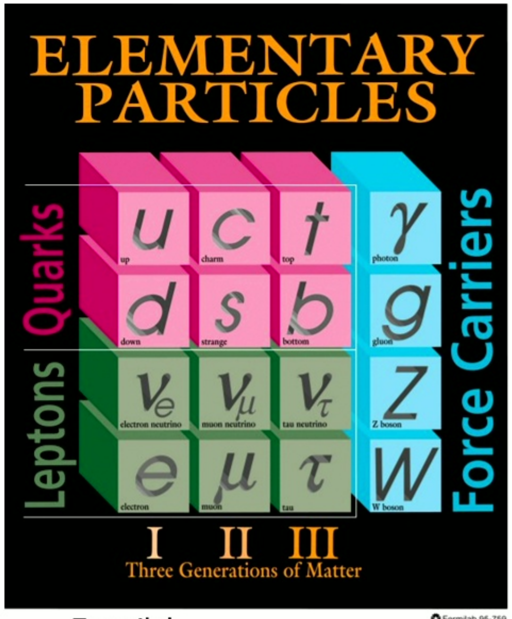
Title: Collider Experiment

Speakers: Manuella Vincter

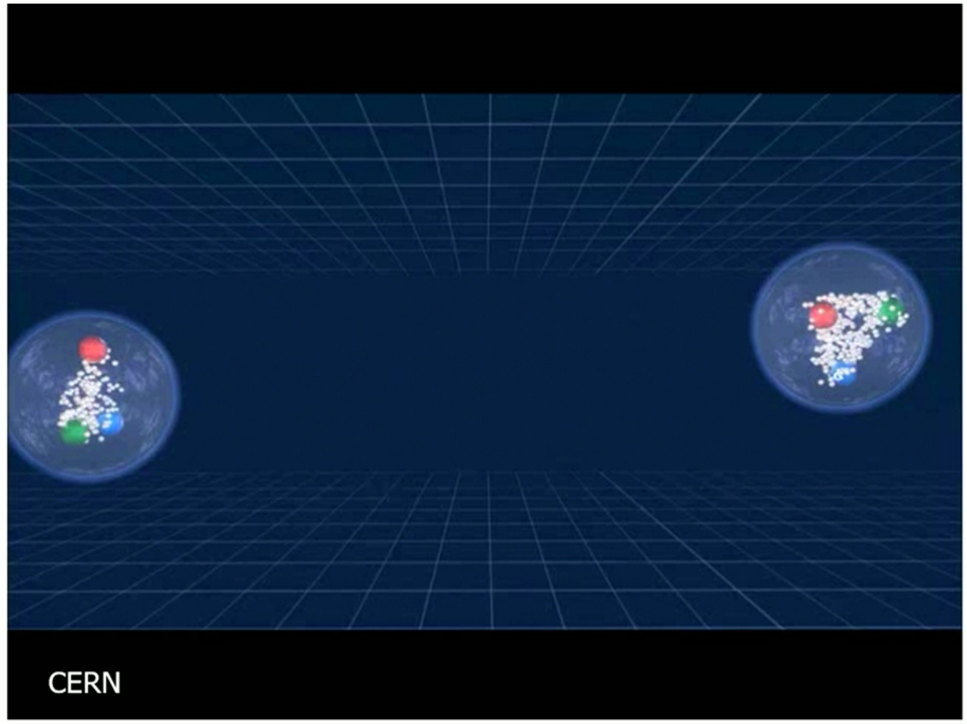
Collection: TRISEP 2023

Date: June 21, 2023 - 11:00 AM

URL: https://pirsa.org/23060059



Fermilab



Z BOSON PRODUCTION

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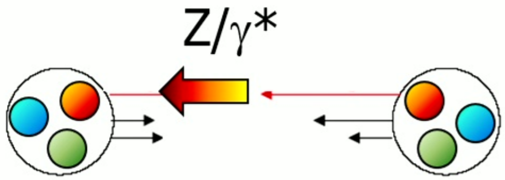
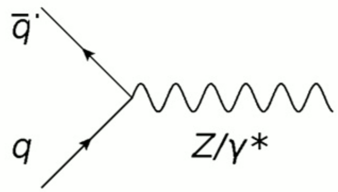
Legal disclaimer: always some small component of γ in the Z sample...

Z/γ^* production

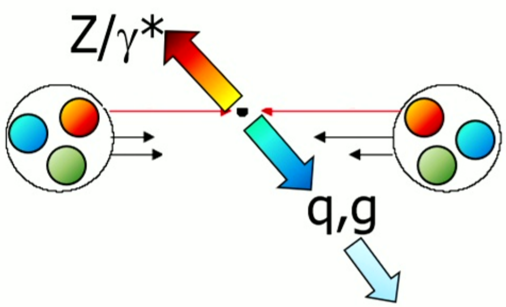
- At born level, Z has nothing to recoil against in the transverse plane
  - Z produced with no transverse momentum p_T

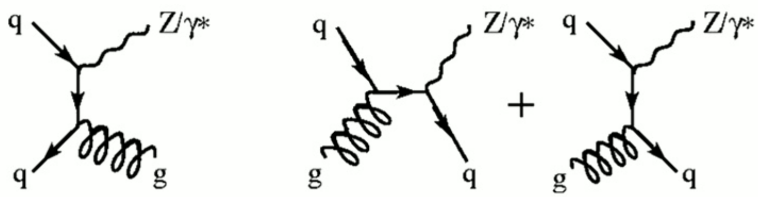




Born-level

- At one gluon emission (order α_s), Z recoils against hadronic products
  - Z produced with transverse momentum!





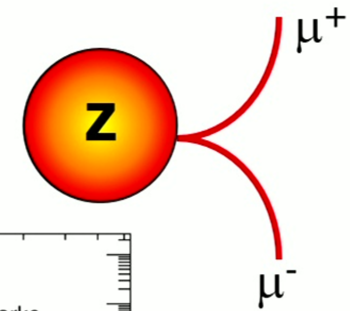
Annihilation

Compton

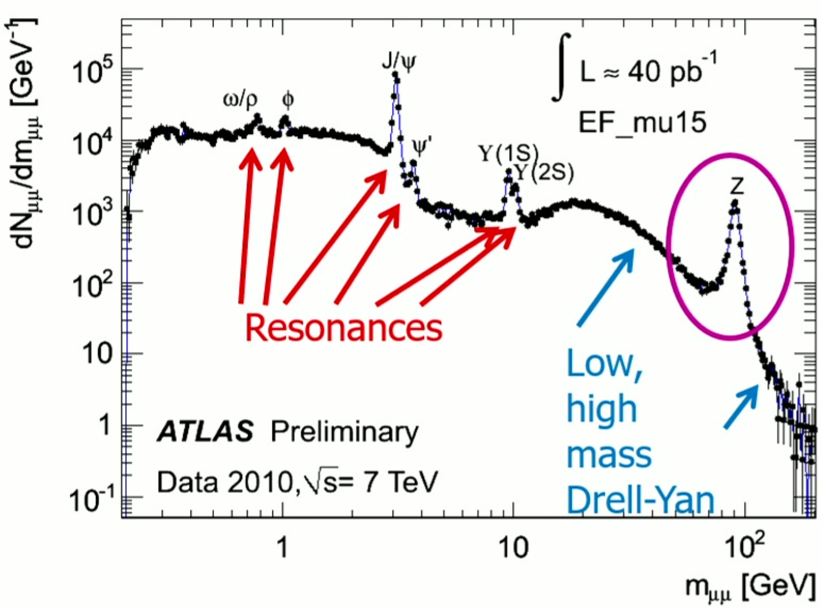
(also other diagrammes...)

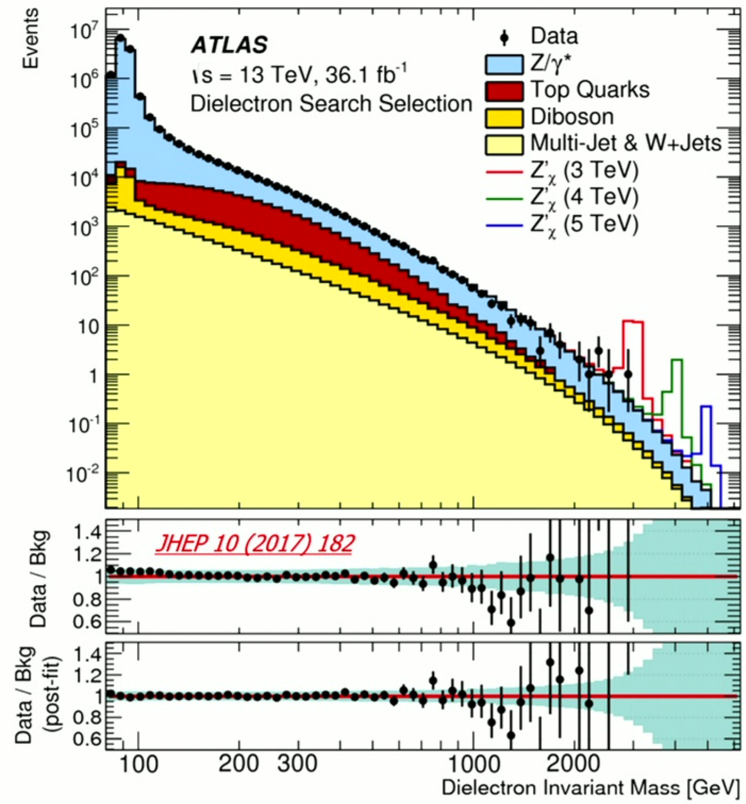
- Z p_T tells us something about the hard interaction!

Z decay



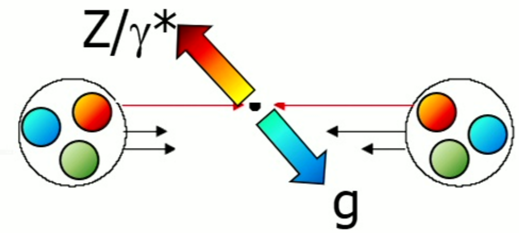
- Z boson (neutral!): decays to quark-antiquark pair or opposite-charge leptons like e^+e^- or $\mu^+\mu^-$
- Use conservation of energy-momentum to build the invariant mass of two-lepton pair: $m_{\ell\ell}$
- A lot going on with this variable!



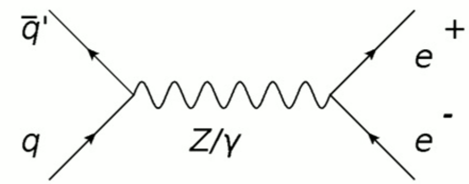


Search for Z′

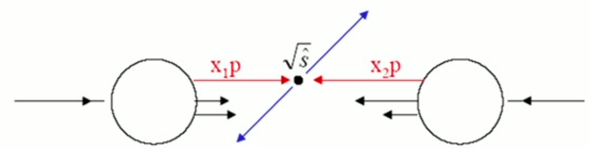
What can we learn from Z production? – Part I



- Via hard scatter, can test perturbative QCD (pQCD) in the absence of colour flow between initial, final states
  - Z balances the hadronic system
    - e.g. gluon hadronises/showers to jet of particles
      - Z+jets production enhances this signature
    - Sensitive to dynamic effects of strong interaction
  - Have predictions up to NNLO → N^{3}LO

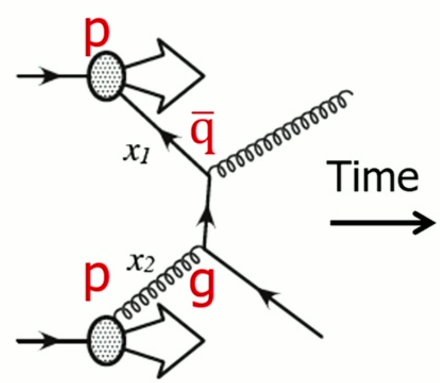


- Sensitive to parton distribution functions of the proton: pdf
  - x_1,x_2 = momentum fraction of partons in protons
  - Hard interaction can be described by perturbative QCD
  - $f_{a,b}$ are the parton distribution functions of partons a,b



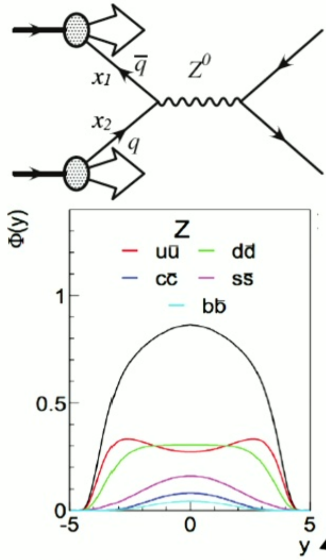
$$\sigma = \sum_{a,b,k} \int dx_1 dx_2 f_a(x_1, Q^2) f_b(x_2, Q^2) \hat{\sigma}^k_{a,b}(x_a, x_b)$$

- Partons a,b can be q, q̄, or g

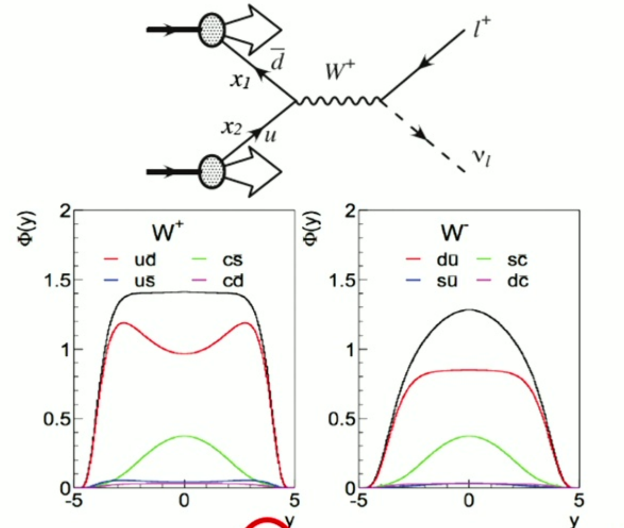


What can we learn from Z production? – Part II

- Electroweak boson production sensitive to valence and sea quark distributions



Rapidity
y



$$Z \quad \sim 0.29(u\bar{u} + c\bar{c}) + 0.37(d\bar{d} + s\bar{s} + b\bar{b})$$

$$W^+ \quad \sim 0.95(u\bar{d} + c\bar{s}) + 0.05(u\bar{s} + c\bar{d})$$

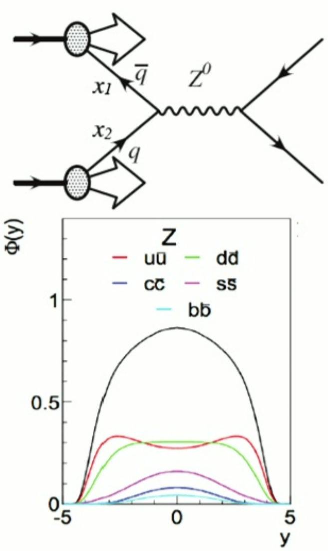
$$W^- \quad \sim 0.95(d\bar{u} + s\bar{c}) + 0.05(d\bar{c} + s\bar{u})$$

- W^+ production dominates over W^- production at the LHC. pp collisions: p = $u_v u_v d_v$
  - Equally produced at Tevatron: p$\bar{\text{p}}$ collisions
- W production constrains valence quark pdfs
- Z production provides sensitivity to poorly known strange quark pdfs

Figs from M. Sutton Moriond 2014, U. Klein DIS 2012

Global fits to extract PDFs

- DY production at LHC probes PDFs in the region $x \approx 10^{-4}$-10^{-1} and $Q^2 \approx 5\times10^2$-10^6 GeV^2
- Feed e.g. $W^{\pm}$, Z/γ^*, W+charm cross section information into global fits to extract PDFs
  - All data have differing sensitivity to different aspects of the proton's PDFs.
  - EW boson production sensitive to valence and sea quark distributions



Rapidity y

(related at LO to momentum fraction x)

$Z \sim 0.29(u\bar{u} + c\bar{c}) + 0.37(d\bar{d} + s\bar{s} + b\bar{b})$

Result: e.g testing relationship between strange and light sea

Parameterise PDFs:

$xg(x) = A_g x^{B_g}(1-x)^{C_g} + \ldots$

$xu_v(x) = \ldots$

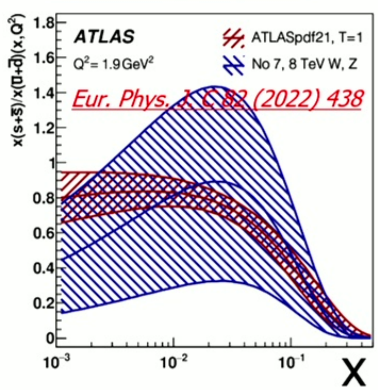
$xd_v(x) = \ldots$

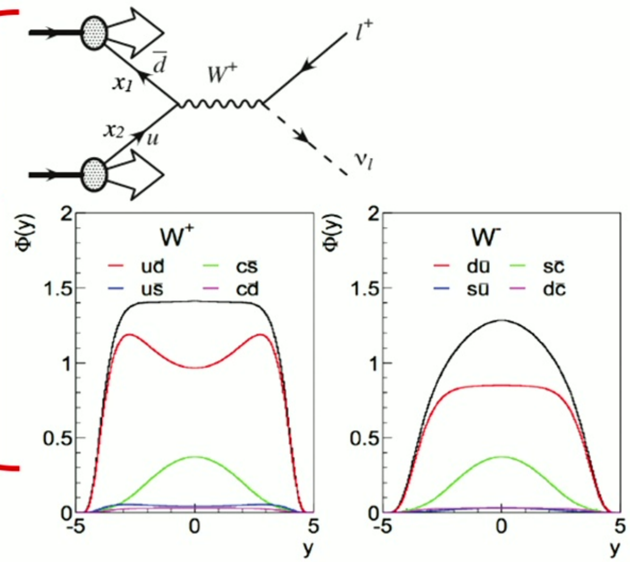
$x\bar{u}(x) = \ldots$

$x\bar{d}(x) = \ldots$

$xs(x) = \ldots$

$x\bar{s}(x) = \ldots$





$W^+ \sim 0.95(u\bar{d} + c\bar{s}) + 0.05(u\bar{s} + c\bar{d})$

$W^- \sim 0.95(d\bar{u} + s\bar{c}) + 0.05(d\bar{c} + s\bar{u})$

$x_1 = \frac{M_W}{\sqrt{s}} e^{y} \qquad x_2 = \frac{M_W}{\sqrt{s}} e^{-y}$

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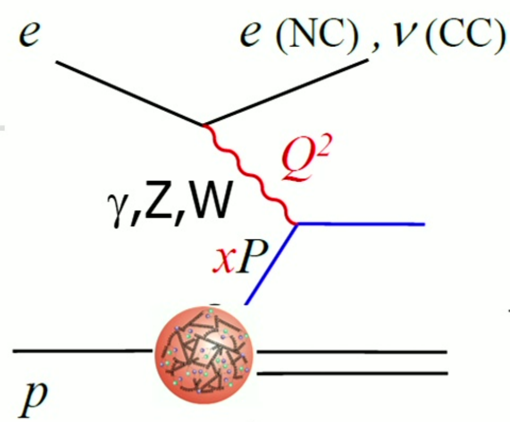
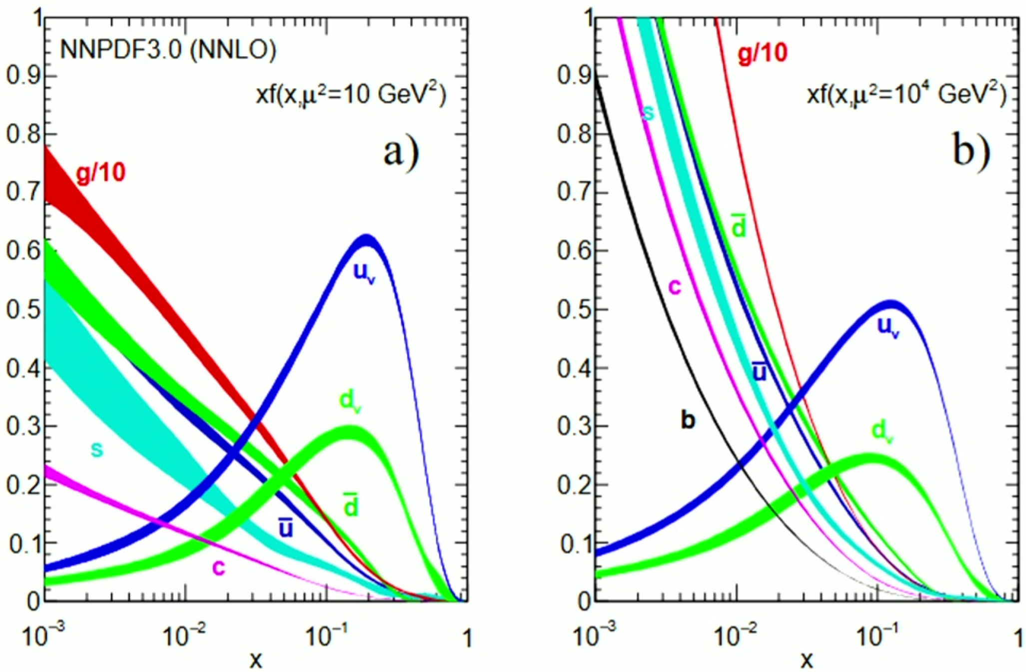
Global fits using proton PDF-sensitive data: HERA

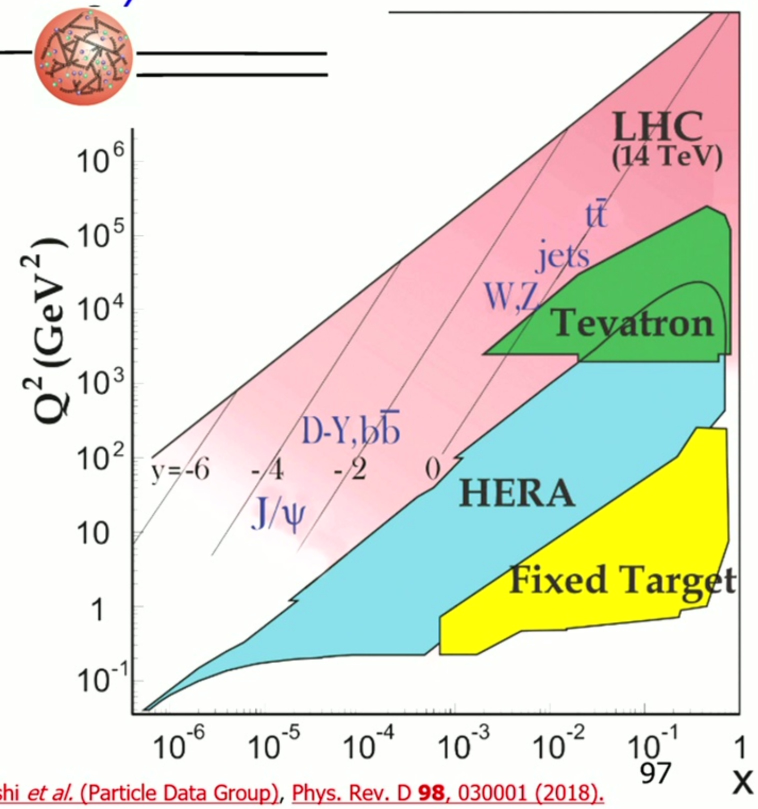
- Even more powerful to combine all world data sensitive to PDF
- HERA (ZEUS and H1) at DESY was the Queen:
  - $e^{\pm}p$ neutral-current (NC) and charged-current (CC)
  - Unpolarised parton distributions f(x) at different scales μ^2

$$(\text{where } f = u_v, d_v, \overline{u}, \overline{d}, s \simeq \bar{s}, c = \bar{c}, b = \bar{b}, g)$$

HERA@DESY
Started: 1992
Ended: 2007





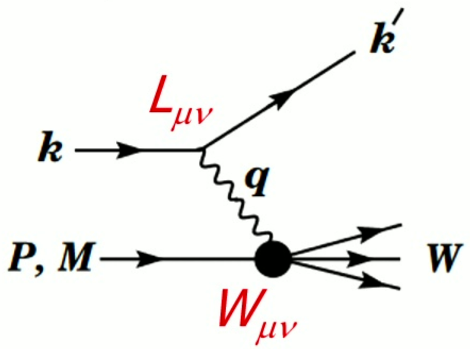


M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).

M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).

Structure functions

x = fraction of nucleon's momentum carried by struck quark
y = fraction of lepton's energy lost in nucleon rest frame
$Q^2 = -q^2$ = exchange particle's four-momentum transfer to nucleon
η = factors related to propagators and couplings



$$\frac{d^2\sigma}{dx\,dy} = \frac{2\pi y\alpha^2}{Q^4}\sum_j \eta_j\, L_j^{\mu\nu}\, W_{\mu\nu}^j \qquad j = \gamma, Z \text{ and } \gamma Z$$

$$\frac{d^2\sigma^i}{dx\,dy} = \frac{4\pi\alpha^2}{xyQ^2}\,\eta^i\left\{\left(1 - y - \frac{x^2y^2M^2}{Q^2}\right)F_2^i + y^2xF_1^i \mp \left(y - \frac{y^2}{2}\right)xF_3^i\right\},$$

For the neutral-current processes $ep \to eX$,

$$\left[F_2^\gamma,\, F_2^{\gamma Z},\, F_2^Z\right] = x\sum_q \left[e_q^2,\, 2e_q g_V^q,\, g_V^{q\,2} + g_A^{q\,2}\right](q + \overline{q}),$$

$$\left[F_3^\gamma,\, F_3^{\gamma Z},\, F_3^Z\right] = \sum_q \left[0,\, 2e_q g_A^q,\, 2g_V^q g_A^q\right](q - \overline{q}),$$

For the charged-current processes $e^- p \to \nu X$ and $\overline{\nu} p \to e^+ X$,

$$F_2^{W^-} = 2x(u + \overline{d} + \overline{s} + c \ldots),$$

$$F_3^{W^-} = 2(u - \overline{d} - \overline{s} + c \ldots),$$

- Lower-Q^2 NC data constrain low-x sea-quark distribution but can't distinguish between quark flavours in the sea at low x, or between the down-type quarks, $\bar{d}$ and $\bar{s}$ at any x.
- Diff between NC e^+p and e^-p cross sections at high Q^2, together with high-Q^2 CC data, constrains valence distributions: u_v, d_v.
- Q^2 dependence measured in the data constrains the gluon distribution

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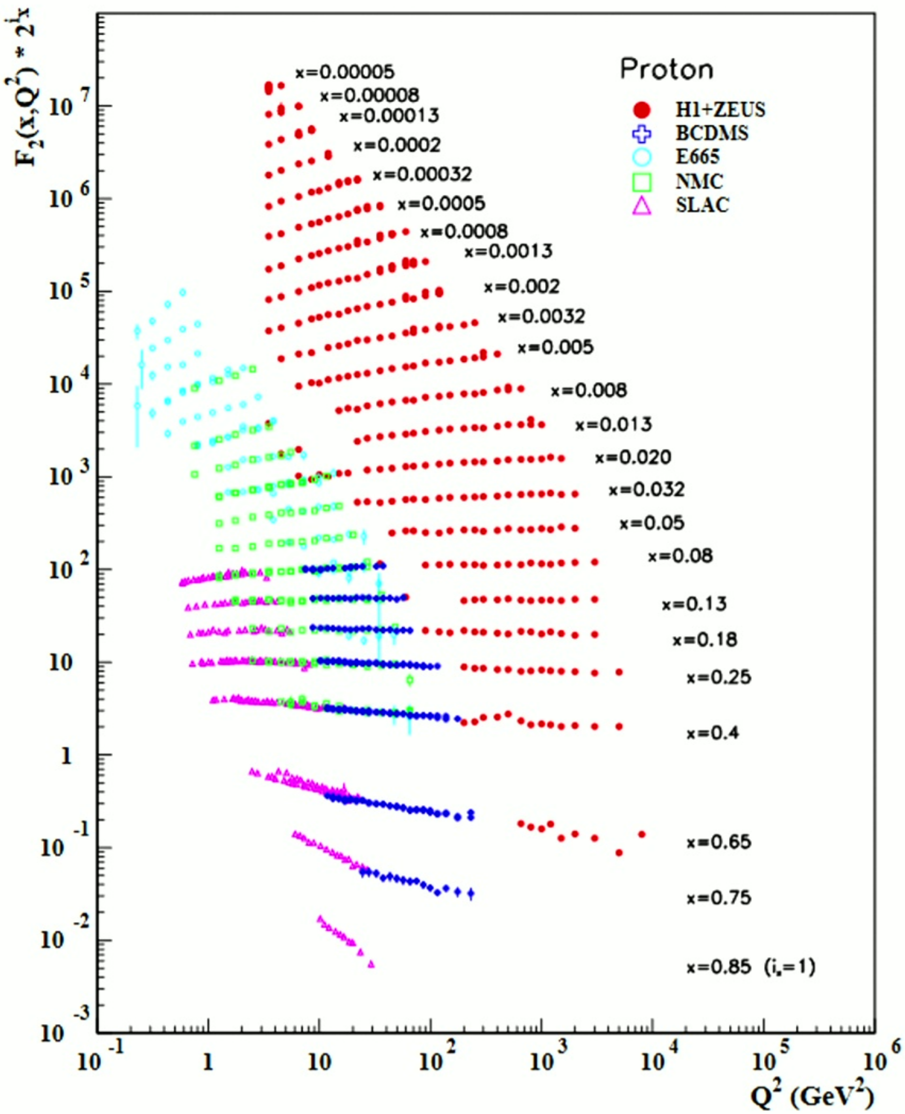
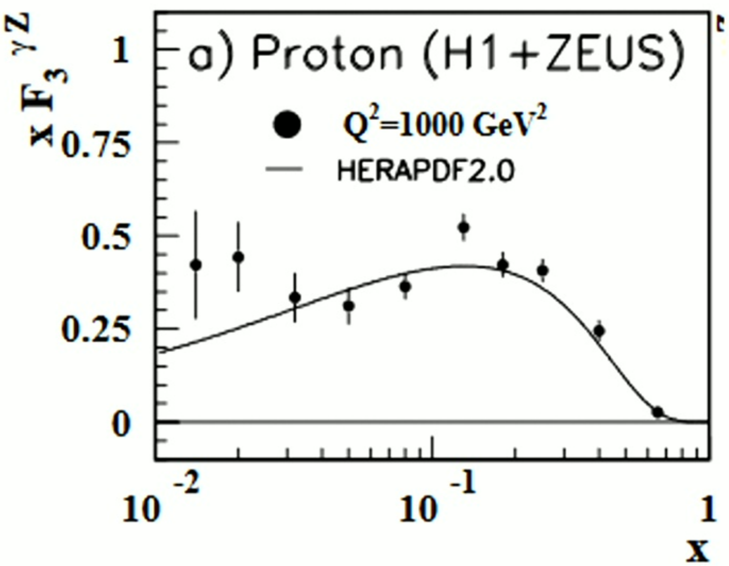


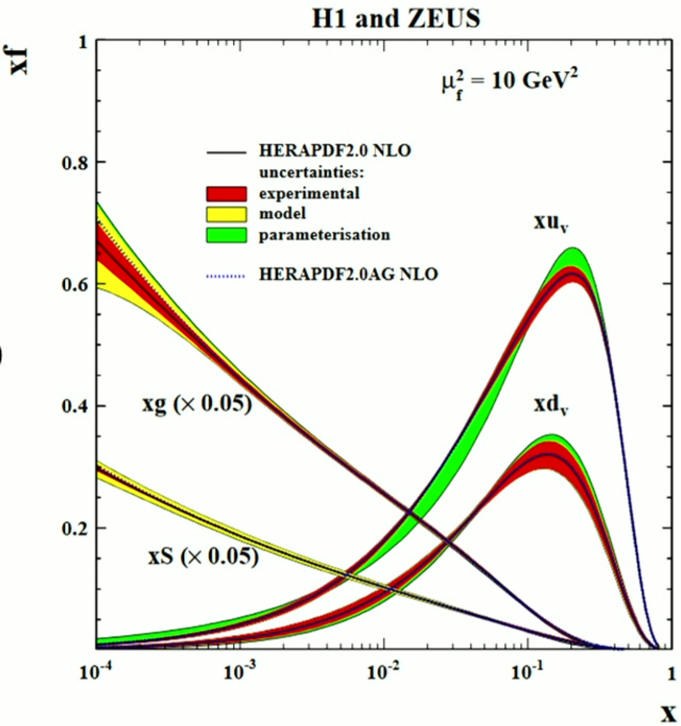


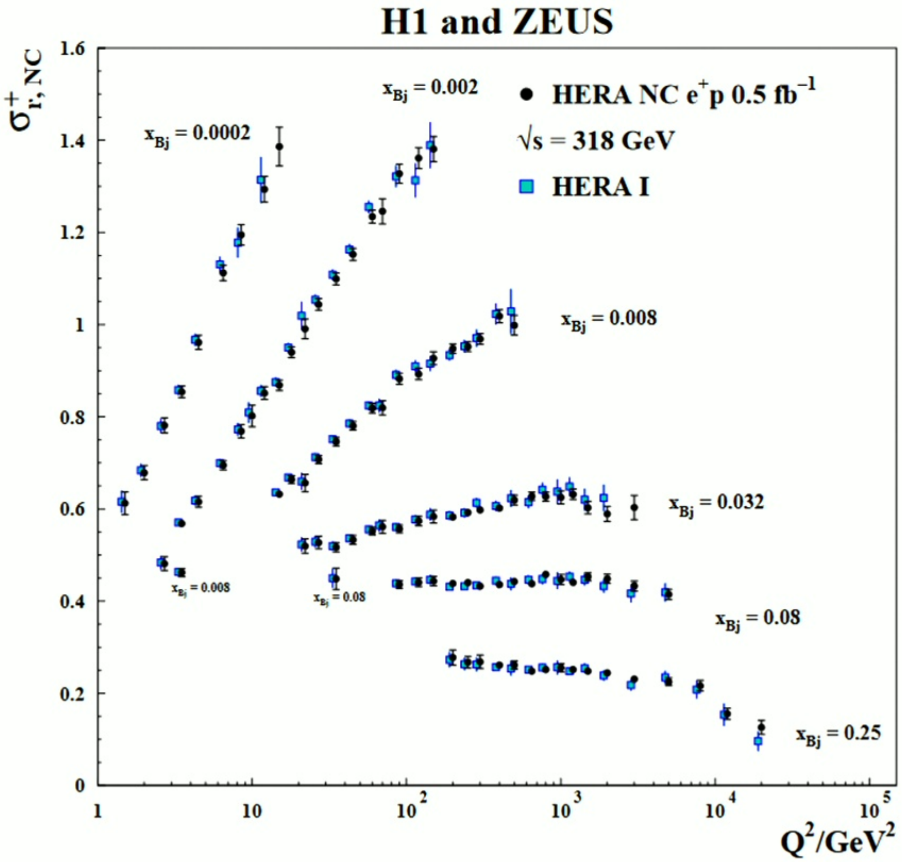
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018). 99

HERA wealth of proton information

- HERA used NC and CC (reduced) deep-inelastic cross sections (related to structure functions) to determine sets of proton quark and gluon momentum distributions
  - HERAPDF2.0 (all HERA data: HERA I+HERA II)

gluon & sea distributions scaled down by factor 20





combined HERA data for the inclusive NC e^+p reduced cross sections as a function of Q^2 for six selected values of x

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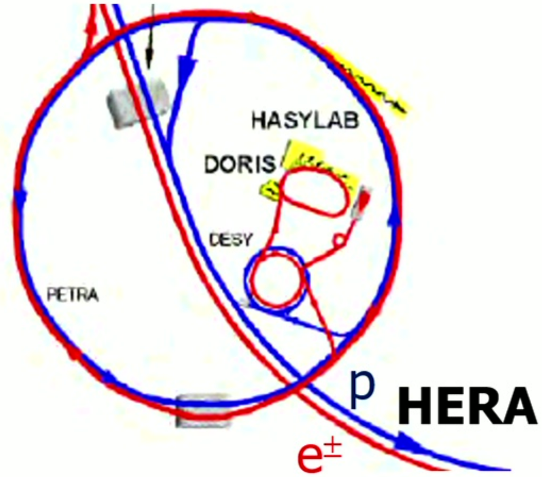
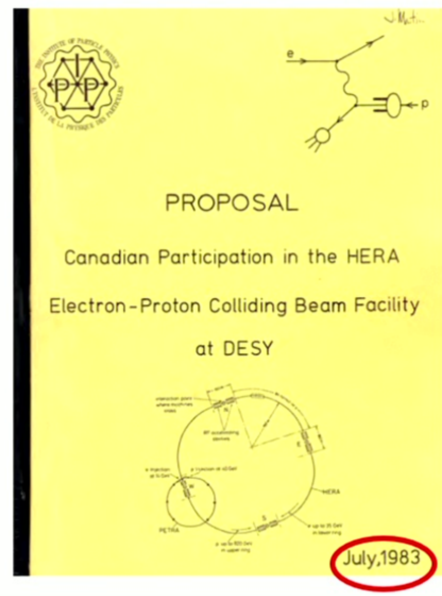
Canadian participation in HERA

HERA proton accelerator complex:

- protons from negatively charged H^- ions, pre-accelerated to 50 MeV in linear accelerator → injected into proton synchrotron DESY-III & accelerated to 7 GeV → transferred PETRA & accelerated to 40 GeV → injected into storage ring in HERA & accelerated to 920 GeV.
- Proposal to NSERC/NRC for HERA (approval end of 1983: $5M)
  - Chalk River Nuclear Laboratories: 52 MHz proton RF cavities installed in proton HERA ring which "captured" proton bunches injected from PETRA before acceleration in HERA.
  - TRIUMF: transfer beam line from H^- ion linac to DESY-III ~$3M
    - Magnets, mechanical, diagnostics, debuncher
- Canada was the first country funded, which led directly to approval in Germany (eventually 11 countries)
- This was first major contribution by Canada to an international accelerator!




