From HERA

to LHC

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DESY Zeuthen

Overview

1. Structure functions + parton distributions
   gluon, α_s
   W,Z, H, $\bar{t}t$ cross section precision

2. Heavy Flavors
   c,b content of proton

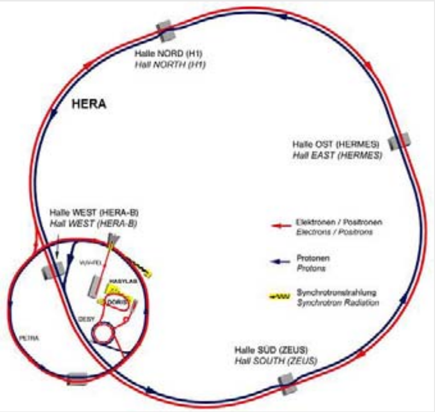
3. Diffraction

4. Final states
   multiple interactions
   underlying event

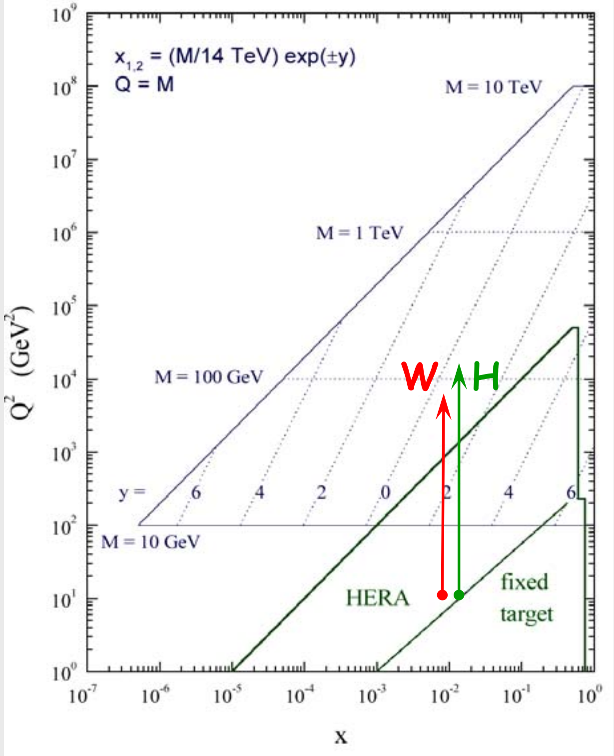
5. MC tools

HERA versus LHC

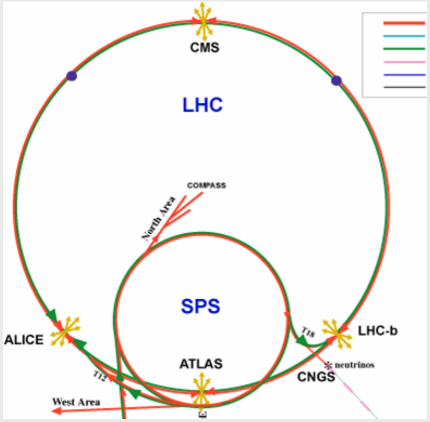
ep $\sqrt{s}$ = 320 GeV



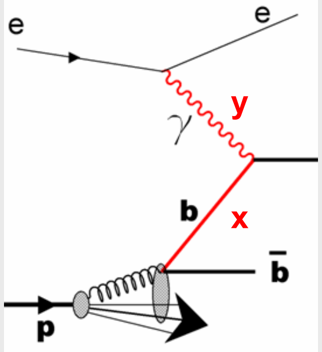
proton structure, QCD



pp $\sqrt{s}$ = 14 TeV



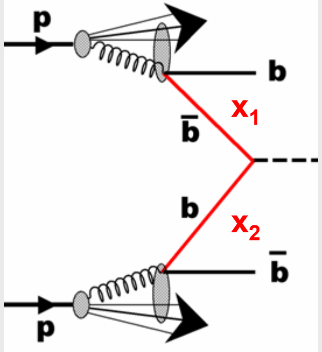
Higgs, SUSY,… QCD backgr.



$\sqrt{(Q^2/s)} = \sqrt{(xy)} \sim 0.01$

for $Q^2 \sim 10\ \mathrm{GeV}^2$

evolve PDFs in ln Q^2



$\sqrt{(M^2/s)} = \sqrt{(x_1 x_2)} \sim 0.01$

for $M \sim 140$ GeV

LHC is a p-p collider

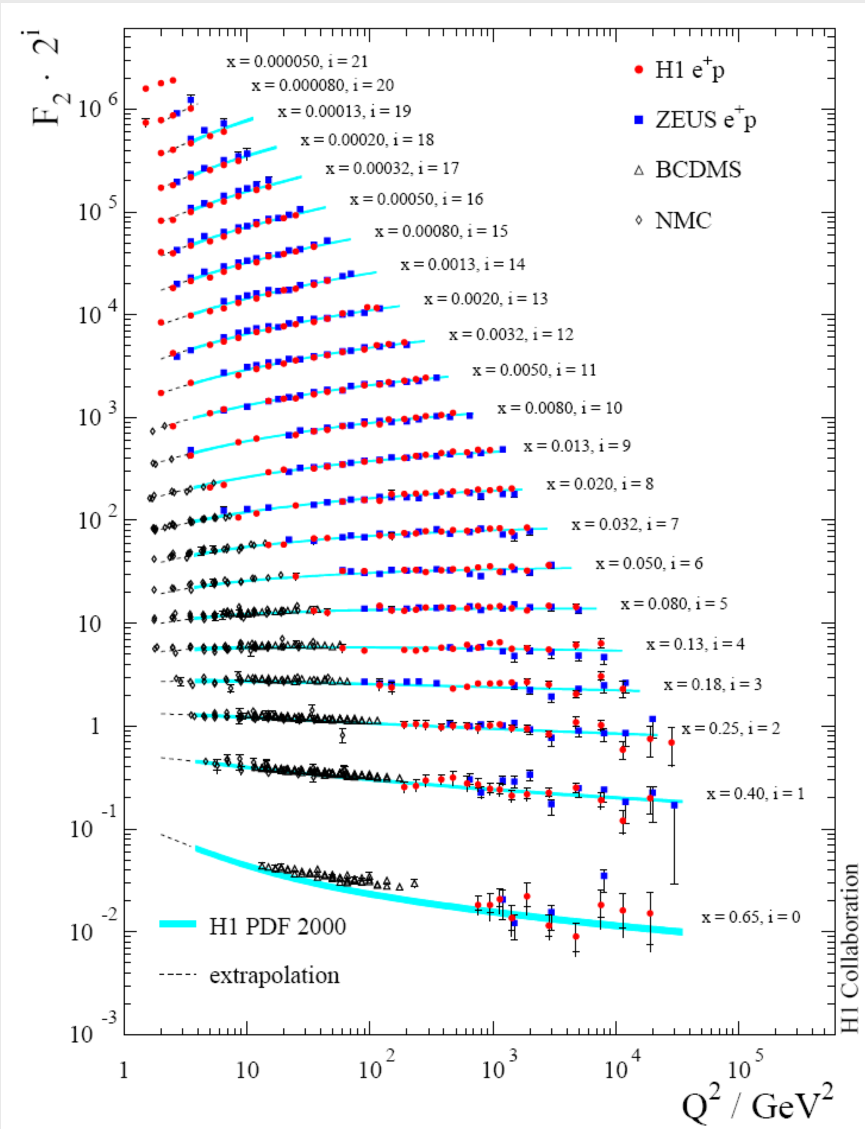
but fundamentally we have
parton-parton scattering:

need precise PDF (x,Q^2) +
their QCD evolution
to highest order

parton-parton luminosities
and energies $\hat{s}$

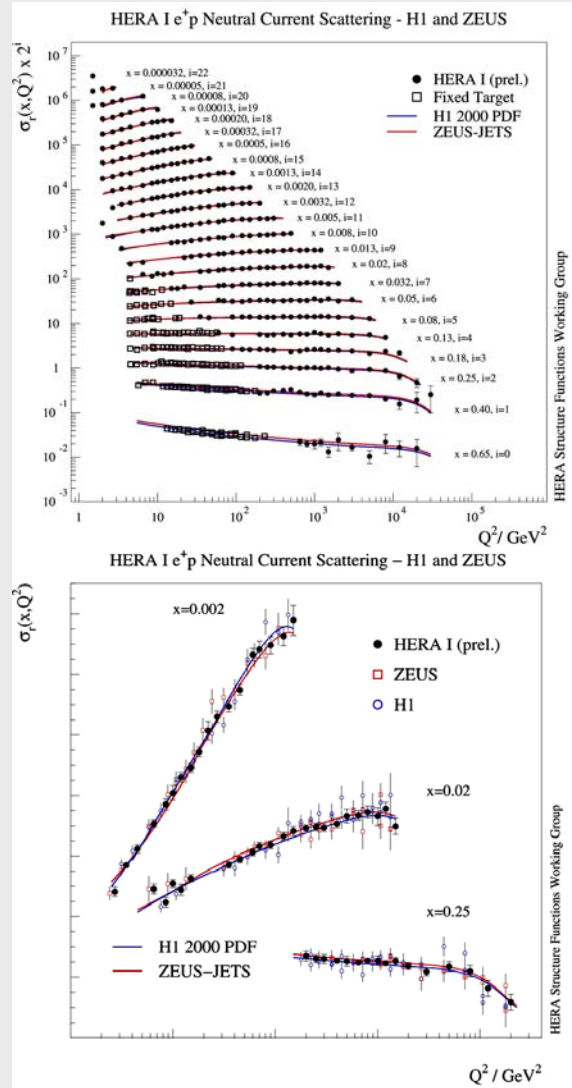
The HERA legacy

H1,ZEUS: F_2 precise to 2–3%



Lepton-Photon 07: H1prelim-07-007, ZEUSprel-07-026.

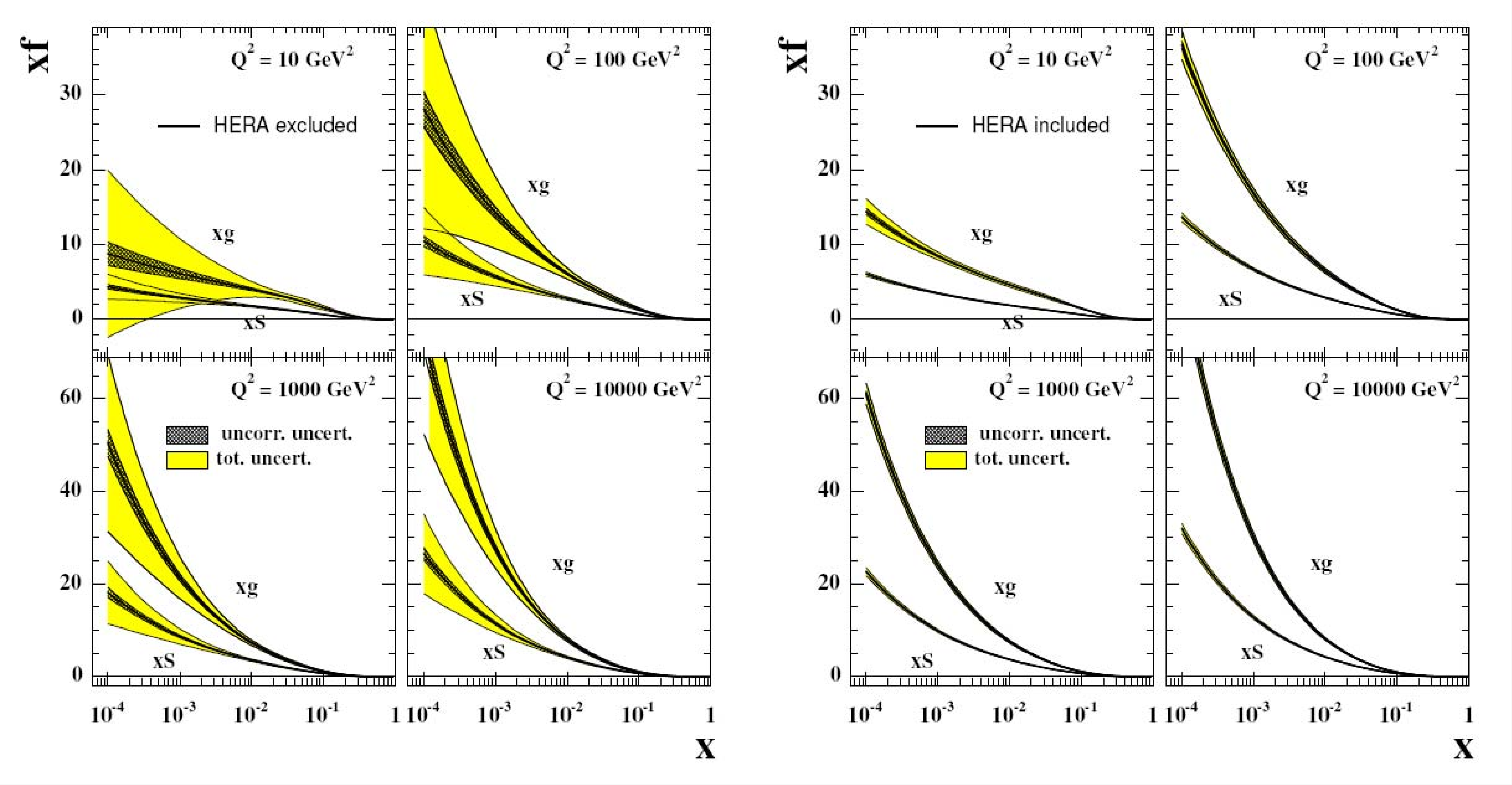
HERA1 combined:



HERA2 final: 1–1.5%

The HERA legacy: PDFs

before HERA the gluon after HERA



Cooper-Sarkar et al., HERA-LHC WS 2005

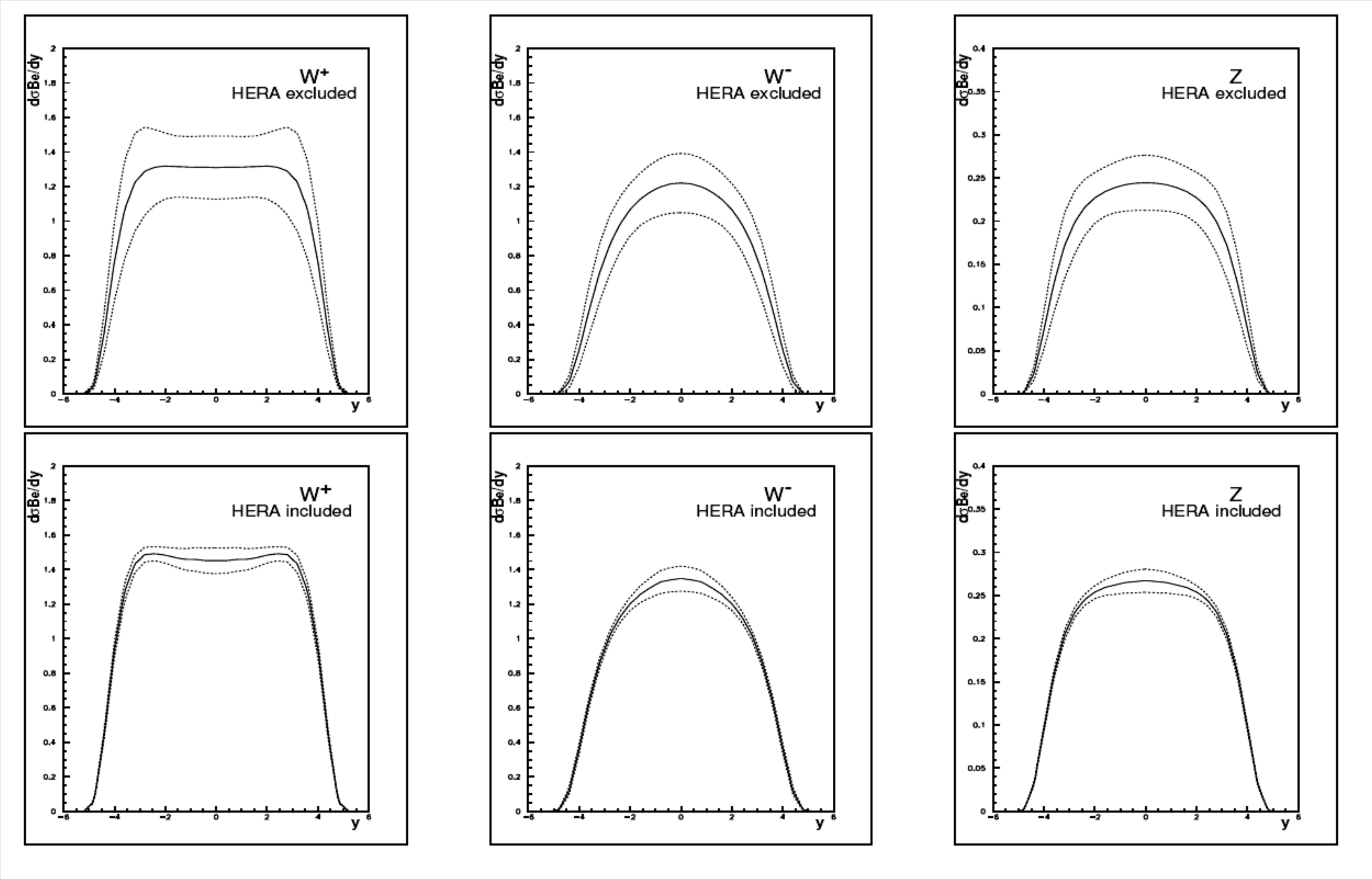
LHC W,Z production

pre HERA:

~15% error

post HERA:

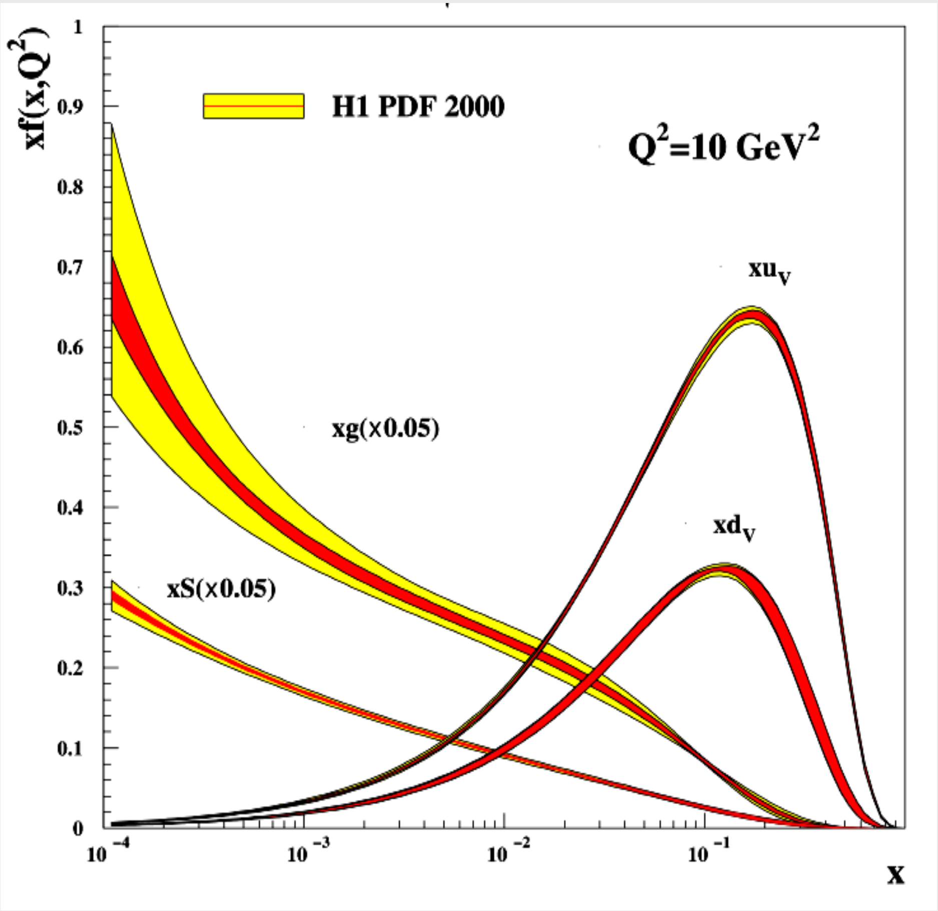
~5% error



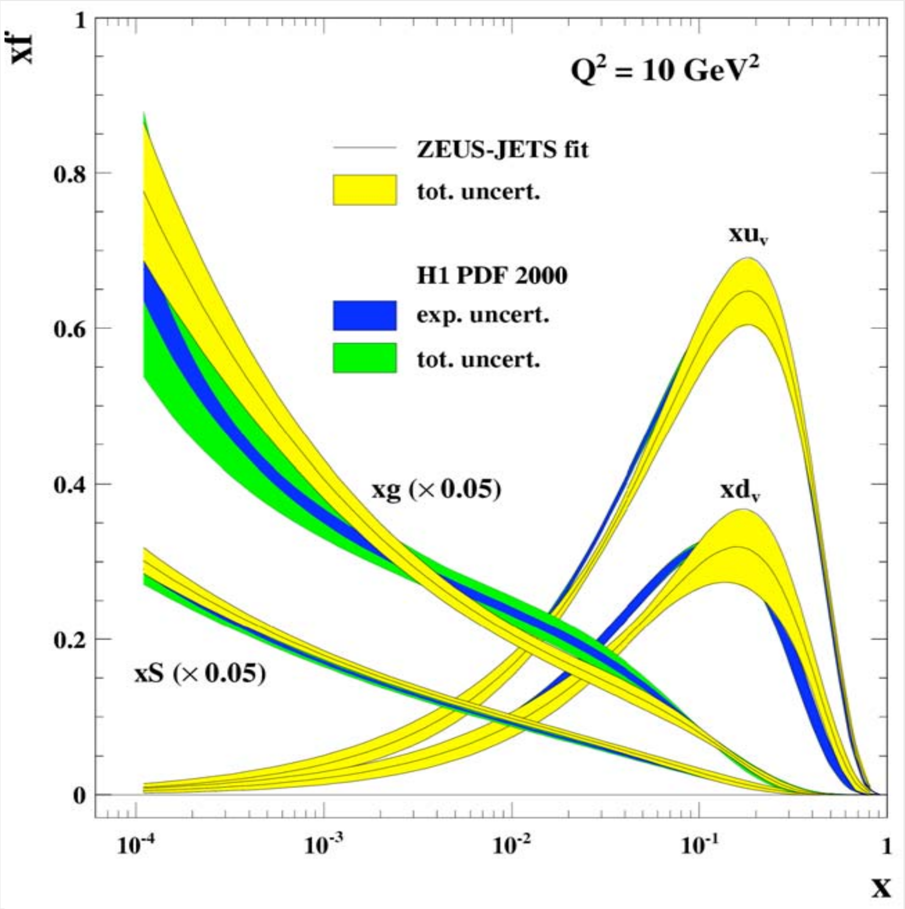
Cooper-Sarkar et al., HERA-LHC WS 2005

$Q^2 = 8315\ GeV^2$

HERA1



xf(x,Q²)
H1 PDF 2000
Q²=10 GeV²
xu_V
xd_V
xg(×0.05)
xS(×0.05)
x

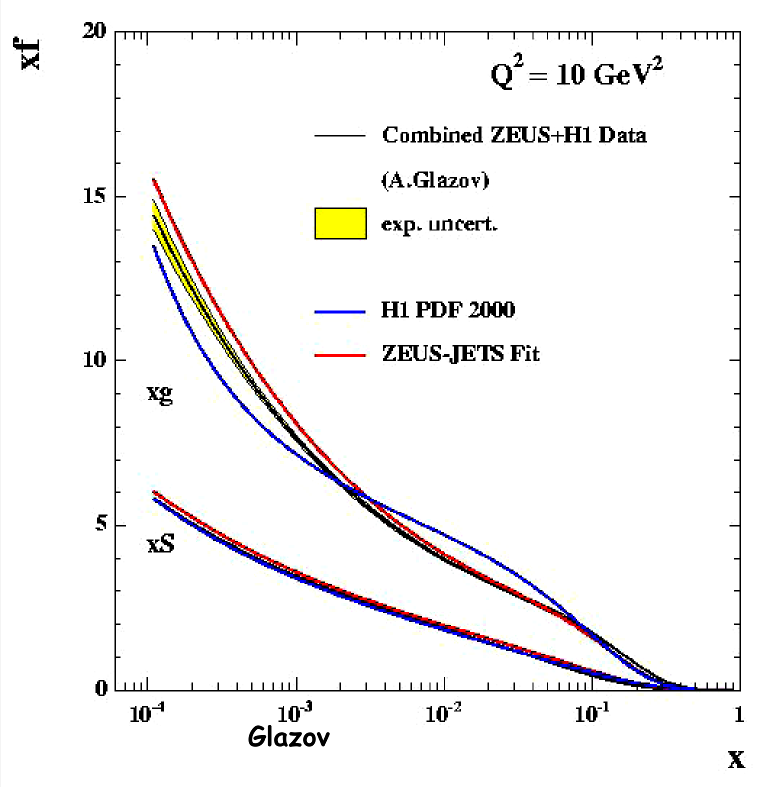


xf
Q² = 10 GeV²
ZEUS-JETS fit
tot. uncert.
H1 PDF 2000
exp. uncert.
tot. uncert.
xu_v
xd_v
xg (× 0.05)
xS (× 0.05)
x

HERA combined

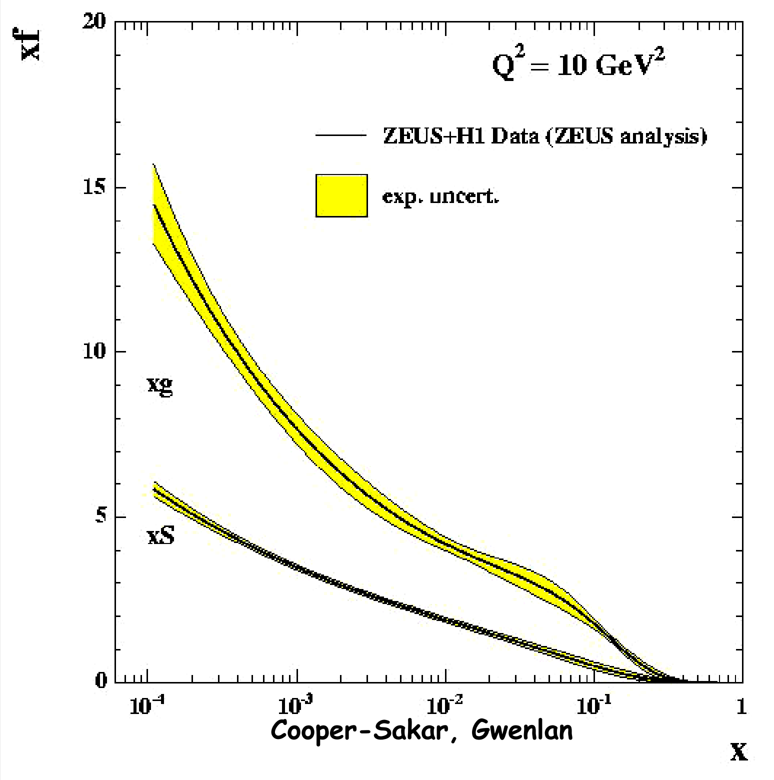
H1

combine H1+ZEUS data + fit



ZEUS

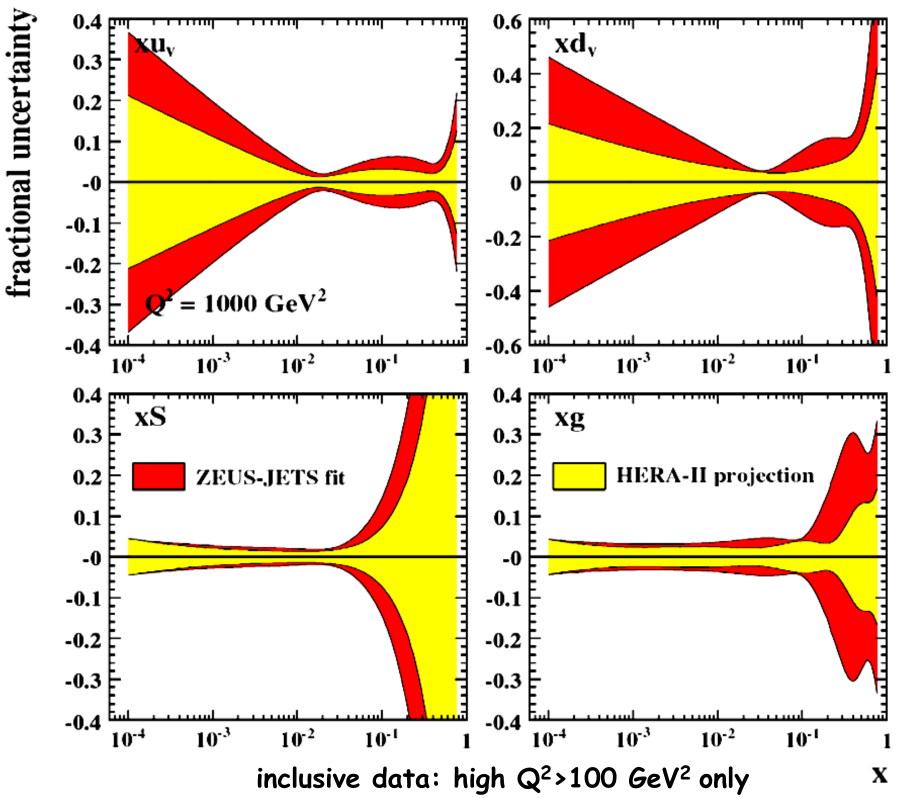
combined PDF fit to H1+ZEUS data



much reduced errors, but reveals gluon uncertainty !

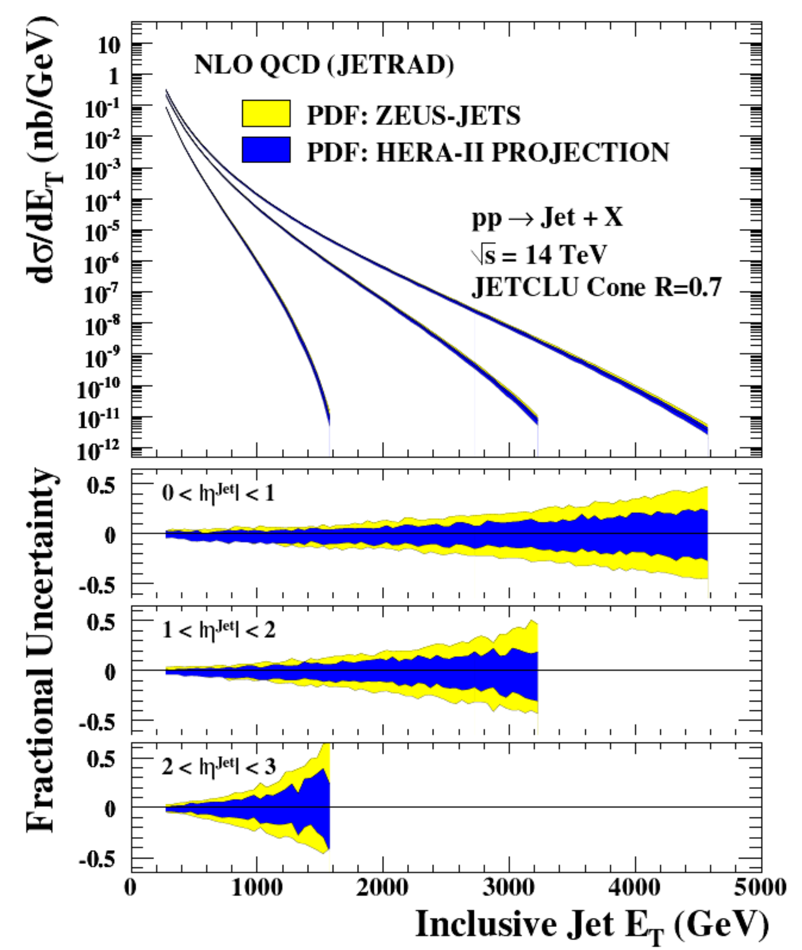
get final HERA PDFs !

- combine H1+ZEUS: lumi ~700 pb^{-1}
- combine with jets
- only more statistics, no better syst.:



inclusive data: high Q^2>100 GeV^2 only

T.Carli et al., Exptl. det. of PDFs, HERA-LHC WS 2005, p.78

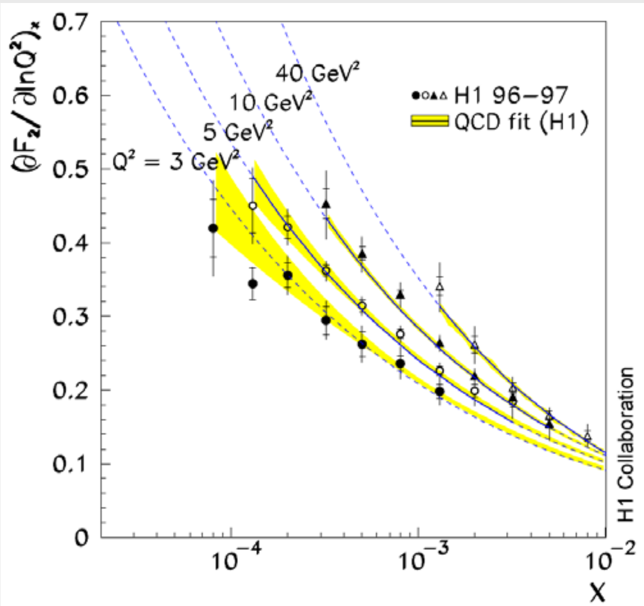


C. Gwenlan et al., hep-ph/0509220

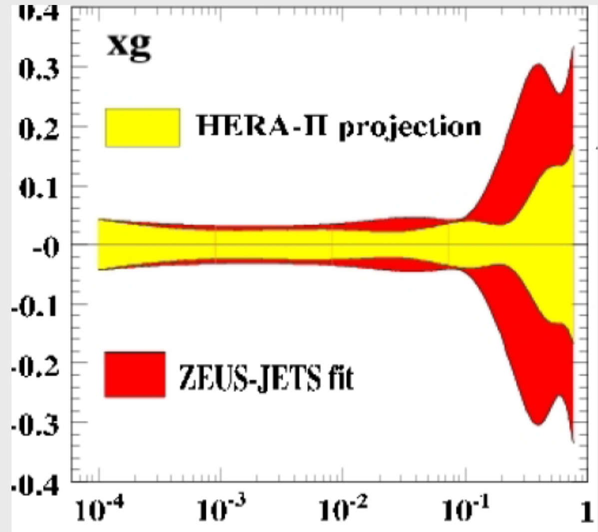
smaller error on LHC jet cross sections + New Physics !

