TLEP:
Part of a Vision for the Future

Exploration of the 10 TeV scale

Direct (VHE-LHC) + Indirect (TLEP)

Need major effort to develop the physics case

Work together

John Ellis

King's College London

The Twin Pillars of TLEP Physics

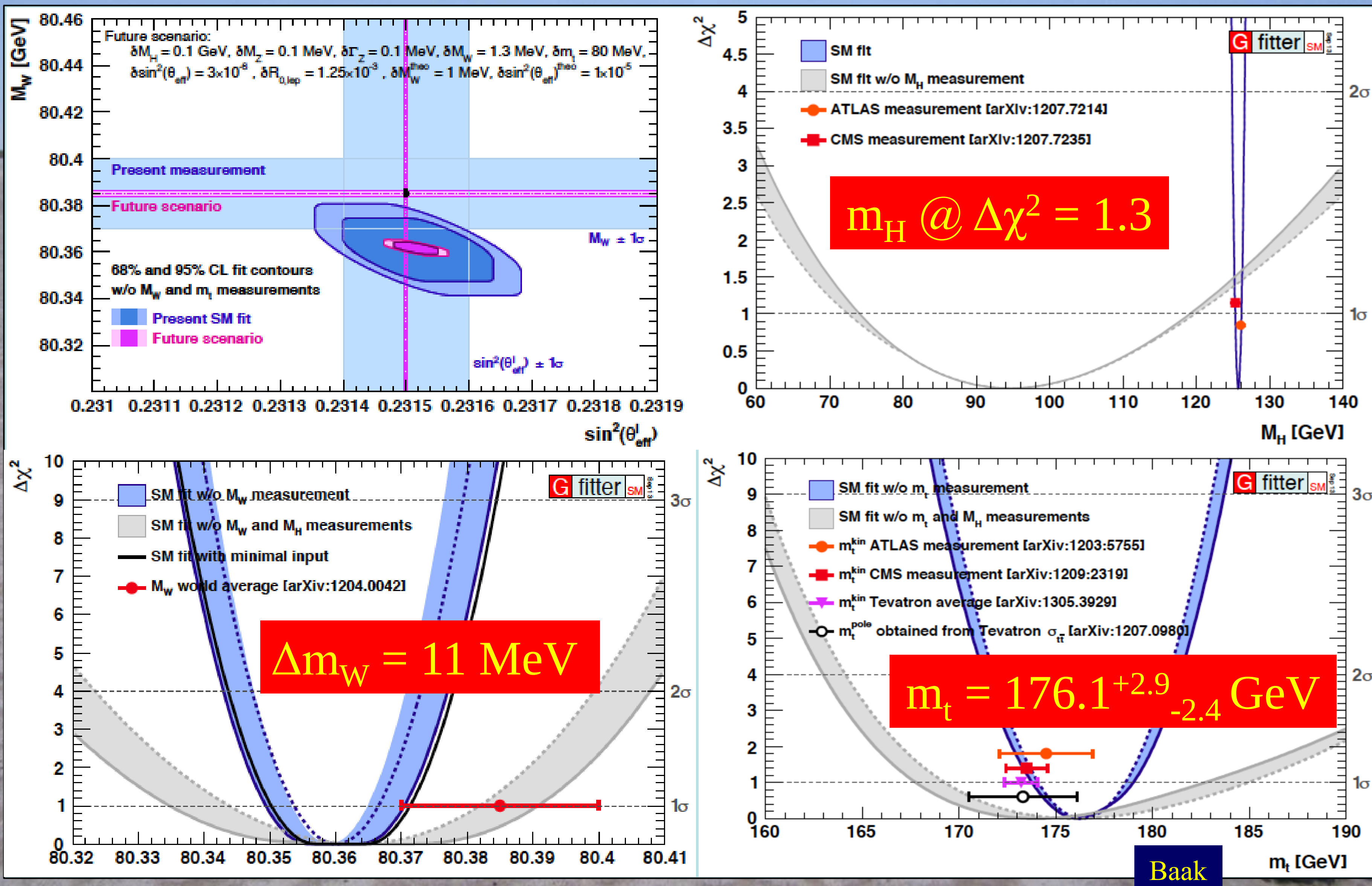
Precision Measurements

- Springboard for sensitivity to new physics
- Theoretical issues:
  - Higher-order QCD
  - Higher-order EW
  - Mixed QCD + EW
- Experimental issues
  - Patrick

Rare Decays

- Direct searches for new physics
- Many opportunities
- Z: 10^{12}
- b, c, τ: 10^{11}
- W: 10^{8}
- H: 10^{6}
- t: 10^{6}

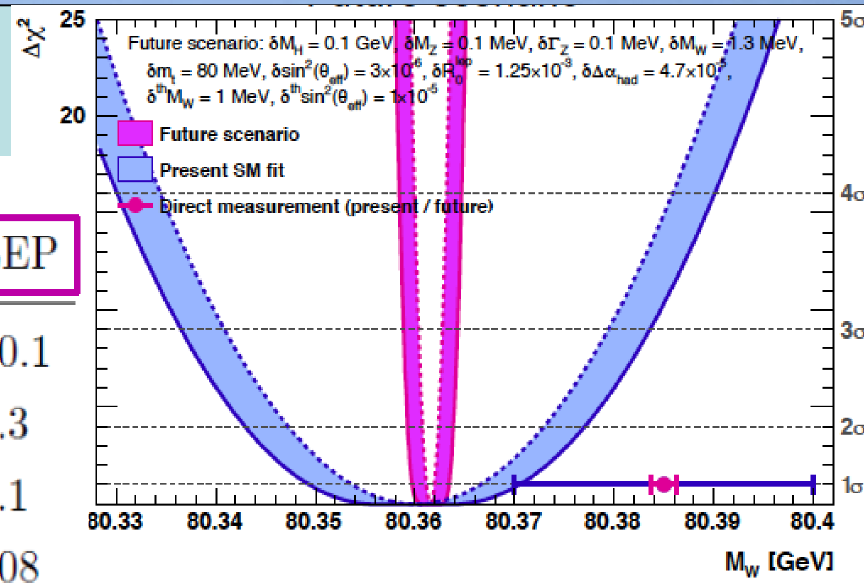
Present Predictions from Gfitter



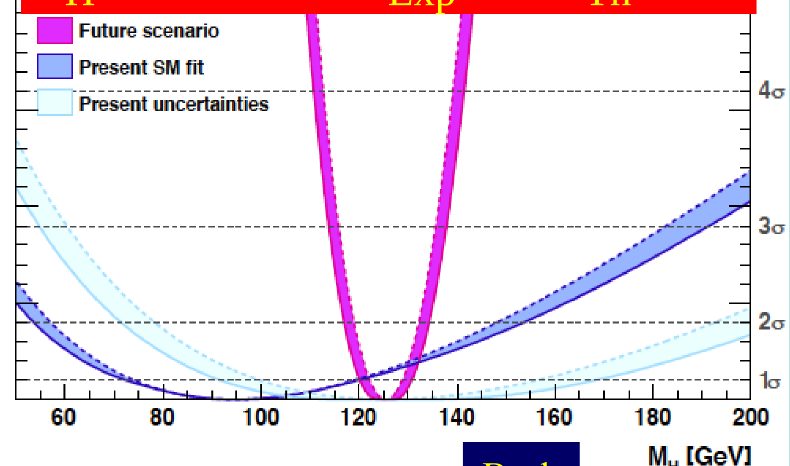
Future Predictions from Gfitter

- Assumed inputs

Parameter	Present		LHC		ILC/GigaZ		TLEP
	Experimental input $[\pm 1\sigma]$						
M_H [GeV]	0.4	⇨	< 0.1		< 0.1		< 0.1
M_W [MeV]	15	⇨	8	⇨	5	⇨	1.3
M_Z [MeV]	2.1		2.1		2.1	⇨	0.1
m_t [GeV]	0.9	⇨	0.6		0.1		0.08
Γ_Z [MeV]	2.3		2.3	⇨	0.8	⇨	0.1
$\sin^2\theta^\ell_{\rm eff}$ $[\cdot 10^{-5}]$	16		16	⇨	1.3	⇨	0.3
R^0_l $[\cdot 10^{-3}]$	25		25	⇨	4	⇨	1.3
$\Delta\alpha^5_{\rm had}(M^2_Z)$ $[\cdot 10^{-5}]$	10	⇨	4.7		4.7		4.7
$\alpha_S(M^2_Z)$ $[\cdot 10^{-4}]$	–		–		–		–
$\delta_{\rm th} M_W$ [MeV]	4	⇨	1		1		1
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $[\cdot 10^{-5}]$	4.7	⇨	1		1		1



