LHC projections for the measurement of the Electroweak mixing angle running

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xFitter external meeting, 04/05/2023

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

$$\sin^2\theta_W \equiv \frac{g_1^2}{g_1^2 + g_2^2} = 1 - \frac{m_\mathrm{W}^2}{m_\mathrm{Z}^2}$$

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

$\sin^2\theta_W$ beyond LO

The following relation is valid at **tree level**

$$\sin^2\theta_W \equiv \frac{g_1^2}{g_1^2+g_2^2} = 1 - \frac{m_\mathrm{W}^2}{m_\mathrm{Z}^2}$$

When considering EW radiative corrections → include **dependence** on **renorm. scheme** + **input param.** → several possible definitions…

On-shell renormalisation

$$\sin^2\theta^\ell_{\mathrm{eff.}} = \kappa_f \sin^2\theta_W$$

EW corrections absorbed into ρ_f and κ_f correction factors

$\kappa_f \sim 1 + \rho_t/\tan^2\theta_W$ and $\rho_f \sim 1 + \rho_t \propto m_t^2$

Definition used in measurements at the Z-boson peak (e.g. at colliders)

Running coupling constant

$$\sin^2\theta_W^{\overline{\mathrm{MS}}}(q^2) \equiv \frac{4\pi\alpha_{\mathrm{EM}}^{\overline{\mathrm{MS}}}(q^2)}{g_2^{2\,\overline{\mathrm{MS}}}(q^2)}$$

In the $\overline{\mathrm{MS}}$ scheme → a "running" quantity (see arXiv:hep-ph/0409169v2)

Can be related to the on-shell definition

$$\bar{s}_W^2(m_Z) \approx s_W^2 + c_W^2(\Delta\rho)_t$$

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

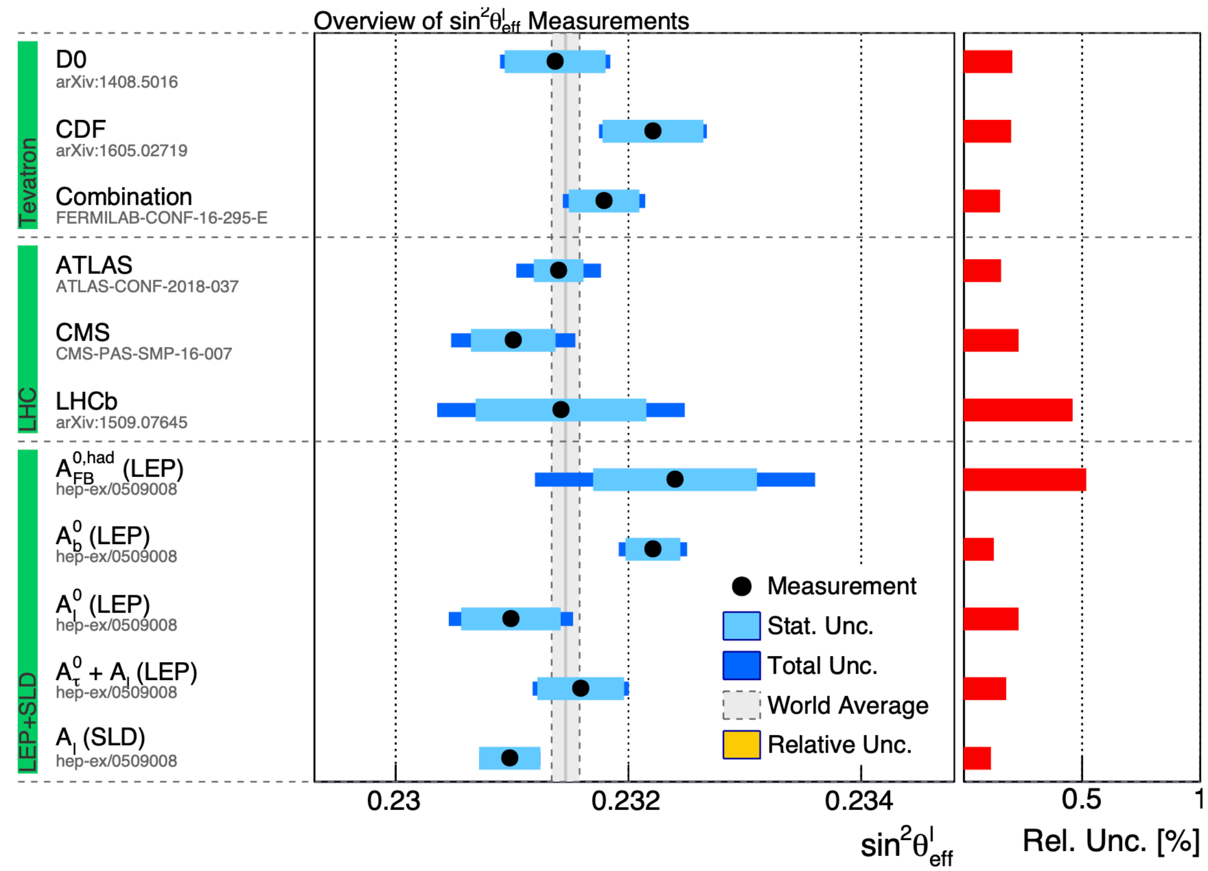
Template fit procedure to measure $\sin^2\theta^f_{\text{eff}}$

