Particle Physics after the Higgs Discovery: Searching for Physics beyond the Standard Model

color meets flavor

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TP1 Theoretical Particle Physics

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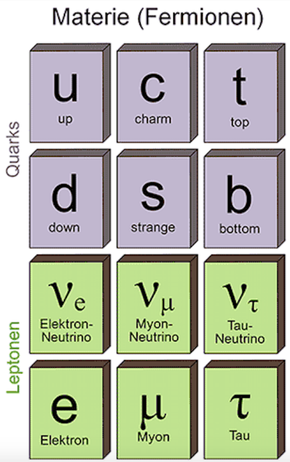
Contents

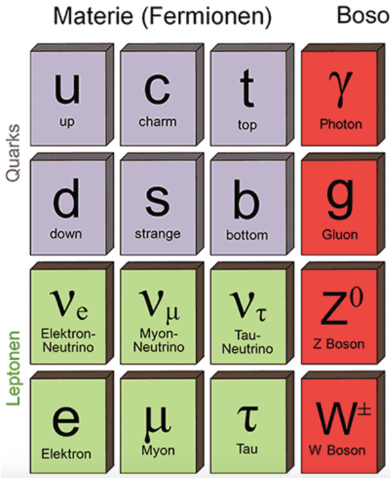
Introduction

Constructing the Standard Theory of Particle Physics:

Observed Matter: Quarks and Leptons:



Add in the oberved interaction (except gravity):

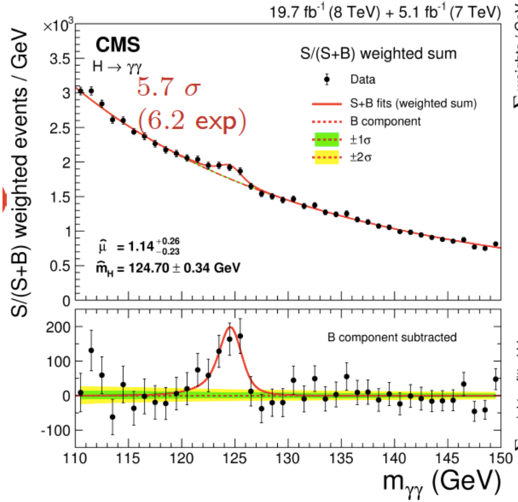


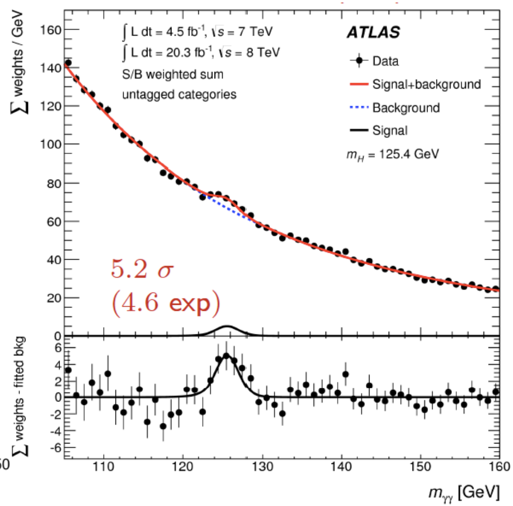
Theoretical Problems before the Higgs Discovery:

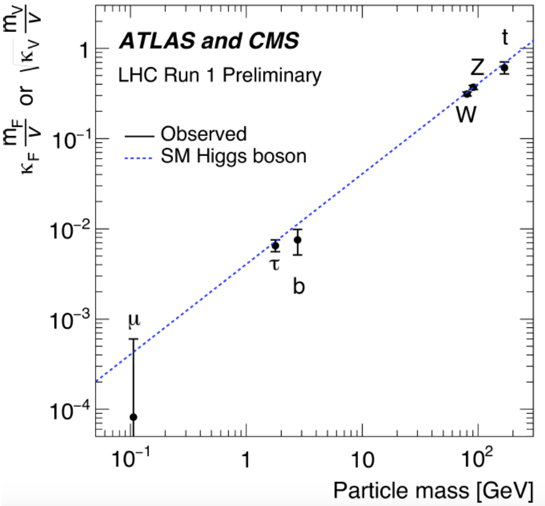
- The weak bosons $W^{\pm}$ and Z^0 have to be very massive:
  Interactions of longitudinal modes generate problems
  Model without (something like) the Higgs becomes invalid at the TeV scale
- Quark and Leptons have masses
  Incompatible with a consistent description of parity violation
- This theory fails at high energy scales of about $\mathcal{O}(1)$ TeV

