Precision measurements of the structure functions F_2 and F_L at HERA and W and Z cross sections at the LHC

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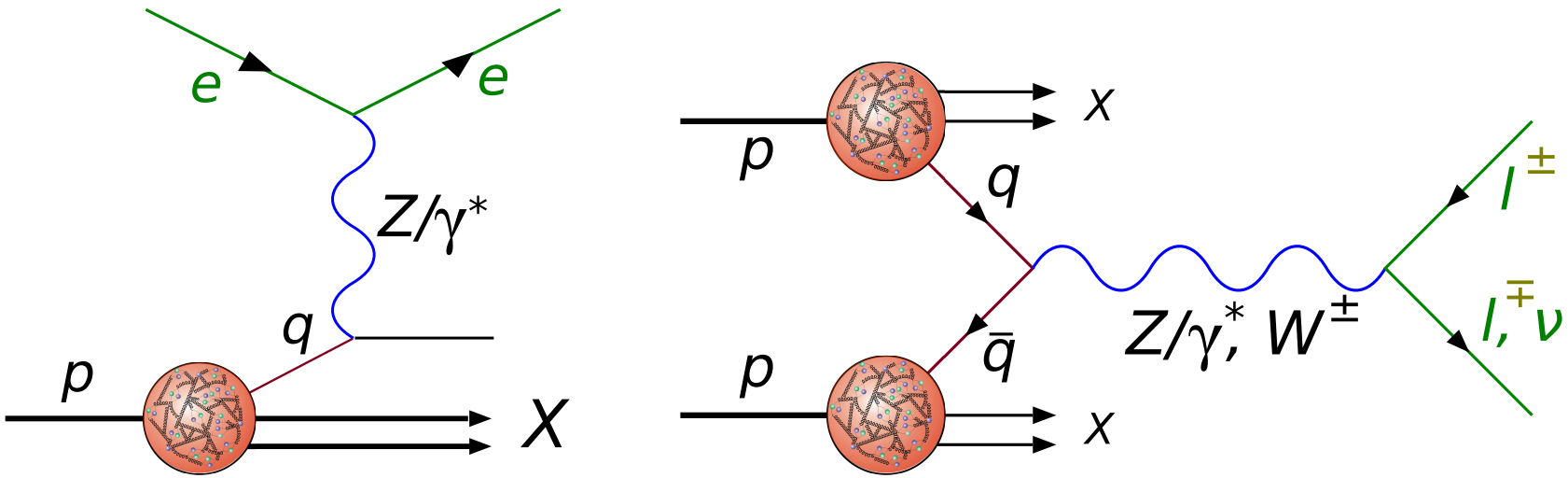
Proton Structure and QCD

- Proton is not a point-like particle: complex structure with *valence quarks*, light and heavy *sea quarks*, and *gluons*
- Proton structure parameterised in terms of *Parton Distribution Functions* (PDFs):
  - A cornerstone of the theory of strong interactions, QCD
  - A fundamental ingredient of any physics in *pp* collisions - factorization theorem
- PDFs primarily determined by *Deep Inelastic Scattering*, complementary information can be obtained from from the *Drell-Yan process* in hadron-hadron collision



- Guido Altarelli's work was connected to these two topics laying the foundation for our understanding of QCD

Inclusive DIS and the DGLAP equations

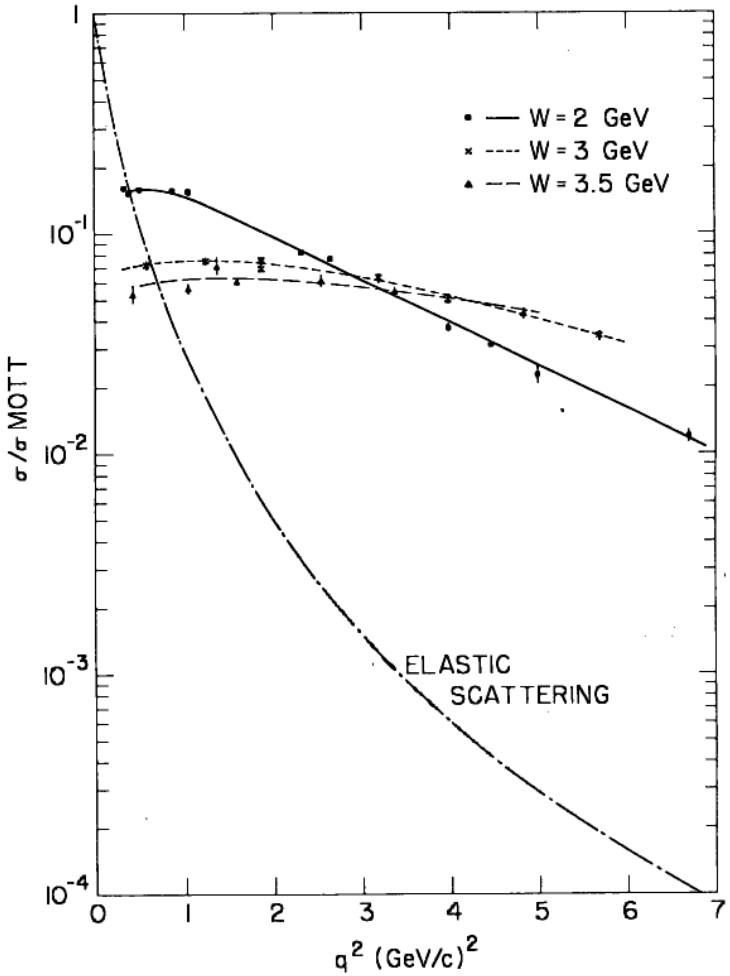
- Double-differential reduced cross section as function of *momentum fraction of the struck parton* x and scale of interaction Q^2 ($\ll m_Z^2$)

$$\sigma_r = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

- At leading order

$$\begin{aligned} F_2(x) &= \sum_i e_i^2 x q_i(x) \\ F_L(x) &= 0 \end{aligned}$$

- Established the Quark-Parton model in early SLAC experiments



Inclusive DIS and the DGLAP equations

- In higher order QCD the evolution of quark $q(x, Q^2)$ and gluon $G(x, Q^2)$ densities with Q^2 of is given by equations as described e.g. in the paper by Altarelli and Parisi (1977) (handwritten from preprint scan):

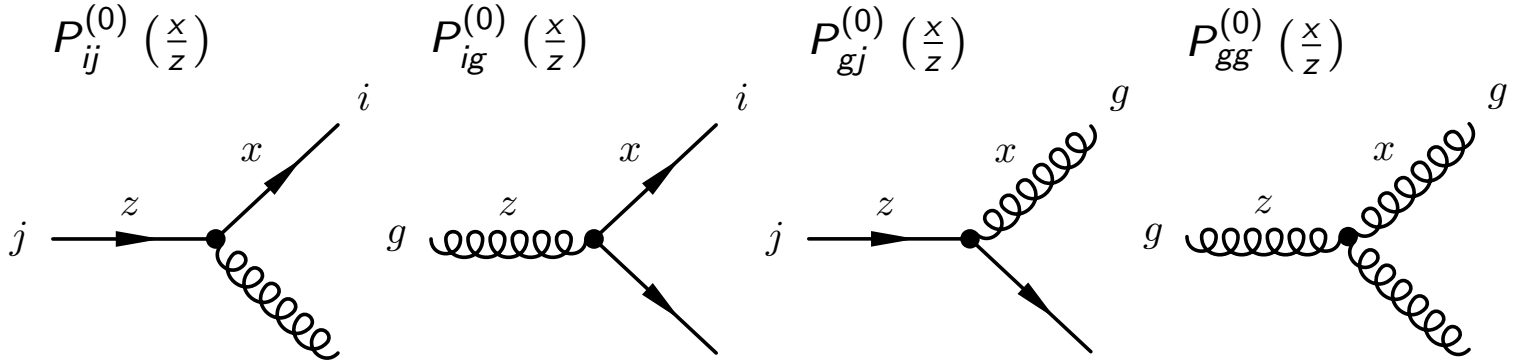
$$\frac{dq^i(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j^{2f} q^j(y,t)\, P_{q^i q^j}\left(\frac{x}{y}\right) + G(y,t)\, P_{q^i G}\left(\frac{x}{y}\right)\right] \qquad (22)$$

$$\frac{dG(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j^{2f} q^j(y,t)\, P_{Gq^j}\left(\frac{x}{y}\right) + G(y,t)\, P_{GG}\left(\frac{x}{y}\right)\right] \qquad (23)$$

$(t = \ln Q^2/Q_0^2)$

  Now commonly referred to as *DGLAP equations*

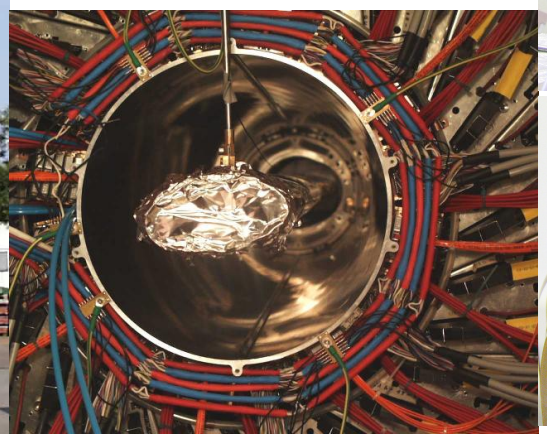
- AP 1977: "In this paper we show that an alternative derivation of all results of current interest for the Q^2 behaviour of deep inelastic structure functions is possible. In this approach all stages of the calculation refer to parton concepts and offer a very illuminating physical interpretation of the scaling violations... all relevant results can be derived in a direct way from the basic vertices of QCD..."

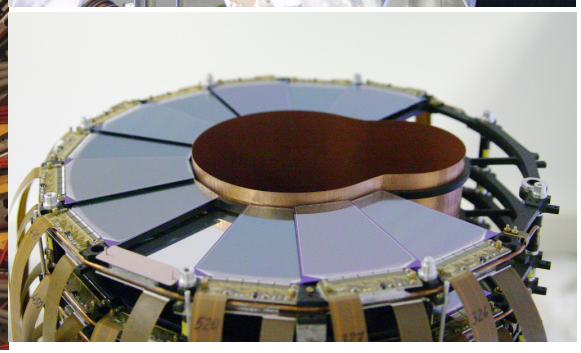


The HERA *ep* Collider

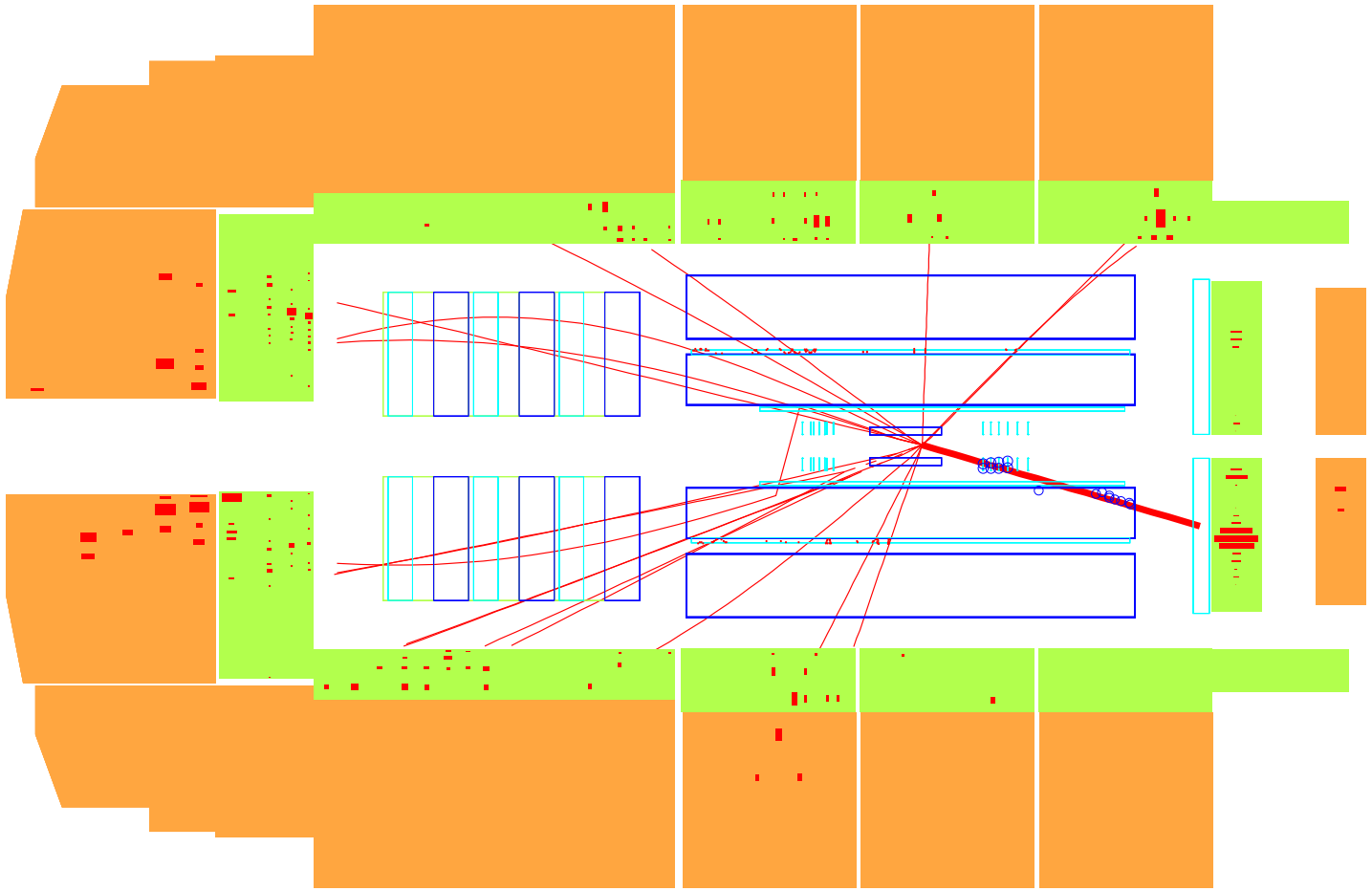
H1 Memories and Silicon Trackers

- Joined the H1 group at DESY Zeuthen in 2003
- Inclusive DIS analyses at low Q^2
- Construction & Repair of dedicated silicon trackers in forward and backward region of H1 (including a track-trigger detector in the backward region)





DIS event in the H1 Detector



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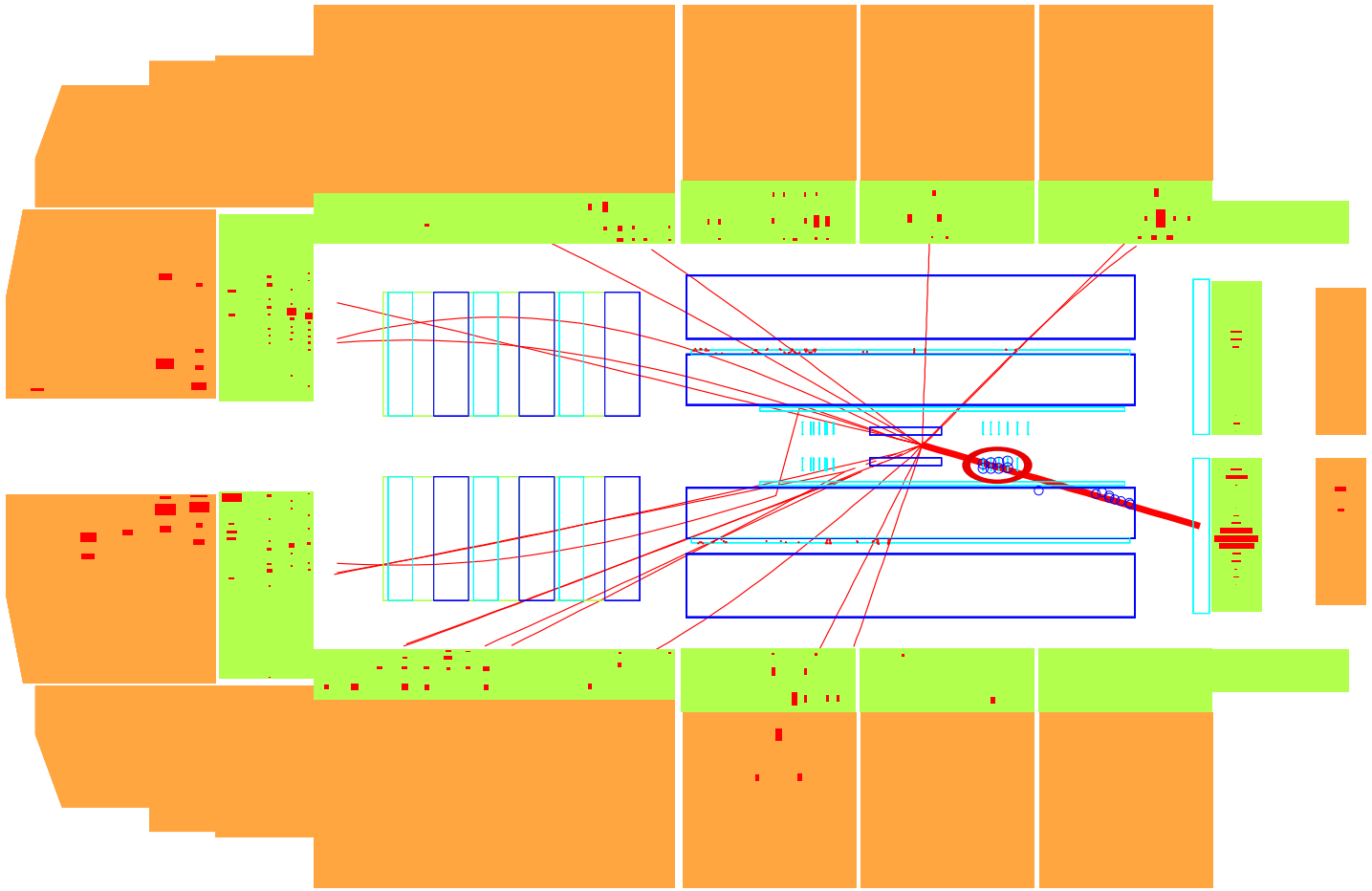
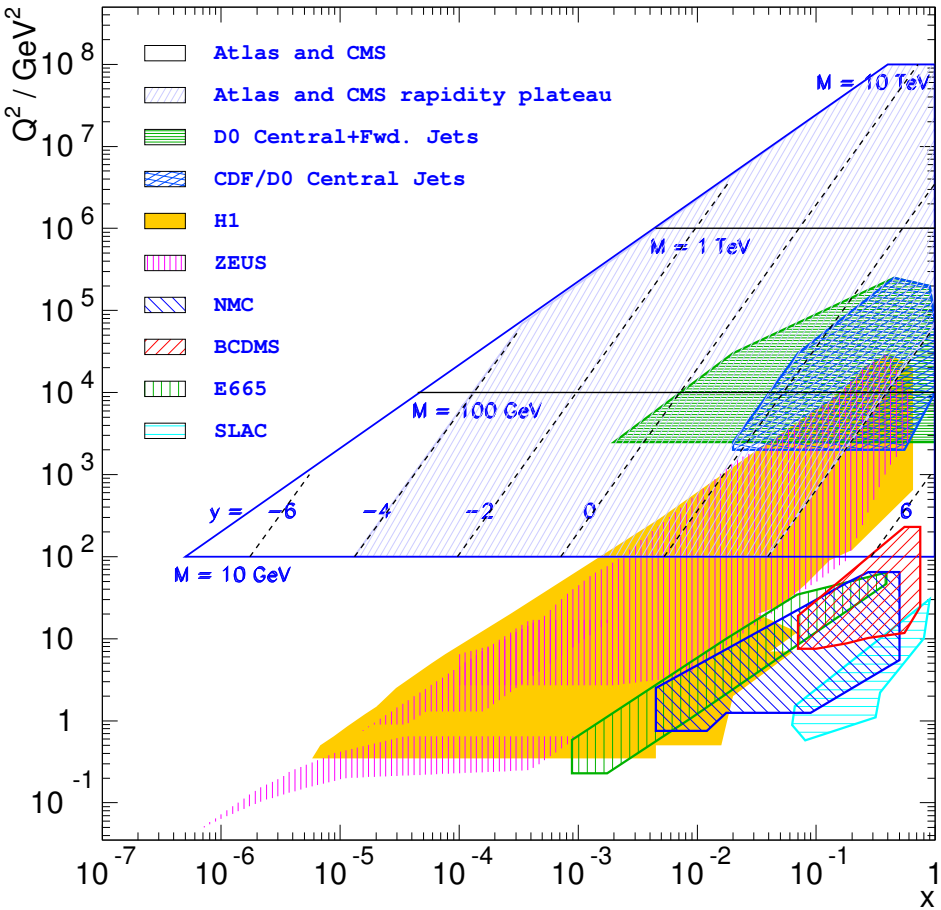
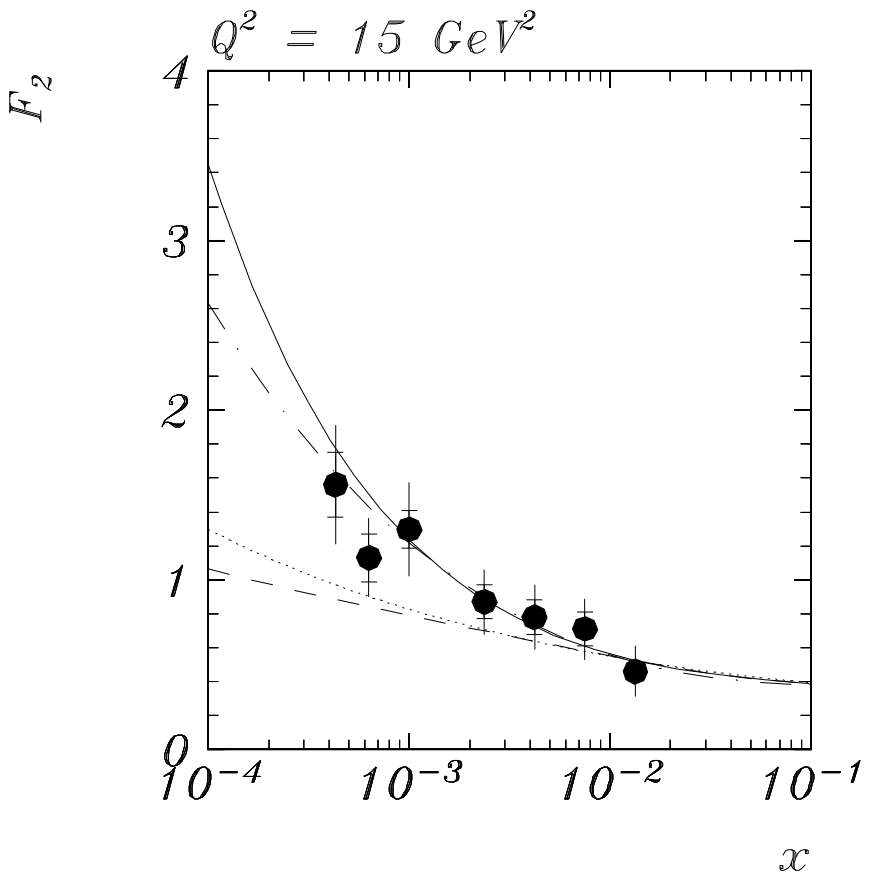