$A_{FB}(m_{ll}, |y_{ll}|)$ 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

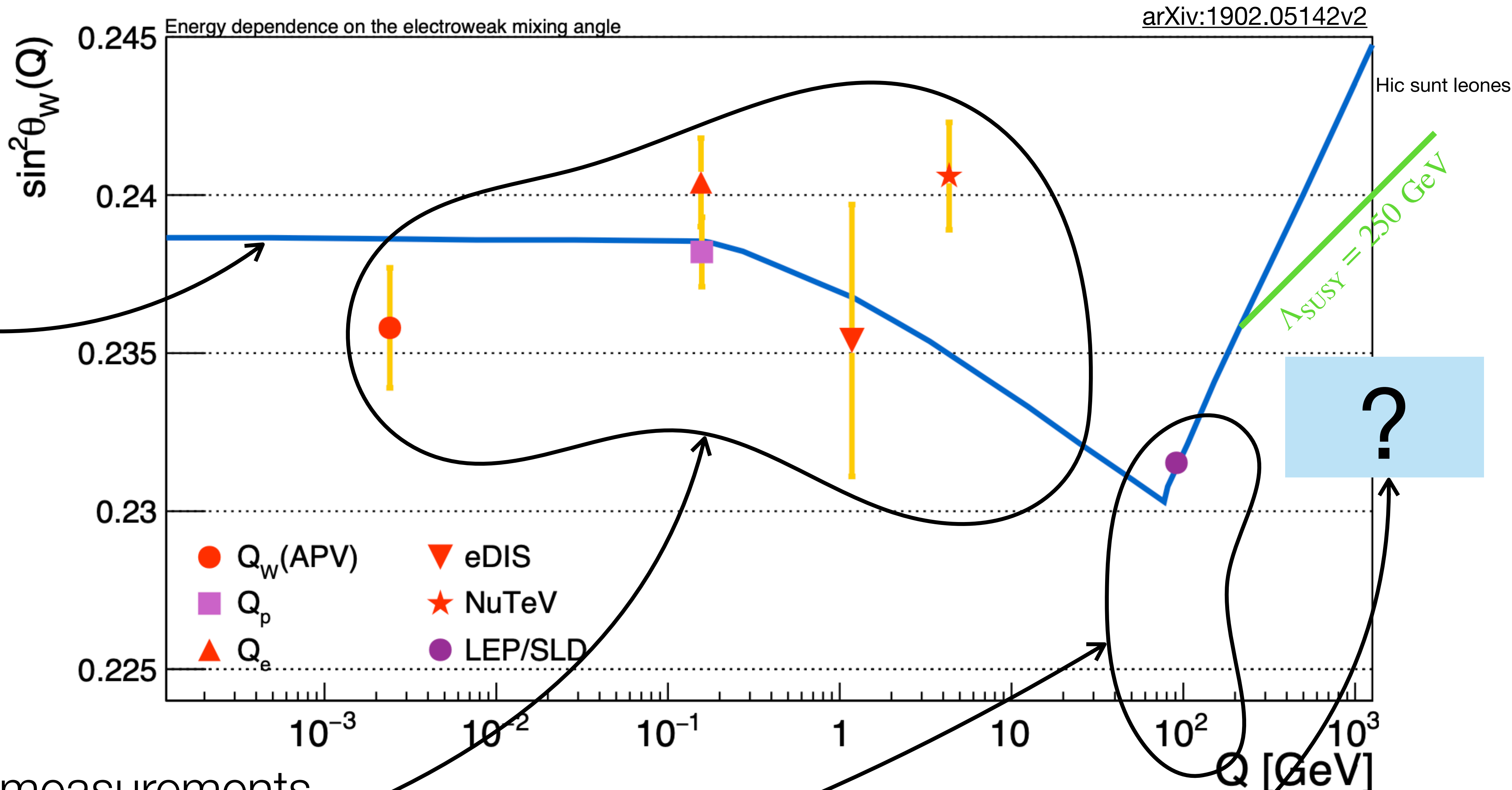


LEP + SLD + Hadron coll. = 0.23151 ± 0.00014

arXiv:1902.05142v2

Available measurements of $\sin^2\theta_W$

Running in the $\overline{\text{MS}}$ renorm. scheme (arXiv:hep-ph/0409169v2)



Many (and planned) measurements at low Q^2 (atomic parity violation, e-DIS, …) and at $Q^2 = m_Z^2$ or slightly above m_Z (HERA, LHC, LHeC, EIC…)

No experimental results on the running of the EW mixing angle at **high energy**

Test the running of $\sin^2\theta_W$ @ the LHC

Recently published a study where we investigated the **sensitivity** of **NCDY measurements** at the LHC to the **energy dependence** of the **Electroweak mixing angle**

- **Full NLO-EW calculation** with an EW scheme with $\sin^2\theta_W^{\overline{\mathrm{MS}}}(q^2)$ as input parameter
- Pseudodata used to extract **expected sensitivities** at the LHC **Run 3** and **HL-LHC** scenarios
- Carefully studied relevant theoretical uncertainties (PDFs + missing HO QCD and EW terms)

Probing the weak mixing angle
at high energies at the LHC and HL-LHC

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Abstract

Measurements of neutral current Drell-Yan production at large invariant dilepton masses can be used to test the energy scale dependence (running) of the electroweak mixing angle. In this work, we make use of a novel implementation of the full next-to-leading order electroweak radiative corrections to the Drell-Yan process using the $\overline{\mathrm{MS}}$ renormalization scheme for the electroweak mixing angle. The potential of future analyses using proton-proton collisions at $\sqrt{s} = 13.6$ TeV in the Run 3 and High-Luminosity phases of the LHC is explored. In this way, the Standard Model predictions for the $\overline{\mathrm{MS}}$ running at TeV scales can be probed.

1. Introduction

The electroweak mixing angle, θ_W, is one of the fundamental parameters of the Standard Model (SM) of particle physics. In the electroweak (EW) SM Lagrangian it is defined as

$$\sin^2\theta_W \equiv \frac{g_1^2}{g_1^2 + g_2^2}, \tag{1}$$

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arXiv:2302.10782 (submitted to PLB)

Test the running of $\sin^2\theta_W$ @ the LHC

How

- In our work, $\mu = m_{ll}$ is used as the dynamic energy scale
- Extract the expected sensitivity to $\sin^2\theta_W^{\overline{MS}}(\hat{m}_{ll})$ in **several mass bin**
- Use one billion events calculated @ NLOQCD + NLOEW (only virtual weak) with POWHEG-BOX, showered with PYTHIA8 to perform a template fit
- Used hybrid scheme $(\alpha^{\overline{\text{MS}}}(\mu), m_Z, \sin^2\theta_W^{\overline{\text{MS}}}(\mu))$ where α and $\sin^2\theta_W$ are running quantities while m_Z is treated as an on-shell quantity
- Templates generated by varying $\sin^2\theta_W^{\overline{MS}}(\hat{m}_{ll}) \pm 0.01$

$\mathrm{m}_{\ell\ell}^{\mathrm{lo}}$ [GeV]	$\mathrm{m}_{\ell\ell}^{\mathrm{hi}}$ [GeV]	$\hat{\mathrm{m}}_{\ell\ell}$ [GeV]	$(\alpha_{\mathrm{EM}}^{\overline{\mathrm{MS}}}(\hat{\mathrm{m}}_{\ell\ell}))^{-1}$	$\sin^2\theta_W^{\overline{\mathrm{MS}}}(\hat{\mathrm{m}}_{\ell\ell})$
66	116	m_Z	127.951	0.23122
116	150	133	127.838	0.23323
150	200	175	127.752	0.23468
200	300	250	127.544	0.23648
300	500	400	127.269	0.23885
500	1500	1000	126.735	0.24350
1500	5000	3250	126.047	0.24954

Test the running of $\sin^2\theta_W$ @ the LHC

How

- The template fit is done using triple differential NCDY cross-sections:

  - The absolute differential cross section is **more suitable observable** w.r.t. A_{FB} for the extraction of $\sin^2\theta_W^{\overline{\mathrm{MS}}}(q^2)$ **above** m_Z (factor ~3 more sensitive, more in the backup)

  - By considering fully differential information combine the sensitivity of the absolute cross-section and A_{FB}

  - Two LHC scenarios considered: **Run 3** $(300\ \mathrm{fb}^{-1})$ and **HL-LHC** $(3000\ \mathrm{fb}^{-1})$

  - Selection cuts and binning choices intended to reproduce a realistic measurement scenario:

