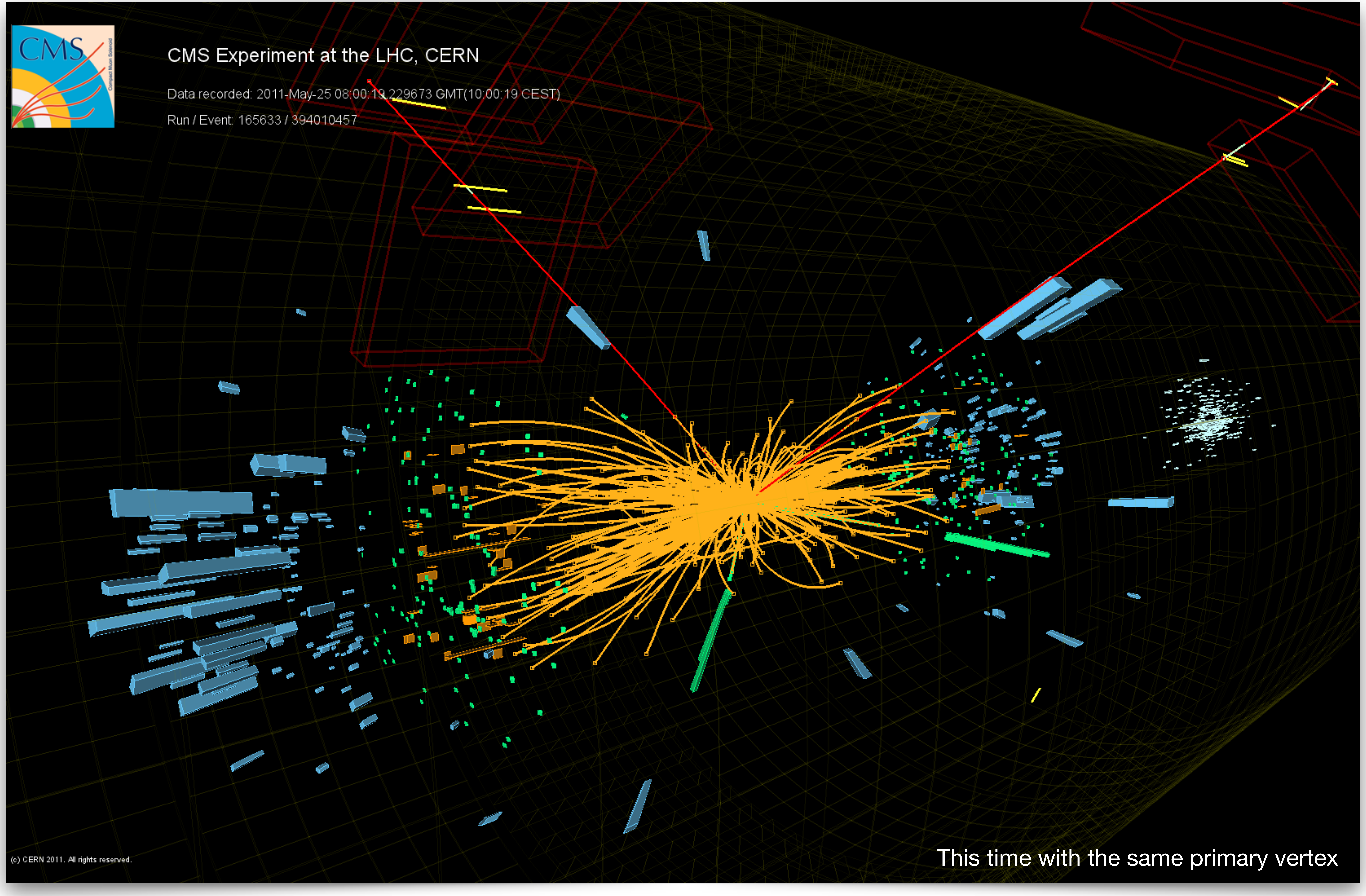
Experimental Physics at Hadron Collider



CMS ZZ event

Lecture 2

Standard Model

Precision Measurements

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Sapienza, Roma and LAL, Orsay

CERN Summer Students Lectures

July 22-25, 2019

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 (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 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:

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

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

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

$$\tan\theta_W = \frac{g'}{g}$$

$$m_W = \frac{gv}{2}$$

$$m_Z = \frac{gv}{2\cos\theta_W}$$

$$m_\gamma = 0$$

No additional parameter for the masses of the Gauge bosons!

The electroweak sector in a tiny nutshell

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

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

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Expanding a bit on the Electroweak sector:

$SU(2)_L \otimes U(1)_Y$ (from the Higgs mechanism)

$SU(2)_L \rightarrow g$, $U(1)_Y \rightarrow g'$, (from the Higgs mechanism) $\rightarrow v$

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

As a consequence, at tree level:

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

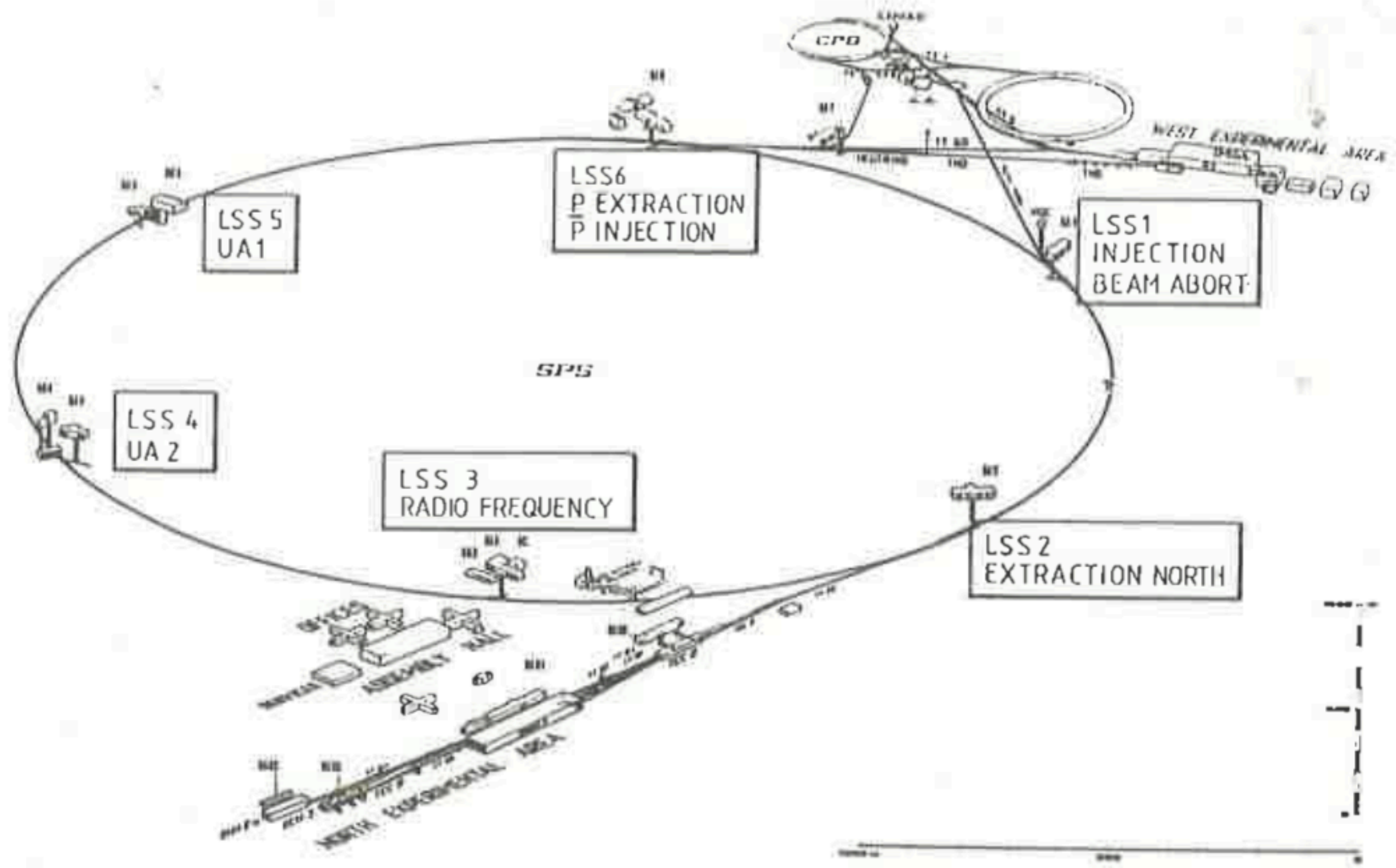
This parameter can be (and has been) measured experimentally well before the discovery of the Higgs.

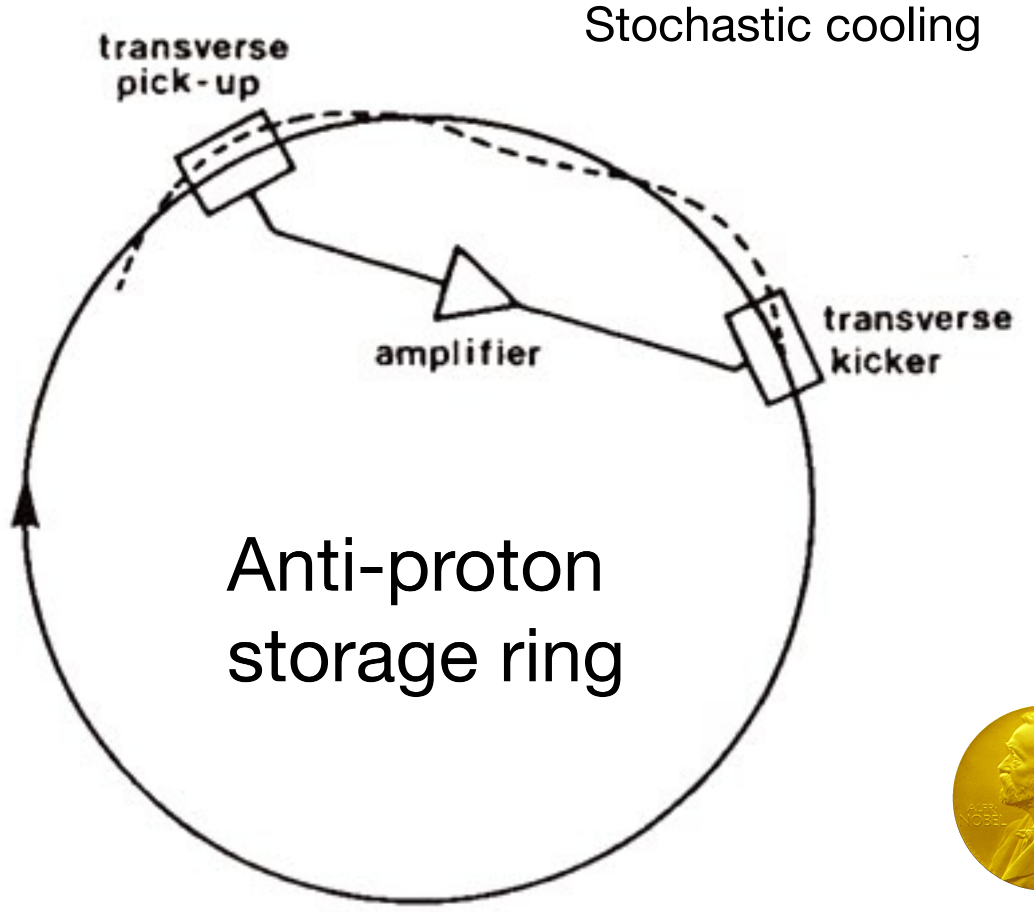
The Drell Yan Z/γ^* production

Measurement of the weak mixing angle

The Spp̄S

The Spp̄S (Super Proton anti-Proton Synchrotron) operated with collisions at 900 GeV from 1981 to 1991.



