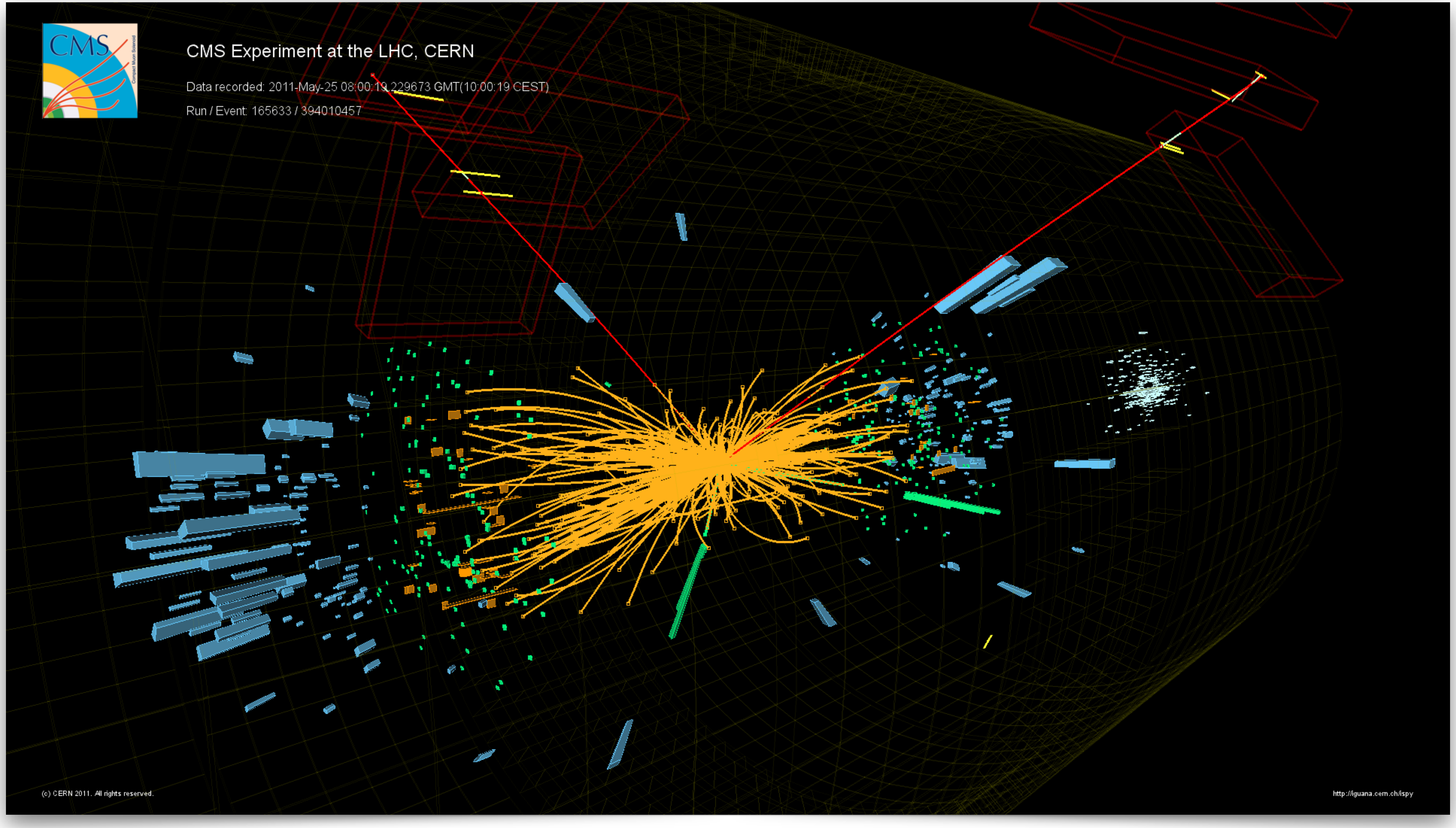
Experimental Physics at Hadron Collider

Lecture 2- *Standard Model (Precision) Measurements*



ZZ event

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LAL, Orsay and Sapienza, Roma

CERN Summer Students
July 16-20, 2018

Outline

Lecture 1: Basic concepts, cross sections and QCD results

- Preamble
- Context and mission of the LHC
- Fundamentals of hadron collisions
- Luminosity and total cross section
- Cross sections measurements
- Jet production measurements
- Measurement of the strong coupling constant

Lecture 2: SM Measurements

- The electroweak sector in a tiny nutshell
- Measurement of the weak mixing angle
- W mass measurement
- Top mass measurement
- Diboson production
- Global fit of the Standard Model

Lecture 3: Higgs physics

- The Higgs mechanism and Higgs production
- The discovery of the Higgs boson
- Precision Higgs physics with diboson channels
- Measuring the Yukawa couplings
- Measurement of Higgs properties
- Rare production and decays
- Global fit of the Standard Model (revisited)

Lecture 4: Searching for new physics BSM and future Hadron Colliders

- Introduction
- Searches for supersymmetry and Dark Matter
- Searches in non SUSY theories
- Searches for unconventional signatures
- EFT and high energy observables
- Outlook on future colliders
- Conclusions

The electroweak sector in a tiny nutshell

The elegant gauge sector (beautifully governed by symmetries and only three parameters for EWK and one parameter for QCD at tree level)

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c.$$

Yesterday (and this morning) discussed unbroken QCD with its massless gluons

For the EW sector it is another story… Gauge bosons and fermions have masses!

Higgs mechanism is needed!

The Higgs is for tomorrow, but the mere presence of a Higgs mechanism introduces predictive relations between gauge boson masses and their couplings.

Expanding a bit on the Electroweak sector:

$$SU(2)_L \otimes U(1)_Y \quad \text{(from the Higgs mechanism)}$$

$$\downarrow \qquad\qquad \downarrow \qquad\qquad \downarrow$$

$$g \qquad\qquad g' \qquad\qquad v$$

The one-to-one relation between the couplings and the masses of gauge bosons (at Tree level) introducing the week mixing angle!

$$\tan\theta_W = \frac{g'}{g} \qquad m_W = \frac{gv}{2} \qquad m_Z = \frac{gv}{2\cos\theta_W}$$

These relations translate into one parameter expected to be 1 at tree level:

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$

This parameter can be (and has been) measured experimentally well before the discovery of the Higgs. Though it is one of its direct consequences!

The Drell Yan Z/γ^* production

Measurement of the weak mixing angle

Composition of Drell Yan production

Flavour content of the $pp \to Z, W^{\pm}$ process

In pp collisions a sizeable charge asymmetry due to the valence quarks (2u vs 1d) in the proton (difference reduces with the COM energy as W production occurs at lower x).

For 13 TeV collisions predictions are:

$$\sigma_{W^-} = 8.54\,^{+0.21}_{-0.24}\,(\mathrm{PDF}) \pm 0.16\,(\mathrm{TH})\ \mathrm{nb}$$

$$\sigma_{W^+} = 11.54\,^{+0.32}_{-0.31}\,(\mathrm{PDF}) \pm 0.22\,(\mathrm{TH})\ \mathrm{nb}$$

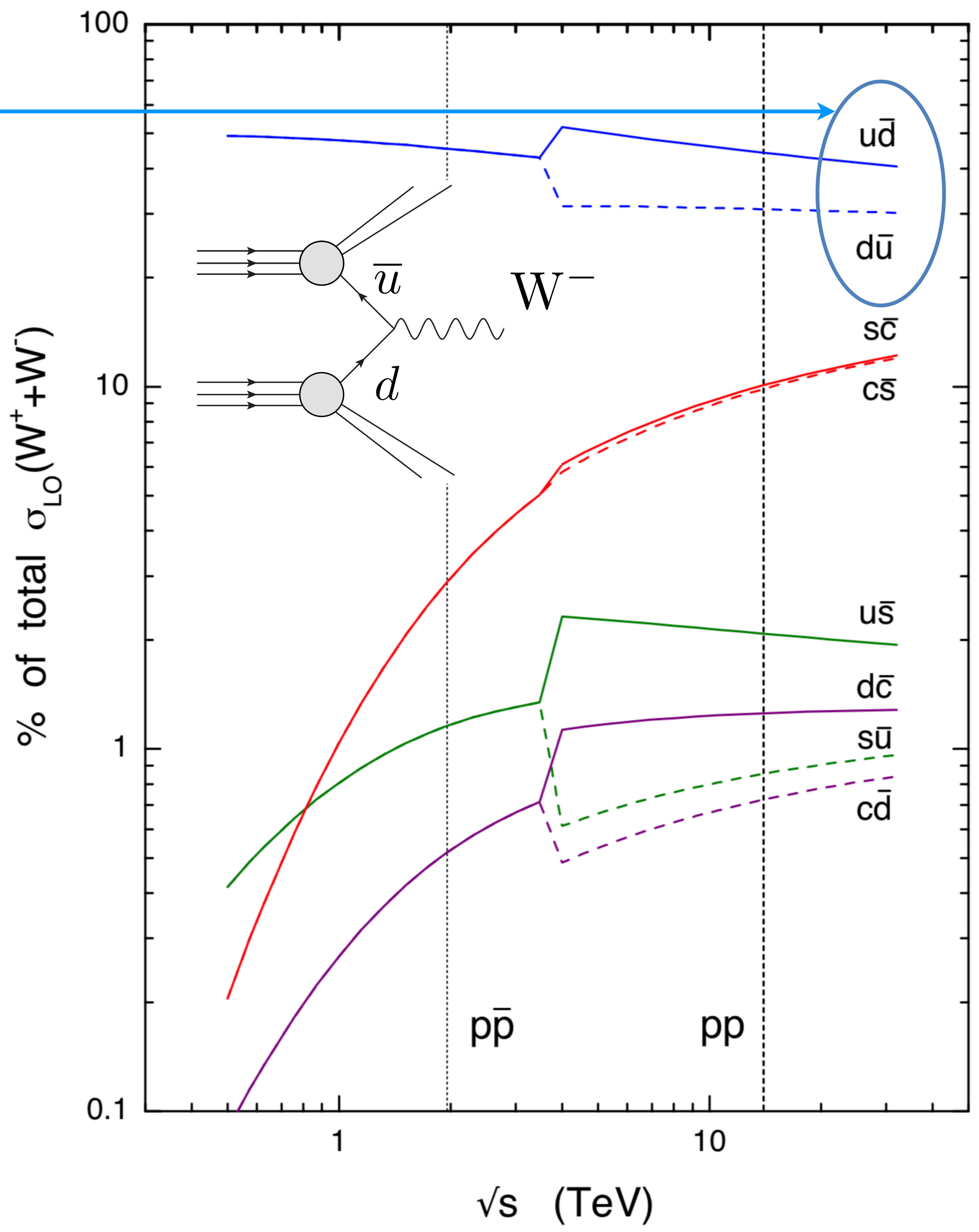
$$\sigma_Z = 1.89 \pm 0.05\,(\mathrm{PDF}) \pm 0.04\,(\mathrm{TH})\ \mathrm{nb}$$

Note: PDF uncertainties are dominant.

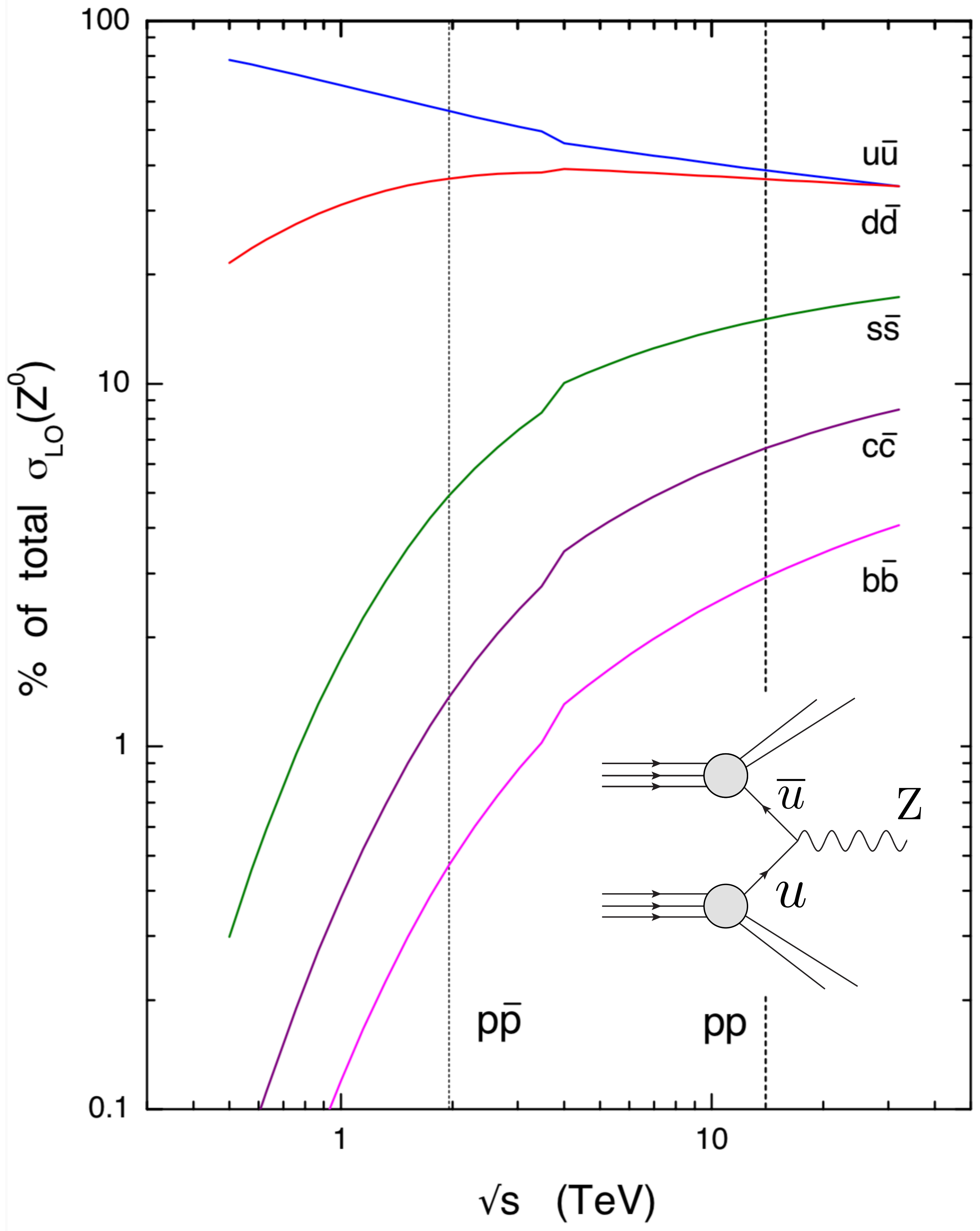
Overall this process is O(3M) times smaller than the total inelastic cross section.

Still O(2) Billion W boson events produced !!

flavour decomposition of W cross sections



flavour decomposition of Z⁰ cross sections



Typically in pp in leptonic modes

$$\ell = e, \mu, \tau$$

$$\mathrm{Br}(W \to q\overline{q'}) \sim 70\%$$

$$\mathrm{Br}(W \to \ell^{\pm}\nu) \sim 10\%$$

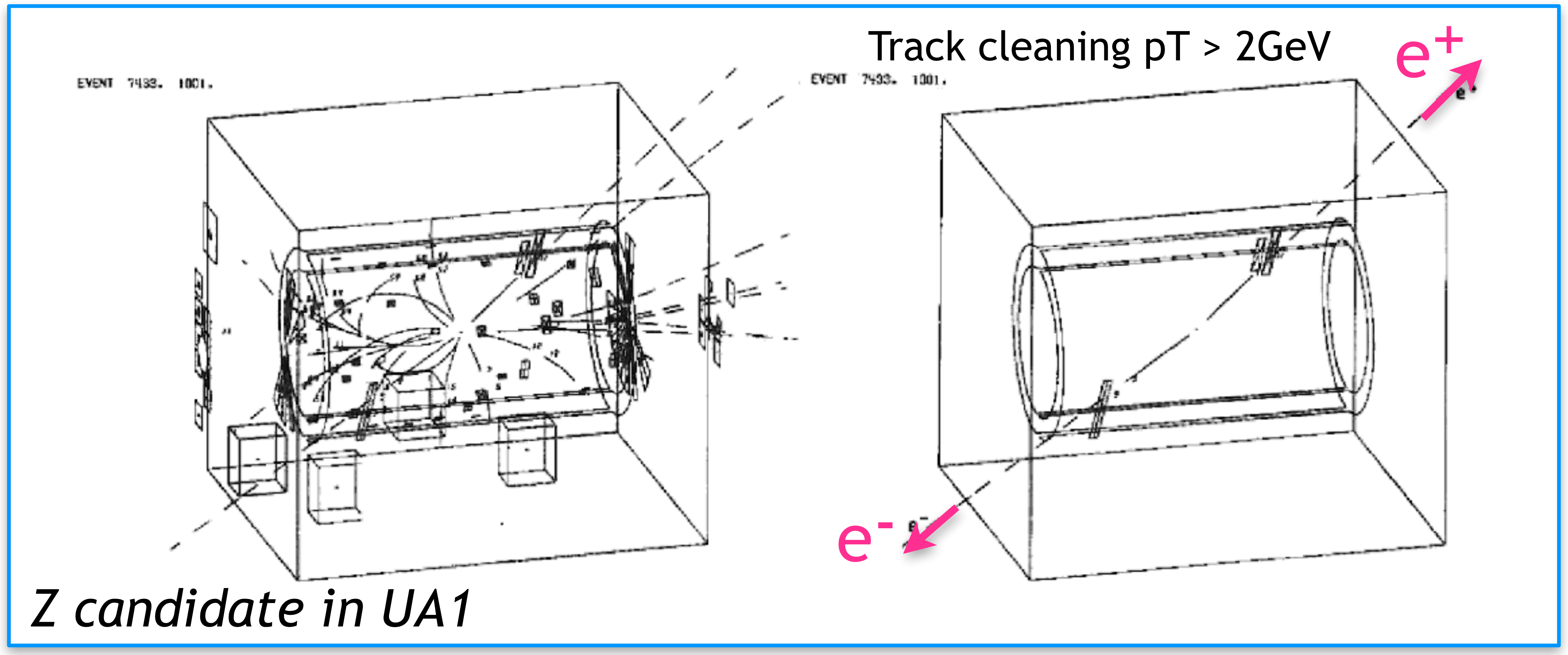
$$\mathrm{Br}(Z \to \nu\overline{\nu}) \sim 20\%$$

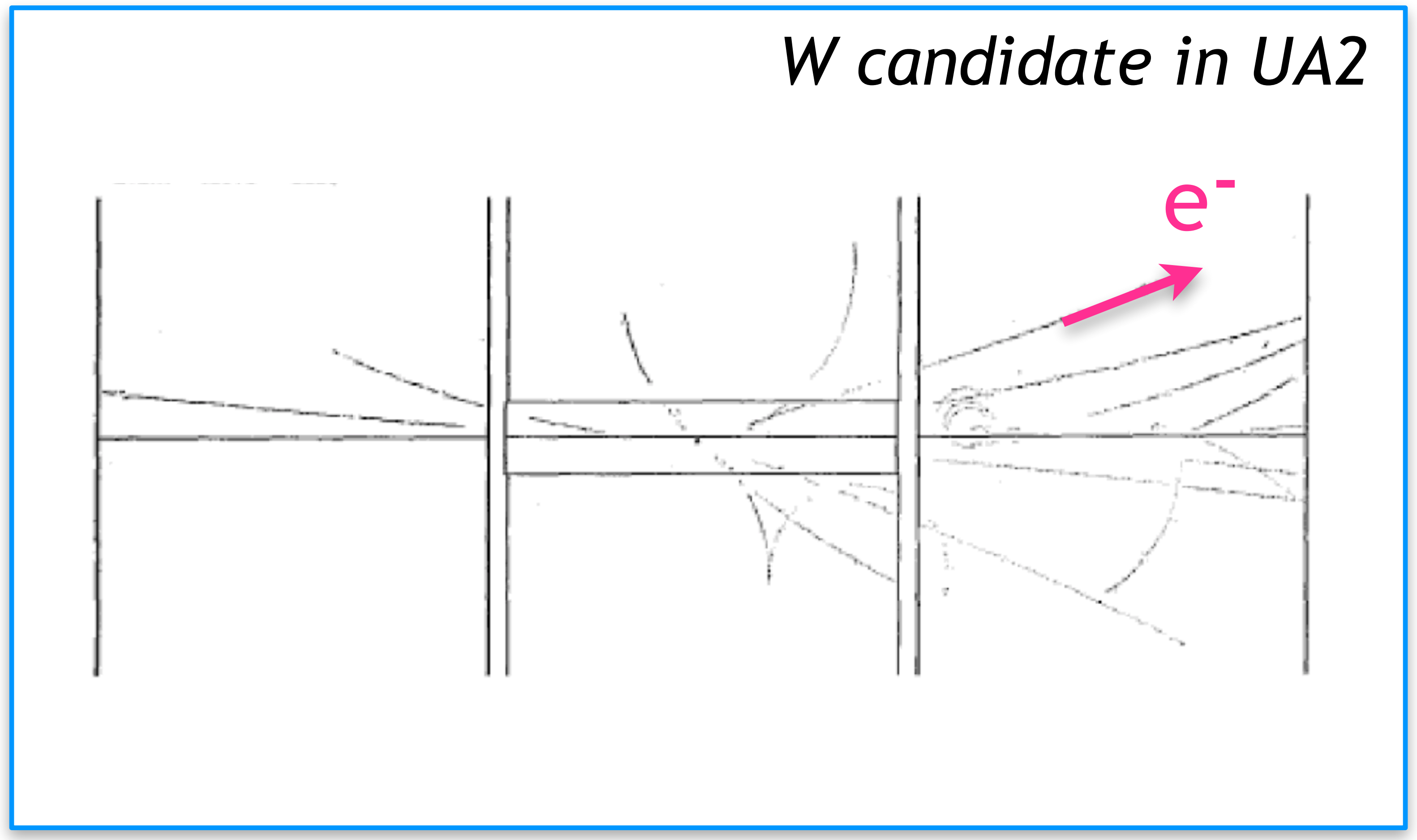
$$\mathrm{Br}(Z \to q\overline{q}) \sim 70\%$$

$$\mathrm{Br}(Z \to \ell^+\ell^-) \sim 3\%$$

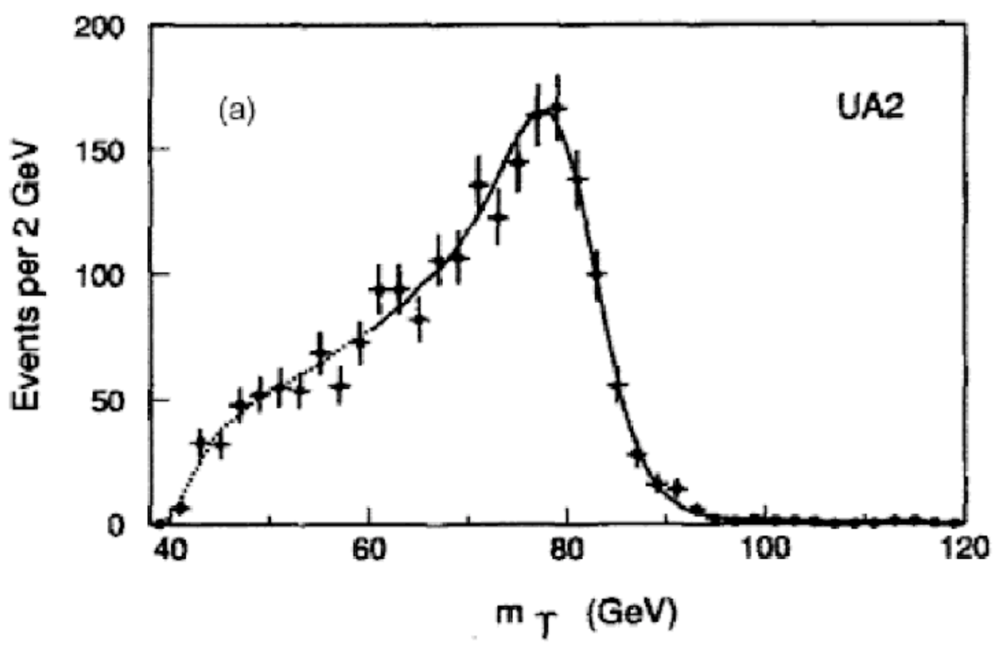
Where it all started: the SppS Legacy

The discovery of the W and Z bosons





Transverse Mass distribution in UA2



$$m_T^2 = m^2 + p_x^2 + p_y^2$$

Altogether O(100) Z events.