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

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

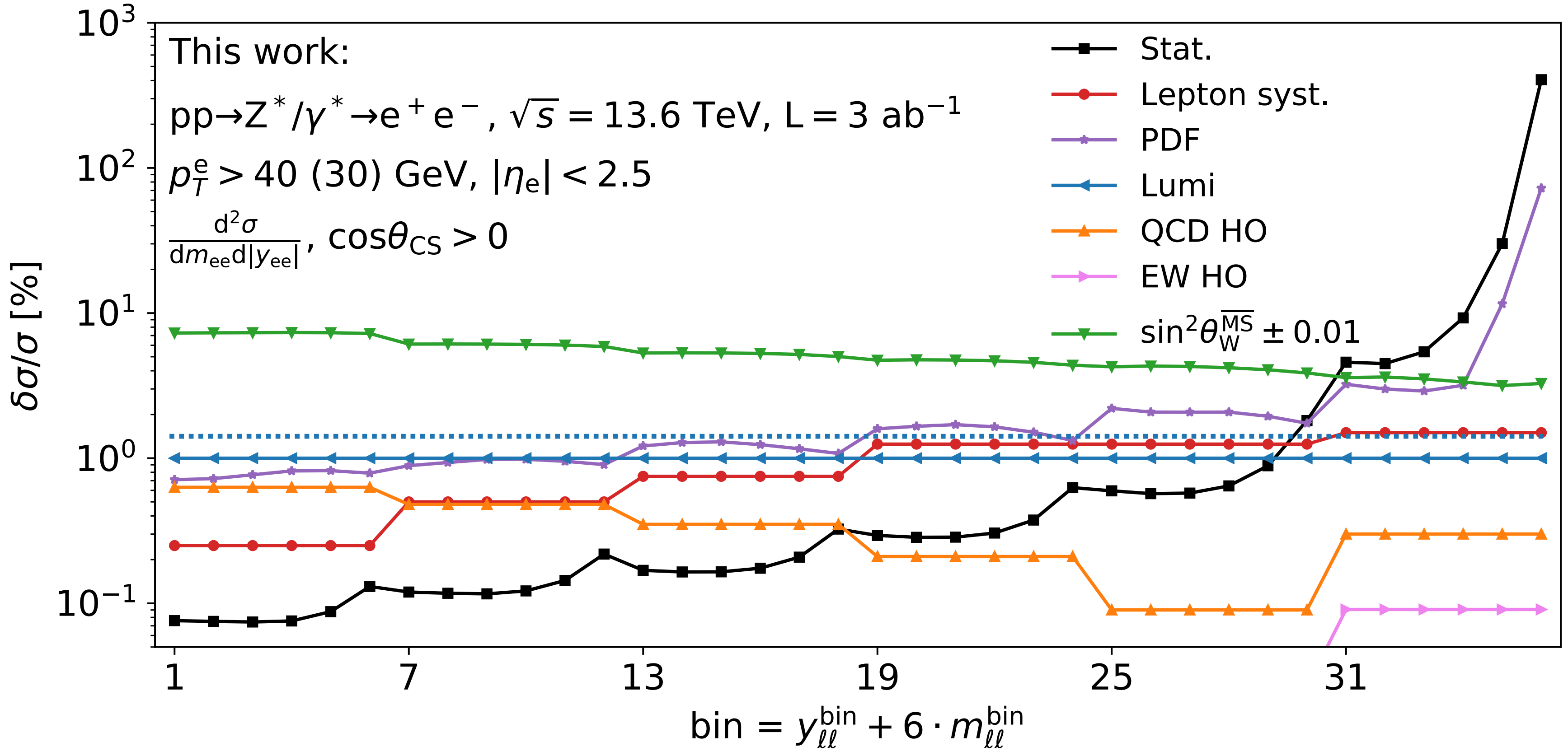
$$y_{ll}\ :\ [0.0, 0.4, 0.8, 1.2, 1.6, 2.0, 2.5]$$

$$\cos\theta_{CS}^{ll}\ :\ [-1.0, 0.0, 1.0]$$

Test the running of $\sin^2\theta_W$ @ the LHC

How

The (expected) relative contribution of different sources of uncertainties to the 3D cross section (HL-LHC extrapolations)



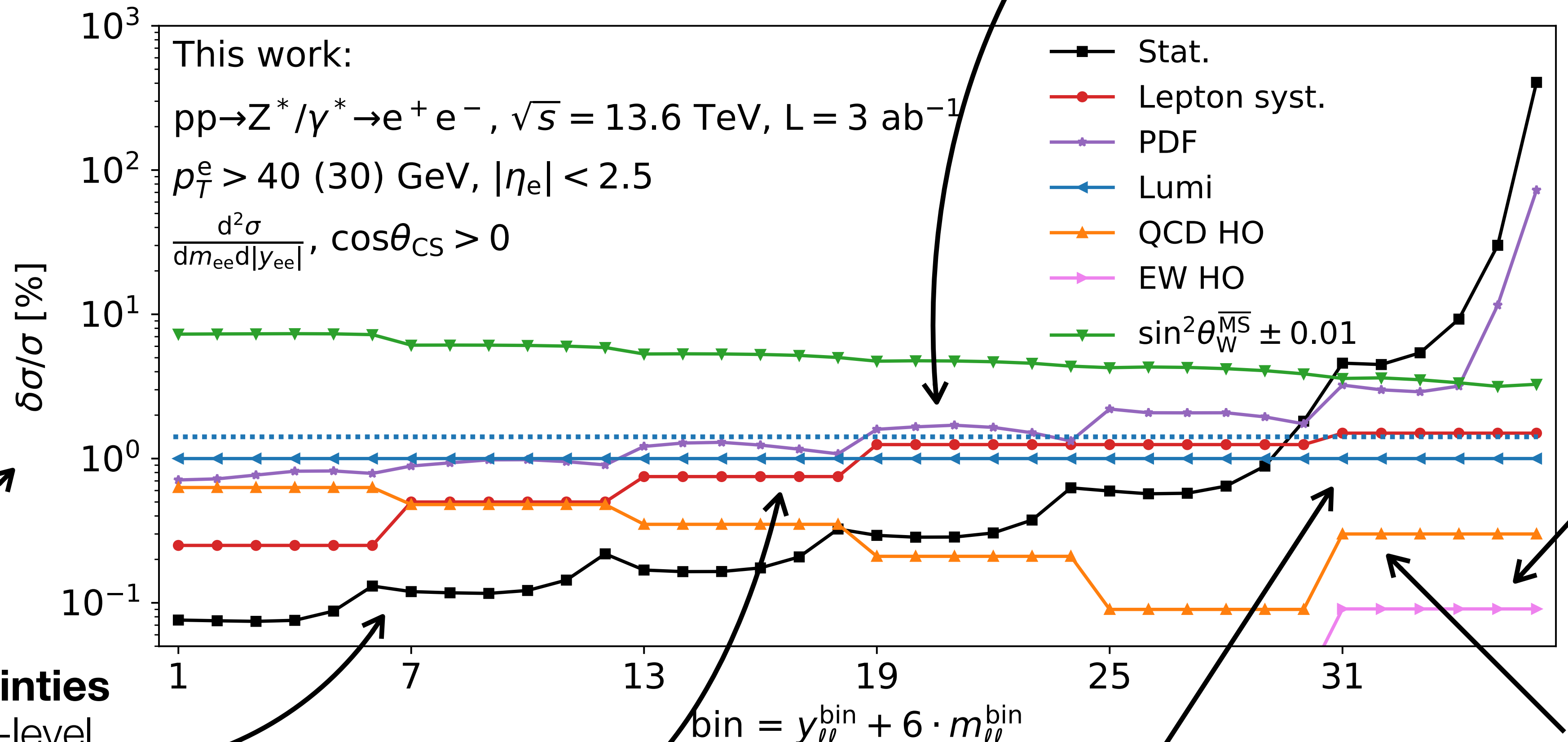
Test the running of $\sin^2\theta_W$ @ the LHC

How

Similar results for backward ($\cos\theta_{CS} < 0$) events and for the $\mu\mu$ channel

The (expected) relative contribution of different sources of uncertainties to the 3D cross section (HL-LHC extrapolations)

Pre-fit impacts of each uncertainty source on $\frac{d\sigma}{d|y_{ll}|dm_{ll}}$ for **forward events** ($\cos\theta_{CS} > 0$) **in the ee channel**



Expected PDF uncertainties using aMCFast grids convoluted with the NNPDF31_nnlo_as_0118_hessian PDF set (reduced in the fitting procedure)

Missing EW higher orders NLO EW adopting $m_{\ell\ell}$ scale variations of a factor of 2

Statistical uncertainties from reconstructed-level expected number of events (emulate realistic detector efficiencies and resolutions (from ATLAS) using RIVET smearing)

Lepton systematic uncertainties from current measurements projected @ Run 3 (reduced by factor 2) and HL-LHC (reduced by factor 4)

luminosity uncertainty at HL-LHC 1% value used (1.5% at Run 3)

Missing QCD higher orders evaluated at N3LO for $d\sigma/dm_{\ell\ell}$, applied to the $(|y_{\ell\ell}|, m_{\ell\ell}, \cos\theta_{CS}^{\ell\ell})$ bins assumed uncorrelated

