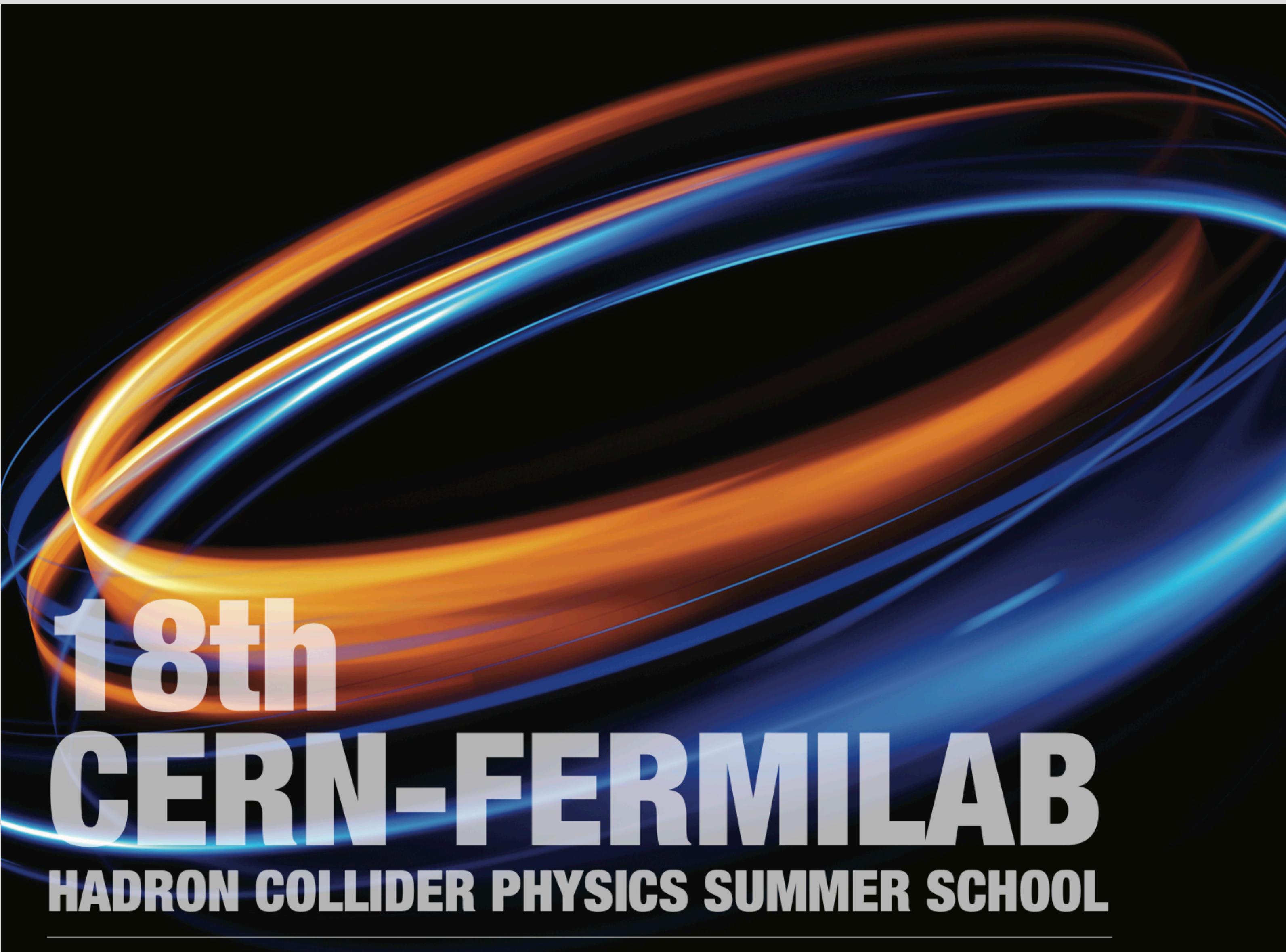


# Experimental SM and Higgs Physics



18th  
**CERN-FERMILAB**  
HADRON COLLIDER PHYSICS SUMMER SCHOOL



Standard Model and Higgs

**Lecture 1** *Basic Concepts,  
QCD, jets and Z production*

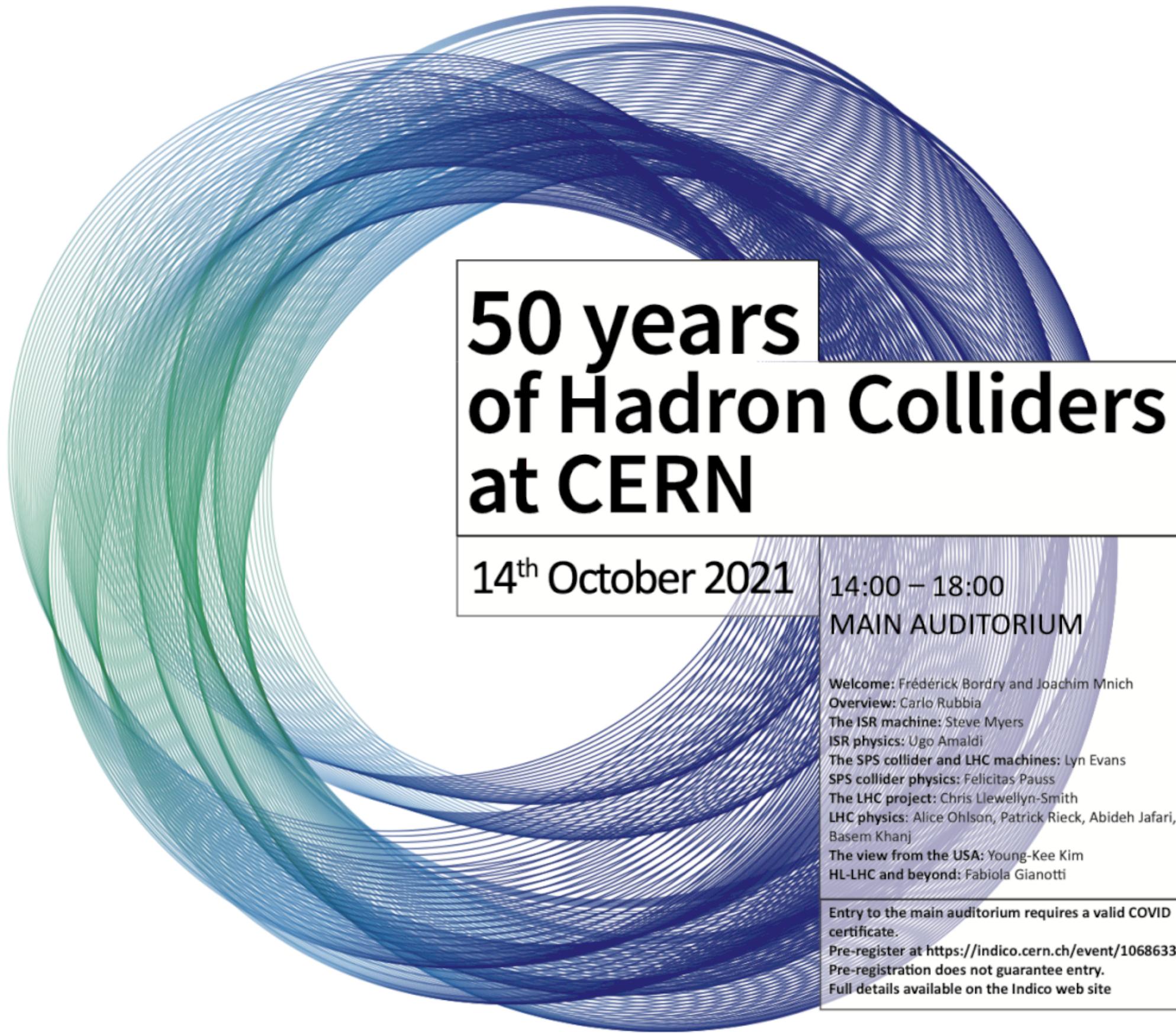
Marumi Kado  
Max Planck Institute for Physics

**CERN-Fermilab School of Physics**  
August 28, 2023

# A few references...

2

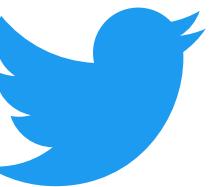
## 50 years of hadron colliders at CERN [symposium](#)



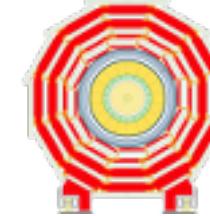
- Follow **CERN** on social media (click on the logos)



- Follow **ATLAS** on social media (click on the logos)



- Follow **CMS** on social media (click on the logos)



# Preamble and Disclaimers

3

**The goal of these lectures** is to give both an overview of the results in the field (there are many, apologies in advance if your favourite result is not covered!) and discuss in some detail specific results.

**If there is any result you would like to discuss in more detail please do not hesitate to ask!**

Do not hesitate to ask at any time if you have any questions!

**These lectures will rely on the following other lectures for fundamental concepts:**

- SM EW and QCD aspects are covered in Tim Cohen and Gregory Soyez lectures.
- Accelerator, detector, trigger and performance of event reconstruction will be covered by Tatiana Peloni and Jochen Klein.

# Outline

4

## **Lecture 1: Basic concepts, QCD, jets and Z production**

- Introduction (rather long)
- Luminosity and total cross section
- Jet production measurements and the measurement of the strong coupling constant
- Drell-Yan Z production and the measurements of the weak mixing angle and the strong coupling constant

## **Lecture 2: EW Precision at Hadron Colliders**

- Drell-Yan W production and the W mass measurement
- Associated production of vector bosons and jets
- Multi-boson production (W, Z and photons)
- Top production and top properties measurements

## **Lecture 3: Higgs Physics**

- Diboson channels for Higgs measurements
- Measuring the Yukawa couplings of the Higgs boson
- Differential and Simplified Template cross sections
- CP properties of the Higgs boson
- Invisible Higgs boson decays
- Rare Higgs boson decays

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

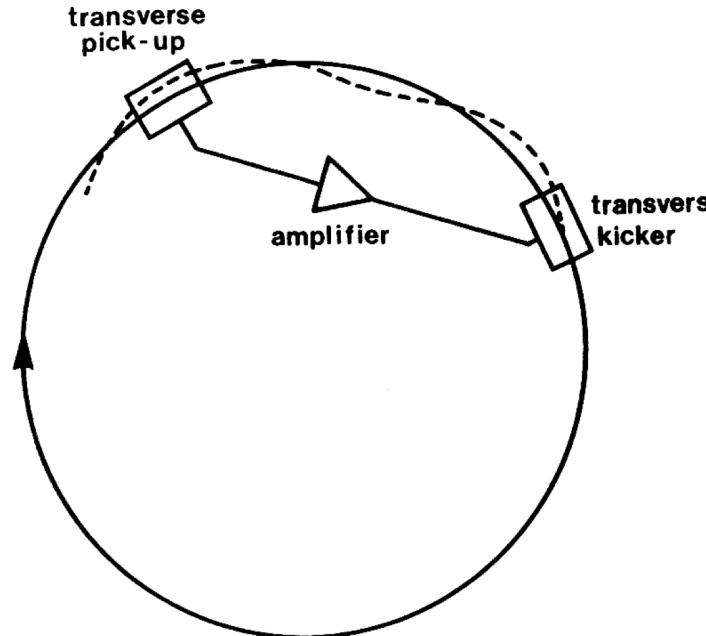
- Higgs couplings measurements
- The Yukawa coupling of the Higgs boson to charm quarks
- Off shell Higgs boson coupling and Higgs width
- Di-Higgs boson production and Higgs boson trilinear self coupling
- Precision EW Fit
- SMEFT Global fits
- Challenges for Run-3 and the HL-LHC

4

# Introduction - The W and Z bosons turn 40!

5

Following the success of putting anti-protons 'on' ICE!  
(Initial Cooling Experiment)

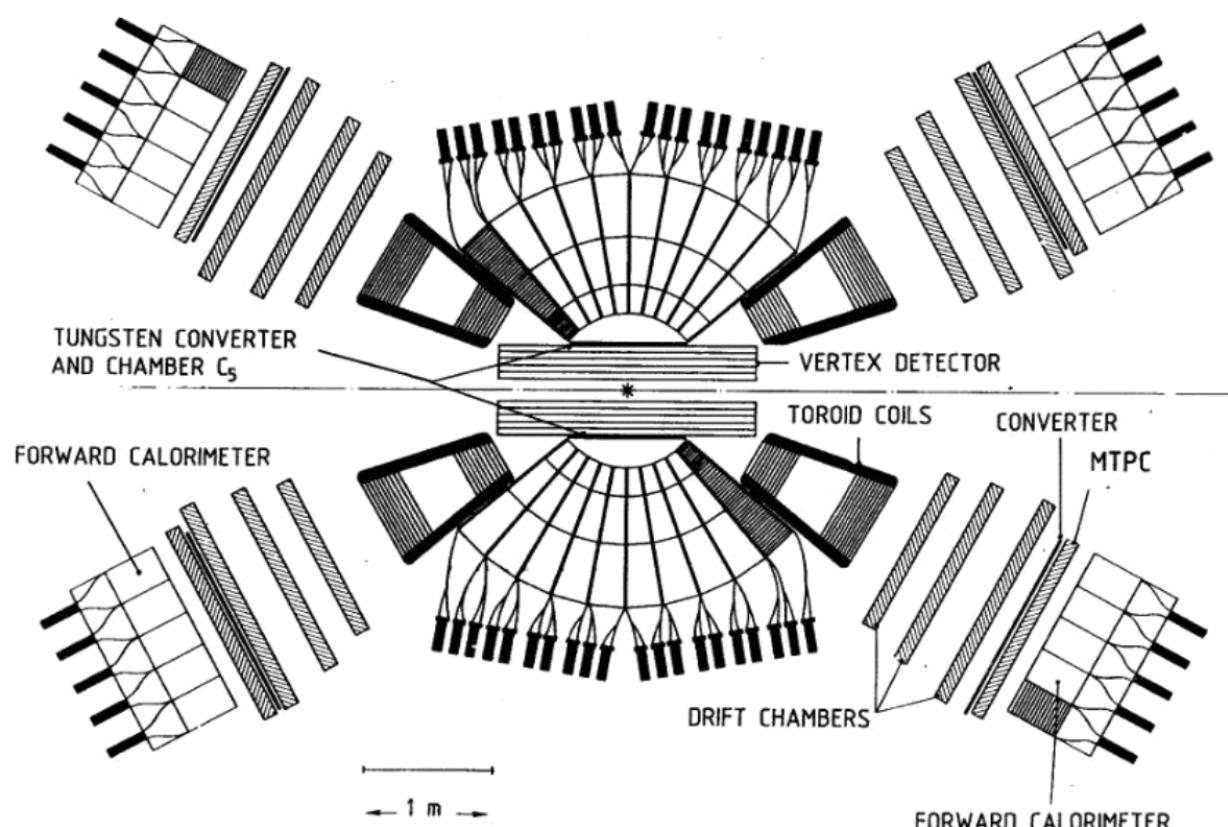


(Stochastic cooling)

In 1978 the SppS approved!

## UA2

Aiming at electron channel, no magnetic field, no muon system, high-granular projective calorimeter (later installed first silicon vertex detector).



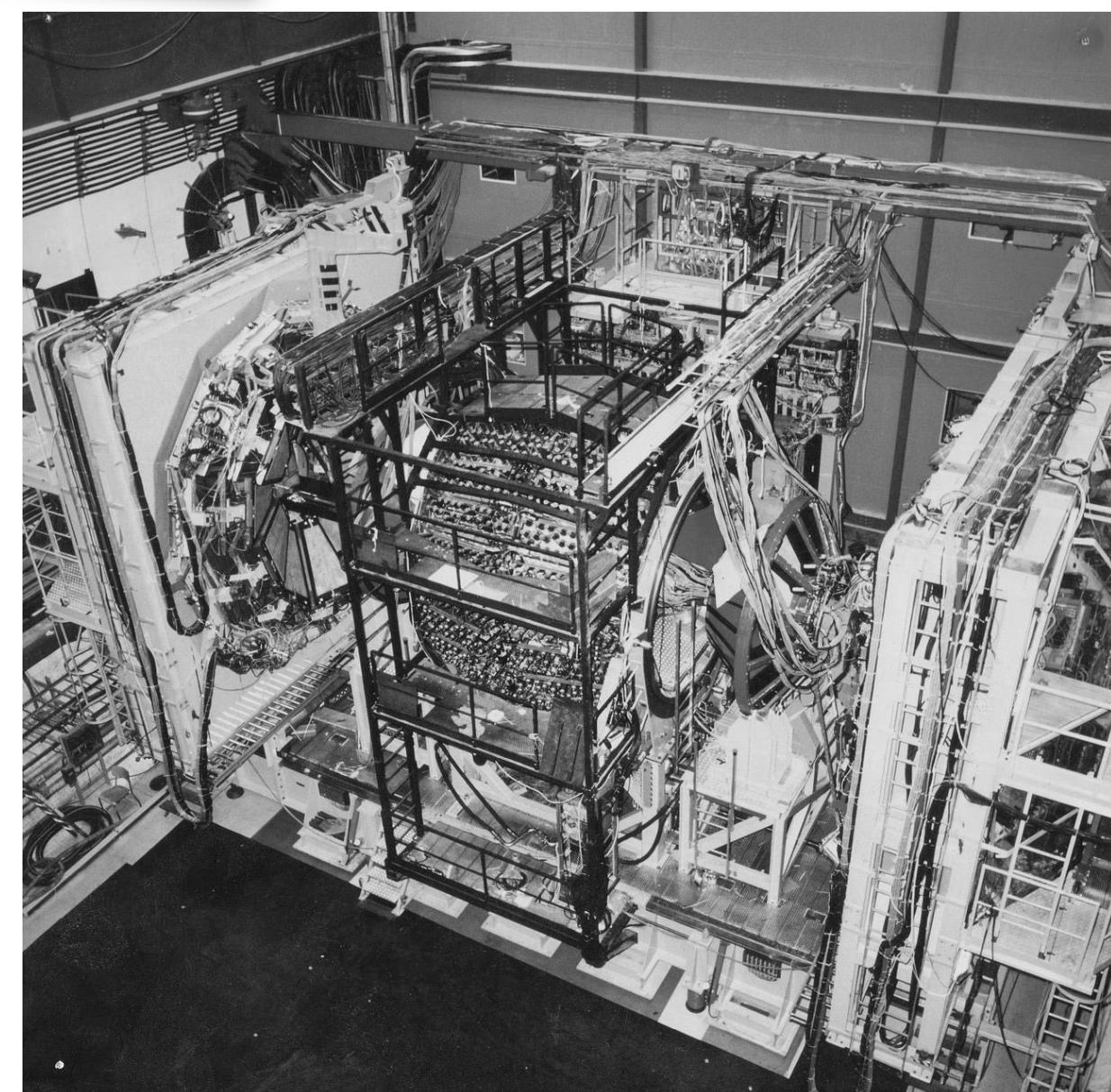
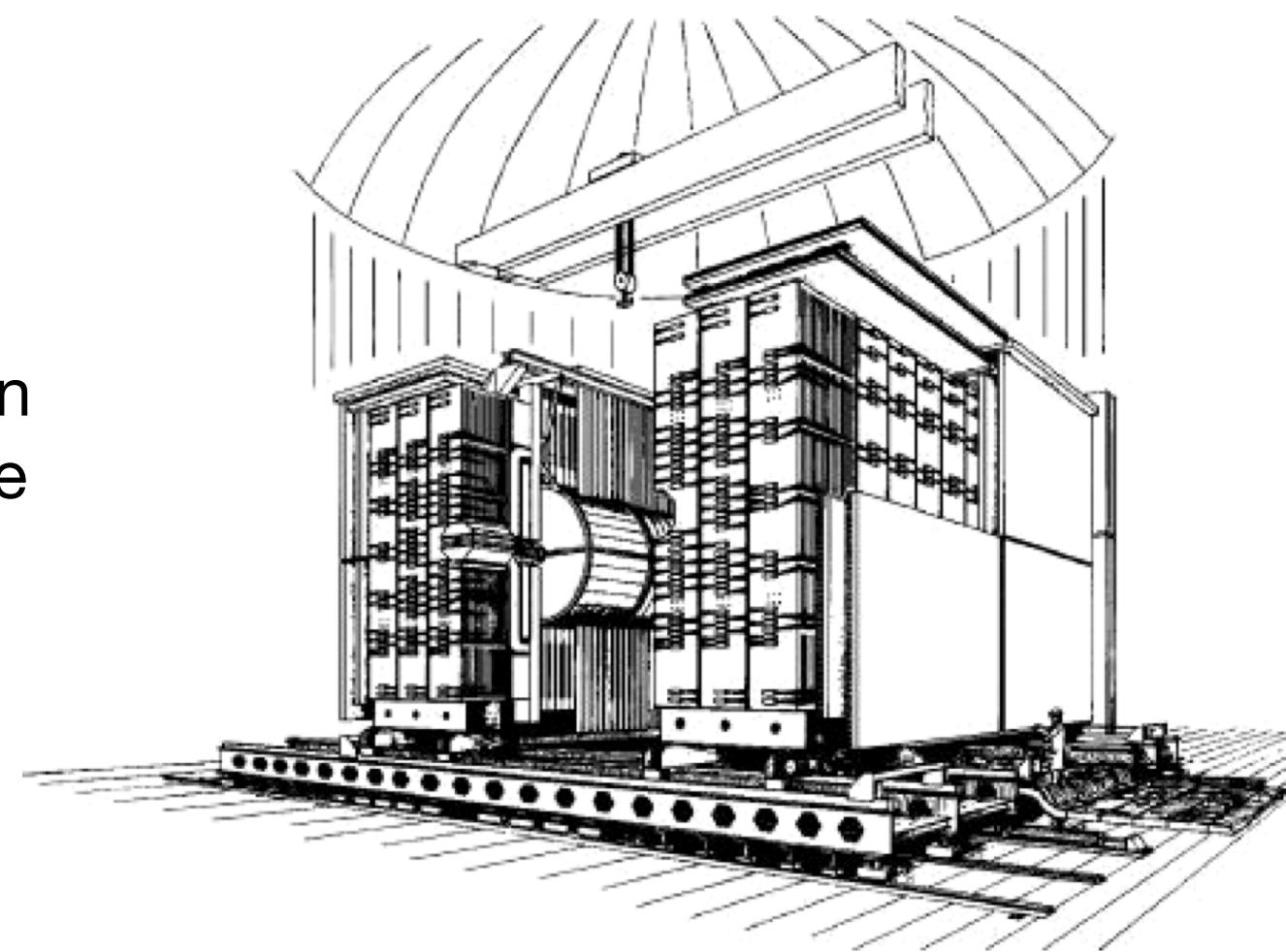
The Antiproton Accumulator



... to first collisions in 1981 !?

## UA1

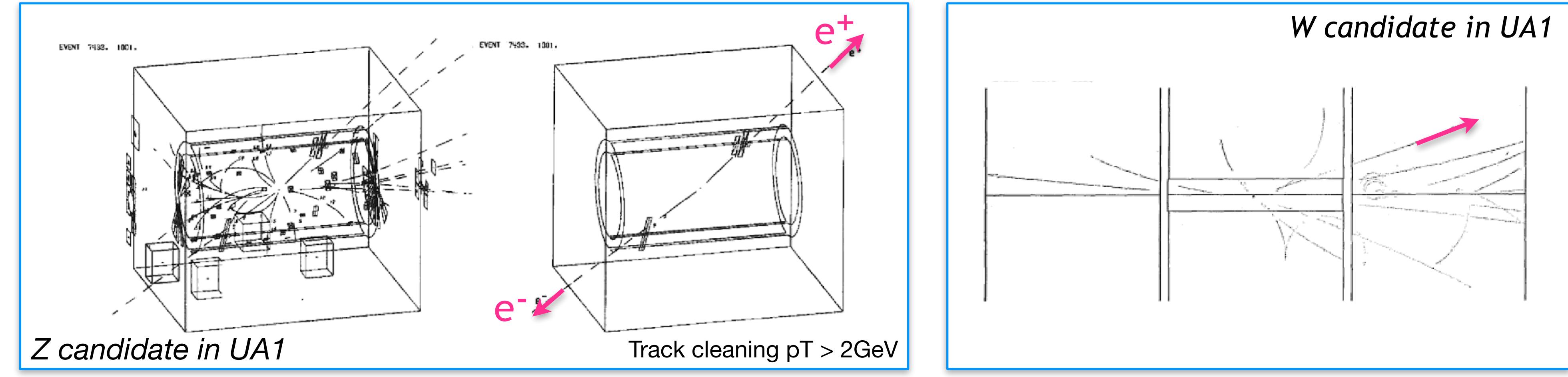
Tracking drift chamber, calorimeters, large muon system, and 0.7 T dipole magnet



# Introduction - The W and Z bosons turn 40!

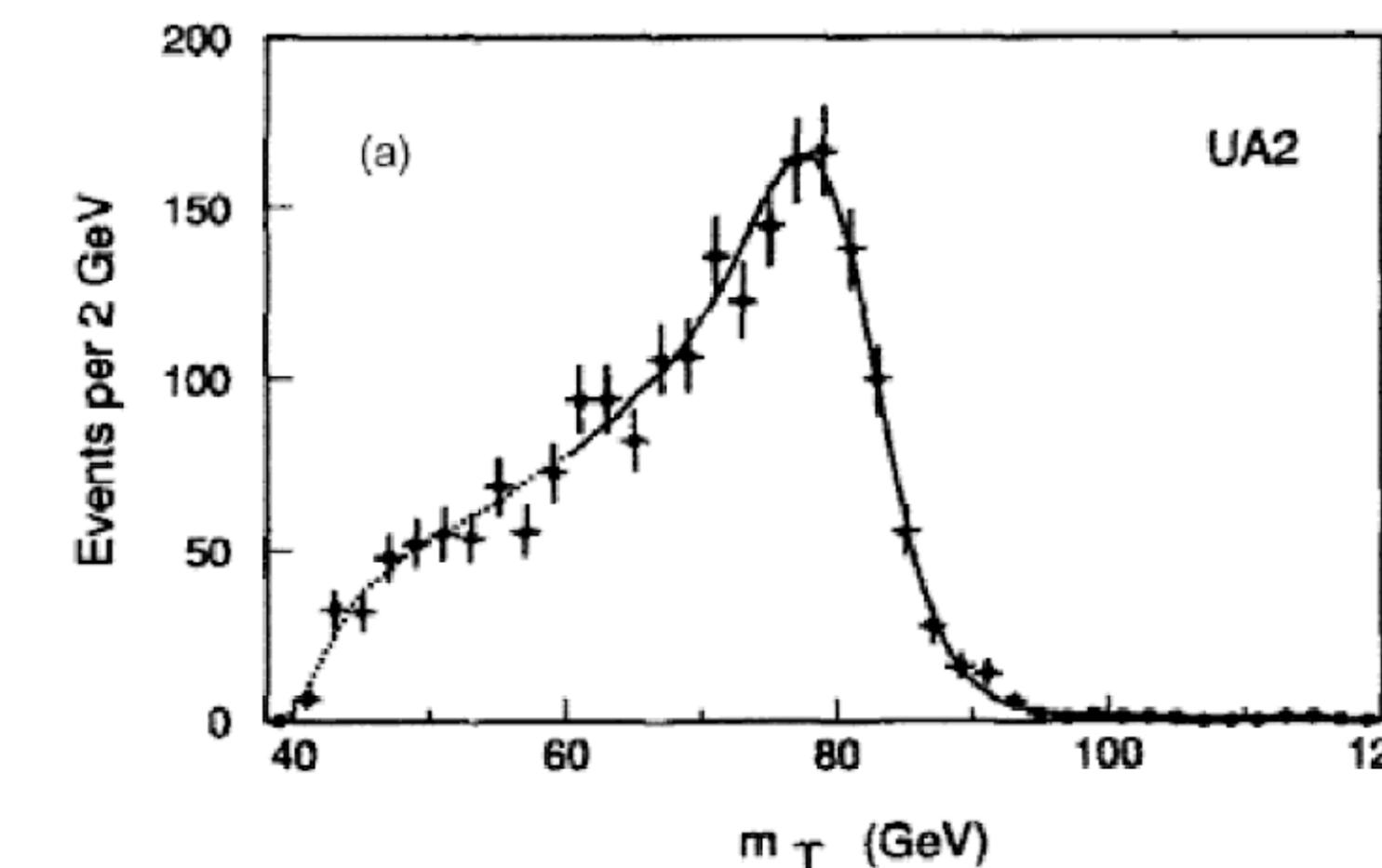
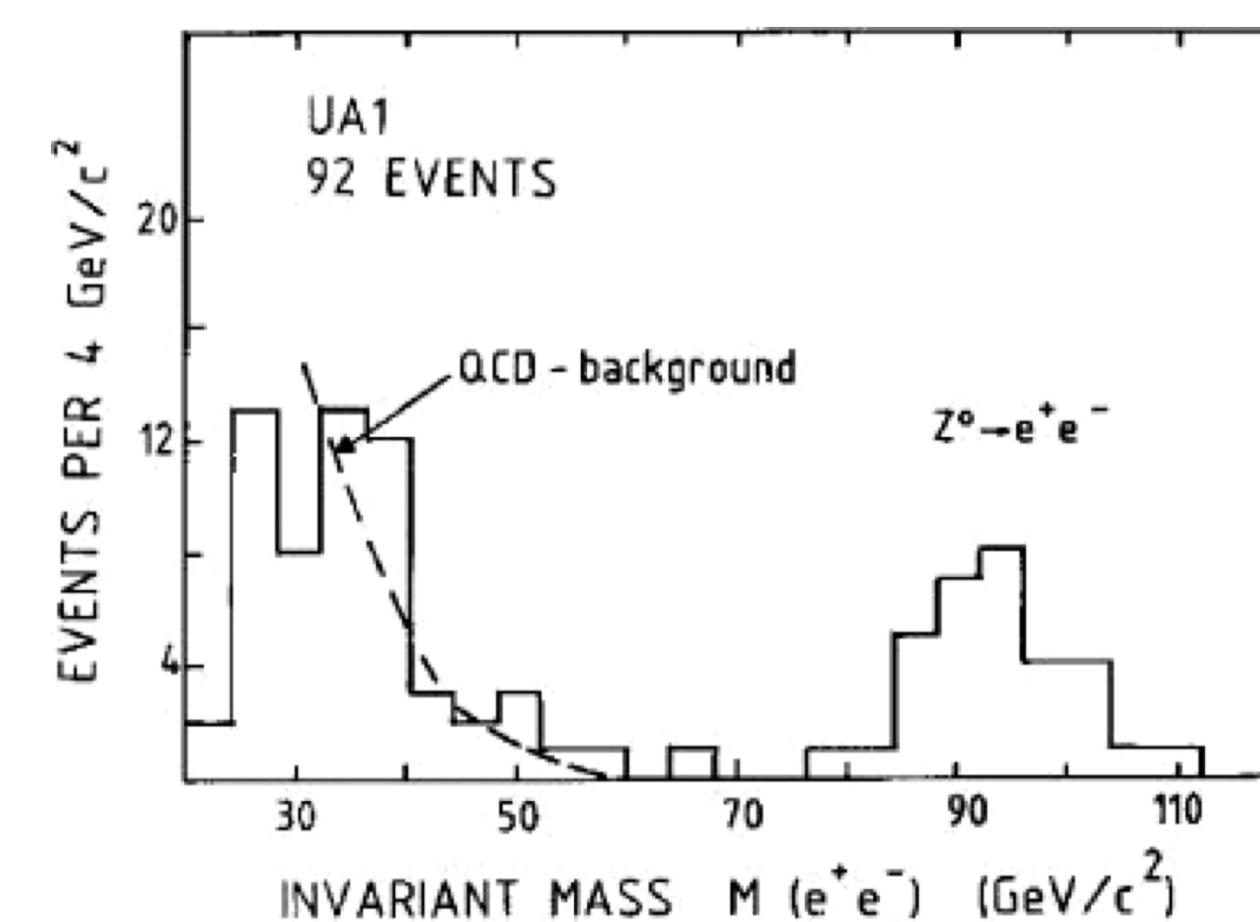
6

Discovery of the W and Z bosons announced in January 1983 with 6 W events in UA1 and four in UA2!