PROPOSAL

Canadian Participation in the HERA

Electron-Proton Colliding Beam Facility

at DESY

July,1983

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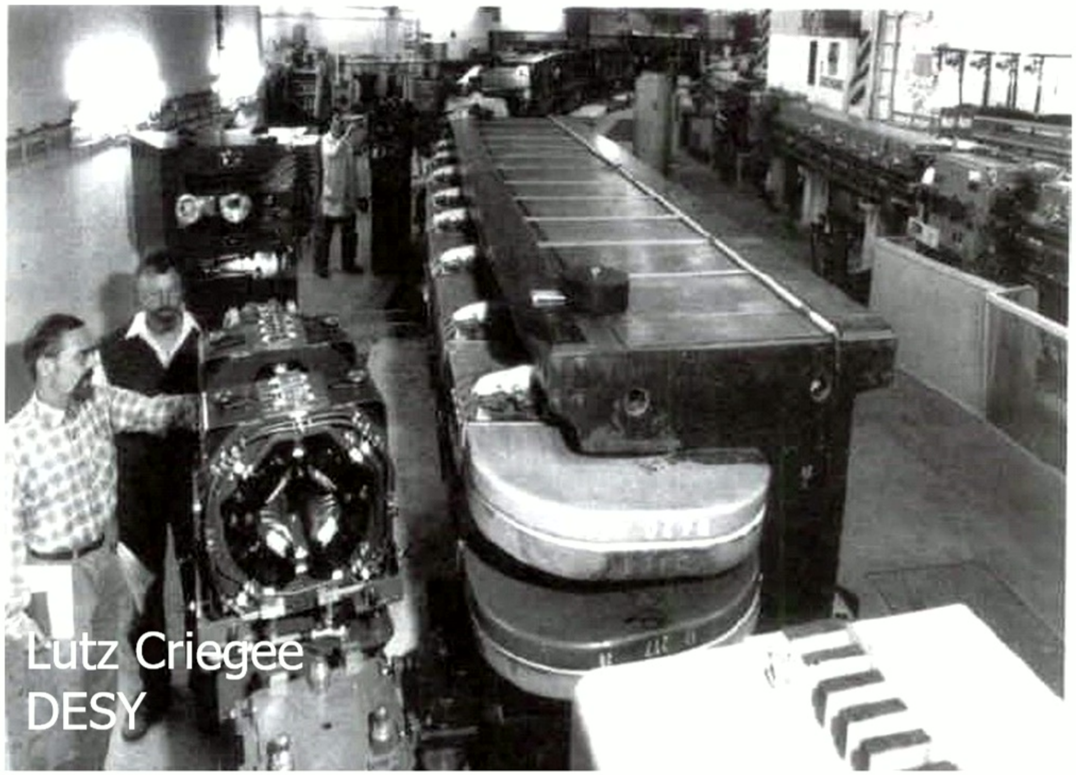
Beam line equipment provided by TRIUMF being installed at DESY in 1986



The magnets were made by a company called K&S Tool and Die located in Winnipeg

ZEUS: proton structure

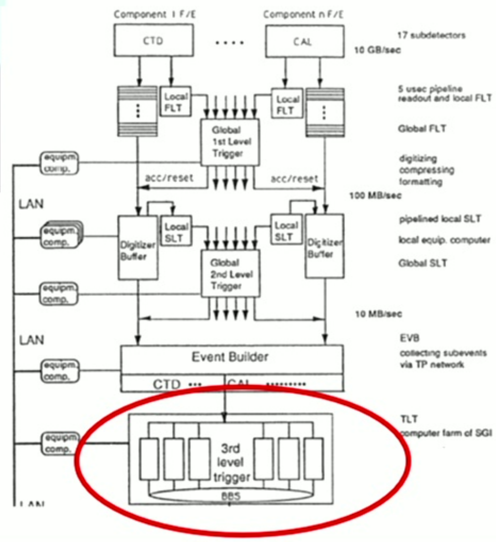
Canada was a founding member of ZEUS

- Joined in 1982, ZEUS approved in 1984
- Manitoba, McGill, Toronto, York
- NSERC funding for calorimeter, trigger: 1986-7 (~$11M)

Sampling calorimeter (fully compensating)

- Layers of absorber DU (uranium) & scintillator

Trigger: first collider where parallel pipelines for data and trigger were developed



HERMES: polarised deep-inelastic scattering (nucleon spin structure)

- Canada was a founding member of HERMES
  - 1988: LoIs and feasibility study.
    - Canada joined just after the LoIs
  - Approval in 1992
  - Firm foundations within TRIUMF!
    - (TRIUMF, SFU, Alberta)

MPI H - 1988 - V24
(August 1988)

Feasibility Studies for an Experiment to Measure the Spin Dependent Nucleon Structure Functions at HERA

P.Delhej, L.G. Greeniaus, O. Häusser, R. Henderson, P. Kitching
C.A. Miller, M. Vetterli
TRIUMF, Vancouver, Canada

  - NSERC funding of Transition Radiation Detector
    - Construction grant 1992-6 $1.3M

DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY
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9.10.1992

To the spokesmen of the HERMES collaboration
Dr. R. Milner, MIT Boston
Dr. K. Rith, MPI Heidelberg

Dear colleagues,

I am pleased to inform you that the DESY directorate has today conditionally approved the HERMES-experiment following the recommendation of the PRC. This approval is subject to a clarification of the contributions to the HERMES-experiment and the funding situation of the participating institutes and also of the technical and financial implications the experiment will have on DESY.

We are all looking forward to an exciting physics program with HERMES at HERA!

Sincerely yours
Volker Soergel

Direktorium: Dr. H. Krech, Dr. J. May, Prof. Dr. V. Soergel (Vorsitzender), Prof. Dr. G.-A. Voss, Prof. Dr. A. Wagner

Letter from the DESY director V. Soergel with conditional approval of HERMES

ATLAS combinations with HERAPDF2.0

- Combine ATLAS W, Z/γ^* data, ttbar data and V+ jets data in a single fit.

Data set	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	Decay channel	Observables entering the fit
Inclusive $W, Z/\gamma^*$ [9]	7	4.6	e, μ combined	η_ℓ (W), y_Z (Z)
Inclusive Z/γ^* [13]	8	20.2	e, μ combined	$\cos\theta^*$ in bins of $y_{\ell\ell}, m_{\ell\ell}$
Inclusive W [12]	8	20.2	μ	η_μ
$W^\pm$ + jets [24]	8	20.2	e	p_T^W
Z + jets [25]	8	20.2	e	p_T^{jet} in bins of $\lvert y^{jet}\rvert$
$t\bar{t}$ [26, 27]	8	20.2	lepton + jets, dilepton	$m_{t\bar{t}}, p_T^t, y_{t\bar{t}}$
$t\bar{t}$ [15]	13	36	lepton + jets	$m_{t\bar{t}}, p_T^t, y_t, y_{t\bar{t}}^b$
Inclusive isolated γ [14]	8, 13	20.2, 3.2	-	E_T^γ in bins of η^γ
Inclusive jets [16–18]	7, 8, 13	4.5, 20.2, 3.2	-	p_T^{jet} in bins of $\lvert y^{jet}\rvert$

- Important to properly take into account correlated systematics!
  - e.g. jets common to many final states
- quark distributions at the starting scale

$$xq_i(x) = A_i x^{B_i}(1-x)^{C_i} P_i(x), \quad \text{where } P_i(x) = (1 + D_i x + E_i x^2 + F_i x^3).$$

  - $xq_i(x)$ chosen to be valence quark (xu_v, xd_v) and light anti-quark sea xubar, xdbar, xsbar
- Gluon distribution

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} P_g(x) - A'_g x^{B'_g}(1-x)^{C'_g}$$

- Contributions of the data sets to the total χ^2 of the fit

Total χ^2/NDF	2010/1620
HERA χ^2/NDP	1112/1016
HERA correlated term	50
ATLAS W, Z 7 TeV χ^2/NDP	68/55
ATLAS Z/γ^* 8 TeV χ^2/NDP	208/184
ATLAS W 8 TeV χ^2/NDP	31/22
ATLAS W and Z/γ^* 7 and 8 TeV correlated term	71 = (38 + 33)
ATLAS direct γ 13/8 TeV χ^2/NDP	27/47
ATLAS direct γ 13/8 TeV correlated term	6
ATLAS V+jets 8 TeV χ^2/NDP	105/93
ATLAS $t\bar{t}$ 8 TeV χ^2/NDP	13/20
ATLAS $t\bar{t}$ 13 TeV χ^2/NDP	25/29
ATLAS inclusive jets 8 TeV χ^2/NDF	207/171
ATLAS V+jets 8 TeV and $t\bar{t}$ + jets 8,13 TeV and R = 0.6 inclusive jets 8 TeV correlated term	87 = (16 + 9 + 21 + 41)

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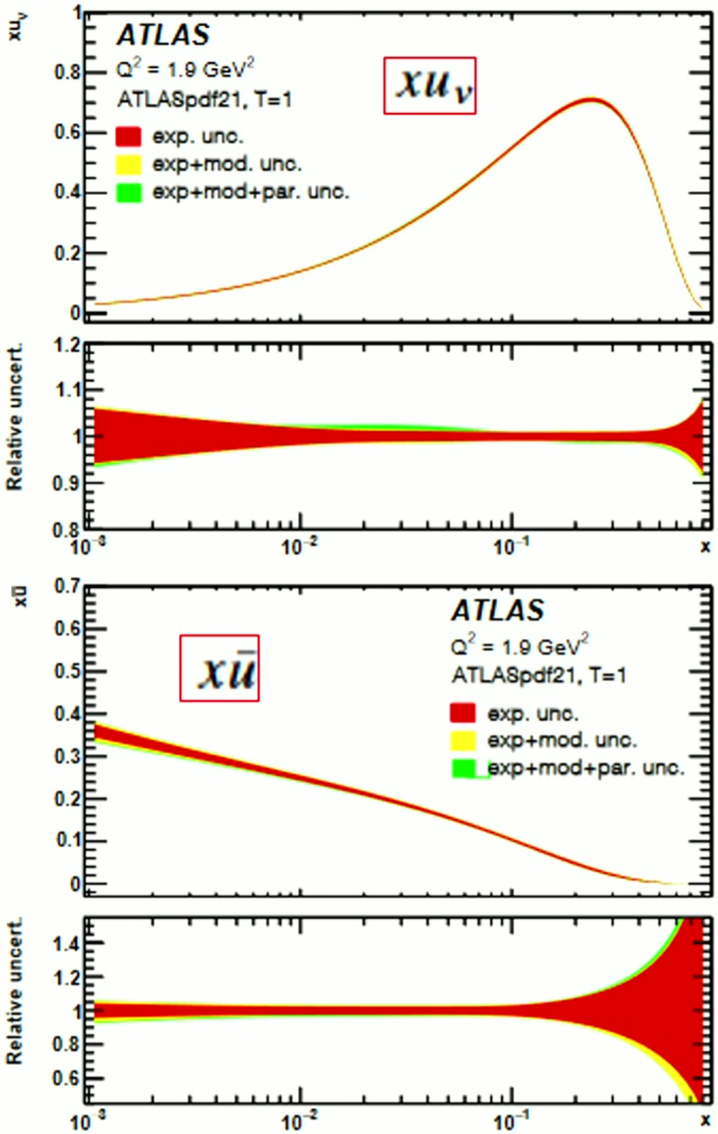
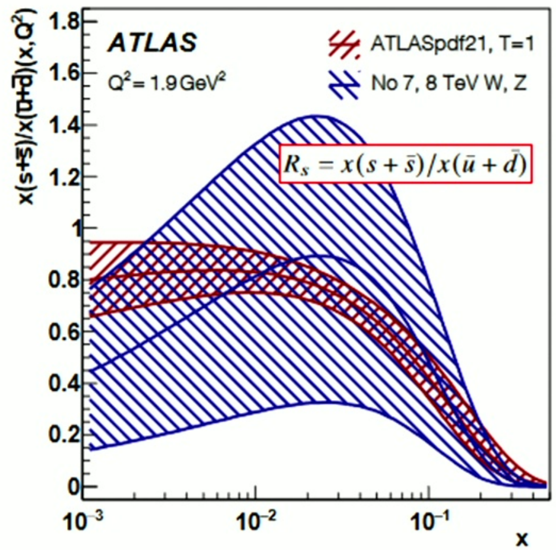
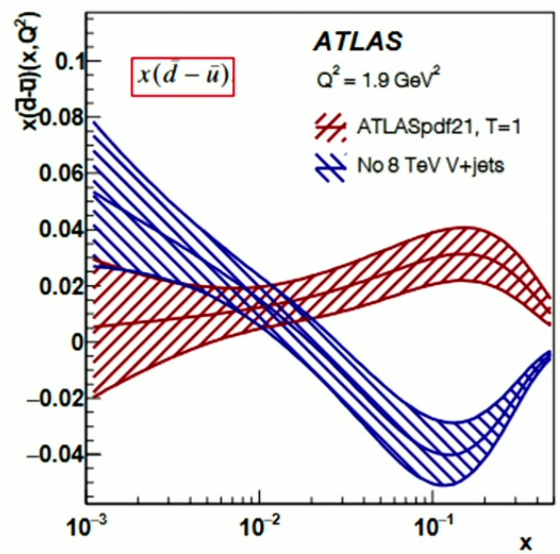


Outcome of global fit

- Precision is exquisite
- Some datasets have a huge impact on the global fit!





- Since proton collisions are at the heart of every physics result at the LHC, it is important that these are measured properly.

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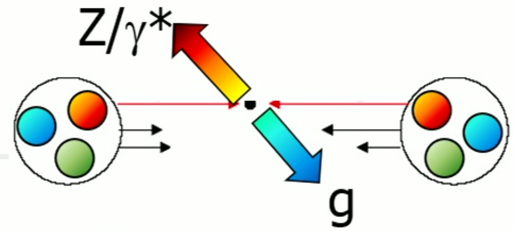
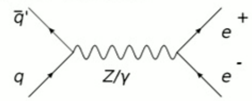
What can we learn from Z production? – Part III

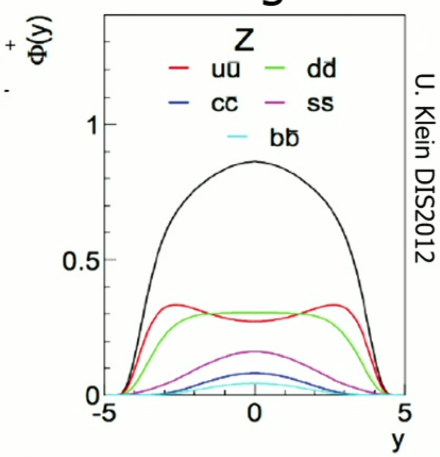


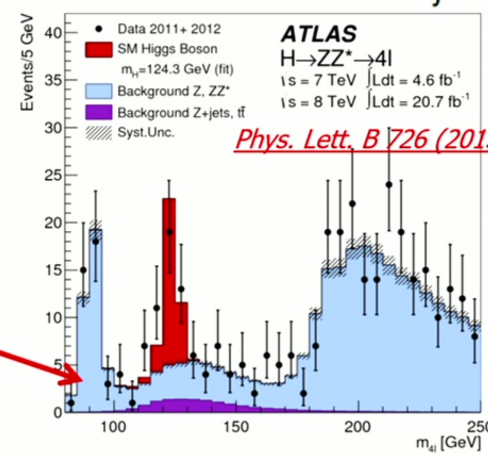
- Via hard scatter, can test perturbative QCD (pQCD) in the absence of colour flow between initial, final states
  - Z balances the hadronic system
    - e.g. gluon hadronises/showers to jet of particles
      - Z+jets production enhances this signature
    - Sensitive to dynamic effects of strong interaction
  - Have predictions up to NNLO
- Sensitive to the parton distribution functions of the proton
  - Antiquarks at large x
  - Some sensitivity to poorly known strange quarks



$$Z \sim 0.29(u\bar{u} + c\bar{c}) + 0.37(d\bar{d} + s\bar{s} + b\bar{b})$$

- Z production can be a significant background in "new physics" processes
  - Exotic new particles: Z′
  - Higgs production H→4ℓ:
    - ZZ(*) →4ℓ is biggest background
  - Precision measurements could reveal new physics!





