Parton Distribution Functions at (present and) Future Colliders

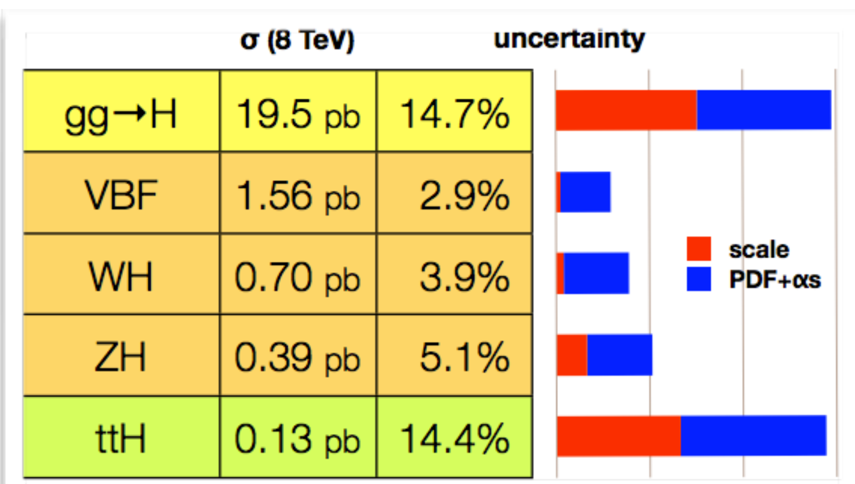
Alberto Guffanti
Università degli Studi di Torino & INFN Torino

LFC15: physics prospects for Linear and other Future Colliders after the discovery of the Higgs
ECT* Trento,
September 7-11, 2015

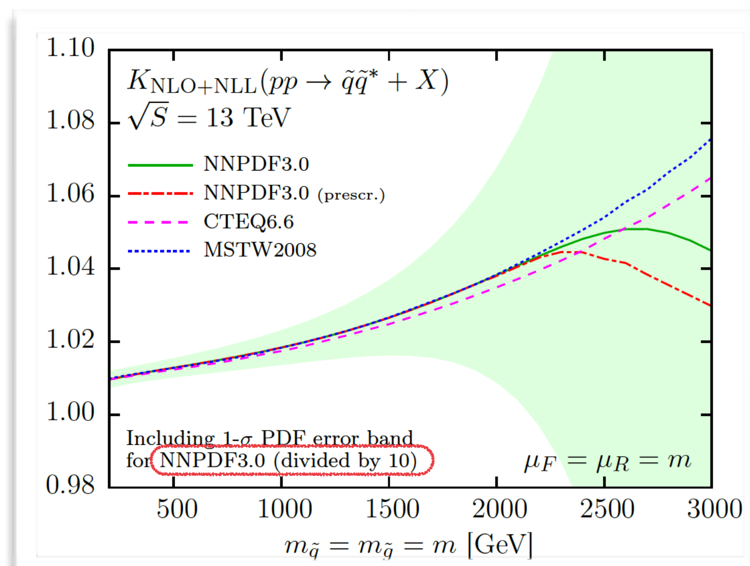
Motivation

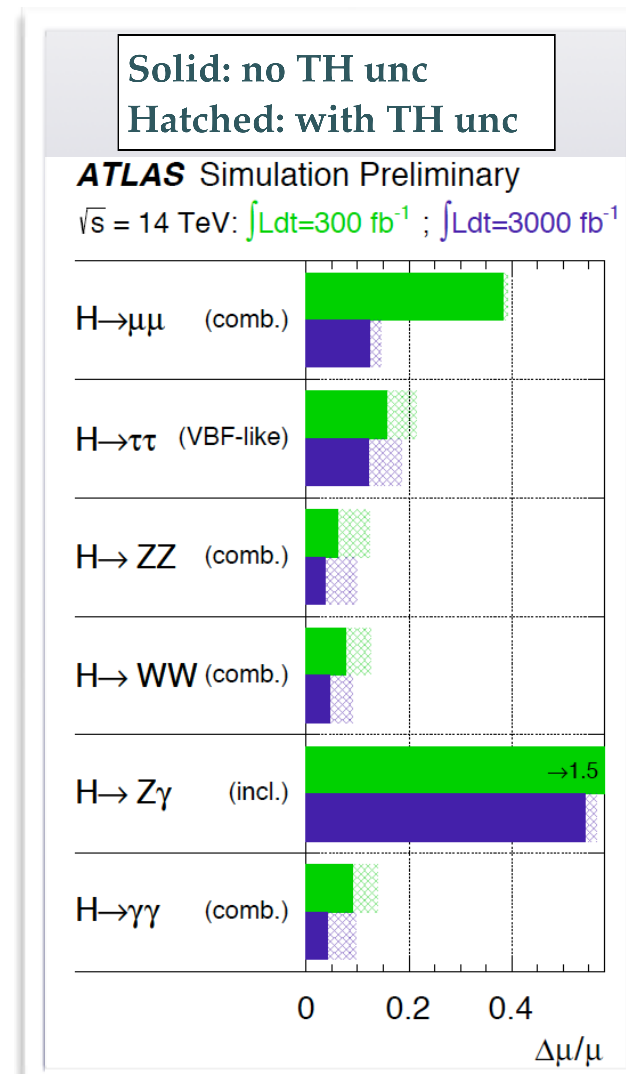
Experimental push

- Uncertainties on Parton Distribution Functions (PDFs) are often the limiting factor in precision Standard Model studies and New Physics searches



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





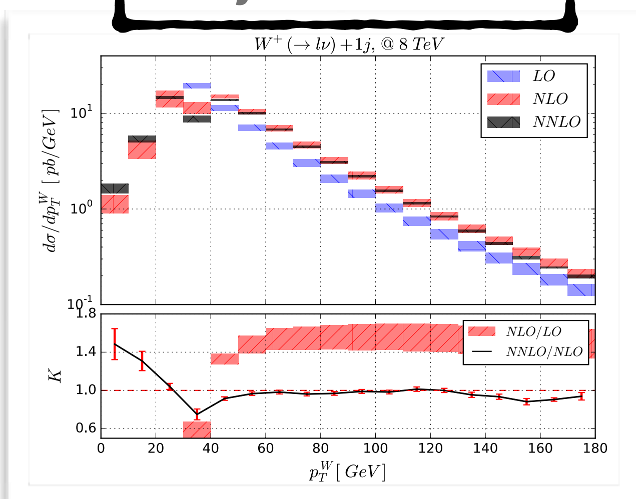
Accurate and reliable PDFs are crucial for exploiting the full potential of LHC experiments

Motivation

Theoretical push

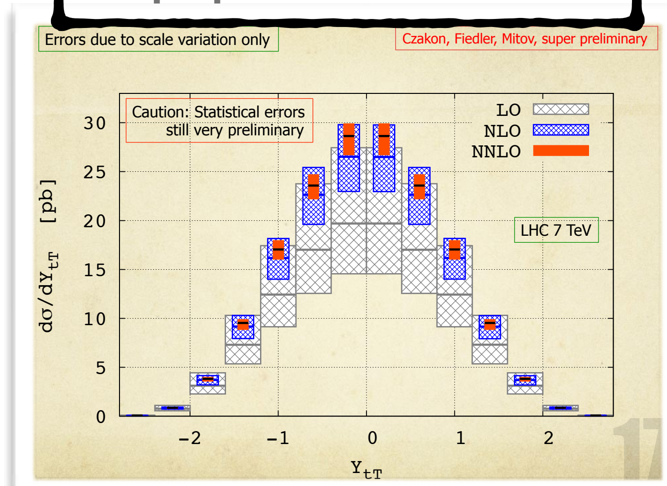
- Impressive progress in computation of higher order corrections (QCD & EW)

W+j at NNLO



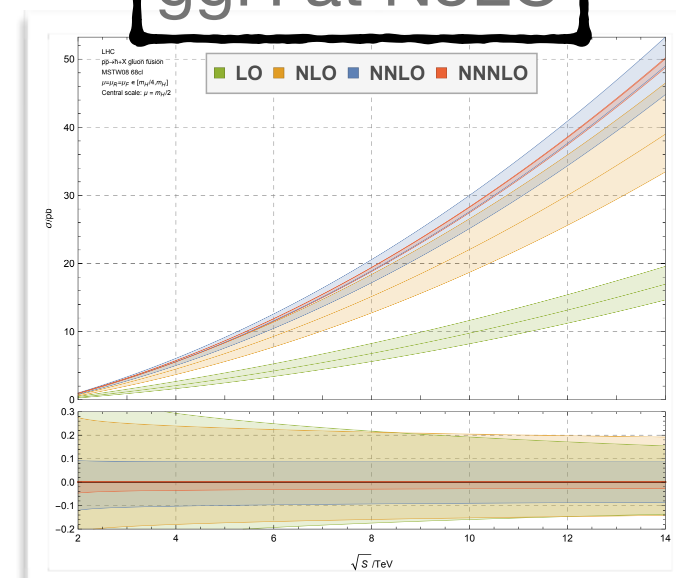
R. Boughezal et al, [arXiv:1504.02131]

Top pair at NNLO



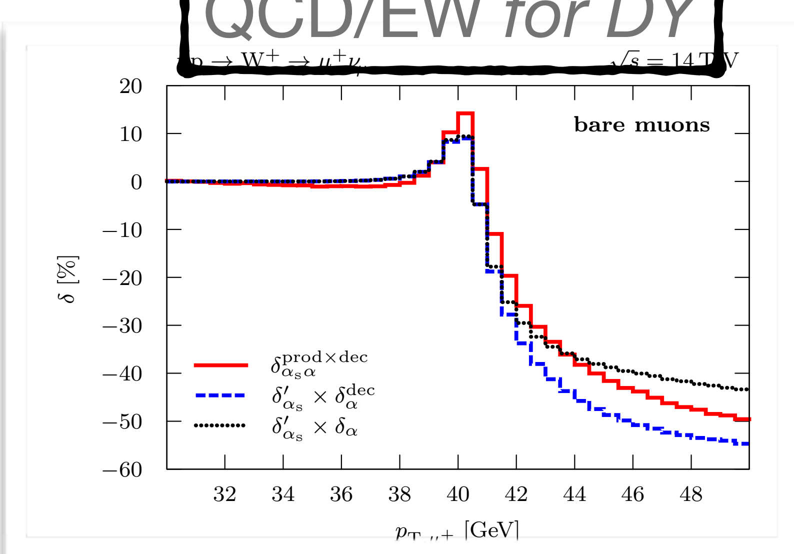
A. Mitov et al, Top2014

ggH at N3LO



C. Anastasiou et al, [arXiv:1503.06056]

QCD/EW *for DY*

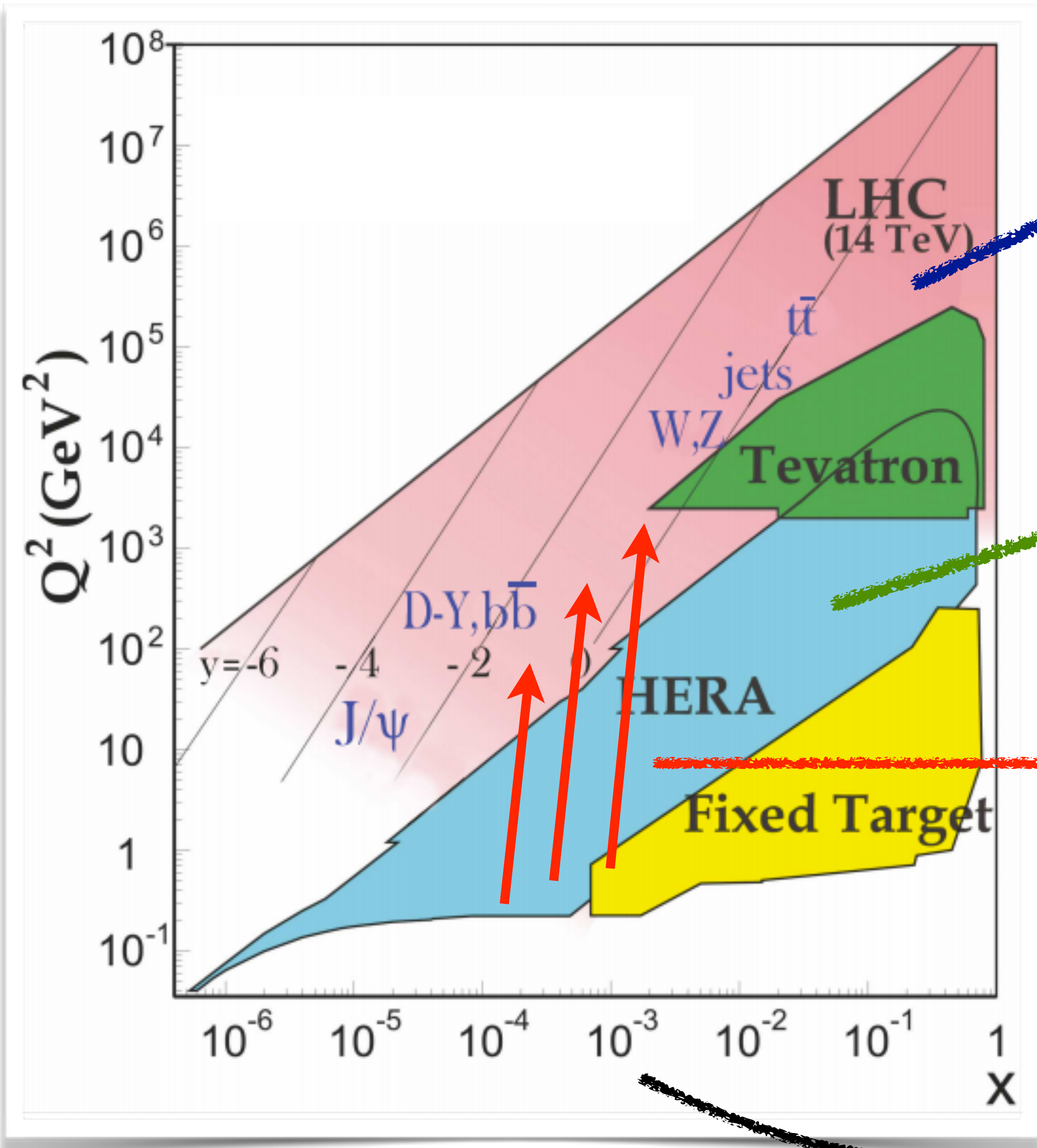


C. Schwinn,SM@LHC2015

Finally, the computation of the hadronic cross-section relies crucially on the knowledge of the strong coupling constant and the parton densities. After our calculation, the uncertainty coming from these quantities has become dominant. Further progress in the determination of parton densities must be anticipated in the next few years due to the inclusion of LHC data in the global fits and the impressive advances in NNLO computations, improving the theoretical accuracy of many standard candle processes.

