Low-x Physics Results from HERA

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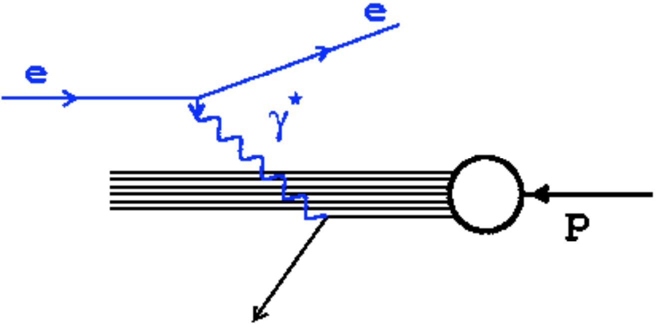
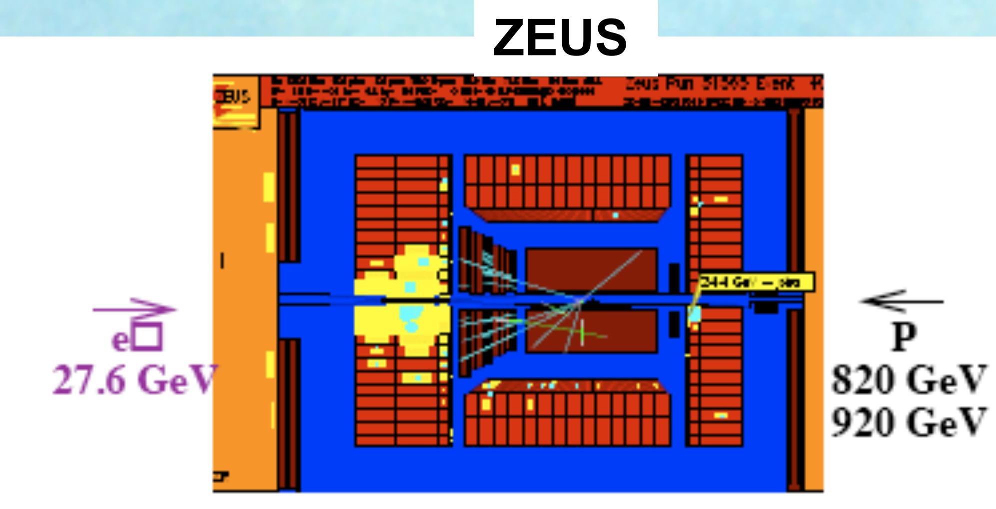
on behalf of H1 and ZEUS Collaborations
EDS Blois 2013, Saariselka, Finnland
9th of September, 2013

DIS at HERA at low x

Inclusive Scattering

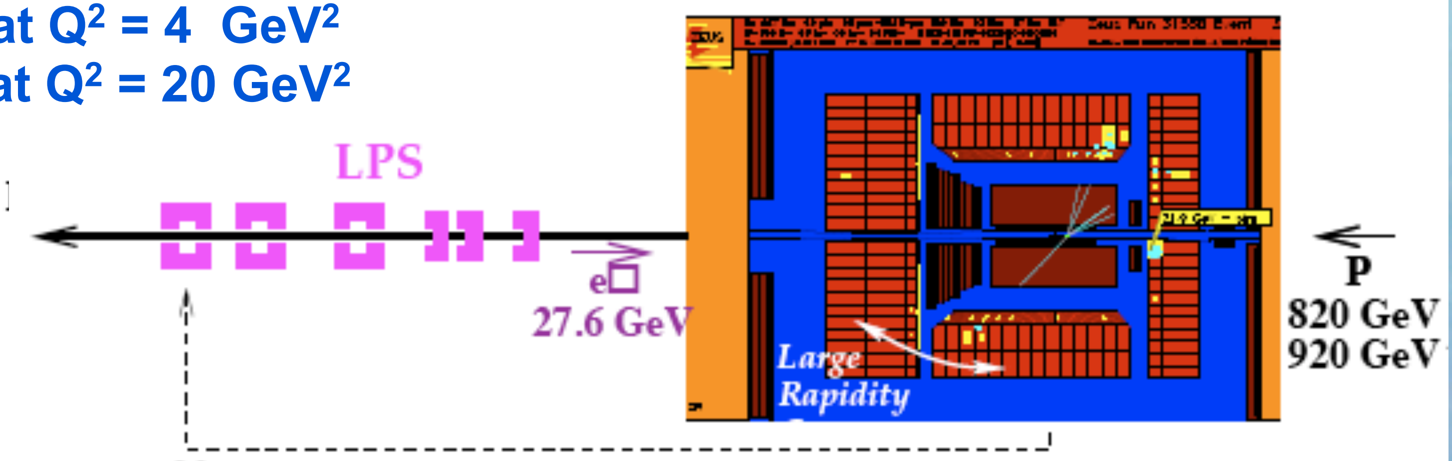




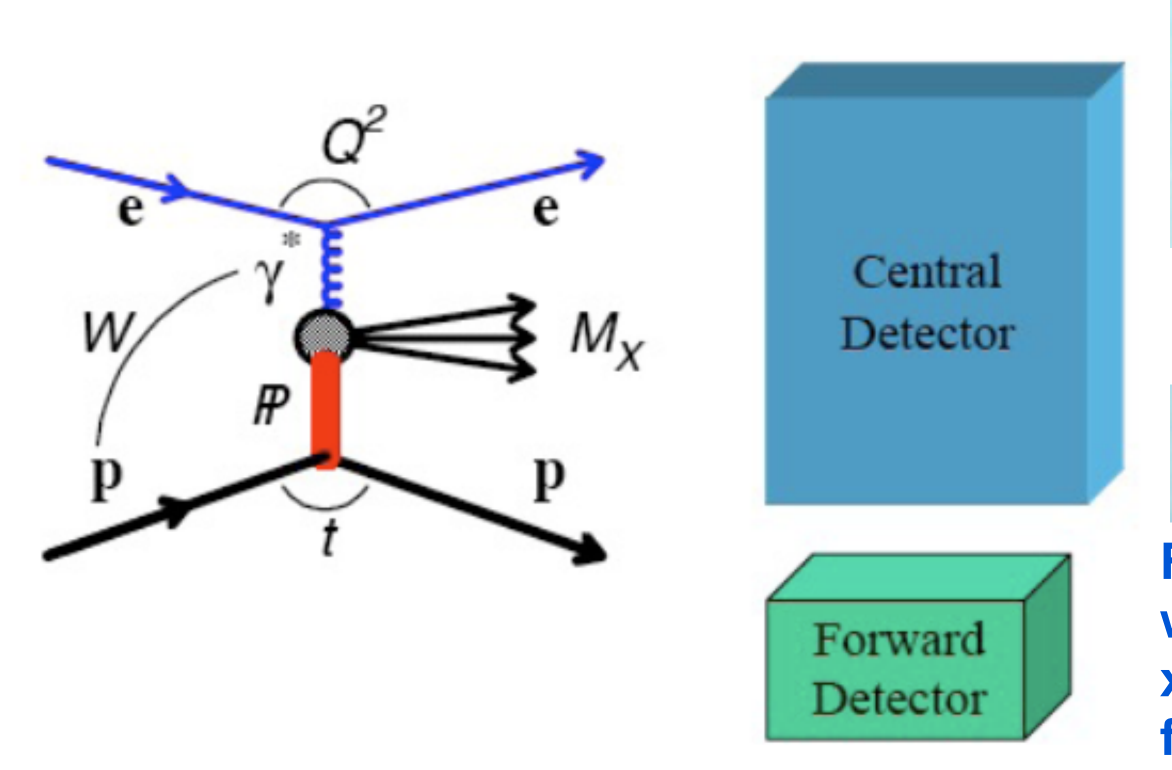
Diffractive Scattering

expectation before HERA
~ 0.01%

seen ~20% at $Q^2 = 4\ \mathrm{GeV}^2$
~10% at $Q^2 = 20\ \mathrm{GeV}^2$



DIS Reactions



Rapidity Gaps
$\Delta Y = \ln(W^2/M^2_X) \approx \Delta\eta$

Forward protons with $x_L = 1 - x_{IP} > 95\%$
x_L ~ longitudinal fraction of proton momentum

Inclusive variables:

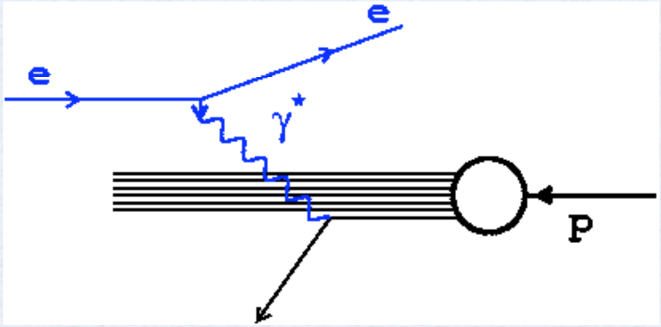
Q^2 - virtuality of the incoming photon
W - CMS energy of the incoming photon-proton system
x - $\approx Q^2/W^2$

Diffractive variables:

M_X - invariant mass of all particles seen in the detector
t - momentum transfer to the diffractively scattered proton

