HIGGS PHYSICS AT FUTURE COLLIDERS

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Yang Institute for Theoretical Physics
Stony Brook University

Based mostly on:
1811.00017 D. Egaña, S. Homiller, PM
1908.11376 D. Egaña, S. Homiller, PM
+ work in progress 1910.?????x2

OUTLINE

- Motivation*
- BSM Flavor physics - Spontaneous Flavor Violation (SFV)
- Higgs and Flavor Physics
- Di-Higgs
- Other BSM SFV examples

LATELY MANY PHENO SEMINARS START WITH SOMETHING LIKE…

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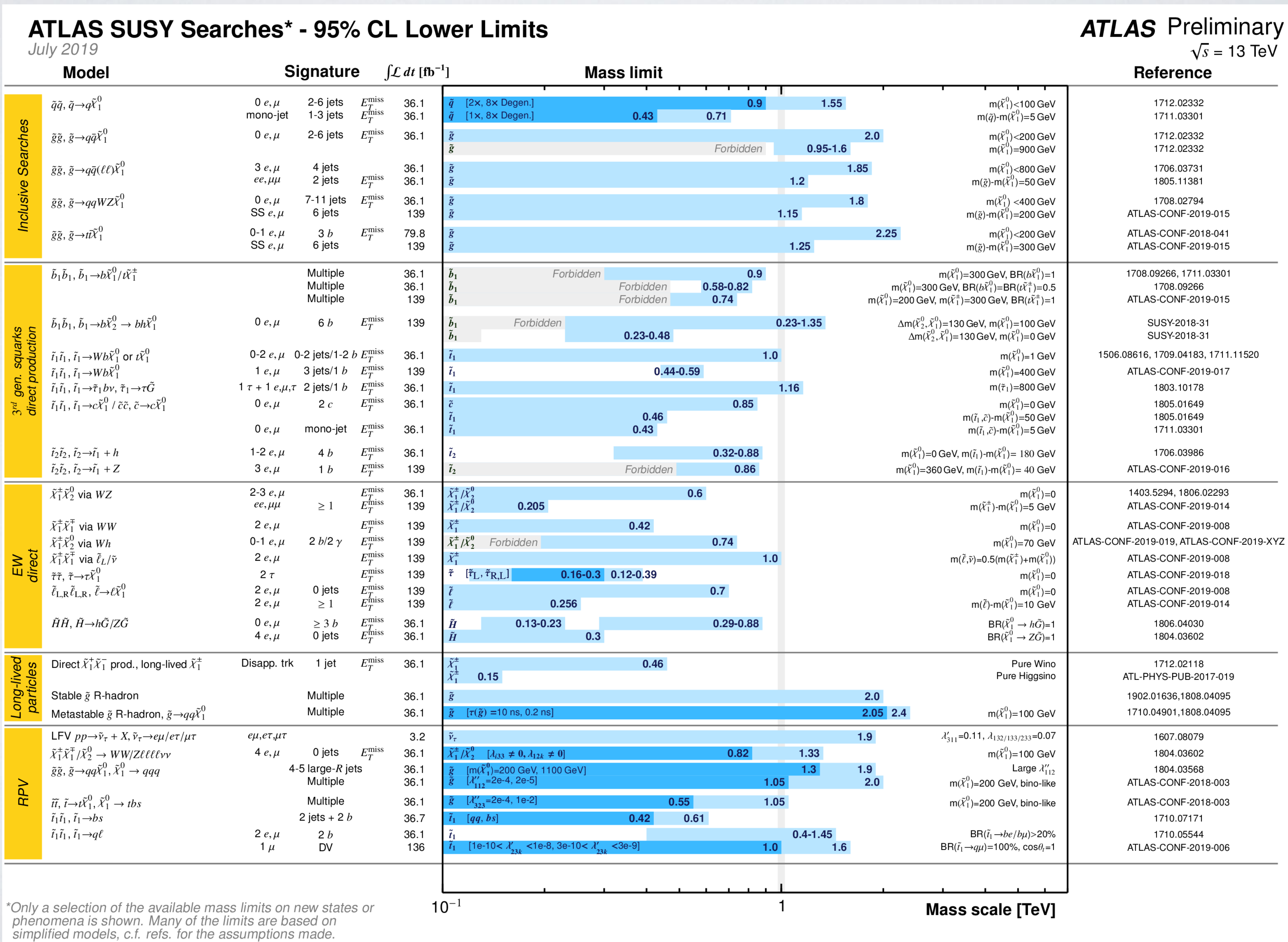
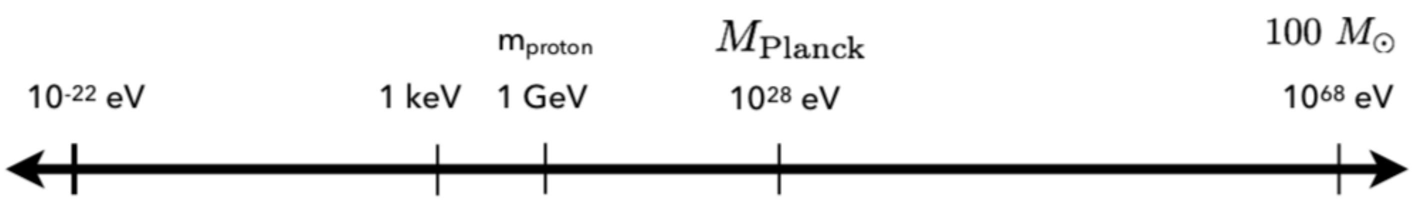


AND THEN THERE'S A PIVOT

AND THEN THERE'S A PIVOT

Where look for DM?



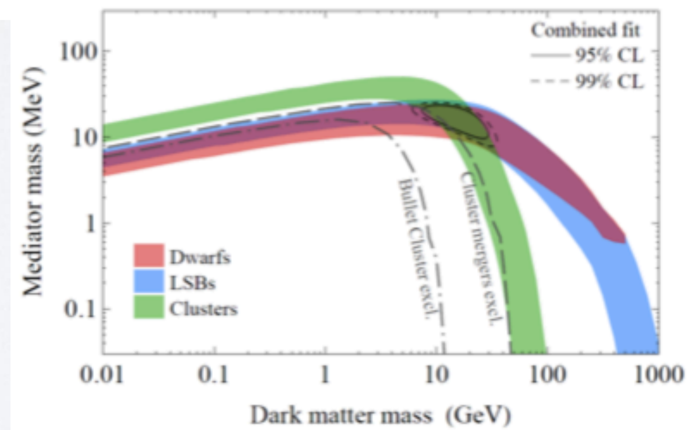
many possibilities

$\Longrightarrow$ target motivated areas

sub GeV-SCALE MEDIATORS & LIGHT DM EXPERIMENTS & OBSERVATIONS

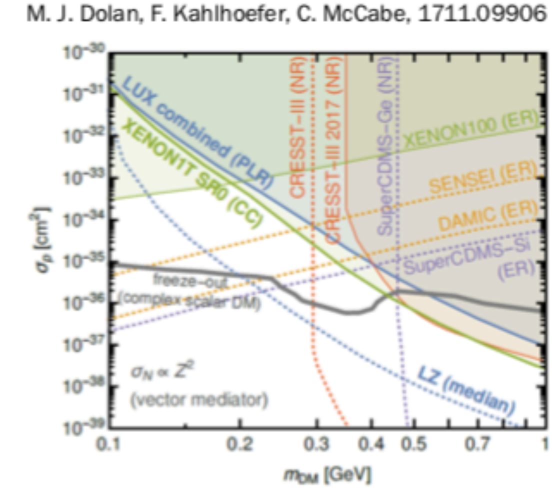
Dark matter self interactions

M. Kaplinghat, S. Tullin, H.-B. Yu, 1508.03339



Light DM direct detection

M. J. Dolan, F. Kahlhoefer, C. McCabe, 1711.09906



Search for light mediators at colliders

FASER

ut also e.g. NA62

nd many proposed exps e.g. Codex-b, MATHUSLA, SHiP, ...

& other...

7

THERE'S NOTHING WRONG WITH A PIVOT…

- I've spent a large part of my career thinking about crazy things…

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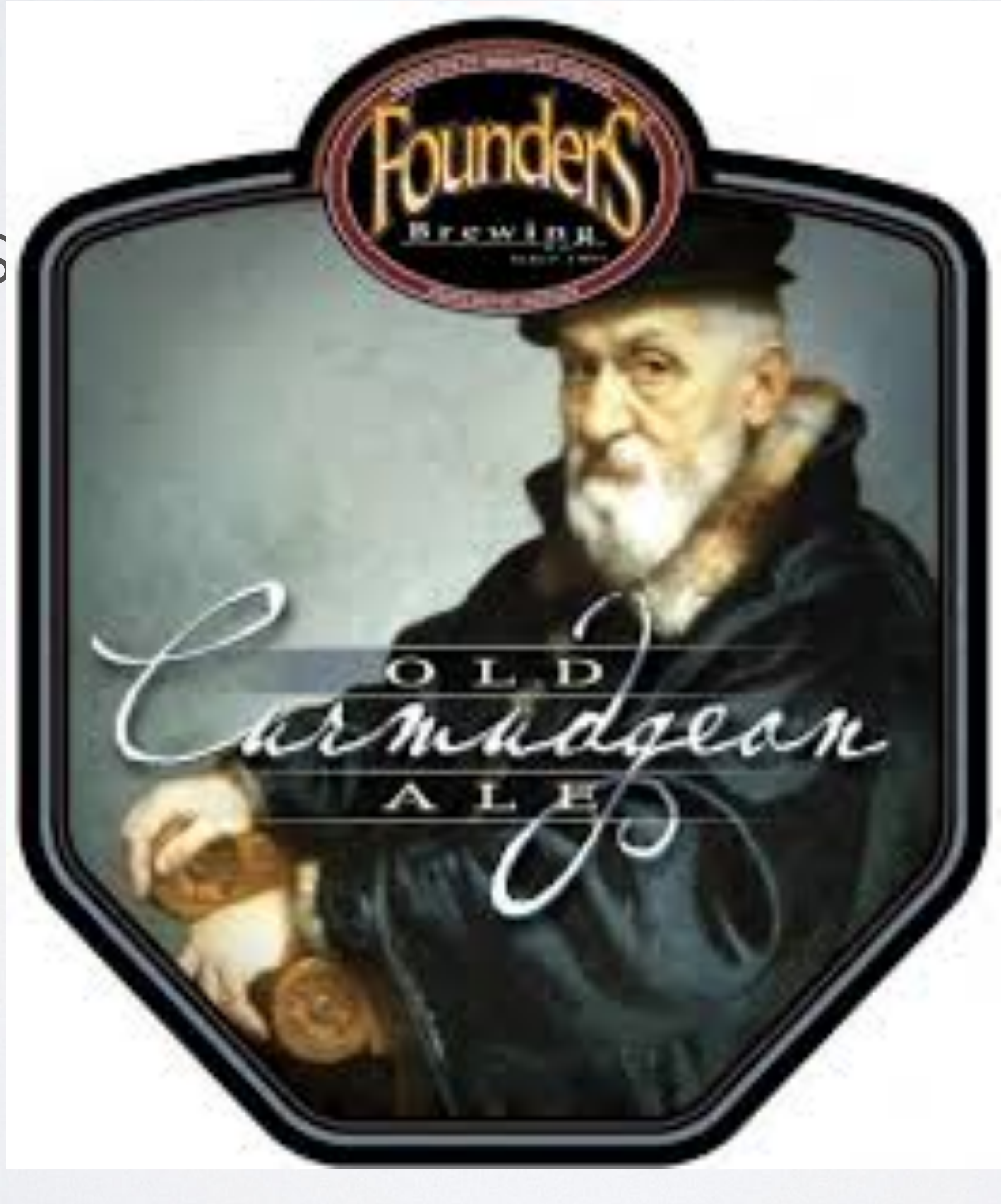
- I've spent a  thinking about crazy things

THERE'S NOTHING WRONG WITH A PIVOT…

- I've spent a large part of my career thinking about crazy things…

- In this talk I want to stress that the **Higgs** - something we know is there - really can unlock so many puzzles about the SM qualitatively by studying it with more quantitative precision


PREACHING TO THE
CHOIR
YOU ARE

NEVERTHELESS…

NEVERTHELESS…

- I think it's important to go through these qualitative questions related to the Higgs to understand their implications and where we might be biased
- Despite the fact that many/all of you will be familiar with the qualitative questions, there are *new* possibilities I want to emphasize in this talk

NEVERTHELESS…

- I think it's important to go through these qualitative questions related to the Higgs to understand their implications and where we might be biased

- Despite the fact that many/all of you will be familiar with the qualitative questions, there are *new* possibilities I want to emphasize in this talk

In the end I'll focus on the **craziest**, but I'm around through tomorrow to talk about any of these…

LET'S START WITH THE BASICS

THE HIGGS AND SPONTANEOUS SYMMETRY BREAKING

Long before the Higgs was discovered we knew the SM was described by a spontaneously broken gauge symmetry

$$SU(3) \times SU(2) \times U(1)_Y$$

$$\big\downarrow \ \textbf{SSB}$$

$$SU(3) \times U(1)_Q$$

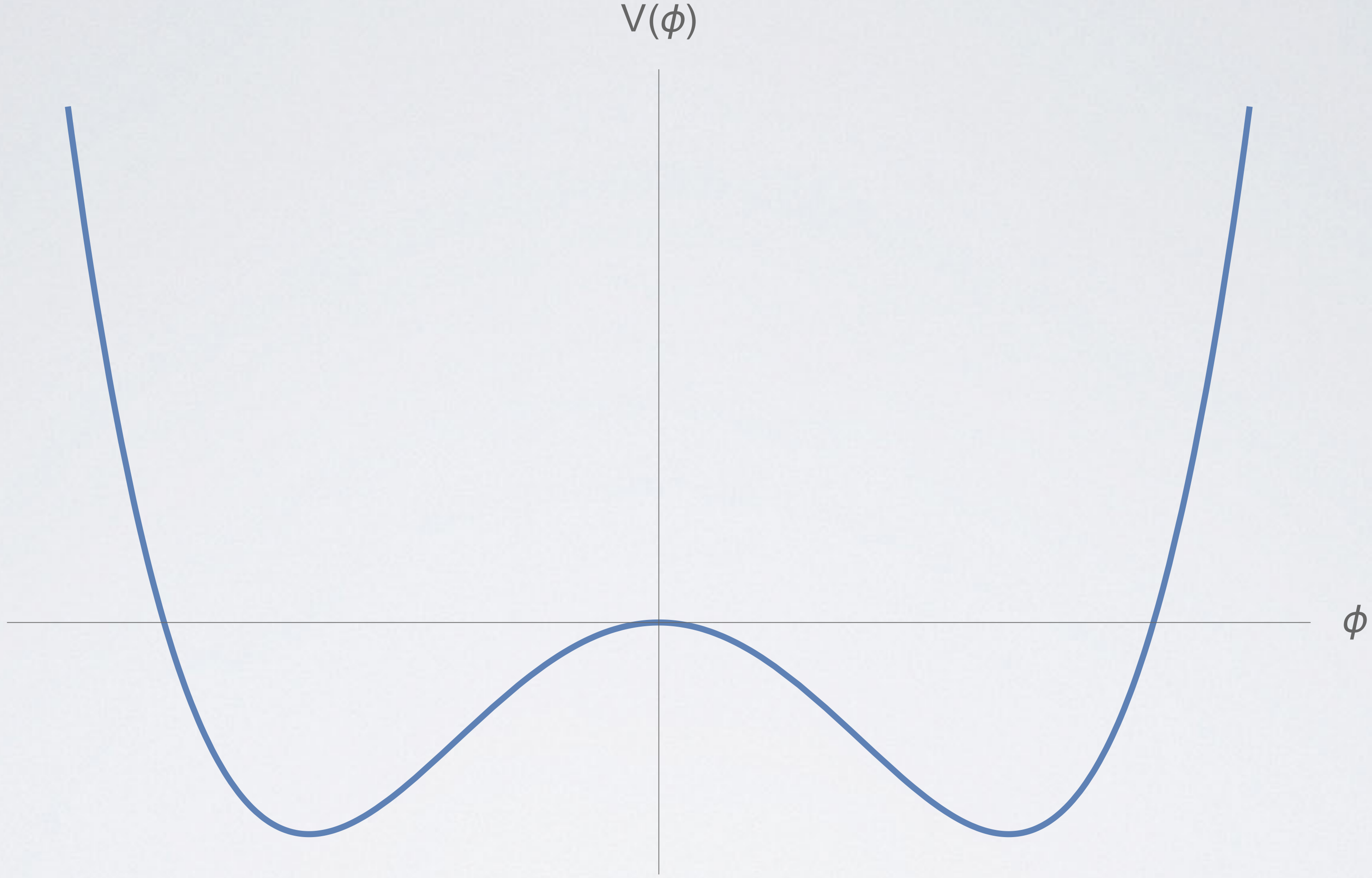
THE HIGGS WASN'T THE ONLY GAME IN TOWN IN PRINCIPLE…

THE HIGGS WASN'T THE ONLY GAME IN TOWN IN PRINCIPLE…

Dynamical Symmetry Breaking has shown up before…

It explains why the symmetry is broken

INSTEAD WE GOT…



$$V(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

EWSB put in ***by hand***

A light fundamental scalar, never seen before in nature without tuning!

NATURALNESS

$$m_h^2 \sim \Lambda^2$$

$$\Lambda \sim \text{~~100~~ GeV}$$

~~200~~ GeV

~~300~~ GeV

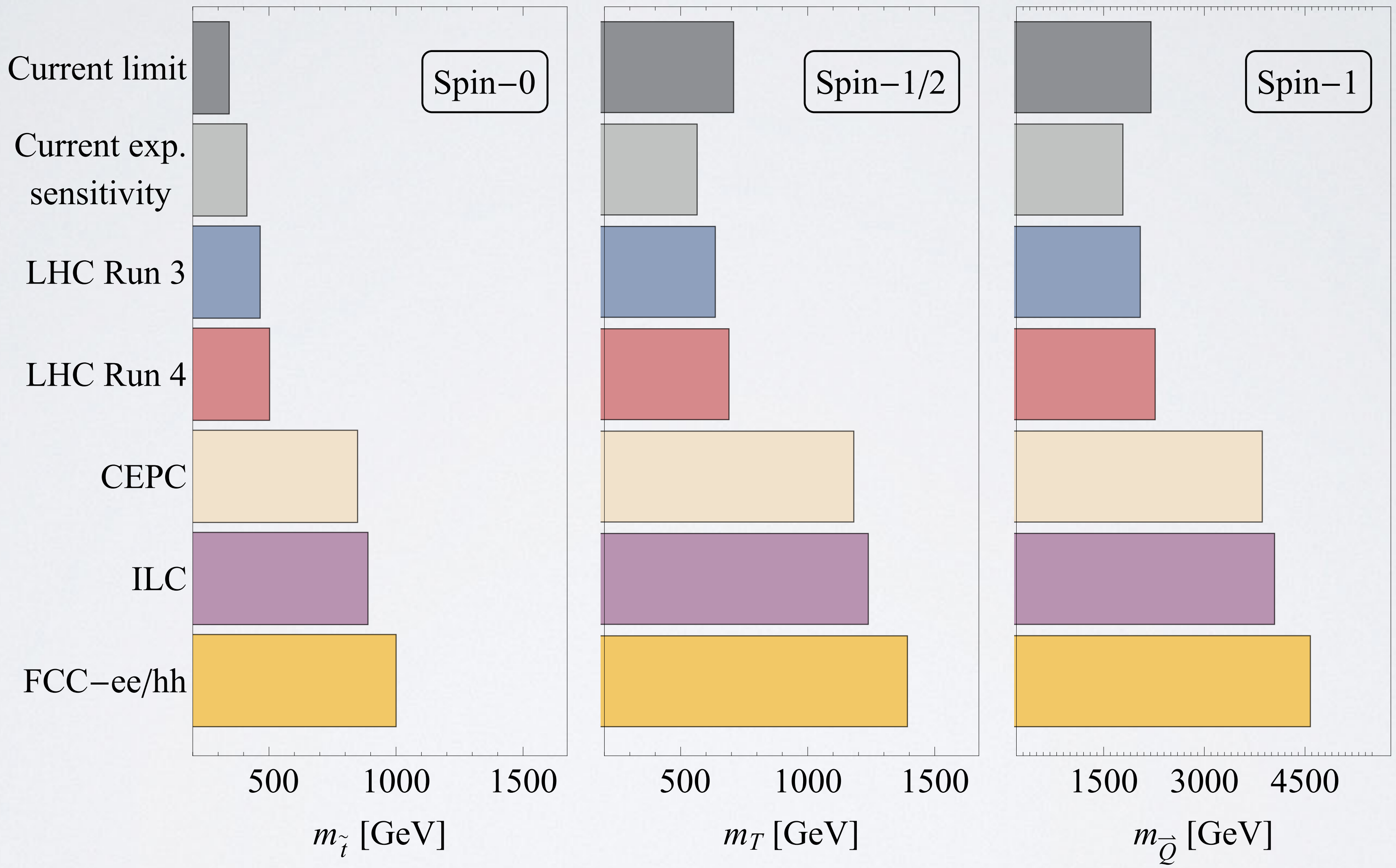
~~500~~ GeV

~~1000~~ GeV

5000 GeV ????

We certainly learn something,
but what it is telling us isn't as clear

THIS WILL OBVIOUSLY BE A FOCUS FOR FUTURE COLLIDERS

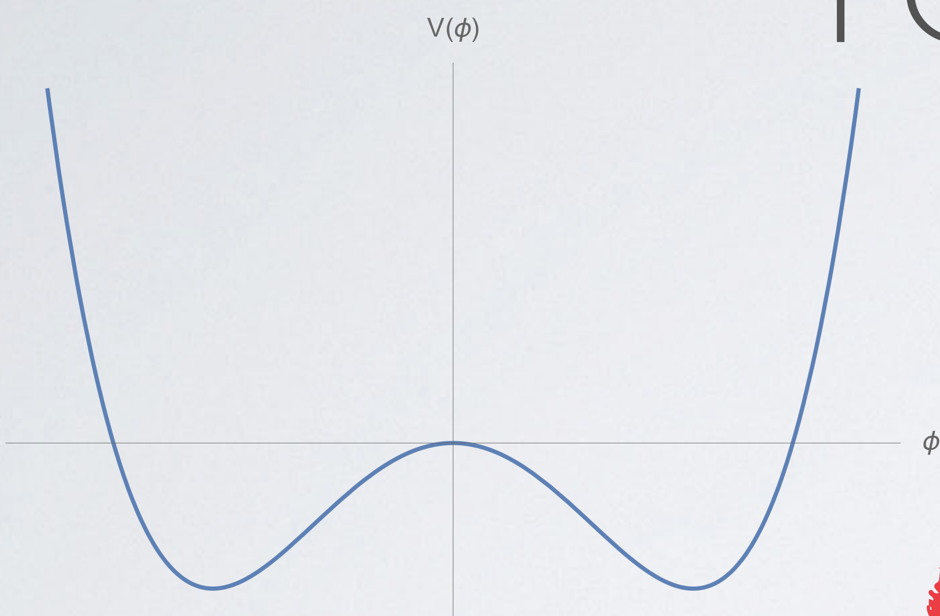


Essig, PM, Ramani, Zhong 1707.03399

IS THE HIGGS PART OF SOME LARGER SECTOR WHICH “EXPLAINS” EWSB?