$\boxed{\text{Rationale for LHC (and btw. SSC): something has to happen at the TeV scale!}}$

The Higgs Discovery


19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
CMS
$H \to \gamma\gamma$
5.7 σ
(6.2 exp)
S/(S+B) weighted sum
Data
S+B fits (weighted sum)
B component
$\pm 1\sigma$
$\pm 2\sigma$
$\hat{\mu} = 1.14^{+0.26}_{-0.23}$
$\hat{m}_H = 124.70 \pm 0.34$ GeV
B component subtracted
S/(S+B) weighted events / GeV
$\times 10^3$
$m_{\gamma\gamma}$ (GeV)

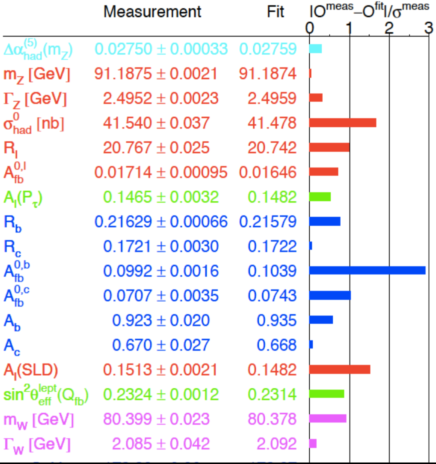

$\int L\,dt = 4.5$ fb^{-1}, $\sqrt{s} = 7$ TeV
$\int L\,dt = 20.3$ fb^{-1}, $\sqrt{s} = 8$ TeV
S/B weighted sum
untagged categories
ATLAS
Data
Signal+background
Background
Signal
$m_H = 125.4$ GeV
5.2 σ
(4.6 exp)
$\sum$ weights / GeV
$\sum$ weights - fitted bkg
$m_{\gamma\gamma}$ [GeV]



- The Higgs has specific couplings
- The Higgs couplings generate all masses of quarks and leptons as well as of the massive gauge bosons
- ... with a possible exception of the neutrinos ...

... this has generated a new problem:

This model (with the Higgs particle) is extremely successful!

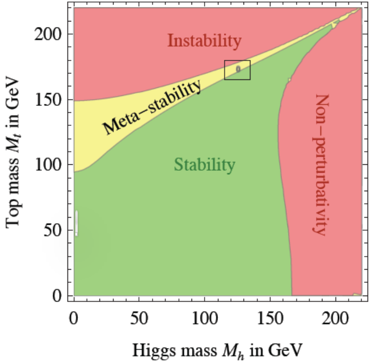


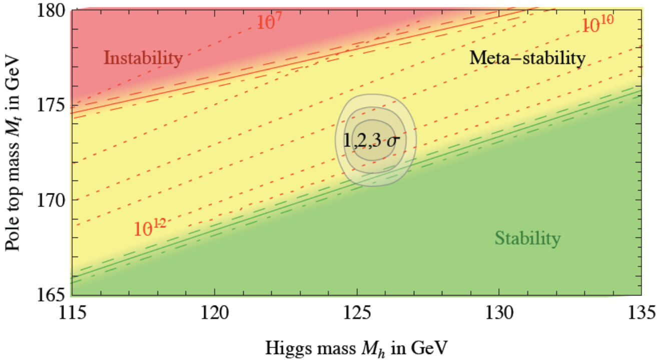
	Measurement	Fit	$\lvert O^{meas} - O^{fit}\rvert / \sigma^{meas}$ (0 1 2 3)
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ^0_{had} [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01646	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1039	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0743	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1482	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.399 ± 0.023	80.378	
Γ_W [GeV]	2.085 ± 0.042	2.092	

- It explains all particle physics phenomenology up to energy scales of $\mathcal{O}(100)$ GeV
- Various observables have been tested even at the quantum level (such as the Lamb shift, g factor of the muon, ...)

From the theory point of view:

- Including the Higgs this becomes a renormalizable theory:
  This model can be valid up to extremely high scales $\mu \sim 10^{12}$ GeV!



