

Electroweak precision (theory)

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LHCP 2021

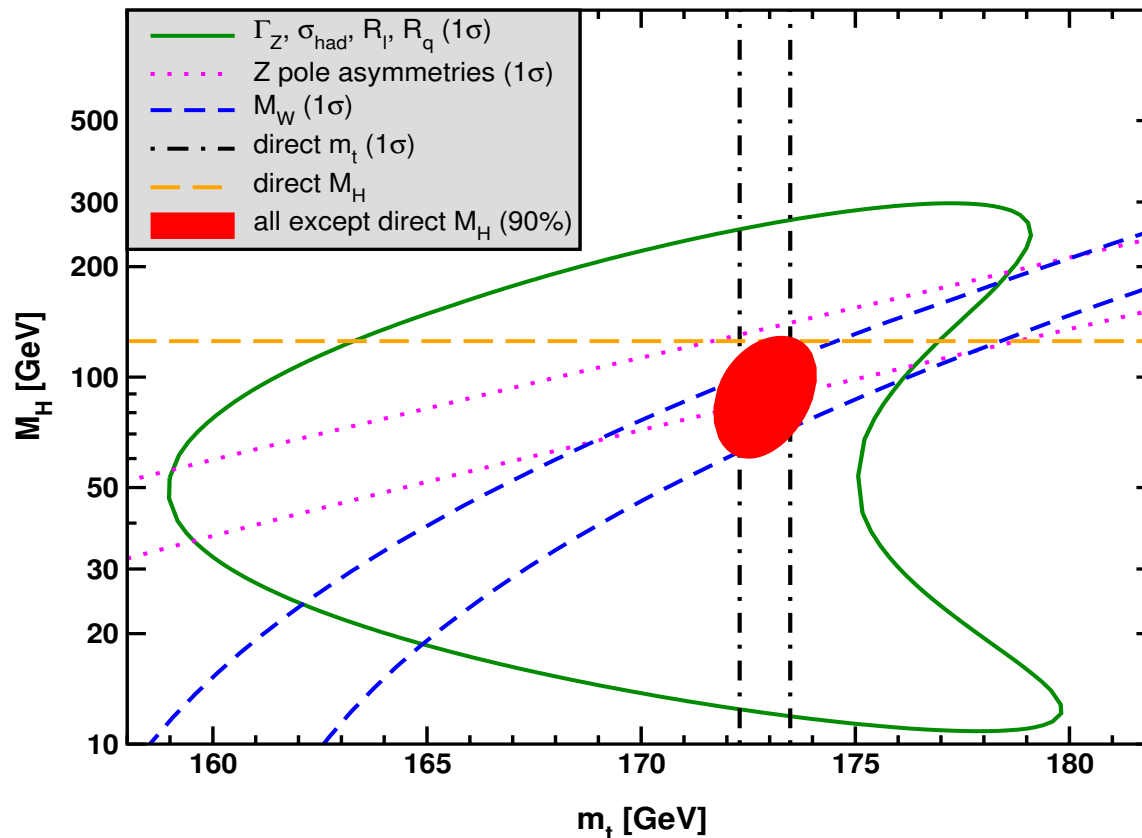
1. Introduction
2. $\sin^2 \theta_{\text{eff}}^l$
3. W mass
4. New physics: SMEFT analysis
5. Future experiments

Standard Model after Higgs discovery:

Erlar, Freitas (RPP) '20

- Good agreement between measured mass and indirect prediction
- Very good agreement over large number of observables:
 $\chi^2/\text{d.o.f.} = 40.8/41$ ($p = 48\%$) [before FNAL g-2]

Erlar '20



Direct measurements:

$$M_H = 125.30 \pm 0.13 \text{ GeV}$$

$$m_t = 172.89 \pm 0.28 \text{ GeV}$$

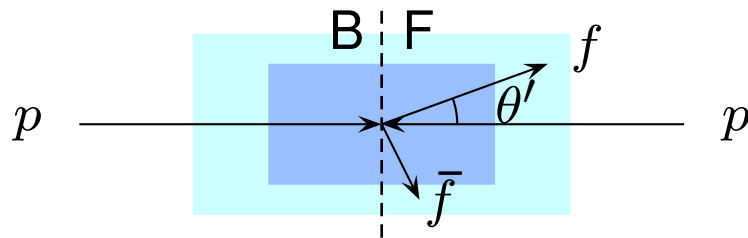
Indirect prediction:

$$M_H = 90^{+18}_{-16} \text{ GeV}$$

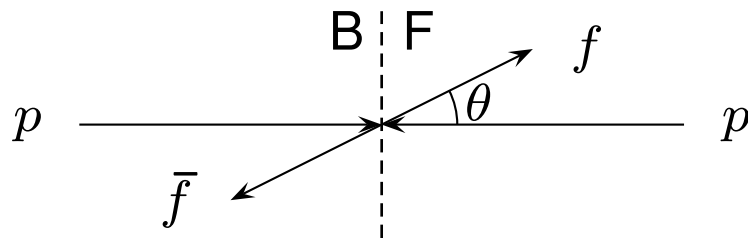
$$m_t = 176.3 \pm 1.9 \text{ GeV}$$

Forward-backward asymmetry:
“forward” defined through event
boost

lab frame:



center-of-mass frame:



→ main systematics:
PDFs, QCD corrections

$$d\sigma \propto (1 + c_\theta^2) + A_0 \frac{1}{2}(1 - 3c_\theta^2) \\ + A_1 s_{2\theta} c_\phi + A_2 \frac{1}{2} s_\theta^2 c_{2\phi} + A_3 s_\theta c_\phi \\ + A_4 c_\theta + A_5 s_\theta^2 s_{2\phi} + A_6 s_{2\theta} s_\phi + A_7 s_\theta s_\phi$$

$c_\theta \equiv \cos \theta$ etc.