$m_H = 126 \pm 3_{\rm Exp} \pm 4_{\rm Th}$ GeV



Baak

TLEP Measurements & New Physics

- Assumed future measurements

	Current data	before TLEP	TLEP-Z	TLEP-Z (pol.)	TLEP-W	TLEP-t
$\alpha_s(M_Z^2)$	0.1184 ± 0.0006	???				
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02750 ± 0.00033	± 0.00005 (?)				
M_Z [GeV]	91.1875 ± 0.0021		± 0.0001			
m_t [GeV]	173.2 ± 0.9	± 0.5 (?)				± 0.016
m_h [GeV]	125.6 ± 0.3	± 0.15 (?)				
M_W [GeV]	80.385 ± 0.015	± 0.010 (?)			± 0.00064	
Γ_W [GeV]	2.085 ± 0.042				???	
Γ_Z [GeV]	2.4952 ± 0.0023		± 0.0001			
σ_h^0 [nb]	41.540 ± 0.037		???			
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012		???			
$P_\tau^{\rm pol}$	0.1465 ± 0.0033		???			
$\mathcal{A}_\ell$	0.1513 ± 0.0021			± 0.000021		
$\mathcal{A}_c$	0.670 ± 0.027			???		
$\mathcal{A}_b$	0.923 ± 0.020			???		
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010		???			
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035		???			
$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016		???			
R_ℓ^0	20.767 ± 0.025		± 0.001			
R_c^0	0.1721 ± 0.0030		???			
R_b^0	0.21629 ± 0.00066		± 0.00006			

Theoretical Uncertanties

- We assume that theoretical uncertainties will be reduced by calculating three-loop contributions of $O(\alpha^2\alpha_s)$ and $O(\alpha^3)$.

	TLEP	Parametric uncertainty						Theoretical uncertainty	
	direct	α_s	$\Delta\alpha^{(5)}_{\rm had}$	M_Z	m_t	m_h	Total	current	future
δM_W [MeV]	±0.64	±0.36	±0.91	±0.13	±0.10	±0.14	±1.00	±4	±1
$\delta\Gamma_Z$ [MeV]	±0.1	±0.3	±0.0	±0.0	±0.0	±0.0	±0.3	±0.5	±0.1
$\delta\mathcal{A}_\ell$ $[10^{-5}]$	±2.1	±1.6	±13.7	±0.6	±0.4	±0.9	±13.9	±37.0	±11.8

$$\delta\sin^2\theta^{\rm lept}_{\rm eff} = 4.7\times10^{-5} \rightarrow 1.5\times10^{-5}$$

- Hadronic contribution to α:

At present: $\Delta\alpha^{(5)}_{\rm had}(M_Z^2) = 0.02750 \pm 0.00033$

Burkhardt & Pietrzyk (11)
(see also Davier et al(11);
Hagiwara et al(11) ; Jegerlehner(11))

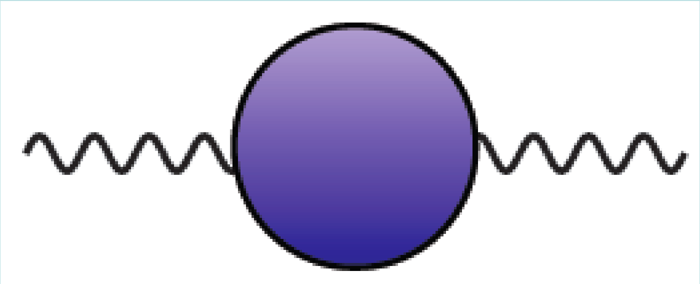
measured with inclusive processes.

smaller uncertainty (~ 0.00010) if using exclusive processes with pQCD, etc.

⇨ assume $\delta(\Delta\alpha^{(5)}_{\rm had}(M_Z^2)) \sim 0.00005$ from low-energy exp's

Sensitivity to New Physics

- Oblique Parameters
- (vacuum polarizations)



$$\delta M_W,\ \delta\Gamma_W \propto -S + 2c_W^2\, T + \frac{(c_W^2 - s_W^2)\, U}{2s_W^2}$$

$$\delta\Gamma_Z \propto -10(3 - 8s_W^2)\, S + (63 - 126s_W^2 - 40s_W^4)\, T$$

$$\text{others} \propto S - 4c_W^2 s_W^2\, T$$

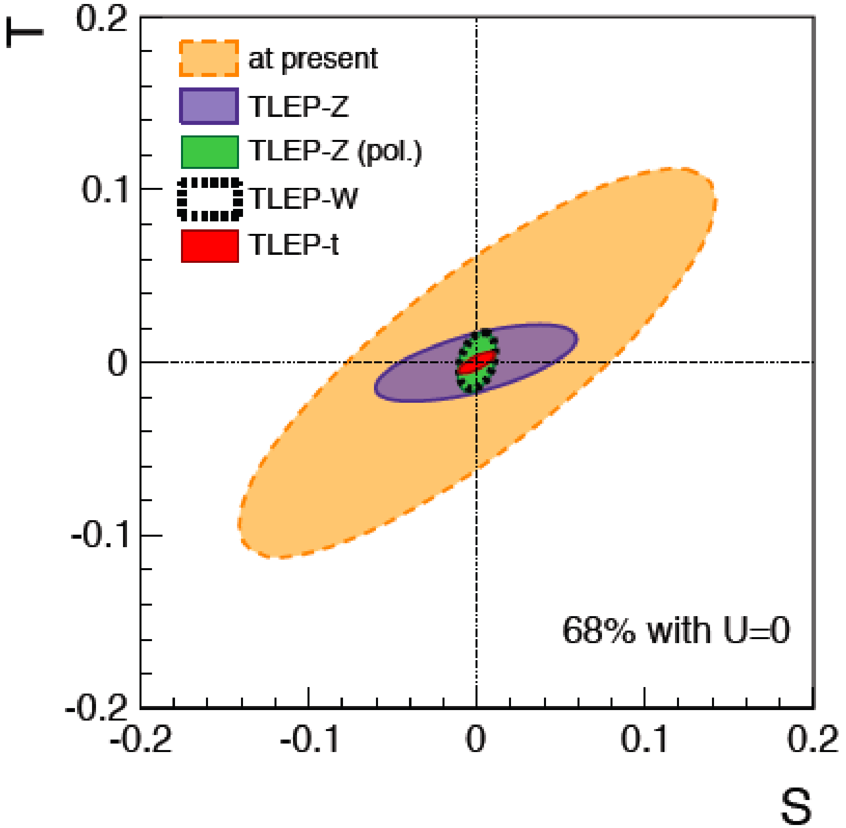
- Expect U << S, T
- Will need effort to reduce theoretical uncertainties to realize sensitivities < 10^{-2}