Phys. Lett. B 726 (2013), pp. 88-119

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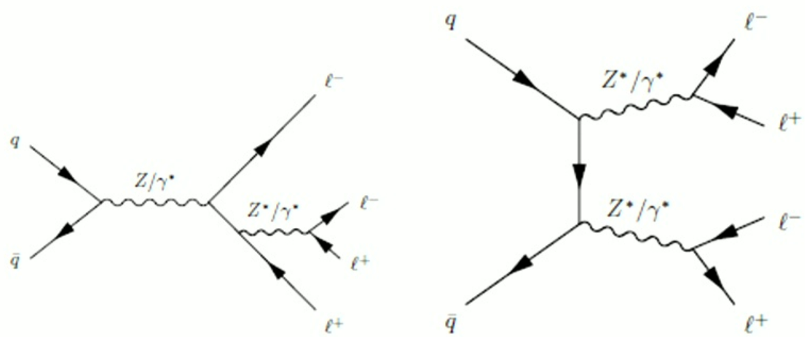
Dedicated measurement: $Z \rightarrow 4l$

- Use this channel to show you how to measure a cross section with real data!
  - Use old Run-1 measurement as data is conveniently displayed
- Measured in a dedicated analysis, combining 3 final states
  - $Z \rightarrow 4e$, 4μ, $2e+2\mu$

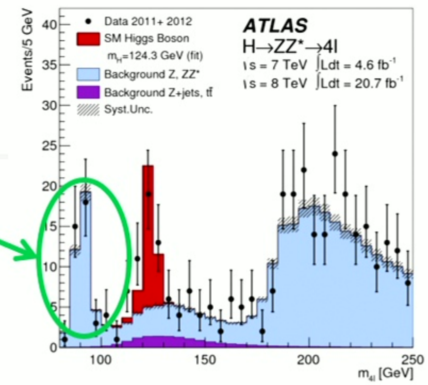
Measurement of the 4ℓ Cross Section at the Z Resonance and Determination of the Branching Fraction of $Z \rightarrow 4\ell$ in pp Collisions at $\sqrt{s}$ = 7 and 8 TeV with ATLAS

arXiv:1403.5657v1 [hep-ex] 22 Mar 2014

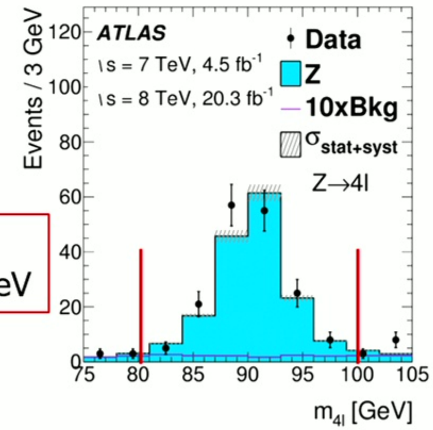


(a) (b)

FIG. 1. Examples of (a) s-channel and (b) t-channel Feynman diagrams for 4ℓ production in pp collisions.



Mass window:
m_{4l} = 80-100GeV



Invariant mass distribution of 4 leptons: m_{4l} (assuming massless leptons)

e.g. for $Z \rightarrow 2l$, m_{ll} is:

$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2$$
$$= m_1^2 + m_2^2 + 2\,(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2)\,.$$

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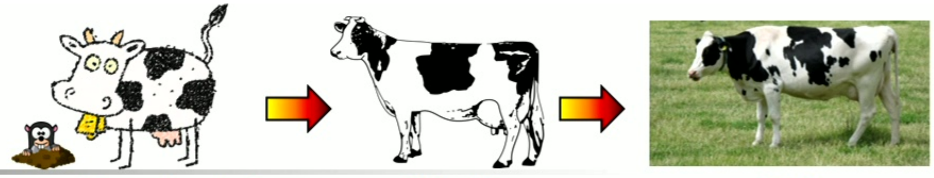
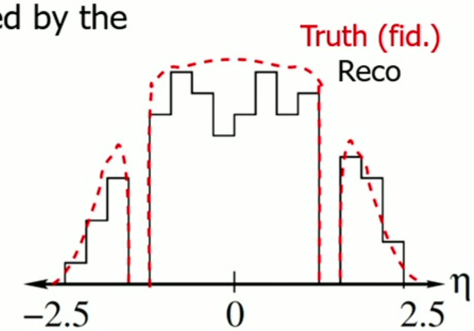
Cross section methodology



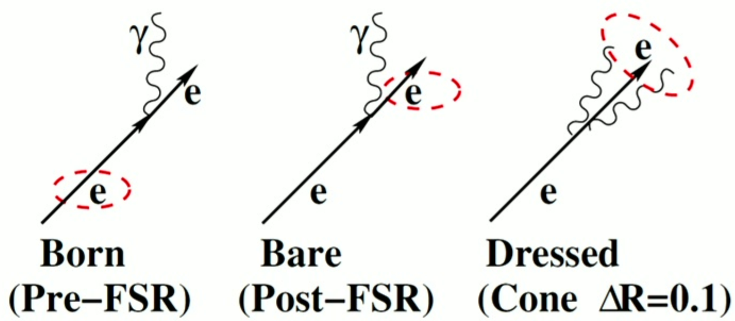
- Experiments select events that enhance the physics signal that they want to measure
  - W: 1 prompt, energetic, isolated charged ℓ + ν giving rise to E_T^{miss}: $W \to \ell\nu$
  - Z: 2 prompt, energetic , isolated charged ℓ, same flavour, opposite sign: $Z \to \ell^+\ell^-$
- Leptons reconstructed within pseudorapidity η and transverse momentum p_T ranges afforded by the detector
  - Fiducial phase space e.g. requirements on:
    - $p_{T,\ell}$, η_ℓ, $p_{T,\nu}$, m_T^W, $m_{\ell\ell}$

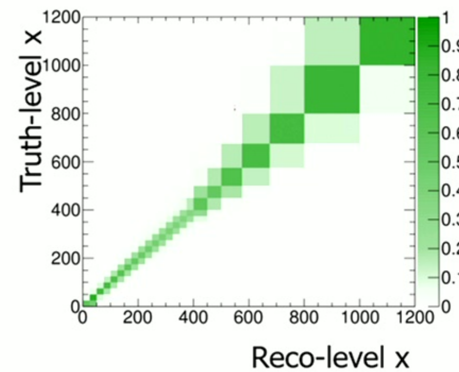


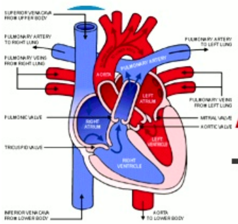
- Measurements reported (to the world) in fiducial or full phase-space
- Use simulation to unfold data from "reconstruction" to "truth" level
- Correction factor: reconstruction $\to$ truth level in fiducial region
- Acceptance: truth fiducial region $\to$ full truth phase-space

Cross-section measurement reported at one or more levels:

- Born, bare, dressed:







Anatomy of a cross section: simple sketch

σ

\# cand. evts

\# bkg evts

$$\sigma_{W,Z} \times BR(W,Z \to l\nu, ll) = \frac{N - B}{A_{W,Z} \cdot C_{W,Z} \cdot \mathcal{L}_{W,Z}}$$

Integrated lumi

A: acceptance factor from fiducial to full phase space (entirely from truth info and so can have considerable theory uncertainties)

C: correction factor from reco to fiducial

$$C = \frac{\text{Expected \# evts passing selection at reco}}{\text{Expected \# evts passing selection at truth}}$$

C includes MC-to-data correction factors (with uncertainties) for object reconstruction, identification, triggering, etc… as well as (usually small) theory uncertainties associated with going from reco to truth.

Going to differential cross sections in 1D, 2D etc… Important to think about the correlations in the uncertainties between the variables

$$\frac{d\sigma}{dx}, \left(\frac{d^2\sigma}{dxdy}\right), \ldots$$

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Steps to measure a cross section, σ – part I

Crudest approximation for a cross section at 8TeV:

Mass window: m_{4l} = 80-100GeV

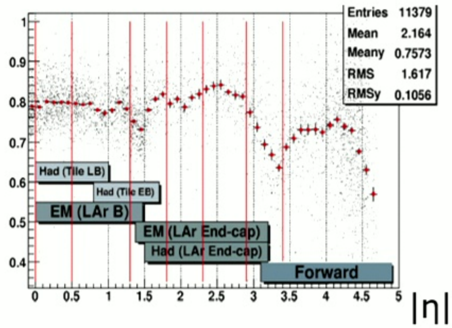
- σ(crudest) = $\dfrac{\sum \text{events observed}}{\sum \text{Luminosity}} = \dfrac{151\ @\ 8\text{TeV}}{20.3\ \text{fb}^{-1} @\ 8\text{TeV}} = \dfrac{151\ \text{events}}{20.3\text{fb}^{-1}}$
- Note: 1 femtobarn (fb) = 10^{-43}m^2 = 10^{-39}cm^2 (i.e. units of area)

$\sqrt{s}$	4ℓ state	$N^{\text{obs}}_{4\ell}$	$N^{\text{exp}}_{4\ell}$	$N^{\text{bkg}}_{4\ell}$	$C_{4\ell}$	$\sigma^{\text{fid}}_{Z4\ell}$ [fb]	$A_{4\ell}$		$\sigma_{Z4\ell}$ [fb]
7 TeV	$ee+ee$	1	1.8 ± 0.3	0.12 ± 0.04	21.5%	$0.9^{+1.4}_{-0.7}\pm0.14\pm0.02$	7.5%	$4e, 4\mu$	$32\pm11\pm1.0\pm0.6$
	$\mu\mu+\mu\mu$	8	11.3 ± 0.5	0.08 ± 0.04	59.2%	$3.0^{+1.2}_{-0.9}\pm0.07\pm0.05$	18.3%		
	$ee+\mu\mu$	7	7.9 ± 0.4	0.18 ± 0.09	49.0%	$3.1^{+1.4}_{-1.1}\pm0.16\pm0.05$	15.8%	$2e2\mu$	$44\pm14\pm3.3\pm0.9$
	$\mu\mu+ee$	5	3.3 ± 0.3	0.07 ± 0.04	36.3%	$3.0^{+1.6}_{-1.2}\pm0.30\pm0.06$	8.8%		
	combined	21	24.2 ± 1.2	0.44 ± 0.14					$76\pm18\pm4\pm1.4$
8 TeV	$ee+ee$	16	14.4 ± 1.4	0.14 ± 0.03	36.1%	$2.2^{+0.6}_{-0.5}\pm0.20\pm0.06$	7.3%	$4e, 4\mu$	$56\pm6\pm1.8\pm1.6$
	$\mu\mu+\mu\mu$	71	68.8 ± 2.7	0.34 ± 0.05	71.1%	$4.9^{+0.7}_{-0.6}\pm0.13\pm0.14$	17.8%		
	$ee+\mu\mu$	48	43.2 ± 2.1	0.32 ± 0.05	55.5%	$4.2^{+0.7}_{-0.6}\pm0.16\pm0.12$	14.8%	$2e2\mu$	$52\pm7\pm2.4\pm1.5$
	$\mu\mu+ee$	16	19.3 ± 1.3	0.18 ± 0.04	46.2%	$1.7^{+0.5}_{-0.4}\pm0.10\pm0.04$	7.9%		
	combined	151	146 ± 7	1.0 ± 0.11					$107\pm9\pm4\pm3.0$

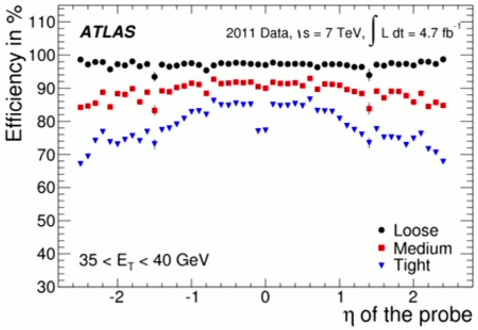
- σ(less crude) = $\dfrac{\sum \text{events observed} - \sum \text{bkg}}{\sum \text{Luminosity}} = \dfrac{(151)-(1.0)}{20.3\ \text{fb}^{-1}} = \dfrac{150\ \text{events}}{20.3\text{fb}^{-1}}$
  - It is a very clean channel with little background

Steps to measure a cross section, σ – part II

- Detector is far from perfect at identifying leptons! Inefficiencies in instrumentation. Holes.
- Recall for jets:



Now for identifying electrons:



- σ(less crude) is useless to anyone EXCEPT an ATLAS person who understands the imperfections of the detector
  - Can't compare to any theoretical prediction
- Need to unfold data to what you would expect to observe with a "perfect" ATLAS
  - i.e. take all the known imperfections in ATLAS (like the plots above) and (very crudely speaking) multiply by the inverse to get a perfect number!
- Use very best Monte Carlo simulation to unfold data from "reconstruction" to "truth" level
- Correction factor:
- $C = \frac{\text{Expected number of events passing the selection at reconstruction level}}{\text{Expected number of events passing the selection at truth level}}$

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Steps to measure a cross section, σ – part III

Fiducial cross section (i.e. within acceptance of the detector)

- $\sigma(\text{fid}) = \dfrac{\sum \text{events observed} - \sum \text{bkg}}{\sum \text{Luminosity} \times C} = \dfrac{150 \text{ events}}{20.3\text{fb}^{-1} \times 0.6} = 12 \text{ fb}$
  - Measurement should be done separately for each final state to account properly for inefficiencies

$\sqrt{s}$	4ℓ state	$N_{4\ell}^{\text{obs}}$	$N_{4\ell}^{\text{exp}}$	$N_{4\ell}^{\text{bkg}}$	$C_{4\ell}$	$\sigma_{Z4\ell}^{\text{fid}}$ [fb]	$A_{4\ell}$		$\sigma_{Z4\ell}$ [fb]
7 TeV	$ee+ee$	1	1.8 ± 0.3	0.12 ± 0.04	21.5%	$0.9^{+1.4}_{-0.7} \pm 0.14 \pm 0.02$	7.5%	} $4e, 4\mu$	$32 \pm 11 \pm 1.0 \pm 0.6$
	$\mu\mu+\mu\mu$	8	11.3 ± 0.5	0.08 ± 0.04	59.2%	$3.0^{+1.2}_{-0.9} \pm 0.07 \pm 0.05$	18.3%		
	$ee+\mu\mu$	7	7.9 ± 0.4	0.18 ± 0.09	49.0%	$3.1^{+1.4}_{-1.1} \pm 0.16 \pm 0.05$	15.8%	} $2e2\mu$	$44 \pm 14 \pm 3.3 \pm 0.9$
	$\mu\mu+ee$	5	3.3 ± 0.3	0.07 ± 0.04	36.3%	$3.0^{+1.6}_{-1.2} \pm 0.30 \pm 0.06$	8.8%		
	combined	21	24.2 ± 1.2	0.44 ± 0.14					$76 \pm 18 \pm 4 \pm 1.4$
8 TeV	$ee+ee$	16	14.4 ± 1.4	0.14 ± 0.03	36.1%	$2.2^{+0.6}_{-0.5} \pm 0.20 \pm 0.06$	7.3%	} $4e, 4\mu$	$56 \pm 6 \pm 1.8 \pm 1.6$
	$\mu\mu+\mu\mu$	71	68.8 ± 2.7	0.34 ± 0.05	71.1%	$4.9^{+0.7}_{-0.6} \pm 0.13 \pm 0.14$	17.8%		
	$ee+\mu\mu$	48	43.2 ± 2.1	0.32 ± 0.05	55.5%	$4.2^{+0.7}_{-0.6} \pm 0.16 \pm 0.12$	14.8%	} $2e2\mu$	$52 \pm 7 \pm 2.4 \pm 1.5$
	$\mu\mu+ee$	16	19.3 ± 1.3	0.18 ± 0.04	46.2%	$1.7^{+0.5}_{-0.4} \pm 0.10 \pm 0.04$	7.9%		
	combined	151	146 ± 7	1.0 ± 0.11	~60%	$\Sigma \cong 13$			$107 \pm 9 \pm 4 \pm 3.0$

- Fiducial cross section is the number closest to the experimental measurement but corrected for all known imperfections
  - Small theoretical uncertainties (not zero, since MC used to correct)
  - This is a number that is useful to people outside of ATLAS

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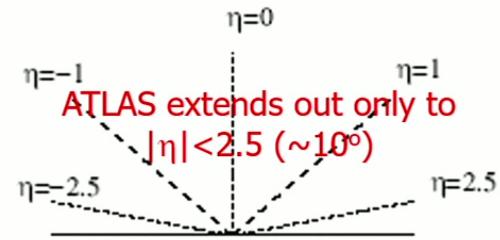
σ – part IV



- Extrapolate to an ATLAS detector that is fully hermetic (encompasses all space around collision) Acceptance factor A

Total cross section

- σ(tot) = $\dfrac{\sum \text{events observed} - \sum \text{bkg}}{\sum \text{Luminosity} \times C \times A} = \dfrac{150 \text{ events}}{20.3\text{fb}^{-1} \times 0.6 \times A}$, final answer = 107 fb
  - Measurements need to be done separately for each final state

