LHC projections for the measurement of the Electroweak mixing angle running

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29/11/2022

The Electroweak mixing angle

Casted by Weinberg (1967) in the full EW theory*

$$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y + \mathrm{Higgs}$$

First appearance of a mixing angle between EW boson fields due to Glashow (1961)

Fundamental **parameter** of the **Standard Model**

The Electroweak mixing angle

Quantifies **relative strengths** of **electromagnetism** and the **weak force** + …

… + governs the **Z-boson couplings** to **fermions**

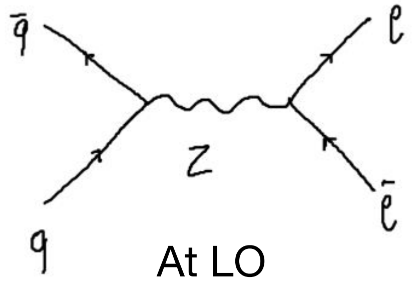
Can be used to probe the structure of the EW theory

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} = \frac{g'^2}{g^2 + g'^2}$$

*renormalizability of the theory proved by ‘tHooft (1971)

Forward-Backward NC DY events

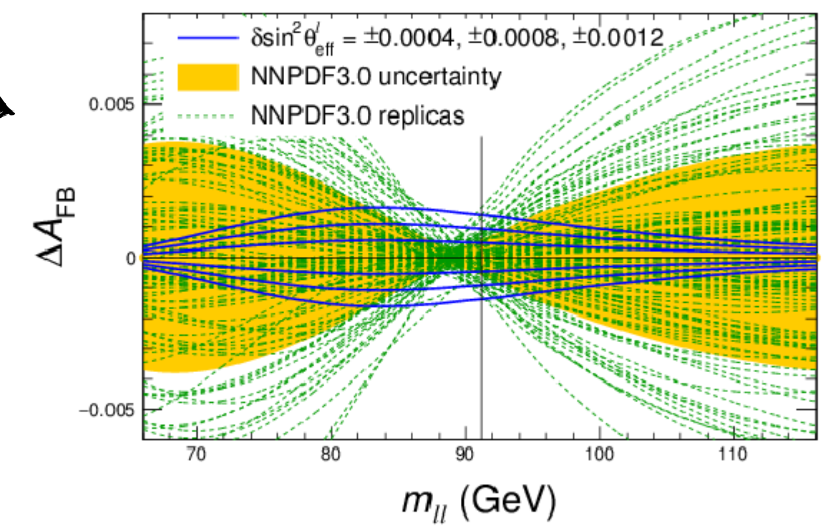
Presence of vector and axial-vector couplings leads to **forward-backward asymmetry** of angular distribution of lepton pairs in DY events



$\propto 1 + \cos^2\theta_{ll} + A_4 \cos\theta_{ll}$

Since $A_4 \propto A_{FB}$ measurement of forward/backward events can be used to determine $\sin^2\theta^f_{\text{eff}}$

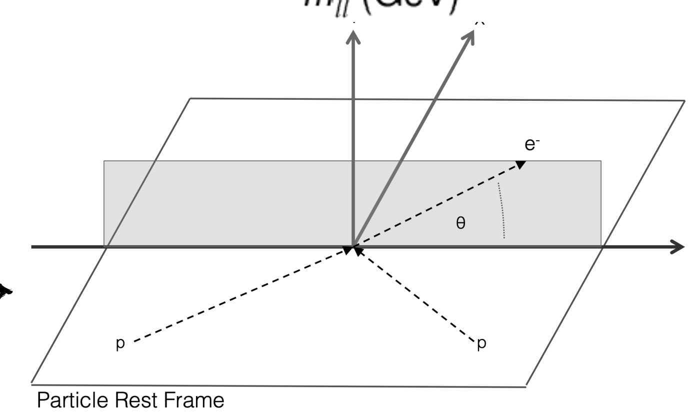
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$



arXiv:1806.00863

At hadron colliders "dilution effect" → direction of incoming quarks not precisely known:

- Enhanced sensitivity of A_{FB} to the EW mixing angle at high $|y_{ll}|$
- Collins-Soper reference frame used



arXiv:1902.05142v2

Direct determination of $\sin^2\theta^f_{\text{eff}}$ around the Z pole

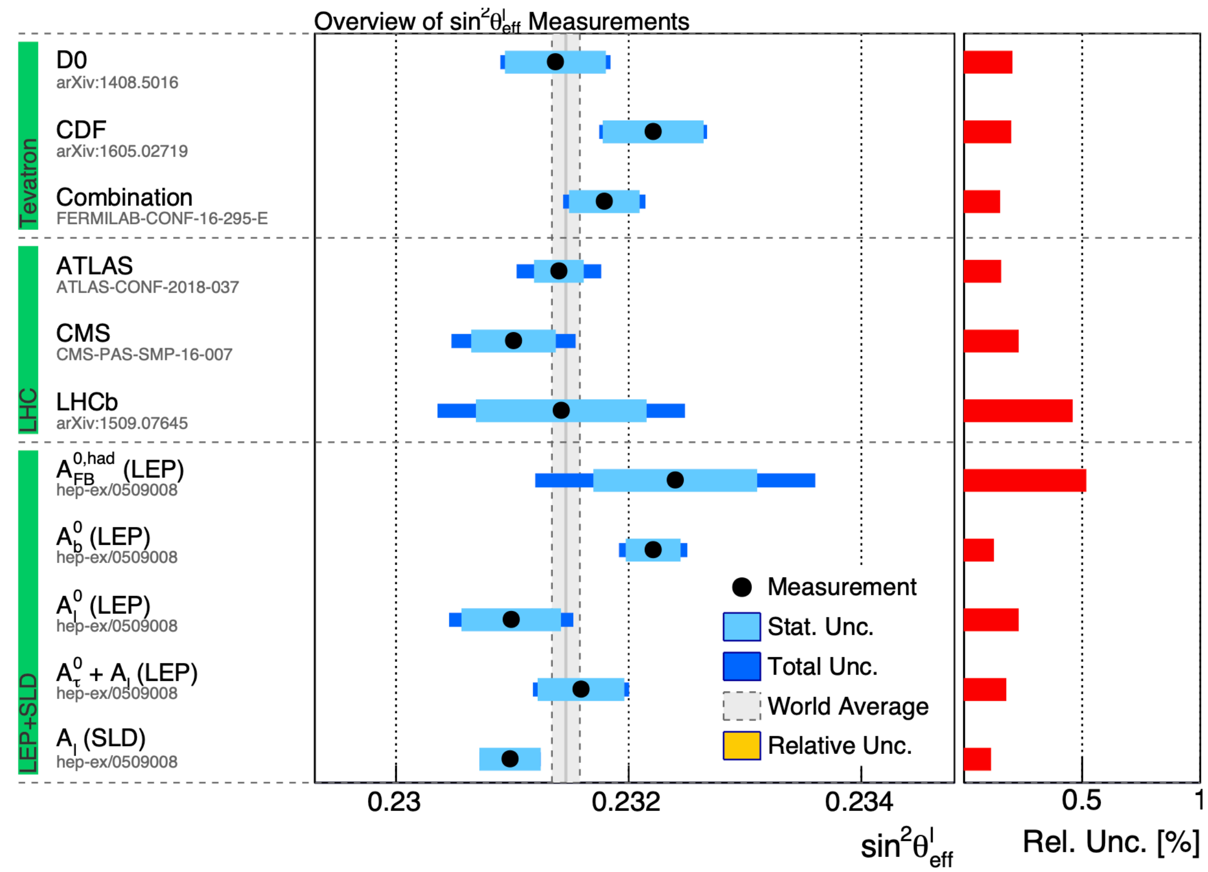
Template fit procedure to measure $\sin^2\theta^f_{\text{eff}}$

$A_{FB}(m_{ll}, |y_{ll}|)$ data → MC samples with different values of $\sin^2\theta^f_{\text{eff}}$ → Measured value = MC sample which best fit the data

Measurements of A_{FB} around the Z pole at lepton (hadron) colliders → relative precision on $\sin^2\theta^f_{eff}$ of $0.1(0.2)\ \%$

Measurements at the LHC has already reached the same precision as the Tevatron → expected big improvement in the nearly future:

- **More statistics** available (from Run 3 and HL-LHC)
- **Improved analysis** techniques and **PDF constraining** methods



LEP + SLD + Hadron coll. = 0.23151 ± 0.00014

arXiv:1902.05142v2

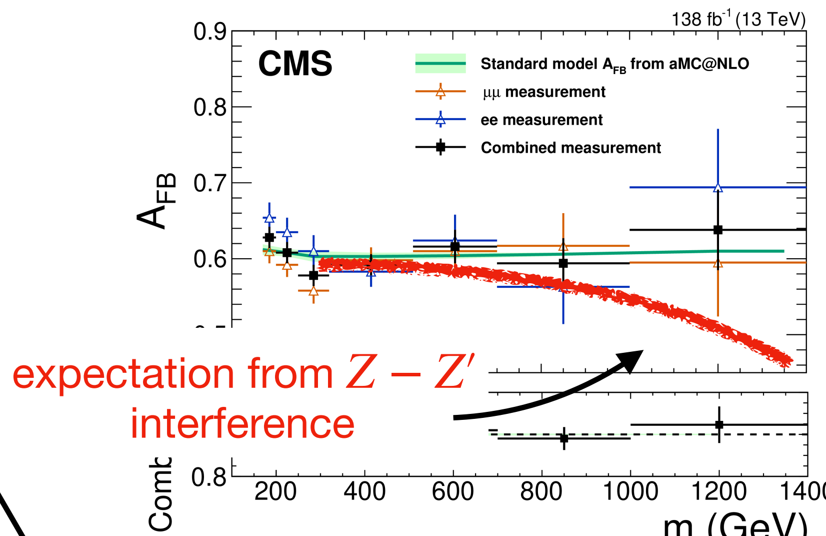
Ongoing work within the **LHCEWWG** to quantify **uncertainties** and **theoretical issues** in the extraction of $\sin^2\theta^f_{\text{eff}}$ (see EW precision measurements subgroup)

The EW mixing angle at high-masses

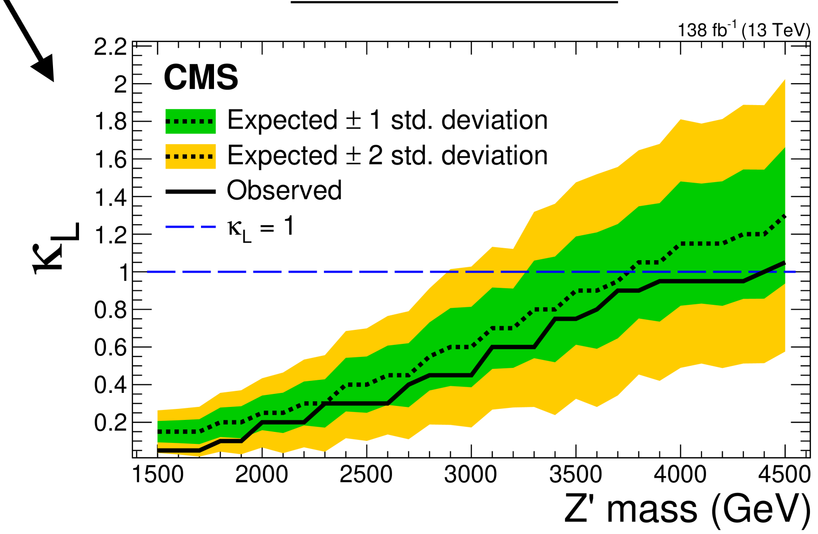
At lepton/hadron colliders $\sin^2\theta^f_{\text{eff}}$ measured at the Z boson peak → at **high-masses** can be used to **probe extra massive gauge bosons**:

- New resonances not visible to direct searches if they have large widths…
- …but can interfere with SM EW bosons introducing structures in the measured A_{FB}

The CMS Collaboration has recently measured A_{FB} at high-masses → extracted exclusion limits For a Z' in the sequential SM



arxiv:2202.12327

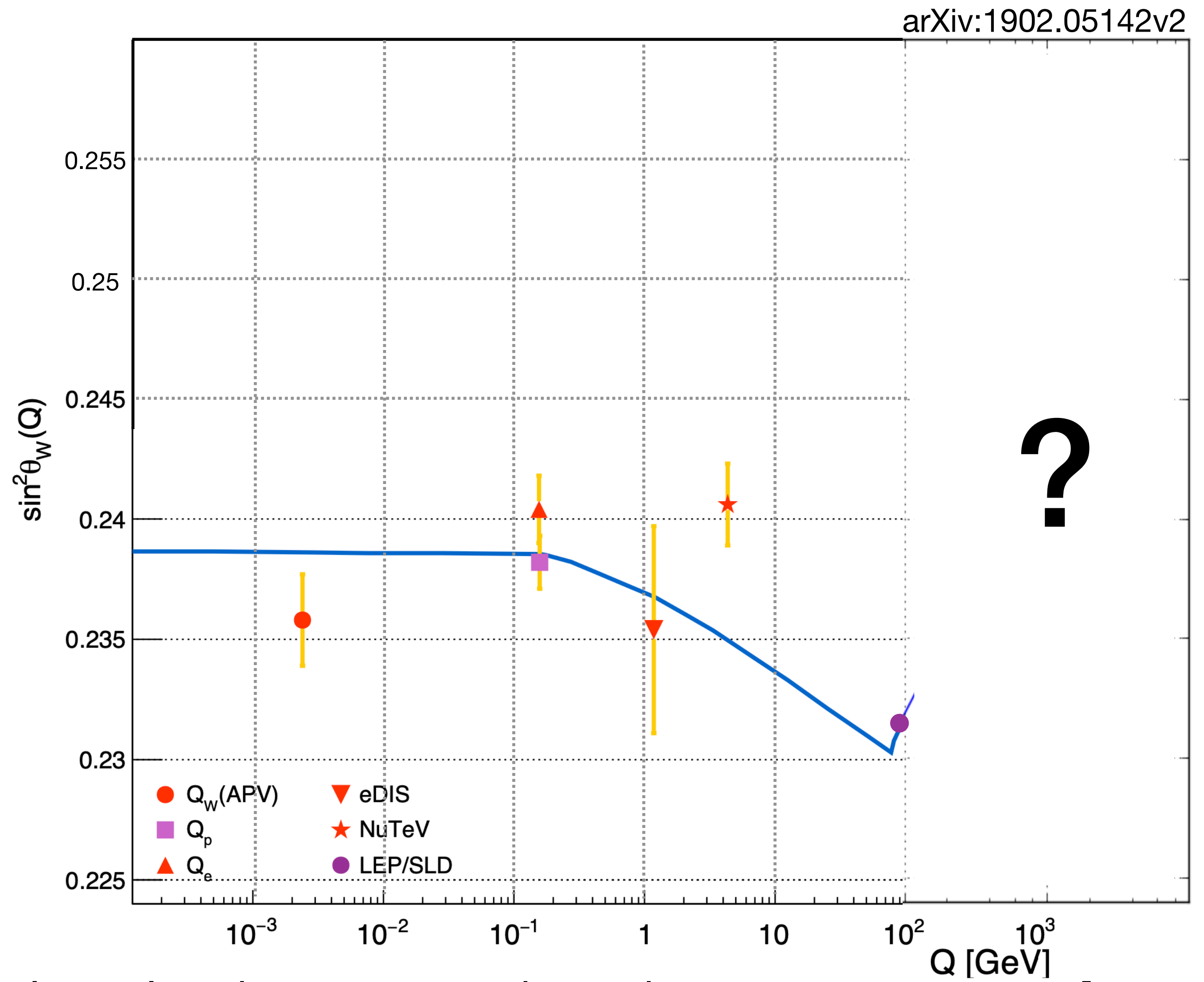


To probe the **presence** of **new physics** outside the Z peak in a **model-independent way**

↓

Need to **compare** the **experimental data** (at high-masses) with theoretical predictions which **include** the **energy dependence of the EW mixing angle**

The energy dependence of $\sin^2\theta_W$



The EW mixing angle value is expected to show an **energy dependence** which can be **predicted** by the RGE for $\sin^2\theta_W^{\bar{M}S}(\mu)$ in the $\bar{M}S$ **renormalisation scheme** (arXiv:hep-ph/0409169v2)

