Cluster of Excellence
PRISMA+
Precision Physics, Fundamental Interactions and Structure of Matter

PDG
particle data group

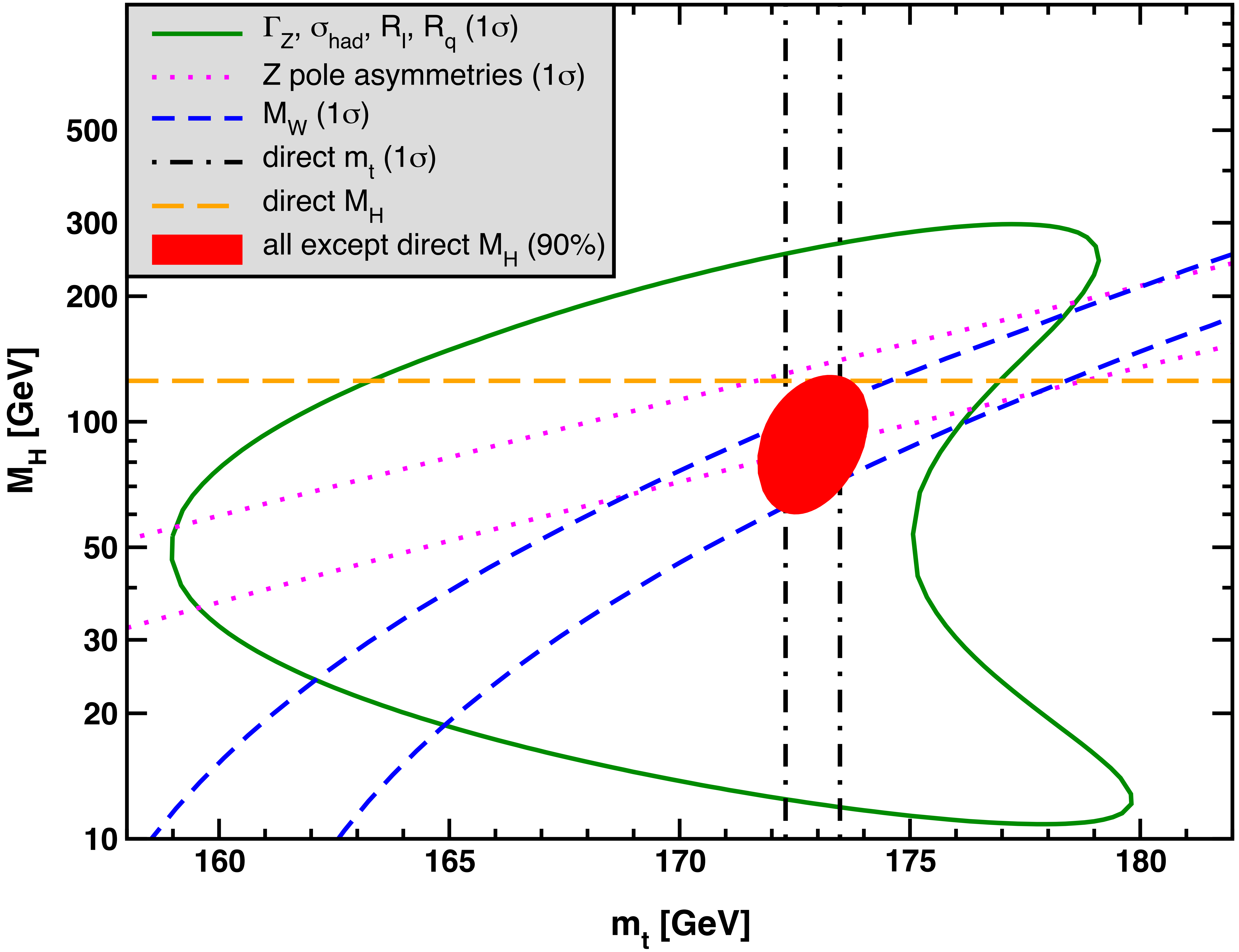
Standard Model Fit

Jens Erler

JG|U

LHC EW WG General Meeting, February 15–17, 2022

M_H – m_t today



χ^2/d.o.f. = 40.8/42

(before g_μ–2 update)

including

correlated theory errors

Freitas & JE, PDG (2020)

