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Consejo Nacional de Ciencia y Tecnología

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Director's Review of SoLID

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PVDIS Theory

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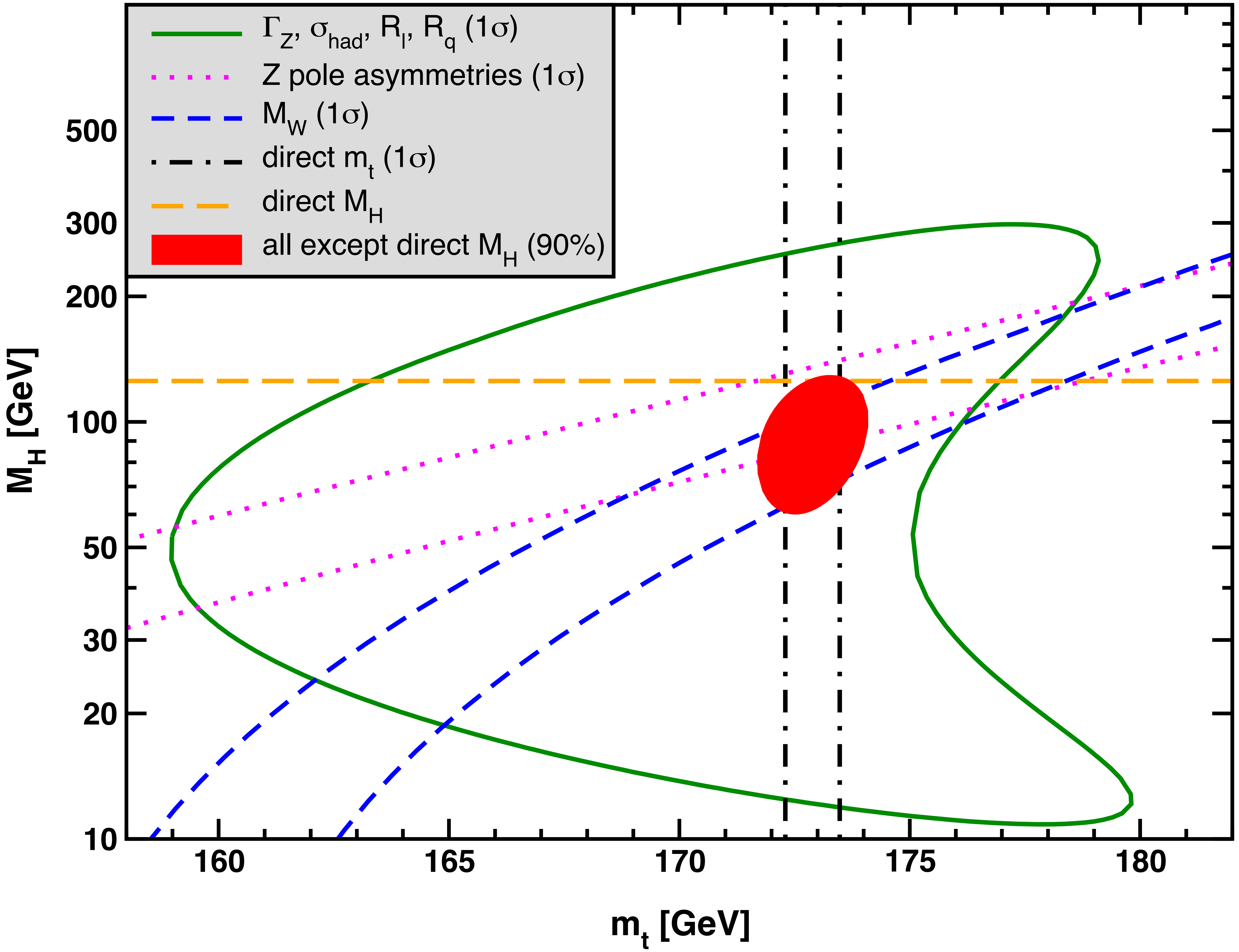
JG|U

Electroweak precision physics

* The electroweak (EW) precision program started about 50 years ago
* M_W, M_Z, m_t, M_H (and m_c) have all been successfully predicted before their discoveries
* 2012 the Standard Model (SM) was completed …

  … and it is as successful as it is unsatisfactory (dark matter, naturalness, …)
* so far no new states discovered at the LHC, so perhaps they show up in EW physics first
* currently some tensions in g_μ–2, M_W, and the first row CKM matrix unitarity constraint
* General remark: the higher the precision, the more physics issues will enter in the interpretation of precision measurements
* this is an obstacle when looking at single observables but may be rather a feature in global analyses (across different observables and subfields of particle, nuclear and atomic physics)
* for SoLID: mostly EW and QCD (higher twist and PDFs)

