Electroweak Precision Tests at the LHC and beyond

A. Freitas
University of Pittsburgh

1. Electroweak precision observables: Introduction and status
2. Electroweak physics at the LHC
3. Prospects for future e^+e^- machines
4. Summary

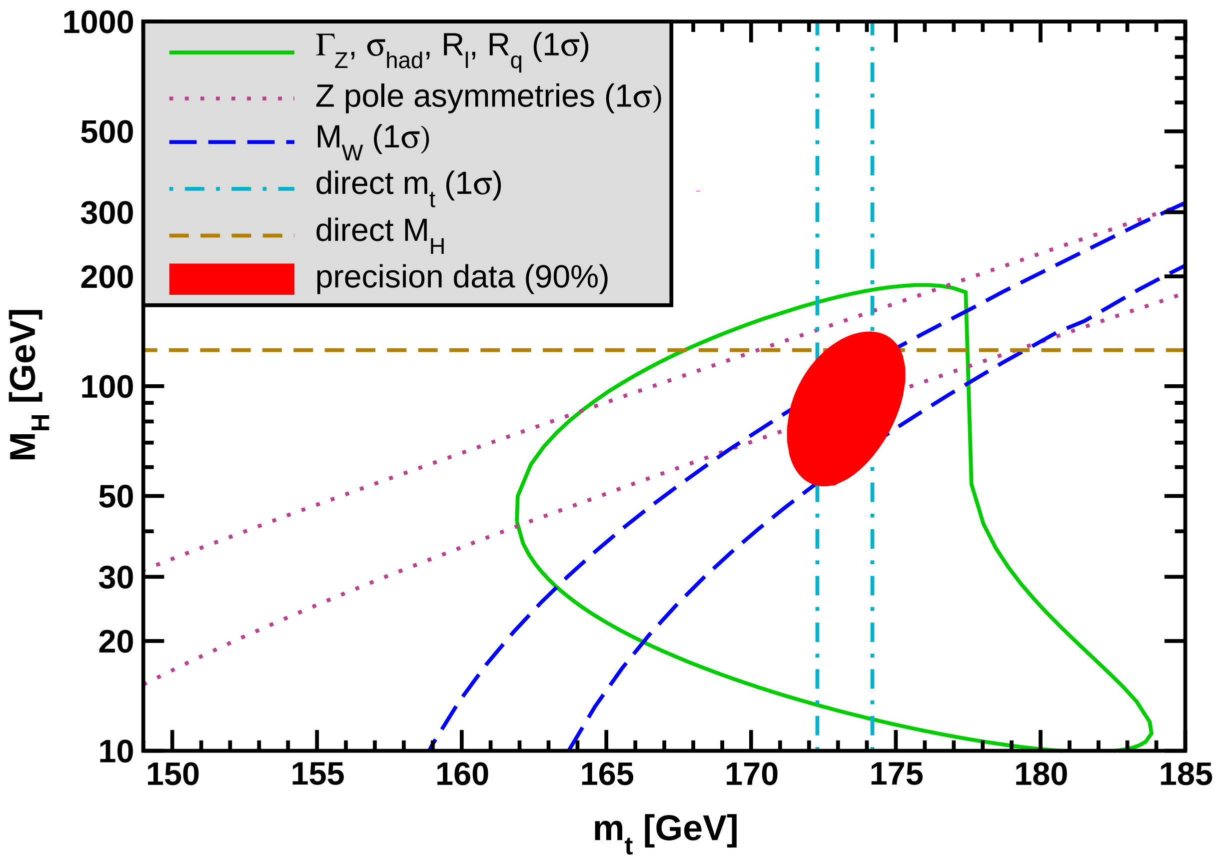
Electroweak precision measurements: Introduction and status

Current status of electroweak precision tests

Standard Model after Higgs discovery:

- Good agreement between measured mass and indirect prediction
- Very good agreement over large number of observables

Erler '13



Direct measurements:

$M_H = 125.1 \pm 0.3$ GeV

$m_t = 173.24 \pm 0.95$ GeV

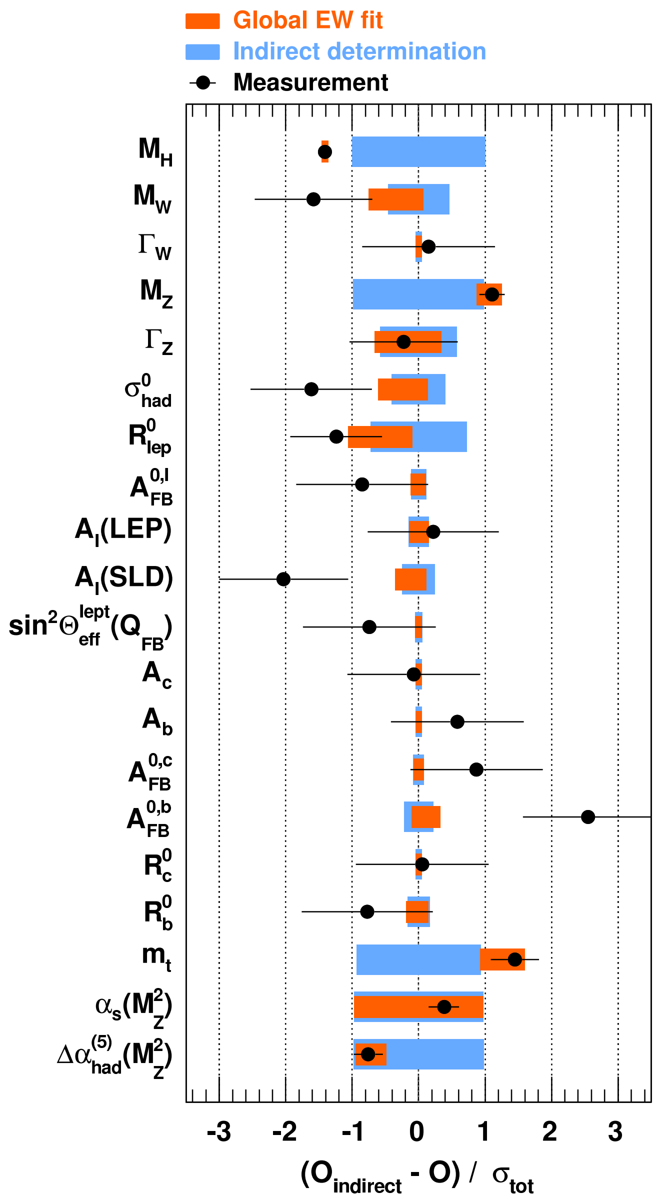
Indirect prediction:

$M_H = 123.7 \pm 2.3$ GeV (with LHC BRs)

$M_H = 89^{+22}_{-18}$ GeV (w/o LHC data)

$m_t = 177.0 \pm 2.1$ GeV

Current status of electroweak precision tests



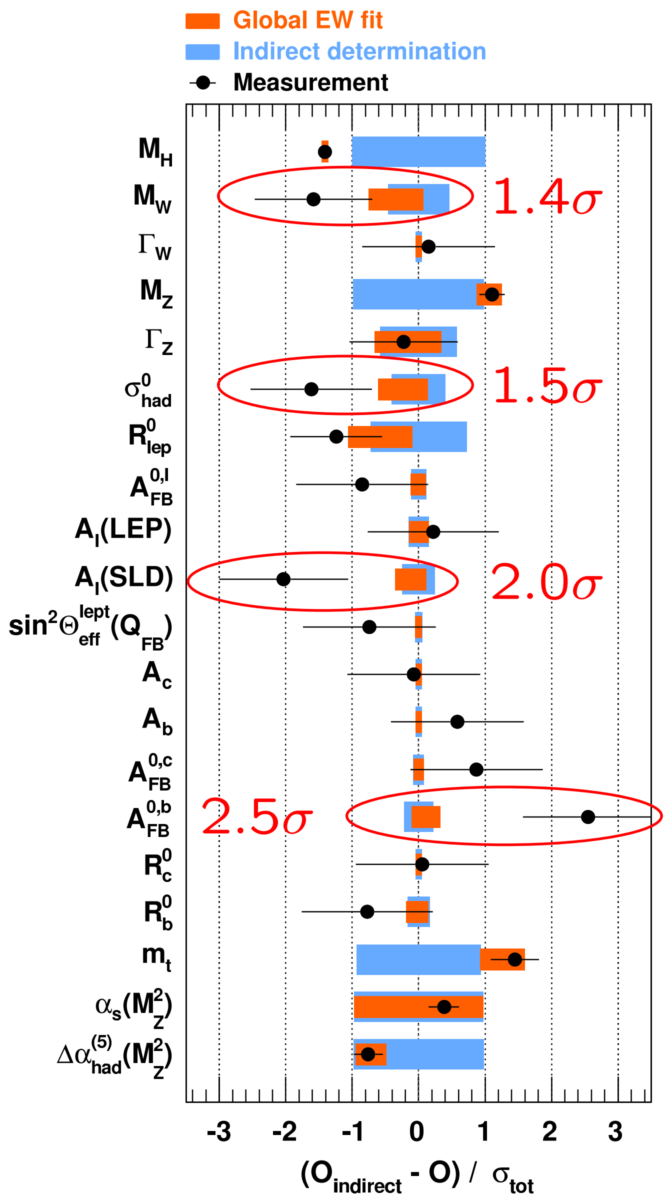
Surprisingly good agreement:

χ^2/d.o.f. $= 18.1/14$ ($p = 20\%$)

Most quantities measured with 1%–0.1% precision

GFitter coll. '14

Current status of electroweak precision tests



Surprisingly good agreement:
χ^2/d.o.f. $= 18.1/14$ ($p = 20\%$)

Most quantities measured with 1%–0.1% precision

A few interesting deviations:

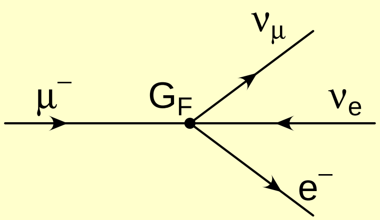
M_W	$(\sim 1.4\sigma)$
σ^0_{had}	$(\sim 1.5\sigma)$
A_ℓ(SLD)	$(\sim 2\sigma)$
A^b_{FB}	$(\sim 2.5\sigma)$
$(g_\mu - 2)$	$(\gtrsim 3\sigma)$

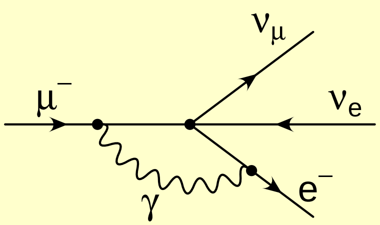
GFitter coll. '14

Electroweak precision observables

W mass

μ decay in Fermi Model



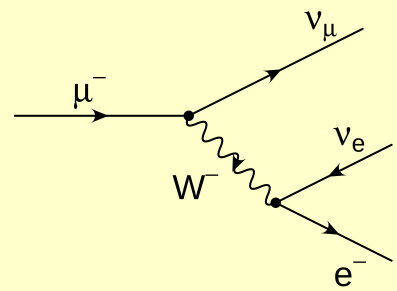


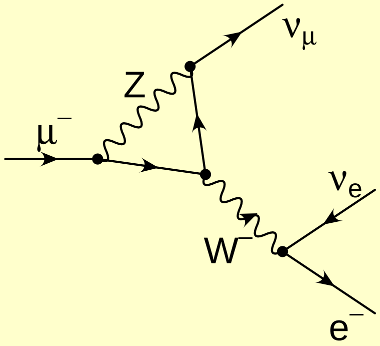
QED corr. (2-loop)

$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^3} F\left(\frac{m_e^2}{m_\mu^2}\right)(1 + \Delta q)$$

Ritbergen, Stuart '98
Pak, Czarnecki '08

μ decay in Standard Model





$$\frac{G_F^2}{\sqrt{2}} = \frac{e^2}{8 s_W^2 M_W^2}(1 + \Delta r)$$

electroweak corrections

Z-pole observables

$e^+e^- \to f\bar{f}$ for $\sqrt{s} \sim m_Z$:

$$\sigma = \mathcal{R}_{\text{ini}}\left[12\pi \frac{\Gamma_{ee}\Gamma_{ff}}{(s-m_Z^2)^2 - m_Z^2\Gamma_Z^2}(1+\delta X)\,(1-\mathcal{P}_e\mathcal{A}_e)\; + \;\sigma_{\text{non-res}}\right],$$

$$\Gamma_{ff} = \mathcal{R}_V^f g_{Vf}^2 + \mathcal{R}_A^f g_{Af}^2, \qquad \Gamma_Z = \sum_f \Gamma_{ff},$$

$$\mathcal{A}_f = 2\frac{g_{Vf}/g_{Af}}{1+(g_{Vf}/g_{Af})^2} = \frac{1-4|Q_f|\sin^2\theta_{\text{eff}}^f}{1-4|Q_f|\sin^2\theta_{\text{eff}}^f + 8(|Q_f|\sin^2\theta_{\text{eff}}^f)^2}.$$

$$A_{\text{FB}}^f = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \qquad A_{\text{LR}} = \mathcal{A}_e$$

Z-pole observables

$e^+e^- \to f\bar{f}$ for $\sqrt{s} \sim m_Z$:

$$\sigma = \mathcal{R}_{\text{ini}}\left[12\pi \frac{\Gamma_{ee}\Gamma_{ff}}{(s-m_Z^2)^2 - m_Z^2\Gamma_Z^2}(1+\delta X)\,(1-\mathcal{P}_e\mathcal{A}_e)\; + \;\sigma_{\text{non-res}}\right],$$

$$\Gamma_{ff} = \mathcal{R}_V^f g_{Vf}^2 + \mathcal{R}_A^f g_{Af}^2, \qquad \Gamma_Z = \sum_f \Gamma_{ff},$$

$$\mathcal{A}_f = 2\frac{g_{Vf}/g_{Af}}{1+(g_{Vf}/g_{Af})^2} = \frac{1-4|Q_f|\sin^2\theta_{\text{eff}}^f}{1-4|Q_f|\sin^2\theta_{\text{eff}}^f + 8(|Q_f|\sin^2\theta_{\text{eff}}^f)^2}.$$

$$A_{\text{FB}}^f = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \qquad A_{\text{LR}} = \mathcal{A}_e$$

QED/QCD corrections on ext. fermions ($\mathcal{R}_V^f$, $\mathcal{R}_A^f$)

Chetyrkin, Kataev, Tkachov ’79
Dine, Saphirstein ’79
Celmaster, Gonsalves ’80
Gorishnii, Kataev, Larin ’88,91

Chetyrkin, Kühn ’90
Surguladze, Samuel ’91
Kataev ’92
Chetyrkin ’93

etc...