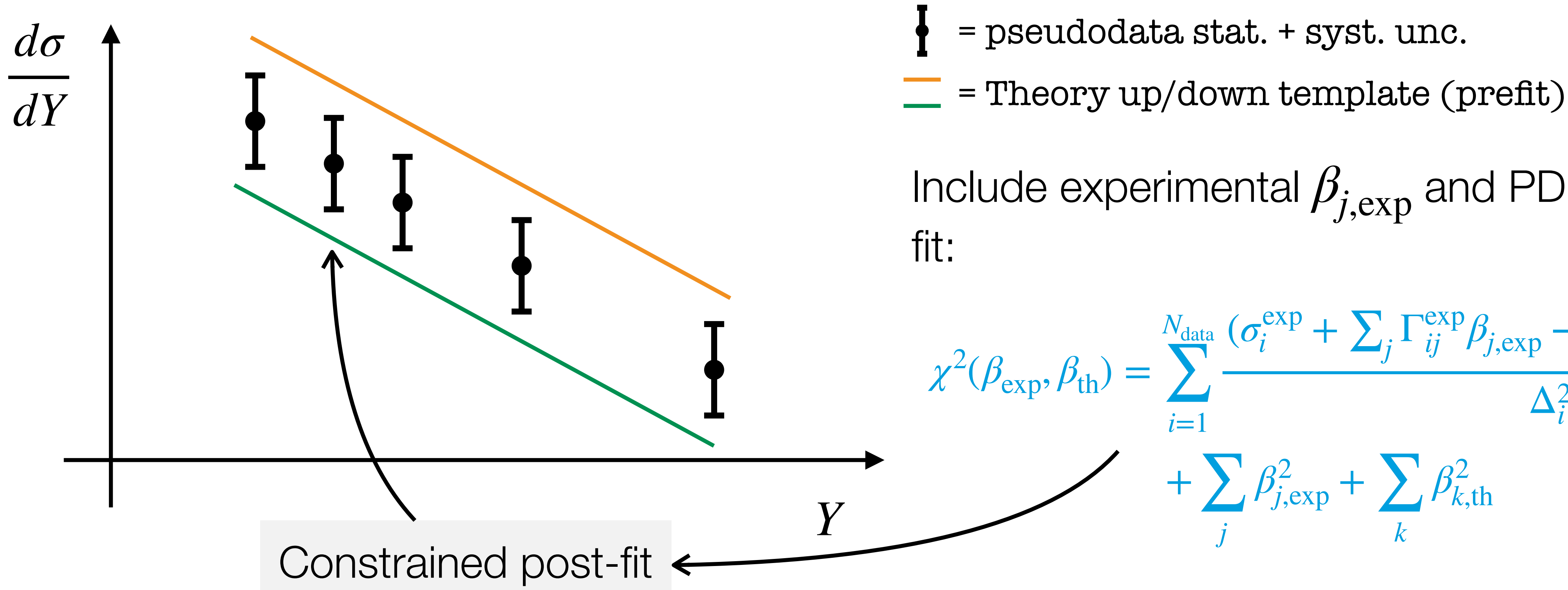
Test the running of $\sin^2\theta_W$ @ the LHC

How

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) using linear approximation for $\delta \sin^2\theta_W^{\bar{MS}}(m_{ll})$



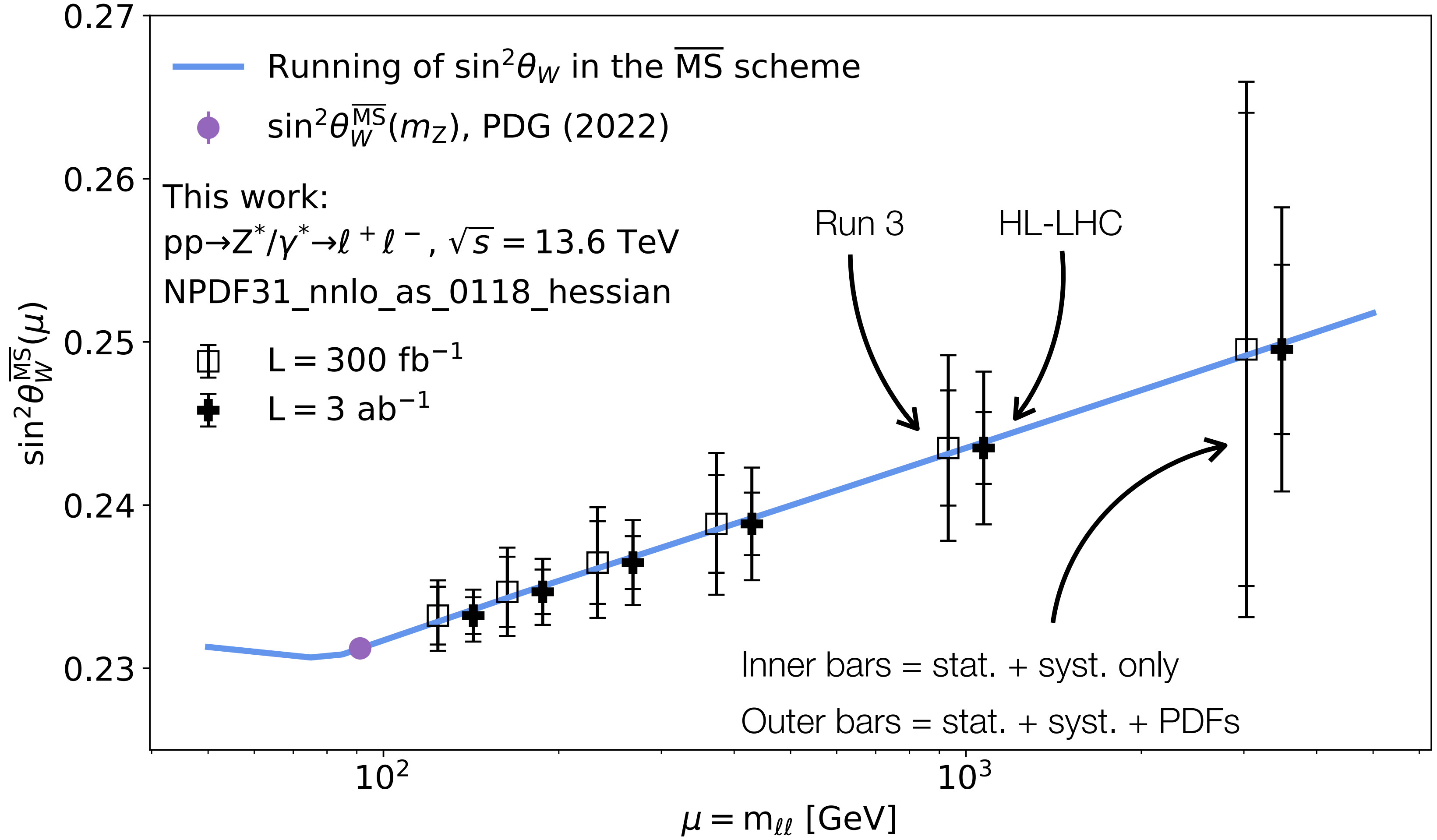
Include experimental $\beta_{j,\text{exp}}$ and PDF unc. β_{th} in the fit:

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

Test the running of $\sin^2\theta_W$ @ the LHC

Results

The expected sensitivity is defined as the post-fit uncertainty on $\sin^2\theta_W^{\overline{MS}}(m_{ll})$



Sensitivity

Run 3: 1% - 7%

HL-LHC: 1% - 3%

$\hat{m}_{\ell\ell}$ [GeV]	$\sin^2\theta_W^{\overline{MS}}(\hat{m}_{\ell\ell})$	Run 3		HL-LHC	
		$\delta\sin^2\theta_W^{\overline{MS}}(\hat{m}_{\ell\ell})$	[%]	$\delta\sin^2\theta_W^{\overline{MS}}(\hat{m}_{\ell\ell})$	[%]
133	0.23323	0.00216	0.9	0.00159	0.7
175	0.23468	0.00271	1.2	0.00202	0.9
250	0.23648	0.00339	1.4	0.00260	1.1
400	0.23885	0.00434	1.8	0.00345	1.4
1000	0.24350	0.00569	2.3	0.00468	1.9
3250	0.24954	0.01640	6.6	0.00870	3.5