Importance of $\sin^2\theta_W$



indirect m_t

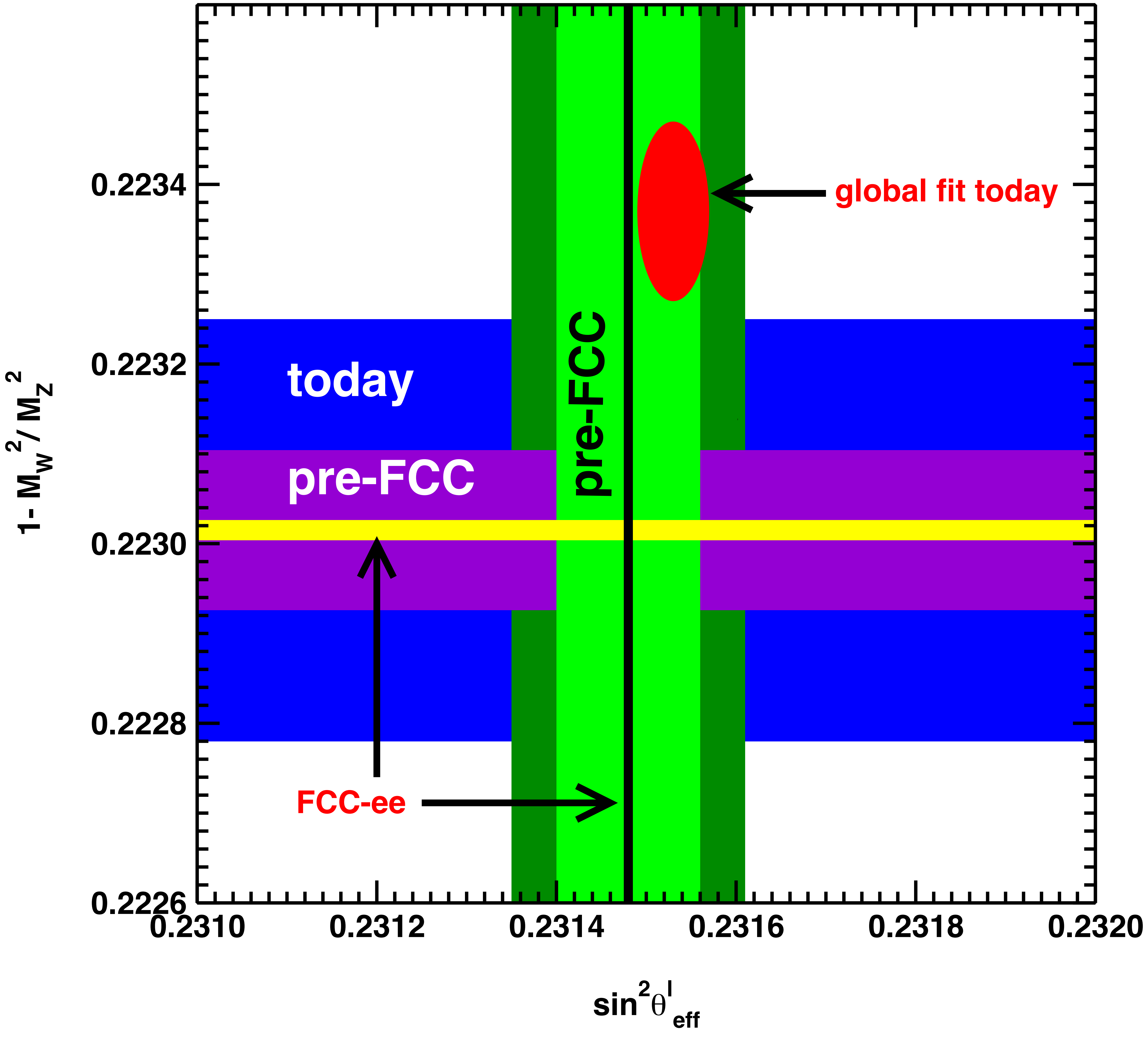
176.4 ± 1.9 GeV

(1.9 σ high)

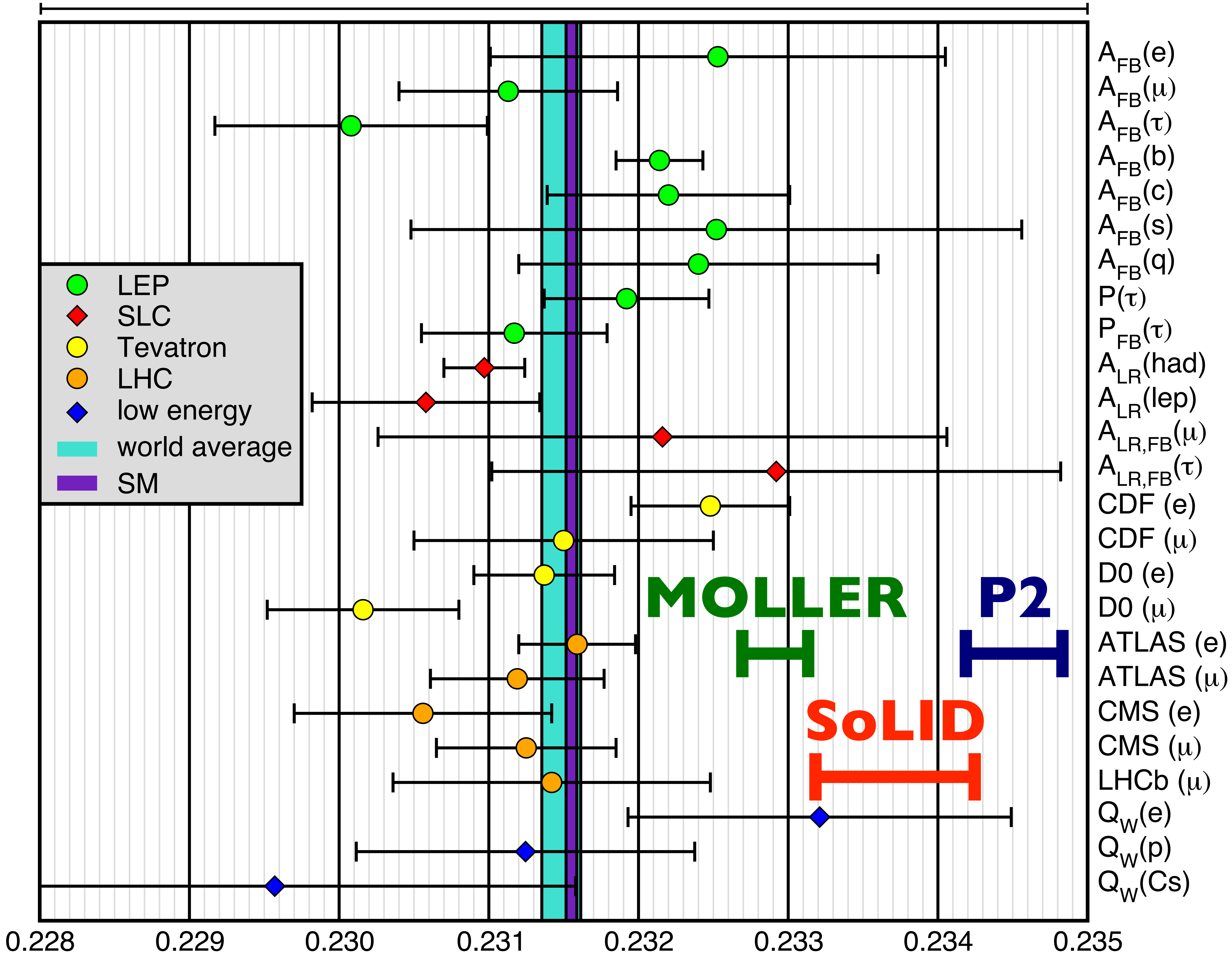
$$\sin^2\theta_W = \frac{g'^2}{g^2 + g'^2}$$

Freitas & JE, PDG 2020

Weak Mixing Angle and Boson Masses



$\sin^2\theta_W$ measurements



LEP & SLC:

0.23151 ± 0.00016

Tevatron:

0.23148 ± 0.00033

LHC:

0.23131 ± 0.00033

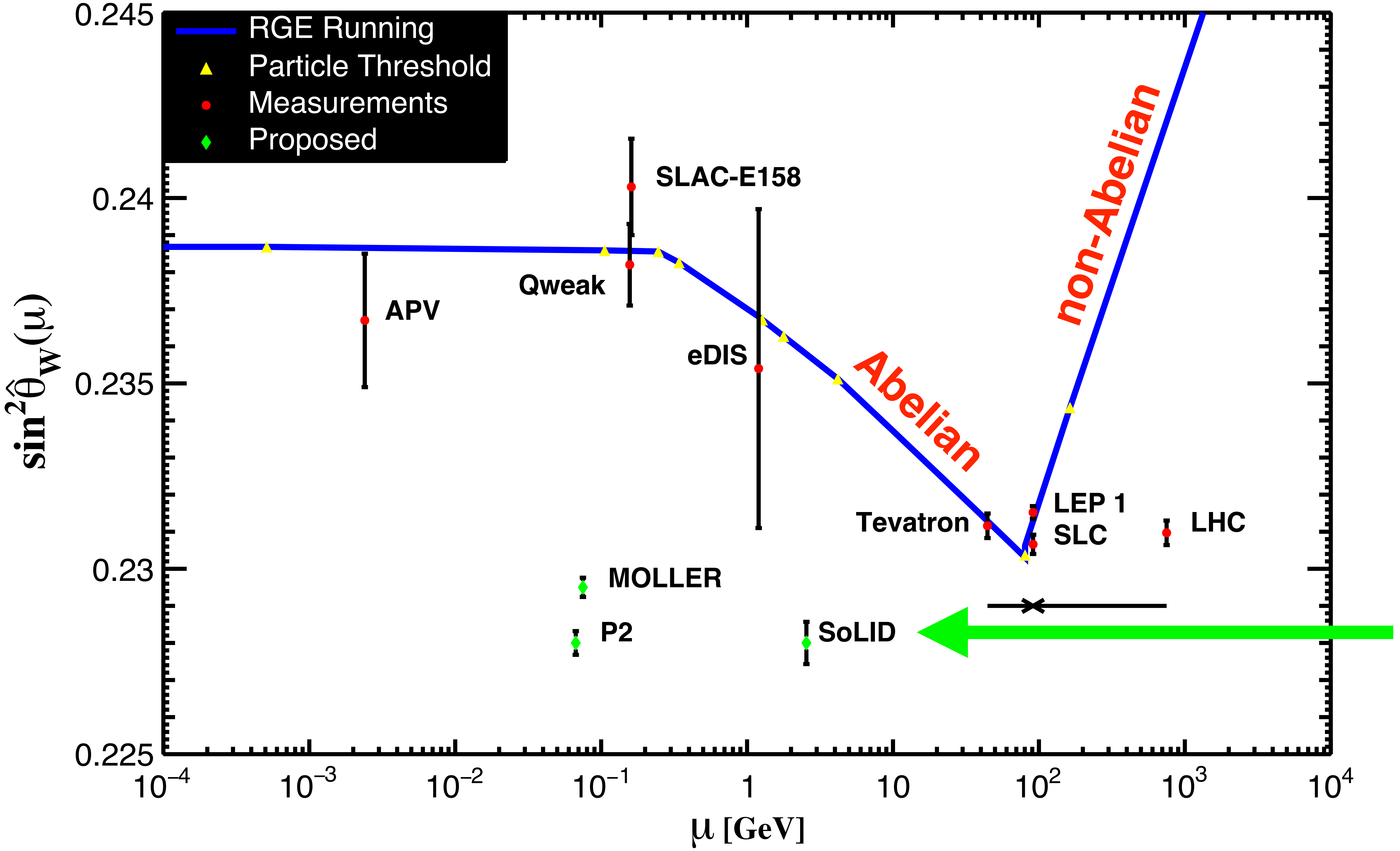
average direct

0.23148 ± 0.00013

global fit

0.23155 ± 0.00004

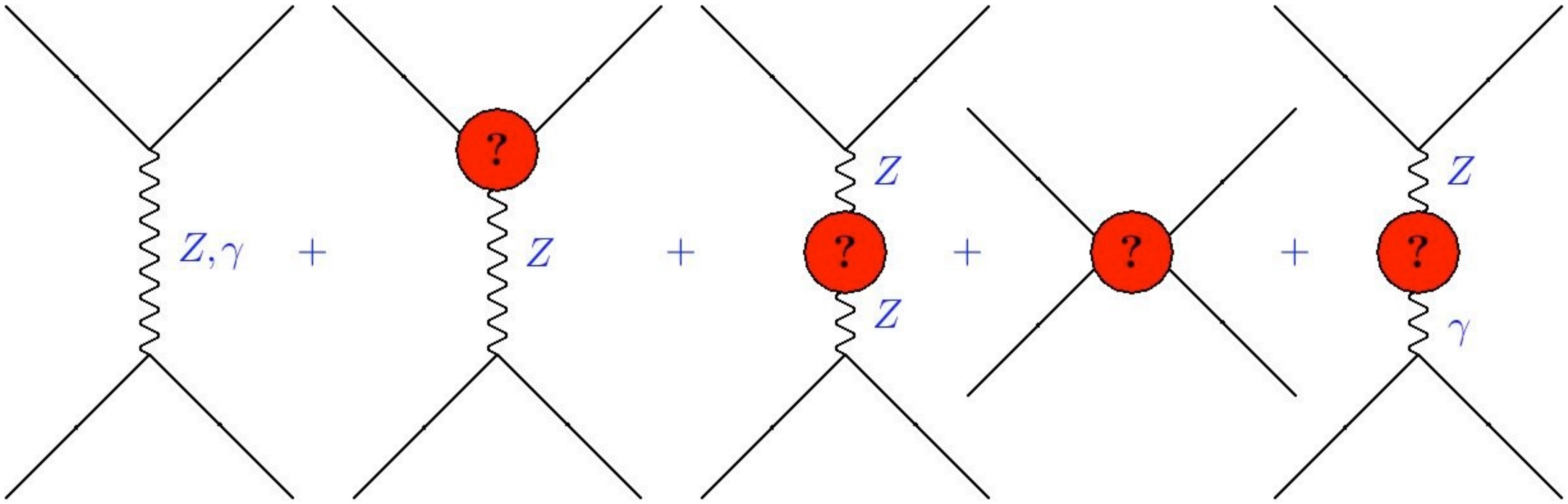
Running weak mixing angle



courtesy of
Rodolfo Ferro,
see also
Ferro-Hernández, JE
arXiv:1712.09146

$\Delta\sin^2\theta_W = \pm\,0.00057$

Discriminating new physics



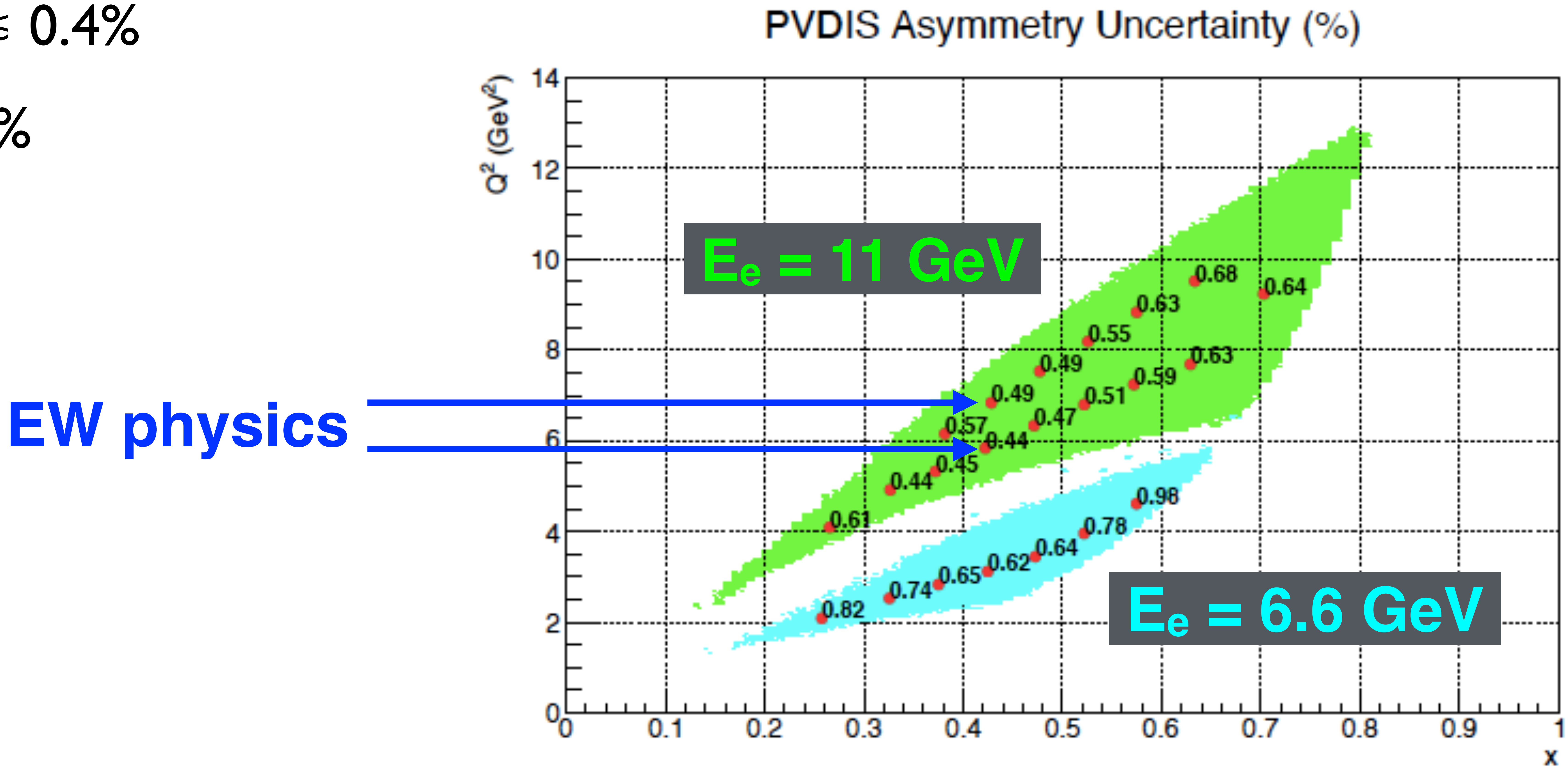
* Z-Z′ mixing: modification of Z vector coupling
* oblique parameters: STU (also need M_W and Γ_Z)
* new amplitudes: off- versus on-Z pole measurements (e.g. heavy Z′)
* dark Z: renormalization group evolution (low versus very low energy measurements)

