From HERA to LHC

HERA – Tevatron – LHC: The decade of Hadron machines

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Strasbourg, March 12th , 2004

HERA – LHC: QCD

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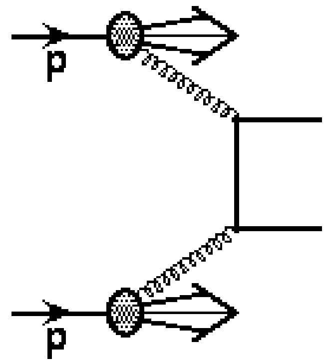
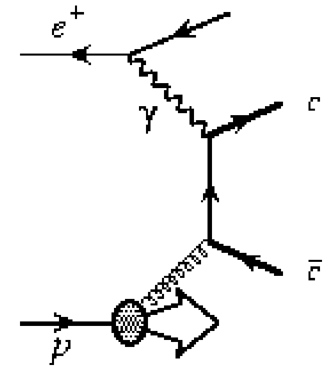
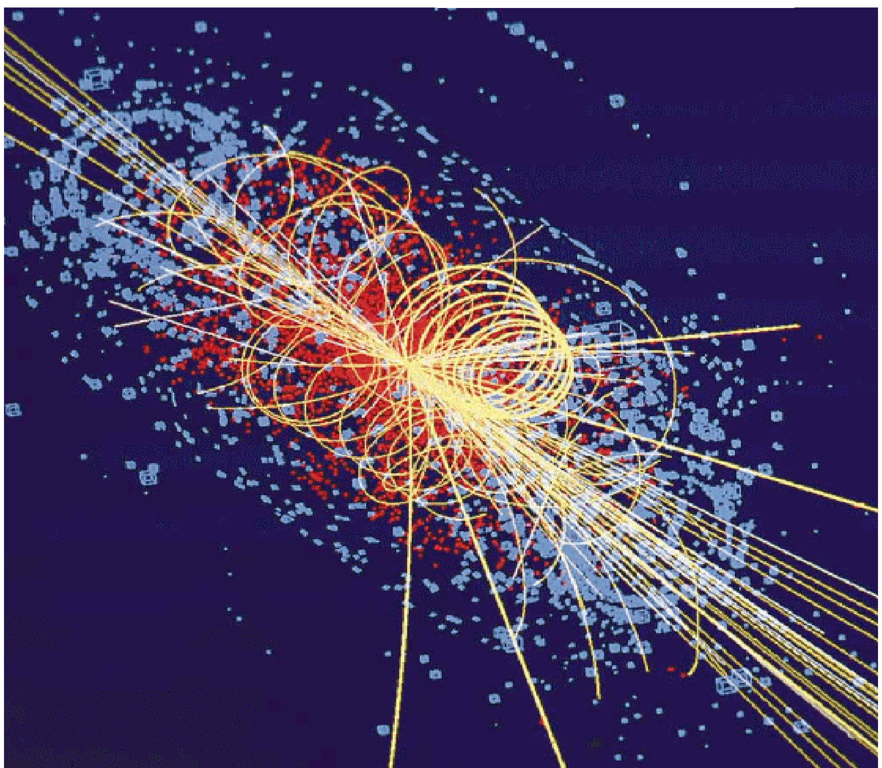
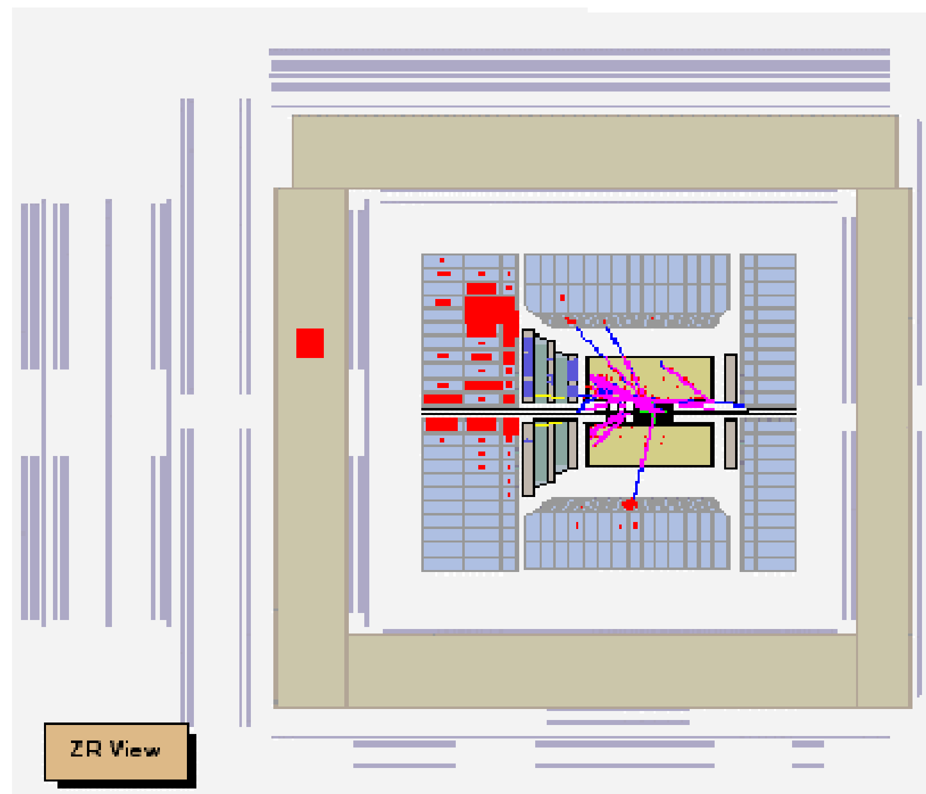
LHC:
Proton-Proton
E_{CMS} = 14 TeV



HERA:
Elektron-Proton
E_{CMS} = 320 GeV

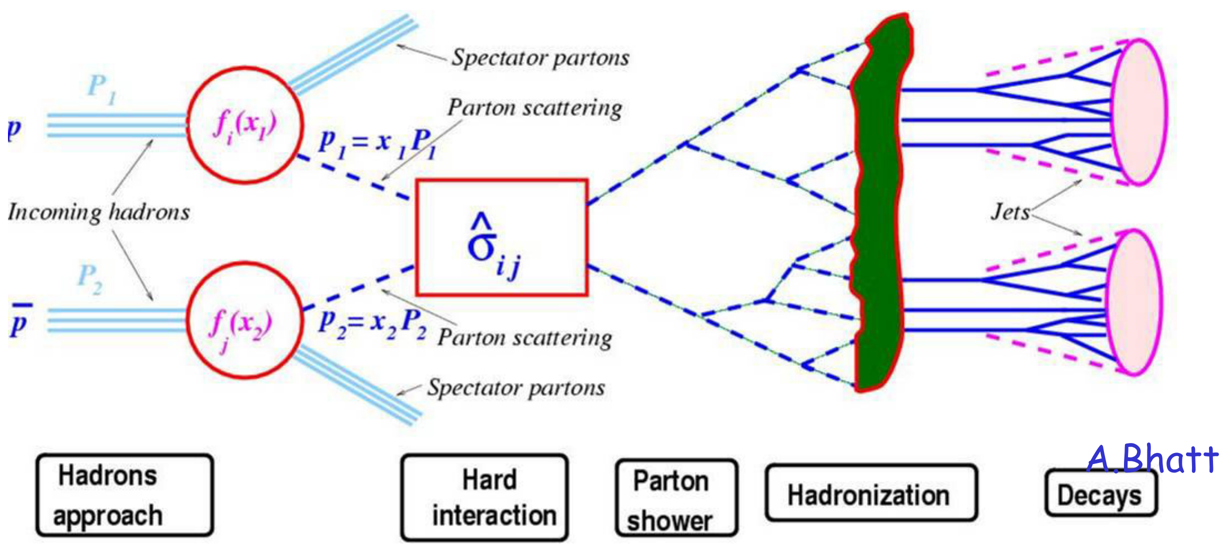






Perturbative approach to QCD

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: $\alpha_s(Q^2)$, $f(x,Q^2)$

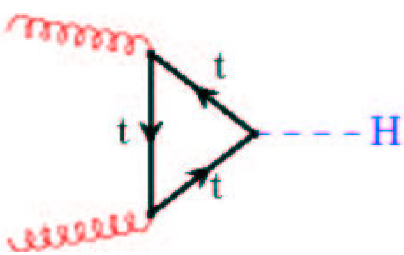
Precision achievable / needed ?

x = P(q,g) / P(p)
momentum fraction
x-dependence of f(x,Q2) not predicted

Benchmarks for Precision QCD

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

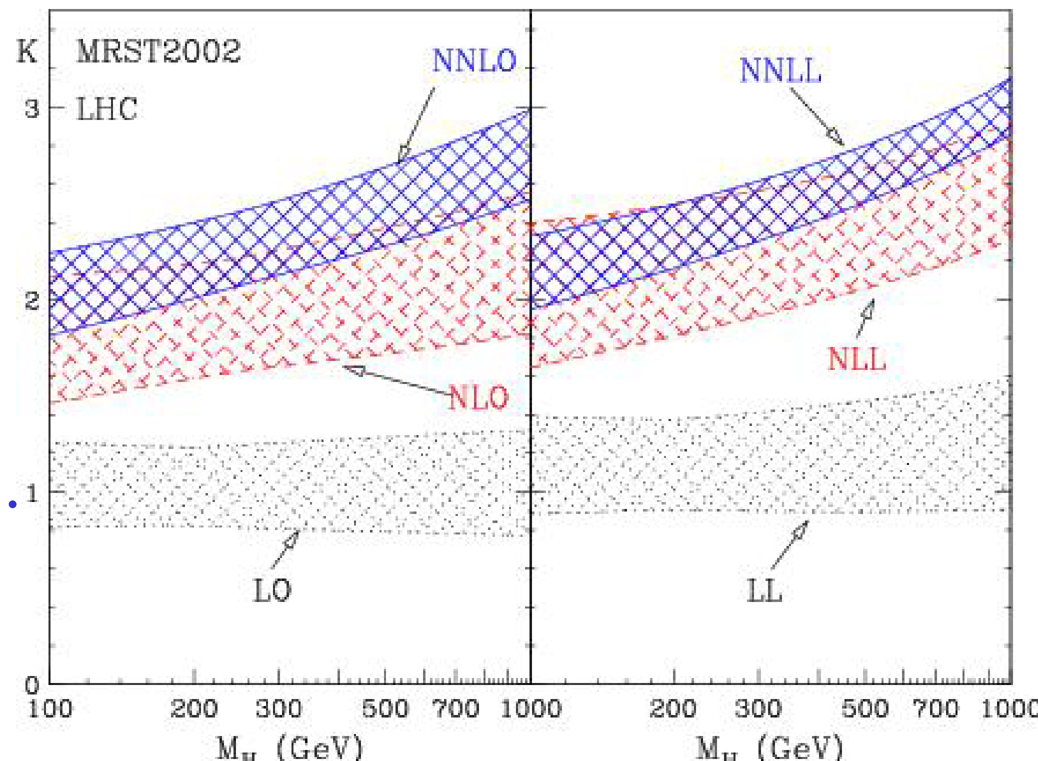
Higgs production at LHC



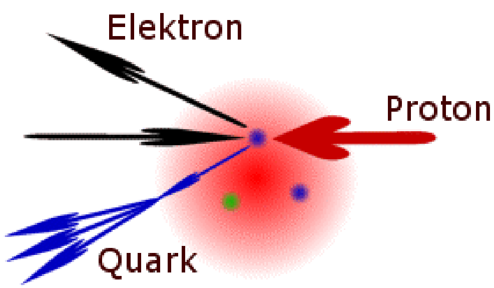
Discoveries depend on
- input parton distributions
- Extrapolation by QCD evol.
- higher order calculations
- non-pert. effects

for signal and background

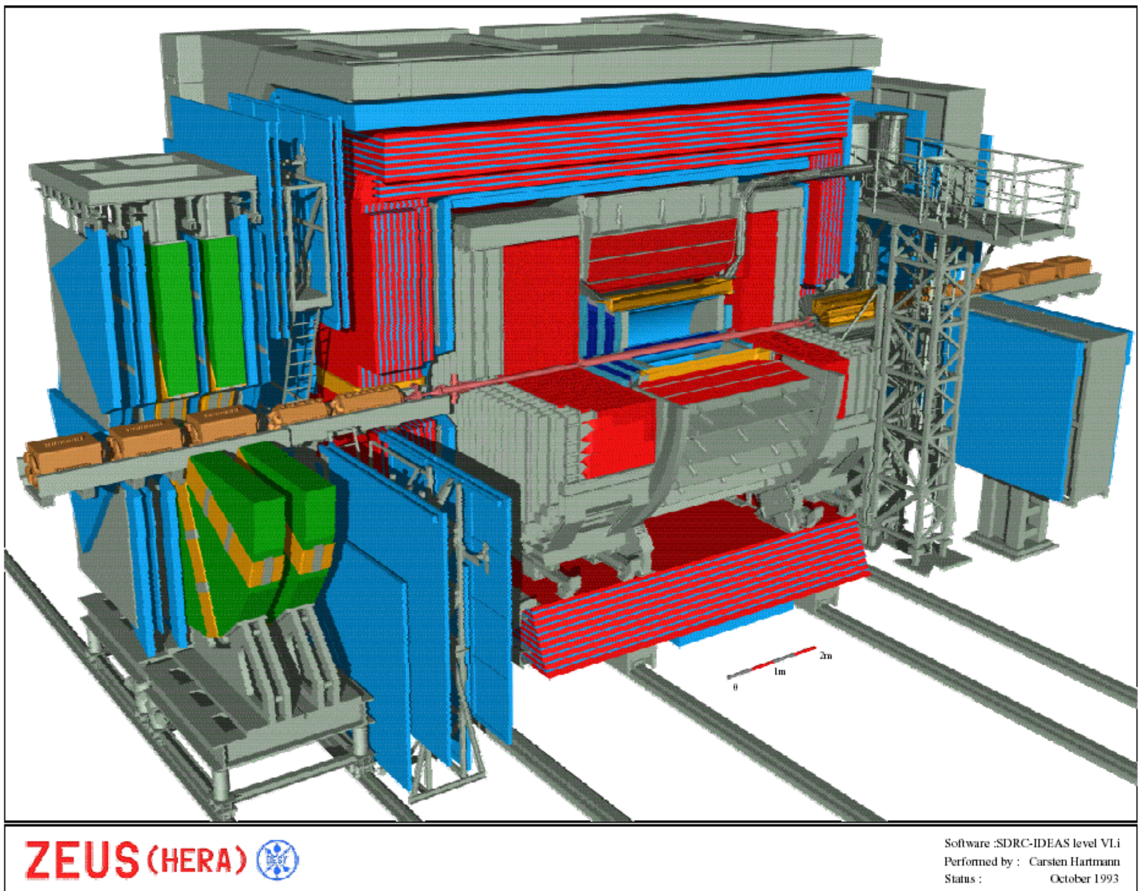
Comparison NLO / NNLO



HERA Experiments: H1 & ZEUS



Ee = 27.5 GeV
Ep = 920 GeV



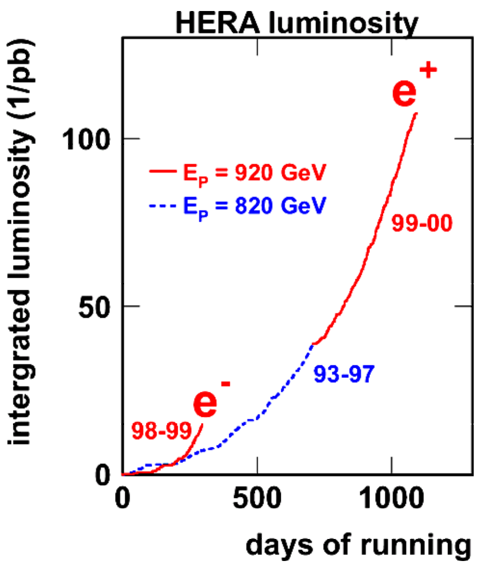
H1 & ZEUS:

- Multi-purpose detectors
- 2-3 layers silicon tracker
- Drift chambers (~60 hits)
- Forward: straw tubes
- Hermetic calorimeters
  (Uran-Sz. or Lar)
  calibration ~ 1.5 %
- B-field: 1.5 Tesla
- Muon drift chambers
- 100 Hz data taking
- Trigger: 6 GeV for el.

HERA 1   HERA 2

HERA I: 93-2000

100pb-1 e^+
15pb-1 e^-

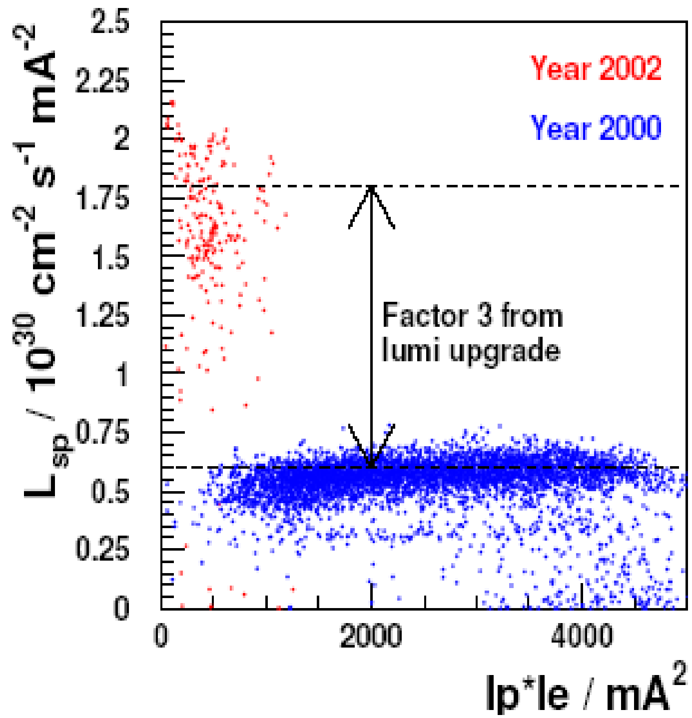


10^7 multi-hadronic events

HERA II goals

500pb-1 e+
500pb-1 e-

e polarisation



Strong focussing by Magnets inside det.