Partons vs Dipoles at low-x

Infinite momentum frame: Partons



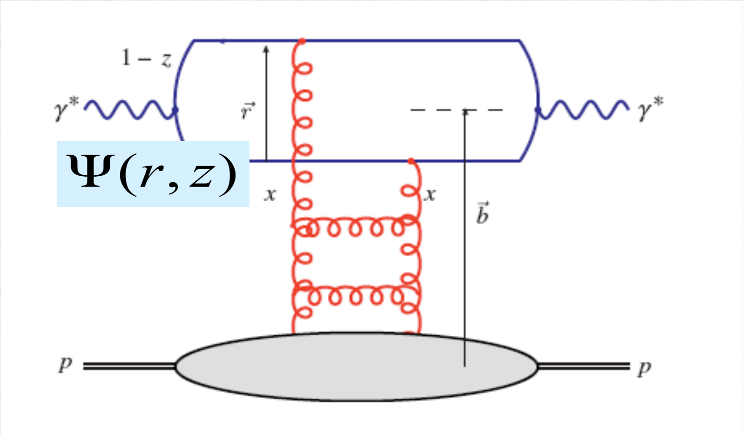
F$_2$ measures parton density at a scale Q^2

$$F_2 = \Sigma_f \; e_f^2 \; xq(x, Q^2)$$

Proton rest frame: Dipoles - long living quark pair interacts with the gluons of the proton

dipole life time ≈ 1/(m_p x)

= 10 - 1000 fm at x = 10^{-2} - 10^{-4}



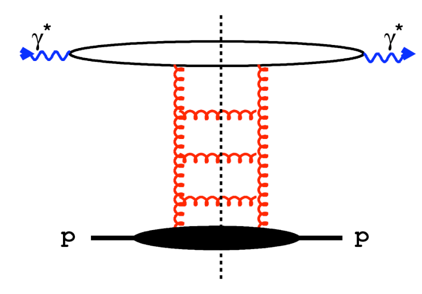
$$\sigma_{tot}^{\gamma^* p} = \int \Psi^* \sigma_{qq} \Psi \; ; \qquad F_2 = \frac{Q^2}{4\pi^2 \alpha_{em}} \sigma_{tot}^{\gamma^* p}$$

for small dipoles, at low-x, dipole picture is equivalent to the QCD parton picture

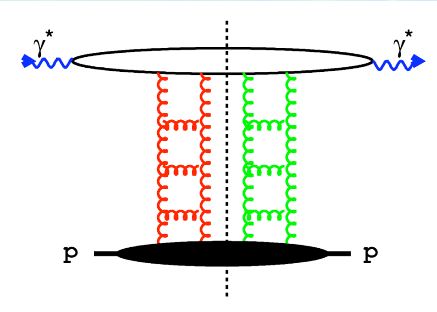
$\sigma_{qq} \sim r^2 \, xg(x, Q^2)$

Low-x phenomena in DIS give access to the properties of the gluon density

- rise of F2 with decreasing x (this talk)
- diffractive reactions (A. Valkarova talk)



← Optical Theorem →



$$\sigma_{tot}^{\gamma^* p} = \int \Psi^* \sigma_{qq} \Psi$$

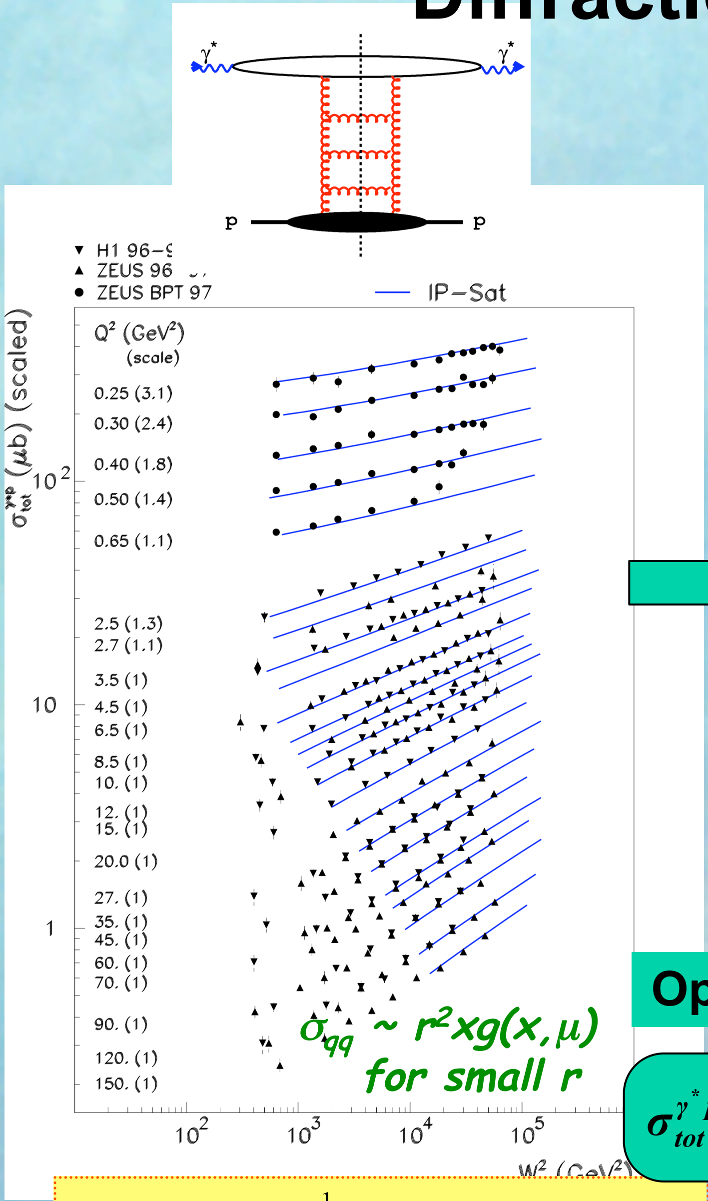
$$\frac{d\sigma^{\gamma^* p \to V p}}{dt} \sim \left| \int d^2 b \, \Psi_V^* \Psi e^{-i\vec{b}\cdot\vec{\Delta}} \frac{d\sigma_{q\bar{q}}}{d^2 b} \right|^2$$

$$\frac{d\sigma_{q\bar{q}}}{d^2 b} \sim r^2 \alpha_S x g(x, \mu^2) T(b)$$

for small dipole size

The same, universal, gluon density describes the properties of many reactions: F_2, F_L, inclusive diffraction, exclusive J/Psi, Phi and Rho production, DVCS, diffractive jets

