

High-precision observables in Drell-Yan

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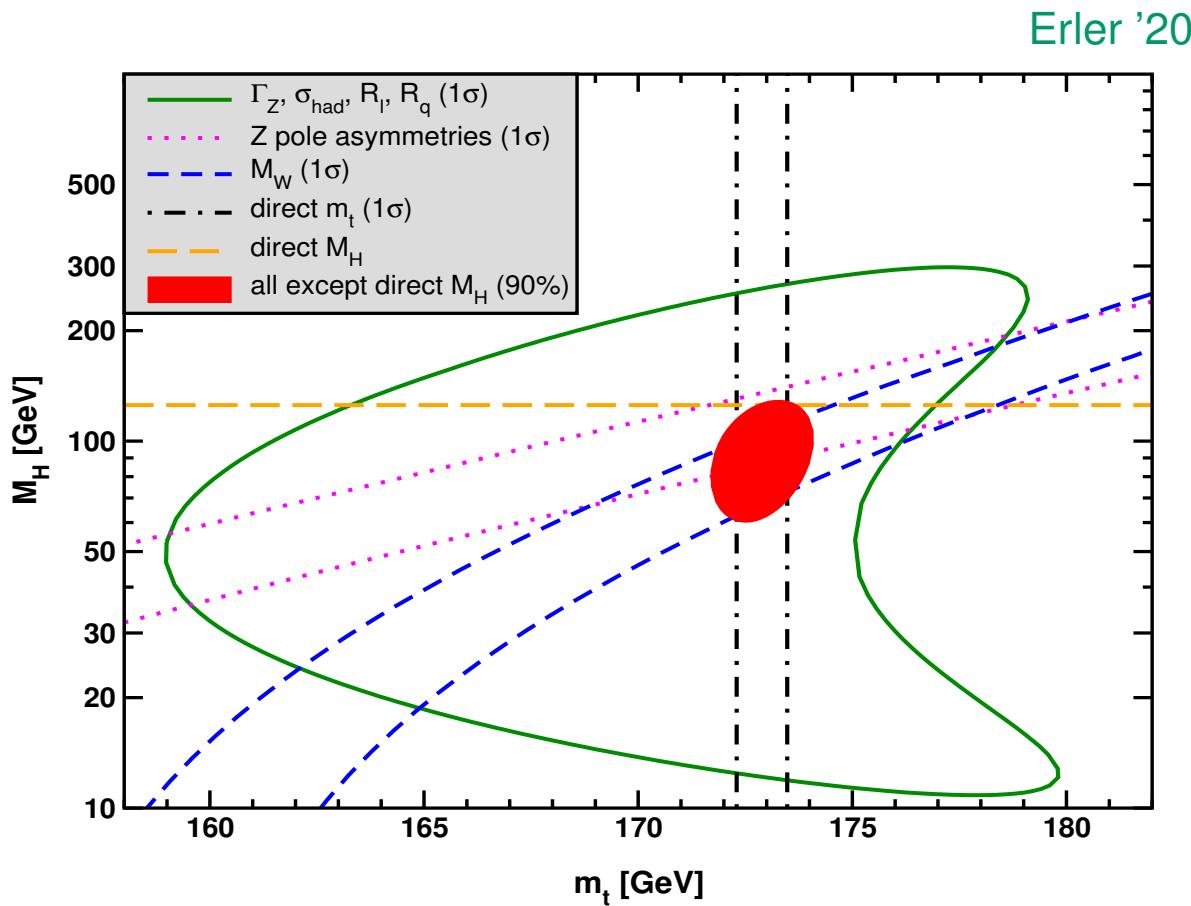
SM@LHC 2022

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

Standard Model after Higgs discovery:

Erler, 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]



Direct measurements:

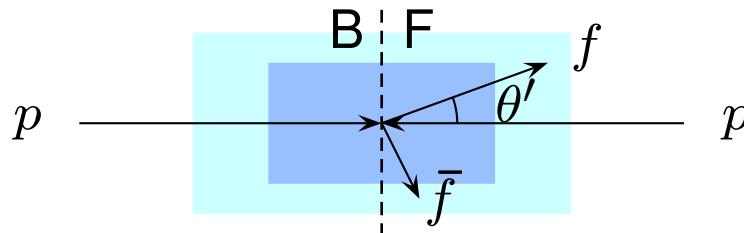
$$M_H = 125.30 \pm 0.13 \text{ GeV}$$
$$m_t = 172.89 \pm 0.28 \text{ GeV}$$

Indirect prediction:

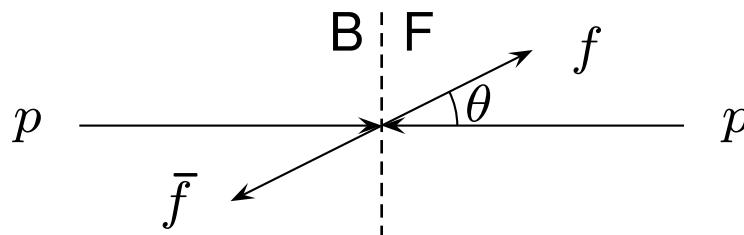
$$M_H = 90^{+18}_{-16} \text{ GeV}$$
$$m_t = 176.3 \pm 1.9 \text{ GeV}$$

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

lab frame:



center-of-mass frame:



→ main systematics:
PDFs, QCD corrections

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

$$c_\theta \equiv \cos \theta \text{ etc.}$$

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

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

$$A_4 \text{ depends on } \frac{v_f}{a_f} = 1 - 4|q_f| \sin^2 \theta_{\text{eff}}^f$$
$$[f = u, d, s, c, \ell]$$

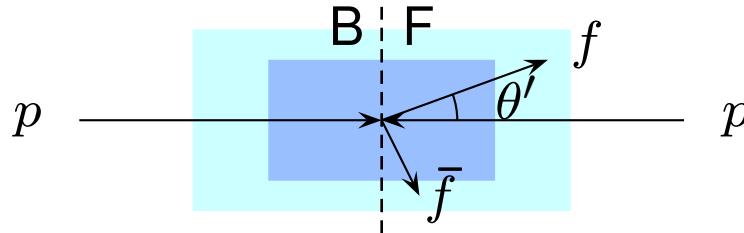
$$\sin^2 \theta_{\text{eff}}^q = \sin^2 \theta_{\text{eff}}^\ell + \Delta_{q\ell}$$

computed in SM

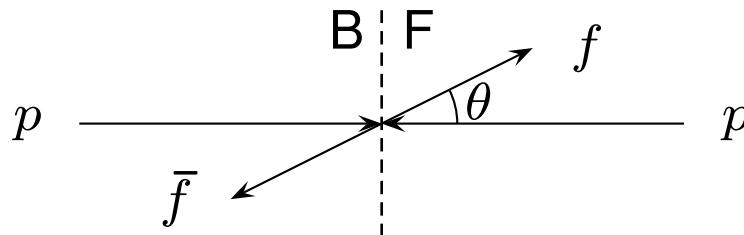
→ Assumption that NP is flavor universal

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

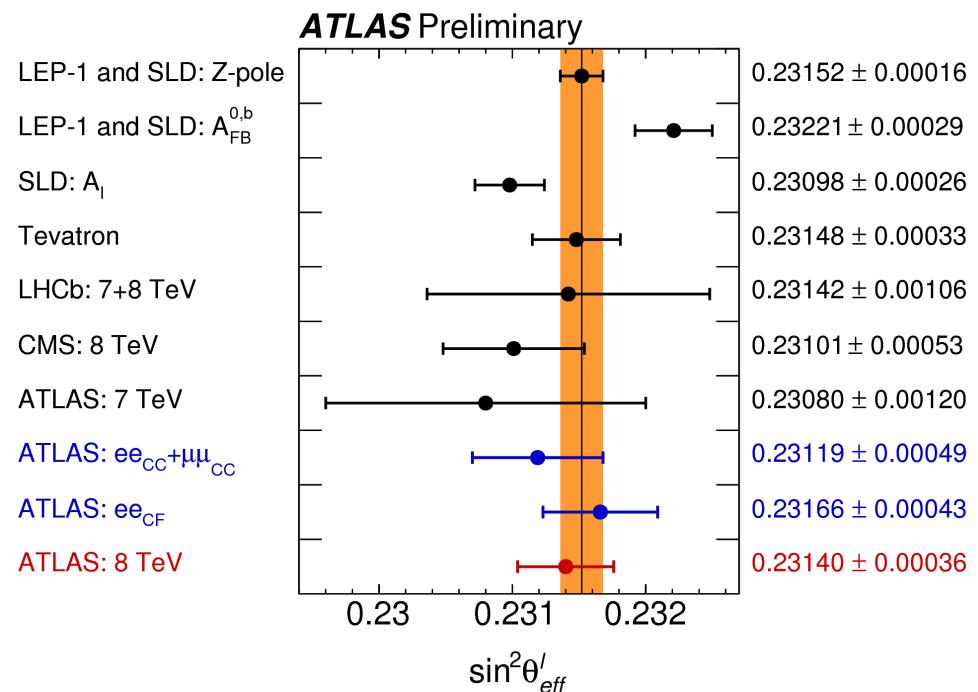
lab frame:



center-of-mass frame:



→ main systematics:
PDFs, QCD corrections



→ talk by Oz Amram

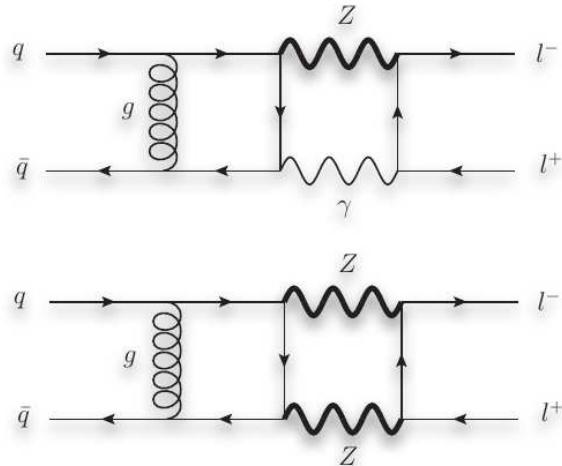
- QCD corrections @ NNLO (MC programs FEWZ, DYTurbo, MATRIX, MCFM)

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

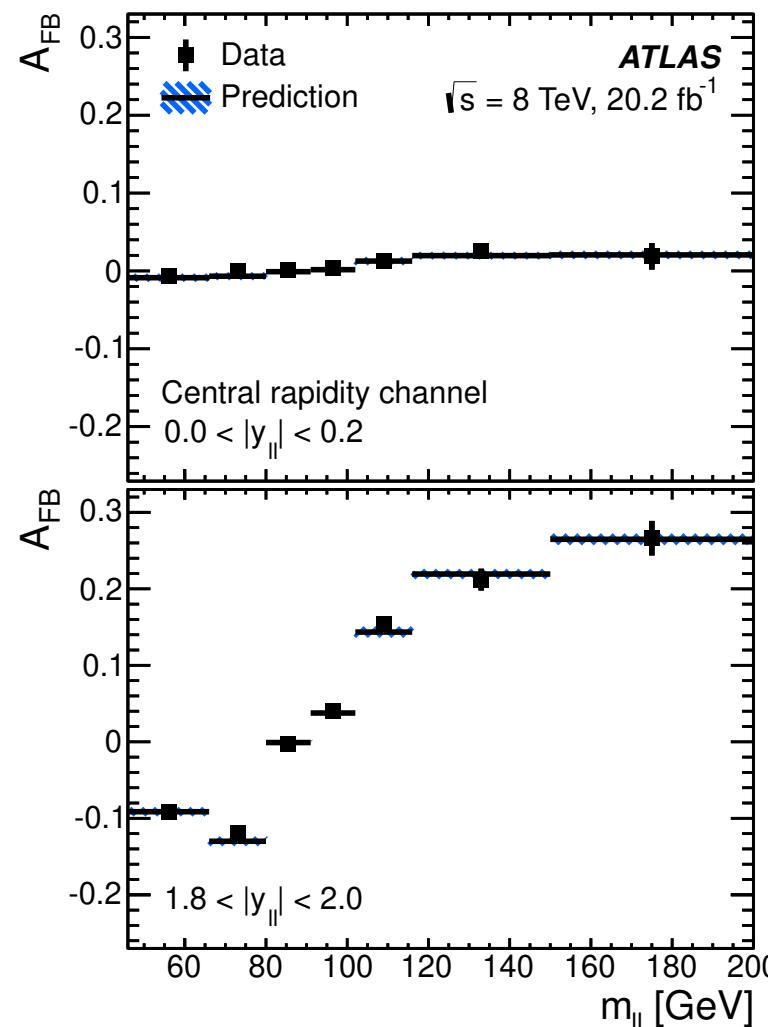
- Mixed QCD×EW corrections,
 also off resonance

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

Recently completed full calculation:



→ talk by A. Vicini



- NLO EW corrections well-known, NNLO mostly not
- More important than at LEP/SLC due to larger $m_{\ell\ell}$ range

A_4 with Z and photon exchange:
 (neglecting boxes and s -dependence of Z form factors)

$$A_4 = \frac{\sum_q X_q \left(\frac{v_\ell}{a_\ell} \frac{v_q}{a_q} + \frac{v_{\ell q}(s)}{a_\ell a_q} \right)}{\sum_q X_q \left(1 + \frac{v_\ell^2}{a_\ell^2} + \frac{v_q^2}{a_q^2} + \frac{v_{\ell q}^2(s)}{a_\ell^2 a_q^2} \right)}$$

$$X_q = f_q(x_1) f_{\bar{q}}(x_2) + f_{\bar{q}}(x_1) f_q(x_2)$$

$$v_{\ell q}(s) = v_\ell v_q + \frac{s - M_Z^2 - i M_Z \Gamma_Z}{s} e^2 e_q (1 + \Delta_{q\ell})$$