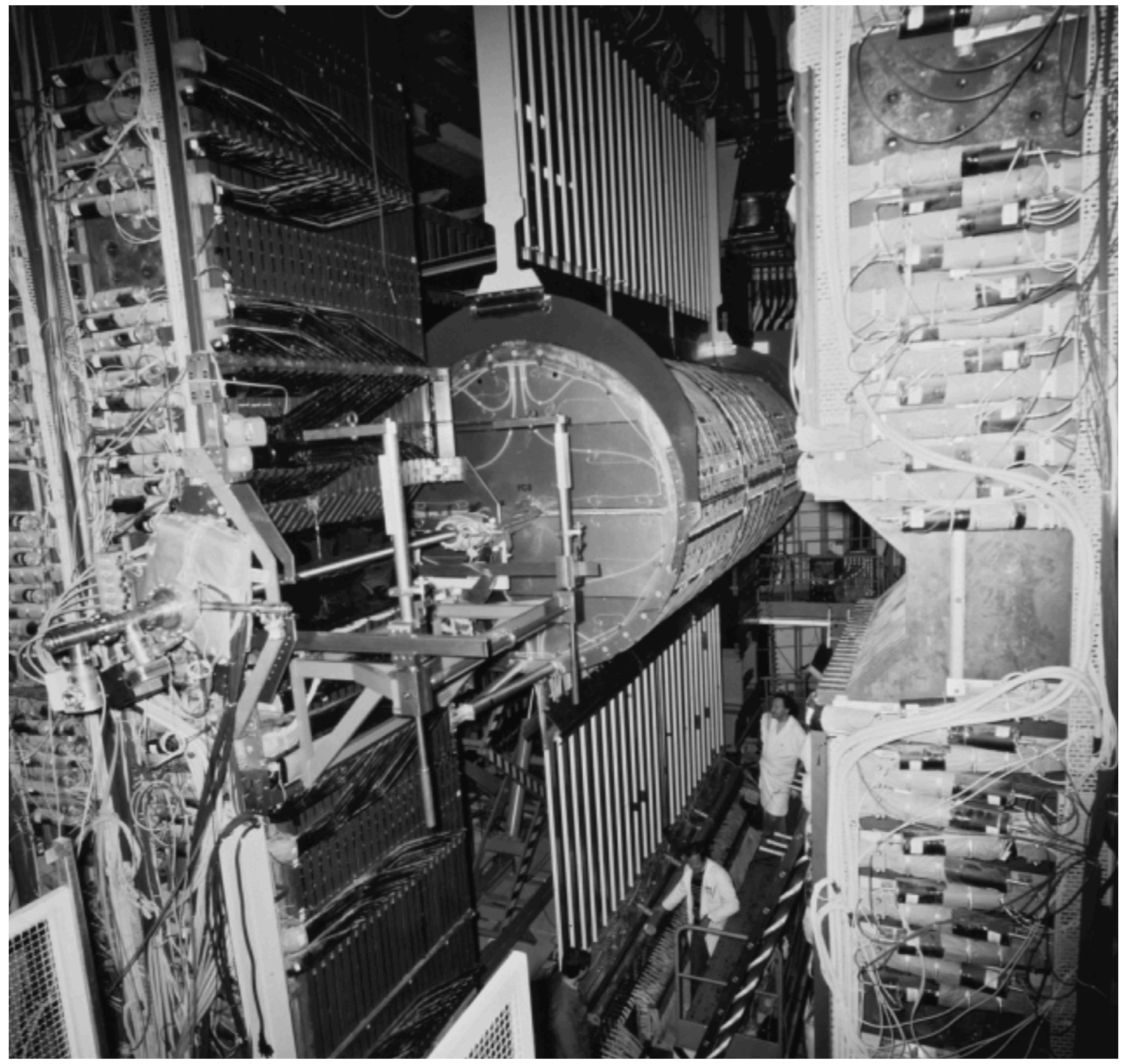


1984

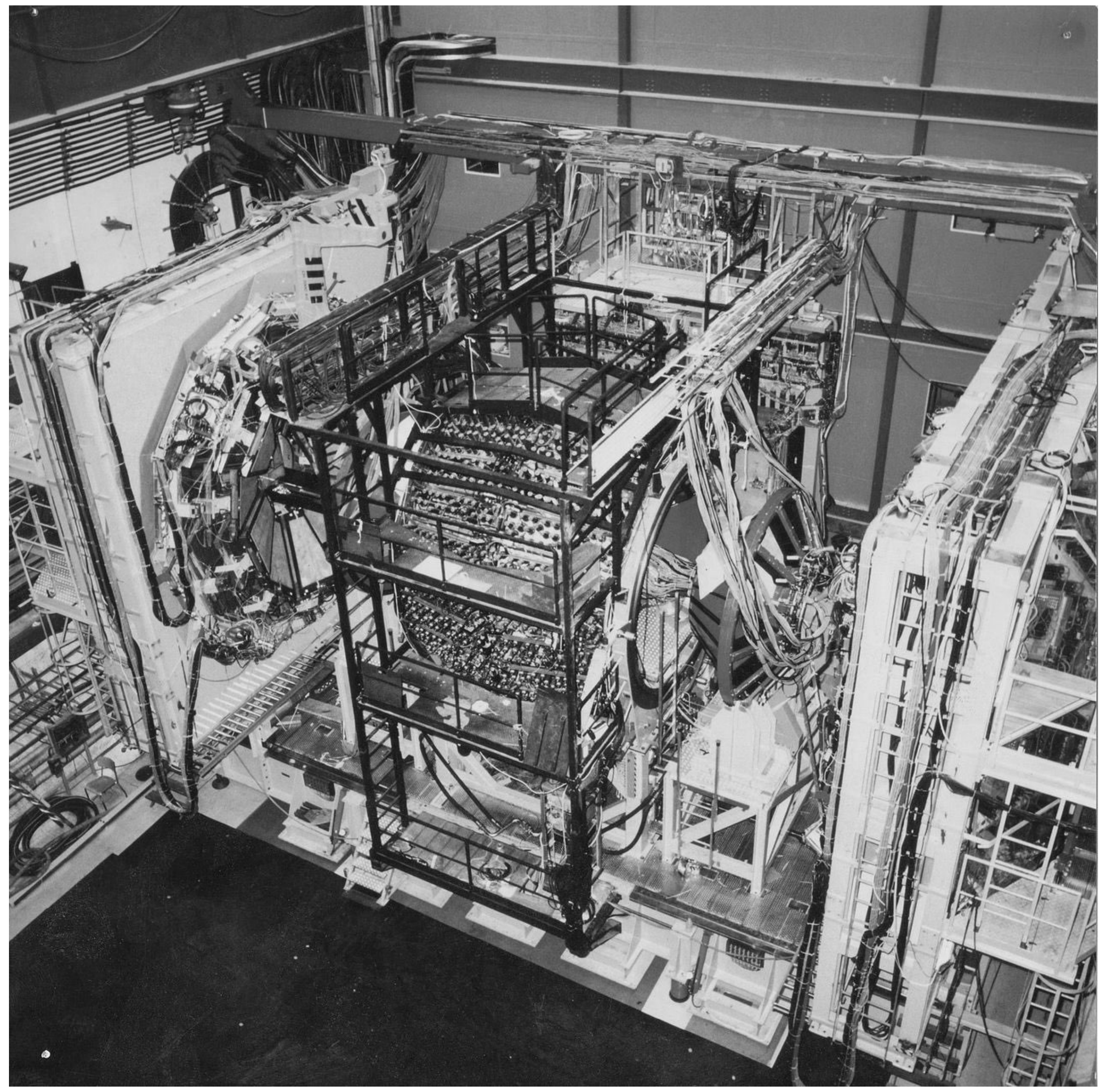
Discovery of the W and Z bosons

Carlo Rubbia, Simon Van der Meer

UA1

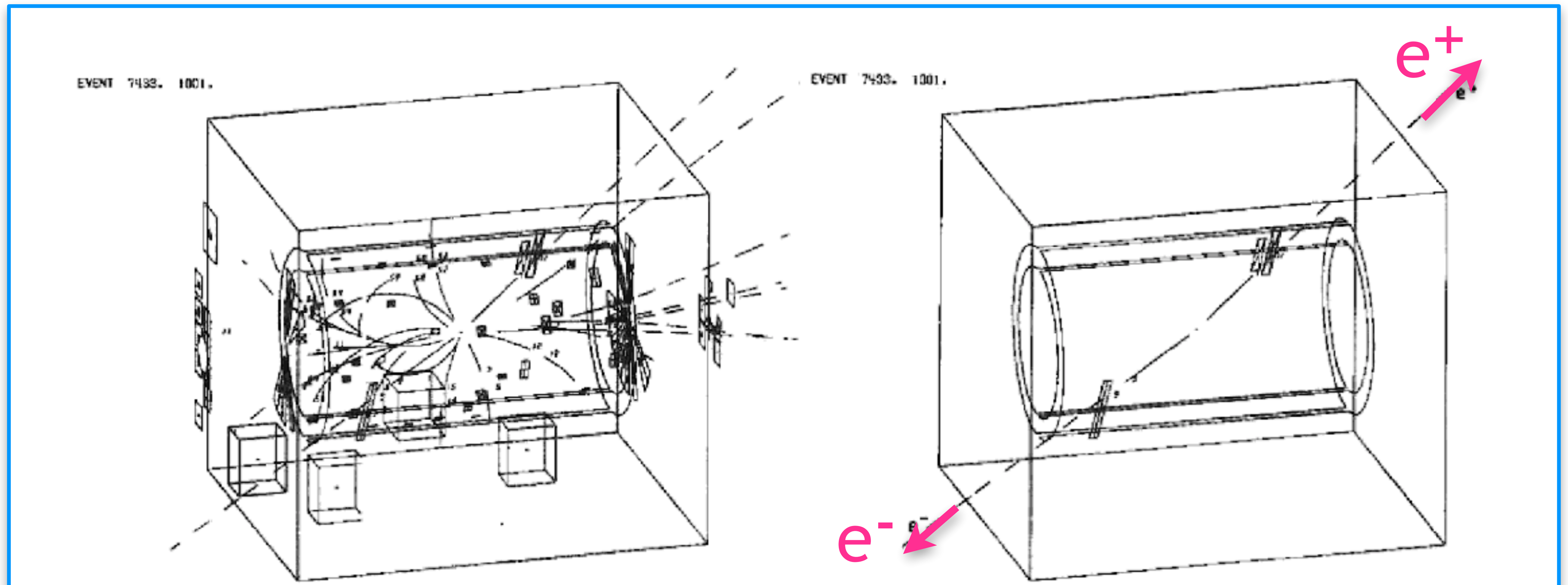


UA2



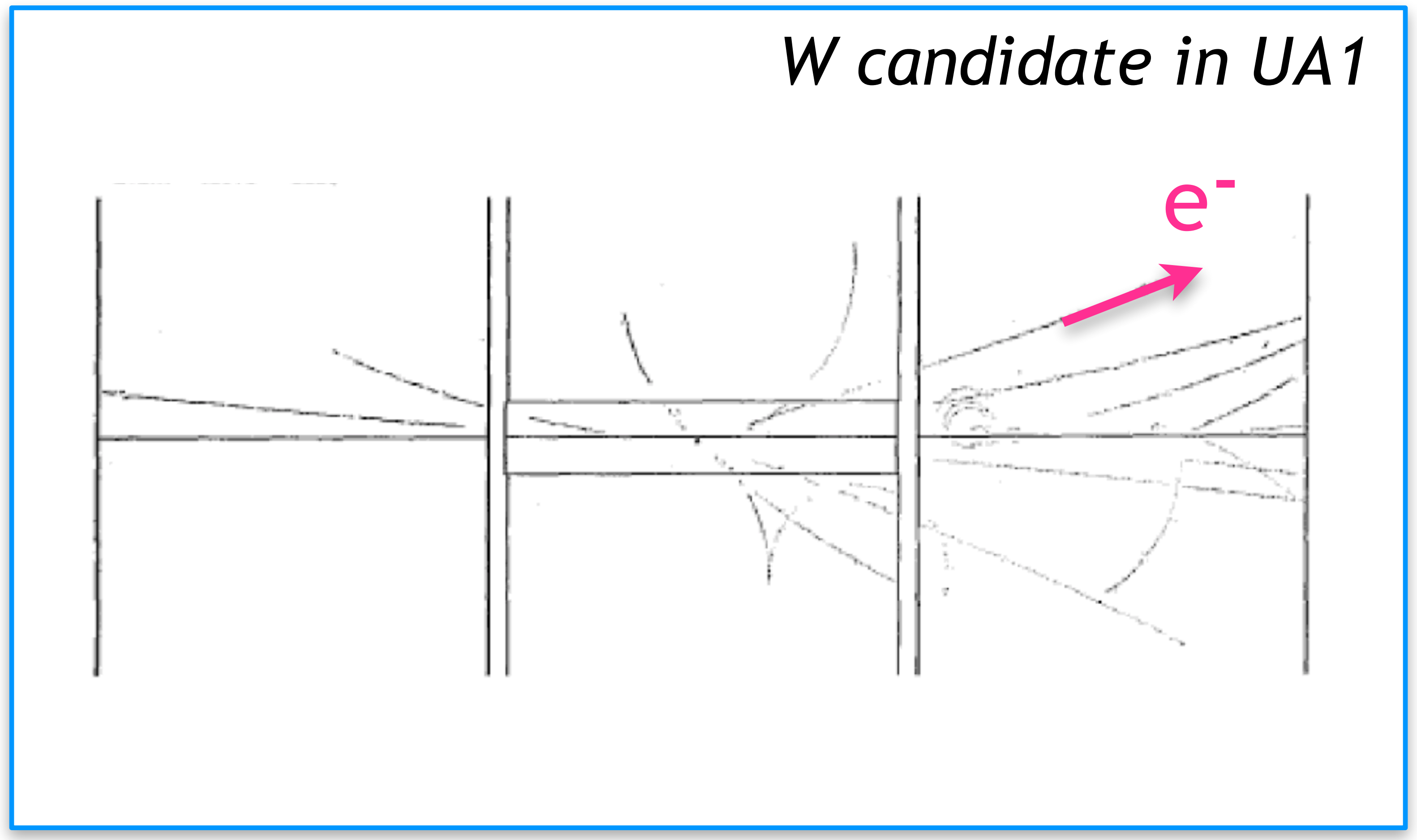
An SppS Legacy

The discovery of the W and Z bosons



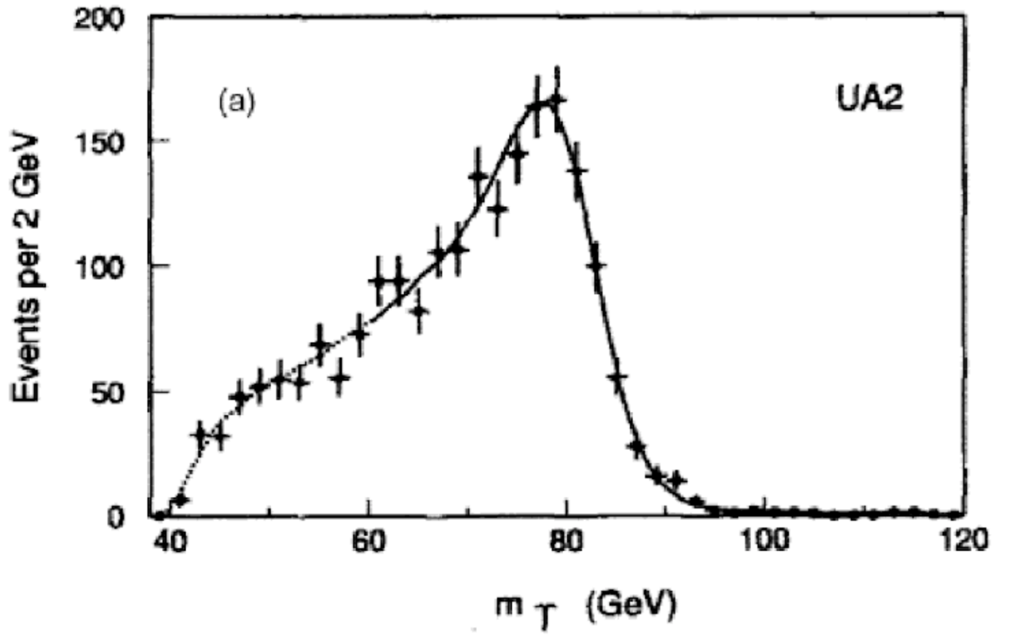
Z candidate in UA2

Track cleaning pT > 2GeV



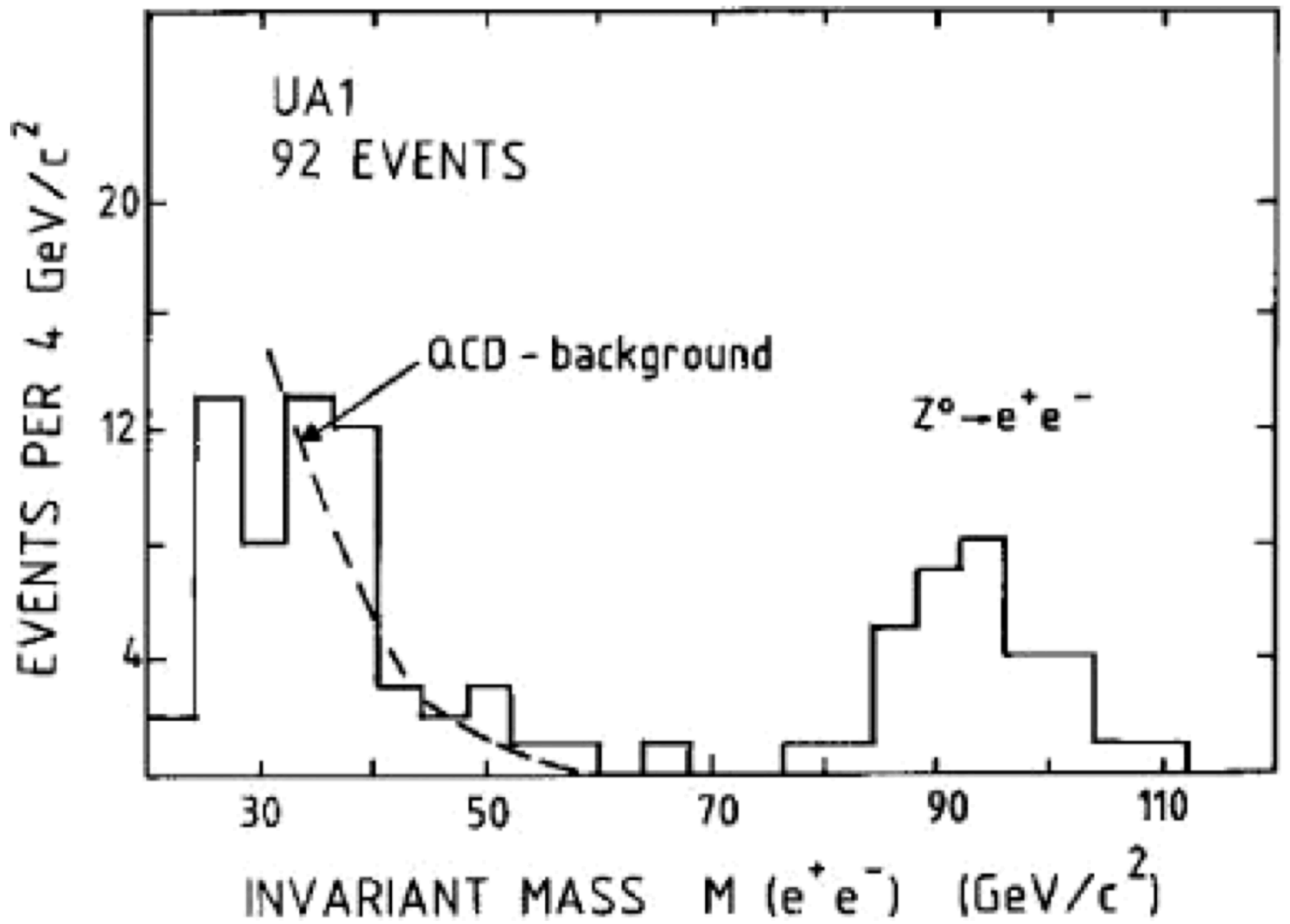
W candidate in UA1

Transverse Mass distribution in UA2



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

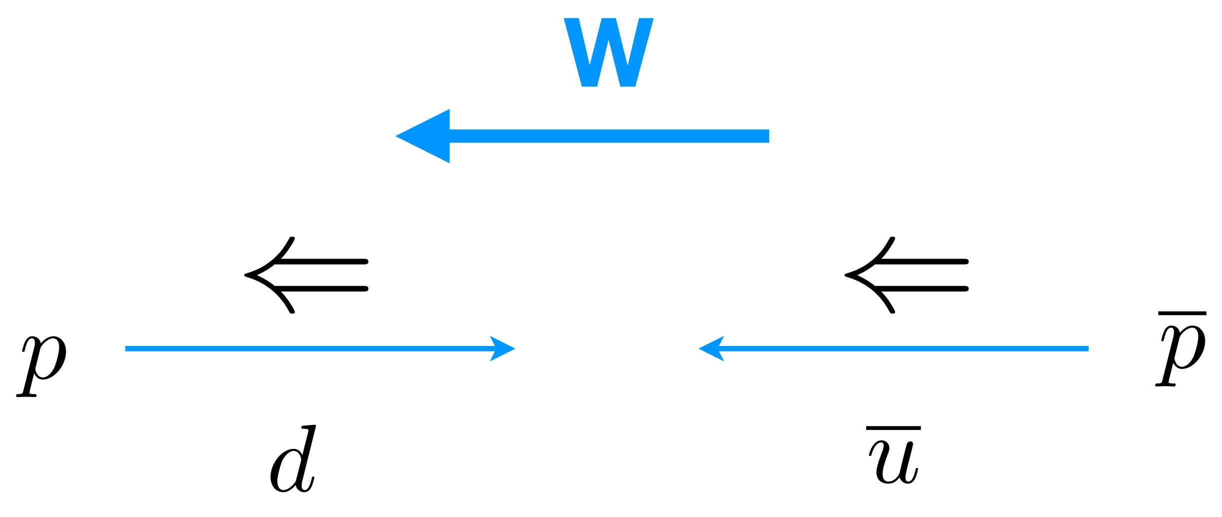
Altogether O(100) Z events



Altogether O(1000) W events

At SppS W production dominated by valence quarks

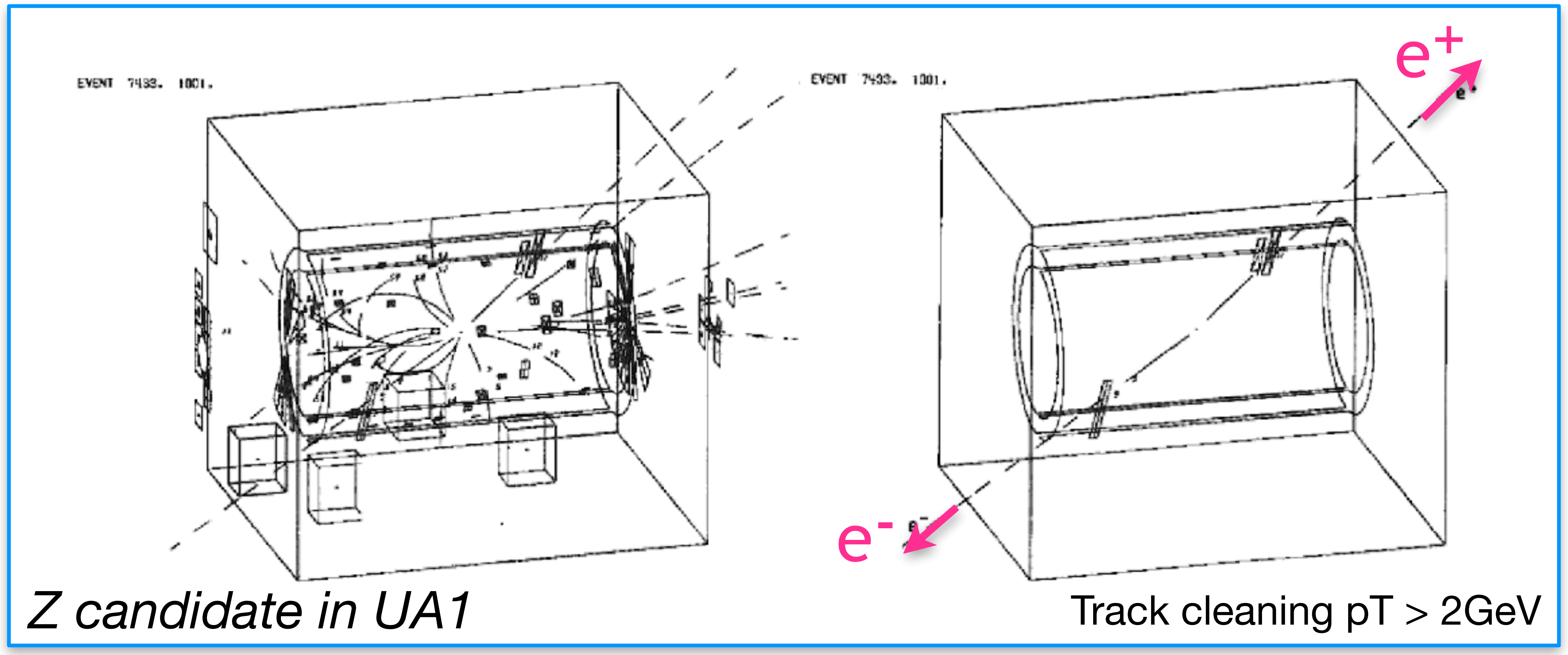
W polarised in the anti-proton direction.

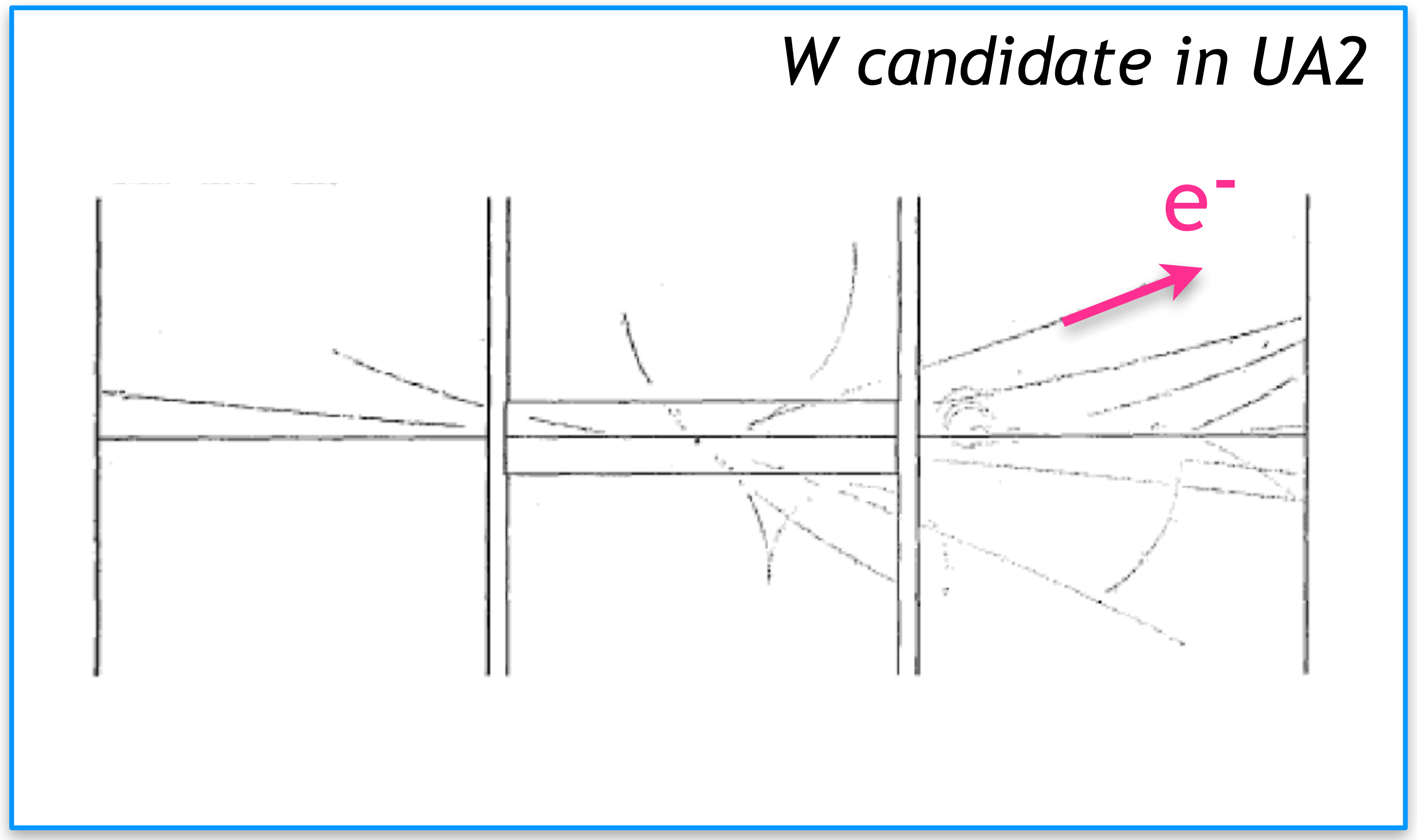


Production

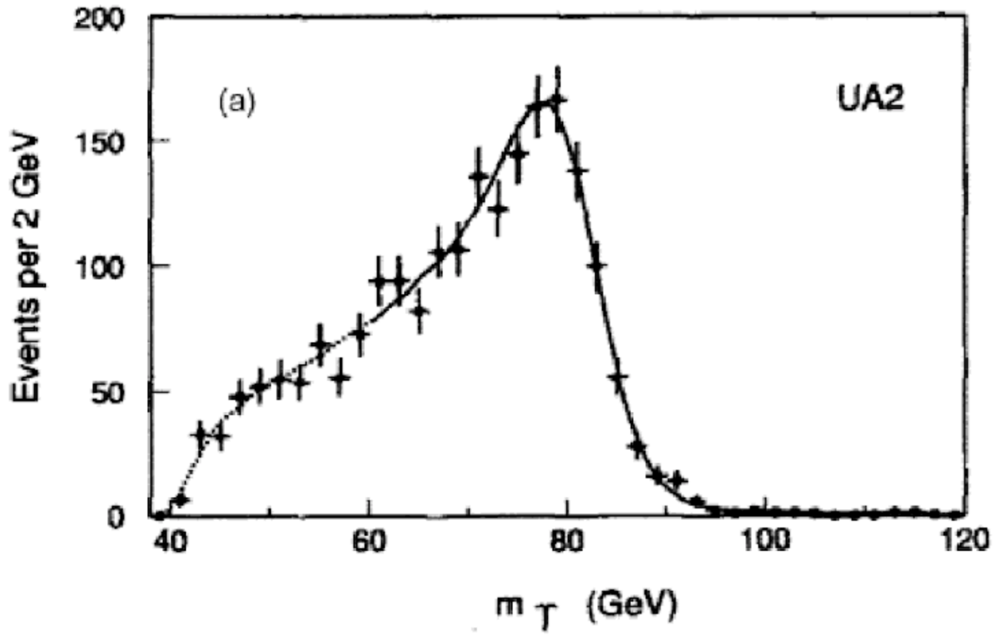
An SppS Legacy

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 very important measurements:

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

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

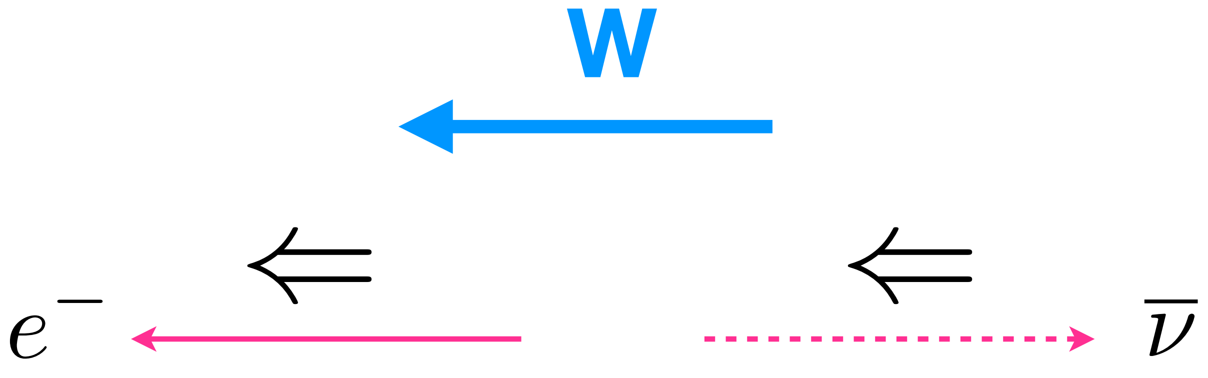
$$\rho = 1.004 \pm 0.052 \quad \textit{(UA1)}$$

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

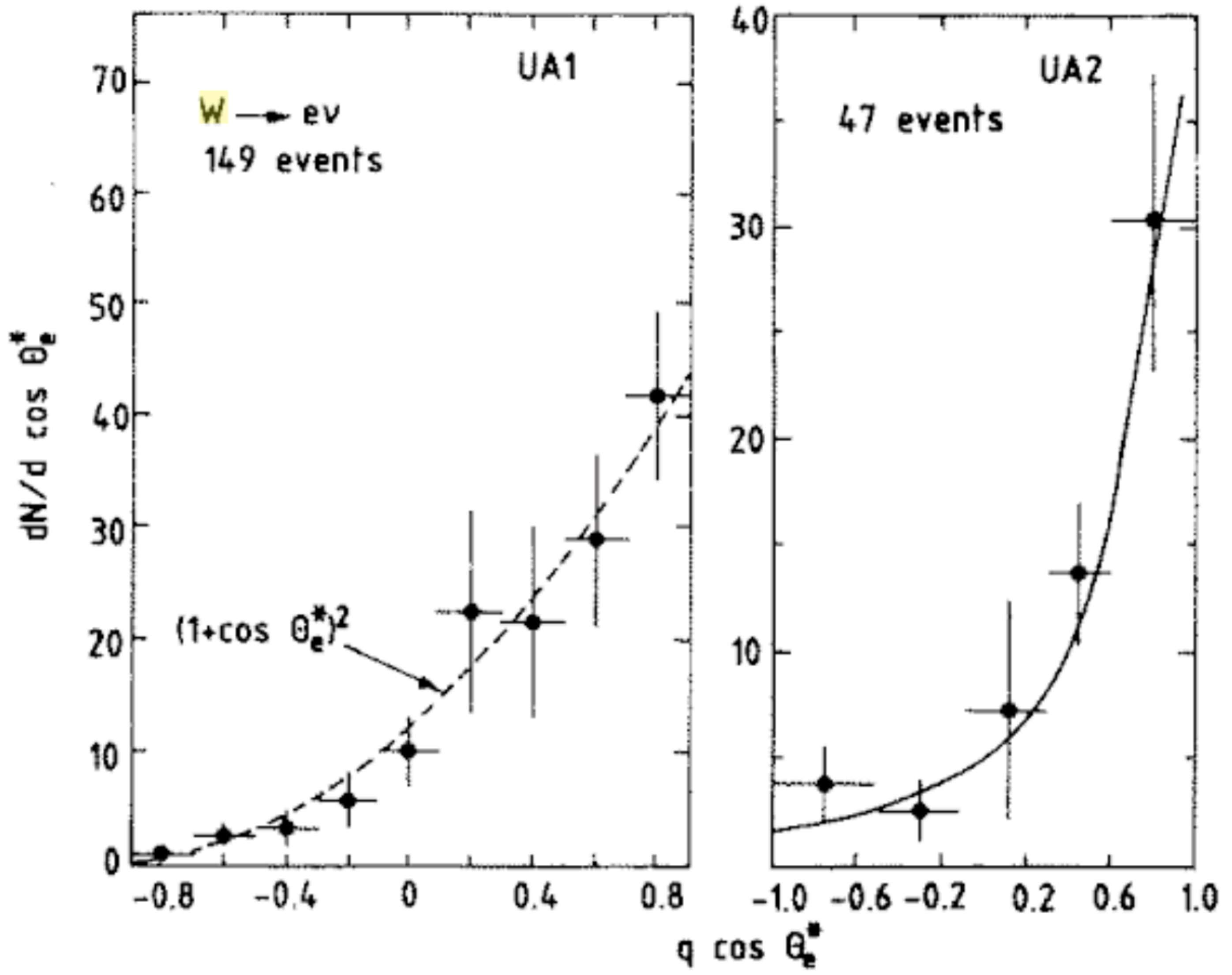
Altogether O(1000) W events

At SppS W production dominated by valence quarks

W polarised in the anti-proton direction.

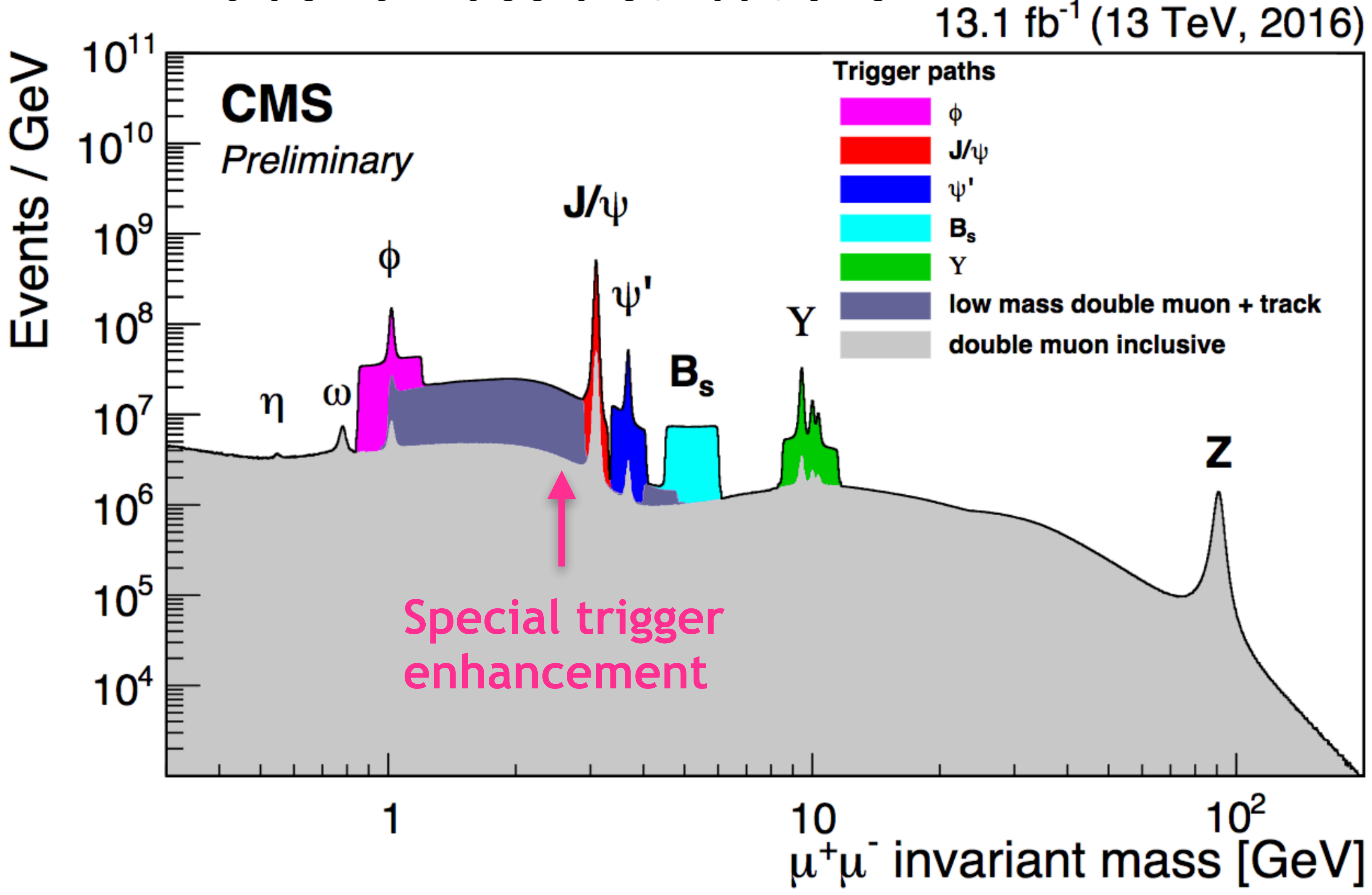


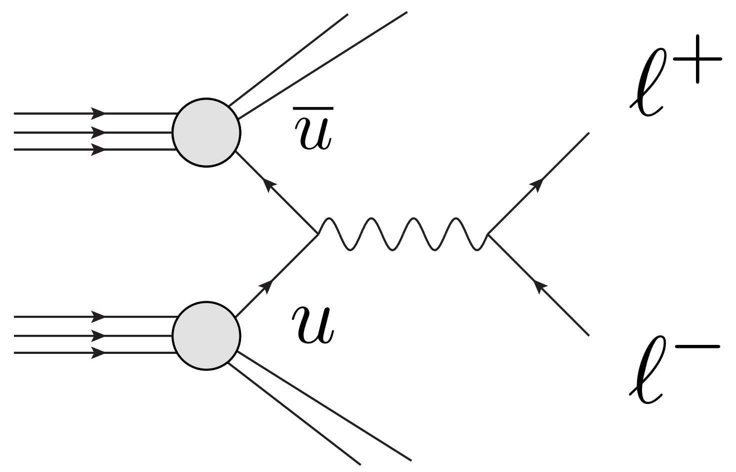
Decay



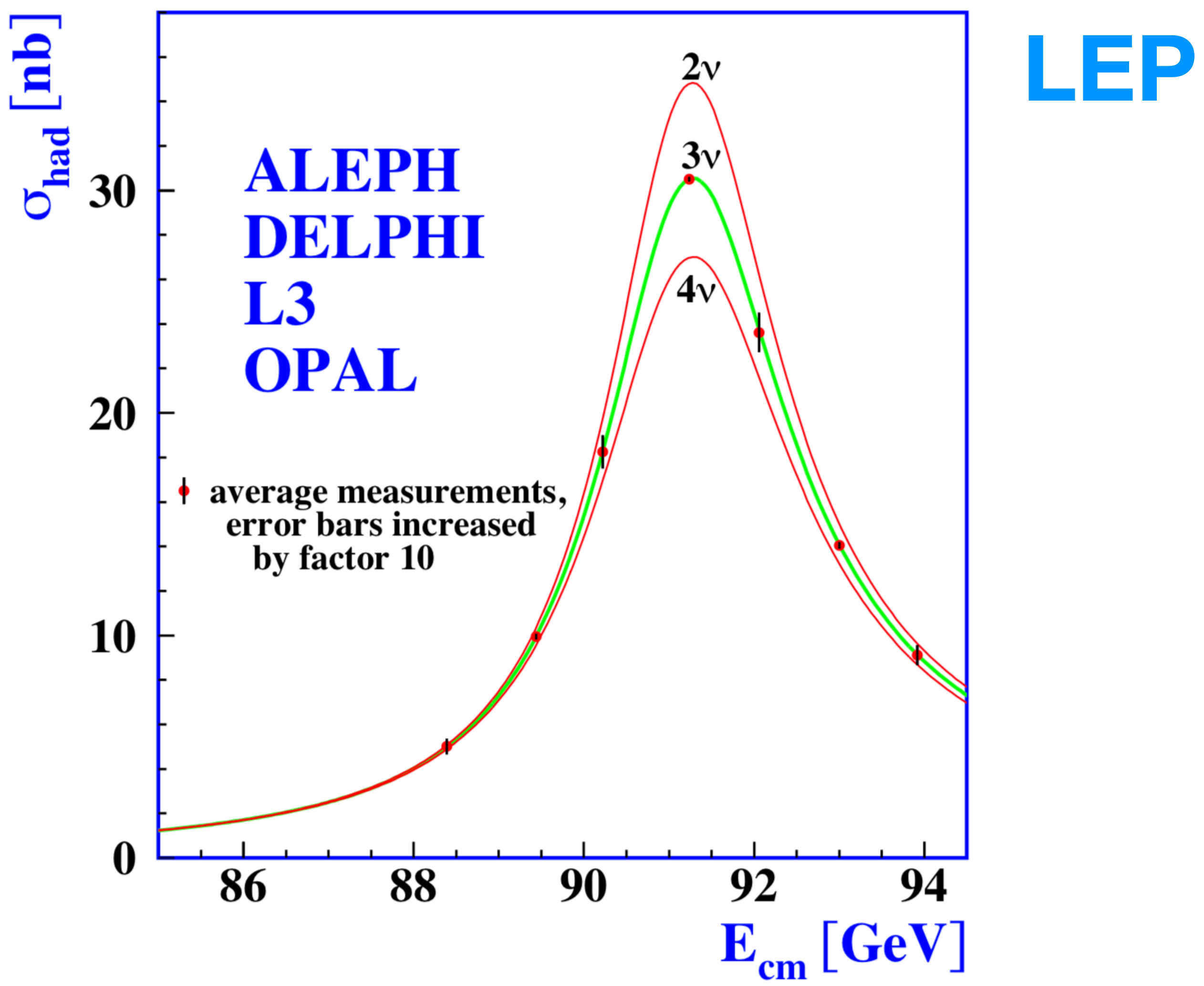
The di-lepton mass spectrum at LHC

Inclusive mass distributions





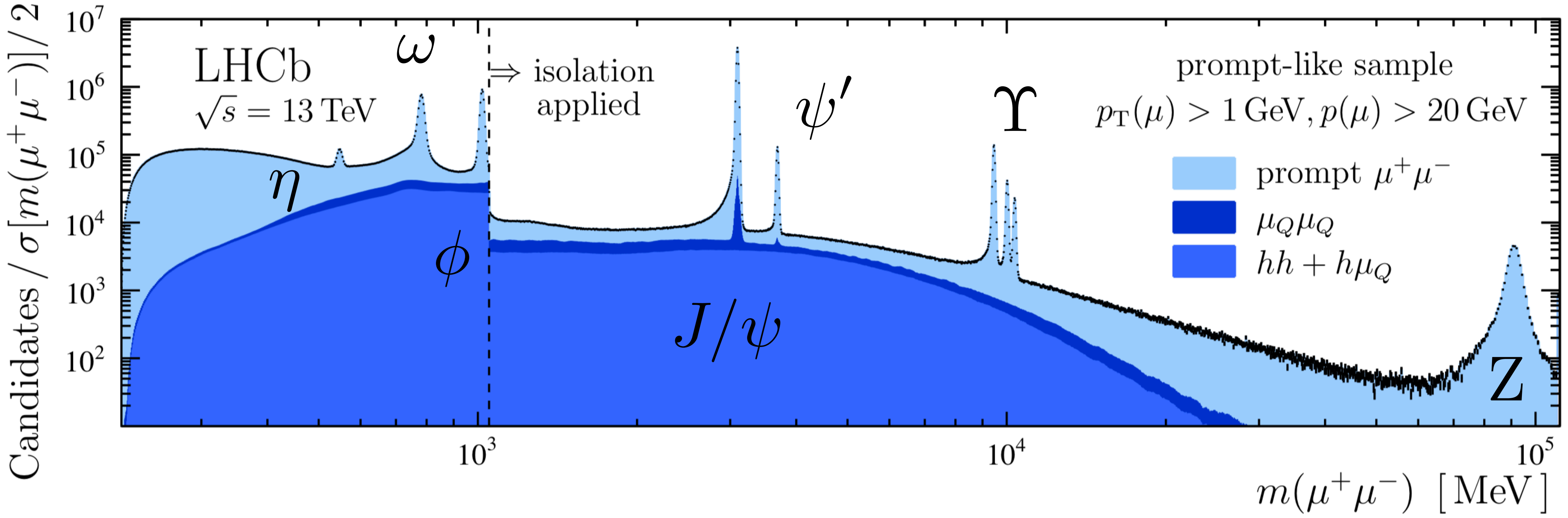
Z, J/Psi and Upsilon in electrons and muons are extremely important standard candles for calibration.



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

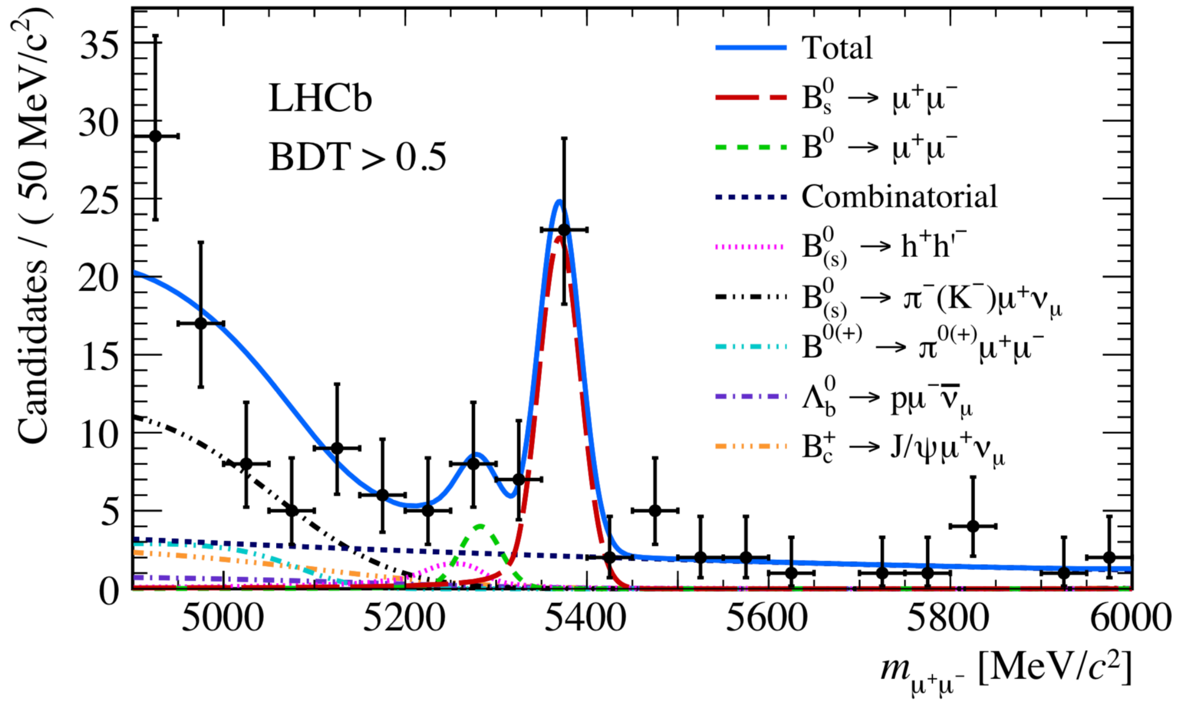
$$\Gamma_Z = 2.4952 \pm 0.0023\,\mathrm{GeV}$$

$$\rho = 1.0050 \pm 0.0010$$



An exclusive analysis scrutinising the Bs mass region

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



Composition of Drell Yan production

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

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

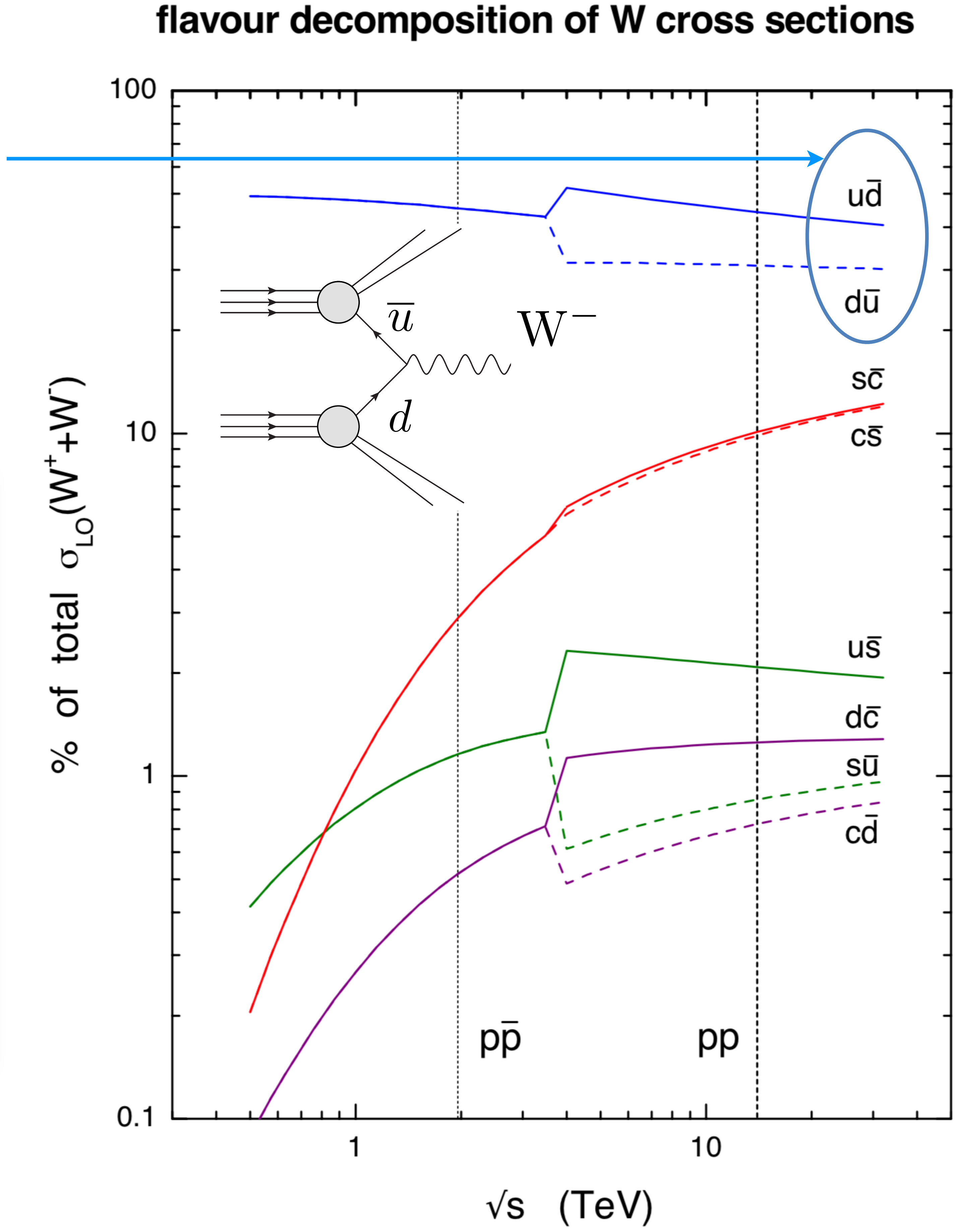
$$\sigma_{W^+} = 11.54\ ^{+0.32}_{-0.31}\,(\mathrm{PDF}) \pm 0.22\,(\mathrm{TH})\ \mathrm{nb}$$

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

Note: PDF uncertainties are dominant.

