Drell-Yan and Other Tools for Proton Structure from the LHC

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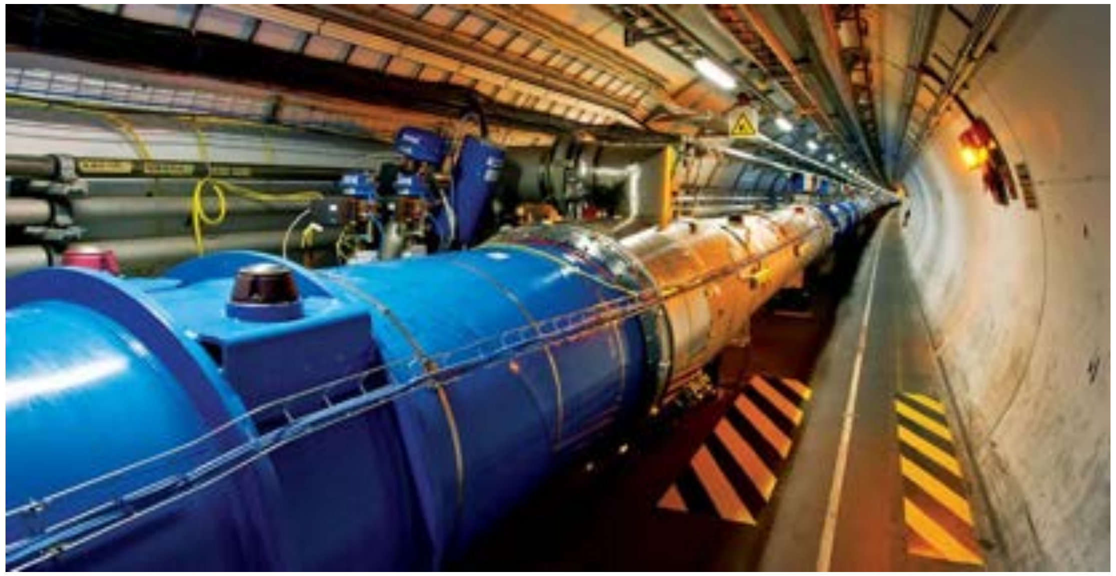
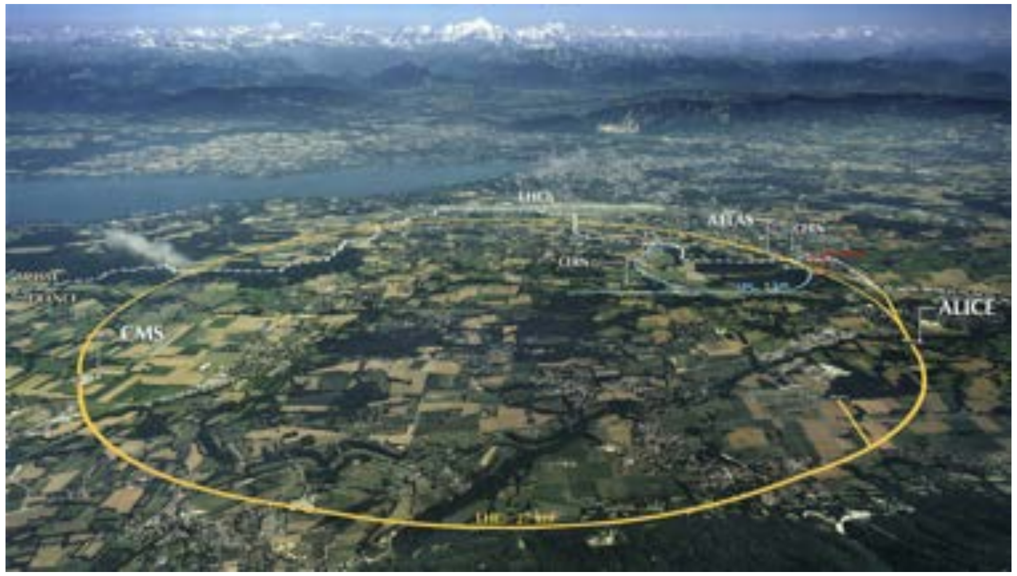
Symposium on Fundamental Physics in Memory of Sidney Drell, SLAC, Jan 12, 2018

Motivation - the LHC

- The **LHC** is the most powerful accelerator ever, with unique sensitivity to Higgs sector and physics within and beyond the Standard Model.
- It is also (predominantly) a **proton-proton** collider $\Rightarrow$ sensitive probe of **proton structure**. What do we know about the structure of the proton and what can the LHC tell us?
- As we will see - the **Drell-Yan** process plays a special role in our understanding of the proton, from the early parton model to the high precision LHC.

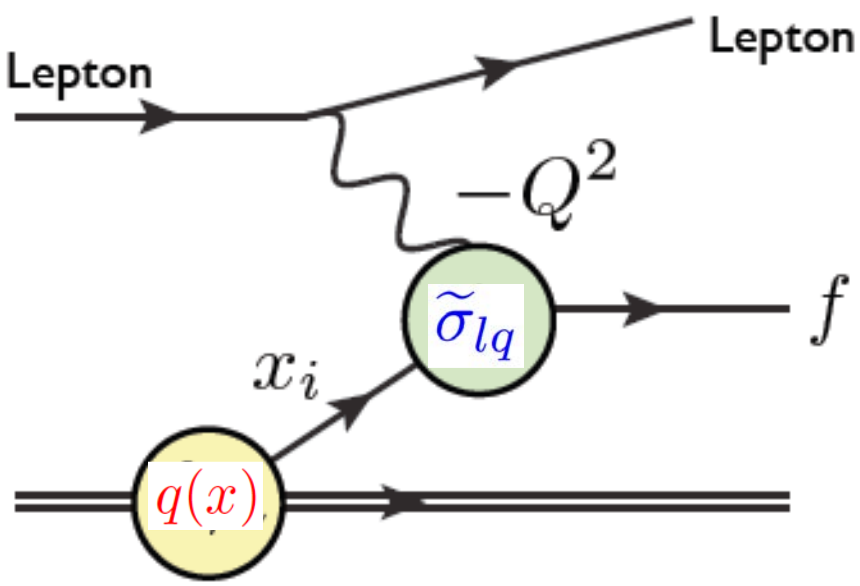




Proton Structure and Parton Distribution Functions

Parton Distribution Functions

- First measurements of proton (sub)structure from Deep Inelastic Scattering (DIS) of lepton off a proton.
- Understood in **parton model** - cross section given in terms of:
  - **Parton-level cross section** for lepton to scatter off quasi-free parton within proton. Calculate using **pQCD**.
  - **Parton Distribution Function** (PDF) - at lowest order, probability to find parton ($q, \overline{q}, g...$) in proton. Cannot (currently) calculate from first principles.



x - proton longitudinal **momentum fraction**.

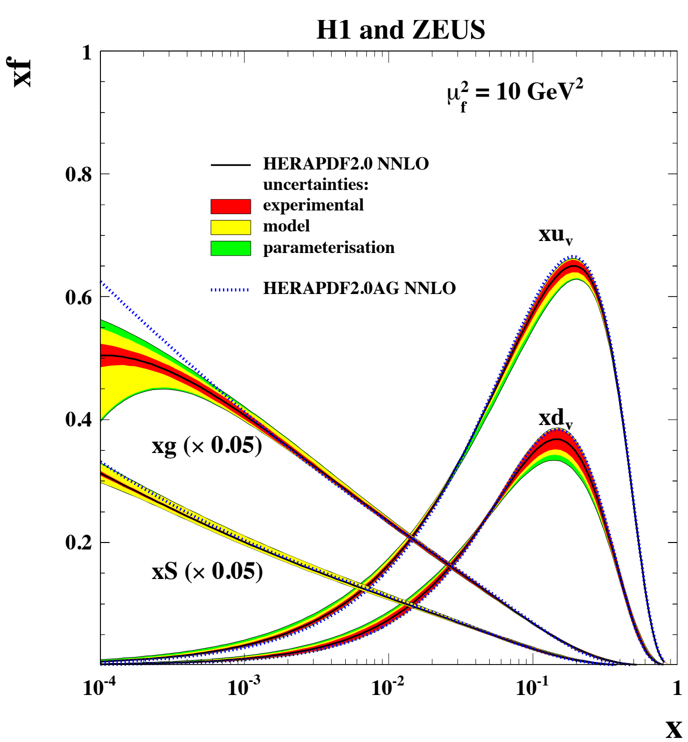
Q - **photon virtuality** ~ resolution scale.

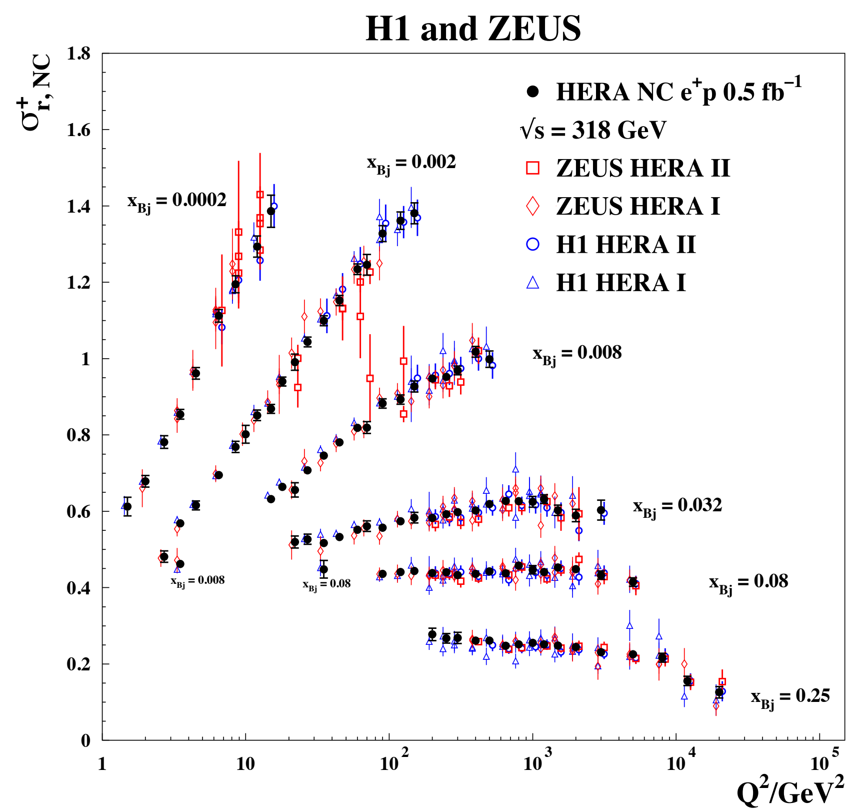
$$\sigma^{lp} \sim \sigma^{lq}(Q^2) \otimes q(x, Q^2)$$

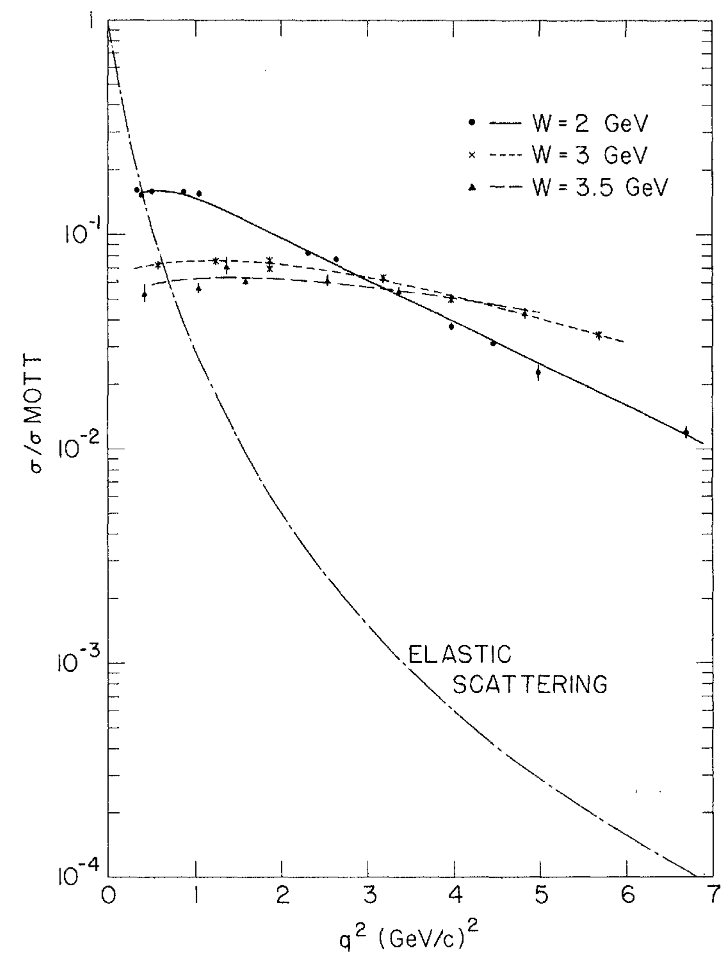
$f(x) \otimes g(x) \sim \int \mathrm{d}y f(x) g(x/y)$,

Deep Inelastic Scattering

- DIS data now taken over many decades:
  - Pioneering measurement at **SLAC** - established parton model.
  - State-of-the-art: combined data from both runs/experiments at **HERA** *ep* collider. High precision data ⇒ extract PDFs.







H1 and ZEUS, Eur. Phys. J C75 (2015) no. 12, 580

M. Breidenbach et al., Phys. Rev. Lett. 23 (1969) 935-939

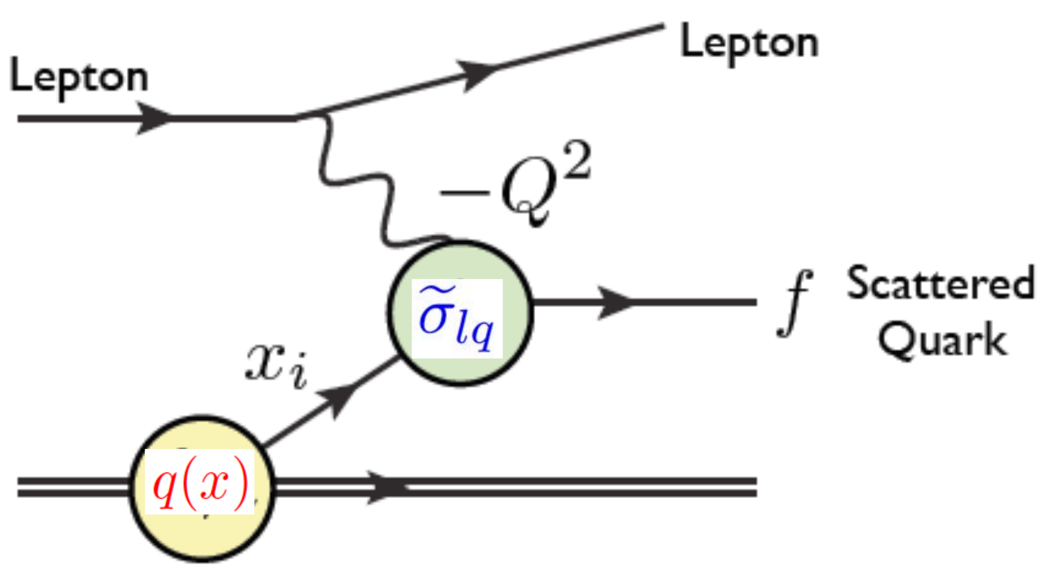
- **However** DIS alone is incomplete probe.

Flavour decomposition, gluon at high x …

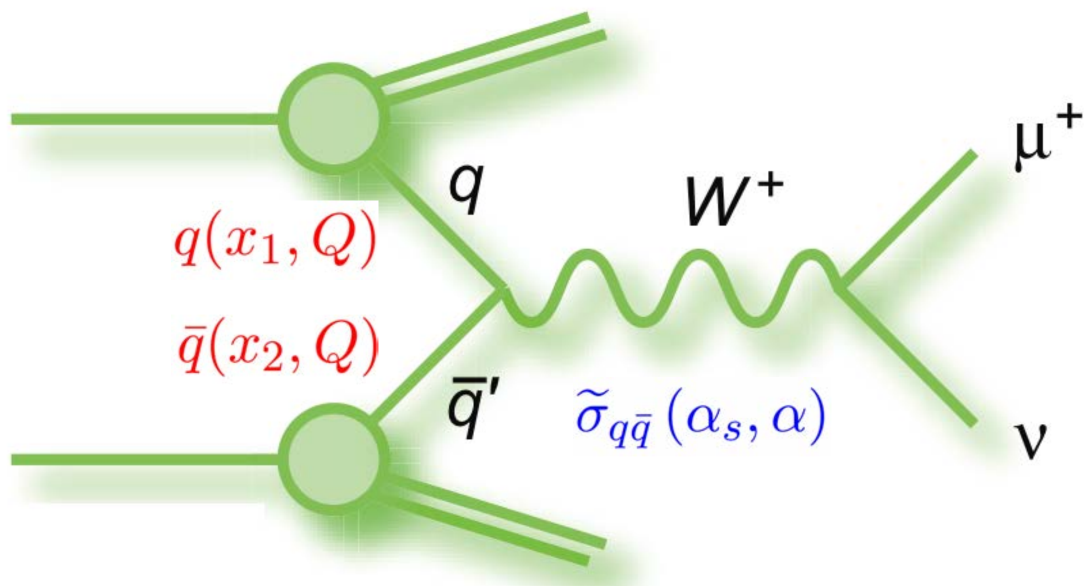
Beyond DIS

- Can apply PDF factorization to hadron-hadron collisions.
- First to be considered: lepton pair production - **Drell-Yan** (DY).

$$\sigma_{lp} \simeq \widetilde{\sigma}_{lq}\,(\alpha_s, \alpha) \otimes q(x, Q)$$



$$\sigma_{pp} \simeq \widetilde{\sigma}_{q\bar{q}}\,(\alpha_s, \alpha) \otimes q(x_1, Q) \otimes \bar{q}(x_2, Q)$$



$$\text{Factorization} \Rightarrow q_{DIS}(x, Q^2) \equiv q_{DY}(x, Q^2)$$

- Approach generic: **apply to range of processes**, both SM (DY, jets, $t\bar{t}\ldots$) and BSM (new resonances, SUSY, Higgs…)

$\longrightarrow$ **Fit** the PDFs to well understood datasets (DIS, DY…) to make predictions for less well understood.

