The Quest for Precision

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Contents

Introduction

- The Standard Model (SM) is tested at all energy scales up to the electroweak scale
  - Static quantities: electric and magnetic dipole moments: $\mu \approx 0$
  - light quark decays: π and K $\mu \approx \Lambda_{\rm QCD}$
  - Charm quark physics $\mu \approx m_c$
  - Bottom quark physics $\mu \approx m_b$
  - Top and Weak boson physics $\mu \approx m_t, M_W, M_Z$
  - Higgs Physics $\mu \approx v_{\rm ewk}$
  - Physics beyond the SM $\mu \approx \Lambda_{\rm BSM}$
- Disparate mass scales: Use Effective Field Theories
- SM: Leading term of Effective-Theory expansion

LHC at the Crossroads:

LHC after the Higgs Discovery is at the Crossroads

- Scenario 1: LHC Discovers plenty of new particles
  - "On shell" production of new particles
  - Study their decays, infer their properties
  - Construct the BSM theory
- Scenario 2: LHC discovers no new particles
  - Detailed study of the Higgs and the top quark
  - Other measurements involving the SM particles, QCD
  - Precision measurements of SM processes
- Scenario 1 is "easier",
  but there are no indications for this.

Scenario 2 puts LHC in the same situation as the low-energy experiments:

- The scales of BSM physics are far larger than the scales of the experiments
- BSM search is necessary indirect, no "on-shell" new physics
- The sensitivity to high scales depends crucially on precision, thus

$\boxed{\text{The Quest for Precision}}$

„, at all scales we can reach!

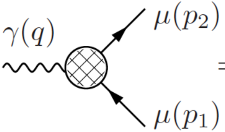
"Traditional" Precision Experiments

"Traditional" Precision Experiments

- Static quantities:
  Electric and magnetic dipole moments
- Michel Parameter Analyses in $\mu \to e\nu\bar{\nu}$
- Lepton Flavour Violation

Static Quantities: Magnetic Dipole Moments

- Coupling of a photon to a spin-1/2 fermion

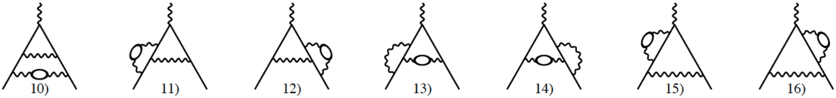


$$= (-\mathrm{i}e)\,\bar{u}(p_2)\left[\gamma^\mu F_{\mathrm{E}}(q^2) + \mathrm{i}\frac{\sigma^{\mu\nu}q_\nu}{2m_\mu}F_{\mathrm{M}}(q^2)\right]u(p_1)$$

- Magnetic moment is for $q^2 \to 0$: g factor

$$\vec{\mu} = g\frac{e}{2m}\vec{s}\,, \quad g = 2(1+a)\,, \quad F_M(0) = a$$

- a: Anomalous magnetic moment Feynman Diagrams:

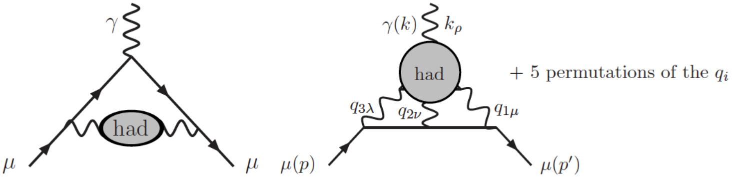


QED Contributions (Jegerlehner 2009)

C_i		$a_\mu^{(2i)\ \mathrm{QED}} \times 10^{11}$	
C_1	0.5	$a^{(2)}$	116140973.289(43)
C_2	0.765 857 410 (27)	$a^{(4)}$	413217.620(14)
C_3	24.050 509 64 (46)	$a^{(6)}$	30141.902(1)
C_4	130.8105(85)	$a^{(8)}$	380.807(25)
C_5	663.0(20.0)(4.6)	$a^{(10)}$	4.483(135)(31)

$$\boxed{a_\mu^{(\mathrm{QED})} = 116584718.104 \times 10^{-11}}$$

- Stumbling Block: Hadronic contributions



- Nonperturbative, can partially be taken from data

$$a_\mu^{(4,\mathrm{vap,had})} = (6903.0 \pm 52.6) \times 10^{-11}$$
$$a_\mu^{(6,\mathrm{vap,had})} = (-100.3 \pm 1.1) \times 10^{-11}$$
$$a_\mu^{(6,\mathrm{lbl,had})} = (116 \pm 39) \times 10^{-11}$$