Test the running of $\sin^2\theta_W$ @ the LHC

Results

The expected sensitivity is defined as the post-fit uncertainty on $\sin^2\theta_W^{\overline{MS}}(m_{ll})$

Sensitivity

Run 3: 1% - 7%

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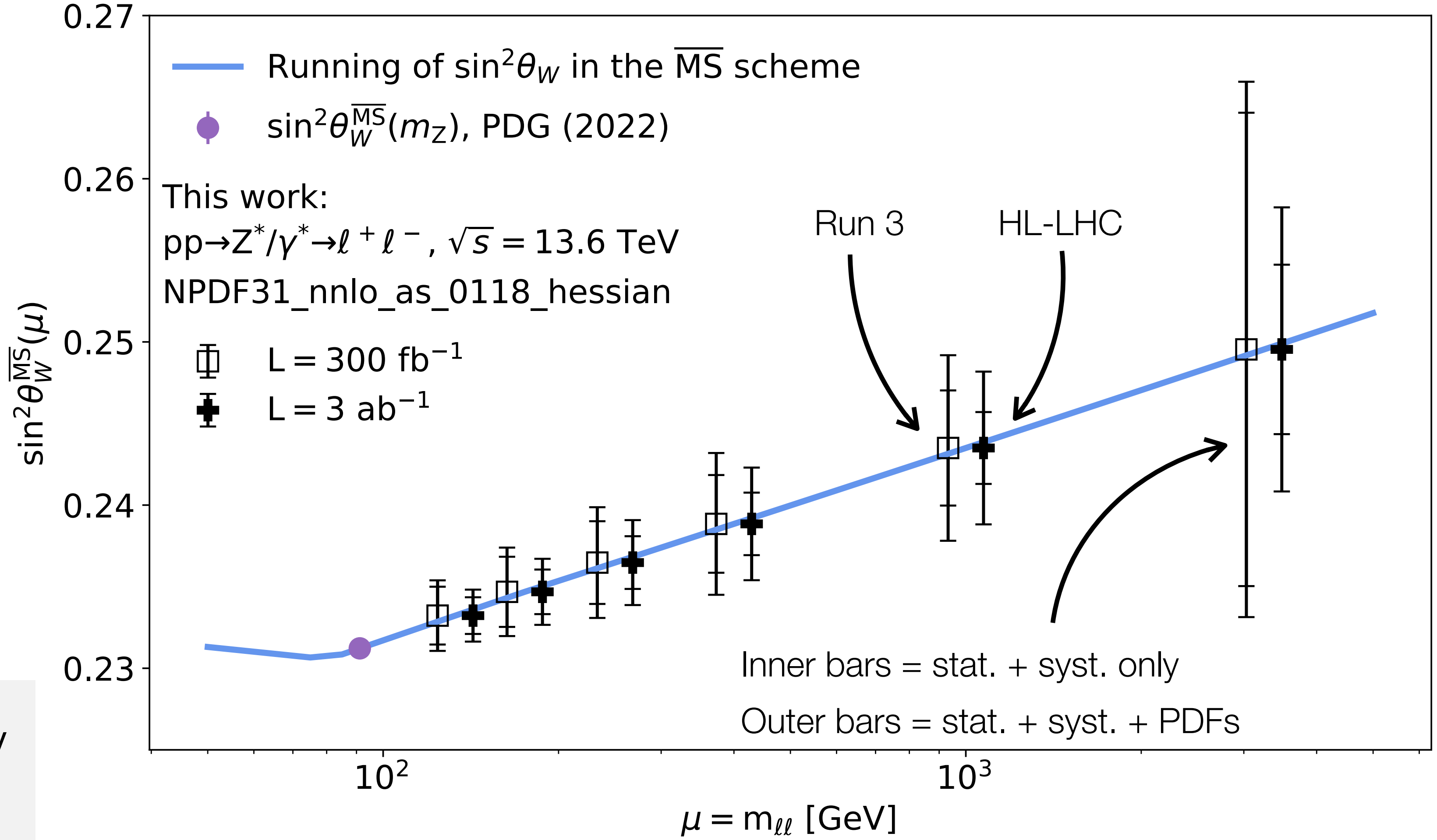


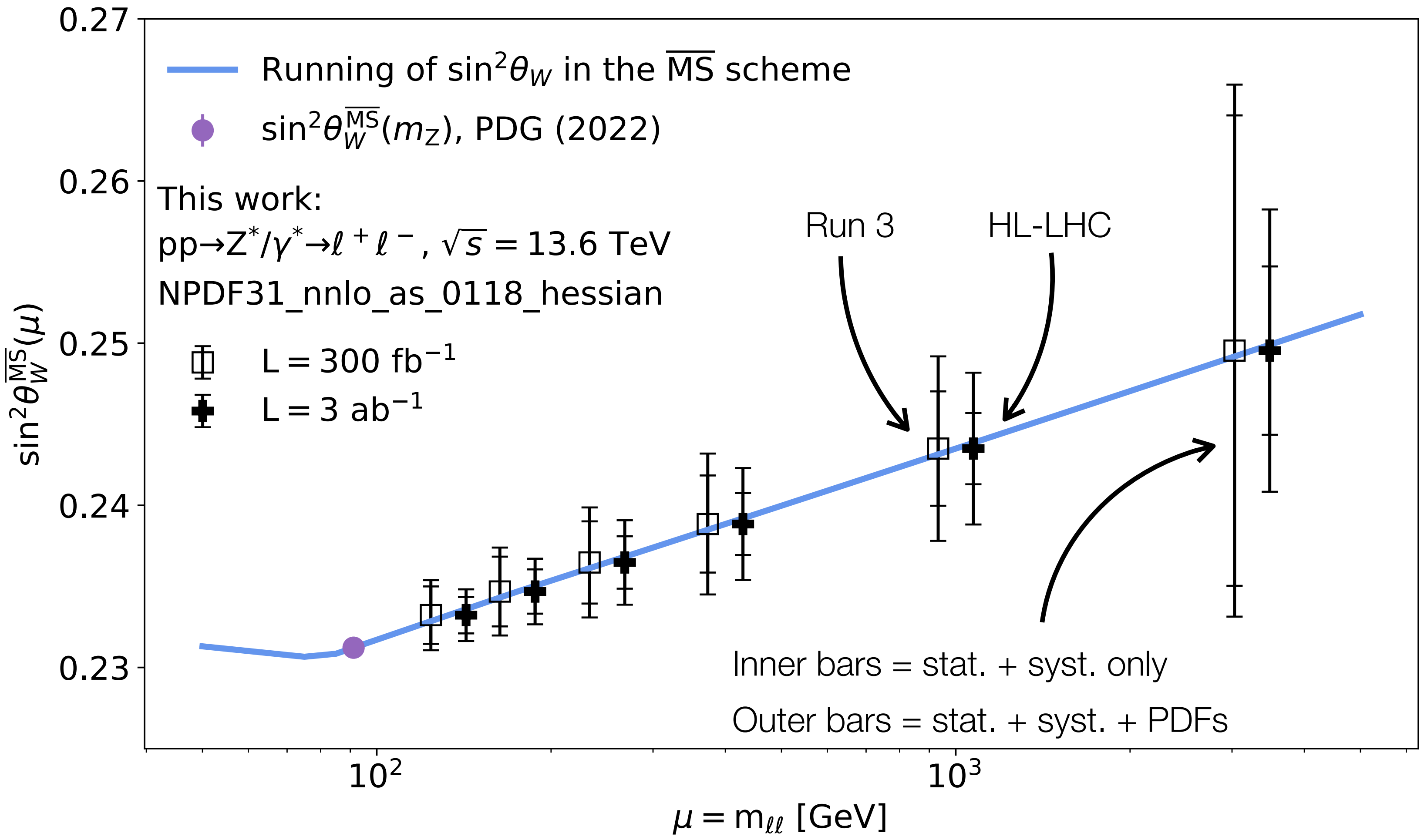
Contribution of the PDF uncertainty in the HL-LHC scenario

