From Flavor to Collider – and Back

Workshop on Implications of LHCb Measurements

CERN
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Plan of Talk

1. The questions
2. Flavor ⇒ Collider
   $A^t_{\rm FB}$ and $\Delta A_{\rm CP}$
3. Collider ⇒ Flavor
   High scale gauge mediation

The Questions

High p_T questions

- What is the mechanism of electroweak symmetry breaking?
- What separates the electroweak scale from the Planck scale?
- What happened at the electroweak phase transition?
- What are the dark matter particles?
- How was the baryon asymmetry generated?

Flavor questions

- The Standard Model flavor puzzle:
  Why are the flavor parameters small and hierarchical?
  (Why) are the neutrino flavor parameters different?
- The New Physics flavor puzzle:
  If there is NP at the TeV scale, why are FCNC so small?
  The solution $\Longrightarrow$ Clues for the subtle structure of the NP
- Are the two puzzles related?

The SM Flavor Puzzle

$$Y_t \sim 1, \quad Y_c \sim 10^{-2}, \quad Y_u \sim 10^{-5}$$
$$Y_b \sim 10^{-2}, \quad Y_s \sim 10^{-3}, \quad Y_d \sim 10^{-4}$$
$$Y_\tau \sim 10^{-2}, \quad Y_\mu \sim 10^{-3}, \quad Y_e \sim 10^{-6}$$
$$|V_{us}| \sim 0.2, \quad |V_{cb}| \sim 0.04, \quad |V_{ub}| \sim 0.004, \quad \delta_{\rm KM} \sim 1$$

- For comparison: $g_s \sim 1, \quad g \sim 0.6, \quad g' \sim 0.3, \quad \lambda \sim 1$
- SM flavor parameters have structure: smallness + hierarchy
- Why? = The SM flavor puzzle
  - Approximate symmetry? [Froggatt-Nielsen]
  - Strong dynamics? [Nelson-Strassler]
  - Location in extra dimension? [Arkani-Hamed-Schmaltz]
  - ?

The NP Flavor Puzzle

$$\frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\rm NP}^2}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu b_L)^2$$

For $\Lambda_{\rm NP} \sim$ TeV: $z_{sd} < 10^{-8},\ z_{cu} < 10^{-7},\ z_{bd} < 10^{-6},\ z_{bs} < 10^{-4}$

- TeV-scale NP flavor parameters must have structure: degenracy and/or alignment
- Why? = The NP flavor puzzle

A partial list for the SUSY flavor puzzle:

- Gauge mediation? [Dine-Nelson]
- Heavy first two s-generations? [Cohen-Kaplan-Lepeintre-Nelson]
- Abelian symmetry? [Nir-Seiberg]
- Non-Abelian symmetry? [Dine-Leigh-Kagan]
- ?

The Interplay

- Flavor $\Longrightarrow$ Collider:
  Are NP models that explain collider data viable?
  How to look for further signals?

- Collider $\Longrightarrow$ Flavor:
  Spectrum and flavor decomposition of new particles;
  Are NP models that explain flavor data viable?

$$\boxed{A_{\rm FB}^t \;\Leftrightarrow\; \Delta A_{\rm CP}}$$

Blum, Hochberg, Nir, 1107.4350; Hochberg, Nir, 1112.5268

$A^t_{\rm FB}$

- CDF: $A^t_{\rm FB}(m_{t\bar t} > 450\ {\rm GeV}) = 0.47 \pm 0.11$
- SM: $A^t_{\rm FB}(m_{t\bar t} > 450\ {\rm GeV}) = 0.09 \pm 0.01$
- Suggestive of a new boson-mediated tree-level $u\bar u \to t\bar t$
- Scalars: t-channel exchange of one of $(1,2), (8,2), (\bar 6,1), (\bar 6,3), (3,1), (3,3)$
- All colored rep's in tension with other t-related measurements
- Focus on $\Phi(1,2)_{-1/2}$ with $m \sim 100$ GeV and $\lambda_{\phi ut} \sim 1$

