Measurements with W and Z bosons at LHC

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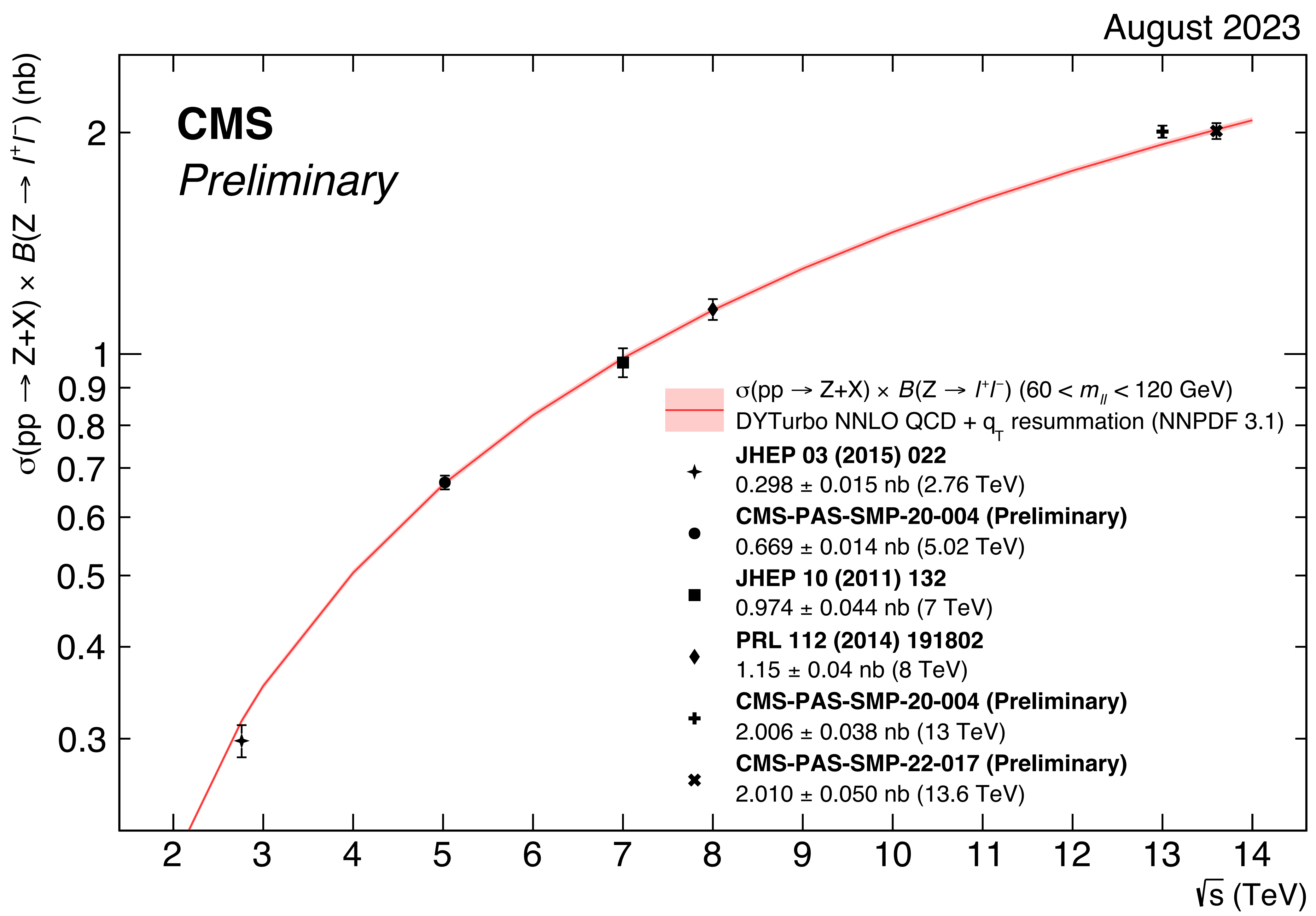
On behalf of ATLAS, CMS and LHCb collaborations

Electroweak milestones - 50 years of neutral currents, 40 years of W and Z bosons

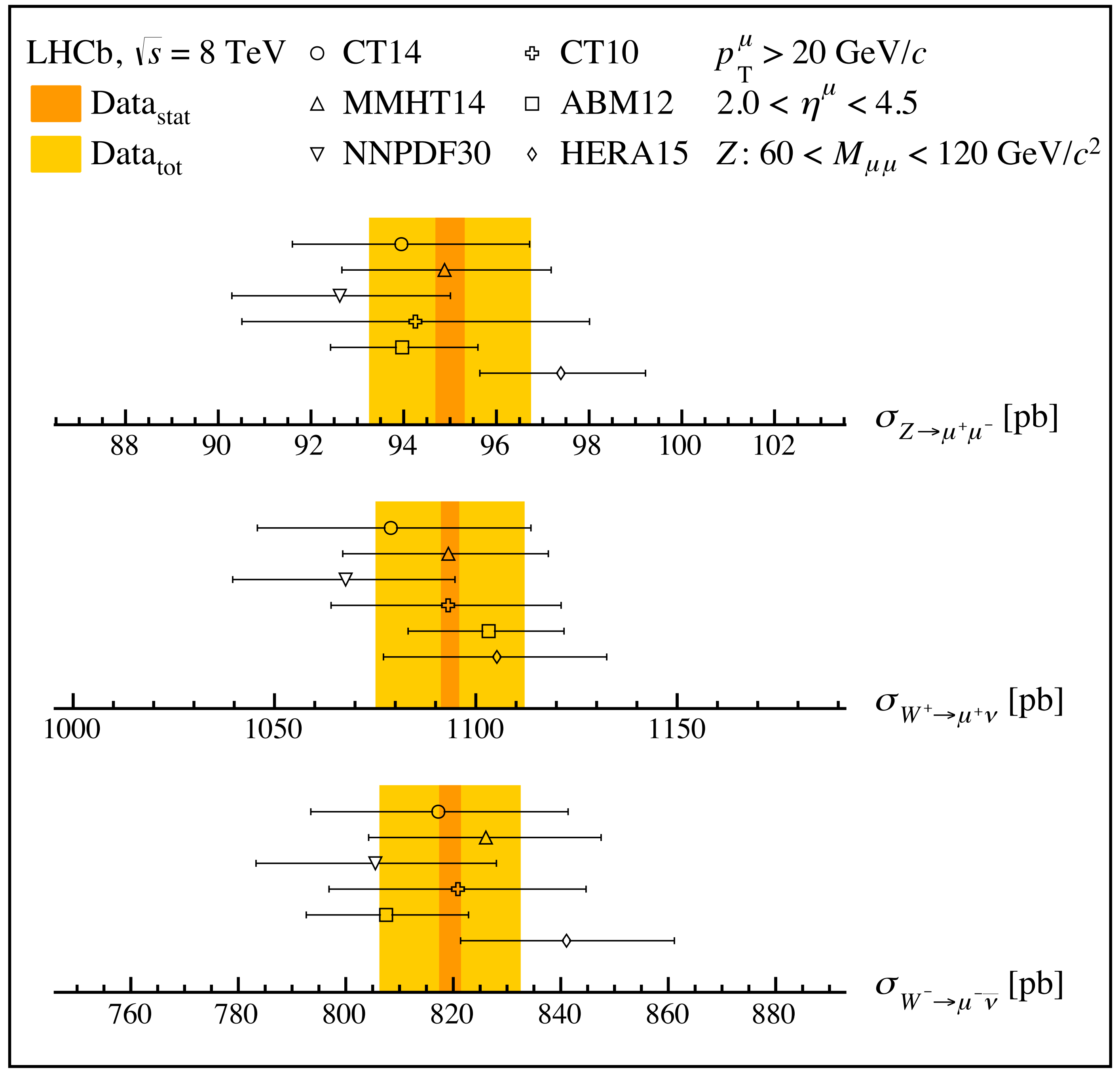
W/Z production at LHC

W and Z copiously produced in pp collisions

- Production has been measured inclusively and differentially in many variables
- CMS and ATLAS provide central and LHCb complements with forward measurements
- After 40 years from discovery W and Z are also a crucial tool for calibrating detectors



JHEP 01 (2016) 155



Electroweak precision measurements at LHC

Designed to be a discovery machine. Is a precision Electroweak program possible?

