Hard QCD at Colliders

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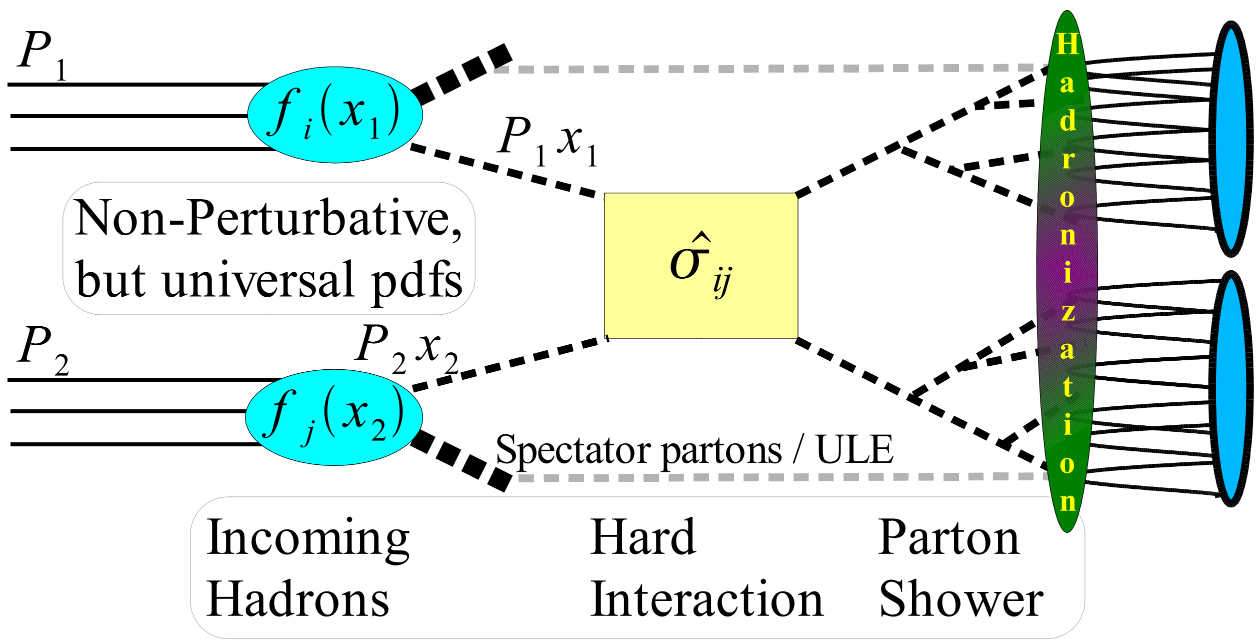
NEW = new for Lepton Photon

- Jet distributions (TeVatron/HERA)
- alpha_s from jets/event shapes (HERA/LEP)
- Photoproduction / $\gamma^{(*)}$structure (HERA/LEP)
- Beauty/charm production

For hard interactions in QCD

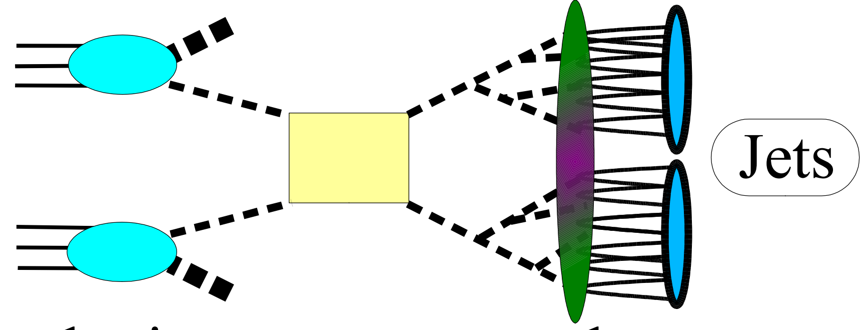
General applicability of perturbation theory

- non abelian gauge theory, running coupling constant $\alpha_s \propto \frac{1}{\ln(\sim Q^2/\Lambda^2)} - \ldots$
- extremely rich phenomenology
- short distances / large p scales: α_s small allowing perturbative calcs.
- factorization of short (pert.) and long (non- pert.) scales



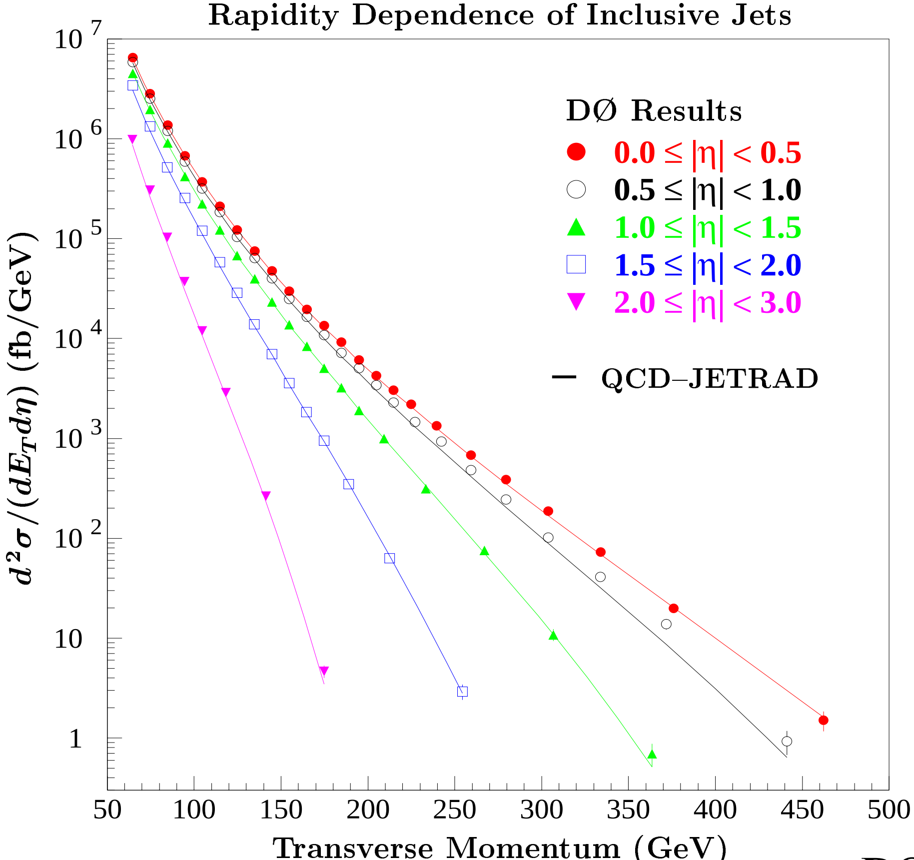
Calculable at (N)NLO w/ scale dependencies: $\alpha_s(Q^2)$, $f(x, Q^2)$

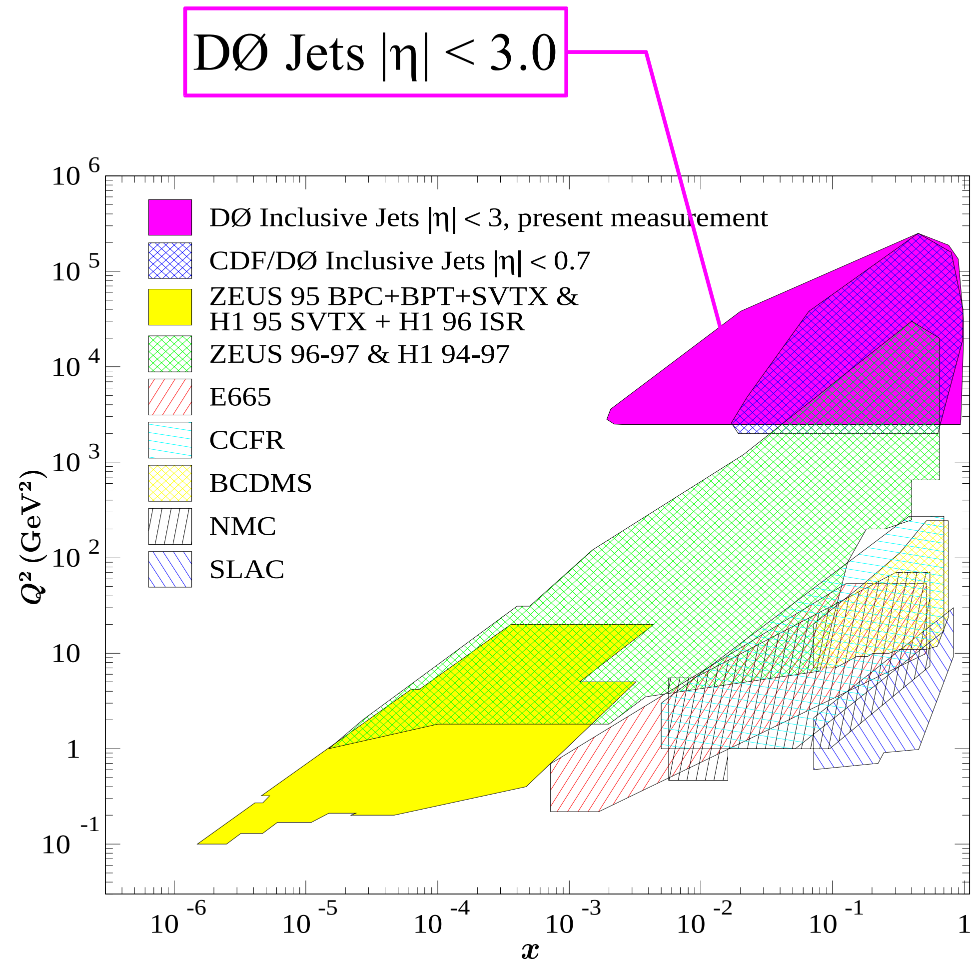
Inclusive Jets (Tevatron)



Cross section for single inclusive jets
probes the hard interaction vertex over many decades in momentum exchange

- probes for deviations from pQCD at small distance scales
- sensitive to pdfs and running of alpha_s

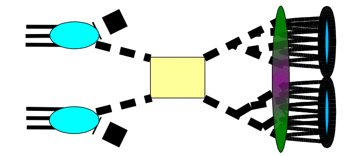




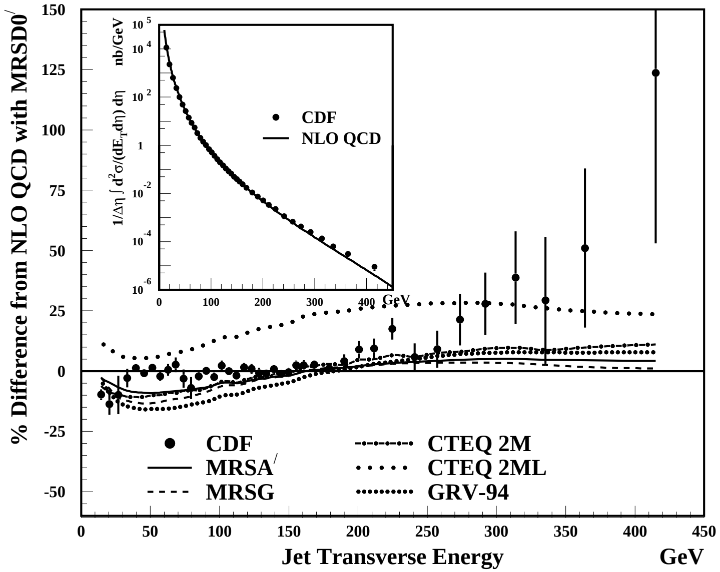
DØ Run I Jets PRL 86, 1707 (2001)

Inclusive Jets (Tevatron)

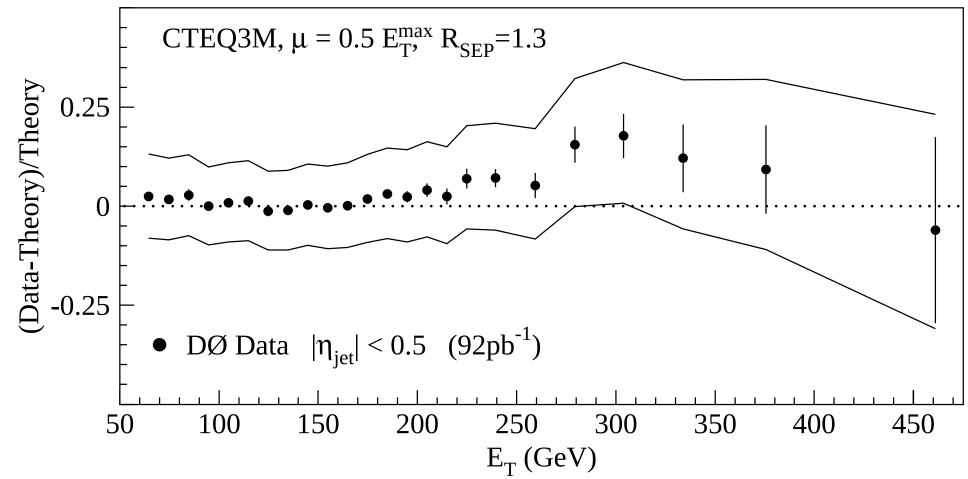
Run I continued



Initially, some excitement over CDF's apparent excess cross section, but...

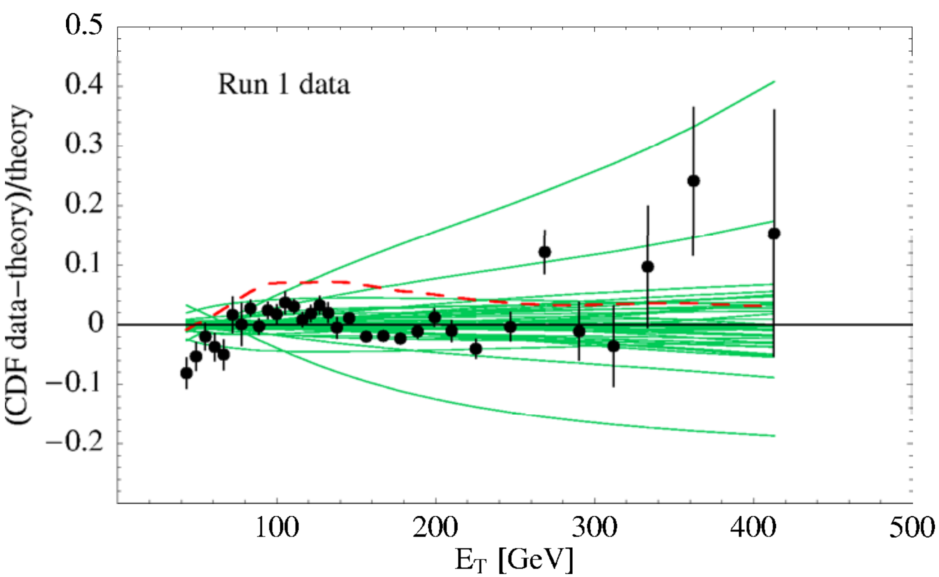


...NLO QCD showed excellent agreement w/ DØ



CTEQ 6 fit ranges vs CDF Run I data (large-x gluons poorly constrained in present fits)

See talk by R. Thorne



The upshot:

QCD is in the news, very fruitful discussions w/ pdf and theory community

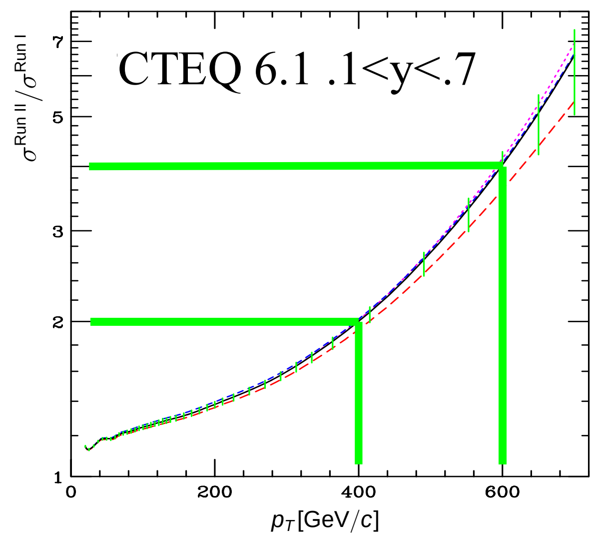
and strong push for quantified pdf uncertainties

...not only important for QCD

Inclusive Jets (Tevatron) in RunII

Run II measurements will ultimately need to include comparisons w/ full range of fits...

$\sigma_{runII}/\sigma_{RunI}$



Run II stats:

versus Run I (higher sqrt(s): 1.8 →1.96 TeV)
cross section : x2 @ ET = 400GeV
x4 @ ET = 600GeV

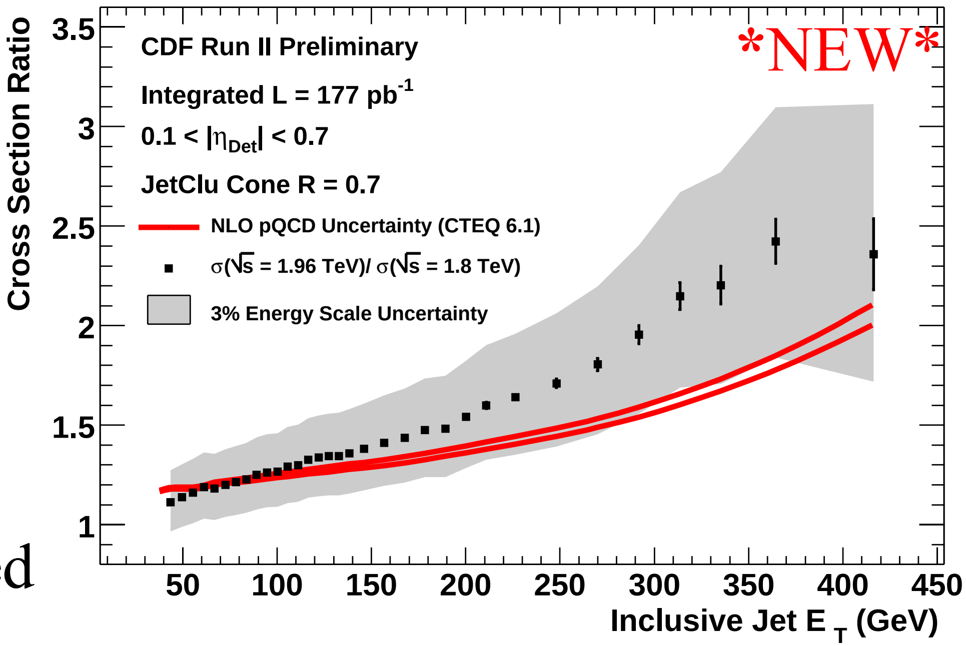
Extend measured E_T spectrum to > 600GeV

1st phase of Run II
integrated luminosity of ~2 fb^{-1}

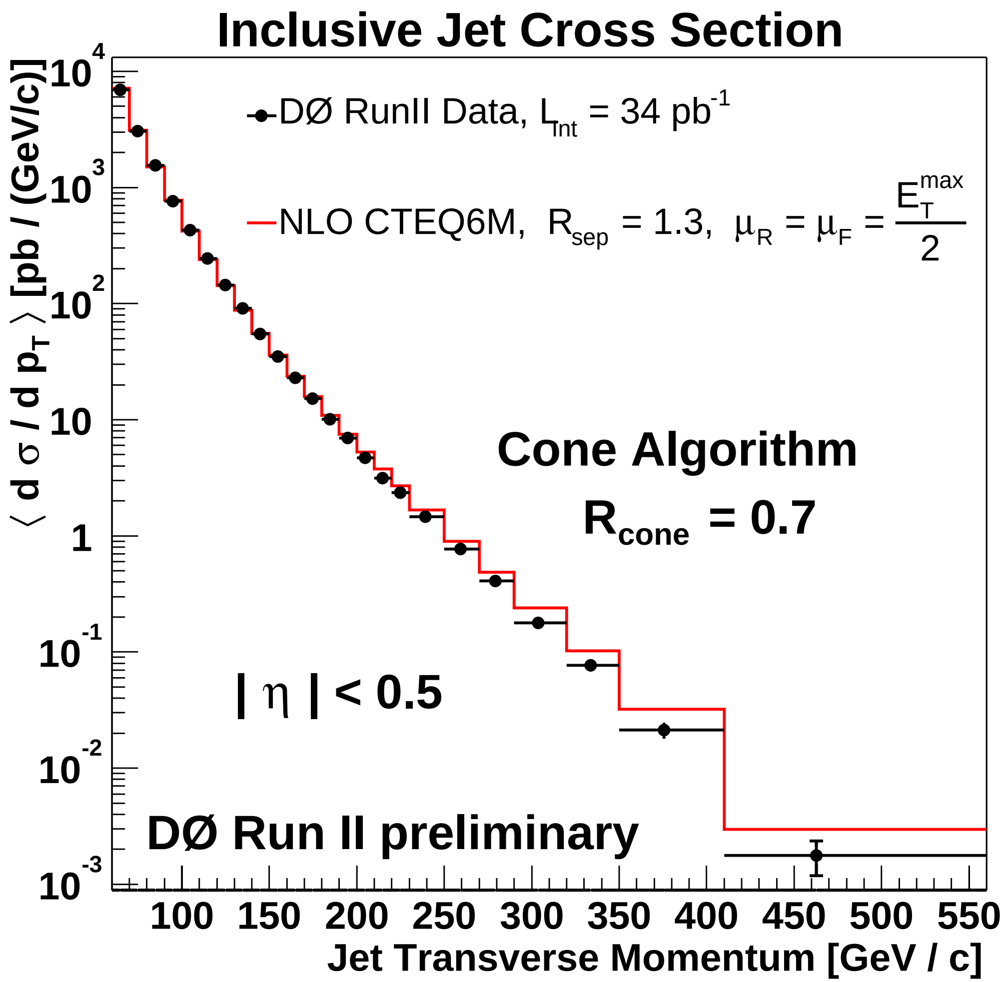
~Few percent statistical error in previously limiting bin

~2x Run I luminosity now collected at CDF/ DØ. Subsets of these data are presented today.