Z-pole observables

$e^+e^- \to f\bar{f}$ for $\sqrt{s} \sim m_Z$:

$$\sigma = \mathcal{R}_{\text{ini}} \left[12\pi \frac{\Gamma_{ee}\Gamma_{ff}}{(s-m_Z^2)^2 - m_Z^2\Gamma_Z^2} (1+\delta X)\,(1-\mathcal{P}_e\mathcal{A}_e) \;+\; \sigma_{\text{non-res}} \right],$$

$$\Gamma_{ff} = \mathcal{R}_V^f g_{Vf}^2 + \mathcal{R}_A^f g_{Af}^2, \qquad \Gamma_Z = \sum_f \Gamma_{ff},$$

$$\mathcal{A}_f = 2\frac{g_{Vf}/g_{Af}}{1+(g_{Vf}/g_{Af})^2} = \frac{1-4|Q_f|\sin^2\theta_{\text{eff}}^f}{1-4|Q_f|\sin^2\theta_{\text{eff}}^f + 8(|Q_f|\sin^2\theta_{\text{eff}}^f)^2}.$$

$$A_{\text{FB}}^f = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \qquad A_{\text{LR}} = \mathcal{A}_e$$

additional initial-state QED corrections

Kuraev, Fadin ’85
Berends, Burgers, v. Neerven ’88
Kniehl, Krawczyk, Kühn, Stuart ’88
Beenakker, Berends, v. Neerven ’89
Bardin et al. ’89,91
Montagna, Nicrosini, Piccinini ’97
etc...

Z-pole observables

$e^+e^- \to f\bar{f}$ for $\sqrt{s} \sim m_Z$:

$$\sigma = \mathcal{R}_{\text{ini}} \left[12\pi \frac{\Gamma_{ee}\Gamma_{ff}}{(s - m_Z^2)^2 - m_Z^2 \Gamma_Z^2} (1 + \delta X)\,(1 - \mathcal{P}_e \mathcal{A}_e) \; + \; \sigma_{\text{non-res}} \right],$$

$$\Gamma_{ff} = \mathcal{R}_V^f g_{Vf}^2 + \mathcal{R}_A^f g_{Af}^2, \qquad \Gamma_Z = \sum_f \Gamma_{ff},$$

$$\mathcal{A}_f = 2 \frac{g_{Vf}/g_{Af}}{1 + (g_{Vf}/g_{Af})^2} = \frac{1 - 4|Q_f| \sin^2 \theta_{\text{eff}}^f}{1 - 4|Q_f| \sin^2 \theta_{\text{eff}}^f + 8(|Q_f| \sin^2 \theta_{\text{eff}}^f)^2}.$$

$$A_{\text{FB}}^f = \frac{3}{4} \mathcal{A}_e \mathcal{A}_f \qquad A_{\text{LR}} = \mathcal{A}_e$$

electroweak corrections

Correction term first at NNLO:

Grassi, Kniehl, Sirlin ’01

Freitas ’13

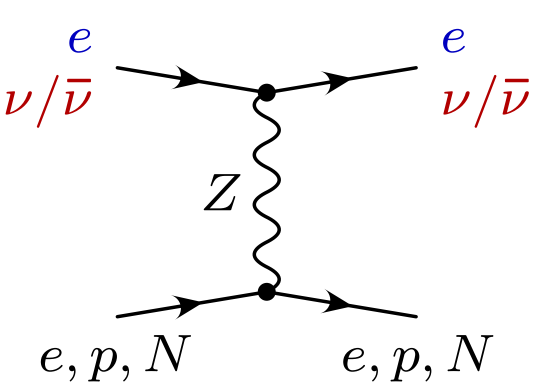
$$\delta X_{(2)} = -(\text{Im}\,\Sigma'_{Z(1)})^2 - 2\overline{\Gamma}_Z \overline{M}_Z \,\text{Im}\,\Sigma''_{Z(1)}$$

Low-energy observables

Test of running $\overline{\text{MS}}$ weak mixing angle $\sin^2\bar{\theta}(\mu)$

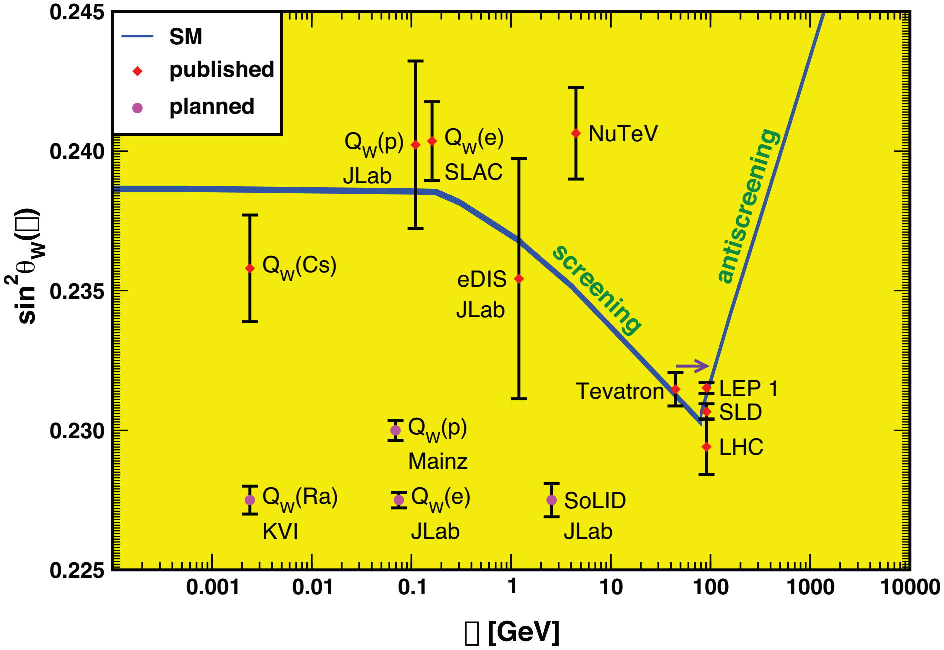
- Polarized $ee,\ ep,\ ed$ scattering ($Q_W(e)$, $Q_W(p)$, eDIS)
  E158 '05; Qweak '13; JLab Hall A '13

- $\nu N/\bar{\nu}N$ scattering NuTeV '02



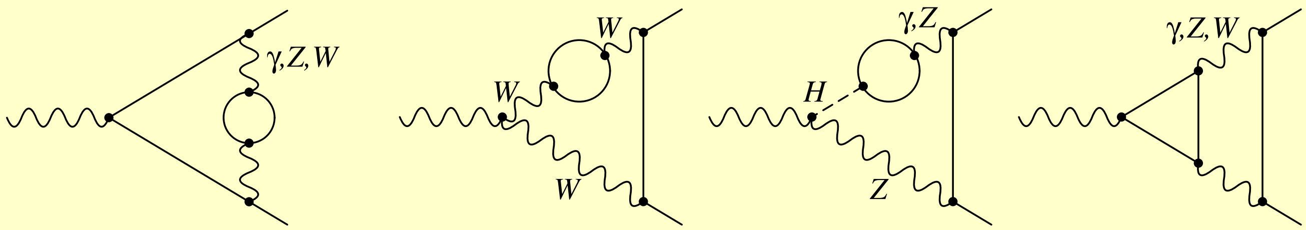
- Atomic parity violation ($Q_W(^{133}\text{Cs})$) Wood et al. '97
  Guéna, Lintz, Bouchiat '05

Erler '14



Current status of SM loop results

Known corrections to Δr, $\sin^2\theta^f_{\rm eff}$, g_{Vf}, g_{Af}:



- Complete NNLO corrections (Δr, $\sin^2\theta^\ell_{\rm eff}$) Freitas, Hollik, Walter, Weiglein '00
  Awramik, Czakon '02; Onishchenko, Veretin '02
  Awramik, Czakon, Freitas, Weiglein '04; Awramik, Czakon, Freitas '06
  Hollik, Meier, Uccirati '05,07; Degrassi, Gambino, Giardino '14

- "Fermionic" NNLO corrections (g_{Vf}, g_{Af}) Czarnecki, Kühn '96
  Harlander, Seidensticker, Steinhauser '98
  Freitas '13,14

- Partial 3/4-loop corrections to ρ/T-parameter
  $\mathcal{O}(\alpha_t\alpha_s^2)$, $\mathcal{O}(\alpha_t^2\alpha_s)$, $\mathcal{O}(\alpha_t\alpha_s^3)$ Chetyrkin, Kühn, Steinhauser '95
  Faisst, Kühn, Seidensticker, Veretin '03
  Boughezal, Tausk, v. d. Bij '05
  Schröder, Steinhauser '05; Chetyrkin et al. '06
  Boughezal, Czakon '06

  $(\alpha_t \equiv \frac{y_t^2}{4\pi})$

Current uncertainties

	Experiment	Theory error	Main source
M_{W}	80.385 ± 0.015 MeV	4 MeV	α^3, $\alpha^2\alpha_{\mathrm{s}}$
Γ_Z	2495.2 ± 2.3 MeV	0.5 MeV	α^2_{bos}, α^3, $\alpha^2\alpha_{\mathrm{s}}$, $\alpha\alpha_{\mathrm{s}}^2$
σ^0_{had}	41540 ± 37 pb	6 pb	α^2_{bos}, α^3, $\alpha^2\alpha_{\mathrm{s}}$
$R_b \equiv \Gamma^b_{\mathrm{Z}}/\Gamma^{\mathrm{had}}_{\mathrm{Z}}$	0.21629 ± 0.00066	0.00015	α^2_{bos}, α^3, $\alpha^2\alpha_{\mathrm{s}}$
$\sin^2\theta^{\ell}_{\mathrm{eff}}$	0.23153 ± 0.00016	4.5×10^{-5}	α^3, $\alpha^2\alpha_{\mathrm{s}}$

- Theory error estimate is not well defined, ideally $\Delta_{\mathrm{th}} \ll \Delta_{\mathrm{exp}}$
- Common methods:
  - Count prefactors (α, N_c, N_f, ...)
  - Extrapolation of perturbative series
  - Renormalization scale dependence
  - Renormalization scheme dependence
- Also parametric error from external inputs (m_{t}, m_b, α_{s}, $\Delta\alpha_{\mathrm{had}}$, ...)

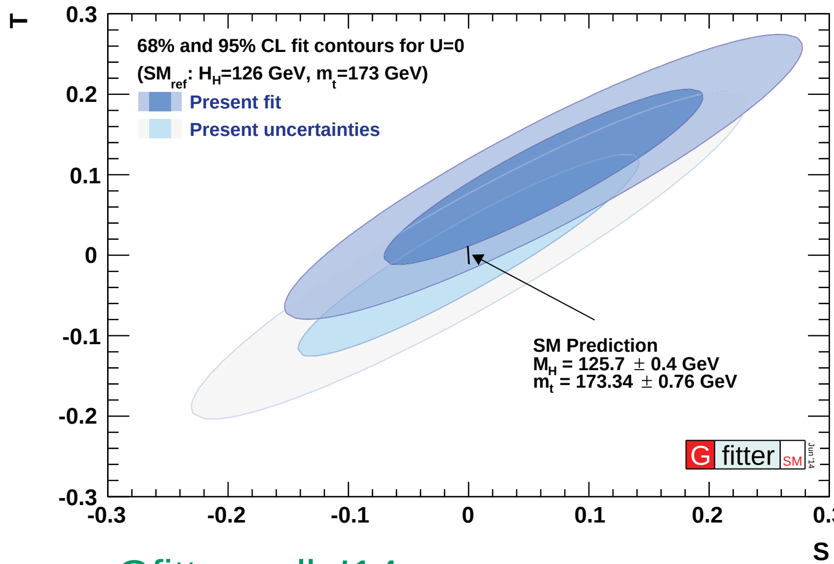
Constraints on new physics

Oblique parameters:

$$\alpha T = \frac{\Sigma_{WW}(0)}{M_W} - \frac{\Sigma_{ZZ}(0)}{M_Z}$$

$$\frac{\alpha}{4s^2c^2} S = \frac{\Sigma_{ZZ}(M_Z^2) - \Sigma_{ZZ}(0)}{M_Z} + \frac{s^2 - c^2}{sc}\frac{\Sigma_{Z\gamma}(M_Z^2)}{M_Z} - \frac{\Sigma_{\gamma\gamma}(M_Z^2)}{M_Z}$$

$$\frac{\alpha}{4s^2}(S+U) = \frac{\Sigma_{WW}(M_W^2) - \Sigma_{WW}(0)}{M_W} - \frac{c}{s}\frac{\Sigma_{Z\gamma}(M_Z^2)}{M_Z} - \frac{\Sigma_{\gamma\gamma}(M_Z^2)}{M_Z}$$



Gfitter coll. ’14

$\longrightarrow$ Not adequate for new physics that affects flavor ($Z \to \ell\ell$, $Z \to bb$, ...)