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

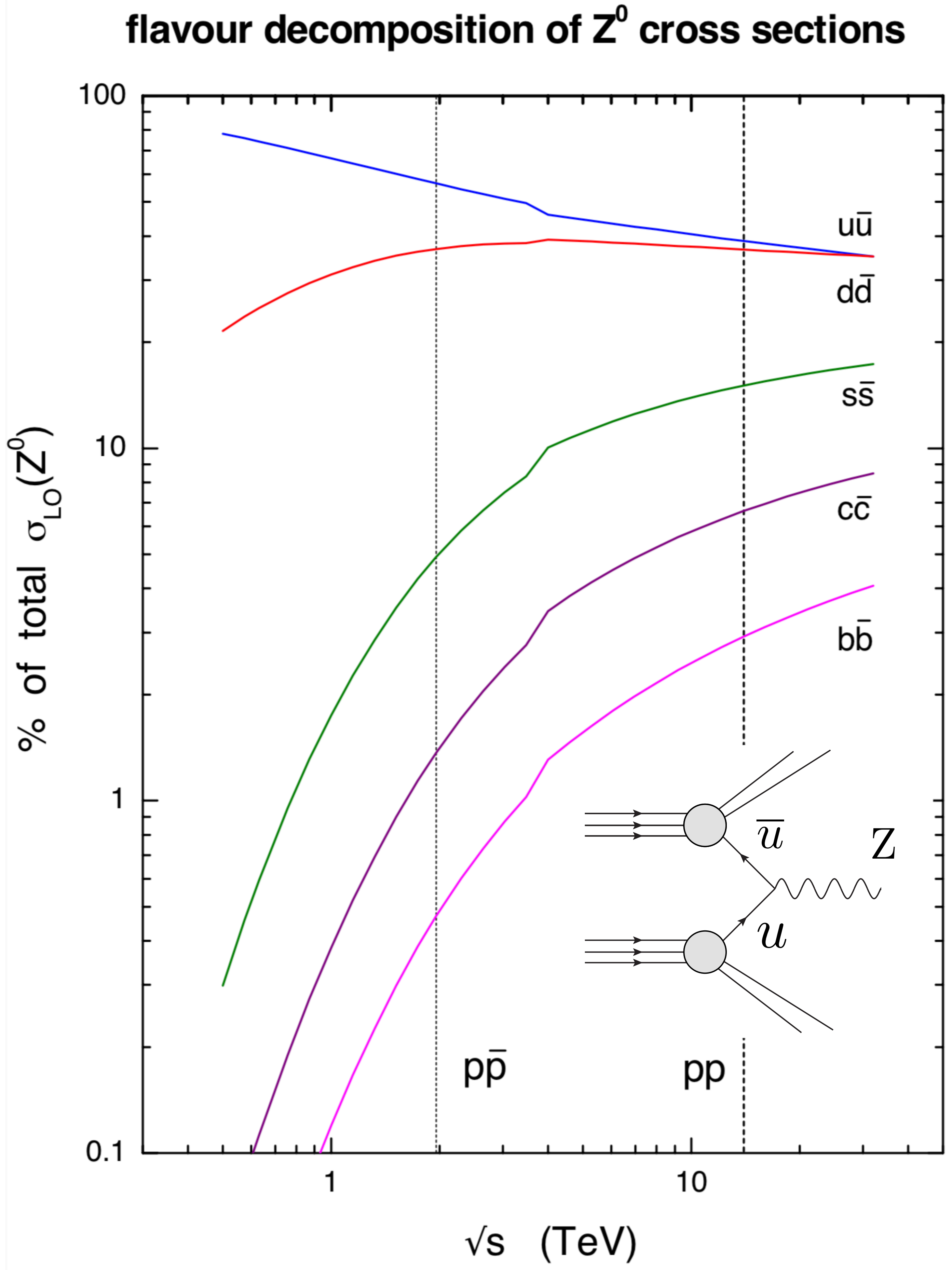
Still O(2) Billion W boson events produced !!



Typically in pp in leptonic modes
$\ell = e, \mu, \tau$

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

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



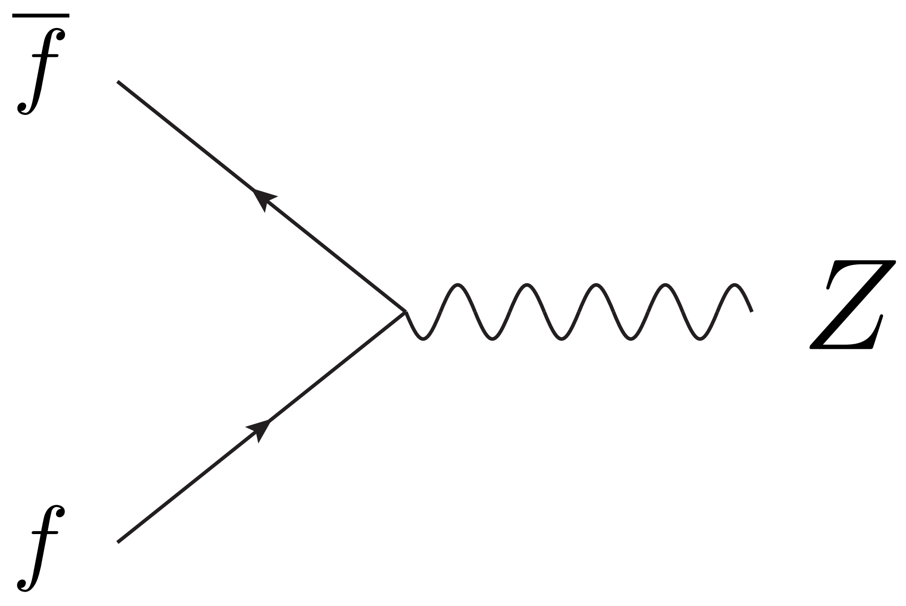
$$\mathrm{Br}(\mathrm{Z} \to \nu\overline{\nu}) \sim 20\%$$

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

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

Formalism of Weak Mixing Angle Measurements

A closer look at the Z coupling to fermions (obtained when mixing the B^μ field with the W_3^μ fields to produce the photon):



$$\frac{g}{2\cos\theta_W}\bar{f}\gamma^\mu\left(R_f(1+\gamma^5)+L_F(1-\gamma^5)\right)fZ_\mu$$

$$a_f = (L_f - R_f)/2 = T_f^3$$

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

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	$-1/3$

There is an explicit asymmetry between the coupling of the Z to left and right handed fermions!

Formalism of Weak Mixing Angle Measurements

Taking into account radiative corrections the above expressions can be replaced by effective couplings and mixing angles:

$$g_{a_f} = \sqrt{\overline{\rho}} T^3_f$$

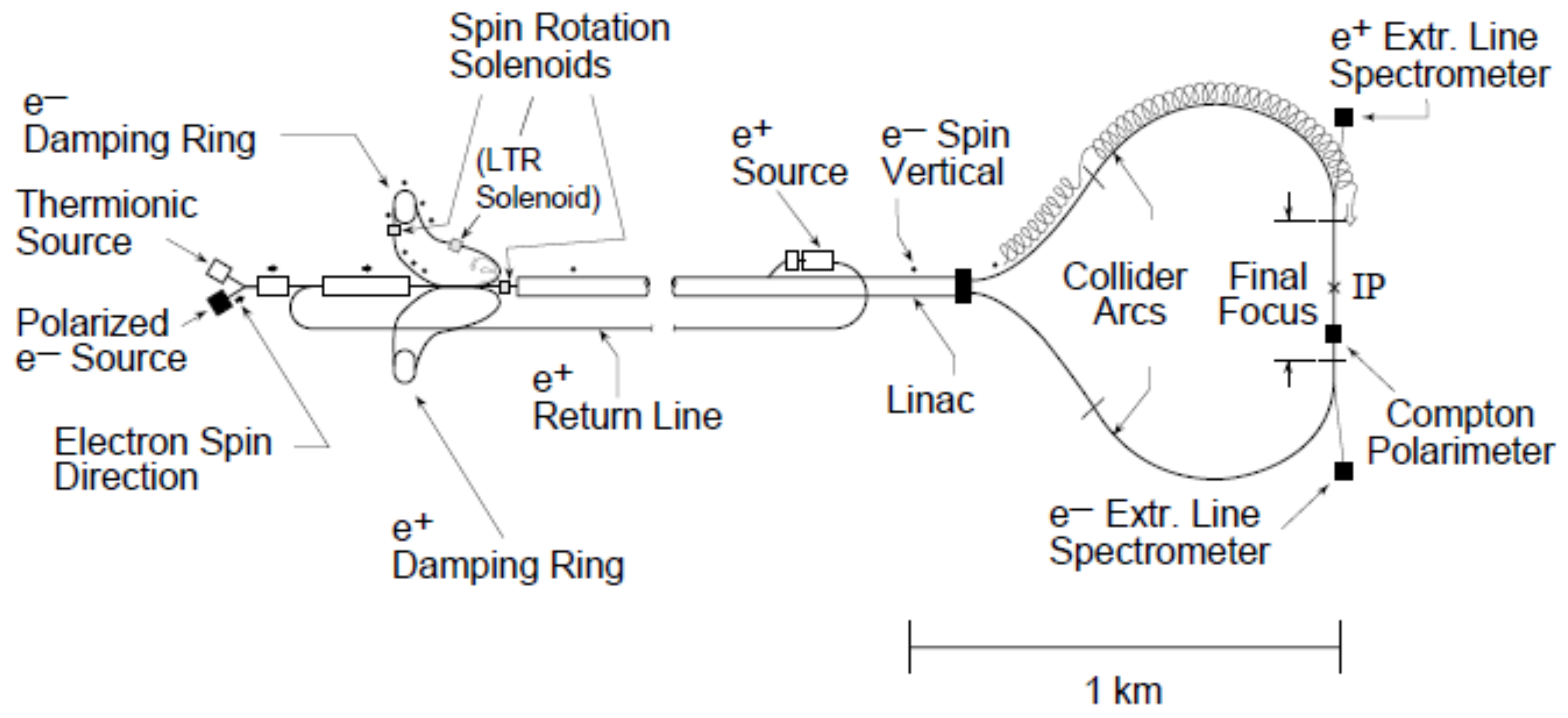
$$g_{v_f} = \sqrt{\overline{\rho}} (T^3_f - 2Q_f \sin^2 \theta^{eff}_W)$$

This allows to quantify the asymmetry in the following way:

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

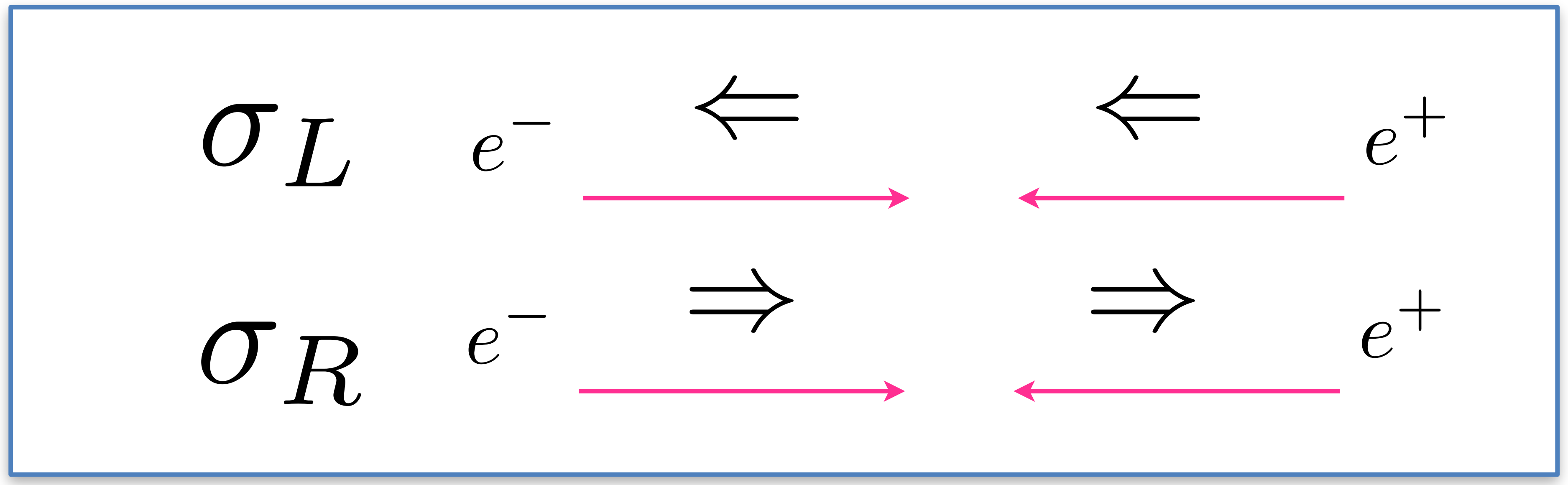
Which is related to the effective weak mixing angle through:

$$(\sin^2 \theta^{\rm eff}_W)^f = \frac{1}{4|Q_f|}(1 - g_{vf}/g_{af})$$



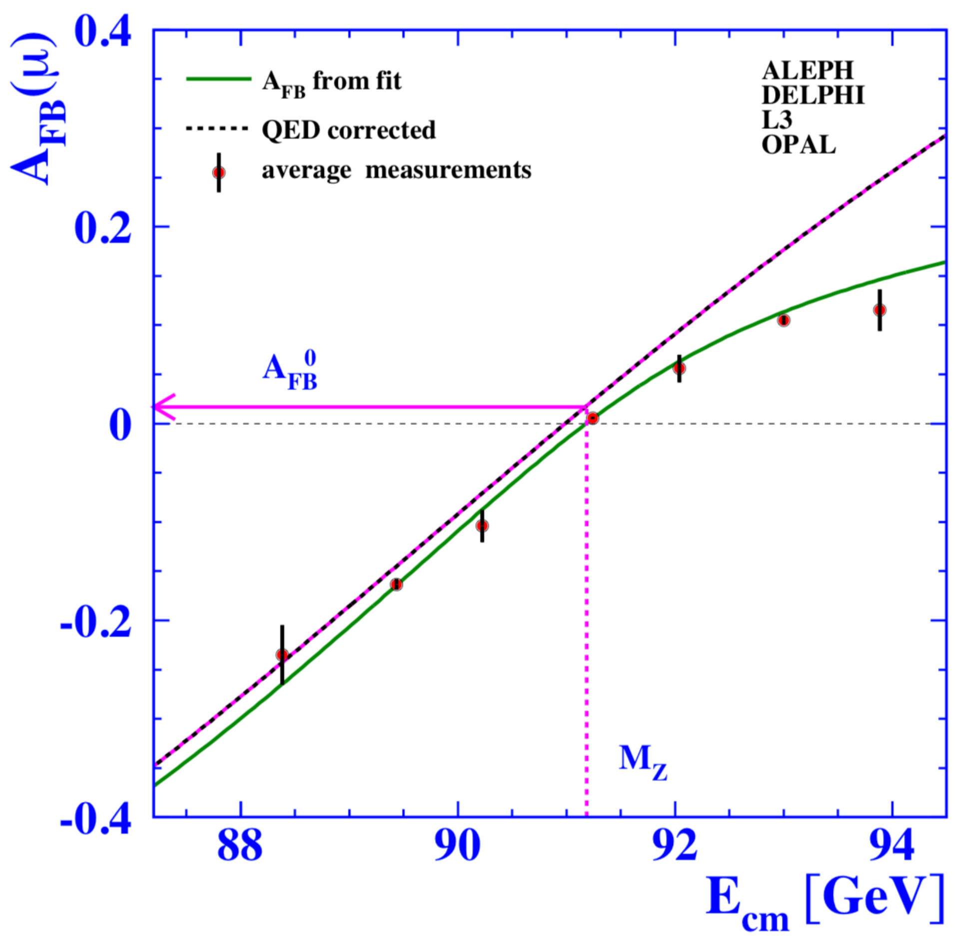
SLC 1988 - 1998
Linear e^+e^- collider w/ longitudinal electron polarisation (at ~91 GeV).

$$\mathcal{A}_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \mathcal{A}_e$$



$$\mathcal{A}_\ell \sim 15\%$$

Forward Backward Asymmetry

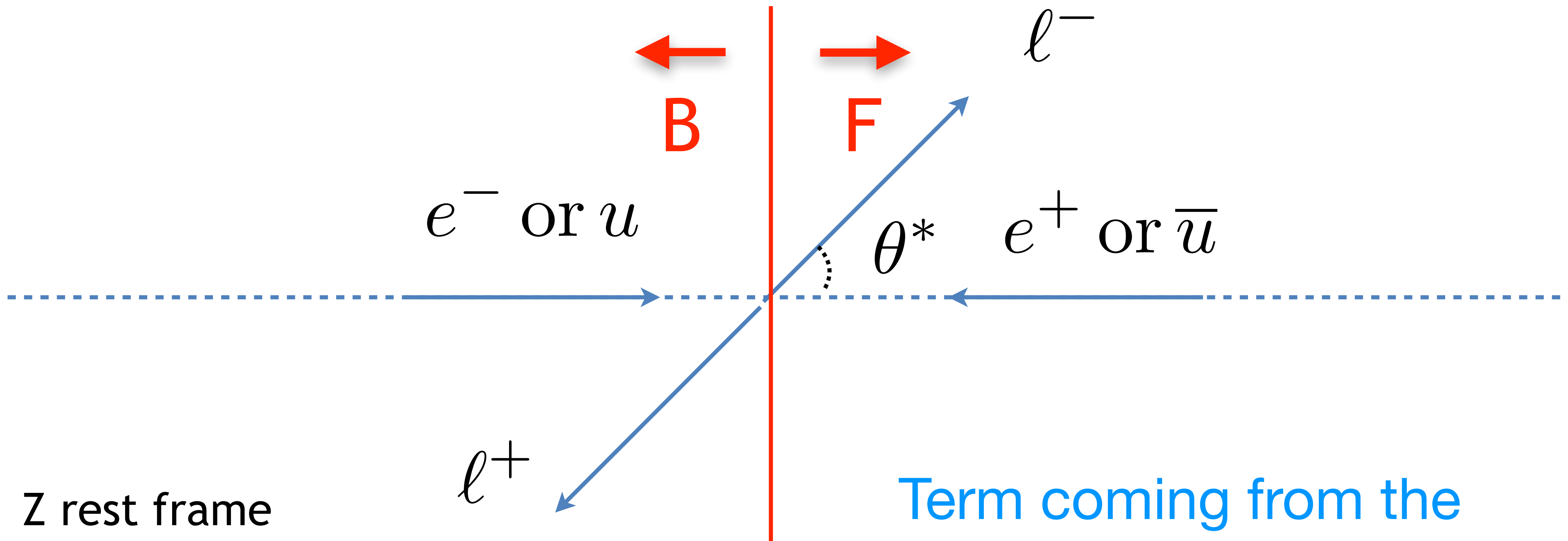


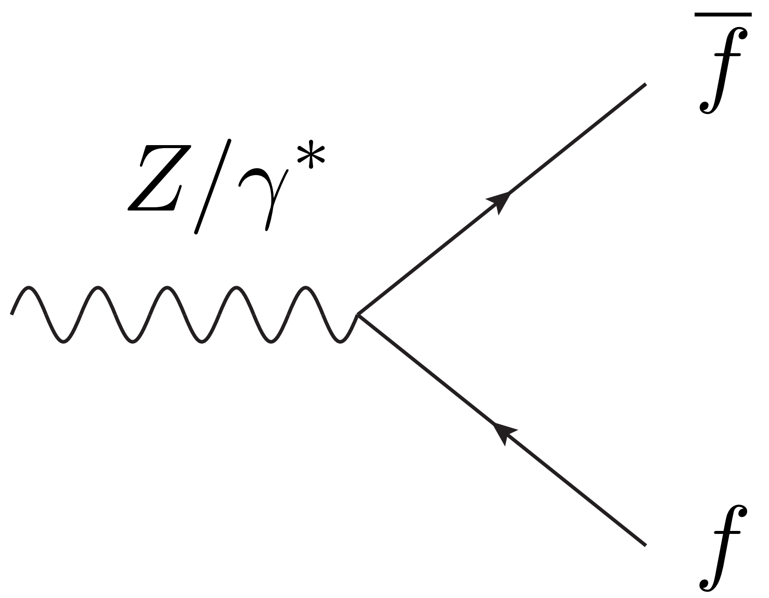
LEP

Forward-Backward asymmetry at LEP

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

At the Z pole: $\mathcal{A}^0_{FB} = 3\mathcal{A}^e\mathcal{A}^f$





Term coming from the Z/gamma* interference

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

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

$$\frac{d\sigma}{d\cos\theta^*} \propto \left((g_{ve}^2 + g_{ae}^2)(g_{vf}^2 + g_{af}^2)(1+\cos^2\theta^*) + 8g_{ve}g_{ae}g_{vf}g_{af}\cos\theta^*\right)$$

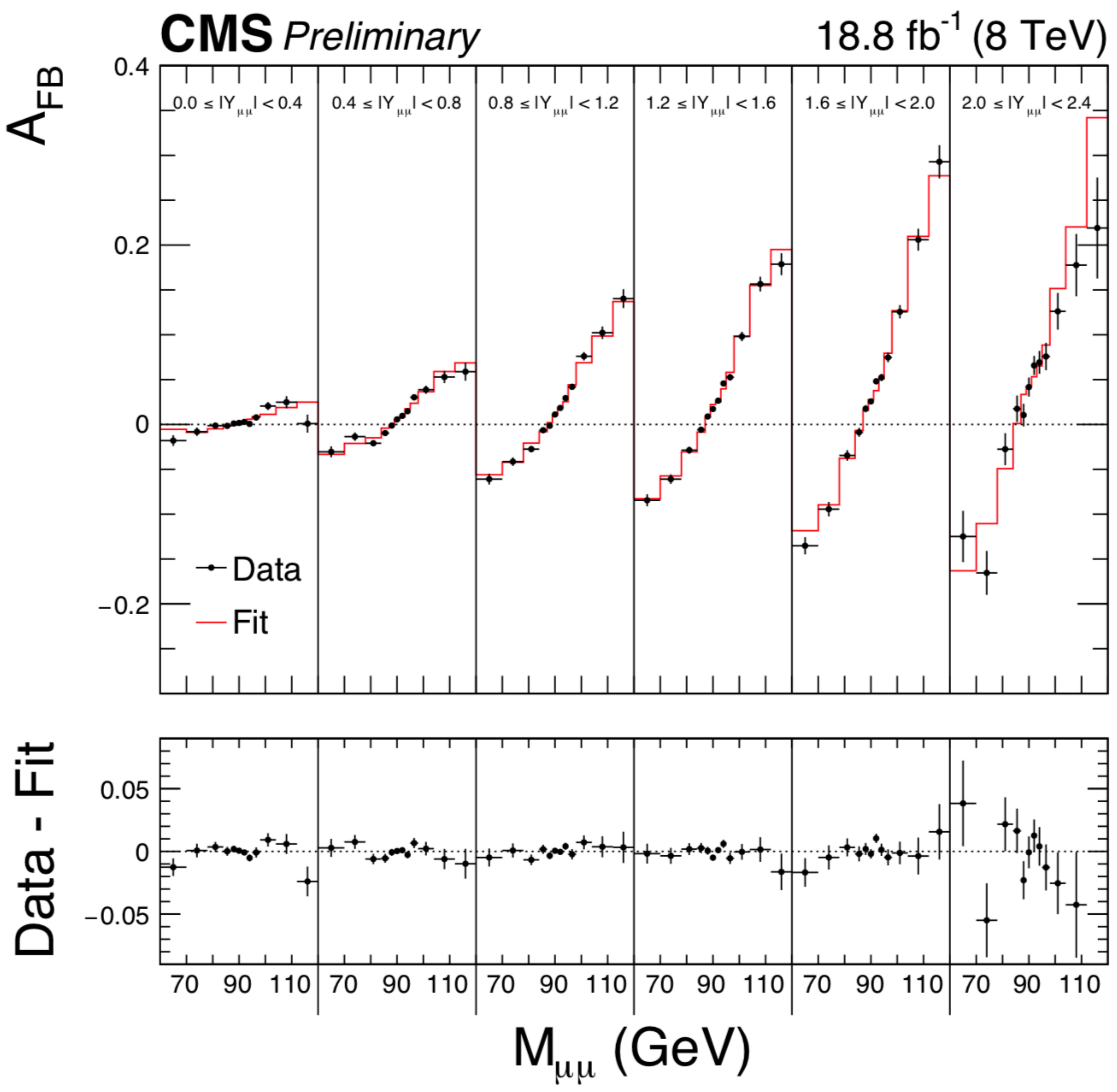
At the LHC the situation is much more intricate: what is the direction of the quark with respect to the direction of the anti-quark?

- The COM frame at LEP is essentially the detector frame, at the LHC the choice of frame is less obvious.

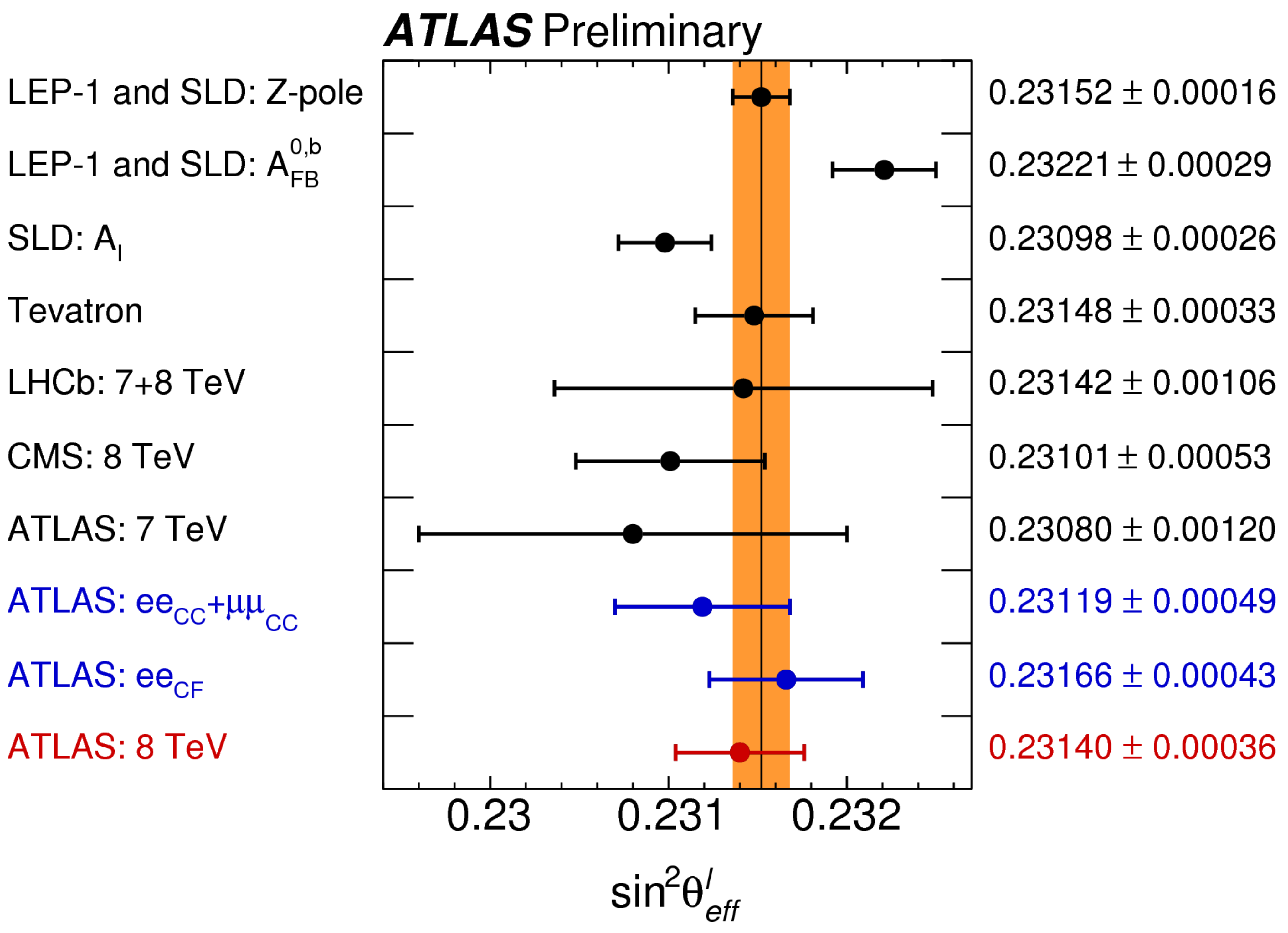
- At LHC because of the valence PDFs the momentum of valence quarks is larger and indicates the direction of the quark! The forward and backward asymmetry can be quantified in the same way.

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.