Parton Distribution Functions

Where do we measure them, where do we use them



This is the region where we want to use PDFs for predictions at the LHC

This is the region where we measure PDFs, from DIS and Tevatron experiments

DGLAP evolution

x dependence of PDFs at the reference scale extracted from (global) fits to data

(Unpolarized proton) ***PDF Determinations Overview***

September 2015

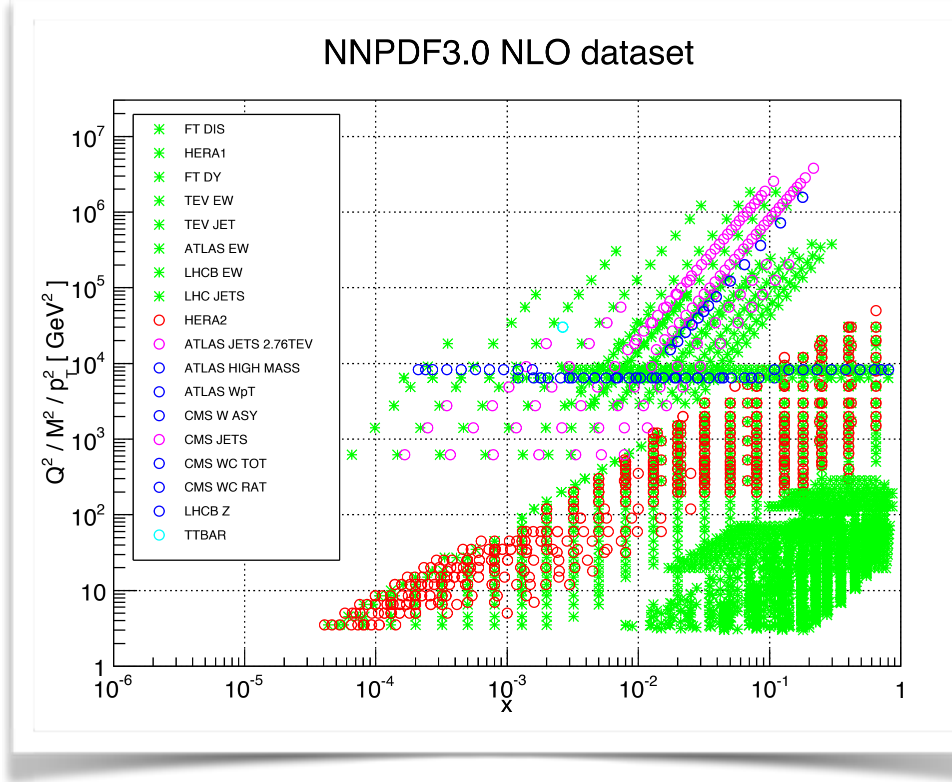
	Dataset	Pert. Order	HQ Treatment	α	Param.	Uncert.
ABM12 [arXiv:1310.3059]	DIS Drell-Yan	NLO NNLO	FFN (BMSN)	Fit (multiple values available)	6 indep. PDFs Polynomial (25 param.)	Hessian (Δ
CT14 [arXiv:1506.07443]	**Global**	LO NLO NNLO	GM-VFNS (S-ACOT)	External (multiple values available)	6 indep. PDFs Polynomial (27 param.)	Hessian Tolerance
HERAPDF2.0 [arxiv:1506.06042]	DIS (HERA I+II)	NLO NNLO	GM-VFNS (TR)	External (multiple values available)	5 indep. PDFs Polynomial (14 param.)	Hessian (Δ
MMHT14 [arXiv:1410.3989]	**Global**	LO NLO NNLO	GM-VFNS (TR)	Fit (multiple values available)	7 indep. PDFs Polynomial (37 param.)	Hessian Dyn. Tolerance
NNPDF3.0 [arXiv:1410.8849]	**Global**	LO NLO NNLO	GM-VFNS (FONLL)	External (multiple values available)	7 indep. PDFs Neural Nets (259 param.)	Monte Carlo

[LHAPDF v6.1.5 - http://lhapdf.hepforge.org/]

Parton Distributions after LHC Run I

Dataset

	NNPDF3.0	MMHT14	CT14(PREL)
SLAC P,D DIS	✔	✔	✗
BCDMS P,D DIS	✔	✔	✔
NMC P,D DIS	✔	✔	✔
E665 P,D DIS	✗	✔	✗
CDHSW NU-DIS	✗	✗	✔
CCFR NU-DIS	✗	✔	✔
CHORUS NU-DIS	✔	✔	✗
CCFR DIMUON	✗	✔	✔
NuTeV DIMUON	✔	✔	✔
HERA I NC,CC	✔	✔	✔
HERA I CHARM	✔	✔	✔
H1,ZEUS JETS	✗	✔	✗
H1 HERA II	✔	✗	✗
ZEUS HERA II	✔	✗	✗
E605 & E866 FT DY	✔	✔	✔
CDF & D0 W ASYM	✗	✔	✔
CDF & D0 Z RAP	✔	✔	✔
CDF Run-II JETS	✔	✔	✔
D0 Run-II JETS	✗	✔	✔
ATLAS HIGH-MASS DY	✔	✔	✔
CMS 2D DY	✔	✔	✗
ATLAS W,Z RAP	✔	✔	✔
ATLAS W PT	✔	✔	✗
CMS W ASY	✔	✔	✔
CMS W +C	✔	✗	✗
LHCb W,Z RAP	✔	✔	✔
ATLAS JETS	✔	✔	✔
CMS JETS	✔	✔	✔
TTBAR TOT XSEC	✔	✔	✗
TOTAL NLO	4276	2996	3248
TOTAL NNLO	4078	2663	3045

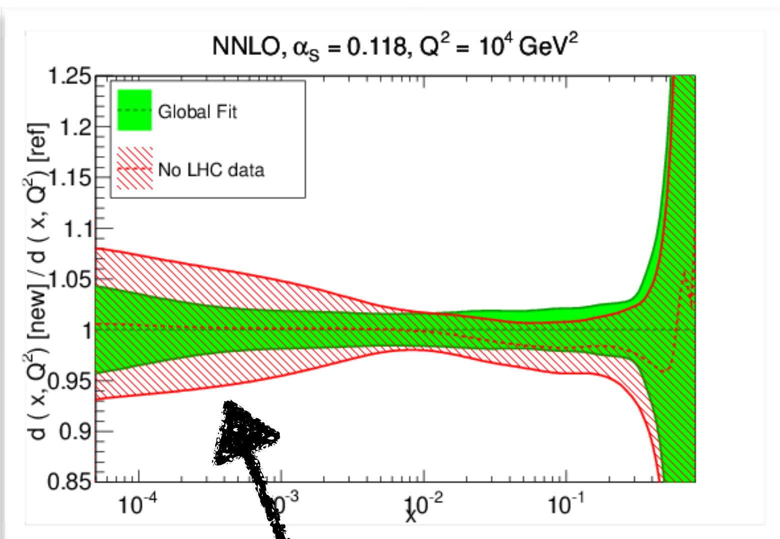


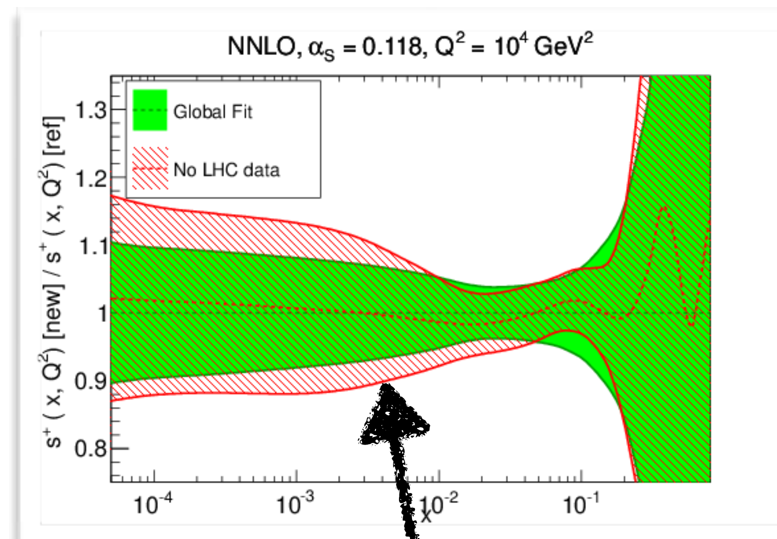
Modern PDF sets include a substantial number of data from the LHC experiments.

Parton Distributions after LHC Run I

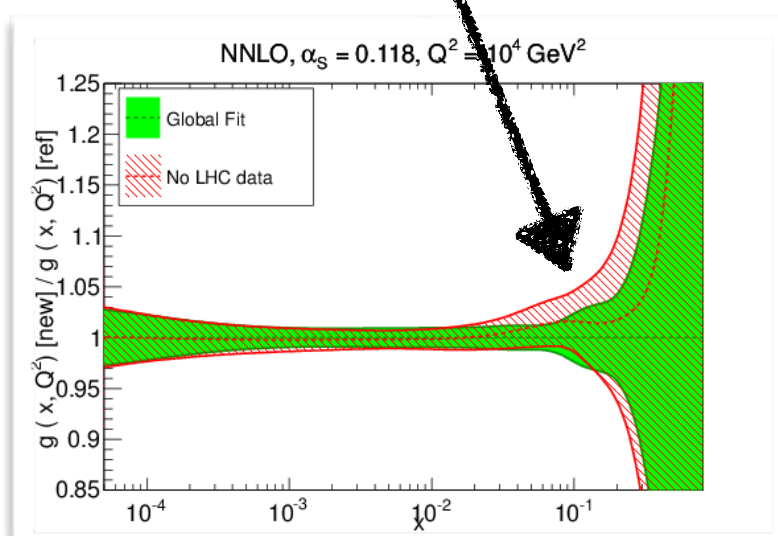
Impact of LHC data

- **Impact** of **LHC** data (still) **moderate** but definitely **noticeable**





Large-*x* gluon
inclusive jet & top



Light flavours
W asymmetry &
(2D) Drell-Yan

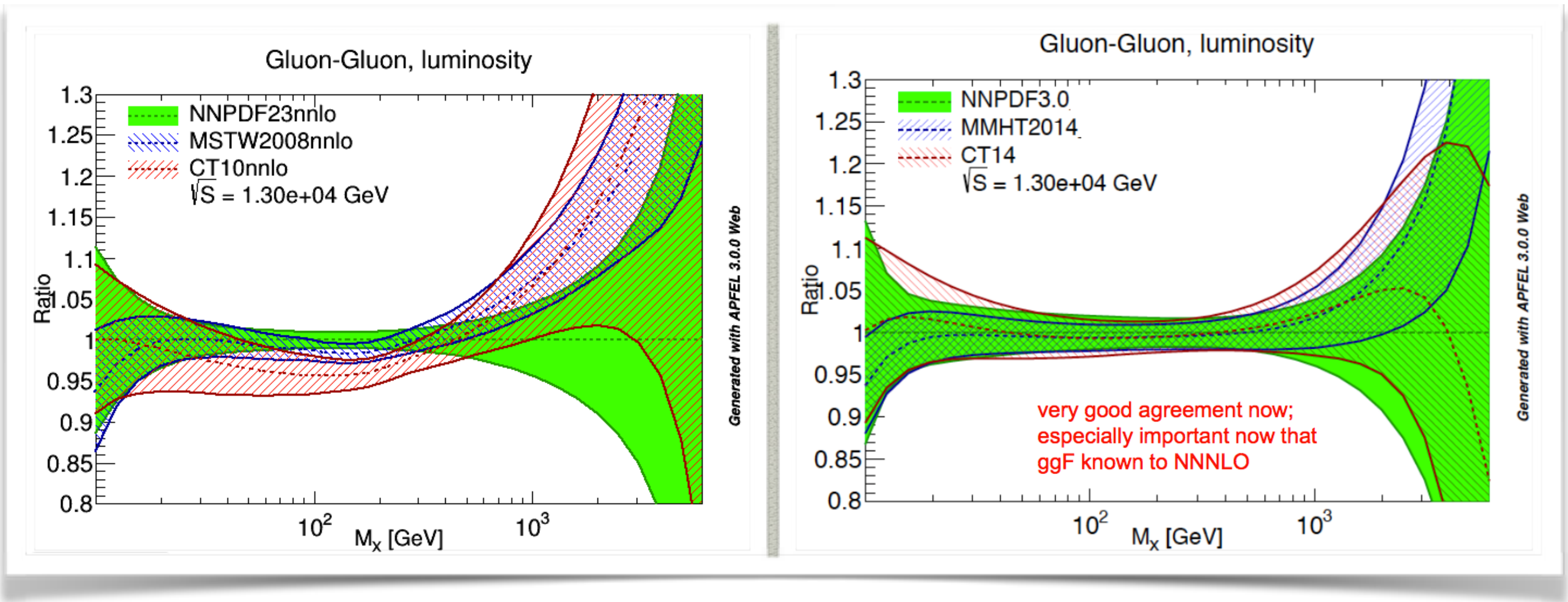
Strangeness
W+charm

Parton Distributions after LHC Run I

Improved agreement among global PDF sets

"Progress in convergence between the parton distribution functions will also be needed in order to reduce the theoretical uncertainties below the experimental measurement uncertainties"

J. Ellis, [arXiv:1504.03654]



J. Houston, PDF4LHC 2015

Almost perfect agreement among the newest releases of global PDF sets for ggH

	CT14	MMHT2014	NNPDF3.0
8 TeV	18.66 pb -2.2% +2.0%	18.65 pb -1.9% +1.4%	18.77 pb -1.8% +1.8%
13 TeV	42.68 pb -2.4% +2.0%	42.70 pb -1.8% +1.3%	42.97 pb -1.9% +1.9%