Already important measurements (examples):

$$M_Z = 91.5 \pm 1.2 \pm 1.7\,(\text{GeV}) \quad \textit{(UA1)}$$

$$M_W = 81.0 \pm 0.8 \pm 1.3\,(\text{GeV}) \quad \textit{(UA2)}$$

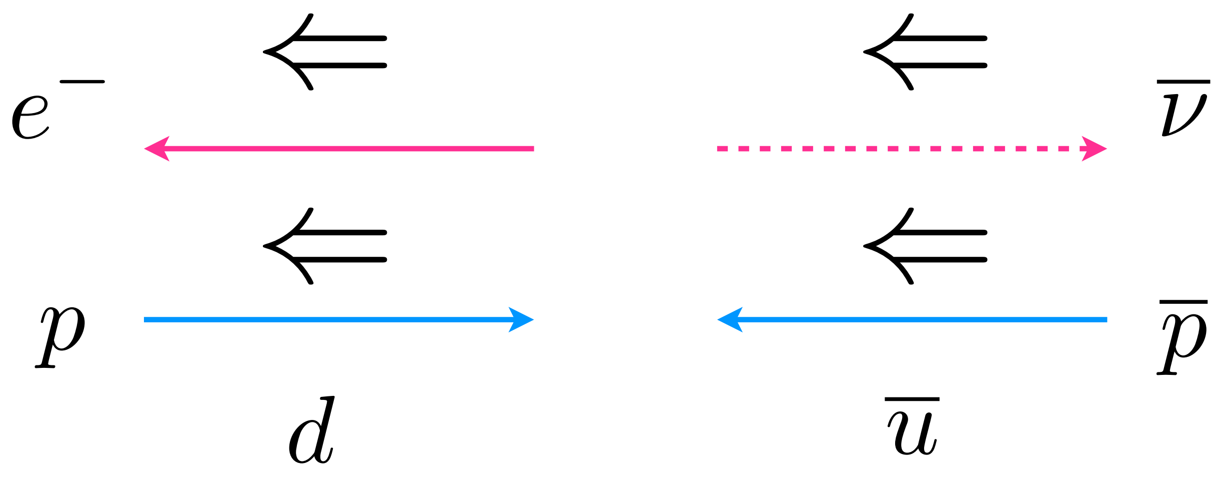
$$\rho = 1.004 \pm 0.052 \quad \textit{(UA1)}$$

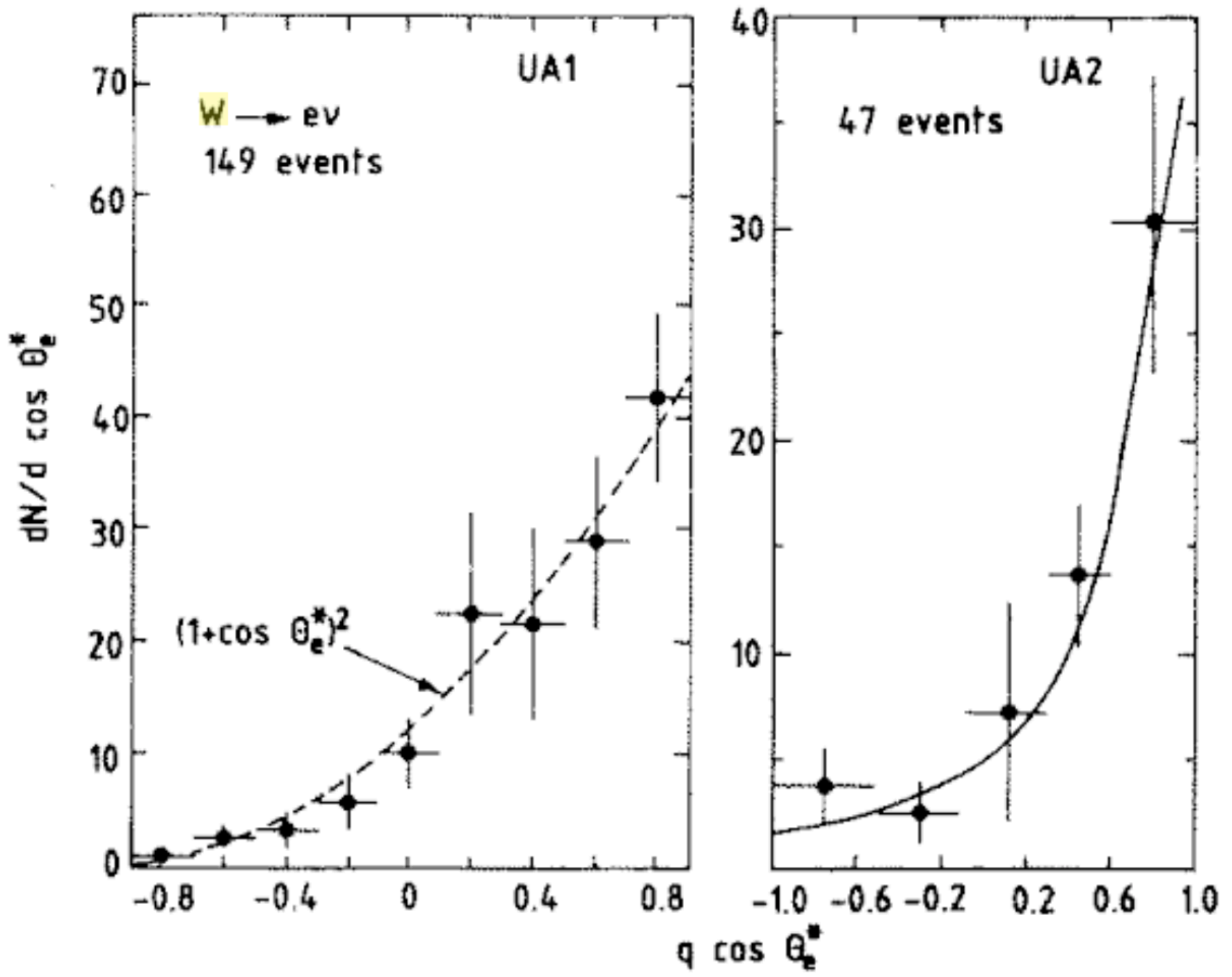
$$\sin^2\theta_W = 0.226 \pm 0.014 \quad \textit{(UA1)}$$

Altogether O(1000) W events

At SppS W production dominated by valence quarks

W polarised in the anti-proton direction.

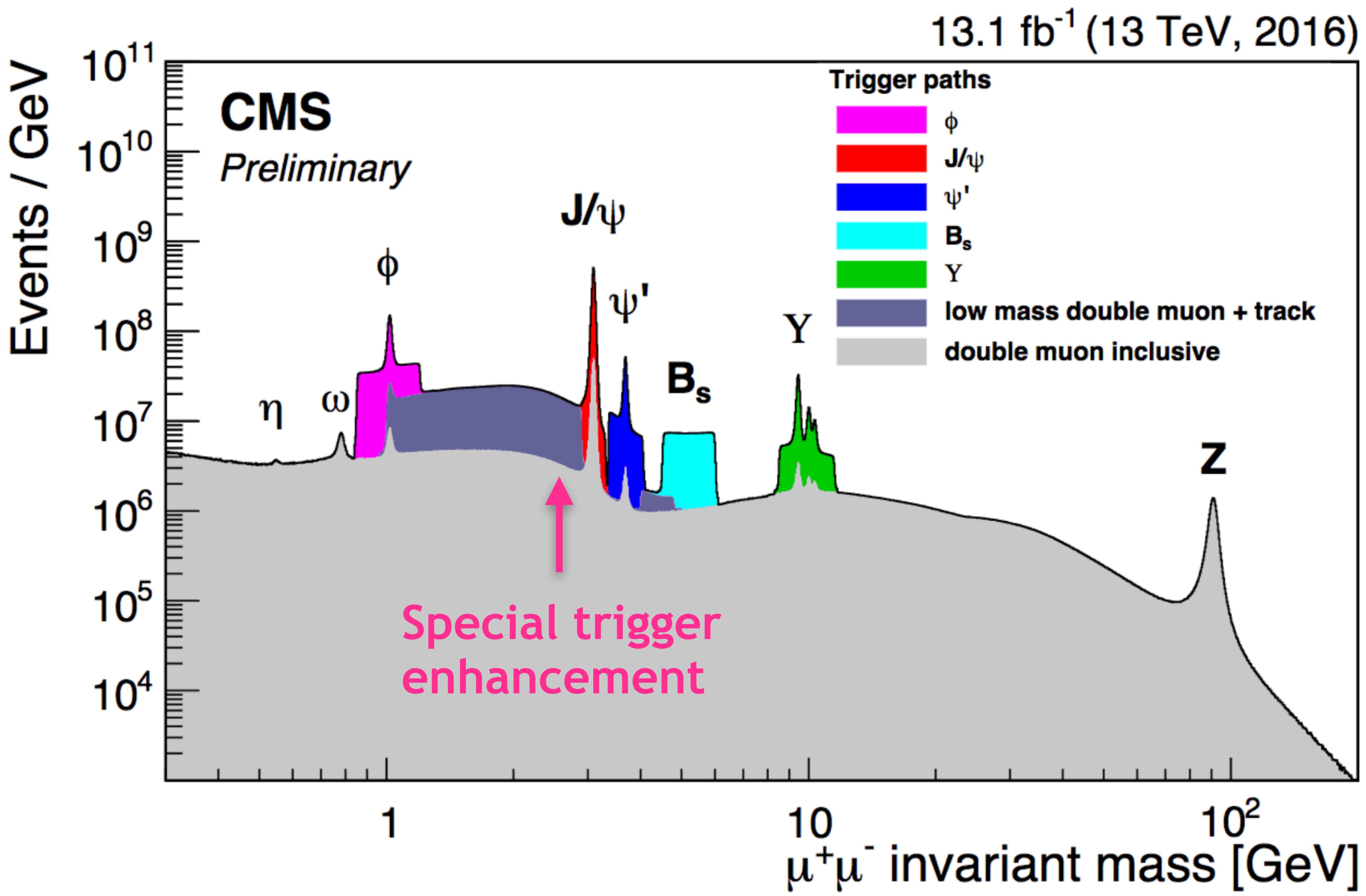


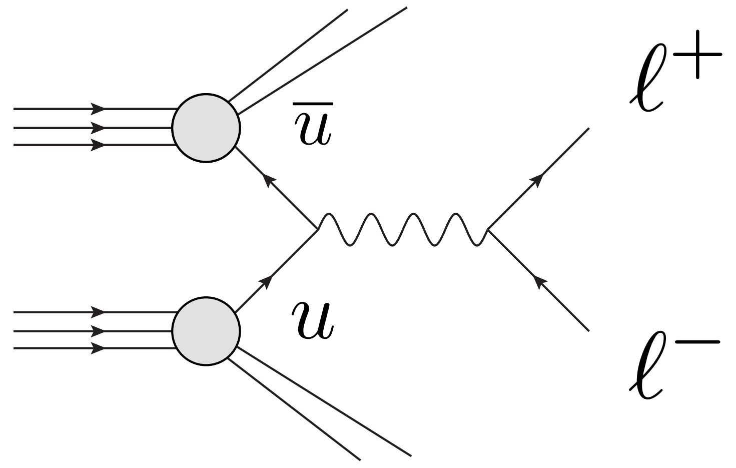


The di-lepton mass spectrum at LHC

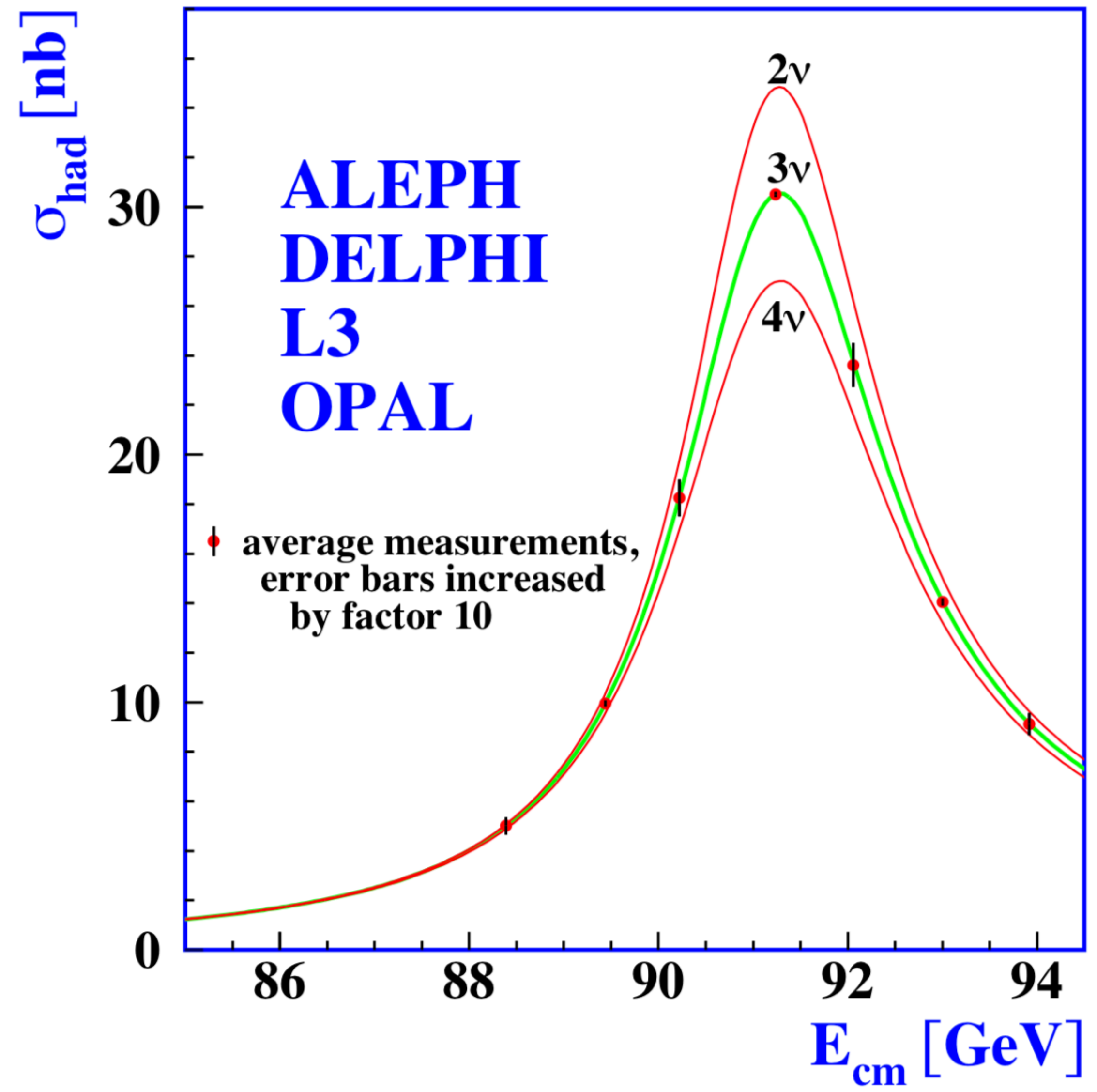
LEP

Inclusive mass distributions





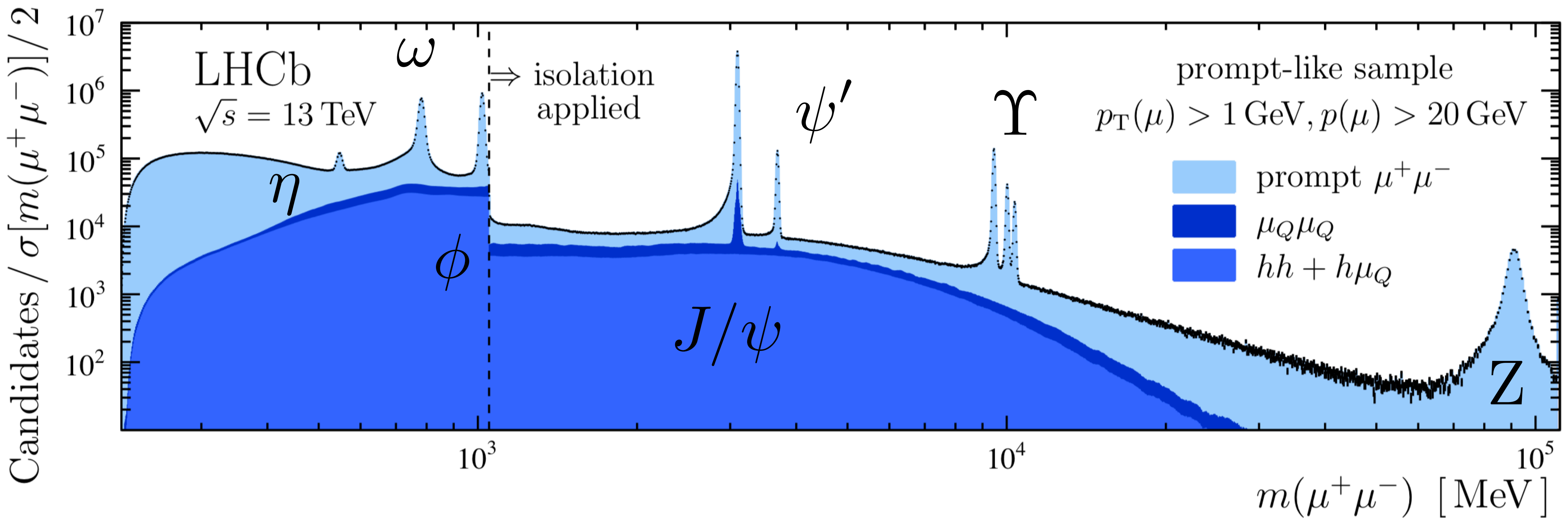
Z, J/Psi and Upsilon in electrons and muons are extremely important standard candles for calibration.



$$m_Z = 91.1875 \pm 0.0021\,\mathrm{GeV}$$

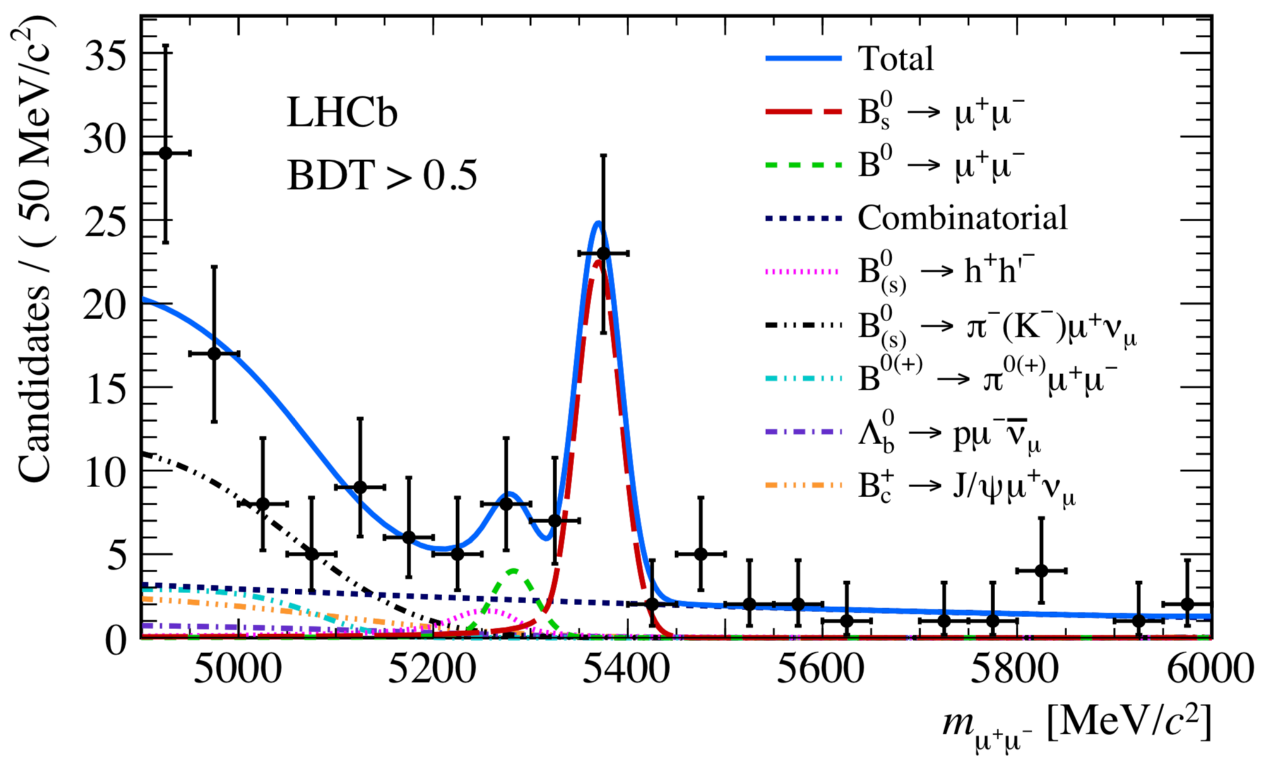
$$\Gamma_Z = 2.4952 \pm 0.0023\,\mathrm{GeV}$$

$$\rho = 1.0050 \pm 0.0010$$



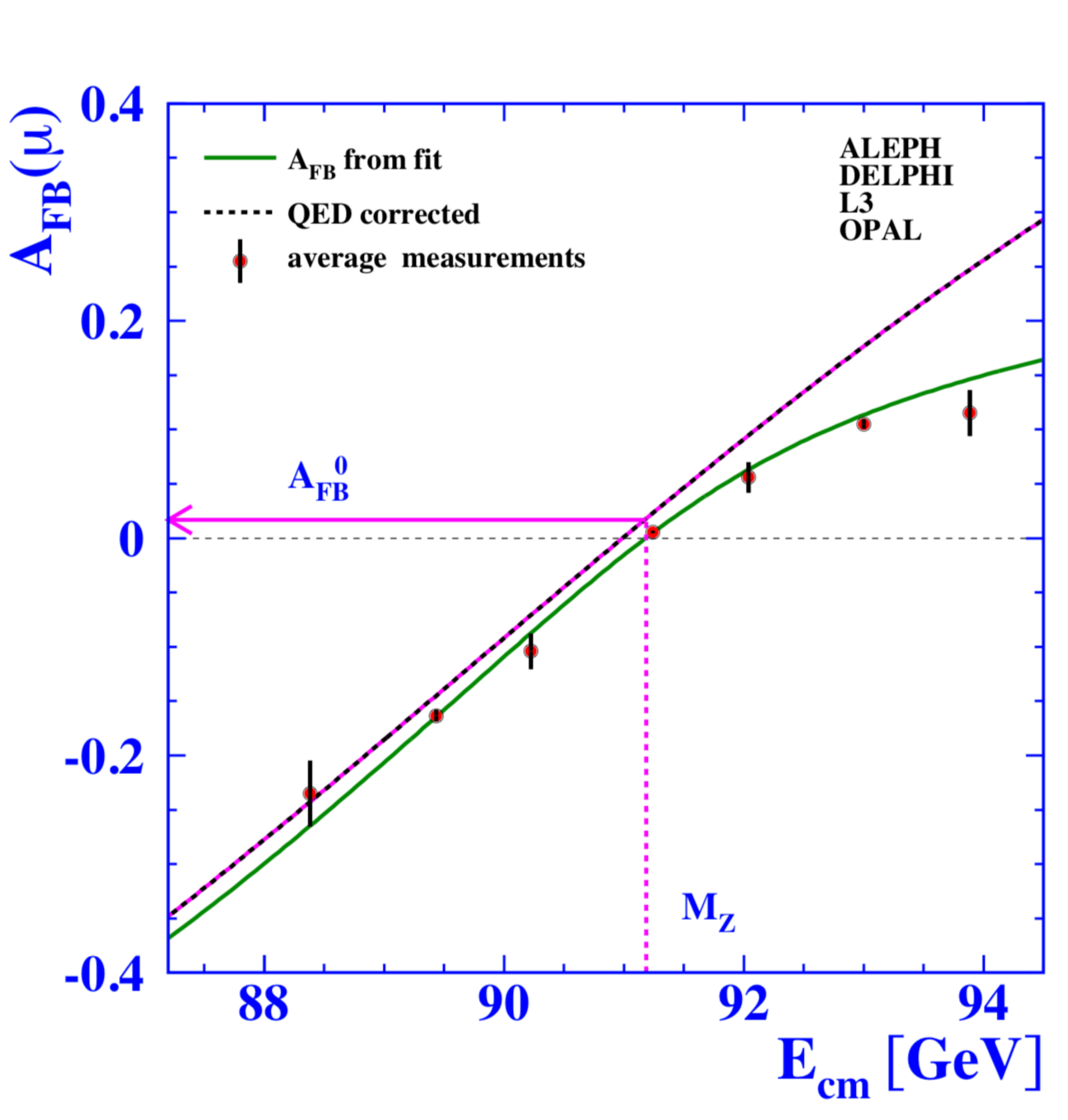
An exclusive analysis scrutinising the Bs mass region