Altogether O(100) Z events

Altogether O(1000) W events

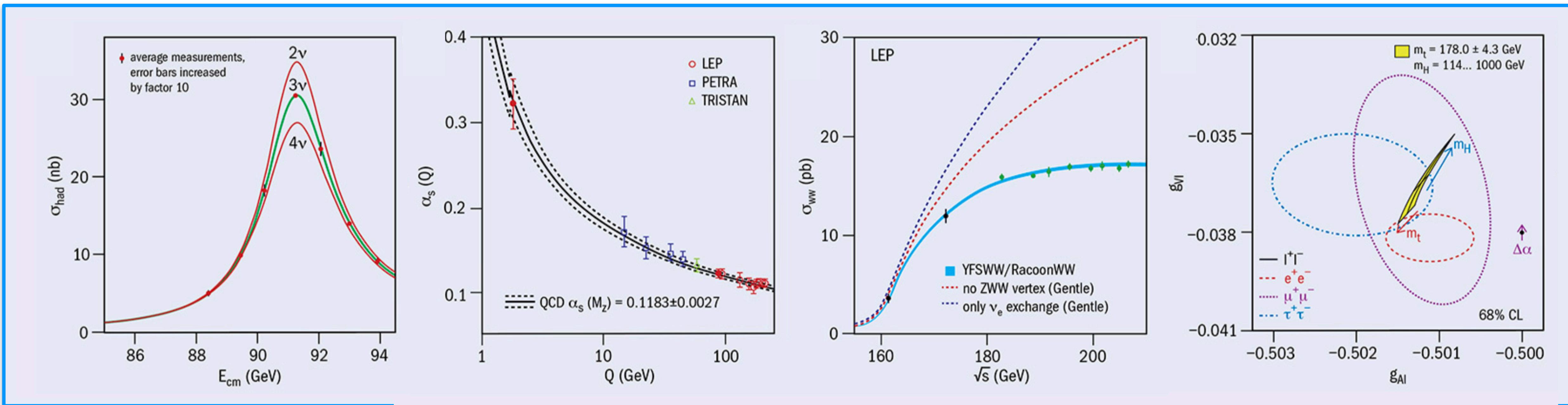


Discovery of the W and Z bosons  
Carlo Rubbia,  
Simon Van der Meer

# Birth of EW Precision at LEP and SLC

7

LEP and SLC an immense legacy!



Z line shape and the hadronic cross section

Strong coupling running

WW cross section at LEP-2 with clear interference pattern demonstrating ZWW interaction i.e. non-abelian structure of EW interaction

Neutral current Axial vs. Vector precise measurements and prediction of the top and Higgs masses



Asymptotic freedom and QCD

David Gross, David Politzer, Frank Wilczek  
(With first results from PETRA)

In general  $e^+e^-$  Collisions have been outstanding machines to understand QCD, essential in the modelling of processes at the LHC.

# The discovery of the Top Quark

8

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 Origin of the CP violation  
and the need for three families of fermions

Makoto Kobayashi, Toshihide Maskawa

Another immense legacy of LEP and SLC: Precision EW predictions, as the top mass in 1993 (to  $172.1 \pm 25$  GeV - see [link](#))



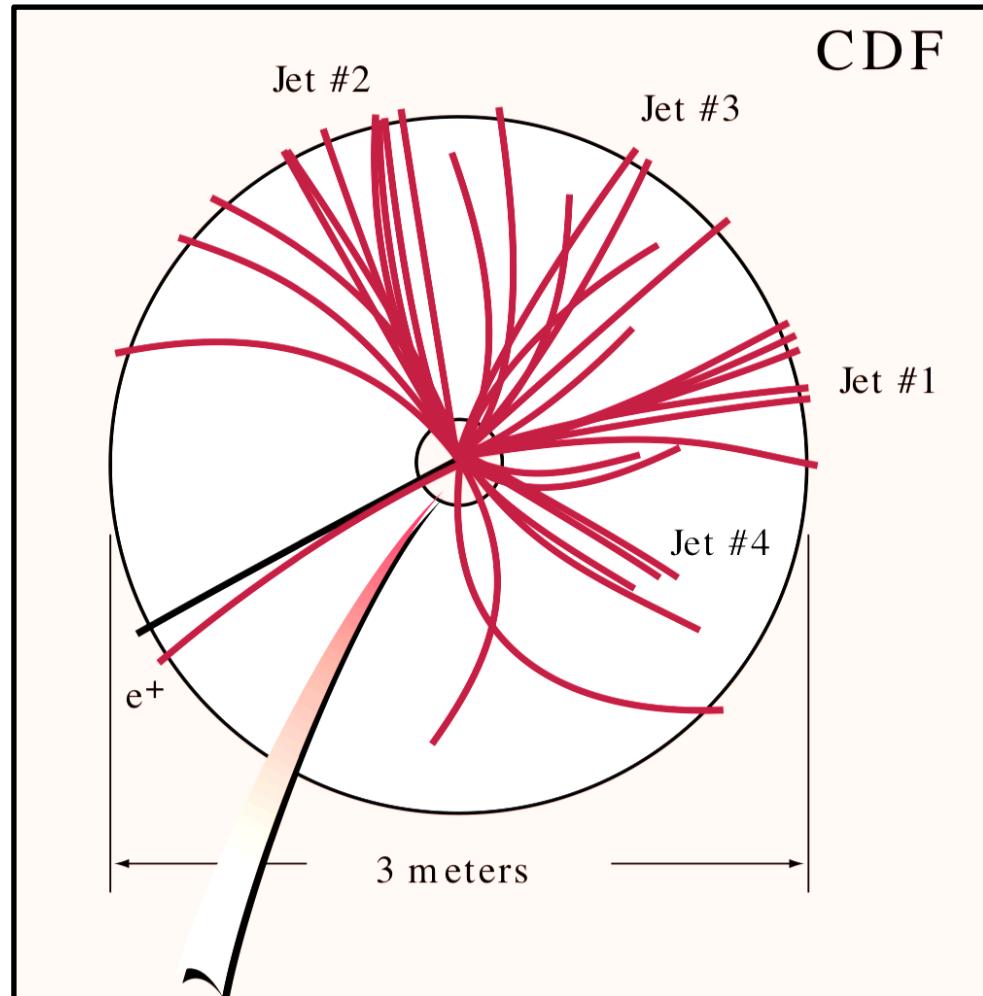
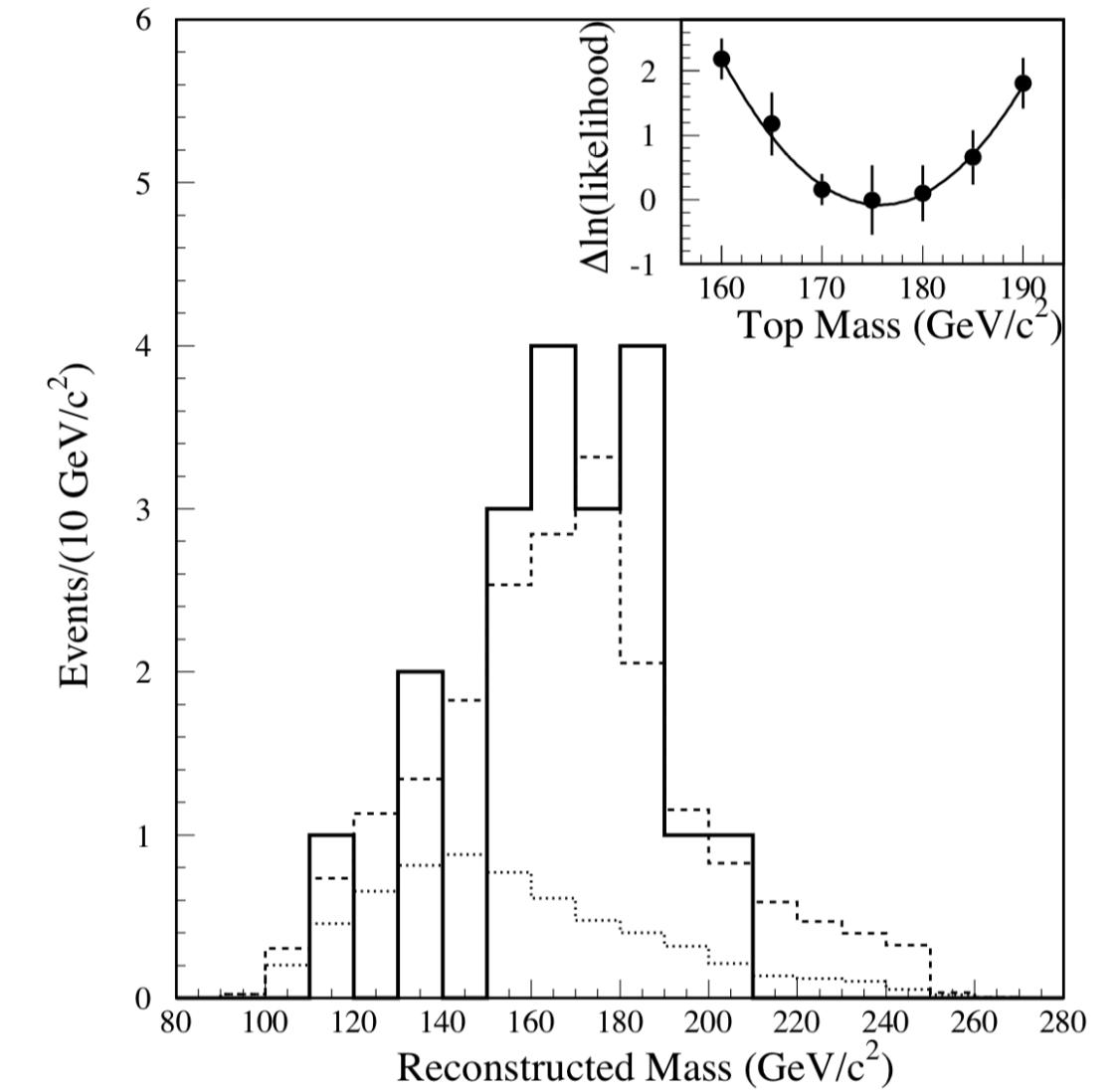
1999

Elucidating the quantum structure of EW interaction

Gerardus 't Hooft, Martinus Veltman

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

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



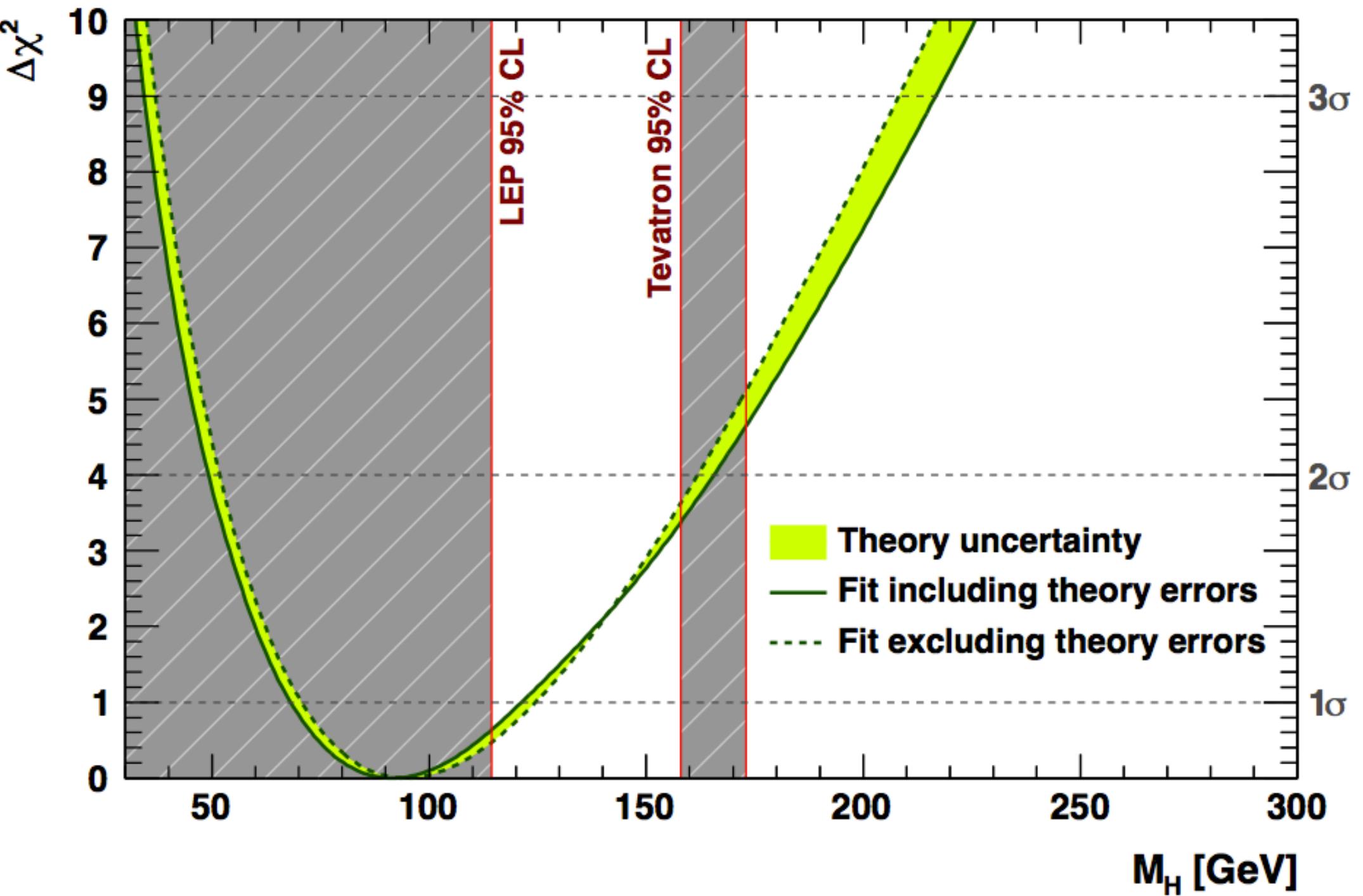
Observation in the 1 lepton - 4 jets topology, yielding a mass measurement of approximately 175 GeV

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

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

# Already More than 10 Years after the Higgs Discovery

9



$$m_H = 91^{+30}_{-23} \text{ GeV}$$



2013

Mechanism contributing to... [\[full\]](#)  
Francois Englert and Peter Higgs

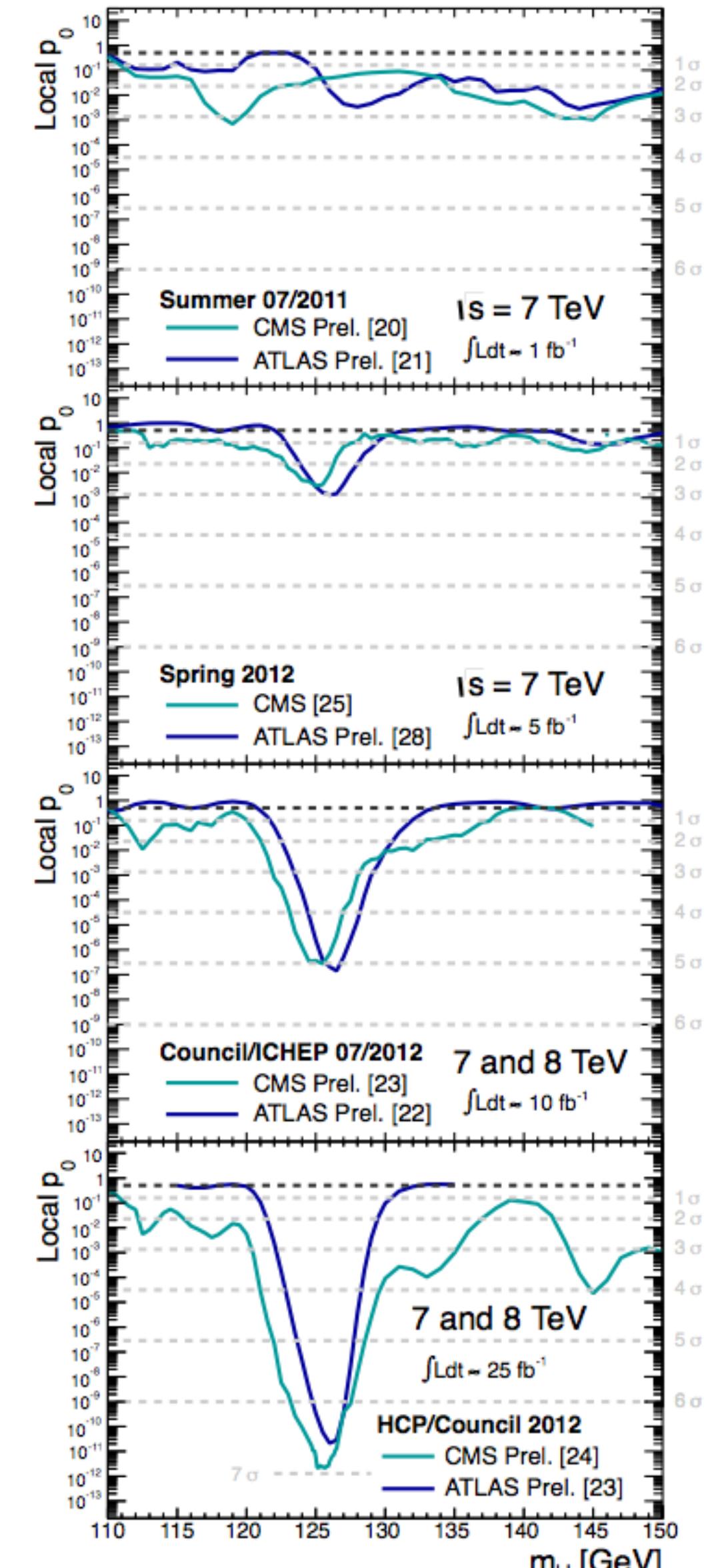
Summer 2011 EPS and Lepton-Photon:  
**Still focused on limits.**

December 2011 CERN Council: **First hints.**

Summer 2012 CERN Council and ICHEP:  
**Discovery!**

December 2012 CERN Council:  
**Beginning of a new era!**

- ✓ Strongly Motivated
- ✓ Significance increased with luminosity to reach unambiguous levels
- ✓ Two experiments
- ✓ Several channels



# Nature Higgs Anniversary Edition

10



NATURE PODCAST | 11 July 2022

## Higgs boson at 10: a deep dive into the mysterious, mass-giving particle

We discuss the discovery of the Higgs boson and the impact it's had on physics.

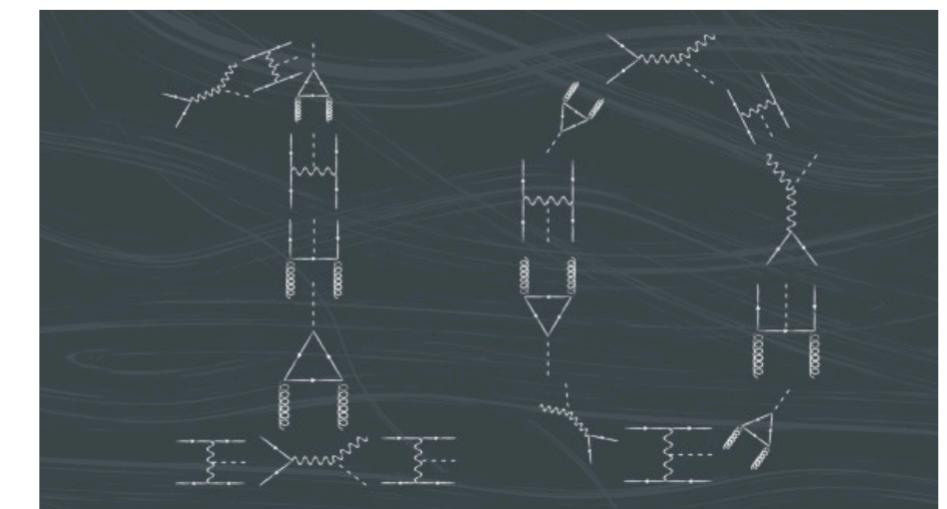
## nature portfolio

nature > collection

Collection | 04 July 2022

### The Higgs boson discovery turns ten

The discovery of the Higgs boson was announced ten years ago on the 4<sup>th</sup> of July 2012 — an event that substantially advanced our understanding of the origin of elementary particles' masses. In this collection of articles from *Nature*, *Nature Physics* and *Nature Reviews Physics* we celebrate this groundbreaking discovery and reflect on what we have learned about the Higgs boson over the intervening years.



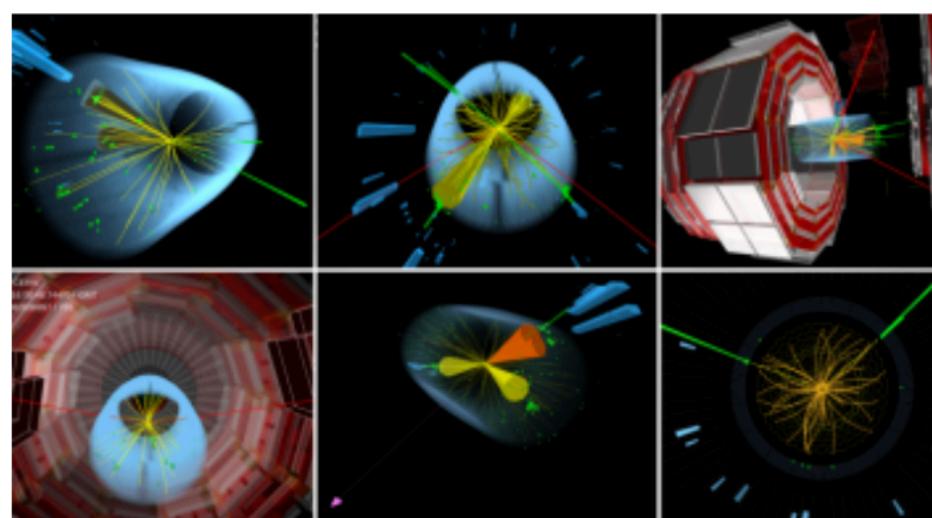
# Further readings...

11

Higgs 10 [symposium](#) at CERN



CMS [news](#)

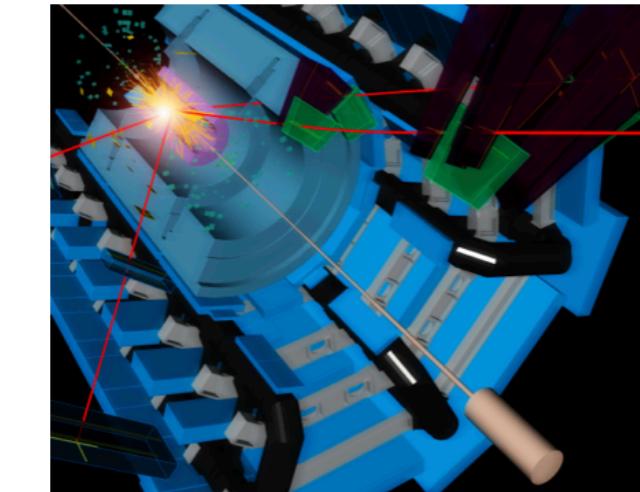


THE HIGGS BOSON TURNS  
10: RESULTS FROM THE  
CMS EXPERIMENT

⌚ 04 JUL 2022 | 🚩 AJAFARI | 📁  
PHYSICS

years  
**HIGGS boson**  
discovery

ATLAS [news](#)

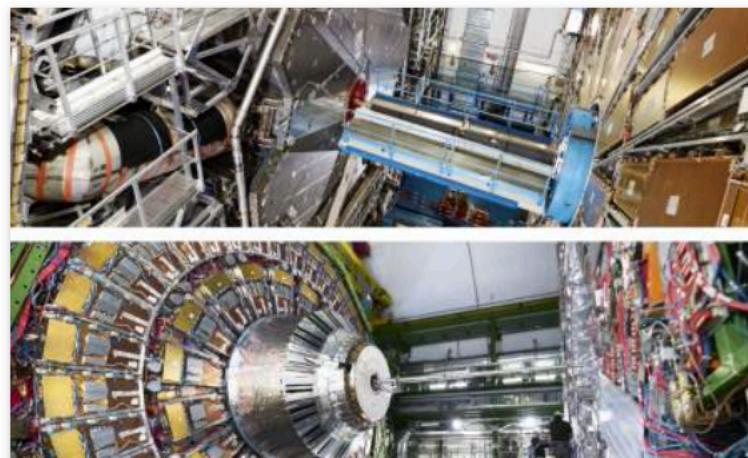


**10 years of Higgs research**

The ATLAS Collaboration at CERN has released its most comprehensive overview of the Higgs boson. The new paper, published in the journal Nature, comes exactly ten years after ATLAS announced the discovery of the Higgs boson. In celebration of this anniversary, a special all-day symposium on the Higgs boson is currently underway at CERN.

Press Statement | 4 July 2022

CERN [news](#)



**ATLAS and CMS release results of most comprehensive studies yet of Higgs boson's properties**

The collaborations have used the largest samples of proton–proton collision data recorded so far by the experiments to study the unique particle in unprecedented detail

News | Physics | 04 July, 2022



**Higgs10: When spring 2012 turned to summer**

It was just a few short weeks in mid-2012, but they were so intense that it felt like years. As 4 July drew near, the ATLAS and CMS experiments could sense that they were homing in on something big.

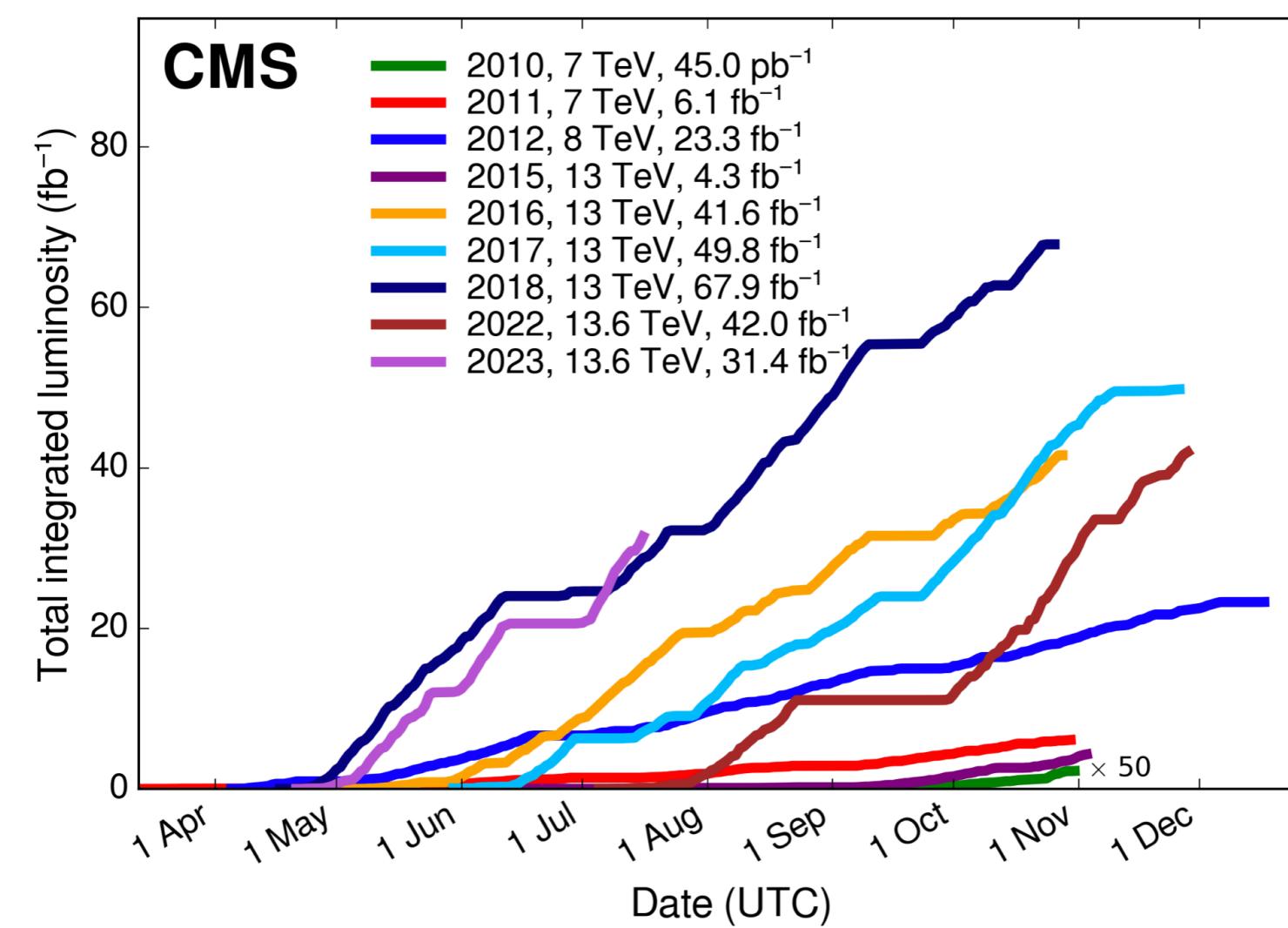
News | At CERN | 04 July, 2022

# The LHC Datasets

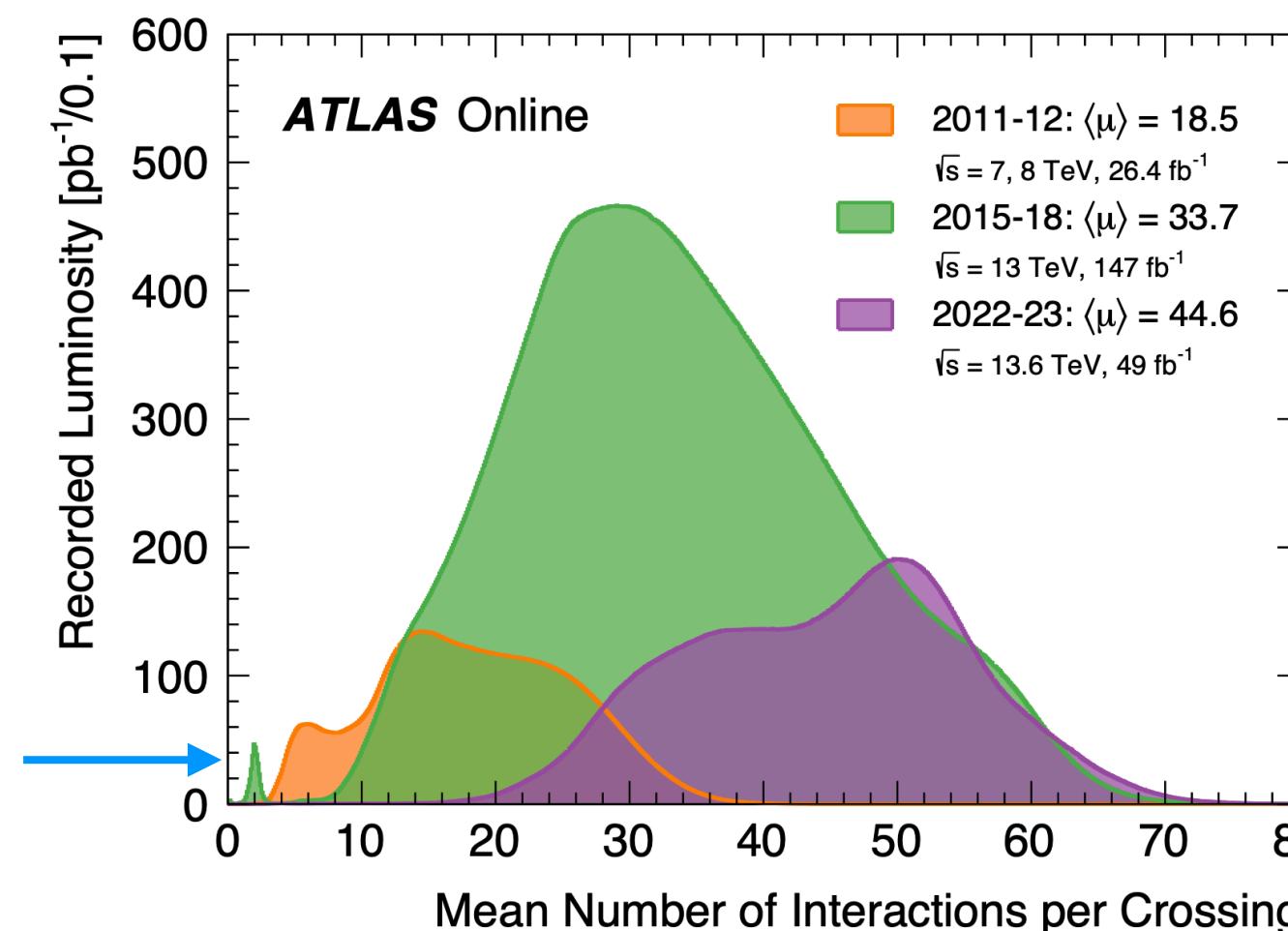
# The LHC datasets

13

## The LHC pp operations for ATLAS and CMS



## PU profile for the LHC Run 2



### Run 3 datasets

**pp 13.6 TeV 2022-2023** ~50 fb<sup>-1</sup> with ~90% data taking and data quality efficiency

### Run 2 datasets

**pp 13 TeV 2015-2018** - ~140 fb<sup>-1</sup> 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<sup>-1</sup> 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<sup>-1</sup>
- 13 TeV - 0.35 fb<sup>-1</sup>

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

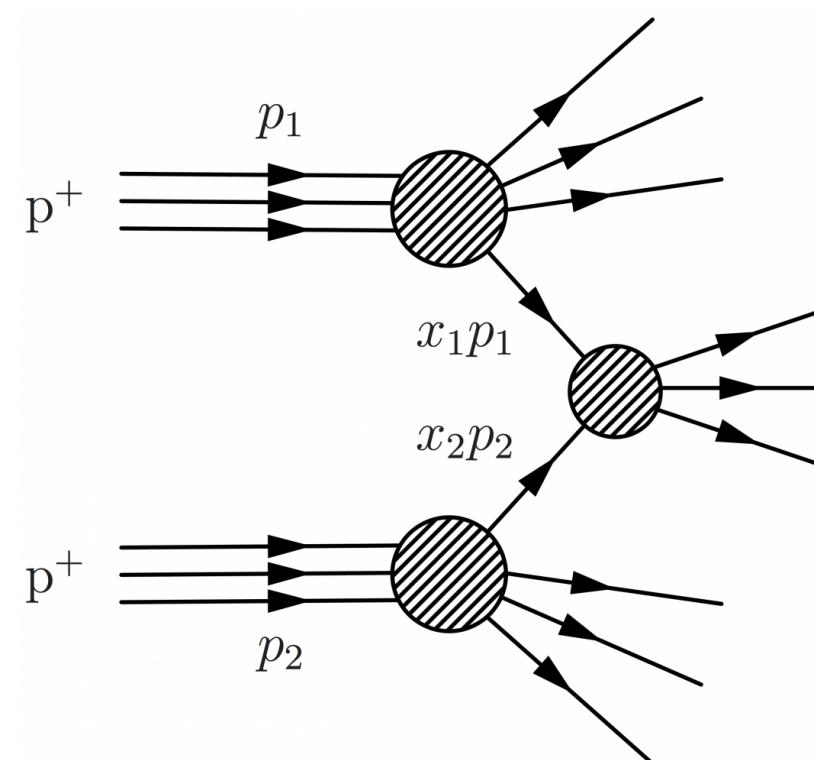
# Total and Elastic Cross Sections

# Measurement of the Total Cross Section

15

**From the size of the proton  $\sim O(80)$  mb naive estimate of the total cross section of  $p\bar{p}$  collisions.**

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



The main subject of these lectures.

