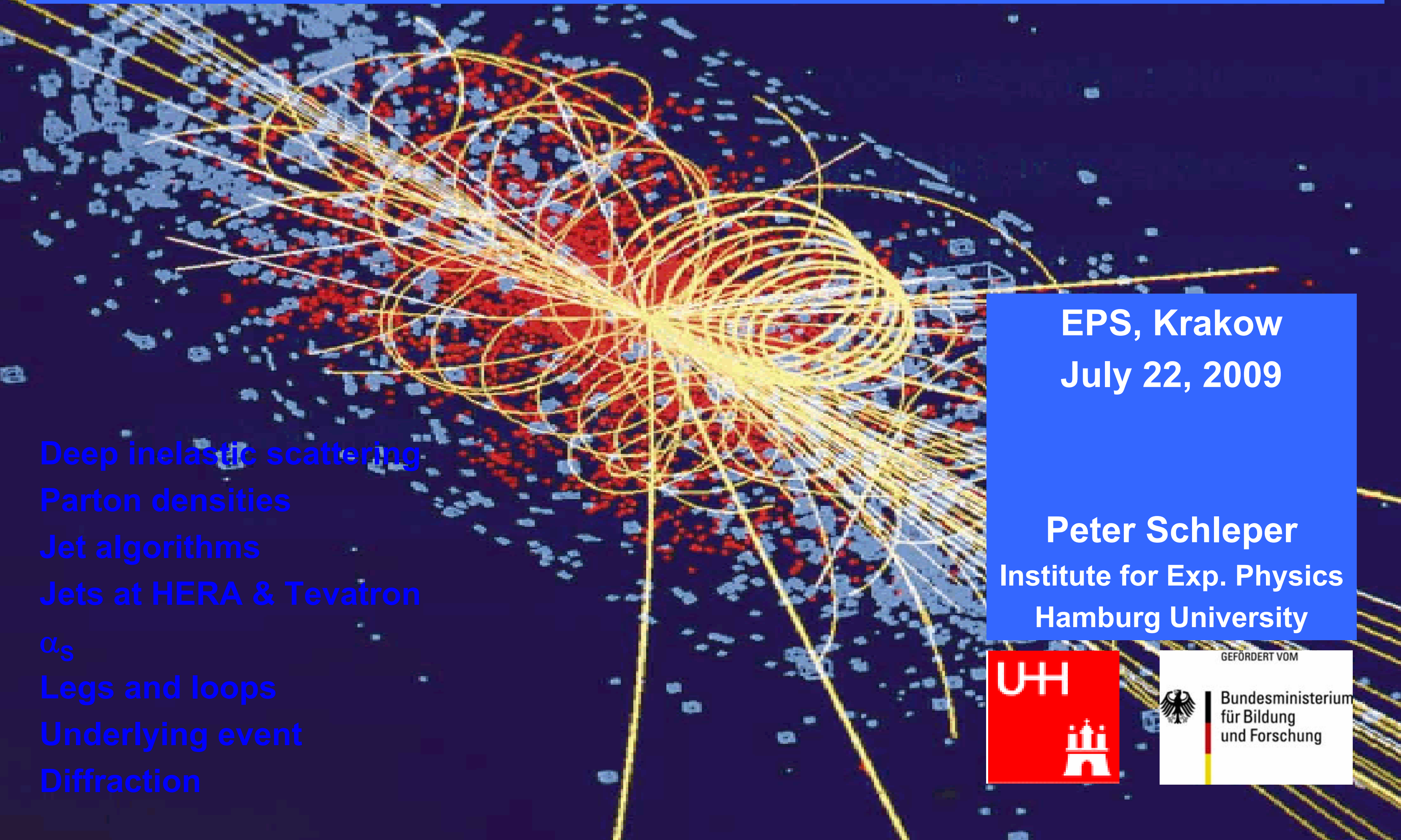
QCD - Experiment



EPS, Krakow
July 22, 2009

Peter Schleper
Institute for Exp. Physics
Hamburg University

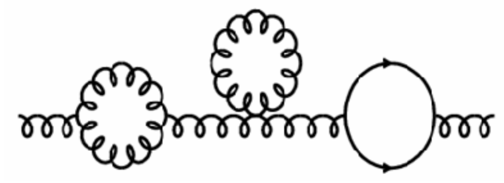
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

- Deep inelastic scattering
- Parton densities
- Jet algorithms
- Jets at HERA & Tevatron
- α_s
- Legs and loops
- Underlying event
- Diffraction

Introduction I

Strong Interaction

- $SU(3)_C$, prototype of non-abelian gauge theory
- Proton as fundamental state of QCD



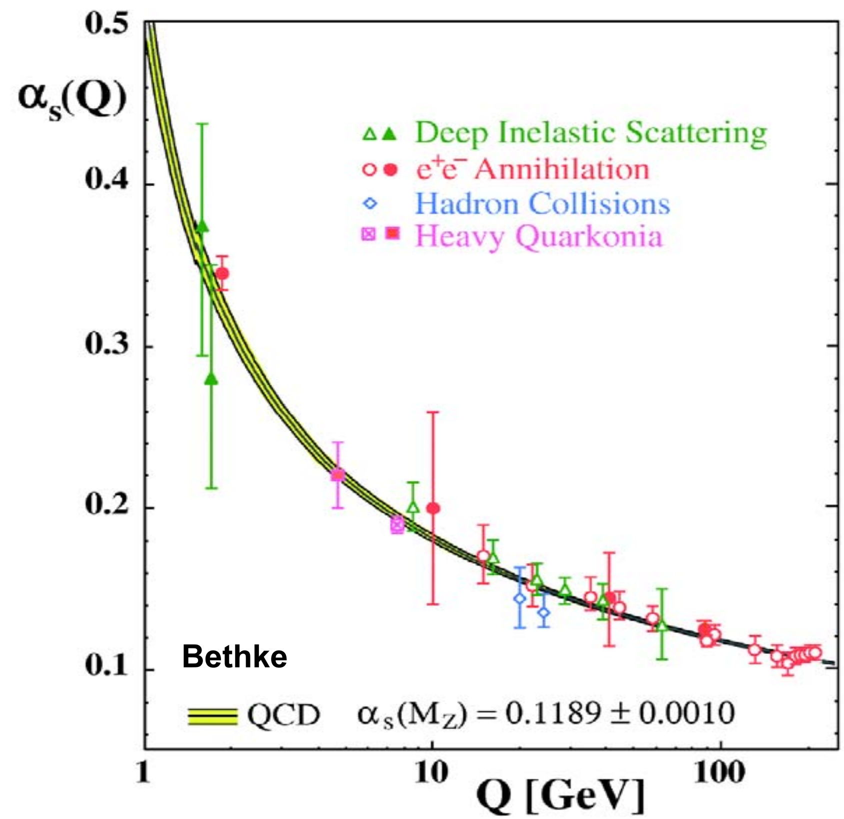
$q \rightarrow q\, g$ Quark-Gluon Vertex
$g \rightarrow g\, g$ 3-Gluon Vertex
$g \rightarrow g\, g\, g$ 4-Gluon Vertex

Predictions of QCD:

- Scale-dependence of $\alpha_s(Q^2)$
- Hard processes: Q^2 large
  Matrix elements in LO, NLO, NNLO, ..
- Scale-dependence of parton densities
  $f_{u,d}(x,Q^2)$ quarks
  $f_g(x,Q^2)$ gluons

$\alpha_s(M_Z^2)$ world averages (data until 2005)

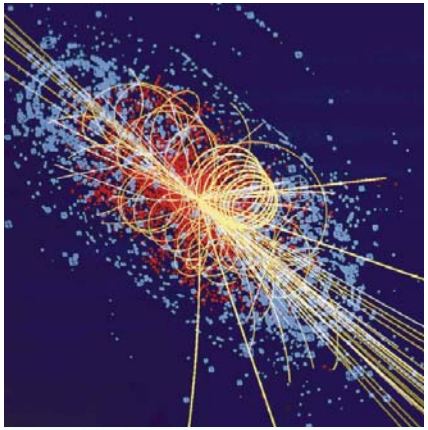
0.1189 (10) Bethke '08 Prog.Part.Nucl.Phys.58:35
0.1176 (20) Particle Data Group '08
see below for more recent data



Introduction II

Area of Hadron- Colliders:

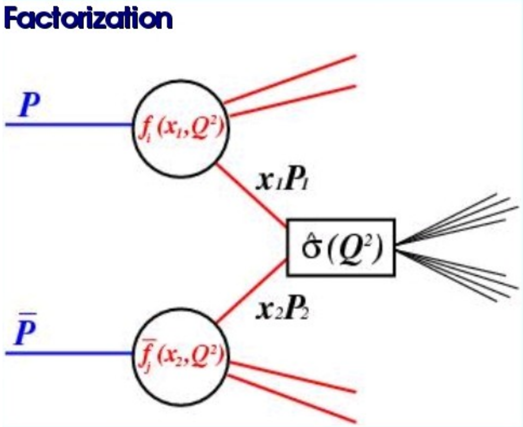
HERA:	$e^{\pm}p$	E_{CMS} = 320 GeV
Tevatron:	p-pbar	E_{CMS} = 2 TeV
LHC:	pp	E_{CMS} = 14 TeV



QCD applications to hadronic collisions:

- QCD factorisation(s)
- Parton-densities of the proton
- α_S
- Jet algorithms
- QCD matrix elements in LO, NLO, NNLO

  (for theory see talk by Anastasiou)
- Multi-leg final states
- Soft processes: underlying event, diffraction

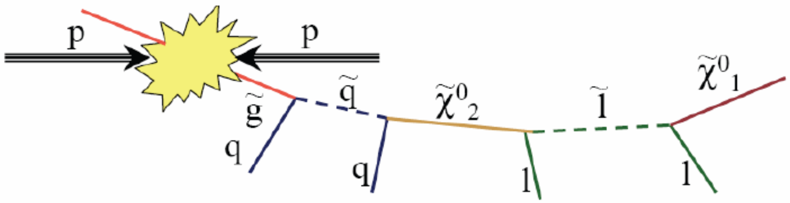


This conference:

- 91 talks in parallel sessions

→ Thank you for the valuable discussions

→ Apologies for results that cannot be shown in 25 min.



