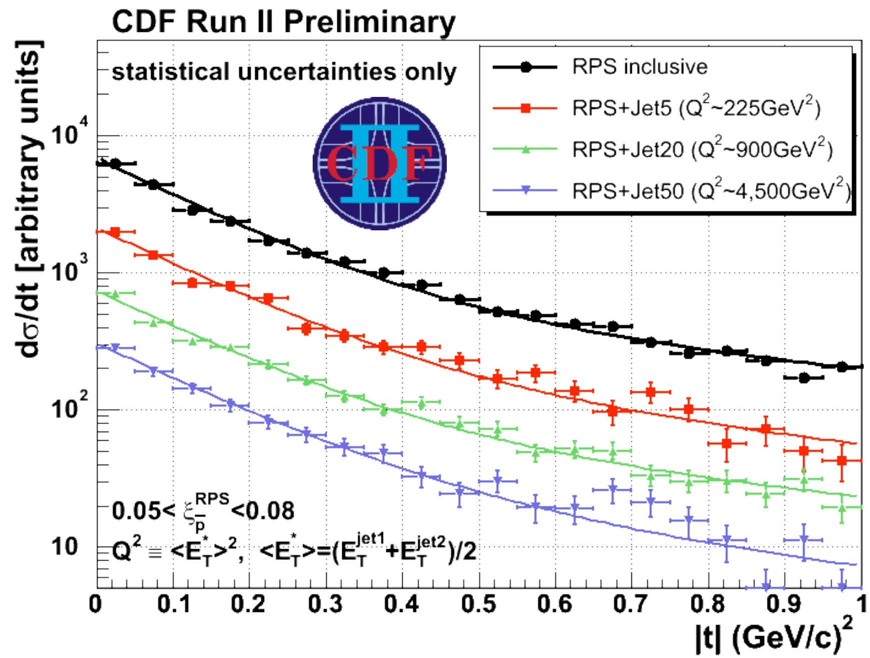
Experimental Determination of F_{jj}^D

$$R(x_{Bj}) \text{ of } \frac{\sigma_{jj}(SD)}{\sigma_{jj}(ND)} = \frac{F_{jj}^D(x_{Bj}, Q^2)}{F_{jj}(x_{Bj}, Q^2)} \text{ (LO QCD)}$$

Data — Known Proton PDF



Slope of $d\sigma/dt$ indep. of Q^2 in SD dijets:



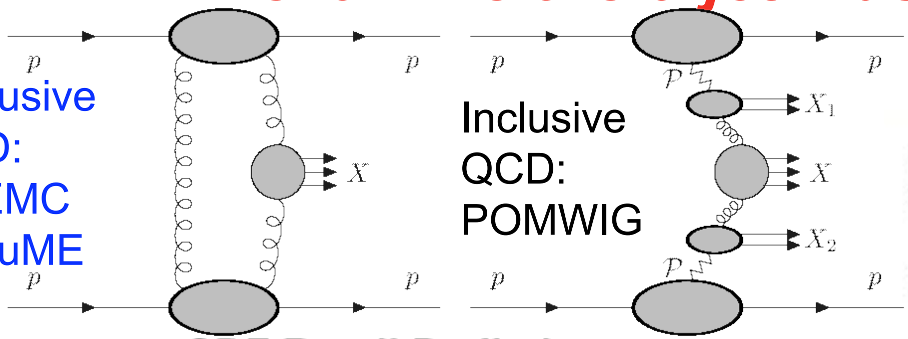
QCD Mediated Dijet Production

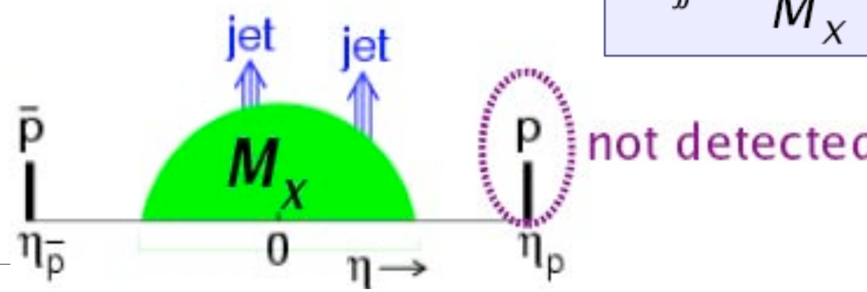
Strategy: •**select DPE dijets:** $\bar{p} + p \rightarrow \bar{p} + X(\geq 2\text{jets}+\ldots) + \text{gap}$

