Experimental Tests of QCD

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session speakers and organizers.

Perturbative approach to QCD

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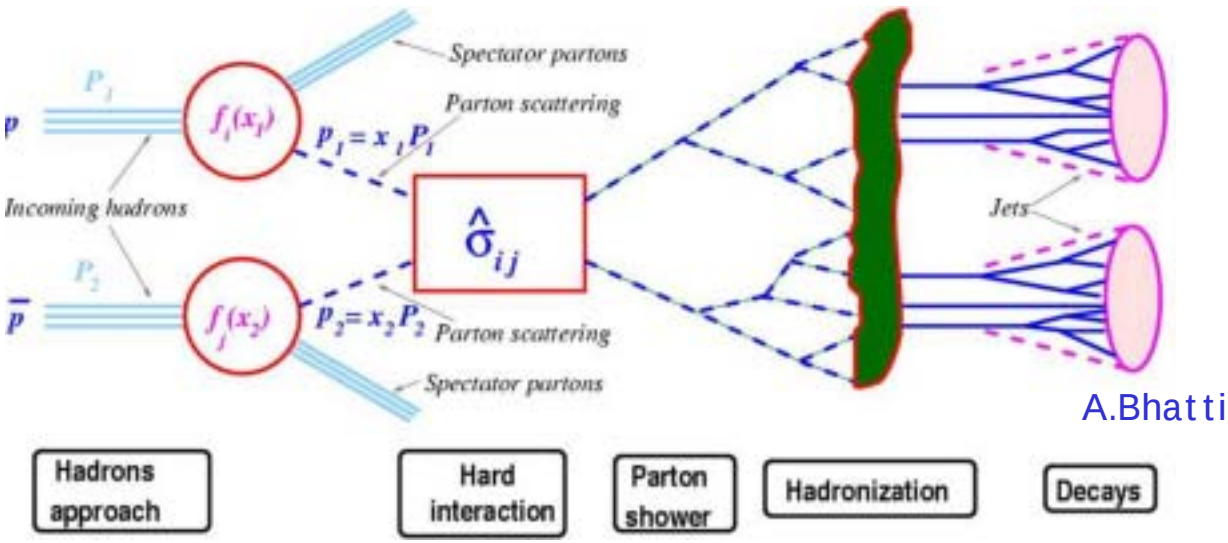
QCD: SU(3) gauge theory

- non abelian, self-interacting gluons, strong ! running coupling
- extremely rich phenomenology
- short distances: α_s small → perturbative calculations
- factorisation of short (pert.) and long (non-pert.) scales



QCD predictions:

- hard inter. (N)NLO
- Scale dependences: $\alpha_s(Q^2)$, $f(x,Q^2)$

Precision achievable / needed ?

Benchmarks for Precision QCD

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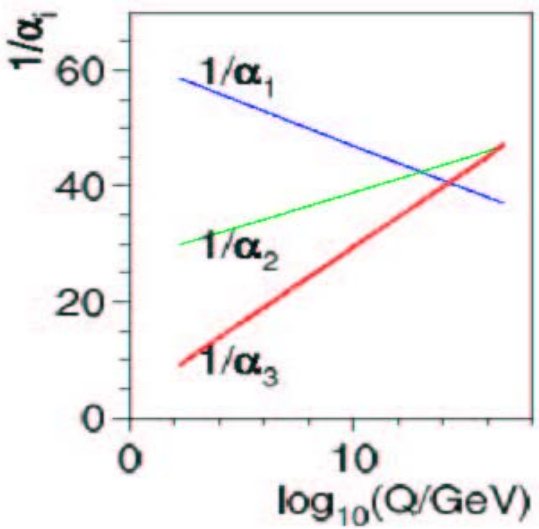
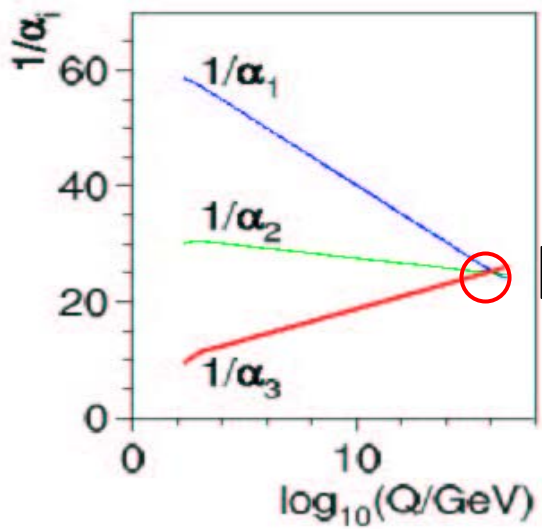
a_s determinations: how good ?

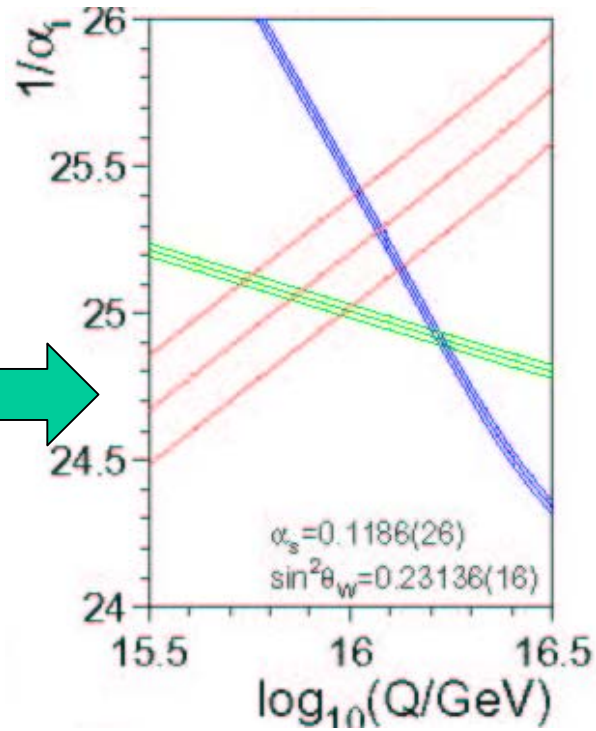
Zoom into SUSY

Standard Model



Supersymmetry





Highest possible precision is vital !

Benchmarks for Precision QCD

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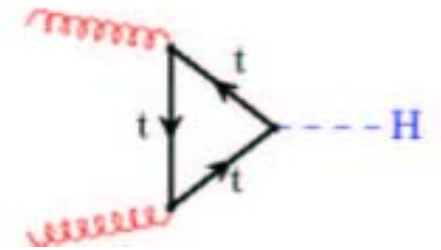
The high energy frontier:
Decade of Hadron colliders: Tevatron,HERA,LHC

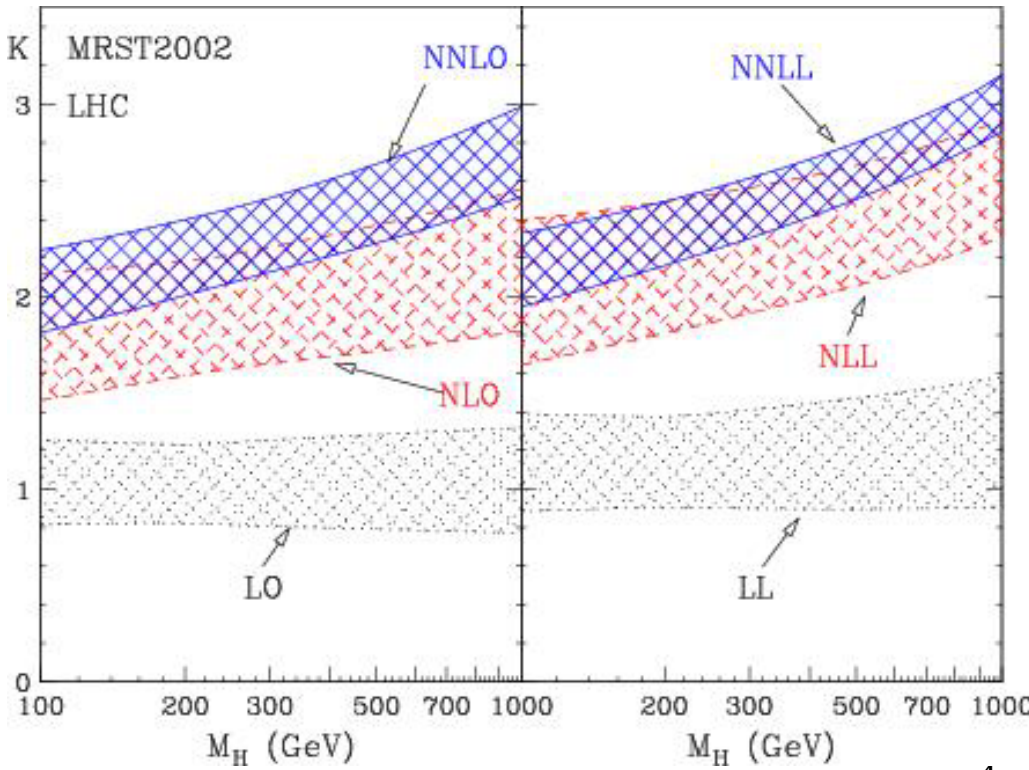
Higgs production at LHC



Discoveries depend on
- input parton distributions
- higher order calculations
- non-pert. effects

for signal and background

Comparison NLO / NNLO



What's New ?

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New Data

- LEP: close to final precision
- HERA I: close to final High Q2 data
- Tevatron: first Run II data

Better Theory

- Fixed order: NLO → NNLO
- All orders: resummed calculations
- factorisation theorems

Event Shapes at LEP

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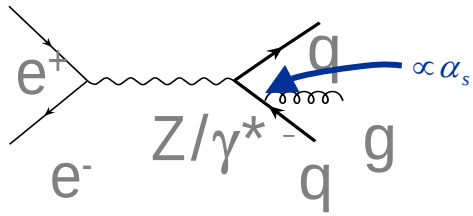
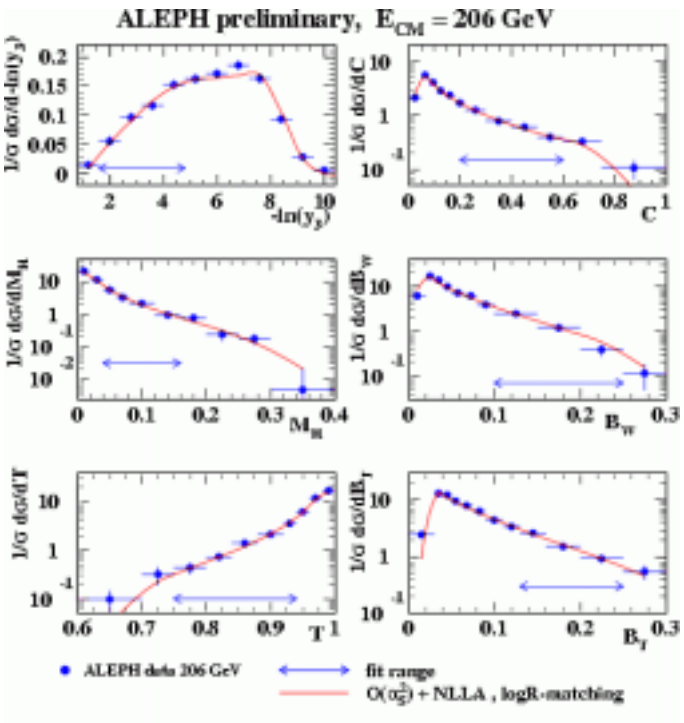
Cleanest measurements for α_s at LEP: $\Gamma(Z \rightarrow hadr.)$, τ decays

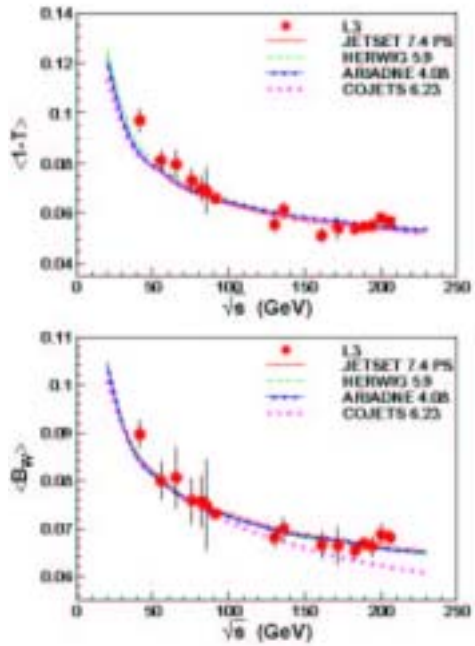
Event shapes: thrust, jet broadening,
3-jet parameter, C parameter, jet mass
New results from LEP1,2, rad events (L3)



NLO resummed calculations



Energy dependence, corrected for hadronisation with MC



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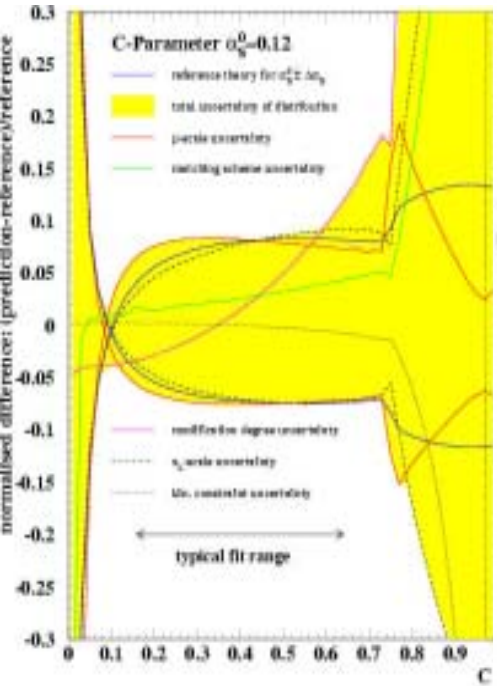
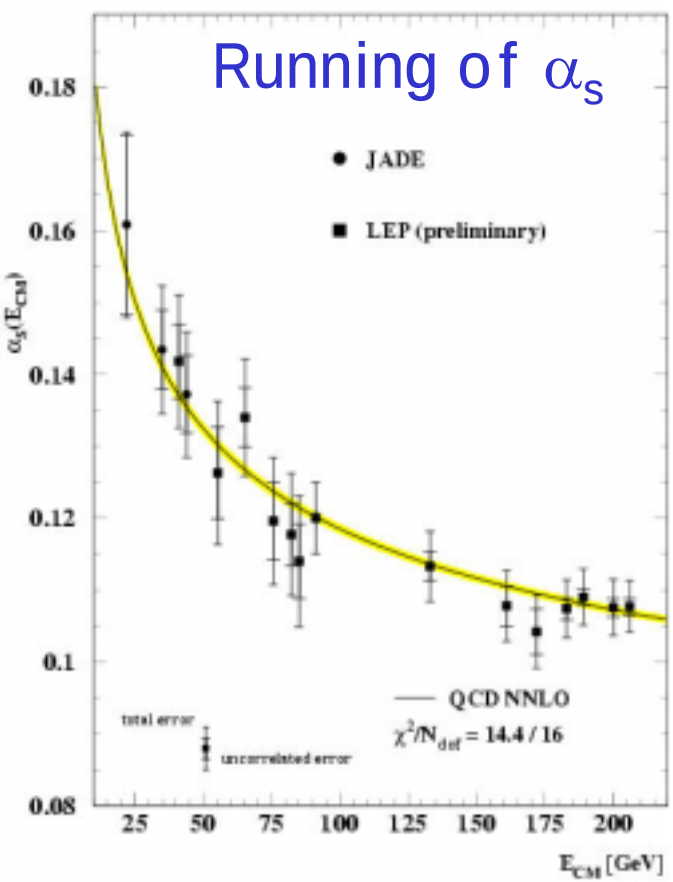
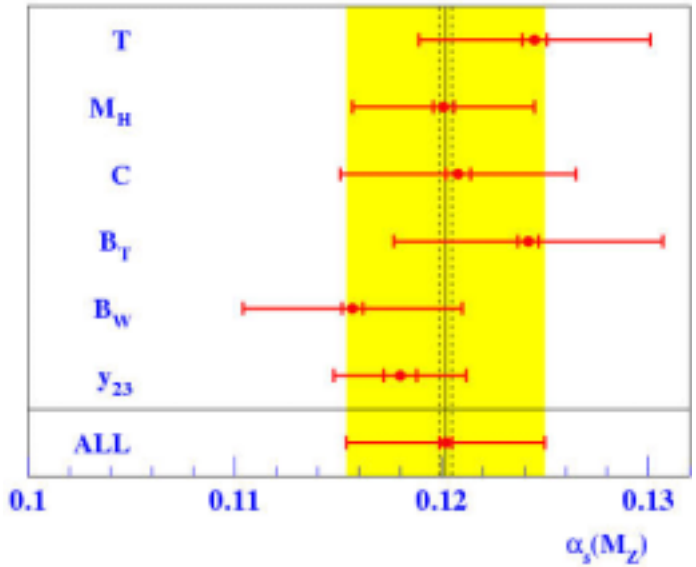
Refined treatment of correlated errors







New LEP average for α_s

$$\alpha_s(M_Z) = 0.1202 \pm 0.0003_{\text{stat}} \pm 0.0009_{\text{exp}} \pm 0.0009_{\text{had}} \pm 0.0047_{\text{pert}}$$

prel.

largest error: scale uncert.

Still: cleanest measurements for α_s at LEP: Γ(Z → hadr.), τ decays

Power Corrections at LEP

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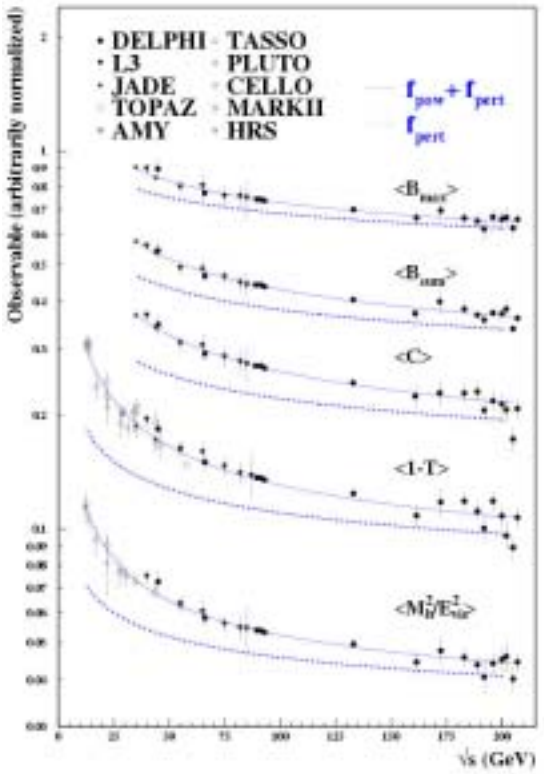
Dokshitzer-Webber ansatz:

- α_0 = effective α_s below μ_I

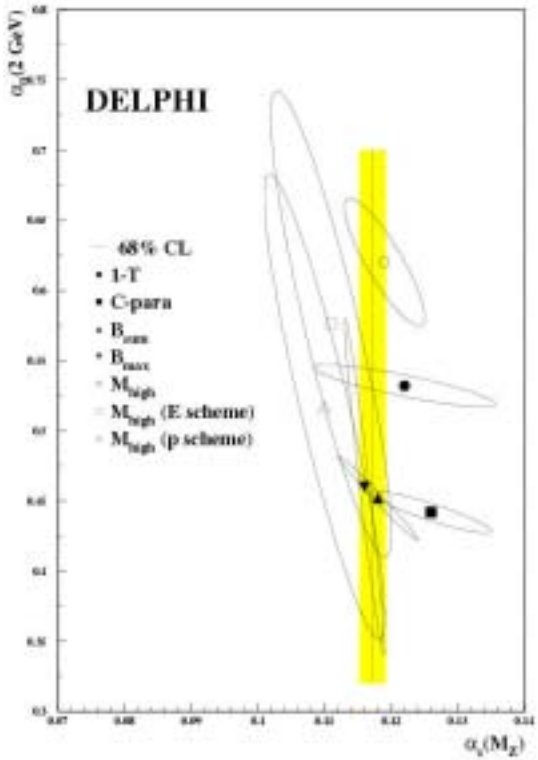
approx. for hadronisation

$$\begin{aligned} \langle y \rangle &= \langle y_{\text{pert}} \rangle + \langle y_{\text{power}} \rangle \\ y_{\text{power}} &= c_y \cdot P(\alpha_0)/Q \\ D_y(y) &= D_{\text{pert}}\,(y - c_y \cdot P(\alpha_0)) \end{aligned}$$