Standard Model Effective Field Theory (SMEFT)

- Systematic expansion in inverse powers of new physics mass scale $\Lambda \gg M_Z$
- no known a priori reason to stop at the level of renormalizable interactions (D = 4)
- ν oscillations accounted for by 2 (12) D = 5 *Weinberg 1979* H^2L^2 + H.c. (ΔL = ±2) operators for 1 (3) fermion generations, counting Hermitian conjugates
- 15 bosonic + 38 fermionic + 31 mixed = 84 (3045) independent D = 6 operators (Λ^{-2}) *Grzadkowski et al., arXiv:1008.4884*
- 38 fermionic operators = 3 L^4 + 13 L^2Q^2 + 8 LQ^3 (ΔB ≠ 0) + 14 Q^4 operators
- 3 L^4 = e_Ve_V + e_Ae_V *(MOLLER)* + e_Ae_A
- 13 L^2Q^2 = 7 vector and axial-vector combinations + 4 scalar + 2 tensor
- 2 e_Vq_V (C_0) + 2 e_Aq_V (C_1) *(APV, Qweak, P2)* + 2 e_Vq_A (C_2) *(SoLID)* + 2 e_Aq_A (C_3) *(e⁺@SoLID)*
  −1 constraint $(\overline{u}_L\gamma^\mu u_L - \overline{d}_L\gamma^\mu d_L)\overline{e}_R\gamma_\mu e_R = 0$

Electroweak physics with SoLID

* $$A_{LR}^{eDIS} \approx -\frac{9}{20\pi\alpha(Q)}\frac{Q^2}{v^2}\left[\left(\frac{2}{3}g_{AV}^{eu}-\frac{1}{3}g_{AV}^{ed}\right)+\left(\frac{2}{3}g_{VA}^{eu}-\frac{1}{3}g_{VA}^{ed}\right)\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$
* polarimetry: $\Delta P/P \lesssim 0.4\%$
* total systematic: 0.5%

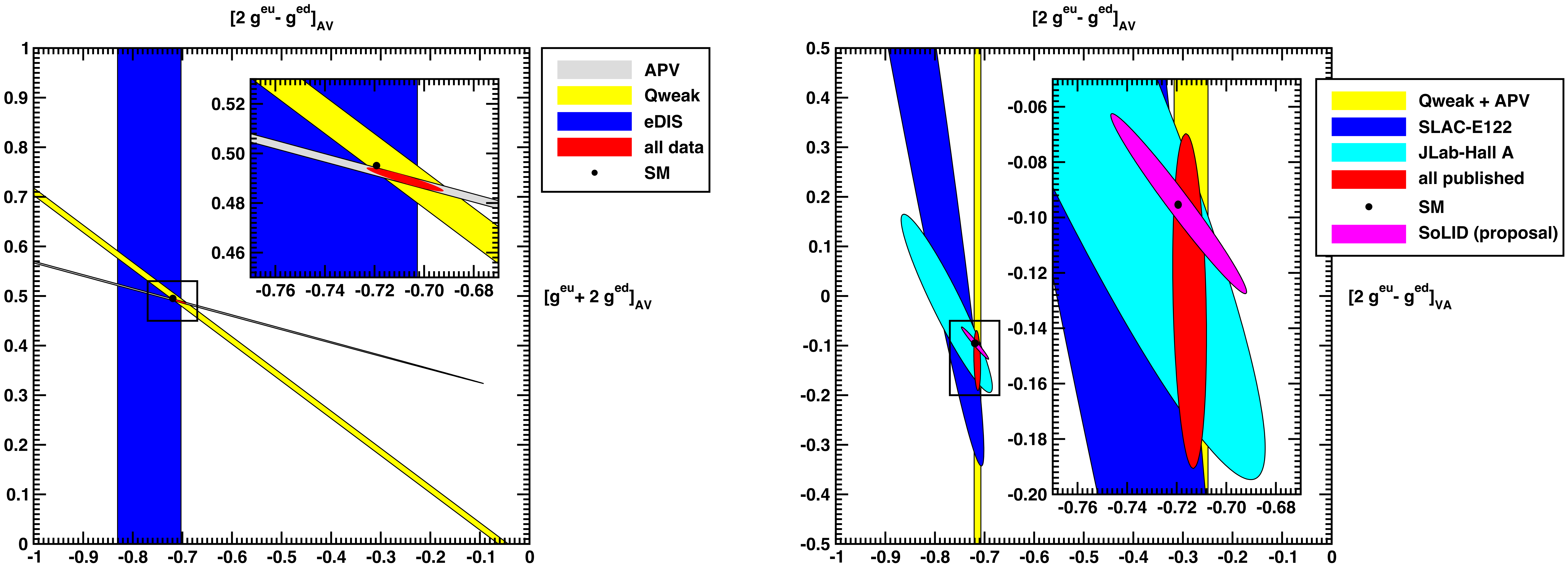


SMEFT and the LHC

* Sensitivity to new physics D = 6 operators through interference (D = 6)$\otimes$SM
* Λ^{-4} effects are negligible at $Q^2 \ll M_Z^2$, *i.e.* in any fixed target experiment
* Drell-Yan lepton pair production is a high-precision tool at the LHC
* $\sin^2\theta_W$ from $A_{FB}(e,\mu)$ in a ± 30 GeV window around M_Z
* in very high Q^2 Drell-Yan production cross-section data