Constraints on new physics: EFT

More general setup: Use pseudo-observables

M_W, Γ_Z, σ^0_{had}, R_b, R_ℓ, A_ℓ, A_b, A_{lq} $(\ell = e, \mu, \tau)$ $\longrightarrow$ 12 quantities

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

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

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

$O^{(3)e}_{LL} = (\bar{L}^e_L \sigma^a \gamma_\mu L^e_L)(\bar{L}^e_L \sigma^a \gamma^\mu L^e_L)$ $\Delta G_F = -\sqrt{2}\frac{c^{(3)e}_{LL}}{\Lambda^2}$

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

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

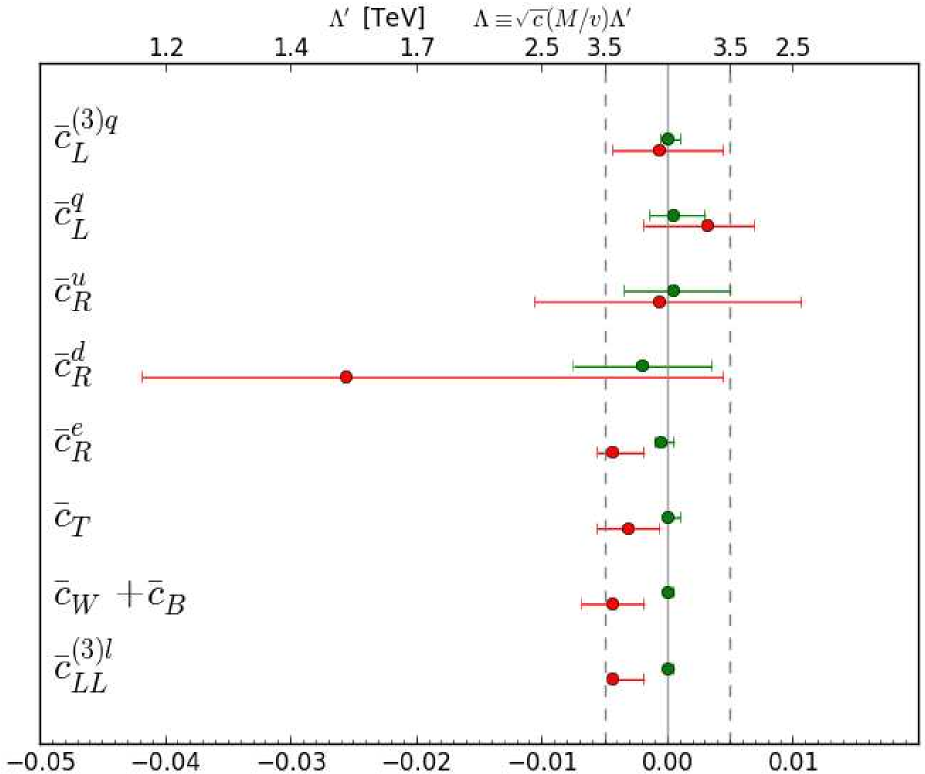
$O^{(3)F}_L = i(\Phi^\dagger \overleftrightarrow{D}^a_\mu \Phi)(\bar{F}_L \sigma_a \gamma^\mu F_L)$

More operators than EWPOs

$\longrightarrow$ Some can be constrained by $W \to \ell\nu$, had., $e^+e^- \to W^+W^-$

Constraints on new physics: EFT

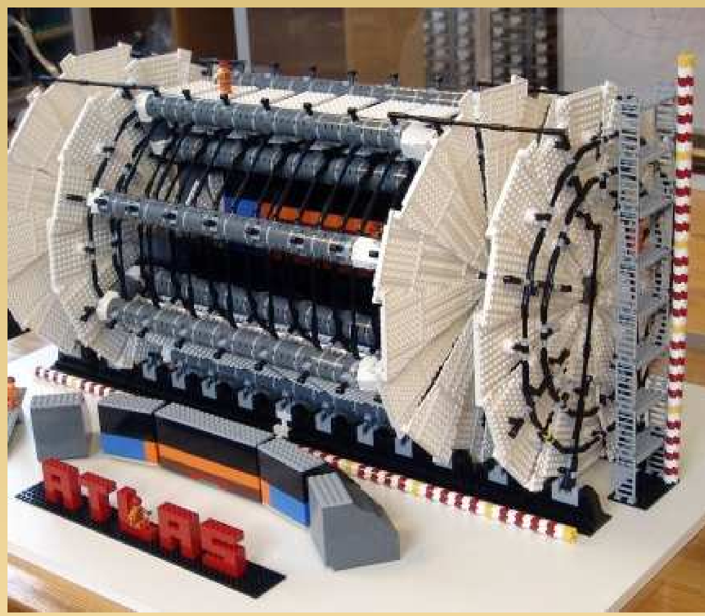
Assuming flavor universality:

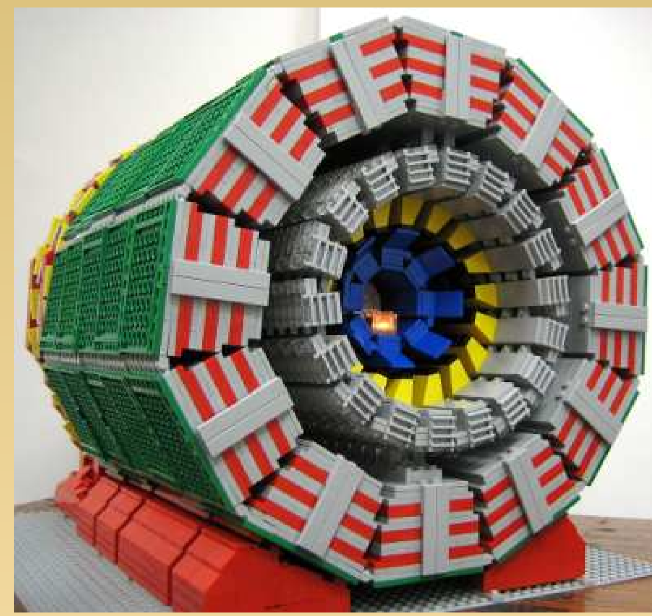


Significant correlation/ degeneracy between different operators

Pomaral, Riva ’13
Ellis, Sanz, You ’14

Electroweak physics at the LHC

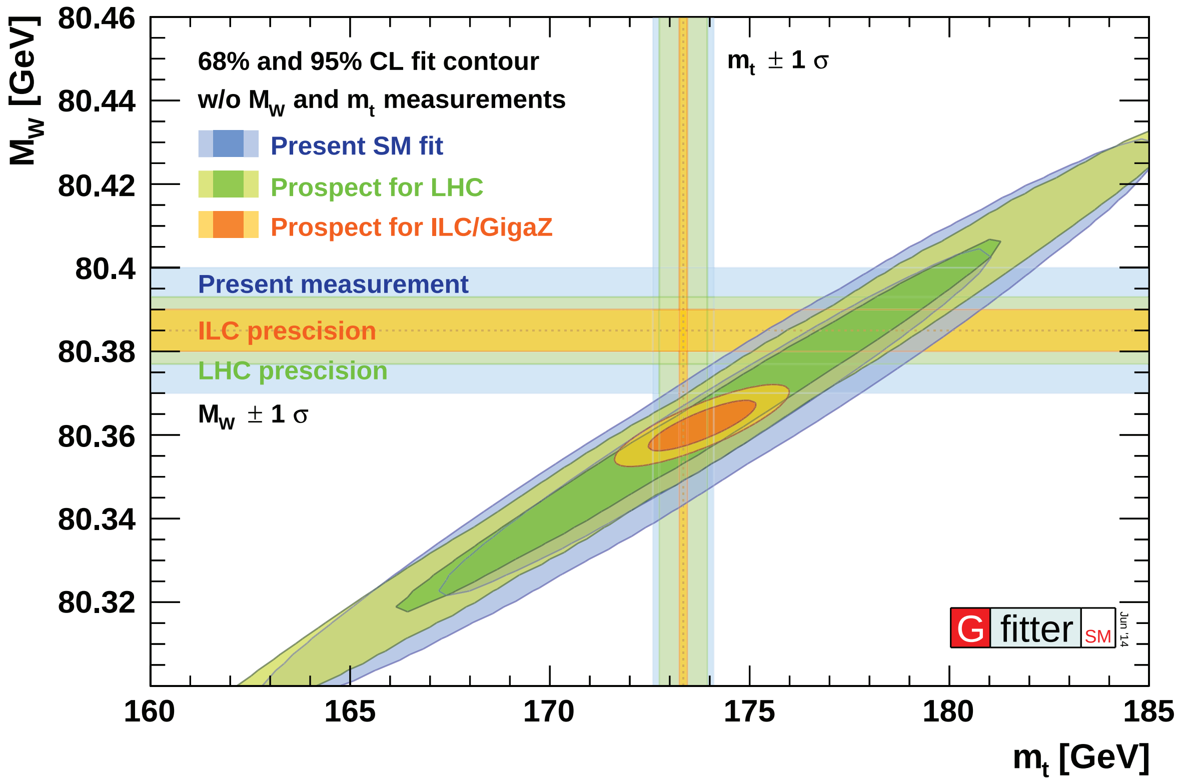




W mass measurement at the LHC

Precision target for LHC: $\delta M_{\mathrm{W}} \sim 8\ \mathrm{MeV}$ Snowmass EW group, Baak et al. ’13

- Requires improvements in PDF uncertainties (currently $\delta M_{\mathrm{W,PDF}} > 10$ MeV)
  $\longrightarrow$ S. Forte’s talk
- Also improvements in **experimental systematics** and **modeling of QED radiation** (state of the art MC programs: `PHOTOS`, `HORACE`)



Gfitter coll. ’14

$\longrightarrow$ Will tighten constraints on SM and BSM physics

Drell-Yan at hadron colliders

Meausurement of $\sin^2\theta^\ell_{\text{eff}}$ from A_{FB} for $pp \to Z \to \ell^+\ell^-$

$\longrightarrow$ Check of discrepancy between SLD and LEP

Current errors:

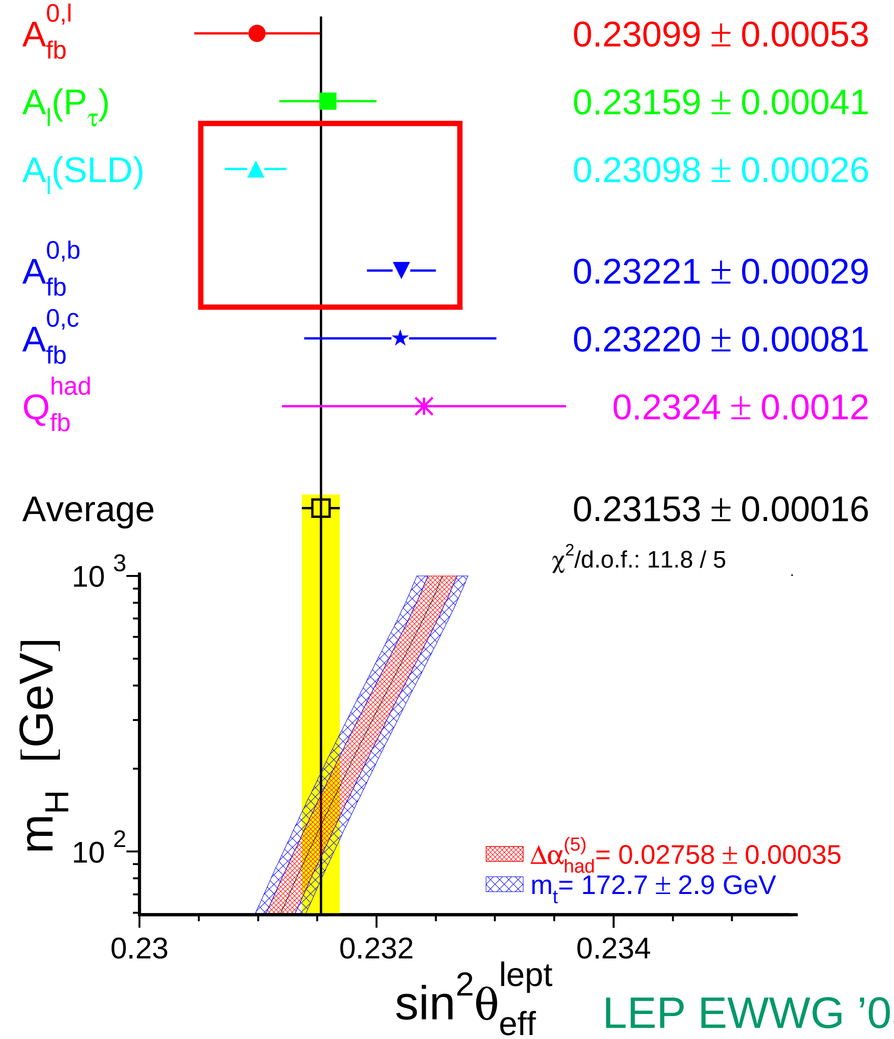
LEP/SLC:	1.6×10^{-4}	2005
ATLAS:	10×10^{-4}	2013
CMS:	32×10^{-4}	2011
CDF:	10×10^{-4}	2014
DØ:	4.7×10^{-4}	2014