Inclusive DIS at low x

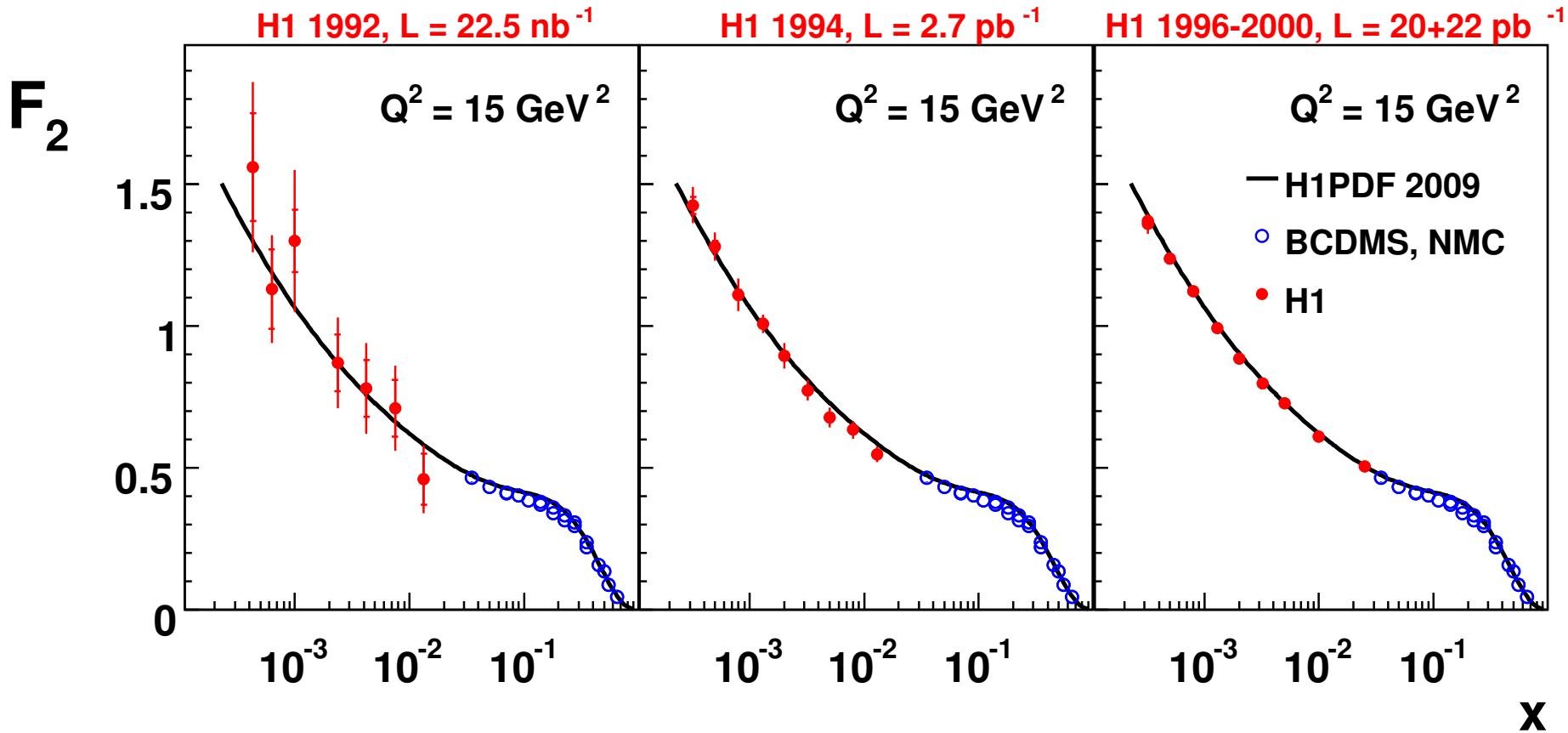
- The HERA collider opened the phase space by > 2 orders of magnitude
- First results in showed a strong rise of F_2 towards low x (e.g. H1 1993)



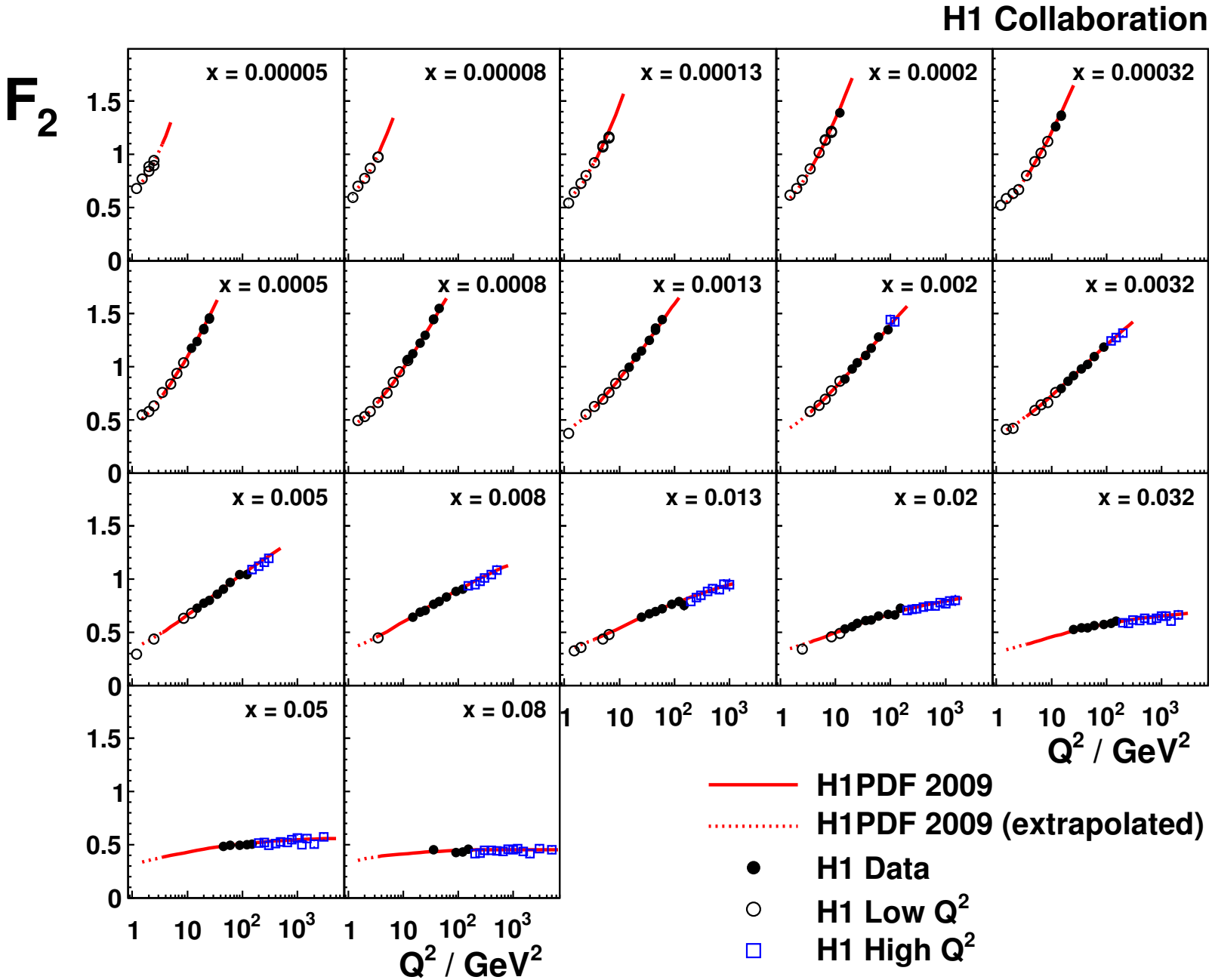


Inclusive DIS at low x

- More data, continuous upgrades of the "backward region" and refined analysis techniques allowed to measure F_2 more precisely
- Analysis of the HERA data from the year 2000 combined with the 1996/97 data increased the precision to $1.3 - 2\%$ (before $2 - 3\%$), H1 2009 "A Precision Measurement of the Inclusive ep Scattering Cross Section at HERA"

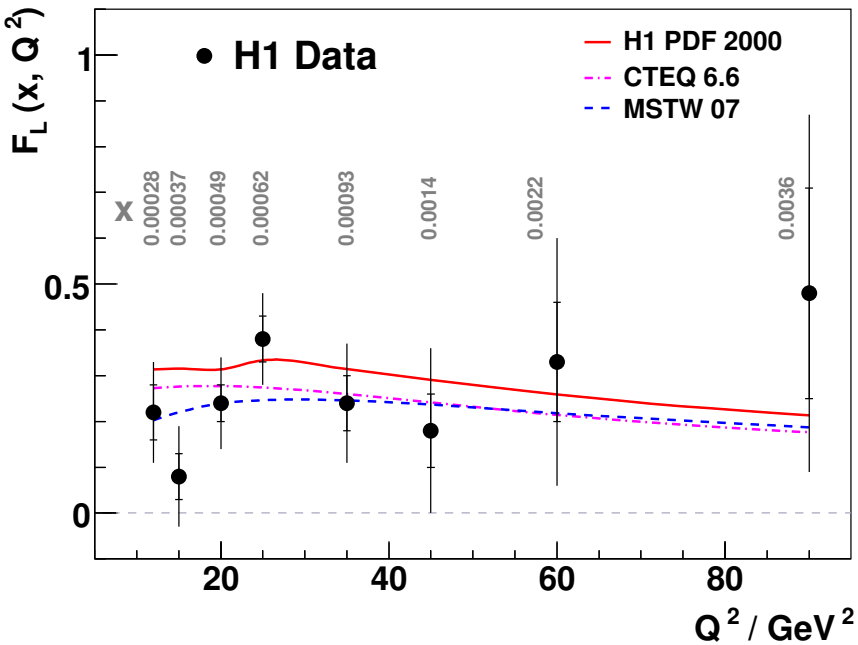


Scaling violations and QCD fit

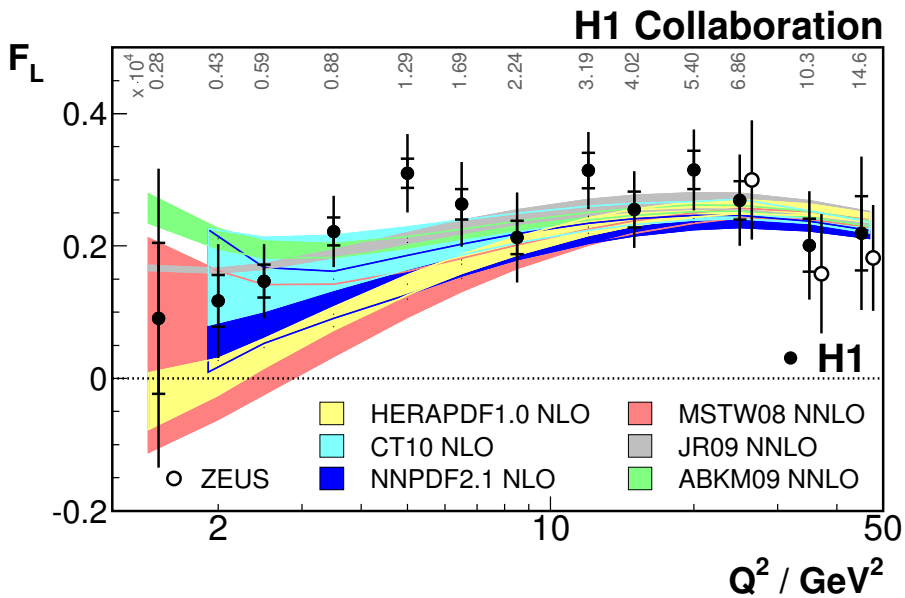


H1 Silicon Tracker and F_L Structure Function

- HERA run at reduced proton beam energies of $E_P = 460$ GeV and $E_P = 575$ GeV enabled the first direct measurement of the structure function F_L at low x
- Upgraded Backward Silicon Tracker crucial to improve electron identification and enable measurement of F_L structure function at low Q^2

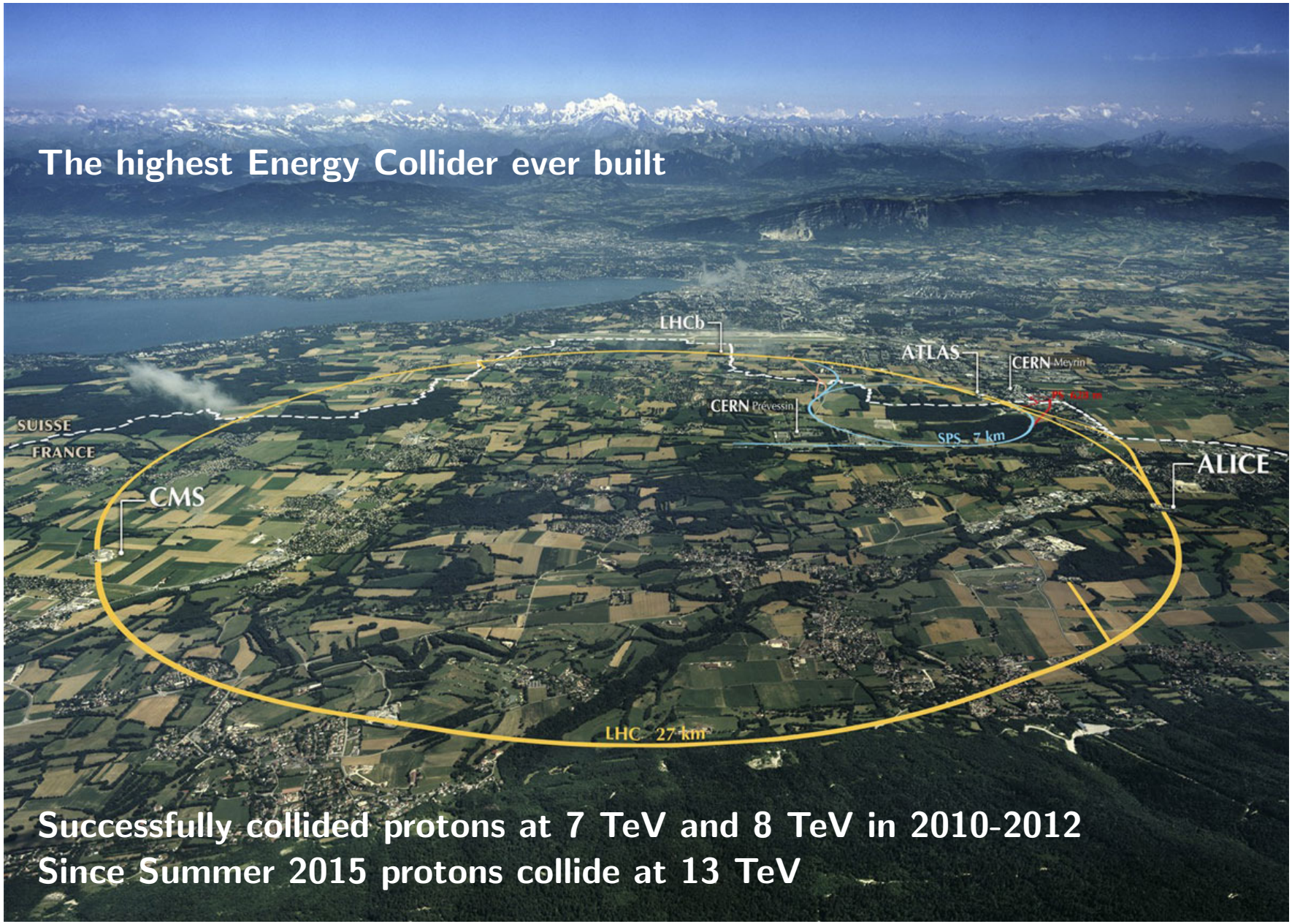


without Backward Silicon Tracker



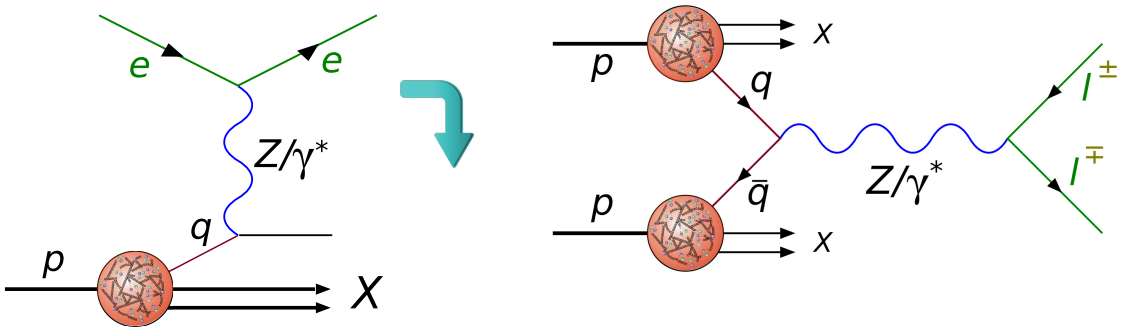
with Backward Silicon Tracker

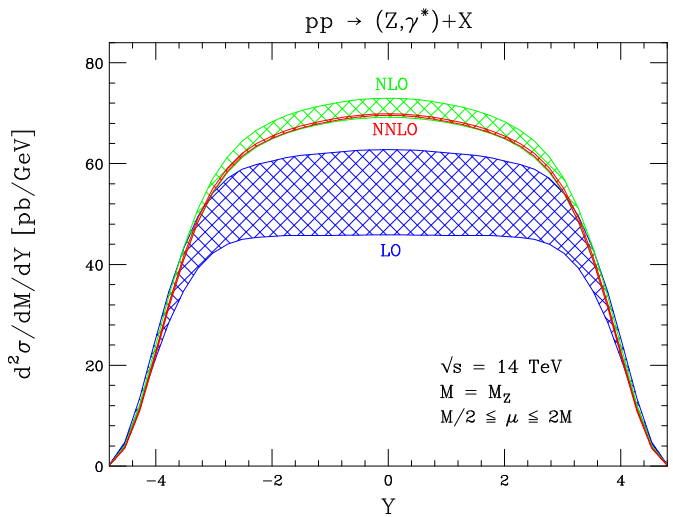
The Large Hadron Collider



From DIS to the Drell-Yan Process

- In 2008 moved to Liverpool to work on ATLAS at the LHC ("Precision Cross Section Measurements and Searches for New Physics")
- The Drell-Yan process in hadron-hadron collisions is closely related to DIS
- Altarelli, Ellis, Martinelli (1979): "The corrections to both these cross sections coming from radiative corrections to the lowest-order $q\bar{q}$ annihilation diagram are found to be large at present values of Q^2 and S when the cross section is expressed in terms of parton densities derived from leptoproduction, for all Drell-Yan processes of practical interest..."
- Subsequent fully differential NNLO calculations make W and Z/γ^* production a tool for precision physics at Hadron Colliders like the LHC

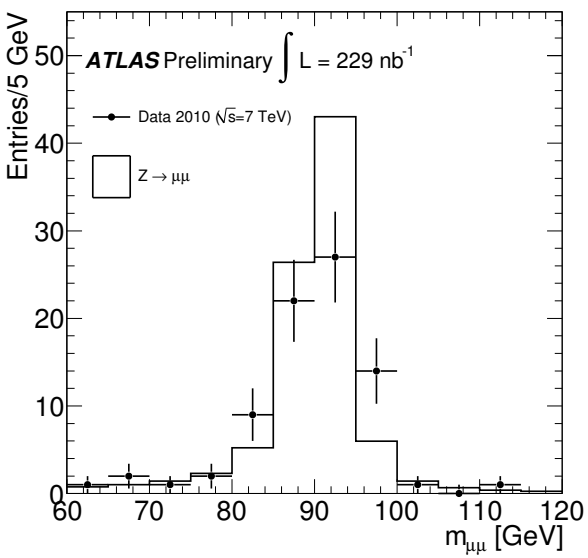




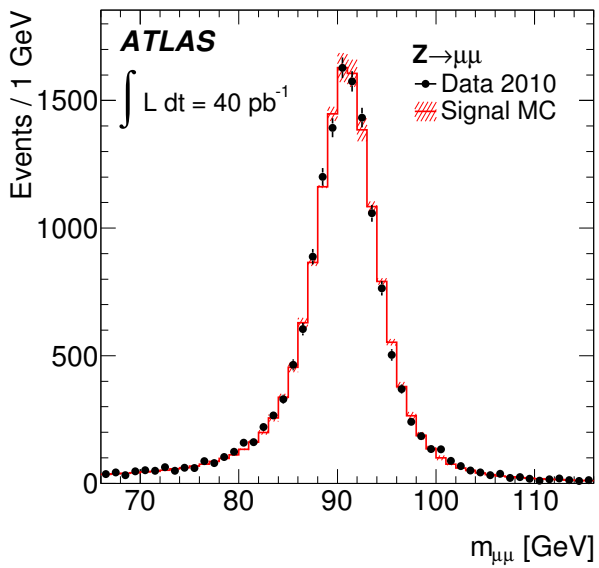
LHC: A W and Z "Factory"