CDF RUN II / RUN I

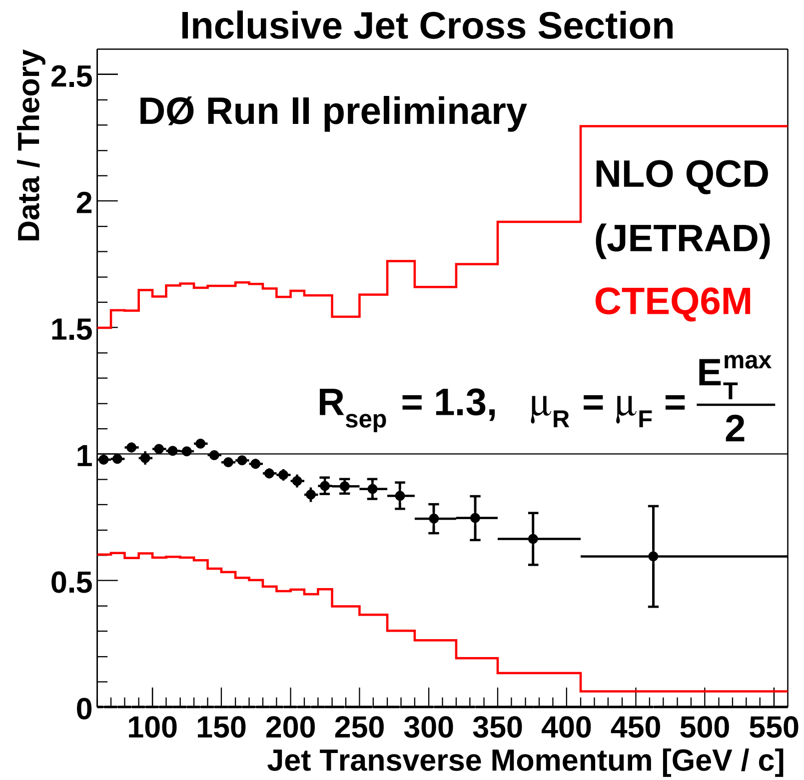


Inclusive Jets



Central |η| < 0.5 inclusive jets
R=0.7 RunII cone algorithm*
$\mathcal{L}$= 34 pb-1

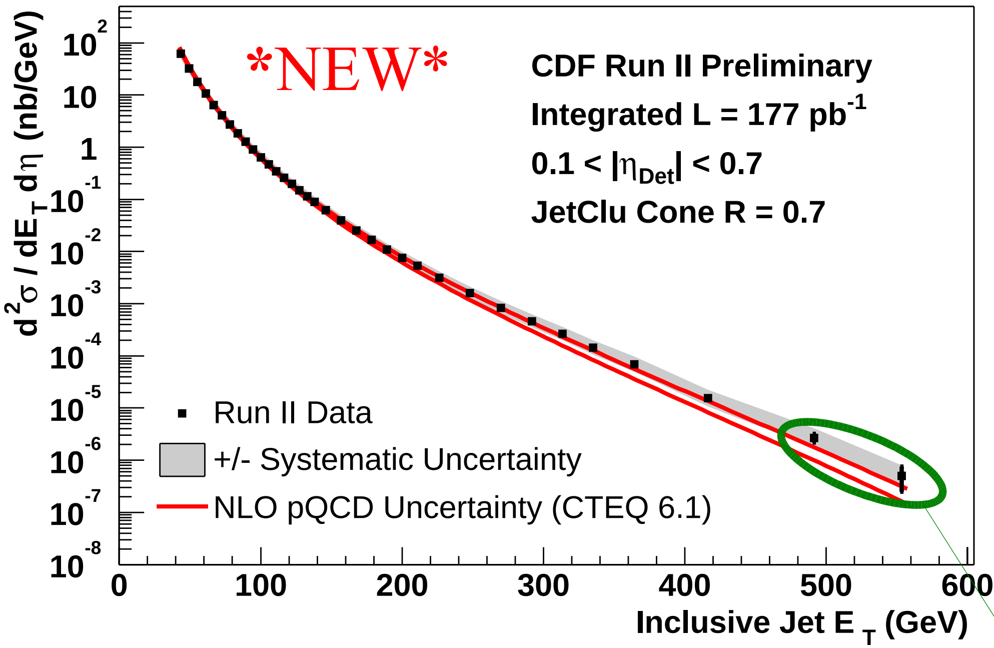
Energy Scale: correct back to hadron level
Full new derivation from Run II data



Scale dominates systematics – will reduce w/ integrated luminosity and further syst. studies
±~10% normalization

* New Run II midpoint algorithm Fermilab-Pub-00/297

Inclusive Jets



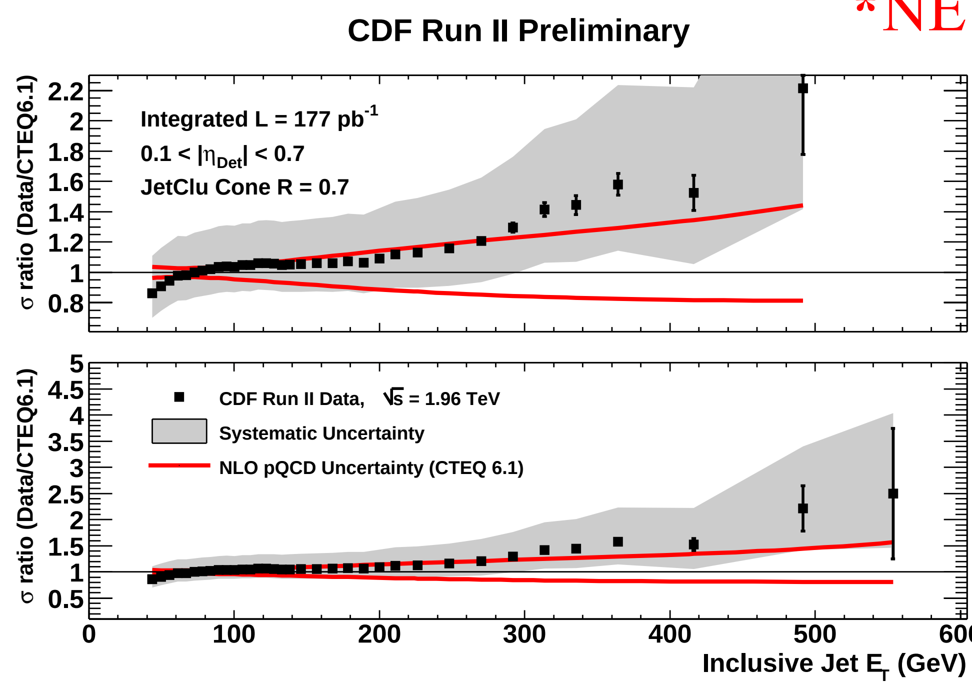
Central 0.1<|η|<0.7 inclusive jets
R=0.7 Run I cone algorithm
$\mathcal{L}$= 177 pb-1

Overall Escale normalized to Run 1
(w/ 5 ± 3% [*NEW*] correction factor)
Reapply PT-dependent systematics from Run I

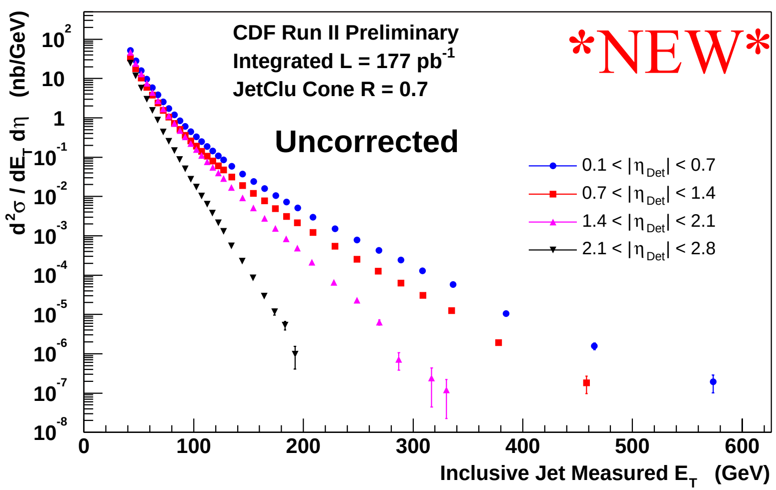
Extended wrt Run I by 150 GeV!

Scale dominates systematics
±~6% normalization

NEW

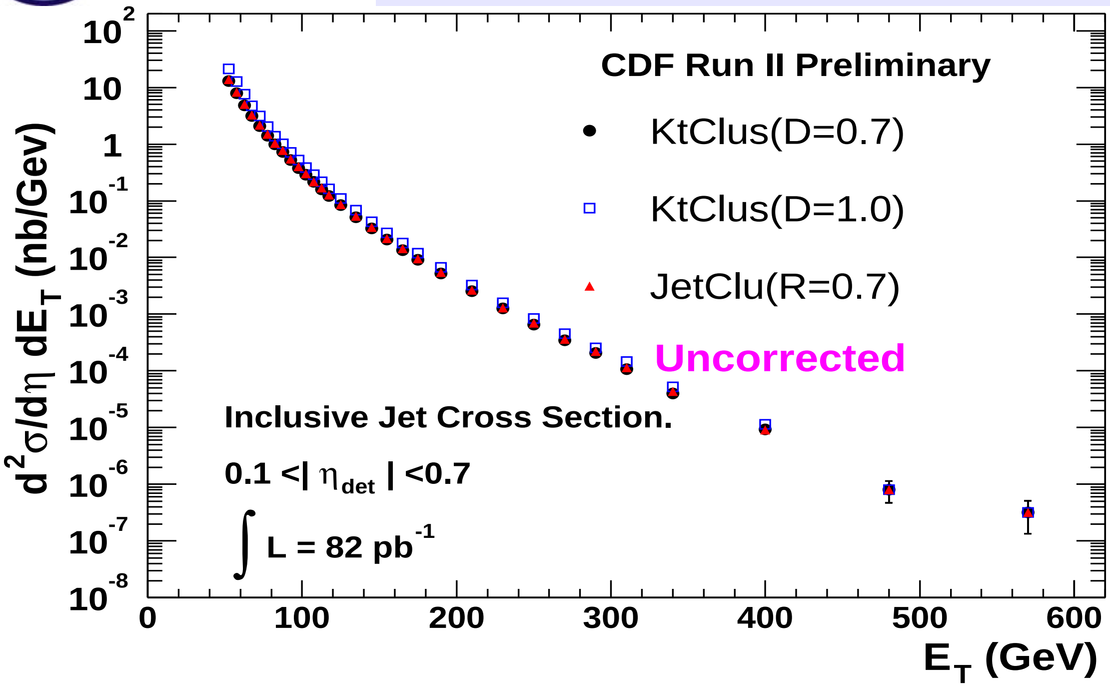


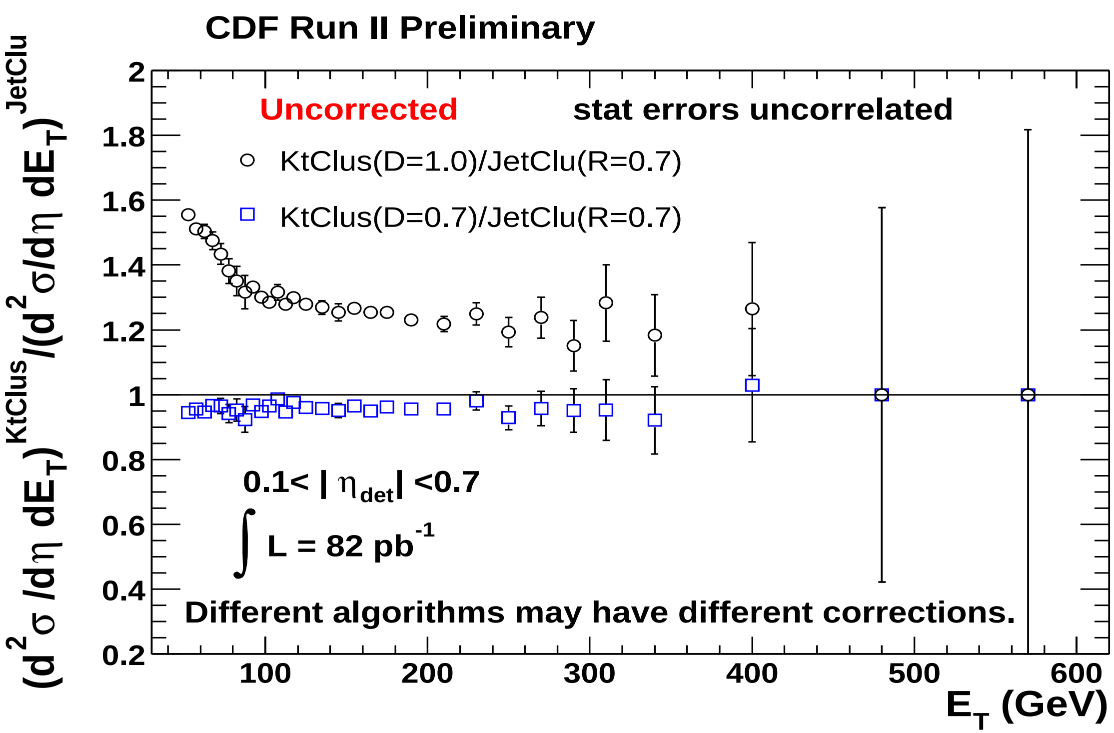
Preliminary distributions for |η| < 2.8

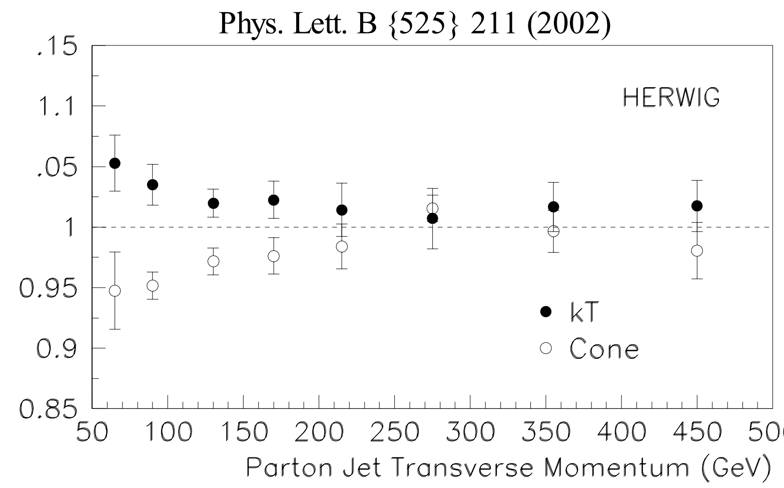


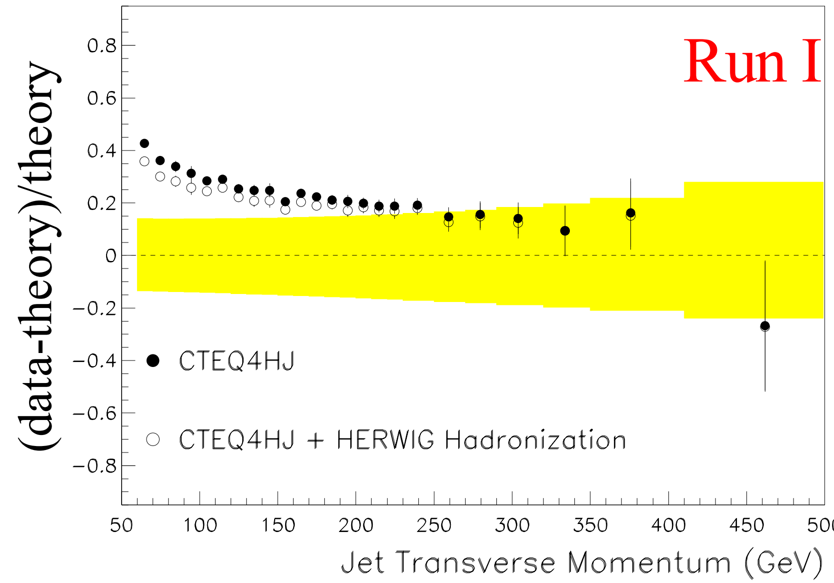
uncorrected

Inclusive CS with KT Jets







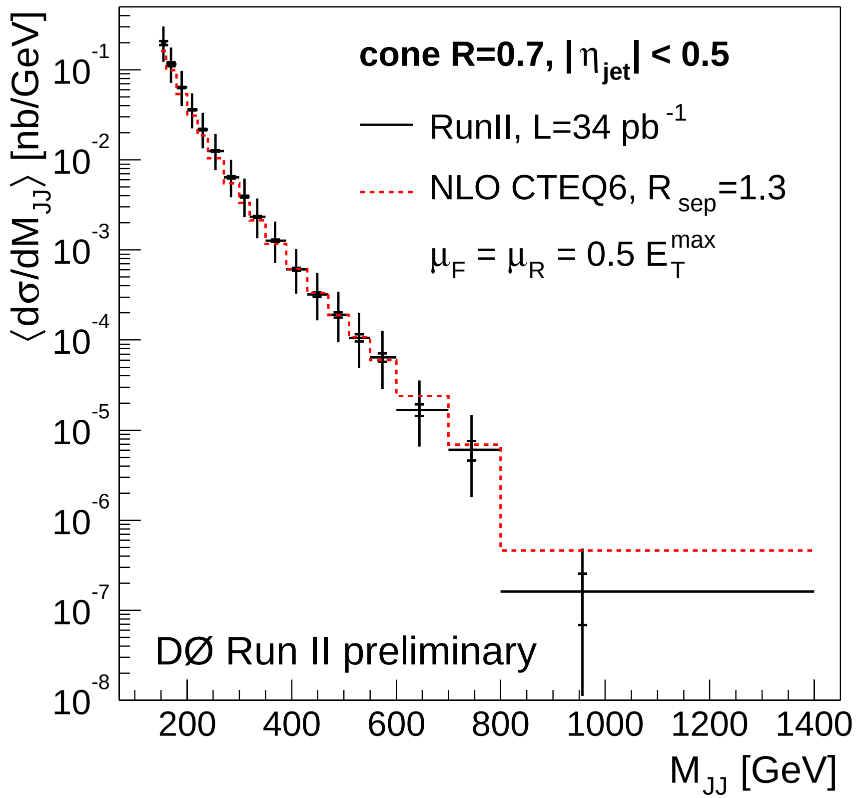


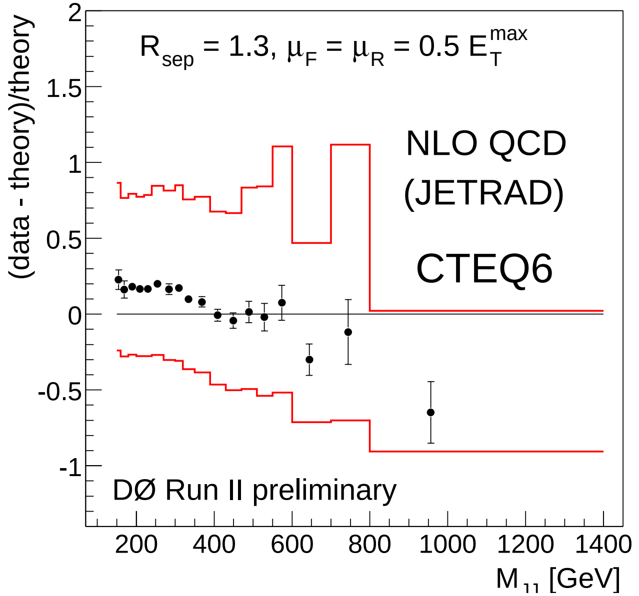
- NLO calculation shows agreement between D=1 and 0.7 cone
- Hadronization effects generated in Herwig are insufficient to cover differences