LHC

- $\sqrt{s}$ varies on event by event basis
- Production mode encoded in Parton Distribution Functions (PDF)
- Access observables through final states; calibrations mandatory
- Kinematics cannot be "closed"

LEP

- $\sqrt{s}$ is determined by beam energy
- Production mode always $e^+ e^-$
- Access observables through beam energy (precisely measured)
- Kinematics always fully determined

$$nZ_{LHC}/nZ_{LEP} \sim 10$$
$$nW_{LHC}/nW_{LEP} \sim 10^4$$

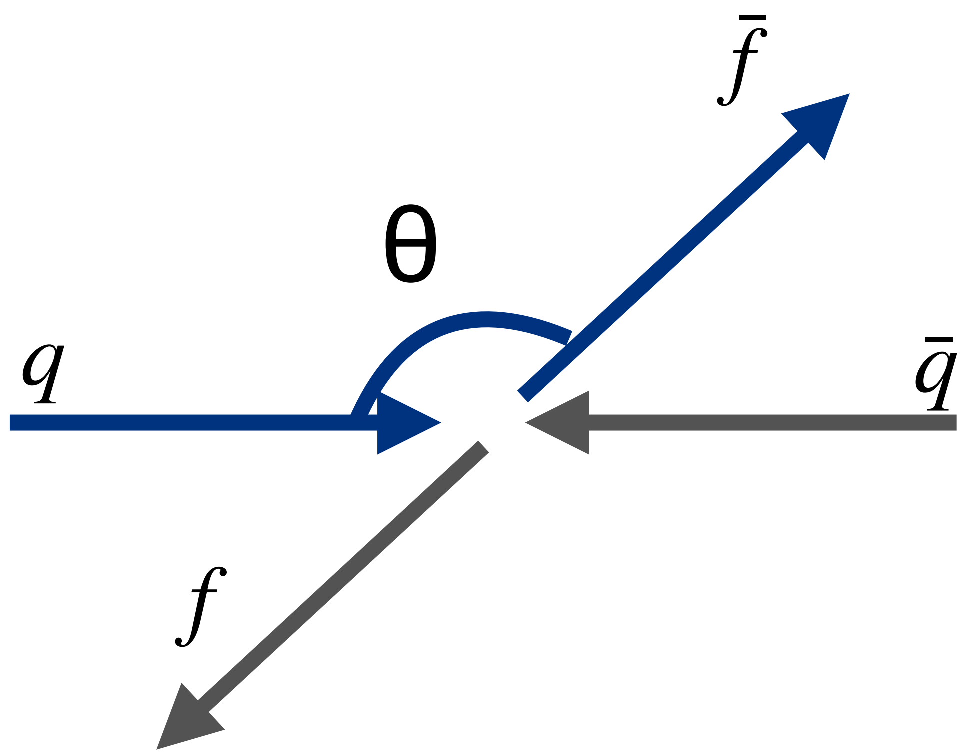
⟶ Considering LHC Run 2 stat

Measurement of the weak mixing angle

At LO in QCD:

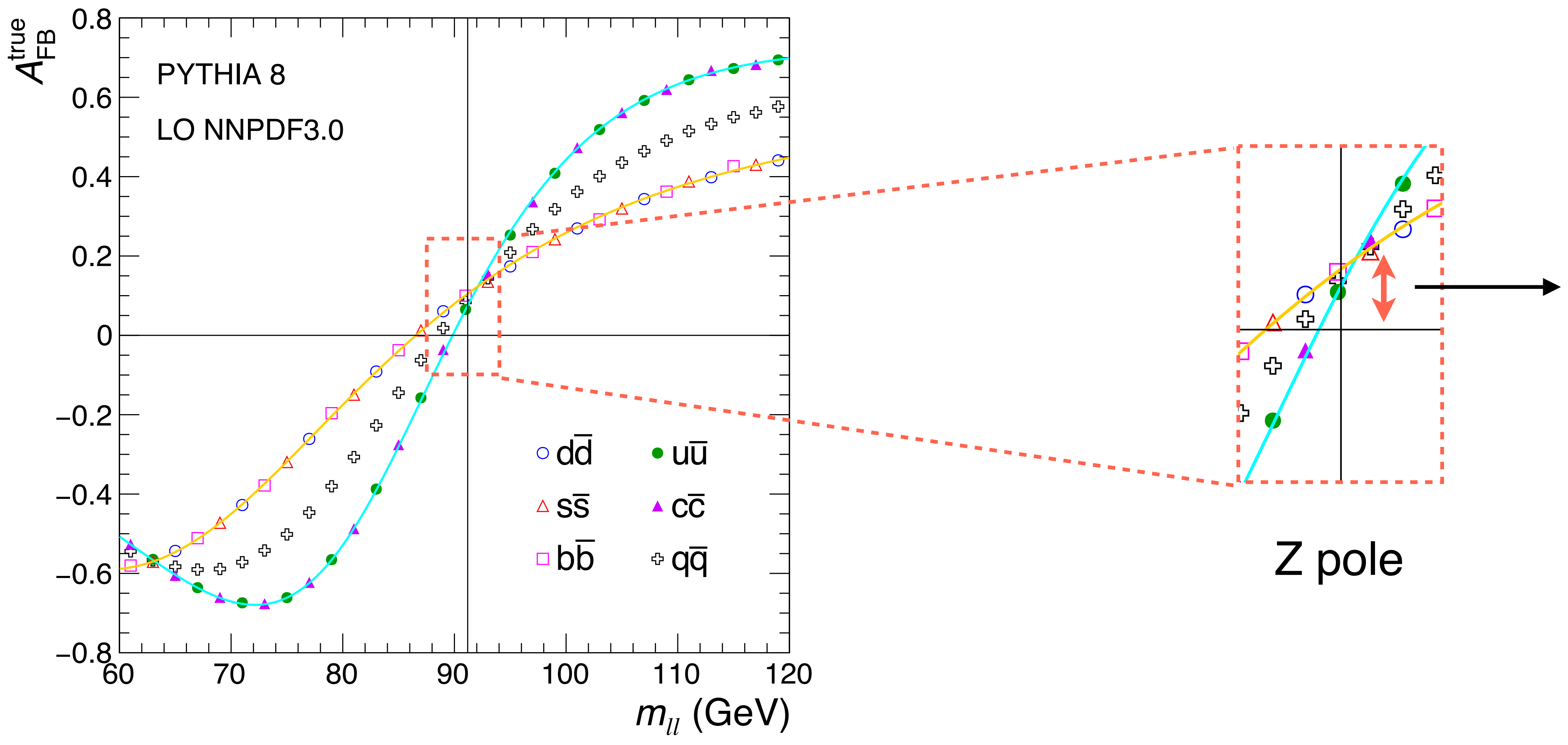
$$\frac{d\sigma}{dy_{ll}dm_{ll}d\cos\theta^*} \propto \frac{d\sigma^{UL}}{dy_{ll}dm_{ll}}(1+\cos^2\theta^* + A_4(y_{ll}, m_{ll})\cos\theta^*)$$

encodes $A_{FB} = \frac{3}{8}A_4 = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$



$$\sigma_{F/B} = \int_{0/-1}^{1/0} \frac{d\sigma}{d\cos\theta^*} d\cos\theta^*$$

using know quark direction



Information about $\sin^2\theta^l_{eff}$

Eur. Phys. J. C 78 (2018) 701

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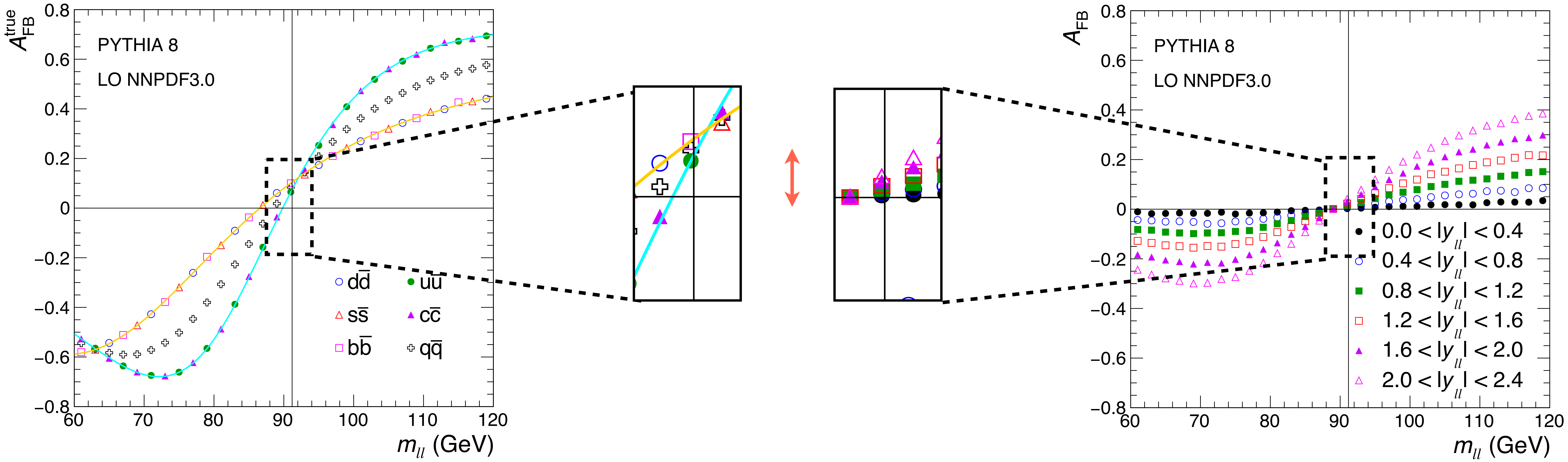
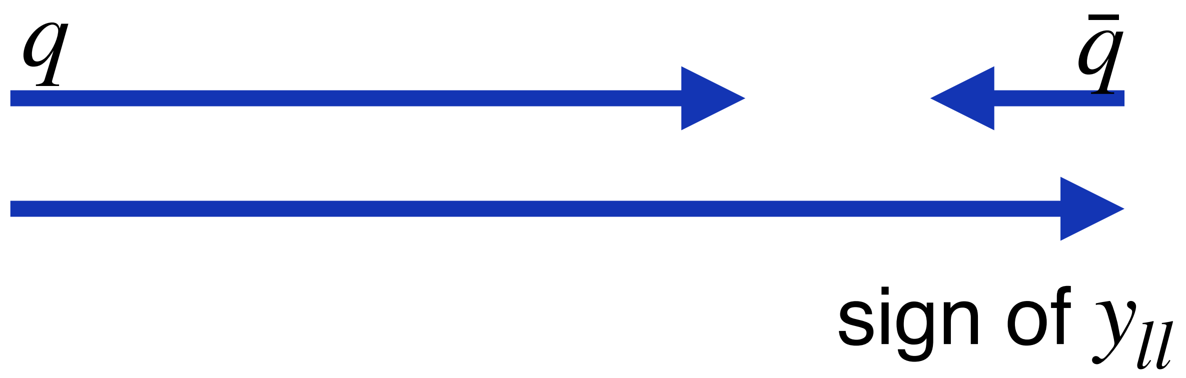
Dilution effect from PDFs:

using know quark direction

using dilepton boost vs y_{ll}





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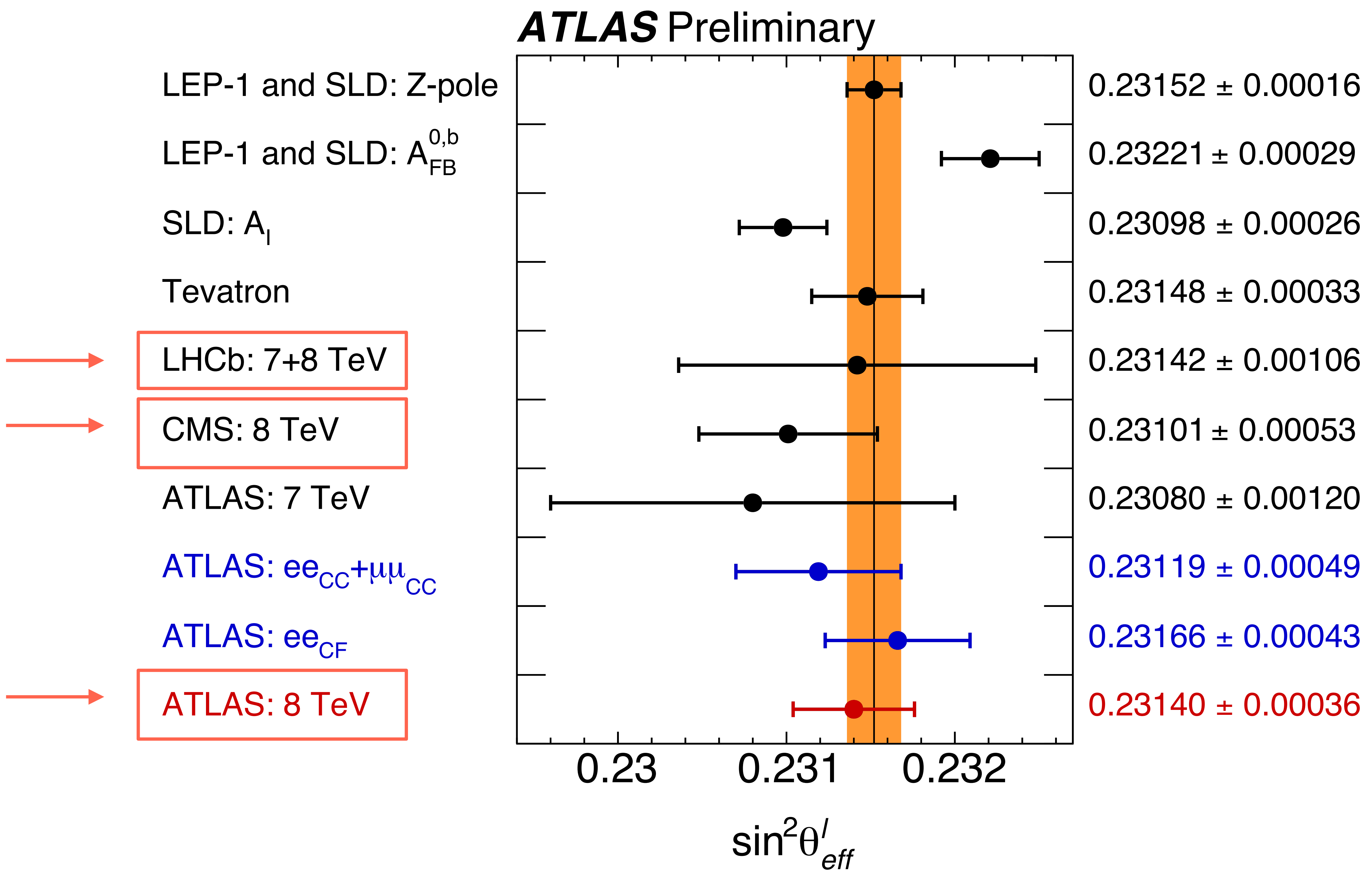
Measurement of the weak mixing angle

This is a flagship measurement of the Electroweak program, together with M_W



ATLAS-CONF-2018-037

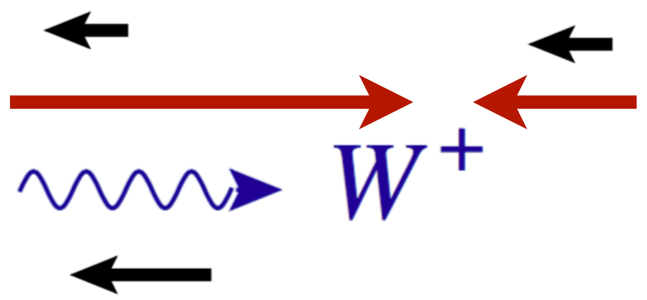
- Great achievements by LHC, but not at level of lepton colliders yet
- Dominated by PDF uncertainty and stat
- Techniques to constrain the PDFs in-situ contribute to lower the final uncertainty
- Potential from future LHCb measurements to exploit low dilution in forward region
- Projections from HL-LHC show potential improvements towards 10^{-5} absolute uncertainty

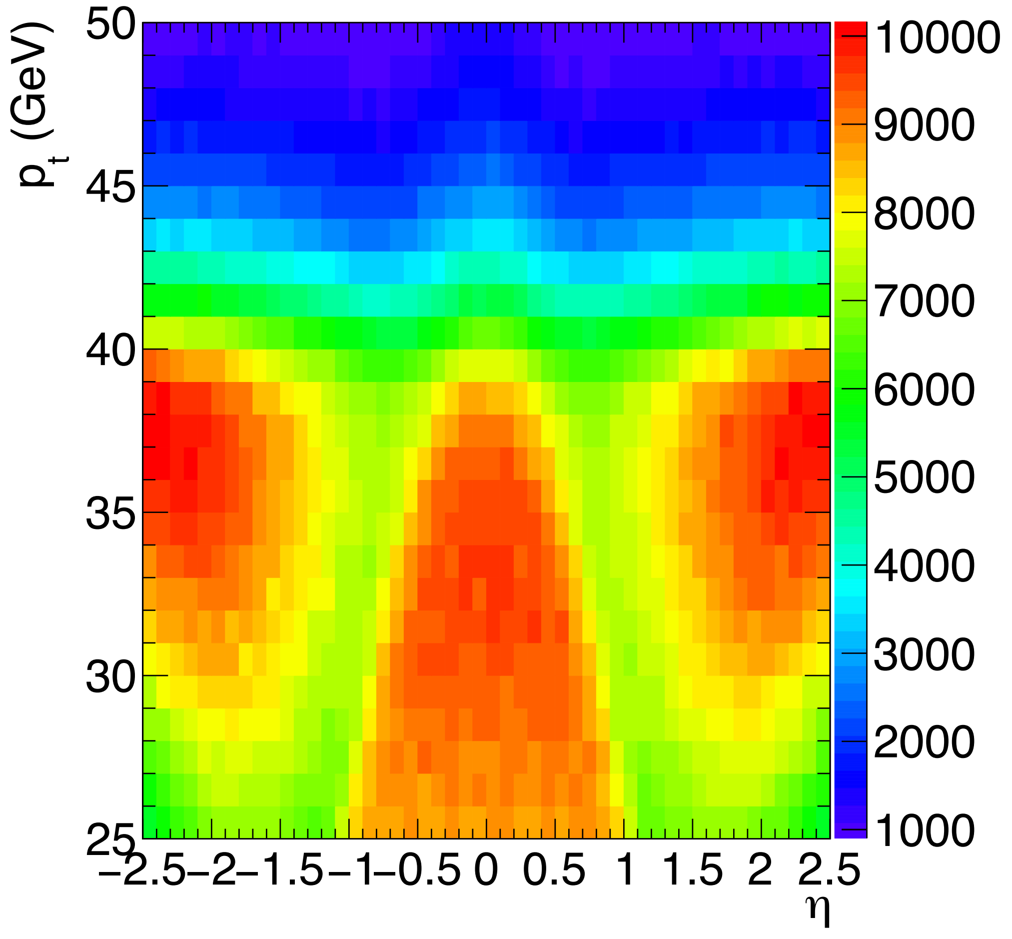
Measurement of *W* polarization, helicity and rapidity