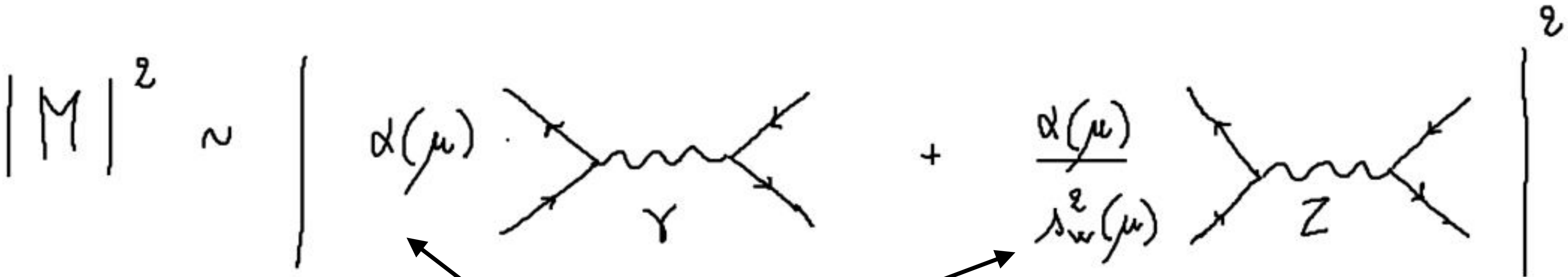
Several measurements at low Q^2 (atomic parity violation) → but **no experimental results** on the running of the EW mixing angle at **high energy**

Will it be possible to test the running of $\sin^2\theta_W$ @ the LHC?

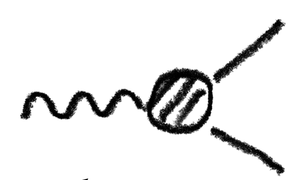
Implementation of $\sin^2\theta_W^{\bar{MS}}(\mu)$ in POWHEG-BOX

The energy dependence of $\sin^2\theta_W$ has recently been implemented into POWHEG-BOX Z_ew_BMNNPV:

- Use an **EW input scheme** where the **EW mixing angle** is **explicit** $(\alpha(\mu), m_Z, \sin^2\theta_W(\mu))$
- Within this “hybrid” scheme the m_Z value is renormalised to its On-Shell value while the **fine structure constant** and the **EW mixing angle** are renormalised in the $\bar{MS}$ scheme, i.e. depend on the energy scale μ
- Predictions used in this work are obtained at an “**improved LO**” with $\alpha(\mu)$ and $\sin^2\theta_W(\mu)$ as running parameters → the matrix element of the NC DY process is expressed as:



Here the contributions from higher order expansion are resummed



Analysis strategy

Extract the expected sensitivity on the running of the EW mixing angle at **high energies** up to the TeV scale → m_{ll} is used as the **dynamic energy scale**

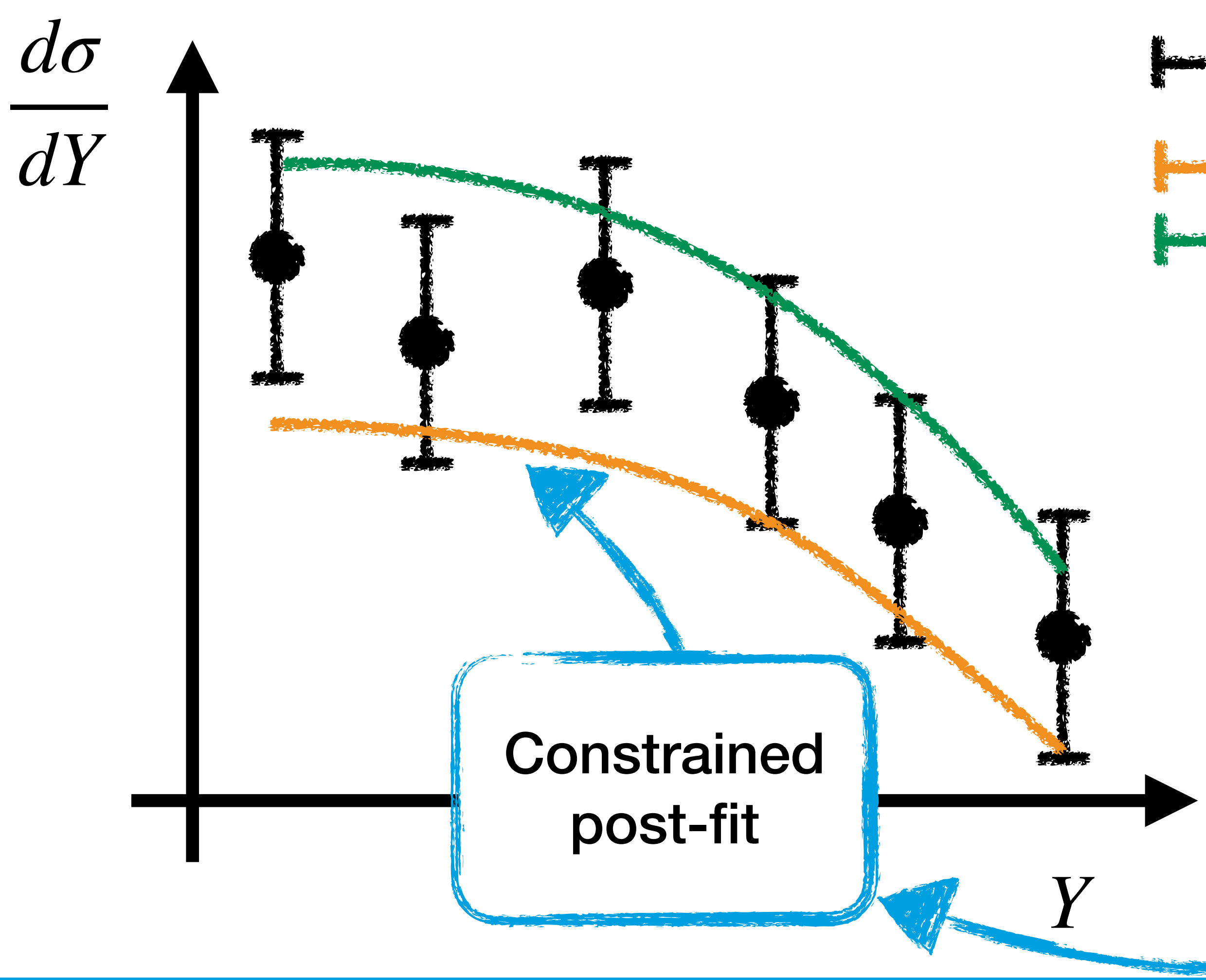
The choice of EW parameters input scheme for theory predictions is **fundamental** → scheme where $\sin^2\theta_W$ can be varied **independently**

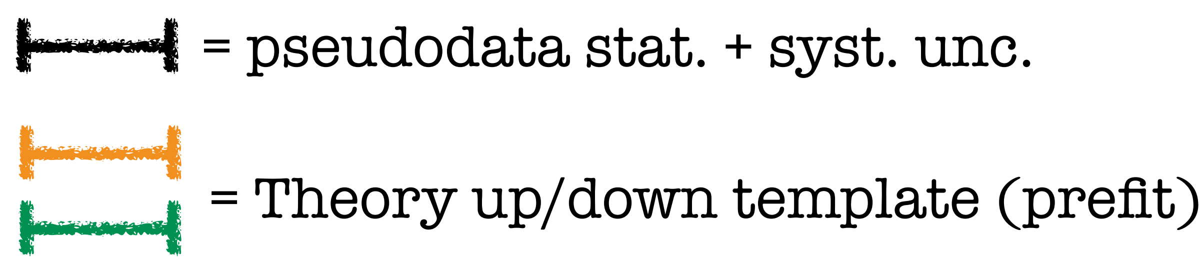
Use one billion events calculated @ NLOQCD + improved LOEW with POWHEG-BOX, showered with PYTHIA8 to perform a template fit

- Extract the expected sensitivity to $\sin^2\theta_W^{\bar{MS}}(m_{ll})$ in **several mass bin**
- Two LHC scenarios considered: **Run 3** $(300\,\mathrm{fb}^{-1})$ and **HL-LHC** $(3000\,\mathrm{fb}^{-1})$