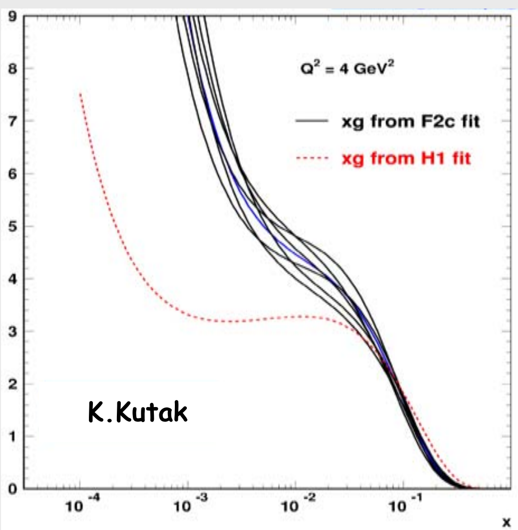
The Gluon

LO: $\partial F_2/\partial \ln Q^2 \sim \alpha_S(Q^2)\, xg(x,Q^2)$



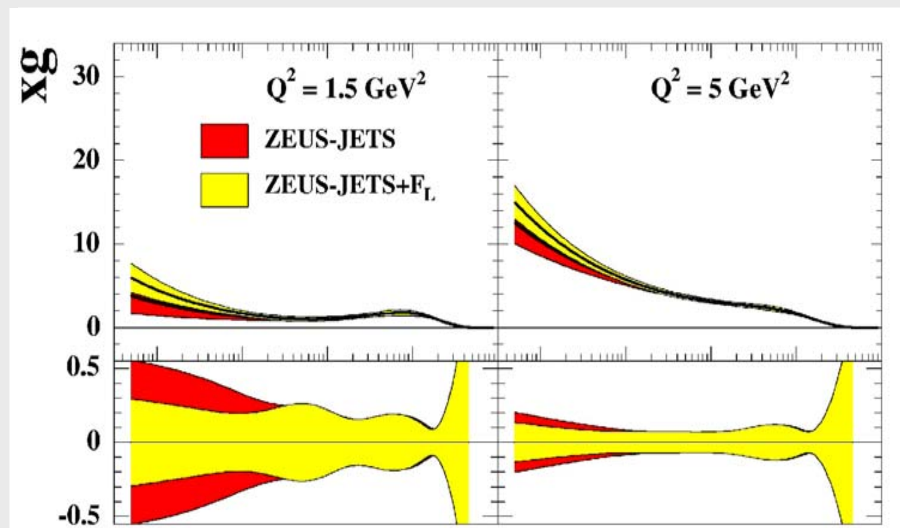
jet cross sections: g(x) at high x





F_2^c and F_L

constrain
g(x)
at low x



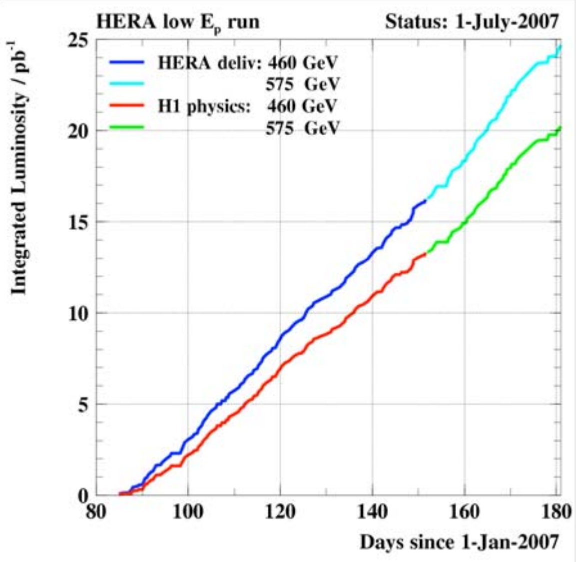
Feltesse, Gwenlan, Glazov, Klein, Moch, HERA-LHC WS 2005.

F_L and Gluon

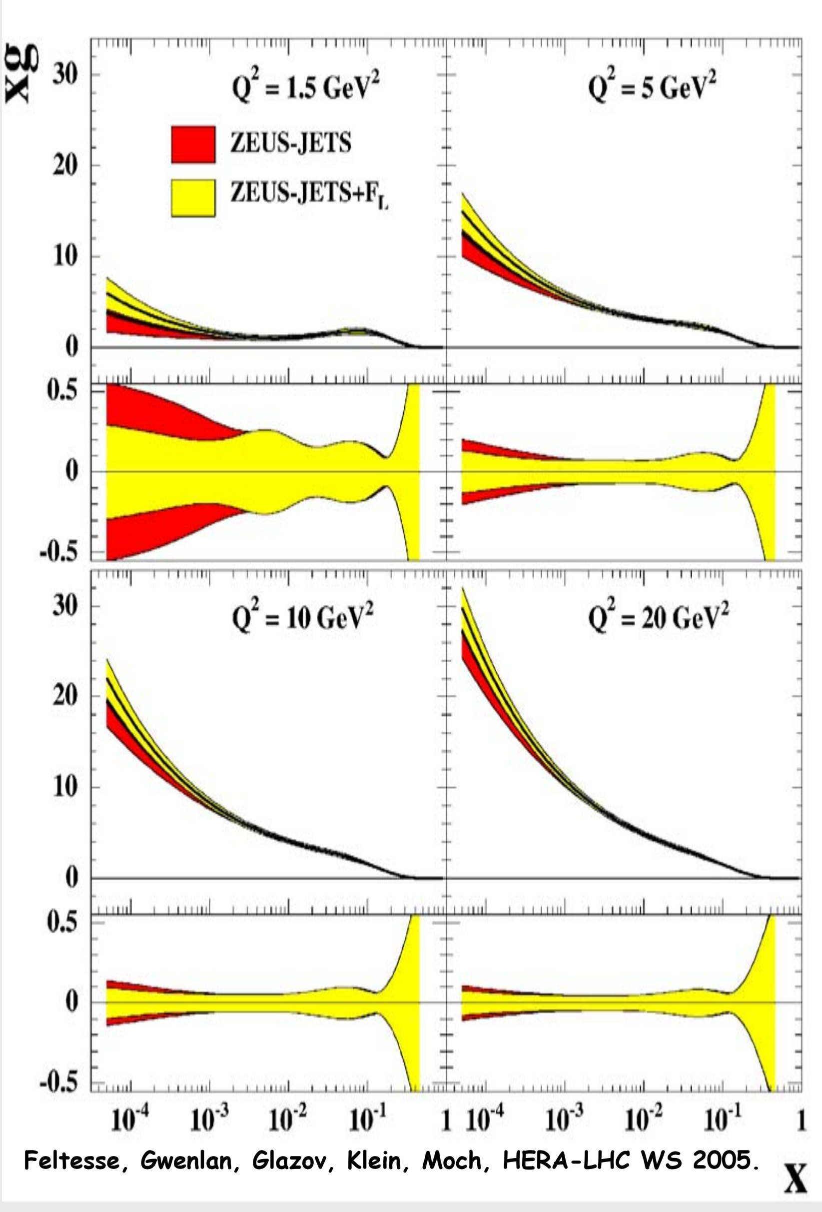
- F_L directly sensitive to gluon

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

- HERA runs at 460+575 GeV with 16+9 pb^{-1}:



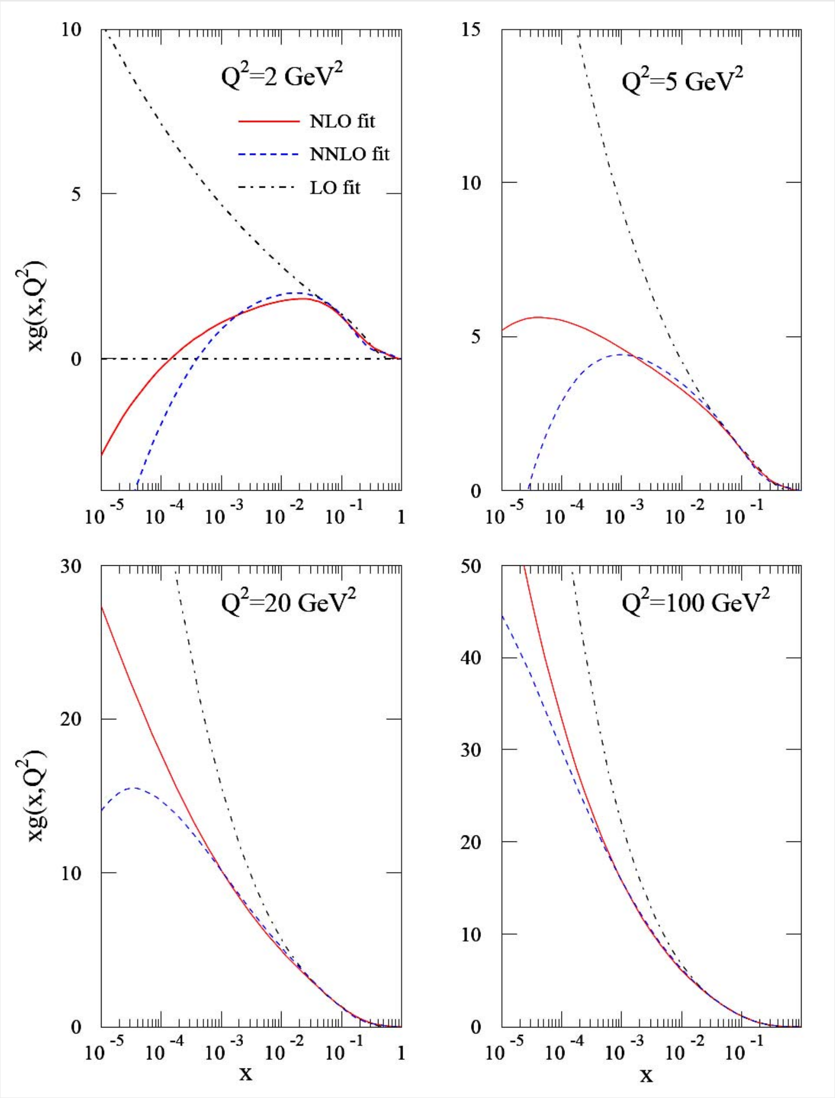
- x check other measurements

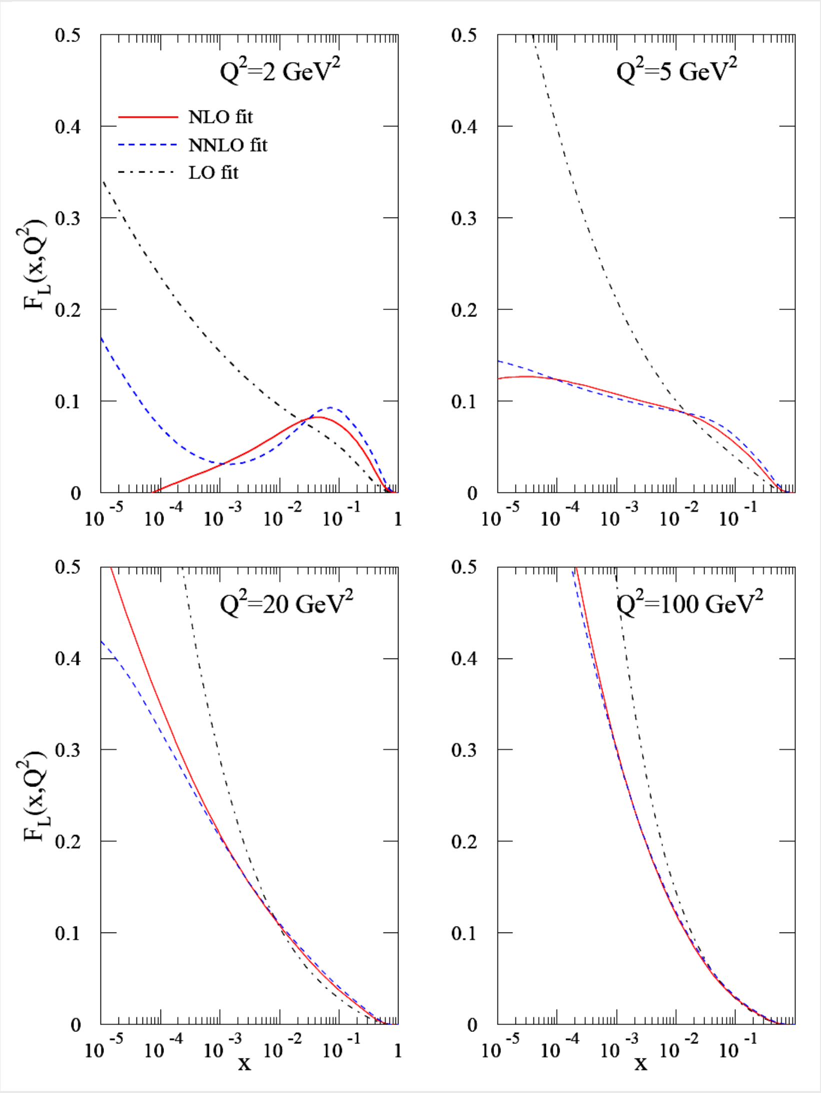


Feltesse, Gwenlan, Glazov, Klein, Moch, HERA-LHC WS 2005.

PDFs at NNLO

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

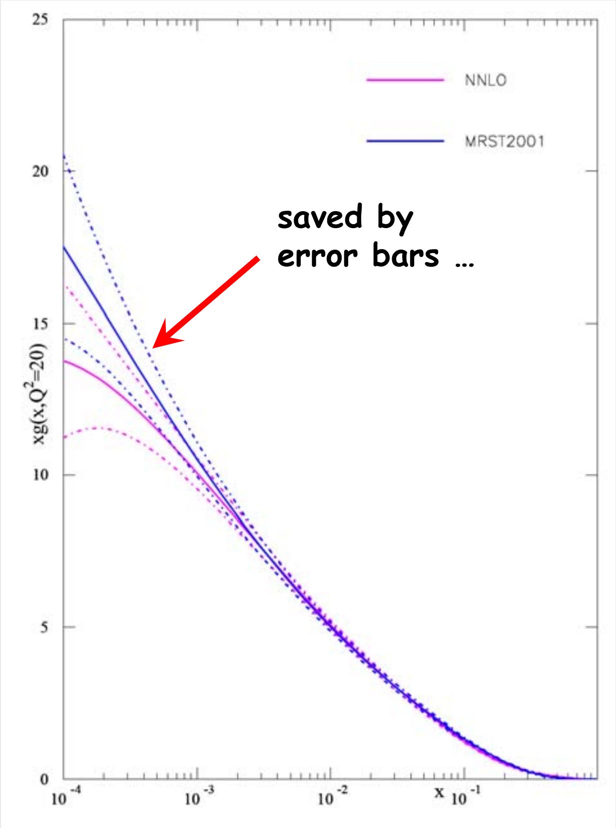


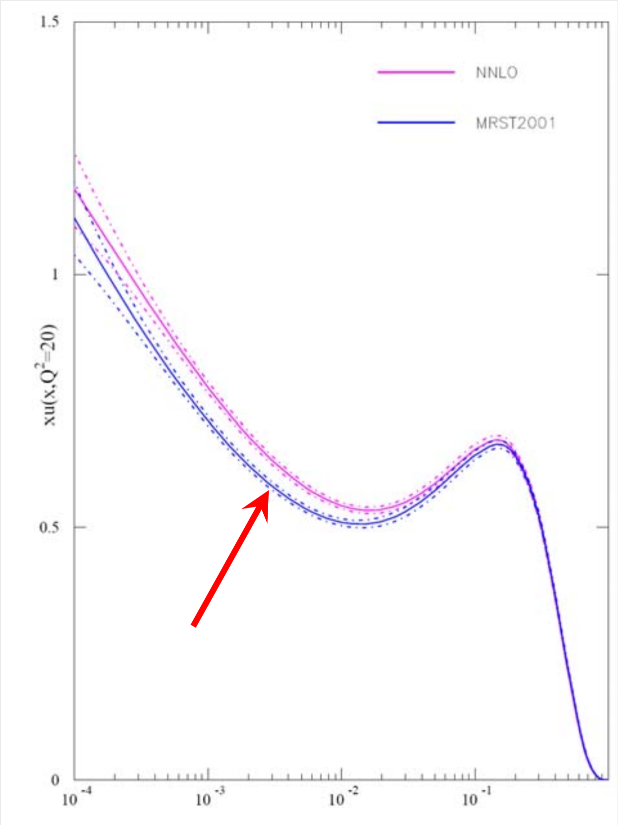


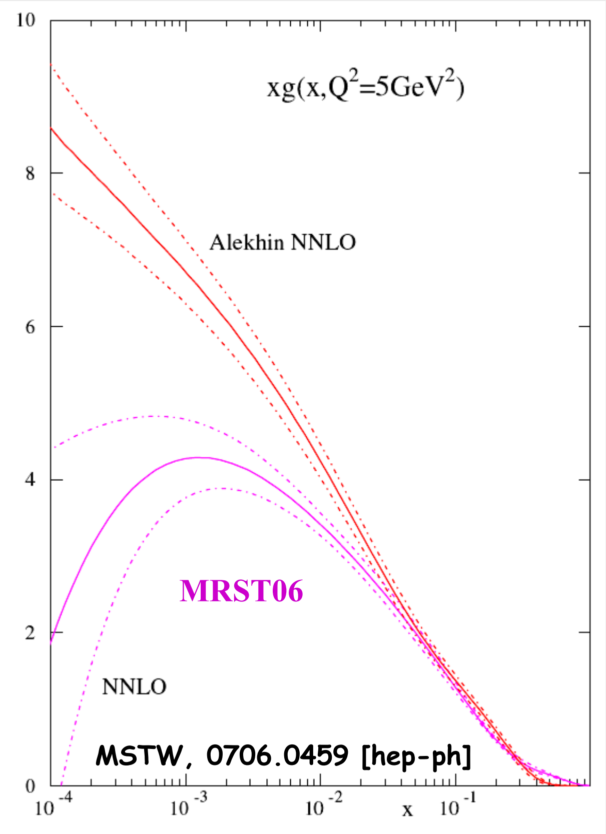
C. White, R. Thorne, 0706.2609 [hep-ph]