- Leptonic decays of W and Z produce isolated, prompt electrons and muons – a special signature at a pp collider
- E.g. in the 2012 data set
  - $\sim$ 10 million $Z \to \ell\ell$ events per channel
  - $\sim$ 100 million $W \to \ell\nu$ events per channel
- This surpasses by far the samples recorded before at LEP or Tevatron

July 2010



Full 2010 data



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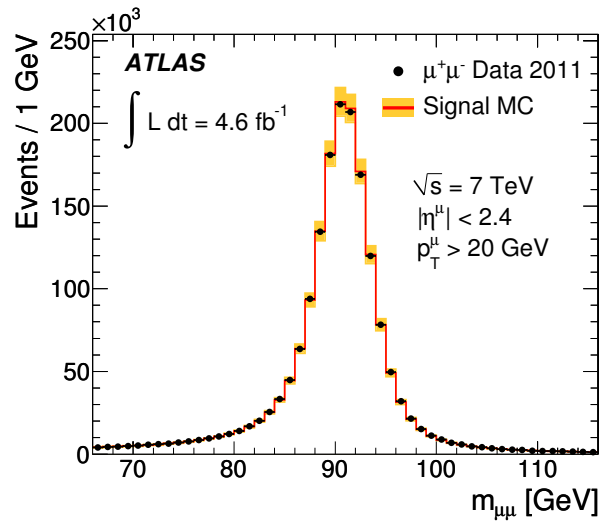

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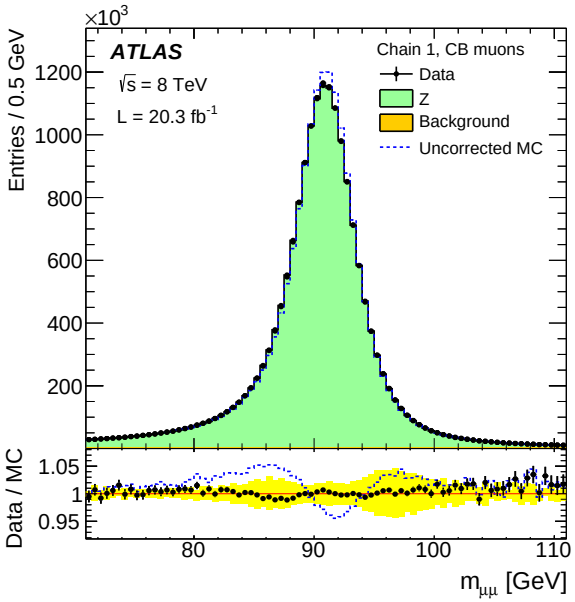
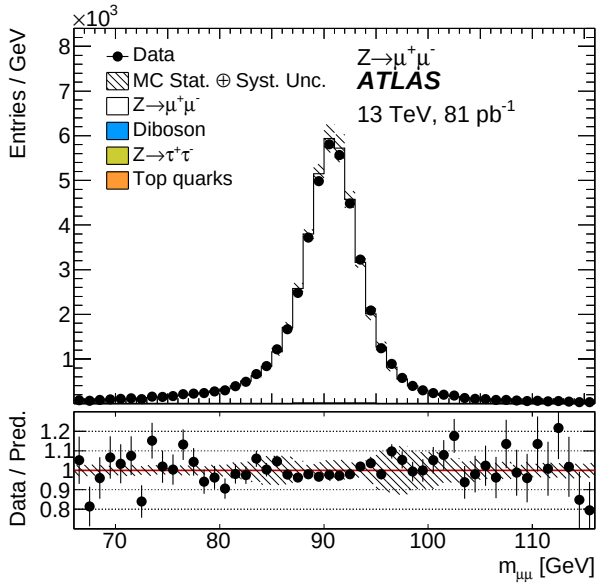
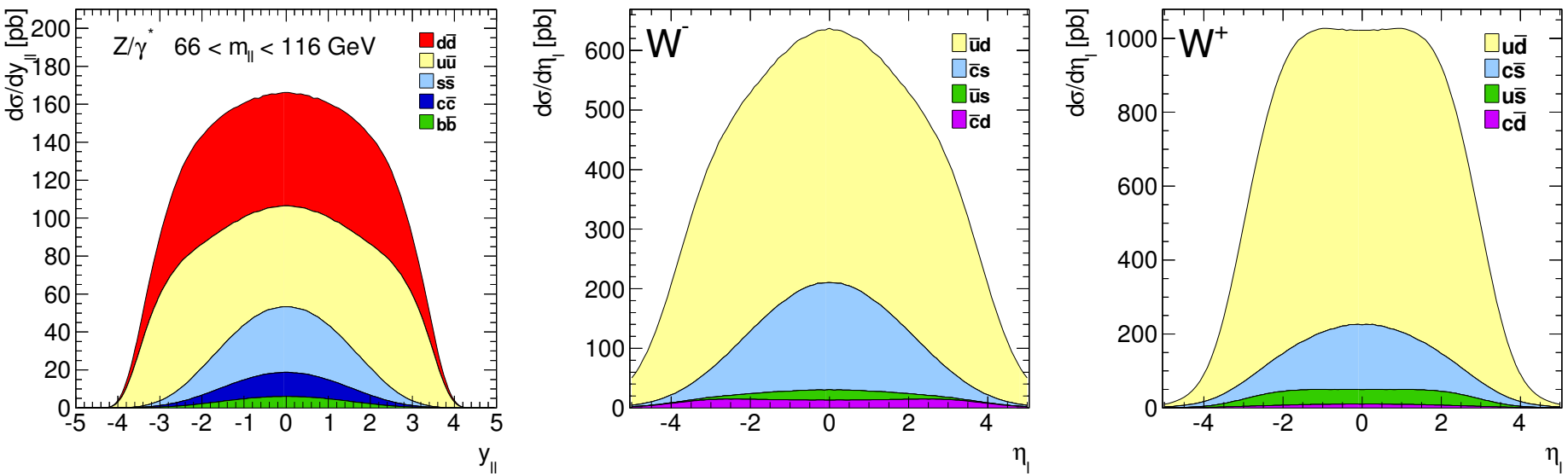


July 2015



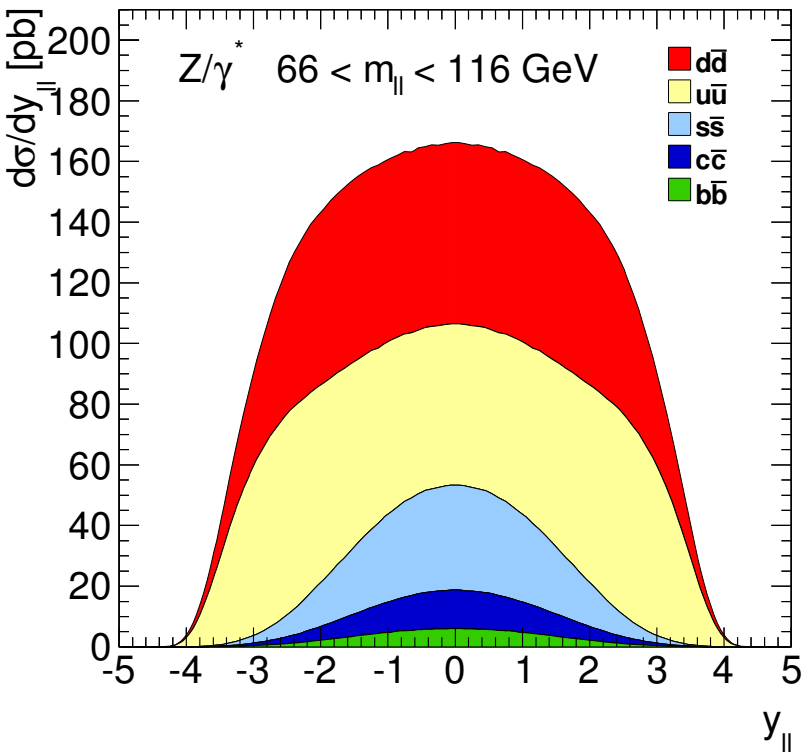
PDFs for W and Z Production at LHC

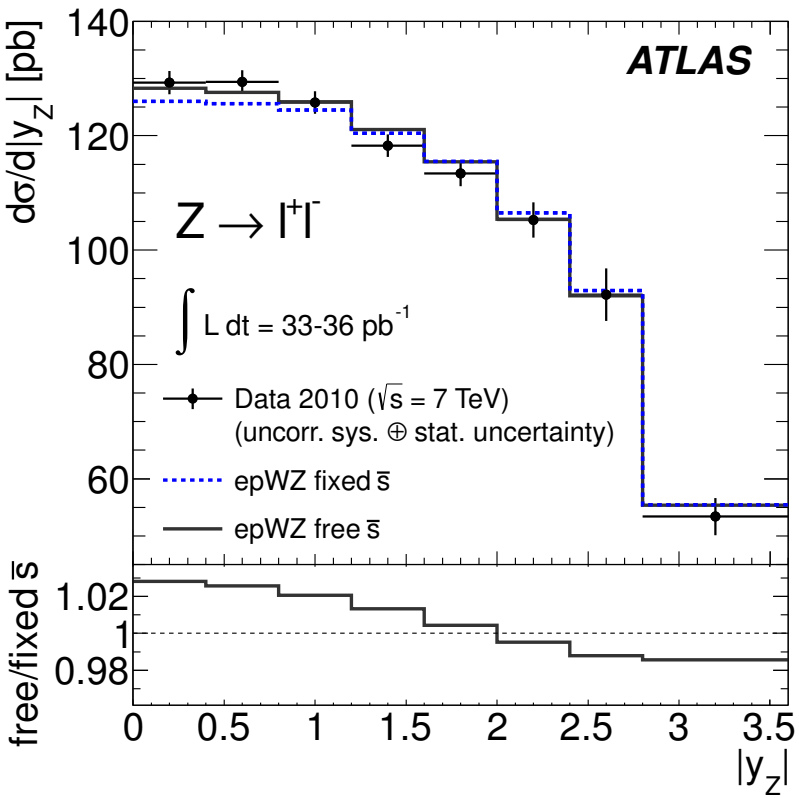
- At LO cross sections determined by sum of different $q\bar{q}$ combinations, weighted by different electro-weak couplings for Z and γ^* (e_q^2) + their interference and CKM elements $V_{q\bar{q}}$ for $W^{\pm}$
- Different composition of flavours than measured in the HERA dataset: precise cross section measurements can give complementary information to the HERA data



How "strange" is the Proton?

- Light sea composition from $\bar{u}, \bar{d}, \bar{s}$ quarks not well constrained by HERA DIS data at low x: neutrino DIS data suggests suppression of $\bar{s}$ by $\sim 50\%$ at low Q^2
- 2010 ATLAS Z data favours instead a symmetric light sea $\bar{u} \approx \bar{d} \approx \bar{s}$ at $Q^2 = 1.9\,\mathrm{GeV}^2$ and $x = 0.023$: $r_s = \bar{s}/\bar{d} = 1.00 \pm 0.20_{\mathrm{exp}}\,{}^{+0.16}_{-0.20}\,{}_{\mathrm{sys}}$
- To be continued with further precise data...





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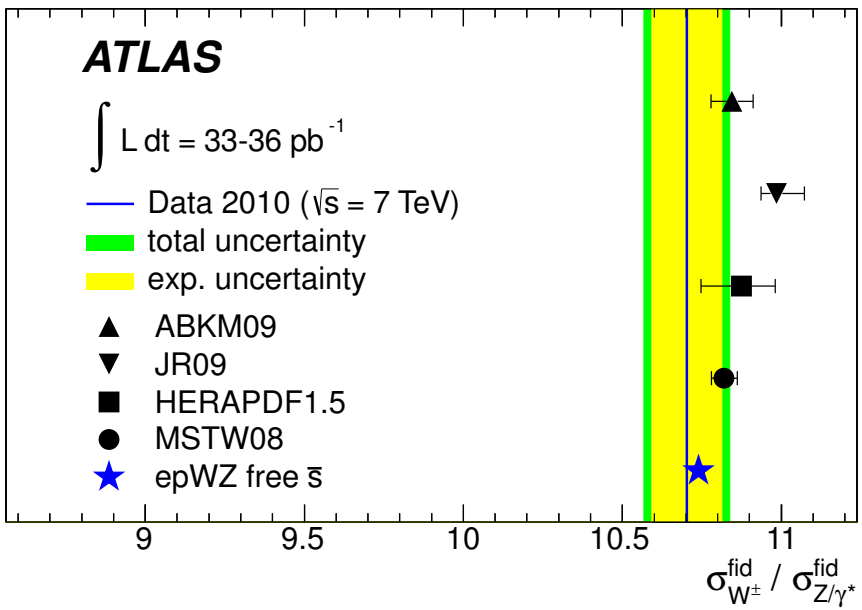

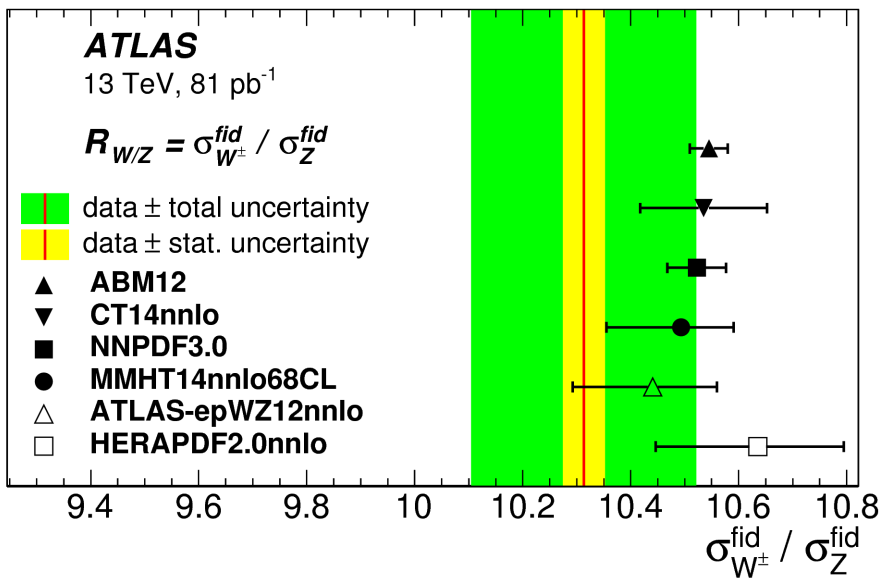

Conclusion

DIS is a very fundamental process in particle physics and Drell-Yan

HERA has very much contributed to our knowledge on the proton structure

A large number of open questions remain in this domain in particular at small x

Additional issues will certainly be prompted by the LHC data and discoveries

It would be a waste not to exploit the 7 TeV beams for eP and eA physics at some stage during the LHC time

Many Thanks

- the DIS conference organizers: well done — keep positive spirit also for future scientific discussions
- Personal thanks to friends and colleagues:
  - the H1 group in DESY Zeuthen
  - the H1 collaboration
  - the University of Liverpool and especially the ATLAS group
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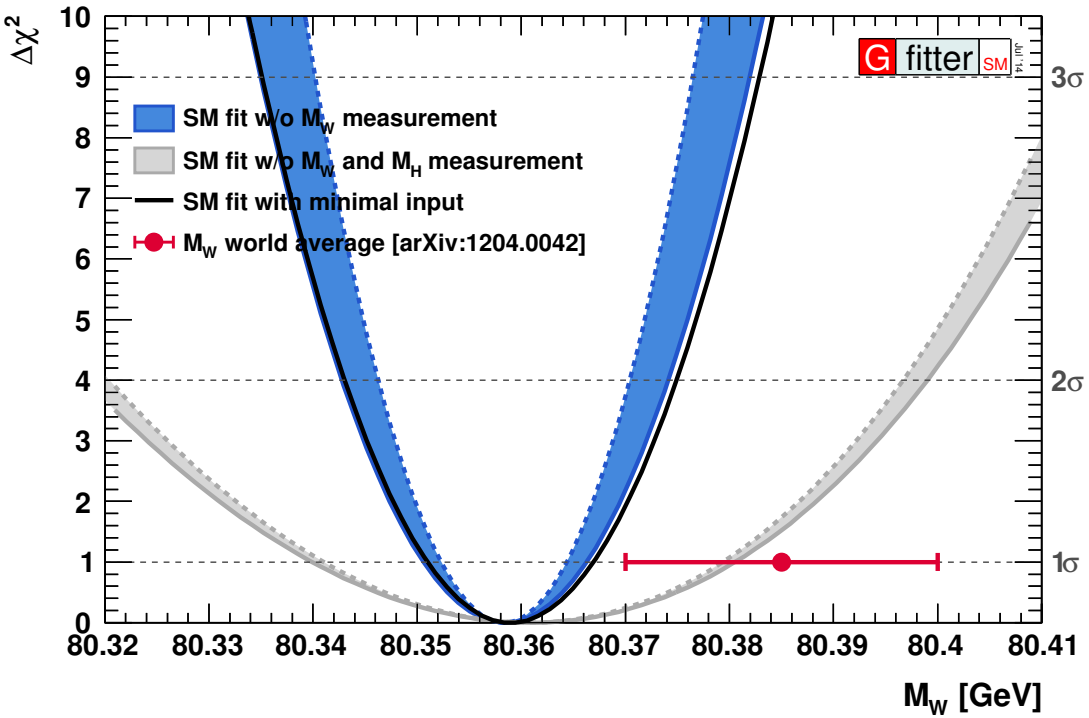
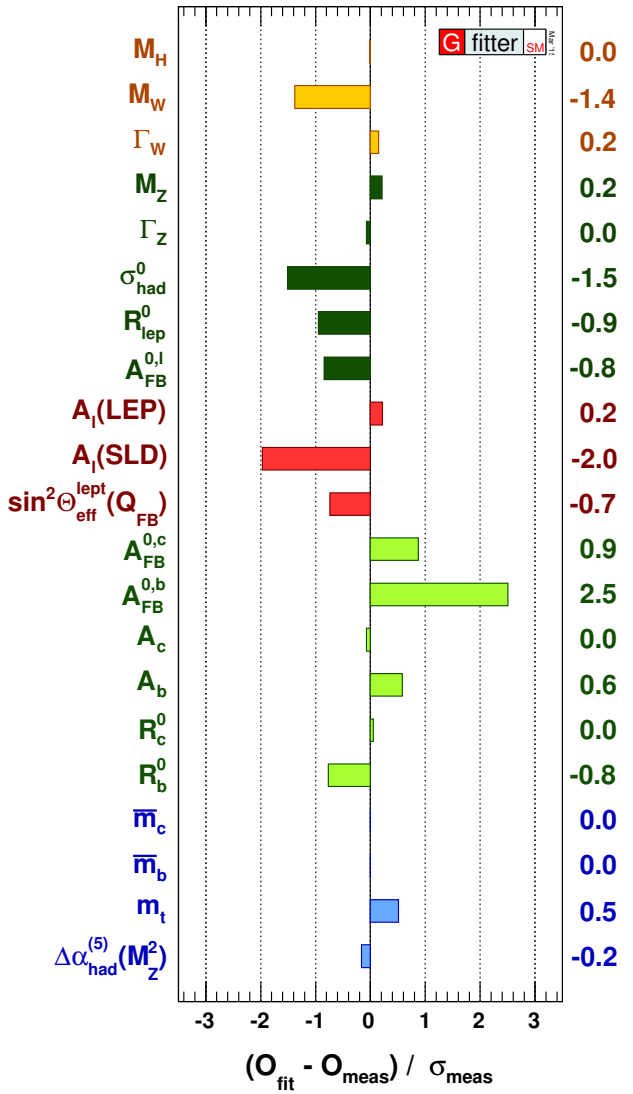
  - Sasha Glazov
  - Max Klein
  - My family

Backup - A largely random collection

Electroweak Measurements at LHC: m_W & $\sin^2\theta_W$ [Gfitter]