Mishima

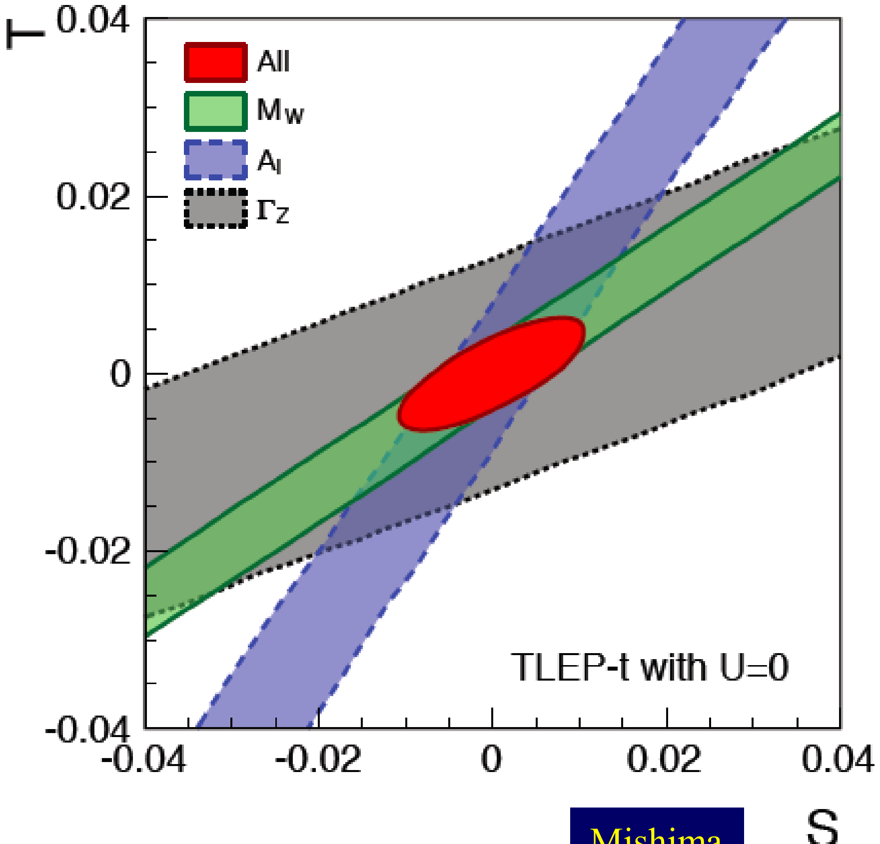
Sensitivity to Oblique Parameters

$$\delta S \sim 7 \times 10^{-3}, \qquad \delta T \sim 4 \times 10^{-3}$$

SM scenario



Contributions to fit



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Sensitivity to New Physics

- Higher-dimensional operators induced by high-E physics

$$\mathcal{O}_{WB} = (H^\dagger \tau^a H) W^a_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{H} = |H^\dagger D_\mu H|^2$$

$$\mathcal{O}_{LL} = \frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$$

$$\mathcal{O}'_{HL} = i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma^\mu \tau^a L)$$

$$\mathcal{O}'_{HQ} = i(H^\dagger D_\mu \tau^a H)(\bar{Q}\gamma^\mu \tau^a Q)$$

$$\mathcal{O}_{HL} = i(H^\dagger D_\mu H)(\bar{L}\gamma^\mu L)$$

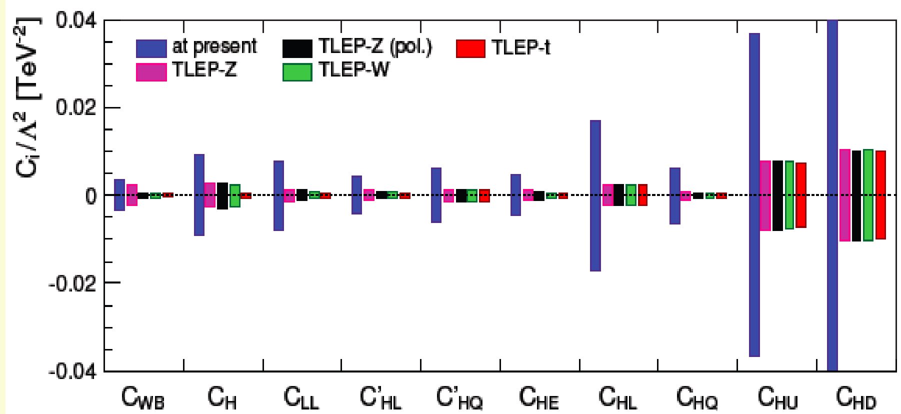
$$\mathcal{O}_{HQ} = i(H^\dagger D_\mu H)(\bar{Q}\gamma^\mu Q)$$

$$\mathcal{O}_{HE} = i(H^\dagger D_\mu H)(\bar{E}\gamma^\mu E)$$

$$\mathcal{O}_{HU} = i(H^\dagger D_\mu H)(\bar{U}\gamma^\mu U)$$

$$\mathcal{O}_{HD} = i(H^\dagger D_\mu H)(\bar{D}\gamma^\mu D)$$

SM scenario



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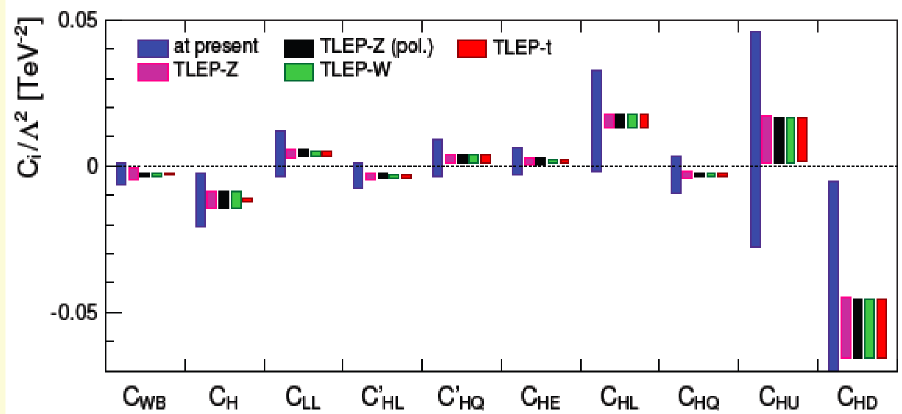
NP scenario



Sensitivity to New Physics

- Sensitivity to coefficients of possible higher-dimensional operators induced by high-E physics

  (in TeV units)

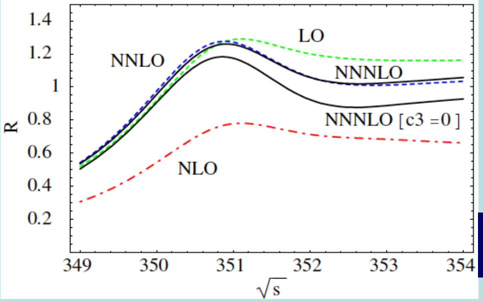
Coefficient	at present $C_i=-1$	at present $C_i=1$	TLEP-Z $C_i=-1$	TLEP-Z $C_i=1$	TLEP-Z (pol.) $C_i=-1$	TLEP-Z (pol.) $C_i=1$	TLEP-W $C_i=-1$	TLEP-W $C_i=1$	TLEP-t $C_i=-1$	TLEP-t $C_i=1$
C_{WB}	12.0	12.0	15.2	15.2	31.3	31.1	31.3	31.5	38.3	38.9
C_H	7.4	7.4	13.6	13.6	13.9	13.7	14.0	14.1	27.9	27.8
C_{LL}	8.1	8.1	19.3	19.3	19.9	19.9	25.4	25.5	27.6	27.7
C'_{HL}	10.9	10.9	21.2	21.1	25.9	25.7	25.8	25.8	31.2	30.9
C'_{HQ}	9.0	9.1	19.5	19.3	19.5	19.4	19.4	19.2	19.6	19.6
C_{HL}	10.4	10.4	21.5	21.5	21.5	21.9	28.6	28.5	28.3	28.4
C_{HQ}	5.4	5.5	14.9	14.9	15.0	14.9	15.1	15.0	15.0	15.0
C_{HE}	8.9	8.9	22.2	22.2	30.2	30.0	30.1	30.3	31.2	31.2
C_{HU}	3.7	3.7	8.0	8.0	8.1	8.1	8.1	8.1	8.3	8.3
C_{HD}	3.2	3.2	7.1	7.0	7.1	7.1	7.0	7.1	7.1	7.1