$$\mathrm{Br}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$



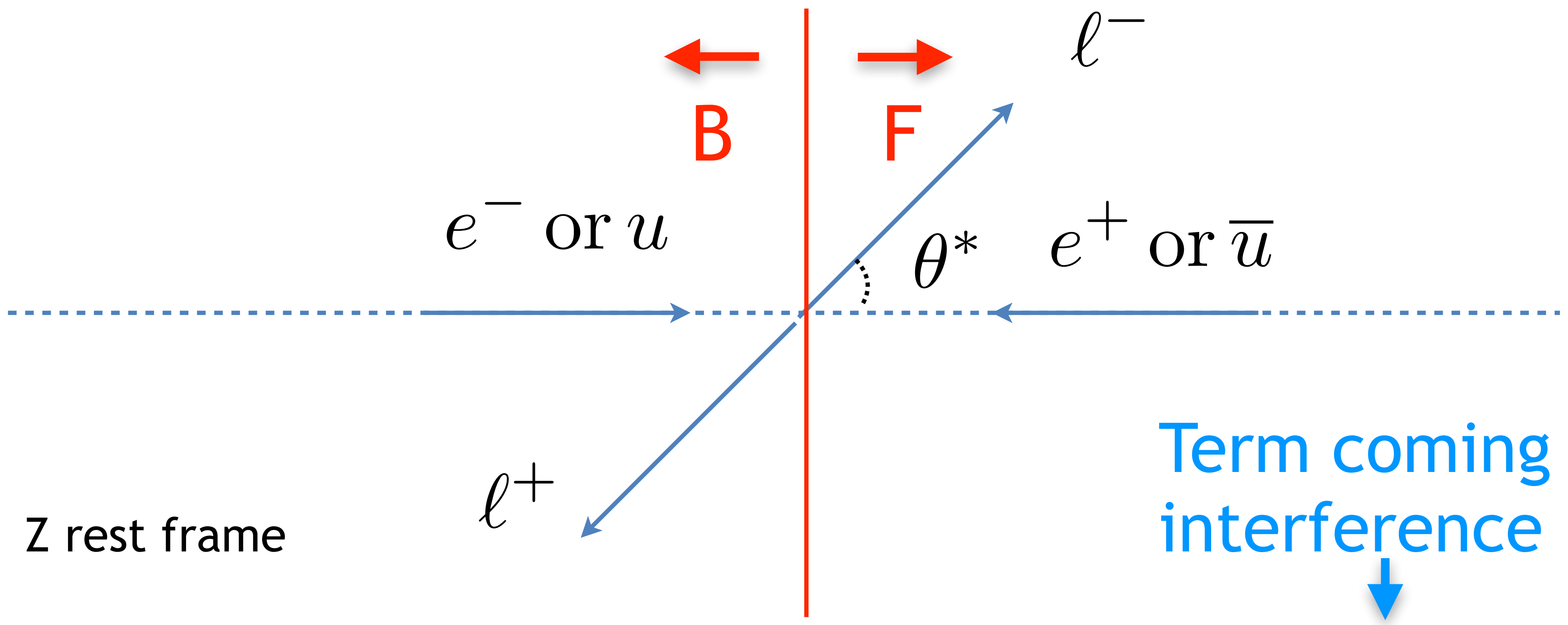
Forward Backward Asymmetry

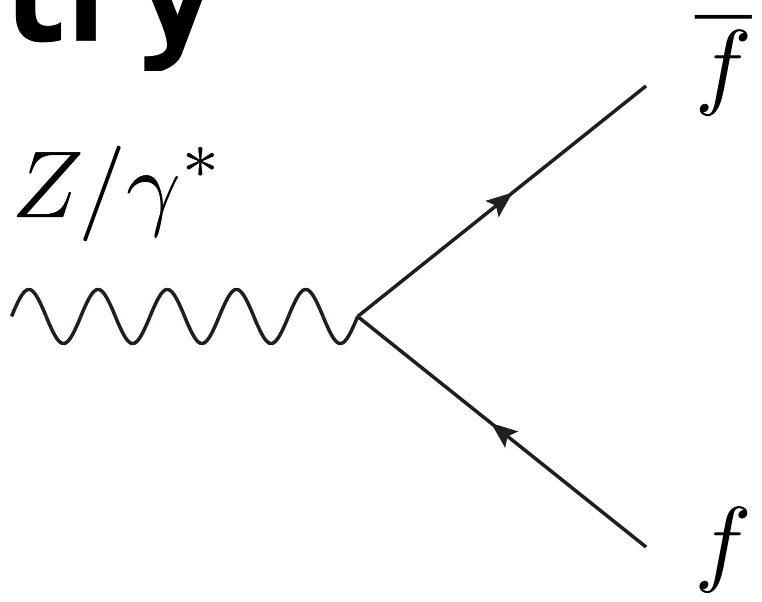
LEP



Forward-Backward asymmetry at LEP

On peak, effect is very small, off peak measurement are also extremely crucial.





Term coming from the Z/gamma* interference

$$\frac{d\sigma}{d\cos\theta^*} = \frac{4\pi\alpha^2}{3\hat{s}}\left[\frac{3}{8}A(1+\cos^2\theta^*) + B\cos\theta^*\right]$$

- The effect of the interference term increases off-peak.

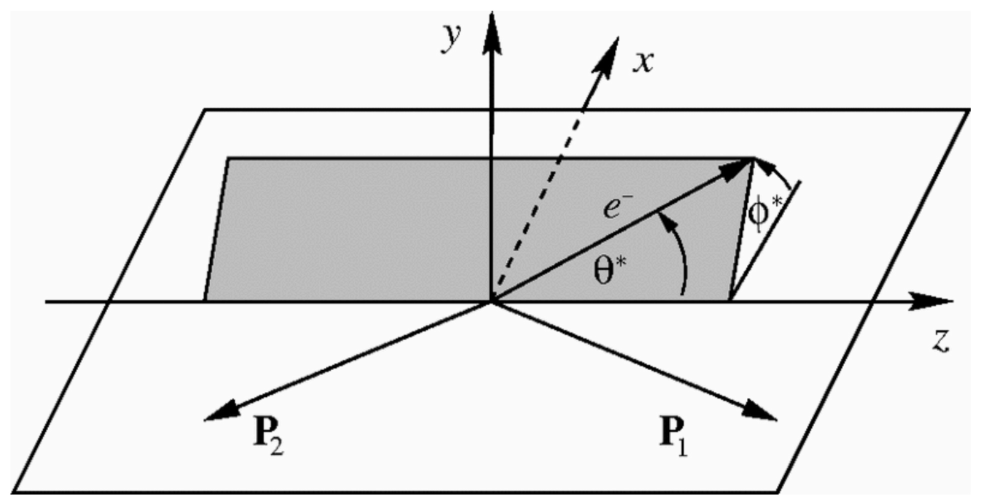
- The COM frame at LEP is essentially the detector frame, at the LHC this is not the case! Choice of frame is subtle.

- At LEP direction of charges is perfectly defined. At LHC the direction of initial charges is less straightforwardly known. However the typically larger momentum of valence quarks do give a direction

- Once the frame is chosen, and the direction chosen (in z boost) to quantify the effect just count events in the forward and backward.

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

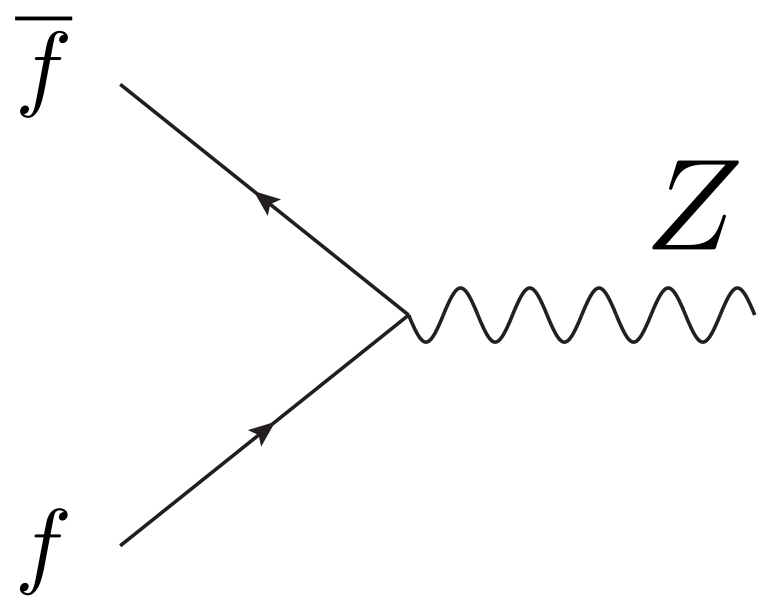
In the Collin-Soper frame:



Direction of the negatively charged lepton, where the axis points in the direction of the boost

Formalism of Weak Mixing Angle Measurements

A closer look at the Z coupling to fermions (through axial and vector currents):



$$a_f = (L_f - R_f)/2 = T_f^3$$
$$v_f = (L_f + R_f)/2 = T_f^3 - 2Q_f \sin^2\theta_W$$

Family			T	T_3	Q
$\begin{pmatrix}\nu_e \\ e\end{pmatrix}_L$	$\begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}_L$	$\begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}_L$	1/2	+1/2 −1/2	0 −1
ν_{eR}	$\nu_{\mu R}$	$\nu_{\tau R}$	0	0	0
e_R	μ_R	τ_R	0	0	−1
$\begin{pmatrix}u \\ d\end{pmatrix}_L$	$\begin{pmatrix}c \\ s\end{pmatrix}_L$	$\begin{pmatrix}t \\ b\end{pmatrix}_L$	1/2	+1/2 −1/2	+2/3 −1/3
u_R	c_R	t_R	0	0	+2/3
d_R	s_R	b_R	0	0	−1/3

At tree level the axial and vector couplings of vector bosons to fermions are expressed as follows:

$$g_{a_f} = \sqrt{\rho}T_f^3$$
$$g_{v_f} = \sqrt{\rho}(T_f^3 - 2Q_f \sin^2\theta_W^{eff})$$

which can be rewritten as and thus related to the weak mixing!

$$\mathcal{A}_f \equiv 2\frac{g_{v_f}/g_{a_f}}{1+(g_{v_f}/g_{a_f})^2}$$

There is an obvious asymmetry between the coupling of the Z to Definition: Left Right asymmetry

$$\mathcal{A}_f \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

SLC

Measured directly at SLAC's SLC with **longitudinally** polarised electrons!

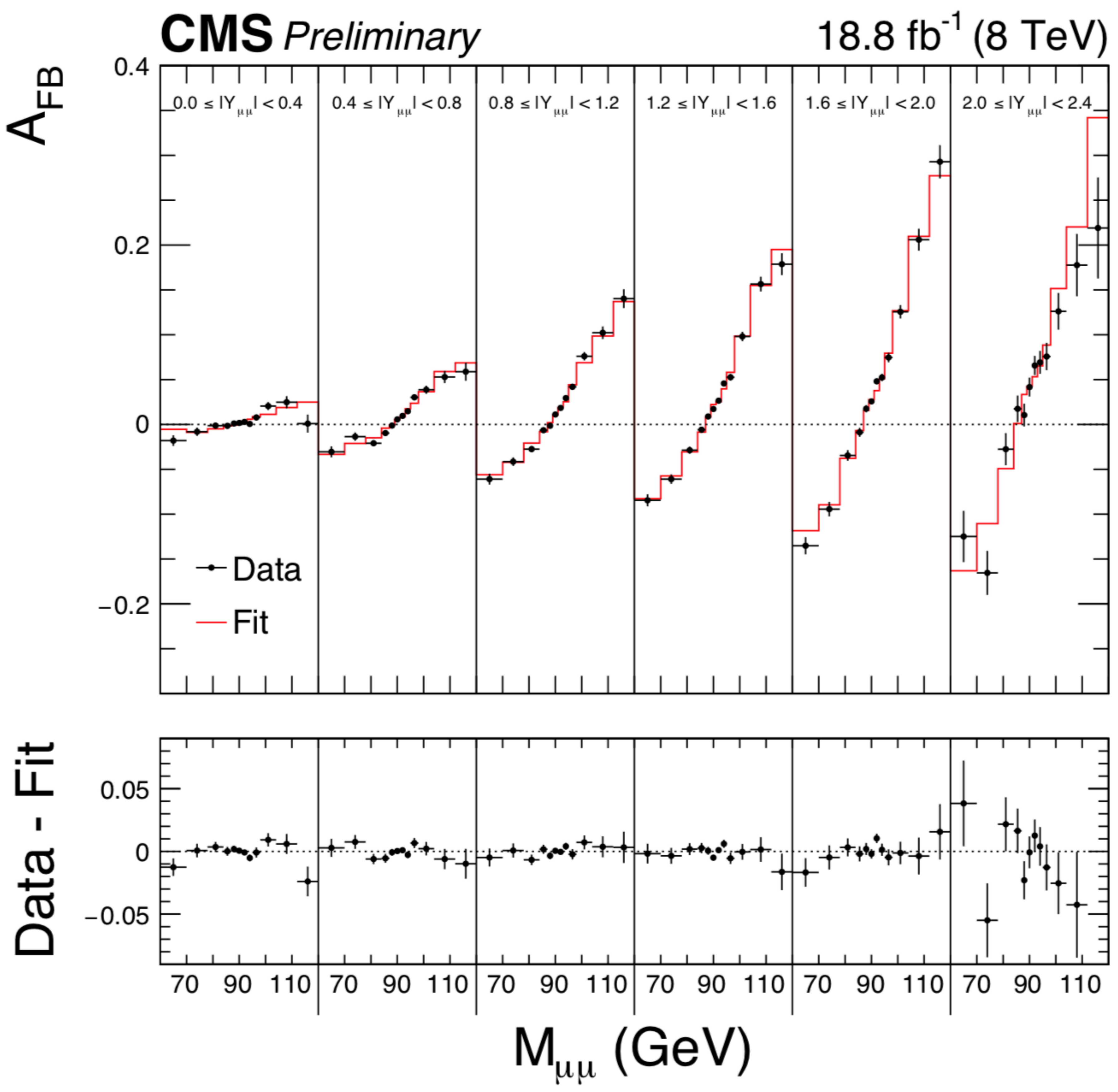
σ_L e^- $\Leftarrow$ → ← $\Leftarrow$ e^+

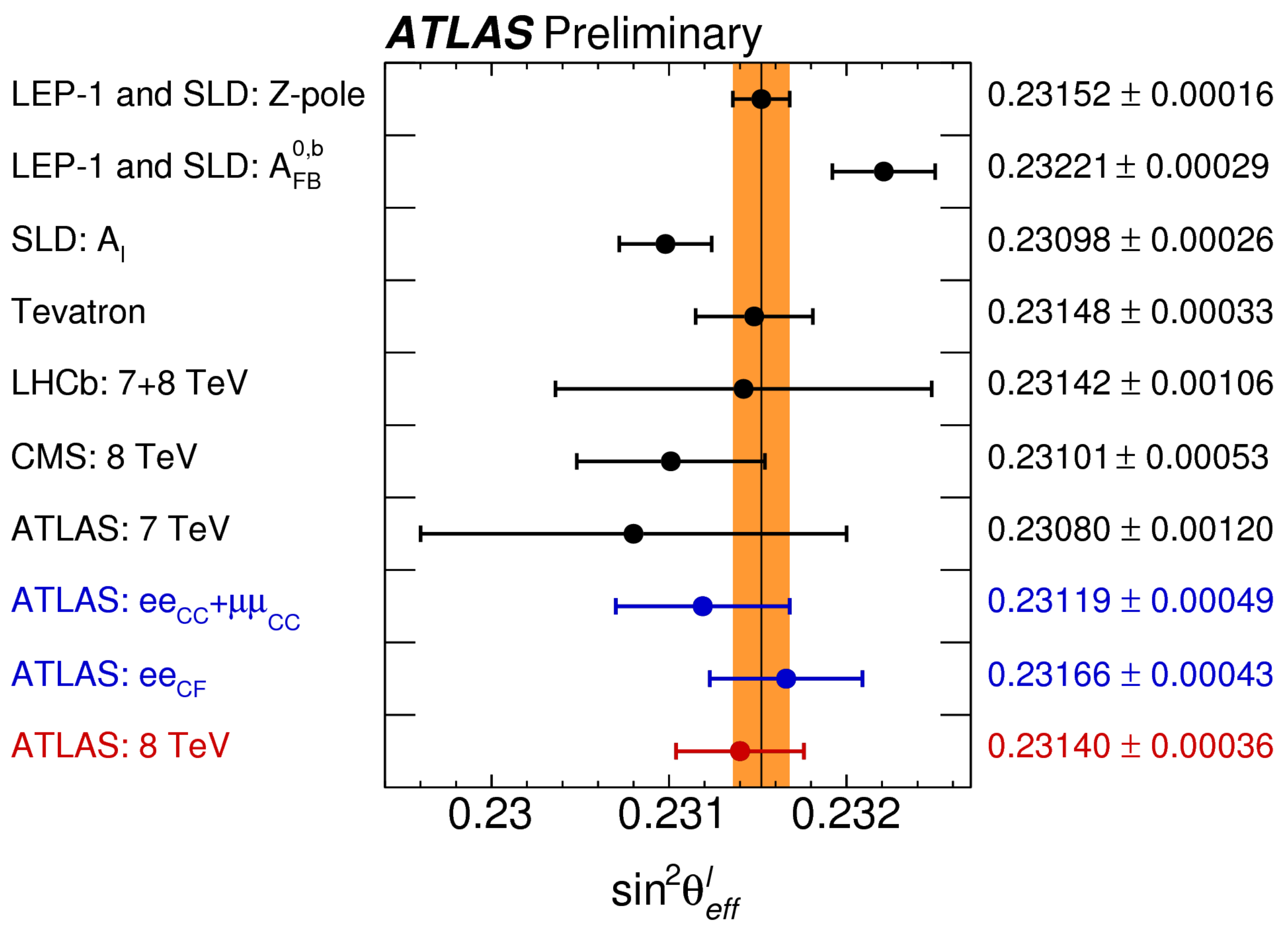
σ_R e^- $\Rightarrow$ → ← $\Rightarrow$ e^+

Measurement of effective weak mixing angle at the LHC

Once the reference frame is defined, the Forward backward asymmetry can be straightforwardly measured, however defining the reference frame and expressing the asymmetry in terms of the effective mixing angle is less straightforward but done.

The size of the asymmetry as a function of the di-lepton mass will depend on the rapidity of the system (how boosted it is in the z direction). Where a high boost generates less ambiguity on the initial direction of the charge (from valence quarks).



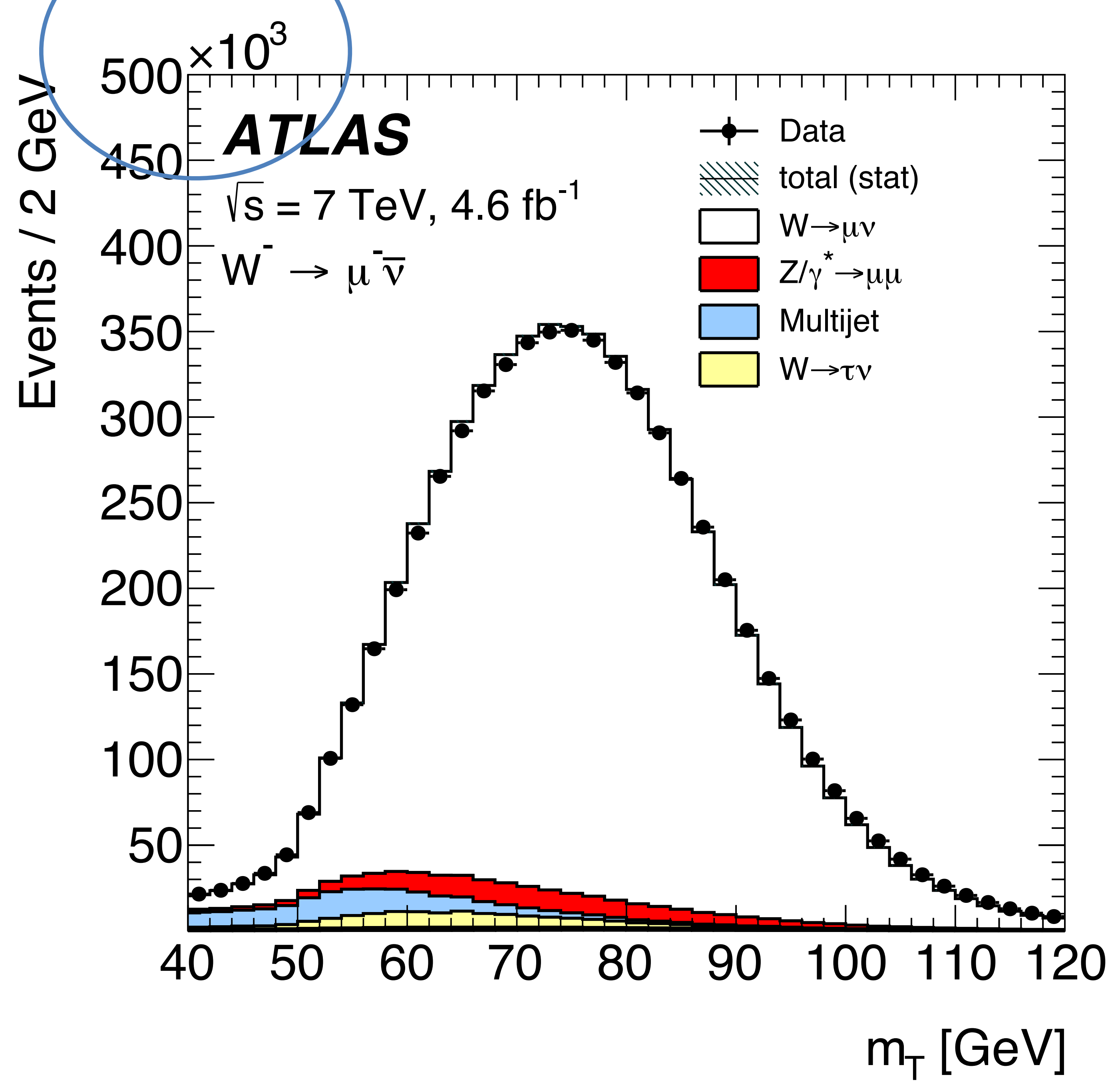


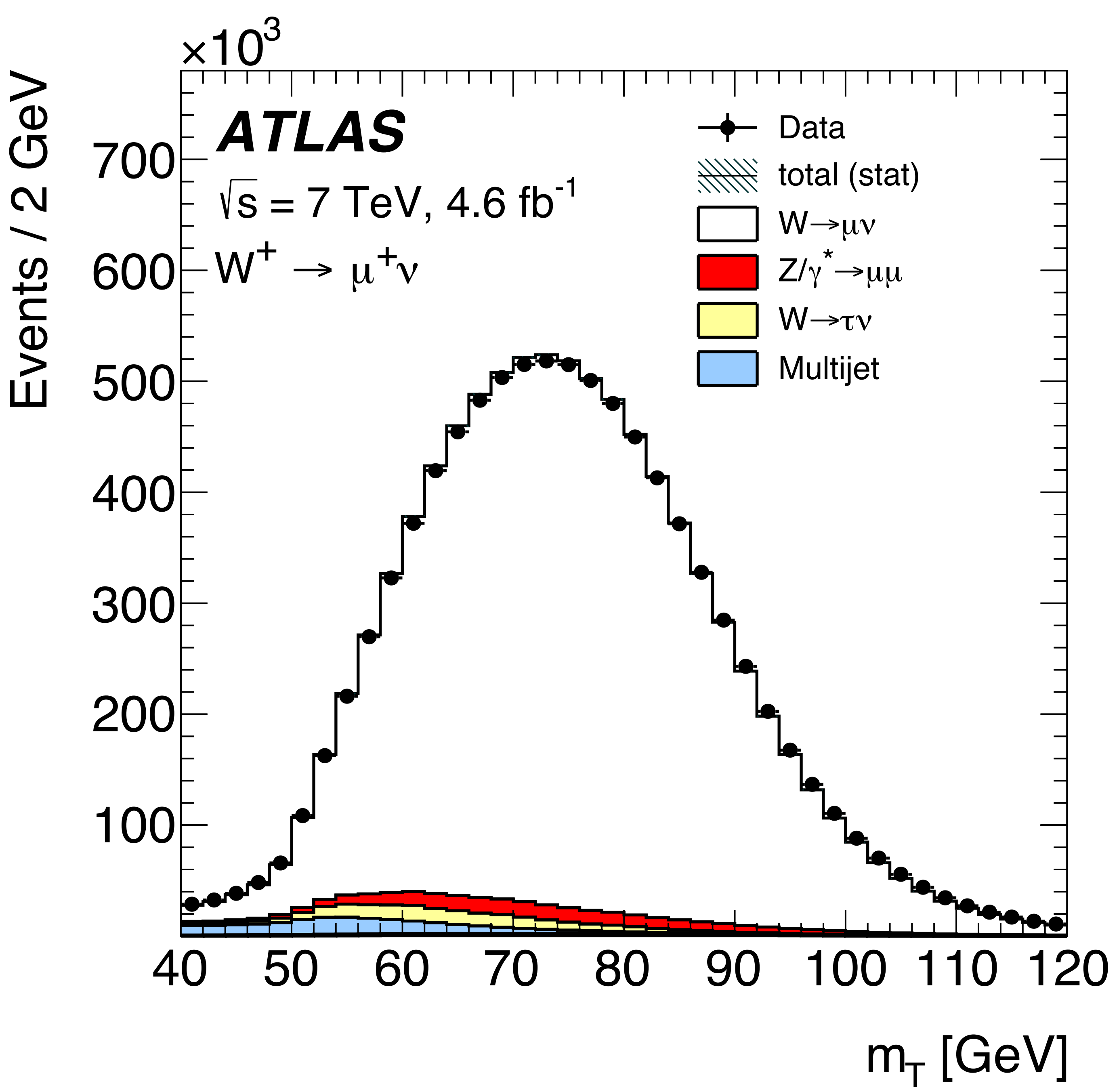
Latest ATLAS result using forward electrons up to eta of 4.9.