[in CMS \approx Collins-Soper frame, with $p_{T,q} = p_{T,\bar{q}}$]

$$A_{\text{FB}} = \frac{3}{8} A_4$$

A_4 depends on $\frac{v_f}{a_f} = 1 - 4|q_f| \sin^2 \theta_{\text{eff}}^f$

[$f = u, d, s, c, \ell$]

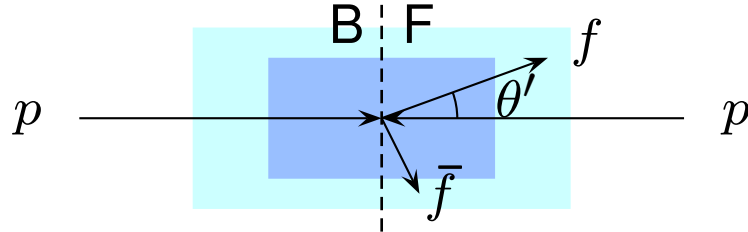
$$\sin^2 \theta_{\text{eff}}^q = \sin^2 \theta_{\text{eff}}^l + \underbrace{\Delta_{ql}}_{\text{computed in SM}}$$

computed in SM

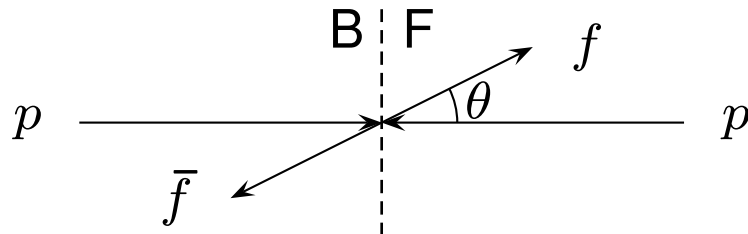
→ Assumption that NP is flavor universal

Forward-backward asymmetry:
“forward” defined through event
boost

lab frame:

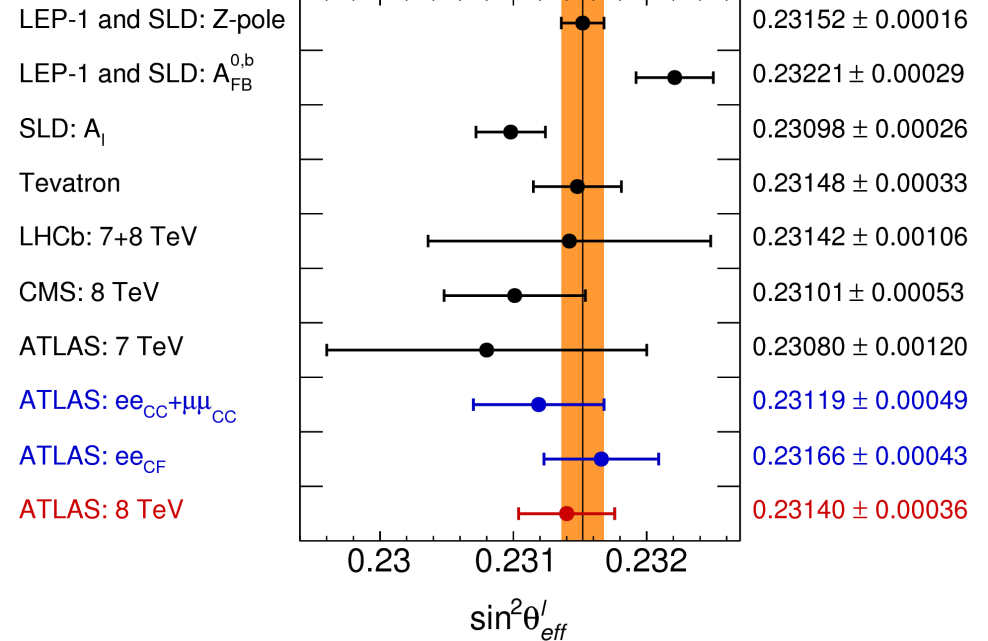


center-of-mass frame:



→ main systematics:
PDFs, QCD corrections

ATLAS Preliminary



→ talk by Ilya Gorbunov

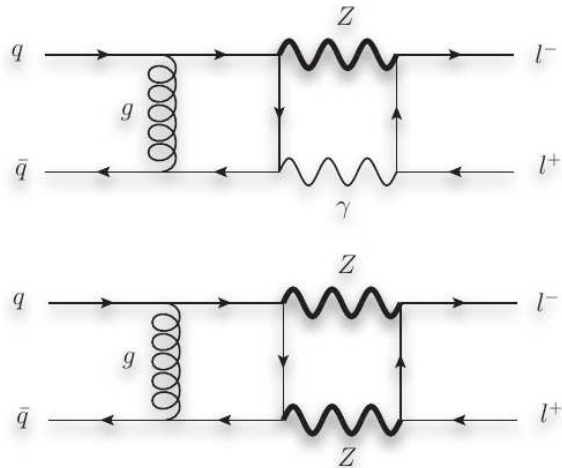
- QCD corrections @ NNLO (MC programs FEWZ, DYTurbo, MATRIX, MCFM)

Gavin, Li, Petriello, Quackenbush '12, Camarda et al. '19
 Grazzini, Kallweit, Wiesemann '17, Boughezal et al. '16

