Flavor 2015

New Physics at High Energy and High Precision

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JG|U

MIAPP topical workshop, June 1, 2015

What is Flavor 2015?

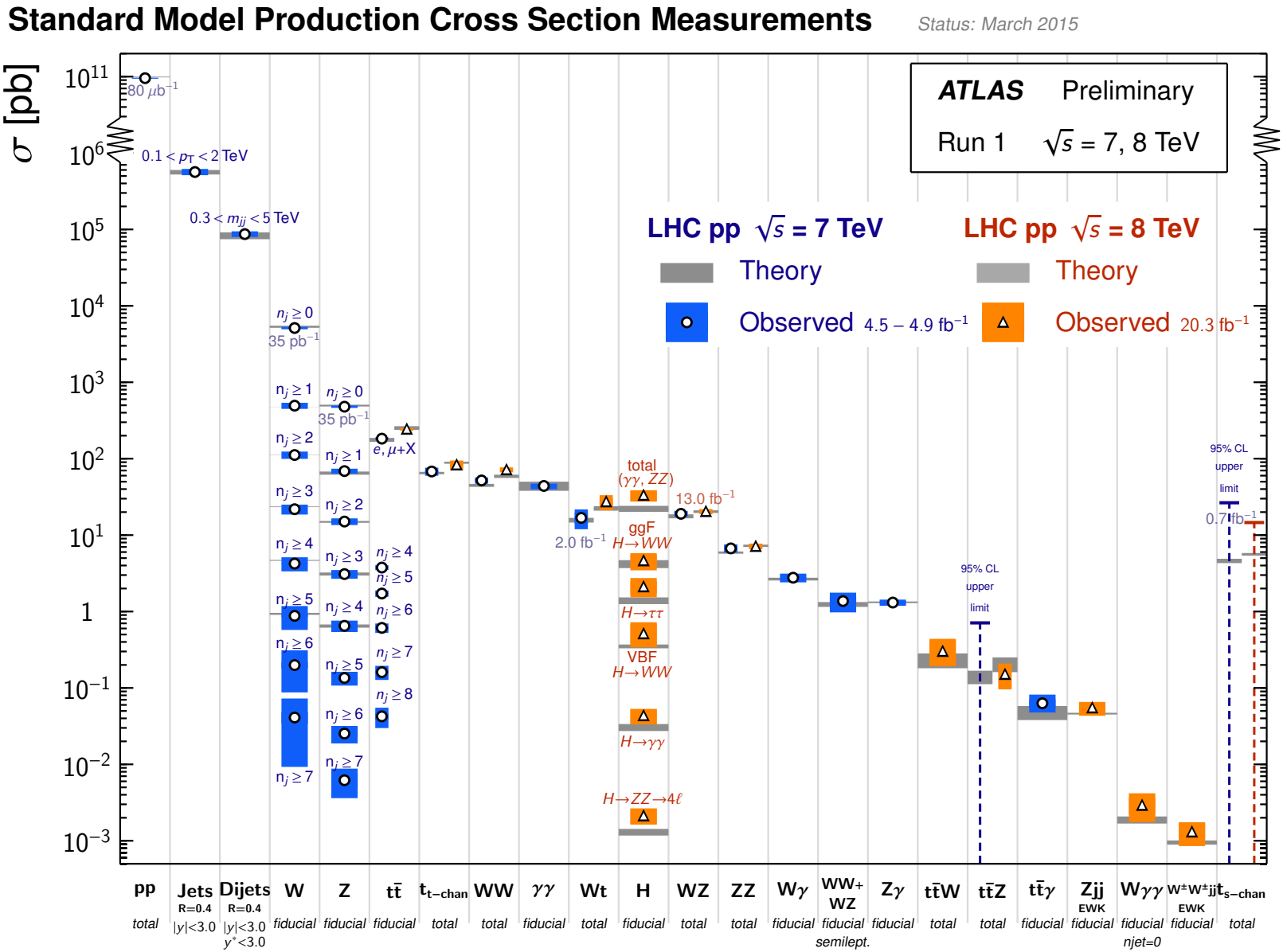
- Flavor after Belle, BaBar, Tevatron
- Flavor after LHC run I
- Expecting LHC run II
- . . . plus many precision experiments!