Future projection:

LHC: $\lesssim 3.5 \times 10^{-4}$

Snowmass EW group, Baak et al. '13

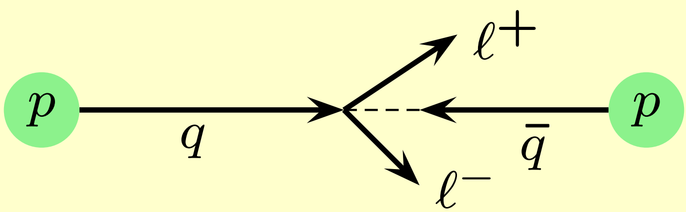
CDF: $\sim 4.5 \times 10^{-4}$ Bodek '14



LEP EWWG '05

Drell-Yan at LHC

At LHC: forward = boost direction

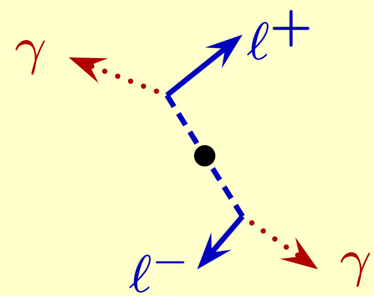


Precise predictions for rapidity distributions crucial

Leadings effects:

- Parton distribution functions
- QED FSR radiation
- QCD corrections
- EW corrections
- mixed QCD–EW contributions

- Multiple photon rad. in final state
  → modifies observed $\ell^\pm$ directions

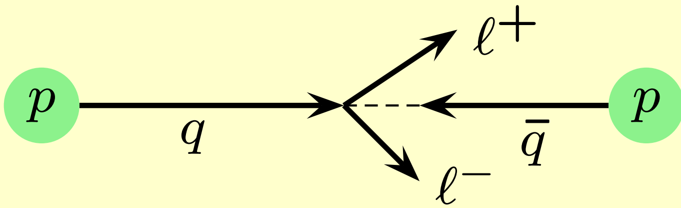


- Current "standard" tool: `PHOTOS`
  Golonka, Was '05
  → Uses factorization approach, accurate to leading-log

- `KKMC 4.22` Jadach, Ward, Was '13
  → $pp \to f\bar{f}$ with integrated QED, accurate to $\mathcal{O}(\alpha^2 L)$, $L = \log \frac{s}{m_f^2}$

Drell-Yan at LHC

At LHC: forward = boost direction

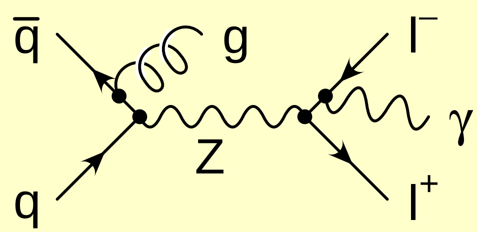


Precise predictions for rapidity distributions crucial

Leadings effects:

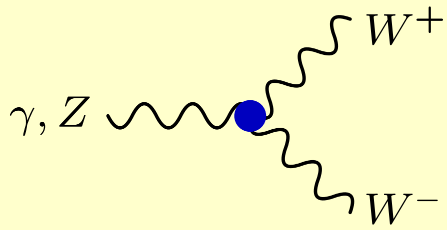
- Parton distribution functions
- QED FSR radiation
- QCD corrections
- EW corrections
- mixed QCD–EW contributions

- NNLO QCD — Melnikov, Petriello '06; Catani et al. '09
- NNLL QCD for p_T distribution — Bozzi et al. '10
- NLO EW — Berends, Kleiss '85; Baur et al. '01; Carloni Calame et al. '07; Li, Petriello '12
- Mixed QCD-EW corrections
  $\longrightarrow$ Work in progress
  Dittmaier, Huss, Schwinn '14-15



Anomalous gauge boson couplings

Example: CP-conserving γWW and ZWW couplings:



$$\mathcal{L} = -ie\Big[g_1^\gamma(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})A^\nu + \kappa_\gamma W^+_\mu W^-_\nu A^{\mu\nu} + \frac{\lambda_\gamma}{M_W^2}W^{+\nu}_\mu W^{-\rho}_\nu A_\rho{}^\mu\Big]$$
$$-igc\Big[g_1^Z(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})Z^\nu + \kappa_Z W^+_\mu W^-_\nu Z^{\mu\nu} + \frac{\lambda_Z}{M_W^2}W^{+\nu}_\mu W^{-\rho}_\nu Z_\rho{}^\mu\Big]$$

Hagiwara, Peccei, Zeppenfeld, Hikasa '87

Limitations:

- Coupling constants are not independent; gauge invariance forces
  $g_1^\gamma = 1, \quad \kappa_Z = g_1^Z + \frac{s^2}{c^2}(1 - \kappa_\gamma), \quad \lambda_\gamma = \lambda_Z$
- Additional terms with derivatives possible, *e. g.* $\kappa_\gamma W^+_\mu W^-_\nu \partial_\rho \partial^\rho A^{\mu\nu}$
- No prescription for ranking terms in numerical size

Effective field theory

Extension of SM by **higher-dimensional operators**:

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \sum_{d=5}^{\infty} \frac{1}{\Lambda^{d-4}} \sum_i c_i \, \mathcal{O}_i^{(d)}$$

- Incorporate knowledge that Higgs boson exists
- Operators must satisfy SM gauge invariance
- Valid description for energies $E \ll \Lambda$ ($\Lambda \sim$ mass of heavy particles)
- Operators ranked by suppression power Λ^{4-d}

Leading CP-even gauge boson operators ($d = 6$):

$$\mathcal{O}_{\mathsf{WWW}} = \mathrm{Tr}[W_{\mu\nu} W^{\nu\rho} W_\rho{}^\mu]$$

Hagiwara, Ishihara, Szalapski, Zeppenfeld '93

$$\mathcal{O}_{\mathsf{W}} = (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{O}_{\mathsf{B}} = (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)$$

$\longrightarrow$ Only 3 indep. parameters

aGC vs. effective field theory

γWW, ZWW couplings:

g_1^γ, g_1^Z, κ_γ, κ_Z, λ_γ, λ_Z

Hagiwara, Peccei, Zeppenfeld, Hikasa '87

$\gamma\gamma WW$ couplings:

a_0^W, a_C^W, $f_{T,0}$

Belanger, Boudjema '92

$\gamma\gamma Z$, γZZ, ZZZ couplings:

f_5^γ, f_5^Z, h_3^γ, h_3^Z, h_4^γ, h_4^Z

f_4^γ, f_4^Z

Gounaris, Layssac, Renard '00

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho{}^\mu]$$
$$\mathcal{O}_W = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_B = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

Hagiwara, Ishihara, Szalapski, Zeppenfeld '93

$\mathcal{O}_{WWW}$, $\mathcal{O}_W$, $d = 8$ operators

e.g. $\mathcal{O}_{T,0} = \mathrm{Tr}[W_{\mu\nu}W^{\mu\nu}]\,\mathrm{Tr}[W_{\rho\sigma}W^{\rho\sigma}]$

Eboli, Gonzalez-Garcia, Mizukoshi '06

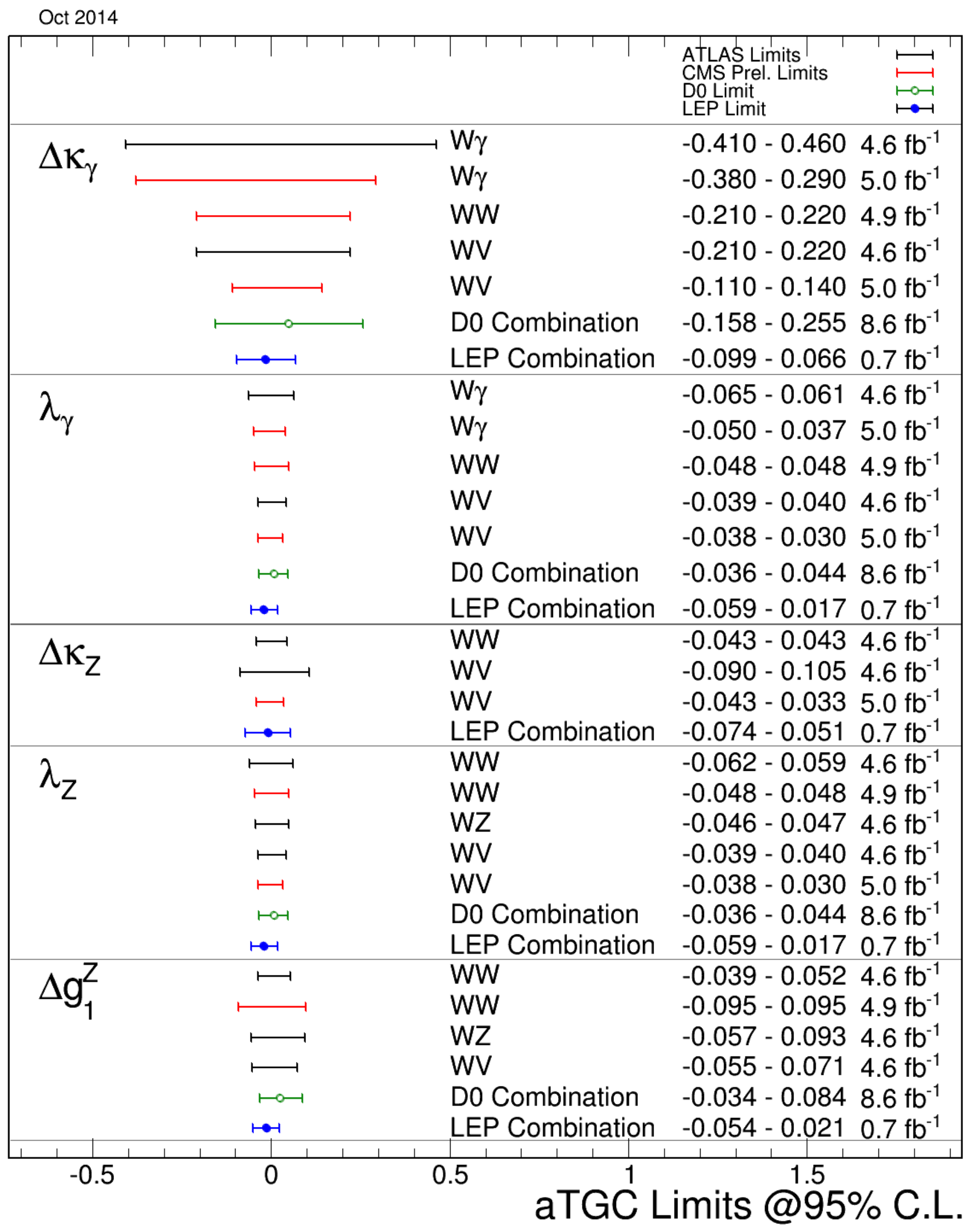
$d = 8$ operators

$$\mathcal{O}^{(8)}_{\tilde{B}W} = \Phi^\dagger \tilde{B}_{\mu\nu}W^{\mu\rho}\{D_\rho, D^\nu\}\Phi$$

$$\mathcal{O}^{(8)}_{\tilde{B}B} = \Phi^\dagger B_{\mu\nu}B^{\mu\rho}\{D_\rho, D^\nu\}\Phi$$
$$\mathcal{O}^{(8)}_{\tilde{B}W} = \Phi^\dagger B_{\mu\nu}W^{\mu\rho}\{D_\rho, D^\nu\}\Phi$$
$$\mathcal{O}^{(8)}_{\tilde{W}W} = \Phi^\dagger W_{\mu\nu}W^{\mu\rho}\{D_\rho, D^\nu\}\Phi$$

Degrande '13

Limits from data



Back of envelope translation:

	Λ_+ [TeV] ($c_i = +1$)	Λ_- [TeV] ($c_i = -1$)
$\mathcal{O}_W$	0.44	0.35
$\mathcal{O}_B$	0.19	0.17
$\mathcal{O}_{WWW}$	0.49	0.34