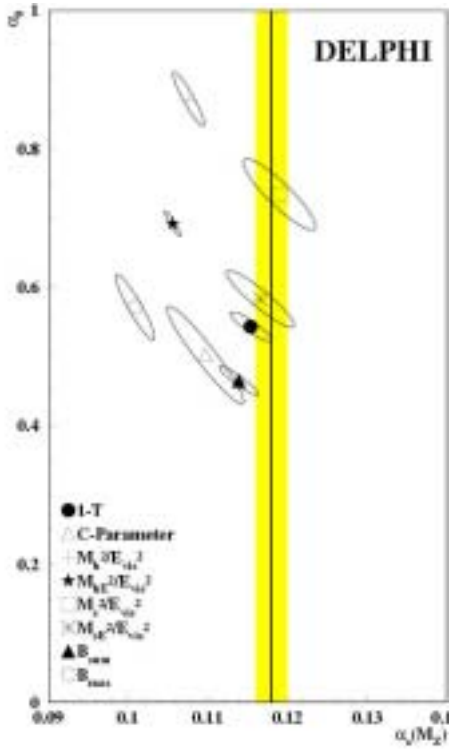
shapes well described

Fit to mean values



α_s = 0.1207

Fit to shapes



no consistent α_s

Event Shapes at HERA

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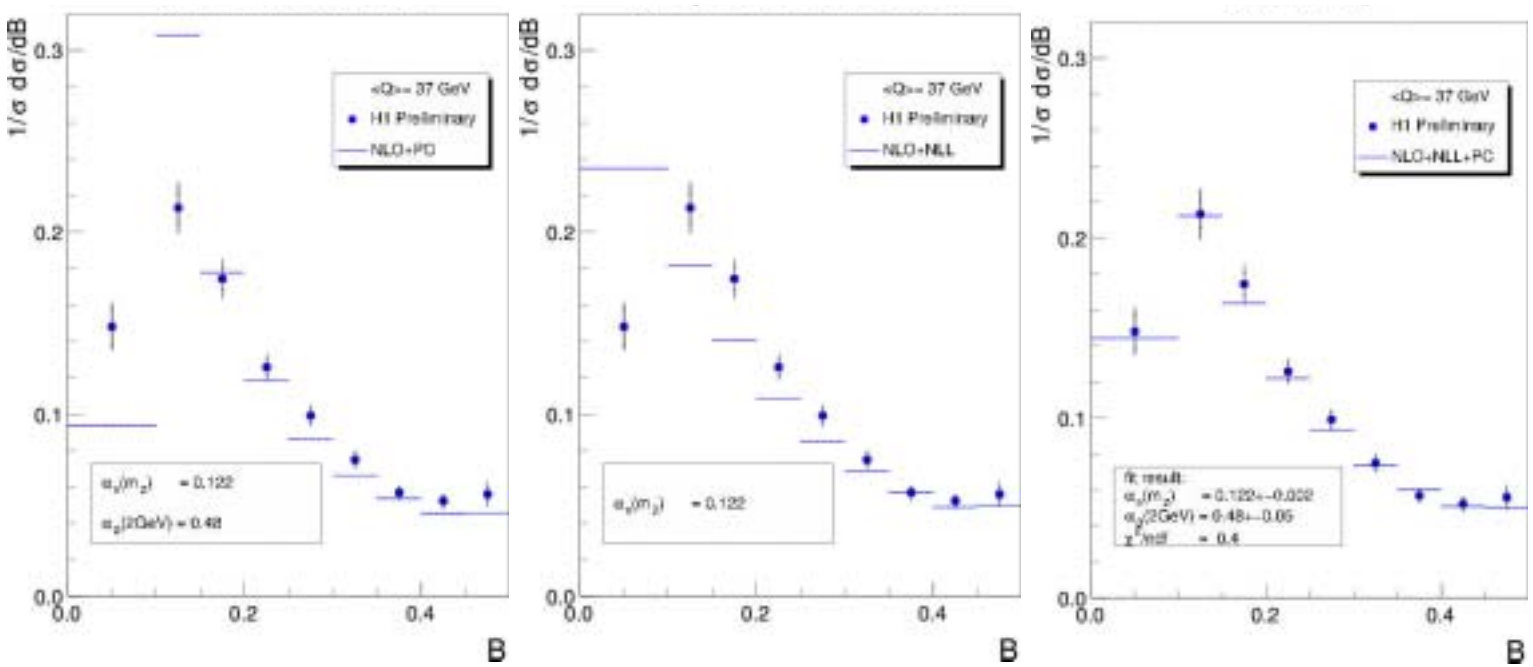
New:

- resummed calculations
- fits to both means and shapes (H1)

NLO + PC | NLO + NLL | NLO + NLL + PC



Jet Broadening

Event Shapes at HERA

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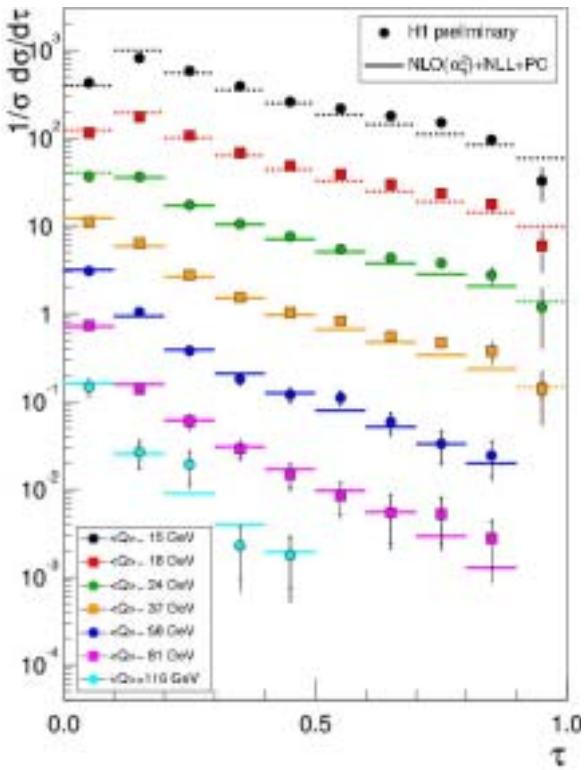
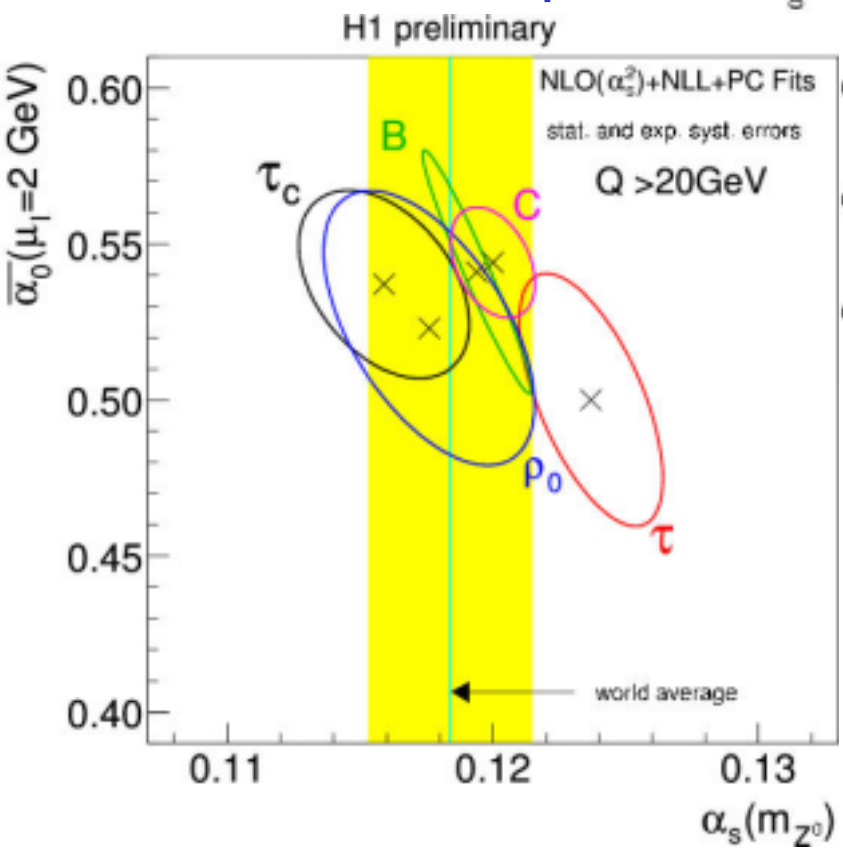
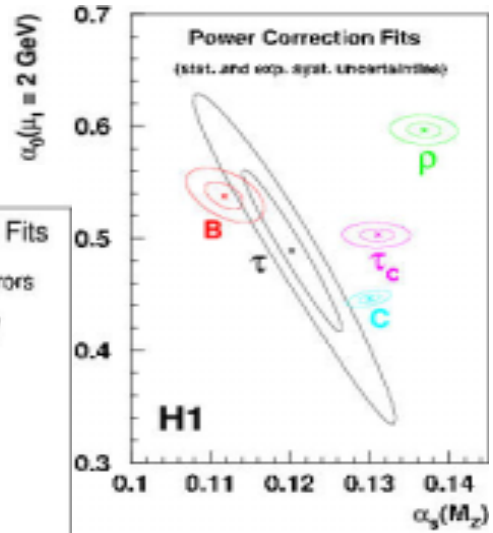
All event shapes well described by NLO + NLL + PC



Fit to shapes



Old result without resummation



Resummation + power correction very successful at HERA

Proton Structure

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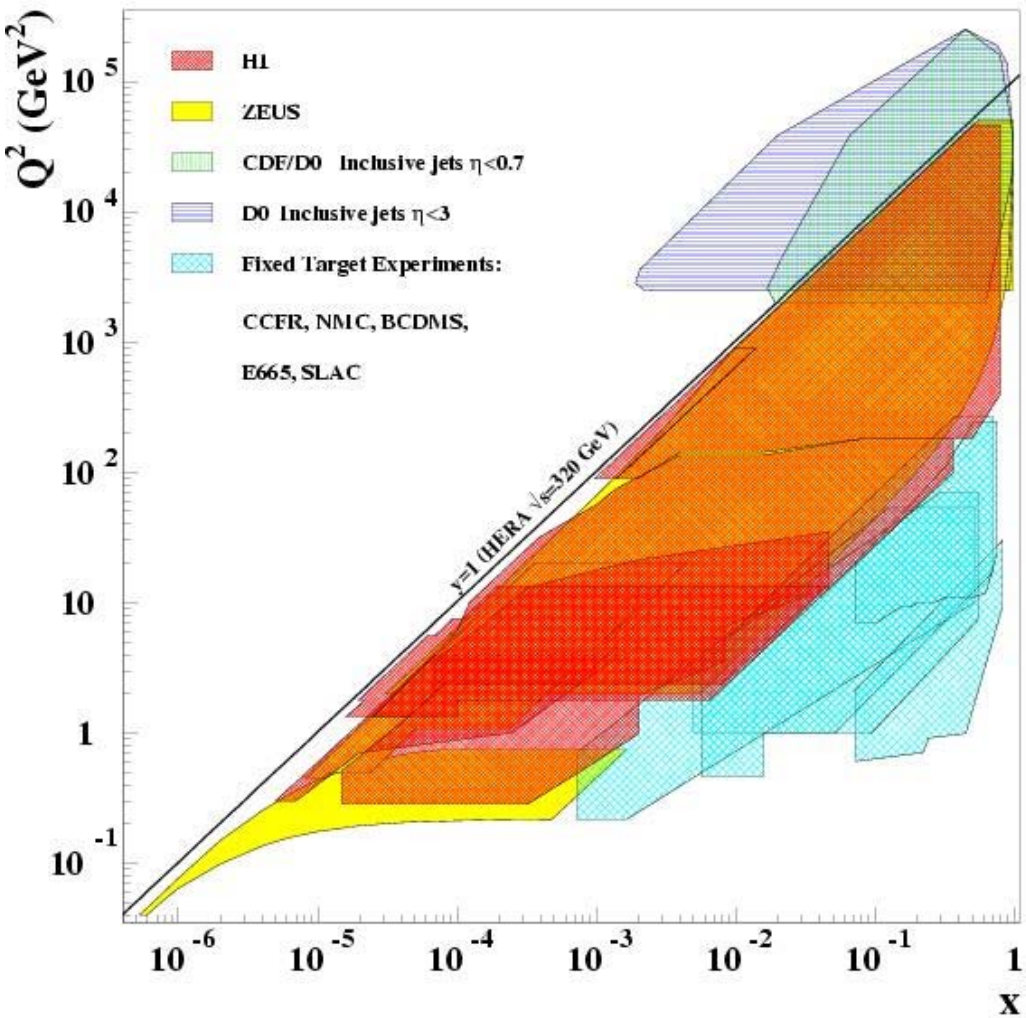
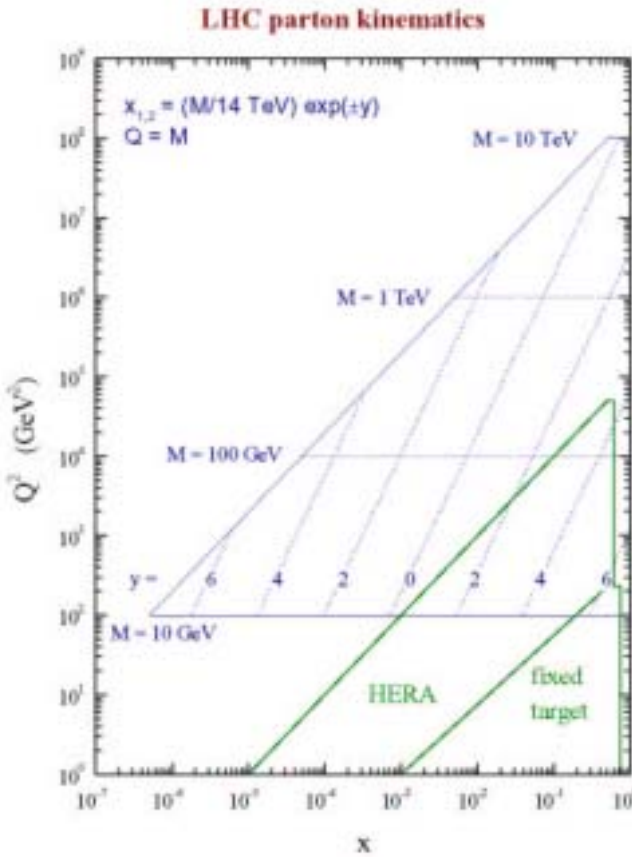
many unknowns: u_v, d_v, u_s, d_s, s, g
many processes: DIS,Drell-Yan,Tevatron





Predictions depend on
- QCD evolution
- PDF's at low Q^2

Quark densities

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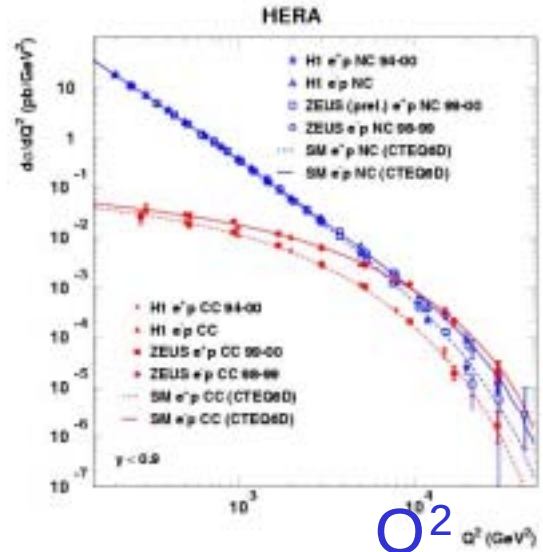
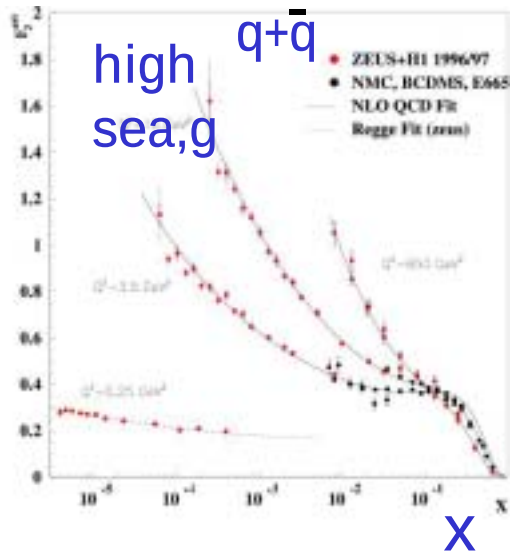
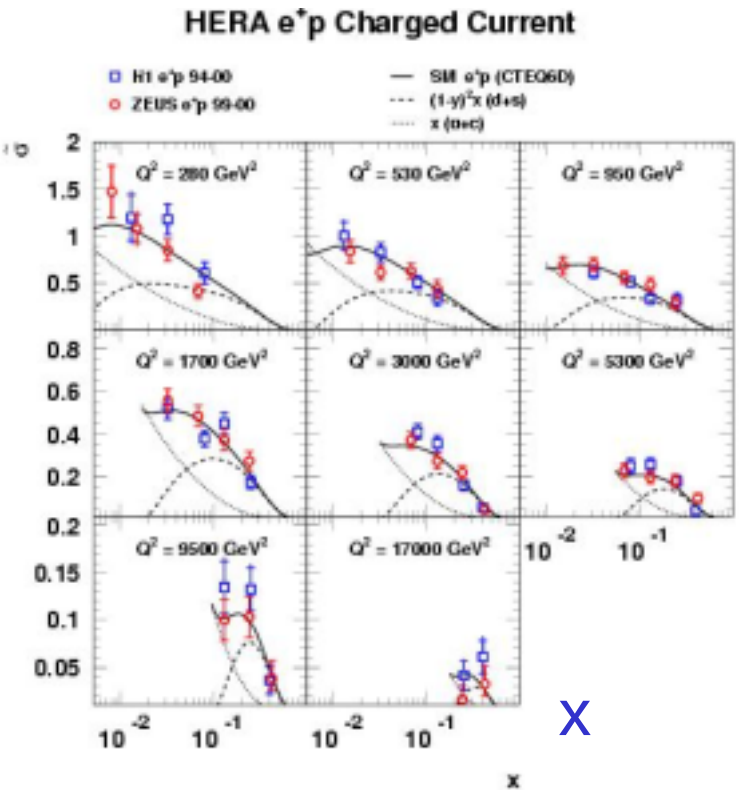
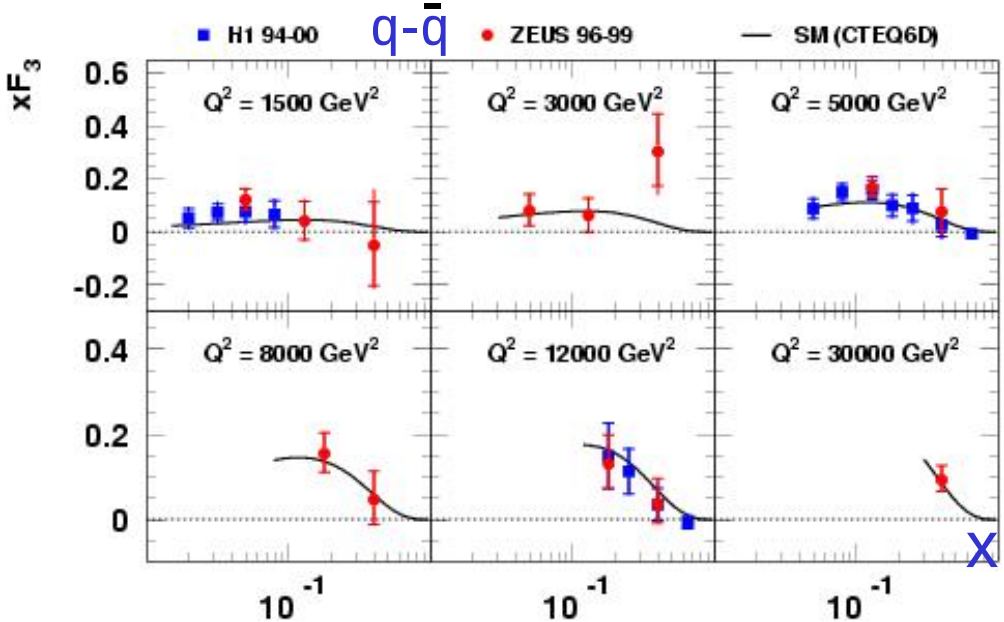
Deep Inelastic Scattering