Flavor constraints

Consider $m_\phi \sim 100$ GeV, $\lambda_{\phi ut} \sim 1$:

- $\lambda(\overline{u_L} t_R \phi^0 + V^*_{ui} \overline{d_{Li}} t_R \phi^-)$:
  Excluded by $\Delta m_K^\phi \sim 10^3 \Delta m_K^{\rm exp}$
- $\lambda(\overline{d_L} t_R \phi^- + V_{id} \overline{u_{Li}} t_R \phi^0)$:
  Excluded by $\Delta m_D^\phi \sim 10^3 \Delta m_D^{\rm exp}$
- $\lambda(\overline{t_L} u_R \phi^0 + V^*_{ti} \overline{d_{Li}} u_R \phi^-)$:
  Excluded by ${\rm BR}(\overline{B^0} \to \pi^+ K^-)^\phi \sim 200 \times {\rm BR}(\overline{B^0} \to \pi^+ K^-)^{\rm exp}$
- Focus on $\lambda(\overline{b_L} u_R \phi^- + V_{ib} \overline{u_{Li}} u_R \phi^0)$

Flavor 'predictions'

- Consider $\lambda(\overline{b_L} u_R \phi^- + V_{ib}\overline{u_{Li}} u_R \phi^0)$
- Generates $\frac{4|\lambda|^2 V_{ub} V^*_{cb}}{m^2_\phi}(\overline{u_R} c_L)(\overline{u_L} u_R)$
- Predicts $\Delta A^\phi_{\rm CP} = 2\sqrt{2}(G_0/G_F) I_{\rm CKM} I_{\rm QCD} \sim (0.02 - 0.07) I_{\rm QCD}$
  - $G_0 \equiv \frac{4|\lambda|^2}{m^2_\phi} = (10-30) \times \frac{G_F}{\sqrt{2}}$
  - $I_{\rm CKM} \equiv 2\mathcal{I}m\left(\frac{V_{ub}V^*_{cb}}{V_{us}V^*_{cs}}\right) \sim 0.001$
- Guess $I_{\rm QCD} \sim f_D/m_D \Longrightarrow |\Delta A^\phi_{\rm CP}| \sim 0.005$

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$$\Delta A_{CP} = \begin{cases} -(8.2\pm 2.4)\times 10^{-3} & [\text{LHCb, 1112.0938}] \\ -(6.2\pm 2.3)\times 10^{-3} & [\text{CDF, note 10784}] \end{cases}$$

Back to collider

- Large cross section for $ug \to t\phi^0$
- Leading decay mode is $\phi^0 \to c\bar{u}$
- Large contribution to $1b/2b$ in top production measurements
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Additional potential problems:

- ϵ'/ϵ Isidori, Kamenik, Ligeti, Perez, 1111.4987
- $t \to u\phi$
- Atomic parity violation Gersham, Kim, Tulin, Zurek, 1203.1320

Supersymmetric $\Delta A_{\rm CP}$

Explaining $|\Delta A_{\rm CP}| \sim 0.006$ with supersymmetry:

- Possible via large chromomagnetic operator C_{8g}

Kagan, Grossman, YN, PRD 75 (2007) 036008

- Possible via large LR mass insertion: $\mathcal{I}m[(\delta^u_{LR})_{12}] \sim 0.001$
- Typically, in non-MFV supersymmetry, $(\delta^u_{LR})_{12} \sim \frac{\tilde a}{\tilde m}\frac{m_c|V_{us}|}{\tilde m}$
- Large $\tilde a/\tilde m$ favored

Giudice, Isidori, Paradisi, arXiv:1201.6204

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Explaining $m_H \sim 125$ GeV with supersymmetry:

- Large $\tilde a/\tilde m$ favored

Flavor@ATLAS/CMS

Flavor at ATLAS/CMS???

- ATLAS/CMS are not optimized for flavor

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But...

- They can identify $e, \mu, (\tau)$
- They can tell 3rd generation quarks (b, t) from light quarks

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But...

