Flavor and Funparticles From F-Theory

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Mainly Based On...

Flavor

- hep-th/0802.3391 w/ C. Beasley, C. Vafa
- hep-th/0811.2417 w/ C. Vafa
- hep-ph/0904.1419 w/ V. Bouchard, J. Seo, C. Vafa
- hep-ph/0910.0477 w/ S. Cecotti, M. Cheng, C. Vafa

Funparticles

- hep-th/1006.5459 w/ C. Vafa
- hep-th/1103.3287 w/ C. Vafa, B. Wecht
- hep-ph/1108.3849 w/ P. Kumar, C. Vafa, B. Wecht
- hep-ph/1204.3640 w/ P. Kumar, B. Wecht

Motivation / Review

Question:

Do Strings Lead To Standard Model + ...?

Question:

Do Strings Lead To Standard Model + ...?

An Unsatisfying Answer:

The Landscape allows for "everything"

so yes...

Why Unsatisfying?

Much as in a math proof:

“Existence” is not “constructive”

What Ingredients go into the Standard Model?

Are certain ingredients correlated?

Predictions?

Strings can point the way to plausible scenarios beyond the Standard Model

Saying more than this is less clear...

Focus of Talk

Main Focus: F-Theory GUTs

What looks simple / natural

Explain:

What looks difficult / contrived

(Instantons in F-theory: see M. Cvetič's talk)

Simplification # 1:

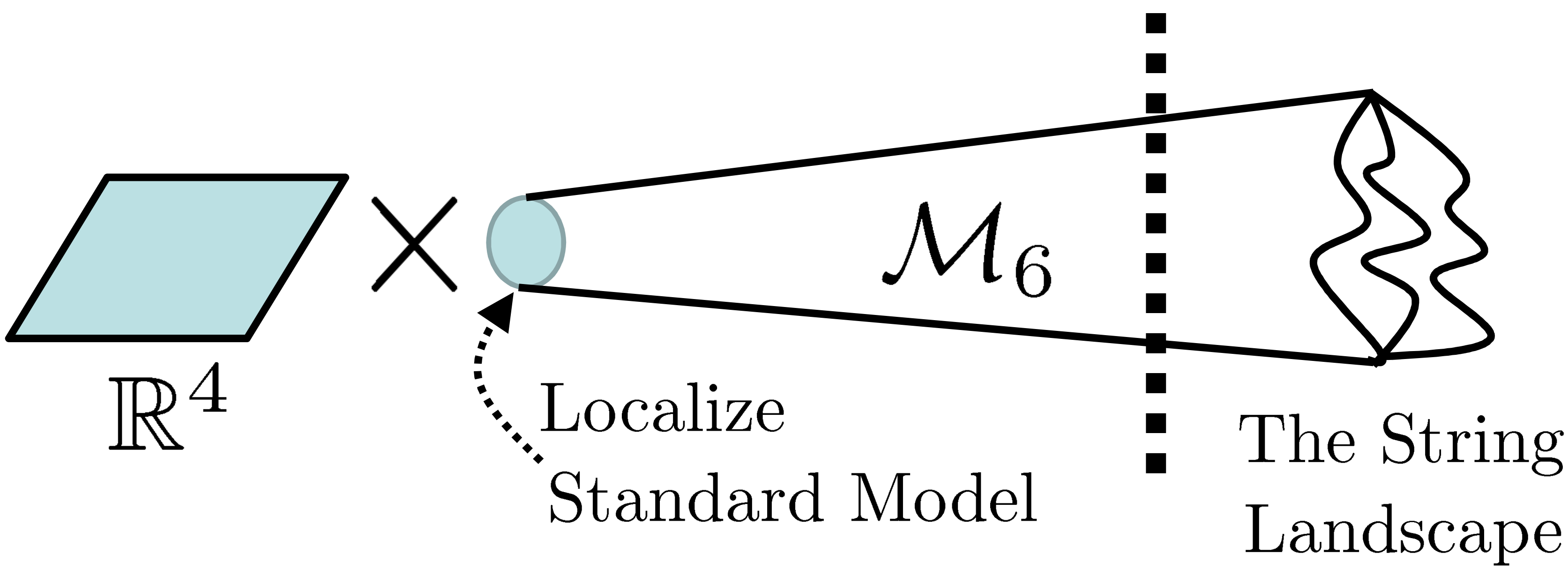
"Local Model Building"

see e.g. Antoniadis, Kiritsis, Tomaras '00
Aldazabal, Ibanez, Quevedo, Uranga '00
Berenstein Jejjala Leigh '01, Verlinde Wijnholt '05
Beasley JJH Vafa '08, Donagi Wijnholt '08, JJH Verlinde '10

Simplification # 1:

Use Extra Dimensions to separate the

Standard Model from the Landscape:



Simplification # 2:

E_8 Symmetry for SM matter and interactions

$E_8 \supset SU(5)_{GUT} \times SU(5)_{\perp}$

$$
\begin{aligned}
248 \rightarrow\ & +(\overline{10}, 5) + (10, \overline{5}) \\
& +(5, 10) + (\overline{5}, \overline{10}) \\
& +(24, 1) + (1, 24)
\end{aligned}
$$

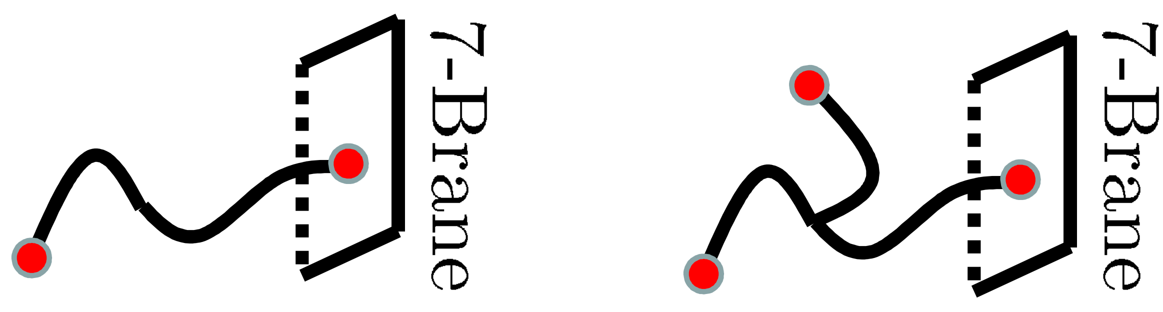
Charged Matter

Extra Singlets

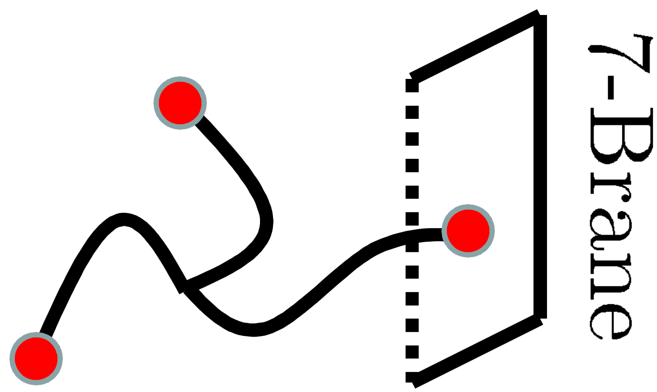
Basic Idea

Localization and E_8 symmetry naturally combine in "F-theory"

F-theory = Strongly coupled formulation of type IIB Superstrings



Main Ingredient: 7-Branes

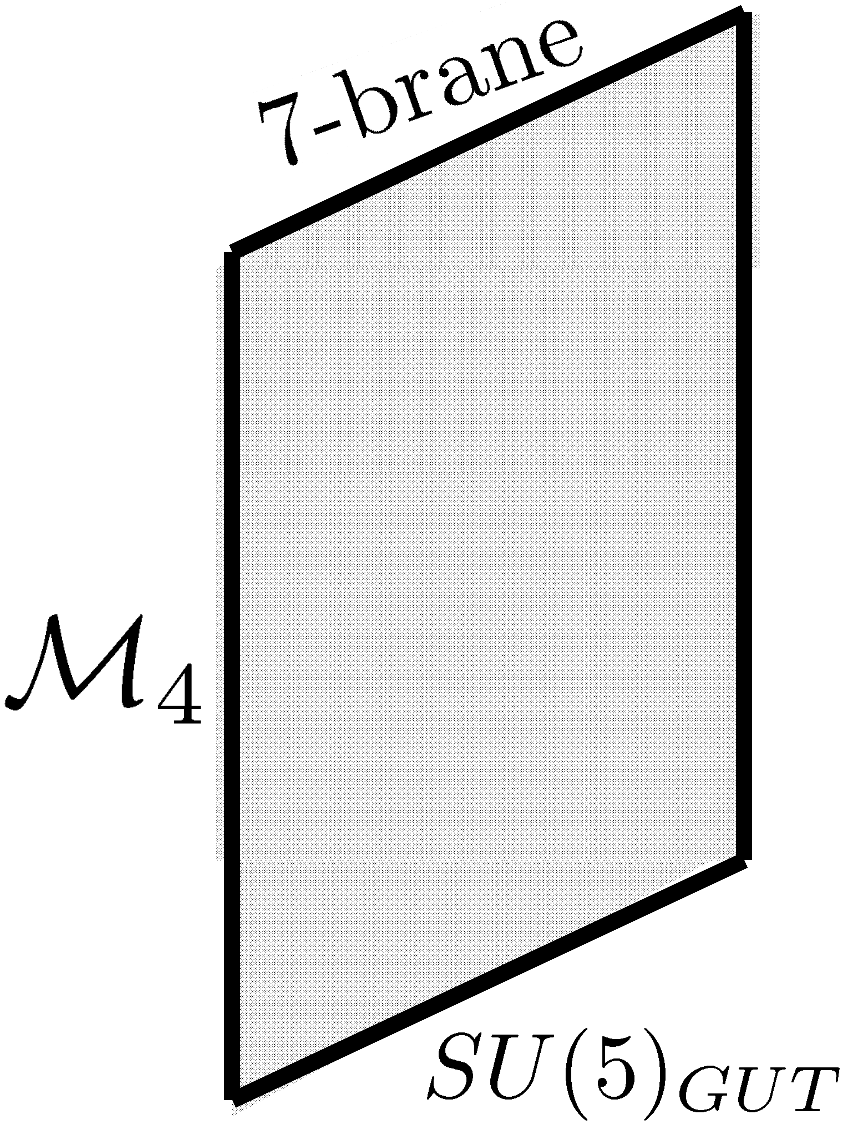


7-Brane Fills

Time $\times$ 7 Spatial

	$\mathbb{R}^{3,1}$				$\mathcal{M}_6$					
	0	1	2	3	4	5	6	7	8	9
7_{GUT}	×	×	×	×	×	×	×	×		