W boson production

Measurement of the W boson mass

Inclusive Precision Vector Boson Production at the LHC

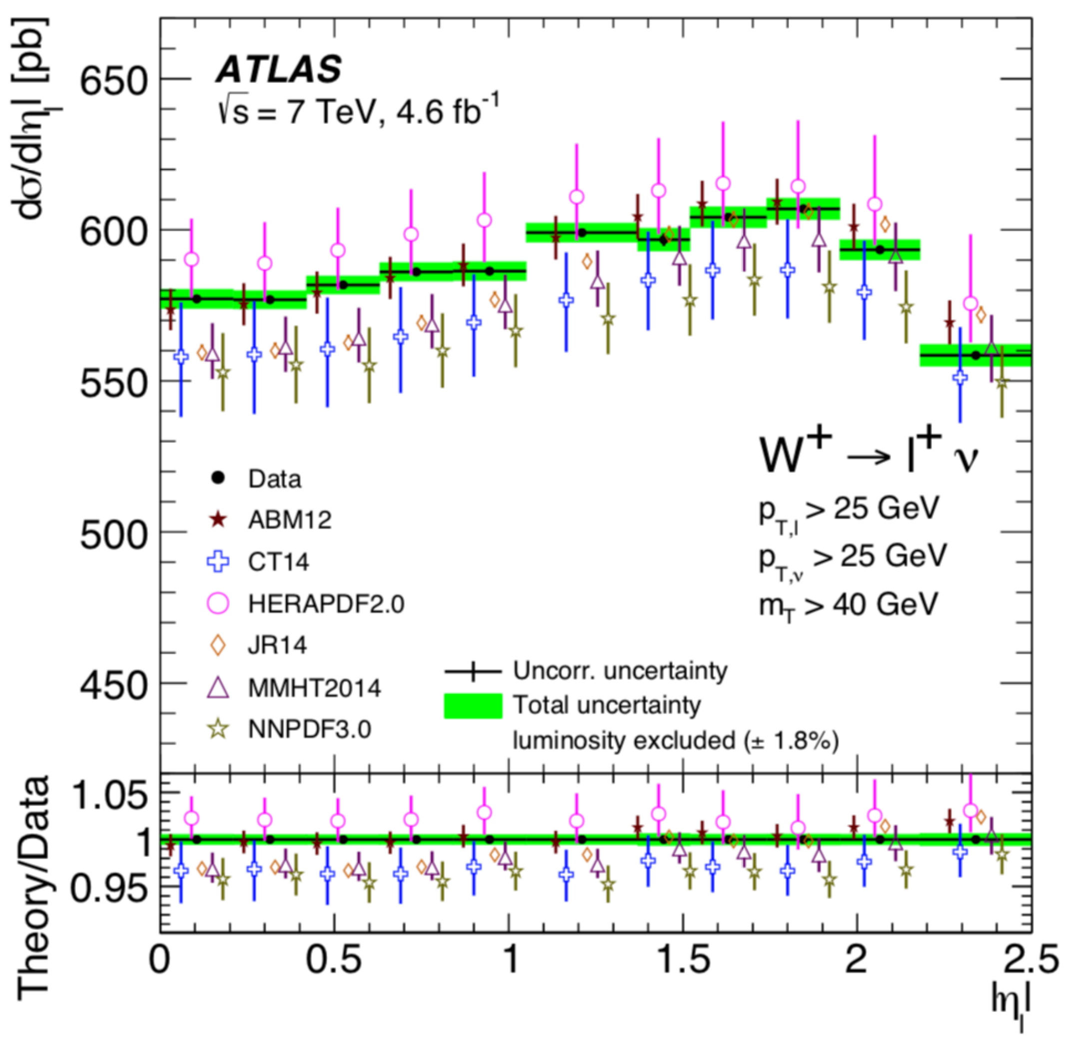


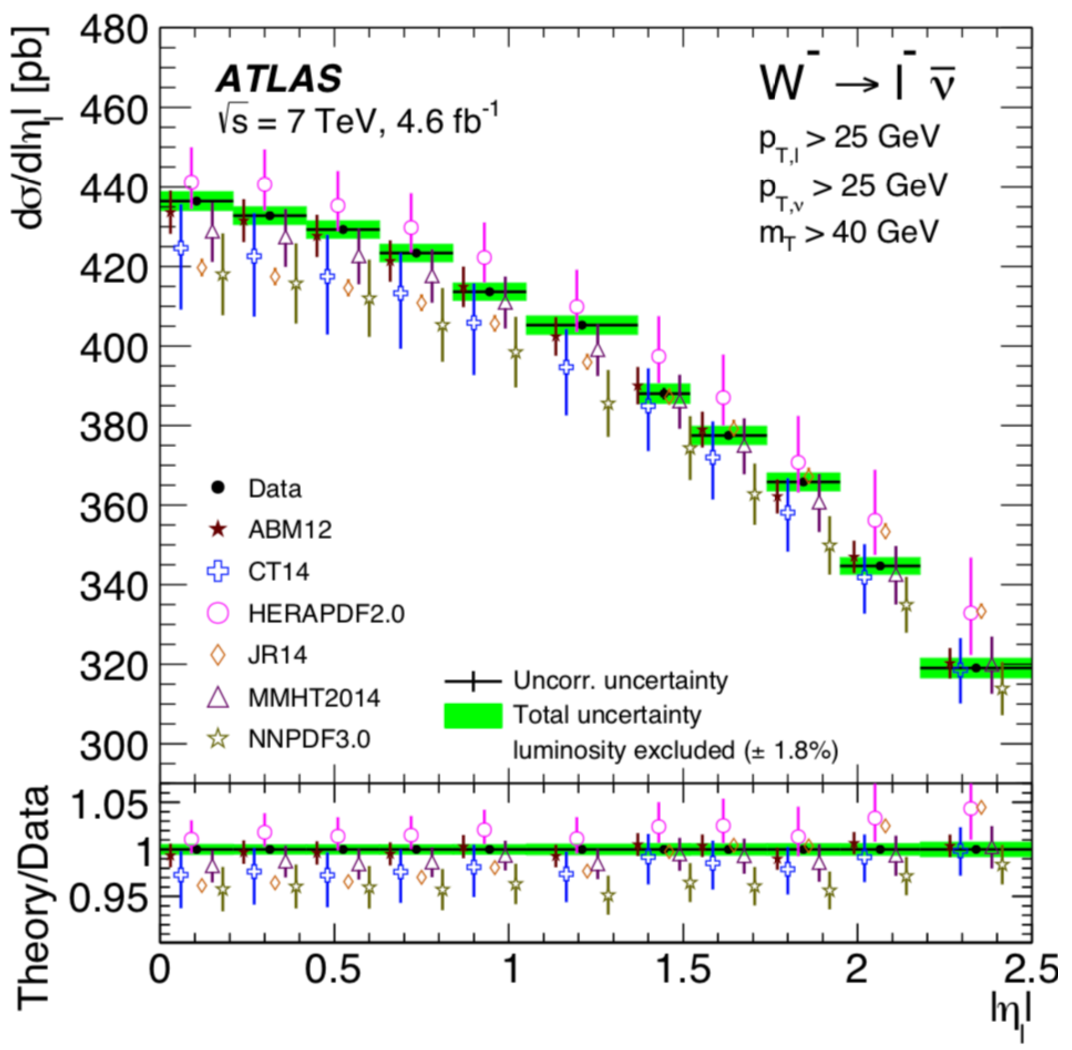


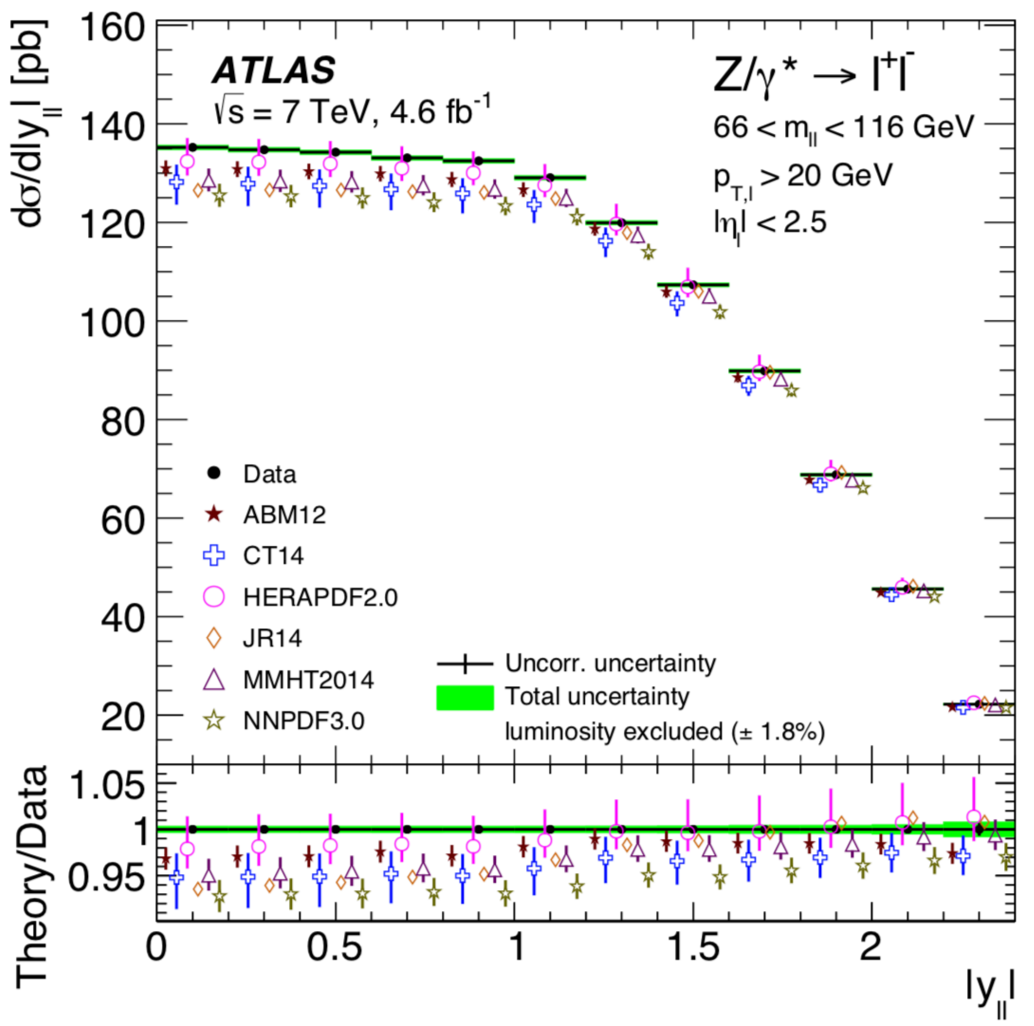
With a dataset of only 4.6 fb-1 at 7 TeV, approximately 15.5 M W+ events and 10.4 W- events (electrons and muons).

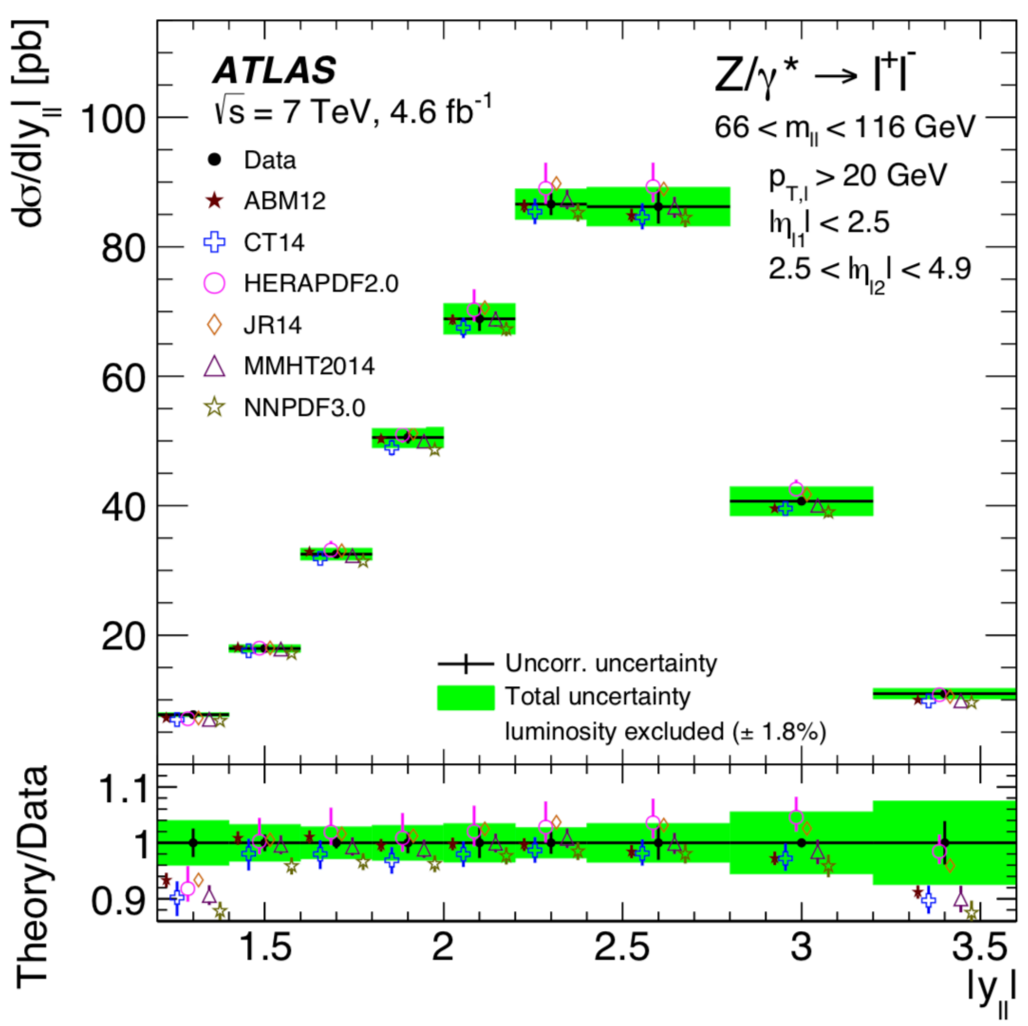
Cross section measurement uncertainty completely dominated by luminosity uncertainty of 1.8%

Differential cross sections for both W, Z, and Z with one forward electron are derived as a function of lepton pseudo-rapidity (W) and the Z rapidity.

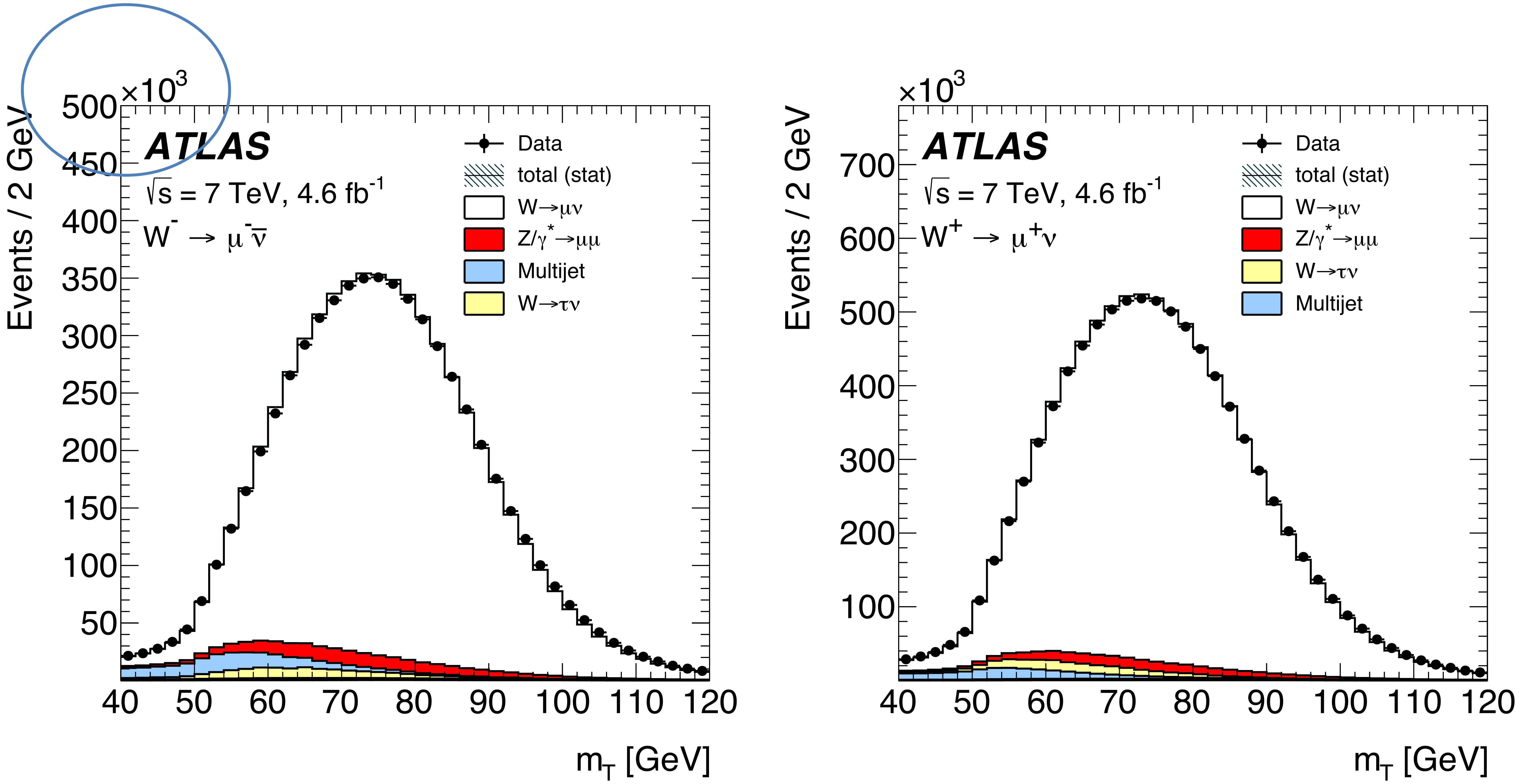








Inclusive Precision Vector Boson Production at the LHC



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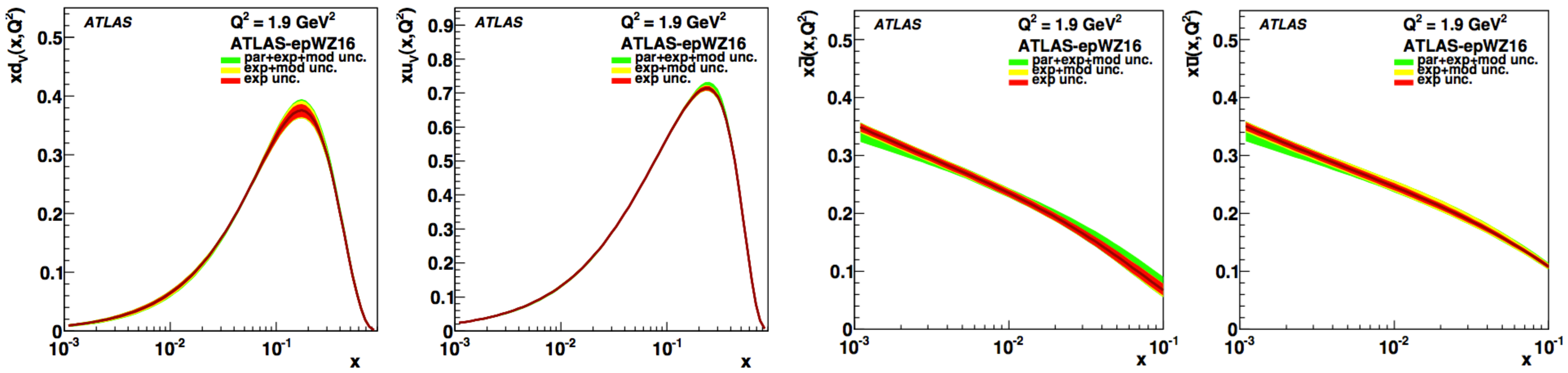
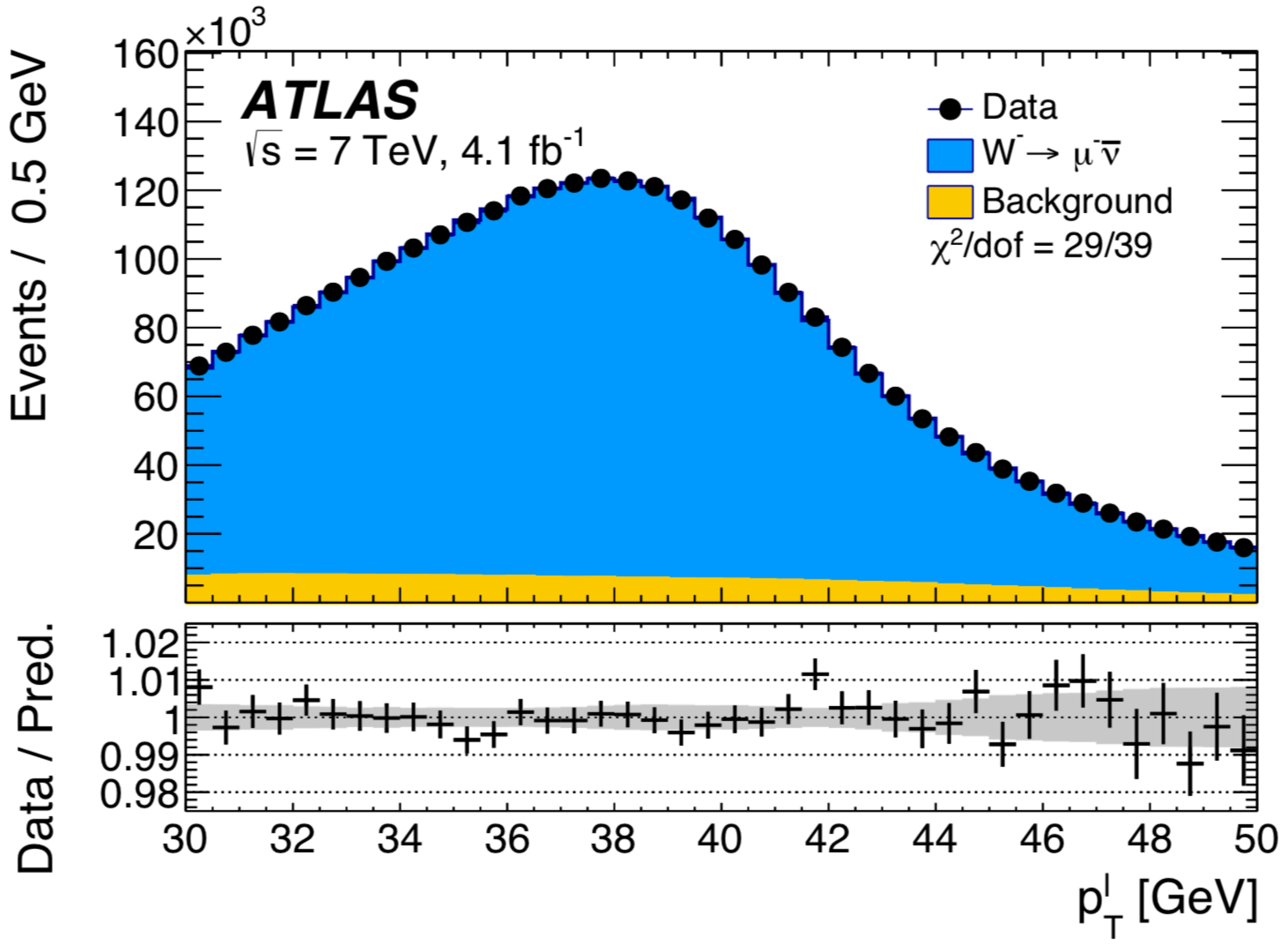