- If new particles that couple to the SM fermions are discovered –
  $\Longrightarrow$ New flavor parameters can be measured
  - Spectrum
  - Flavor decomposition

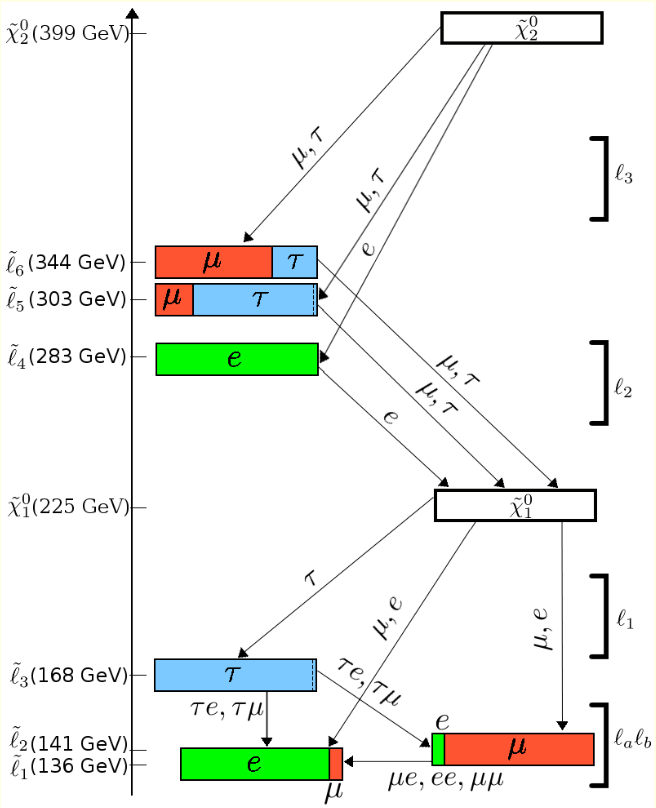
Gauge+Gravity Mediation

- Example: High (but not too high) scale gauge mediation
  - Gravity mediation sub-dominant but non-negligible
  - $r = \frac{\text{gravity-med}}{\text{gauge-med}} \sim \left(\frac{\pi m_M}{\alpha m_P}\right)^2 \frac{1}{n_M}$
  - $\widetilde{M}^2_{\tilde{E}_{L,R}}(m_M) = \tilde{m}^2_{\tilde{E}_{L,R}}(\mathbf{1} + rX_{\tilde{E}_{L,R}})$
  - Degeneracy depends on r

Assume: The flavor structure of X determined by FN:

- $X_{\tilde{E}_L} \sim \begin{pmatrix} 1 & U_{e2} & U_{e3} \\ \cdot & 1 & U_{\mu 3} \\ \cdot & \cdot & 1 \end{pmatrix}; \quad X_{\tilde{E}_R} \sim \begin{pmatrix} 1 & \frac{m_e/m_\mu}{U_{e2}} & \frac{m_e/m_\tau}{U_{e3}} \\ \cdot & 1 & \frac{m_\mu/m_\tau}{U_{\mu 3}} \\ \cdot & \cdot & 1 \end{pmatrix}$
- Mixing depends only on X which is related to the SM flavor

SUSY flavor parameters from $\tilde{\ell}_1, e, \mu$



	True	Measured
$\tilde{\ell}_1$	135.83 GeV	135.9 ± 0.1 GeV
χ_1^0	224.83 GeV	225.10 ± 0.04 GeV
$\Delta m(\tilde{\ell}_{1,2})$	4.95 GeV	5.06 ± 0.06 GeV
$\tilde{\ell}_4$	282.86 GeV	283.1 ± 0.2 GeV
$\tilde{\ell}_5$	303.41 GeV	306 ± 1 GeV
$\tilde{\ell}_6$	343.53 GeV	341 ± 1 GeV
$\lvert K_{e2}/K_{\mu 2}\rvert^2$	0.069	0.054 ± 0.008

