Introduction to SM measurements

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Outline

- The Standard Model of Particle Physics
- The global electroweak fit : where do we stand ?
  - m_W, $\sin^2\theta_W$, m_{top}
- α_S
- Going beyond the SM with EFT

The Standard Model (SM)

$$
\begin{aligned}
\mathcal{L} \\
&= -\frac{1}{4} W_{\mu\nu} \cdot W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} \cdot B^{\mu\nu} \\
&+ \bar{L}\gamma^{\mu}\left(i\partial_{\mu} - g\frac{1}{2}\tau \cdot W_{\mu} - g'\frac{Y}{2}B_{\mu}\right)L \\
&+ \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - g'\frac{Y}{2}B_{\mu}\right)R \\
&+ \left|\left(i\partial_{\mu} - g\frac{1}{2}\tau \cdot W_{\mu} - g'\frac{Y}{2}B_{\mu}\right)\phi\right|^{2} \\
&- V(\phi) - (G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.) \\
&- g(\bar{q}\gamma^{\mu}T_a q)G_{\mu}^{a} - \frac{1}{4}G_{\mu\nu}^{a}G_{a}^{\mu\nu}
\end{aligned}
$$

- electromagnetic force — photon γ
- weak interaction — Z, W^+, W^-
- strong interaction — 8 gluons
- Higgs boson — confers mass to the other particles ; discovered in 2012 by ATLAS and CMS
- —> See Anne-Catherine's talk and Higgs session
- Gravitational interaction — not described by the SM

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&+ \bar{R}\gamma^{\mu} \left(i\partial_{\mu} - g'\frac{Y}{2}B_{\mu} \right) R \\
&+ \left| \left(i\partial_{\mu} - g\frac{1}{2}\tau \cdot W \cdots \right) \phi \right| \\
&- V(\phi) - (G \cdots L\phi_{c}R + h.c.) \\
&- g(\bar{q} \cdots - \frac{1}{4} G^{a}_{\mu\nu} G_{a}^{\mu\nu}
\end{aligned}
$$

Can we go beyond this ?

- electromagnet… force — photon γ…
- w… …on — Z, W+, …
- …rong interaction — 8 gluons
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Looking for deviations to the SM via the Global electroweak fits

- Electroweak theory (true at all orders, need to remove ('tree')) (1)
- Also, one has (2)
- After solving the 2nd order equation in m_W^2 one gets (3)
- Where radiative corrections to the W boson propagator (dominated by top and Higgs contributions) can be expressed as :

$$\Delta r = \Delta\alpha - \frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho + \Delta r_{res},$$

- Top quark mass dependence dominated by :

$$\Delta\rho^{top} \approx \frac{3\sqrt{2}G_\mu m_{\rm top}^2}{16\pi^2}$$

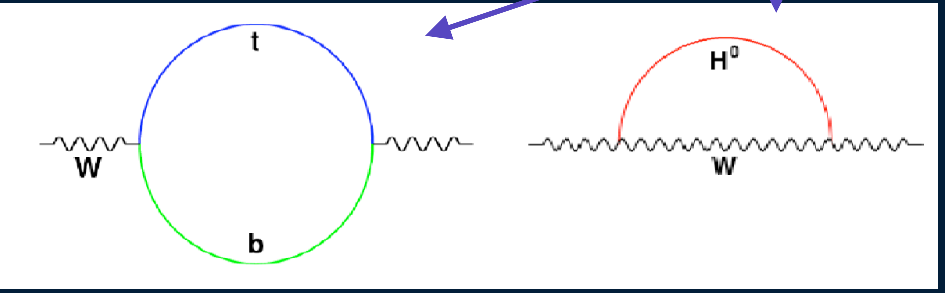
- Higgs boson mass dependence dominated by :

$$\Delta r_{res}^{Higgs} \approx \frac{\sqrt{2}G_\mu m_W^2}{16\pi^2}[\frac{11}{3}(\ln\frac{m_h^2}{m_W^2} - 5/6)].$$

$$m_W^2 = \frac{\pi\alpha_{tree}}{\sqrt{2}G_\mu \sin^2\theta_{W,tree}} \quad (1)$$

$$m_W^2 = \frac{g_W^2 v^2}{4}, \quad m_Z^2 = \frac{g_W^2 v^2}{4\rho_0\cos^2\theta_W} = \frac{m_W^2}{\rho_0\cos^2\theta_W} \quad (2)$$

$$\begin{aligned} m_W^2 &= \frac{m_Z^2}{2}(1+\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_\mu m_Z^2}}) \\ &= \frac{m_Z^2}{2}(1+\sqrt{1-\frac{4\pi\alpha_{tree}}{\sqrt{2}G_\mu m_Z^2}\frac{1}{1-\Delta r}}) \end{aligned} \quad (3)$$



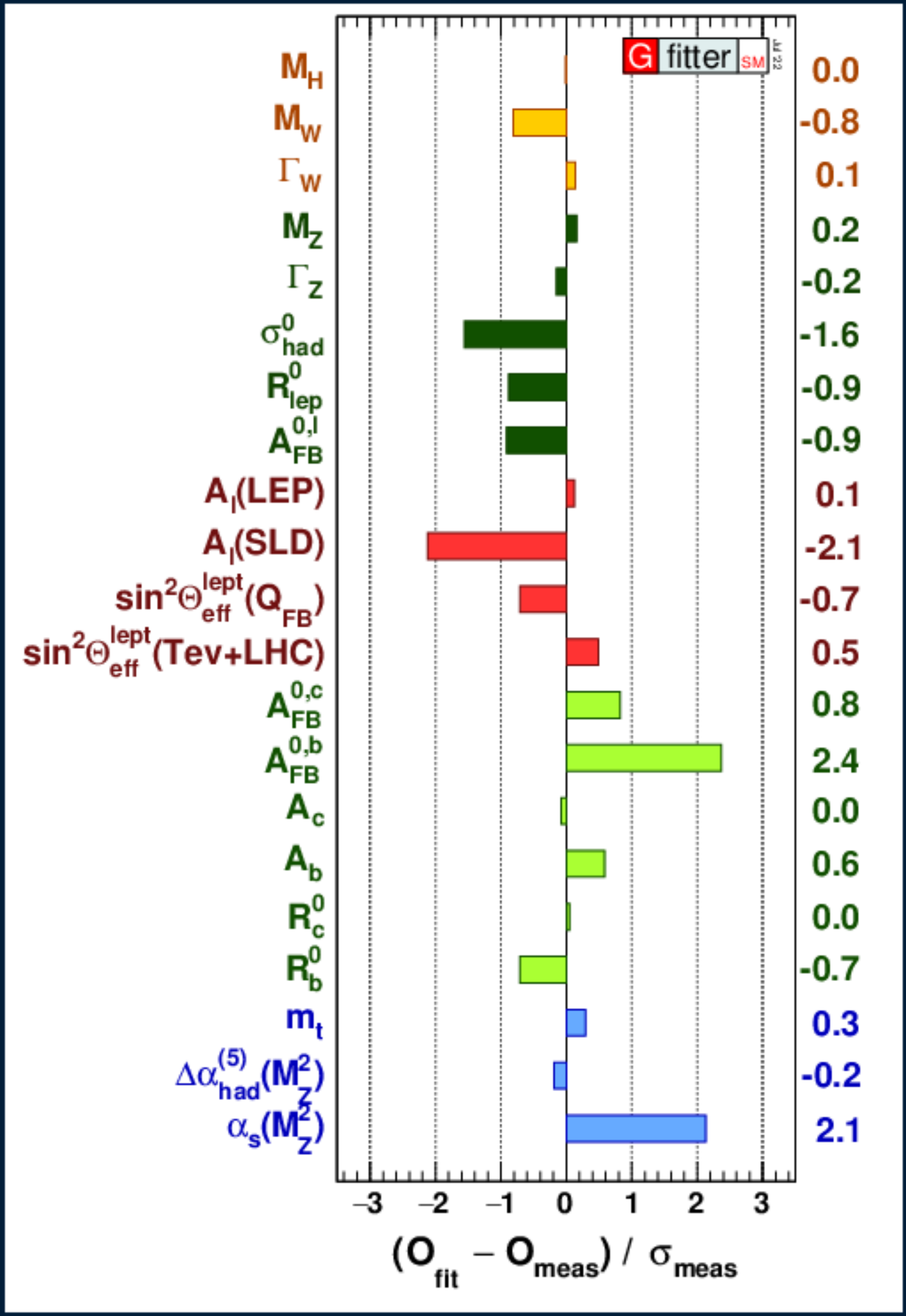
G. Burgers and F. Jegerlehner
10.5170/CERN-1989-008-V-1.55