- Substantial improvement in sensitivity
- Reach well into multi-TeV range

Mishima

(Mainly) QCD Uncertainties

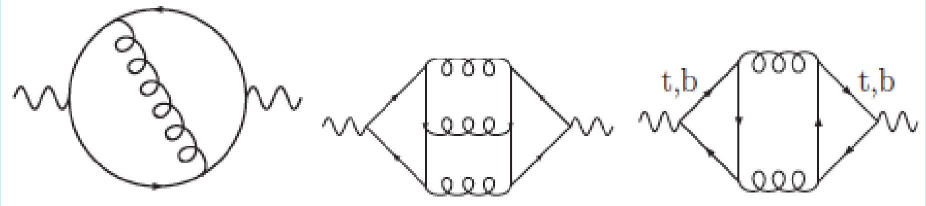
- Γ_b: Higgs WG: $\Delta\Gamma_b$ = ~~7.5%~~ should be 1.7%
  - Higher-order QCD 0.25%
  - m_b uncertainty overstated by factor 4
  - Error could be reduced by running SuperKEK-B above Υ
  - 5-loop running underway
  - Need inputs from LE: m_b, m_c, α_{EM}, α_s
  - 0.3% possible
- M_W:
  - 4-loop uncertainty of 2.1 MeV insufficient: use $\overline{MS}$ m_t
  - Could do 4-loop mixed EW/QCD
- m_t:
  - calculation of σ at NNNLO underway



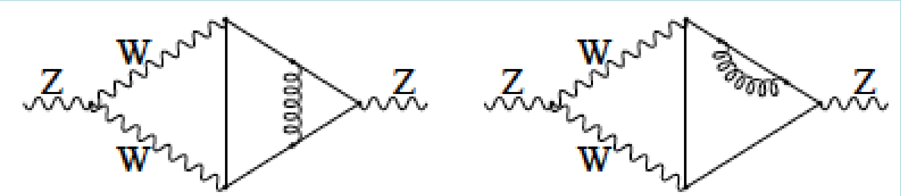
Kuehn

(Mainly) QCD Uncertainties

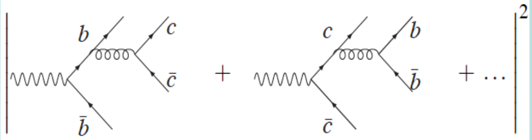
- Γ_Z:



  - Δ(non-singlet) = 101 KeV
  - Δ(singlet) V (3g) = 2.7 KeV, A (2g) = 42 KeV
  - Difficult to do next order



- Γ_b:
  - Correction @ $G_F m_t^2 \alpha_s^2$ = 0.1 MeV
  - Smaller corrections if use MSbar m_t, but need to know 4-loop conversion (underway)
  - Not well-defined at higher order: $b\bar{b}c\bar{c}$ final states!

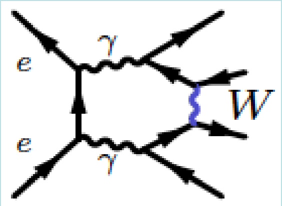


- Γ_W:
  - Mixed EW/QCD calculated @ 2-loop: – 0.55 MeV
  - 3-loop $\alpha_W \alpha_s^2$ difficult but feasible

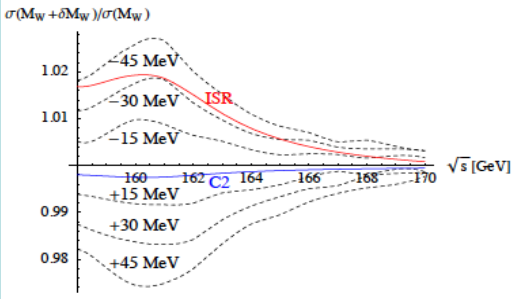
Kuehn

WW Production at Threshold

- Aim at $\Delta m_W < 1$ MeV: need $\Delta\sigma << 0.1\%$
- Current $\Delta m_W < 4$ MeV
  - Should make off-shell treatment:



  - 4-fermion production known @ NLO and leading NNLO



  - Threshold corrections included
  - Need more understanding of ISR
  - NNLO EW calculation of on-shell WW within reach
  - Sufficient for $\Delta m_W < 1$ MeV
  - NNLO off-shell calculation beyond current reach

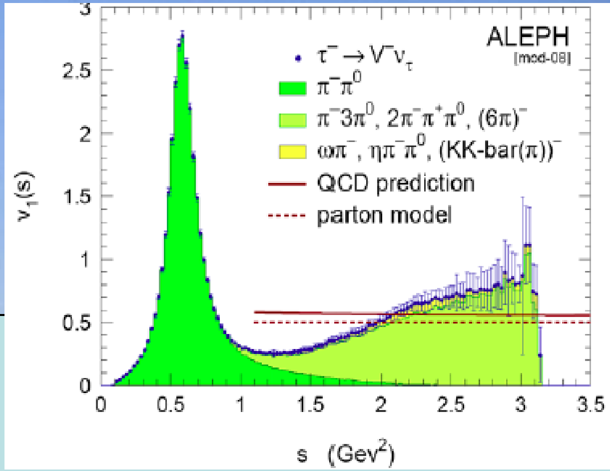
Schwinn

High-Energy Measurements of α_s

- TLEP study quotes $\Delta\alpha_s = 0.0002$ from Z decays based on NNNLO calculation
- W decays could yield $\Delta\alpha_s = 0.00015$?
- Important CKM uncertainty, mainly due to ΔV_{cs}
  - Assume unitarity? Measure V_{cs} better?
- Possible strategy: Use Z value @ W to measure V, use @ τ to constrain non-perturbative effects
- Need to study uncertainty in running

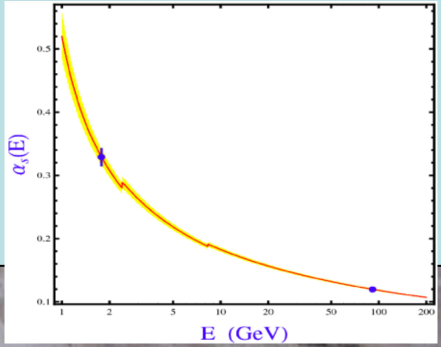
Dissertori

Measurement of α_s in τ Decays



- LEP data still dominate τ analyses
  - Systematic uncertainties at B factories
- Assume charged-current universality OK, but check W to $\tau\nu/\mu\nu$
- QCD predicts moments of spectral function
  - Expect small non-perturbative piece, can be fitted from data
- 2 ways of summing QCD give estimate of error:

  $\alpha_s(m_\tau) = 0.339$ vs 0.318, $\alpha_s(m_Z) = 0.1210$ vs 0.1198
- Uncertainty due to running: c threshold!