**The simplest measurement** of the cross section counting events:

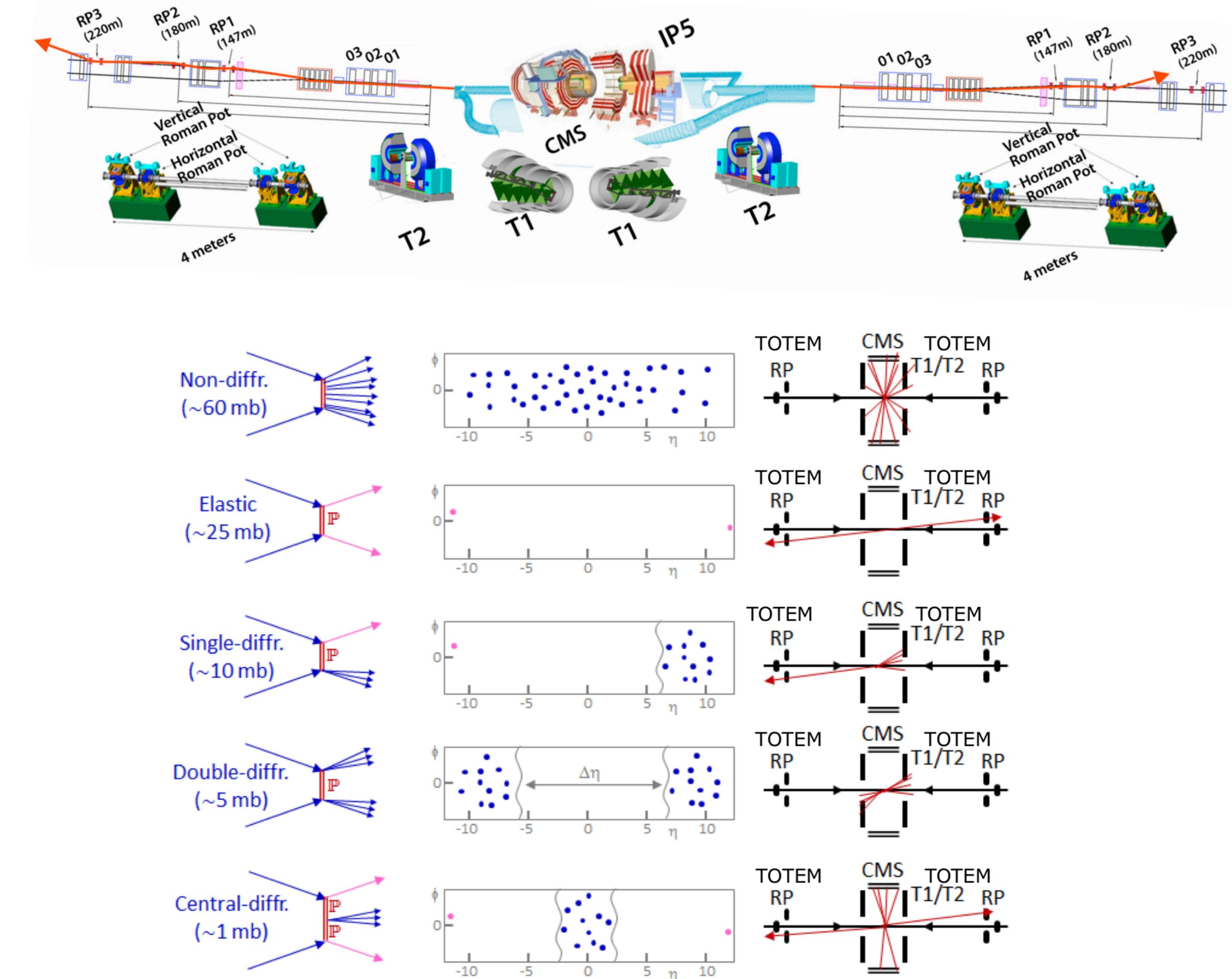
$$\sigma_{tot} = \frac{N_{el} + N_{inel}}{\mathcal{L}}$$

**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.

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)

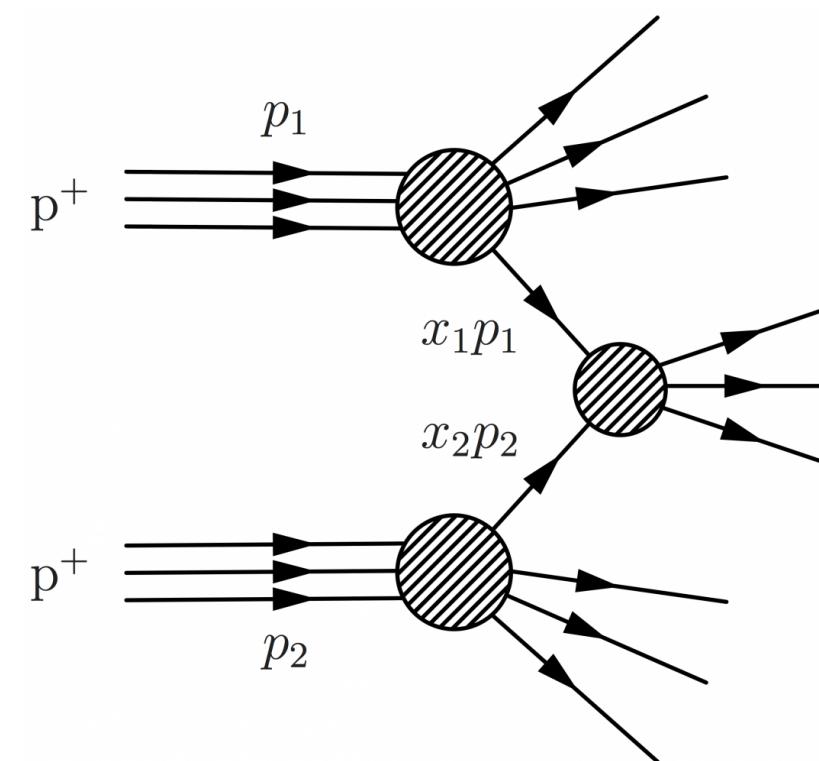


# Measurement of the Total Cross Section

16

From the initial  $O(80)$  mb naive estimate of the total cross section of  $p\bar{p}$  collisions.

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



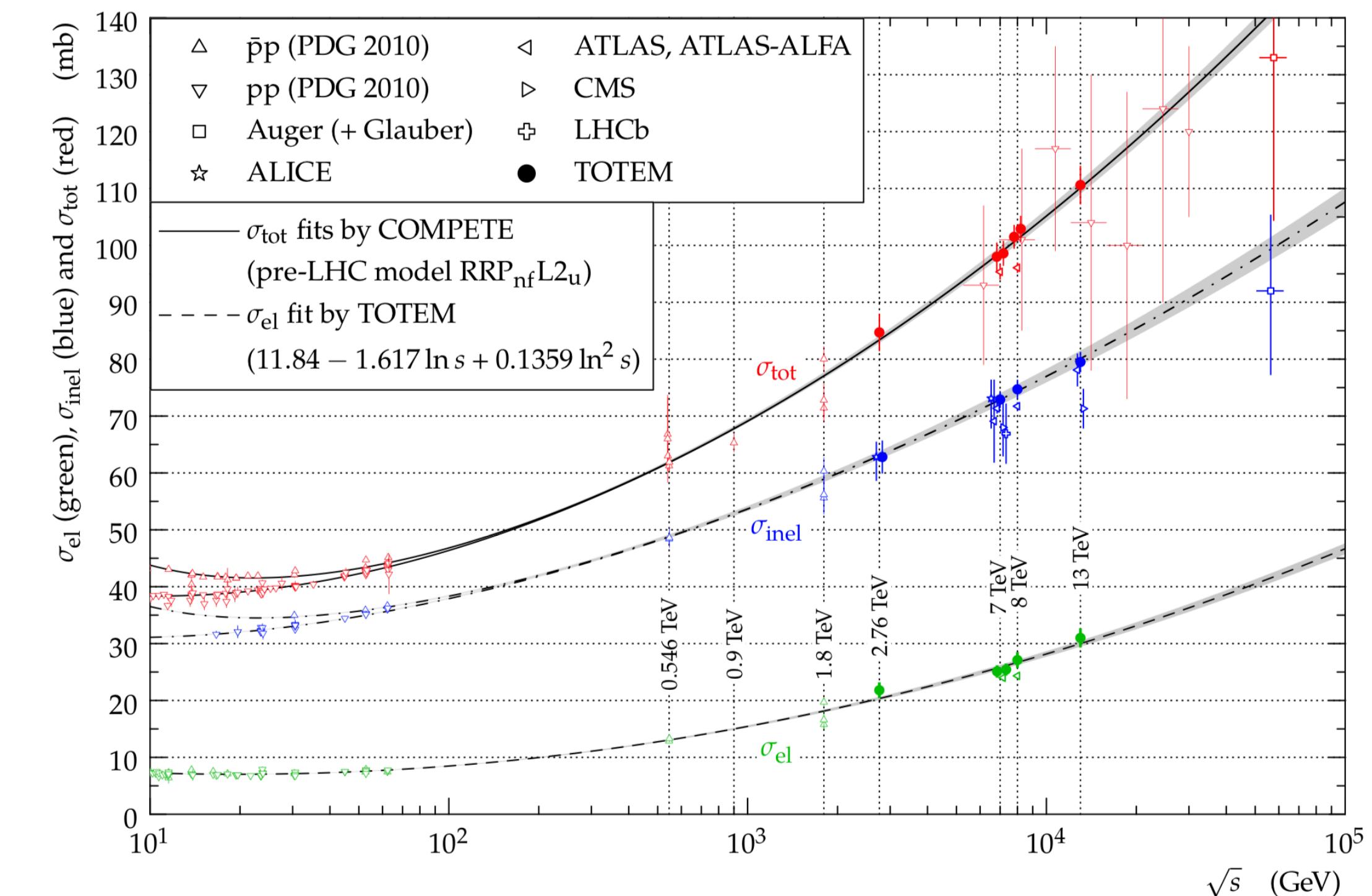
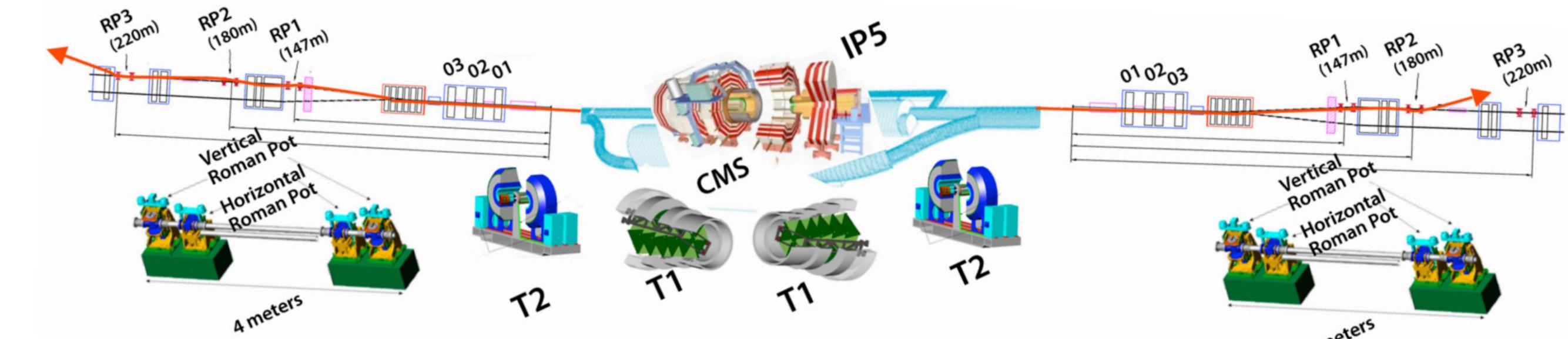
The main subject of these lectures.

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!

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

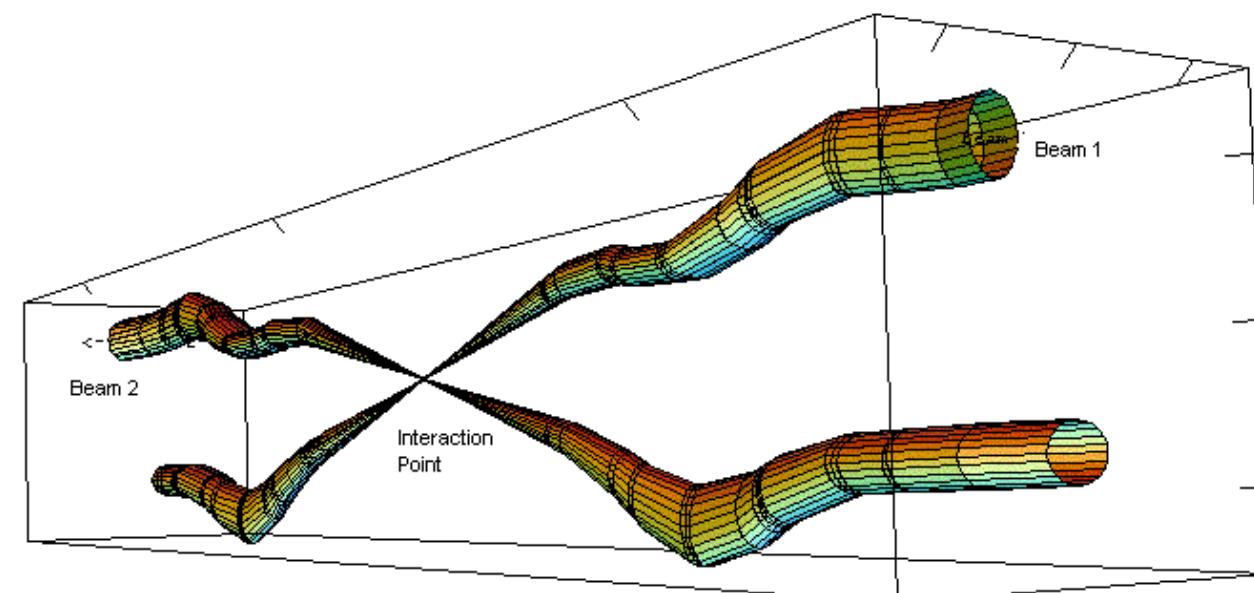
$$\begin{array}{c} p_1 \quad \quad \quad p_3 \\ \diagdown \quad \diagup \\ p_2 \quad \quad \quad p_4 \\ t = (p_1 - p_3)^2 \end{array}$$

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



# Measurement of the differential elastic cross section

17



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

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

Relative beam sizes around IP1 (Atlas) in collision

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

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

$f_{el}$  is the forward elastic scattering amplitude.

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

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

Requires measurement of inelastic events

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).

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

$\rho \sim 0.14$  is taken from TH predictions (known typically at 0.5%)

$$\rho = 0.10 \pm 0.01$$

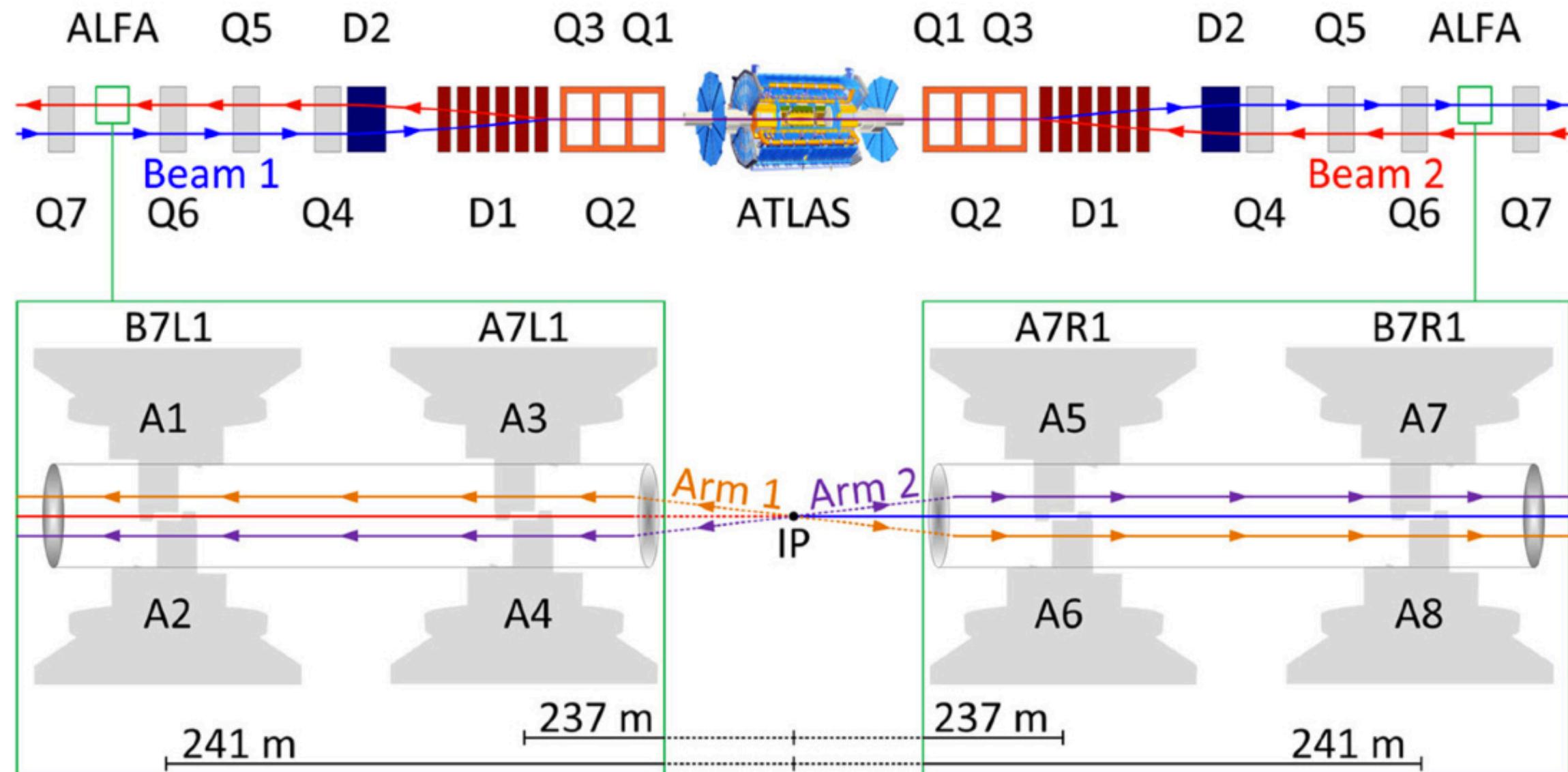
Lower than the predicted value.

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

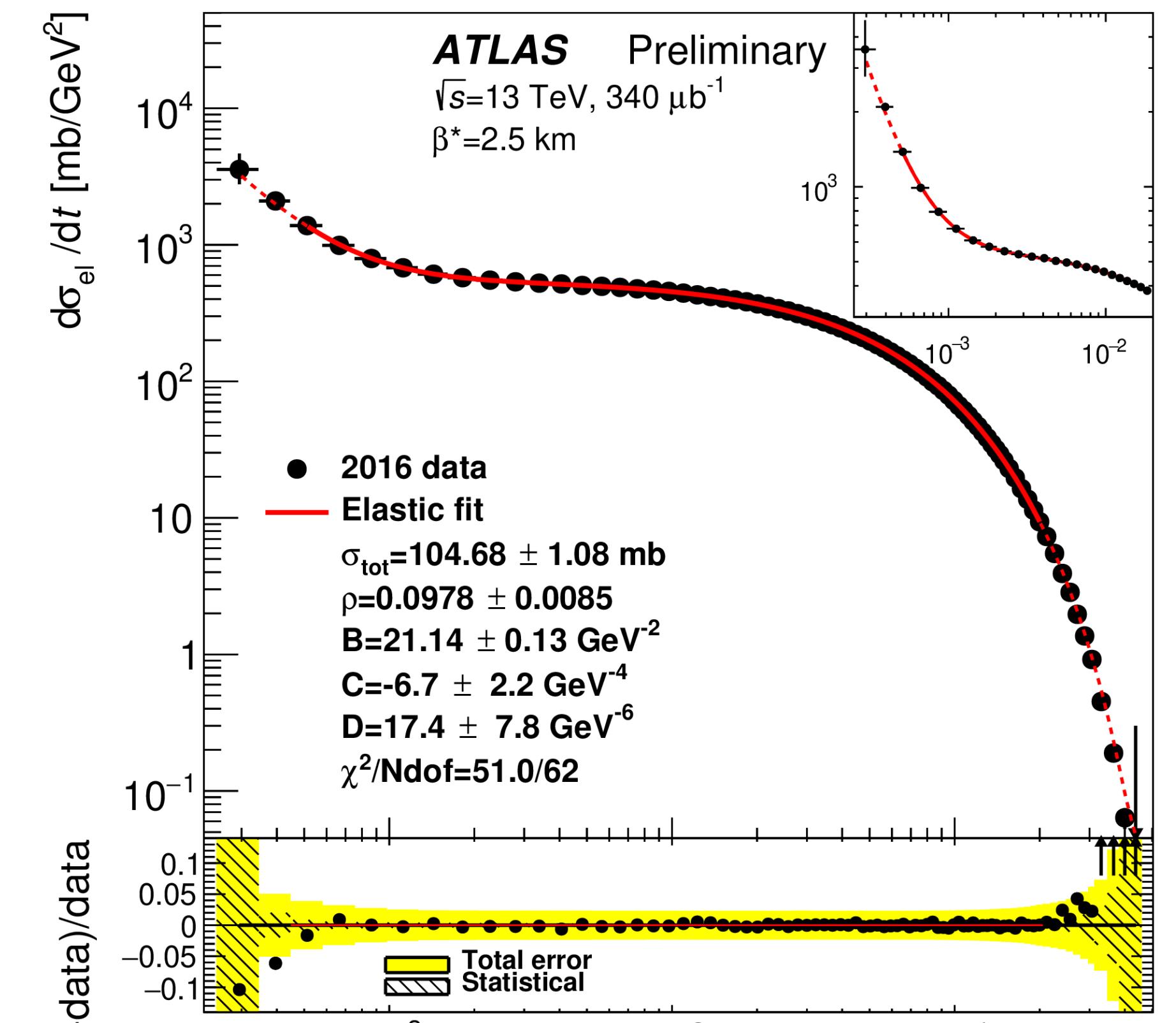
18



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

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

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



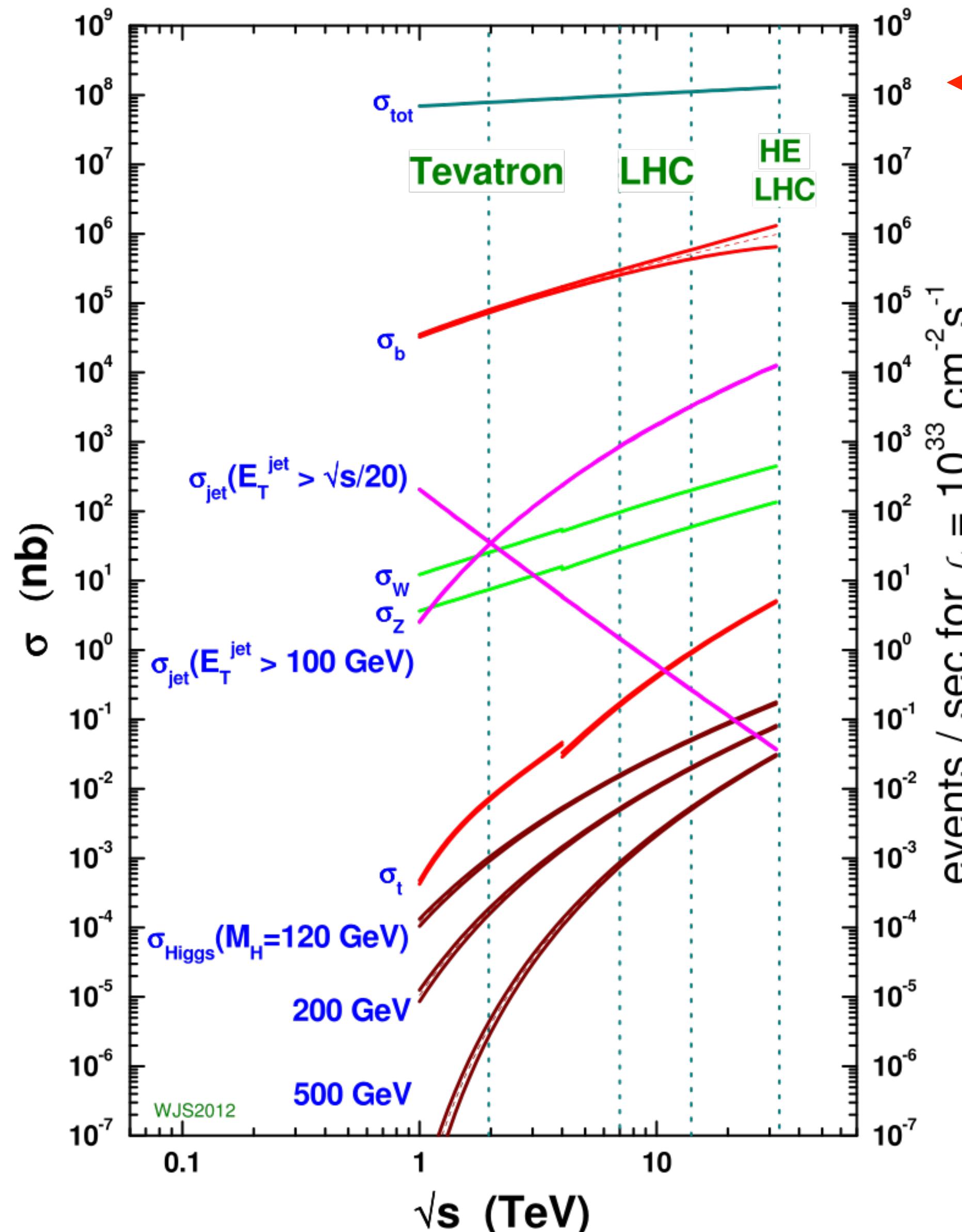
$$\begin{aligned} \sigma_{tot}(pp \rightarrow X) &= 104.7 \pm 1.0 \text{ (exp.)} \pm 0.12 \text{ (th.) mb,} \\ \rho &= 0.0975 \pm 0.0085 \text{ (exp.)} \pm 0.0064 \text{ (th.)} \end{aligned}$$

...can also measure the luminosity!

(See ALFA [paper](#))

# Dissecting the total cross section

19



100 mb      Total cross section

60 mb      Inelastic, start seeing events in the detector!  
Starting point of everything!!

From the nominal LHC luminosity:

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

With a total cross section of approximately 100mb:

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

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

# Cross Section Measurements

# Fiducial volume and Acceptance

21

**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.

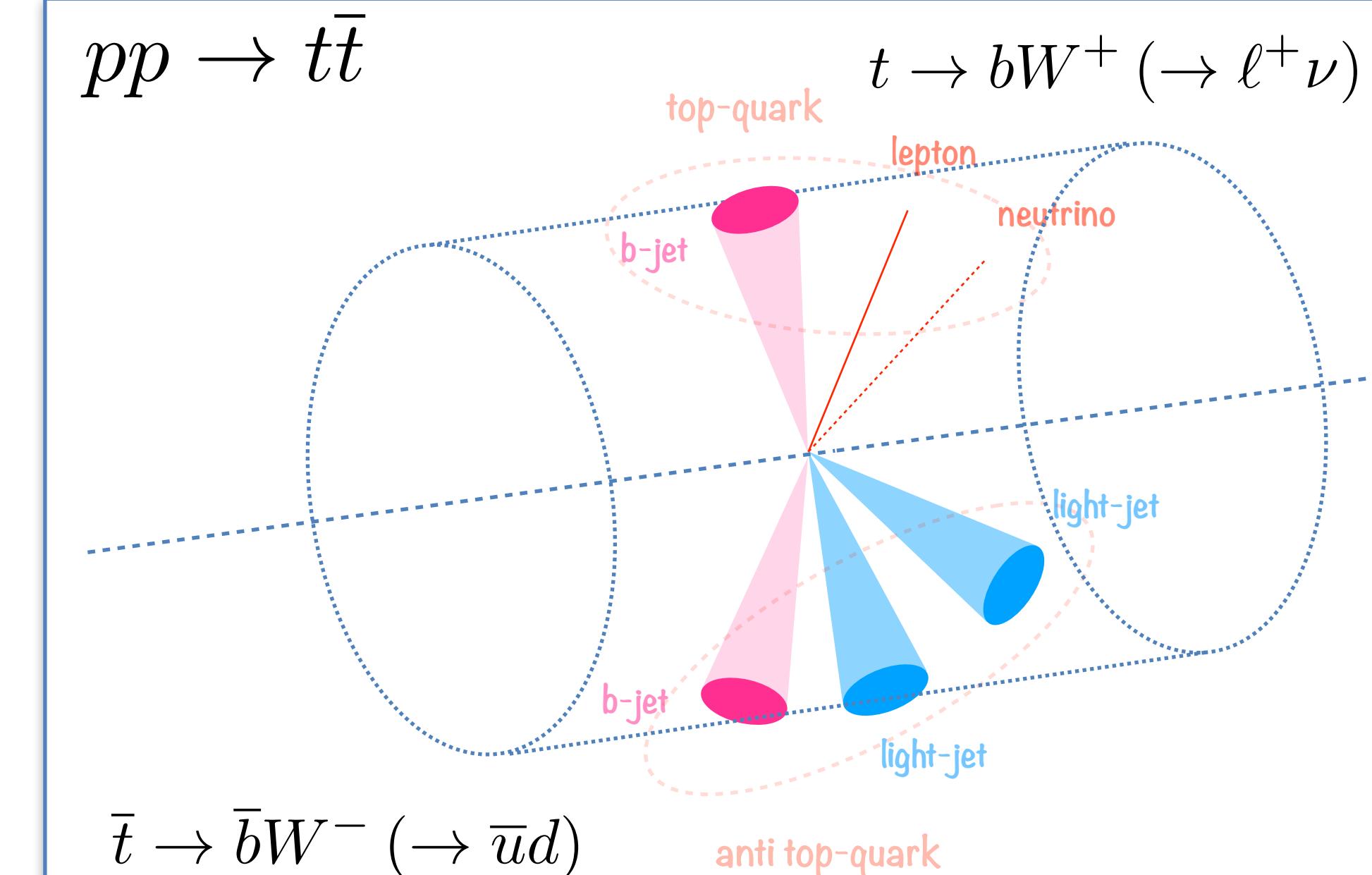
**Definition of a fiducial volume:** the phase space in which a given final state is measurable (this does not only include the volume of the detector and its thresholds in energy, but also aspects such as the isolation)

## Corresponding (typical) fiducial volume

- One true lepton (electron or muon)  $\text{ET}/\text{pT} > 25 \text{ GeV}$  and with  $|\eta| < 2.5$ .
- 4 Truth particle jets with  $\text{ET} > 35 \text{ GeV}$  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)  $\text{ET}/\text{pT} > 25 \text{ GeV}$  and with  $|\eta| < 2.5$ .
- Missing transverse momentum in excess of 20 GeV.
- Four jets with  $\text{ET} > 35 \text{ GeV}$  and  $|\eta| < 2.5$ .
- Two jets tagged as b-jets.