- Mixed QCD \times EW corrections, also off resonance

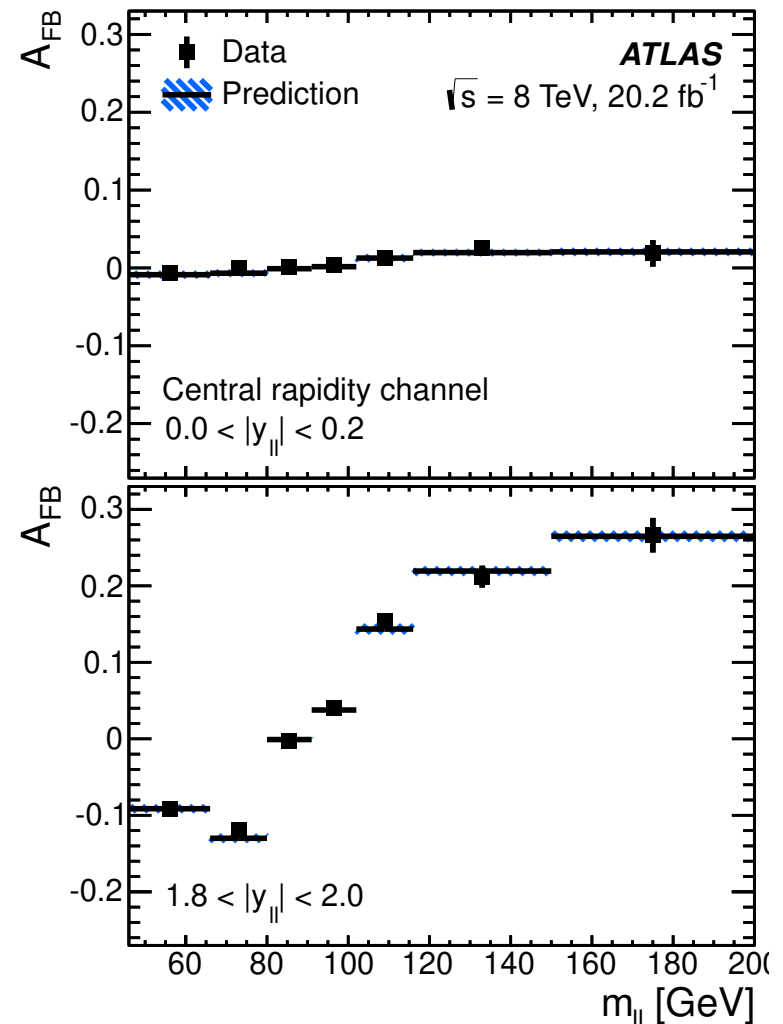
$\rightarrow 70 \text{ GeV} < m_{\ell\ell} < 125 \text{ GeV}$ used for $\sin^2 \theta_{\text{eff}}^l$ determination ATLAS '18

Ongoing work for complete calculation:



Heller, v.Manteuffel, Schabinger, Spiesberger '20

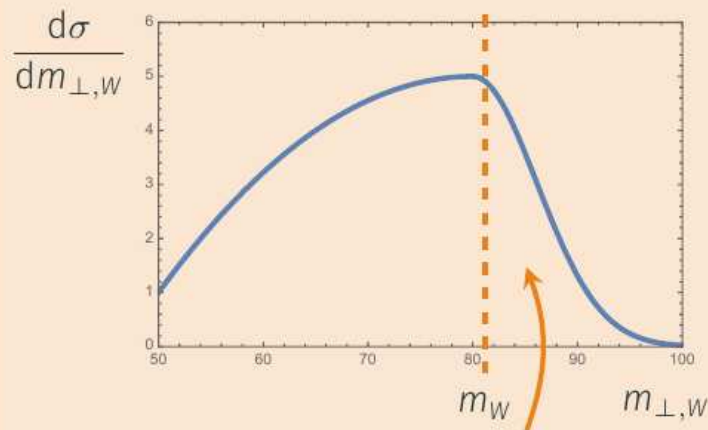
Buonocore, Grazzini, Kallweit, Savoini, Tramontano '21



How to measure m_W at hadron colliders

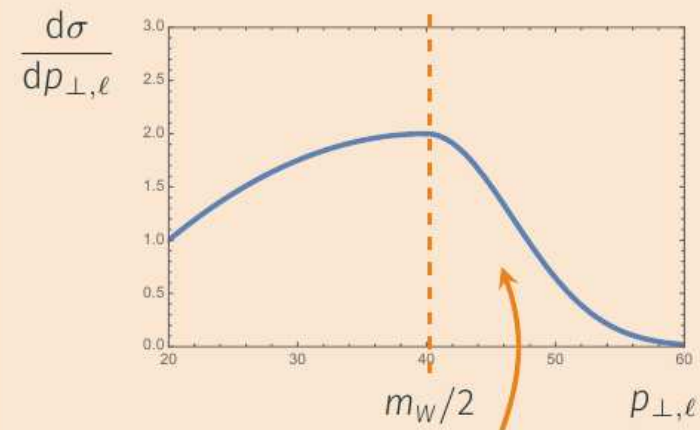
Need observables that are sensitive to m_W :

Transverse mass of W



Beyond the edge: Mostly detector effects

Transverse momentum of ℓ



Mostly QCD & QED initial state radiation

Starting from NLO and with realistic detectors the edges are washed out

Slide from A. Behring @ RADCOR '21

■ QCD corrections @ NNLO (MC programs FEWZ, DYTurbo, MATRIX, MCFM)

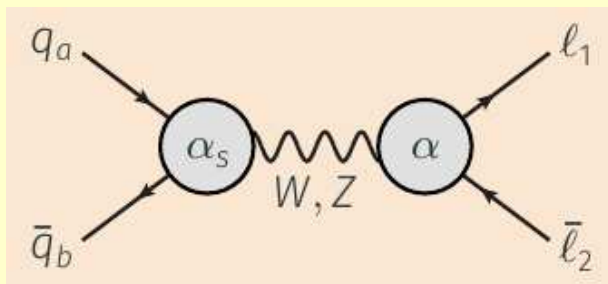
Gavin, Li, Petriello, Quackenbush '12, Camarda et al. '19

