Experimental SM and Higgs Physics at LHC

Lecture 1

Basic Concepts, the LHC and precision measurements with Drell-Yan W and Z processes.

Herbstschule HEP
formerly Maria Laach

Herbschule HEP - Bad Honnef
September 4, 2024

MAX-PLANCK-INSTITUT FÜR PHYSIK

Marumi Kado
Max Planck Institute for Physics

Outline

Experimental SM and Higgs Physics at LHC

***Lecture 1**: Basic Concepts, the LHC and precision measurements with Drell-Yan W and Z processes.*

***Lecture 2**: Associated and multi- Vector boson production, and top quark*

***Lecture 3**: Higgs Physics*

***Lecture 4:** More Higgs Physics and Global interpretation*

- **Disclaimer:** These lectures will be focused mostly on ATLAS and CMS (LHCb covered by Marco Gersabeck and QCD and jet physics covered by Peter Uwer)
- **Excellent resources for keeping up-to-date with the latest results**: Physics Briefings from ATLAS and CMS.

In Case you Missed it!

Link to the page

The General Framework in a Nutshell

Two main outcomes of the LHC: The discovery of the Higgs boson and nothing else (so far)!

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

Simplicity, governed by symmetries only 3 (EW) and 2 (QCD) parameters!

$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c. + \frac{c_{ij}}{\Lambda} L_i L_j H H \; ?$$

$$+ |D_\mu \phi|^2 - V(\phi) + \Lambda^4 \; ?$$

Not governed by symmetries and with **26 parameters set by the “hand” of experiments!**

Open problems

Hierarchies

- Gauge Hierarchy and Naturalness
- Flavour hierarchy including neutrino masses

The strong CP problem

$$\theta \frac{\alpha_s}{8\pi} F^A_{\mu\nu} \tilde{F}^{A\mu\nu} \qquad \theta < 10^{-10}$$

From neutron electric dipole moment

The existence of Dark Matter (new field?)

The nature of Dark energy

Open questions

- What is the origin of the asymmetry between matter and anti-matter in the universe?
- What are the properties of QCD confinement?
- Why do electrons have precisely the same charge as the protons?

The Mission of the LHC

Fundamental physics at the energy Frontier

- **The no-loose theorem**: Discover the Higgs boson or reveal strong dynamics in vector boson scattering

- **Probe the electroweak scale**: with direct searches for new phenomena beyond the Standard Model.

- **Probe the Standard model and higher scales indirectly**: Through CP-violation in Heavy Flavors, rare B decays, etc… **Through precision measurements of Higgs couplings, standard EW parameters, anomalous couplings, etc…**

- **Study strongly interacting matter at extreme energy densities**.

In all these areas the LHC is already an immense success

The LHC a « Marvel of Technology »

27 km tunnel originally built for the LEP collider (at an average depth of 100m - lowest point 175m)

LHC facts sheet see:

http://cds.cern.ch/record/2255762

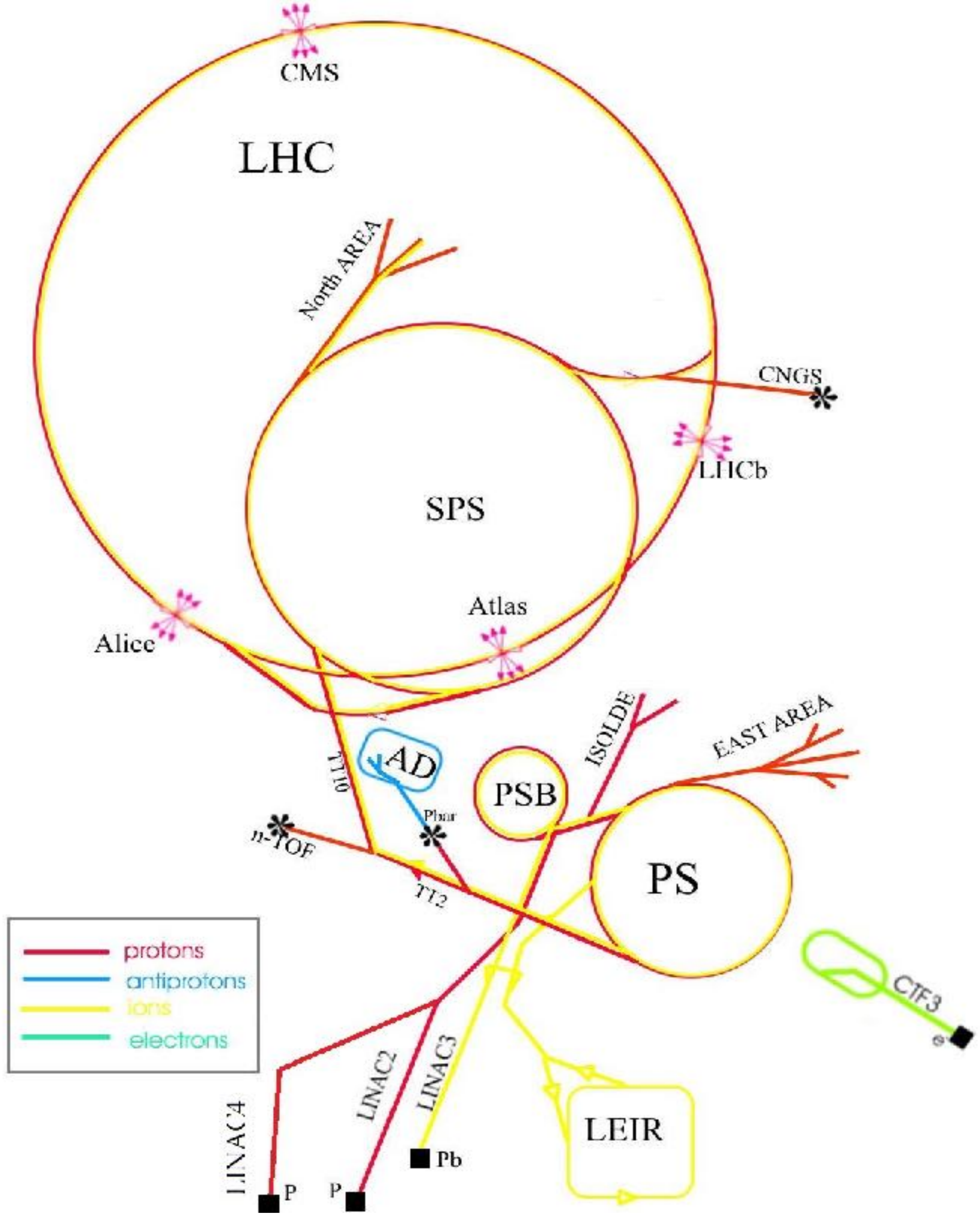
« The most ambitious scientific experiment in history »

Unrivalled at the Energy Frontier

13.6 TeV (centre-of-mass energy)

Outstanding at Intensity Frontier

Record Luminosity* of $2.33 \times 10^{34}\ cm^2 s^{-1}$



*Surpassed in June 2022 by SuperKEKB at $4.71 \times 10^{34}\ cm^2 s^{-1}$

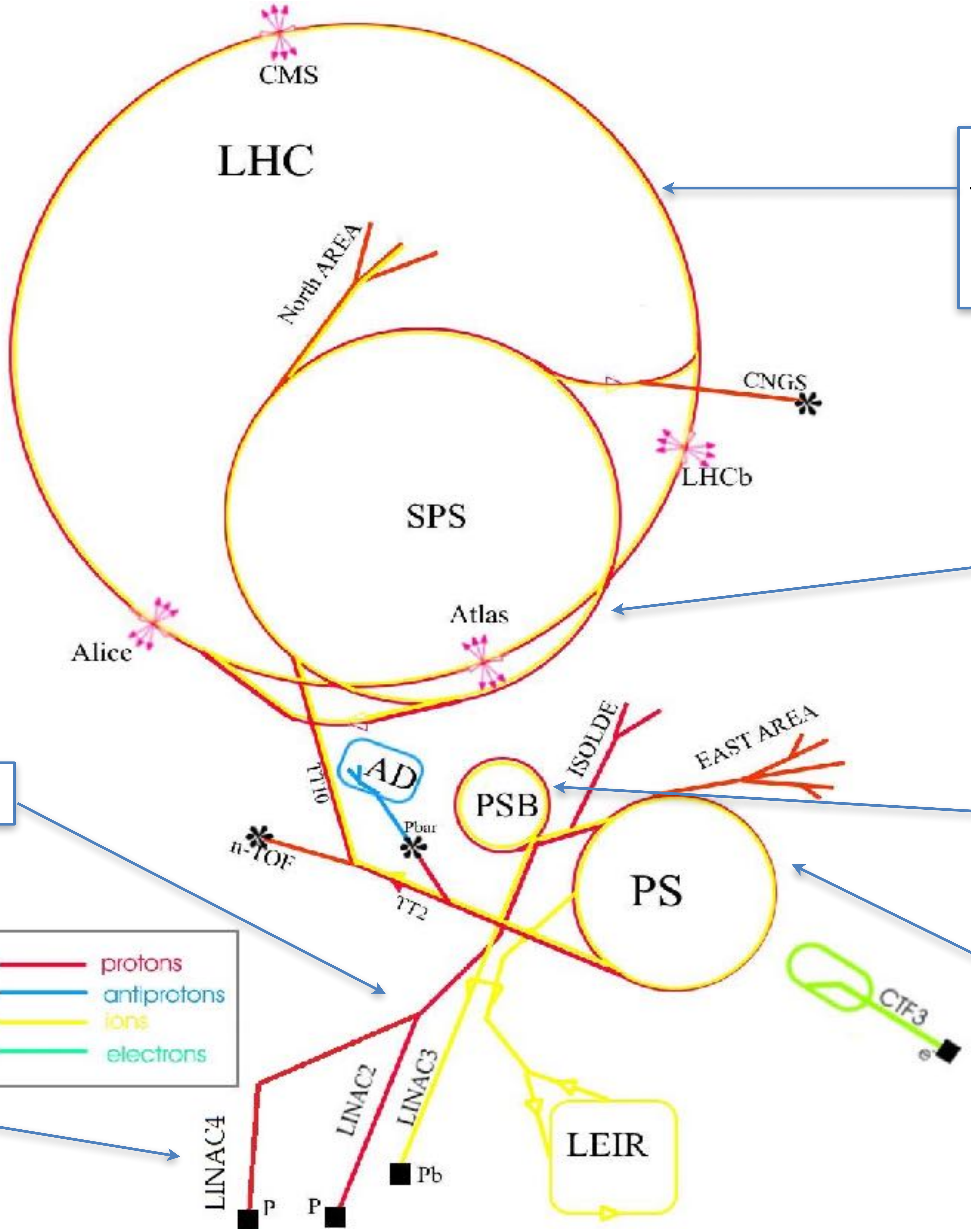
« The most ambitious scientific experiment in history »

Few interesting facts

9300 Magnets (among which 1232 bending dipoles) reaching 8.3T with current of 11,400 A.

Beams are made of trains with a total nominal number of bunches of 2808 each containing approximately 100 Billion protons. Bunches are separated within trains by 25ns (approximately 7m).

Each proton has the kinetic energy of a mosquito and the total energy of the beams is 350 MJ ~ 1 TGV à 150 km/h.



Ramped to 7.5 TeV in the LHC
The maximum number of bunches (2808) not reached at Run 2 is limited by the injection kickers (~1 µs) and by the beam dump extraction (~3 µs)

SPS accelerates protons to 450 GeV, bunches before injection in the LHC.

The booster accelerates protons at 1.4 GeV.

PS brings them to 26 GeV, it is in the PS that bunches are formed with a 25ns spacing.

Accelerated at 50 MeV in a LINAC

Hydrogen (gas) is ionized in a duoplasmotron.

First accelerated with a RF quadrupole at 750 keV.

Construction and Commissioning of the LHC

LHC Operation challenge:

Unprecedented beam energy and luminosities (for a hadron machine)

- Main challenge : Stored beam energy 2 orders of magnitude higher than previous machines… **350 MJ**
- Total stored energy in the magnets (**11 GJ**, enough to melt 15 tons of copper)

The Detectors

10 Years of Design

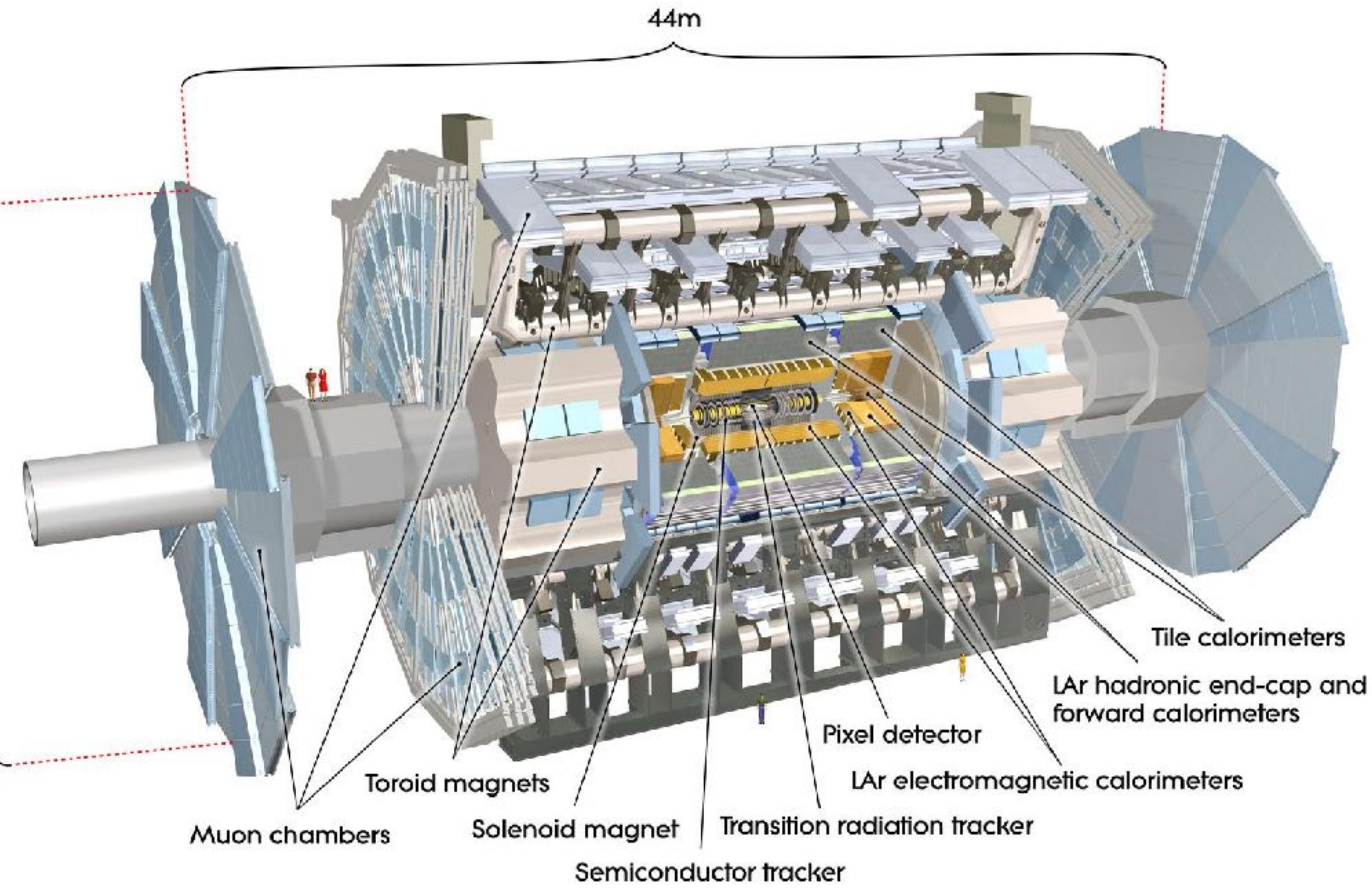
General Purpose Detectors

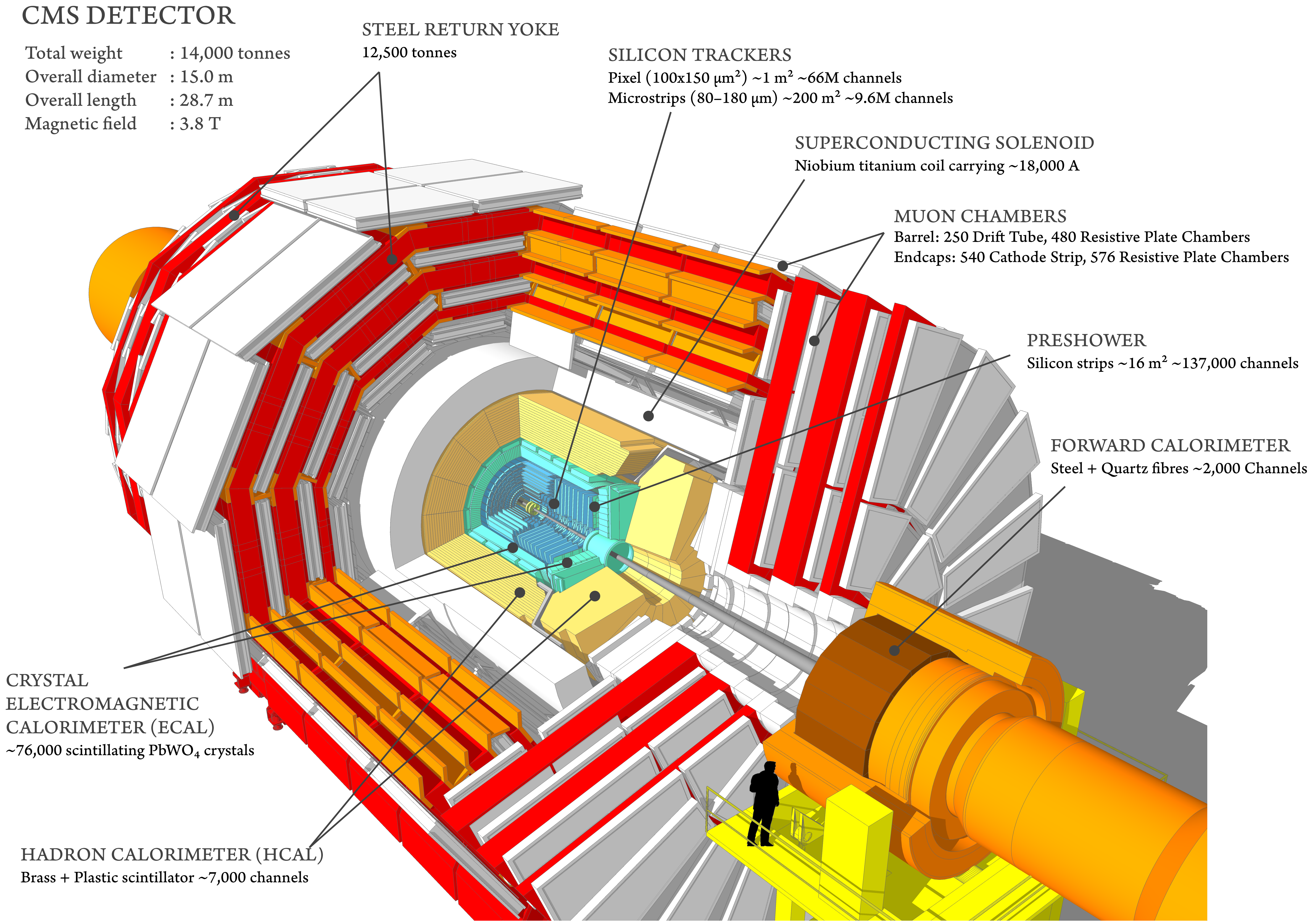
ATLAS nano fact sheet

- 25m Diameter and 44m length
- Over 7000 tons
- O(100) Million readout channels

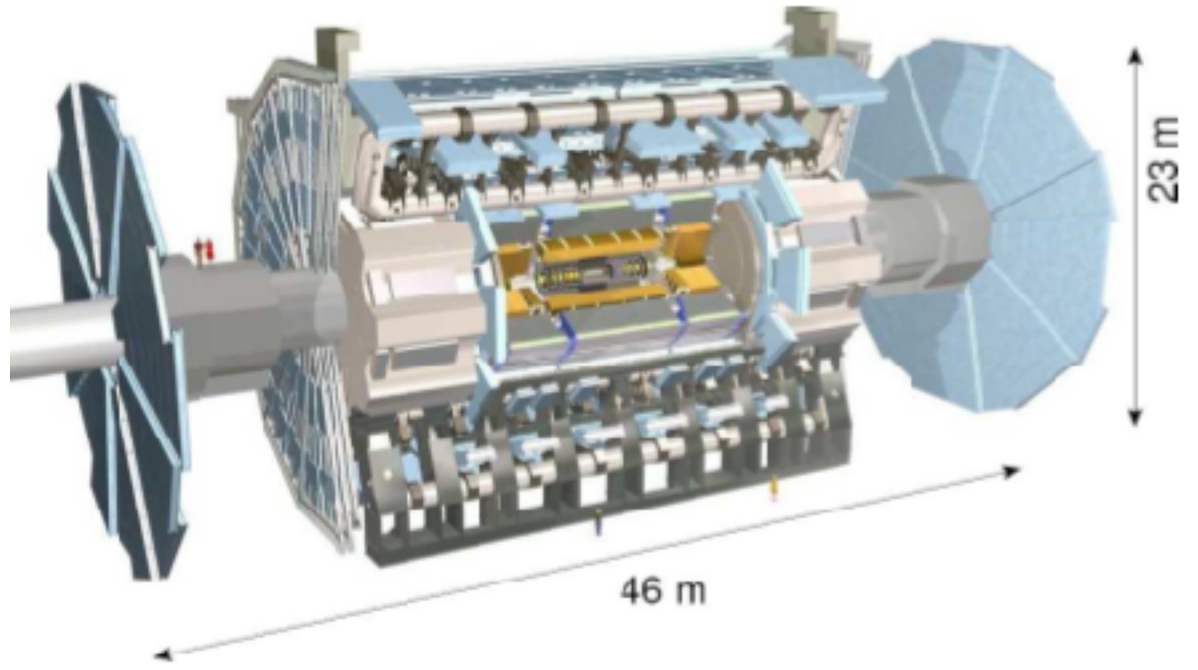
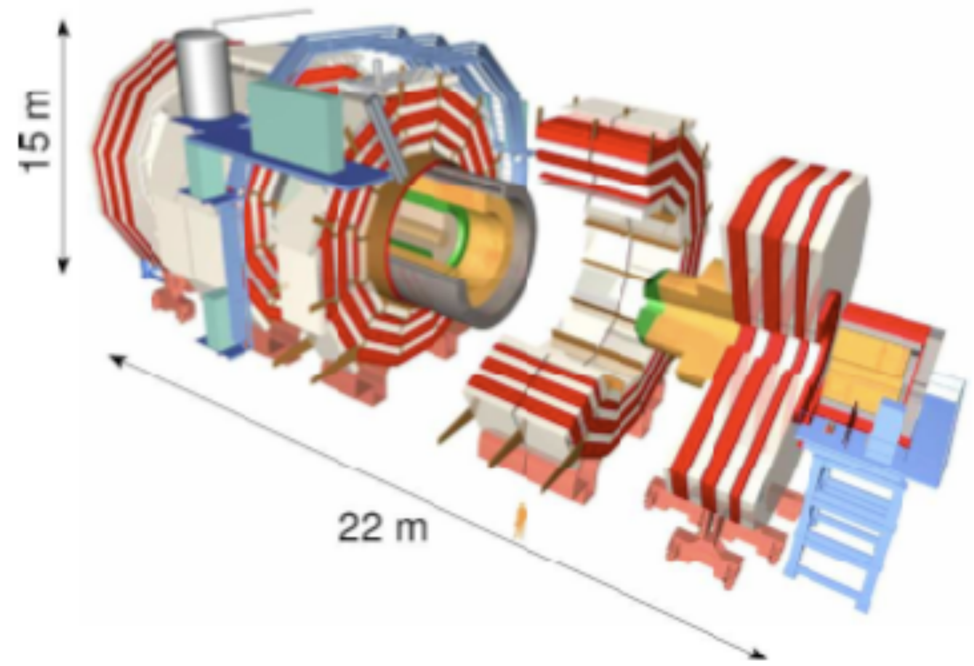
CMS nano fact sheet

- 15m Diameter and 21m length
- 14000 tons
- O(75) Million readout channels

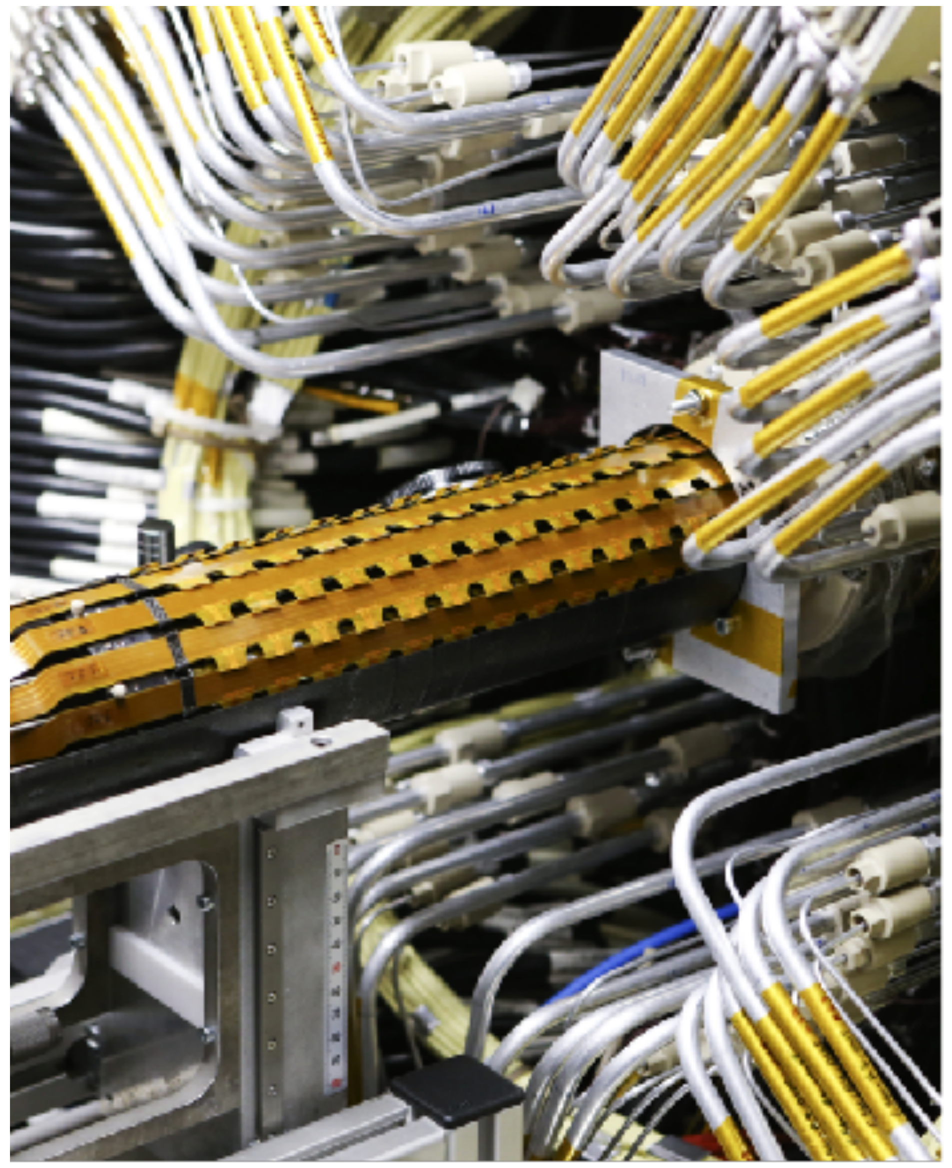


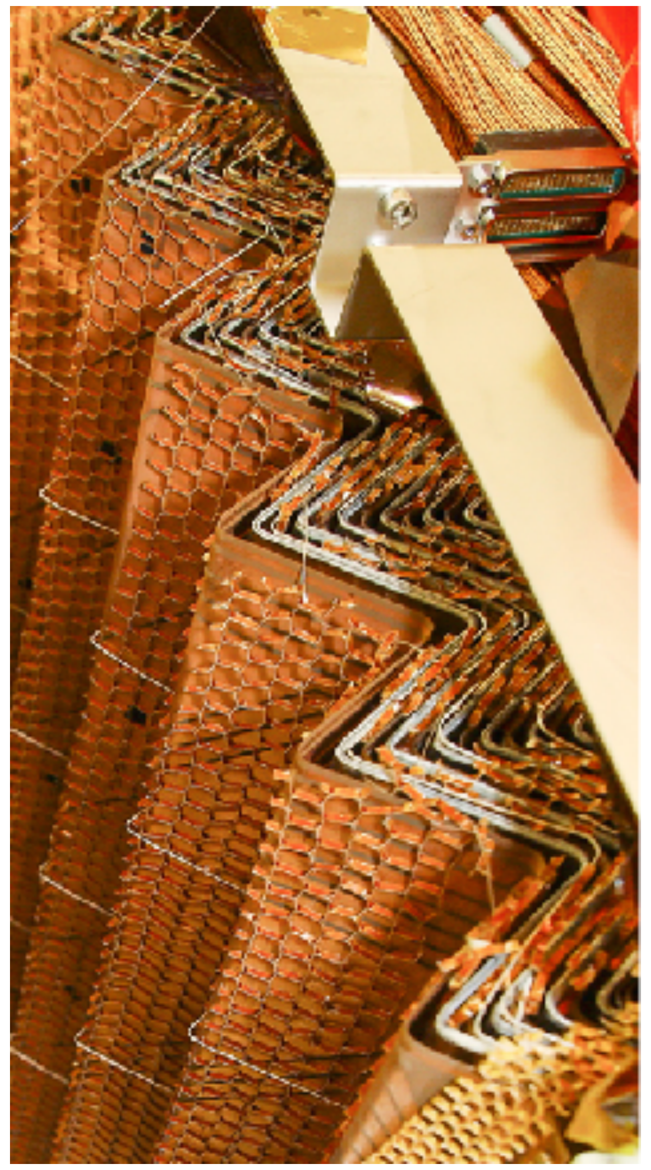


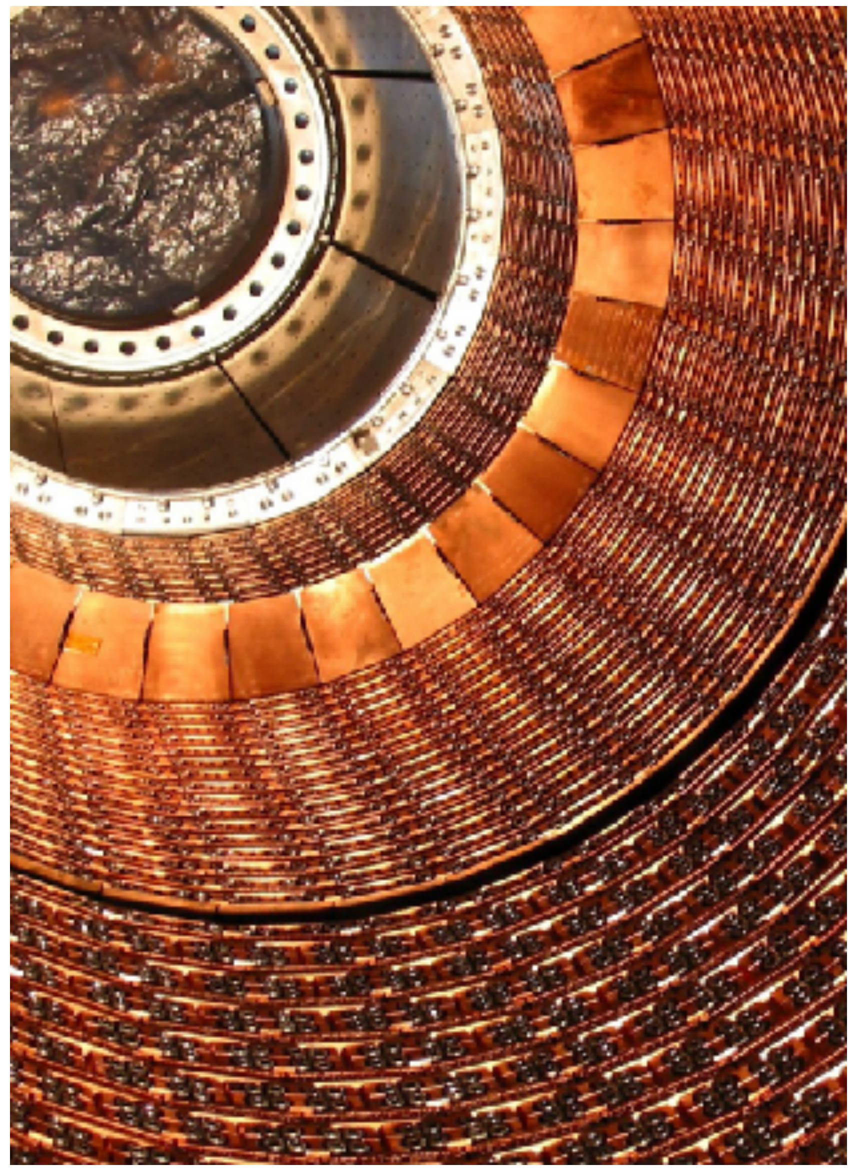
General Purpose Detectors

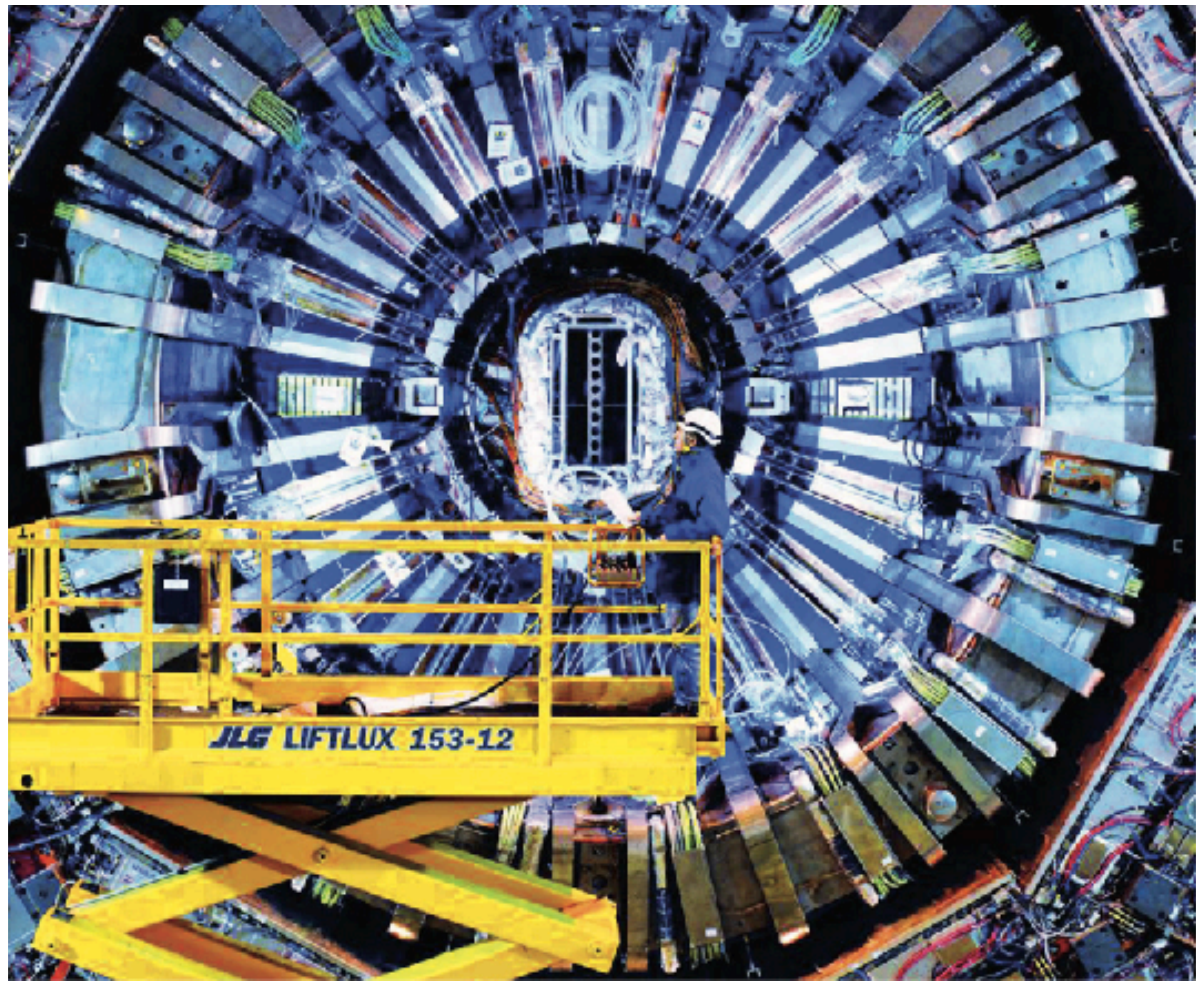
Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ & Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV) $\sim 11\,\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