# More Cross Sections Definitions

## Total, fiducial, differential and unfolded

22

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

$\mathcal{A}$

The acceptance  $\mathcal{A}$  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,  $\varepsilon$  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:

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

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

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

$\mathbf{A}$  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

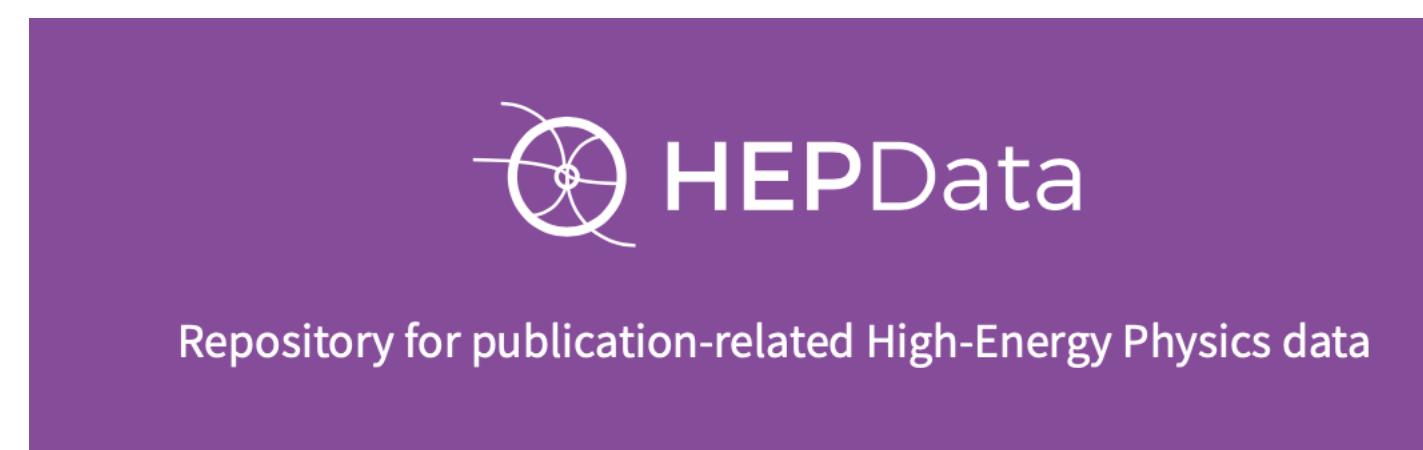
23

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 measurement on truth particle that are reconstructable.

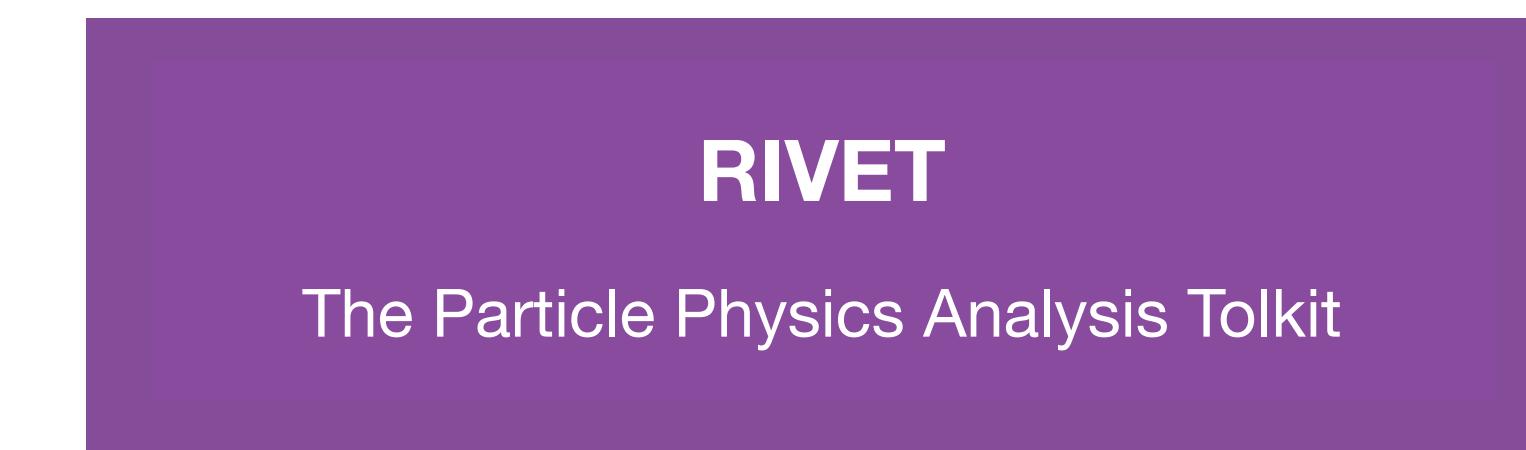
These will allow future interpretations of the data with and when new TH and modelling tools will be available.

Very important data preservation tools excellent database and tools:



[Link](#)

Most LHC results implemented!

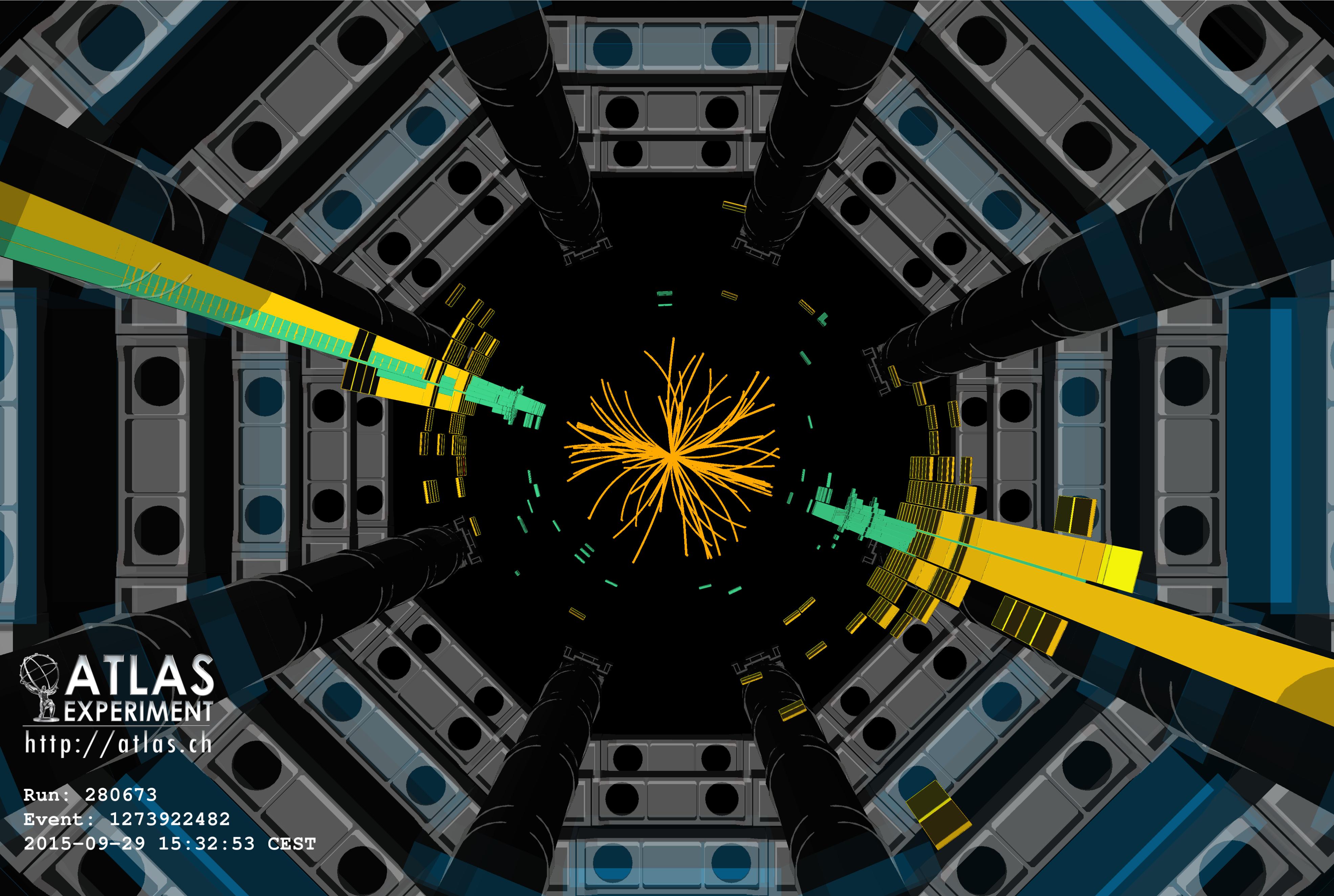


[Link](#)

Large number of analyses implemented!

**(Outstanding contribution from IPPP Durham!)**

# Jet Cross Sections and the Measurement of $\alpha_S$



A detailed 3D simulation of the ATLAS particle detector. The central part shows a complex arrangement of cylindrical and rectangular detector modules. Several yellow and green lines represent simulated particle tracks, some forming distinct jets. A large, dense yellow starburst-like pattern represents a central collision vertex. The background is black, making the detector components and tracks stand out.

# Jet Cross Sections

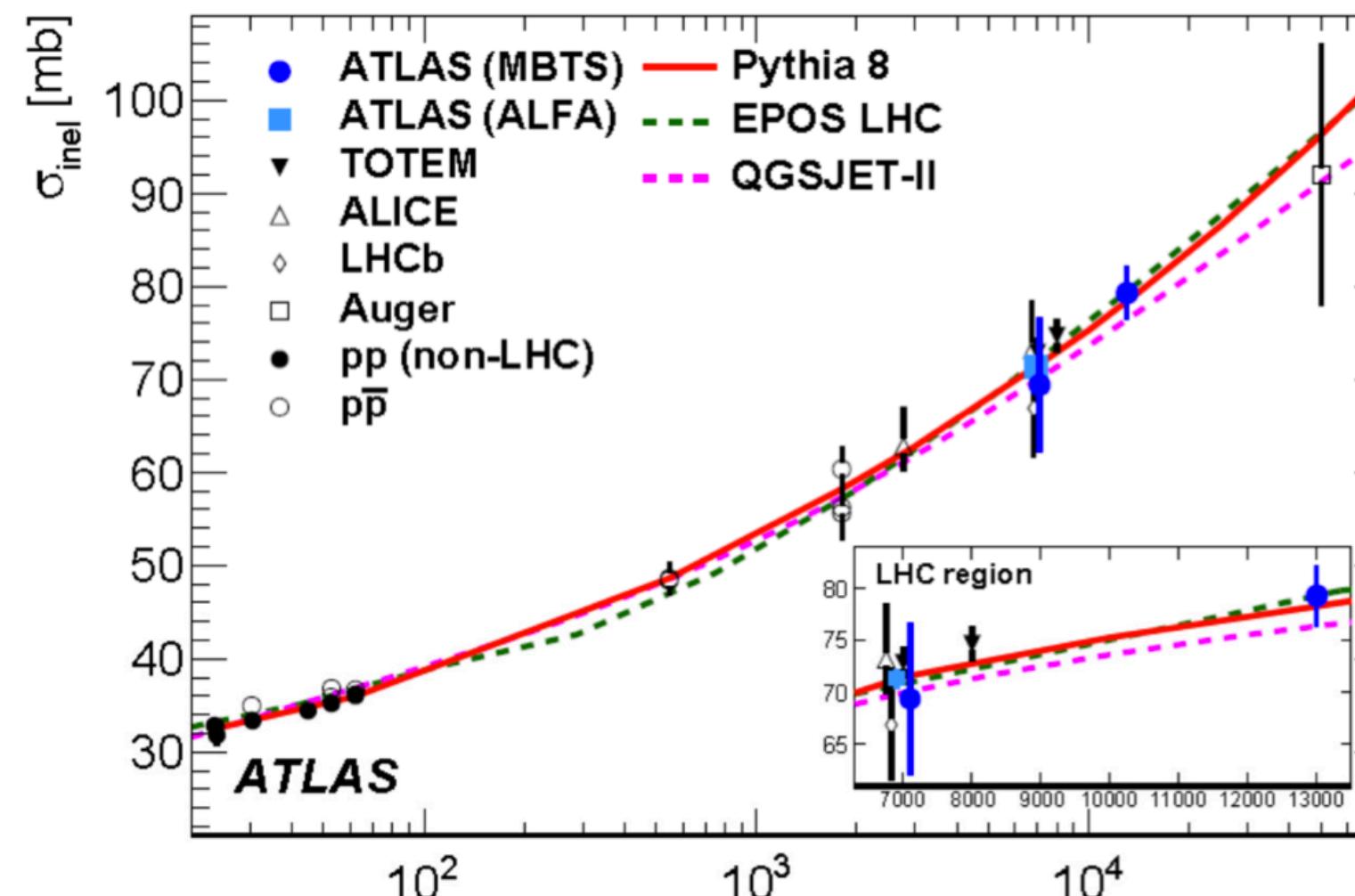
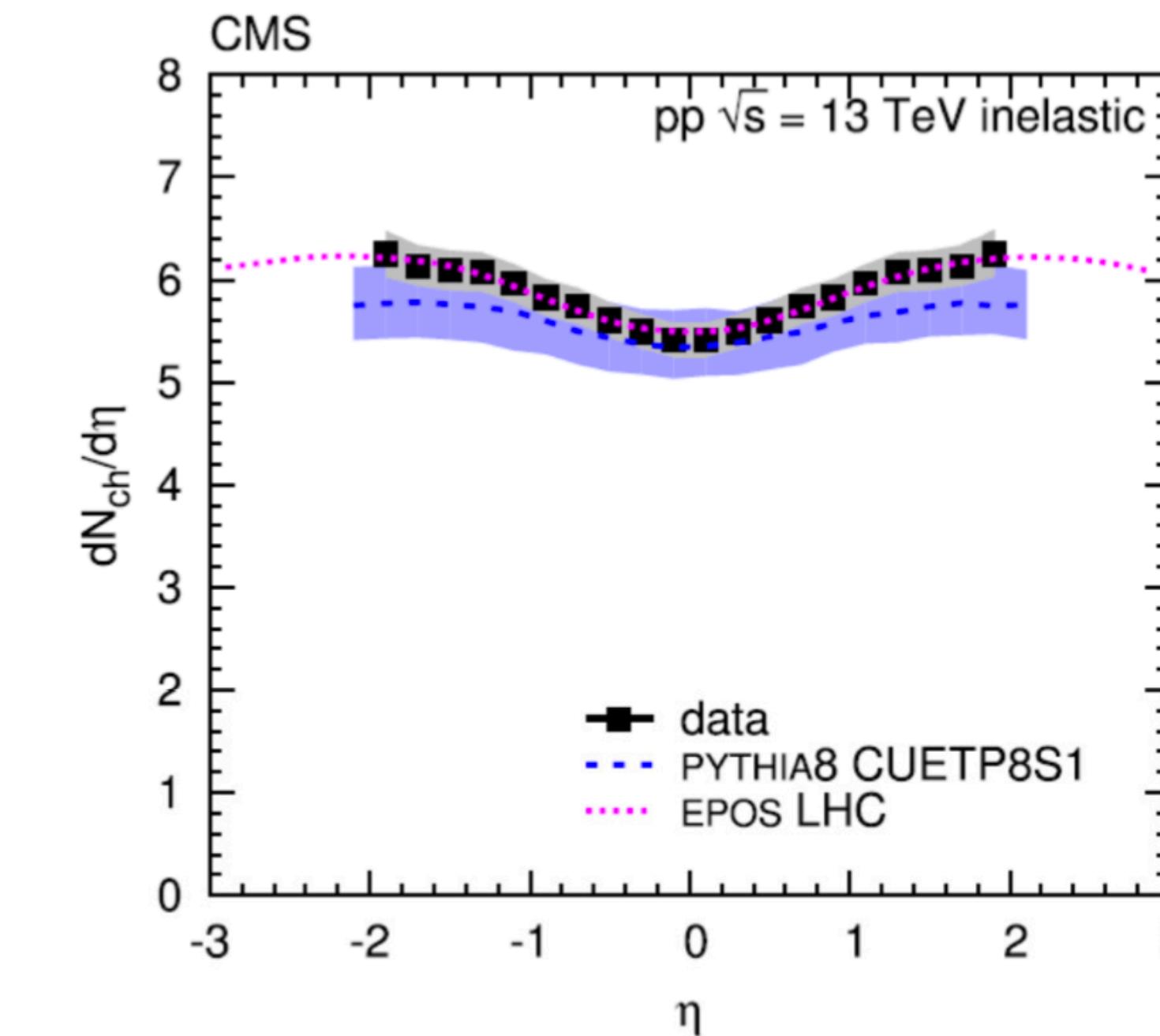
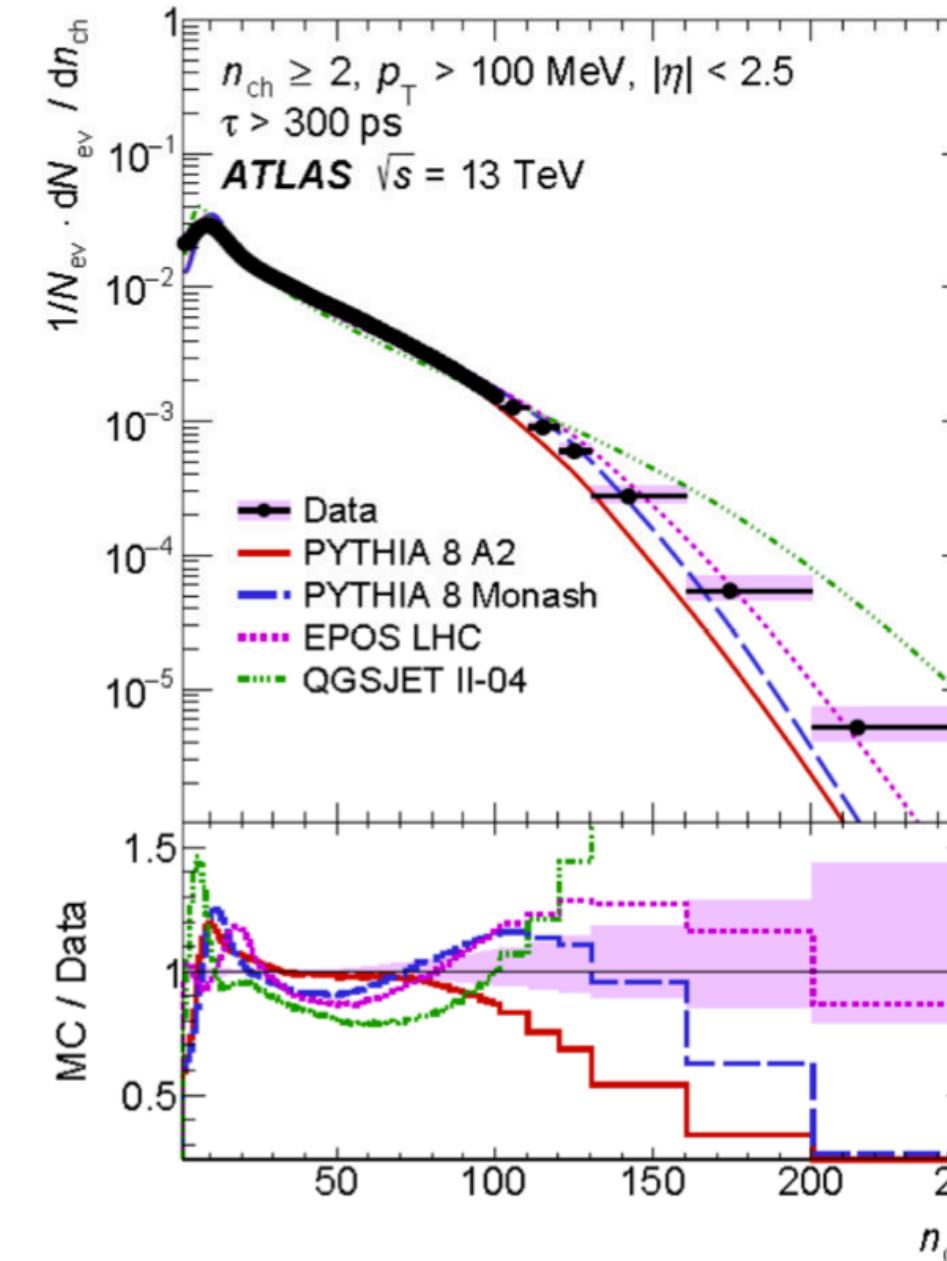
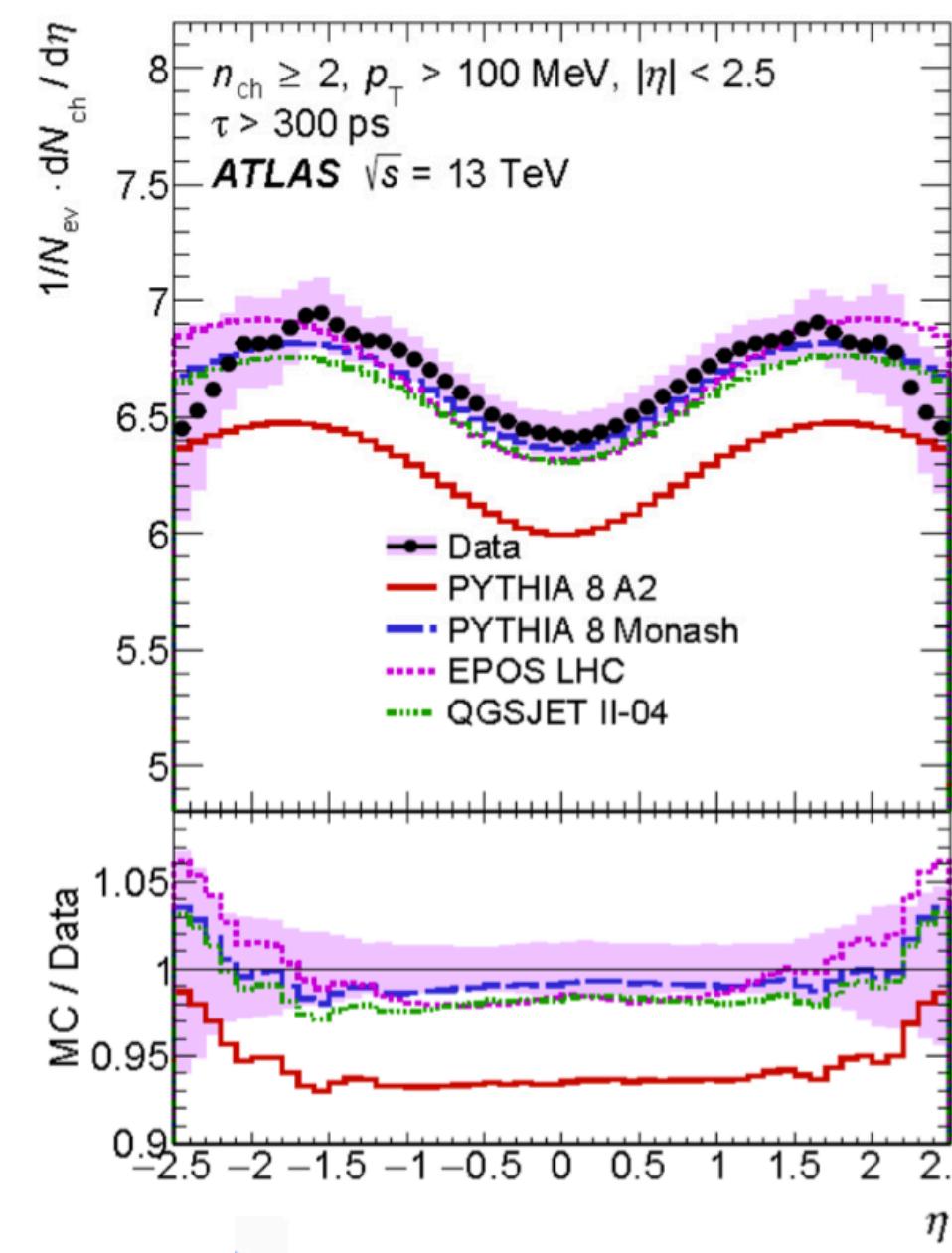
and  
Measurement of  
the strong  
coupling constant

 $\alpha_S$ 

 **ATLAS**  
EXPERIMENT  
<http://atlas.ch>

Run: 280673  
Event: 1273922482  
2015-09-29 15:32:53 CEST

# Soft QCD Measurements



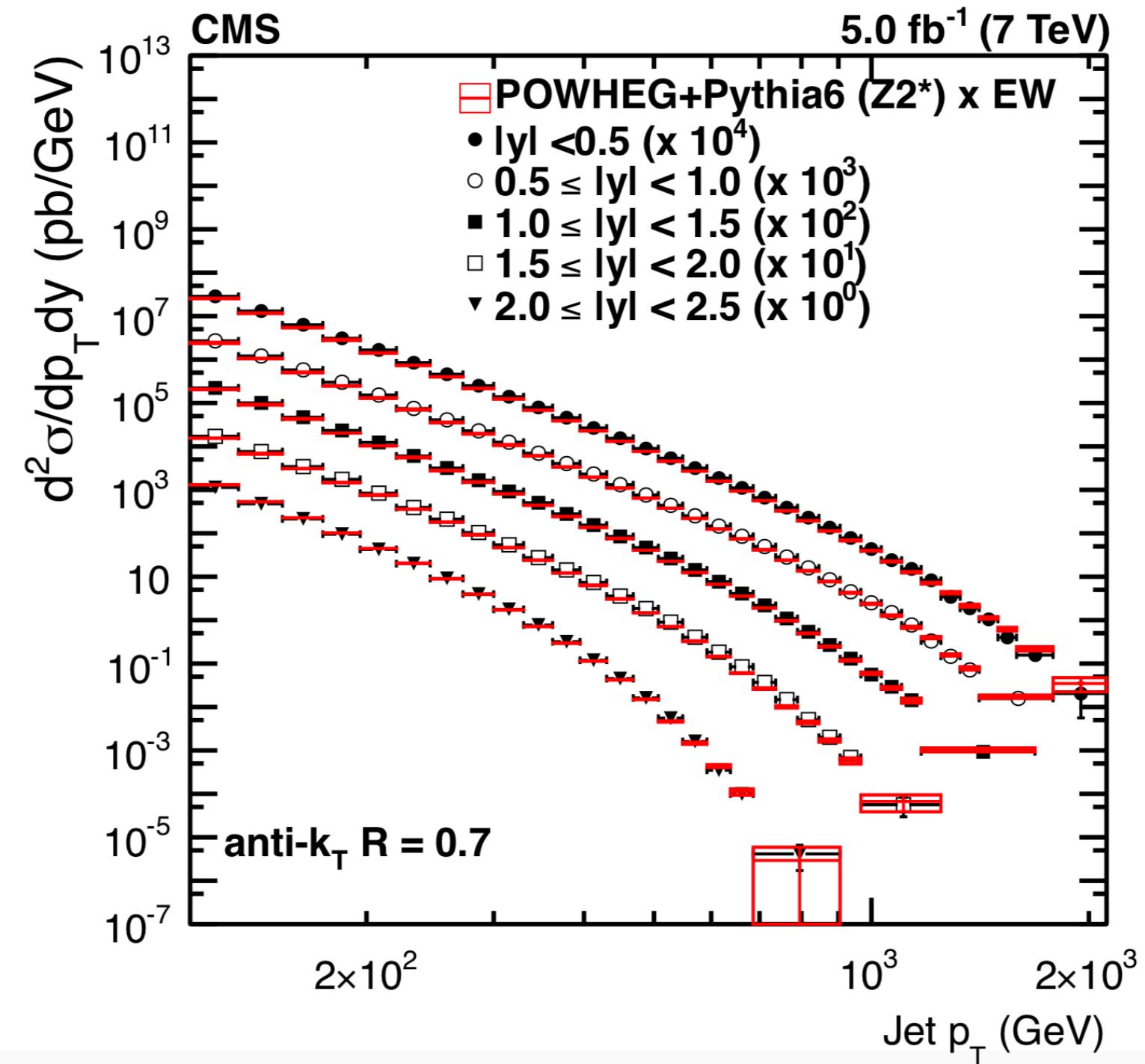
Essential track multiplicity measurements to tune the Underlying Event and Minimum Bias modelling (as well as probing tracking and the detector geometry)

- **Many more:**
  - Total inelastic cross section measurements
  - Exclusive cross section measurement
  - MPI measurements