PDFs at NNLO

- NNLO partons with uncertainties from experimental errors
- NNLO uncertainties ≲ than NLO, at medium xu(x) (NLO-NNLO) > uncertainties
- NNLO fit better than NLO





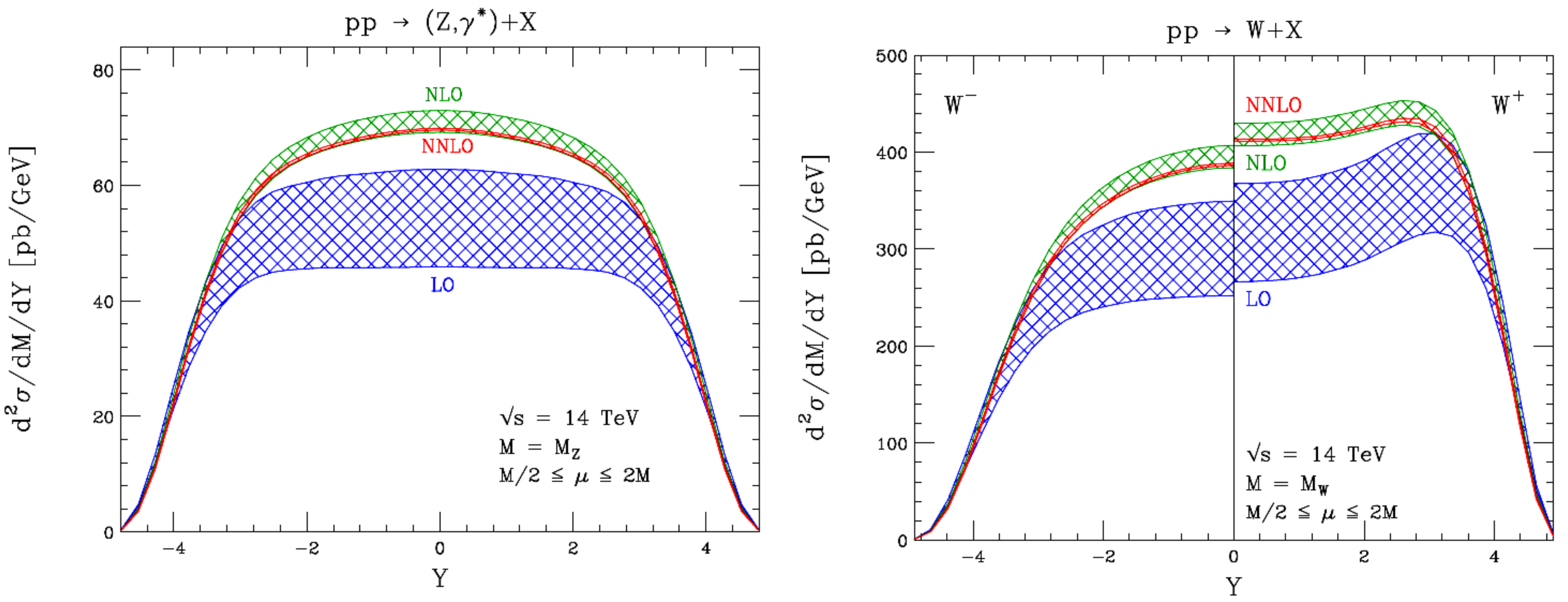


- NNLO resolves more features of theory: q_s, q_v, $\bar{q}$ evolve with different kernels
- Heavy flavors still an issue. DIS07: MRST(MSTW) 3

Campbell, Huston, Stirling, LHC QCD primer
Rep.Prog.Phys. 70 (2007) 89-193. http://www.iop.org/EJ/abstract/0034-4885/70/1/R02/

Standard candle: W, Z production

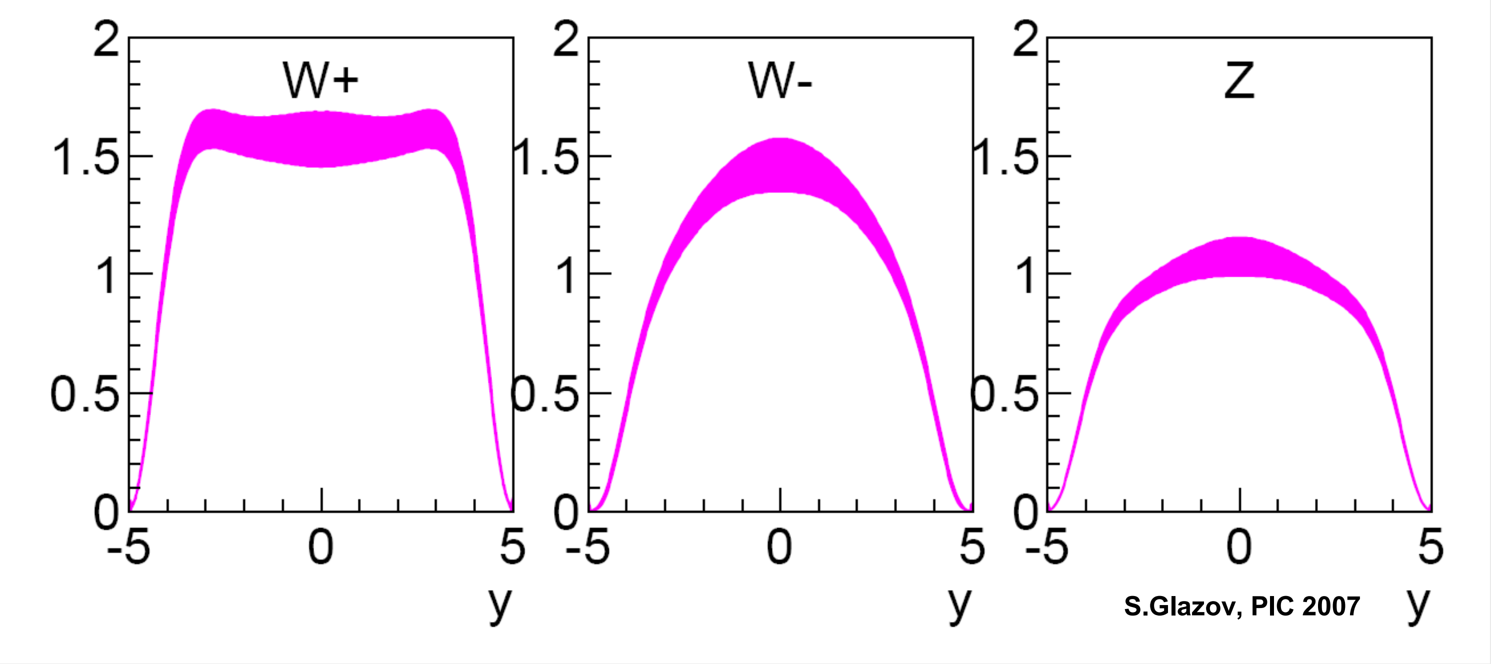
- W,Z rapidity distribution with scale variation $m_{W,Z}/2 \leq \mu \leq 2m_{W,Z}$
- NNLO renorm./fact. scale dependence ~1%
  (Anastasiou, Petriello, Melnikov '05; Dissertori '05)
- LO -> NLO -> NNLO: ~ normalization only !



Campbell, Huston, Stirling, LHC QCD primer, Rep.Prog.Phys. 70 (2007) 174 f.

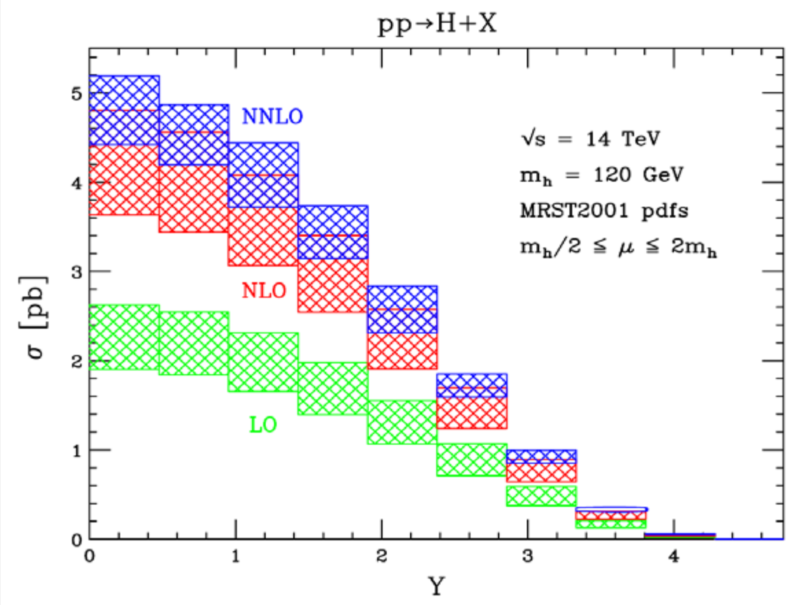
Standard candle: W,Z production ?

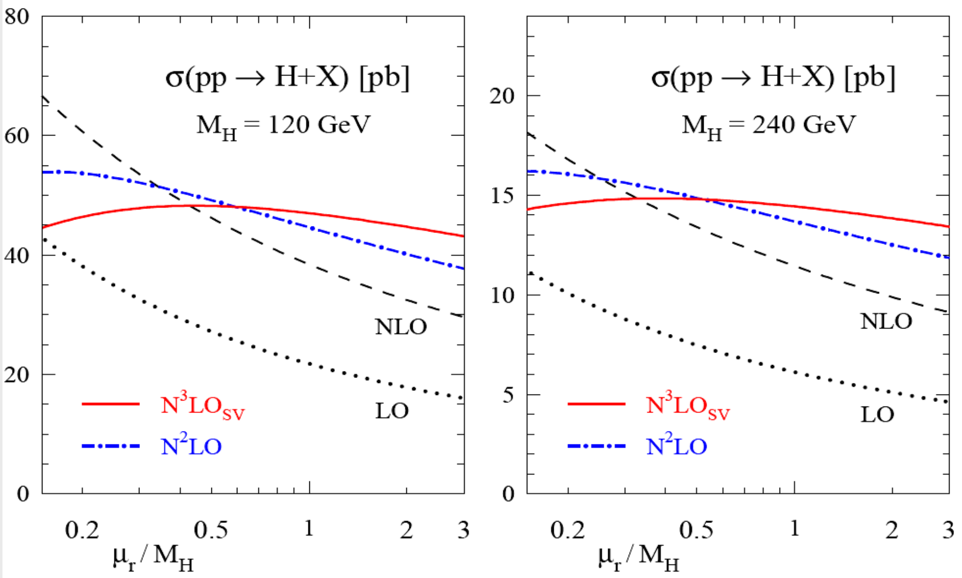
- 1-2% theory error
- 2% ultimate LHC precision, BUT:
- PDF uncertainties ~7% (CTEQ) dominate !
- more precision needed from HERA medium 0.001<x<0.03



Gluon Gluon -> Higgs theor.

- gets large positive corrections from order to order
- renormalization scale uncertainty for scale variation $m_h/2 \leq \mu \leq 2m_h$ at NNLO still ~10%



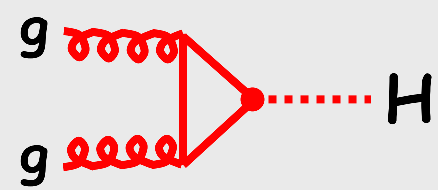


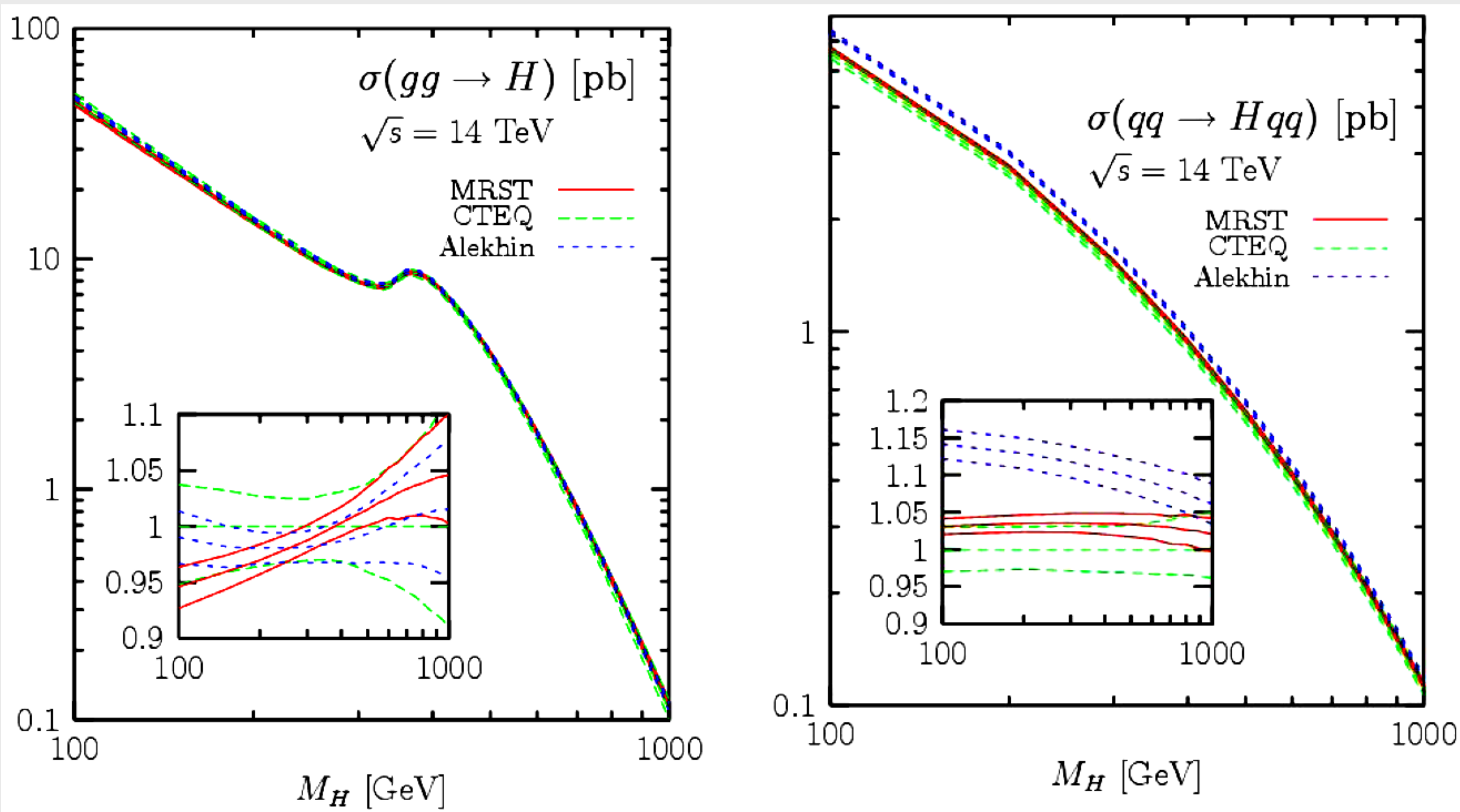
Campbell, Huston, Stirling, LHC QCD primer, Rep.Prog.Phys. 70 (2007) 182.
see also: Catani, de Florian, Grazzini, Nason, 2003; Anastasiou, Petriello, Melnikov 2005

NNLO: Harlander, Kilgore '02
Anastasiou, Melnikov '02
Ravindran, Smith, van Neerven '03
N^3LO soft: Moch, Vogt 05

Gluon Gluon -> Higgs exptl.

- PDF uncertainties 3–5% set dep.
- gluon dominates precision
- qq smaller

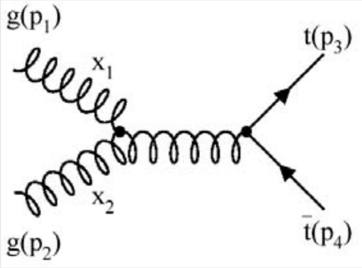


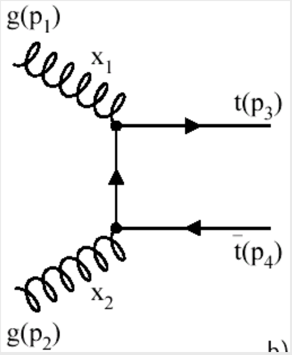


A.Djouadi, S.Ferrag, hep-ph/0310209.

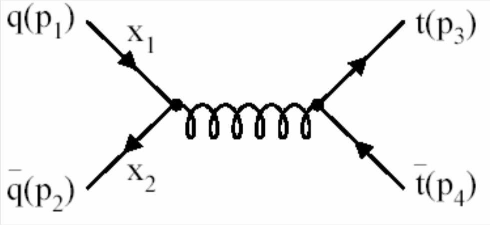
$\bar{t}t$ production

87% gluon-gluon fusion





13% $\bar{q}q$ annihilation

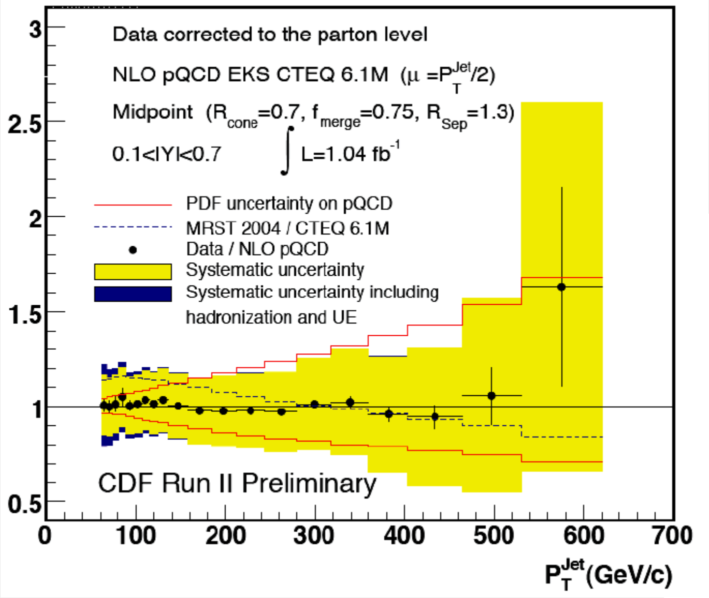


- **Tevatron**: large x valence quarks produce top: opposite ratio !