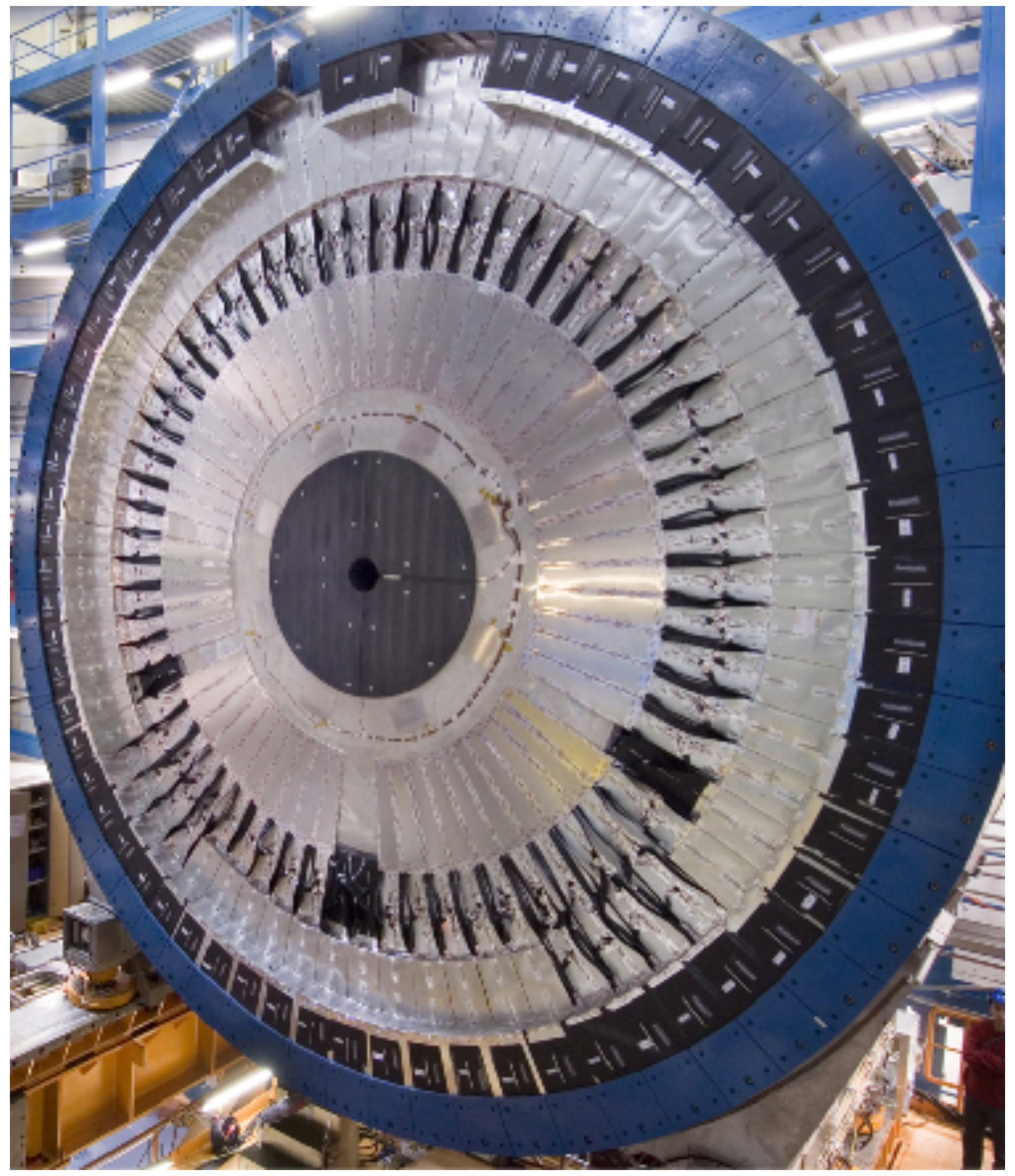
10 Years of Construction

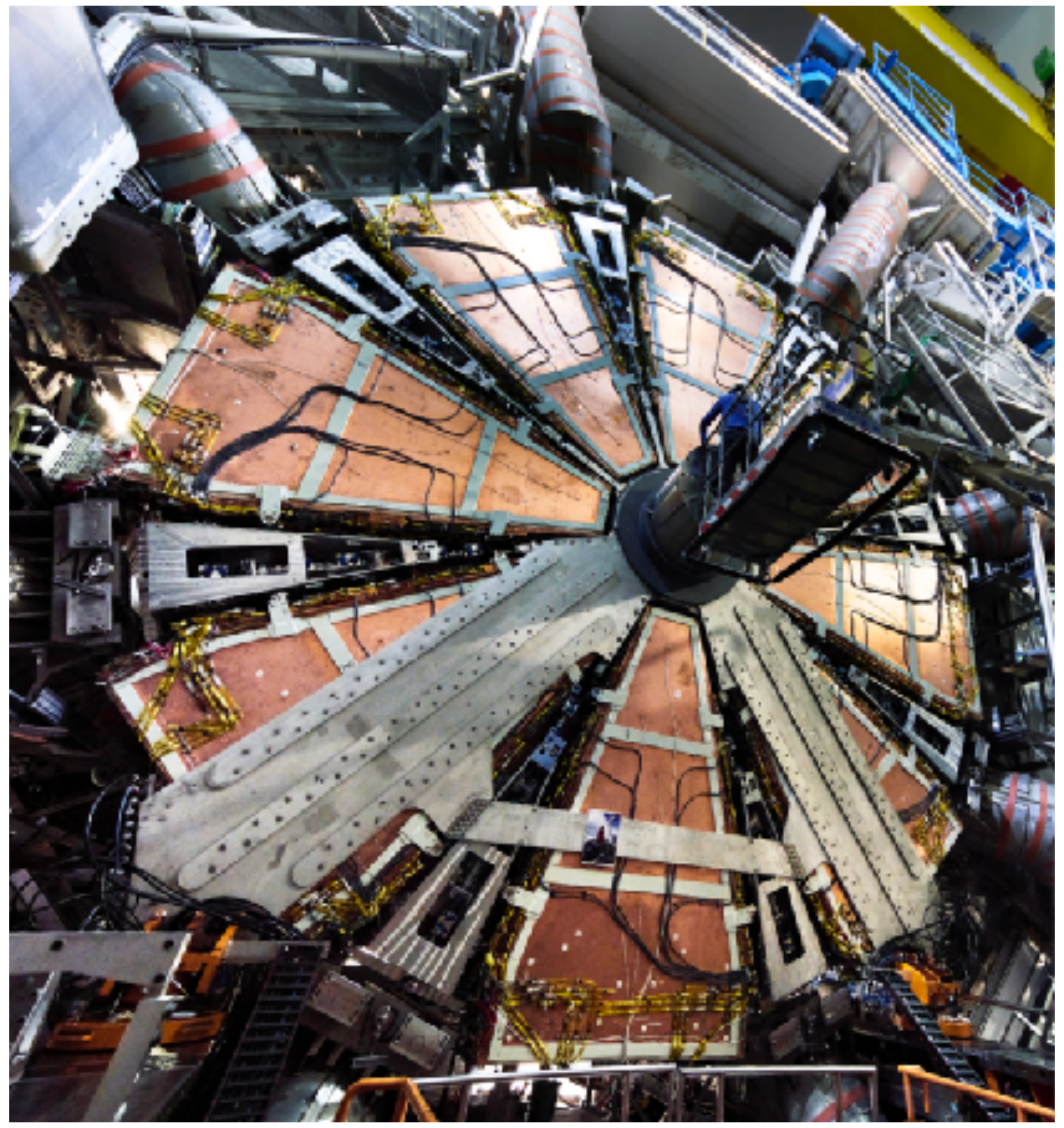


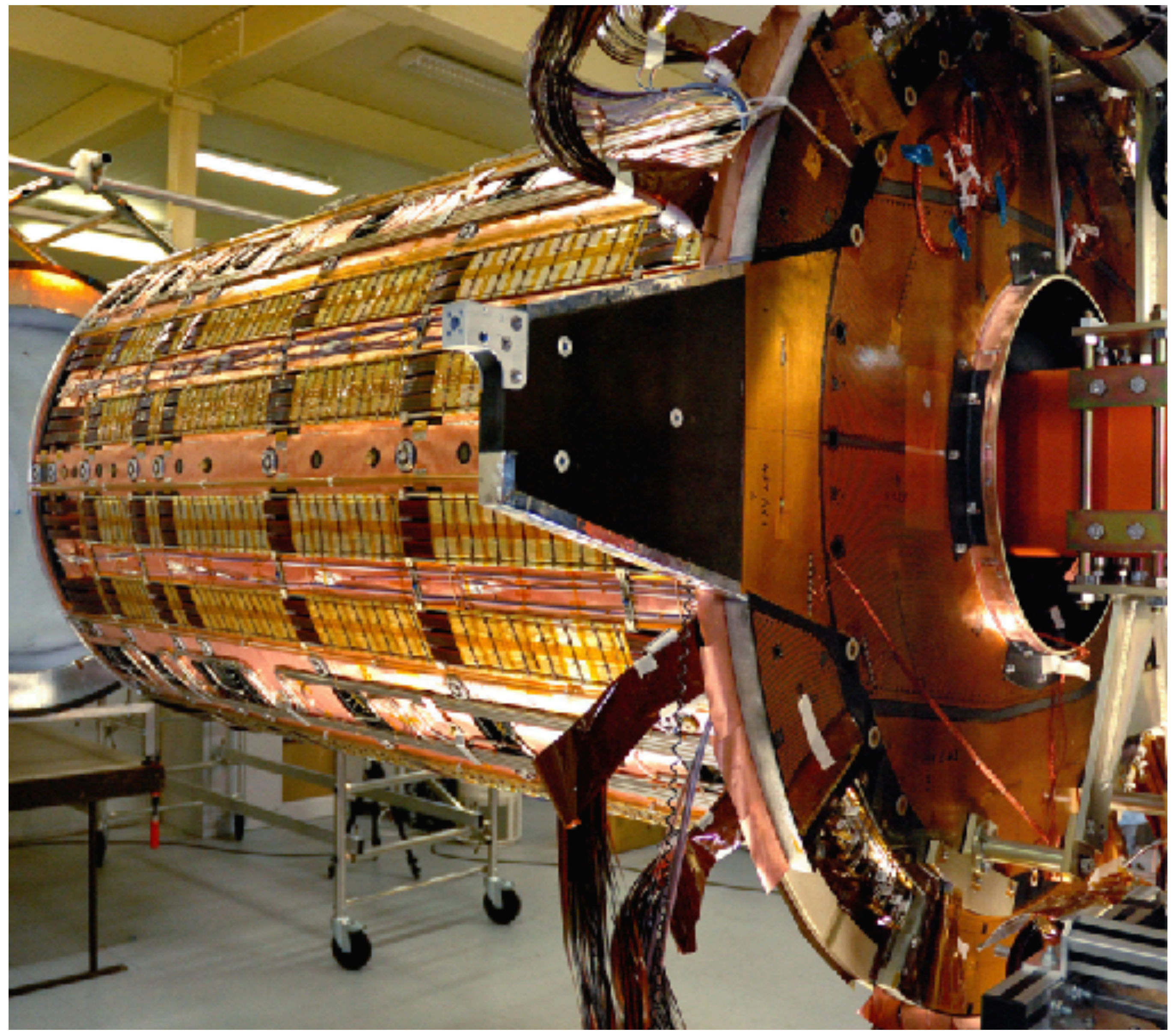


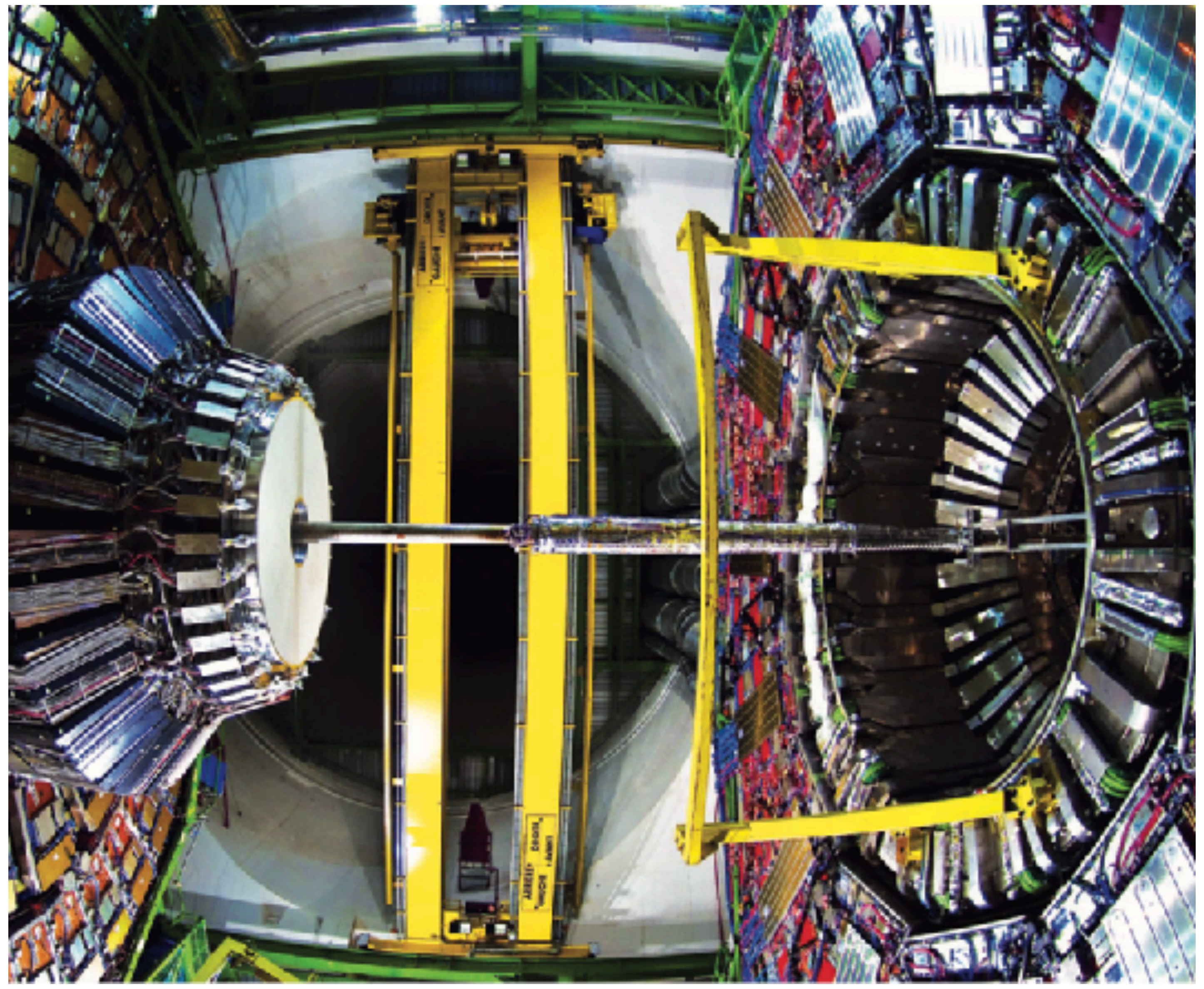






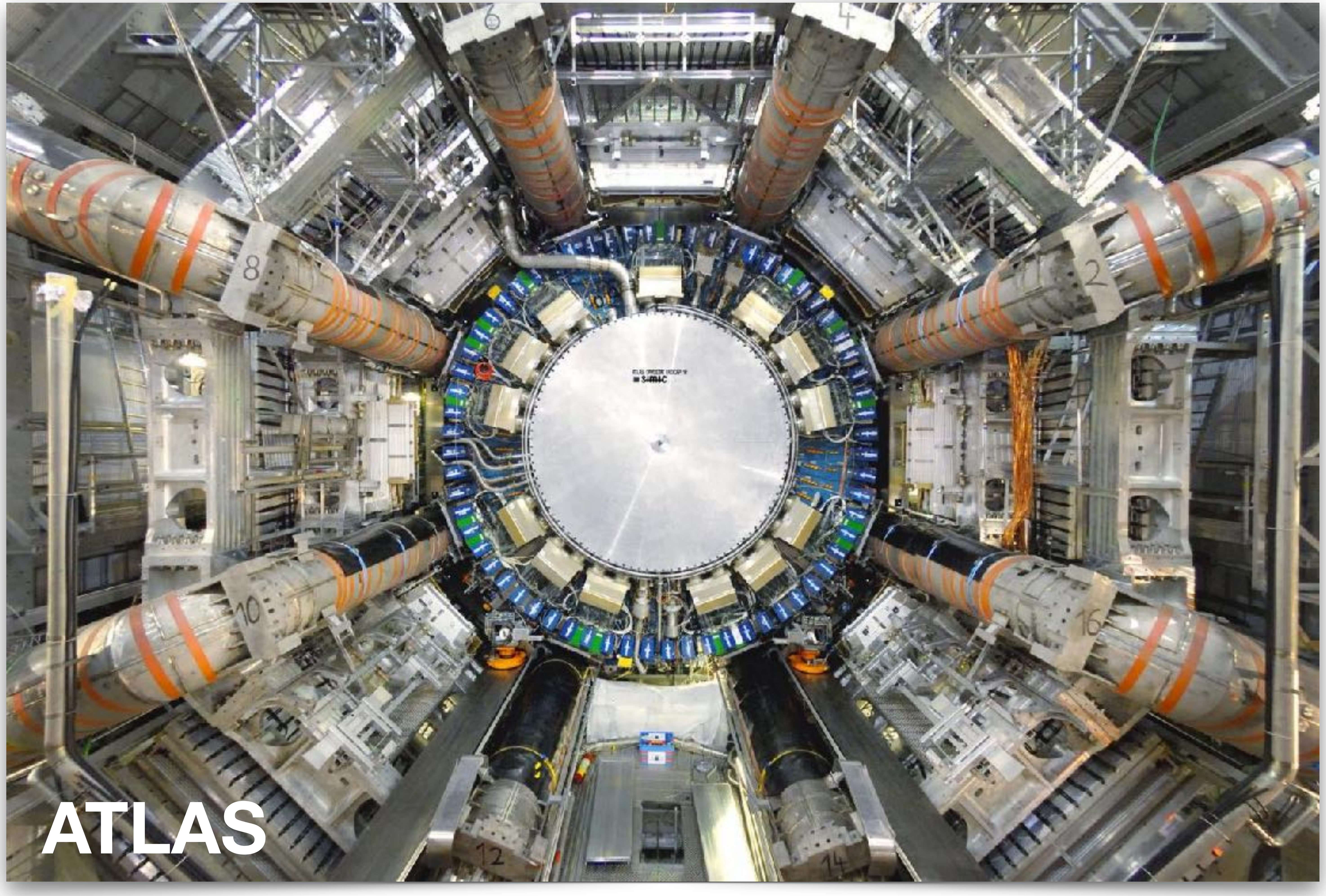


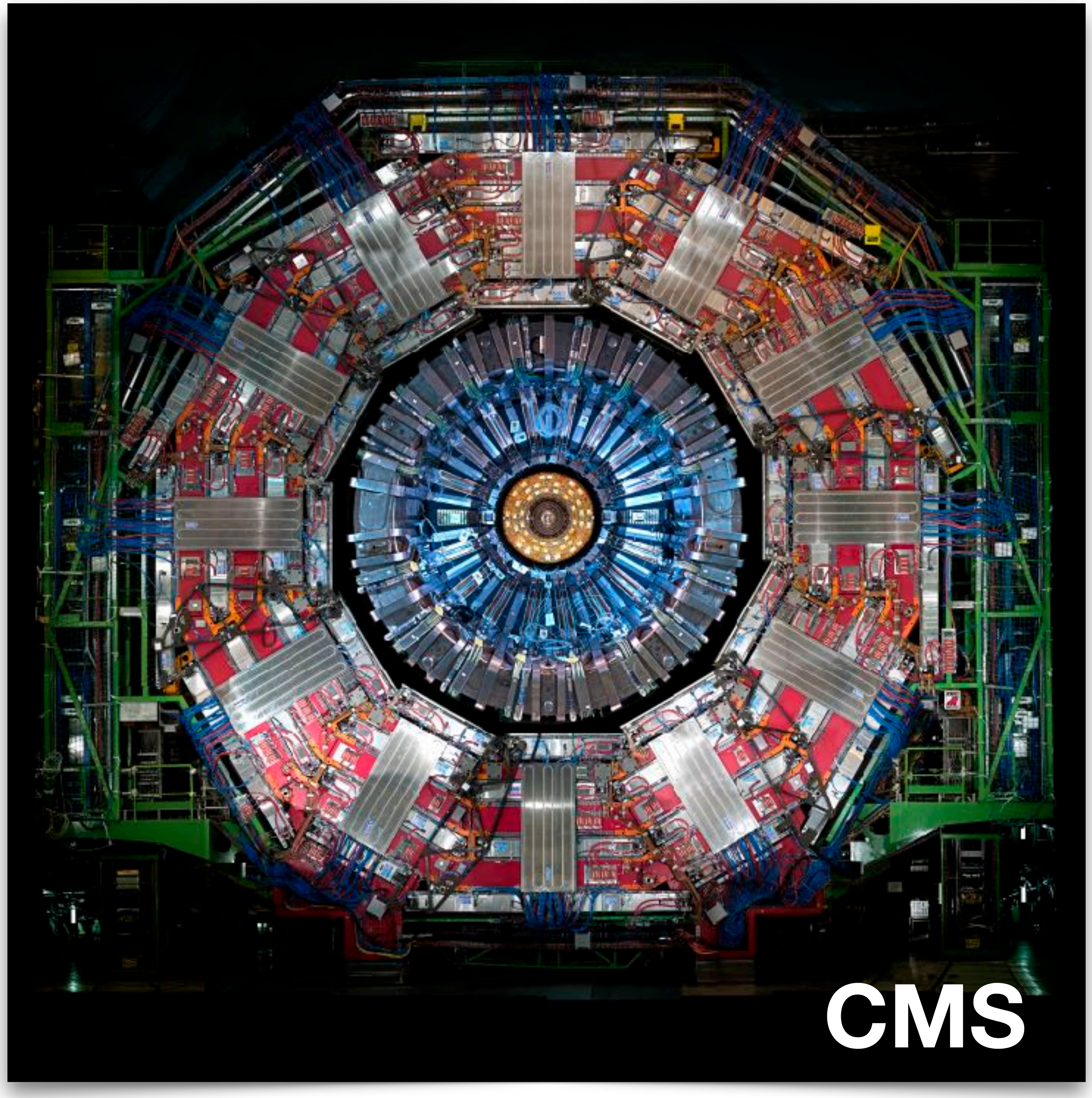




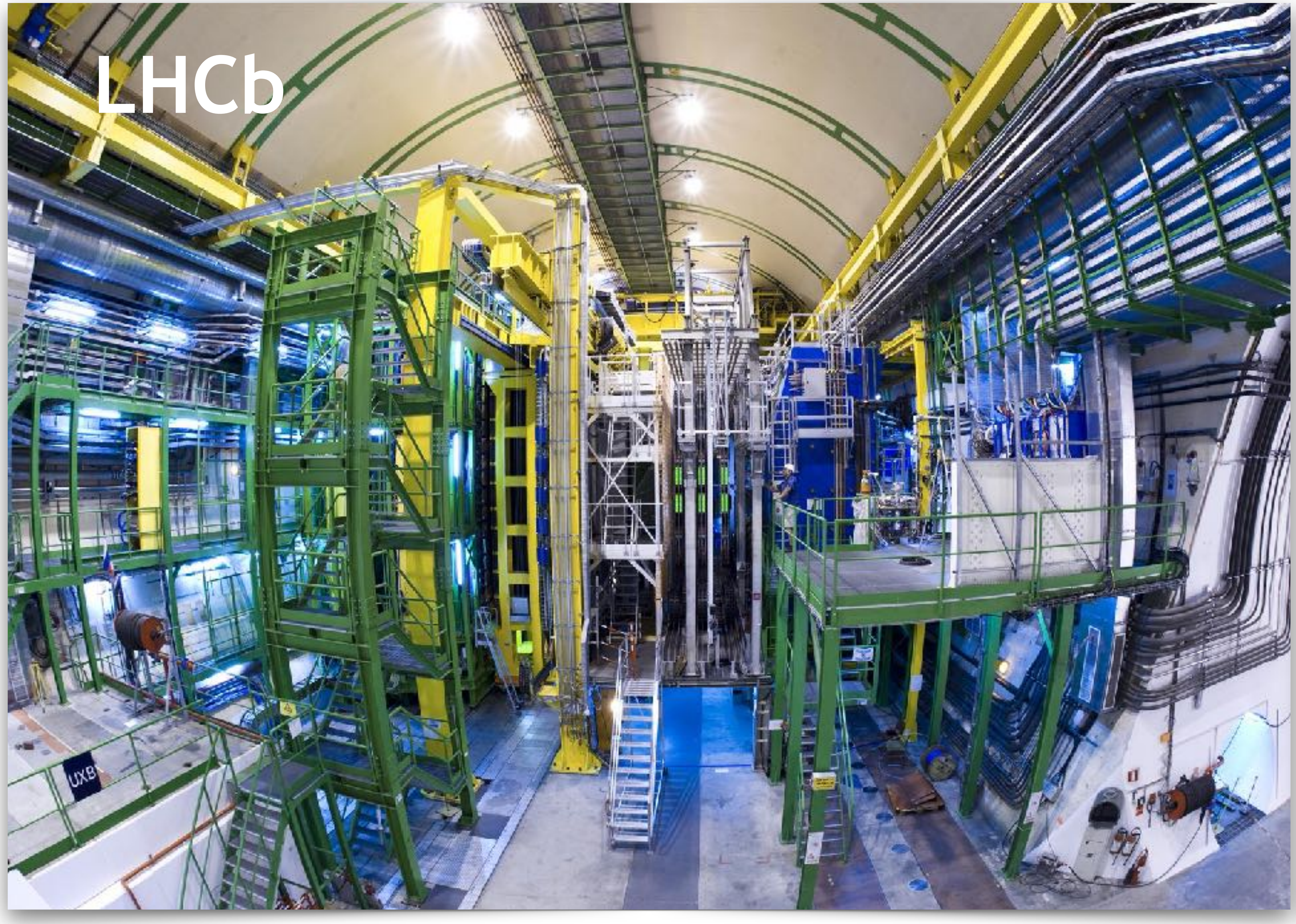
LHC Experiments

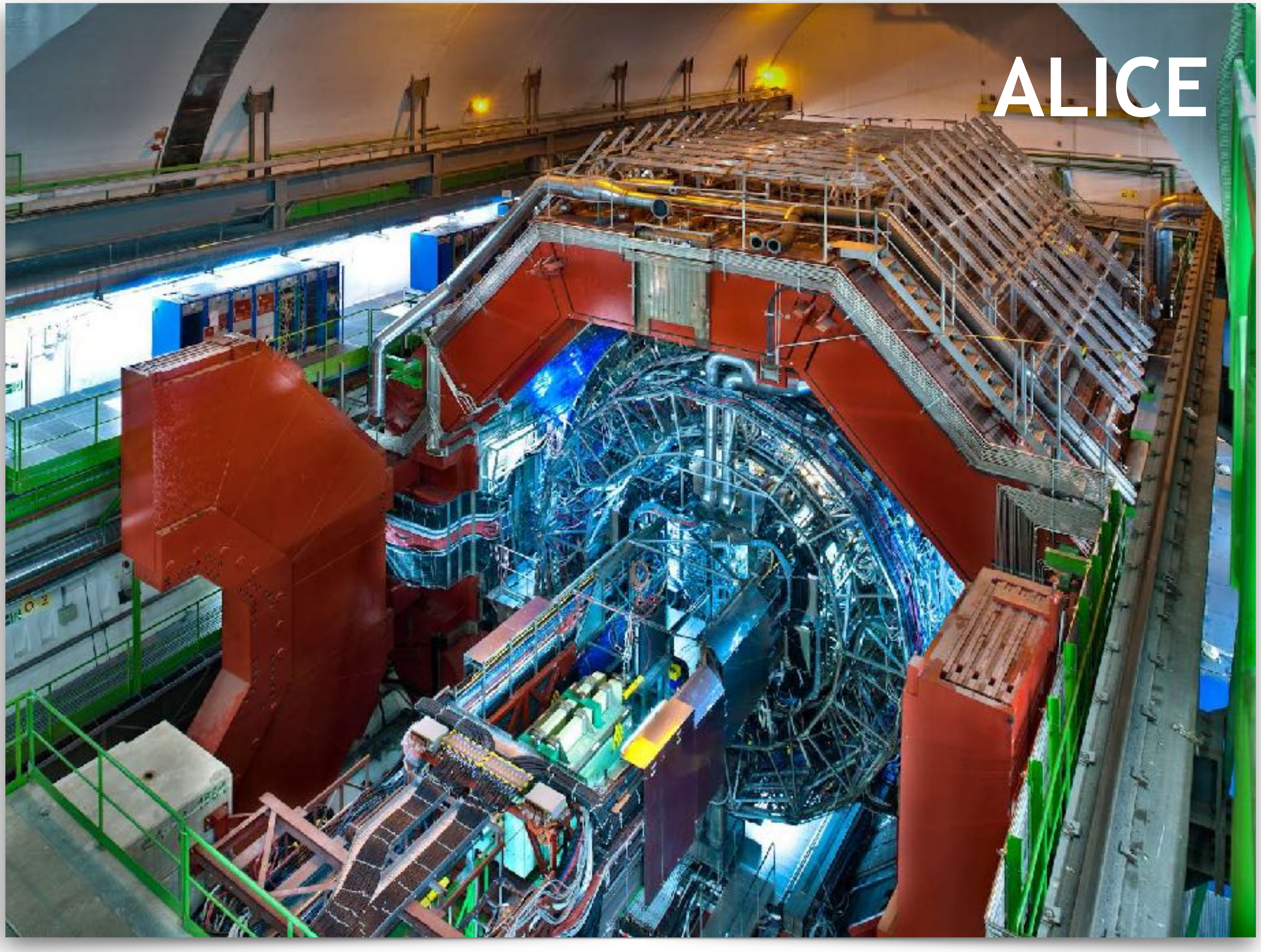
General Purpose Detectors





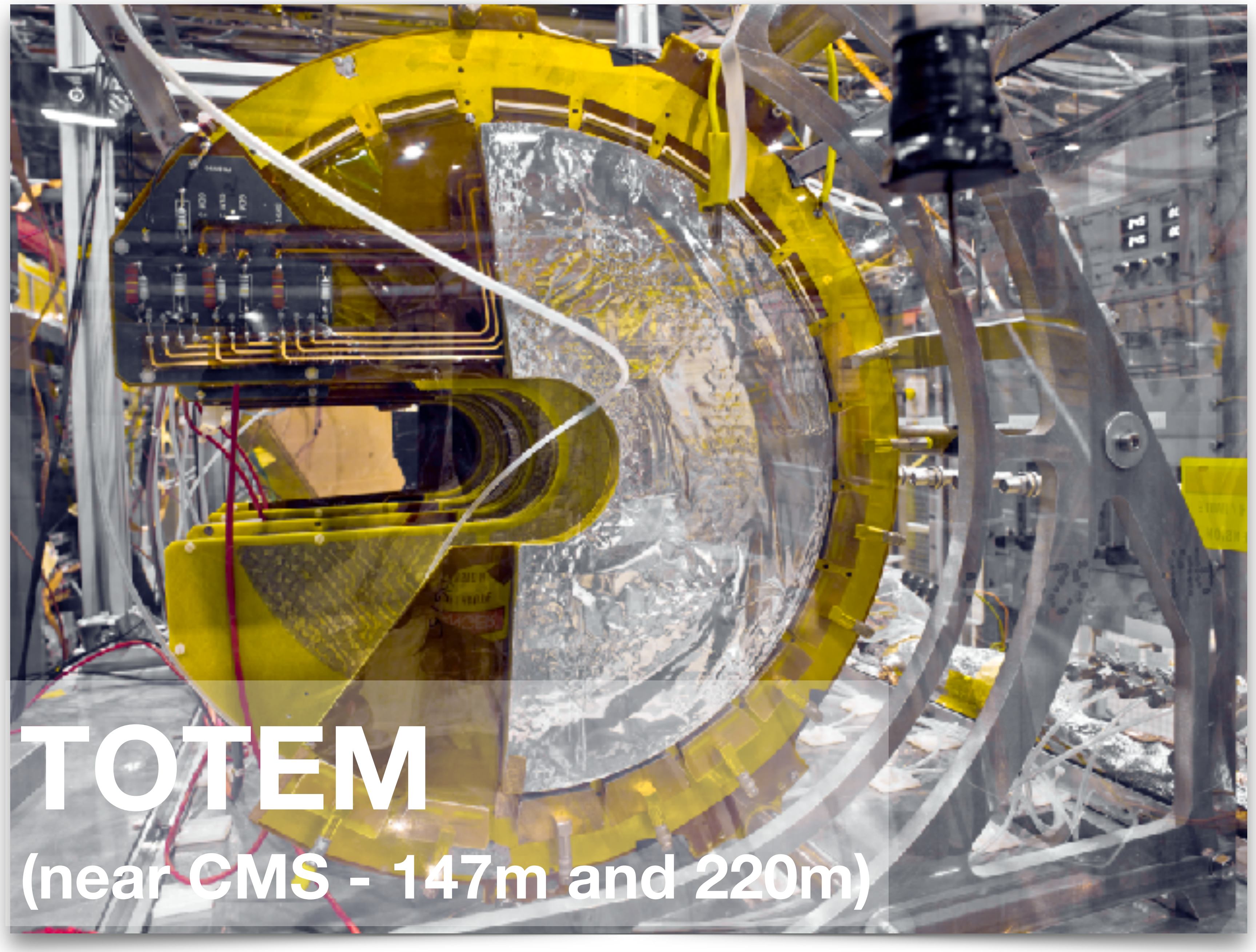
LHC Experiments
Specialised Detectors

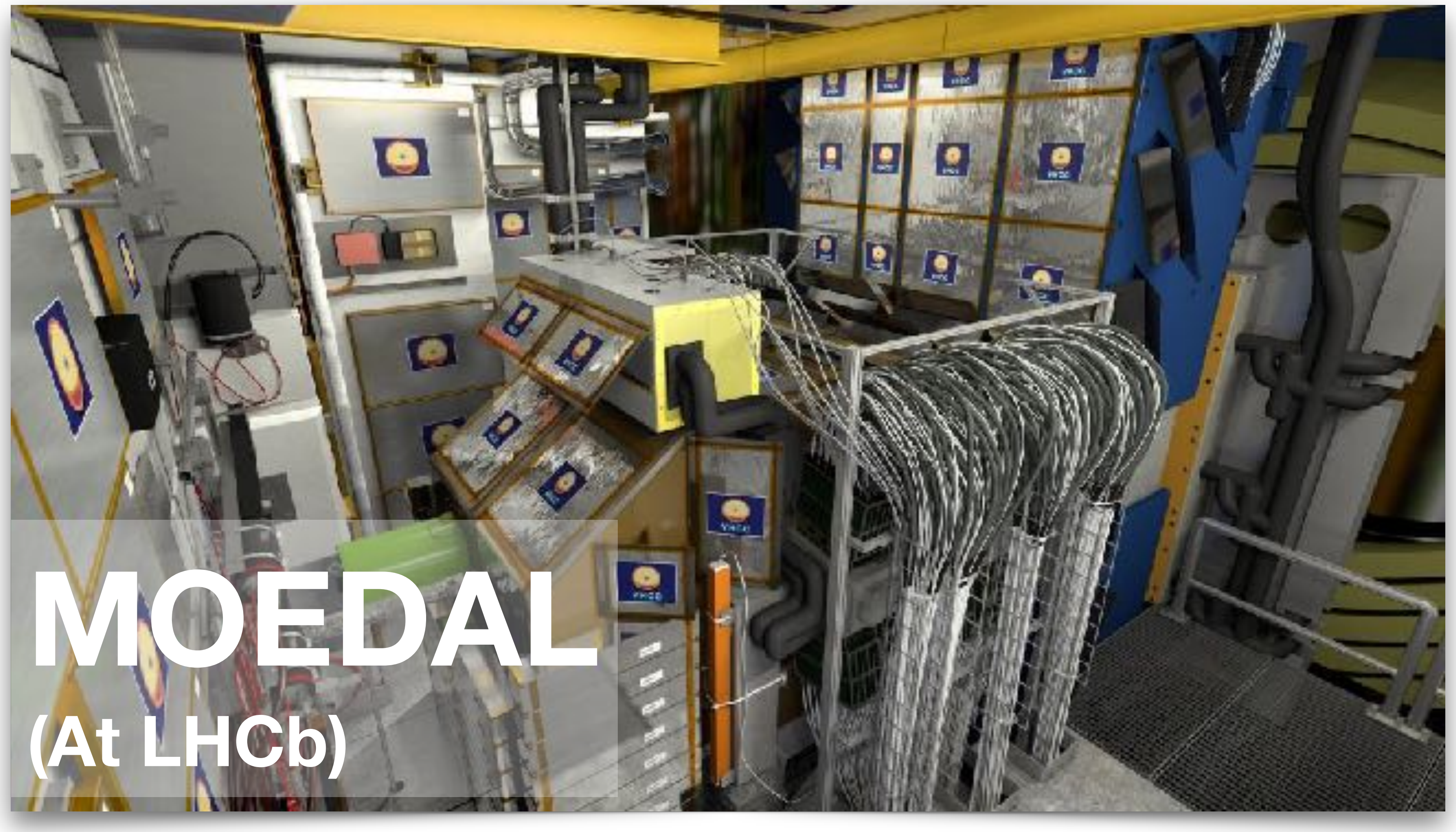




Lecture by Mark Williams

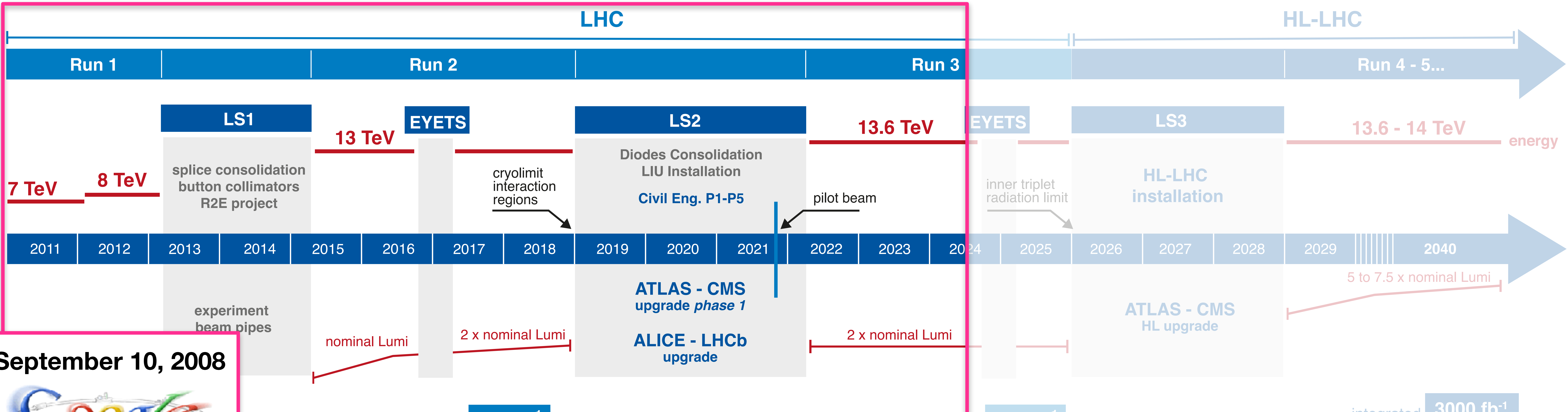
LHC More Specialised Detectors





Latest experiments on board!

10 Years of LHC Operations

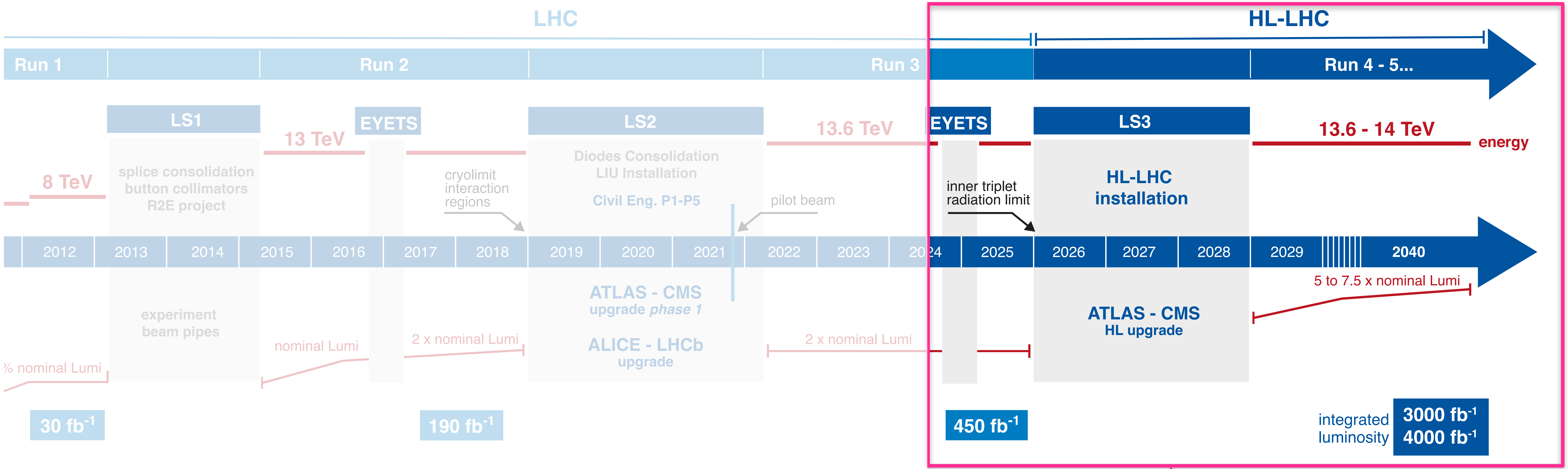


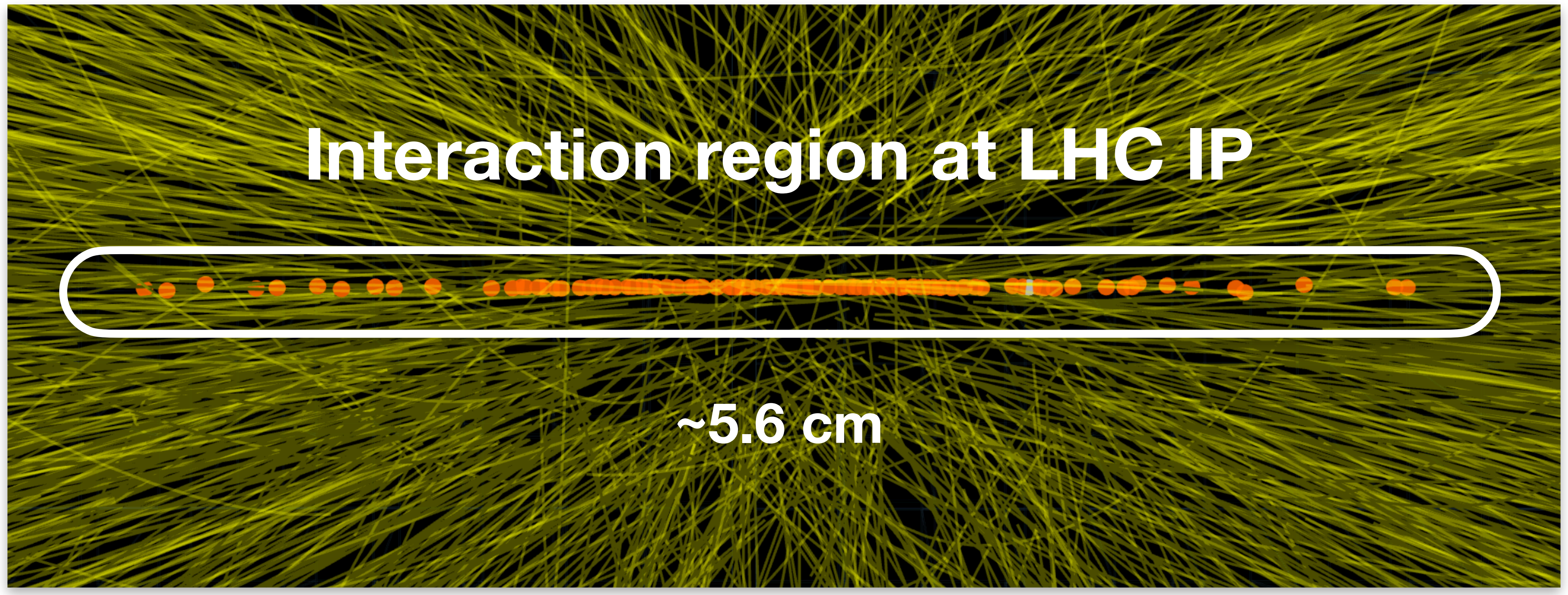
September 10, 2008

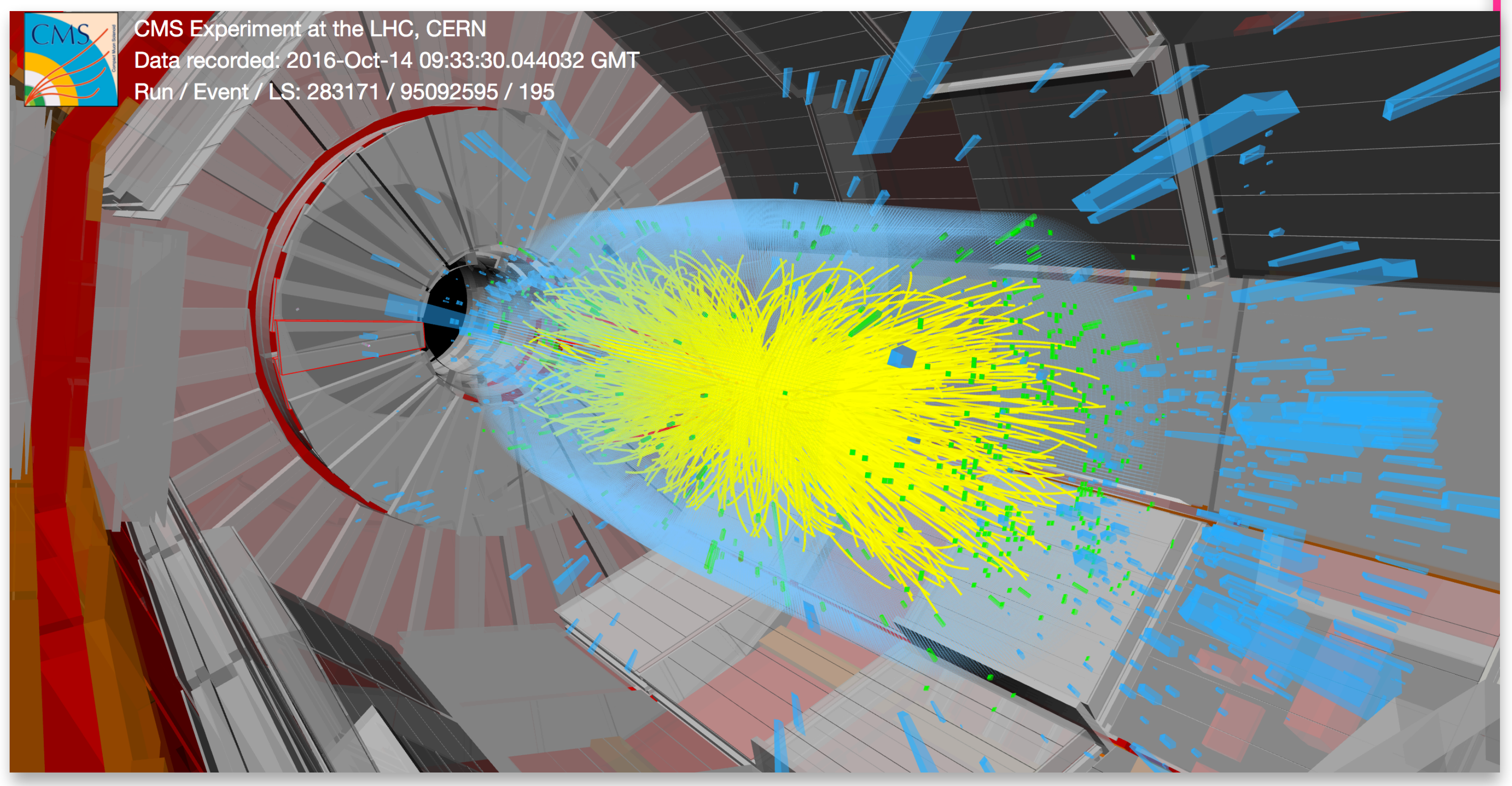
The day the world switched on to particle physics

We are here!!

The next 20 Years of LHC: Towards HL-LHC





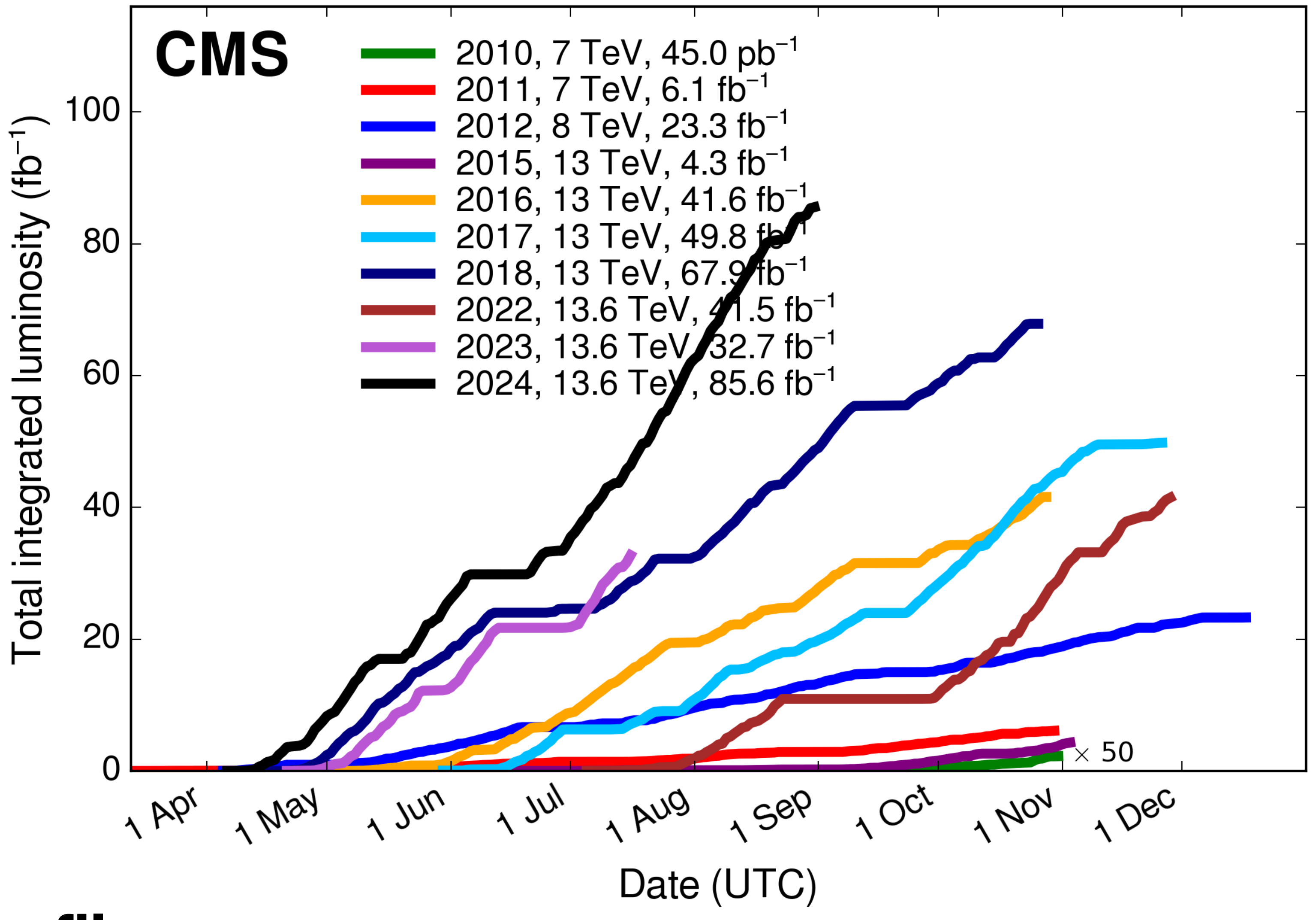


Higher intensity comes at a cost PU (up to 140-200) and requires major upgrades (LS3)!

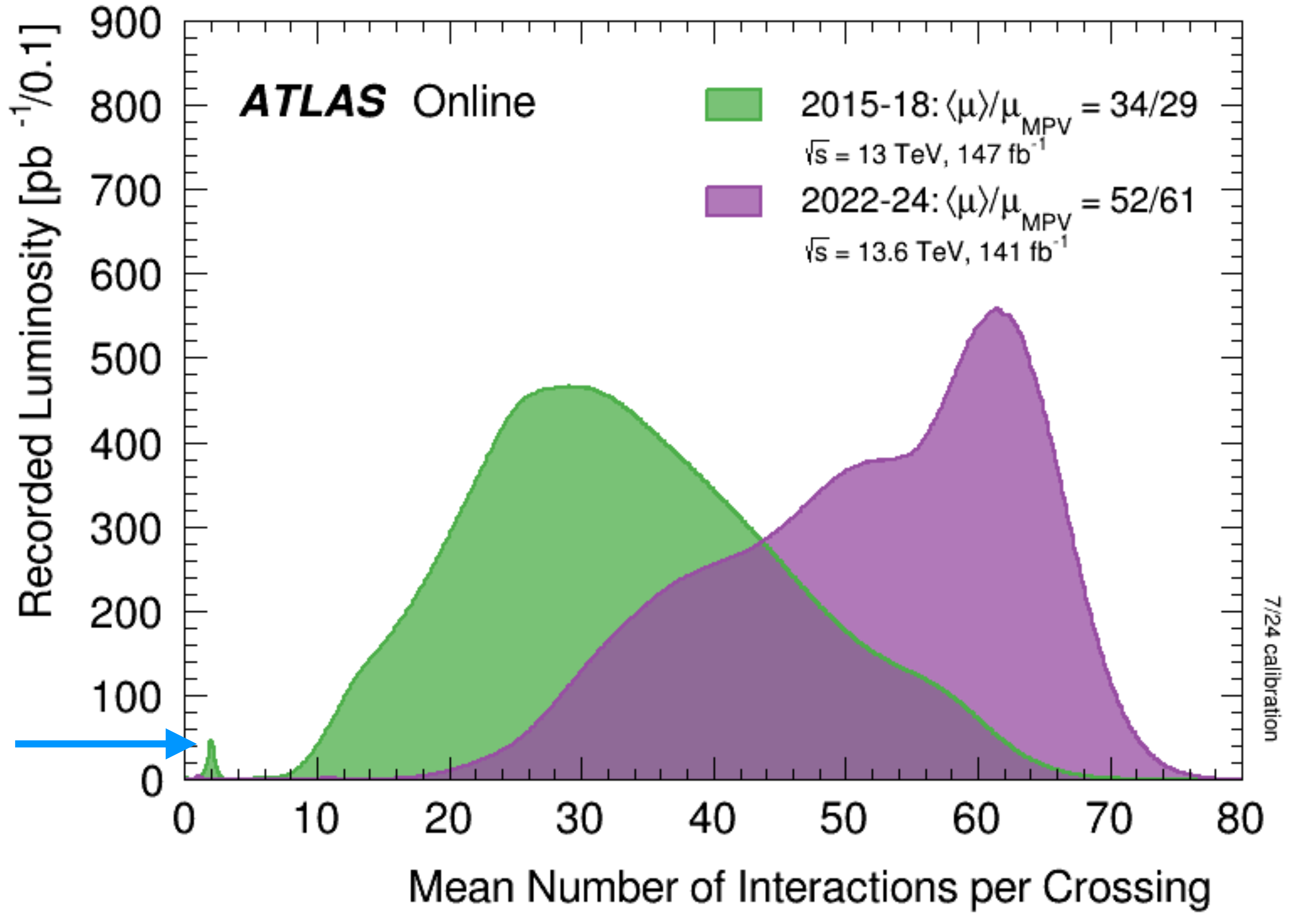
Approximately x10 Luminosity delivered (in terms of results x20)

The LHC datasets

The LHC pp operations for ATLAS and CMS



PU profile



Special low mu runs for precision EW measurements

Run 3 datasets — pp **13.6 TeV** 2022-2024 ~85 **fb^{-1}** with ~90% data taking and data quality efficiency

Run 2 datasets — pp **13 TeV** 2015-2018 - ~**140 fb^{-1}** with ~95% data taking efficiency and ~95% data quality efficiency

(8M Higgs, 300M top quarks, 8B Z's, 30B W's)

Run 1 datasets — pp **7-8 TeV** 2010-2012 - ~**25 fb^{-1}** with ~95% data taking efficiency and ~95% data quality efficiency

LHCb

Run 1
2011: 1.0 1/fb
2012: 2.0 1/fb

Run 2
2015: 0.3 1/fb
2016: 1.6 1/fb
2017: 1.7 1/fb
2018: 2.1 1/fb

L~9 1/fb and PU ~ 2-3

Rich Heavy Ions datasets — With **PbPb, XeXe, pPb** and in LHCb fixed target p or Pb on **He, Ne, Ar**.

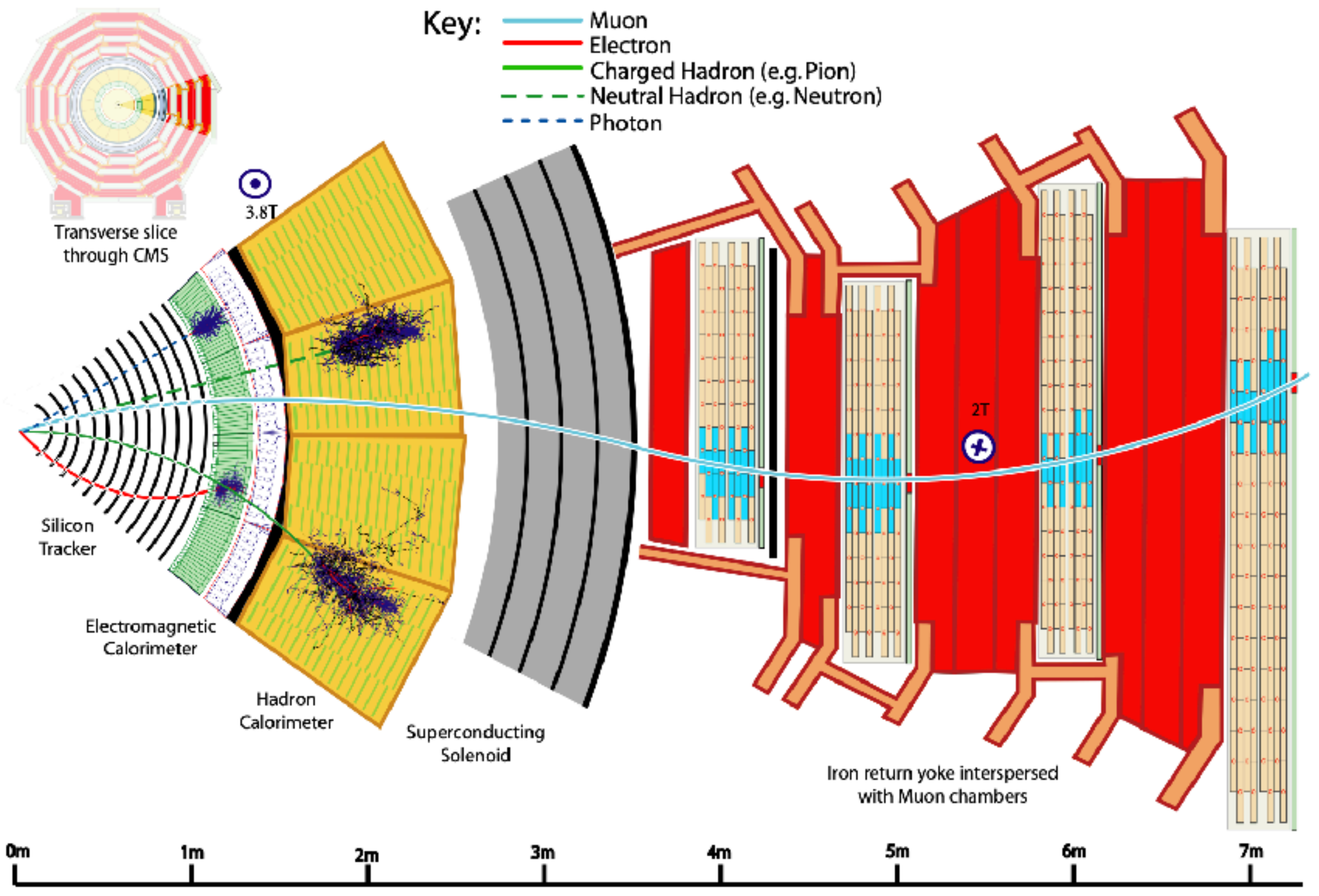
Low PU pp references (e.g. for ATLAS)

- 5.02 TeV - 0.26 fb^{-1}
- 13 TeV - 0.35 fb^{-1}

Well calibrated datasets for a vast, diverse and thrilling physics program!

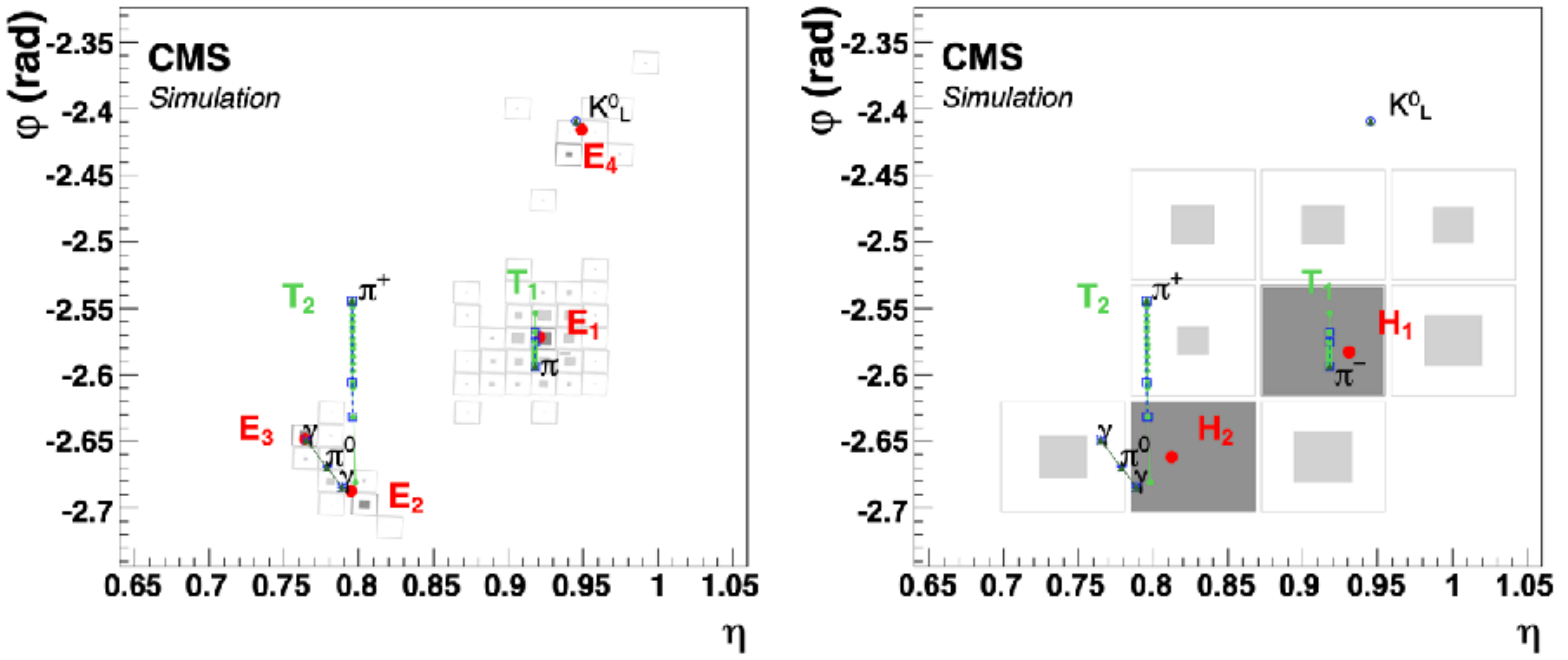
Event Particle (and Energy) Flow

From the **detector signals** (ionisation, electron-hole, Scintillation, Cherenkov, Transition Radiation, etc.) reconstruct tracks of charged particles, energy deposits and the particle content of the event (not all and not perfectly well)!



The optimal reconstruction of the event Particle and Energy Flow in the event is the basis of all analyses in HEP!

e.g. CMS very successful global PFlow algorithm (paper)



From the main Particle and Energy flow of the event, all higher level information: e.g. jets, HF-jets, taus, and MET are reconstructed.

See exercises by Jan Kiessler!