Impact of PDFs uncertainties is not negligible with the current knowledge of PFDs

NNPDF31 uncertainty conservative

$\hat{m}_{\ell\ell}$ [GeV]	$\delta\sin^2\theta_W^{\overline{MS}}(\hat{m}_{\ell\ell})$ [%]				
	NNPDF31	NNPDF40	MSHT20	CT18A	ABMP16
133	0.5	0.3	0.6	0.9	0.5
175	0.6	0.4	0.8	1.0	0.6
250	0.8	0.5	0.9	1.2	0.7
400	1.2	0.6	1.2	1.5	0.8
1000	1.6	0.8	1.6	1.8	1.0
3250	2.7	1.6	2.5	2.8	1.3

Summary

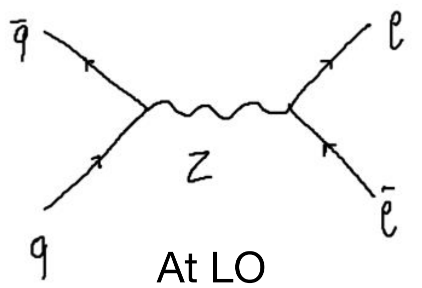


- First projections for the measurement of the the running of $\sin^2\theta_W^{\overline{\text{MS}}}(\mu)$ at NLO at high masses
- NLO EW MC code with $\sin^2\theta_W^{\overline{\text{MS}}}(\mu)$ as input parameter → direct (and consistent) determination of this parameter at hadron colliders
- In principle possible to test the running already at the end of LHC Run 3
- Precision of few % up to ~ 3 TeV → large uncertainty due to PDFs

Backup

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

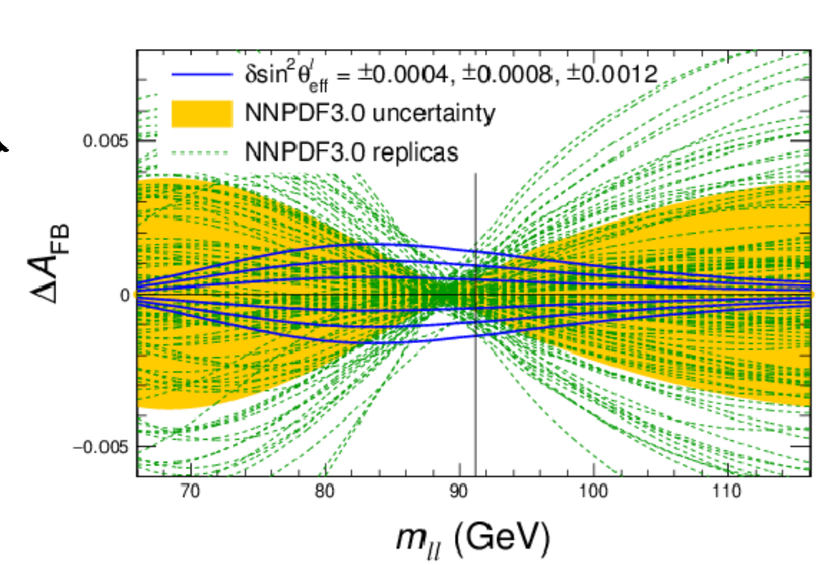


At LO

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

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

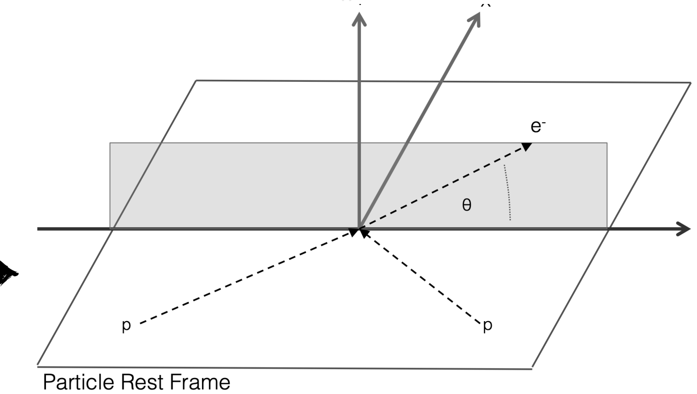
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$



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

Why absolute cross sections instead of A_{FB}

At LO the triple differential NCDY cross section can be expressed as

In the limit $m_{\ell\ell} \gg m_Z$

$$\frac{d\sigma}{dM_{\ell\ell}} = \frac{\pi}{648\, M_{\ell\ell}^3} \sum_q C_q(\alpha_Y, \alpha_2, M_{\ell\ell}) \times \int_{-\ln\frac{\sqrt{s}}{M_{\ell\ell}}}^{\ln\frac{\sqrt{s}}{M_{\ell\ell}}} dy\, [x_1 f_q(x_1)\, x_2 f_{\bar{q}}(x_2)]$$

$$C_u(\alpha_i) = 85\alpha_Y^2 + 6\alpha_Y\alpha_2 + 9\alpha_2^2$$
$$C_d(\alpha_i) = 25\alpha_Y^2 - 6\alpha_Y\alpha_2 + 9\alpha_2^2$$

where $s_W^2 = \alpha_Y/(\alpha_2 + \alpha_Y)$

(see 1602.03877)

At high $m_{\ell\ell}$ the 3D cross section is a more suitable observable for the extraction of $\sin^2\theta_W^{\overline{\rm MS}}(\mu)$ then A_{FB}

If we look at the logarithmic derivatives w.r.t. $\sin^2\theta_W^{\overline{\rm MS}}(\mu)$ at $m_{\ell\ell} = 1$ TeV and $\sqrt{s} = 13$ TeV