Parton Distributions (PDF)

Collider interest: gg → H

Scale: $Q^2 = M_H^2 = x_1\, x_2\, s$

Mass: $M_H = x_{1,2}\, e^{\pm y} \sqrt{s}$

Rapidity: $y_H = ½ \ln (x_1 / x_2)$

For LHC ($y_H \approx \pm 2.5$)

$M_H \approx$ 140 GeV → $10^{-3} < x < 0.1$

$M_H \approx$ 1400 GeV → $10^{-2} < x < 1$

Deep inelastic scattering

$Q^2 \le x\, s$

➔ HERA: factor 500 in x, Q^2

$10^{-5} < x < 0.6$,

$1 < Q^2 < 50000$ GeV^2

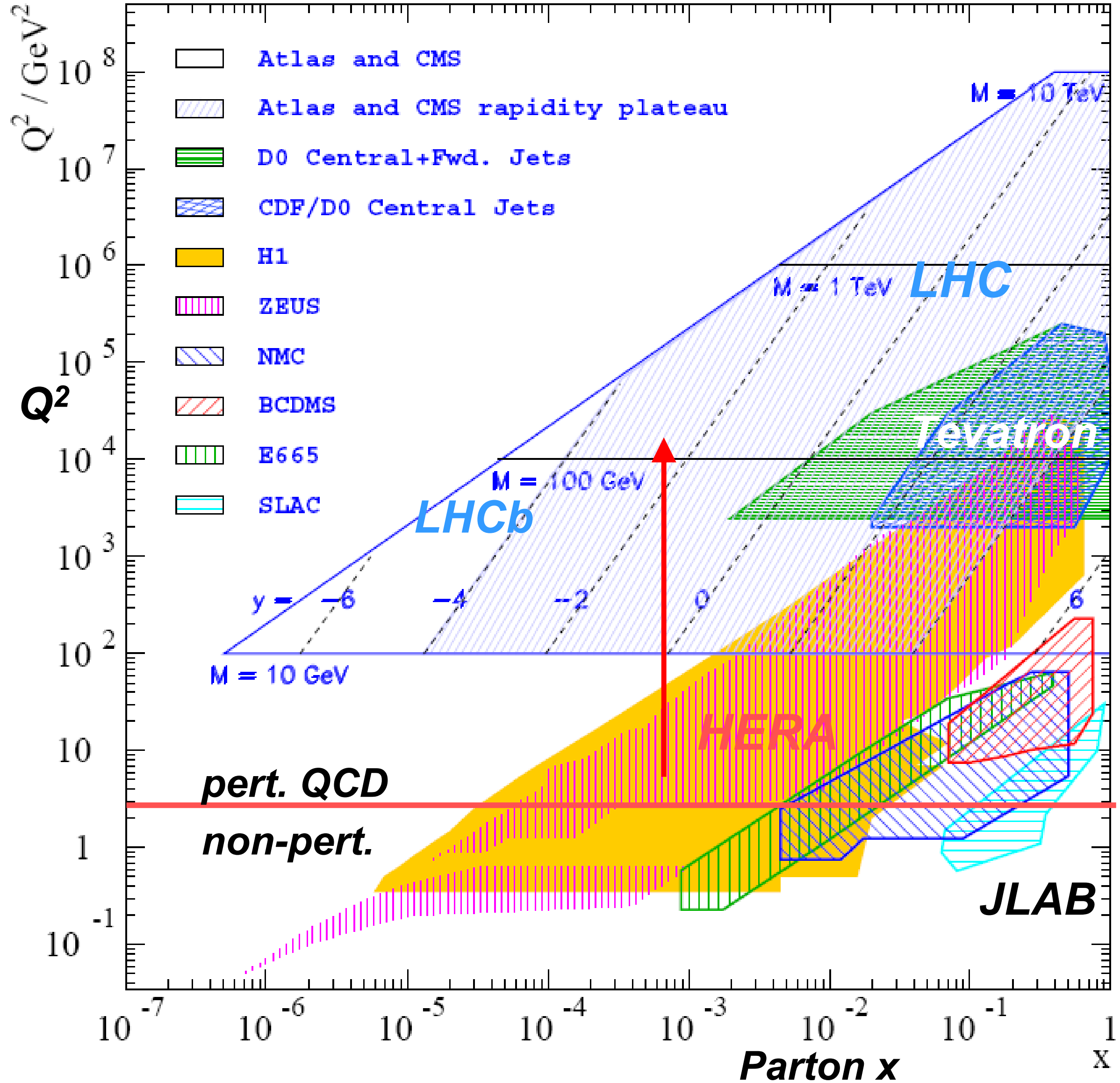
Dominates knowledge on parton distributions

LHC – HERA:

same x - range,

factor 100-1000 in Q^2

➔ *QCD fit of scaling violation*

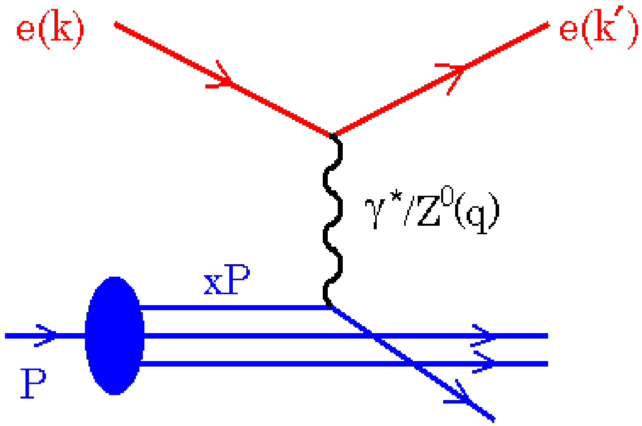


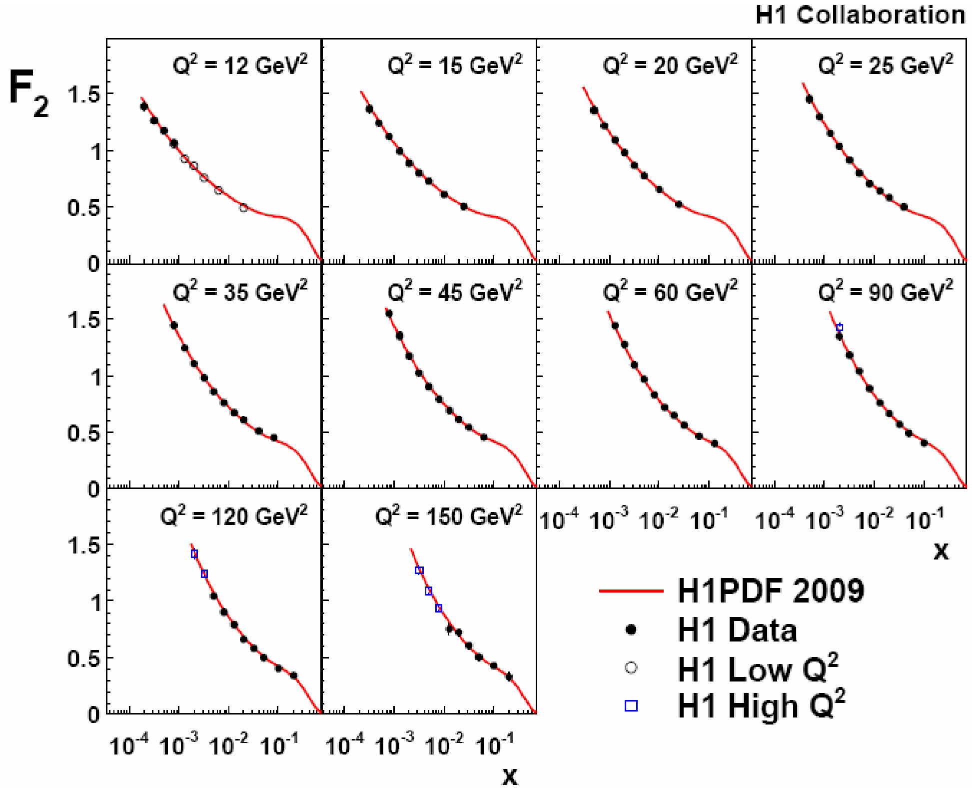
Inclusive Deep Inelastic Scattering

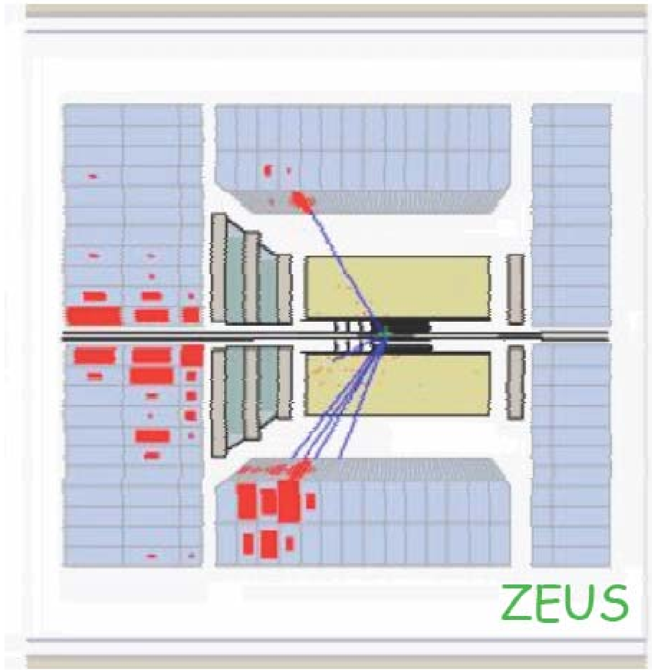
HERA data: e_L^-, e_R^-, e_L^+, e_R^+

- ~ 500 pb^{-1} data per experiment final statistics
- ~ 10^8 ep collisions triggered by H1 & ZEUS
- Thresholds: $P_T > 5 \ldots 10$ GeV for electrons and jets
- H1, ZEUS: newly published data

  $\Delta\sigma \sim 1.3 \ldots 3$ %, except at high x, Q^2







Inclusive Deep Inelastic Scattering

HERA Structure function working group

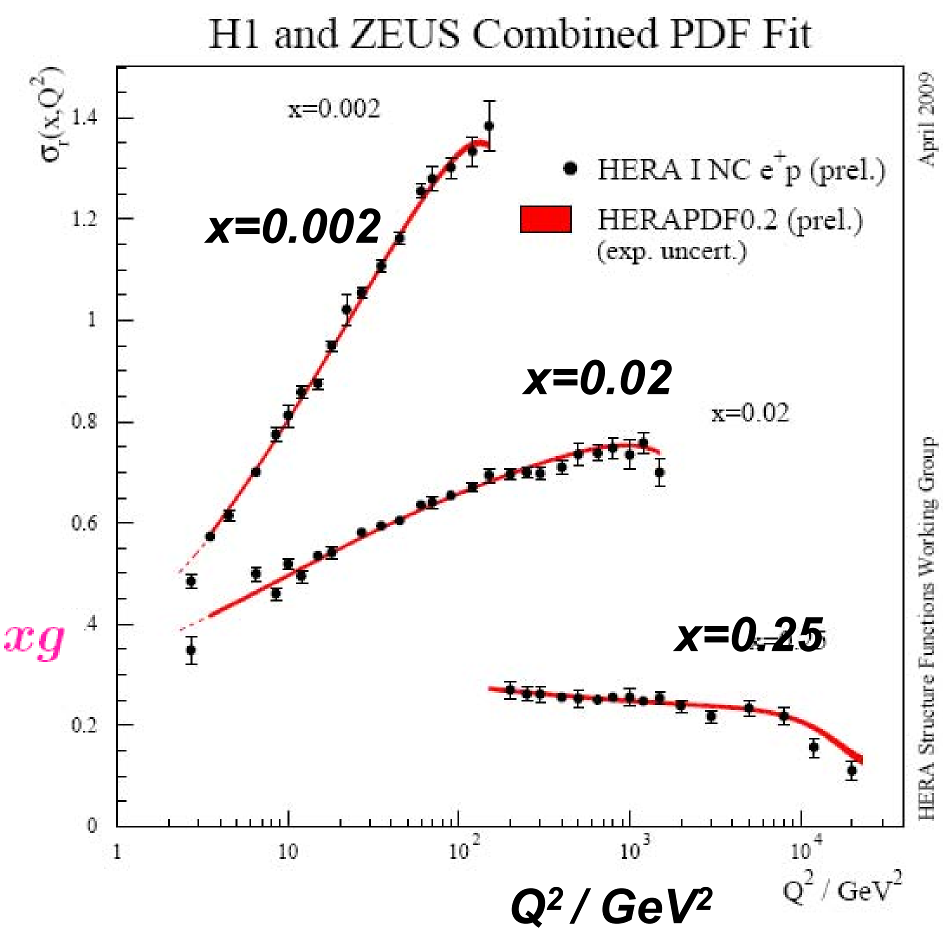
- **Combined cross section: cross calibration of systematics: $\Delta\sigma \sim 1 \ldots 2\ \%$**
  H1, ZEUS results are compatible: χ^2/ ndf = 637 / 656
- **NLO QCD Fit: HERA-PDF 0.2**

$$\sim x \sum_i e_i^2 \cdot (q_i + \bar{q}_i)$$

Gluon density from

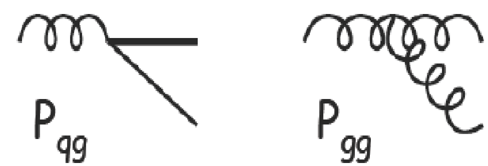
$$\partial F_2 / \partial \ln Q^2 \sim \alpha_s \cdot xg$$