Performance Achievements: Object Reconstruction

Electrons, photons and muons

- Multivariate methods used for identification (at many levels) and calibration
- In-situ calibration using Z, W, J/Psi and Upsilons

Jets/MET

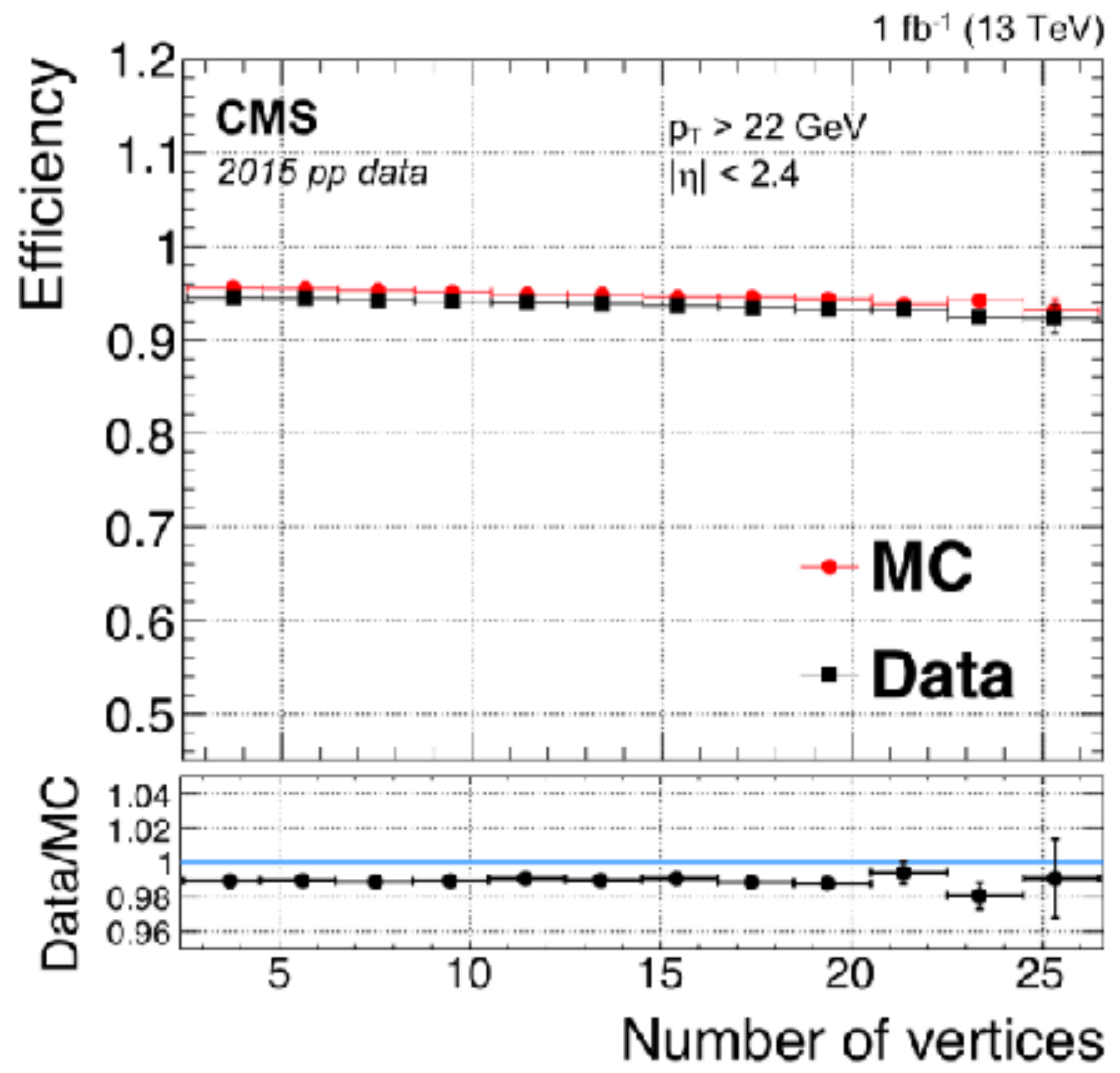
- JES *in situ* uncertainty reach ~1% level already (central and intermediate pT range) – using Z, γ and multi-jets.
- PU mitigation using associated tracks (jets and soft term in MET)

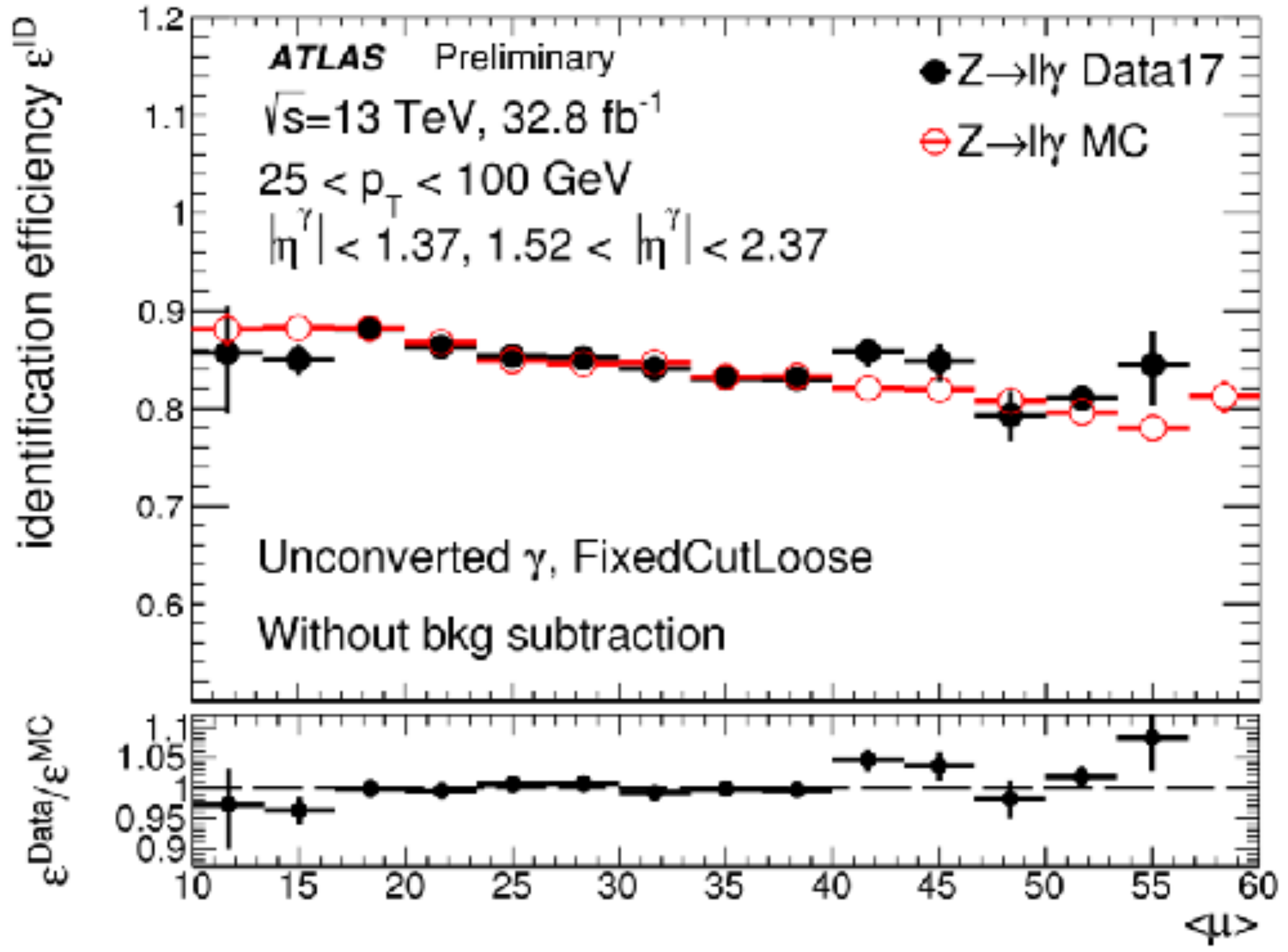
Taus

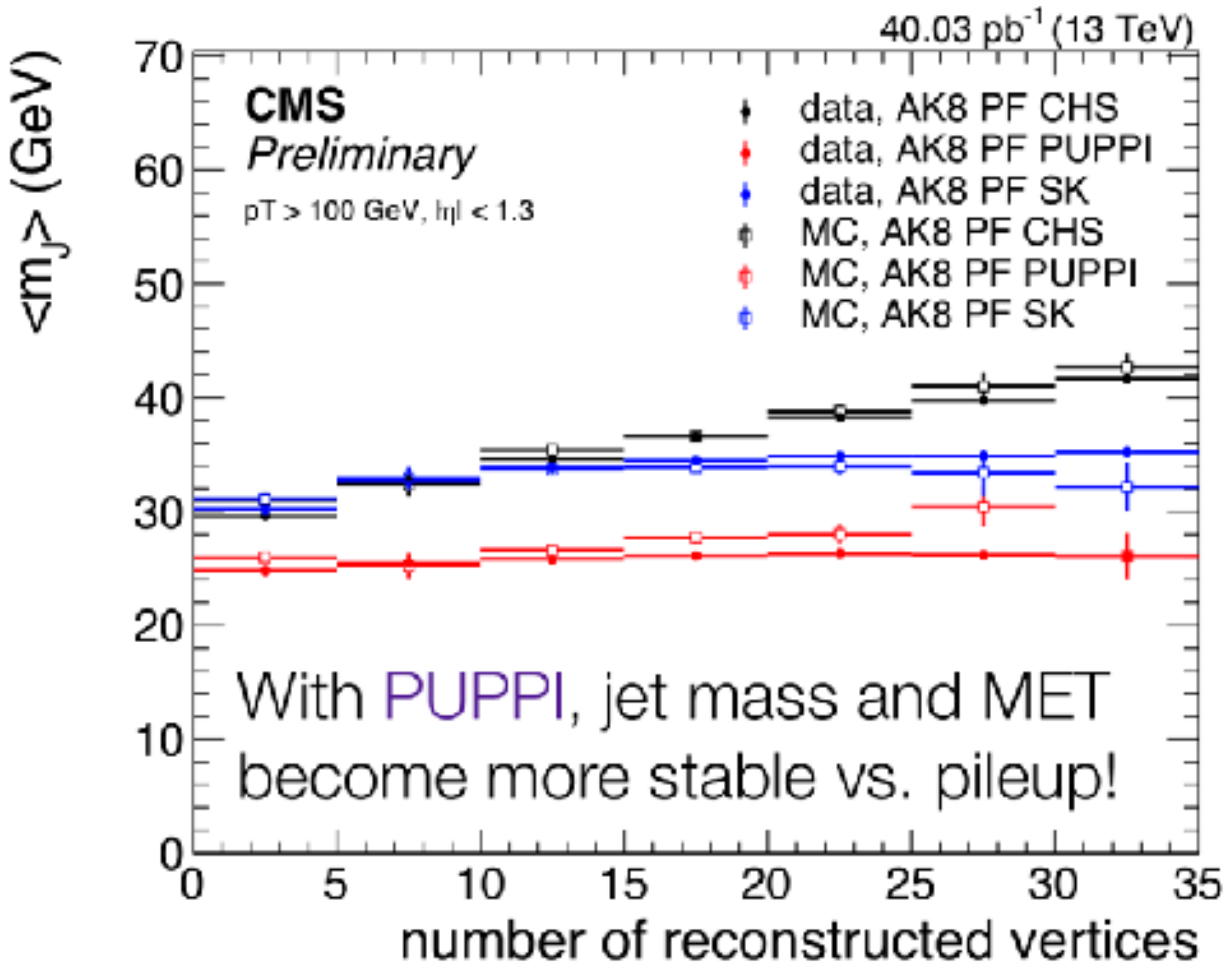
- DL based identification (70% eff. and ~50 rej.)
- In-situ calibration based on Z events

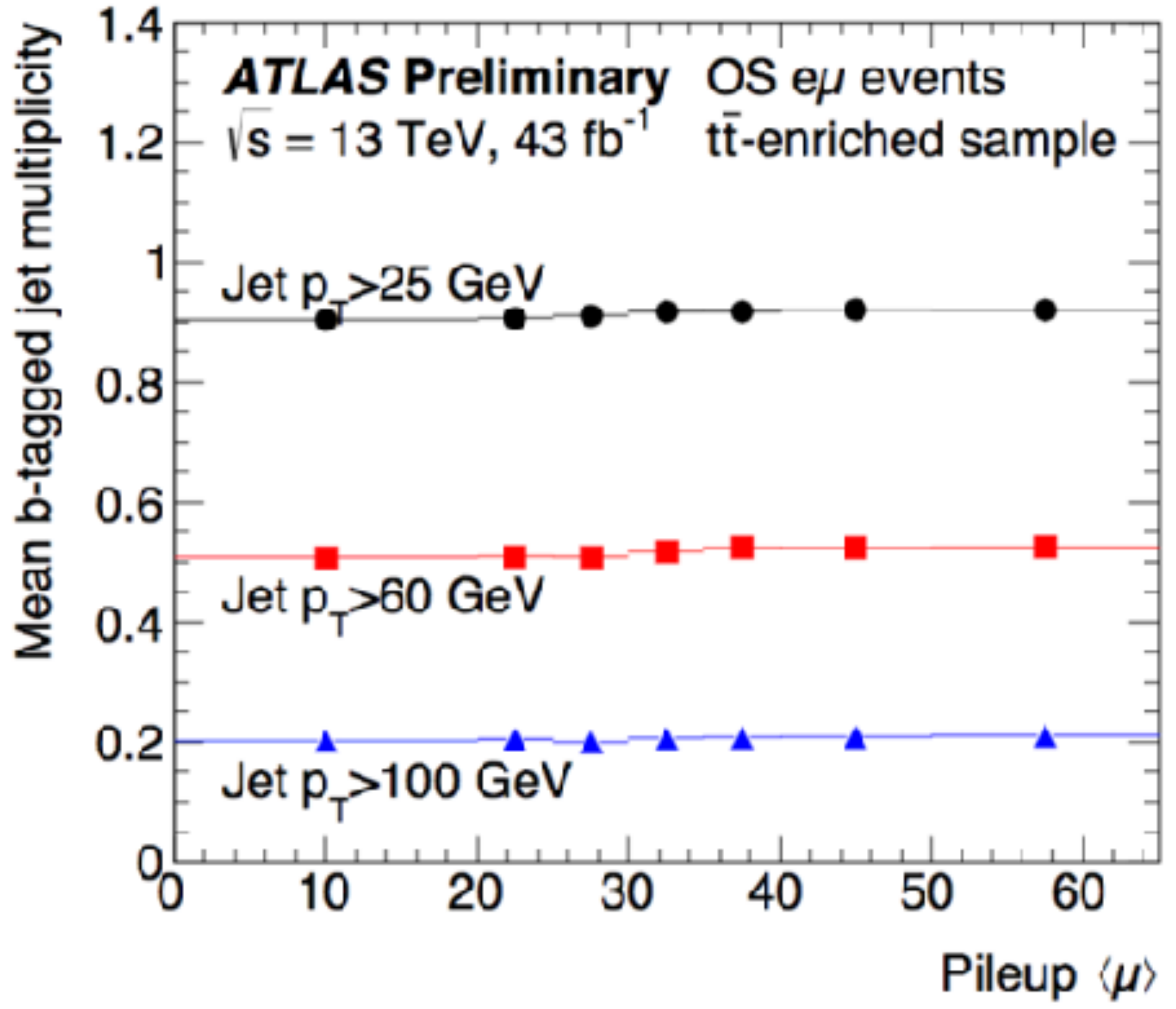
B- and C-jets

- In-situ calibration of b-tag efficiency (using top events and/ or diet events)
- DL techniques from low level variables bring significant improvements









Performance Achievements: Object Reconstruction

Electrons, photons and muons

- Multivariate methods used for identification (at many levels) and calibration
- In-situ calibration using Z, W, J/Psi and Upsilons

Jets/MET

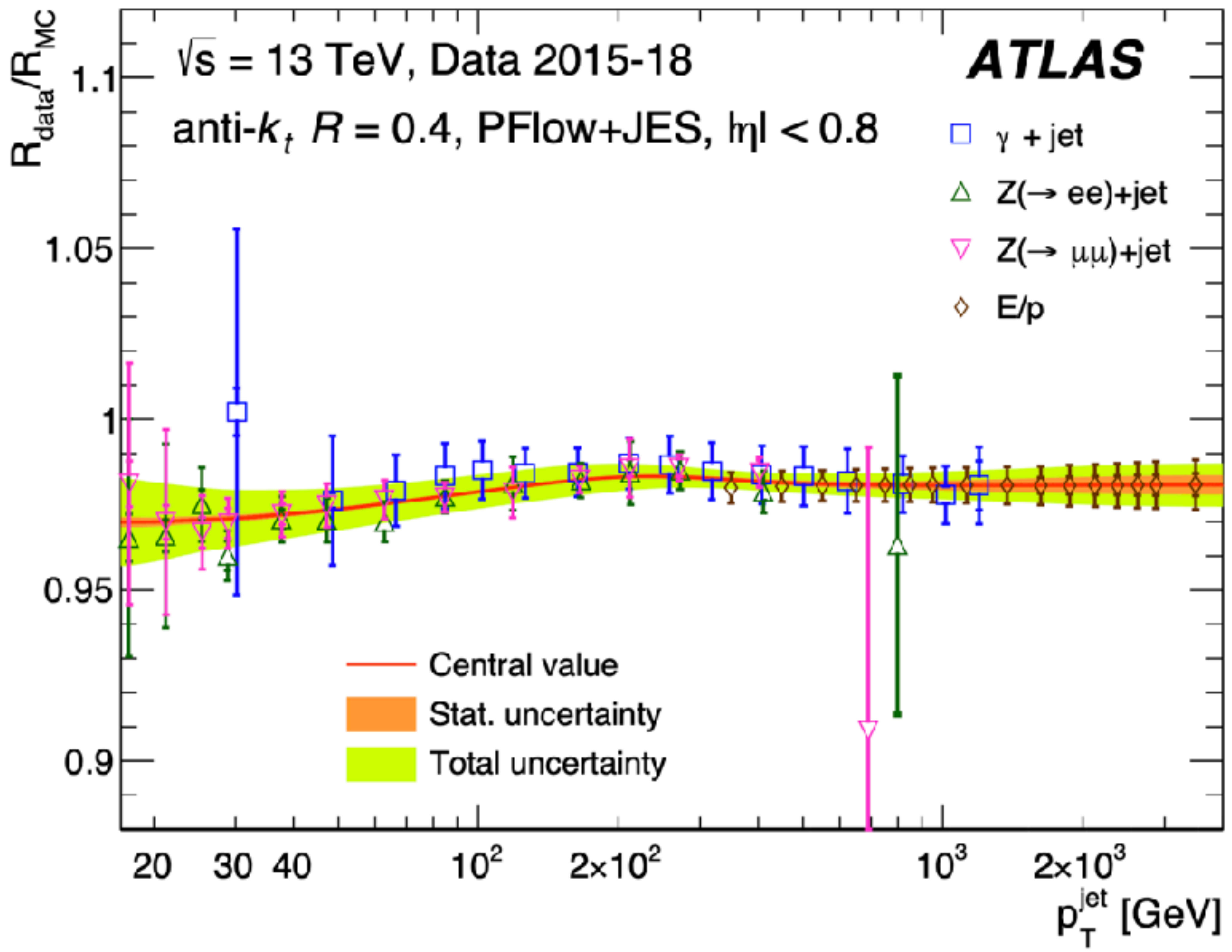
- JES *in situ* uncertainty reach ~1% level already (central and intermediate pT range) – using Z, γ and multi-jets.
- PU mitigation using associated tracks (jets and soft term in MET)

Taus

- DL based identification (70% eff. and ~50 rej.)
- In-situ calibration based on Z events

B- and C-jets

- In-situ calibration of b-tag efficiency (using top events and/ or diet events)
- DL techniques from low level variables bring significant improvements



E.g. **recent development**: use $W \to \tau\,(\to h)\,\nu$ to calibrate single hadron energy response through E/p allowed to greatly improve jet calibration in particular in the extrapolation at high energies!

Total PFlow JES uncertainty in ATLAS down to **0.3% at 400 GeV** !

Performance Achievements: Object Reconstruction

Electrons, photons and muons

- Multivariate methods used for identification (at many levels) and calibration
- In-situ calibration using Z, W, J/Psi and Upsilons

Jets/MET

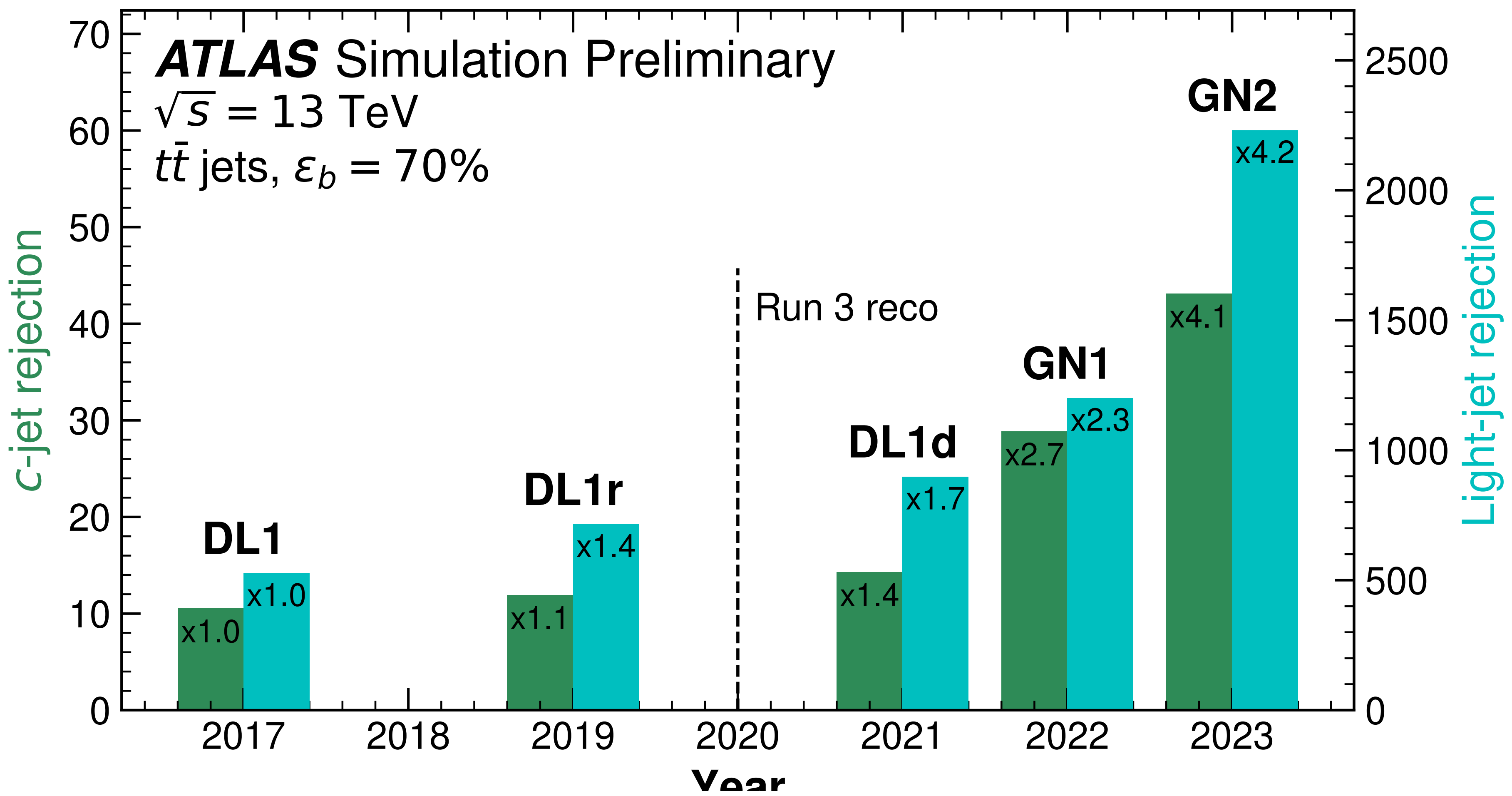
- JES *in situ* uncertainty reach ~1% level already (central and intermediate pT range) – using Z, γ and multi-jets.
- PU mitigation using associated tracks (jets and soft term in MET)

Taus

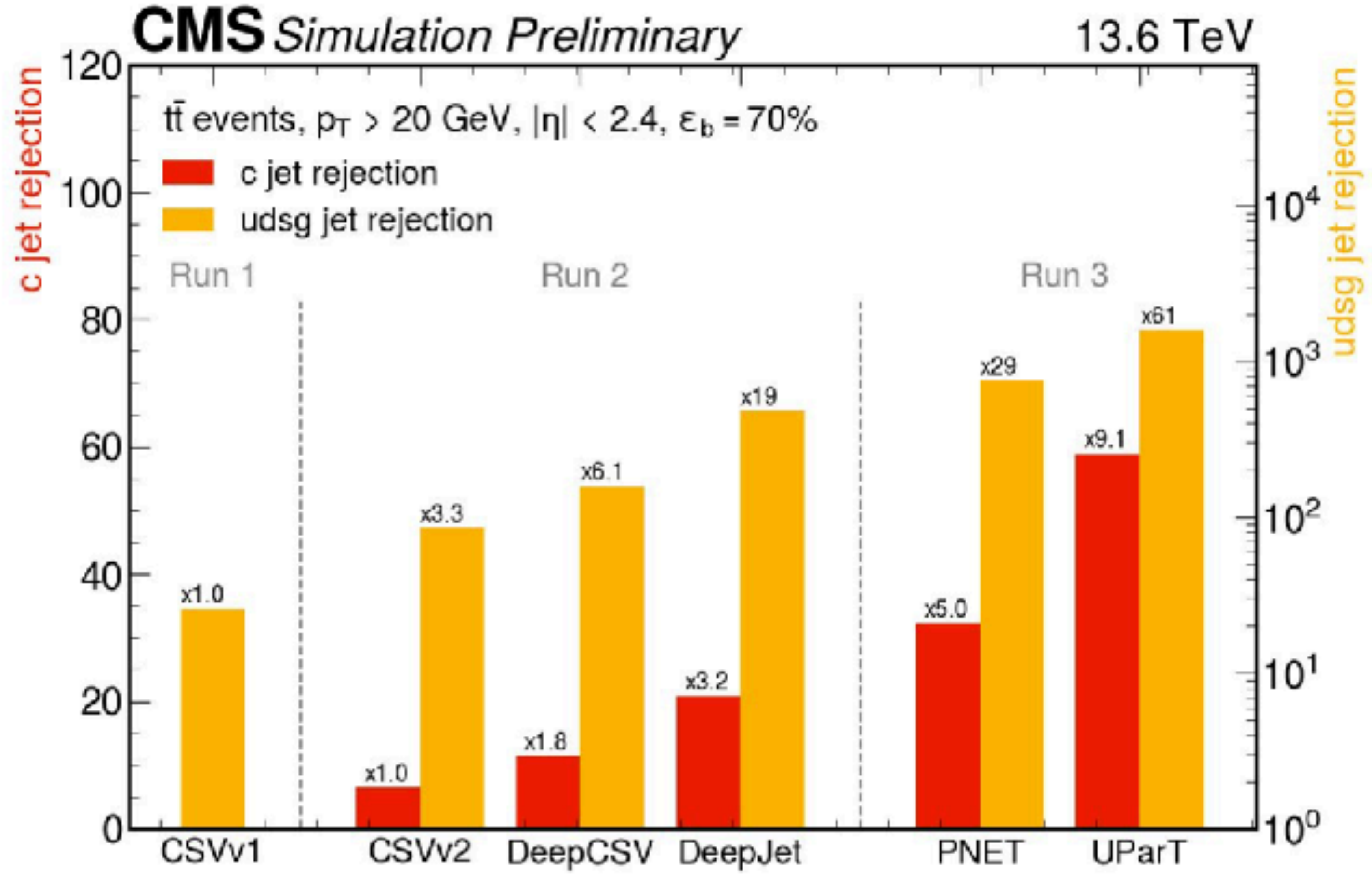
- BDT and RNN based identification (70% eff. and ~50 rej.)
- In-situ calibration based on Z events

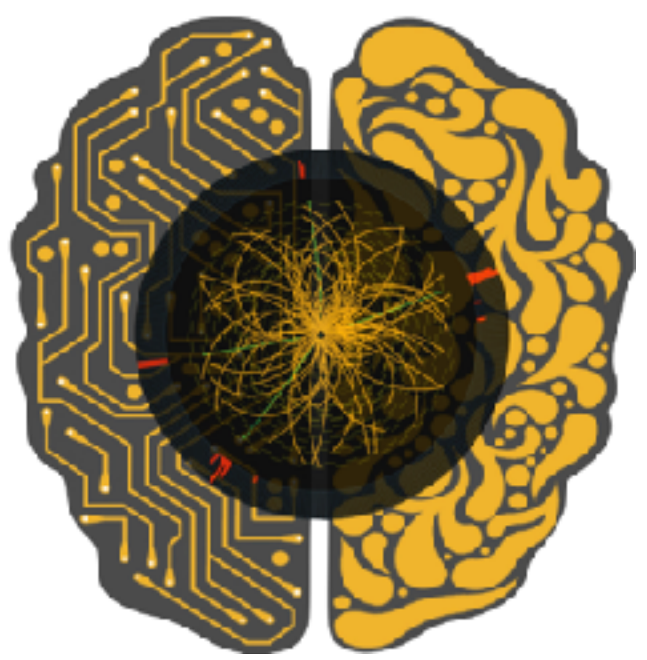
B- and C-jets

- In-situ calibration of b-tag efficiency (using top events and/ or diet events)
- DL techniques from low level variables bring significant improvements



ATLAS LOVES ML/AI





CMS does too…

Reconstruction performance: Well calibrated, robust to PU and… well exceeding expectations!

Reconstruction Performance

- Run 1 - 3: So far excellent trigger and object reconstruction performance in **increasing levels of PU**. Trigger Thresholds kept stable throughout!

- **Going to HL-LHC**: The gain in acceptance and in performance with new detectors (to improve PU mitigation), new algorithms and new computing capabilities is expected to at least match current experimental performance.

    - Keeping Trigger thresholds at similar levels
    - Object reconstruction performance (efficiency vs rejection and energy scale and resolution) at stable levels.
    - Challenge: improve calibrations not only with more data to come but also improved strategies.

Menus at LHC and for HL-LHC (example from ATLAS)

Signature	Run 1	Run 2	HL-LHC
Single e (isolated)	25	27	22 / 27
Single photon	120	140	120*
HT	700	700	375 / 350
MET	150	200	200

From A. Sfyrla LHCP 2018

For **Run 3 similar thresholds** (with upgraded TDAQ)

- Increase readout rate 750-1000 kHz (currently 100 kHz).
- Increased latency and higher granularity.
- Enhanced data processing capabilities, storage rate up to 10 kHz (currently 1-2 kHz).

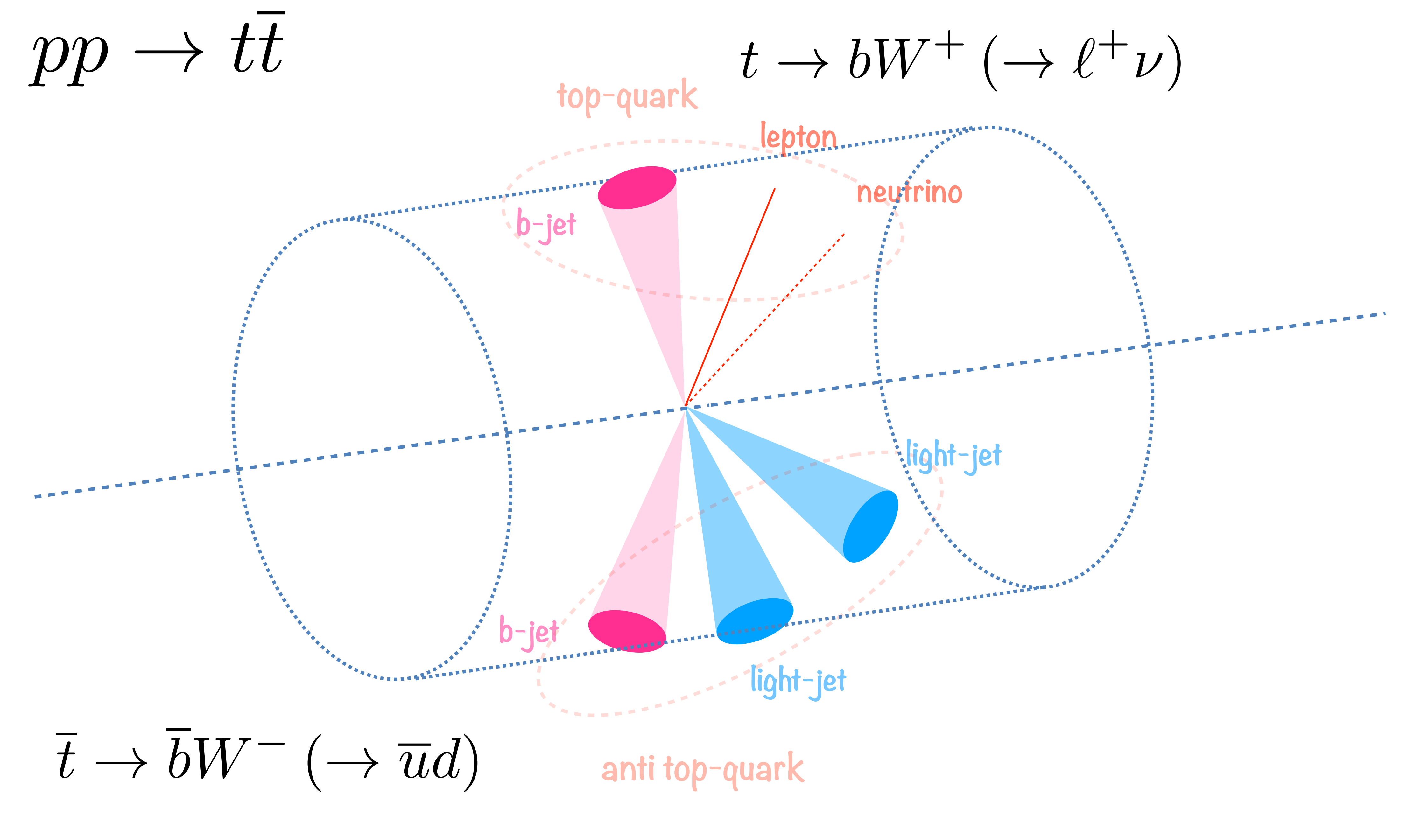
Measuring Physical Processes

Fiducial volume and Acceptance

The detector can measure photons, charged leptons, hadrons, and missing transverse momentum **only within its detector/ trigger capabilities** (limited in pseudo rapidity and in transverse momentum/energy of the particles).

A measurement of a total cross section necessarily involves the extrapolation from the fiducial volume.

Definition of a fiducial volume: the phase space in which a given final state is measurable (this does not only include the volume of the detector and its thresholds in energy, but also aspects such as the isolation)



Corresponding (typical) fiducial volume

- One true lepton (electron or muon) ET/pT> 25 GeV and with in |eta|<2.5.
- 4 Truth particle jets wit ET> 35 GeV and |eta|<2.5.

More complete fiducial volume

- Truth level missing transverse energy larger than 30 GeV.
- 2 of the truth particle jets originate from a b-quark.
- Truth particle level lepton isolation

Reconstruction level typical selection

- One identified and isolated lepton (electron or muon) ET/ pT> 25 GeV and with in |eta|<2.5.
- Missing transverse momentum in excess of 20 GeV.
- Four jets wit ET> 35 GeV and |eta|<2.5.
- Two jets tagged as b-jets.

More Cross Sections Definitions

Total, fiducial, differential and unfolded

Being a bit more precise on how to derive the cross section from the counted number of events with specific analysis selection criteria:

Total cross section

$$\sigma_{tot} = \frac{N_{evts}}{\mathcal{A} \times \varepsilon \times \int \mathcal{L}dt}$$

Where σ_{tot} is the total cross section for a given process (which includes the decay branching fractions), A the acceptance of the process, ε is experimental efficiency (online and offline) and L is the integrated luminosity.

$\mathcal{A}$ The acceptance A defined by the ratio of number of events produced in the fiducial volume to the total number of events. It is an extrapolation factor estimated by theory (typically with Monte Carlo).

Fiducial cross section

$$\sigma_{fid} = \frac{N_{evts}}{\varepsilon \times \int \mathcal{L}dt}$$

With a definition of the fiducial region, ε should be large and the fiducial cross section bear little model dependence

Differential cross section w.r.t. (truth level) variable t

The notion of differential cross section in HEP is binned in truth level variables and measurements in corresponding reconstruction level variable: r

Truth distribution $f(t)$

Reconstructed distribution $g(r)$

Generating the reconstructed distribution (detect. simulation) $f(t) \rightarrow g(r)$

Unfolding estimating the truth from the reconstructed $g(r) \rightarrow f(t)$

To be solved numerically the problem needs to be discretised:

$$f(t) \rightarrow \mathbf{x} \qquad g(r) \rightarrow \mathbf{y}$$

$$\mathbf{x} = \mathbf{A}^{-1}\mathbf{y}$$

For the case where the number of truth and reconstructed bins are the same

A is the response matrix - Of course there are many intricacies arising in particular from non accurate response matrix.

More Cross Sections Definitions

Total, fiducial, differential and unfolded

Take home message: ideally a well defined fiducial cross section will minimise the dependence on TH and modelling assumptions.

This draws the focus on the experimental understanding of the measurements on truth particles that are reconstructable.

These will allow improved future interpretations of the data with and when new TH and modelling tools will be available.

Very important data preservation tools excellent database and tools:

HEPData

Repository for publication-related High-Energy Physics data

Link

Most LHC results implemented!

RIVET

The Particle Physics Analysis Tolkit

Link

Large number of analyses implemented!

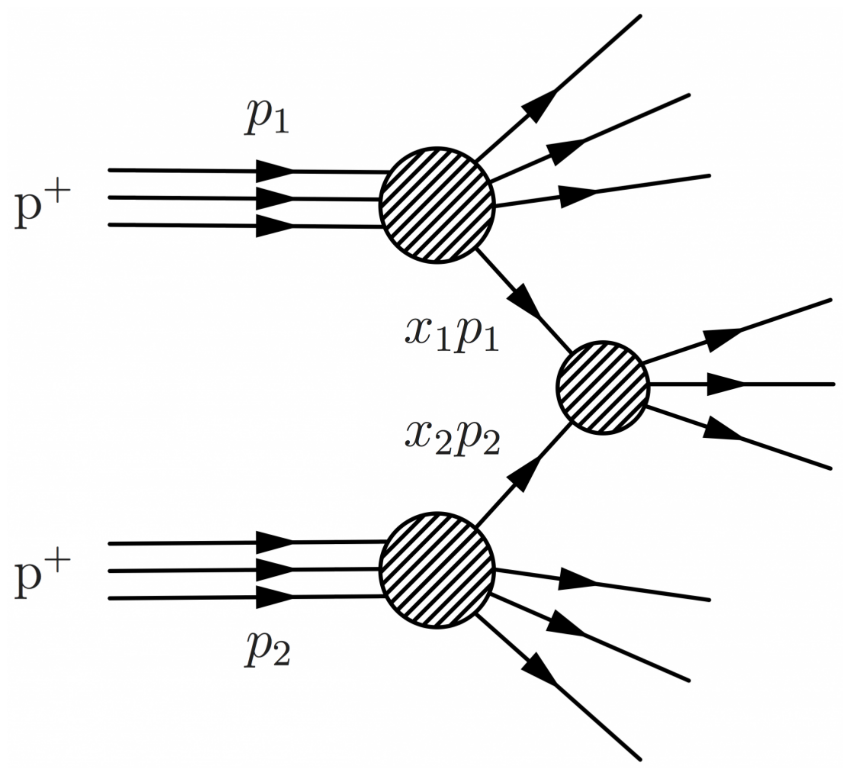
(Outstanding contribution from IPPP Durham!)

Total and Elastic Cross Sections

Measurement of the Total Cross Section

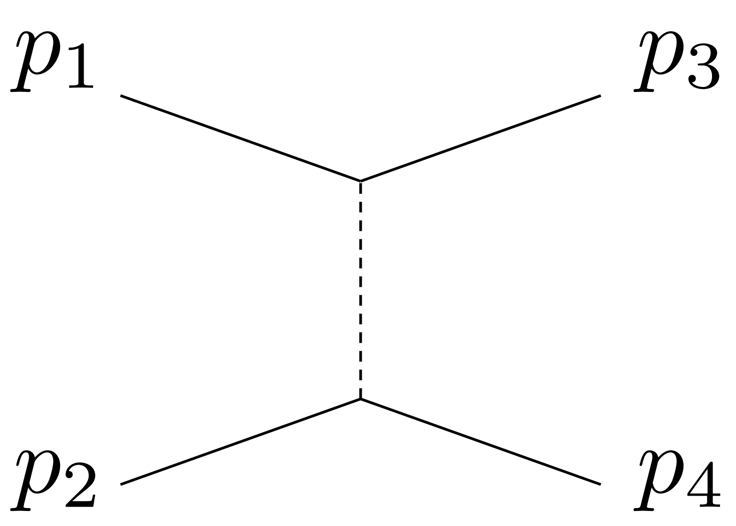
From the size of the proton ~O(80) mb naive estimate of the total cross section of pp collisions.

The total cross section is dominated (60 mb) by inelastic interactions.



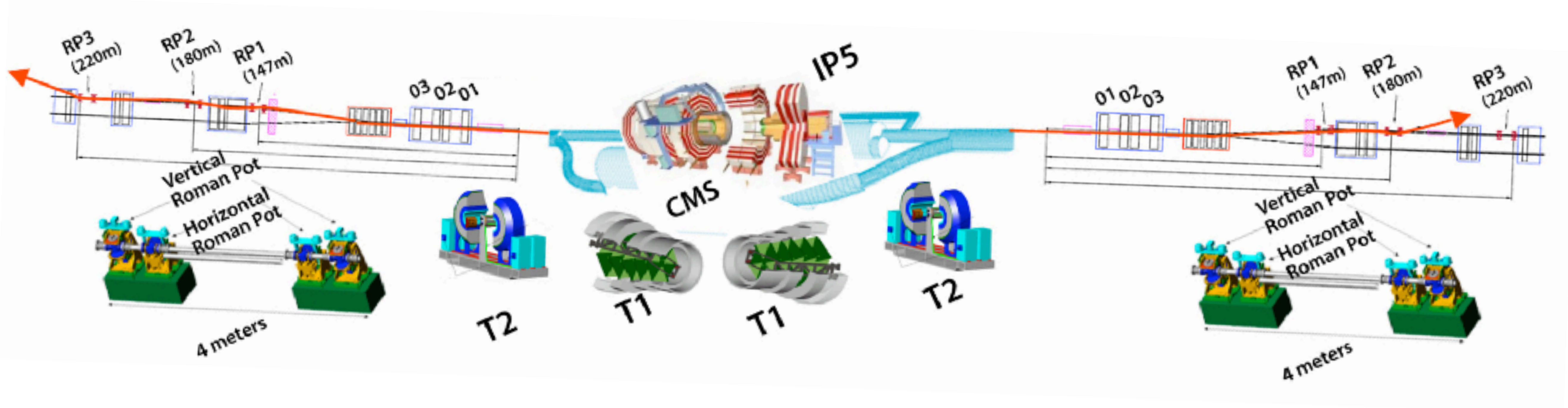
The main subject of these lectures.

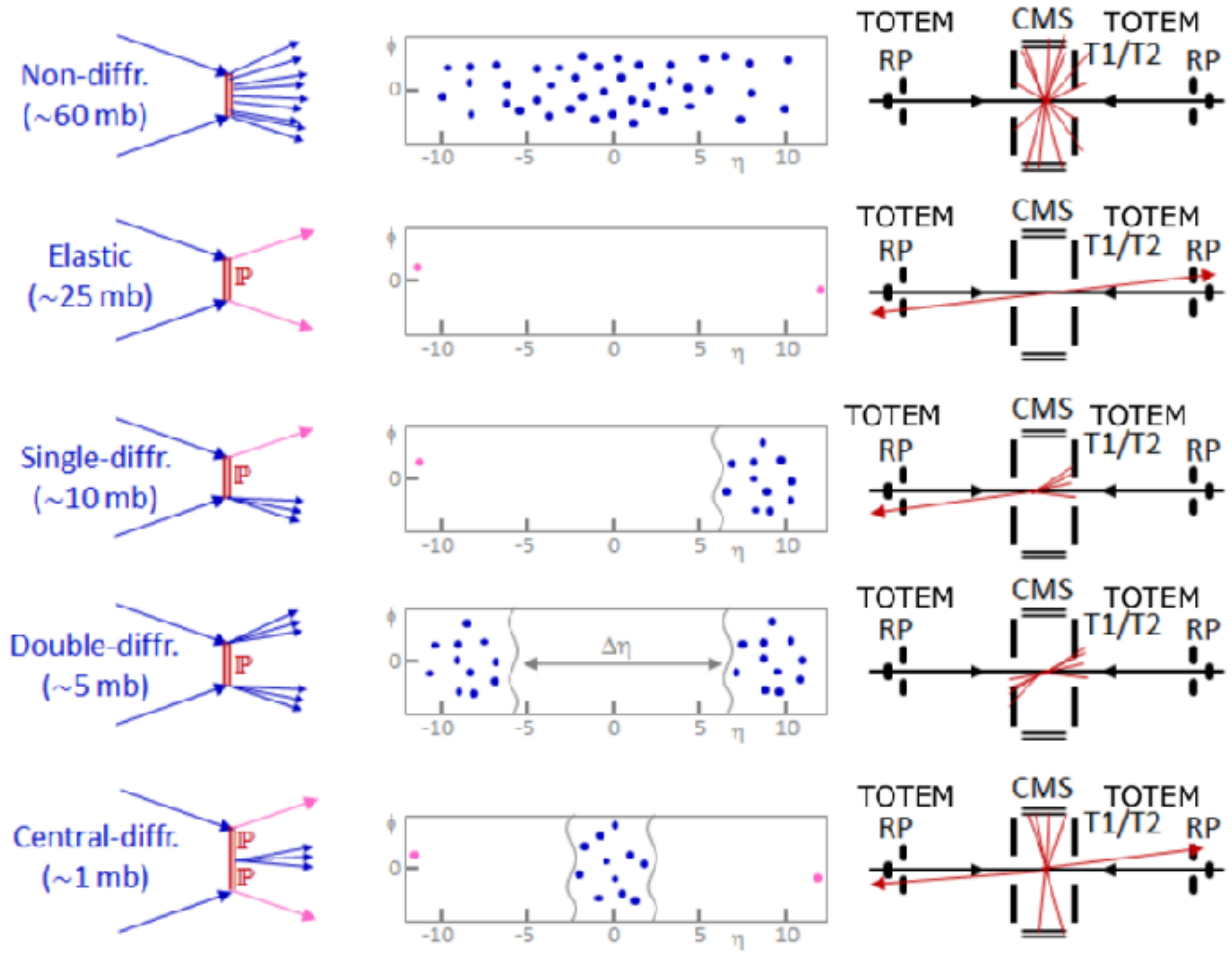
Includes elastic interactions from exchange of photons or pomerons (20 mb).



$$t = (p_1 - p_3)^2$$

(very naive view of the pomeron is a colorless pair of gluons)





The simplest measurement of the cross section counting events:

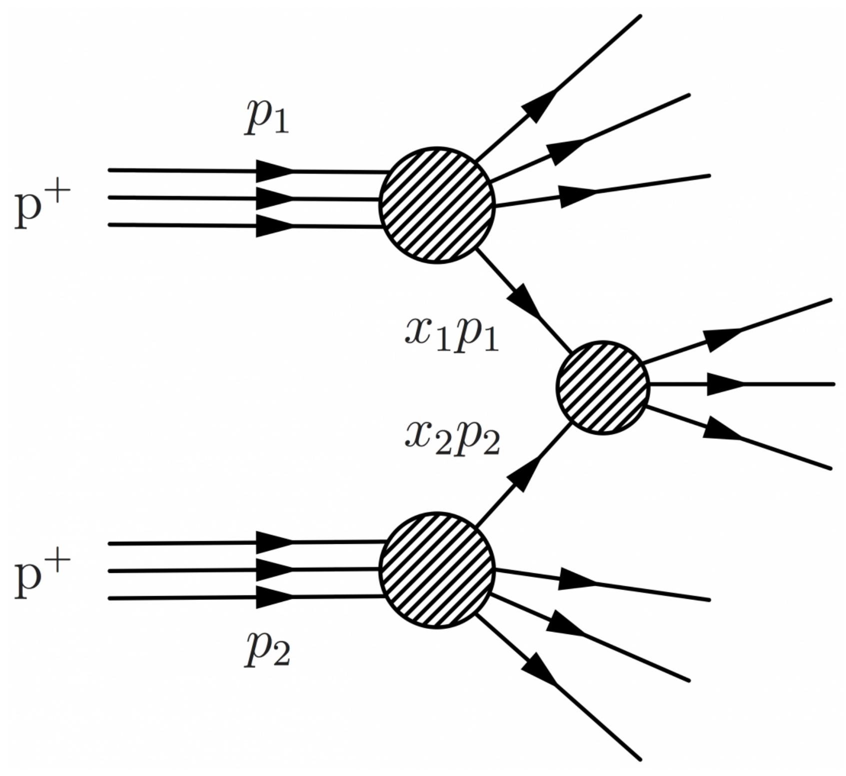
$$\sigma_{tot} = \frac{N_{el} + N_{inel}}{\mathcal{L}}$$

The Totem experiment can measure both the elastic (with detectors in Roman Pots from 150m to 220m) and the inelastic with detectors near the IP.

Measurement of the Total Cross Section

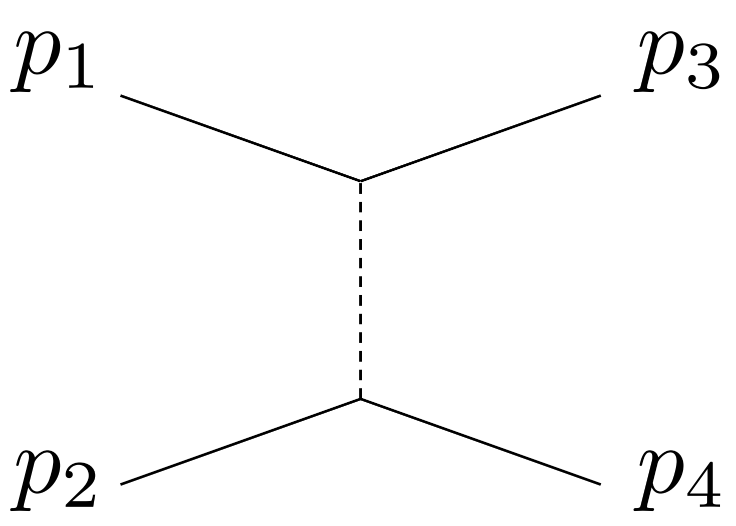
From the initial O(80) mb naive estimate of the total cross section of pp collisions.

The total cross section is dominated (60 mb) by inelastic interactions.



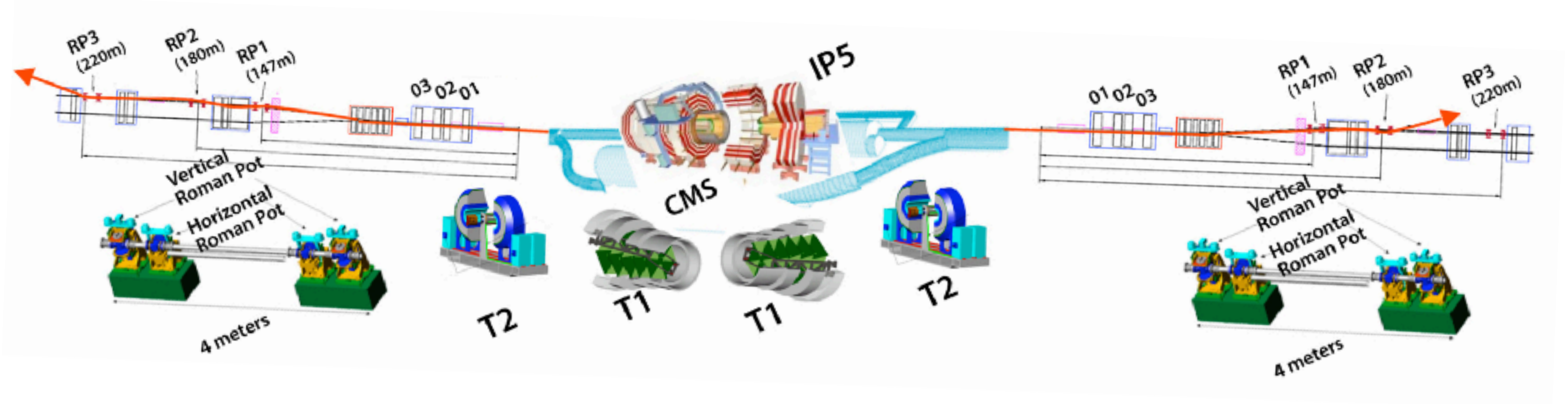
The main subject of these lectures.