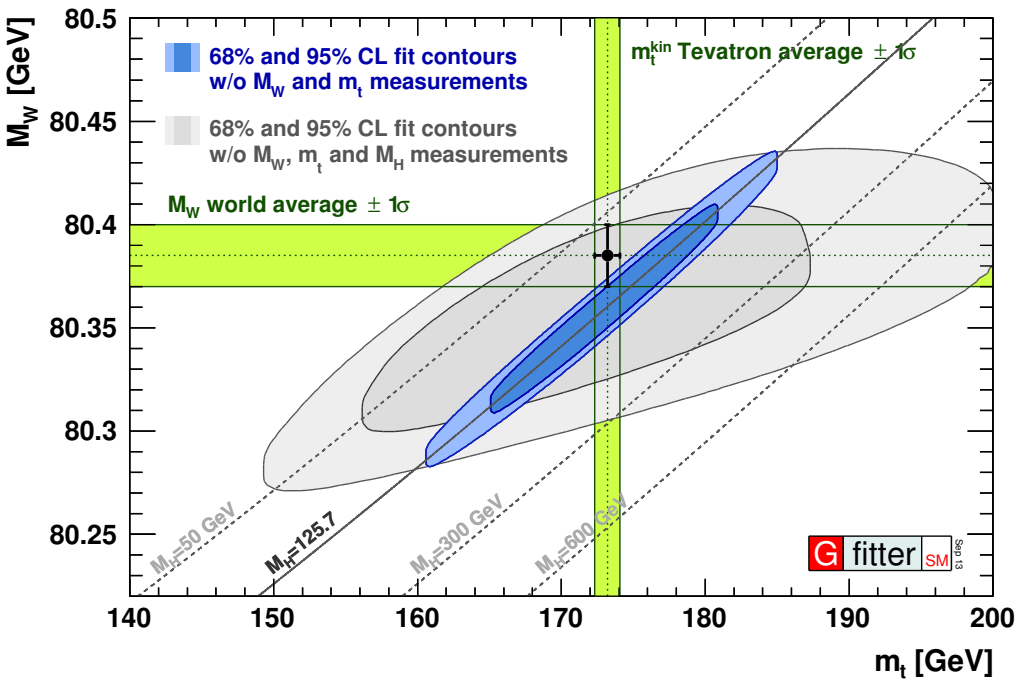
- Very precise m_W and $\sin^2\theta_W$ measurements remain interesting tests for the overall consistency of the SM
- m_W: current World Average 15 MeV vs. 8 MeV prediction in EWK fit
- $\sin^2\theta_W$: "indirect" m_W measurement $\sim m_Z \cos^2\theta_W$, LEP-SLD discrepancy





Electroweak Precision at LHC: m_W

- A very precise m_W measurement remains an interesting test for the consistency of the SM
- Tevatron measurements with "just" $\sim 100,000$ Z and ~ 1 W million events
- Measurement at LHC will be completely systematics dominated, PDF uncertainties ($\sim 10\,\mathrm{MeV}$ at Tevatron) eventually a limiting factor

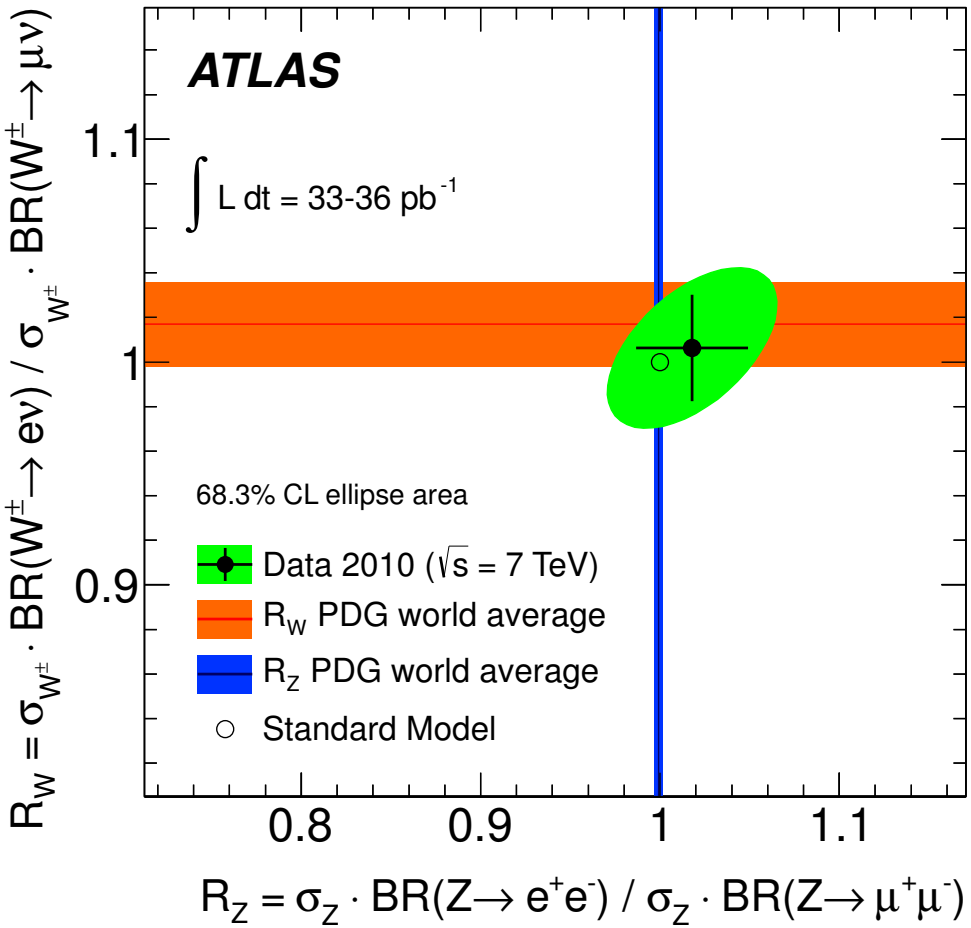


CDF m_W uncertainty in $[\mathrm{MeV}]$

Source	Uncertainty
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton tower removal	2
Backgrounds	3
PDFs	10
$p_T(W)$ model	5
Photon radiation	4
Statistical	12
Total	19

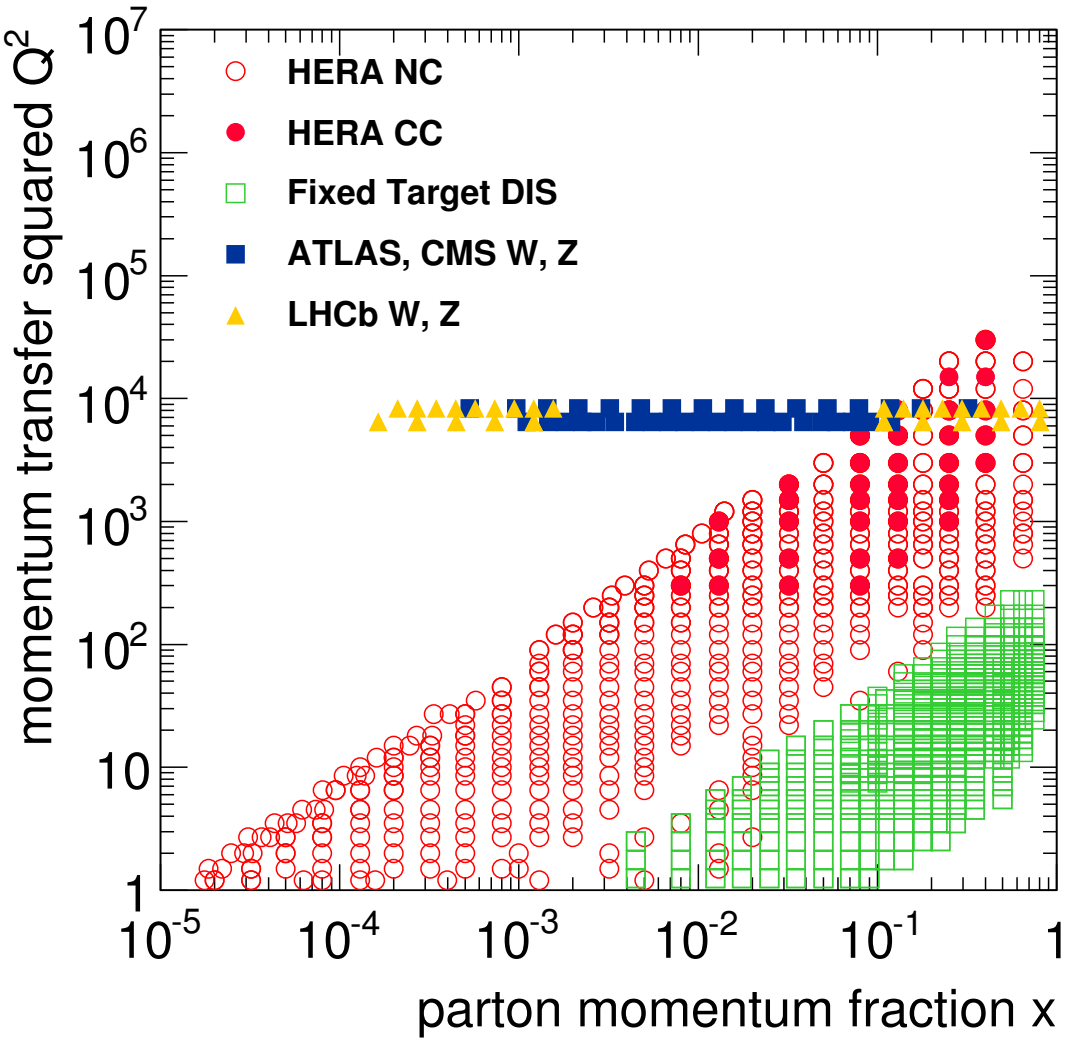
Electroweak Precision at LHC

- $e - \mu$ lepton universality in W and Z decays primarily limited by lepton performance and statistics



x, Q^2 plane

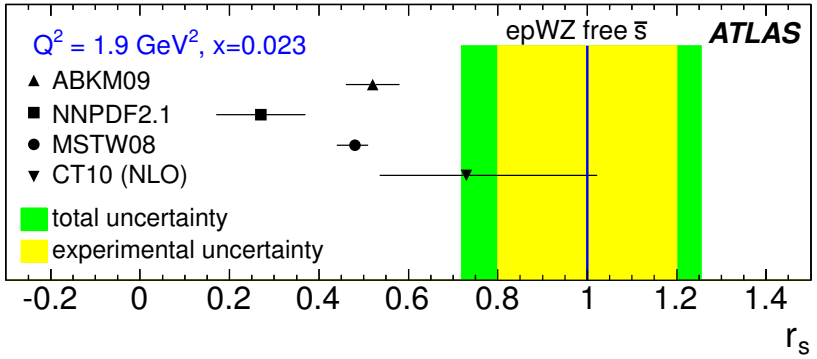
- Parametrise all PDFs at fixed starting scale $f(x, Q_0^2)$: DGLAP evolution gives result for all $f(x, Q^2)$
- Full LHC W, Z production x range only covered by HERA NC data

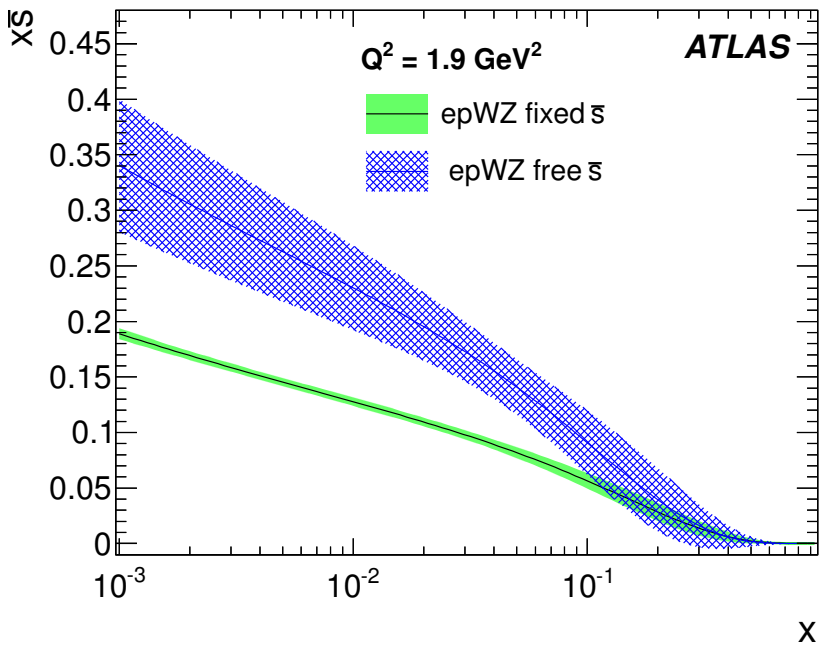


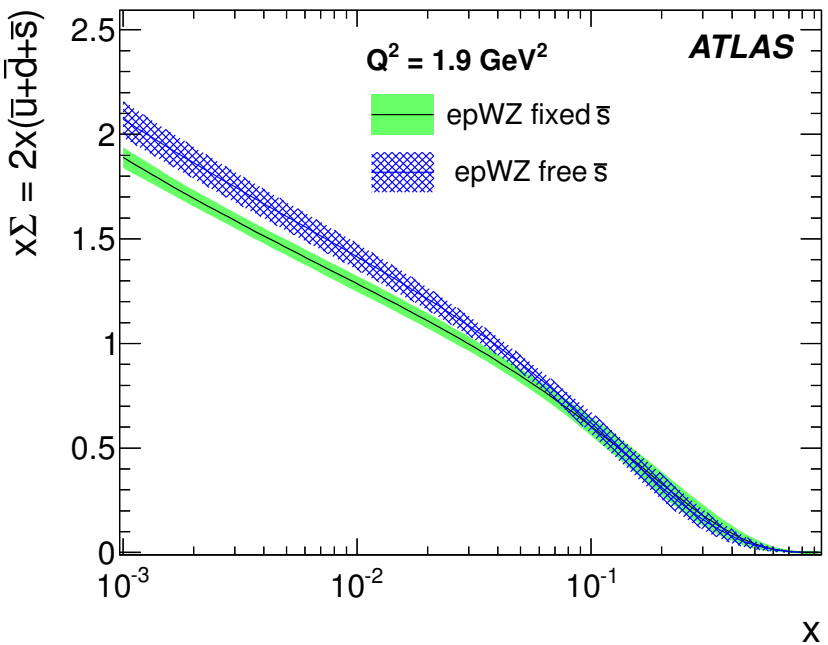
W, Z data sensitivity to strange sea

- Fit with free strange sea indicates no strange sea suppression at $Q^2 = 1.9\,\mathrm{GeV}^2$ and $x = 0.023$: $r_s = 1.00 \pm 0.20_{\mathrm{exp}}\,^{+0.16}_{-0.20}\,\mathrm{sys}$

- Knock-on effect on the remaining light sea as HERA constrains $\sim \sum e_q^2 (q + \bar{q})$
- $r_s = 1$!

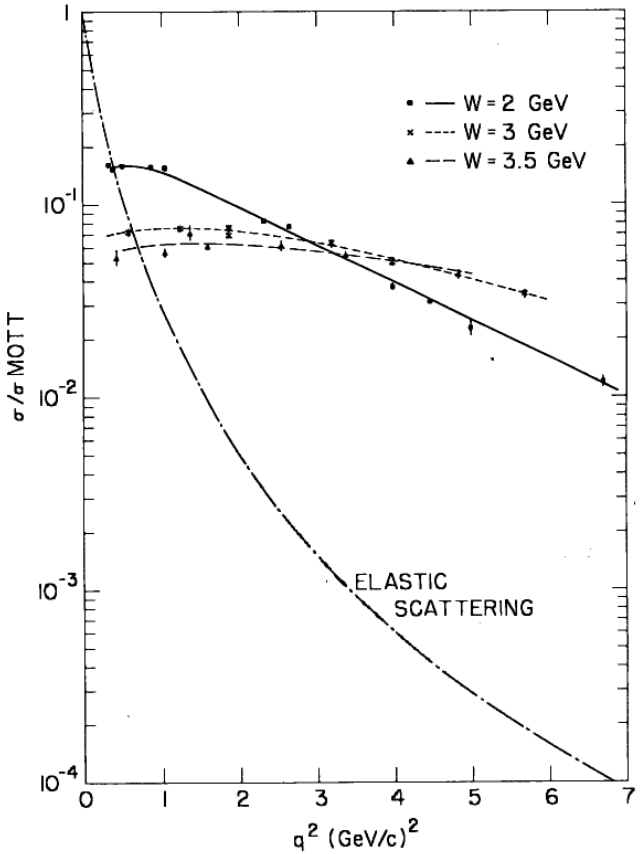


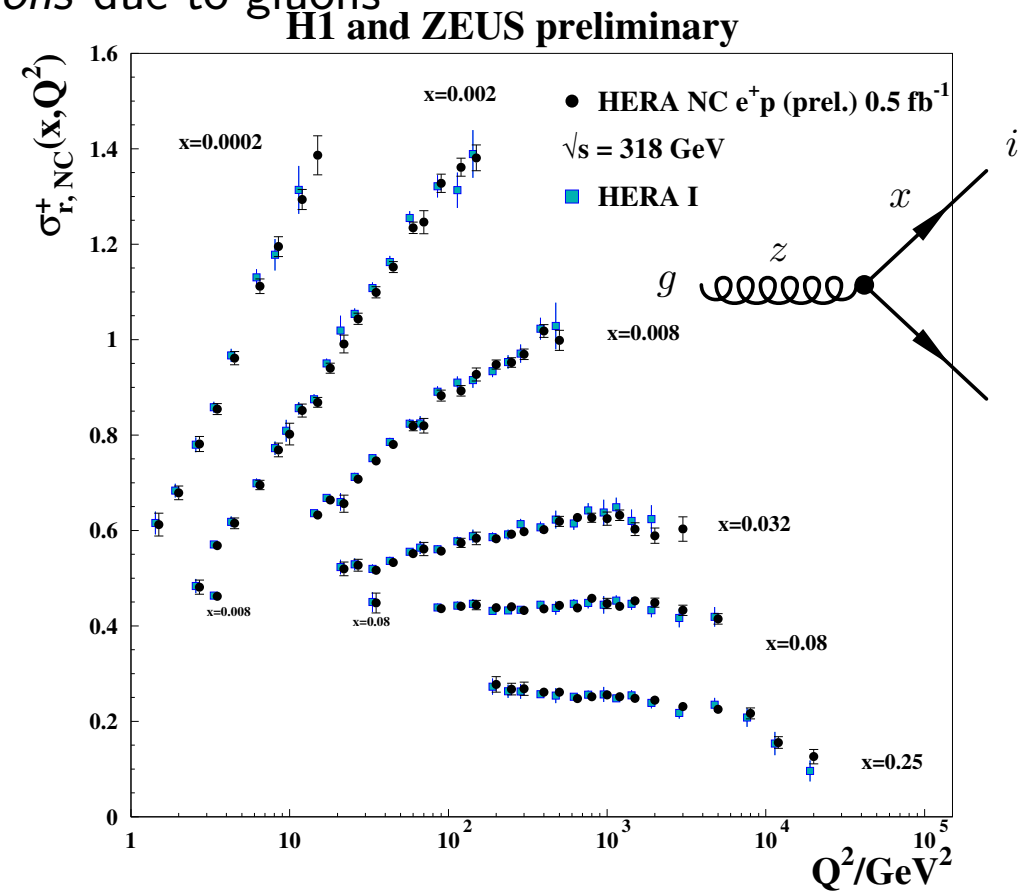




Proton Content: Quarks and Gluons

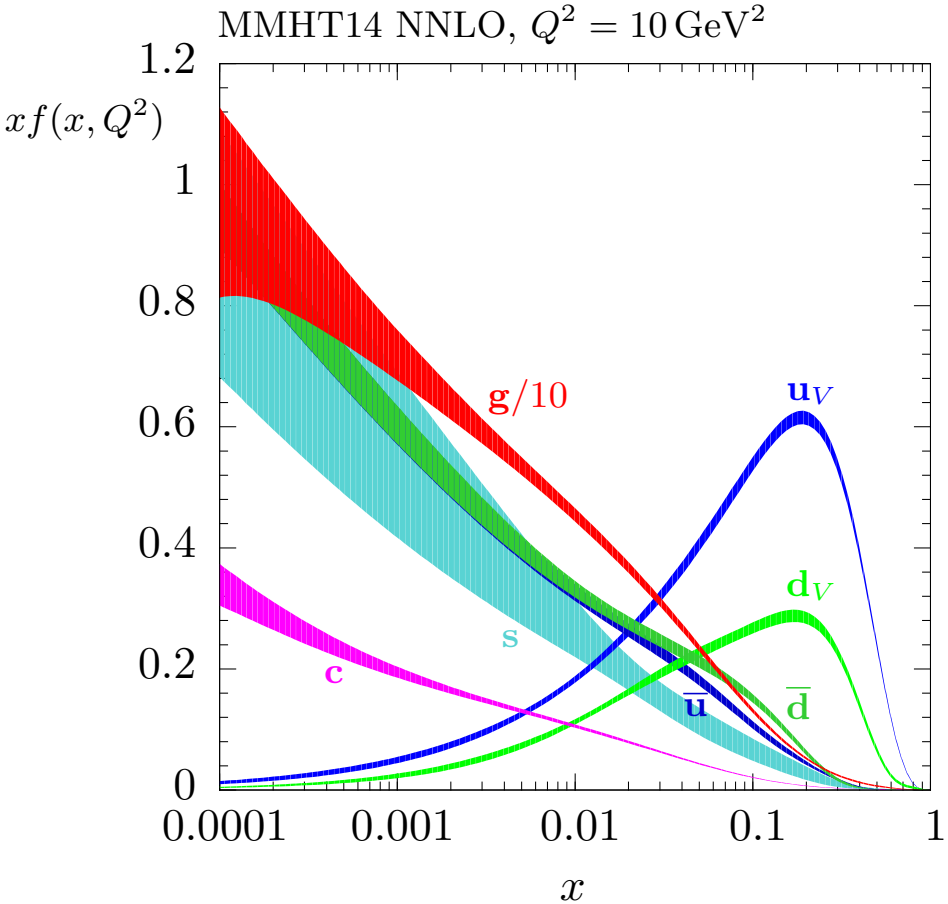
- *ep* scattering experiments at SLAC in 1969 found the cross section to be $\sim$ independent of momentum transfer Q^2 (*scaling*): proton is made up of point-like *quarks*
- Most recent HERA combination gives very precise information in wide range of x, Q^2: at low x strong *scaling violations* due to gluons