1/10 of full dataset

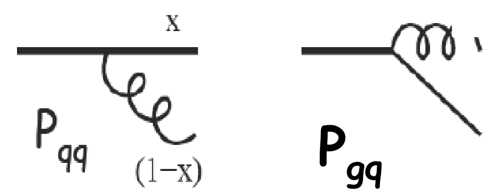


QCD splitting functions

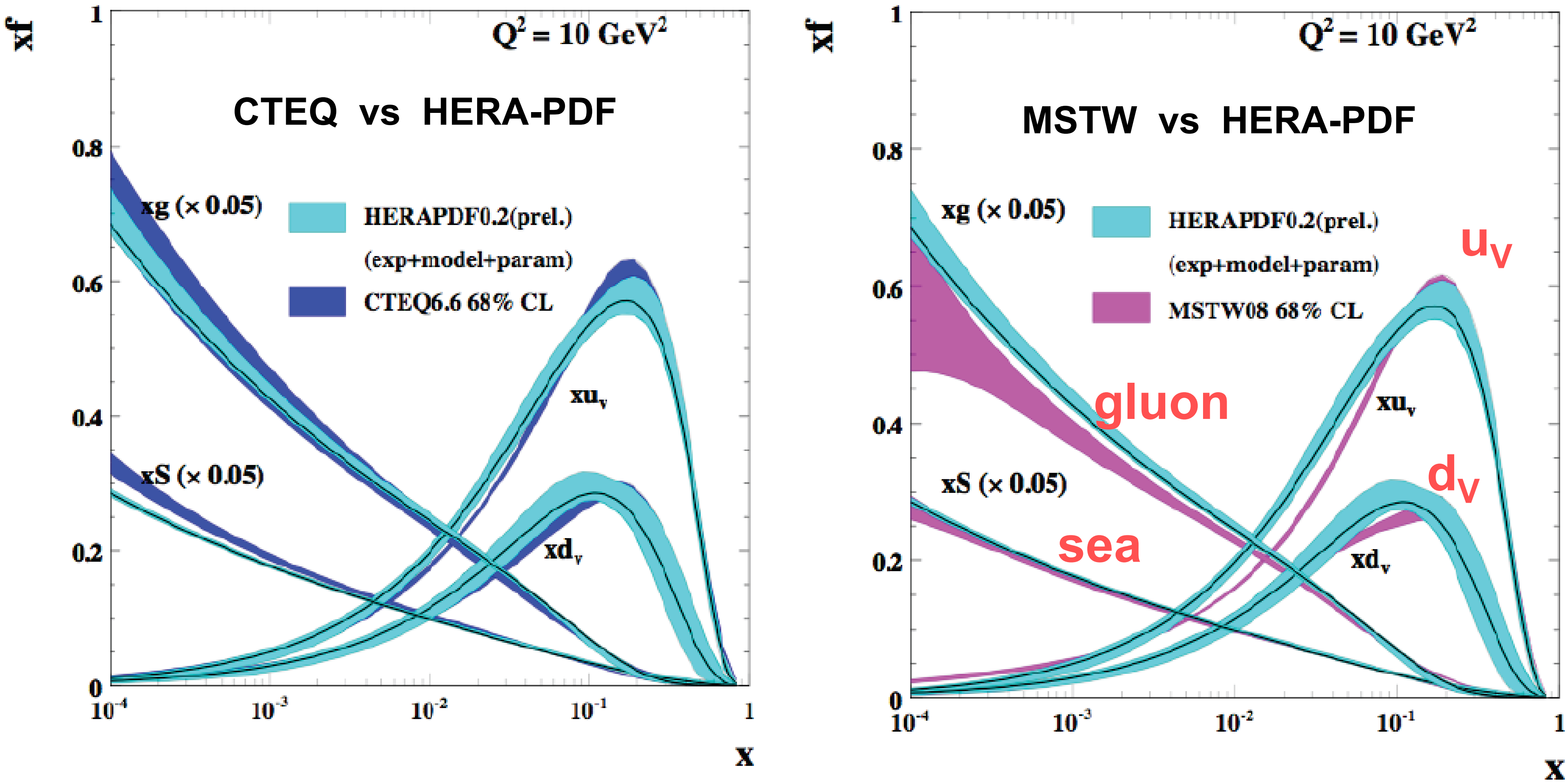
low-x: gluons



high-x: valence quarks



QCD Fits of Parton Densities I



Errors reflect different treatment of experiments, model uncertainties, α_S, …

QCD Fits of Parton Densities II

1. Heavy flavour treatment at threshold

- Thorne-Roberts variable flavour number scheme

2. Choice of PDF parameterization at $Q_0^2 \sim 2\text{GeV}^2$

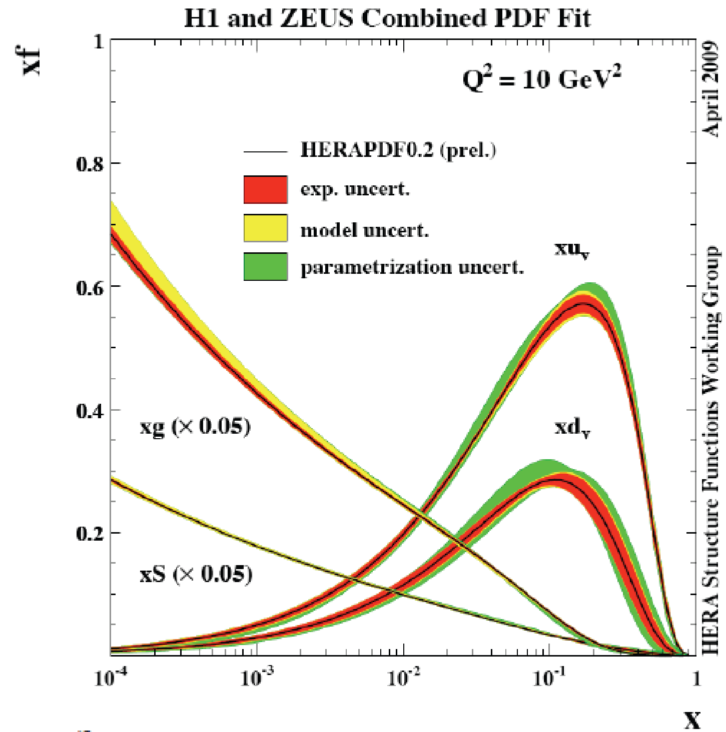
- Restrictive: valence-like gluon at low-x
- Fixed
- Free: Neural-Network approach
- HERA-PDF: allow to vary (for high-x)

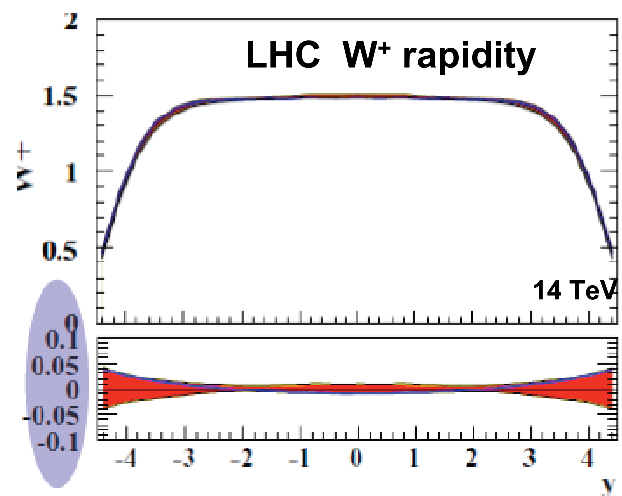
3. Choice of experimental data

- MRSW, CTEQ: fits HERA, fixed target, DY, Jets, ..
  - ➔ Incompatible experiments
    - $\Delta\chi^2 \sim 50$ to compensate for unknowns
  - ➔ Errors of PDF do not have a statistical meaning
- HERA-PDF: only fits own data
  - ➔ excellent understanding, $\Delta\chi^2 \sim 1$
  - ➔ Need to improve on u/d separation
    - with HERA-II data of Z,W exchange, Jets

4. NNLO Alekhin, MRSW

➔ Test PDF with F_L, heavy quark, Jet production





F_L and gluon density

Cross section:

$$\sigma_r \propto F_2 - \frac{y^2}{1+(1-y)^2} F_L$$

F_2 : transversely polar. γ^*

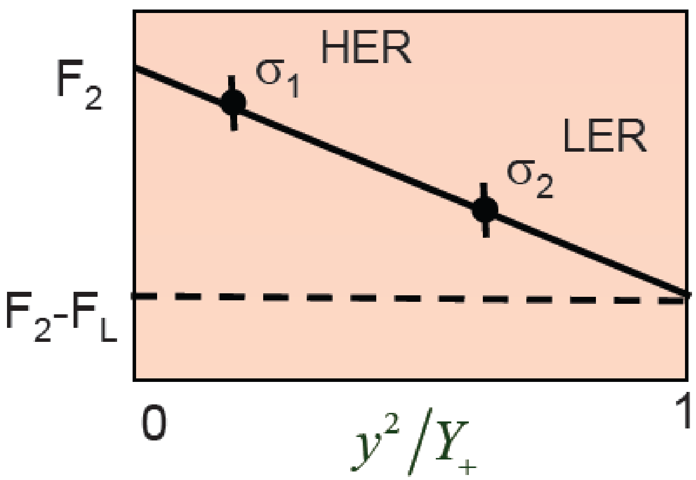
- sea and valence quarks,
- gluon via scaling violations

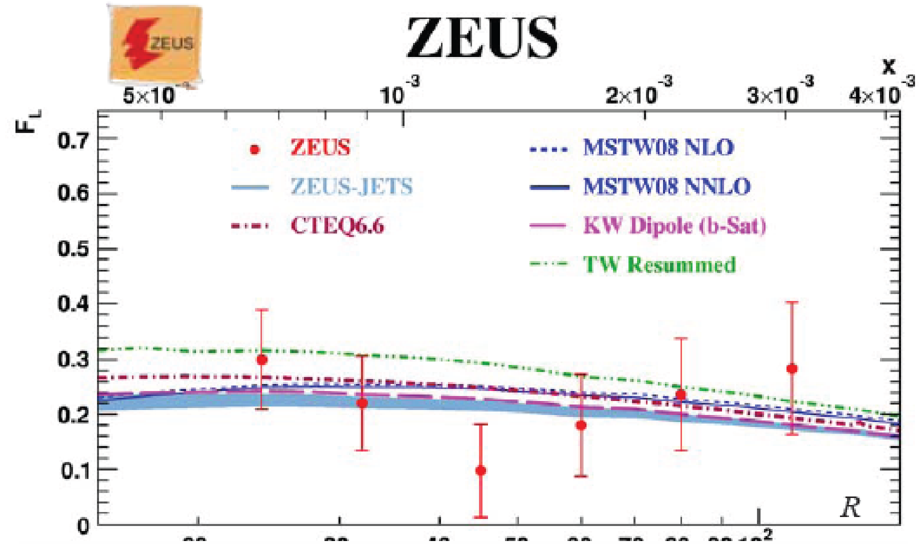
F_L : long. polar. γ^*

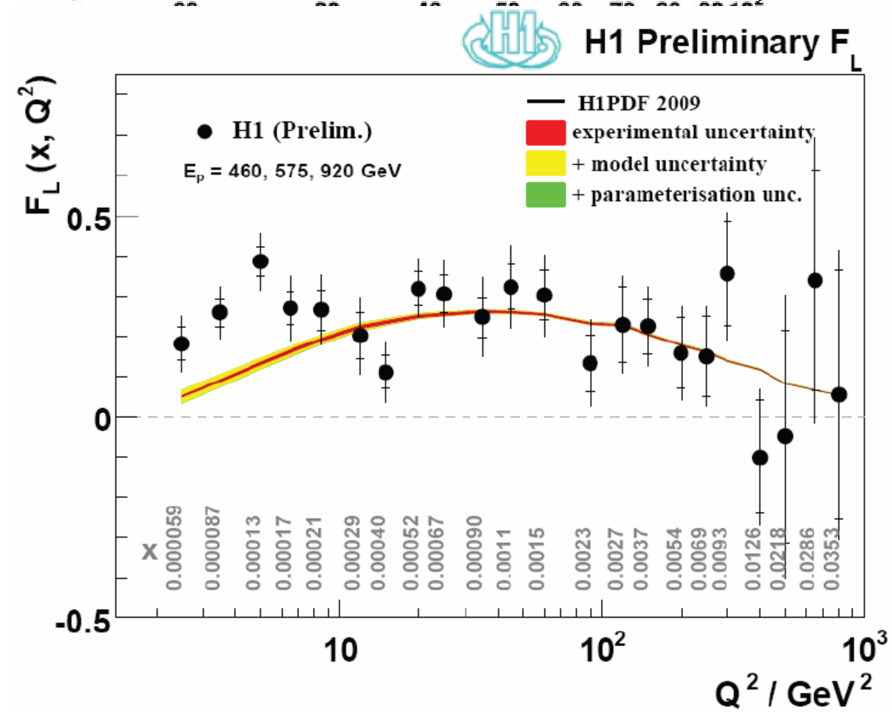
- direct measure of gluon density
- different helicity structure