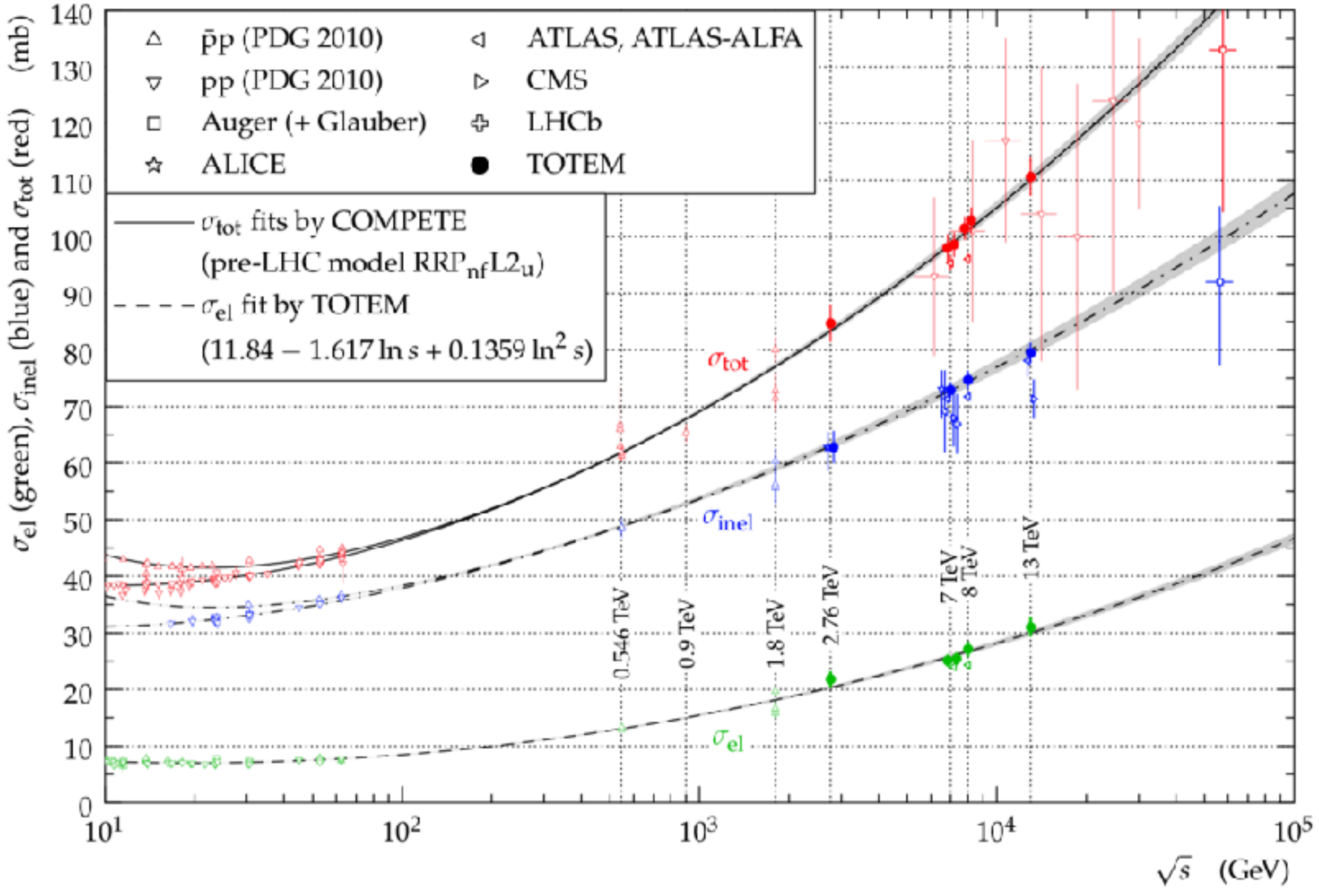
Includes elastic interactions from exchange of photons or pomerons (20 mb).



$$t = (p_1 - p_3)^2$$

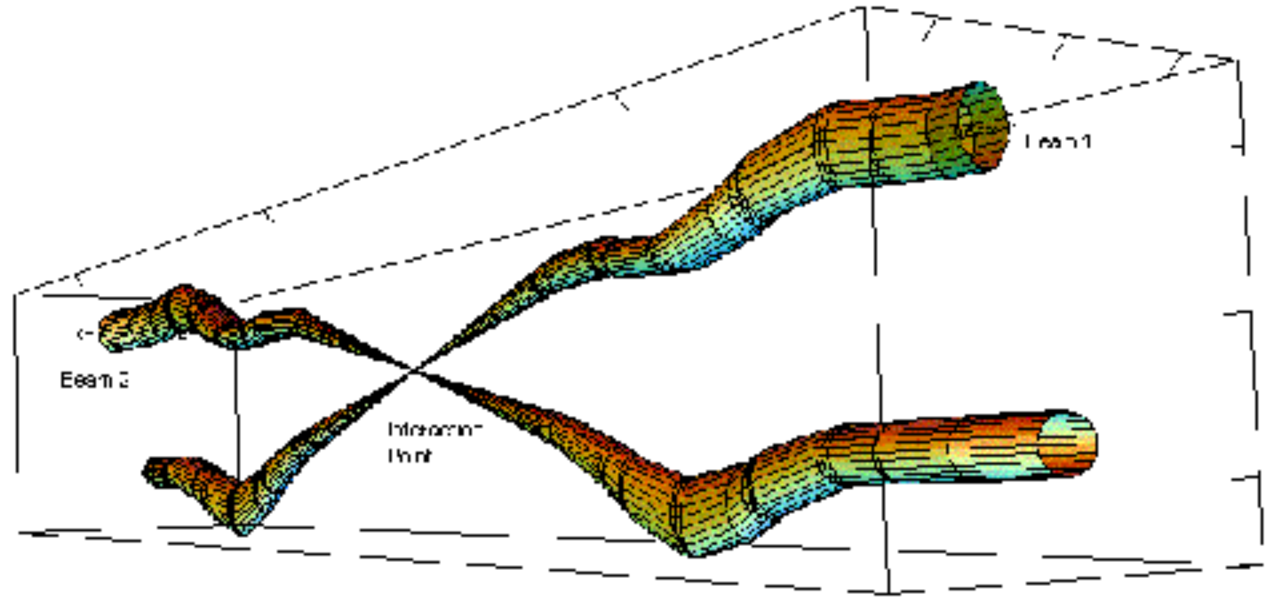
(very naive view of the pomeron is a colorless pair of gluons)





The measurement of the total cross section can also be done through the measurement of the **elastic cross section at (very) low momentum transfer and the optical theorem!**

Measurement of the differential elastic cross section



Requires special beam optics with very large beta* (90m - 2.5km) and no crossing angle.

Using the Optical Theorem: relates the forward elastic cross section (scattering at 0 momentum transfer) and the total cross section.

$$\sigma_{tot} = 4\pi \, \mathrm{Im}[f_{el}(0)]$$

f_{el} is the forward elastic scattering amplitude.

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{(dN_{el}/dt)_{t=0}}{N_{el} + N_{inel}}$$

Requires measurement of inelastic events

$$\rho = \mathrm{Re}[f_{el}(0)]/\mathrm{Im}[f_{el}(0)]$$

ρ~0.14 is taken from TH predictions (known typically at 0.5%)

To reach the CNI (Coulomb Nuclear Interference) region requires very special beam optics with a β* of 2.5 km.

LHC also requires « de-squeezing », reaching such large beta* is another great achievement of the LHC!!

An analysis by TOTEM with recent run at 13 TeV and beta* 2.5 km yields a measurement of rho with a fit to the CNI region (see next slide).

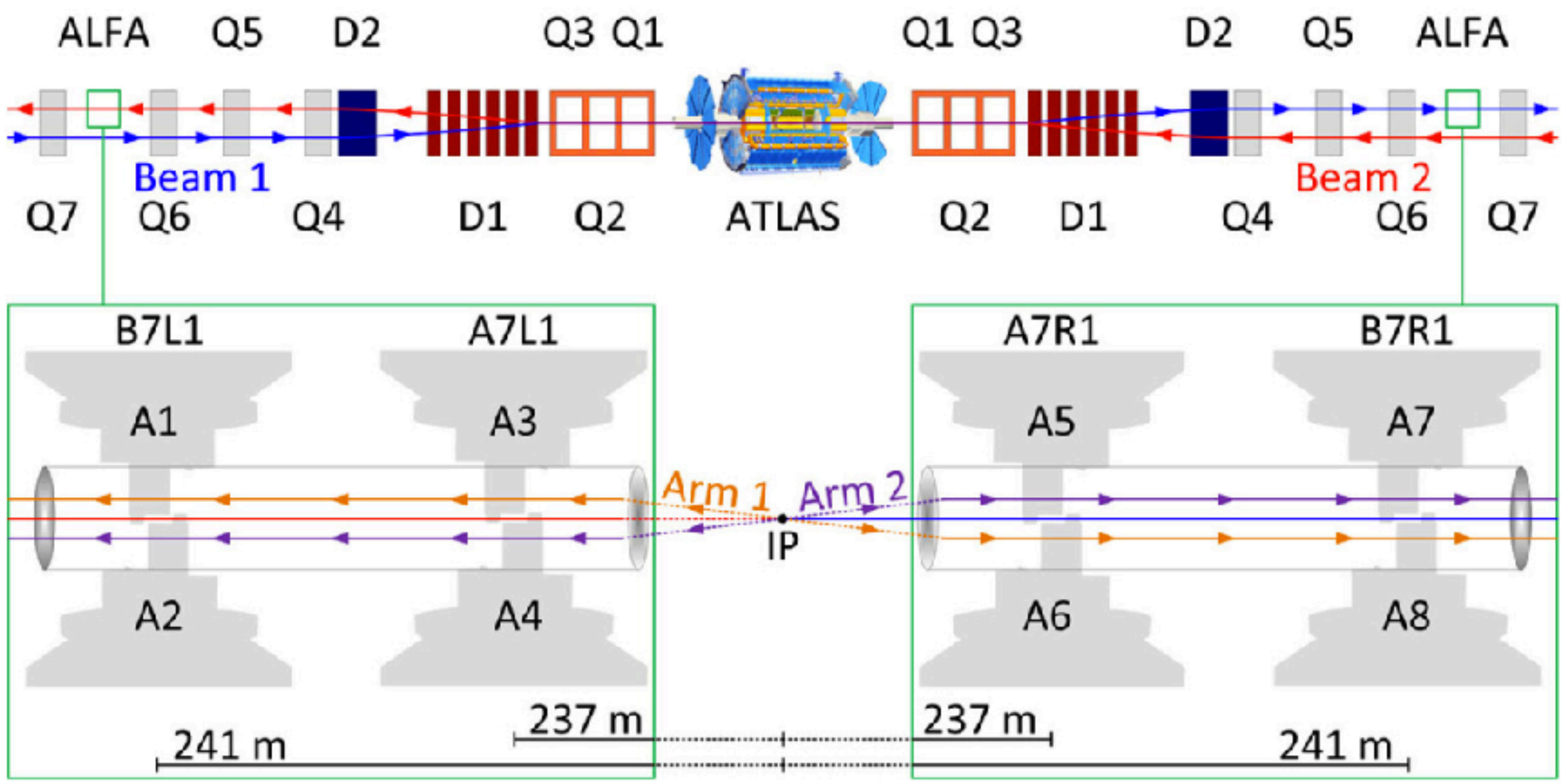
$$\rho = 0.10 \pm 0.01$$

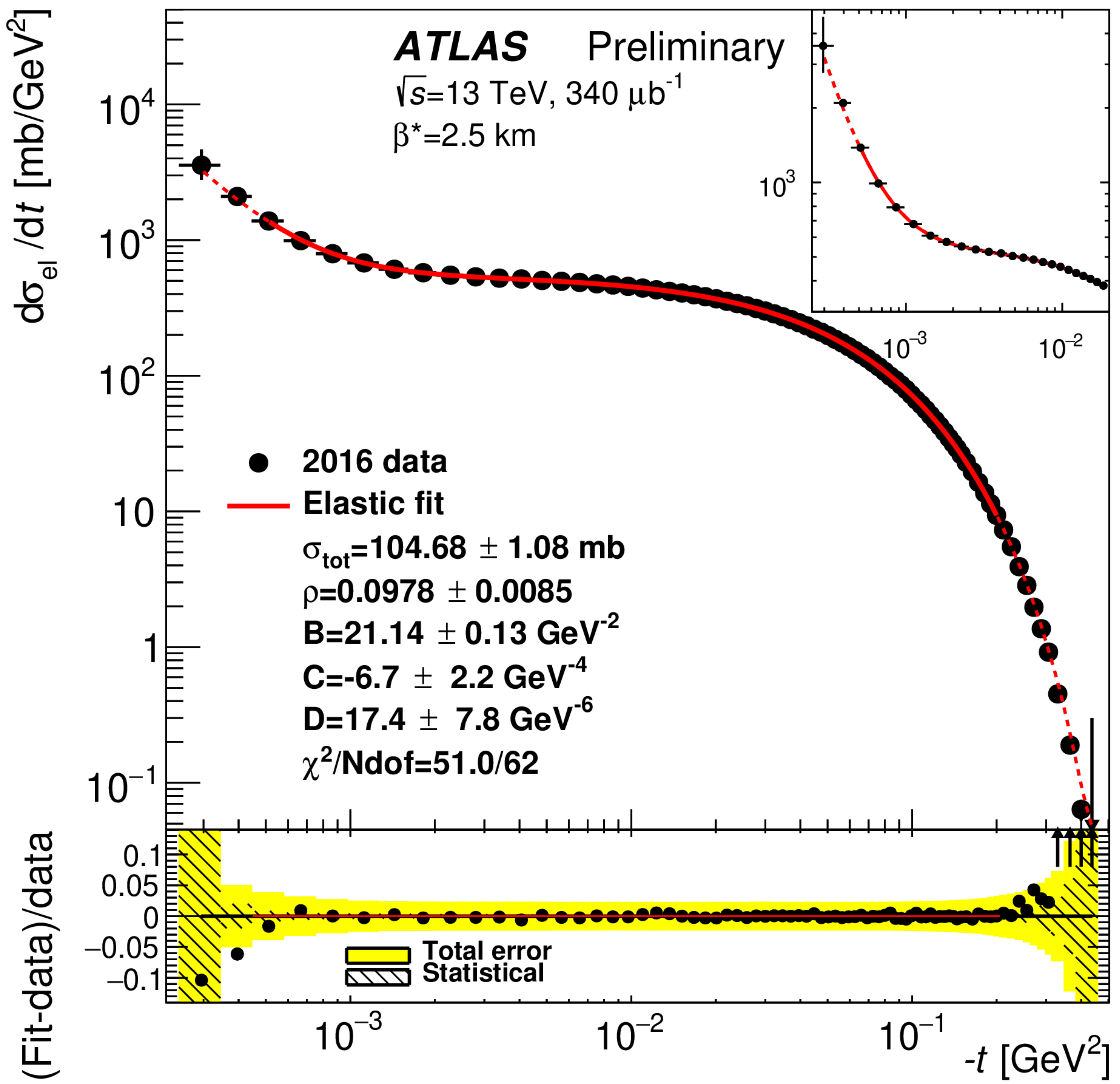
Lower than the predicted value.

Model did not take into account « odderons » three gluon colourless bound states exchange. First evidence by TOTEM.

(See TOTEM paper)

Measurement of the differential elastic cross section





At very low momentum transfer (t ~ 5 10^{-4} GeV^2) transition from Nuclear to Coulomb scattering with an interference (CNI)

$$\left(\frac{dN_{el}}{dt}\right)_{t=0} = \mathcal{L}\pi\left(\frac{-2\alpha_{\text{QED}}}{|t|} + \frac{\sigma_{tot}}{4\pi}(i+\rho)e^{-b|t|/2}\right)^2$$

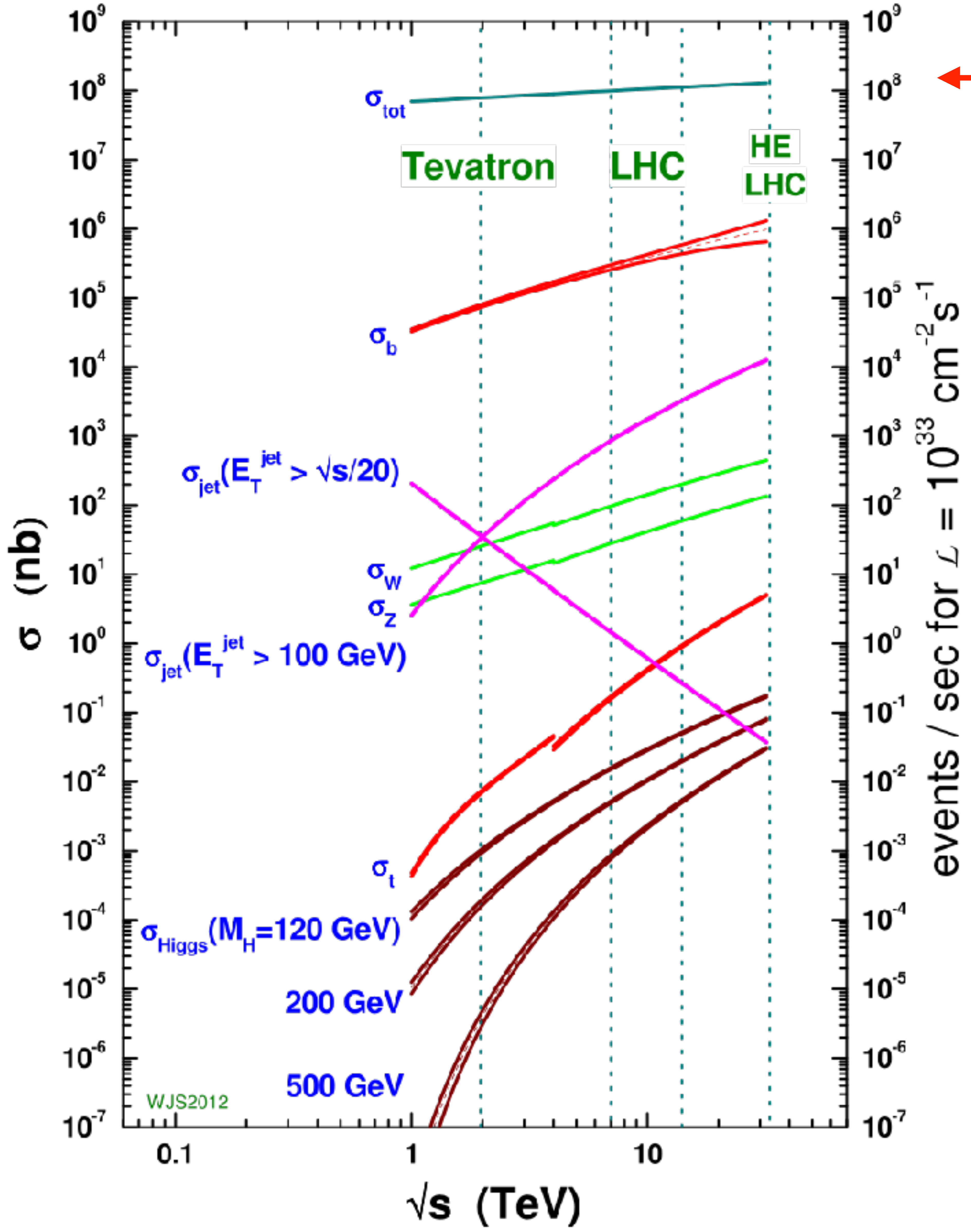
$$\begin{aligned}\sigma_{\text{tot}}(pp \to X) &= 104.7 \pm 1.0\,(\text{exp.}) \pm 0.12\,(\text{th.})\ \text{mb},\\ \rho &= 0.0975 \pm 0.0085\,(\text{exp.}) \pm 0.0064\,(\text{th.})\end{aligned}$$

The parameters can be fit to the measured differential cross section and all the parameters determined.

…can also measure the luminosity!

(See ALFA paper)

Dissecting the total cross section



$100\ \mathrm{mb}$ Total cross section

$60\ \mathrm{mb}$ Inelastic, start seeing events in the detector! Starting point of everything!!

From the nominal LHC luminosity:

$$2 \times 10^{34} cm^{-2} s^{-1}$$

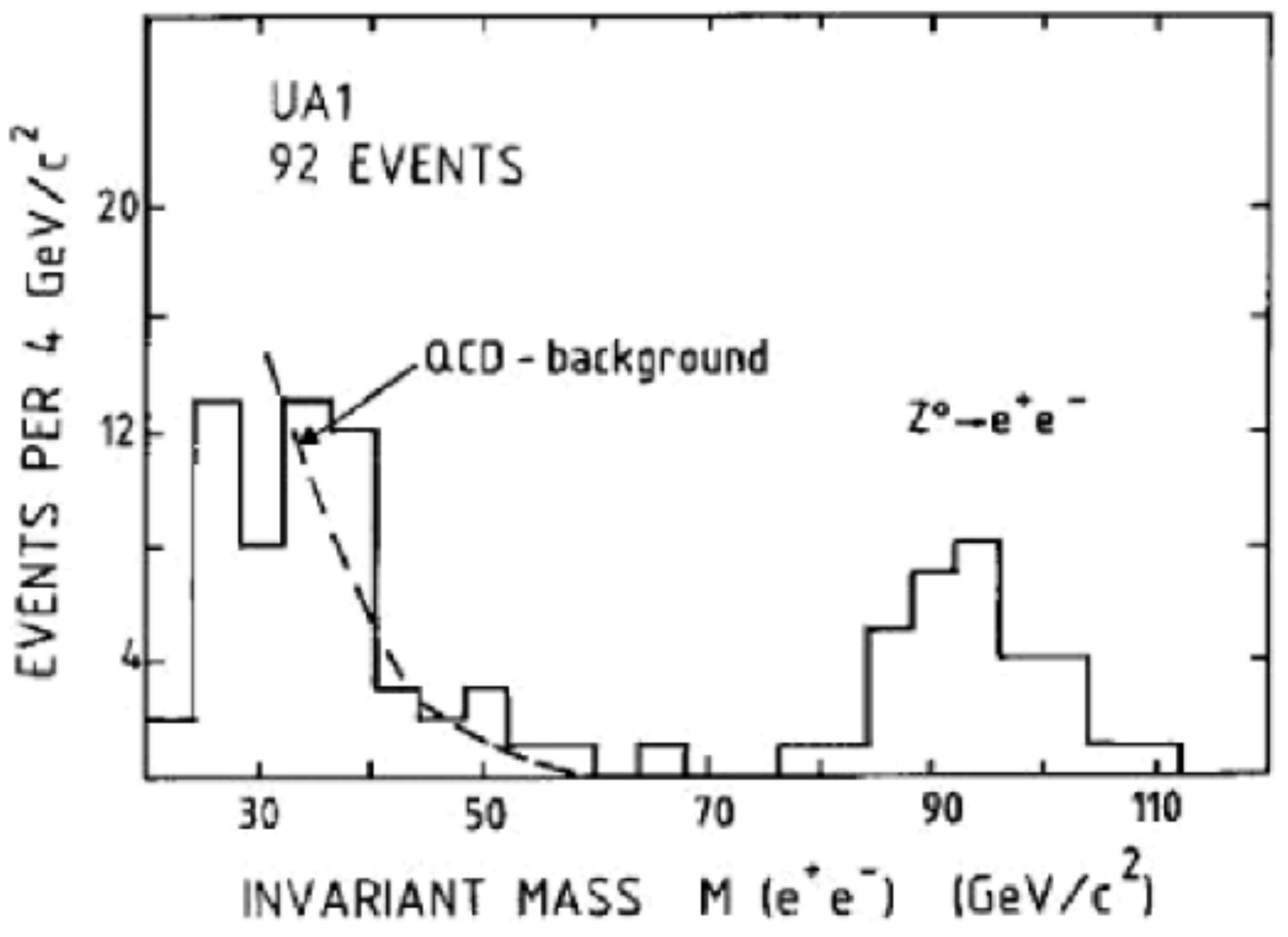
With a total cross section of approximately 100mb:

$$100 \times 10^{-27}\,(cm^2) \times 2 \times 10^{34}\,cm^{-2}s^{-1}$$

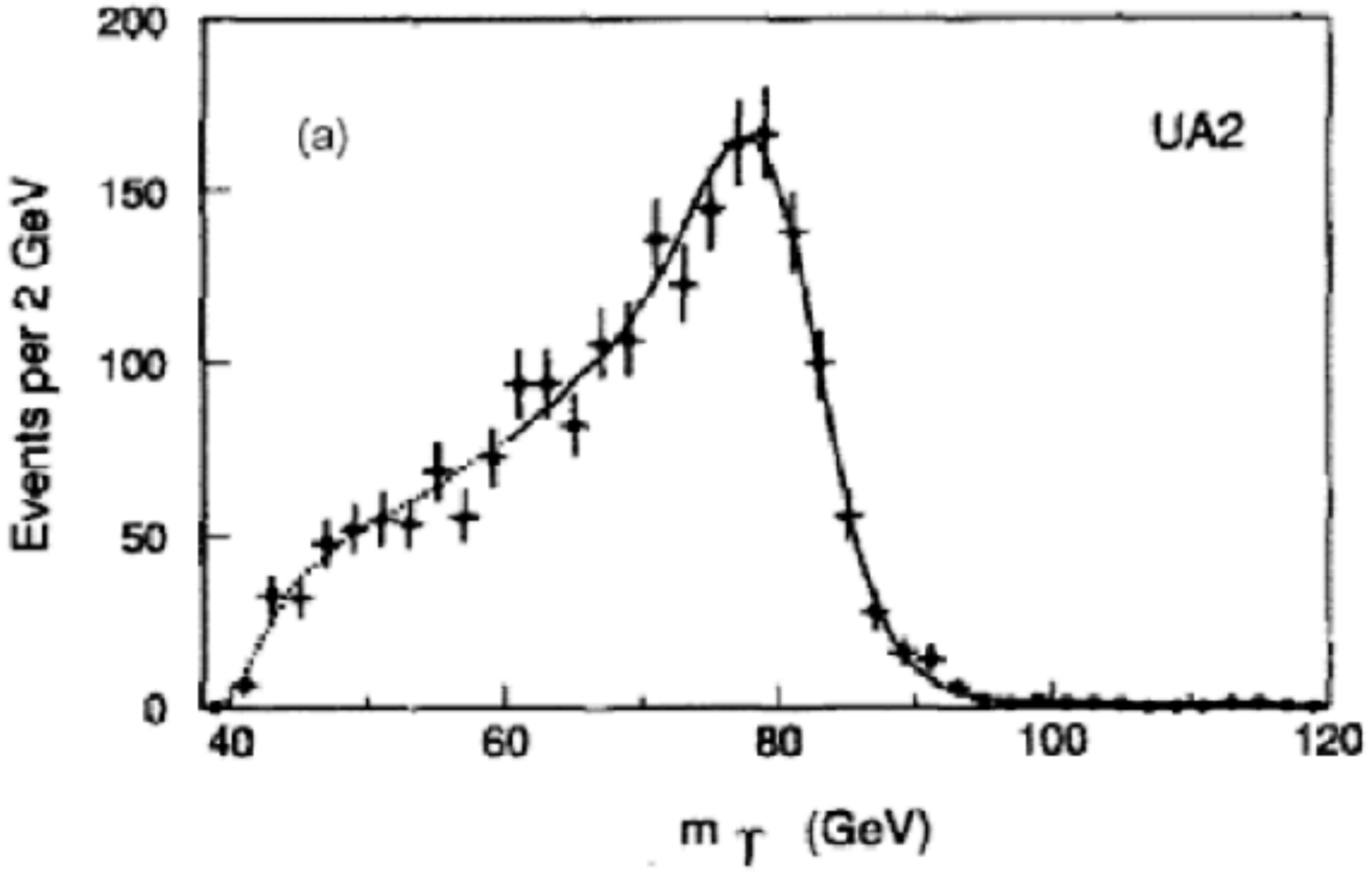
$$\sim 2 \times 10^{9}\ \mathrm{evts/s}$$

Drell-Yan W and Z processes

The SppS Legacy



Altogether O(100) Z events



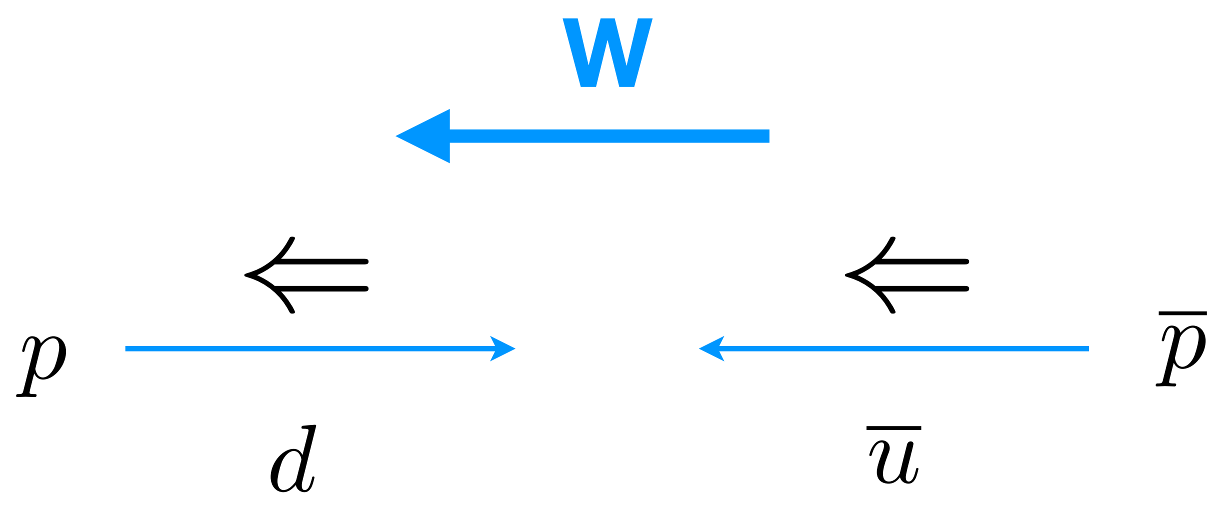
Altogether O(1000) W events

Transverse Mass distribution in UA2

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

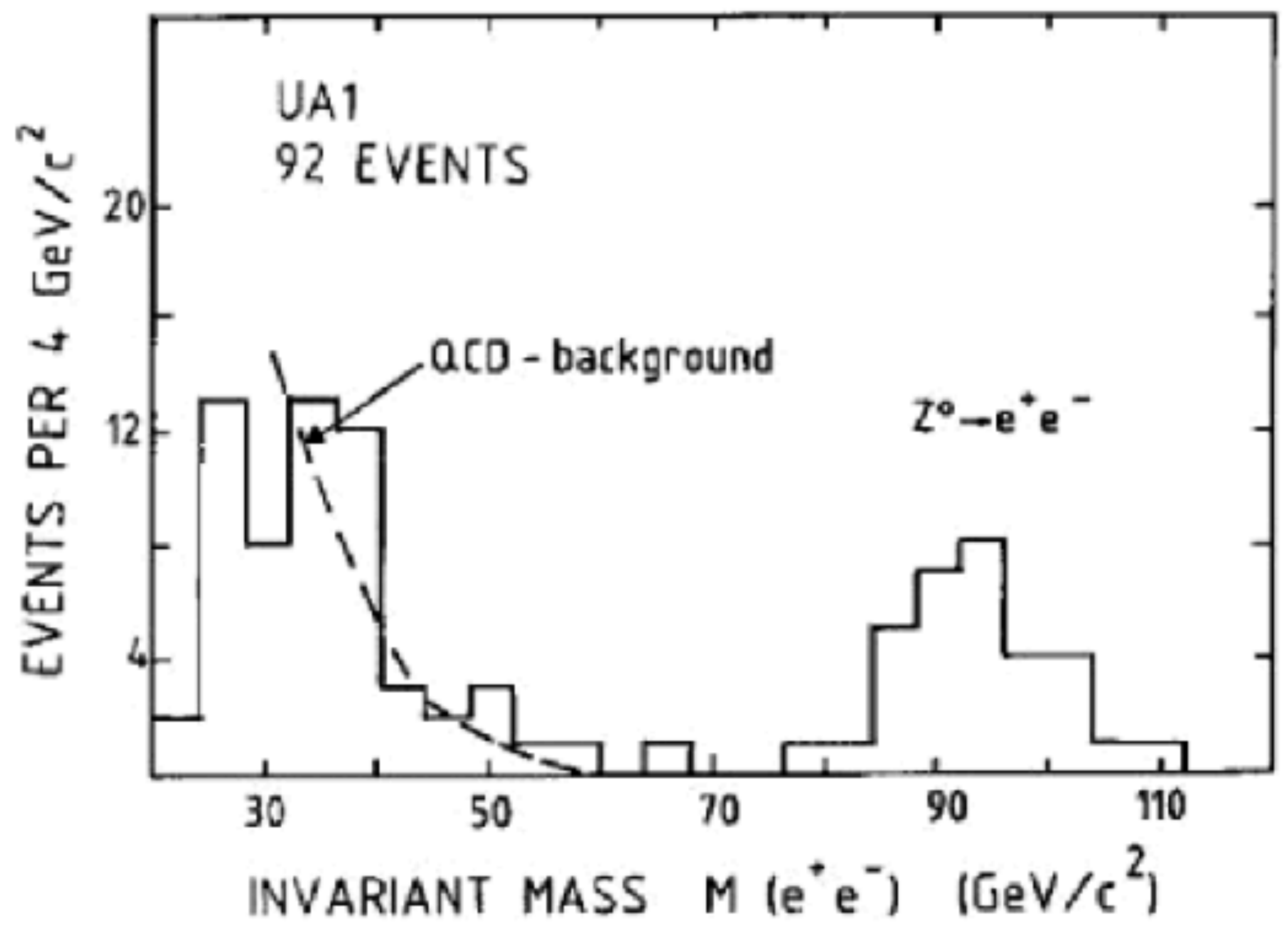
At SppS W production dominated by valence quarks

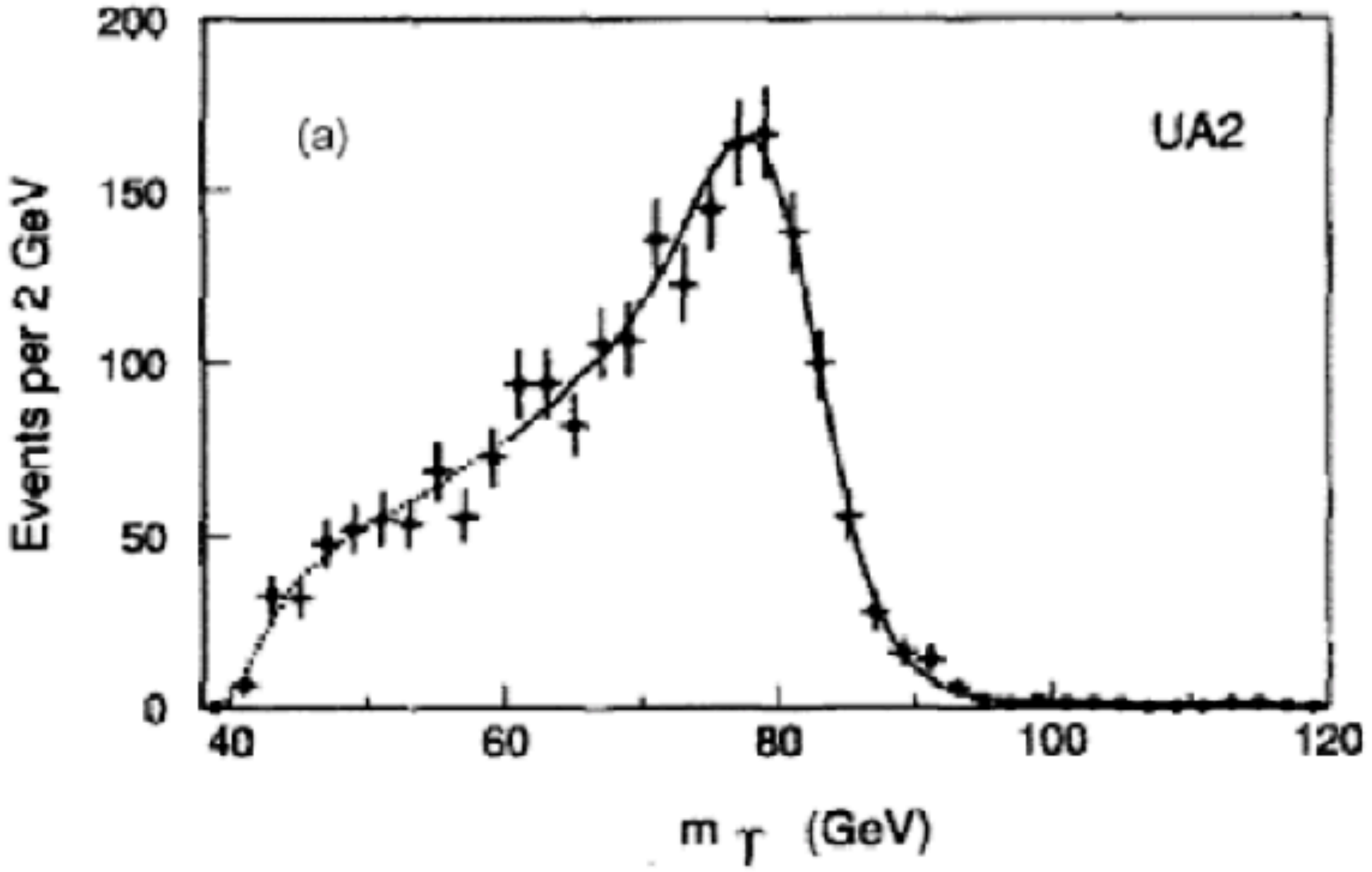
W polarised in the anti-proton direction.



Production

The SppS Legacy





Transverse Mass distribution in UA2

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

Altogether O(100) Z events

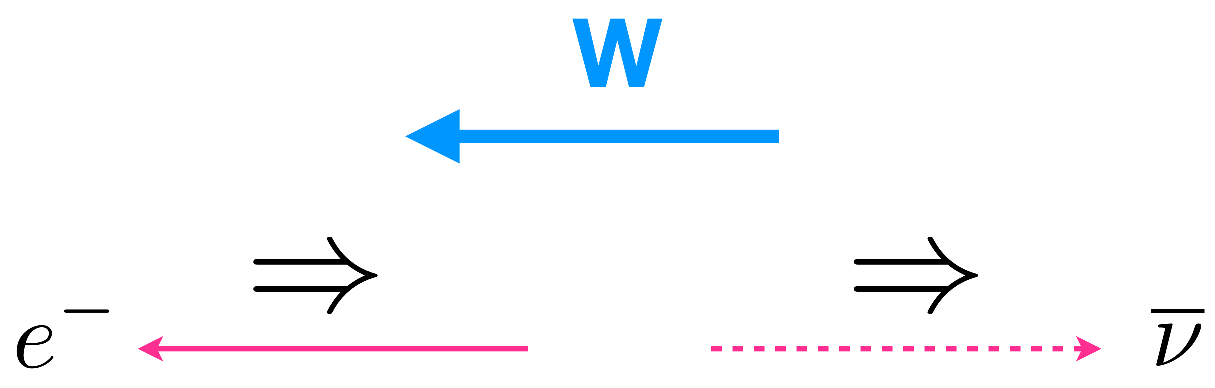
Altogether O(1000) W events

Precision reached:

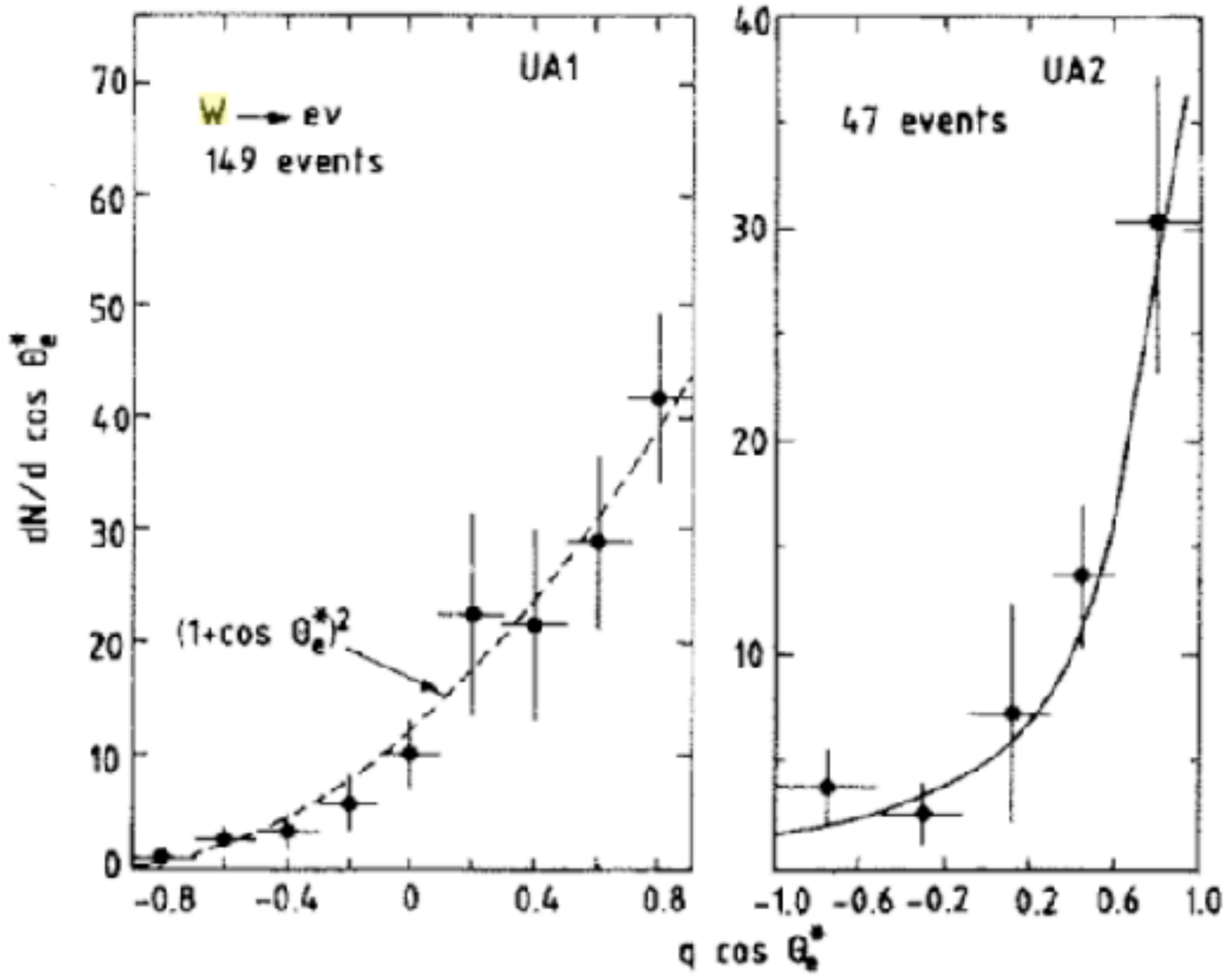
$M_Z = 91.5 \pm 1.2 \pm 1.7\,(\mathrm{GeV})$	*(UA1)*
$M_W = 81.0 \pm 0.8 \pm 1.3\,(\mathrm{GeV})$	*(UA2)*
$\rho = 1.004 \pm 0.052$	*(UA1)*
$\sin^2\theta_W = 0.226 \pm 0.014$	*(UA1)*

At SppS W production dominated by valence quarks

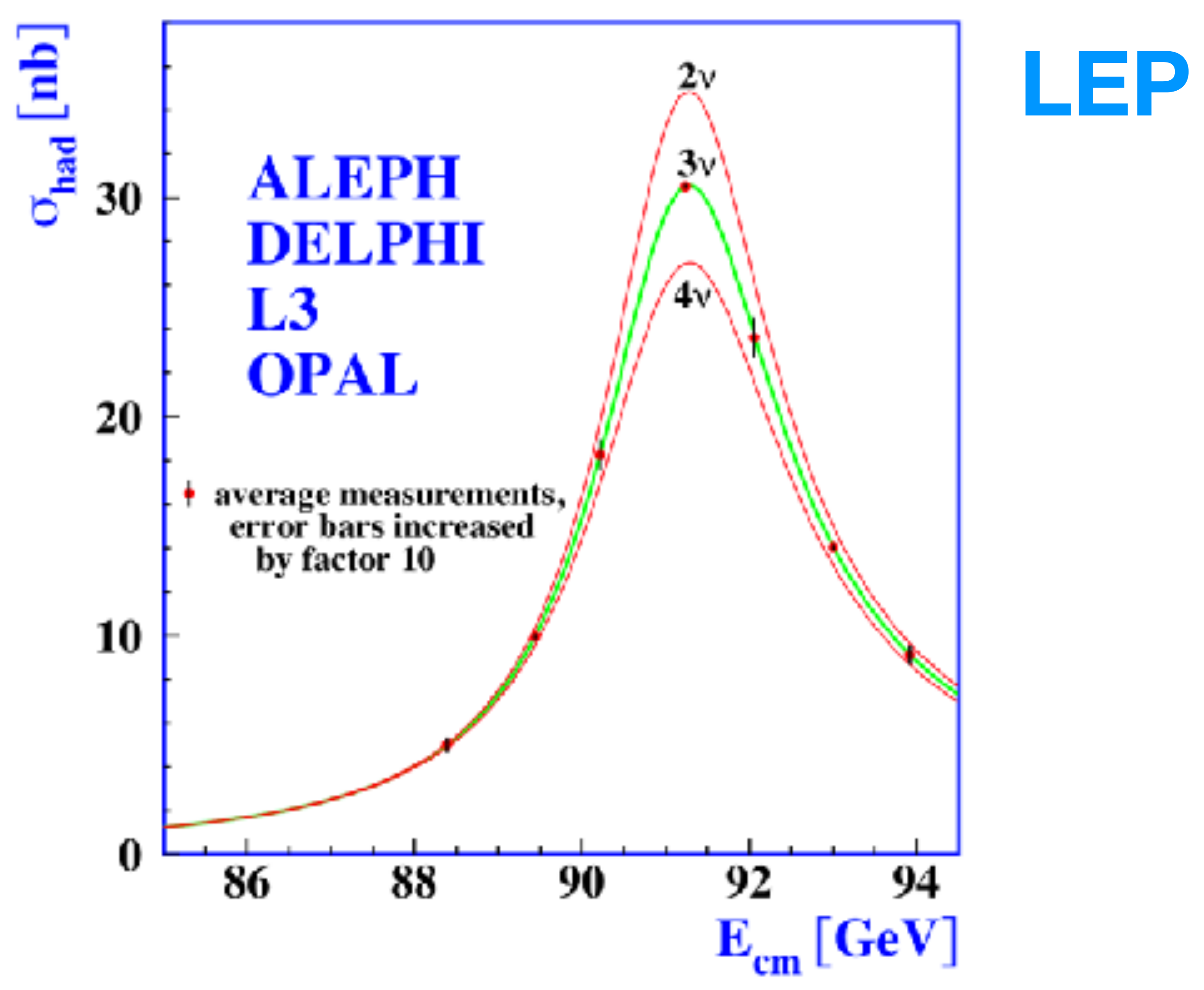
W polarised in the anti-proton direction.



Decay



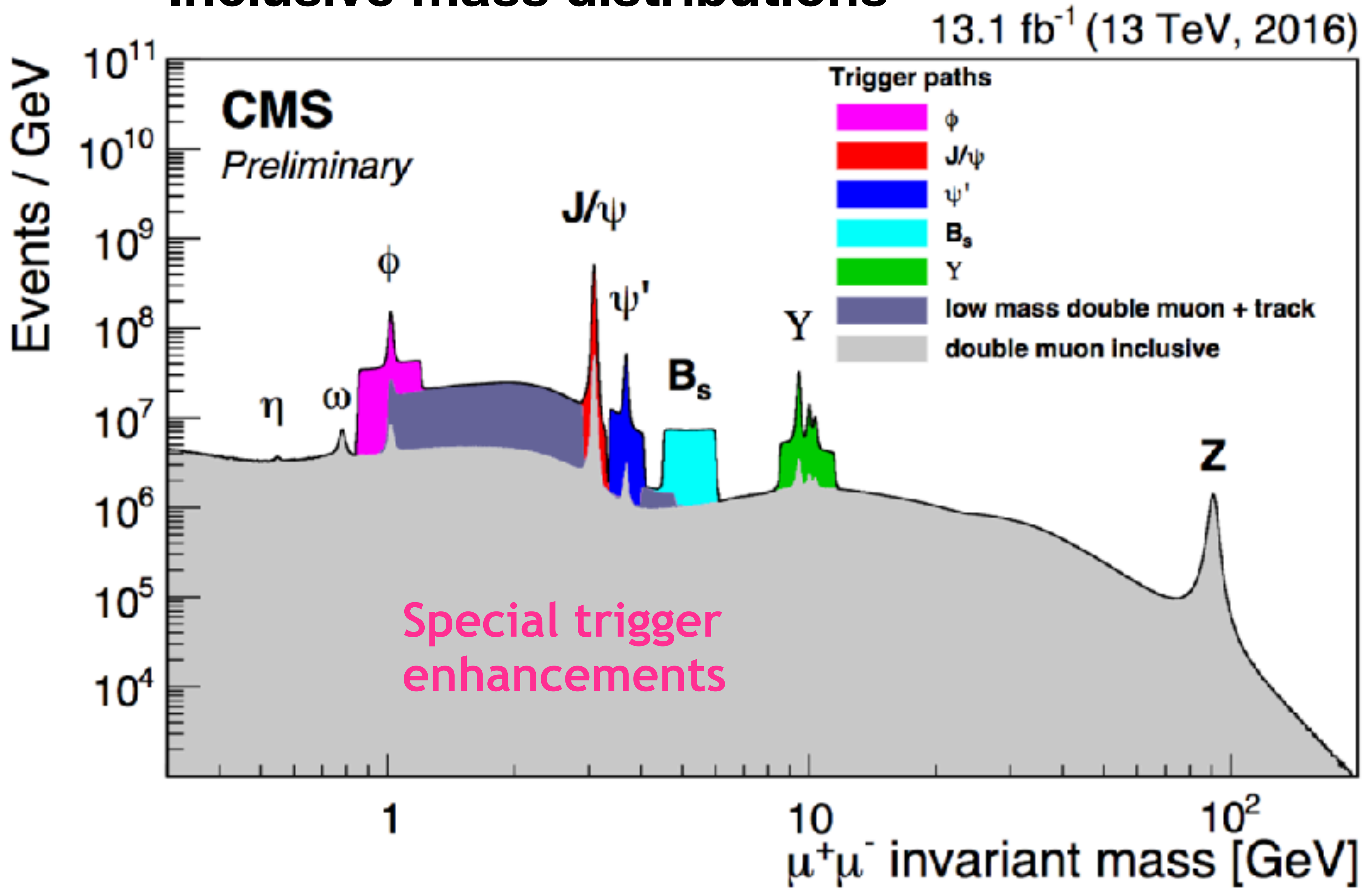
The di-lepton mass spectrum at LHC

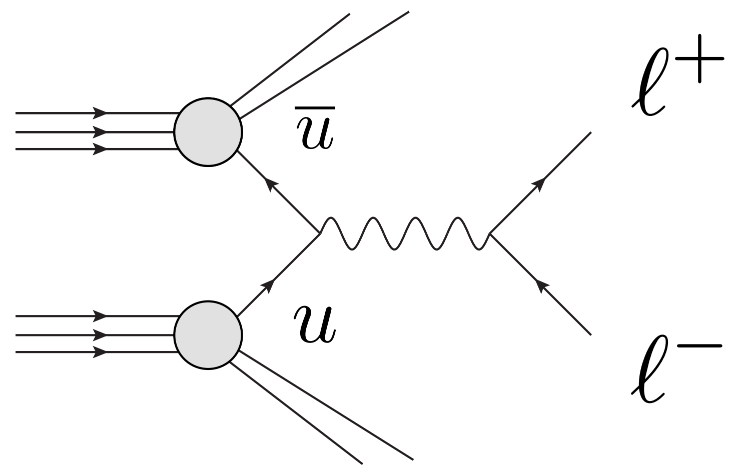


$$m_Z = 91.1875 \pm 0.0021\,\text{GeV}$$
$$\Gamma_Z = 2.4952 \pm 0.0023\,\text{GeV}$$
$$\rho = 1.0050 \pm 0.0010$$

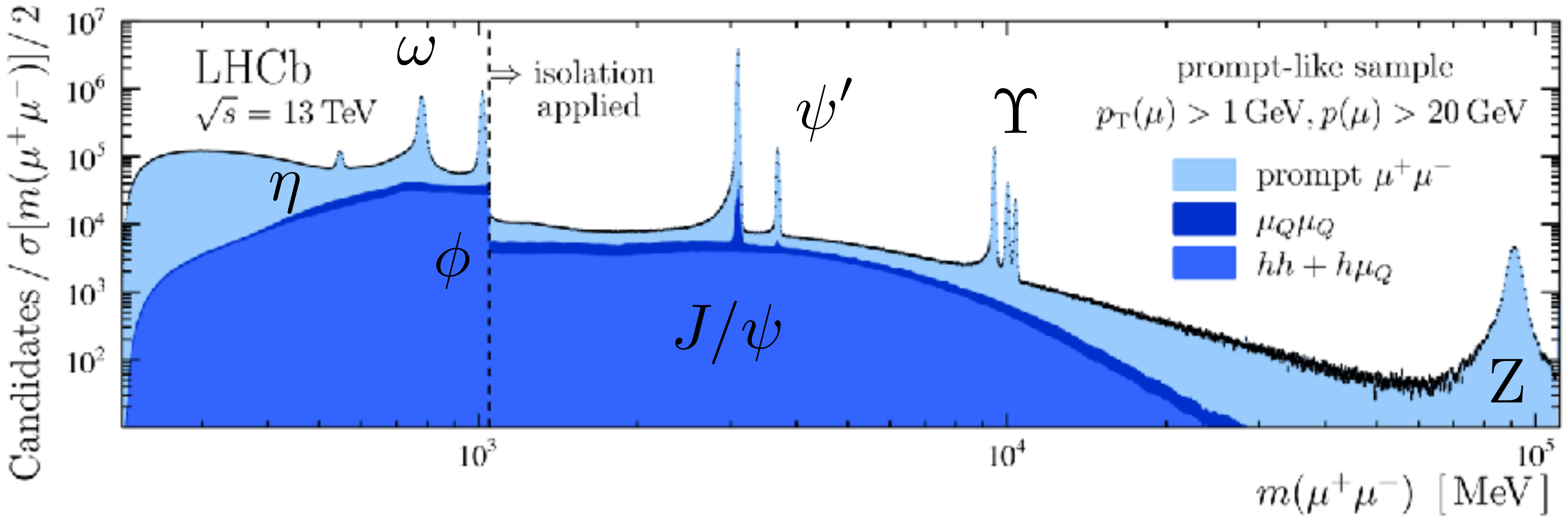
At LEP ~4.5M Z per experiment

Inclusive mass distributions





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



LHCb di-muon mass spectrum

At LHC Z events are produced in Billions!