$$\frac{v_\ell}{a_\ell} = 1 - 4 s_\ell^2,$$

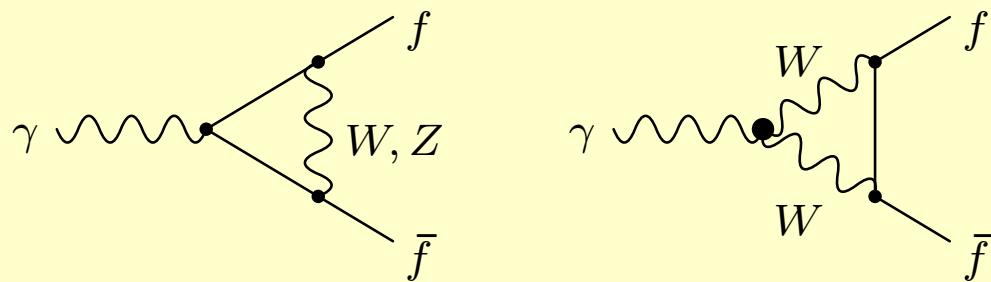
$$s_\ell^2 \equiv \sin^2 \theta_{\text{eff}}^\ell$$

$$\frac{v_q}{a_q} = 1 - 4 |e_q| (s_\ell^2 + \Delta_{q\ell})$$

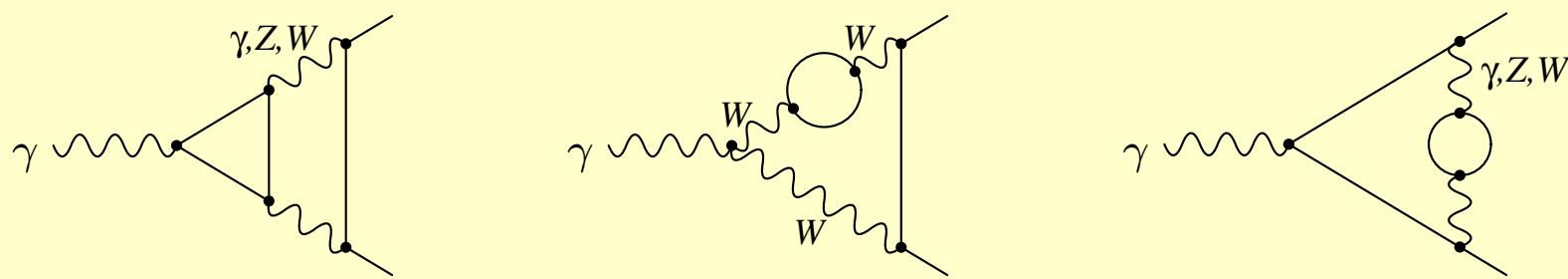
$$\Delta_{q\ell} = \Delta_{q\ell(1)} + \Delta_{q\ell(2)} + \dots$$

$$\overline{\Delta}_{q\ell} = \overline{\Delta}_{q\ell(1)} + \overline{\Delta}_{q\ell(2)} + \dots$$

Example contributions to $\Delta_{q\ell(1)}, \overline{\Delta}_{q\ell(1)}$:



Example contributions to $\Delta_{q\ell(1)}, \overline{\Delta}_{q\ell(2)}$:



$\Delta_{q\ell(2)}$ is known (in SM) for leading Z pole term

$$\overline{\Delta}_{q\ell(2)} = \pm \overline{\Delta}_{q\ell(1)} \times \frac{g^2}{16\pi^2} n_f, \quad n_f = 6 + 6N_c \quad (\text{maybe underestimate?})$$

Impact of missing EW 2-loop contributions:

$\delta A_4/A_4$: [10⁻⁴]

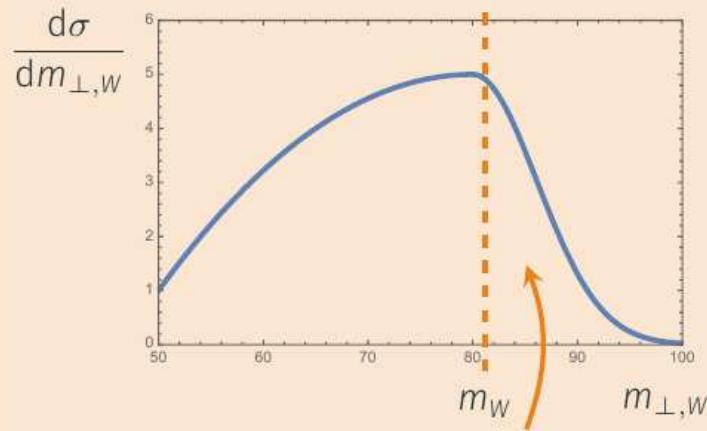
$m_{\ell\ell}$ [GeV]	Scheme:	α'	α
60		0.37	0.35
70		0.52	0.60
80		1.53	1.61
$M_Z - 2$		17.54	10.27
$M_Z - 1$		2.14	1.97
M_Z		0.58	0.59
$M_Z + 2$		0.45	0.46
$M_Z + 1$		0.55	0.55
100		0.84	0.83
110		0.80	0.81
130		0.53	0.56