[Feng, Lester, Nir, Shadmi *et al.*, PRD77(2008)076002; PRD80(2009)114004; JHEP01(2010)047]

Lessons from $\tilde{\ell}_1, e, \mu$

- Determine $\frac{m(\tilde{\ell}_2)-m(\tilde{\ell}_1)}{m(\tilde{\ell}_2)+m(\tilde{\ell}_1)}$ and $K_{e2}K_{\mu 2}$:
  It is consistent with $\mu \to e\gamma$?
  How the SUSY flavor problem is solved

- Determine Δm_{21}, Δm_{54}, ...:
  What is messenger scale of gauge mediation (M_m)?
  Probe physics at $M_m \sim 10^{15}$ GeV

- Determine $|K_{e2}/K_{\mu 2}|$:
  Is the FN mechanism at work?
  How the SM flavor puzzle is solved

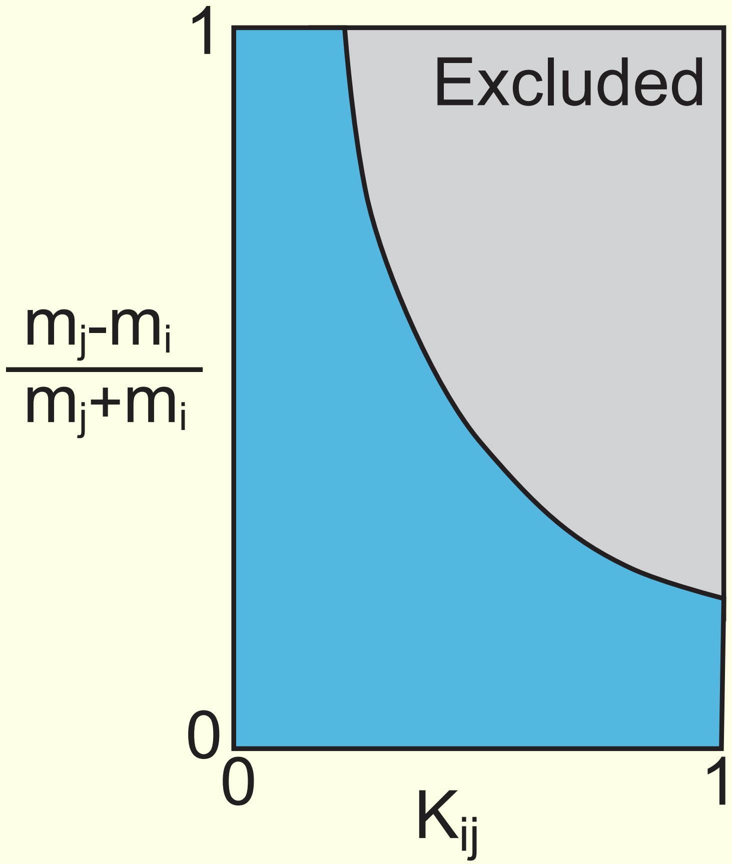
The role of flavor factories (FF)

ATLAS/CMS and flavor factories give complementary information

- In the absence of NP at ATLAS/CMS:
  flavor factories will be crucial to find $\Lambda_{\rm NP}$
- Consistency between ATLAS/CMS and FF:
  necessary to understand the NP flavor puzzle
- NP in $c \to u$? $s \to d$? $b \to d$? $b \to s$? $t \to c$? $t \to u$?
  $\mu \to e$? $\tau \to \mu$? $\tau \to e$?
  - MFV?
  - Structure related to SM?
  - Structure unrelated to SM?
  - Anarchy?