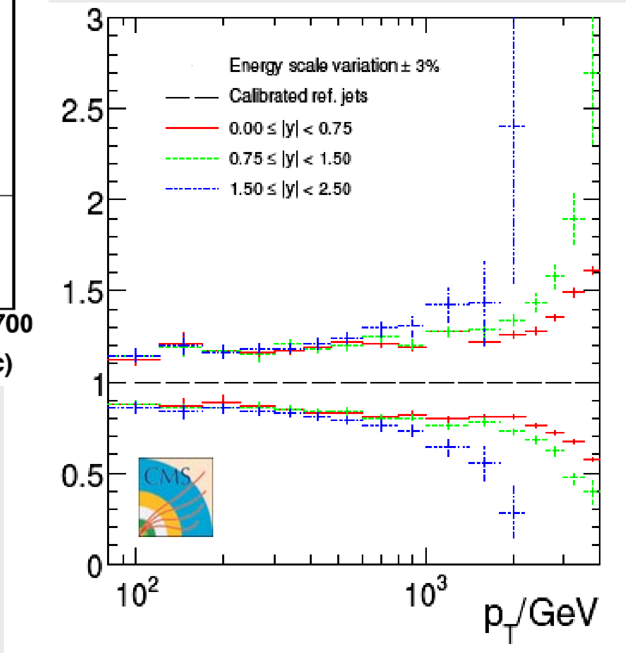
- **gluon** important:
  - PDF uncertainty 3-4%
  - NLO + NLL ~10%
  - total exptl. ~10%

Tevatron

$\sigma_{DATA} / \sigma_{THEORY}$

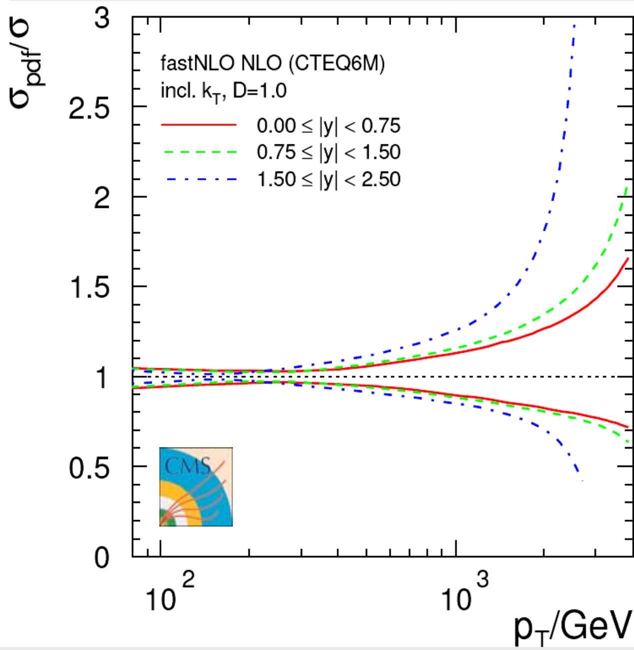


experimental:
jet energy scale
~Tevatron



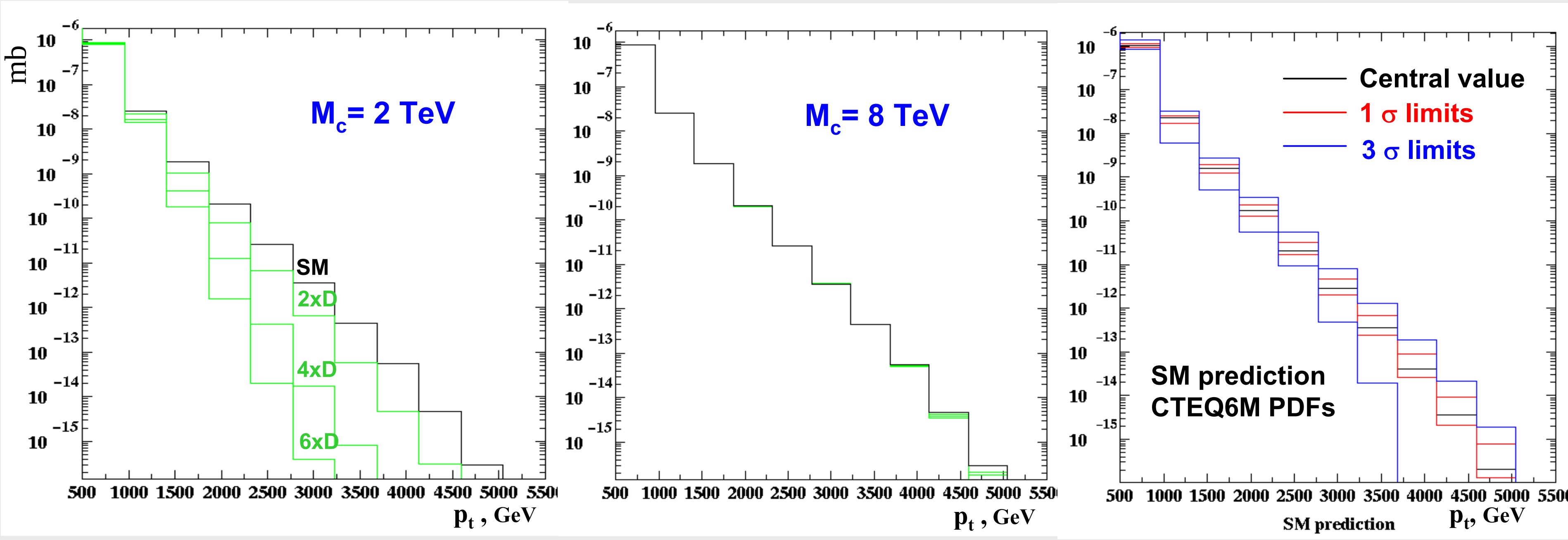
LHC

large PDF uncertainty



Extra Dimensions

- affect dijet cross section through running α_s
- parameterized by nr of extra dimensions D + compactification scale M_c



S.Ferrag, hep-ph/0407303

- high x gluon dominates high E_t jet cross section.
- PDF uncertainties reduce M_c sensitivity from ~5 to 2 TeV

α_s from HERA jets

- H1 incl. jets (NLO) hep-ex/0706.3722, DESY 07-073.

  $\alpha_s(M_Z)$ = 0.1193 ± 0.0023 (stat) + 0.0032 (th) ± 0.0010 (pdf) 700<Q^2<5000 GeV^2

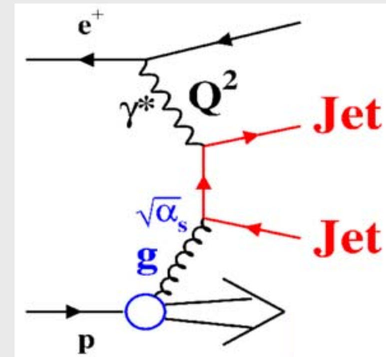
  $\alpha_s(M_Z)$ = 0.1171 ± 0.0014 (stat) + 0.0047 (th) ± 0.0016 (pdf)

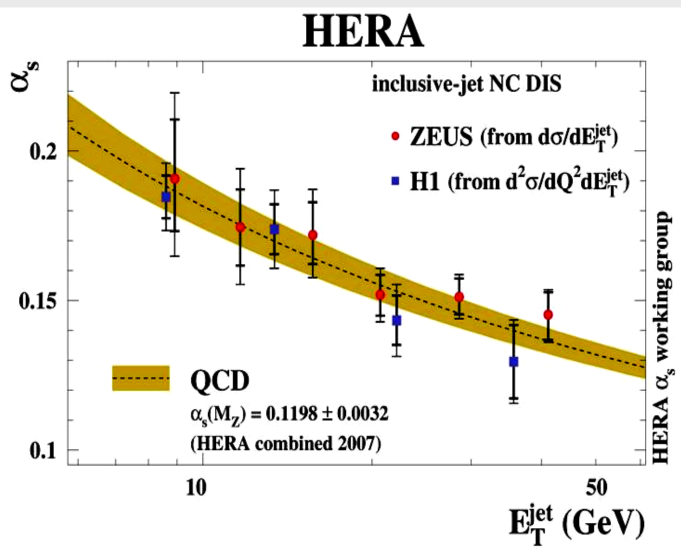
- ZEUS incl. jets (NLO)

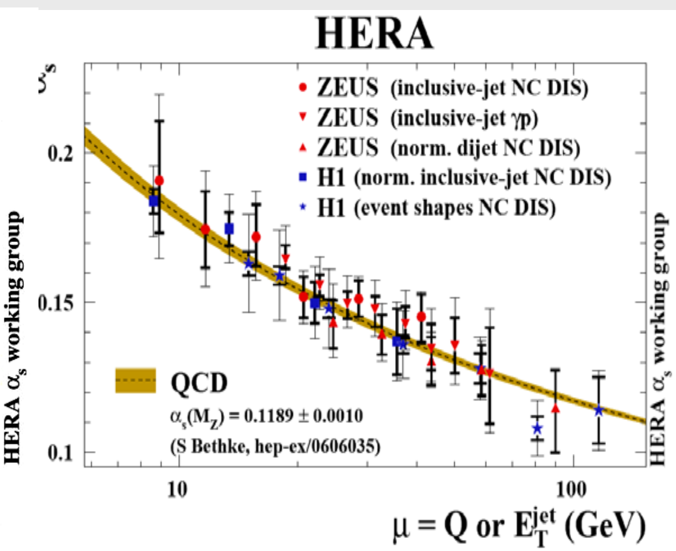
  $\alpha_s(M_Z)$ = 0.1207 ± 0.0014 (stat) ± 0.0034 (exp) ± 0.0023 (th)

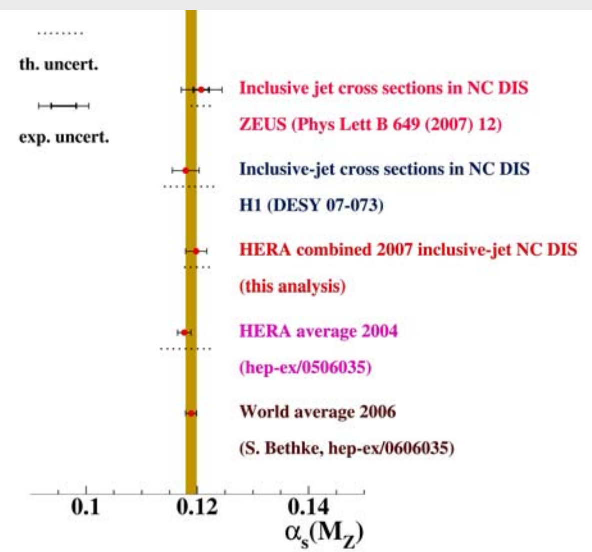
- HERA incl. jets (NLO)

  $\alpha_s(M_Z)$ = 0.1198 ± 0.0019 (exp) ± 0.0026 (th)









H1: DESY 07-073, ZEUS: DESY 06-241. EPS Manchester 07.

α_s - the run to unification

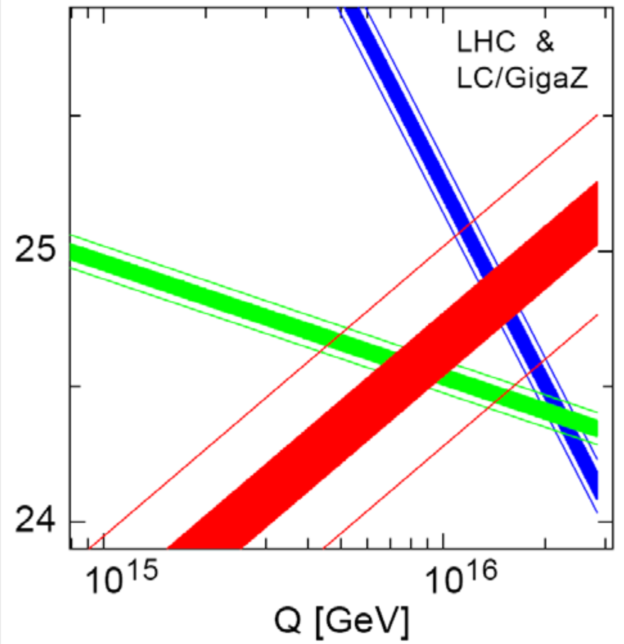
- need precise α_s to check SUSY GUT unification

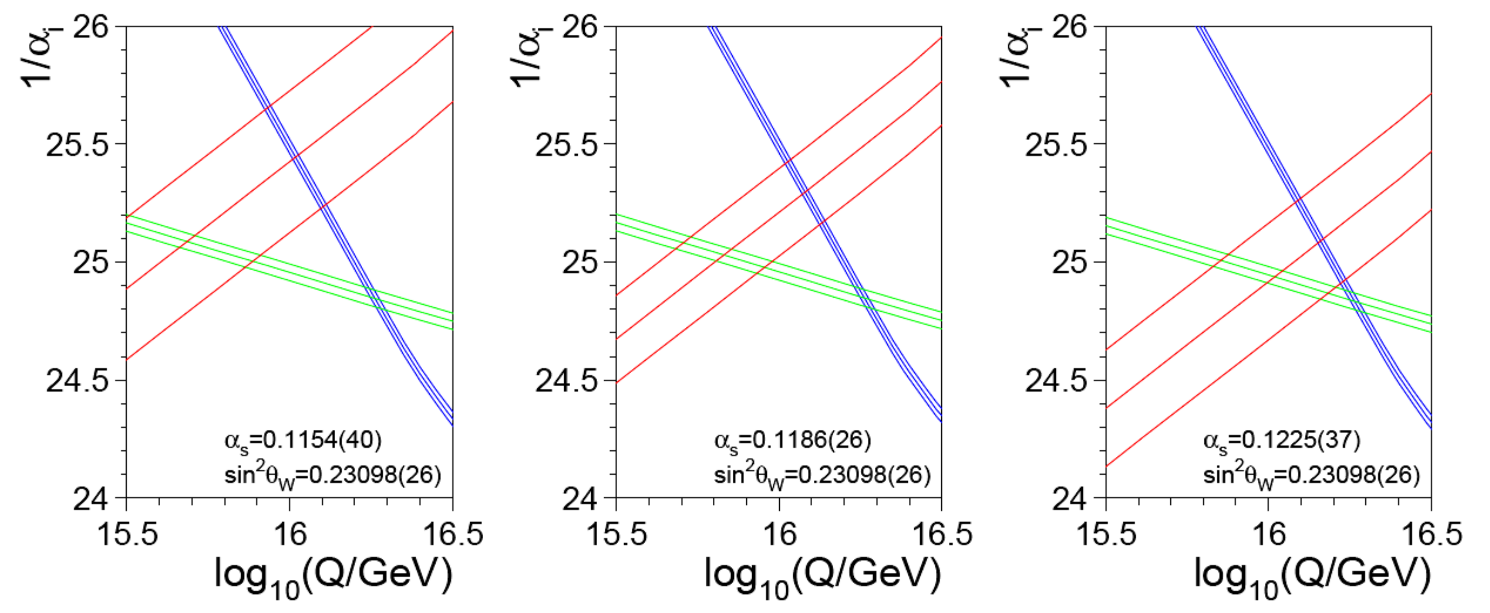
  α_1 = (5/3) $\alpha/\cos^2\theta_W$

  α_2 = $\alpha/\sin\theta_W$

  α_3 = α_s

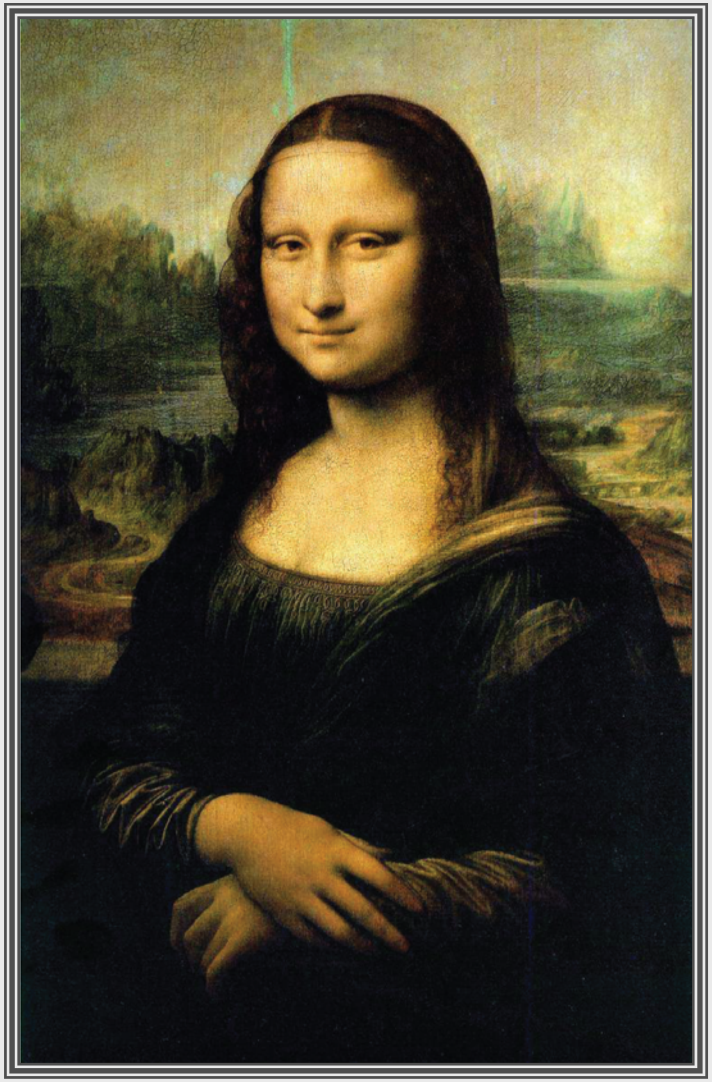
- $\delta\alpha_s$ ~ 0.002 is the limitation !
- can lattice take over from expt: 0.1170±0.0012 ?