IS THERE SOMETHING MAKING THE HIGGS “NATURAL”?

A MORE FUNDAMENTAL EXPERIMENTAL QUESTION, WHAT IS THE HIGGS POTENTIAL?

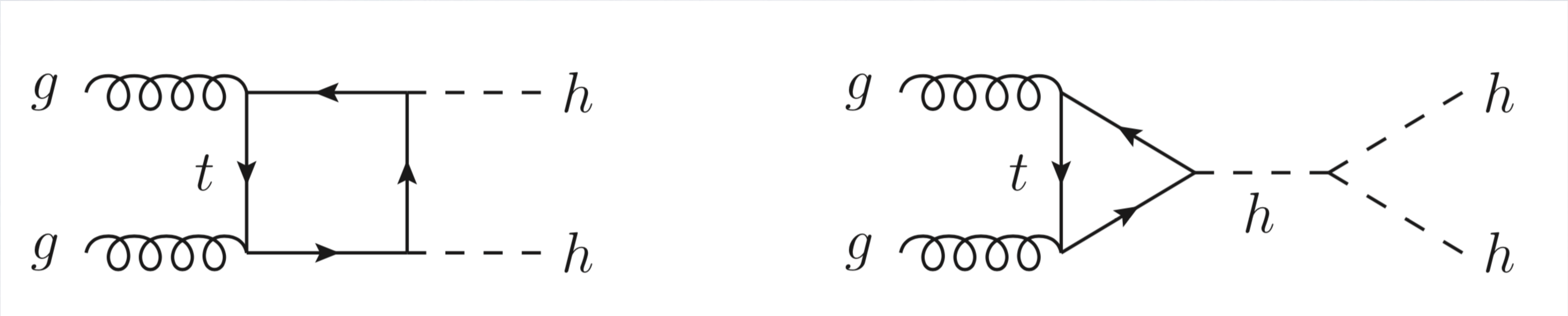


$$\left.\frac{\partial V(\phi)}{\partial \phi}\right|_{\phi=v} = 0$$

$$\left.\frac{\partial^2 V(\phi)}{\partial \phi^2}\right|_{\phi=v} = m_h^2$$

OR

NEXT UP IS THE TRIPLE HIGGS COUPLING IN THE SM…

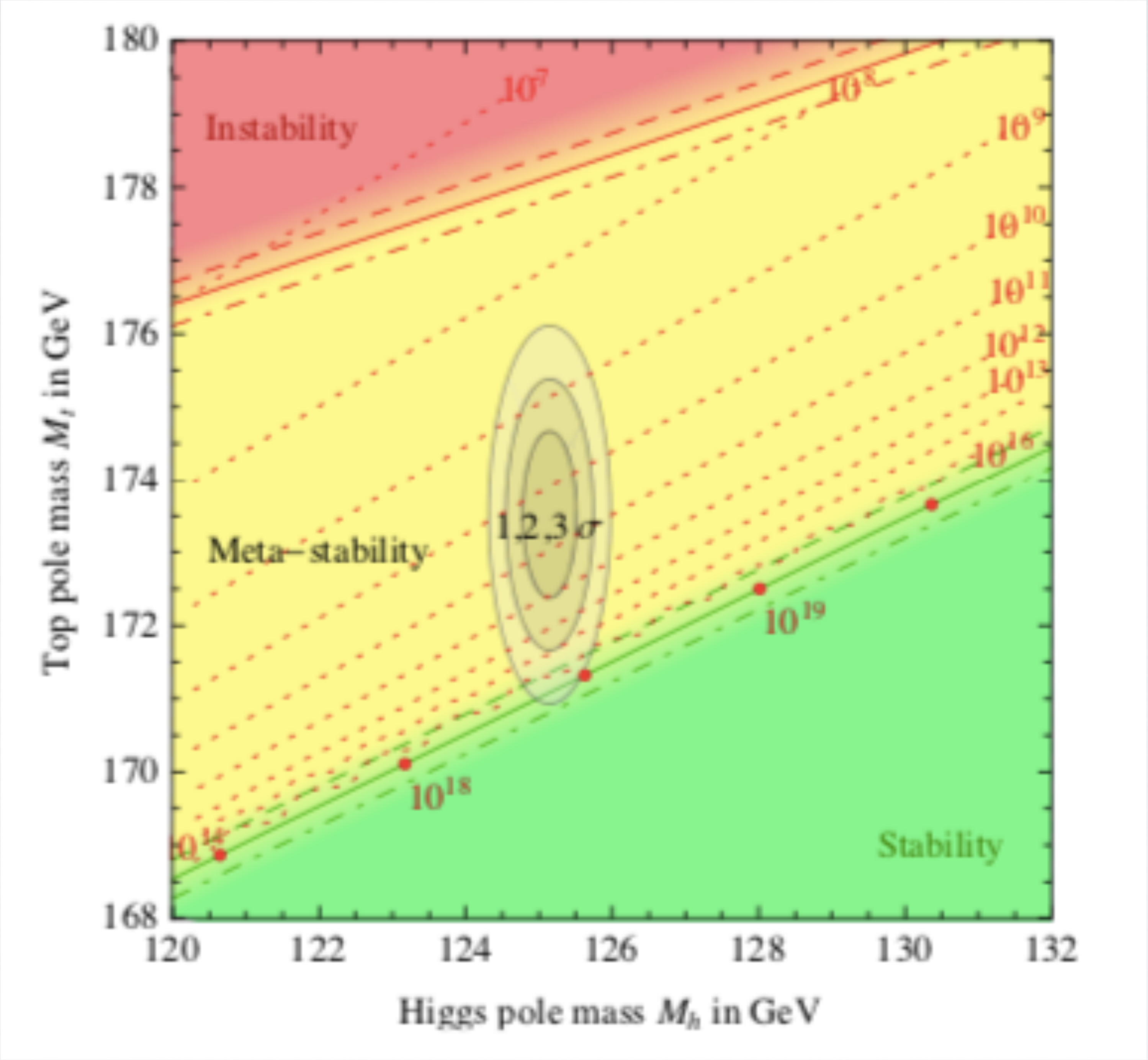


Unfortunately it's very difficult and it interferes with itself

However, just measuring the SM value would be seeing something qualitatively new!

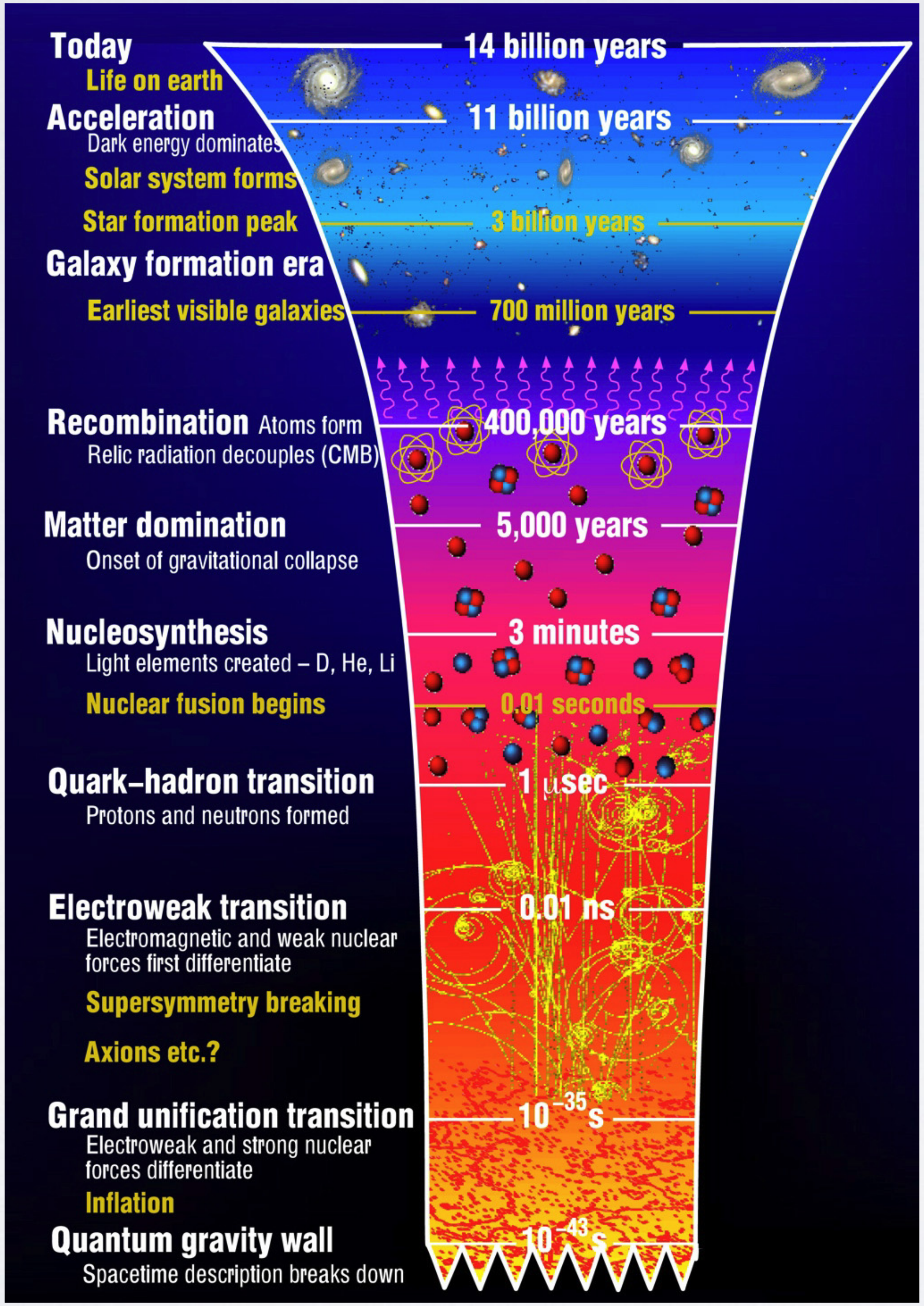
To go beyond though it though
how precisely do we need to measure it?

METASTABILITY?



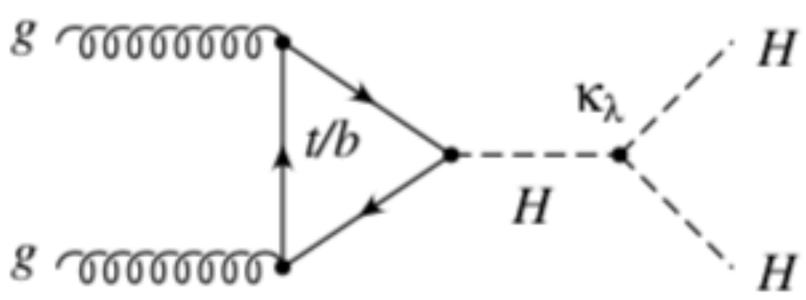
There's a lot of room between here and the Planck scale so maybe this problem is less pressing

THE ELECTROWEAK PHASE TRANSITION



THE ELECTROWEAK PHASE TRANSITION

Higgs boson pair production at colliders:
status and perspectives



Double Higgs production at colliders allows for a direct probe of the couplings in the Higgs potential responsible for strengthening the electroweak phase transition.

Editors:

Biagio Di Micco, Maxime Gouzevitch, Javier Mazzitelli and Caterina Vernieri

The Higgs program and open questions in particle physics and cosmology

Beate Heinemann[1,2a], and Yosef Nir[3b1]

In contrast to the question of electroweak phase transition, for the flavor measurements there is no lower bound on the size of new physics effects. Instead, the better accuracy, the higher the scale of new physics to which there is sensitivity.

THE ELECTROWEAK PHASE TRANSITION

Higgs boson pair production at colliders:

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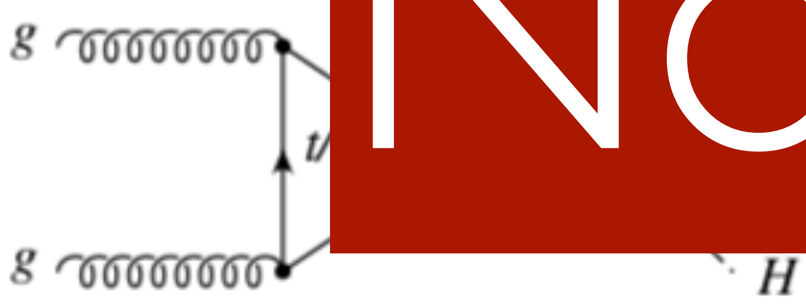

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The Higgs program and open questions in particle physics and cosmology

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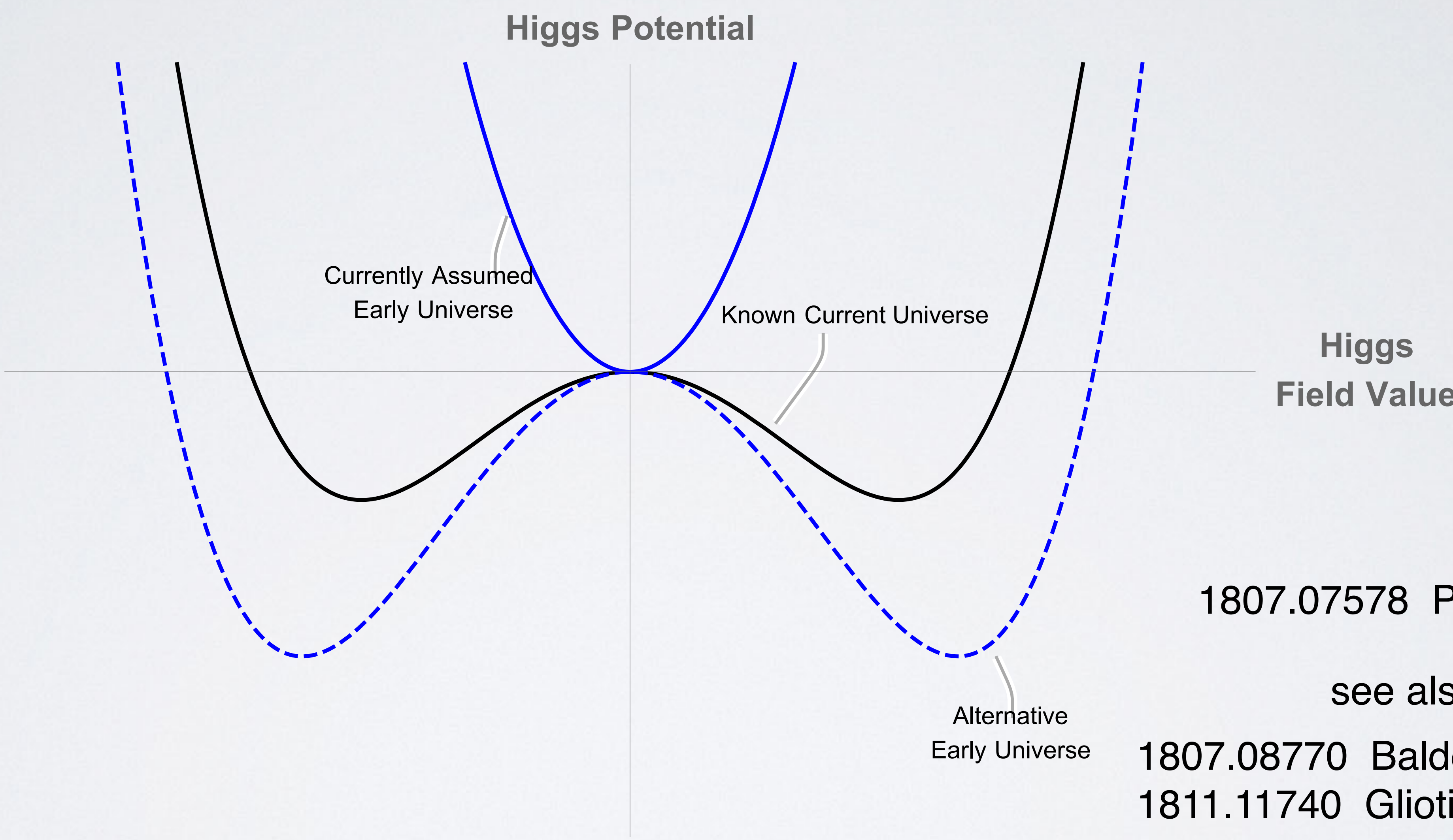
physics to which there is sensitivity.

Not True!

SYMMETRY NON-RESTORATION OR DELAYED RESTORATION!



1807.07578 PM, H. Ramani

see also

1807.08770 Baldes, Servant
1811.11740 Glioti, Rattazzi, Vecchi

Need a precise measurement of the triple Higgs coupling to differentiate!

THE HIGGS CAN TELL US LOTS OF THINGS QUALITATIVELY ABOUT OUR UNIVERSE

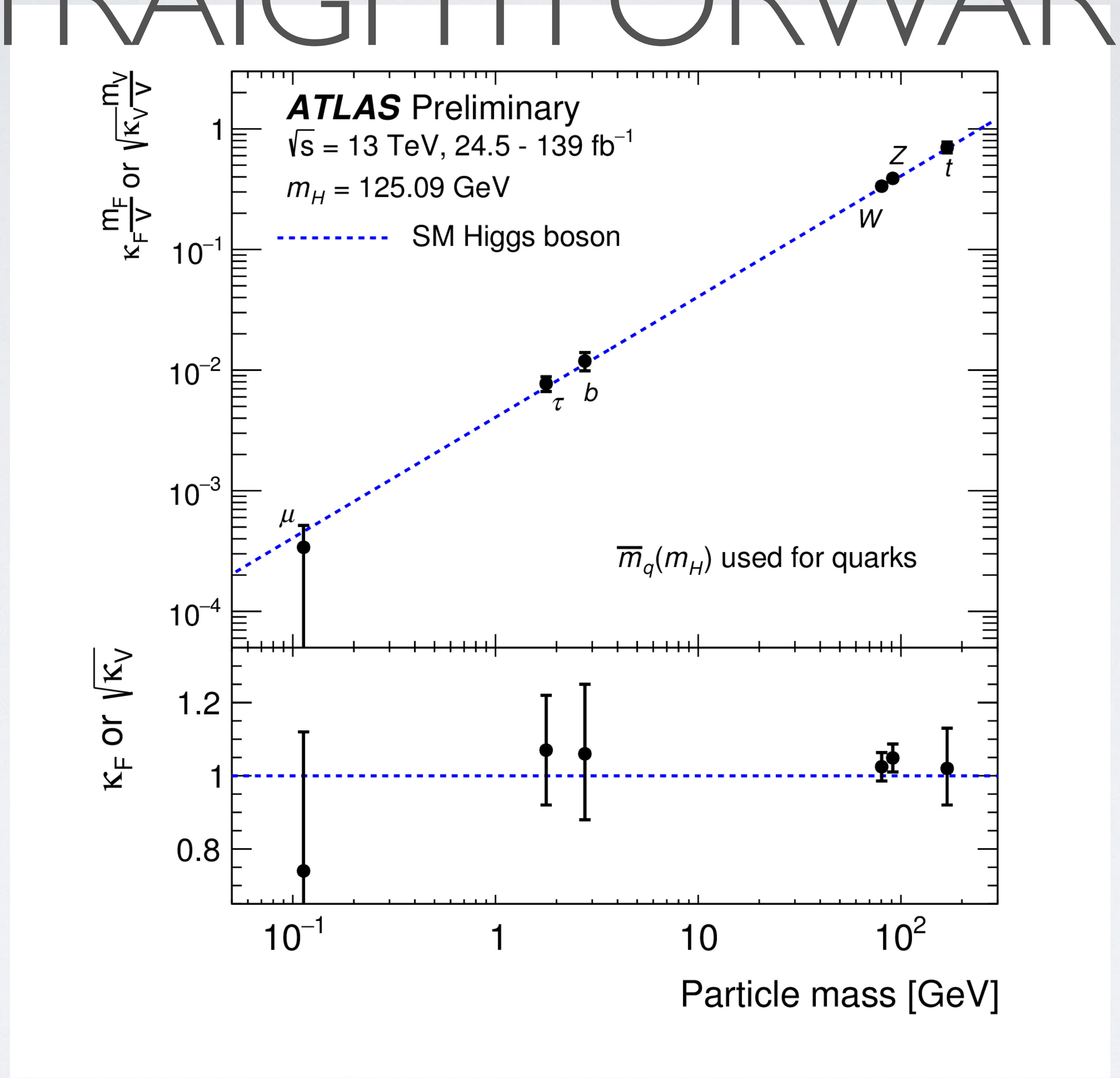
IF WE MEASURE IT WELL ENOUGH!

<u>Origin of EWSB</u>
<u>naturalness</u>
<u>stability of universe</u>
<u>cosmological history of the universe</u>

All pretty impressive, but let's go next to where the Higgs really does the heavy lifting in the SM

TV G
CC
Flavor!!!!!
Pause (k)

FLAVOR FOR HIGGS SEEMS STRAIGHTFORWARD



Actually it's responsible for so much more of course…

JUST REMEMBER THE SM WOULD BE BEAUTIFUL WITHOUT THE HIGGS…

Gauge theories :

Gauge group + matter reps + gauge coupling

Everything is fixed!

JUST REMEMBER THE SM WOULD BE BEAUTIFUL WITHOUT THE HIGGS…

Scalars can have Yukawa couplings

$$\mathcal{L} \supset Y^d_{ij}\overline{Q}_{Li}\phi D_{Rj} + Y^u_{ij}\overline{Q}_{Li}\tilde{\phi}U_{Rj}$$

We shove these Yukawa's into masses and CKM matrix in mass basis

Majority of SM parameters come from Flavor i.e. couplings of Higgs

WHY DON'T WE TALK ABOUT FLAVOR MORE?

We talk about it a lot when there are anomalies...