- α' : Use α, M_W, M_Z as inputs, perturb. exp. in α
- α : Use α, G_μ, M_Z as inputs, perturb. exp. in α
- Uncertainty dominated by photon form factor $\bar{\Delta}_q$
- Dependence of form factors on $s = m_{\ell\ell}$ and box contributions not taken into account so far
(in particular γZ box)

How to measure m_W at hadron colliders

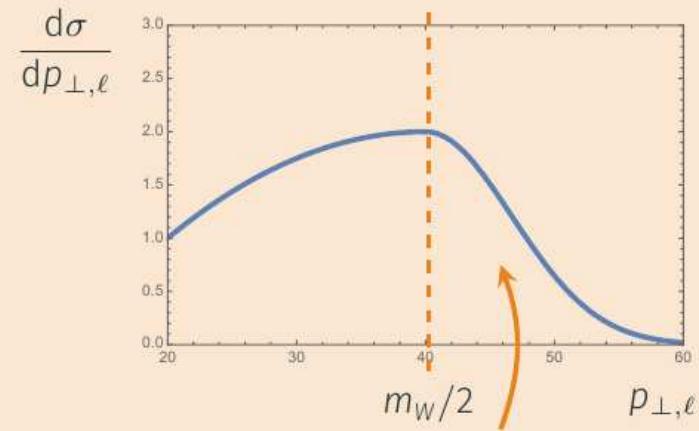
Need observables that are sensitive to m_W :

Transverse mass of W



Beyond the edge: Mostly detector effects

Transverse momentum of ℓ

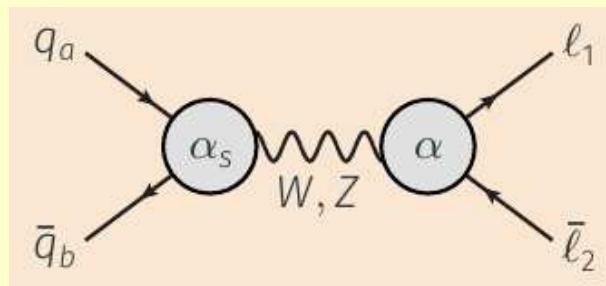


Mostly QCD & QED initial state radiation

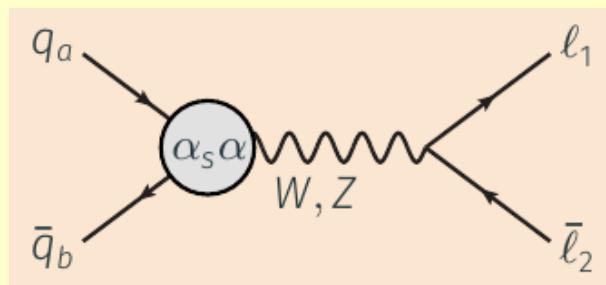
Starting from NLO and with realistic detectors the edges are washed out

Slide from A. Behring @ RADCOR '21

- QCD corrections @ NNLO (MC programs FEWZ, DYTurbo, MATRIX, MCFM)
Gavin, Li, Petriello, Quackenbush '12, Camarda et al. '19
Grazzini, Kallweit, Wiesemann '17, Boughezal et al. '16
and (inclusive) NNNLO
Duhr, Dulat, Mistlberger '20, Duhr, Mistlberger '21
- 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 $\mathcal{O}(10 \text{ MeV})$

- q_T resummation to NNLL (MC programs ResBos, DYQT)

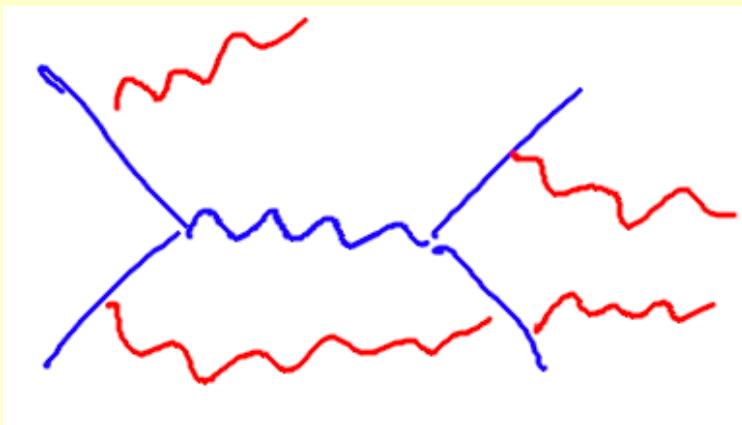
Landry, Brock, Nadolsky, Yuan '03

Bozzi, Catani, Ferrera, de Florian, Grazzini '11

- QED corrections: exact @ NLO, approximate multi-photon radiation
(PHOTOS, HORACE)