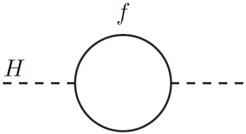


(Too) many open questions:

- The model has 27 free parameters,
  22 of these are due to the fact that there are three families
- Many parameters turn out to be “hierarchical” (instead of being $\mathcal{O}(1)$)
  - $m_e = 511$ keV compared to $m_\tau = 1.777$ GeV
  - $m_u =$ few MeV compared to $m_{\rm top} = 175$ GeV
  - All masses turn (except of the top-quark mass) out to be small compared to the electroweak scale
- Why do we have three families?
- Violation of the CP Symmetry is very small!
  Despite of the possibility to have large CPV from the strong sector:
  Strong CP problem
- What are “Dark Matter” and “Dark Energy”?

A theoretical problem, or:
Why many people believe/believed in TeV scale “new physics”?

- Theoretical argument: Related to the mass of the Higgs
- Stabilization of the electroweak scale:

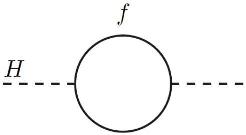


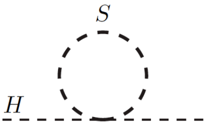
- Quadratic Dependence on the cut-off

$$\Delta m_H^2 = -\frac{\lambda_f^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2$$

- Drives the Higgs mass up to the UV cut off $\Lambda_{\mathrm{UV}} \sim M_{\mathrm{PL}}$

- Stabilization at the TeV scale: Needs to introduce something at the TeV scale (e.g. SuperSymmetry):





- Only logarithmic divergence

$$\Delta m_H^2 = m_{\mathrm{soft}}^2 \frac{\lambda}{16\pi^2} \ln\left(\frac{\Lambda_{\mathrm{UV}}}{m_{\mathrm{soft}}}\right)$$

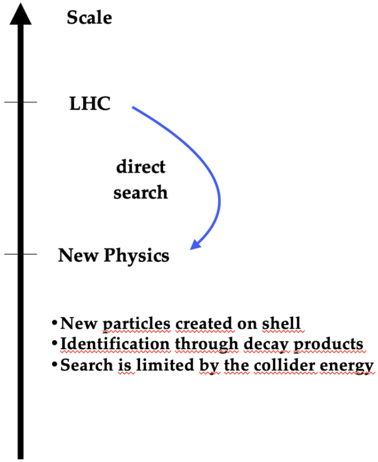
- $m_{\mathrm{soft}} \sim \mathcal{O}(\mathrm{TeV})$: Scale of "new physics"

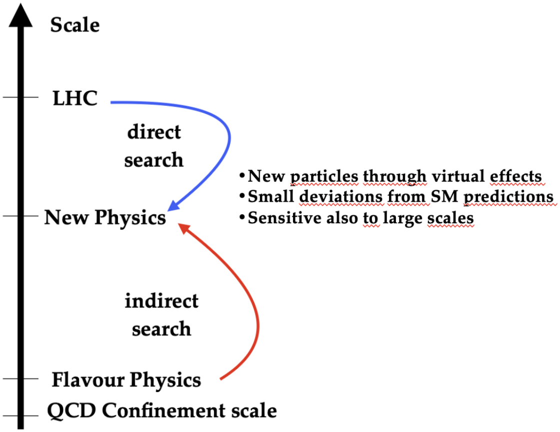
- How strong are these arguments?
- Could there something be wrong with our understanding of
  - electroweak symmetry breaking?
  - scale and conformal invariance?
    (c.f. Lee Wick Model)
  - ...
- Maybe it is “just so”

Currently there is no evidence for any effects beyond the SM from particle physics

Beyond the Standard Theory

Search Strategies for new Effects





General Tool: Effective (Quantum) Field Theories

Integrating out heavy degrees of freedom

- ϕ: light fields, Φ: heavy fields with mass Λ
- Generating functional as a functional integral
  Integration over the heavy degrees of freedom

$$Z[j] = \int [d\phi][d\Phi] \exp\left(\int d^4x \, [\mathcal{L}(\phi, \Phi) + j\phi]\right)$$

$$= \int [d\phi] \exp\left(\int d^4x \, [\mathcal{L}_{\text{eff}}(\phi) + j\phi]\right) \quad \text{with}$$

$$\exp\left(\int d^4x \, \mathcal{L}_{\text{eff}}(\phi)\right) = \int [d\Phi] \exp\left(\int d^4x \, \mathcal{L}(\phi, \Phi)\right)$$