Relationship between W mass, top mass and Higgs mass (and EW parameters) !

The global EW fit

arXiv:2211.07665

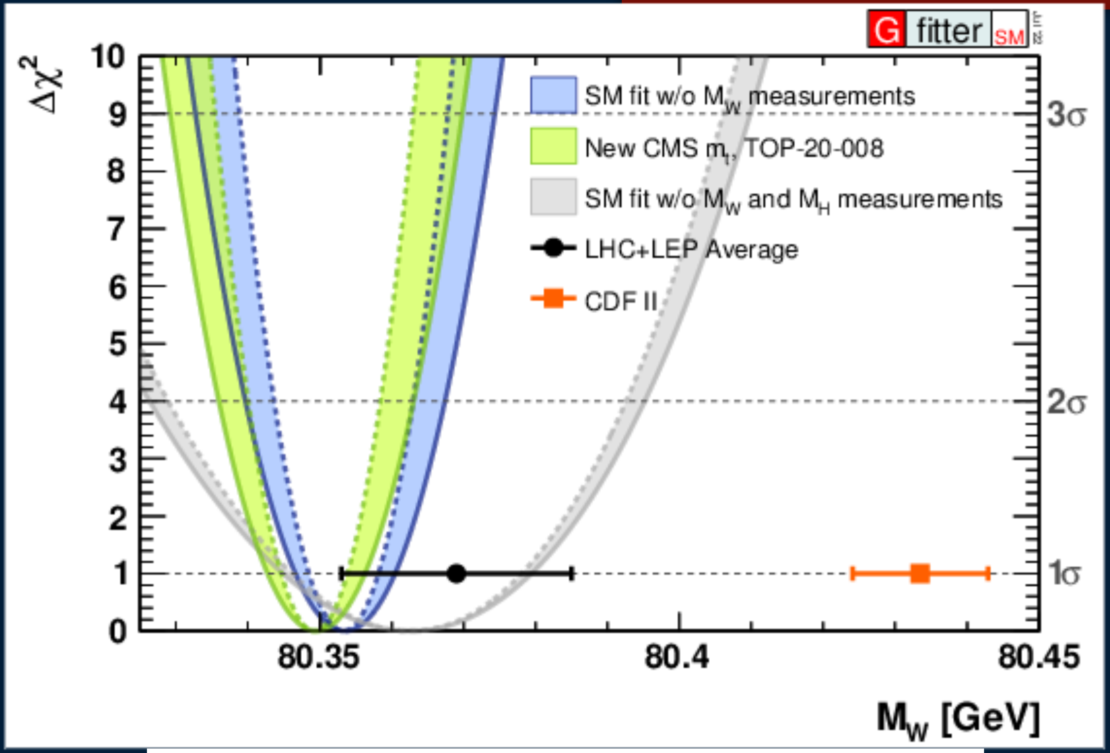
- Idea of electroweak fits
  - Measure many different observables in experiments
  - Calculate the relations between all observables in the Standard Model
  - Probe the consistency of the SM by predicting observables
- Input for the gobal electroweak fit mostly from
  - LEP: Z boson observables (e.g. $\sin^2\theta_W$)
  - Tevatron: W boson, top quark mass
  - LHC: Higgs boson, W boson, top quark mass
- When not including the latest CDFII mW measurement, overall good consistency between indirect determination (i.e. physics parameter left free) and the direct measurements
  - p-value : 0.34