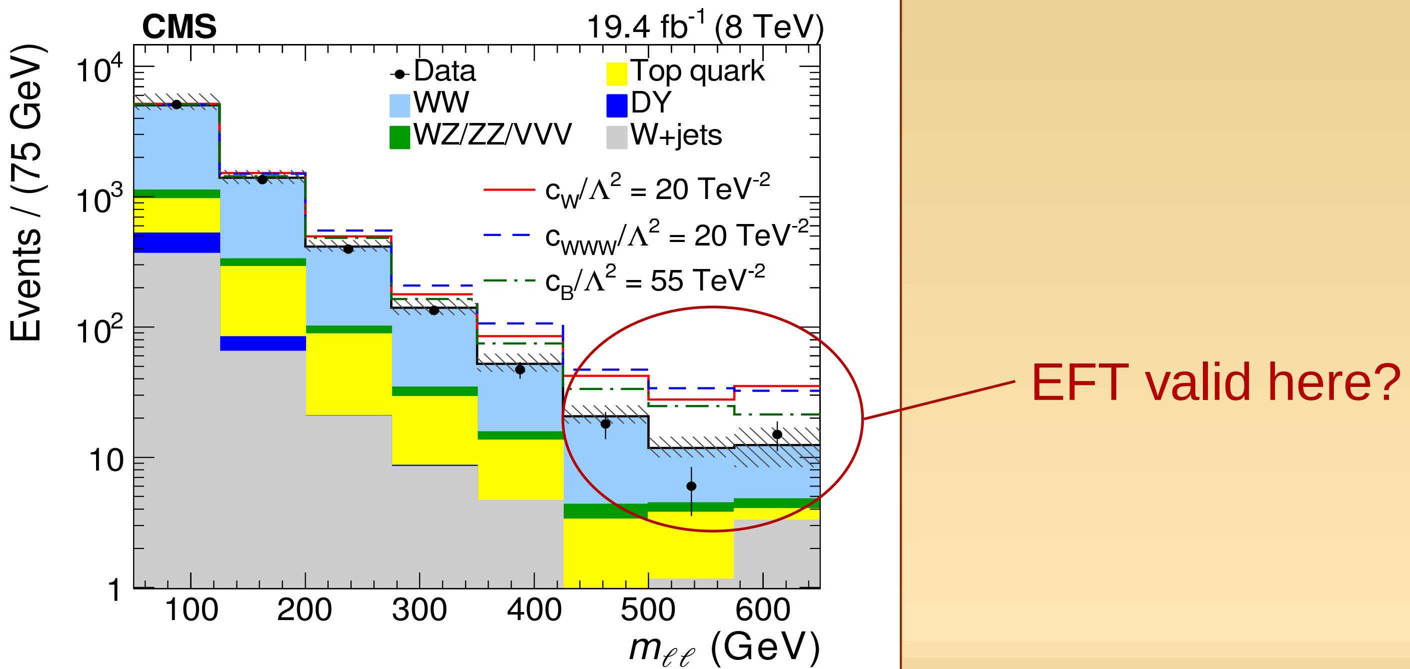
Complementary information from EWPOs
$\longrightarrow$ Both needed to constrain all $d{=}6$ operators

Limitations of the EFT

EFT becomes invalid for $E \gtrsim \Lambda$:

$\longrightarrow$ $d = 8, 10, \ldots$ operators become equally important as $d = 6$

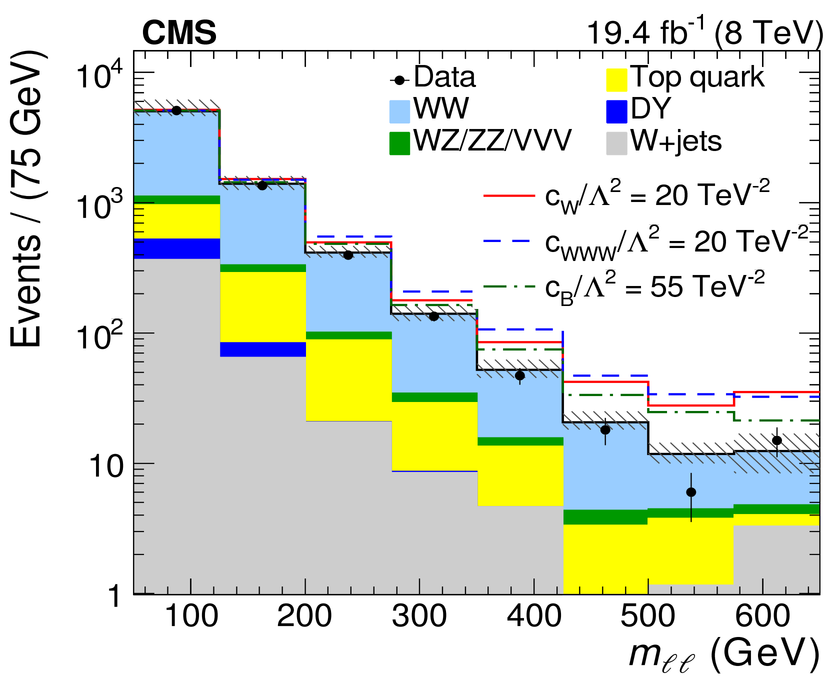
- New resonances or thresholds
- Off-shell effects below resonance
- Matching ambiguity in multi-scale models



Limitations of the EFT

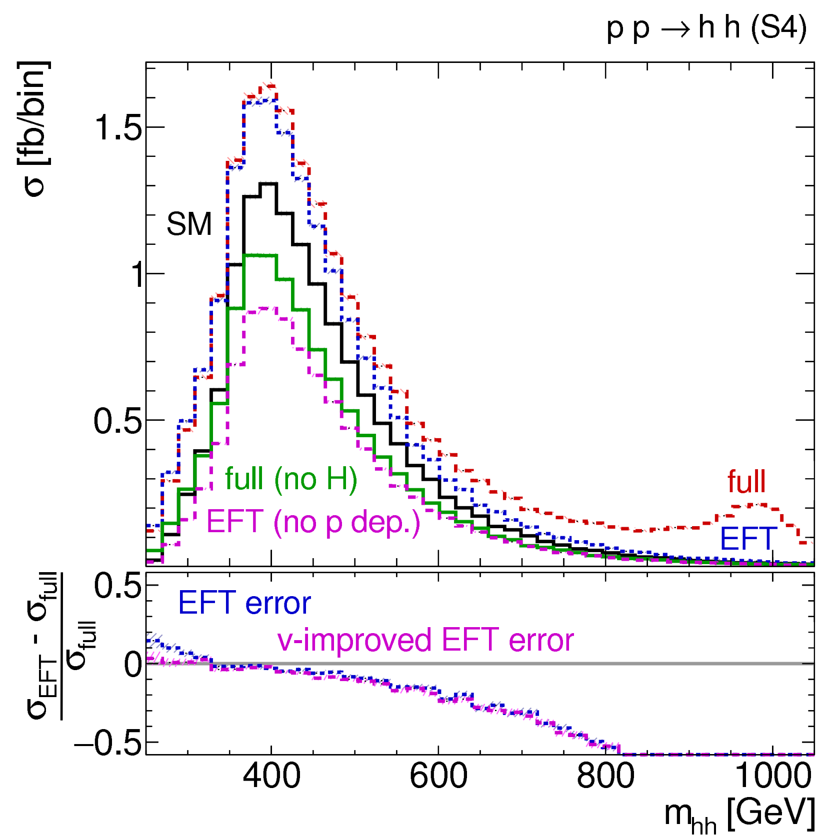
EFT becomes invalid for $E \gtrsim \Lambda$:
$\longrightarrow$ $d = 8, 10, \ldots$ operators become equally important as $d = 6$

- New resonances or thresholds
- Off-shell effects below resonance
- Matching ambiguity in multi-scale models



Test through comparison with explicit models $\longrightarrow$ D. Lopez-Val's talk

Singlet scalar, $m_S = 1$ TeV, $\sin\alpha = 0.4$



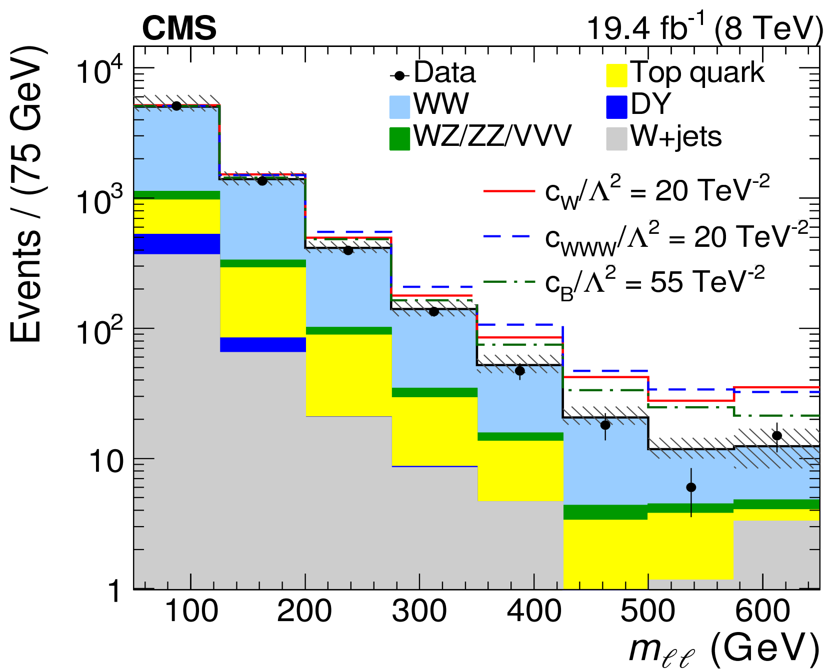
Brehmer, Freitas, Lopez-Val, Plehn '15

Limitations of the EFT

EFT becomes invalid for $E \gtrsim \Lambda$:

$\longrightarrow$ $d = 8, 10, \ldots$ operators become equally important as $d = 6$

- New resonances or thresholds
- Off-shell effects below resonance
- Matching ambiguity in multi-scale models

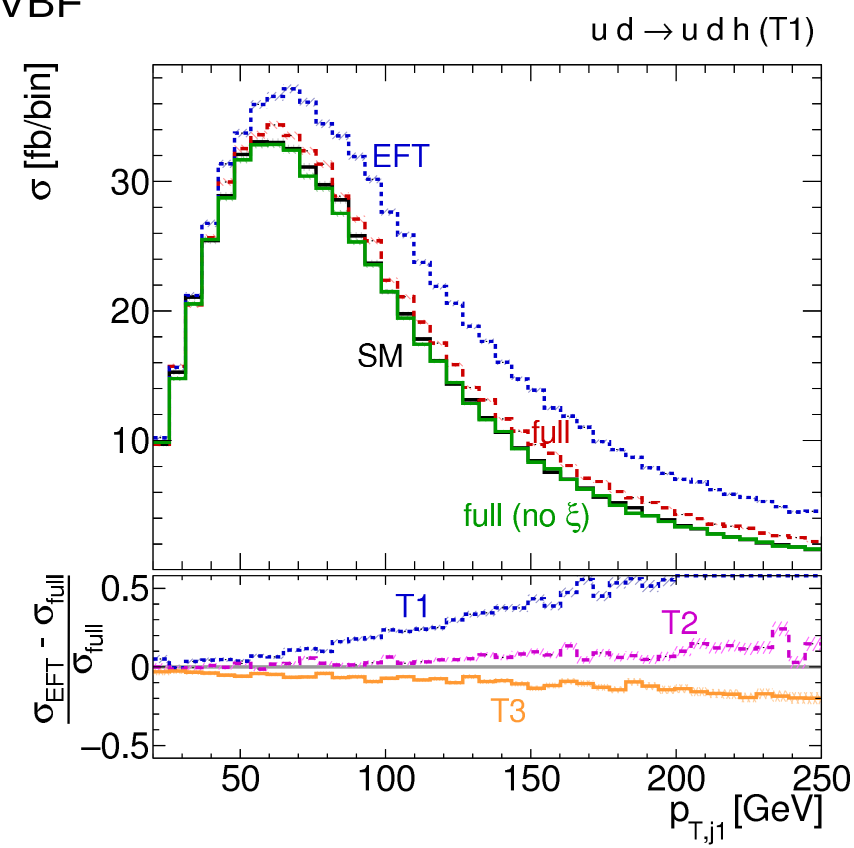


Test through comparison with explicit models

$\longrightarrow$ D. Lopez-Val's talk

Triplet vector, $m_\xi = 1.2$ TeV, $g_V = 3$

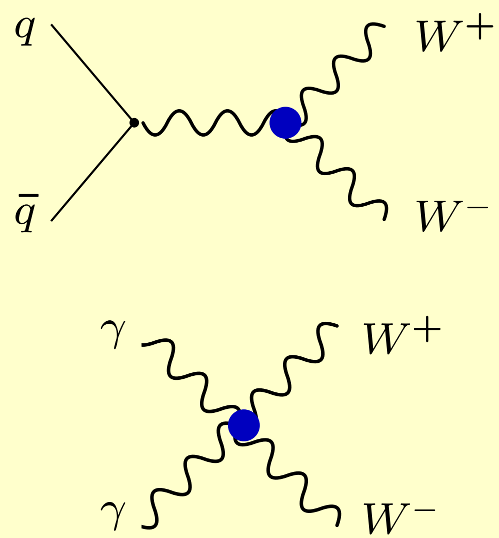
VBF

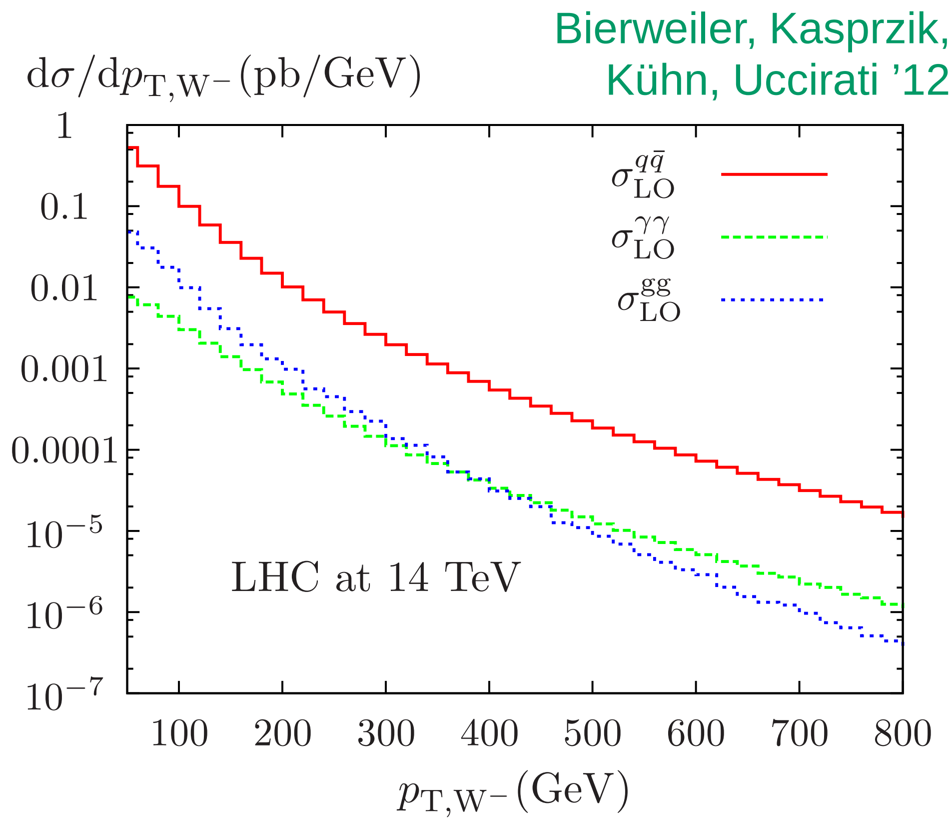


Brehmer, Freitas, Lopez-Val, Plehn '15

WW production

- $q\bar{q} \rightarrow W^+W^-$: Sensitive probe of **triple aGC** at LHC
  (also $q\bar{q}' \rightarrow W\gamma,\ WZ, \ldots$)
- Important contributions from $\gamma\gamma \rightarrow W^+W^-$
  $\longrightarrow$ Dependence on **quartic aGC**
  $\longrightarrow$ Difficult but possible to separate experimentally CMS Coll. '13