- For length scales $x \gg 1/\Lambda$: local effective Lagrangian
- Technically: (Operator Product) Expansion in inverse powers of Λ

$$\mathcal{L}_{\text{eff}}(\phi) = \mathcal{L}_{\text{eff}}^{(4)}(\phi) + \frac{1}{\Lambda}\mathcal{L}_{\text{eff}}^{(5)}(\phi) + \frac{1}{\Lambda^2}\mathcal{L}_{\text{eff}}^{(6)}(\phi) + \cdots$$

- $\mathcal{L}_{\text{eff}}$ is in general non-renormalizable, but ...
- $\mathcal{L}_{\text{eff}}^{(4)}$ is the renormalizable piece
- For a fixed order in $1/\Lambda$: Only a finite number of insertions of $\mathcal{L}_{\text{eff}}^{(4)}$ is needed!
- $\rightarrow$ can be renormalized
- Renormalizability is not an issue here

Effective field Theory as used by the practitioneer

Effective Field Theories are everywhere:

- Effective (local) Lagrangian

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

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

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

  - $O_n^{(i)}$: Operators of dimension n,
  - $C_n^{(i)}$: (dimensionless) couplings
  - Λ scale of "new physics"

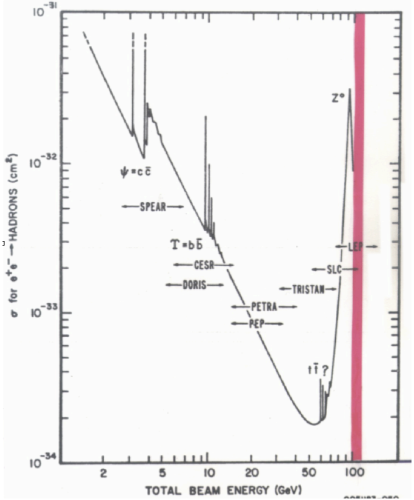
Towers of effective field theories

Depending on the Scale:

- $\Lambda_{BSM} \geq \mu \geq v$: Standard Model Effective Theory (SMEFT)
  matching to an unknown theory BSM
- $v \geq \mu \geq m_b$: Weak Effective Theory (WET)
  matching to the SM or SMEFT
- $m_b \geq \mu\Lambda_{\mathrm{QCD}}$: Heavy Quark Effective Theory
  matching to WET
- $\Lambda_{\chi SB} \geq \mu \geq 0$: Chiral Perturbation Theory
  matching to ...

Excursion: It worked in the past: 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)
- Clear indication if a very heavy top quark!



- The consequences:

  Mass of the top quark must be well above 100 GeV!

  (–) No Toponium
  (–) No Top quark discovery at LEP and SLC
  (–) No “New Physcis $\mathcal{O}(30\text{ GeV})$” just around the corner
  (+) CP violation in the B sector may become observable
  large asymmetries, however, for decays with small branching fractions

- This was actually good for Flavour Physics
  (B mesons and Kaons)

What can we say today about the "new physics" scale?

Pick some processes that are very sensitive to "new physics"
= well measurable and well under theoretical control

- Anomalous magnetic moment of the muon $(g-2)_\mu$,
  looks now SM like, lmits based on EFT arguments have to be re-evaluated
- Mixing phenomena in the neutral flavoured meson systems:
  (B-$\overline{B}$-Mixing, D-$\overline{D}$-Mixing, K-$\overline{K}$-Mixing)
- Processes forbidden at leading order: "Flavour Changing Neutral Currents":
  $b \to s$ transitions and alike
- Flavour Violation in the leptonic sector: $\mu \to e\gamma$ and alike
- Patterns of the violations of the CP symmetry, Unitarity Triangel fits etc.

From lepton physics:

- Majorana masses for the ν's are generated by a unique dim-5 operator:

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

- 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}
- We know that Neutrinos have small masses: Δm_{ij}^2 are measured!
  We know that there is a family mixing for leptons.
- Use these inputs: $\Lambda_{\mathrm{LNV}} \sim 10^{14}$ GeV!

Good News:

- Neutrino masses induces non-trivial charged lepton flavour physics
- LFV muon decays: $\mu \to e\gamma$, $\mu \to 3e$
- LFV τ decays: $\tau \to e/\mu\gamma$, $\tau \to 3\mu$, $\tau \to e2\mu$ ...