Heavy Flavor

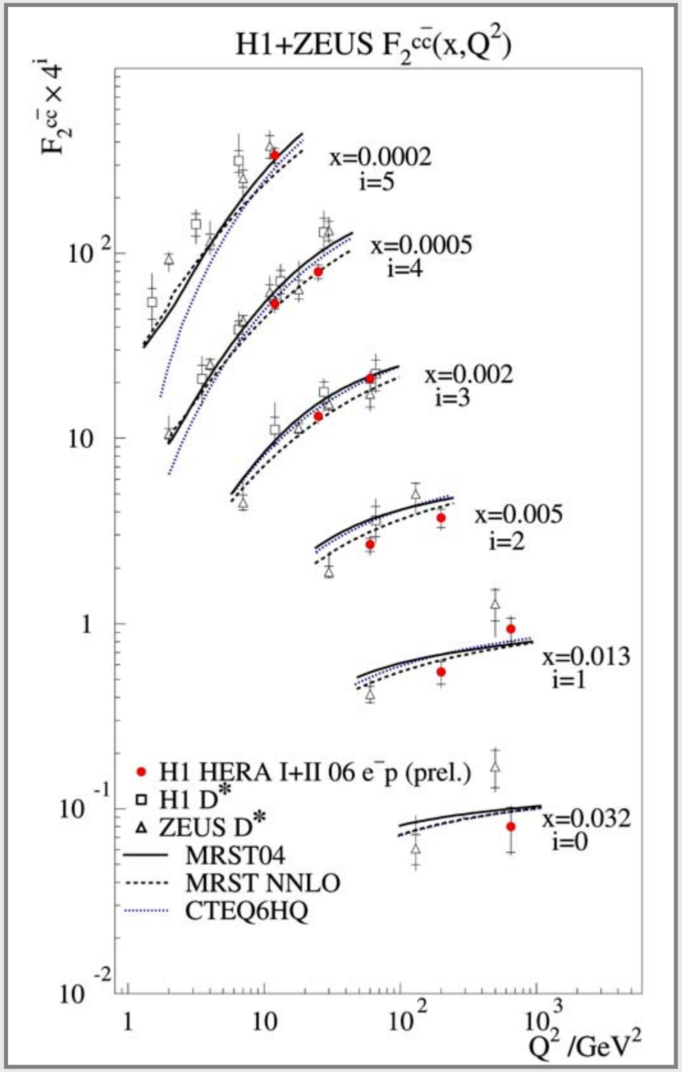
Charm



Beauty

$F_2^{c,b}$: proton flavor content

HERA2: H1+ZEUS: Si vertex detectors - c,b lifetime tag



F_2^c errors

HERA I: H1 displaced tracks:			
Q^2 [GeV^2]	σ_{stat}	σ_{sys}	σ_{tot}
25	~6%	~8%	~10%
650	~22%	~15%	~27%

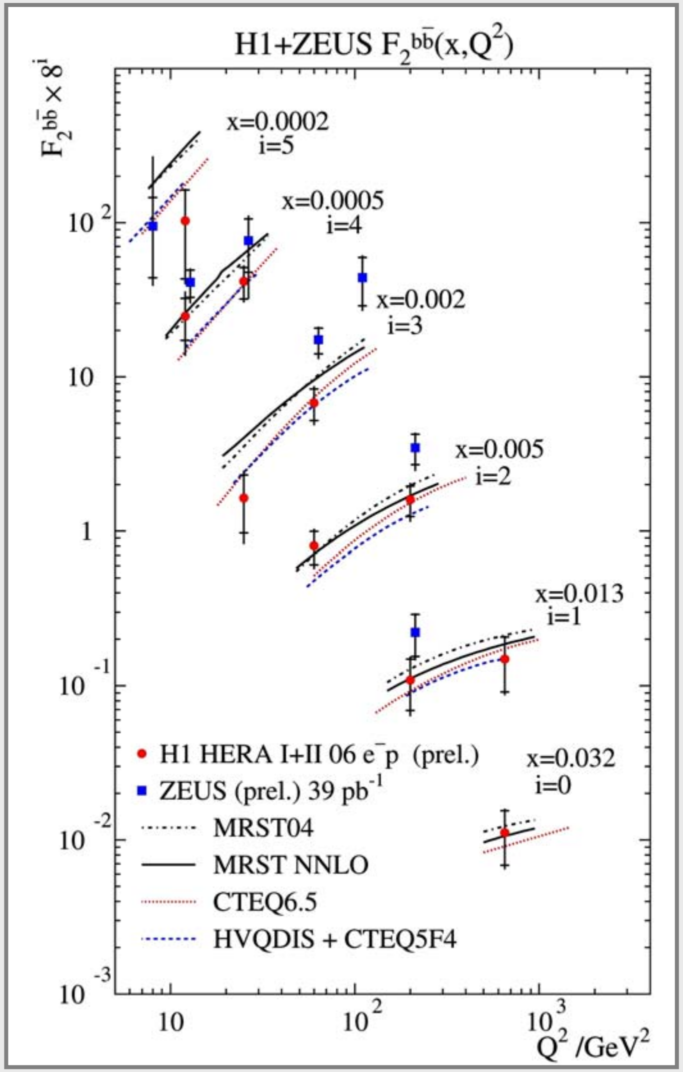
HERA II Projection:			
Q^2 [GeV^2]	σ_{stat}	σ_{sys}	σ_{tot}
25	~3%	~4%	~5%
650	~10%	~10%	~14%

F_2^b errors

HERA I: H1 displaced tracks:			
Q^2 [GeV^2]	σ_{stat}	σ_{sys}	σ_{tot}
25	~20%	~20%	~30%
650	~40%	~25%	~50%

HERA II projection:			
Q^2 [GeV^2]	σ_{stat}	σ_{sys}	σ_{tot}
25	~10%	~10%	~15%
650	~20%	~20%	~30%

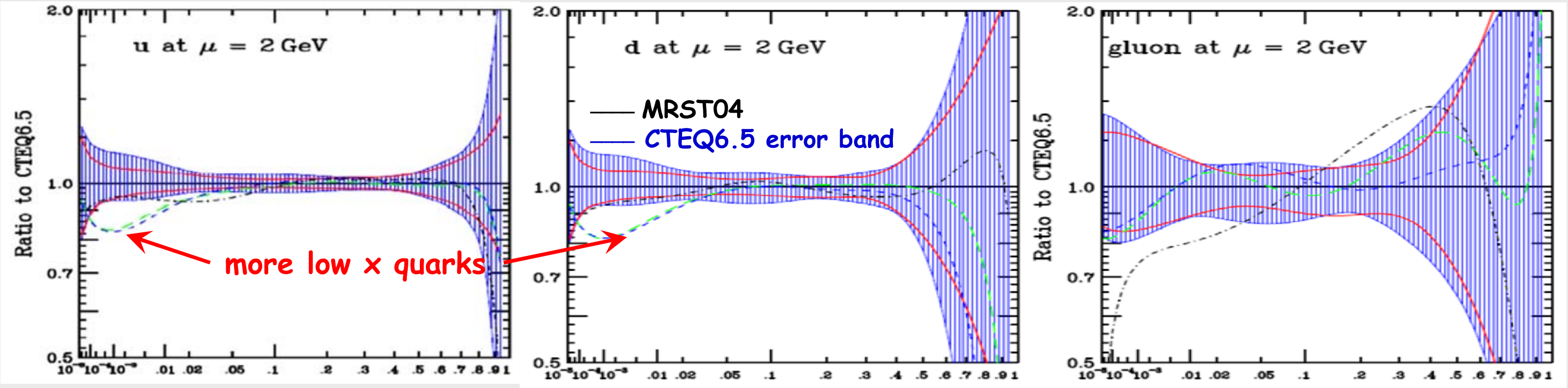
combine H1+ZEUS



H1 prelim-07-171, LP 07; ZEUS: DIS Munich 07

Heavy Flavor schemes

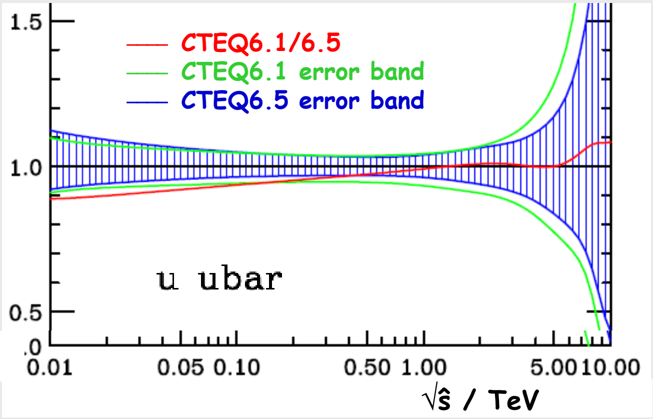
PDF ratios CTEQ6.1M charm mass neglected to CTEQ6.5M charm mass implemented

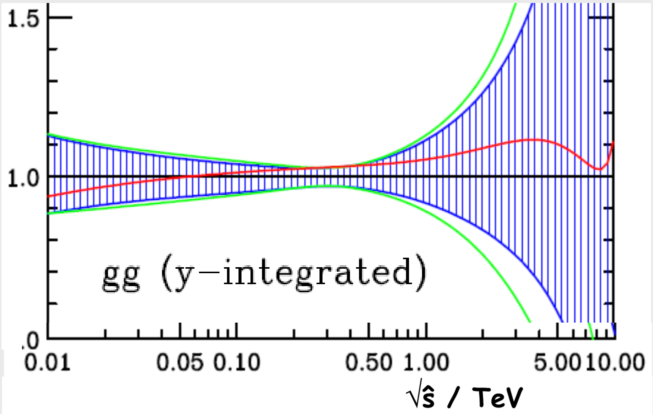


changes quark PDFs outside error bands !

gluon within errors

LHC parton-parton lumi ratios vs $\sqrt{\hat{s}}$



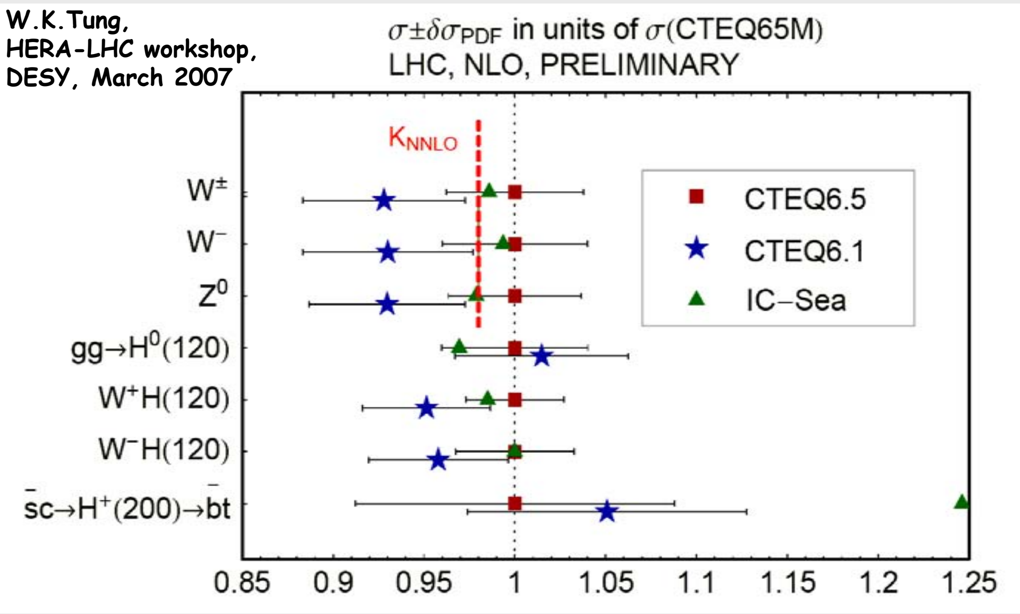


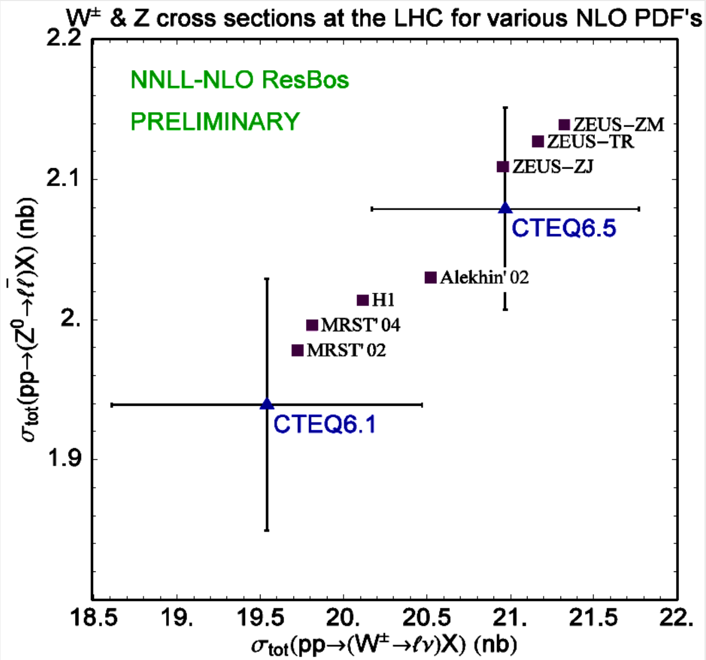
$\bar{q}q$ lumi at $\hat{s}$<0.1 ~10% higher
(outside error band)

W.K.Tung: HERA-LHC WS, DESY 2007.
hep-ph/0611254, 0702268, 0701220.

CTEQ6.5M vs. CTEQ6.1: W,Z cross section prediction: ~10 % error

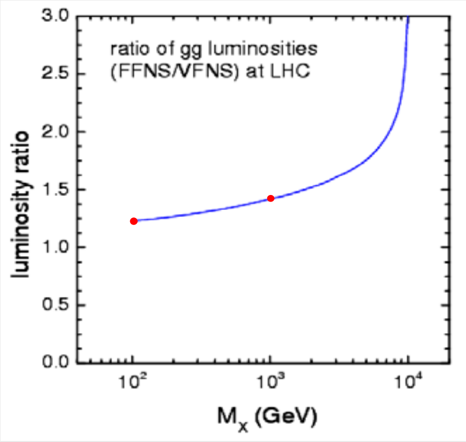
W.K.Tung,
HERA-LHC workshop,
DESY, March 2007





- ratio FFNS/VFNS
  Fixed/Variable Flavor Nr Scheme:
- large uncertainty of LHC gg luminosities:
  20,30% at M_X=0.1,1 TeV
- VFNS exptl. not favored over FFNS

treat heavy flavors correctly - otherwise obscure Standard Candle !