Electroweak Contributions

- Z Boson Contribution

$$a_\mu^{(2,\mathrm{EW,Z})} = -193.89 \times 10^{-11}$$

- W Boson Contribution

$$a_\mu^{(2,\mathrm{EW,Z})} = 388.70 \times 10^{-11}$$

- Higgs Boson Contribution is too small to matter

$$\boxed{a_\mu^{(\mathrm{EWK})} = (152.2 \pm 2.0) \times 10^{-11}}$$

Overall Result

Contribution	Value	Error
QED incl. 4-loops+LO 5-loops	116 584 718.1	0.2
Leading hadronic vacuum polarization	6 903.0	52.6
Subleading hadronic vacuum polarization	-100.3	1.1
Hadronic light–by–light	116.0	39.0
Weak incl. 2-loops	153.2	1.8
Theory	116 591 790.0	64.6
Experiment	116 592 080.0	63.0
Exp. - The. 3.2 standard deviations	290.0	90.3

Static Quantities: Electric Dipole Moments

- Electric dipole moments in classical physics

$$\vec{d} = \int d^3\vec{r}\ \rho(\vec{r})\vec{r} \quad \text{Energy: } U = \vec{d}\cdot\vec{E}$$

- Quantum Field theory:
  States are characterized by momentum $\vec{p}$ and Spin $\vec{J}$:
  $\vec{d}$ must be proportional to $\vec{J}$

$$U = d\,\vec{J}\cdot\vec{E}$$

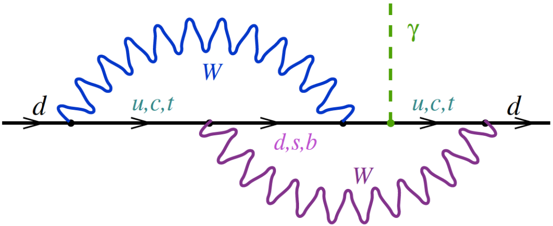
- d mud be parity odd:
  P Violation (and also T Violation) $\rightarrow$ CP violation

EDM's of elementary particles

- Electromagnetic interaction with EDM: (Flavour diagonal)

$$\mathcal{L}_{\mathrm{EDM}} = \frac{d}{2} \bar{\psi} i \sigma_{\mu\nu} \gamma_5 \psi \, F^{\mu\nu}$$

- SM Scenario without Strong CP: CKM Phase
  d must be proportional to $\Delta = \mathrm{Im}\, V_{cs}^* V_{us} V_{cd} V_{ud}^*$!
- Thus we have two W exchanges:



- However, sum of all the two-loop diagrams vanishes for quark edm's $\to$ need another (gluon) loop Shabalin 78
- Result for d quark (similar for the up qark)

$$d_d = e \frac{m_d \alpha_s G_F^2 m_c^2 \Delta}{108\pi^5} \left[\ln^2 \frac{m_b^2}{m_c^2} \ln \frac{M_W^2}{m_b^2} + .. \right] \sim -0.3 \times 10^{-34} \text{e cm}$$

Khiplovich 86, Czarnecki, Krause 97

Naive composition of the Neutron edm:

$$d_N = \frac{4}{3} d_d - \frac{1}{3} d_u \sim 10^{-34} \text{e cm}$$

This is too small, neutron is a composite object.