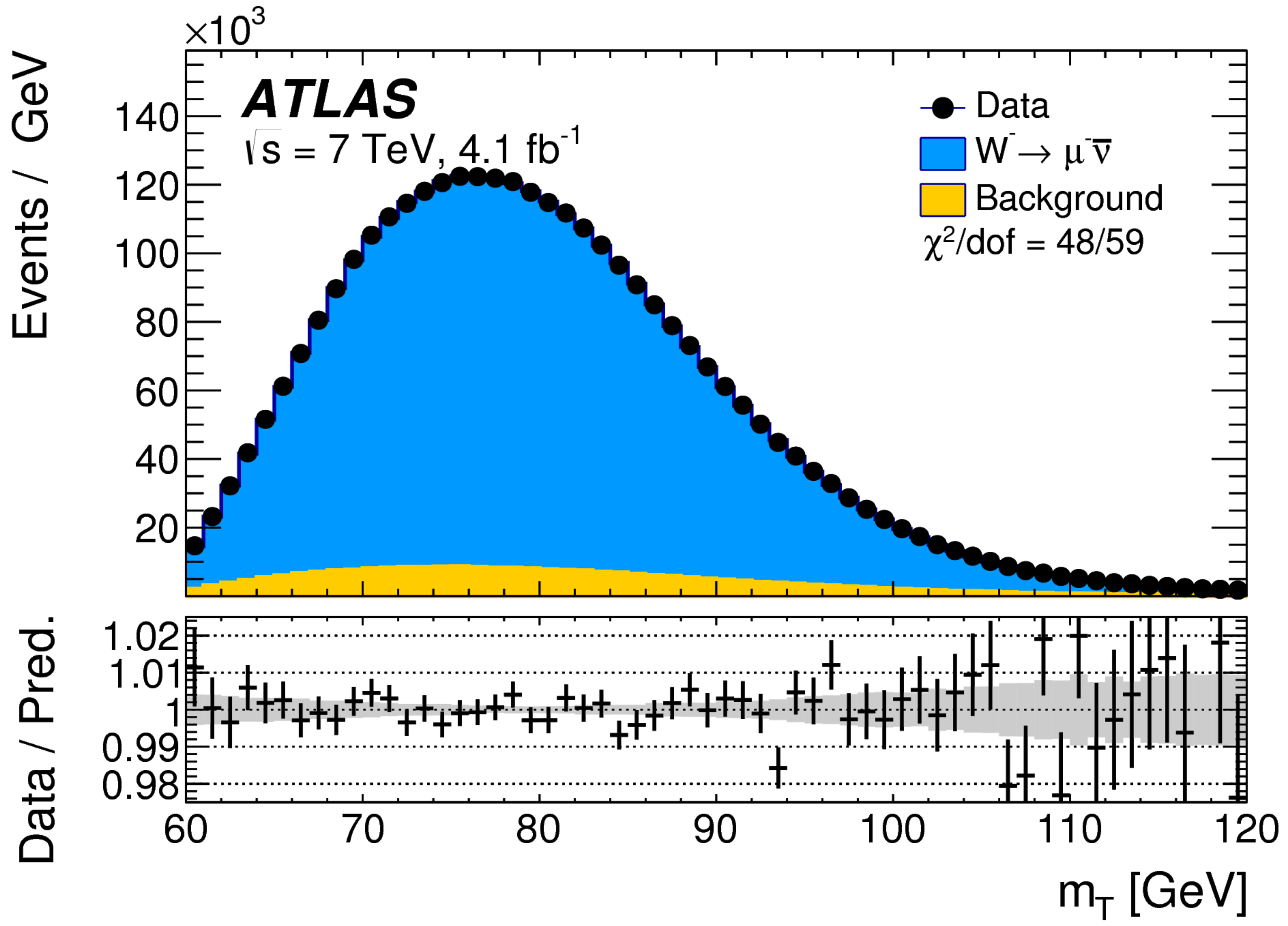
Using these cross section measurements and the the Deep Inelastic Scattering data from Hera new set of PDFs can be estimated (ATLAS-epWZ16 same was done in CMS).

Measurement of the W Mass at the LHC

A Milestone measurement!

Analysis strategy based on two kinematic distributions fitted in several categories





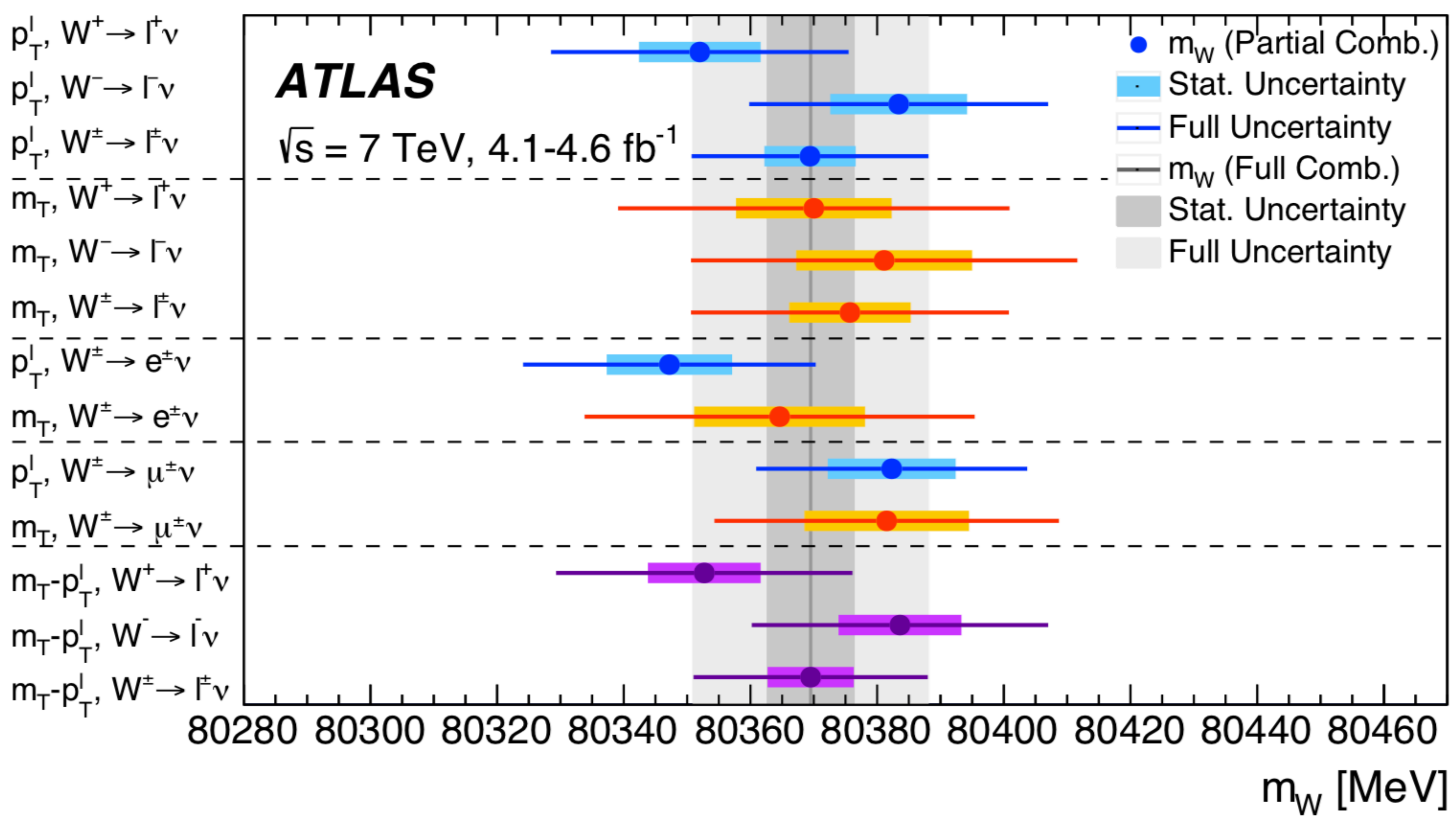
$$p_T^\ell$$ Clean energy measurement, but more sensitive to the modelling of the W transverse momentum

$$m_T$$ Less sensitive to modelling but more difficult from to reconstruct (based on the missing transverse energy.

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

Categories are defined by the charge of the reconstructed lepton, its flavor (electron or muon) and its pseudo rapidity.

$$m_W = 80369.5 \pm 18.5 MeV$$
$$(\pm 6.8\,(Stat)$$
$$\pm 10.6\,(Exp.\,Sys.)$$
$$\pm 13.6\,(Mod.\,Sys.)\,MeV)$$



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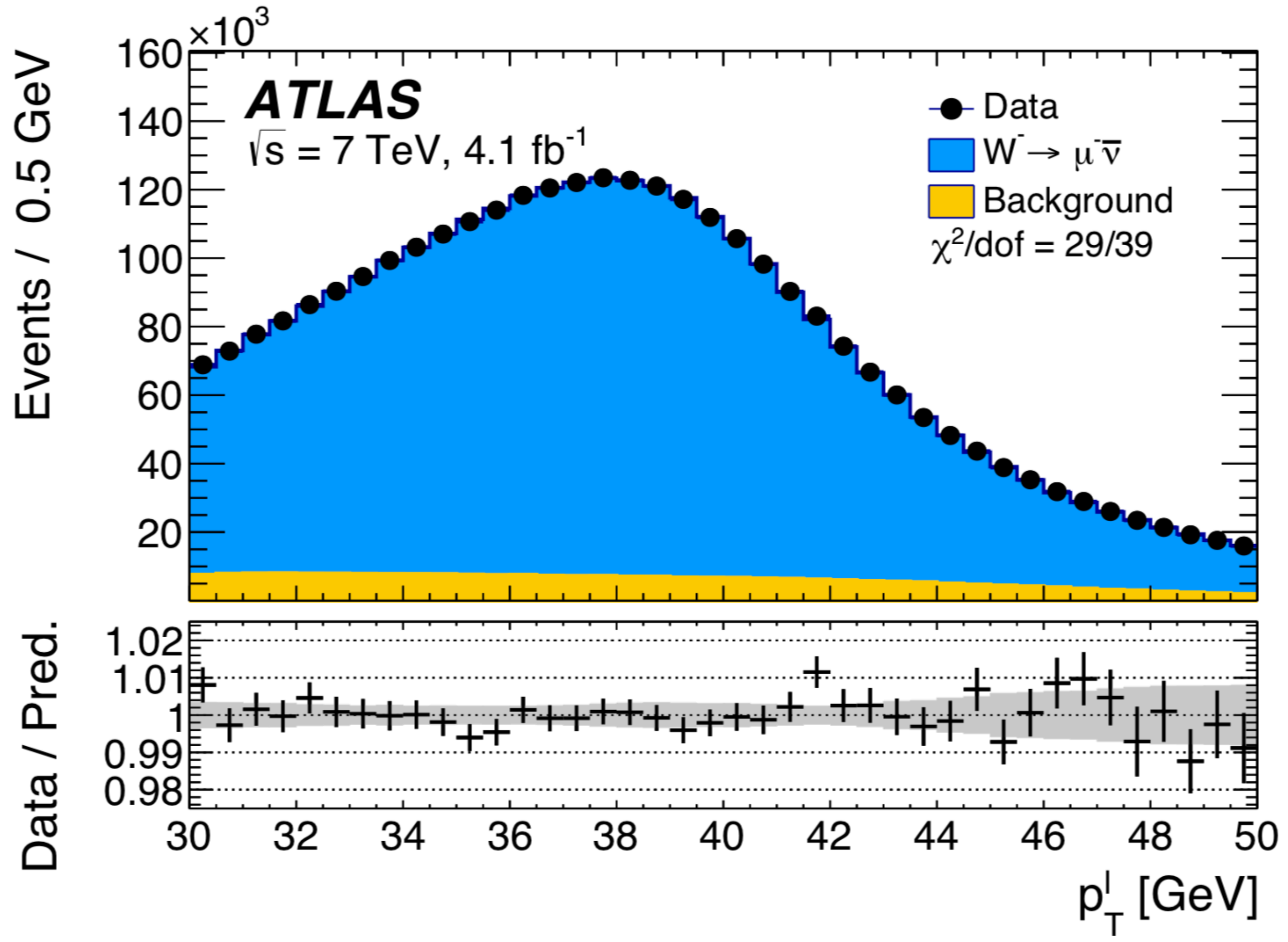

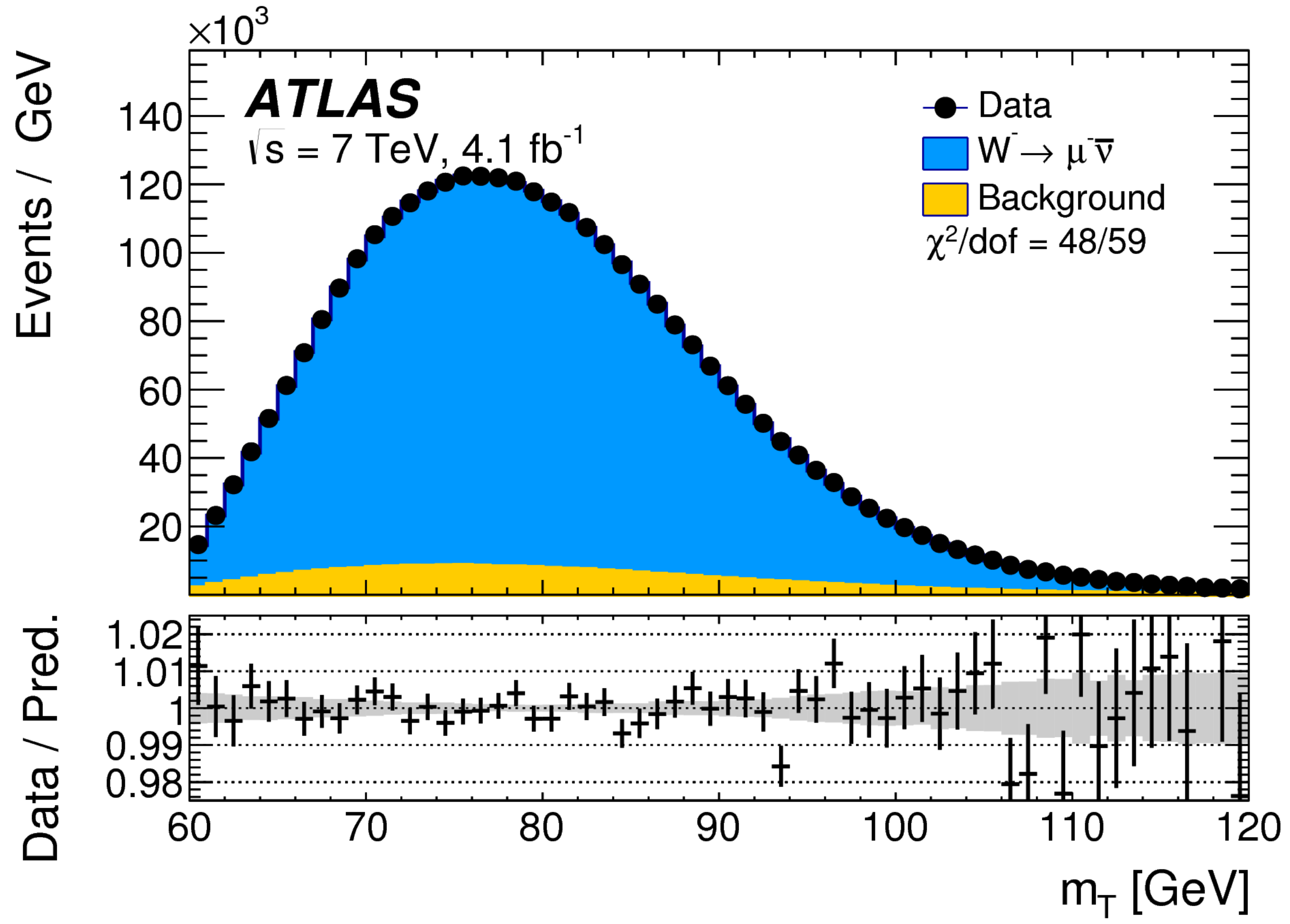

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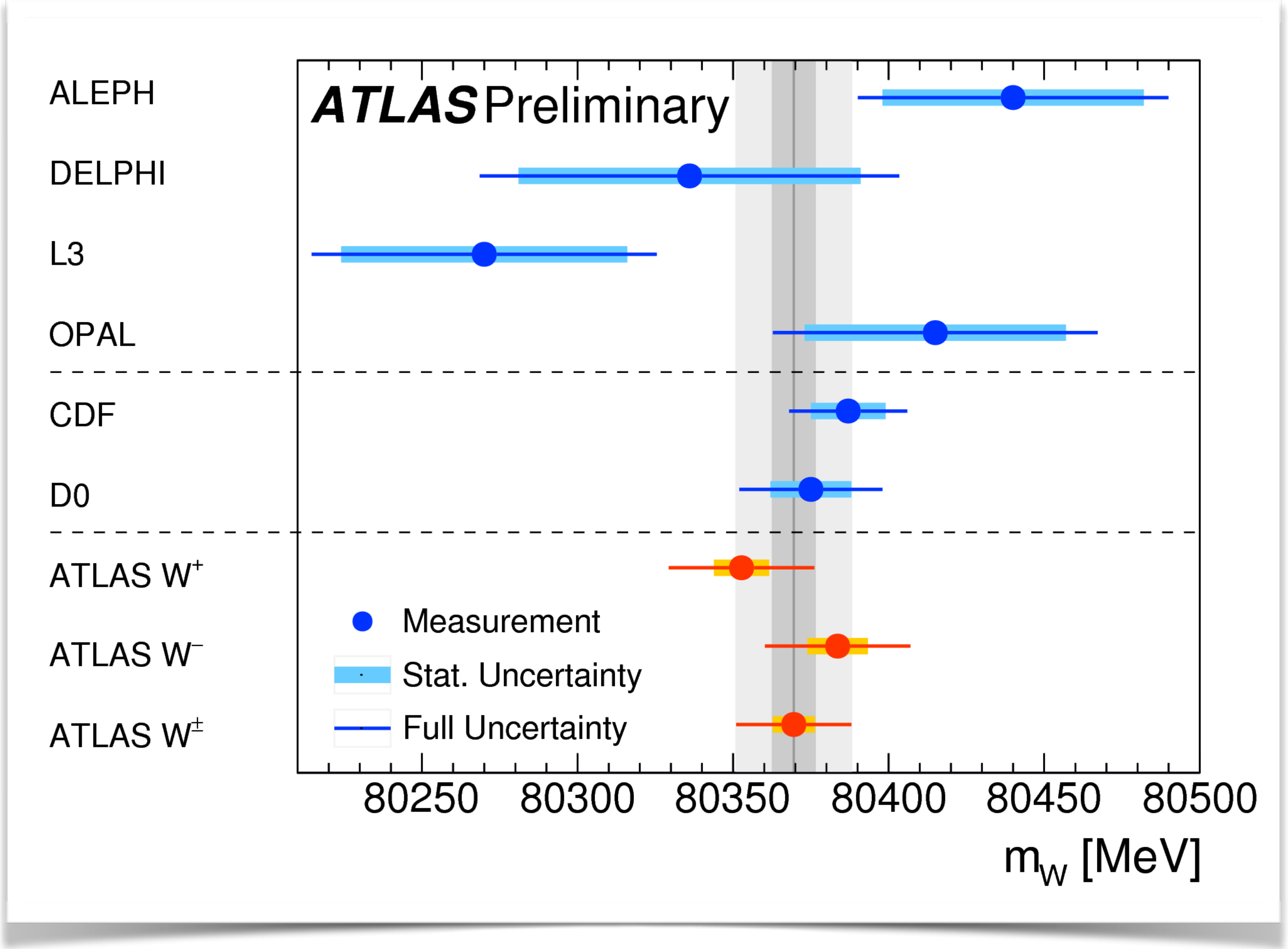
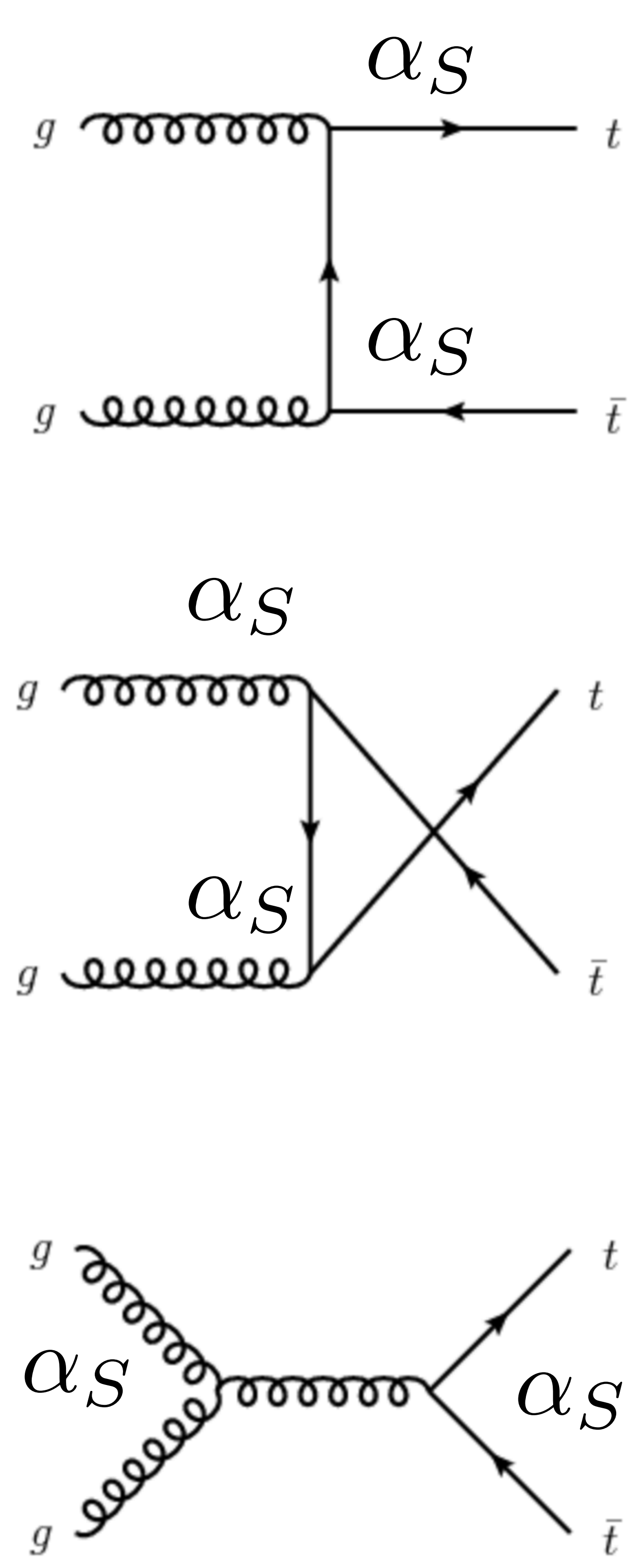