Disentangle F_2 and F_L

- data at different E_{CMS} (225 … 318 GeV)

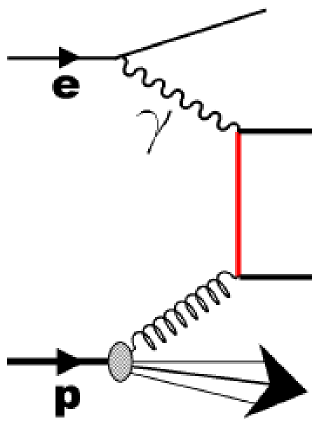






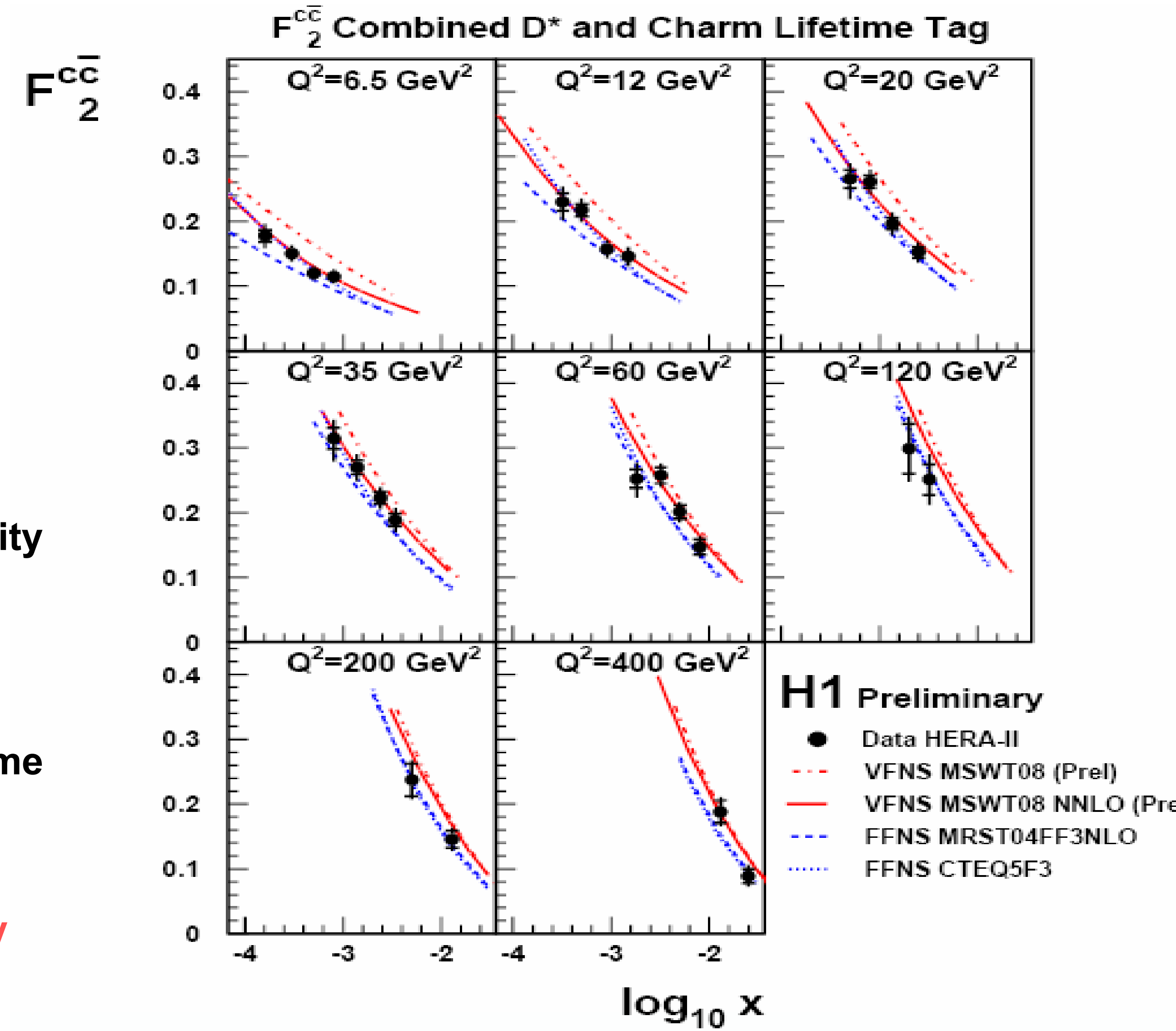
Parton Densities and Charm

Charm Production at HERA

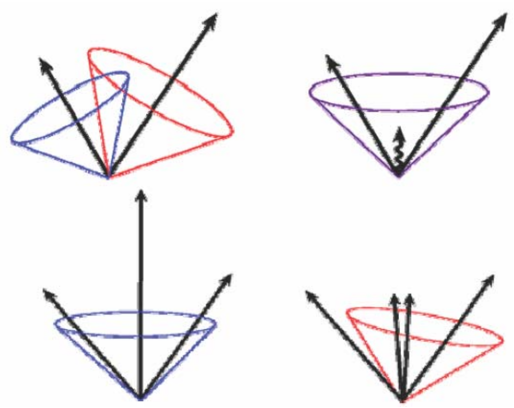


- Depends in LO on gluon density
- NLO known
- multiple scales (m_Q,Q^2, p_T)
  e.g. large logs when Q ≫ m
- Test of Variable Flavour scheme
  massive for $\mu^2 \approx mc^2$
  massless at $\mu^2 \gg mc^2$

➔ Few % check of gluon density and VFNS



Jet Algorithms 1/2



Infrared safe

- Jet reconstruction insensitive to emmission of soft gluons
- Experiments: soft energy from noise, underlying event, pile-up supressed by detector thresholds, B-field

Collinear safe

- Jet reconstruction insensitive to collinear splitting of partons
- Experiments: non-linear calorimeters

➔ **Yes, for experimental and theoretical reasons for cross sections and for searches:**

- discoveries should be safe against noise, underlying event, pile-up, NLO tests

Sequential algorithms: safe

combine particles with min D_{nm}

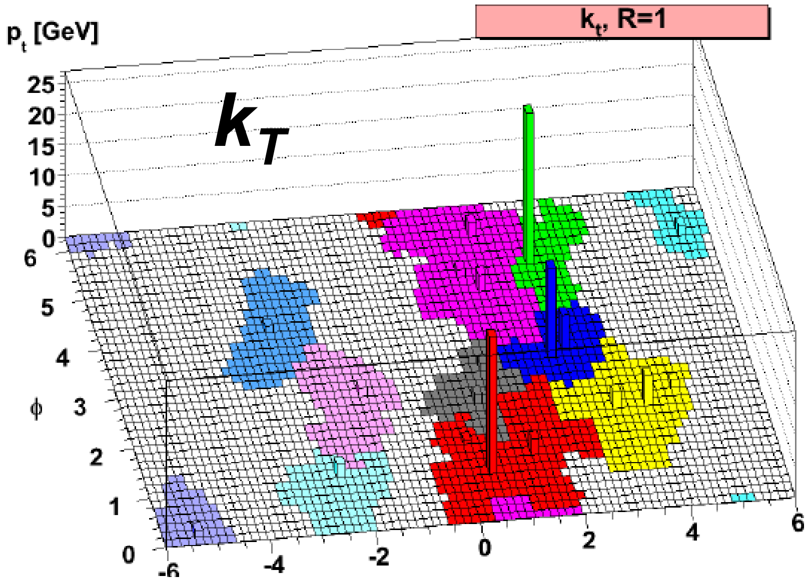
- Durham (e^+e^-) or k_T (ep, pp) — $D_{nm} = min(k_{Tn}^{2}, k_{Tm}^{2})\ R/R_0$ — *low-k_T first*
- anti-k_T (Cacciari, Salam, Soyez 08) — $D_{nm} = min(k_{Tn}^{-2}, k_{Tm}^{-2})\ R/R_0$ — *high-k_T first*

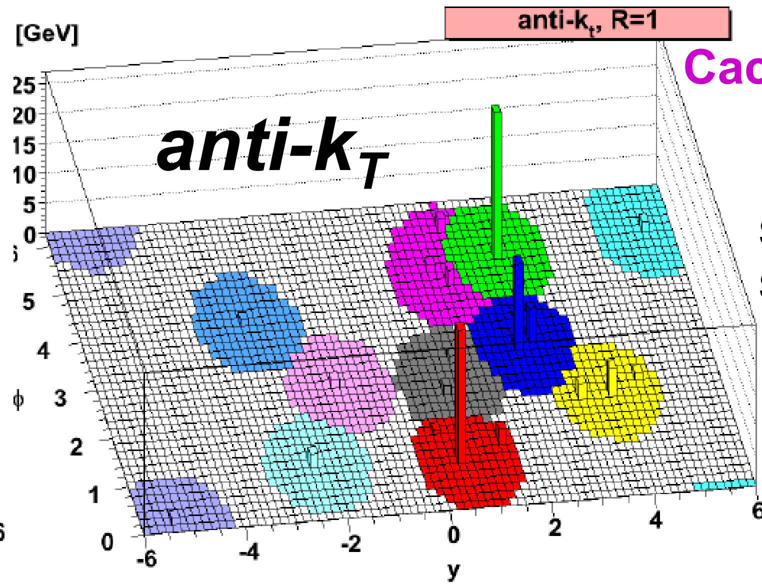
Cone-Algorithms

$$R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

- SisCone: seedless infrared-safe (Salam, Soyez 07)
- Others: not infrared-safe

Jet Algorithms 2/2





Cacciari, Salam, Soyez 08

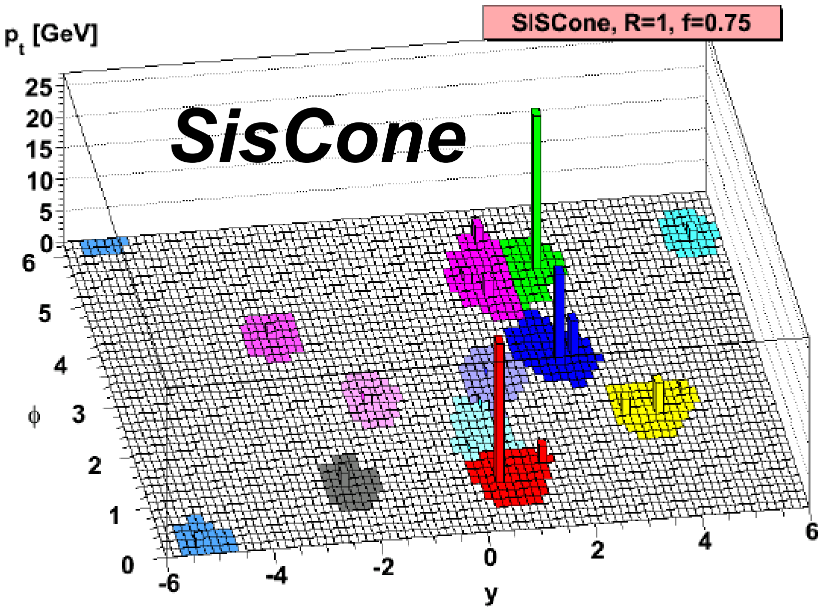
🡐 **toy-event**

Shape like fixed cone

Split: high-Pt jet profits from low-PT jet

Jet counting ?