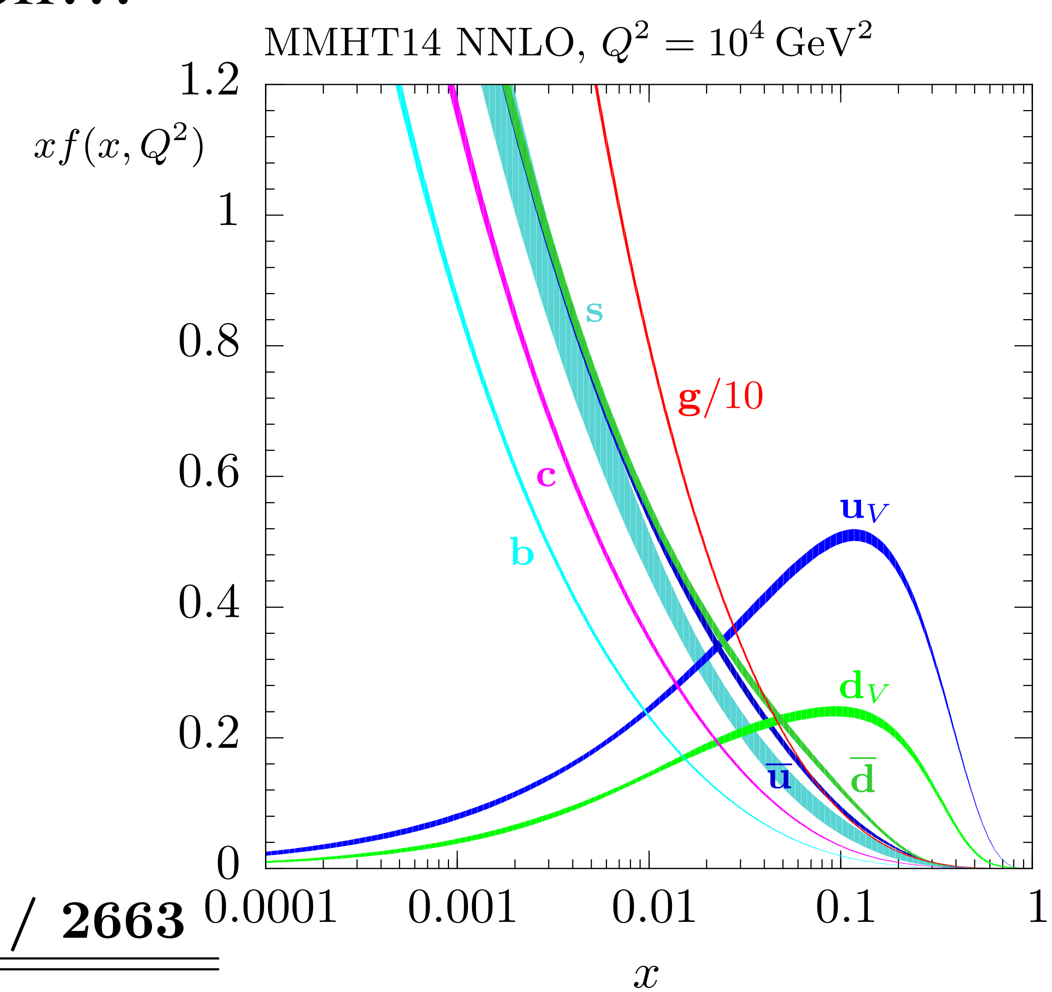
Global fits

- For LHC (and elsewhere) aim to constrain PDFs to high precision for all flavours (q, $\overline{q}$, $g\ldots$) over a wide x region.
- Perform **global PDF fits** to wide range of data (DIS, fixed nuclear targets with l, ν beams, hadron collider data - jets, W, Z, $t\bar{t}\ldots$).
- Three major global fitters - **CT, MMHT, NNPDF**. Vary in fitting approach, data included, error evaluation…

$$\chi^2/\text{dof} \sim 1$$

$\Rightarrow$ **Non-trivial check of QCD.**

Data set	LO	NLO	NNLO
BCDMS μp F_2 [125]	162 / 153	176 / 163	173 / 163
BCDMS μd F_2 [19]	140 / 142	143 / 151	143 / 151
NMC μp F_2 [20]	141 / 115	132 / 123	123 / 123
NMC μd F_2 [20]	134 / 115	115 / 123	108 / 123
NMC $\mu n/\mu p$ [21]	122 / 137	131 / 148	127 / 148
E665 μp F_2 [22]	59 / 53	60 / 53	65 / 53
E665 μd F_2 [22]	52 / 53	52 / 53	60 / 53
SLAC ep F_2 [23, 24]	21 / 18	31 / 37	31 / 37
SLAC ed F_2 [23, 24]	13 / 18	30 / 38	26 / 38
NMC/BCDMS/SLAC/HERA F_L [20, 125, 24, 63, 64, 65]	113 / 53	68 / 57	63 / 57
E866/NuSea pp DY [88]	229 / 184	221 / 184	227 / 184
E866/NuSea pd/pp DY [89]	29 / 15	11 / 15	11 / 15
NuTeV νN F_2 [29]	35 / 49	39 / 53	38 / 53
CHORUS νN F_2 [30]	25 / 37	26 / 42	28 / 42
NuTeV νN xF_3 [29]	49 / 42	37 / 42	31 / 42
CHORUS νN xF_3 [30]	35 / 28	22 / 28	19 / 28
CCFR $\nu N \to \mu\mu X$ [31]	65 / 86	71 / 86	76 / 86
NuTeV $\nu N \to \mu\mu X$ [31]	53 / 40	38 / 40	43 / 40
HERA e^+p NC 820 GeV[61]	125 / 78	93 / 78	89 / 78
HERA e^+p NC 920 GeV[61]	479 /330	402 /330	373/ 330
HERA e^-p NC 920 GeV [61]	158/ 145	129/ 145	125 /145
HERA e^+p CC [61]	41 / 34	34 / 34	32 / 34
HERA e^-p CC [61]	29 / 34	23 / 34	21 / 34
HERA ep F_2^{charm} [62]	105 /52	72 / 52	82 / 52
H1 99–00 e^+p incl. jets [126]	77 / 24	14 / 24	—
ZEUS incl. jets [127, 128]	140/60	45 / 60	—
DØ II $p\bar{p}$ incl. jets [119]	125 / 110	116 / 110	119 / 110
CDF II $p\bar{p}$ incl. jets [118]	78 / 76	63 / 76	59 / 76
CDF II W asym. [66]	55 / 13	32 / 13	30 / 13
DØ II $W \to \nu e$ asym. [67]	47 / 12	28 / 12	27 / 12
DØ II $W \to \nu\mu$ asym. [68]	16 / 10	19 / 10	21 / 10
DØ II Z rap. [90]	34 / 28	16 / 28	16 / 28
CDF II Z rap. [70]	95 / 28	36 / 28	40 / 28
ATLAS W^+, W^-, Z [10]	94/30	38/30	39/30
CMS W asymm $p_T > 35$ GeV [9]	10/11	7/11	9/11
CMS asymm $p_T > 25$ GeV, 30 GeV[77]	7/24	8/24	10/24
LHCb $Z \to e^+e^-$[79]	76/9	13/9	20/9
LHCb W asymm $p_T > 20$ GeV[78]	27/10	12/10	16/10
CMS $Z \to e^+e^-$ [84]	46/35	19/35	22/35
ATLAS high-mass Drell-Yan [83]	42/13	21/13	17/13
CMS double diff. Drell-Yan [86]	—	372/132	149/132
Tevatron, ATLAS, CMS $\sigma_{t\bar{t}}$ [91]–[97]	53/13	7/13	8/13
ATLAS jets (2.76 TeV+7 TeV)[108, 107]	162/116	106/116	—
CMS jets (7 TeV) [106]	150/133	138/133	—
All data sets	**3706 / 2763**	**3267 / 2996**	**2717 / 2663**

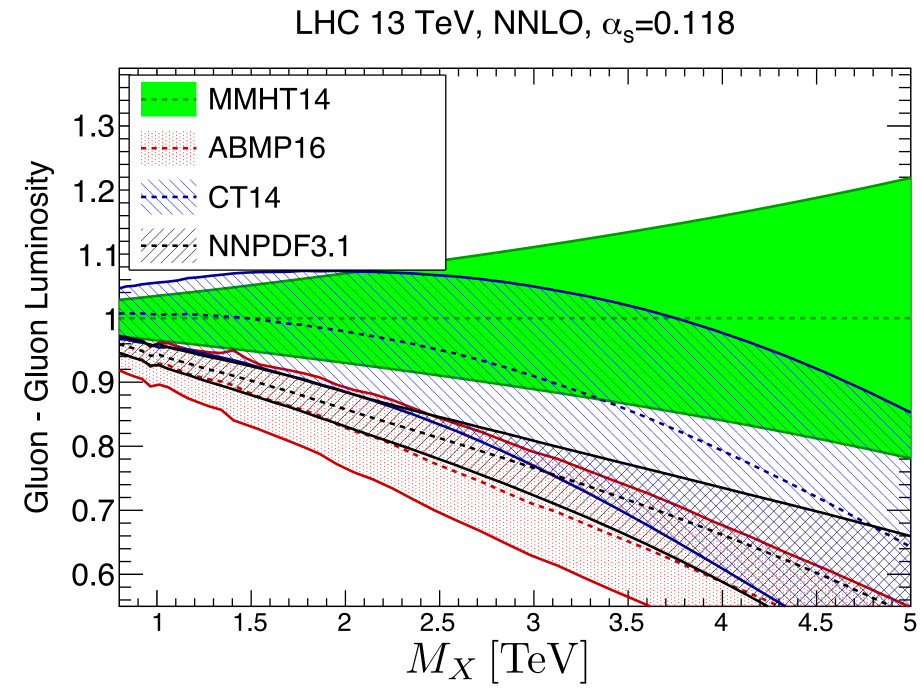


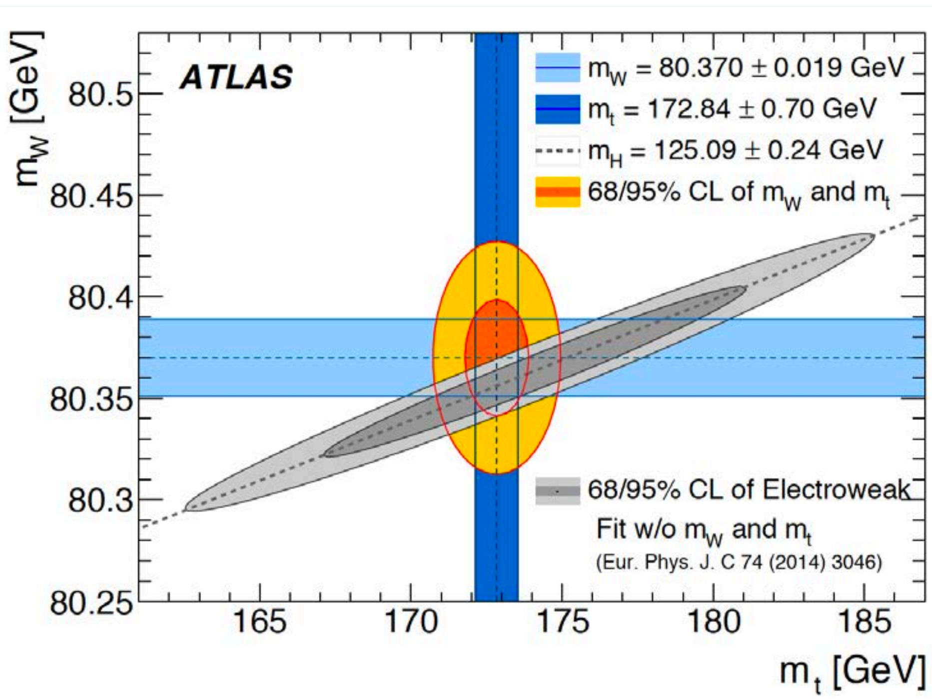
LHL et al., Eur. Phys. J. C75 (2015) no.5 204

Precise PDFs for the LHC

- Ultimate reach of LHC limited by knowledge of PDFs.

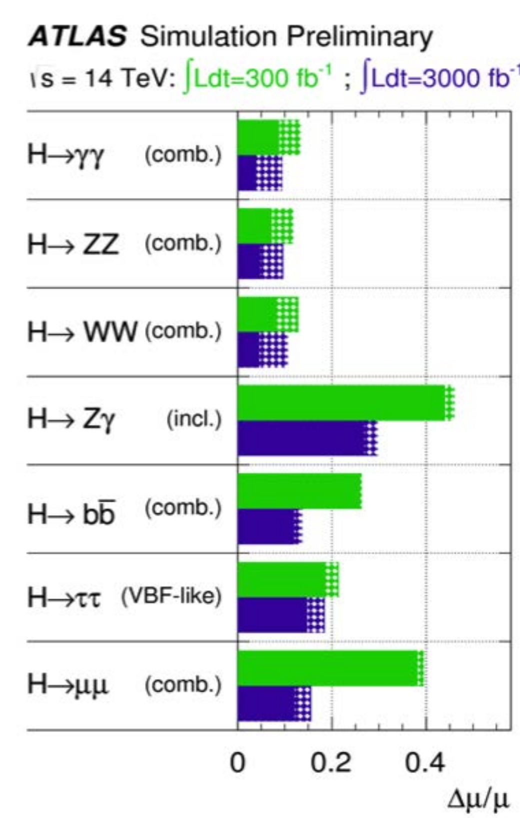
- **High mass searches** - PDFs in high x region (currently constraints poor)





Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5

- **Higgs couplings** $\rightarrow$ need to model SM production precisely.

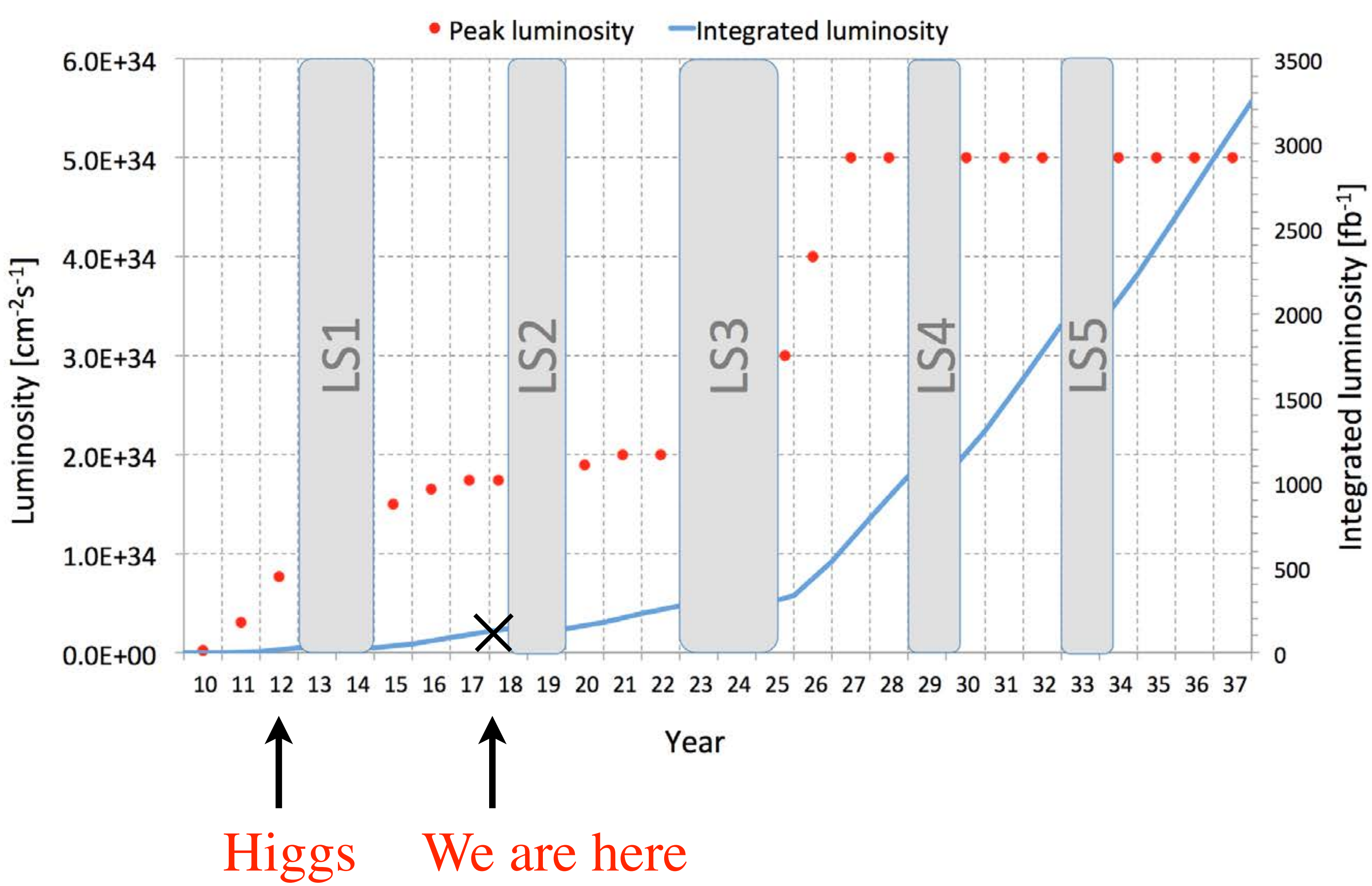


- **Precision SM** measurements - PDFs dominant uncertainty for e.g. W mass.

LHC: The Future

- We are at a very **early stage** in LHC running: so far only a few percent of the final projected data sample collected.