•**examine the *dijet mass fraction R_{jj}***

$$R_{jj} = \frac{M_{jj}}{M_X}$$

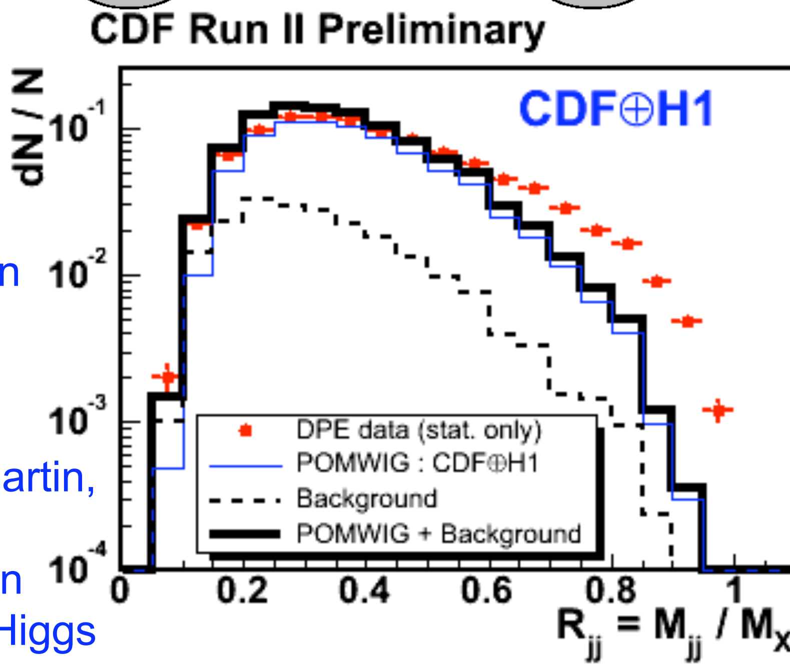
Exclusive QCD: DPEMC ExHuME



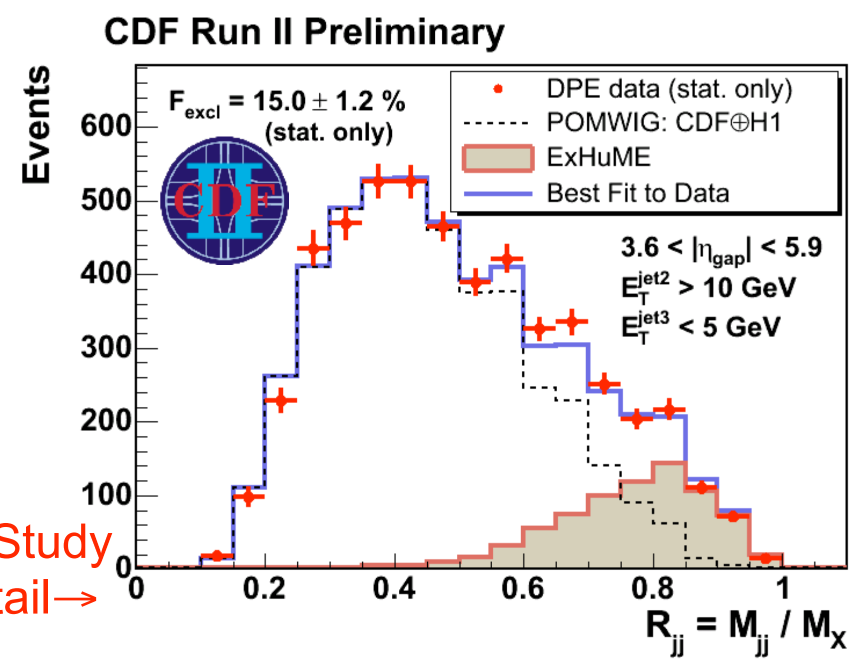


Similar to central exclusive Higgs production

ExHuME based on Khoze, Martin, Ryskin calculation used for Higgs



Study tail→



Experimental QCD Summary

Jet data constrains gluon & PDFs at high-x & α_S

- Final HERA PDFs should improve by 50% from inclusive measurements, jets, cross-sections, NNLO fits, etc.

Improved measurements of heavy flavor PDFs

QCD evolution has been studied at lower x

- Region over which DGLAP works is extended, but may need BFKL
- Better understanding of extrapolation of PDFs to the LHC

Multijets measure higher order pQCD processes

- Need theoretical calculations to higher order

Multiple Parton Interactions are important

NLO QCD describes new jet data & prompt γ well.

Diffractive DIS factorizes into DPDF + hard scatter σ

- Consistent with NLO QCD

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