Bad News:

- If the dim-5 Operator is the only source of LFV (and LNV), these effects are super-small!
- Naive counting

$$\mathcal{A}(\ell \to \ell'\gamma) \propto \frac{G_F}{16\pi^2} |V_{\mathrm{PMNS}}|^2 \frac{\Delta m_\nu^2}{M_W^2} \quad \to \quad \mathrm{Br}(\tau \to \mu\gamma) \le 10^{-54}$$

Hopefully Λ_{QFV} and Λ_{LFV} is not that high!

From the mixing in the flavoured neutral meson systems:

- For Quarks there is no contribution to $\mathcal{L}_{\text{dim }5}$
- Look at $\Delta F = 2$ flavour transitions:

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

- With generic couplings $C_i \sim \mathcal{O}(1)$:
  - $\Lambda \sim 1000$ TeV from Kaon mixing
  - $\Lambda \sim 1000$ TeV from D mixing
  - $\Lambda \sim 400$ TeV from B_d mixing
  - $\Lambda \sim 70$ TeV from B_s mixing

Current "Tensions"

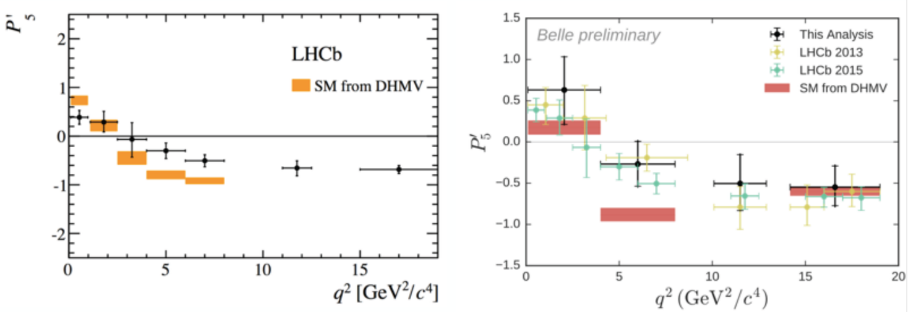
There are currently a few "tensions" (Tension = Deviation with a significance of less than 5 σ, so normally nothing to worry about!)

- Anomalous Magnetic Moment Moment of the Muon, very likely disappeared
- $b \to s\ell\ell$ Transitions:
  - P_5': Angular distribution in $B \to K^*\ell\ell$
  - Rates for $B \to K\mu\mu$ and $B_s \to \phi\mu\mu$
  - Lepton-Universality Violation: Disappeared!
- $R(D)$ and $R(D^*)$: Rates for $B \to D^{(*)}\ell\bar{\nu}$
- V_{xb}^{incl} vs. V_{xb}^{excl}: $b \to q\ell\bar{\nu}$ transitions

$b \to s\ell\ell$ anomalies: Angular distribution in $B \to K^*\ell\ell$

- $B \to K^*\ell\ell \to K\pi\ell\ell$ contains a lot of information
- Angular distributions in the final state
- Set up clever ratios to reduce hadronic uncertainties

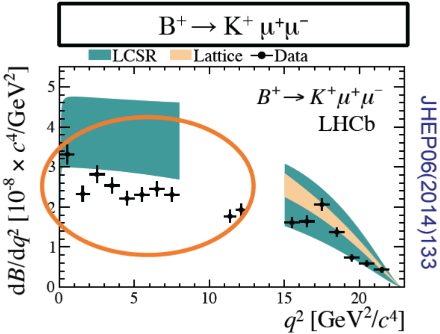
Anomalies in the angular distributions:

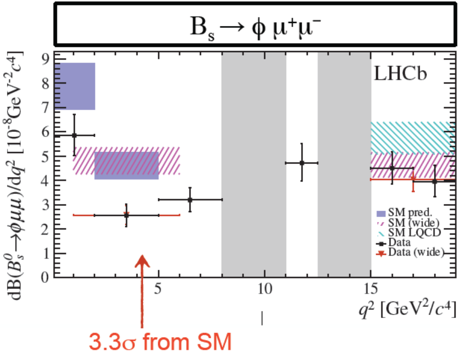


However, how well can we compute this?

- There are various hadronic uncertainties
- Needs additional scrutiny within the Standard Model!