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:

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

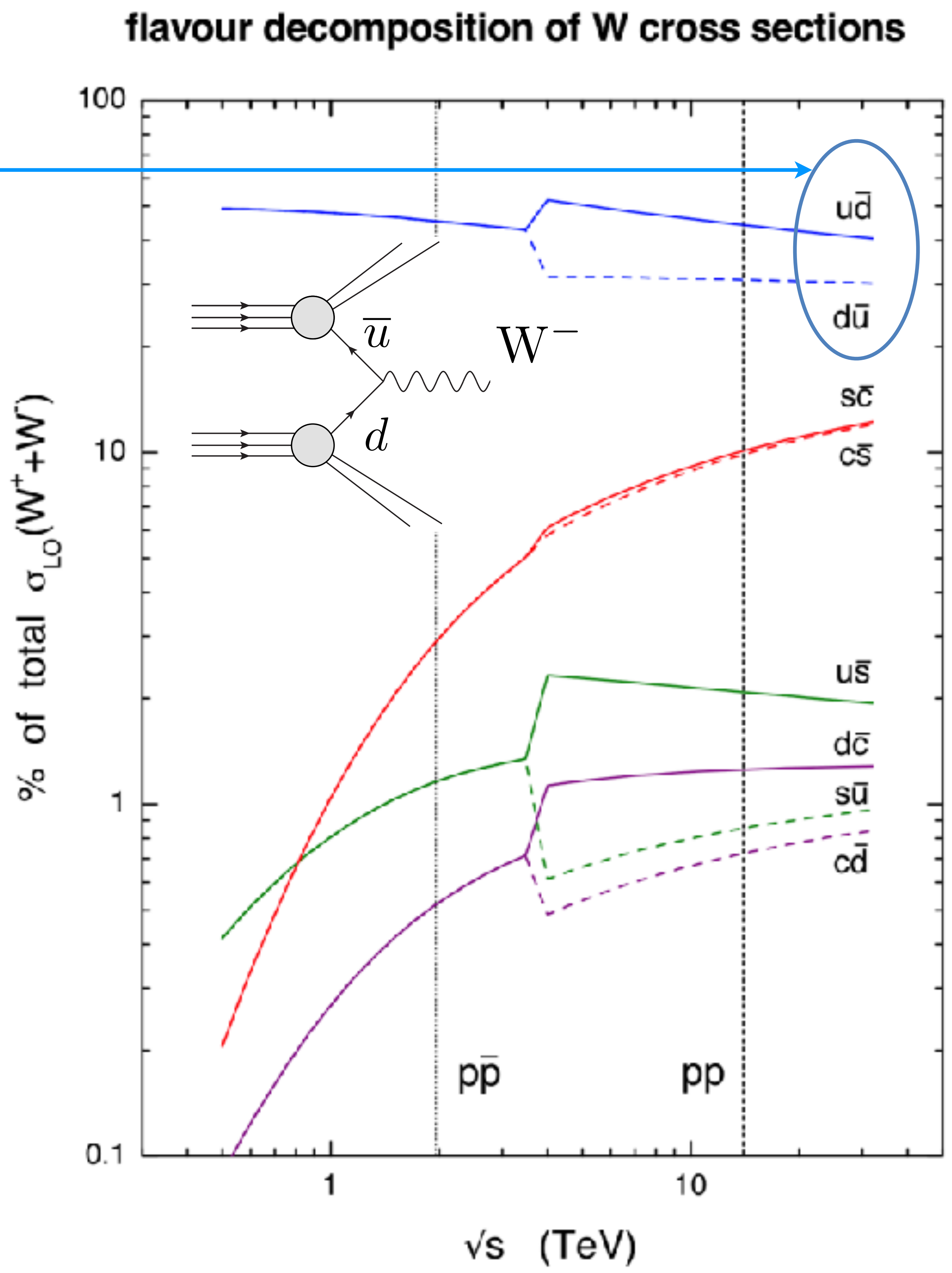
$$\sigma_{W^+} = 11.54\,^{+0.32}_{-0.31}\,(\mathrm{PDF}) \pm 0.22\,(\mathrm{TH})\ \mathrm{nb}$$

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

Numbers with leptonic branching fractions

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

Still O(30) Billion W boson events produced !!

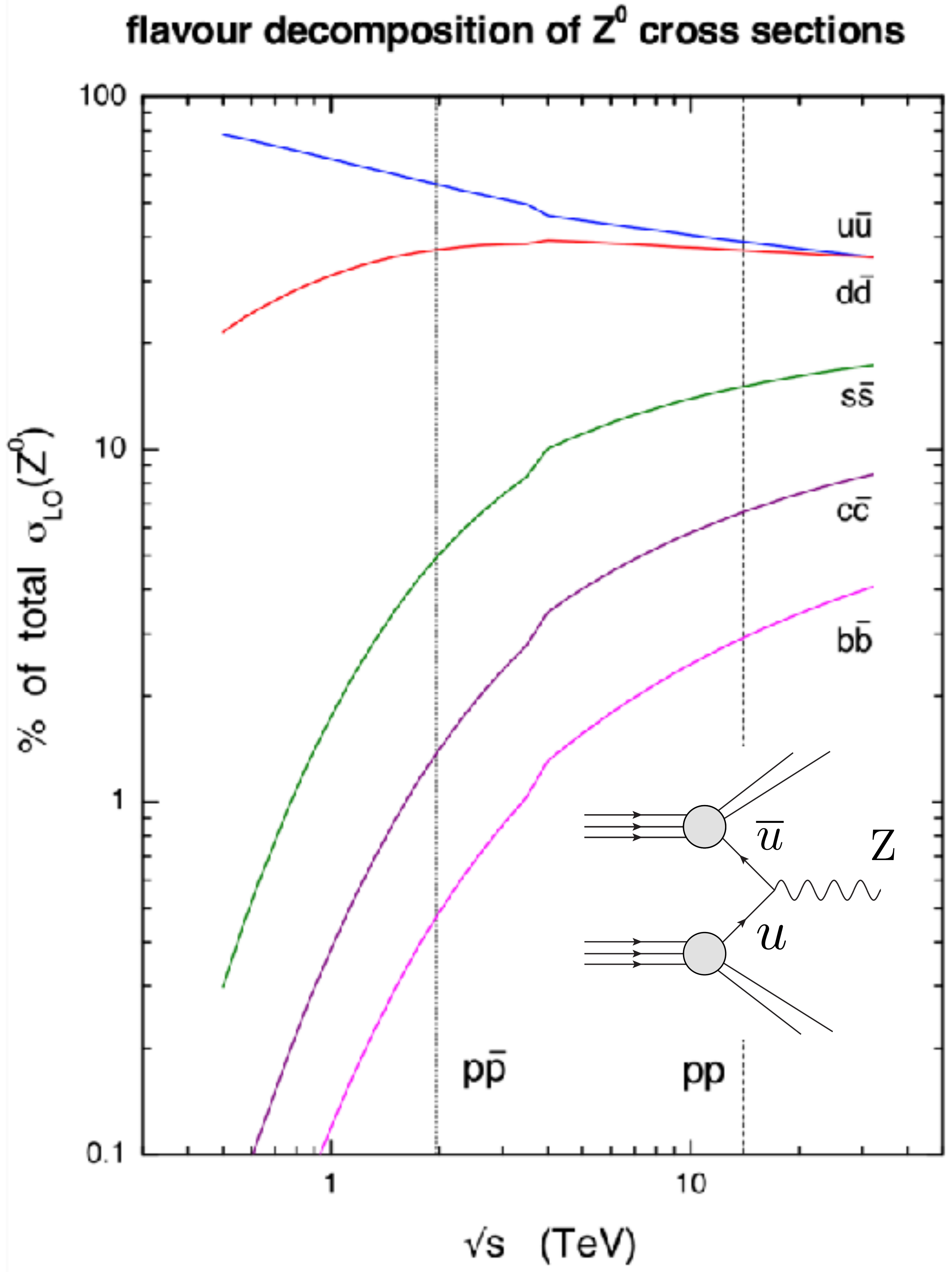


Typically in pp in leptonic modes

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

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

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

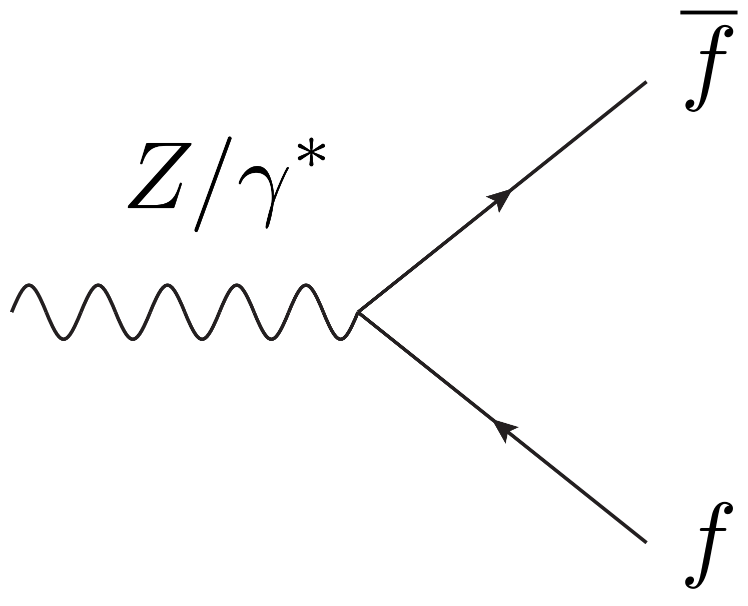


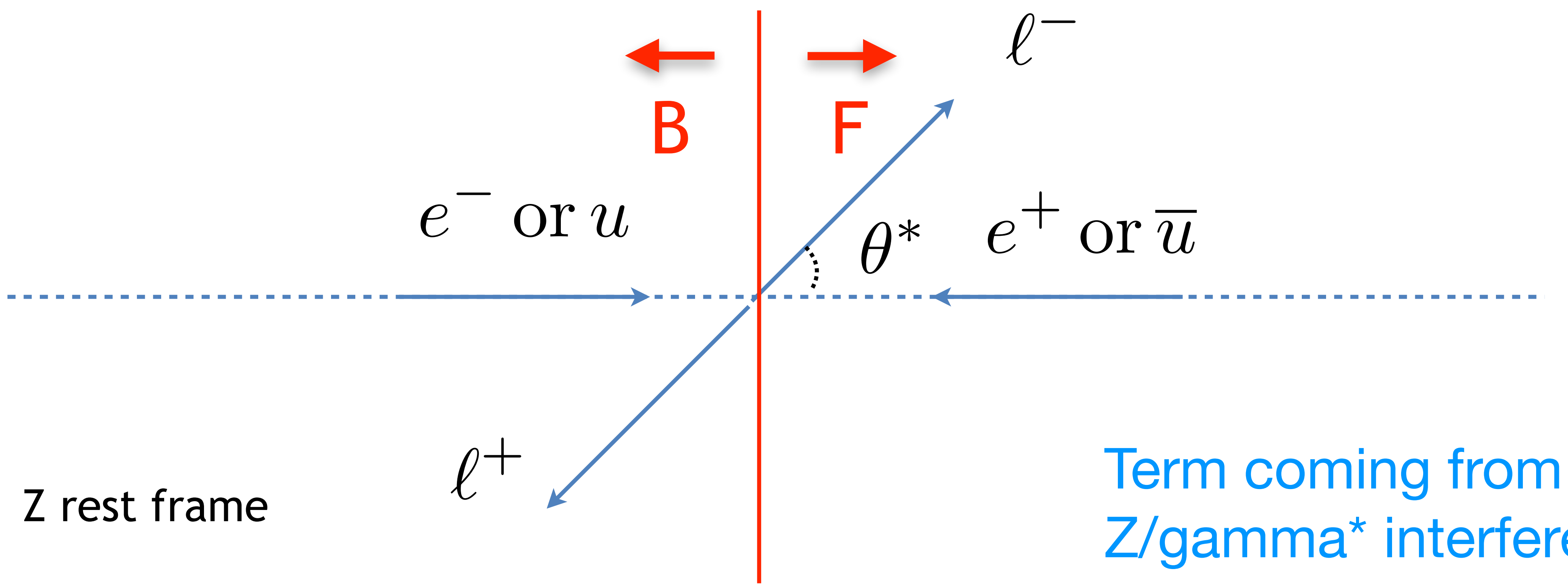
$\mathrm{Br}(\mathrm{Z} \to \nu\bar{\nu}) \sim 20\%$

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

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

Forward Backward Asymmetry





Term coming from the Z/gamma* interference

$$\bar{f}\gamma^{\mu}\left(R_f(1+\gamma^5)+L_f\,(1-\gamma^5)\right) f Z_{\mu}$$

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

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

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

The size of the effect will depend on the mass of the di-lepton system

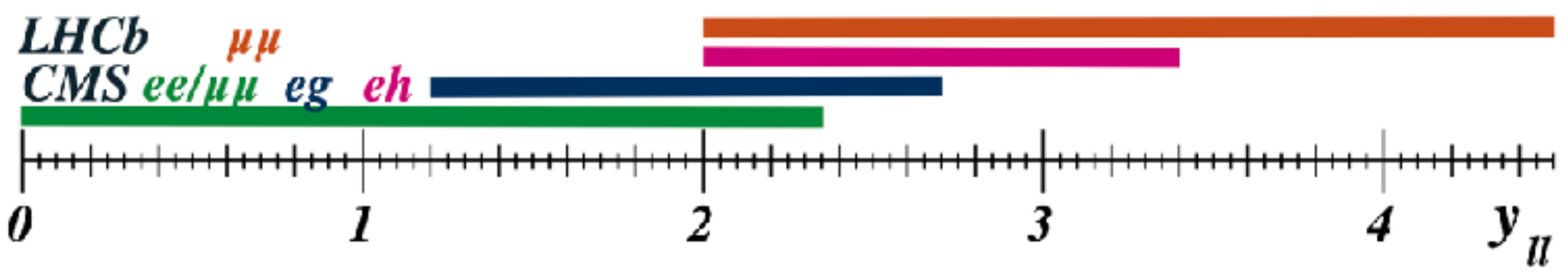
$$B \propto \; A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

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

In e^+e^- collisions the FB asymmetry is obvious as the direction of the incoming electron w.r.t. positron is known: what is the direction of the quark with respect to the direction of the anti-quark?

Measurement of the weak mixing angle at the LHC

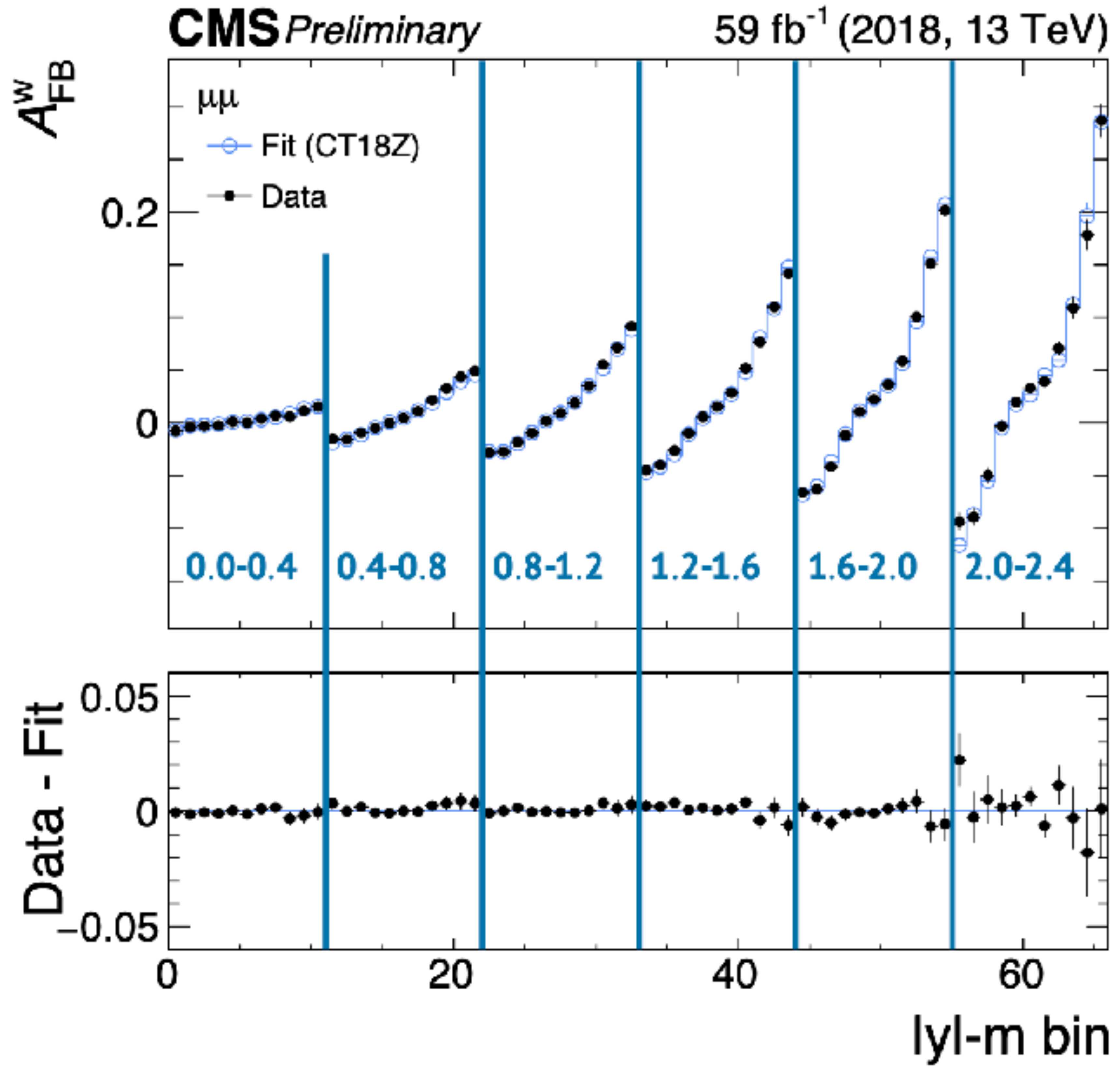
Because of the valence PDFs the momentum of valence quarks is larger and indicates the direction of the quark! The forward and backward asymmetry can be quantified in the same way.



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).

Very important to reconstruct electrons at highest possible pseudo rapidity with forward calorimeters (muons are limited to the tracking volume!)

CMS up to 4.4 and ATLAS up to 4.9… but careful, energy resolution is also very important! LHCb bound to forward region (2-5) thus reaches higher $\ell\ell$ rapidities (with less stats).



With mass bins typically between 55 GeV and 150 GeV

Channel	$\|\eta\|$		min p_T^{lead} (GeV)	min p_T^{trail} (GeV)
$\mu\mu$	0.00–2.40		20	10
ee	0.00–2.50		25	15
	$\|\eta_e\|$	$\|\eta_{g,h}\|$	min p_T^{e} (GeV)	min $p_T^{g,h}$ (GeV)
eg	0.00–2.50	2.50–2.87	30	20
eh	1.57–2.50	3.14–4.36	30	20

Measurement of the weak mixing angle at the LHC

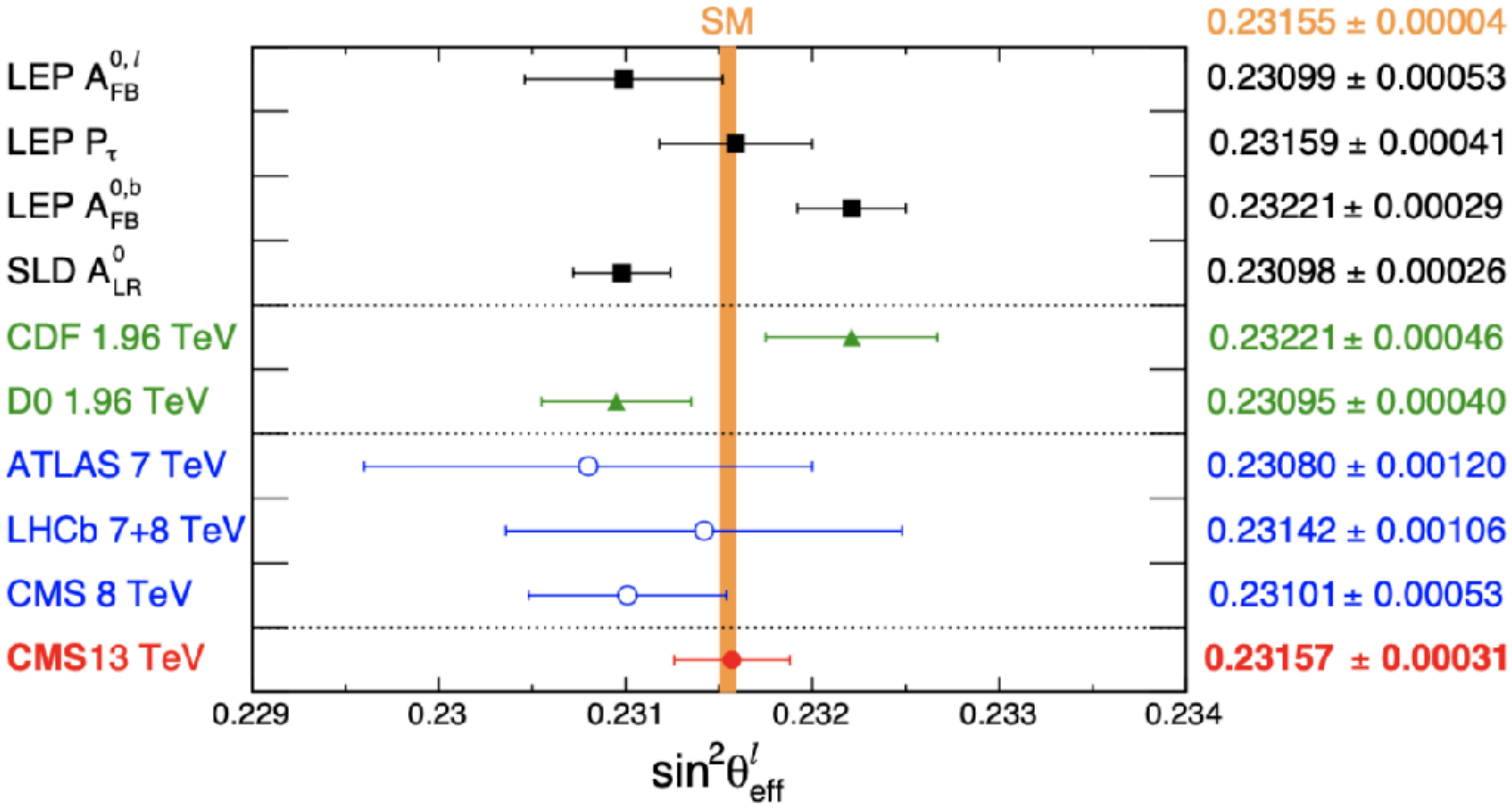
New measurements of $\sin^2\theta_W$ by LHCb and CMS

Precision comparable to the most precise single measurements at LEP A_{FB}^b and SLD A_{LR} determination

TOWARDS A NEW PRECISION ERA IN THE STUDY OF ELECTROWEAK INTERACTIONS

03 APR 2024

A fundamental parameter of the Standard Model, the electroweak mixing angle plays a key role in the "Higgs mechanism", when the W and Z gauge bosons get their masses through electroweak symmetry breaking. CMS has now reported a new measurement of...



CMS Briefing Link

LHCb CERN Seminar! Link

CMS: $\sin^2\theta^\ell_{eff} = 0.23157 \pm 0.00010\text{ (stat)} \pm 0.00015\text{ (syst)} \pm 0.00009\text{ (theo)} \pm 0.00027\text{(PDF)}$

LHCb: $\sin^2\theta^\ell_{eff} = 0.23152 \pm 0.00044\text{ (stat)} \pm 0.00005\text{ (syst)} \pm 0.00022\text{ (theo/PDF)}$

Measurement of the weak mixing angle at the LHC

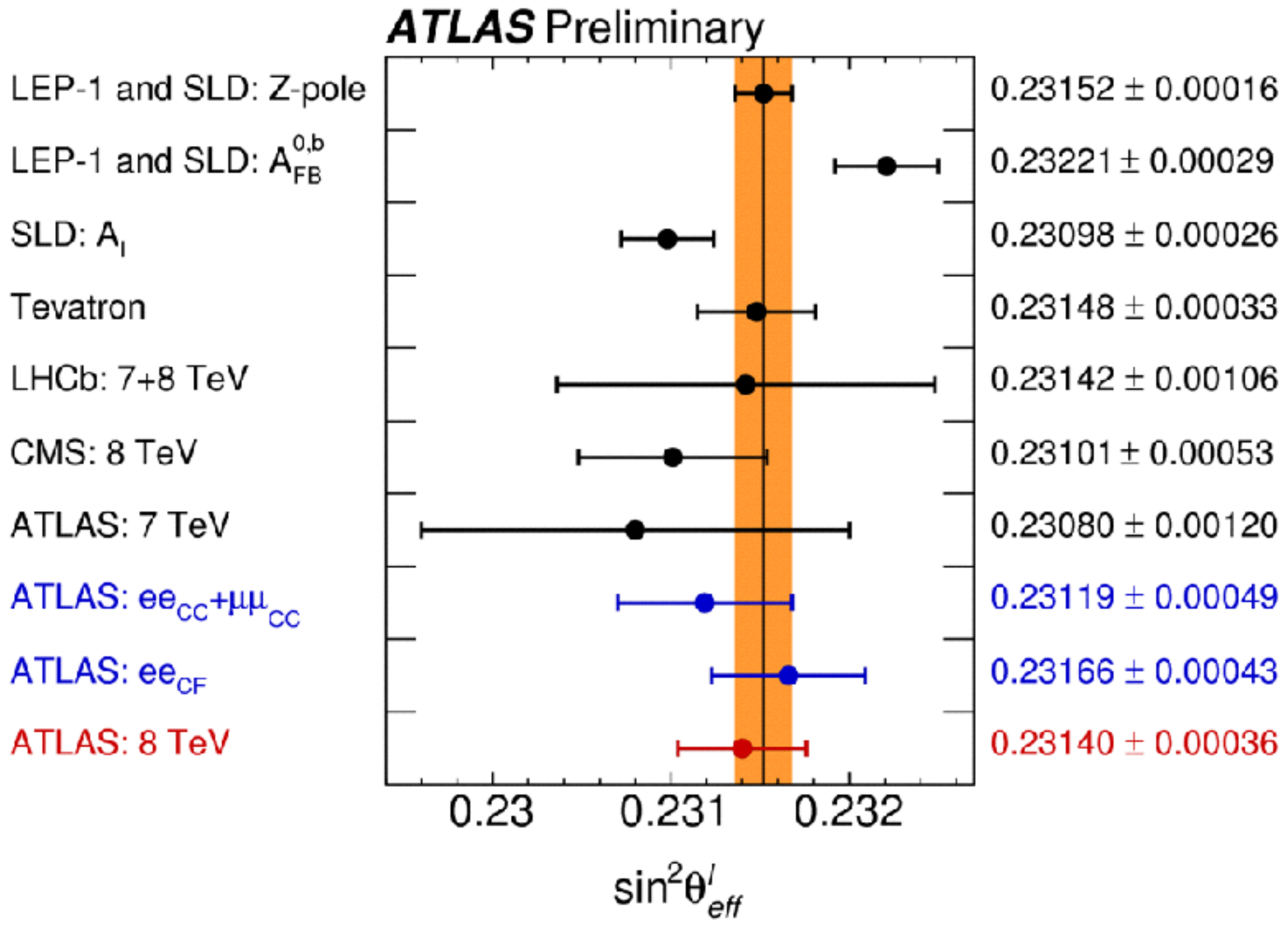
New measurements of $\sin^2\theta_W$ by LHCb and CMS

Precision comparable to the most precise single measurements at LEP A_{FB}^b and SLD A_{LR} determination

TOWARDS A NEW PRECISION ERA IN THE STUDY OF ELECTROWEAK INTERACTIONS

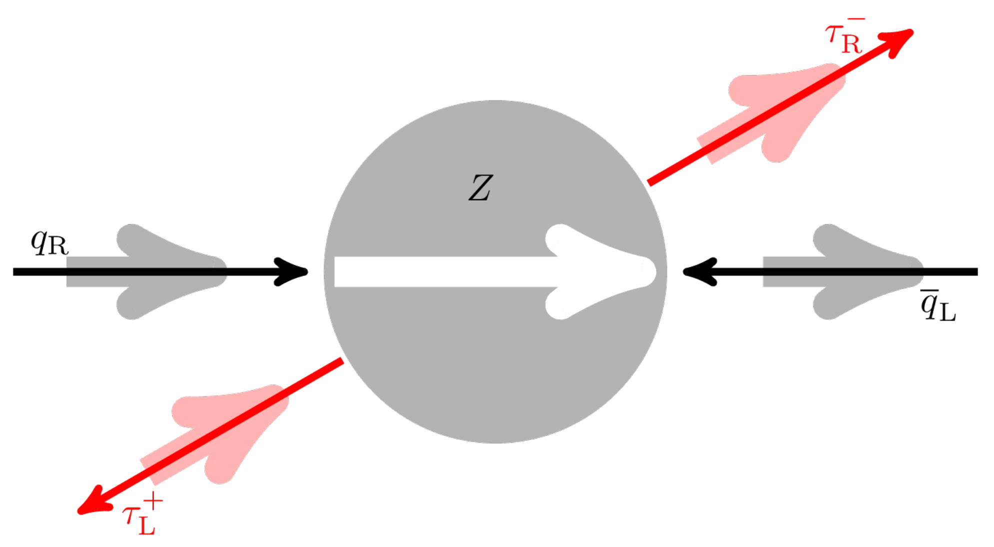
03 APR 2024

A fundamental parameter of the Standard Model, the electroweak mixing angle plays a key role in the "Higgs mechanism", when the W and Z gauge bosons get their masses through electroweak symmetry breaking. CMS has now reported a new measurement of...

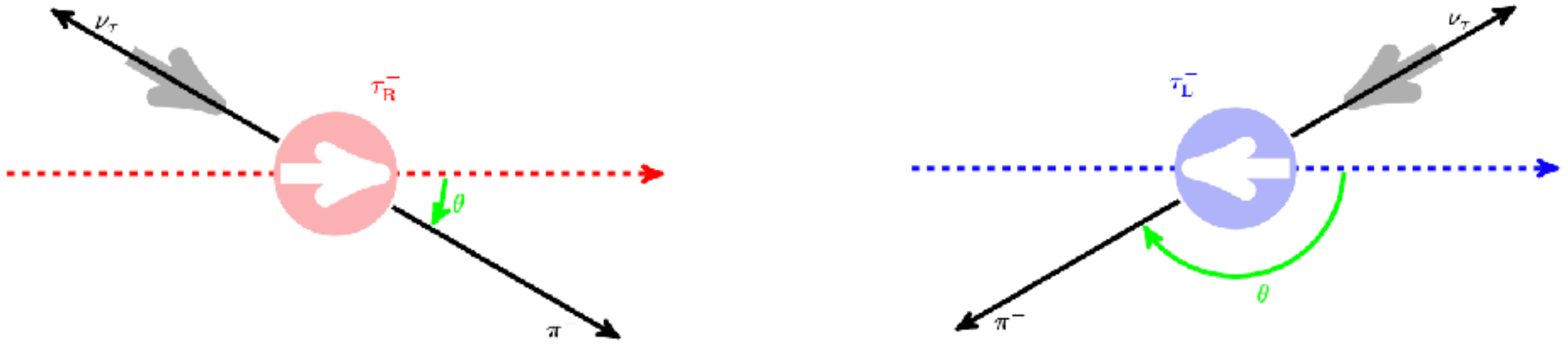


CMS Briefing Link	CMS:	$\sin^2\theta^\ell_{\text{eff}} = 0.23157 \pm 0.00010\,(\text{stat}) \pm 0.00015\,(\text{syst}) \pm 0.00009\,(\text{theo}) \pm 0.00027(\text{PDF})$
LHCb CERN Seminar! Link	LHCb:	$\sin^2\theta^\ell_{\text{eff}} = 0.23152 \pm 0.00044\,(\text{stat}) \pm 0.00005\,(\text{syst}) \pm 0.00022\,(\text{theo/PDF})$
ATLAS Result	ATLAS	$\sin^2\theta^\ell_{\text{eff}} = 0.23140 \pm 0.00021\,(\text{stat}) \pm 0.00024(\text{PDFs}) \pm 0.00016\,(\text{syst})$

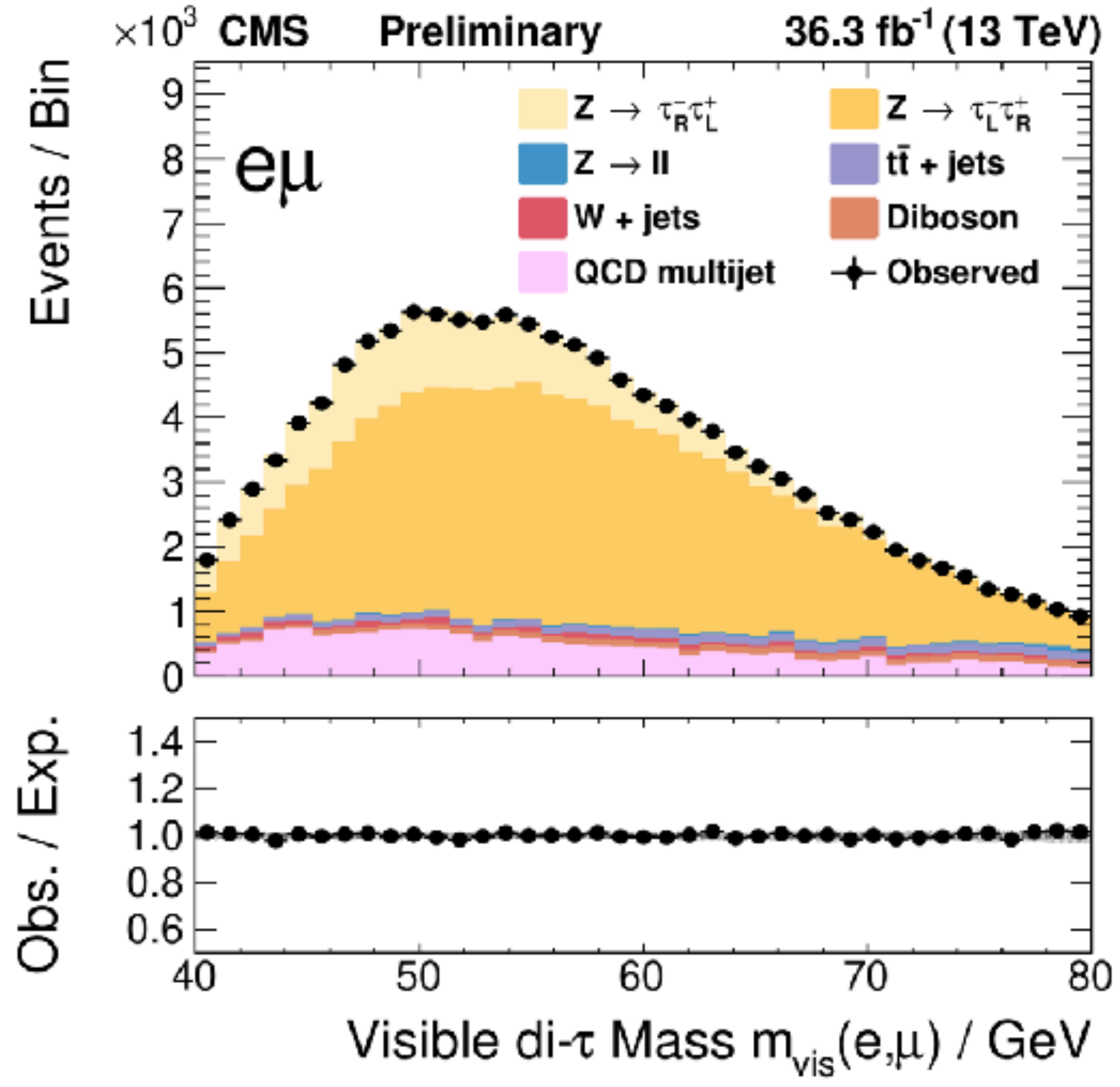
Tau Polarisation in Z Decays



Measurement relies in measuring the fraction of tau helicity states, using polarisation sensitive variables! Using both leptonic and hadronic taus deca



$$\langle P_\tau \rangle = \frac{N(Z \to \tau_R^- \tau_L^+) - N(Z \to \tau_L^- \tau_R^+)}{N(Z \to \tau_R^- \tau_L^+) + N(Z \to \tau_L^- \tau_R^+)}$$



Energy and angular variables are used!

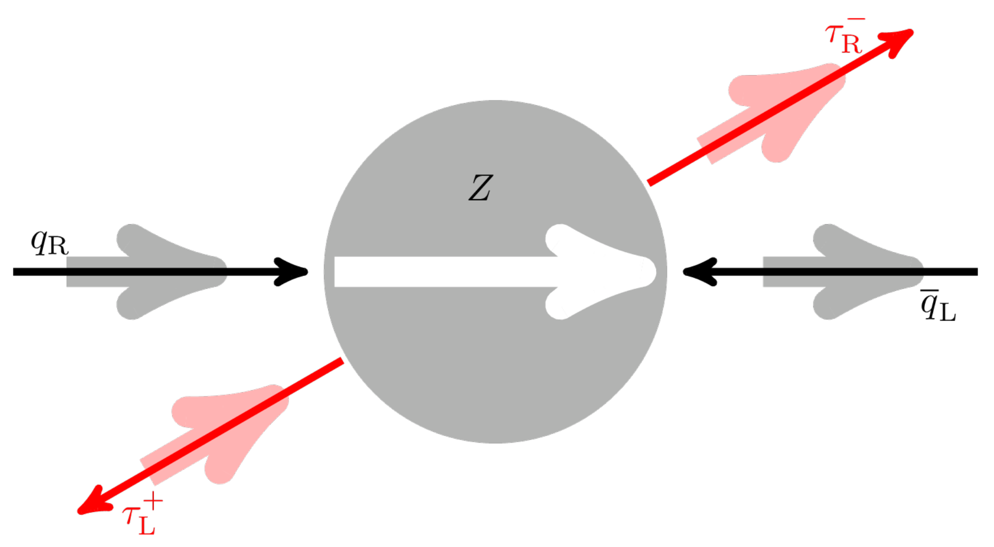
$$P_\tau = -A_\tau = -\frac{2 v_\tau a_\tau}{v_\tau^2 + a_\tau^2} \approx -2 \cdot \frac{v_\tau}{a_\tau} = -2(1 - 4\sin^2\theta_W^{\text{eff}}).$$

Tau polarisation directly measures the ratio of vector to axial Z couplings.

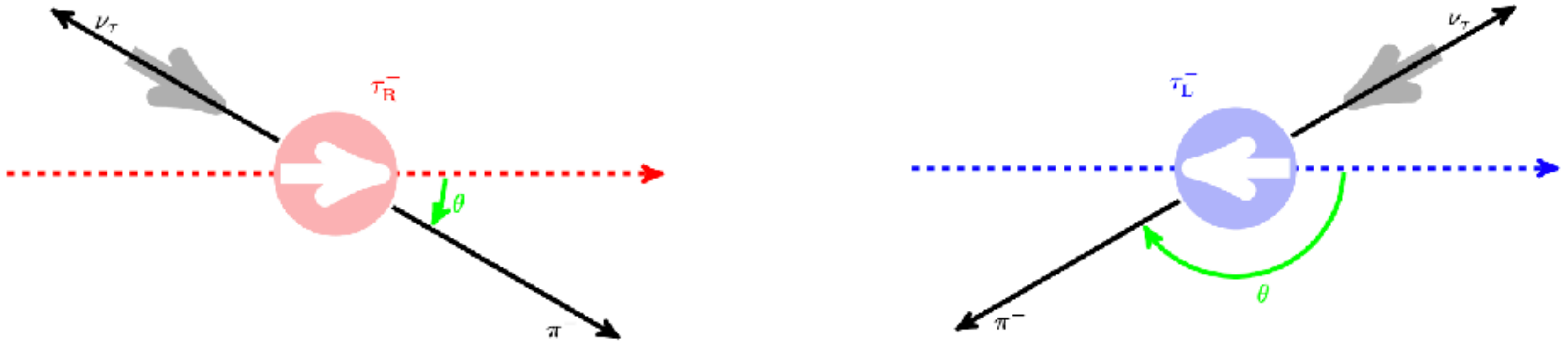
$$\mathcal{P}_\tau(Z^0) = -0.144 \pm 0.015 = -0.144 \pm 0.006\,(\text{stat}) \pm 0.014\,(\text{syst}).$$

$$\sin^2\theta_W^{\text{eff}} = 0.2319 \pm 0.0019 = 0.2319 \pm 0.0008\,(\text{stat}) \pm 0.0018\,(\text{syst}).$$

Tau Polarisation in Z Decays

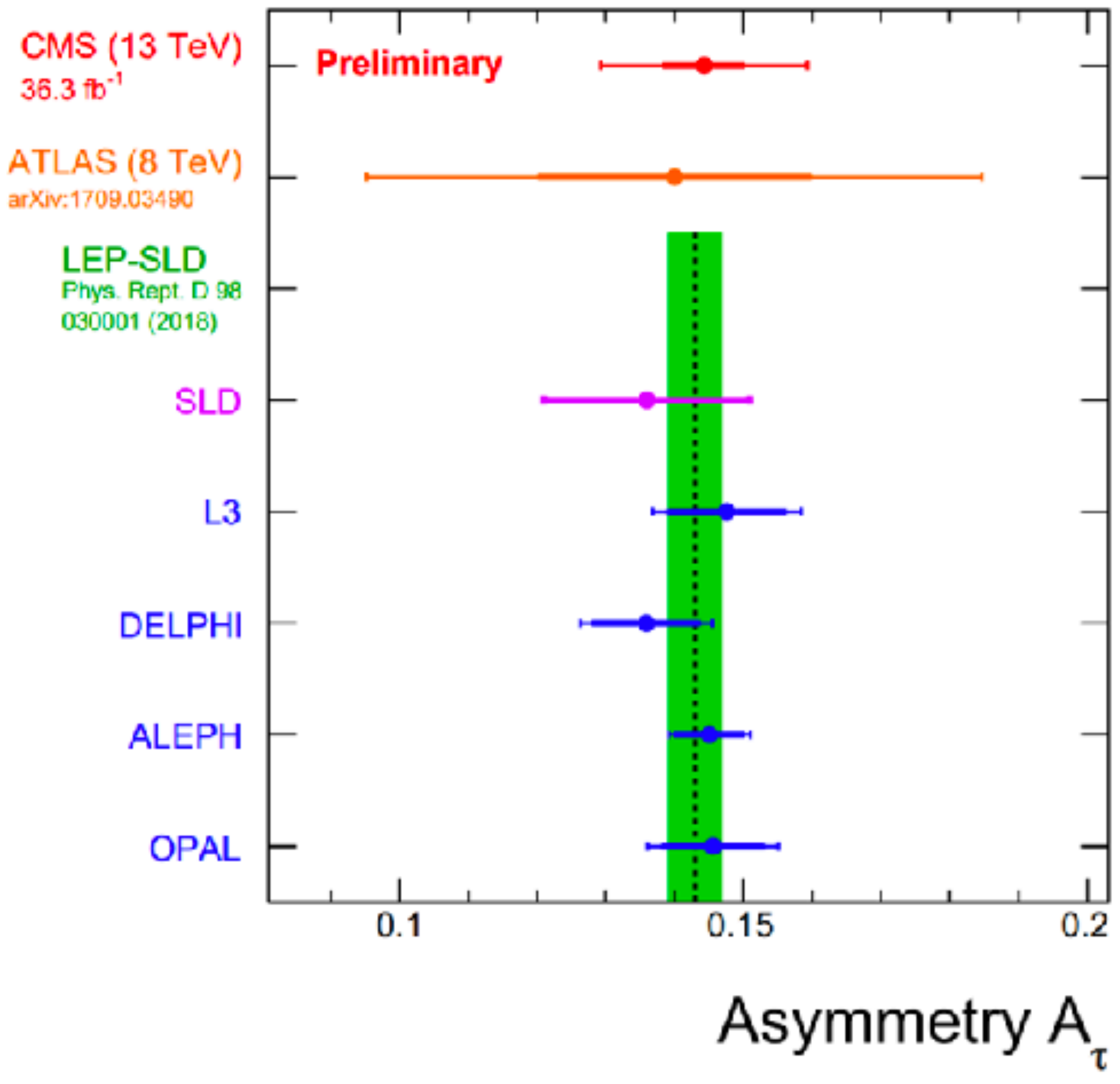


Measurement relies in measuring the fraction of tau helicity states, using polarisation sensitive variables! Using both leptonic and hadronic taus deca



$$\langle P_\tau \rangle = \frac{N(Z \to \tau_R^- \tau_L^+) - N(Z \to \tau_L^- \tau_R^+)}{N(Z \to \tau_R^- \tau_L^+) + N(Z \to \tau_L^- \tau_R^+)}$$

Also done in ATLAS at 8 TeV



Energy and angular variables are used!

$$P_\tau = -A_\tau = -\frac{2v_\tau a_\tau}{v_\tau^2 + a_\tau^2} \approx -2 \cdot \frac{v_\tau}{a_\tau} = -2(1 - 4\sin^2\theta_W^{\text{eff}}).$$

Tau polarisation directly measures the ratio of vector to axial Z couplings.

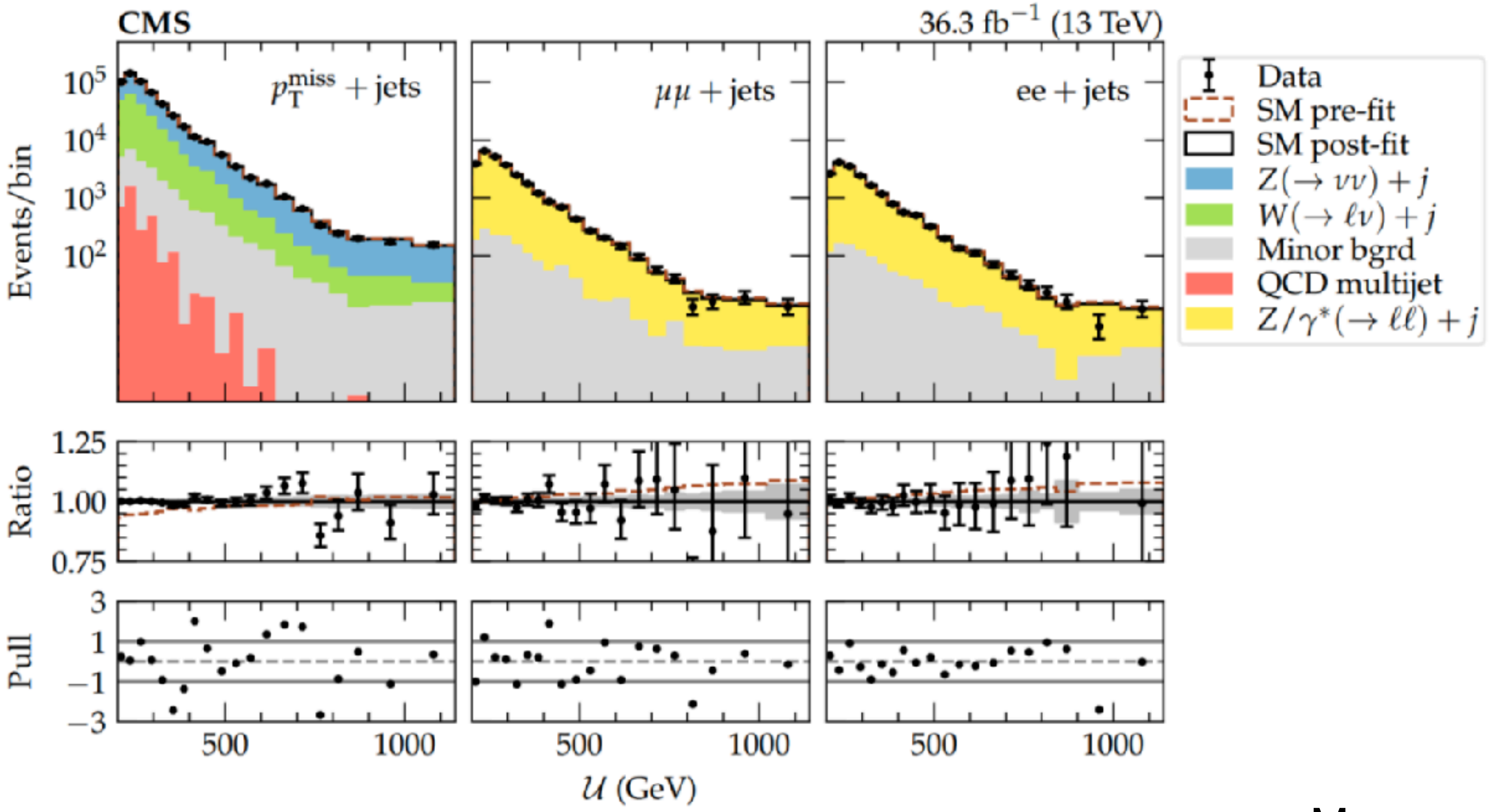
$$\mathcal{P}_\tau(Z^0) = -0.144 \pm 0.015 = -0.144 \pm 0.006\,(\text{stat}) \pm 0.014\,(\text{syst}).$$

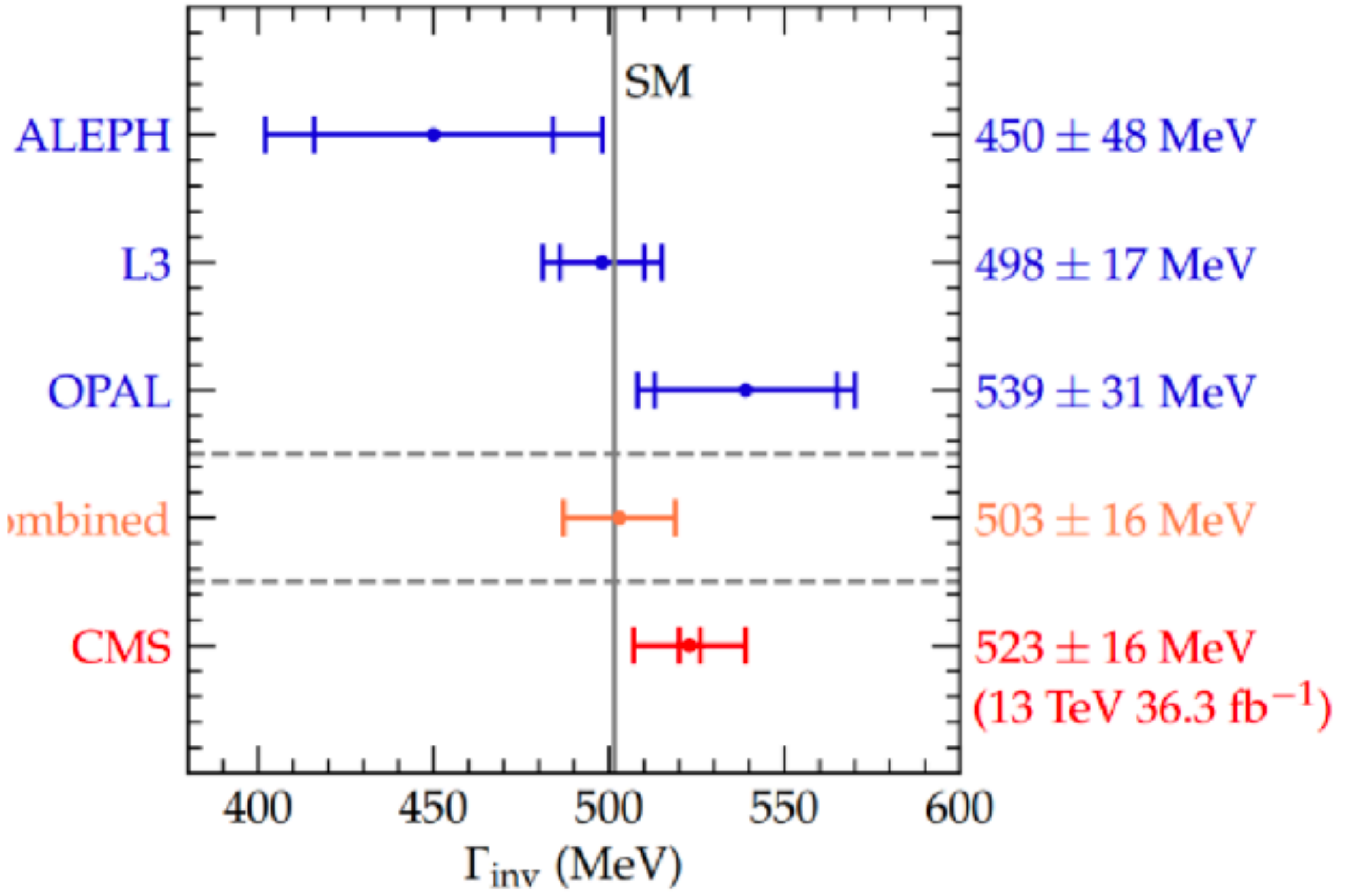
$$\sin^2\theta_W^{\text{eff}} = 0.2319 \pm 0.0019 = 0.2319 \pm 0.0008\,(\text{stat}) \pm 0.0018\,(\text{syst}).$$

Measurement already dominated by systematic uncertainties already! But not competitive with AFB measurements (in e and mu channels)!

Precise direct invisible Z Width by CMS!