Parton Distributions for LHC Run II

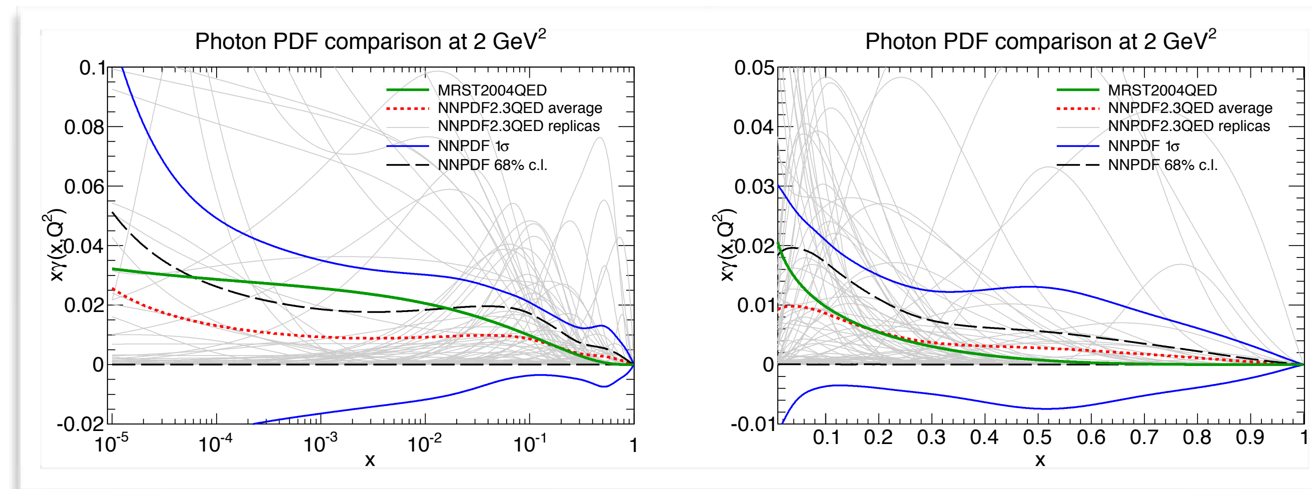
Parton Distributions with QED corrections (NNPDF2.3 QED)

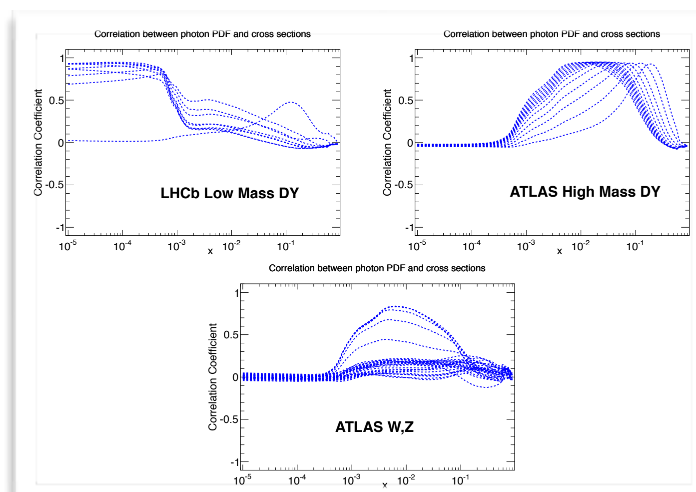
- Precision LHC phenomenology, including EW effects, requires **parton distributions with QED effects** included in the evolution and a **photon PDF**

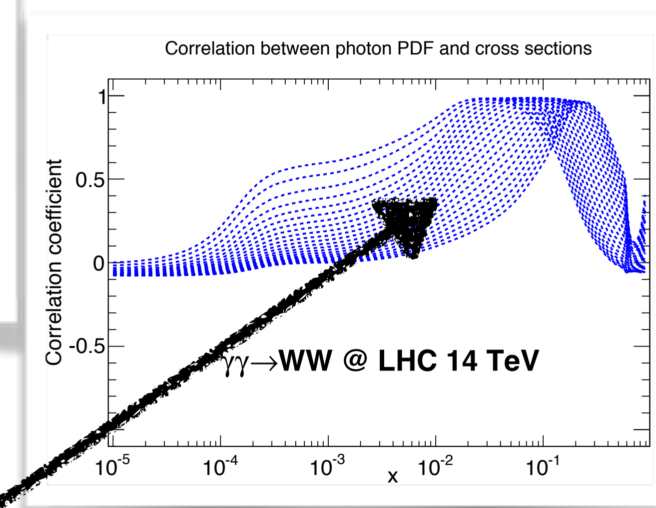
- **NNPDF2.3 QED** is the most recent PDF fit based on **(N)NLO QCD + LO QED** evolution and with a photon PDF determined from DIS and Drell-Yan (low-mass LHCb, *W* & *Z* peak and high-mass ATLAS) production

  [R. D. Ball et al, arXiv:1308.0598]

- LHC data are crucial for a reliable determination of the photon PDF

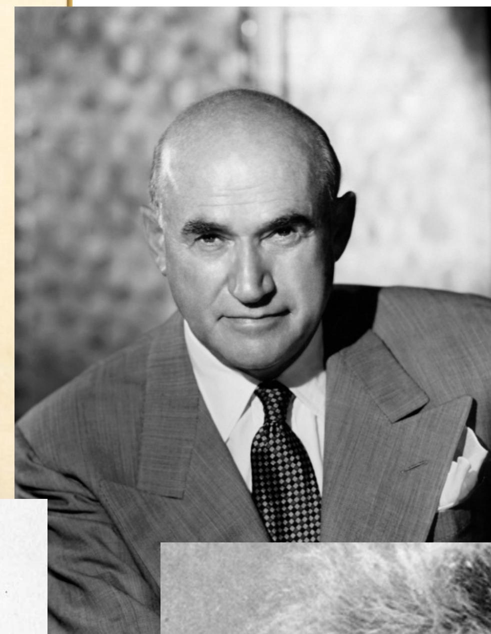


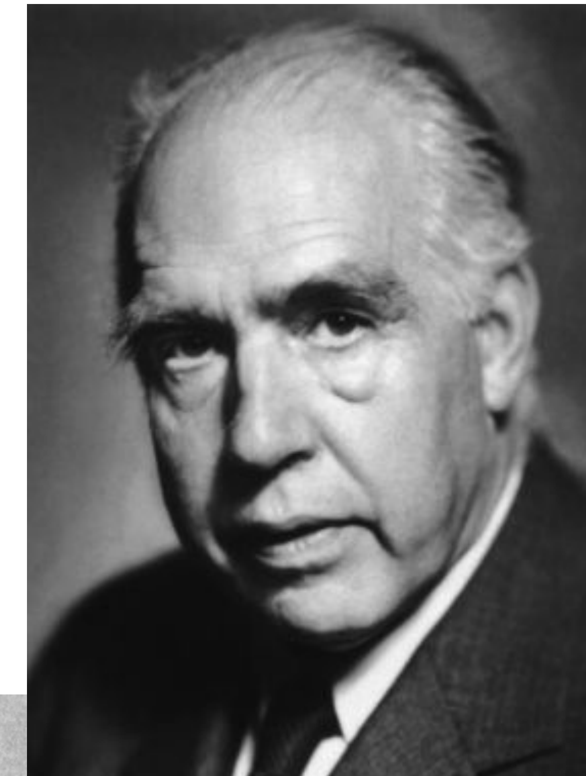


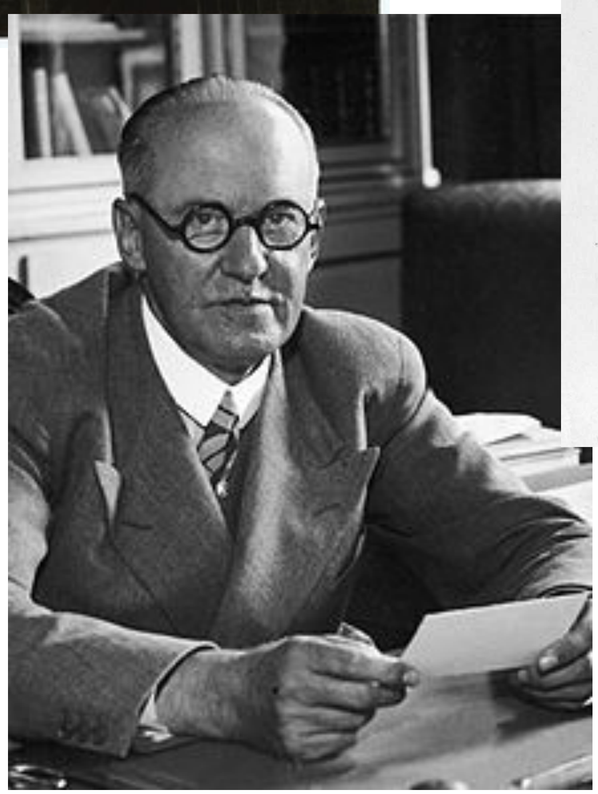


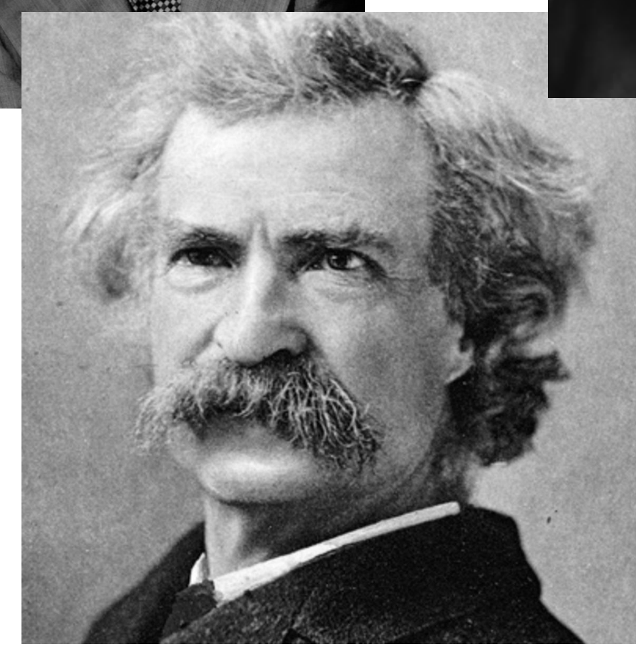
Photon PDF strongly correlated with **WW production** at the LHC

“Prediction is very difficult,
especially if it's about the future.”
(…………)









“Prediction is very difficult, especially if it's about the future.”

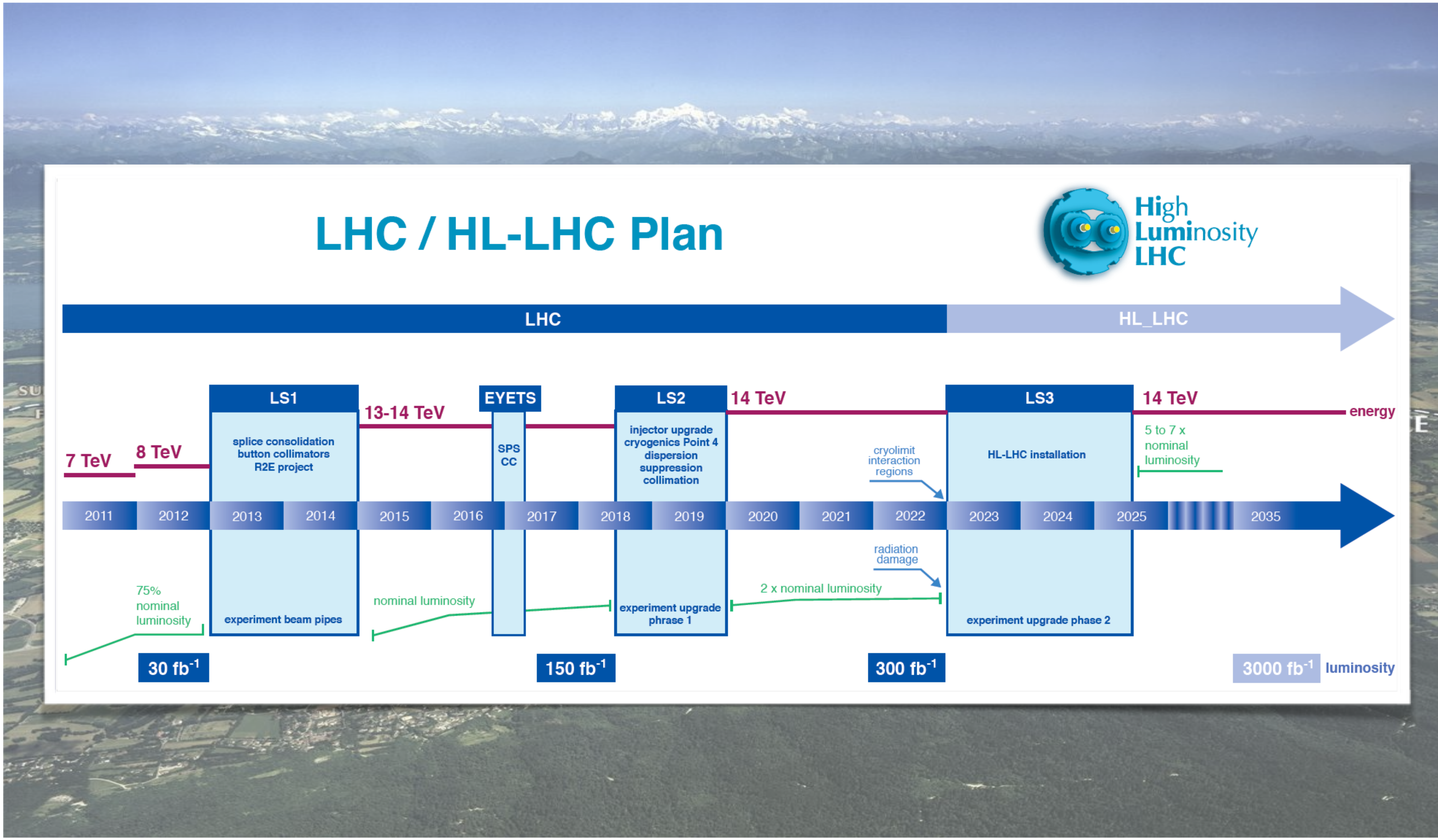
(............)