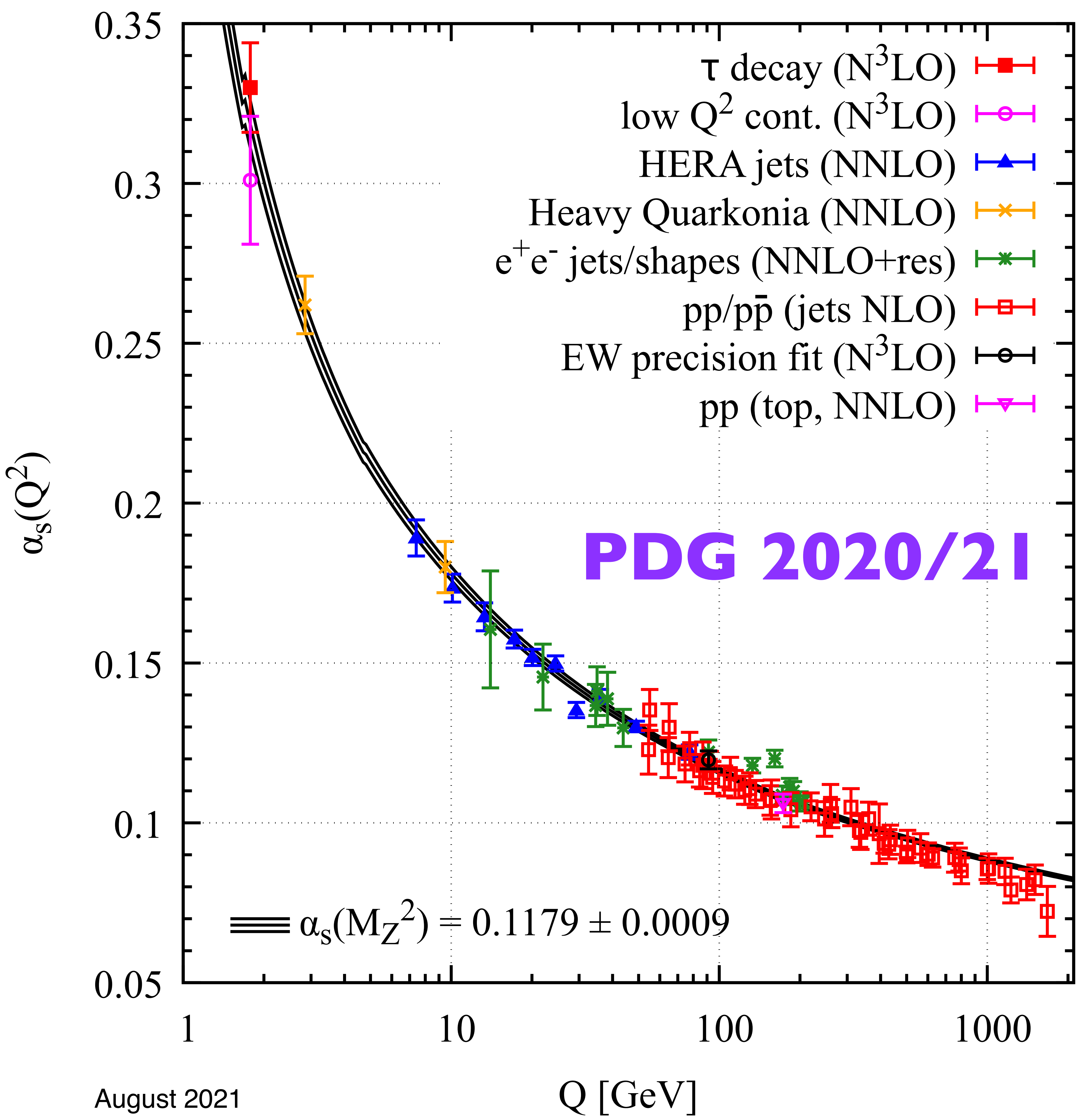
Contents

* $\alpha_s(M_Z)$
* M_W and M_Z
* $\sin^2\theta^{\ell}_{eff}$
* m_t

$\alpha_s(M_Z)$

α_s world average

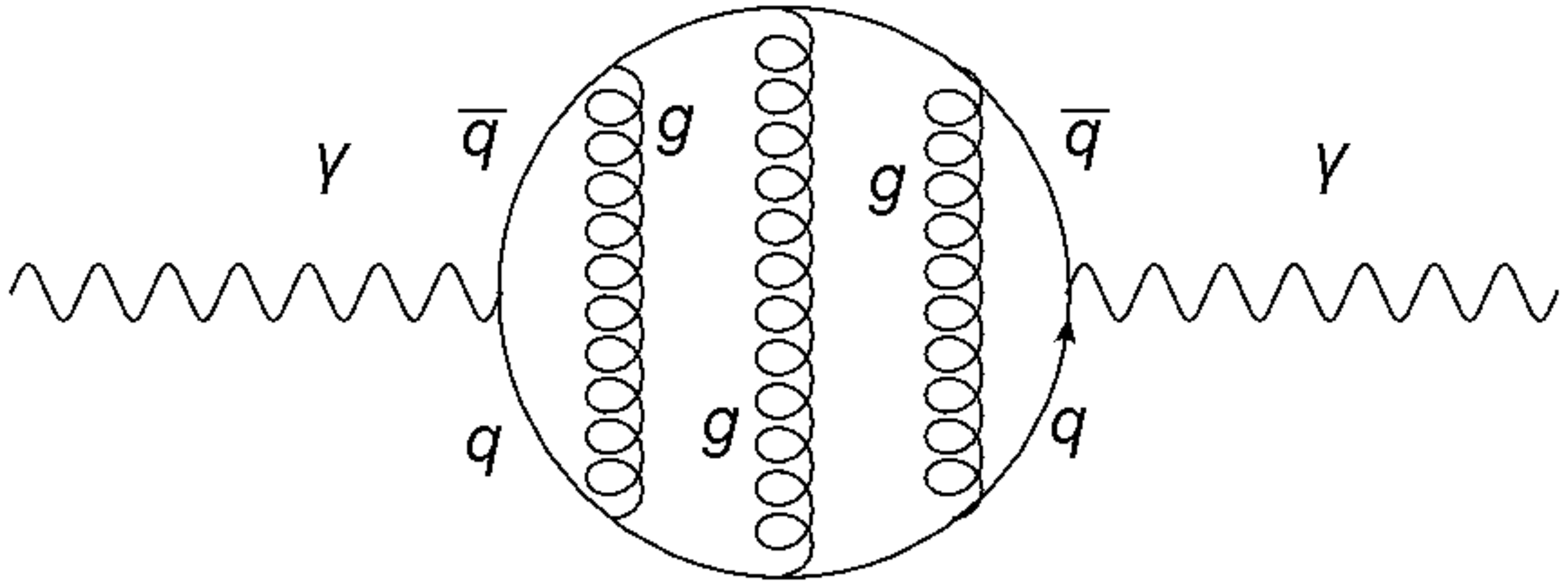
- ✱ only 3 determinations at N^3LO
- ✱ only Z pole value not dominated by QCD uncertainties ➟ very clean
- ✱ sensitive to many types of new physics especially if family non-universal (vertex corrections)
- ✱ α_s from W decays also clean (N^3LO) and less sensitive to new physics (except CKM non-unitarity)