Neutron EDM: Long Distance Effects

- Difficult to compute due to Long Distance Effects
- "Loopless" Estimate (order of magnitude) (Uraltsev, M)

$$\boxed{|d_n| = 10^{-31}\, e\,\mathrm{cm}}$$

- Short distance loops will be parametrically small by loop factors $1/(16\pi^2)$
- The EDM's of the constituents do not play any role
- Strong CP remains a problem:

$$|d_n| \approx 2.3 \cdot 10^{-16}\, e\,\mathrm{cm} \times \theta$$

- Given the current experimental bound:

$$|d_n| \leq 2.9 \cdot 10^{-26}\, e\,\mathrm{cm} \quad (90\% CL)$$

Other Leptonic Proceses

- Michel Parameters in $\ell \to \ell' \nu \bar{\nu}$
  - Precision measurement of the $V - A$ structure
  - $\rho(\mu) = 0.74979 \pm 0.00026$
- Charged Lepton Number and/or Flavour violation
  - $\ell \to \ell' \gamma$ and $\ell \to \ell' \ell'' \ell'''$
  - Muonium-Antimuonium Oscillations
  - Experimental efforts! (MEG, Mu3e etc.)
- Leptonic CP Violation

Quark Flavour Physics

What can Flavour tell us?

- Effective field theory picture:
- Standard model (without right handed ν's) is the (dim-4) starting point.
- Any new physics manifests itself as higher dimensional operators:

$$\mathcal{L} = \mathcal{L}_{\rm dim\,4}^{SM} + \mathcal{L}_{\rm dim\,5} + \mathcal{L}_{\rm dim\,6} + \cdots$$

- $\mathcal{L}_{\rm dim\,n}$ are suppressed by large mass scales

$$\mathcal{L}_{\rm dim\,n} = \frac{1}{\Lambda^{n-4}} \sum_i C_n^{(i)} O_n^{(i)}$$

$O_n^{(i)}$: Operators of dimension n,
$SU(3)_C \times SU(2)_W \times U(1)_Y$ gauge invariant
$C_n^{(i)}$: dimensionless couplings

Quark Flavour Physics

- For Quarks there is no contribution to $\mathcal{L}_{\mathrm{dim}\,5}$
- Some of the $O_j^{(n)}$ mediate $\Delta F = 2$ flavour transitions:

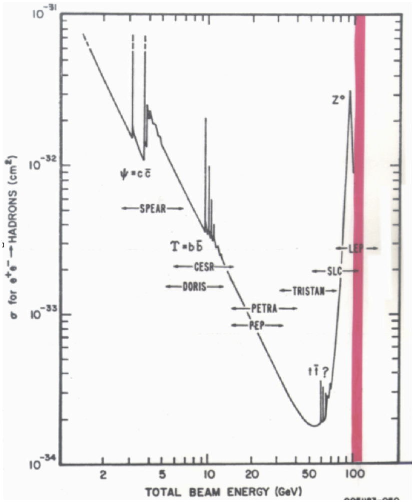
$$
\begin{aligned}
O_1^{(6)} &= (\bar{s}_L \gamma_\mu d)(\bar{s}_L \gamma^\mu d) && \text{(Kaon Mixing)} \\
O_2^{(6)} &= (\bar{b}_L \gamma_\mu d)(\bar{b}_L \gamma^\mu d) && (B_d \text{ Mixing}) \\
O_3^{(6)} &= (\bar{b}_L \gamma_\mu 2)(\bar{b}_L \gamma^\mu s) && (B_s \text{ Mixing}) \\
O_4^{(6)} &= (\bar{c}_L \gamma_\mu u)(\bar{c}_L \gamma^\mu u) && (D \text{ Mixing})
\end{aligned}
$$

- $\Lambda \sim 1000$ TeV from Kaon mixing ($C_i = 1$)
- $\Lambda \sim 1000$ TeV from D mixing
- $\Lambda \sim 400$ TeV from B_d mixing
- $\Lambda \sim 70$ TeV from B_s mixing

- "New physics" is around the corner??
- Are the flavour data a hint at a new physics scale well above the TeV scale?
- ... there are a few corners where $\mathcal{O}(1)$ flavour effects are still possible, c.f. Charm CPV
- Are there lessons from history?