- This talk: Flavor between now and 25 min later

The Standard Model

– a Spectacular Success

The SM – a Spectacular Success



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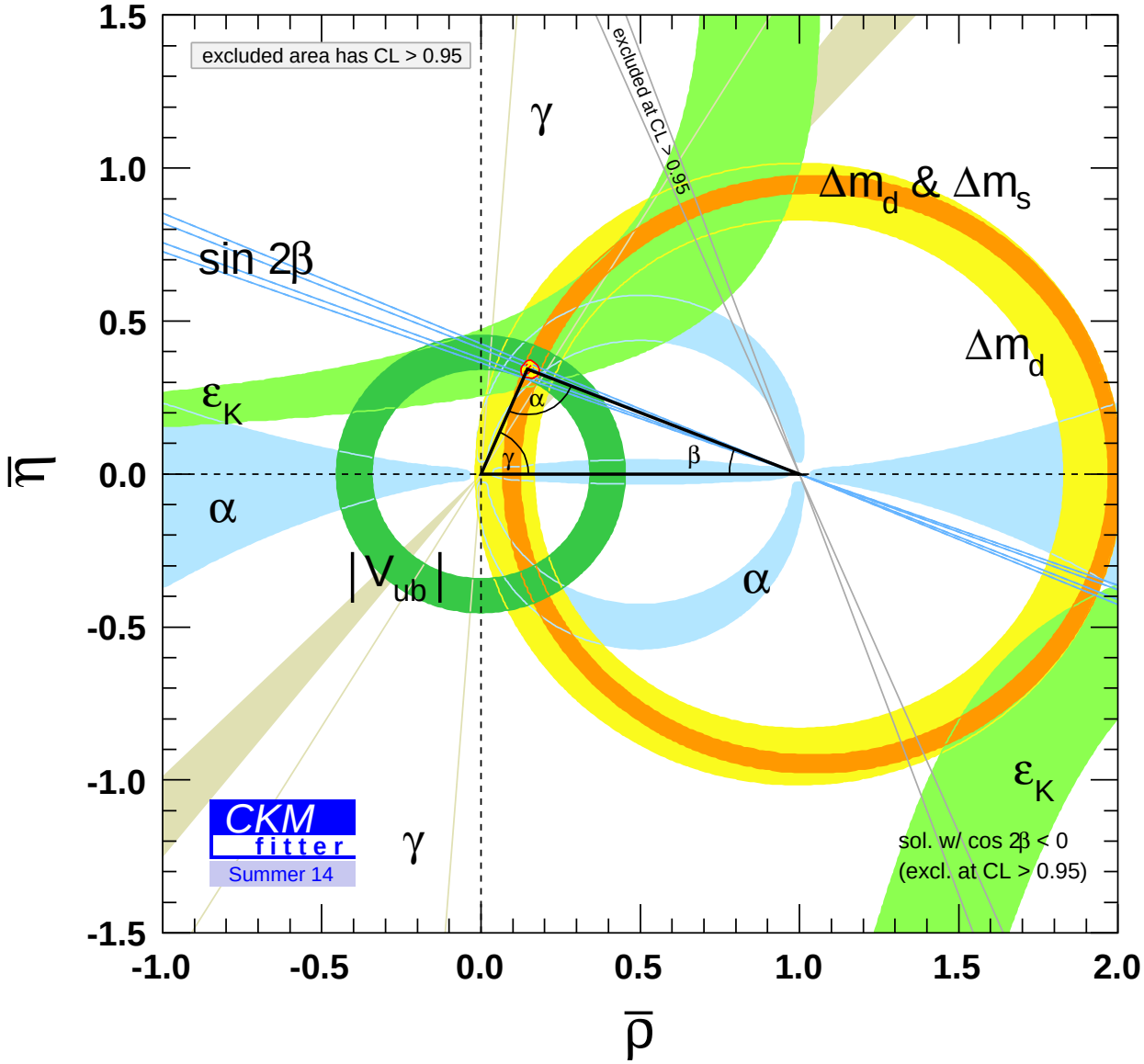

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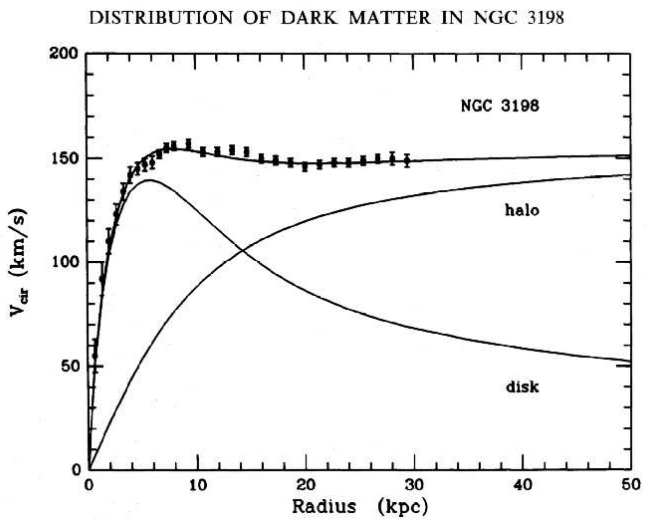
The SM – a Spectacular Failure

- What is the nature of Dark Matter?
- Baryon Asymmetry of the Universe?
- Fermion masses and mixings?
- Gravity – Hierarchy Problem?



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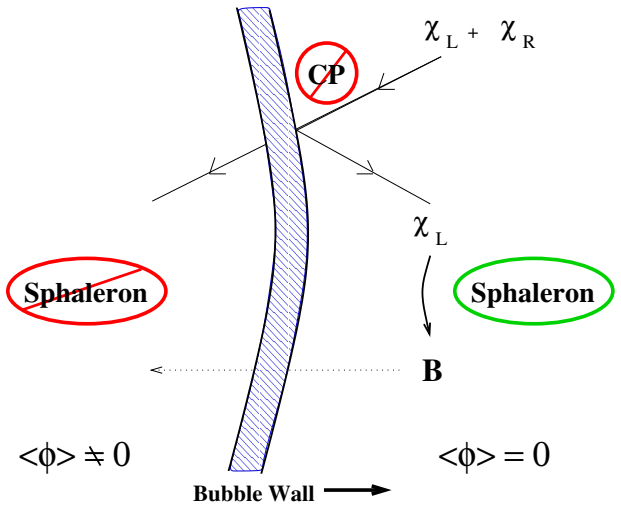

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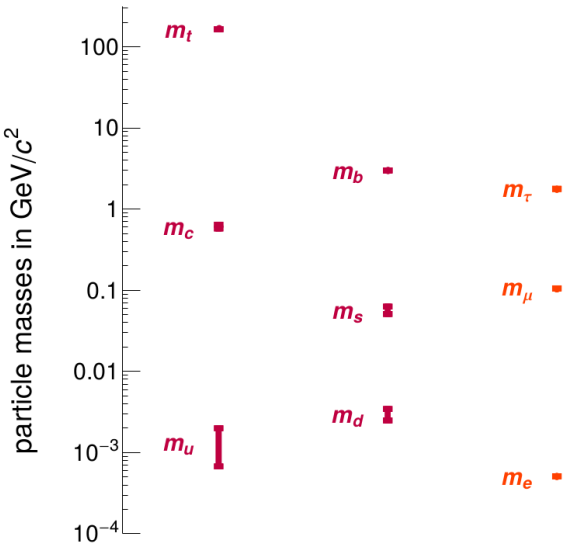