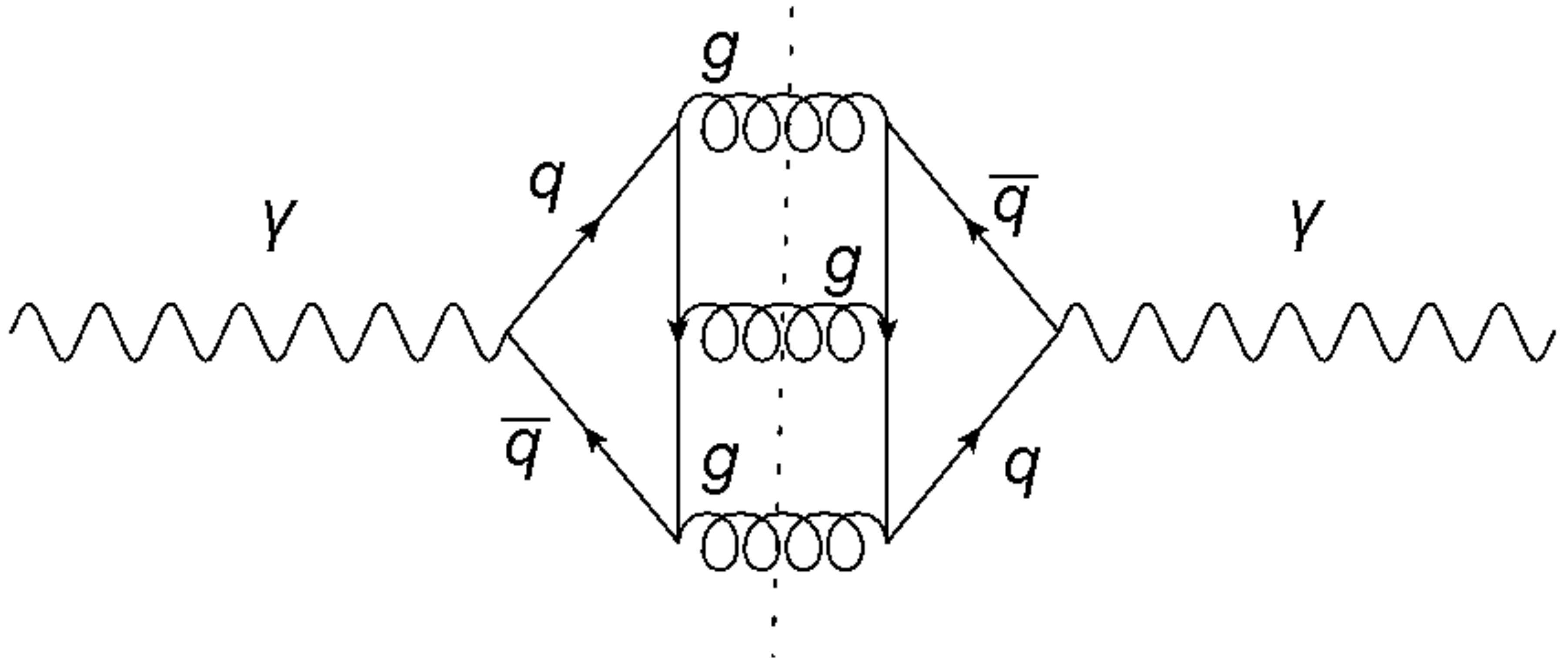
α_s from the Z pole

$$R_V^q = R_A^q = 1 + \frac{\alpha_s(M_Z)}{\pi} + 1.409\frac{\alpha_s^2}{\pi^2} - 12.77\frac{\alpha_s^3}{\pi^3} - 80.0\frac{\alpha_s^4}{\pi^4} + Q_q^2\left[\frac{3}{4} - \frac{\alpha_s}{4\pi} - \left(1.106 + \frac{3}{32}Q_q^2\right)\frac{\alpha}{\pi}\right]\frac{\alpha(M_Z)}{\pi}$$

for massless quarks (non-singlet)



$$\Gamma_Z^{\mathrm{had}} \propto \rho\left(1 + \frac{\alpha_s(M_Z)}{\pi} + 0.79\frac{\alpha_s^2}{\pi^2} - 15.52\frac{\alpha_s^3}{\pi^3} - 69.3\frac{\alpha_s^4}{\pi^4}\right)$$



after large (top quark driven) singlet corrections (Z boson only) starting at order α_s^2

α_s from the Z pole

observable	$\alpha_s(M_Z)$	comment
$\Gamma_Z = 2495.5 \pm 2.3$ MeV	0.1215 ± 0.0048	recent (Γ_Z = +0.3 MeV)
$\sigma_{had} = 41.481 \pm 0.033$ nb	0.1201 ± 0.0065	recent ($\Delta\sigma_{had}$ = –60 pb)
$R_e = \Gamma_{had}/\Gamma_e = 20.804 \pm 0.050$	0.1295 ± 0.0082	
$R_\mu = \Gamma_{had}/\Gamma_\mu = 20.784 \pm 0.034$	0.1264 ± 0.0054	
$R_\tau = \Gamma_{had}/\Gamma_\tau = 20.764 \pm 0.045$	0.1157 ± 0.0072	
$B_W(had) = 0.6736 \pm 0.0018$	0.098 ± 0.025	new (LEP 2 + CMS)
combination	0.1223 ± 0.0028	
global fit	0.1185 ± 0.0016	includes τ decays

electromagnetic beam-beam effects
improved Bhabha X section (luminosity)

Voutsinas et al., arXiv:1908.01704
Janot & Jadach, arXiv:1912.02067

α_s improvement @ the LHC?