Future of PDFs

LHC running schedule

Future of PDFs

LHC running schedule



The Future of PDF fits

More data from LHC

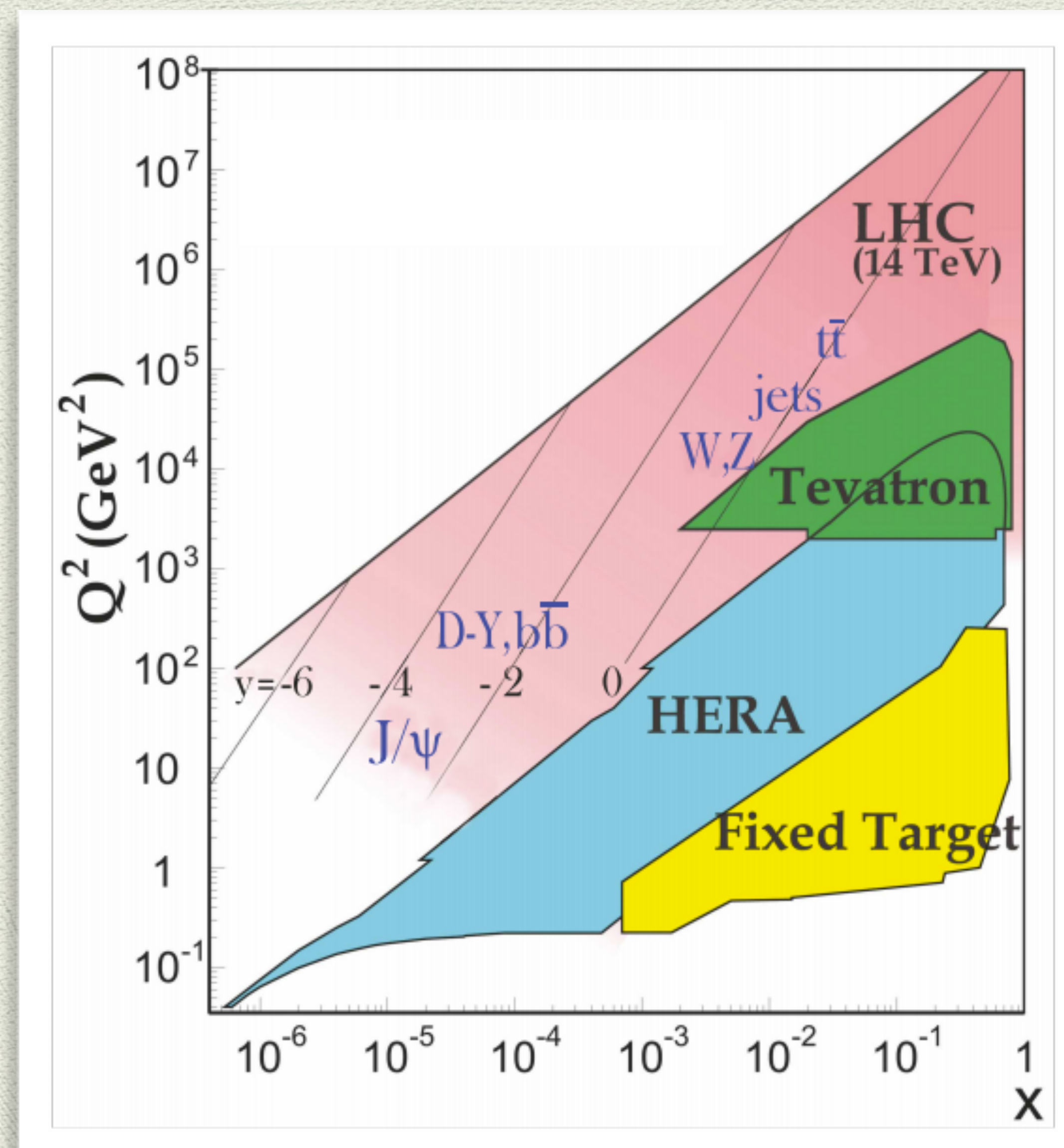
- **LHC data** (both from Run I and Run II) to provide **substantial constraints** on PDFs in the (near) future

M.Ubiali, SM@LHC 2015

GLUON
- Inclusive jets and dijets **(medium/large x)**
- Isolated photon and γ+jets **(medium/large x)**
- Top pair production **(large x)**
- High p_T Z(+jets) distribution **(small/medium x)**

QUARKS
- High p_T W(+jets) ratios **(medium/large x)**
- W and Z production **(medium x)**
- Low and high mass Drell-Yan **(small and large x)**
- Wc **(strangeness at medium x)**

PHOTON
- Low and high mass Drell-Yan
- WW production



The future of PDF fits

Run I data not yet included in PDF fits

[PDF4LHC Report, arXiv:1507.00556]

CMS

Measurement	$\sqrt{s}$, $\mathcal{L}_{\rm int}$	Motivation	Reference	Used in PDF or α_S fits
High and low mass Drell-Yan	7 TeV, 5 fb^{-1}	Sect. 3.4.	[36]	[21, 118]
High and low mass Drell-Yan	8 TeV, 20 fb^{-1}	Sect. 3.4.	[45]	–
Drell-Yan AFB	7 TeV, 5 fb^{-1}	Sect. 3.4.	[176]	–
W asymmetry	7 TeV, 36 pb^{-1}	Sect. 3.3.	[177]	–
W e asymmetry	7 TeV, 880 pb^{-1}	Sect. 3.3.	[178]	–
W μ asymmetry	7 TeV, 4.7 fb^{-1}	Sect. 3.3.	[26]	[26, 118]
W, Z production and rapidity	7 TeV, 3 pb^{-1}	Sect. 3.3.	[179]	–
W, Z inclusive production	7 TeV, 36 pb^{-1}	Sect. 3.3.	[180]	–
W, Z inclusive production	8 TeV, 19 pb^{-1}	Sect. 3.3.	[181]	–
Z p_T and rapidity	7 TeV, 36 pb^{-1}	Sect. 3.5.,3.3.	[182]	–
Z p_T and rapidity	8 TeV, 19.7 fb^{-1}	Sect. 3.5.,3.3.	[132]	–
Inclusive jets	7 TeV, 5 fb^{-1}	Sect. 3.1.	[25, 183]	[21, 48, 91]
Dijets	7 TeV, 5 fb^{-1}	Sect. 3.1.	[25]	–
Three-jets	7 TeV, 5 fb^{-1}	Sect. 3.1.	[184]	[184]
Three-jets/Di-jets ratio	7 TeV, 5 fb^{-1}	Sect. 3.1.	[49]	[49]
W+charm	7 TeV, 5 fb^{-1}	Sect. 3.6.	[29]	[26, 31, 91]
Z+beauty	7 TeV, 5 fb^{-1}	Sect. 3.6.	[185]	–
γ inclusive production	7 TeV, 36 pb^{-1}	Sect. 3.2.	[186]	[28]
γ+jets	7 TeV, 2.1 fb^{-1}	Sect. 3.2.	[187]	–
$t\bar{t}$ inclusive	7 TeV, 2.3 fb^{-1}	Sect. 3.7.	[188]	[32, 33, 139]
$t\bar{t}$ differential	7 TeV, 5.0 fb^{-1}	Sect. 3.7.	[189]	[33]
$t\bar{t}$ inclusive	8 TeV, 1.14 fb^{-1}	Sect. 3.7.	[190]	[32]
$t\bar{t}$ inclusive	8 TeV, 2.8 fb^{-1}	Sect. 3.7.	[191]	[32]
$t\bar{t}$ inclusive	8 TeV, 2.4 fb^{-1}	Sect. 3.7.	[192]	[33]
$t\bar{t}$ differential	8 TeV, 19.7 fb^{-1}	Sect. 3.7.	[193]	–

ATLAS

Measurement	$\sqrt{s}$, year of data, $\mathcal{L}_{\rm int}$	Motivation	Reference	PDF fits
W, Z rapidity	7 TeV, 2010, 36 pb^{-1}	Sect. 3.3.	[123]	[16, 21, 22, 27, 91]
High mass Drell-Yan	7 TeV, 2011, 4.9 fb^{-1}	Sect. 3.4.	[37]	[21, 22, 130]
Low mass Drell-Yan	7 TeV, 2011+2010, 1.6 fb^{-1}+35 pb^{-1}	Sect. 3.4.	[145]	-
Z A_{FB}	7 TeV, 2011, 4.8 fb^{-1}	Sect. 3.4.	[14]	-
W+charm production	7 TeV, 2011, 4.6 fb^{-1}	Sect. 3.6.	[30]	[30]
W+beauty production	7 TeV, 2010, 35 pb^{-1}	Sect. 3.6.	[146]	-
W+beauty production	7 TeV, 2011, 4.6 fb^{-1}	Sect. 3.6.	[147]	-
Z+beauty production	7 TeV, 2010, 36 pb^{-1}	Sect. 3.6.	[148]	-
Z+beauty production	7 TeV, 2011, 4.6 fb^{-1}	Sect. 3.6.	[149]	-
Z p_T	7 TeV, 2010, 40 pb^{-1}	Sect. 3.5.	[150]	-
Z p_T	7 TeV, 2011, 4.7 fb^{-1}	Sect. 3.5.	[131]	-
W p_T	7 TeV, 2010, 31 pb^{-1}	Sect. 3.5.	[151]	[22]
Z+jets	7 TeV, 2010, 36 pb^{-1}	Sect. 3.5.	[152]	-
Z+jets	7 TeV, 2011, 4.6 fb^{-1}	Sect. 3.5.	[153]	-
W+jets	7 TeV, 2010, 36 pb^{-1}	Sect. 3.5.	[154]	-
W+jets	7 TeV, 2011, 4.6 fb^{-1}	Sect. 3.5.	[155]	-
$R_{\rm jets}$ (W+jets/Z+jets)	7 TeV, 2011, 4.6 fb^{-1}	Sect. 3.5.	[156]	-
Inclusive jets	7 TeV, 2010, 37 pb^{-1}	Sect. 3.1.	[157]	[21, 22, 91]
Inclusive jets	7 TeV, 2011, 4.5 fb^{-1}	Sect. 3.1.	[158]	-
Inclusive jets (+ 7 TeV ratio)	2.76 TeV, 2010, 0.2 pb^{-1}	Sect. 3.1., 3.10.	[24]	[21, 22, 24]
Dijets	7 TeV, 2010, 37 pb^{-1}	Sect. 3.1.	[157]	-
Dijets	7 TeV, 2011, 4.6 fb^{-1}	Sect. 3.1.	[159]	-
Trijets	7 TeV, 2011, 4.5 fb^{-1}	Sect. 3.1.	[160]	-
γ inclusive production	7 TeV, 2010, 35 pb^{-1}	Sect. 3.2.	[161]	-
γ inclusive production	7 TeV, 2011, 4.6 fb^{-1}	Sect. 3.2.	[162]	[122]
γ+jets	7 TeV, 2010, 37 pb^{-1}	Sect. 3.2.	[163]	-
$t\bar{t}$ incl (single lepton, dilepton)	7 TeV, 2010, 2.9 pb^{-1}	Sect. 3.7.	[164]	[21]
$t\bar{t}$ incl (dilepton)	7 TeV, 2010, 35 pb^{-1}	Sect. 3.7.	[165]	[21]
$t\bar{t}$ incl (single lepton)	7 TeV, 2010, 35 pb^{-1}	Sect. 3.7.	[166]	[21]
$t\bar{t}$ incl (dilepton)	7 TeV, 2011, 0.70 fb^{-1}	Sect. 3.7.	[167]	[21, 22]
$t\bar{t}$ incl ($e/\mu + \tau$)	7 TeV, 2011, 2.05 fb^{-1}	Sect. 3.7.	[168]	[21]
$t\bar{t}$ incl (tau+jets)	7 TeV, 2011, 1.67 fb^{-1}	Sect. 3.7.	[169]	[21]
$t\bar{t}$ incl ($e\mu$ b-tag jets)	7+8 TeV, 2012, 24.9 fb^{-1}	Sect. 3.7.	[170]	[22]
$t\bar{t}$ differential	7 TeV, 2011, 2.05 fb^{-1}	Sect. 3.7.	[171]	-
$t\bar{t}$ differential	7 TeV, 2011, 4.6 fb^{-1}	Sect. 3.7.	[172]	-
WW, $Z \to \tau\tau$, $t\bar{t}$ xsec	7 TeV, 2011, 4.6 fb^{-1}	Sect. 3.3.	[173]	-

LHCb

Measurement	$\sqrt{s}$, $\mathcal{L}_{\rm int}$	Motivation	Reference	Used in PDF fits
W, Z muon rap dist	7 TeV, 1.0 fb^{-1}	Sect. 3.3.	[201]	[21, 22]
$Z \to ee$ rap dist	7 TeV, 0.94 fb^{-1}	Sect. 3.3.	[199]	[21, 22]
$Z \to ee$ rap dist	8 TeV, 2.0 fb^{-1}	Sect. 3.3.	[203]	–
$W + b/c$	7,8 TeV, 3.0 fb^{-1}	Sect. 3.6.	[207]	–
$c\bar{c}$ production	7 TeV, 15 nb^{-1}	Sect. 3.8.	[35]	[34, 43]
$b\bar{b}$ production	7 TeV, 0.36 fb^{-1}	Sect. 3.8.	[210]	[34]
Exclusive J/ψ production	7 TeV, 1.0 fb^{-1}	Sect. 3.9.	[143]	–
Exclusive Υ production	7, 8 TeV, 3.0 fb^{-1}	Sect. 3.9.	[211]	–

The future of PDF fits

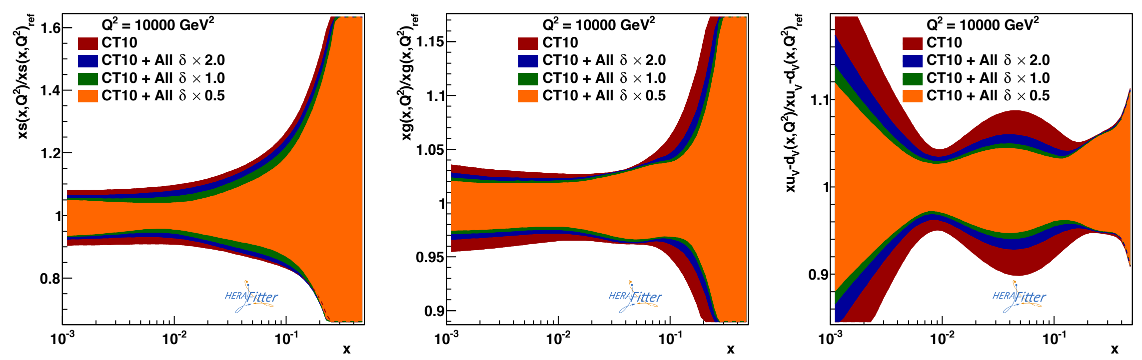
Run II measurements

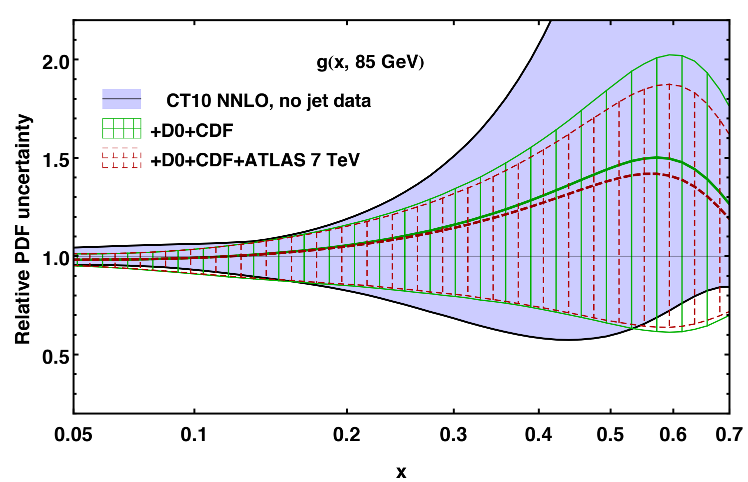
[PDF4LHC Report, arXiv:1507.00556]