Measurement based on missing transverse momentum





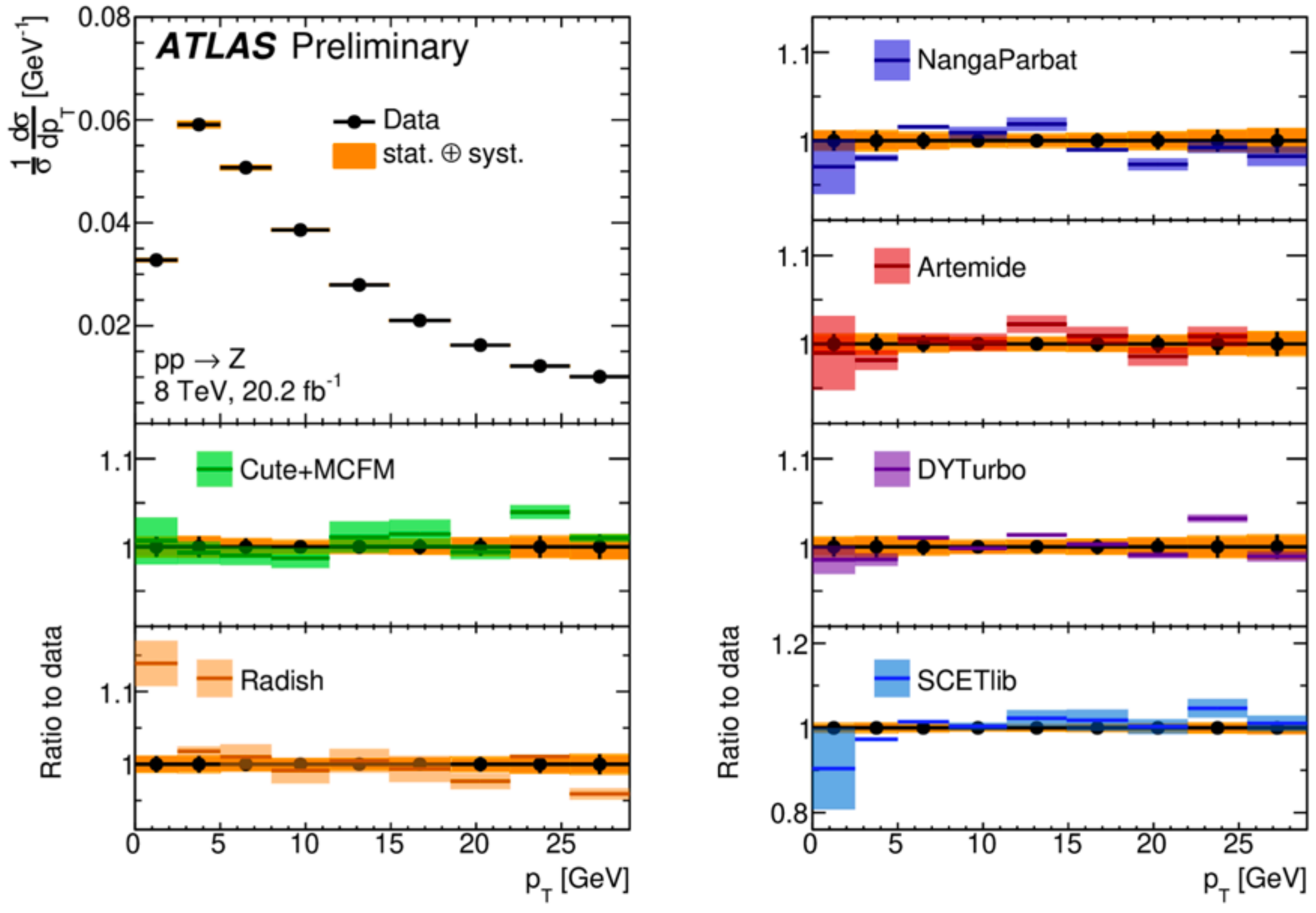
$$\Gamma_{inv} = 523 \pm 3\,(stat) \pm 16\,(syst)\,\text{MeV}$$

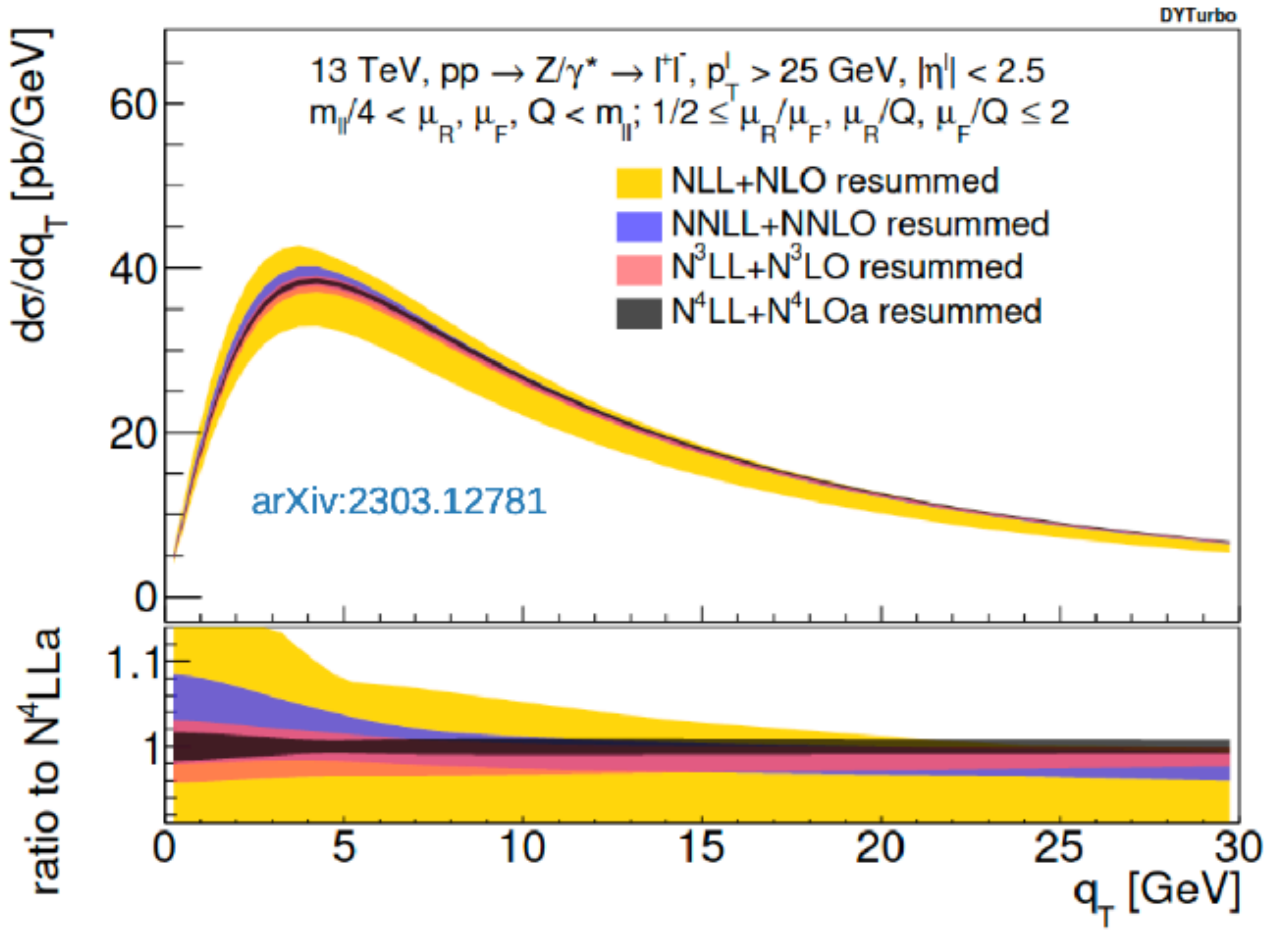
Measurement already dominated by systematic uncertainties!

Precise Determination of α_S - ATLAS

Measurement of the differential **full-lepton phase space** Z cross section!

$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma^{U+L}}{dp_T\, dy\, dm}\left(1+\cos^2\theta + \sum_{i=0}^{7} A_i(y,p_T,m)P_i(\cos\theta,\phi)\right)$$

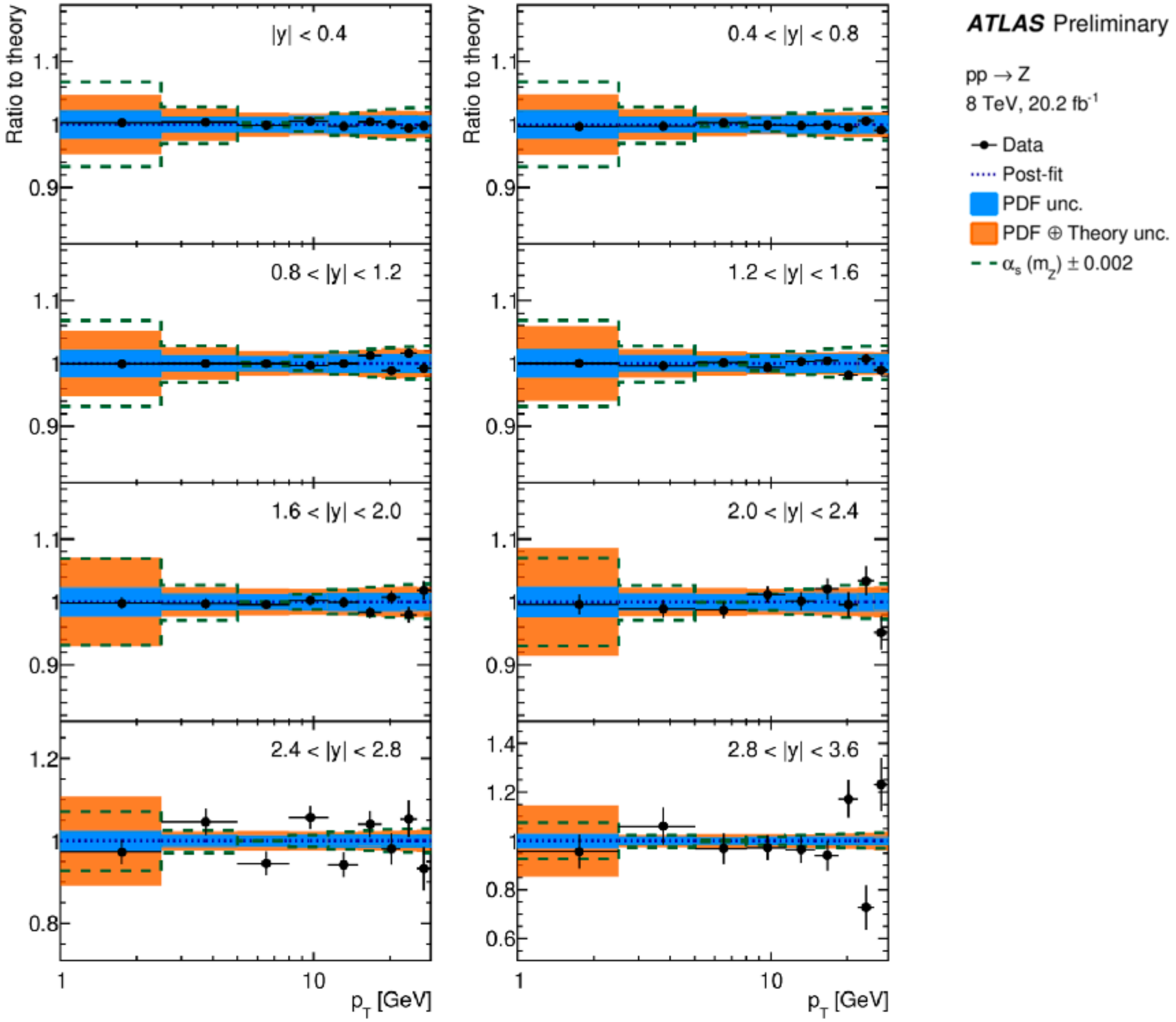


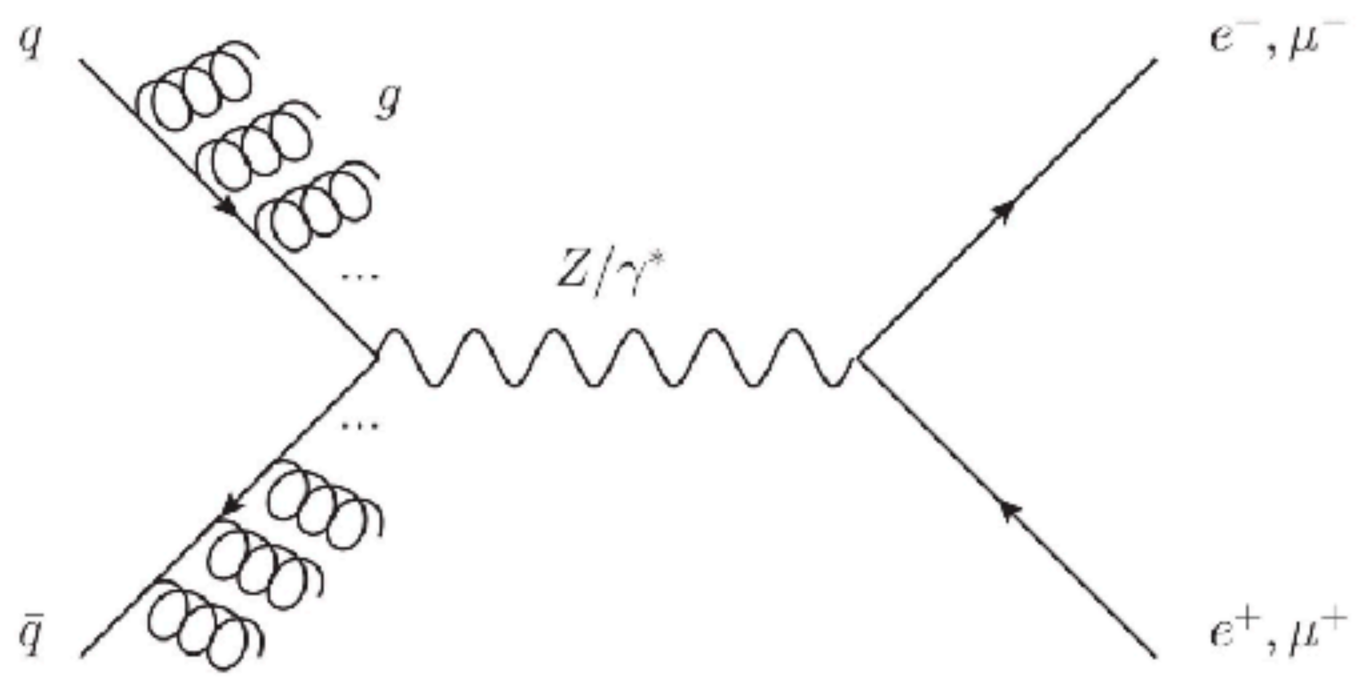


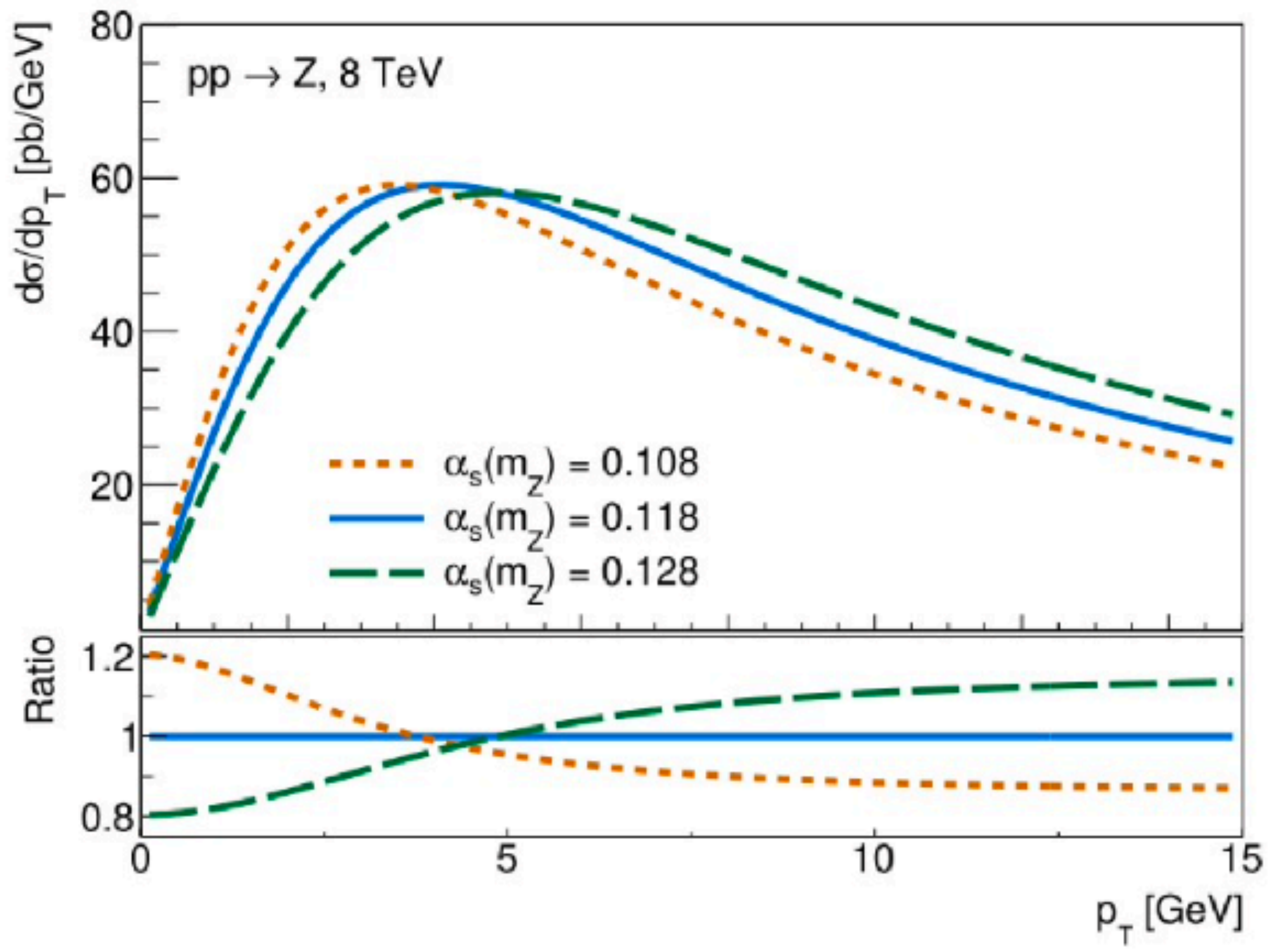
Comparisons done at N3LO-N4LL with N3LO PDFs

Precise Determination of α_S - ATLAS

Most precise determination of α_S based on the Sudakof peak, first measurement based on resummation

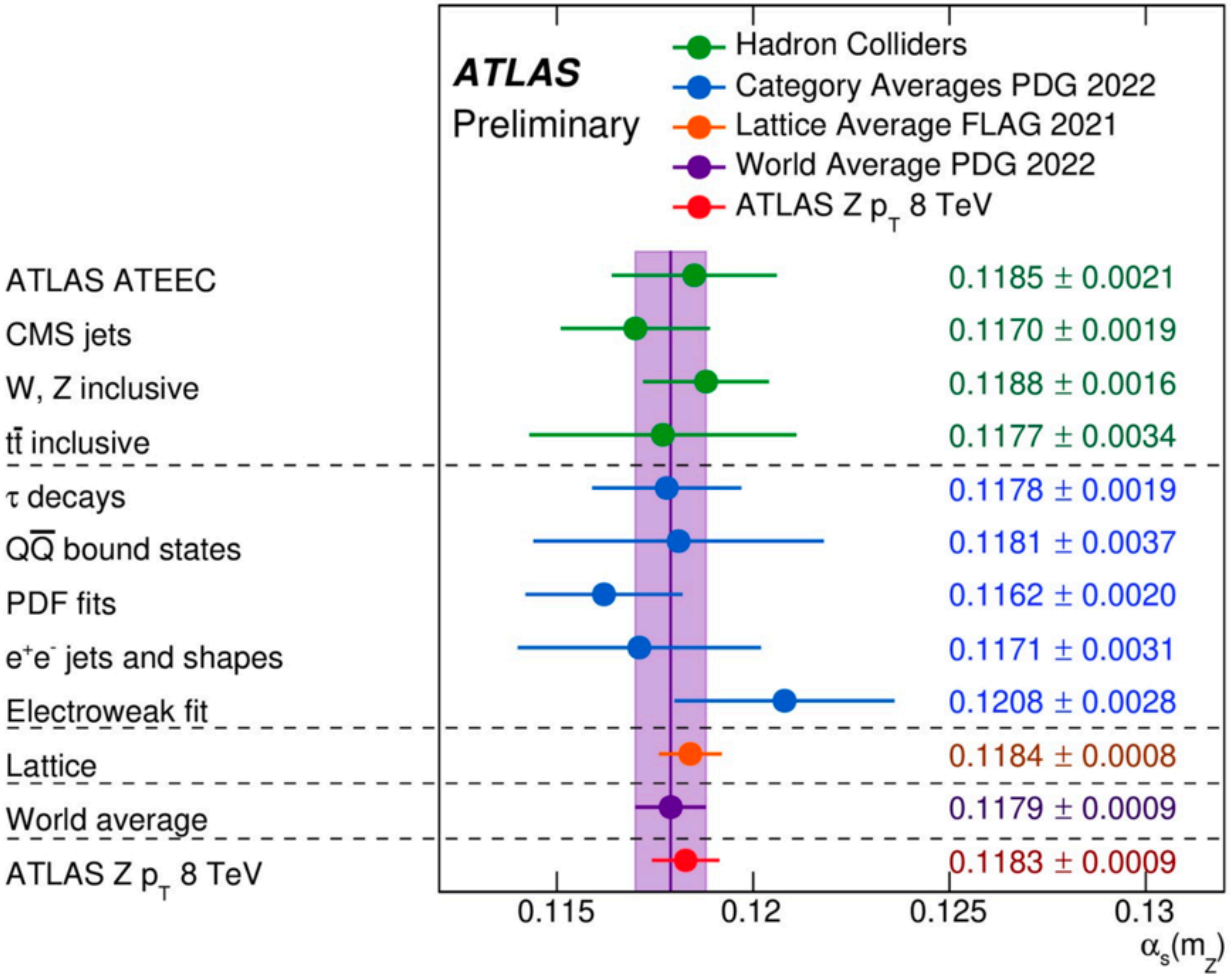


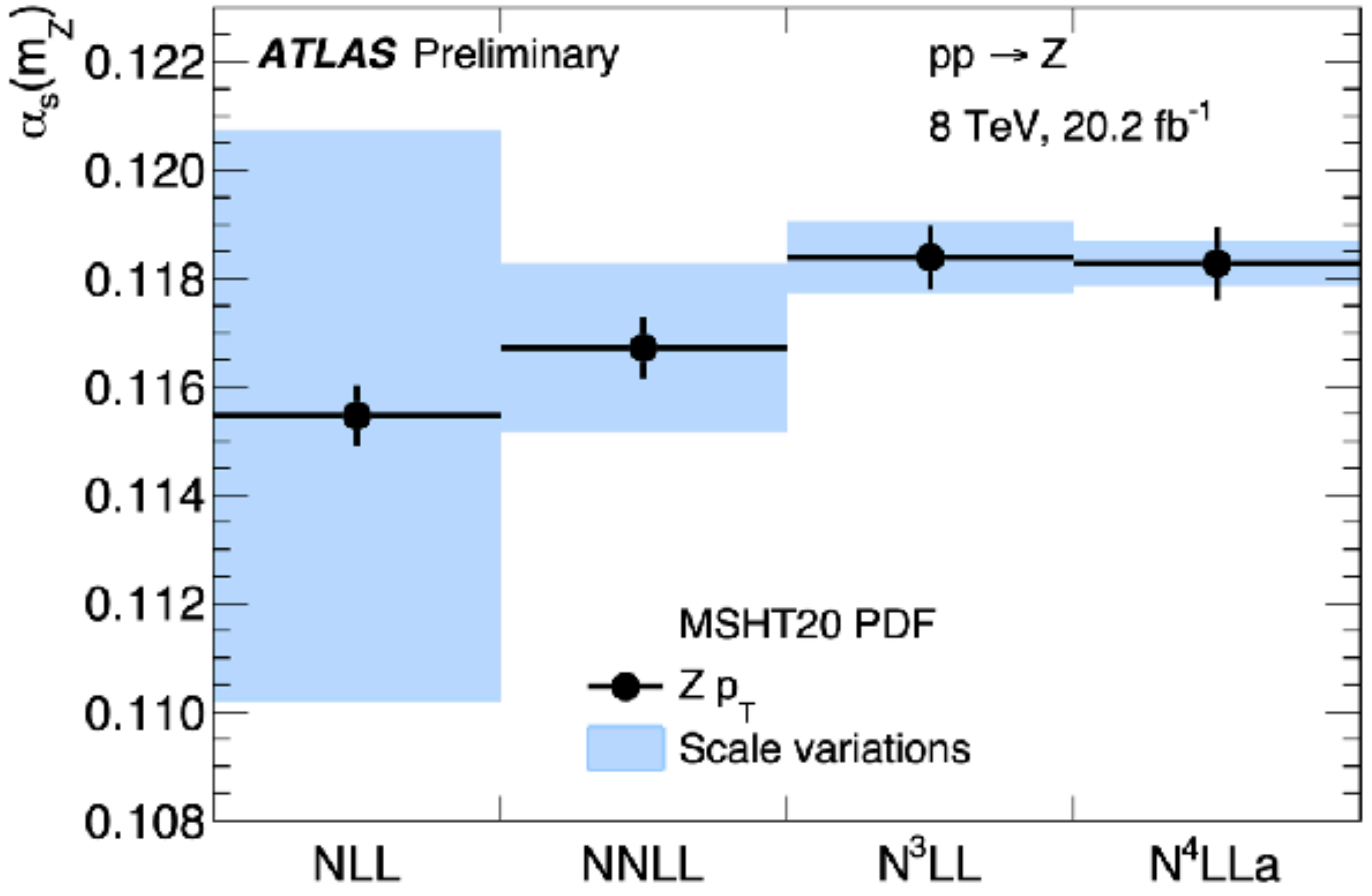




Precise Determination of α_S - ATLAS

Most precise determination of α_S based on the Sudakof peak, first measurement based on resummation





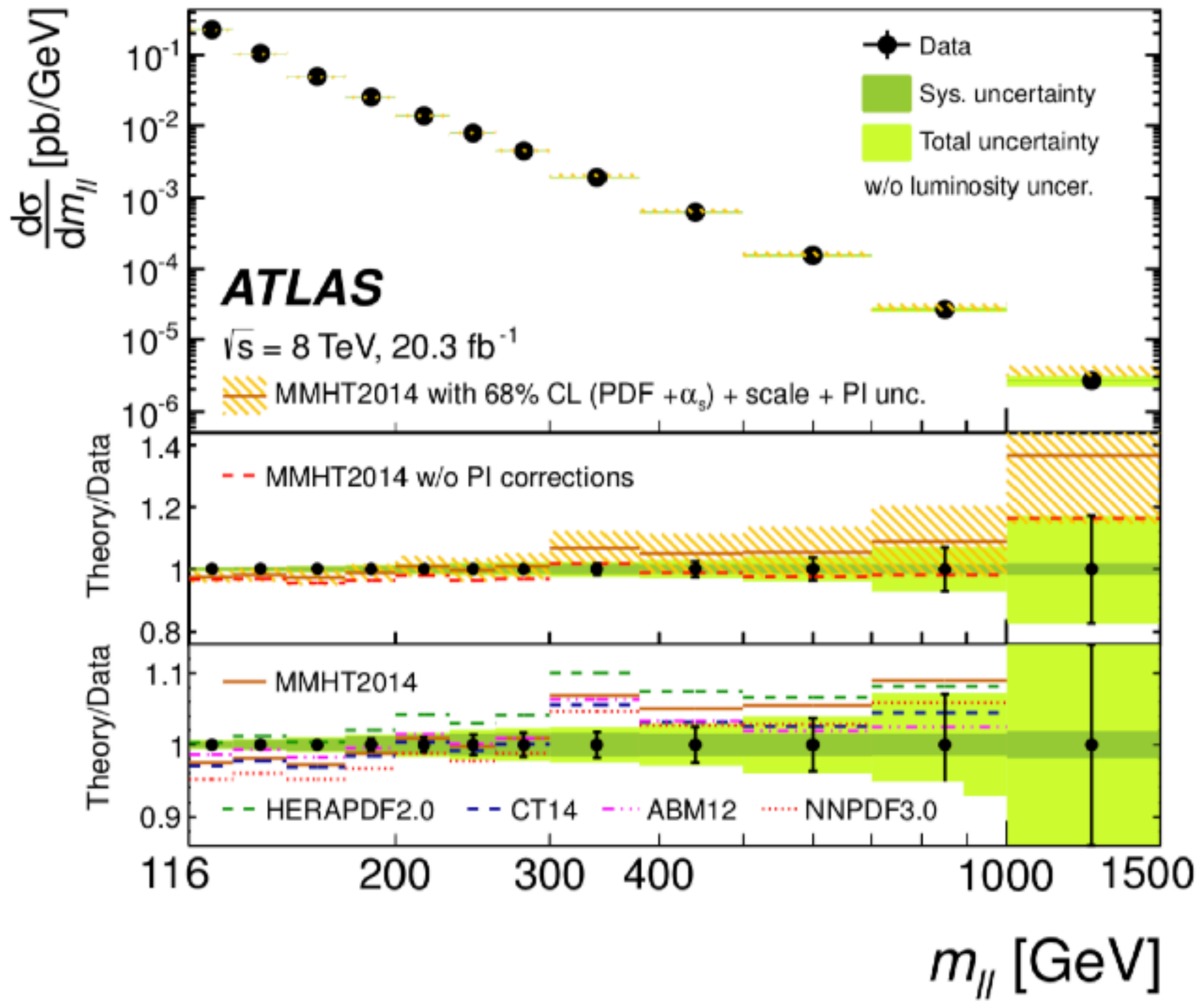
Such precision would not be possible without precise TH predictions (K. Melnikov's lectures)!

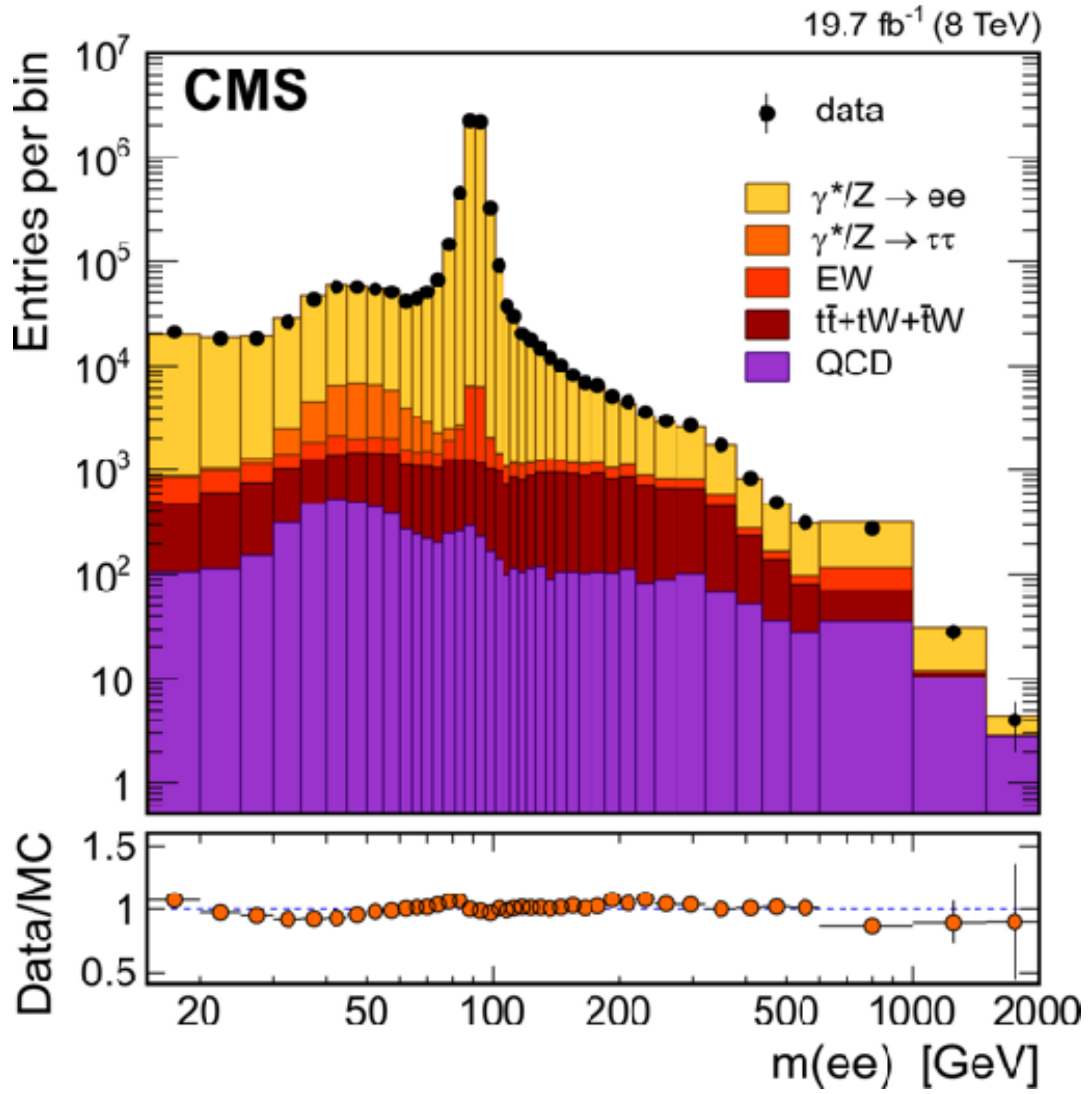
Precision on par with Lattice QCD estimates!

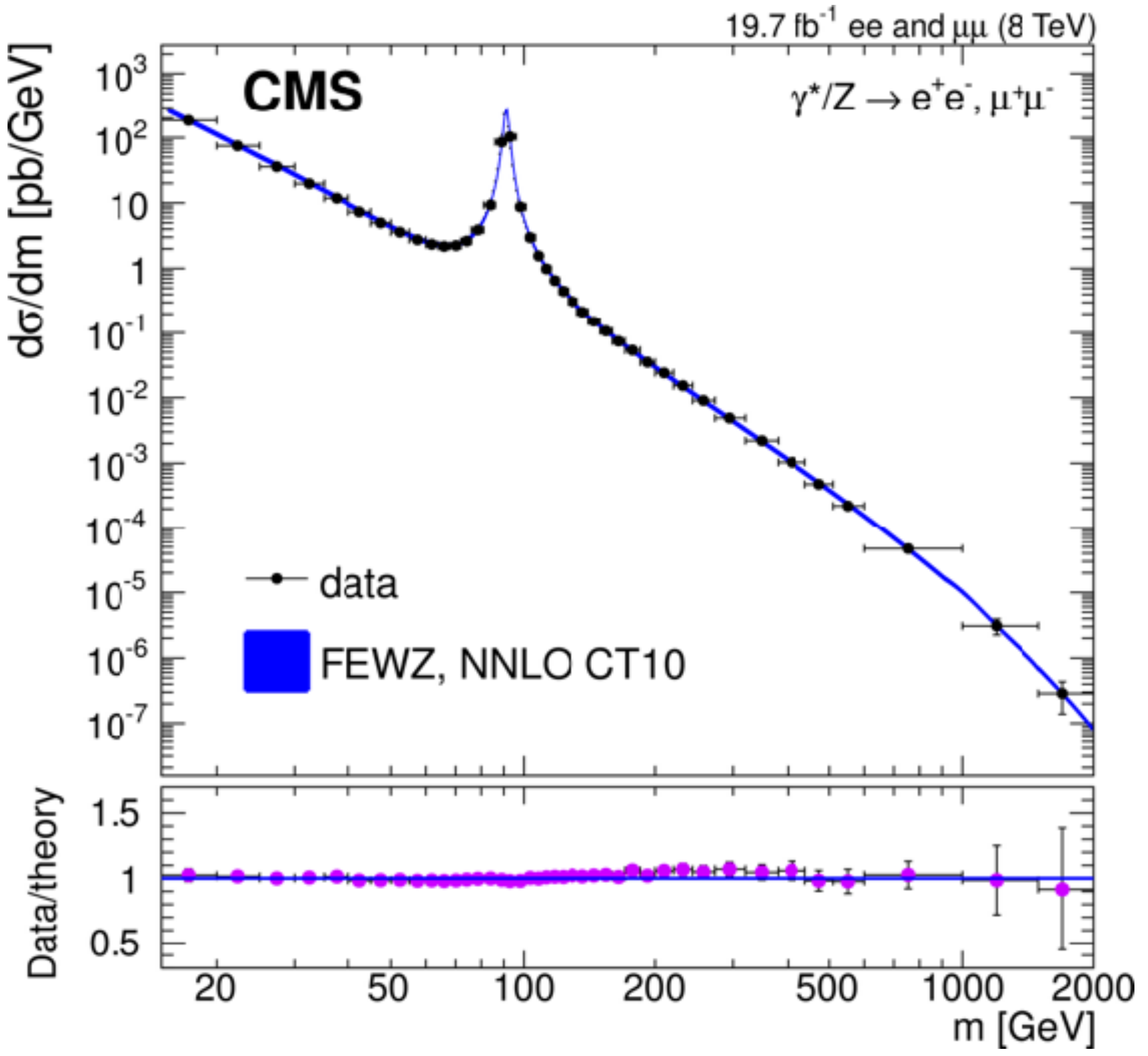
High Mass Drell Yan Measurements

Measuring DY in the high mass region is very interesting for EW and Effective field theory constraints.

A highly non trivial measurement!





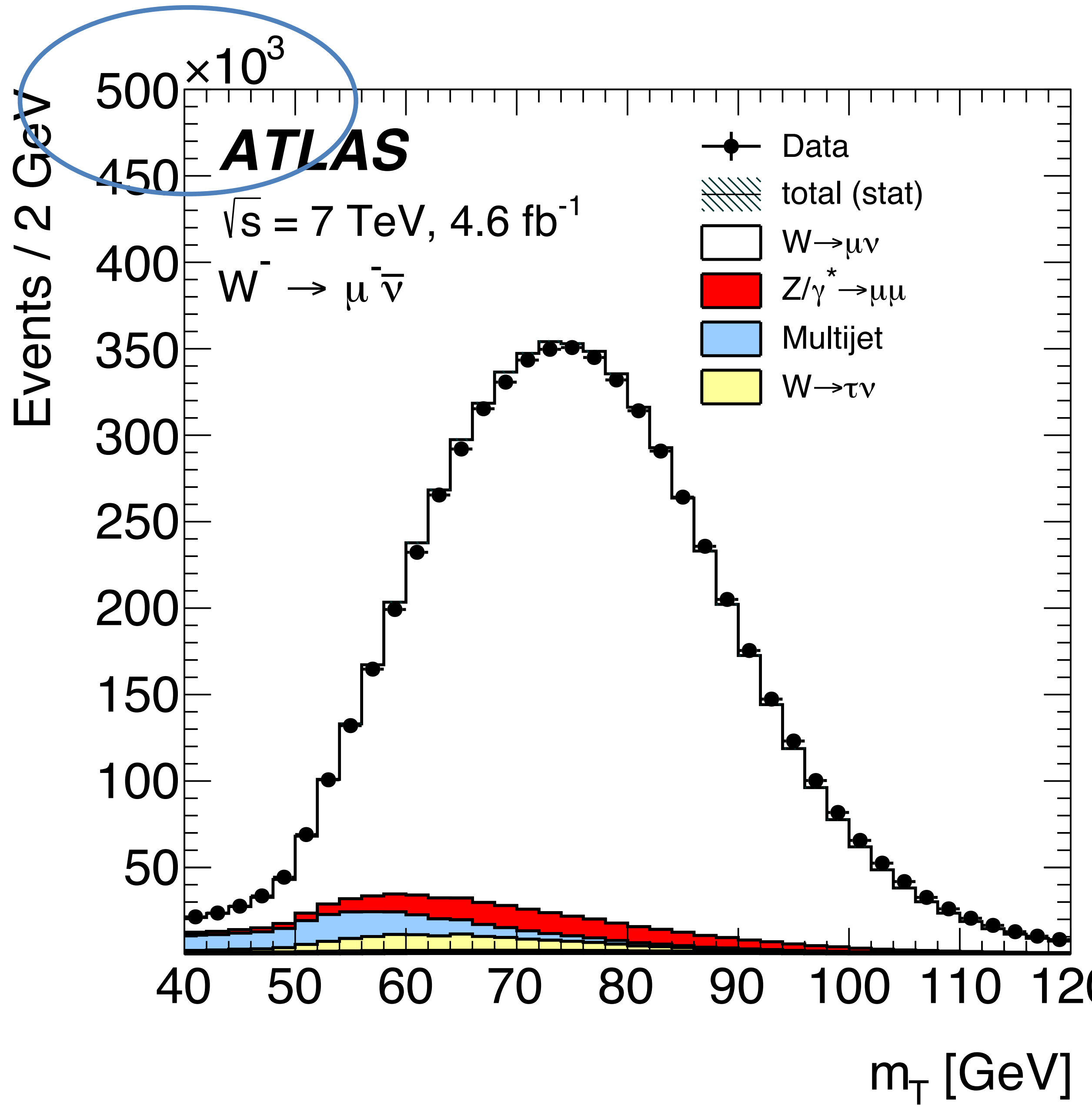


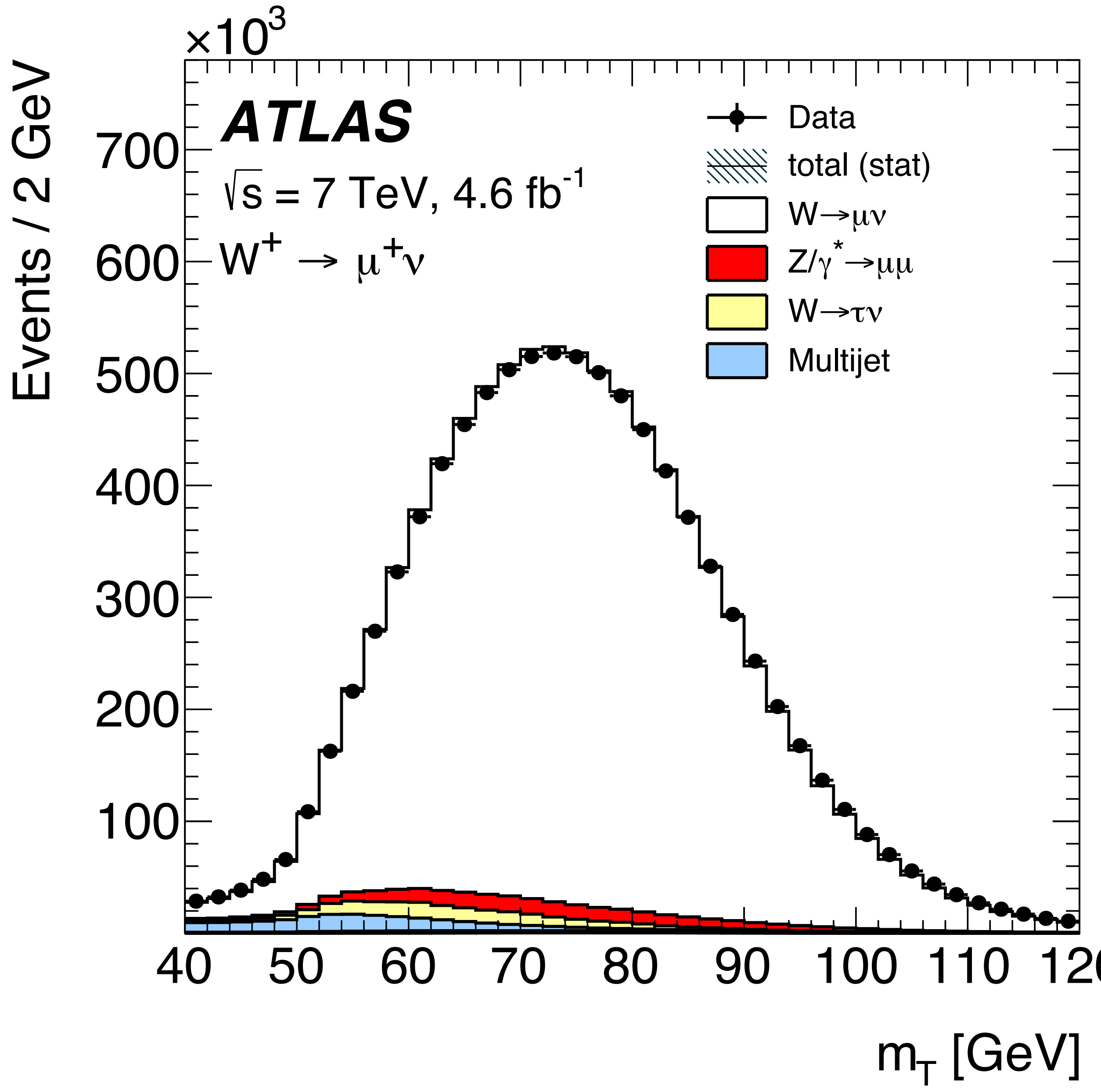
Drell-Yan W boson production

ATLAS EXPERIMENT

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

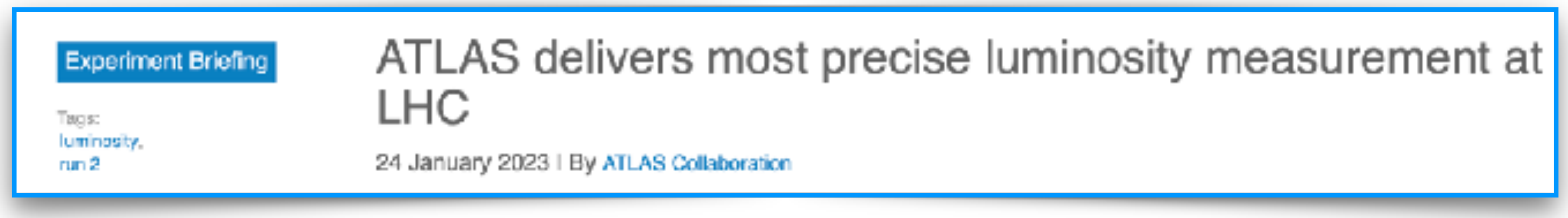
Inclusive Precision Vector Boson Production at the LHC

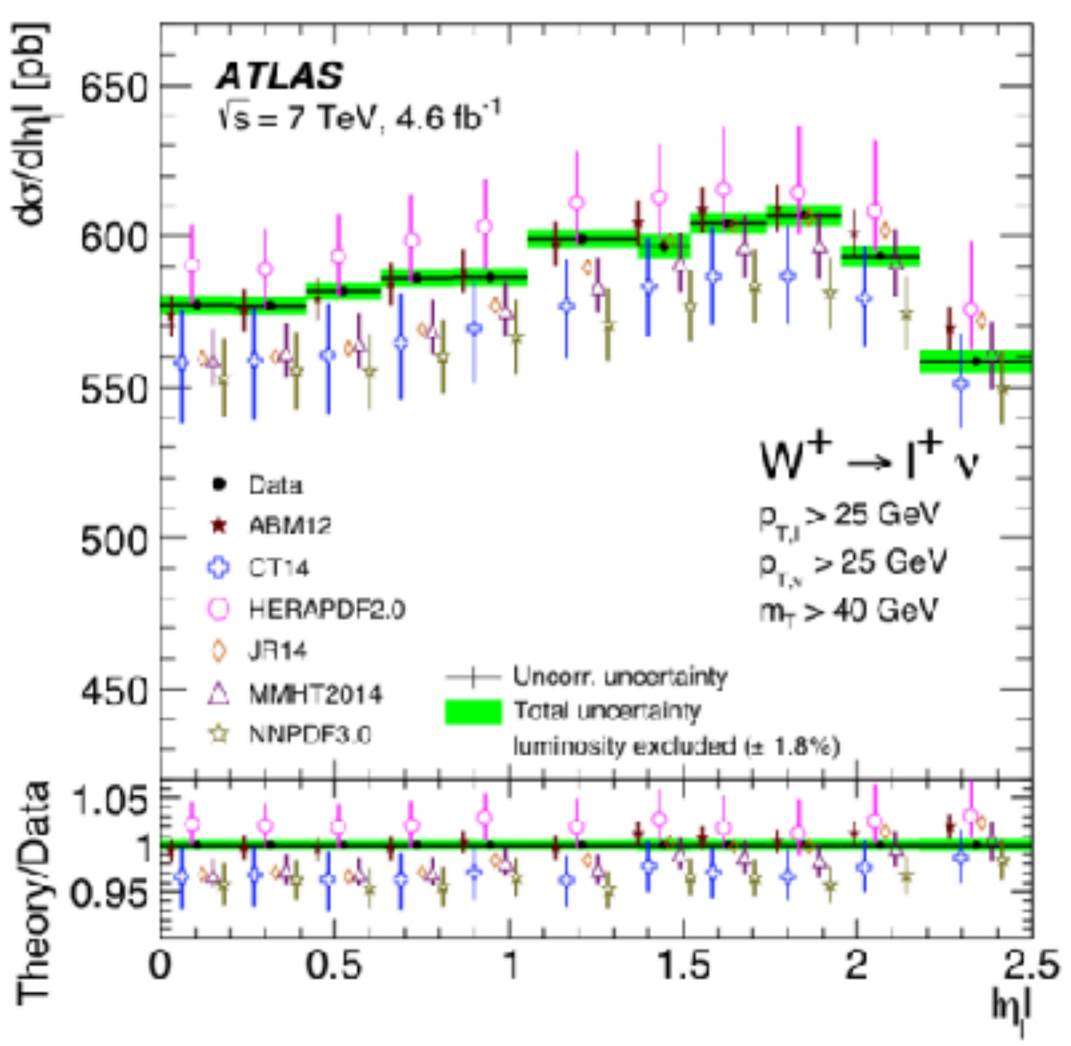


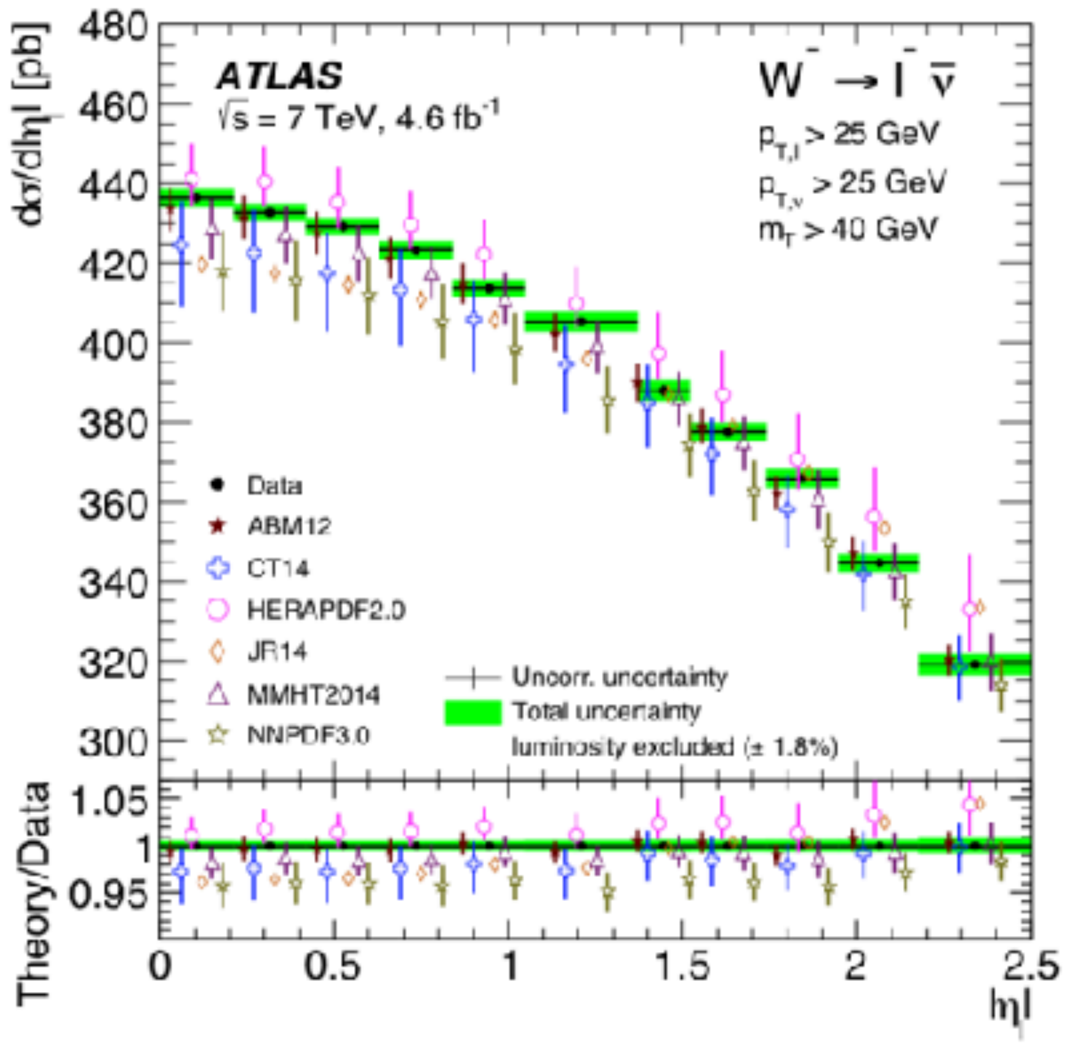


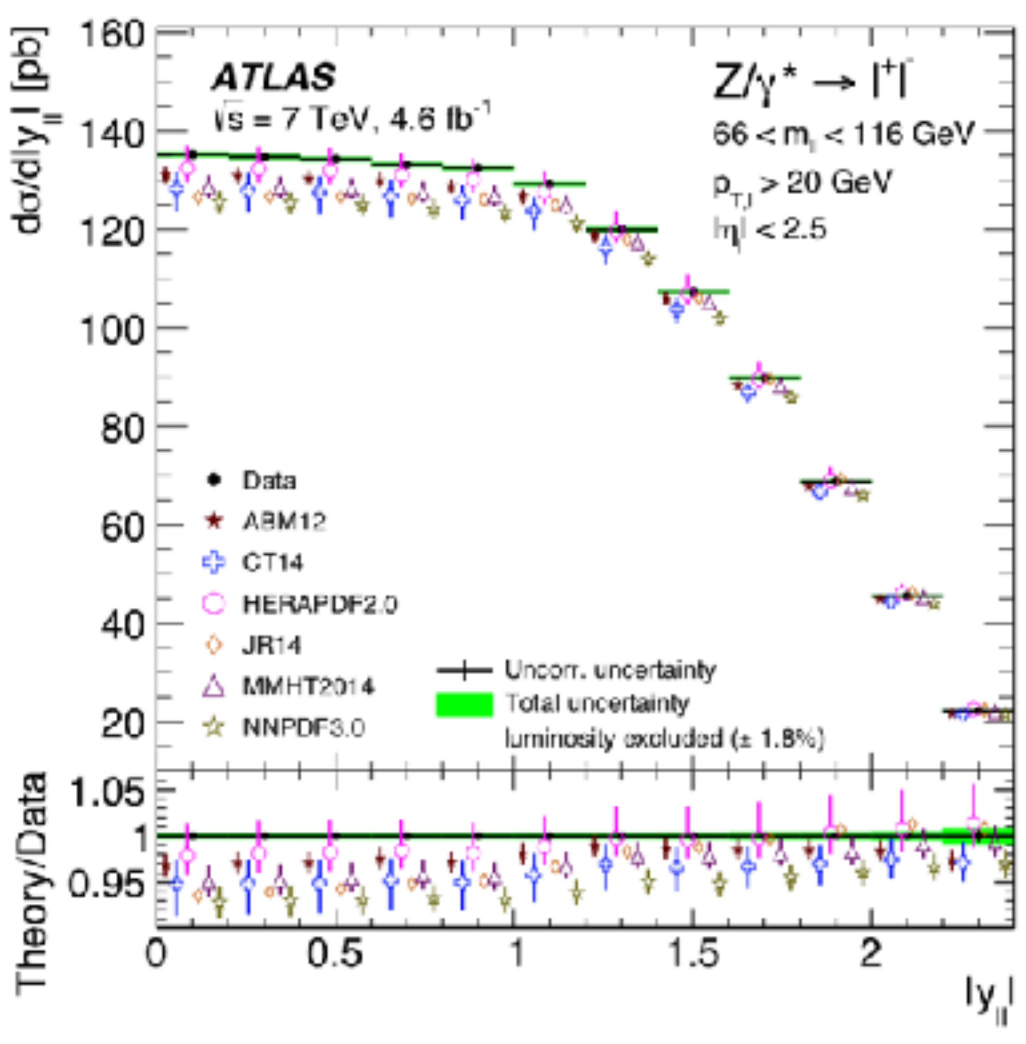
With a dataset of only 4.6 fb-1 at **7 TeV**, approximately 15.5 M W+ events and 10.4 W- events (electrons and muons). **Low PU !**