- Neutral Current: e^-
- low Q2: $q+\bar{q}$
- high Q2: $e^-p - e^+p \sim q-\bar{q}$
- Charged Current:
- e+p: $\bar{u}+\bar{c} + (1-y^2)(d+s)$









Gluon density

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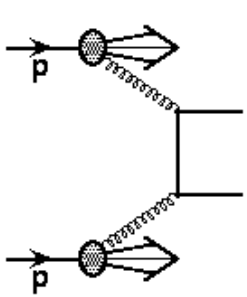
HERA: Scaling violations, F_L ,charm

Tevatron: Jets



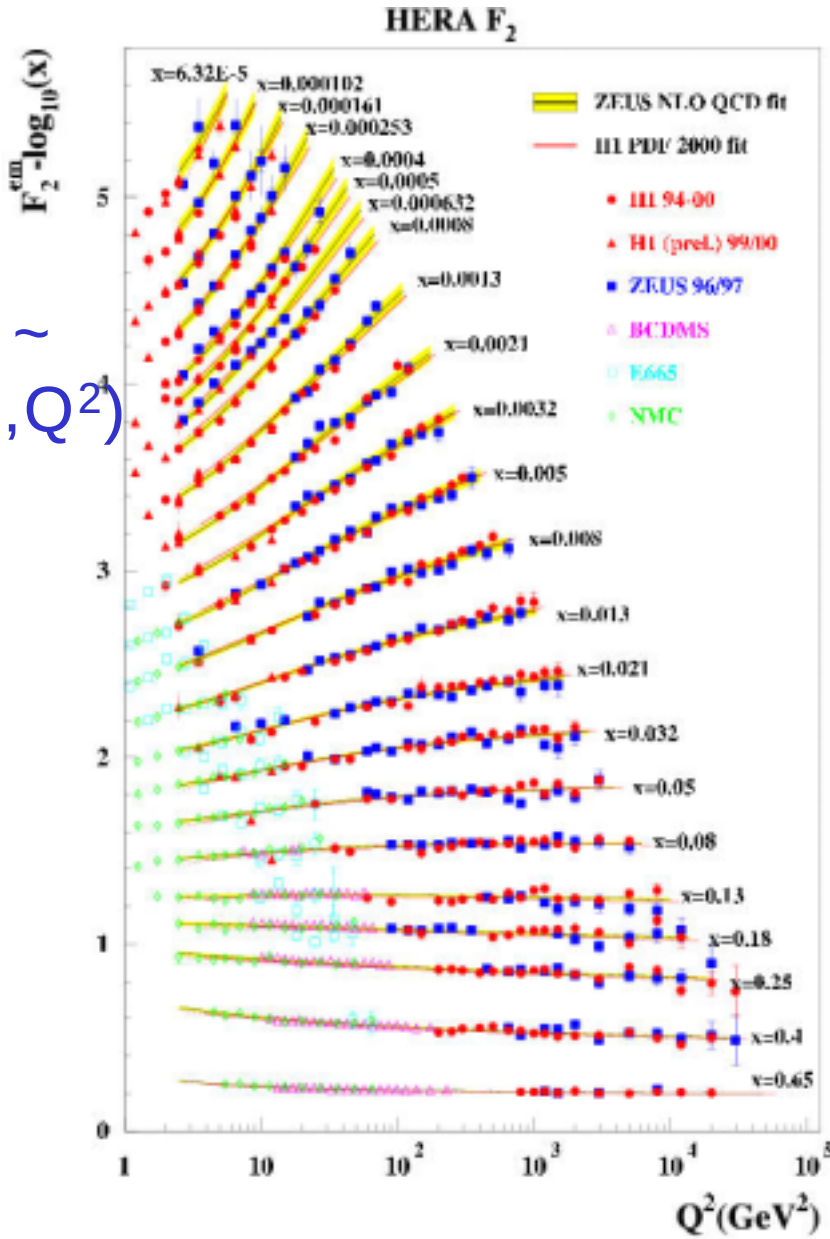
Slope ~ $\alpha_s\, g(x,Q^2)$

qq

qg

gg

E_T



Tevatron Jets

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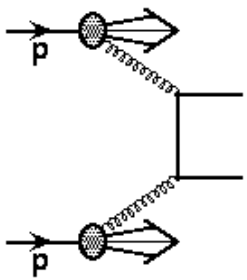
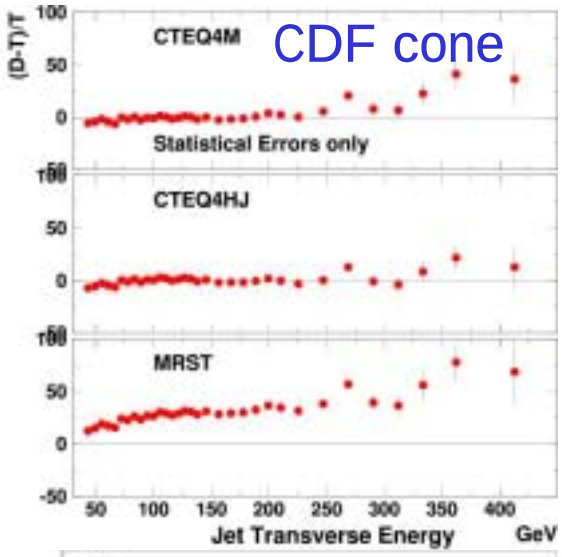
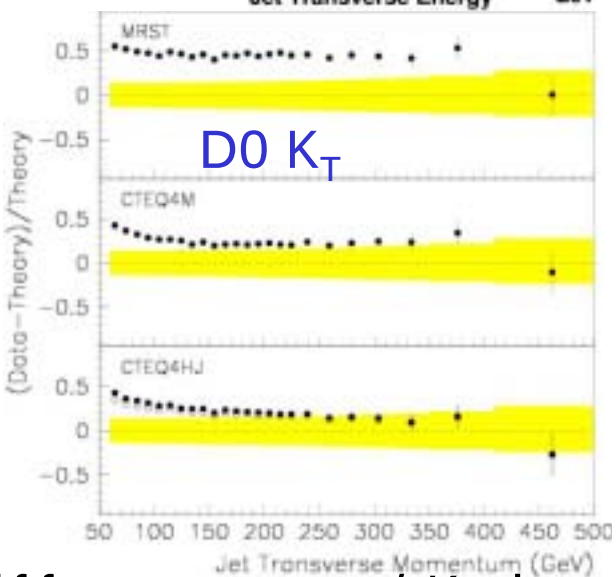
- **Run I: 100 pb^{-1}**
- **Run II: 200 pb^{-1} recorded**
- **first prelim. results**
  CDF: 85 pb-1, D0: 34 pb**-1**



gluon density not constrained at high x

Run I





Jet algorithms:
Run I: cone, K_T (D0)
RUN II: also modified cone algor:
midpoint algor.: additional seed allowed between found jets
(P recomb. scheme, instead E)

differences cone/ K_T due to hadr. corrections

Tevatron Run II: D0

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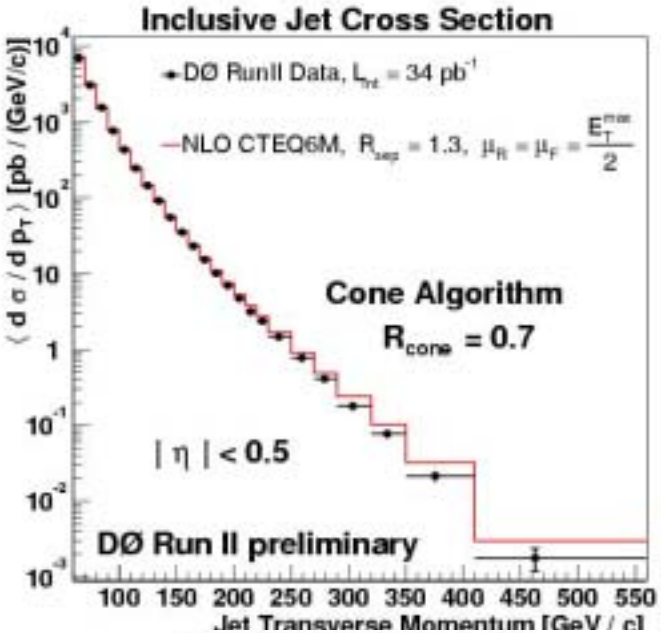
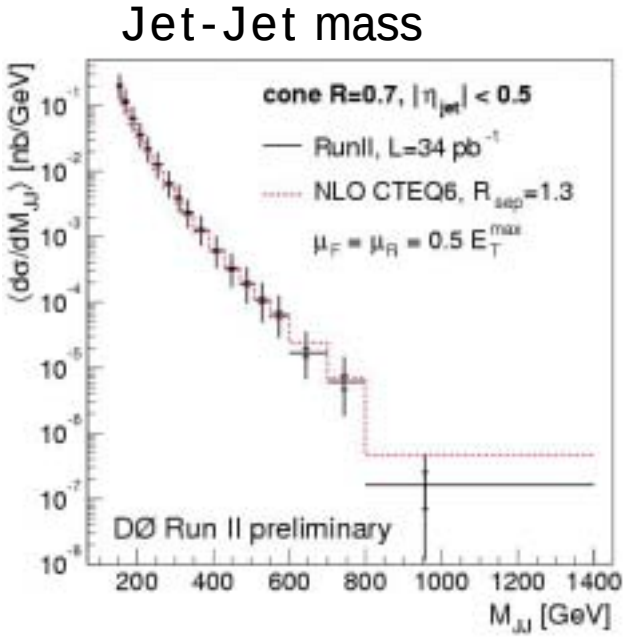
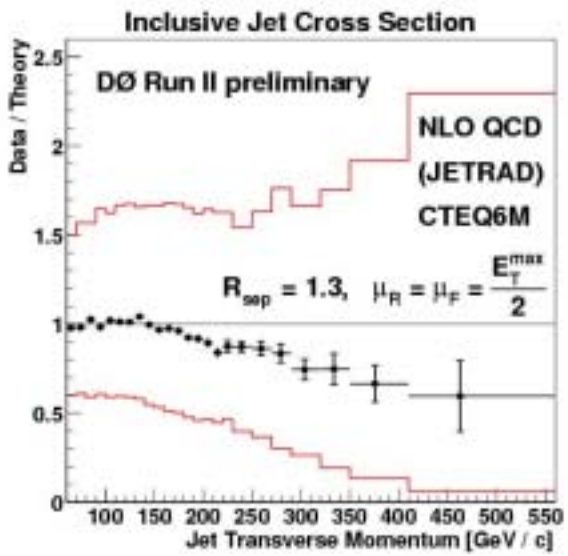


midpoint algor.

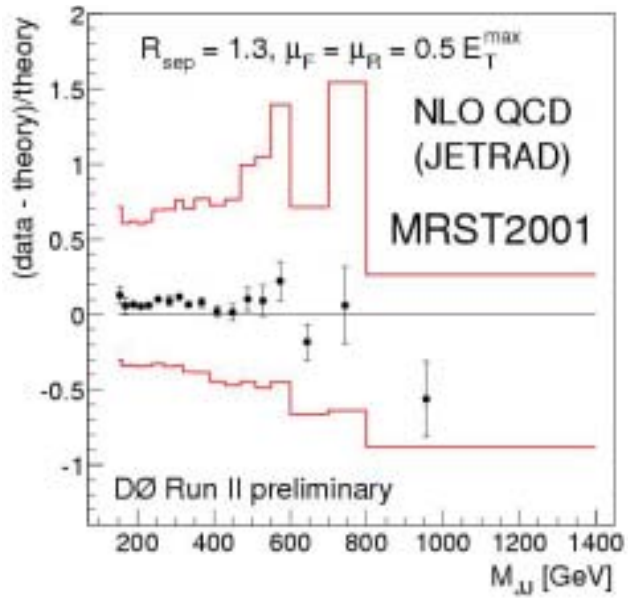
Inclusive jets
di-jet mass





P_T

Calor. Energy
scale error
dominates



Tevatron Run II: CDF incl.

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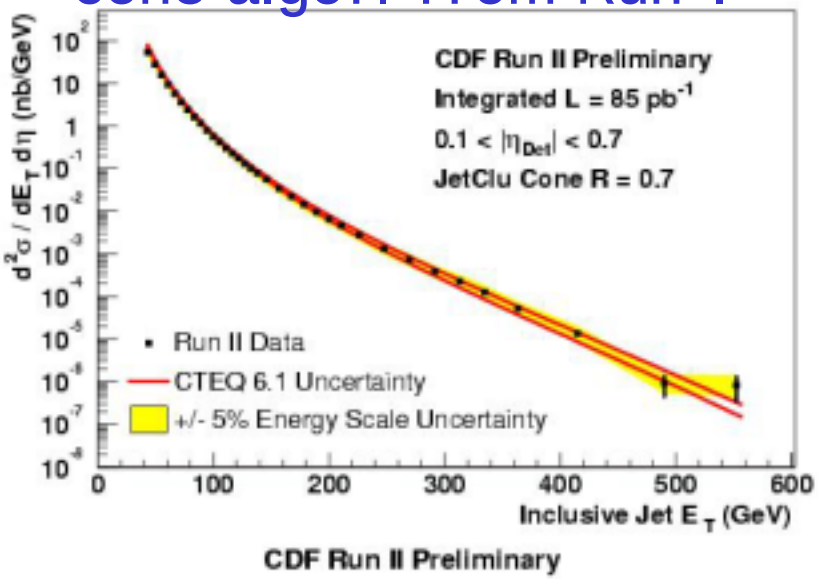
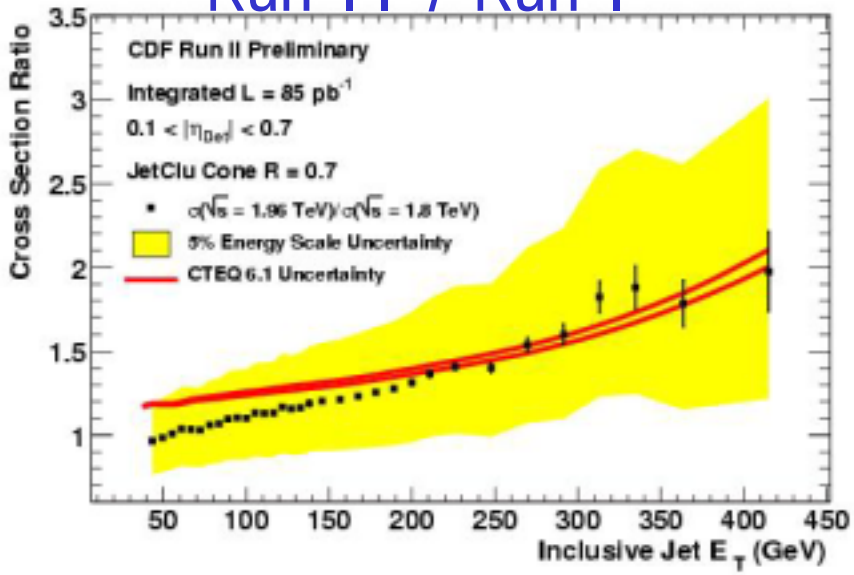
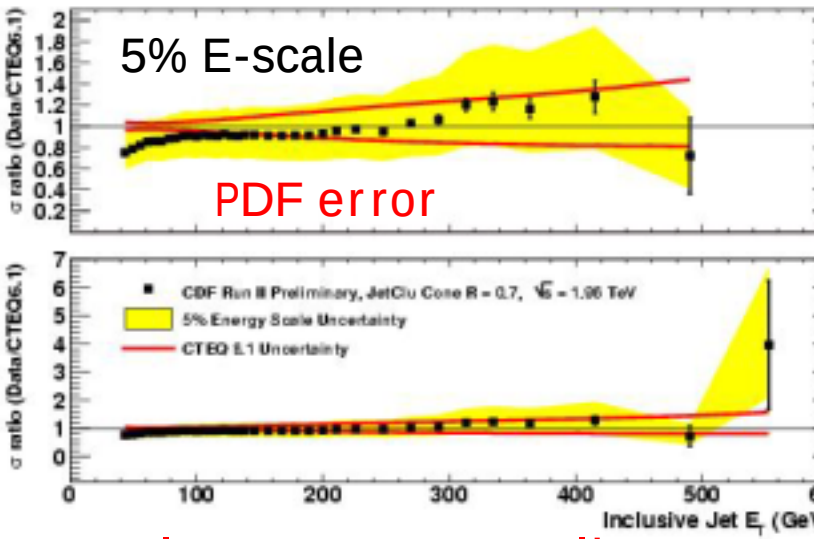
cone algor. from Run I



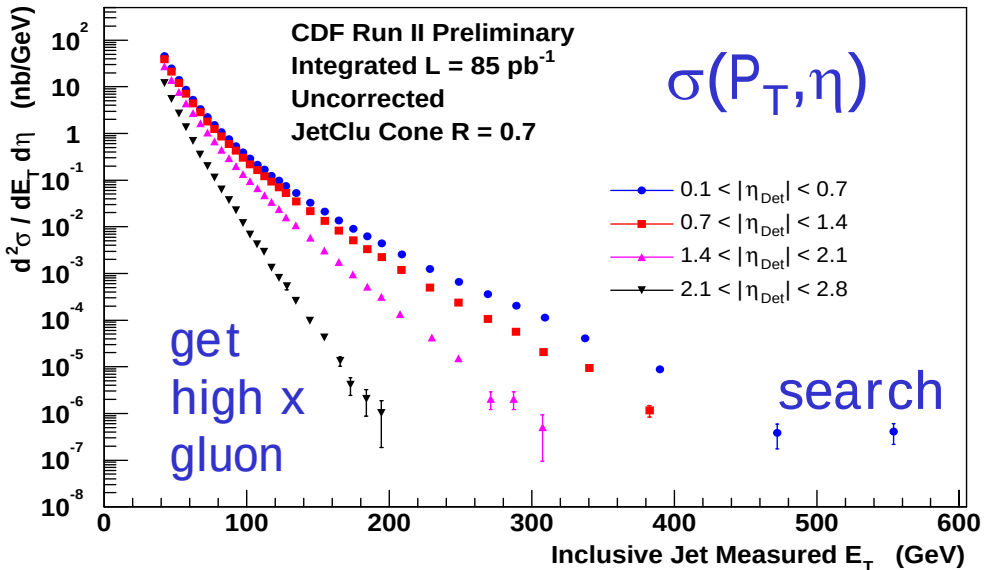
Run II / Run I



CDF Run II Preliminary



close to Run I quality



Parton Density fits

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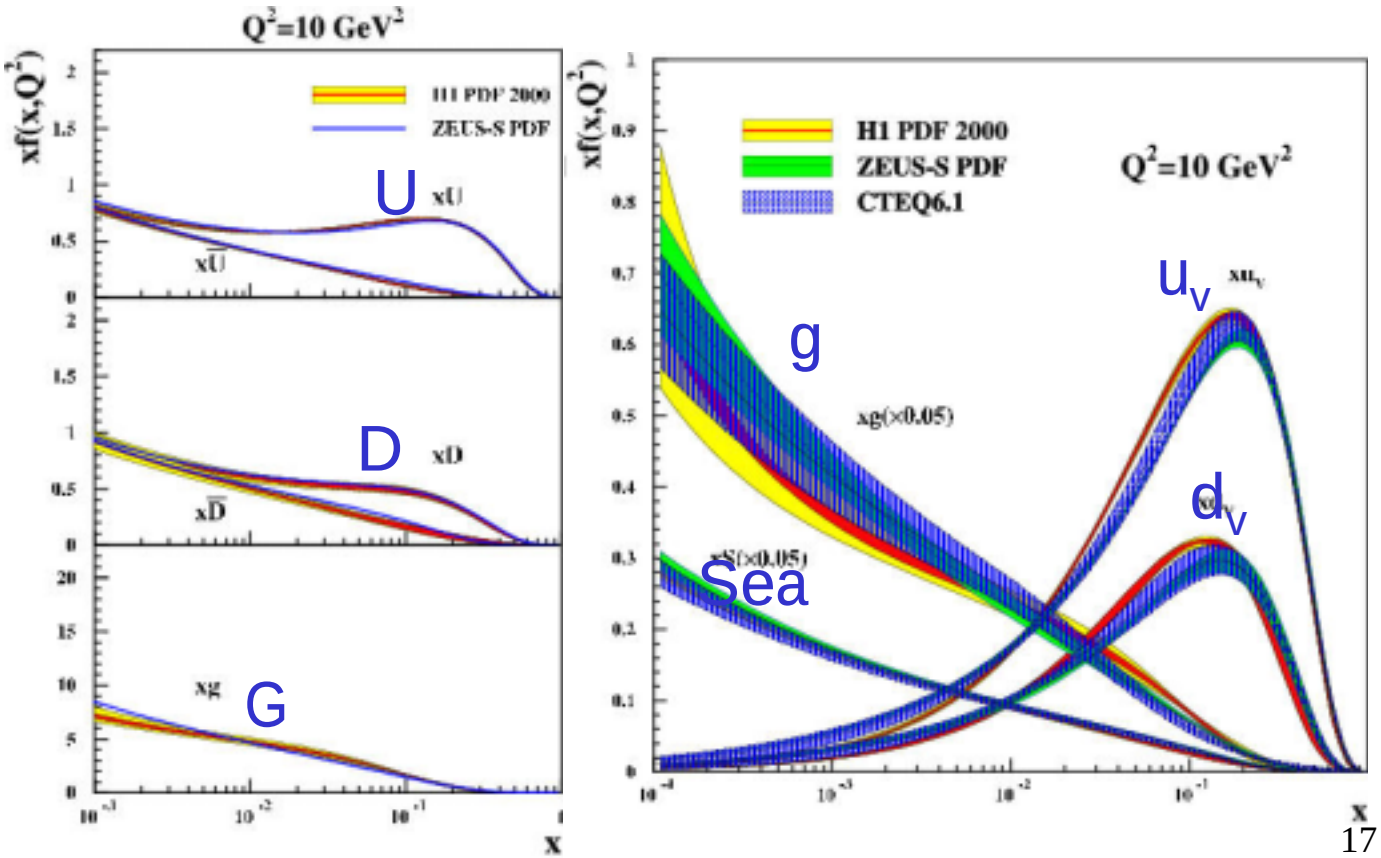
QCD fits to parton densities

- Fit only inclusive DIS data: theoretically clean (H1,ZEUS,Alekhin)
- Global fits: inclusive DIS, DY, Tevatron: jets, W/Z

  more constraints (CTEQ,MRST,...)