Detector upgrades
- Silicon tracking
- Forward tracking
- trigger

Background reduction

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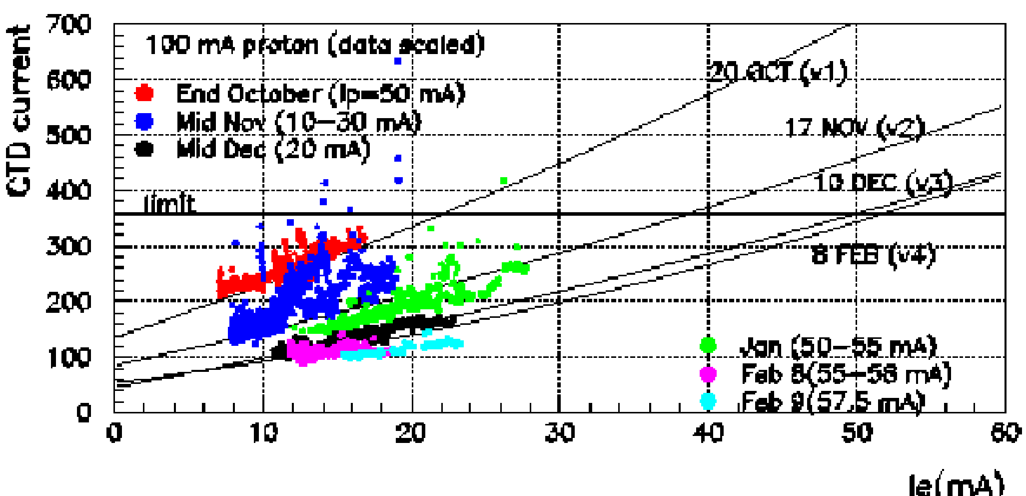
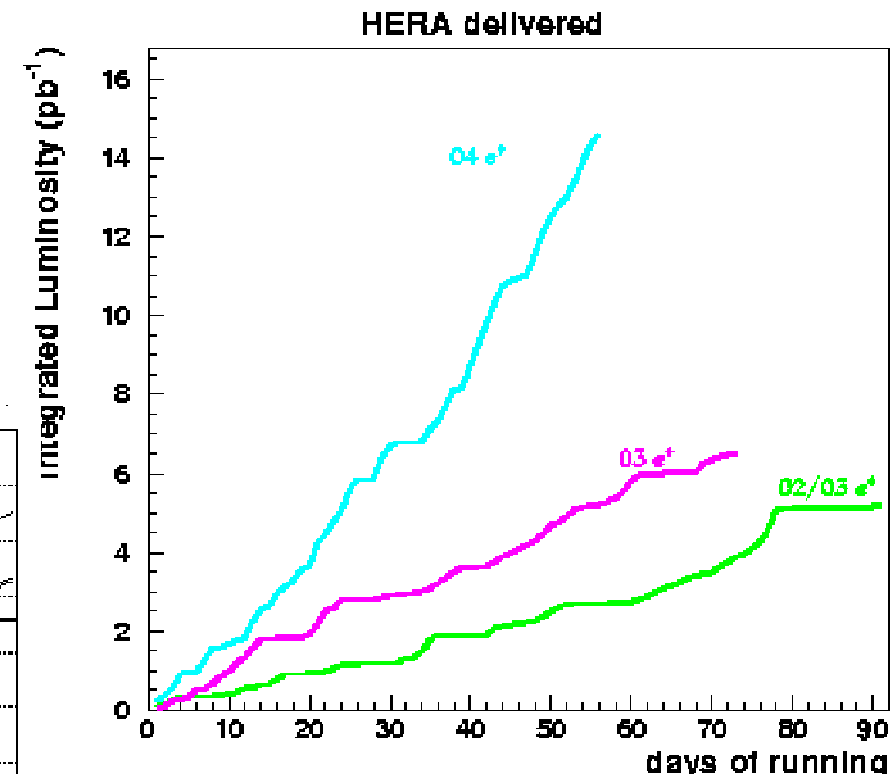
Focussing magnets ~1.5 m from vertex
→ Synchrotron radiation from e-beam
→ Direct synchr. largely shielded
→ Heating of beam pipe
→ bad dynamic vacuum
→ p-beam scatters on beam gas
→ high bkgr.
→ better shielding & vacuum system



Background problems solved:
No limit on beam currents from experiments

Accumulated Luminosity



Expect: 135 pb^{-1} in 2004
~ 1 fb^{-1} until 2007

Kinematics at HERA and LHC

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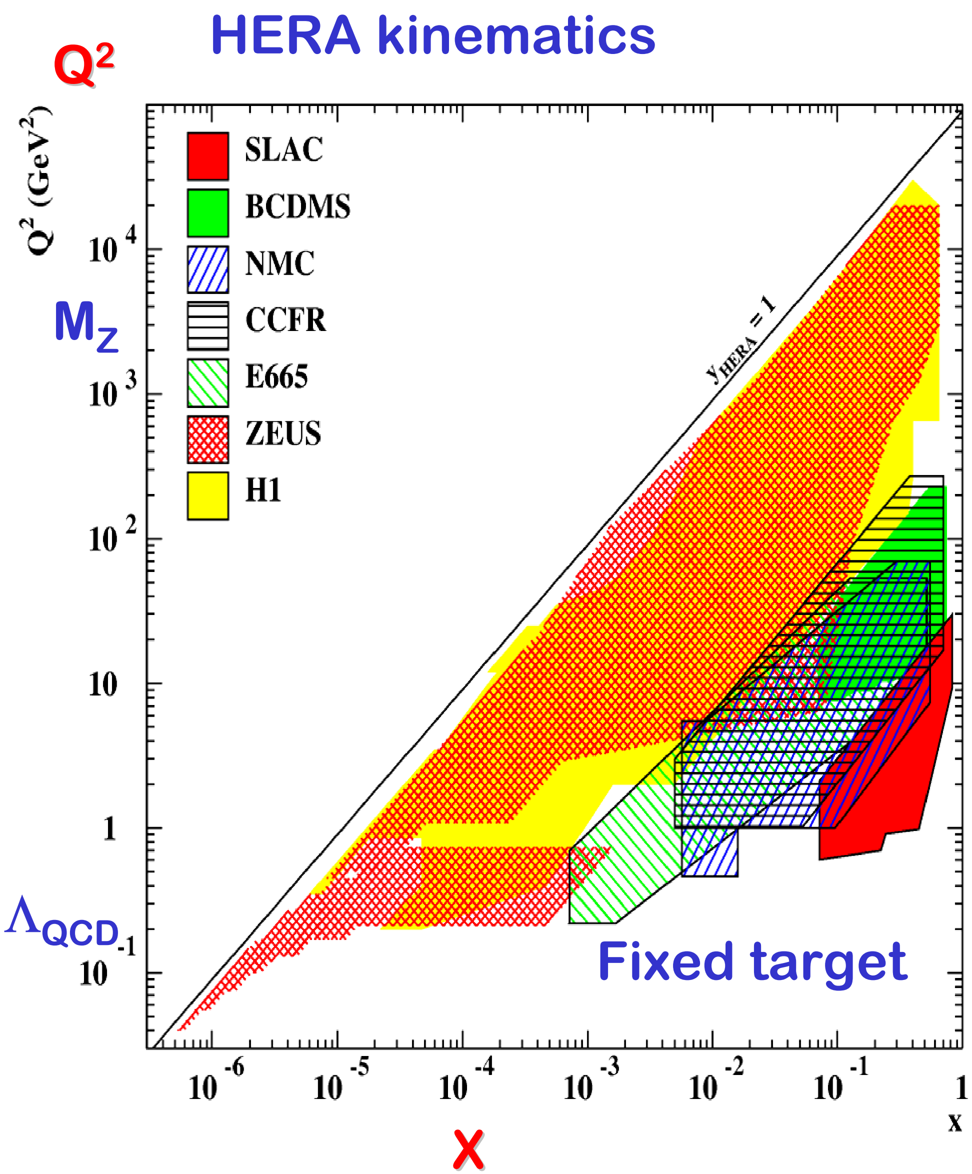
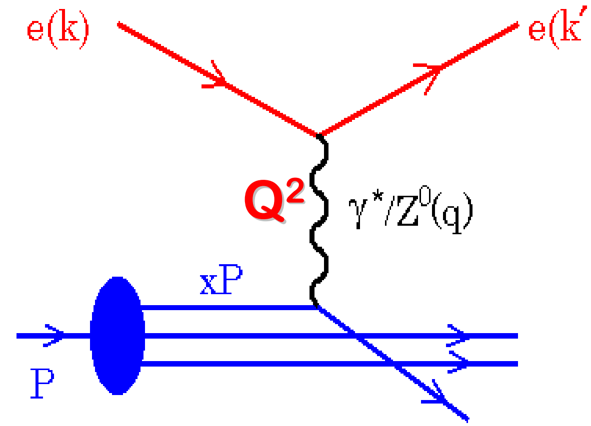
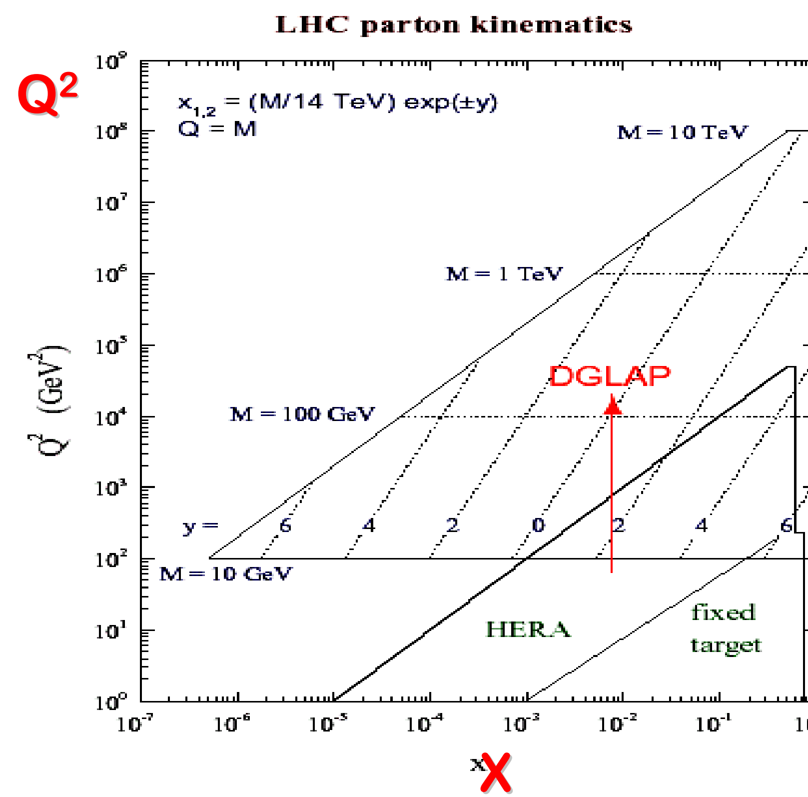




Neutral + Charged currents



Quark densities

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Deep Inelastic Scattering

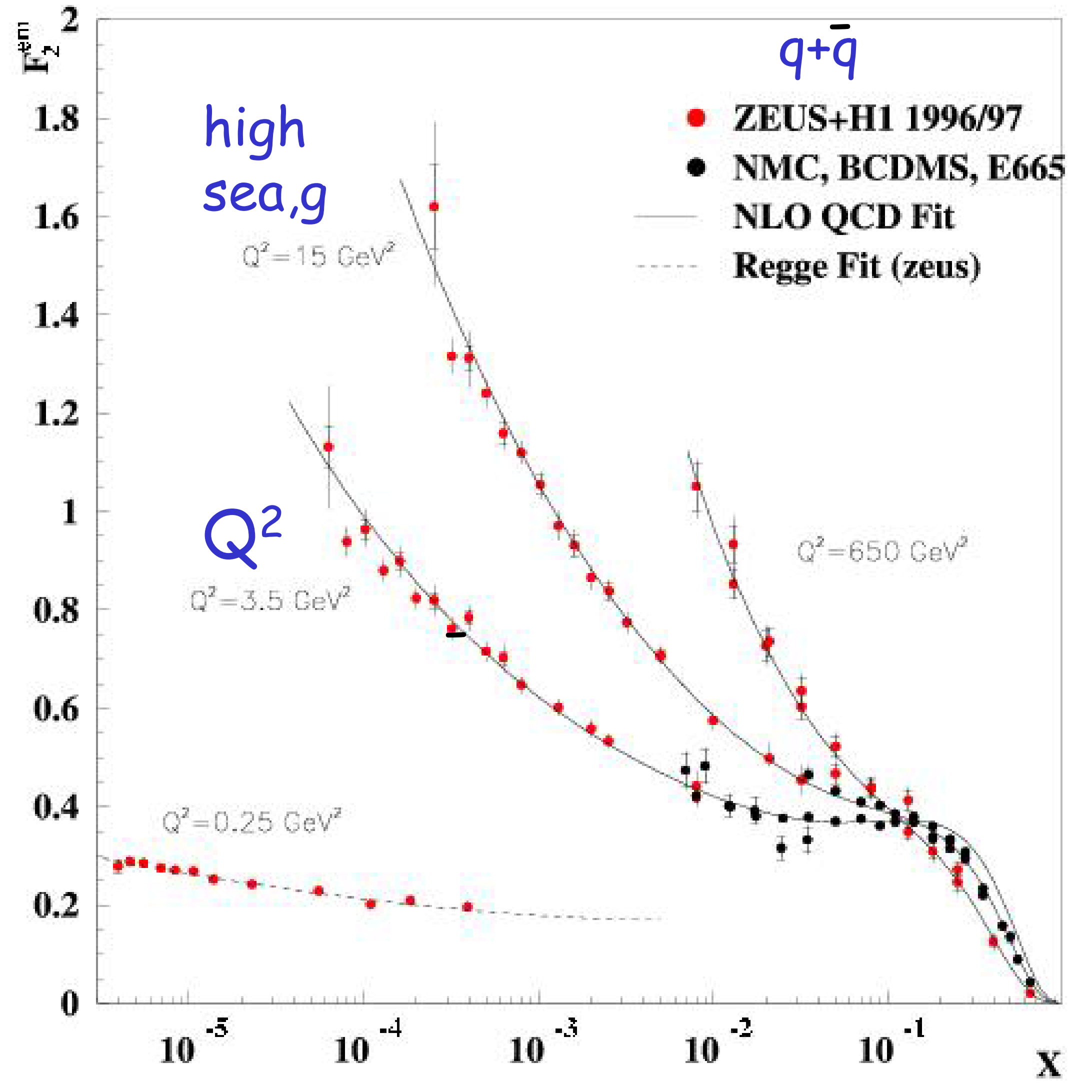
Neutral Current:

low Q2: $\boxed{q+\bar{q}}$

high Q2: $e^-p - e^+p \sim \boxed{q-\bar{q}}$

Charged Current:

e+p: $\boxed{\bar{u}+\bar{c} + (1-y^2)(d+s)}$



high sea quark density implies high gluon density

Connection to Quark-Gluon Plasma: Colour Glass Condensate

High Q^2

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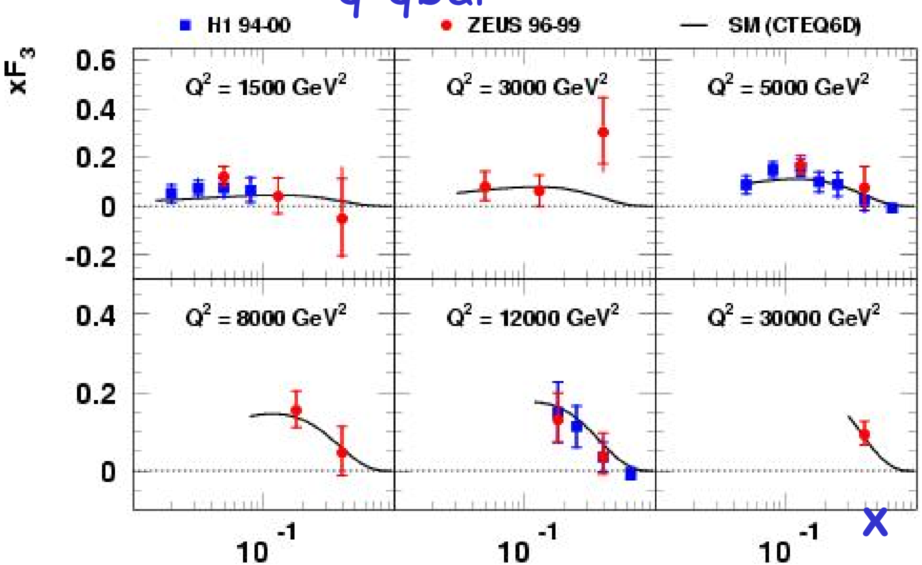
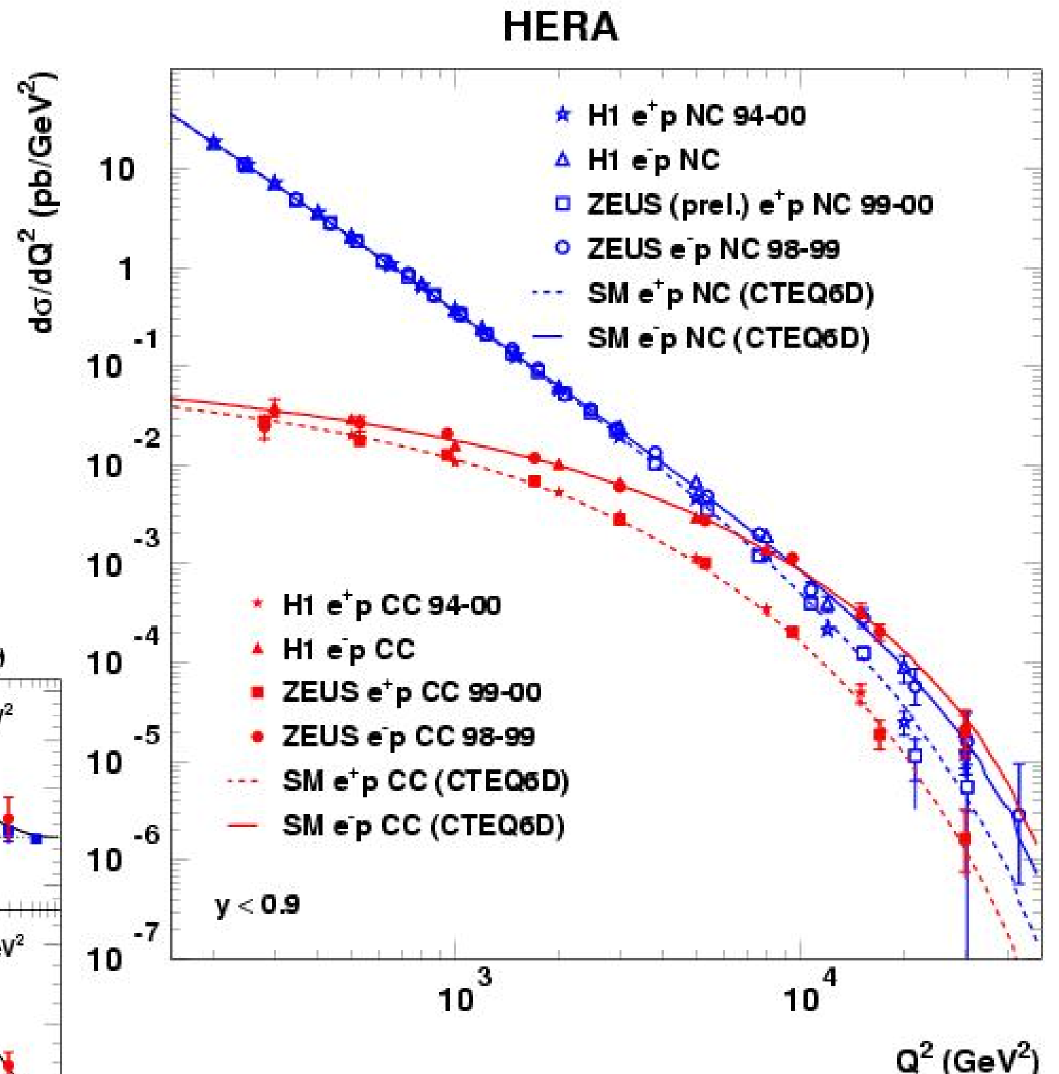
$\gamma - Z$ interference
W exchange
e^+ e^- NC / CC