$\longrightarrow$ Precision requirements at the LHC rapidly increasing.



Precise Theory

- Past years has seen an explosion in calculations for LHC processes at Next-to-Next-to-Leading-Order (**NNLO**) in the strong couplings ($\sim$ % level precision).
- Thus, precision in data and theory at unprecedented level. Provides **opportunities** and **challenges** for PDF fitters.

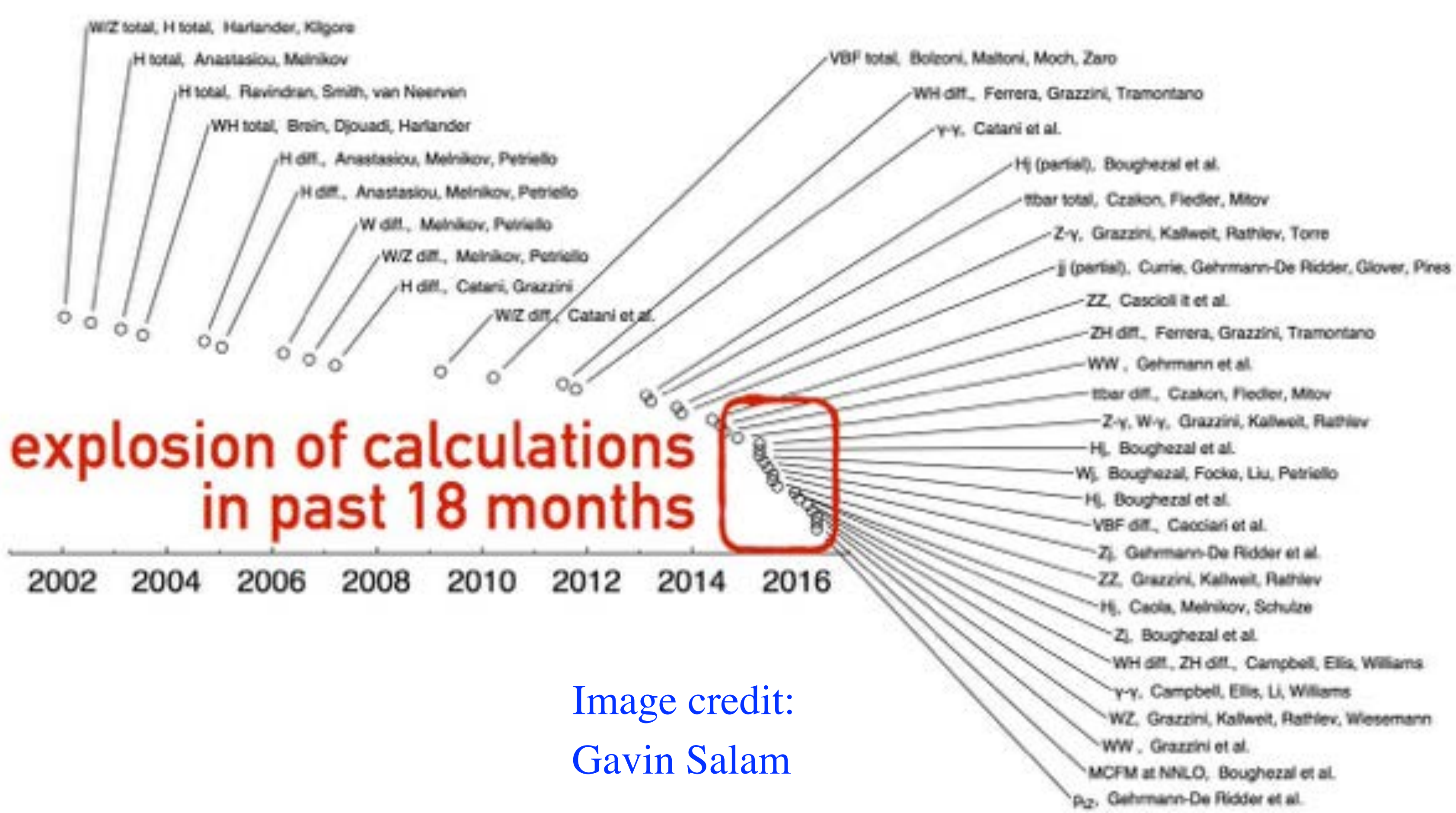


Image credit:
Gavin Salam

Drell-Yan and the Road to High Precision

The Drell-Yan Proposal

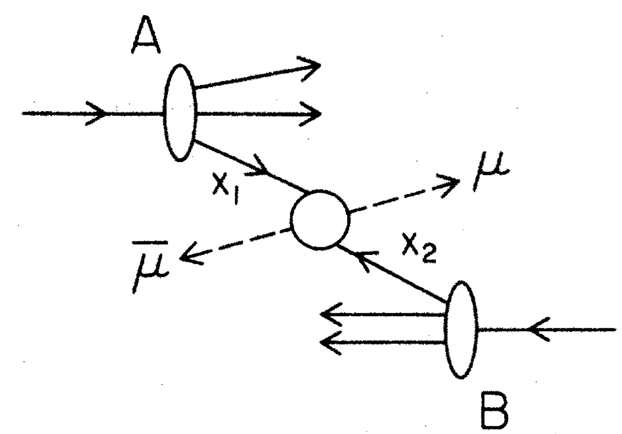
- **1970** paper - parton model prediction for lepton pair production in hadronic collisions.

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

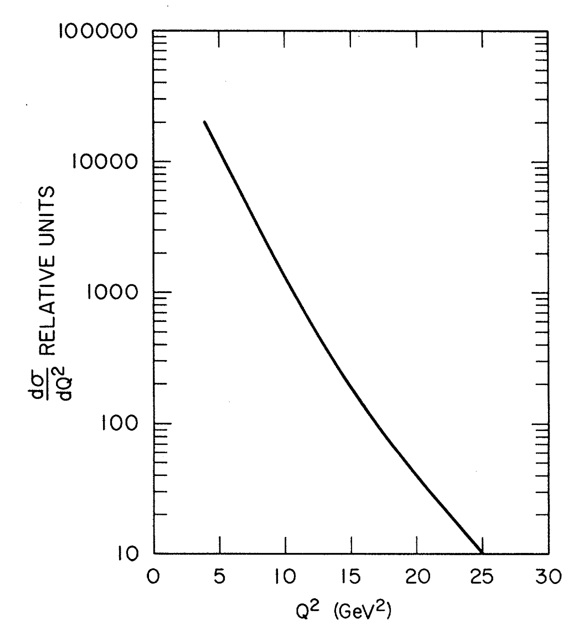
On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s \to \infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.

$$\frac{d\sigma}{dQ^2} = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\mathfrak{F}(\tau) = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\int_0^1 dx_1 \int_0^1 dx_2\, \delta(x_1x_2-\tau)\sum_a \lambda_a^{-2} F_{2a}(x_1) F_{2\bar{a}}{}'(x_2),$$



$Q^2 = x_1 x_2 s$

- First numerical prediction - **rapid fall off** with M_{ll} due to high x behaviour of PDFs $f(x \sim 1, Q^2) \sim 0$.



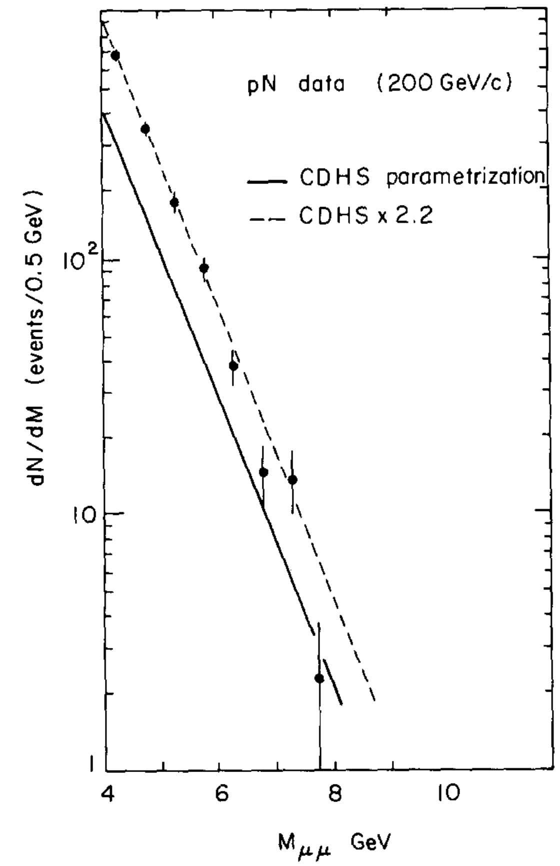
- Remark in opening paragraph:

called "partons." Nucleons are the "partons" of the nucleus and the "partons" of a nucleon itself are still to be deciphered. If we specify

$\longrightarrow$ **Crucial step** along road to deciphering this!

J. Badier et al., Phys. Lett. 89B (1979) 145

Comparisons to Data

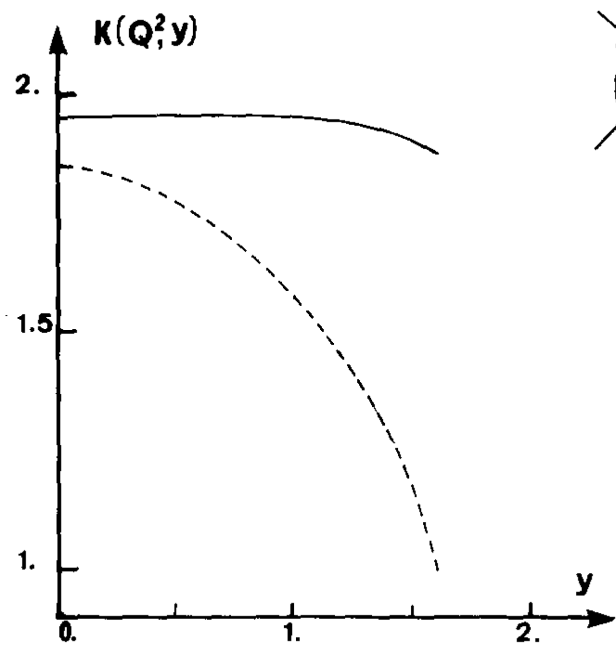


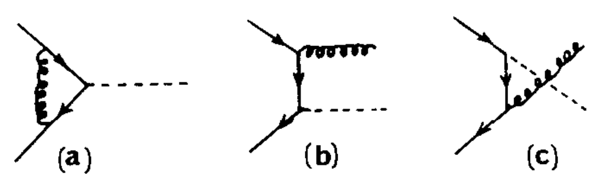
- First data (pN fixed target) **overshot** parton model predictions by a factor of ~ 2. What was missing?

- The data were compared to the LO theory prediction - by late 70s full **NLO** corrections were known.
- Corrections found to be sizeable, resolving apparent discrepancy.

Table 1 Experimental K factor

Group (ref.)	Beam/Target	Momentum [$\sqrt{s}$] (GeV)	K
NA3 (27)	($\bar{p}$-p)/Pt	150	2.3 ± 0.4
E537 (28)	$\bar{p}$/W	125	$2.45 \pm 0.12 \pm 0.20$
E288 (12)	p/Pt	300/400	~ 1.7
E439 (29)	p/W	400	1.6 ± 0.3
NA3 (19)	p/Pt	400	$3.1 \pm 0.5 \pm 0.3$
CHFMNP (30)	pp	[44, 63]	1.6 ± 0.2
A²BCSY (15)	pp	[44, 63]	~ 1.7
OMEGA (31)	$\pi^{\pm}$/W	39.5	~ 2.4
NA3 (32)	$\pi^{\pm}$/Pt	200	2.3 ± 0.5
	π^{-}/Pt	150	2.49 ± 0.37
	π^{-}/Pt	280	2.22 ± 0.33
NA10 (33)	π^{-}/W	194	2.77 ± 0.12
E326 (18)	π^{-}/W	225	$2.70 \pm 0.08 \pm 0.40$





C. Grosso-Pilcher, M.J. Shochet, Ann. Rev. Nucl. Sci. Part. 36 (1986) 1-28

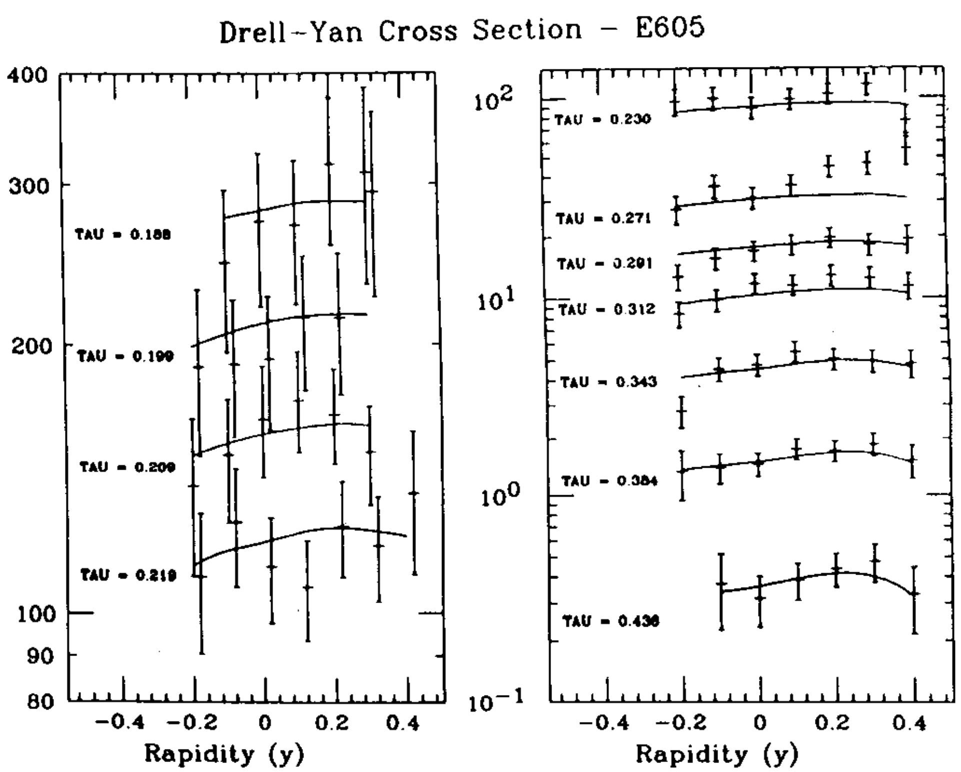
$\longrightarrow$ First indication of importance of **precise theory**.

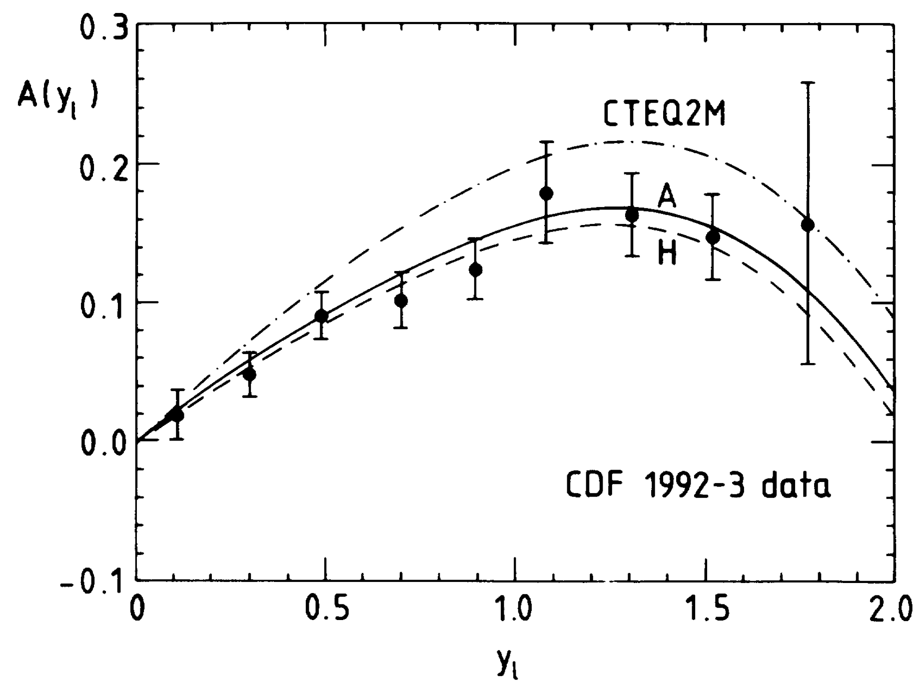
J. Kubar et al., Nucl. Phys. B175 (1980) 251-275

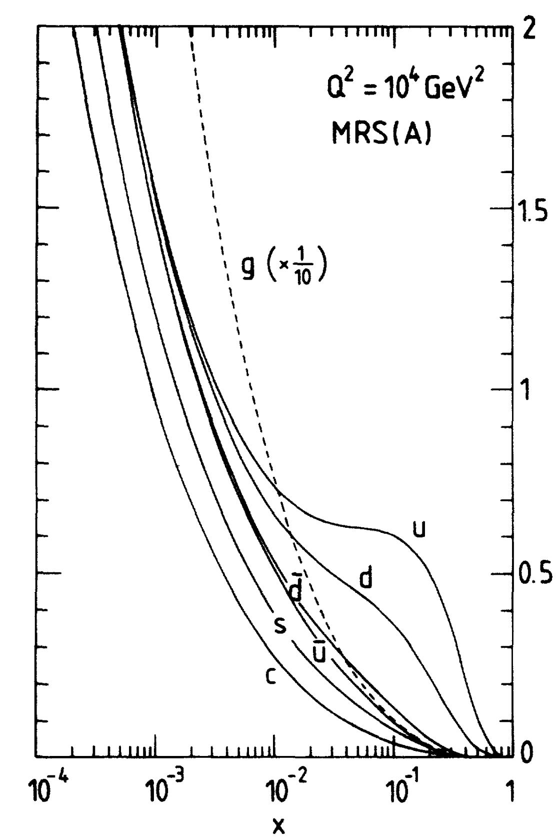
Early Fits

- The first **global PDF fits** to include Drell-Yan data appeared in 90s (NLO theory).
- Initially fixed target, but following that the **Tevatron** as well.
- Data well fit by NLO theory, placed important constraints on proton flavour structure.