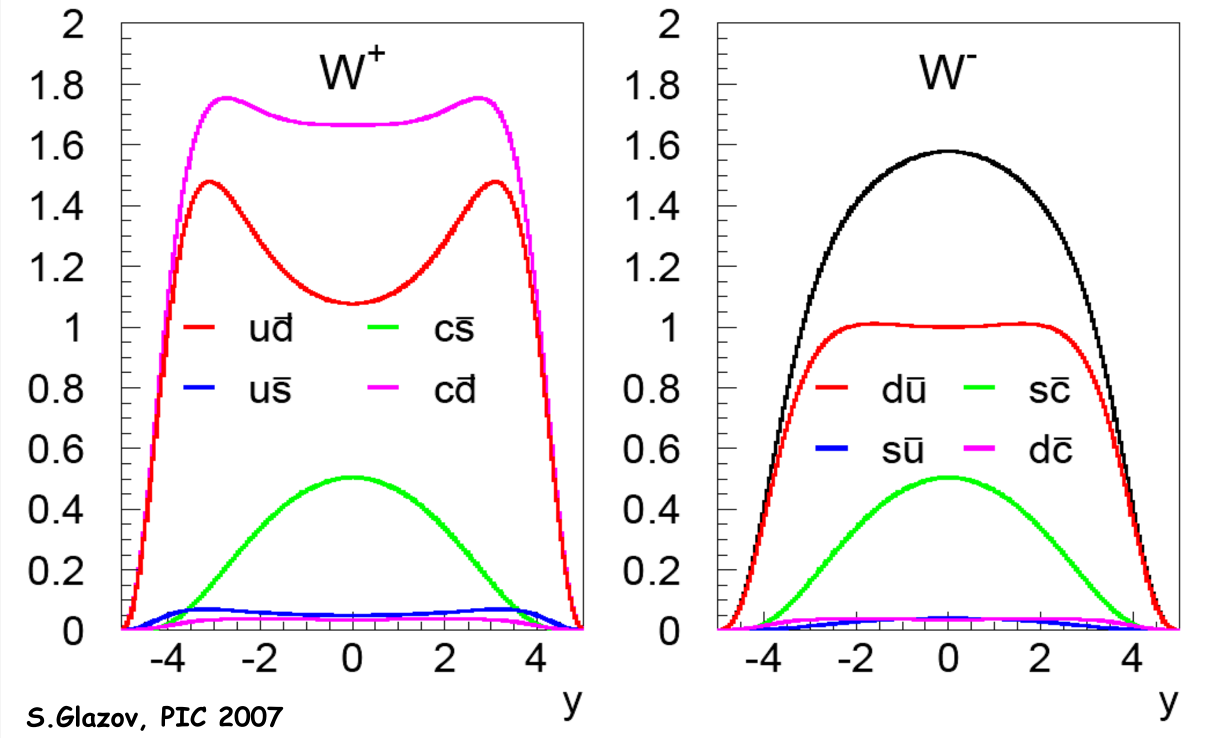


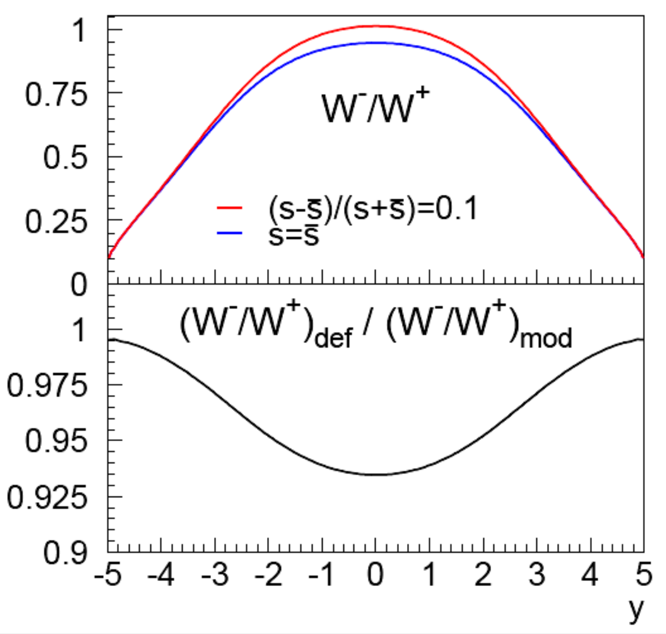
Flavor in W production

only u,d,s,c contribute:

Cabibbo favored valence $\bar{u}d$	70%
Cabibbo favored sea $\bar{c}s$	25%
Cabibbo suppressed sea	5%

change **sea symmetry**:
change **W^-/W^+** ratio

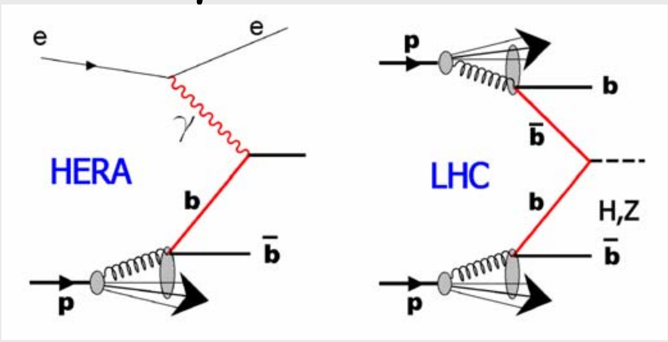




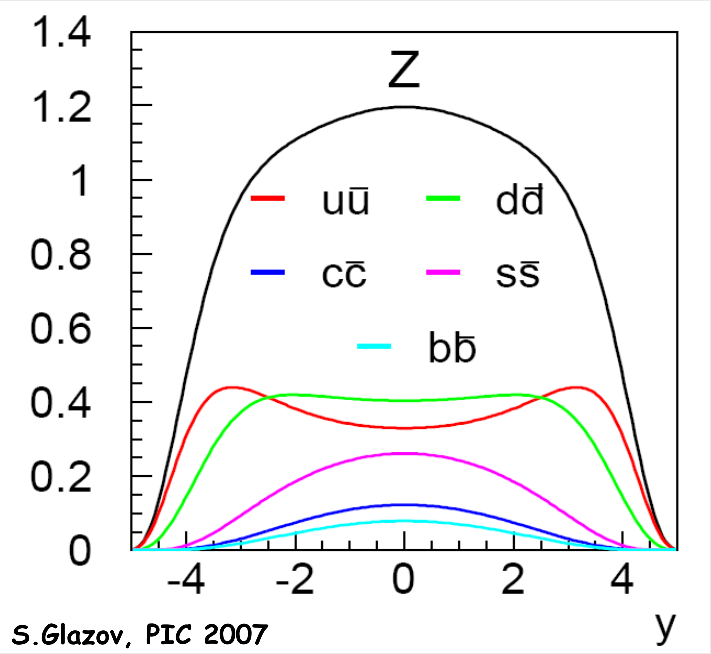
Flavor in Z production

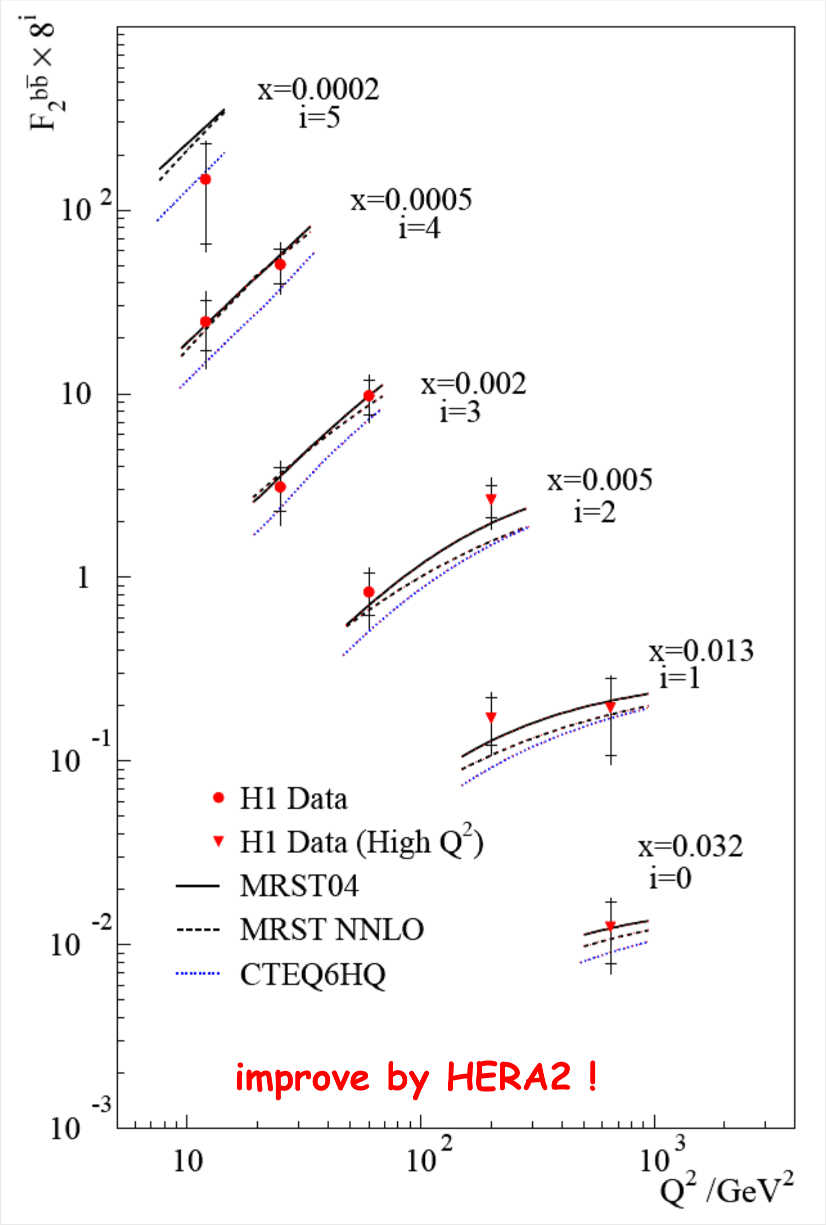
couplings:

$\bar{b}b\gamma$ < $\bar{b}bZ$



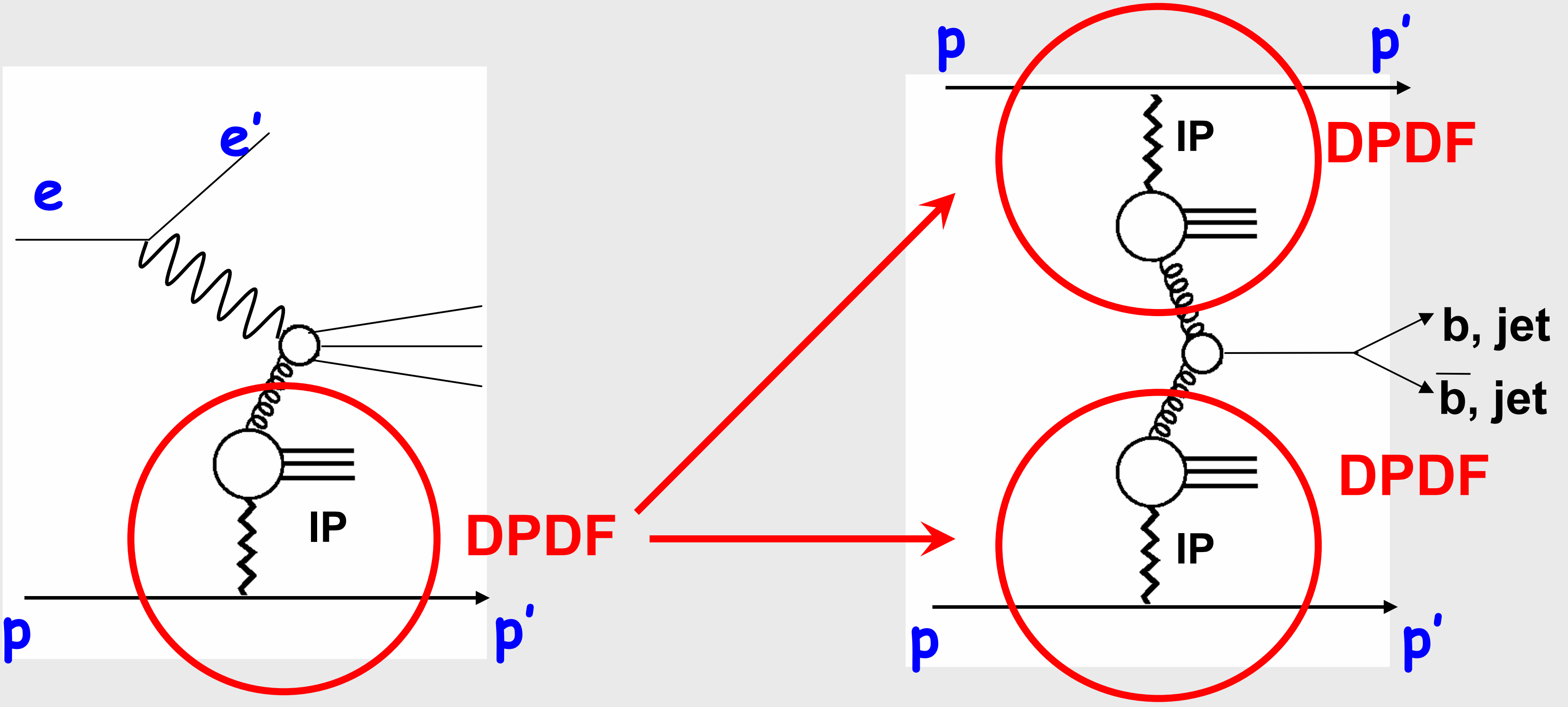
F_2^b enhanced vs. F_2:






Diffraction

Diffraction from HERA to LHC

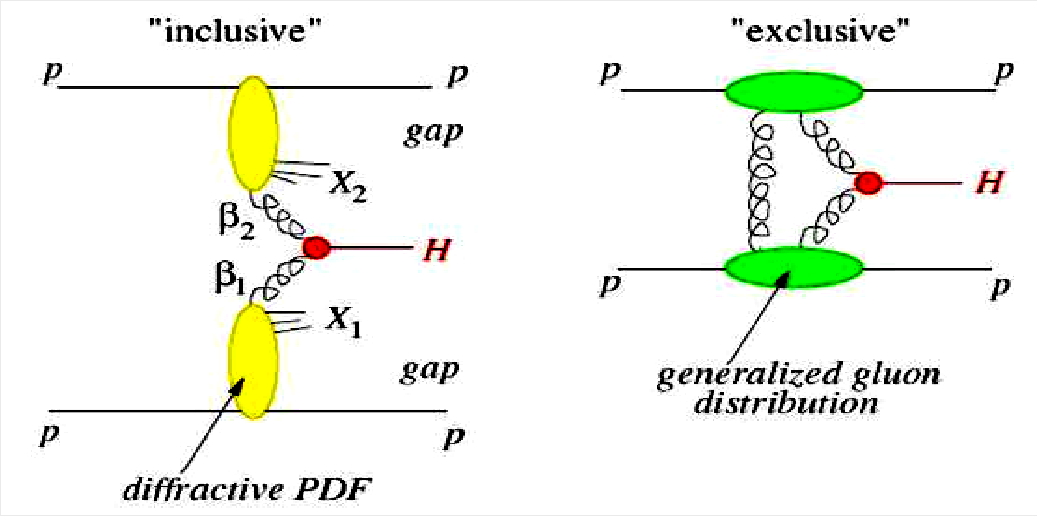


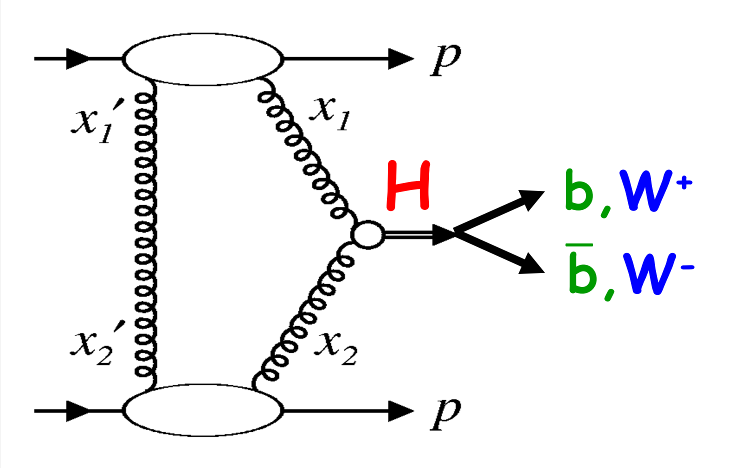
Diffractive Higgs production

- for M_H=120-250 GeV
  mass resolution ~ 1 GeV
  from energy of protons
- $J^{CP}=0^{++}$
  C+P even state (mostly)
- need diff. PDF at β -> 1
  and $Q^2 \sim M_H^2$
- sensitive to unintegrated PDFs
- inclusive = background to
  exclusive