Zeus/H1:
fit to only
HERA data !

similar precision
as global fits



Gluon Density: Charm at HERA

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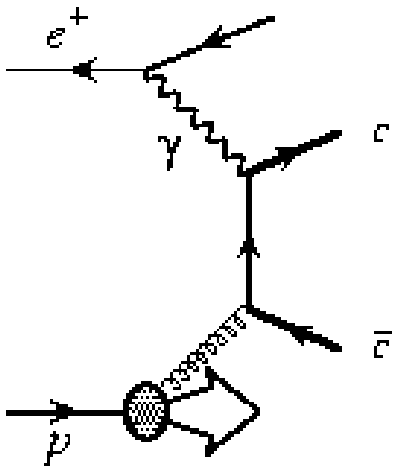
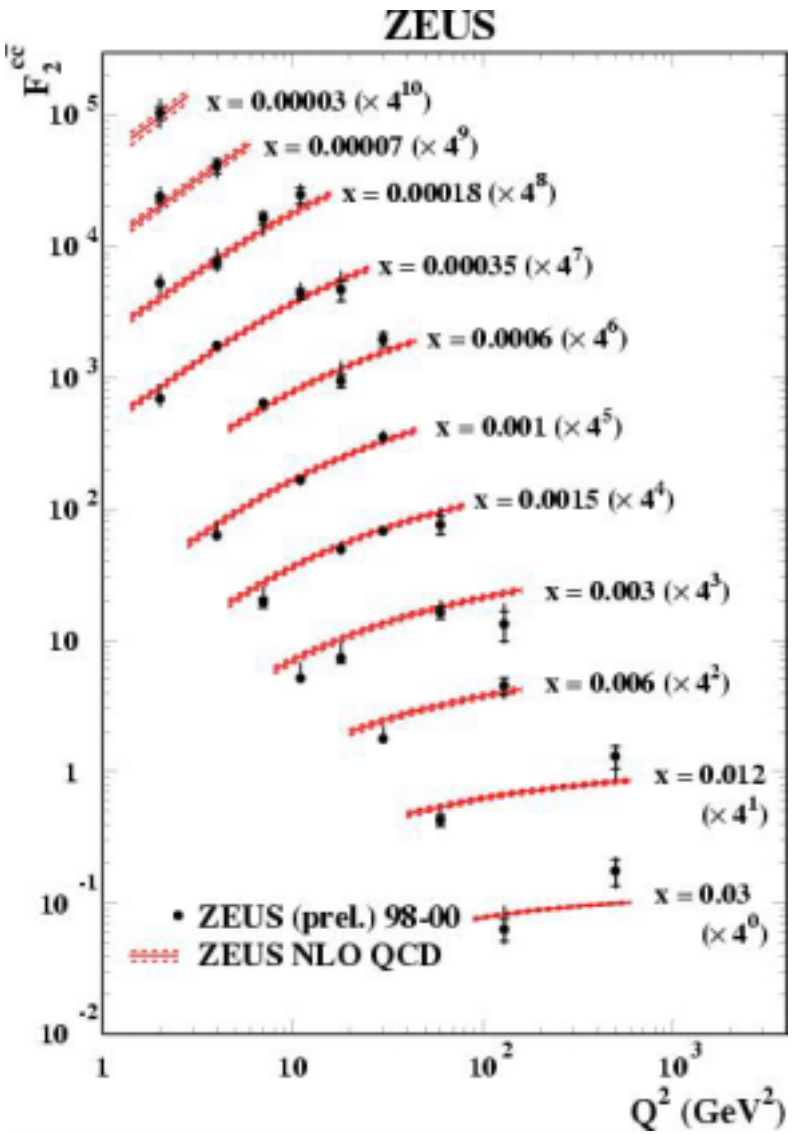
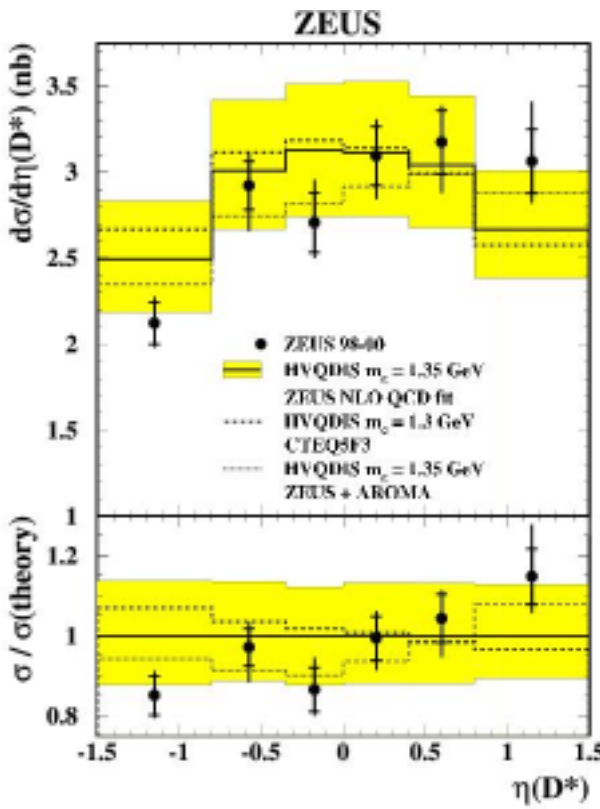


depends in
LO on gluon





agrees with ZEUS
NLO QCD fit

Gluon Density: F_L

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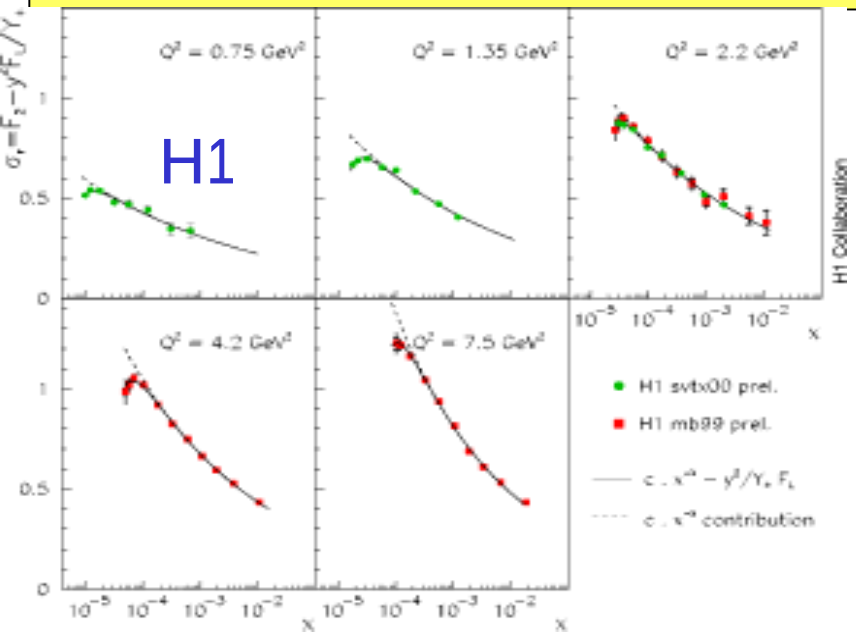
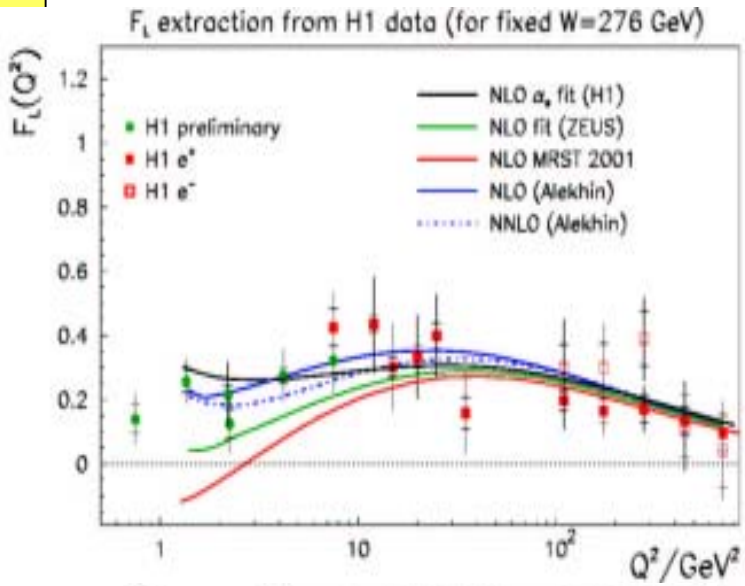
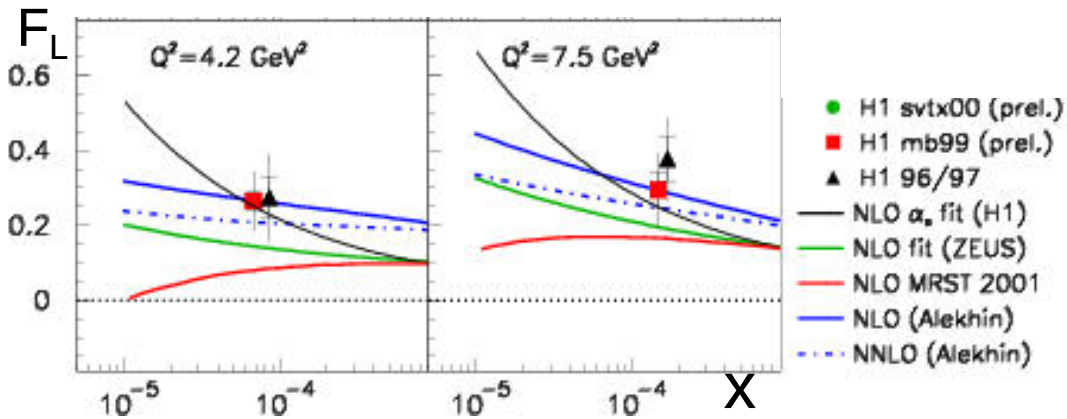
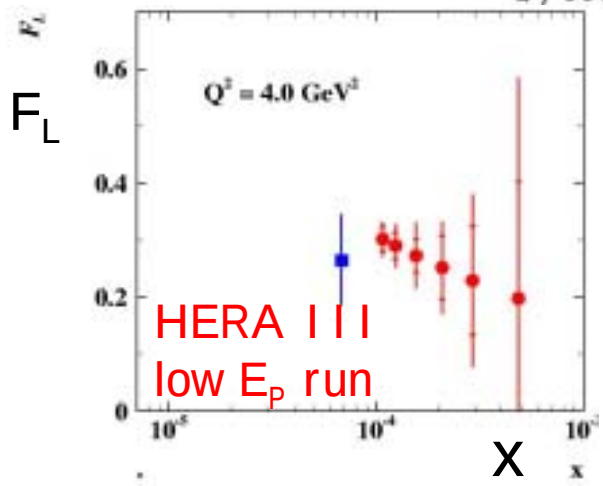
- NLO: contribution from gluons to F_L









very sensitive: disfavors MRST

Multijet: LEP 4-jet

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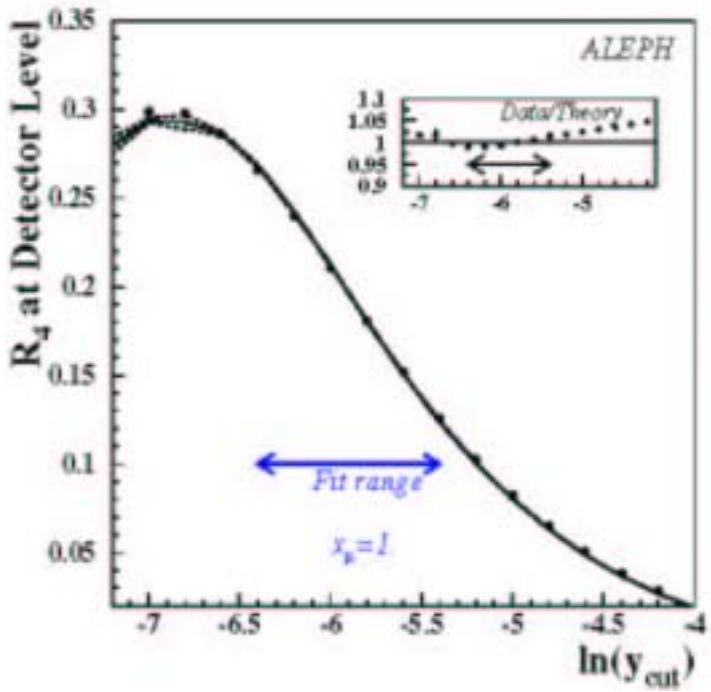
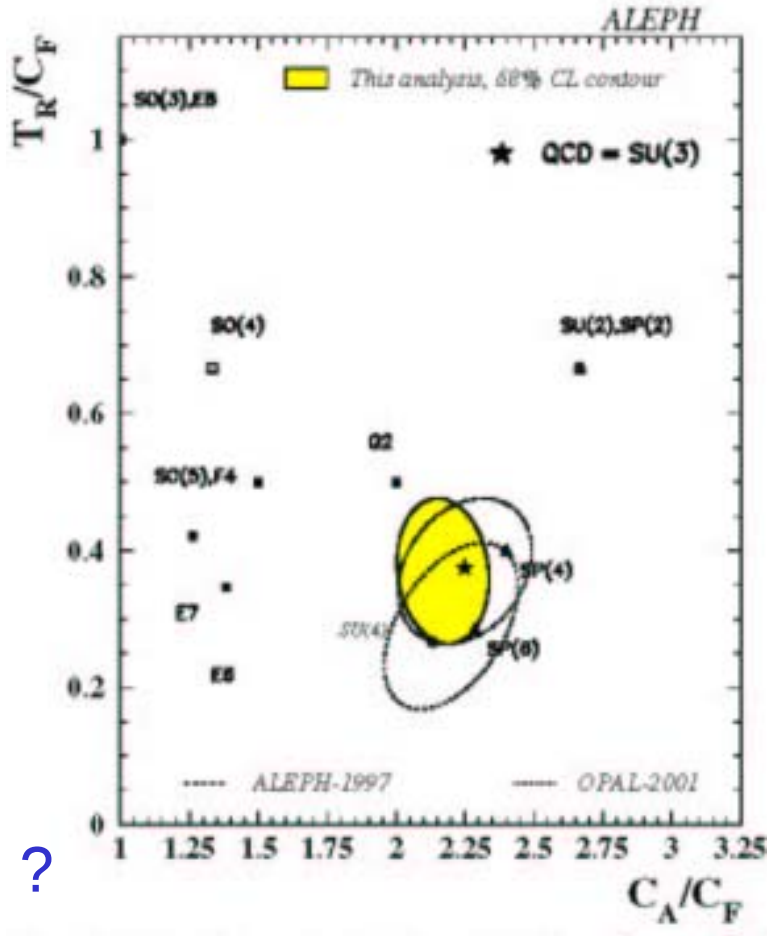
- Aleph 4 jet rate and angular correlations
- NLO + resummed (small scale variation)

α_s = 0.1170+-0.0001(stat)+-0.0013(sys)

Different error treatment: syst: 0.0022



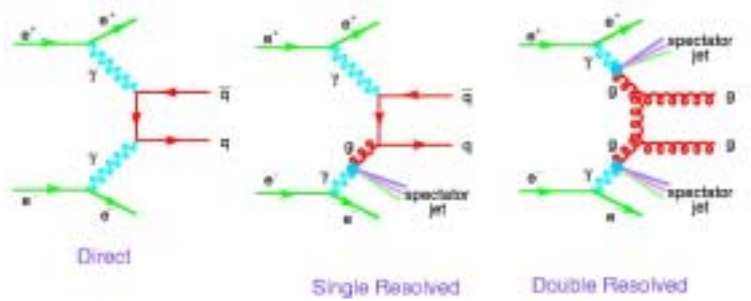
Colour factors



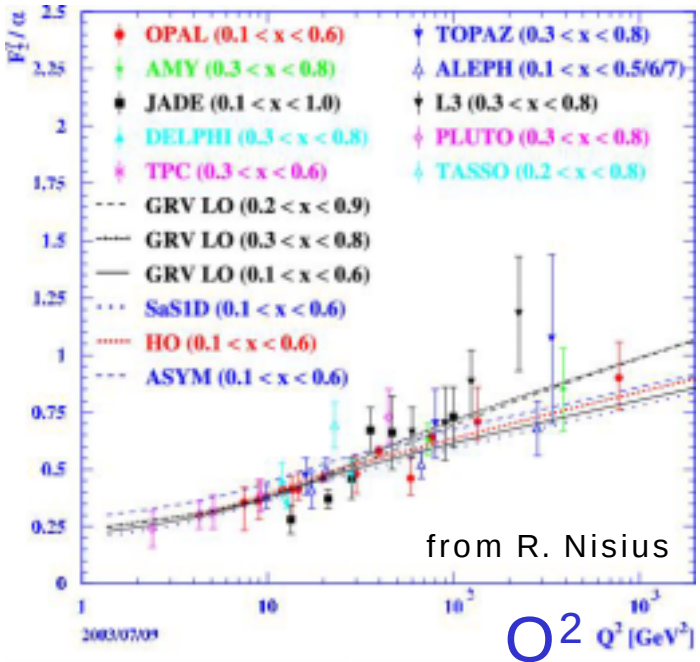
Very small scale error ! Accidental ?