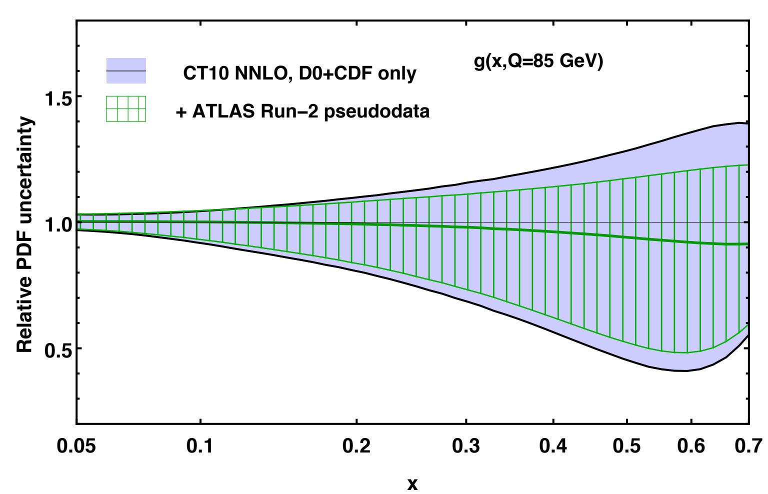
Profiling analysis to estimate the impact of (some) Run II data on quark combinations

Study performed using the HeraFitter tool

	$R_{W/Z}$	$R_{t\bar{t}/Z}$	A_ℓ	y_Z
Kinematic range			$p_{t,\ell} > 25$ GeV, $\lvert\eta_\ell\rvert < 2.5$	
Number of bins	1	1	10	12
Baseline accuracy per bin	1%	2%	$\approx 1.5\%$	$\approx 1.5\%$







Run II jet data to further improve constraints on large-*x* gluon

The future of PDF fits

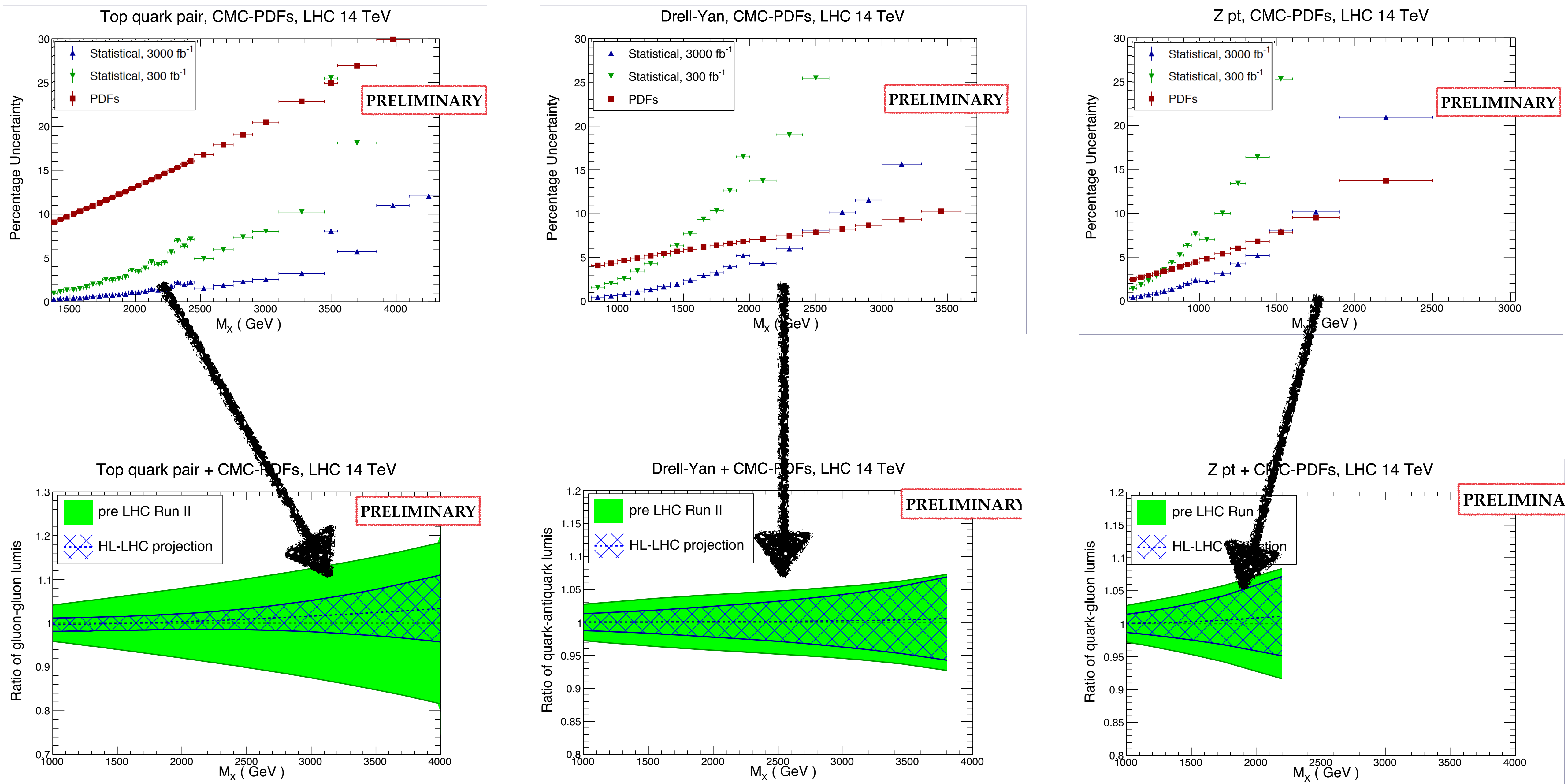
HL-LHC

Based on an exercise by J. Rojo

- Most PDF relevant measurements at LHC are systematics limited, difficult to quantify how uncertainties will improve
- **Notable exception**: high-mass tails of distributions, probing PDFs at large-x
- Preliminary studies based on pseudodata for three representative processes, constraining different parton-parton luminosities
  - **Top quark pair** production (gluon-gluon luminosity)
  - **High-mass Drell-Yan** (quark-antiquark luminosity)
  - **Z transverse momentum distribution** (quark-gluon luminosity)
- Generate pseudodata using CMC-PDFs (combination of MMHT14, CT14 and NNPDF3.0)
- Add ~2-3% systematic uncertainty on top of expected statistical one

The future of PDF fits

HL-LHC studies



LHeC - Lepton-Hadron collision at the LHC

arXiv:1206.2913

http://cern.ch/lhec

J.L.Abelleira Fernandez[16,23], C.Adolphsen[57], P.Adzic[74], A.N.Akay[03], H.Aksakal[39], J.L.Albacete[52], B.Allanach[73], S.Alekhin[17,54], P.Allport[24], V.Andreev[34], R.B.Appleby[14,30], E.Arikan[39], N.Armesto[53,a], G.Azuelos[33,64], M.Bai[37], D.Barber[14,17,24], J.Bartels[18], O.Behnke[17], J.Behr[17], A.S.Belyaev[15,56], I.Ben-Zvi[37], N.Bernard[25], S.Bertolucci[16], S.Bettoni[16], S.Biswal[41], J.Blümlein[17], H.Böttcher[17], A.Bogacz[36], C.Bracco[16], J.Bracinik[06], G.Brandt[44], H.Braun[65], S.Brodsky[57,b], O.Brüning[16], E.Bulyak[12], A.Buniatyan[17], H.Burkhardt[16], I.T.Cakir[02], O.Cakir[01], R.Calaga[16], A.Caldwell[70], V.Cetinkaya[01], V.Chekelian[70], E.Ciapala[16], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[38], J.C.Collins[48], O.Dadoun[42], J.Dainton[24], A.De.Roeck[16], D.d'Enterria[16], P.DiNezza[72], M.D'Onofrio[24], A.Dudarev[16], A.Eide[60], R.Enberg[63], E.Eroglu[62], K.J.Eskola[21], L.Favart[08], M.Fitterer[16], S.Forte[32], A.Gaddi[16], P.Gambino[59], H.García Morales[16], T.Gehrmann[69], P.Gladkikh[12], C.Glasman[28], A.Glazov[17], R.Godbole[35], B.Goddard[16], T.Greenshaw[24], A.Guffanti[13], V.Guzey[19,36], C.Gwenlan[44], T.Han[50], Y.Hao[37], F.Haug[16], W.Herr[16], A.Hervé[27], B.J.Holzer[16], M.Ishitsuka[58], M.Jacquet[42], B.Jeanneret[16], E.Jensen[16], J.M.Jimenez[16], J.M.Jowett[16], H.Jung[17], H.Karadeniz[02], D.Kayran[37], A.Kilic[62], K.Kimura[58], R.Klees[75], M.Klein[24], U.Klein[24], T.Kluge[24], F.Kocak[62], M.Korostelev[24], A.Kosmicki[16], P.Kostka[17], H.Kowalski[17], M.Kraemer[75], G.Kramer[18], D.Kuchler[16], M.Kuze[58], T.Lappi[21,c], P.Laycock[24], E.Levichev[40], S.Levonian[17], V.N.Litvinenko[37], A.Lombardi[16], J.Maeda[58], C.Marquet[16], B.Mellado[27], K.H.Mess[16], A.Milanese[16], J.G.Milhano[76], S.Moch[17], I.I.Morozov[40], Y.Muttoni[16], S.Myers[16], S.Nandi[55], Z.Nergiz[39], P.R.Newman[06], T.Omori[61], J.Osborne[16], E.Paoloni[49], Y.Papaphilippou[16], C.Pascaud[42], H.Paukkunen[53], E.Perez[16], T.Pieloni[23], E.Pilicer[62], B.Pire[45], R.Placakyte[17], A.Polini[07], V.Ptitsyn[37], Y.Pupkov[40], V.Radescu[17], S.Raychaudhuri[35], L.Rinolfi[16], E.Rizvi[71], R.Rohini[35], J.Rojo[16,31], S.Russenschuck[16], M.Sahin[03], C.A.Salgado[53,a], K.Sampei[58], R.Sassot[09], E.Sauvan[04], M.Schaefer[75], U.Schneekloth[17], T.Schörner-Sadenius[17], D.Schulte[16], A.Senol[22], A.Seryi[44], P.Sievers[16], A.N.Skrinsky[40], W.Smith[27], D.South[17], H.Spiesberger[29], A.M.Stasto[48,d], M.Strikman[48], M.Sullivan[57], S.Sultansoy[03,e], Y.P.Sun[57], B.Surrow[11], L.Szymanowski[66,f], P.Taels[05], I.Tapan[62], T.Tasci[22], E.Tassi[10], H.Ten.Kate[16], J.Terron[28], H.Thiesen[16], L.Thompson[14,30], P.Thompson[06], K.Tokushuku[61], R.Tomás García[16], D.Tommasini[16], D.Trbojevic[37], N.Tsoupas[37], J.Tuckmantel[16], S.Turkoz[01], T.N.Trinh[47], K.Tywoniuk[26], G.Unel[20], T.Ullrich[37], J.Urakawa[61], P.VanMechelen[05], A.Variola[52], R.Veness[16], A.Vivoli[16], P.Vobly[40], J.Wagner[66], R.Wallny[68], S.Wallon[43,46,f], G.Watt[69], C.Weiss[36], U.A.Wiedemann[16], U.Wienands[57], F.Willeke[37], B.-W.Xiao[48], V.Yakimenko[37], A.F.Zarnecki[67], Z.Zhang[42], F.Zimmermann[16], R.Zlebcik[51], F.Zomer[42]

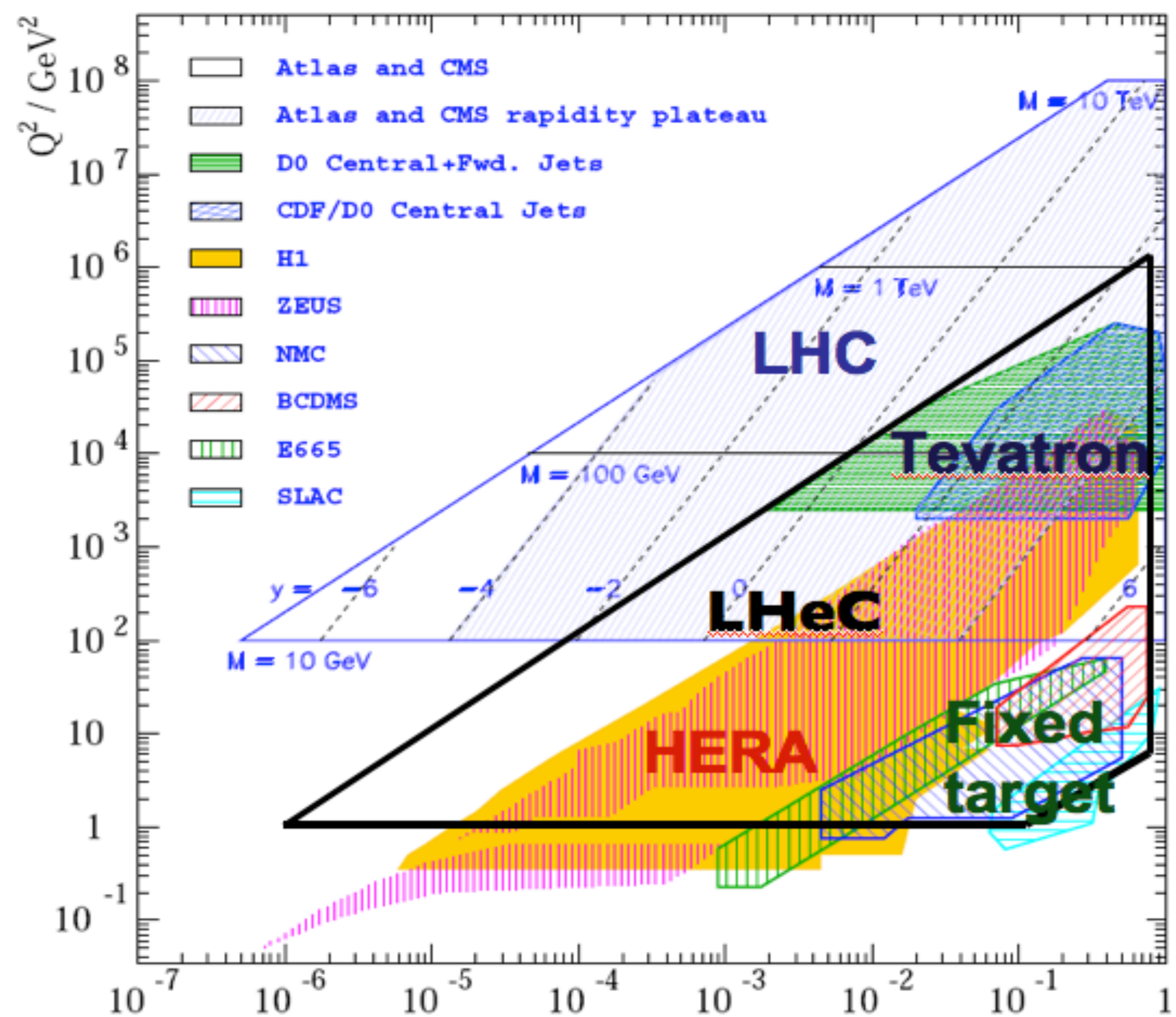
Present LHeC Study group and CDR authors