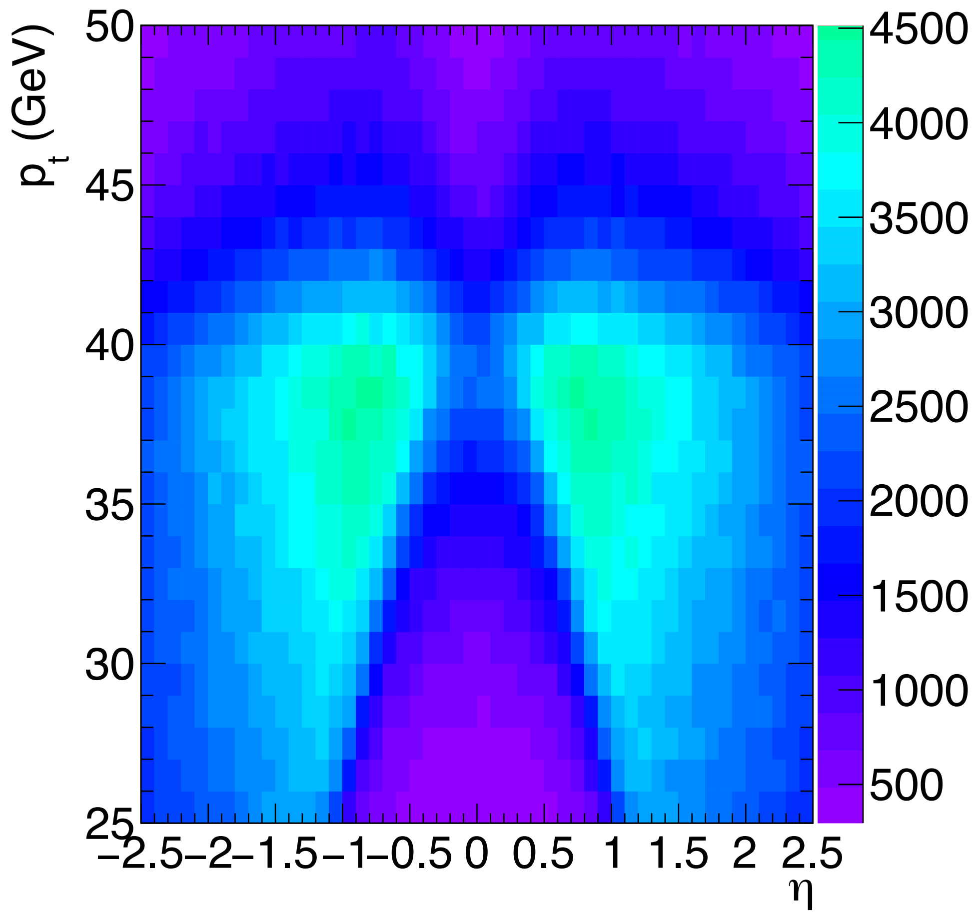
Novel technique invented by CMS collaborators exploiting total parity violation in *W* decays and symmetry of proton collisions