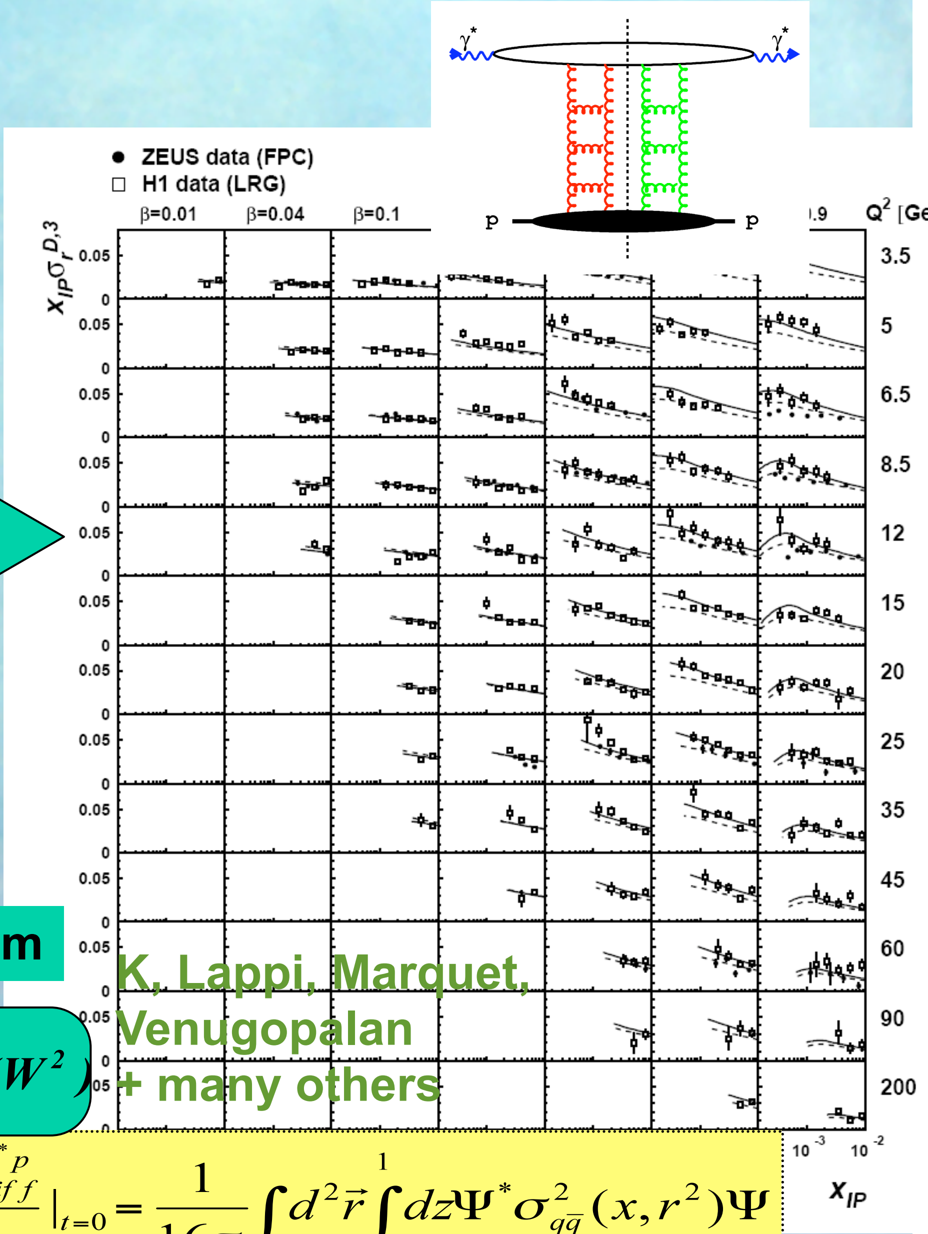
Diffraction as a shadow of DIS



$\sigma_{qq} \sim r^2 xg(x,\mu)$
for small r

Optical Theorem

$$\sigma_{tot}^{\gamma^* p} = \frac{1}{W^2} Im A_{el}(W^2)$$



K, Lappi, Marquet, Venugopalan + many others

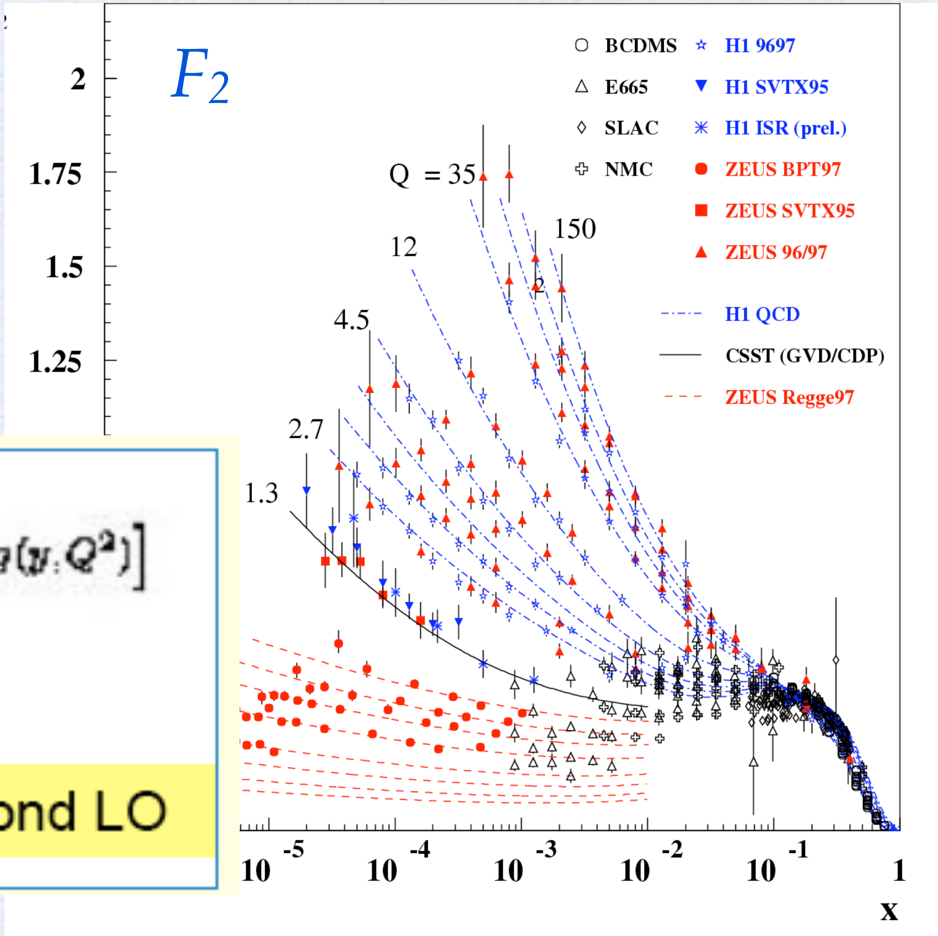
$$\sigma_{tot}^{\gamma^* p} = \int d^2\vec{r}\int_0^1 dz\,\Psi^* \sigma_{q\bar{q}}(x,r^2)\Psi$$

$$\frac{d\sigma_{diff}^{\gamma^* p}}{dt}\Big|_{t=0} = \frac{1}{16\pi}\int d^2\vec{r}\int_0^1 dz\,\Psi^* \sigma_{q\bar{q}}^2(x,r^2)\Psi$$

Determination of Gluon Density in pdf's

GD is determined from the increase of F_2 with x and Q^2 in low-x region

Determine pdf's densities from the χ^2 fit to the data



$$\frac{F_2(x,Q^2)}{x} = \int_0^1 \frac{dy}{y}\left[\Sigma_i C_2(z,\alpha_s)q_i(x,Q^2) + C_g(z,\alpha_s)g(y,Q^2)\right]$$

$$C_2(z,\alpha_s) = e_i^2\left[\delta(1-z) + \alpha_s f_2(z)\right]$$

$$C_g(z,\alpha_s) = \alpha_s f_g(z)$$

beyond LO

Who? ABM, MSTW, CT(EQ), HERAPDF, (G)JR, NNPDF

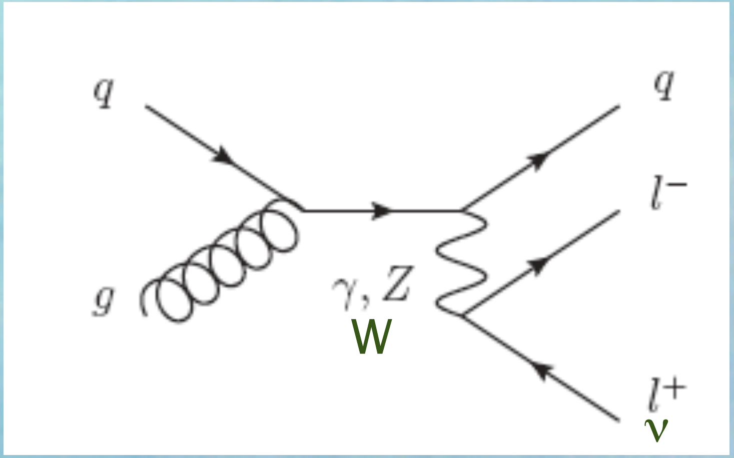
How? Start from parametrized form of $g(q)(x,Q_0^2)$ at Q_0^2 1-7 GeV^2
use N(N)LO DGLAP, MSbar factorisation, Heavy quark scheme

DATA

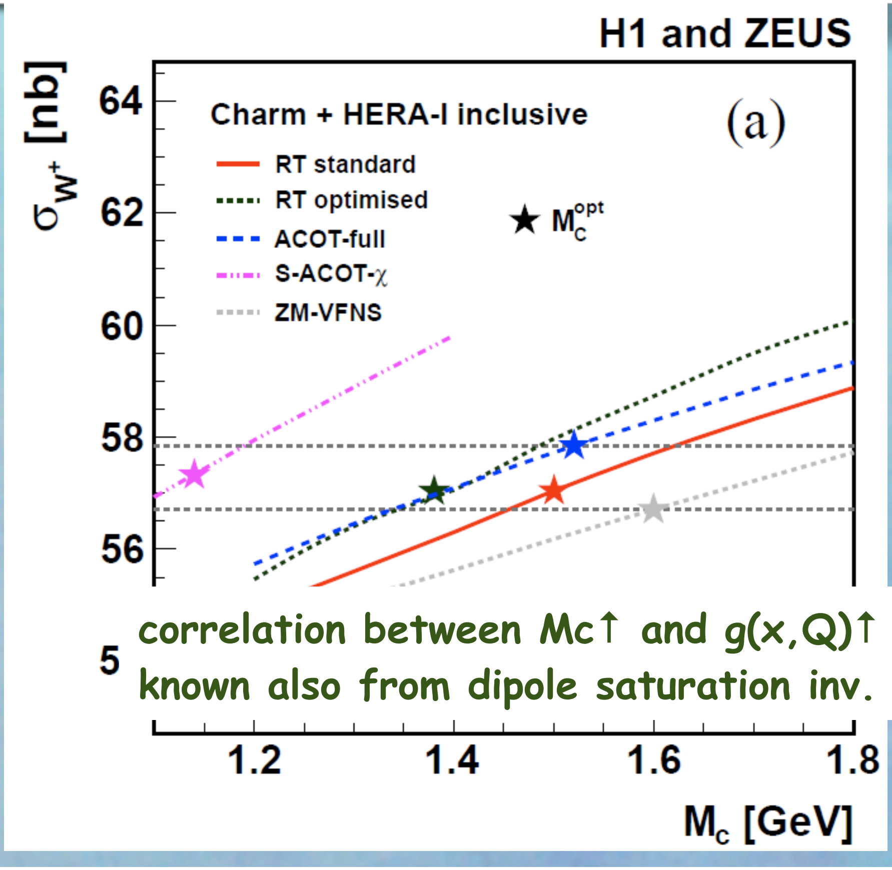
DIS (HERA and fixed target..), Drell-Yan processes (fixed target)
High E_T jets (Tevatron), W,Z rapidity (Tevatron)
νN dimuon (CCFR, NuteV)....

HERAPDF 1.0 uses combined H1 and ZEUS HERA I xs data
HERAPDF 1.5 uses, in addition, combined HERA charm data ..

Excellent test reaction
W, Z production at LHC



W, Z production at LHC is
a low-x effect



correlation between Mc↑ and g(x,Q)↑
known also from dipole saturation inv.