Photon Structure from LEP

Peter Schleper
Exp. Tests of QCD
EPS 2003, Aachen



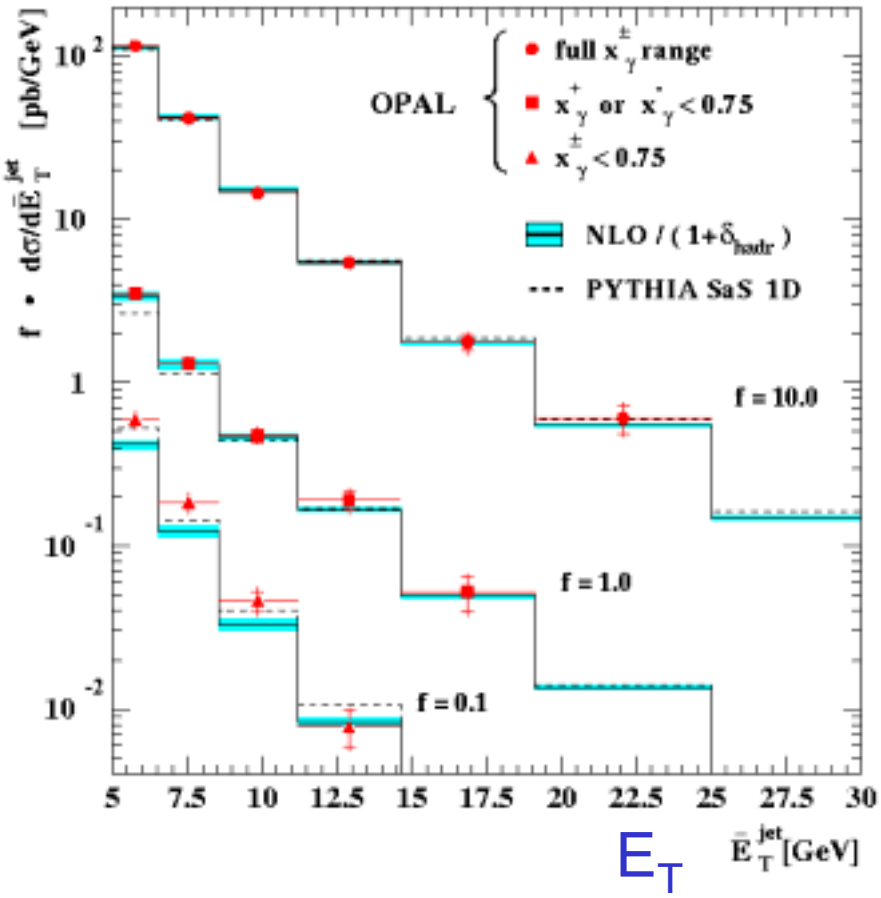
Scale dependence of γ-structure



Albino, Klasen & Soldner Rembold, hep-ph/0205069

$$\alpha_s(M_Z^2) = 0.1198 \pm 0.0028(\text{exp.})^{+0.0034}_{-0.0046}(\text{theo.})$$

Jet production (OPAL)



Confirmation of partonic deconvolution of γ

L3: γ–γ at high PT

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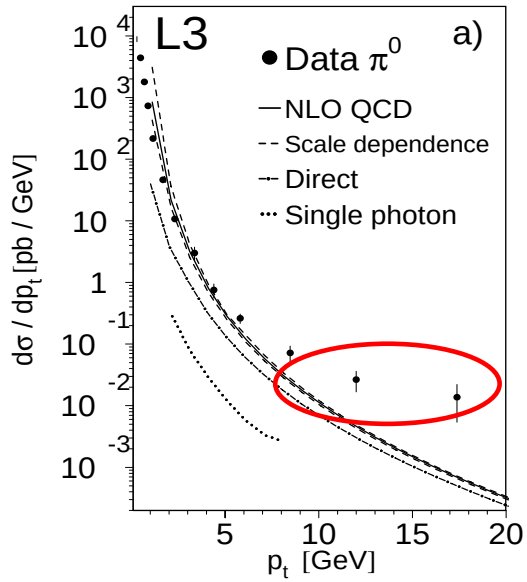
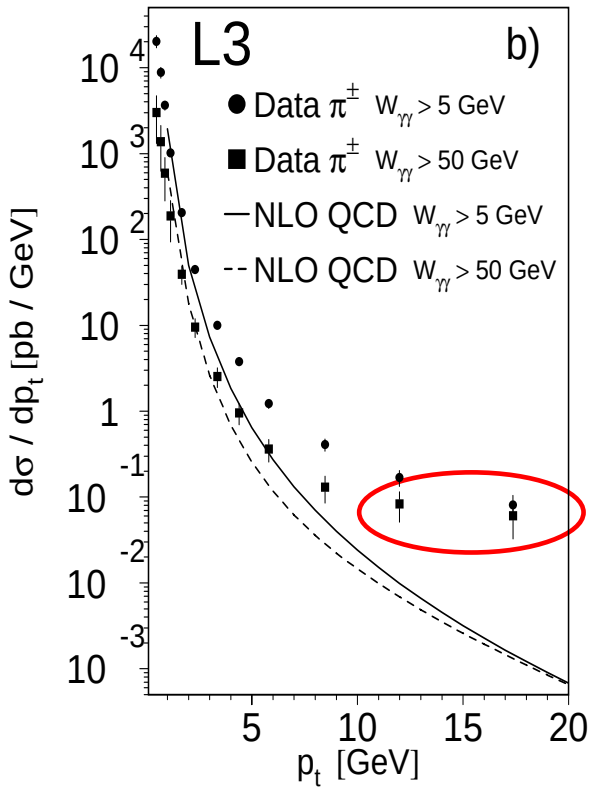
full LEP II data:
access to very high PT particles/jets

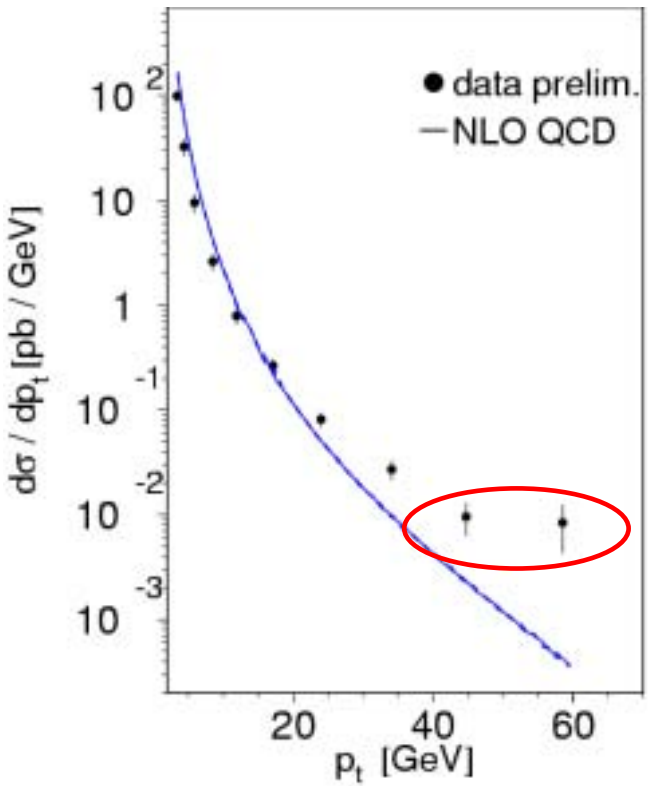
earlier reported:
excess in π^0



New: π+,π-



New: incl.jet data



Huge effect:
needs
confirmation by
other experiments

Jets in γ-p: HERA

Peter Schleper
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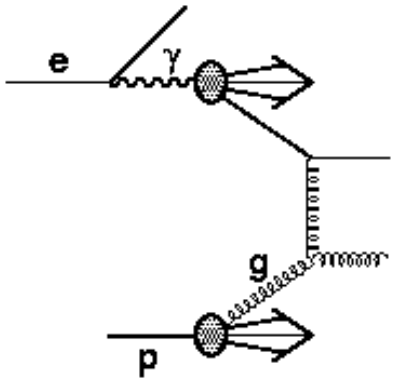
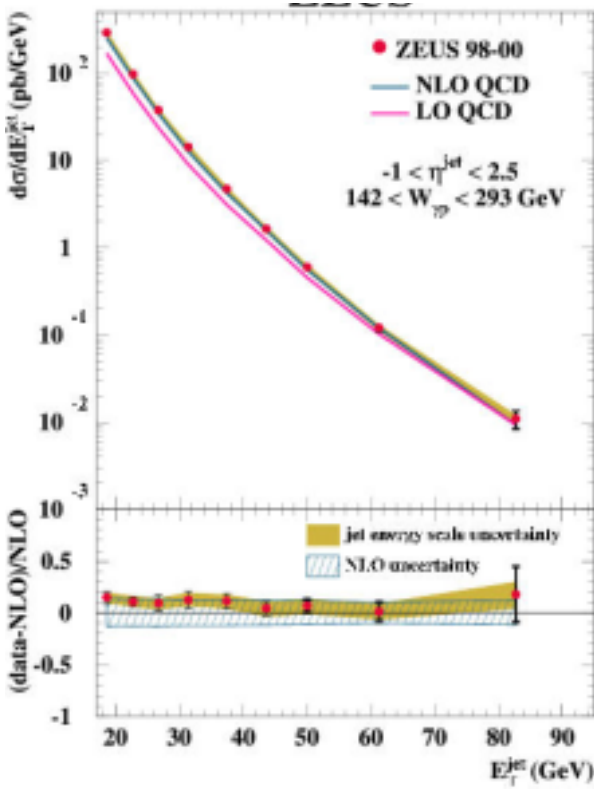
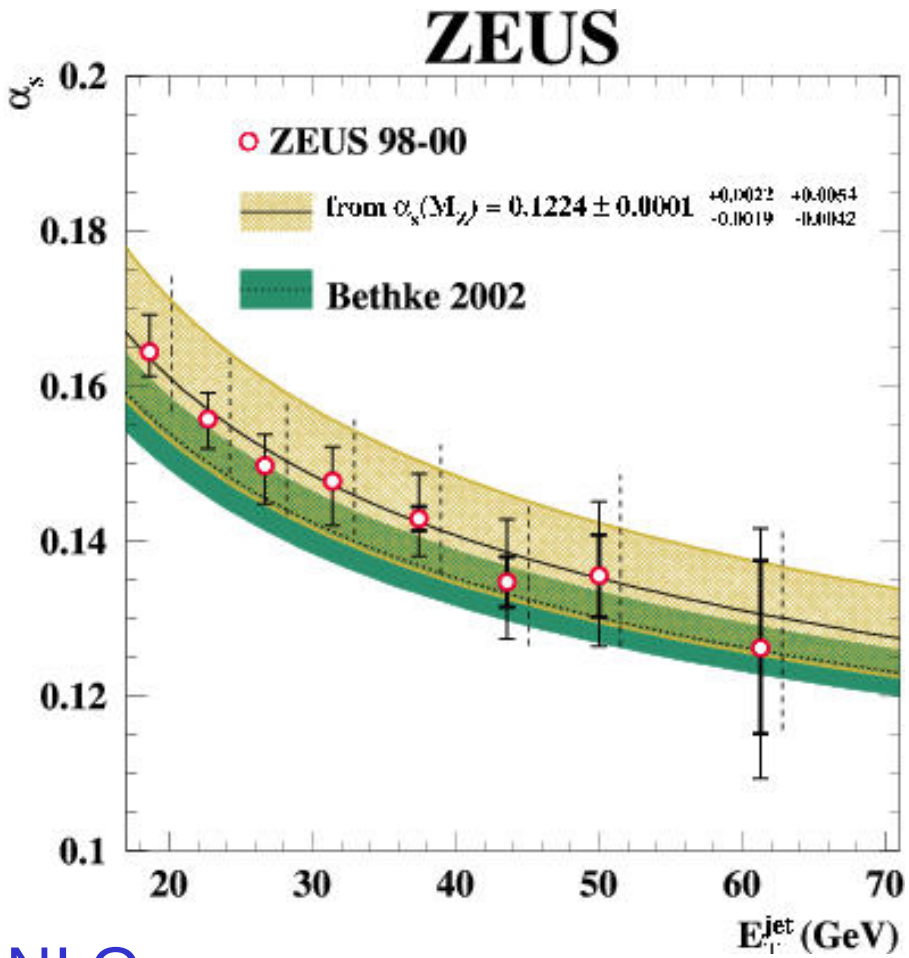
EPS 2003, Aachen







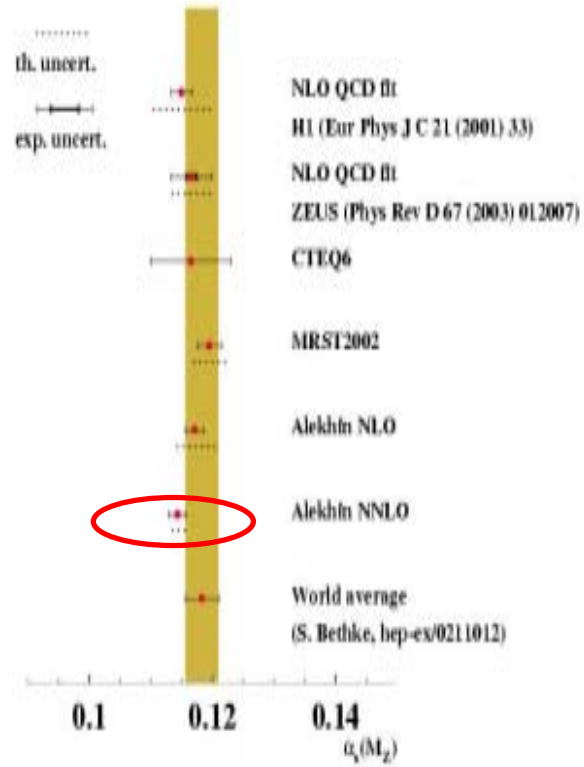
γ-PDF & NLO describes data

full HERA I luminosity
Future: high x gluon
~ c.f.Tevatron

α_s global

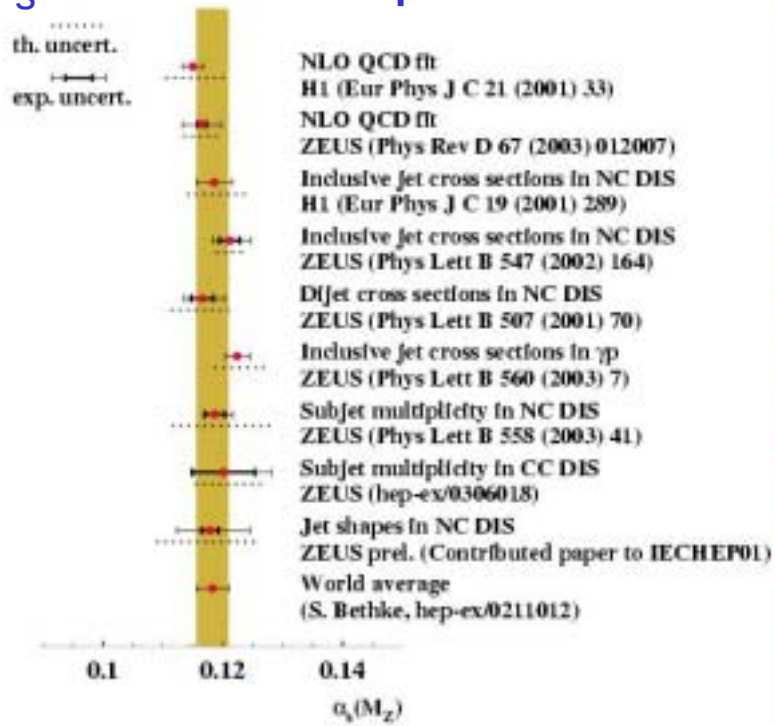
Peter Schleper
Exp. Tests of QCD
EPS 2003, Aachen

α_s from QCD fits

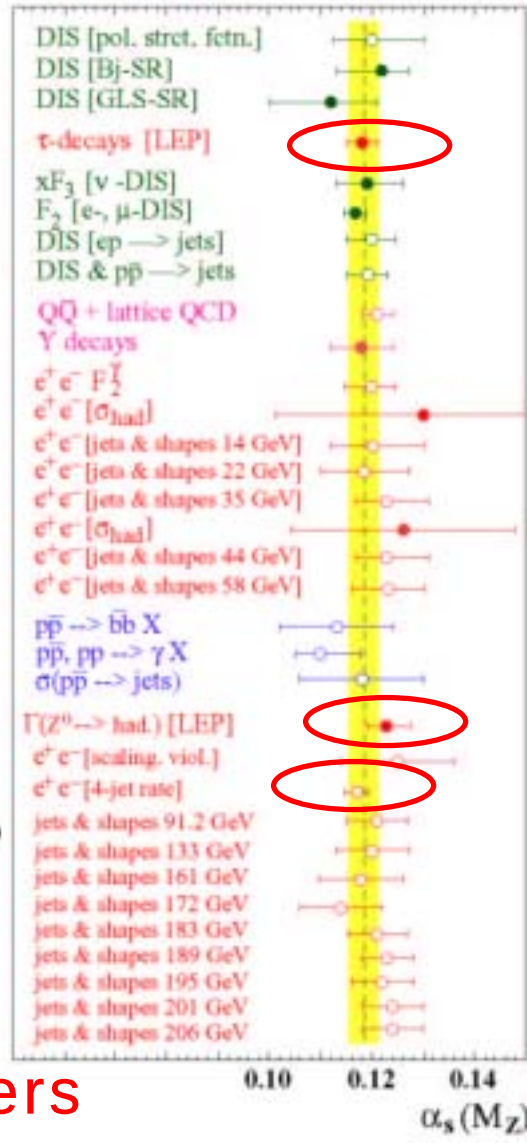


Very impressive success of QCD

α_s from hadr. processses



Bethke 2002



Limited everywhere by missing higher orders

Higher Order Calculations

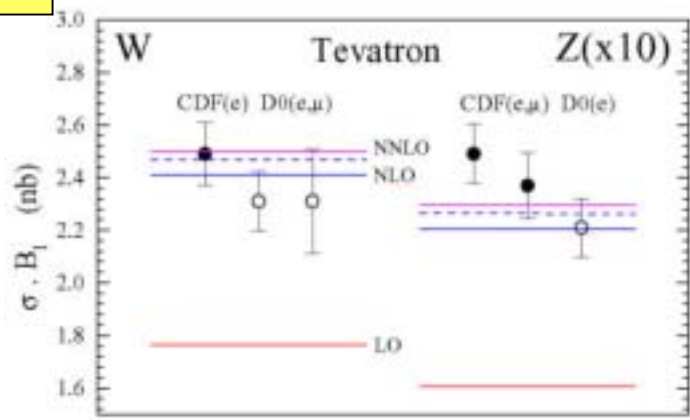
Peter Schleper
Exp. Tests of QCD
EPS 2003, Aachen

State of the art:
- data unfolded with LO+PS monte carlo
- results compared to NLO (+NLL) + hadr.cor.(LO+PS monte carlo)

NNLO: building blocks known/calculated
First results for DIS, Drell-Yan, Higgs,..
Within 1 ? year:
3 jets at LEP, 2-jet pp, 2-jet DIS
→ the only way to precise α_s, σ_H

Monte Carlo: (the experimentalists view)
Since ~5 years: 2→2,3,4 processes, LO+PS
Needed: NLO + PS for unfolding data !
Better: NLO + NLL + PS
→ the only way to precise data

Drell Yan at NNLO



Both need strong support from the community !

Higgs Production at LHC

Peter Schleper
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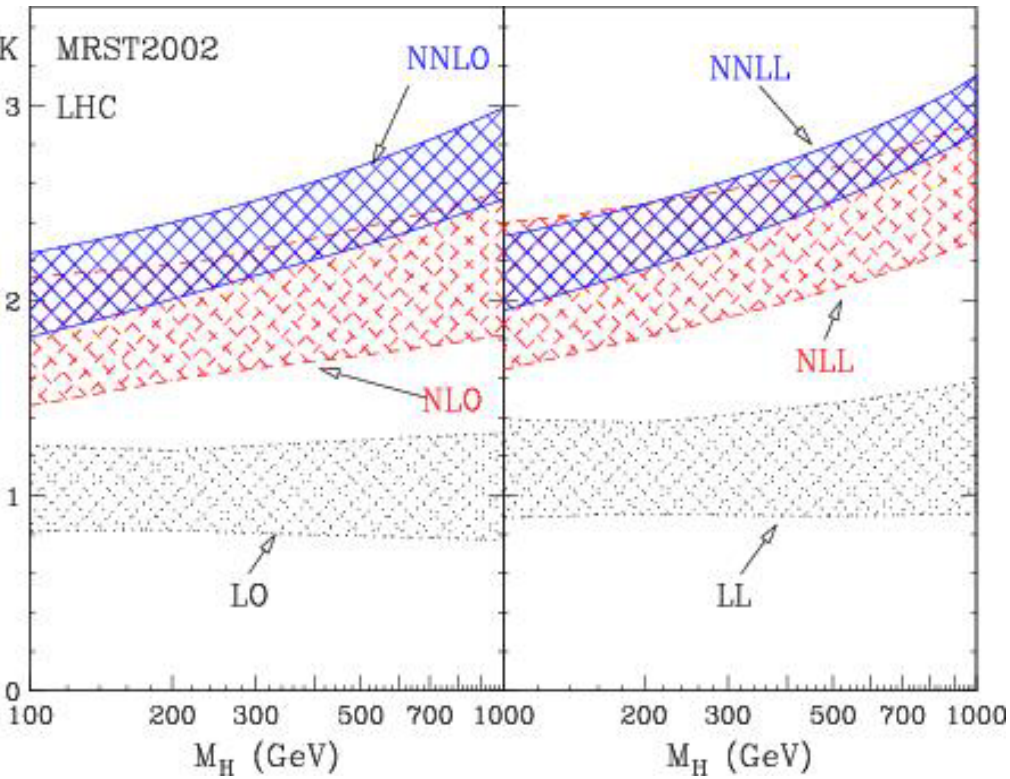
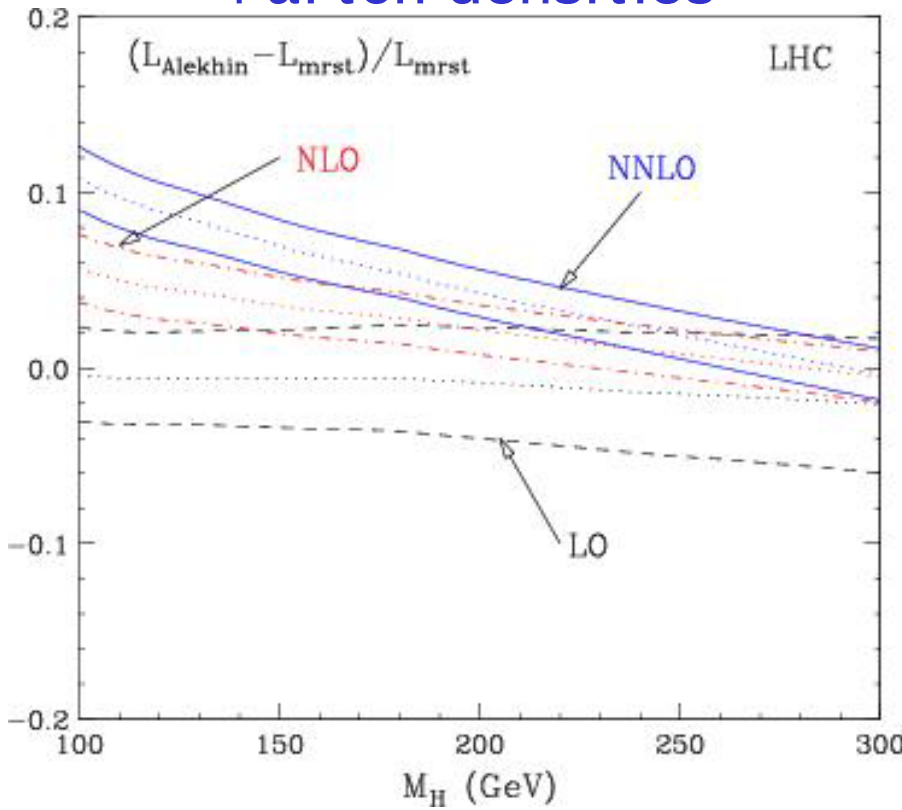
Benchmark test for status of QCD calculations

Higher orders



uncertainty ~ 10 %

Parton densities



uncertainty ~ 10 %

Beauty & Charm Production

Beauty: Problem for QCD ?