A.D. Martin et al., Phys. Rev. D50 (1994) 6734-6752





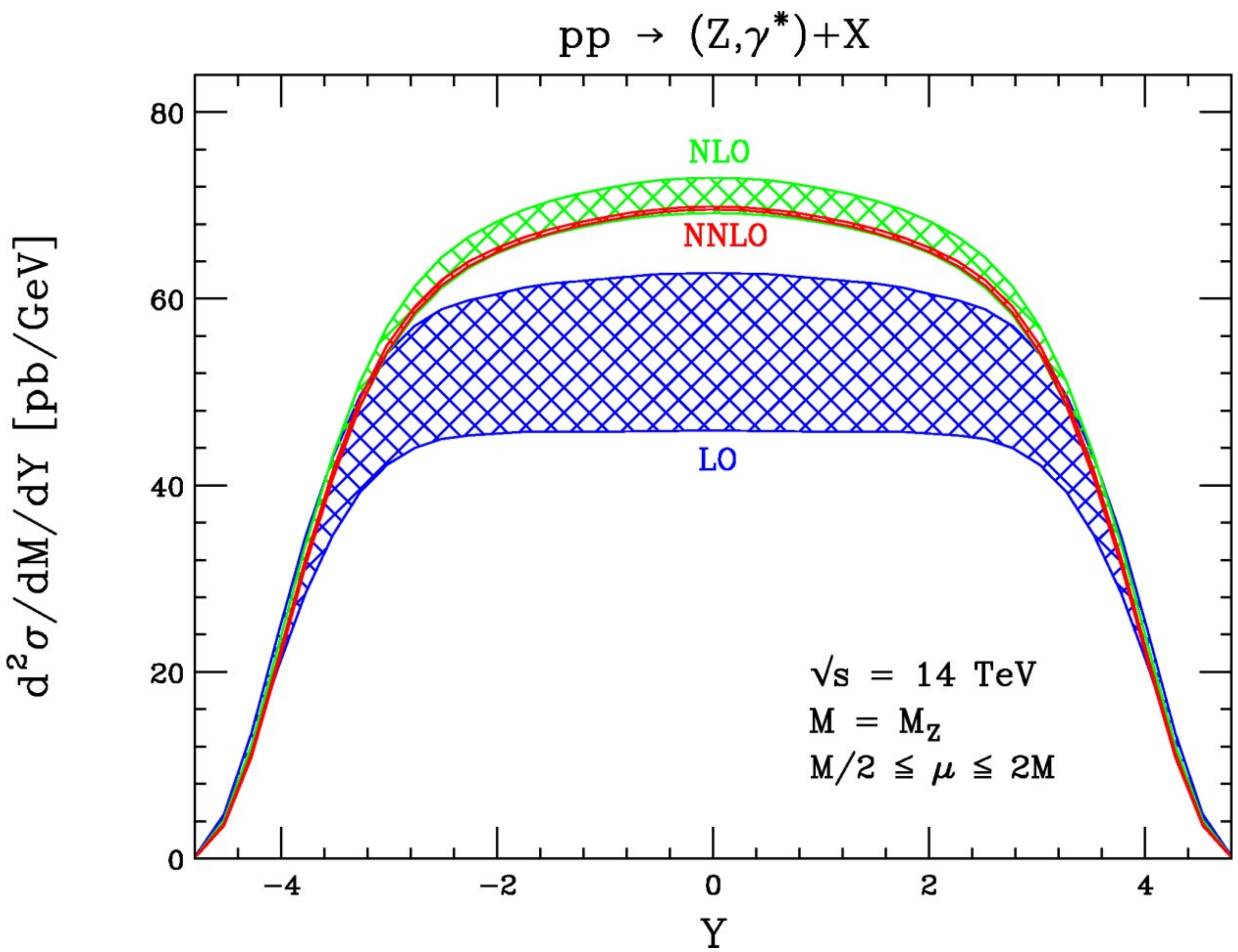


J.G. Morfin and W.K. Tung, Z.Phys. C52 (1991) 13-30

Precision Theory

- Drell-Yan **first** hadroproduction process computed at **NNLO** - total cross section in early 90s.
- Predictions differential in W, Z rapidity presented decade later - **first** of their kind. Corrections convergent, and with $\sim 1\%$ level uncertainty.

- Subsequently implemented in range of Monte Carlo generators (FEWZ, DYNNLO, MATRIX, MCFM).
- Includes full leptonic decay, with spin effects $\longrightarrow$ **direct comparison** to data.



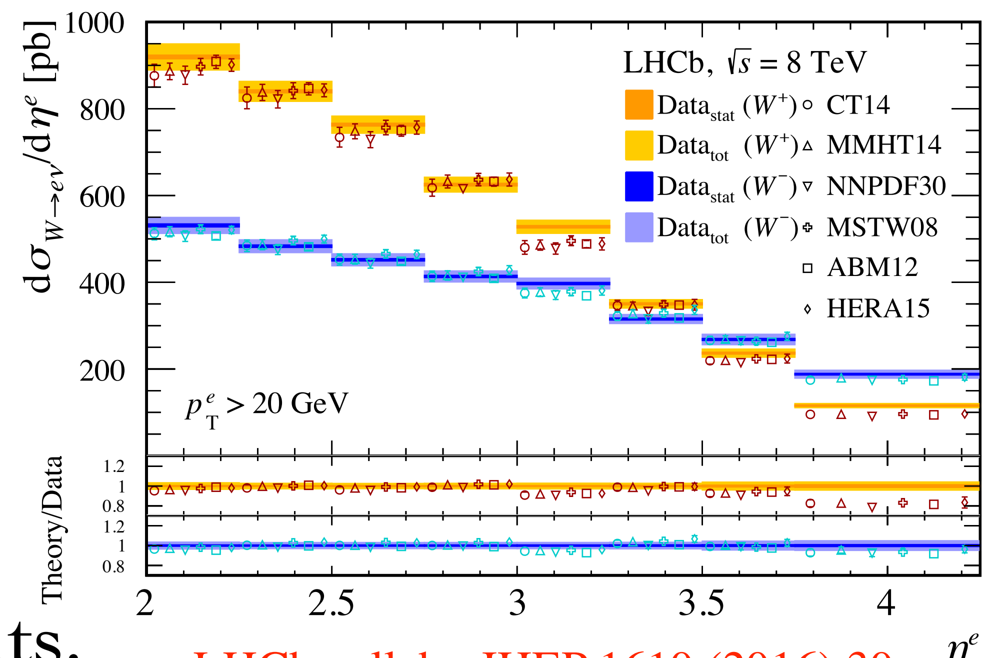
C. Anastasiou et al., Phys. Rev. D69 (2004) 094008

- NNLO now the **standard** for PDF fitting.

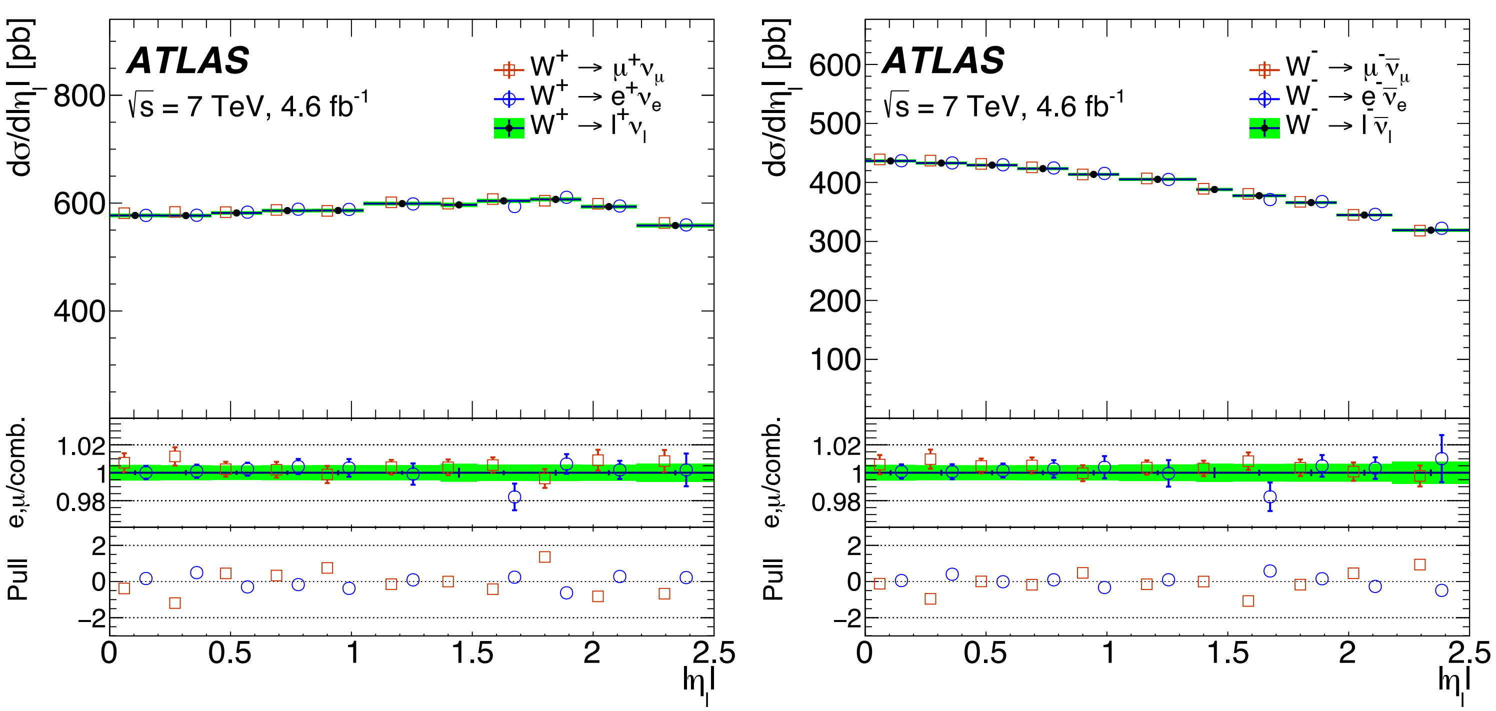
Precision Data

- Now in the **LHC era** - dramatic increase in availability of precise DY data, from multiple experiments, spanning range of phase space.

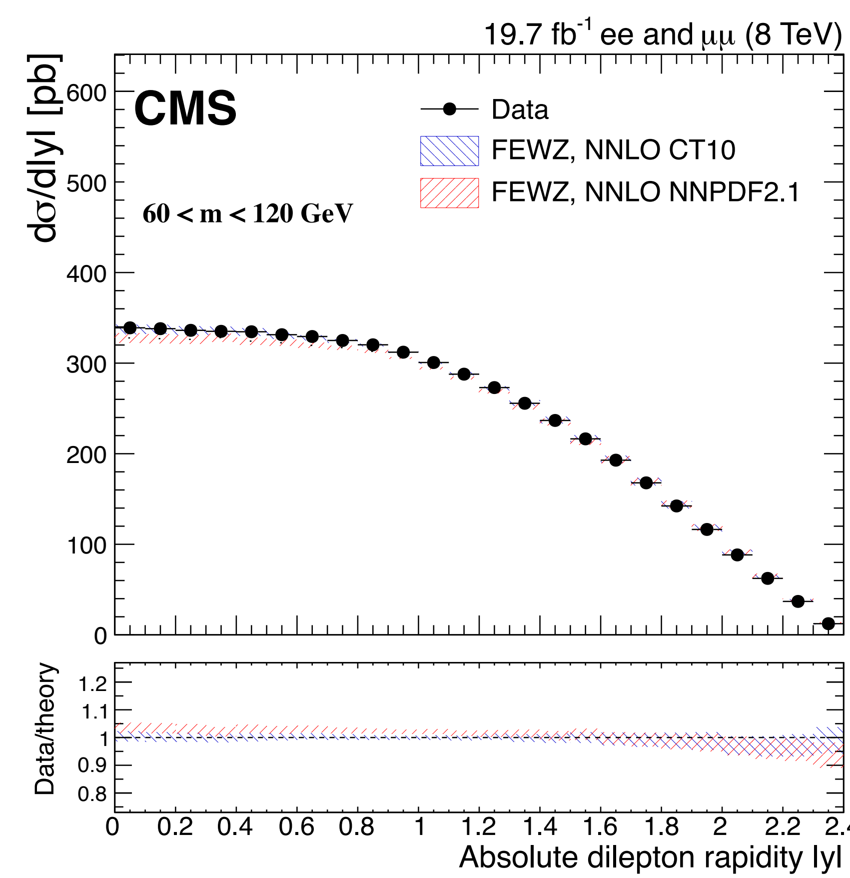
→ Playing increasingly **major role** in PDF fits.



LHCb collab., JHEP 1610 (2016) 30



ATLAS collab., Eur. Phys. J C77 (2017) no.6, 367

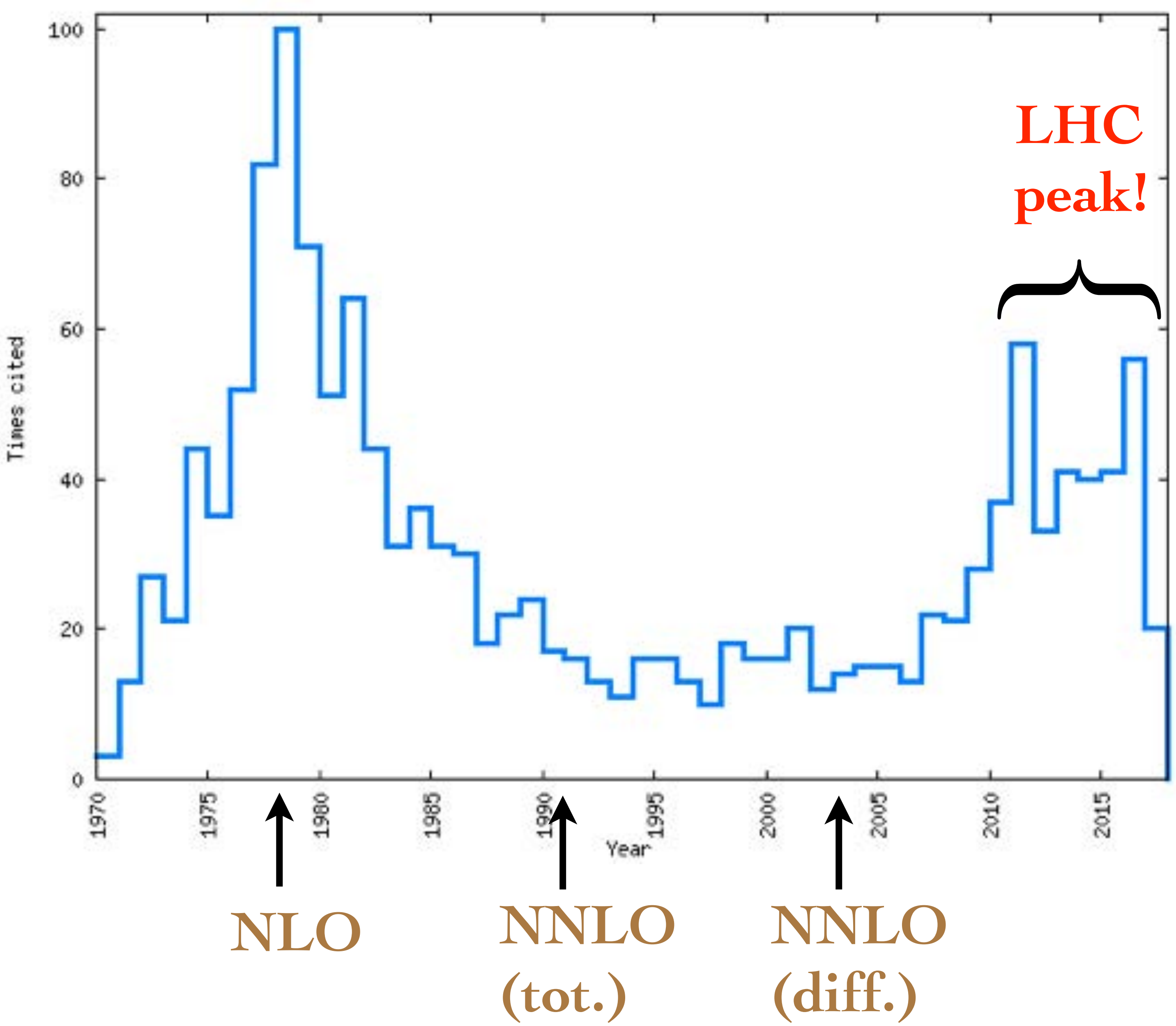


CMS collab., Eur. Phys. J C75 (2015) no.4, 147

Charting the Progress

- As of today - original **Drell** + **Yan** paper has **1448** citations.
- Going differential?

Massive Lepton Pair Production in Hadron-Hadron Collisions at High-Energies
S.D. Drell, Tung-Mow Yan (SLAC). Jun 1970. 12 pp.
Published in **Phys.Rev.Lett. 25 (1970) 316-320**, Erratum: **Phys.Rev.Lett. 25 (1970) 902**
SLAC-PUB-0755
DOI: 10.1103/PhysRevLett.25.316
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI Information Bridge Server; SLAC Document Server; Link to Fulltext
Detailed record - Cited by 1448 records 1000+



→ Key role of Drell-Yan in LHC physics.