J. High Energ. Phys. (2017) 2017: 130.

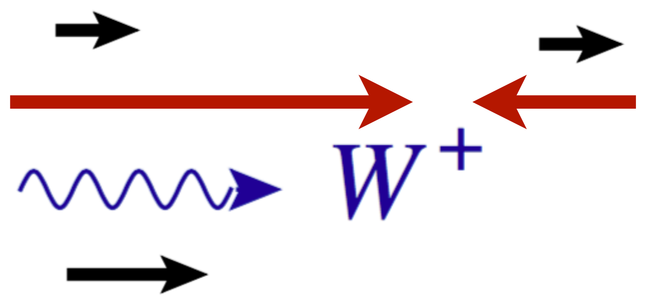
a left-handed W+





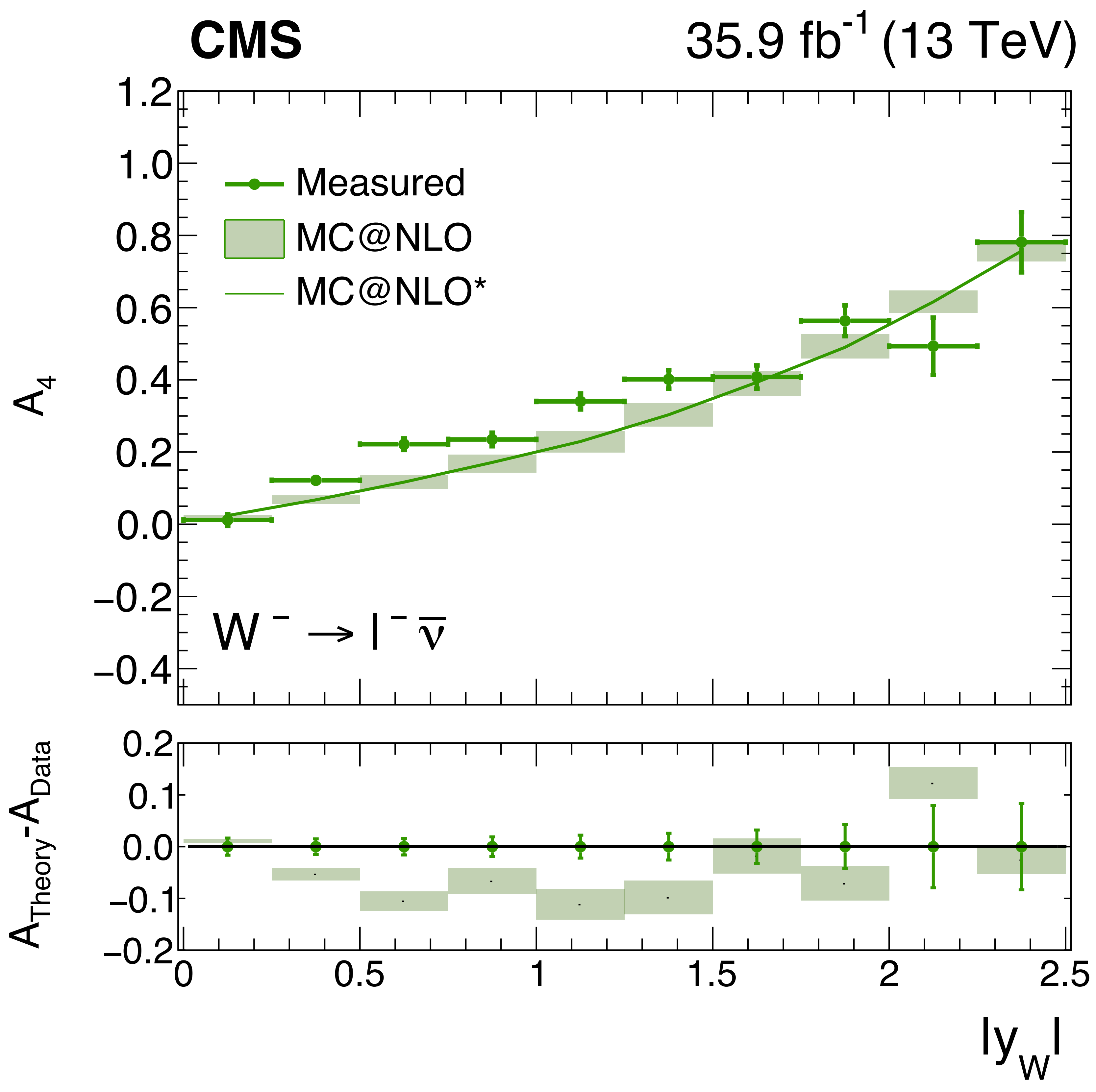


a right-handed W+



lepton p_T vs pseudorapidity distribution can discriminate *W* helicity

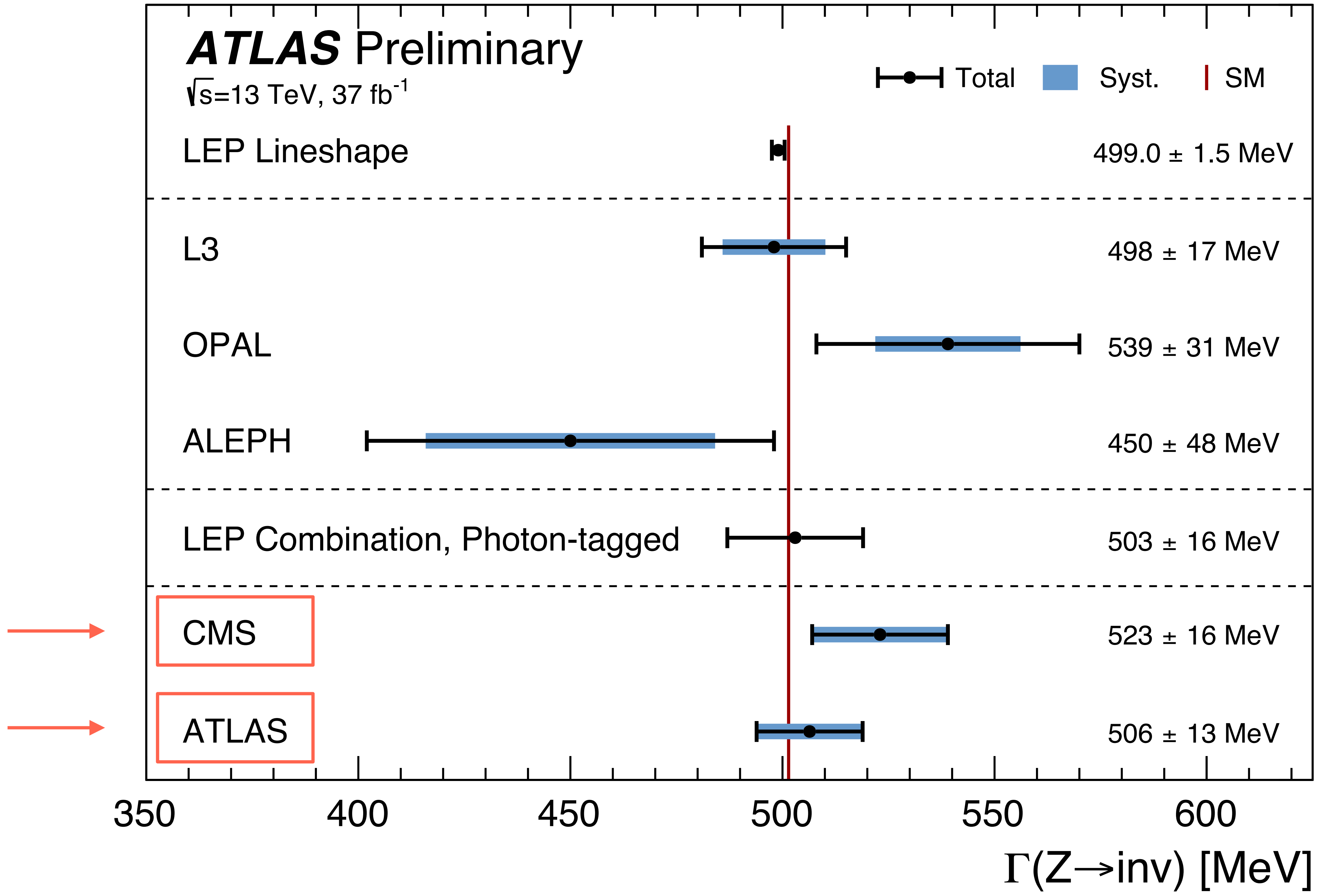
Measurement of *W* polarization, helicity and rapidity



Phys. Rev. D 102 (2020) 092012

- A_4 as a function of *W* rapidity has been measured directly for the first time with a smaller uncertainty than PDF predictions
- Exploiting very large number O(100M) of *W* produced in CMS
- In addition, this result can be used to constrain the value of the PDFs
- Constraints of *W* production *in-situ* are valuable to extract other observables, e.g. *W* mass

Measurement of Z to invisible width



ATLAS-CONF-2023-053

- Crucial precision test of Standard Model: sensitive to number of light neutrinos
- Very recents measurements from CMS and ATLAS, improve precision of LEP direct measurement

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z{+}\text{jets})\mathcal{B}(Z \to \nu\bar{\nu})}{\sigma(Z{+}\text{jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$$

- Z to invisible width measured in events with high initial state radiation
- Dominated by uncertainty on muon efficiency scale factors
- Direct measurements cannot compete with indirect result from LEP lineshape

Measurement of W branching ratios

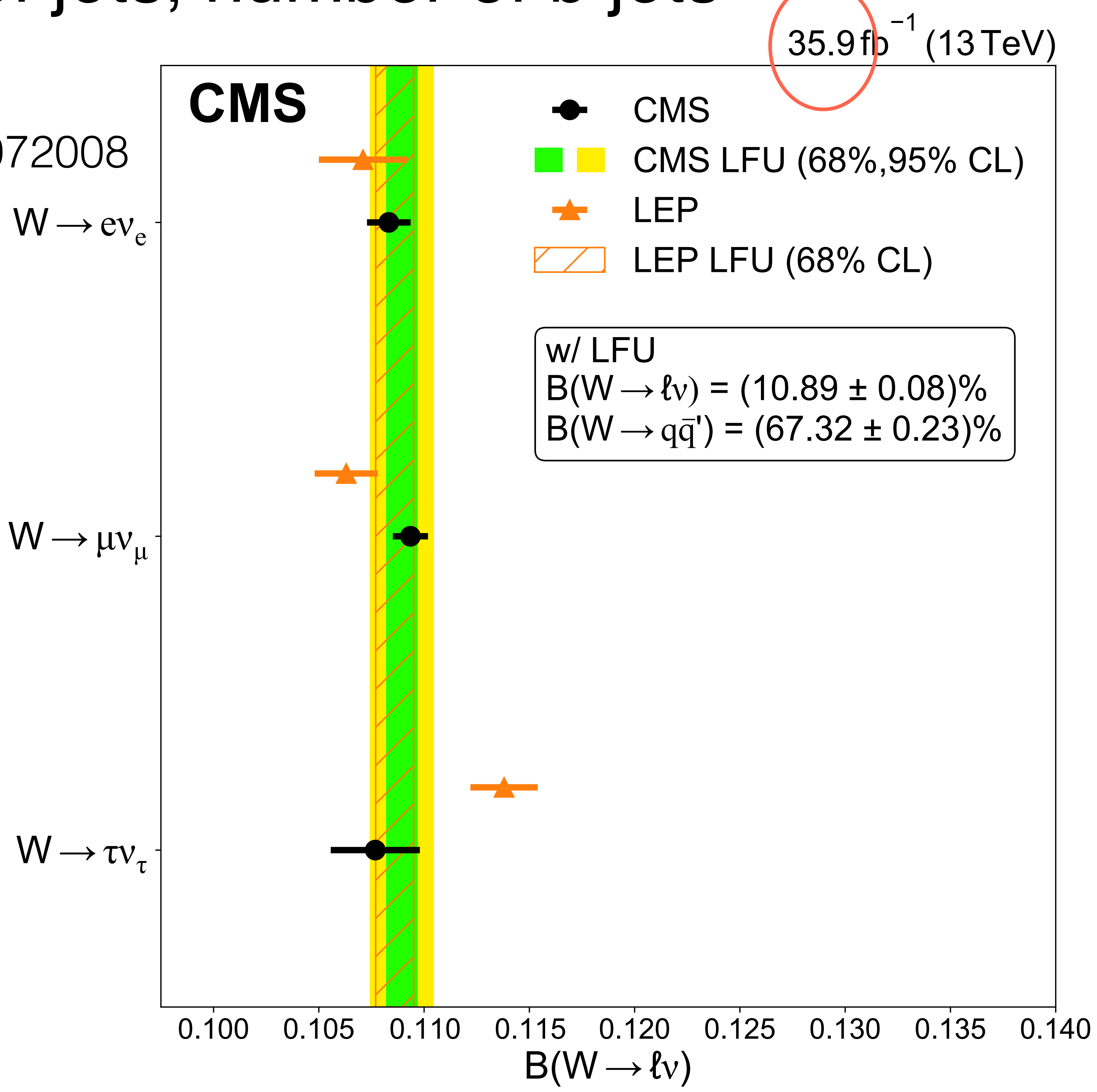
Exploit the unprecedented statistics of W events produced at LHC to probe LFU