The Top Quark Story

- First indirect hint to a heavy top quark: $B-\overline{B}$ Oscillation of ARGUS (1987)
- The world in 1987 ("PETRA Days"): The top was believed to be at $\sim$ 25 GeV
  ... based on good theoretical arguments
- ARGUS could not have seen anything with a 25 GeV Top (within SM)



- The consequences:
  - (–) No Toponium
  - (–) No Top quark discovery at LEP and SLC
  - (–) No "New Physcis $\mathcal{O}$(30 GeV)" just around the corner
  - (+) CP violation in the B sector may become observable
  - (+) GIM is weak for bottom quarks
- This was actually good for Flavour Physics ...
- GIM suppressed decays as a probe for large scales
- From current data: TeV "New Physics" must have a flavour structure close to the one of the SM
- $\rightarrow$ Concept of "Minimal Flavour Violation" (MFV)

Hints from Quark Flavor?

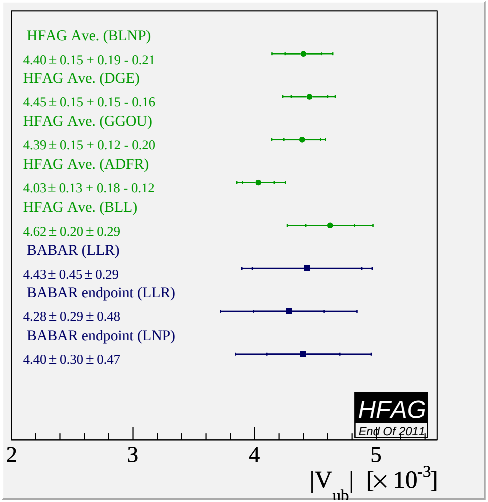
FCNC Decays: $b \to s$ and $b \to d$ transitions

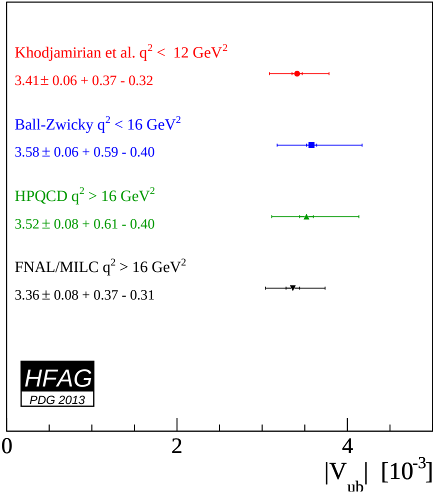
- $B_{s/d} \to \mu\mu$
  - Theoretically simple, hadronic input mainly f_b
  - Measurement (LHCb and CMS), Combined:

$$\mathrm{Br}(B_s \to \mu\mu) = (3.1 \pm 0.7) \times 10^{-9}$$

- $B \to K^{(*)}\ell\ell$
  - Theoretically more complicated, long distance effects
  - Complete angular analysis, some "tensions"
  - Lepton Universality Violation?

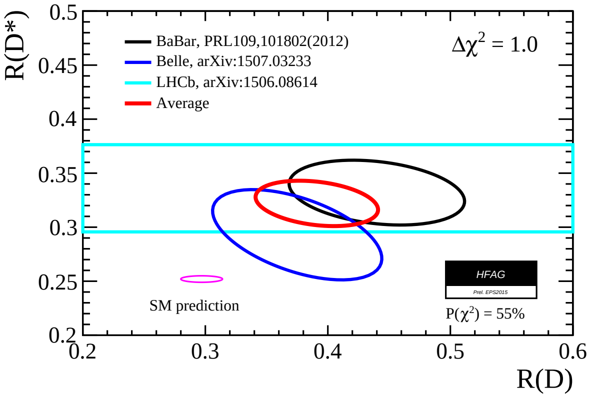
Charmless Semileptonics: $b \to u \ell \bar{\nu}$ V_{ub} Puzzle





Standard Semitauonics: $b \to c\tau\bar{\nu}$

$$R(D^{(*)}) = \frac{\mathrm{Br}(B \to D^{(*)}\tau\bar{\nu})}{\mathrm{Br}(B \to D^{(*)}\ell\bar{\nu})}$$