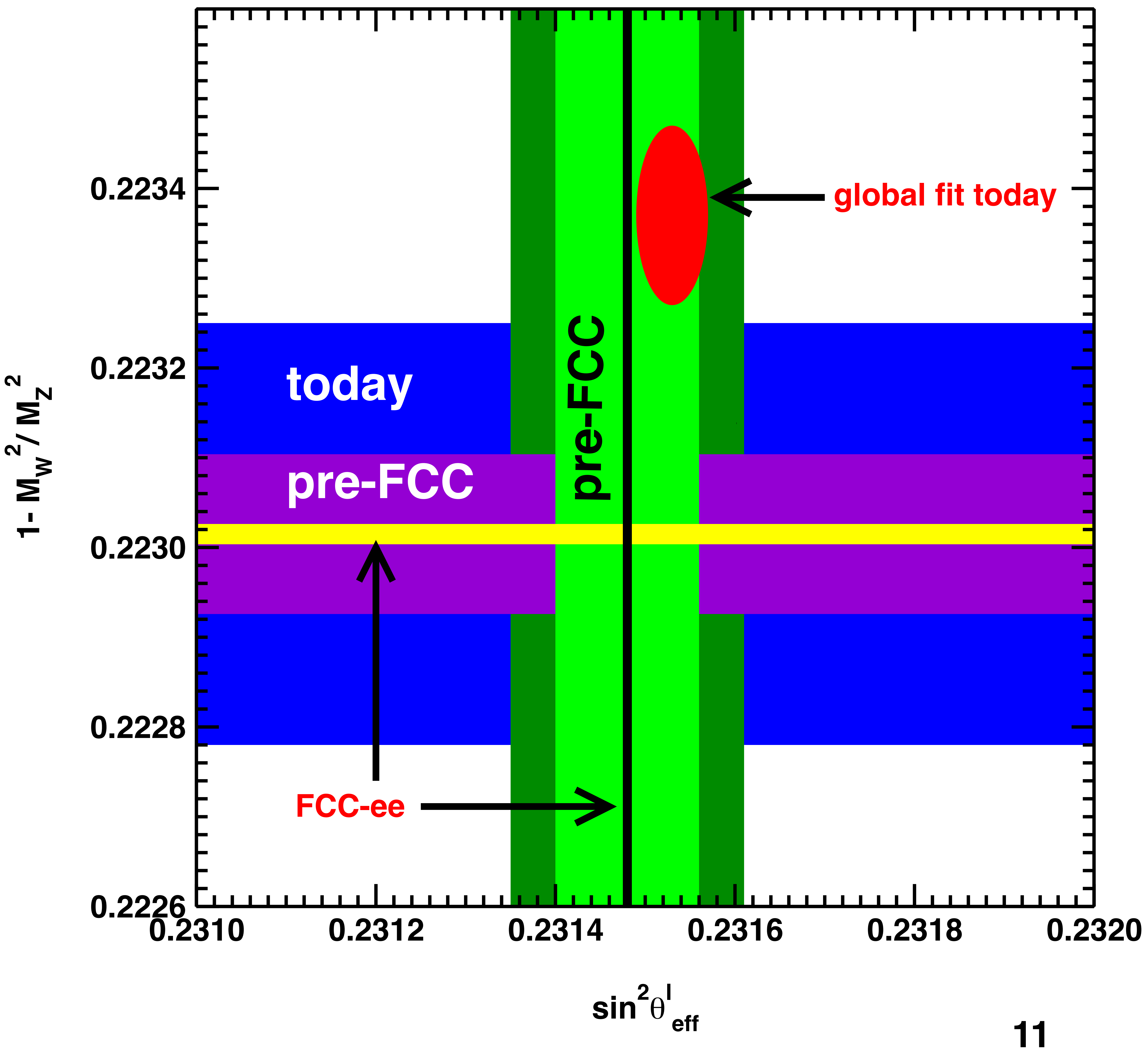
- today: Γ_W = 2085 ± 42 MeV (LEP + Tevatron) ➟ no useful α_s constraint
- α_s rule of thumb: $\Delta\Gamma_W \sim \Gamma_W(had)/\Gamma_Z(had)\ \Delta\Gamma_Z \sim (1441/1745)\times 2.3$ MeV ~ 1.9 MeV
- assuming: Γ_W = 2090 ± 2 MeV ➟ $\alpha_s(M_Z)$ = 0.1203 ± 0.0054 (assuming CKM unitarity)
  possible at FCC-ee but unlikely at LHC ➟ $B_W(had)$
- LEP 2: $B_W(had)$ = 0.6741 ± 0.0027
  CMS: $B_W(had)$ = 0.6732 ± 0.0023
  combined: $B_W(had)$ = 0.6736 ± 0.0018 ➟ $\alpha_s(M_Z)$ = 0.098 ± 0.025
- Some greedy reference values:
- Run 3: $B_W(had)$ = 0.6752 ± 0.0010 (1.5‰) ➟ $\alpha_s(M_Z)$ = 0.1196 ± 0.014
  HL-LHC: $B_W(had)$ = 0.6752 ± 0.0004 (0.6‰) ➟ $\alpha_s(M_Z)$ = 0.1196 ± 0.0056
- ΔR_μ = ± 0.6‰ ➟ $\alpha_s(M_Z)$ = 0.1196 ± 0.0020