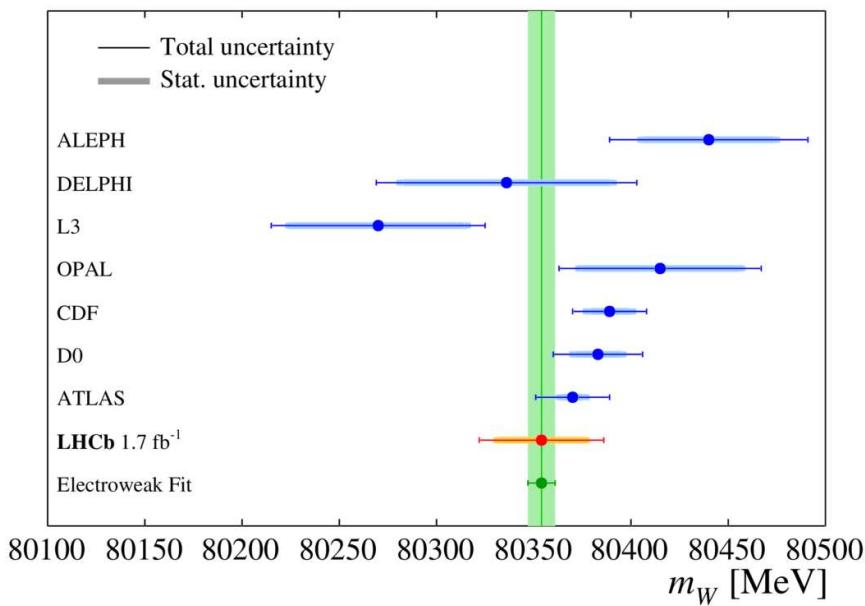
Golonka, Was '06

Carloni Calame, Montagna, Nicrosini, Vicini '07



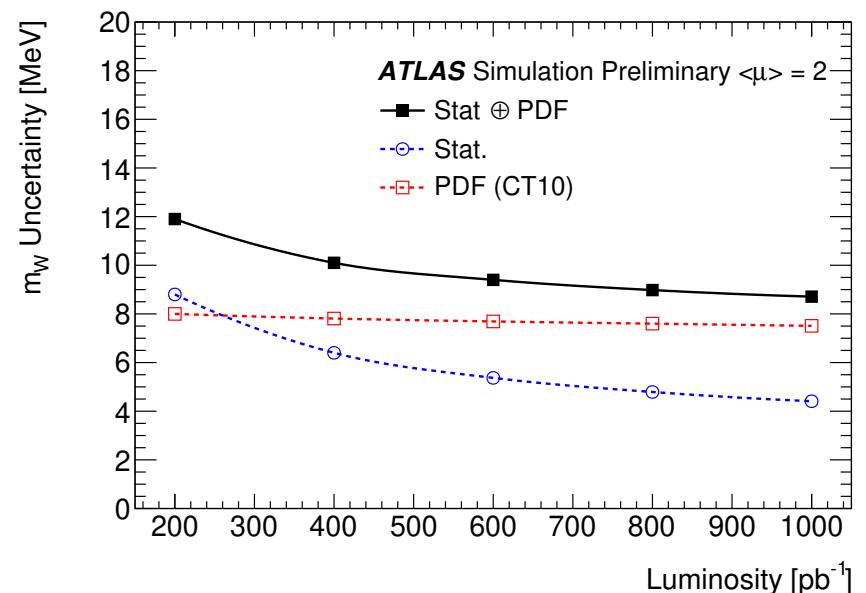
W mass:

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



→ talk by Menglin Xu

Ultimate precision at HL-LHC:
 $\delta M_W < 10 \text{ MeV}$



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

$$\mathcal{O}_{\phi 1} = (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D^\mu \Phi)$$

$$\mathcal{O}_{BW} = \Phi^\dagger B_{\mu\nu} W^{\mu\nu} \Phi$$

$$\mathcal{O}_{LL}^{(3)e} = (\bar{L}_L^e \sigma^a \gamma_\mu L_L^e)(\bar{L}_L^e \sigma^a \gamma^\mu L_L^e)$$

$$\mathcal{O}_R^f = i(\Phi^\dagger \overset{\leftrightarrow}{D}_\mu \Phi)(\bar{f}_R \gamma^\mu f_R)$$

$$\mathcal{O}_L^F = i(\Phi^\dagger \overset{\leftrightarrow}{D}_\mu \Phi)(\bar{F}_L \gamma^\mu F_L)$$