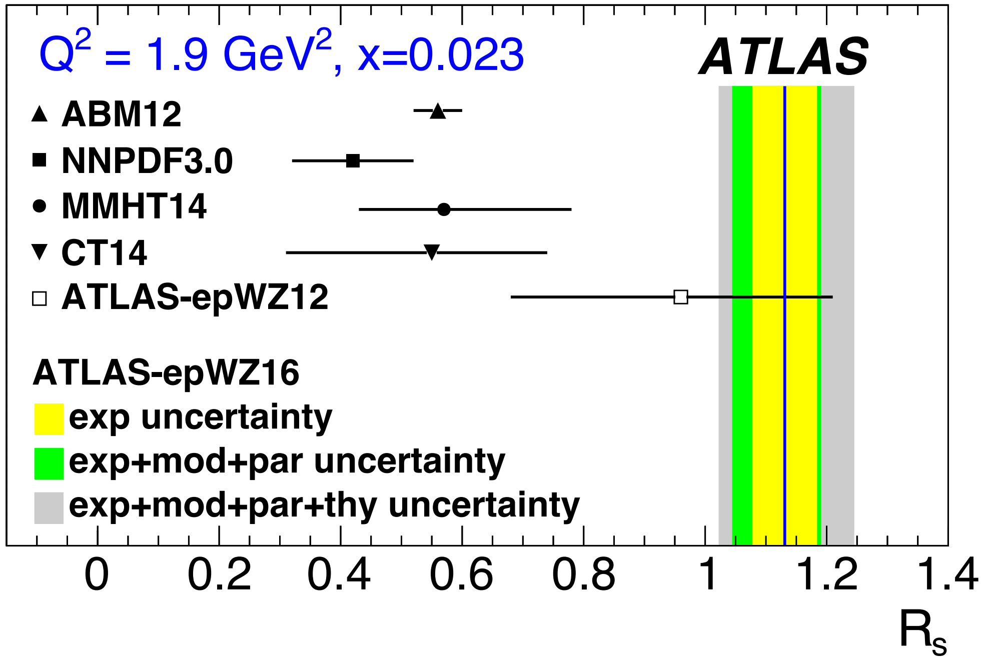
Drell-Yan at the LHC

What Can Drell-Yan Tell us?

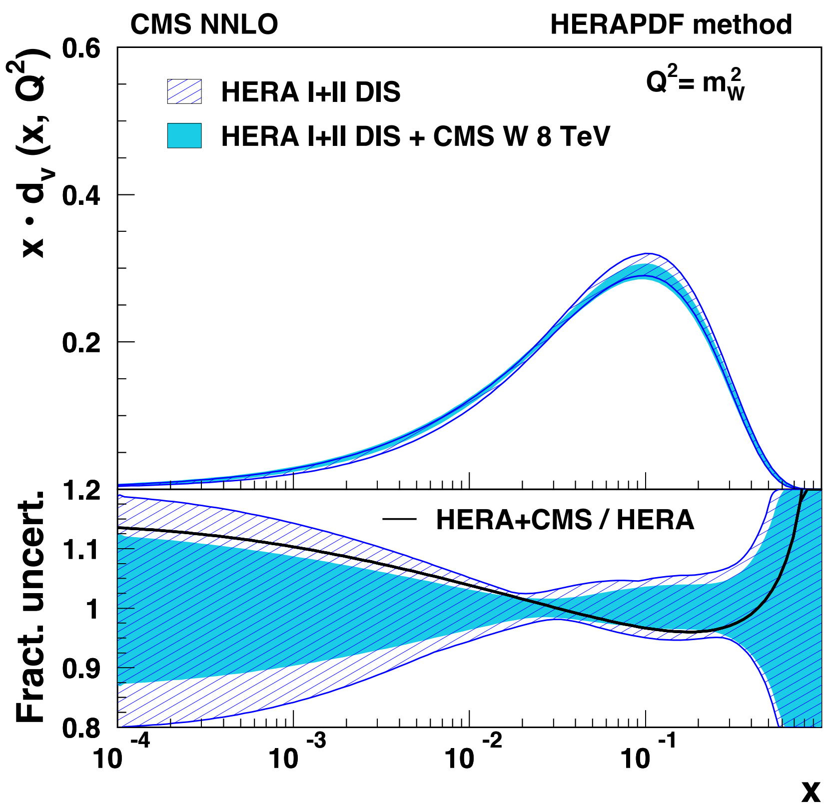
- Initial-state $q\bar{q}$ combination $\Rightarrow$ **proton flavour** decomposition (DIS $\sim$ various sums of $q + \bar{q}$).

$$u\bar{d},\ c\bar{s} \quad (u\bar{s},\ c\bar{d}) \to W^+ ,$$
$$d\bar{u},\ s\bar{c} \quad (s\bar{u},\ d\bar{c}) \to W^- ,$$
$$q\bar{q} \to Z/\gamma^* ,$$

- Depending on kinematics, sensitive to u_V, d_V and/or $\bar{u}, \bar{d}$.
- If data is precise enough, sensitive to least constrained (but small) $s, \bar{s}$ component $\Rightarrow$ sensitive to proton strangeness.



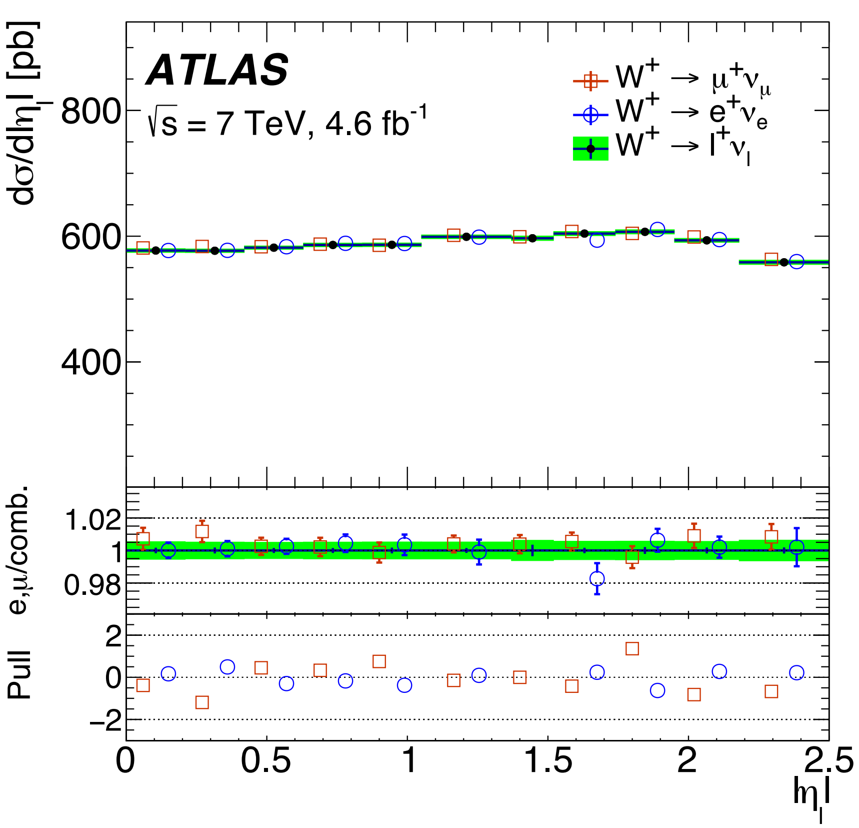
ATLAS collab., Eur. Phys. J C77 (2017) 367

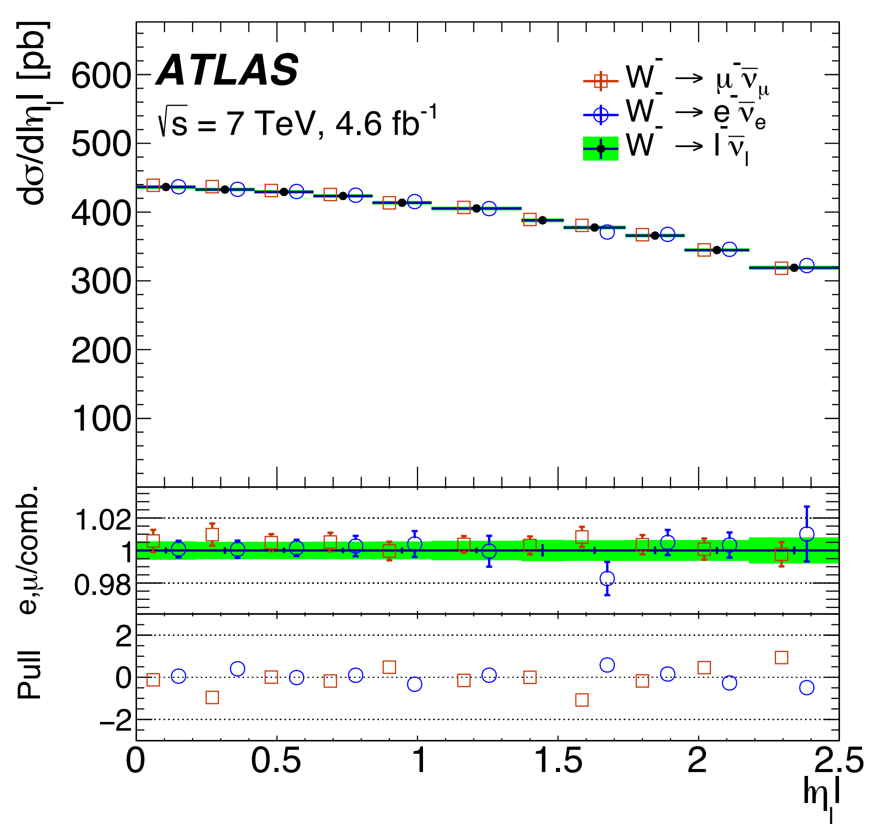


CMS collab., Eur. Phys. J C76 (2016) 469

ATLAS data

- **Highest ever precision** measurement of W, Z production by the **ATLAS** collaboration at the LHC.
- Data uncertainties at the sub-% level. Statistical errors negligible completely dominated by systematics.
- Uses *7* TeV dataset taken in **2011**. Understanding these systematic errors as well as possible has taken many years.





EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Eur. Phys. J. C 77 (2017) 367
DOI: 10.1140/epjc/s10052-017-4911-9

CERN-EP-2016-272
9th June 2017

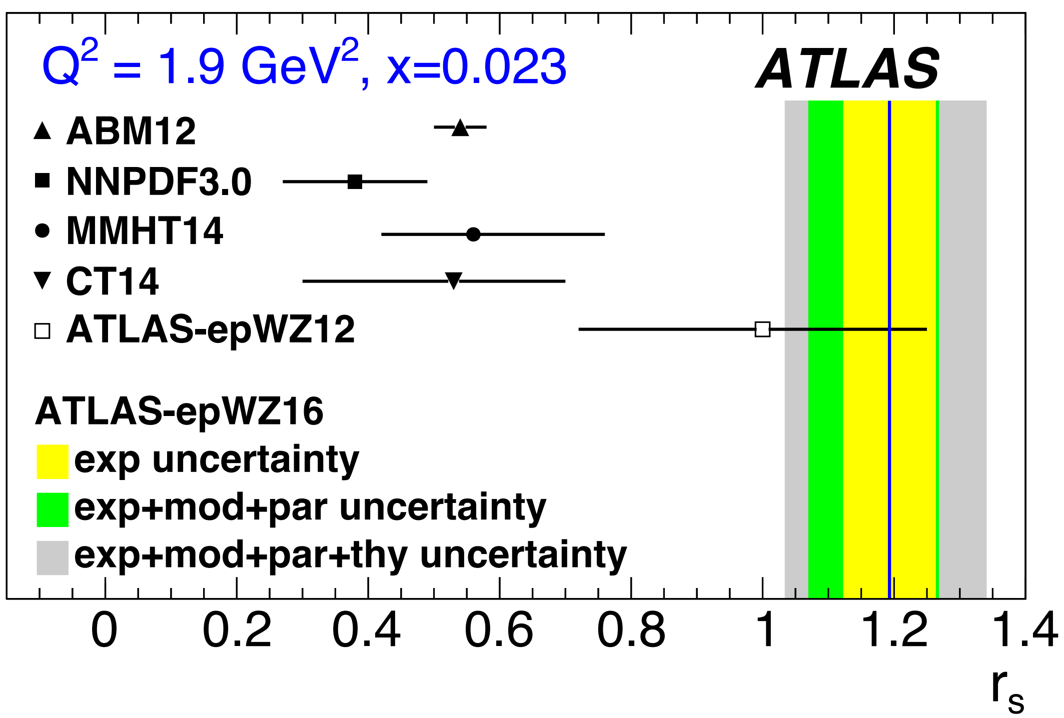
Precision measurement and interpretation of inclusive W^+, W^- and Z/γ^* production cross sections with the ATLAS detector

ATLAS collab., Eur. Phys. J C77 (2017) 367

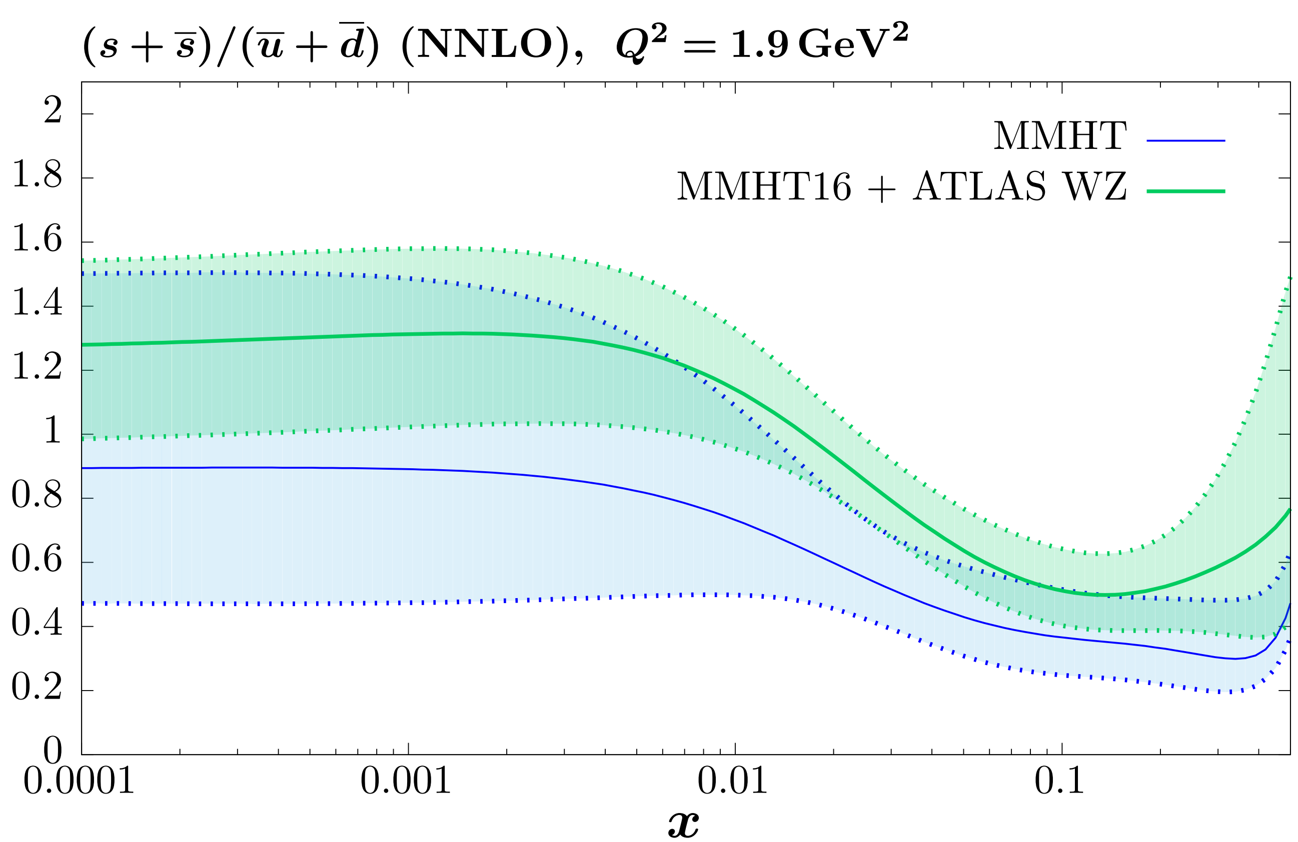
Impact

- ATLAS data precise enough to have large impact on proton strangeness - prefer **larger value** than global fits (some constraints from $\overline{\nu} s \to l c$ DIS).

- Strangeness ratio: $R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$

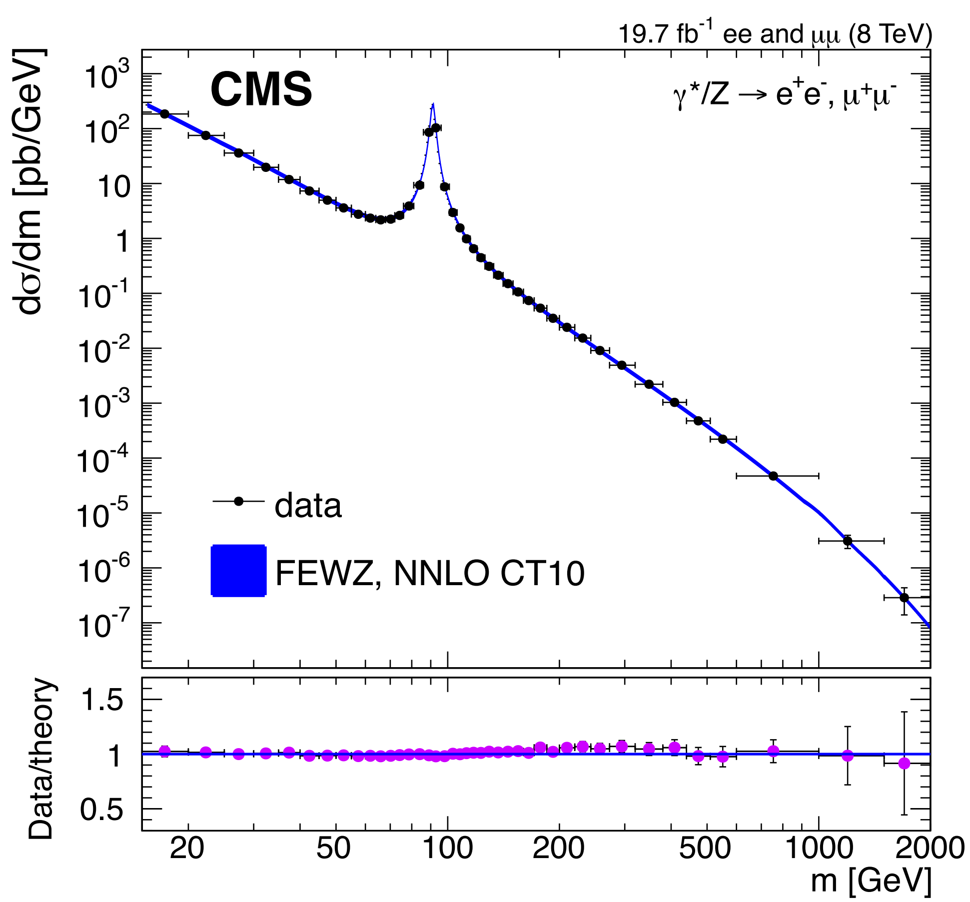


- Including in global fits (**MMHT**) $\to$ higher strangeness:



Going (Double) Differential

- Parton momentum fractions related to rapidity, y_{ll} and invariant mass, m_{ll}, of dilepton system, $x_{1,2} = \frac{m_{ll}}{\sqrt{s}} e^{\pm y_{ll}}$.
- CMS Drell-Yan data double differential in y_{ll}, m_{ll} , over wide mass region $15 < m_{ll} < 2000\,\text{GeV}$
  - Low mass $m_{ll} < M_Z$: γ^* - different $q, \bar{q}$ combinations at low/mid x .
  - High mass $m_{ll} \gg M_Z$: $q, \bar{q}$ at high x (poorly determined). Some sensitivity to `photon-induced' production $\gamma\gamma \to ll$.