$\sqrt{s}$	4ℓ state	$N_{4\ell}^{\text{obs}}$	$N_{4\ell}^{\text{exp}}$	$N_{4\ell}^{\text{bkg}}$	$C_{4\ell}$	$\sigma_{Z4\ell}^{\text{fid}}$ [fb]	$A_{4\ell}$		$\sigma_{Z4\ell}$ [fb]
7 TeV	$ee+ee$	1	1.8 ± 0.3	0.12 ± 0.04	21.5%	$0.9^{+1.4}_{-0.7} \pm 0.14 \pm 0.02$	7.5%	} $4e, 4\mu$	$32 \pm 11 \pm 1.0 \pm 0.6$
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	$ee+\mu\mu$	7	7.9 ± 0.4	0.18 ± 0.09	49.0%	$3.1^{+1.4}_{-1.1} \pm 0.16 \pm 0.05$	15.8%	} $2e2\mu$	$44 \pm 14 \pm 3.3 \pm 0.9$
	$\mu\mu+ee$	5	3.3 ± 0.3	0.07 ± 0.04	36.3%	$3.0^{+1.6}_{-1.2} \pm 0.30 \pm 0.06$	8.8%		
	combined	21	24.2 ± 1.2	0.44 ± 0.14	~50%				$76 \pm 18 \pm 4 \pm 1.4$
8 TeV	$ee+ee$	16	14.4 ± 1.4	0.14 ± 0.03	36.1%	$2.2^{+0.6}_{-0.5} \pm 0.20 \pm 0.06$	7.3%	} $4e, 4\mu$	$56 \pm 6 \pm 1.8 \pm 1.6$
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	$\mu\mu+ee$	16	19.3 ± 1.3	0.18 ± 0.04	46.2%	$1.7^{+0.5}_{-0.4} \pm 0.10 \pm 0.04$	7.9%		
	combined	151	146 ± 7	1.0 ± 0.11	~60%	$\Sigma \cong 13$	~12%		$107 \pm 9 \pm 4 \pm 3.0$

- Total cross section also a well-defined quantity, excellent for sharing outside of ATLAS, but does come with larger theoretical uncertainties due to the extrapolation
  - σ(tot) is usually what a theorist will predict for an experiment

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Steps to measure a cross section, σ – part V

- $\sigma(\text{tot}) = \dfrac{\sum \text{events observed} - \sum \text{bkg}}{\sum \text{Luminosity} \times C \times A}$
- All terms above have their own sources of either statistical and/or systematic uncertainties

$\sqrt{s}$	4ℓ state	$N_{4\ell}^{\text{obs}}$	$N_{4\ell}^{\text{exp}}$	$N_{4\ell}^{\text{bkg}}$	$C_{4\ell}$	$\sigma_{Z4\ell}^{\text{fid}}$ [fb]	$A_{4\ell}$		$\sigma_{Z4\ell}$ [fb]
8 TeV	$ee+ee$	16	14.4 ± 1.4	0.14 ± 0.03	36.1%	$2.2^{+0.6}_{-0.5} \pm 0.20 \pm 0.06$	7.3%	$4e, 4\mu$	$56 \pm 6 \pm 1.8 \pm 1.6$
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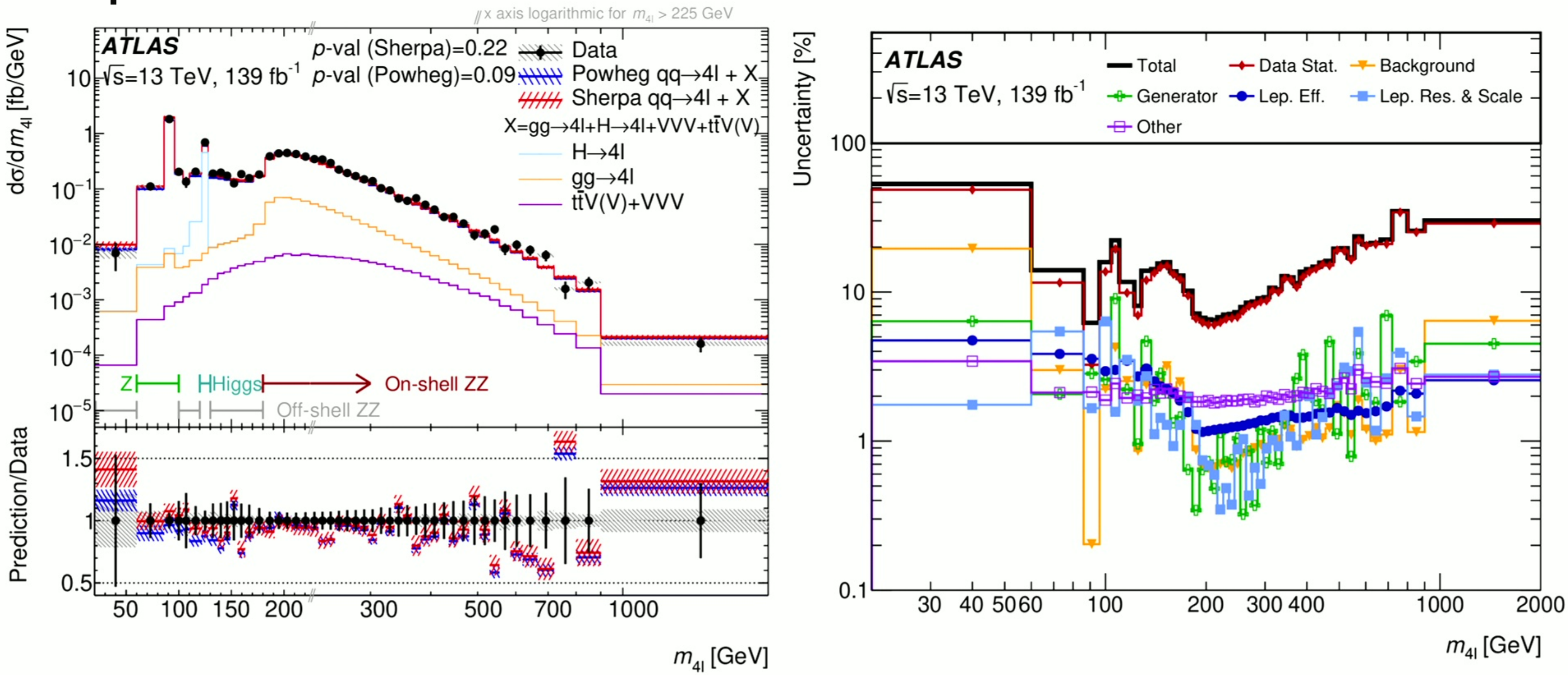
	combined	151	146 ± 7	1.0 ± 0.11					$107 \pm 9 \pm 4 \pm 3.0$

stat ~ √N   stat ⊕ sys   Not given   Not given   stat ± sys ± lumi

- Uncertainties determined through error propagation:
  - Neglecting correlations between uncertainties (not always a good assumption!)
  - σ = f(x,y,z,…),   uncertainty: $s_f = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 s_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 s_y^2 + \left(\frac{\partial f}{\partial z}\right)^2 s_z^2 + \dots}$
- Final answer given decomposed into: statistical ± systematic ± luminosity

Recent differential(!) cross section to four leptons measurement



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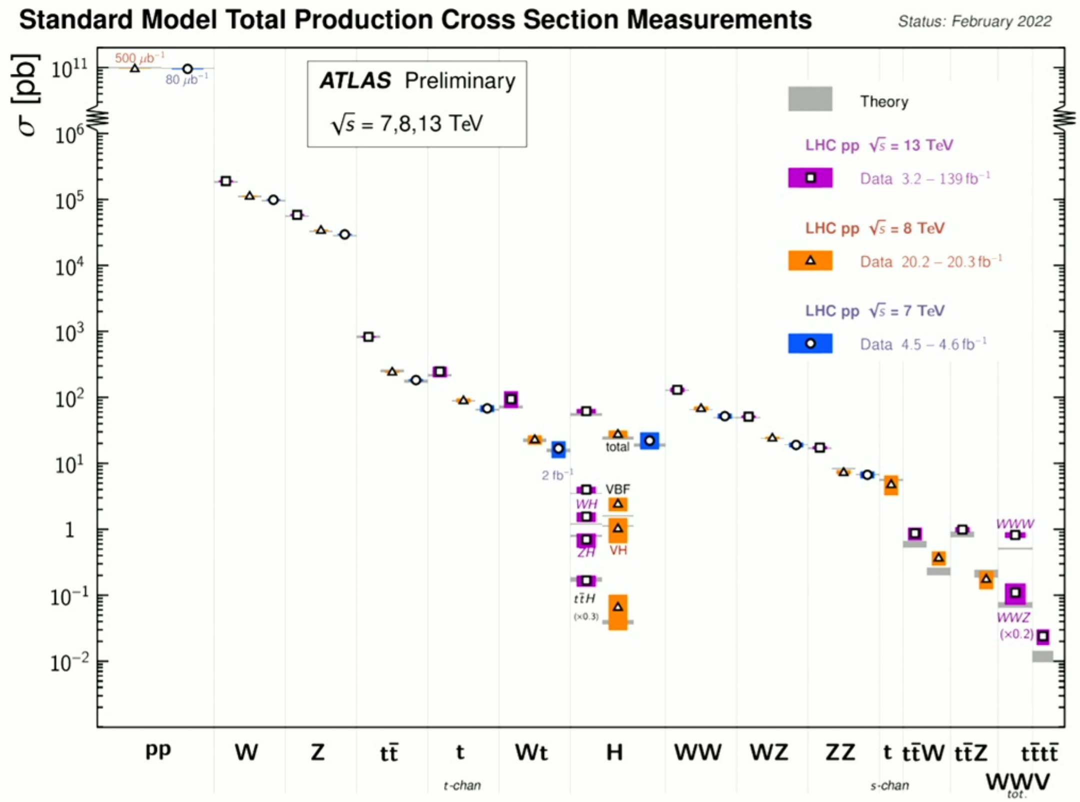
Summary of SM measurements at ATLAS: production cross section pp → something

- Something = W, Z, $t\bar{t}$, t, Wt, H, WW, WZ, ZZ, $t\bar{t}W$, $t\bar{t}Z$, WWV, 4-top
- Related to the probability to produce these particles at the LHC



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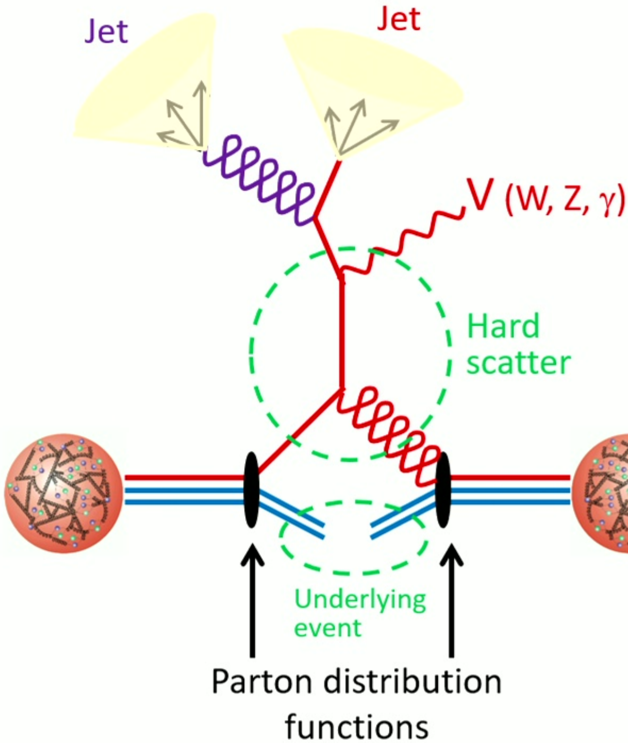
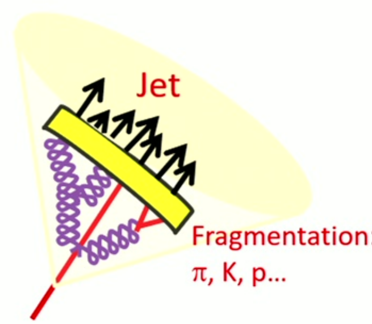
V+jet production, V = W,Z



Probing QCD with V+jet production

- Hard scatter (matrix element, ME)
- Parton shower (PS), matching to ME
- Fragmentation to jets
- Jet composition/dynamics
- Multiparton interactions (MPI) from underlying event (UE)
- Parton distribution functions (PDF)



Z+jets

- Benchmark the validity range of our various generators!

Generator+PS:

- BLACKHAT+SHERPA: parton-level fixed-order predictions at NLO up to four partons
- SHERPA: matrix elements (ME) up to two additional partons at NLO and up to four partons at leading order (LO) interfaced to SHERPA showering
- ALPGEN+Py6: multiparton LO ME
- MG5_aMC+Py8 CKKWL: ME including up to four partons at LO, interfaced to Py8, using CKKWL merging scheme
- MG5_aMC+Py8 FxFx: ME up to two jets and with PS beyond, using FxFx merging scheme

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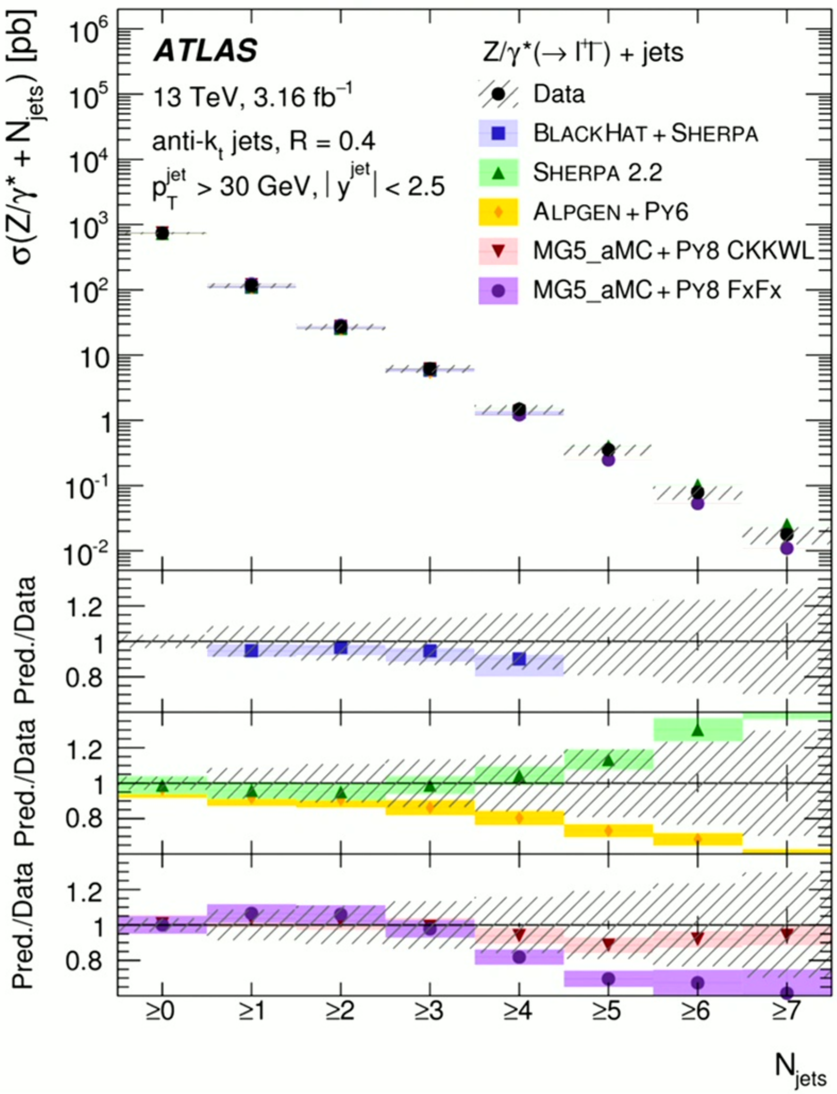

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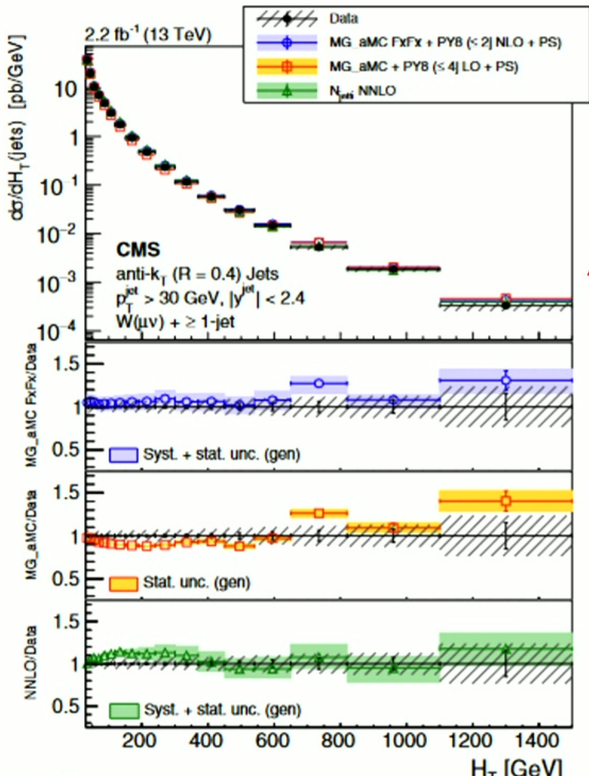
W+jets

- W+jets: non-negligible background for Higgs boson production and in BSM searches
  - kinematics of jets exploited to achieve separation of the signal of interest from SM bkg



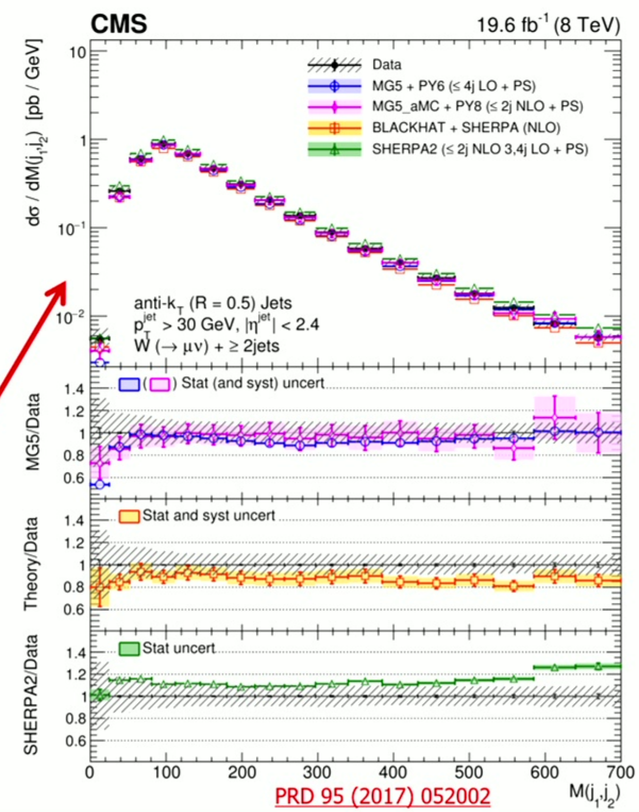
PRD 95 (2017) 052002

W+≥1jet:

H_T, the scalar p_T sum of all visible objects, employed in BSM searches, to enrich final states resulting from the decay of heavy particles

W+≥2jets:

Di-jet invariant mass: modeling of correlations among jets important for BSM searched in dijet final states



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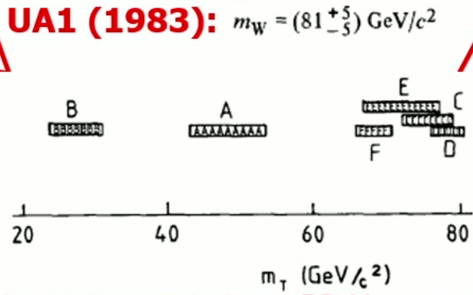
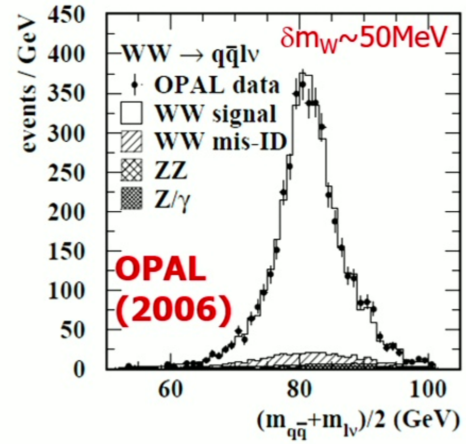
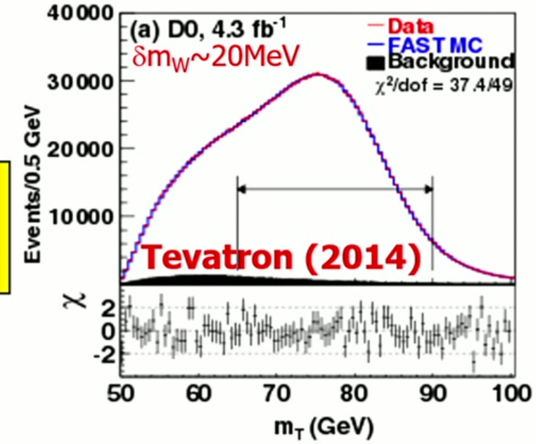
UA1 (1983):



First measurement: $\delta m_W \sim 5$GeV





MASS OF THE

ATLAS ← Tevatron ← ATLAS

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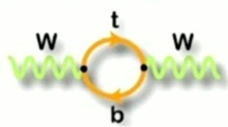
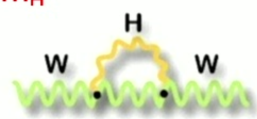
The mass of the W boson: m_W

- EW sector of SM relates important parameters such as m_W, α_{EM}, G_F and $\sin^2\theta_W$
- Quantum corrections to m_W dominated by contributions depending quadratically on the top mass m_t and logarithmically on the Higgs mass m_H





$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\boxed{\Delta r}),$$

Higher orders, new physics?

- Precision measurements of m_W were first used to predict m_H before the Higgs was observed
- Now use comparisons of predicted m_H to measured m_H to look for new physics!
- Current SM prediction to ~8 MeV precision
- Extraction of m_W from hadron collisions
  - $u\bar{d}\rightarrow W^+(\rightarrow\ell^+\nu)+X$ → Can't fully reconstruct the final state!
  - Look at transverse plane balance
- Most recent measurements from
  - Tevatron: $p\bar{p}$ collider
  - ATLAS&LHCb@LHC: pp collider
  - ➡ Different $\sqrt{s}$ and sensitivity to PDFs

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Observables in W, Z decay

- Lepton ℓ: p_T^ℓ, η_ℓ, ϕ_ℓ
- Dilepton (Z): $m_{\ell\ell}$, $y_{\ell\ell}$, $p_T^{\ell\ell}$
- Recoil: $\vec{u}_T$, $u_\perp$, $u_\parallel$
- $\vec{u}_T$ a measure of $p_T^{W,Z}$
  - Excluding ℓ:

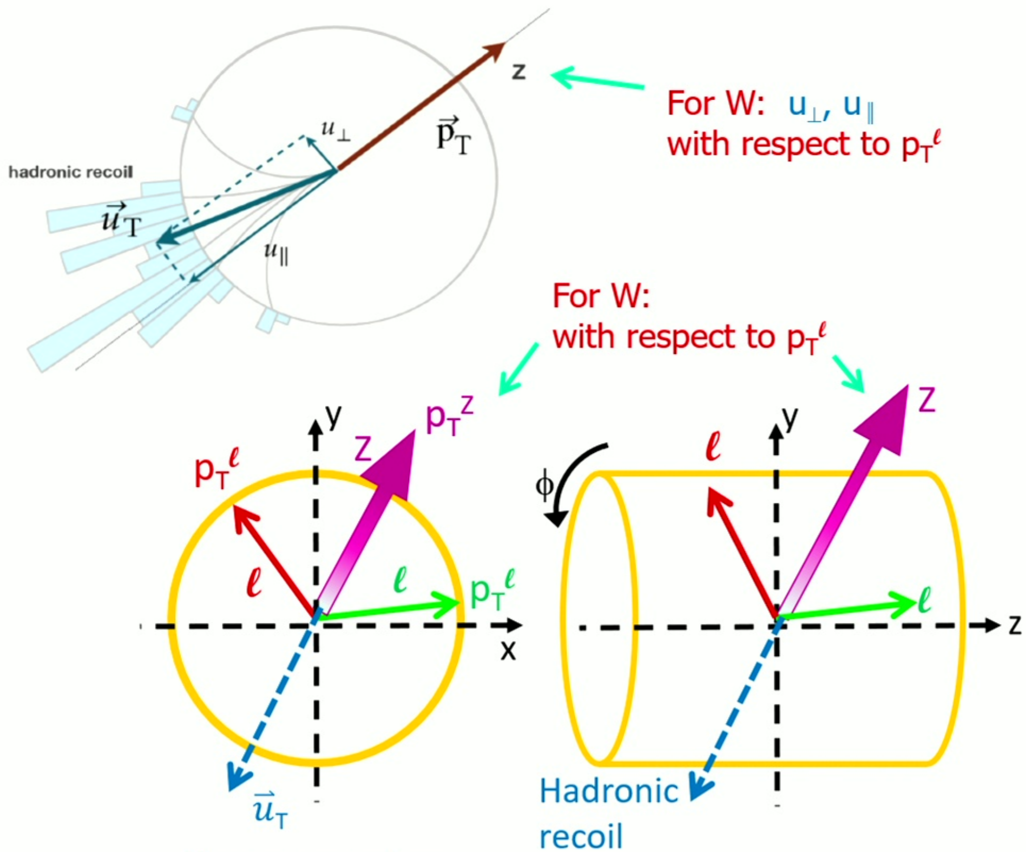
$$\vec{u}_T = \sum_i \vec{E}_{T,i},$$

- W transverse missing momentum:

$$\vec{p}_T^{\,\text{miss}} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right)$$

- W transverse mass:

$$m_T = \sqrt{2 p_T^\ell p_T^{\text{miss}}(1 - \cos\Delta\phi)}$$

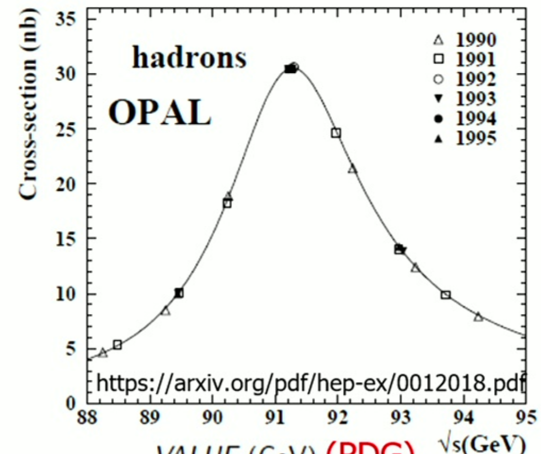


Transverse plane

The role of the Z

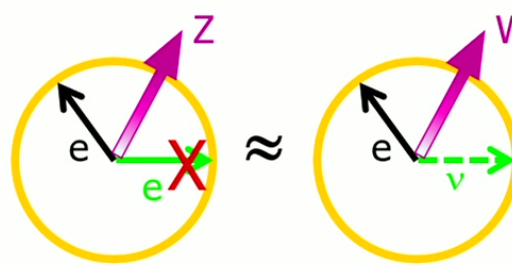
And the Oscar for best supporting boson in a measurement goes to…

- Properties of the Z measured to exquisite precision at LEP
- Use this information at hadron colliders to nail down the experimental uncertainties e.g.
  - p_T^{ℓ}, p_T^{miss} : affected by lepton energy calibration
    - Use leptonic decay $Z \to \ell\ell$
  - Recoil calibration
    - $u_{\parallel}$ can be compared to - p_T^{ll} : probes the detector response to recoil RE: linearity, resolution
    - $u_{\perp}$ satisfies $<u_{\perp}>=0$: width provides an estimate of recoil resolution
  - Shape of kinematic distributions affected by lepton identification/reconstruction efficiency
    - From Z "Tag and probe" measurements
- Z used as an (approximate) avatar for the W of m_W
  - Use the Z to make "W-like" measurements
    - Measure m_Z using m_W techniques
      - Treat one ℓ as a ν
      - Extract m_Z from $m_{\ell\ell}$, p_T^{ℓ}, m_T



VALUE (GeV) (PDG)

$m_Z = 91.1876 \pm 0.0021$



Eur. Phys. J. C 78 (2018) 110
ATLAS-CONF-2023-004

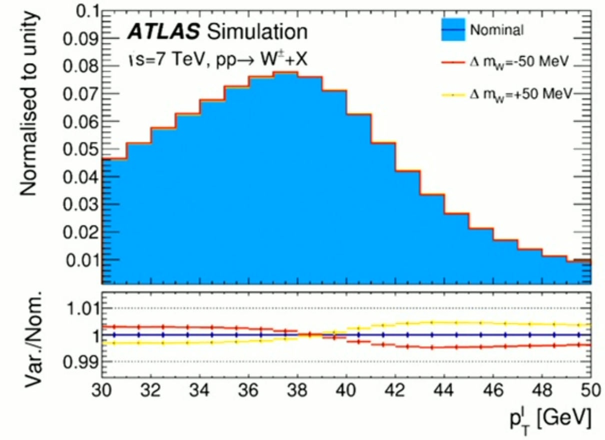
2018 measurement of m_W at ATLAS

Compare expectations of p_T^ℓ, m_T for various values of m_W to measured distributions

- Build templates using a single reference sample (+background) for a given m_W, reweight to other m_W using a relativistic Breit-Wigner

$$\frac{d\sigma}{dm} \propto \frac{m^2}{(m^2 - m_V^2)^2 + m^4\Gamma_V^2/m_V^2}$$

  (width scaling as $\Gamma_W \propto m_W^3$)
- Signal expectations from Powheg+Pythia8, reweighted event-by-event for
  - Improvements in kinematics (better match data)
  - Missing higher-order terms e.g. EW
- Performed for several categories
- χ^2 compatibility test to judge best m_W value



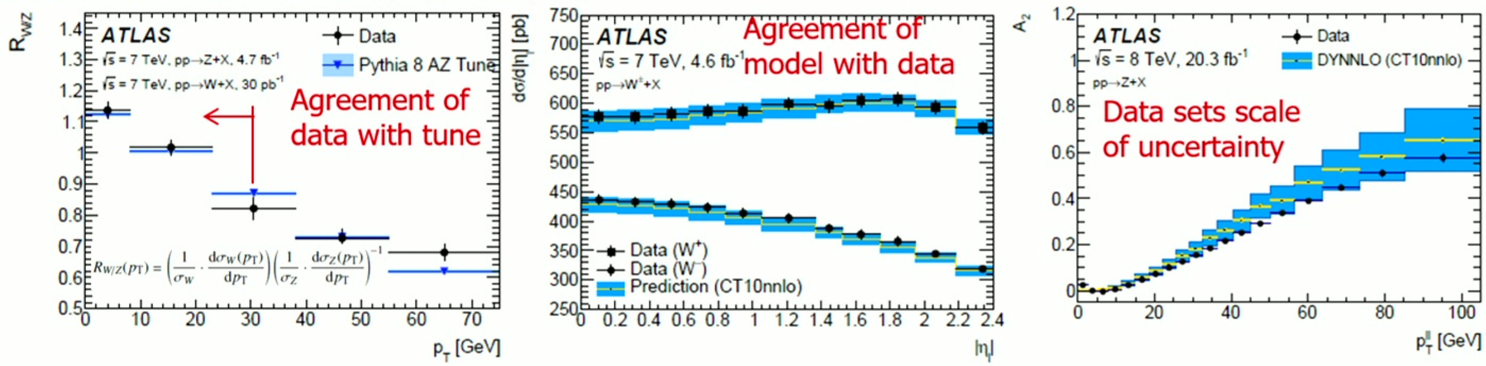
Decay channel	$W \to e\nu$	$W \to \mu\nu$
Kinematic distributions	p_T^ℓ, m_T	p_T^ℓ, m_T
Charge categories	W^+, W^-	W^+, W^-
$\|\eta_\ell\|$ categories	[0, 0.6], [0.6, 1.2], [1.8, 2.4]	[0, 0.8], [0.8, 1.4], [1.4, 2.0], [2.0, 2.4]

The model, guided by data: Powheg+Pythia8 → best Drell-Yan cross section

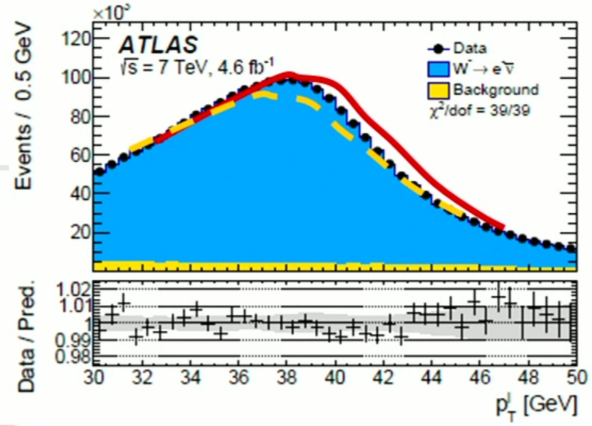
- Factorisation of fully differential leptonic Drell-Yan cross section:

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y) P_i(\cos\theta, \phi)\right],$$

- Modelling: dσ/dm with a BW, dσ/dy and A_i with fixed-order pQCD predictions (optimised DYNNLO), remaining component with Pythia8 MC
- Data-driven improvements in the modelling:
  - √s=7TeV Z data used to tune pQCD parameters in Pythia8 parton shower generator
- Validation of: dσ/dy with √s=7TeV W,Z σ meas., A_i with √s=8TeV Z angular coefficients meas.
- Sources of uncertainties related to the above plus other important sources such as choice of PDF (CT10nnlo+variations and alternate PDFs: MMHT2014, CT14), effects of missing high orders on the NNLO predictions, contributions from heavy quarks (b,c)



Experimental considerations - I



Shape of p_T^ℓ, m_T sensitive to m_W: e.g. Jacobian edge at $m_W/2$ of p_T^ℓ → could be shifted or distorted by experimental effects?

→ Correct and calibrate (mostly done to the MC)!

Select leptons

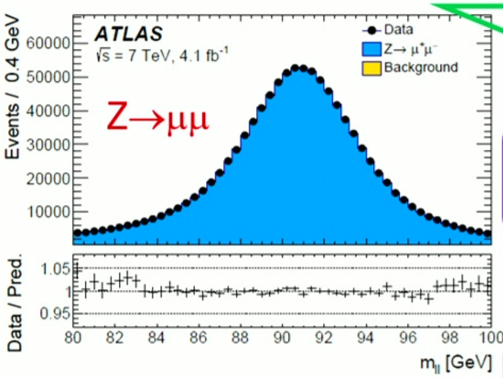
- Trigger
- Reconstruct
- Identify
- Isolate

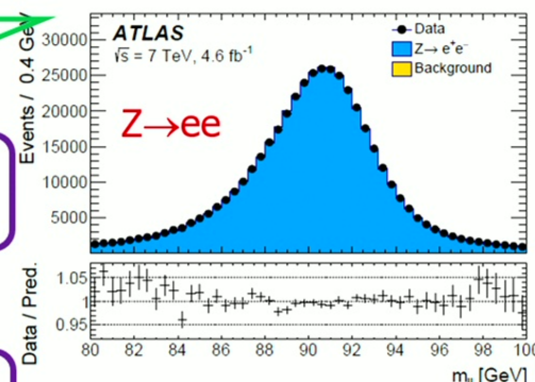
Efficiencies(p_T^ℓ, η_ℓ, ϕ_ℓ, q, $u_\parallel$)

Calibrate leptons

- Energy/momentum scale
- Resolution
- Biases

Use:
$Z \to \ell\ell$





Data/MC agreement?
→ Scale factors!