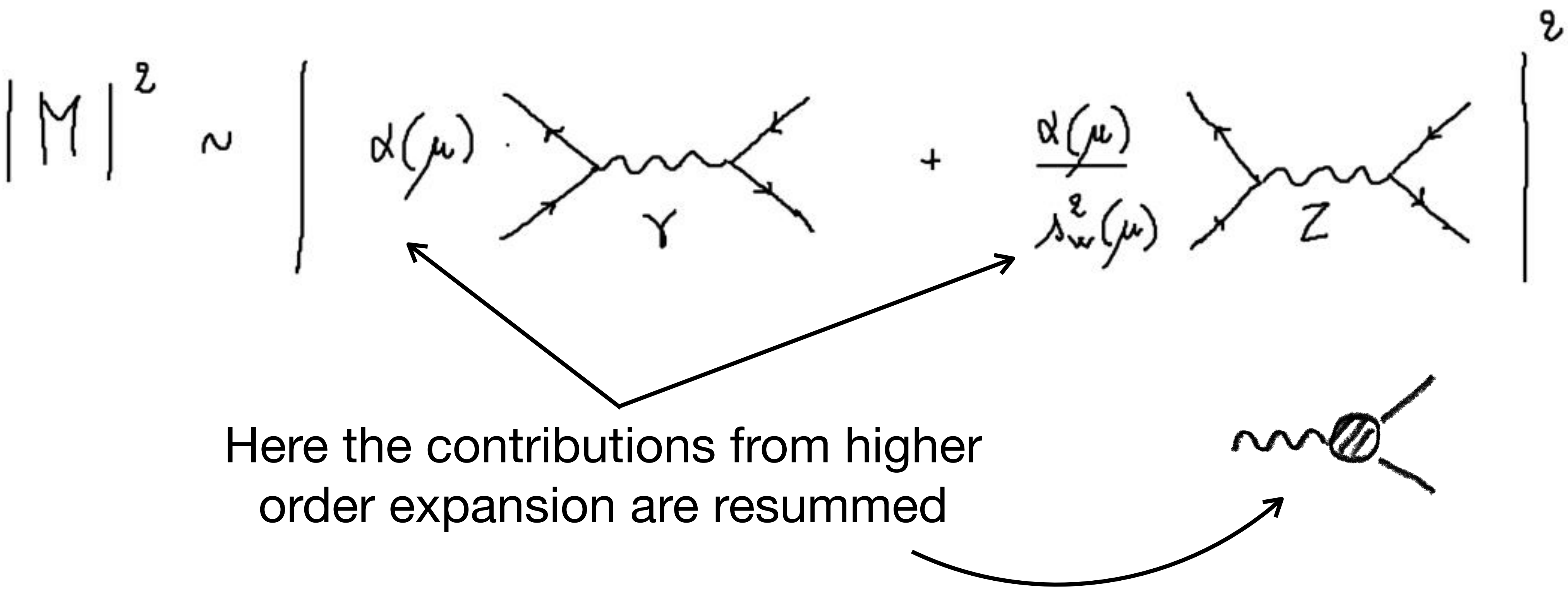
$$\left.\frac{\delta\, \frac{\mathrm{d}^3\sigma}{\mathrm{dm}_{\ell\ell}\mathrm{d}y_{\ell\ell}\mathrm{d}\cos\theta_{CS}}}{\frac{\mathrm{d}^3\sigma}{\mathrm{dm}_{\ell\ell}\mathrm{d}y_{\ell\ell}\mathrm{d}\cos\theta_{CS}}}\right|_{\mu=1\ \mathrm{TeV}} \sim 0.9\, \frac{\delta\, \sin^2\theta_w^{\overline{MS}}(\mu)}{\sin^2\theta_w^{\overline{MS}}(\mu)}$$

$$\left.\frac{\delta\, A_{FB}}{A_{FB}}\right|_{\mu=1\ \mathrm{TeV}} \sim 0.3\, \frac{\delta\, \sin^2\theta_w^{\overline{MS}}(\mu)}{\sin^2\theta_w^{\overline{MS}}(\mu)}$$

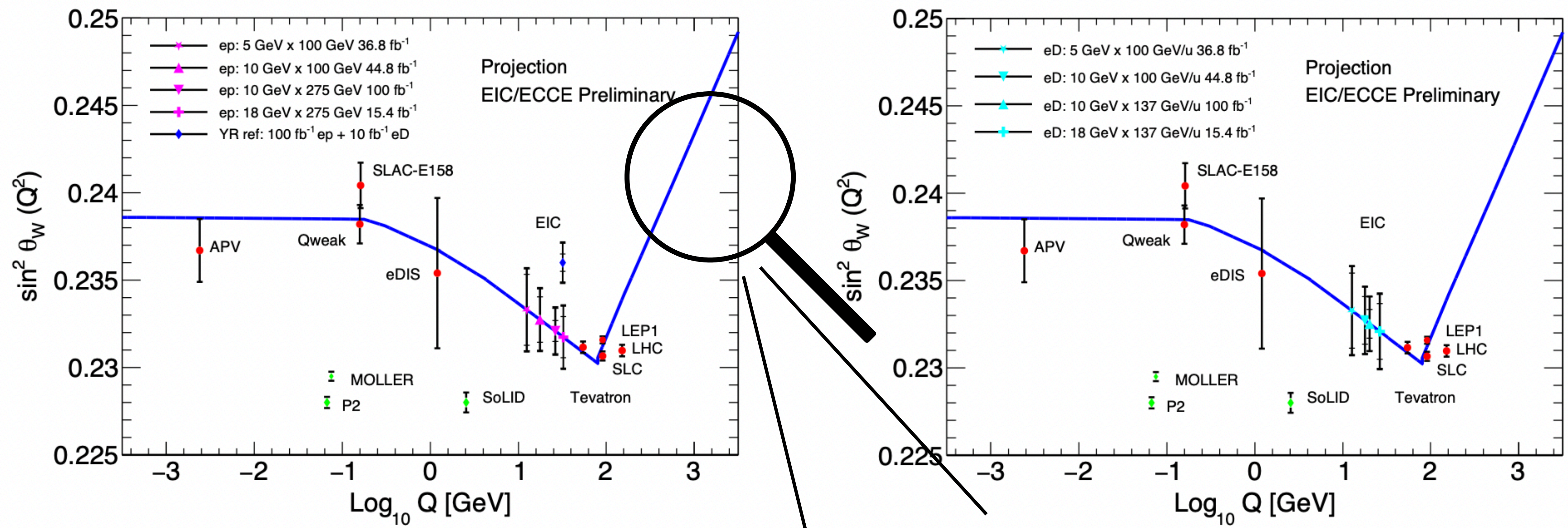
Implementation of $\sin^2\theta_W^{\overline{\mathrm{MS}}}(\mu)$ in POWHEG-BOX

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

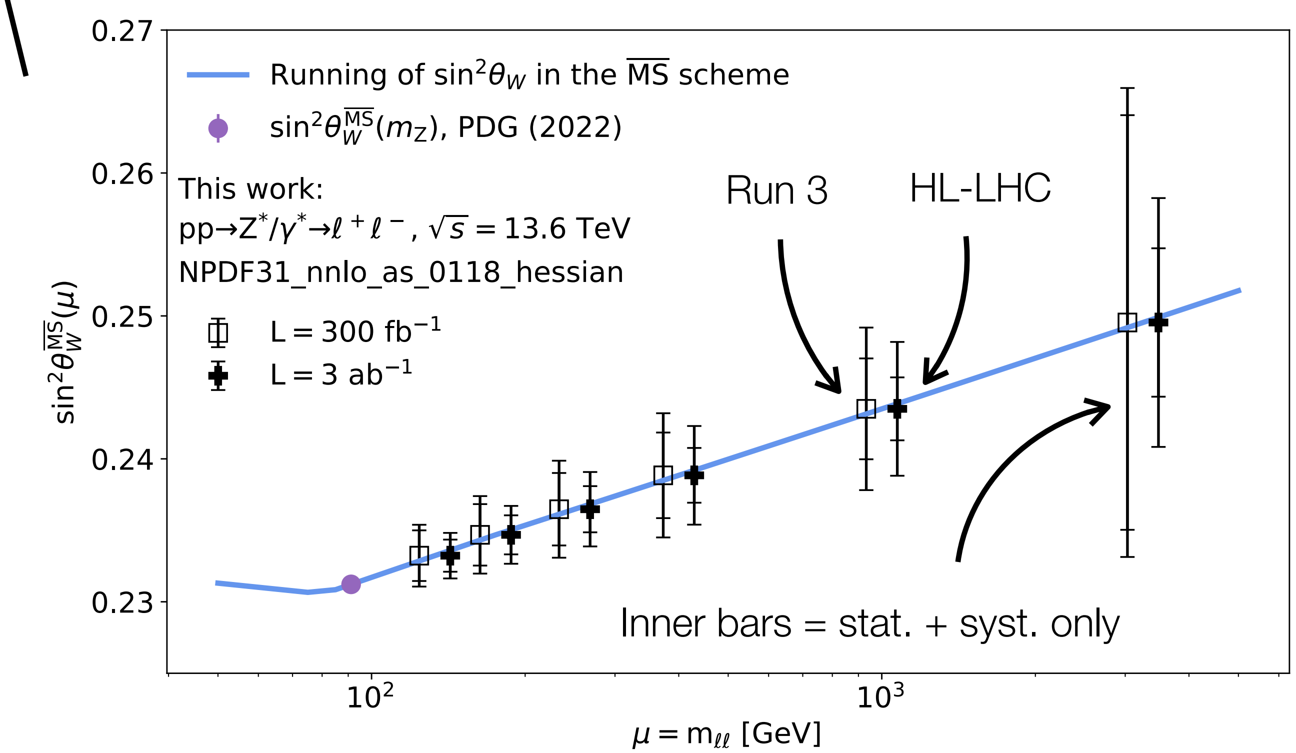
- Use an **EW input scheme** where the **EW mixing angle** is **explicit** $(\alpha(\mu), m_Z, \sin^2\theta_W(\mu))$
- Within this "hybrid" scheme the m_Z value is renormalised to its On-Shell value while the **fine structure constant** and the **EW mixing angle** are renormalised in the $\bar{M}S$ scheme,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