- Tevatron: data/theory ~3
- HERA: data/theory ~3
- LEP-$\gamma\gamma$: data/theory ~ 3

Charm:

- Tevatron slightly high
- HERA and LEP-$\gamma\gamma$ ~o.k.

- 2 (3) scale problem: M_b, P_{Tb}, (Q2)
- HERA/LEP-$\gamma\gamma$: $M_b \sim P_{Tb}$ small,

  Experimentally difficult: S/B ~ 1000
- B as part of gamma structure ?

Charm & Beauty at Tevatron

Peter Schleper
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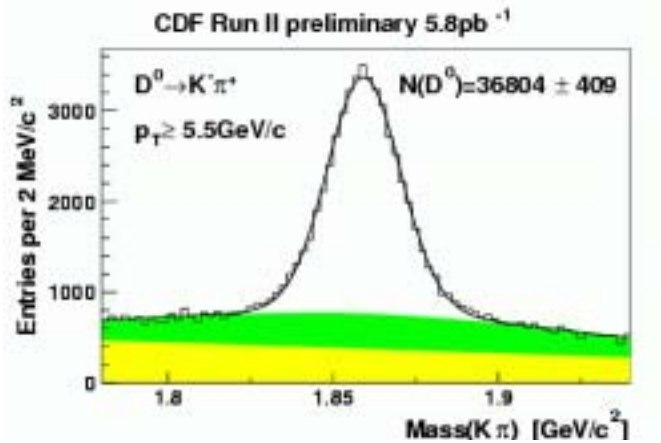
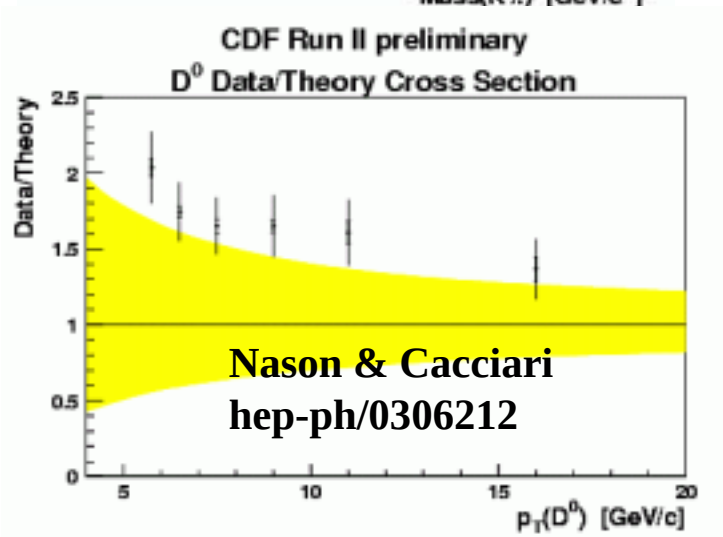
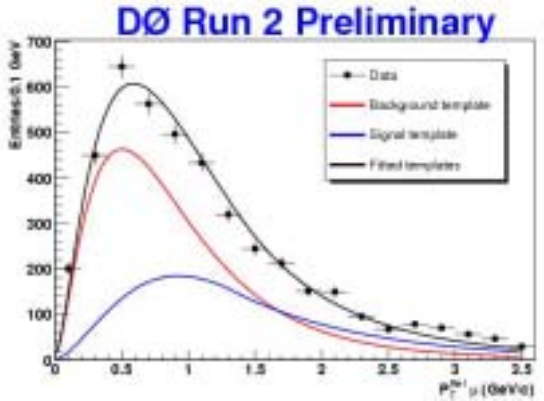
CDF: charm, 5.8 pb^{-1},
but new silicon trigger

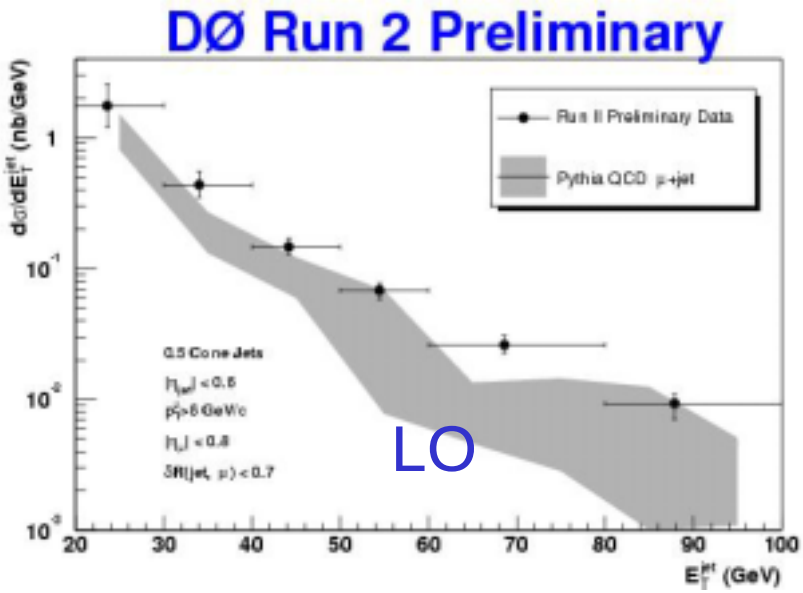




theory factor 1.7 low



New D0
silicon tracker



first beauty results from Run II

Beauty at Tevatron

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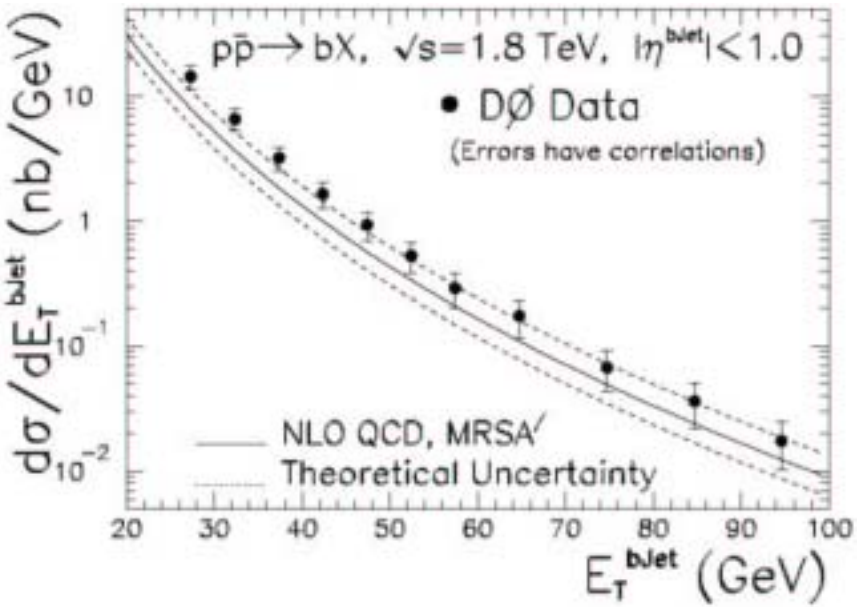
Previous excess partially explained by:

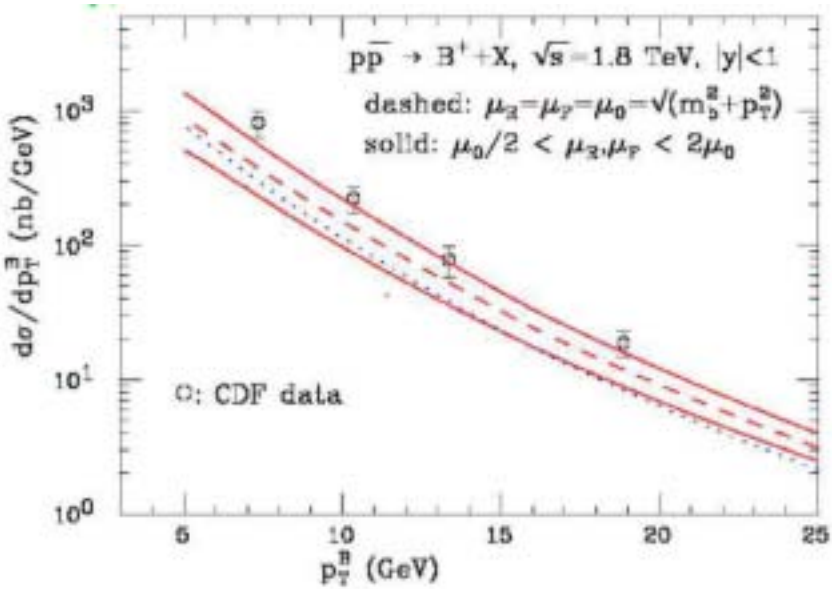
- resummation of $\ln(P_T/M_b)$
- data: jet with b
- theory: b only



Now: data/theory ~ 1.6

Exclusive B Production

Update to more recent fragmentation functions



Now: data/theory ~ 1.7

Problem partially solved

Beauty at HERA

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Exp. Tests of QCD
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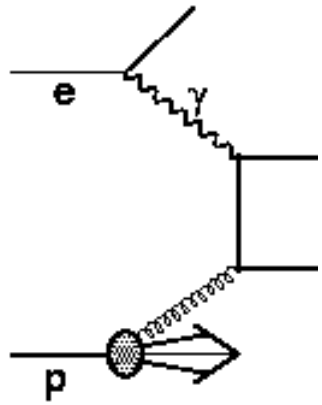
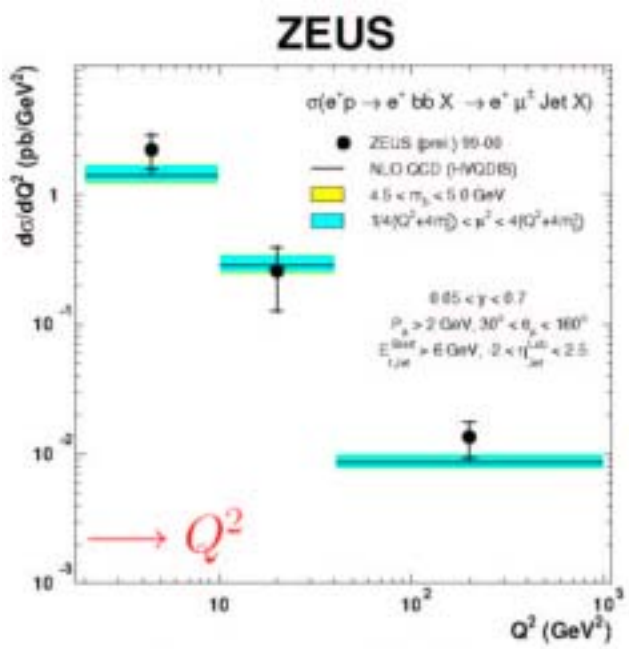
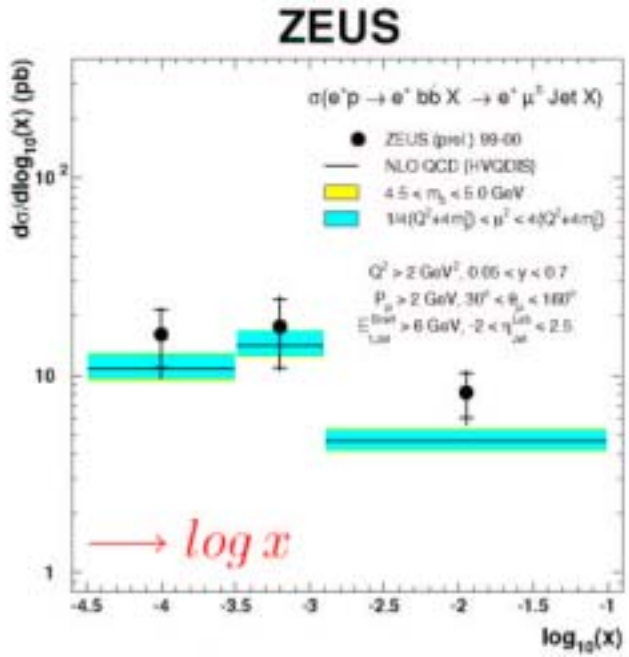
- Exp difficult: low PT jets, S/B ~ 1000
- Comparison data/theorie
- Former: extrapolation of data to parton level and full phase space with LO+PS monte carlo
- Now: data as is, apply hadronisation corr. to NLO in visible phase space



Deep inelastic

Now agreement with NLO





Beauty at HERA

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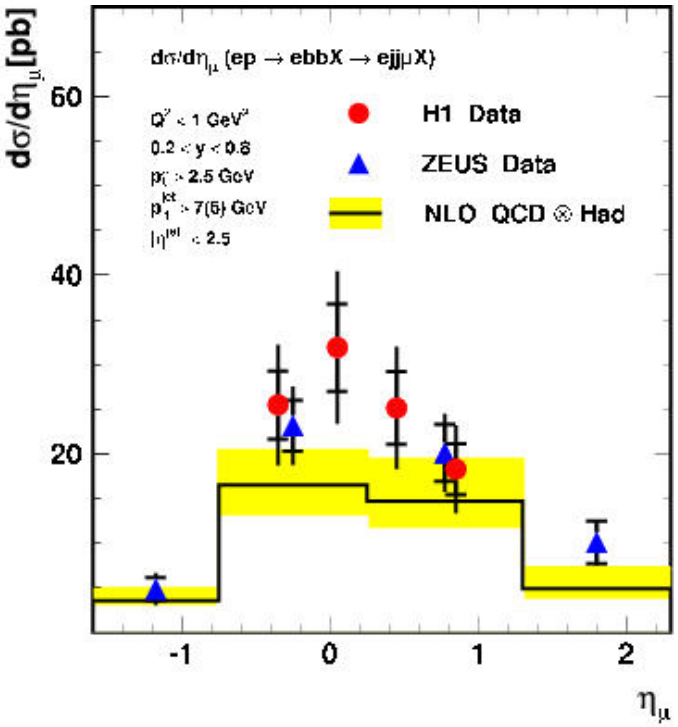
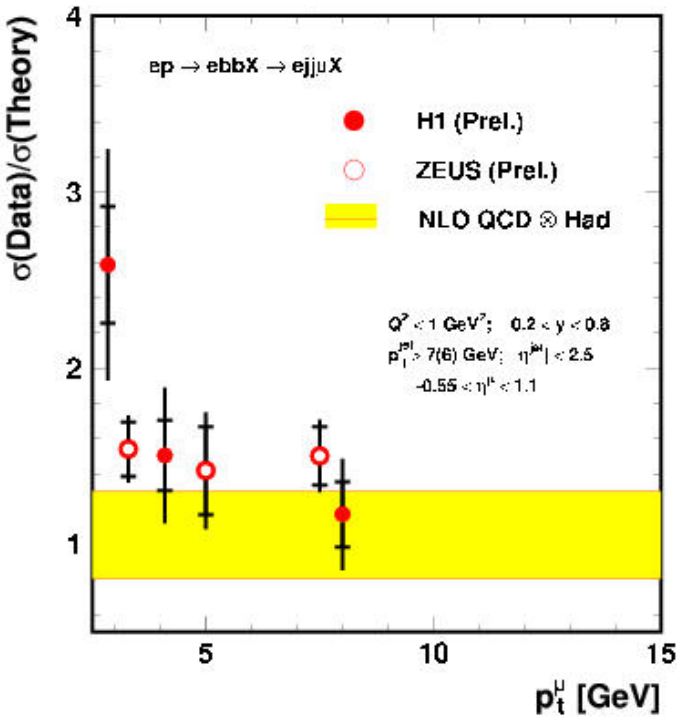
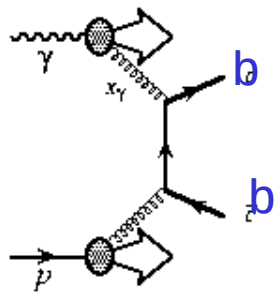
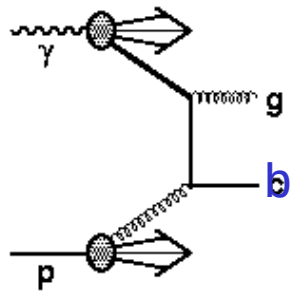
Photoproduction









Data still slightly above NLO, but main effect found:
LO+PS differs from NLO invisible part of PS.