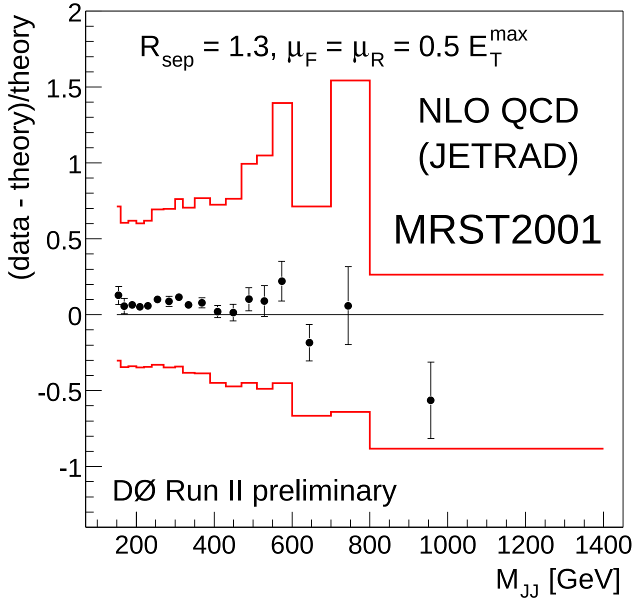
Dijet mass spectrum $\frac{d^2\sigma}{d M_{jj} \, d\eta}$

Central $|\eta| < 0.5$ jets

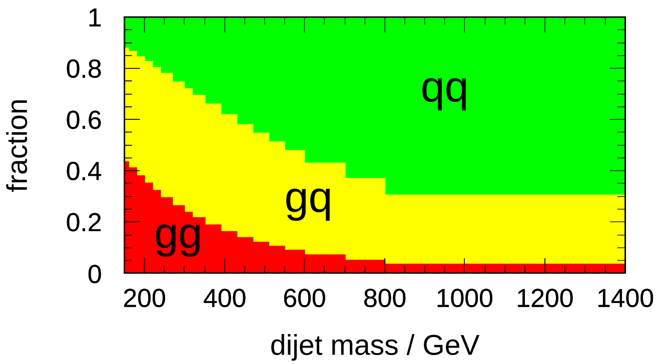
$\mathcal{L} = 34\ \text{pb}^{-1}$





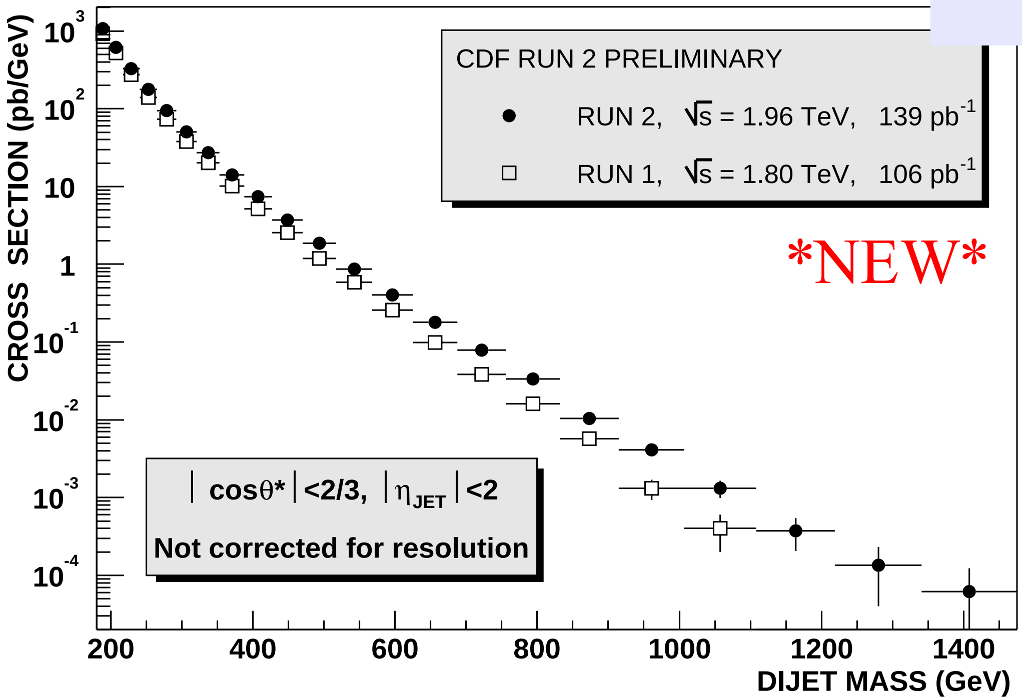


Highest limits in Run I for compositeness from this analysis



Also good sensitivity to gluons at large-x

Dijet mass spectrum

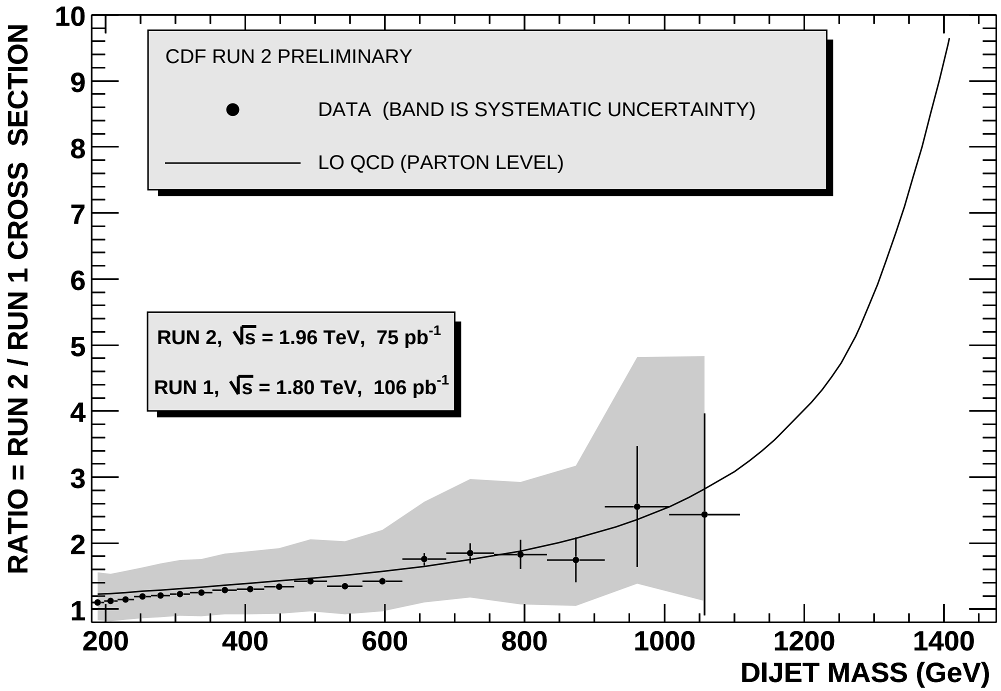


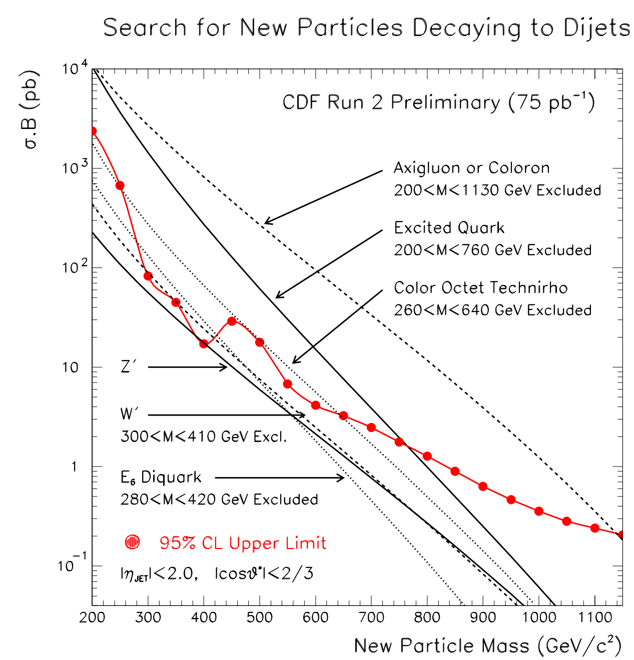
Larger Run II data sample $\mathcal{L}$= 106 pb^{-1}

Preliminary Run II limits set in “bump hunt” for resonances in 2-jet mass in $\mathcal{L}$= 75 pb-1 sample.

already reaching comparable or higher limits than in Run 1

(see limits talk - Yabsley)

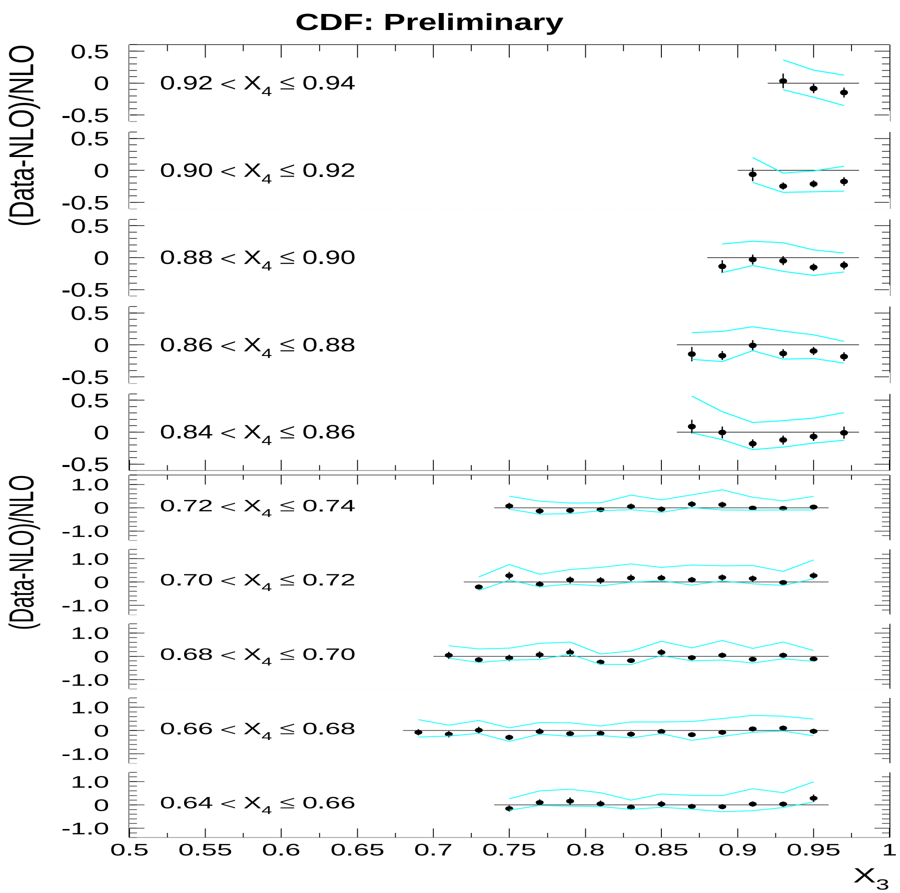




CDF 3 jets

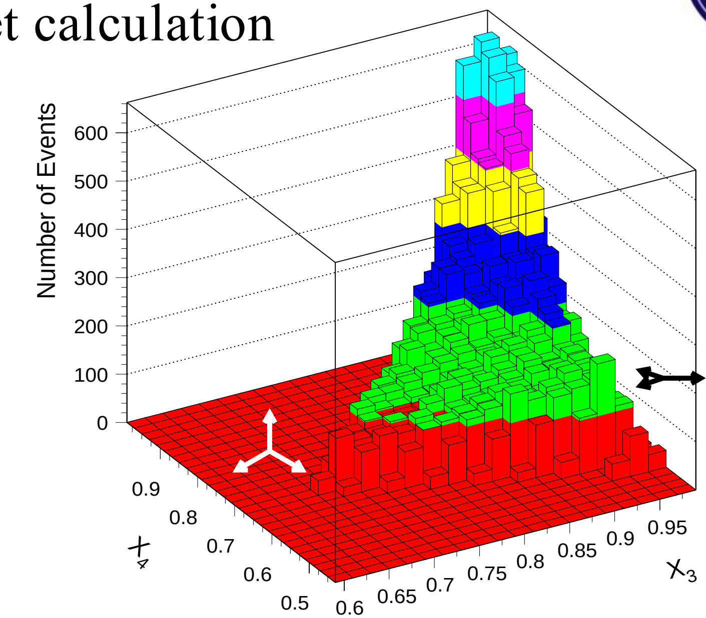
Kilgore/Geile hep-ph/0009193
NLO 3-jet calculation

- determine alpha_s from R_32 or event shapes
- in 3 jet frame: E3>E4>E5 (1+2 → 3+4+5)
- Dalitz variables: x_i = 2E_i/m_3jets

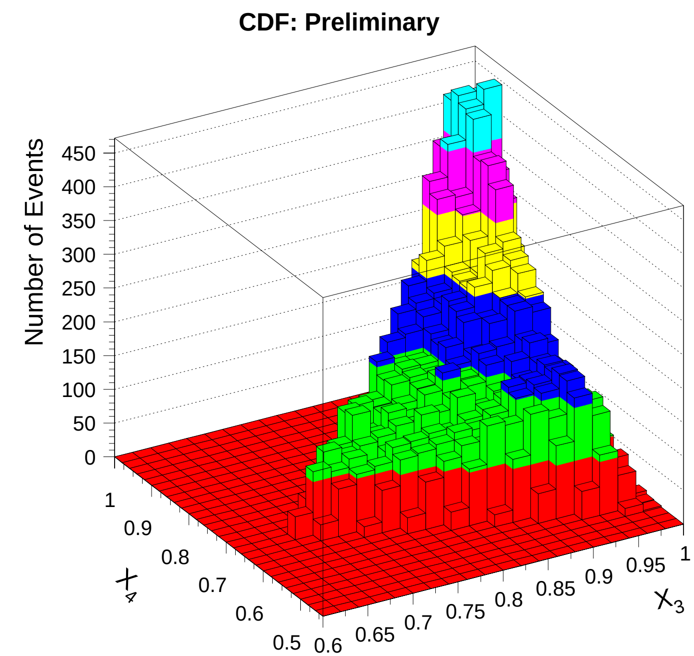


50% of bins shown...

χ2 analysis: no sensitivity to α_s



NLO QCD + CTEQ 4M (α_s = 0.1155)

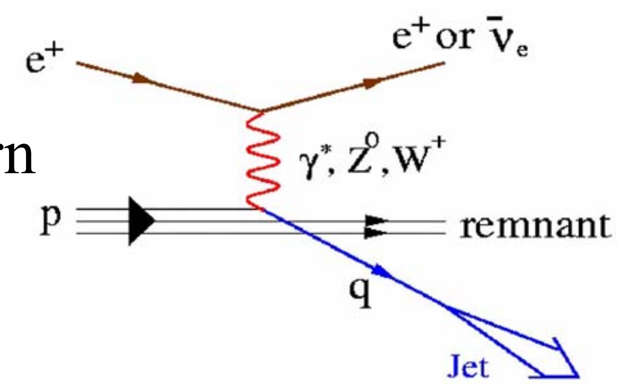


CDF Run I Data

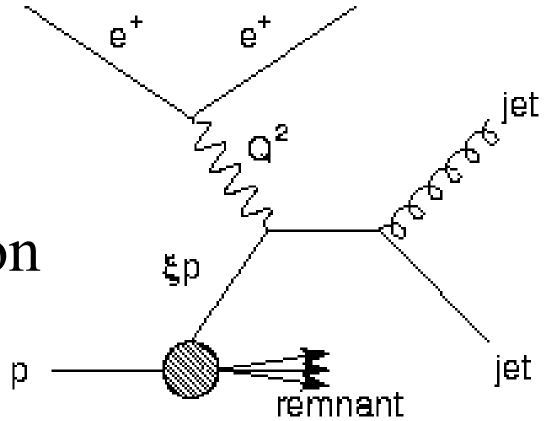
- Reasonable agreement w/ predictions w/in systematic and theoretical uncertainties
- Possible measure of α_s from R32 or event shapes
- Requires more stats., reduced systematics, precise calculation (CPU!)

Jets in DIS

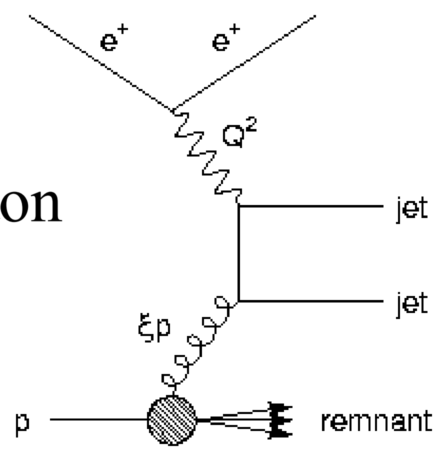
Born



QCD Compton



Boson-gluon Fusion



$$e^+ p \rightarrow e^+ (\bar{\nu}_e) + jets + X$$

Jet production in deep inelastic scattering described in the standard model at O(α_s) by these classes of diagrams

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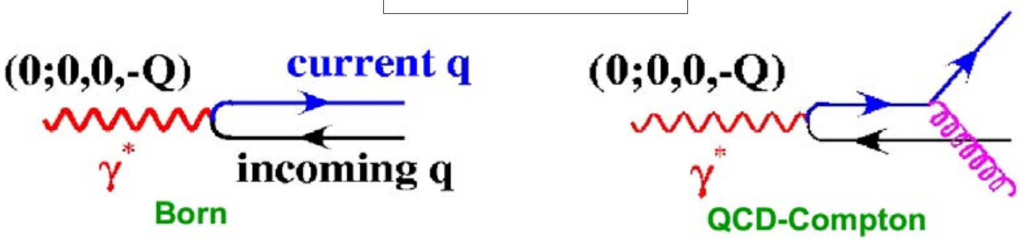
Breit Frame



In Breit Frame Born level diagram is suppressed (quark jet has no ET)

improves separation from proton remnant

Directly sensitive to QCD processes at O(α_s)