M_W & M_Z

M_W

group	M_W [GeV]	comment
ATLAS	80.370 ± 0.019	13.7 million W decays @ 7 TeV
LHCb	80.354 ± 0.032	new (2.4 million W decays @ 13 TeV)
LHC	80.366 ± 0.017	assumes 9 MeV (= LHCb PDF) common error
Tevatron	80.387 ± 0.016	CDF & DØ
hadron colliders	80.377 ± 0.013	assumes 7 MeV common PDF error
LEP 2	80.376 ± 0.033	includes low statistics threshold scan
direct	80.377 ± 0.012	world average
indirect	80.357 ± 0.006	1.5 σ
all data	80.361 ± 0.006	global fit

on-shell *vs.* effective weak mixing angle



ΔM_W (LHC)

$\approx 3.8_{stat} + 3.8_{syst} + 3.8_{PDF}$ MeV

$\approx (5/3)^{1/2} \times 3.8$ MeV ≈ 5 MeV

(for 3 detectors) based on

Azzi et al.
arXiv:1902.04070

$\Delta\sin^2\theta_W$ (LHC) $\approx 10^{-4}$

M_W improvement @ the LHC?

- today: $M_W = 80.377 \pm 0.012$ GeV
  - ➟ M_H (indirect) $= 92^{+19}_{-17}$ GeV
  - M_H (direct) $= 125.14 \pm 0.15$ GeV (1.5 σ tension)
- assuming $M_W = 80.377 \pm 0.005$ GeV from LHC
  - ➟ M_H (indirect) $= 88 \pm 12$ GeV (2.8 σ tension)
- assuming instead $M_W = 80.389 \pm 0.005$ GeV from LHC
  - ➟ M_H (indirect) $= 75 \pm 11$ GeV (3.9 σ tension)
- assuming in addition negligible theory errors
  - ➟ M_H (indirect) $= 74 \pm 9$ GeV (4.6 σ tension)

M_Z improvement @ the LHC?

- ✱ today (LEP 1): $M_Z = 91.1876 \pm 0.0021$ GeV (resonant depolarization)
  - ➟ M_H (indirect) $= 92^{+19}_{-17}$ GeV
  - M_H (direct) $= 125.14 \pm 0.15$ GeV (1.5 σ tension)
- ✱ assuming: $M_Z = 91.1897 \pm 0.001$ GeV from LHC (1σ higher)
  - ➟ ΔM_H (indirect) = 3.3 GeV
  - ➟ non-negligible impact
  - ➟ important cross-check for LEP energy calibration

  (corrections for sun, moon, water level in lake Geneva, trains…)

  what if something was missed?