Hints from the leptonic sector

- $\mathcal{L}^{SM}_{\dim 4}$ does not have a right handed neutrino
- ... thus no mixing for the leptons
- Discovery of Neutrino Oscillations: Nontrivial Flavour Physics of Leptons
- Important observation: The combination

$$N_i = (H^{c,\dagger} L_i) , \quad L_i = \begin{pmatrix} \nu_{L,i} \\ \ell_{L,i} \end{pmatrix} , \, H^c = (i\tau^2)H^* \, , H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

has no SM Quantum numbers

- This allows for a Unique dim -5 Operator:
  Generates Majorana masses for the ν's

$$\mathcal{L}_{\mathrm{dim}\,5} = \frac{1}{\Lambda_{\mathrm{LNV}}} \sum_{ij} C_5^{ij} (\bar{L}_j H^c)^c (H^{c,\dagger} L_i)$$

- Generates a mixing matrix for the leptons (PMNS Matrix), analogous to the CKM Matrix
- This term is Lepton Number Violating, related to the scale Λ_{LNV}
- Small Neutrino masses: Λ_{LNV} must be high, almost as big as the GUT scale?
- Hopefully Λ_{QFV} and Λ_{LFV} is not that high!

- Some more tensions in charmless nonleptonics
- Could be something exciting,
  but as well only a statistical fluctuation
- Increasing the reach:
  - More Data
  - Better Theory

High Energy Frontier

High Energy Frontier

Two "modes of operation"

- Direct Searches:
  - "on -shell production of new particles
  - Direct observation of their decays
  - Study their properties by analyzing their decay products
- Indirect Searches:
  - No "on -shell production of new particles
  - Only indirect observation through virtual effects
  - Requires precise calculations

... let's assume no new particles below 10 TeV ...

Precision SM Physics at High Energies

- Top Physics
- Weak Boson Physics
- Higgs Physics

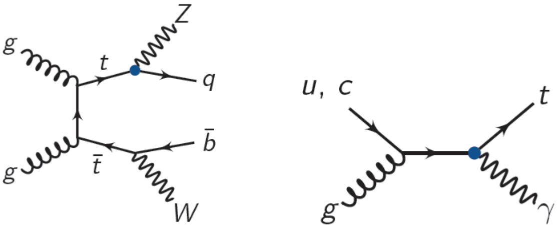
... to be done at the LHC and a possible ILC ...

Top Physics

Top quark is special because of its large mass

Anomalous couplings of the top quark

- Right handed admixtures in $t \to (b, s, d)W$
- Measurement of the top quark charge
- CP Violation in top processes
- FCNC couplings of the top quark:
  $t \to (c, u)(Z/\gamma)$ with all helicity combinations

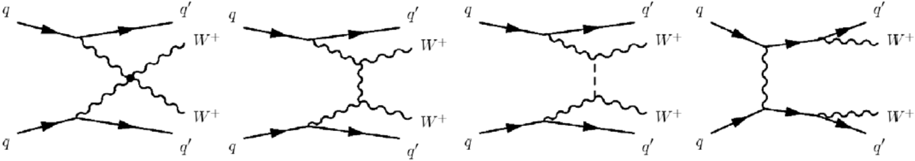


LP2015 Summary in Top FCNC (A.B.Meyer)