Inclusive jets in NC DIS at low Q^2

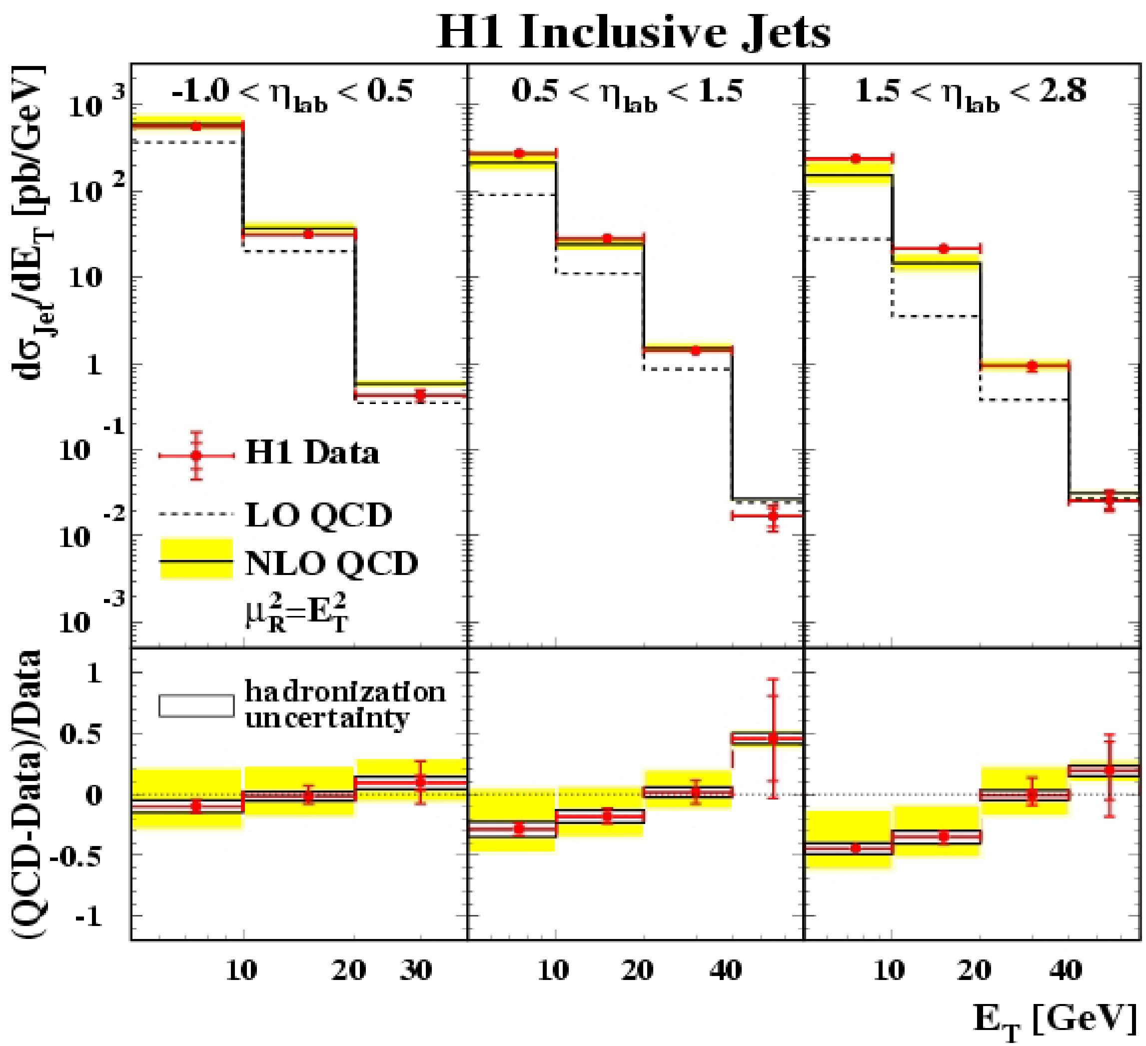
$5 < Q^2 < 100$ GeV^2

$e^+ p \rightarrow e^+ + jets + X$

hep-ex/0206029

Jet E_T >5 GeV, KT algorithm, Breit Frame

Incident proton → Forward direction



Good agreement of NLO QCD with data in backward and central regions

Large NLO corrections for low E_T and in the forward regions: NLO/LO ~ 5

Large virtualities $Q^2 > 125$ GeV^2 data agrees well with NLO QCD predictions (not shown)

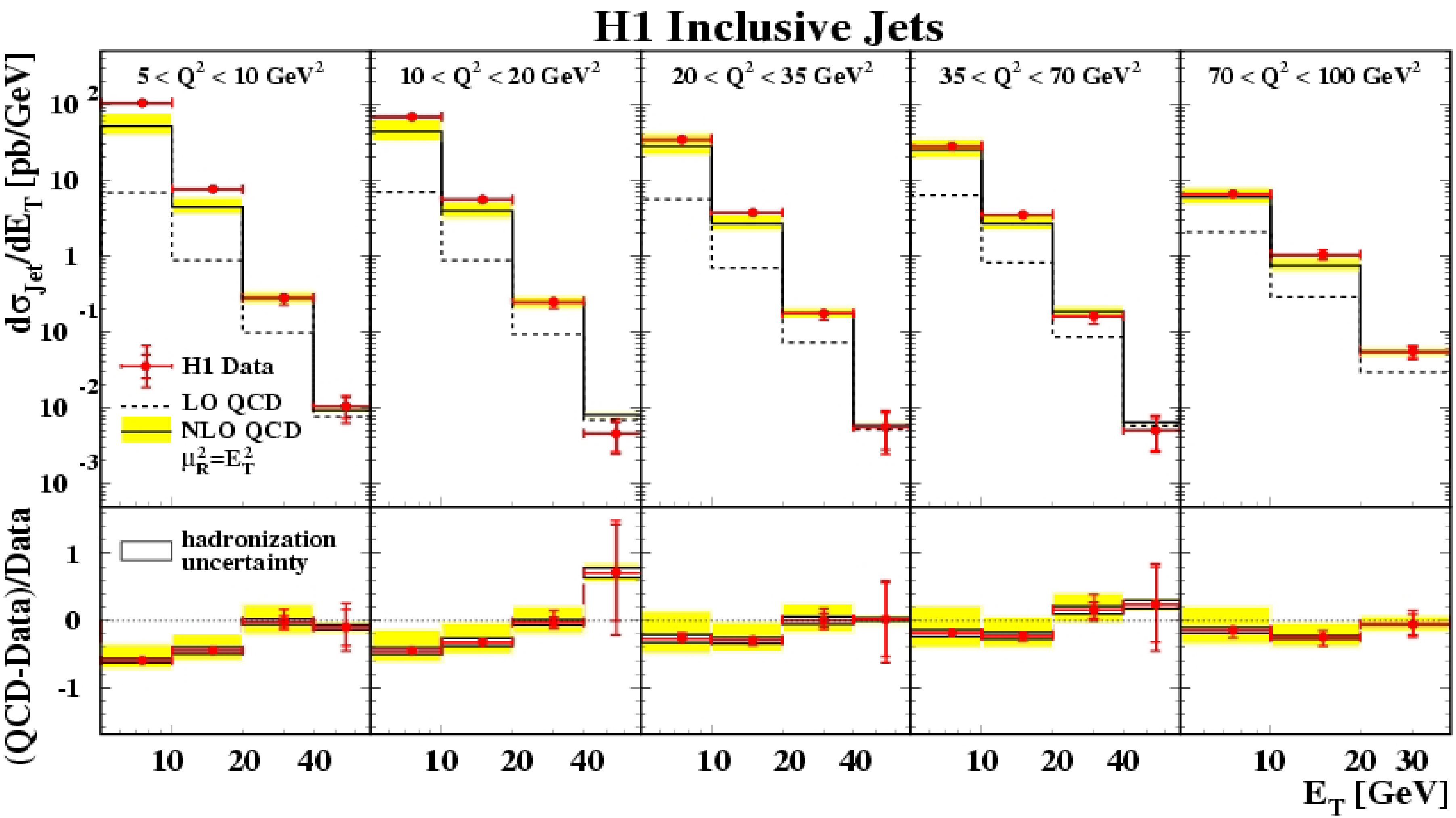
Discrepancies evident at low virtualities...studied in more detail...

Hadronization corrections applied to the predictions

μ Scale uncertainty

Inclusive jets in NC DIS at low Q^2

Forward region: $1.1 < \eta^{lab} < 2.8$ Incident proton → Forward direction hep-ex/0206029



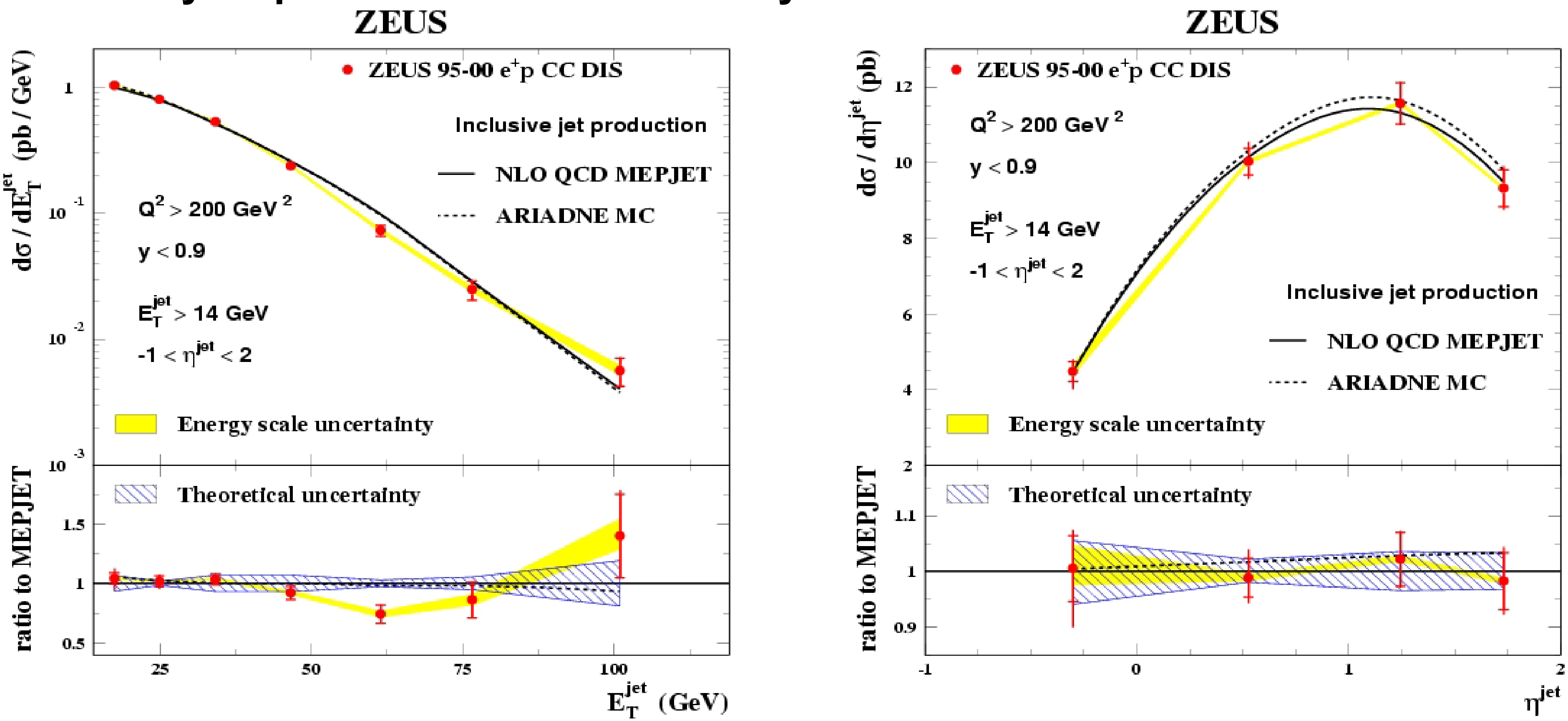
NLO ~ 50% lower than data where LO/NLO corrections are largest...

Inclusive jets in CC DIS

$$e^{+} p \rightarrow \bar{\nu}_e + jet + X$$

hep-ex/0306018

- Test **flavour changing electroweak theory** and **QCD** in **one type of events**
- **Analysis peformed in the laboratory frame**



1. **NLO QCD calculations (MEPJET)**
2. **Matrix elements+parton showers (ARIADNE MC)**

have been compared to the data

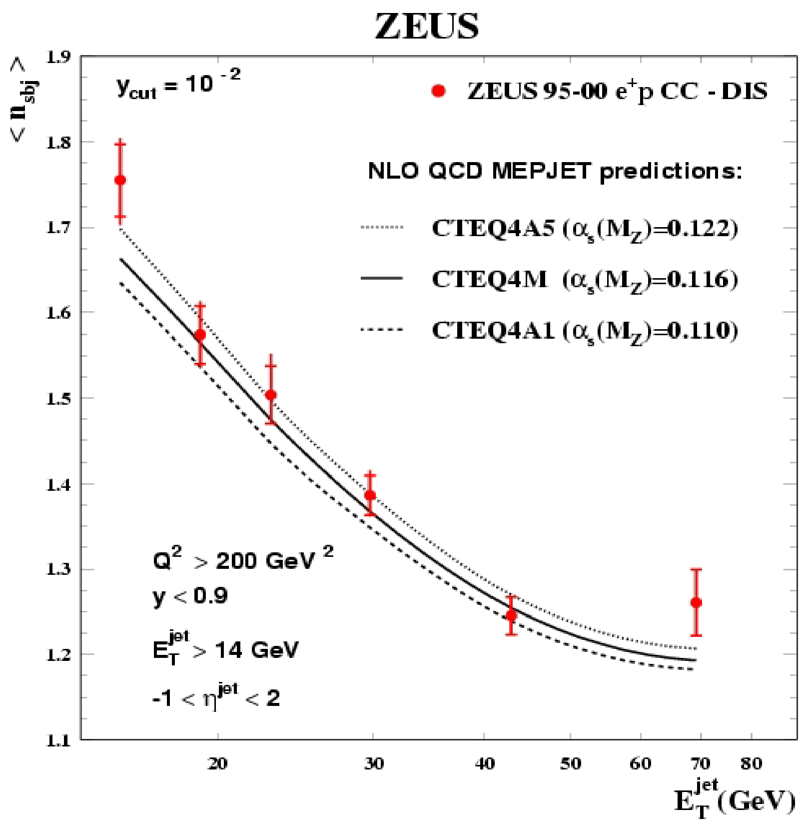
Mirkes and Zeppenfeld, Phys. Lett. B380 (1996) 205
Lönnblad, Z. Phys. C 65 (1995) 285

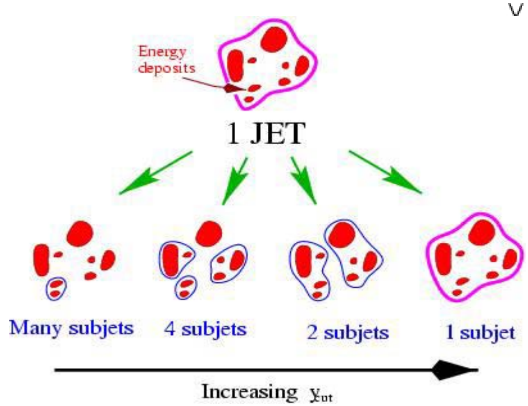
Both the NLO QCD and MC calculations describe well the data

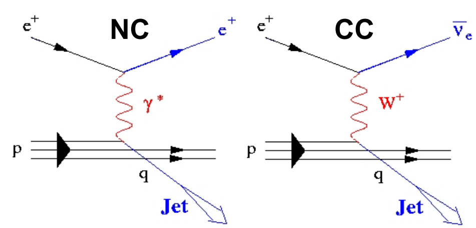
Inclusive jets in CC DIS at low Q^2

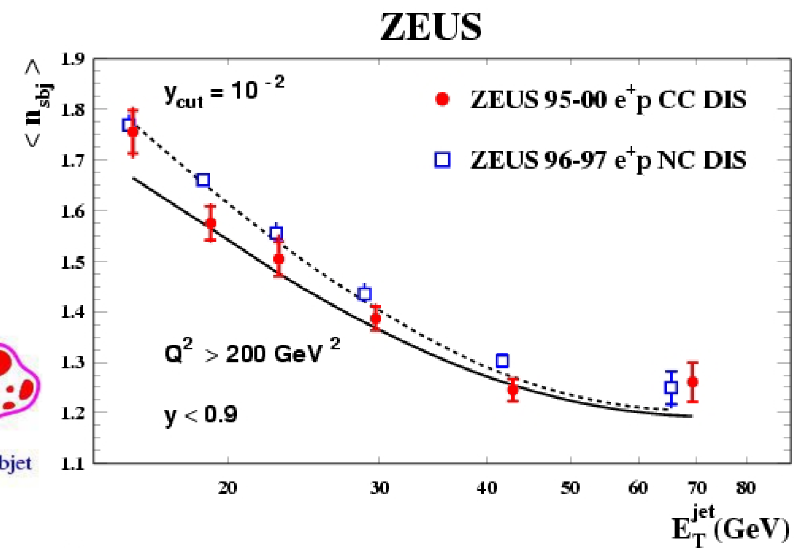
hep-ex/0306018

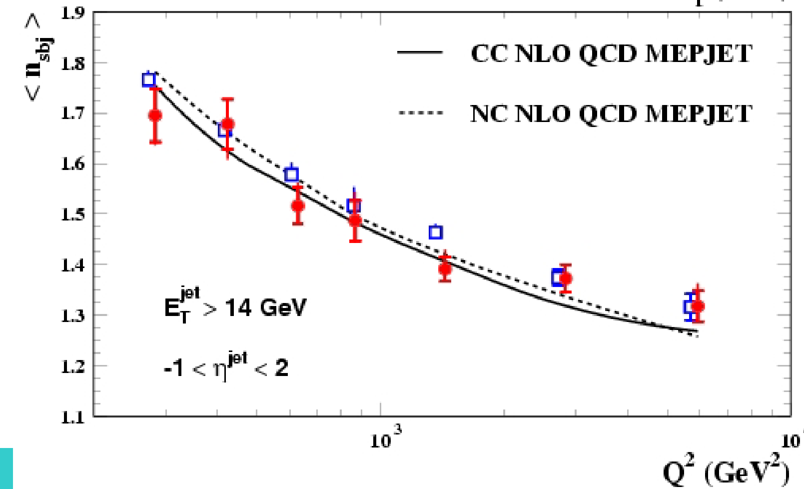
Mean subjet multiplicity











The measurement is sensitive to the value of $\alpha_S(M_Z)$

A χ^2–fit to the region E_t^{jet} > 25 GeV where the parton-to-hadron corrections are <10% gives a value of $\alpha_S(M_Z)$ of:

$$\alpha_S(M_Z) = 0.1202 \pm 0.0052\ (\text{stat.})\ ^{+0.0060}_{-0.0019}\ (\text{syst.})\ ^{+0.0065}_{-0.0053}\ (\text{th.})$$

QCD does not distinguish if W (CC) or γ (NC) is exchanged

Jets in Photoproduction

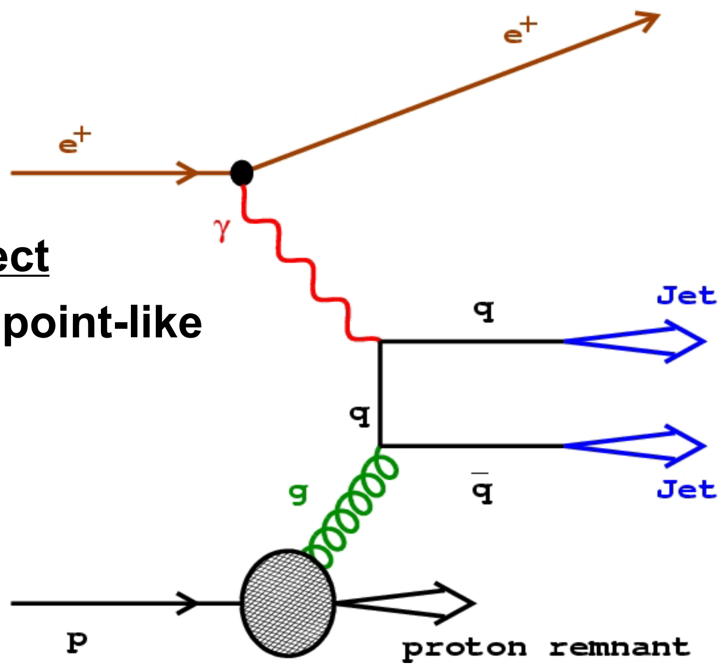
In photoproduction exchanged photon has low virtuality, $Q^2 \sim 0$

High E_T jets described to $O(\alpha\,\alpha_s)$ by the following diagrams

Jets provide hard scale ($E_T^{\,2} >> Q^2$)