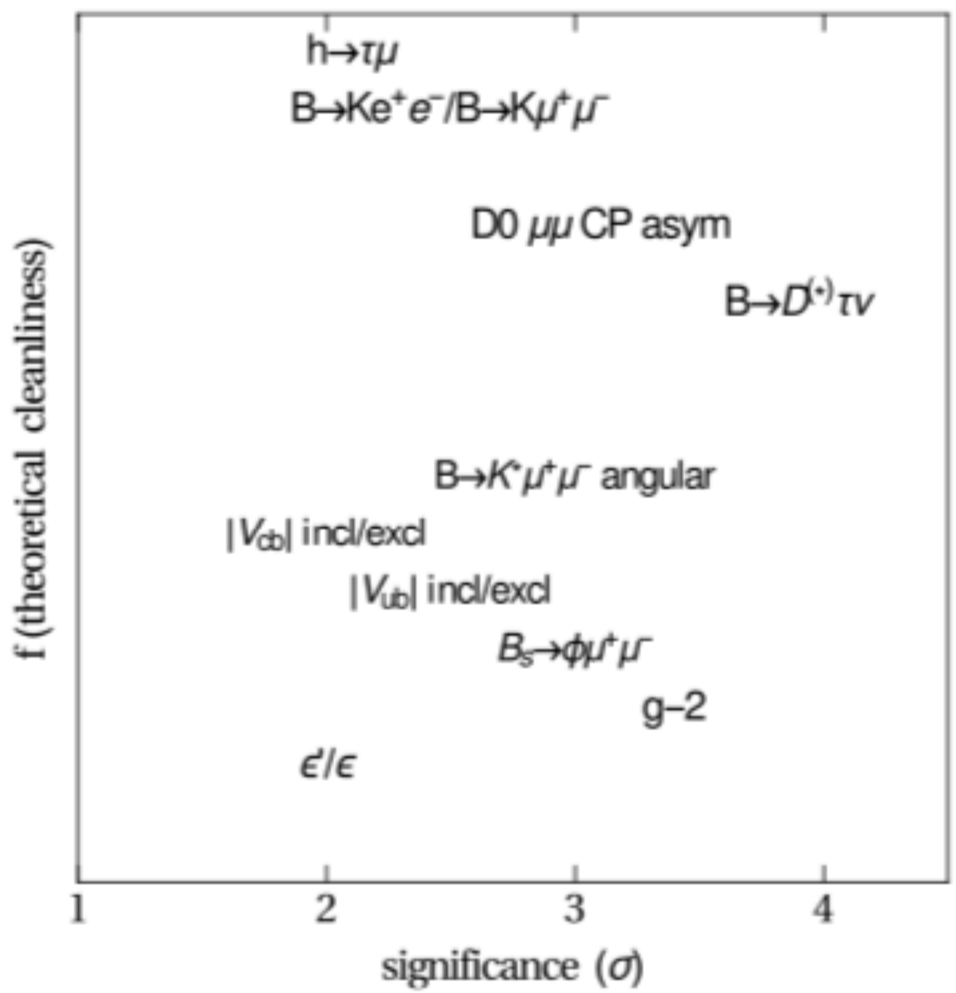


Figure 3: Some recent measurements in tension with the SM. The horizontal axis shows the nominal significance. The vertical axis shows (monotonically, in my opinion) an undefined function of an ill-defined variable: the theoretical cleanliness. That is, the level of plausibility that a really conservative estimate of the theory uncertainty of each observable may affect the significance of its deviation from the SM by 1σ.

From Z. Ligeti 1704.02938

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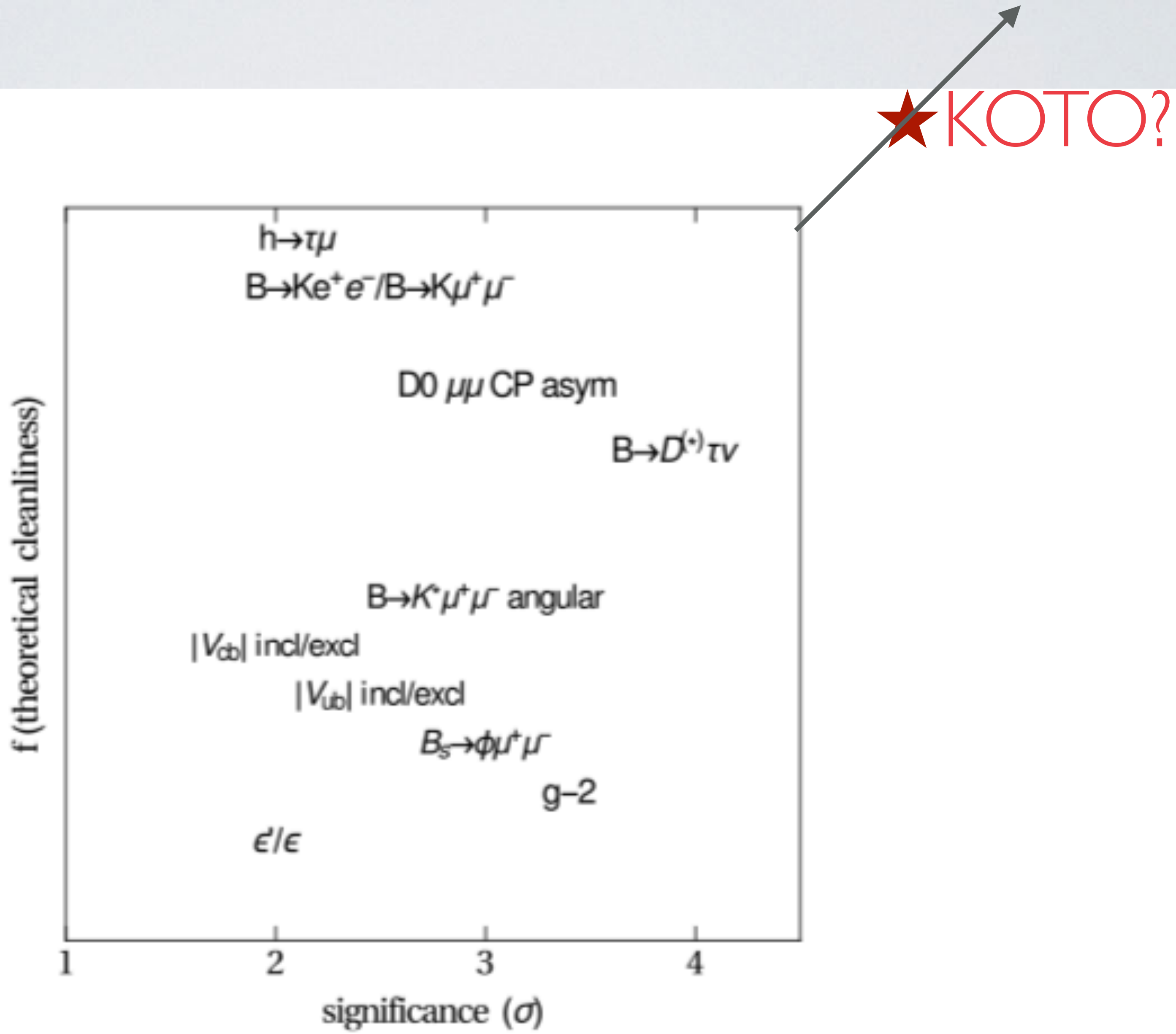

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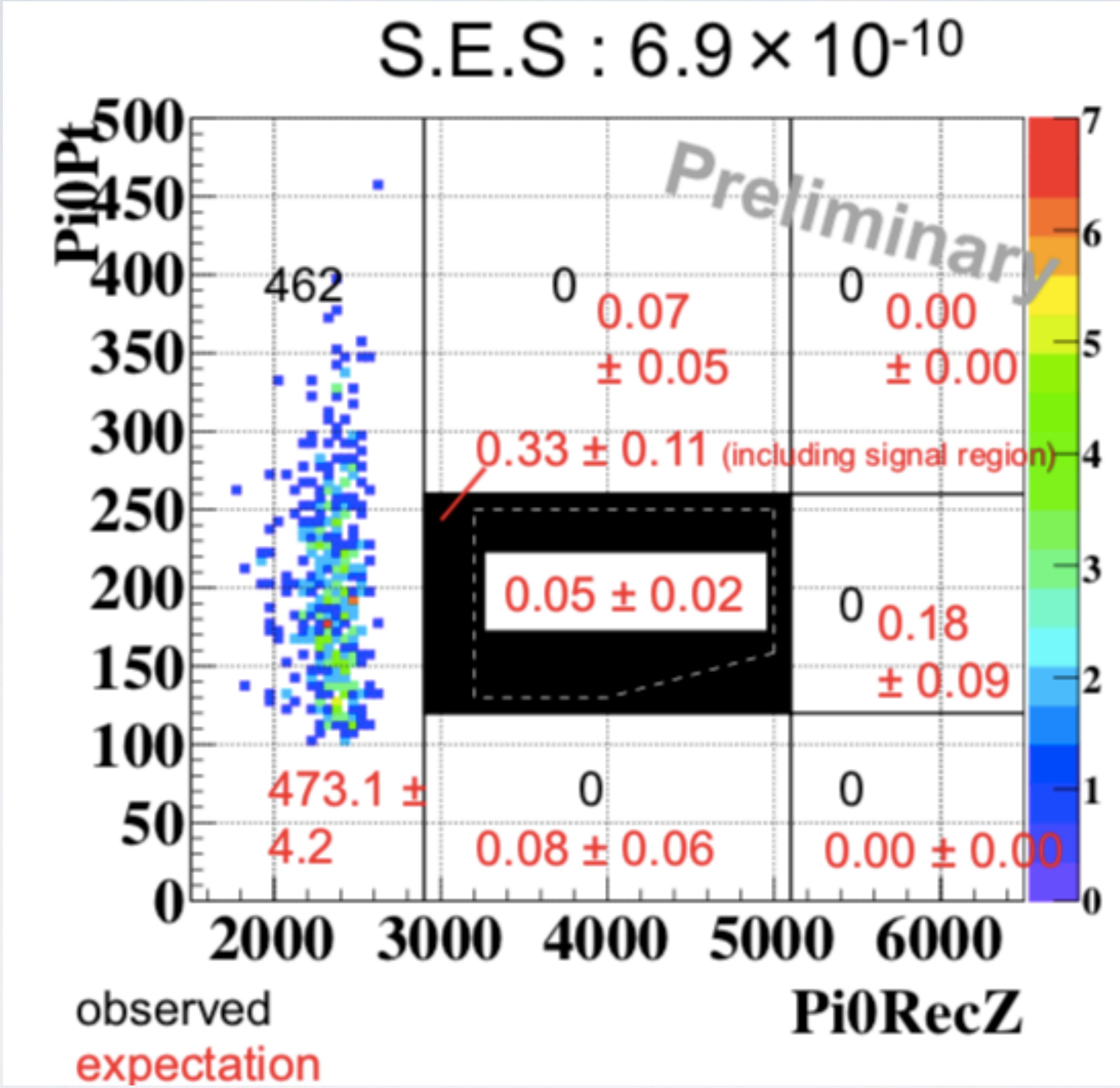
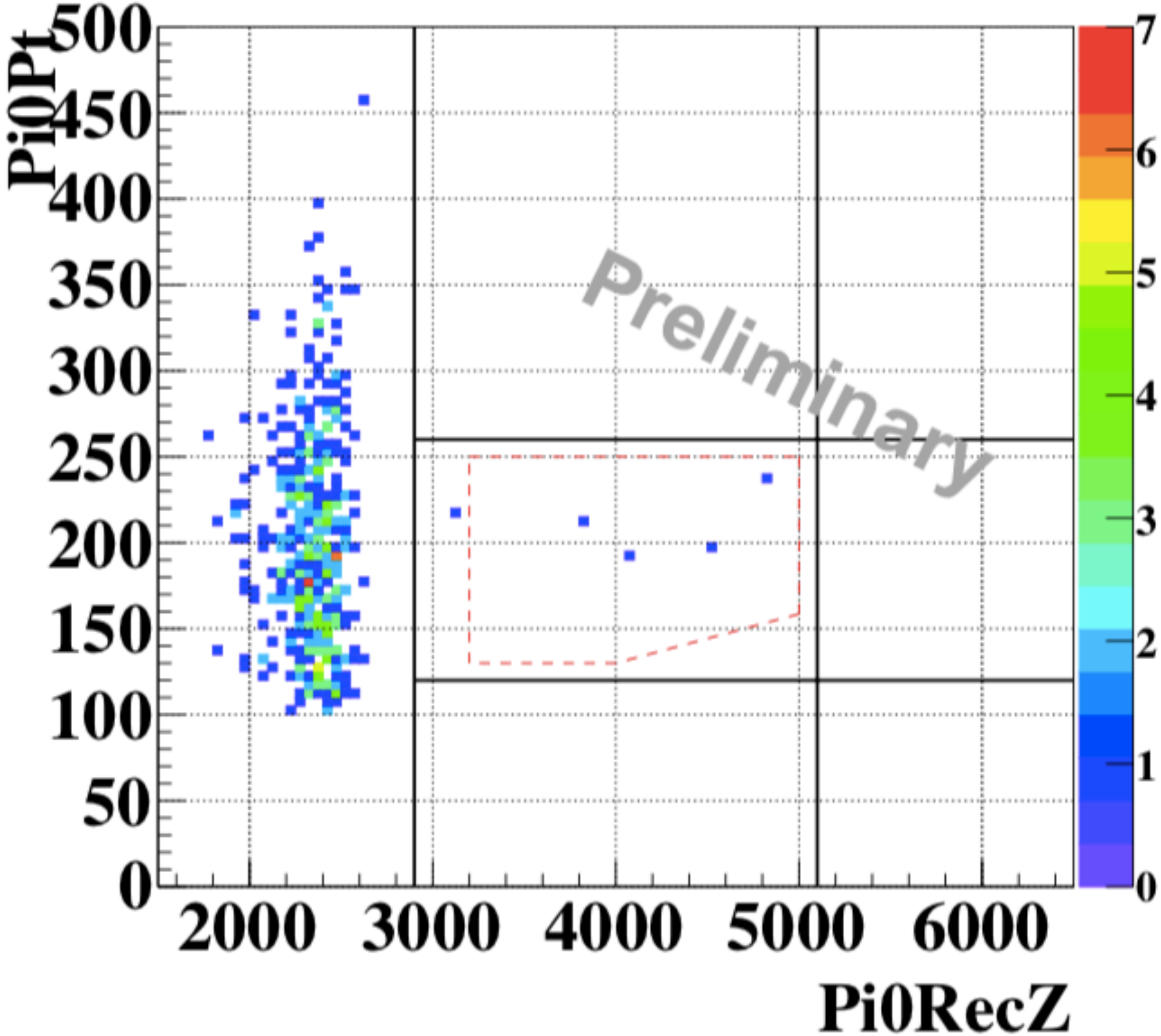


S.E.S : 6.9 × 10^-10
Pi0Pt
Preliminary
462
0
0.07
± 0.05
0
0.00
± 0.00
0.33 ± 0.11 (including signal region)
0.05 ± 0.02
0
0.18
± 0.09
473.1 ±
4.2
0
0.08 ± 0.06
0
0.00 ± 0.00
Pi0RecZ
observed
expectation



unblinded in the end of Aug. 2019

MODELS OF FLAVOR RELATED TO COLLIDER PHYSICS GET A LOT LESS DISCUSSION…

IN FACT AN APT ANALOGY IS:

Flavor, the third rail of BSM theory!

BSM Flavor @ TeV Scale

IT'S NOT JUST A MATTER OF TASTE, THERE **IS** A PHYSICS REASON

TYPICAL FLAVOR BOUNDS

Dimension 6 operators suppressing Dirac structure

$$\frac{C_s}{\Lambda^2} s\bar{d}s\bar{d}$$

$$\frac{C_c}{\Lambda^2} c\bar{u}c\bar{u}$$

$$\frac{C_b}{\Lambda^2} b\bar{d}b\bar{d}$$

TYPICAL FLAVOR BOUNDS

Dimension 6 operators suppressing Dirac structure

$$\frac{C_s}{\Lambda^2} s\bar{d}s\bar{d} \longrightarrow \Lambda \gtrsim 10^4\,\mathrm{TeV}$$

$$\frac{C_c}{\Lambda^2} c\bar{u}c\bar{u} \longrightarrow \Lambda \gtrsim 10^3\,\mathrm{TeV}$$

$$\frac{C_b}{\Lambda^2} b\bar{d}b\bar{d} \longrightarrow \Lambda \gtrsim 10^4\,\mathrm{TeV}$$

Assuming O(1) Wilson Coefficients

FLAVOR IS MEASURED REALLY WELL!

- So unless it's a very clean and large deviation it's probably hard to make an anomaly work
- For LHC BSM physics it's even crazier to think we'll see something flavor dependent, right?

TYPICAL FLAVOR BOUNDS

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$$\frac{C_b}{\Lambda^2} b\bar{d}b\bar{d} \longrightarrow \Lambda \gtrsim 10^4\,\mathrm{TeV}$$

$\Lambda \gg$ **LHC COM Energy**

WHY WOULD ONE EVEN BUILD THE LHC?

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Bounds come from assuming O(1) Wilson Coefficients

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Bounds come from assuming O(1) Wilson Coefficients

Similar problems for Electroweak Precision before the LHC

$$\frac{C_T}{\Lambda^2}(H^\dagger D_\mu H)^2 \longrightarrow \Lambda \gtrsim 10\,\mathrm{TeV}$$

If you throw in a weak coupling and a loop factor…

$$\Lambda \gtrsim 10\,\mathrm{TeV} \longrightarrow \Lambda \gtrsim v$$

Weak scale is no problem!

WHY WOULD ONE EVEN BUILD THE LHC?

However...

$\Lambda \gtrsim 10\,\mathrm{TeV}$	is much weaker than	$\Lambda \gtrsim 10^4\,\mathrm{TeV}$
EWPT		FLAVOR

So you have to make ***much stronger assumptions*** about flavor physics if you want to have any hint of it at the LHC

TYPICAL BSM
LHC FLAVOR BIASES

TYPICAL BSM LHC FLAVOR BIASES

Flavor is super constrained so *new* physics is completely flavor blind

or

TYPICAL BSM LHC FLAVOR BIASES

Flavor is super constrained so *new* physics is completely flavor blind

or

“MFV”

Minimal **F**lavor **V**iolation

TYPICAL BSM
LHC FLAVOR BIASES

Flavor is super constrained so *new* physics is completely flavor blind

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"MFV"

23. **Minimal flavor violation: An Effective field theory approach**
G. D'Ambrosio (CERN & INFN, Naples), G.F. Giudice (CERN), G. Isidori (CERN & Frascati), A. Strumia (CERN & Pisa U. & INFN, Pisa). Jul 2002. 29 pp.
Published in **Nucl.Phys. B645 (2002) 155-187**
CERN-TH-2002-147, IFUP-TH-2002-17
DOI: 10.1016/S0550-3213(02)00836-2
e-Print: **hep-ph/0207036** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Link to Fulltext
Detailed record - Cited by 1442 records 1000+

MINIMAL FLAVOR VIOLATION

If we ignore SM Yukawa couplings
SM has a very large global flavor symmetry

$$U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E \times U(1)^5$$

$$U(1)^5 = U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_{PQ} \times U(1)_E$$

Badly broken by e.g. SM quark Yukawas
which are arbitrary 3x3 complex matrices

$$\mathcal{L} \supset Y^d_{ij} \overline{Q_L}_\phi D_{R_j} + Y^u_{ij} \overline{Q_L}_i \tilde{\phi} U_{R_j}$$

Seibergology spurions to the rescue

MINIMAL FLAVOR VIOLATION

$$\mathcal{L} \supset Y^d_{ij}\overline{Q_L}_\phi D_{R_j} + Y^u_{ij}\overline{Q_L}_i\tilde{\phi}U_{R_j}$$

Assume Yukawas transform under the global symmetry and they are some background field which spontaneously breaks the symmetry

e.g. under $SU(3)_Q \times SU(3)_U \times SU(3)_D$

$$Y^u \sim (3,\bar{3},1) \qquad Y^d \sim (3,1,\bar{3})$$

Why is this way of thinking useful?

MINIMAL FLAVOR VIOLATION

Assume the only spurions which break the SM global flavor symmetry are the SM Yukawas!

(D'Ambrosio, Giudice, Isidori, Strumia)

MINIMAL FLAVOR VIOLATION

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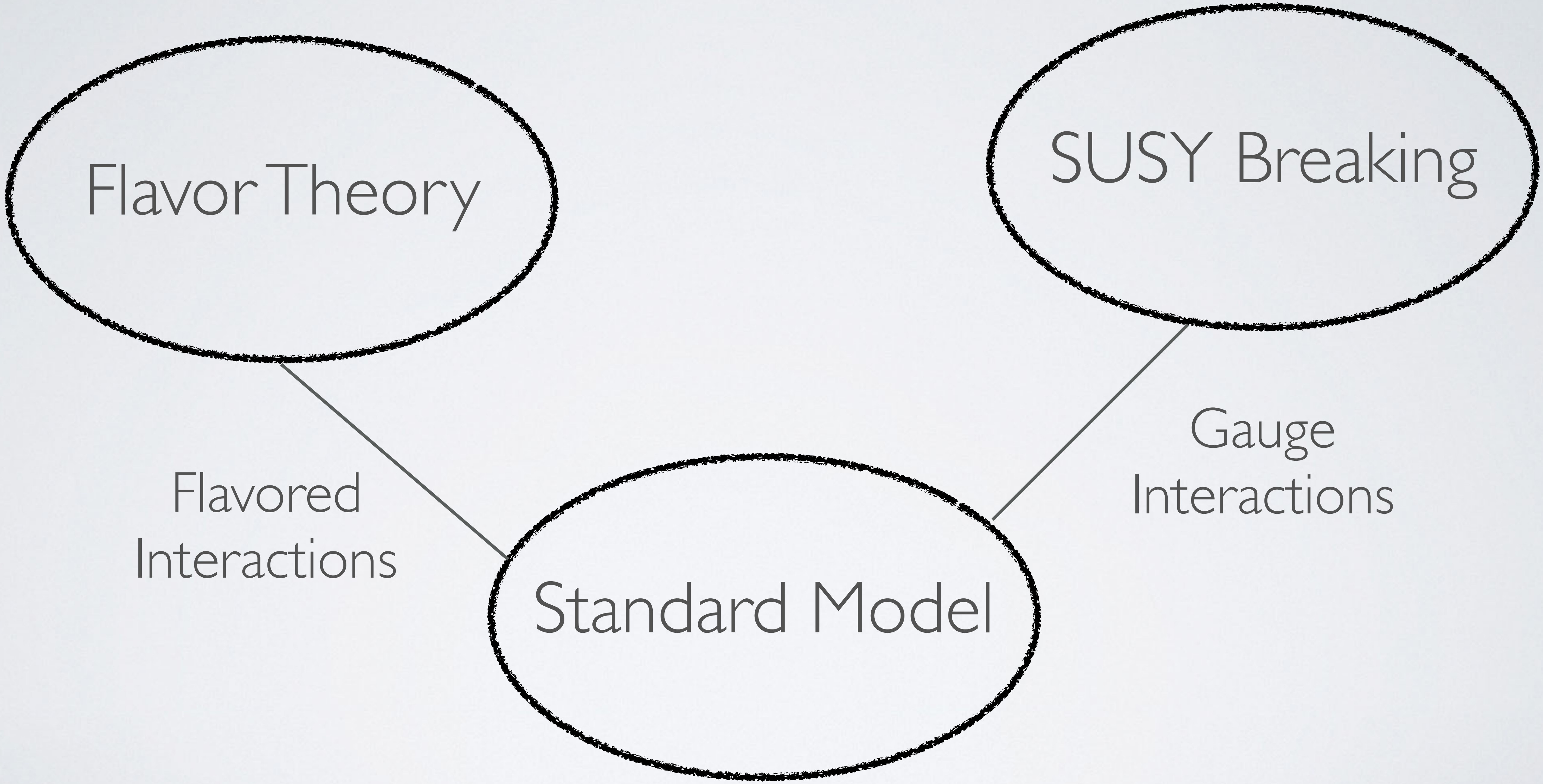
<u>This is **NOT** a theory of FLAVOR</u>

MFV EXAMPLE: GAUGE MEDIATED SUSY BREAKING



In the end of the day SUSY only knows about flavor through SM

MINIMAL FLAVOR VIOLATION

Assume the only spurious which break the SM global flavor symmetry are the SM Yukawas!