Subjets ?



Shape ➔ regular is good for pileup, calibration

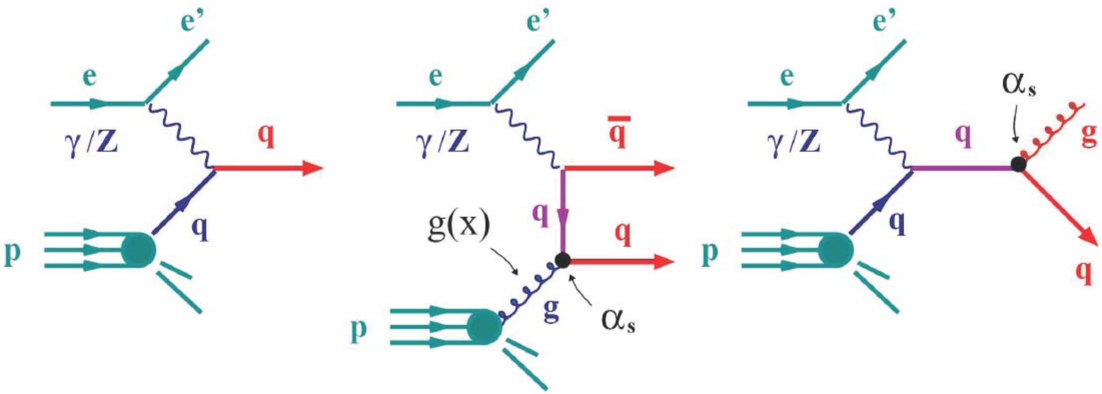
Split/merge ➔ close-by jets, E-sharing, subjets counting

Best choice depends on application

LEP, HERA:	k_T (no pileup, UE)
Tevatron:	other cones ☹ ➔ k_T, (SisCone)
ATLAS:	first anti-k_T, then k_T, SisCone
CMS:	first SisCone, then k_T, anti-k_T

No test yet of SisCone, anti-k_T with real data …

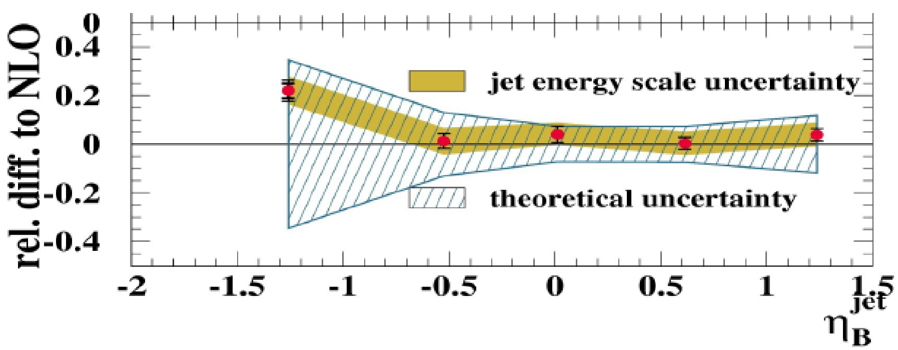
Parton Densities and Jets

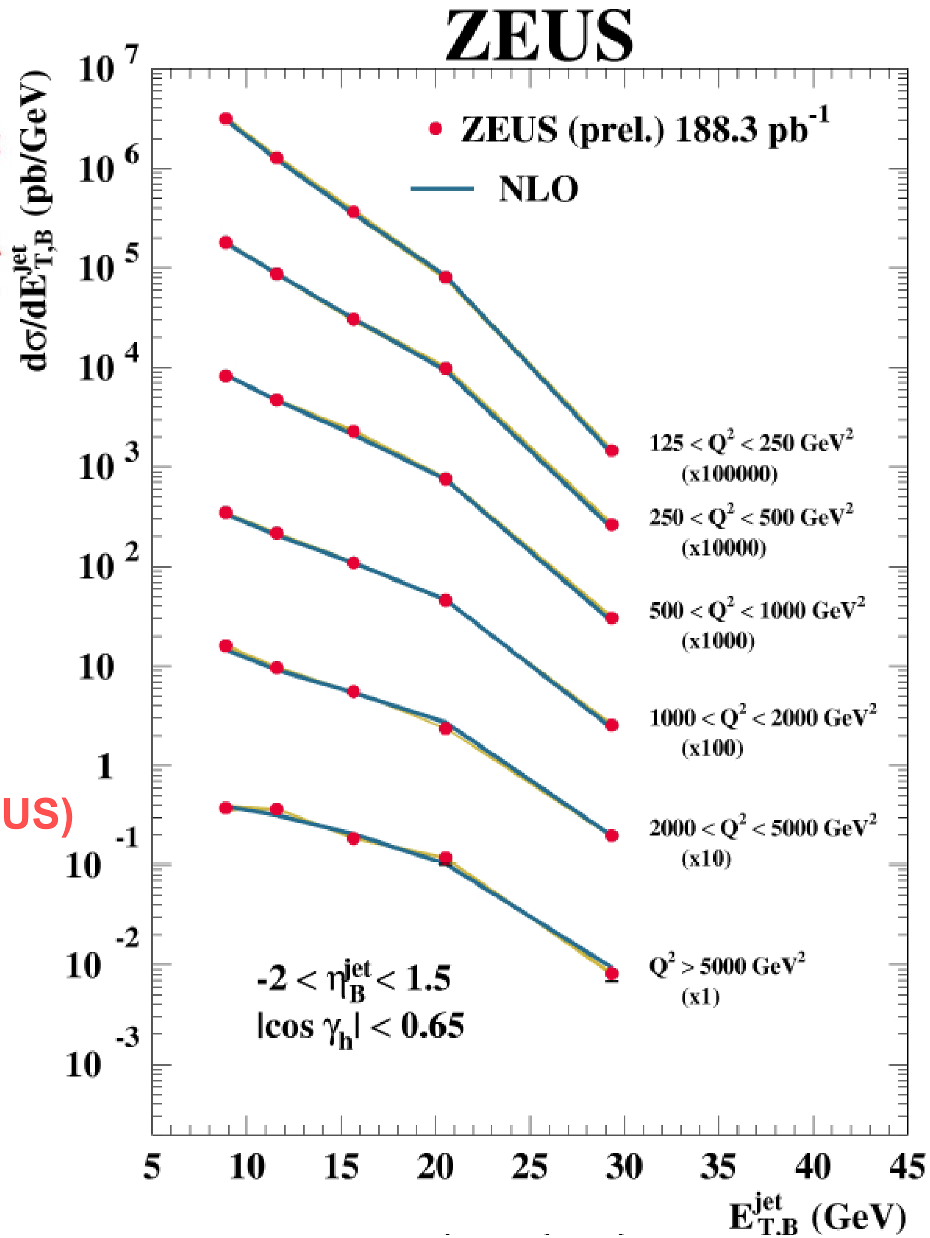


Jets at HERA (k_T algorithm)

- test of QCD factorisation: σ = *PDF x ME*
- NLO calculations for 2,3 Jets
- sensitive to α_s * (gluon + quark-density)
- experimental errors ~ 5%
- theory error at high $E_{T,B}$: PDF dominates

➔ add HERA jets in PDF fits (demonstrated by ZEUS)





Collider Jet Data

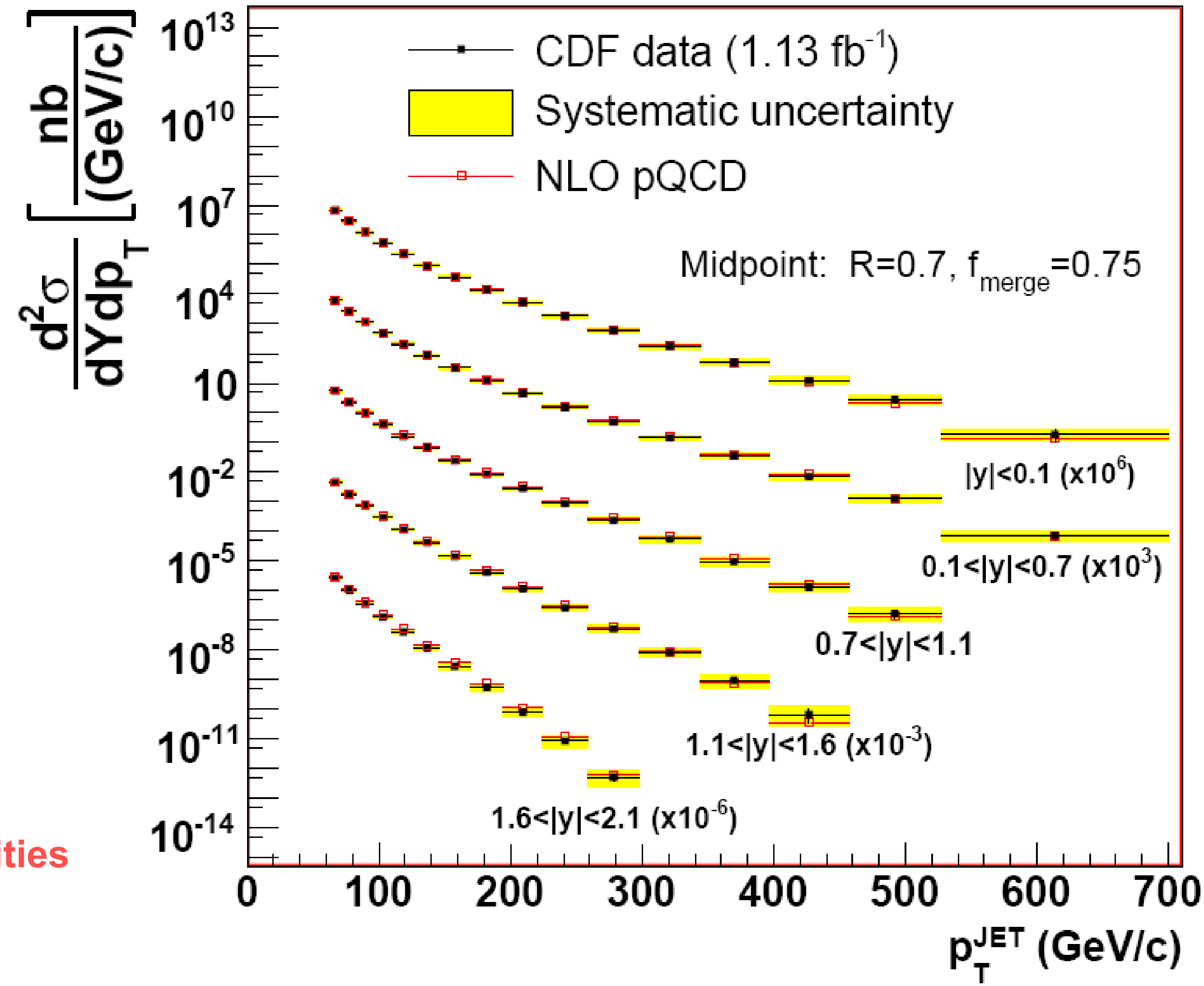
CDF & D0:

- **Much improved calibration and error analysis**

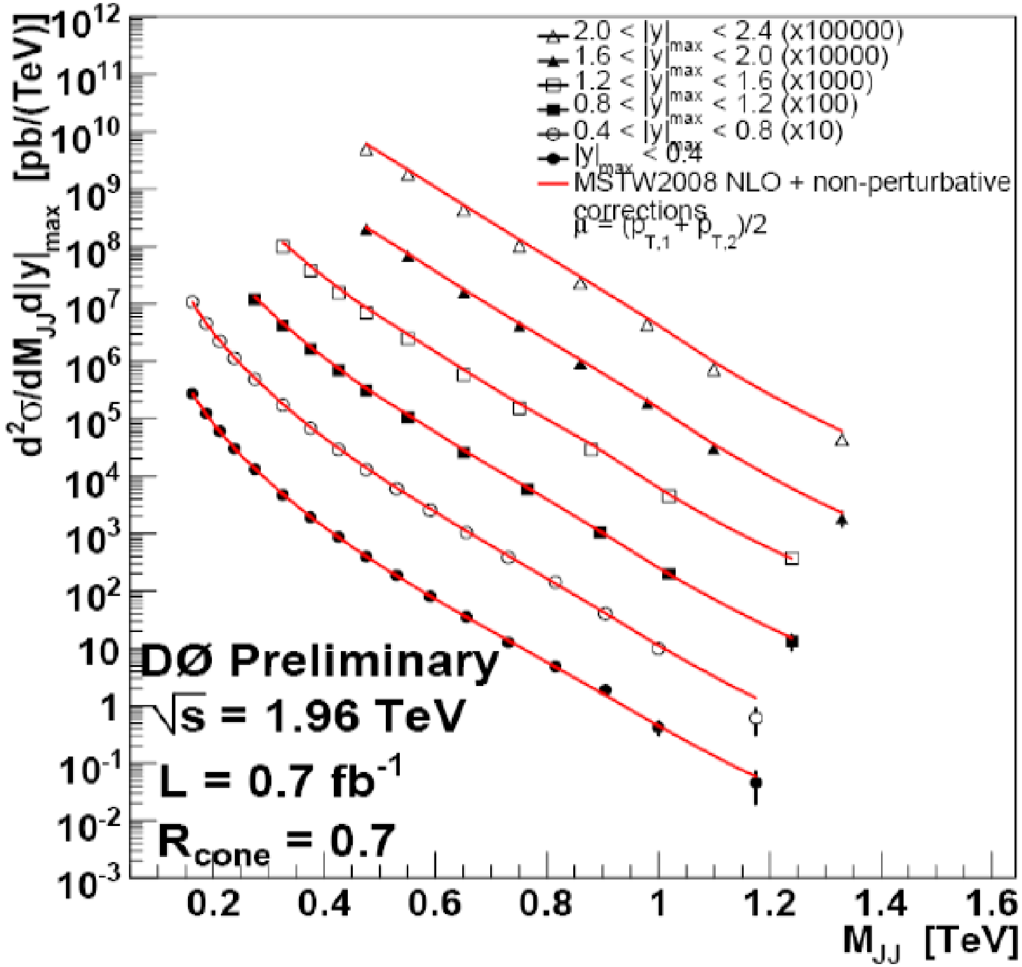
CDF:

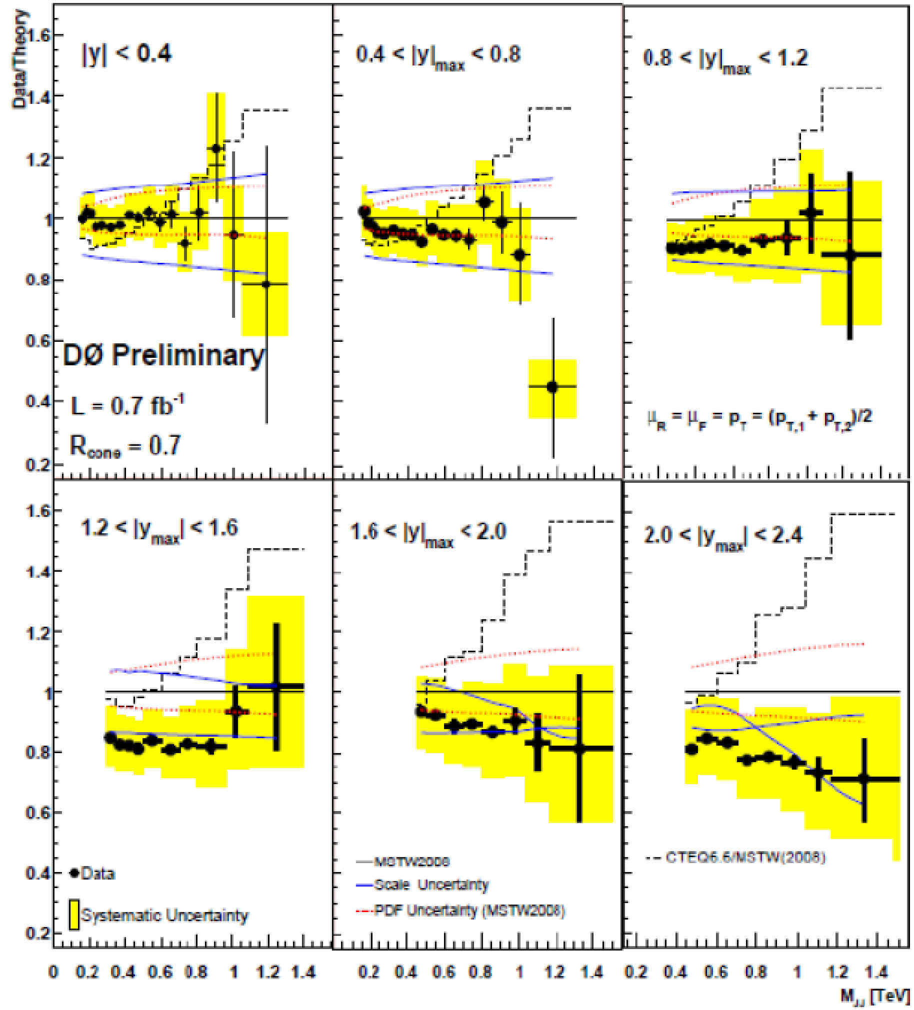
- **Inclusive jet cross-section**
- **Midpoint algorithm for data**
- **„Similar agreement for Kt and SisCone“, dominated by simple 2-jet configurations**

➔ **Input for fits of parton densities**



Collider Jet Data





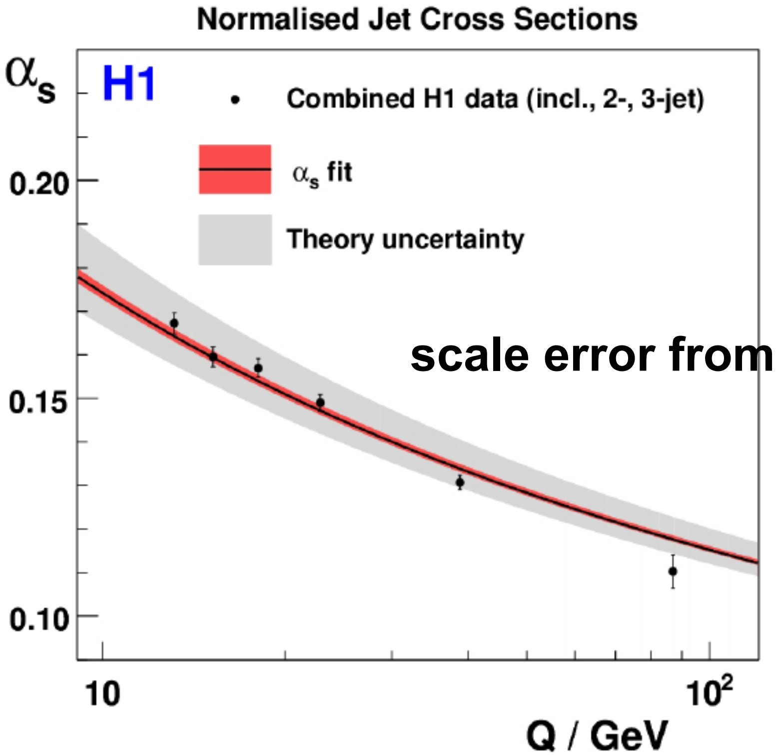
D0: similar size of experimental error, NLO scale uncertainty, and PDF uncertainty used to constrain new physics

Jets and α_s

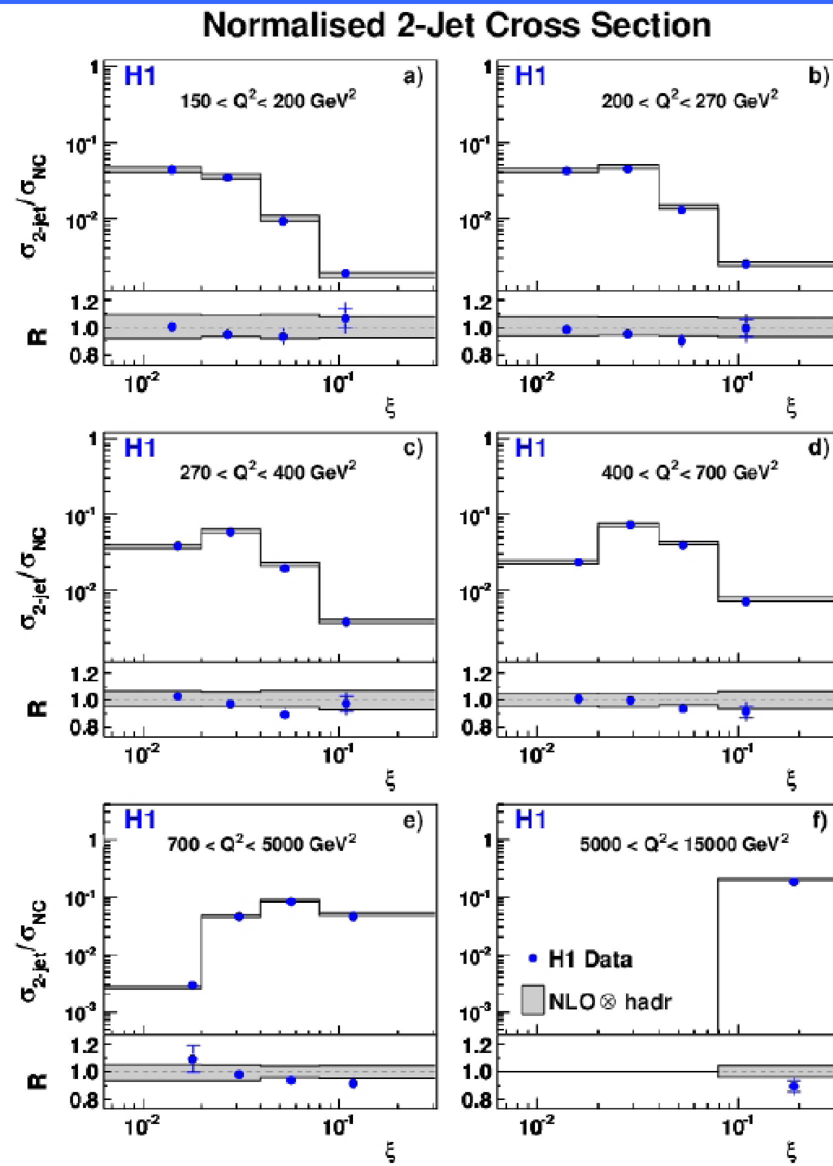
Jet ratios from HERA

- σ(2-jet) / $\sigma_{incl.}$, σ(3-jet) / $\sigma_{incl.}$
- PDF uncertainties cancel in bins of x-parton

precise α_s (M_Z) = 0.1168   ±0.0007 (exp.)
±0.0016 (PDF)
+0.0046 −0.0030 (th.)