χ^2 function

→ nuisance parameters: $\chi^2 = \sum_i \frac{(D_i - T_i^*)^2}{(\delta_i^{unc})^2}$ $T_i^* = T_i + \sum_j \xi_j \delta_i^{cor,j}$

Nuisance parameter

Correlated error

→ covariance matrix: $\chi^2 = \sum_{i,j} (D_i - T_i) Cov_{i,j}^{-1} (D_j - T_j)$

→ mixed

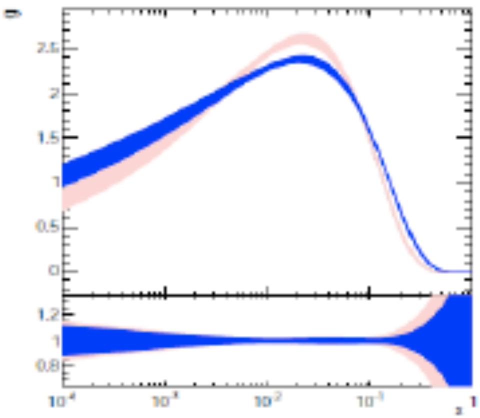
Various types of uncertainty treatment for experimental data:

→ Hessian, Monte Carlo, Offset

Hessian

Error inflation by a tolerance parameter (nuisance) to accommodate inconsistencies between data sets

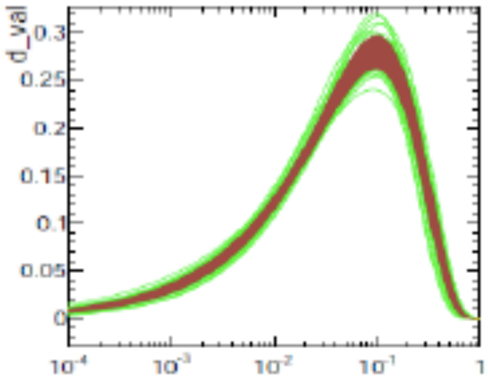
Phys.Rev. D65 (2001) 014013, [hep-ph/0101032]



Monte Carlo

MC replica method shifting data cross section points randomly within their uncertainties

Phys.Rev. D58 (1998) 094023, [hep-ph/9803393]



Various forms of parametrisation ansatz

→ HERAPDF, CTEQ style, Chebyshev, bi-log normal

JHEP 1001:109 (2010) arXiv:1302.6246 Phys. Let. B 695 (2011) 238

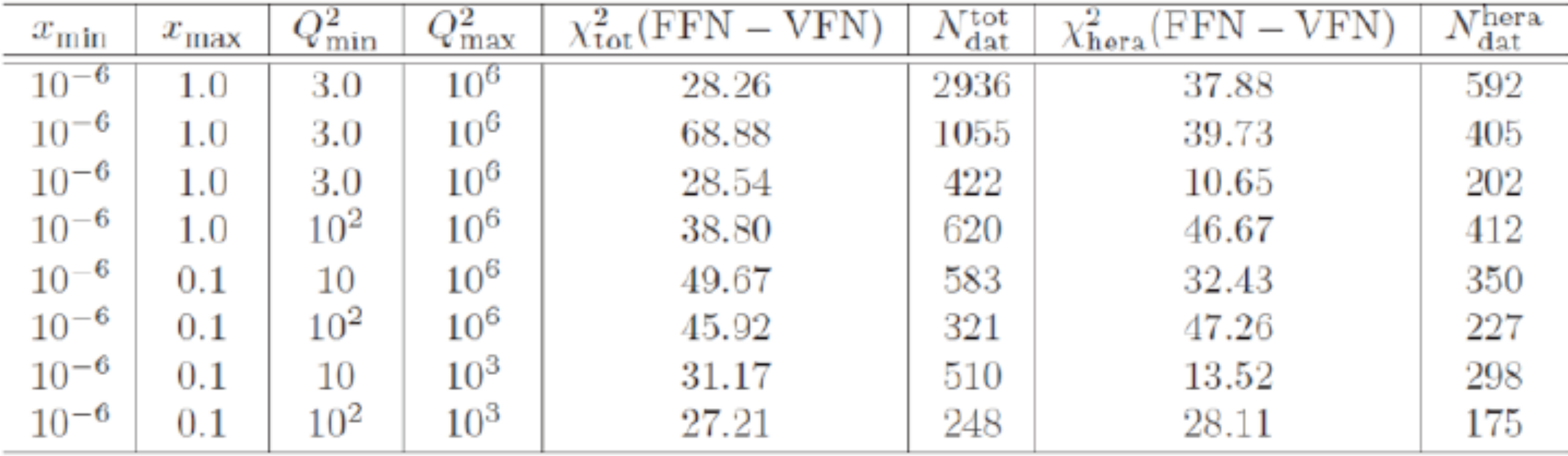
Bayesian Reweighting technique

Nucl.Phys. B855, 608 (2012),[arXiv:1108.1758,]JHEP 1208, 052 (2012), [arXiv:1205.4024]

→ a method to study data sensitivity on PDFs without fitting the data

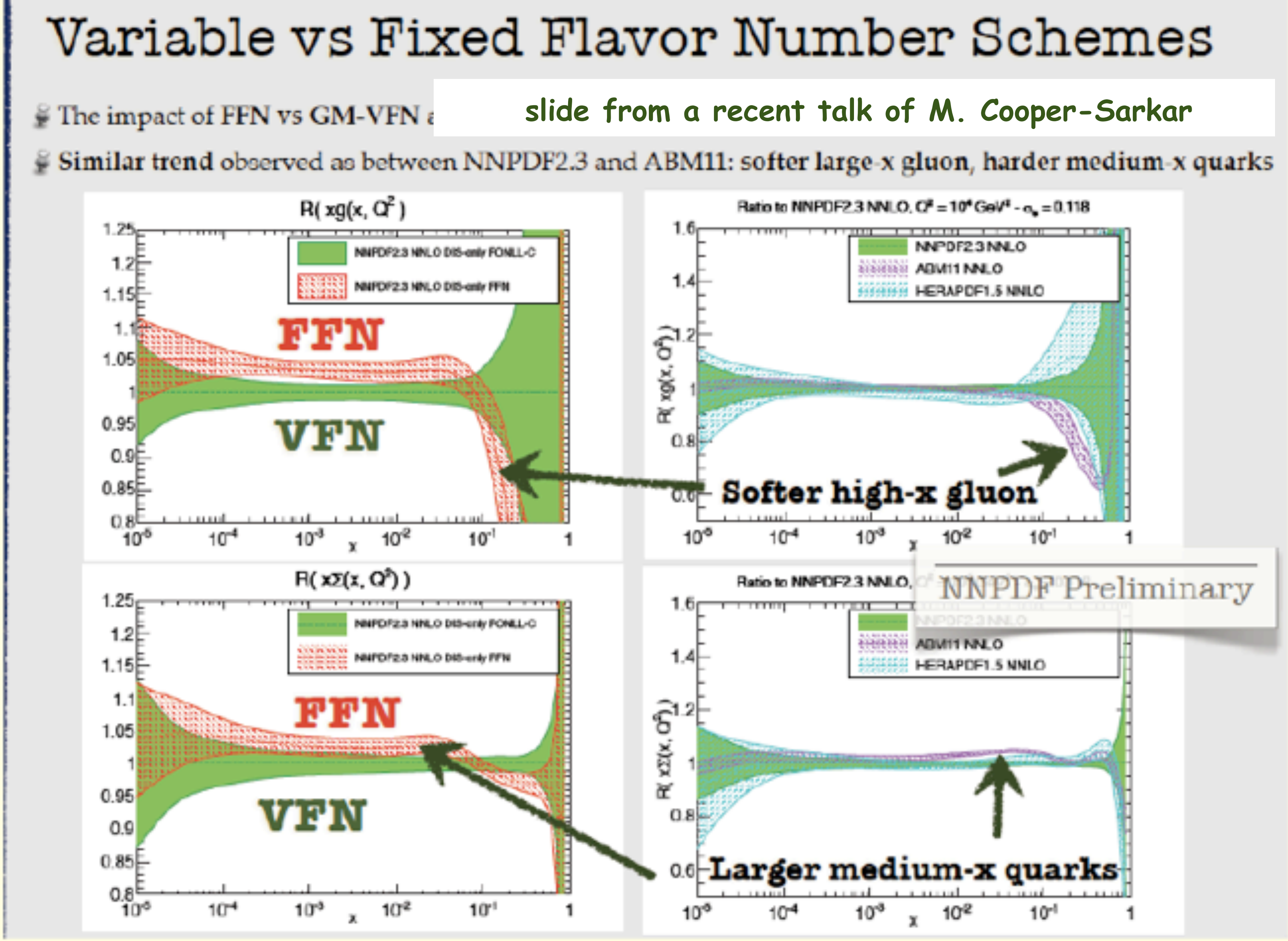
Heavy Quark treatment in pdf’s

Fixed Flavour Number Scheme - FFNS (exact calculation at fixed order)
Variable Flavour - VFNS (approx. eval.: Mc=0, resums large logs



$x_{\rm min}$	$x_{\rm max}$	$Q^2_{\rm min}$	$Q^2_{\rm max}$	$\chi^2_{\rm tot}({\rm FFN-VFN})$	$N_{\rm dat}^{\rm tot}$	$\chi^2_{\rm hera}({\rm FFN-VFN})$	$N_{\rm dat}^{\rm hera}$
10^{-6}	1.0	3.0	10^6	28.26	2936	37.88	592
10^{-6}	1.0	3.0	10^6	68.88	1055	39.73	405
10^{-6}	1.0	3.0	10^6	28.54	422	10.65	202
10^{-6}	1.0	10^2	10^6	38.80	620	46.67	412
10^{-6}	0.1	10	10^6	49.67	583	32.43	350
10^{-6}	0.1	10^2	10^6	45.92	321	47.26	227
10^{-6}	0.1	10	10^3	31.17	510	13.52	298
10^{-6}	0.1	10^2	10^3	27.21	248	28.11	175

VFNS provides consistently better fits than FFNS
=> importance of resummation



Variable vs Fixed Flavor Number Schemes

slide from a recent talk of M. Cooper-Sarkar

- The impact of FFN vs GM-VFN a
- Similar trend observed as between NNPDF2.3 and ABM11: softer large-x gluon, harder medium-x quarks