(D' Ambrosio, Giudice, Isidori, Strumia)

This is **NOT** a theory of FLAVOR

This is an **ansatz**, but one when combined with the symmetry group tells you exactly how any new physics operator transforms

If you **USE** MFV, you can typical bring the flavorful scale of NP down to the few TeV scale rather than 10^4 TeV

Inherit SM suppression of Yukawa and CKM

MFV IN PRACTICE

EFT only

$$\frac{1}{\Lambda^2}(\bar{Q}_L\gamma^\mu Q_L)^2$$

Coupling to BSM physics!

$$(\bar{Q}_L\gamma^\mu Q_L)\mathcal{O}_\mu^{BSM}$$

Tells you what to put as
coefficient in terms of Yukawa's of SM

IT'S SOMEWHAT "NEEDED" IF YOU WANT TO DO SM EFT

Even at Dimension 6, the number of operators blows up if you have a general flavor structure

Case	CP even	CP odd	WHZ Pole parameters
General SMEFT ($n_f = 1$)	53 [10]	23 [10]	~ 23
General SMEFT ($n_f = 3$)	1350 [10]	1149 [10]	~ 46
$U(3)^5$ SMEFT	~ 52	~ 17	~ 24
MFV SMEFT	~ 108	-	~ 30

Brivio, Jiang, MT https://arxiv.org/abs/1709.06492

Michael Trott

EVEN THOUGH IT ALLOWS FOR "FLAVORFUL" COUPLINGS

Coupling to BSM physics!

$$(\bar{Q}_L \gamma^\mu Q_L)\mathcal{O}_\mu^{BSM}$$

It's still kind of boring!
Looks just like the SM: 3rd gen domination

EXTENSIONS OF MFV

NMFV: Next to Minimal Flavor Violation (Agashe, Papucci, Perez, Pirjol)

MFV + more flavor violation in 3rd gen

GMFV: General Minimal Flavor Violation (Kagan, Perez, Volansky, Zupan)

MFV + polynomials of Yukawa when needed because of 3rd gen

<u>Amusingly, "flavored" BSM ansatz basically give the same guidance as naturalness</u>

ARE WE BIASING OURSELVES INTO LOOKING ONLY IN CERTAIN PLACES?

HOW DO WE GET AROUND OUR BIASES?

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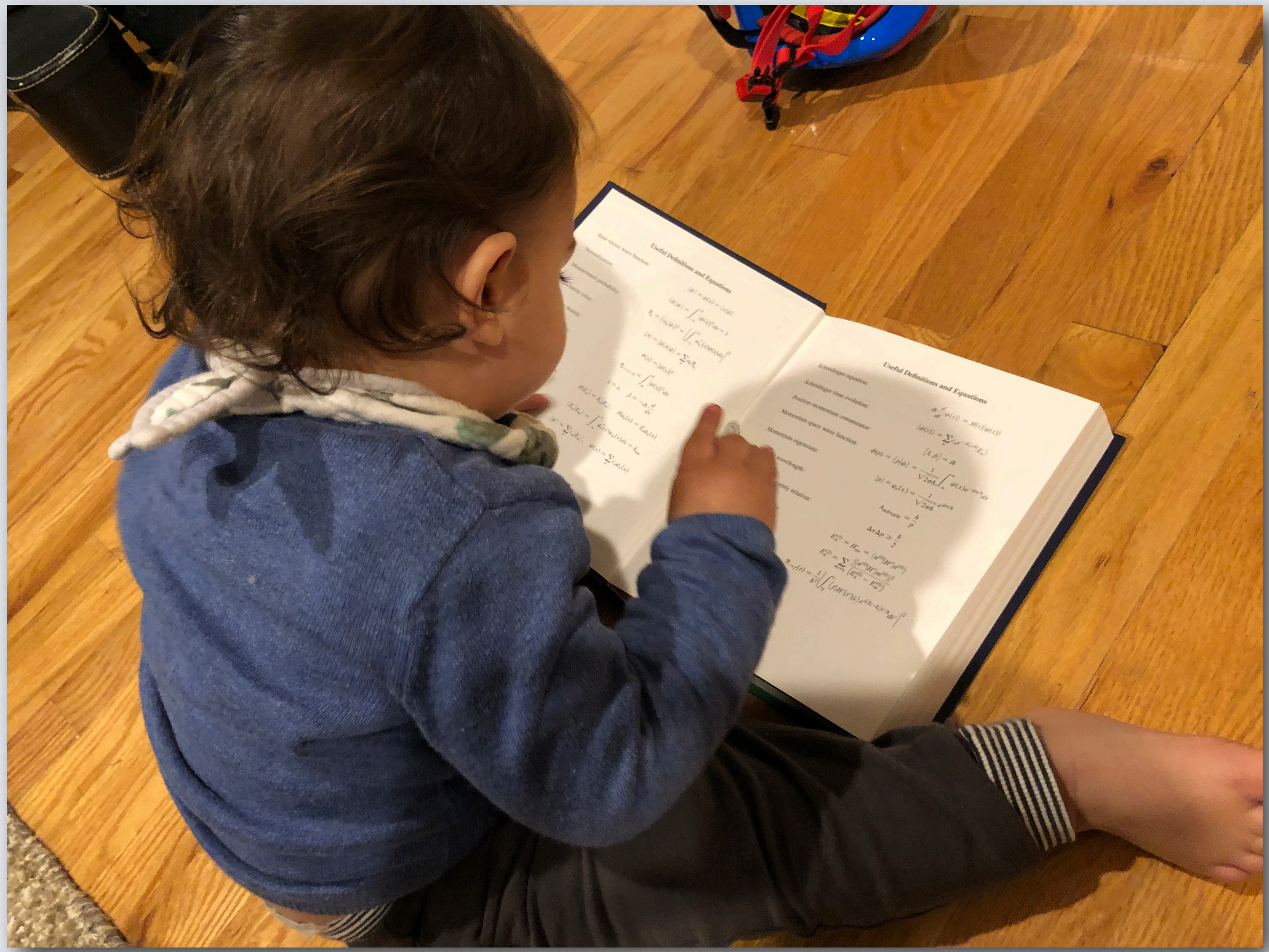

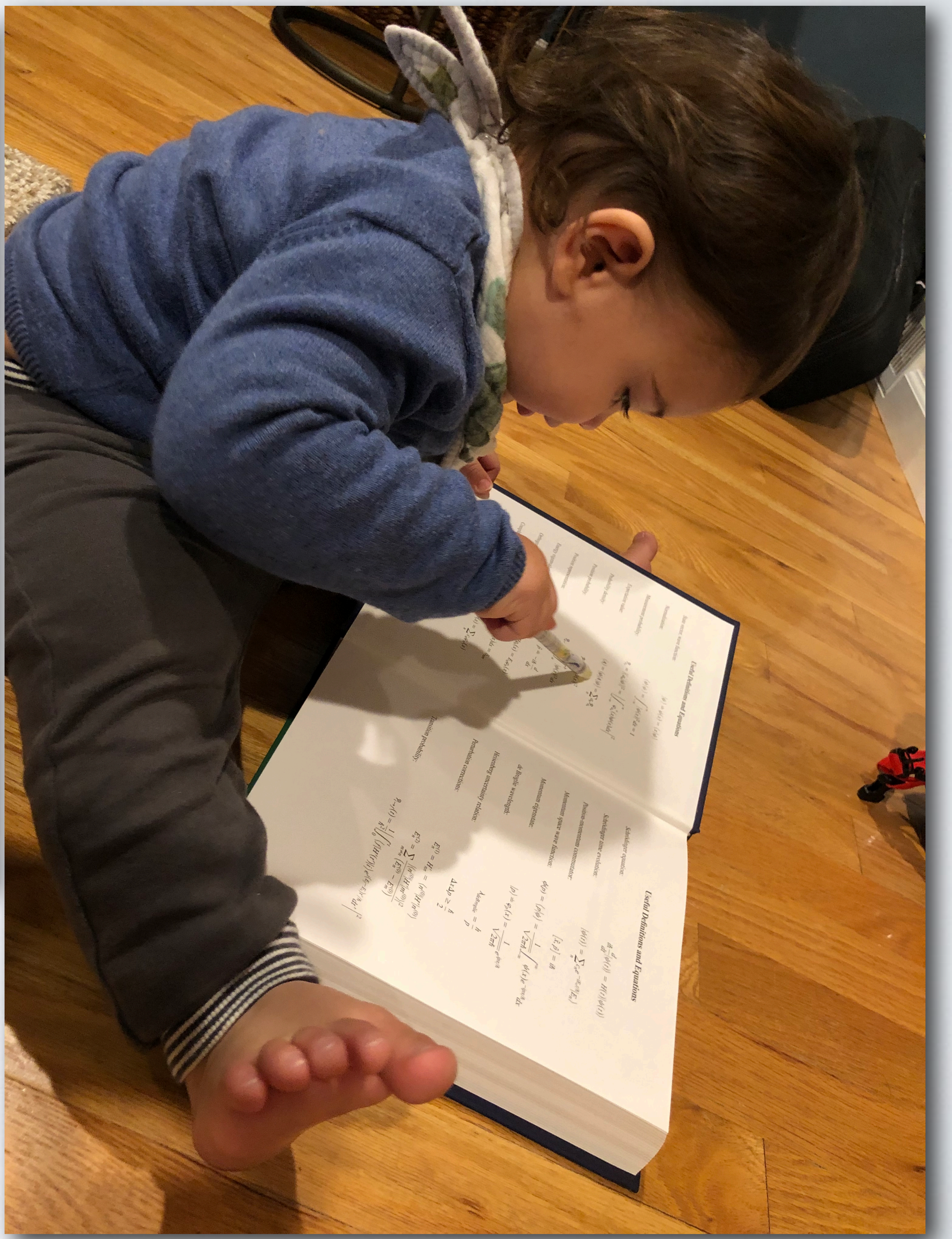

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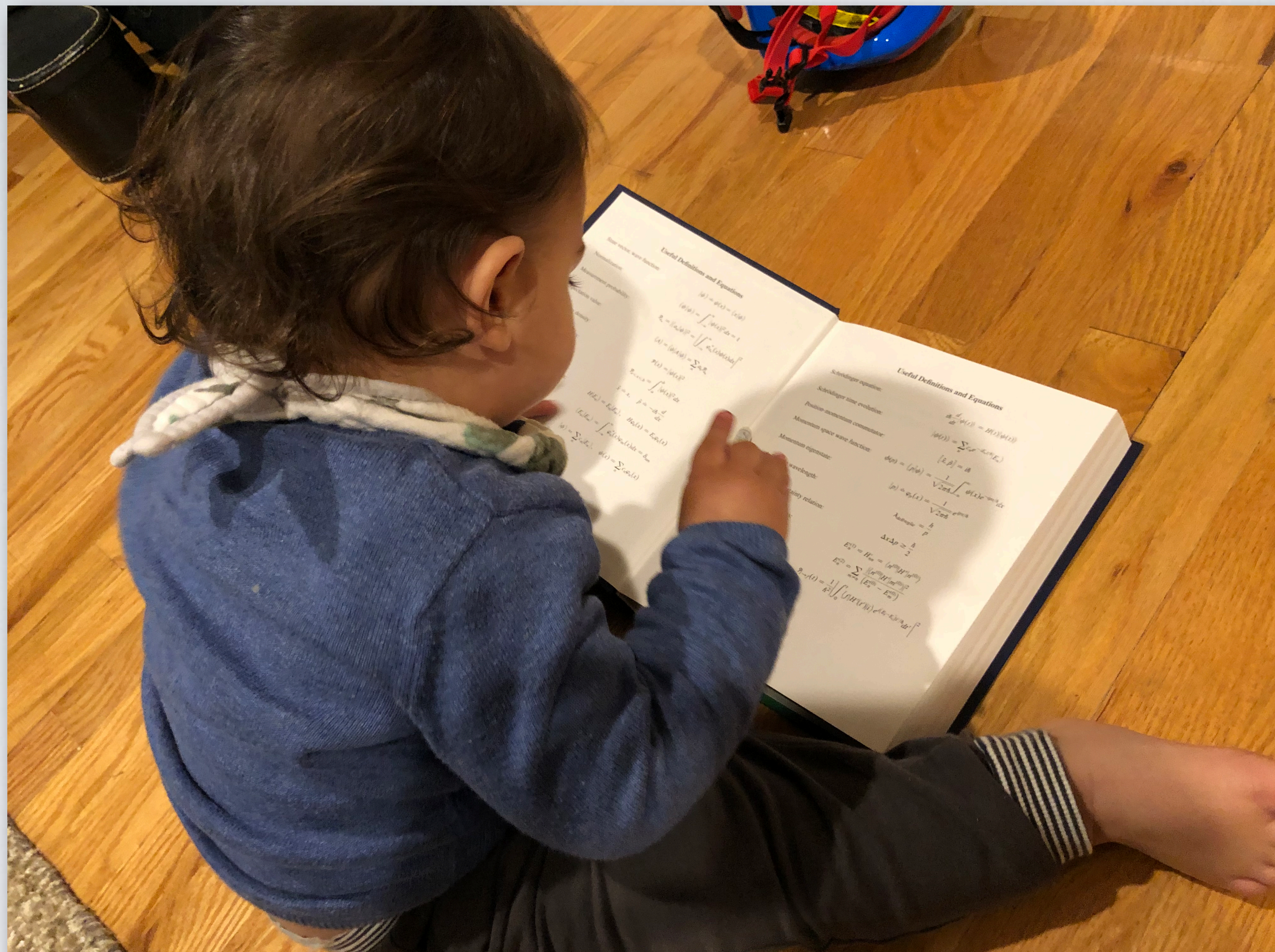

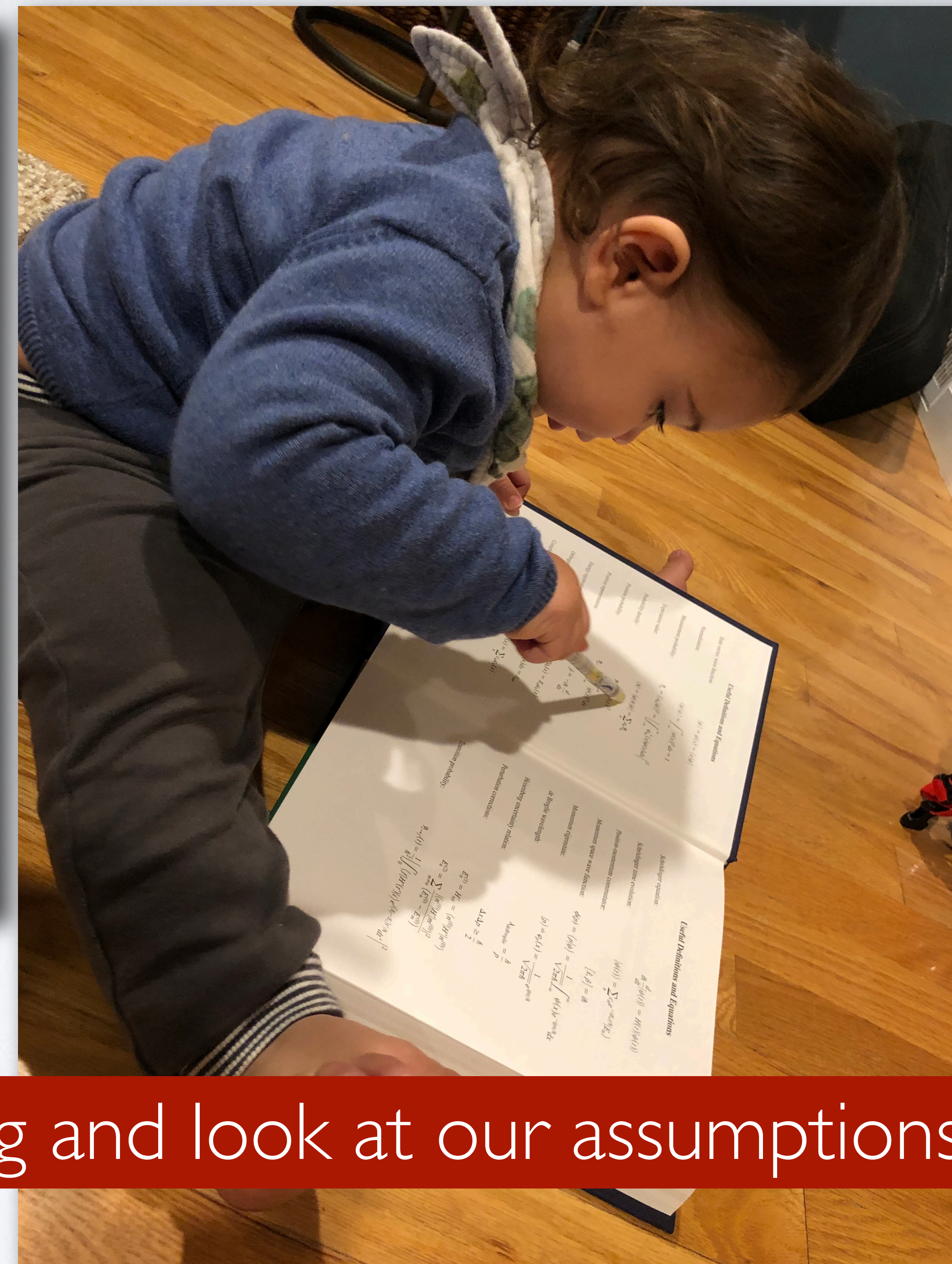

We have to go back to the beginning and look at our assumptions

ALIGNED FLAVOR VIOLATION
AND
SPONTANEOUS FLAVOR VIOLATION

WE'RE ALL FAMILIAR WITH THE *MASS* BASIS OF THE SM

All SM Yukawas are **Diagonal** and all non-trivial flavor lives in the CKM matrix for charged current interactions

We get there by using all those extra global (symmetry) rotations of our matter fields

WE'RE ALL FAMILIAR WITH THE *MASS* BASIS OF THE SM

All SM Yukawas are **Diagonal** and all non-trivial flavor lives in the CKM matrix for charged current interactions

We get there by using all those extra global (symmetry) rotations of our matter fields

In the **gauge** basis we can think of a **"special basis"** where

$Y_d = \lambda_d$ and $Y_u = V^\dagger \lambda_u$

or

$Y_d = V \lambda_d$ and $Y_u = \lambda_u$

IN ONE OF THESE SPECIAL BASIS CHOICES…

$Y_d = \lambda_d$ and $Y_u = V^\dagger \lambda_u$

or

$Y_d = V \lambda_d$ and $Y_u = \lambda_u$

For instance the first choice…

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For instance the first choice…

I don't need to do anything more to the down sector to go to the mass basis, it's already diagonal… all non-trivial flavor violation is up-type

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$Y_d = \lambda_d$ and $Y_u = V^\dagger \lambda_u$

or

$Y_d = V\lambda_d$ and $Y_u = \lambda_u$

For instance the first choice…

I don't need to do anything more to the down sector to go to the mass basis, it's already diagonal… all non-trivial flavor violation is up-type

If I had some new down-type spurion that coupled BSM physics beyond Y_d , I'd just need it to be diagonal in this basis and no new tree level FCNCs!!

Alignment (Nir, Seiberg)

ALIGNMENT

Seiberg and Nir are great physicists, so they wouldn't just make a basis dependent statement…

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If you had a "complete" model of flavor, you could actually make statements about the form of the Yukawas

Implemented Frogatt-Nielsen models for SUSY Flavor Alignment

ALIGNMENT

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If you had a "complete" model of flavor, you could actually make statements about the form of the Yukawas

Implemented Frogatt-Nielsen models for SUSY Flavor Alignment

Unfortunately you don't gain a lot in collider pheno

CAN WE GET:

- Successes of Flavor Alignment in a Basis Independent way
  - Fancier way of saying: if we introduce a new spurion such as κ^u, κ^d transforming like y^u, y^d is it auto-aligned?
- Can we write down a UV complete model that has parametrically **new** collider phenomenology
- Can we do it in a way that's modular, i.e. can be applied to many BSM theories?

CAN WE GET:

- Successes of Flavor Alignment in a Basis independent way
  - Fancier way of saying: if we introduce a new spurion such as κ^u, κ^d transforming like y^u, y^d is it auto-aligned?
- Can we write down a UV complete model that has parametrically new collider phenomenology
- Can we do it in a way that's modular, i.e. can be applied to many BSM theories?

YES

SPONTANEOUS FLAVOR VIOLATION (SFV)

Ansatz to see alignment:

- No renormalizable breaking of $U(1)_f^3 \times CP$ other than WF renormalization of RH u **or** d quarks
- No flavor breaking spurions or fields other than SM ones and WF transforming under $U(3)_{\bar{u}}$ **or** $U(3)_{\bar{d}}$

SFV

$$\mathcal{L} \supset iZ^u_{ij}\bar{u}^\dagger_i \bar{\sigma}^\mu D_\mu \bar{u}_j + i\bar{d}^\dagger_i \bar{\sigma}^\mu D_\mu \bar{d}_i + i\bar{Q}^\dagger_i \bar{\sigma}^\mu D_\mu \bar{Q}_i$$
$$- \left[\eta^u_{ij}\; Q_i H \bar{u}_j - \eta^d_{ij} Q_i H^c \bar{d}_j + \text{h.c.}\right] + \mathcal{L}_{\text{BSM}}$$

WLOG η are real diagonal
go to canonical kinetic terms

SFV

$$\mathcal{L} \supset iZ^u_{ij}\bar{u}^\dagger_i \bar{\sigma}^\mu D_\mu \bar{u}_j + i\bar{d}^\dagger_i \bar{\sigma}^\mu D_\mu \bar{d}_i + i\bar{Q}^\dagger_i \bar{\sigma}^\mu D_\mu \bar{Q}_i$$
$$- \left[\eta^u_{ij}\ Q_i H \bar{u}_j - \eta^d_{ij} Q_i H^c \bar{d}_j + \text{h.c.}\right] + \mathcal{L}_{\text{BSM}}$$

WLOG η are real diagonal
go to canonical kinetic terms

$$\bar{u}'_i = \left(\sqrt{Z^u}\right)_{ij} \bar{u}_j$$

$$\mathcal{L} \supset i\bar{u}^\dagger_i \bar{\sigma}^\mu D_\mu \bar{u}_i + i\bar{d}^\dagger_i \bar{\sigma}^\mu D_\mu \bar{d}_i + i\bar{Q}^\dagger_i \bar{\sigma}^\mu D_\mu \bar{Q}_i$$
$$- \left[y^u_{ij}\ Q_i H \bar{u}_j - y^{d\dagger}_{ij} Q_i H^c \bar{d}_j + \text{h.c.}\right] + \mathcal{L}_{\text{BSM}}$$

$$y^u = \eta^u \left(\sqrt{Z^u}\right)^{-1} = V^T Y^u$$
$$y^{d\dagger} = \eta^d = Y^d \quad .$$

SFV

If one introduced a new spurion that transformed like the down-type Yukawa, it's **automatically** diagonal if flavor comes from WF renormalization of the RH up type quarks!