scale error from NLO



x - parton

Jets at HERA

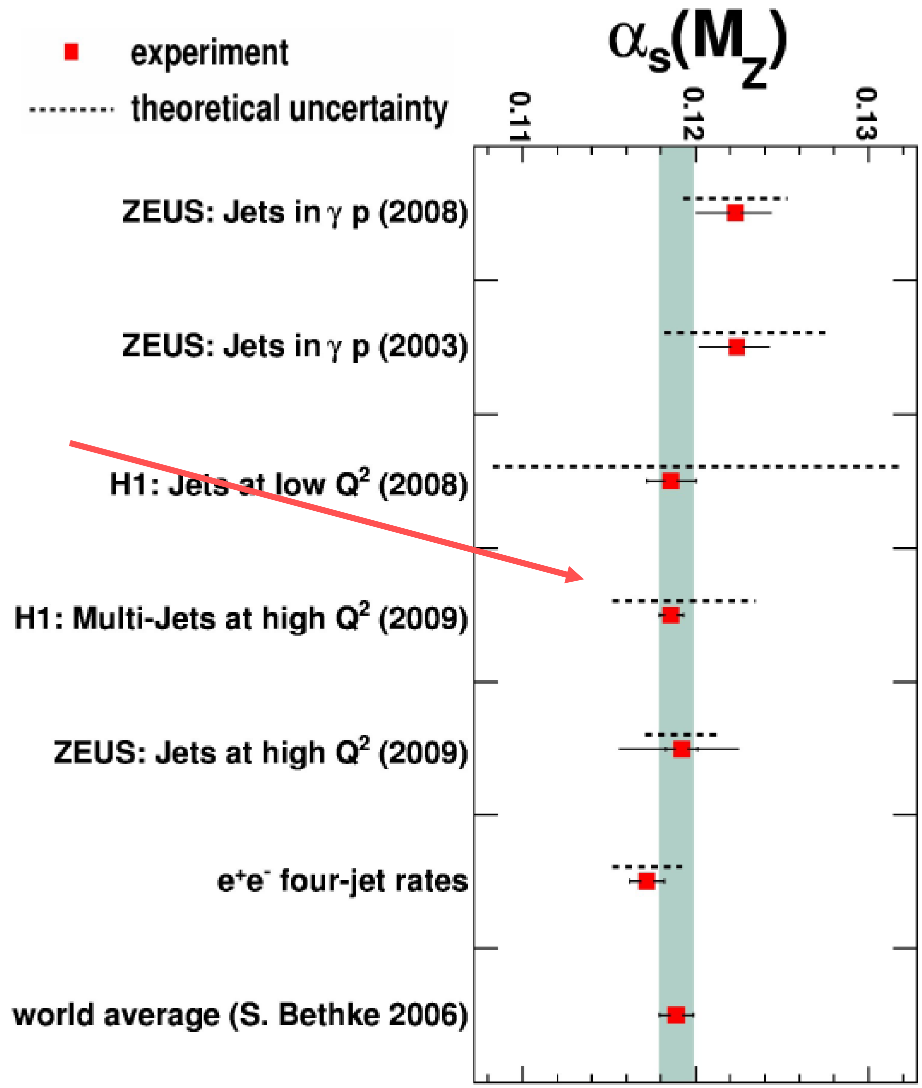
- Inclusive, 2, 3- jets, shaoes, subjets
- Best value so far
- α_s (M_Z) = 0.1168 ± 0.0007 (exp.)
- ± 0.0016 (PDF)
- + 0.0046 −0.0030 (theo.)
- Progress on α_s and PDF requires NNLO

Event shapes at LEP

Dissertori et al, arXiv:0906.3436

see talk by Anastasiou

- first NNLO+NLLA
- ~ 5% spread between observables
- α_s (M_Z) = 0.1224 ± 0.0014 (exp)
- ± 0.0012 (had)
- ± 0.0035 (theory)



Multi-Leg Monte Carlos

Top, Higgs, Susy:

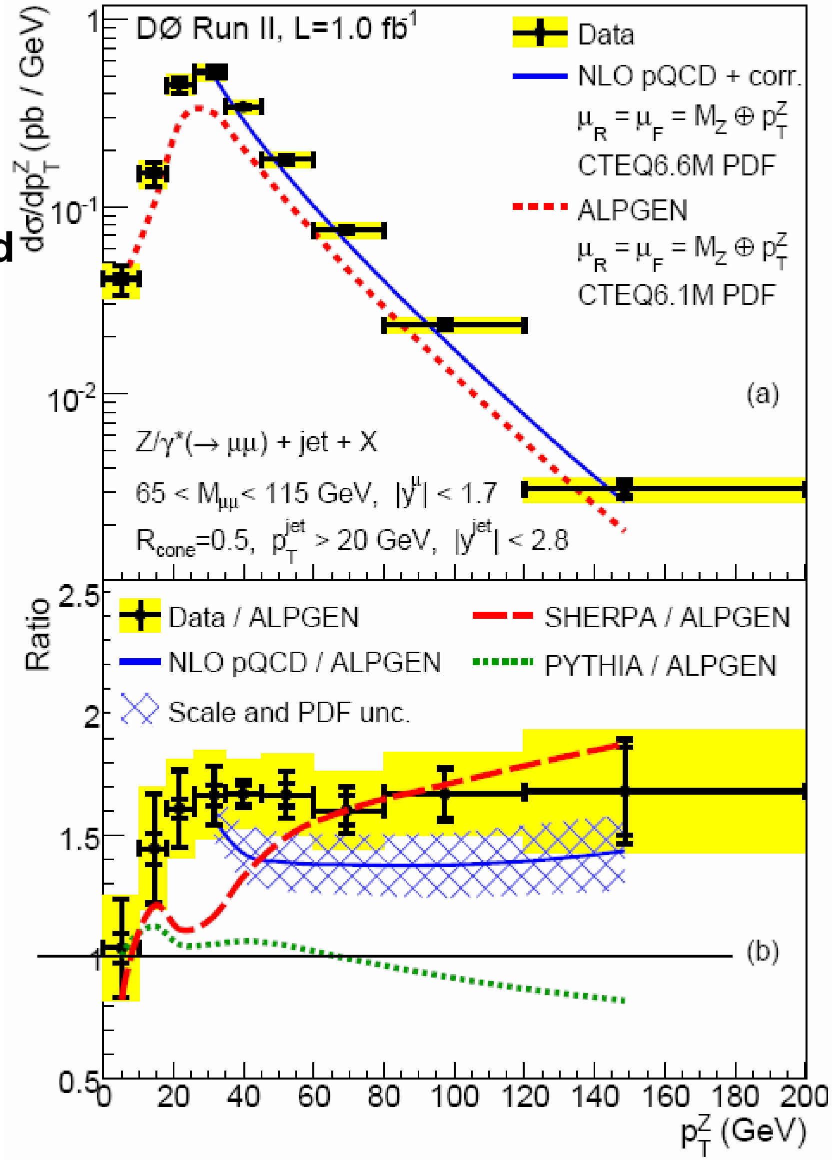
- complicated analysis
- very sensitive to proper modelling of kinematics
- Tevatron, LHC potential can only be fully exploited with excellent multi-leg Monte Carlos

Monte Carlo:

- LO 2 → 2 + PS has dominated the field (Pythia, Herwig)
- LHC: LO multi-leg Monte Carlos widely used (Sherpa, Alpgen, MadGraph, …)
- Interface between Parton-Showers and NLO MC@NLO, …

Tevatron Z + jet analysis

- Midpoint algorithm
- above P_{TZ}>30 GeV
  - NLO agrees within errors
  - Alpgen, Pythia predict lower cross sections (1.7)
  - SHERPA has different slope in PT



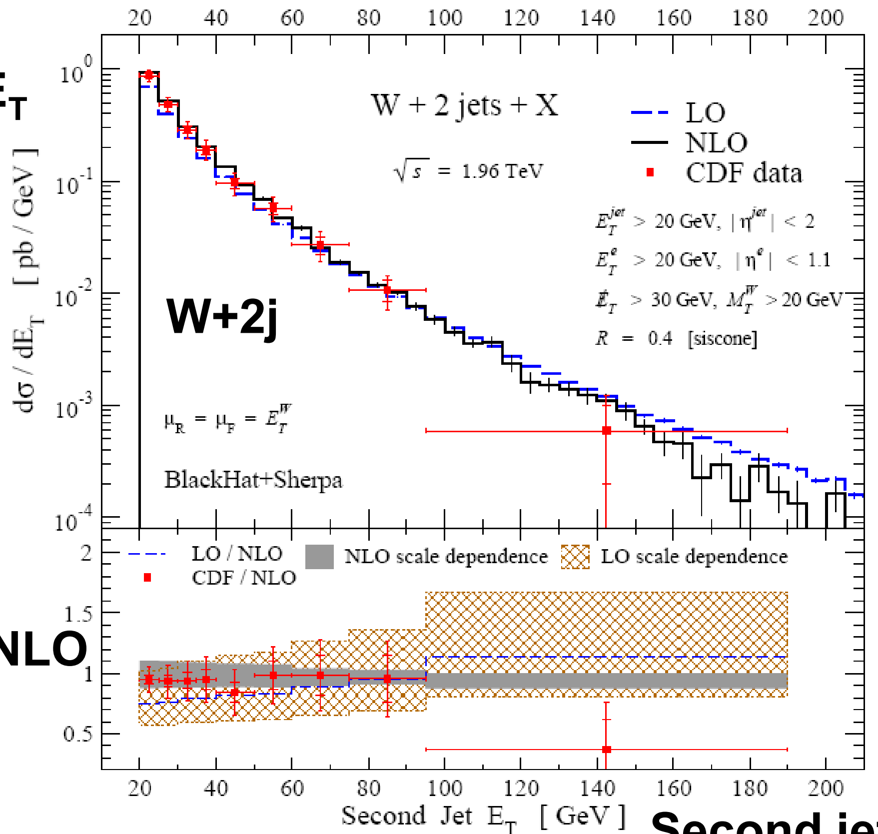
Multi-Leg NLO

New techniques for multi-leg NLO calculations (see talk by Anastasiou)

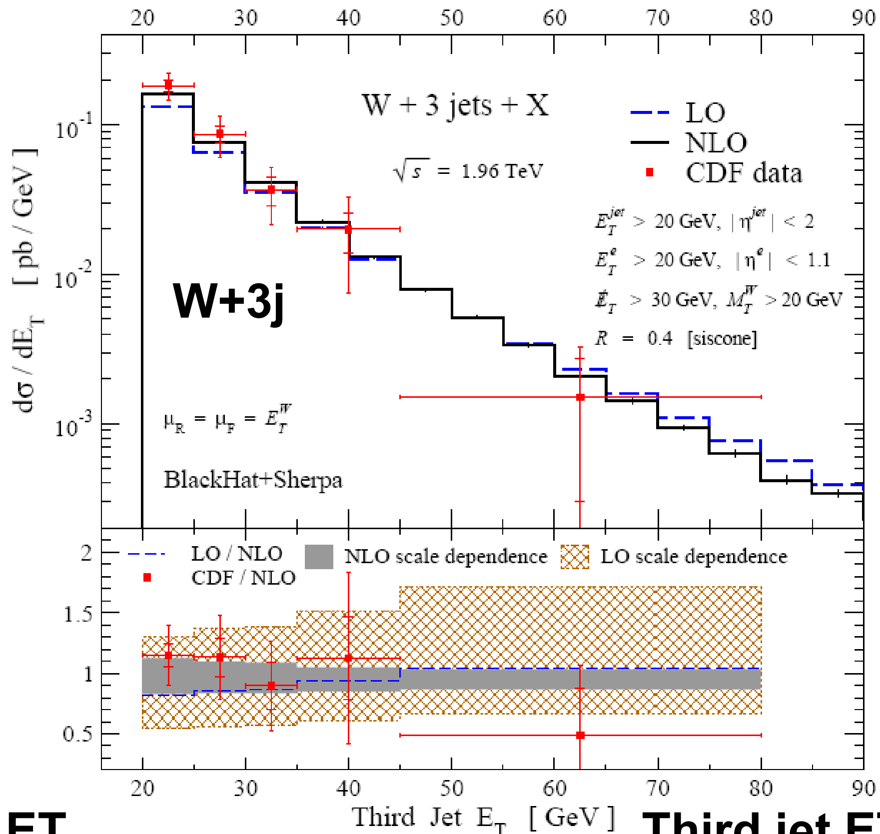
- full NLO for W+3jet at Tevatron — Berger et al, arXiv:0907.1984
- Much reduced scale uncertainty (~10%)
- NLO: SisCone CDF: JETCLU $0.32\ fb^{-1}$
- First successful test of NLO automation, much more precise data to come