About 200 Experimentalists and Theorists from 76 Institutes

Supported by
CERN, ECFA, NuPECC

The LHeC project

- The **LHeC kinematics** represents a **substantial extension** to the **coverage** of the data which are used today in **PDF fits**
- Increase in the precision of PDF in regions which are now extrapolation regions
- **Unique opportunity** to study the **small-x** region ($x \sim 10^{-6}$) and look for evidence of **deviations from DGLAP evolution** (resummation/ saturation effects)



LHeC simulated dataset

- **Scenario B**
  - Integrated Luminosity: $e^{\pm}p$=50 fb^{-1}
  - E_p = 7 TeV, E_e = 50 GeV, Pol = ± 0.4
  - Kinematic coverage: $2 < Q^2 < 5 \cdot 10^5$ GeV^2; $2 \cdot 10^{-6} < x < 0.8$
- **Uncertainties**
  - Full simulation of Neutral and Charged current measurements
  - Including Statistical, Uncorrelated and Correlated Systematic uncertaities
  - Based on H1 best values
- **Typical uncertainties**
  - **Stat.**: from ~0.1% (low Q^2, NC) to ~10% (CC, x = 0.7)
  - **Uncorr. Syst.**: 0.7 %
  - **Corr. Syst.**: typically 1-3% (up to 9% for high-x CC)

source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y < 0.01$)	1-3 %
radiative corrections	0.5%
photoproduction background (only $y > 0.5$)	1 %
global efficiency error	0.7 %

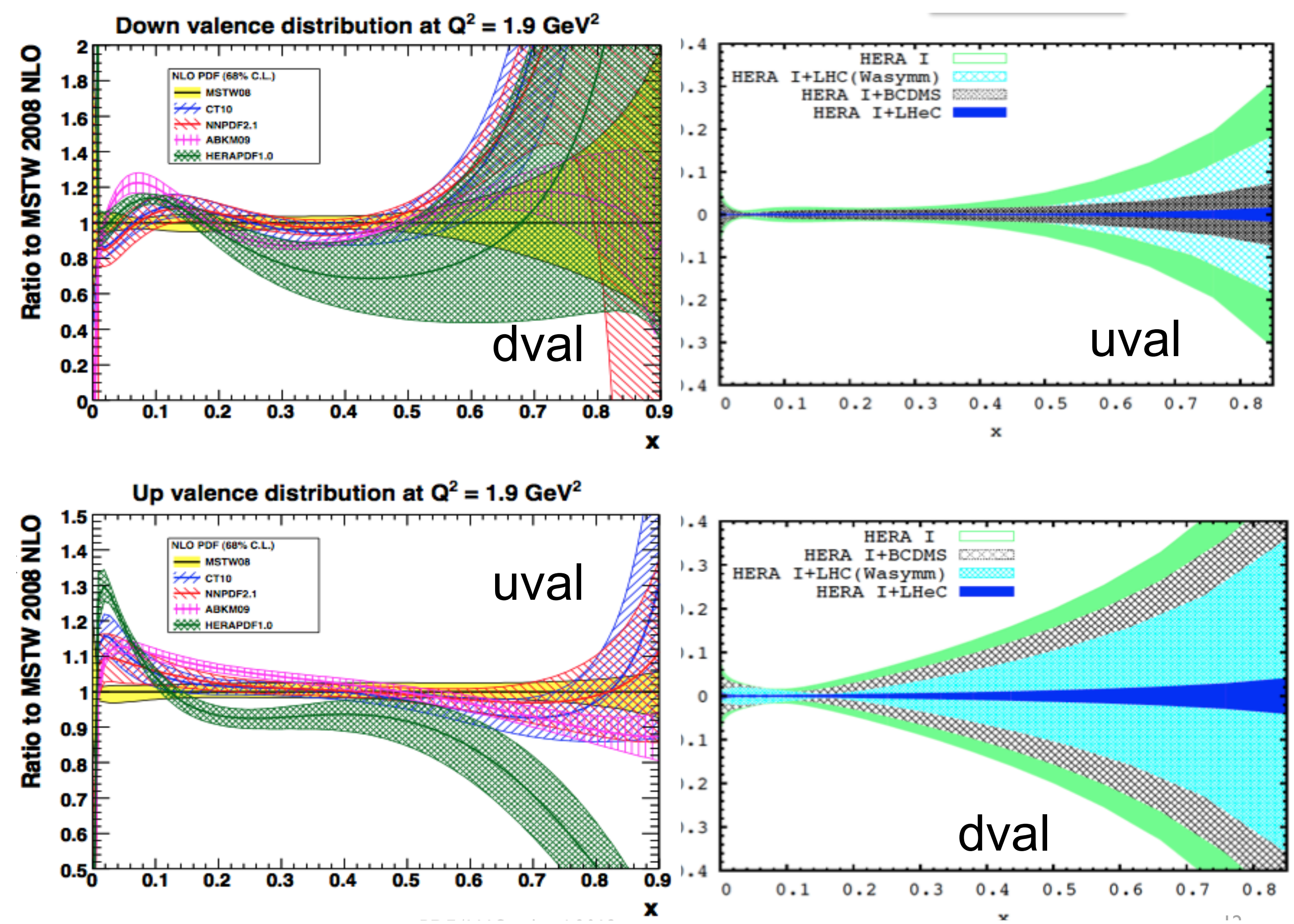
PDF determination setup

- **Data**
  - **Hera I** combined dataset
  - **BCDMS** fixed target proton/duteron DIS
  - ATLAS W asymmetry data (adjusted uncertainties: stat/unc. syst: 0.5%, total:1%)
  - LHeC simulated data Scenario B (e$^{\pm}$p NC/CC red. cross sections, pol = ± 0.4)
- **Theory setup**
  - HERAPDF1.0 settings
  - NLO DGLAP, Thorne-Roberts scheme for HQ treatment
  - Fitted PDFs
    - u_V, d_V, g, U = u+c, D = d+b
    - strange sea distribution proportional to non-strange sea
  - One small-x exp. for sea and one valence
  - Valence and Momentum sum rules imposed

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}(1+D_g x)\,, \\
xu_v(x) &= A_{u_v} x^{B_{uv}}(1-x)^{C_{uv}}(1+E_{u_v}x^2)\,, \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}\,, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\,, \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}\,.
\end{aligned}
$$

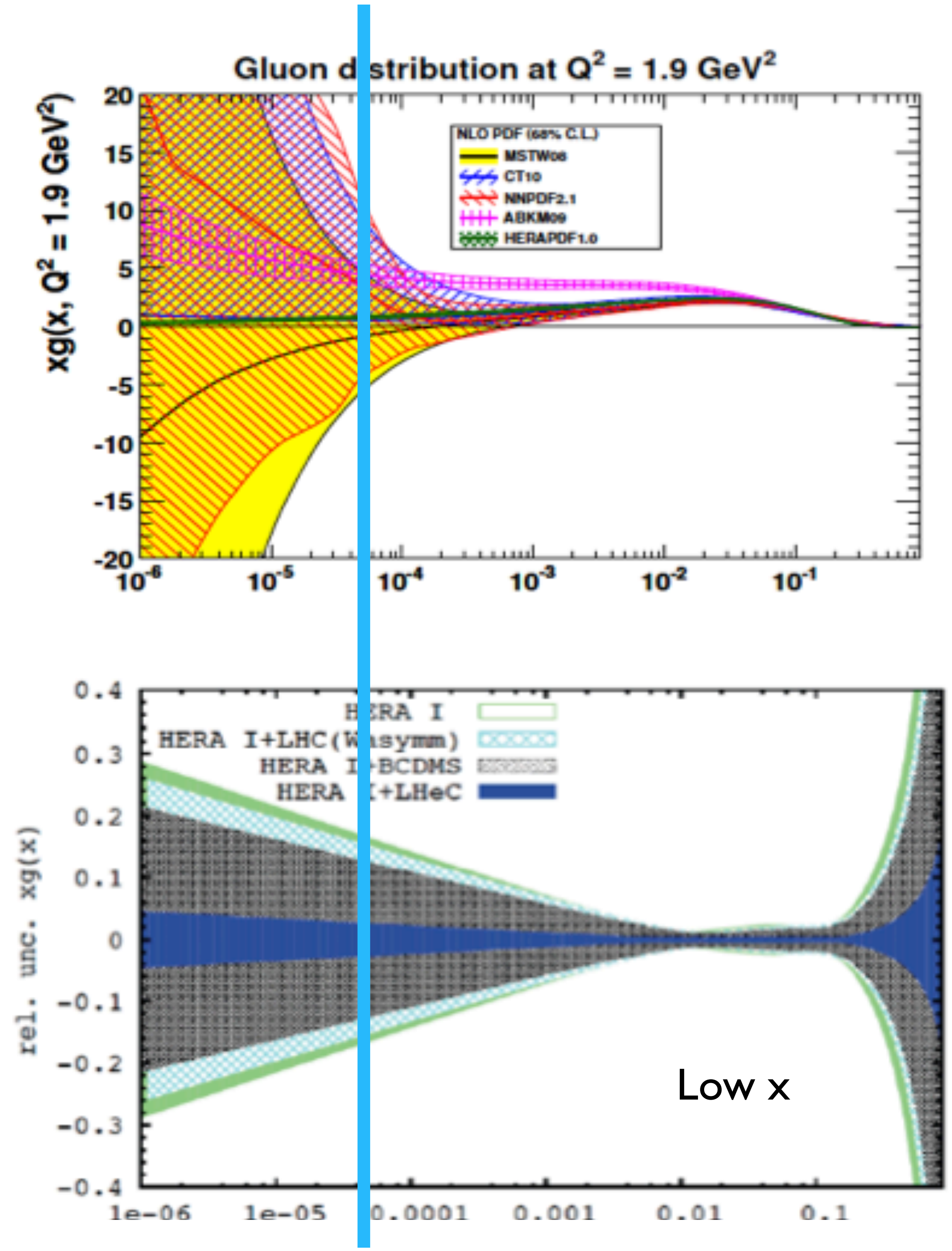
PDF constraints from LHeC - valence sector

- Knowledge of **PDFs** at **large *x*** currently limited by
  - Luminosity barrier
  - Challenging systematics
  - Nuclear/higher twist effects
- LHeC data could help reduce the uncertainties on large-*x* valence distributions to
  - **2%** for $\mathbf{u_v}$ at x=0.8
  - **4%** for $\mathbf{d_v}$ at x=0.8
- Crucial to study the **d/u ratio** at large *x*



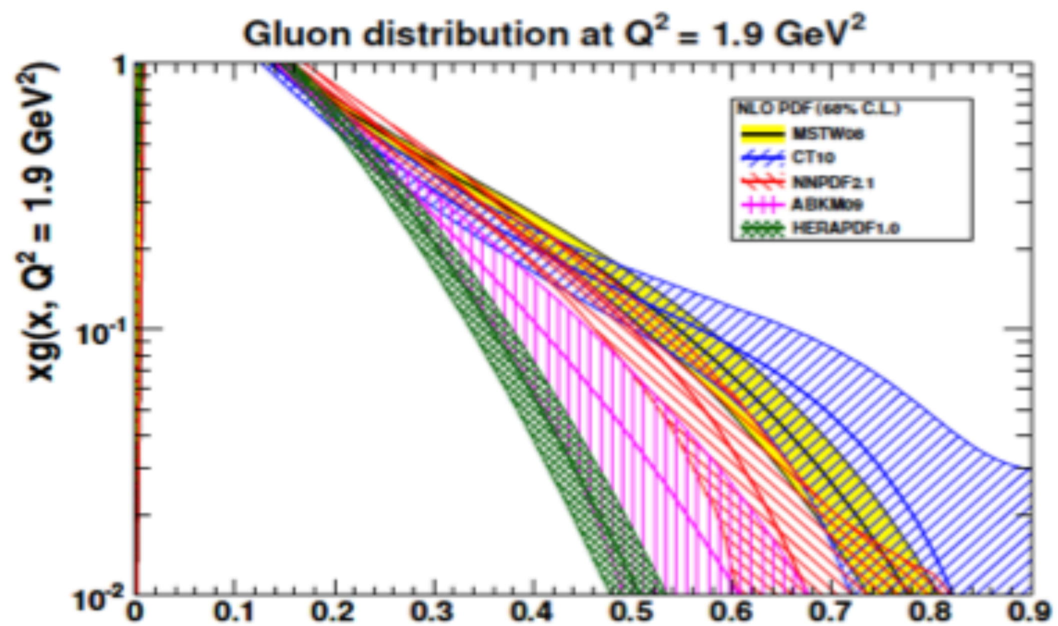
PDF constraints from LHeC - small-x gluon