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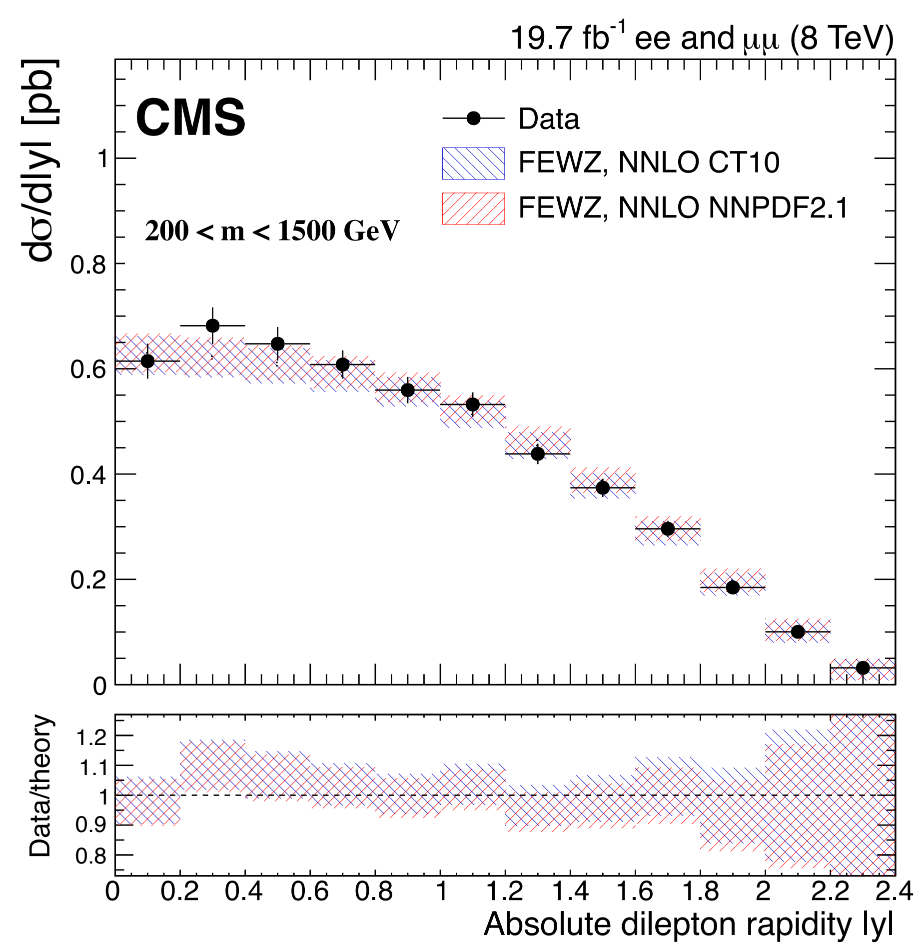


CMS collab., Eur. Phys. J C75 (2015) no.4, 147

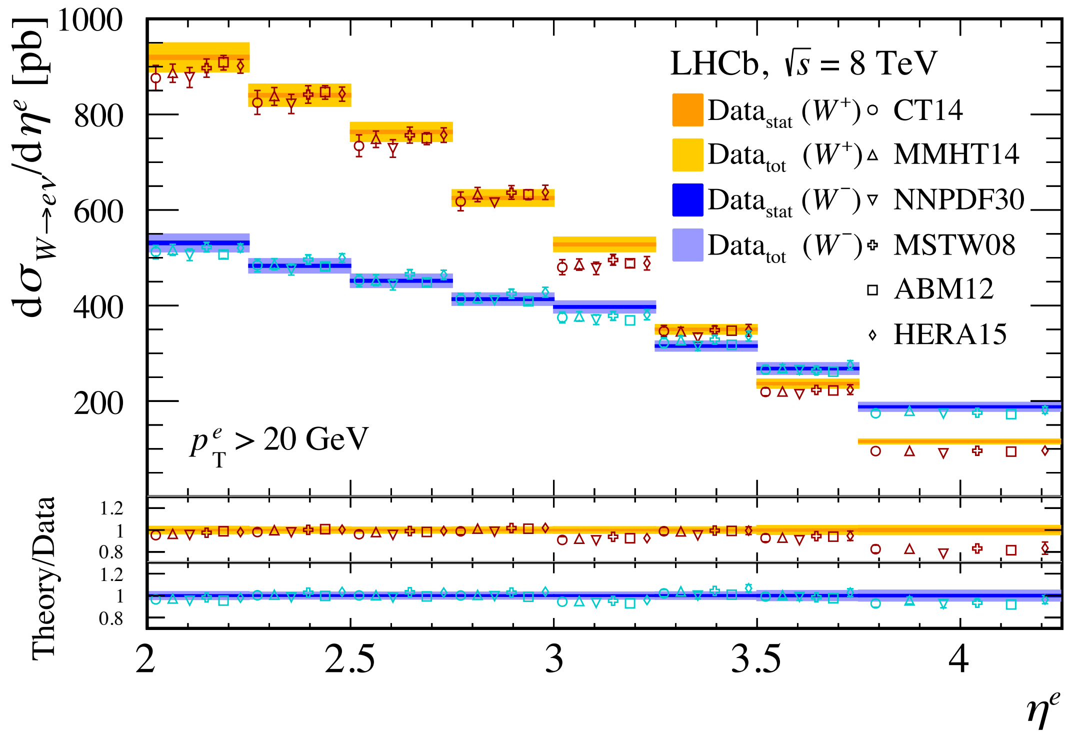
Going Forward

$x_{1,2} = \frac{m_{ll}}{\sqrt{s}} e^{\pm y_{ll}}$

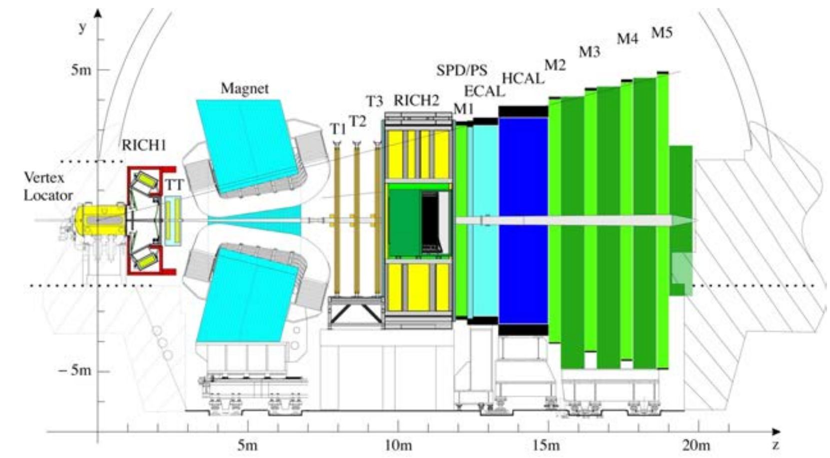
- The **LHCb** detector - acceptance for pseudorapidities $2 < \eta < 4.5$.

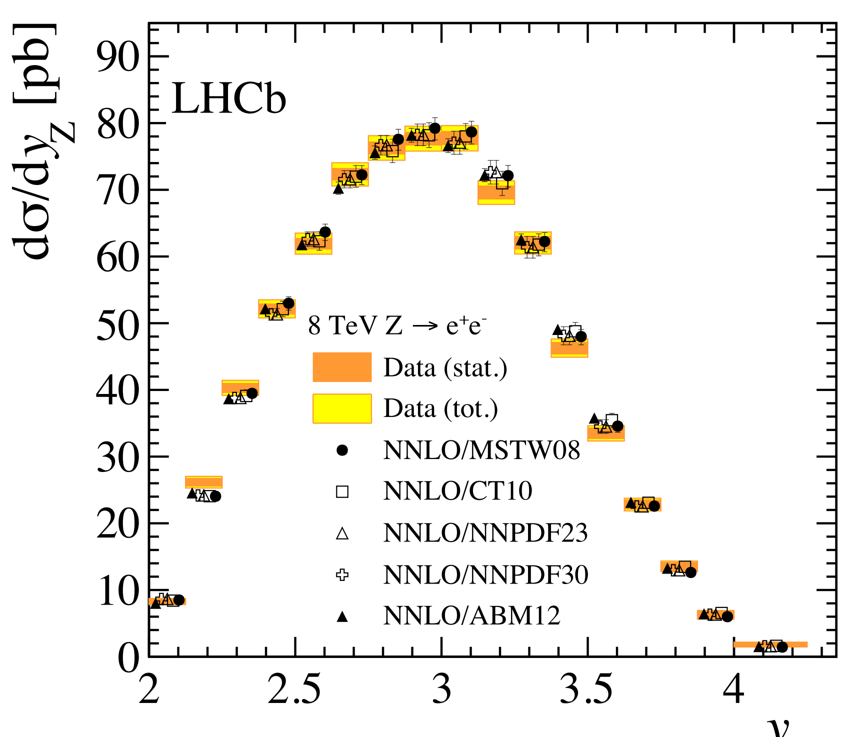
ATLAS, CMS: $|\eta| \lesssim 2.5$

$\rightarrow$ LHCb data on forward Drell-Yan production provides unique LHC sensitivity from low to high $10^{-4} \lesssim x \lesssim 1$.



LHCb collab., JHEP 1610 (2016) 30





LHCb collab., JHEP 1505 (2015) 109

PDFs at the LHC

LHC data for PDF determination

- LHC now producing wide range of precise data for PDF determination. Already having a **major impact** on global fits.
- **Drell-Yan** has significant role, but many other processes included, and new studies ongoing - a few examples follow!

New datasets in NNPDF3.1

Measurement	Data taking	Motivation
Combined HERA inclusive data	Run I+II	quark singlet and gluon
D0 legacy W asymmetries	Run II	quark flavor separation
ATLAS inclusive W, Z rap 7 TeV	2011	strangeness
ATLAS inclusive jets 7 TeV	2011	large-x gluon
ATLAS low-mass Drell-Yan 7 TeV	2010+2011	small-x quarks
ATLAS Z pT 7,8 TeV	2011+2012	medium-x gluon and quarks
ATLAS and CMS tt differential 8 TeV	2012	large-x gluon
CMS Z (pT,y) 2D xsecs 8 TeV	2012	medium-x gluon and quarks
CMS Drell-Yan low+high mass 8 TeV	2012	small-x and large-x quarks
CMS W asymmetry 8 TeV	2012	quark flavor separation
CMS 2.76 TeV jets	2012	medium and large-x gluon
LHCb W,Z rapidity dists 7 TeV	2011	large-x quarks
LHCb W,Z rapidity dists 8 TeV	2012	large-x quarks

CT17p — data to be included

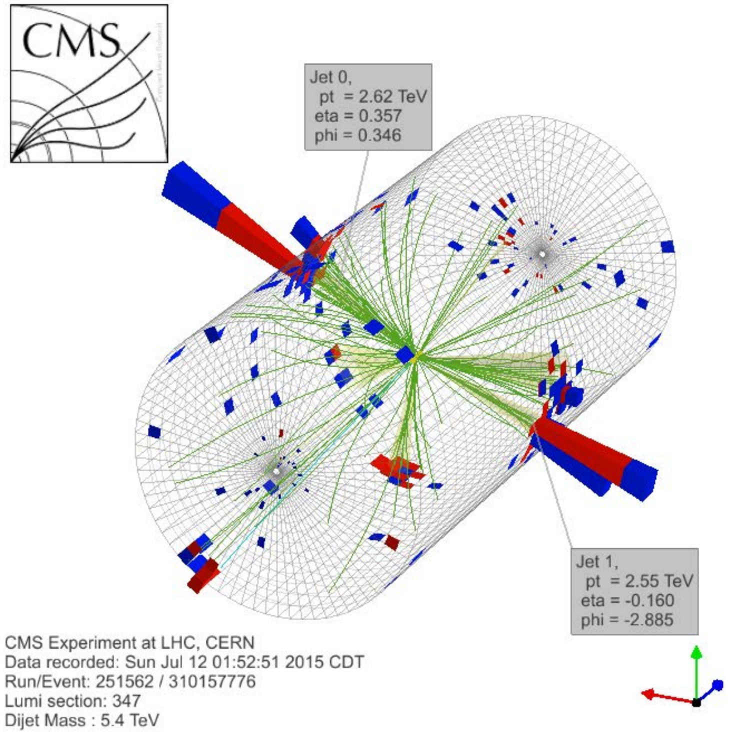
- Previous LHC and HERA 1 data included in CT14 will be superseded by updated Run 1 and HERA 1+2 data; adding new LHC data, especially on Z boson p_T and top quark differential distributions
  - Combined HERA1+2 DIS [1506.06042] update
  - LHCb 7 TeV Z, W muon rapidity dist. [1505.07024] update
  - LHCb 8 TeV Z rapidity dist. [1503.00963] update
  - ATLAS 7 TeV inclusive jet [1410.8857] update
  - CMS 7 TeV inclusive jet (extended y range)[1406.0324] update
  - ATLAS 7 TeV Z pT dist. [1406.3660] new
  - LHCb 13 TeV Z rapidity dist. [1607.06495] update
  - CMS 8 TeV Z pT and rapidity dist. (double diff.) [1504.03511] new
  - CMS 8 TeV W, muon asymmetry dist. [1603.01803] update
  - ATLAS 7 TeV W/Z, lepton(s) rapidity dist. [1612.03016] update
  - CMS 7,8 TeV tT differential distributions new
  - ATLAS 7,8 TeV tT differential distributions new

MMHT (2016 fit)

	no. points	NLO χ^2_{pred}	NLO χ^2_{new}	NNLO χ^2_{pred}	NNLO χ^2_{new}
$\sigma_{t\bar{t}}$ Tevatron +CMS+ATLAS	18	19.6	20.5	14.7	15.5
LHCb 7 TeV $W+Z$	33	50.1	45.4	46.5	42.9
LHCb 8 TeV $W+Z$	34	77.0	58.9	62.6	59.0
LHCb 8TeV e	17	37.4	33.4	30.3	28.9
CMS 8 TeV W	22	32.6	18.6	34.9	20.5
CMS 7 TeV $W+c$	10	8.5	10.0	8.7	8.0
D0 e asymmetry	13	22.2	21.5	27.3	25.8
total	3738/3405	4375.9	4336.1	3741.5	3723.7

Taken from DIS'17

Jet production



- At the LHC, **jet** production is dominated by the **gluon-initiated** parton-level processes:

$$gg \to gg,\ gg \to q\bar{q},\ gq \to gq,\ q\bar{q} \to gg\ ,$$

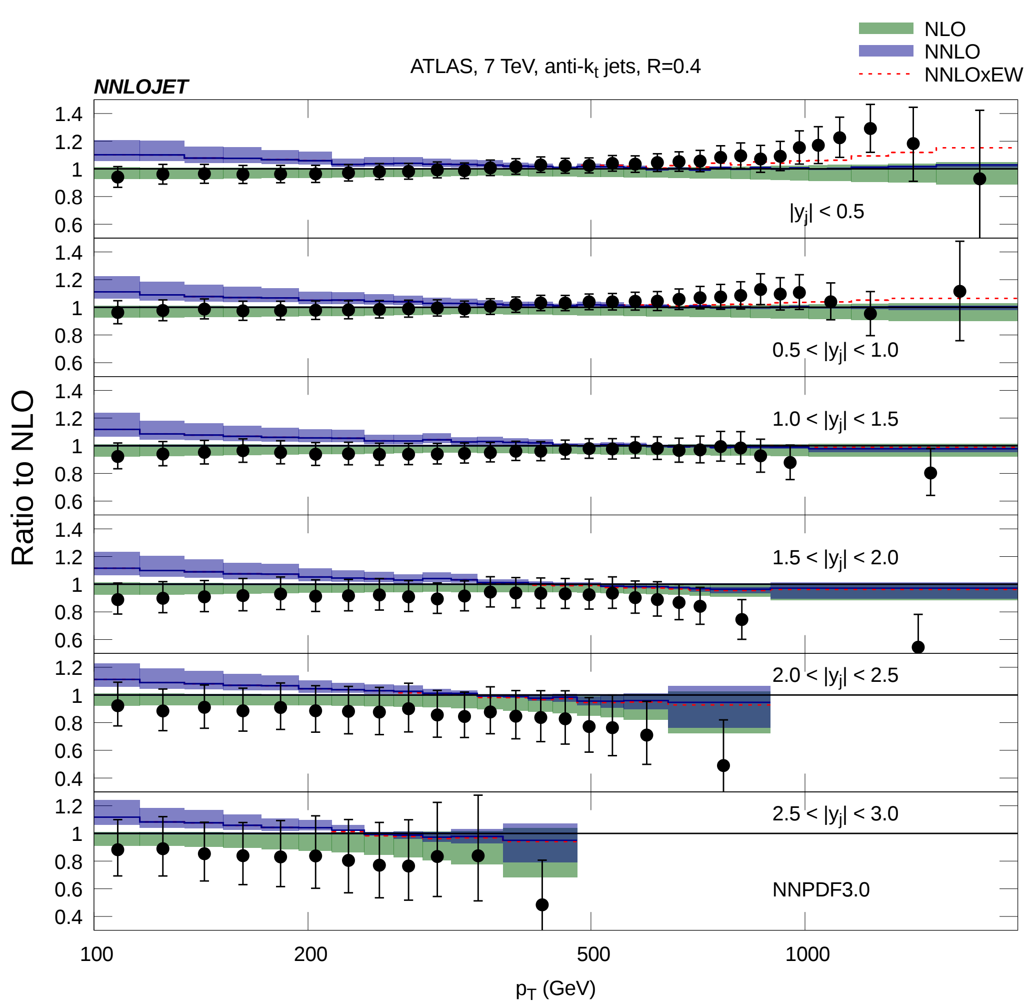
- Kinematics: $$x_1 = \frac{p_T}{\sqrt{s}}(e^{y_1} + e^{y_2}), \quad x_2 = \frac{p_T}{\sqrt{s}}(e^{-y_1} + e^{-y_2})\ ,$$

$\longrightarrow$ Data on jets at high transverse momenta, $p_\perp$, sensitive to **gluon PDF** at high x .