$sin^2\theta_W$

$\sin^2\theta^\ell_{eff}$

group	$\sin^2\theta^\ell_{eff}$	comment
ATLAS	0.2308 ± 0.0012	4.8 fb^{-1} @ 7 TeV
ATLAS	0.23140 ± 0.00036	15 million lepton pairs @ 8 TeV (20.1 fb^{-1})
CMS	0.23101 ± 0.00053	13.1 million lepton pairs @ 8 TeV
LHCb	0.23142 ± 0.00106	1 fb^{-1} @ 7 TeV and 2 fb^{-1} @ 8 TeV
LHC	0.23129 ± 0.00033	assumes common ±0.00024 (= ATLAS PDF)
Tevatron	0.23148 ± 0.00033	1.8 million lepton pairs @ CDF and DØ
LEP 1	0.23184 ± 0.00021	includes theory update for $A_{FB}(b)$
SLC	0.23098 ± 0.00026	polarized e^- beam (2.6 σ lower than LEP)
low energy PV	0.23151 ± 0.00076	APV, SLAC–E–158, (PVDIS & Qweak)@JLab
direct	0.23147 ± 0.00013	world average
indirect	0.23154 ± 0.00004	SM prediction
all data	0.23153 ± 0.00004	global fit

$\sin^2\theta^{\ell}_{\mathrm{eff}}$ improvement @ the LHC?

- today: $\sin^2\theta^{\ell}_{\mathrm{eff}} = 0.23147 \pm 0.00013$

  ➠ M_H (indirect) = 92^{+19}_{-17} GeV

  M_H (direct) = 125.14 ± 0.15 GeV (1.5 σ tension)

- assuming $\sin^2\theta^{\ell}_{\mathrm{eff}} = 0.2316 \pm 0.0001$ from LHC

  ➠ M_H (indirect) = 107 ± 16 GeV (tension reduced to 1 σ)

m_t

m_t

group	m_t [GeV]	comment
ATLAS	172.69 ± 0.48	Run 1
ATLAS	174.48 ± 0.78	Run 2 (lepton + jet channel)
CMS	172.43 ± 0.48	Run 1
CMS	172.26 ± 0.61	Run 2 (hadronic channels)
CMS	172.33 ± 0.70	Run 2 (di-lepton channel)
Tevatron	174.30 ± 0.64	CDF & DØ
direct	172.89 ± 0.28 + Δm_{MC}	assumes common ±0.17 GeV (= ATLAS Run 2 theory)
indirect	176.0 ± 1.9	1.6 σ
all data	173.2 ± 0.6	assumes Δm_{MC} = 0 ± 0.52 GeV

m_t improvement @ the LHC?

- today: m_t = 172.89 ± 0.28 GeV + Δm_{MC} very precise but there are discrepancies (e.g. 2.8 σ or 2.73 GeV between DØ and CMS Run 2 lepton + jets channels)

- difficult to estimate $\Delta m_{MC} = m_{pole} - m_{MC}$
  Hoang, Plätzer & Samitz, arXiv:1807.06617

- Δm_{MC} expected to be of order $\alpha_s(Q_0)\, Q_0$ with a low scale $Q_0 \sim \mathcal{O}(1\text{ GeV})$
  but its value unknown in hadron collider environments
  $\alpha_s(Q_0)\, Q_0$ = 0.52 GeV for reference $Q_0 = \Gamma_t$ = 1.42 GeV