# Differential Jet Production Cross Sections

27

**Example:** Double differential jet cross section measurement by CMS



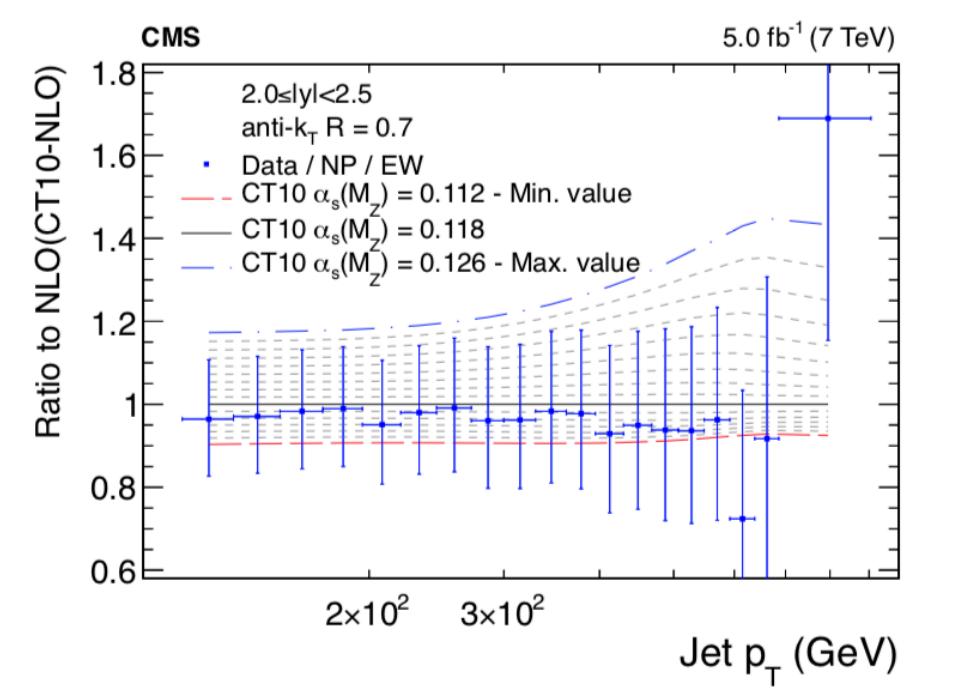
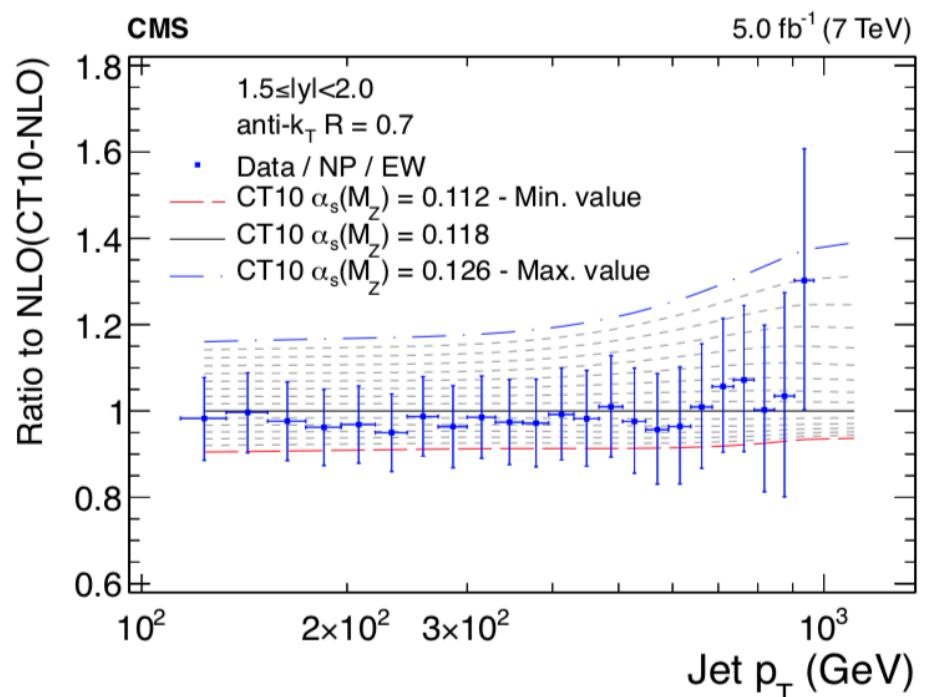
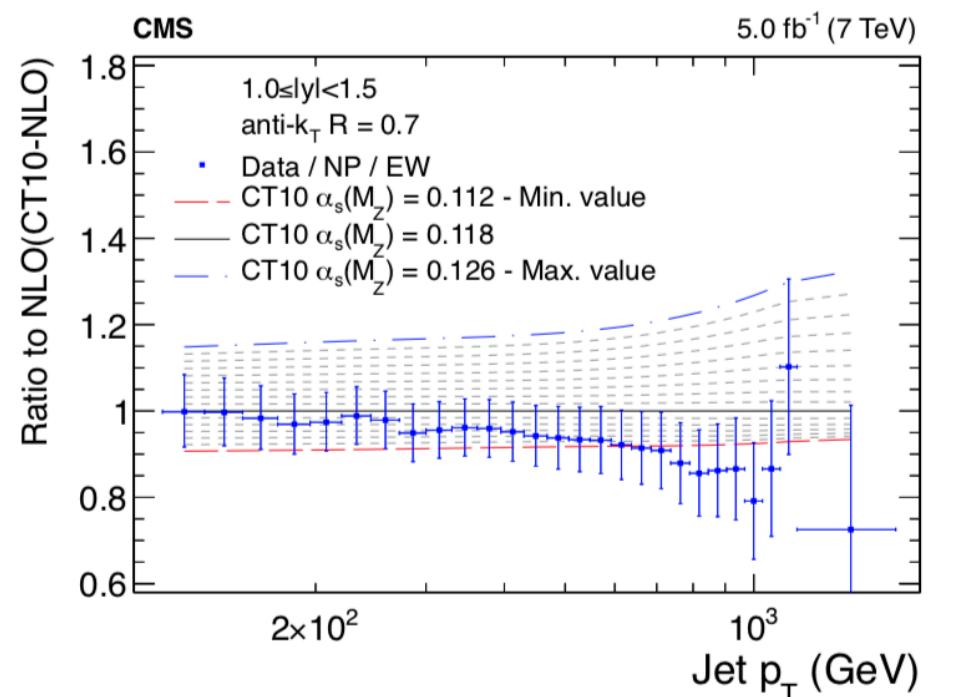
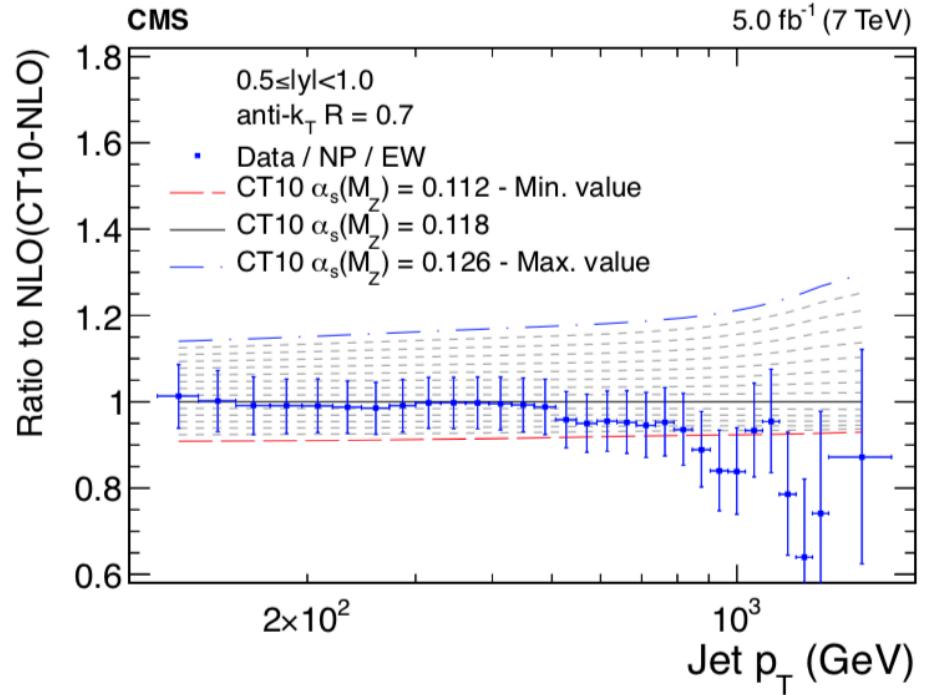
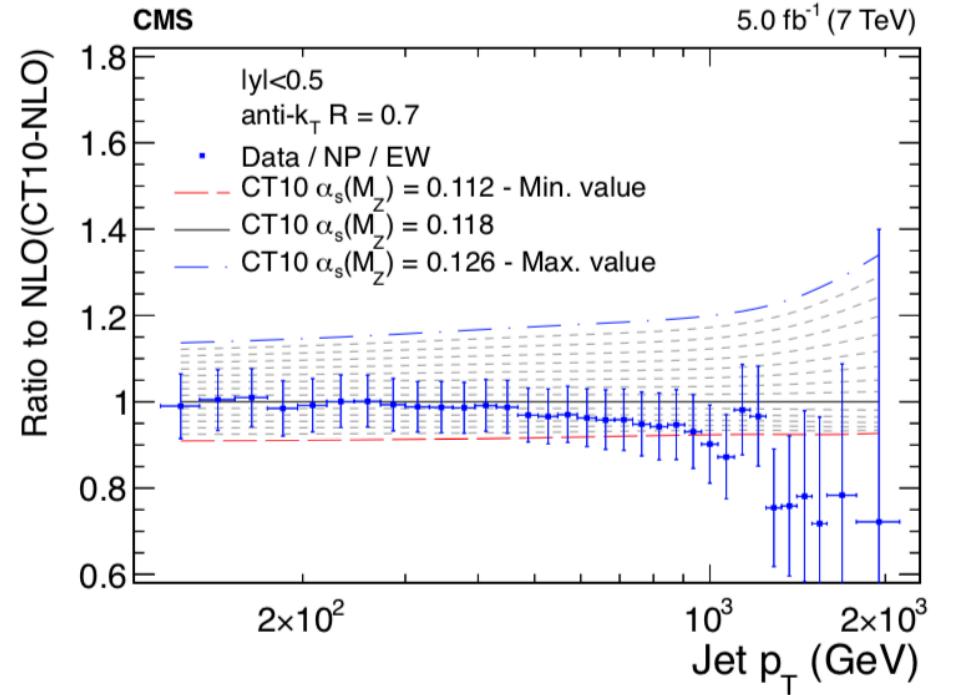
- Count number of events in reconstructed bins of  $(\Delta p_T, \Delta y)$
- Unfold to truth particle jet quantities taking into account reconstruction and trigger efficiencies and unfolding resolution matrix

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\varepsilon \mathcal{L}} \frac{N_j}{\Delta p_T \Delta y}$$

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28

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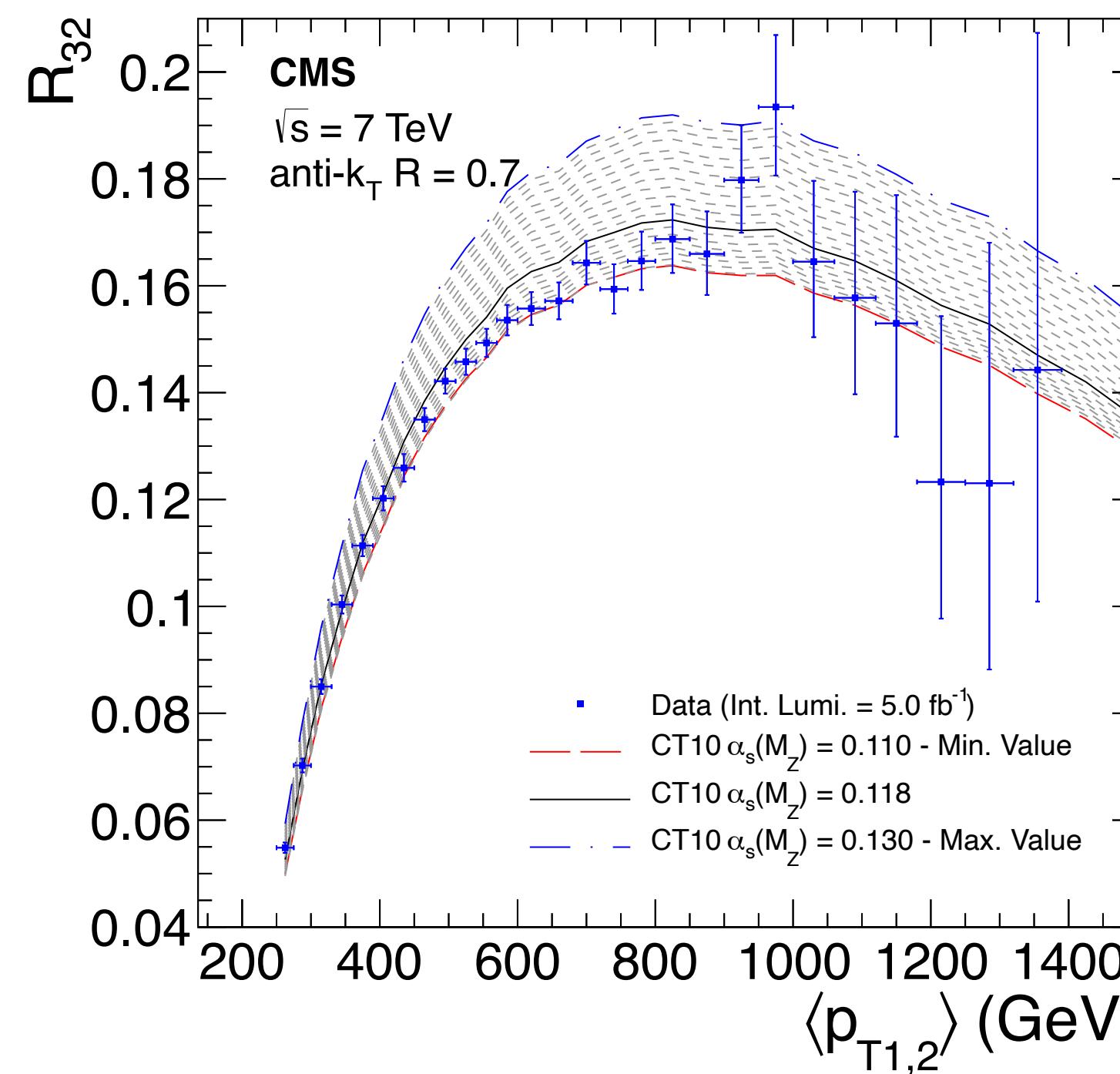
## Comparison with State-of-the-art predictions

- Main experimental uncertainty is the Jet Energy Scale uncertainties.
- Very important checks of (very very intricate) NLO predictions
- Interesting dependence on the strong coupling constant.

# Ratio of Differential Jet Production Cross Sections

29

$$R_{3/2} = \frac{\sigma_{3-jets}}{\sigma_{2-jets}} = \frac{\alpha_S \alpha_S \alpha_S}{\alpha_S \alpha_S \alpha_S} \propto \alpha_S$$



## Measurement of the ratio of cross sections

- **R3/2** is the ratio of inclusive 3-jet to inclusive 2-jet cross sections as a function of the average pT of the two leading jets:

$$\langle p_{T1,2} \rangle$$

Using ratios can improve precision by cancelling systematic uncertainties.

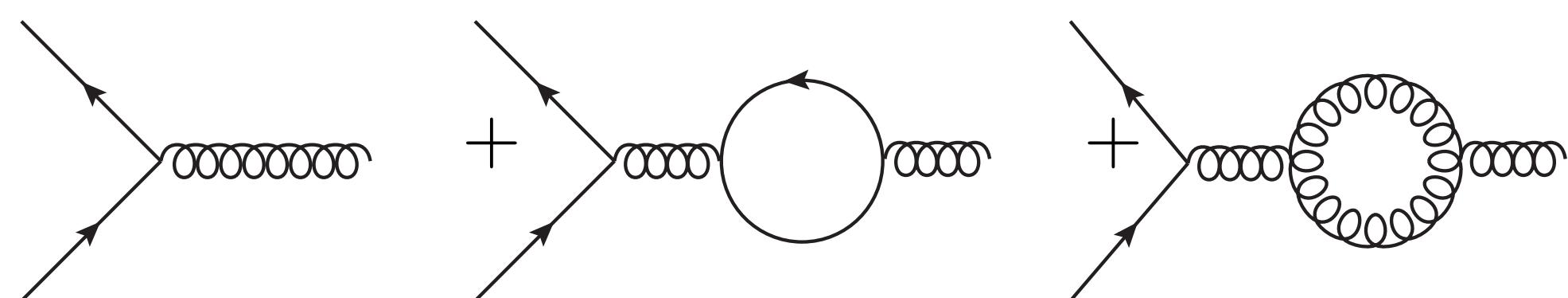
- Again interesting dependence in strong coupling constant.
- Main experimental uncertainty partly canceled but still dominant.
- With the transverse momenta of all the jets can infer the energy scale of the process.

# Measurement of the Strong Coupling constant

30

## From QCD:

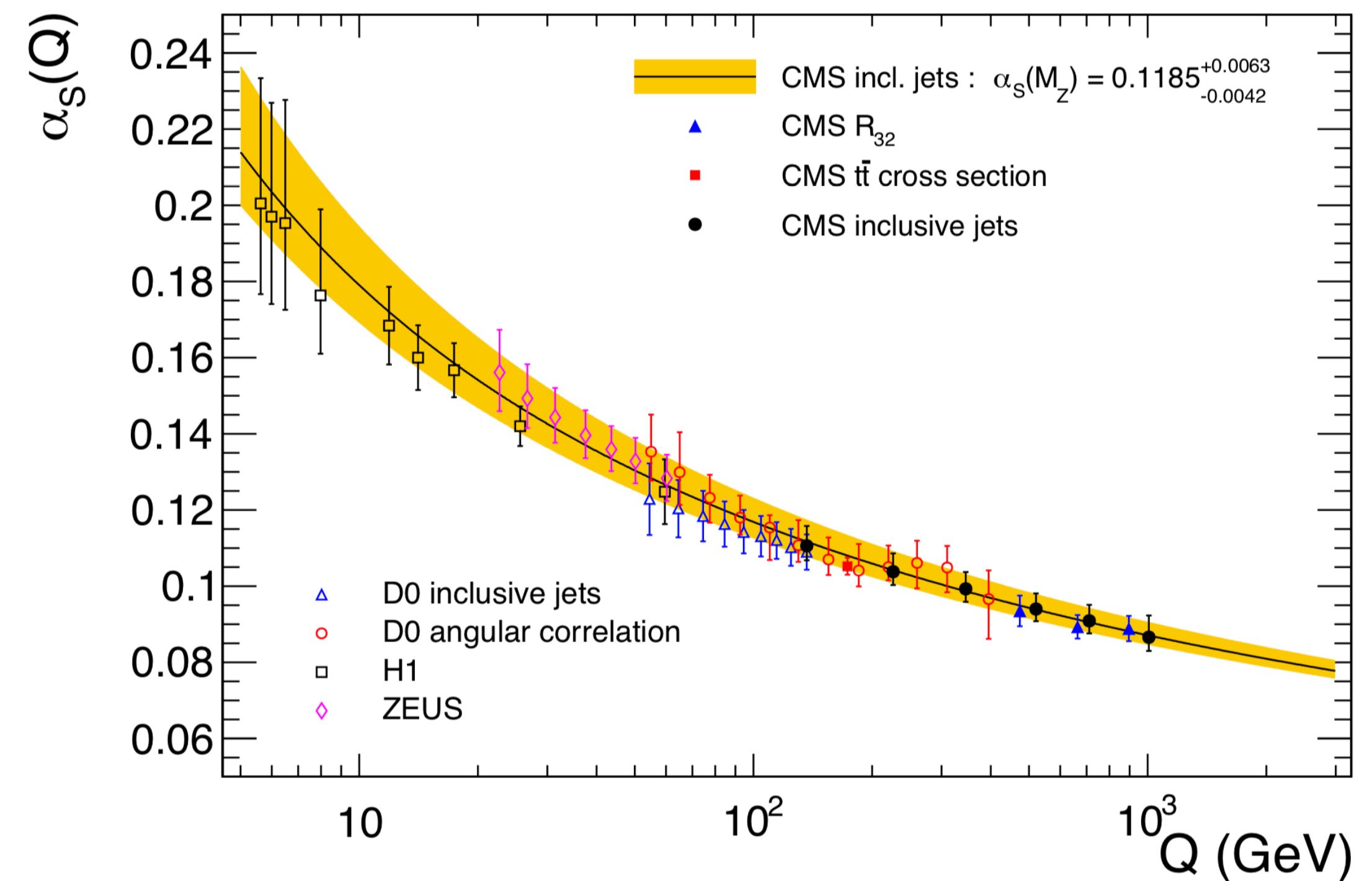
Crucial dependence of the strong coupling constant with the energy scale predicted (1973):



$$\alpha_S^{-1}(Q^2) = \alpha_S^{-1}(Q_0^2) \left[ 1 + \frac{33 - 2n_f}{12\pi} \alpha_S(Q_0^2) \ln \left( \frac{Q^2}{Q_0^2} \right) \right]$$

**Asymptotic freedom:** QCD is perturbative at high energies

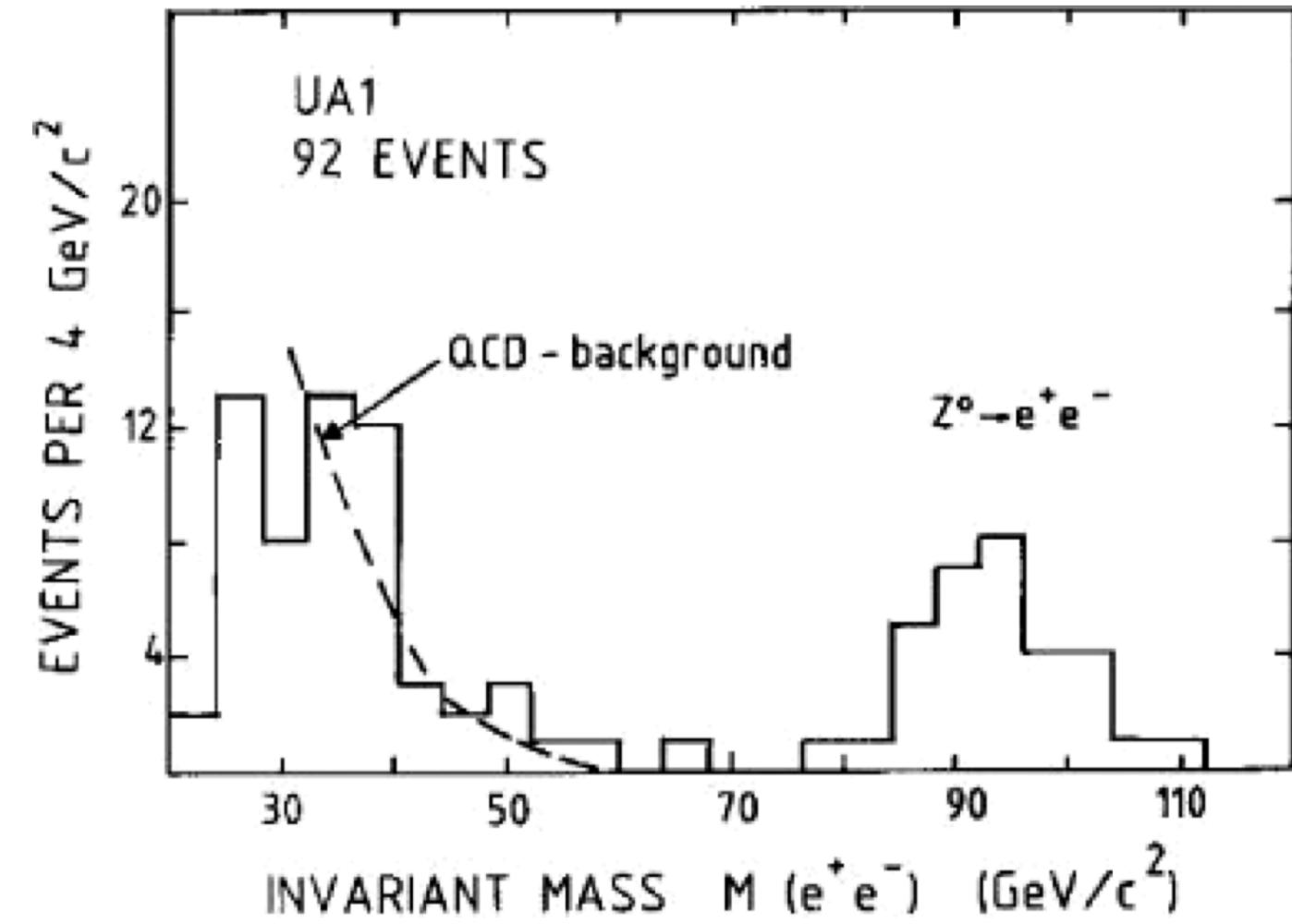
From the measurements of jet cross sections and their ratios, the strong coupling constant can be measured at the highest energy scales!



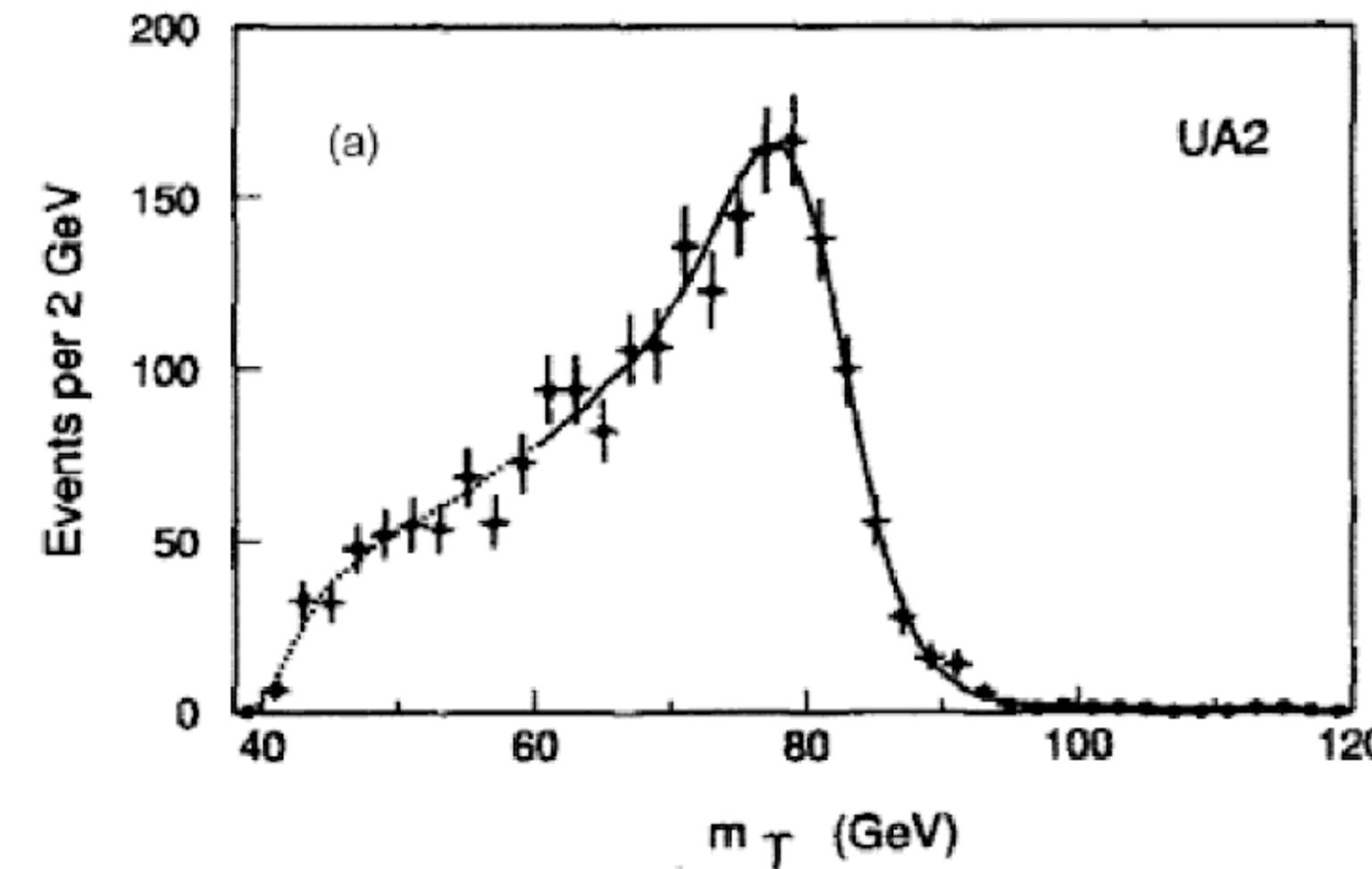
# The Drell Yan $Z/\gamma^*$ production

# The SppS Legacy

32



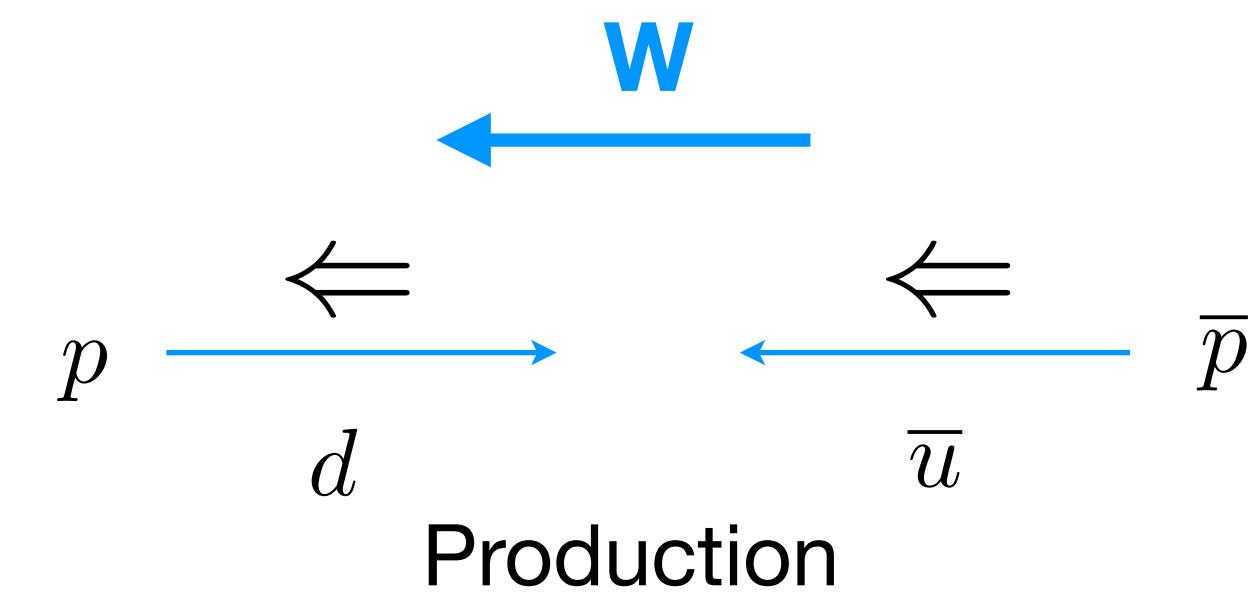
Altogether O(100) Z events



Altogether O(1000) W events

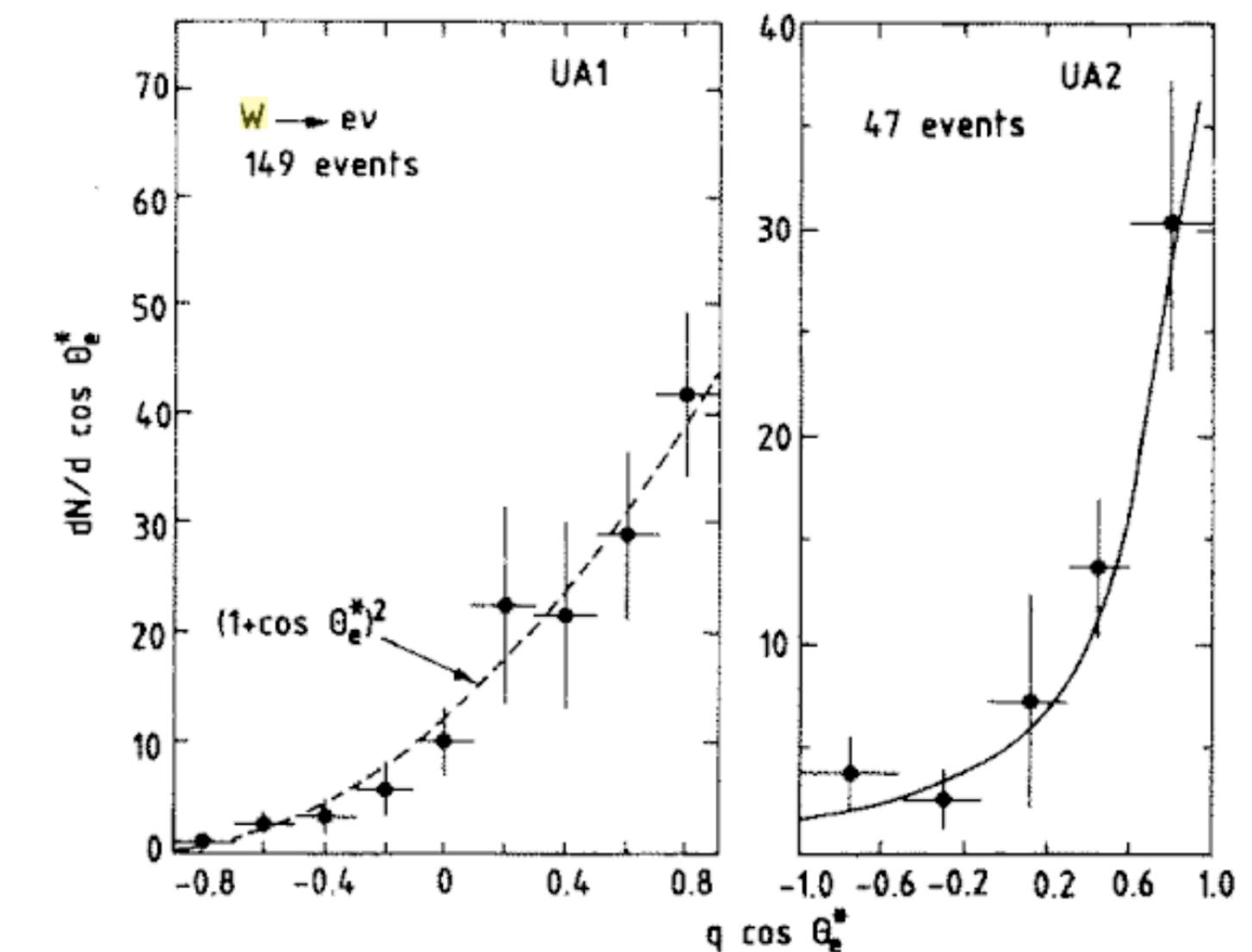
At SppS W production  
dominated by valence quarks

W polarised in the anti-proton  
direction.