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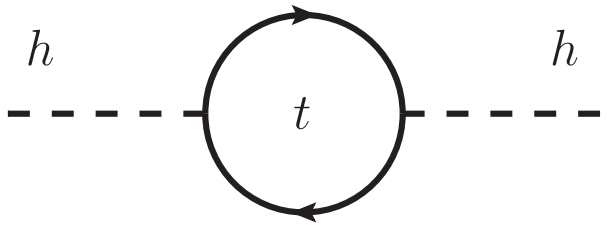


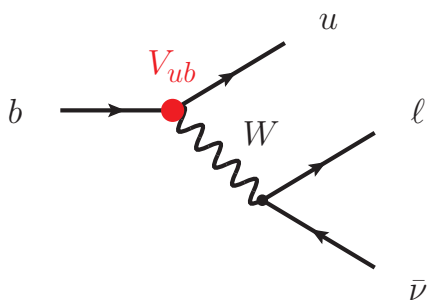
Flavor and NP

- Some models mainly address the flavor puzzle
  - Can we explain the mass hierarchies and mixing angles?
- Naturalness was driving force for model building in last decades
- Many models:
  - E.g. MSSM, warped extra dimensions, Higgs as a pNGB, ...
- All of them face constraints from flavor ("flavor problem")
  - Naturalness: $M \lesssim$ TeV
  - Flavor: $M \gtrsim 10^3$ TeV
- Modification of Higgs sector – potentially testable!

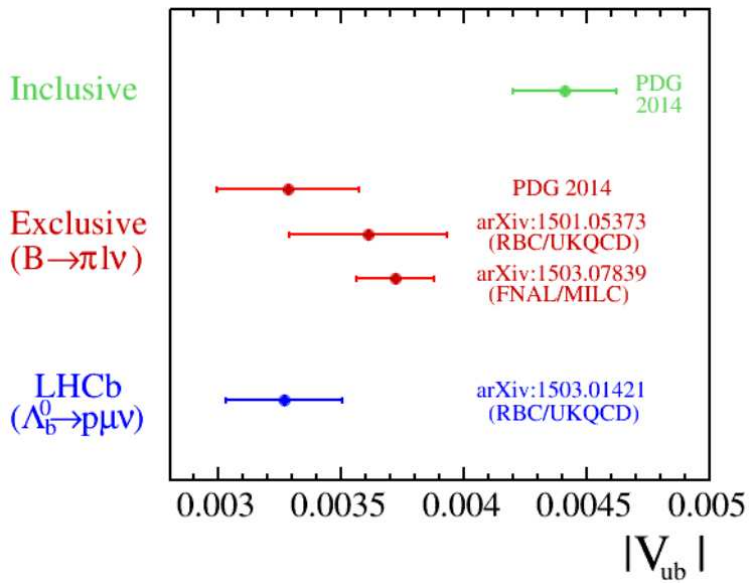
B Physics and CKM Parameters

[Talks by Johannes Albrecht, Jernej Kamenik, Christian Kiesling, Mikołaj Misiak]

- Measured in semileptonic B decays



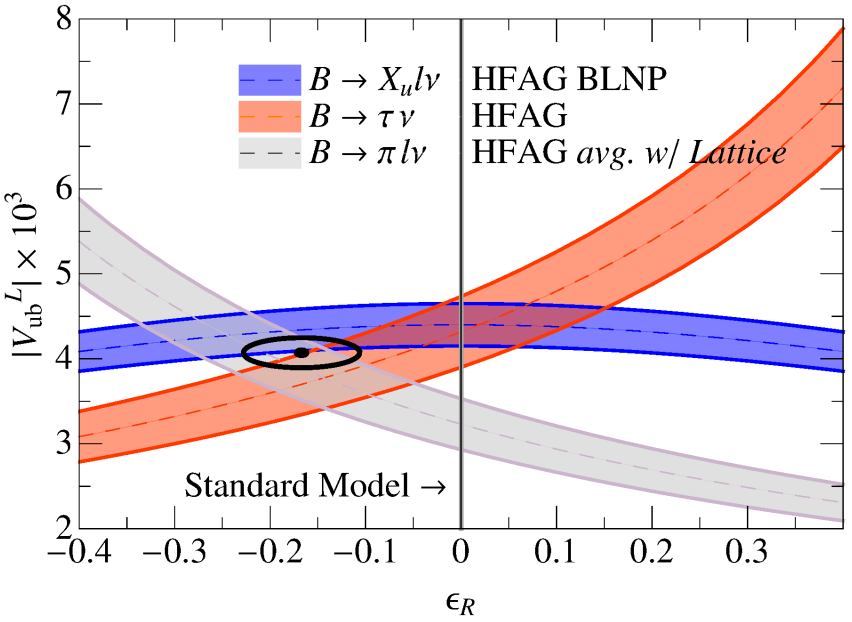
- Inclusive ($B \to X_u \ell \nu$):
  - Operator product expansion
  - Large charm background
- Exclusive ($B \to \pi \ell \nu$, $\rho \ell \nu$):
  - Form factors (lattice, QCD sum rules)
- New LHCb Λ_b measurement
  [LHCb 2015]