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

$$\alpha \Delta T = -\frac{v^2}{2} \frac{c_{\phi 1}}{\Lambda^2}$$

$$\alpha \Delta S = -e^2 v^2 \frac{c_{BW}}{\Lambda^2}$$

$$\Delta G_F = -\sqrt{2} \frac{c_{LL}^{(3)e}}{\Lambda^2}$$

$$f = e, \mu, \tau, b, lq$$

$$F = \binom{\nu_e}{e}, \binom{\nu_\mu}{\mu}, \binom{\nu_\tau}{\tau}, \binom{u, c}{d, s}, \binom{t}{b}$$

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

Energy-enhanced operators

12/15

Some operators enhanced for high m_{inv} in

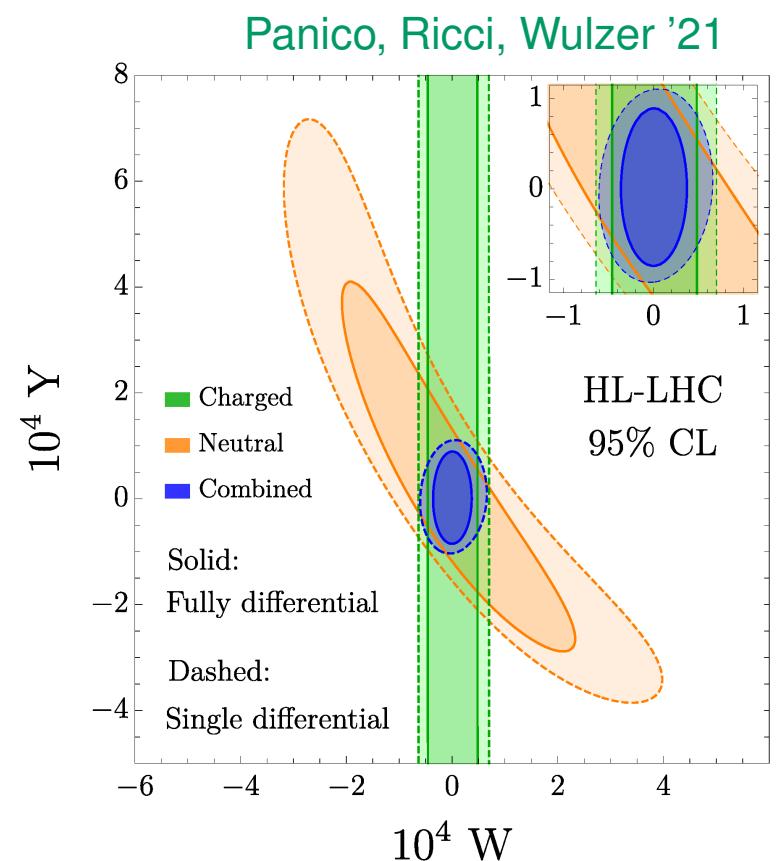
$$pp \rightarrow \ell^+ \ell^-$$

$$pp \rightarrow \ell^\pm \nu$$

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

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

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



Energy-enhanced operators

13/15

Some operators enhanced for high m_{inv} in

$$pp \rightarrow \ell^+ \ell^-$$

$$pp \rightarrow \ell^\pm \nu$$

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

$$\mathcal{O}_{lq}^{(1)} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{q}_L \gamma_\mu q_L)$$

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

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

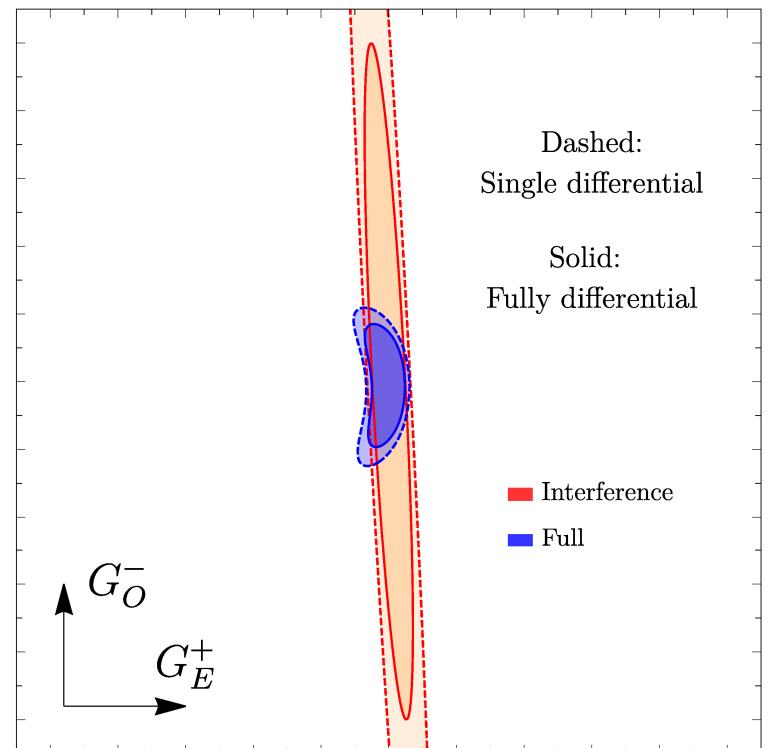
$$\mathcal{O}_{lu} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{u}_R \gamma_\mu u_R)$$