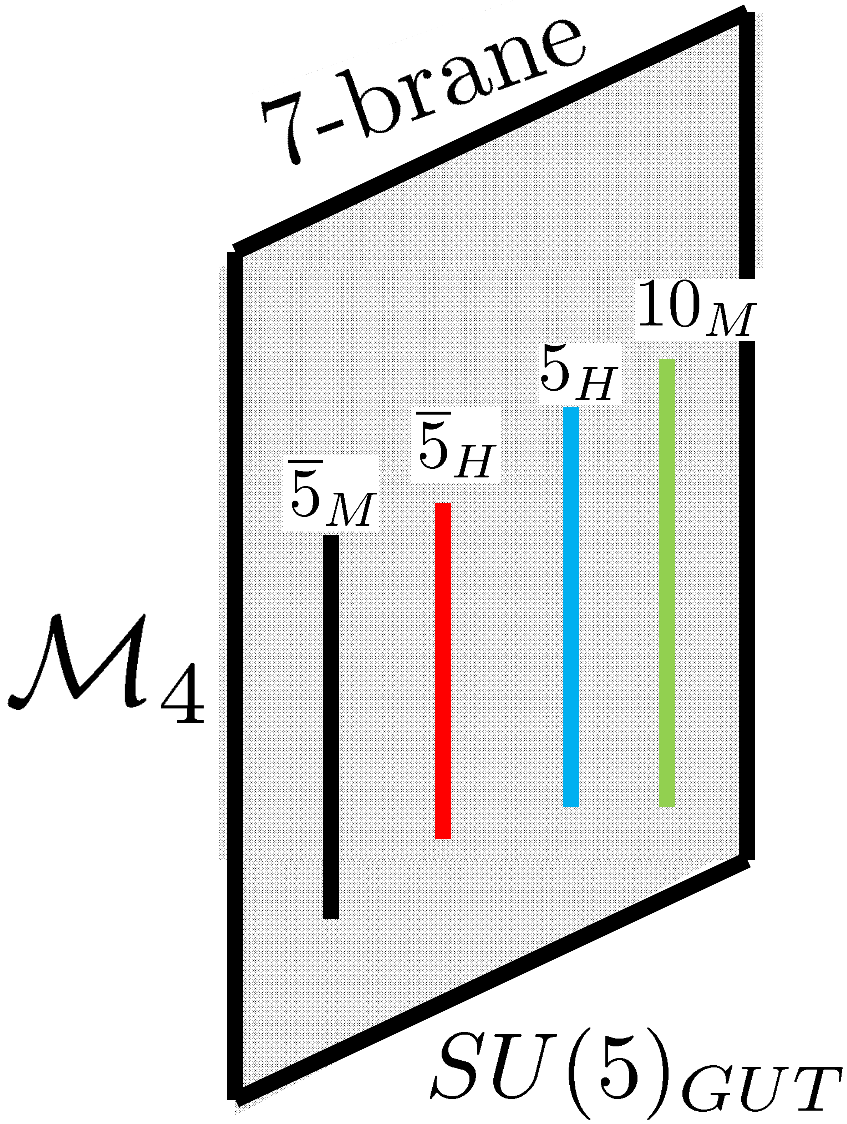
Building an F-GUT

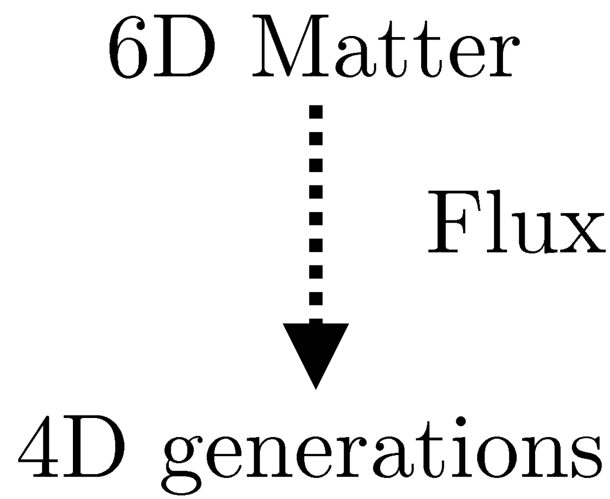


8D Gauge Group: $SU(5)$

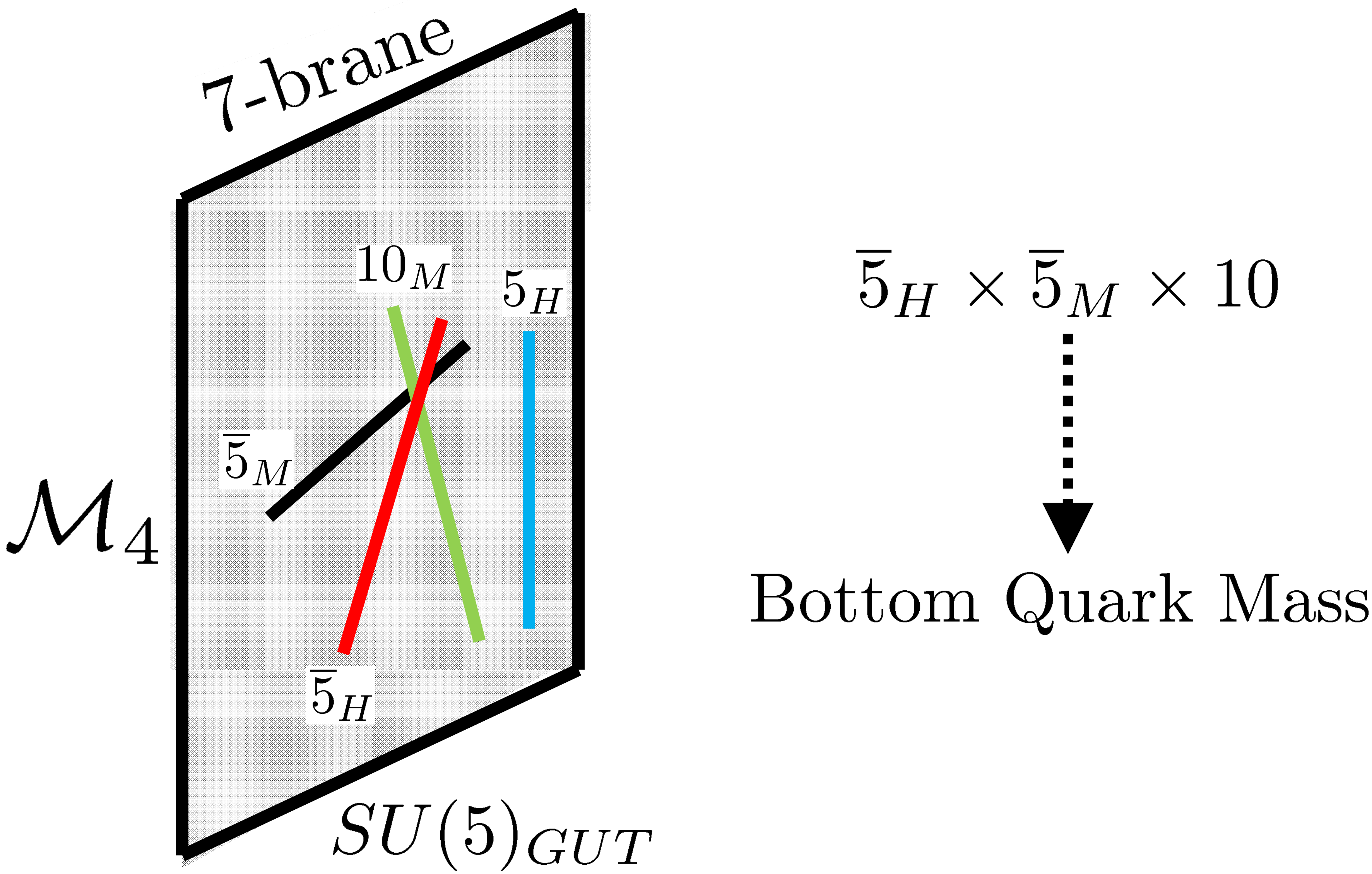
4D Gauge Group: G_{SM}

Building an F-GUT

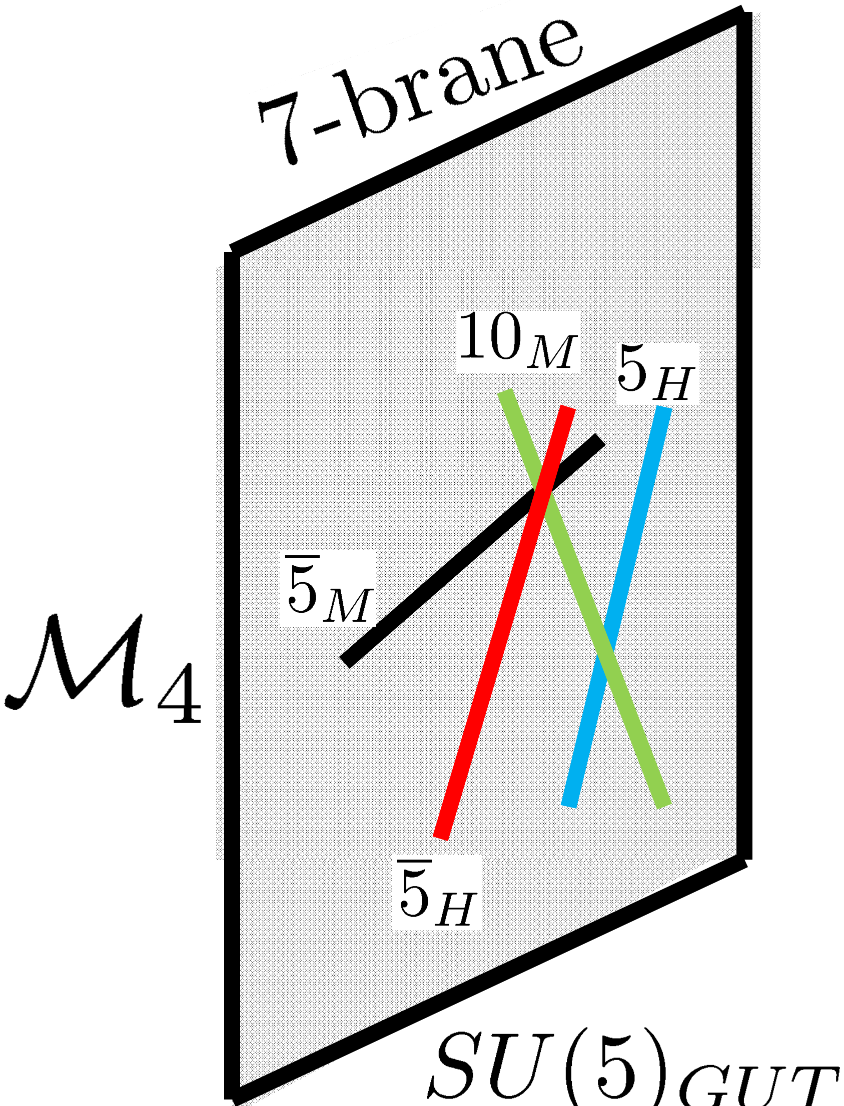




Building an F-GUT



Building an F-GUT

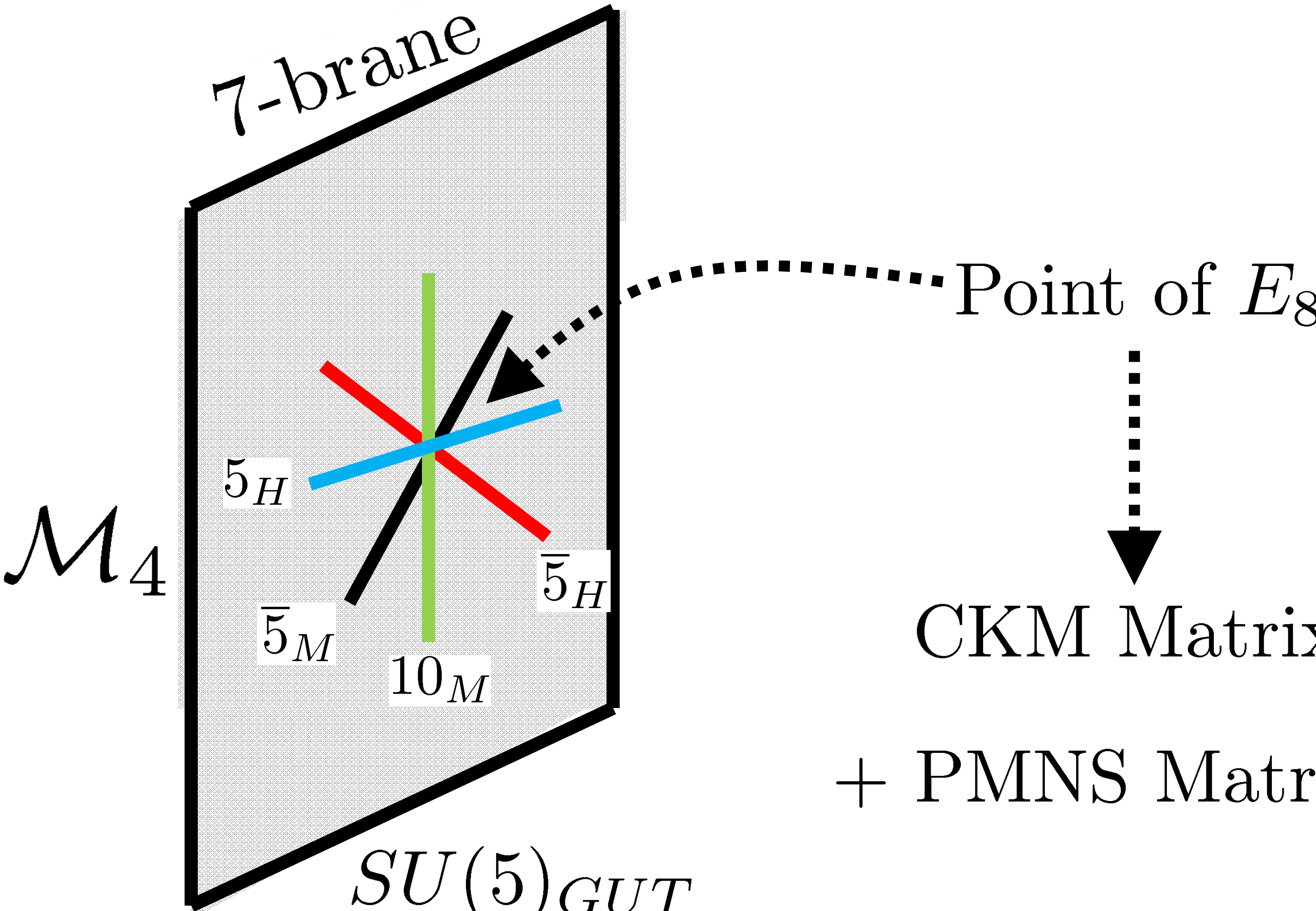


$$5_H \times 10_M \times 10_M$$

↓

Top Quark Mass

Building an F-GUT



CKM Matrix

+ PMNS Matrix

F is For Flavor

An Elegant Old Idea...

Froggatt Nielsen '79:

Yukawa Hierarchies from $U(1)_{FN}$ breaking:

$$\mathcal{L} \supset \left(\frac{\phi}{\Lambda_{UV}}\right)^{q_i+u_j} HQ^iU^j \rightarrow \varepsilon_{FN}^{q_i+u_j} HQ^iU^j$$