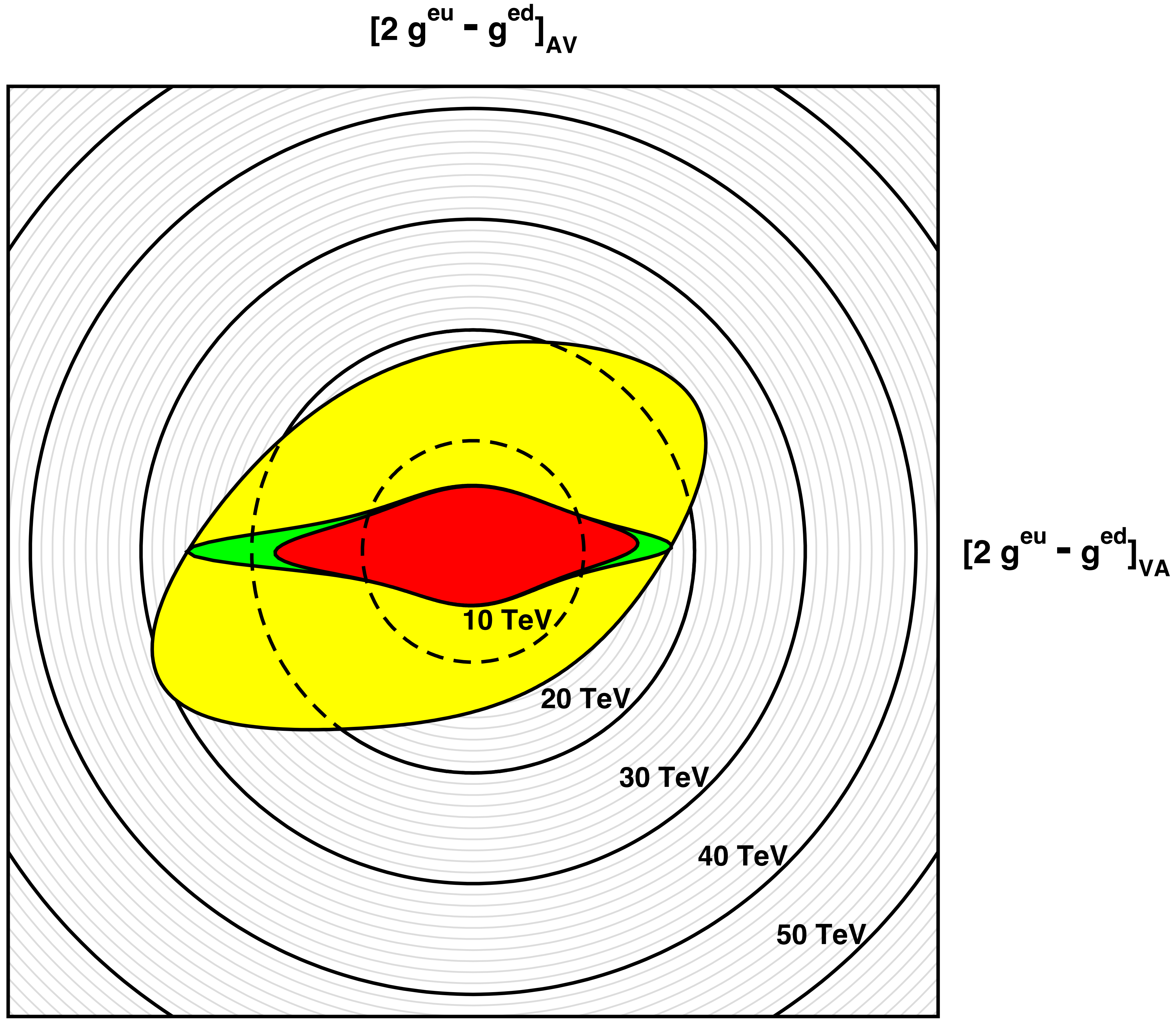
  $\sum_i |D = 6|^2 \geq 0$ enters at the order (Λ^{-4}) of D = 8 operators (D = 8)$\otimes$SM
* in principle they constrain all D = 6 operators at $Q^2 \gg M_Z^2$
* however, there are 993 (44807) D = 8 operators *Henning et al., arXiv:1512.03433*
* effectively, they introduce an extra theory uncertainty on the D = 6 LHC constraints arising dominantly from total cross-sections and A_{FB} *Alte et al., arXiv:1812.07575*