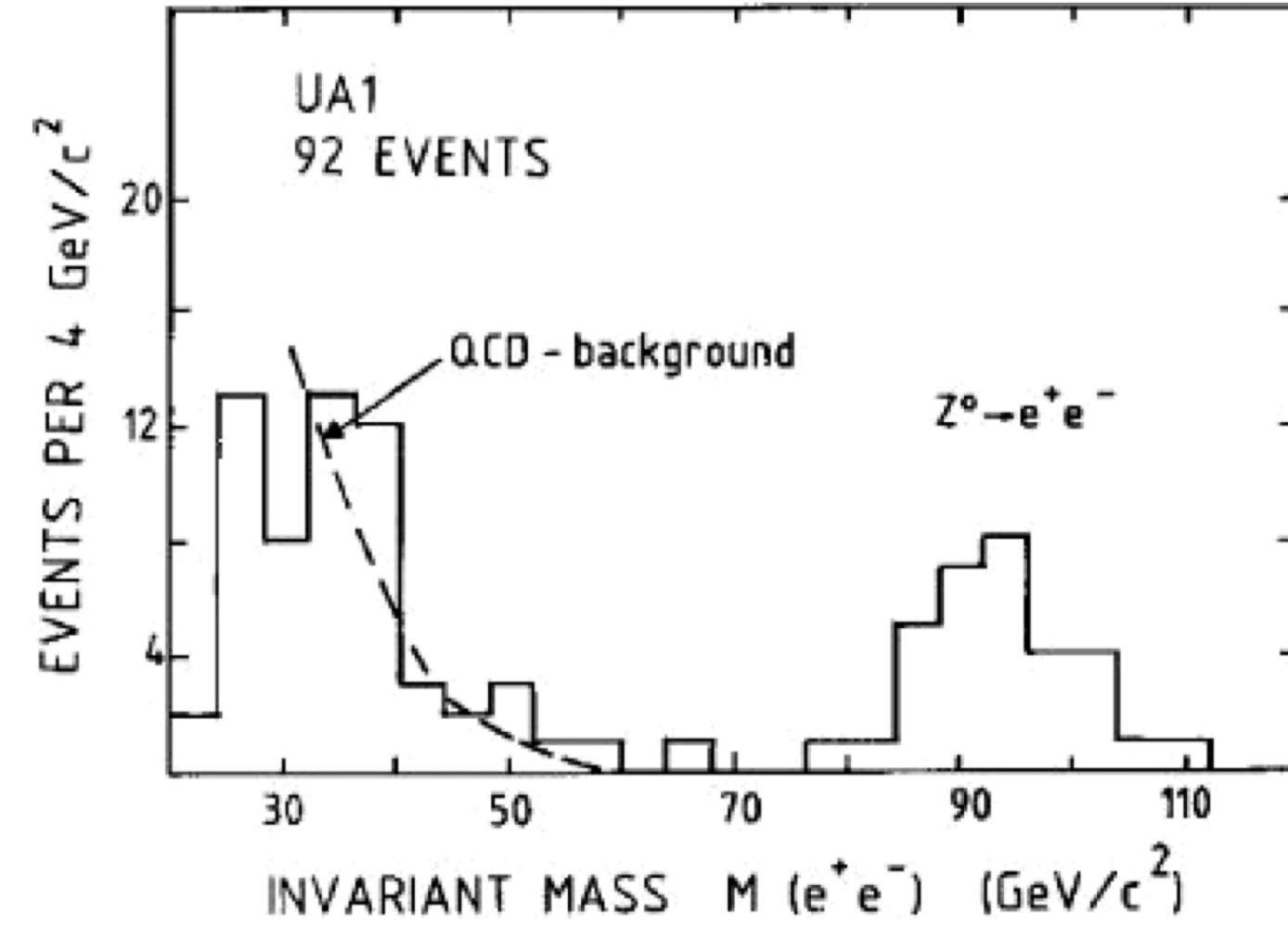
Transverse Mass distribution in UA2

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



# The SppS Legacy

33



**Altogether O(100) Z events**

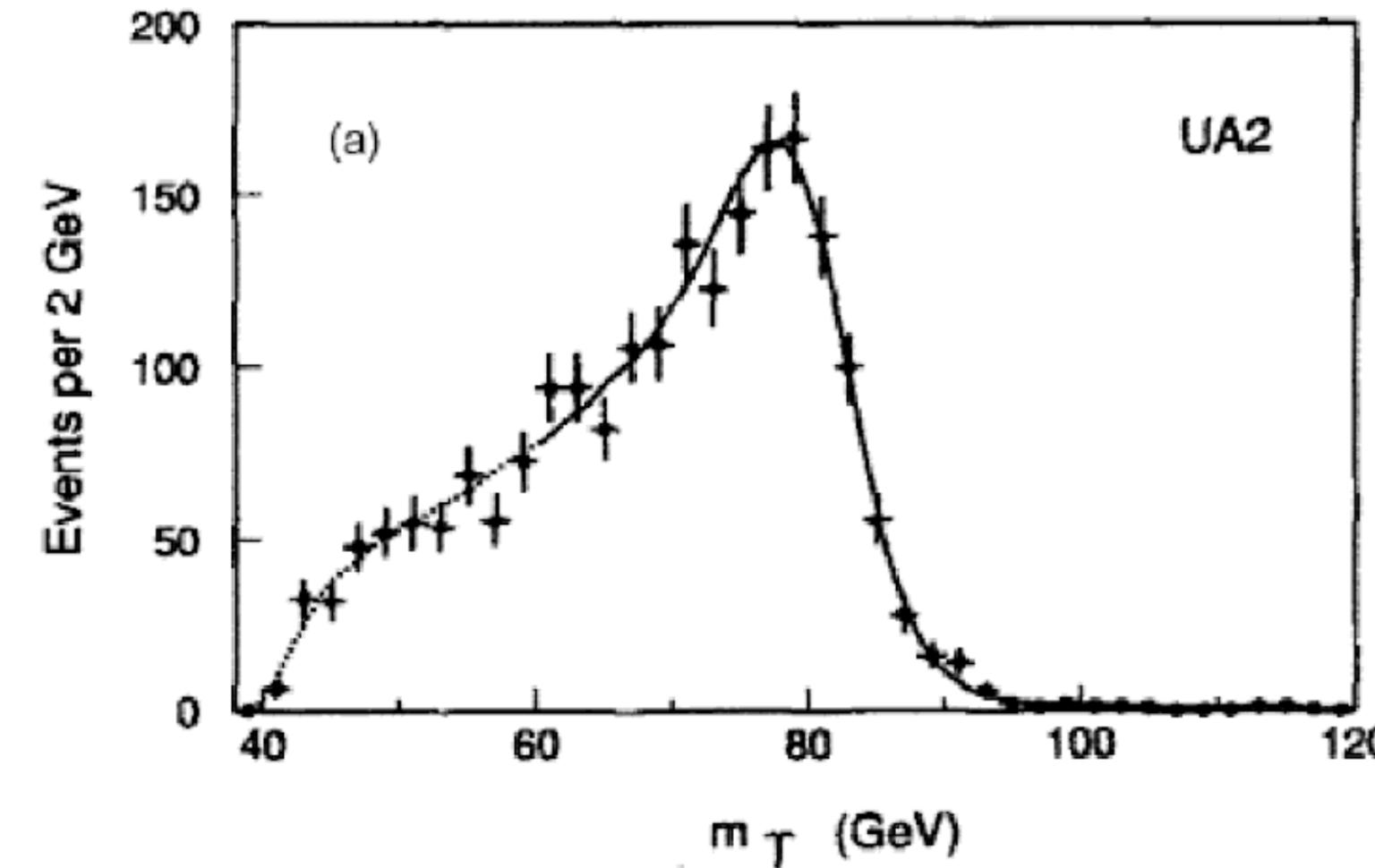
Precision reached:

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

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

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

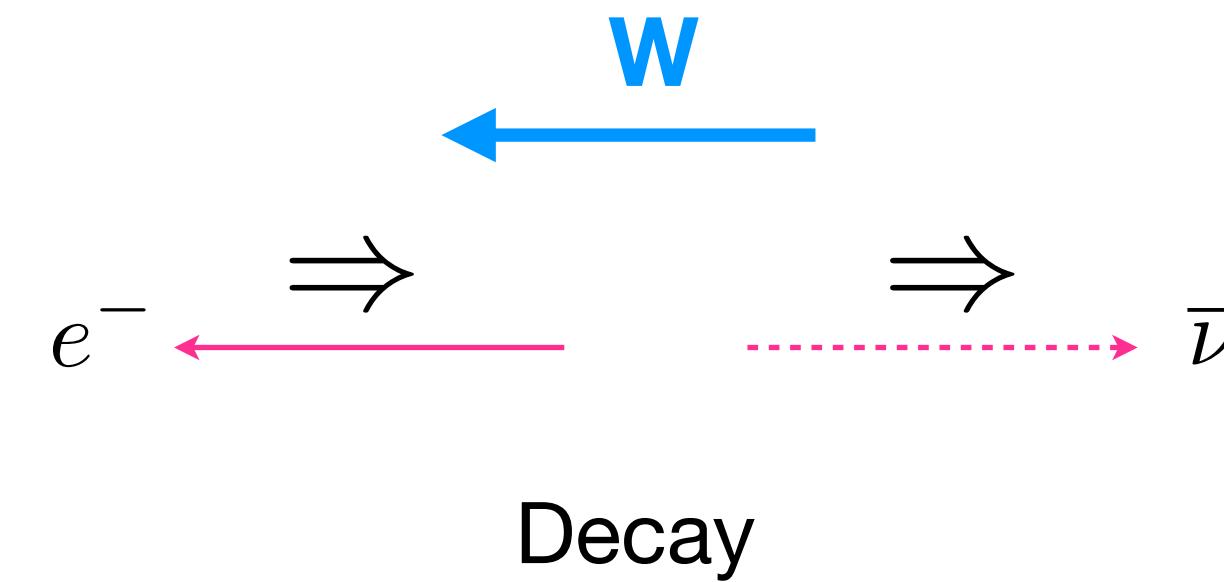
$$\sin^2 \theta_W = 0.226 \pm 0.014 \quad (\text{UA1})$$



**Altogether O(1000) W events**

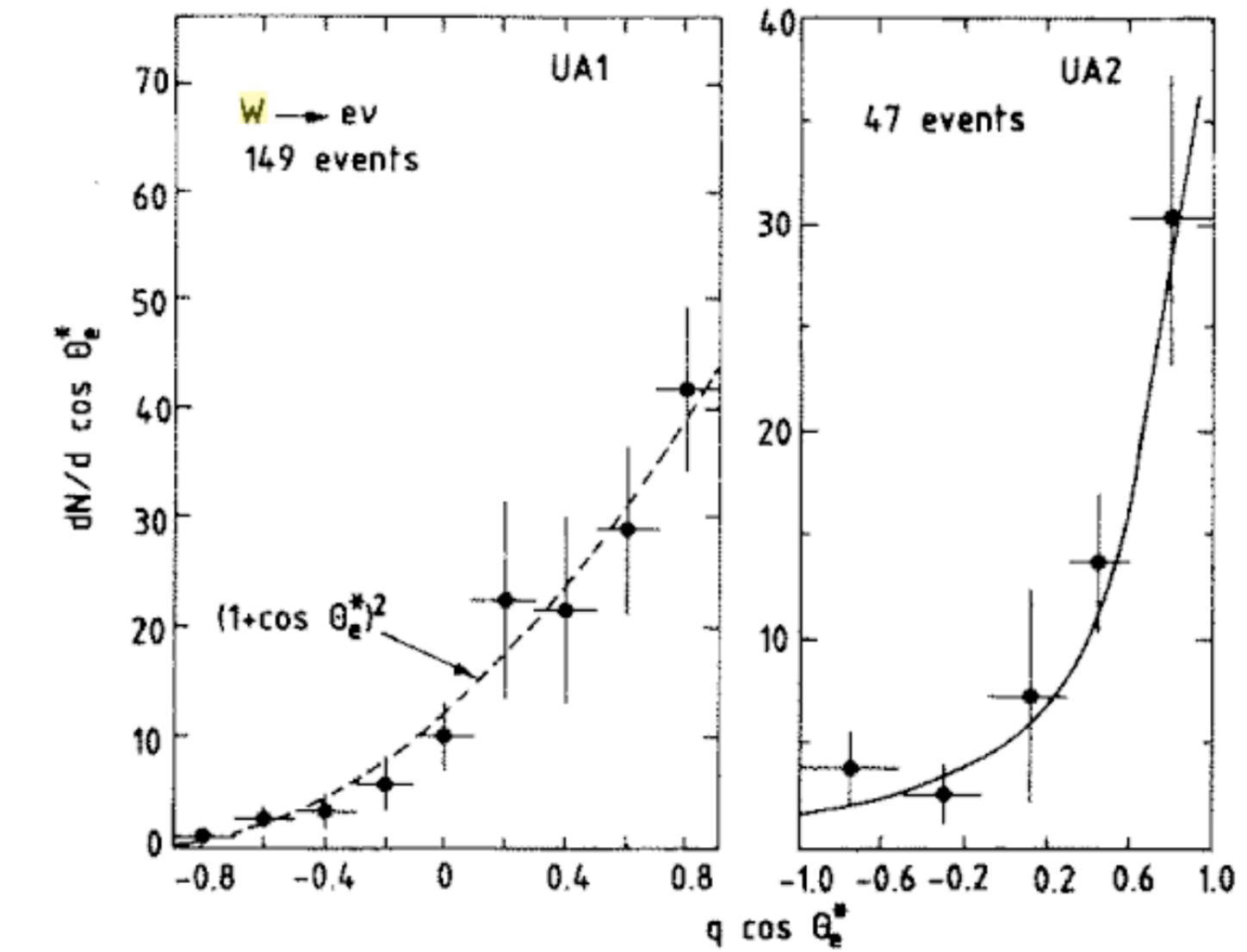
At SppS W production dominated by valence quarks

W polarised in the anti-proton direction.



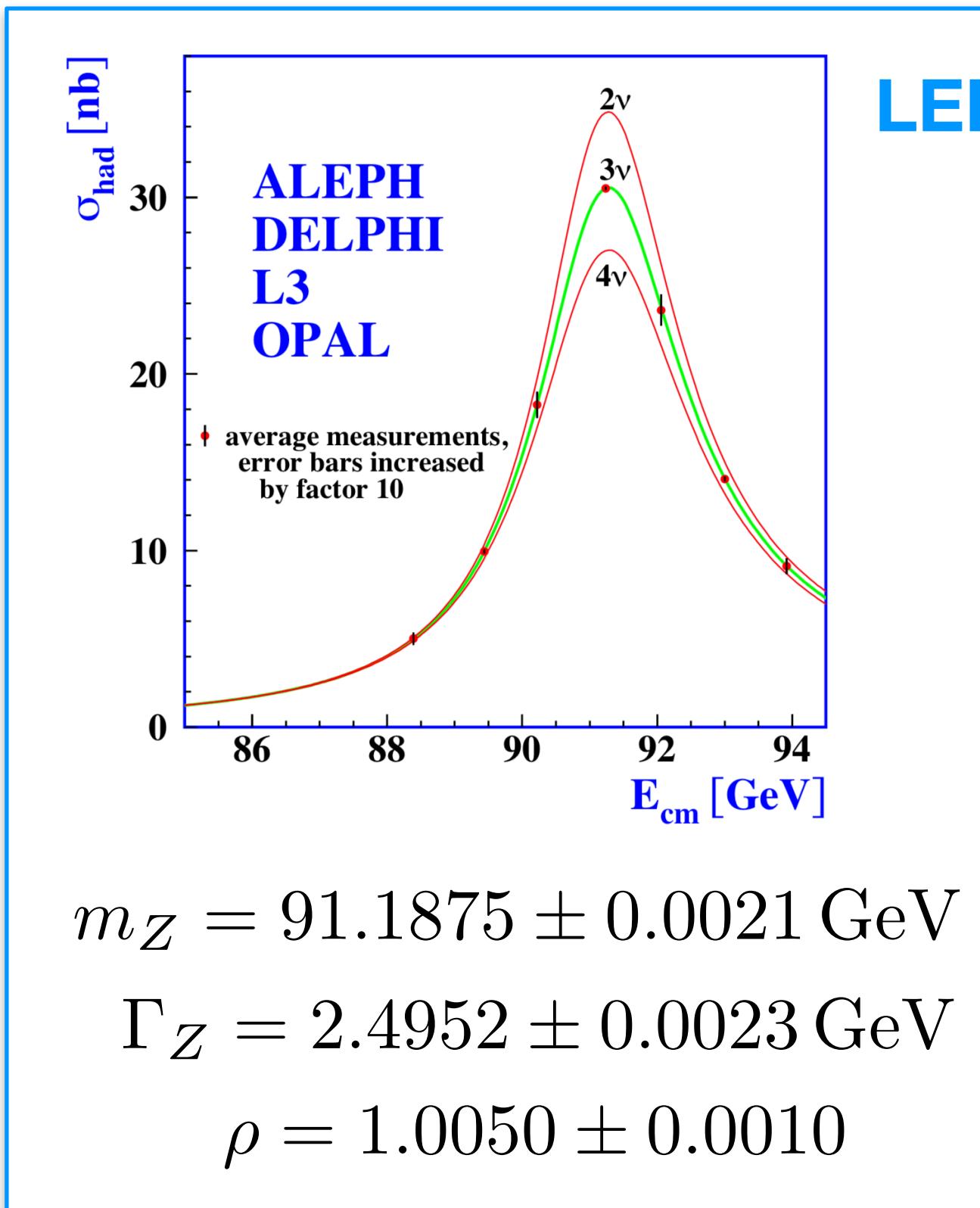
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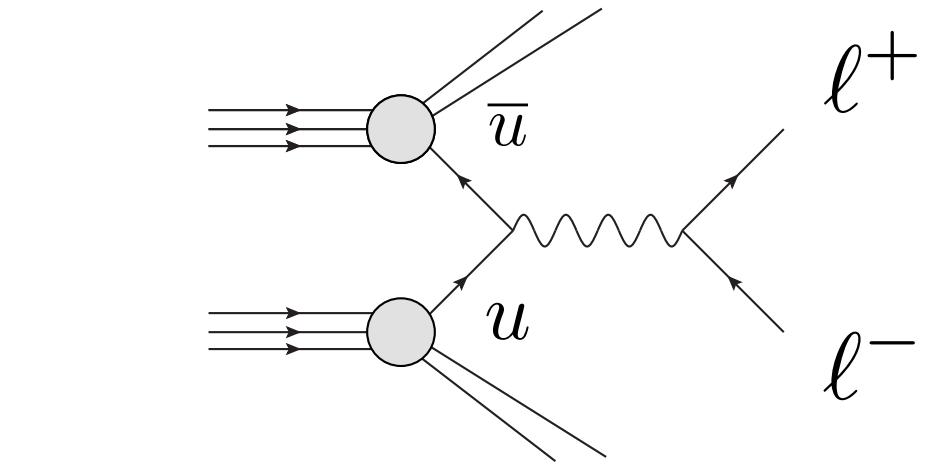
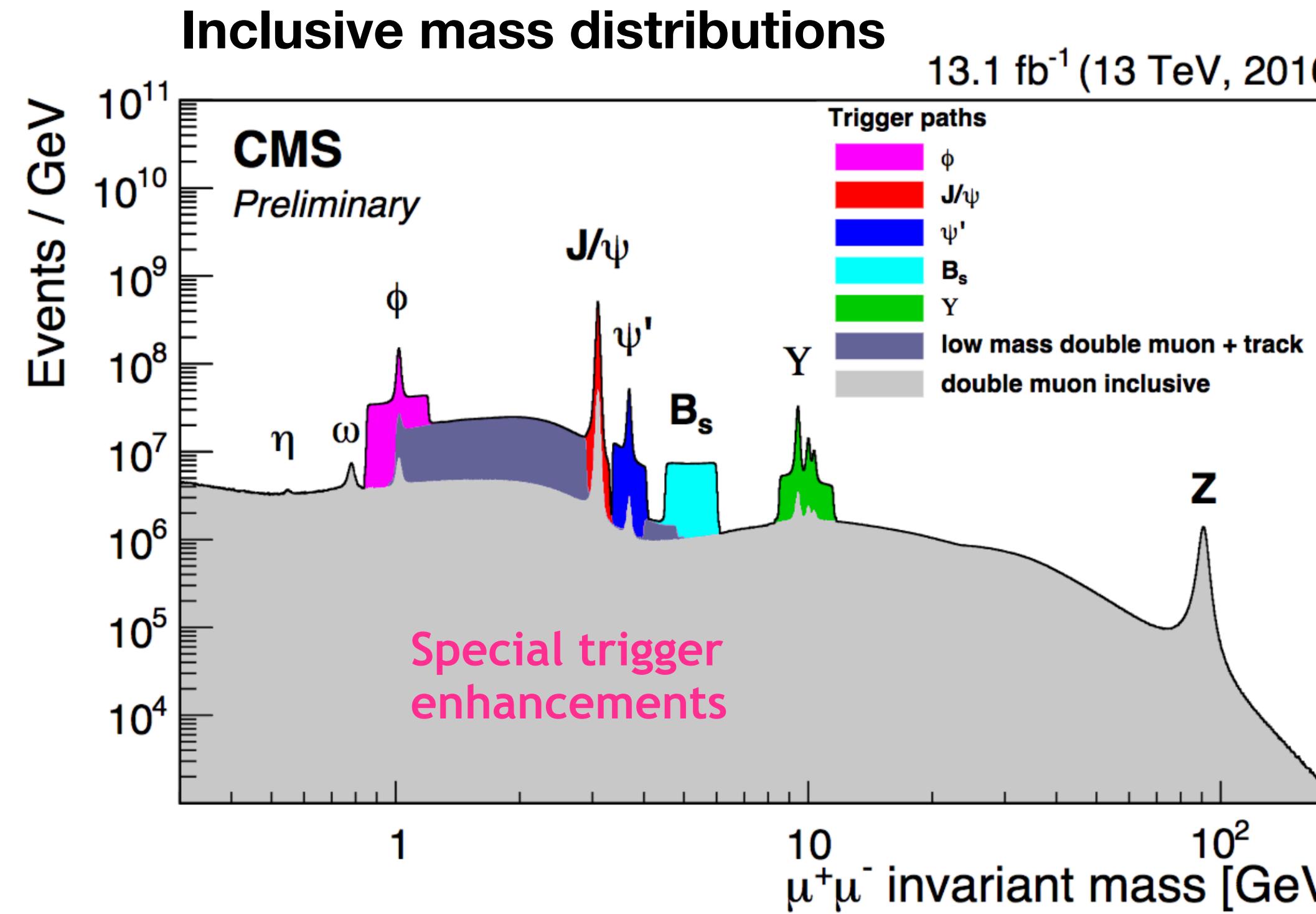


# The di-lepton mass spectrum at LHC

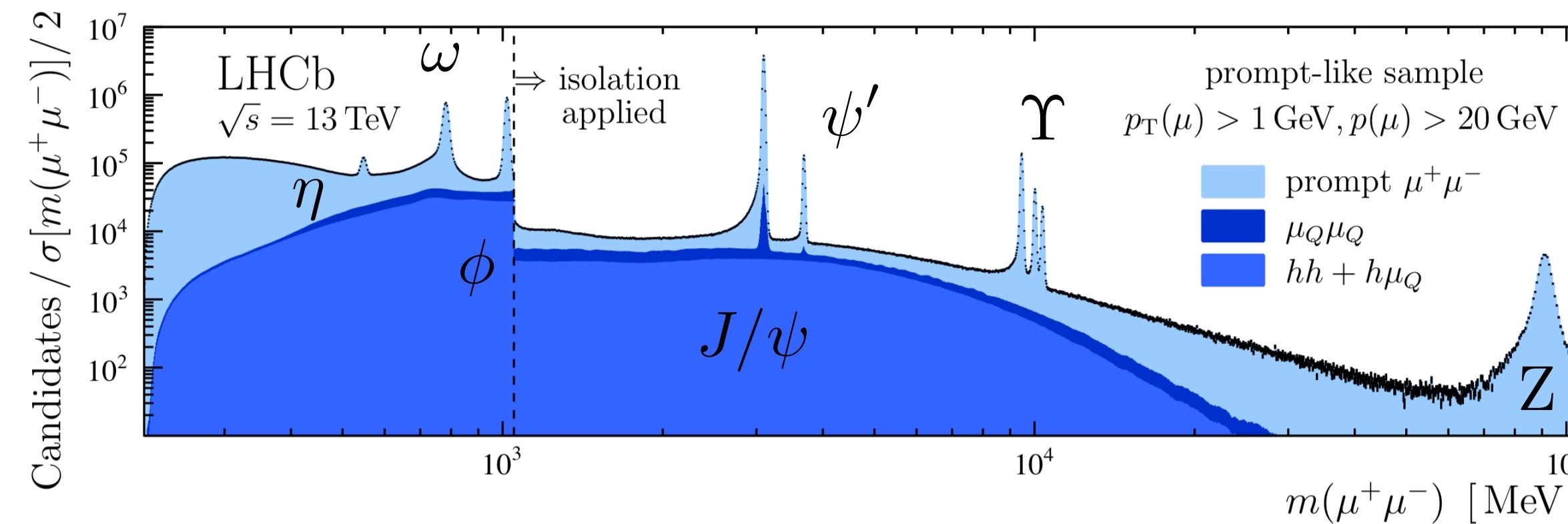
34



At LEP ~4.5M Z per experiment



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



**LHCb** di-muon mass spectrum

8B events produced at LHC

# Composition of Drell Yan production

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## Flavour content of the $pp \rightarrow Z, W^\pm$ process

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

For 13 TeV collisions predictions are:

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

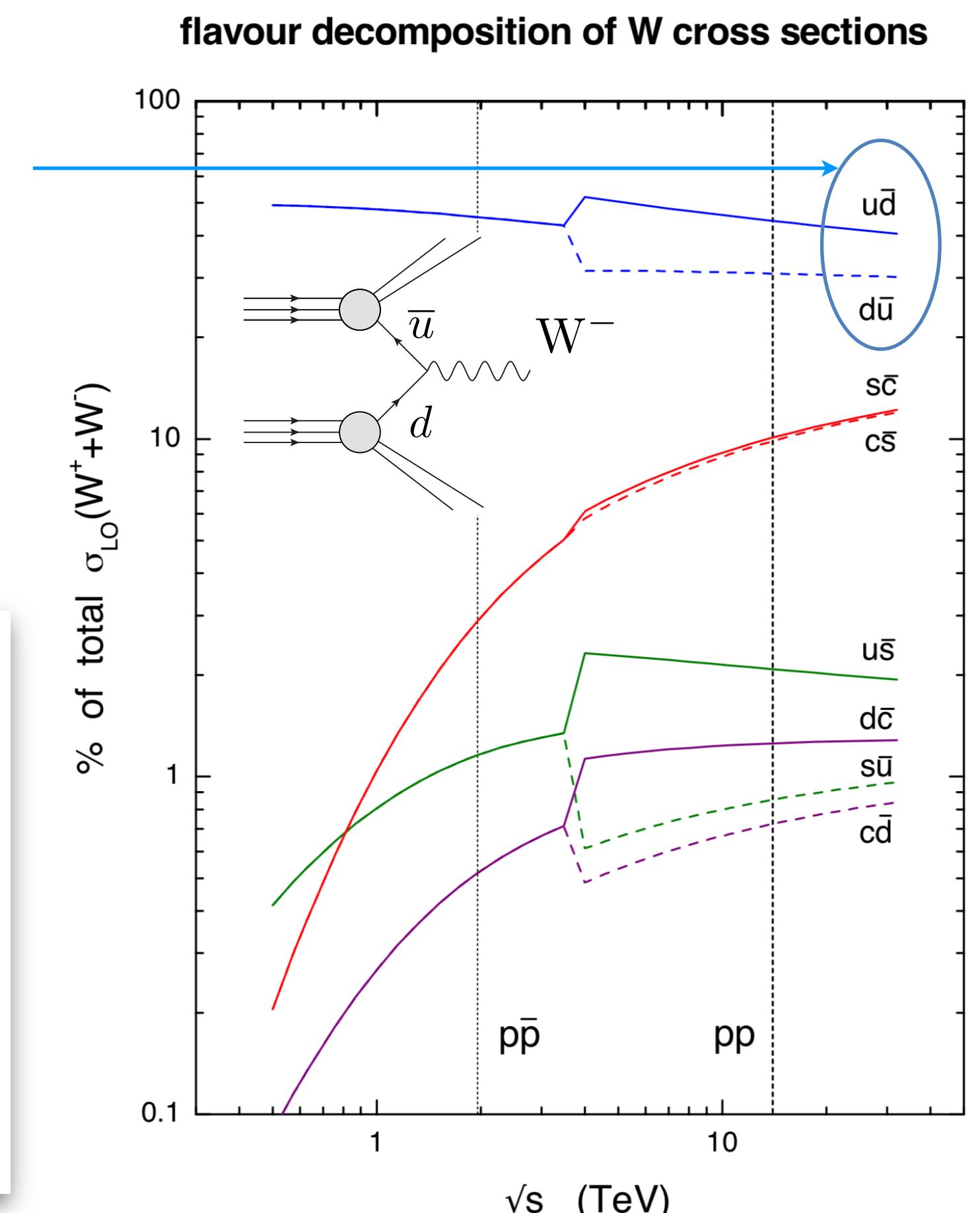
$$\sigma_{W^+} = 11.54^{+0.32}_{-0.31} \text{ (PDF)} \pm 0.22 \text{ (TH)} \text{ nb}$$

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

*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 !!*

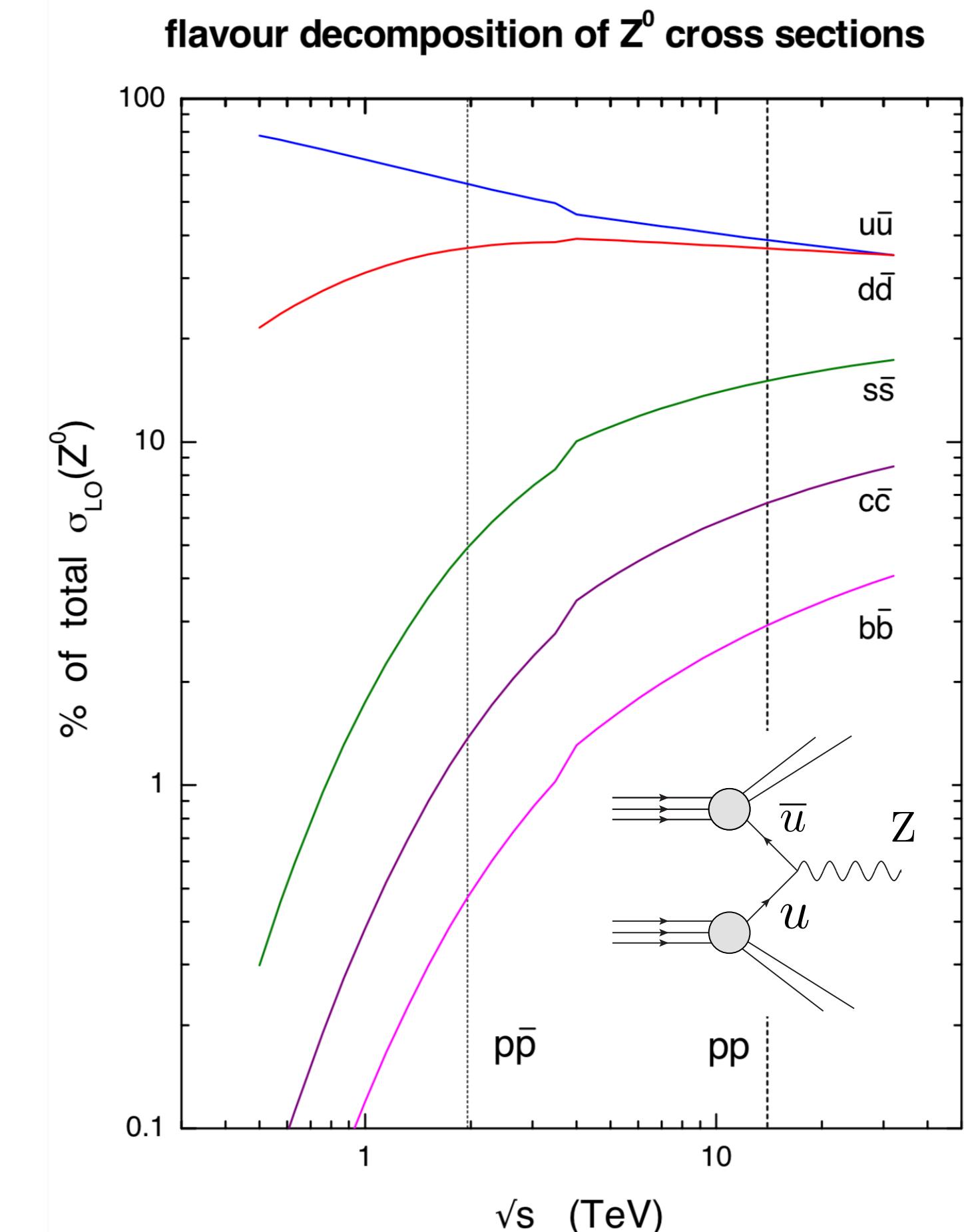


Typically in  $pp$  in leptonic modes

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

$$\text{Br}(W \rightarrow q\bar{q}') \sim 70\%$$

$$\text{Br}(W \rightarrow \ell^\pm \nu) \sim 10\%$$



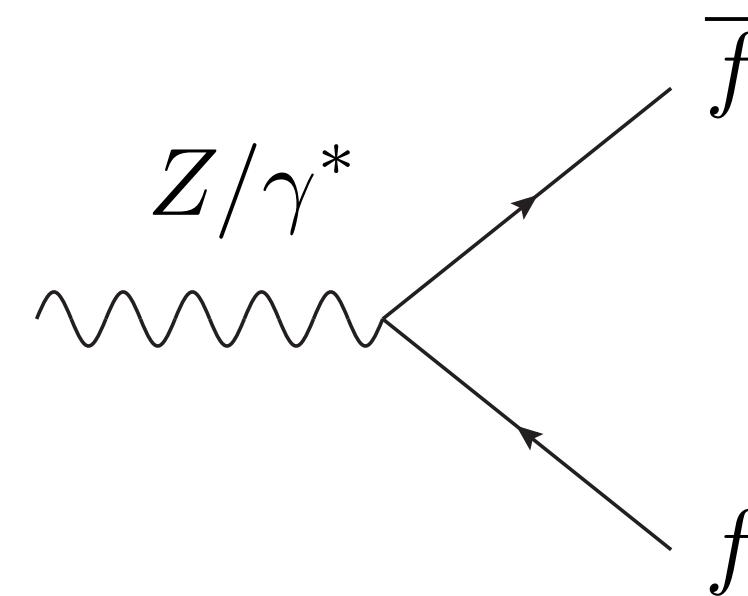
$$\text{Br}(Z \rightarrow \nu\bar{\nu}) \sim 20\%$$