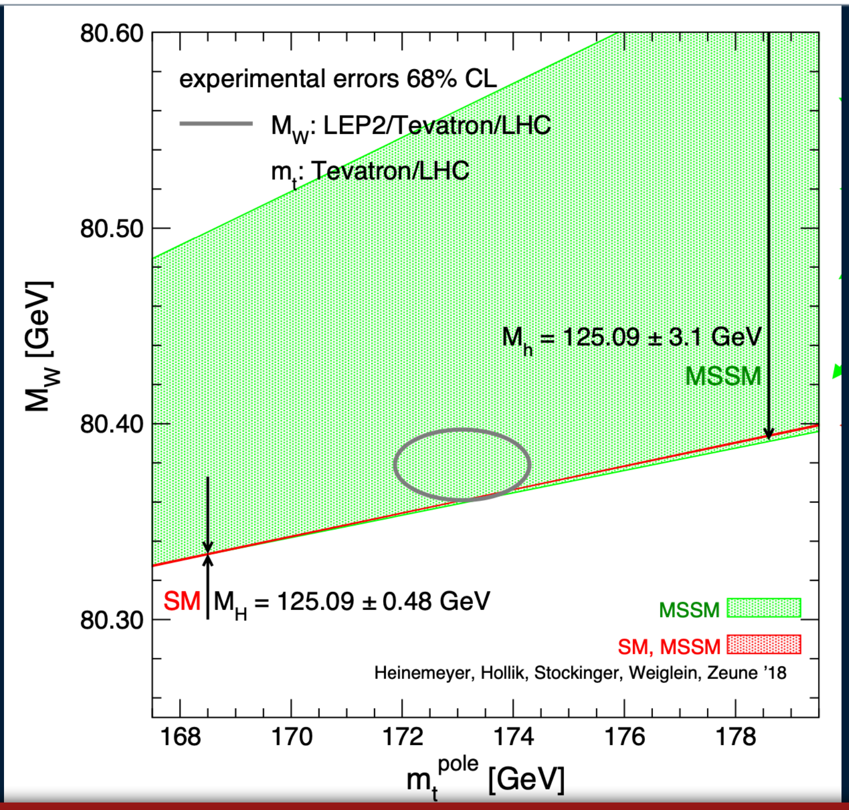


The global EW fit

- Test the consistency of the Standard Model
  - e.g. predict m_W, provided all other input measurements
- needs 6 MeV precision on m_W to compete with indirect determination from theory fit (10^{-4} relative uncertainty!)
- Electroweak precision measurements also sensitive to several new physics scenarios
- —>m_W measurement needs very accurate prediction for W production and kinematics of decay products :
  - W p_T and rapidity spectrum
  - polarisation (spin correlations)
  - high order EW (NLO)
- Proton PDFs are an essential ingredient for this
- It also needs detector calibration at the same level of precision!
- More on this measurement in Eram's talk !

arXiv:2211.07665





[S. Heinemeyer, W. Hollik, G. Weiglein, L. Zeune '18]

The weak mixing angle, $\sin^2\theta_W$

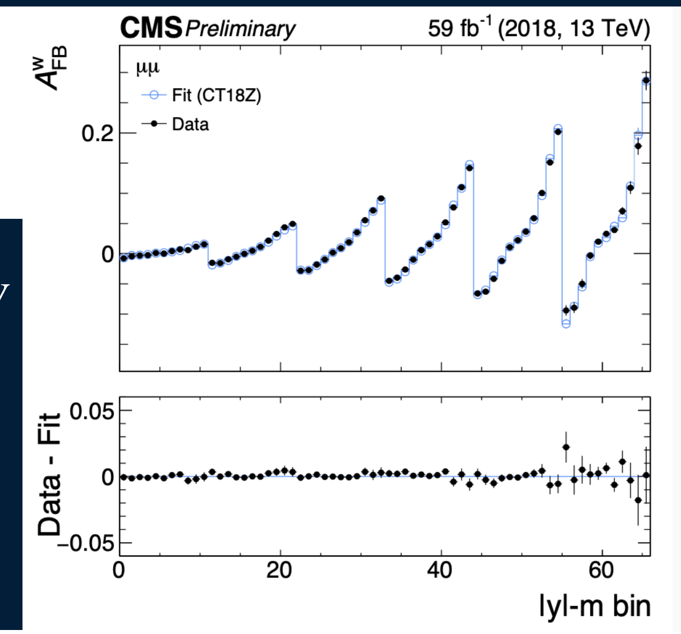
- Weak mixing angle is an SM parameter of paramount importance
  - The main parameter of electroweak unification
  - At leading order, defines the ratio of the W and Z masses
  - and the parity-violating vector coupling of the Z to the fermions
    - Radiative corrections in the SM
- Best (preliminary) result of WMA in a hadron collider released by CMS last Winter
  - Measure $\sin^2\theta_{\ell,\,\mathrm{eff}}$ through forward-backward asymmetry (A_{FB}) of leptons in Z events, in mass and rapidity bins
- See also Qiang's talk

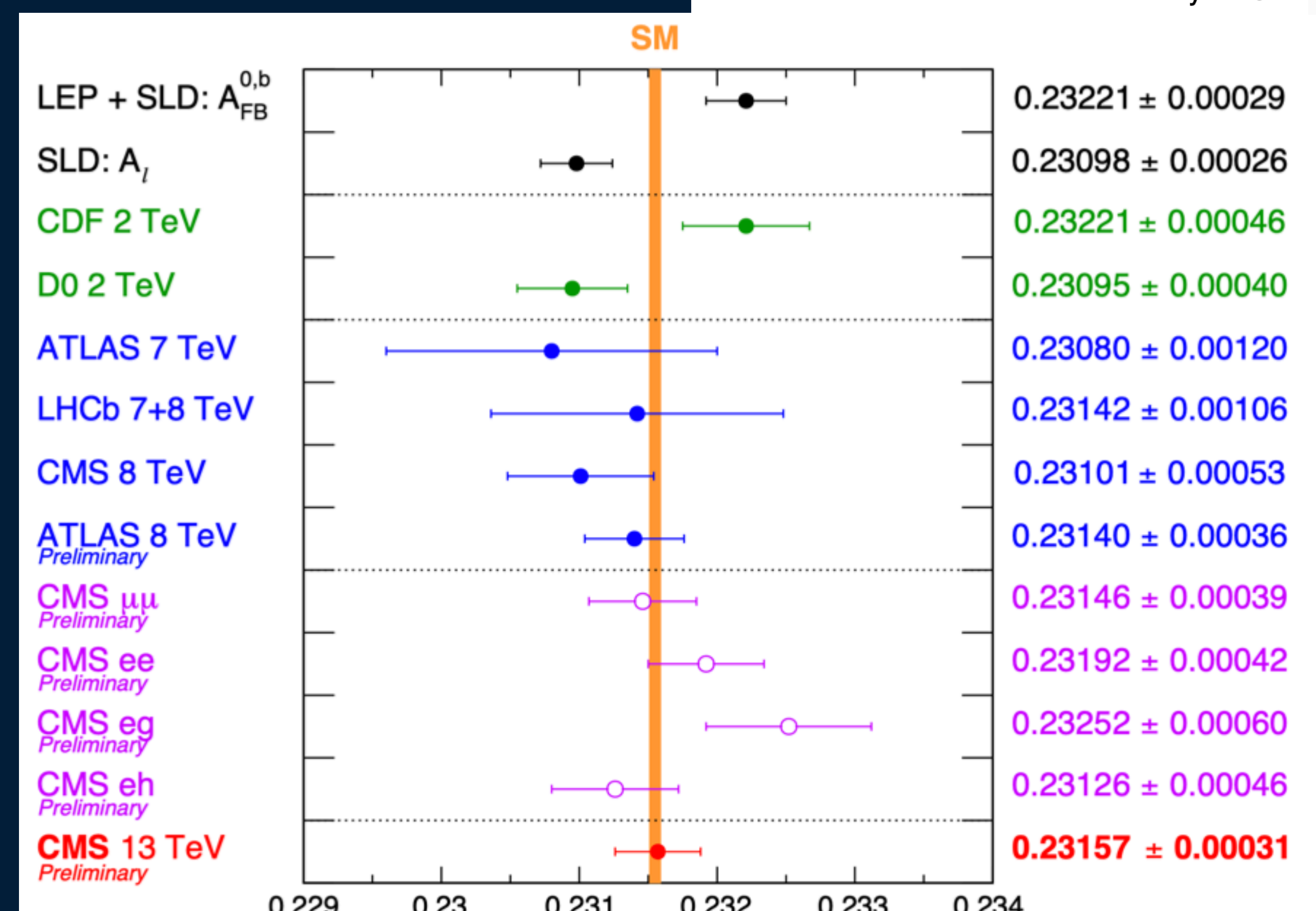
$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ W^3_\mu \end{pmatrix}$$