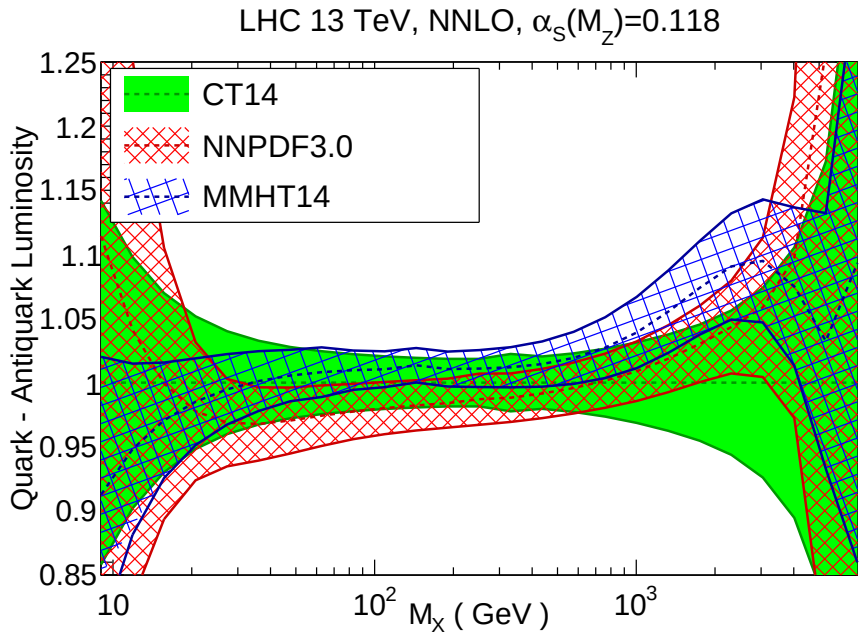




PDF Knowledge (and limitations)

[arXiv:1412.3989, arXiv:1510.03865]

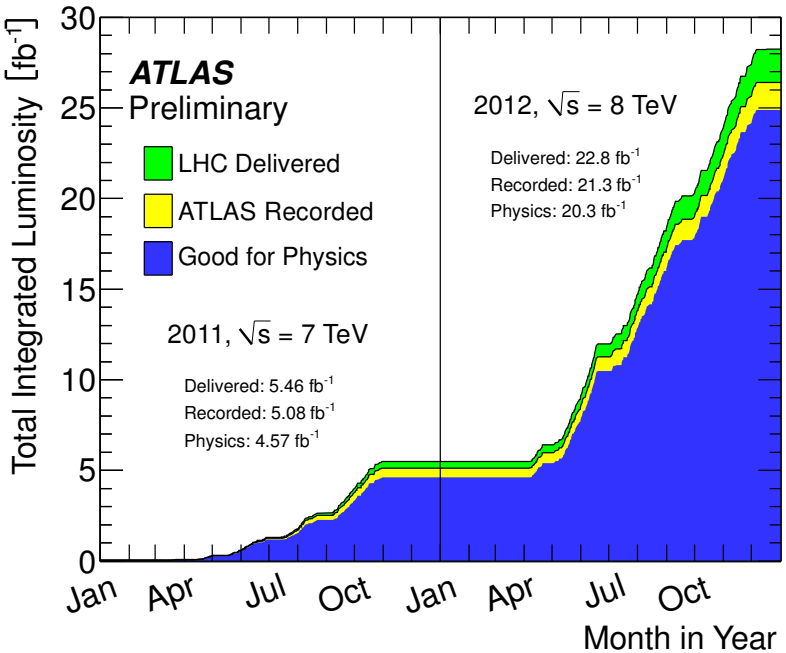


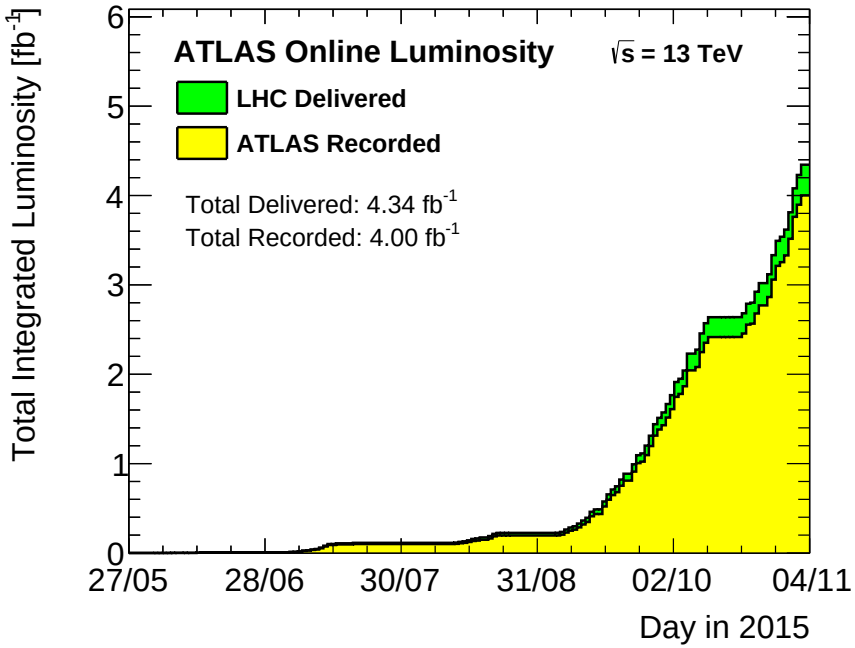


- One of the big unknowns is the flavour decomposition of light sea at low $x < 10^{-2}$ mostly an educated guess: $\bar{u} \sim \bar{d}$, strange suppressed?
- Procedural differences in fits of different groups to (mostly) same data
- In general limited knowledge of low and high momentum fractions x, translates into large uncertainties for *parton luminosities* at low and high masses $M_X = \sqrt{x_1 x_2 s}$

ATLAS Operation and Data Sets

- Run 1 (2010-2012) was overall a huge success: recorded data good for physics analysis correspond to luminosities of $5\,\mathrm{fb}^{-1}$ at 7 TeV and $20\,\mathrm{fb}^{-1}$ at 8 TeV
- Run 2 has started well this summer at 13 TeV, although a little slower than anticipated: *pp* data taking to stopped with $\sim 3.3\,\mathrm{fb}^{-1}$ good ATLAS data



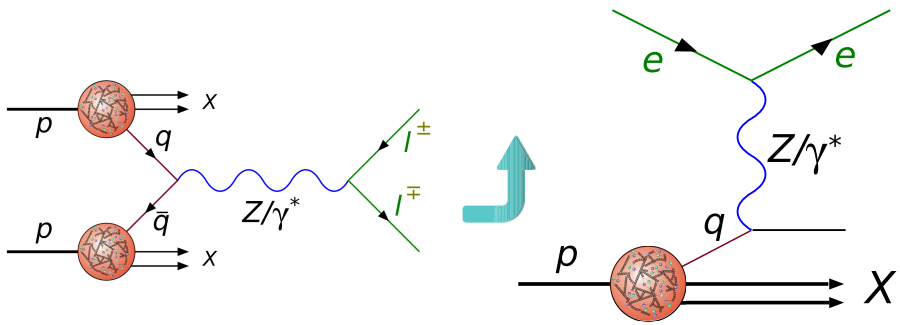


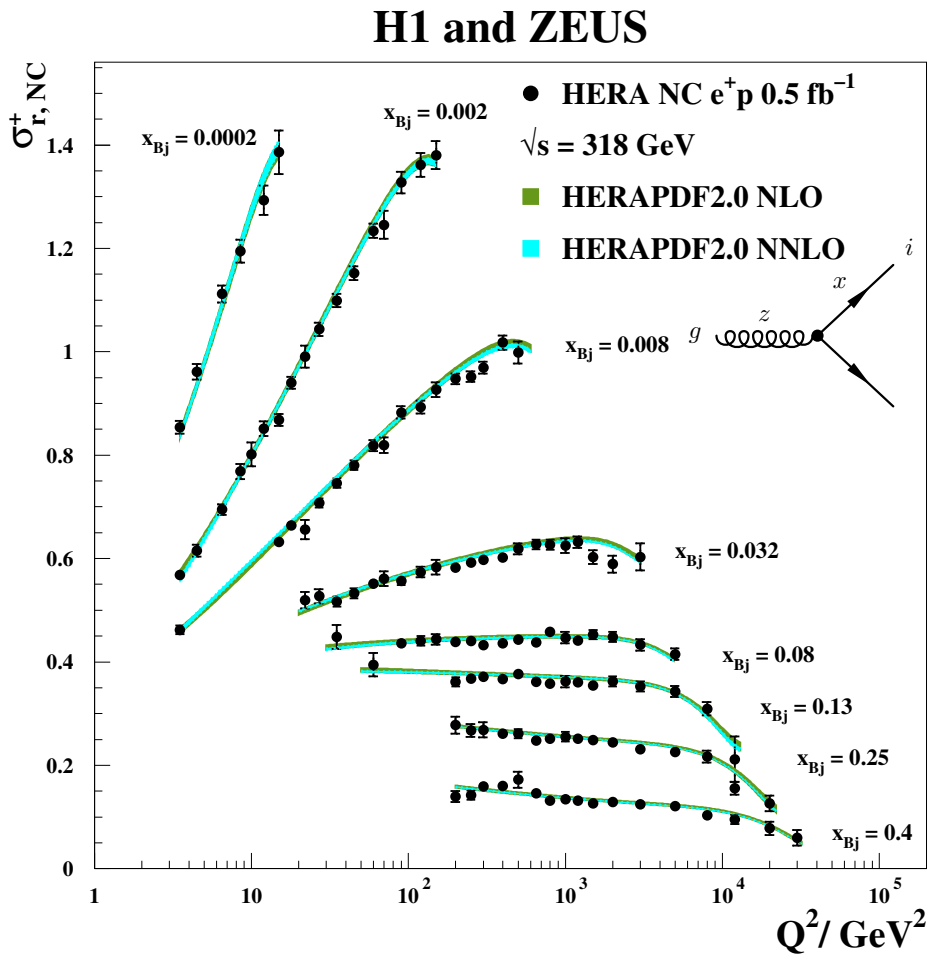
PDFs and Deep Inelastic Scattering

[arXiv:1506.06042]

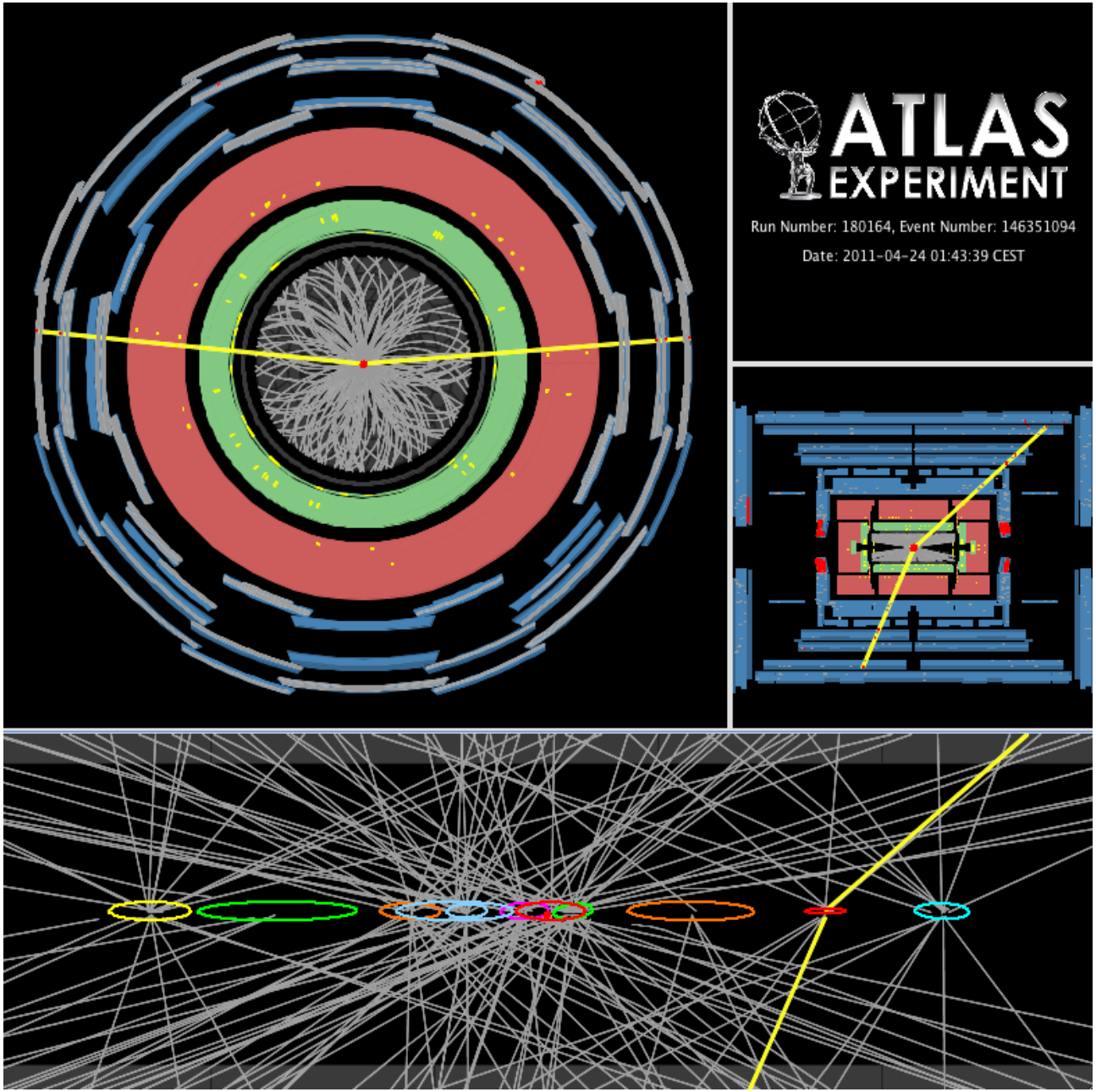
- PDFs primarily determined by *Deep Inelastic Scattering*
- Experiments at SLAC in 1969 found the *ep* cross section to be $\sim$ independent of momentum transfer Q^2 (*scaling*): proton consists of point-like *quarks*
- Further fixed target experiments and HERA measured very precisely over wide range of x, Q^2: at low x strong *scaling violations* due to gluons

- *Neutral current* (NC) primarily constrains $\sum e_q^2(q + \bar{q})$ (γ^* exchange) and gluon through scaling violations
- Some additional information from *Charged current* (CC) processes, Deuterons, neutrinos; jet production in $pp, p\bar{p}$... extraction of PDFs via "global fit" to sensitive data

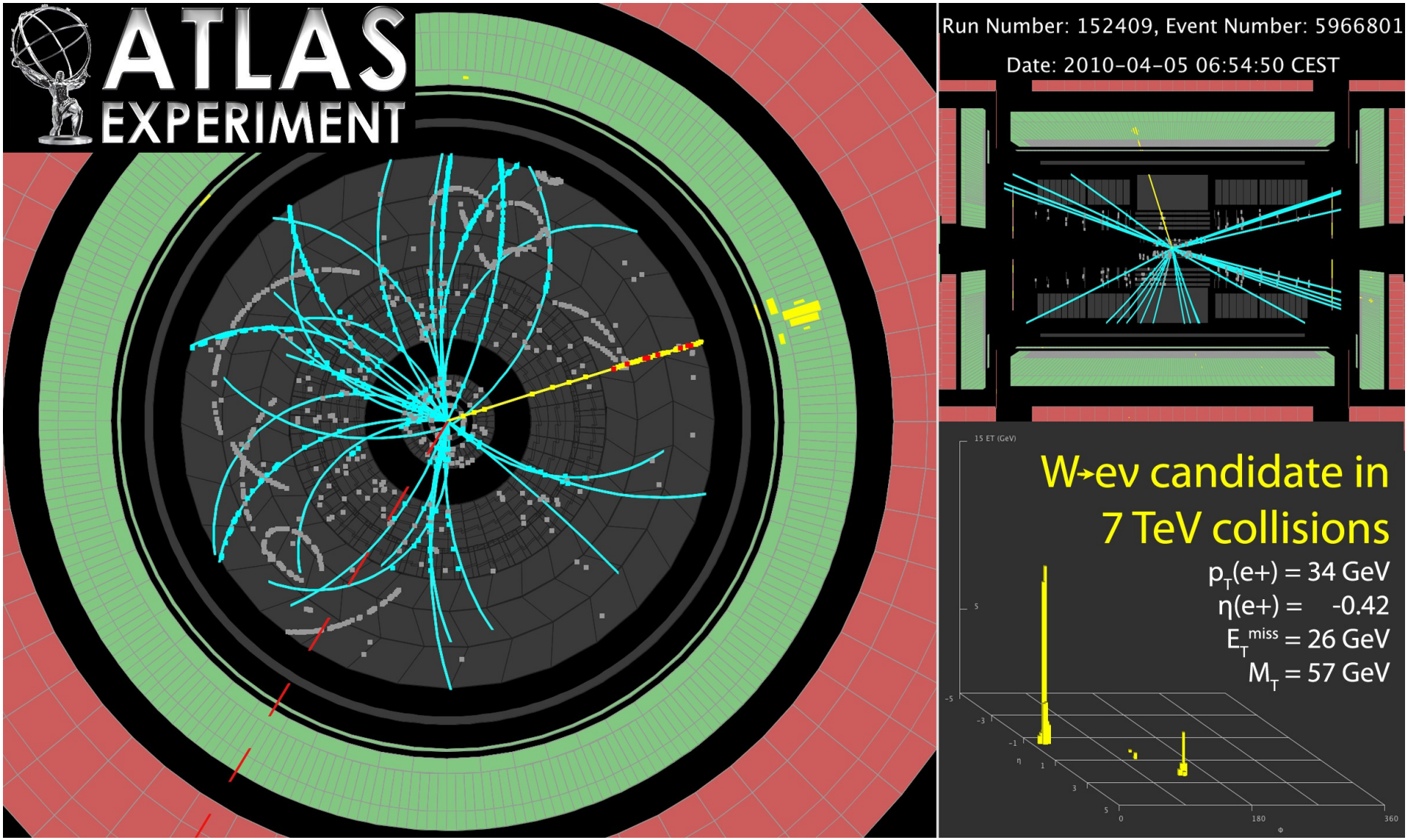




A $Z \to \mu\mu$ candidate



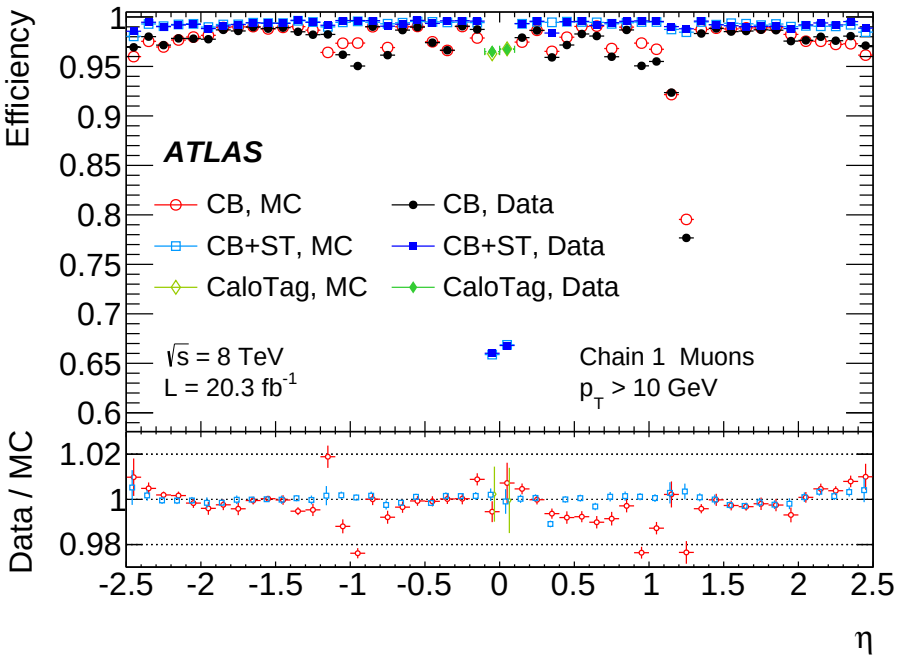
A $W \to e\nu$ candidate

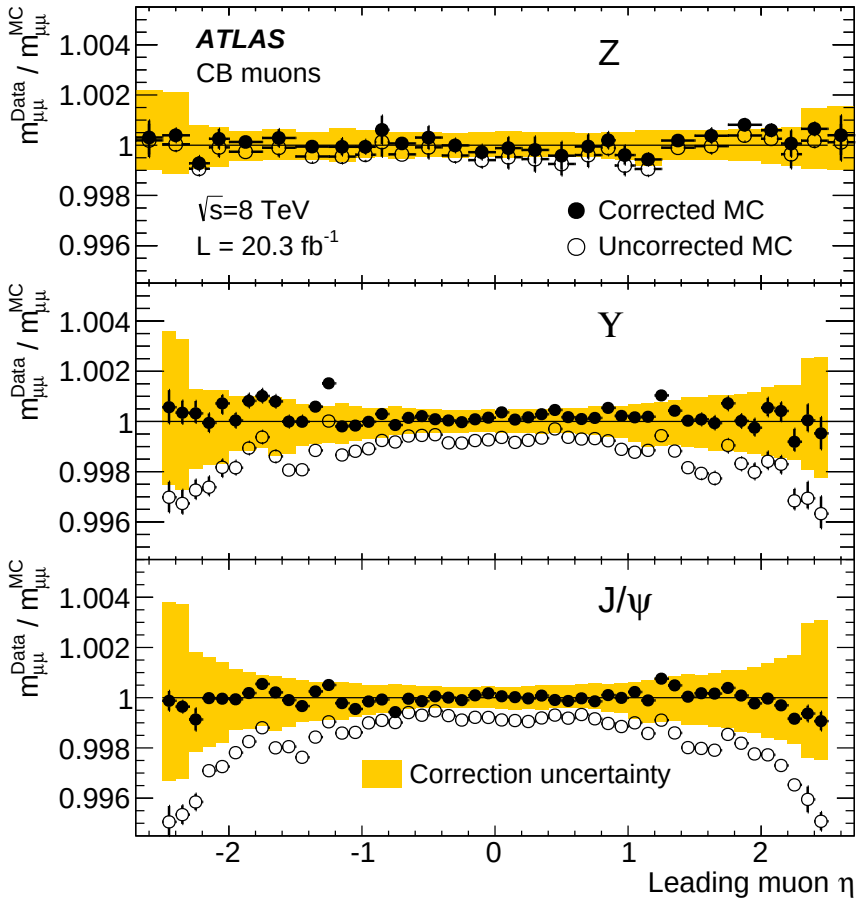


Run 1 Lepton Performance: Muons

[EPJ C74 (2014) 3130]