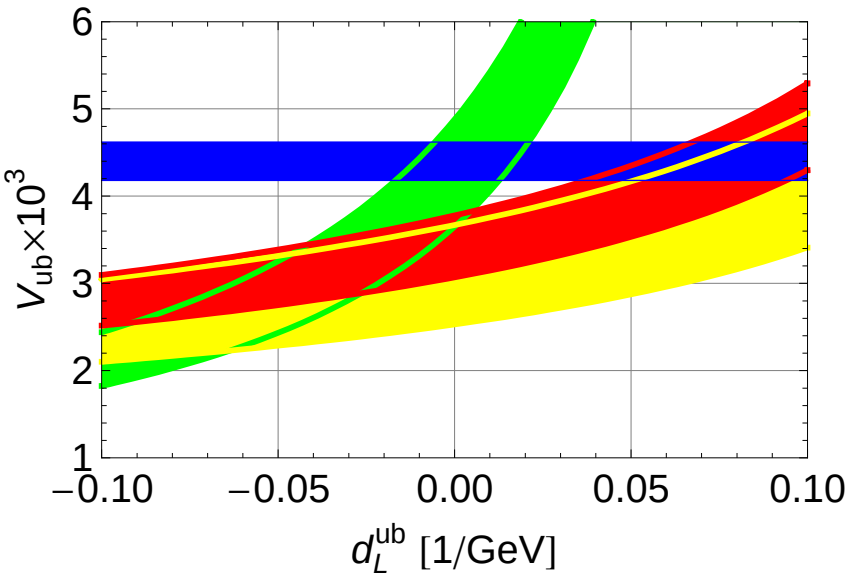


[U. Egede, Talk at MITP 2015]

$|V_{ub}|$ – Tree-level new Physics?

Blue: incl.; Red: $B \to \pi \ell \nu$, Yellow: $B \to \rho \ell \nu$, Green: $B \to \tau \nu$.

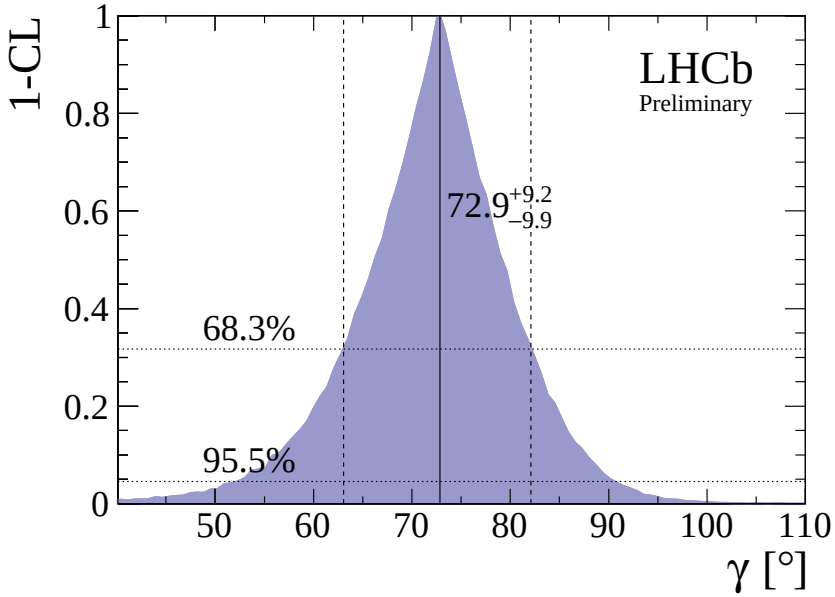




- Assume RH charged current [Bernlochner et al. 2014]
- LH tensor current in principle also possible [Crivellin et al. 2014]
  - Apart from $B \to \tau\nu$
- However excluded if NP $SU(2) \times U(1)$ invariant [Crivellin et al. 2014]

The phase of V_{ub}

- $V_{ub} \approx |V_{ub}| e^{i\gamma}$
- γ from $B \to DK$ extremely clean
  [Bigi et al. 1981; Brod et al. 2013]
- $\gamma = (73^{+\ 9}_{-10})^\circ$ [LHCb-CONF-2014-004]
- $\delta\gamma = \mathcal{O}(1^\circ)$ at LHCb / Belle II



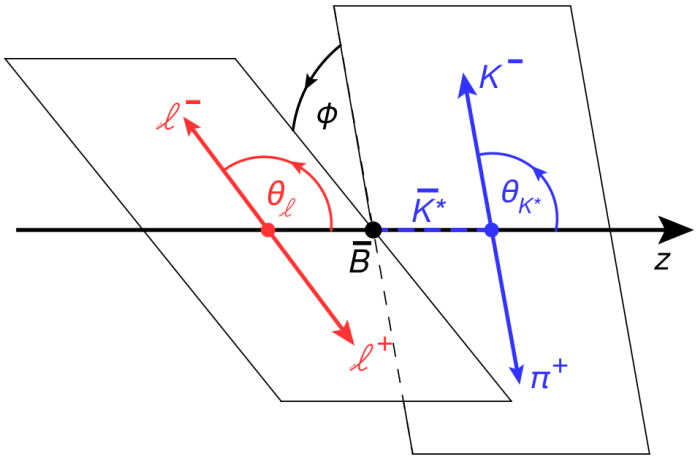
Recent Anomalies

[Talks by Javier Virto, David Straub]

Recent Anomalies?