Analysis strategy

1. Pseudo-data generated using the EW parameters values at the Z peak as inputs
2. Templates obtained by shifting up/down the expected input value of the EW mixing angle by ± 0.01
3. The expected sensitivity $\delta \sin^2 \theta_W^{\bar{MS}}(m_{ll})$ extracted by fitting the pseudo-data using the xFitter fitting tool (arXiv:1410.4412)

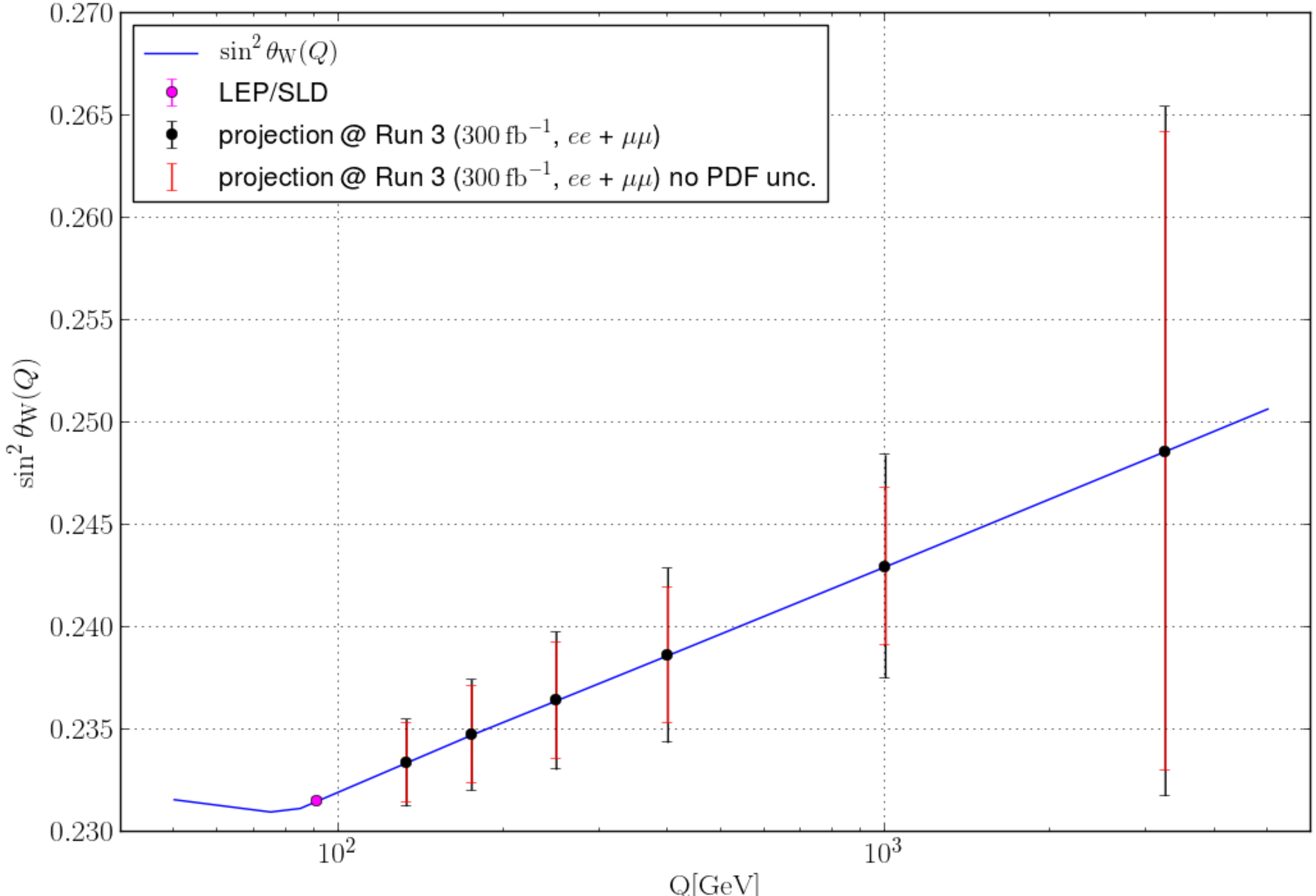




Include experimental $\beta_{j,\mathrm{exp}}$ and PDF unc. β_{th} in the fit:

$$\chi^2(\beta_{\mathrm{exp}}, \beta_{\mathrm{th}}) = \sum_{i=1}^{N_{\mathrm{data}}} \frac{\left(\sigma_i^{\mathrm{exp}} + \sum_j \Gamma_{ij}^{\mathrm{exp}} \beta_{j,\mathrm{exp}} - \sigma_i^{\mathrm{th}} - \sum_k \Gamma_{ik}^{\mathrm{th}} \beta_{k,\mathrm{th}}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\mathrm{exp}}^2 + \sum_k \beta_{k,\mathrm{th}}^2$$

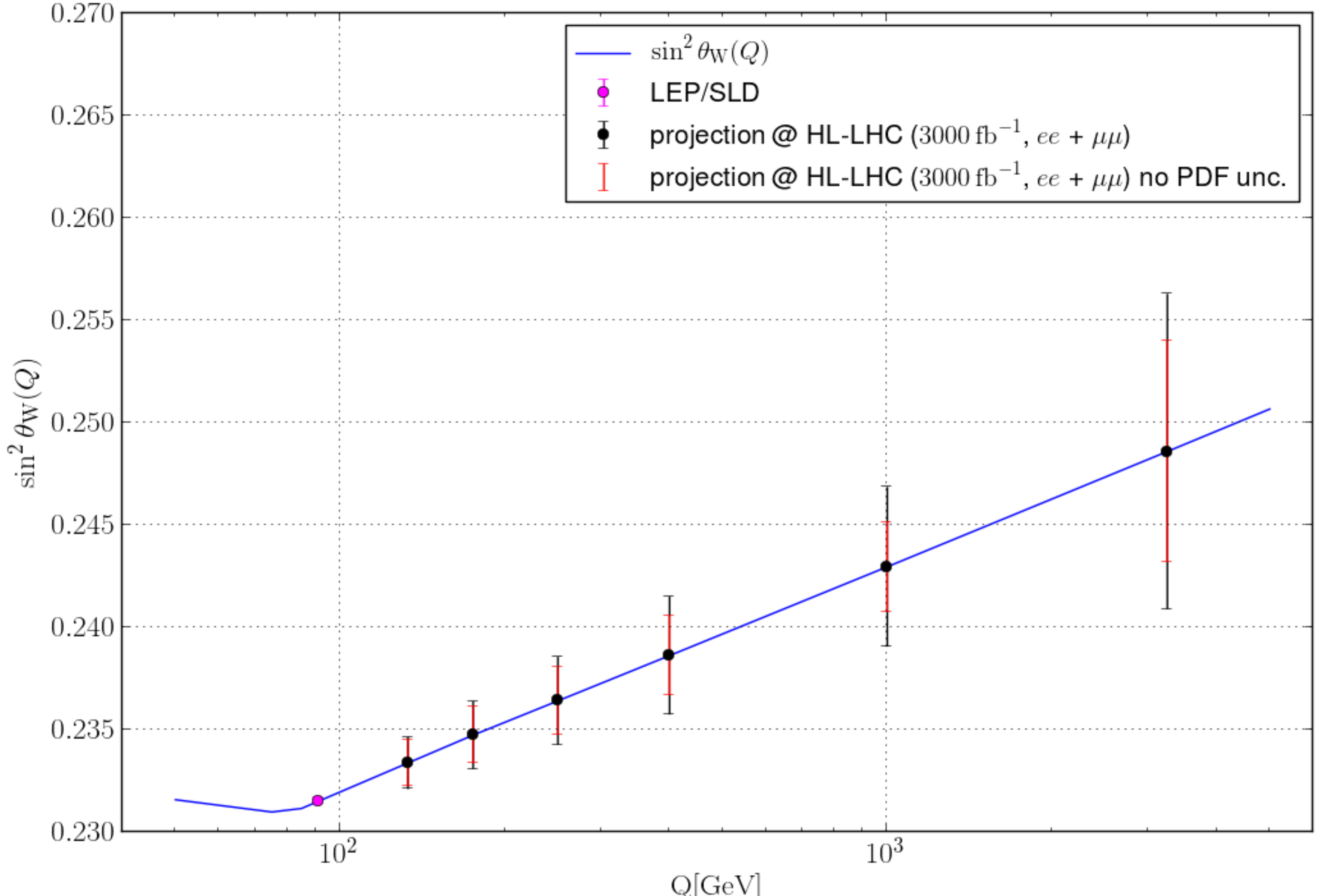
Results @ $300\ \mathrm{fb}^{-1}$ (LHC Run 3)



m_{ll}	$\sin^2\theta_W(m_{ll})$	$\delta \sin^2\theta_W(m_{ll})$	$\delta \sin^2\theta_W(m_{ll})$ (%)
133	0,2334	0,0021	**0,9**
175	0,2347	0,0027	**1,2**
250	0,2364	0,0034	**1,4**
400	0,2386	0,0043	**1,8**
1000	0,2430	0,0055	**2,2**
3250	0,2486	0,0168	**6,8**