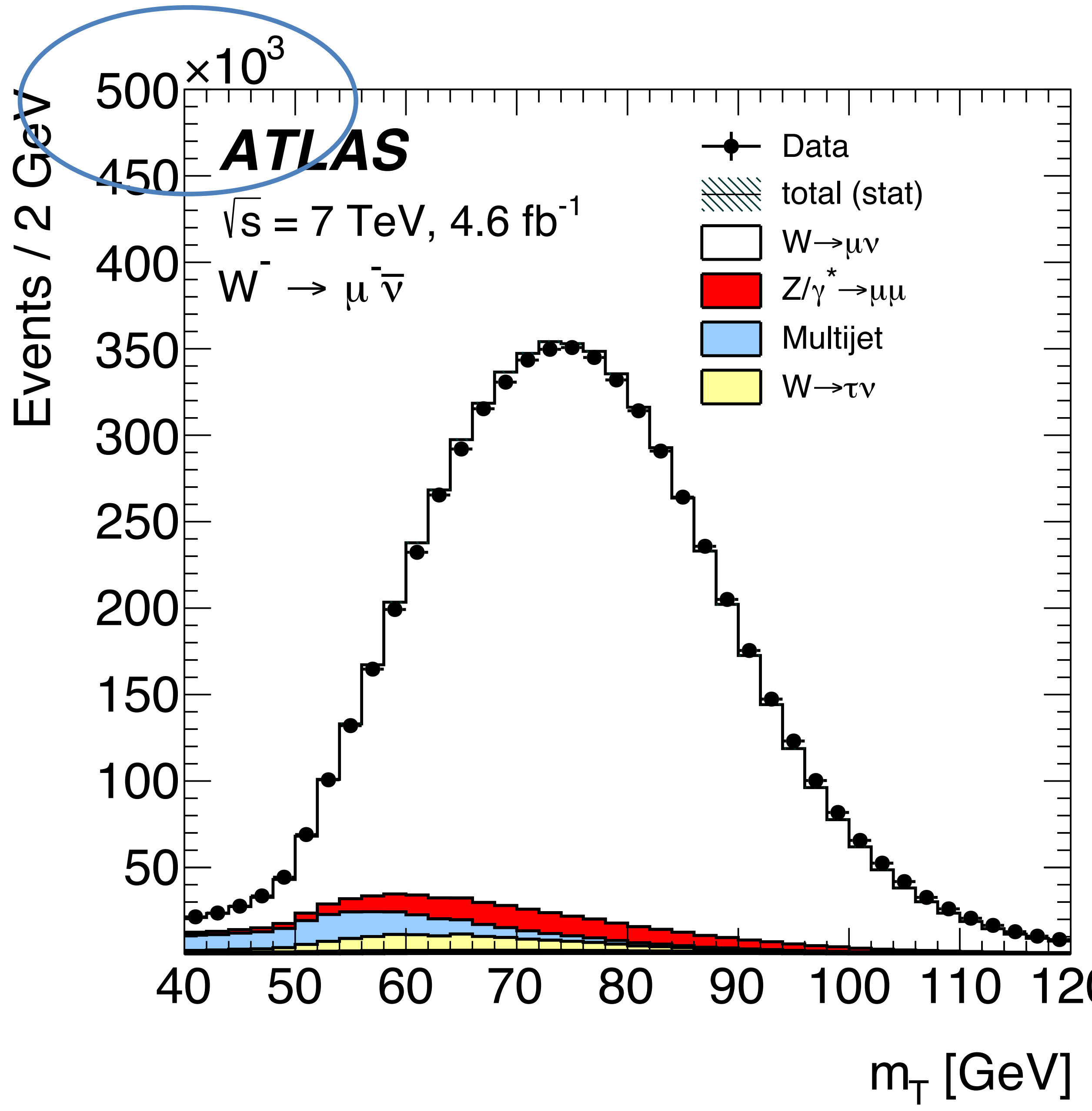
$$\sin^2\theta^\ell_{\rm eff} = 0.23140 \pm 0.00021\,({\rm stat}) \pm 0.00024\,({\rm PDFs}) \pm 0.00016\,({\rm syst})$$

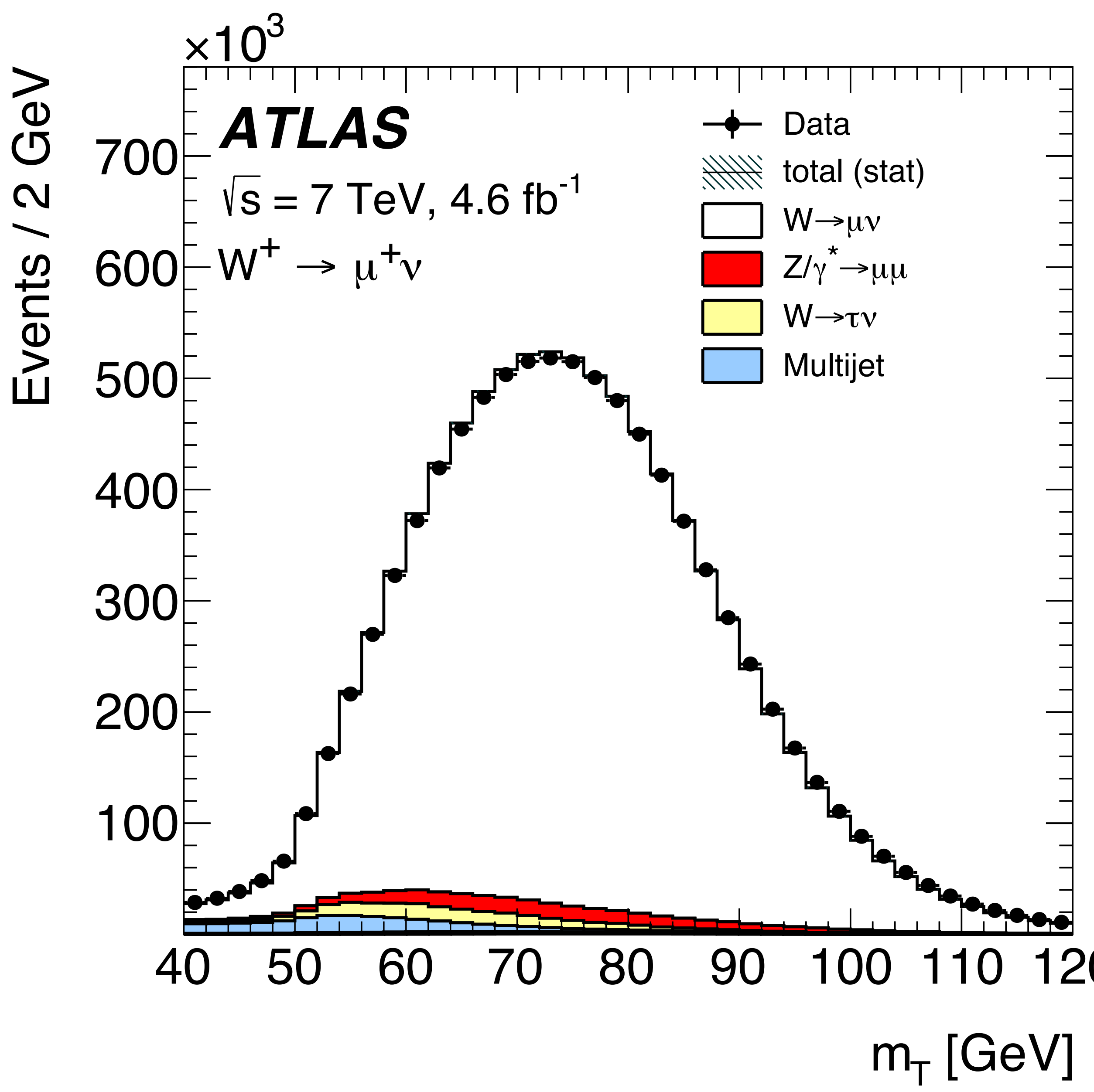
W boson production

Measurement of the W boson mass

$\mathbf{pp} \rightarrow \mathbf{W} \rightarrow \mu\nu_\mu$

Inclusive Precision Vector Boson Production at the LHC

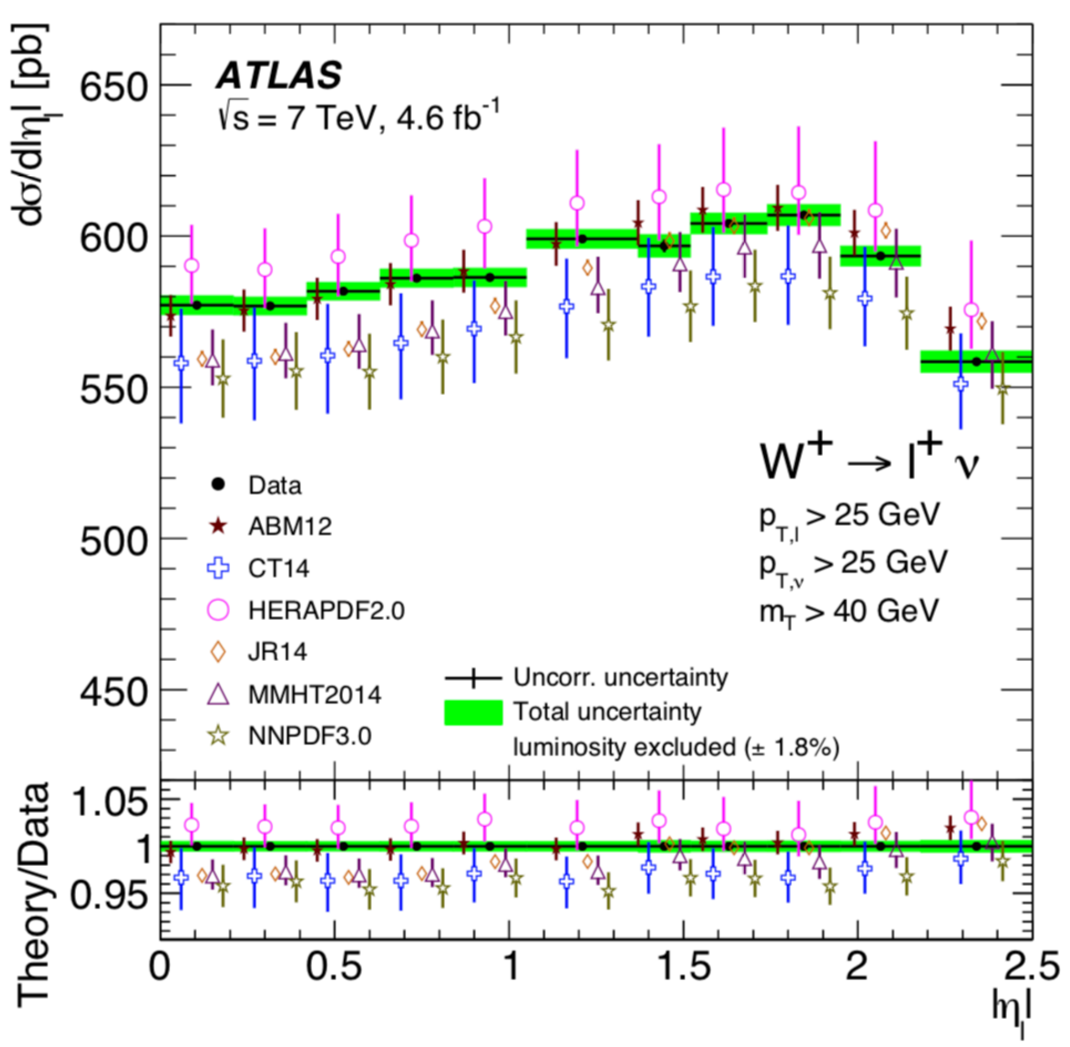


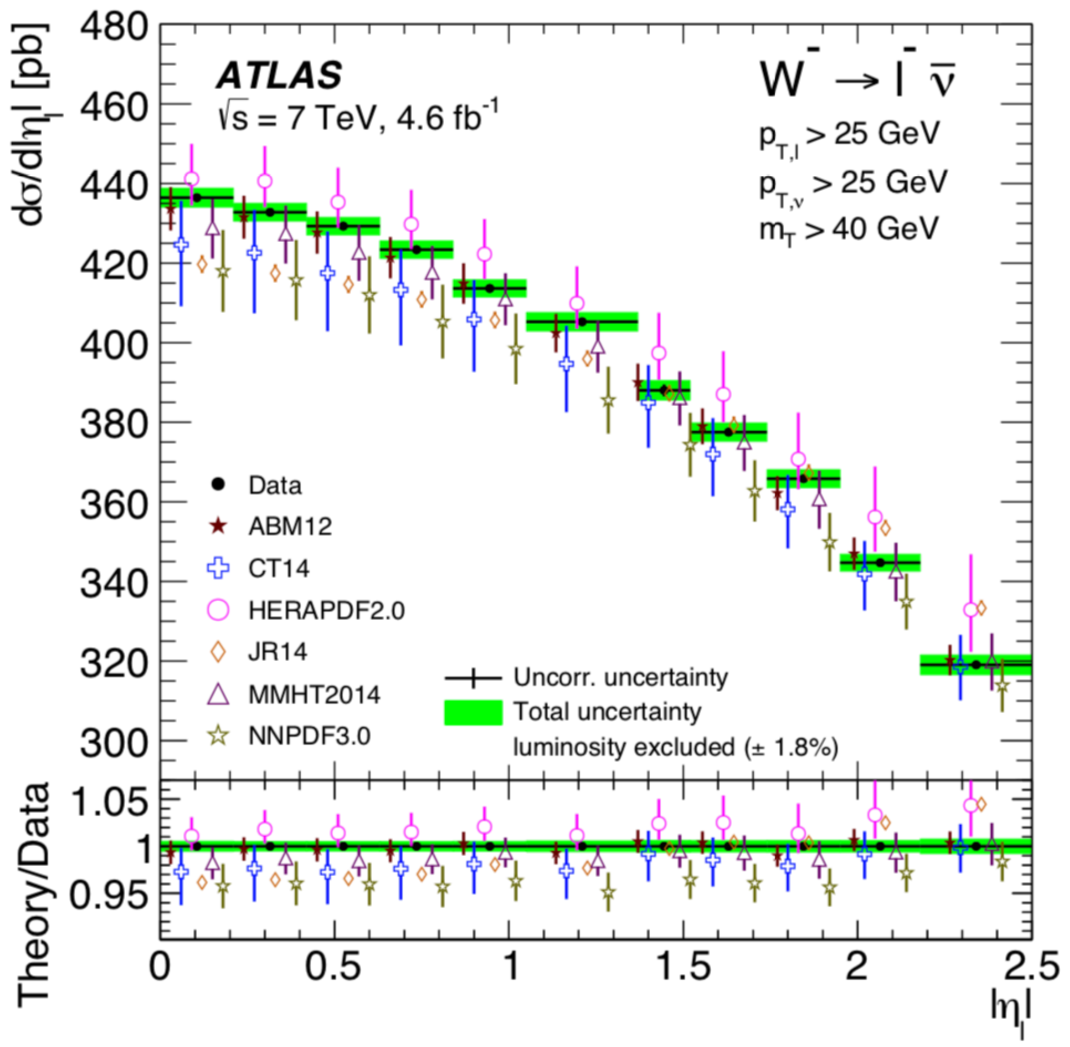


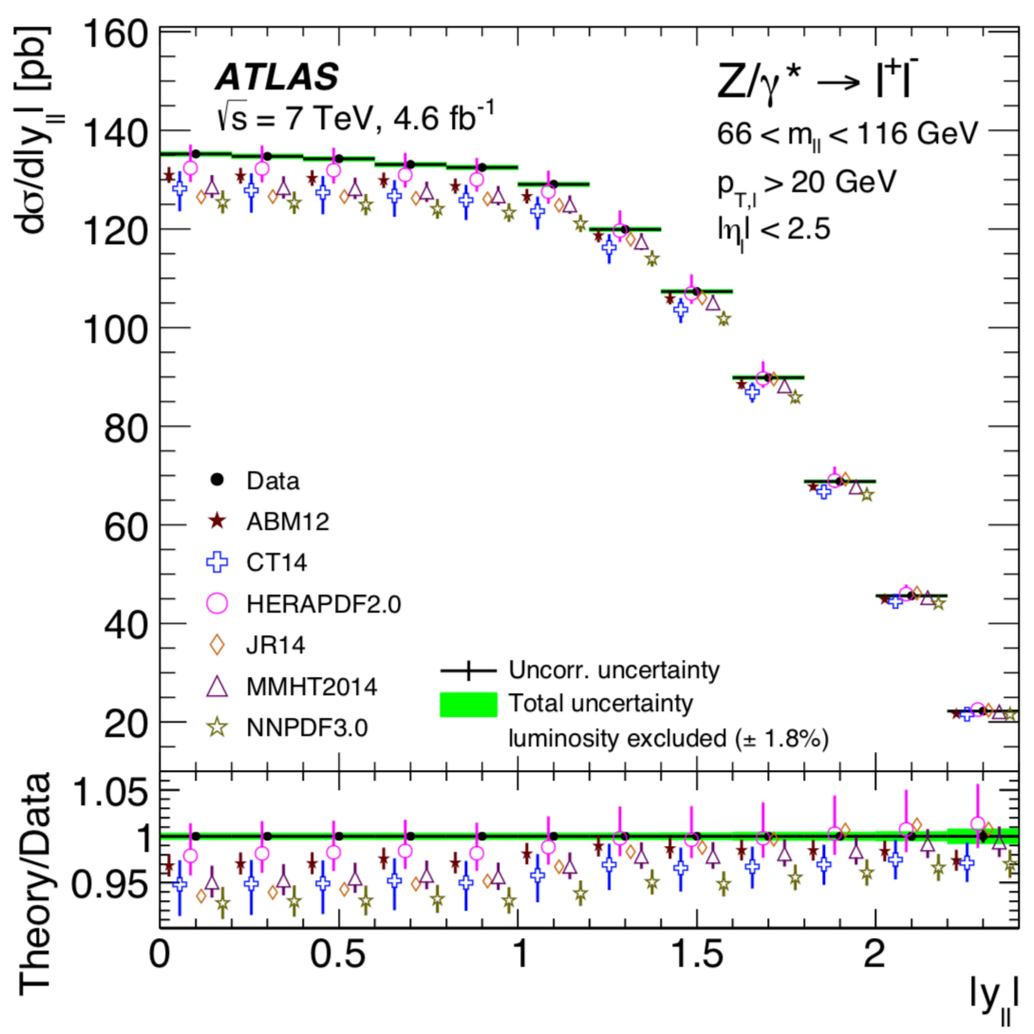
With a dataset of only 4.6 fb-1 at 7 TeV, approximately 15.5 M W+ events and 10.4 W- events (electrons and muons). **Low mu !**

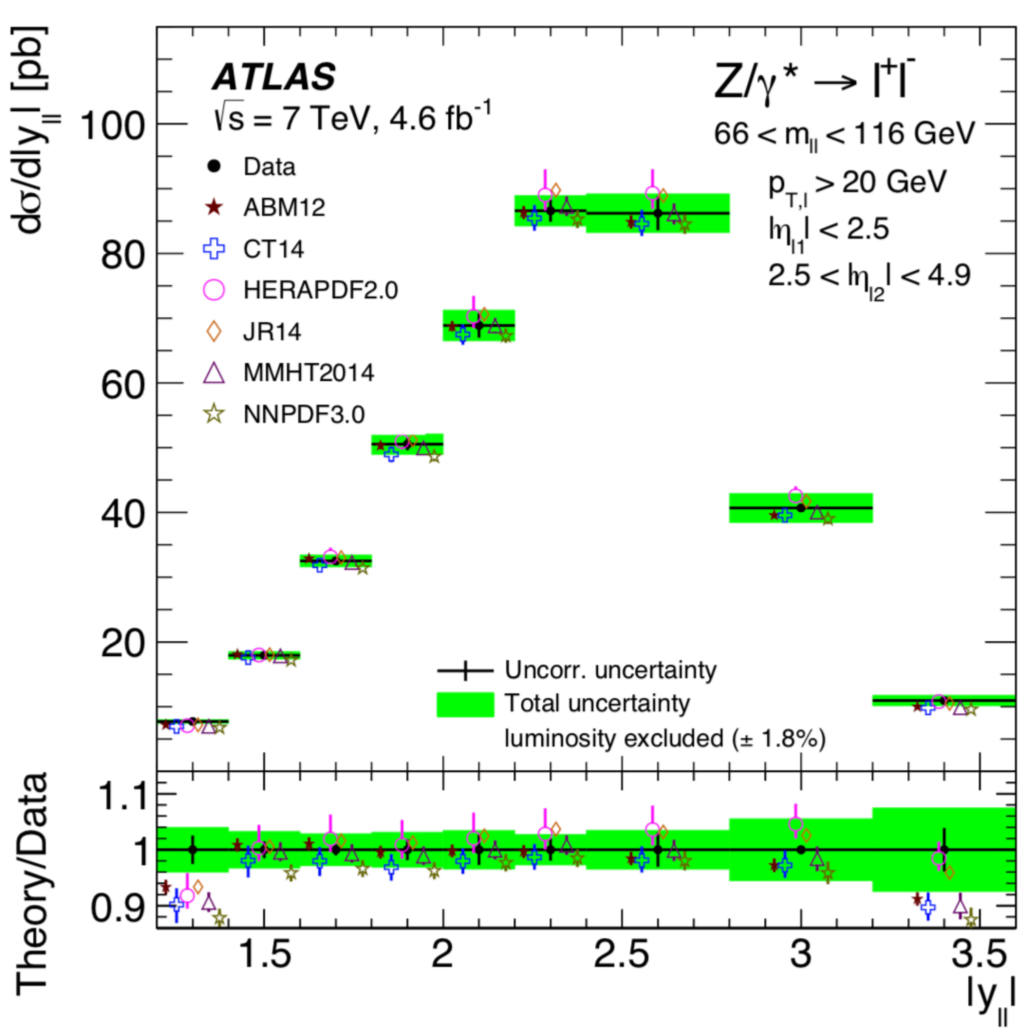
Cross section measurement uncertainty **completely dominated by luminosity uncertainty of 1.8%**

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.

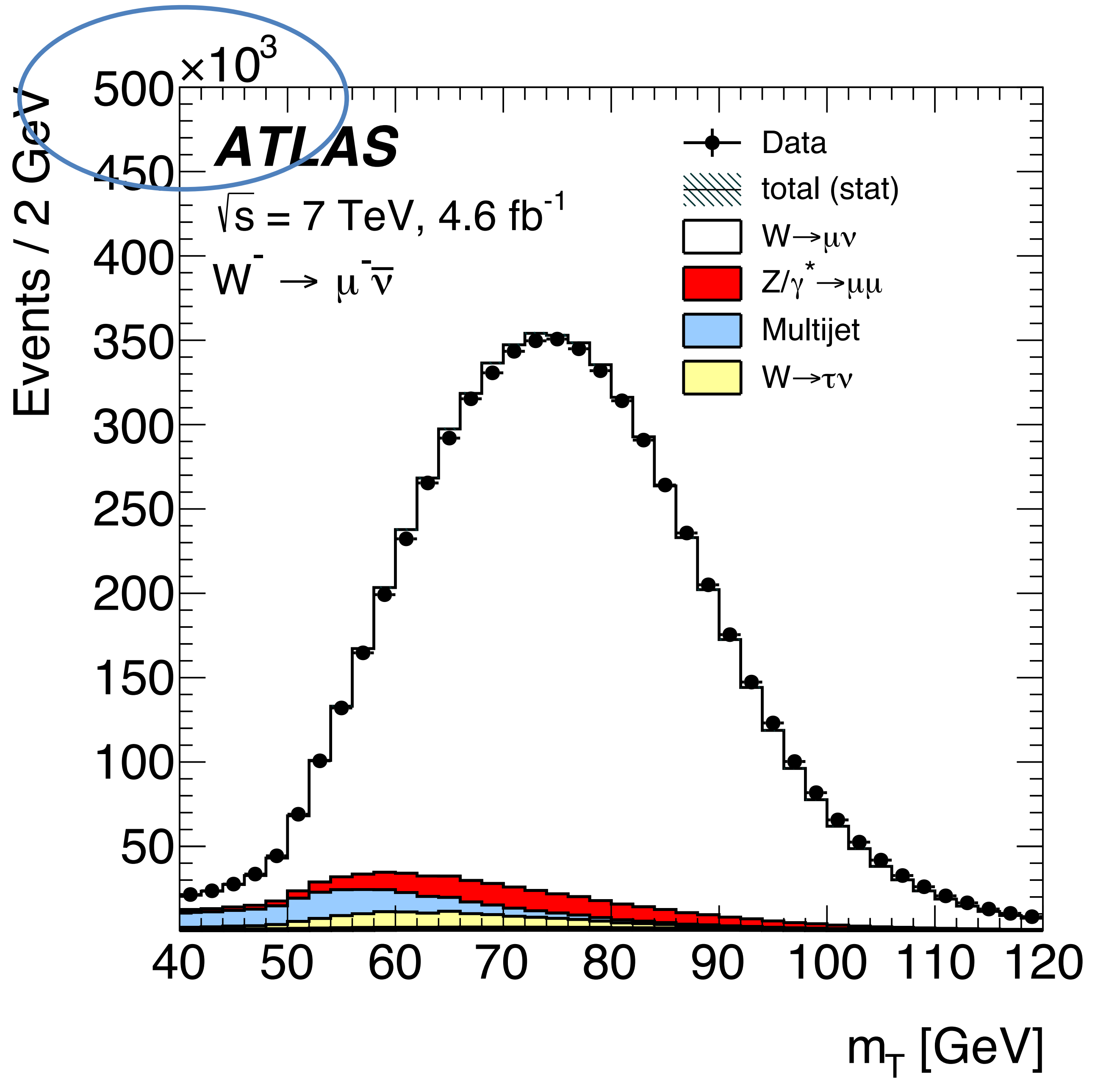


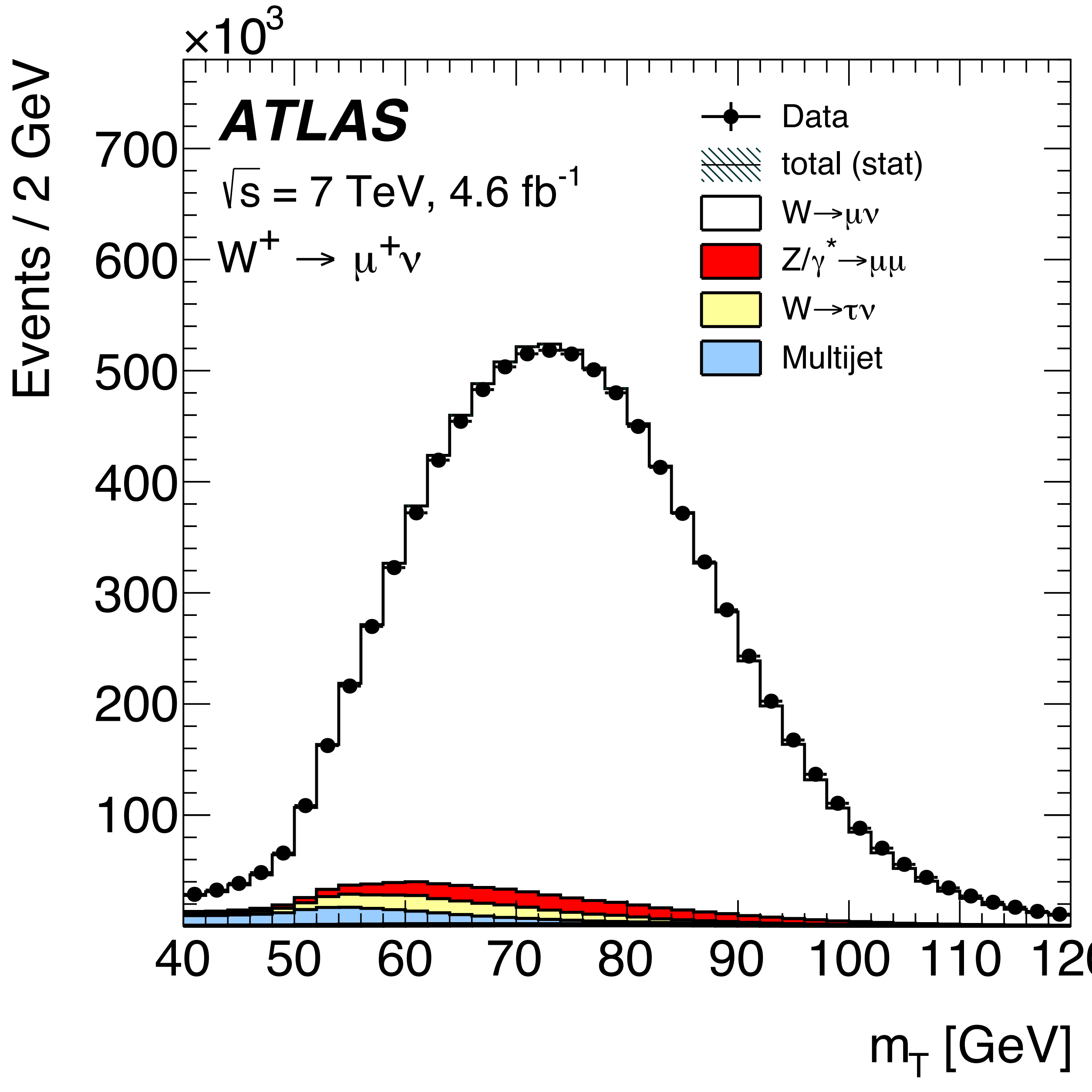






Inclusive Precision Vector Boson Production at the LHC





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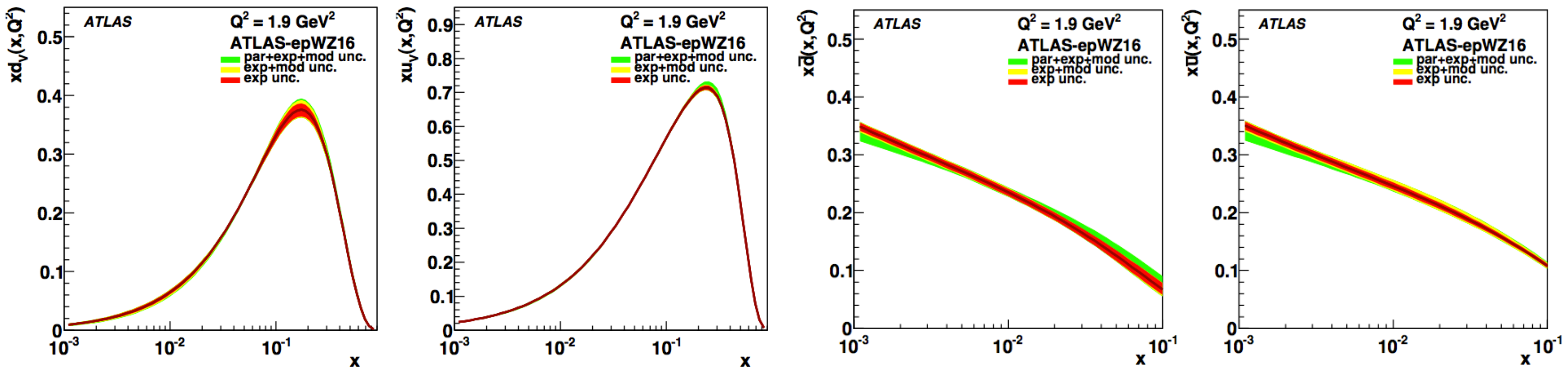
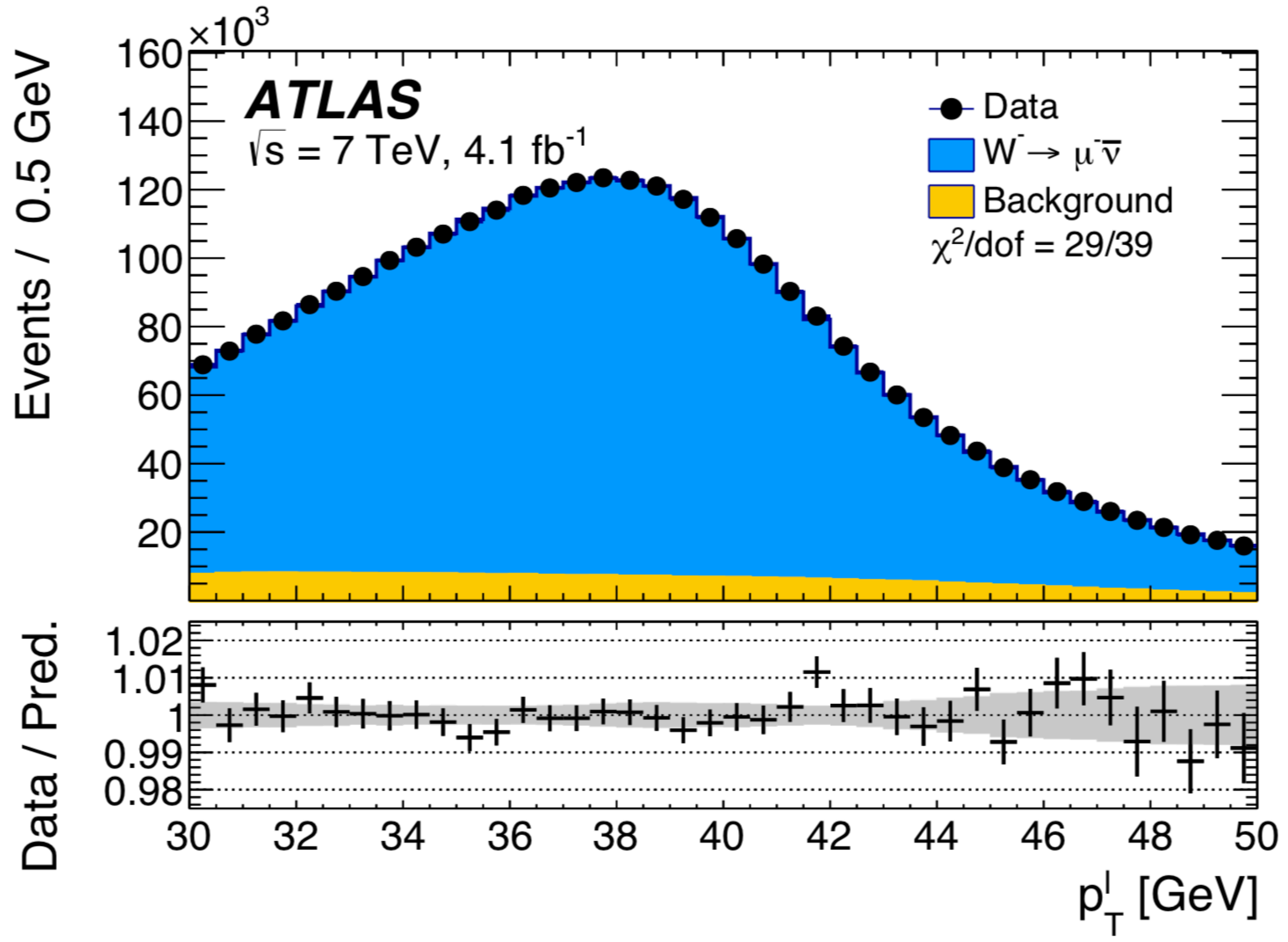