- Gluon at high x is both important for **BSM searches** and quite **poorly constrained** from DIS $\Rightarrow$ LHC data such as jet production plays crucial role in PDF determination.

NNLO jet calculation

- Full **NNLO** calculation for inclusive jet production in hadron-hadron collisions now **available**. Completion of large scale, long term project.
- Combined with availability of **high precision jet data** from ATLAS/CMS $\rightarrow$ can consider the impact on a NNLO fit for first time!



NNLO QCD predictions for single jet inclusive production at the LHC

J. Currie[a], E.W.N. Glover[a], J. Pires[b]
[a] *Institute for Particle Physics Phenomenology, University of Durham, Durham DH1 3LE, England*
[b] *Max-Planck-Institut für Physik, Föhringer Ring 6 D-80805 Munich, Germany*

We report the first calculation of fully differential jet production in all partonic channels at next-to-next-to leading order (NNLO) in perturbative QCD and compare to the available ATLAS 7 TeV data. We discuss the size and shape of the perturbative corrections along with their associated scale variation across a wide range in jet transverse momentum, p_T, and rapidity, y. We find significant effects, especially at low p_T, and discuss the possible implications for Parton Distribution Function fits.

J. Currie et al., Phys.Rev.Lett. 118 (2017) no.7, 072002

NNLO jet impact

- **Recent MMHT study** - inclusion of ATLAS + CMS 7 TeV jet data in full NNLO fit.

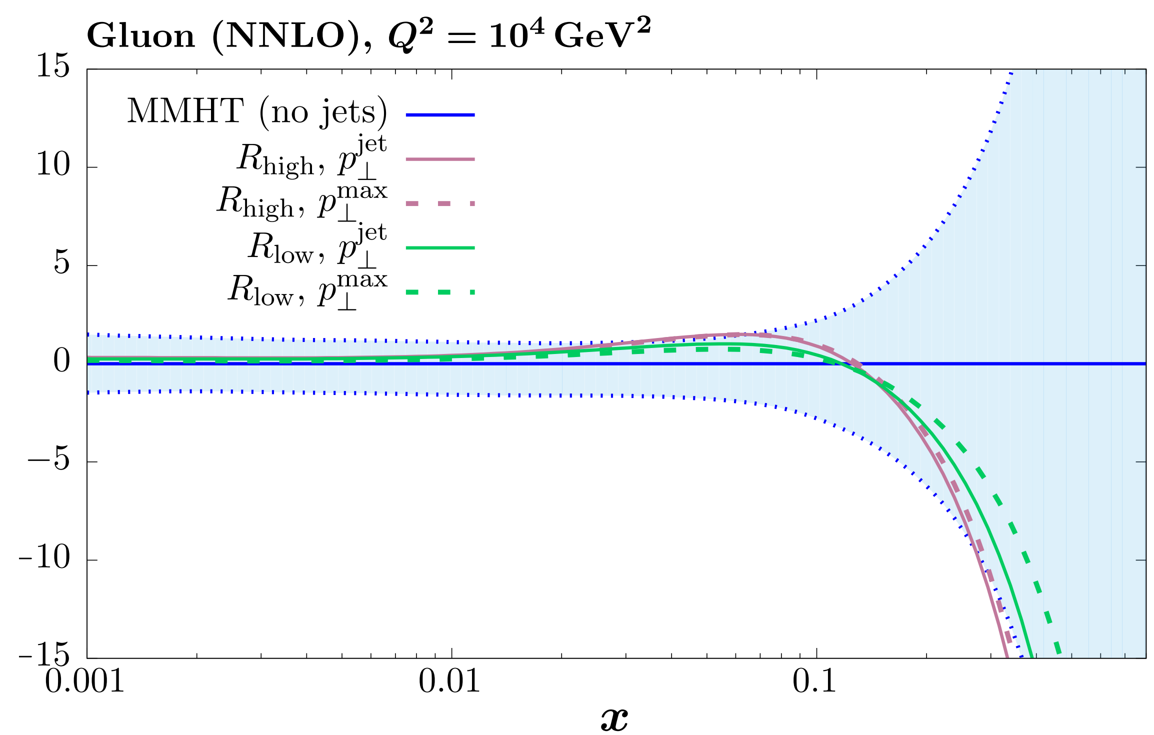
- **Improvement** in description from **NLO** to **NNLO** - pQCD working as it should.

χ^2

	NLO theory	NNLO
ATLAS, $R_{\rm low}$	215.3	172.3
ATLAS, $R_{\rm high}$	159.2	149.8
CMS, $R_{\rm low}$	194.2	177.8
CMS, $R_{\rm high}$	198.5	182.3

- Results stable with different choices of factorization/ renormalization scale and jet radius.

- Find softer gluon at high x, with ~20-50% lower uncertainty.



A.D. Martin et al., arXiv:171105757

Differential Top

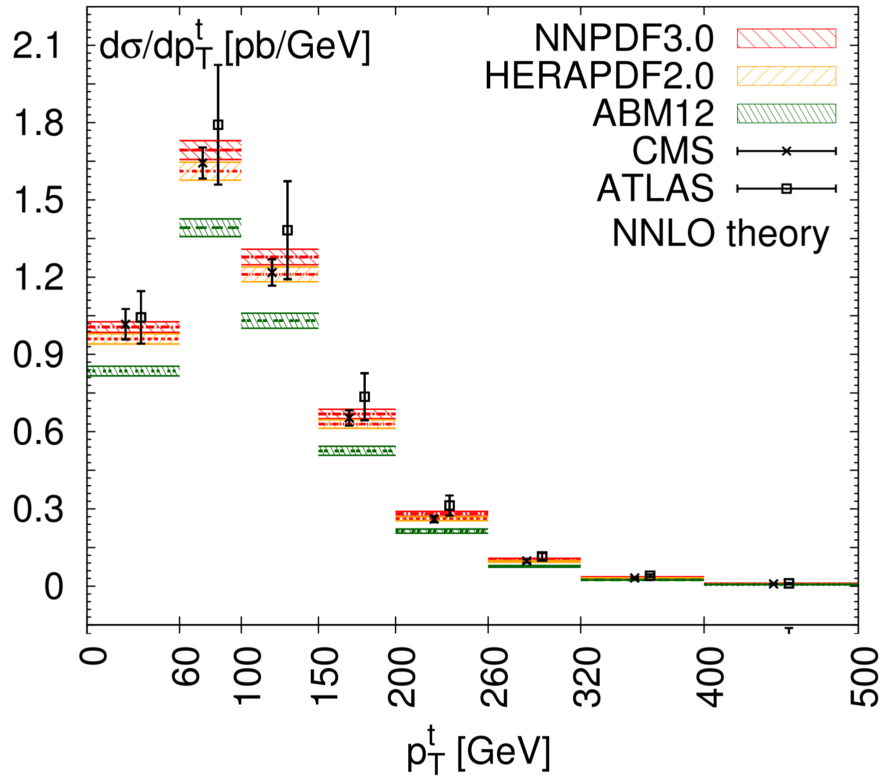
- Top quark pair production at LHC dominated by $gg \to t\bar{t}$ - by going to high $m_{t\bar{t}}, p_\perp^t$ probe gluon at high x.
- We have:

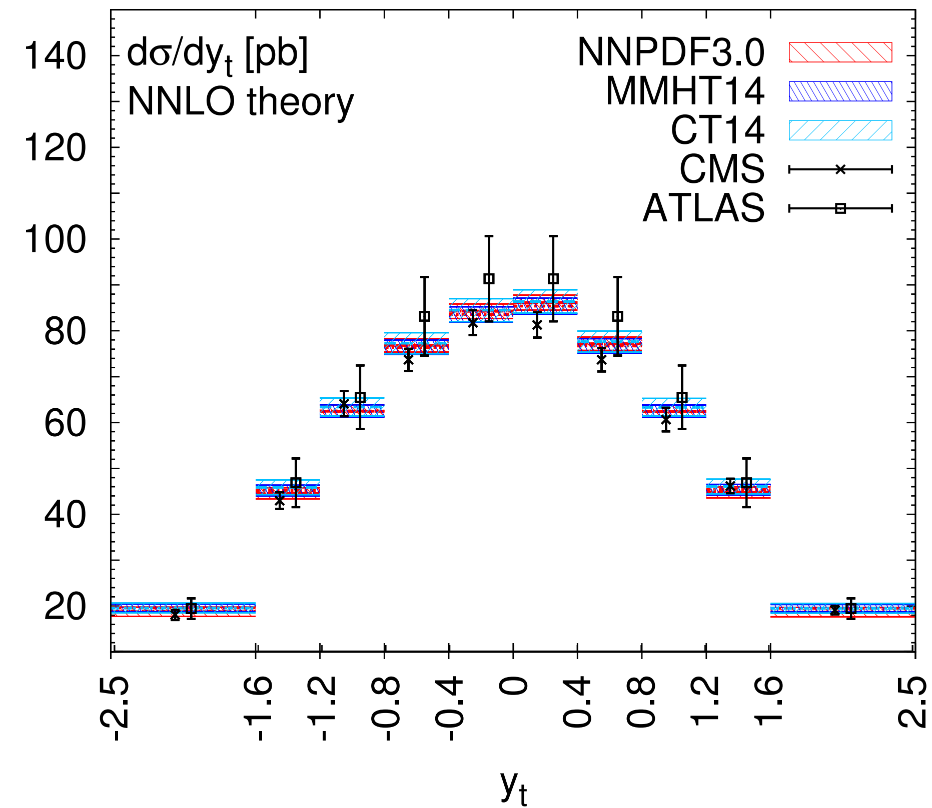
M. Czakon et al., Phys. Rev. Lett. 116 (2016) no.8, 082003

  - Recent **NNLO** calculation for differential top production.
  - ATLAS/CMS data now available with sufficient **precision** to present differentially.

$\longrightarrow$ Can now include in fits for first time.

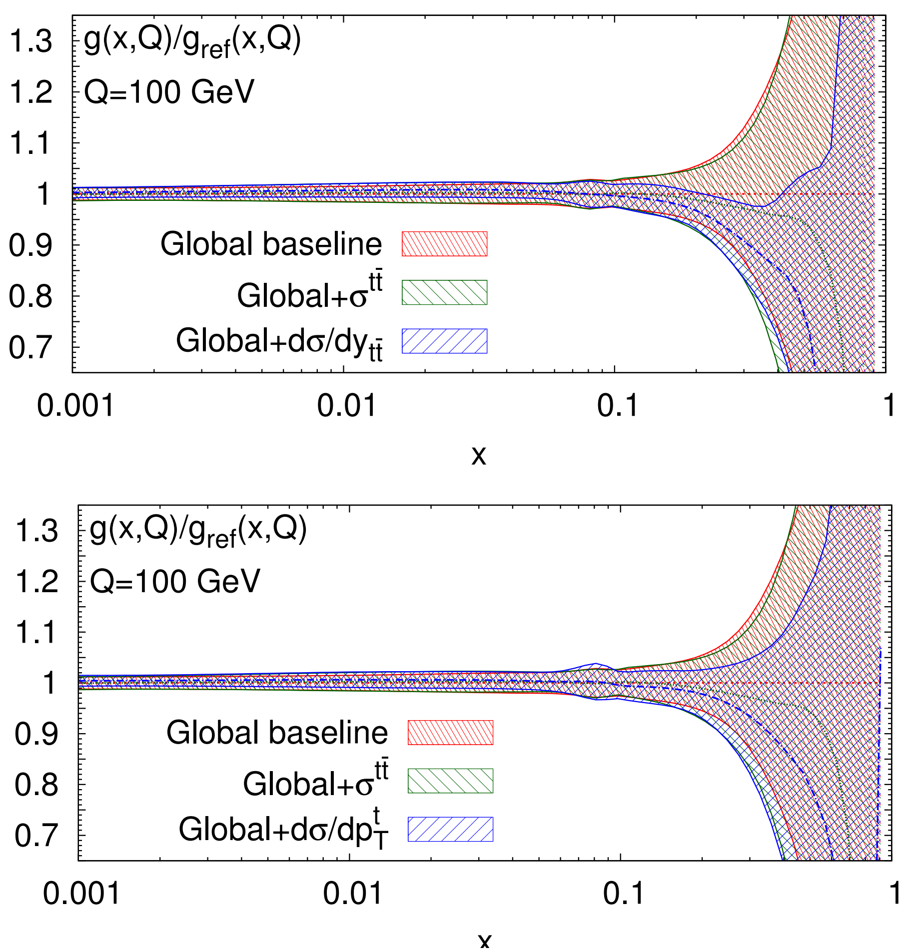
M. Czakon et al., JHEP 1704 (2017) 044



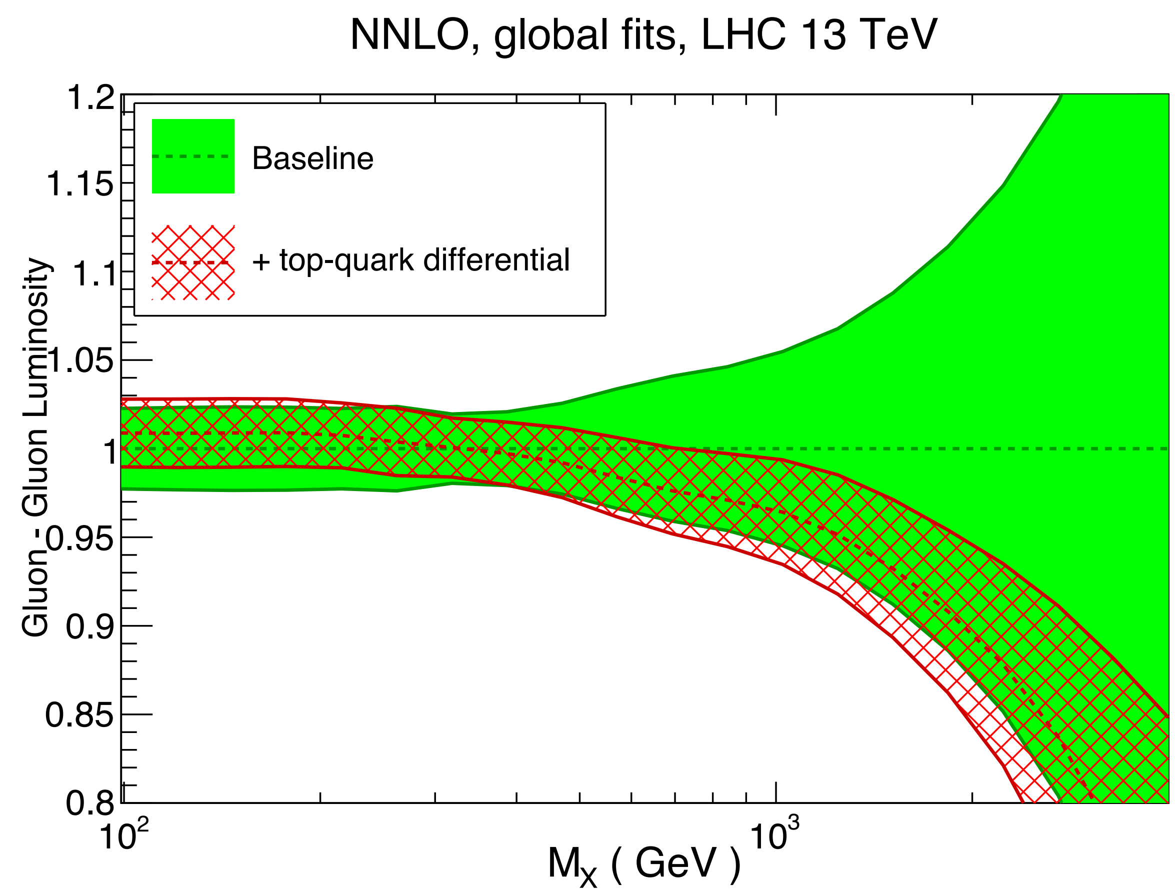


Impact on PDFs

- Dedicated study (**NNPDF** + collaborators) - consider impact of ATLAS/CMS 8 TeV $t\bar{t}$ differential data on gluon.
- Find that top rapidity ($y_t, y_{t\bar{t}}$) distributions have biggest impact on high gluon. Less sensitive to any BSM effects in high $m_{t\bar{t}}$ tail.