$b \to s\ell\ell$ anomalies: Rates in $B \to K\mu\mu$ and $B_s \to \phi\mu\mu$



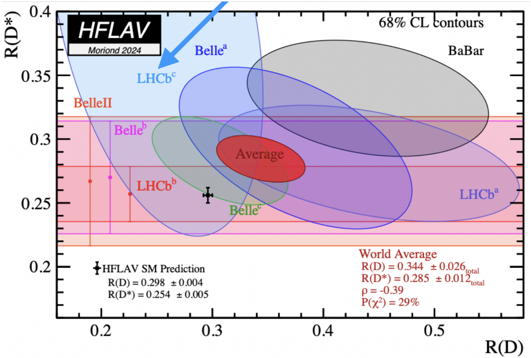


Rates at low q^2 seem to be lower than the SM prediction!

Semileptonic Decays with a τ Lepton

Tension in the exclusive semileptonic $B \to D^{(*)}\tau\bar{\nu}$ decays

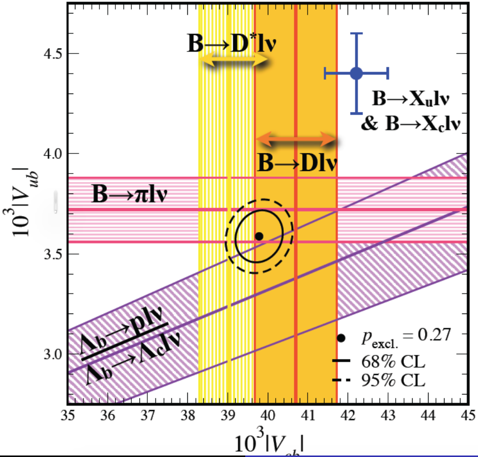
$$R(D) = \frac{\Gamma(B \to D\tau\bar{\nu})}{\Gamma(B \to D\ell\bar{\nu})} \qquad R(D^*) = \frac{\Gamma(B \to D^*\tau\bar{\nu})}{\Gamma(B \to D^*\ell\bar{\nu})}$$



- Theory predictions are quite precise:
- Heavy Quark Symmetry fixes the longitudinal form factor f_0
- in Addition, its contribution is supressed by m_τ^2/m_b^2

Determinations of CKM Matrix Elements

V_{cb} and V_{ub} can be determined from various decay modes:



How do we continue form here?

Narrative from 2019 (Start of P3H): Particle Physics at the crossroads

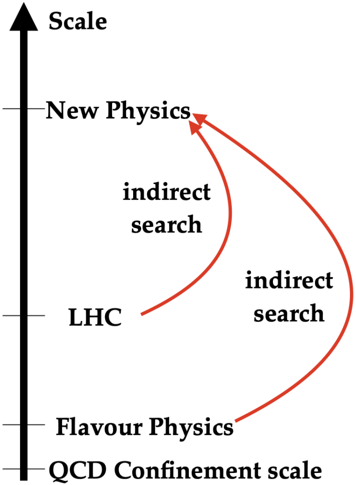
LHC finds New Particles

- Find our what it is!
- How does this become compatible with the precision data?
- Why do we have MFV?
- ... and where does it come from?

LHC finds no New Particles

- Era of indirect searches
- Quark and Lepton Flavor Physics
- Indirect searches at highest energies
- “Precision Colllider Physics” at LHC

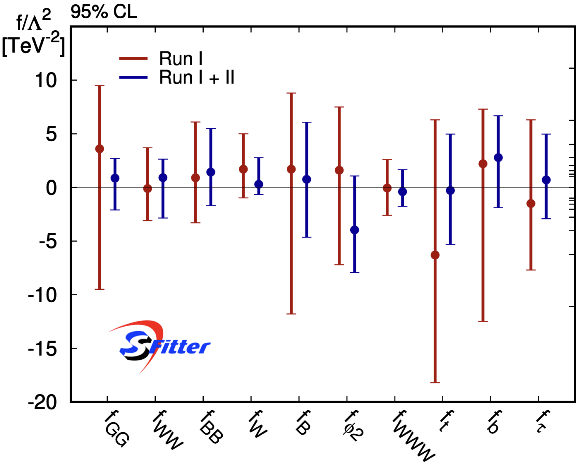
Perspective for a direct detection has shrunk!