NC low Q^2: $1/Q^4$ γ propagator
High Q^2: $M(Z,W) < Q$
propagators similar to γ
E-weak unification

q-qbar

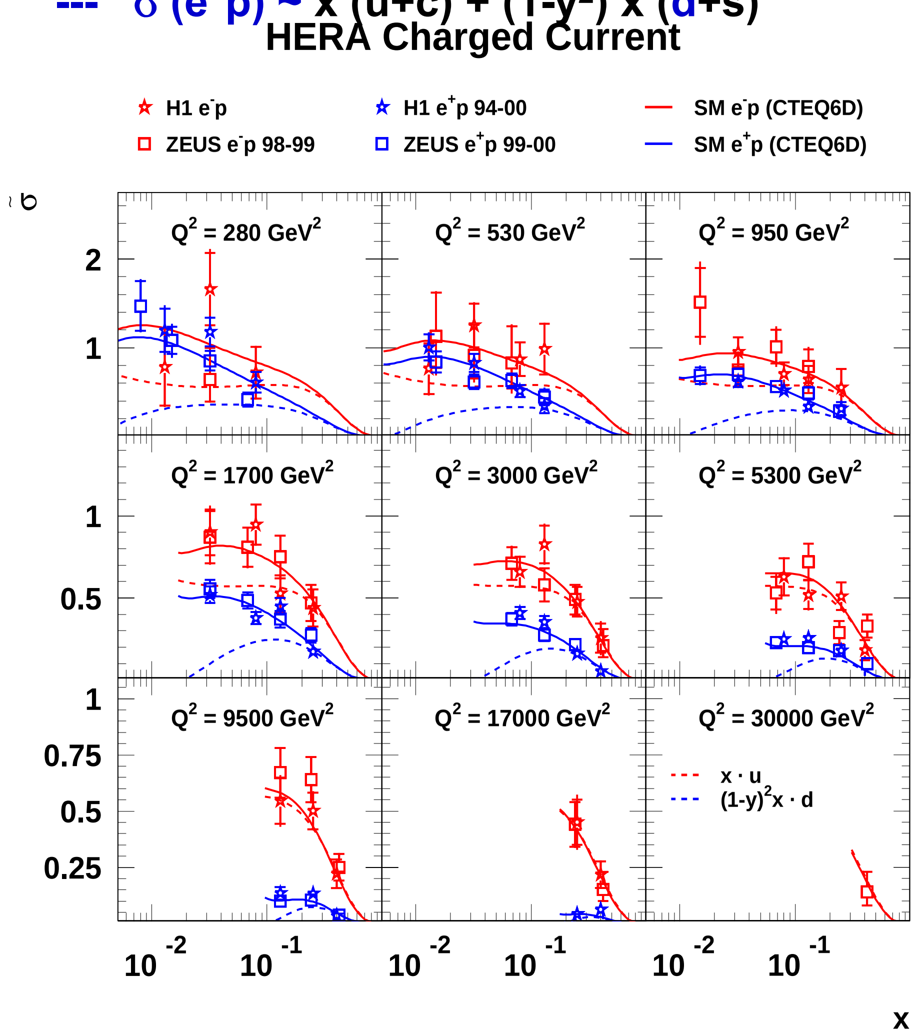




Charged Currents

--- $\sigma(e^-p) \sim x\,(u+c) + (1-y^2)\,x\,(\bar{d}+\bar{s})$

--- $\sigma(e^+p) \sim x\,(\bar{u}+\bar{c}) + (1-y^2)\,x\,(d+s)$

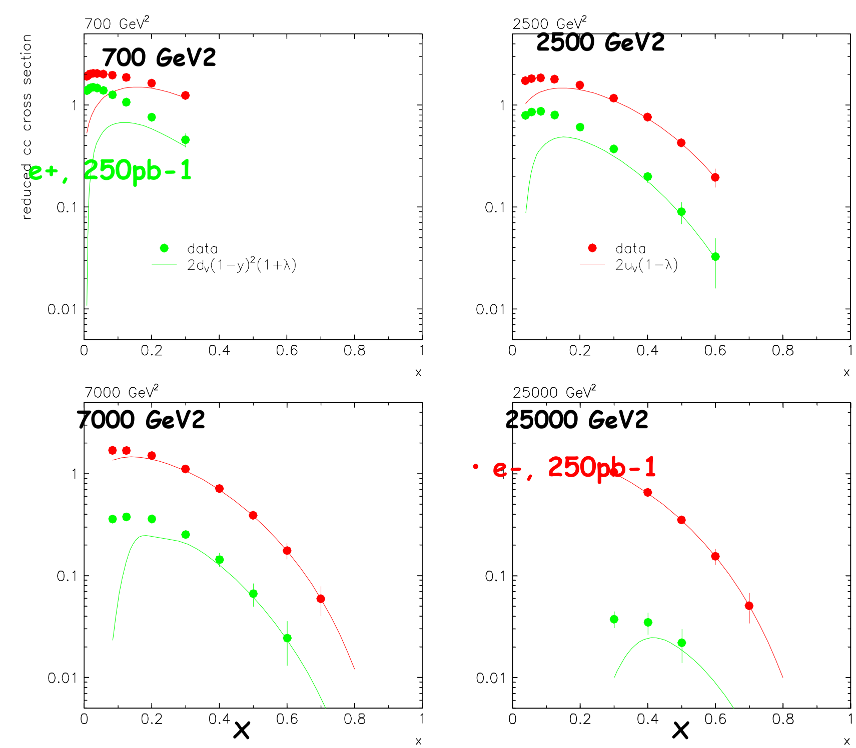


Charged currents HERA II

Unfolding of parton distributions using CC and NC cross sections

difficult to reach very large x>0.7

reduced cc cross section



Gluon density

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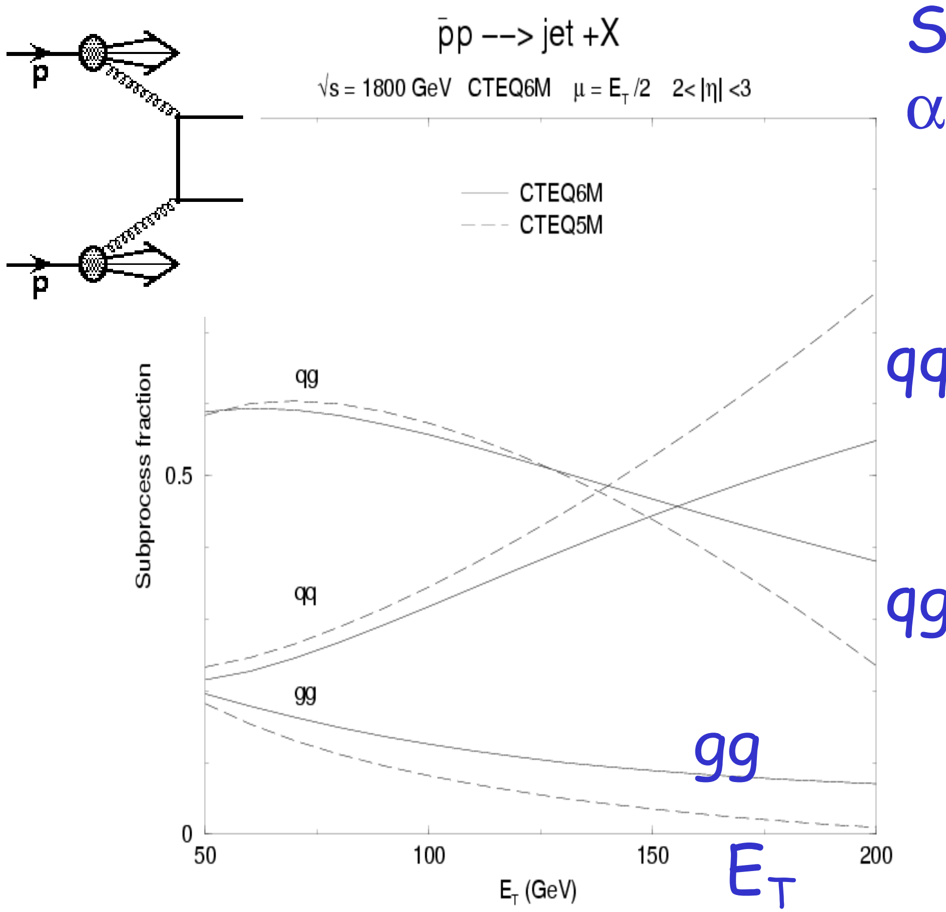
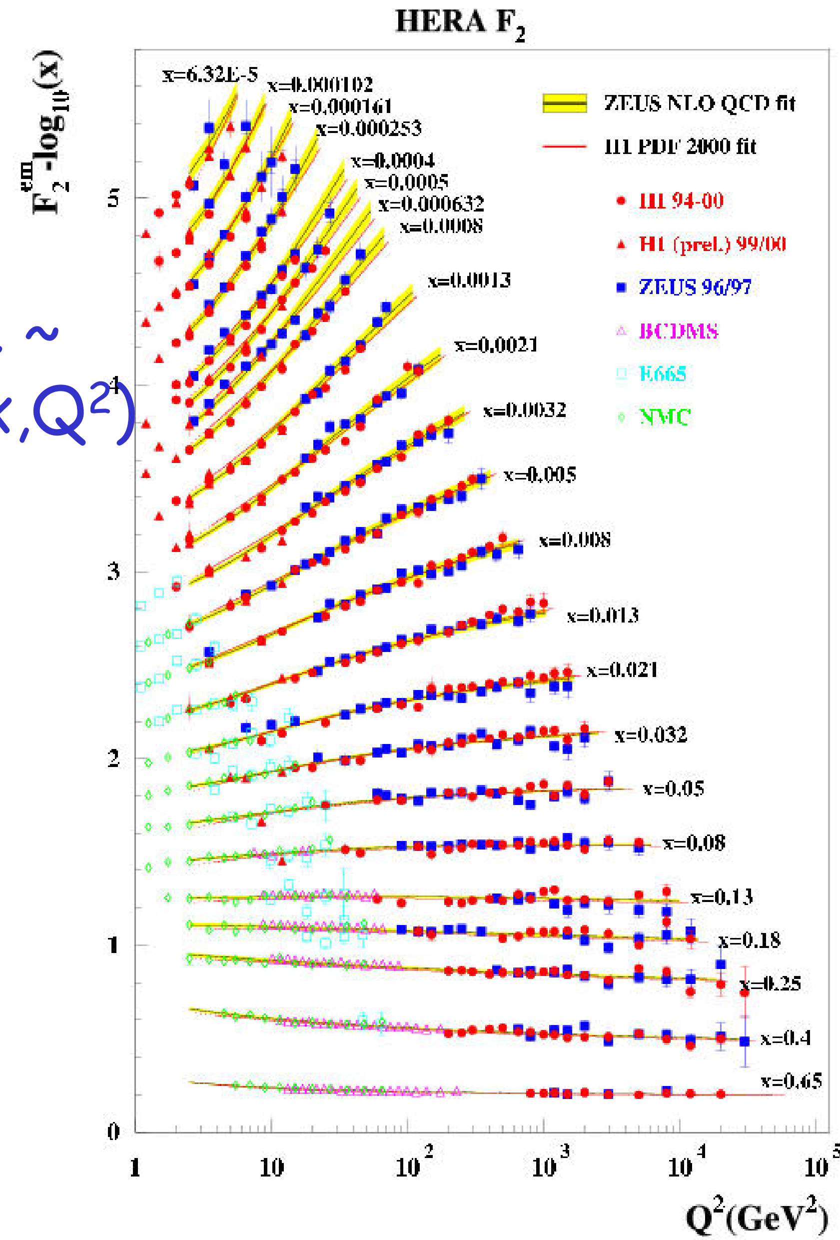
HERA: Scaling violations, F_L, charm
Tevatron: Jets



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



Parton Density fits

QCD fits to parton densities

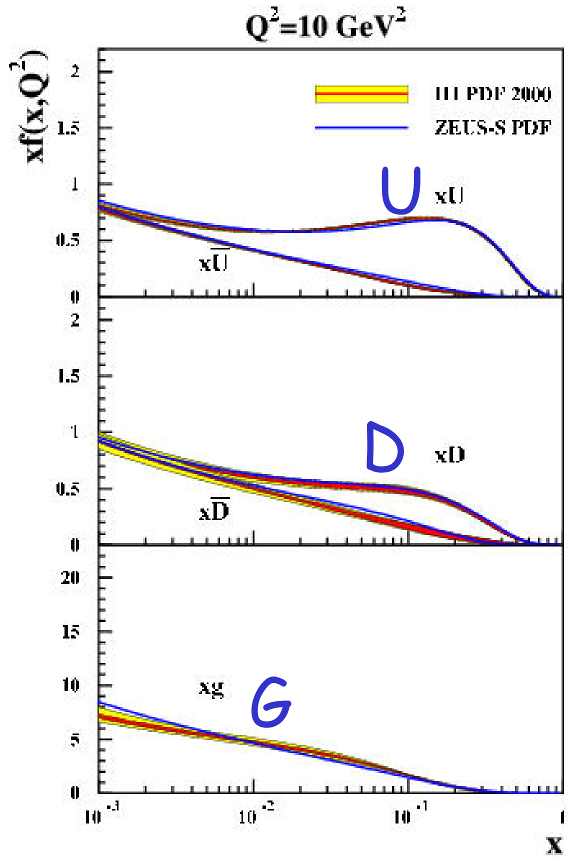
•Fit only inclusive DIS data: theoretically clean (H1,ZEUS,Alekhin)

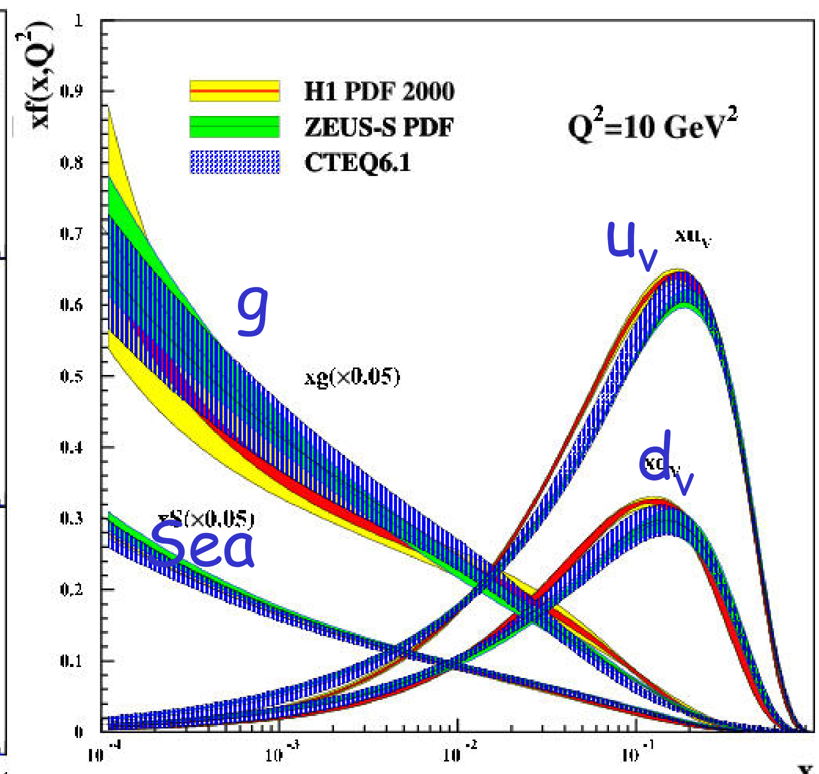
•Global fits: inclusive DIS, DY, Tevatron: jets, W/Z

more constraints (CTEQ,MRST,...)

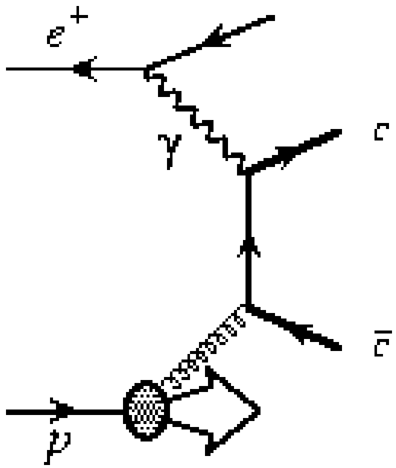
Zeus/H1:
fit to only
HERA data !