Pich

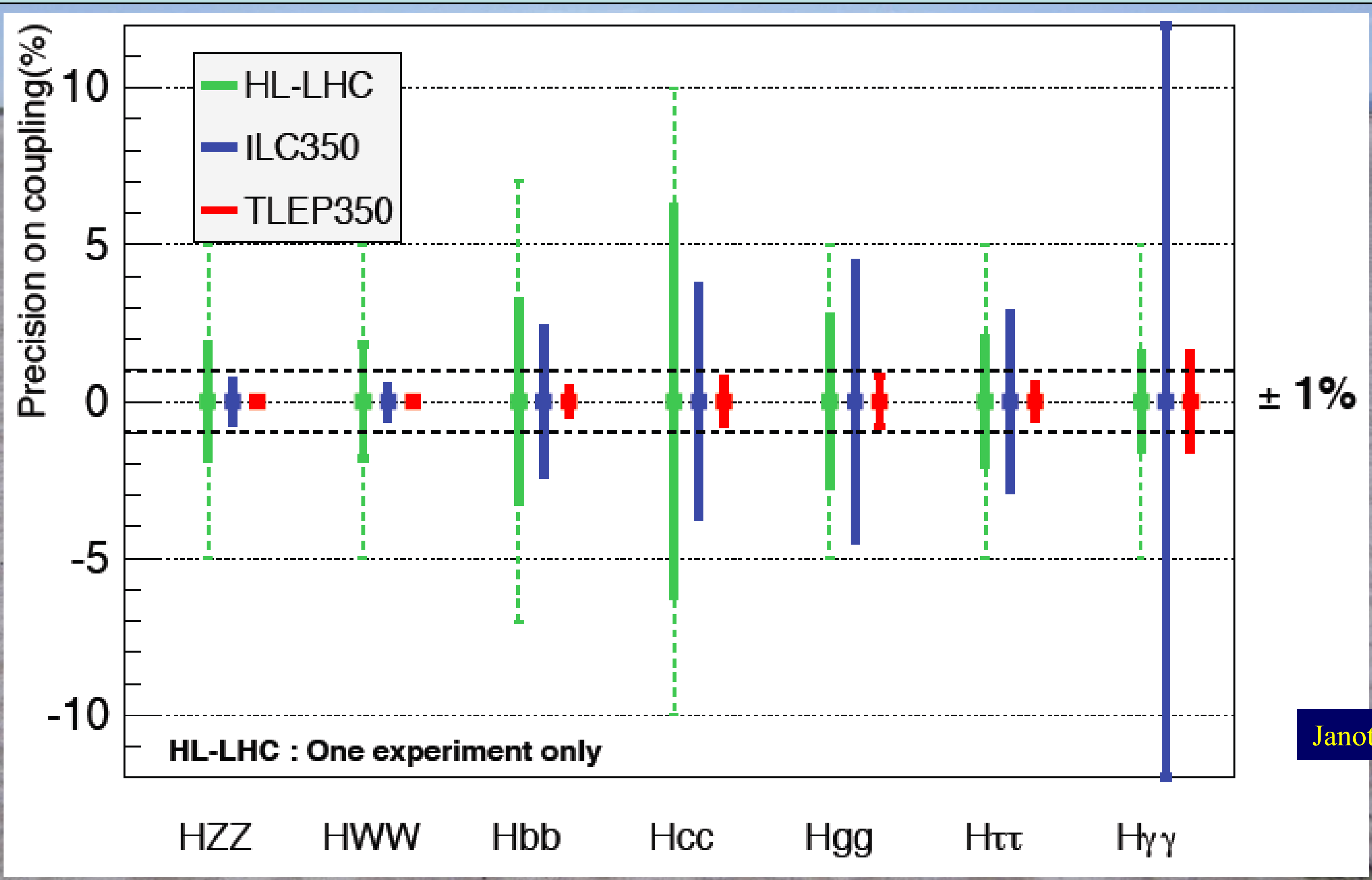
Possible Future Higgs Measurements

Facility		ILC		ILC(LumiUp)	TLEP (4 IP)			CLIC	
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	$< 0.9\%$	$< 0.9\%$	0.4%	0.19%	$< 0.19\%$			