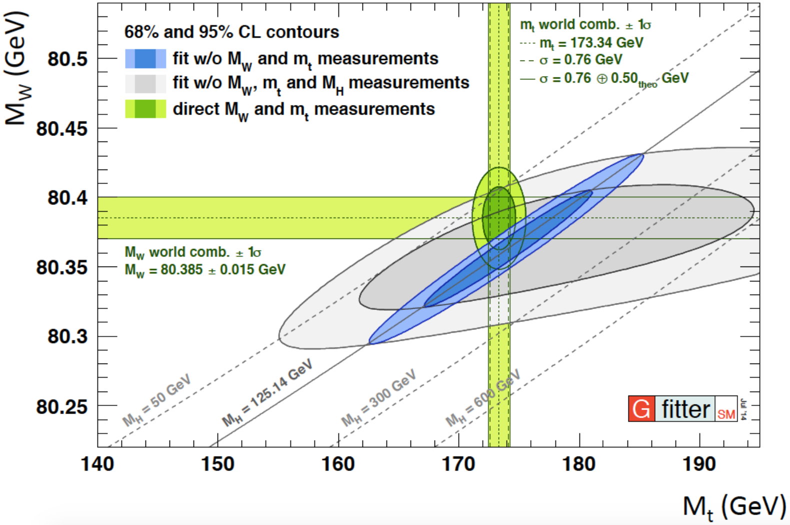
Exp.	$\sqrt{s}$	$\mathcal{B}(t \to u\gamma)$	$\mathcal{B}(t \to c\gamma)$	Reference
CDF	1.96 TeV	$3.2 \cdot 10^{-2}$		PRL 80 (1998) 2525
CMS	8 TeV	$1.6 \cdot 10^{-4}$	$1.8 \cdot 10^{-3}$	CMS TOP-14-003
		$\mathcal{B}(t \to uZ)$	$\mathcal{B}(t \to cZ)$	
CDF	1.96 TeV	$3.7 \cdot 10^{-2}$		PRL 101 (2008) 192002
DØ	1.96 TeV	$3.2 \cdot 10^{-2}$		PLB 701 (2011) 313
ATLAS	7 TeV	$7.3 \cdot 10^{-3}$		JHEP 09 (2012) 139
CMS	7 TeV	$5.1 \cdot 10^{-3}$	$1.1 \cdot 10^{-1}$	CMS TOP-12-021
CMS	7+8 TeV	$5 \cdot 10^{-4}$		PRL 112 (2014) 171802
ATLAS	8 TeV	$7 \cdot 10^{-4}$		ATLAS TOPQ-2014-08
		$\mathcal{B}(t \to ug)$	$\mathcal{B}(t \to cg)$	
CDF	1.96 TeV	$3.9 \cdot 10^{-4}$	$5.7 \cdot 10^{-3}$	PRL 102 (2009) 151801
DØ	1.96 TeV	$2.0 \cdot 10^{-4}$	$3.9 \cdot 10^{-3}$	PLB 693 (2010) 81
ATLAS	7 TeV	$5.7 \cdot 10^{-5}$	$2.7 \cdot 10^{-4}$	PLB 712 (2012) 351
ATLAS	8 TeV	$3.1 \cdot 10^{-5}$	$1.6 \cdot 10^{-4}$	ATLAS CONF-2013-063
CMS	7 TeV	$3.6 \cdot 10^{-4}$	$3.4 \cdot 10^{-3}$	CMS TOP-14-007
ATLAS	8 TeV	$4 \cdot 10^{-5}$	$1.7 \cdot 10^{-4}$	ATLAS TOPQ-2014-13
		$\mathcal{B}(t \to uH)$	$\mathcal{B}(t \to cH)$	
ATLAS	7+8 TeV	$7.9 \cdot 10^{-3}$		JHEP 06 (2014) 008
CMS	8 TeV	—	$5.6 \cdot 10^{-3}$	PRD 90 (2014) 112013
CMS	8 TeV	—	$9.3 \cdot 10^{-3}$	CMS TOP-13-017
CMS	8 TeV	$4.2 \cdot 10^{-3}$	$4.7 \cdot 10^{-3}$	CMS TOP-14-019

Weak Boson Physics

- All kinds of elektroweak processes:
  in particular *WW* scattering

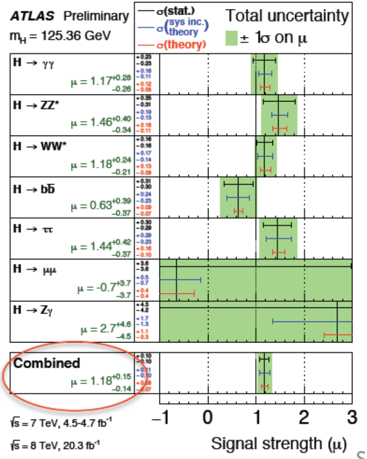


LP2015 SM fit (A.K.Einsweiler)