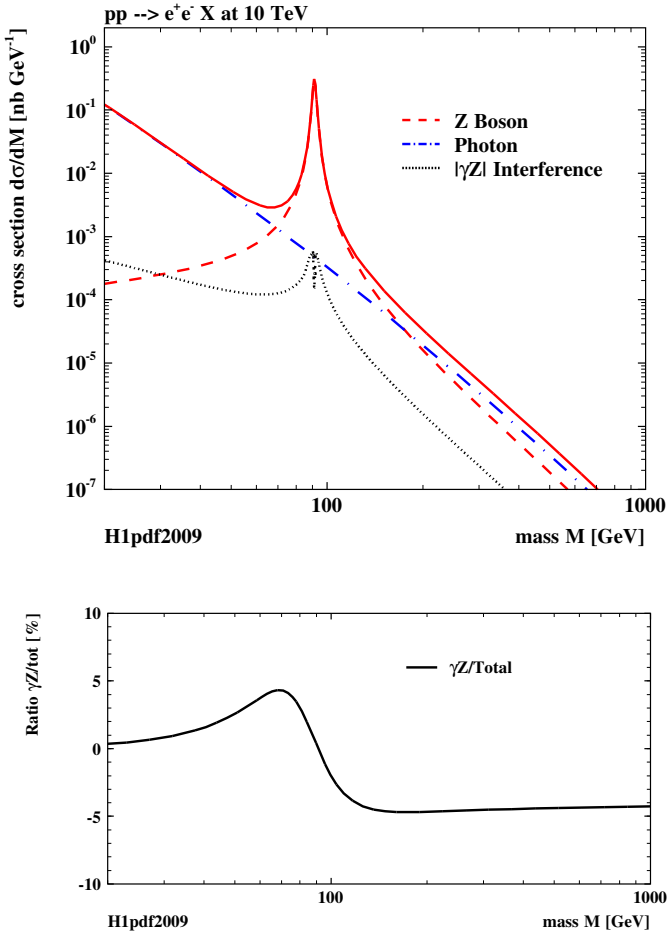
- Main experimental issue for W and Z is quantitative understanding of lepton performance: selection efficiencies, energy/momentum scales
- Thanks to the large $Z \to \ell\ell$ samples this is mostly an exercise in time and dedication
- Muon efficiencies and calibration both known at the $< 0.1\%$ level (non-uniformities in muon spectrometer and ID+MS alignment at μm level)





5-dimensional cross sections

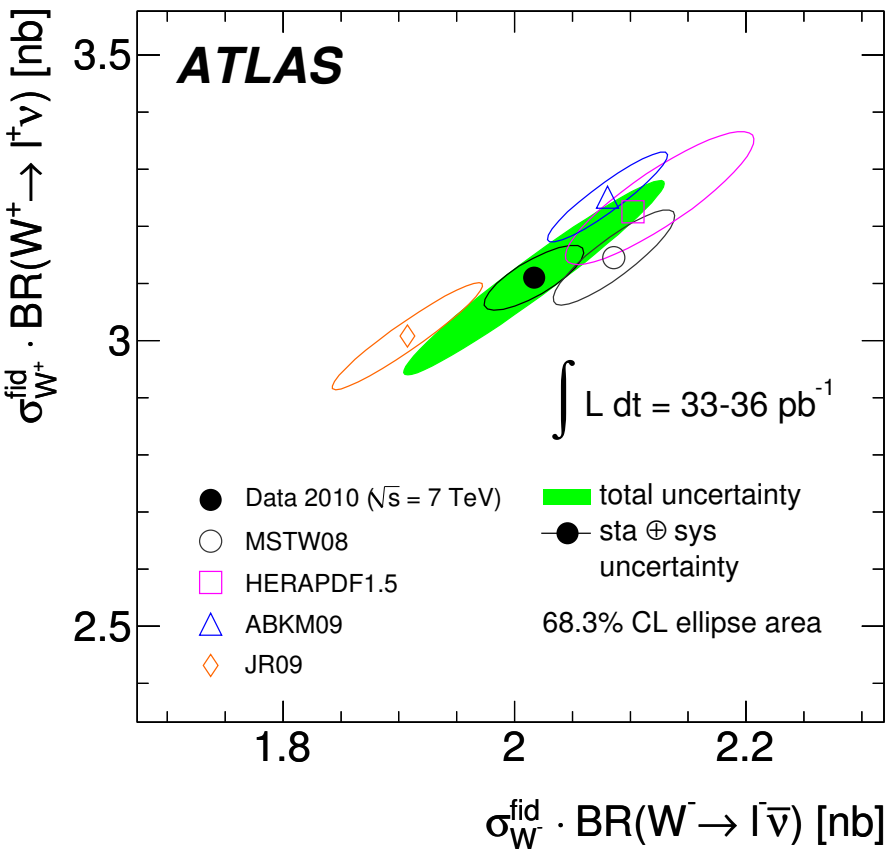
- Full description of production and decay of single $W^{\pm} \to \ell\nu$ and $Z/\gamma^* \to \ell\ell$ depends on many kinematic variables:
  - The boson 4-vector, usually expressed in terms of di-lepton mass $m_{\ell\ell}$, transverse momentum $p_{T,\ell\ell}$ and rapidity $y_{\ell\ell}$
  - Due to spin-1 nature of the $W/Z/\gamma^*$ bosons and EWK coupling effects the two decay leptons have non-trivial angular correlations (θ^* and ϕ^*)
- So far ATLAS has explored integrated and $1-2$ dimensional projections
  (analyses exploring 3 dimensions at once are close to publication)

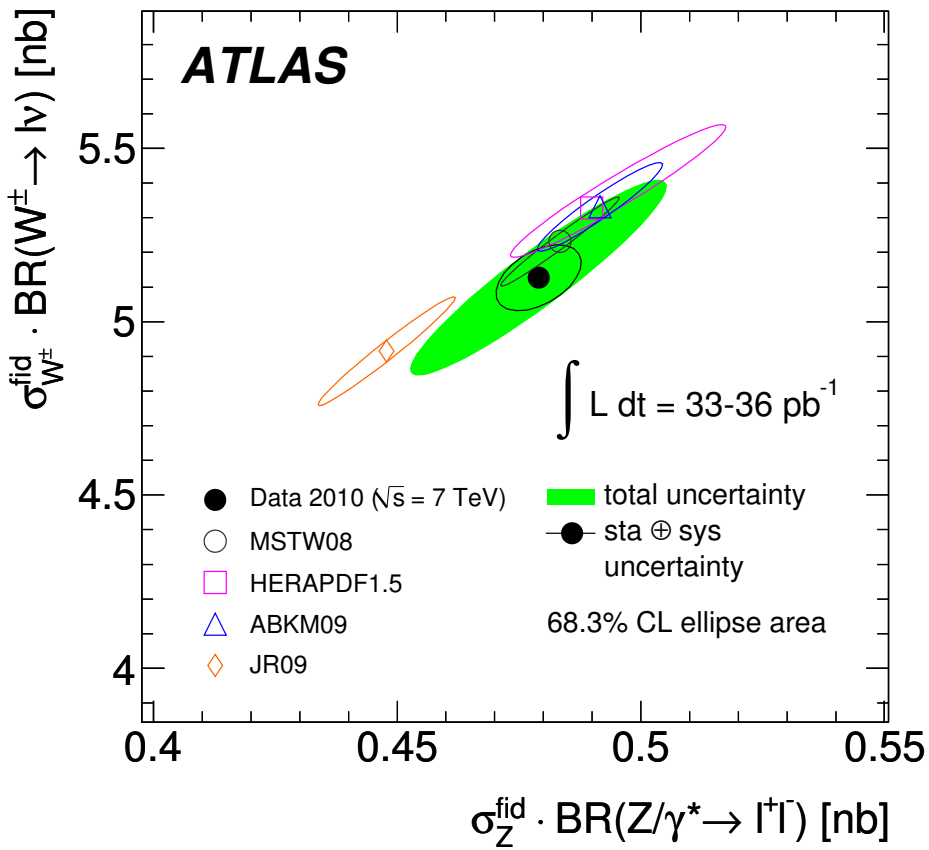


Integrated cross section: 2010 Results

[PRD 85 072004 (2012)]

- A first stringent test of QCD in 7 TeV pp collisions: with the first 35 pb^{-1} the integrated W and Z cross sections were measured to $\sim$ 1.5% experimental precision $\oplus$ 3.5% luminosity

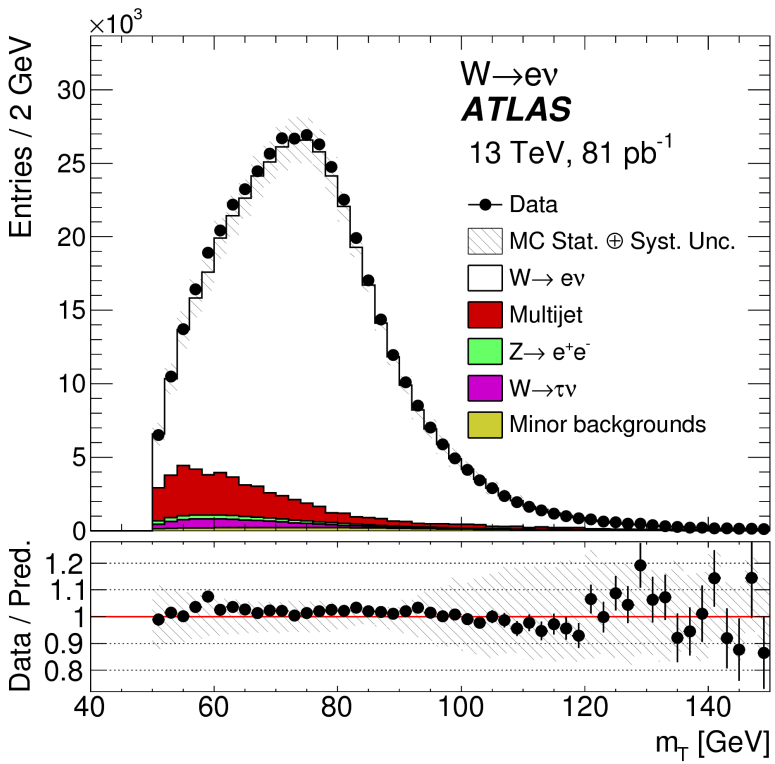


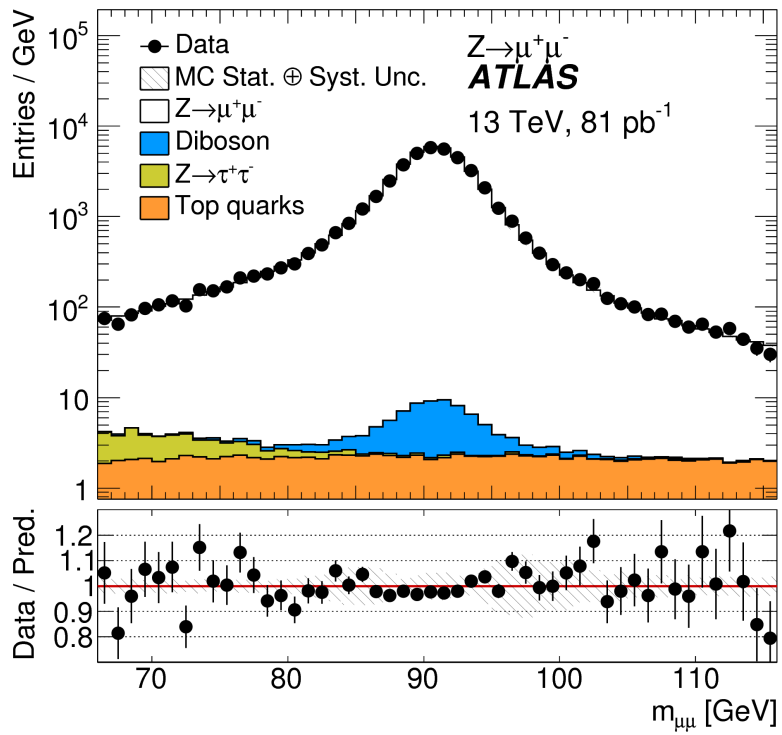


13 TeV W and Z cross sections

[arXiv:1603.09222]

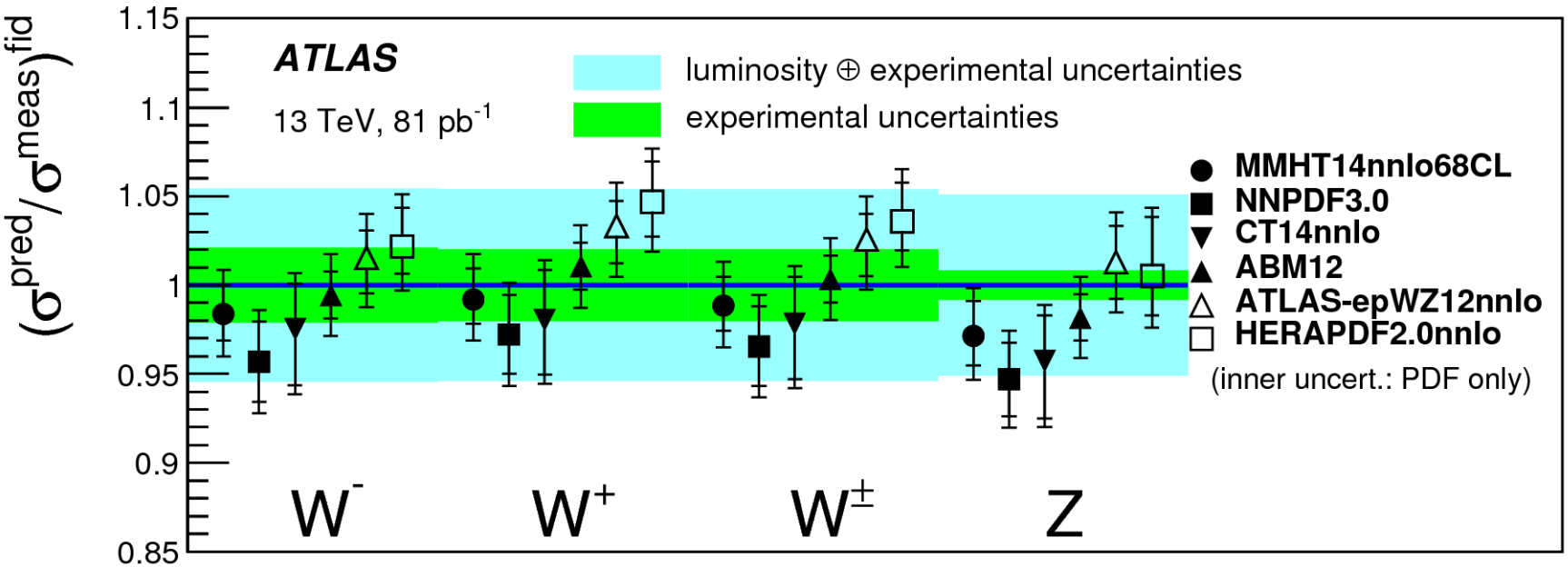
- First pp collisions in June 2015 recreated some excitement to measure W and Z cross sections on a short time scale
- Already first plots indicated reasonable understanding of the detector after the first long shutdown
- About 2 months after data was taken, first measurements were approved
- Paper meanwhile published at improved precision





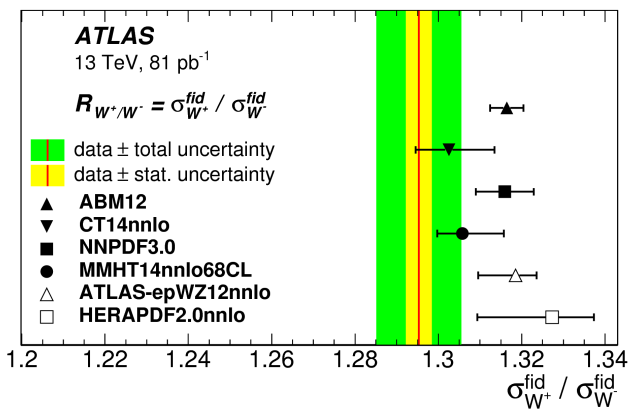
First 13 TeV W and Z cross sections

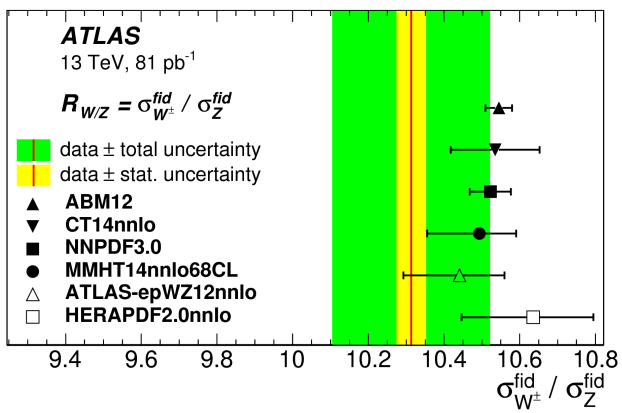
- Reached 1% experimental precision on the Z and 2% on the W, $\oplus$ 5% from the preliminary luminosity – good agreement with predictions

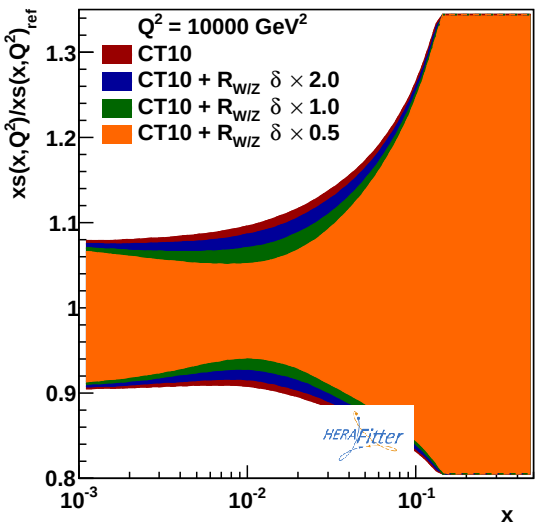


13 TeV W and Z cross section ratios

- Also produced first ratio measurements $W^{\pm}/Z$ and W^{+}/W^{-}
- In general good agreement with predictions, but also starting to test differences between PDF sets
- Once measurement precision on $W^{\pm}/Z$ ratio $\lesssim 1\%$ some visible impact on strange PDF in global fits can be expected

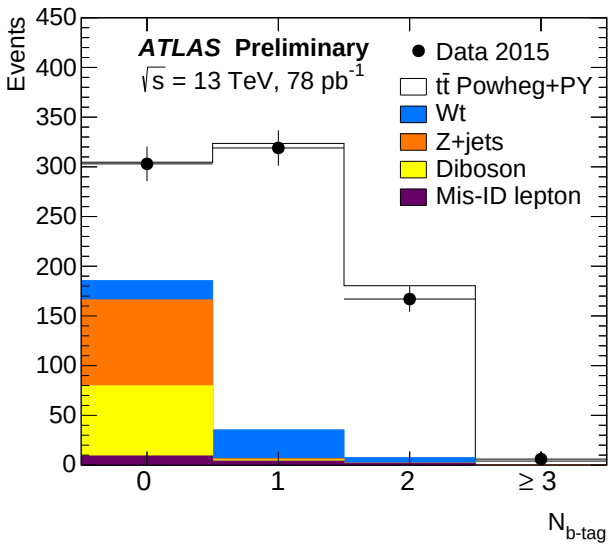


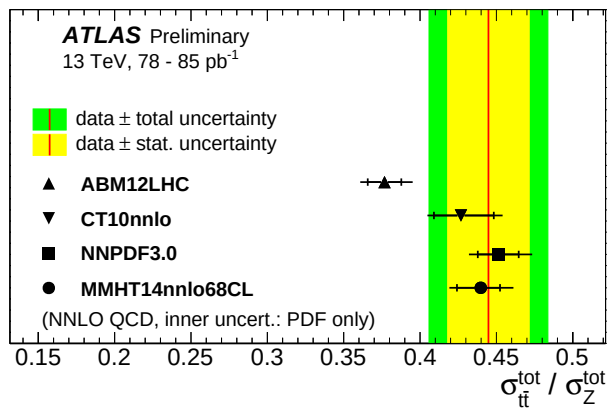


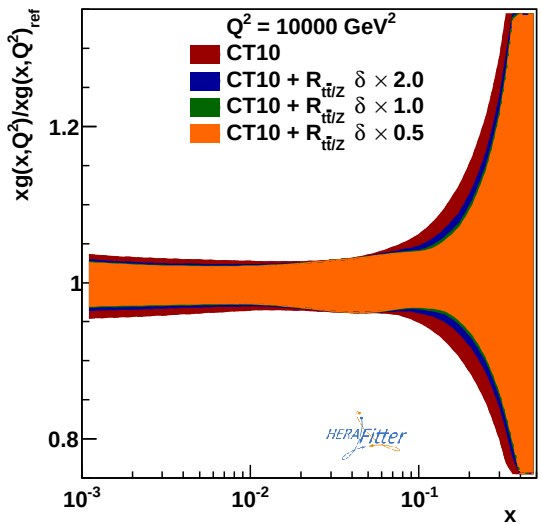


First 13 TeV $t\bar{t}/Z$ cross section ratio [ATLAS-CONF-2015-049]