Softer high-x gluon

Larger medium-x quarks

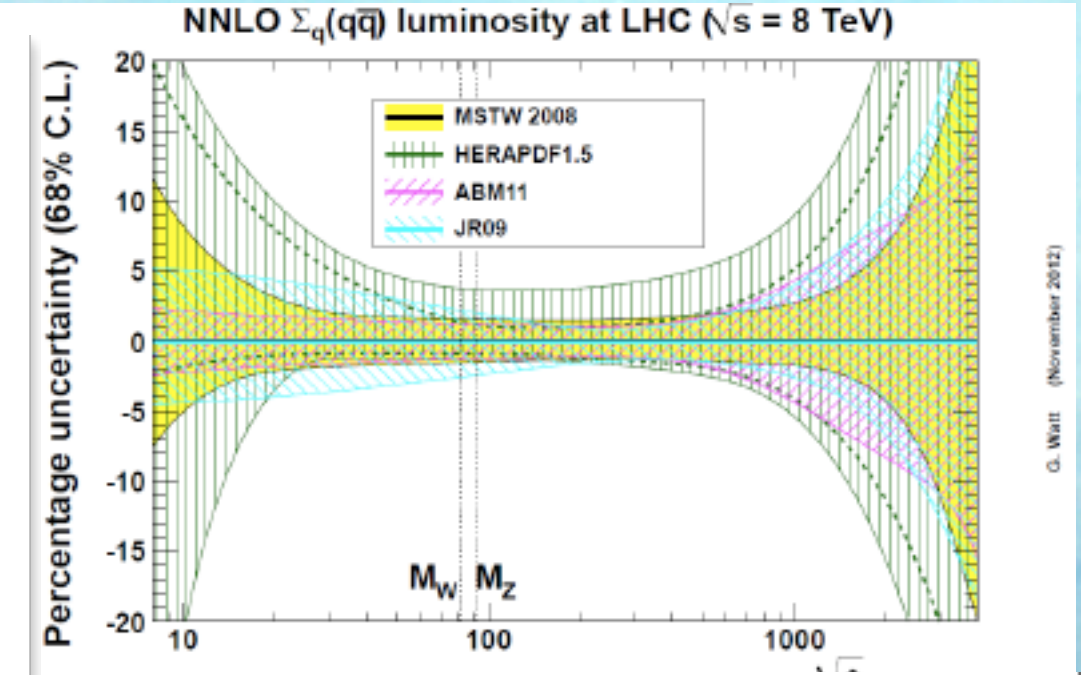
These fits are done with the same value of alphas- so the PDF shape change does not come just from difference of $\alpha_S(M_Z)$

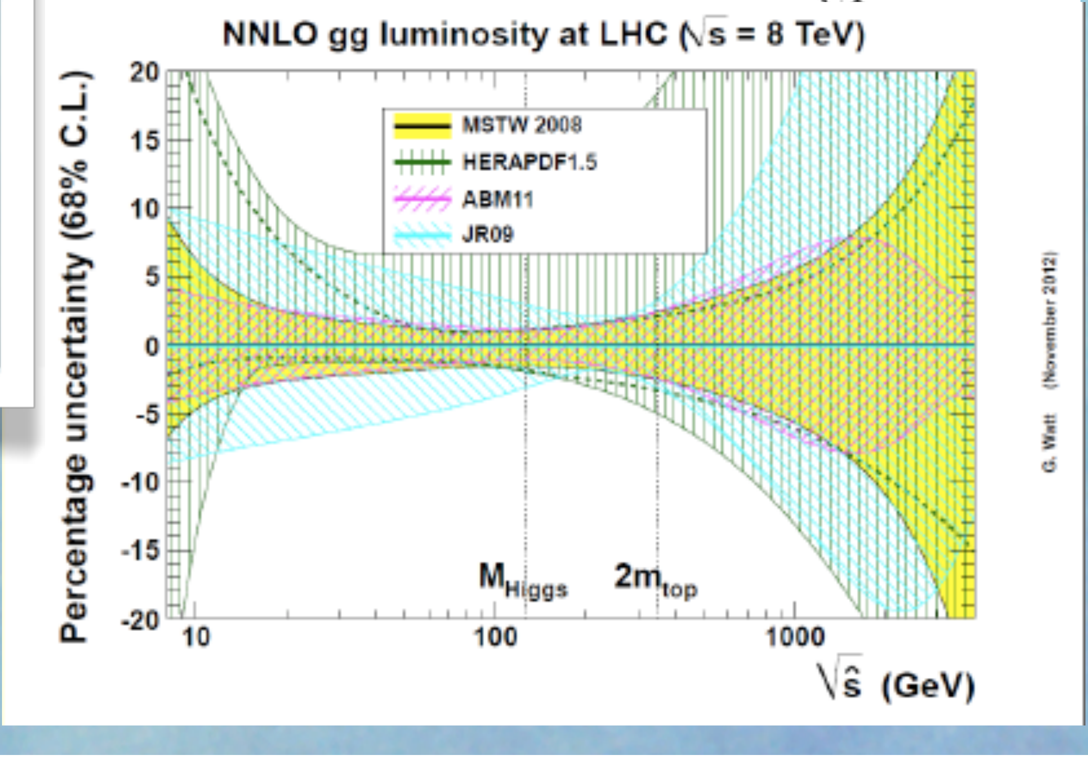
Sources of uncertainty

example: HERAPDF

- st. and sys. errors of data
- variation of Q_0^2
  range - 1.5 to 2.5 GeV^2
- variation of the Q^2_{cut}
  range - 2.5 to 5 GeV^2

(relatively large uncertainties of HERAPDF are due presumably to the use of HERA data only)

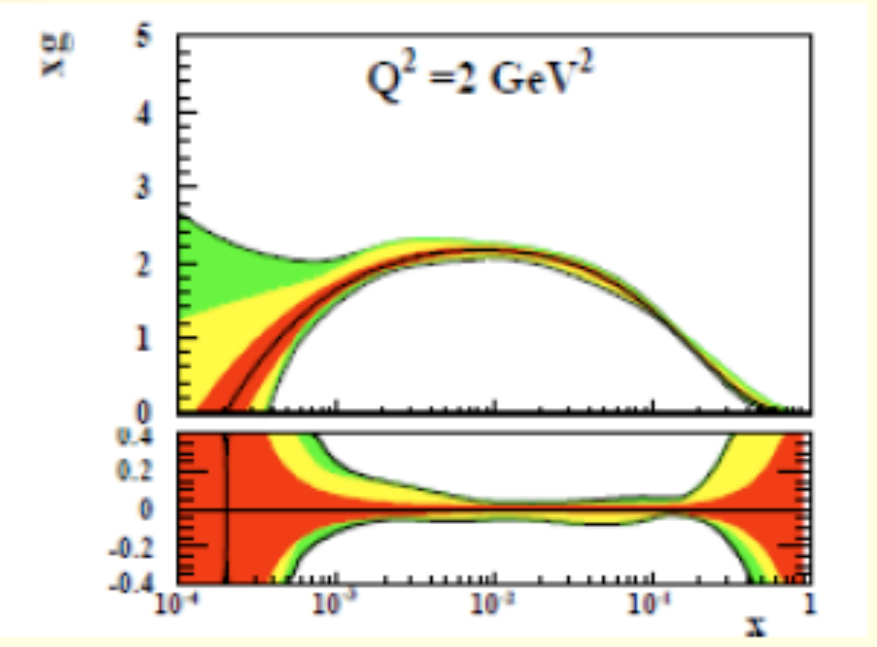


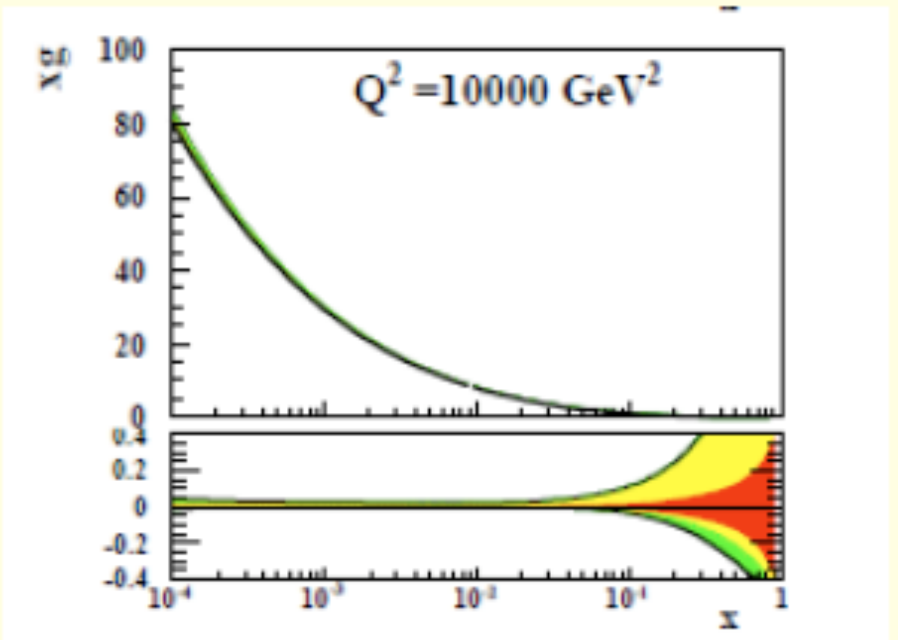


from a recent talk of M. Cooper-Sarkar
(DESY QCD Workshop, 2nd of Sep. 2013)

Study of uncertainties

- st. and sys. errors of data (red)
- variation of Q_0^2, range - 1.9 to 2.5 GeV^2 (green)