This is **NOT** a basis dependent alignment

$$\kappa^{d\dagger} = K^d \equiv \mathrm{diag}(\kappa_d, \kappa_s, \kappa_b)$$

These kappa don't have to have **anything** to do with SM Yukawas

For example new physics could couple (1,0,0) or (0,1,0) …

Z' , 2HDM, …

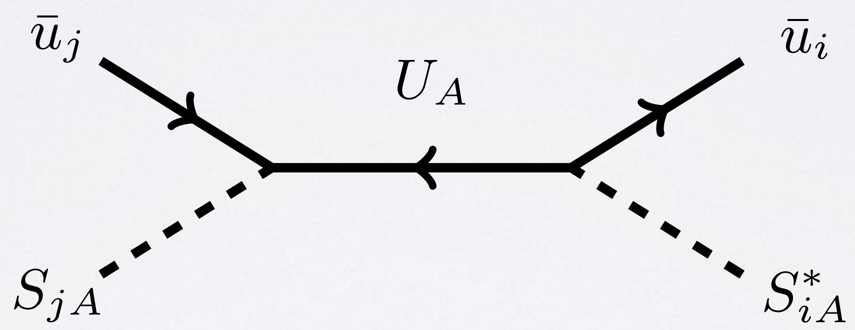
IS THERE A THEORY THAT CAN GENERATE SFV ANSATZ?

YES

SFV UV COMPLETION

$$\mathcal{L} \supset M_{AB} U_A \bar{U}_B + \xi S_{iA} \bar{u}_i U_A \\ - \left[\eta^u_{ij}\, Q_i H \bar{u}_j - \eta^d_{ij} Q_i H^c \bar{d}_j + \text{h.c.}\right] + \mathcal{L}_{\text{BSM}}$$

Integrate out vector like quarks U



$$Z^u_{ij} = \delta_{ij} + \frac{\xi^* \xi}{M^*_A M_A} S^*_{iA} S_{jA}$$

HAVEN'T SPECIFIED BSM…

2HDM Example:

$$D_\mu H_a^\dagger D^\mu H_a - V(H_1, H_2) - \left[\lambda^u_{aij} Q_i H_a \bar{u}_j - \lambda^{d\dagger}_{aij} Q_i {H_a}^c \bar{d}_j - \lambda^{\ell\dagger}_{aij} L_i {H_a}^c \bar{\ell}_j + \text{h.c.}\right]$$

Nothing says the 2nd Higgs has to have the same Yukawas

Work in the "Higgs" basis where only one Higgs gets a VEV

SFV 2HDM UP-TYPE

$$\lambda_1^u = V^T Y^u \qquad \lambda_1^d = Y^d$$

$$\lambda_2^u = \xi V^T Y^u \qquad \lambda_2^d = K^d\,.$$

$$K^d \equiv \mathrm{diag}(\kappa_d, \kappa_s, \kappa_b)$$

Can just as easily do this for down-type

THERE WILL BE FLAVOR CONSTRAINTS

- We just got rid of tree-level FCNCs, but we still get to inherit the protections of the SM at loop-level

FLAVOR CONSTRAINTS

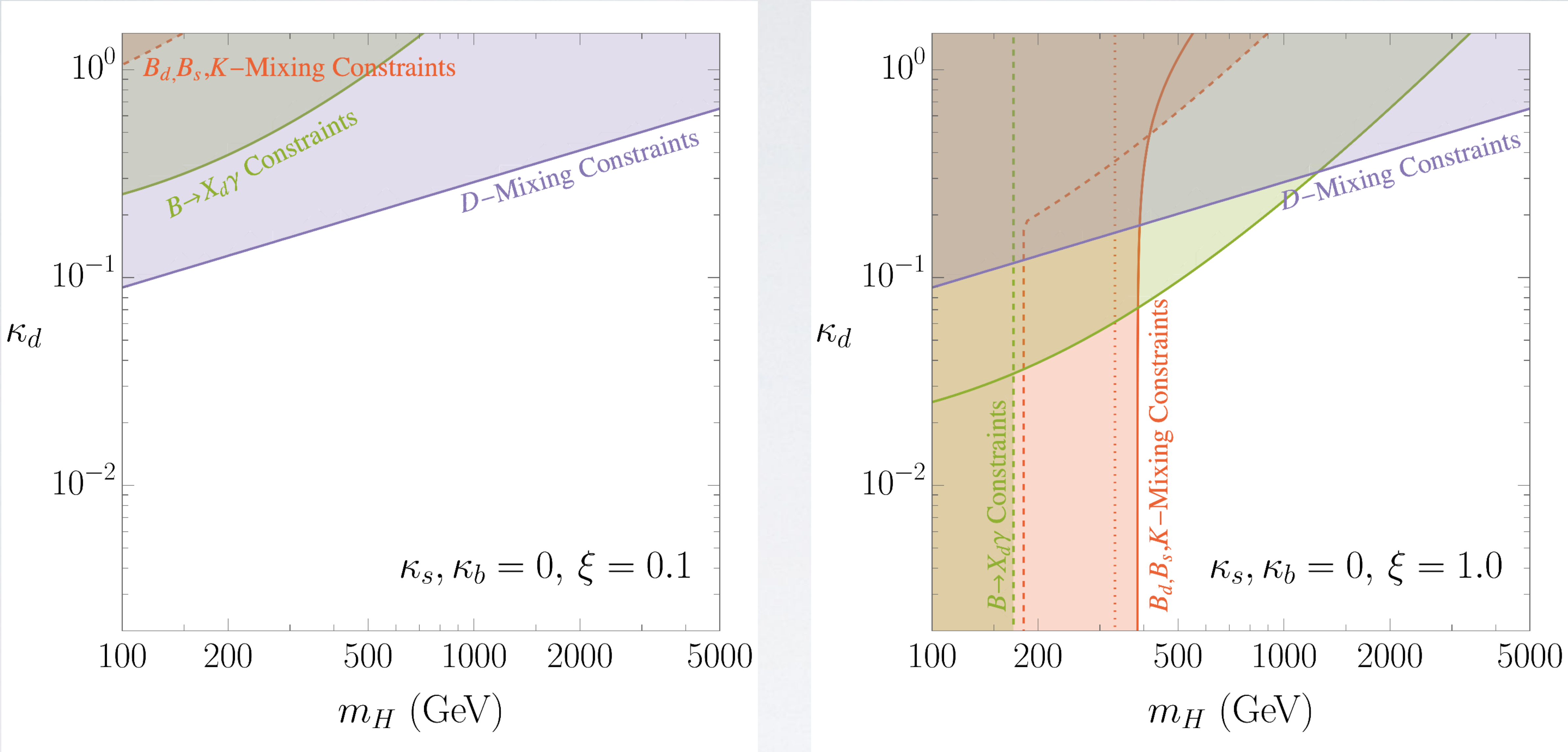


Figure 2: Constraints on the up-type SFV 2HDM from one-loop FCNC measurements in the m_H vs. κ_d plane, assuming $\kappa_s = \kappa_b = 0$. We show results both for $\xi = 0.1$ and 1.0. Constraints from $b \to s\gamma$ and $b \to d\gamma$ transitions are shown in green, with the constraint on $C_{7'}^{bd}$ (C_7^{bs}) indicated by the solid (dashed) line, respecitvely. Constraints from B_d, B_s and K mixing are shown as solid, dotted and dashed red lines respectively. The constraint from requiring the absence of fine-tuning in $D - \bar{D}$ mixing is shown in purple.

FLAVOR CONSTRAINTS

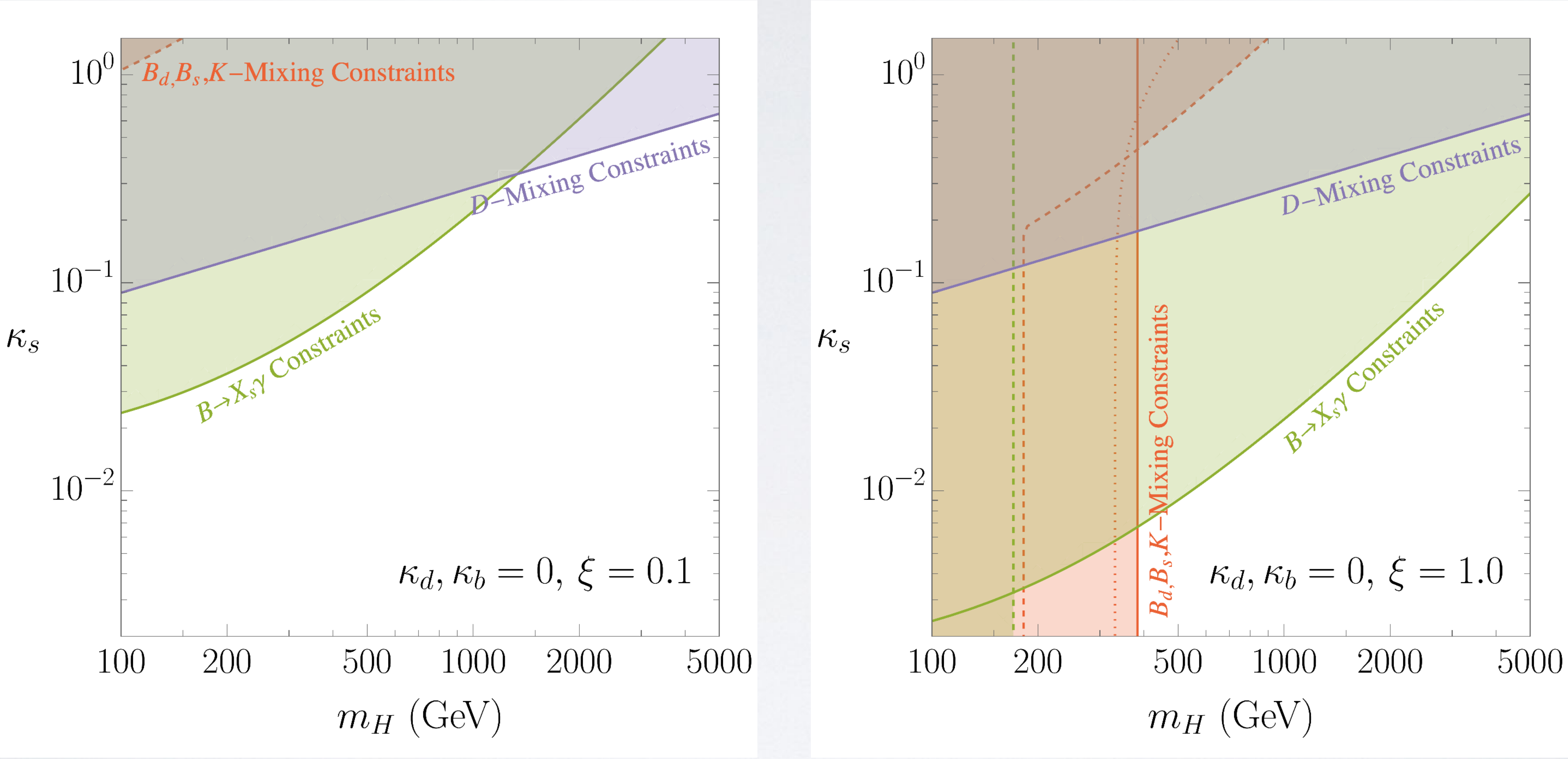


Figure 3: The same as Fig. 2, but for κ_s, with $\kappa_d = \kappa_b = 0$.

FLAVOR CONSTRAINTS

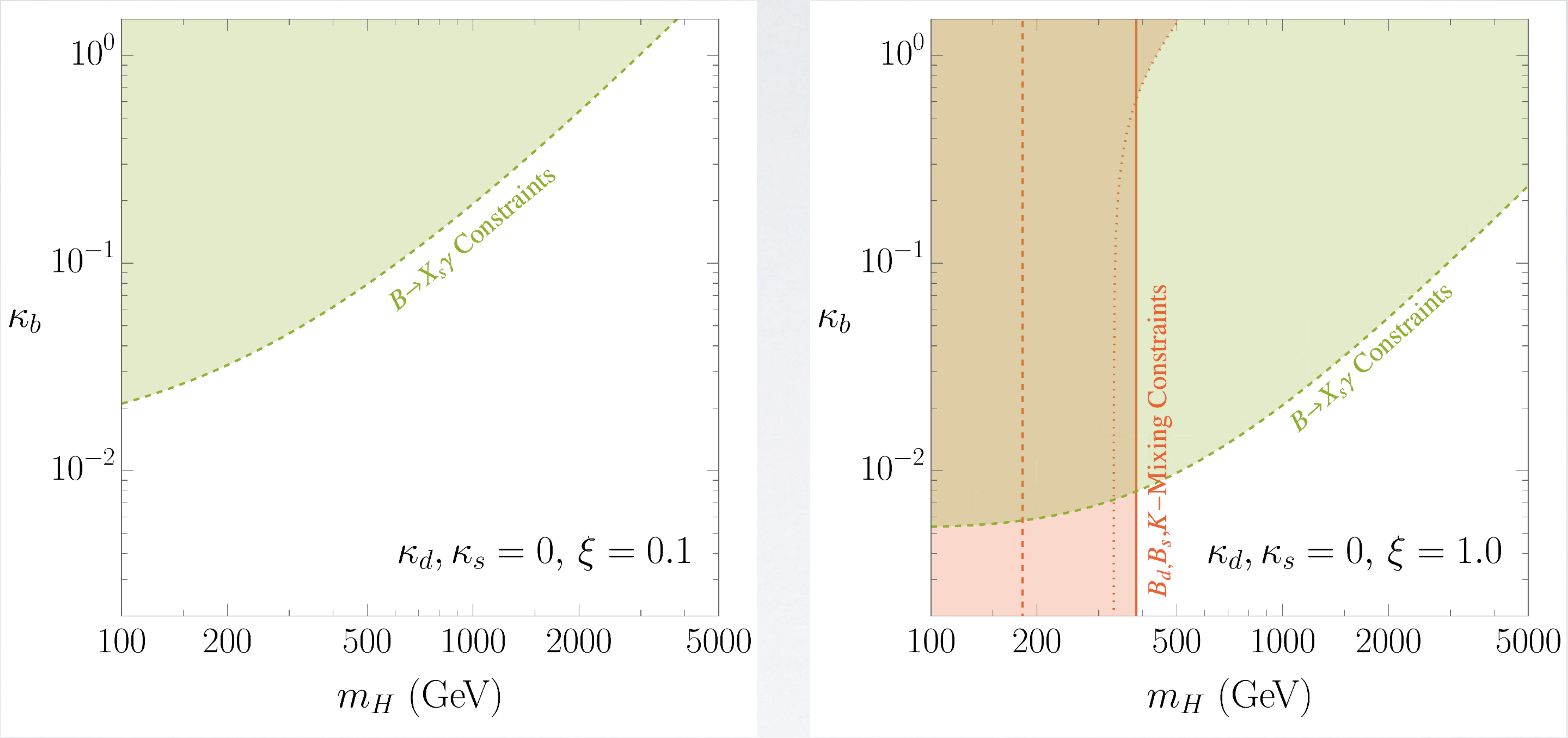
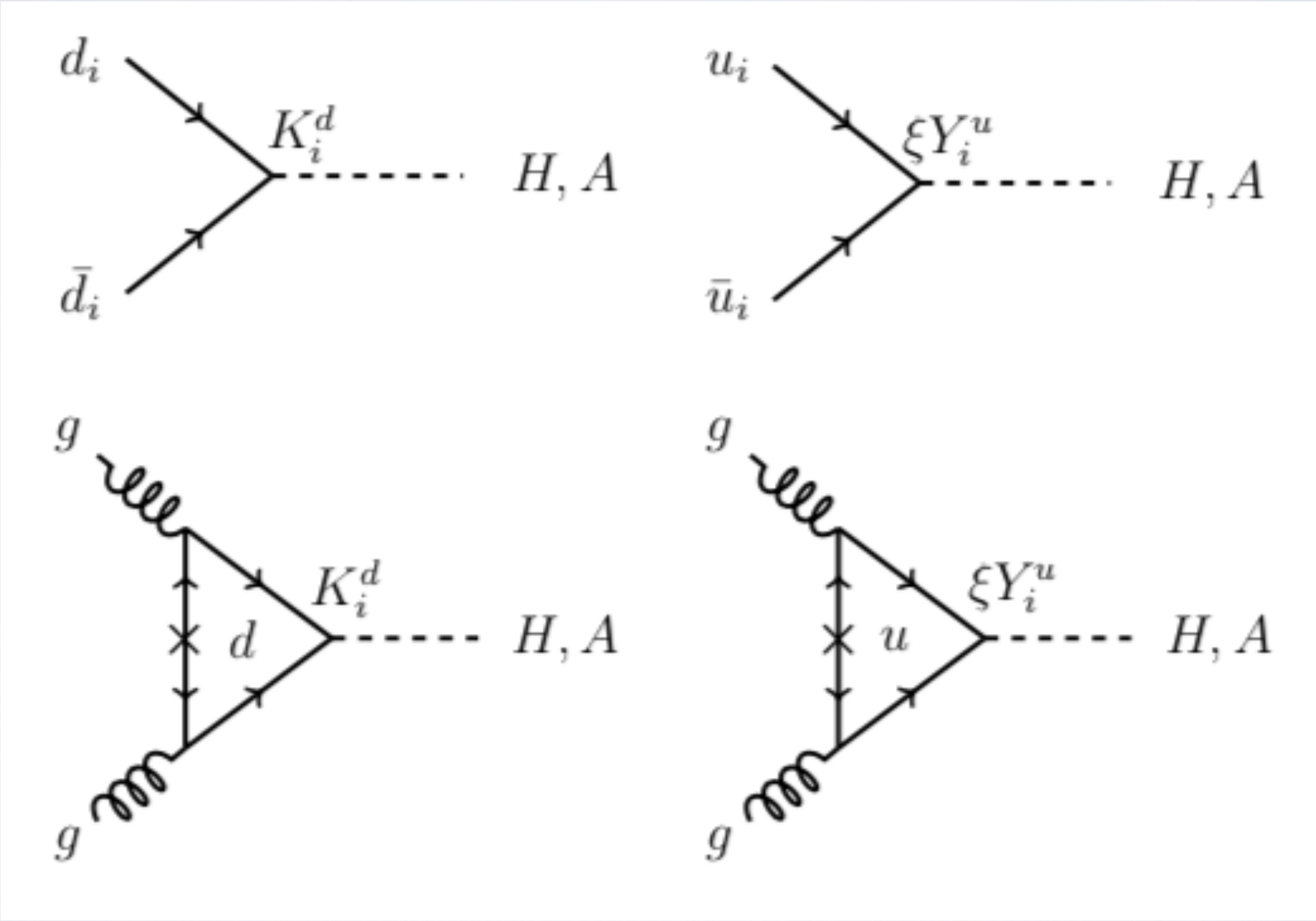
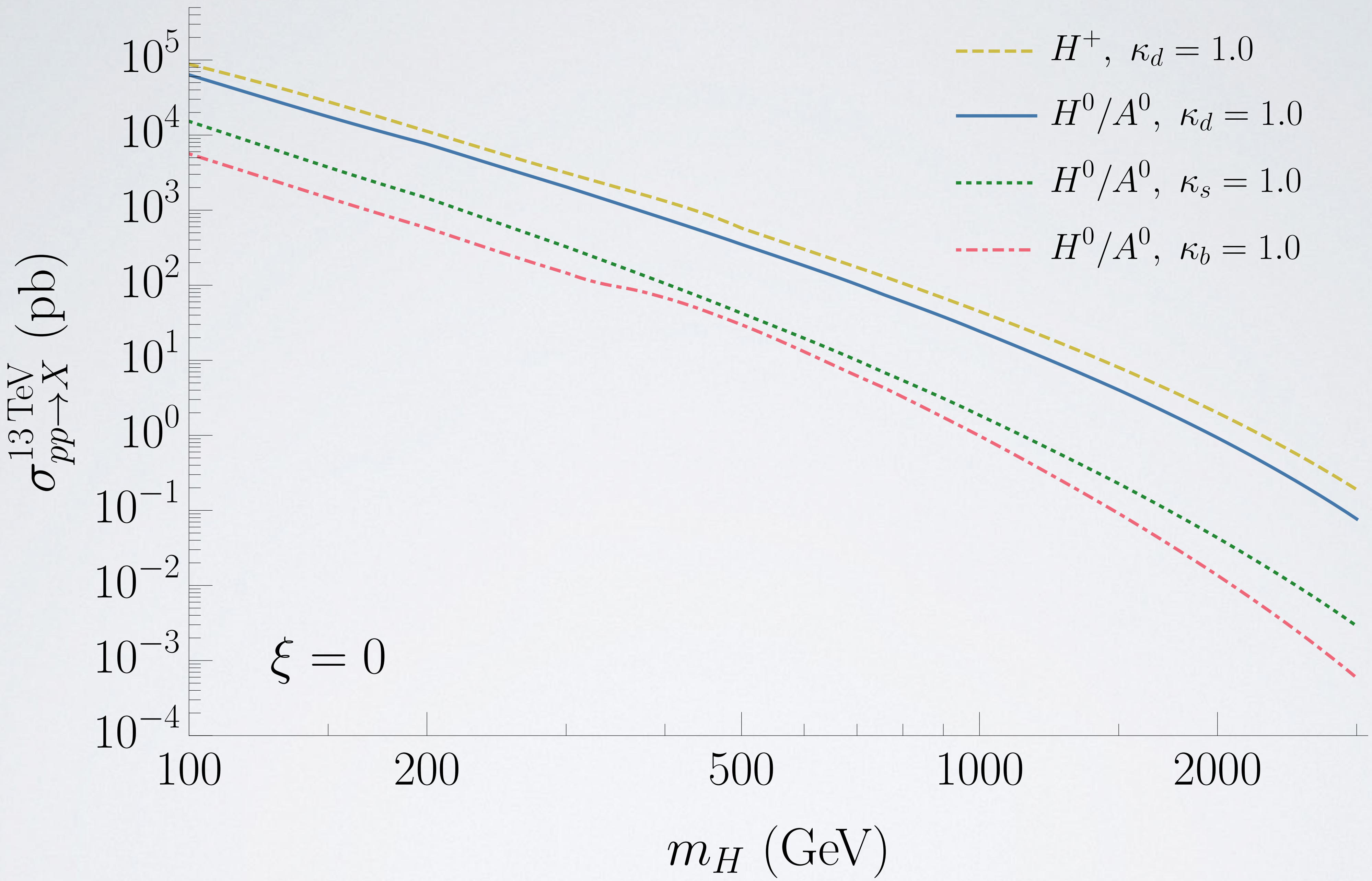


Figure 4: The same as Fig. 2 but for κ_b, with $\kappa_d = \kappa_s = 0$.