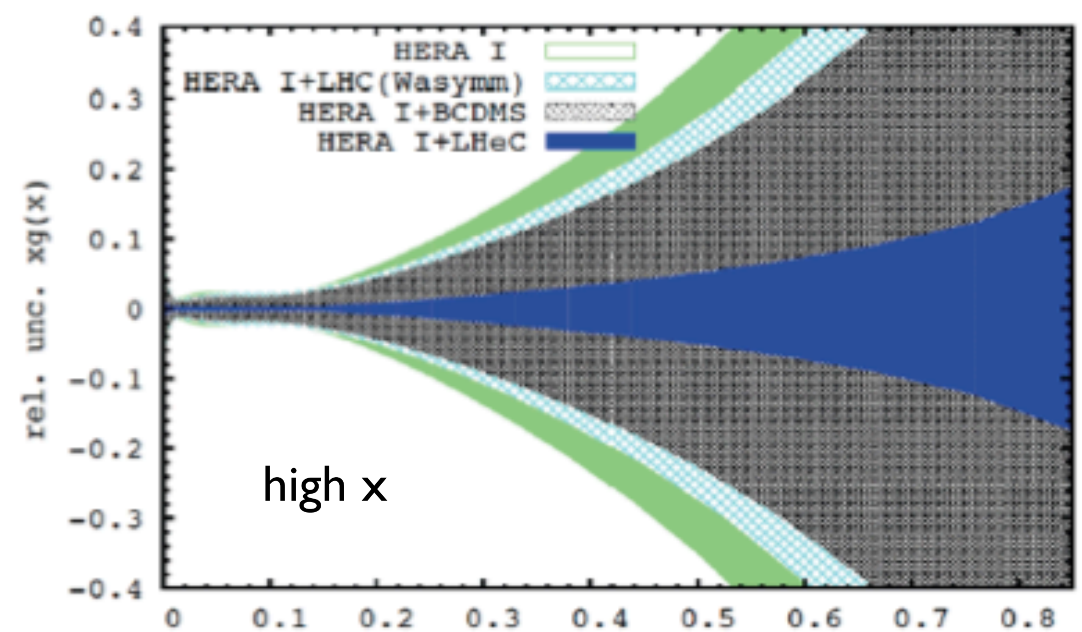
- **Sensitivity** of **HERA** data stops at **$x \sim 5 \cdot 10^{-4}$**
- **Uncertainties** on **small-x gluon** driven by the **parametrization**
- **LHeC** data extend down to **$x \sim 10^{-6}$**, allowing for detailed studies of possible **deviation from DGLAP** evolution and **evidence** for **BFKL** resummation or **saturation** effects
- **LHeC sensitivity** to small-x gluon **improved** by use of **F_L data** (not considered in the present study)



PDF constraints from LHeC - large-x gluon

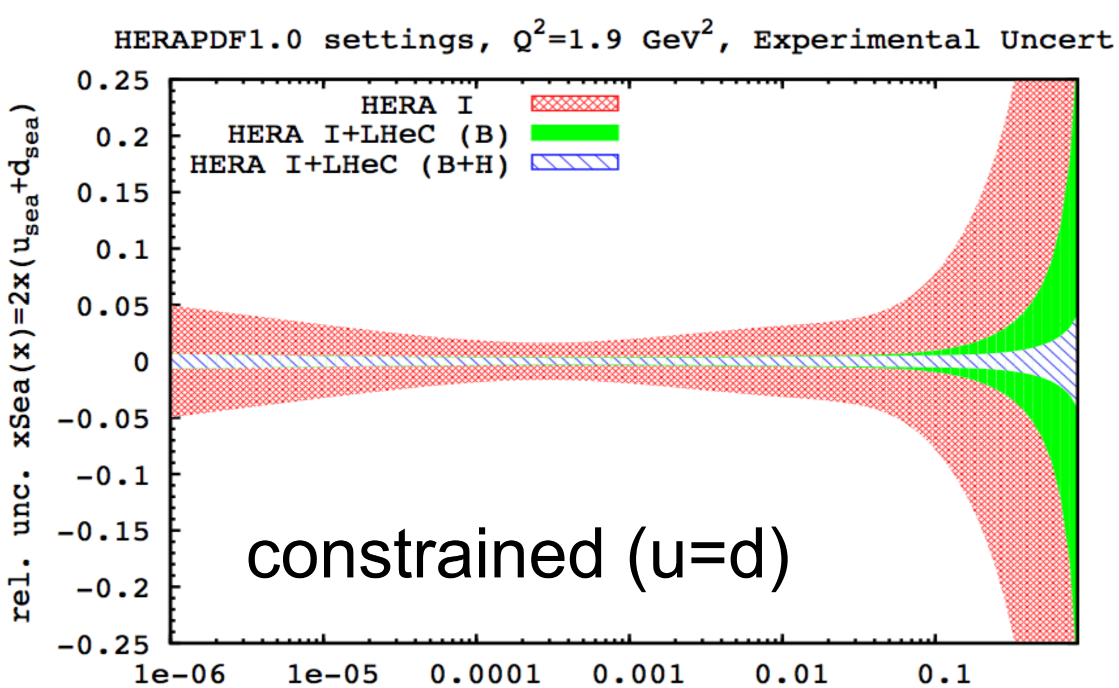
- **Large-x gluon uncertainty** in PDF fits **quite large**, mostly due to **limited statistics** (constrained by inclusive jet data)
- **Related** by evolution to **large-x sea quarks** (DGLAP evolution of valence distribution decouples)
- **LHeC** can **disentangle** the **sea** from the **valence** at **large-x** through measurements of **CC** reduced cross sections, $\mathbf{F_2}$, $\mathbf{F_2^{\gamma Z}}$, $\mathbf{xF_3}$
- **Crucial** for searches of **high-mass resonances** in **BSM** scenarios (gluino pair production)

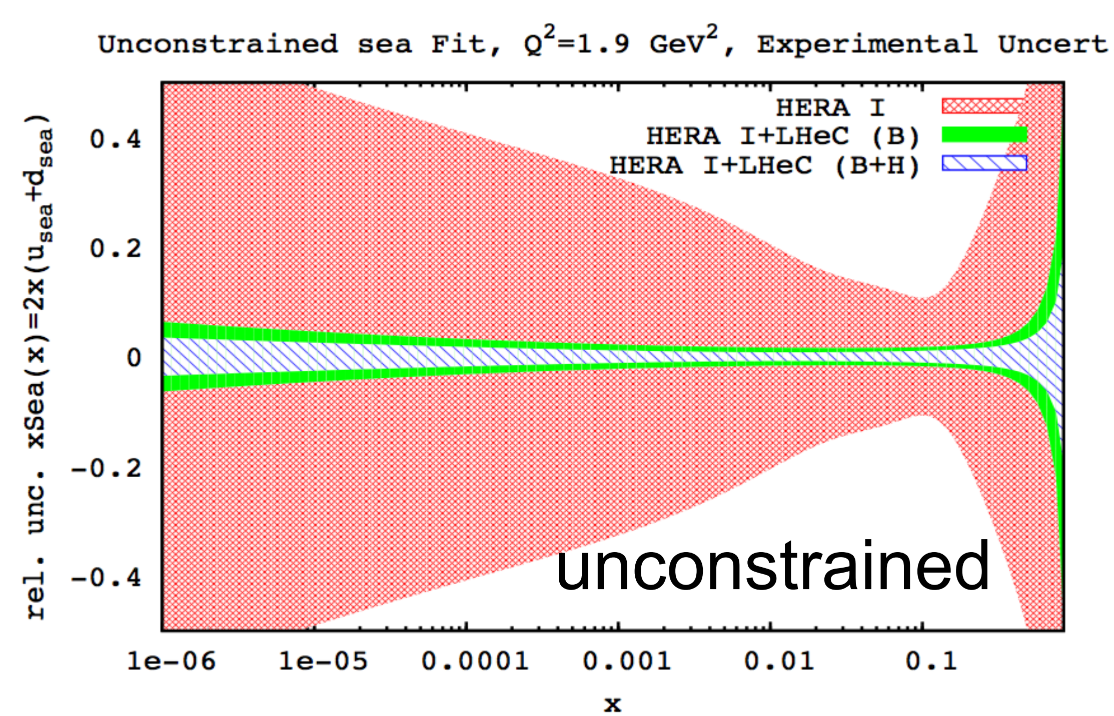




Releasing standard assumptions (u=d at small-x)

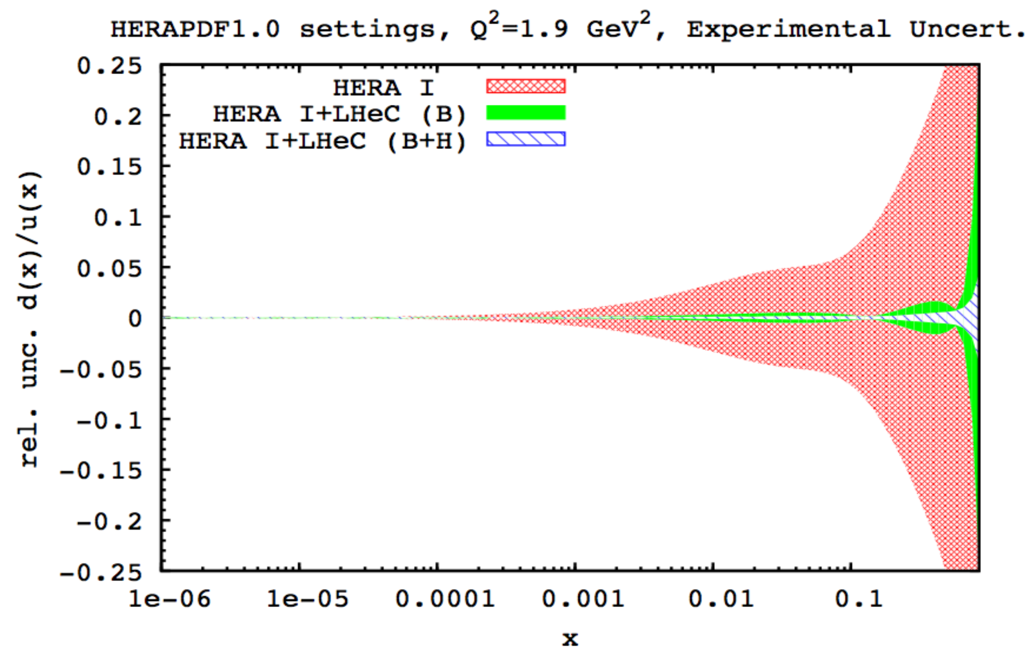
- Due to lack of constraining data standard PDF fits assume d=u at small-x
- HERA data do not constrain flavour separation at small-x, uncertainties grow substantially when theoretical assumptions are released
- LHeC data provide enough experimental constraints to keep uncertainties on small-x light flavour under control

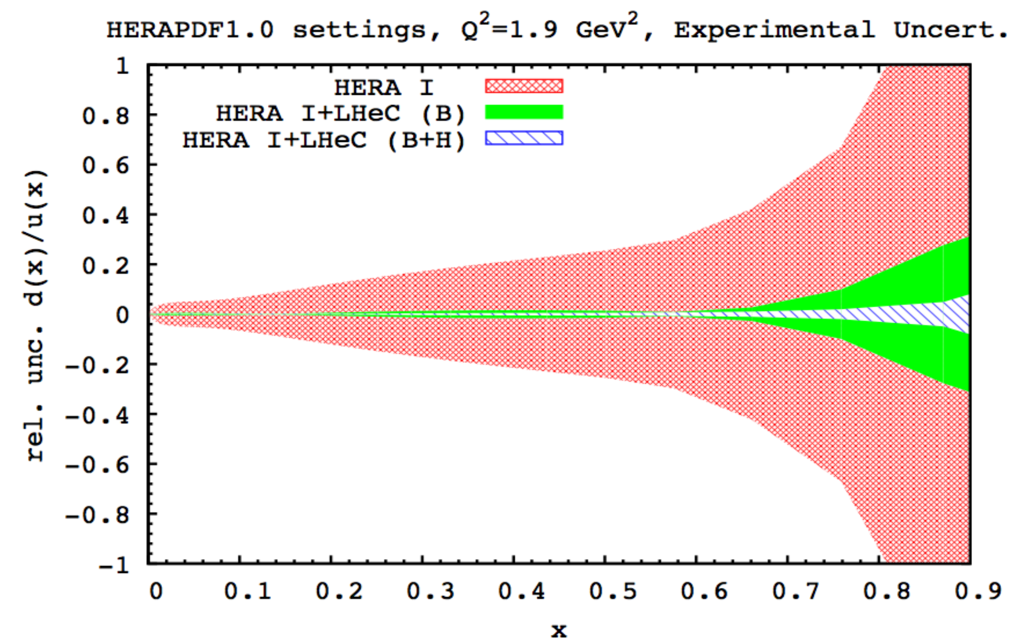




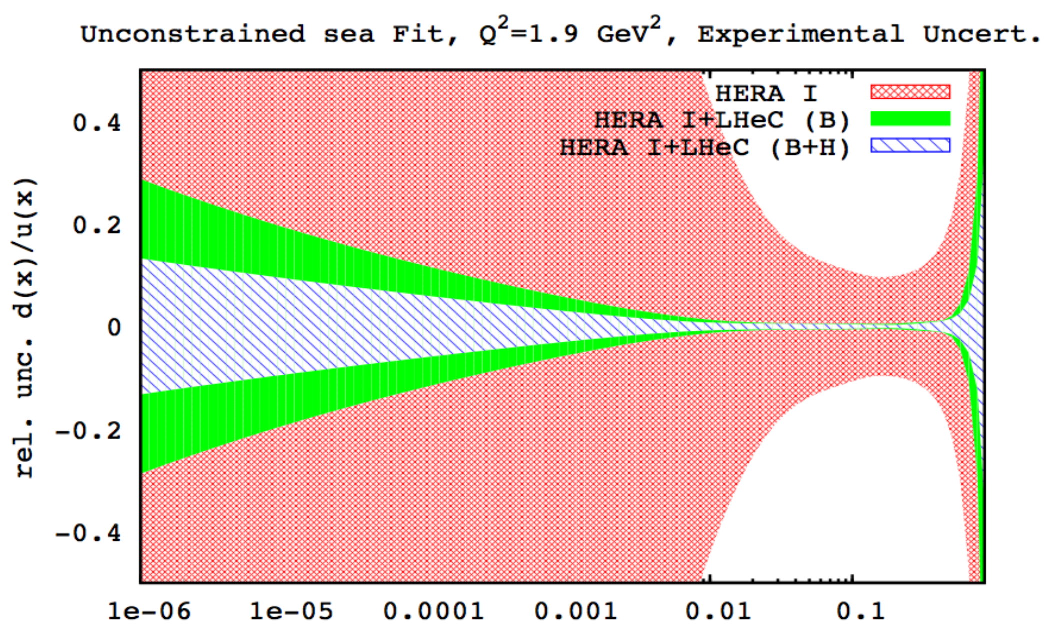
Releasing standard assumptions (d/u ratio)