similar precision
as global fits

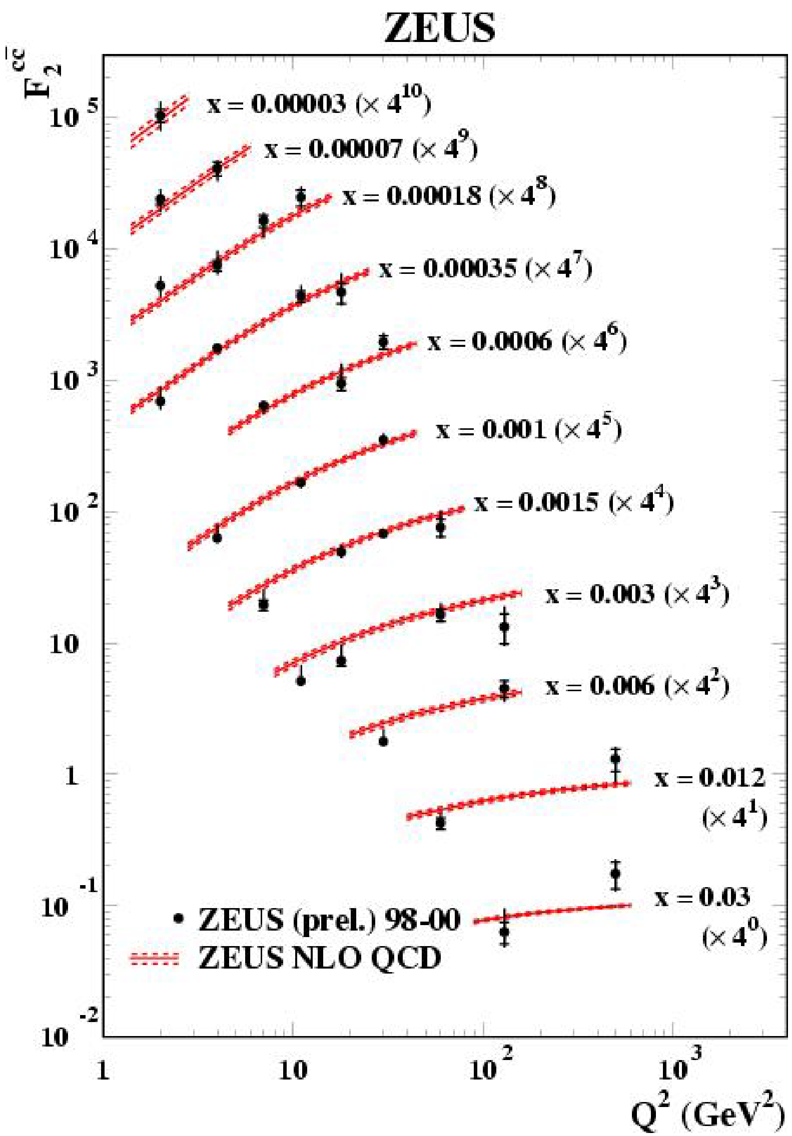


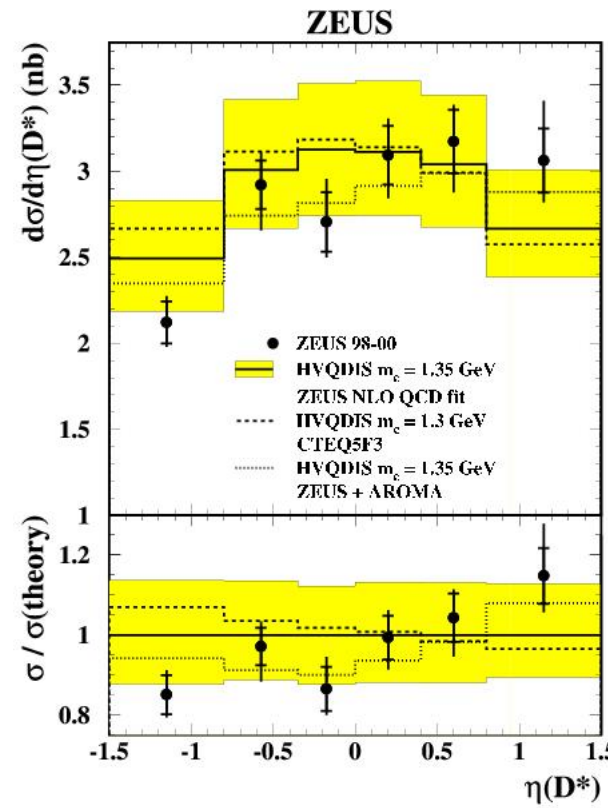


Gluon Density: Charm at HERA



depends in
LO on gluon





agrees with ZEUS
NLO QCD fit

Gluon Density: F_L

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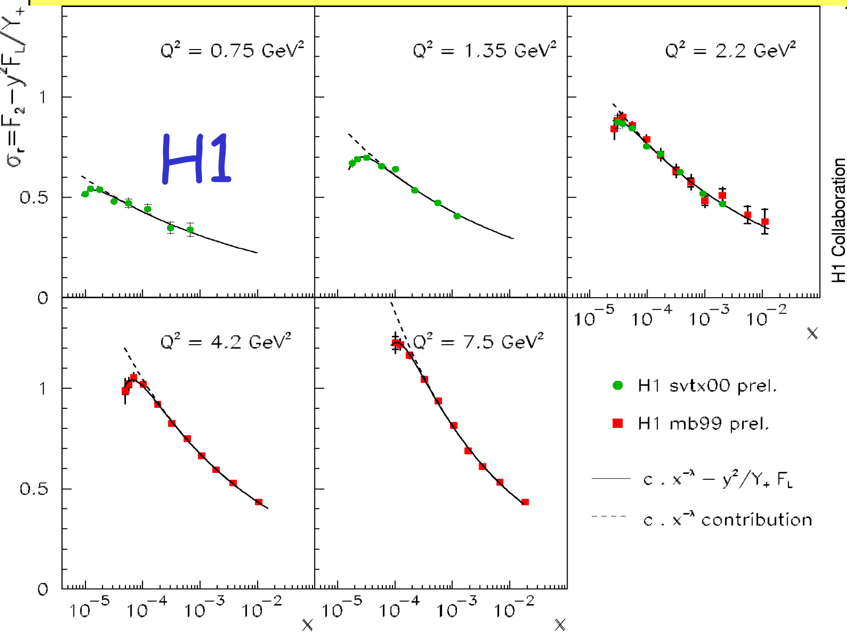
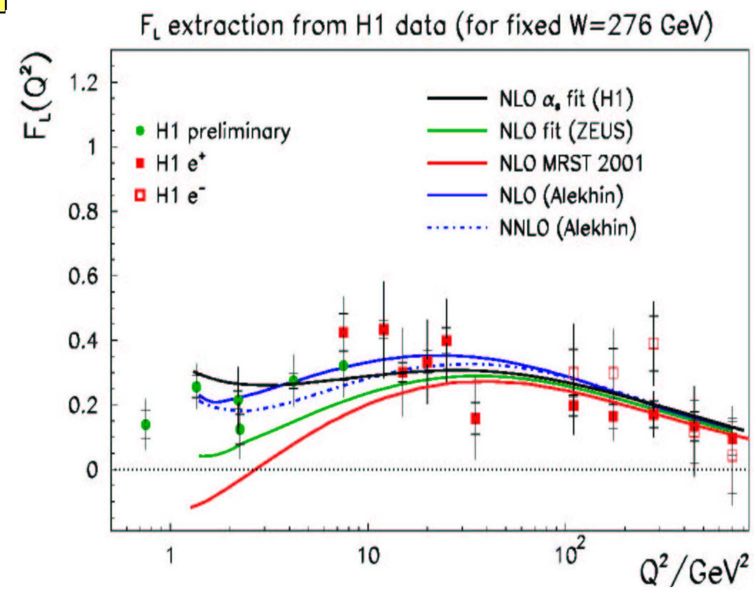
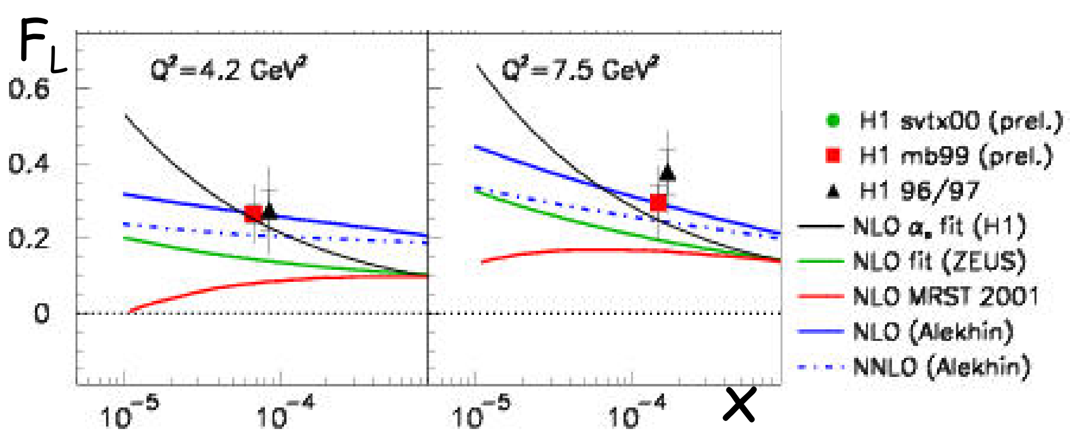
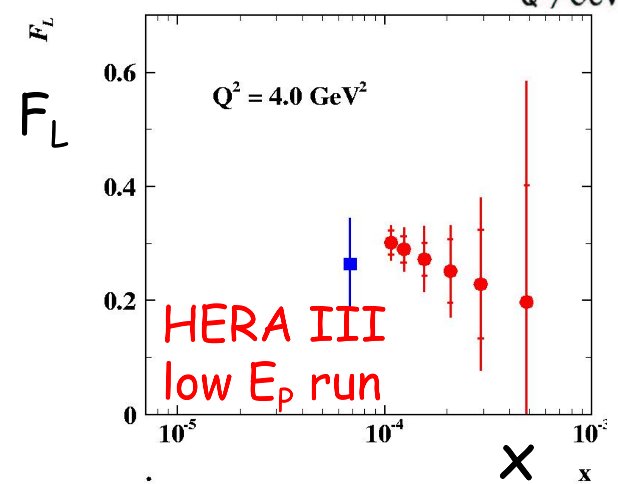
NLO: contribution from gluons to F_L



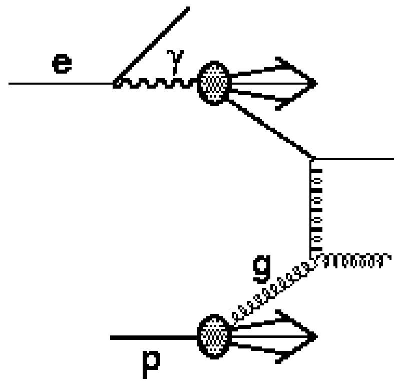


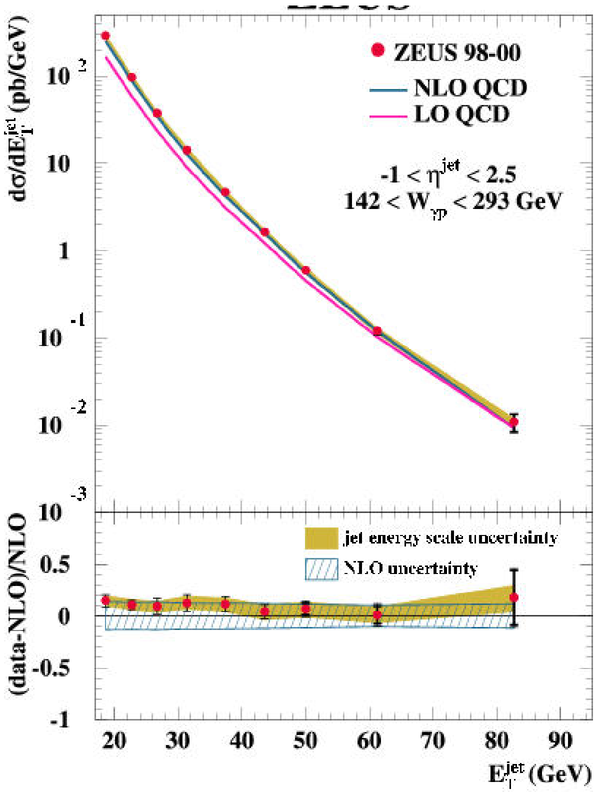


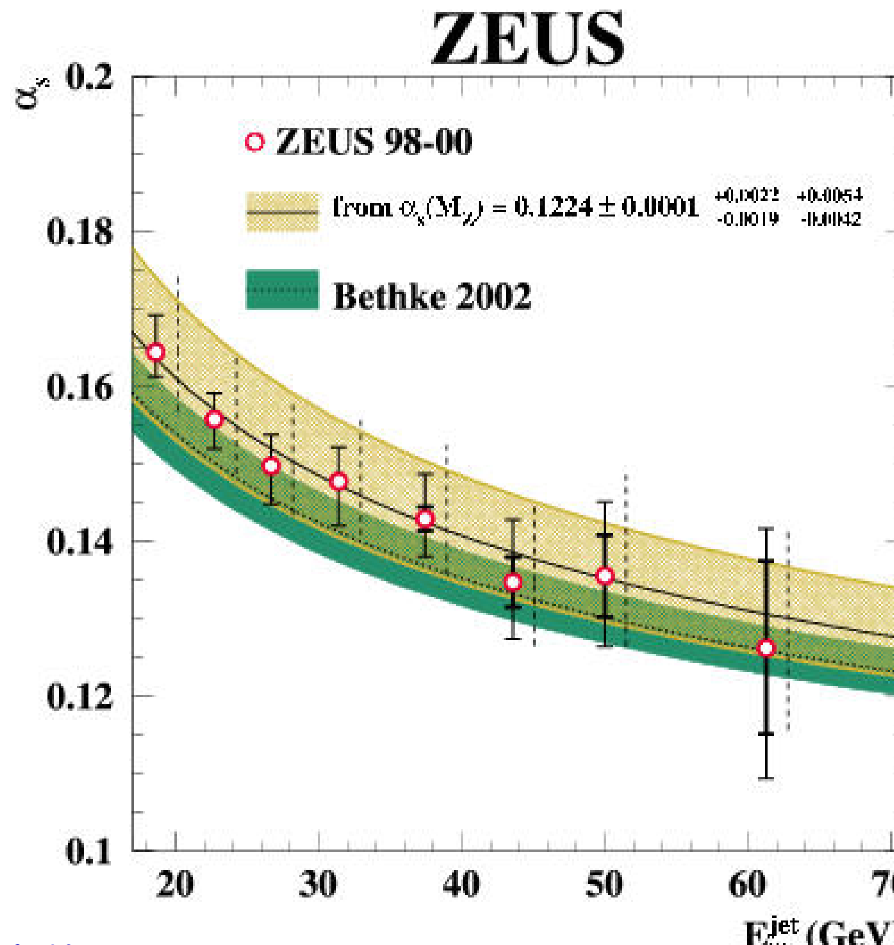


very sensitive: disfavors MRST

Jets in γ-p: HERA





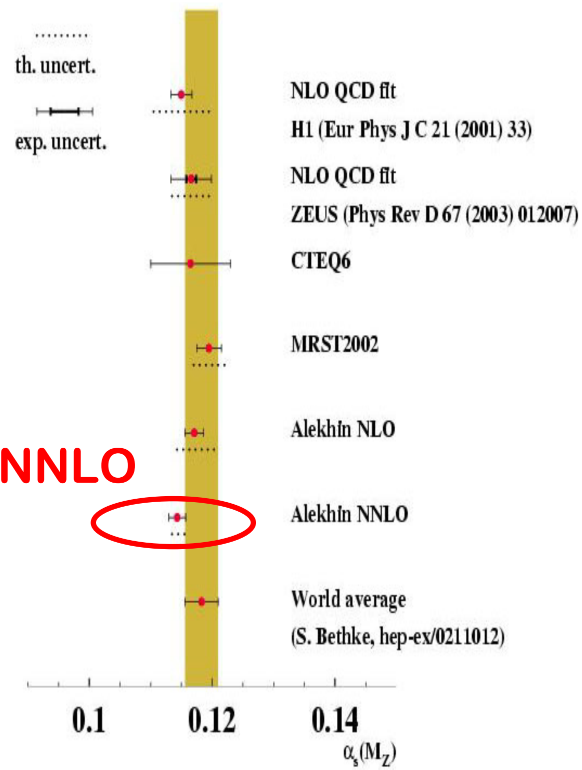


γ-PDF & NLO describes data

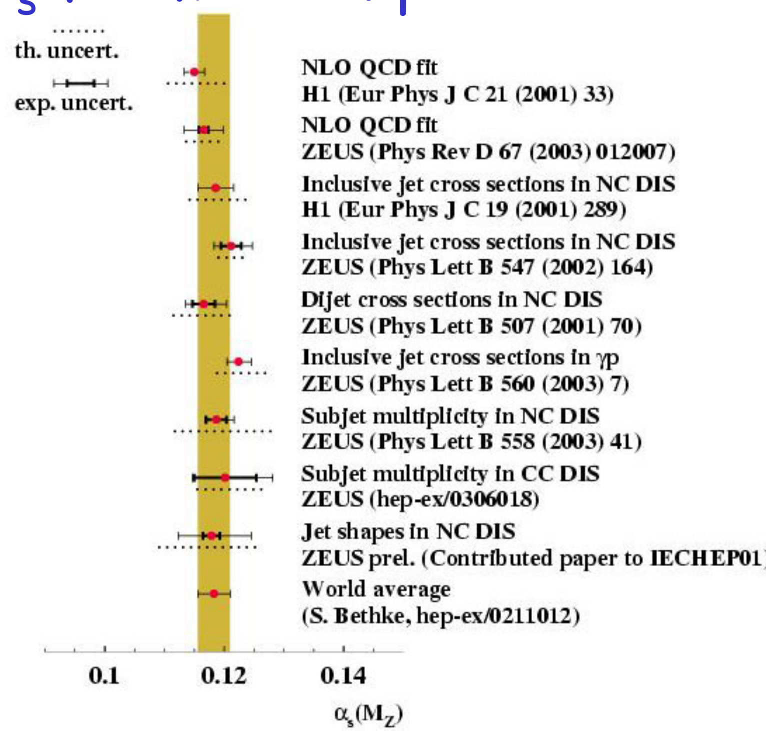
full HERA I luminosity
Future: high x gluon
~ c.f.Tevatron

α_s global

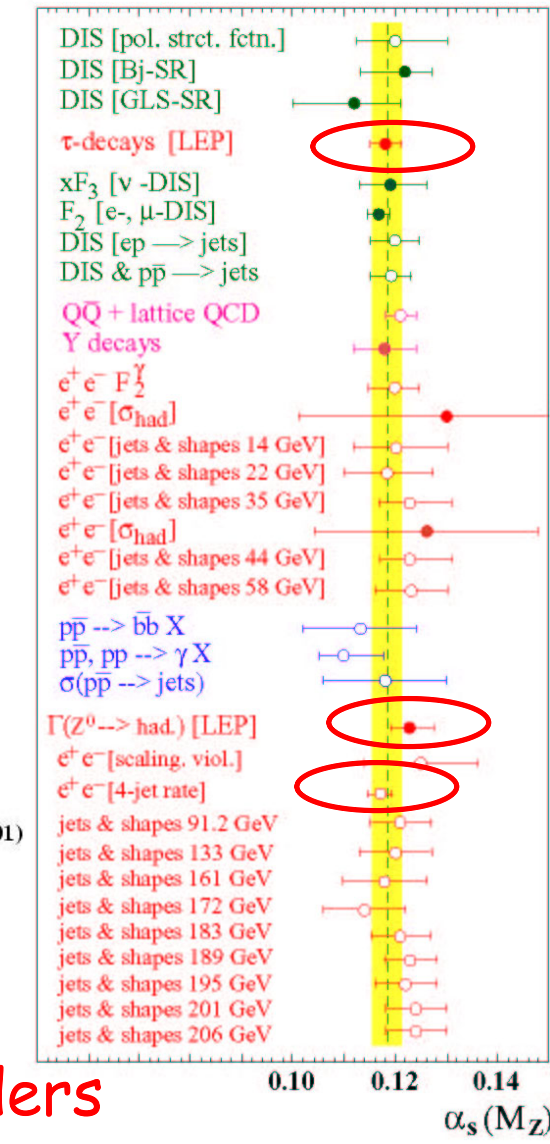
α_s from QCD fits



α_s from hadr. processses



Bethke 2002



Very impressive success of QCD

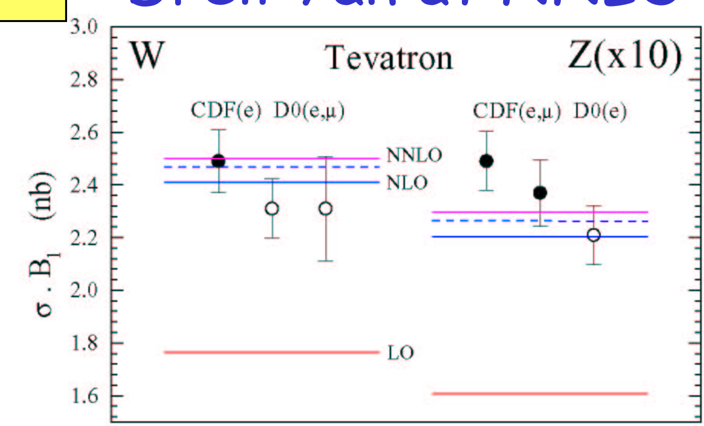
Limited everywhere by missing higher orders

Higher Order Calculations

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

Drell Yan at NNLO



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

Both need strong support from the community !

Higgs Production at LHC

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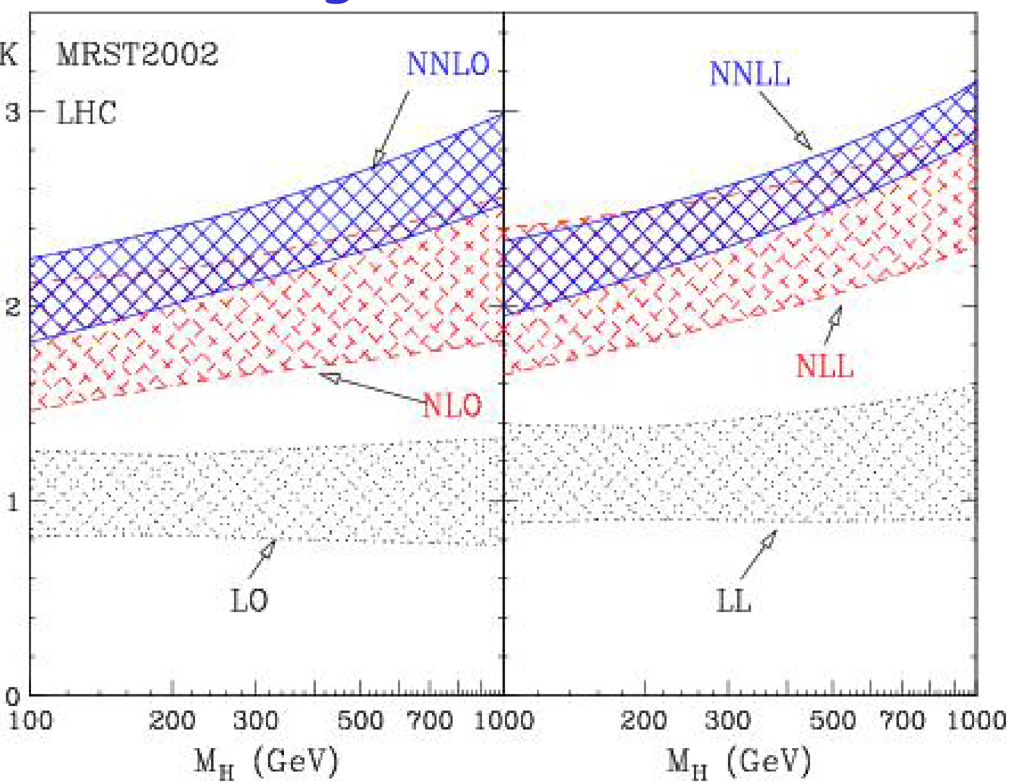
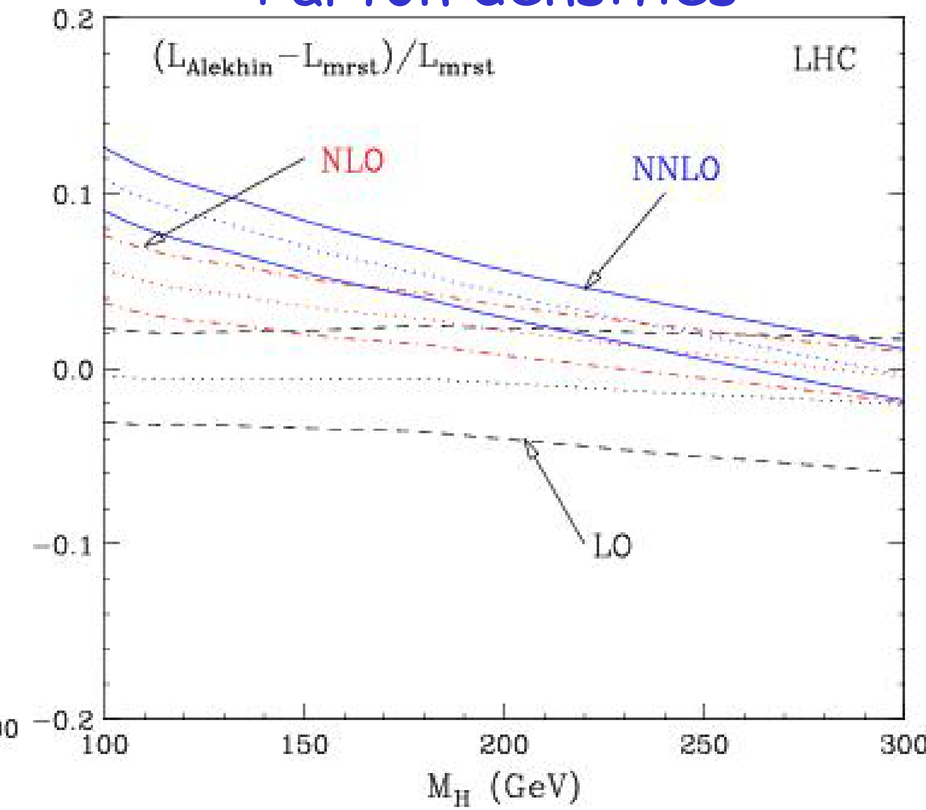
Benchmark test for status of QCD calculations

Higher orders



uncertainty ~ 10 %

Parton densities



uncertainty ~ 10 %

Beauty & Charm Production

Beauty: Problem for QCD ?