FN Charges:

$$\mathrm{FN}(\phi) = -1,\ \mathrm{FN}(Q^i) = q_i,\ \mathrm{FN}(U^j) = u_j$$

But...

- How many $U(1)_{FN}$'s?

- What are the $U(1)_{FN}$ charges?

- What sets ε_{FN}?

F-theory Adds More

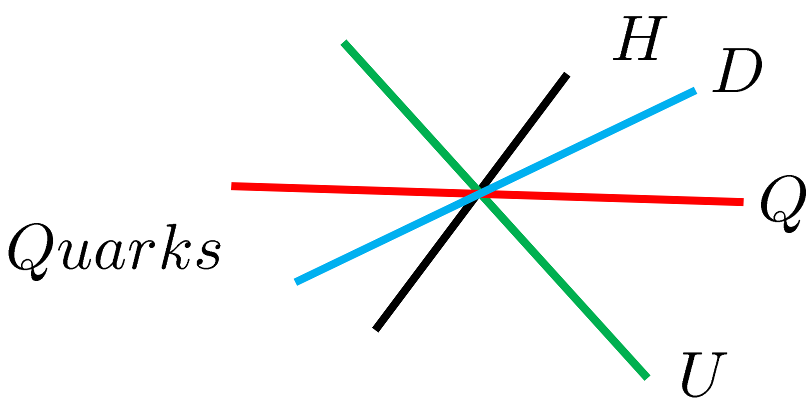
- FN $U(1) \times U(1)$ From *Geometry*

- *Specifies* FN Charges

- *Specifies* Size of $U(1)_{FN}$ breaking $\varepsilon \sim \sqrt{\alpha_{GUT}}$

Geometry ⇒ Flavor

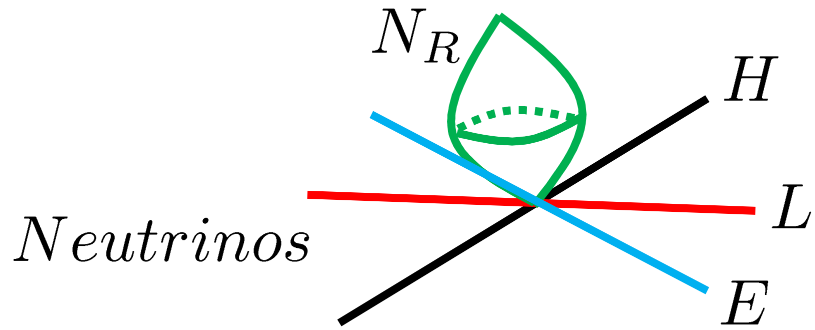
JJH, Vafa '08, Cecotti, Cheng, JJH Vafa '09



Mixing Matrix:

$$\begin{bmatrix} 1 & \alpha_{GUT}^{1/2} & \alpha_{GUT}^{3/2} \\ \alpha_{GUT}^{1/2} & 1 & \alpha_{GUT} \\ \alpha_{GUT}^{3/2} & \alpha_{GUT} & 1 \end{bmatrix}$$