Scale
New Physics
indirect search
LHC
indirect search
Flavour Physics
QCD Confinement scale

Generic searches at highest energies: SMEFT fits (Biekotter et al., 1812.07587)

$$\mathcal{L}_{\rm eff} \supset + \frac{f_{\phi 1}}{\Lambda^2}\mathcal{O}_{\phi 1} + \frac{f_{BW}}{\Lambda^2}\mathcal{O}_{BW} + \frac{f_{LLLL}}{\Lambda^2}\mathcal{O}_{LLLL}$$
$$+ \frac{f^{(1)}_{\phi Q}}{\Lambda^2}\mathcal{O}^{(1)}_{\phi Q} + \frac{f^{(1)}_{\phi d}}{\Lambda^2}\mathcal{O}^{(1)}_{\phi d} + \frac{f^{(1)}_{\phi u}}{\Lambda^2}\mathcal{O}^{(1)}_{\phi u} + \frac{f^{(1)}_{\phi e}}{\Lambda^2}\mathcal{O}^{(1)}_{\phi e} + \frac{f^{(3)}_{\phi Q}}{\Lambda^2}\mathcal{O}^{(3)}_{\phi Q}$$

$$\begin{aligned}
\mathcal{O}_{\phi 1} &= (D_\mu\phi)^\dagger \phi\phi^\dagger (D^\mu\phi) \\
\mathcal{O}_{BW} &= \phi^\dagger B_{\mu\nu} W^{\mu\nu}\phi \\
\mathcal{O}_{LLLL} &= (\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L) \\
\mathcal{O}^{(1)}_{\phi Q} &= (\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{Q}\gamma^\mu Q) \\
\mathcal{O}^{(1)}_{\phi q} &= (\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{q}_R\gamma^\mu q_R) \\
\mathcal{O}^{(1)}_{\phi e} &= (\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{e}_R\gamma^\mu e_R) \\
\mathcal{O}^{(3)}_{\phi Q} &= (\phi^\dagger \overleftrightarrow{D}^a_\mu \phi)(\bar{Q}\tau^a\gamma^\mu Q)
\end{aligned}$$



There are too many operators at dim 6

- Pick some operators to study
- ... and fit them “one by one”
- Results are compatible with $f_i = 0$

Uncertainties are (still) too large:

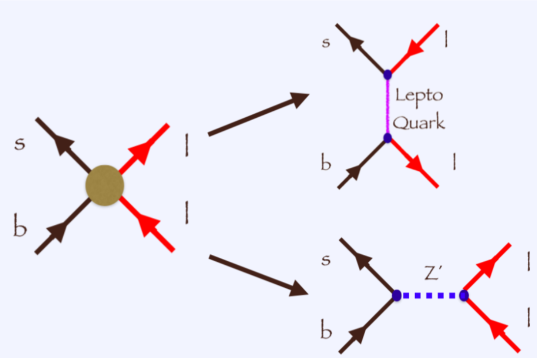
- Assuming a scale $\Lambda = 10$ TeV (which is still too low for LHC!) we get

$$-1000 \leq f_i \leq 1000$$

SMEFT is not (yet?) the proper tool to analyse LHC data!

- No sufficient sensitivity (yet?)
- Too many parameters

Simplified Models



- "Resolve" the dim 6 operators by introducing exchanged (heavy) particles
- Restricts the number of operators in SMEFT
- "Reverse Engineering"

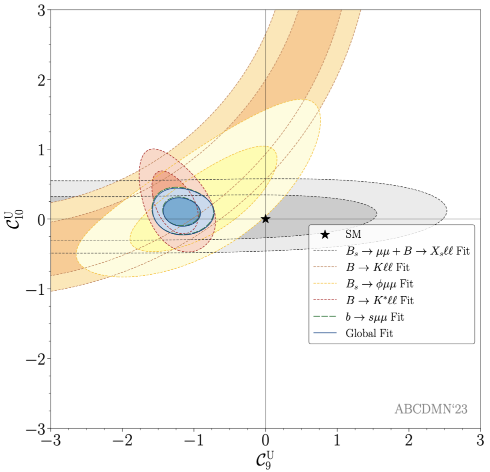
Quark-Flavor Physics and WET fits

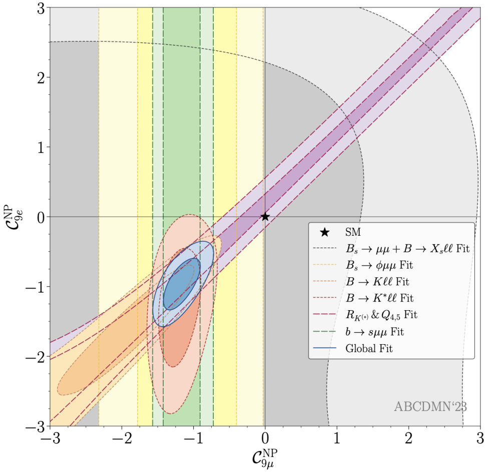
This works much better as for Collider Physics and SMEFT