Expected sensitivity defined as the post-fit uncertainty on $\sin^2\theta_W^{\bar{MS}}(m_{ll})$

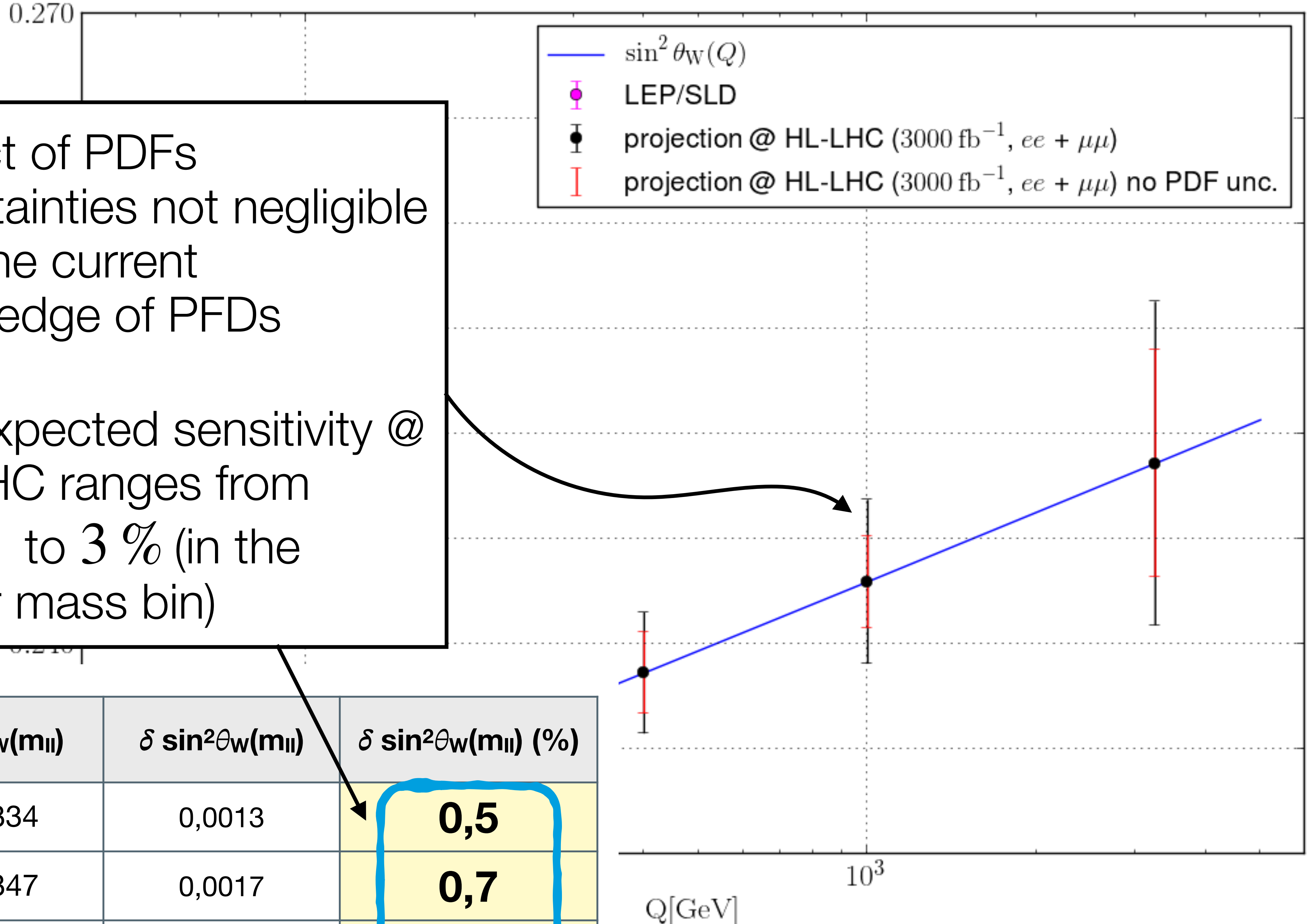
Results @ $3000\ \mathrm{fb}^{-1}$ (HL-LHC)



m_{ll}	$\sin^2\theta_W(m_{ll})$	$\delta \sin^2\theta_W(m_{ll})$	$\delta \sin^2\theta_W(m_{ll})$ (%)
133	0,2334	0,0013	**0,5**
175	0,2347	0,0017	**0,7**
250	0,2364	0,0021	**0,9**
400	0,2386	0,0029	**1,2**
1000	0,2430	0,0039	**1,6**
3250	0,2486	0,0077	**3,1**

← Expected sensitivity defined as the post-fit uncertainty on $\sin^2\theta_W^{\bar{MS}}(m_{ll})$

Results @ $3000\ \mathrm{fb}^{-1}$ (HL-LHC)



- Impact of PDFs uncertainties not negligible with the current knowledge of PFDs
- The expected sensitivity @ HL-LHC ranges from $0.5\ \%$ to $3\ \%$ (in the higher mass bin)

m_{ll}	$\sin^2\theta_W(m_{ll})$	$\delta \sin^2\theta_W(m_{ll})$	$\delta \sin^2\theta_W(m_{ll})$ (%)
133	0,2334	0,0013	**0,5**
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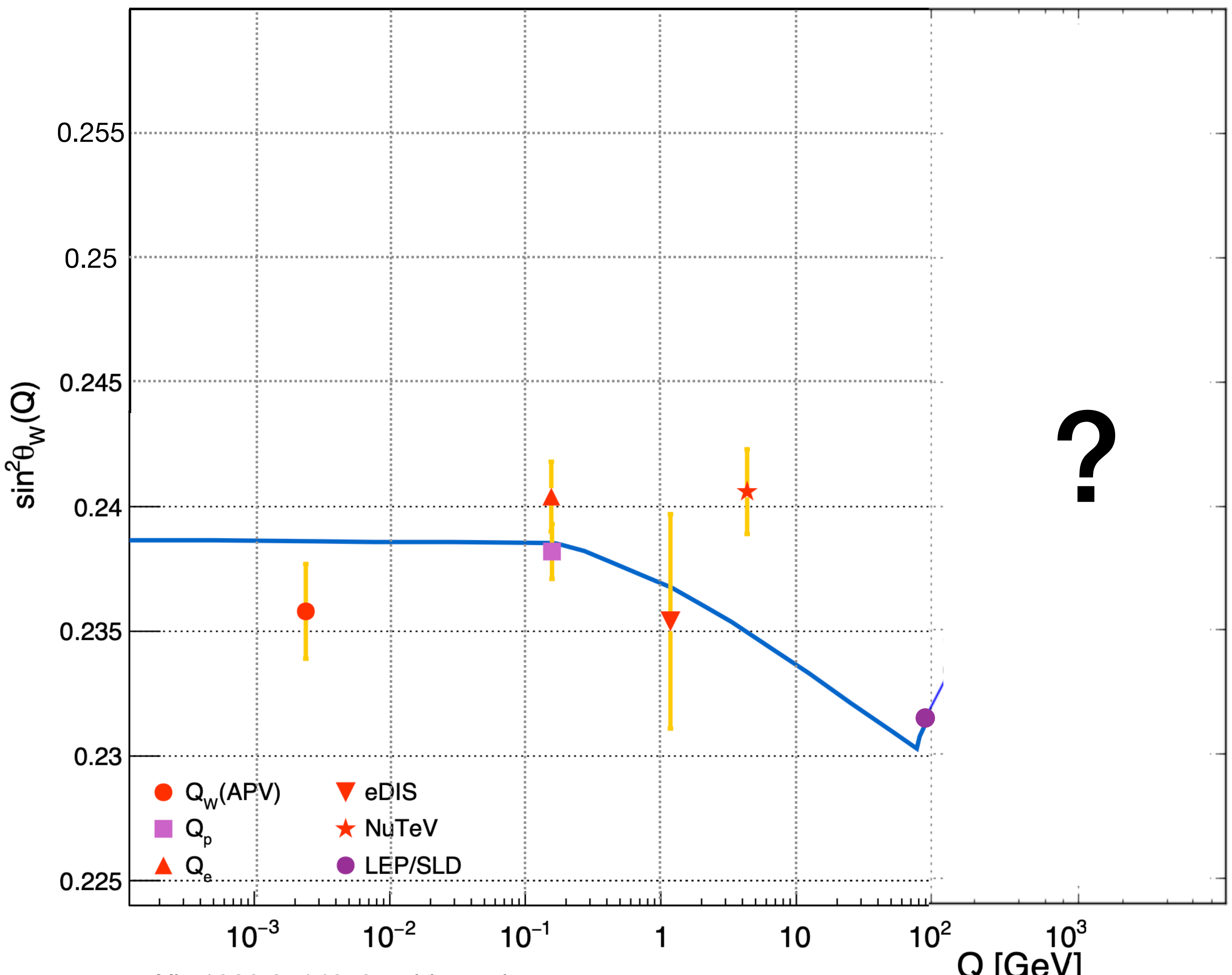
Expected sensitivity defined as the post-fit uncertainty on $\sin^2\theta_W^{\bar{MS}}(m_{ll})$