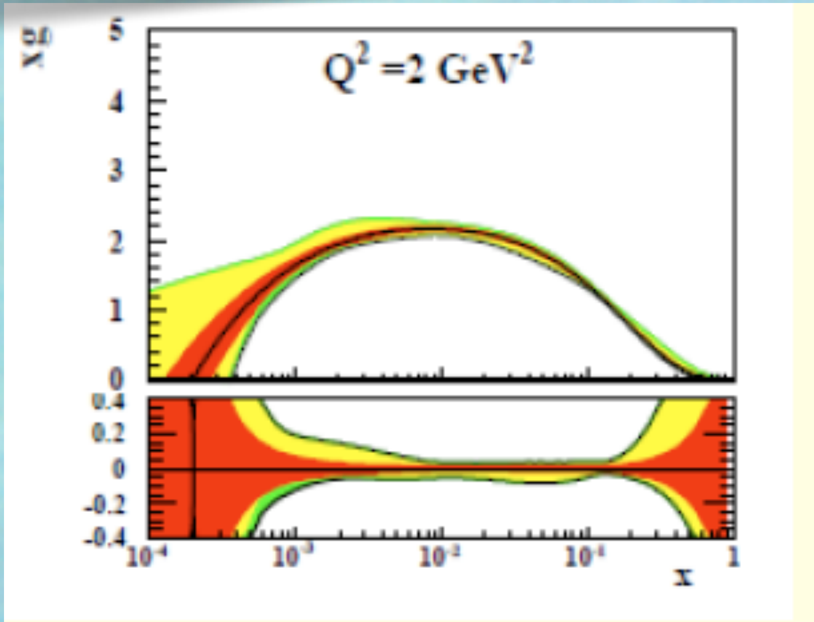


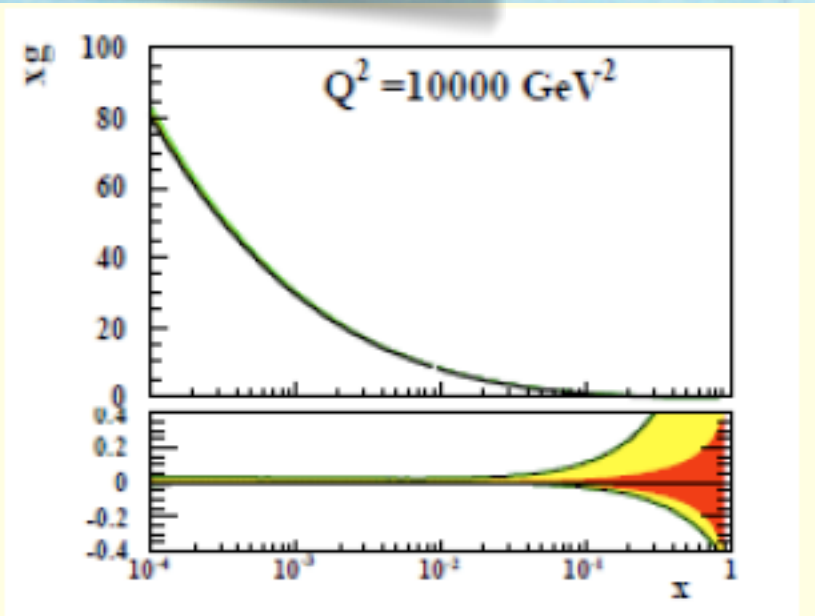


▶ behaviour of gluon density at large x and/or large Q^2's is strongly correlated with its behaviour at small x and small Q^2's

Study of uncertainties

- variation of the Q^2_{cut} , range - 2.5 to 5 GeV^2 (yellow) (most of the effect is coming from the change from 3.5 to 5 GeV^2)



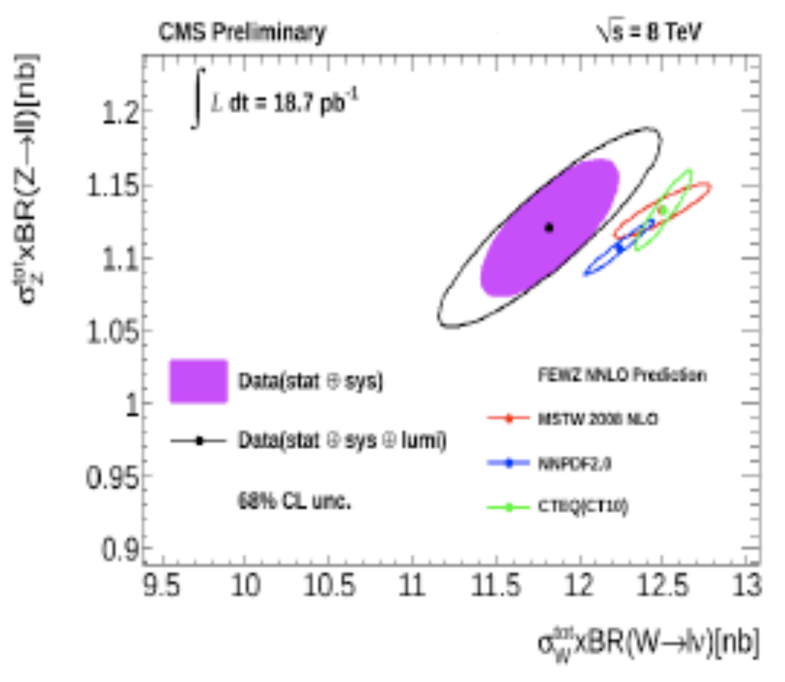


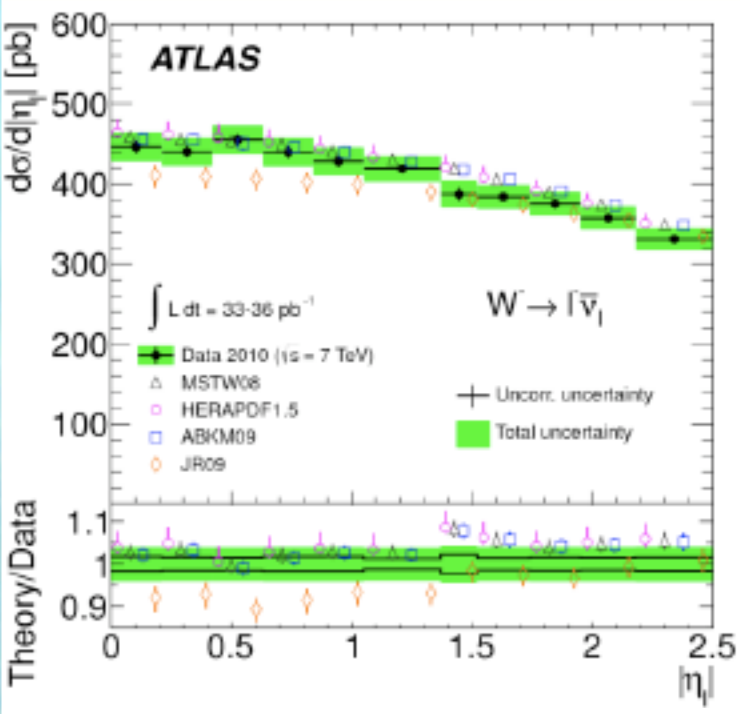
▶ behaviour of gluon density in the saturation region could be correlated with its large Q^2 behaviour

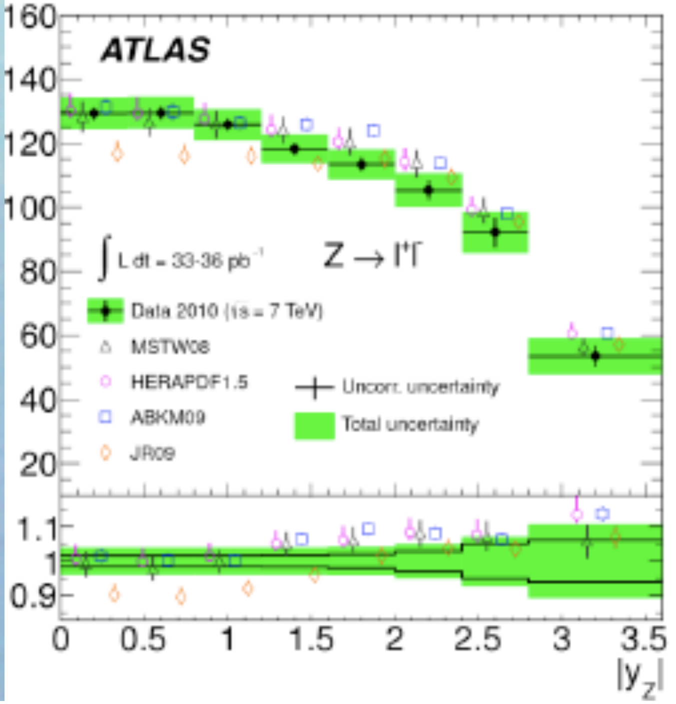
more investigations are in progress, wait for HERAPDF2.0 which will also use HERA II inclusive combined data