Bouchard, JJH, Seo, Vafa '09



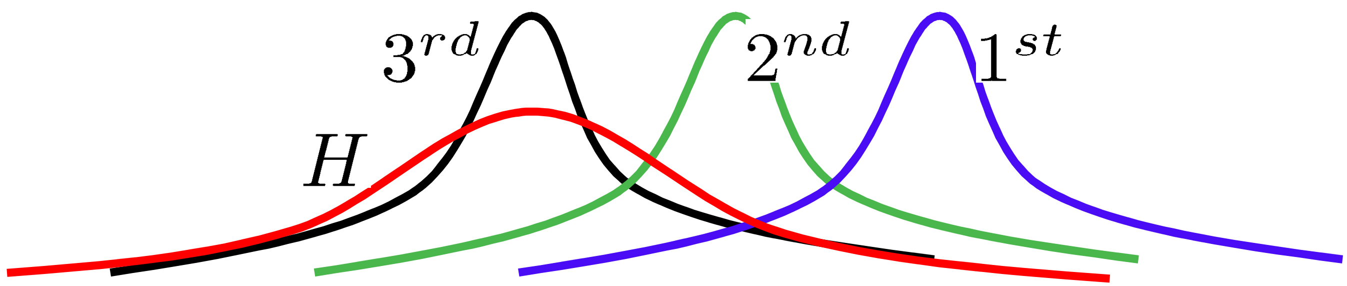
Mixing Matrix:

$$\begin{bmatrix} U_{1e} & \alpha_{GUT}^{1/4} & \alpha_{GUT}^{1/2} \\ \alpha_{GUT}^{1/4} & U_{2\mu} & \alpha_{GUT}^{1/4} \\ \alpha_{GUT}^{1/2} & \alpha_{GUT}^{1/4} & U_{3\tau} \end{bmatrix}$$

* order of magnitude estimates only

Flavor and F-Theory

Yukawas: Controlled by Ψ_{matter} Overlaps:



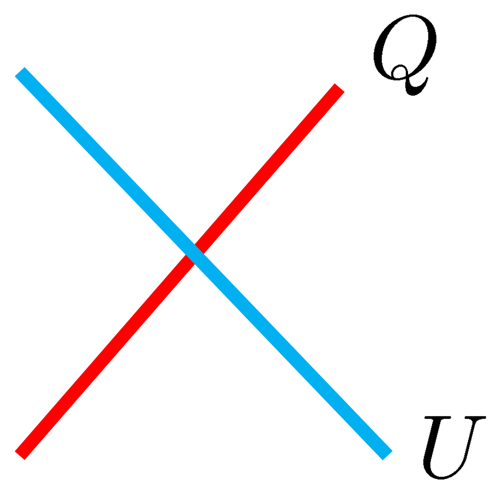
$$\lambda_{ij}^{up} = \int \Psi_{Higgs} \Psi_{Q}^{i} \Psi_{U}^{j}$$

Wave Function Estimates

Introduce hol. coords for $\mathbb{C}^2$: x and y:

$$\Psi^i_Q \sim x^i \exp(-|y|^2)$$

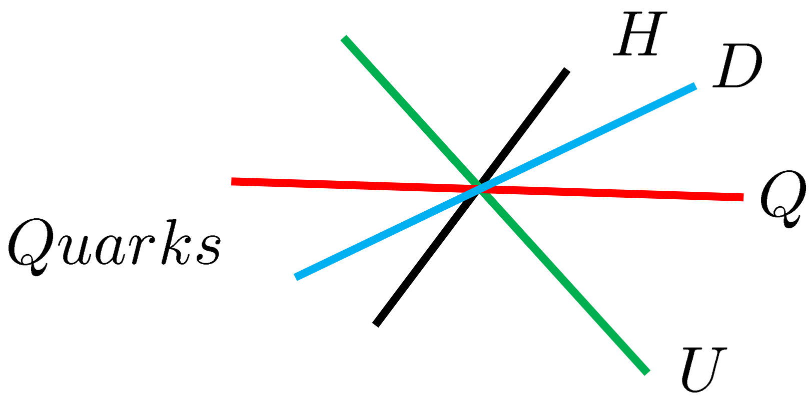
$$\Psi^i_U \sim y^i \exp(-|x|^2)$$



$$U(1)_x \times U(1)_y\colon\ (x, y) \rightarrow (e^{i\theta_x} x, e^{i\theta_y} y)$$

Geometry $\Rightarrow$ Flavor

JJH, Vafa '08, Cecotti, Cheng, JJH Vafa '09



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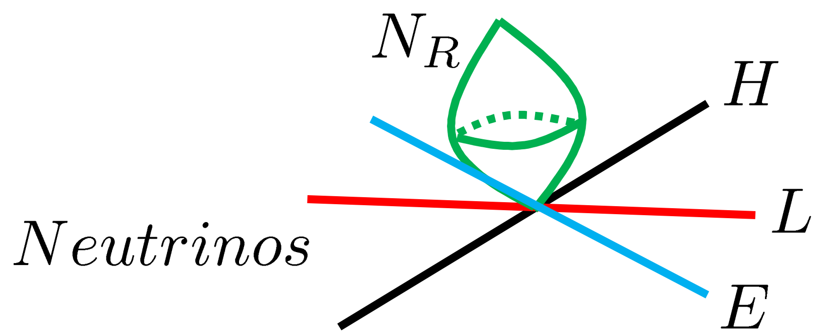
Bouchard, JJH, Seo, Vafa '09



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* order of magnitude estimates only

Postdiction: Quark Mixing

JJH Vafa '08, Cecotti Cheng JJH Vafa '09

$$|V_{CKM}| =$$

F-theory

$$\begin{bmatrix} 1 & 0.2 & 0.008 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{bmatrix}$$

Experiment

$$\begin{bmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 0.99 \end{bmatrix}$$

Pretty Good!

* order of magnitude estimates only

Prediction: No 4^{th} Quark

$$3 \text{ gens} \Rightarrow \; |V_{CKM}| \sim \begin{array}{c} \begin{matrix} d & s & b \end{matrix} \\ \begin{bmatrix} 1 & \varepsilon & \varepsilon^3 \\ \varepsilon & 1 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & 1 \end{bmatrix} \end{array} \begin{matrix} u \\ c \\ t \end{matrix}$$

$$4 \text{ gens} \Rightarrow \; |V_{CKM}| \sim \begin{array}{c} \begin{matrix} d & s & b & 4_D \end{matrix} \\ \begin{bmatrix} 1 & \varepsilon & \varepsilon^2 & \varepsilon^4 \\ \varepsilon & 1 & \varepsilon & \varepsilon^3 \\ \varepsilon^2 & \varepsilon & 1 & \varepsilon^2 \\ \varepsilon^4 & \varepsilon^3 & \varepsilon^2 & 1 \end{bmatrix} \end{array} \begin{matrix} u \\ c \\ t \\ 4_U \end{matrix}$$

(4G constraints, c.f. J. Erler's talk)

* order of magnitude estimates only

Neutrino Mixing

ν_R come from KK modes for seesaw

$(M_{KK} \sim 10^{15}$ GeV$)$

NOT zero modes $\Rightarrow$ lower FN Charge

Mixing Matrix:

$\Rightarrow$ Hierarchy Dilution:

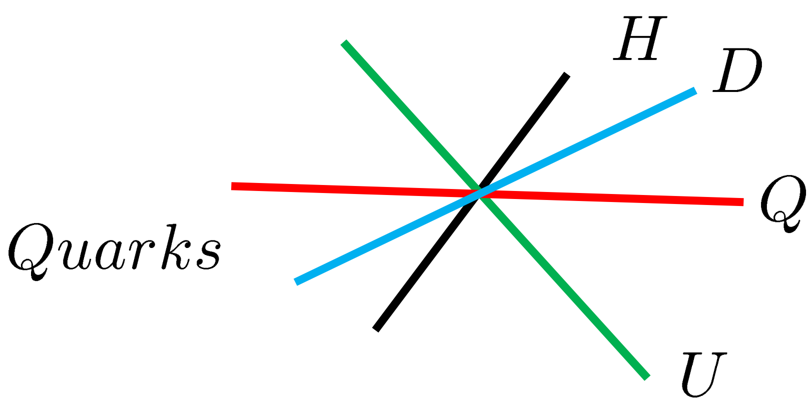
$$\begin{bmatrix} U_{1e} & \alpha_{GUT}^{1/4} & \alpha_{GUT}^{1/2} \\ \alpha_{GUT}^{1/4} & U_{2\mu} & \alpha_{GUT}^{1/4} \\ \alpha_{GUT}^{1/2} & \alpha_{GUT}^{1/4} & U_{3\tau} \end{bmatrix}$$

Dirac and Majorana Both Possible

* order of magnitude estimates only

Geometry $\Rightarrow$ Flavor

JJH, Vafa '08, Cecotti, Cheng, JJH Vafa '09



Mixing Matrix:

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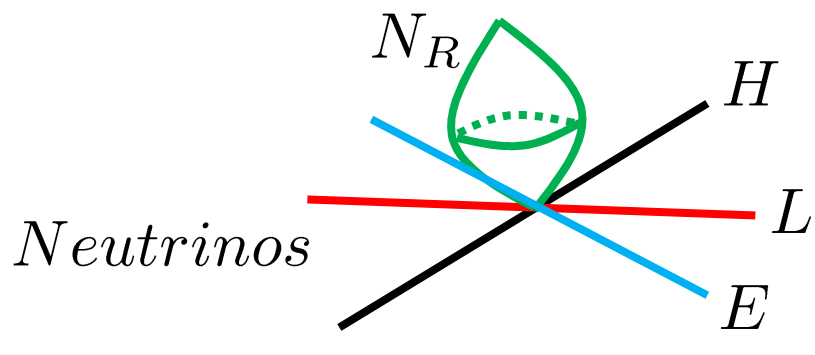
Bouchard, JJH, Seo, Vafa '09



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* order of magnitude estimates only

A Prediction: ν Mixing

Bouchard JJH Seo Vafa 2009

$$|V_{PMNS}| =$$

F-theory

$$\begin{bmatrix} 0.87 & 0.45 & 0.2 \\ 0.45 & 0.77 & 0.45 \\ 0.2 & 0.45 & 0.87 \end{bmatrix}$$

Experiment

$$\begin{bmatrix} 0.77-0.86 & 0.50-0.63 & 0.1-0.2 \\ 0.22-0.56 & 0.44-0.73 & 0.57-0.80 \\ 0.21-0.55 & 0.40-0.71 & 0.59-0.82 \end{bmatrix}$$

2012 Update: $\theta_{13} \sim 0.15$, c.f. Daya Bay,...

Note:

Main Ingredient here

is SUSY / holomorphy at GUT scale

TeV Scale SUSY not required for this to work...