[Talk by Sebastian Jäger]

$B \to K^* \mu^+ \mu^-$



- $B \to K^*(\to K\pi)\mu^+\mu^-$
- Four-body final state

- Can construct many differential observables
- Fit all Wilson coefficients of semileptonic weak Hamiltonian
  - $(\bar{s}\gamma_\mu P_{L/R} b)(\bar{\mu}\gamma^\mu\gamma_5\mu)$ constrained by $B_s \to \mu\mu$
  - $(\bar{s}\sigma_{\mu\nu}F^{\mu\nu}P_{L/R}b)$ constrained by $b \to s\gamma$
  - $(\bar{s}\gamma_\mu b)(\bar{\mu}\gamma^\mu\mu)$ sensitive to "non-factorizable" contributions

Lepton Universality in $B \to K \ell^+ \ell^-$

$$R_K = \frac{\Gamma(B^+ \to K^+ \mu^+ \mu^-)_{[1,6]\,\text{GeV}}}{\Gamma(B^+ \to K^+ e^+ e^-)_{[1,6]\,\text{GeV}}}$$

- Very clean SM prediction: [Bouchard et al. 2014]

$$R_K = 1.00074(35)$$

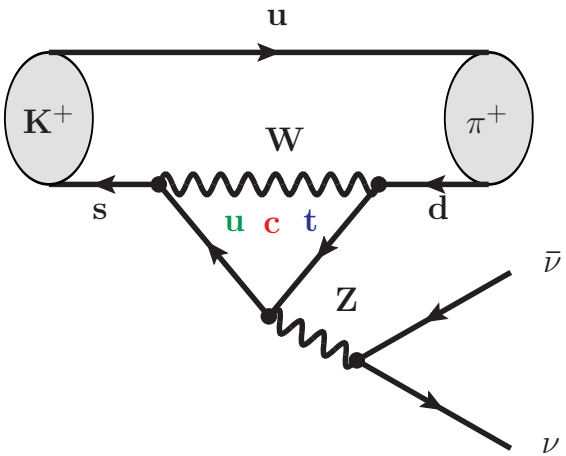
- LHCb 2014:

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

Kaon physics

[No further talk. . . need to pay attention now]

Rare K decays



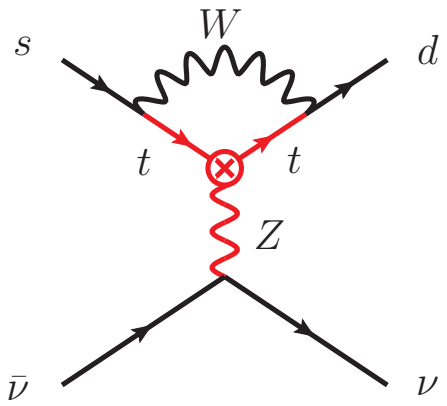
- Theoretically extremely clean:
  - SM $\mathcal{H}_{\text{eff}}$ known to NNLO QCD
    [Misiak et al., Buchalla et al. 1999; Buras et al. 2006]
    NLO EW [Brod et al. 2008, 2010]
  - Hadronic matrix elements from $K \to \pi\ell\nu$
    [Mescia et al. 2007]
  - $\mathcal{O}$(few %) theory uncertainty

$$\mathcal{H}_{\text{eff}} \propto \left[V_{cs}^* V_{cd} P_c\left(\frac{m_c^2}{M_W^2}\right) + V_{ts}^* V_{td} X_t\left(\frac{m_t^2}{M_W^2}\right)\right] \times \left(\bar{s}_L \gamma^\mu d_L\right)\left(\bar{\nu}_L \gamma_\mu \nu_L\right)$$

- $K^+ \to \pi^+ \nu\bar{\nu}$ is CP-conserving $\Rightarrow$ sensitive to $|X_t|$
- $K_L \to \pi^0 \nu\bar{\nu}$ is CP-violating $\Rightarrow$ sensitive to $\operatorname{Im} X_t$
- Correlation between two modes allows to disentagle NP scenarios

Anomalous gauge boson couplings

- E.g. $t\bar{t}Z$
- High-lumi LHC: 20 – 30 % uncertainty
  [Röntsch et al., 2014]
- Precision observables: $\sim$ few % uncertainty
  [Brod et al., 2014]
- Similarly:
  - FCNC Z couplings [Li et al., 2011; Gong et al., 2013]
  - Anomalous W couplings [Drobnak et al., 2011]
  - Triple gauge boson couplings [Bobeth et al., 2015]

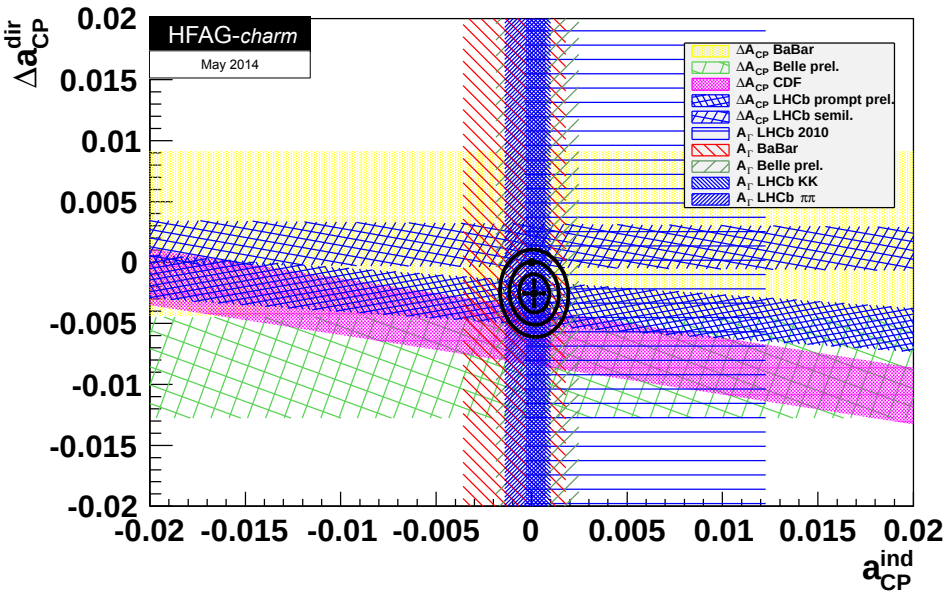


Charm

[Talk by Martin Jung]