Transfer from Z to W

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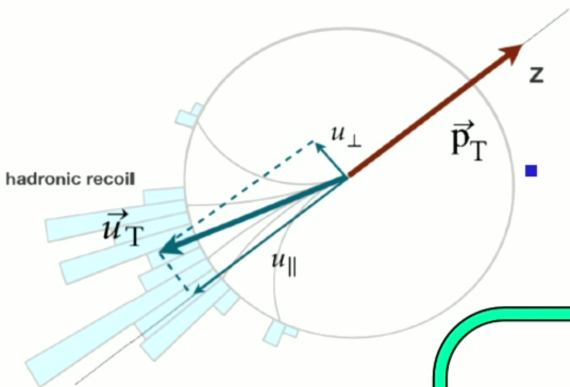
Experimental considerations - II

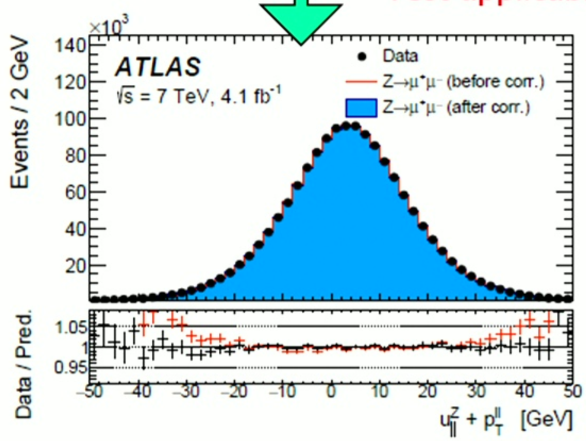
Recoil response

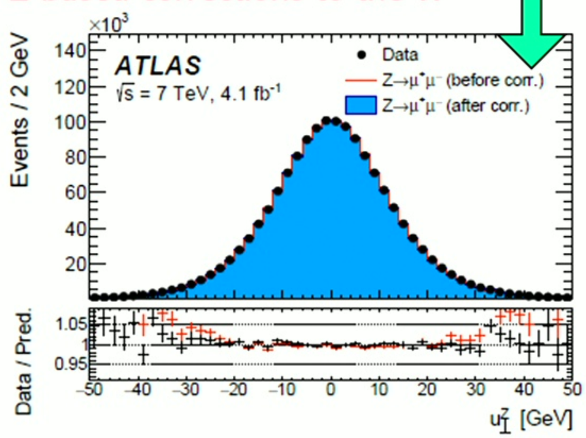


Correct for:

- Event activity
  - Pileup <μ>: match MC to what is observed in data
  - Sum E_T: $\Sigma \bar{E}_T$ residual data-MC differences responsible for remaining $u_\perp$ mismodeling
- Residual corrections:
  - Non-zero crossing angle of the beam
  - Energy scale and resolution
    - Z: $u_\parallel + p_T^{\ell\ell}$ → calibrates energy scale
    - Z: $u_\perp$ → resolution

Test applicability of Z-based corrections to the W





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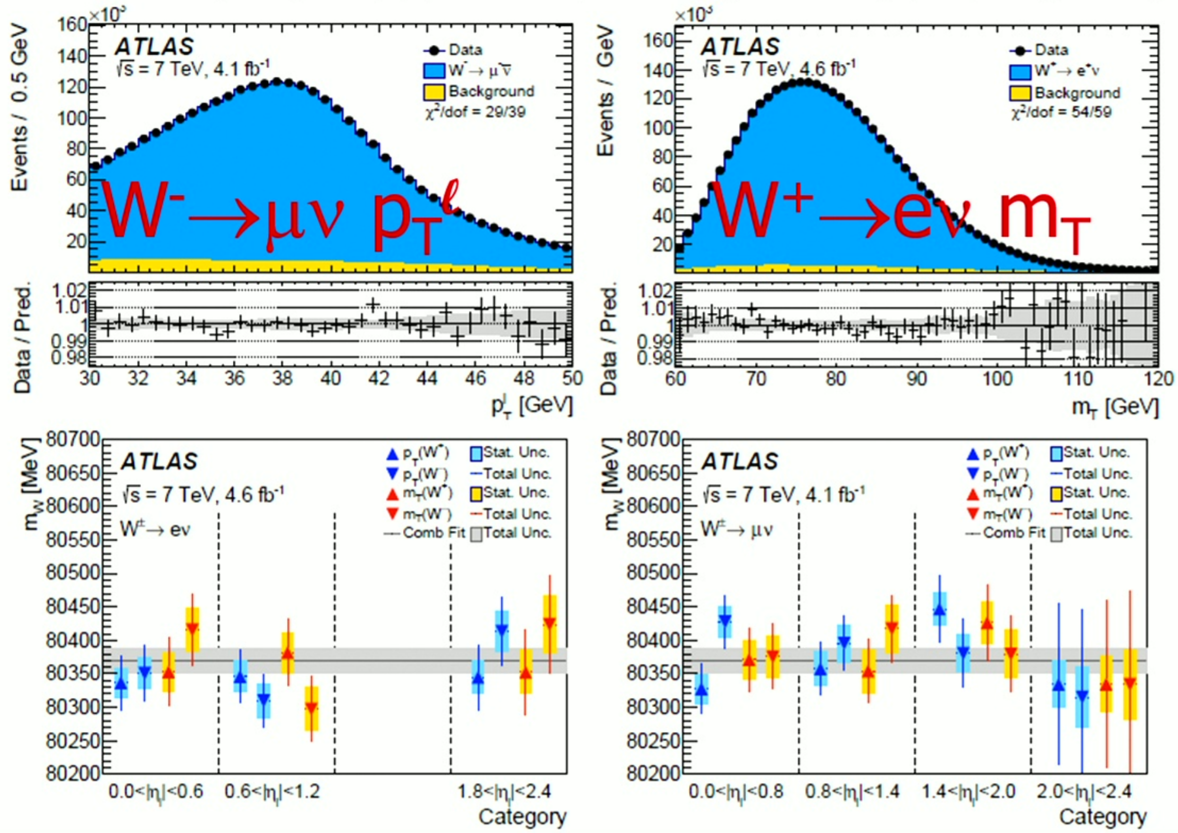
Measurement of m_W

7.8M $W\to\mu\nu$
5.9M $W\to e\nu$
4.6fb^{-1}

- 28 measurements of m_W $\quad \begin{pmatrix} W^+ \\ W^- \end{pmatrix} \times \begin{pmatrix} 3e \\ 4\mu \end{pmatrix} \eta \text{ bins} \times \begin{pmatrix} p_T \\ m_T \end{pmatrix}$
- Optimise the fitting range of p_T (32-45GeV) and m_T (66-99GeV) (vary range as systematic)



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W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

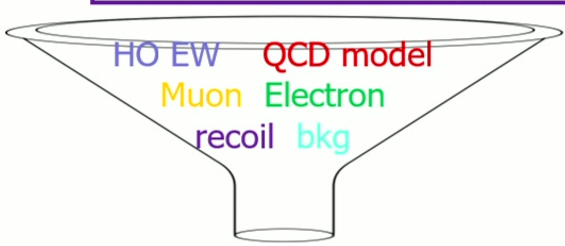
Decay channel	$W \to e\nu$		$W \to \mu\nu$	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]				
FSR (real)	< 0.1	< 0.1	< 0.1	< 0.1
Pure weak and IFI corrections	3.3	2.5	3.5	2.5
FSR (pair production)	3.6	0.8	4.4	0.8
Total	4.9	2.6	5.6	2.6

$\lvert\eta_\ell\rvert$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0	1.2
Sagitta bias	0.7	0.8	1.7	1.7	3.1	3.1	4.5	4.3	0.6	0.6
Reconstruction and isolation efficiencies	4.0	3.6	5.1	3.7	4.7	3.5	6.4	5.5	2.7	2.2
Trigger efficiency	5.6	5.0	7.1	5.0	11.8	9.1	12.1	9.9	4.1	3.2
Total	11.4	11.4	16.9	17.0	30.4	31.0	112.0	116.1	9.8	9.7

$\lvert\eta_\ell\rvert$ range	[0.0, 0.6]		[0.6, 1.2]		[1.82, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6	3.4	5.5
Energy tails	2.3	3.3	2.3	3.3	2.3	3.3	2.3	3.3
Reconstruction efficiency	10.5	8.8	9.9	7.8	14.5	11.0	7.2	6.0
Identification efficiency	10.4	7.7	11.7	8.8	16.7	12.1	7.3	5.6
Trigger and isolation efficiencies	0.2	0.5	0.3	0.5	2.0	2.2	0.8	0.9
Charge mismeasurement	0.2	0.2	0.2	0.2	1.5	1.5	0.1	0.1
Total	19.0	17.5	21.1	19.4	30.7	30.5	14.2	14.3

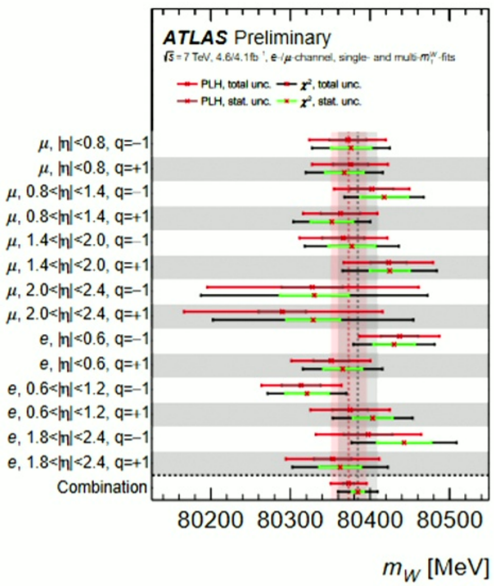
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma\bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

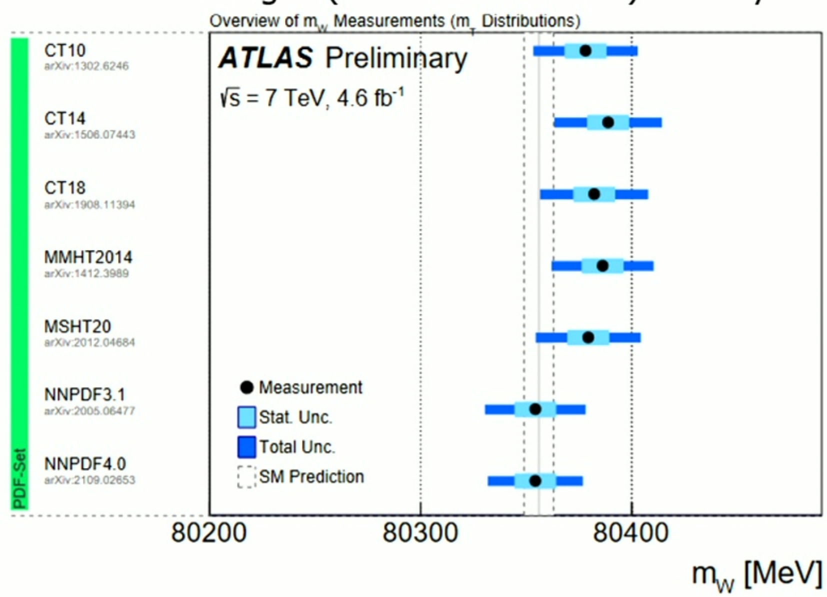
Kinematic distribution	p_T^ℓ				m_T			
Decay channel	$W \to e\nu$		$W \to \mu\nu$		$W \to e\nu$		$W \to \mu\nu$	
W-boson charge	W^+	W^-	W^+	W^-	W^+	W^-	W^+	W^-
δm_W [MeV]								
$W \to \tau\nu$ (fraction, shape)	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.3
$Z \to ee$ (fraction, shape)	3.3	4.8	–	–	4.3	6.4	–	–
$Z \to \mu\mu$ (fraction, shape)	–	–	3.5	4.5	–	–	4.3	5.2
$Z \to \tau\tau$ (fraction, shape)	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.3
WW, WZ, ZZ (fraction)	0.1	0.1	0.1	0.1	0.4	0.4	0.3	0.4
Top (fraction)	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3
Multijet (fraction)	3.2	3.6	1.8	2.4	8.1	8.6	3.7	4.6
Multijet (shape)	3.8	3.1	1.6	1.5	8.6	8.0	2.5	2.4
Total	6.0	6.8	4.3	5.3	12.6	13.4	6.2	7.4



Re-analysis in 2023: the same dataset

- No new understand of the detector nor effects of contributions from electroweak and top quark background processes
- Improved fitting technique based on profile-likelihood test statistics (+ improved mulitjet background)
- Understanding of PDFs has evolved a lot! Baseline PDF changed (from CT10 to CT18) + many other PDFs





Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
p_T^ℓ	80360.1	8.0	7.7	7.0	6.0	4.7	2.4	2.0	1.9	1.2	0.6	15.5	4.9	16.3
m_T	80382.2	9.2	14.6	9.8	5.9	10.3	6.0	7.0	2.4	1.8	11.7	24.4	6.7	25.3

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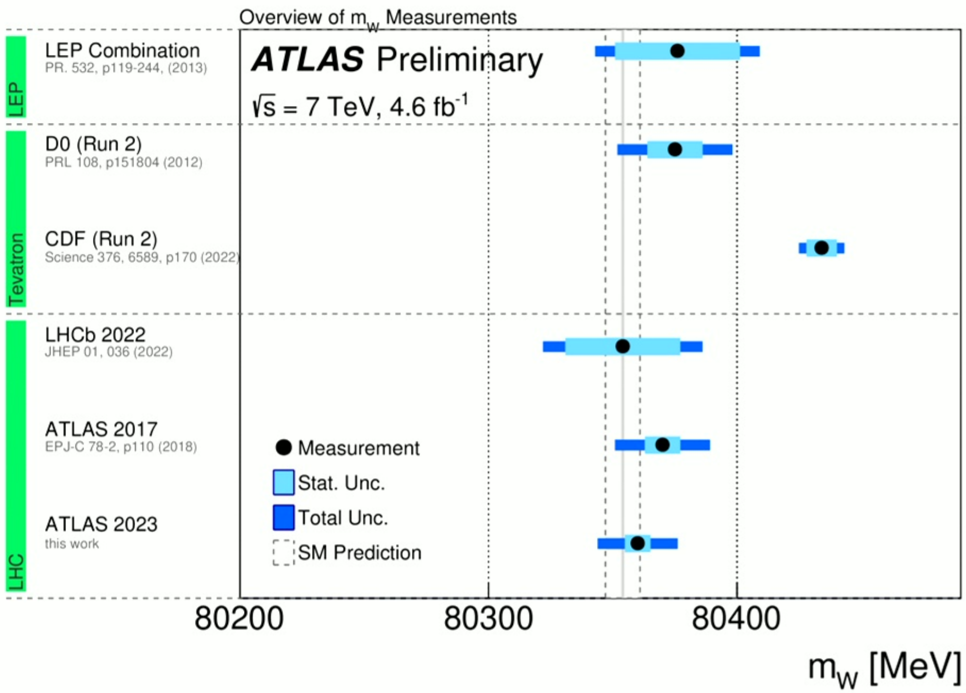
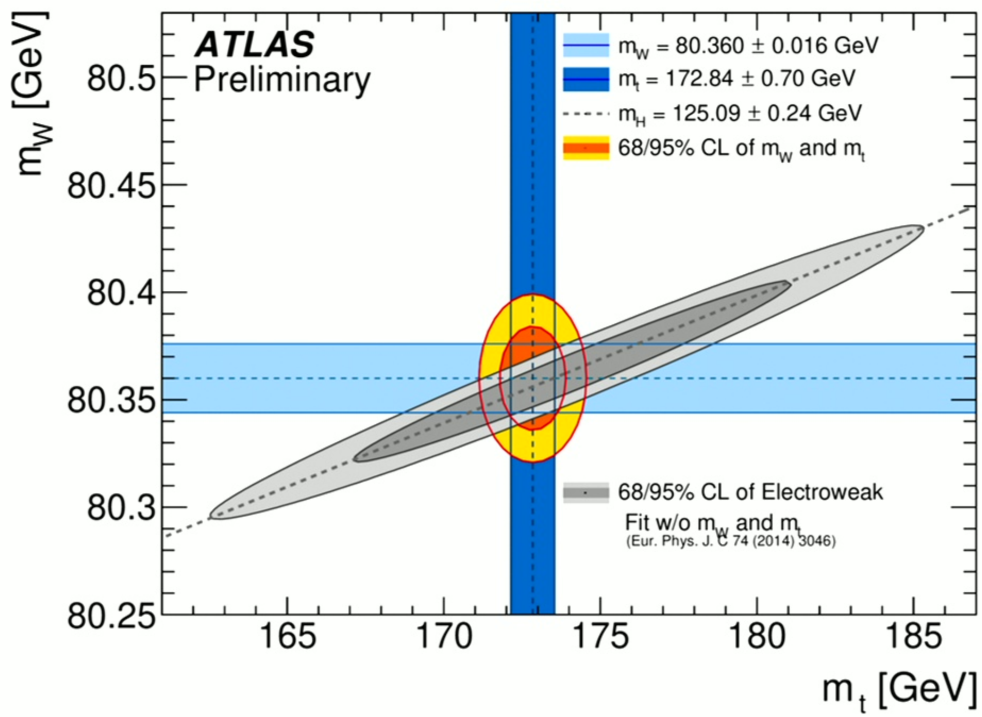
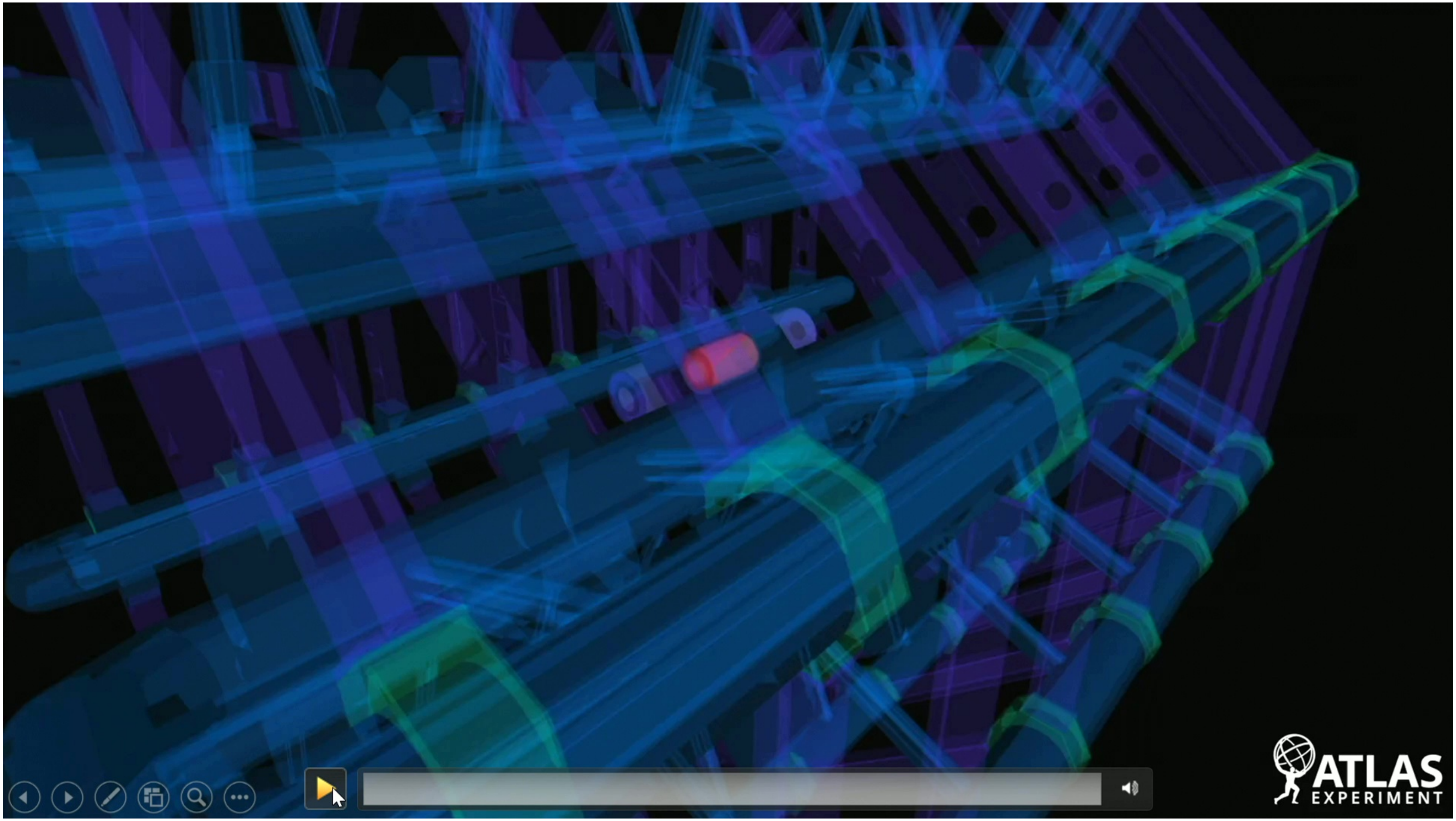
The final result