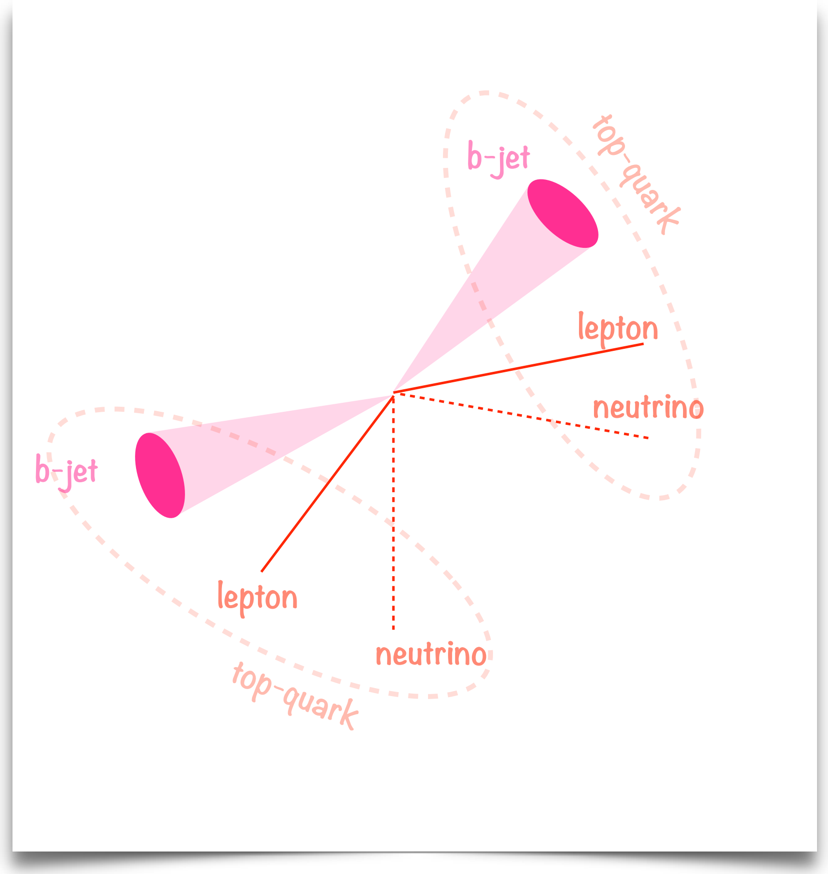
Top production

Measurement of the top mass

Top pair production Cross Sections

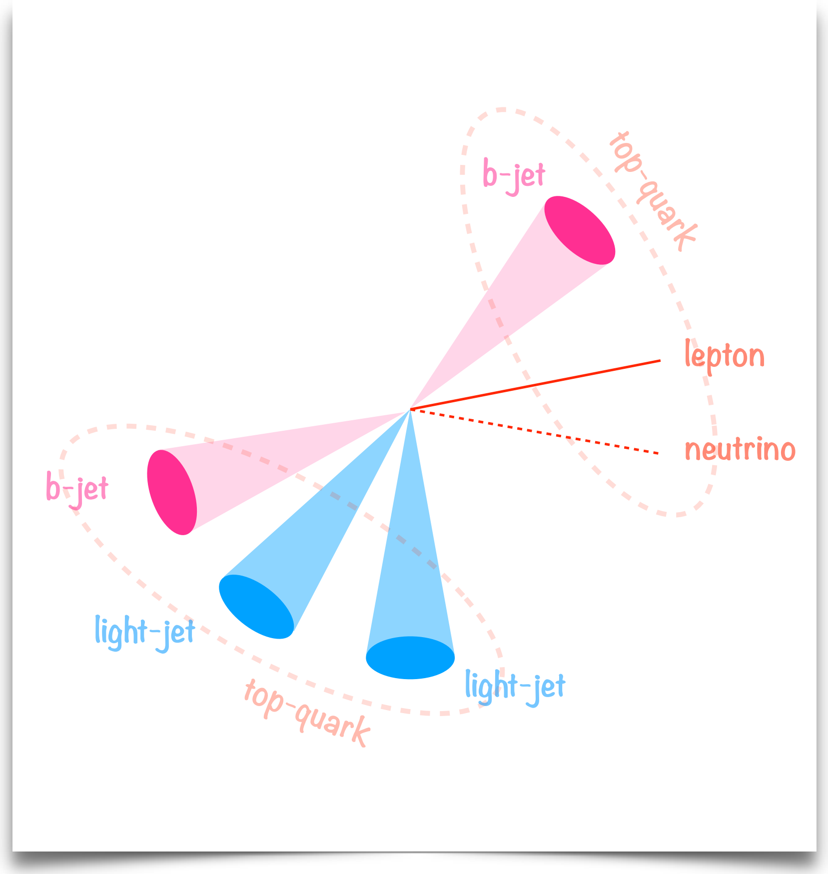
Main production diagrams
At tree level leading order
$$O(\alpha_S^2)$$





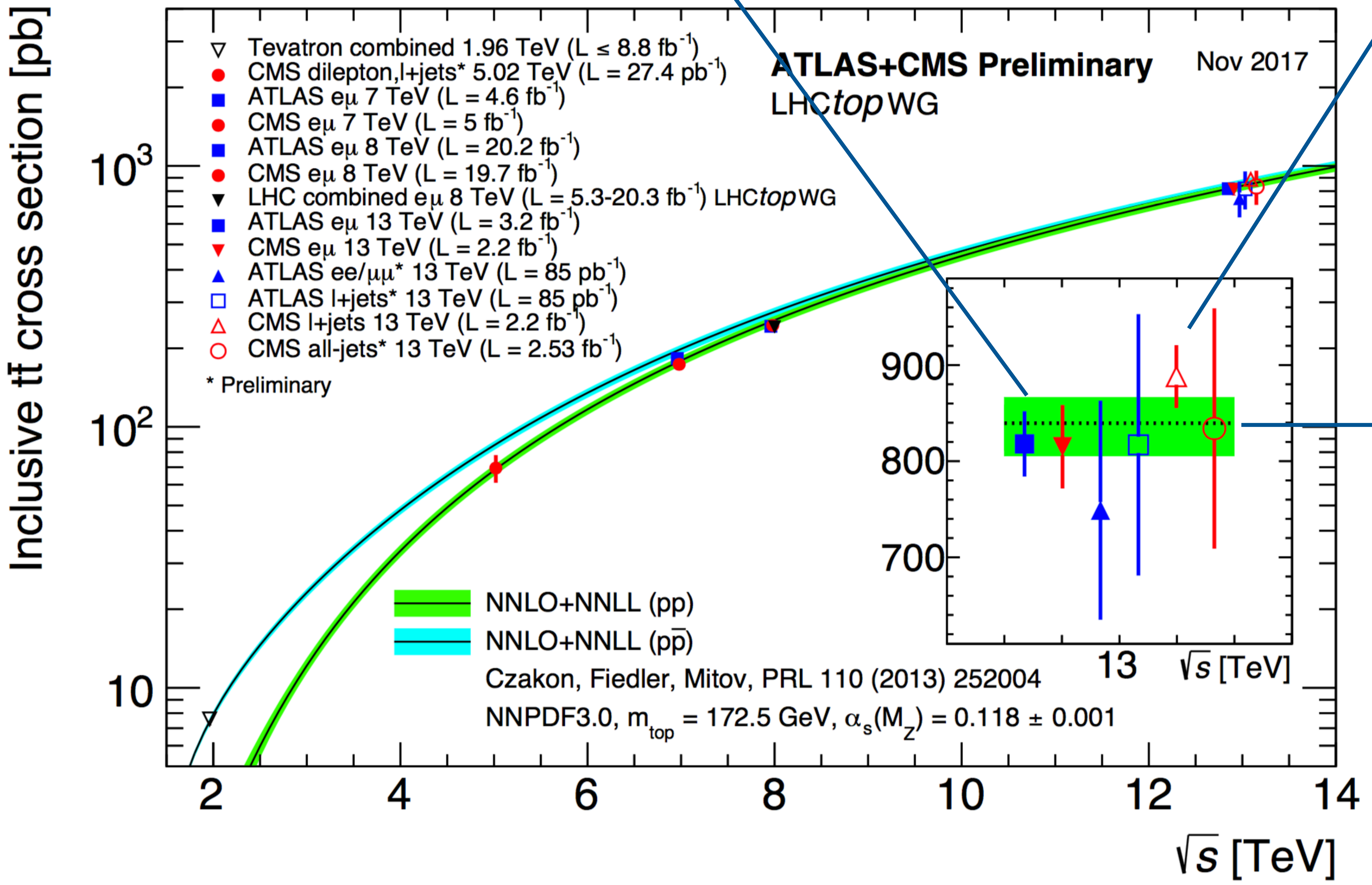
Di-lepton topology:

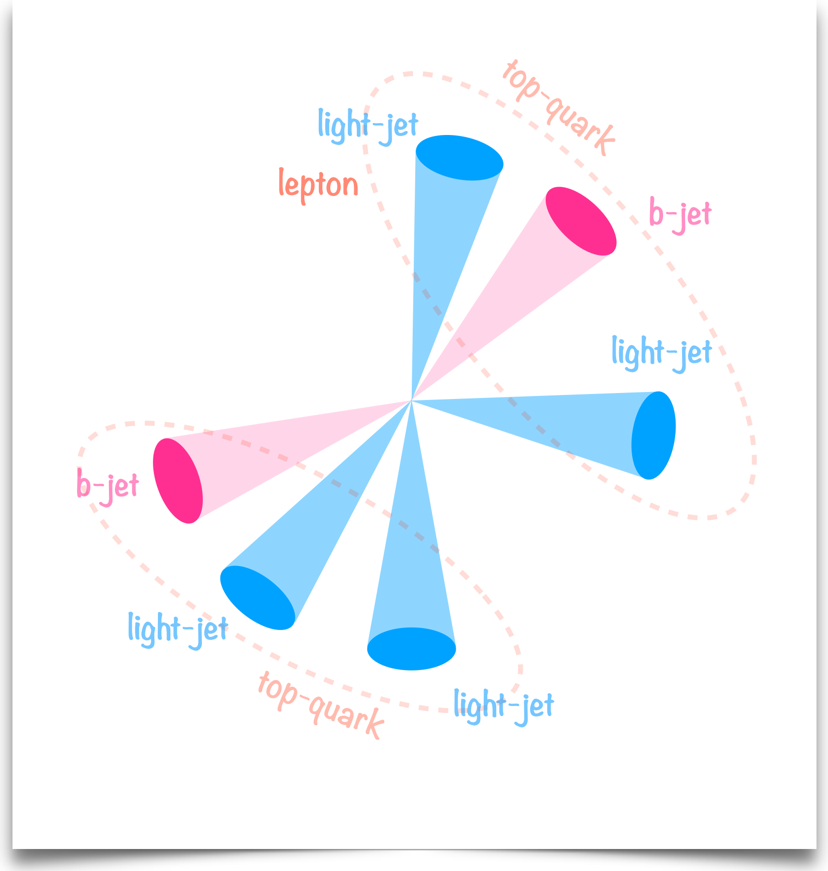
Precise determination of cross section in the different flavour electron-muon channel in particular. Excellent signal to background ratio. Lower stats (4%).



Semi-leptonic topology:

Best compromise between statistics (30%) and signal to background ratio.

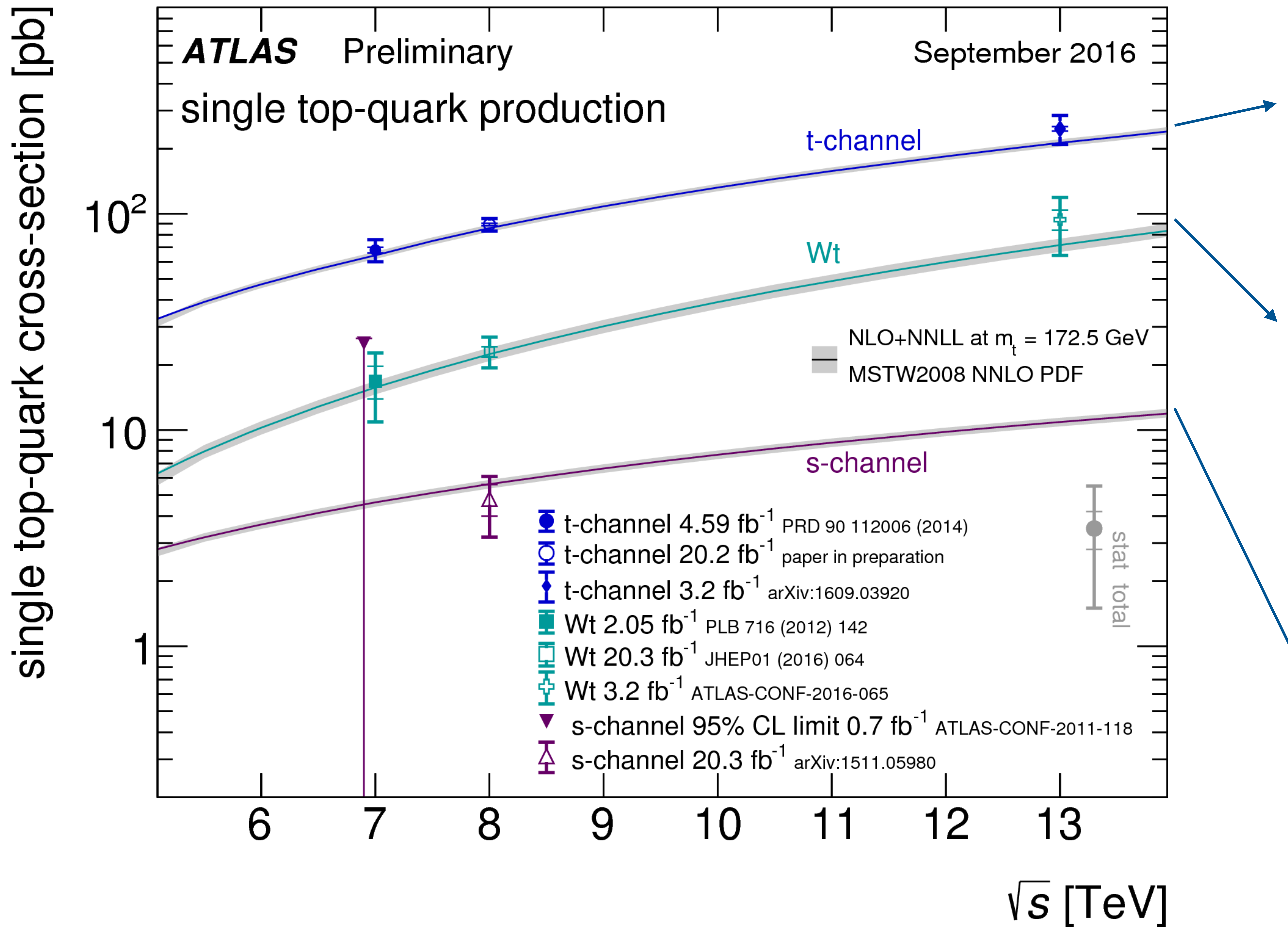


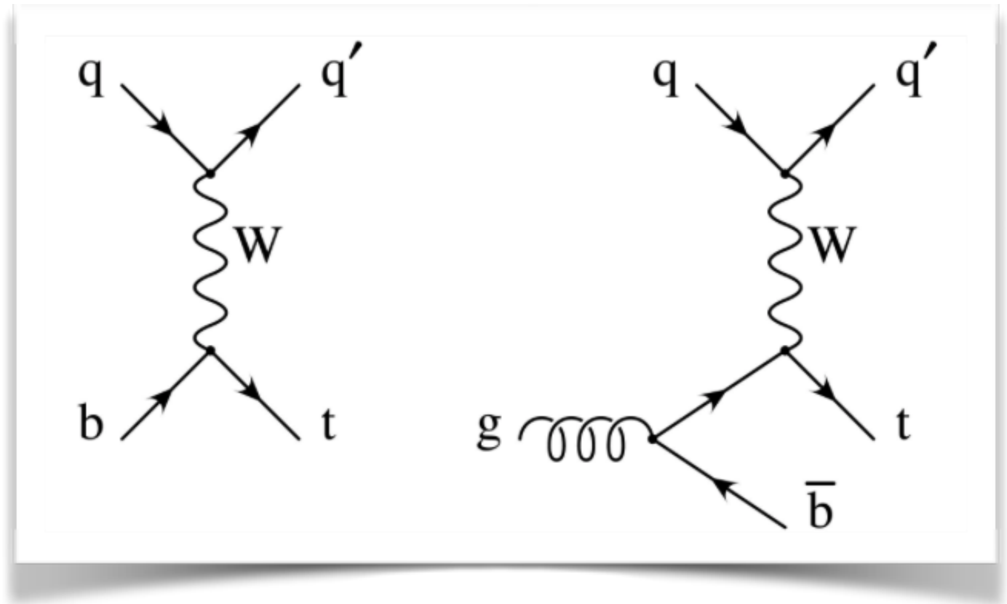


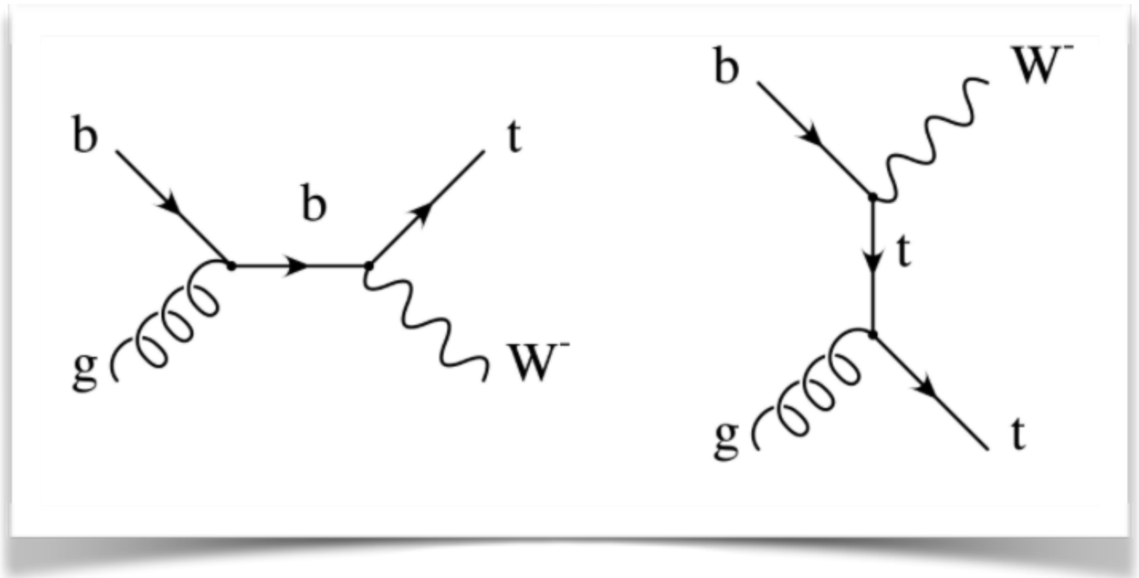
Full hadronic topology:

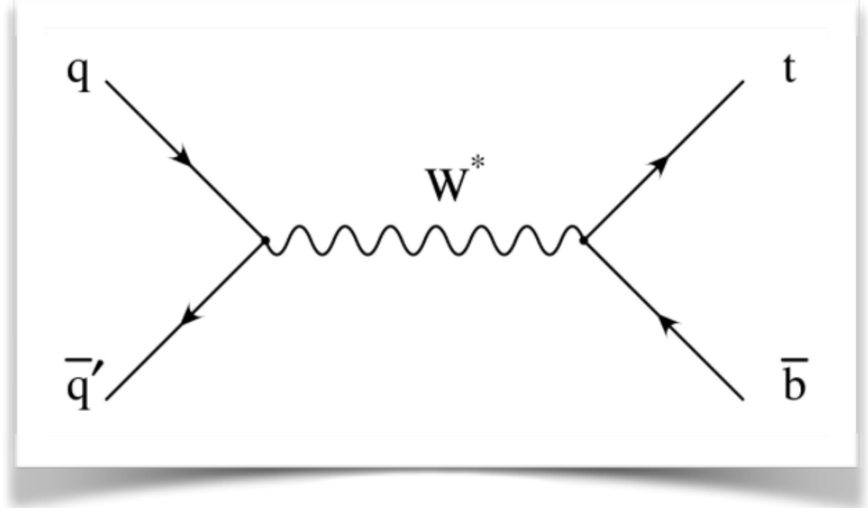
Largest stats (50%) but larger multi-jet background and large combinatorial.