Results

The **expected sensitivity @ HL-LHC** compared to the experimental determinations of $\sin^2\theta_W^{MS}(\mu)$ at lower energies:

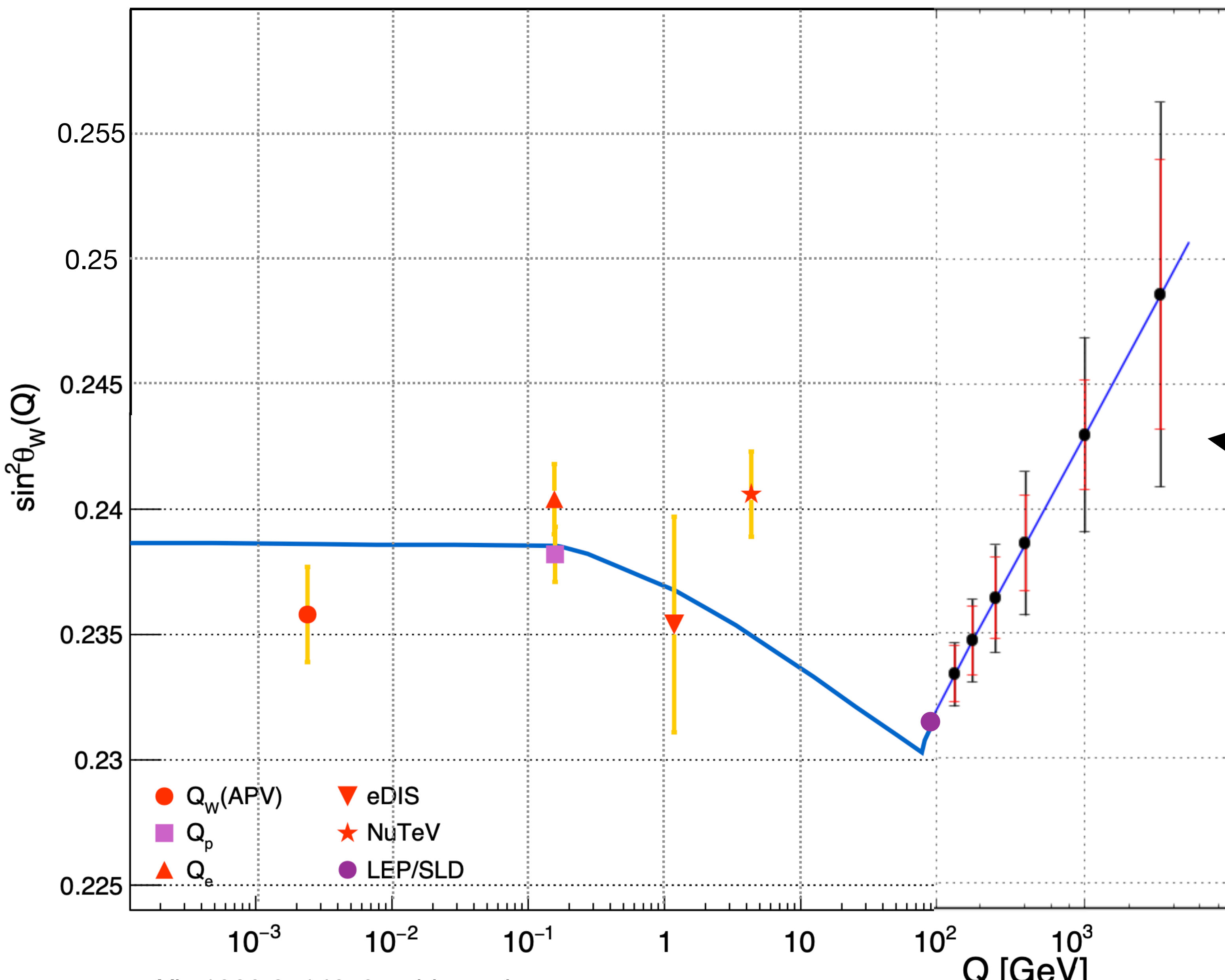


arXiv:1902.05142v2 + this work

Results

The **expected sensitivity @ HL-LHC** compared to the experimental determinations of $\sin^2\theta_W^{MS}(\mu)$ at lower energies:

HL-LHC projections (this work)



arXiv:1902.05142v2 + this work

Summary

First projections for the LHC measurement of $\sin^2\theta_W$ at **high masses!**

Paved the road to **future measurements** of the EW mixing @ the LHC:

- The **running** of the EW mixing angle is **implemented** in a a **public event generator code** (POWHEG-BOX Z_ew_BMNNPV) → allows for extraction of $\sin^2\theta_W$ at high-energy scale
- This sensitivity study shows that the **HL-LHC** is expected to measure the **energy dependence** of $\sin^2\theta_W$ with a **precision of few** $\%$ up to $\approx 3\,\mathrm{TeV}$ (conservative estimate)

Future improvements:

- From a theoretical perspective predictions using full NLO EW calculations → ongoing
- From the phenomenology point of view the impact and constraints of PDFs uncertainties →under investigation

Stay tuned!