COLLIDER PHENO



COLLIDER PHENO



Remember GGF for SM higgs is ~ 49 pb

COLLIDER PHENO

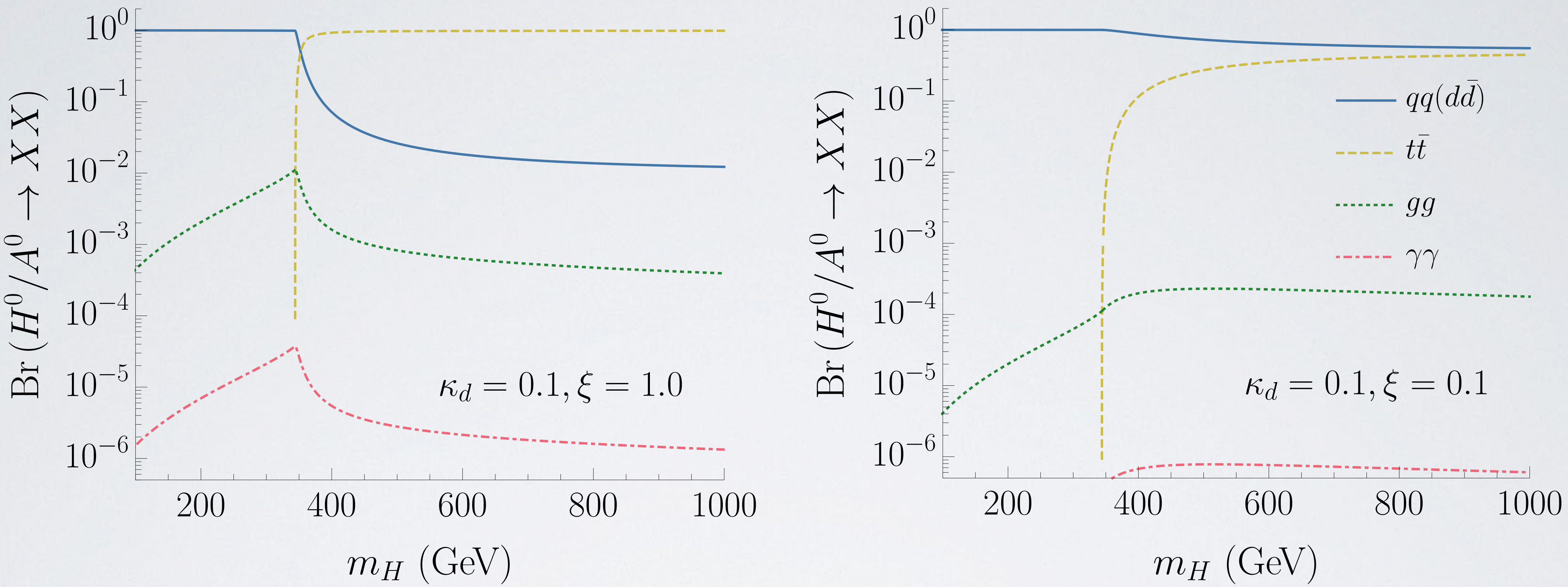


Figure 8: Plot of the branching fraction of H to $d\bar{d}$ (solid blue), $t\bar{t}$ (dashed yellow), gg (dotted green) and $\gamma\gamma$ (dot-dashed red), as a function of m_H with $\kappa_d = 0.1$ for both $\xi = 1.0$ (left) and $\xi = 0.1$ (right). In both plots we've taken $\kappa_s = \kappa_b = 0$. The behavior when replacing κ_d with either κ_s or κ_b is similar, with the decays to $d\bar{d}$ replaced by $s\bar{s}$ or $b\bar{b}$ correspondingly.

COLLIDER PHENO

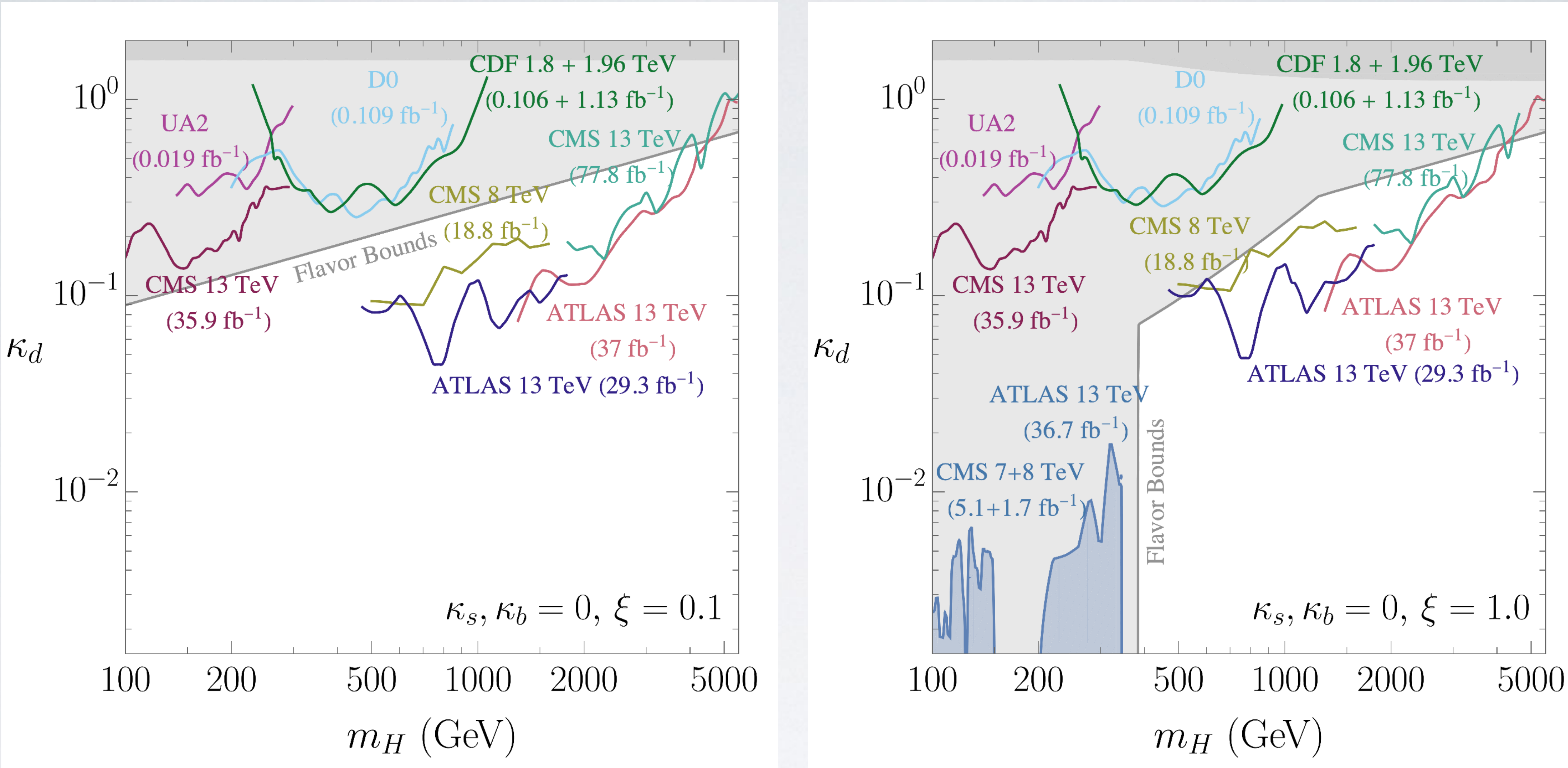
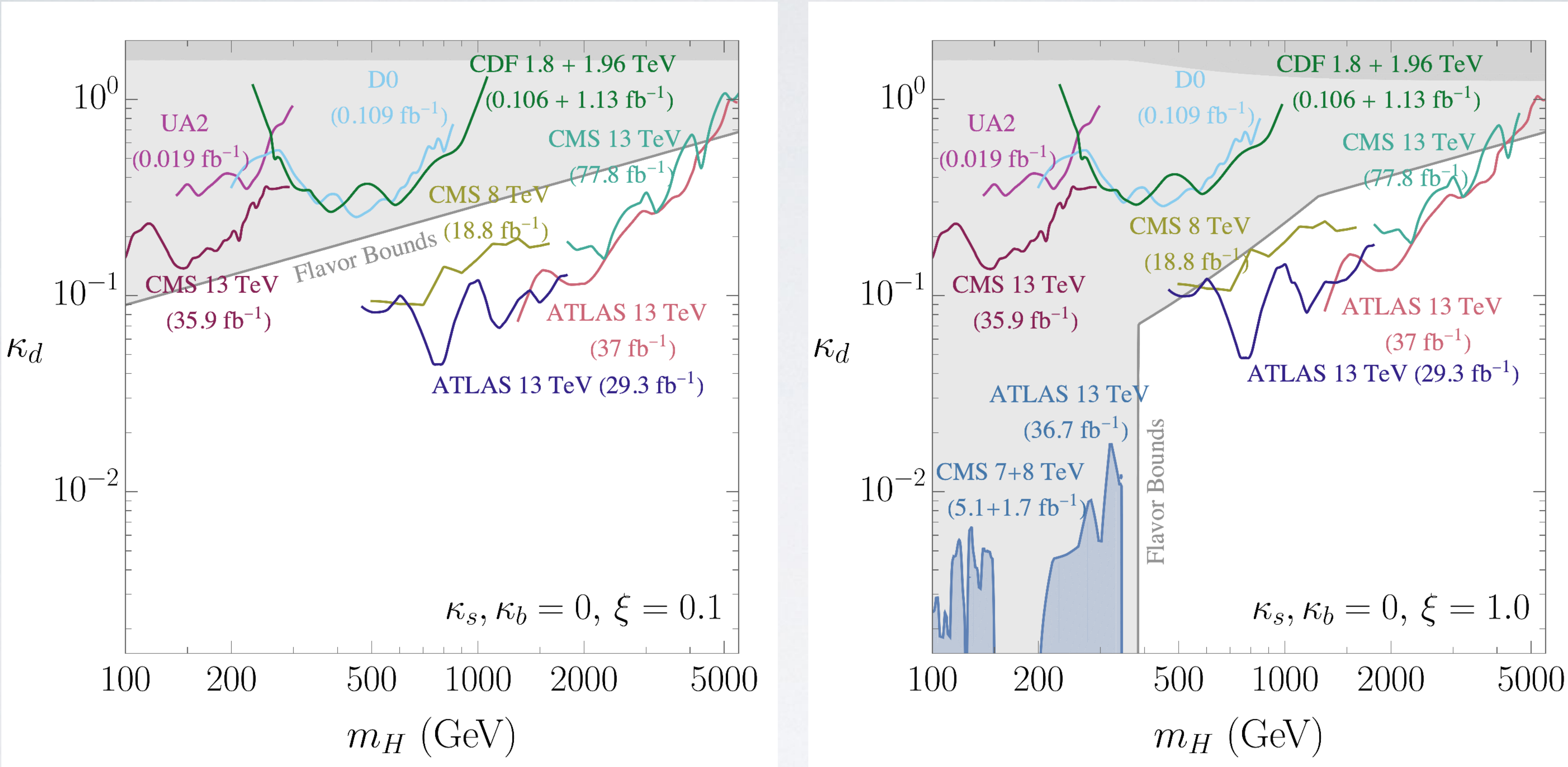


Figure 10: Constraints on the up-type SFV 2HDM from dijet and diphoton searches in the m_H vs. κ_d plane, assuming $\kappa_s = \kappa_b = 0$. We show results both for $\xi = 0.1$ (left) and $\xi = 1.0$ (right). Constraints from flavor observables, detailed in Fig. 2 are shown as the gray shaded region. The dark gray region above $\kappa_d \sim 1.0$ indicates values of κ_d for which $\Gamma/m_H \gtrsim 0.15$ for the heavy neutral Higgs, at which point dijet searches become less reliable and the results should be interpreted with care.

COLLIDER PHENO



Keep in mind analogous SM coupling is 10^(-5)

Figure 10: … hes in the m_H vs. κ_d plane, assuming $\kappa_s = \kappa_b = 0$. We show results both for $\xi = 0.1$ (left) and $\xi = 1.0$ (right). Constraints from flavor observables, detailed in Fig. 2 are shown as the gray shaded region. The dark gray region above $\kappa_d \sim 1.0$ indicates values of κ_d for which $\Gamma/m_H \gtrsim 0.15$ for the heavy neutral Higgs, at which point dijet searches become less reliable and the results should be interpreted with care.

THIS IS AN EXAMPLE OF A HADRONIC - **QUARK DRIVEN** RESONANCE

- Most searches for hadronic resonances either have gluons, or are flavor universal or have leptons i.e. Z' : $U(1)_{B-L}\,\mathrm{or}\,U(1)_B$

  e.g. Dobrescu and Yu 1306.2629

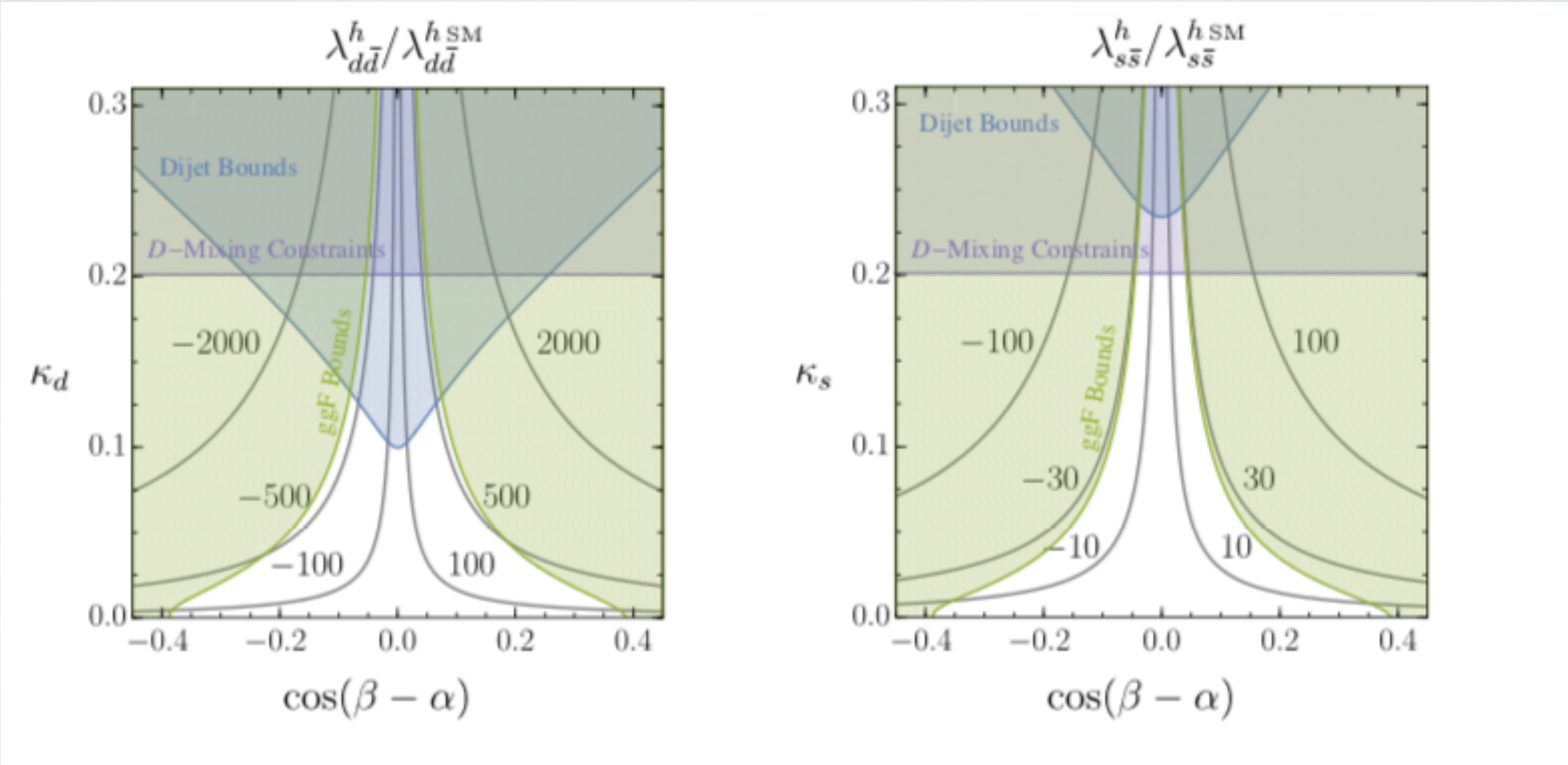
- Signal generator!

IS THIS JUST FOR NEW BSM PARTICLES?

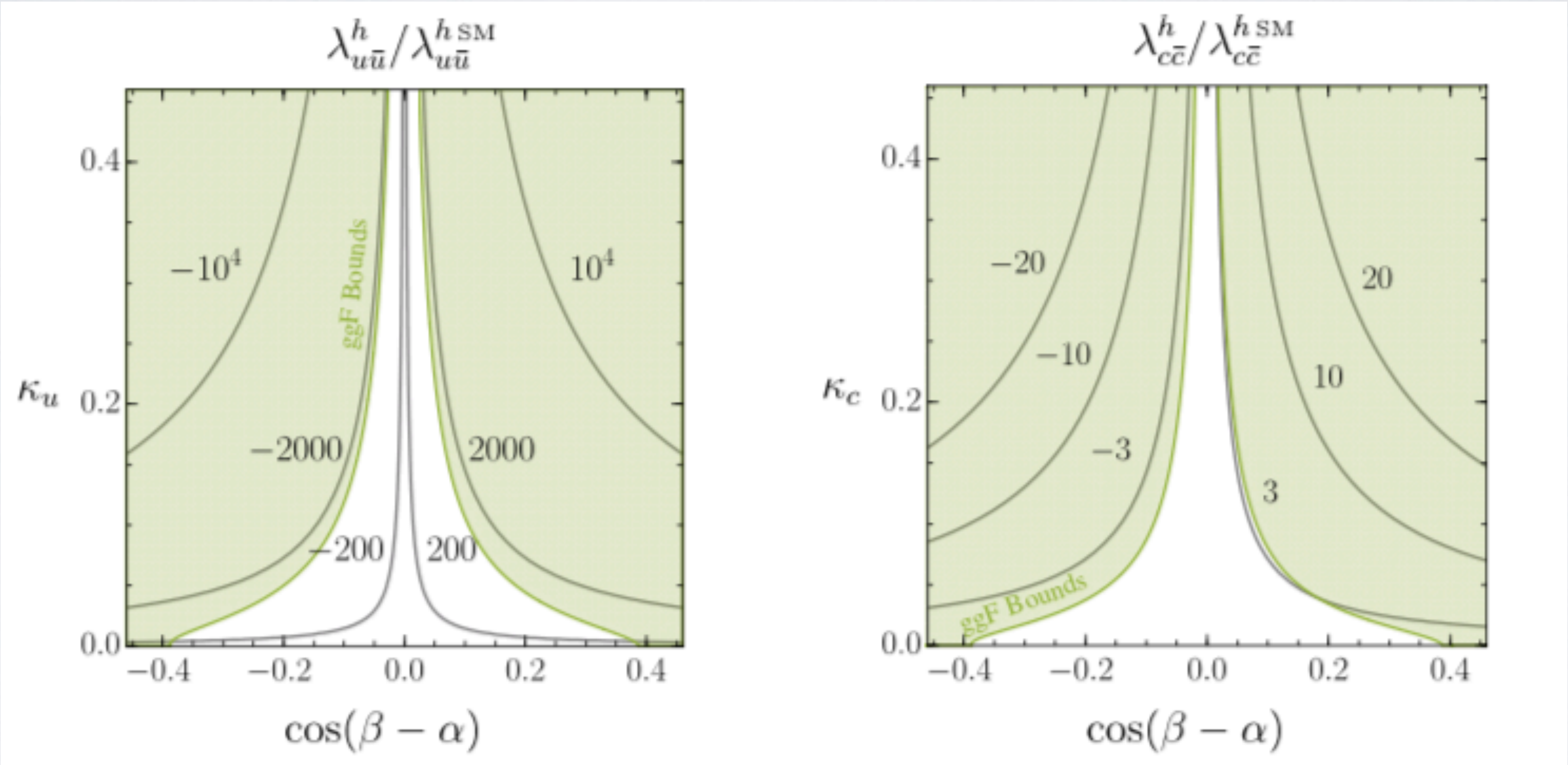
IS THIS JUST FOR NEW BSM PARTICLES?

NO! IT CAN CHANGE THE PROPERTIES OF OUR HIGGS

A REASON TO MEASURE LIGHT SM HIGGS YUKAWAS?



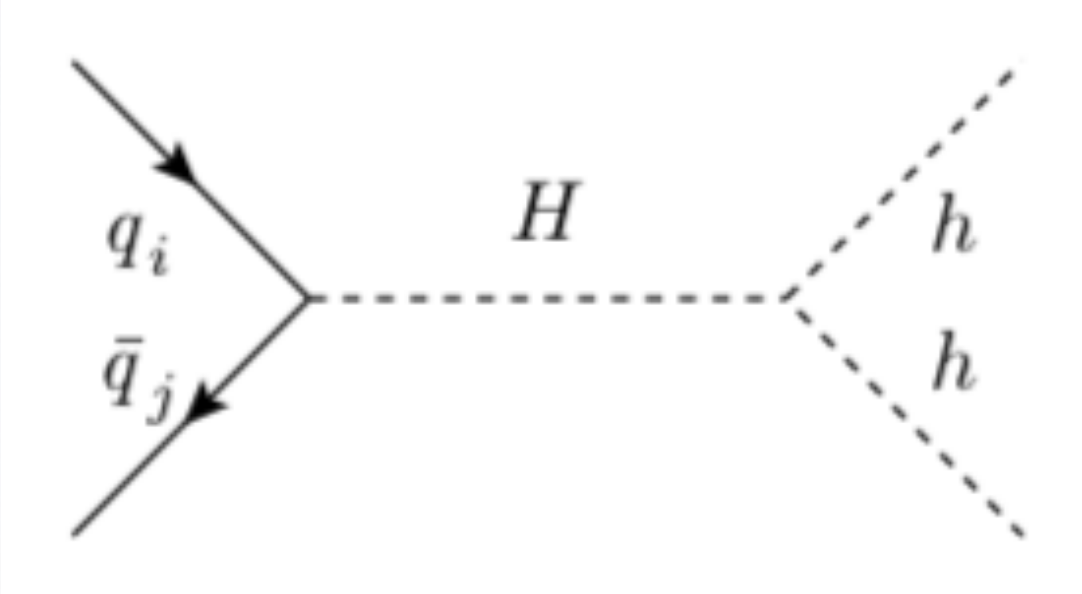
A REASON TO MEASURE LIGHT SM HIGGS YUKAWAS?