- Interpretation?
- Theoretical uncertainties and new physics interpretations

Janot

Possible Future Higgs Measurements

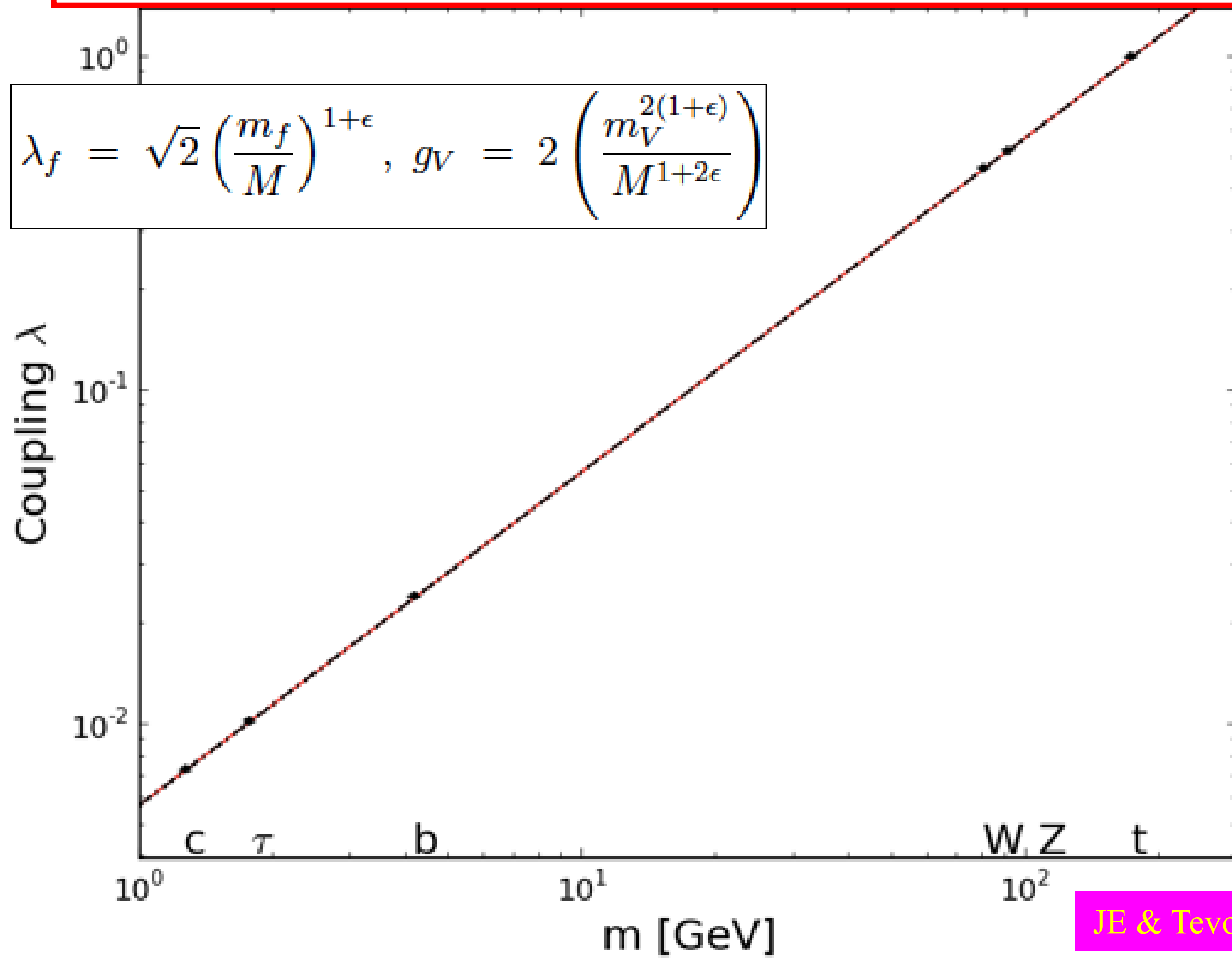


Janot

H Coupling Measurements @TLEP

M = 246.0 ± 0.8 GeV, $\varepsilon = 0.0000^{+0.0015}_{-0.0010}$

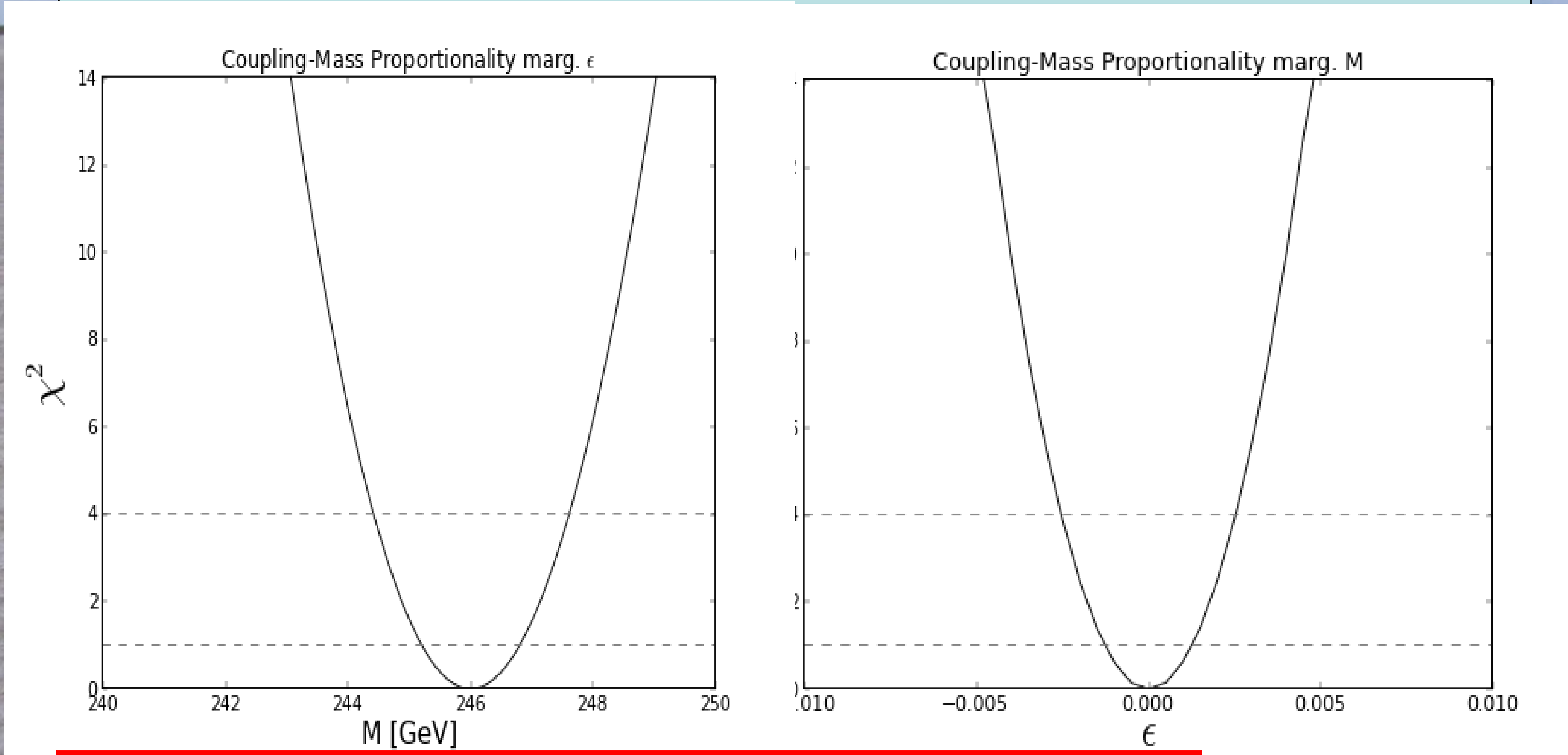
$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$



JE & Tevong You

Global Analysis of Higgs @ TLEP

- One-dimensional χ^2 for M, ε



$M = 246.0 \pm 0.8$ GeV, $\varepsilon = 0.0000^{+0.0015}_{-0.0010}$

JE & Tevong You

Rare Leptonic Z Decays?

Silvestrini

- Upper limits from flavour-changing neutral currents (FCNC)
  - Current and future bounds on LFV μ and τ decays:
    - $BR(\mu \to eee) < 10^{-12}$
    - $BR(\tau \to \mu\mu\mu) < 2\ 10^{-8}\ (10^{-9})$
    - $BR(\tau \to eee) < 3\ 10^{-8}\ (10^{-9})$
  - These bounds imply:
    - $BR(Z \to \mu e) < 3\ 10^{-13}$
    - $BR(Z \to \tau\mu) < 4\ 10^{-8}\ (2\ 10^{-9})$
    - $BR(Z \to \tau e) < 6\ 10^{-8}\ (2\ 10^{-9})$

Opportunities

- Measuring $BR(Z \to \tau e)$ & $BR(Z \to \tau\mu)$ better than 10^{-9} would overcome future bounds on LFV decays

Rare Hadronic Z Decays?

Silvestrini

- Upper limits from flavour-changing neutral currents (FCNC)
- From present expts in B physics one gets

$|U_{bs}|$ <~ 4 10^{-4} and $|U_{bd}|$ <~ 10^{-4} Buras et al.

$\Rightarrow$ BR($Z \rightarrow bd$) <~ 10^{-9}, BR($Z \rightarrow bs$) <~ 2 10^{-8}

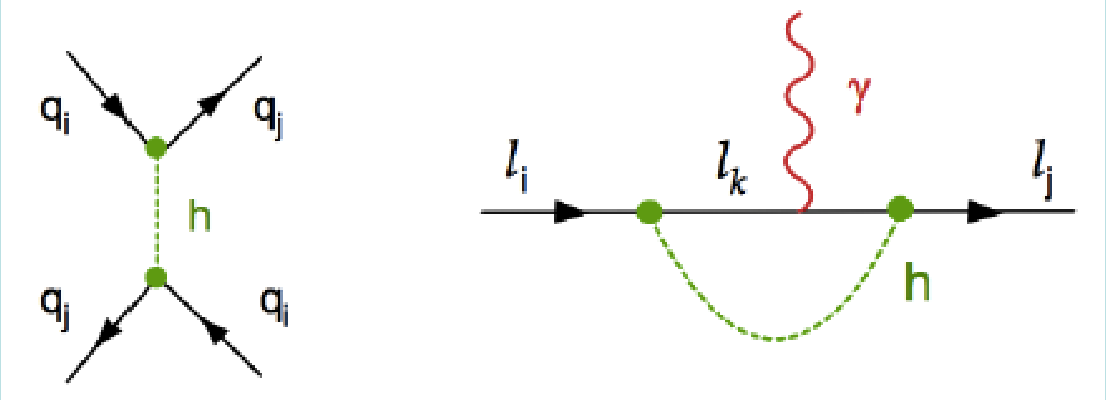
- How far can TLEP go? How will b id perform?
- From D mixing one gets $|U_{uc}|$ < ~2 10^{-3}

$\Rightarrow$ BR($Z \rightarrow cu$) <~ 5 10^{-7}

Opportunities

Rare Higgs Decays?