- Mostly $t\bar{t}$ events decaying to WW
- Classify and fit number of events on multiple categories based on multiplicity and flavor of reconstructed leptons, number of jets, number of b jets

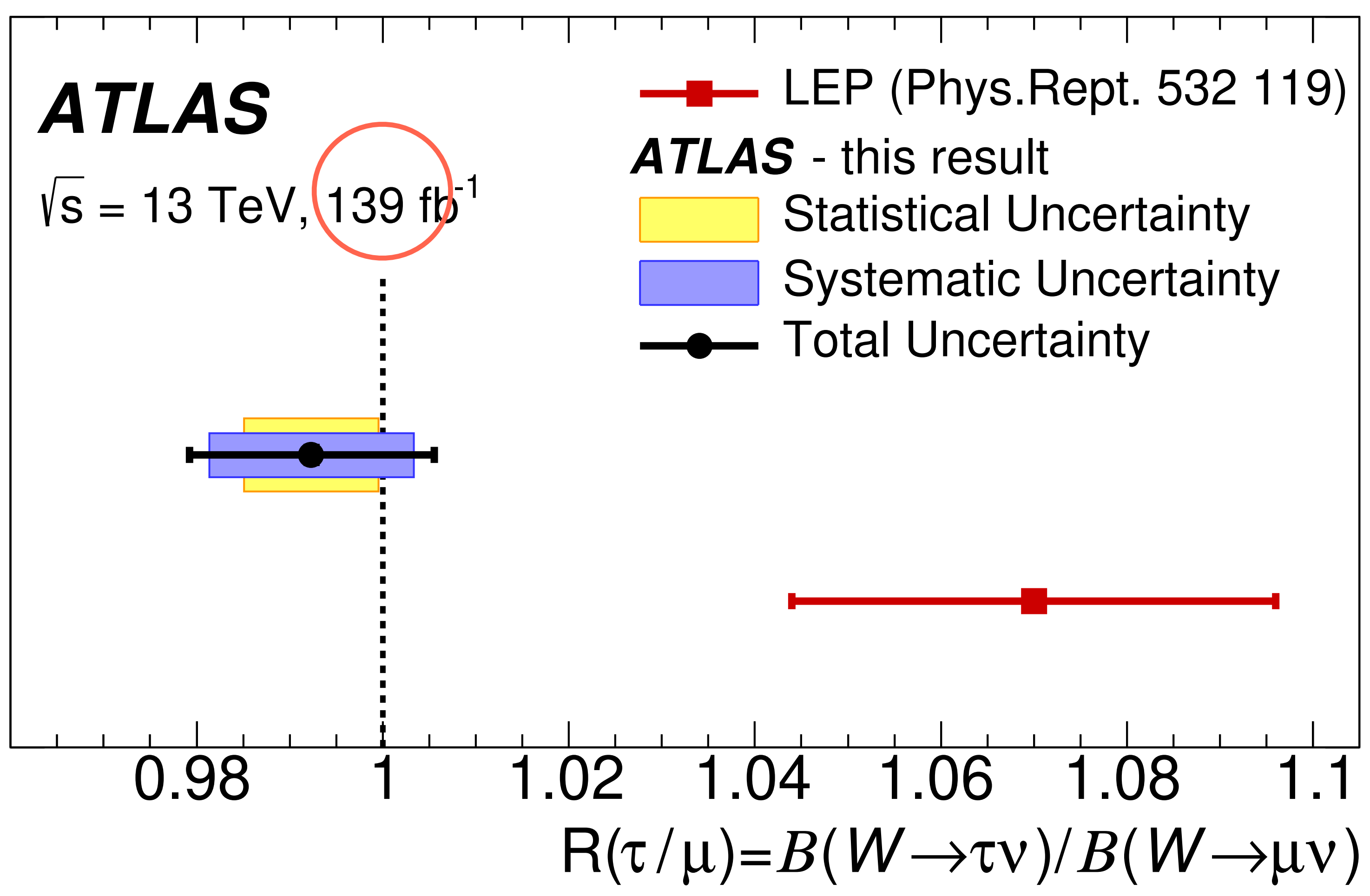
Phys. Rev. D 105 (2022) 072008

	CMS	LEP
$\mathcal{B}(W \to e\overline{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\%$
$\mathcal{B}(W \to \mu\overline{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\%$
$\mathcal{B}(W \to \tau\overline{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)\%$
$\mathcal{B}(W \to q\overline{q}')$	$(67.46 \pm 0.04 \pm 0.28)\%$	—
Assuming LFU		
$\mathcal{B}(W \to \ell\overline{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \to q\overline{q}')$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$