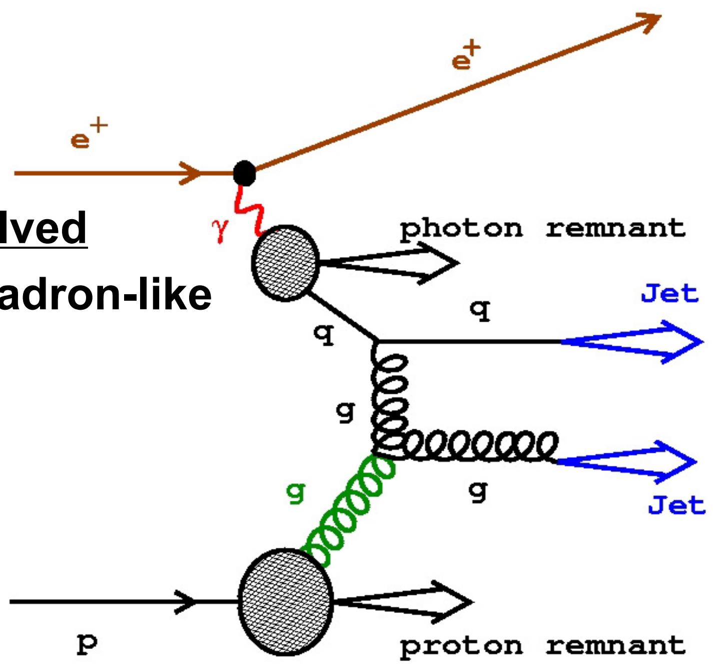
Direct

γ **is point-like**



Resolved

γ **is hadron-like**



Inclusive jets in photoproduction

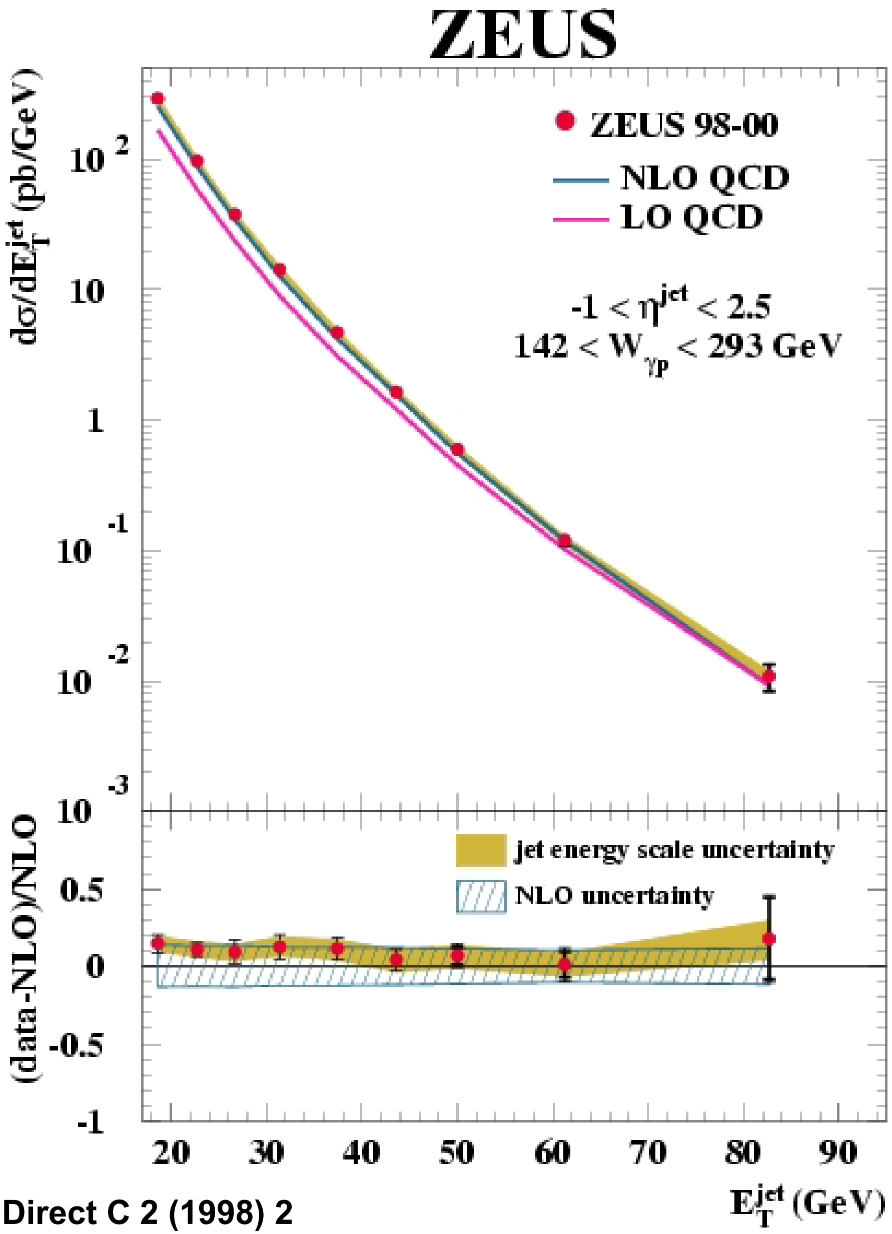
hep-ex/0212064

- Cross sections for jets with

  $17 < E_T^{jet} < 95\,\mathrm{GeV}, -1 < \eta^{jet} < 2.5$

  $142 < W_{\gamma p} < 293\,\mathrm{GeV}, Q^2 \leq 1\,\mathrm{GeV}^2$

Good agreement of **NLO QCD** calculation with the **measured cross section** over 5 orders of magnitude



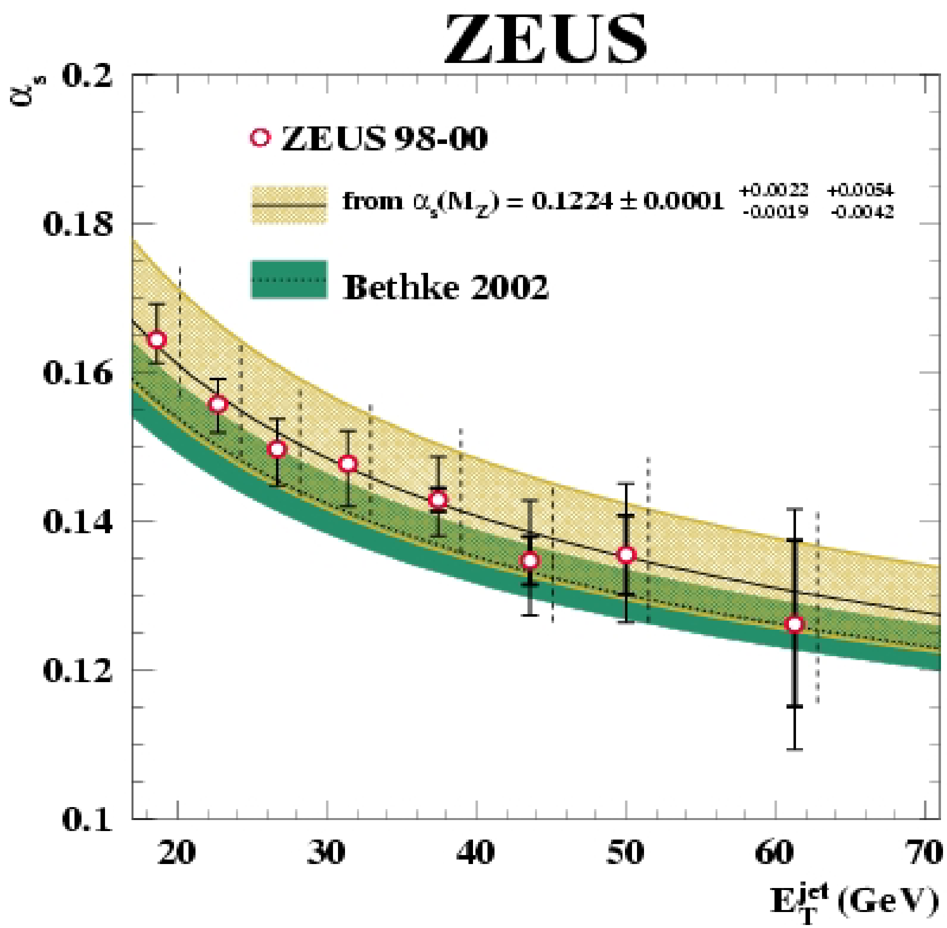
Small theoretical uncertainties

- uncertainty due to missing higher orders in the perturbative series ~10%
- photon and proton PDFs ~ 5%

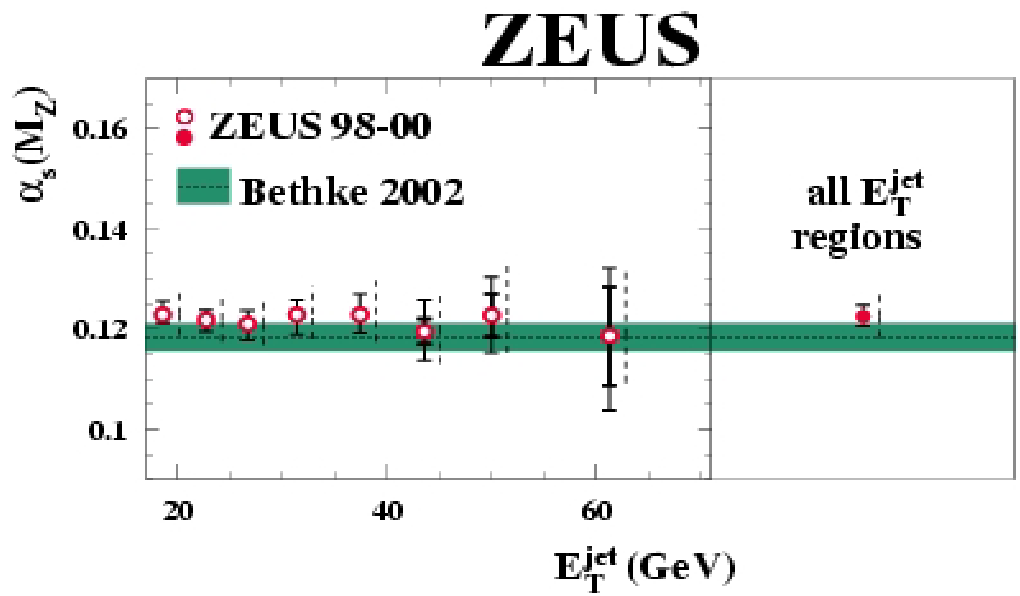
Theoretical calculation from Klasen, Kleinwort and Kramer - Eur. Phys. J. Direct C 2 (1998) 2

Inclusive jets in photoproduction

hep-ex/0212064



Running of α_s in a single measurement



- $\alpha_s(M_Z)$ values determined from a QCD fit to $d\sigma/dE_T^{jet}$ in different E_T^{jet} regions
- Small experimental uncertainties
- Theoretical error dominates
- Consistent with recent determination of Bethke

A χ^2–fit to all the E_t^{jet} regions gives a value of $\alpha_s(M_Z)$ of:

$$\alpha_s(M_Z) = 0.1224 \pm 0.0001\,(\text{stat.})^{+0.0022}_{-0.0019}\,(\text{exp.})^{+0.0054}_{-0.0042}\,(\text{th.})$$

Bethke: hep-ex/0211012

Inclusive jets in photoproduction

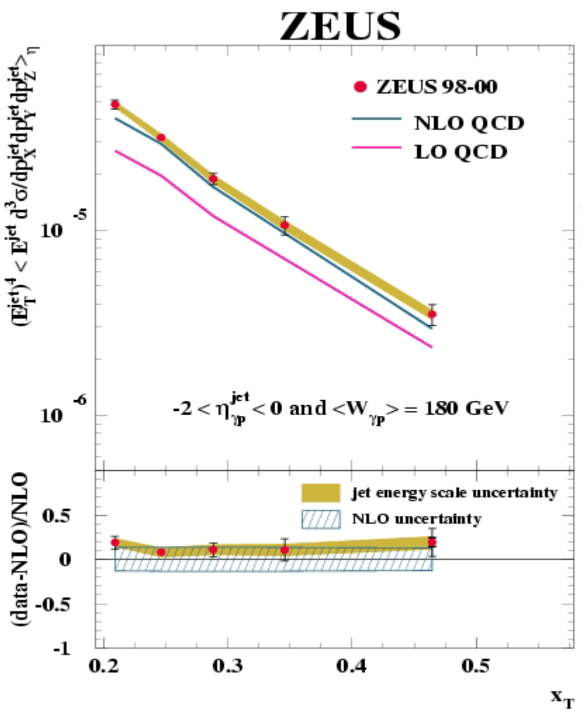
hep-ex/0212064

Scaling hypothesis: the **scaled jet invariant cross section**

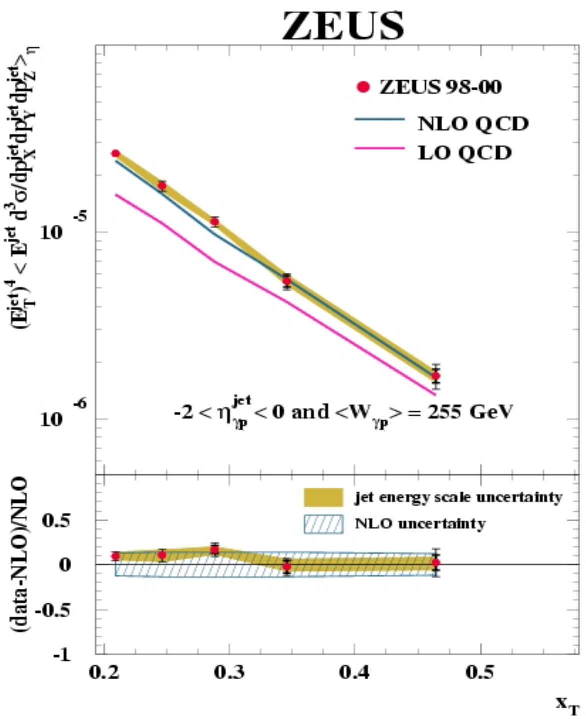
$$\left(E_T^{jet}\right)^4 \cdot \left\langle E^{jet} \cdot \frac{d^3\sigma}{dp_x^{jet}\, dp_y^{jet}\, dp_z^{jet}} \right\rangle_\eta$$

averaged over $-2 < \eta_{\gamma p}^{jet} < 0$ **as a function of** $x_T \equiv \frac{2E_T^{jet}}{W}$

should be independent of $W_{\gamma p}$



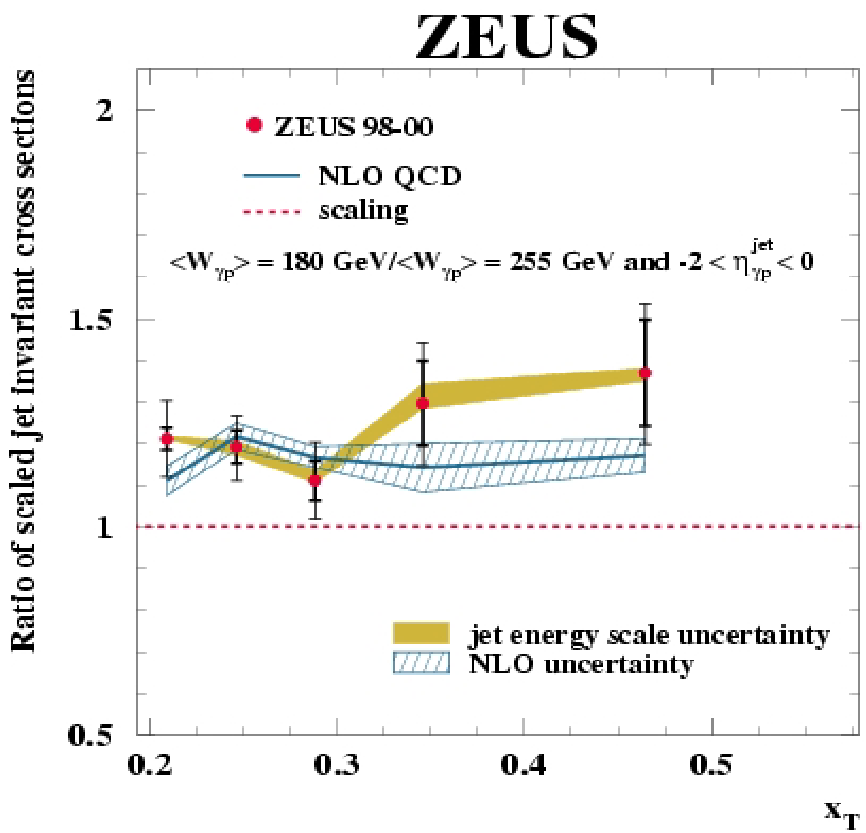
$169 < W_{\gamma p} < 191$ GeV



$240 < W_{\gamma p} < 270$ GeV

Effectively equivalent to running with two different beam energies

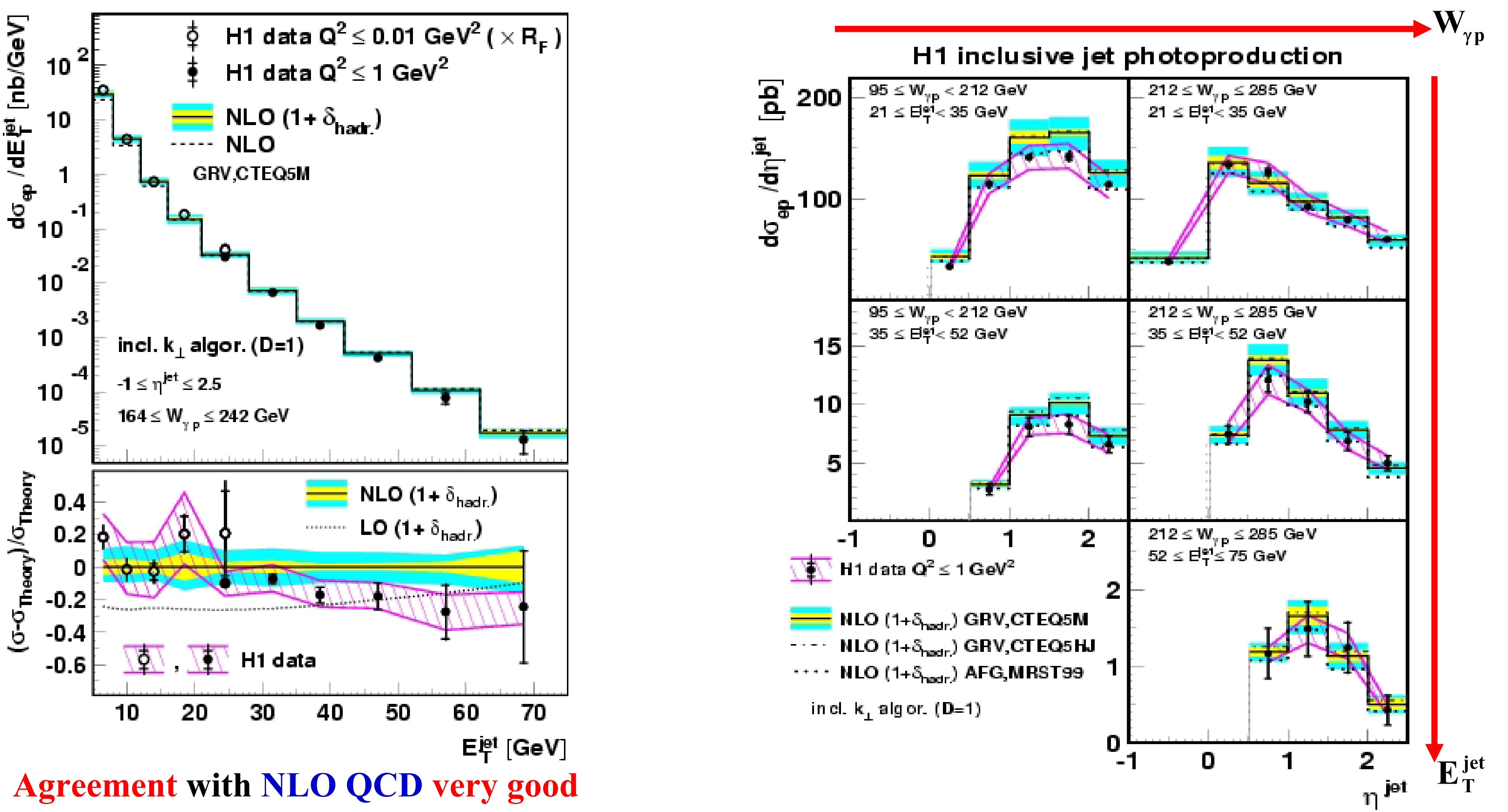
NLO QCD calculations are consistent with the data



- **Theoretical uncertainties reduced**
- **Scaling violation due to: parton evolution and running of α_s**
- **First observation of scaling violations in jet photoproduction**

Inclusive jets in photoproduction

hep-ex/0302034



- Agreement with NLO QCD very good
- All predictions obtained using different proton (MRST99,CTEQ5) and photon (GRV,AFG) PDFs agree with the data