What About TeV SUSY?

IF one assumes TeV SUSY, then

Point of E_8 naturally accommodates a

stringy deform^n of minimal gauge mediation

Main Features:
- 10-100 MeV Gravitino LSP
- 1 sec - 1 hr $\widetilde{\tau}$ NLSP

Caveats

"TeV SUSY" could have some tuning...

Colored Superpartners could be heavy
(and thus hard to produce)

At this point, limits on $\widetilde{\tau}$ pair production
(i.e. not from cascade decays)
still rather weak

Mini-Hierarchy?

M_{weak} versus M_{SUSY}?

IF Hints of 125 GeV Higgs are real...

this is consistent with a "tuned" MSSM ...

Reducing the Tuning?

Natural to consider mixing with new operators:

Mixing terms: $\int d^2\theta \, (H_u \mathcal{O}_u + H_d \mathcal{O}_d)$

In this talk discuss a speculative possibility:

F is For Funparticles

F is For Funparticles*

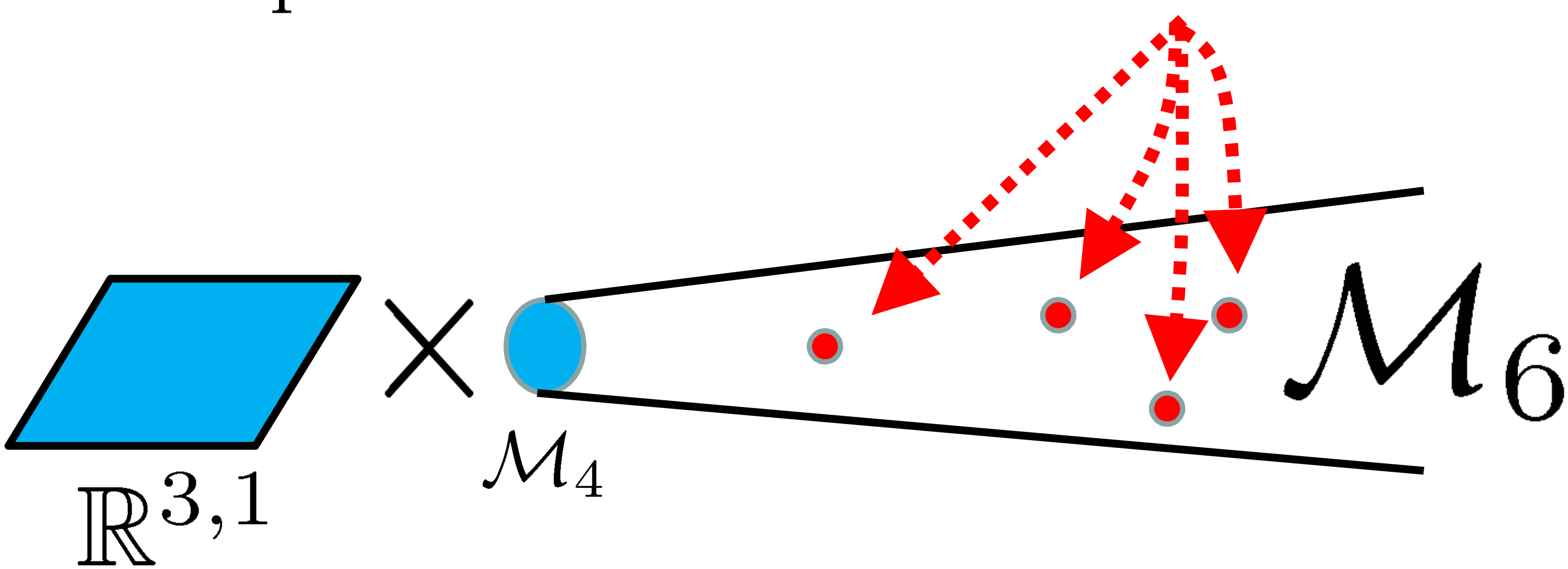
* Unparticles with a mass gap in F-theory

Unparticles = scale invariant field theory, c.f. Georgi '07

Extra Sectors

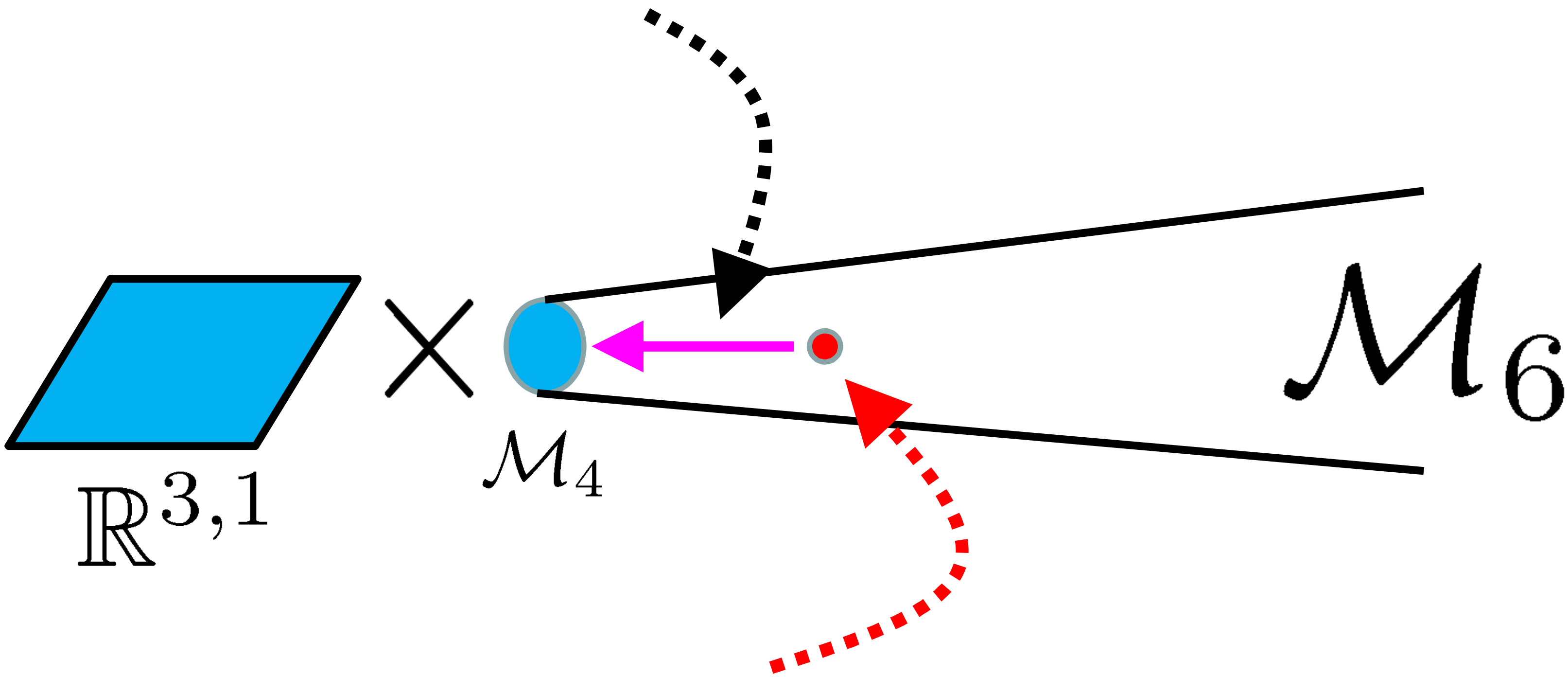
Very common in string constructions:

10D Tadpole Cancellation $\Rightarrow$ D3-Branes



Attraction

Flavor fluxes *attracts* D3 to Standard Model

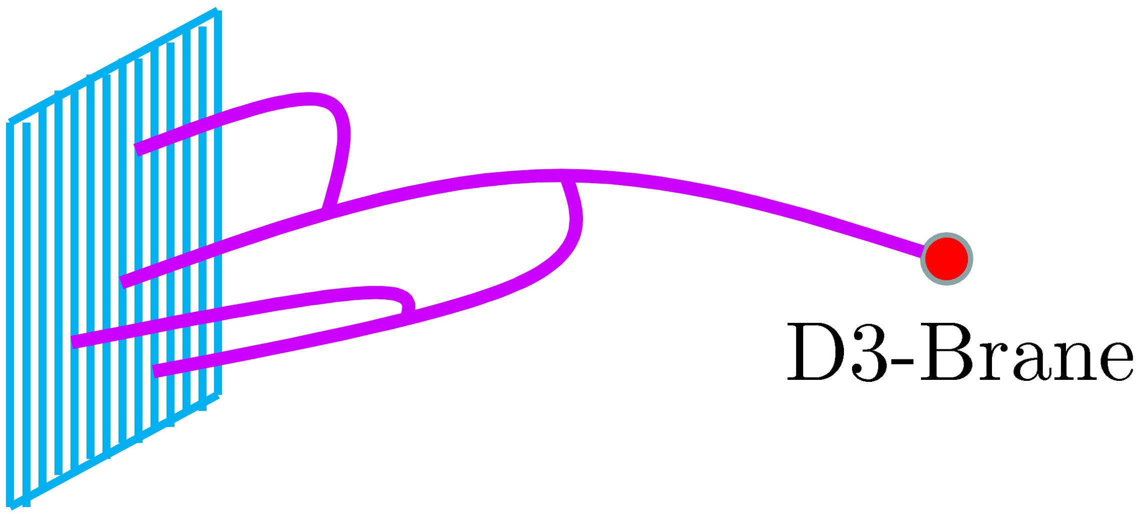


Extra Sector from 3-brane on $\mathbb{R}^{3,1} \times pt$

JJH Vafa '10

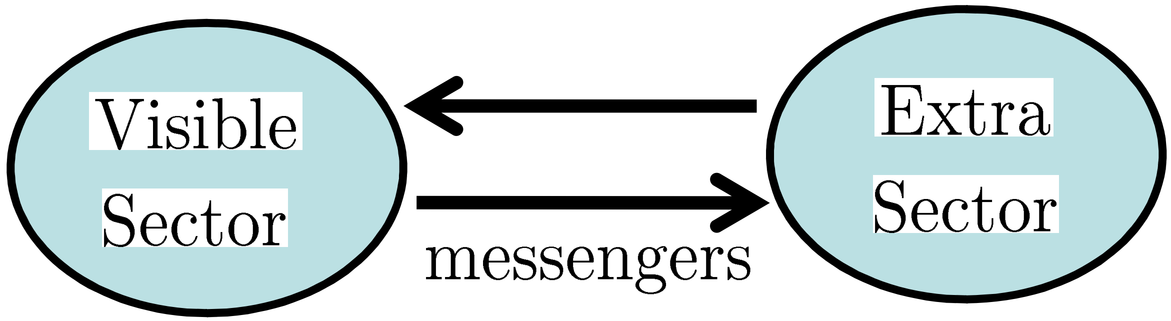
D3 $\Rightarrow$ Strongly Coupled CFT

E_8 + open strings $\Rightarrow g_s \sim O(1)$:



Note: Typically No Lagrangian Description

SM / D3 Mixing



Gauge Fields: $\mathcal{L} \supset A_\mu^{vis} \cdot J_\mu^{extra}$

Yukawas: $\mathcal{L} \supset \int d^2\theta \; \Psi_R^{vis} \cdot \mathcal{O}_{\overline{R}}^{extra}$

Surprise: The Mixing is *Small*

JJH Vafa Wecht '11

Test in limit where SM + D3 is a CFT

- Scaling Dimension $\Delta(\Psi^{SM}) = \Delta_{free} + \underbrace{\varepsilon_{SM} + \varepsilon_{D3}}_{\text{similar sizes}}$

- Beta functions: $b_G \sim 2 - 4 \Rightarrow$ Retains Unification

Applications

This depends on scale of CFT breaking

$$10^9 \sim 10^{12}\ \mathrm{GeV} \Rightarrow \mathrm{Baryo\ /\ DM\ cogenesis}$$

JJH S-J Rey ’11

$$10^2 \sim 10^3\ \mathrm{GeV} \Rightarrow \mathrm{LHC\ /\ Higgs\ Physics}$$

JJH et al. ’11-’12

Applications

This depends on scale of CFT breaking

$10^9 \sim 10^{12}$ GeV $\Rightarrow$ Baryo / DM genesis

$10^2 \sim 10^3$ GeV $\Rightarrow$ LHC / Higgs Physics

Why TeV Scale ~~CFT~~?

It is (potentially) much more interesting

& New Higgs Couplings: $\int d^2\theta \; H \cdot \mathcal{O}$

- This changes Higgs pot^l rel. to MSSM

  c.f. "DSSM" JJH Kumar Vafa Wecht '11

- Can also improve 2-loop unification

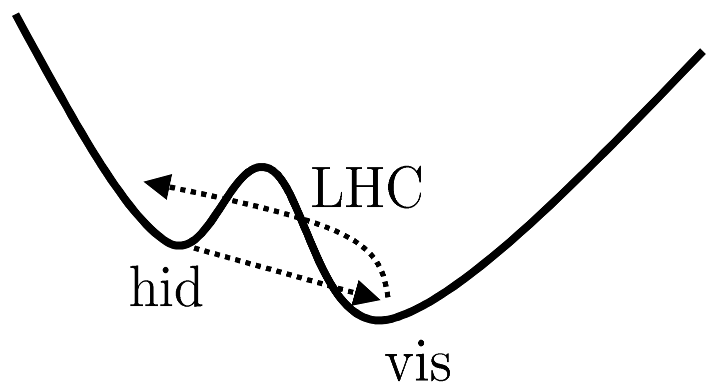
  c.f. JJH Vafa Wecht '11

TeV Scale ~~CFT~~

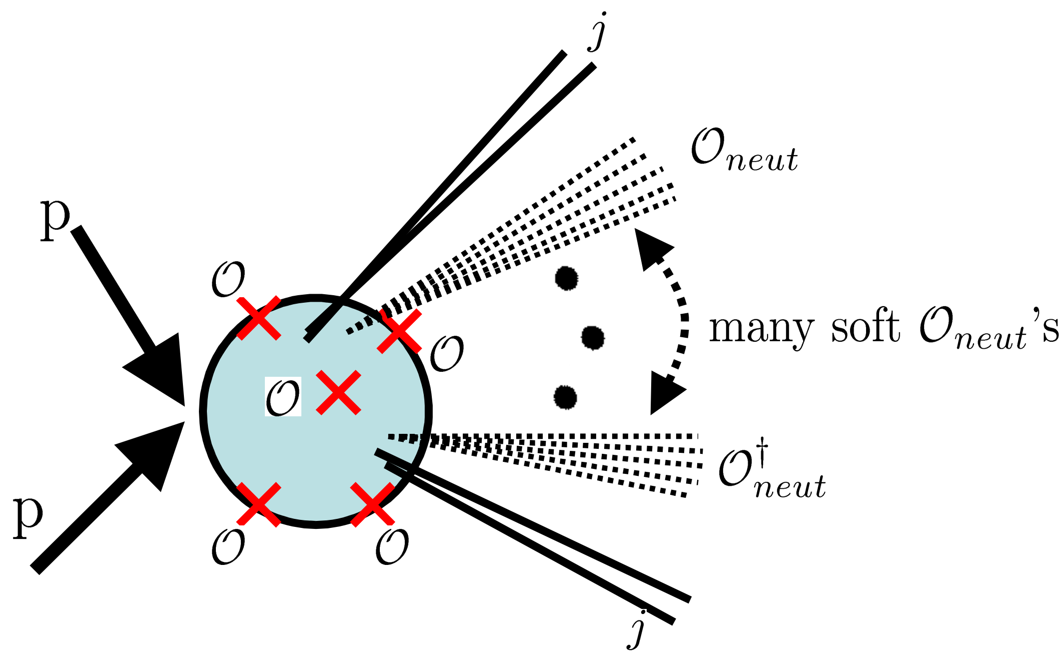
At Energies $\gg M_{\cancel{CFT}}$, restore conformality

Examples of “Hidden Valley” Scenario

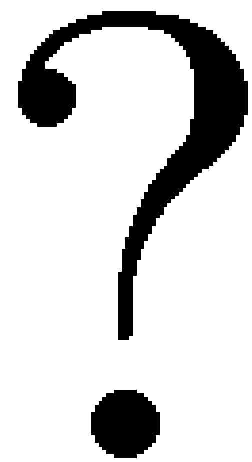
Strassler Zurek ’06
Georgi ’07
Strassler ’07
Grinstein Intriligator Rothstein ’08,…



Signatures?



j
$\mathcal{O}_{neut}$
p
$\mathcal{O}$
many soft $\mathcal{O}_{neut}$'s
$\mathcal{O}$
$\mathcal{O}$
$\mathcal{O}^{\dagger}_{neut}$
p
$\mathcal{O}$
$\mathcal{O}$
j



But...

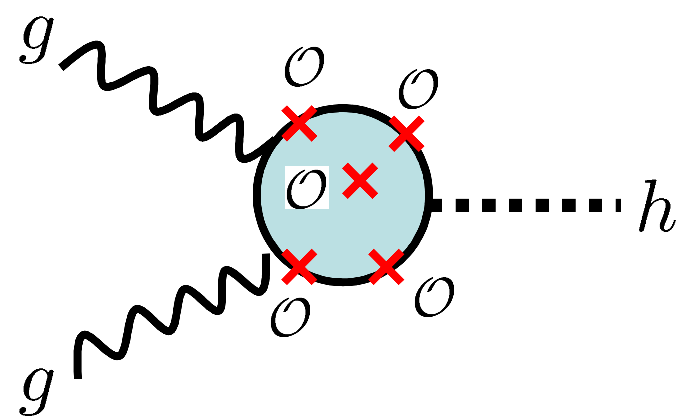
- Hard to study directly...

- Also, extra states may be too heavy...