- Upper limits from FCNC, EDMs, …



- Quark FCNC bounds exclude observability of quark-flavour-violating *h* decays
- Lepton-flavour-violating *h* decays could be large:

BR(τμ) or BR(τe) could be O(10)%

Blankenburg, JE, Isidori: arXiv:1202.5704

BR(μe) must be $< 2 \times 10^{-5}$

Flavour-Changing Higgs Couplings?

- Constraints on quark-flavour-changing couplings from FCNC

Operator	Eff. couplings	95% C.L. Bound $\lvert c_{\text{eff}}\rvert$	95% C.L. Bound $\lvert\text{Im}(c_{\text{eff}})\rvert$	Observables
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	$c_{sd}\, c^*_{ds}$	1.1×10^{-10}	4.1×10^{-13}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R d_L)^2,\ (\bar{s}_L d_R)^2$	$c^2_{ds},\ c^2_{sd}$	2.2×10^{-10}	0.8×10^{-12}	
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	$c_{cu}\, c^*_{uc}$	0.9×10^{-9}	1.7×10^{-10}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R u_L)^2,\ (\bar{c}_L u_R)^2$	$c^2_{uc},\ c^2_{cu}$	1.4×10^{-9}	2.5×10^{-10}	
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	$c_{bd}\, c^*_{db}$	0.9×10^{-8}	2.7×10^{-9}	$\Delta m_{B_d};\ S_{B_d \to \psi K}$
$(\bar{b}_R d_L)^2,\ (\bar{b}_L d_R)^2$	$c^2_{db},\ c^2_{bd}$	1.0×10^{-8}	3.0×10^{-9}	
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	$c_{bs}\, c^*_{sb}$	2.0×10^{-7}	2.0×10^{-7}	Δm_{B_s}
$(\bar{b}_R s_L)^2,\ (\bar{b}_L s_R)^2$	$c^2_{sb},\ c^2_{bs}$	2.2×10^{-7}	2.2×10^{-7}	

Eff. couplings	Bound	Constraint
$\lvert c_{sb}\rvert^2,\ \lvert c_{bs}\rvert^2$	2.9×10^{-5}	$\mathcal{B}(B_s \to \mu^+\mu^-) < 1.4 \times 10^{-8}$
$\lvert c_{db}\rvert^2,\ \lvert c_{bd}\rvert^2$	1.3×10^{-5}	$\mathcal{B}(B_d \to \mu^+\mu^-) < 3.2 \times 10^{-9}$

Blankenburg, JE, Isidori: arXiv:1202.5704

- Constraints on lepton-flavour-changing couplings

Operator	Eff. couplings	Bound	Constraint
$(\bar{\mu}_R e_L)(\bar{q}_L q_R),\ (\bar{\mu}_L e_R)(\bar{q}_L q_R)$	$\lvert c_{\mu e}\rvert^2,\ \lvert c_{e\mu}\rvert^2$	3.0×10^{-8}	$\mathcal{B}_{\mu \to e}(\text{Ti}) < 4.3 \times 10^{-12}$
$(\bar{\tau}_R \mu_L)(\bar{\mu}_L \mu_R),\ (\bar{\tau}_L \mu_R)(\bar{\mu}_L \mu_R)$	$\lvert c_{\tau\mu}\rvert^2,\ \lvert c_{\mu\tau}\rvert^2$	2.0×10^{-1}	$\Gamma(\tau \to \mu\bar{\mu}\mu) < 2.1 \times 10^{-8}$
$(\bar{\tau}_R e_L)(\bar{\mu}_L \mu_R),\ (\bar{\tau}_L e_R)(\bar{\mu}_L \mu_R)$	$\lvert c_{\tau e}\rvert^2,\ \lvert c_{e\tau}\rvert^2$	4.8×10^{-1}	$\Gamma(\tau \to e\bar{\mu}\mu) < 2.7 \times 10^{-8}$
$(\bar{\tau}_R e_L)(\bar{\mu}_L e_R),\ (\bar{\tau}_L e_R)(\bar{\mu}_L e_R)$	$\lvert c_{\mu e} c^*_{e\tau}\rvert,\ \lvert c_{\mu e} c_{\tau e}\rvert$	0.9×10^{-4}	$\Gamma(\tau \to \bar{\mu} e e) < 1.5 \times 10^{-8}$
$(\bar{\tau}_R e_L)(\bar{\mu}_R e_L),\ (\bar{\tau}_L e_R)(\bar{\mu}_R e_L)$	$\lvert c^*_{e\mu} c^*_{e\tau}\rvert,\ \lvert c^*_{e\mu} c_{\tau e}\rvert$		
$(\bar{\tau}_R \mu_L)(\bar{e}_L \mu_R),\ (\bar{\tau}_L \mu_R)(\bar{e}_L \mu_R)$	$\lvert c_{e\mu} c^*_{\mu\tau}\rvert,\ \lvert c_{e\mu} c_{\tau\mu}\rvert$	1.0×10^{-4}	$\Gamma(\tau \to \bar{e}\mu\mu) < 1.7 \times 10^{-8}$
$(\bar{\tau}_R \mu_L)(\bar{e}_R \mu_L),\ (\bar{\tau}_L \mu_R)(\bar{e}_R \mu_L)$	$\lvert c^*_{\mu e} c^*_{\mu\tau}\rvert,\ \lvert c^*_{\mu e} c_{\tau\mu}\rvert$		

Eff. couplings		Bound		Constraint
$\lvert c_{e\tau} c_{\tau e}\rvert$	$(\lvert c_{e\mu} c_{\mu e}\rvert)$	1.1×10^{-2}	(1.8×10^{-1})	$\lvert\delta m_e\rvert < m_e$
$\lvert\text{Re}(c_{e\tau} c_{\tau e})\rvert$	$(\lvert\text{Re}(c_{e\mu} c_{\mu e})\rvert)$	0.8×10^{-2}	(1.4×10^{-1})	$\lvert\delta a_e\rvert < 6 \times 10^{-12}$
$\lvert\text{Im}(c_{e\tau} c_{\tau e})\rvert$	$(\lvert\text{Im}(c_{e\mu} c_{\mu e})\rvert)$	1.1×10^{-7}	(1.9×10^{-6})	$\lvert d_e\rvert < 1.6 \times 10^{-27}$ ecm
$\lvert c_{\mu\tau} c_{\tau\mu}\rvert$		2		$\lvert\delta m_\mu\rvert < m_\mu$
$\lvert\text{Re}(c_{\mu\tau} c_{\tau\mu})\rvert$		2×10^{-2}		$\lvert\delta a_\mu\rvert < 4 \times 10^{-9}$
$\lvert\text{Im}(c_{\mu\tau} c_{\tau\mu})\rvert$		8		$\lvert d_\mu\rvert < 1.2 \times 10^{-19}$ ecm
$\lvert c_{e\tau} c_{\tau\mu}\rvert,\ \lvert c_{\tau e} c_{\mu\tau}\rvert$		2.4×10^{-6}		$\mathcal{B}(\mu \to e\gamma) < 2.4 \times 10^{-12}$
$\lvert c_{\mu\tau}\rvert^2,\ \lvert c_{\tau\mu}\rvert^2$		6.6×10^{-1}		$\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$
$\lvert c_{e\tau}\rvert^2,\ \lvert c^*_{\tau e}\rvert^2$		4.7×10^{-1}		$\mathcal{B}(\tau \to e\gamma) < 3.3 \times 10^{-8}$

Neutrino Counting?

Blondel

- Z line shape
- Jarlskog's theorem

Theorem.