Theoretical calculation from Frixione, Ridolfi Nucl. Phys. B 507 (1997) 315

Inclusive jets in photoproduction

hep-ex/0302034

Scaled cross section: independent of energy up to scaling violations

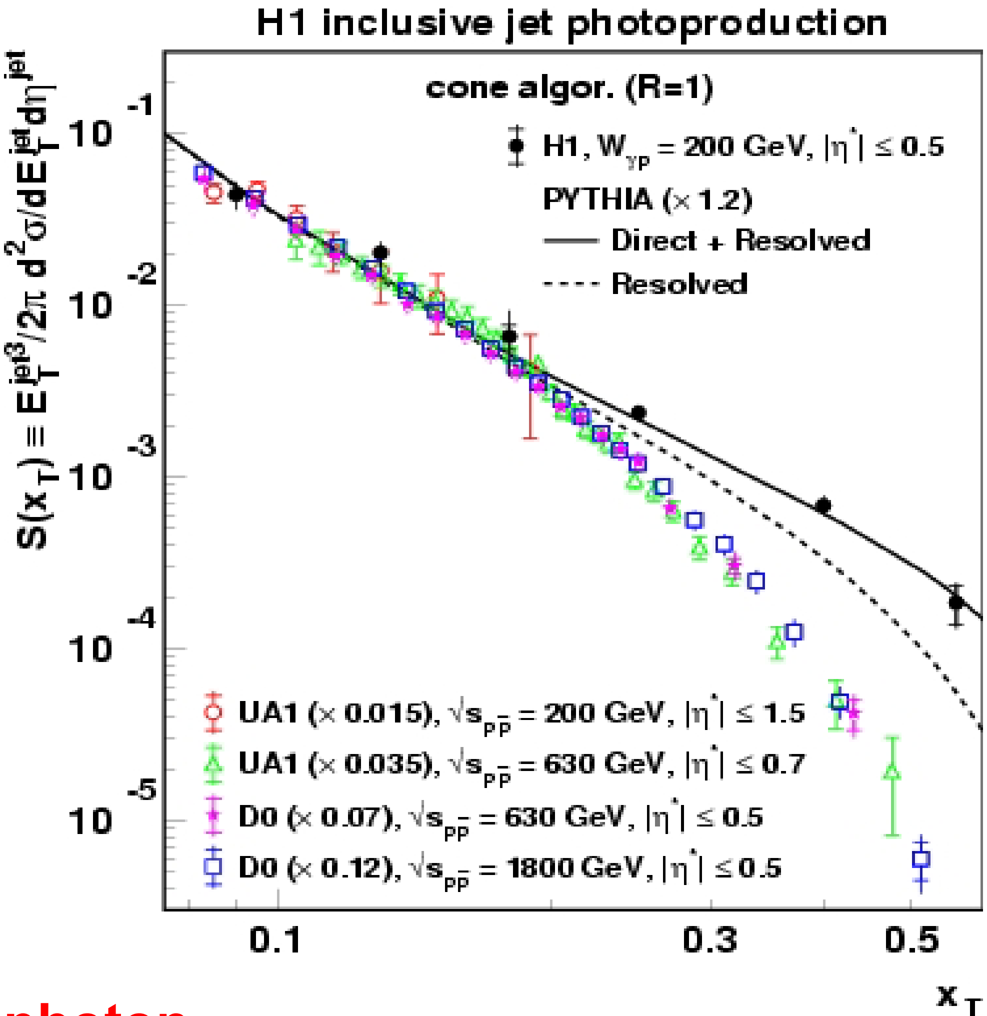
$$S(x_T) \equiv \frac{E_T^3}{2\pi} \frac{d^2\sigma}{dE_T \, d\eta} \; ; \; x_T \equiv \frac{2E_T}{W_{\gamma p}}$$

$x_T < 0.2$

- ⇨ **shape similar for γp and $p\bar{p}$**
- ⇨ **resolved photon ~ hadron**

$x_T > 0.2$

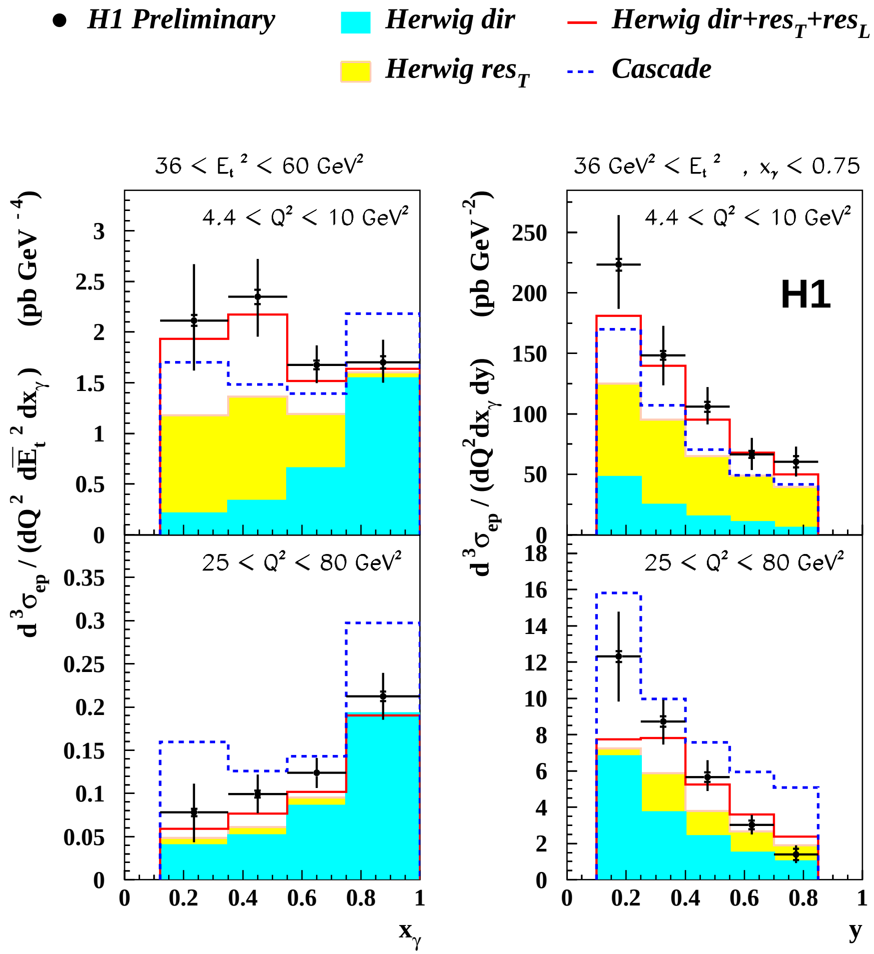
- ⇨ **γp harder than $p\bar{p}$ spectrum**
  - **enhanced quark density in the resolved photon w.r.t. a hadron**
  - **dominance of direct**
- ⇨ **point-like photon**



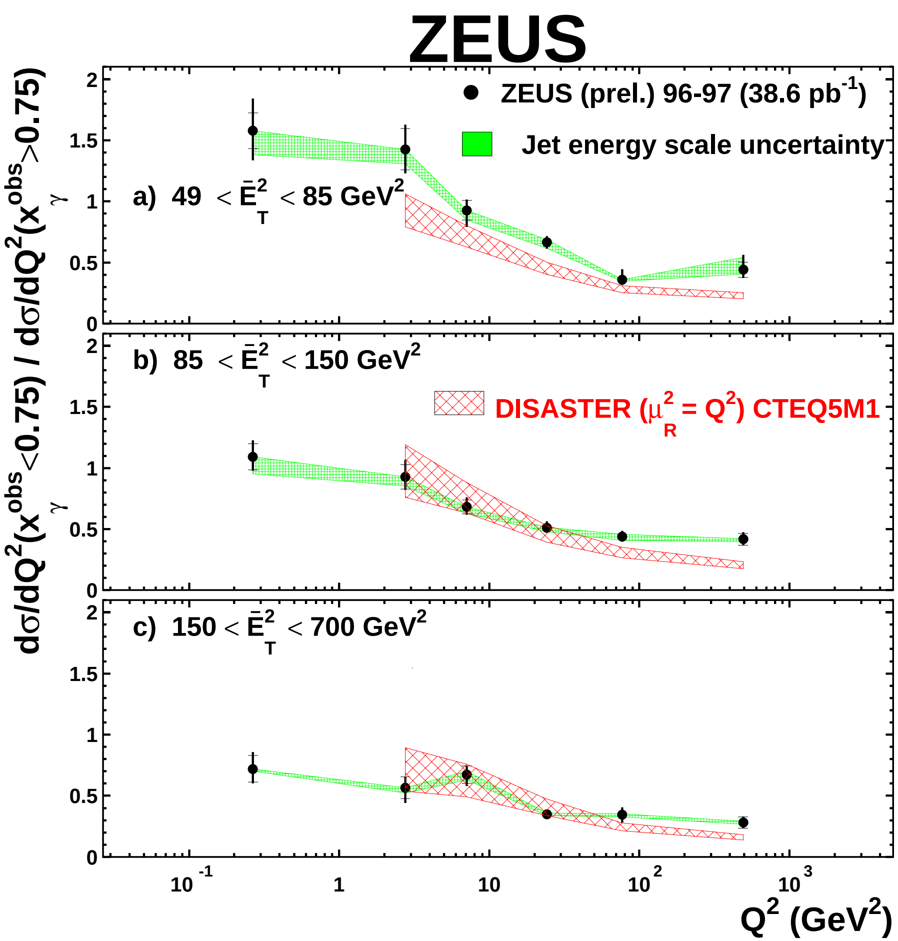
⇨ Confirmation of the dual nature of the photon

Dijet production versus Q^2

see EPS abstract 085



see EPS abstract 585



- Best agreement using HERWIG + resolved photon w/ transversely/ longitudinally polarized resolved photons ($E_T > Q^2$, even for ~high Q^2)

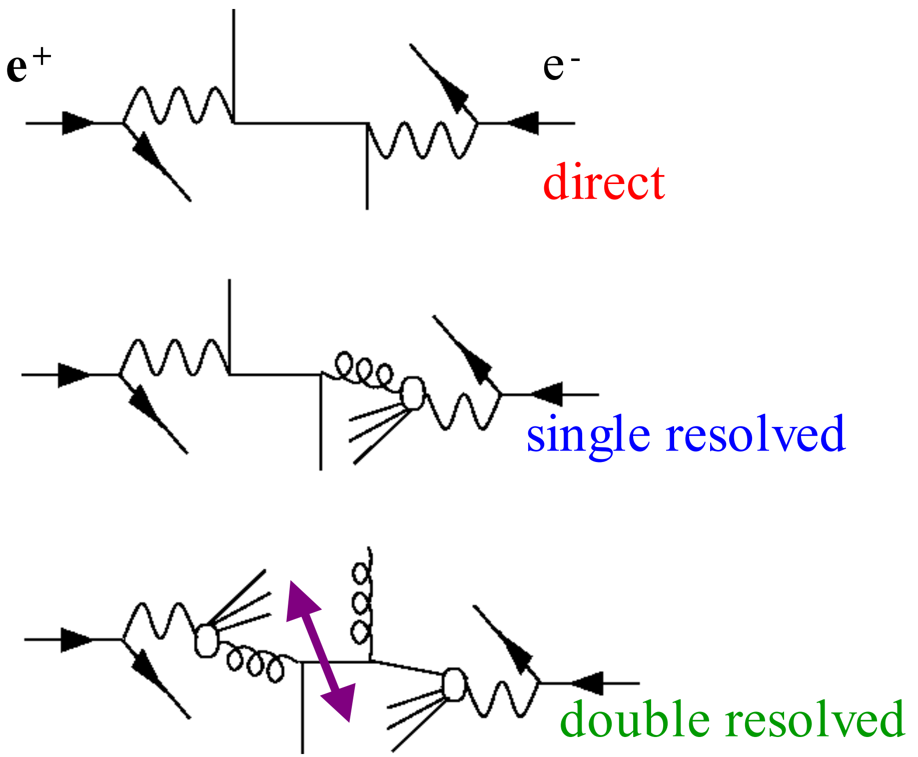
- But reasonable (though not perfect) agreement in unordered KT cascades (CCFM/BFKL model)

Ratio of dijet cross secs. for $x_\gamma^{low}/x_\gamma^{high}$

- Data falls w/ Q^2,<ET>. Resolved effects suppressed as virtuality increases.

- Compatible w/ needing resolved contribution for scales up to Q^2~10GeV^2

Jet production in γγ collisions at LEP

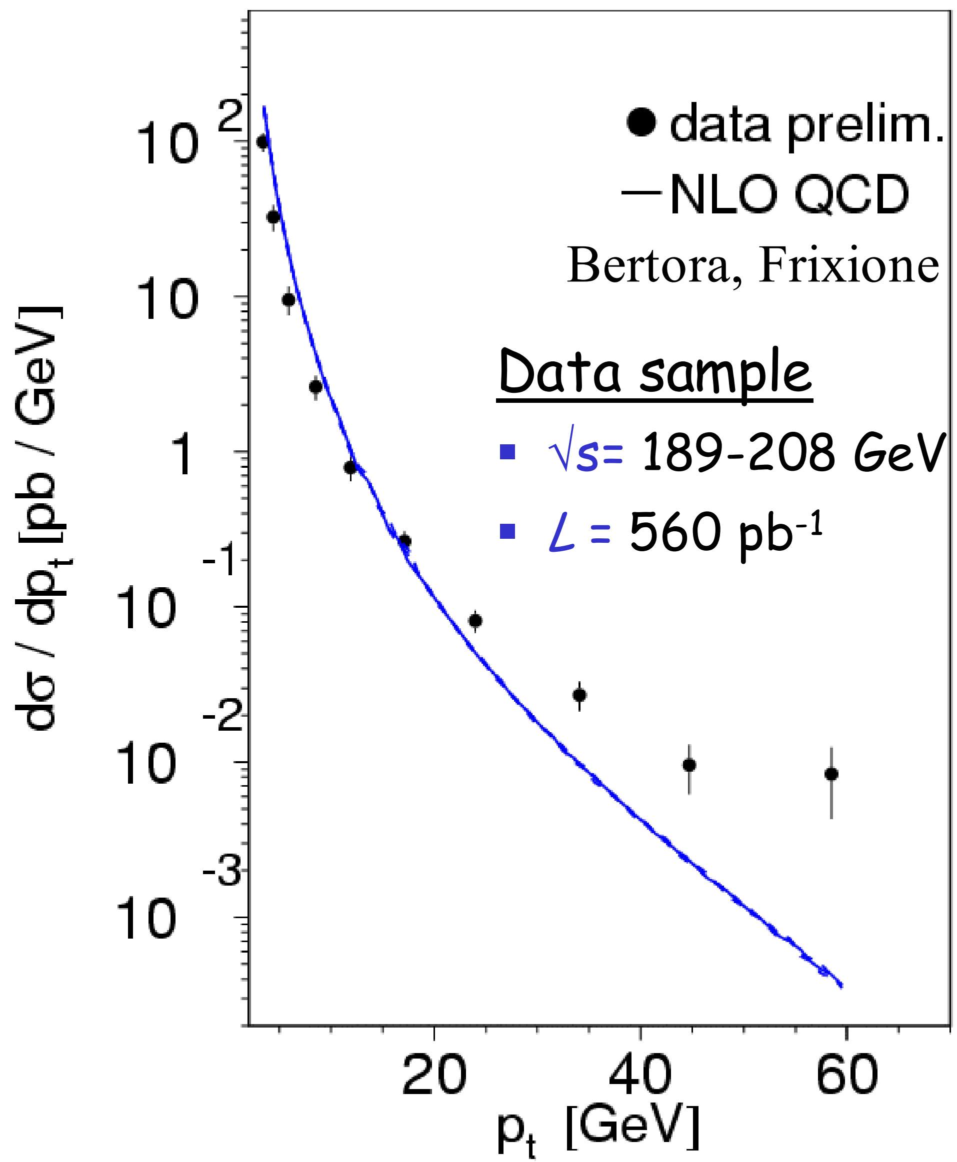


Deviation from NLO consistent with previous charged/neutral hadron results

But NOT understood...

NLO + γ pdfs describe HERA data well!

New single jet inclusive from L3

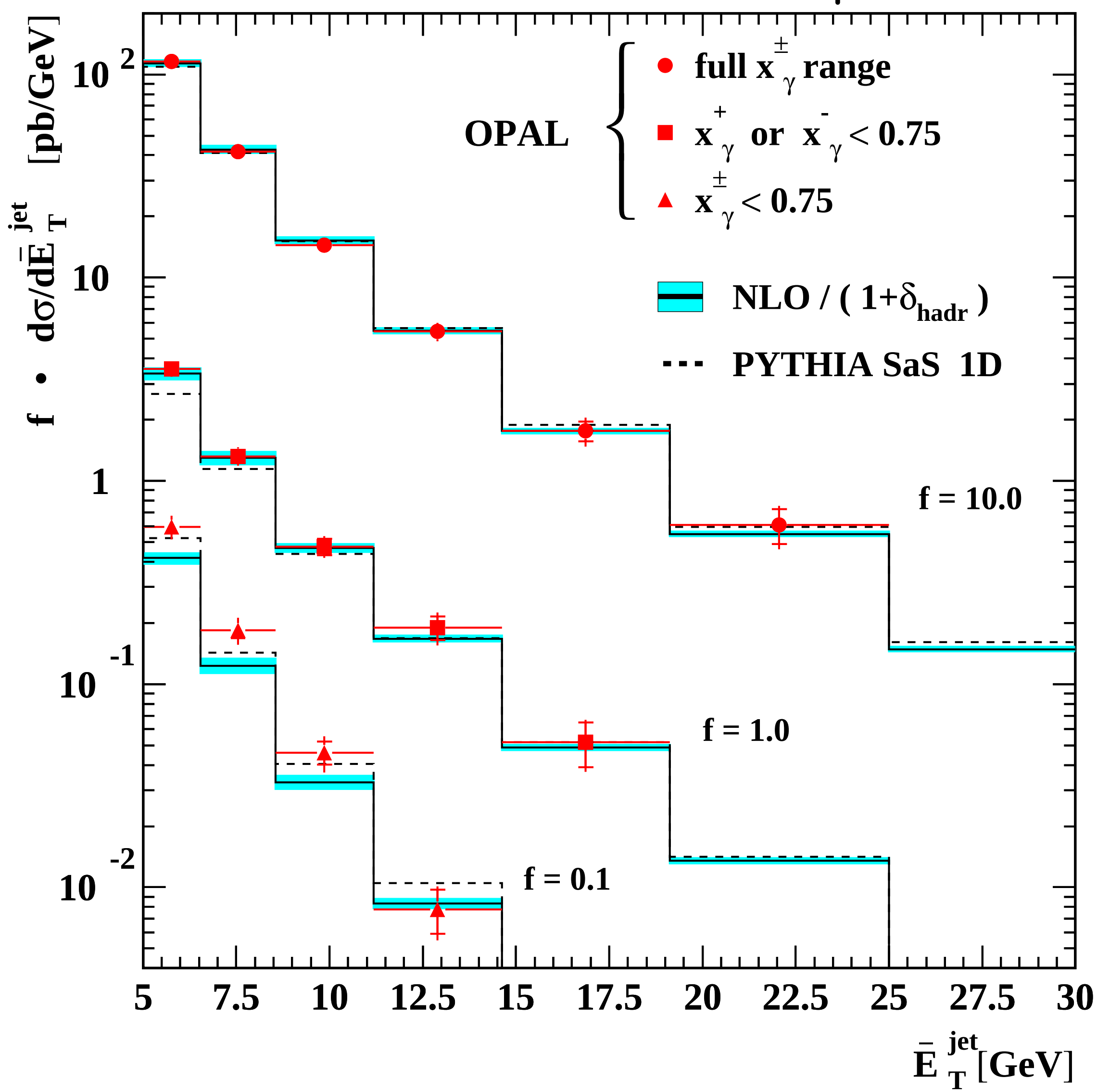


Di-Jet production in γγ collisions at LEP

Data sample

- $\sqrt{s}$ = 189-209 GeV
- $\mathcal{L}$ = 593 pb^{-1}

Split events into regions:
1) all
2) single resolved enhanced
3) double resolved enhanced

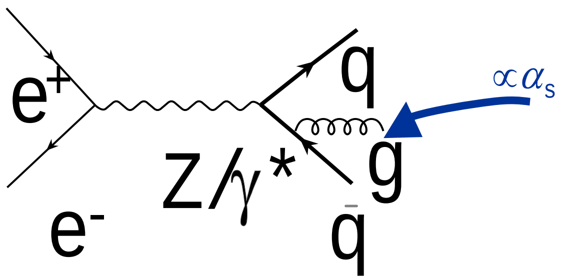


Data well described for full sample and single resolved enhanced,

too low for double resolved enhanced sample.

Possibly due to underlying event effects...