Backup

Analysis strategy

Fitted $\frac{d\sigma}{d|yll|dm_{ll}}$ simultaneously for **forward** and **backward** events

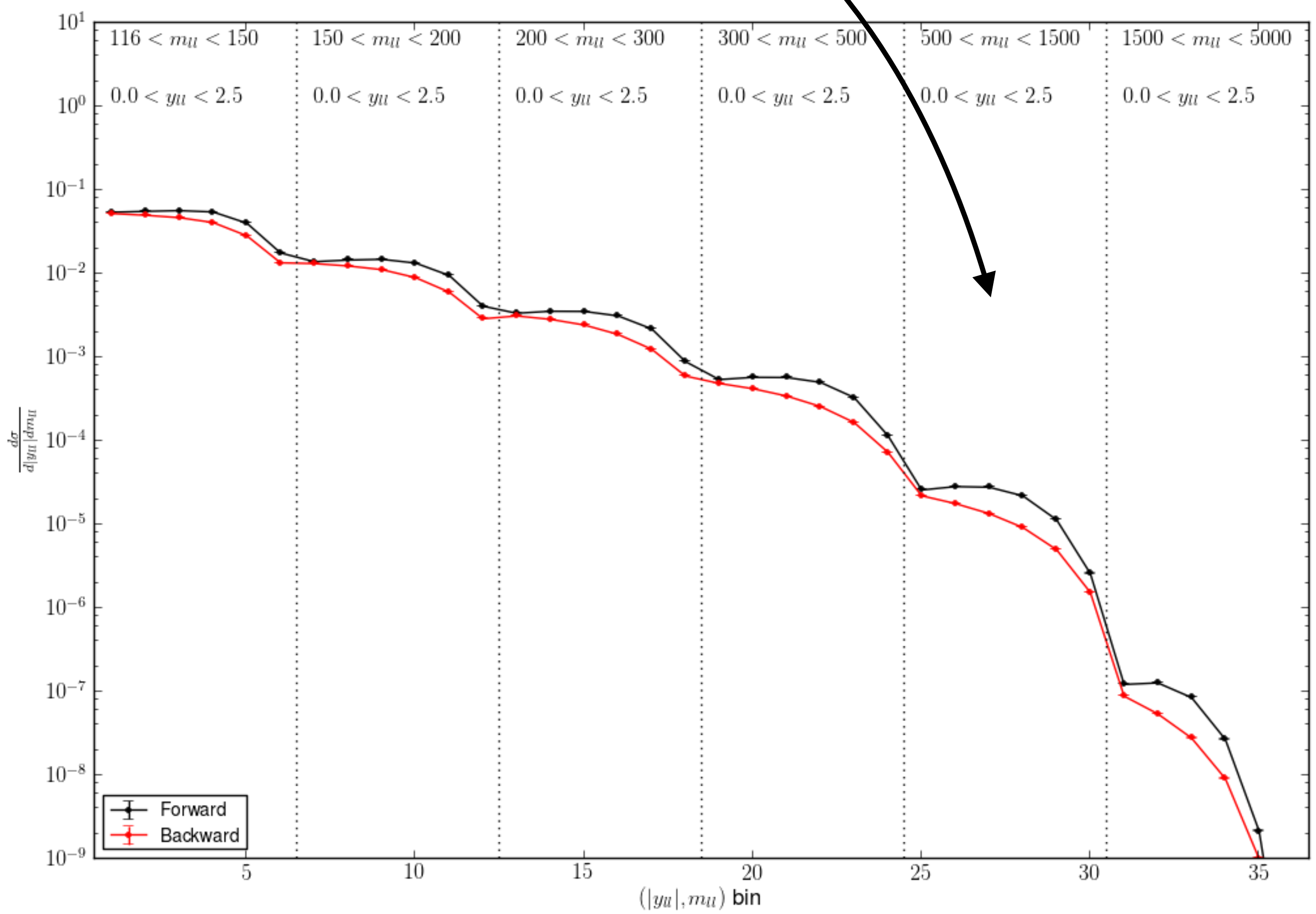
Selection cuts intended to **reproduce** a **realistic** measurement **scenario**:

$p_T^l > 40\,(30)\ \mathrm{GeV},\ |\eta^l| < 2.5$

Binning choice to **balance** between **sensitivity** and expected **number of events**

$m_{ll}\ :\ [116, 150, 200, 300, 500, 1500, 5000]$

$y_{ll}\ :\ [0.0, 0.4, 0.8, 1.2, 1.6, 2.0, 2.5]$



Emulate detector efficiencies using the in RIVET:

- ATLAS Run2 ID/reco efficiencies and smearing for electrons (Eur. Phys. J. C 79 (2019) 639) and muons used (ATL-PHYS-PUB-2015-037)
- Selection efficiencies: $\approx 50\,\%$ flat as a function of m_{ll} for ee and $\mu\mu$ events

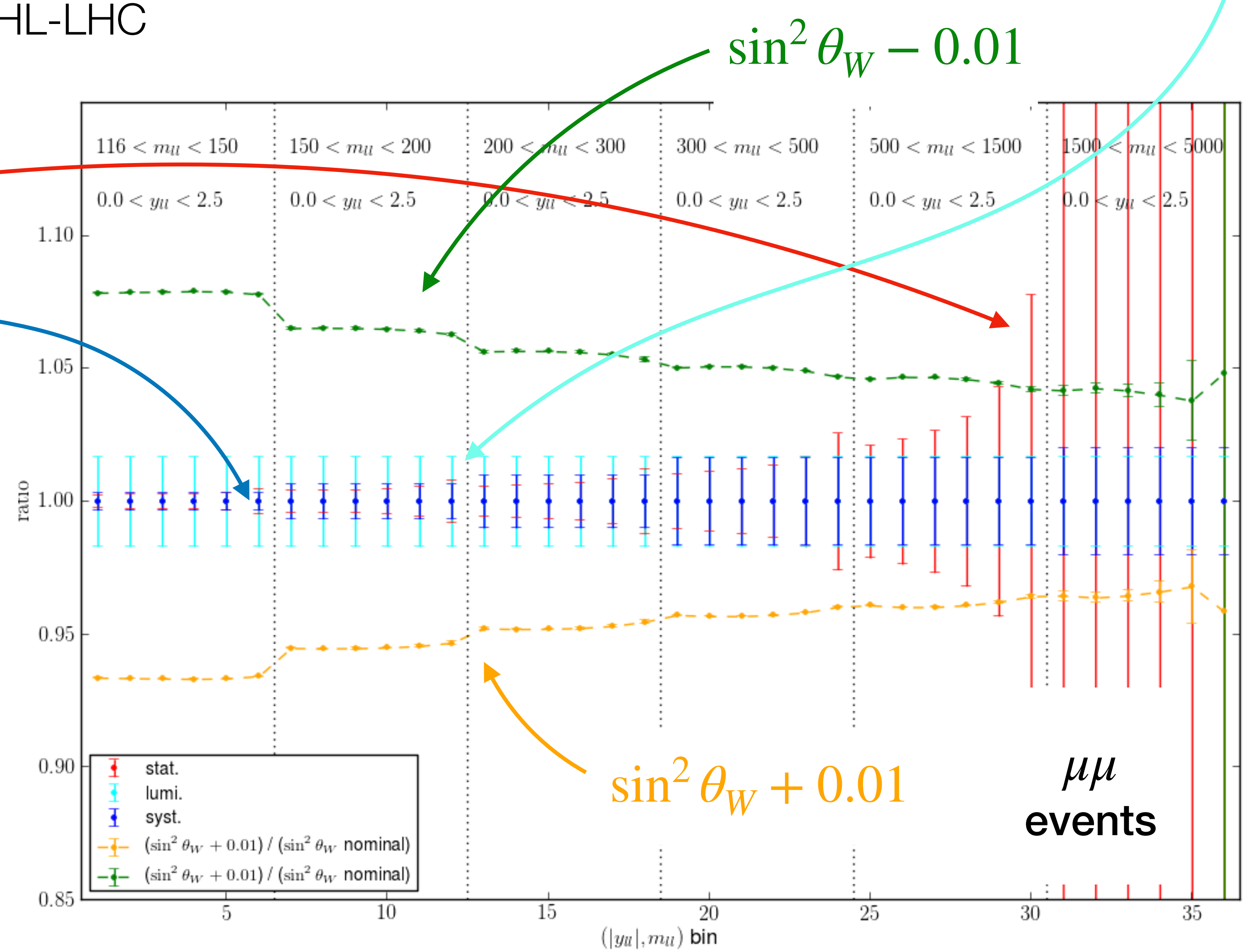
Measurement uncertainties

- **Expected statistical uncertainties** from reconstructed-level expected number of events (for different luminosities)
- **Expected systematic uncertainties** from the current measurements projected @ Run 3 (reduced by factor 2) and HL-LHC (reduced by factor 4)
- **Expected luminosity uncertainty** at HL-LHC → 1% value used