Tevatron: data/theory ~3 ... now much less

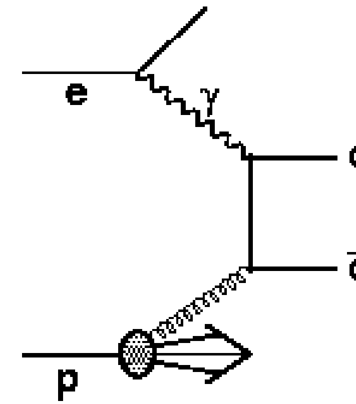
HERA: data/theory ~3 .... now ...

LEP-$\gamma\gamma$: data/theory ~ 3 .... still high

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 ~ P_{Tb} small,
  Experimentally difficult: S/B ~ 1000
- B as part of gamma structure ?

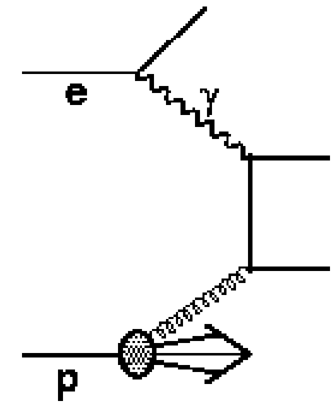
Beauty at HERA

Exp difficult: low PT jets, S/B ~ 1000

Comparison data/theorie

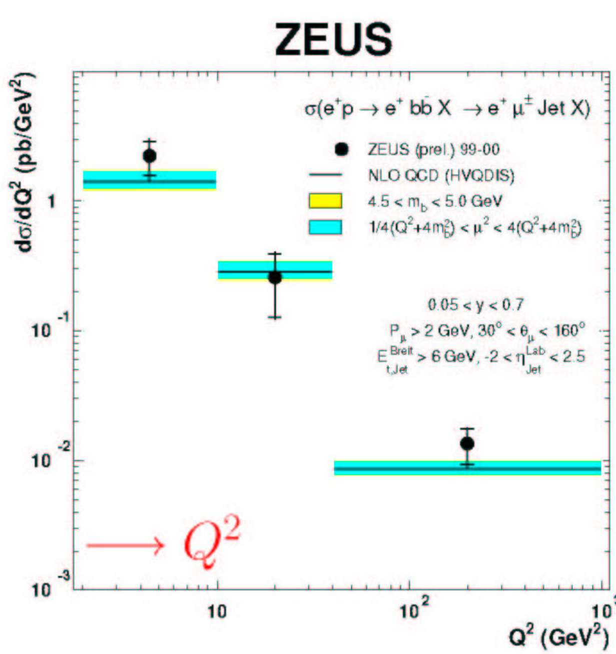
Former: extrapolation of data to parton level and full phase space with LO+PS monte carlo

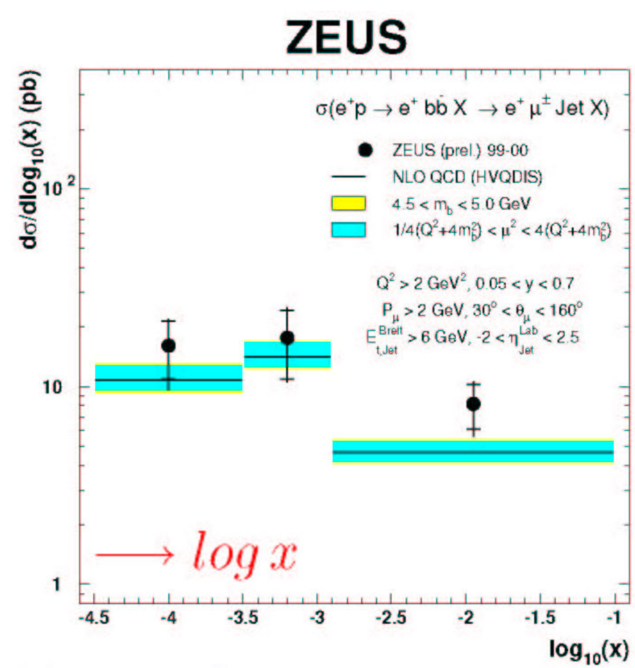
Now: data as is, apply hadronisation corr. to NLO in visible phase space



Deep inelastic

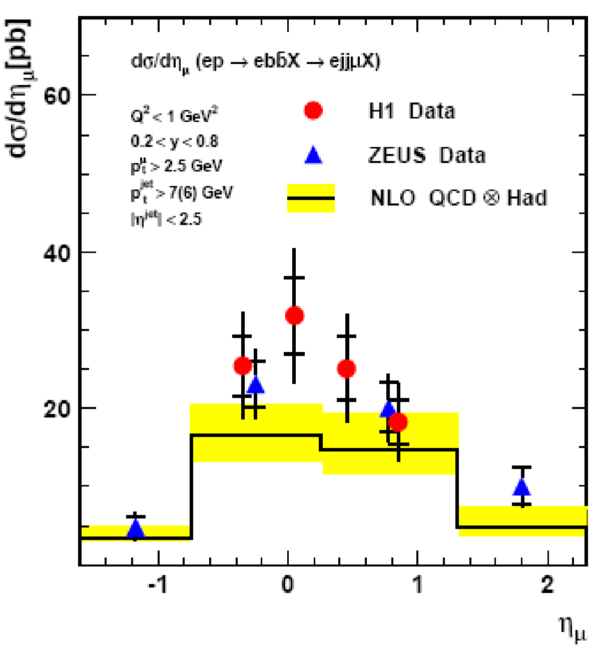
Now agreement with NLO

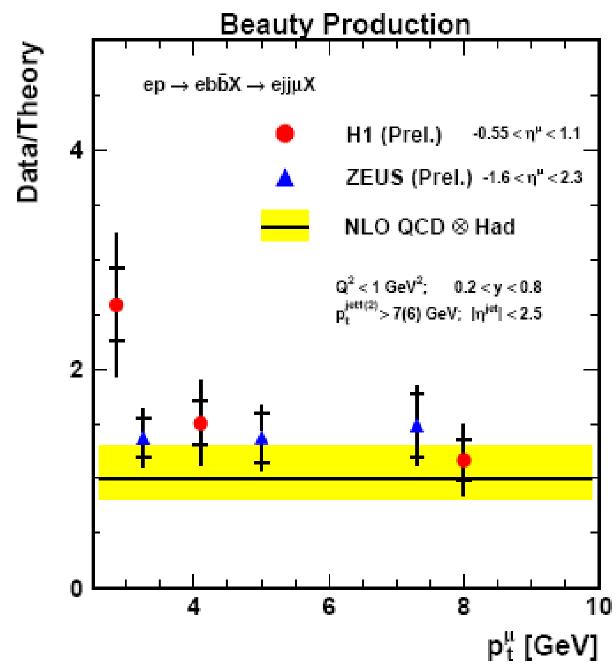


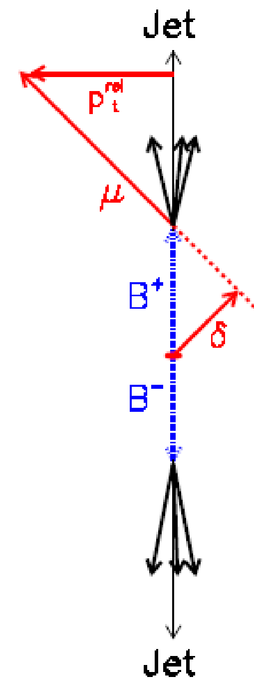


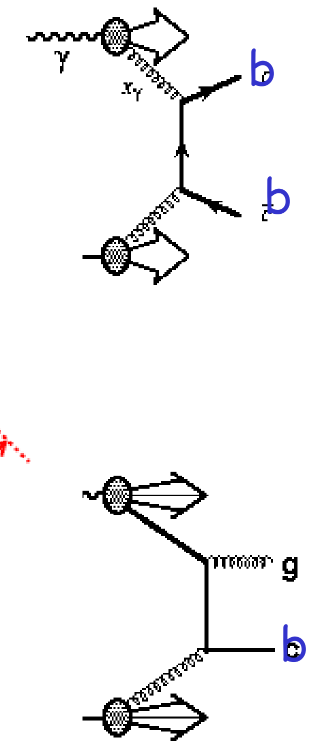
Beauty at HERA

Photoproduction









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

Event Shapes at HERA

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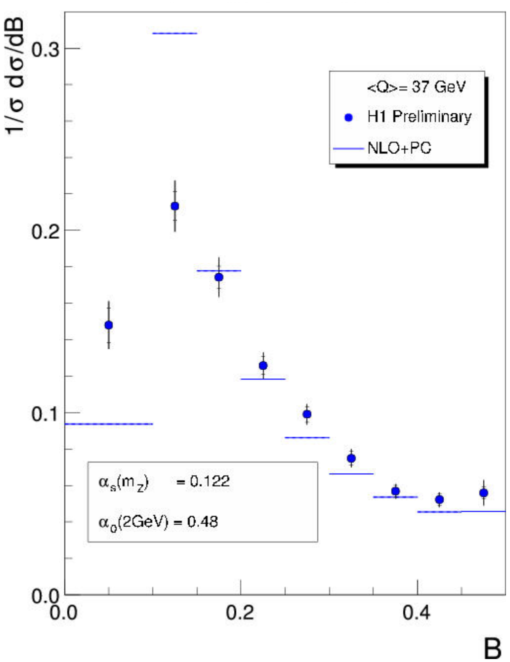
Dokshitzer-Webber ansatz:
α_0 = effective α_s below μ_I
approx. for hadronisation

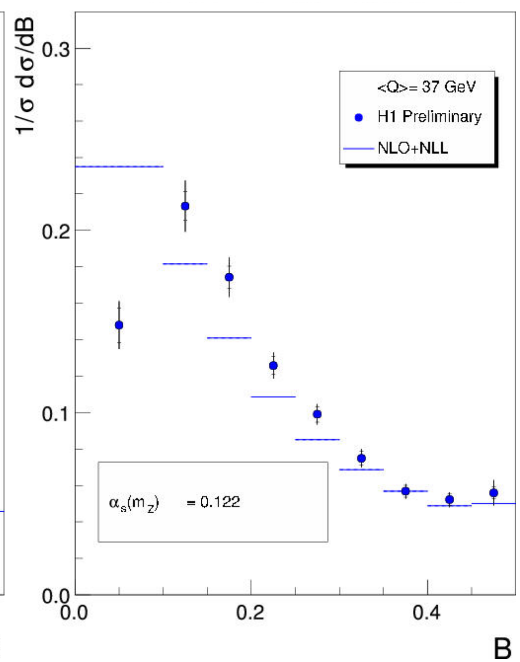
$$
\begin{aligned}
< y > &= < y_{\text{pert}} > + < y_{\text{power}} > \\
y_{\text{power}} &= c_y \cdot P(\alpha_0)/Q \\
D_y(y) &= D_{\text{pert}}\,(y - c_y \cdot P(\alpha_0))
\end{aligned}
$$

New: resummed calculations
fits to both means and shapes (H1)

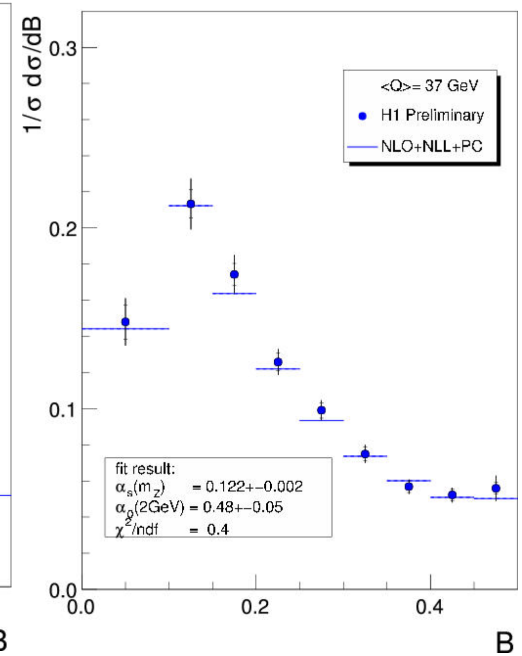
NLO + PC



NLO + NLL



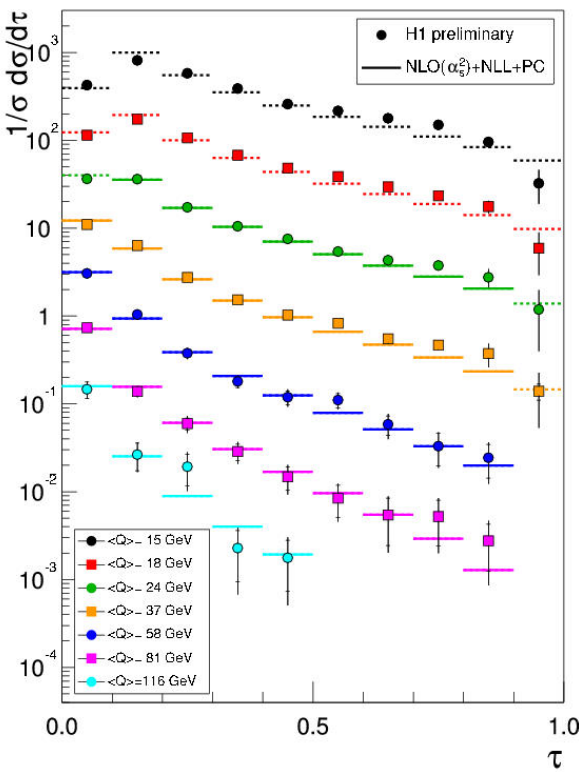
NLO + NLL + PC



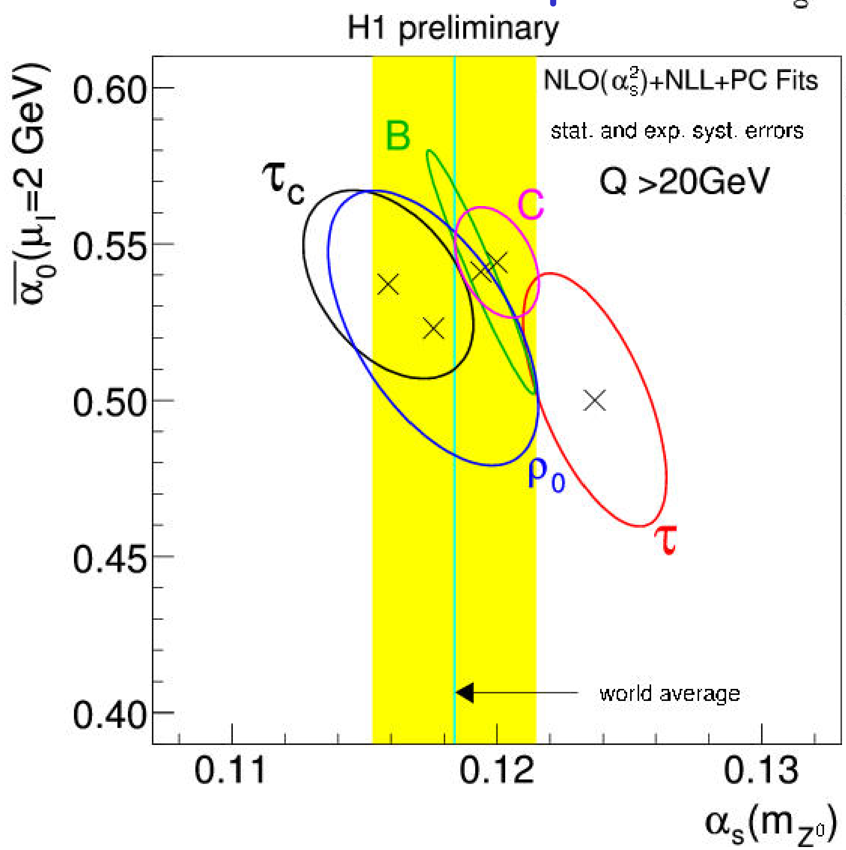
Jet Broadening

Event Shapes at HERA

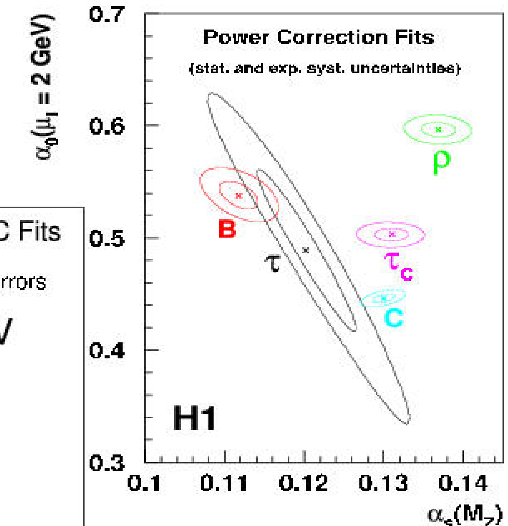
All event shapes well described by NLO + NLL + PC



Fit to shapes



Old result without resummation



Resummation + power correction very successful at HERA

Parton Dynamics

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DGLAP factorisation:

integrated over trans. momentum

$f(x,Q^2)$

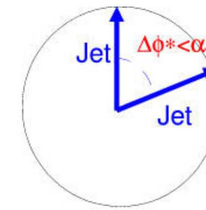
expected to fail when $Q \sim K_T$

un-integrated PDFs:

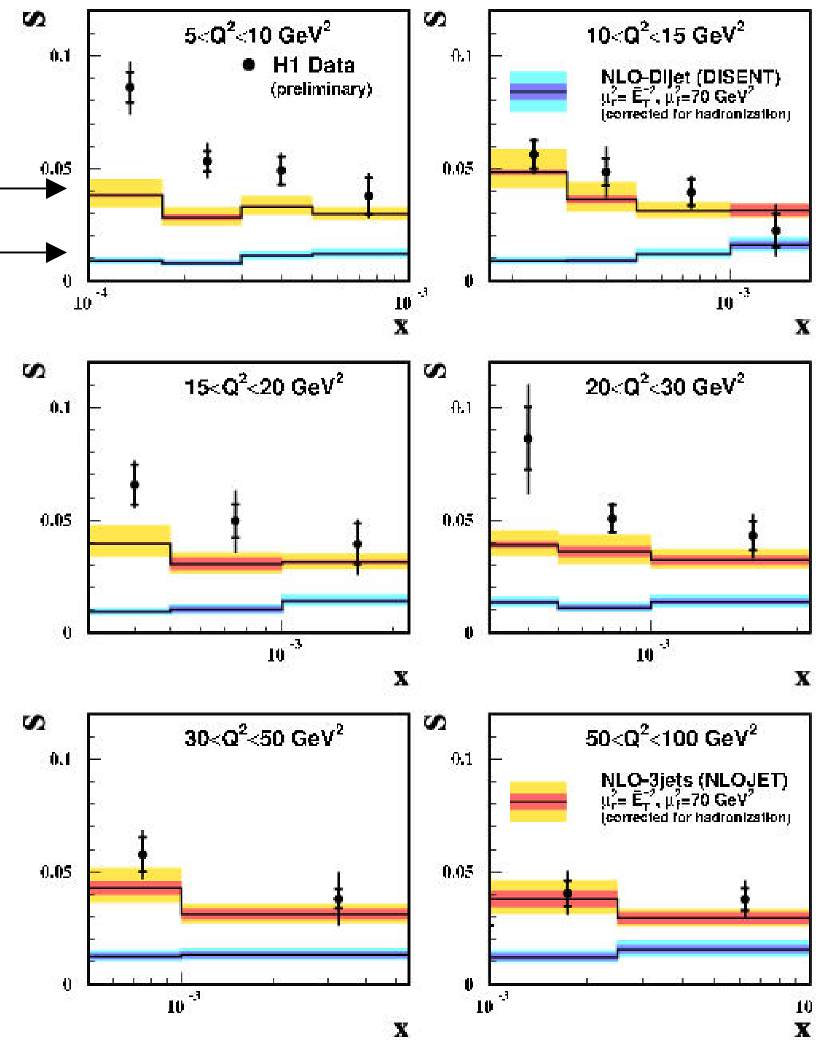
$f(x,Q^2,K_T)$

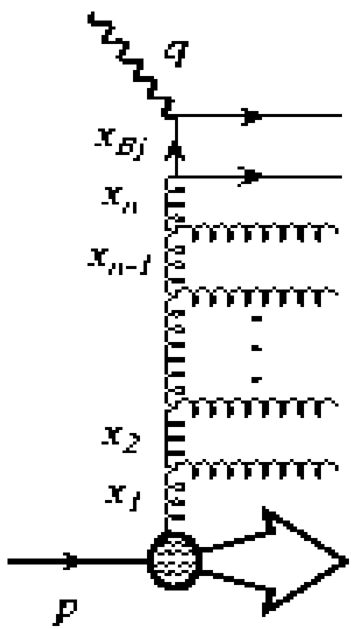
BFKL,CCFM evolution

Selection:
2jets, unbalance



NLO 3j
NLO 2j





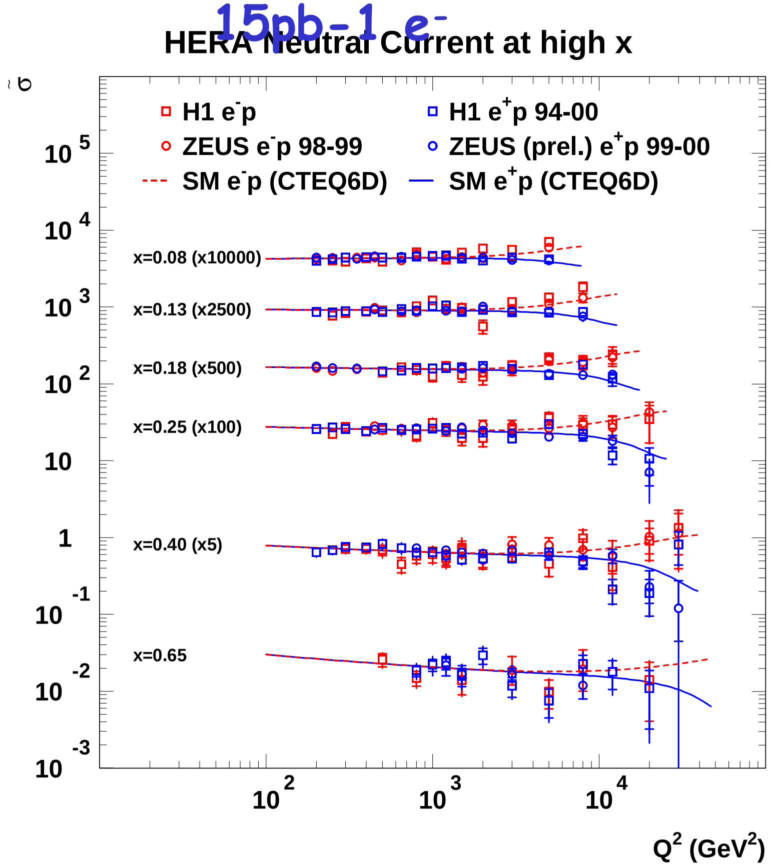
Important at low -x
High parton density

HERA 2

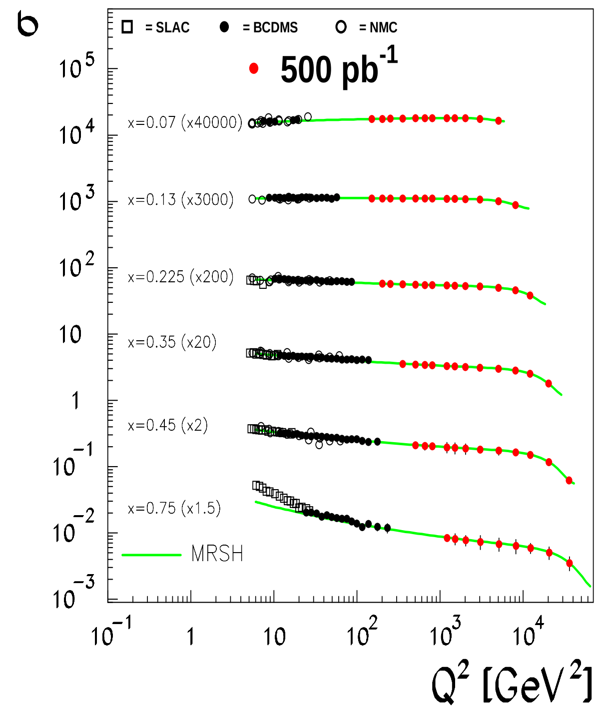
HERA I

100pb-1 e^+

15pb-1 e^-



γ-Z interference:
e^- constructive / e^+ destructive



HERA II

500pb-1 e+

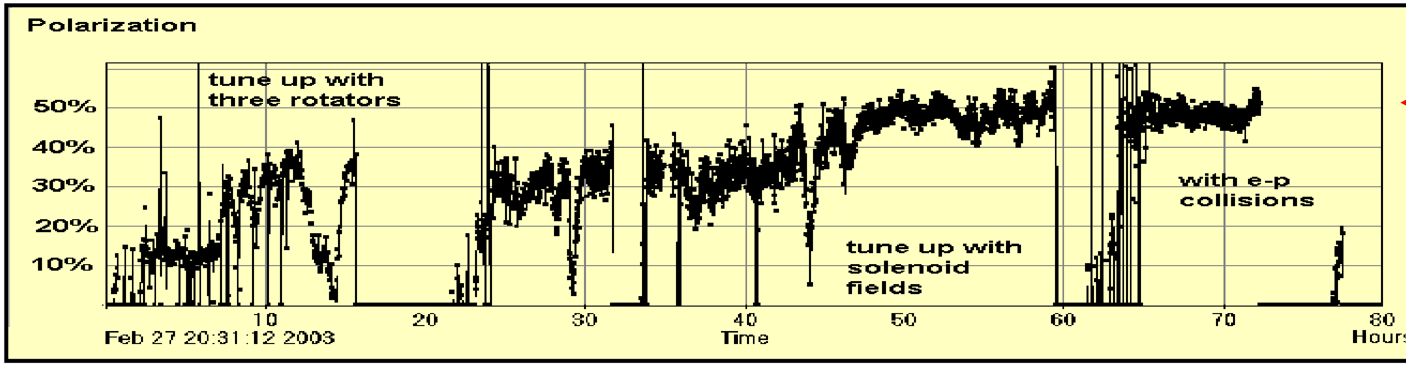
500pb-1 e-

expected

10 % error for
$Q^2 > 16.000\ GeV^2$

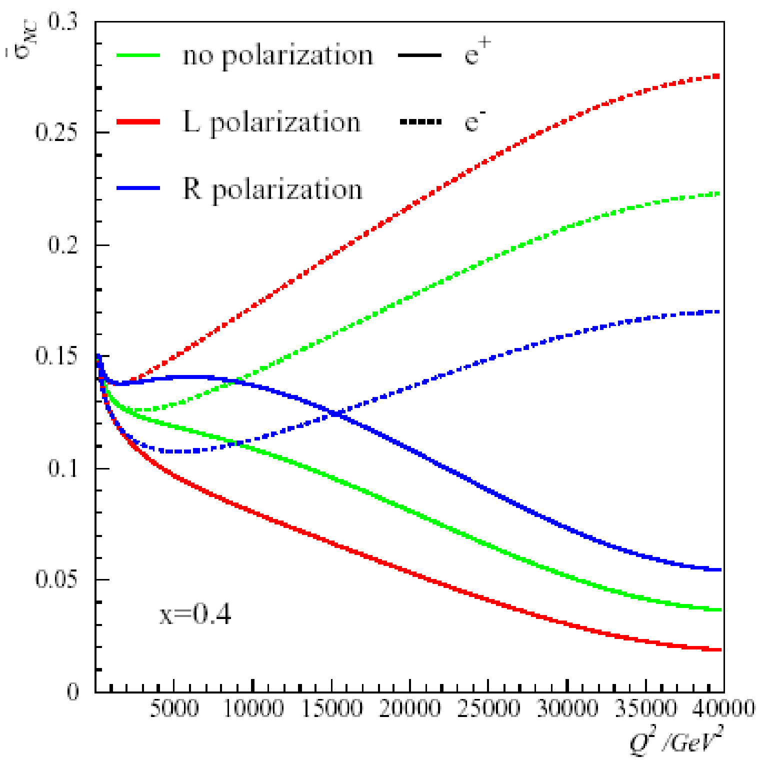
you can never have enough luminosity
to beat 1/Q^4 and (1-x)^3

e^+ beam polarisation

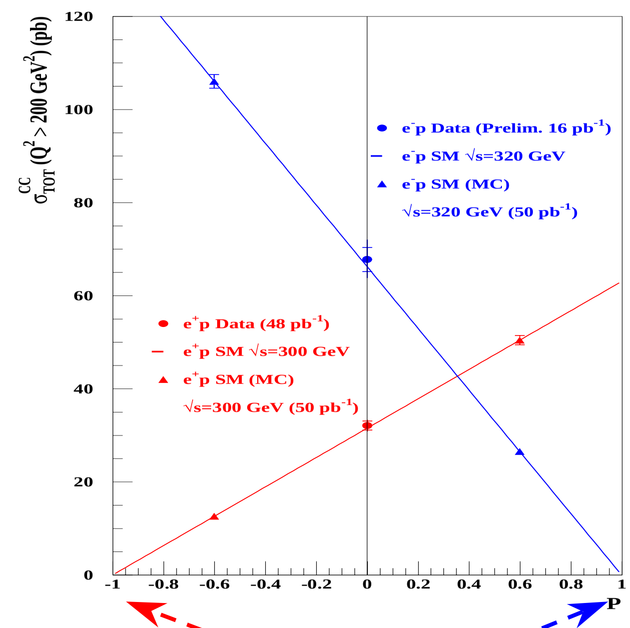


Feb 03
60 %

Neutral current



Charged current



helicity suppression

Conclusion

Overall: QCD at HERA 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

Beauty puzzle:

- Much better agreement with theorie
- Lack of good Monte Carlos
- NLO Monte Carlo → LHC

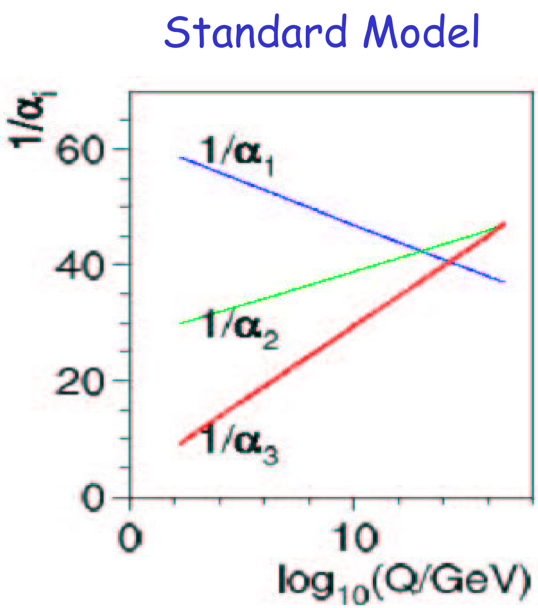
Much progress in resummat., power corr., diffraction

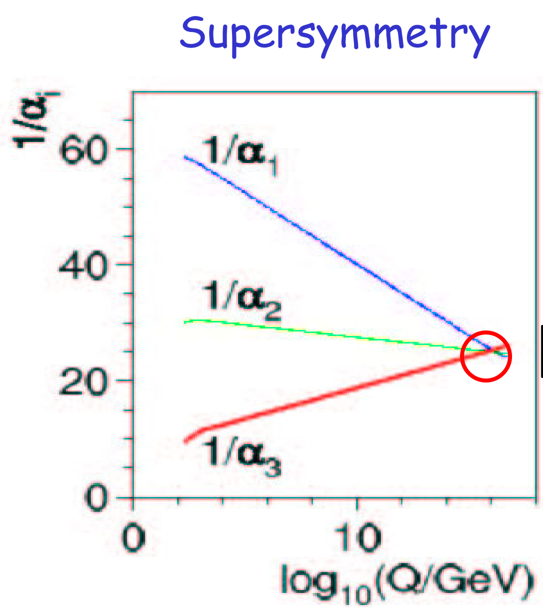
Ready for LHC ?
not quite, but Tevatron RUN II, HERA II, THEORY...

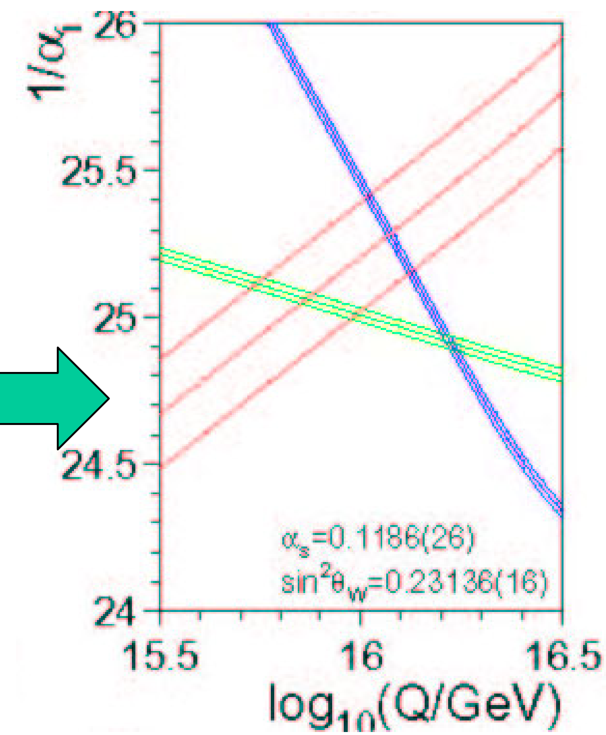
Benchmarks for Precision QCD

α_s determinations: how good ?

Zoom into SUSY





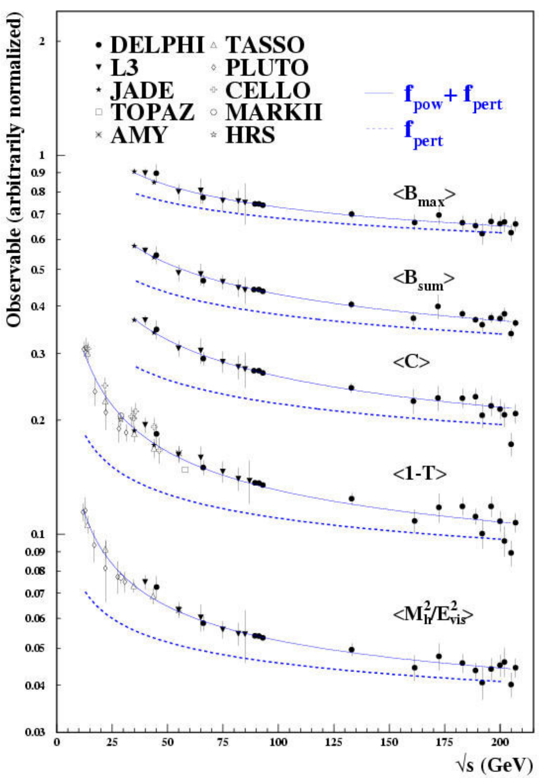


Highest possible precision is vital !