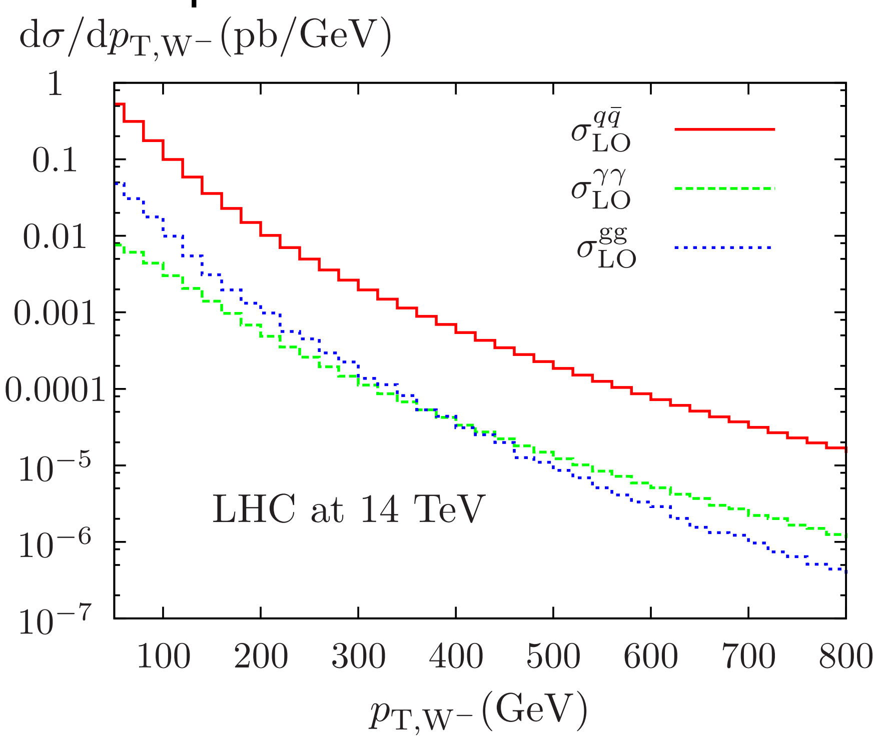


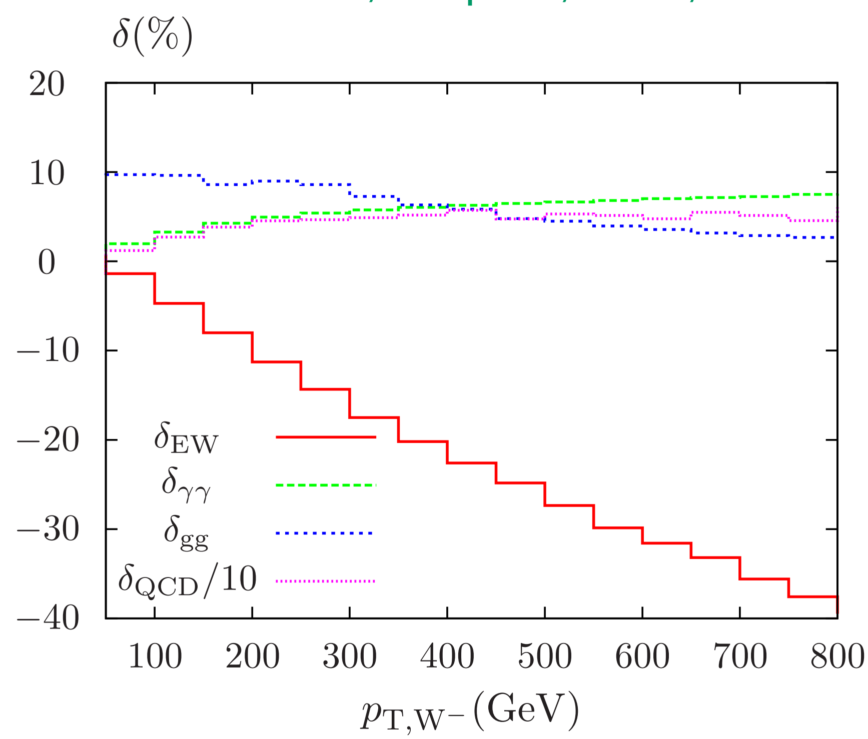


WW production

- Large QCD (NLO+NNLL) corrections (up to 50%) Dawson, Lewis, Zeng '13
  $\longrightarrow$ Few % uncertainty
- Large EW corrections for high-energy tail,
  from Sudakov logarithms $\alpha^n \log^{2n} \frac{\hat{s}}{M_W^2}, \ \alpha^n \log^{2n-1} \frac{\hat{s}}{M_W^2}, \ldots$
  (known to NNLL) Fadin, Lipatov, Martin, Melles '99; Accomando, Denner, Kaiser '04
  Kühn, Metzler, Penin, Uccirati '11

One-loop corrections: Bierweiler, Kasprzik, Kühn, Uccirati '12





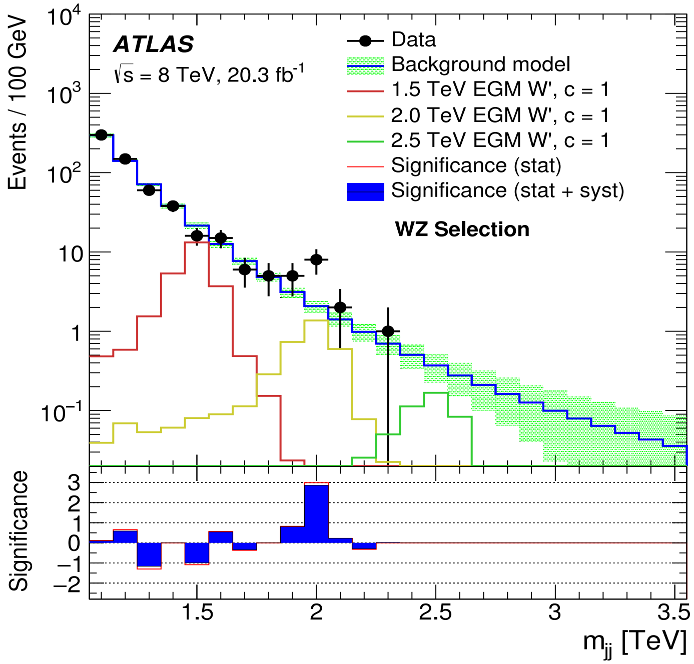
Separate hints from ATLAS and CMS for $M \sim 2$ TeV resonance:

- ATLAS $VV \to JJ$, $\sim 3.4\sigma$ ($V = W/Z$, $J =$ fat jet)
- CMS $eejj$, $\sim 2.8\sigma$
- CMS $VH \to \ell\nu b\bar{b}$, $\sim 2.2\sigma$
- CMS jj, $\sim 2\sigma$

Interpretation as $W' \to WZ, WH \ldots$

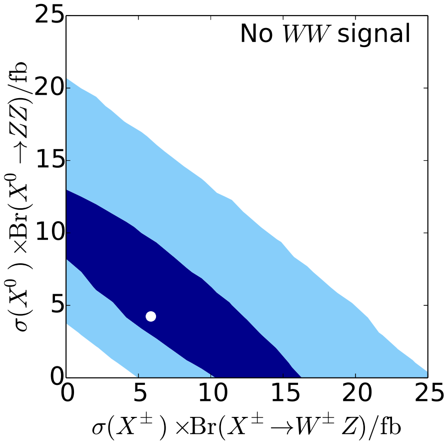
Fukano et al. '15; Hisano, Nagata, Omura '15
Cheung, Keung, Tseng, Yuan '15; Dobrescu, Liu '15
Abe, Kitahara, Nojiri '15; ...

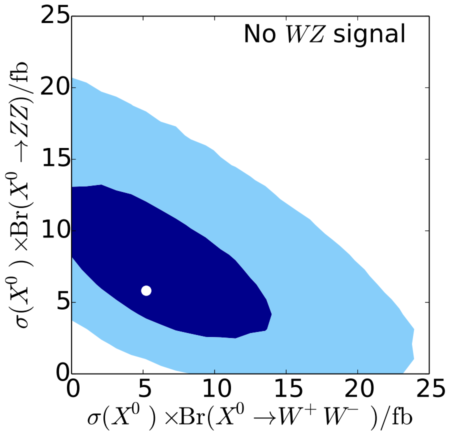
But no excess in $WZ \to \ell\nu jj$

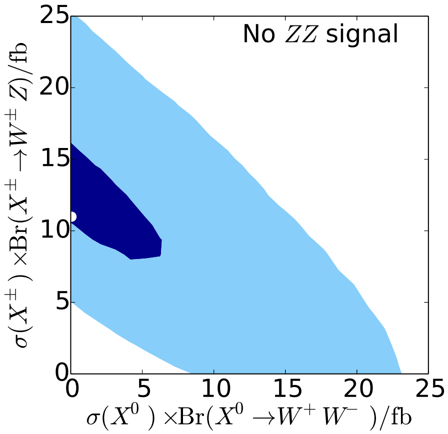


Can also be analyzed through EFT with 2-TeV resonance

Allanach, Gripaios, Sutherland '15

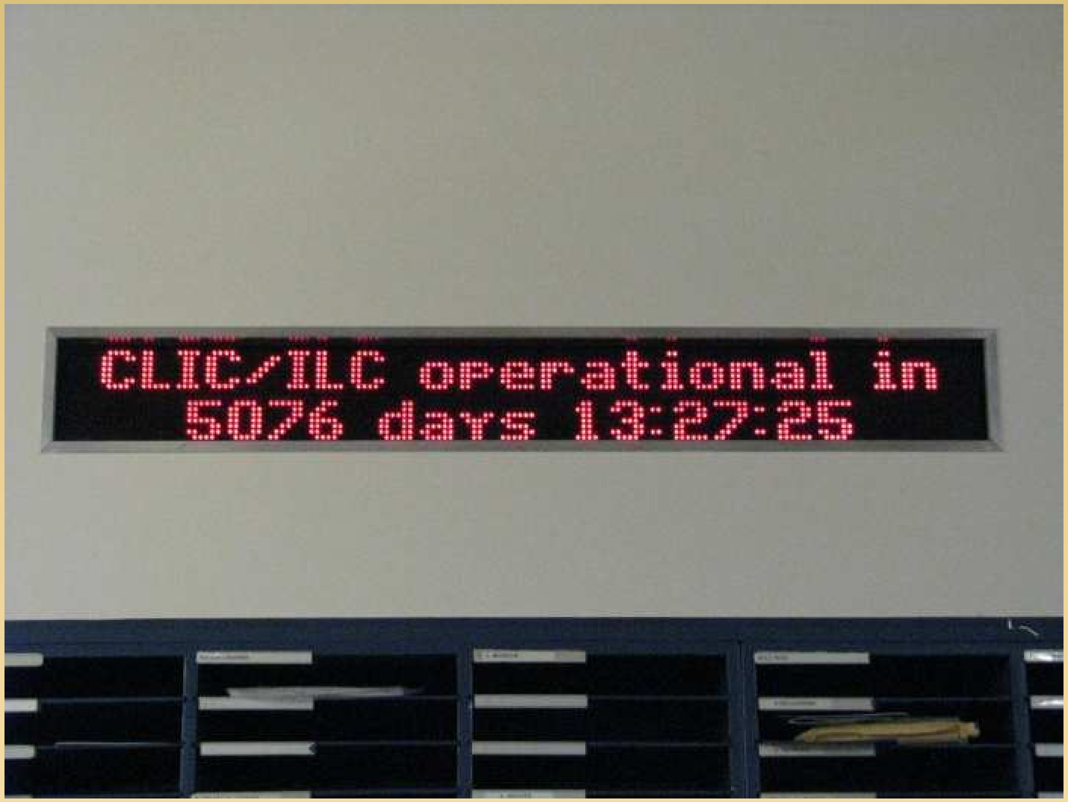






$\longrightarrow$ J. Brehmer's talk

Prospects for future e^+e^- machines



Electroweak precision tests

	ILC	FCC-ee	perturb. error with 3-loop†	Param. error ILC*	Param. error FCC-ee**
M_{W} [MeV]	3–5	~ 1	1	2.6	1
Γ_Z [MeV]	~ 1	~ 0.1	$\lesssim 0.2$	0.5	0.06
R_b $[10^{-5}]$	15	$\lesssim 5$	5–10	< 1	< 1
$\sin^2\theta^{\ell}_{\mathrm{eff}}$ $[10^{-5}]$	1.3	0.3	1.5	2	2