Pre-fit impacts of each uncertainty source on

$$\frac{d\sigma}{d|yll|dm_{ll}}$$

for **forward events in the $\mu\mu$ channel**



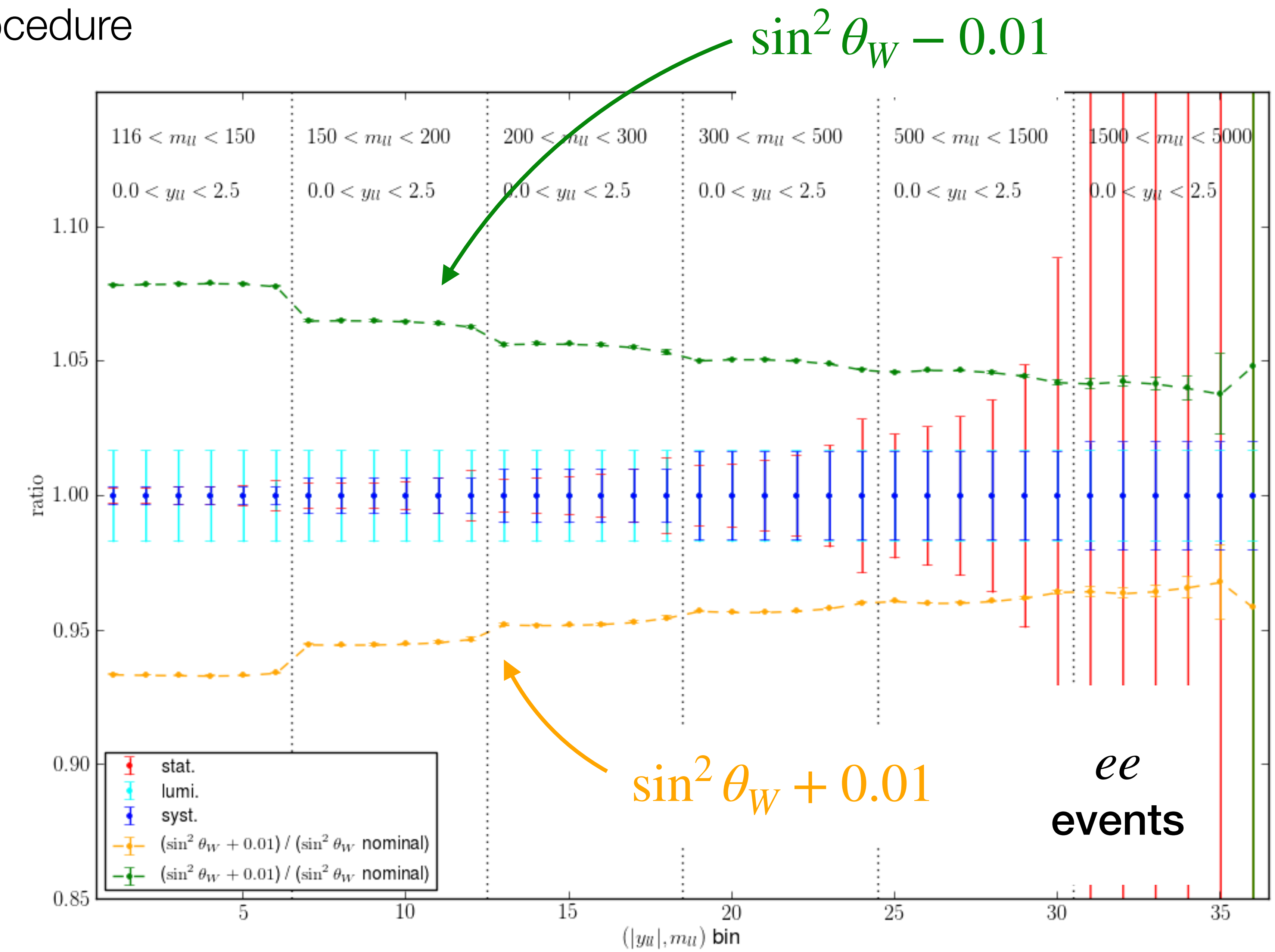
Measurement uncertainties

- **Expected PDF uncertainties** using aMCFast grids convoluted with the NNPDF31_nnlo_as_0118_hessian PDF set:
  - **not showed** here but included in the fit
  - reduced in the fitting procedure
- **Scale uncertainties** are **not considered** → expected to be $< 0.5\ \%$ at NNNLO QCD (JHEP03(2022)116)

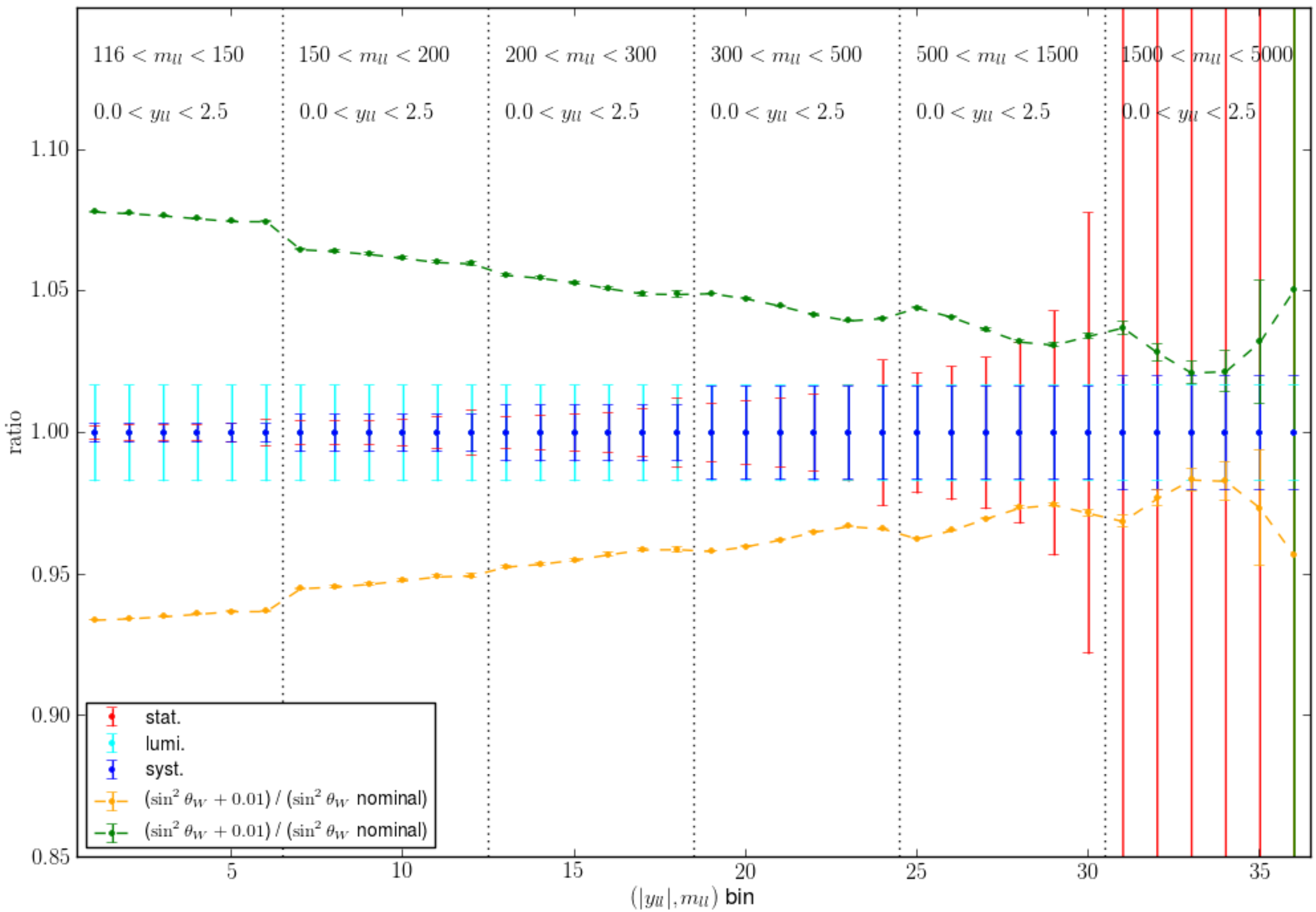
Pre-fit impacts of each uncertainty source on

$$\frac{d\sigma}{d|yll|dm_{ll}}$$

for **forward events in the** ee **channel**



$\frac{d\sigma}{d|yll|dm_{ll}}$ for backward $\mu\mu$ events



$\frac{d\sigma}{d|yll|dm_{ll}}$ for backward ee events