Power Corrections at LEP

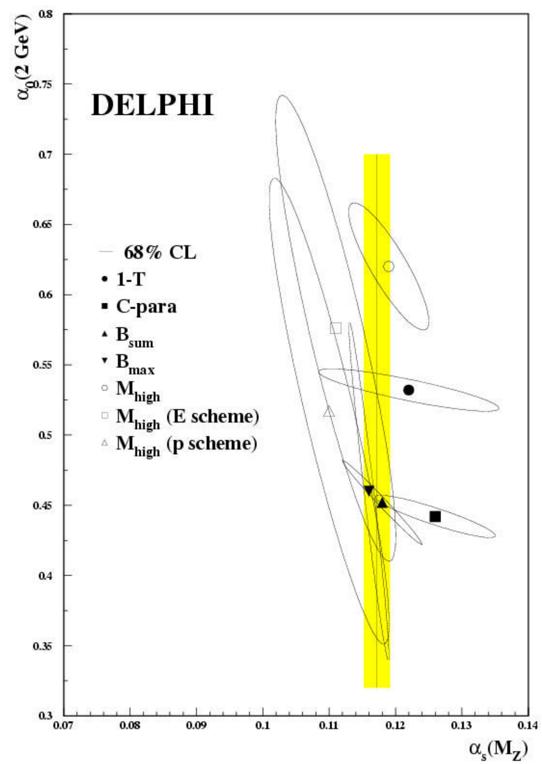
Dokshitzer-Webber ansatz:
α_0 = effective α_s below μ_I
approx. for hadronisation

$$
\begin{aligned}
<y> &= <y_{\mathrm{pert}}> + <y_{\mathrm{power}}> \\
y_{\mathrm{power}} &= c_y \cdot P(\alpha_0)/Q \\
D_y(y) &= D_{\mathrm{pert}}\left(y - c_y \cdot P(\alpha_0)\right)
\end{aligned}
$$



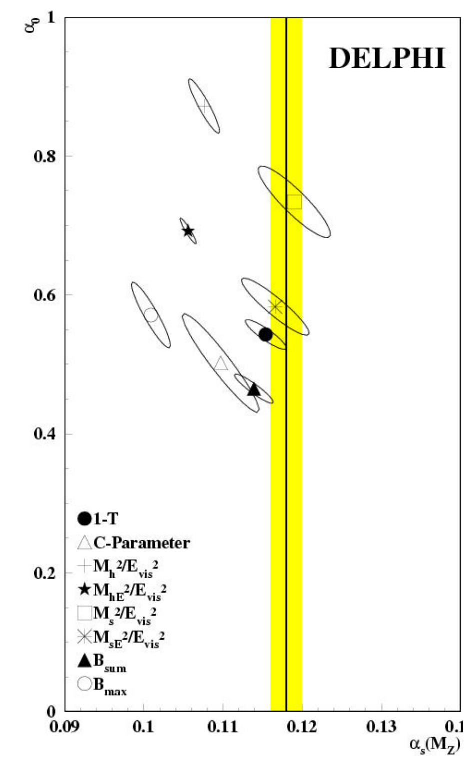
shapes well described

Fit to mean values



α_s = 0.1207

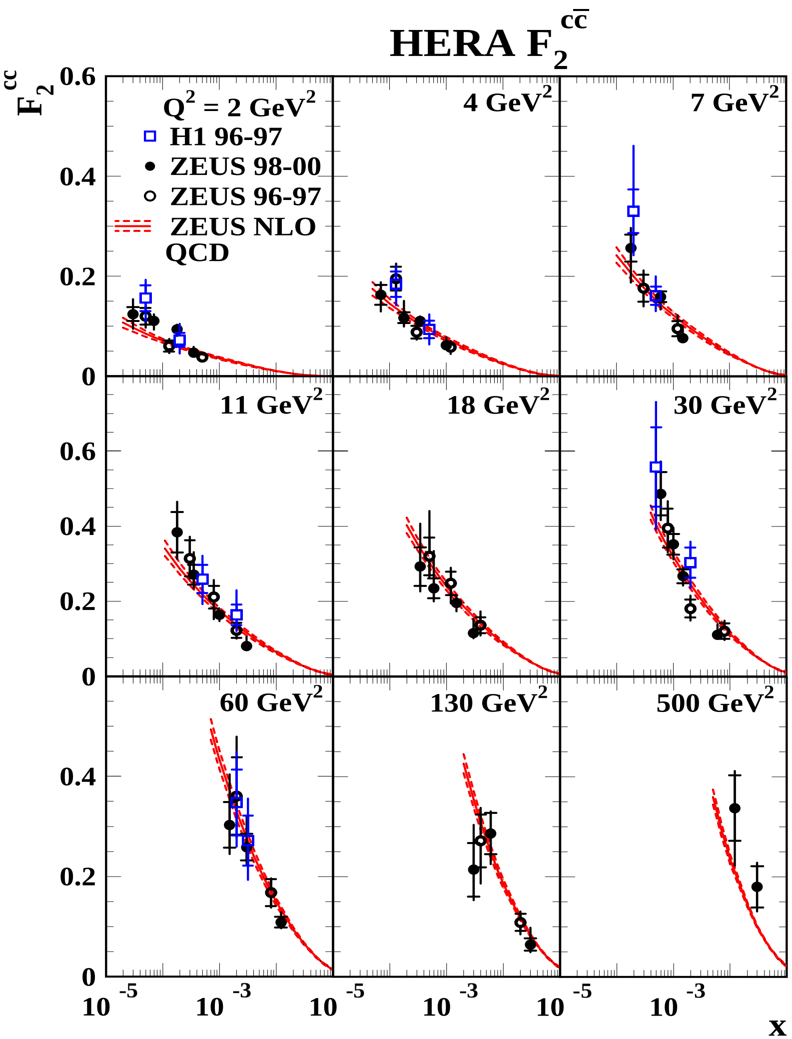
Fit to shapes

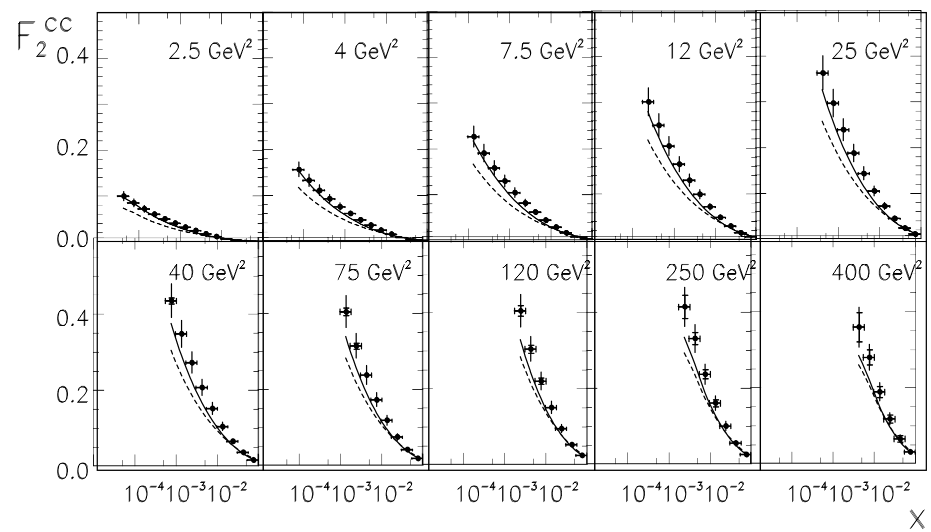


no consistent α_s

Charm at HERA

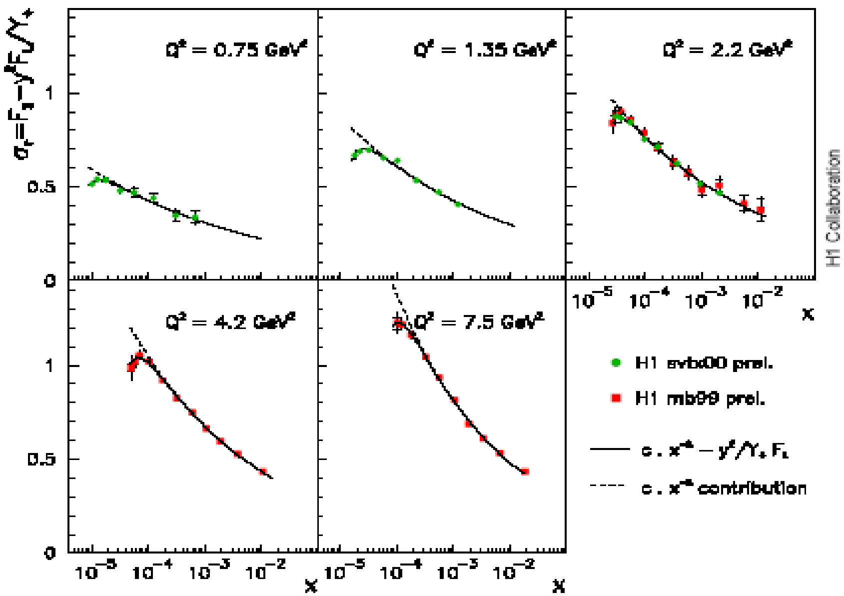
Peter Schleper
From HERA to LHC
Strasbourg, March 04



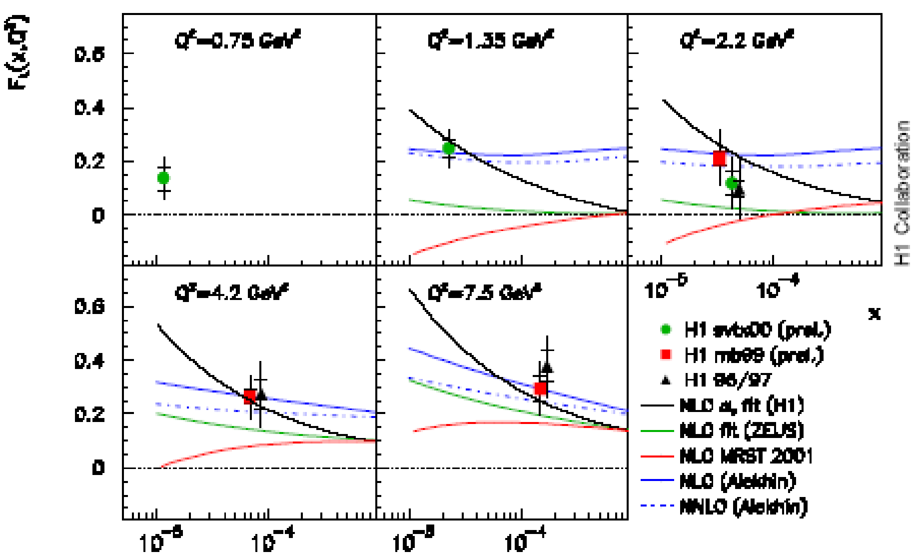


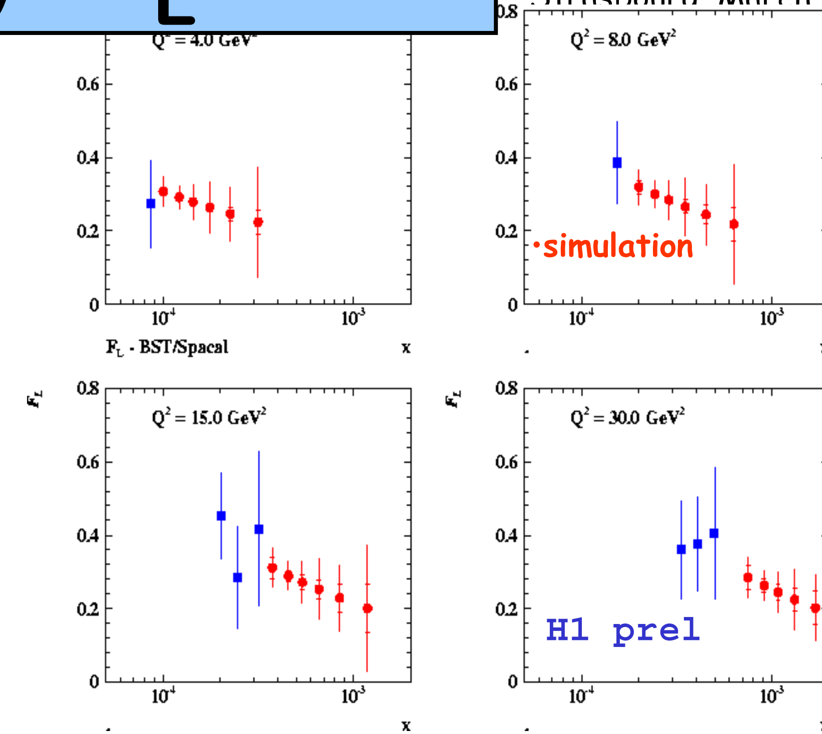
ty: F_L

HERA II



Longitudinal structure function

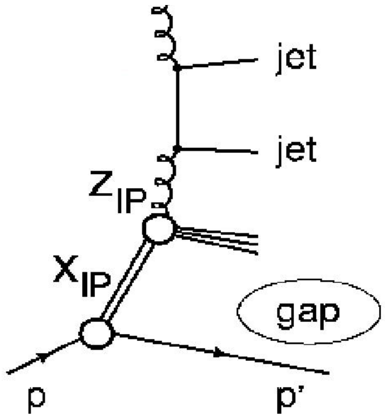




simulation of low Ep data
[~ 460, 575, 920 GeV]

$$F_L \propto \alpha_s \cdot xg$$

Diffraction: factorization



No colour exchange from Proton

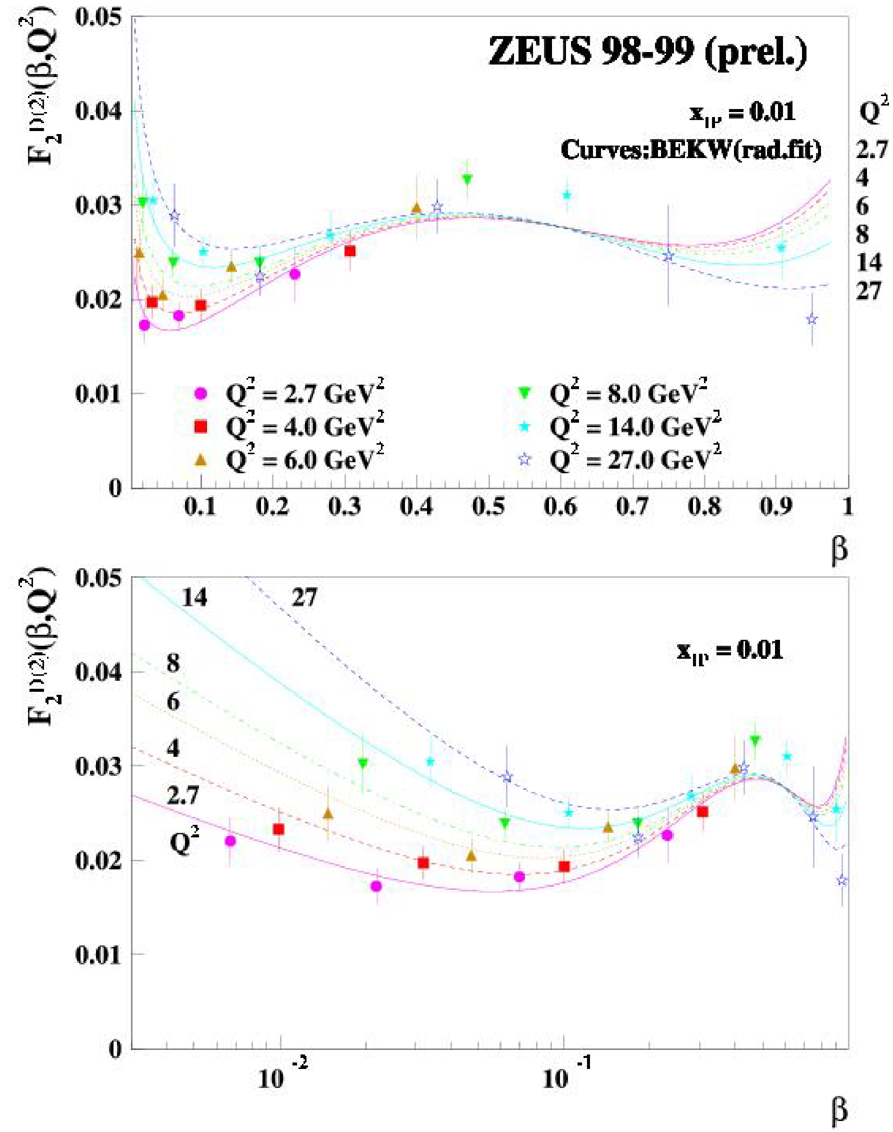
Soft QCD ?

Hard scattering: Q2 large

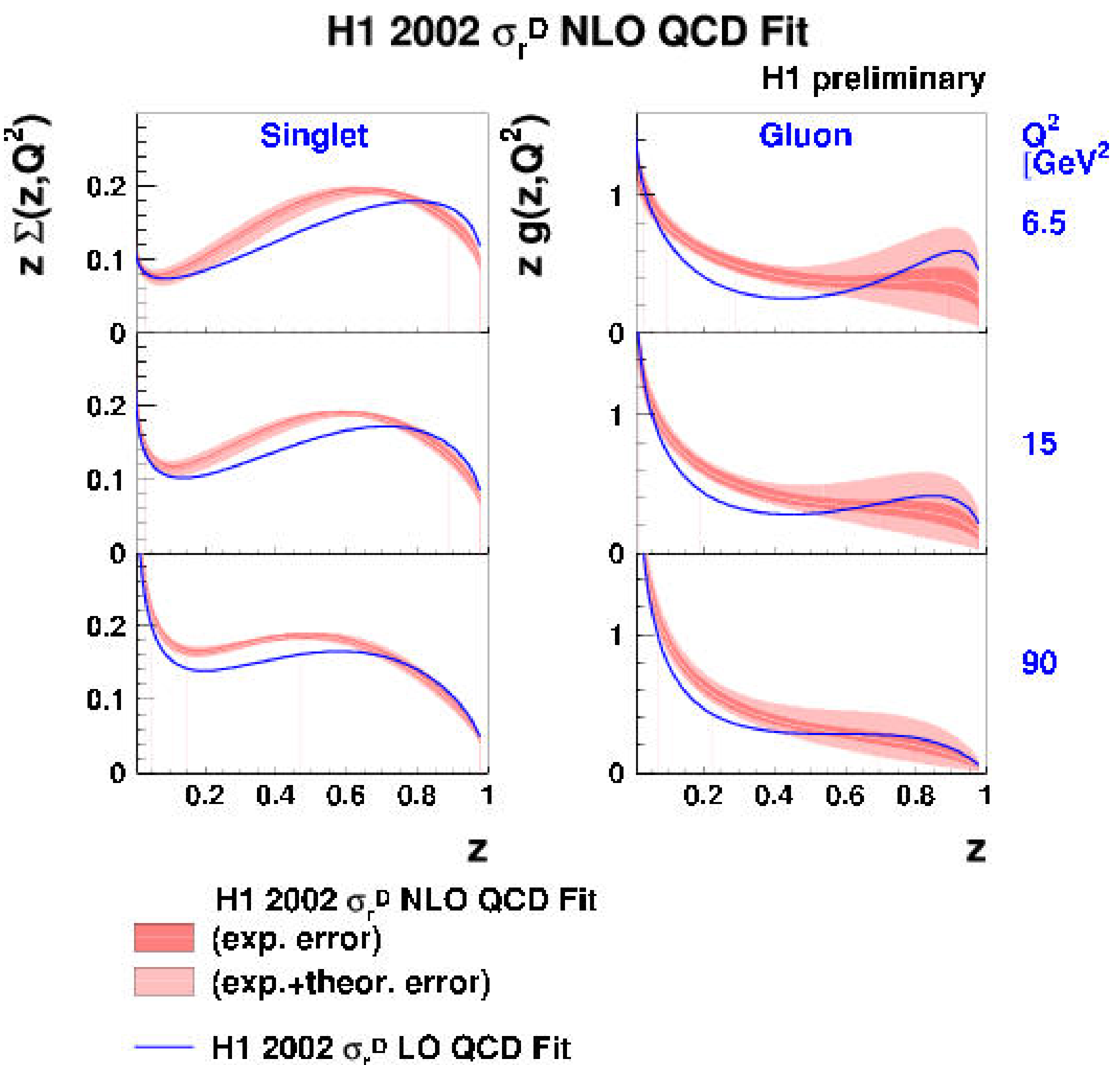
Factorisation in diffract. PDF and partonic σ