† **Theory scenario:** $\mathcal{O}(\alpha\alpha_s^2)$, $\mathcal{O}(N_f\alpha^2\alpha_s)$, $\mathcal{O}(N_f^2\alpha^2\alpha_s)$

(N_f^n = at least n closed fermion loops)

Parametric inputs:

*** ILC:** $\delta m_t = 100$ MeV, $\delta\alpha_s = 0.001$, $\delta M_Z = 2.1$ MeV

****FCC-ee:** $\delta m_t \lesssim 50$ MeV, $\delta\alpha_s = 0.0001$, $\delta M_Z = 0.1$ MeV

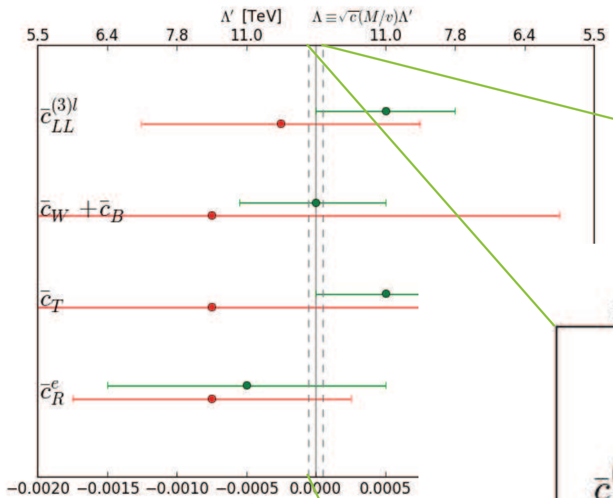
also: $\delta(\Delta\alpha) = 5 \times 10^{-5}$

Sensitivity to new physics

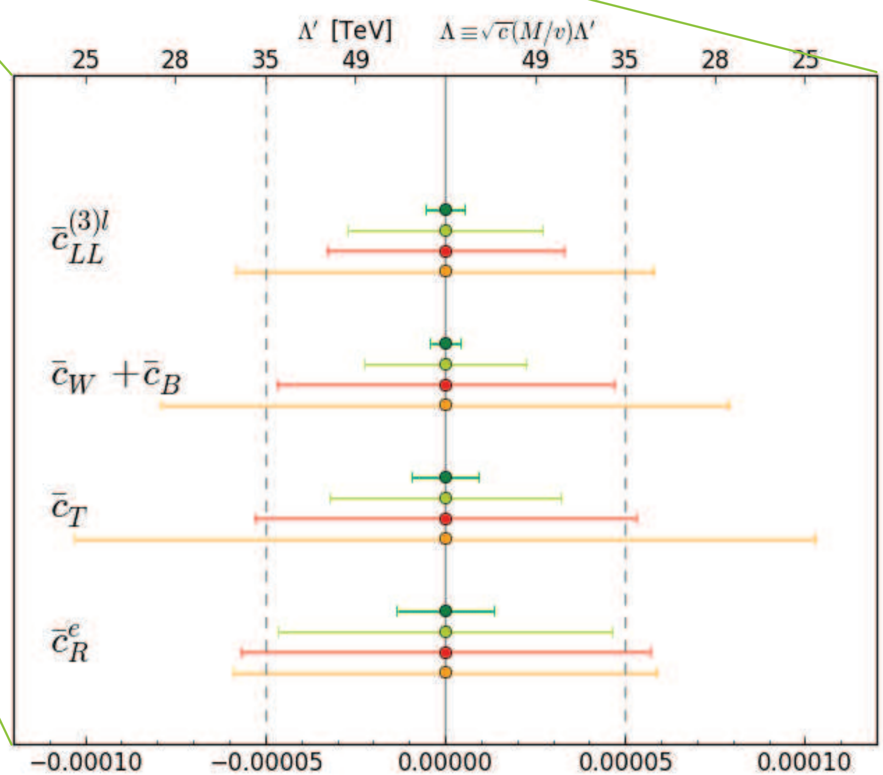
T. You

Tevong You (KCL)

FCC-ee Summary



LEP



FCC-ee

-Dark green: One-by-one (exp. uncertainty only)

-Light green: One-by-one (exp + TH uncertainty)

-Red: Marginalised (exp. uncertainty only)

-Orange: Marginalised (exp + TH uncertainty

Theory challenges

- Electroweak 3-loop calculations for **EWPO** necessary + leading 4-loop (5-loop?) [leading $O(\alpha\alpha_{\mathrm{s}}^3)$ already known]

- Need consistent use of **short-distance definition** of m_{t} across all sectors

- Control of **parametric uncertainties** crucial:
  - m_{t}: Several error sources, extracted value of m_{t} depends itself on α_s
  - m_b: No agreement between groups on error estimate, path forward unclear
  - M_{W}: May need 2-loop corrections for $e^+e^- \to WW \to 4f$ near threshold to achieve $\delta M_{\mathrm{W}} \sim 1$ MeV
  - α_s: Big improvement expected from FCC-ee, but discrenpancy to event shapes and DIS must be understood
  - $\Delta\alpha_{\mathrm{had}}$: Could be limiting factor, but possibly determined directly at FCC-ee

$\longrightarrow$ FCC-ee phenomenology WG2: Precision electroweak calculations
Convenors: S. Heinemeyer, A. Freitas

Conclusions

- **Electroweak precision tests** and **VV production** probe physics at the **TeV scale**
- **Higher-order radiative corrections** mandatory for SM predictions to meet experimental precision
- Understanding of **QCD systematics** (jet binning, PDFs, ...) essential for controlling uncertainties in electroweak processes at LHC
- **Effective field theory** is well-defined framework for describing electroweak new physics in
  - Electroweak precision data
  - High energy VV and VVV production
  - Higgs physics
- Future e^+e^- collider will probe much deeper!

Conclusions

- **Electroweak precision tests** and **VV production** probe physics at the **TeV scale**
- **Higher-order radiative corrections** mandatory for SM predictions to meet experimental precision
- Understanding of **QCD systematics** (jet binning, PDFs, ...) essential for controlling uncertainties in electroweak processes at LHC
- **Effective field theory** is well-defined framework for describing electroweak new physics in
  - Electroweak precision data
  - High energy VV and VVV production
  - Higgs physics
- Future e^+e^- collider will probe much deeper!

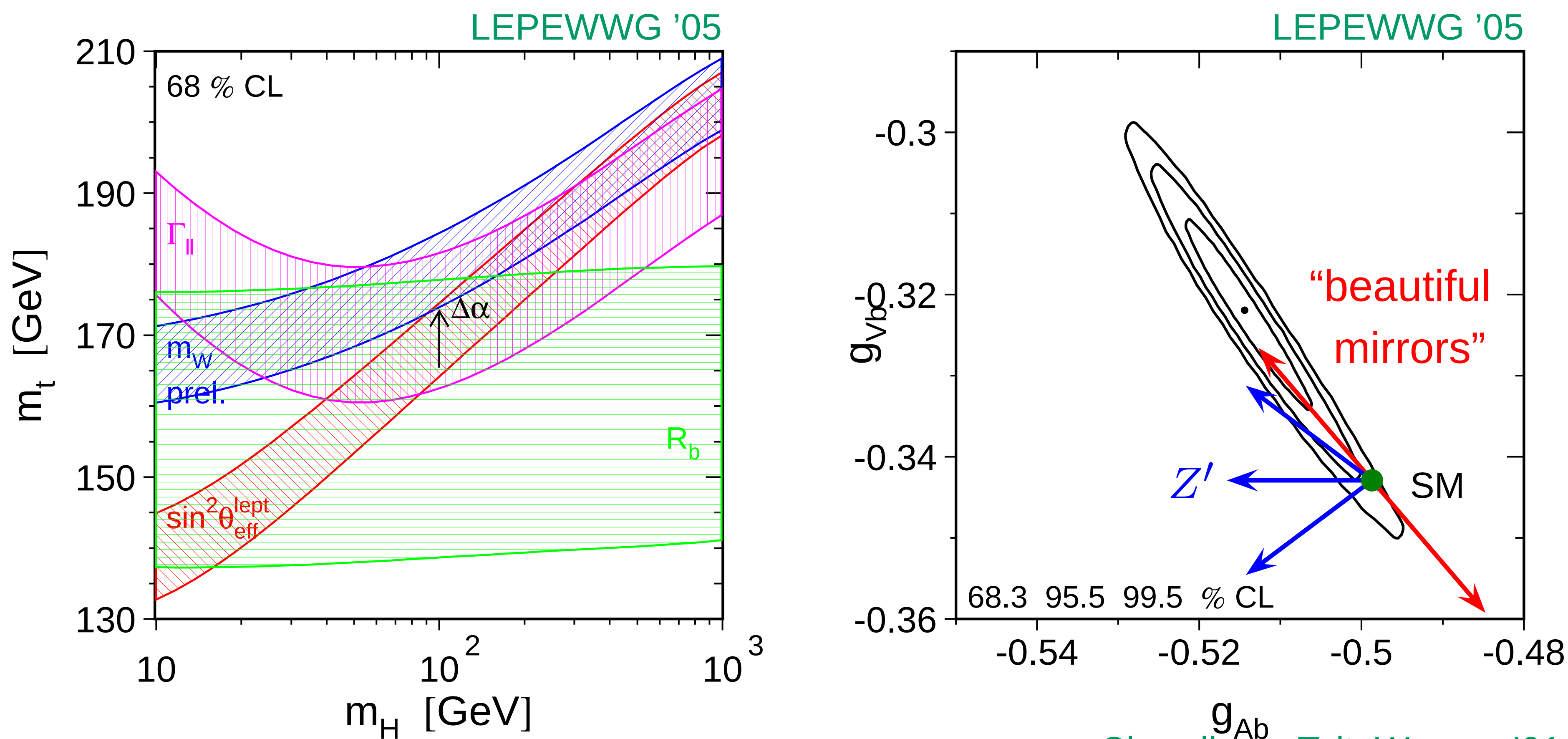
Backup slides

Electroweak precision observables

Impact of different observables:

M_W (from G_μ) $R_b = \Gamma[Z \to b\bar{b}]/\Gamma[Z \to \text{had.}]$

$\Gamma_{ll} = \Gamma_Z \, \text{BR}[Z \to ll]$ $\sin^2\theta^\ell_{\text{eff}}$ (from A_{LR} and A_{FB})



Choudhury, Tait, Wagner '01

Z-pole observables

After deconvolution of initial-state QED radiation and subtraction of γ-exchange:

$$\mathcal{A}[e^+e^- \to f\bar{f}] = \frac{R}{s - s_0} + S + (s - s_0)S'$$

$$s_0 \equiv M_Z^2 - iM_Z\Gamma_Z$$

$s_0,\ R,\ S,\ S'$ are gauge-invariant

Willenbrock, Valencia '91; Sirlin '91; Stuart '91

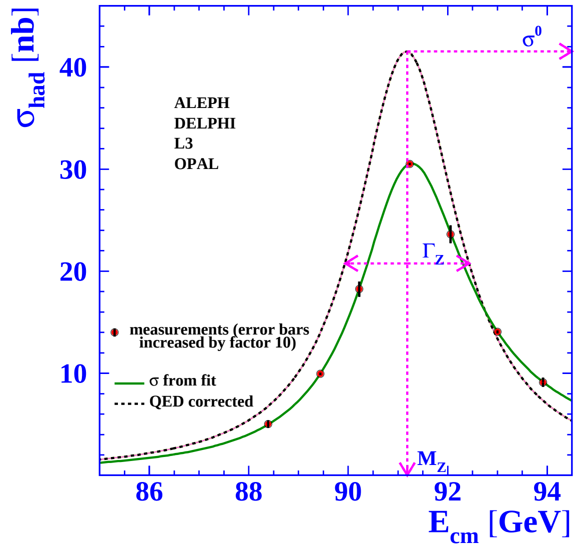
Gambino, Grassi '00

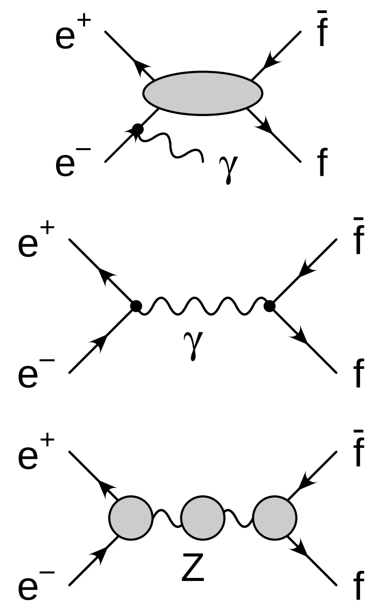
$$\sigma \sim \frac{1}{(s - M_Z^2)^2 + M_Z^2\Gamma_Z^2} + \text{non.res.}$$