- Another early 13 TeV highlight: ATLAS first measurement of the $t\bar{t}/Z$ cross section ratio using $t\bar{t} \to e^{\pm}\mu^{\mp}b\bar{b}\nu\bar{\nu}$
- The ratio measurement cancels luminosity, but also some experimental lepton systematics: limited mostly by the $t\bar{t}$ statistics (6%) to about 9%
- Once measurement precision $\lesssim 4\%$ some visible impact on gluon PDF in global fits can be expected



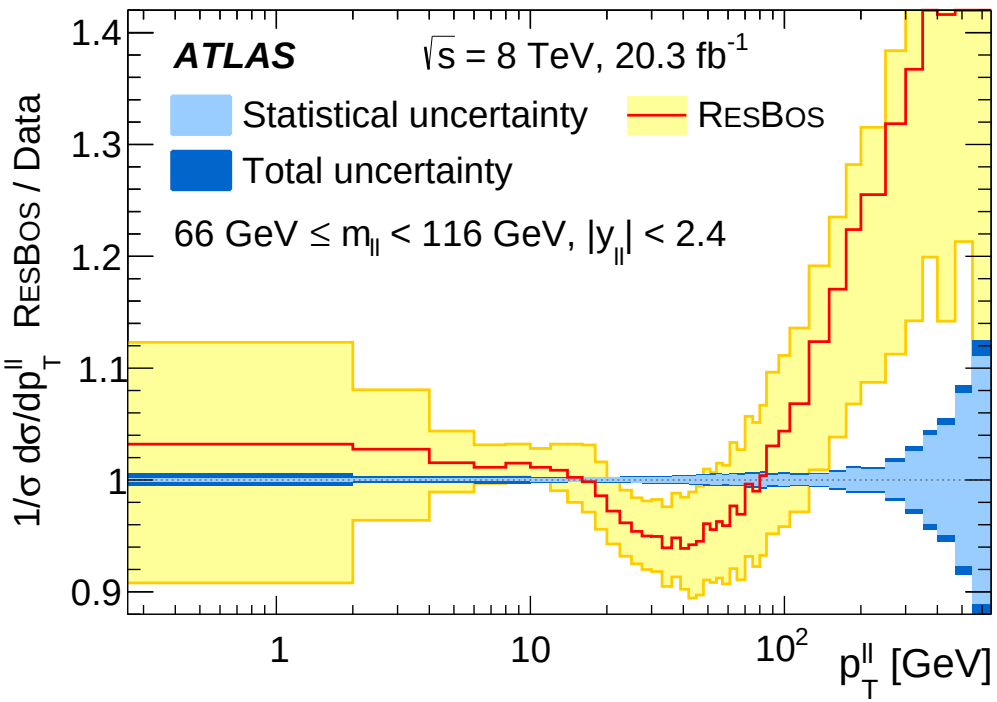


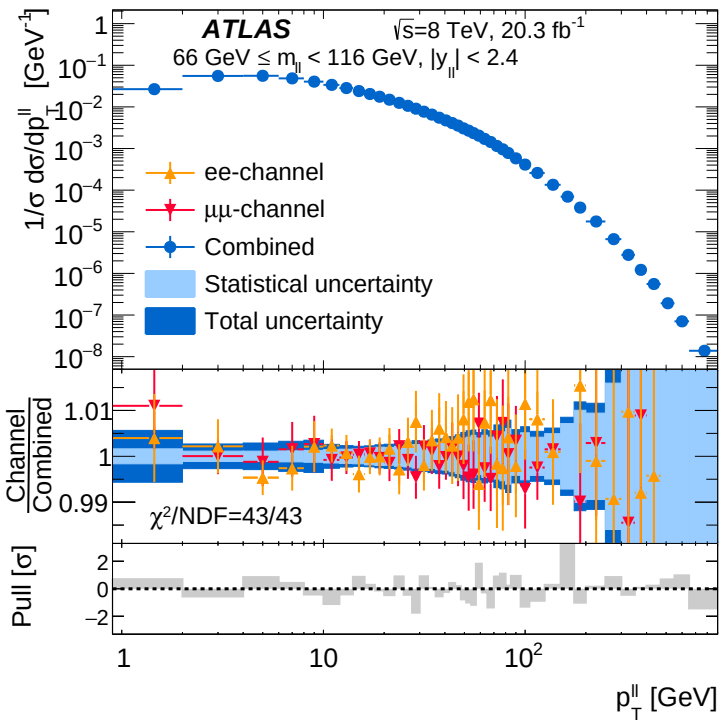


Z/γ^* transverse momentum

[ATLAS-STDM-2014-12, Huss et.al. @ Moriond QCD]

- Vector bosons are produced with non-zero transverse momentum: interesting interplay of effects from resummation and hard (jet) emissions
- High precision 2011 and 2012 results with $\lesssim 0.5\%$ precision after $ee + \mu\mu$ combination over a wide range!
- 2012 analysis extent to off-peak measurements: data/theory agreement not good at $\mathcal{O}(\alpha_s^2)$, possibly improved with very recent $\mathcal{O}(\alpha_s^3)$ calculation
- Important for W mass measurement, Higgs predictions, BSM searches...





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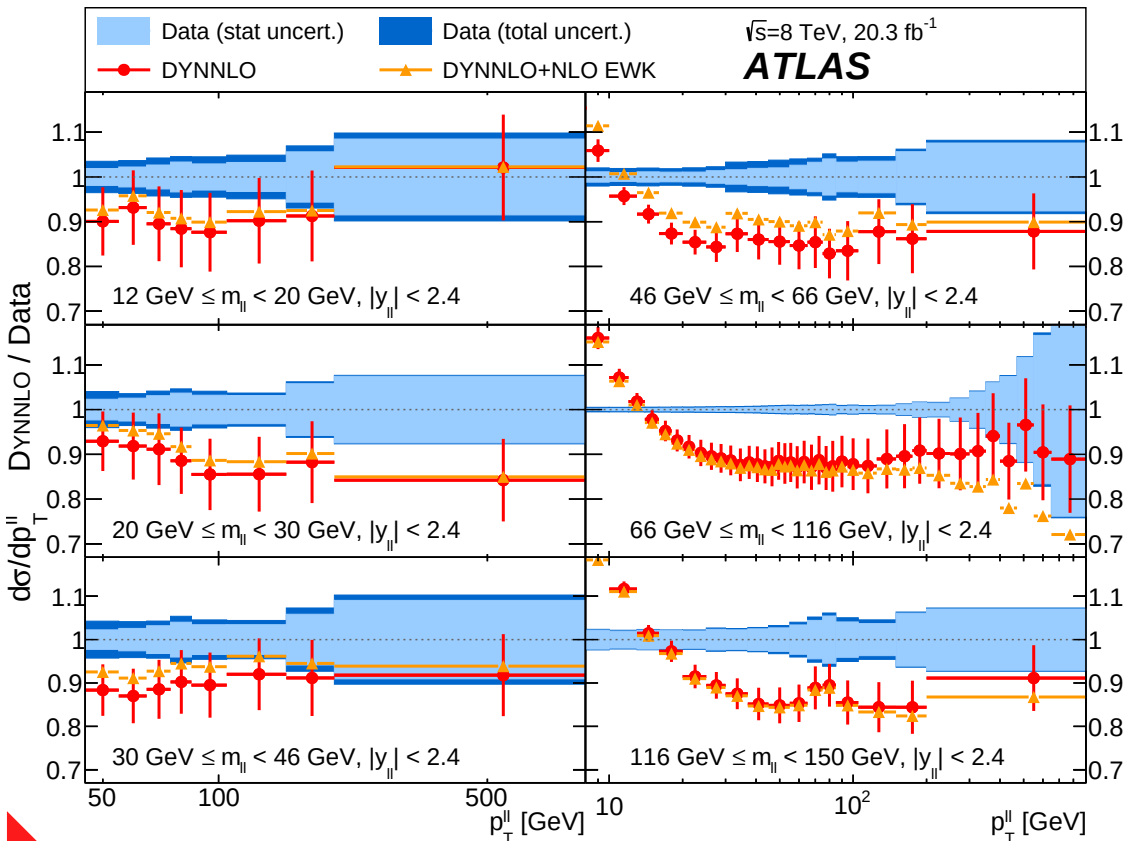

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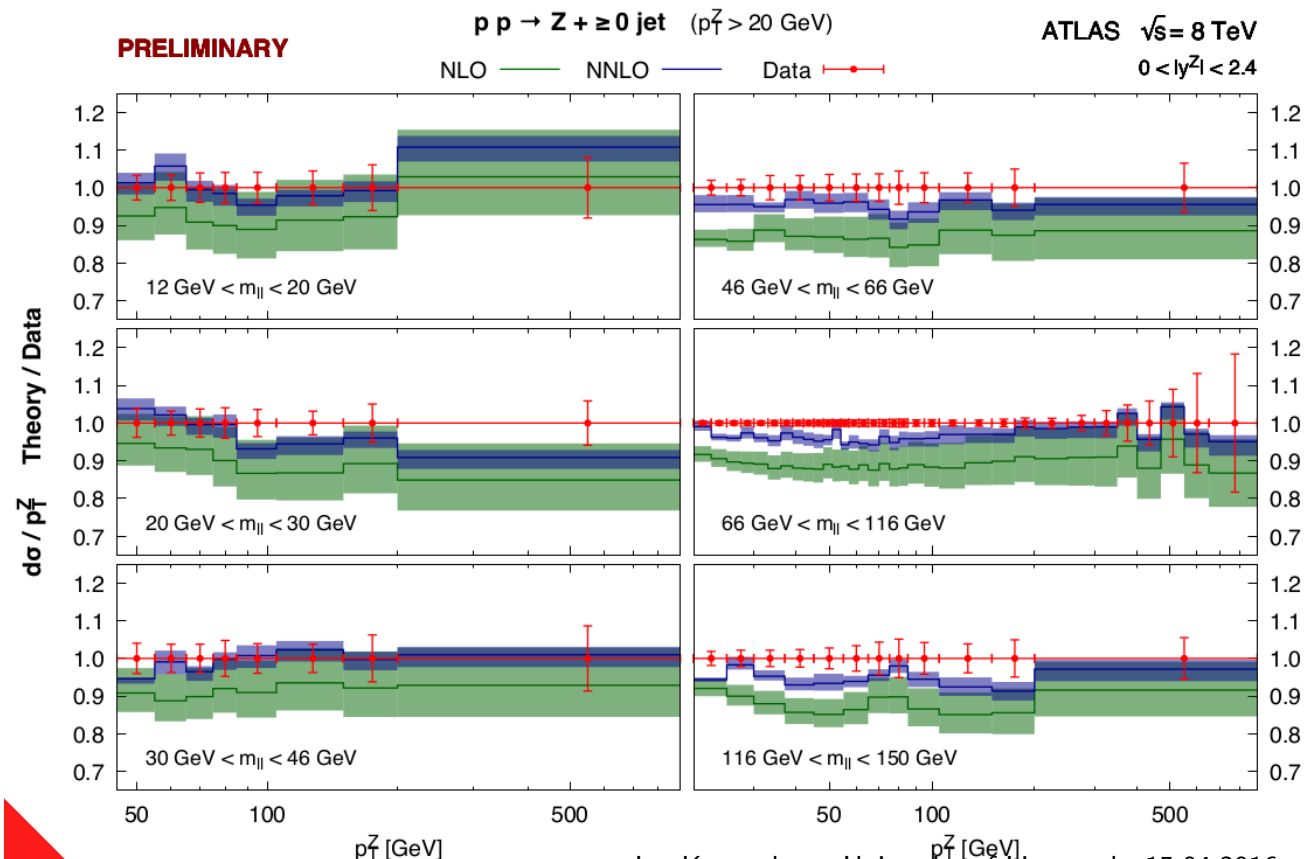
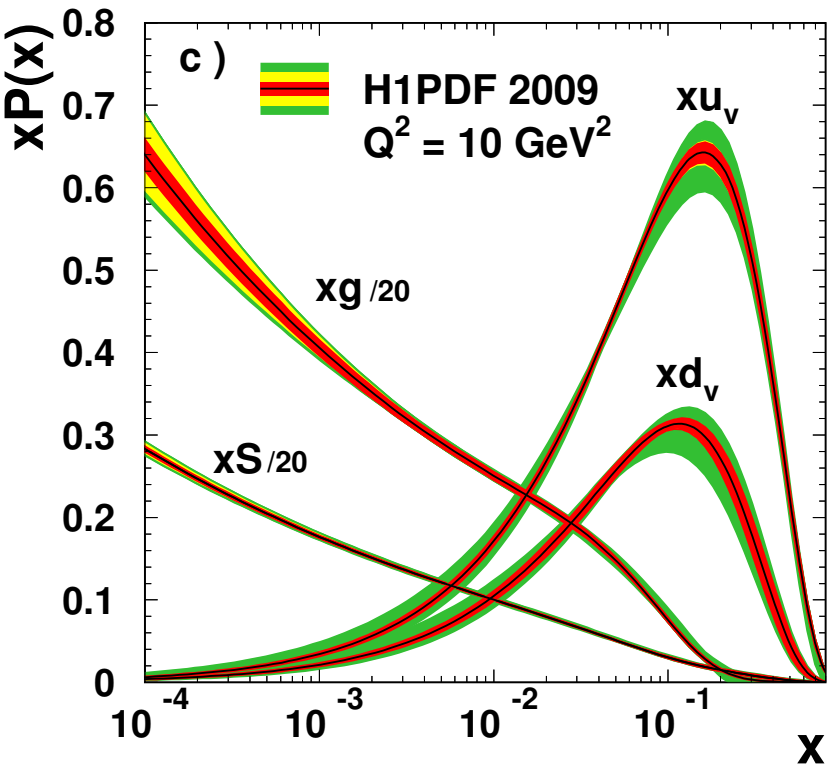
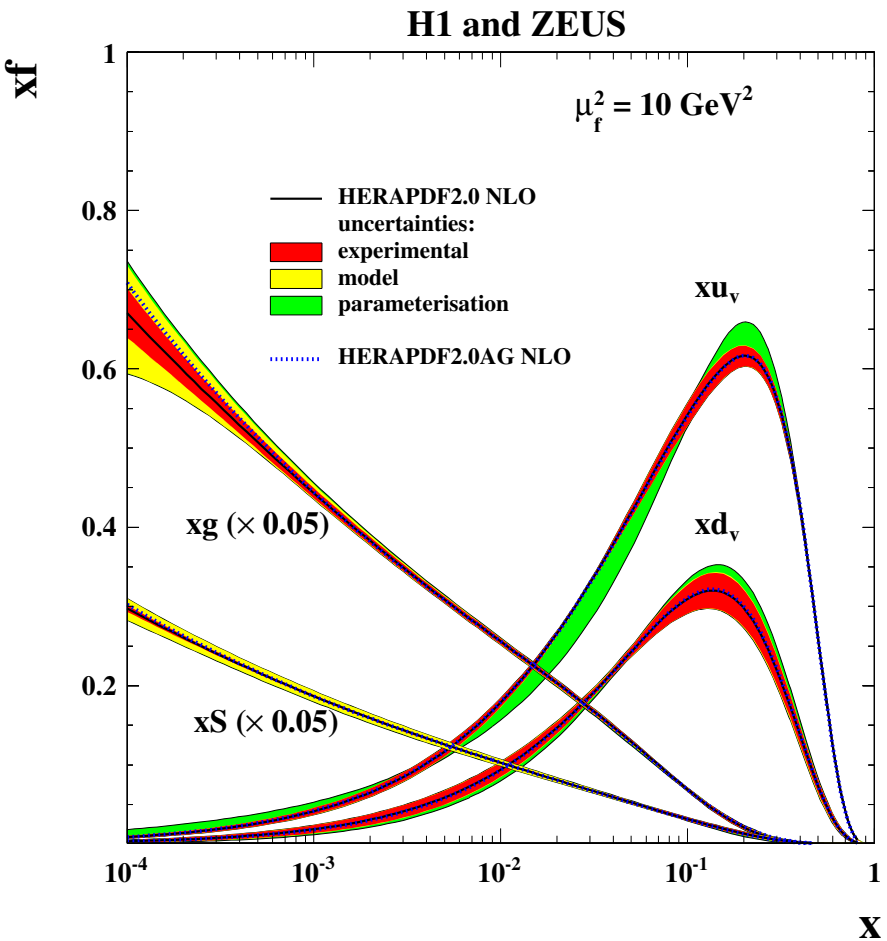


PDF Fit

[EPJ C64 (2009) 561, arXiv:1506.06042]

- Performed a full PDF fit with "H1Fitter", the precursor of "HERAFitter"
- Some new methodology also entering the combined H1+ZEUS PDF fit ("HERAPDF"): decomposition of fitted PDFs, parameterisation uncertainty

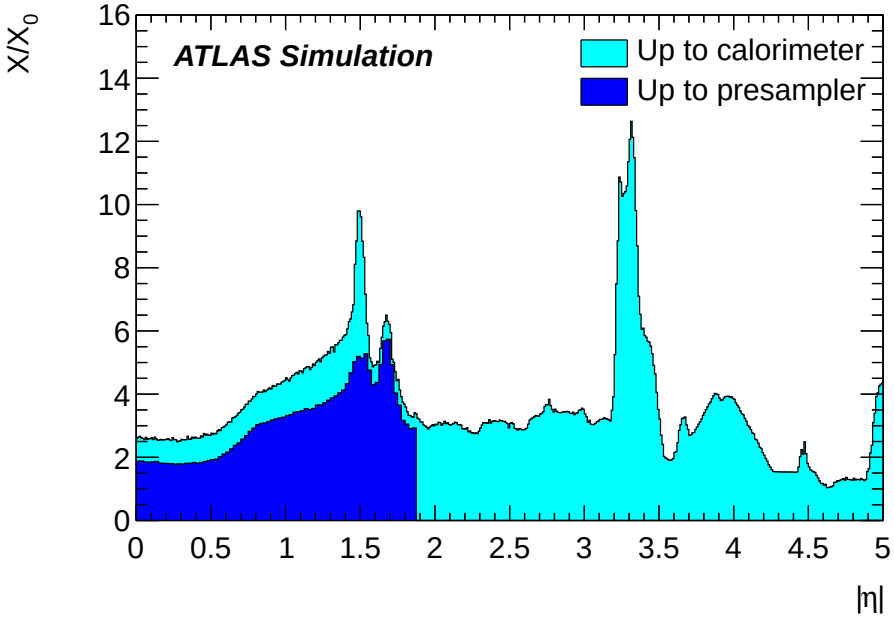


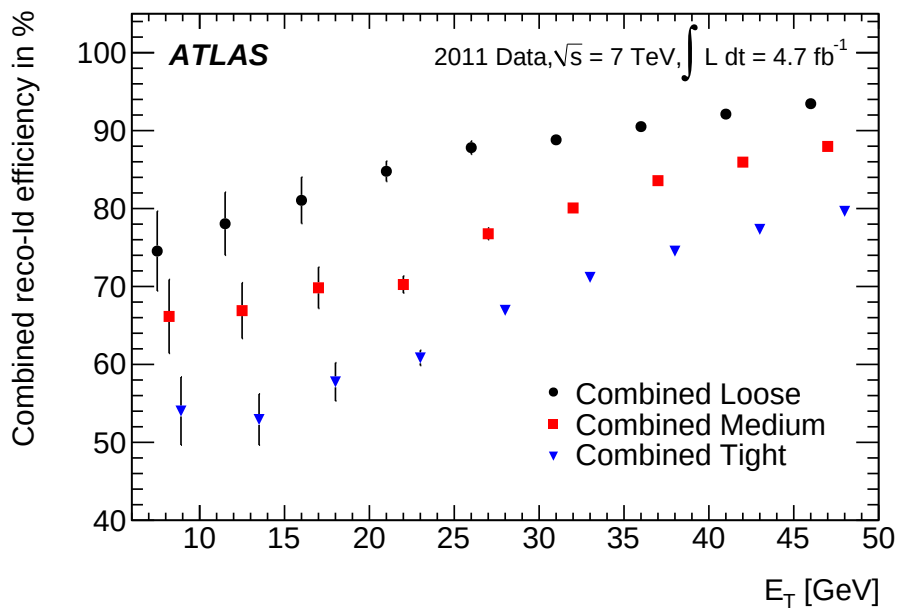


ATLAS Electrons Performance

[EPJ C74 (2014) 3071, EPJ C74 (2014) 2941]

- Worked actively on quantitative understanding of electron performance, electron efficiency co-coordinator for two years
- Published efficiency measurements on 2011 data with $0.2 - 1\%$ precision in the range relevant for W and Z studies through combination of complementary methods