Significant gain in stat uncertainty wrt LEP



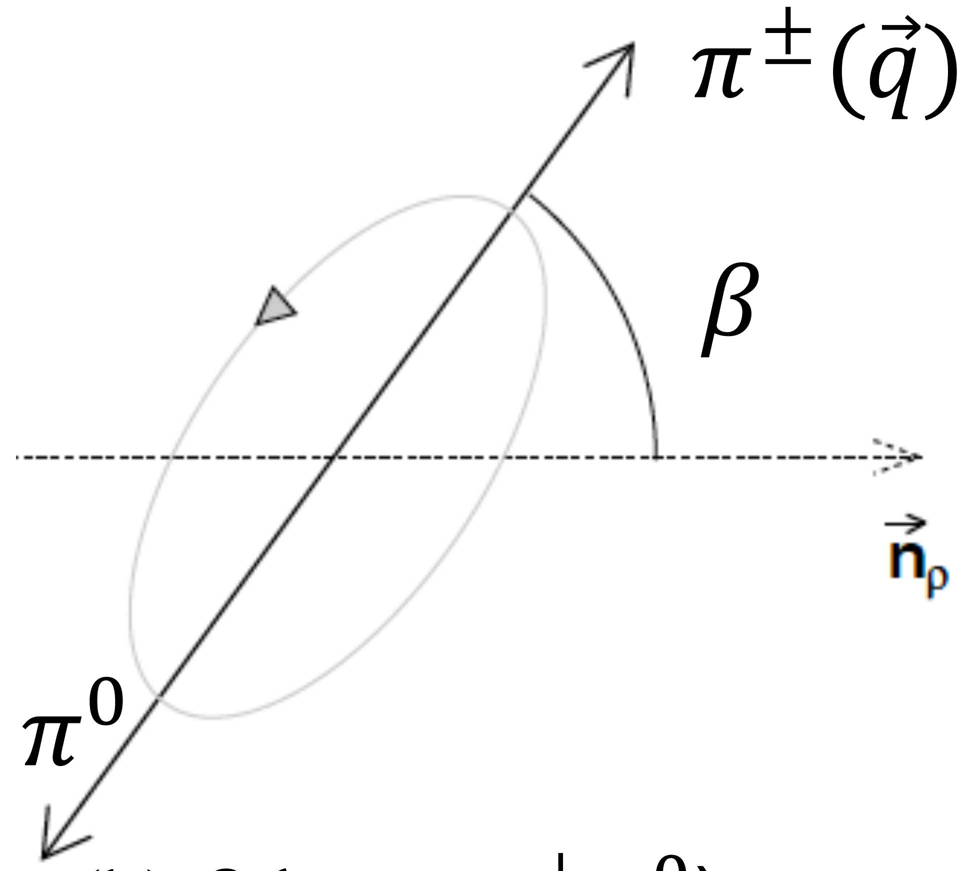
Nature Phys. 17 (2021) 813



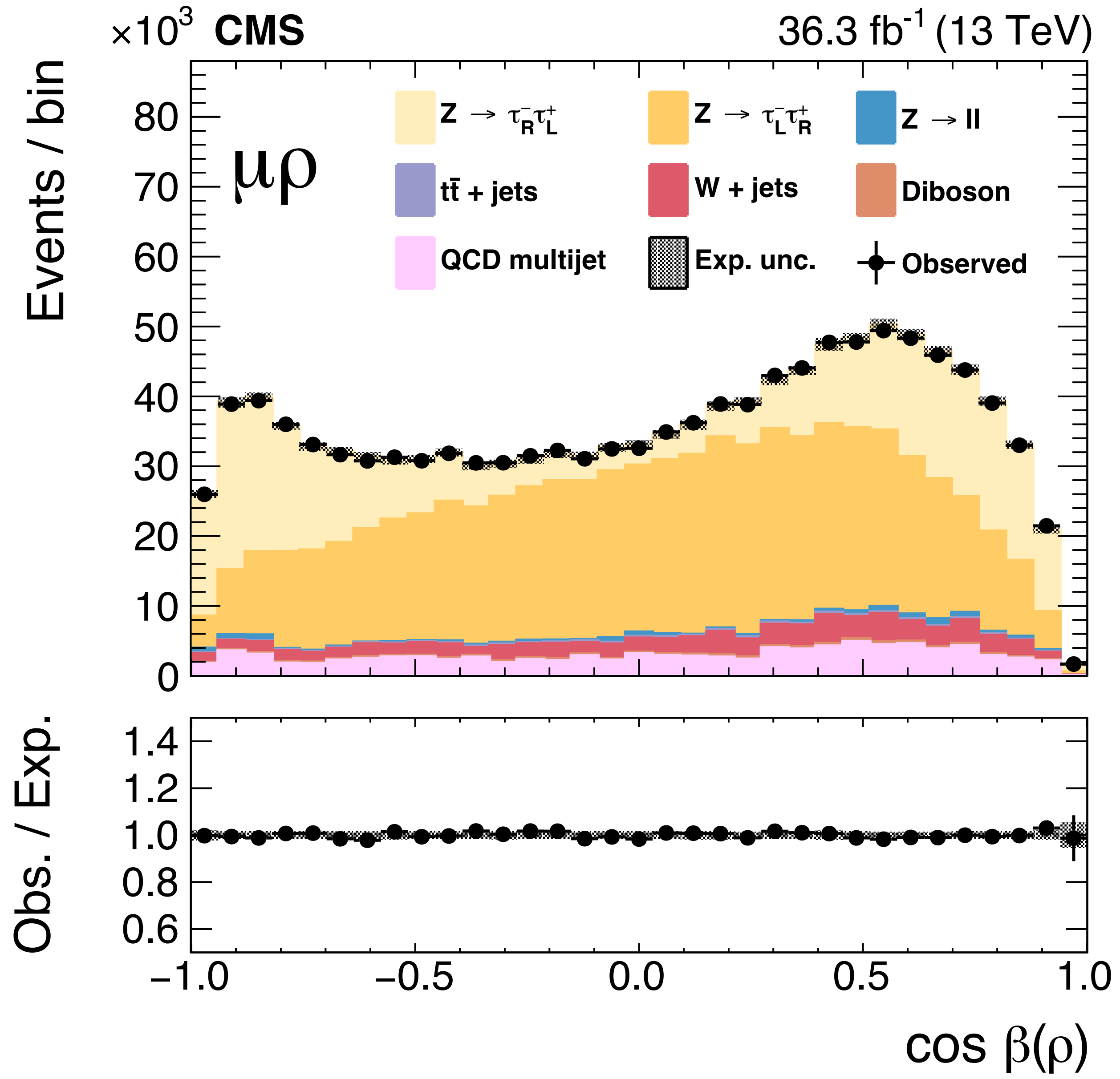
Measurement of τ polarization

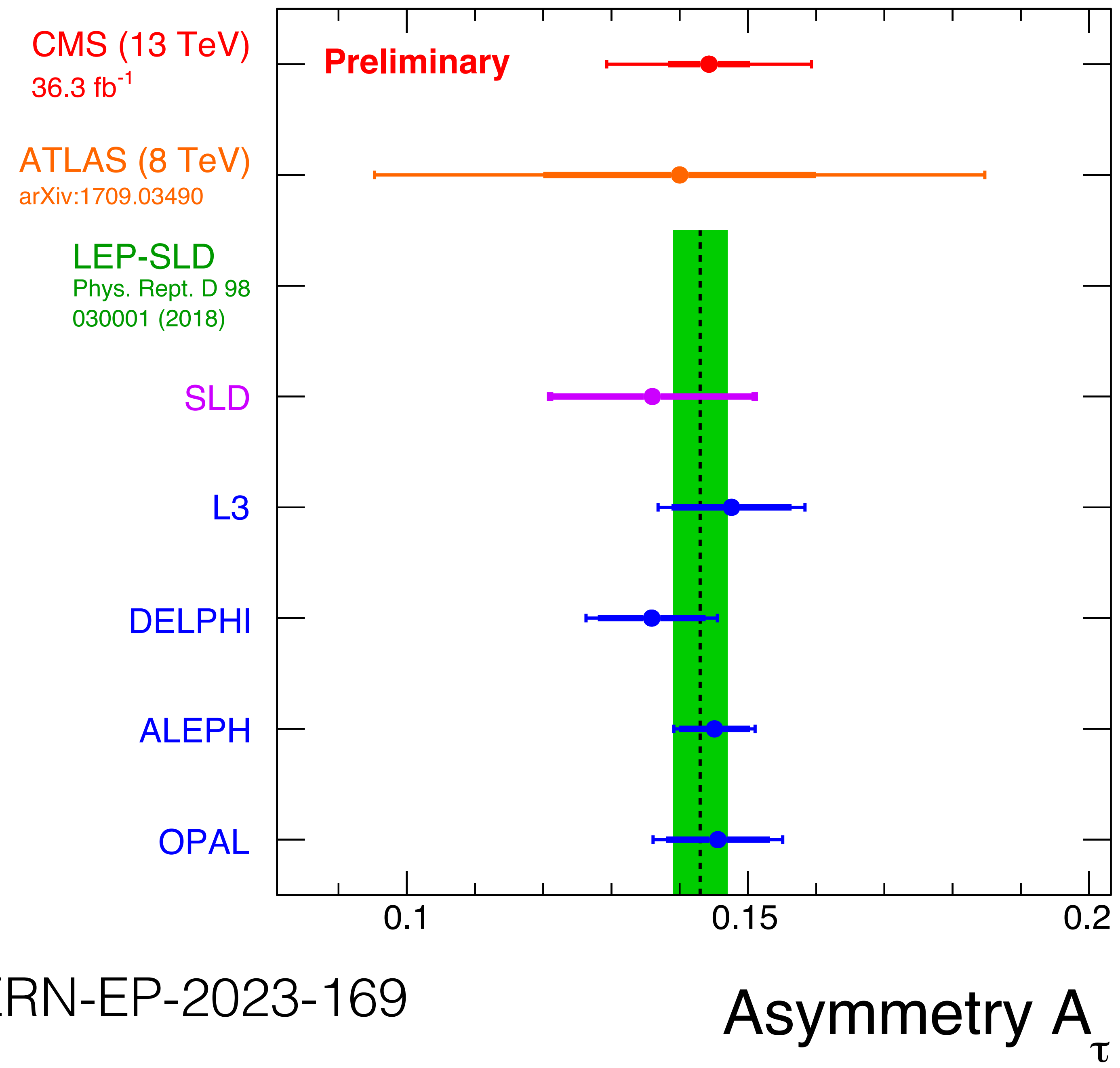
Measuring τ polarization from Z to τ decays to extract the value of the weak mixing angle

- Independent of polarization of the initial state: measuring $A_f \propto 1 - 4\sin^2\theta^f_{eff}$
- Polar emission angle θ_τ very poorly determined: rely on other sensitive observables using τ decay products
- Additional effort at LHC to estrapolate measurement to Z pole and second order corrections over flavor of initial state