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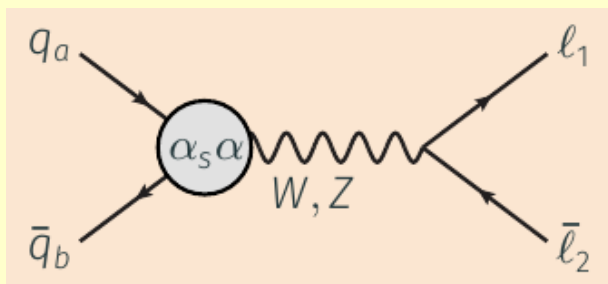
and (inclusive) NNNLO

Duhr, Dulat, Mistlberger '20

■ Mixed QCD \times EW corrections



Dittmaier, Huss, Schwinn '15, Carloni Calame et al. '16



Bonciani, Buccioni, Rana, Triscari, Vicini '19

Bonciani, Buccioni, Rana, Vicini '20

Dittmaier, Schmidt, Schwarz '19

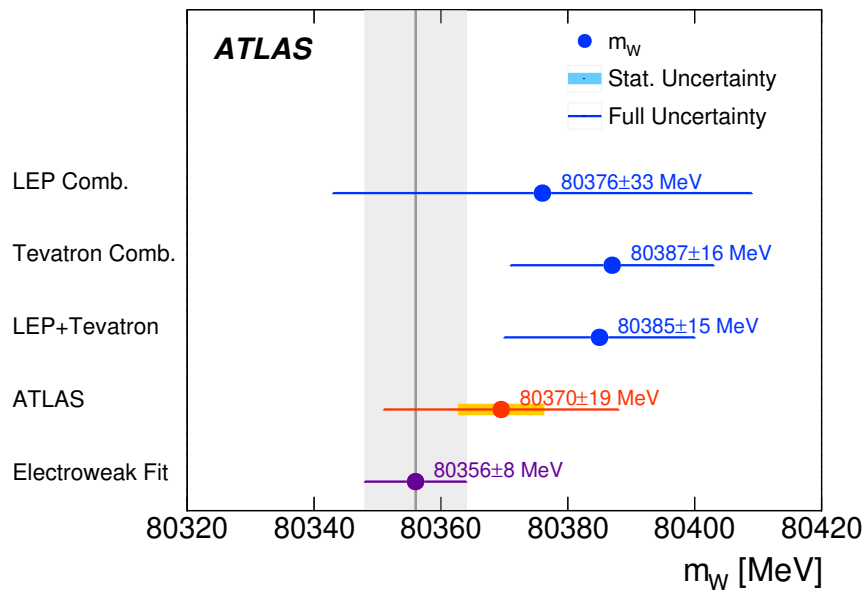
Buonocore, Grazzini, Kallweit, Savioni, Tramontano '21

Buccioni et al. '19, Behring et al. '20,21

→ Impact on M_W measurement $\mathcal{O}(10 \text{ MeV})$

W mass:

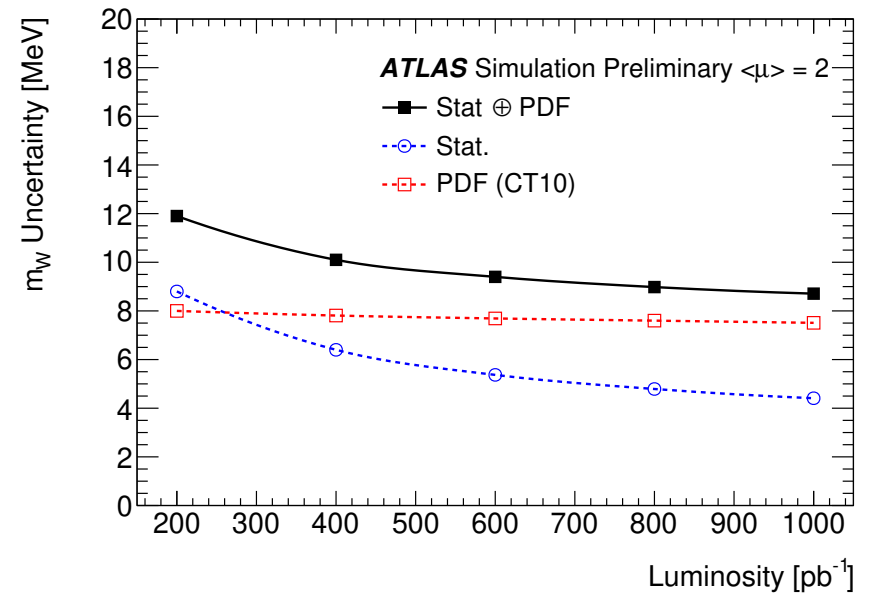
from $pp \rightarrow W^\pm \rightarrow \ell^\pm \nu$,
using m_T and $p_{\ell,\perp}$ distributions



→ talk by Martina Pili

Ultimate precision at HL-LHC:

$\delta M_W < 10$ MeV



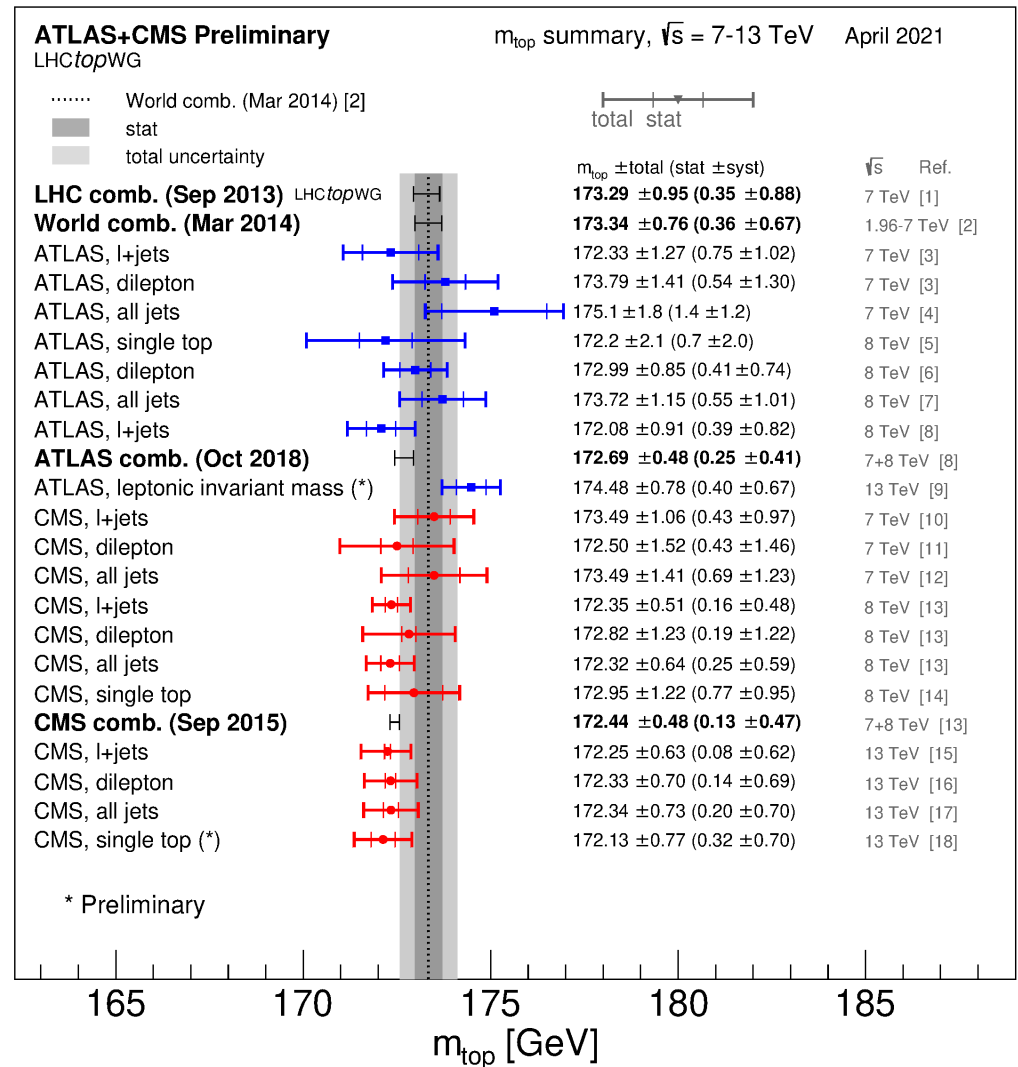
- m_t is input for global EW fits
- Most precise measurement
 $\delta m_t \sim 0.3 \text{ GeV}$ at LHC

PDG '20

- Theoretical ambiguity in mass definition:

$$\begin{aligned}
 & m_t^{\text{CB}}(Q_0) - m_t^{\text{pole}} \\
 &= -\frac{2}{3}\alpha_s(Q_0) Q_0 + \mathcal{O}(\alpha_s^2 Q_0) \\
 &\approx 0.5 \pm 0.2_{\text{pert.}} \pm 0.2_{\text{np.}} \text{ GeV}
 \end{aligned}$$

Hoang, Plätzer, Samitz '18



Effective field theory: $\mathcal{L} = \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \mathcal{O}(\Lambda^{-3}) \quad (\Lambda \gg M_Z)$

$$\mathcal{O}_{\phi 1} = (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D^\mu \Phi) \quad \alpha \Delta T = -\frac{v^2}{2} \frac{c_{\phi 1}}{\Lambda^2}$$

$$\mathcal{O}_{\text{BW}} = \Phi^\dagger B_{\mu\nu} W^{\mu\nu} \Phi \quad \alpha \Delta S = -e^2 v^2 \frac{c_{\text{BW}}}{\Lambda^2}$$

$$\mathcal{O}_{\text{LL}}^{(3)e} = (\bar{L}_L^e \sigma^a \gamma_\mu L_L^e) (\bar{L}_L^e \sigma^a \gamma^\mu L_L^e) \quad \Delta G_F = -\sqrt{2} \frac{c_{\text{LL}}^{(3)e}}{\Lambda^2}$$

$$\mathcal{O}_R^f = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) (\bar{f}_R \gamma^\mu f_R) \quad f = e, \mu, \tau, b, lq$$

$$\mathcal{O}_L^F = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) (\bar{F}_L \gamma^\mu F_L) \quad F = \begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}, \begin{pmatrix} u, c \\ d, s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\mathcal{O}_L^{(3)F} = i(\Phi^\dagger \overleftrightarrow{D}_\mu^a \Phi) (\bar{F}_L \sigma_a \gamma^\mu F_L)$$

More operators than EWPOs \rightarrow need to make assumptions
[e.g. U(3) or U(2) \times U(1) flavor symmetries]