$$v_f = T_3^f - 2Q_f(1+\Delta\kappa)\sin^2\theta_W$$

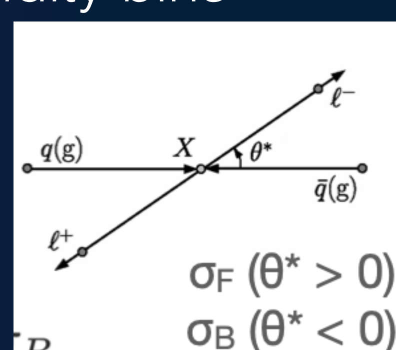
$$a_f = T_3^f$$

$$\sin^2\theta^\ell_{eff} = (1 - m_W^2/m_Z^2)\kappa^\ell$$





CMS-SMP-22-010

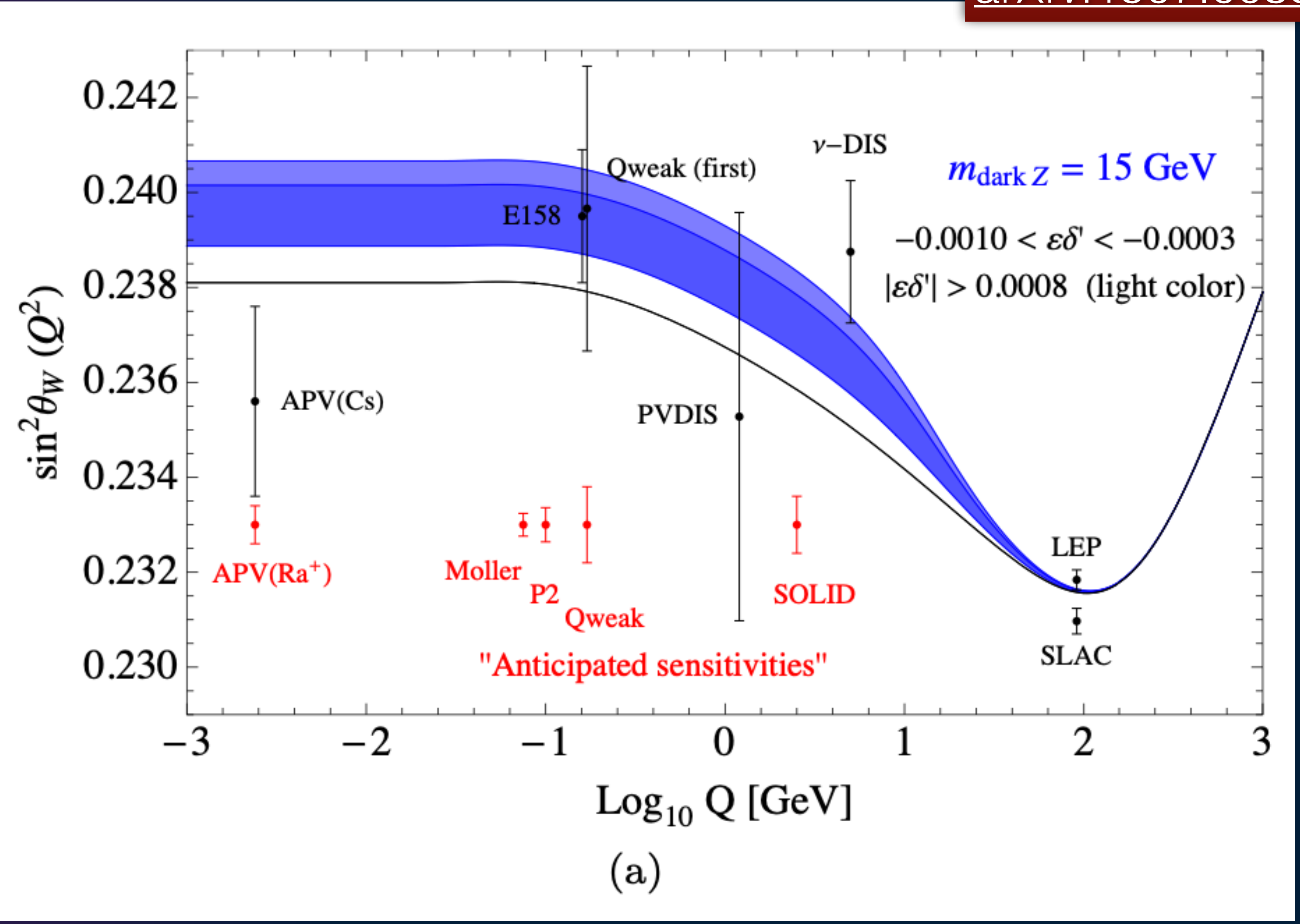


$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$\sin^2\theta_W$: low/high energy perspective

- New particles or interactions influence $\sin^2\theta_W$ and its energy dependence
- New generation of experiments will allow to probe these with better precision!