(b) $\beta(\rho \to \pi^\pm\pi^0)$



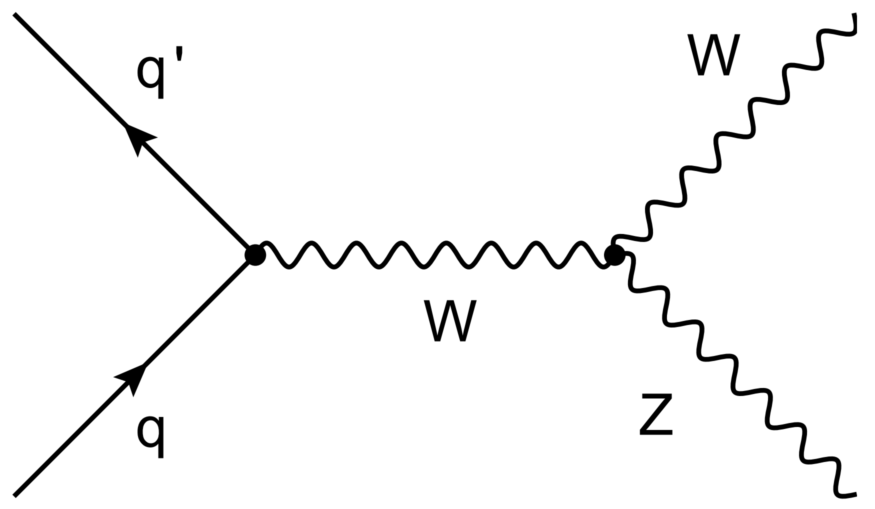


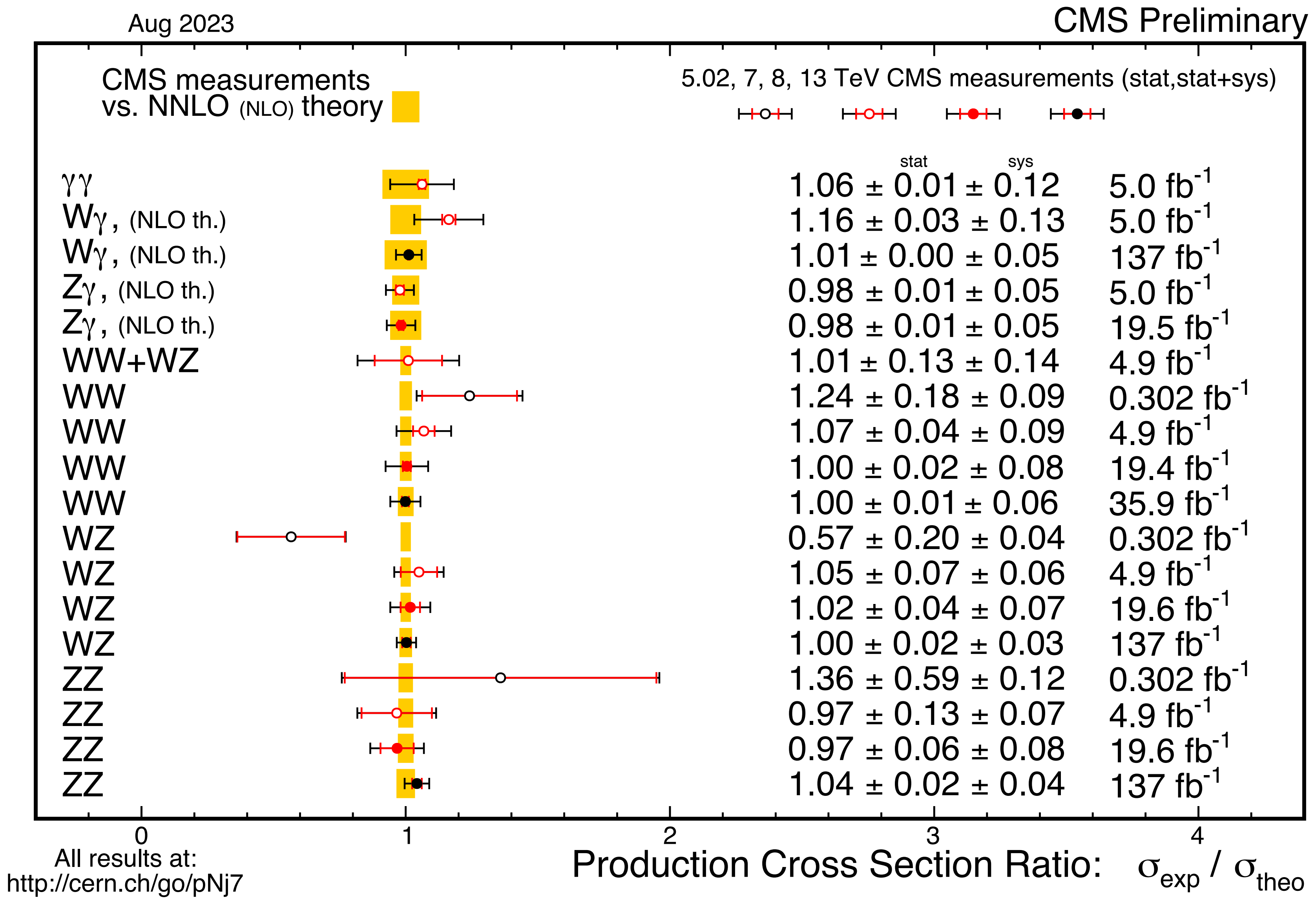
CERN-EP-2023-169

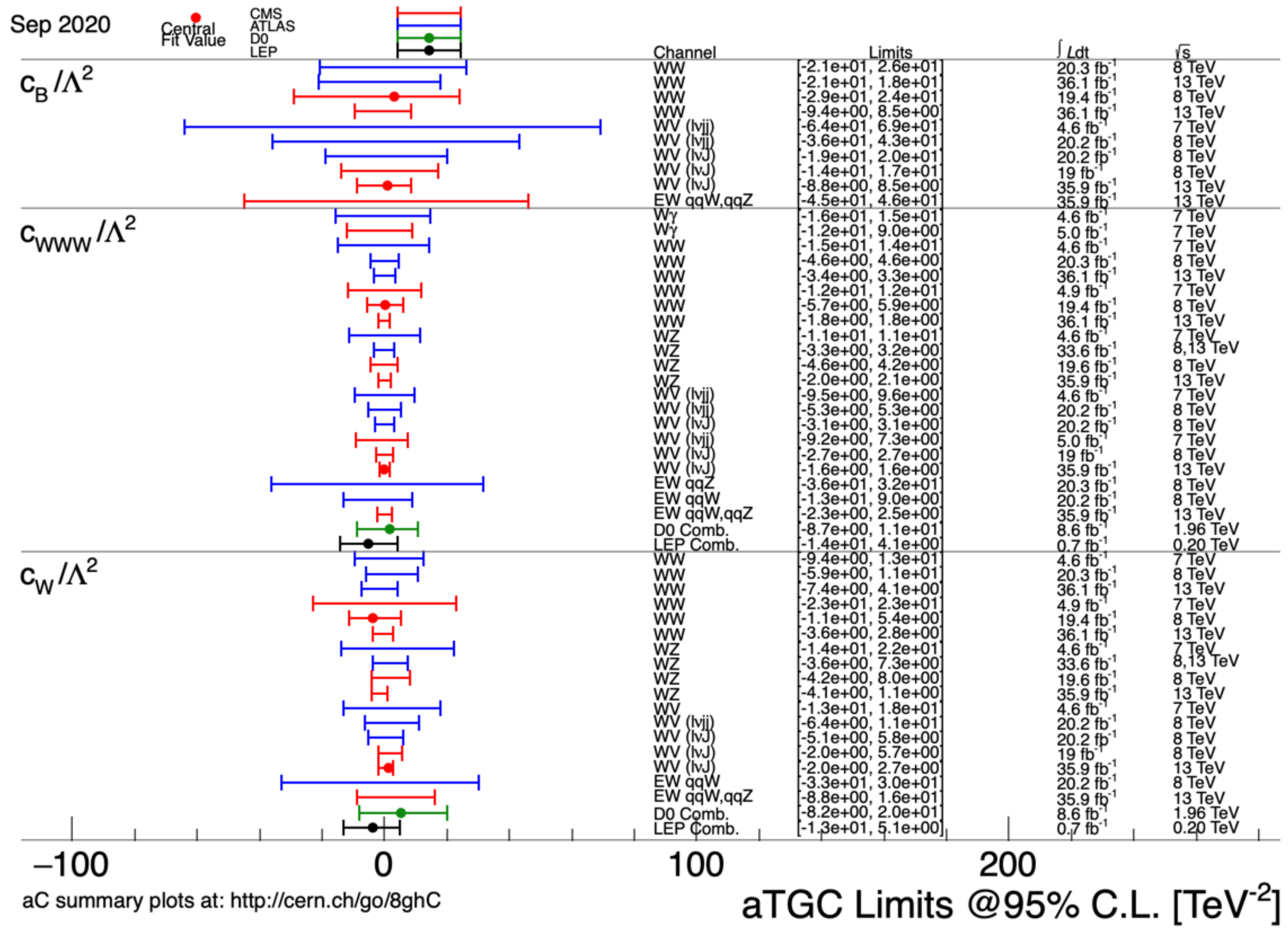
Measurements of multiboson processes

Di/tri-boson productions and vector boson fusion and scattering processes are sensitive to triple and quartic gauge couplings

- Exploit large number of events to measure cross sections and impose limits on anomalous couplings in the context of Effective Field Theory (EFT)
- Observing longitudinally polarized *W* and *Z* for the first time at 5 standard deviations







W and *Z* as a tool for understanding QCD

The highlight of this talk has been on purely Electroweak measurements.
However, *W* and *Z* bosons have also been largely employed to validate and improve QCD:

- Measurement of *Z* p_T and α_S: CERN-EP-2023-171 and JHEP12(2019)061
- Measurement of *W* p_T using low pile-up run: ATLAS-CONF-2023-028
- Measurements of associated production of *W*/*Z* and jets: CERN-EP-2020-206, JHEP 05 (2016) 131

Summary: the electroweak program at LHC

Despite being designed as a discovery machine, LHC has provided valuable results in the context of Electroweak precision measurements

- Exploit larger number of events compared to lepton colliders
- Invent new and smart techniques to access previously hidden observables

The electroweak precision measurement program at LHC is tightly interconnected to QCD through knowledge of PDFs

- A synergic effort: more precise electroweak measurements in turn improve the precision of PDFs which in turn enable for more precise electroweak measurements…

Many more results to come in the next future exploiting data collected at Run 3 and HL-LHC, hopefully improving the precision set by lepton colliders

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