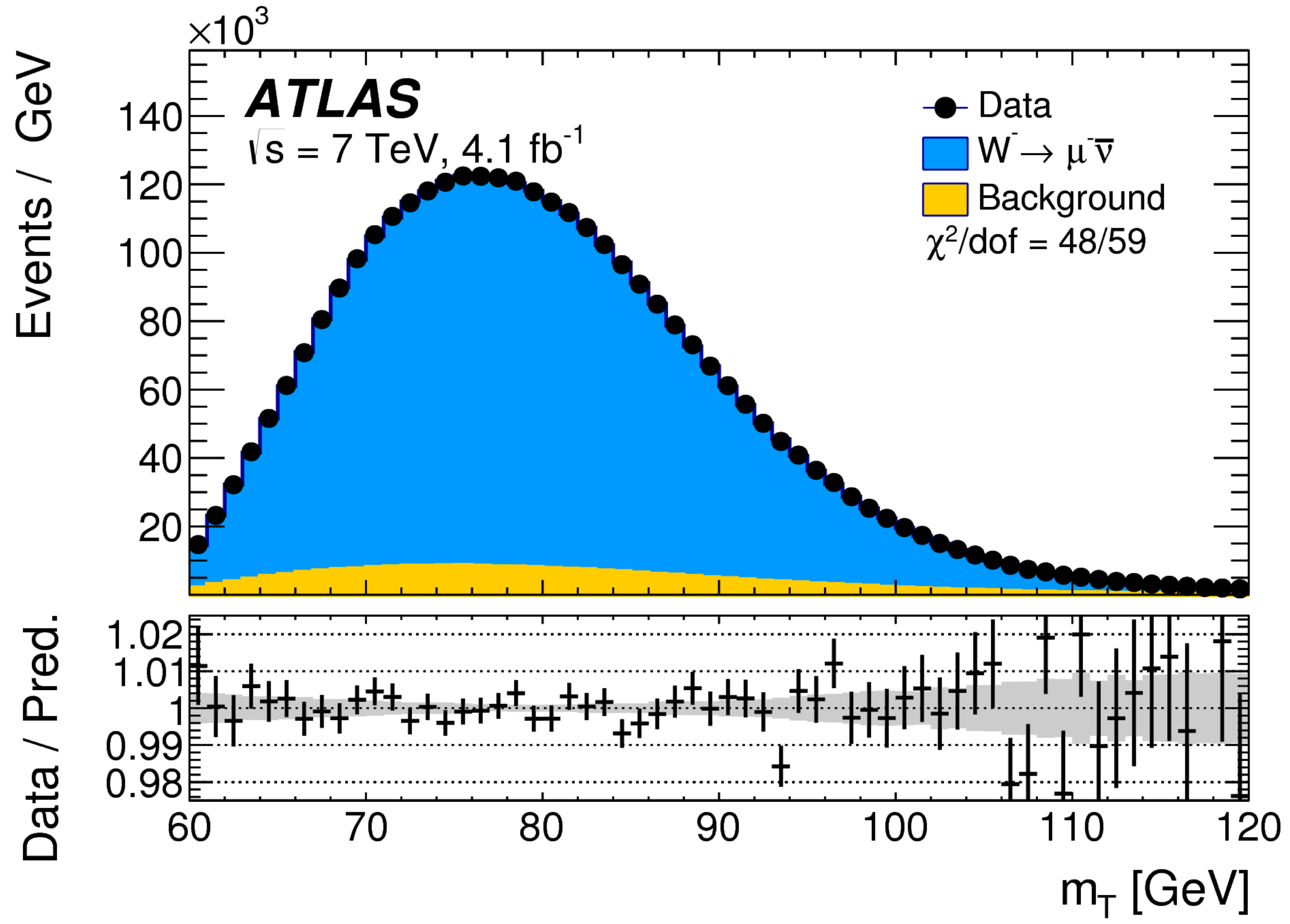
Using these cross section measurements and the the Deep Inelastic Scattering data from Hera new set of PDFs can be estimated (ATLAS-epWZ16 same was done in CMS).

Measurement of the W Mass at the LHC

A Milestone measurement!

Analysis strategy based on two kinematic distributions fitted in several categories





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

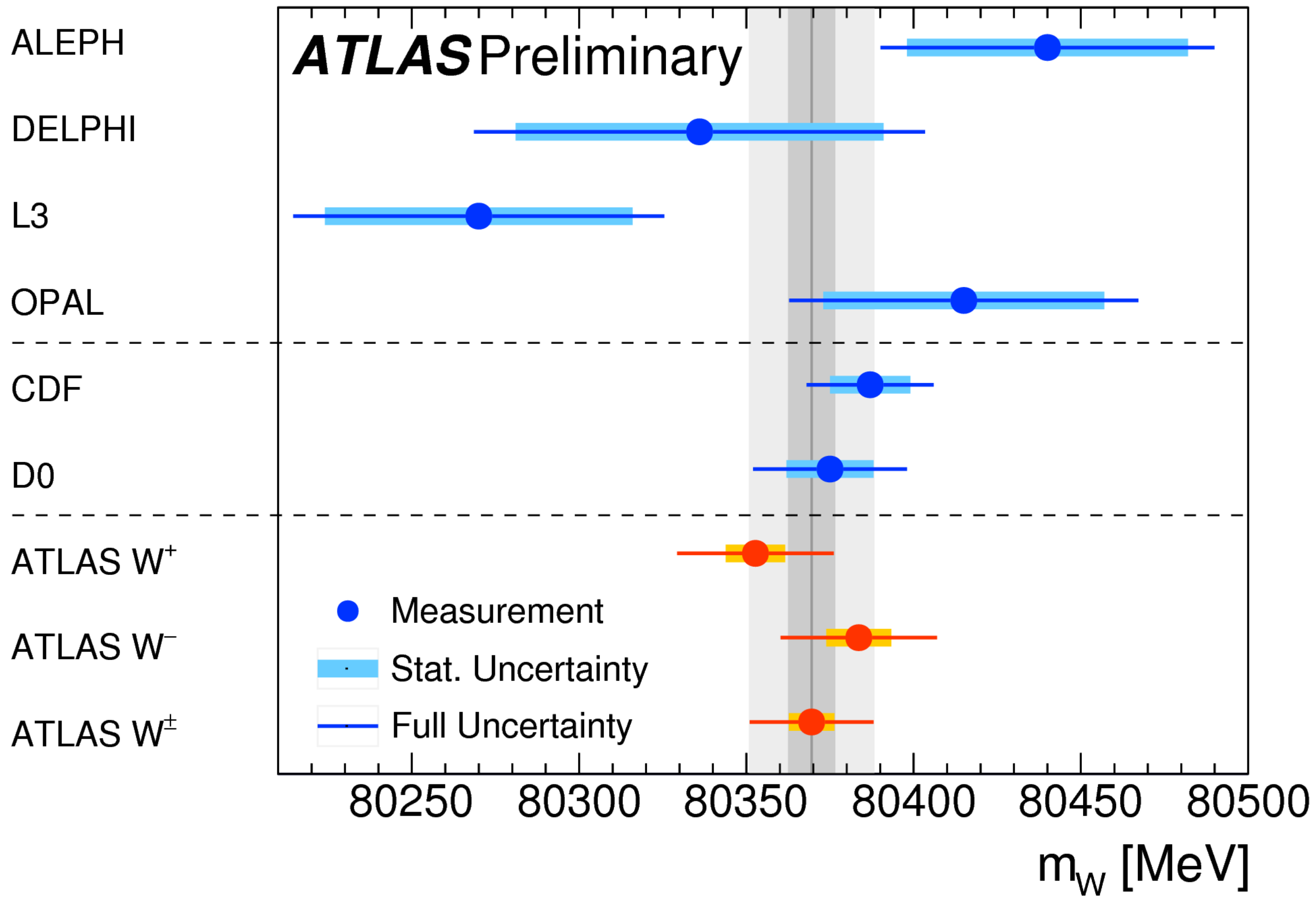
m_T Less sensitive to modelling but more difficult from to reconstruct (based on the missing transverse energy.

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

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

$$m_W = 80369.5 \pm 18.5 \text{ MeV}$$

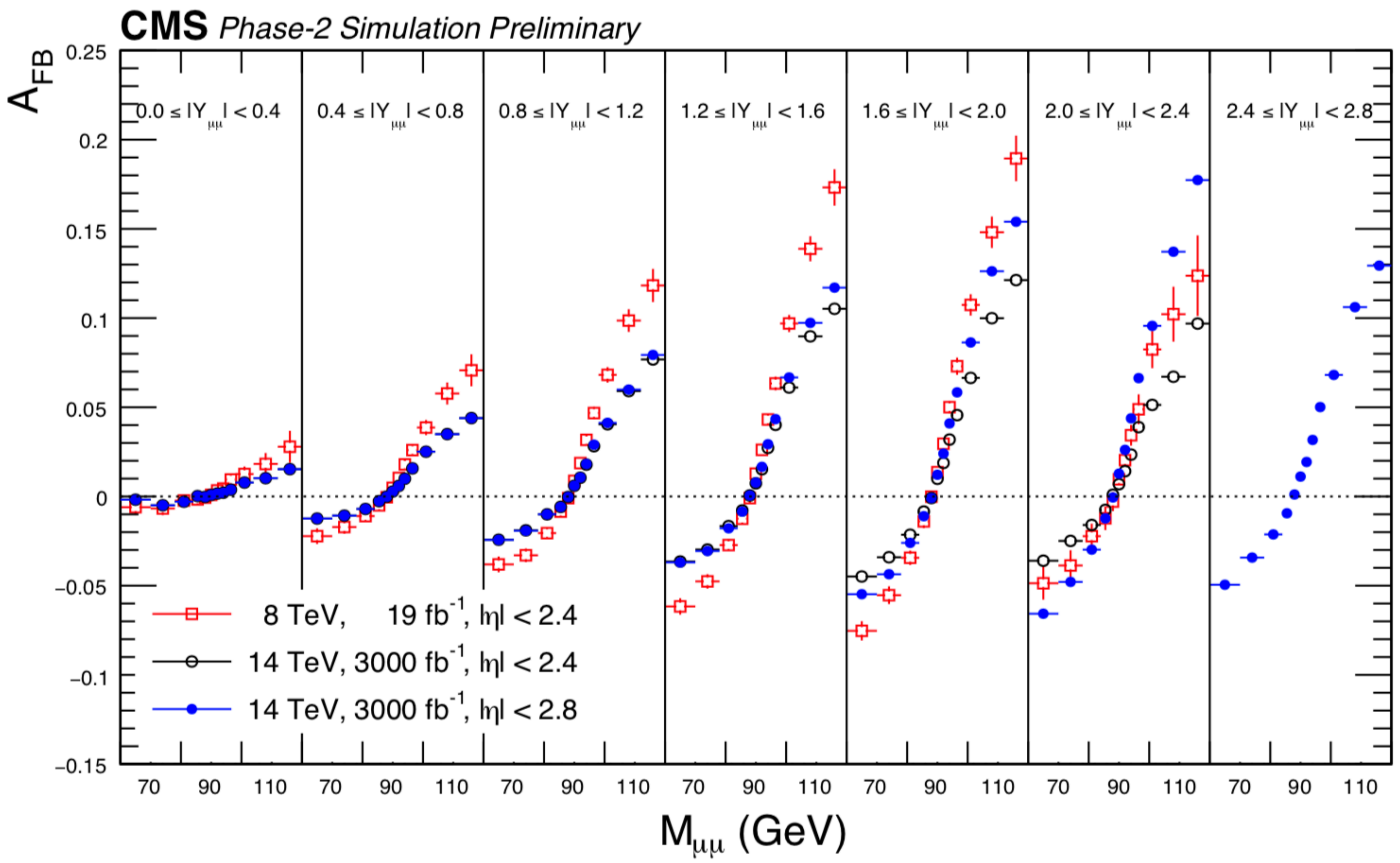
$$\pm 6.8\ (\text{Stat})\ \pm 10.6\ (\text{Exp})\ \pm 13.6 (\text{Mod})\ \text{MeV}$$



Reach at HL-LHC in EW Precision measurements

EW Mixing angle

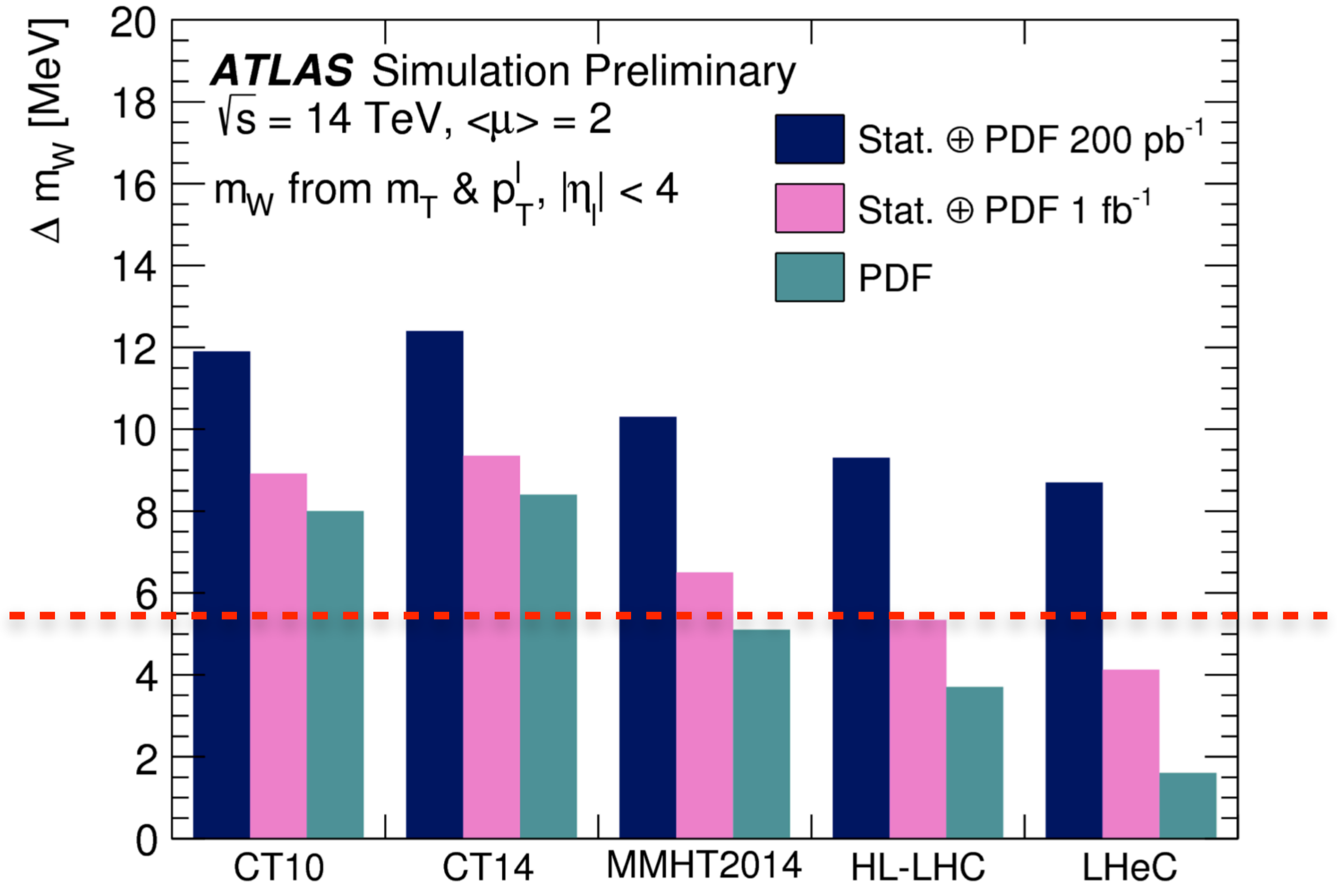
With the increased luminosity and muon acceptance in CMS (from eta 2.4 to 2.8 - for this study)



Individual measurements reach the level of the current World Average of **16 (10^{-5})** CMS estimate alone with muons.

W Mass

- Need for low PU (~2)
- Need from ~200 pb^{-1} (already a good start only approximately one week at 14 TeV) to 1 fb^{-1}
- Larger TRK acceptance: reduce PDF systematics



Precision reach at HL-LHC

~10 MeV for 200 pb^{-1}
~6 MeV for 1 fb^{-1}
(~4 MeV with LHeC)

Top production

Measurement of the top mass

Top Quark

The existence of the top quark was first predicted to explain CP violation in Kaons by Kobayashi and Maskawa in 1973

2008

Discovery of the W and Z bosons

Makoto Kobayashi, Toshihide Maskawa

« The mass of the top quark could be predicted (with quantum corrections in the electroweak theory) from the precision LEP measurements » [Reference]

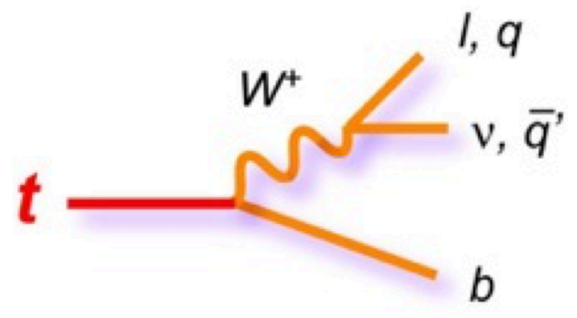
1999

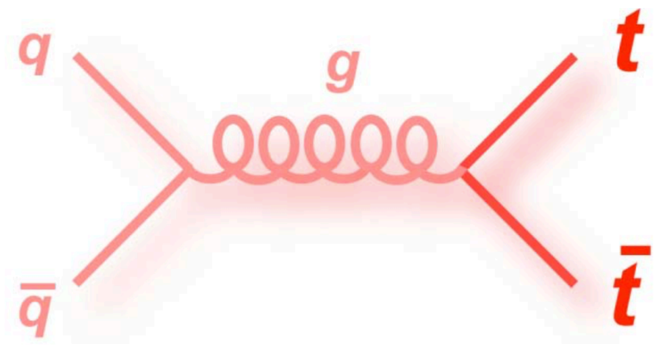
Elucidating the quantum structure of EW interaction

Gerardus ’t Hooft, Martinus Veltman

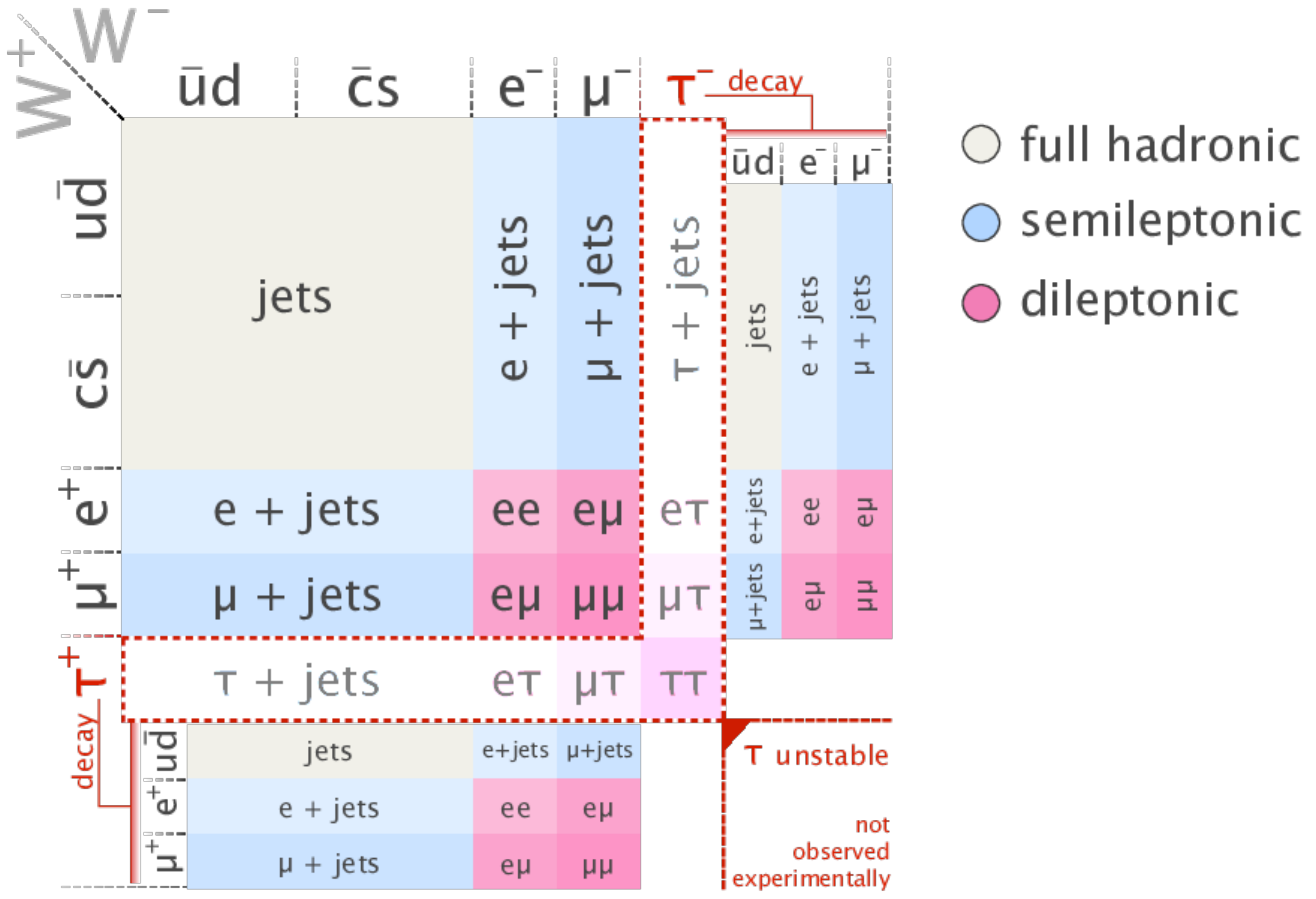
The top quark was discovered in 1994 at the Tevatron by the CDF and D0 Experiments.

The top quark decays mostly into a W boson and a b quark, and at the Tevatron is produced mainly in pairs.





Gives rise to multitude of signatures (the most sensitive being the leptons-4jets)



$$Br(W \to \ell\nu) = 10.9\,\%$$
$$Br(W \to u\bar{d}, c\bar{s}) = 67.4\,\%$$

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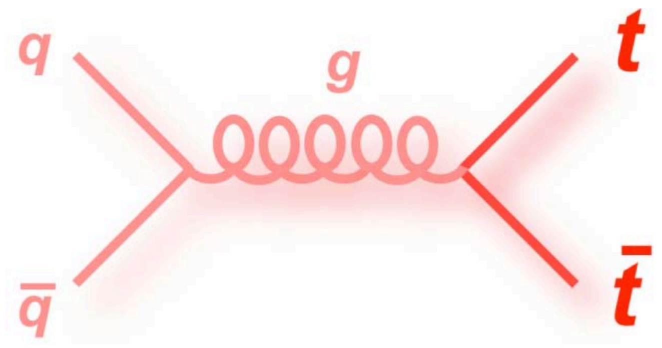

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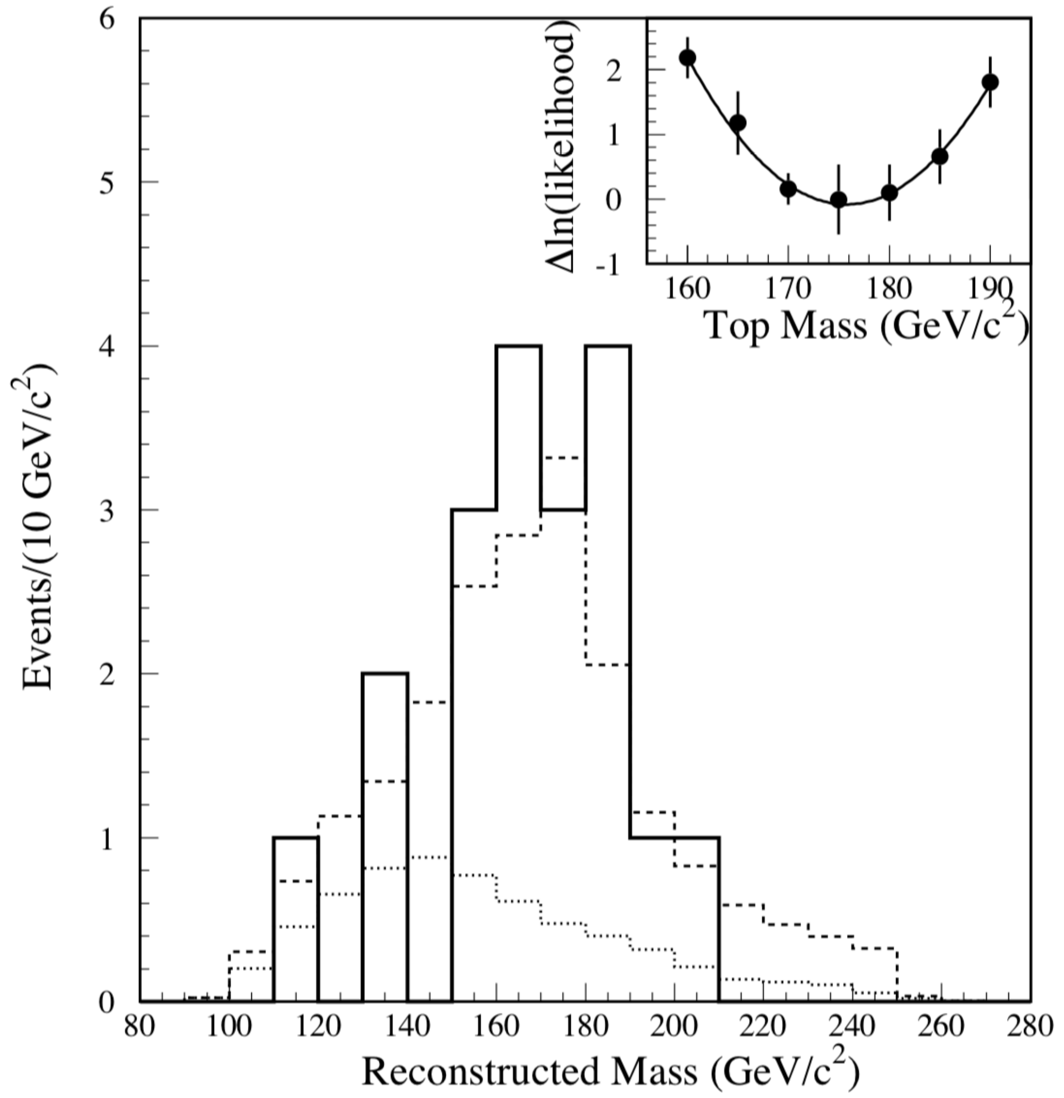
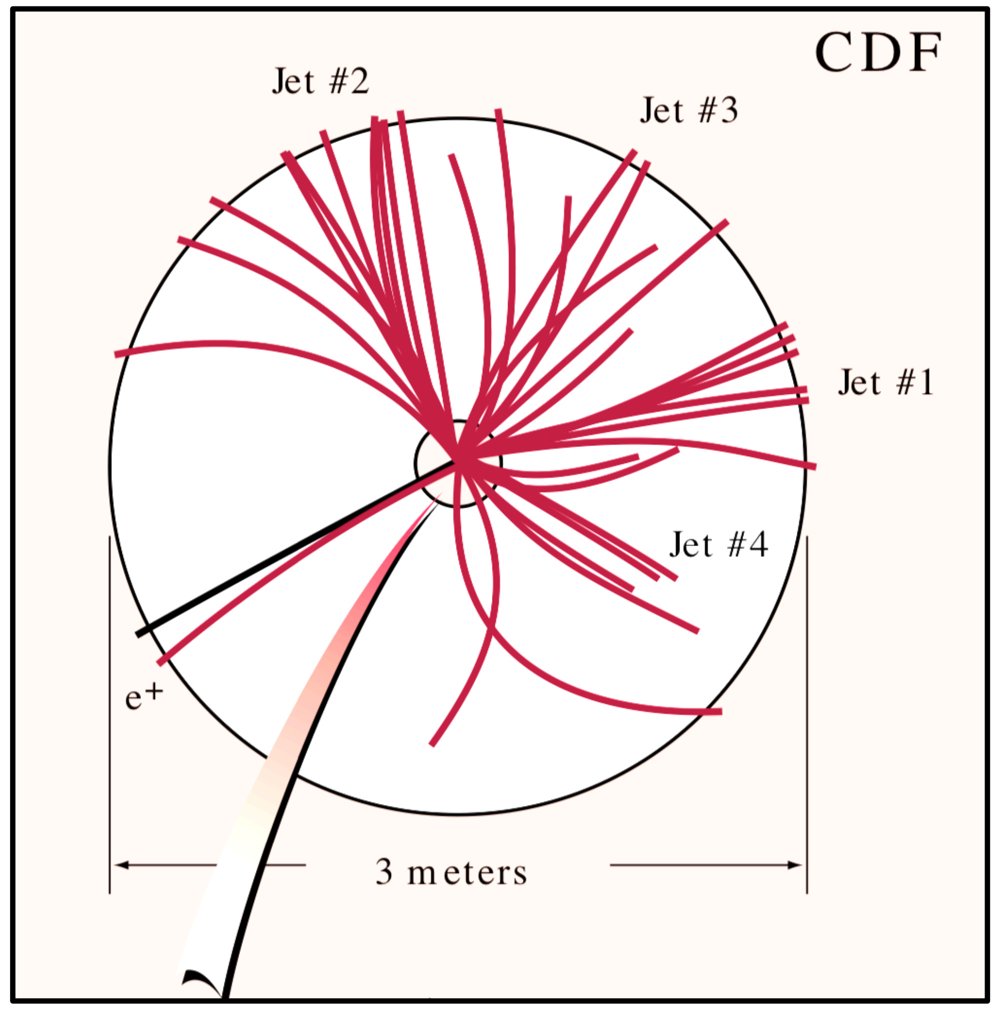




Observation in the 1 lepton - 4 jets topology, yielding a mass measurement of approximately 175 GeV