[Hiller, Hochberg, Nir, JHEP0903(09)115; JHEP1003(10)079]]

Summary



Flavor Factories

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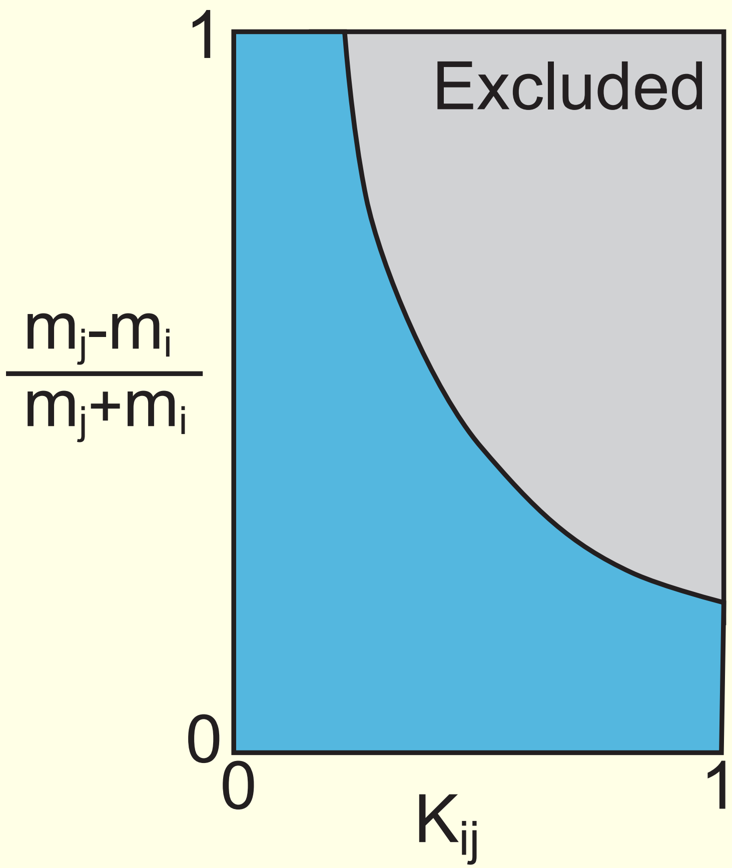

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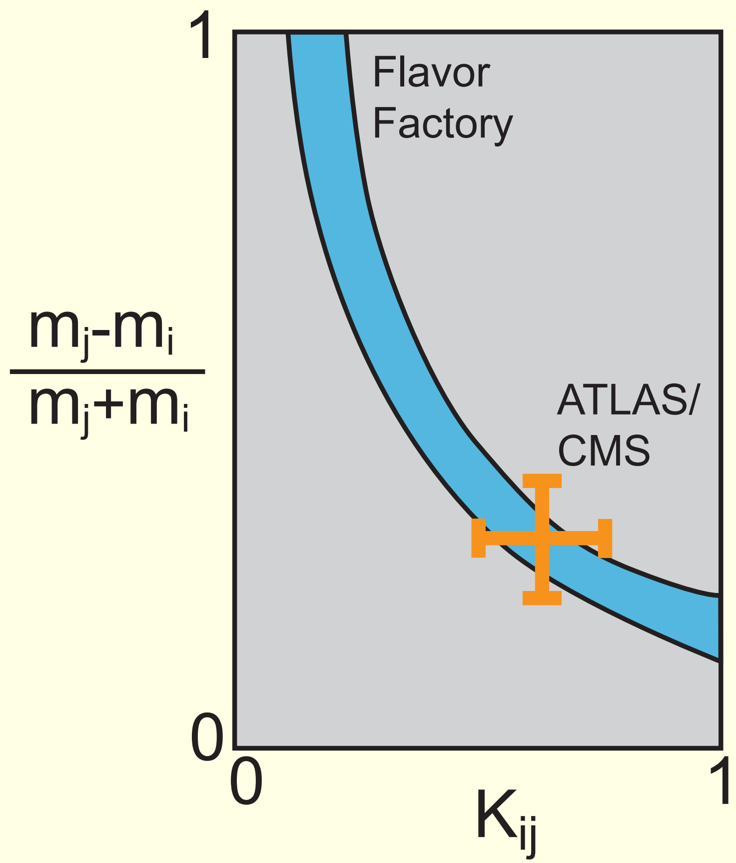

FF+ATLAS/CMS

[Grossman, Ligeti, Nir, PTP122(09)125 [0904.4262]]

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