Charm & Beauty in $\gamma\gamma$ at LEP

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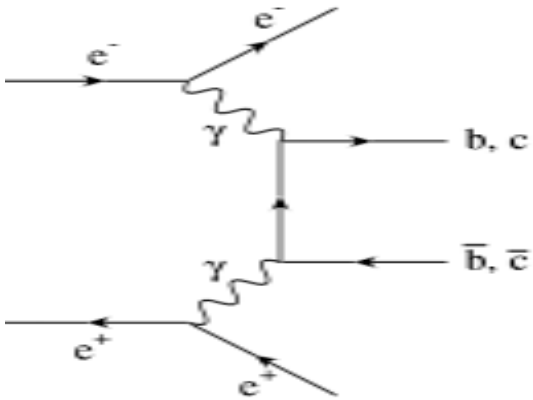
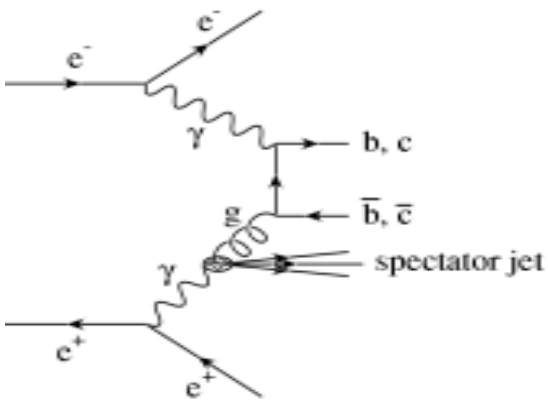
EPS 2003, Aachen

Direct Process

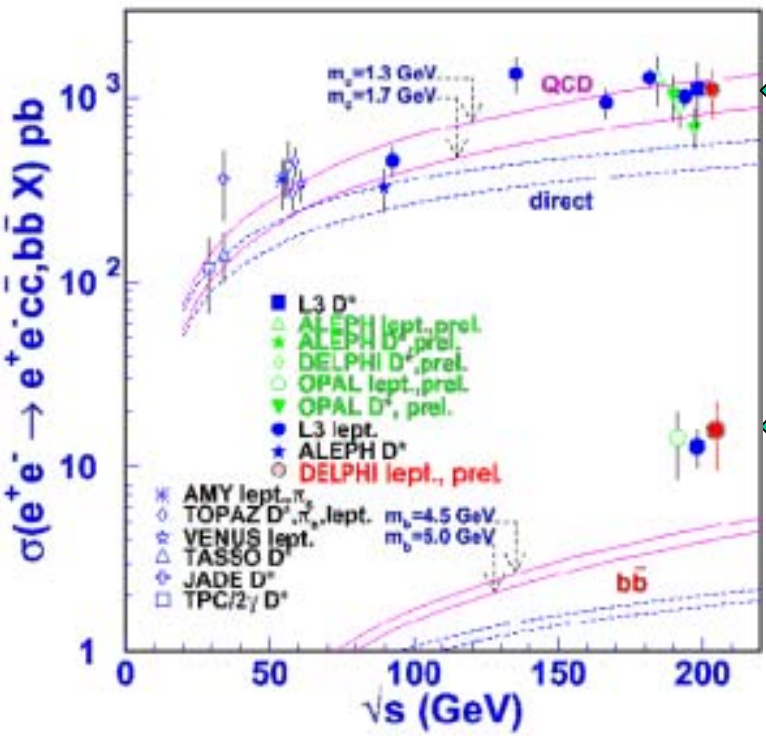


Single resolved process



New data

- L3: full LEP 2 data
- Delphi: first analysis (K in RICH)



Confirmation of previous results

- Charm o.k., beauty low
- no explanation yet

Parton Dynamics

Peter Schleper
Exp. Tests of QCD
EPS 2003, Aachen

DGLAP factorisation:

integrated over trans. momentum

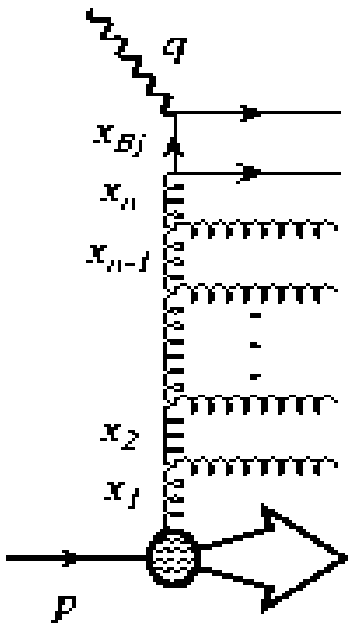
$f(x,Q^2)$

expected to fail when $Q \sim K_T$

un-integrated PDFs:

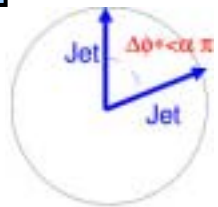
$f(x,Q^2,K_T)$

BFKL,CCFM evolution

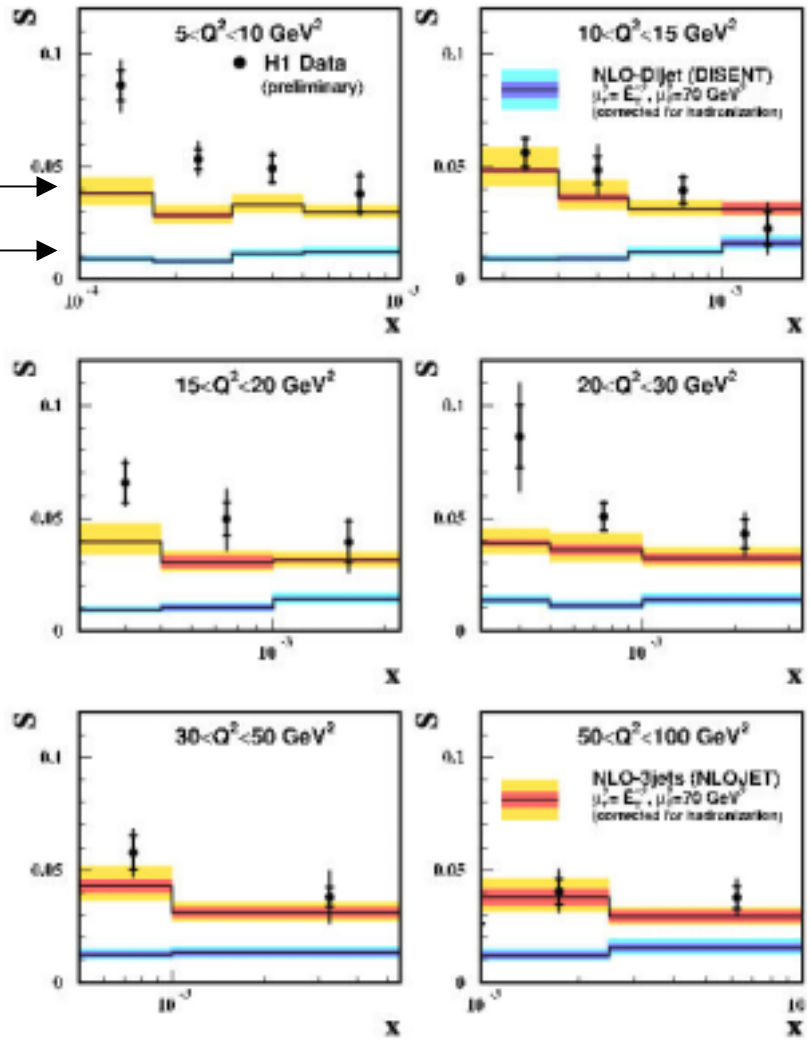


Important at low –x
High parton density

Selection:
2jets, unbalance



NLO 3j →
NLO 2j →



Low – x physics: LEP

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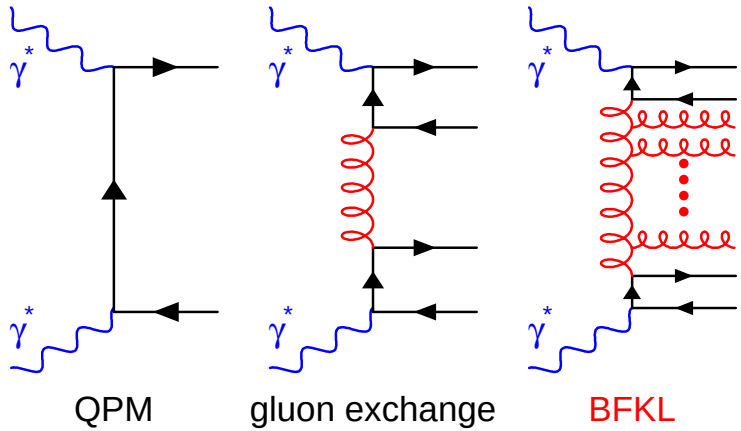
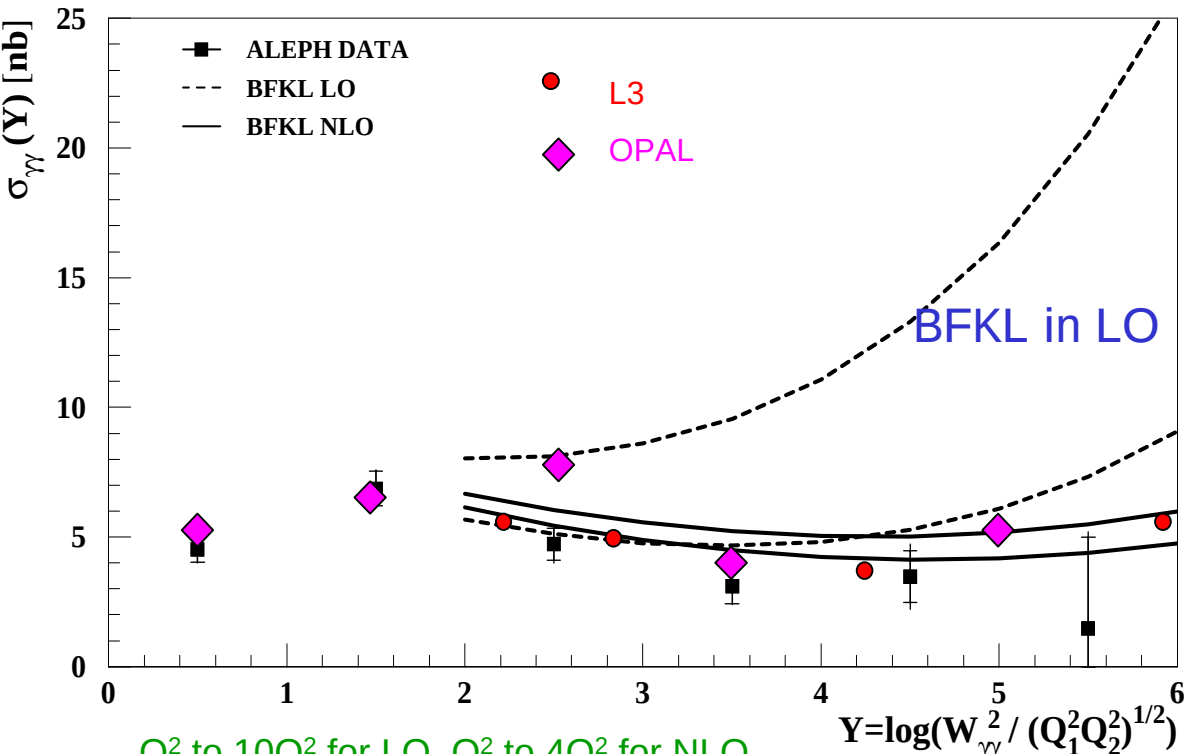
$\gamma^*\gamma^*$ scattering:

- 2 hard scales
- test case for BFKL dynamics





BFKL in NLO

Q^2 to $10Q^2$ for LO, Q^2 to $4Q^2$ for NLO

Diffraction: factorization

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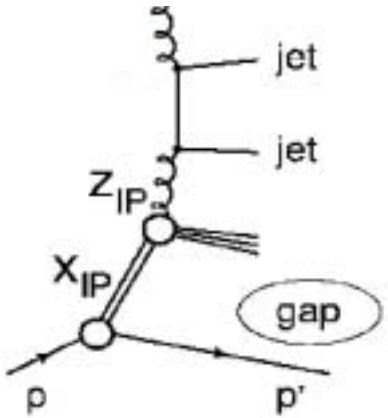
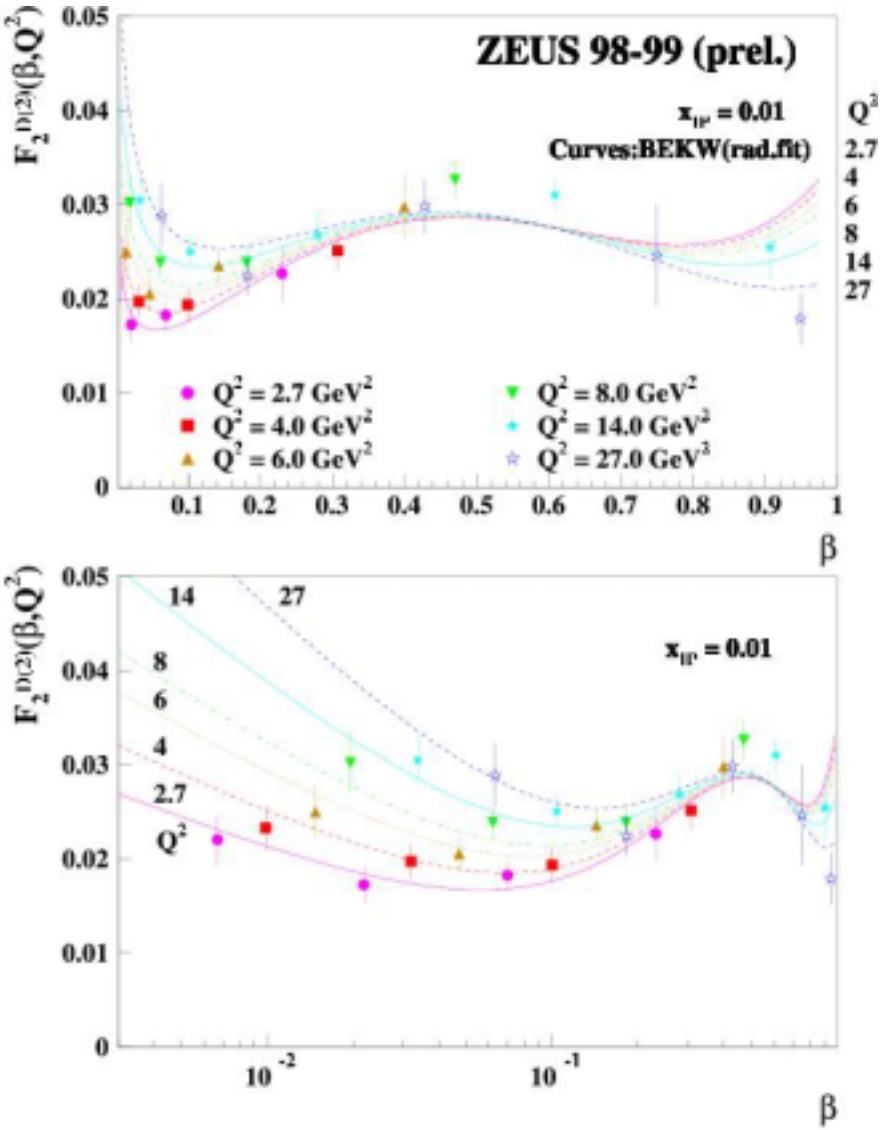


No colour exchange from Proton

Soft QCD ?



Hard scattering: Q2 large

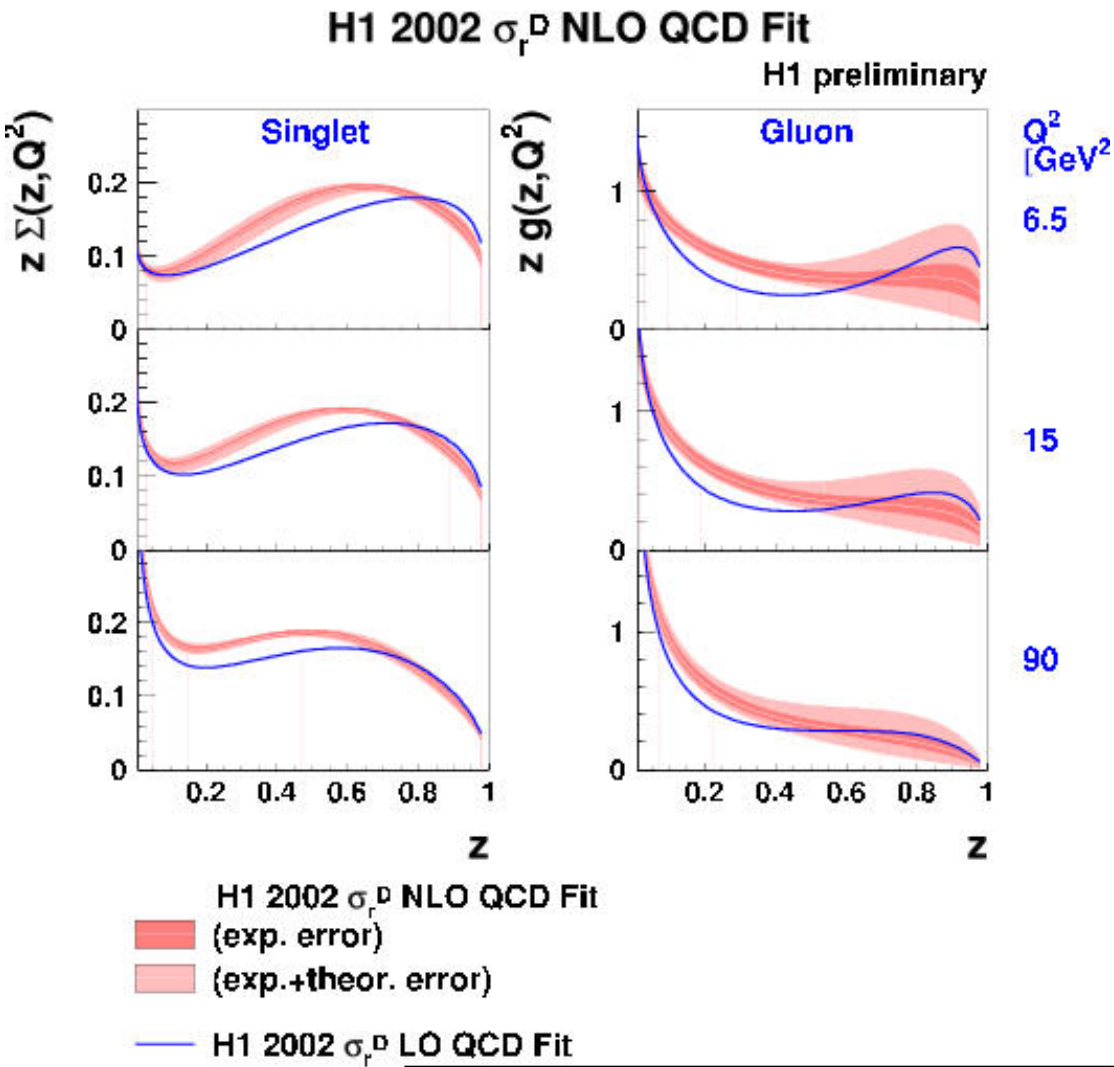
Factorisation in diffract. PDF and partonic σ

$$\sigma_{\mathrm{DIS}}^{\mathrm{Dif}} \sim p_q^D(x_{I\!P}, t, x, Q^2) \otimes \hat{\sigma}_{\mathrm{pQCD}}$$

should follow DGLAP QCD evolution with Q^2

Diffraction in NLO QCD

Peter Schleper
Exp. Tests of QCD
EPS 2003, Aachen



NLO QCD fits to incl data

Same as in standard QCD fits to DIS

PDF(x,Q2) for fixed Proton momentum

Large gluon contribution

Use diffr. PDF to predict σ(jet) , σ(charm)

Diffraction in NLO QCD

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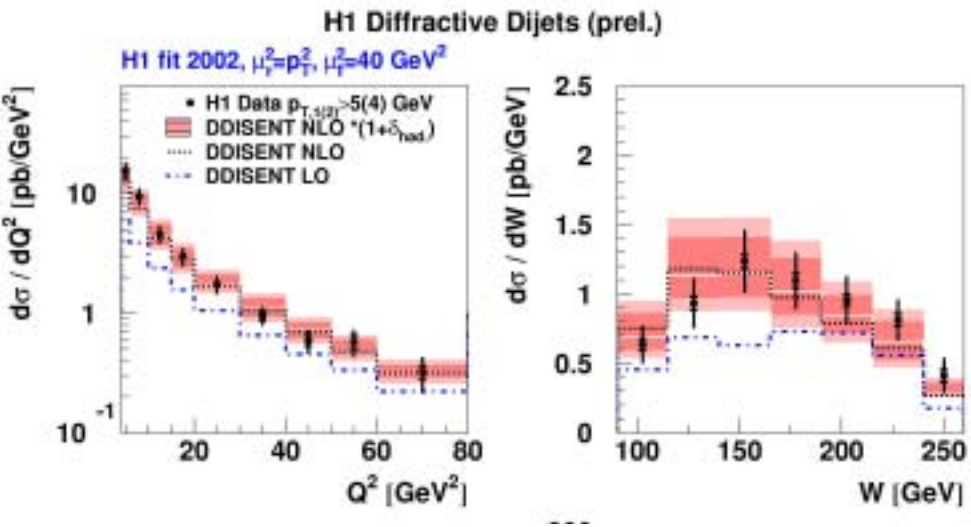
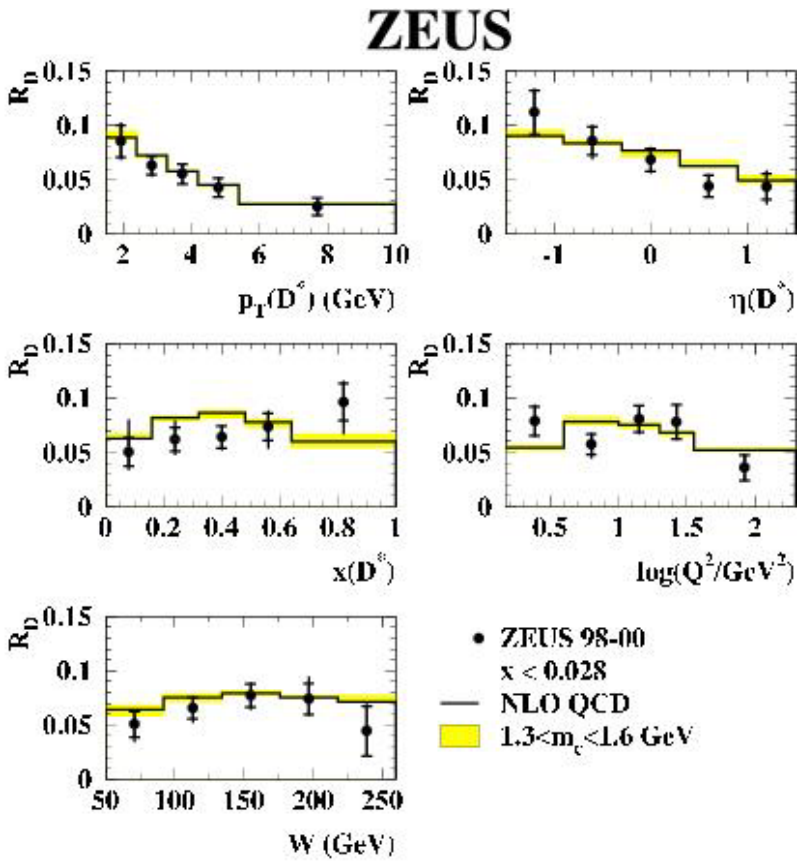
Jets