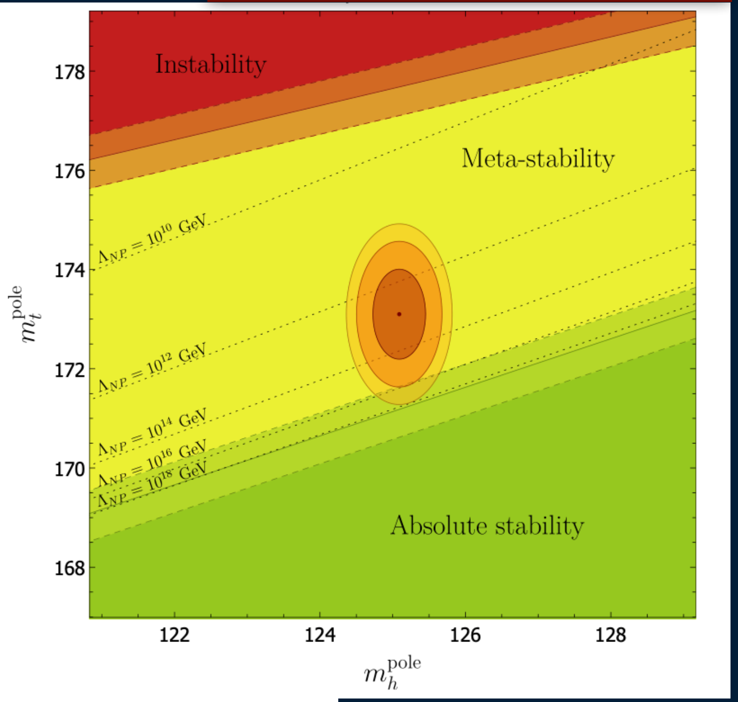
arXiV:1507.00352

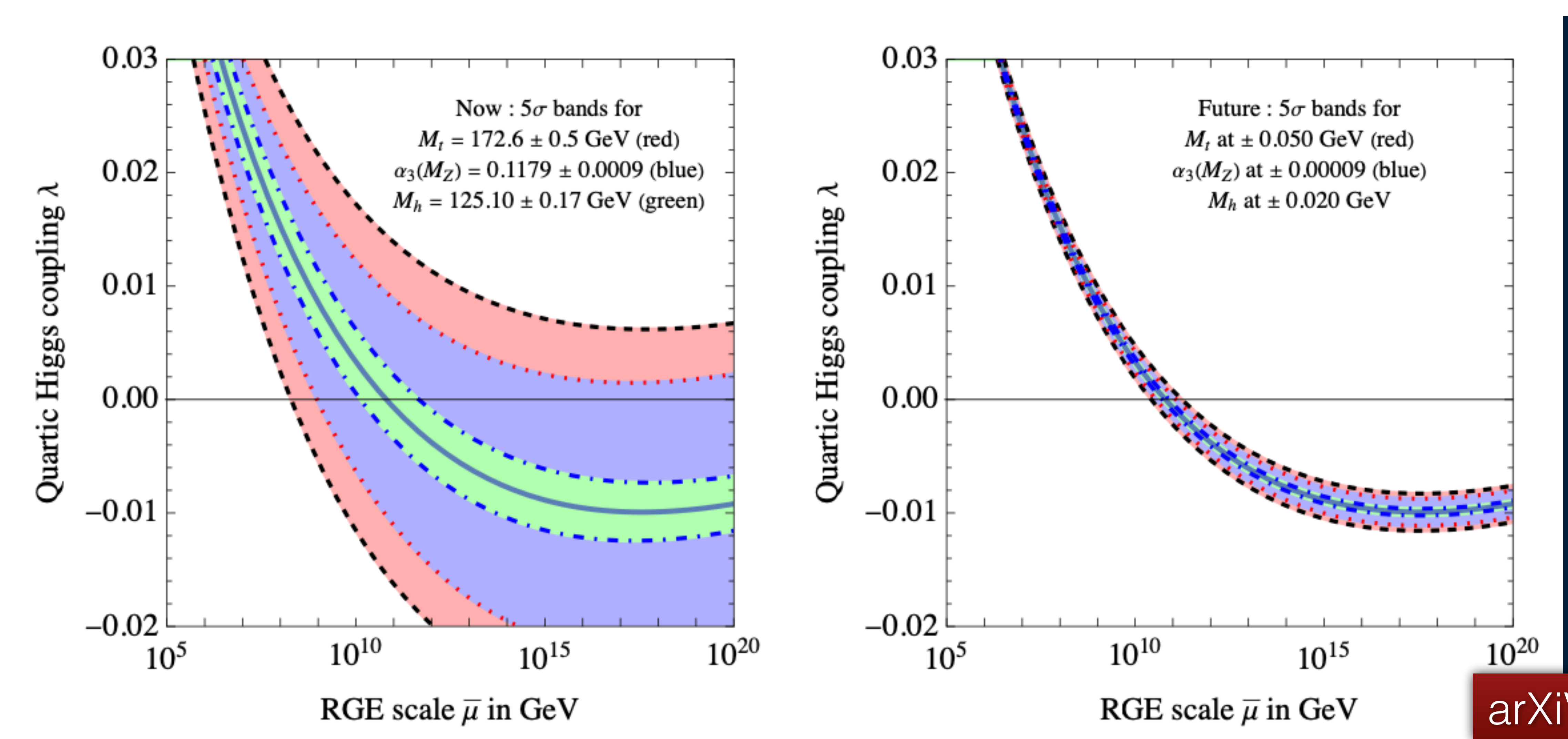


The top quark mass

arXiV:1707.08124

- Important role in the SM electroweak fit
- Also key parameter for vacuum stability
- Higgs potential shape: $V(\Phi) = -m_h^2(\mu)|\Phi|^2 + \lambda(\mu)|\Phi|^4$
- Potential stability depends on the sign of λ(μ), quartic coupling
- Picture could change radically when top quark mass (and α_S) are measured in future colliders at the ttbar production threshold! (e.g. FCC-ee, muon colliders)