Single-top production Cross Sections





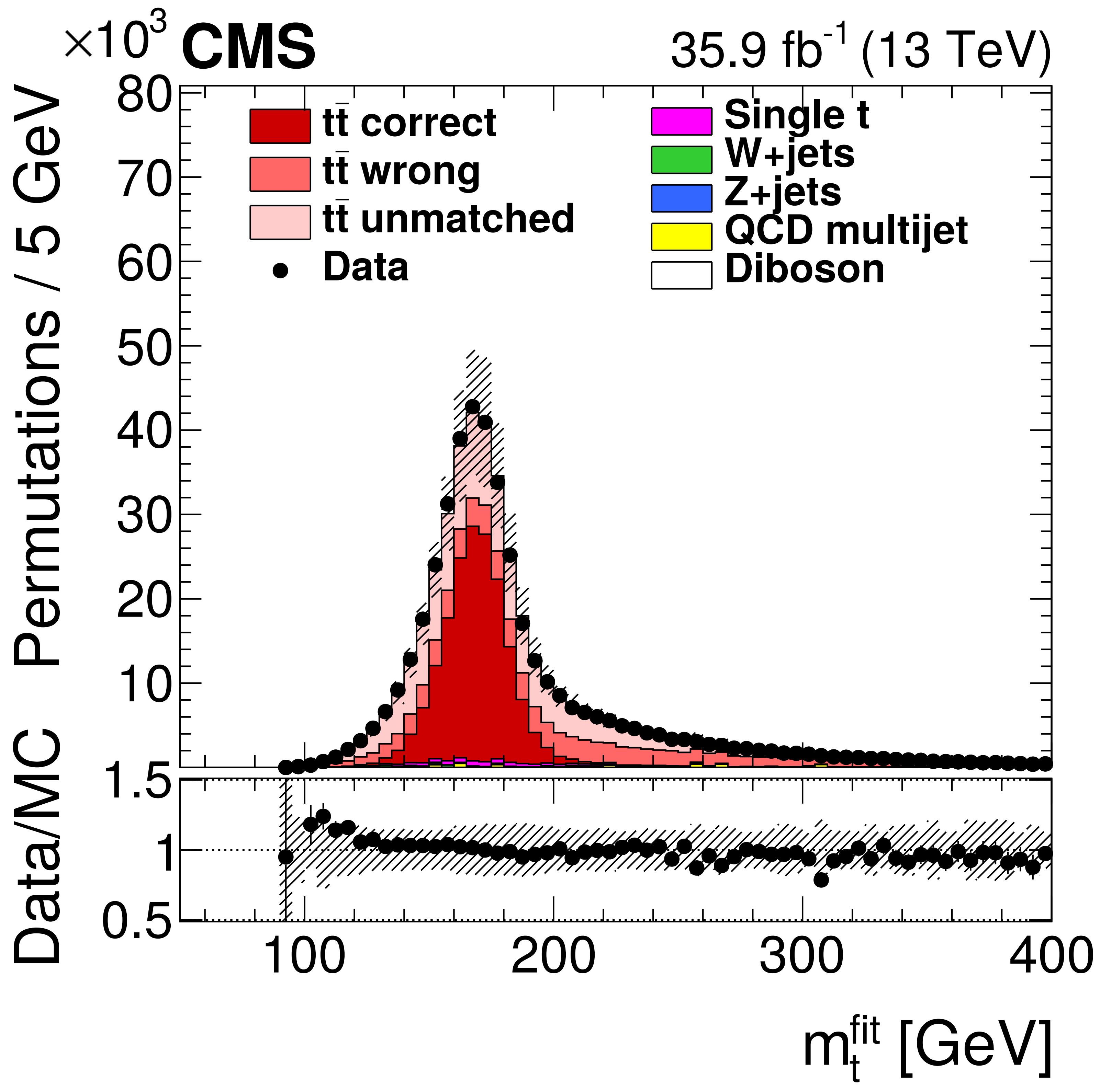




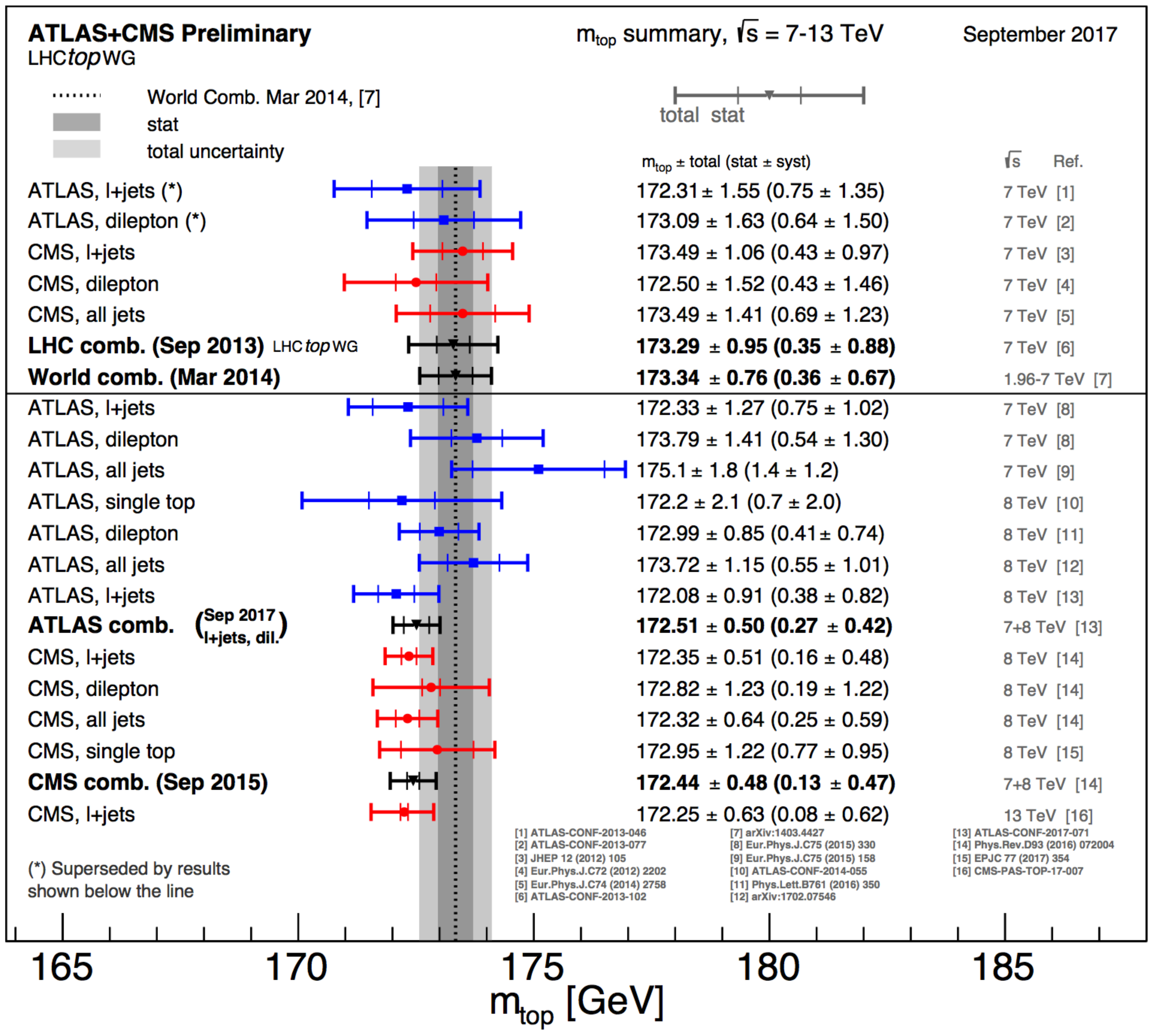
Measuring the top mass from event kinematics

Direct measurements made using template fit to the reconstructed mass spectrum.

Latest CMS result



$$172.34 \pm 0.20\,(\text{stat}+\text{JSF}) \pm 0.76\,(\text{syst})\ \text{GeV}$$



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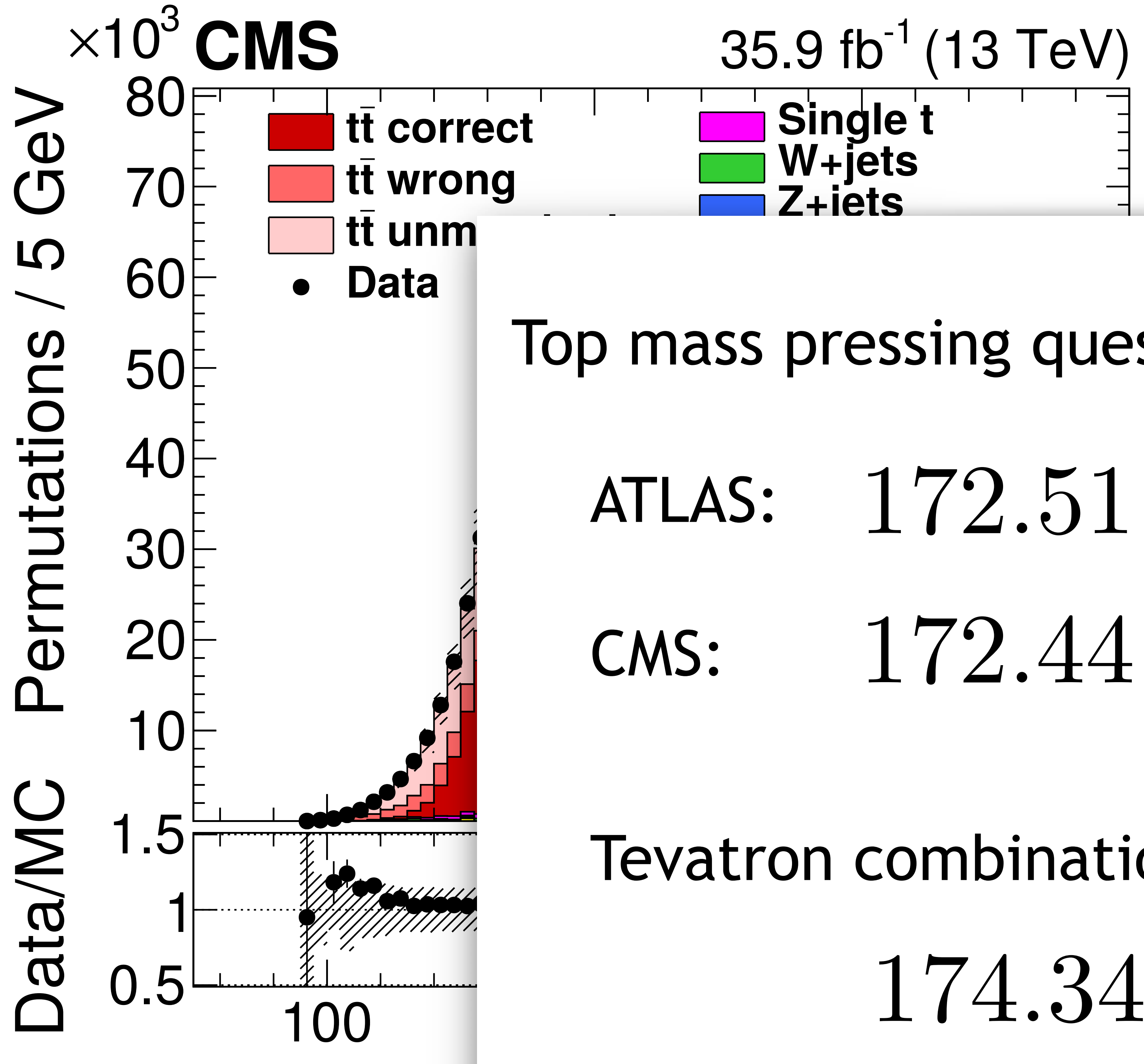
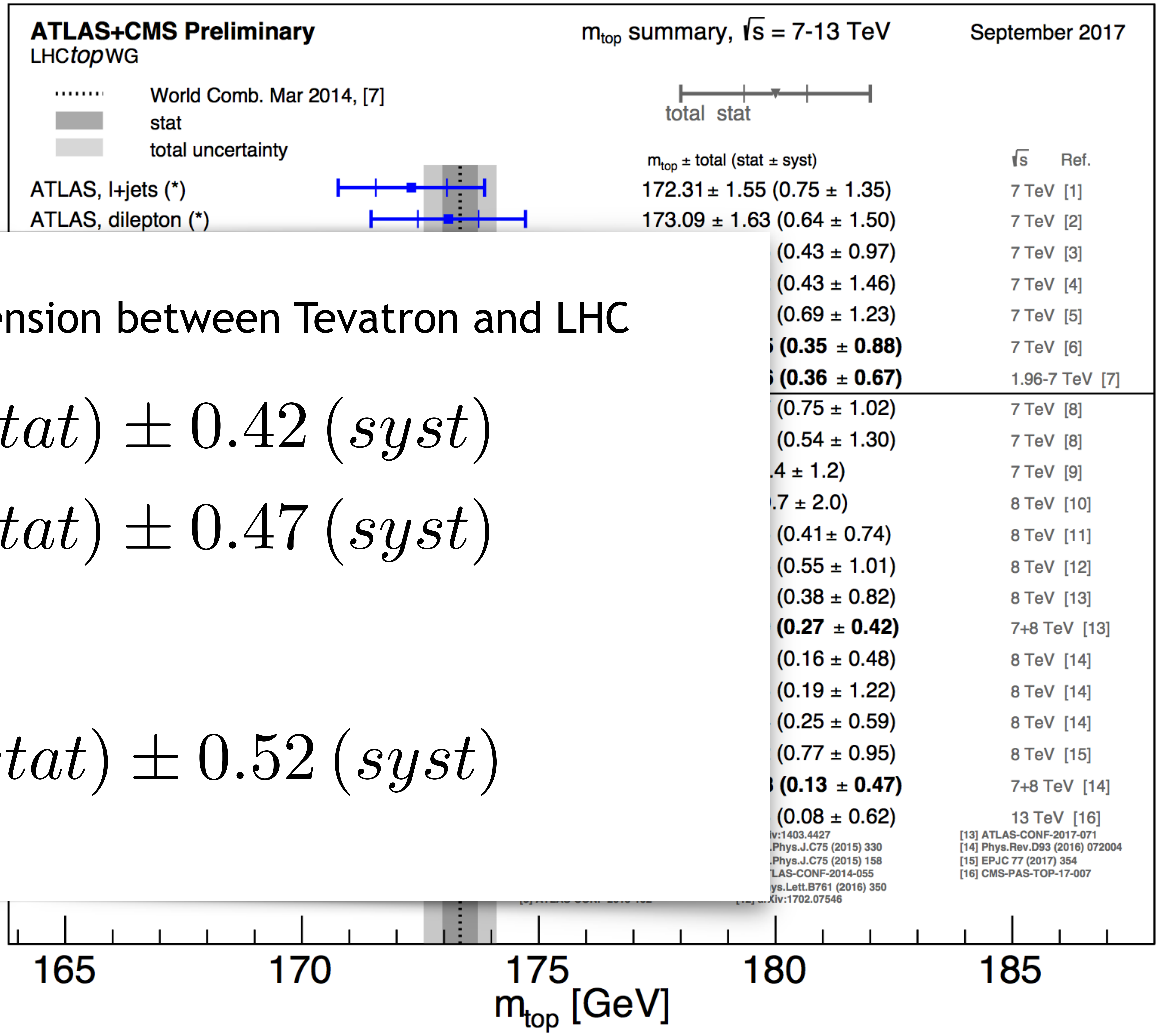
Direct measurements made using template fit to the reconstructed mass spectrum.

Latest CMS result





Top mass pressing question: slight tension between Tevatron and LHC

ATLAS: $172.51 \pm 0.27\,(stat) \pm 0.42\,(syst)$

CMS: $172.44 \pm 0.13\,(stat) \pm 0.47\,(syst)$

Tevatron combination:

$$174.34 \pm 0.37\,(stat) \pm 0.52\,(syst)$$

$$172.34 \pm 0.20\,(\mathrm{stat + JSF}) \pm 0.76\,(\mathrm{syst})\ \mathrm{GeV}$$

Digression on the Mass Measurement

The relation between the parameter which is varied in the Monte Carlo to derive templates and the Field Theoretical parameter of the pole mass is not straightforward.

The top decays before it hadronizes.

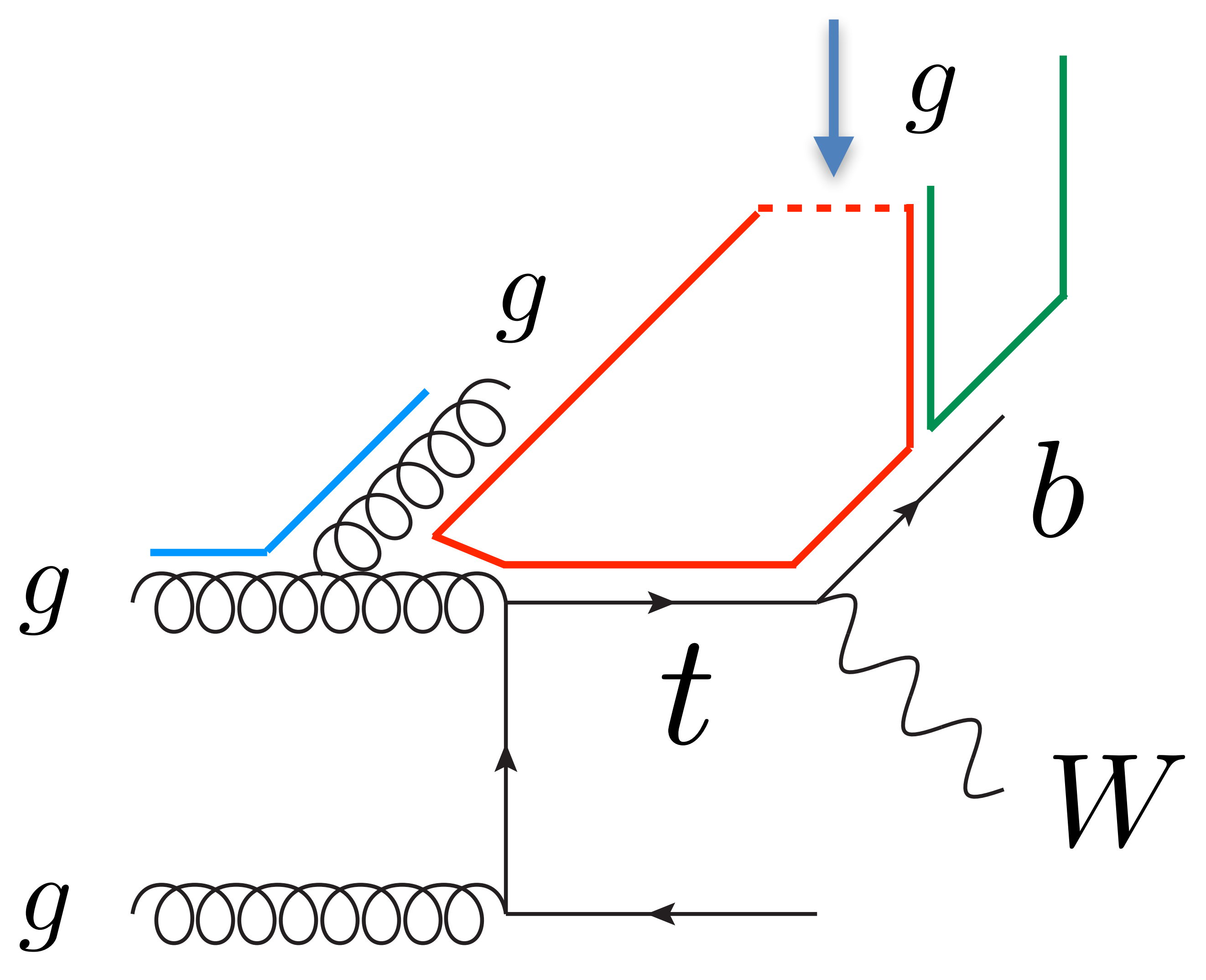
But the top is coloured, so it is impossible to unambiguously associate every object in the final state to it!

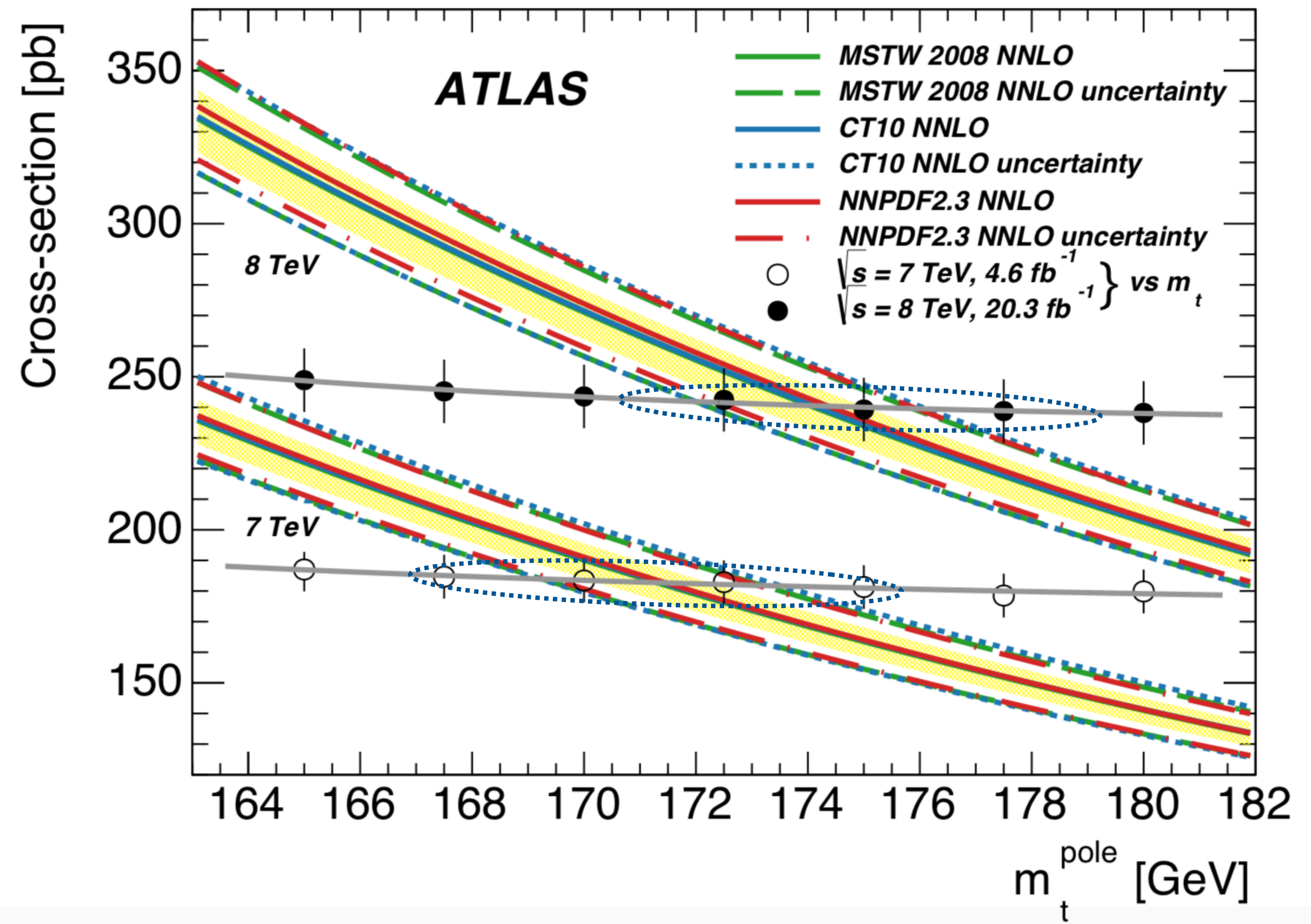
These ambiguities lead to an uncertainty on the top mass measurement, these are for stated as uncertainties on the top mass measurement. The uncertainty or the ambiguity varies between 1 GeV and 200 MeV.

The Field theoretical parameter pole mass can be measured using the top production cross section!

The Field theoretical parameter pole mass can be measured using the top production cross section (at the cost of introducing a dependence on the production prediction).