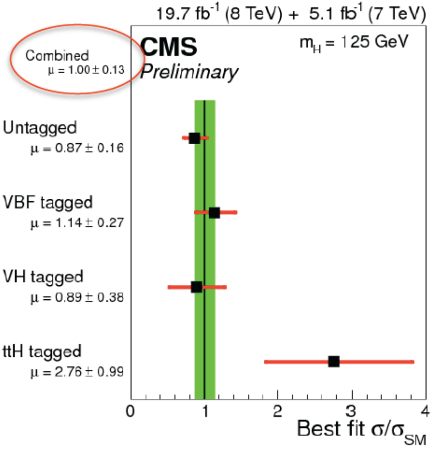


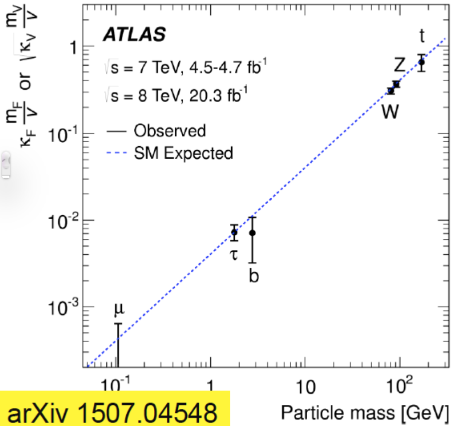
Higgs Physics

- Precise measurement of Higgs Properties
- ... in particular of its couplings

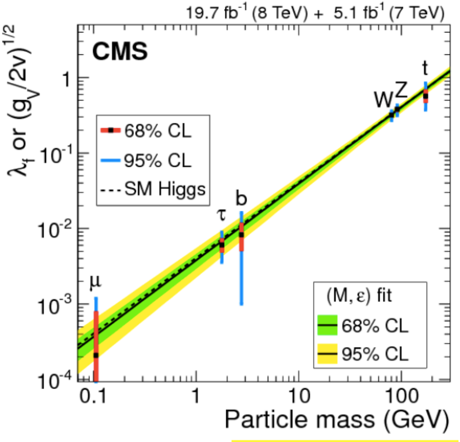

ATLAS Preliminary
m_H = 125.36 GeV
σ(stat.)
σ(sys inc. theory)
σ(theory)
Total uncertainty
± 1σ on μ
H → γγ
μ = $1.17^{+0.28}_{-0.26}$
H → ZZ*
μ = $1.46^{+0.40}_{-0.34}$
H → WW*
μ = $1.18^{+0.24}_{-0.21}$
H → $b\bar{b}$
μ = $0.63^{+0.39}_{-0.37}$
H → ττ
μ = $1.44^{+0.42}_{-0.37}$
H → μμ
μ = $-0.7^{+3.7}_{-3.7}$
H → Zγ
μ = $2.7^{+4.6}_{-4.5}$
Combined
μ = $1.18^{+0.15}_{-0.14}$
$\sqrt{s}$ = 7 TeV, 4.5-4.7 fb^{-1}
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
−1
0
1
2
3
Signal strength (μ)

S. Dawson


19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
Combined
μ = 1.00 ± 0.13
CMS
Preliminary
m_H = 125 GeV
Untagged
μ = 0.87 ± 0.16
VBF tagged
μ = 1.14 ± 0.27
VH tagged
μ = 0.89 ± 0.38
ttH tagged
μ = 2.76 ± 0.99
0
1
2
3
4
Best fit σ/σ_{SM}



arXiv 1507.04548



Conclusion

- In case no no particles are found at the LHC
  the "new physics scale" may be large
- This puts LHC (and possibly even ILC) in the same situation as Flavor and low energy experiments
- This is a change of paradigm at the high energy frontier
- Identifying "new physics" requires to have precise measurement as well as precise theory
- Unique identification may be difficult,
  Thus measurement in as many processes are required!