Some operators enhanced for high m_{inv} in

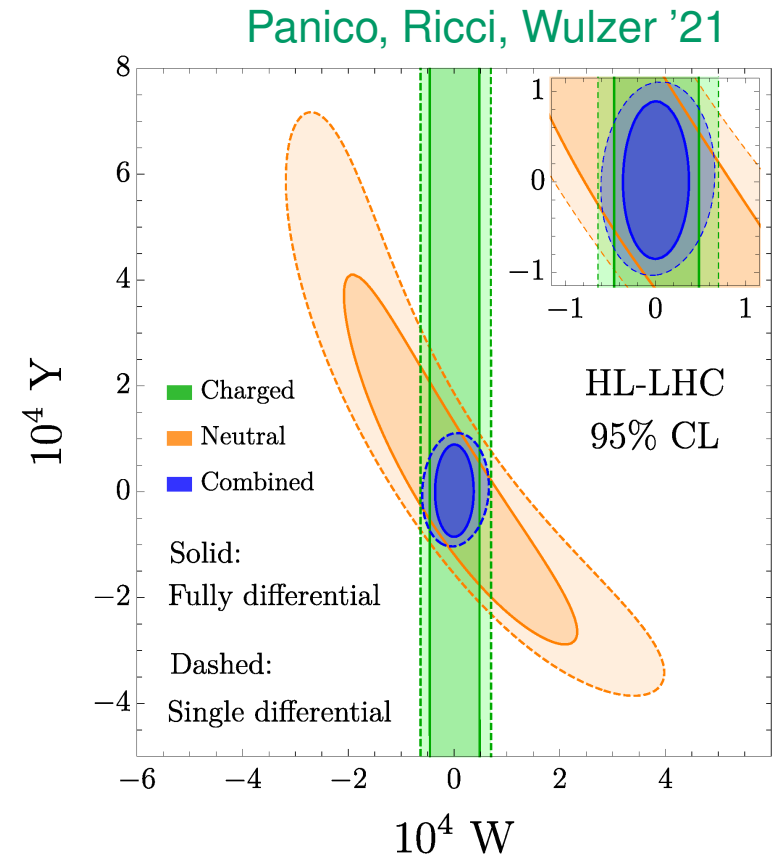
$$pp \rightarrow l^+ l^-$$

$$pp \rightarrow l^\pm \nu$$

$$\mathcal{L}_{\text{EFT}} = -\frac{g^2}{2M_W^2} W \mathcal{O}'_{2W} - \frac{g'^2}{2M_W^2} Y \mathcal{O}'_{2B}$$

$$\mathcal{O}'_{2W} = J_L^{a,\mu} J_{L,\mu}^a, \quad J_L^{a,\mu} = \sum_f \bar{f} \gamma^\mu t^a f$$

$$\mathcal{O}'_{2B} = J_Y^{a,\mu} J_{Y,\mu}^a, \quad J_Y^{a,\mu} = \sum_f \bar{f} \gamma^\mu Y_f f$$



Some operators enhanced for high m_{inv} in

$$pp \rightarrow l^+ l^-$$

$$pp \rightarrow l^\pm \nu$$

$$\mathcal{O}_{lq}^{(3)} = (\bar{l}_L \sigma_I \gamma^\mu l_L) (\bar{q}_L \sigma_I \gamma_\mu q)$$

$$\mathcal{O}_{lq}^{(1)} = (\bar{l}_L \gamma^\mu l_L) (\bar{q}_L \gamma_\mu q)$$

$$\mathcal{O}_{eu} = (\bar{e}_R \gamma^\mu e_R) (\bar{u}_R \gamma_\mu u_R)$$

$$\mathcal{O}_{ed} = (\bar{e}_R \gamma^\mu e_R) (\bar{d}_R \gamma_\mu d_R)$$

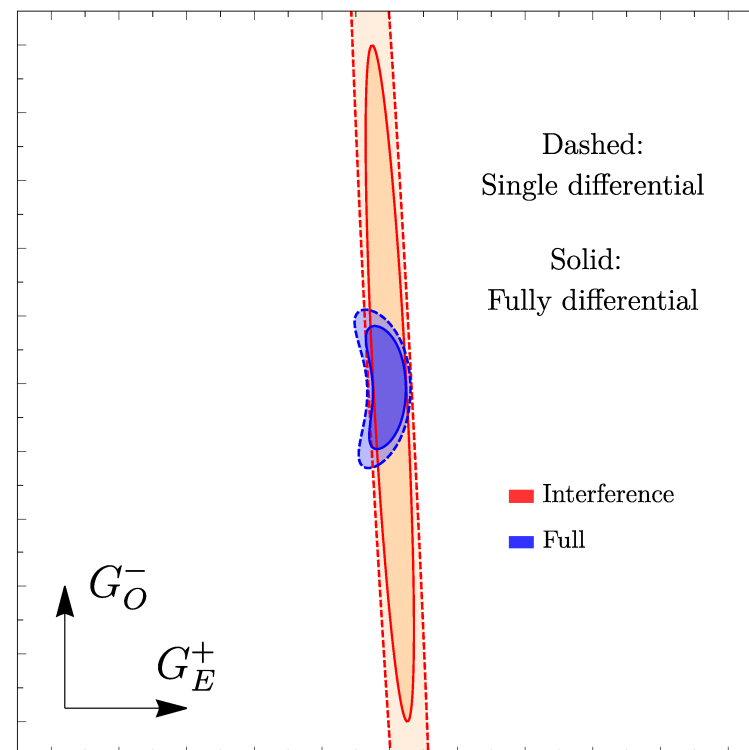
$$\mathcal{O}_{lu} = (\bar{l}_L \gamma^\mu l_L) (\bar{u}_R \gamma_\mu u_R)$$

$$\mathcal{O}_{ld} = (\bar{l}_L \gamma^\mu l_L) (\bar{d}_R \gamma_\mu d_R)$$

$$\mathcal{O}_{qe} = (\bar{q}_L \gamma_\mu q_L) (\bar{e}_R \gamma^\mu e_R)$$

Some degeneracies (flat parameter directions) difficult to resolve at LHC

Panico, Ricci, Wulzer '21



Electron-Ion Collider (EIC)