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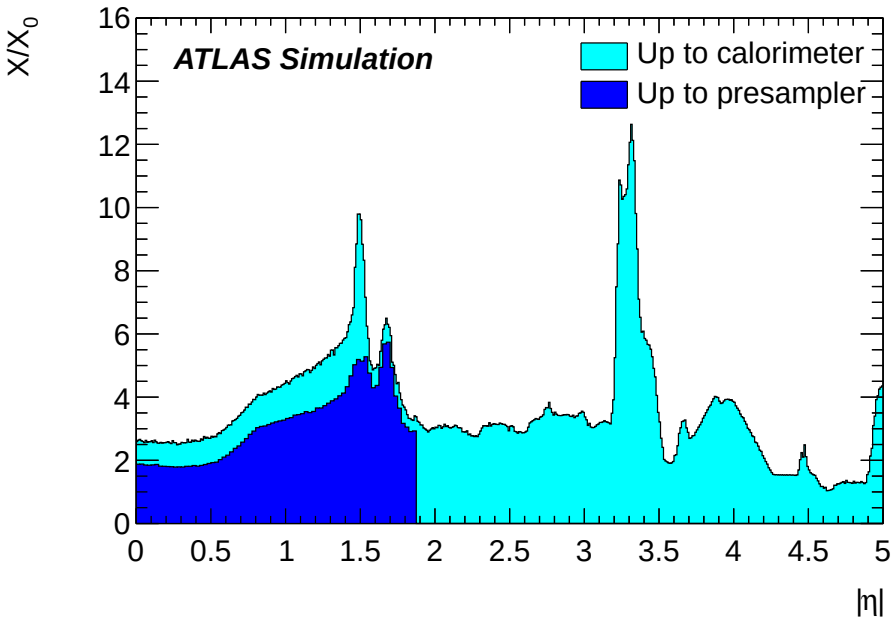
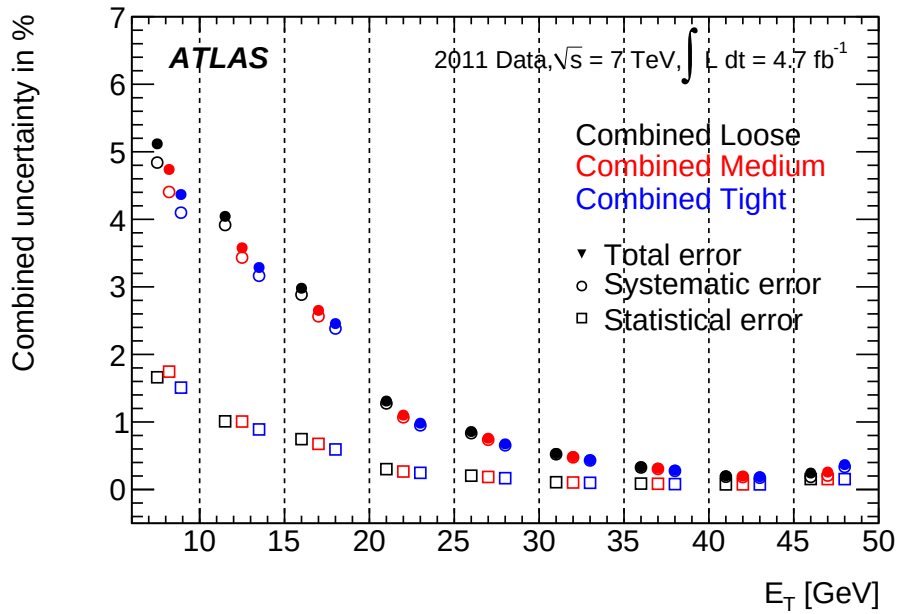
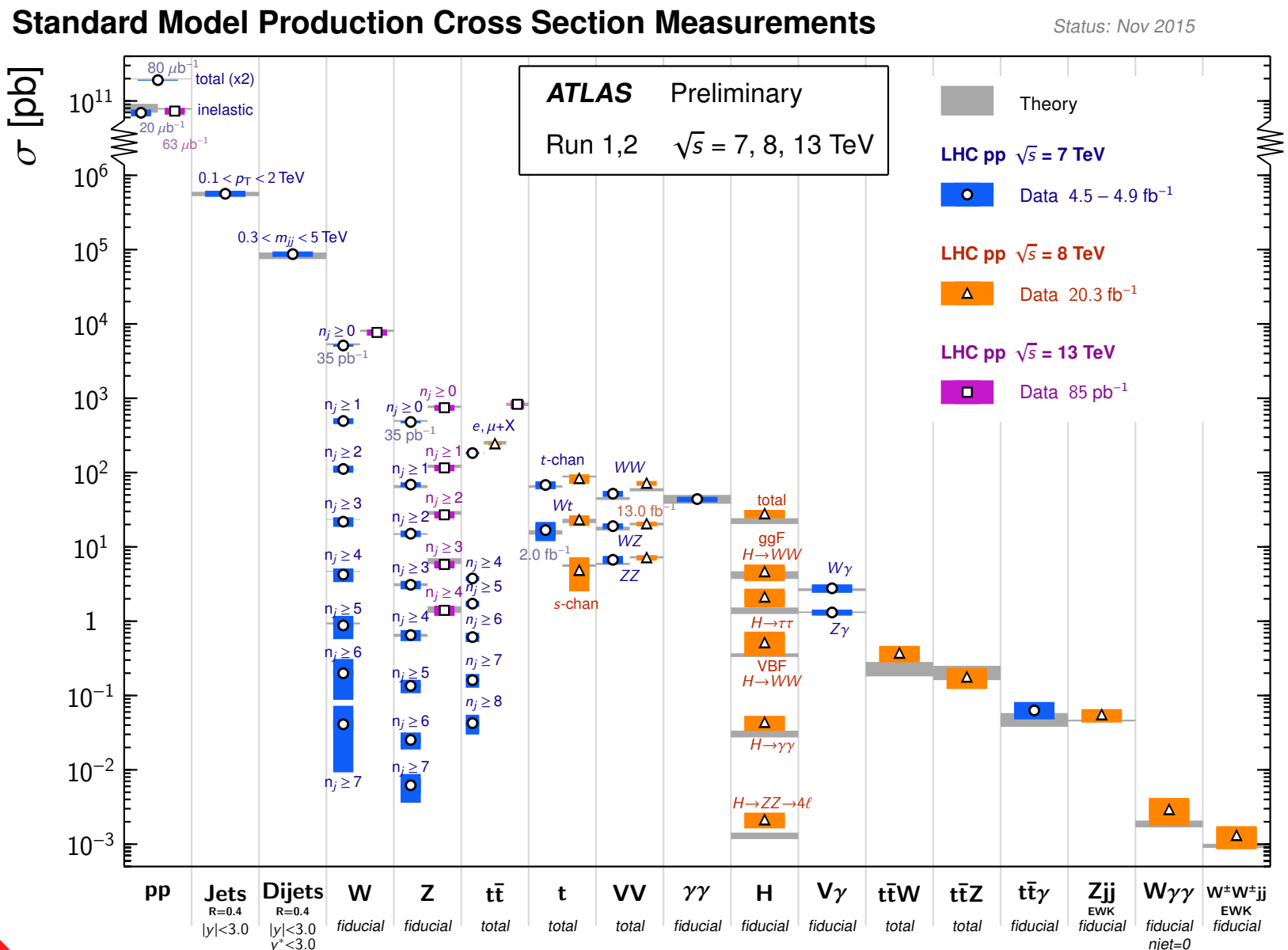




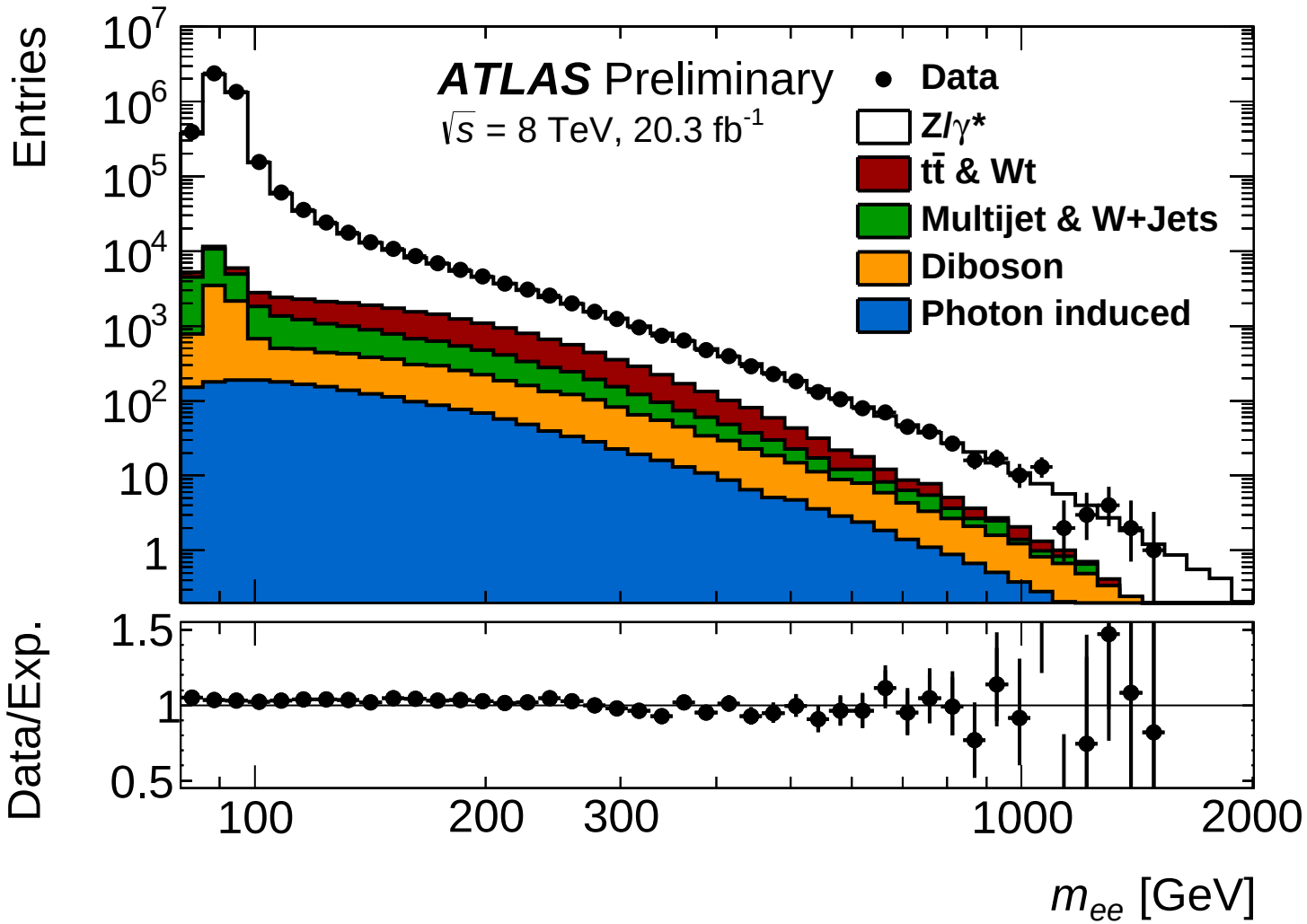
ATLAS Standard Model Group

From the total inelastic pp cross section to $W^{\pm}W^{\pm}jj$ VBS scattering



Dilepton Physics

- High mass $Z/\gamma^* \to \ell\ell$ rich source of physics with high integrated luminosity



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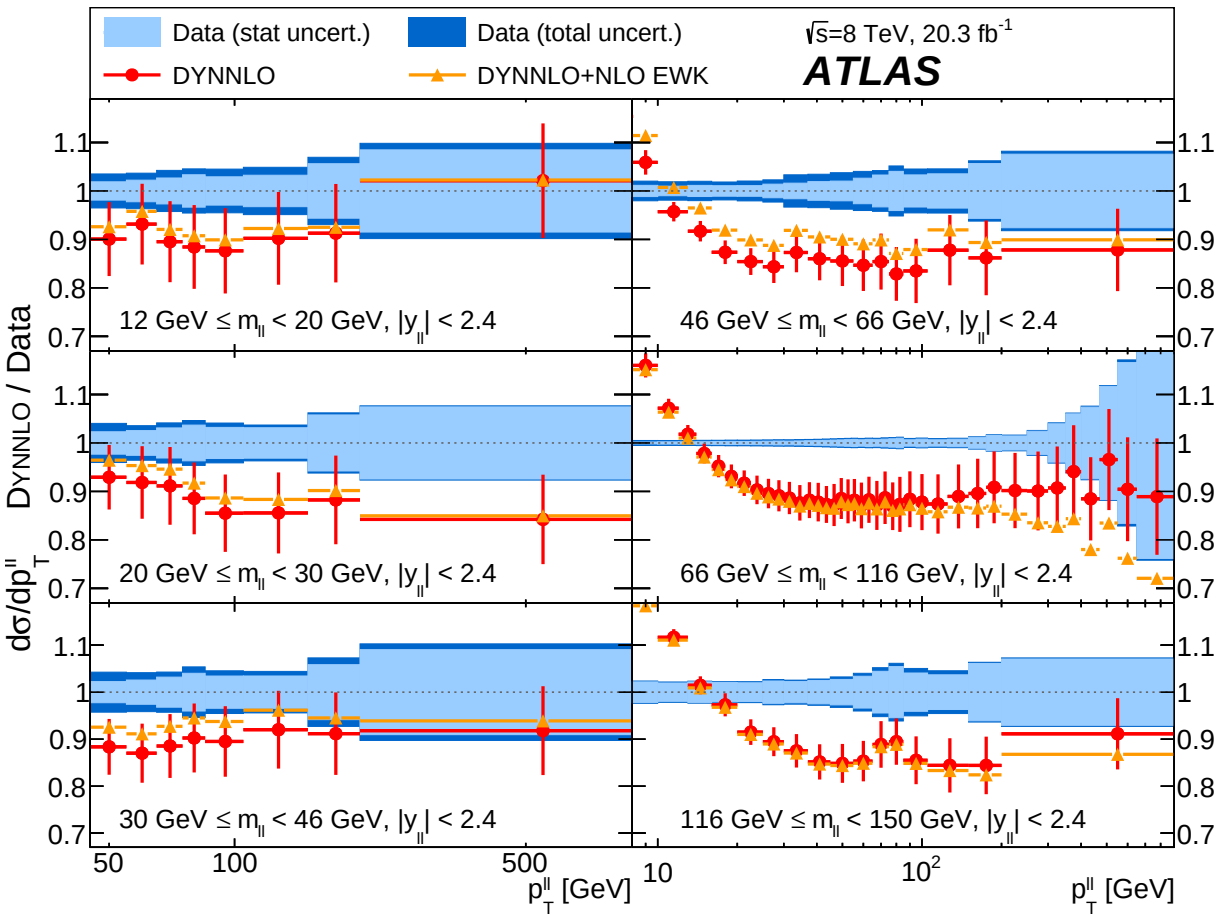
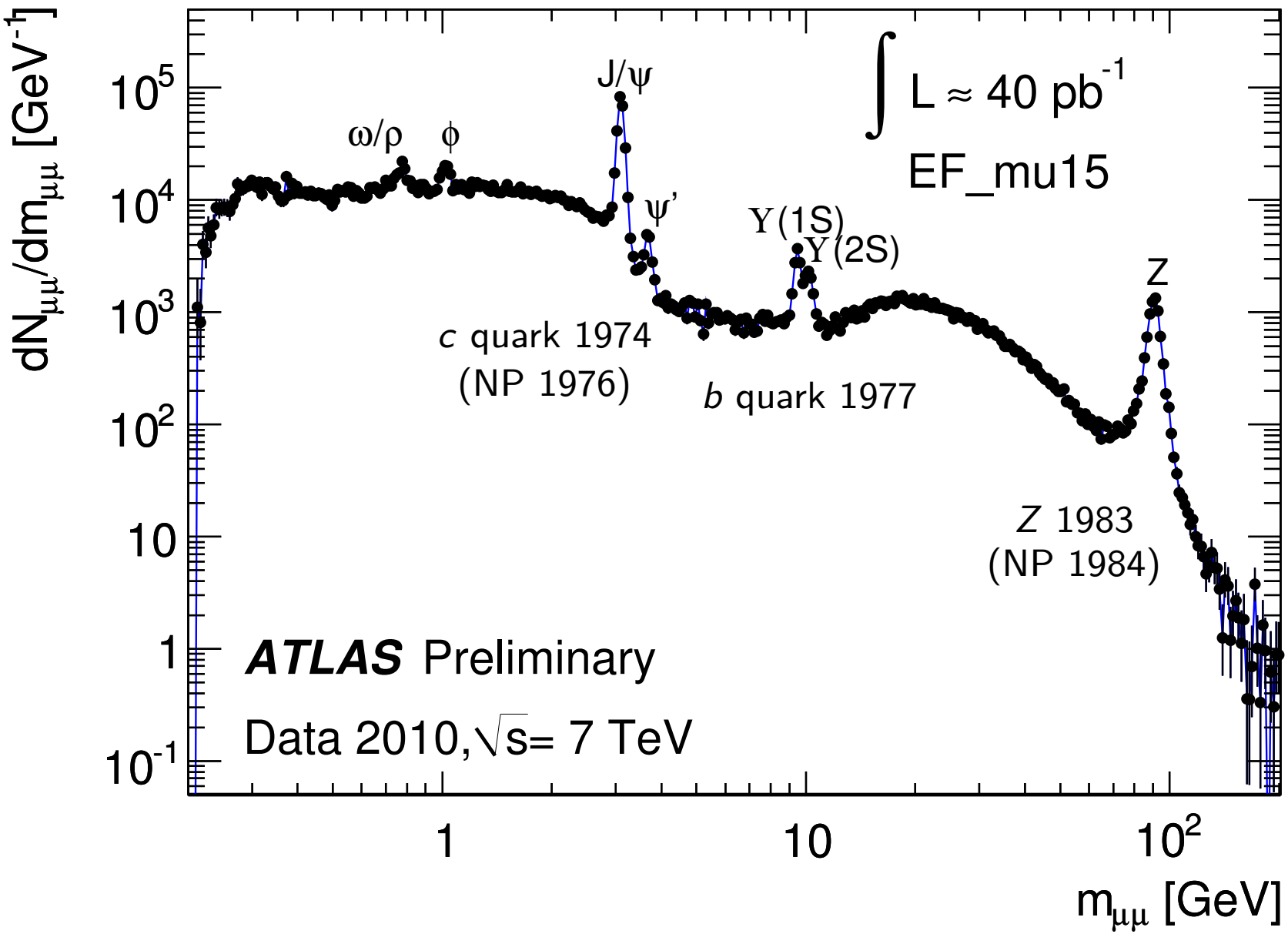
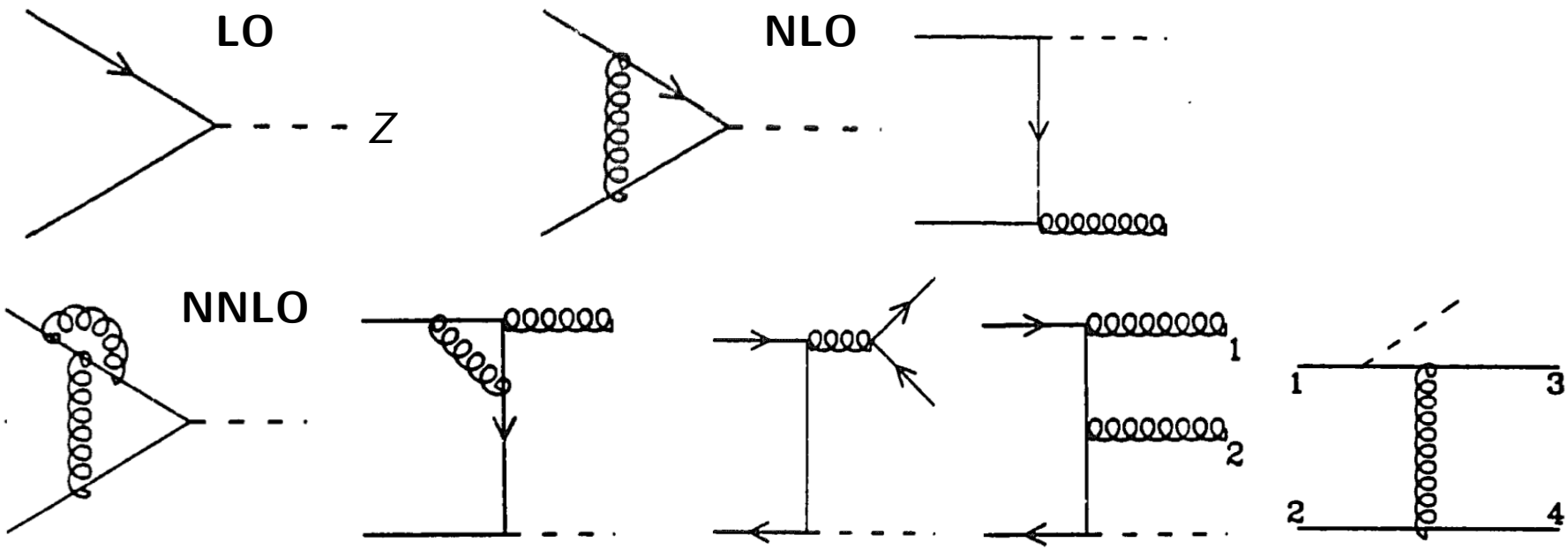


Di-Leptons: A History of Discoveries



W and Z Production in Hadron Collisions

- Study of $W \to \ell\nu$ and $Z/\gamma^* \to \ell\ell$:
  - High experimental precision because of final state isolated leptons and large event samples (e.g. $\sim$ 100M $W \to \ell\nu$ so far)
  - Theory calculations very advanced because of simple, colourless final state: known fully differentially at NNLO QCD (plus NNLL resummation and NLO EWK effects known)
- Enables measurements and interpretation at unique precision level for a Hadron collider, Interesting physics in QCD and Electroweak sector of the SM



Example Diagrams from Hamberg, van Neerven, Matsuura, 1991