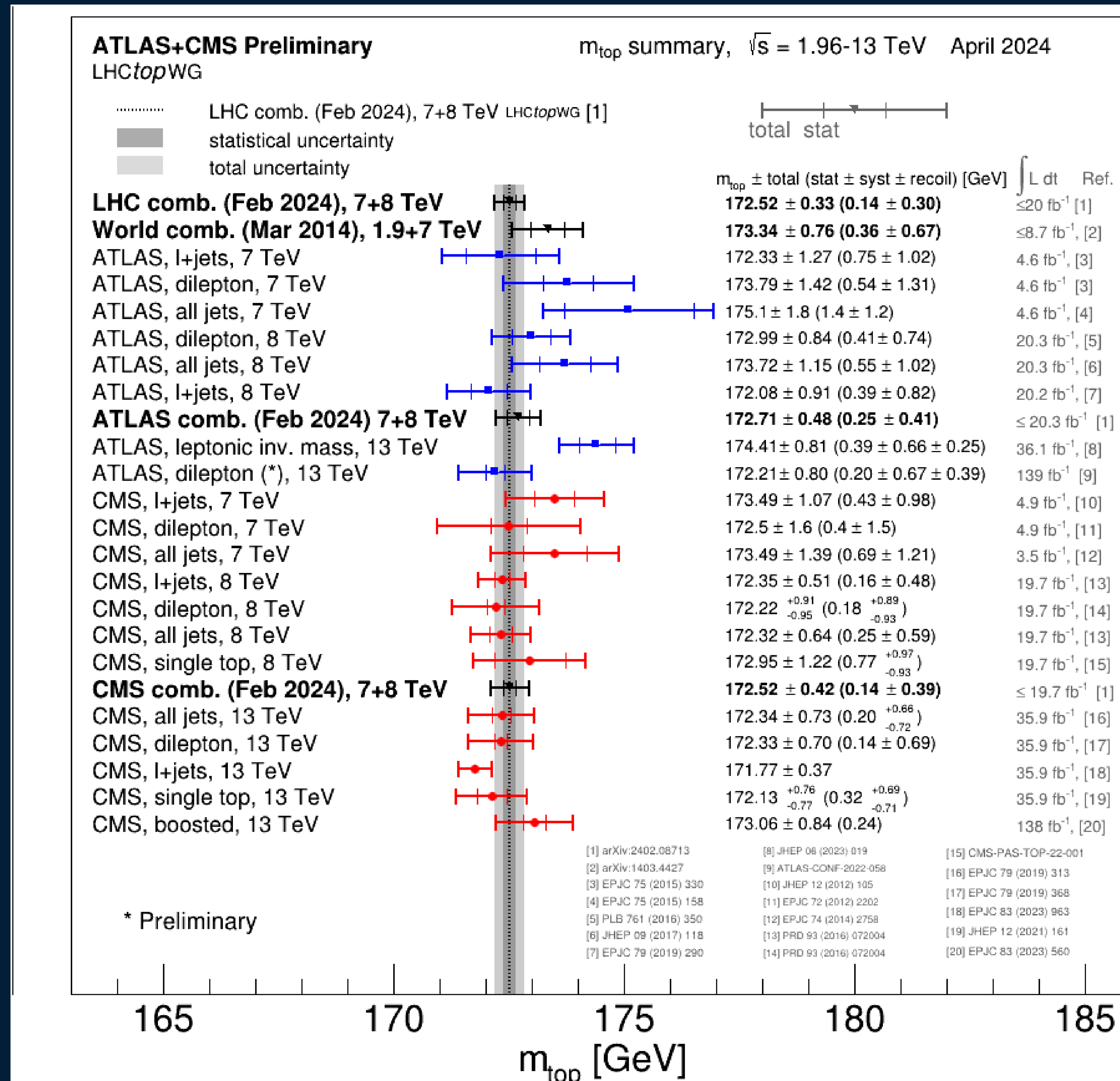




arXiV:2203.17197

The top quark mass

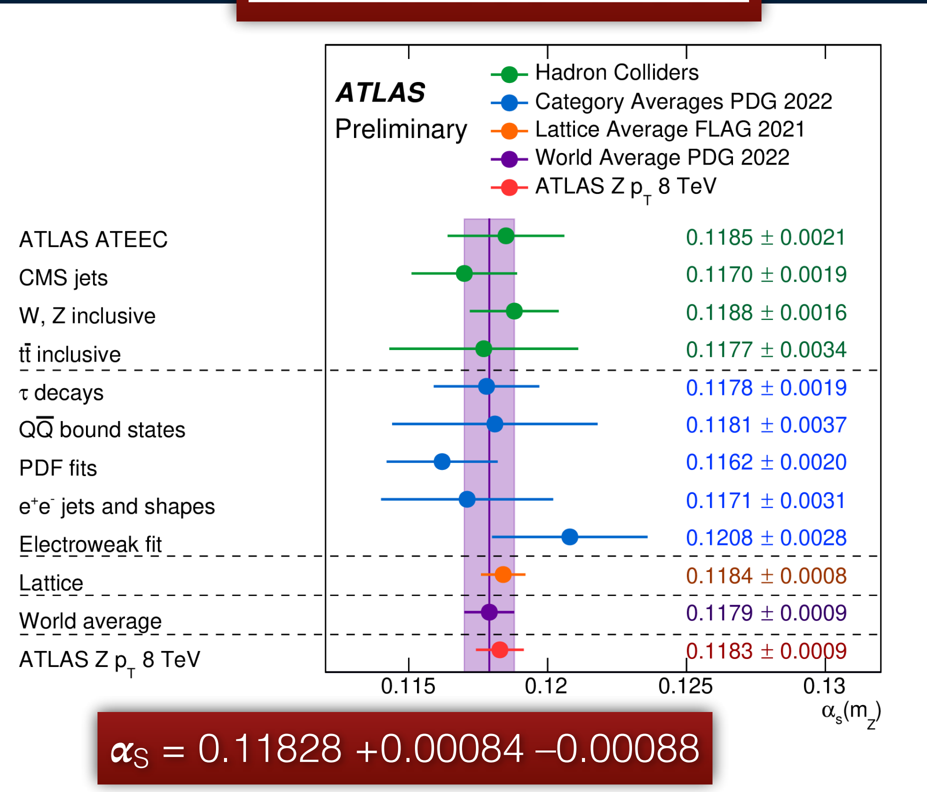
- Legacy Run1 measurements
  - Latest combination reaches exquisite precision!
    - 172.52+-0.33 GeV!
    - Dominated by b-jet uncertainties
- More progress being made in the topic
  - Indirect measurements (from cross-section) : avoid ambiguity on 'MC mass vs pole mass'
  - Improvements on modeling with *e.g.* 'bb4l' generator:
    - correct treatment of $t\bar{t}$/tW interference at NLO
    - off-shell effects accurate at NLO
    - top decay description at NLO
    - exact spin correlations at NLO
- See also Harish' talk