Fitting Methodology (68% CL):

For EIC/DIS:

- Integrate over (x, Q^2) bins
- Assume uncorrelated errors
- $\Delta\sigma_{SMFT}$ measures deviation from SM

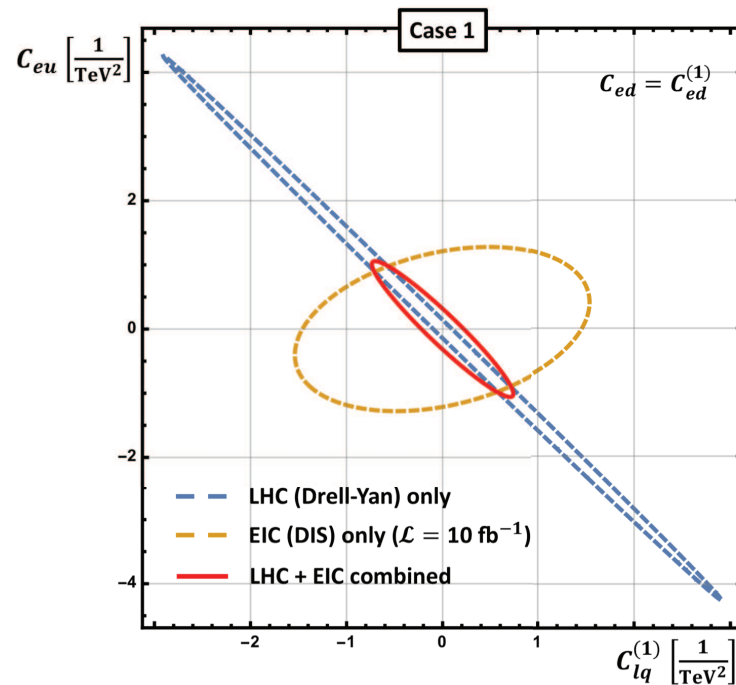
For LHC/DY:

- Integrate over m_{ll} bins
- Error Correlation from *ATLAS*
- Data deviation from SM

Define χ^2 test statistic (DIS case):

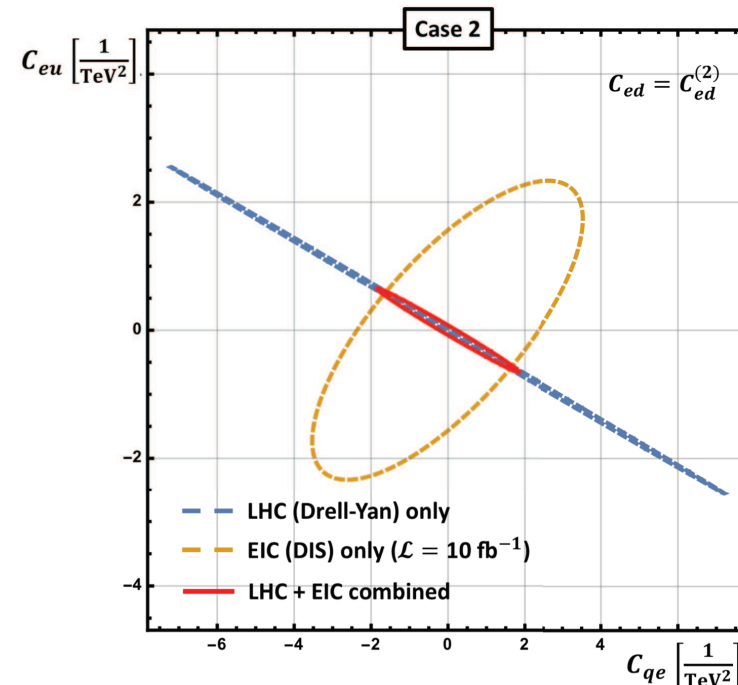
$$\chi^2 = \sum_{\text{Bins}} \sum_{\text{Pol}/\pm} \left(\frac{\Delta\sigma_{SMFT}}{\Delta\sigma_{Err}} \right)^2$$

ATLAS Collab. (1606.01736)

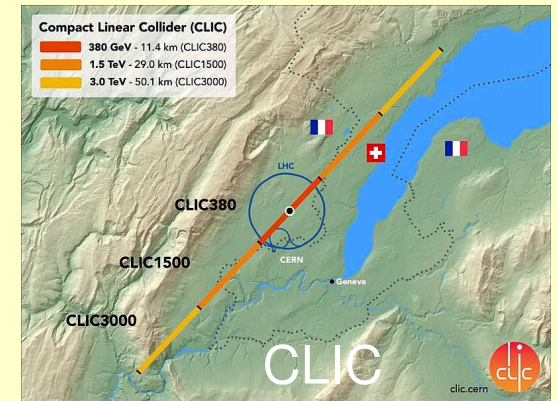
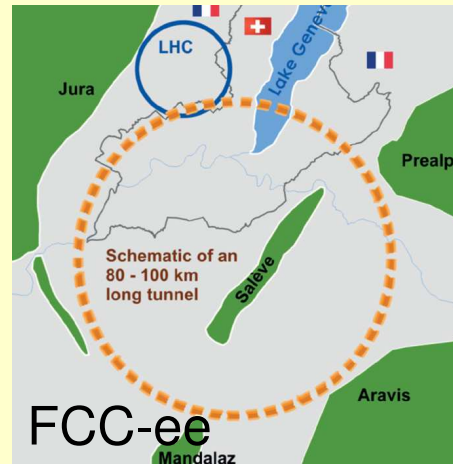
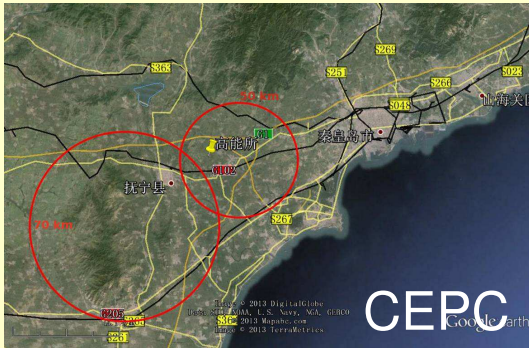
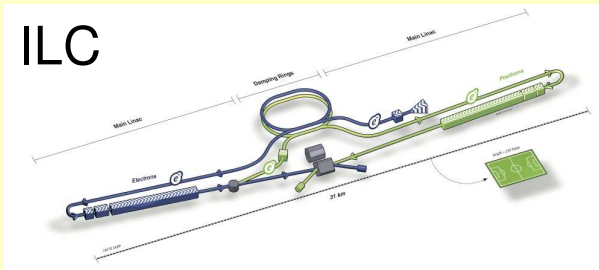