Parity-violating 4-fermion electron-quark couplings



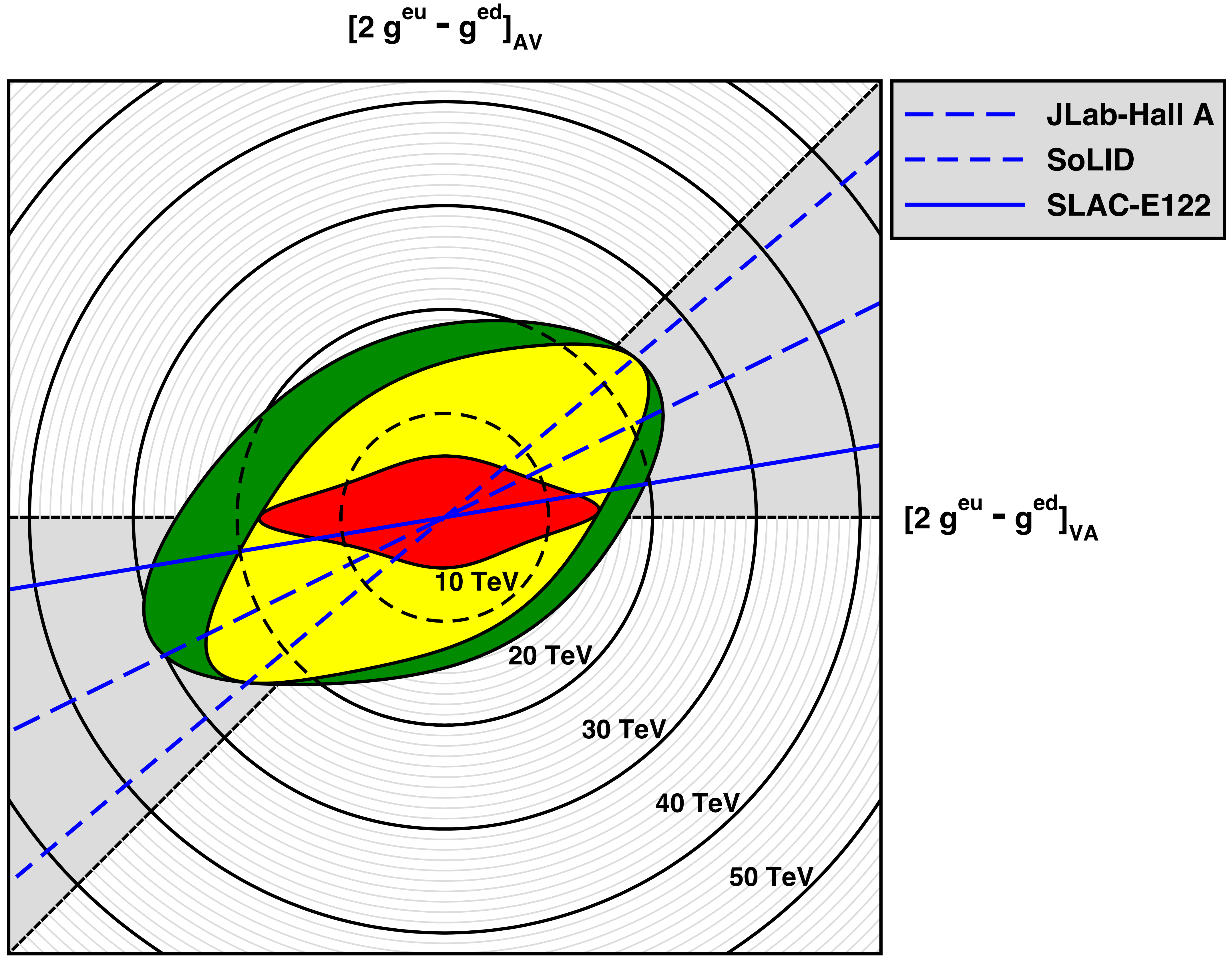
JE et al., arXiv:1401.6199

Scale exclusion from PVDIS and SoLID

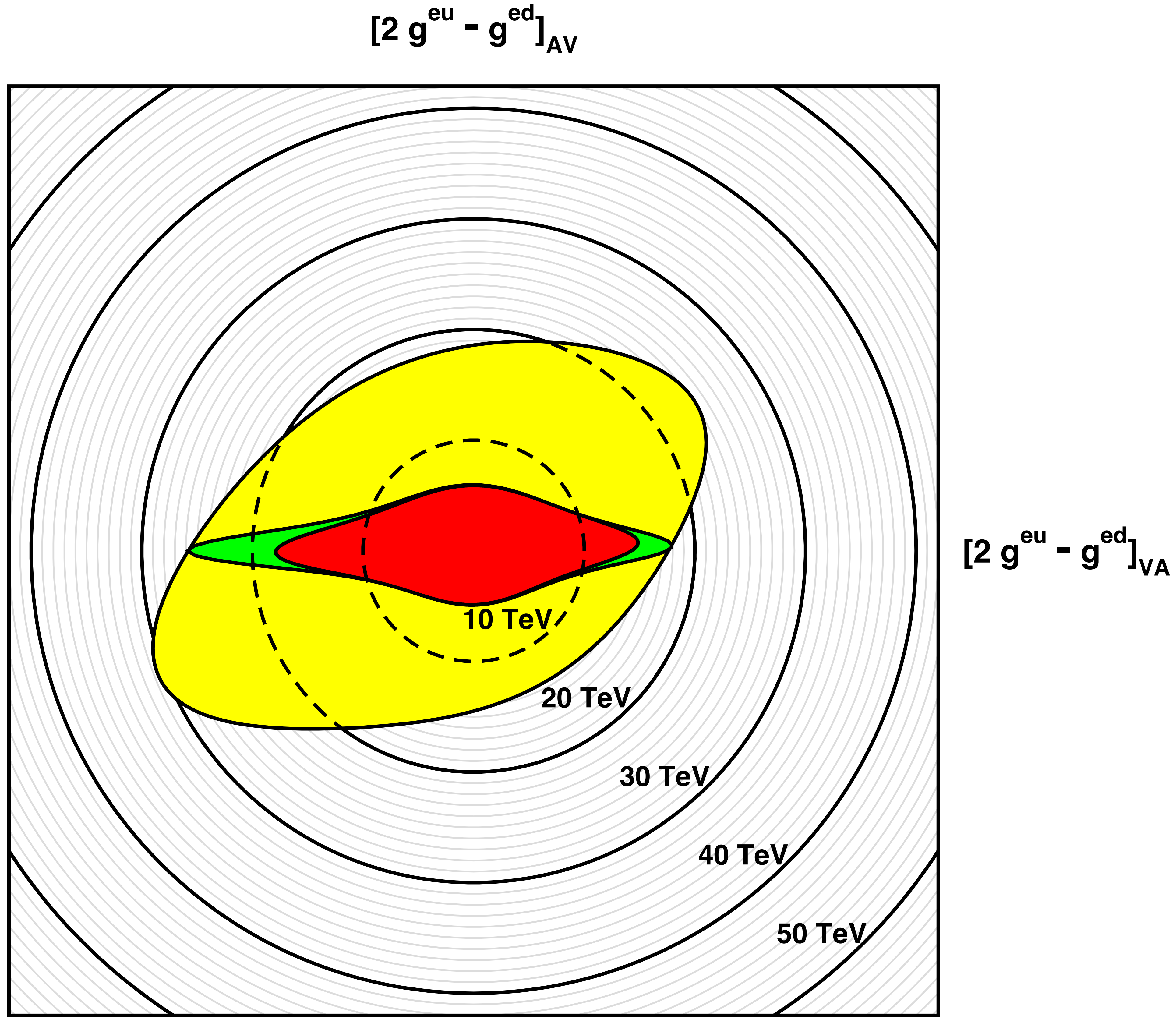


all data