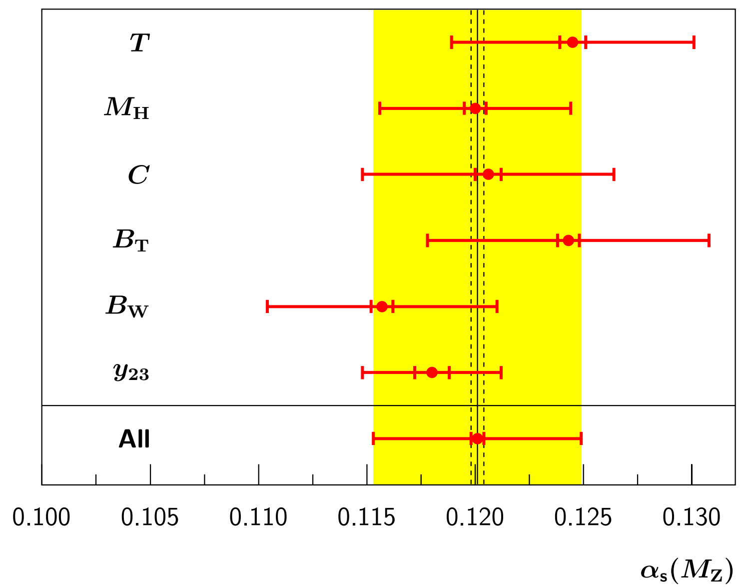
Event Shapes at LEP

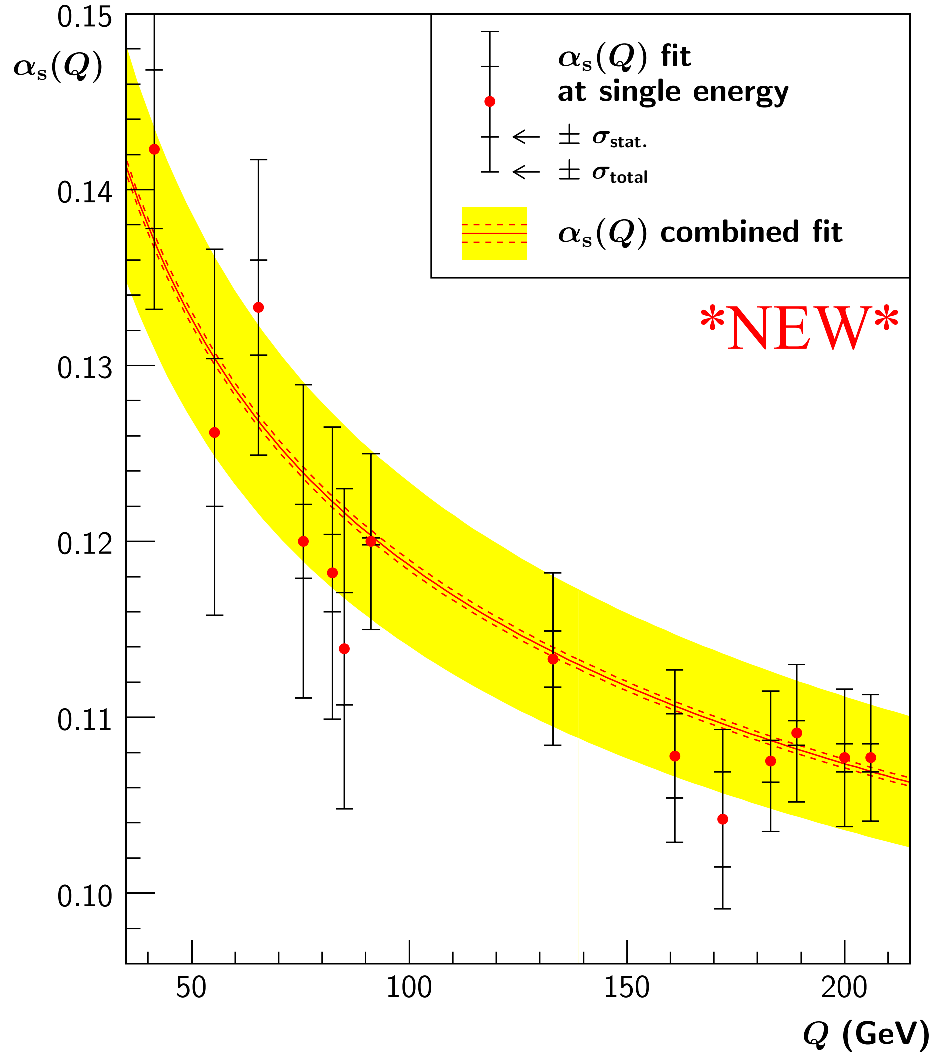


6 Variables,
15 c.o.m. energies → 194 measurements of $\alpha_s(Q)$!

Event Shape variables:
Thrust: T
Heavy jet mass: $\rho = M_H^2/s$
C-Parameter: C
Total (Wide) jet broadening: B_T (B_W)
Three-jet parameter: -ln y23

NEW





NEW

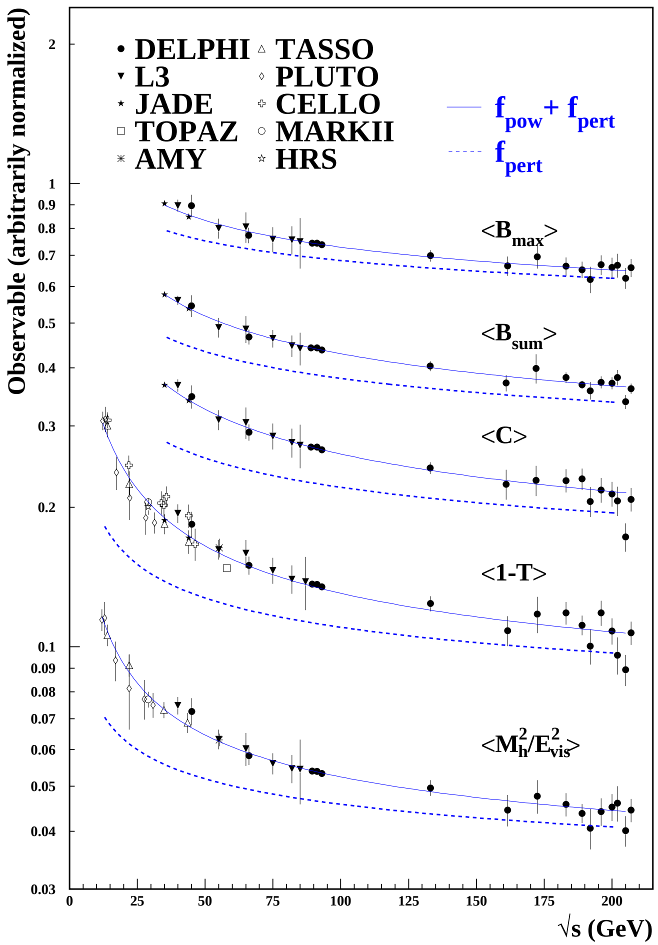
NEW Prelim. LEP combined result: $\alpha_s(M_Z) = 0.1201 \pm 0.0003(stat) \pm 0.0048(syst)$

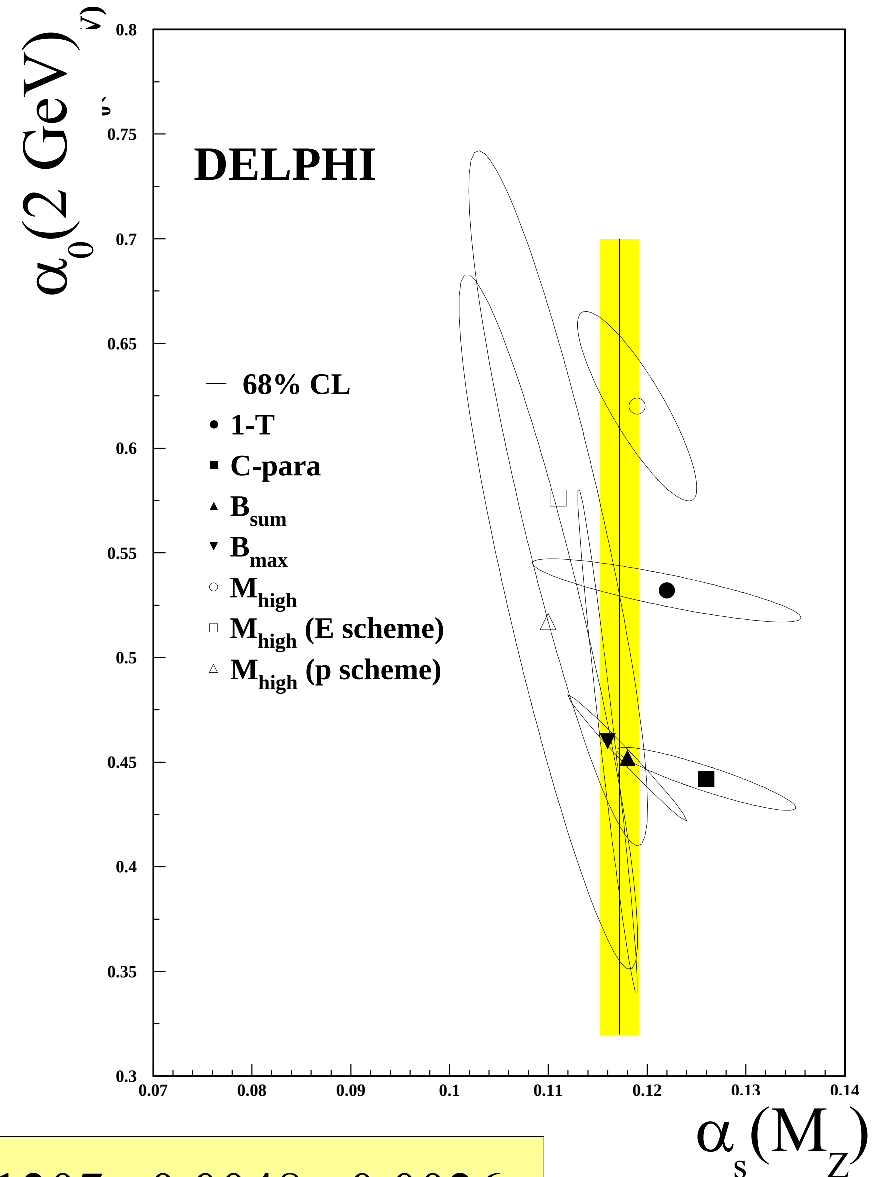
Power Corrections at LEP

DELPHI 2003-019 CONF 639

New analysis extends tests of Dokshitzer-Webber model

Introduce parameter α_0 = effective α_s below a scale (μ_I). Approximate for hadronization effects.





$$\alpha_s(M_Z)=0.1207\pm0.0048\pm0.0026$$
$$\alpha_0(2\,GeV)=0.468\pm0.080\pm0.008$$

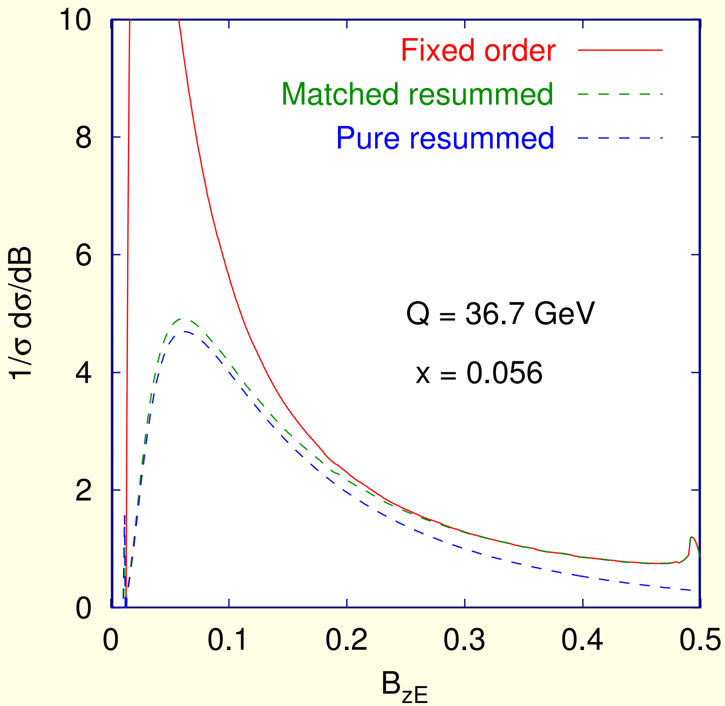
...no consistent fits w/o averaging shape variables...

Event shapes at HERA

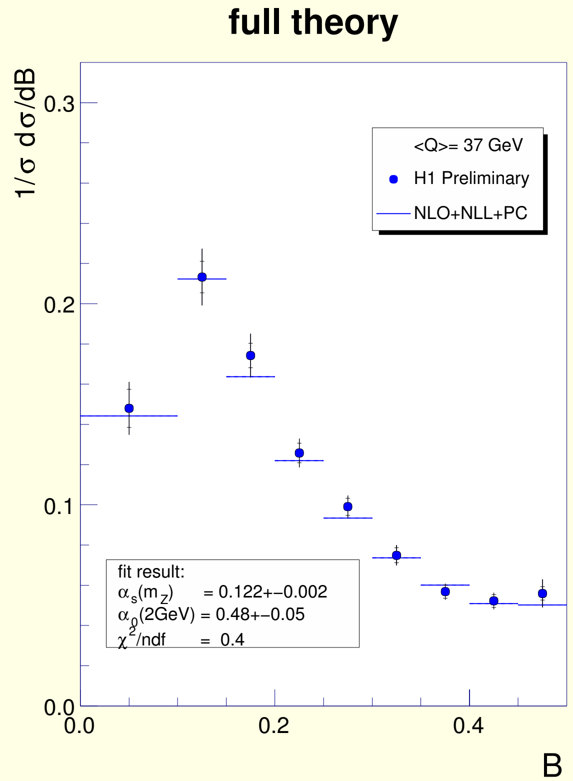
Studied in Breit frame to separate proton remnant

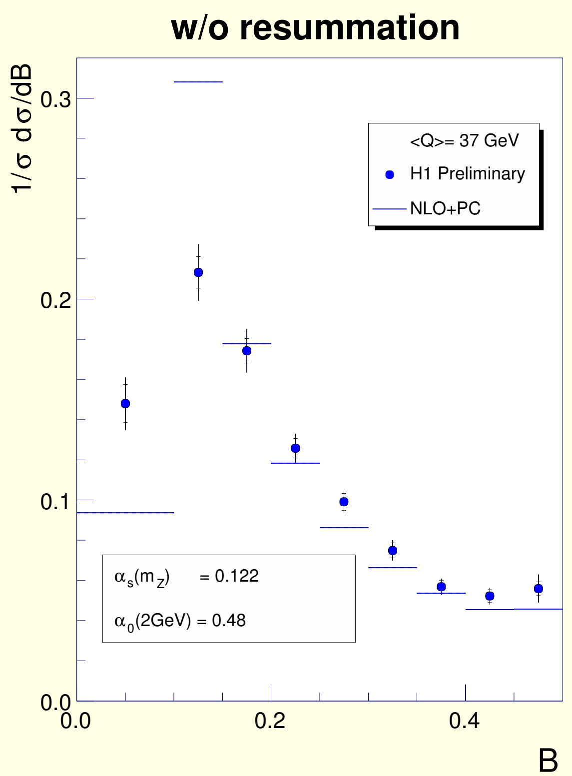
mean value: $\langle F \rangle = \langle F \rangle_{\text{pQCD}} + \alpha_F P$

Jet broadening variable shown



M. Dasgupta G.P. Salam





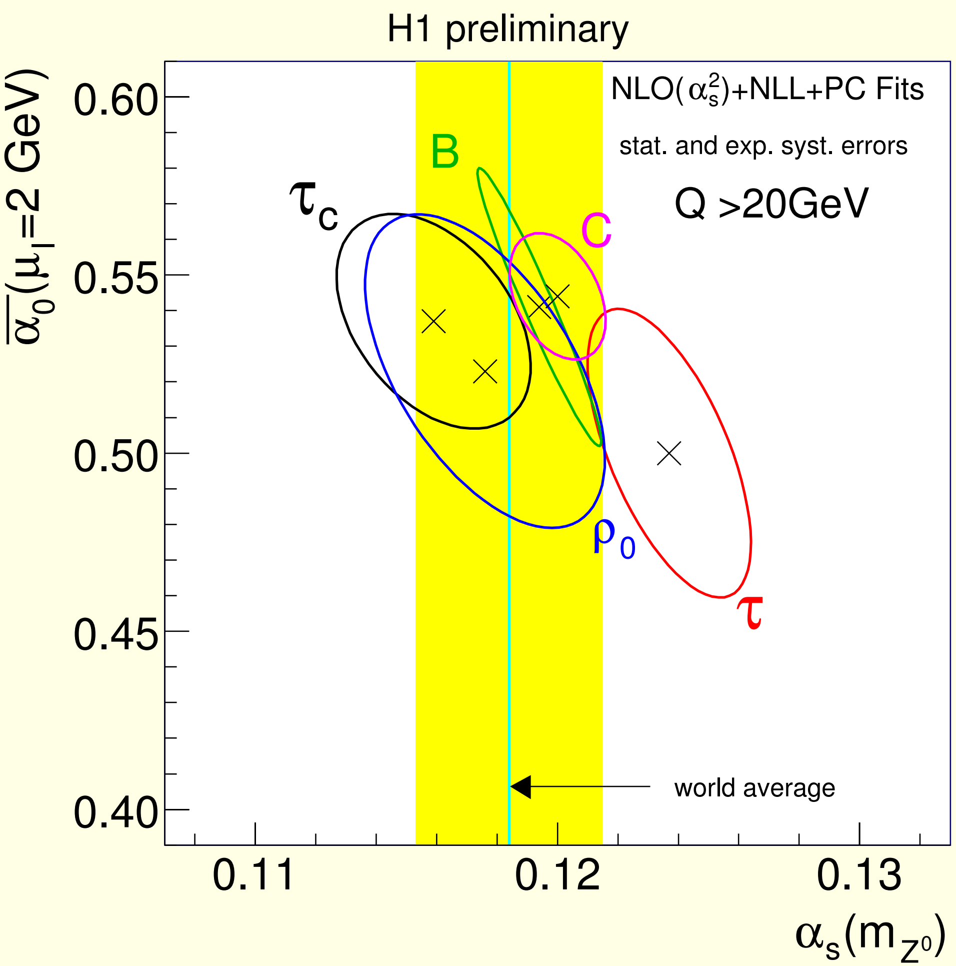
resum terms $(\alpha_s \log^2 1/F)^n$ to all orders, log-R matching to fixed order