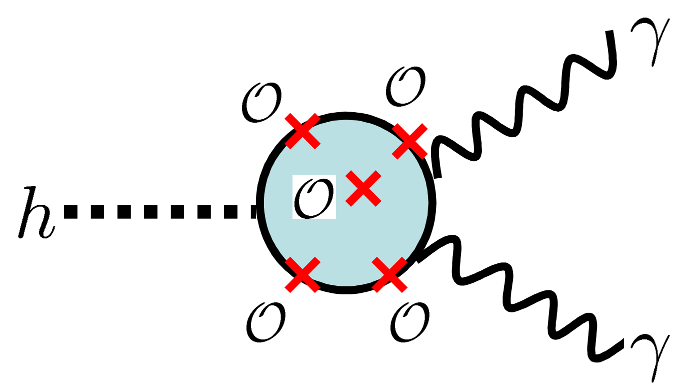
- But they will still enter in loops...

Higgs and Loops

Production: $gg \to h$



Decays: $h \to \gamma\gamma$



This is Calculable

In a SUSY CFT, this can be computed!

JJH Kumar Wecht '12

View as a threshold:
See Shifman Vainshtein,
Voloshin, Zakharov '79

Basic tools:

- Holomorphy
- $SU(3) \times U(1)_{EM}$ gauge invariance
- Beta f^n $b_G = -3\mathrm{Tr}(R_{IR} J_G J_G)$ is calculable

The Calculable Contribution

$$\mathcal{L}_{hGG} \supset \frac{b_G}{16\pi^2} \frac{\cos(\alpha+\beta)}{\Lambda_{eff}^2/v^2} \frac{h}{v} \mathrm{Tr}_G F^2$$

2HDM with $h, H, A, H^{\pm}$ and Mixing Angles: α and β

Mass scales: $v \sim 246$ GeV and Λ_{eff}

limiting case:
$\Lambda_{eff}^2 \to v_u v_d$

Calculable $b_G = -3\mathrm{Tr}(R_{IR} J_G J_G)$

LHC Limits

Compare with expectation for a SM Higgs:

(Disclaimer: preliminary # ' s, subject to change...)

$$\sigma(gg \to h \to \gamma\gamma):\ 1.4^{+0.7}_{-0.7}$$

see CMS and ATLAS

Carmi et al. '12

Barger et al. '12, ...

$$\sigma(gg \to h \to VV^*):\ 0.8^{+0.8}_{-0.4}$$

$$\sigma(pp \to hjj \to \gamma\gamma jj):\ 3.7^{+2.5}_{-1.8}$$

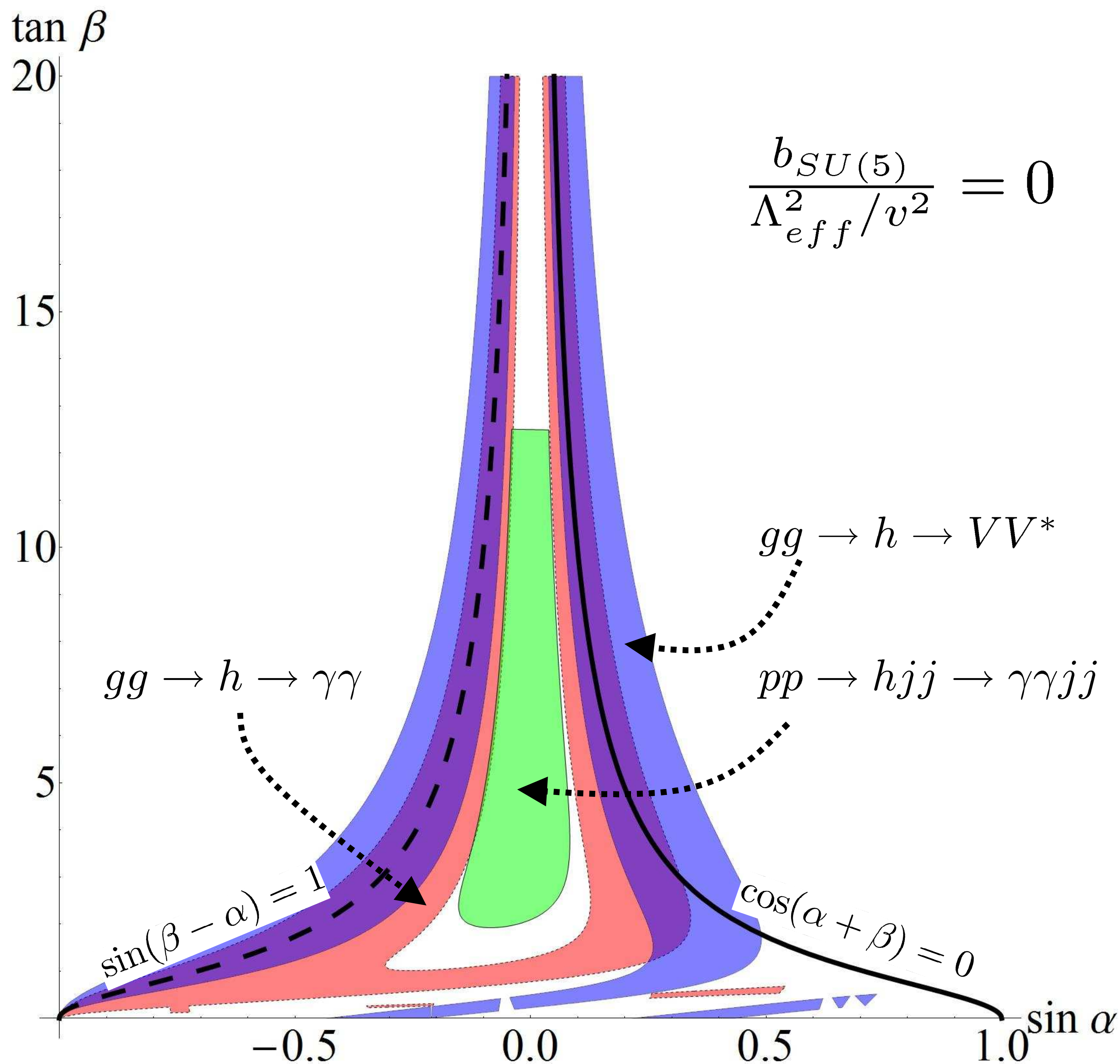
(some from VBF and gluon fusion)

Comparing with the Limits

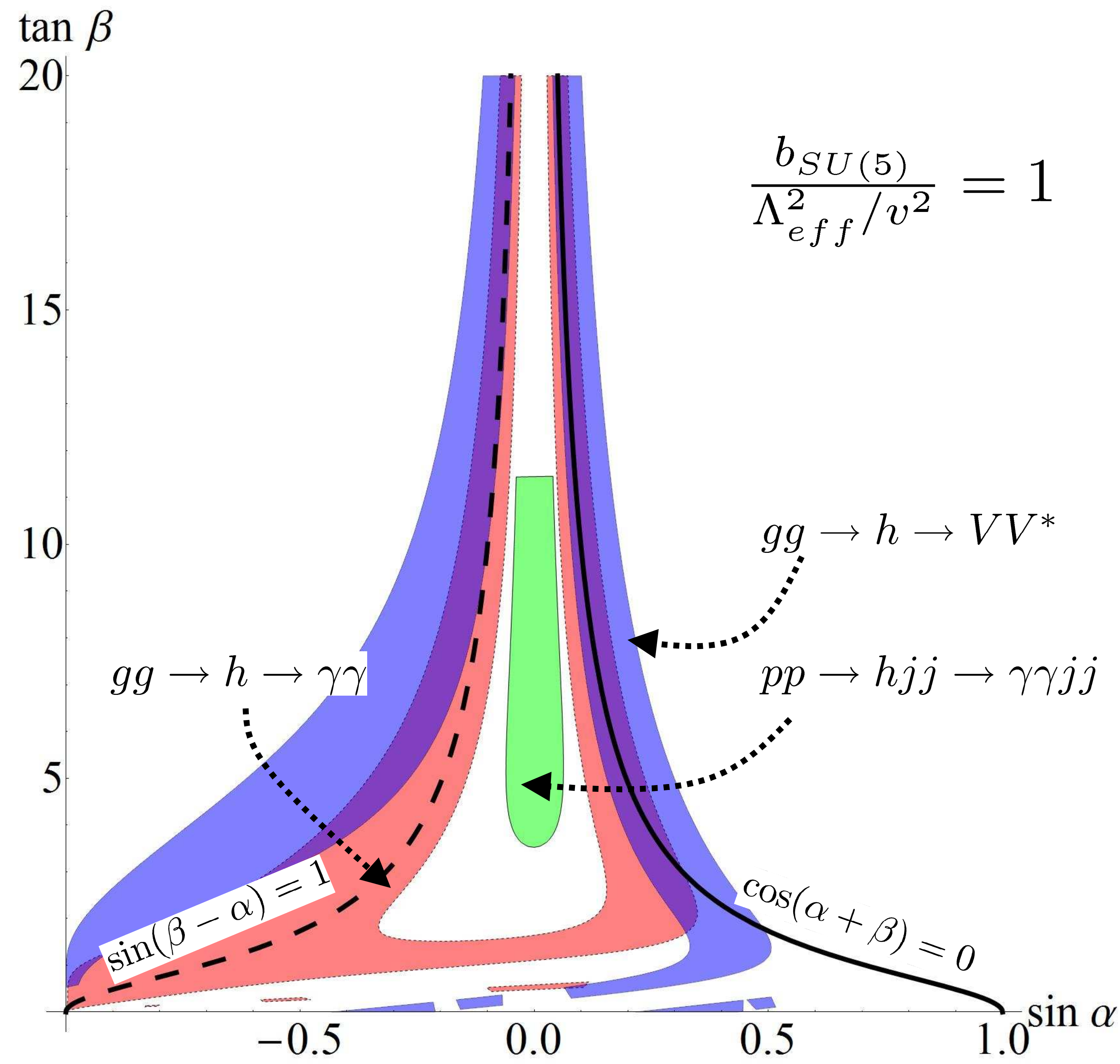
Plot in limit of 2HDM + D3, i.e.,

Assume superpartners decoupled

to order $\frac{v^2}{M_{SUSY}^2}$



$\tan\beta$
20
15
10
5
-0.5
0.0
0.5
1.0
$\sin\alpha$
$\frac{b_{SU(5)}}{\Lambda^2_{eff}/v^2} = 0$
$gg \to h \to VV^*$
$pp \to hjj \to \gamma\gamma jj$
$gg \to h \to \gamma\gamma$
$\sin(\beta - \alpha) = 1$
$\cos(\alpha + \beta) = 0$