In the standard model, with n left-handed lepton doublets and $N-n$ right-handed neutrinos, the effective number of neutrinos, $\langle n \rangle$, defined by

$$\Gamma(Z \to \text{neutrinos}) \equiv \langle n \rangle \Gamma_0 ,$$

where Γ_0 is the standard width for one massless neutrino, satisfies the inequality

$$\langle n \rangle \leqslant n . \qquad (15)$$

"Neutrino Counting"

Blondel

- **On Z peak:** $N_\nu = 2.984 \pm 0.008$
  - -2σ :^) !!
- Error ΔN_ν dominated by ΔL, theory dominated:
- Bhabha uncertainty $\pm$ 0.0046
- Building blocks available to bring perturbative error < 0.1%
- **Radiative return:** $N_\nu = 2.92 \pm 0.05$

Piccinini

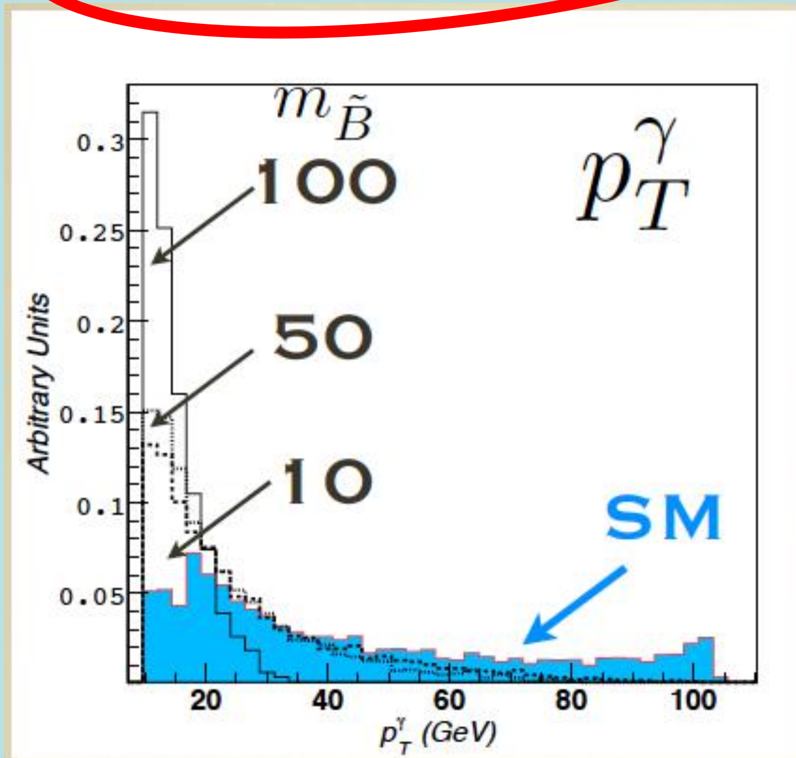
- EW corrections!
- Useful to study WWγ vertex: EW NLO

Direct Searches for New Particles?

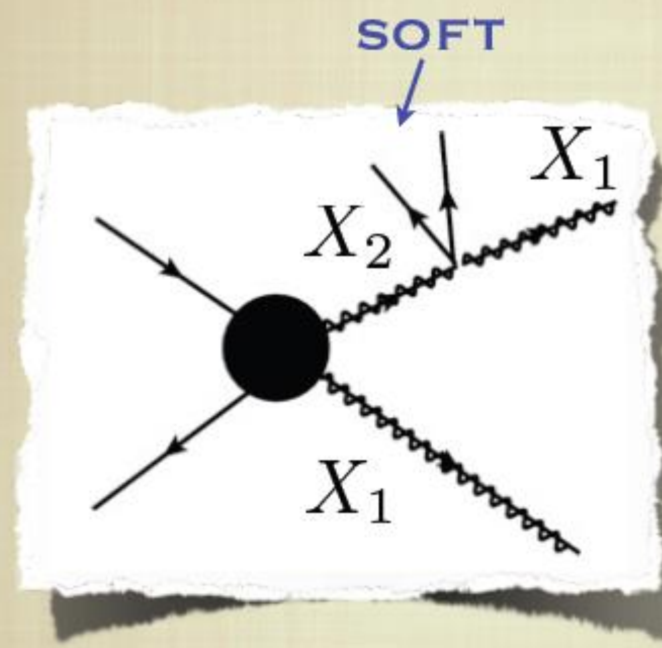
Sanz

- Best chance may be pair-production of dark matter particles + soft γ, …
- Way to get "$N_\nu > 3$"

Compressed spectra

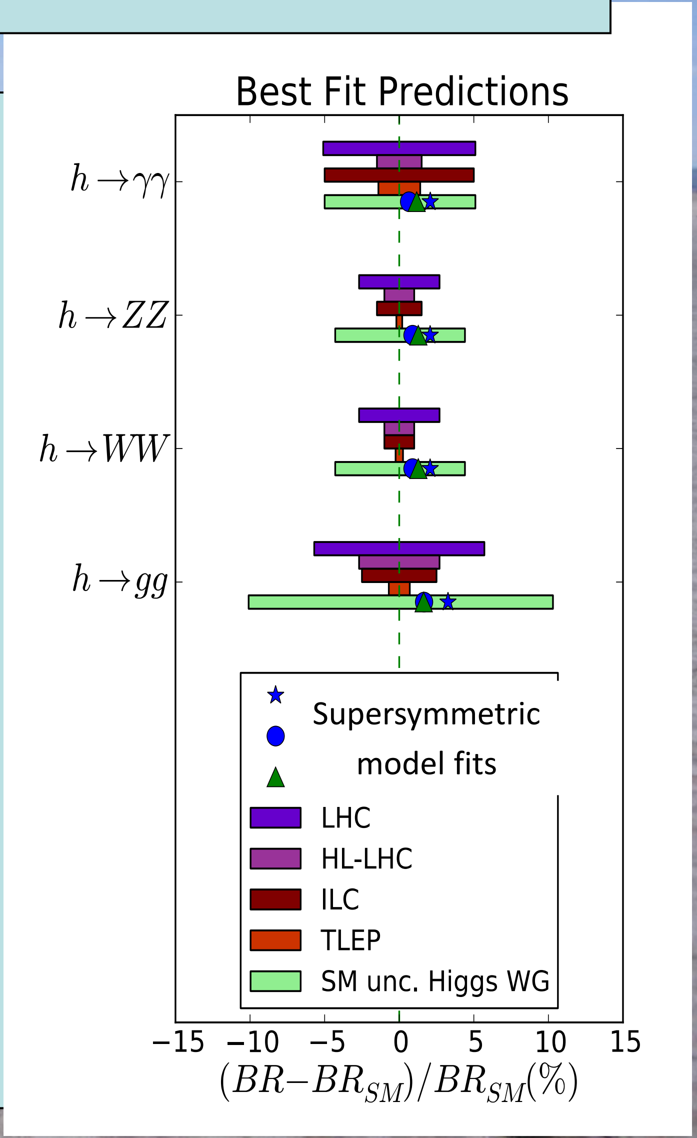


$$\Delta m = m_{X_2} - m_{X_1} \ll m_{X_1}$$



Impact of Higgs Measurements

- Predictions of current best fits in simple SUSY models
- Current uncertainties in SM calculations [LHC Higgs WG]
- Comparisons with
  - **LHC**
  - **HL-LHC**
  - **ILC**
  - **TLEP**
- **Don't decide before LHC 13/4**



cf, LEP and LHC

- *"Those who don't know history are doomed to repeat it…"*
  - Edmund Burke
- *"… and maybe also those who do."*
- LEP: Precision Z studies ✔, W+W-, search for Higgs ✖, anything else
- LHC: search for Higgs ✔, anything else
- **Do not decide anything until LHC 13/4**