$d\sigma / dE_T$

data / NLO



Second jet ET

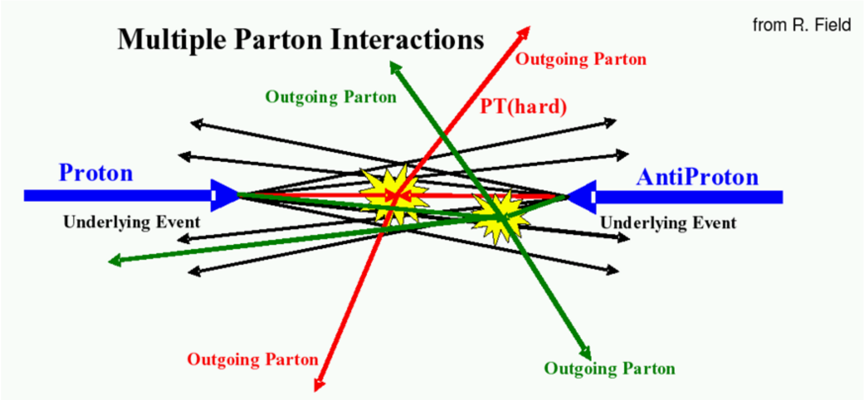


Third jet ET

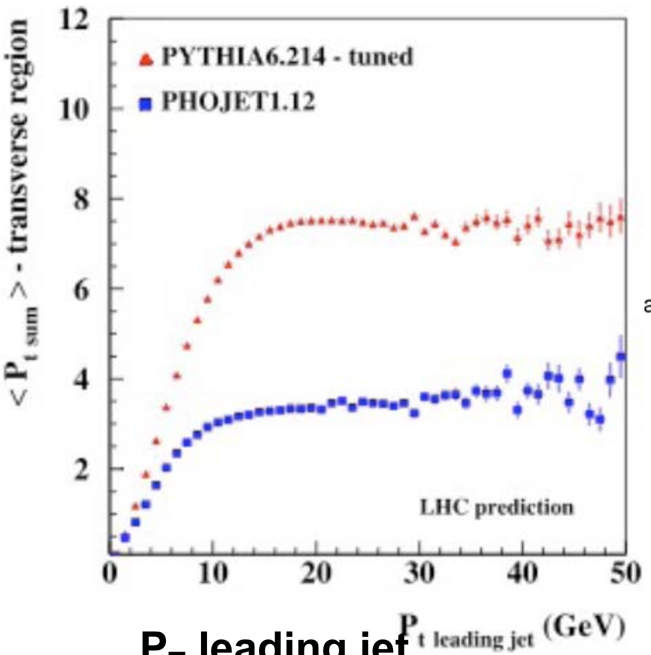
Underlying Event

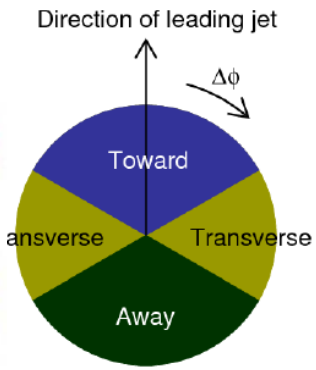
- Large correction to jet rates at Tevatron
- Models, no firm QCD predictions
- Needs to be measured in early data a la CDF, D0

➔ Mean values and fluctuations



$\langle P_T \rangle$ in transverse region

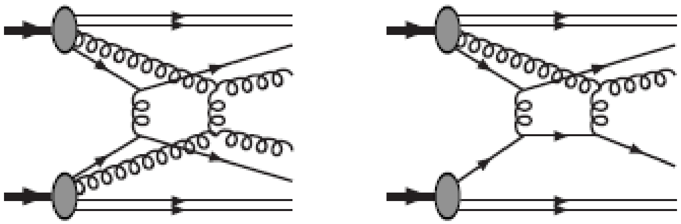




P_T leading jet

Modelling of Underlying event

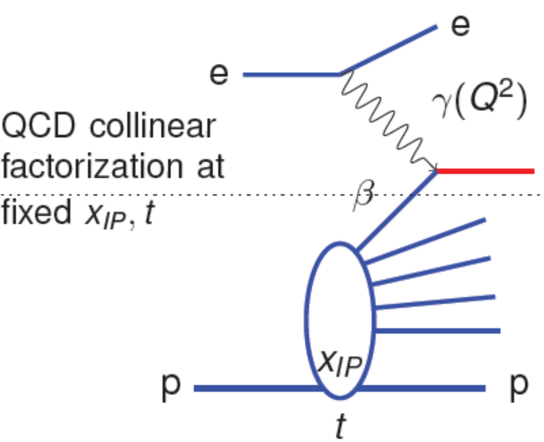
- Multi-parton interaction (MPI) or rescattering



- CDF,D0 measure topology of γ +3jet
- 25% of events due to MPI at P_{TJ2} = 25 GeV

Physics of MPI strongly related to low-x physics, transverse proton structure, skewed PDF, diffraction, …

Diffraction



Exclusive hard scattering

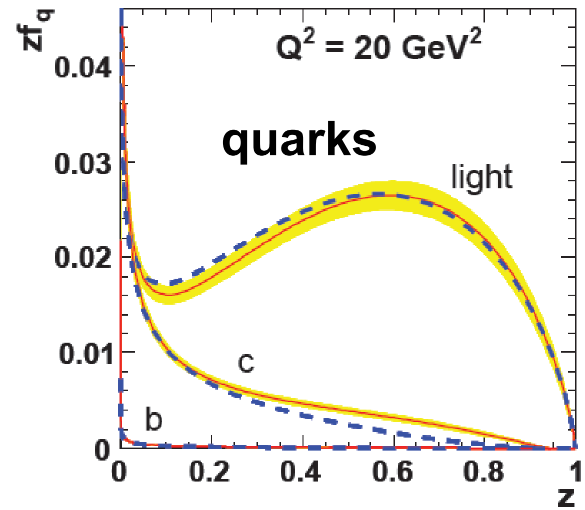
- ep → ep +X
- QCD factorisation (Collins)
- Test Universality via NLO QCD fit
- works for inclusive, 2-jet, charm

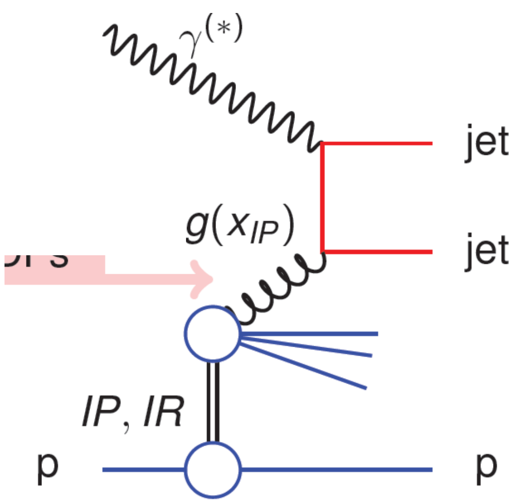
HERA: Consistent picture

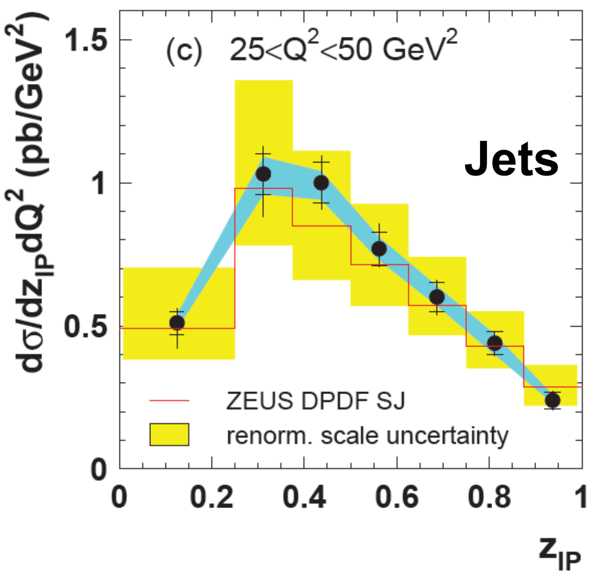
Gluon dominated process

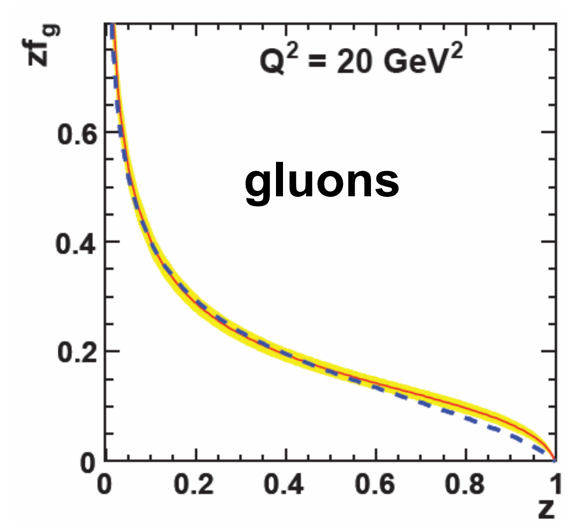
Tevatron:

Needs large non-pert. corrections

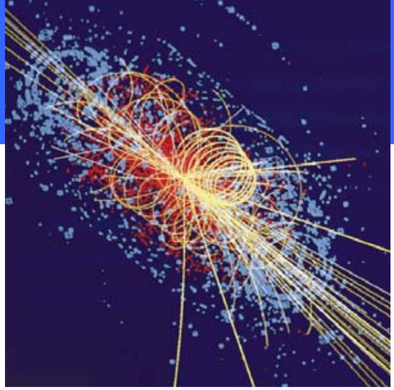








Conclusion



Parton densities:

- big step seen in HERA-PDF from combining HERA-I data,
- HERA-II will improve at high-x
- major improvement will need NNLO for jets in ep collisions: eq→e jj, also for α_s

Legs and Loops:

- ground breaking new developments for NLO with 3,4 … legs
- tests at Tevatron require (again) change of jet cone algorithms
- physics program of LHC requires excellent understanding of multi-leg (NLO) Monte-Carlos

Soft processes:

- Underlying event and minimum bias processes poorly modeled
- Hopefully not a bottleneck for understanding first LHC data

- **New QCD toolbox needs to be tested / tuned at Tevatron and HERA**

- **QCD at LHC will be much more exciting than anticipated with these tools in place**

LHC program for start-up

- Underlying Event
- Jet Shapes
- Dijet Angular Decorrelation
- Inclusive Jet Cross Section
- Dijet Mass and Ratio, Angle
- Event Shapes
- Multi-Jets