$\tan\beta$
20
15
10
5
-0.5
0.0
0.5
1.0
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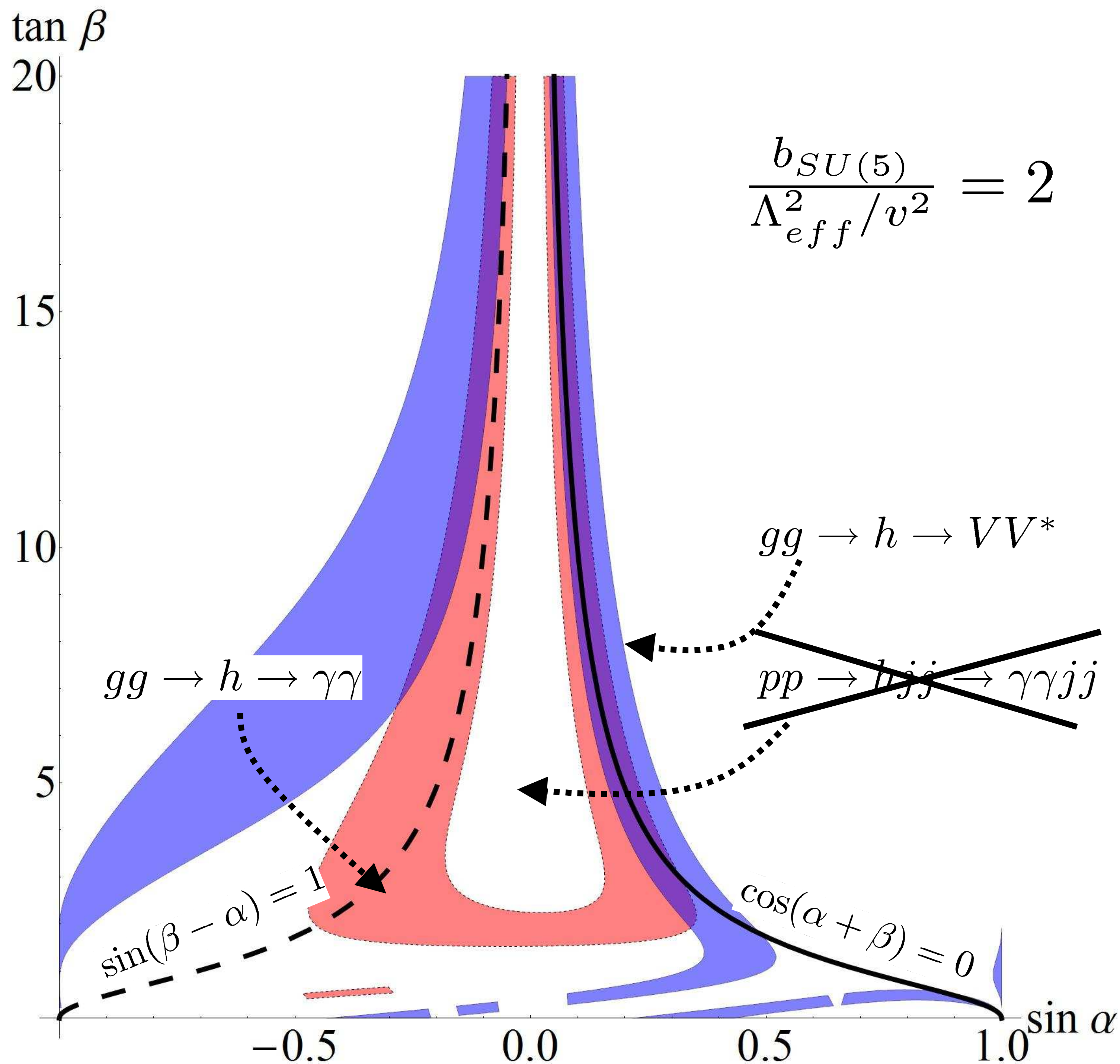
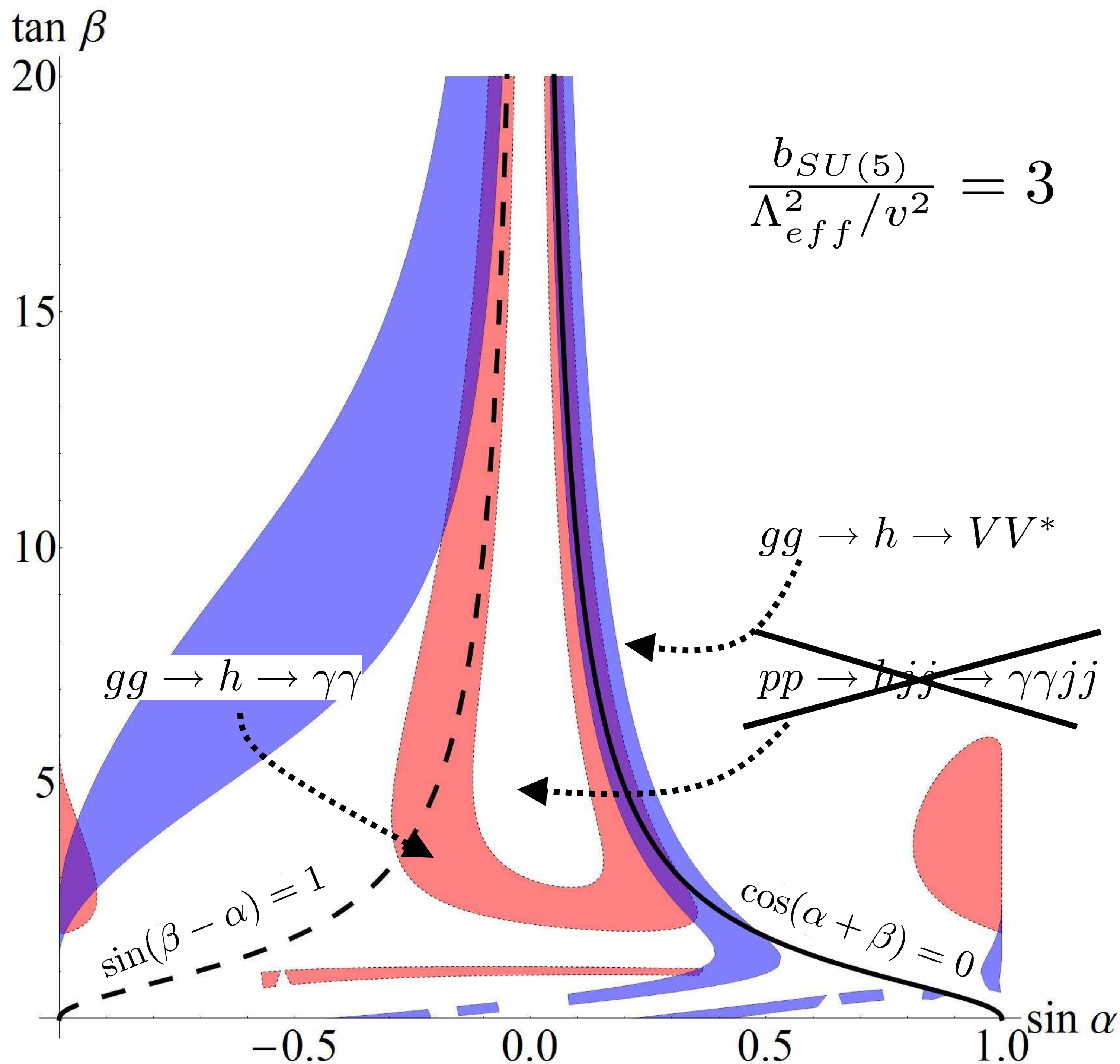
$\frac{b_{SU(5)}}{\Lambda_{eff}^2/v^2} = 1$
$gg \to h \to VV^*$
$gg \to h \to \gamma\gamma$
$pp \to hjj \to \gamma\gamma jj$
$\sin(\beta-\alpha) = 1$
$\cos(\alpha+\beta) = 0$



tan β
20
15
10
5
−0.5
0.0
0.5
1.0
sin α
$\frac{b_{SU(5)}}{\Lambda^2_{eff}/v^2} = 2$
$gg \to h \to VV^*$
$pp \to hjj \to \gamma\gamma jj$
$gg \to h \to \gamma\gamma$
$\sin(\beta - \alpha) = 1$
$\cos(\alpha + \beta) = 0$



tan β
20
15
10
5
−0.5
0.0
0.5
1.0
sin α
$\frac{b_{SU(5)}}{\Lambda^2_{eff}/v^2} = 3$
$gg \to h \to VV^*$
$pp \to hjj \to \gamma\gamma jj$
$gg \to h \to \gamma\gamma$
$\sin(\beta - \alpha) = 1$
$\cos(\alpha + \beta) = 0$

Basic Point

Still preliminary, but Higgs physics will soon be a helpful probe of such scenarios

Summary / Conclusions

Summary

F-Theory GUTs combine:

- Localization
- E_8 symmetry

F Is For:

- Flavor: $\theta_C \sim \theta_{13} \sim \sqrt{\alpha_{GUT}} \sim 0.2$
- Funparticles w/ a mass gap:
  - probe via Higgs processes
  - probe directly?