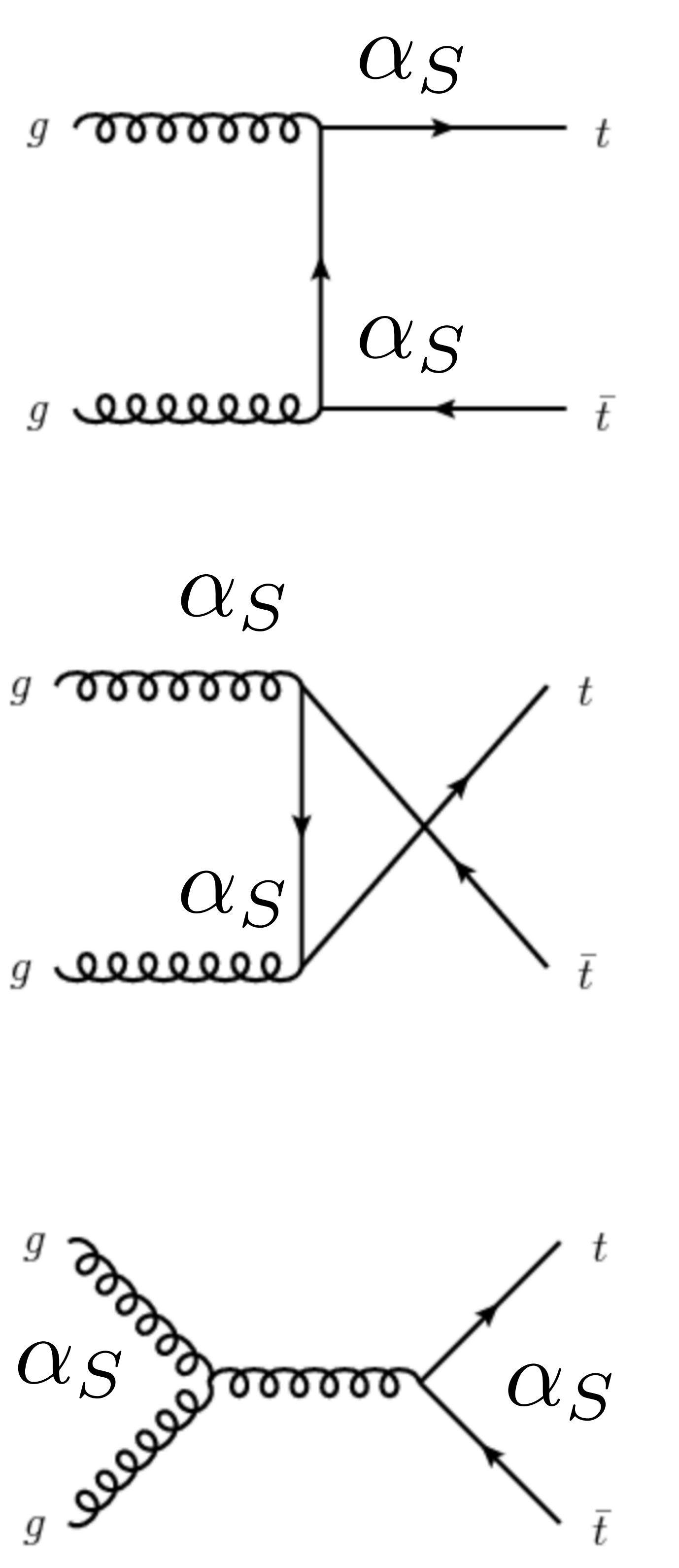
$$y_t = \frac{\sqrt{2} m_t}{v} \sim 1 \qquad v = 246 \text{ (GeV)}$$

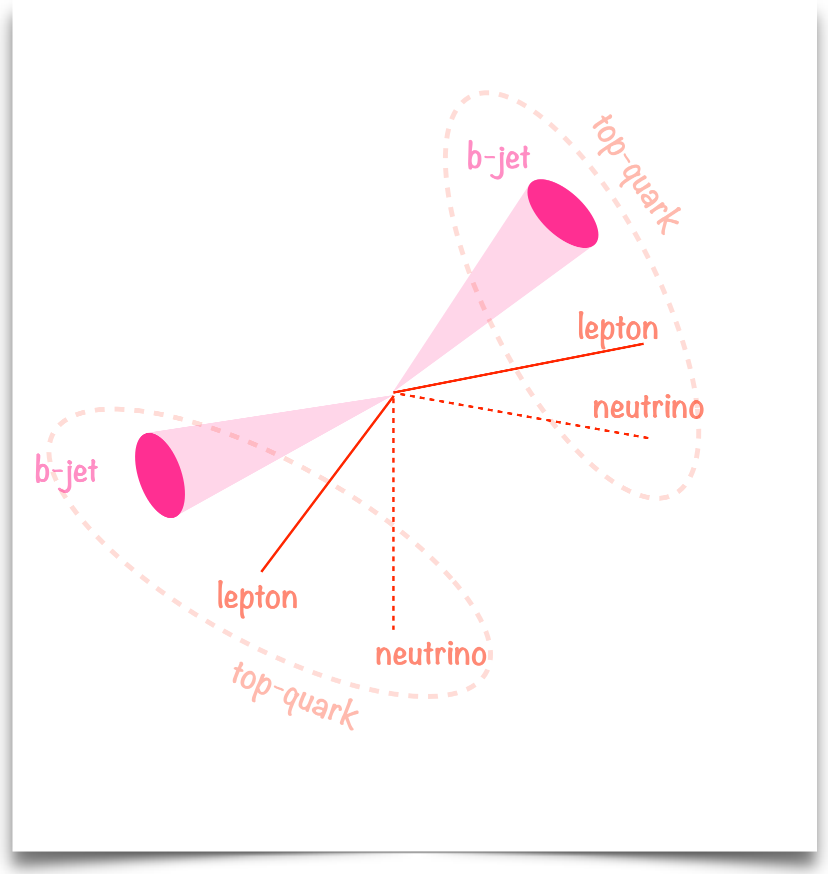
The top quark is the only quark observed directly as a physical state, since it decays before it hadronises!

Top pair production Cross Sections at the LHC

Main production diagrams
At tree level leading order

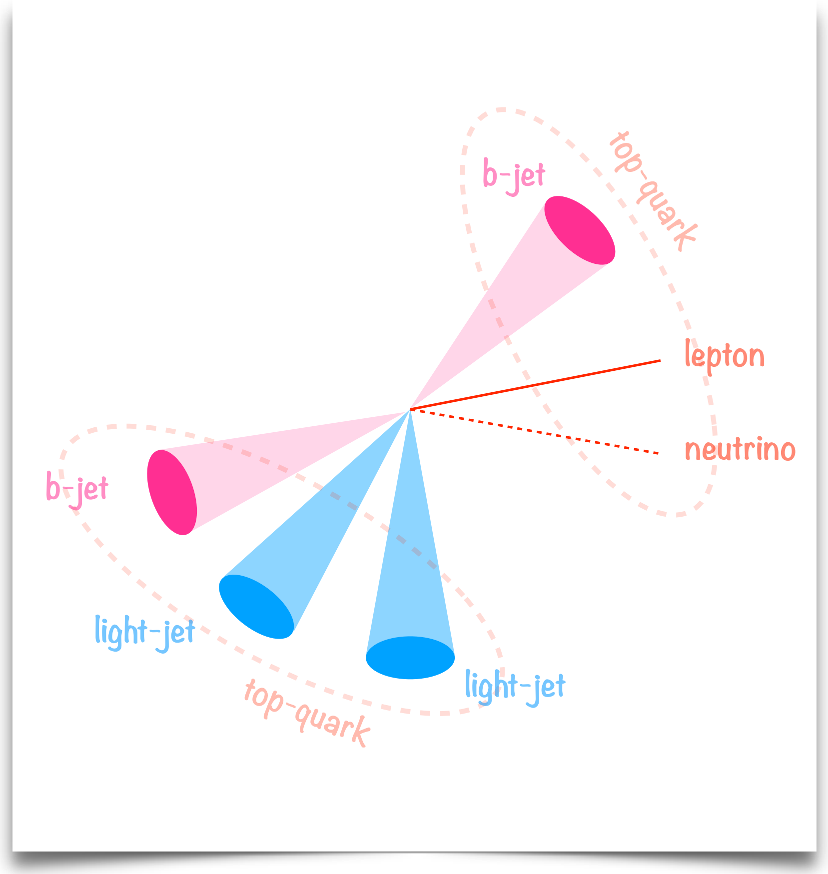
$$O(\alpha_S^2)$$





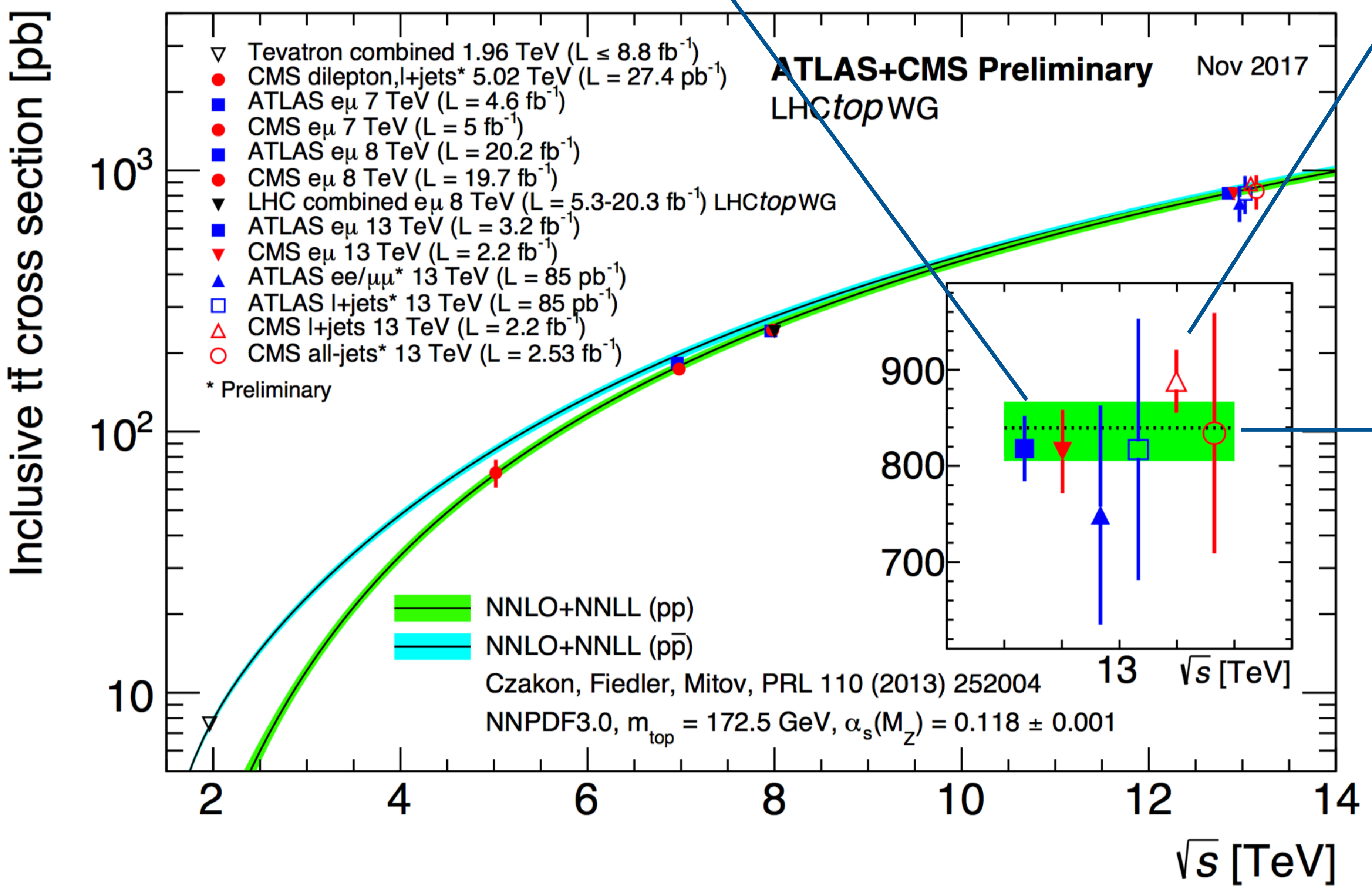
Di-lepton topology:

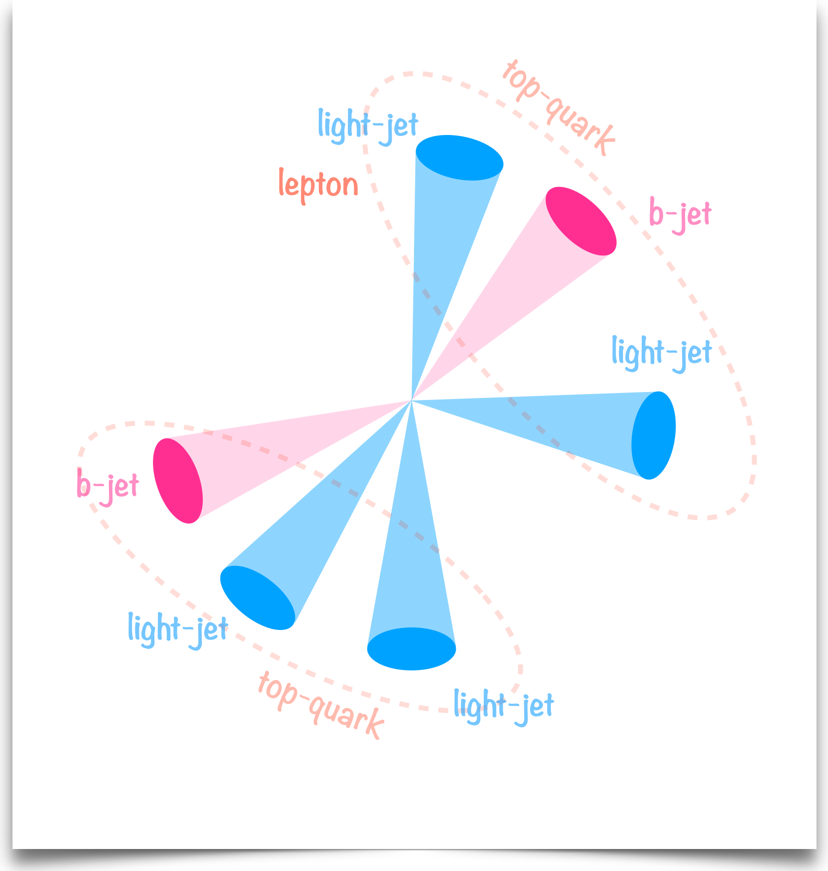
Precise determination of cross section in the different flavour electron-muon channel in particular. Excellent signal to background ratio. Lower stats (4%).



Semi-leptonic topology:

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

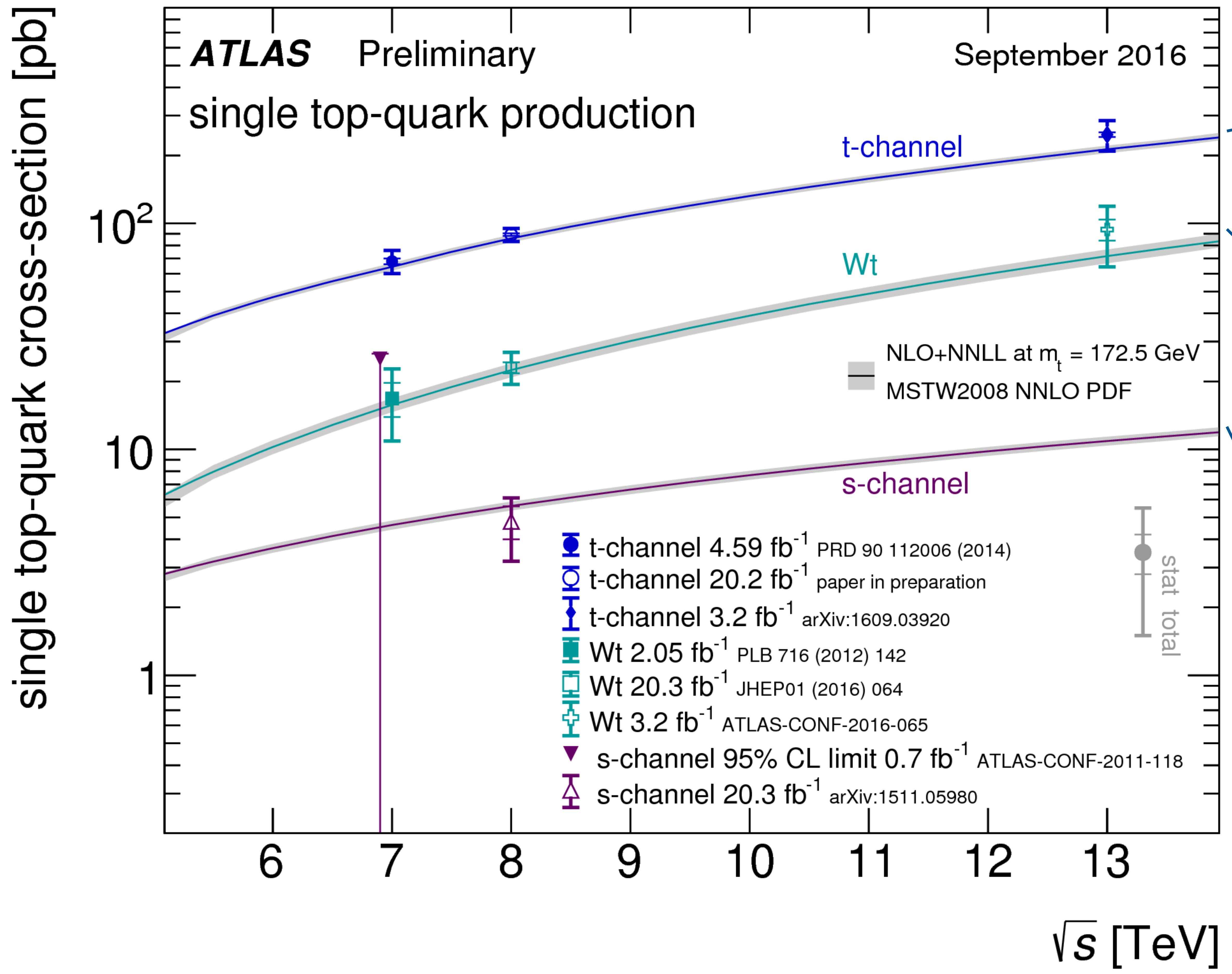


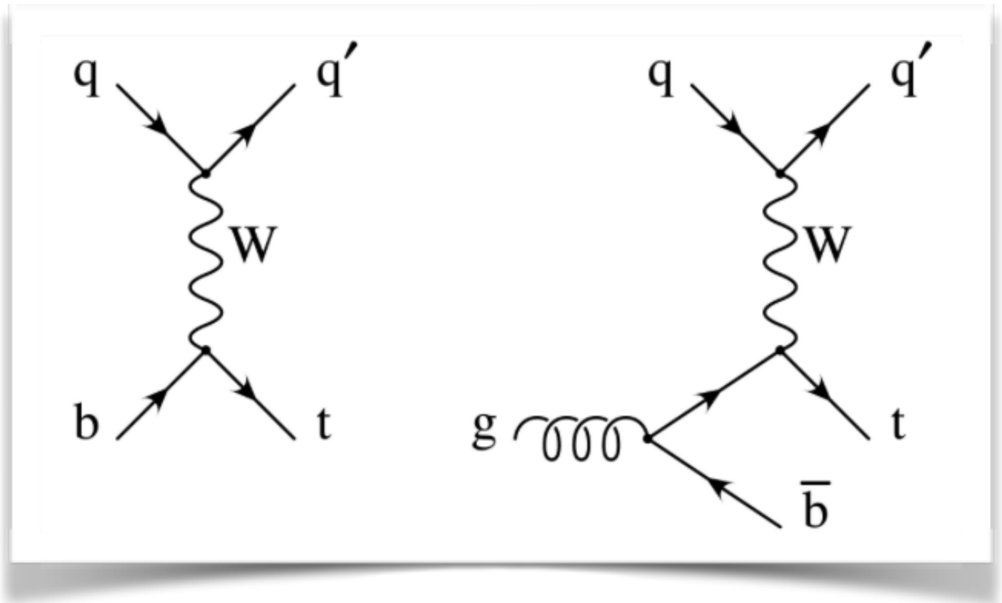


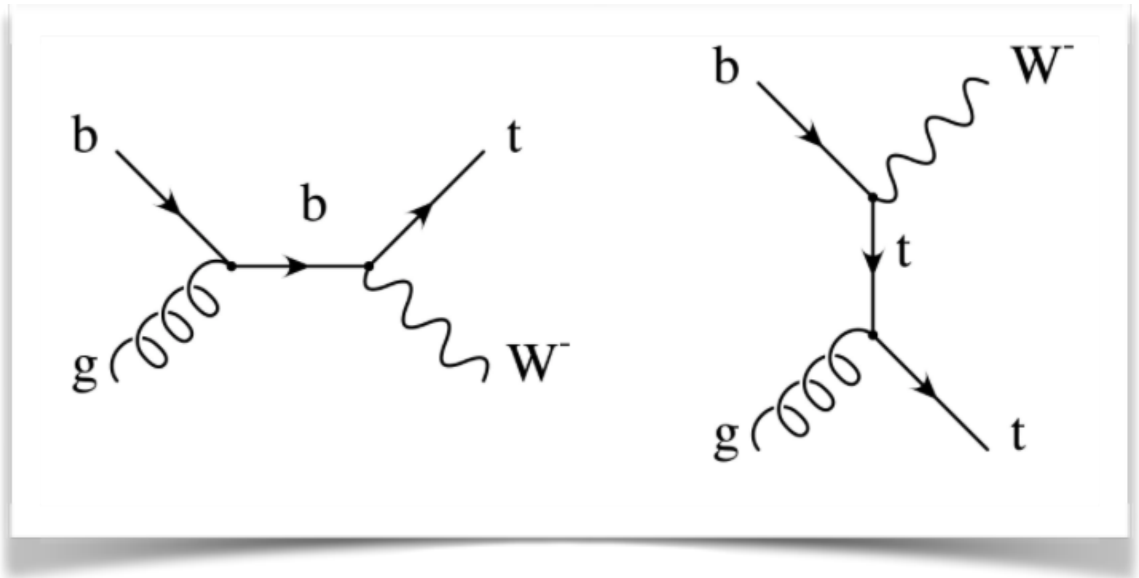
Full hadronic topology:

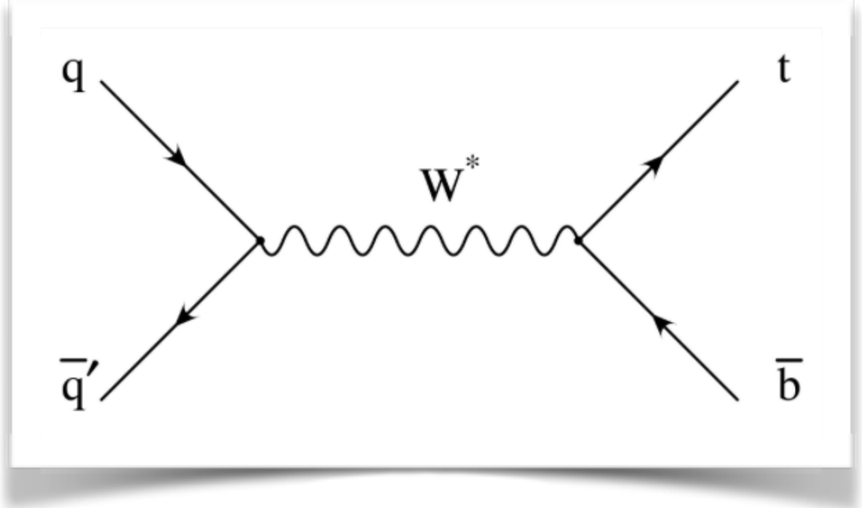
Largest stats (50%) but larger multi-jet background and large combinatorial.

Single-top production Cross Sections





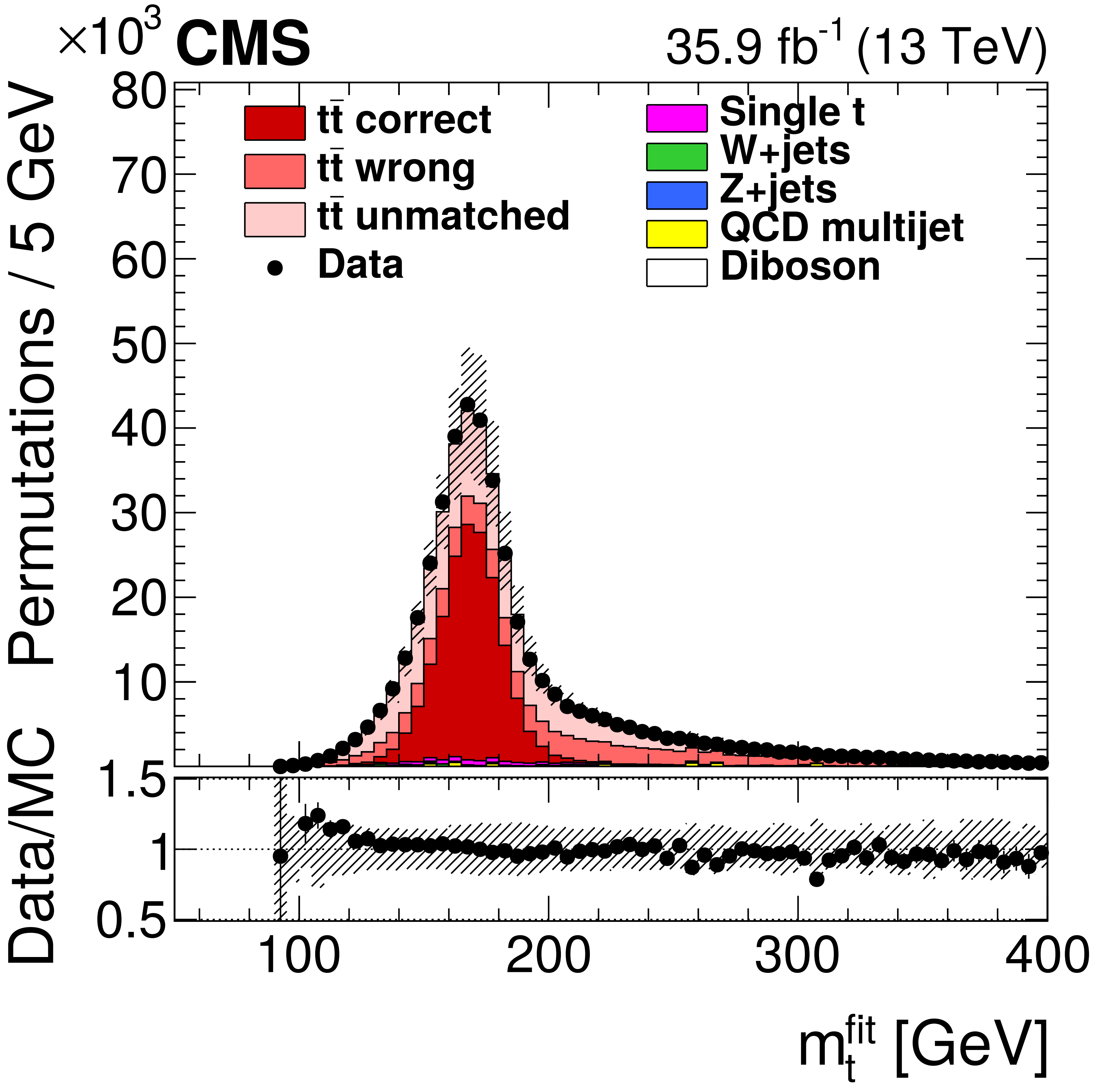




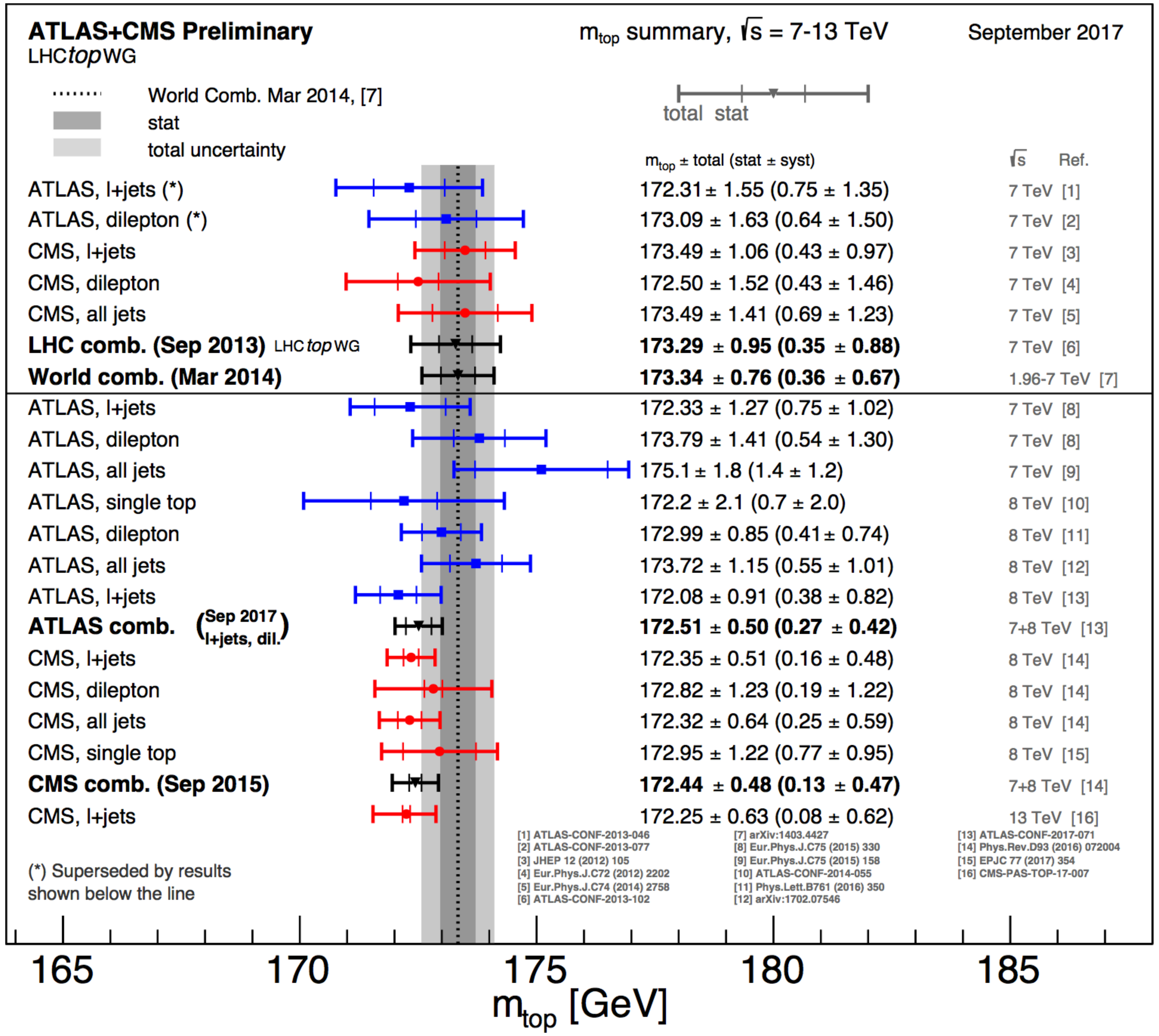
Measuring the top mass from event kinematics