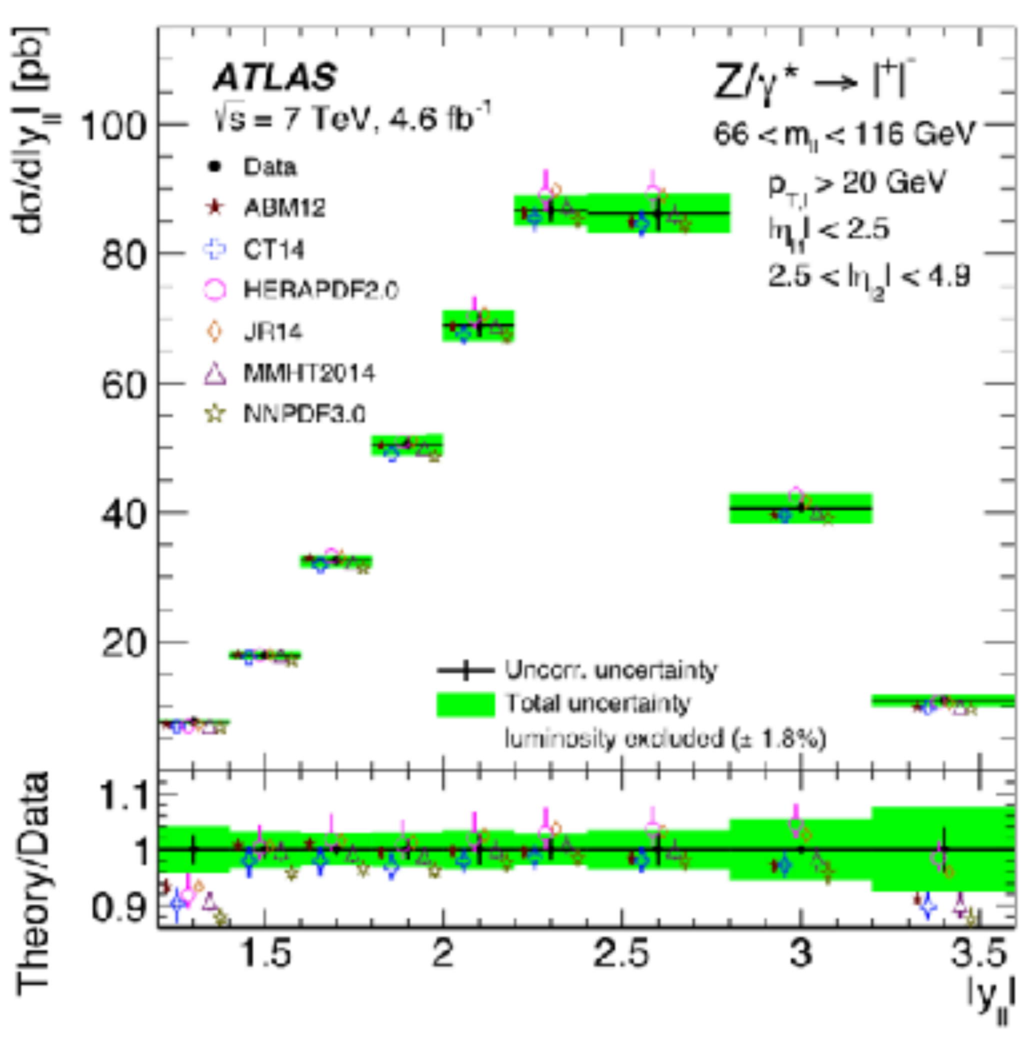
Cross section measurement (as a function of rapidity) the uncertainty **completely dominated by luminosity uncertainty of 1.8% - Now reached less than 1% (see ATLAS briefing) !!!**



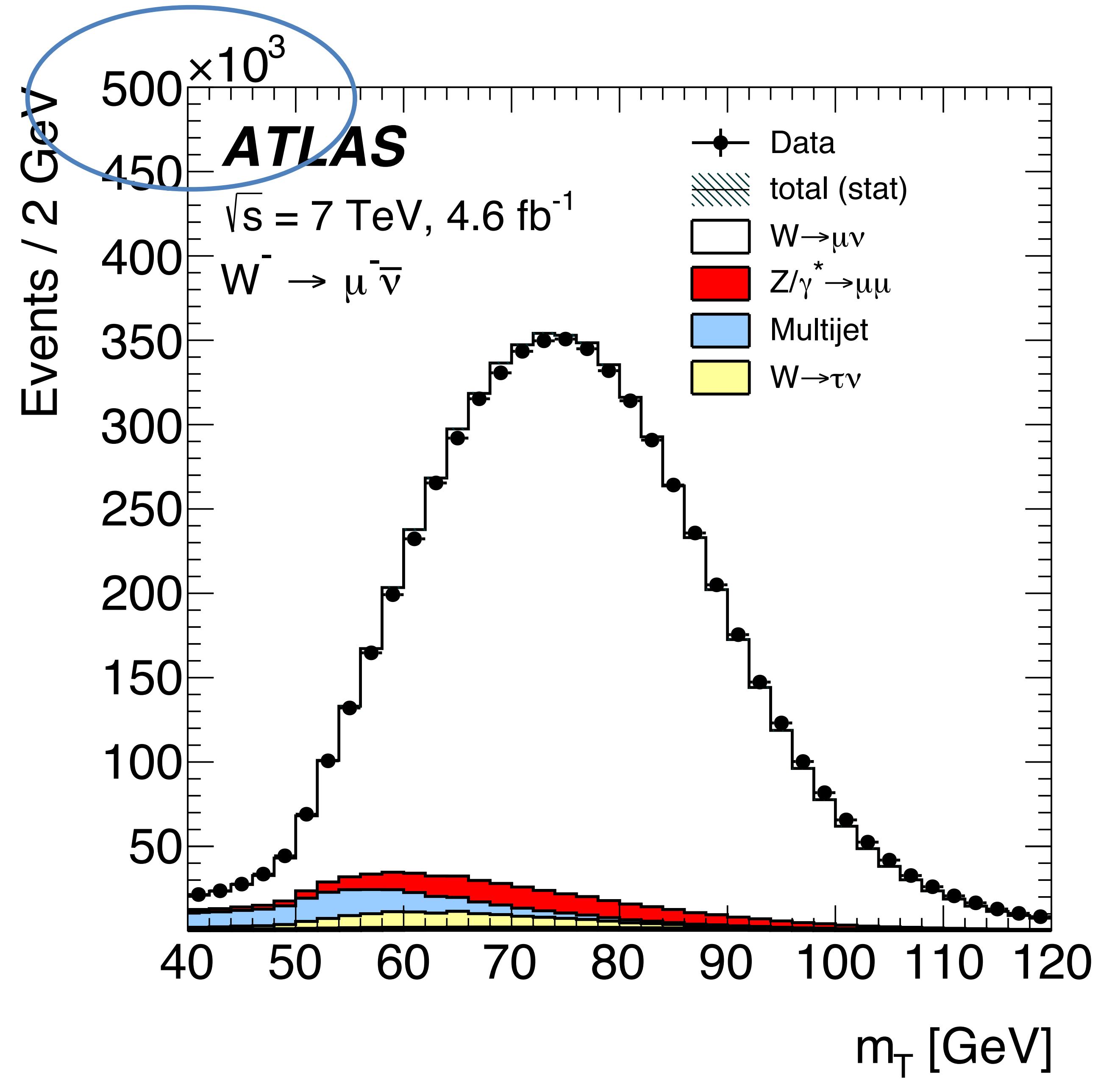


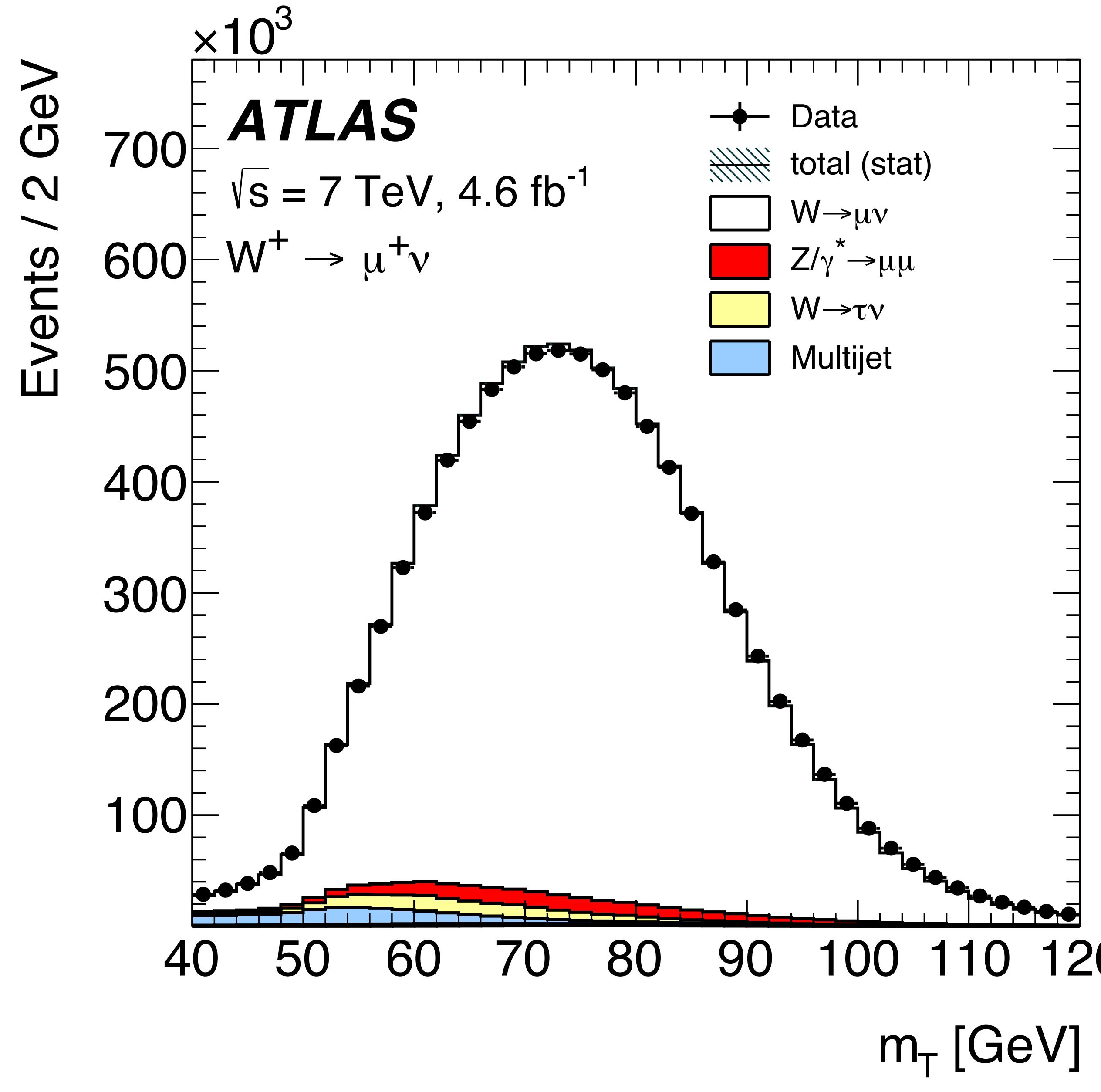






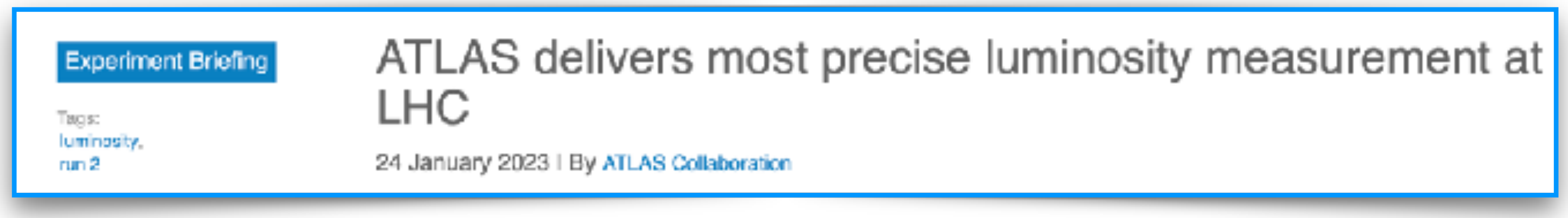
Inclusive Precision Vector Boson Production at the LHC

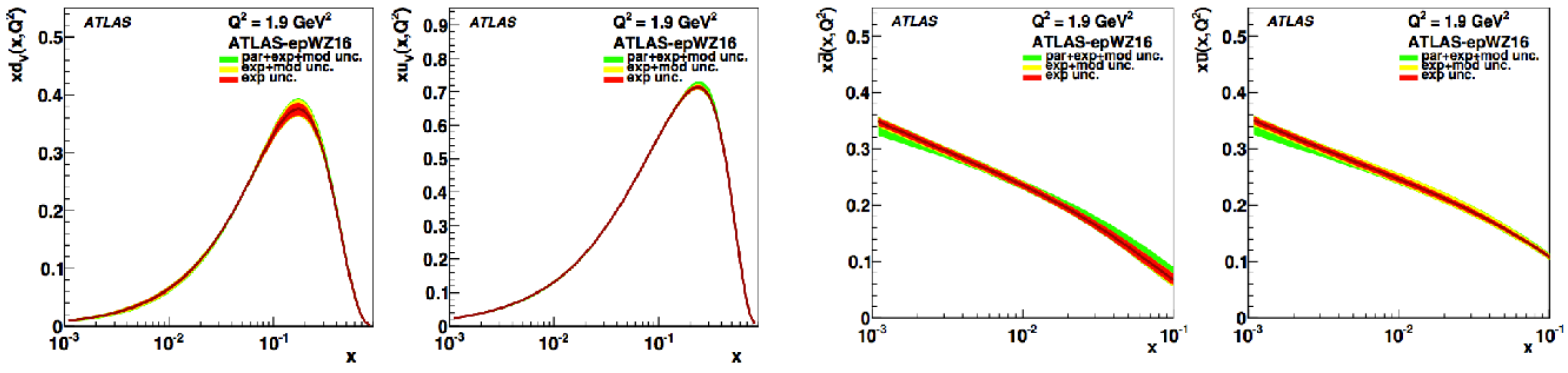




With a dataset of only 4.6 fb-1 at **7 TeV**, approximately 15.5 M W+ events and 10.4 W- events (electrons and muons). **Low PU !**

Cross section measurement (as a function of rapidity) the uncertainty **completely dominated by luminosity uncertainty of 1.8% - Now reached less than 1% (see ATLAS briefing) !!!**



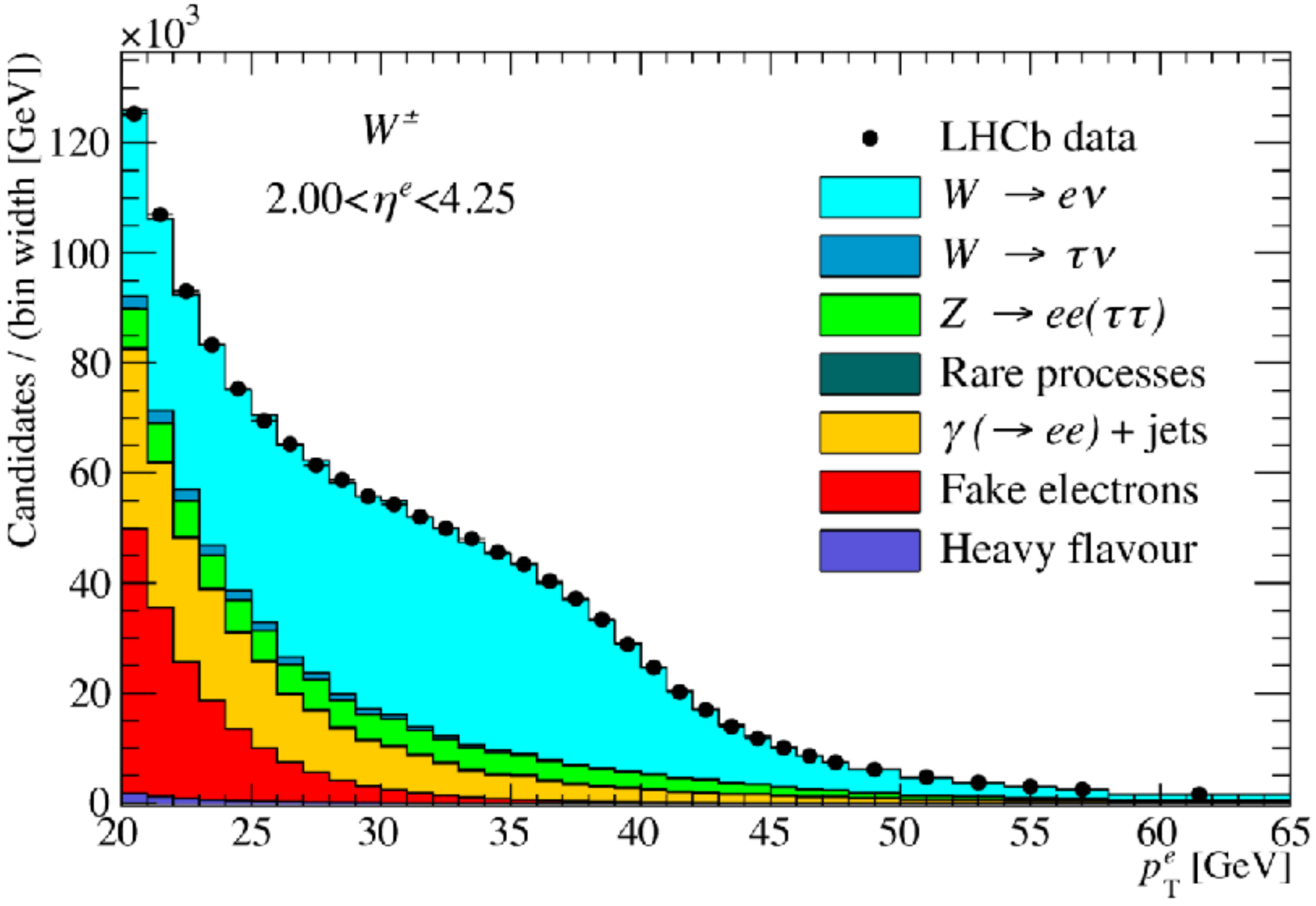


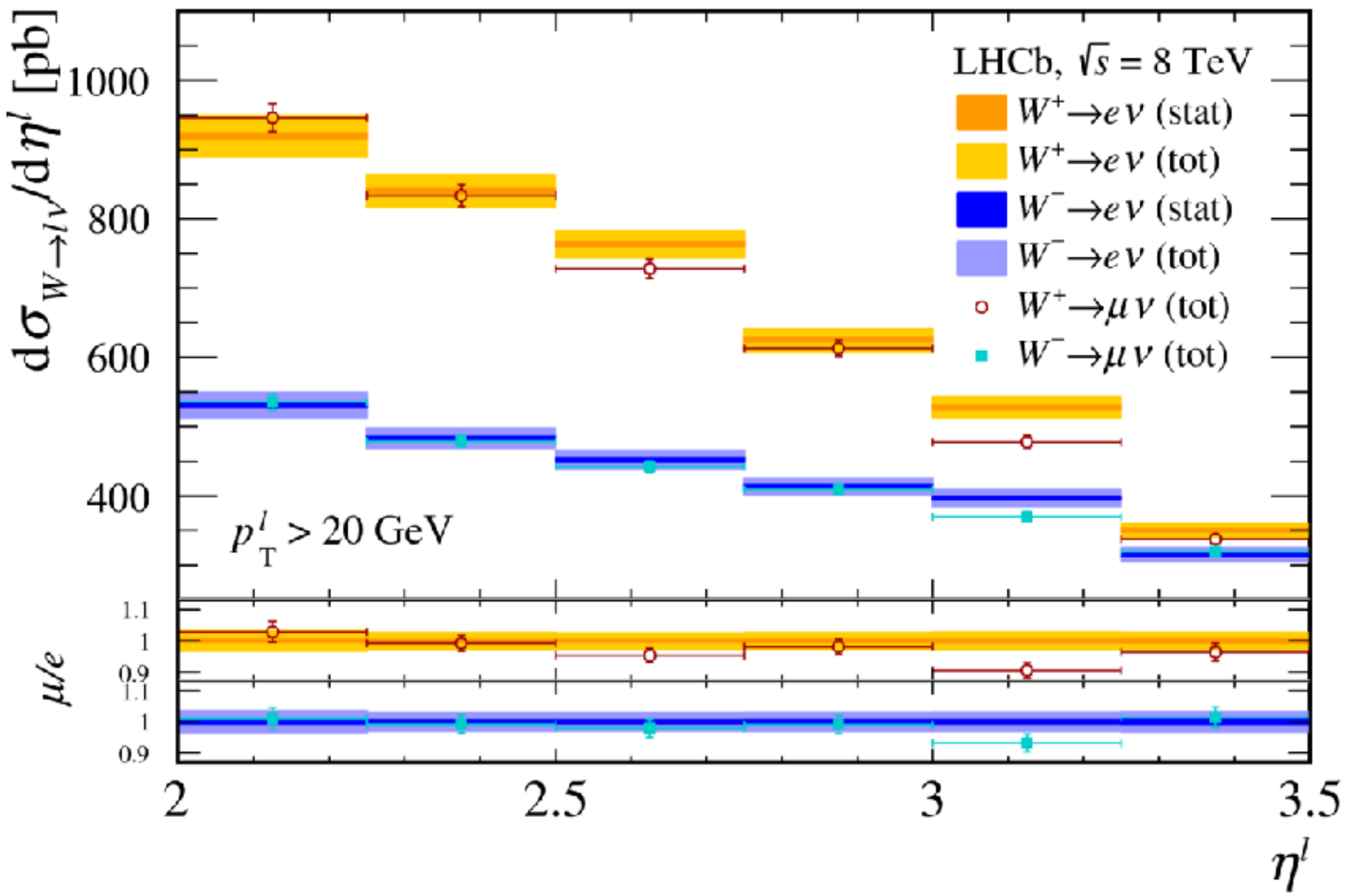
Using these cross section measurements and the the Deep Inelastic Scattering data from Hera new set of PDFs can be estimated (ATLAS-epWZ16 same was done in CMS).

Inclusive Vector Boson Production at LHCb

LHCb

Precision W production measurements (at 8 TeV) complement the pseudo-rapidity distribution of the leptons in the [2-5] region.



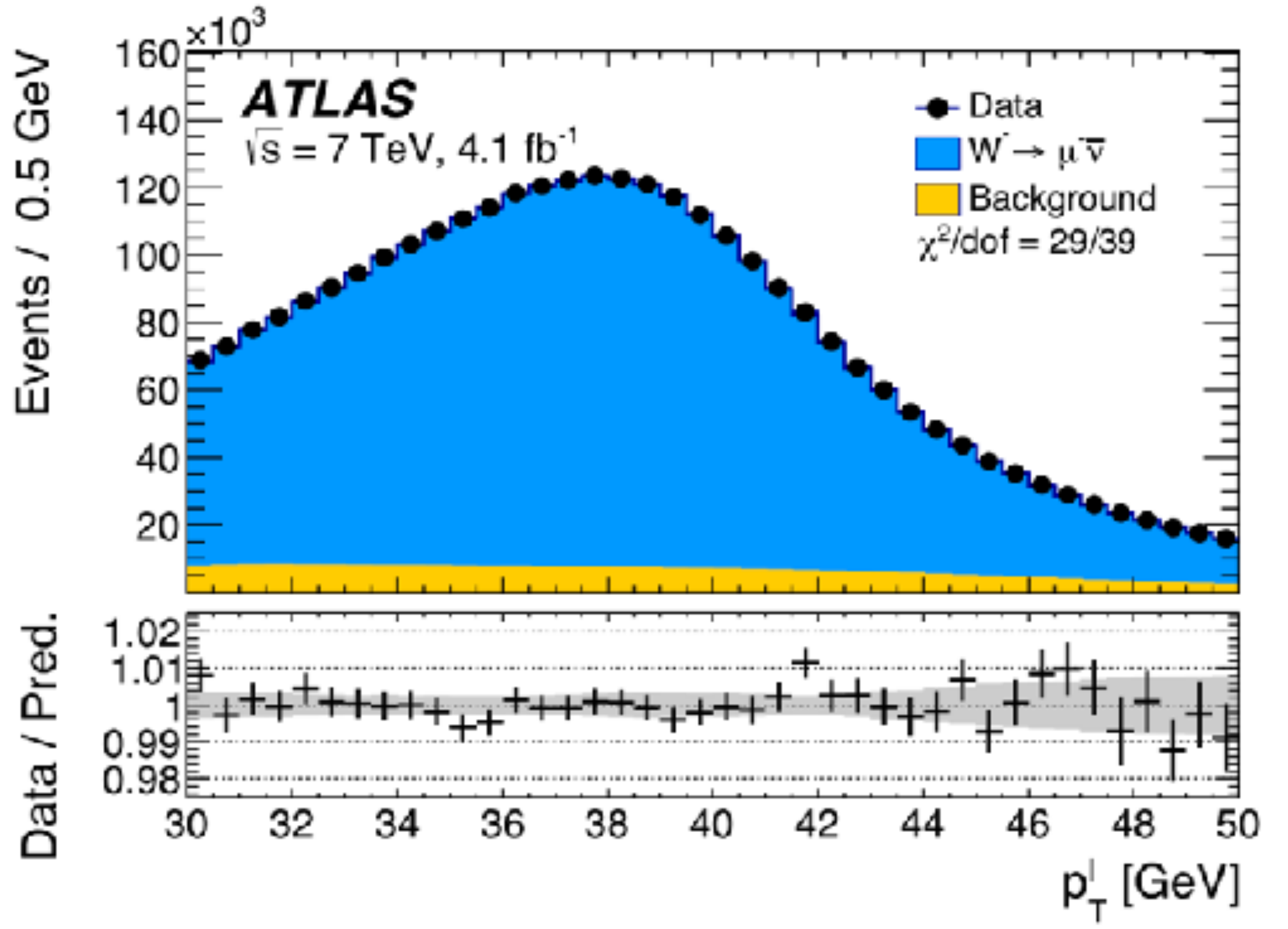


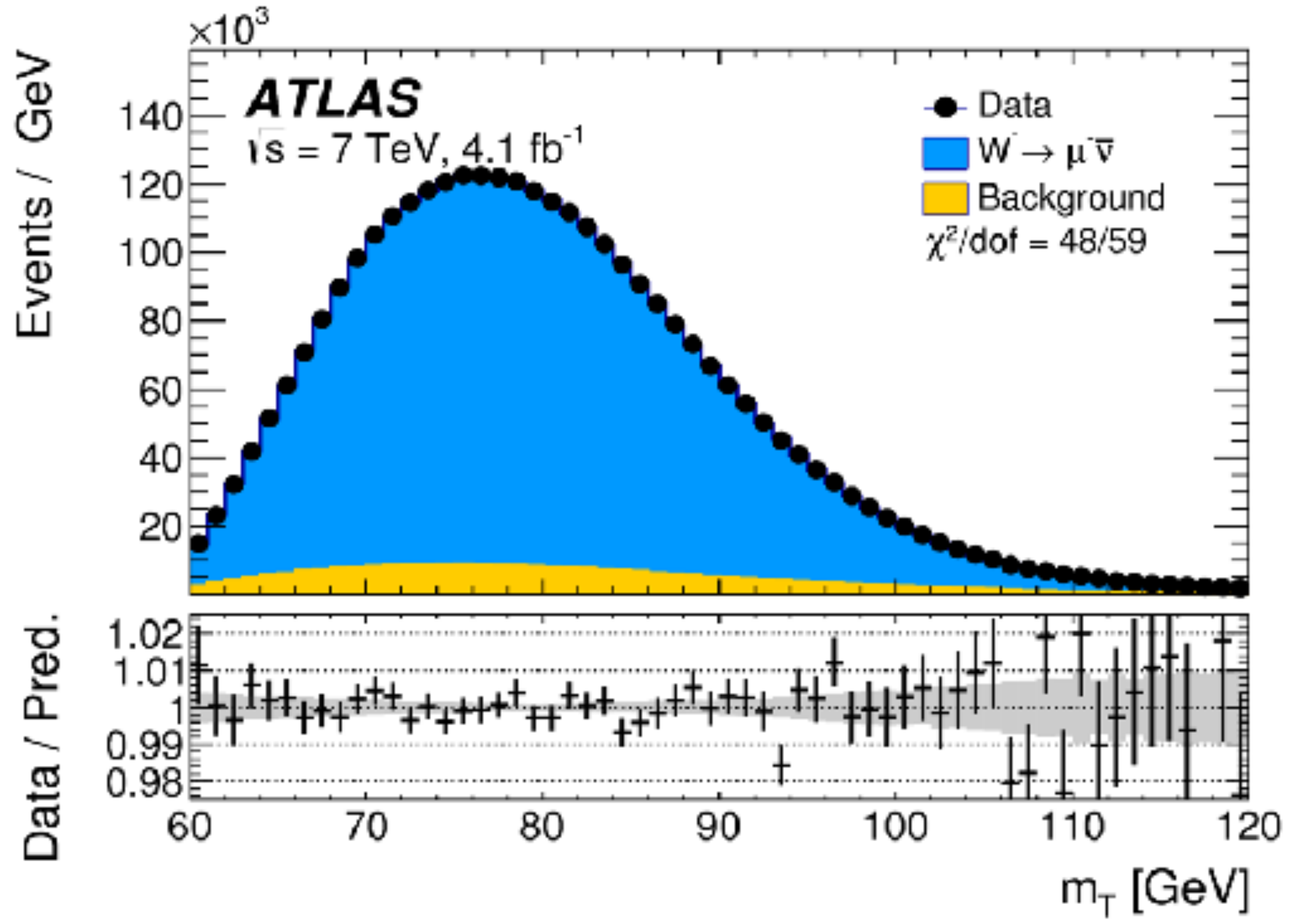
Important complementarity for PDF fits.

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

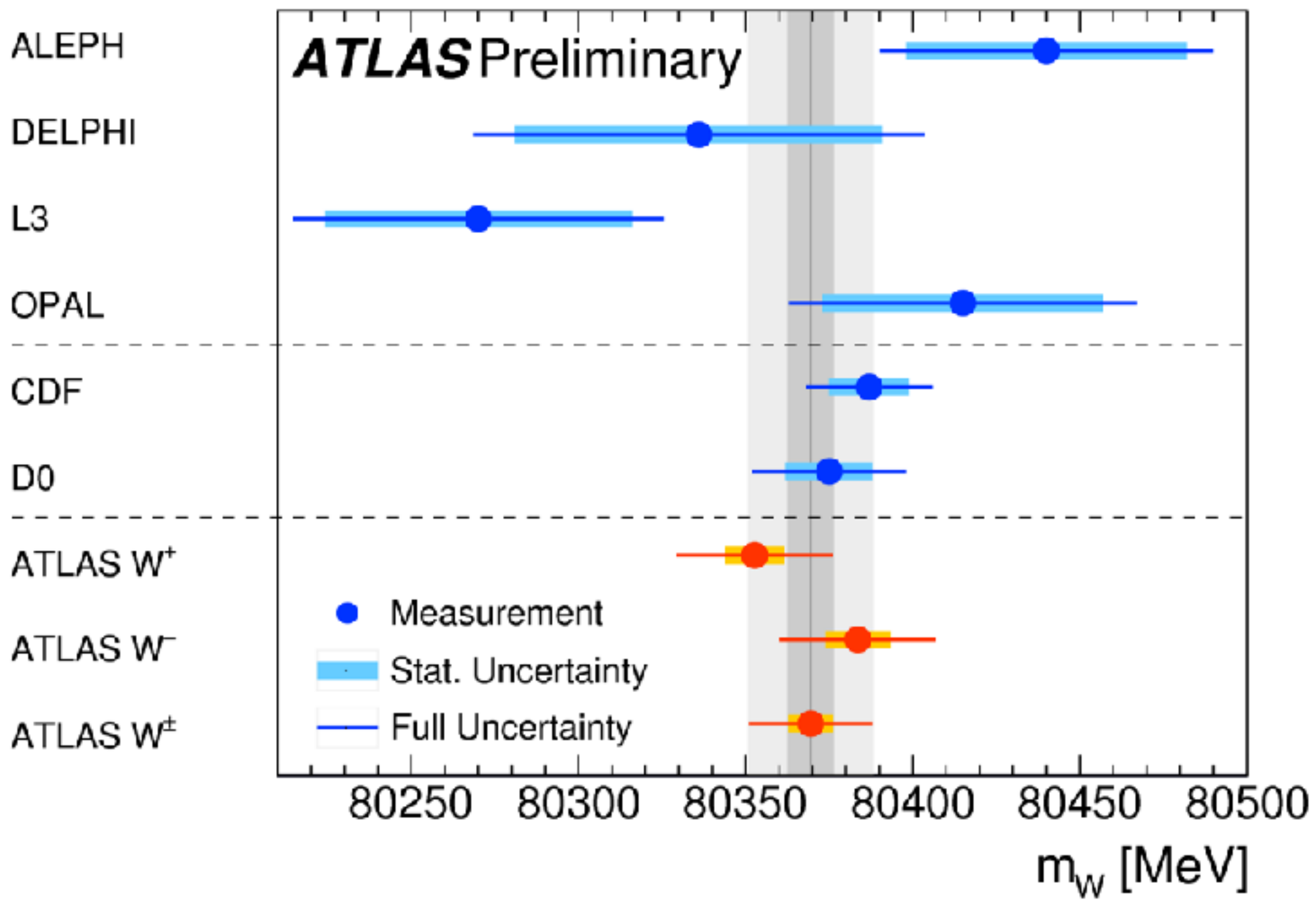
m_T Less sensitive to modelling but more difficult from to reconstruct (based on the missing transverse energy.

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

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

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

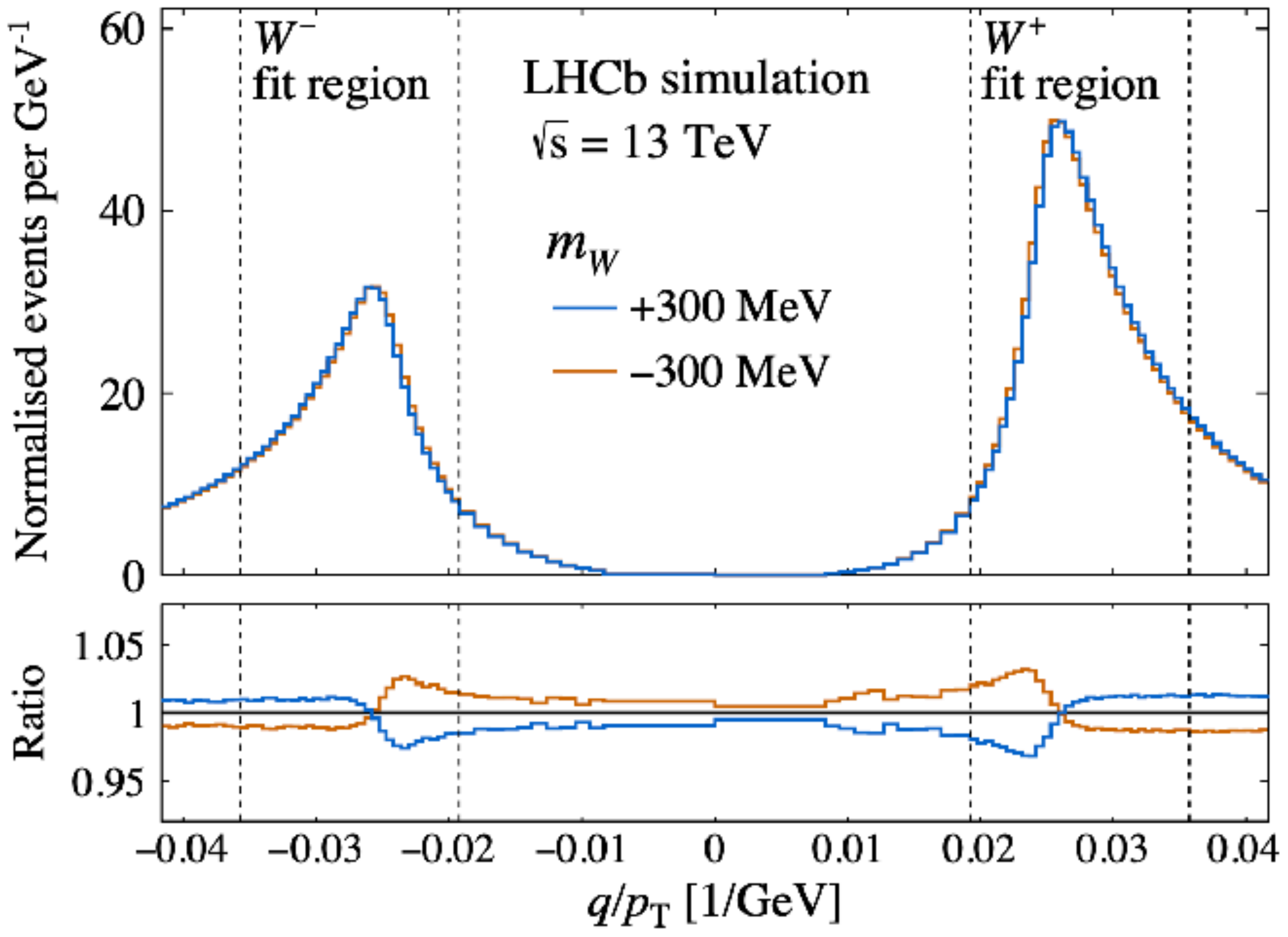
$$\pm 6.8 \text{ (Stat)} \pm 10.6 \text{ (Exp)} \pm 13.6 \text{(Mod) MeV}$$

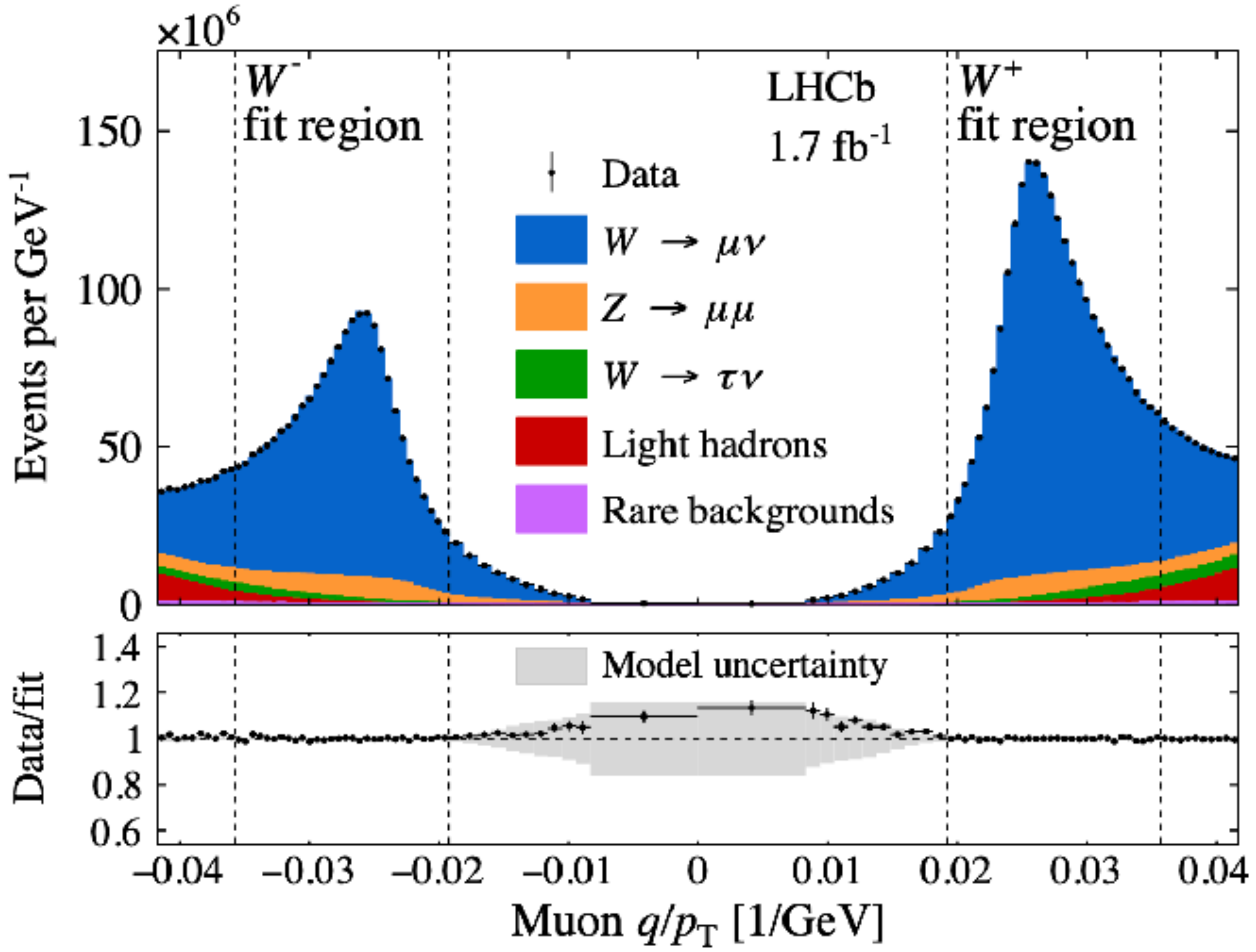


LHCb Measurement of the W Mass

Measurement done using the q/p distribution (dominant in ATLAS as well) for W events and simultaneously the Collins-Soper ϕ^* distribution for the Z events:

$$\phi^* = \frac{\tan((\pi - \Delta\phi)/2)}{\cosh(\Delta\eta/2)} \sim \frac{p_T^Z}{M}$$



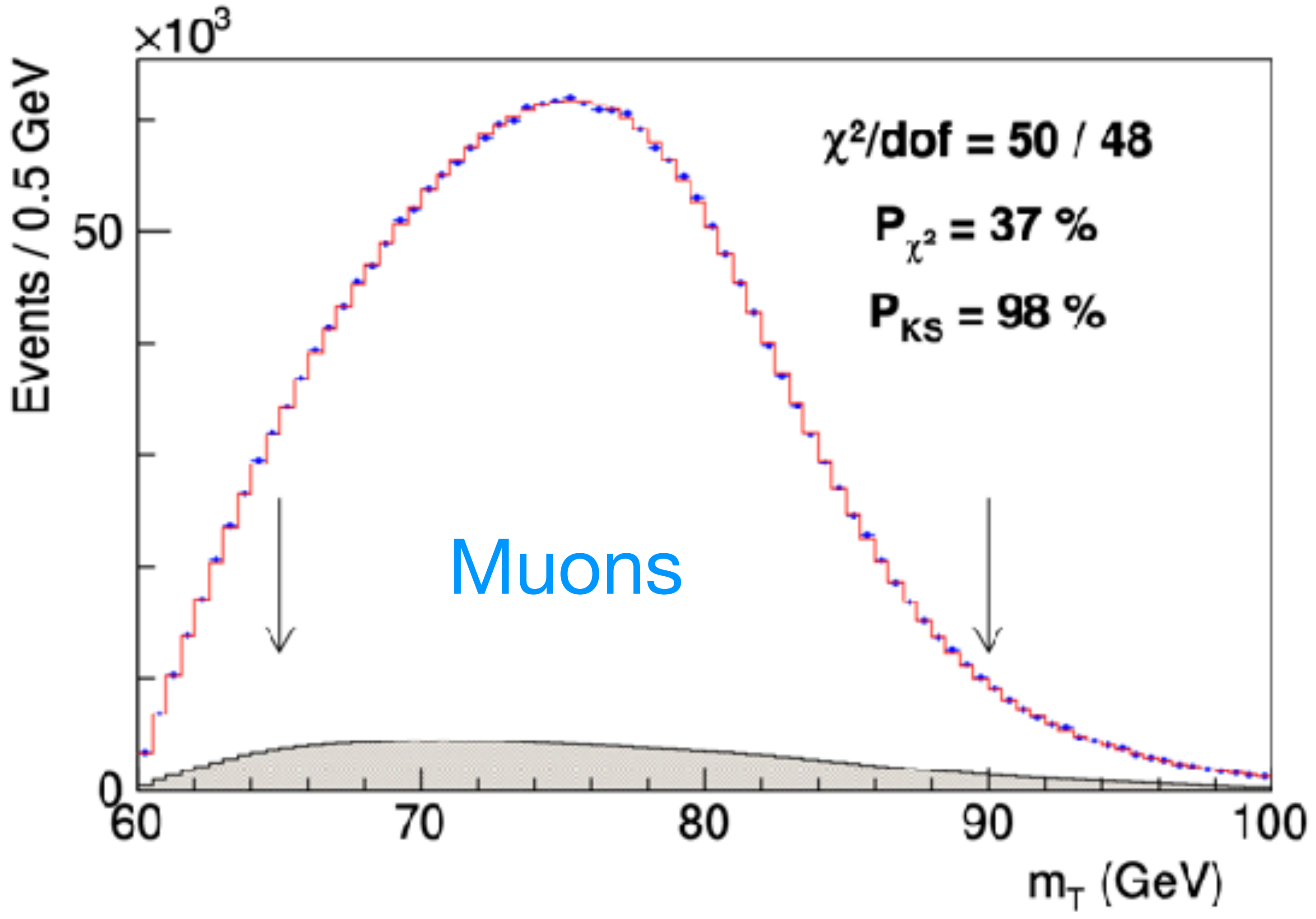


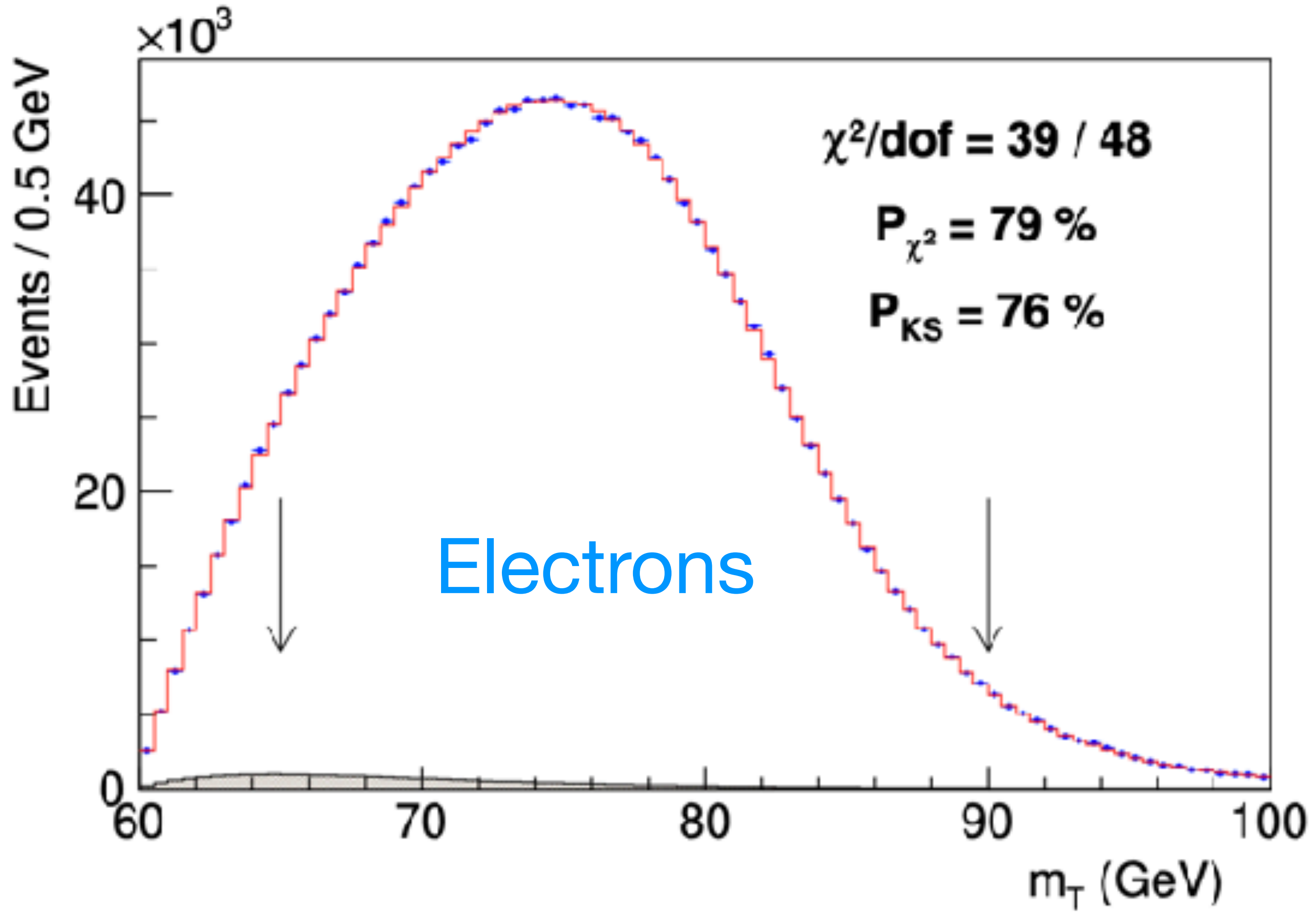
As for the case of ATLAS this **measurement relies on the fine calibration of the lepton energy scale**, savvy methods elaborated to correct for charge dependent curvature (sagitta) bias corrections using a pseudo mass definition.