O(100) fb

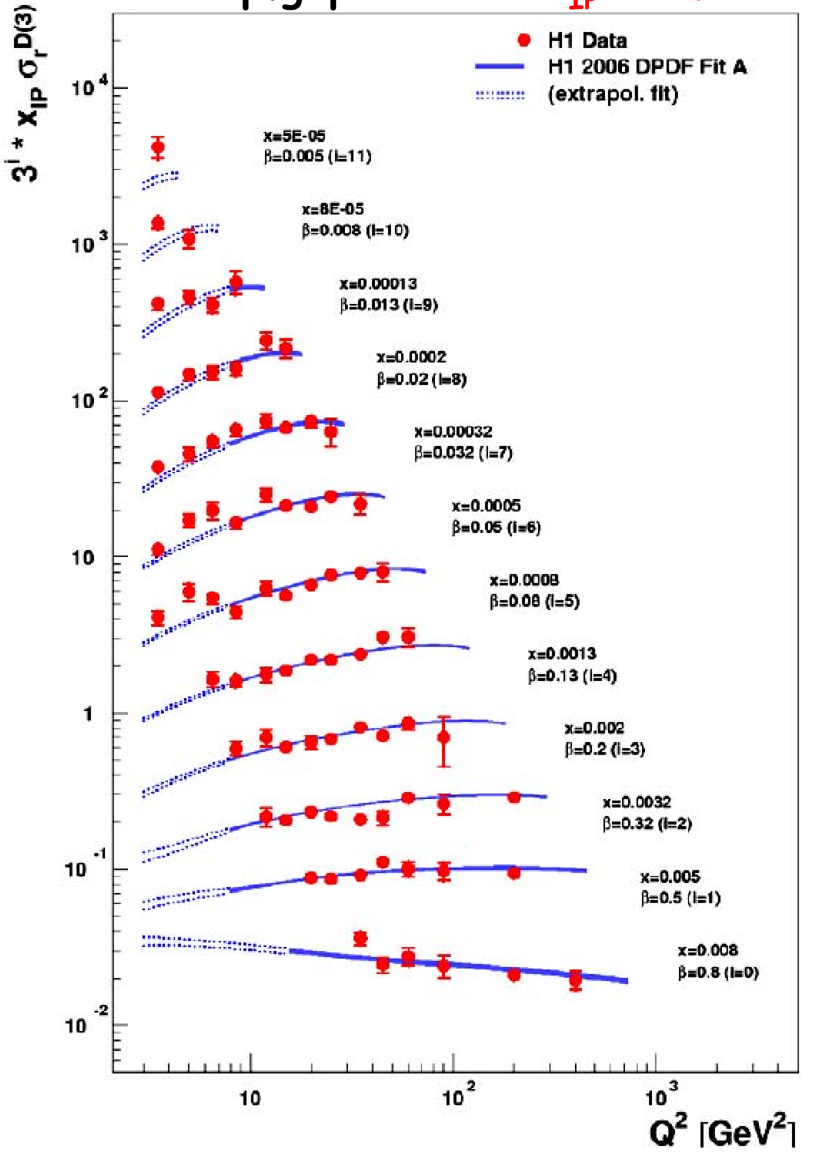
2-10 fb

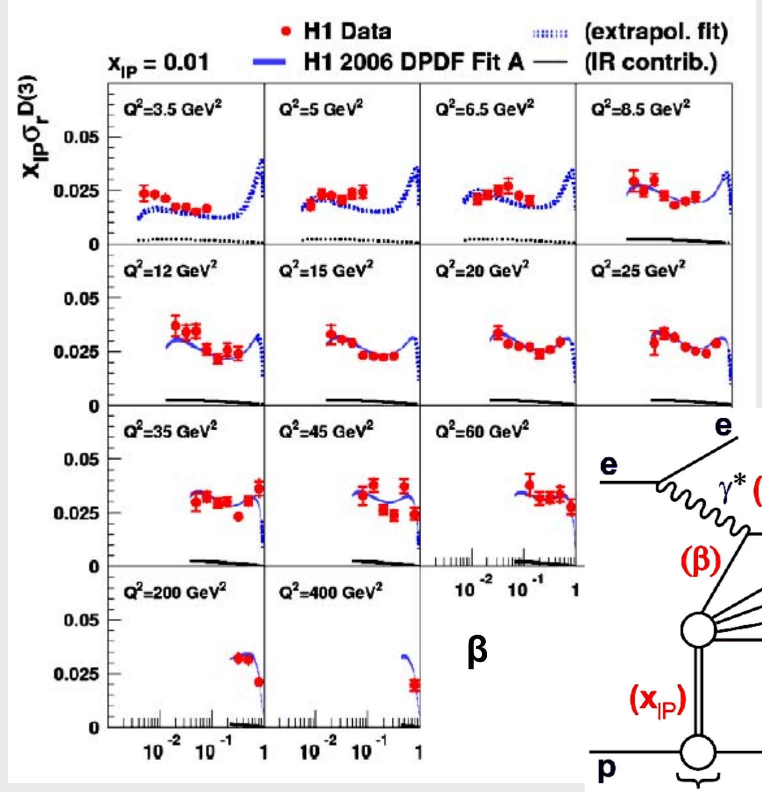


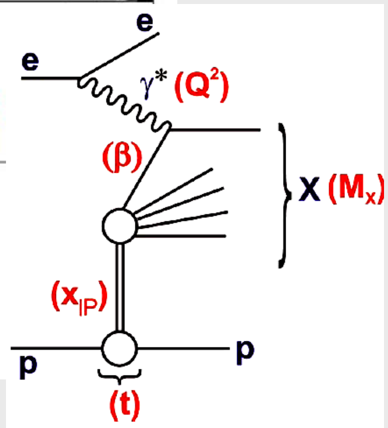


Diffractive F_2^D

H1 rap.gap data at x_{IP} = 0.01







- $x = \beta x_{IP}$ and Q^2 dependence at fix x_{IP}
- Pomeron QCD structure !
- best precision:
  5% stat., 5% syst., 6% norm.

Pomeron PDFs

diffractive QCD fit

H1 2006:

$$\frac{d^2\sigma(x,Q^2,x_{I\!P},t)^{\gamma^* p\to p' X}}{dx_{I\!P}\, dt} = \sum_i \int_x^{x_{I\!P}} d\xi \hat{\sigma}^{\gamma^* i}(x,Q^2,\xi)\, p_i^D(\xi,Q^2,x_{I\!P},t)$$

~70% gluons

z-integrated

singlet known to ~5%,

gluon to ~15%

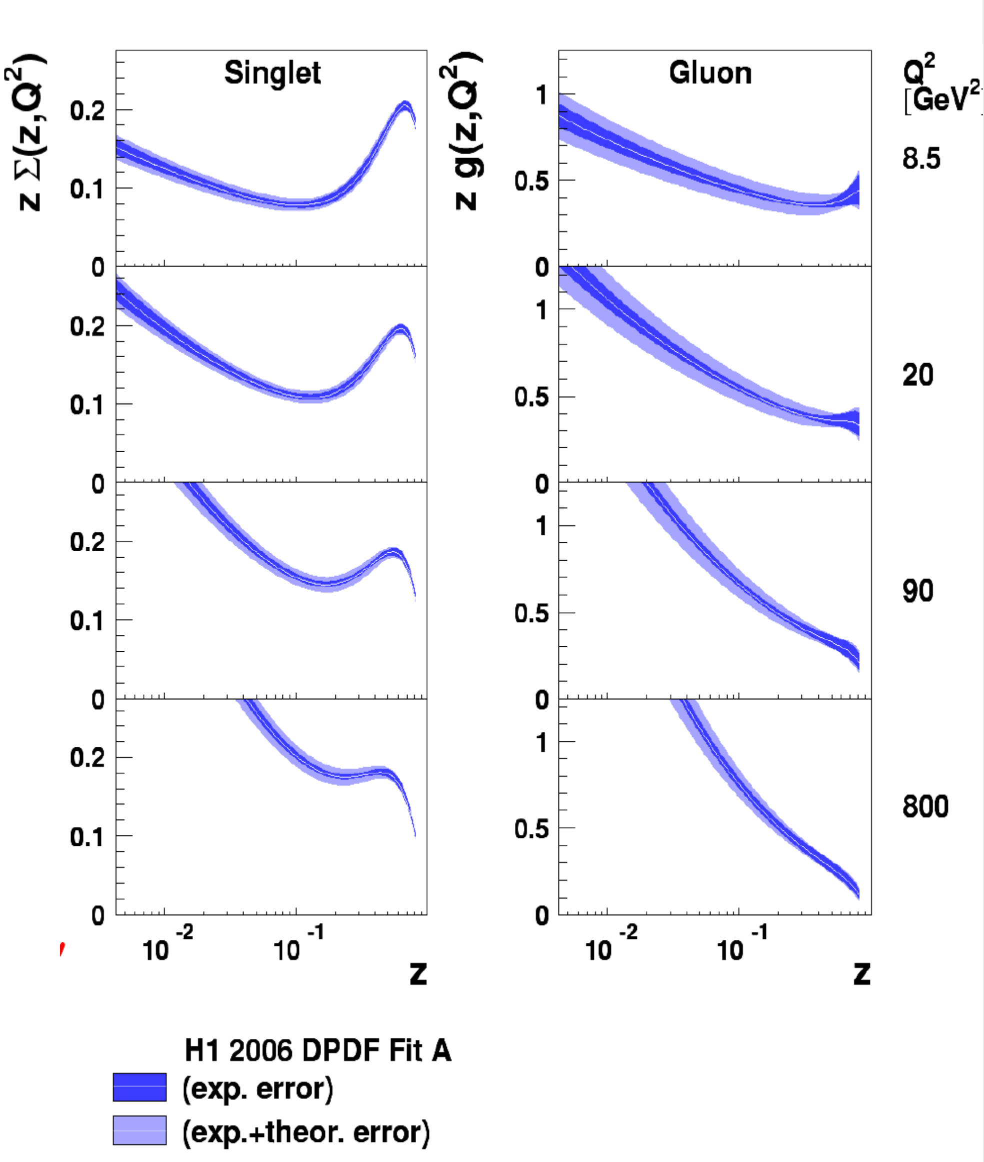
(from ln Q^2 dep.)

H1+ZEUS combined fit:

C.Royon, DIS 2007.

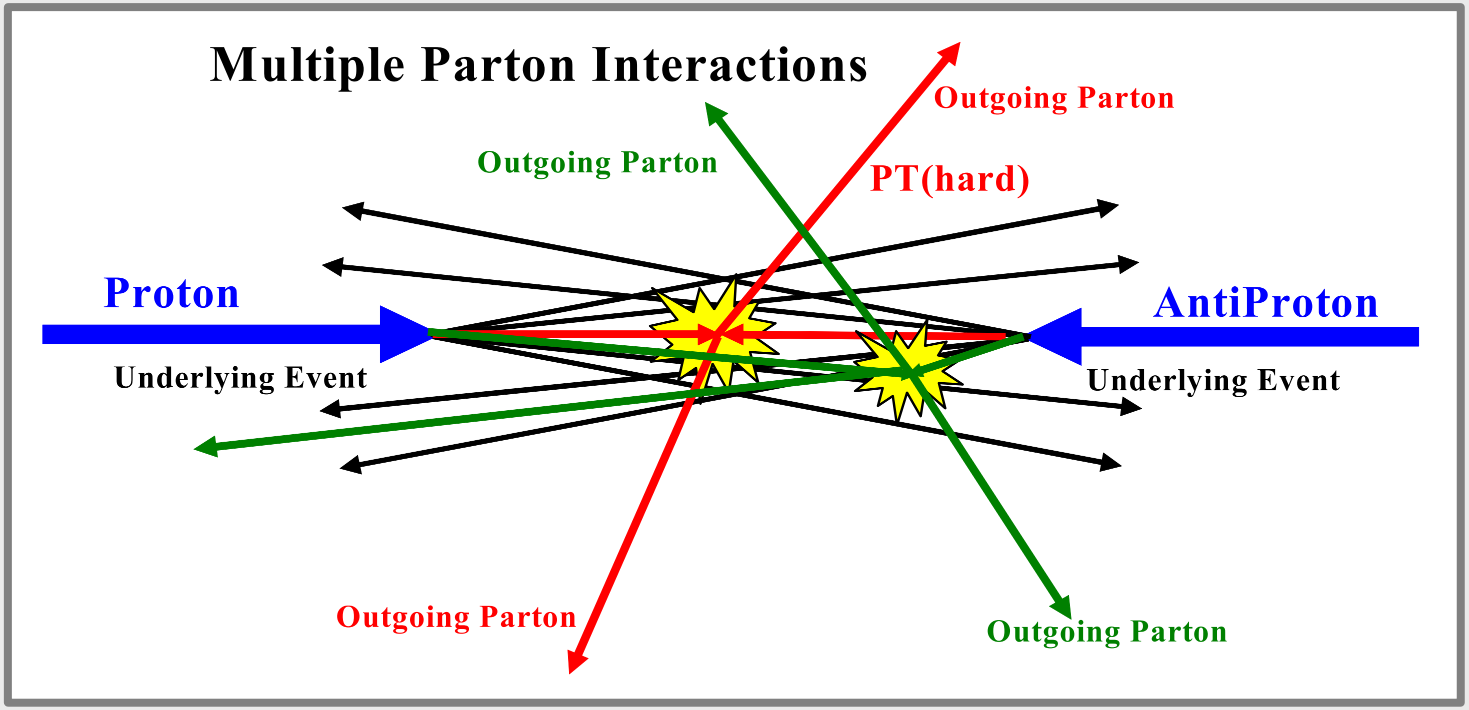
hep-ph/0609291.

hep-ph/0602228.



Underlying Event

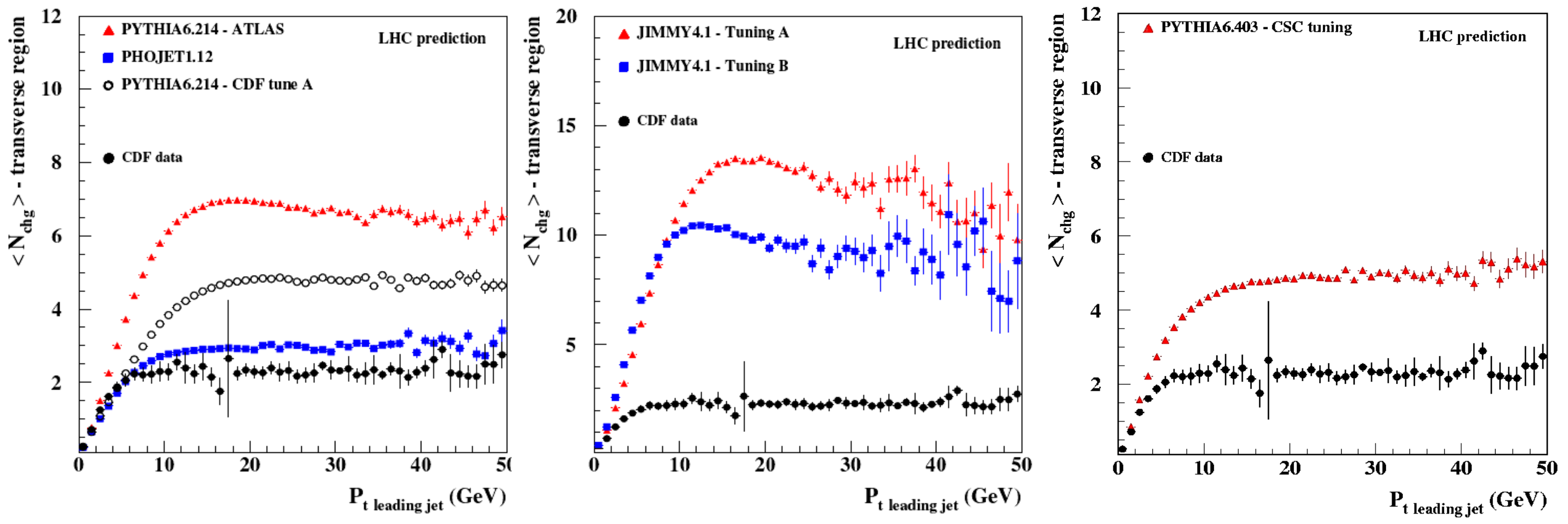
- and Multiple Interactions:
- on top of LO: parton showers, remnant-remnant interactions
- NOT lumi dependent pile-up !



- not calculable from QCD
- adapt MC models to Tevatron + HERA data
- measure $dN_{ch}/d\eta$, dN_{ch}/dp_T at LHC

Underlying Event

dN_{ch}/dp_t leading jet



- MC models tuned to Tevatron+HERA data differ strongly at LHC !
- PHOJET (DPM) ~ $\ln(s)$ PYTHIA (MPI) ~ $\ln^2(s)$
- better understanding + tuning:
  PYTHIA dual-core? PHOJET? JIMMY?

QCD + MC event generators

Instead of having defined LO, NLO and shower calculation separately and patching the gap between them by matching schemes

we should define a new shower concept that can naturally cooperate with NLO calculations

Z.Nagy, DIS, Munich 2007.

MC generators

Algorithms for NLO matching:

MC@NLO

Avoiding double counting
introduce extra subtract terms

S. Frixione and B. Webber: JHEP 0206:029,2002
S. Frixione, P. Nason and B. Webber: JHEP 0308:007,2003

Krämer-Soper:

include first shower step in NLO calculation +
start shower from this configuration.

M. Krämer and D. Soper: Phys.Rev. D69:054019,2004
Z. Nagy and D. Soper: JHEP 0510:024,2005
P. Nason: JHEP 0411:040,2004

From HERA …

- F_2, $F_2^{c,b}$, F_2^D, F_L proton structure functions
- PDFs:
  - $xq(x)$: $u(x)$ error ~3%
  - $xg(x)$: large uncertainty
- α_s: error ~2%

To do:

- HERA final $F_2^{c,b}$, F_L
- HERA combined F_2, $F_2^{c,b}$, F_L, $g(x)$, PDFs !
- PDFs, $xg(x)$:
  - combine input from F_2, $F_2^{c,b}$, F_L, jets
  - consistent charm treatment + NNLO use
- α_s: final inclusive + jet data

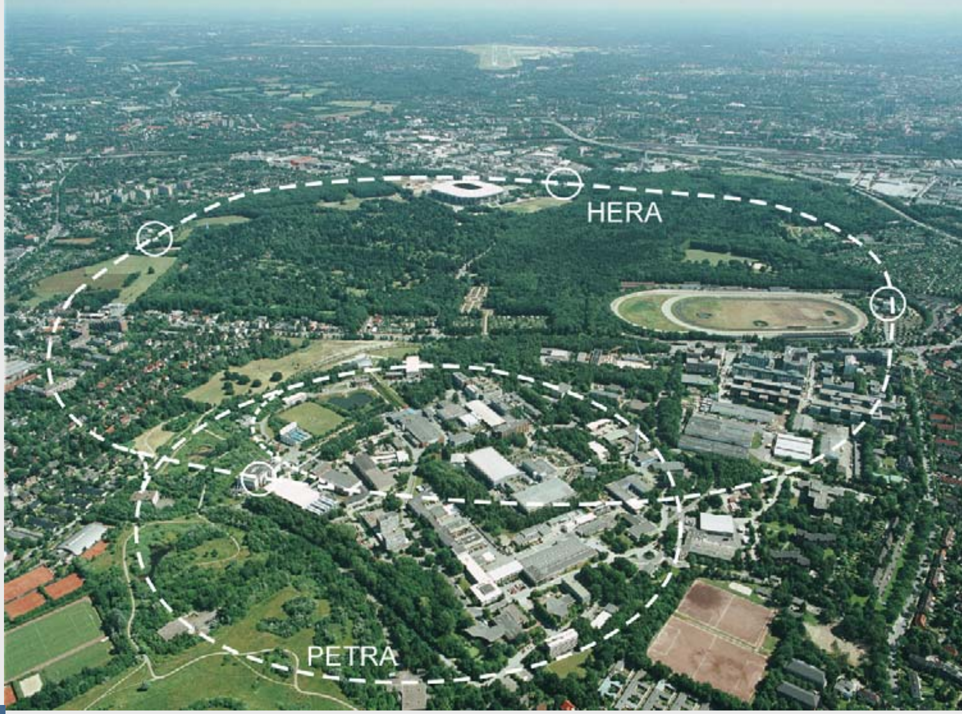
… to LHC

Production	errors in % PDF	Theory	Expt.	
W,Z	7	1-2	2	standard candle
Higgs	3-5	10	5-10	
$t\bar{t}$	3-4	10	10	
high E_T jets	10-50	10	15-50	new physics

- uncertainties due to
  - missing NNLO
  - errors of xg(x)
  - heavy flavor treatment
  - errors on jet energy scale
- underlying event + multiple interactions
  - better understand
- tune MC generators PYTHIA, JIMMY, PHOJET

HERA

2007



LHC

2008