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

Recent CMS result



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



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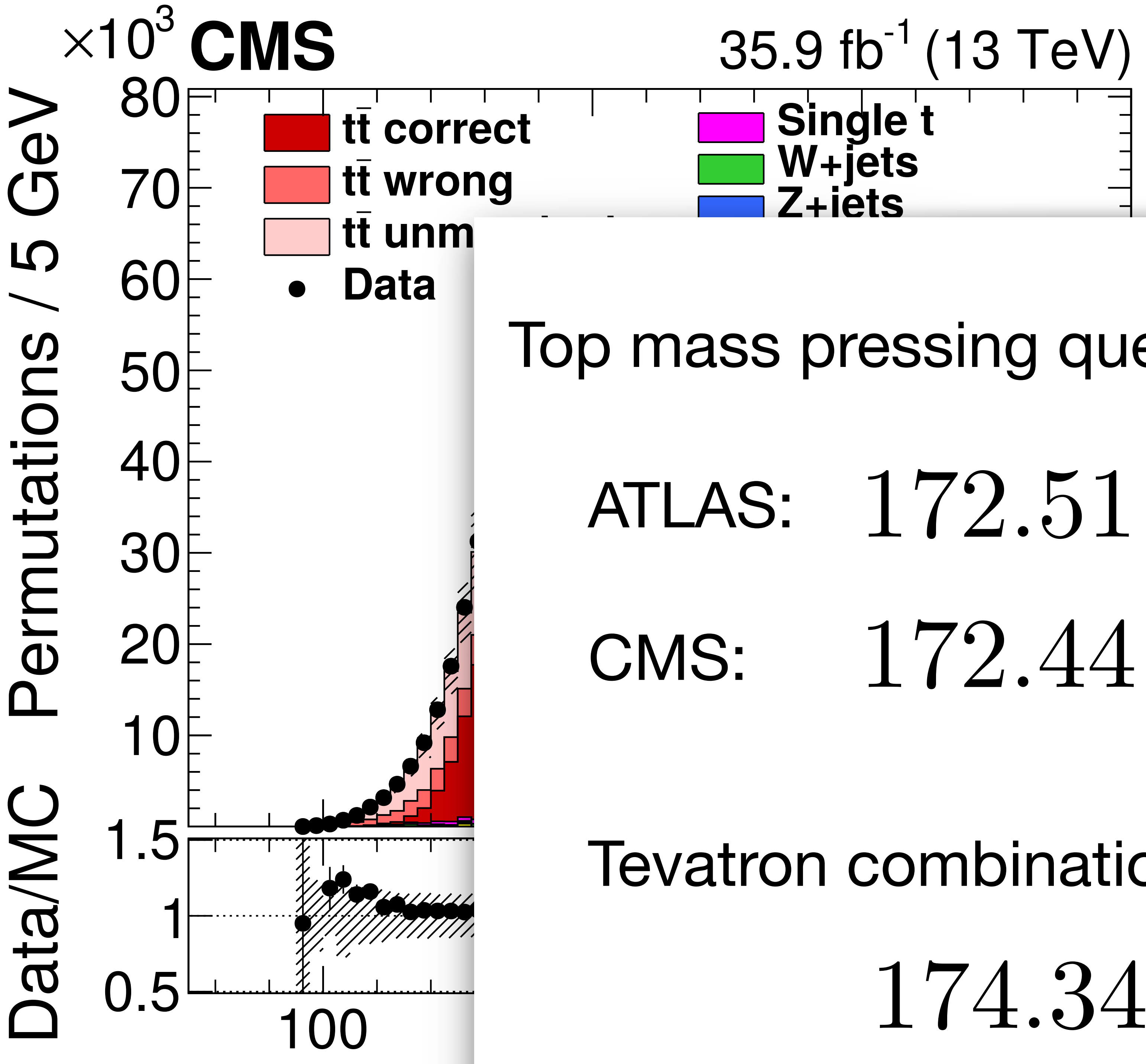

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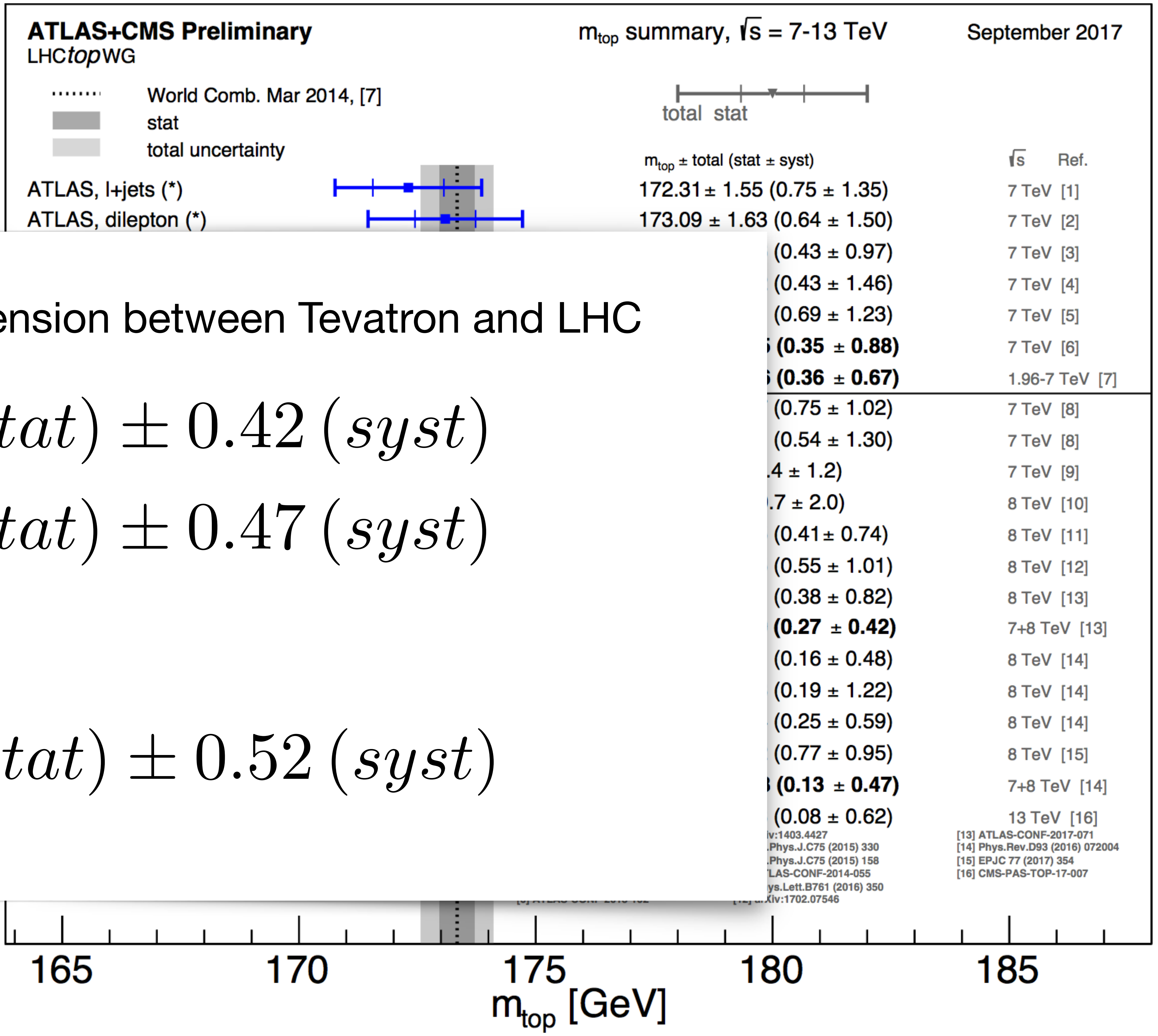


Top mass pressing question: slight tension between Tevatron and LHC

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

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

Tevatron combination:

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

Digression on the Mass Measurement

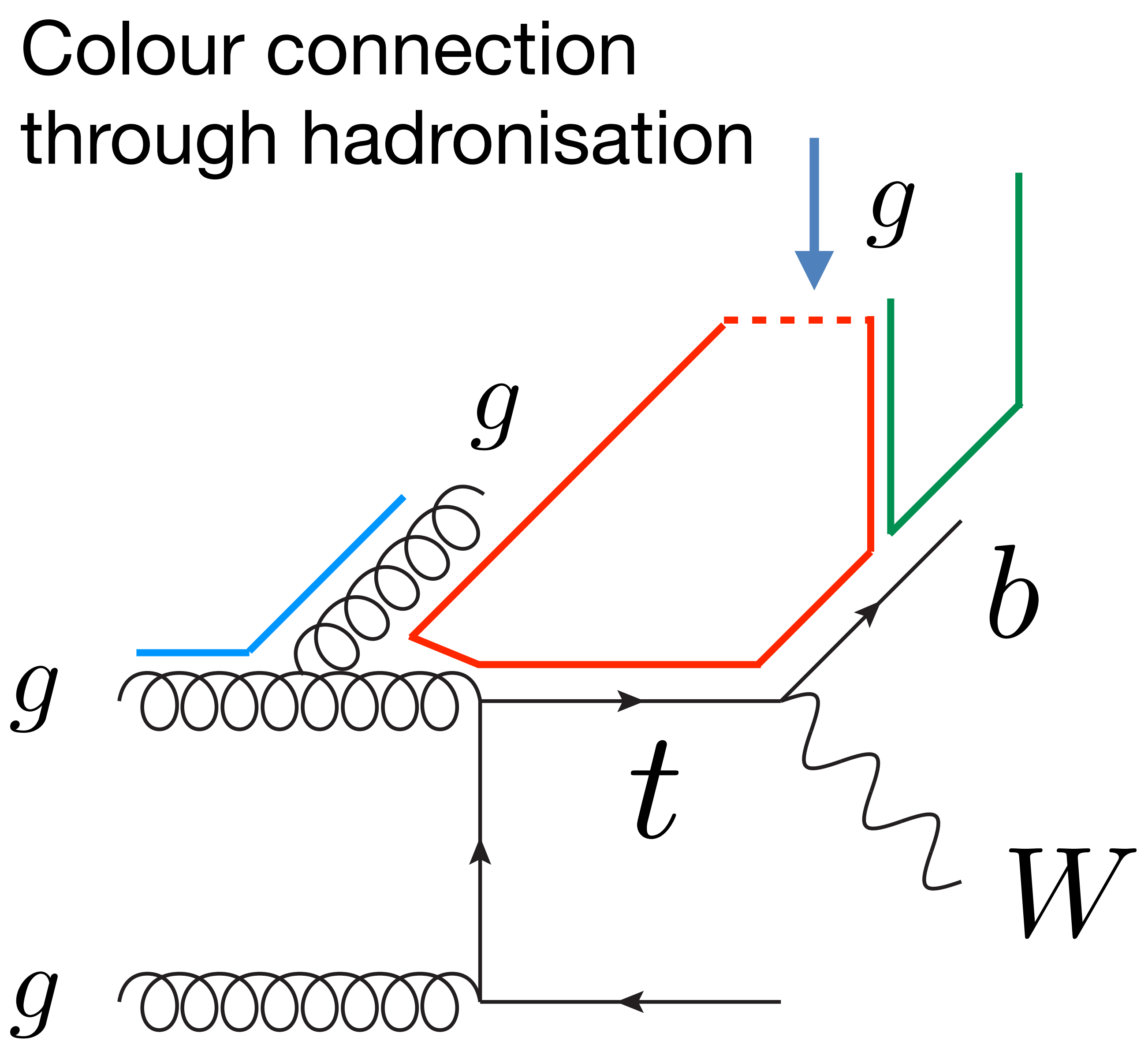
The relation between the Monte Carlo template used to fit the mass spectrum and the Field Theoretical parameter of the pole mass is not straightforward.

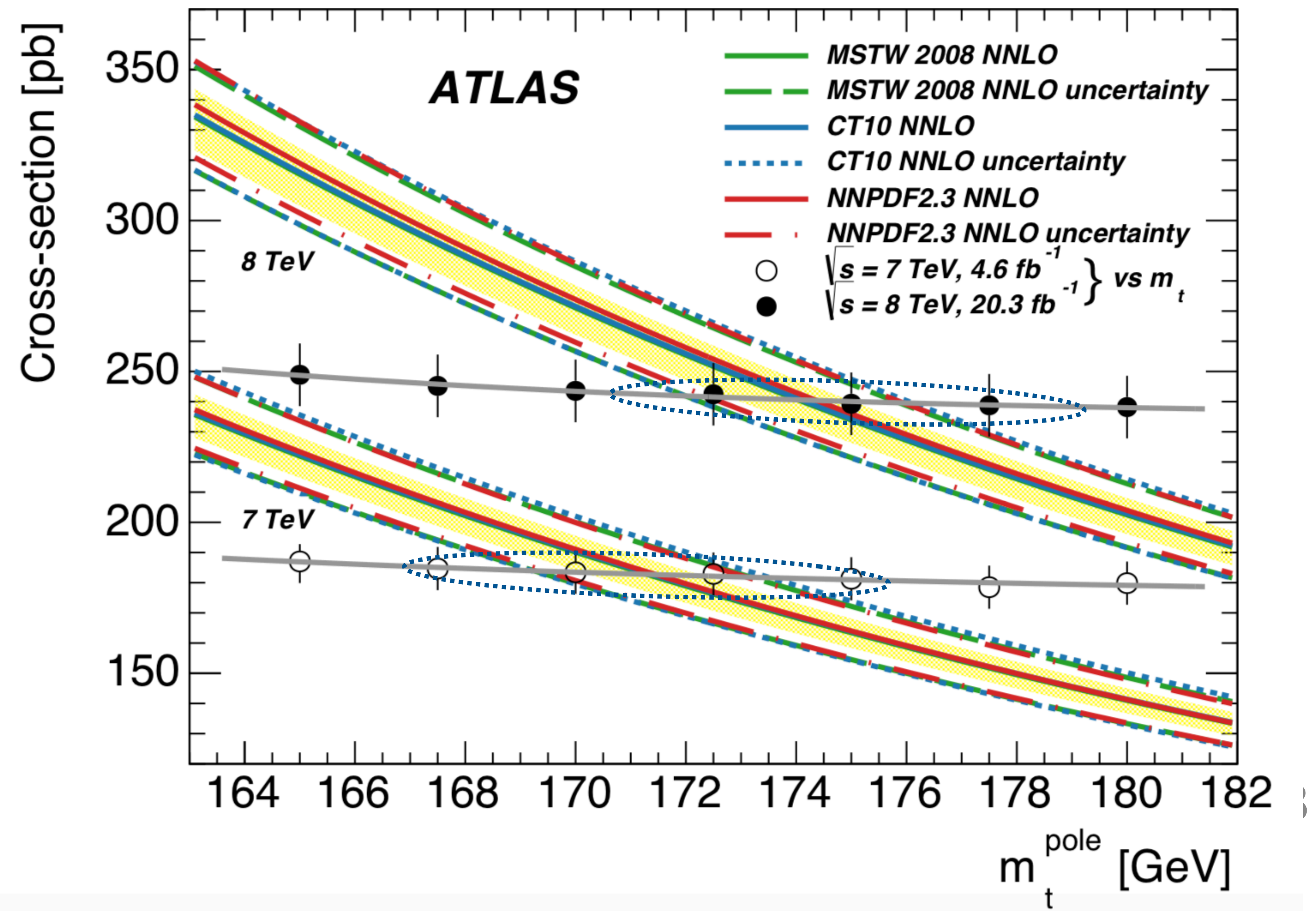
The top is coloured, so it is impossible to unambiguously associate every object in the final state to it!

These ambiguities lead to an uncertainty on the top mass measurement varying between 1 GeV and 200 MeV.

The pole mass can be measured using observables that are not dependent on the detailed reconstruction of the top system.

e.g. the pole mass can be measured using the top production cross section (at the cost of introducing a dependence on the production prediction).





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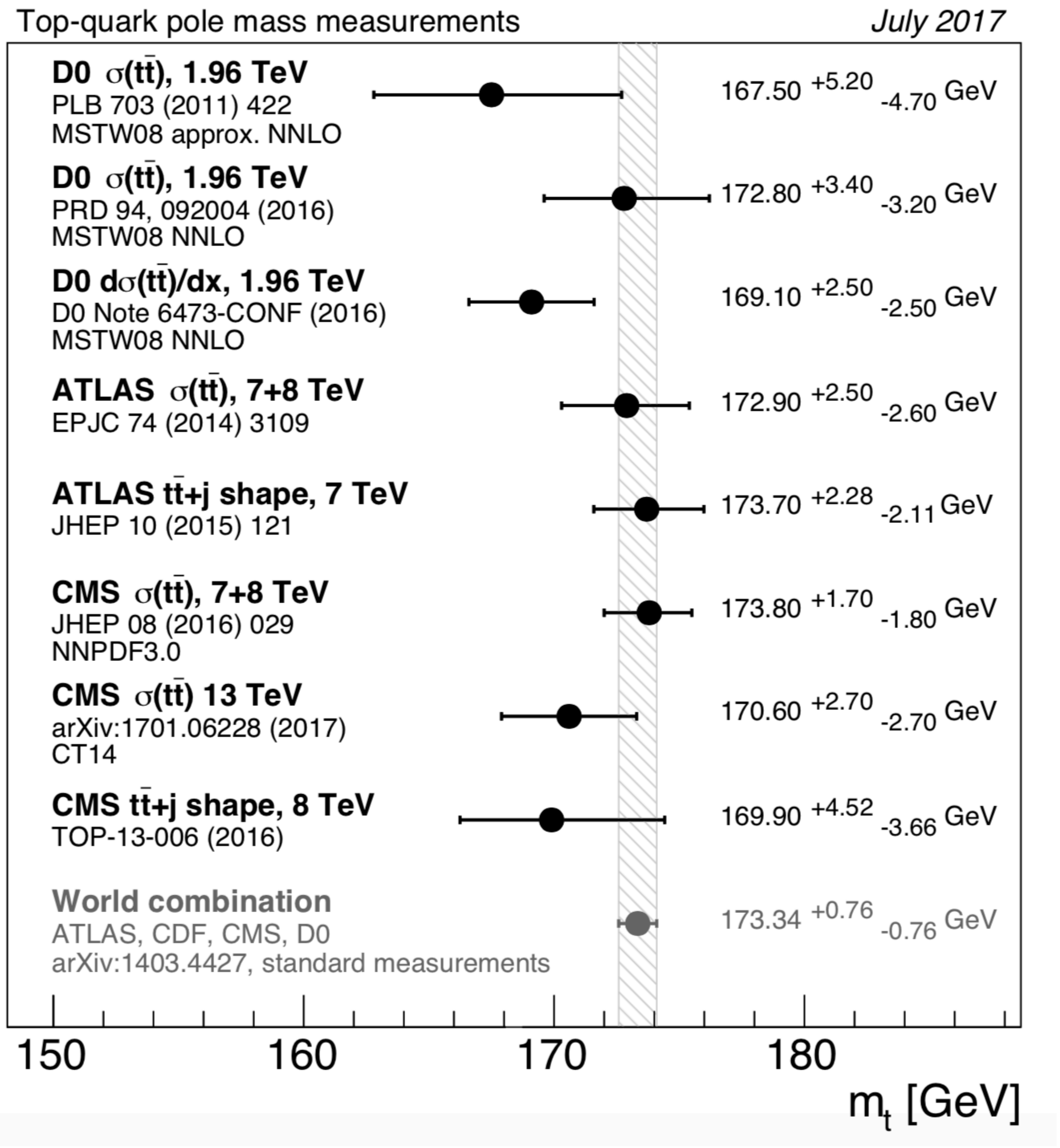
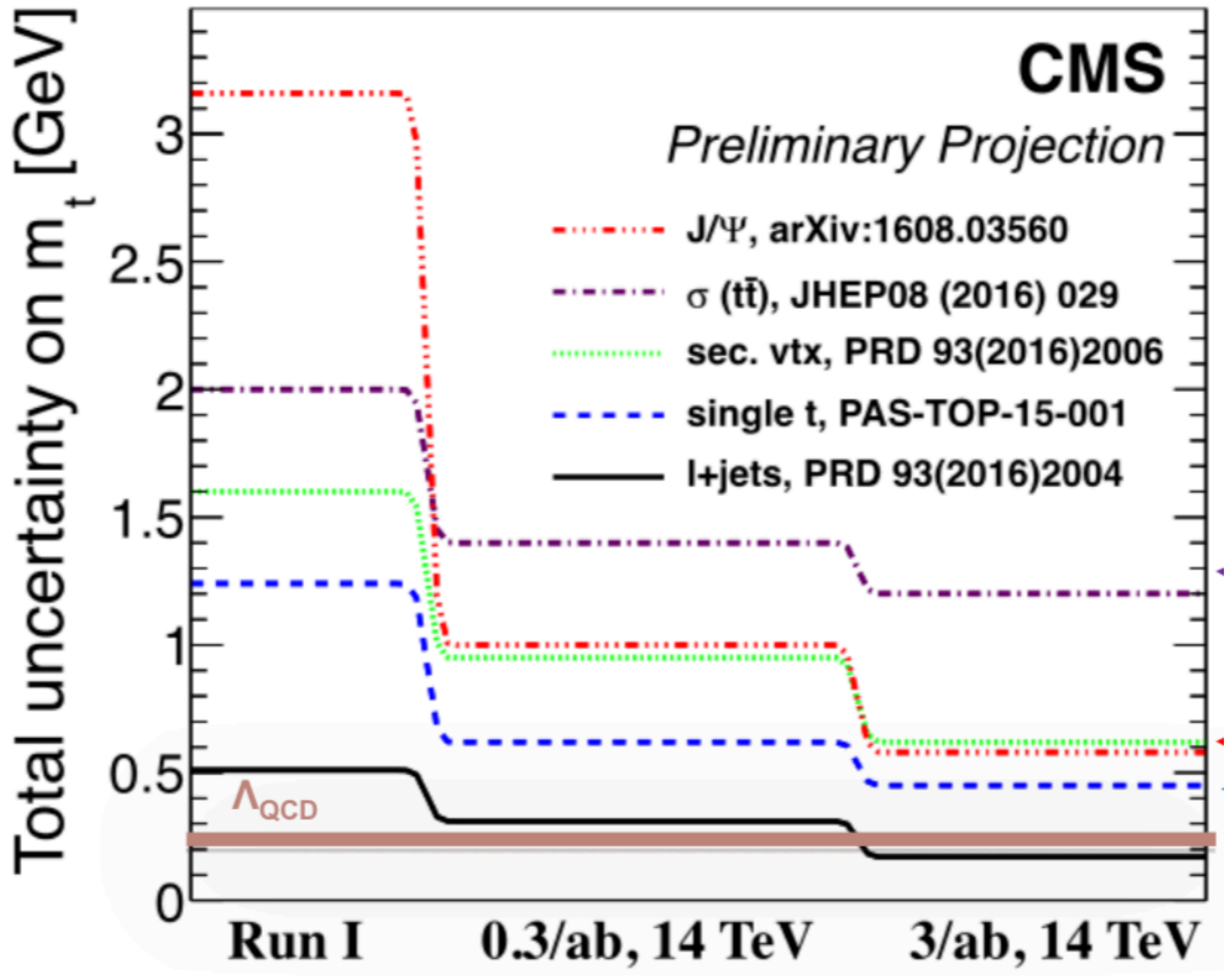


Measurements from cross sections will be limited by prediction uncertainties and luminosity.

Study of the reach in precision at HL-LHC

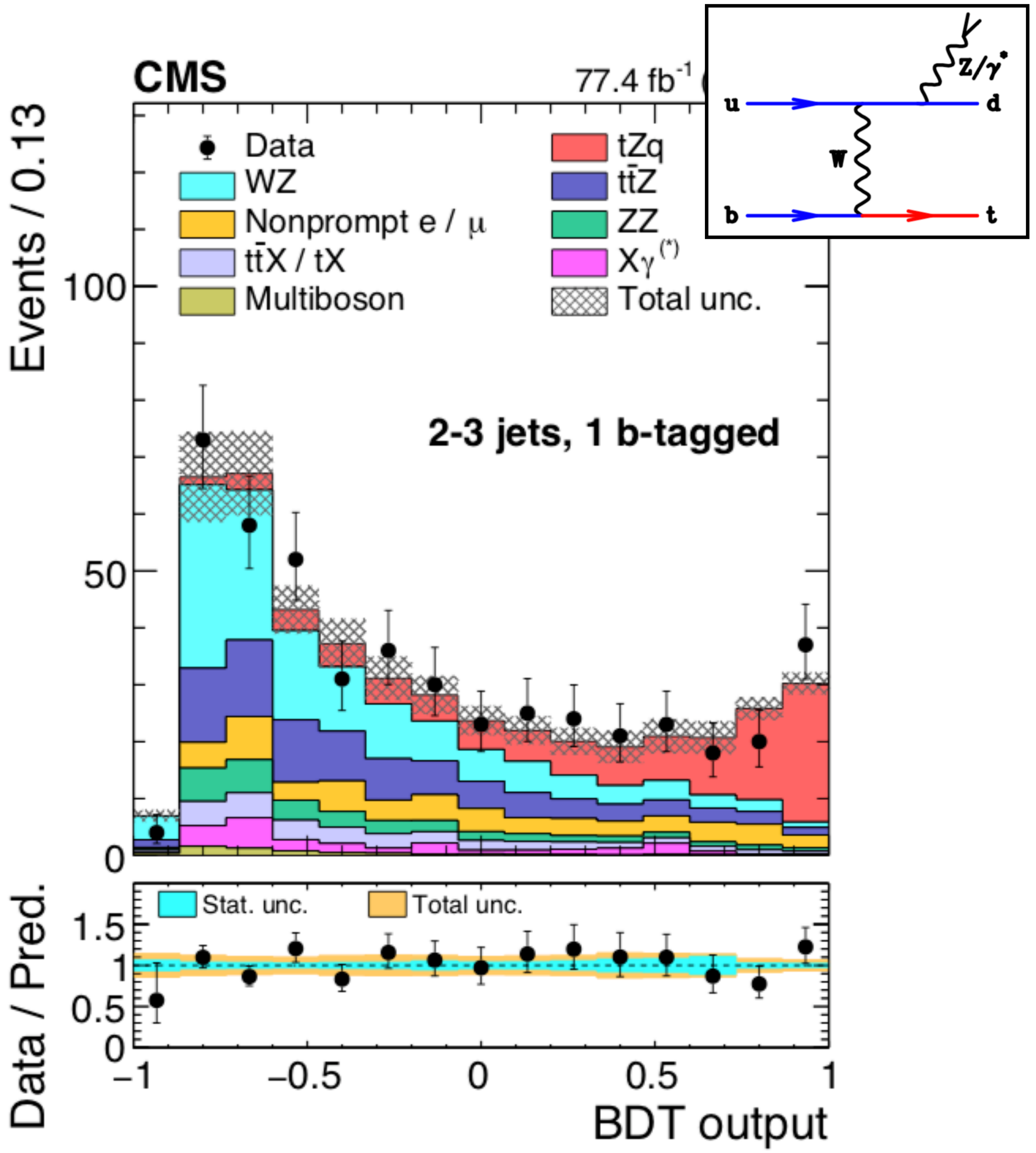


Reaching a floor in the precision on the top mass at around HL-LHC Lambda QCD ~180 MeV

Top Physics

Single Top in association with Zq

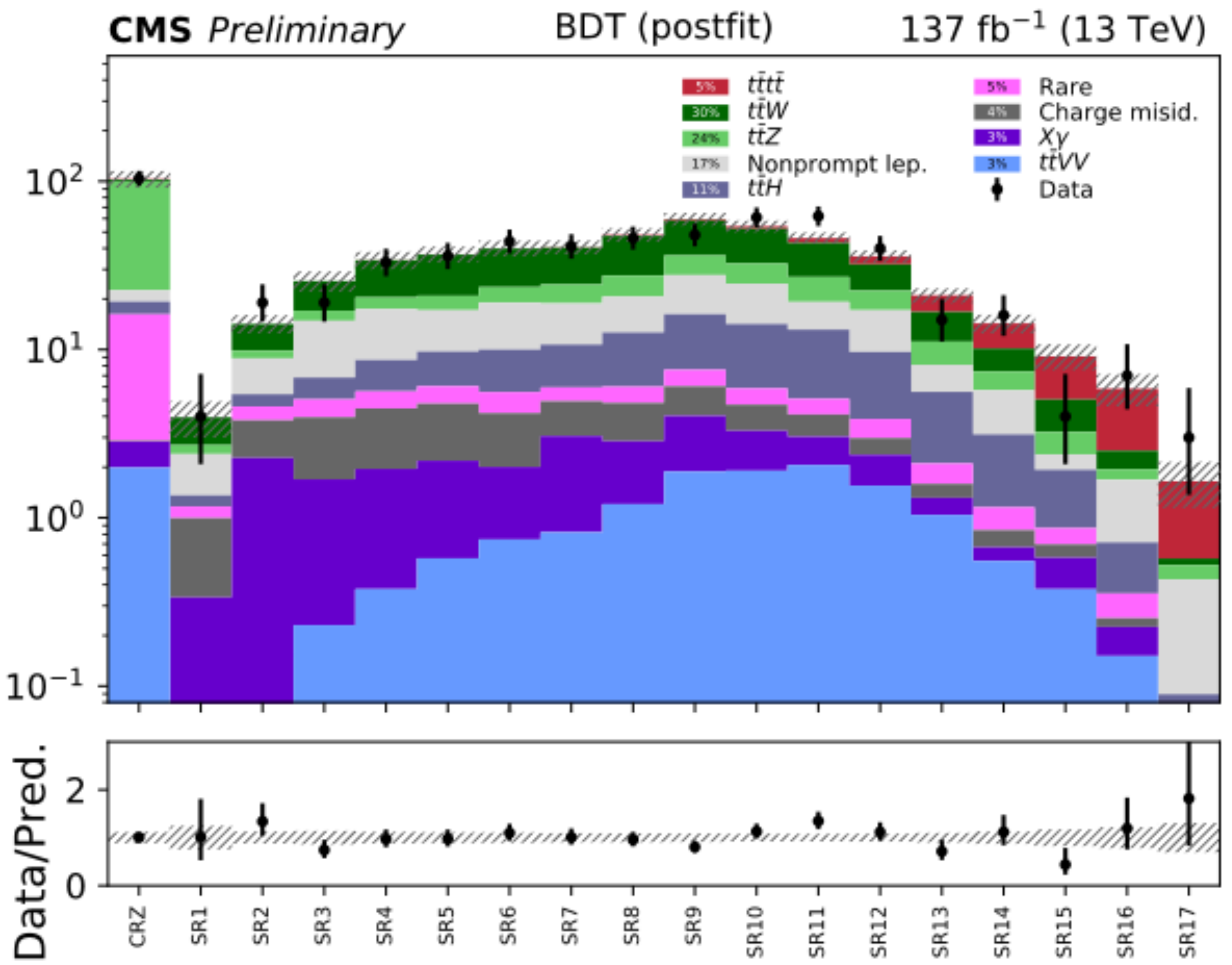
In the 3-lepton channel (with Z to leptons).

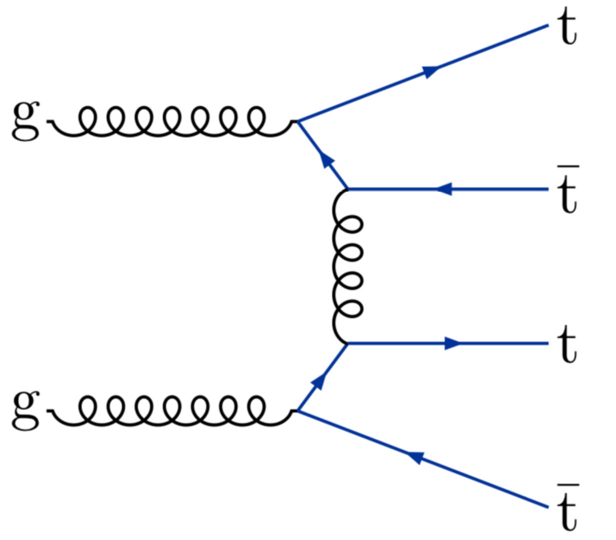


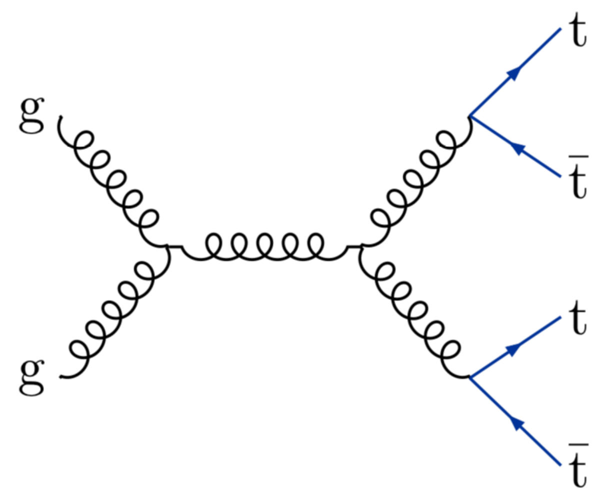
Campbell, Ellis and Rontsch 1302.3856

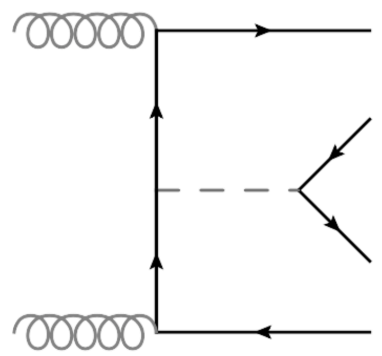
Four top process

Very rare process (~10 fb) sensitive to the top Yukawa coupling (here using same sign dilepton and 3-leptons)!