WHAT ELSE CAN IT DO FOR **OUR** HIGGS?

WHAT ELSE CAN IT DO FOR **OUR** HIGGS?

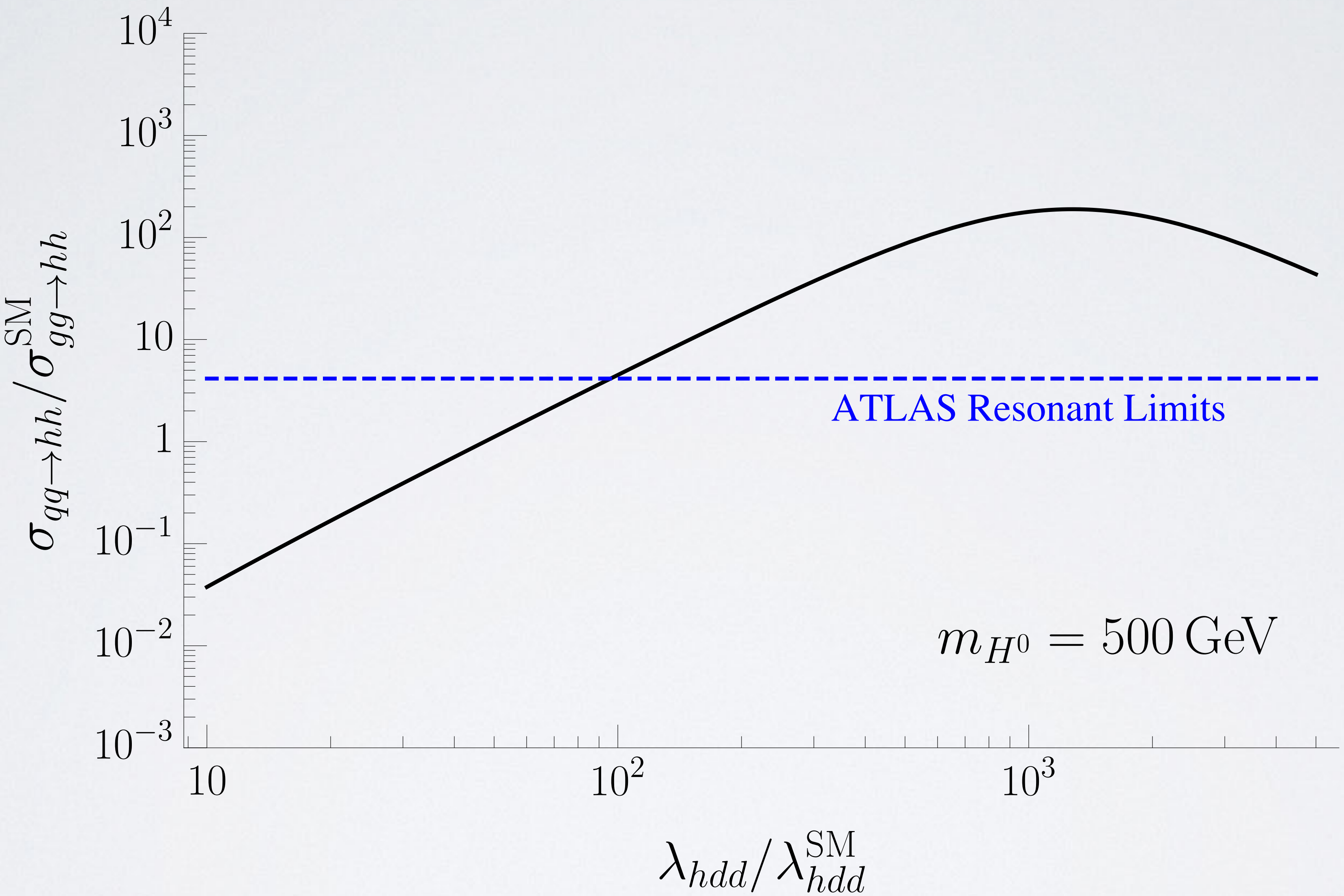
QUARK INITIATED DI-HIGGS PRODUCTION!



Others have thought about this, e.g:
1801.00363 Bauer, Carena, Carmona
1909.05279 Alasfar, Corral Lopez, Grober

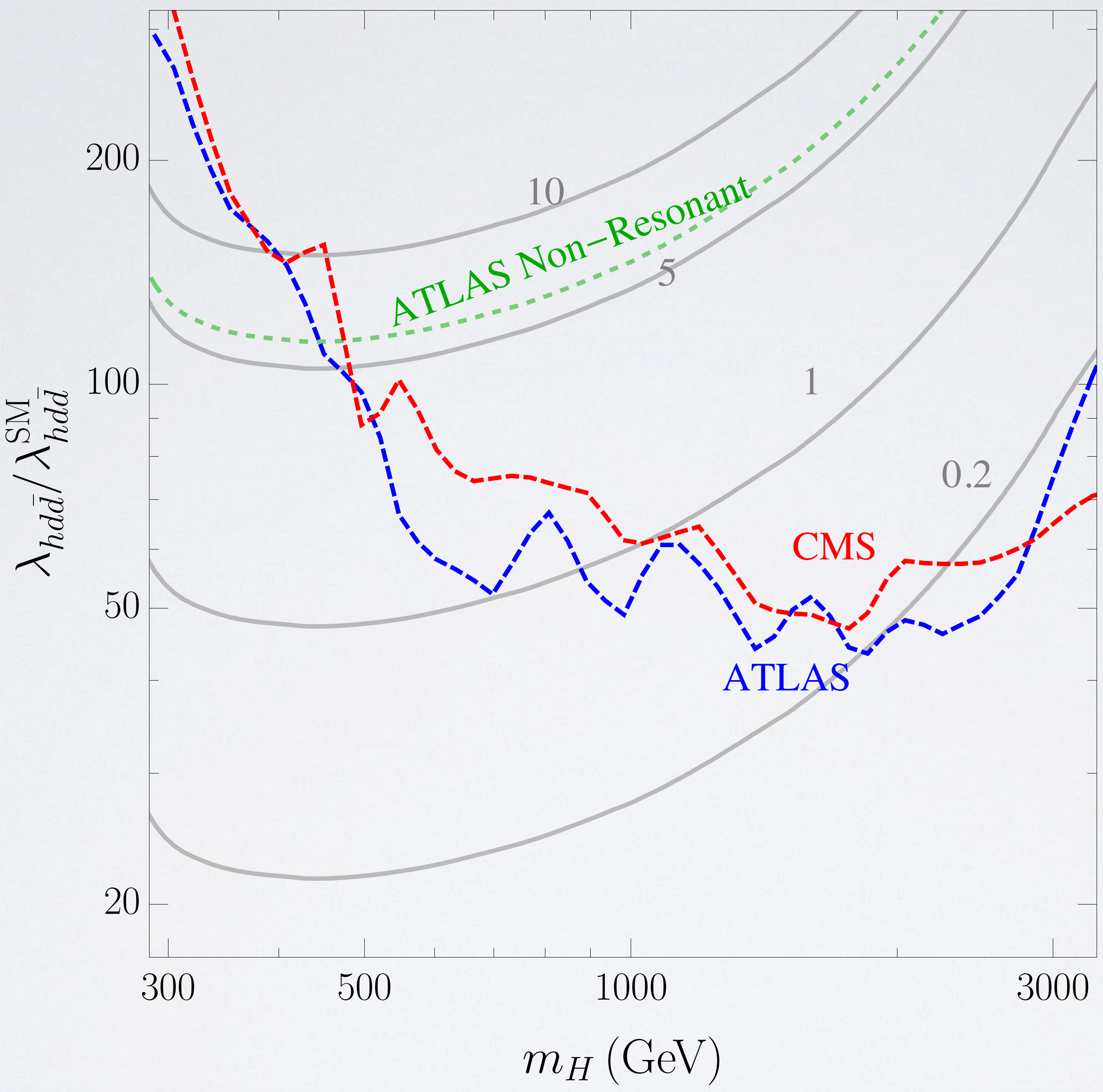
Can get wider range of effects in SFV

DI-HIGGS



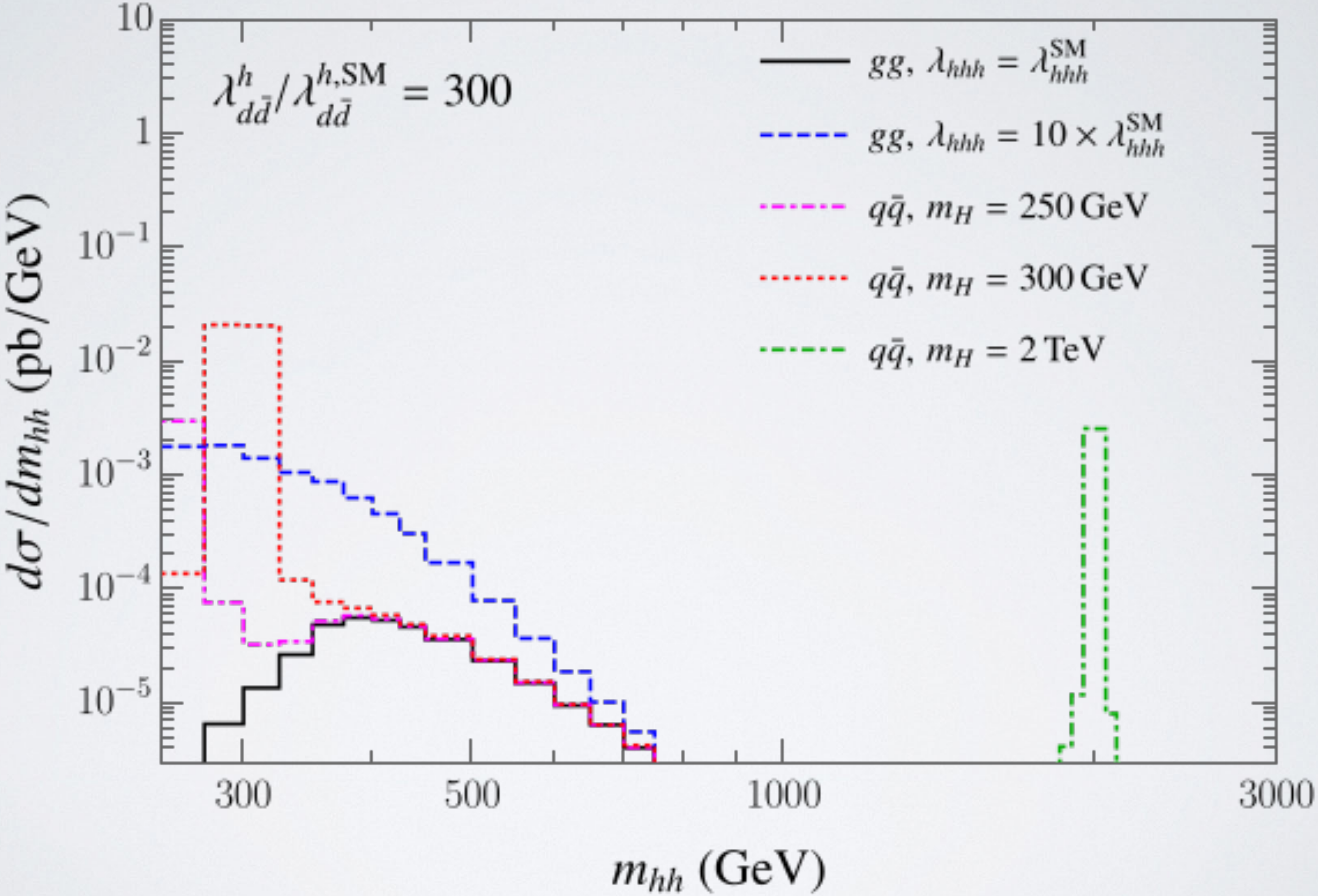
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10
10^2
10^3
$\sigma_{qq\to hh}/\sigma^{\rm SM}_{gg\to hh}$
$\lambda_{hdd}/\lambda^{\rm SM}_{hdd}$
ATLAS Resonant Limits
$m_{H^0} = 500\,\mathrm{GeV}$

DI-HIGGS



200
100
50
20
300
500
1000
3000
m_H (GeV)
$\lambda_{hd\bar{d}}/\lambda_{hd\bar{d}}^{\rm SM}$
10
5
1
0.2
ATLAS Non–Resonant
CMS
ATLAS

DI-HIGGS



$\lambda^h_{d\bar{d}}/\lambda^{h,\mathrm{SM}}_{d\bar{d}} = 300$
$gg,\ \lambda_{hhh} = \lambda_{hhh}^{\mathrm{SM}}$
$gg,\ \lambda_{hhh} = 10 \times \lambda_{hhh}^{\mathrm{SM}}$
$q\bar{q},\ m_H = 250\,\mathrm{GeV}$
$q\bar{q},\ m_H = 300\,\mathrm{GeV}$
$q\bar{q},\ m_H = 2\,\mathrm{TeV}$
$d\sigma/dm_{hh}$ (pb/GeV)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
300
500
1000
3000
m_{hh} (GeV)

IS THIS JUST FOR HEAVY NEW PHYSICS OR THE HIGGS?

VERY LIGHT NEW SCALARS WITH FLAVOR DEPENDENT COUPLINGS

Simply take the model just discussed, and add a singlet S

Allow S to mix with the heavy Higgs

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Allow S to mix with the heavy Higgs

From the low energy point of view…

$$\mathcal{L} \supset \frac{S}{M}\left[c^{u}_{Sij} Q_i H \bar{u}_j - c^{d\dagger}_{Sij} Q_i H^c \bar{d}_j - c^{\ell\dagger}_{Sij} L_i H^c \bar{\ell}_j\right]$$

I can inherit large flavor dependent couplings from up-type or down-type SFV!

VERY LIGHT SCALAR WITH COUPLINGS TO THE 1ST GENERATION… E.G.

Light meson decay phenomenology!

$$\eta \to S\pi^0$$
$$S \to ee, \mu\mu, \pi\pi$$

Others have thought about flavor dependent light quark couplings e.g:
1712.10022 Batell, Freitas, Ismail, Mckeen without a UV model

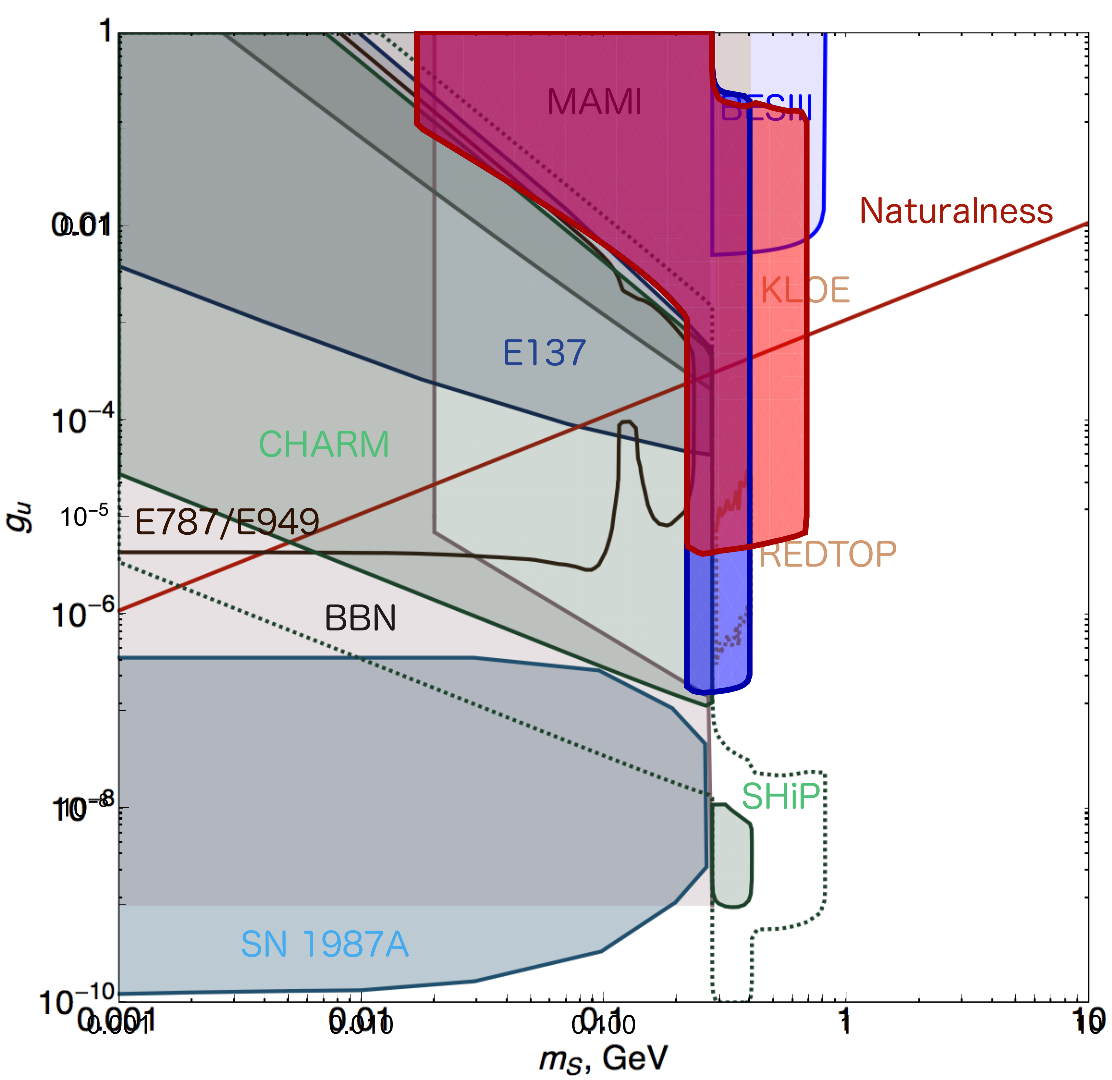
VERY LIGHT SCALAR WITH COUPLINGS TO THE 1ST GENERATION… E.G.

Light meson decay phenomenology!