Comparison with the W and Z production at LHC

combined muon and electron data







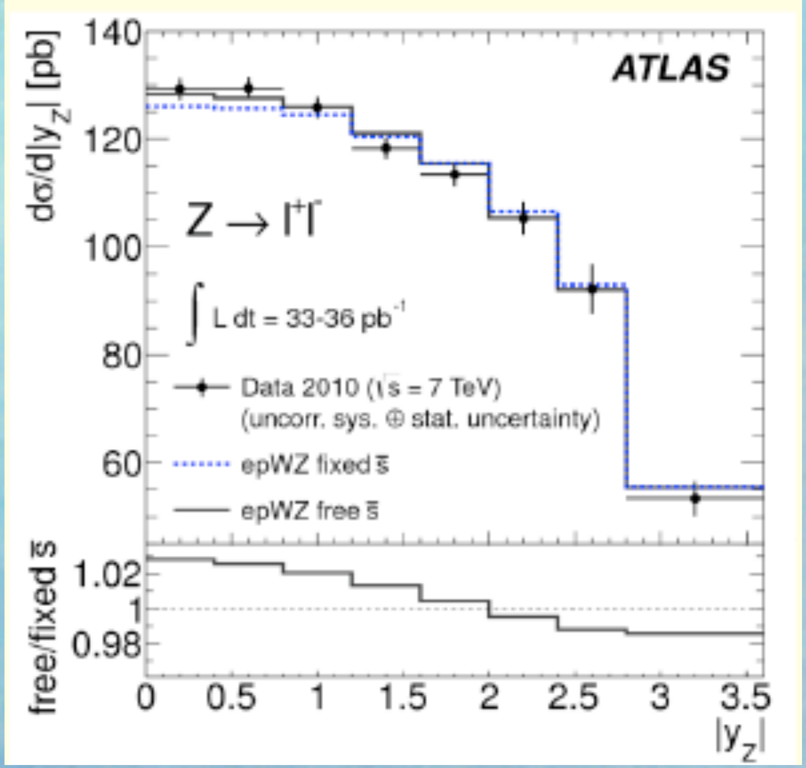
Strangeness suppression at low-x?

dimuon production in νN DIS suggested that s/d ~ 0.5

this was accepted by e.g.: MSTW08, NNPDF2.3, but contested by CTEQ

(also difficult to understand in the dipole picture)

this is a 4% effect at LHC, could we see it?

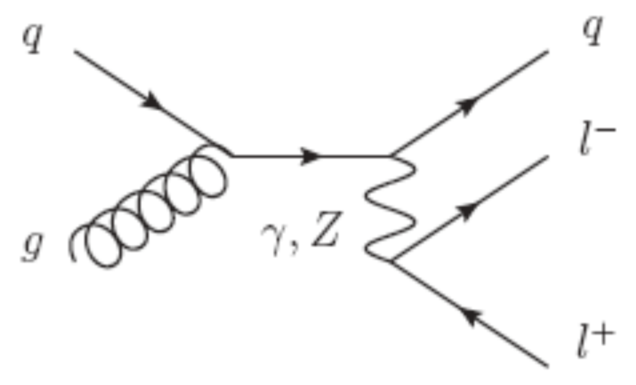


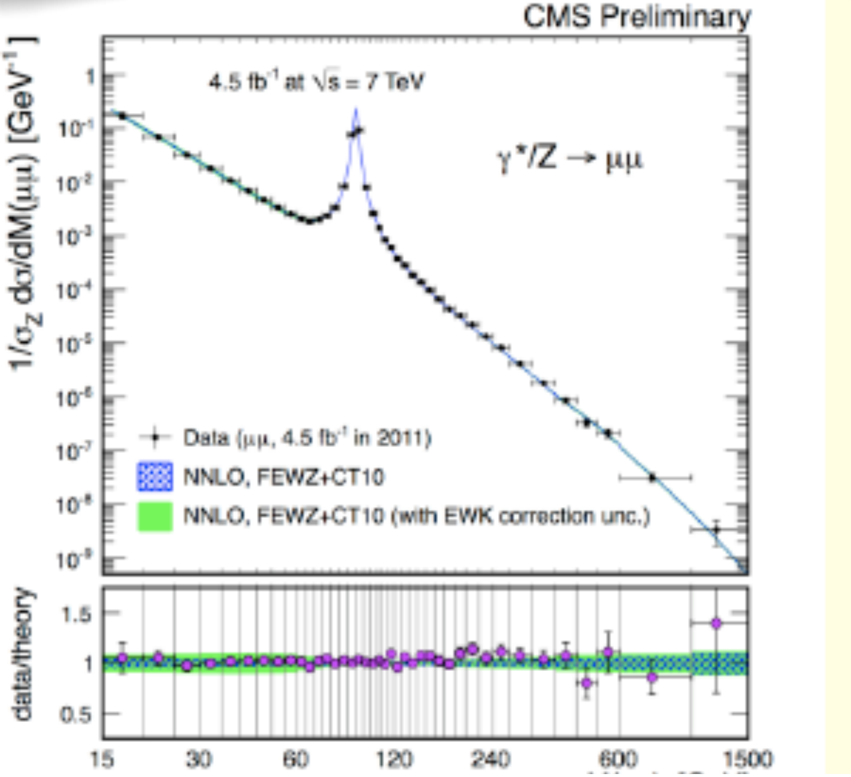
fit within HERAfitter:

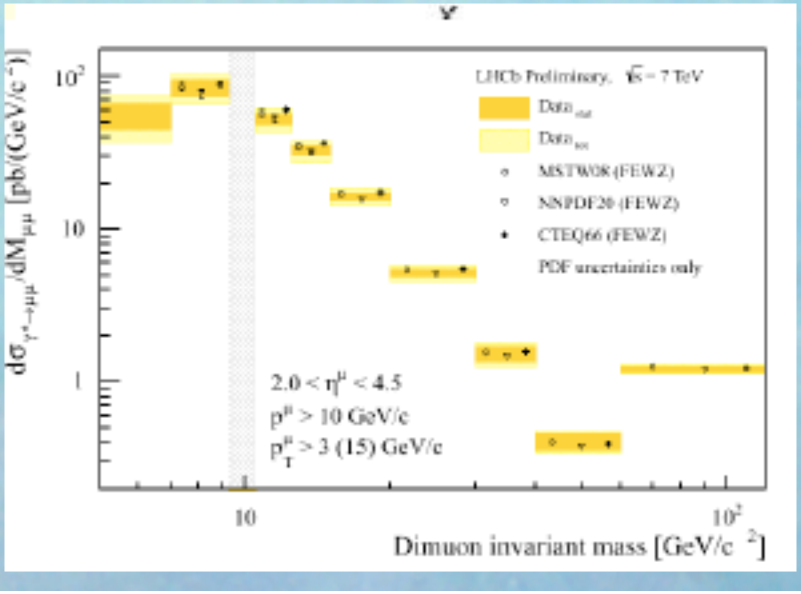
s/d = 1.0 +/- 0.25

Drell-Yan at LHC

(a potentially very interesting reaction for low-x physics)

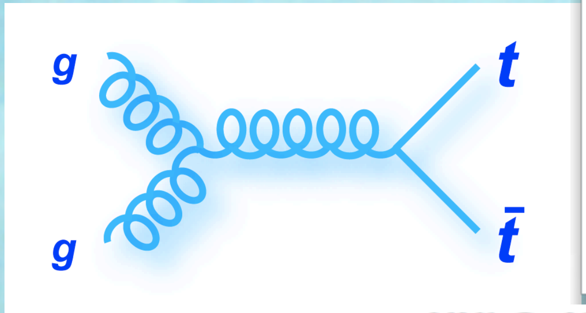






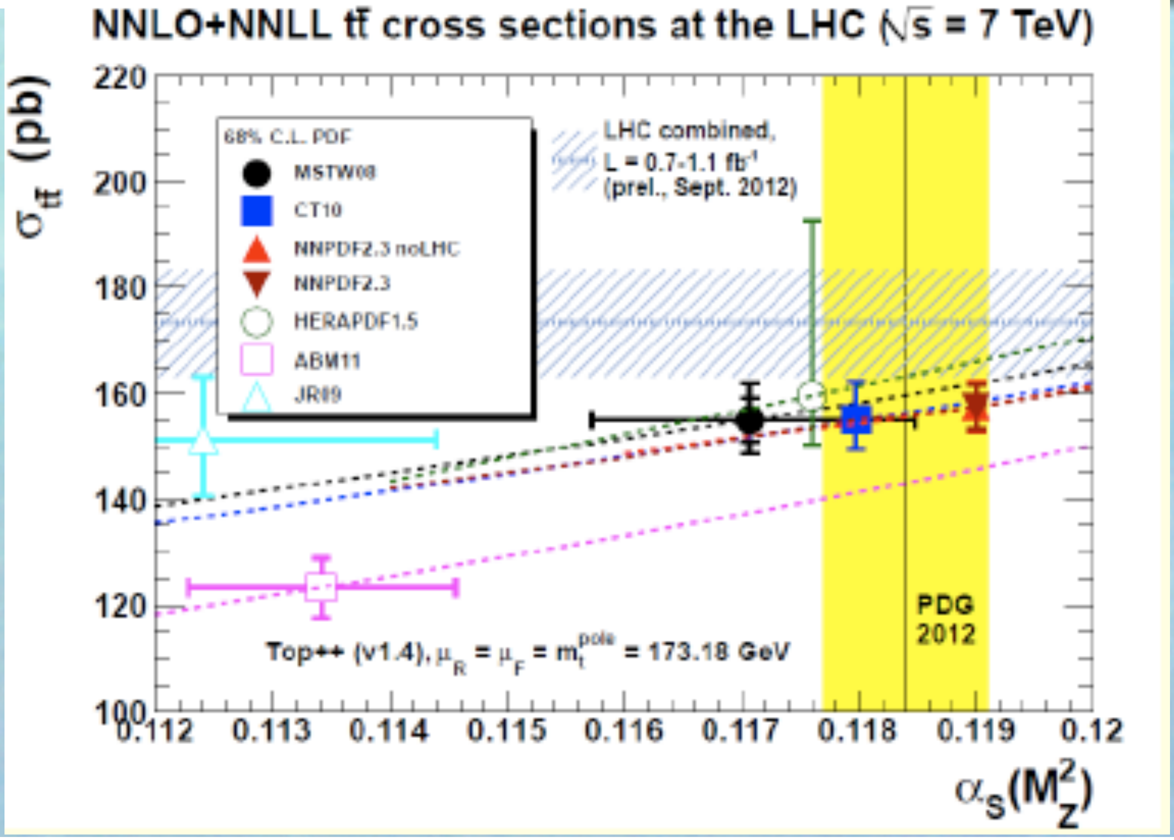
very good agreement between theory and data at high mass