slide from D. Wiegand

DY+EIC: Best Bounds Yet



Boughezal, Petriello, Wiegand '20



- circular colliders: high-lumi run at $\sqrt{s} \sim M_Z$
- linear colliders: radiative return $e^+e^- \rightarrow \gamma Z$

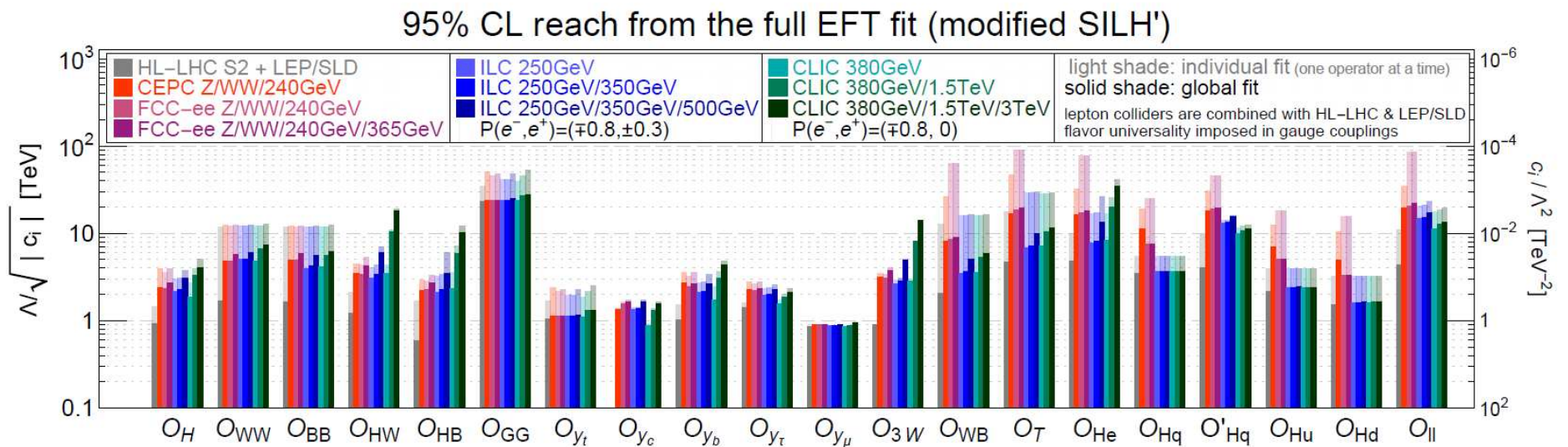
\sqrt{s}	M_Z	$2M_W$	240–250 GeV	350–380 GeV
ILC	100 fb^{-1}	500 fb^{-1}	2 ab^{-1}	200 fb^{-1} (10 pts.)
CLIC	–	–	–	1 ab^{-1}
FCC-ee	230 ab^{-1}	10 ab^{-1} (2 pts.)	irrel. for EW phys.	200 fb^{-1} (8 pts.)
CEPC	45 ab^{-1}	2.6 ab^{-1} (3 pts.)	irrel. for EW phys.	–

Anticipated precision for EWPOs:

Quantity	current	ILC	CLIC	FCC-ee	CEPC
M_Z [MeV]	2.1	–	–	0.1	0.5
Γ_Z [MeV]	2.3	–	–	0.1	0.5
M_W [MeV]	12	2.5	?	0.7	1.0
$\sin^2 \theta_{\text{eff}}^\ell$ [10^{-5}]	14	2	7.8	0.5	2.3
$R_b = \Gamma_Z^b / \Gamma_Z^{\text{had}}$ [10^{-5}]	66	23	38	6	4.3

- Can be optimized with different run scenarios
- Polarized beams at ILC ($P_{e^-}=0.8$, $P_{e^+}=0.3$) and CLIC ($P_{e^-}=0.8$)

- SMEFT dim-6 operators provide framework for comparing experiments
- Correlations between sectors (e.g. Higgs and EW)



de Blas, Durieux, Grojean, Gu, Paul '19

- **Electroweak precision tests** have played an important role in testing the Standard Model
- **LHC** will improve measurements of $\sin^2 \theta_{\text{eff}}$, M_W and m_t
 - Theory input (higher-order corrections) needed to exploit full potential
- In **SMEFT framework**, significant improvements for several operators from LHC data, but other experiments needed to lift degeneracies in parameter-space
- **Future e^+e^- colliders** will push the reach into the **multi-TeV** regime