all data + P2
all data + P2 + SoLID

Scale exclusion from PVDIS and SoLID

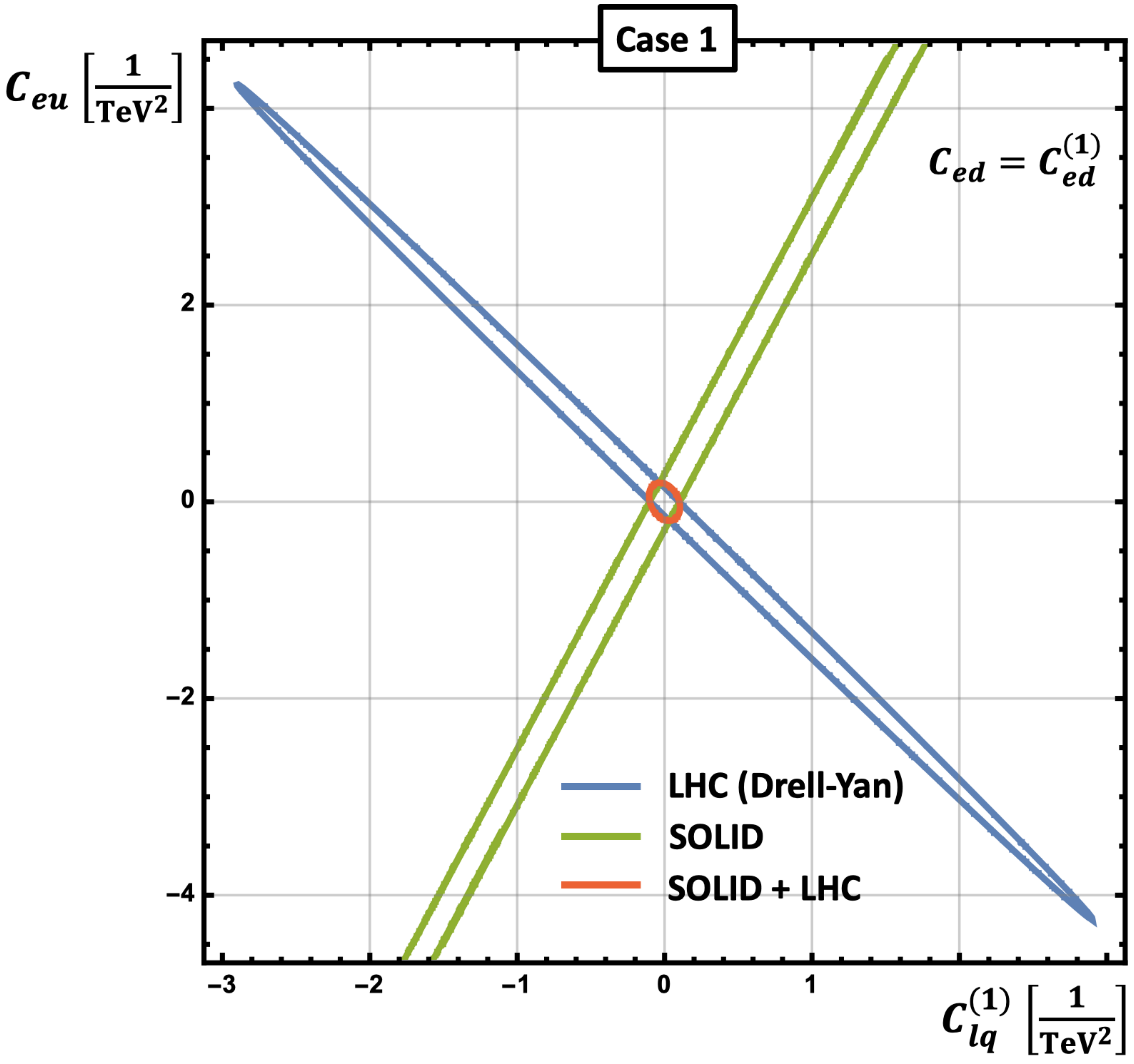


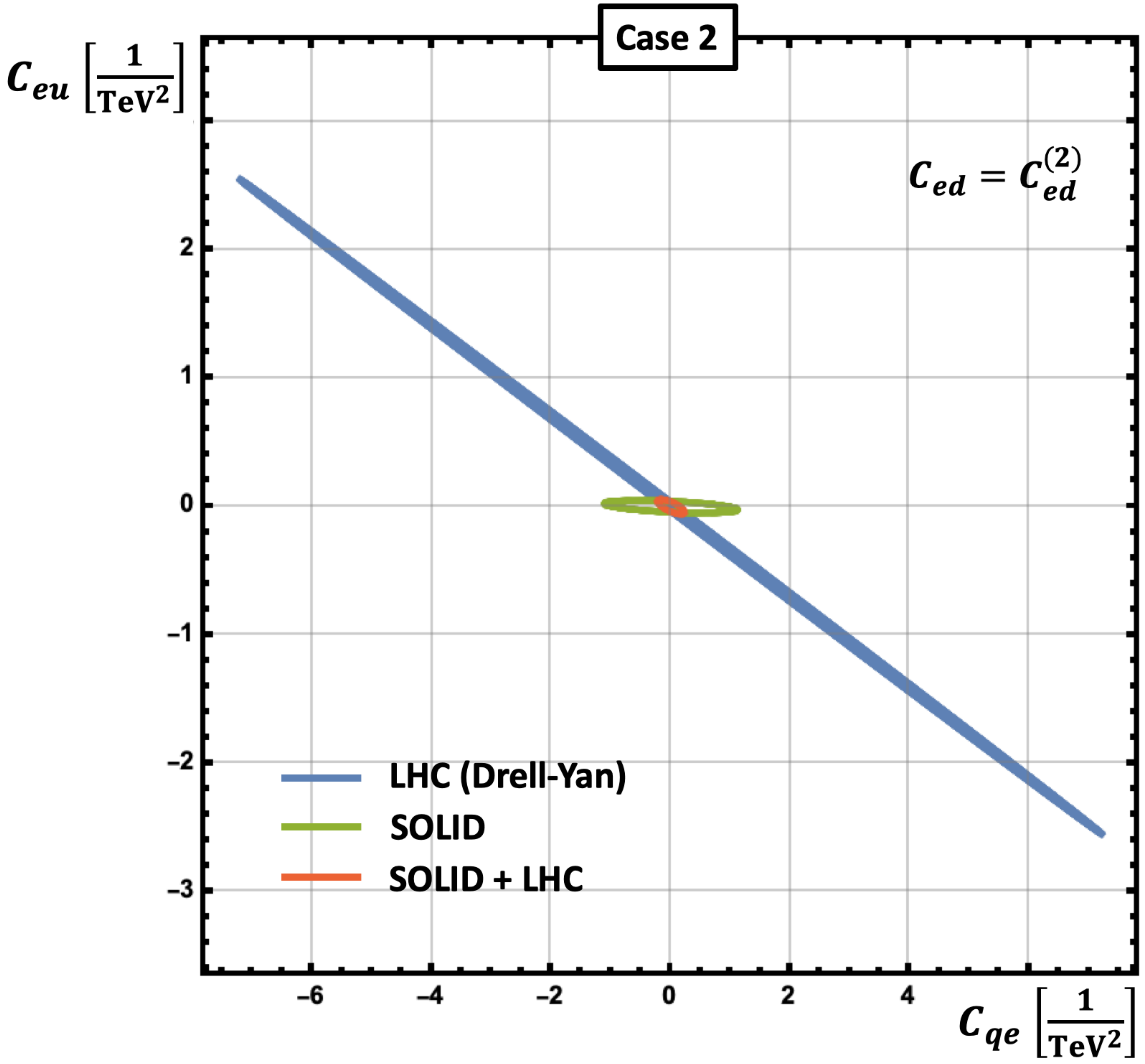
all data
all data + SoLID
all data + SoLID + P2