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) \mathcal{O}_i(\mu)$$

$$\begin{aligned}
\mathcal{O}_7^{(\prime)} &= (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}, \\
\mathcal{O}_{9\ell}^{(\prime)} &= (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell), \\
\mathcal{O}_{10\ell}^{(\prime)} &= (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),
\end{aligned}$$

- Fit the coefficients $C_i(m_b)$ from the data
- compare to the values in the Standard Model





(Capdevila1, Crivellin, Matias: 2309.01311)

- *B* anomalies seem to follow a simple picture:

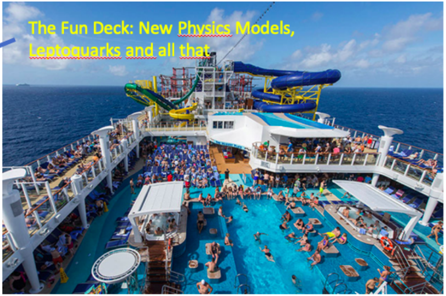
$$C_{9\mu}^{(NP)} = C_{9e}^{(NP)} \quad \text{and} \quad C_{9}^{(NP)} = -C_{10}^{(NP)}$$

- Interpretations in terms of Leptoquarks and/or Z'
- ... or still Standard Model???

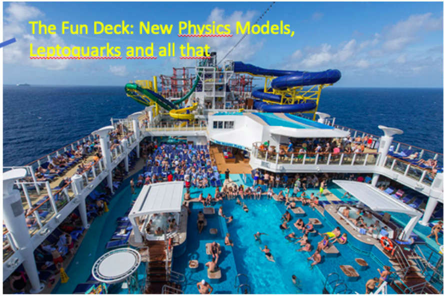
more work is needed ...


Ship of Flavour Theory


Ship of Flavour Theory


The Fun Deck: New Physics Models,
Leptoquarks and all that


Ship of Flavour Theory


The Fun Deck: New Physics Models,
Leptoquarks and all that


The Machine Deck: QCD Loops,
Hadronic Matrix Elements and all that
alamy stock photo

Outlook

Discussion on the European Strategy in Particle Physics is in full swing!

Should be oriented along physics questions!

- What is the solution of the strong CP problem?
  - Is there a light axion or other feebly interacting light particles?
- What is Dark Energy / Dark Energy?
  - Has Dark Matter a particle-physics explanation?
  - ... if yes, does it consist of light pr heavy pqarticles?
- Where is the missing CP Violation?
  - Is there PMNS CP violation and/or other CP violation in the lepton sector?
  - Are there other sources of CP violation in the quark sector?

... and maybe more...

Conclusion

100 Years of Quantum Theory: From $i\hbar\frac{\partial}{\partial t}\psi(t,\vec{x}) = H\psi(t,\vec{x})$ to

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

- Quantum mechanics was a dramatic change of paradigm
- ... triggered by experimental evidences
- and so was the (special) theory of relativty

$$
\begin{tikzcd}
 & \boxed{\begin{array}{c}\text{Classical Physics}\\ \hbar = 0, c = \infty\end{array}} \arrow[dl] \arrow[dr] & \\
\boxed{\begin{array}{c}\text{Special Relativity}\\ \hbar = 0, c \neq \infty\end{array}} \arrow[dr] & & \boxed{\begin{array}{c}\text{Quantum Mechanics}\\ \hbar \neq 0, c = \infty\end{array}} \arrow[dl] \\
 & \boxed{\begin{array}{c}\text{Quantum Field Theory}\\ \hbar \neq 0, c \neq \infty\end{array}} &
\end{tikzcd}
$$

- The gravitational constant $G$is the conversion factor relating energy-momentum to space-time geometry
- it is still missing in the figure! Does this indicate that – after 100 years – a new paradigm shift is around the corner?

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