$$\text{Br}(Z \rightarrow q\bar{q}) \sim 70\%$$

$$\text{Br}(Z \rightarrow \ell^+\ell^-) \sim 3\%$$

# Forward Backward Asymmetry in pp Collisions

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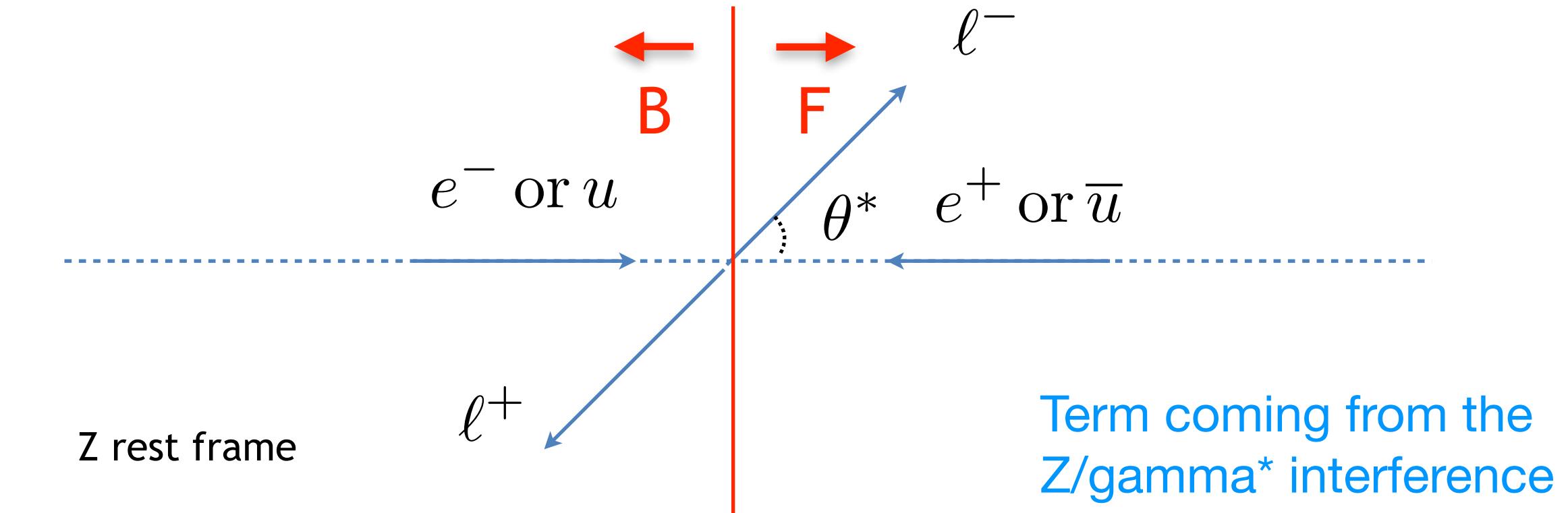


$$\cdot \bar{f} \gamma^\mu (R_f(1 + \gamma^5) + L_f(1 - \gamma^5)) f Z_\mu$$

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

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

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



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

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

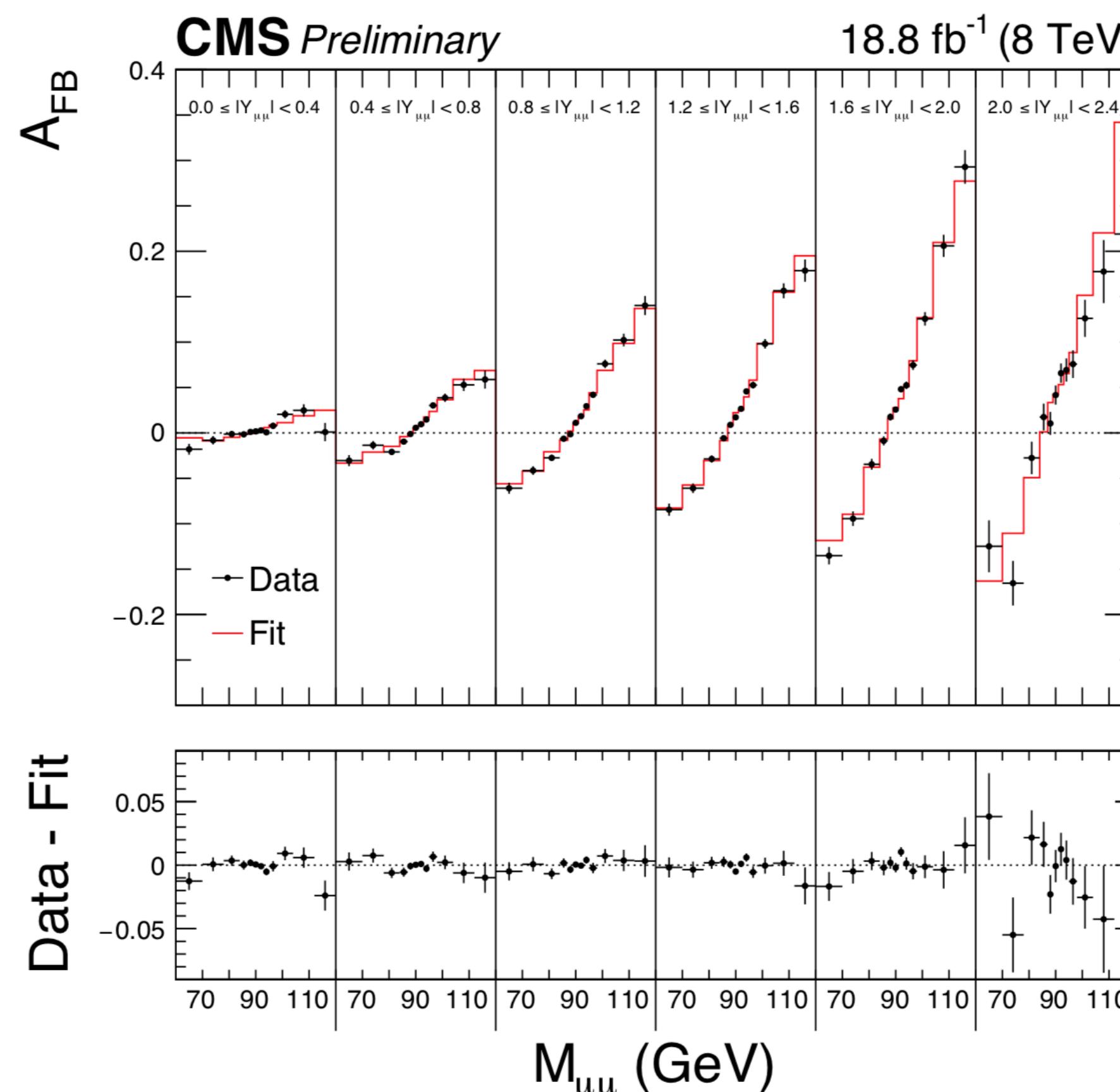
**In  $e^+e^-$  collisions the FB asymmetry is obvious as the direction of the incoming electron w.r.t. positron is known:** what is the direction of the quark with respect to the direction of the anti-quark?

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.

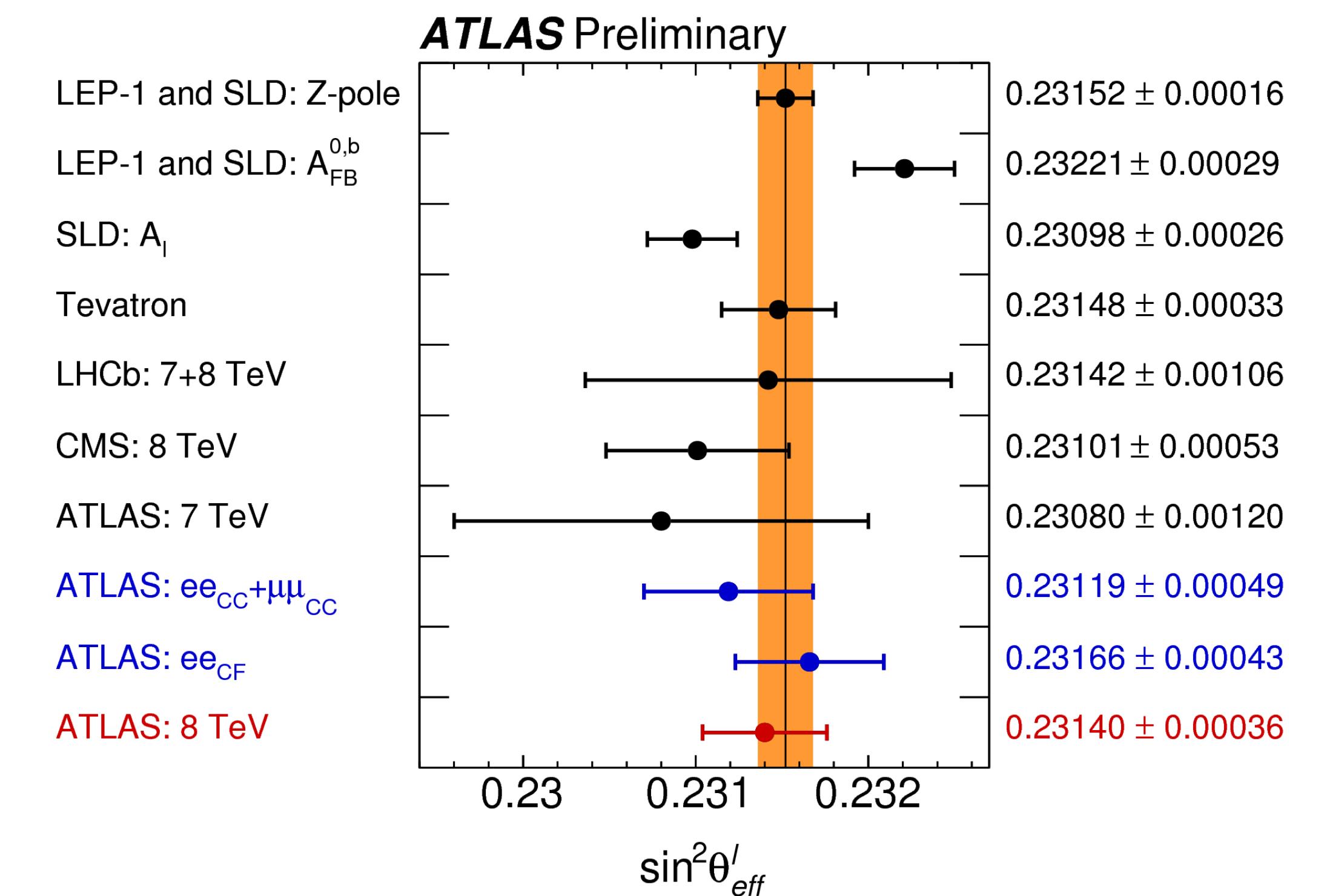
# Measurement of effective weak mixing angle at the LHC

37

Once the reference frame is defined, the Forward backward asymmetry can be straightforwardly measured, 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).

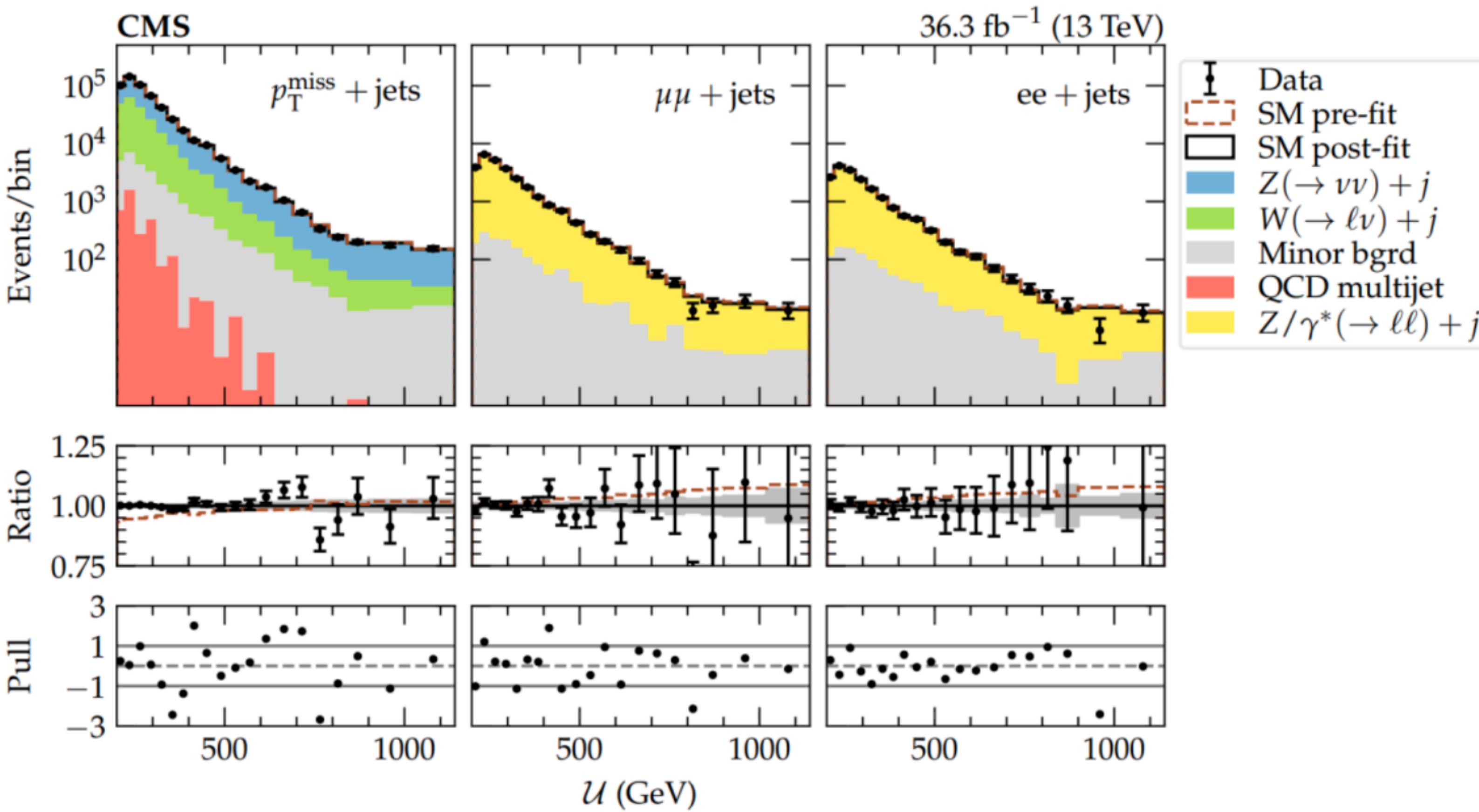


Latest ATLAS result using forward electrons up to eta of 4.9.  
 $\sin^2 \theta_{\text{eff}}^\ell = 0.23140 \pm 0.00021 \text{ (stat)}$   
 $\pm 0.00024 \text{ (PDFs)} \pm 0.00016 \text{ (syst)}$

# Precise direct invisible Z Width by CMS!

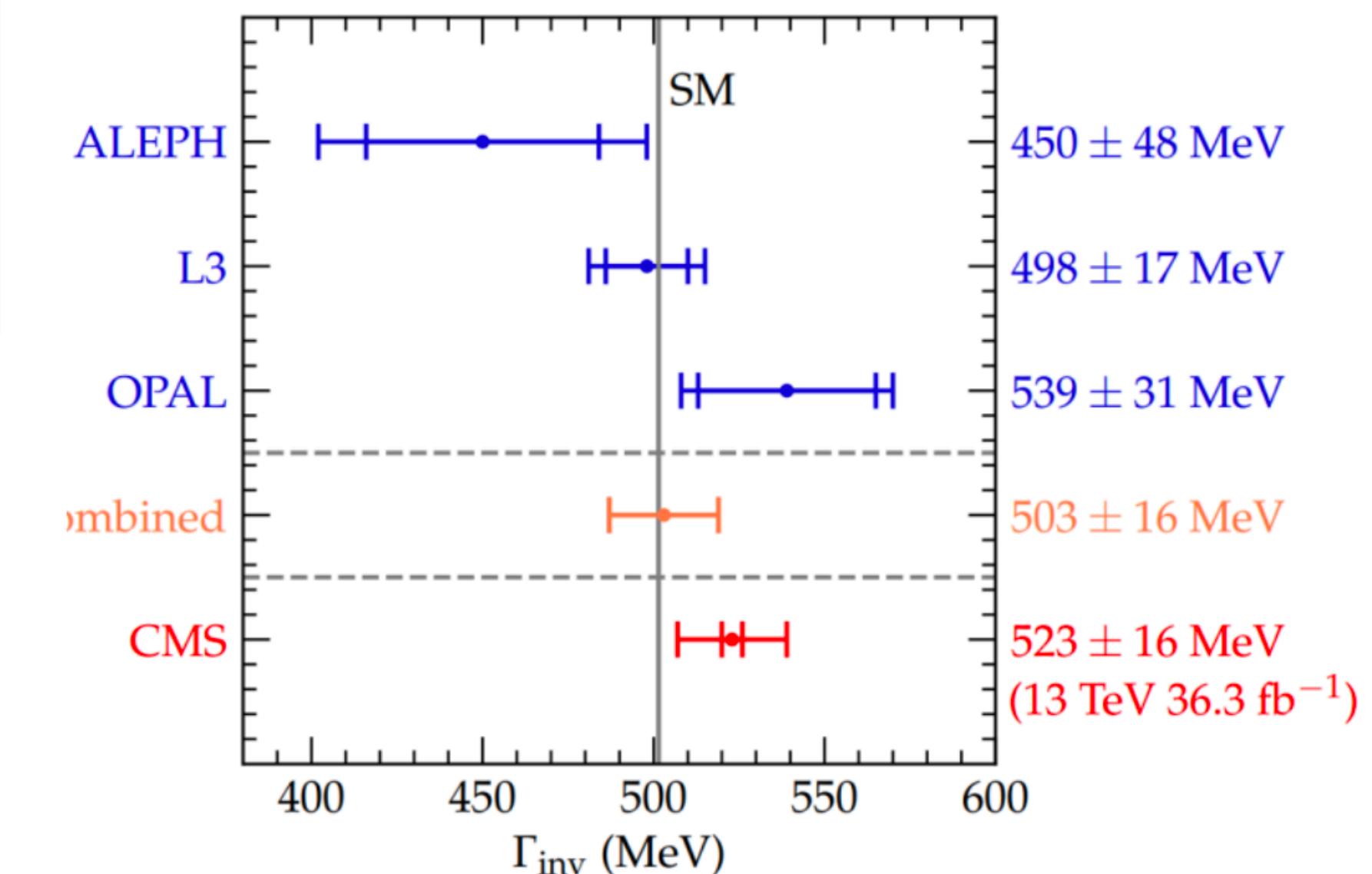
38

Measurement based on missing transverse momentum



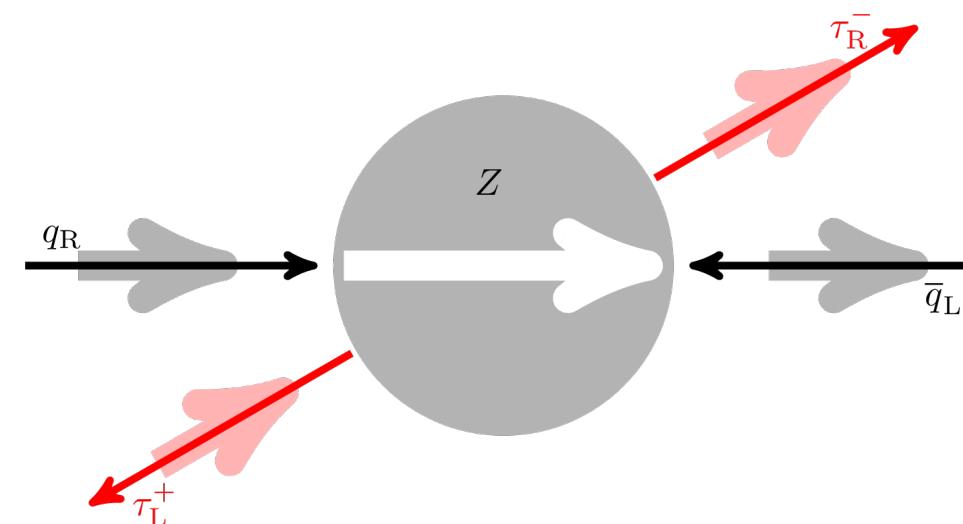
$$\Gamma_{\text{inv}} = 523 \pm 3 \text{ (stat)} \pm 16 \text{ (syst)} \text{ MeV}$$

Measurement already dominated by systematic uncertainties!



# Tau Polarisation in Z Decays - CMS

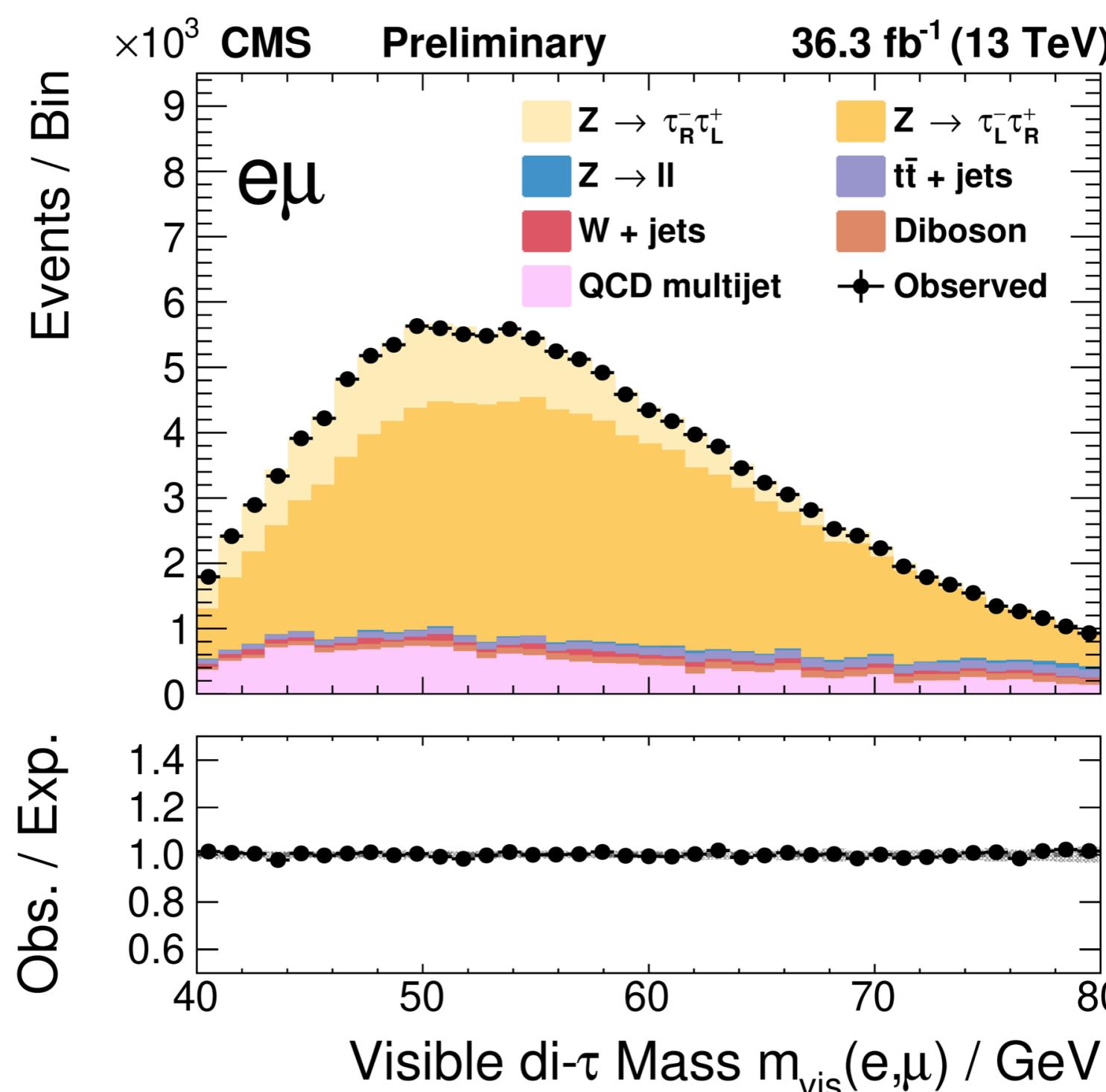
39



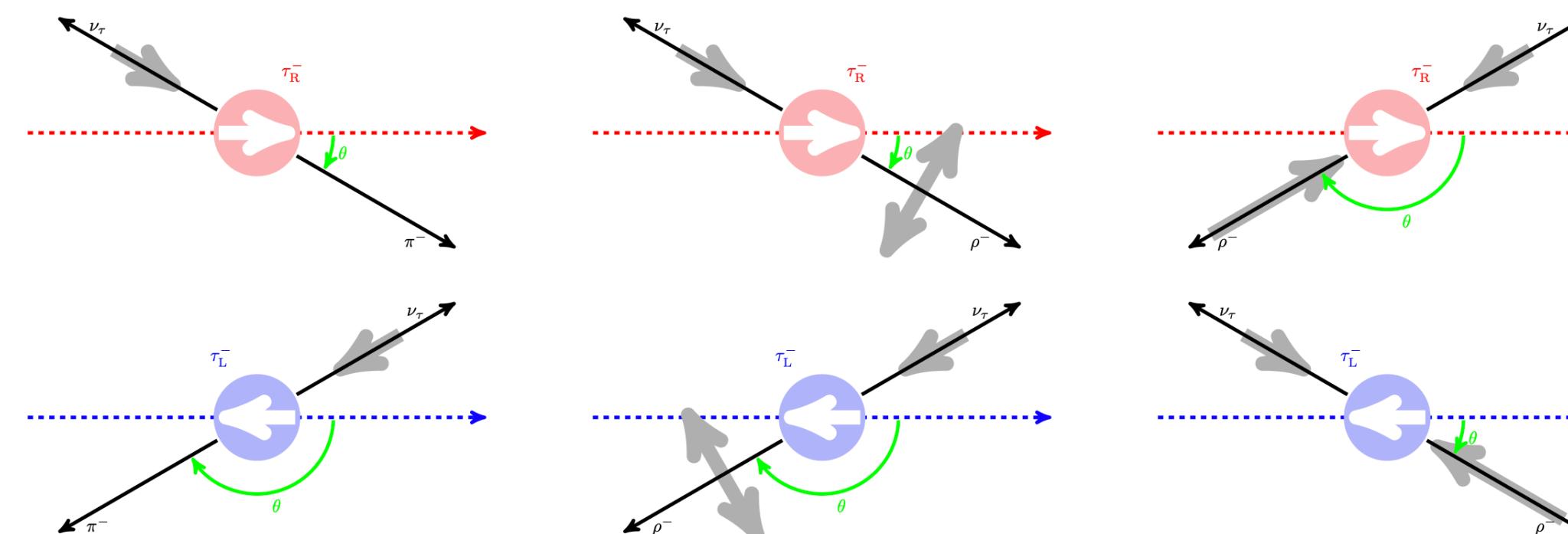
Measurement relies in measuring the fraction of tau helicity states, using polarisation sensitive variables! Using both leptonic and hadronic taus decays.

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

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



Energy and angular variables are used!



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

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

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

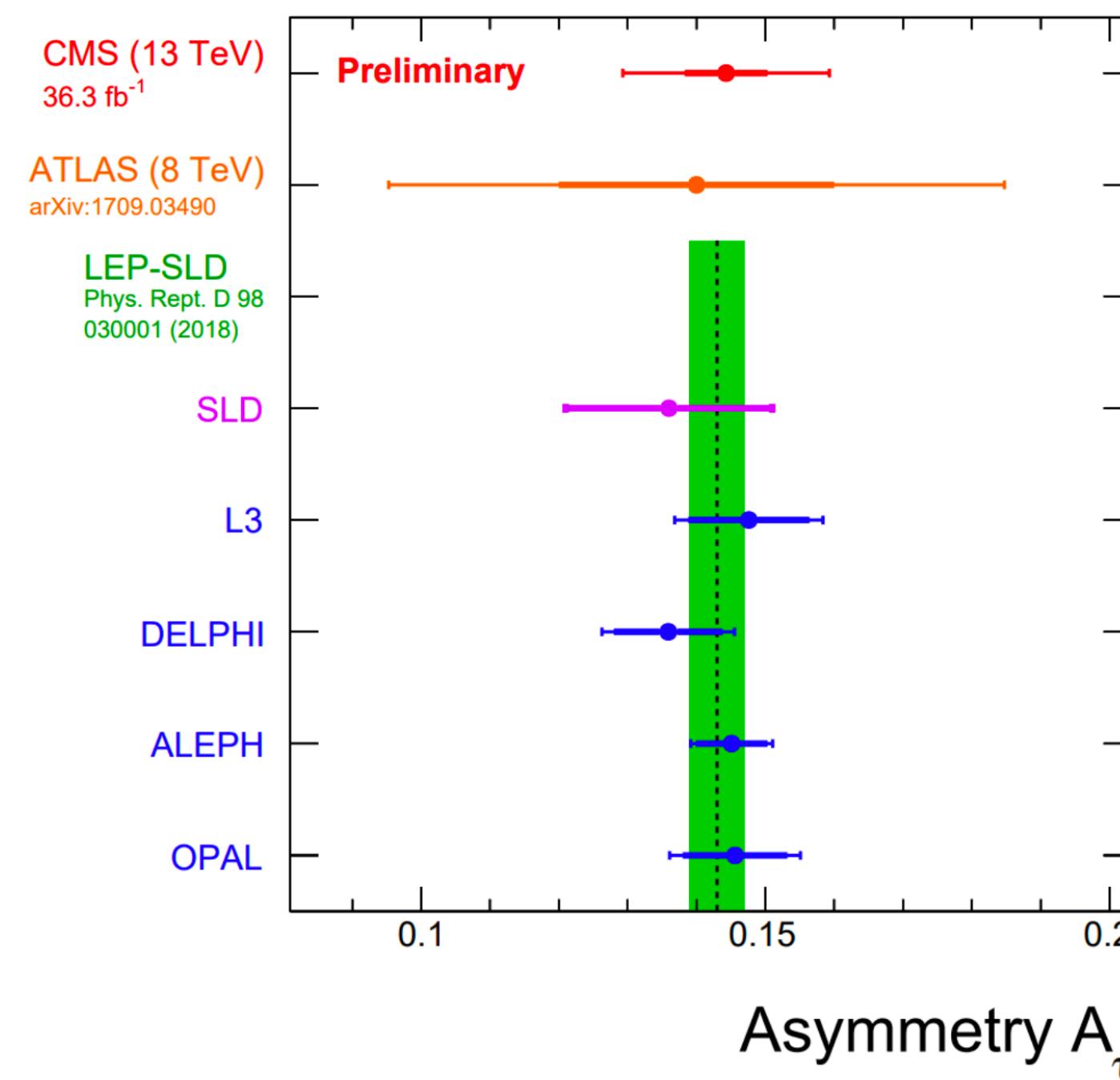
For R-Tau lepton the V (V = rho, a1) resonance tends to be longitudinal ( $\lambda V = 0$ ). Conversely, for L-Tau is left-handed, the V tends to be transverse,  $\lambda V = -1$ .