Charm



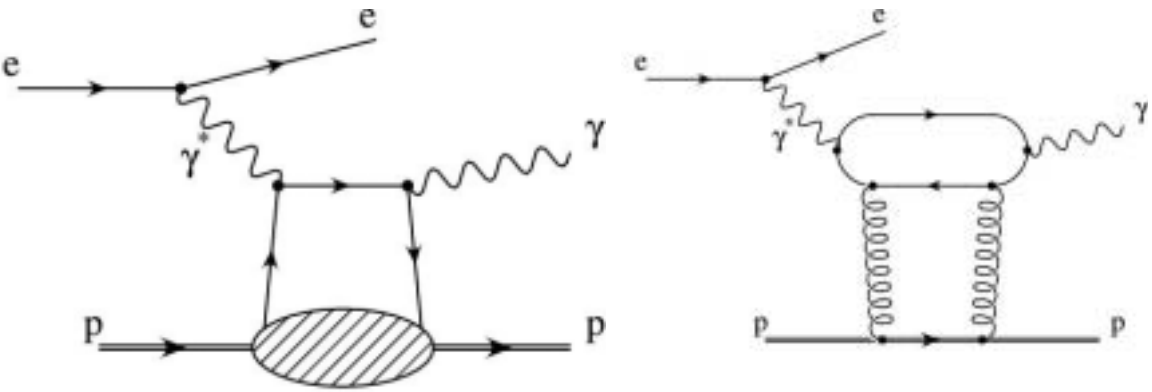
- **NLO QCD fit to inclusive data describes jet and charm**
- **successful test of hard scattering factorisation**

Current state: ~ all hard diffractive processes at HERA are described by NLO QCD

Skewed partons

Peter Schleper
Exp. Tests of QCD
EPS 2003, Aachen

e.g.: DVCS (deeply virtual compton scattering)

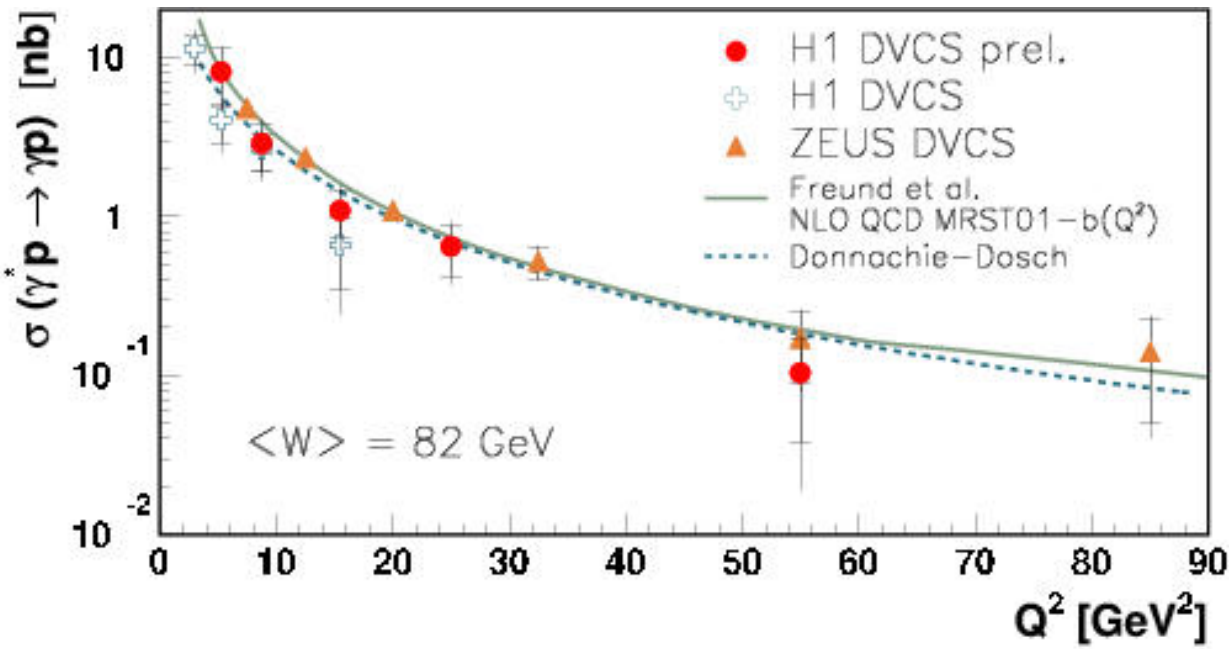


correlation between initial quarks and gluons

$f(x_1, x_2, Q^2)$

Factorisation for large Q^2

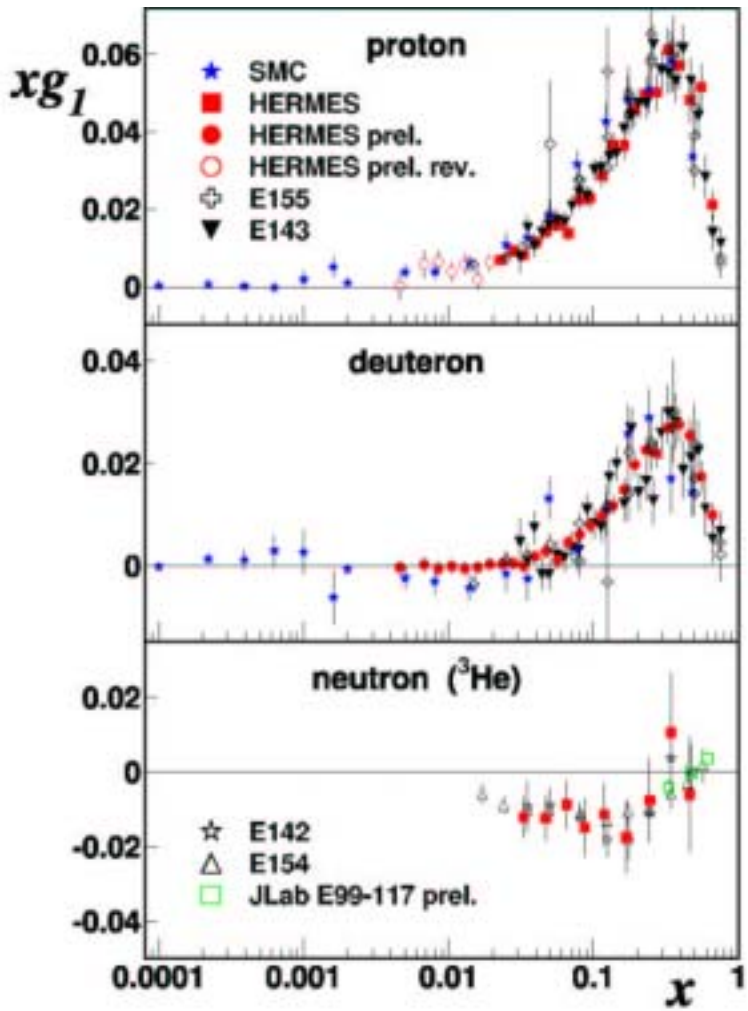
NLO successful

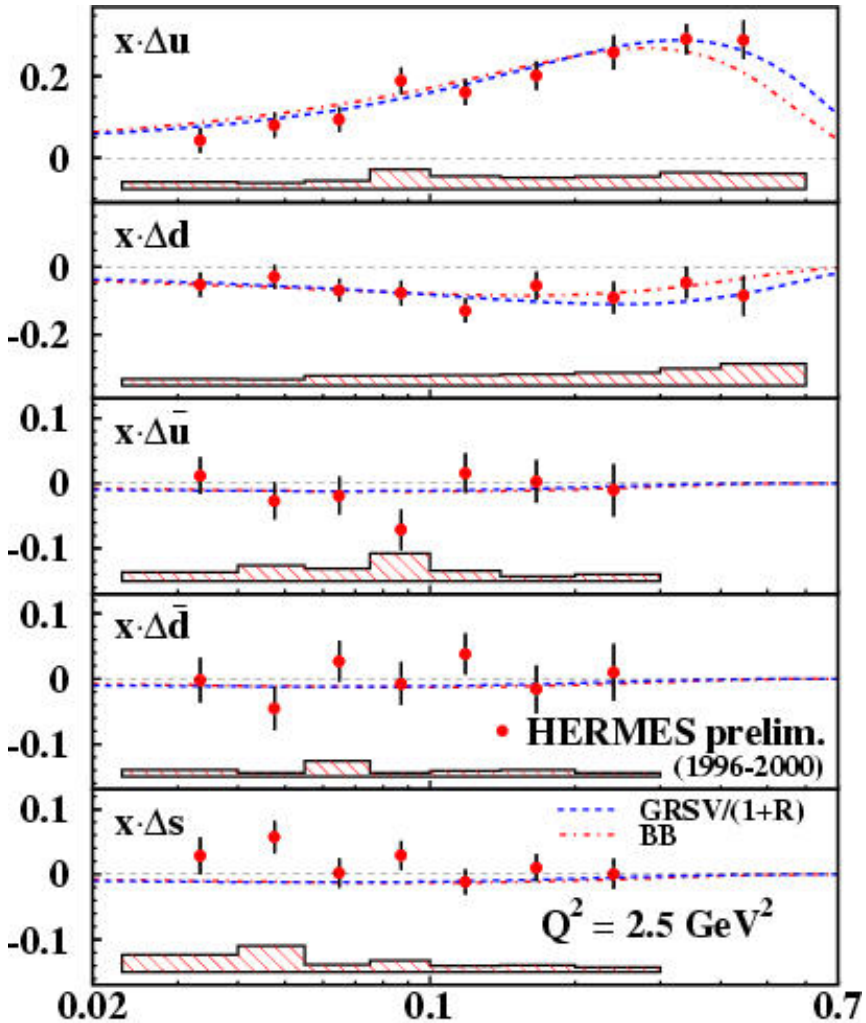


Spin Parton Distributions

Peter Schleper
Exp. Tests of QCD
EPS 2003, Aachen

proton spin: $\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v + \Delta q_{sea}) + \Delta g + Lq + Lg$





Spin Parton Distributions

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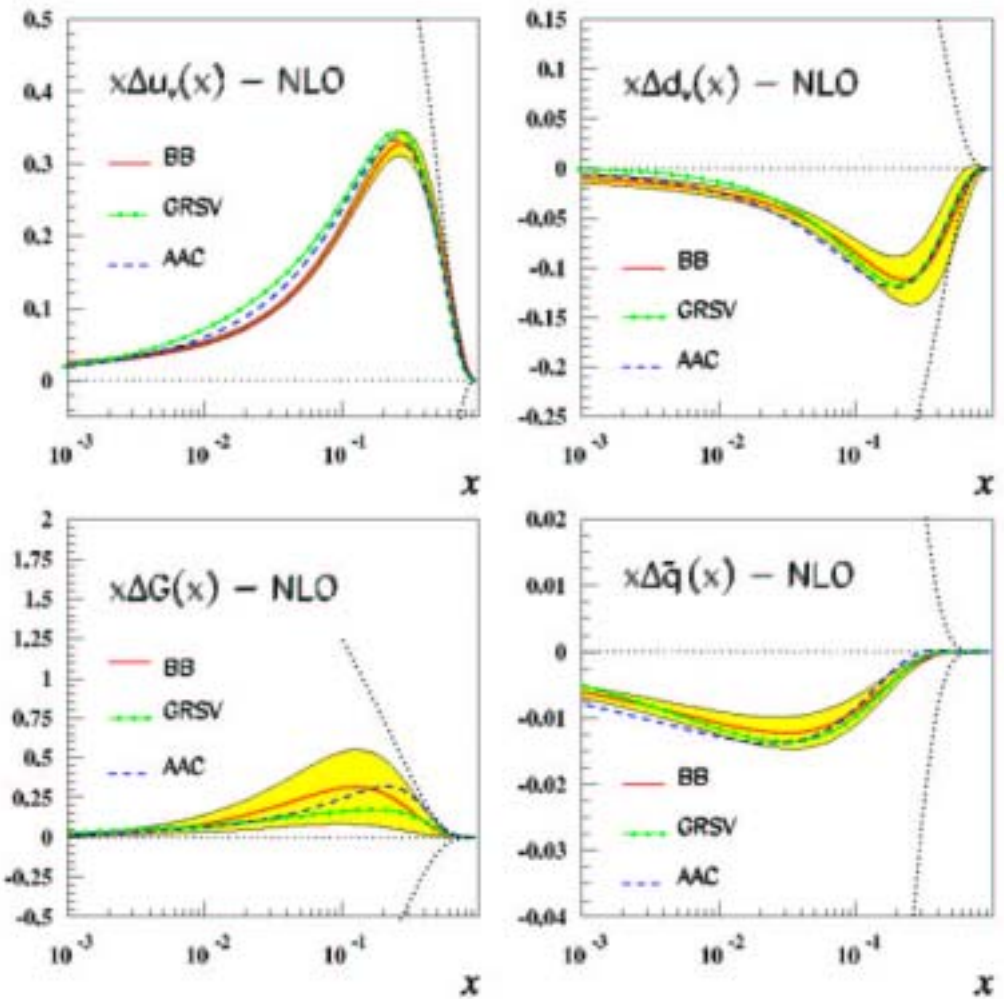
NLO QCD fit



well determined: u, d

Next:
Gluon distribution

Compass Experiment:
data taking started 2002

- first results on particle production
- gluon density from $\gamma^* g \rightarrow c\bar{c} X$ … soon

Pentaquarks: I

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Evidence from 3 experiments: LEPS,DIANA,CLAS

LEPS: $\gamma n \rightarrow K^- K^+ n$ hep-ex/0301020

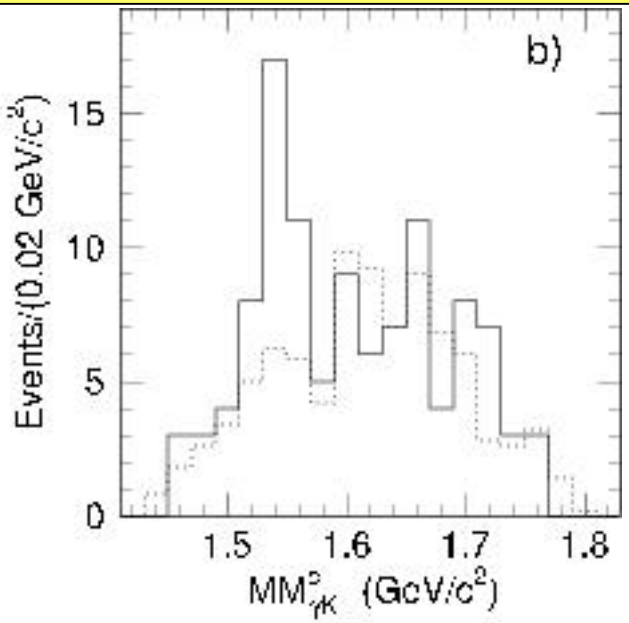
γ beam up to 2.4 GeV

- Mass($K^+ n$) from K^- recoil
- background from comparison γn and γp

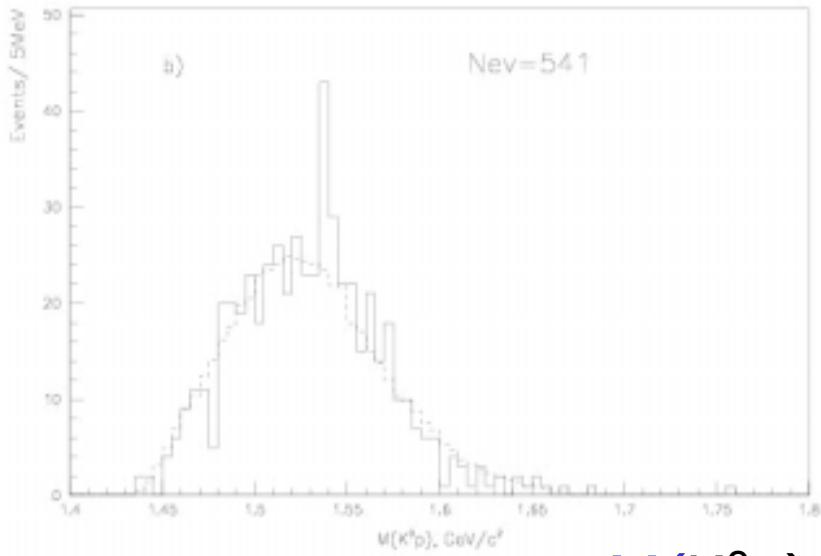
DIANA: $K^+ n \rightarrow K^0 p$ hep-ex/0304040

In Xe bubble chamber

- Mass($K^+ n$) from K^- recoil



Claim: 4.6 σ evidence



M(K^0p)

Claim: 4.4 σ evidence

Pentaquarks: 2

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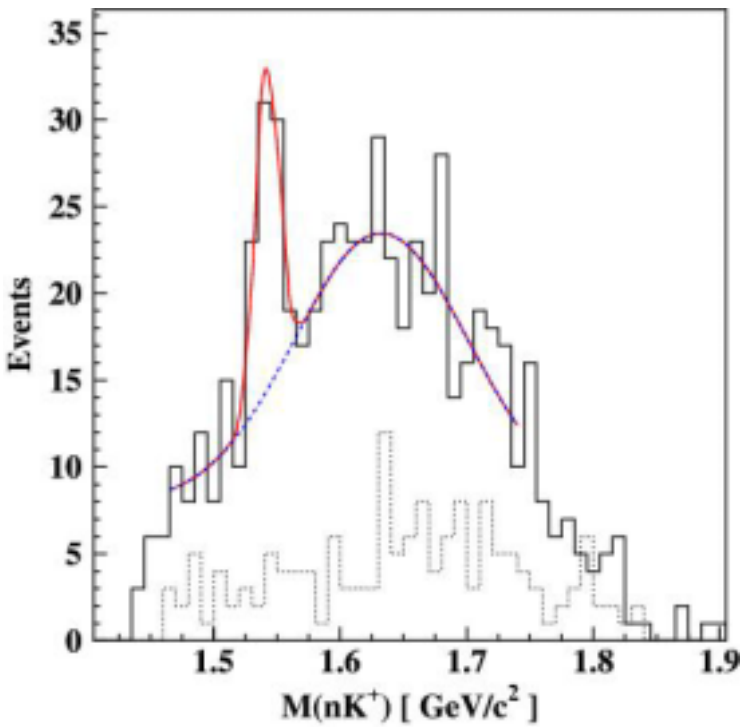
CLAS: γ d → K^+ K^- p n



Claim 5.8 σ observation

3 experiments taken together:

- Observation of a new state
  (although size of effect in each experiment can be debated)

mass consistent: 1540 ± 10 MeV
width smaller than exp. resolution (10…20 MeV)

Interpretation:
Bound system of uudd$\bar{s}$

1. Constituent Quark Model
2. Chiral symmetry breaking:
   - Prediction from Diakonov, Petrov,Polyakov:
   - decuplet of strange 5-quark systems

M_θ =1530 MeV , Γ_θ < 15 MeV hep-ph/9703373

Related to di-baryon, 4-quark states

Conclusion

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Overall: QCD is in excellent shape

α_s: higher orders vital

- Now: uncert. ~ 3 %
- NNLO: 1-2 % possible

Parton distributions:

- pp→ H: uncert. 10 %
- Requires new data from Tevatron/DY/HERA

Much progress in resummat., power corr., diffraction, spin, …

Beauty puzzle:

- Tevatron and HERA slighty high, but much better with new calculations/observables
- Lecture for LEP $\gamma\gamma$?

L3 $\gamma\gamma$

- Huge excess seen, needs to be confirmed

Ready for LHC ?
not quite, but Tevatron RUN II, HERA II, THEORY…