ΔA_{CP}

$$A_f = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$



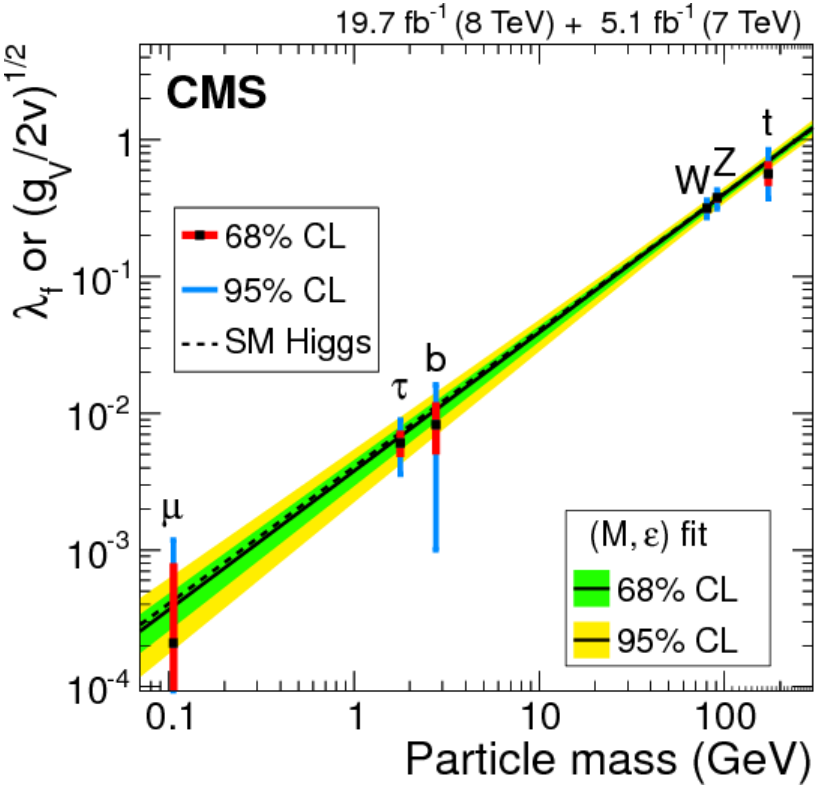
- $\Delta A_{CP} = A_{K^+K^-} - A_{\pi^+\pi^-}$
- LHCb 2011: $\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$
- LHCb 2013: $\Delta A_{CP} = (-0.15 \pm 0.16)\%$
- We still have learned something:
  - Consistent picture of singly Cabibbo-suppressed D decays
  - $SU(3)$ sum rules: e.g. CPV $D^+ \to \pi^+\pi^0$ is sign of isospin-violating NP

Higgs and Flavor

[Talks by Shikma Bressler, Gilad Perez, Admir Greljo, Emmanuel Stamou]

NP in Higgs Interactions?

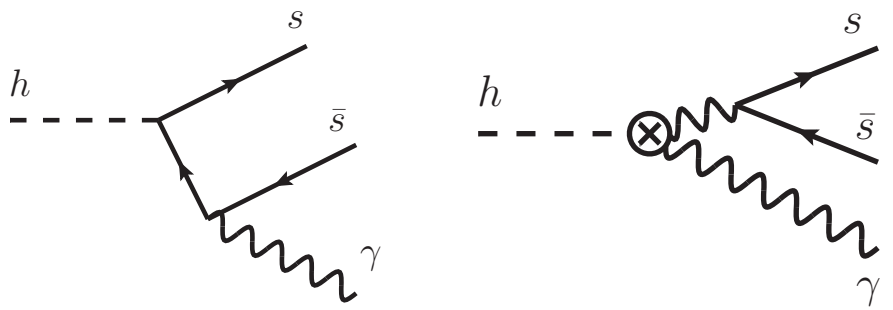
- Higgs and Flavor connected via Yukawa interactions
- Measure Yukawas
- Are there FC transitions?
- Is there *CP* violation?



[CMS, arxiv:1412.8662]

Measuring Yukawa Couplings

- Lighter Yukawas get increasingly difficult to measure
  - Global fits show y_u, y_d, y_s could be of $\mathcal{O}(y_b)$ [Kagan et al. 2014]
- Processes with off-shell Higgs and external SM particles difficult:
  - Scalar Higgs current competes with neutral currents induced by g, γ, Z
- On-shell Higgs decays (e.g. $h \to \phi\gamma$) [Kagan et al. 2014, König et al. 2015]



Electroweak Baryogenesis

- Sakharov conditions:
  - Baryon number non-conservation
  - P, CP violation
  - Thermal non-equilibrium
- A minimal setup:

$$\mathcal{L} = \frac{1}{\Lambda^2}(H^\dagger H)^3 + \frac{Z_t}{\Lambda^2}(H^\dagger H)\bar{Q}_3 H^c t_R$$

- Can we test it?