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

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

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

Panico, Ricci, Wulzer '21



Fitting Methodology (68% CL):

For EIC/DIS:

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

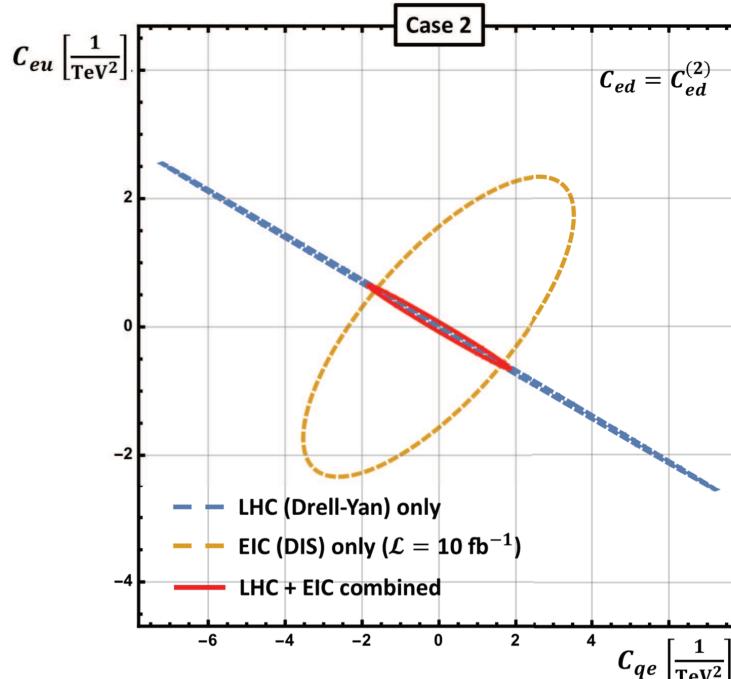
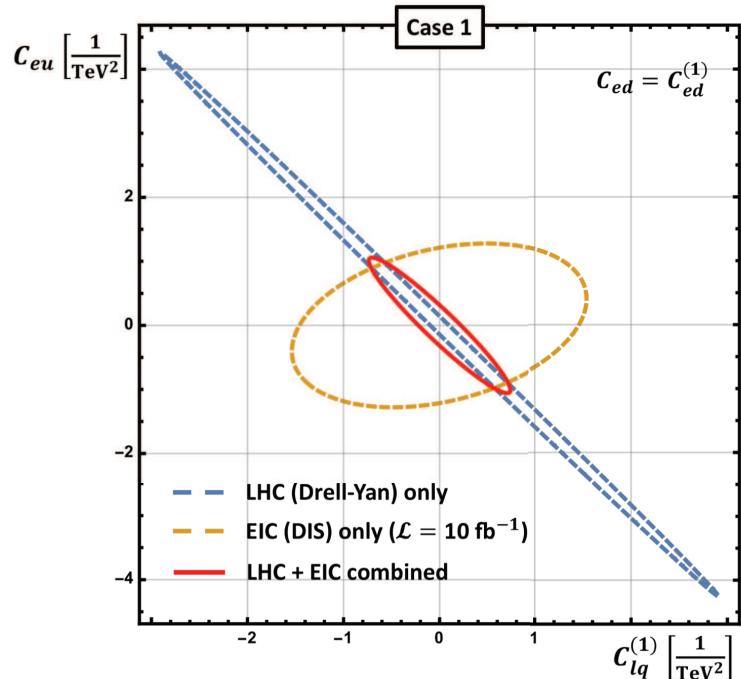
For LHC/DY:

- 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

Boughezal, Petriello, Wiegand '20

- **Electroweak precision tests** have played an important role in testing the Standard Model
- **LHC** will improve measurements of $\sin^2 \theta_{\text{eff}}$ and M_W
 - 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