all data
all data + P2
all data + P2 + SoLID

Lifting flat LHC directions



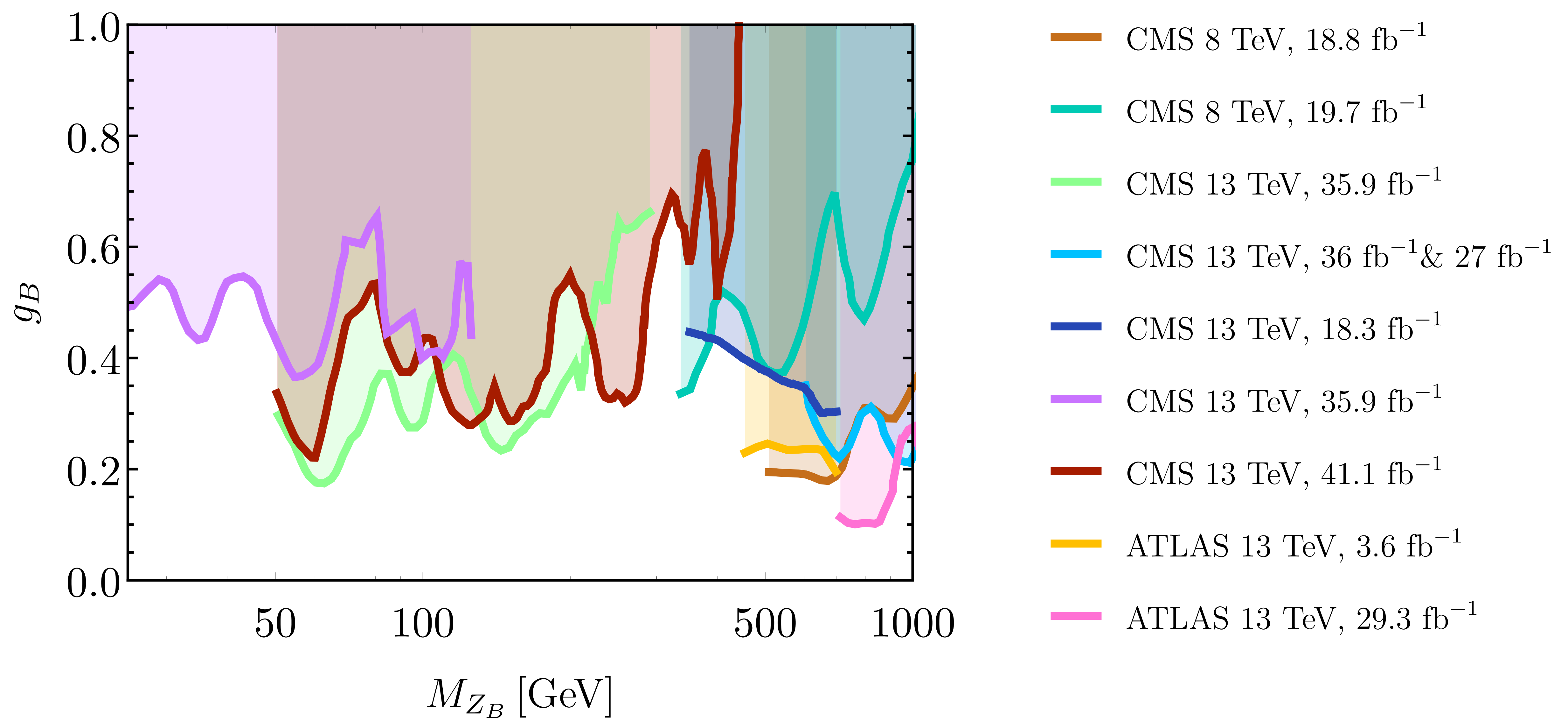


courtesy of *Frank Petriello* ; see also *Boughezal et al. arXiv:2004.00748*

Leptophobic Z's

* Extra Z bosons one of the most well-motivated new physics scenarios
* very strong mass limits from the LHC, but simplified analyses allow loopholes
* e.g., leptophobic Z's decaying into supersymmetric or dark matter particles need different search strategies *González-Alonso et al., arXiv:1211.4581*
* $M_{Z'} \gtrsim 800$ GeV from precision data from ZZ'-mixing for the unique leptophobic Z' from E₆, but $\theta_{ZZ'} \propto C\dfrac{M_Z}{M_{Z'}}$ where C can be tuned to vanish

JE et al., arXiv:0906.2435

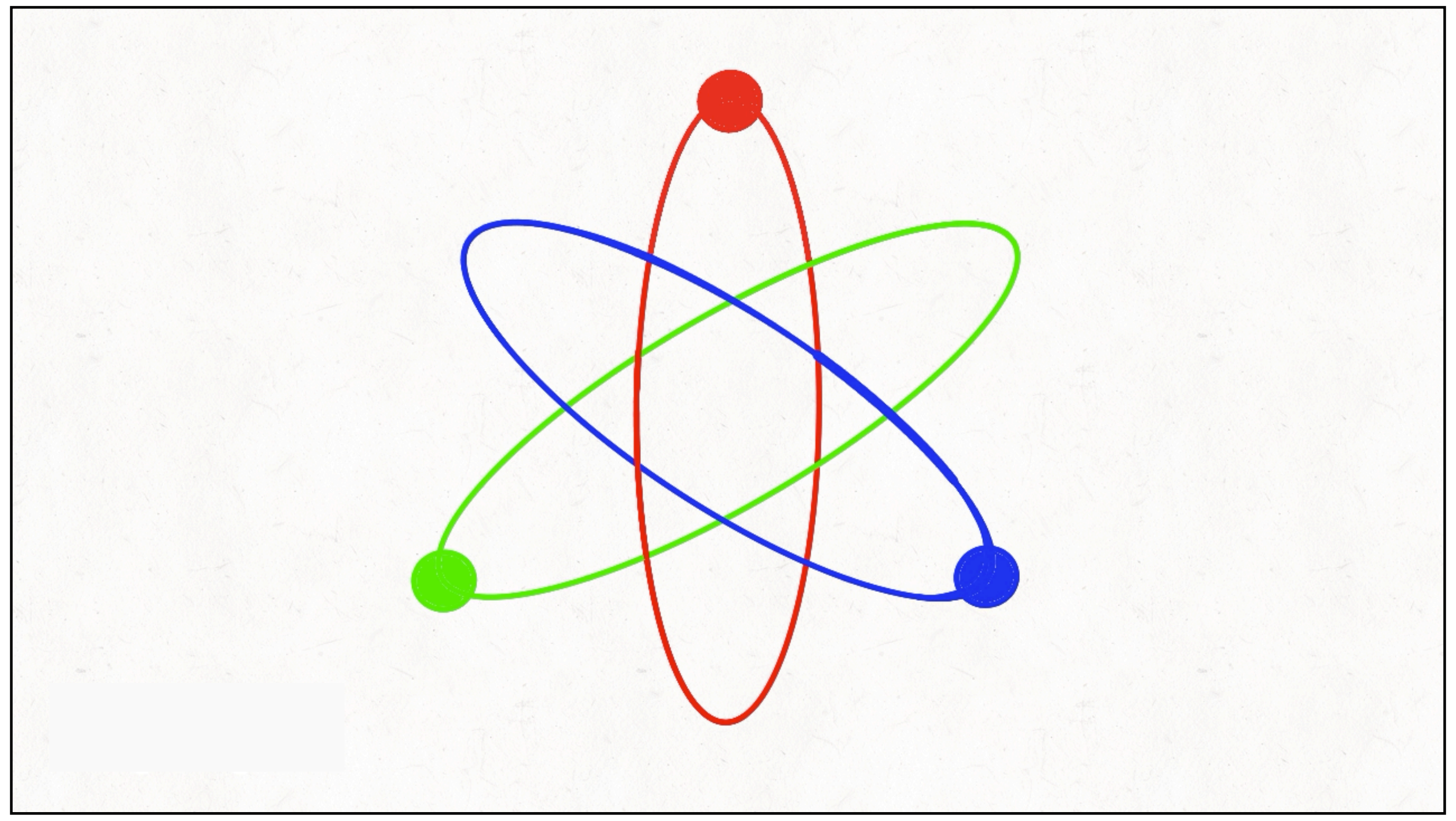


Pérez et al., arXiv:2003.09426

Conclusions

* νDIS very important in establishing the SM, but the complicated physics of heavy nuclei presents bottle neck to high precision; the scepter is handed on to eDIS
* SoLID will be perfectly synchronized with ultra-high precision PVES with P2 (Mainz) and MOLLER, APV (including isotope ratios) and precision CEνNS
* PVDIS with SoLID precision at sub-% level
* no convincing new physics signal at LHC yet: need to look under each ~~rock~~ lamppost
* PVDIS provides such a lamppost (a concrete direction in SMEFT operator space)
* viable models relevant to SoLID need tuning (nowadays a generic feature in NP searches); parameter space becomes fractal (each available piece of parameter space unlikely and contrived, but probably many of these)
* but SoLID explores directions in SMEFT parameter space to which the LHC is blind

Thank You



Backup

New Physics scales Λ_{NP} (95% CL)

	precision	$\Delta\sin^2\theta_W$	Λ_{NP}		precision	$\Delta\sin^2\theta_W$	Λ_{NP}
E158	14 %	0,0013	17.0 TeV	MOLLER	2,4 %	0,00028	38 TeV
PVDIS	4,1 %	0,0043	7.8 TeV	SoLID	0,6 %	0,00057	22 TeV
Qweak	6,3 %	0,0011	27.8 TeV	P2	1,83 %	0,00033	51 TeV
				P2 ^{12}C	0,3 %	0,0007	49 TeV
APV ^{133}Cs	0,58 %	0,0019	32.3 TeV	APV ^{225}Ra	0,5 %	0,0018	34 TeV
$^{176}Yb/^{170}Yb$	0,78 %	0,052	4.3 TeV	$^{225}Ra/^{213}Ra$	0,1 %	0,0037	16 TeV