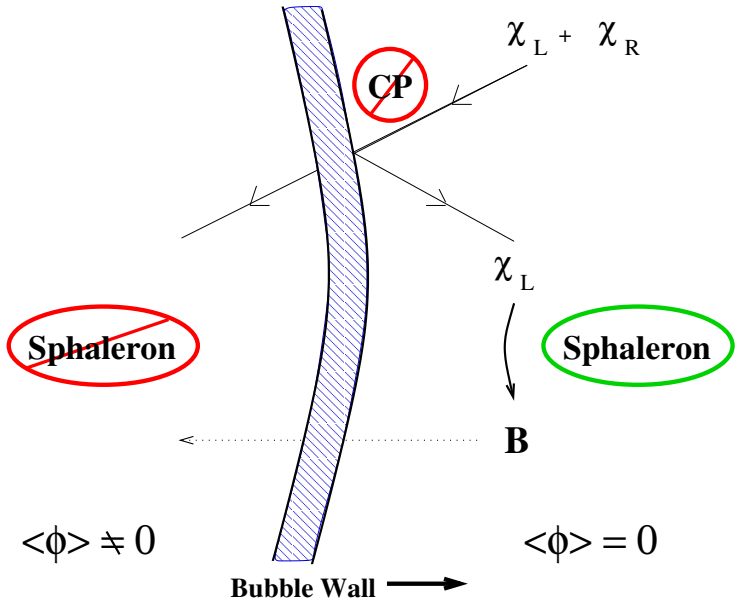
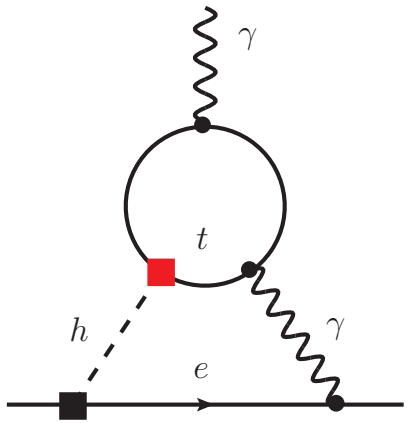
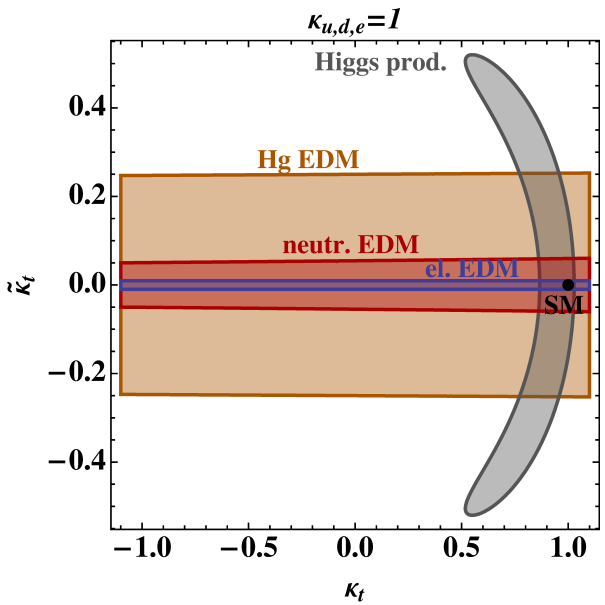


Image Credit: D. Morrisey et al.

CP violation

- Higgs CPV hard to see at colliders
  - Study angular correlations, e.g.
    - $pp \to h + 2j$
      [Del Duca et al. 2006; Klamke et al. 2007]
    - $h \to \tau\tau$ [Harnik et al. 2013]
    - $h \to \gamma\gamma$ [Bishara et al. 2013]
    - $h \to bb$ [Galanti et al. 2015]
  - Need high statistics
- Main constraints from EDMs
  - Can we distentangle different contributions?





[Brod et al. 2013]

New Physics / Leptons

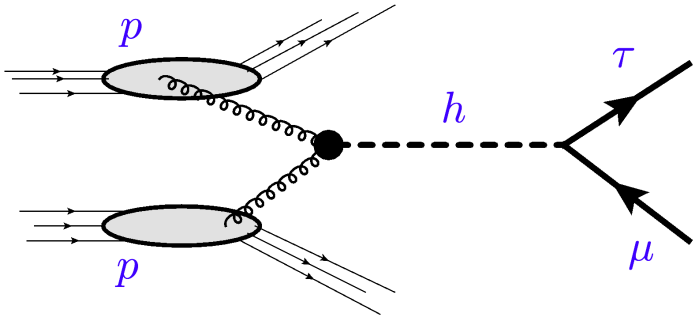
[Talks by Tobias Golling, Philippe Mermod, Emilie Passemar, Maxim Pospelov, Frank Rathmann, Yael Shadmi, Adrian Signer, Robert Ziegler]

$h \to \tau\mu$ at CMS

- CMS has hint for $h \to \tau\mu$
- Bound $\mathrm{BR}(h \to \tau\mu) < 1.57\%$

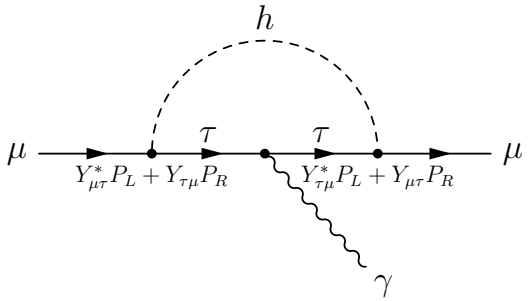
  $\Rightarrow \sqrt{Y^2_{\tau\mu} + Y^2_{\mu\tau}} < 3.6 \times 10^{-3}$

  [Zupan 2015]



- $\tau \to \mu\gamma$, $\tau \to 3\mu$, $(g-2)_\mu$, μEDM allow for $\mathrm{BR}(h \to \tau\mu) = \mathcal{O}(10\%)$

  [Harnik et al. 2012]