Colour connection
through hadronisation





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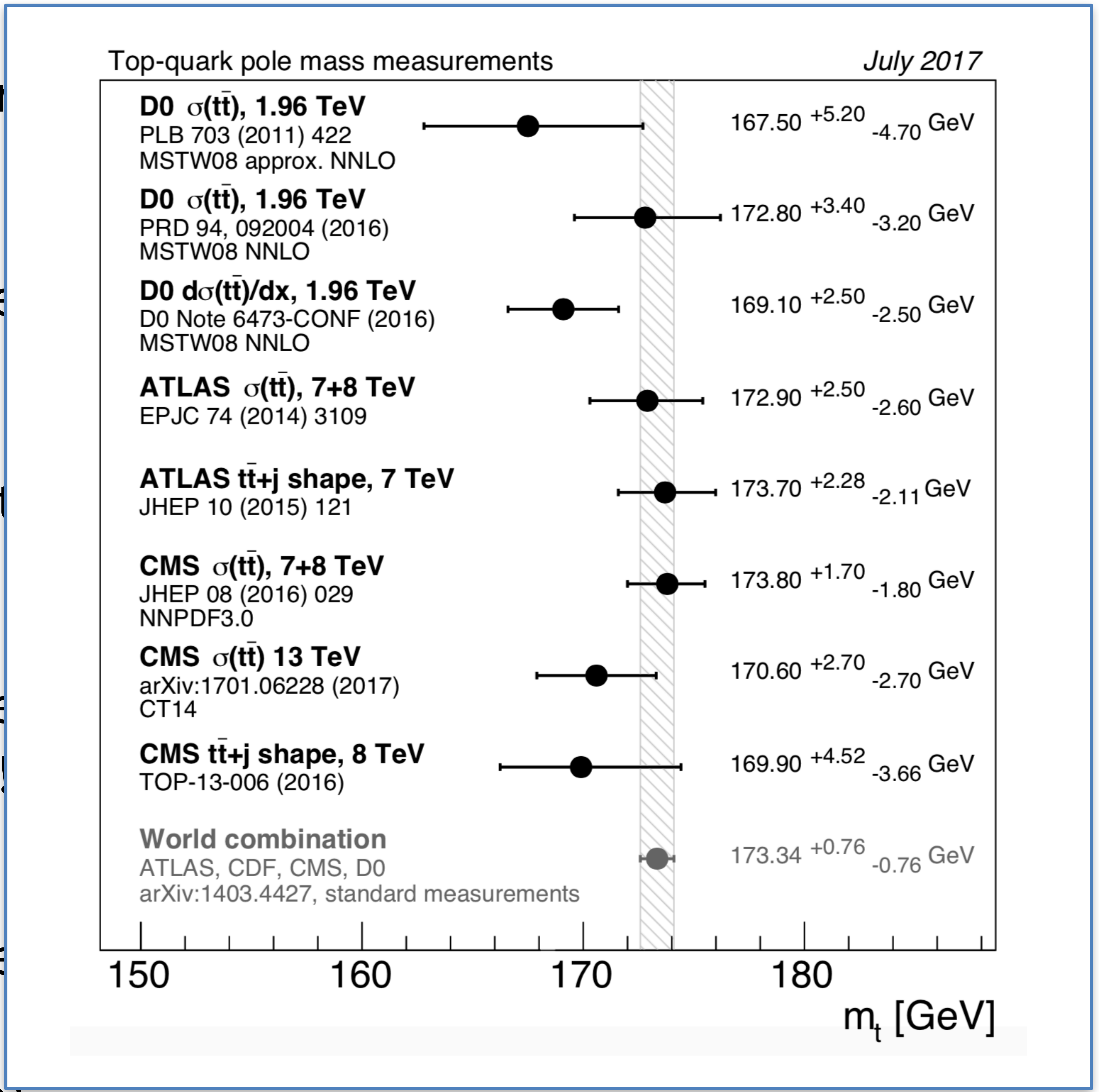
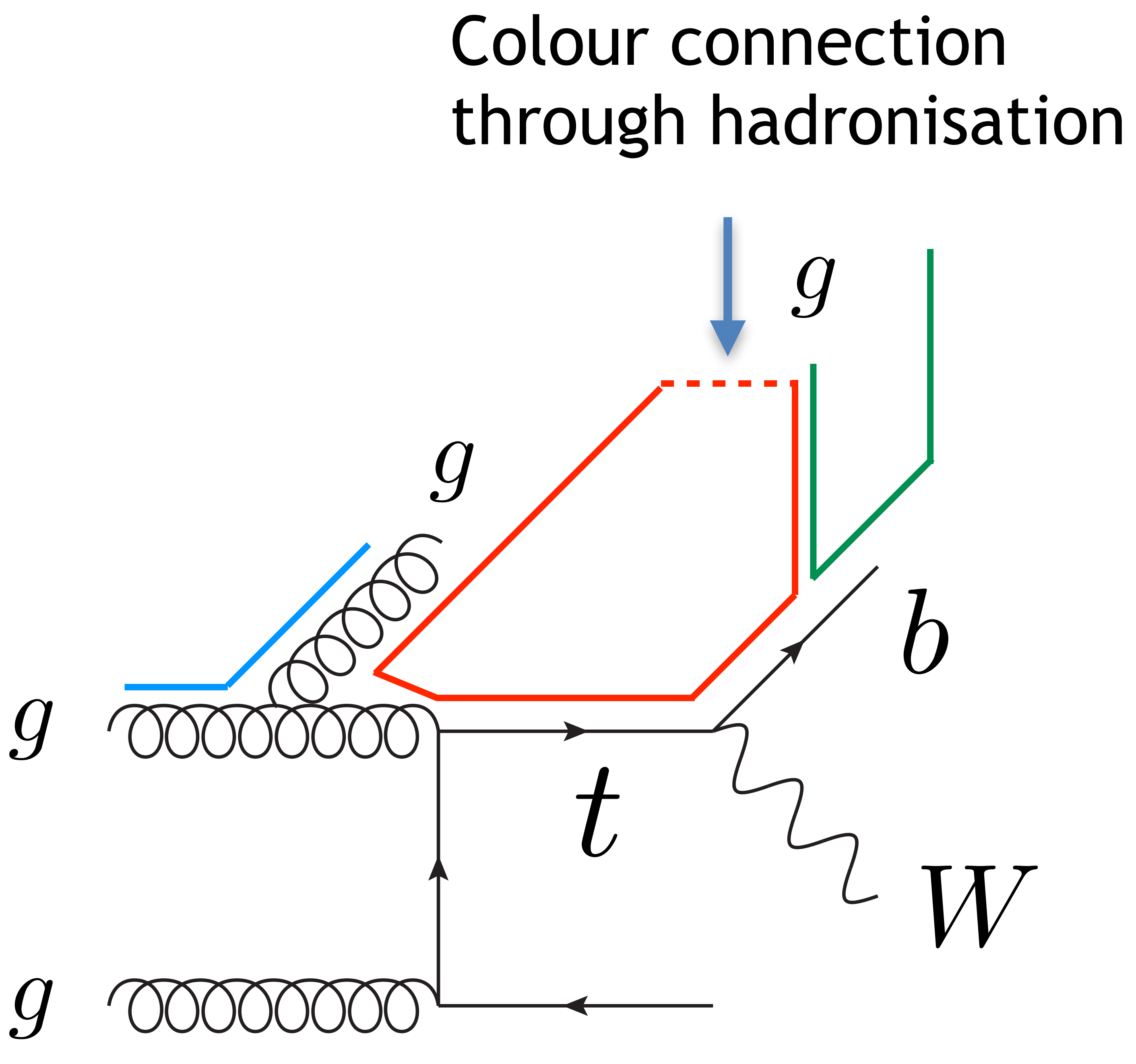
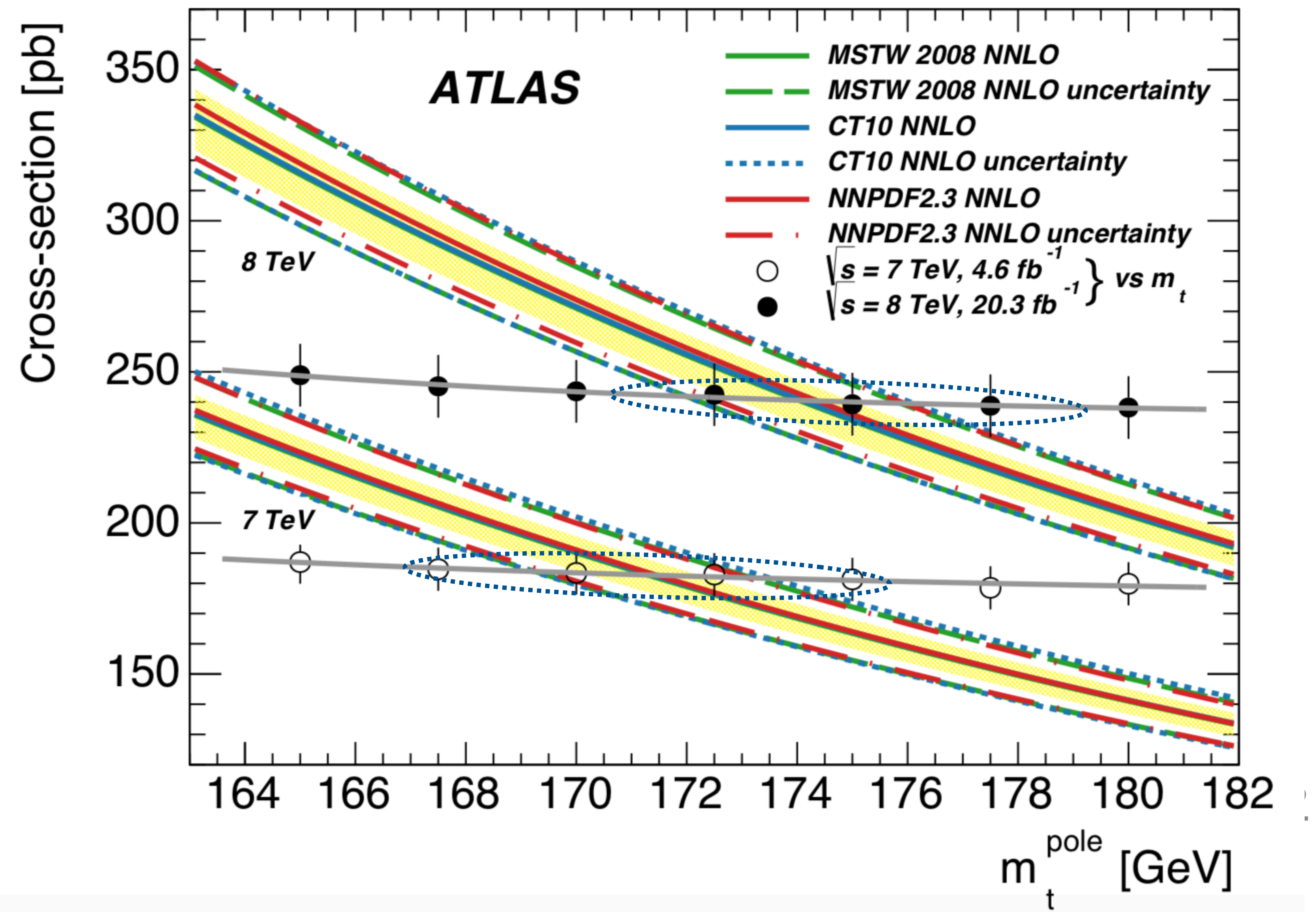




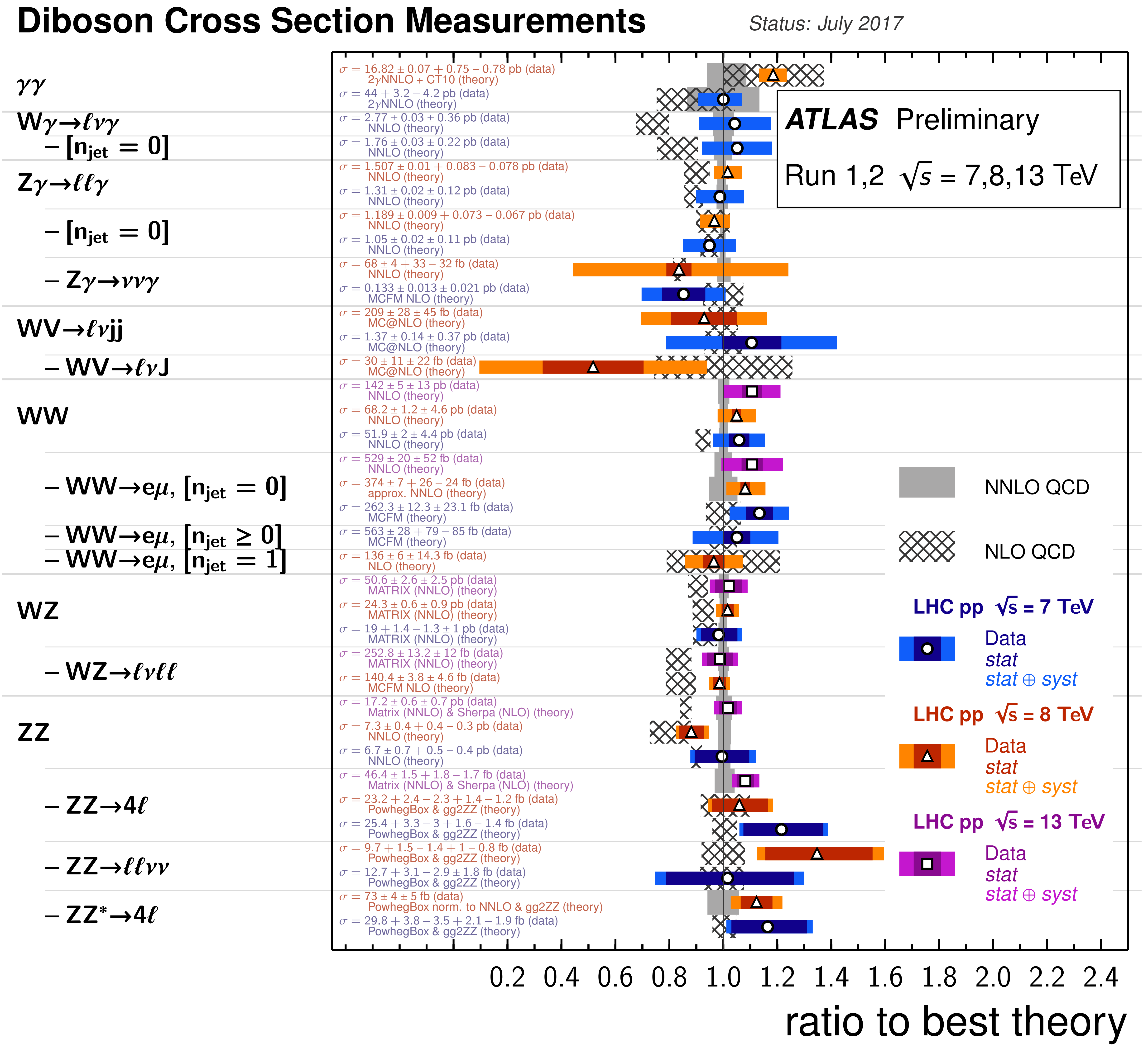


Diboson production

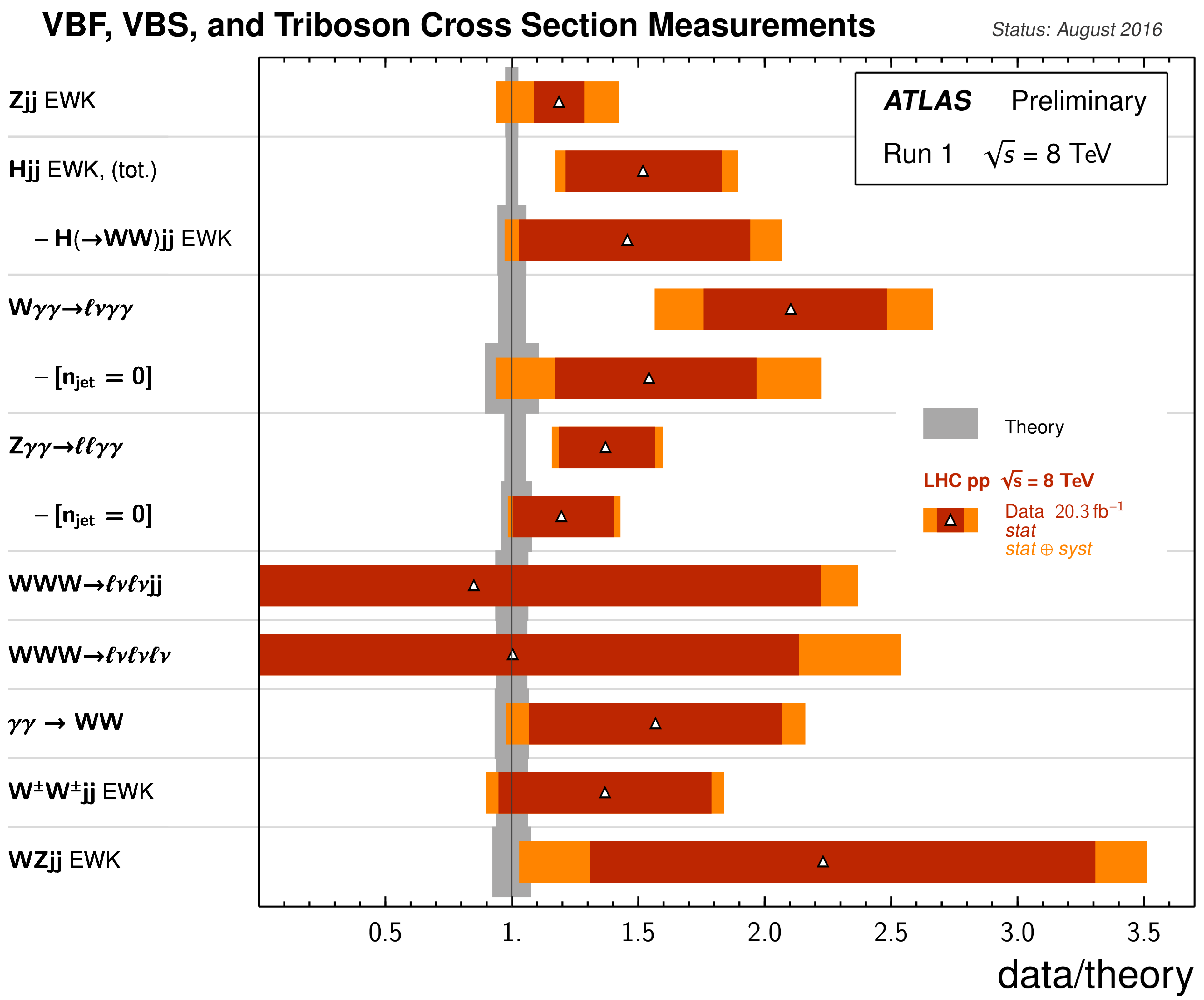
In a nano nutshell

Di- (and Tri-) boson measurements at the LHC

Large number of diboson processes measured and used to constrain anomalous gauge couplings



Measuring more rare and difficult processes



Global Fit of the Standard Model

Global Fit of the Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c.$$

The Electroweak gauge sector

At tree level, fully described by three parameters

$$g,\ g',\ \text{and}\ v \qquad \rho = 1$$

Trade these parameters for precisely measured observables

- The fine structure constant :

$$\alpha = 1/137.035999679(94) \quad 10^{-9}$$

Determined at low energy by electron anomalous magnetic moment and quantum Hall effect

- The Fermi constant :

$$G_F = 1.166367(5) \times 10^{-5}\,\mathrm{GeV}^{-2} \quad 10^{-5}$$

Determined from muon lifetime

- The Z mass :

$$M_Z = 91.1876(21)\,\mathrm{GeV} \quad 10^{-5}$$

Measured from the Z lineshape scan at LEP

Note: we have assumed the existence of a Higgs field giving a vev (v), but have not sensed any of the effects of the Higgs particle.

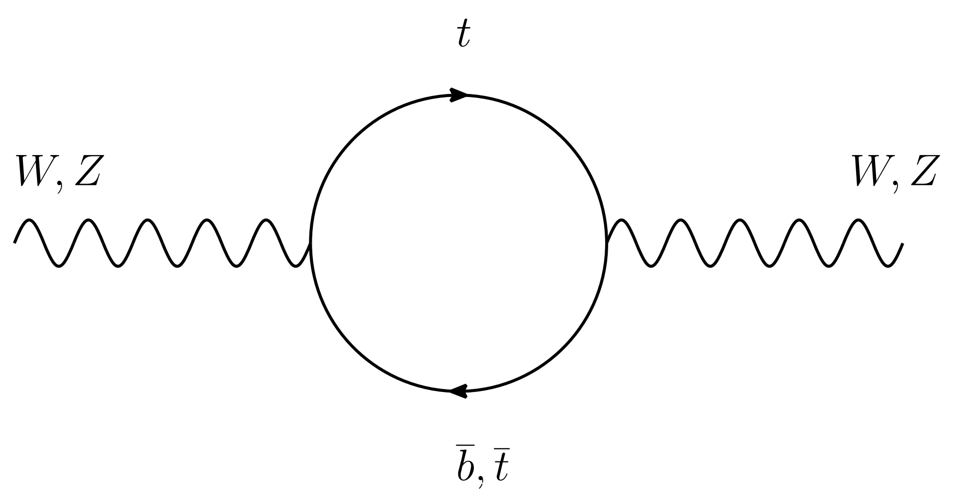
At loop level: all other fields enter the game through loop corrections which can be parametrized.

$$G_F = \frac{\pi\alpha}{\sqrt{2} M_W^2 (1 - \frac{M_W^2}{M_Z^2})}(1 + \Delta r)$$

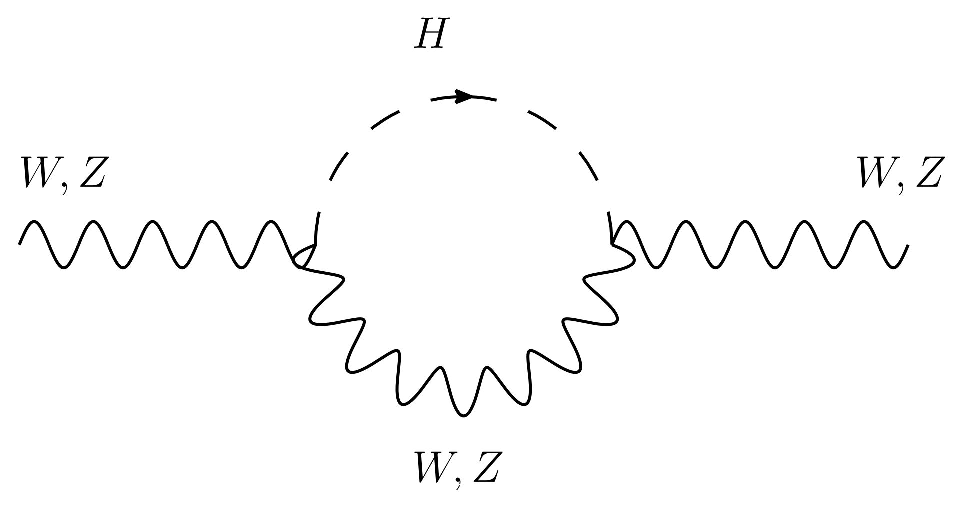
$$\sin^2\theta_W^{eff} = sin^2\theta_W \times (1 + \Delta\kappa)$$

$$\bar{\rho} = 1 + \Delta\rho$$

These corrections can then be computed as a function of all other parameters of the Standard Model



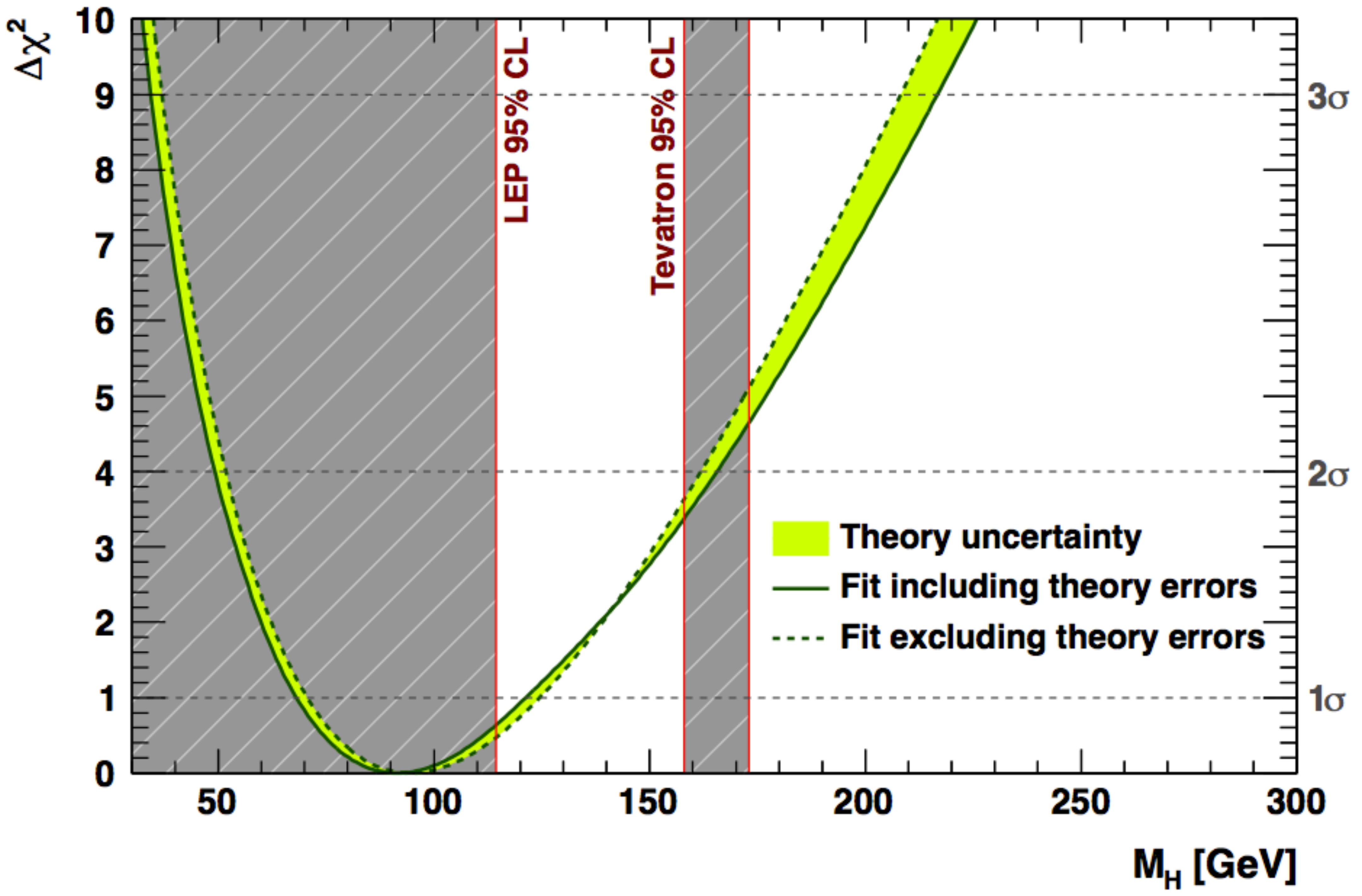
$$\propto m_t^2$$



$$\propto \log \frac{M_H}{M_Z}$$

Global Fit of the Standard Model

A global fit of all relevant measurements can be then done to check the consistency of the Standard Model and predict parameters that are unknown: Higgs boson mass!



Indirect measurement of the Higgs boson mass through its quantum effect on the precision observables.

$$m_{\mathrm{H}} = 91^{+30}_{-23}\,\mathrm{GeV}$$

Before the discovery of the Higgs boson!

Tomorrow: The Higgs!!