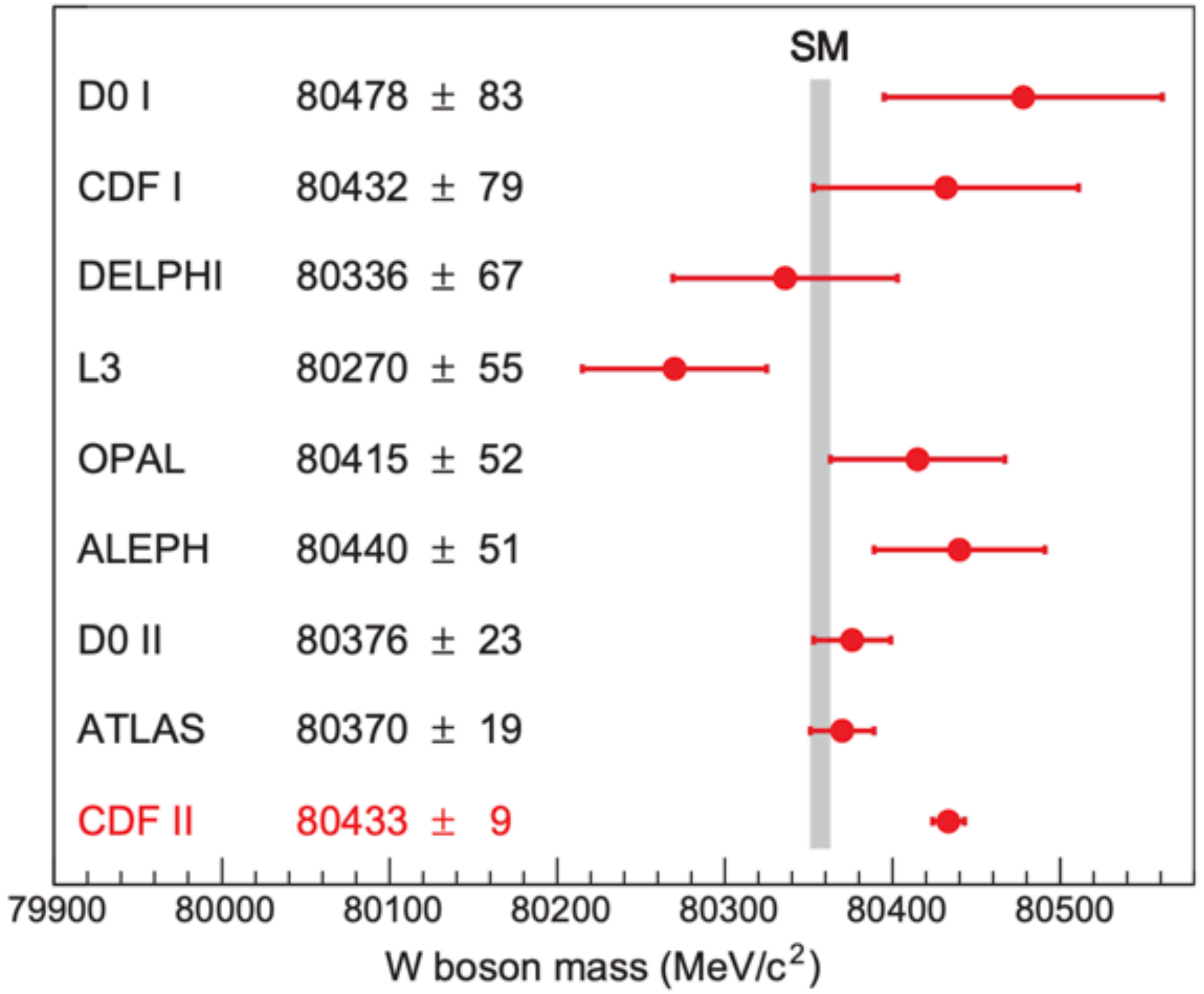
$$\mathcal{M}^{\pm} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1-\cos\theta)}$$

$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

CDF Mass Measurement







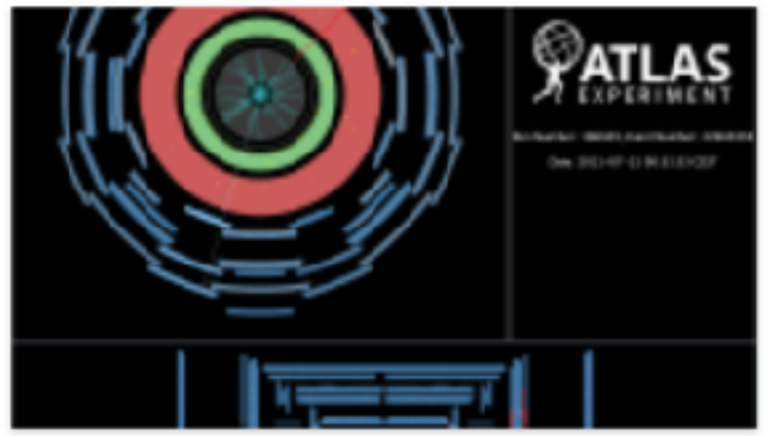
Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

- **The tension with the CDF W mass with ATLAS only was at the 3.4σ level**

- (Tension of CDF measurement with the SM 7σ)

Since an update of the W mass measurement was made by ATLAS…

The W boson Mass Puzzle



Improved ATLAS result weighs in on W boson

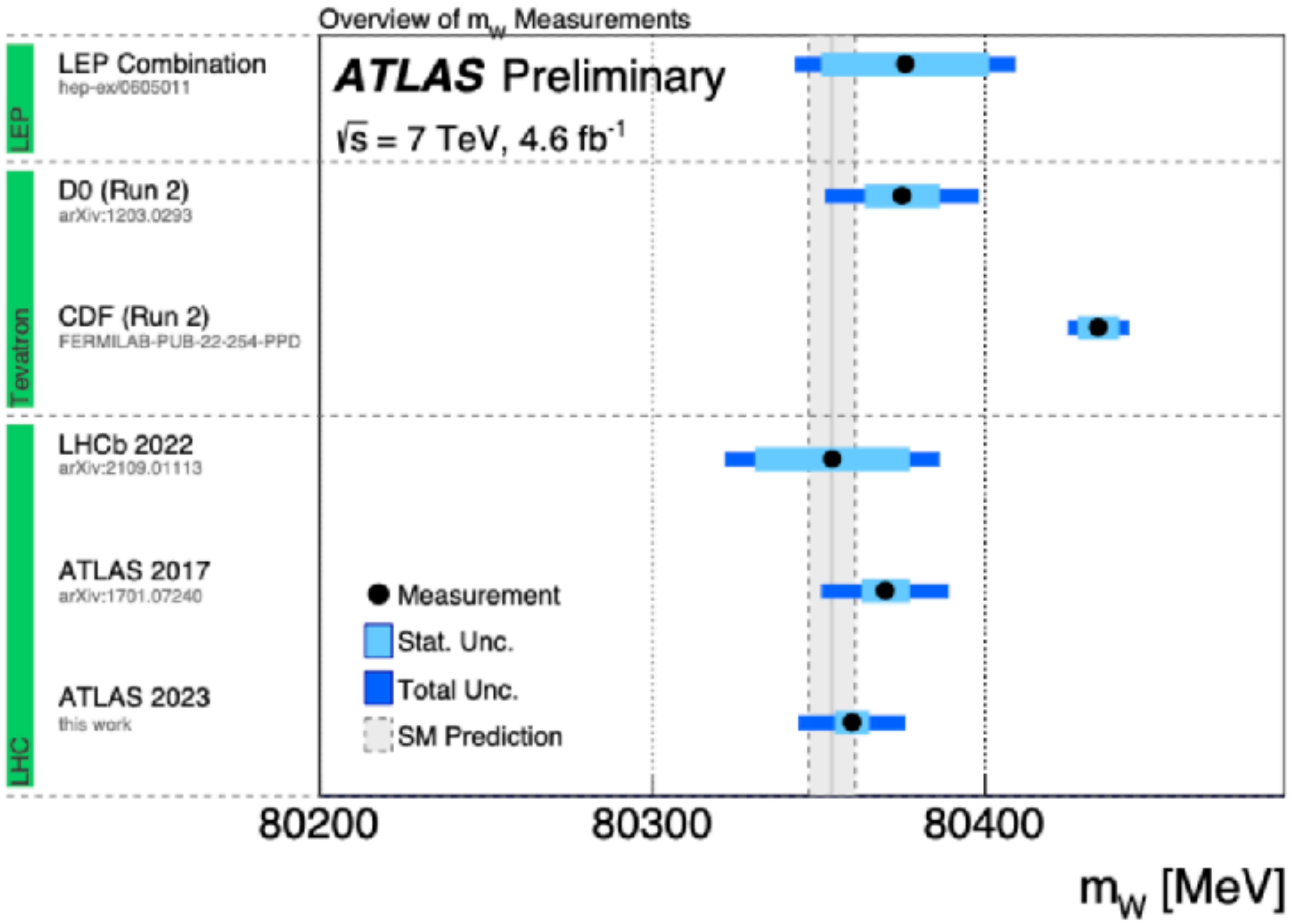
An improved ATLAS measurement of the W boson mass is in line with the Standard Model

Press release | Physics | 23 March, 2023

CERN press release

Several small improvements, but mostly **relying on the huge analysis effort of the first 7 TeV result** but reformulated using the **profile likelihood paradigm**.

Observed shift 10 MeV and precision improved by 16 MeV!



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

$m_W = 80370 \pm 19$ MeV

Before discussing the tension of the CDF measurement with the SM, need to address the tension between measurements!

The tension with the CDF W mass increases to 4σ

Where do we go from here?

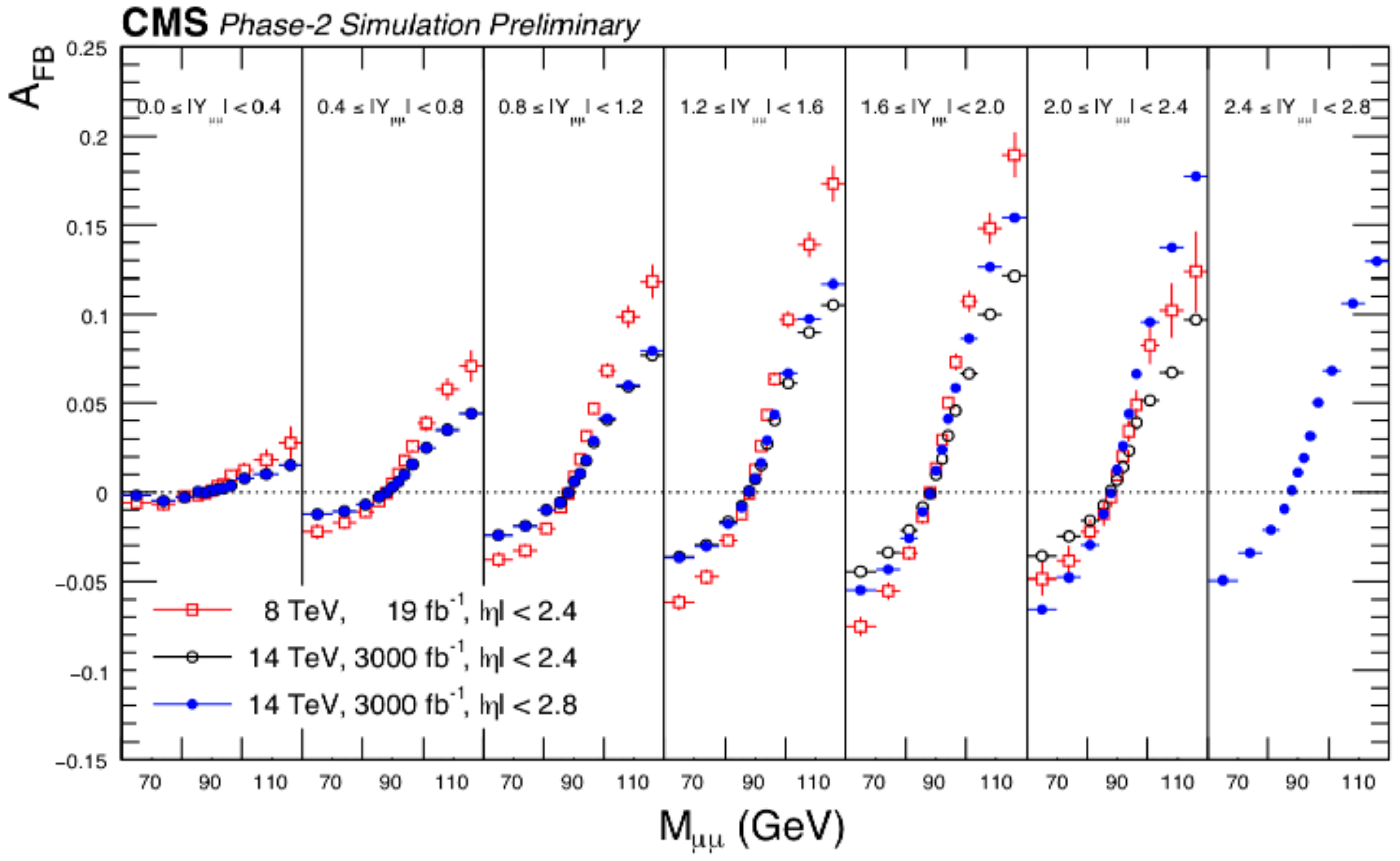
Significant evidence of measurement systematic bias: need a collective effort to understand this puzzle!

For a detailed discussion see Paper by Amoroso et al. Link

Reach at HL-LHC in EW Precision measurements

EW Mixing angle

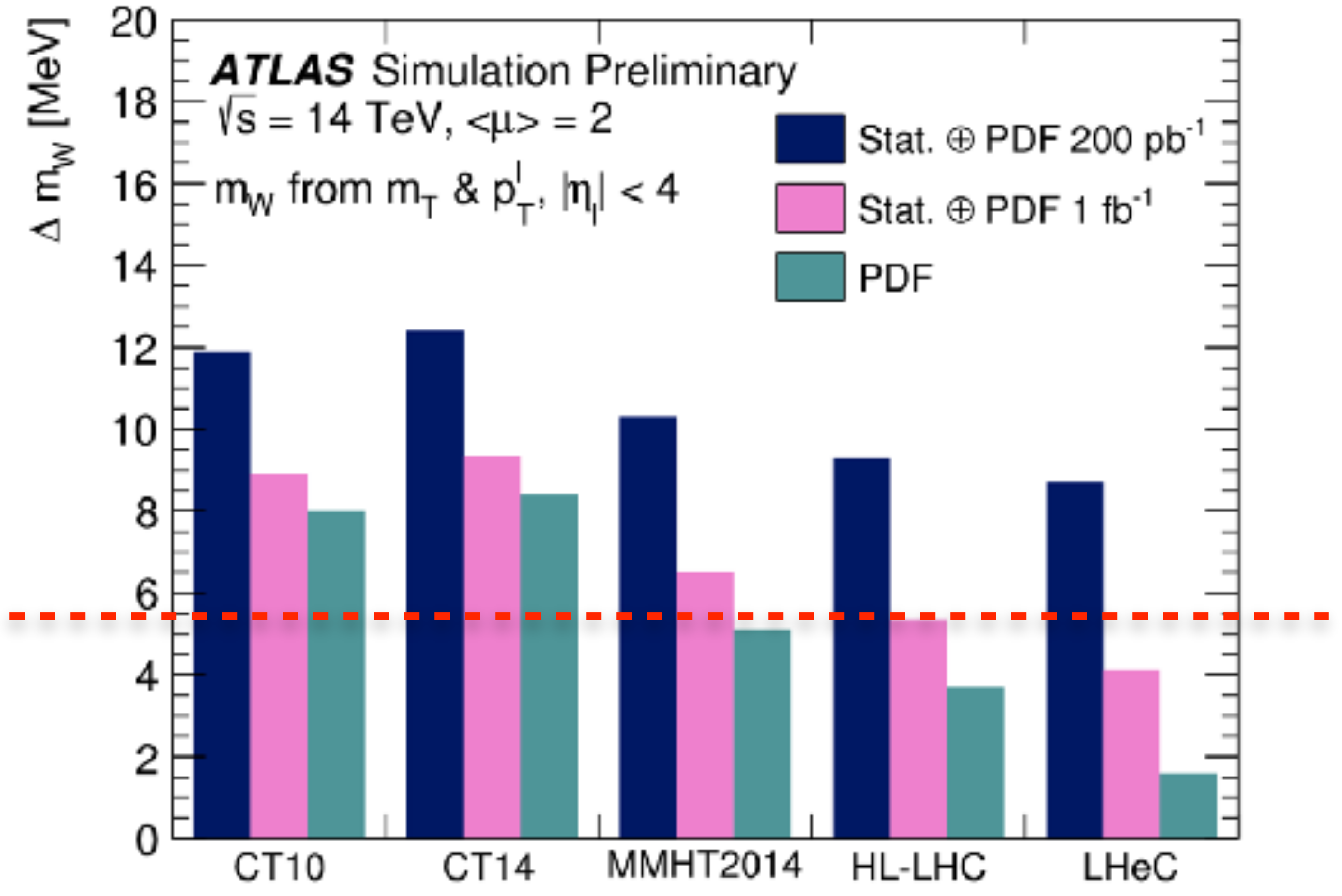
With the increased luminosity and muon acceptance in CMS (from eta 2.4 to 2.8 - for this study)



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 (dated projection)

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

Nano-summary

The LHC has entered the Precision Era: producing EW measurements with precisions comparable with the e^+e^- LEP and SLD colliders.

Backup

The ATLAS W Mass Measurement

Milestone measurement demonstrating the LHC capabilities in precision measurements!

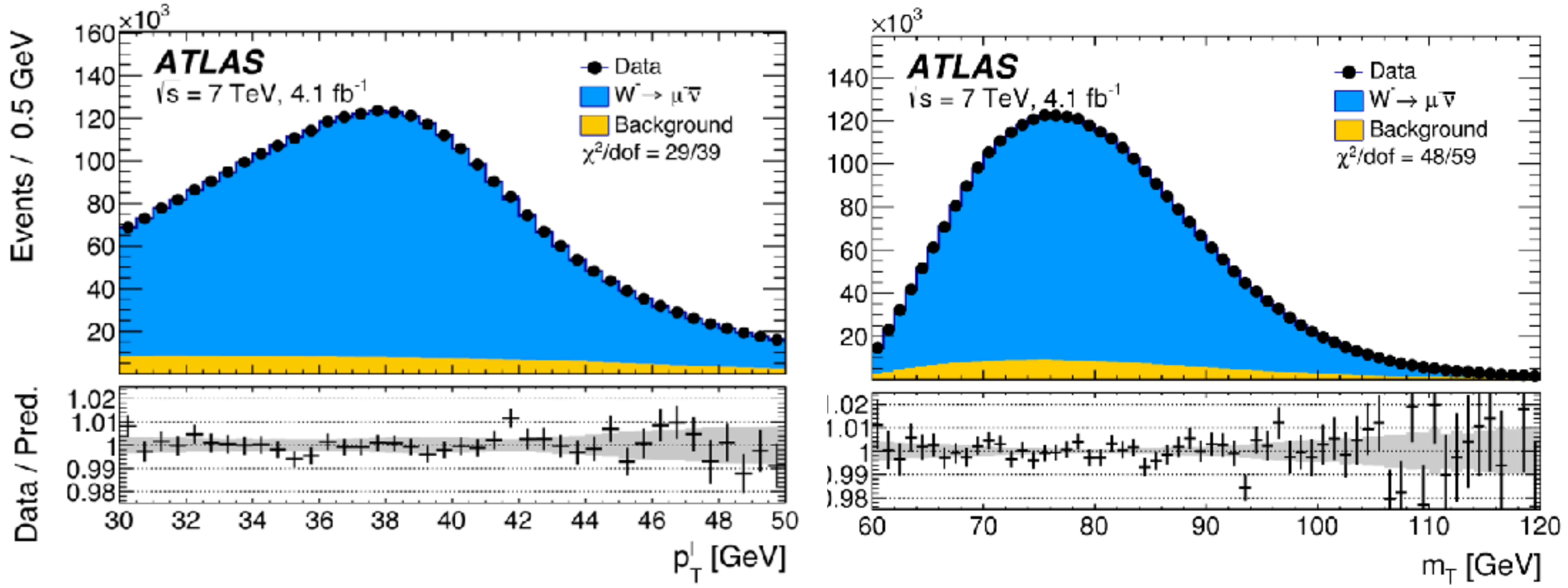
Analysis strategy based on two kinematic distributions fitted in several categories

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^-
$\lvert\eta_\ell\rvert$ categories	$[0, 0.6]$, $[0.6, 1.2]$, $[1.8, 2.4]$	$[0, 0.8]$, $[0.8, 1.4]$, $[1.4, 2.0]$, $[2.0, 2.4]$

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).

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



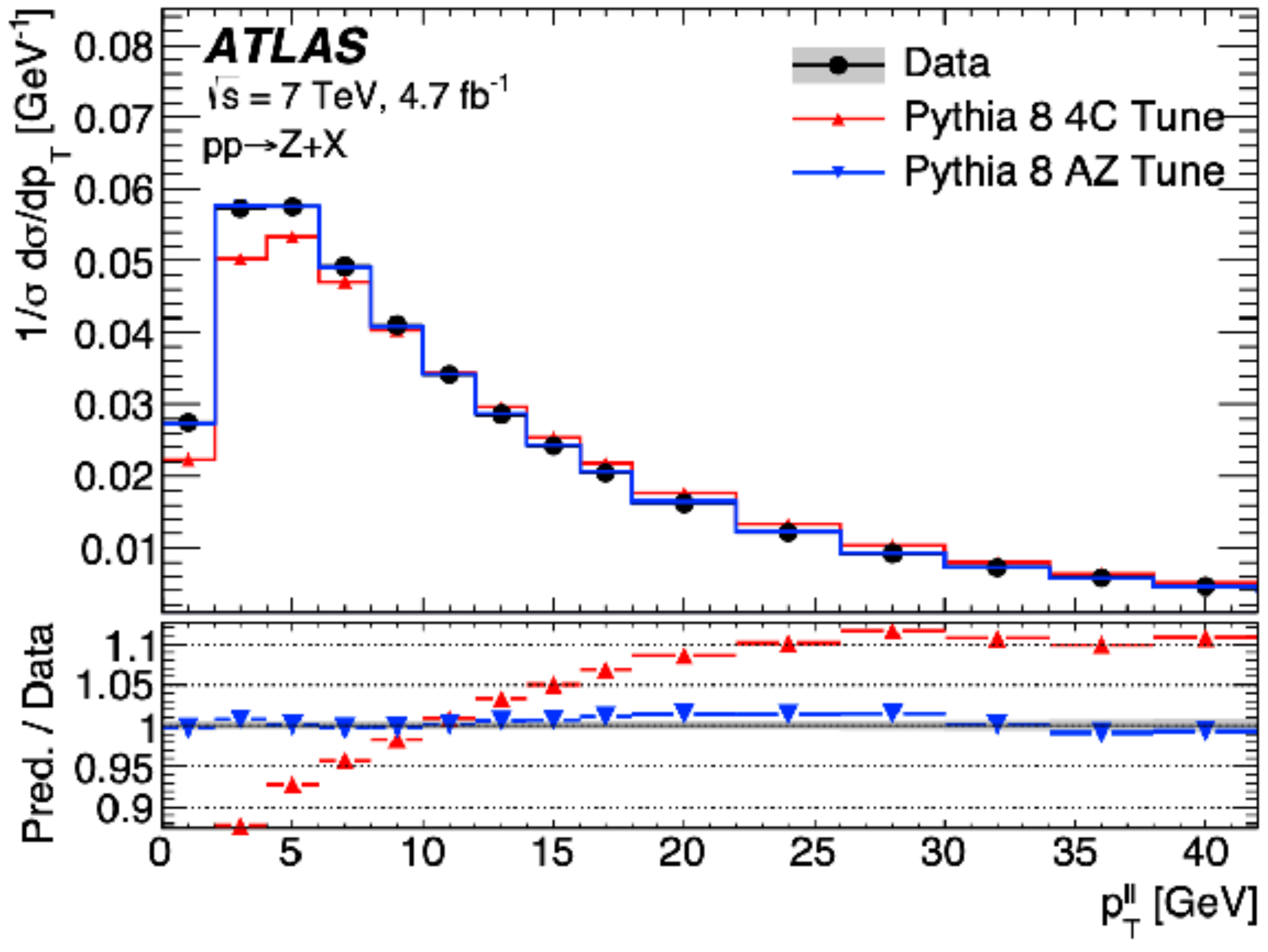
Prediction

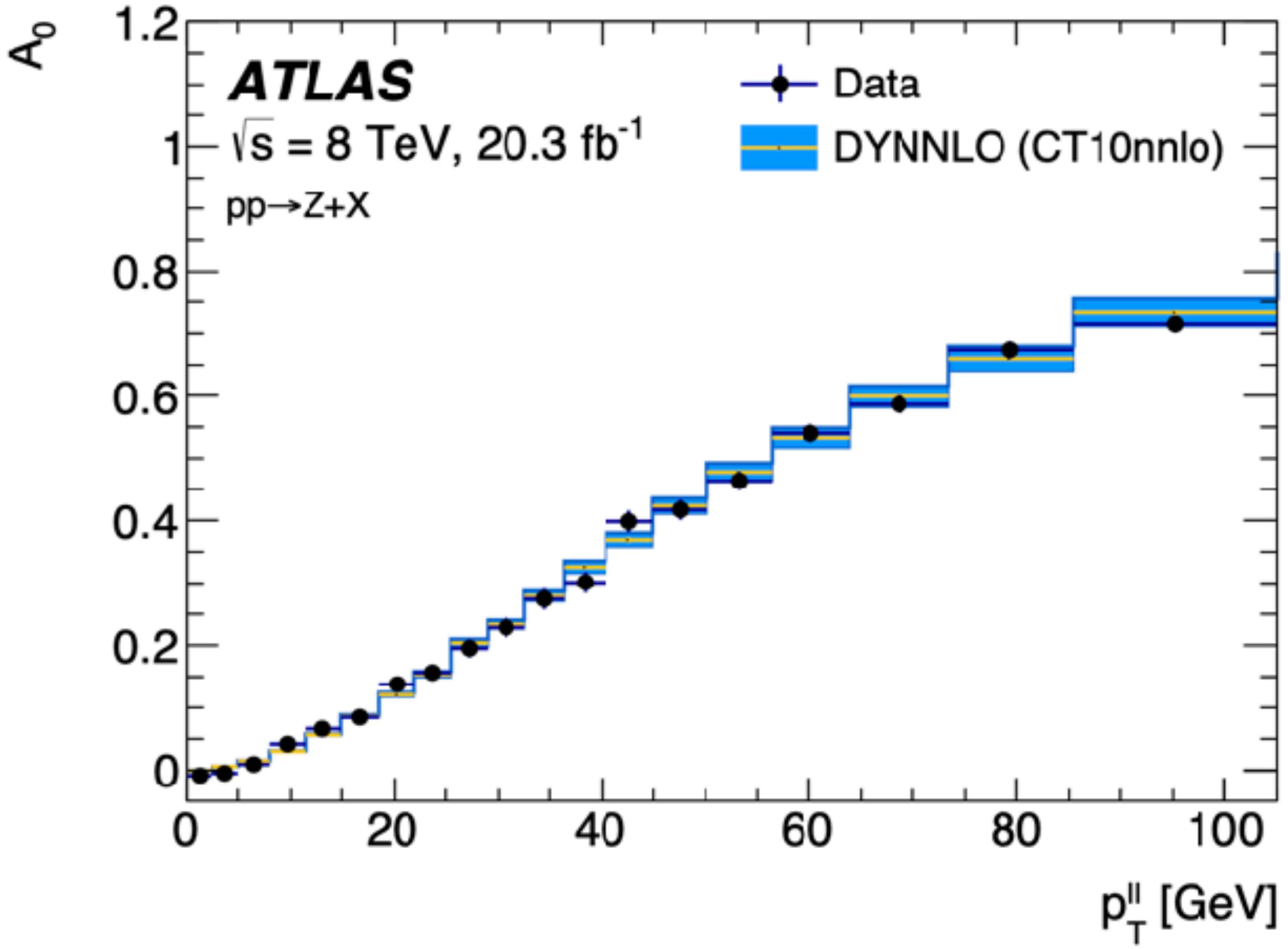
- Reweighted fully simulated events using Powheg v1 – Pythia 8.170 – CT10 for HS (and CTEQ6L1 for PS) with AZNLO tune (QED ISR with Pythia 8 and FSR with Photos) – NLO EW effects not taken into account in baseline but uncertainty taken into account)
- Three steps reweighting procedure using factorized fully differential cross section:

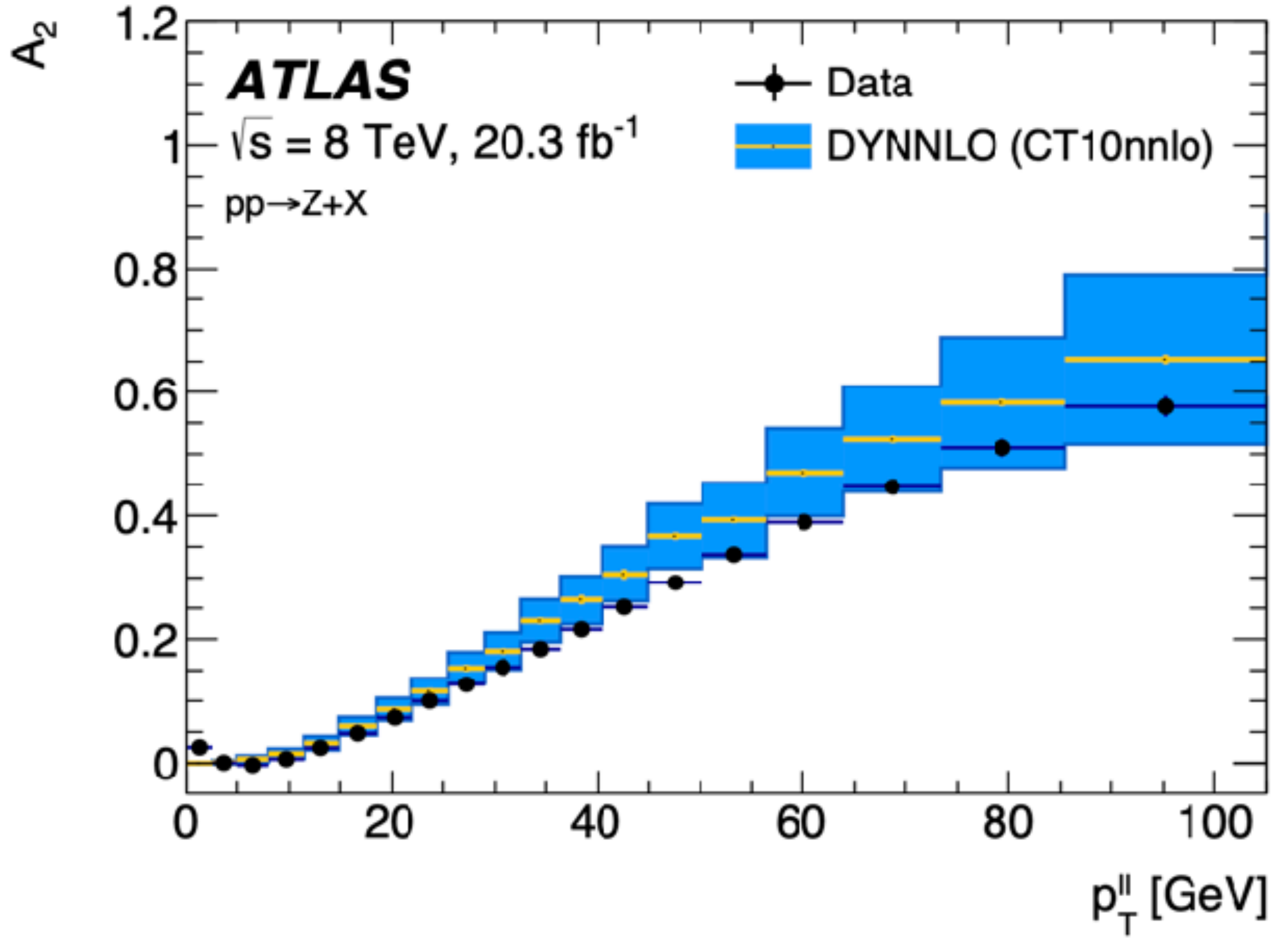
$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y) P_i(\cos\theta, \phi)\right]$$

  - First reweight rapidity distribution to DYNNLO with CT10nnlo
  - Then at given rapidity reweight in pT to Pythia 8 AZ tune
  - Finally reweight to angular (A_i) coefficients estimated at $O(\alpha_s^2)$

Uncertainty added for the small disagreement in A2



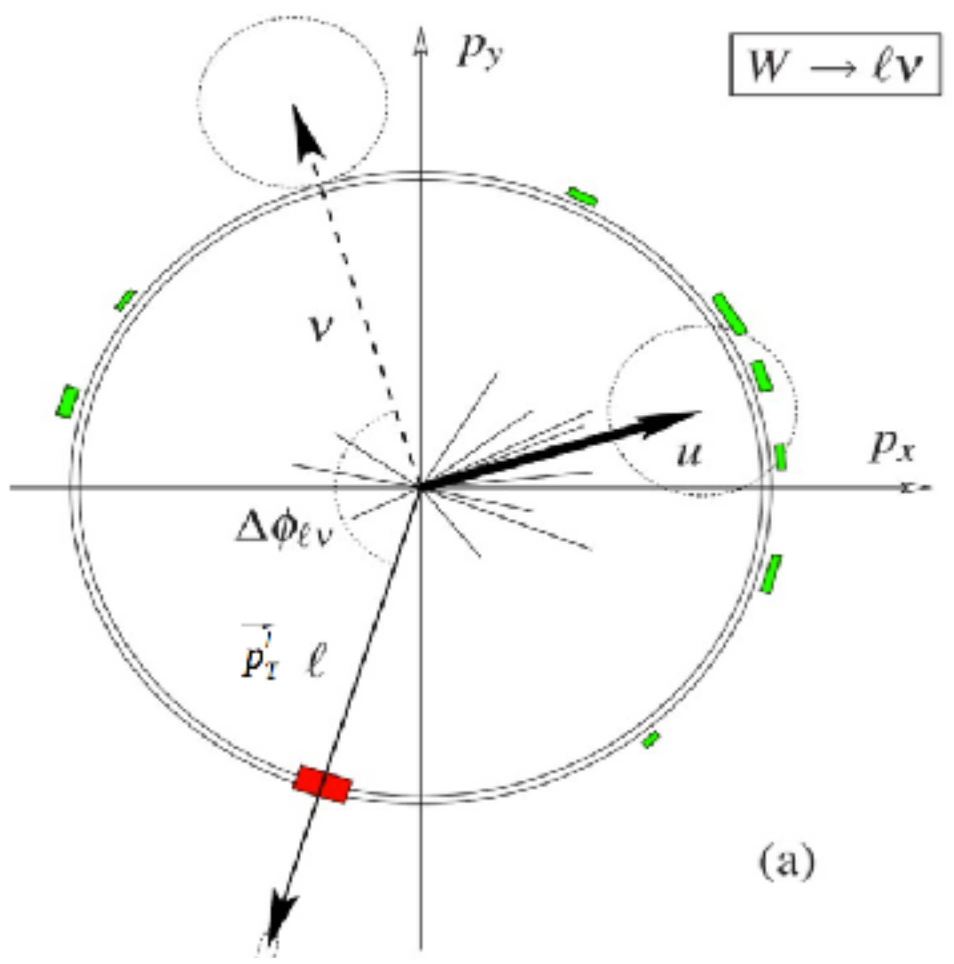




Experimental Setup

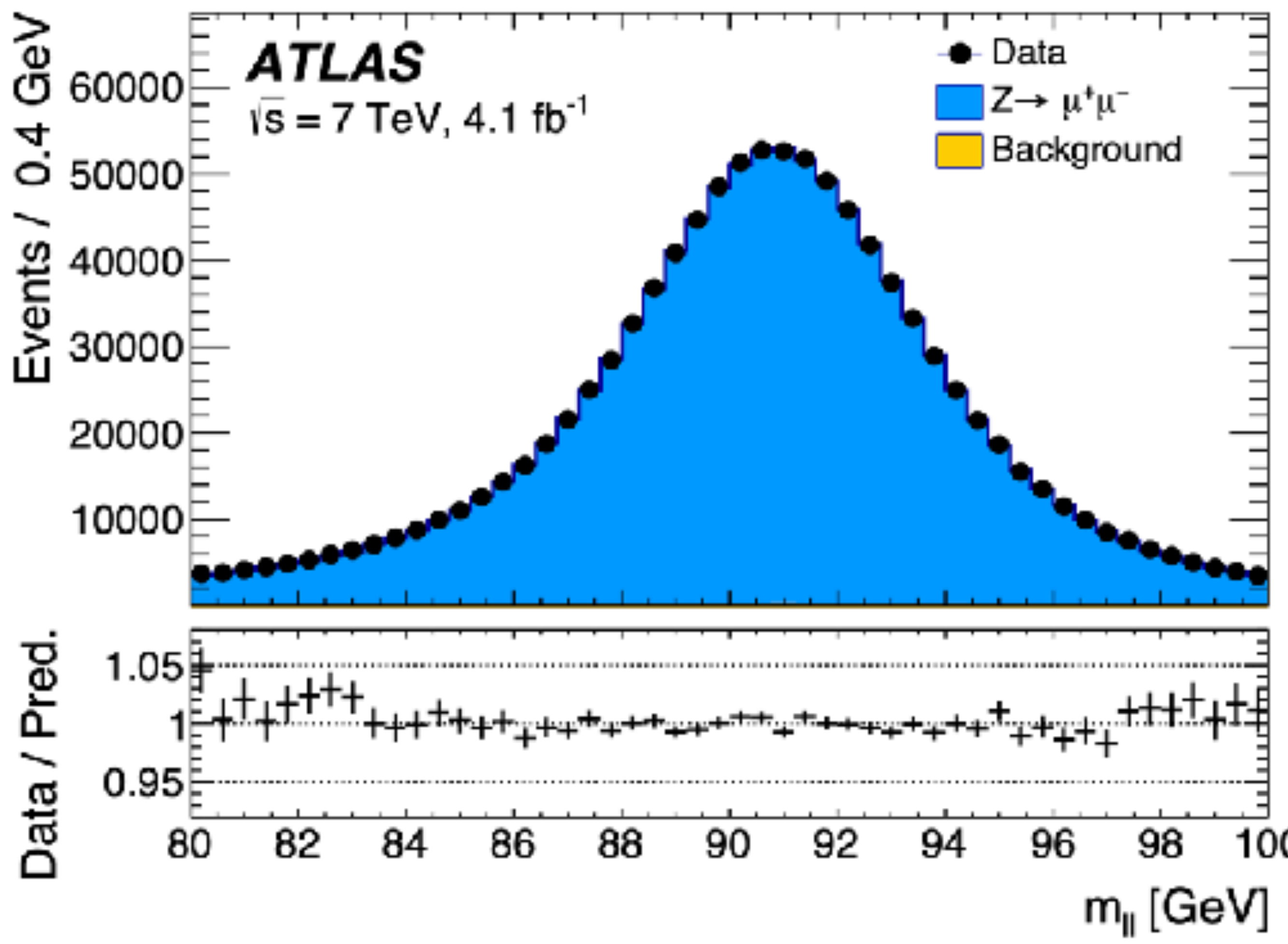
Dataset

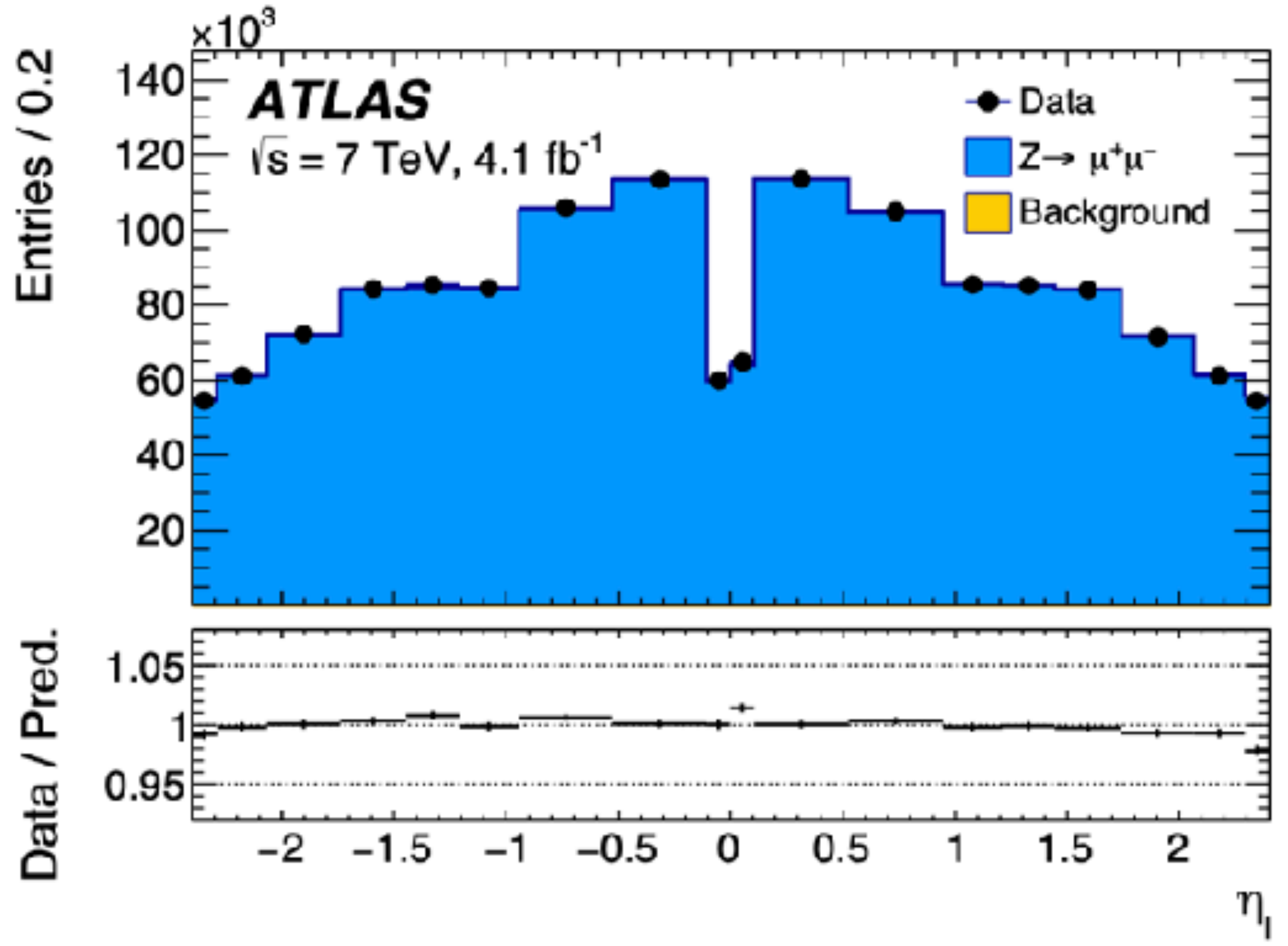
- 7 TeV only, 4.6 fb-1 (electrons) and 4.1 fb-1 (muons) well probed data at moderate PU
- e, μ with pseudo-rapidity of 2.4 with transverse momentum > 30 GeV (MT > 60 GeV, MET > 30 GeV, recoil < 30 GeV)

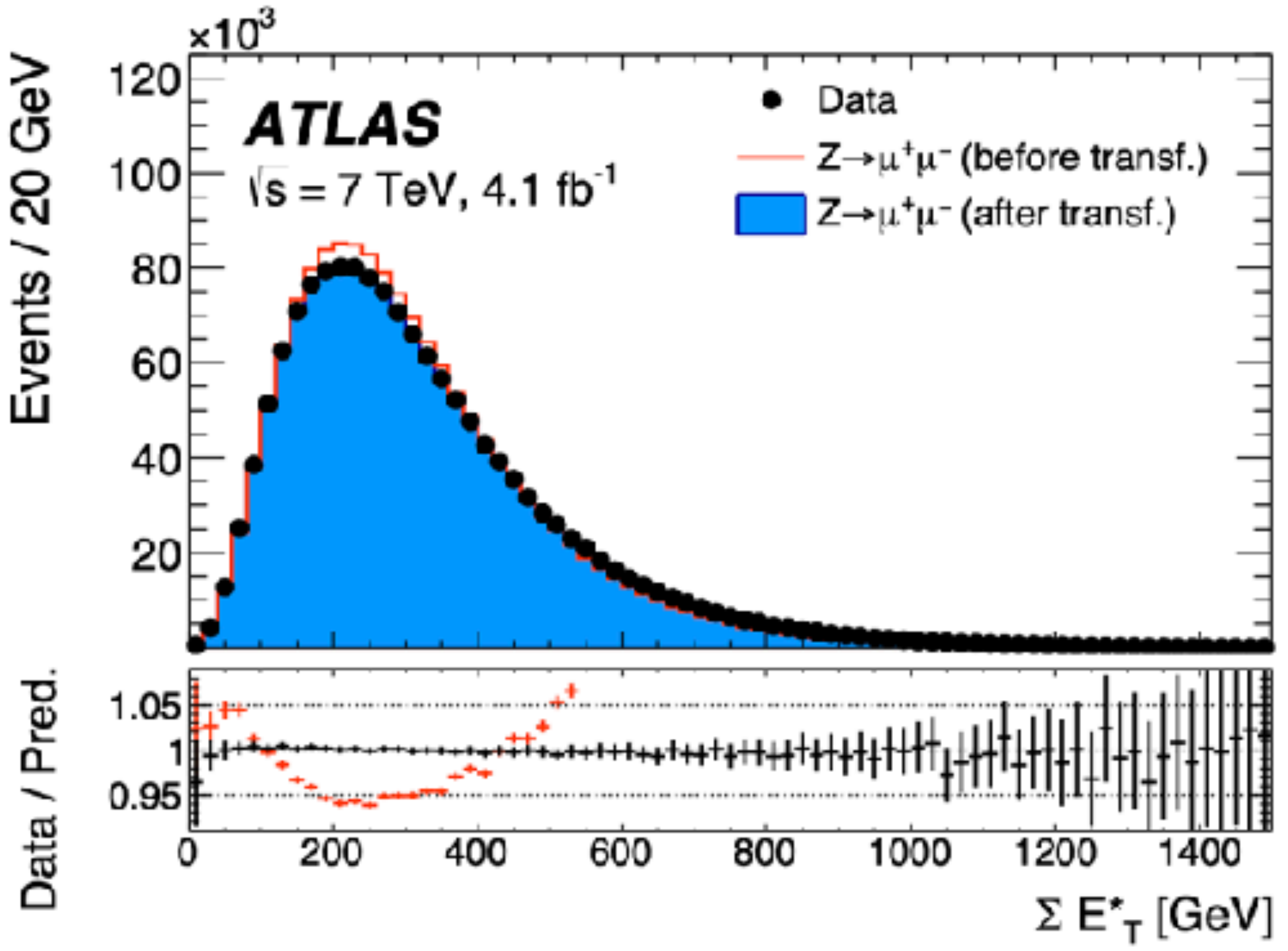


$$\vec{p}_{\mathrm{T}}^{\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\ell} + \vec{u}_{\mathrm{T}}\right) \qquad m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}$$

- Specific improved calibration of leptons (**precision dominated by muons** - relatively low pT)
- Specific calibration of the recoil energy
  - First equalise PU multiplicities
  - Then correct for residual differences based on Z events





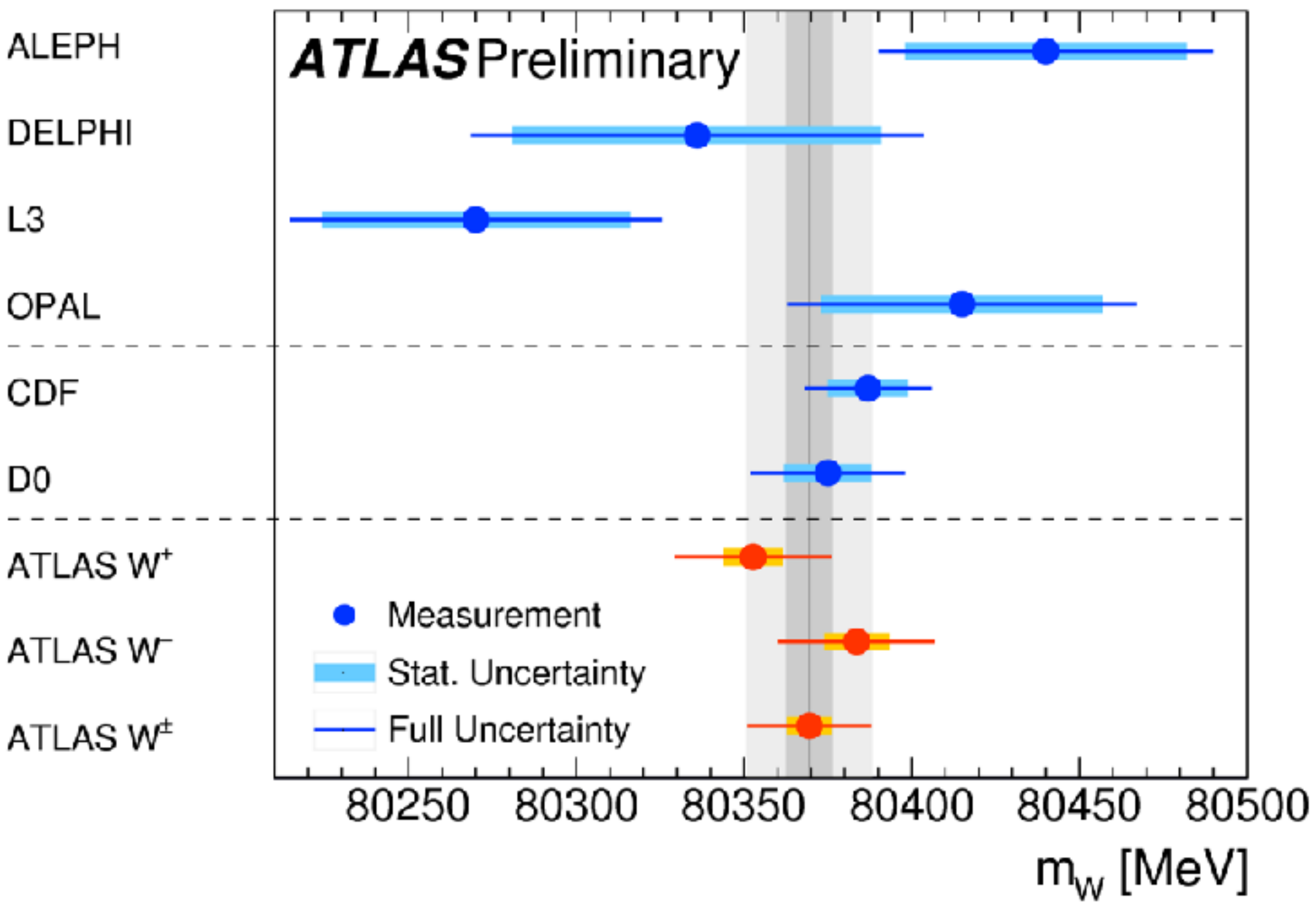


ATLAS W Mass Measurement

A Milestone measurement!

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

± 6.8 (Stat) $\pm$ 10.6 (Exp) $\pm$ 13.6(Mod) MeV



Modeling QCD and PDFs

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

PDF uncertainties: full CT10 variations but taking only effects affecting the W/Z ratio

Modeling EW

FSR and weak corrections sub-dominant

Experimental

Uncertainties dominated by lepton energy and momentum scale, and reconstruction and identification efficiencies

Sensitivity dominated by pT (individually 18.7 MeV uncertainty) w.r.t. MT (ind. 25.1 MeV uncertainty).