Observed

2.6σ

Expected

(2.7σ)

Limit on the top-Yukawa coupling:

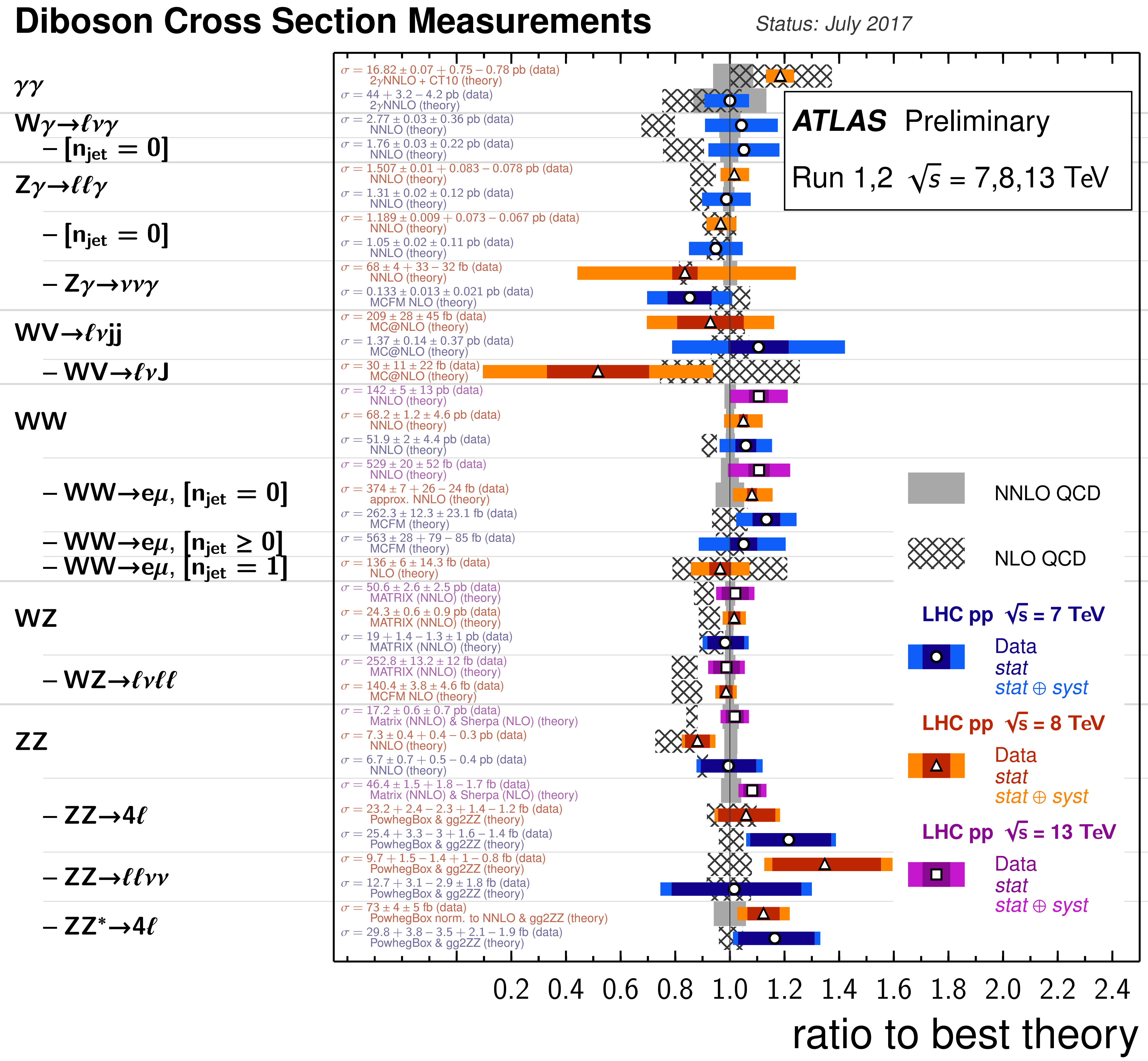
$$y_t/y_t^{SM} < 1.7$$

Diboson production

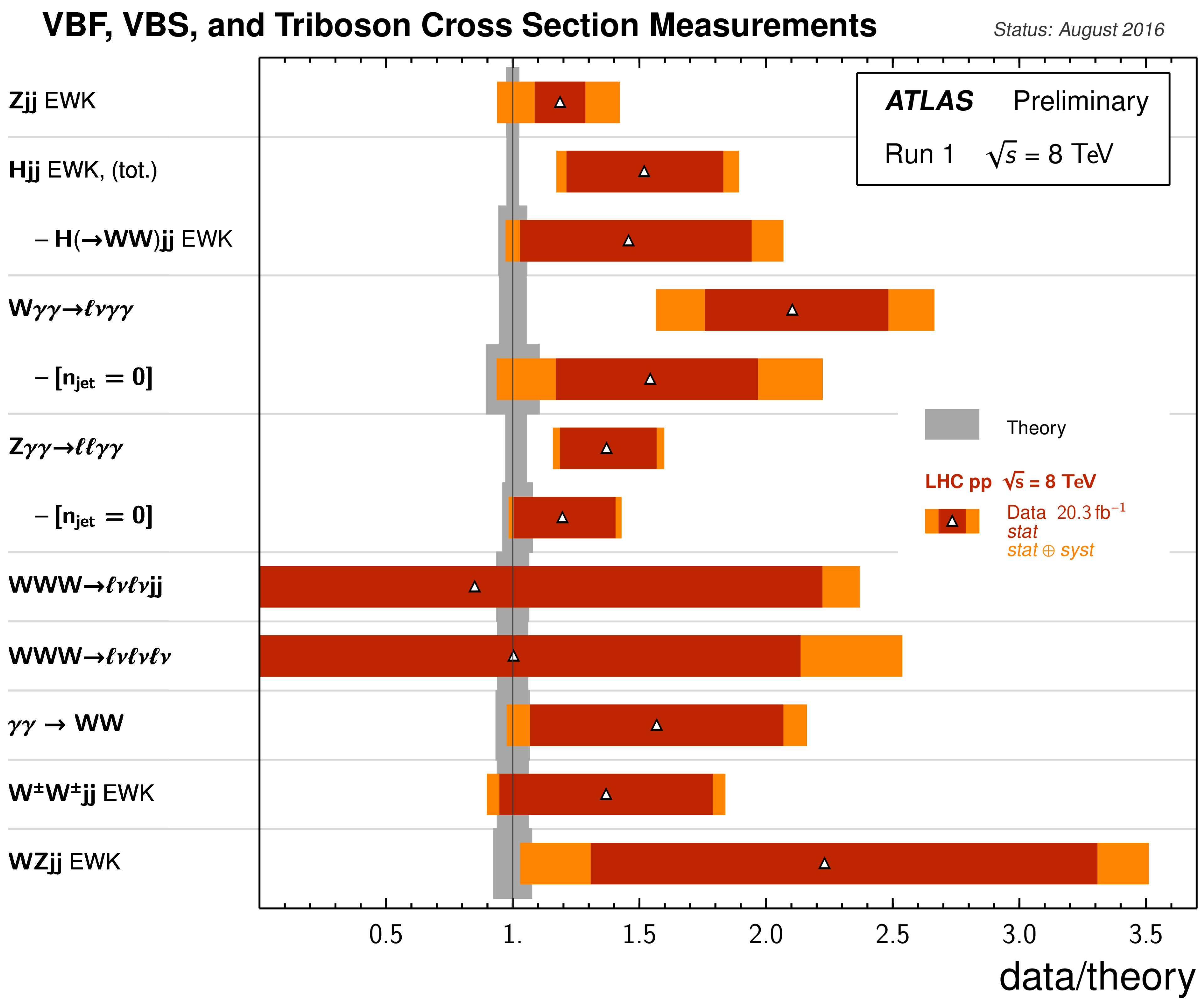
In a nano nutshell

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

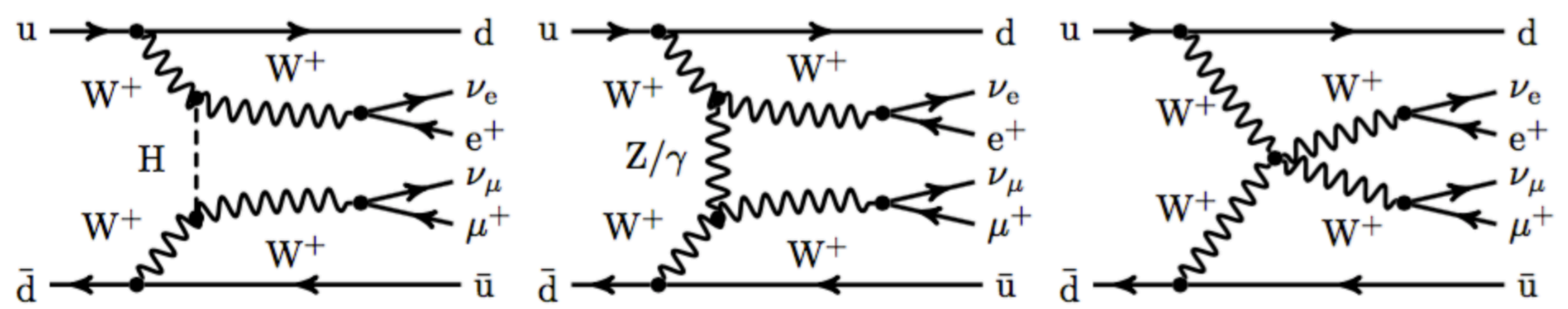
Large number of diboson processes measured and used to constrain anomalous gauge couplings



Measuring more rare and difficult processes



EW Vector Boson Scattering



EW Vector Boson Scattering process

Unambiguously observed by both ATLAS and CMS (at more than 5σ) in the Same sign WW mode. Evidences in the WZ mode.

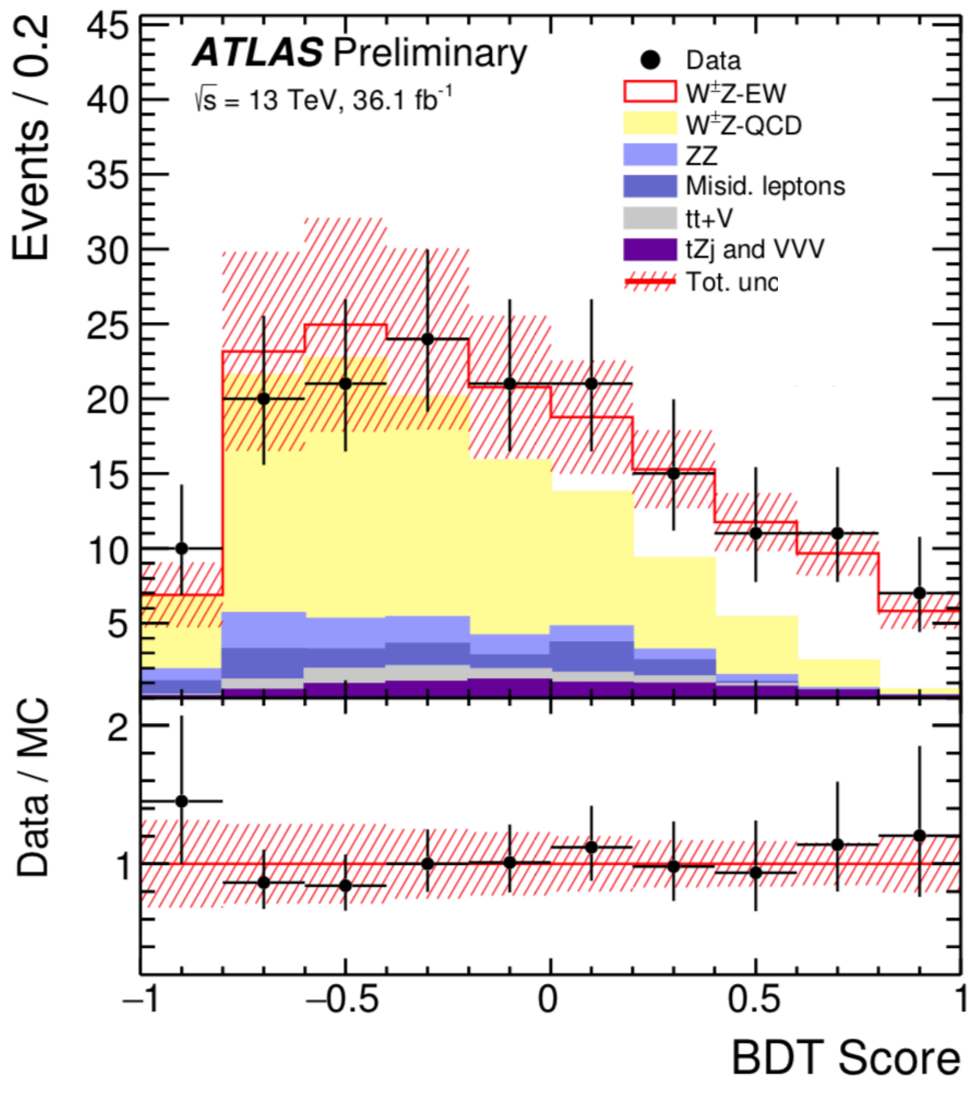
Longitudinal-Longitudinal Scattering

Important additional check of the EWSB sector.

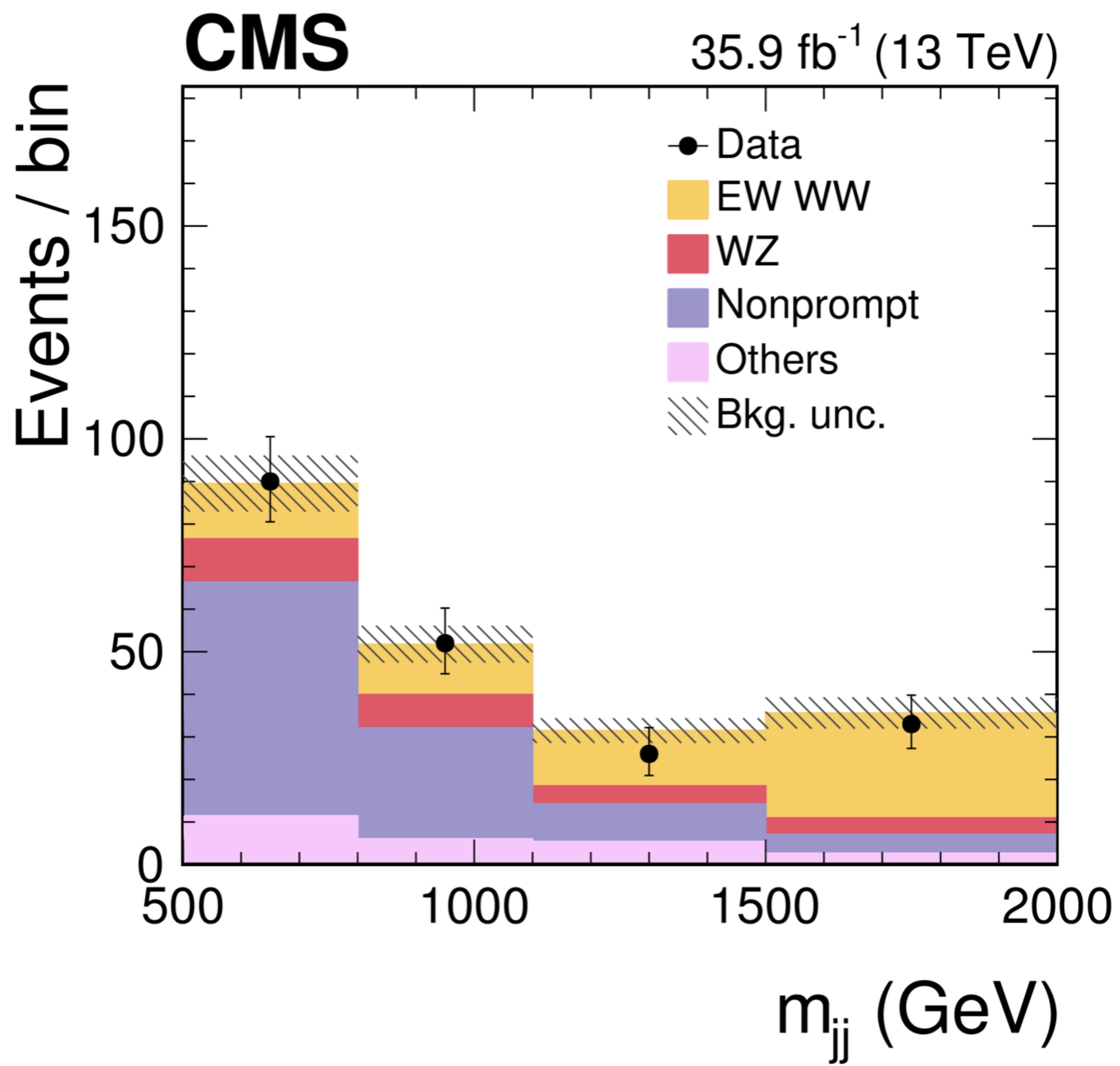
Suppressed from Higgs cancellation however with very large statistics and polarisation sensitive variables, there is sensitivity to SM LL signal almost 3σ for CMS alone.

With ATLAS and more channels WZ and ZZ well above 3σ

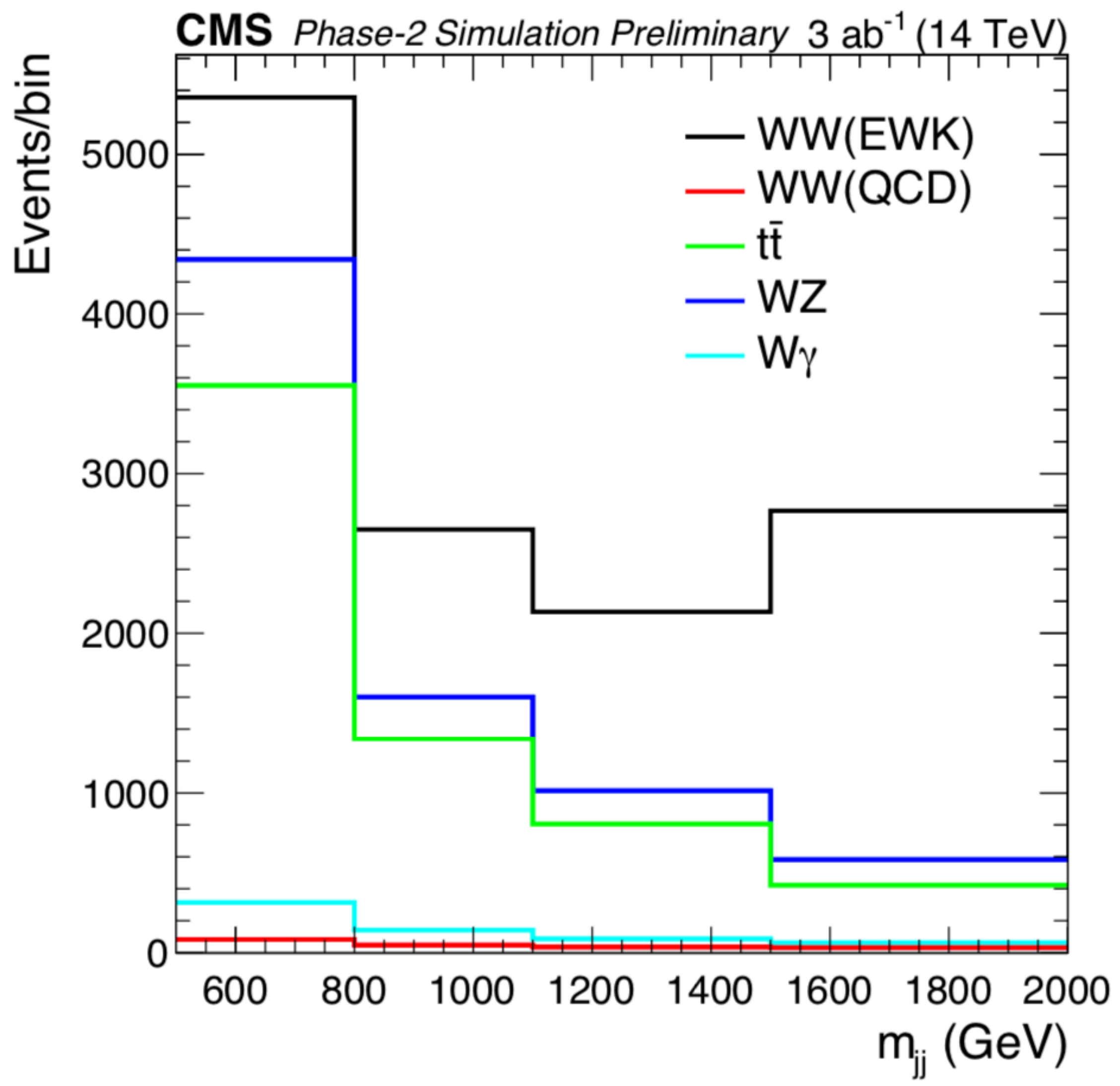
WZ $5.6\sigma\ (3.3\sigma)$

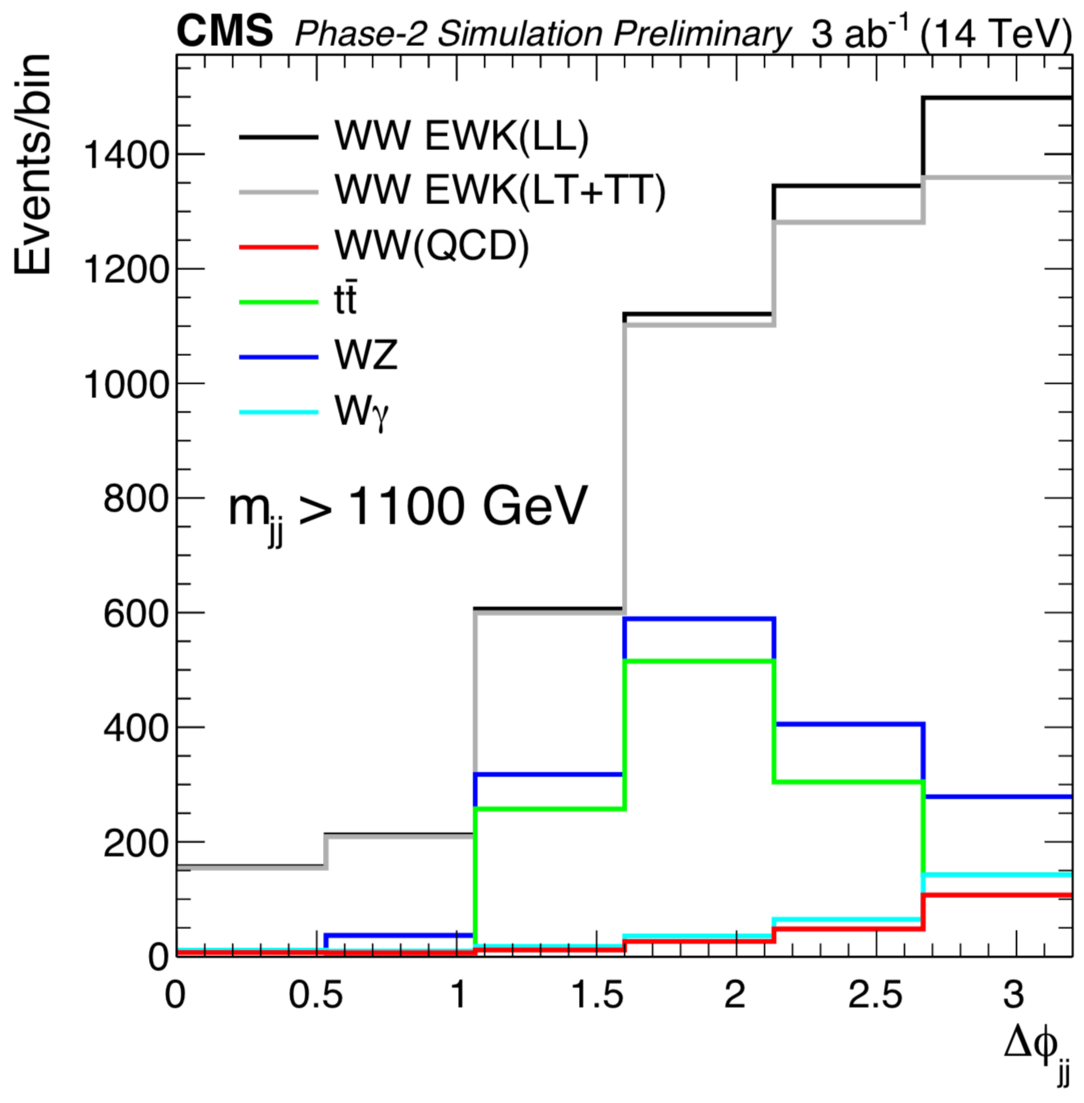


WW $5.5\sigma\ (5.7\sigma)$



CMS FTR-2018-005





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 :

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

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

- The Fermi constant :

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

Determined from muon lifetime

- The Z mass :

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

Measured from the Z lineshape scan at LEP

Note: we have assumed the existence of a Higgs field giving a vev (v) throughout (though we have not discussed the Higgs in detail yet)

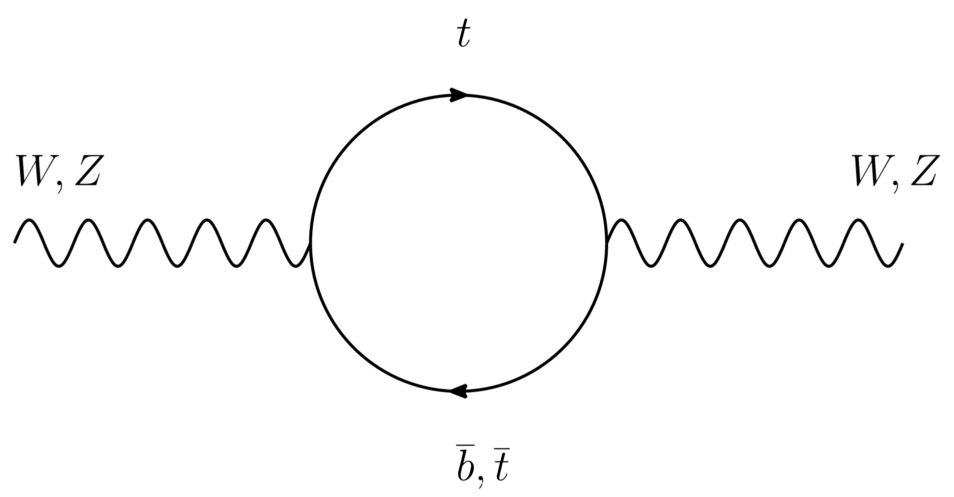
At loop level: all other fields enter the game through loop corrections which can be parametrized.

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

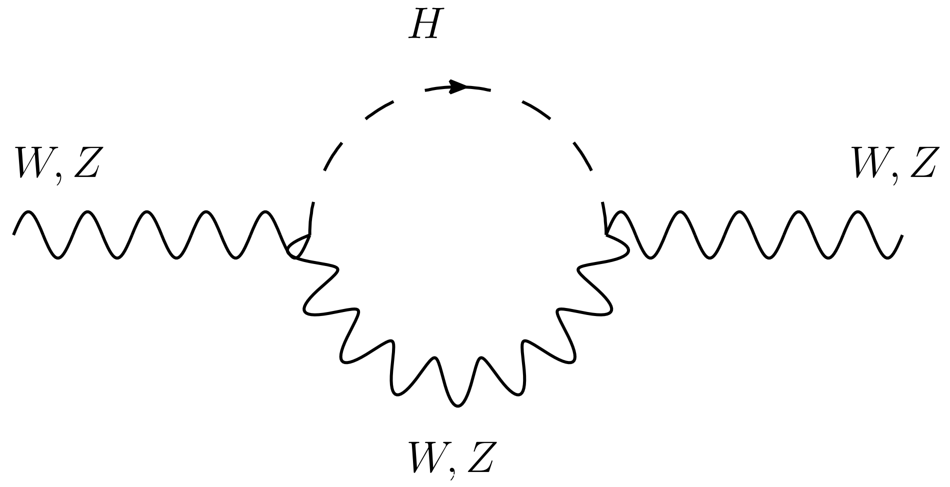
$$\sin^2\theta_W^{eff} = sin^2\theta_W \times (1+\Delta\kappa)$$

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

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



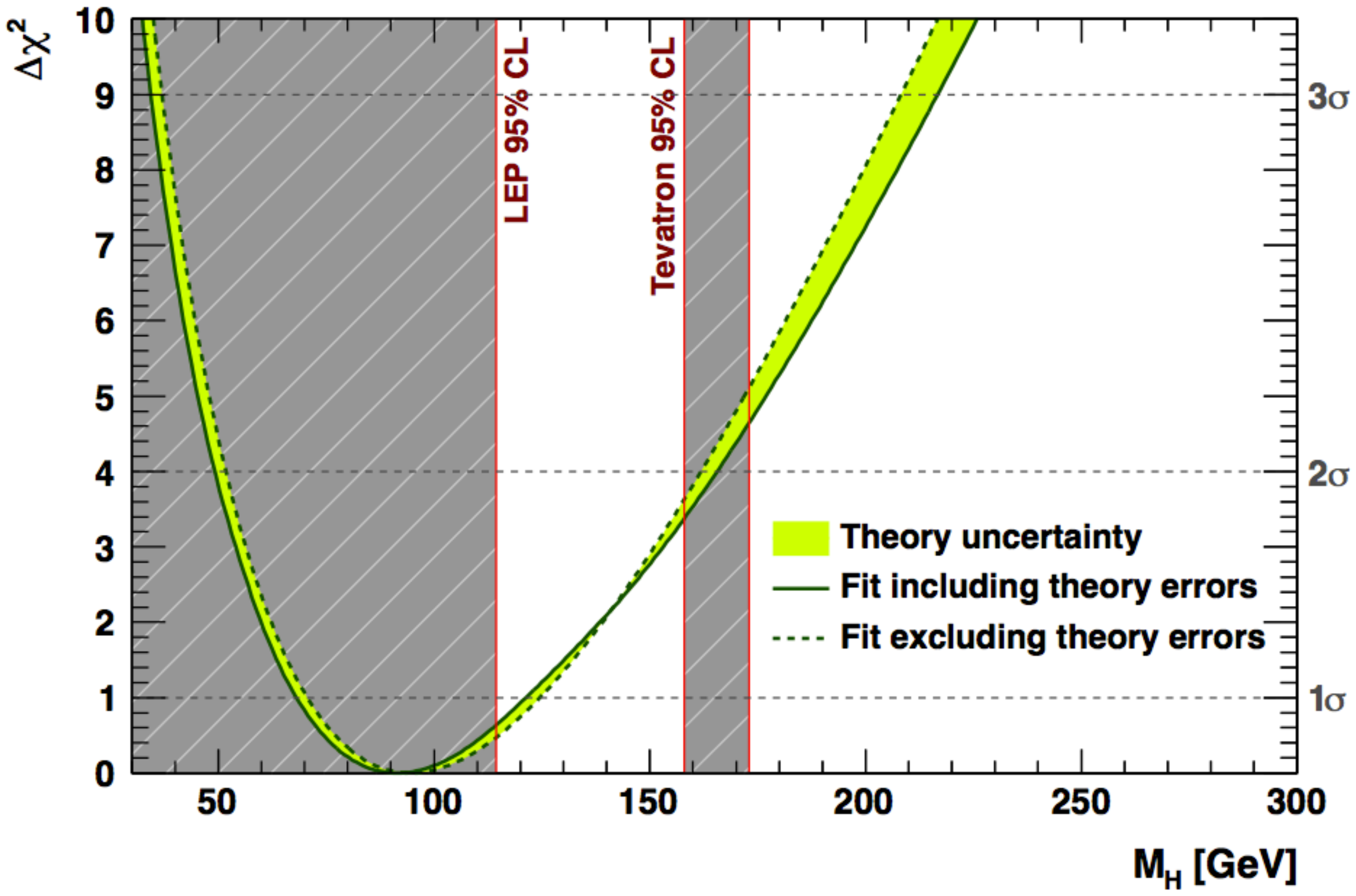
$$\propto m_t^2$$



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

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**!!

Asymmetries - Exercise

Exercise

The b, c and leptonic asymmetries were measured at LEP and SLD (SLAC)

$\mathcal{A}_b = 0.923 \pm 0.020$	SLD	2.2 %
$\mathcal{A}_c = 0.670 \pm 0.027$	SLD	3.9 %
$\mathcal{A}_\tau = 0.1439 \pm 0.0043$	LEP	3.0 %
$\mathcal{A}_e = 0.1498 \pm 0.0049$	LEP	3.3 %
$\mathcal{A}_l = 0.1513 \pm 0.0021$	SLD	1.4 %

Compute a rough prediction of these asymmetries.