- Combine the measurements into one determination of m_W

$$m_W = 80360 \pm 5(\text{stat.}) \pm 15(\text{syst.}) = 80360 \pm 16 \text{ MeV}$$



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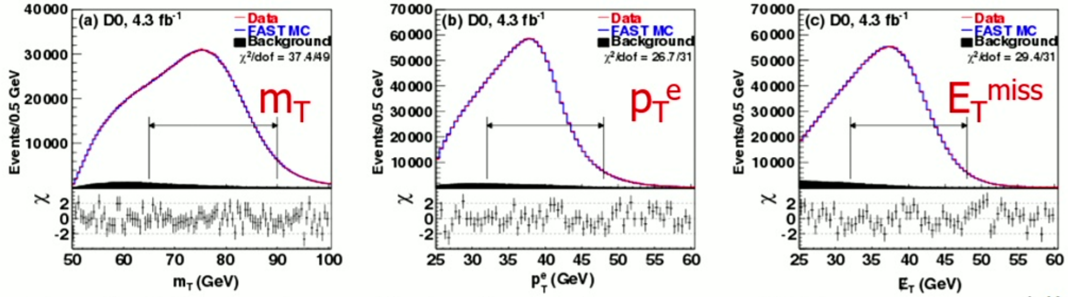
Tevatron m_W: earlier measurement for CDF

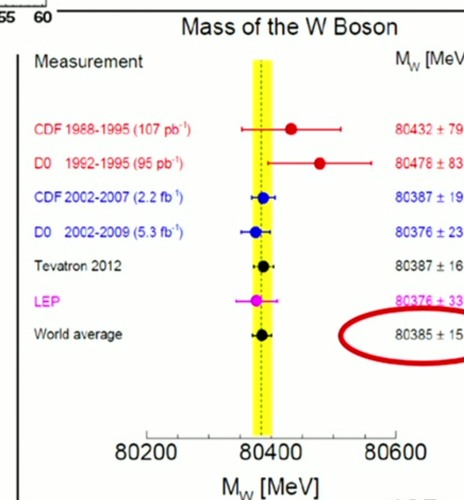
- Fermilab Tevatron measurements
  - D0: $W \to e\nu$, 4.3fb^{-1}, 1.68M evts (+earlier 1fb^{-1}) [PRD89 (2014) 012005, PRL108 (2012) 151804]
  - CDF: $W \to e,\mu\nu$, 2.2fb^{-1}, 1.10M evts [PRD89 (2014) 072003, PRL108 (2012) 151803]



- Dominant expt sys: lepton E scale & hadronic recoil, dominant theo uncert: PDF
  - ➡ δm_W^{D0} = 23MeV, δm_W^{CDF}= 19MeV $m_W^{Tevatron}$=80387±16MeV
  - ➡ World avg at the time known to 15MeV!

TABLE II. Uncertainties for the final combined result on M_W.

Source CDF	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton distributions	10
QED radiation	4
W-boson statistics	12
Total	19



Updated from arXiv:1204.0042

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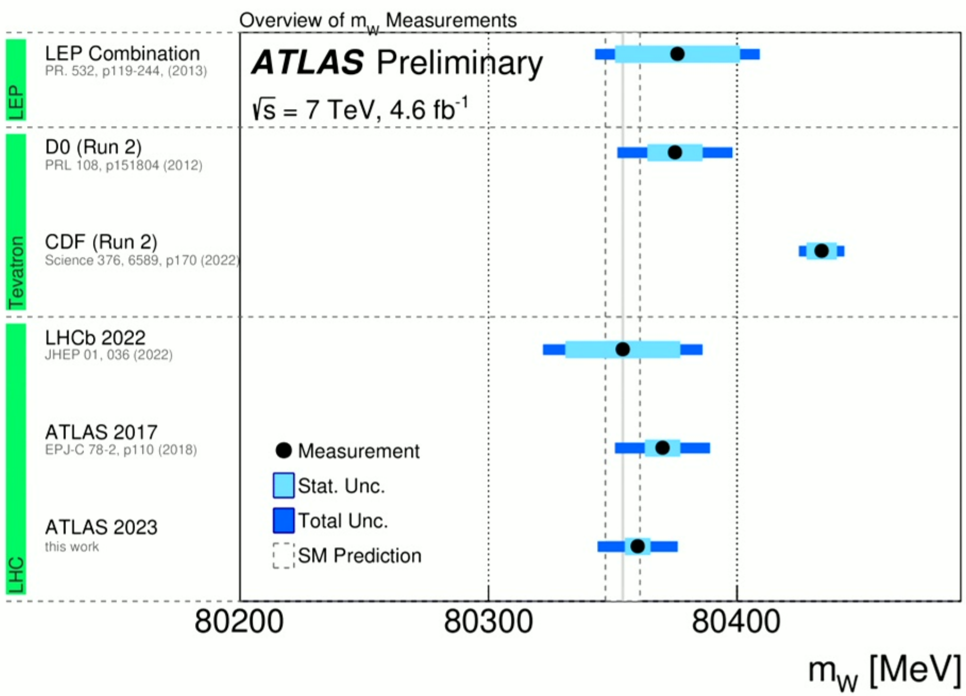
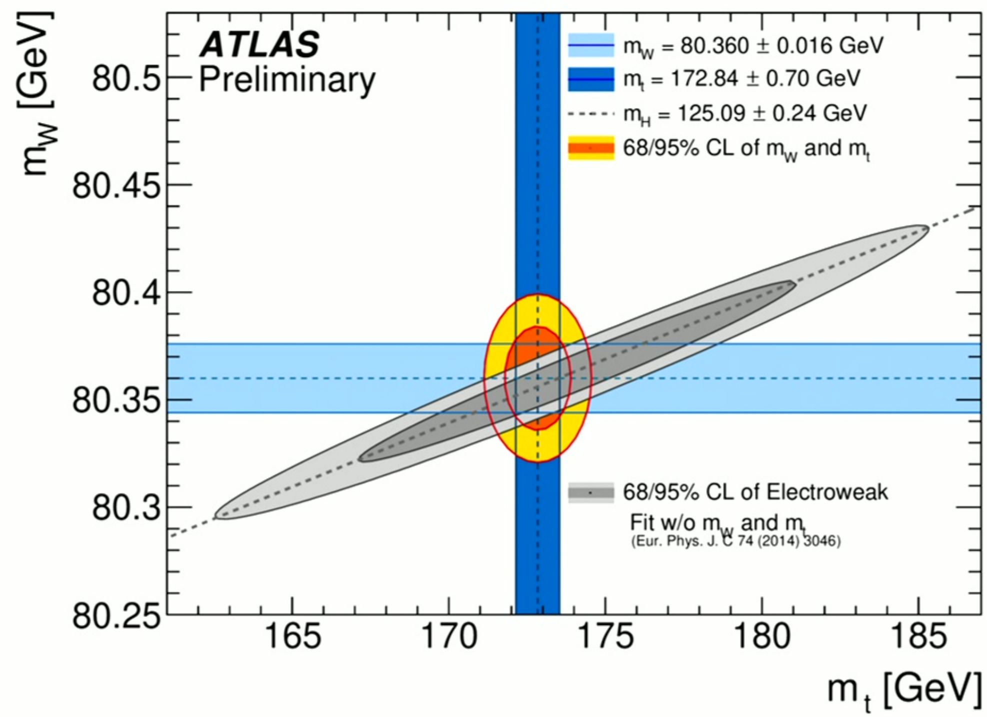
The final result

- Combine the measurements into one determination of m_W

$$m_W = 80360 \pm 5(\text{stat.}) \pm 15(\text{syst.}) = 80360 \pm 16 \text{ MeV}$$

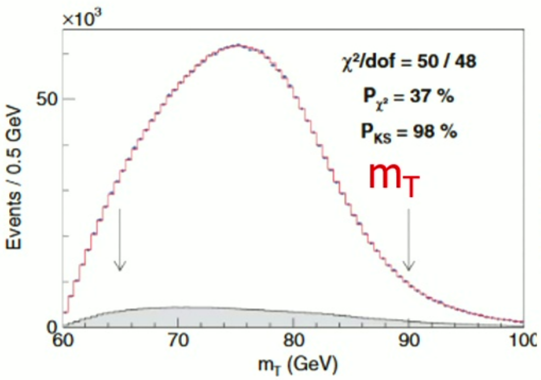


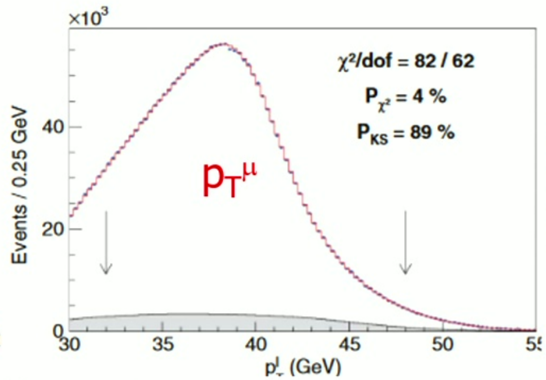


Science, vol 376, Issue 6589, 170-176

Tevatron m_W: latest measurement for CDF

- CDF measurement: $W \to e, \mu\nu$, 8.8fb^{-1}, 4M evts with m_W^{CDF}=80433.5 ± 9.4MeV → **7 σ difference from SM prediction**!





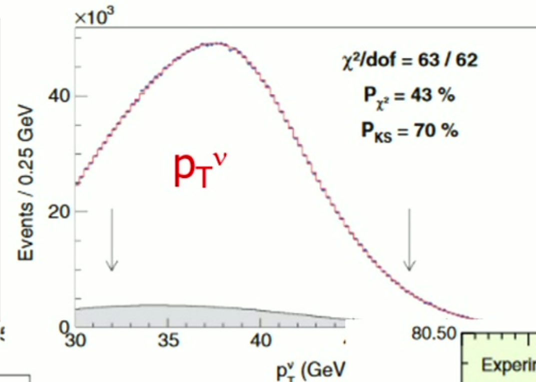
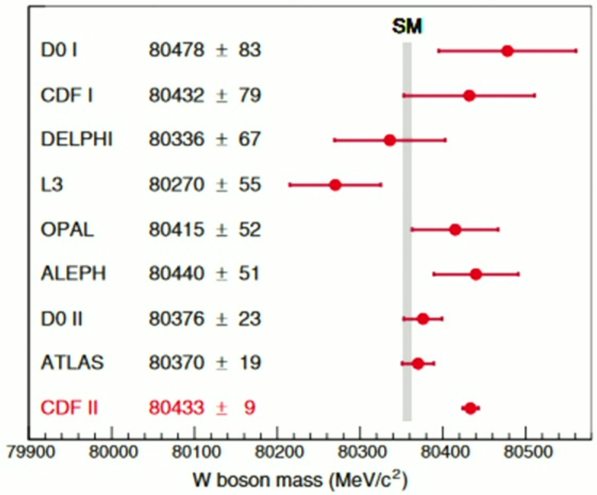
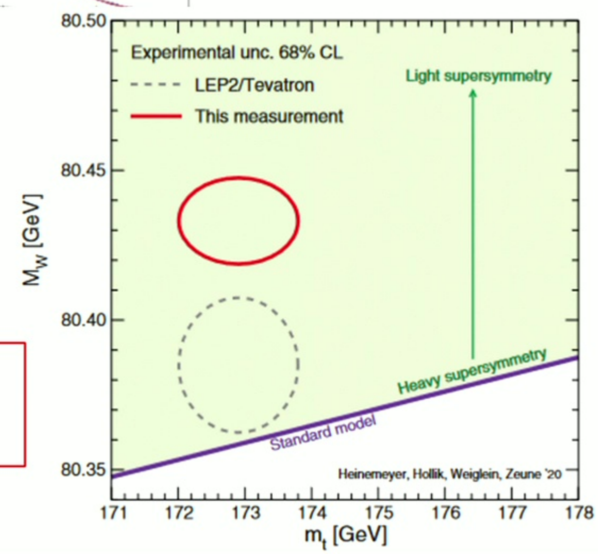


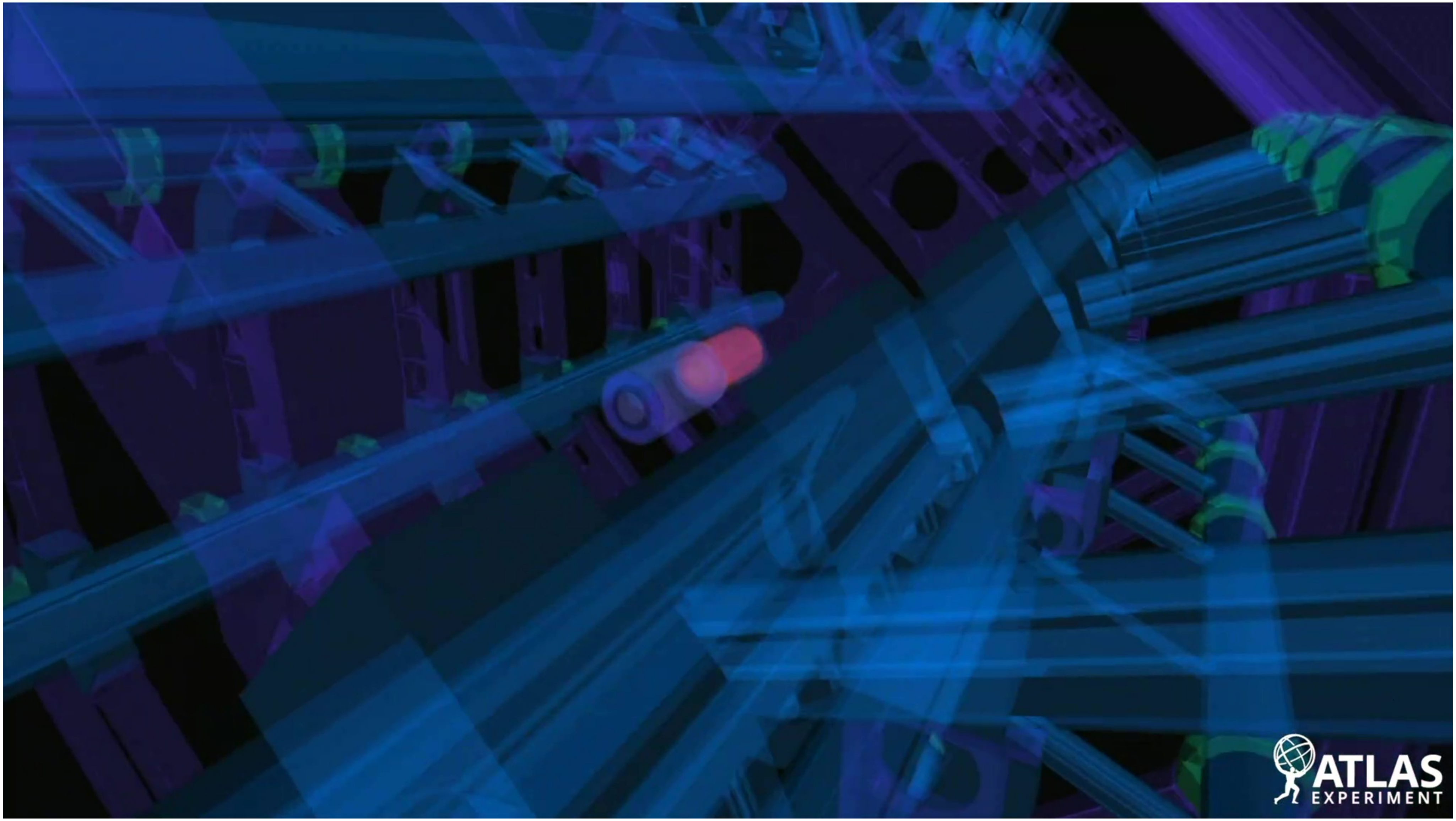
Table 2. Uncertainties on the combined M_W result.

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4



New physics?
Measurement issues?
SM calculations?

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