good agreement at low mass but error on data is still large



top production at LHC

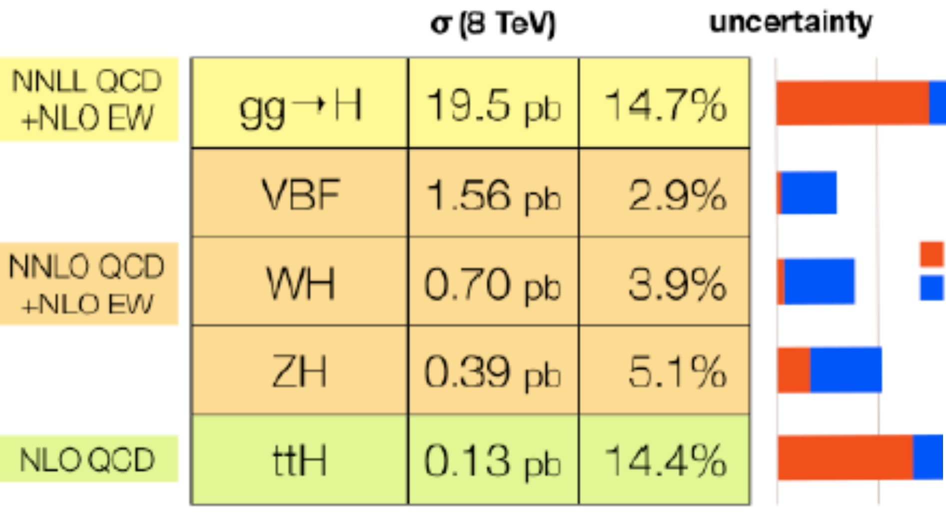
test of gluon density, $\alpha_S(M_Z)$ dependence and top mass



top production is also very sensitive to top mass, which in turn determines the running of the Higgs potential to high scales, which in turn determines the stability of our universe

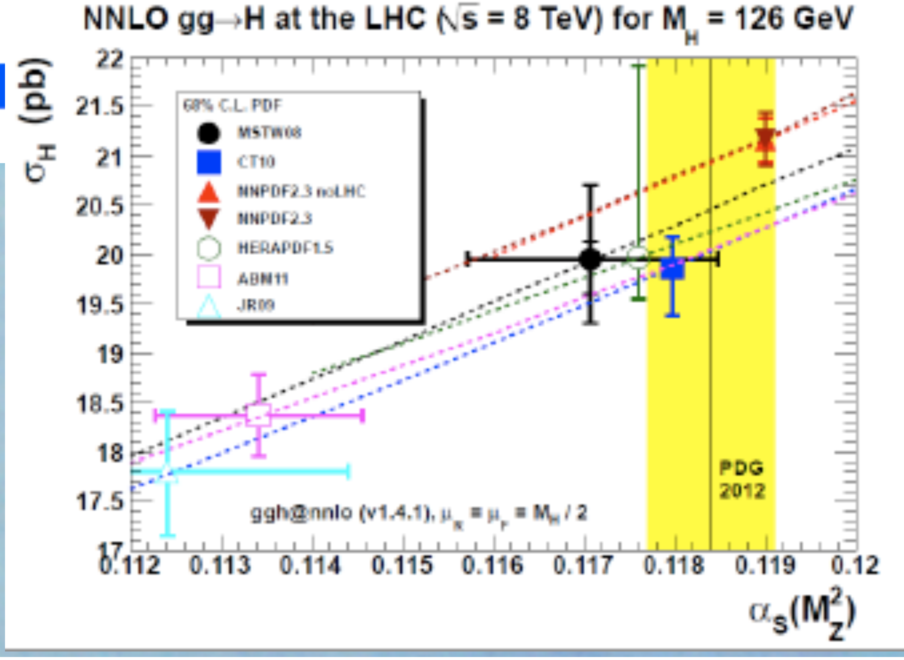
Higgs production

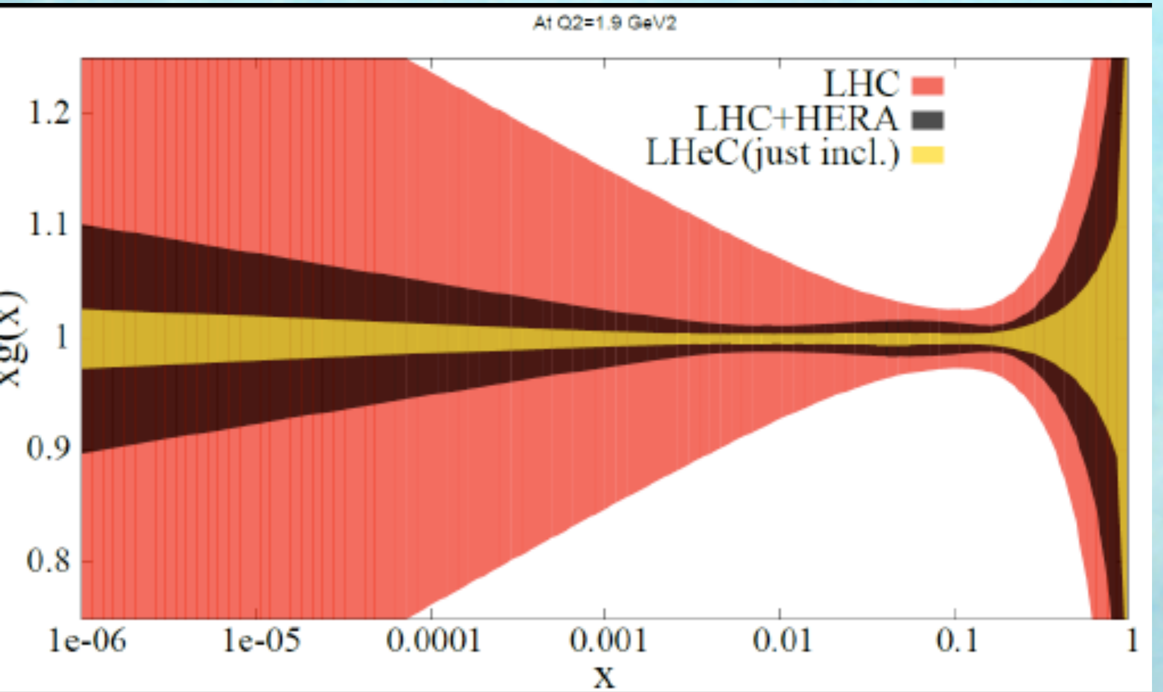
Higgs xsection is strongly dependent on the gluon density and $\alpha_S(M_Z)$, as the top xsection but at smaller x

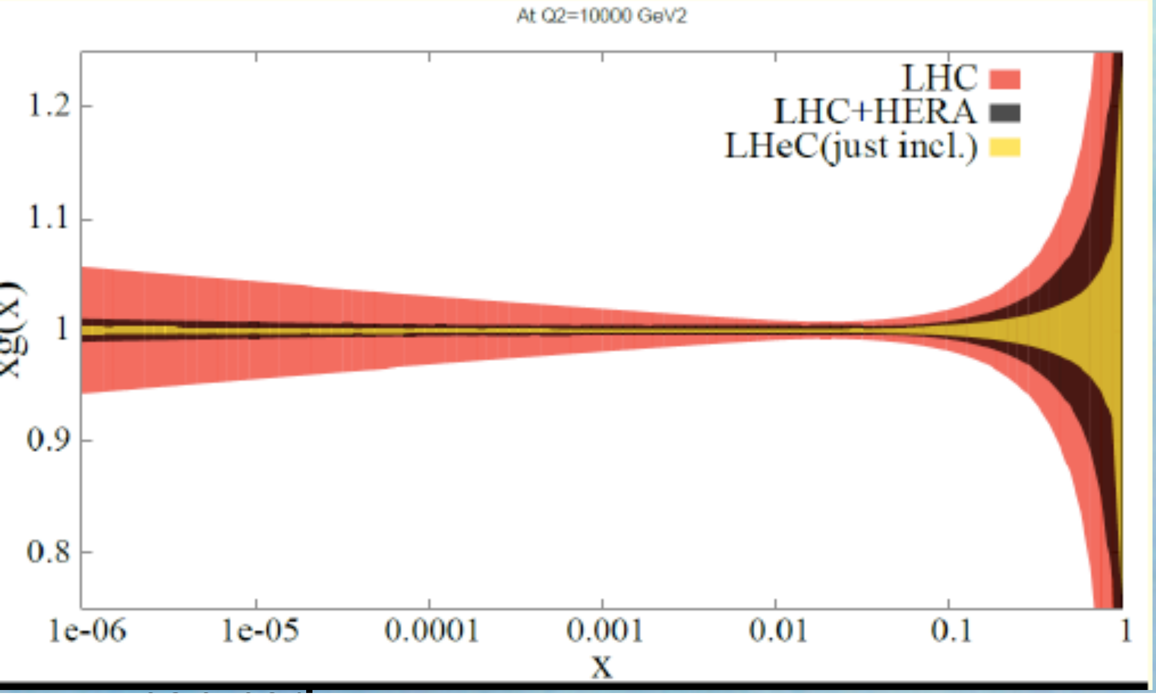


		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%

🟥 scale
🟦 PDF+αs







Instead of conclusions

HERA data combined with LHC data will teach us a lot about gluon density