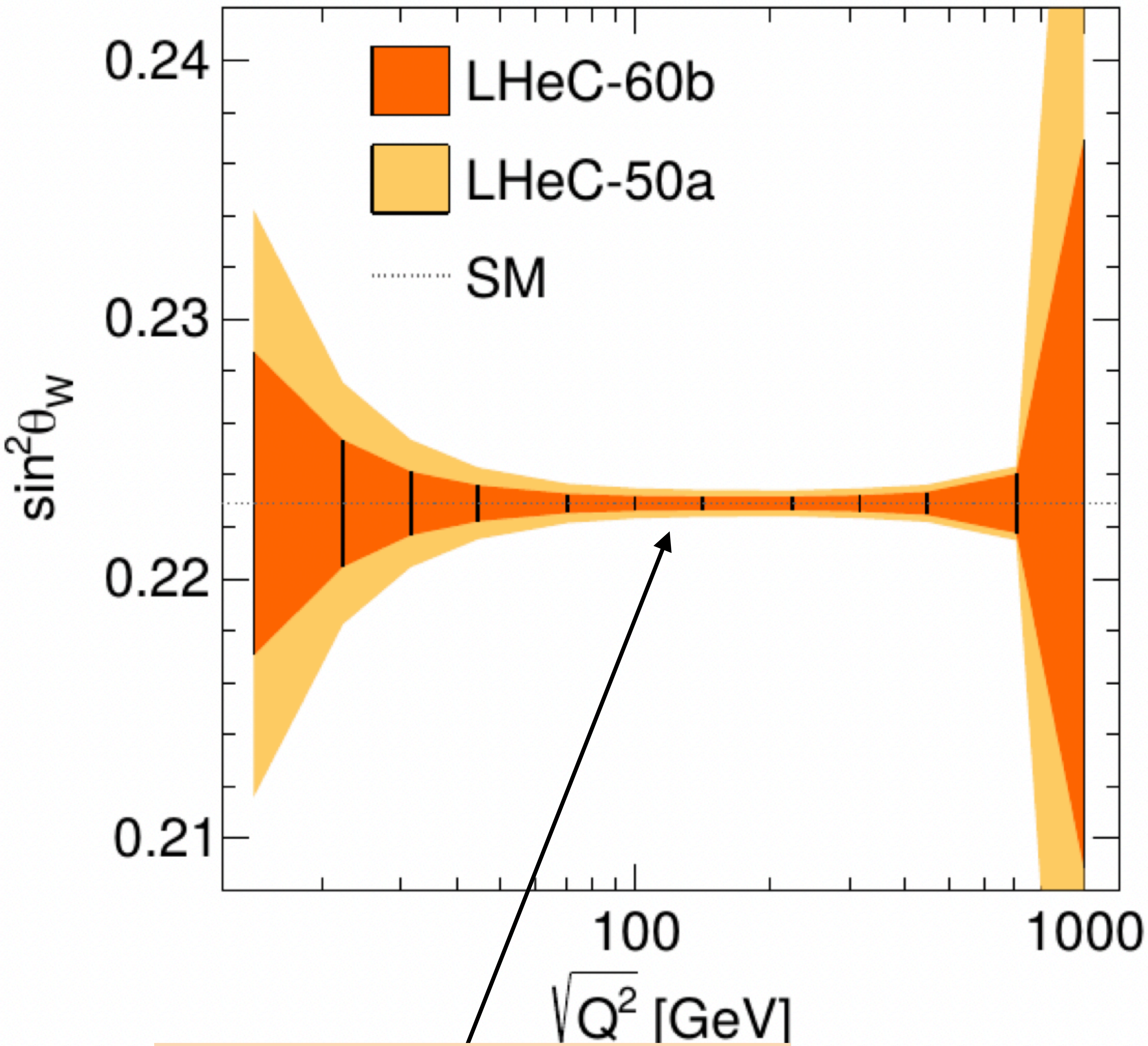
Predicted running at the EIC



Boughezal et al. 2204.07557



Predicted running at the LHeC

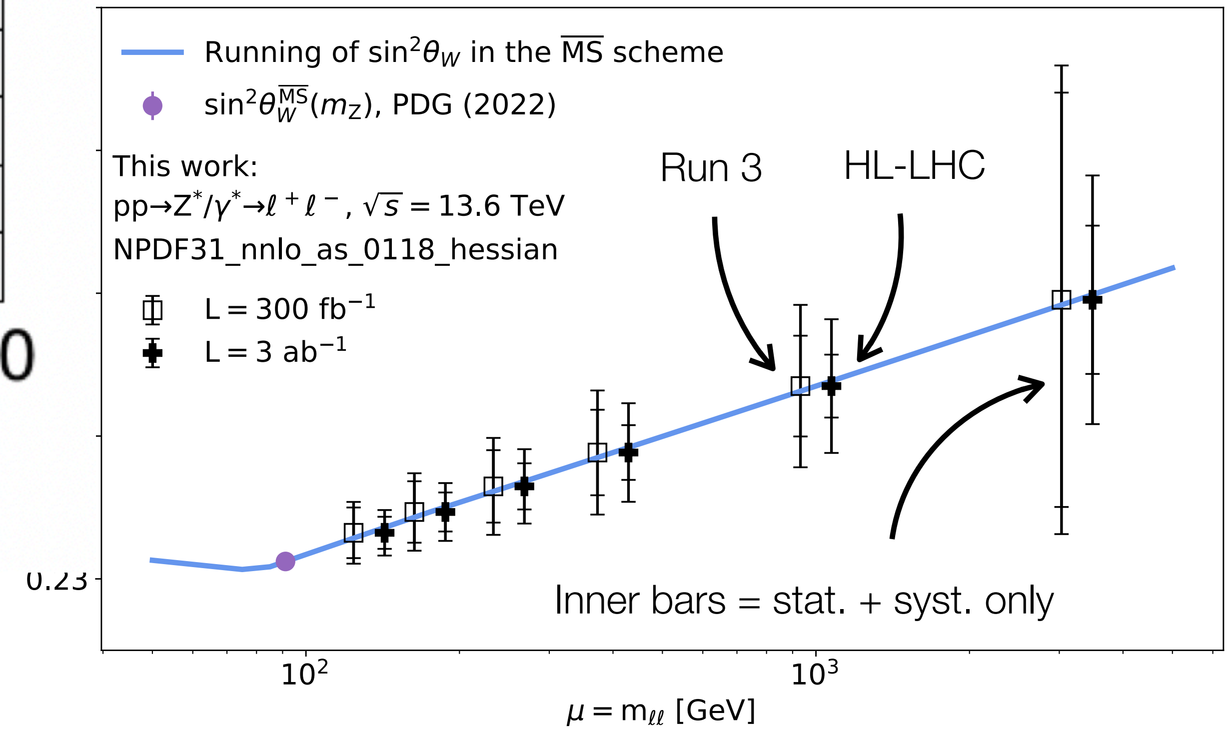


D. Britzger ICHEP 2020

Sensitivity

Run 3: 1% - 7%

HL-LHC: 1% - 3%



Per-mille uncertainties in
$25 < Q < 700\,\mathrm{GeV}$
spacelike region