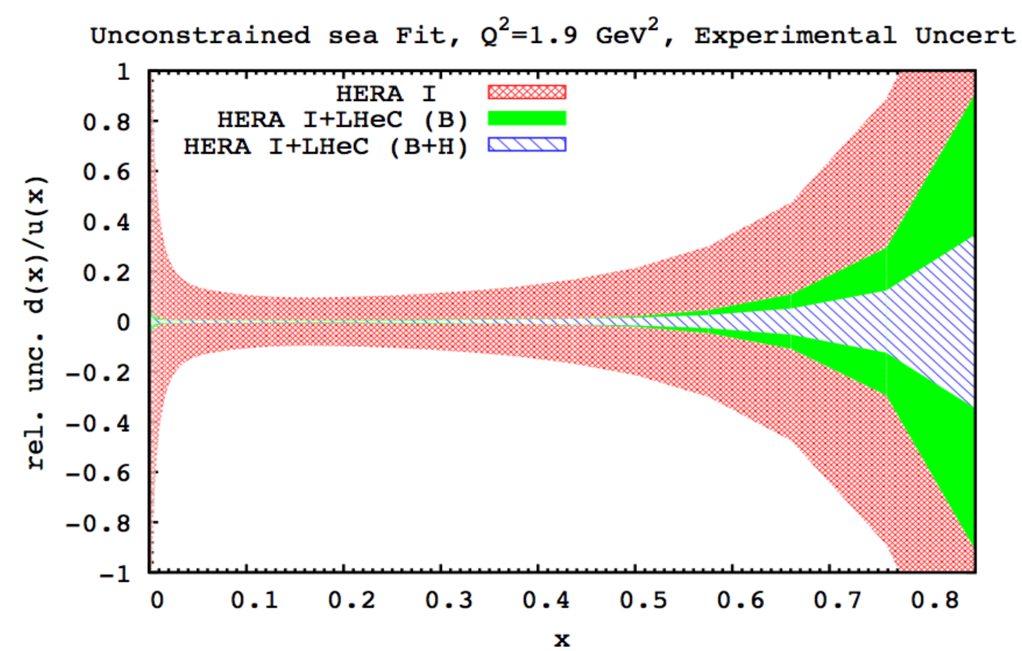
- Constrained decomposition:

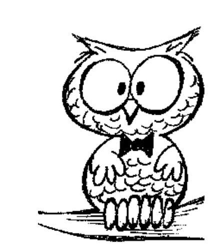




- Unconstrained sea decomposition:

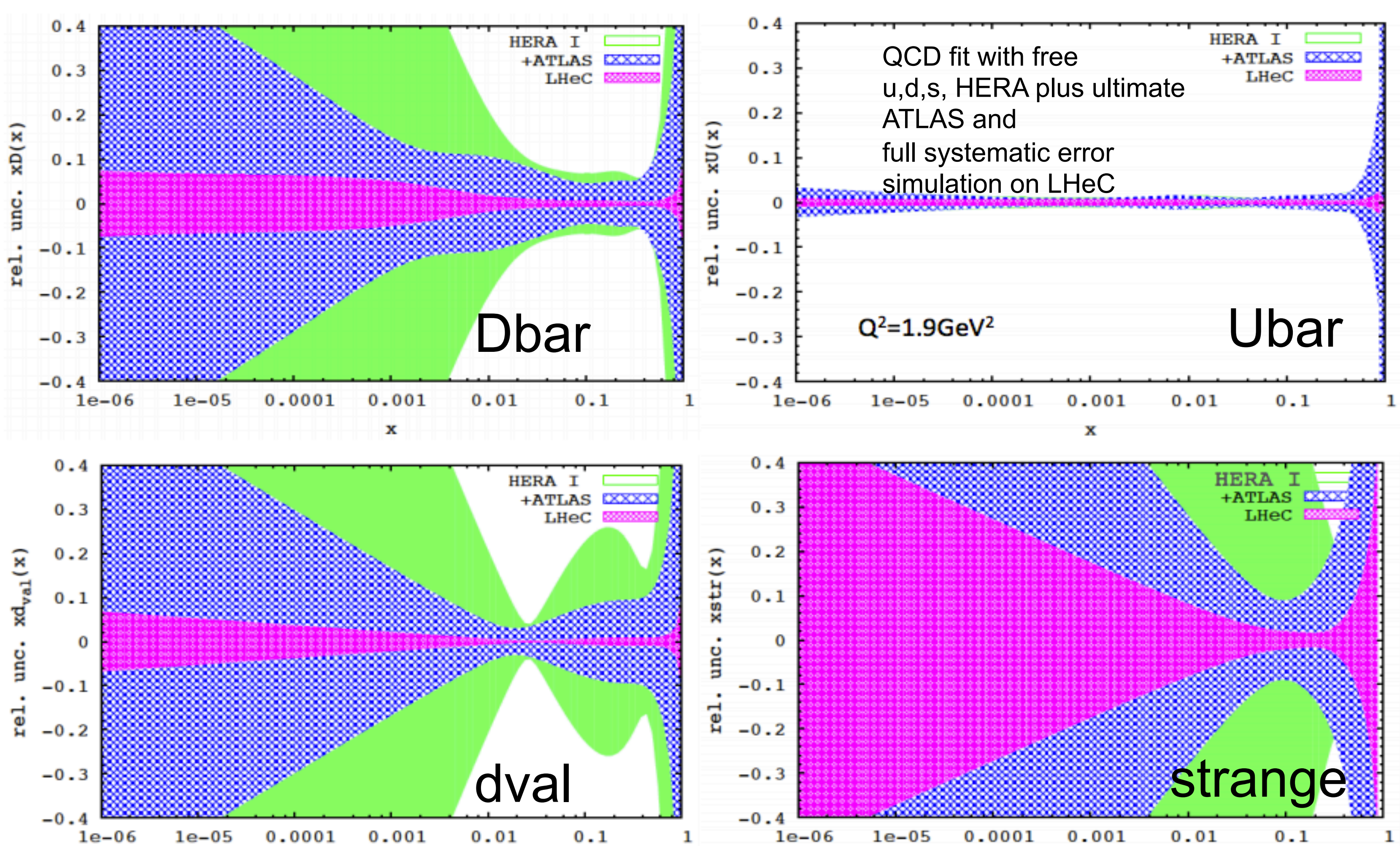






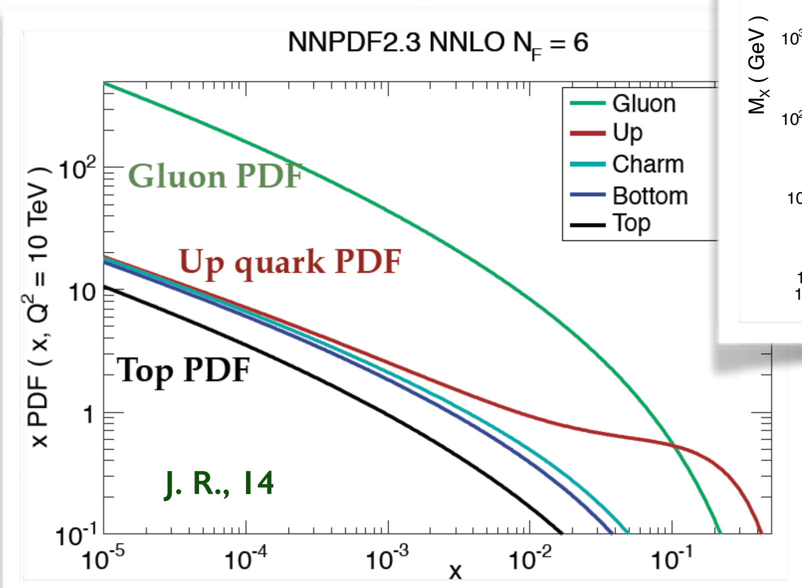
The "ultimate" proton-only fit

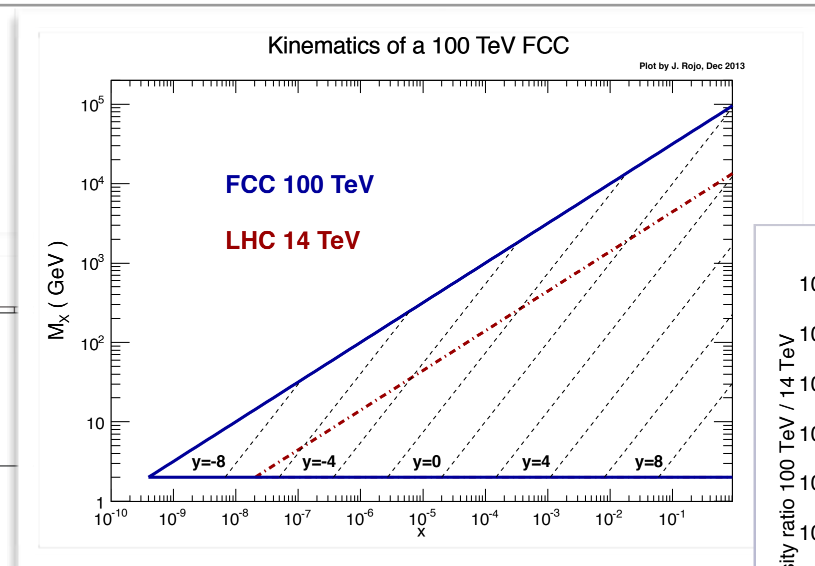
- **Combined fit** to **HERA, LHC** and **LHeC** data has the **potential** to deliver a **PDF set** with **very small, reliable, uncertainties** even when releasing most of the standard assumptions (u=d at small-x, free strange parametrization)
- Only on **high-energy**, **proton data**: **no higher-twist** or **nuclear corrections**

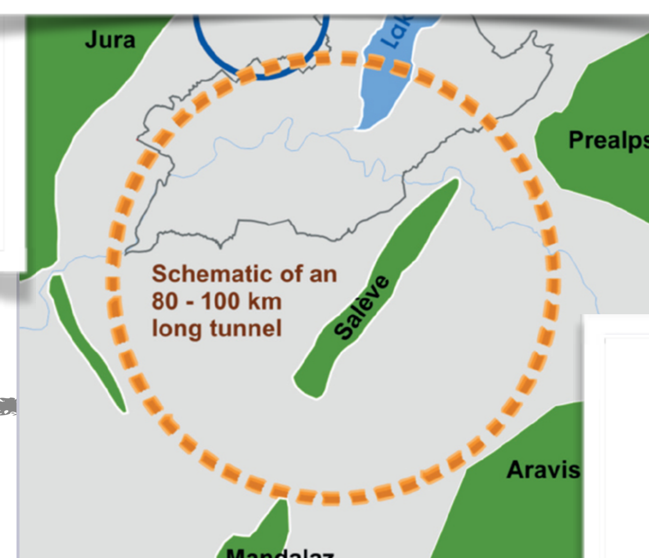


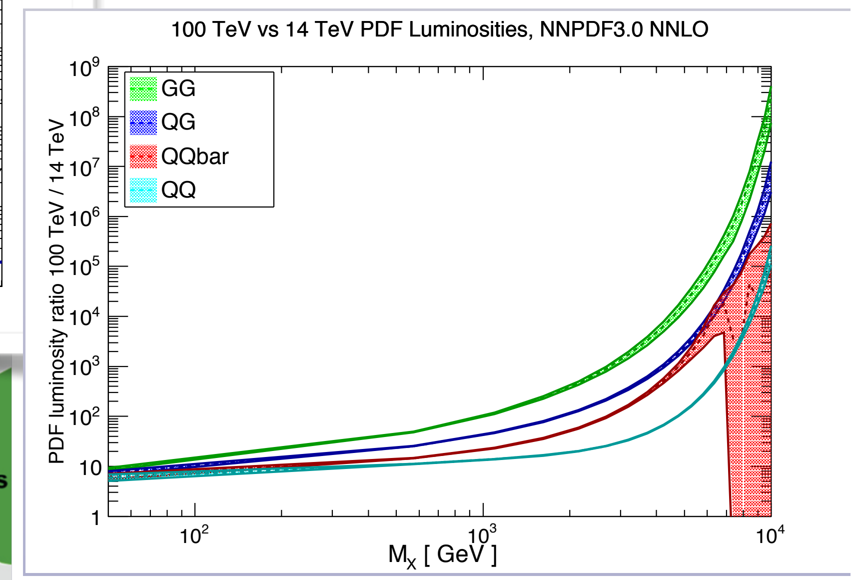
PDFs at a 100 TeV collider

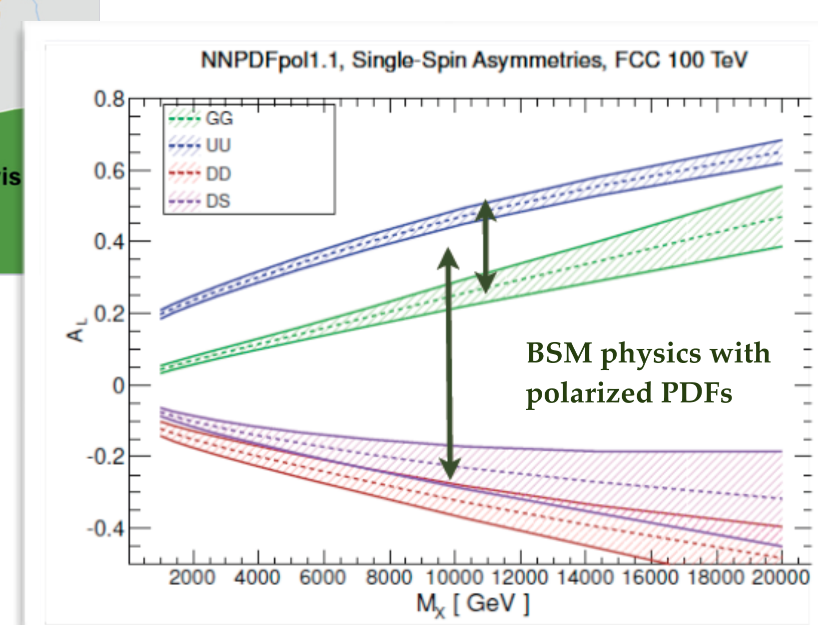
A whole new playground











- Substantial widening of kinematic coverage
- Extreme increase of parton-parton luminosities, especially for high-mass states
- "Massless" top?
- EW effects in the evolution
- Polarised PDFs for BSM studies

Conclusions & Outlook

- **Parton Distribution Functions** will remain a **crucial ingredient** of our **theoretical predictions** as long as we will be dealing with **hadron colliders** …
- **Uncertainties on PDFs** are, often, the **limiting theoretical uncertainty** on **precision measurements** at the LHC (M_W is one example)
- **LHC** (Run I) **measurements** are already providing **constraints** on **some PDF combinations** and **more will come** in the future
- **Future machines**, in particular **LHeC**, offer **unique possibilities** for PDF determinations
- A 100 TeV collider would be a whole new playground for PDF studies, with a plethora of new effects playing an important role (top PDFs, EW corrections/ evolution, ….)