# Tau Polarisation in Z Decays - CMS

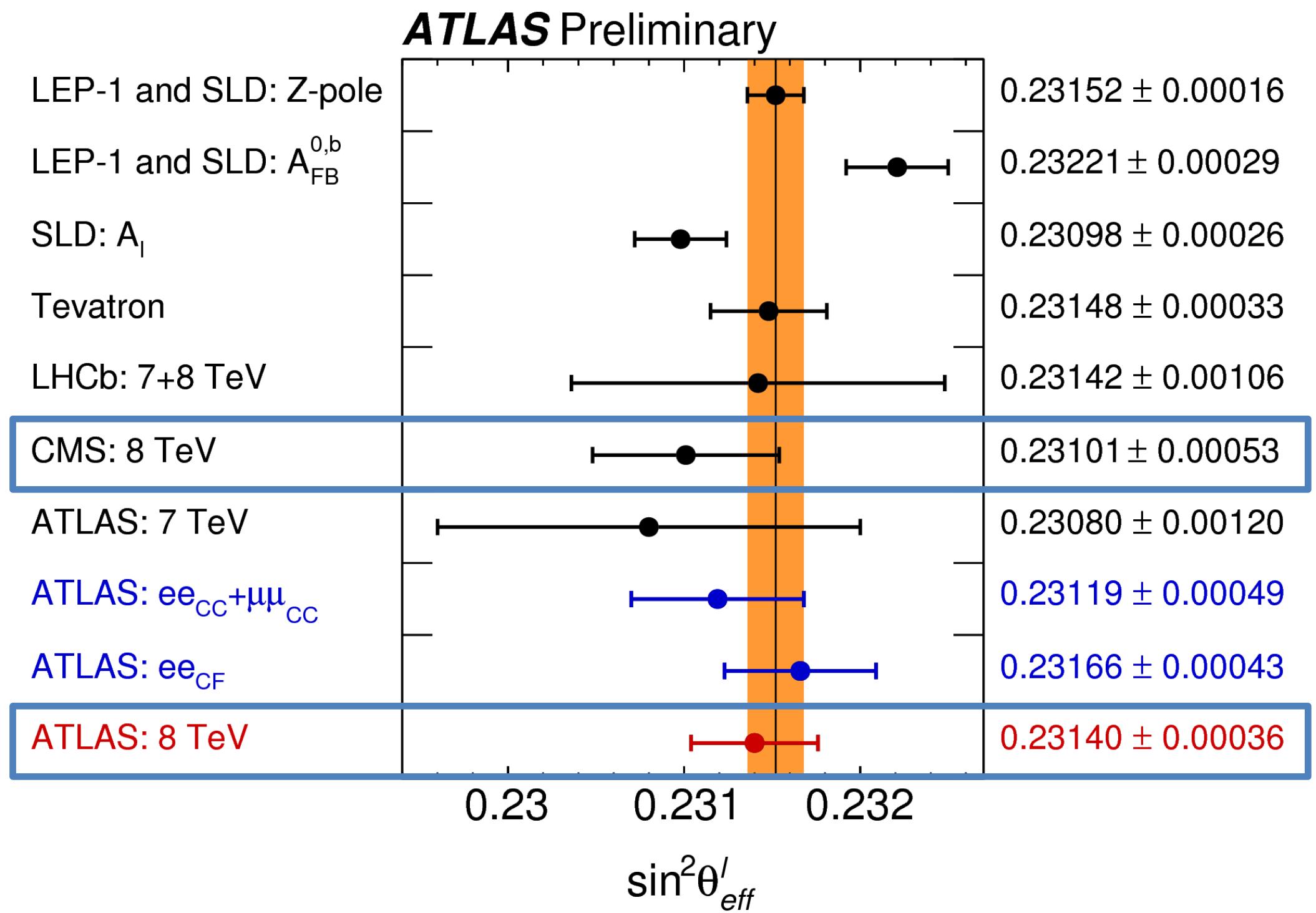
40

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

New CMS measurement with partial Run 2 dataset  
comparable precision as measurements at  $e^+e^-$  colliders



Measurement already dominated by systematic uncertainties already! But...



ATLAS and CMS measurements in  $e^+e^-$  and  $\mu^+\mu^-$  final states dominate the precision.

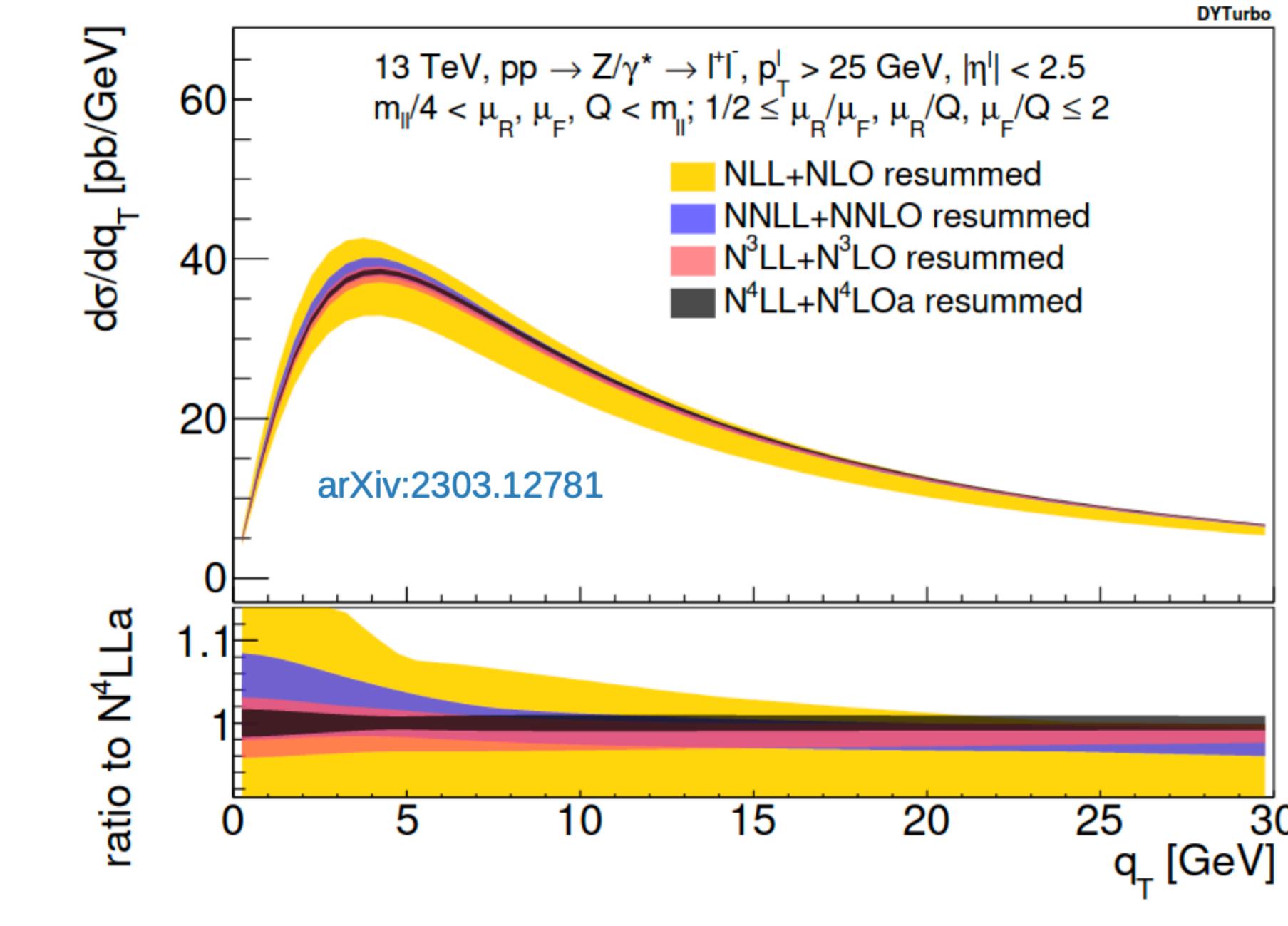
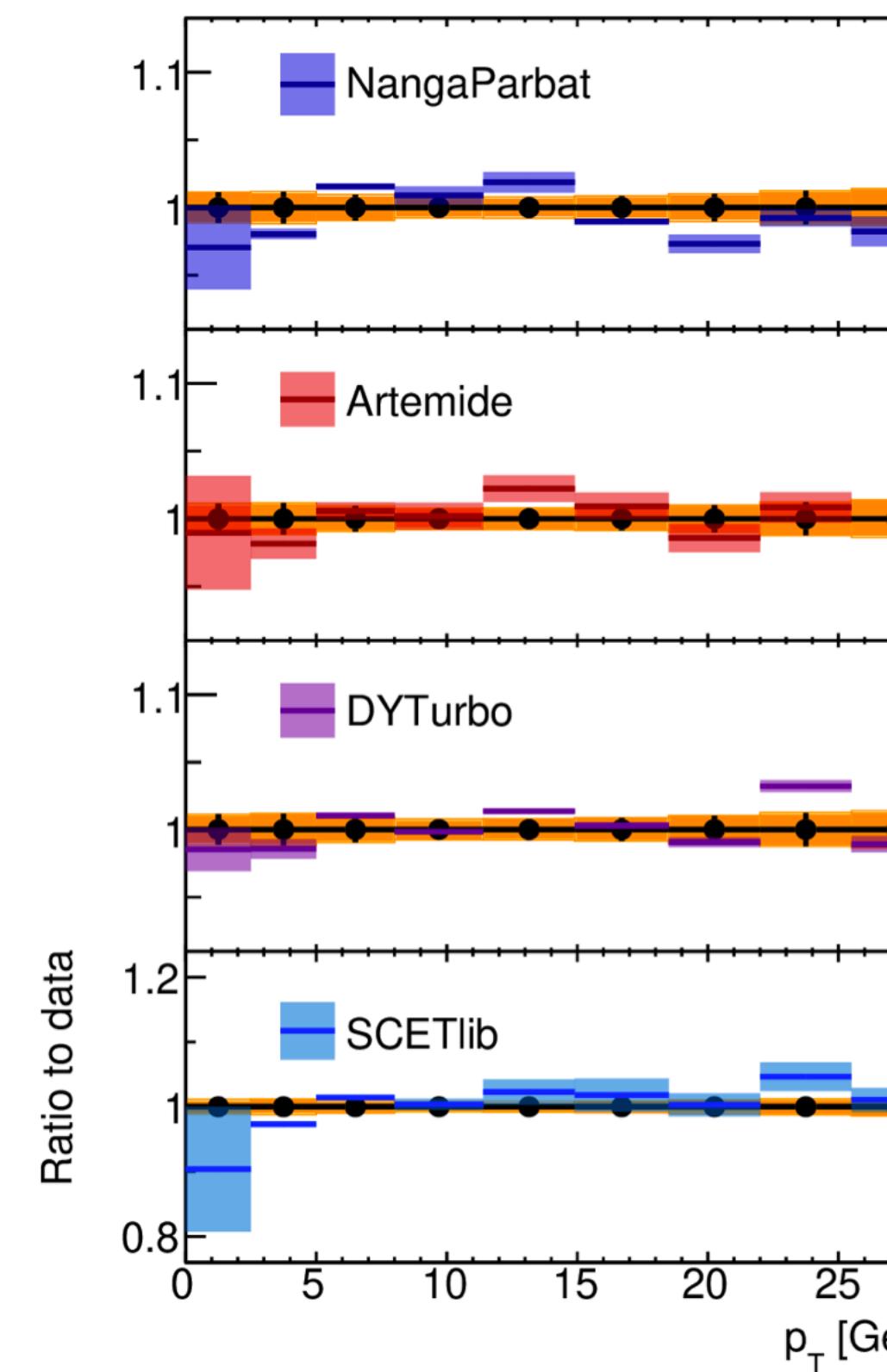
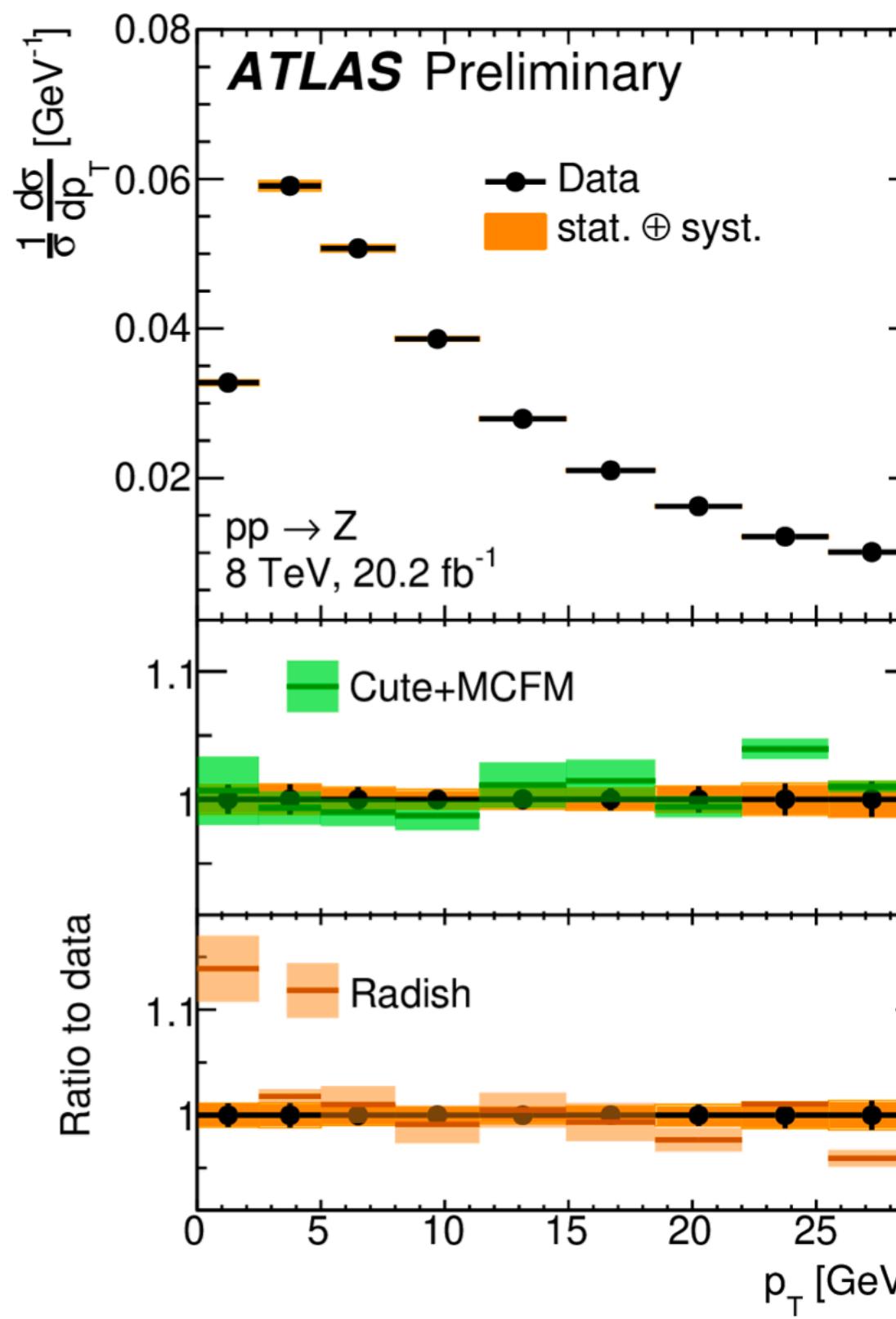
PDF uncertainties are dominant in this measurement!

# Precise Determination of $\alpha_S$ - ATLAS

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

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

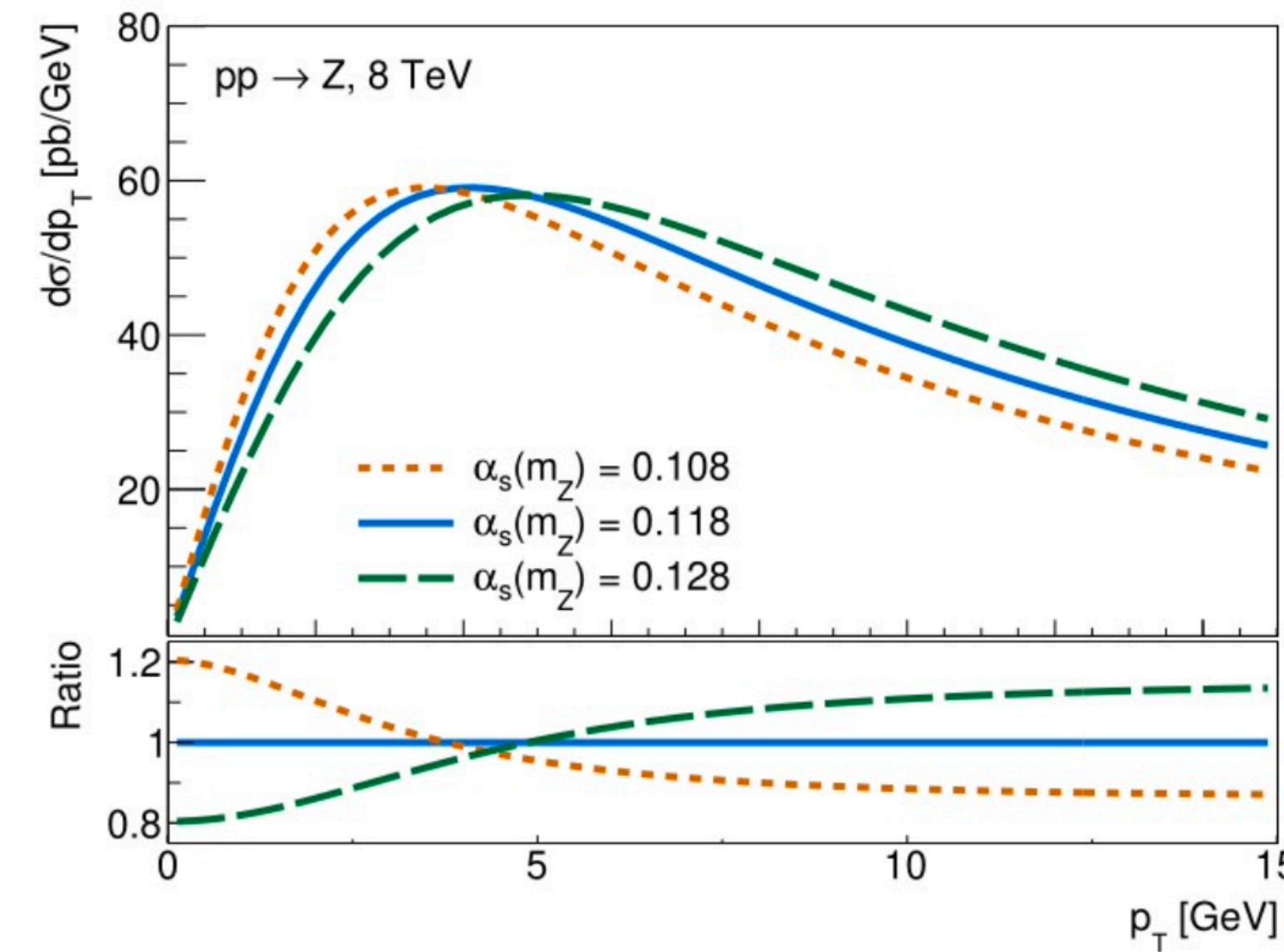
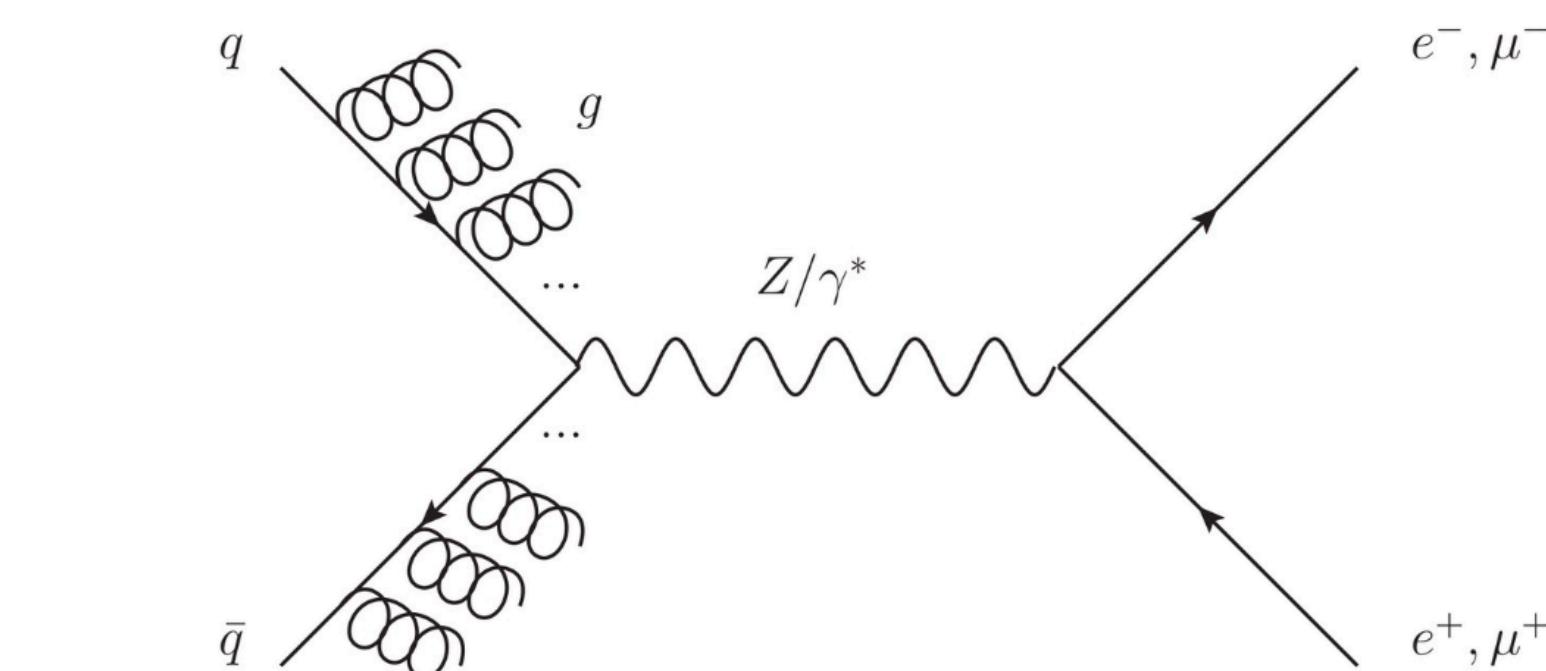
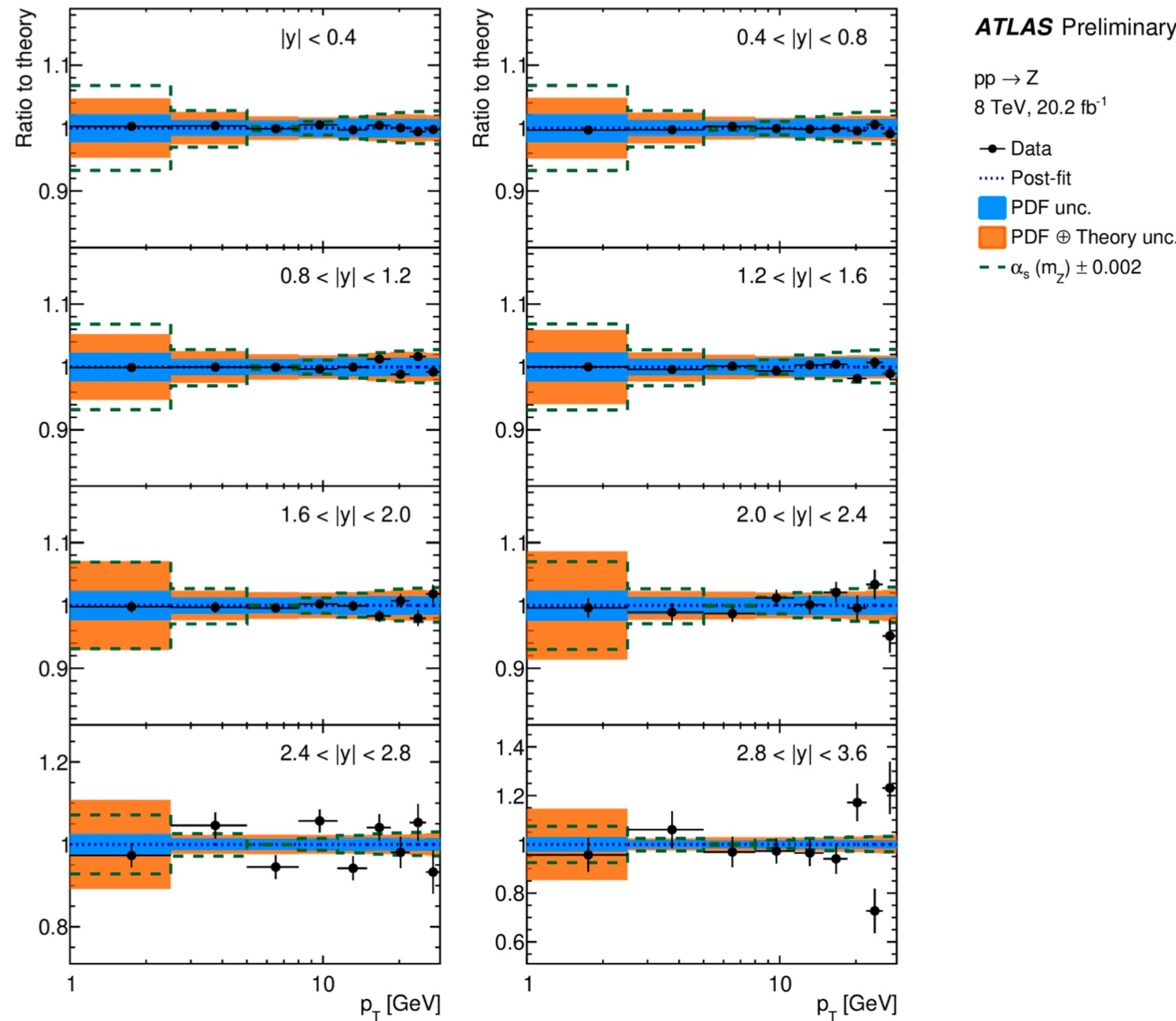


Comparisons done at N3LO-N4LL with N3LO PDFs

# Precise Determination of $\alpha_S$ - ATLAS

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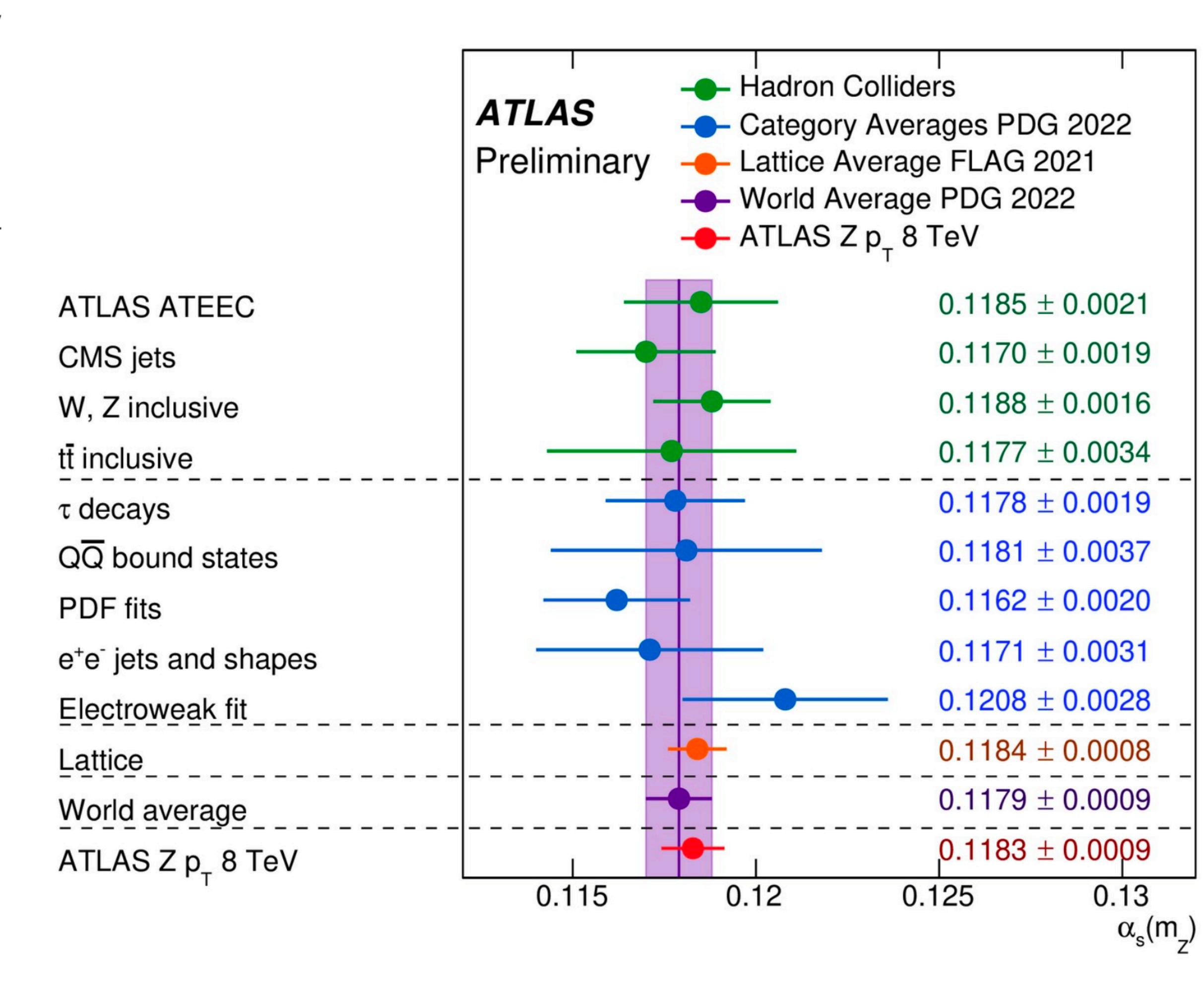
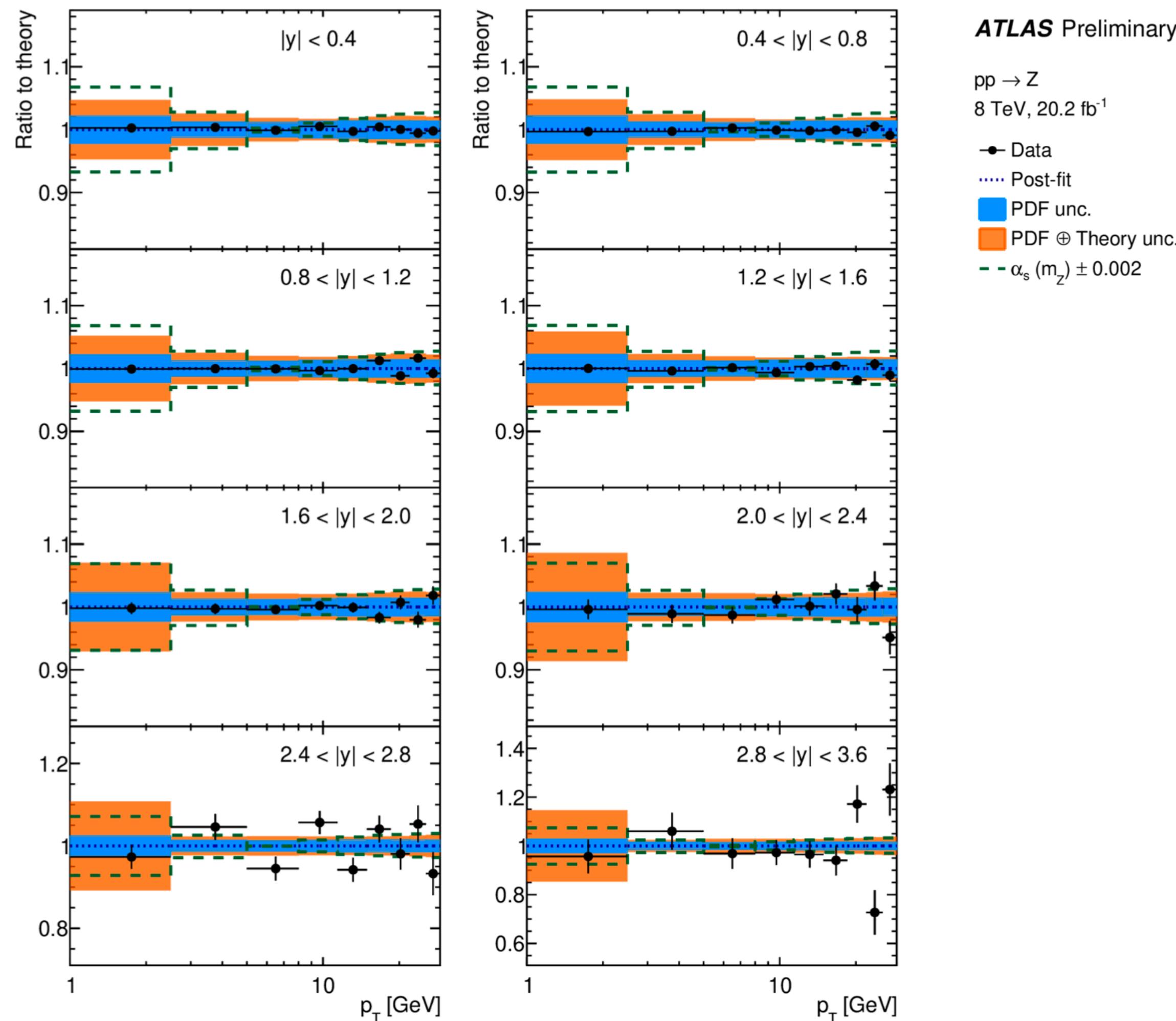
Most precise determination of  $\alpha_S$  based on the Sudakov peak, first measurement based on resummation



# Precise Determination of $\alpha_S$ - ATLAS

43

Most precise determination of  $\alpha_S$  based on the Sudakov peak, first measurement based on resummation



# 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!