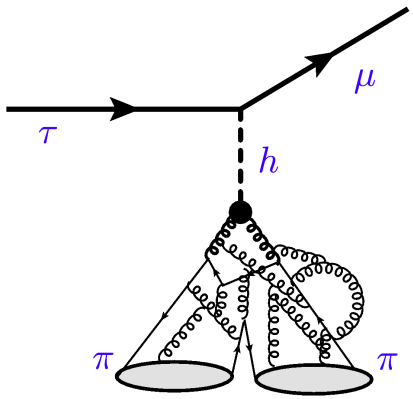


- "Most direct" indirect constraint: $\tau \to \mu\pi\pi$

  [Celis et al. 2013]

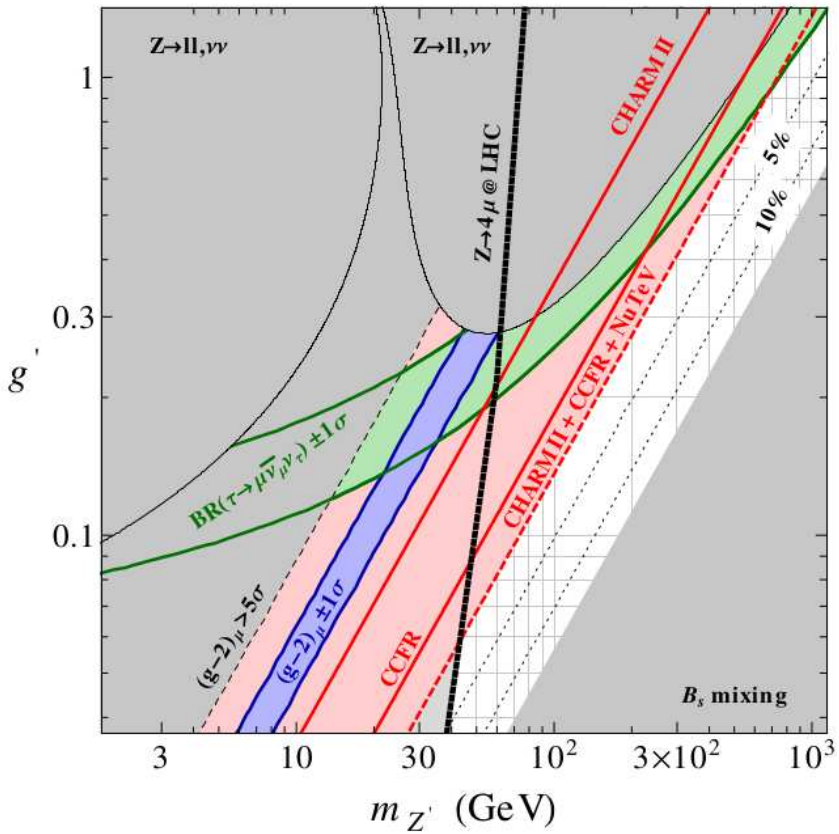
- CMS result implies

  $\mathrm{BR}(\tau \to \mu\pi^+\pi^-) < 1.6 \times 10^{-11}$



Light New Physics

- Examples for light NP:
  - Dim.-4 operators ("portals")
  - Gauged $B - L$, $L_\mu - L_\tau$



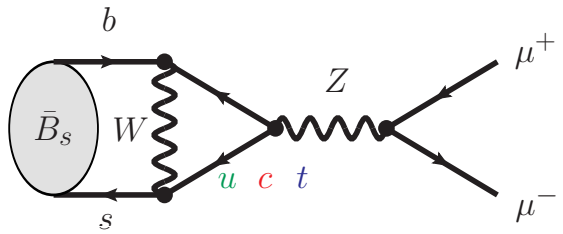
[Altmannshofer et al. 2014]

New Physics and EFT

[Talk by Oscar Catá]

Consequences of LHC run I for Flavor Physics

- E.g. $B_s \to \mu^+\mu^-$

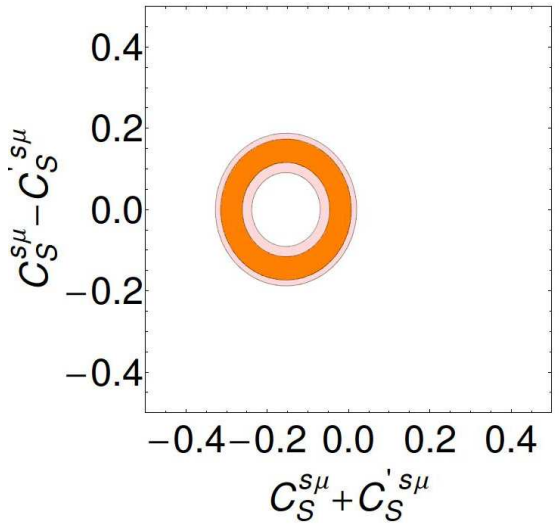


- Four scalar operators:

$$Q_S^{(\prime)} = m_b\left(\bar{s}P_{R(L)}b_R\right)\left(\bar{\ell}\ell\right), \quad Q_P^{(\prime)} = m_b\left(\bar{s}P_{R(L)}b\right)\left(\bar{\ell}\gamma_5\ell\right)$$

- $SU(2) \times U(1)$ imposes two relations
  $C_s = -C_P$, $C_s' = C_P'$
  [Camalich et al. 2014]

- No tensor operators
- Can be evaded if NP is strongly coupled
  [Catá et al. 2015]



Outlook

[Talk by Andrzej Buras]

Summary

- We know the SM must break down at some point
- Many directions of attack
- Combine all information
- Looking forward to more detailed talks...
- ...and many discussions during the next four weeks