M. Czakon et al., JHEP 1704 (2017) 044

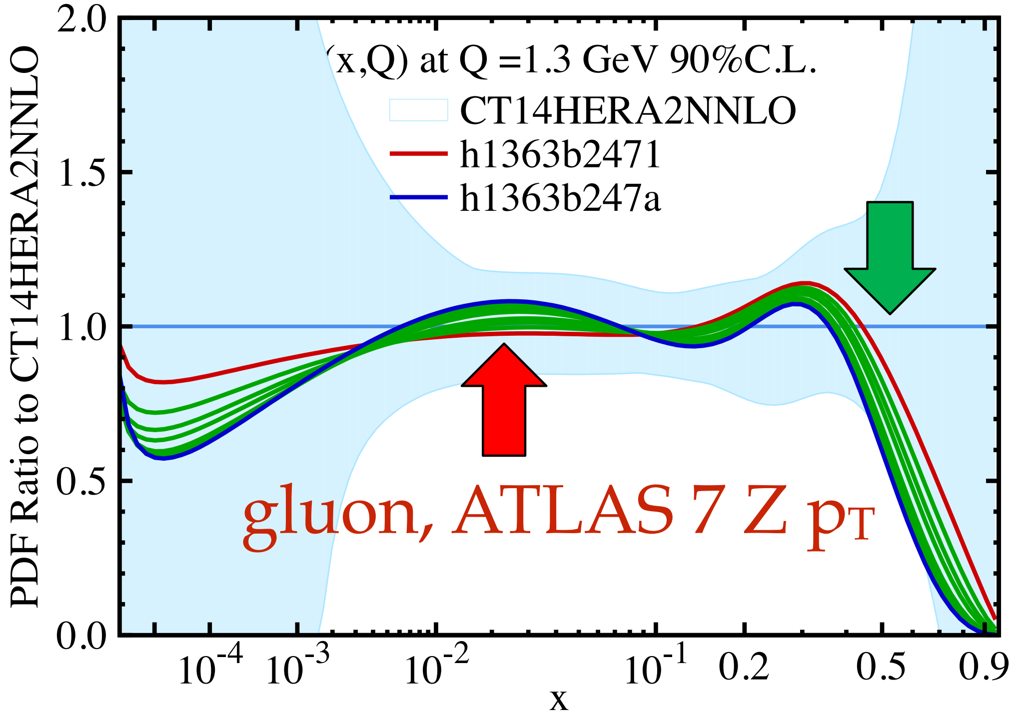


Other Processes

- To give a flavour, two other nice examples in the **Drell-Yan family**…

J. Gao, "Progress on CTEQ-TEA PDFs", DIS2017

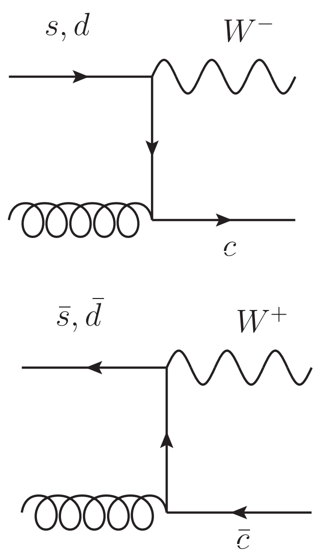
CT17p best-fit vs. CT14 HERA2

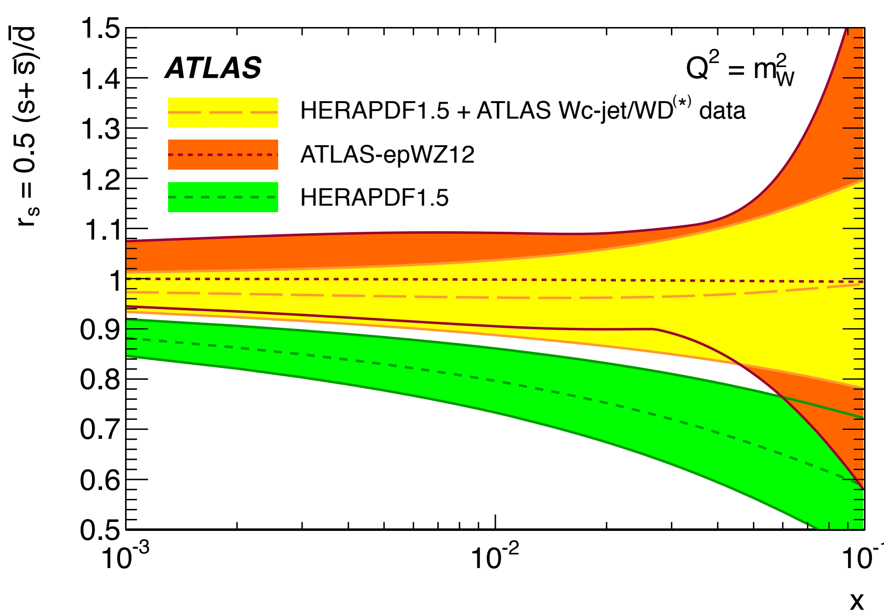


- **W+ charm quark**. More direct probe of proton strangeness. Data from ATLAS/CMS at both parton and hadron level.

- ***Z* boson $p_\perp$ distribution**. Sensitive to gluon at high $p_\perp$. New NNLO calculation allows constraints on PDFs at this order.

Boughezal et al., Phys. Rev. Lett. 116 (2016) no 15 152001





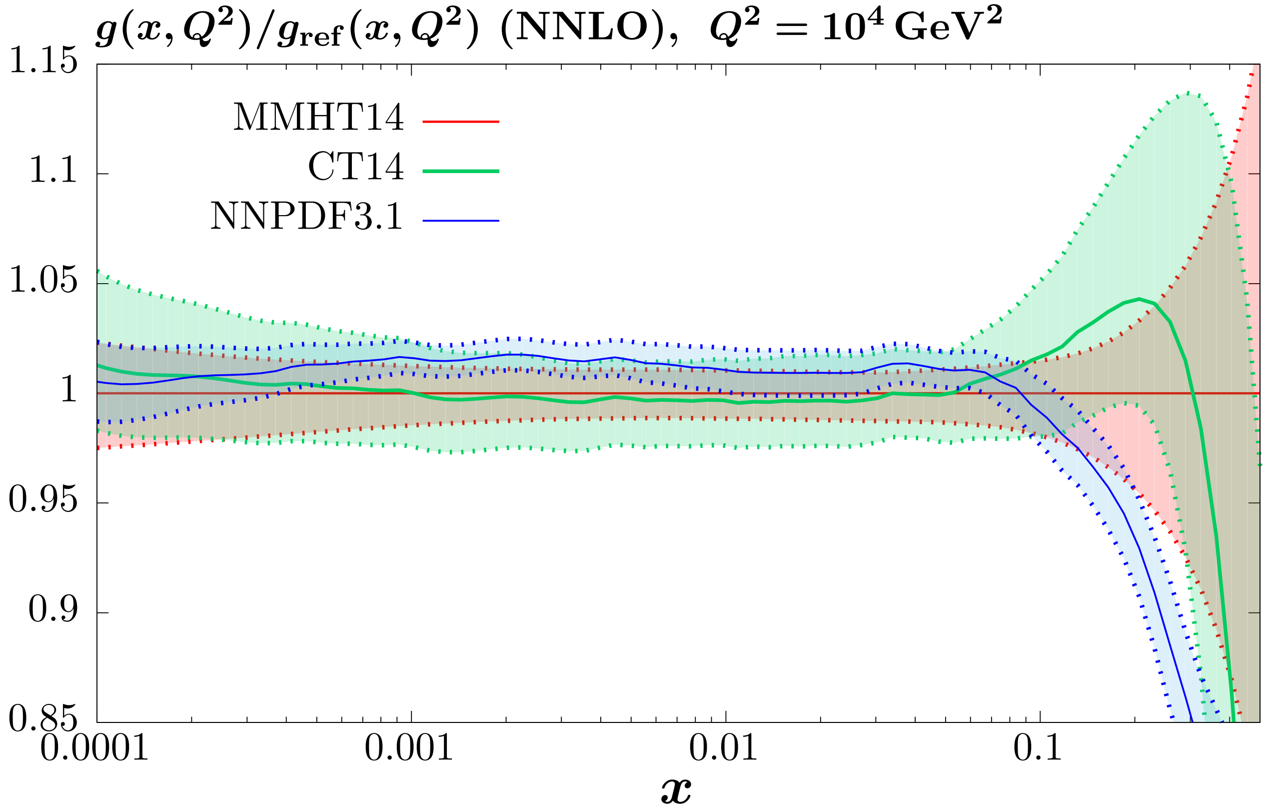
ATLAS Collab., JHEP 1405 (2014) 068

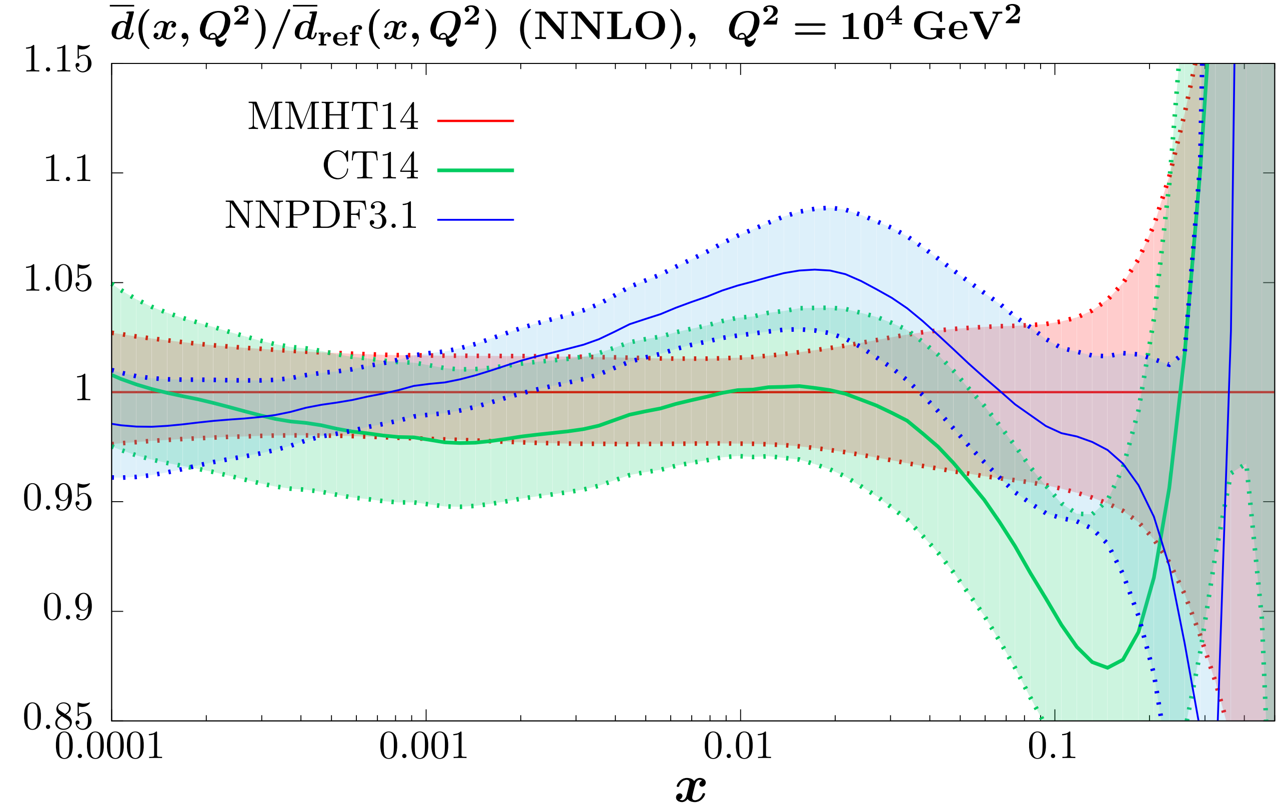
Where do we Stand?

- Gluon:
  - Despite varying approaches, global fits ~ **consistent** (not true in past). Uncertainties $\sim 2\%$ in some regions.
  - Biggest difference at high x, with NNPDF3.1 lower - includes more LHC data ($t\bar{t}$, jets…). Expect updates from other groups soon.

- $\bar{d}$:
  - **More variation**, in particular at high x (less constraints), more sensitive to methodological differences in this region.

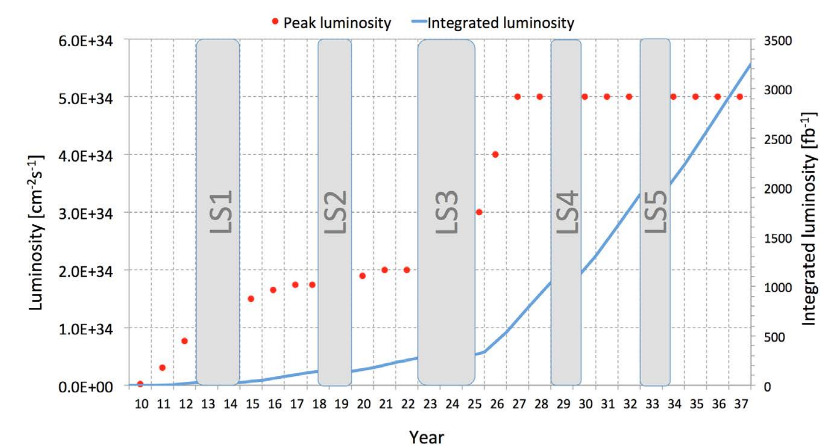
- Reasonable agreement for other PDFs. Not perfect - **still work to do**.



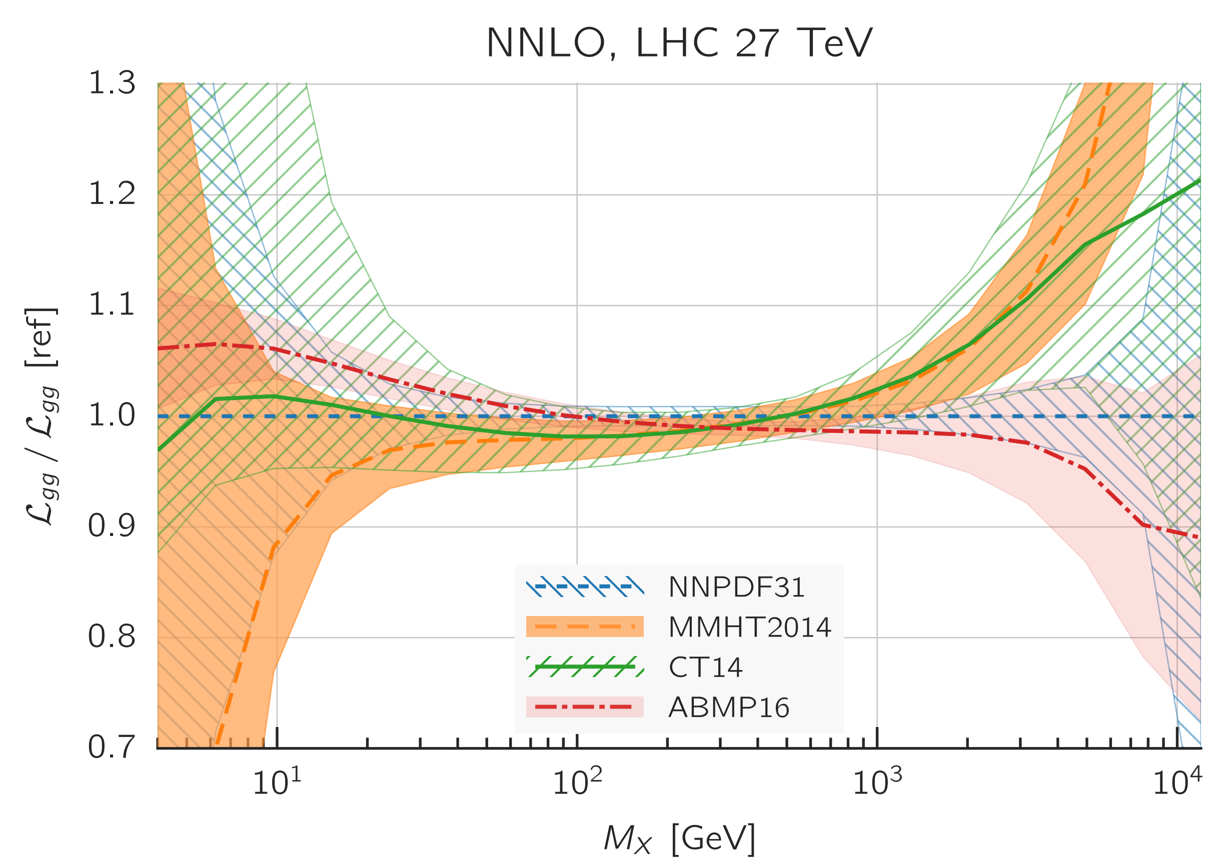


Looking to the Future

- Many years of **HL-LHC** running ahead:
  - How precisely can we expect future data to constrain PDFs? Studies underway.
  - New questions becoming important - EW corrections, theory uncertainties, resummation (low x limit)…
  - NNLO the standard - new tools needed?



- Proposal to run at ~27 TeV following upgrade- `**HE-LHC**'. Again new questions from larger coverage in x, Q^2.



Recent review summarising our current knowledge of the proton in the high precision LHC era. Please have a look if you would like to learn more:

The Structure of the Proton in the LHC Precision Era

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[b] *Department of Physics and Astronomy, University College London, WC1E 6BT, United Kingdom*
[c] *Department of Physics and Astronomy, VU University, De Boelelaan 1081, 1081HV Amsterdam, The Netherlands*
[d] *Nikhef, Science Park 105, NL-1098 XG Amsterdam, The Netherlands*

Abstract

We review recent progress in the determination of the parton distribution functions (PDFs) of the proton,

arXiv:1709.04922

(To appear in
Physics Reports).

- Drell-Yan has played key role in our understanding of proton structure, from early parton model to the high precision LHC era.
- Still a great deal more to learn from the LHC (and Drell-Yan) - stay tuned.

Thank you for listening!