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

should follow DGLAP QCD evolution with Q^2



Diffraction in NLO QCD



NLO QCD fits to
incl data
Same as in standard
QCD fits to DIS

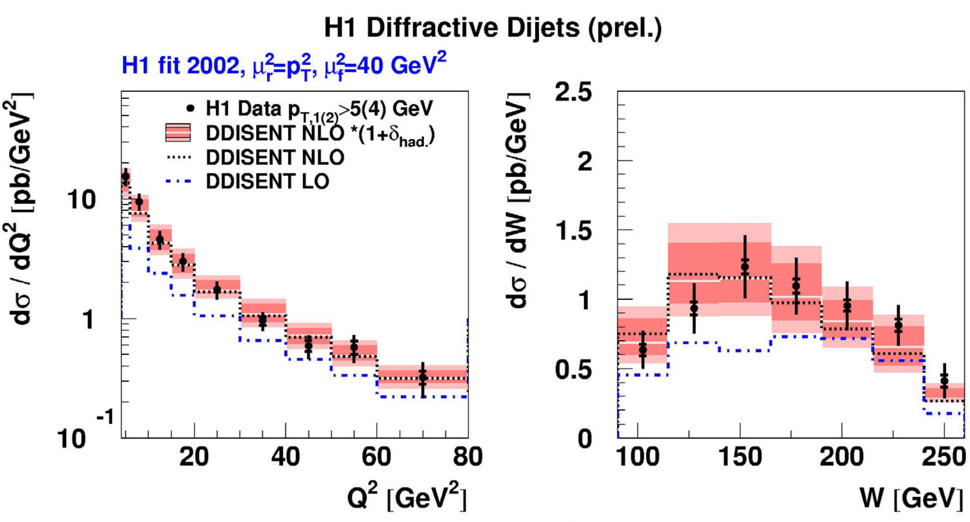
PDF(x,Q2) for fixed
Proton momentum

Large gluon contribution

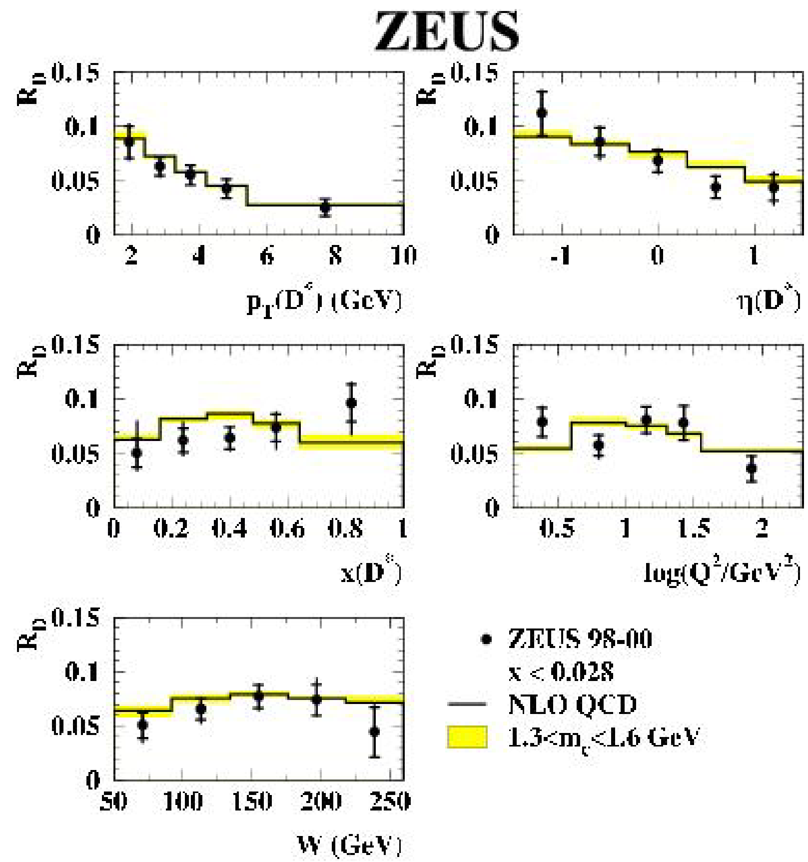
Use diffr. PDF to predict σ(jet) , σ(charm)

Diffraction in NLO QCD

Jets



Charm

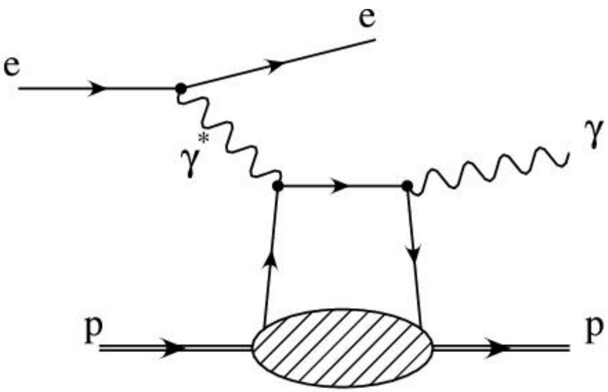


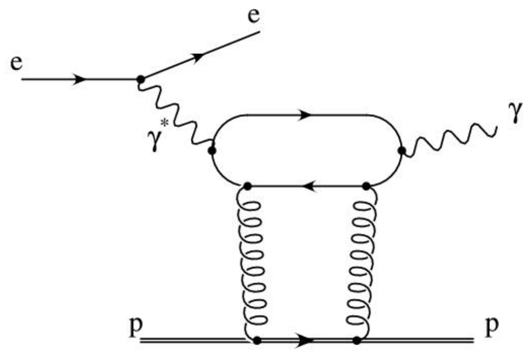
- NLO QCD fit to inclusive data describes jet and charm
- successful test of hard scattering factorisation

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

Skewed partons

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



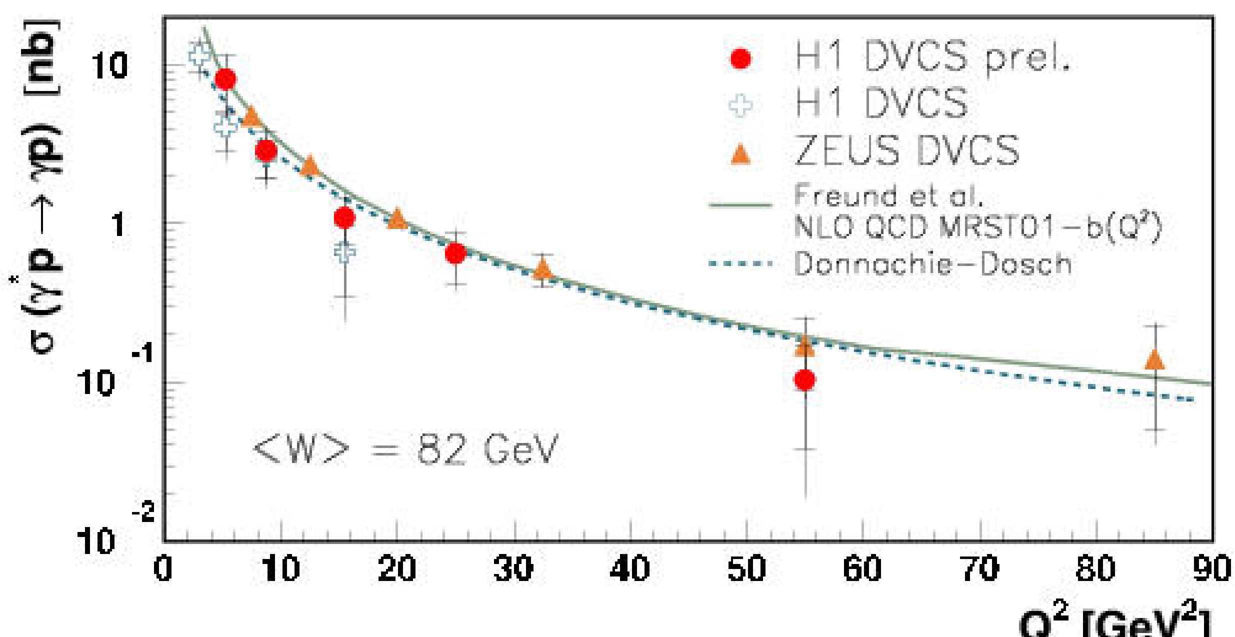


correlation between initial
quarks and gluons

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

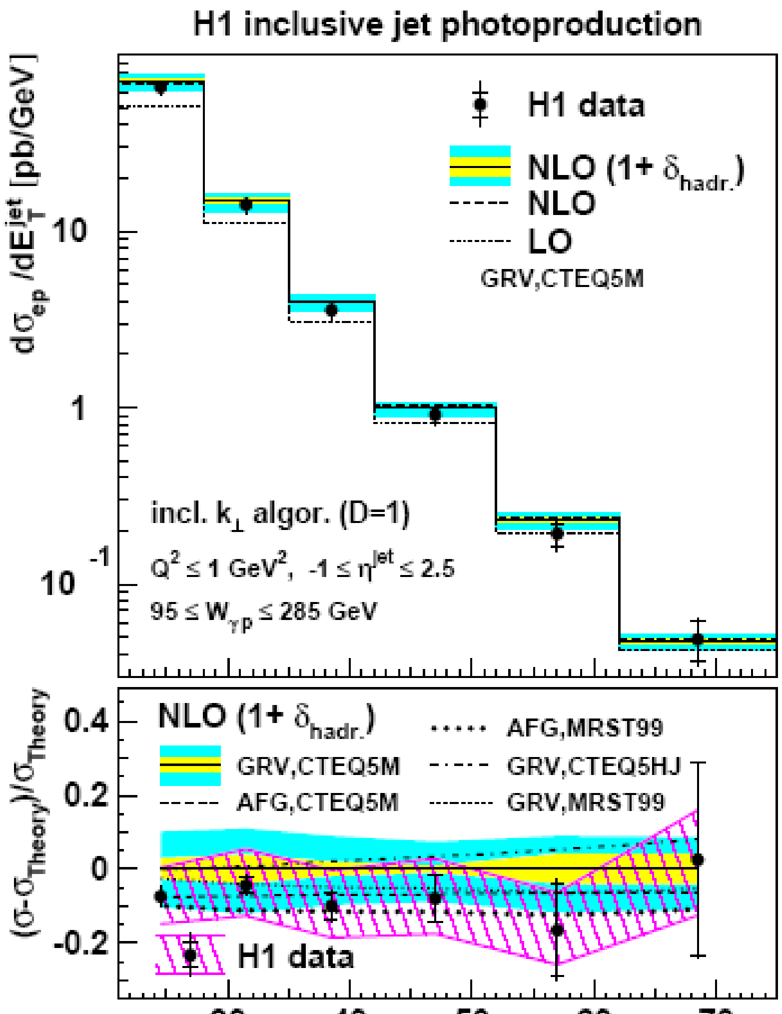
Factorisation for large Q^2

NLO successful

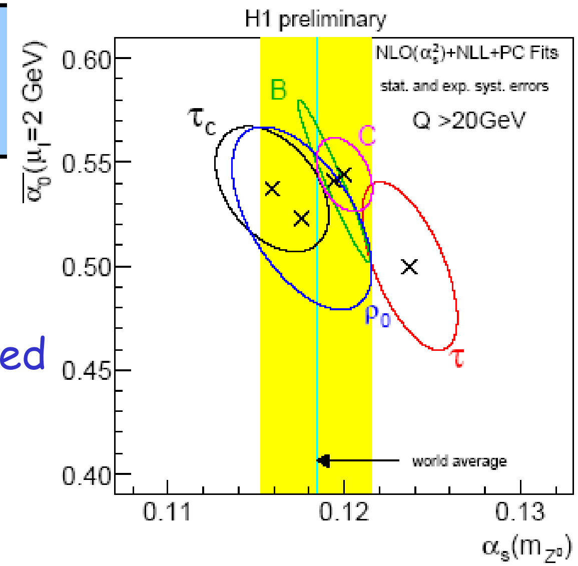


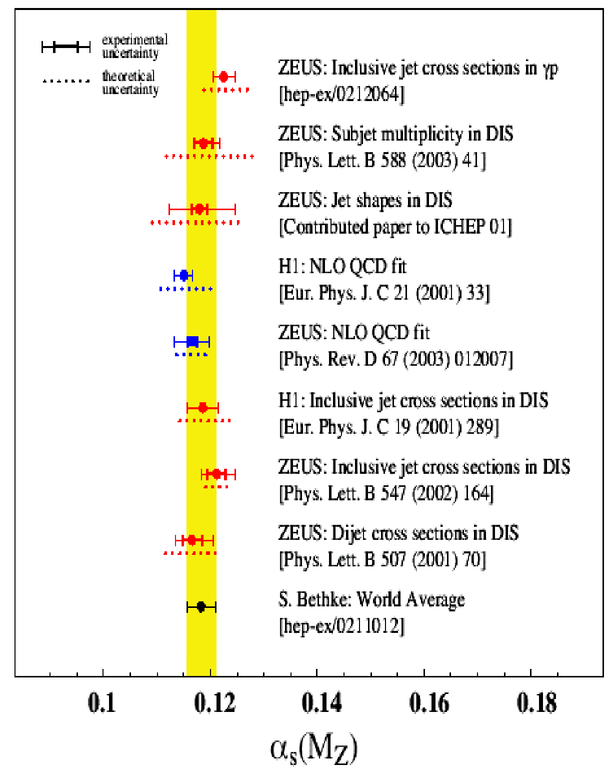
chleper
to LHC
rch 04

event
shapes
& QCD
resummed



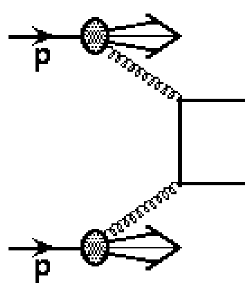
Inclusive jets: well described by NLO QCD





Tevatron Jets

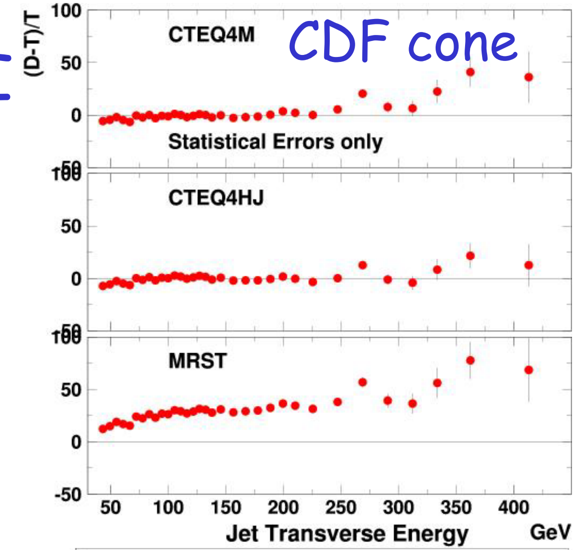
- Run I: 100 pb^{-1}
- Run II: 200 pb^{-1} recorded
- first prelim. results
  CDF: 85 pb**-1, D0: 34 pb**-1

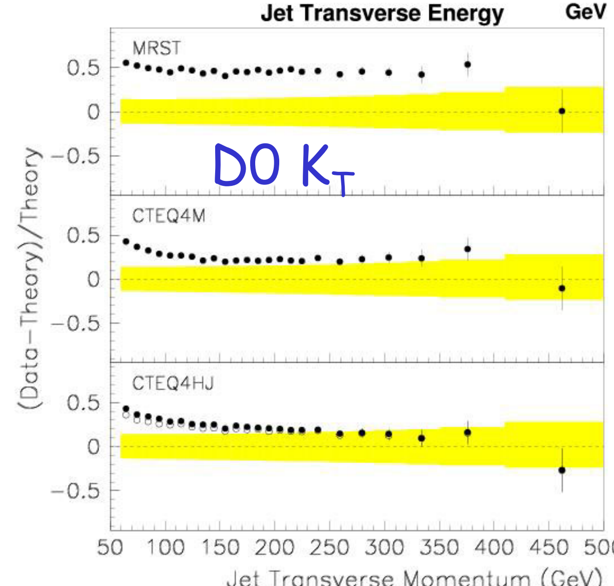


gluon density not constrained at high x

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)

Run I

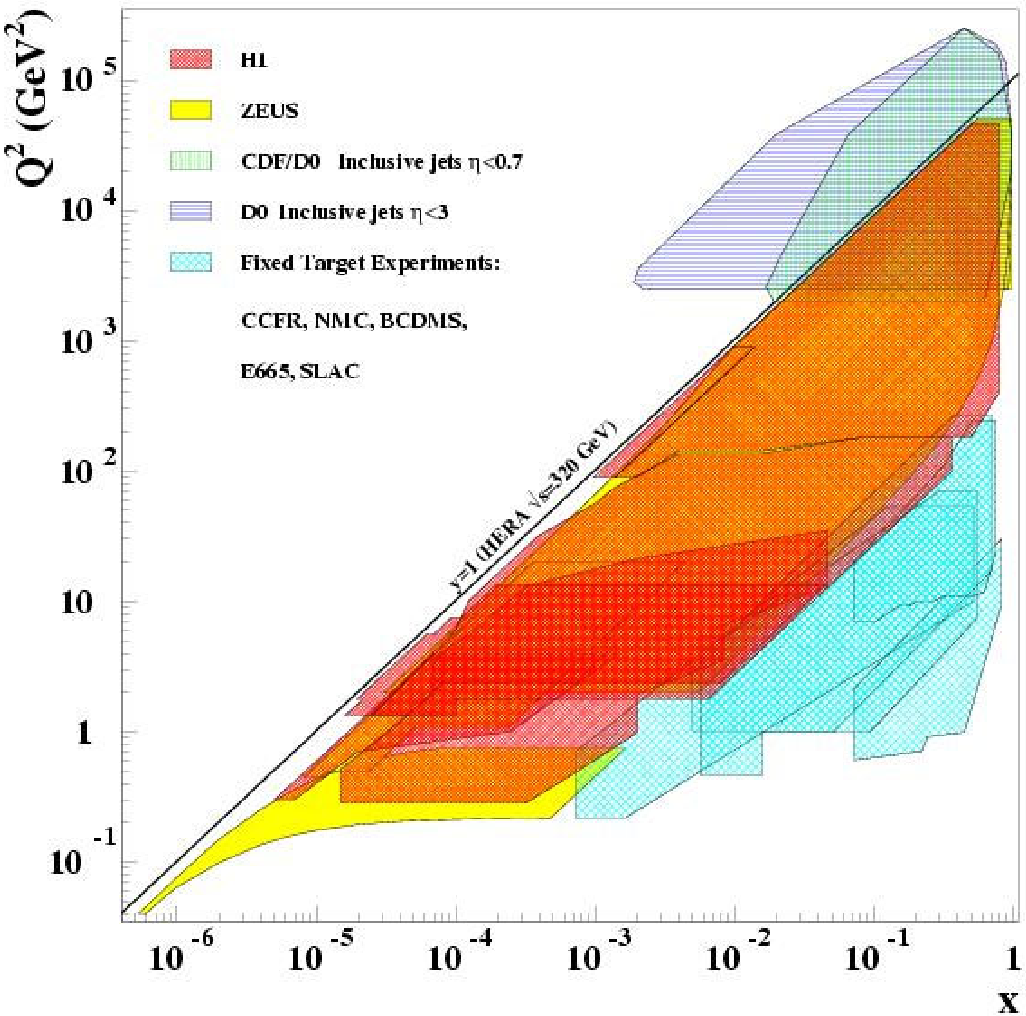


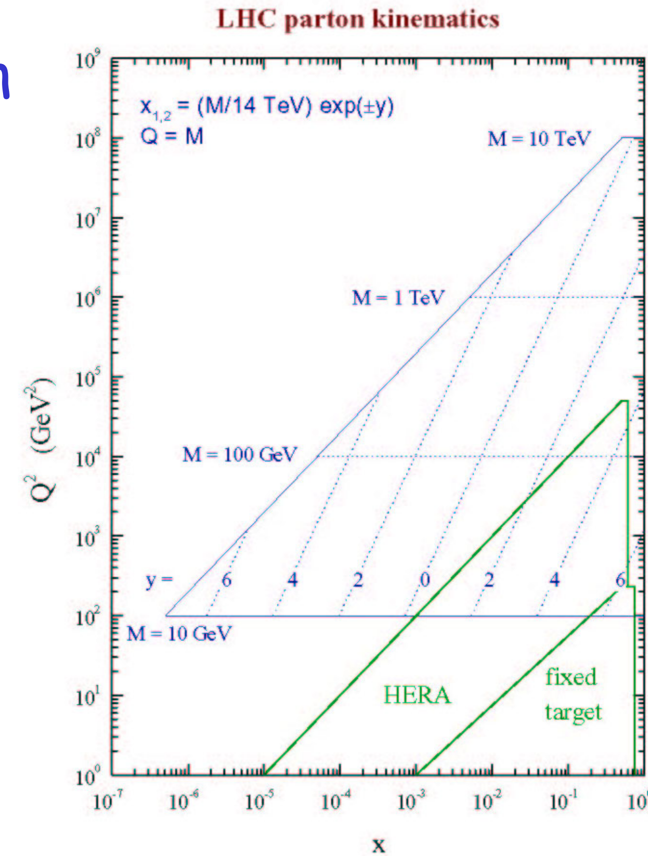


differences cone/ K_T due to hadr. corrections

Proton Structure

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