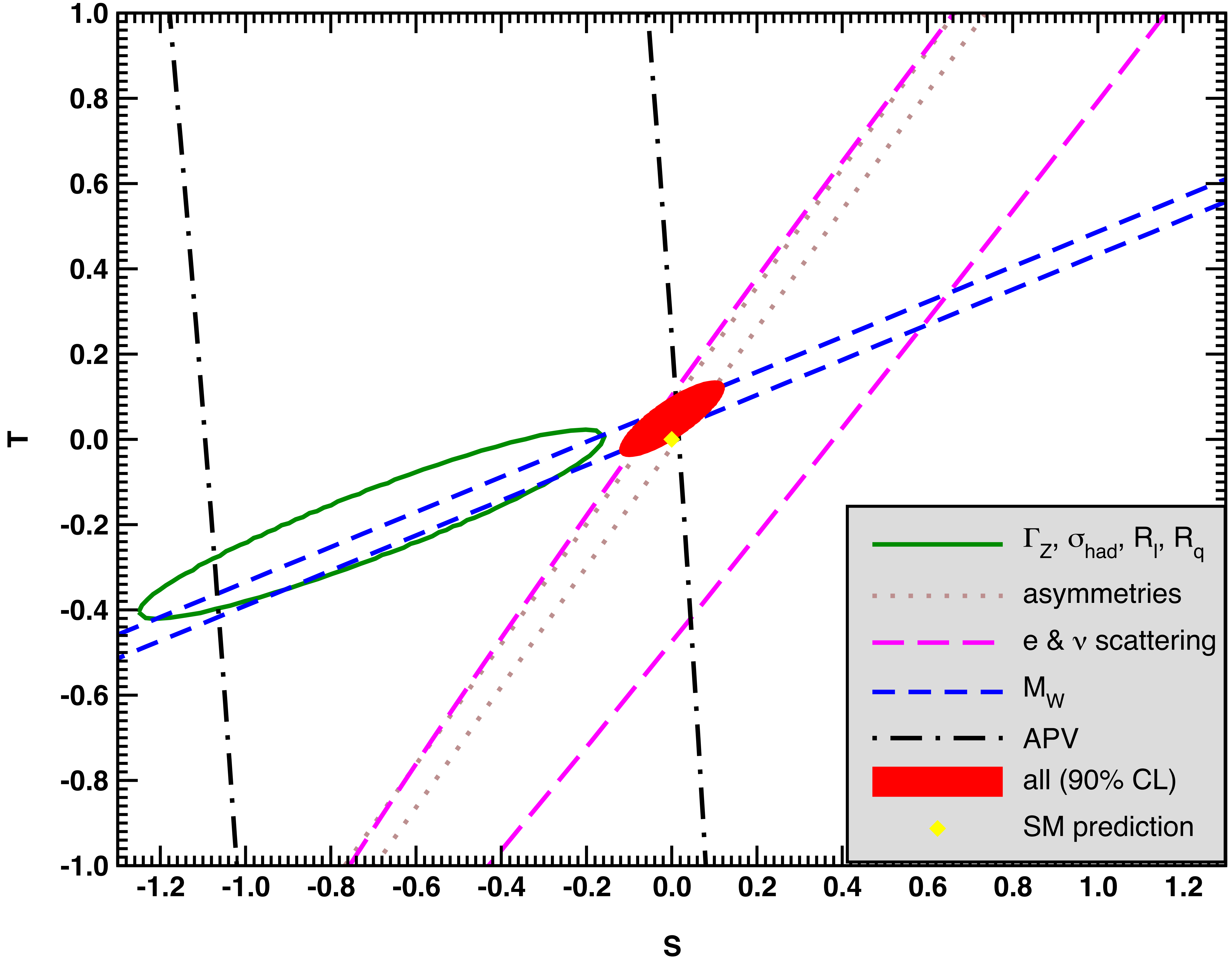
- however, Δm_{MC} only bookkeeping device: only MS-bar $\bar{m}_t(\bar{m}_t)$ (short-distance) matters

- Δm_t = 1 GeV ➟ ΔM_H (indirect) = 8.6 GeV

- Δm_t = 1 GeV ➟ $\Delta\rho = -10^{-4}$ ➟ mass splittings within new iso-doublets, SUSY, triplet VEVs…

- alternative: differential $t\bar{t}$ production cross-sections at NNLO (easier to interpret)
  Catani et al., arXiv:1906.06535

S and T



S	0.00 ± 0.07
T (ρ)	0.05 ± 0.06
$\Delta\chi^2$	– 3.9

* $M_{KK} \gtrsim 3.6$ TeV in warped extra dimension models

* $M_V \gtrsim 4$ TeV in minimal composite Higgs models

Freitas & JE, PDG (2020)

Conclusions

* *Only part of Run 2 precision data analyzed, but LHC already entering its high-precision era*
* recent LEP luminosity update confirms $N_\nu = 3$ active neutrinos, but α_s from Z pole now somewhat puzzling ➟ need more (better) W and Z decay measurements
* greatest opportunity is M_W as there remains a small tension with the SM
  so far no 8 or 13 TeV data exploited by ATLAS and CMS ➟ should be a priority
* currently $\sin^2\theta_W$ faces PDF bottleneck
  ➟ exploit complementary PDF dependences (M_W, high rapidity, pp vs. $p\bar{p}$)
  anti-correlations!
* m_t nominally quite precise, but kinematic reconstruction comes with severe strong interaction uncertainties.
  There are also experimental discrepancies ➟ alternative determinations desired

Thank You