$$\eta \to S\pi^0$$
$$S \to ee, \mu\mu, \pi\pi$$

REDTOP

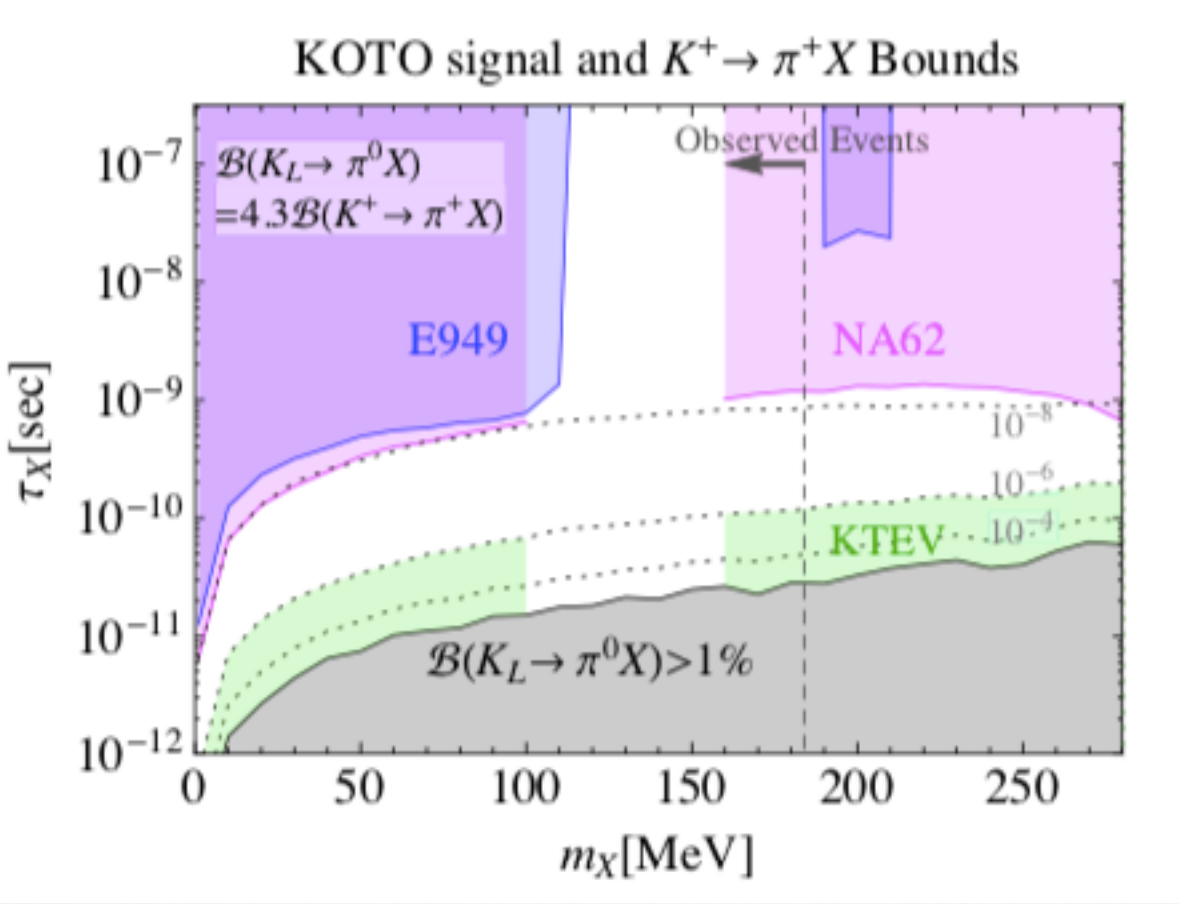
The η/η′ factory



WHAT COULD BE EVEN CRAZIER…

KOTO $K \to \pi^0 \nu \bar{\nu}$

What if it was? $K \to \pi^0 S$

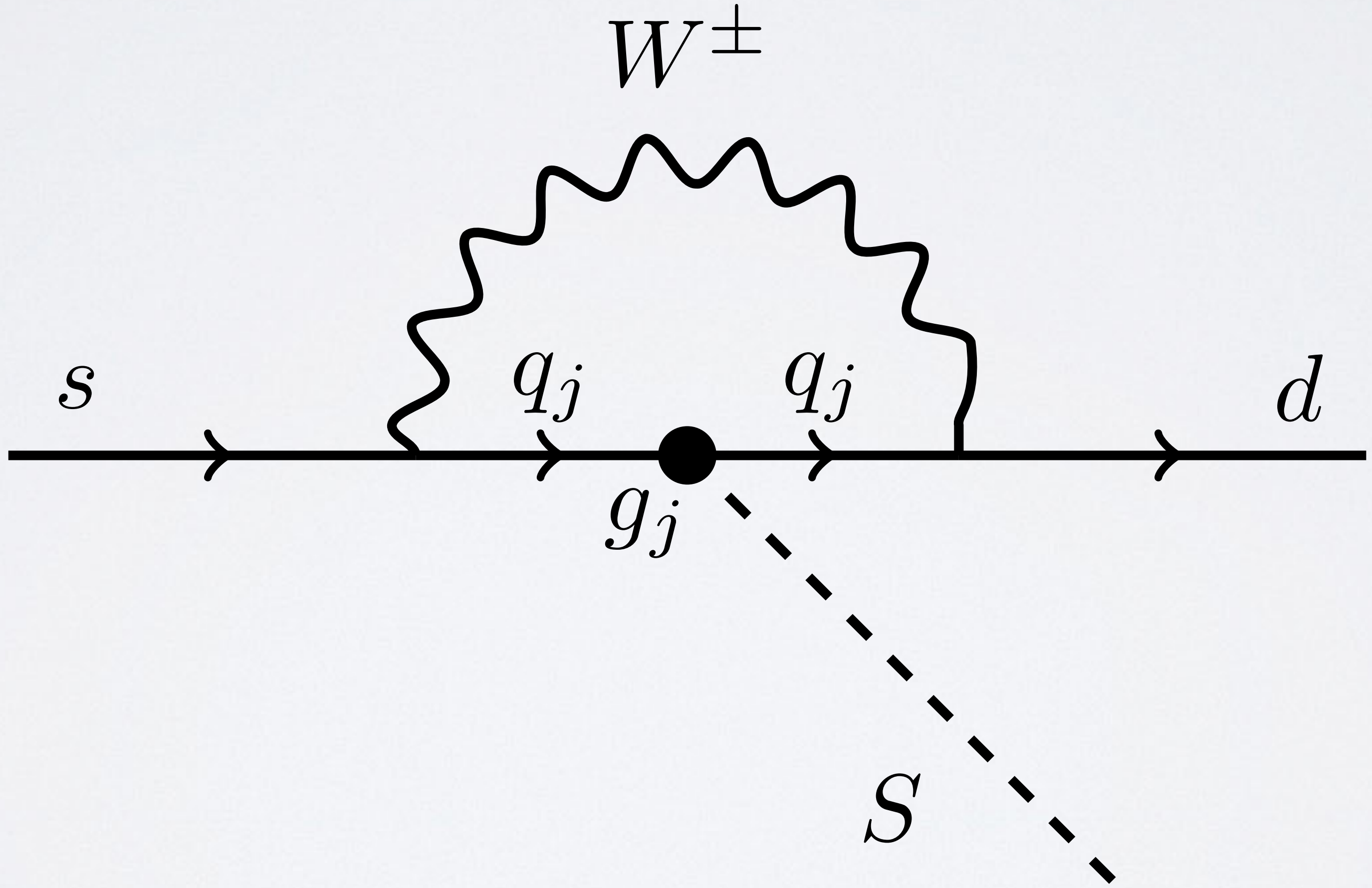


1909.11111. Kitahara, Okui, Perez, Soreq, Tobioka

didn't have a model just an explanation…

WHAT COULD BE EVEN CRAZIER…

KOTO $K \to \pi^0 S$



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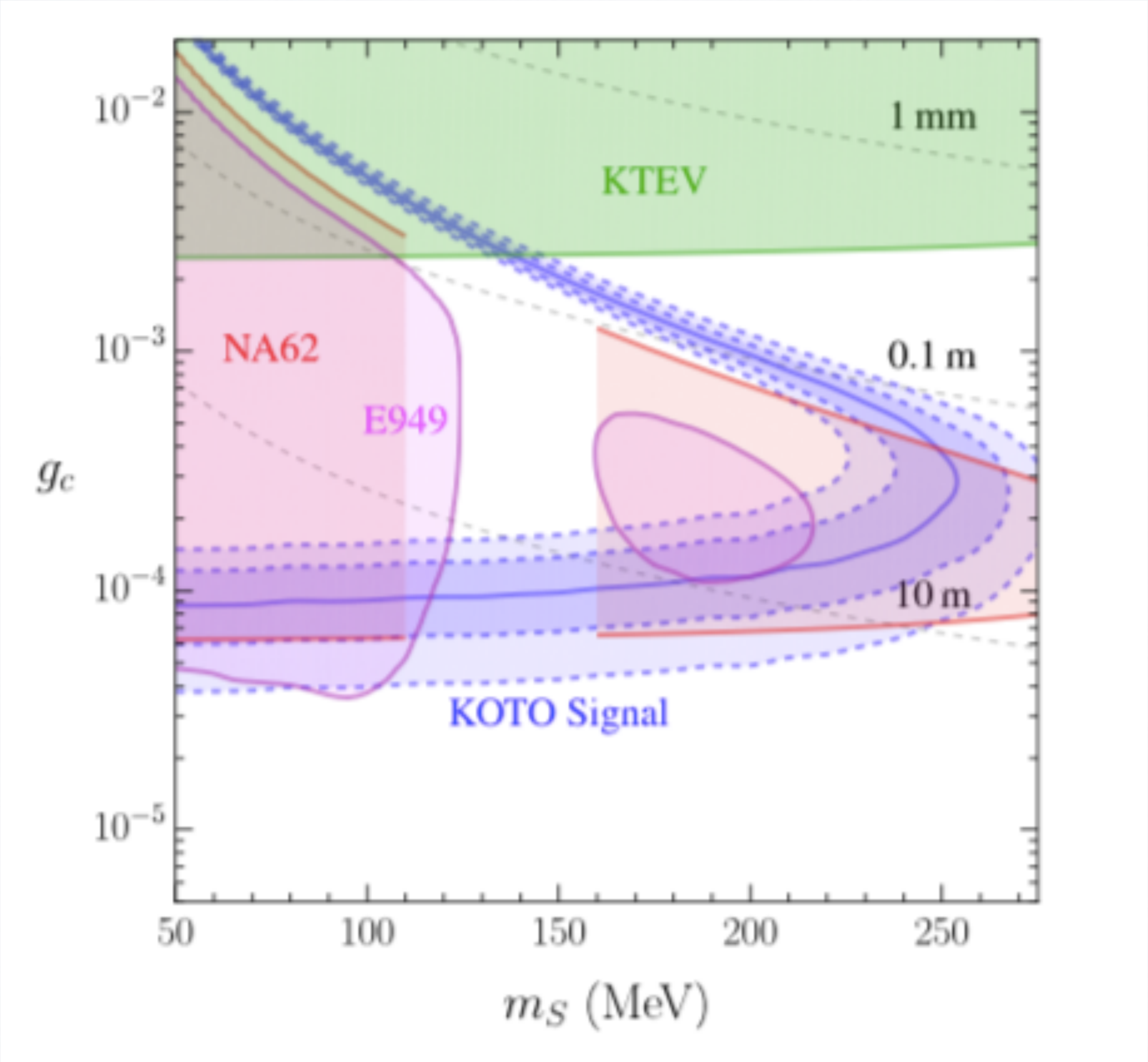

CONCLUSIONS

- Flavorful BSM physics is typically the third rail of theory… but avoiding it biases us to flavor universal or third generation searches
- Flavorful physics of the 1st and 2nd generation (and 3rd) CAN exist at LHC energies with Spontaneous Flavor Violation (SFV) AND have big cross sections while being compatible with current LHC constraints
- SFV can also **the** Higgs -
    - Light Yukawa couplings need measured!
    - Di-Higgs confusion with triple Higgs!
- Flavor dependence can also occur at LOW energies, so instead of just thinking about dark photons proportional to charge/mass and universal scalars, you need to think about individual quark flavor couplings if you want to cover the space!

FIN

CAN WE GENERALIZE CONCEPT OF ALIGNMENT WITHOUT A FULL THEORY?

YES… Aligned Flavor Violation (AFV)

Introduce new spurions κ^u, κ^d transforming like y^u, y^d

We want alignment, but without a "basis" dependence"

The mass eigenbasis is defined only up to a U(1)^6 reparametrization symmetry

This symmetry is really what forbids tree level FCNCs…

FLAVOR + REPARAMETRIZATION

$$y^u = U_{Q_u}\, Y^u\, U_{\bar{u}}^\dagger \equiv U_{Q_u}\, \mathrm{diag}(y_u^{\mathrm{SM}}, y_c^{\mathrm{SM}}, y_t^{\mathrm{SM}})\, U_{\bar{u}}^\dagger$$
$$y^{d\dagger} = U_{Q_d}\, Y^d\, U_{\bar{d}}^\dagger \equiv U_{Q_d}\, \mathrm{diag}(y_d^{\mathrm{SM}}, y_s^{\mathrm{SM}}, y_b^{\mathrm{SM}})\, U_{\bar{d}}^\dagger$$

V is charged under reparametrization so we have to expand in it

$$\kappa^u = U_{Q_u}\left[\, K^u + K^{u'} V^* K^{u'} V^T K^{u'''} + \mathcal{O}\left(V^4 \right)\right] U_{\bar{u}}^\dagger$$
$$\kappa^{d\dagger} = U_{Q_d}\left[\, K^d + K^{d'} V^T K^{d''} V^* K^{d'''} + \mathcal{O}\left(V^4 \right)\right] U_{\bar{d}}^\dagger$$

K's are diagonal because of Reparametrization symmetry

ALIGNED FLAVOR VIOLATION

- Interesting extension of MFV but…
- Relies on a “fictitious” symmetry
- And only is aligned up to CKM which isn’t enough to get flavor physics down to the TeV scale

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ALIGNED FLAVOR VIOLATION

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- And only is aligned up to CKM which isn't enough to get flavor physics down to the TeV scale
- Special "aligned" basis really meant up or down only, not both

Is there a way to get this, that isn't basis dependent and also doesn't require a full theory of flavor?

Operator	$\Lambda_{\rm NP}^{\rm anarchic}$ [TeV]	$\Lambda_{\rm NP}^{\rm SFV}$ [TeV]	$\Lambda_{\rm NP}^{\rm MFV}$ [TeV]
$(Q_1^\dagger \bar\sigma^\mu Q_2)^2$	1.5×10^4 (Im)	$262.7\,\lvert\kappa_d^2 - \kappa_s^2\rvert$	5.1
$(Q_1 \bar d_3)(Q_3^\dagger \bar d_1^\dagger)$	2.1×10^3 (Abs)	$19.3\,\sqrt{\lvert\kappa_d \kappa_b\rvert}$	–
$(Q_1 \bar d_2)(Q_2^\dagger \bar d_1^\dagger)$	2.4×10^5 (Im)	$72.7\,\sqrt{\lvert\kappa_d \kappa_s\rvert}$	–
$2eH\sigma^{\mu\nu} Q_2\, \bar d_3\, F_{\mu\nu}$	276.3 (Re)	$54.3\,\sqrt{\lvert\kappa_b\rvert}$	7.0
$2eH\sigma^{\mu\nu} Q_3\, \bar d_2\, F_{\mu\nu}$	276.3 (Re)	$54.3\,\sqrt{\lvert\kappa_s\rvert}$	7.0
$2eH\sigma^{\mu\nu} Q_3\, \bar d_1\, F_{\mu\nu}$	140.5 (Abs)	$13.2\,\sqrt{\lvert\kappa_d\rvert}$	7.0

TABLE II. 95% CL bounds on the new physics scale $\Lambda_{\rm NP}$, for anarchic, SFV and MFV operator coefficients (from [1, 31–33]). Subscripts on the anarchic operator limits indicates that the limit is on the real, imaginary or absolute value of the operator coefficient.

$$
\begin{aligned}
V(H_1,H_2) &= m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + \left(m_{12}^2 H_1^\dagger H_2 + \text{h.c.}\right) \\
&+ \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_2^\dagger H_2)(H_1^\dagger H_1) + \lambda_4 (H_2^\dagger H_1)(H_1^\dagger H_2) \\
&+ \left[\, \frac{1}{2}\lambda_5 (H_1^\dagger H_2)^2 + \lambda_6 H_1^\dagger H_1 H_1^\dagger H_2 + \lambda_7 (H_2^\dagger H_2)(H_1^\dagger H_2) + \text{h.c.}\,\right].
\end{aligned}
$$

$$
H_1 = \begin{pmatrix} 0 \\ H_1^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h_1 \end{pmatrix}
$$

$$
H_2 = \begin{pmatrix} H^+ \\ H_2^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}H^+ \\ h_2 + i h_3 \end{pmatrix}
$$

$$
\begin{aligned}
\tan\left[2(\beta-\alpha)\right] &= \frac{-2\mathcal{M}_{12}^2}{\mathcal{M}_{22}^2 - \mathcal{M}_{11}^2} \\
&= \frac{2\lambda_6 v^2}{\lambda_1 v^2 - \left(m_2^2 + \frac{1}{2}(\lambda_3+\lambda_4+\lambda_5)v^2\right)}
\end{aligned}
$$

$$
h \equiv \sin(\beta-\alpha) h_1 + \cos(\beta-\alpha) h_2
$$

$$
H \equiv -\cos(\beta-\alpha) h_1 + \sin(\beta-\alpha) h_2
$$

$\lambda_{hu_i\bar{u}_j}$	$\delta_{ij}Y_i^u\left[\sin(\beta-\alpha)+\xi\cos(\beta-\alpha)\right]$	$\lambda_{Hu_i\bar{u}_j}$	$\delta_{ij}Y_i^u\left[-\cos(\beta-\alpha)+\xi\sin(\beta-\alpha)\right],$
$\lambda_{hd_i\bar{d}_j}$	$\delta_{ij}\left[Y_i^d\sin(\beta-\alpha)+K_i^d\cos(\beta-\alpha)\right]$	$\lambda_{Hd_i\bar{d}_j}$	$\delta_{ij}\left[-Y_i^d\cos(\beta-\alpha)+K_i^d\sin(\beta-\alpha)\right]$
$\lambda_{h\ell_i\bar{\ell}_j}$	$\delta_{ij}Y_i^\ell\left[\sin(\beta-\alpha)+\xi^\ell\cos(\beta-\alpha)\right]$	$\lambda_{H\ell_i\bar{\ell}_j}$	$\delta_{ij}Y_i^\ell\left[-\cos(\beta-\alpha)+\xi^\ell\sin(\beta-\alpha)\right]$
$\lambda_{Au_i\bar{u}_j}$	$i\xi\delta_{ij}Y_i^u$	$\lambda_{H^+d_i\bar{u}_j}$	$-\left[\xi\,V^T\,Y^u\,\right]_{ij}$
$\lambda_{Ad_i\bar{d}_j}$	$-i\delta_{ij}K_i^d$	$\lambda_{H^-u_i\bar{d}_j}$	$\left[V^*K^d\right]_{ij}$
$\lambda_{A\ell_i\bar{\ell}_j}$	$-i\xi^\ell\delta_{ij}Y_i^\ell$	$\lambda_{H^-\ell_i\bar{\ell}_j}$	$\left[\xi^\ell Y^\ell\right]_{ij}$

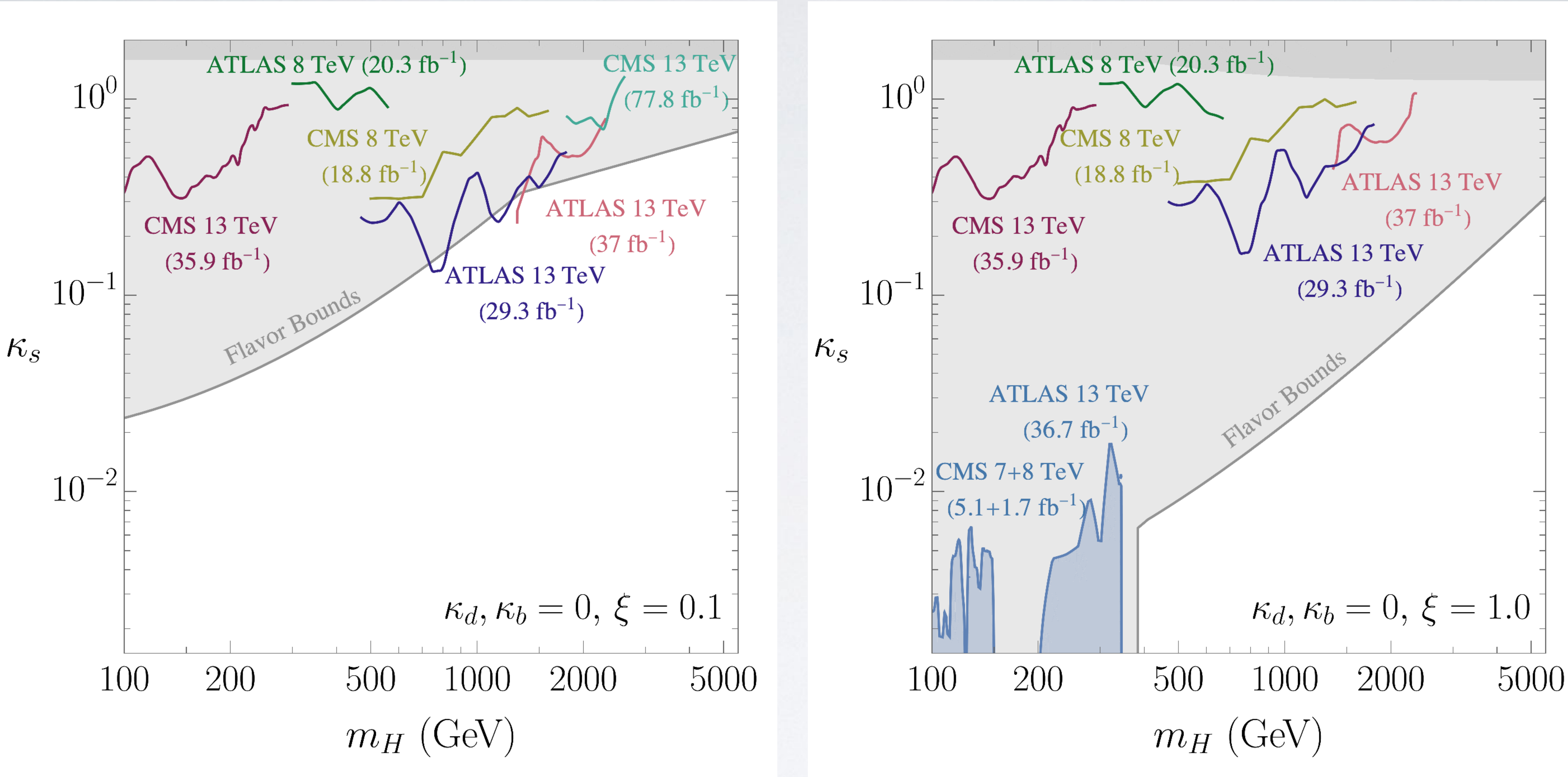

Figure 11: The same as Fig. 10, but for κ_s, with $\kappa_d = \kappa_b = 0$.

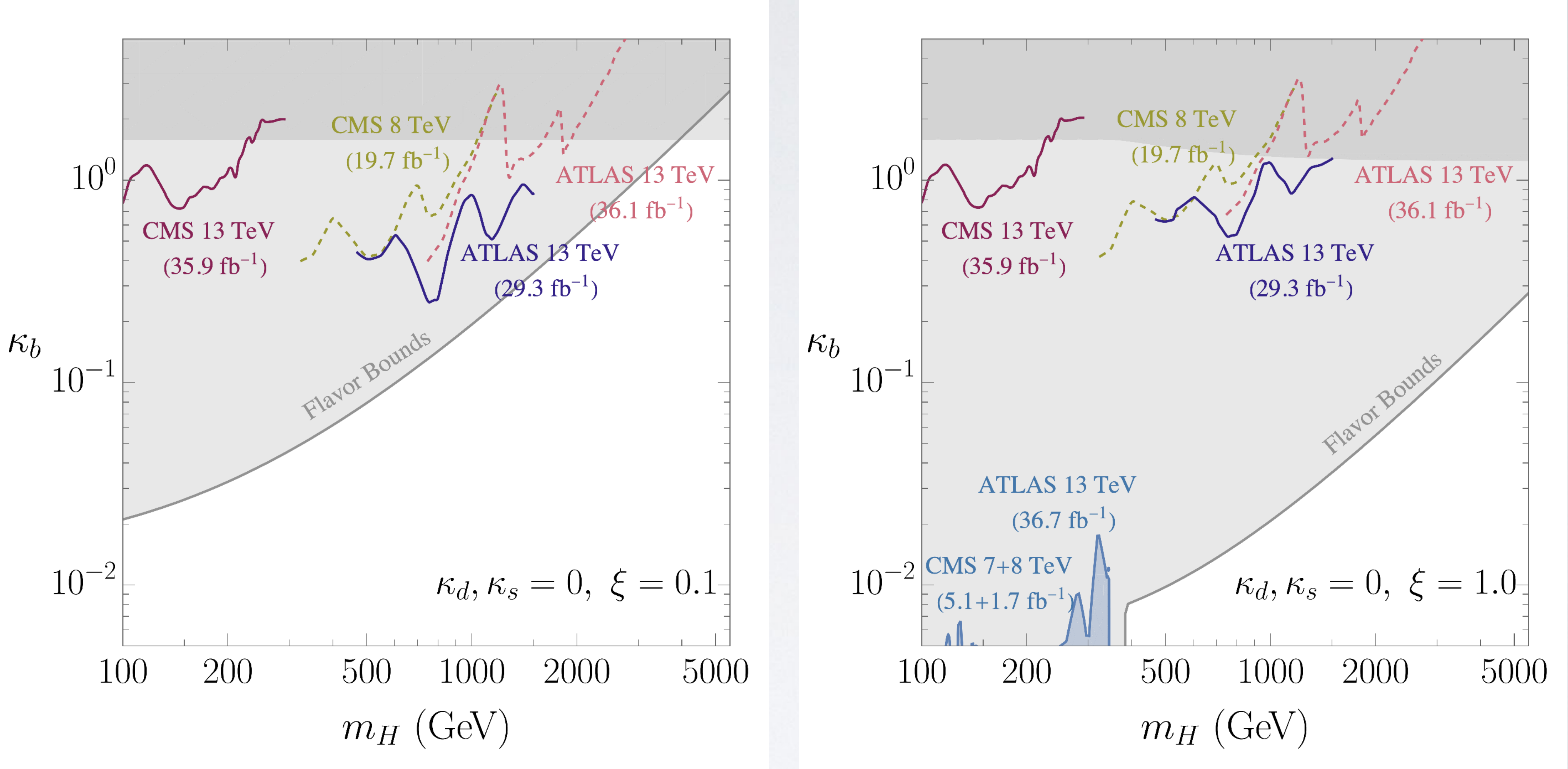

Figure 12: The same as Fig. 10 but for κ_b, with $\kappa_d = \kappa_s = 0$. Solid lines indicate limits from ordinary dijet searches while the dashed lines indicate searches using b-tagging information (see text for details.)