$M_Z = M_Z^{\text{exp}} - 34$ MeV

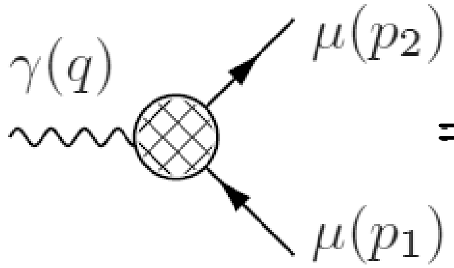
$\Gamma_Z = \Gamma_Z^{\text{exp}} - 0.9$ MeV

LEP EWWG '05





Muon anomalous magnetic moment



$$= (-ie)\,\bar{u}(p_2)\left[\gamma^\mu F_{\mathsf{E}}(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2m_\mu}F_{\mathsf{M}}(q^2)\right]u(p_1)$$

$a_\mu = F_{\mathsf{M}}(0)$

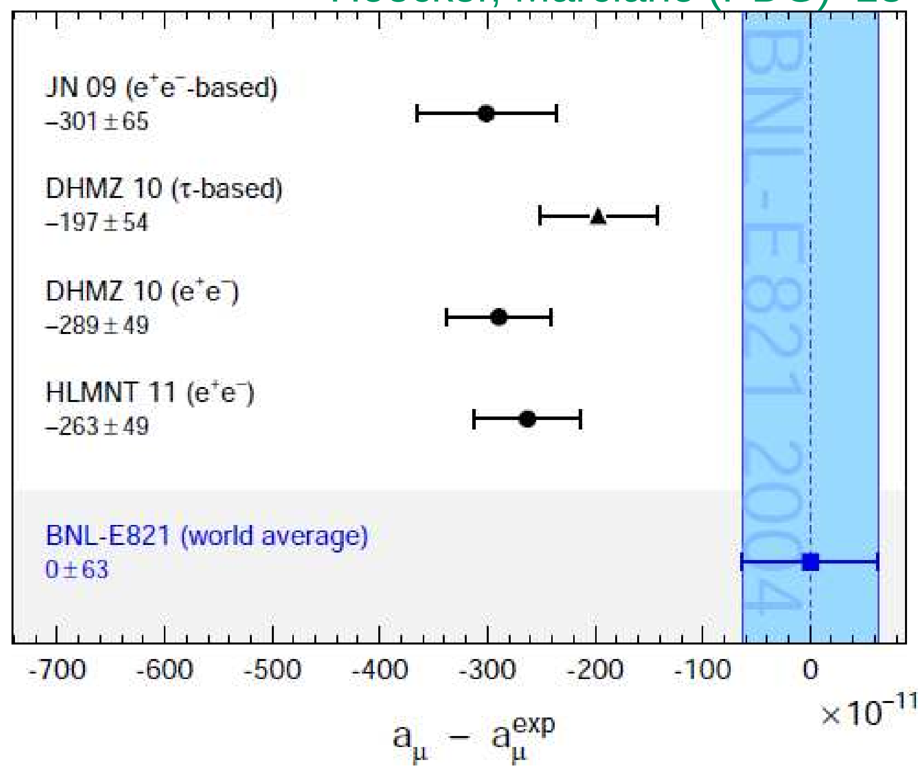
BNL g–2 experiment:

$a_\mu = (11\,659\,208.0 \pm 6.3) \times 10^{-10}$

$\gtrsim 3\sigma$ discrepancy to SM prediction

- Underestimated uncertainty of non-perturbative QCD (from data & models)?
- Cross-check from Fermilab g–2 experiment

Hoecker, Marciano (PDG) '13

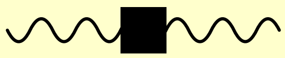


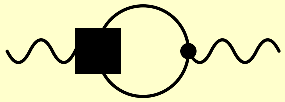
EFT matching

For precision measurements, may need EW loop corrections in EFT fits

Mebane, Greiner, Zhang, Willenbrock ’13; Chen, Dawson, Zhang ’14
Ghezzi, Gomez-Ambrosio, Passarino, Uccirati ’15

1. Match EFT at weak scale with NLO Wilson coefficients
2. Include LO effective operators in SM loops
3. Perform renormalization at weak scale
4. Obtain bounds on Wilson coefficients at weak scale from data
5. Bounds on Wilson coefficient at high scale Λ from RG running





Alternative approch: NLO effects from operator mixing

Grojean, Jenkins, Mahohar, Trott ’13; Jenkins, Mahohar, Trott ’13
Elias-Miro, Espinosa, Masso, Pomarol ’13

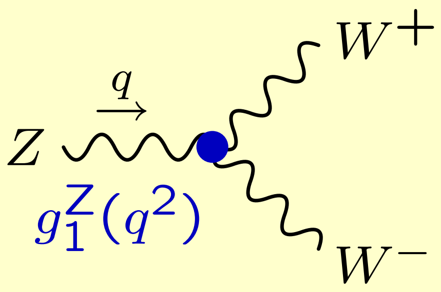
Note: Leading-log running not sufficient for precision observables

Unitarity constraints

Amplitudes with aGC grow $\propto E^2$

$\longrightarrow$ **Perturbative unitarity** violated

One approach: promote couplings to form factors



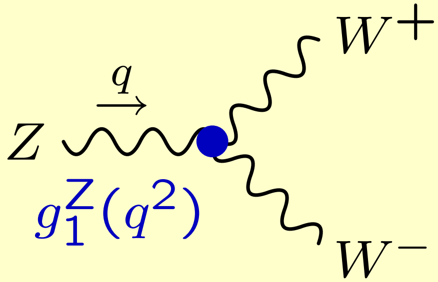
- Functional form of form factors is ad hoc/unknown
- Gauge invariance still violated

Unitarity constraints

Amplitudes with aGC grow $\propto E^2$

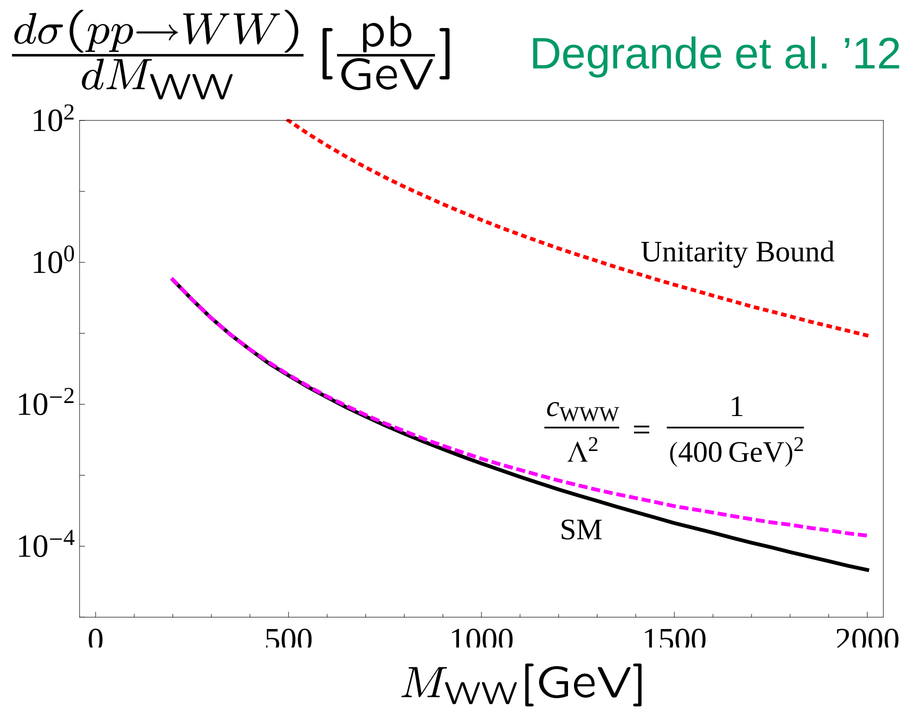
$\longrightarrow$ **Perturbative unitarity** violated

One approach: promote couplings to form factors



- Functional form of form factors is ad hoc/unknown
- Gauge invariance still violated

Effective theory:

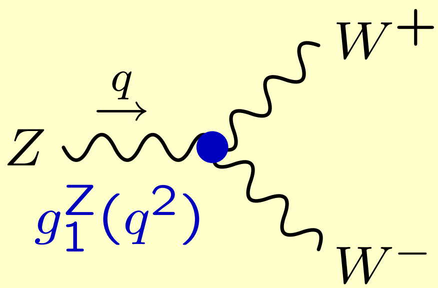


Unitarity constraints

Amplitudes with aGC grow $\propto E^2$

$\longrightarrow$ **Perturbative unitarity** violated

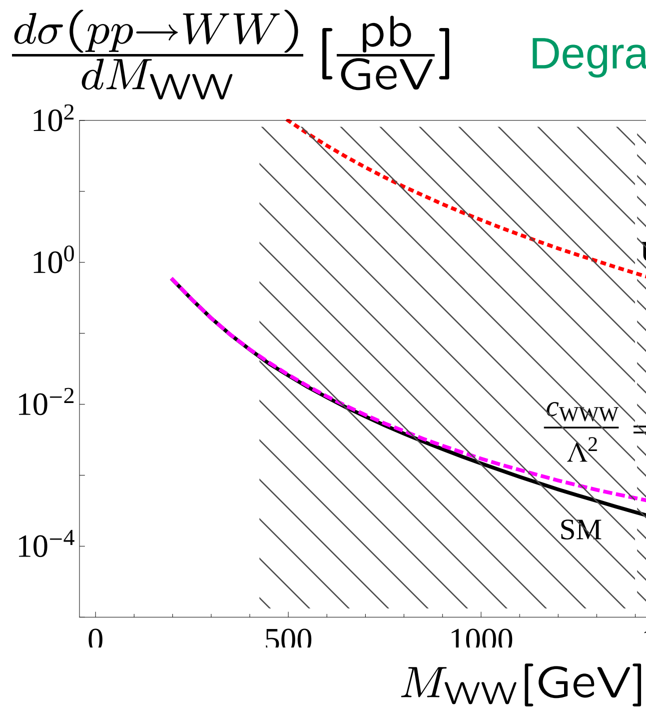
One approach: promote couplings to form factors



- Functional form of form factors is ad hoc/unknown
- Gauge invariance still violated

Effective theory:

Degrande et al. '12



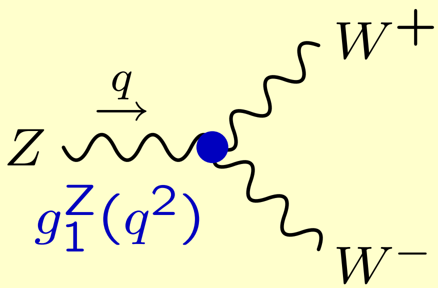
- $E \sim \Lambda$: Higher-dim. ($d = 8, ...$) operators become important

Unitarity constraints

Amplitudes with aGC grow $\propto E^2$

$\longrightarrow$ **Perturbative unitarity** violated

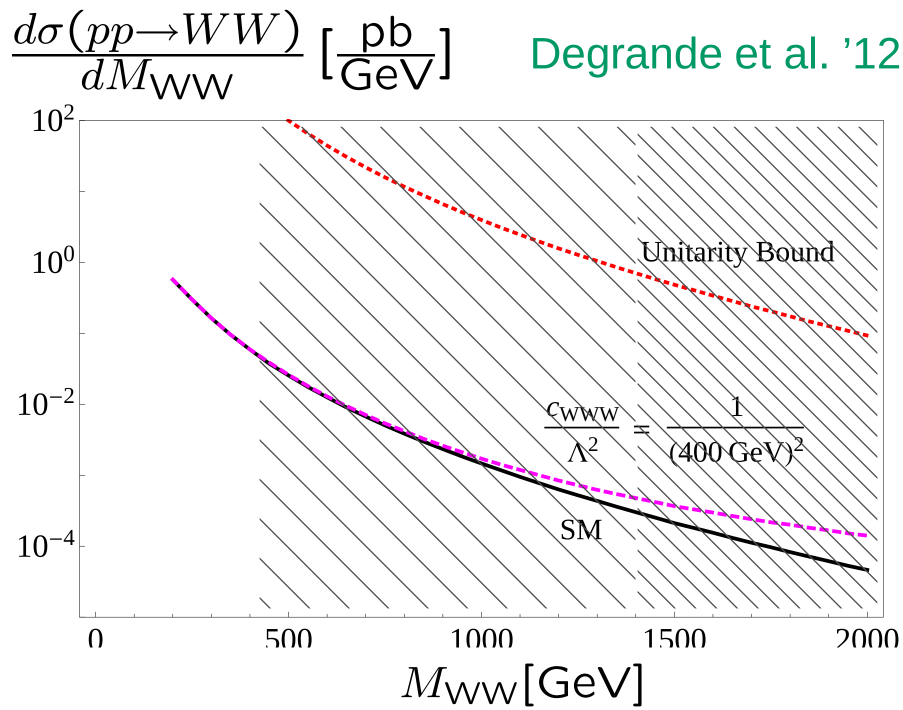
One approach: promote couplings to form factors



- Functional form of form factors is ad hoc/unknown
- Gauge invariance still violated

Effective theory:

Degrande et al. '12



- $E \sim \Lambda$: Higher-dim. ($d = 8, \ldots$) operators become important
- $E \gtrsim \Lambda$: New resonances, pair production thresholds, etc.
  $\longrightarrow$ EFT **and** aGC break down