α_S

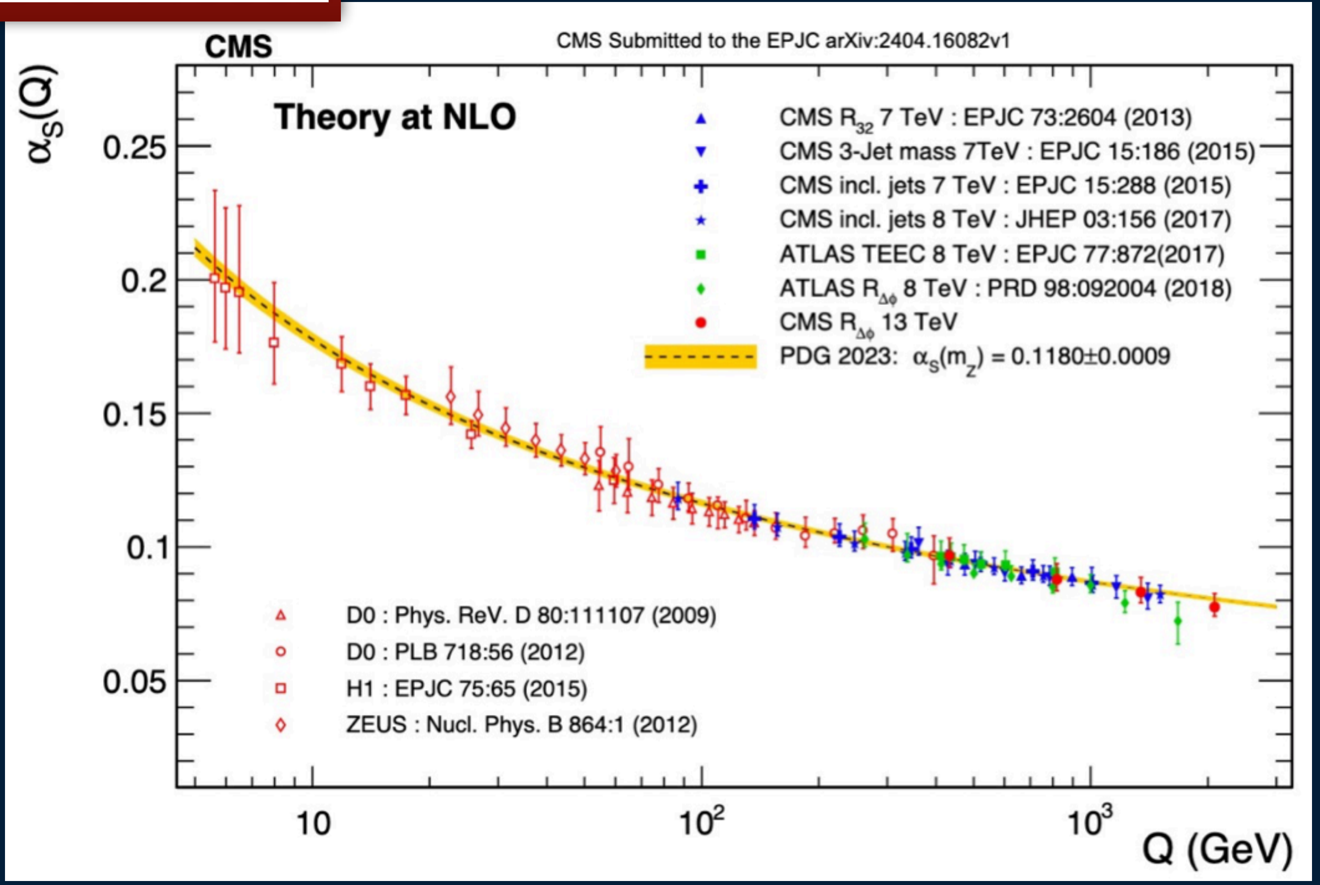
- The only QCD free parameter (except for quark masses)
- The least precisely known of the SM couplings (~0.8%)
- Best results typically obtained with lattice QCD
- Recent measurement has competitive precision using Z differential cross-section measurement (Z p_T) compared to theory accurate at N3LO+N4LL
- Running is typically tested using highly energetic jets at LHC
  - Azimuthal correlations among jets
  - Energy correlators inside jets
  - Jet cross-sections and their ratios (e.g. 3-jet to 2-jet cross-section ratio)
  - —> Simultaneous determination of PDFs
  - Different beta function in BSM physics, affect the running!