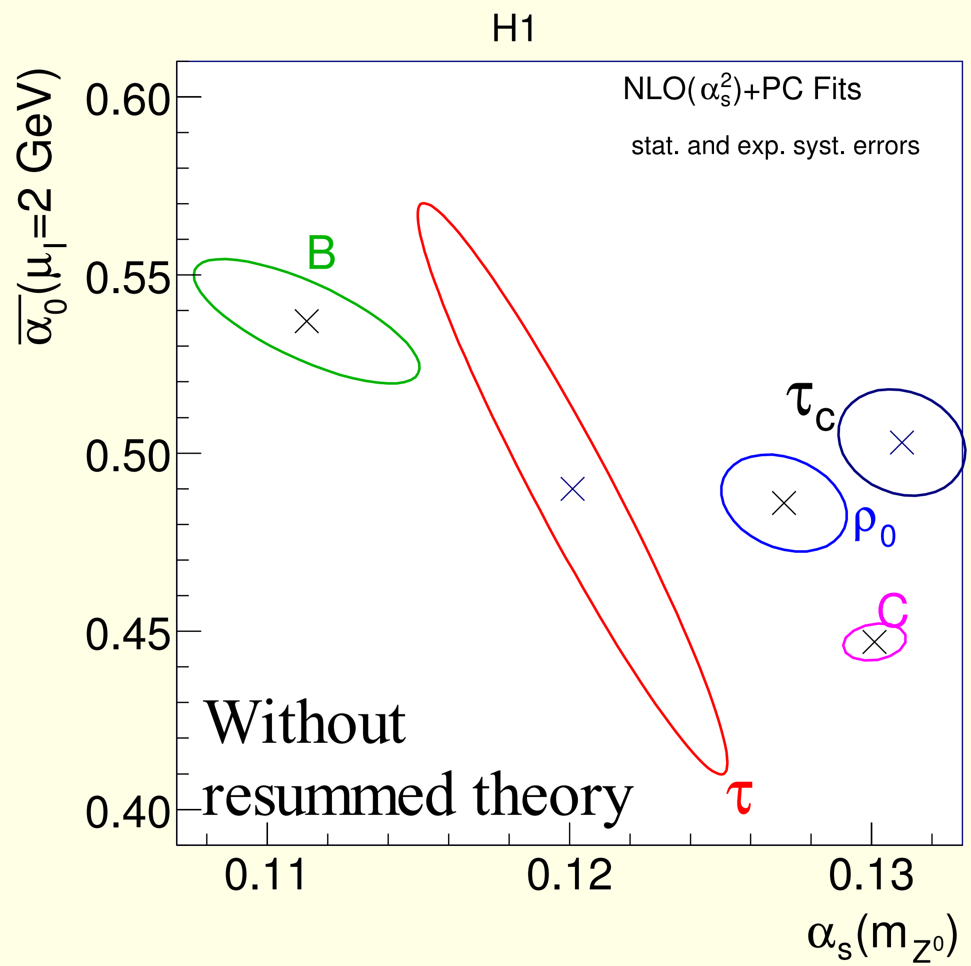
important at low values→ QPM limit

larger interval described

All event shapes modeled well by resummed pQCD + power corrections

Event shapes at HERA

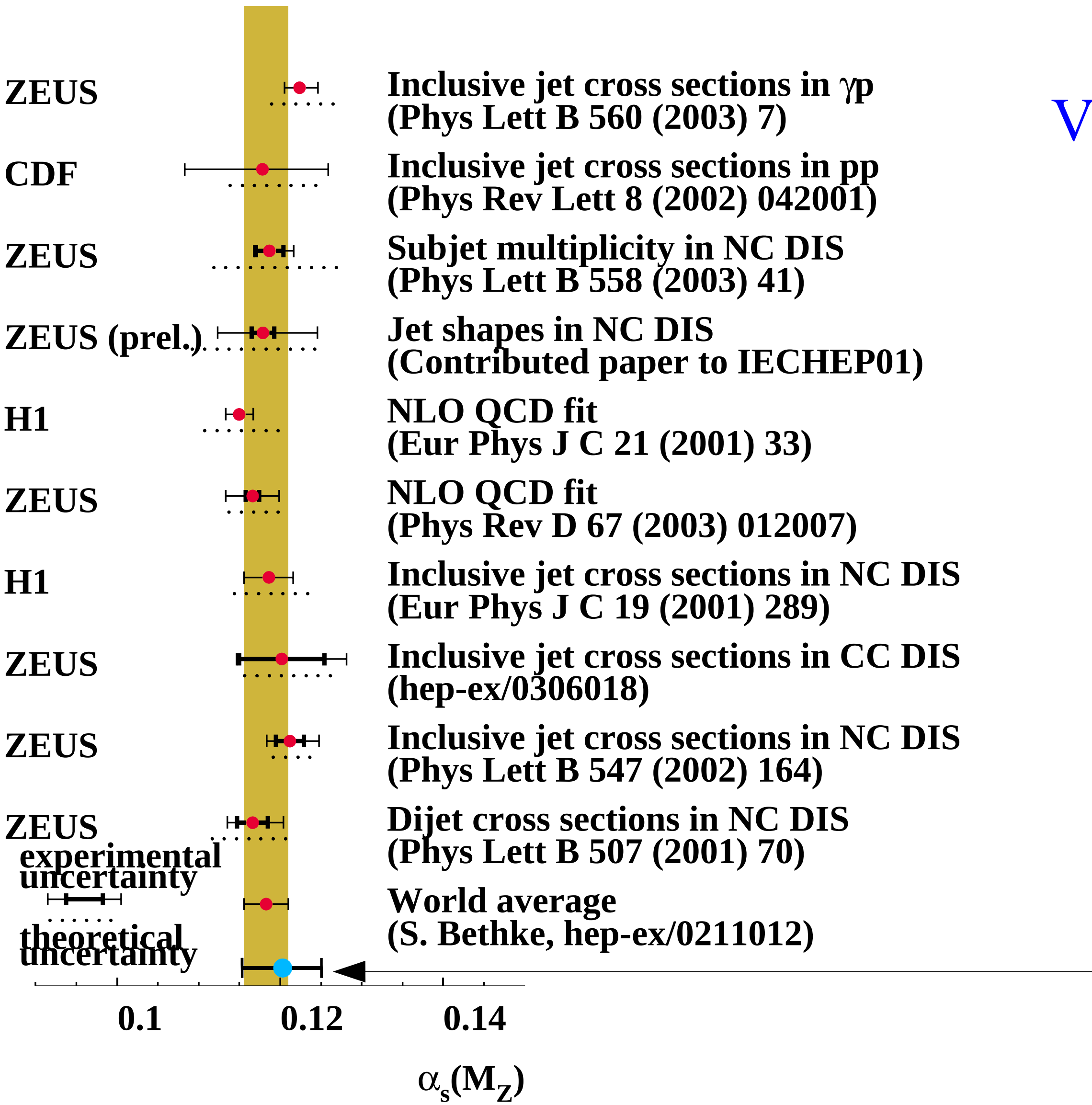




results are consistent with $\bar{\alpha}_0 = 0.5$, within 10%

- Theoretical uncertainty ~ 5-10%
- Determination of strong coupling from event shapes, and jet distributions in good agreement with world average.

Alpha_s from hadronic processes



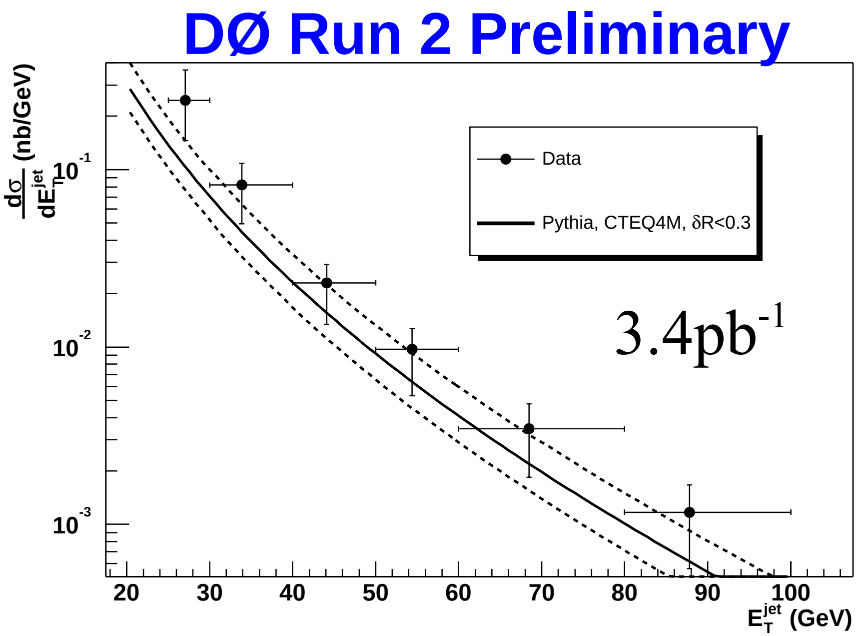
Very impressive success of QCD!

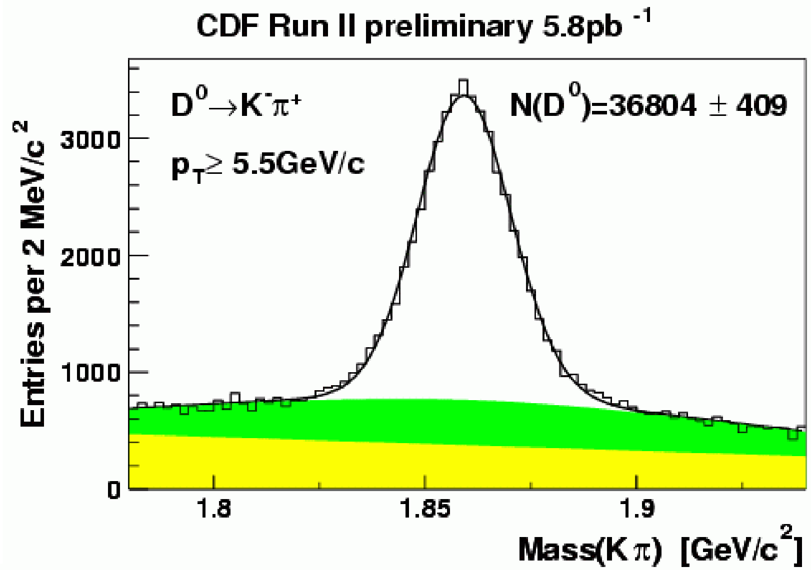
New LEP Event shapes

Measurements limited everywhere by missing higher order calculations

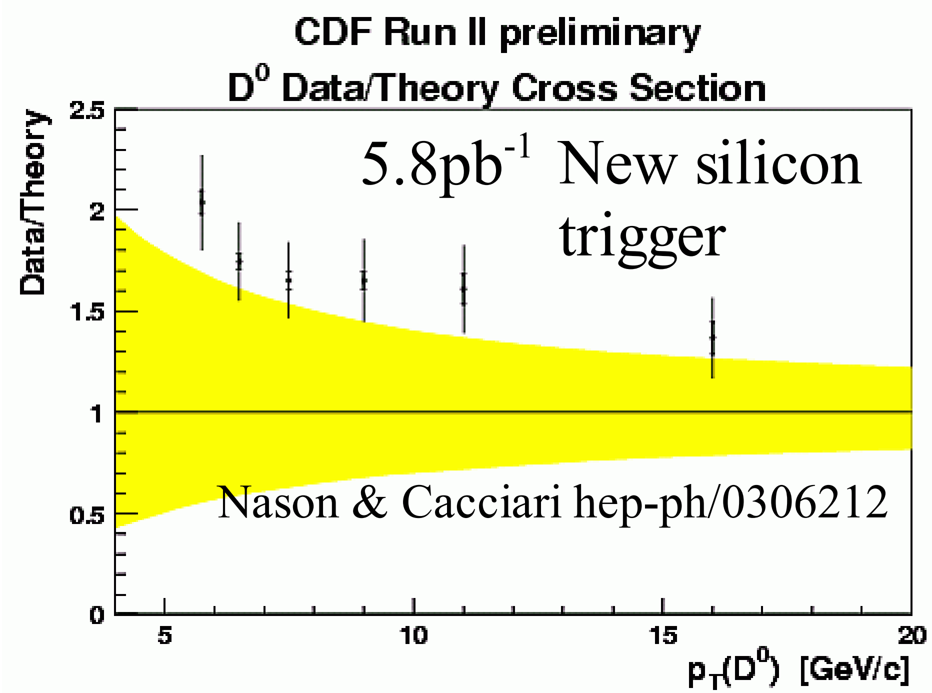
Cleanest measurements to beat are still LEP: $\Gamma(Z\rightarrow \tau\tau)$, τ decays

Tevatron: Beauty and Charm





Dominant uncertainties:
Jet energy resolution
Jet energy scale



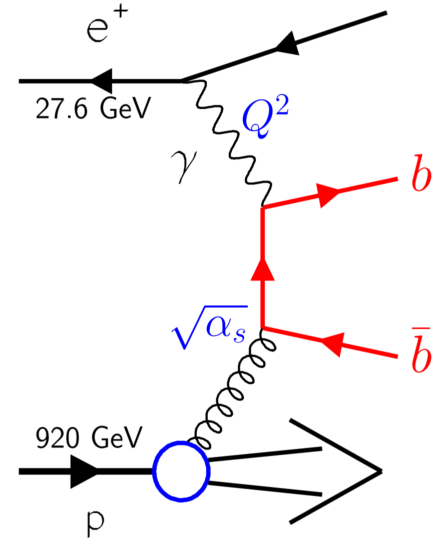
Theory = Pythia + CTEQ4M
Not directly comparable to Run I, sqrt(s) difference
But still ~2+ times higher than pQCD predictions

Factor of 1.7 too high

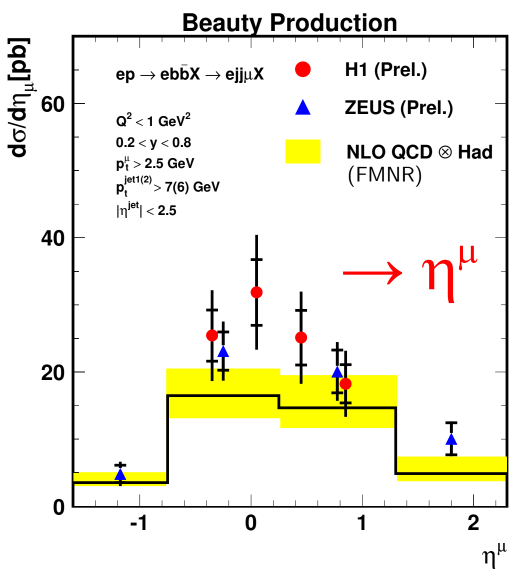
Beauty at HERA

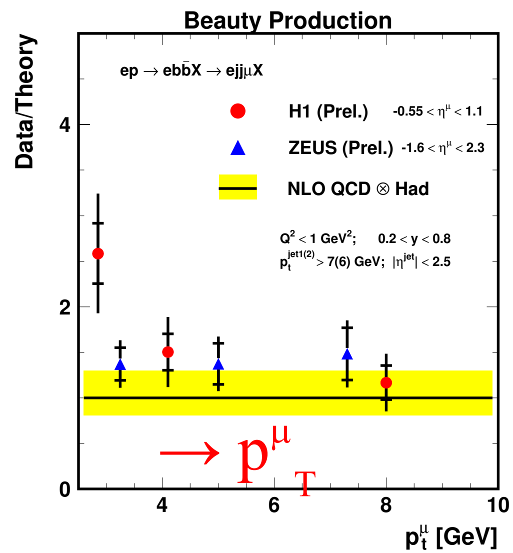
$DIS\ Regime\ Q^2 < \sim 1\ GeV^2$

$Photoproduction\ Q^2 > \sim 1\ GeV^2$

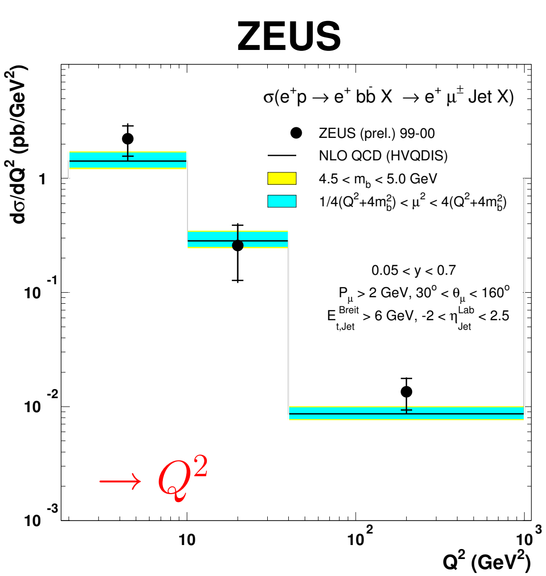


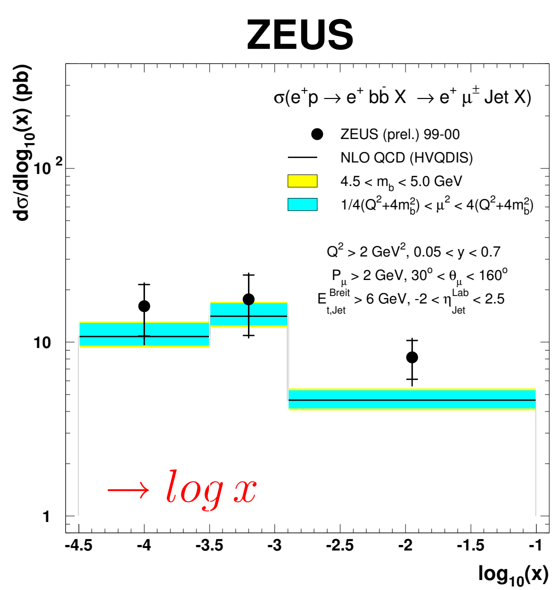
H1/Zeus: Photoproduction $ep \to e\, b\bar{b}\, X \to e\, j\, j\, \mu\, X$





Zeus DIS: B → μ X





Correct NLO for hadronization effects.

Good agreement between H1/ZEUS

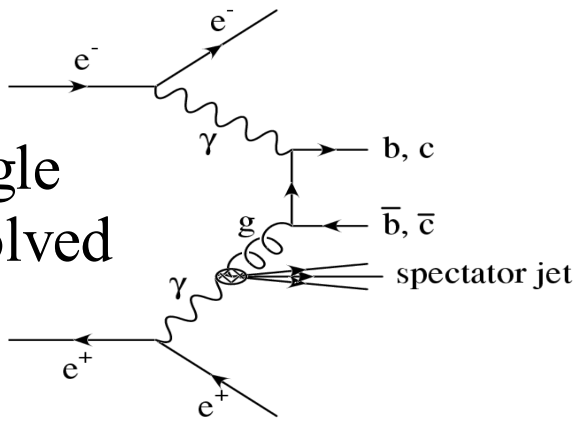
Measurements mostly above NLO QCD predictions:

discrepancies ≤ 1.5 sigma
possibly better descriptions towards large Q^2, p^{μ}_{T}

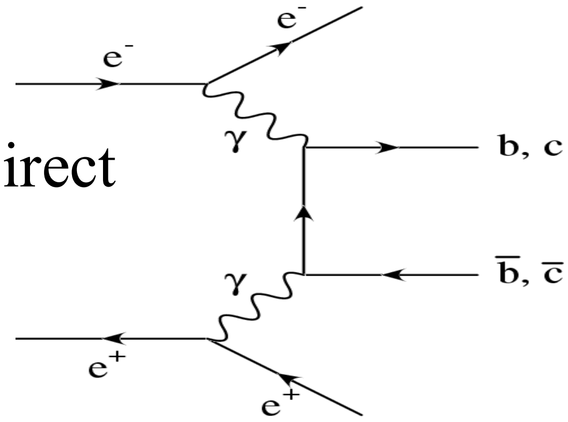
Beauty and Charm Production at LEP

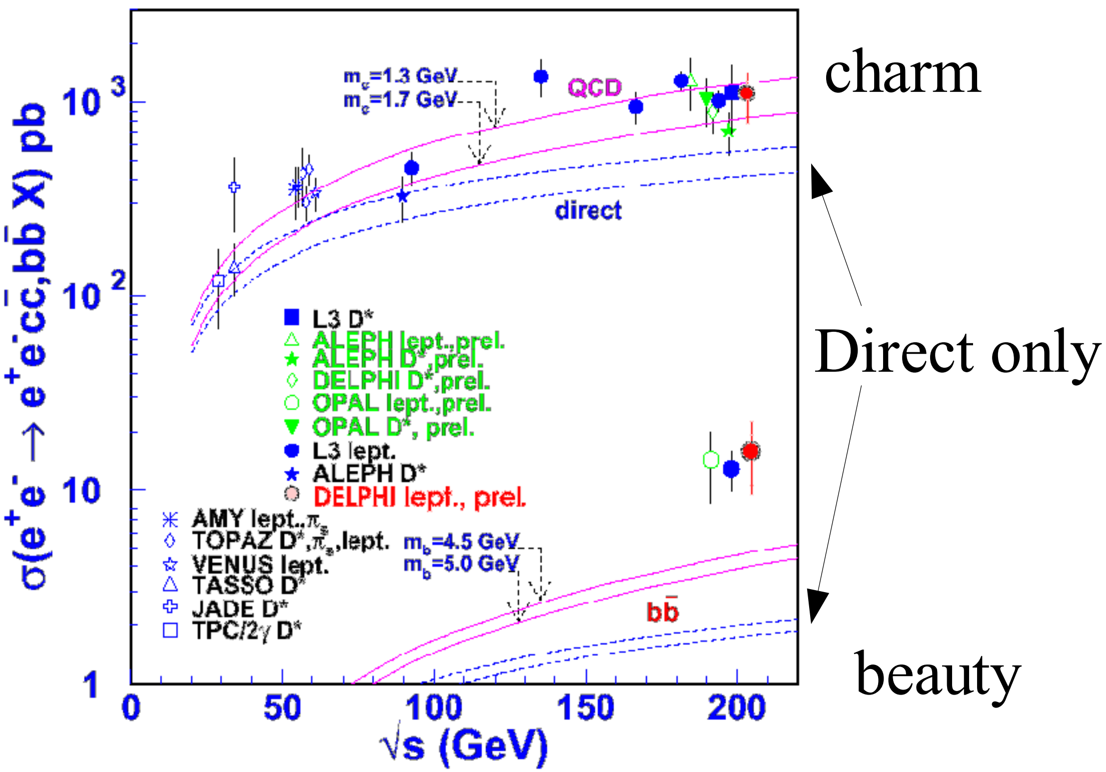
Main contributions at LO
both ~ same order at LEP2

Single resolved



Direct





Single resolved process needed to describe b/c data

LEP results consistent

New DELPHI result confirms L3/OPAL beauty excess

Charm looks OK, beauty predictions are low. Difference not understood.

(DELPHI: first analysis w/ K-lepton charge correlations in γγ)

Final Remarks

QCD is in great shape after thirty years of tough experimental challenges

Although a few puzzles stand out in these slides:

Can there really be too much beauty (or charm) in physics?

Huge excess in $\gamma\gamma\rightarrow$jets at L3 (needs confirmation)...

Experiments continue to push the limits of perturbative calculations, with improved precision and luminosity accumulated, higher order contributions are vital to extracting the most from the data.

Progress in resummation and QCD inspired power corrections is encouraging.

Improved parton distributions will continue to be a driving need for new and precision physics. HERA jet data has improved significantly – ready for inclusion in global fits! New Tevatron and HERA data still required to constrain fits for the LHC physics era.

The road before us includes an order of magnitude increase in HERA luminosity and at least a 50 fold increase for the Tevatron experiments!

The next 5 years promise an exciting journey into the mysterious "last bin" of everything we know so far...