arXiV:2309.12986



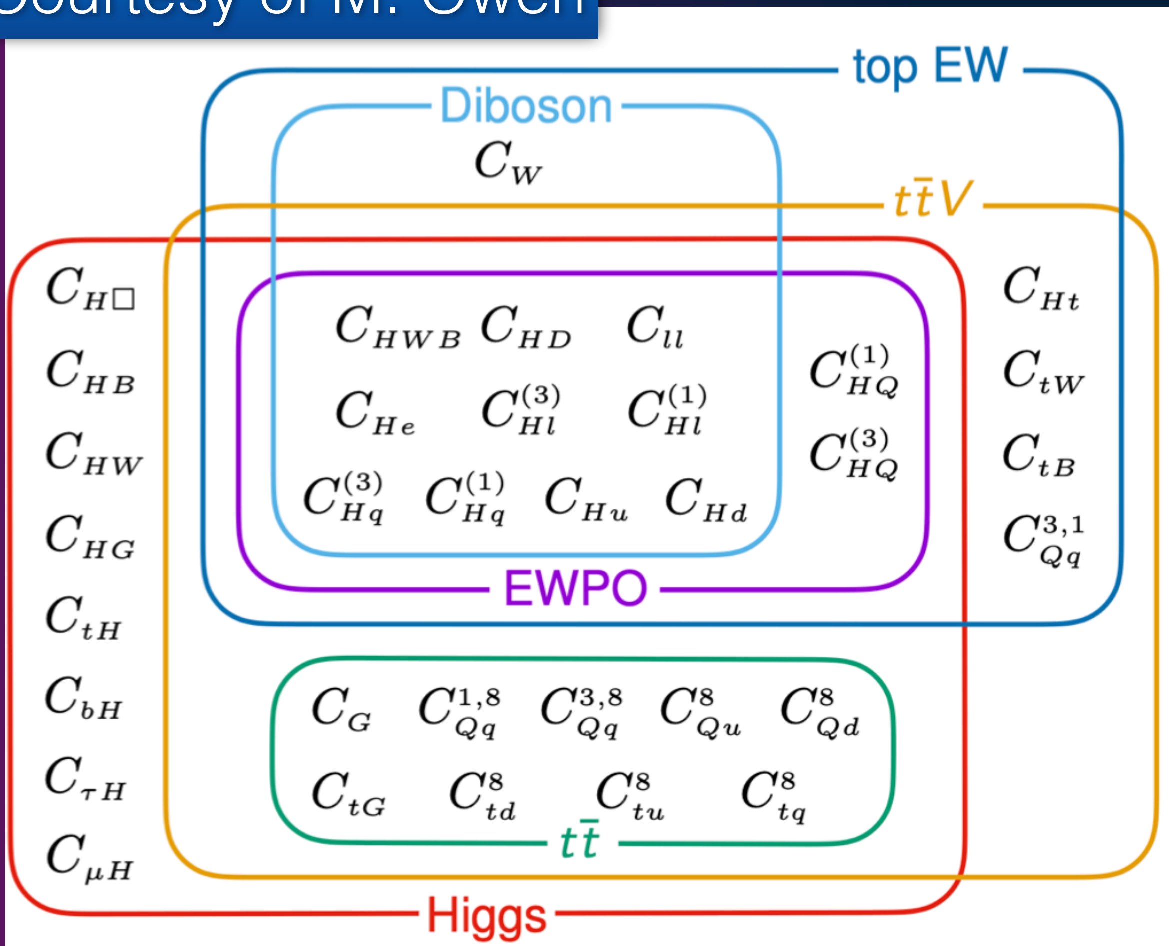
α_S = 0.11828 +0.00084 –0.00088

arXiV: 2404.16082

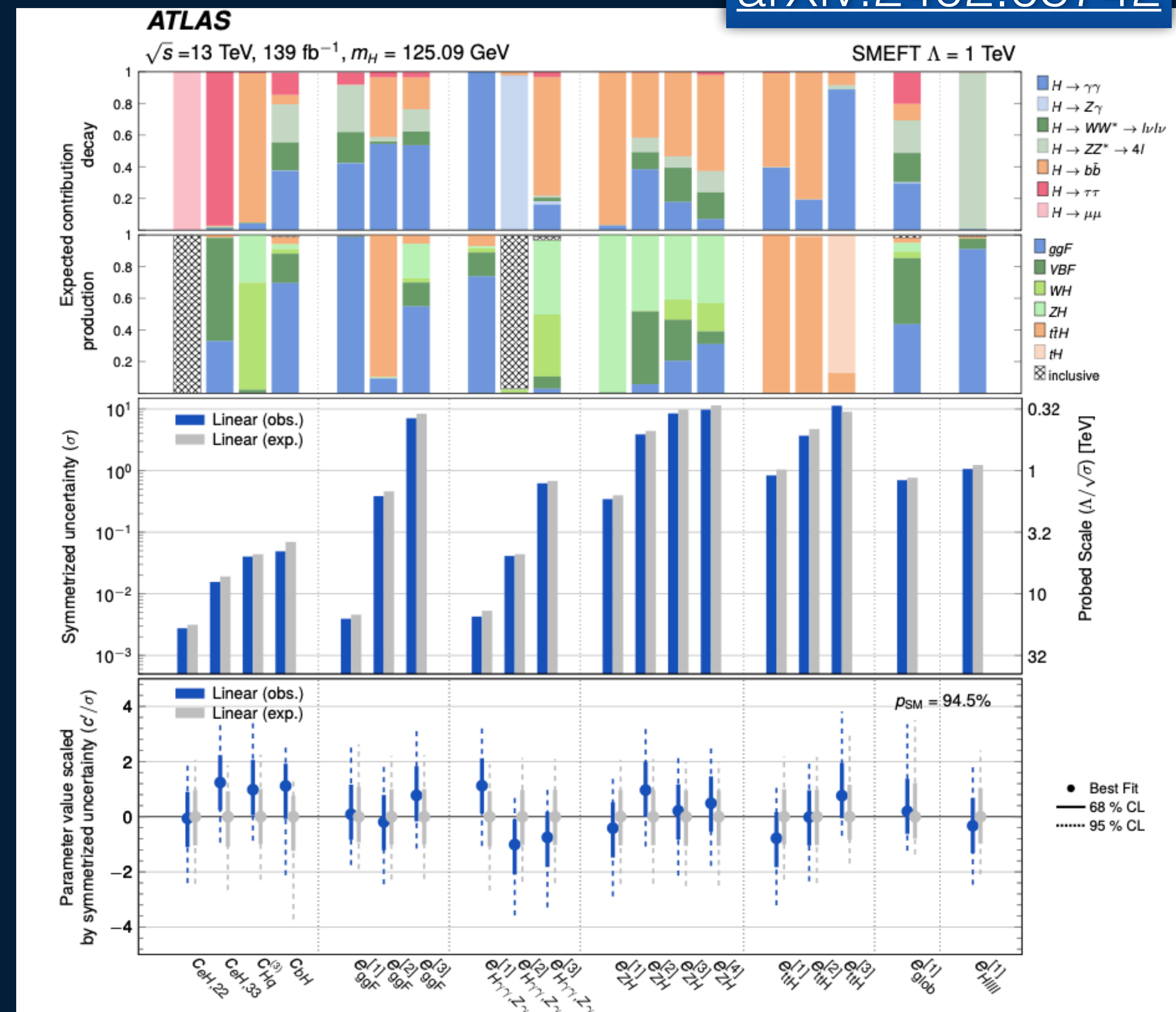


Going beyond the SM : SM EFT

Courtesy of M. Owen



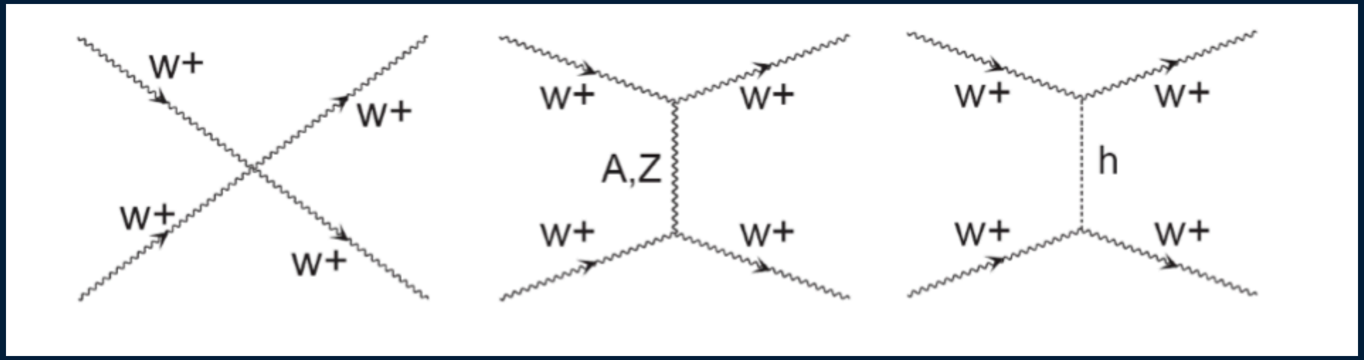
arXiv:2402.05742



- Try to constrain higher dimensional operators from all available data
  - New physics could be at such a high energy scale that we cannot see the new resonances at the LHC, but still impact observables at lower energies —> Parametrise with operators of dimension n, Wilson coefficients and energy scale of NP
- Example : Combined Higgs fit
  - p-value of compatibility between data and SM is 94.5%
- See also Anne-Catherine’s and Tevong’s talks

SM EFT and multiboson processes

$$\mathcal{L}_{\text{SM EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{\text{dim6}}}{\Lambda^2} Q_i^{\text{dim6}} + \sum_i \frac{c_i^{\text{dim8}}}{\Lambda^4} Q_i^{\text{dim8}} + \ldots$$



- Effect of operators typically growing with $(E/\Lambda)^n$ —> measure in energy tails —> cf Dario's talk!
    - Anomalous triple gauge couplings (aTGCs): Dibosons (WW, WZ, Wγ) and VBF production (Zjj, Wjj)
    - Neutral triple gauge couplings (nTGCs): ZZ and Zγ
    - Anomalous quartic gauge couplings (aQGCs): Triboson, VBS production of boson pairs, exclusive WW
- VBS: provides a direct probe of the triple and quartic gauge boson couplings.
    - Scattering amplitude is expected to increase with centre of mass energy. Violation of unitarity is avoided thanks to contribution of Higgs exchanges in the s- and t-channels
        - Modification of Higgs coupling to vector bosons will change this - more visible in longitudinally polarized boson scattering amplitudes
- More on this in Zhen's talk!

Concluding remarks

- Standard Model: several loopholes, need to hunt for deviations
  - Ball is in the camp of experimentalists, but strong theory input is required!
  - Precise measurements help tracking these and improve knowledge of QCD/EW physics