UNIFICATION, OBSERVABLE LANDSCAPES AND NEW PARTICLES AT THE LHC

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A First Glance Beyond the Energy Frontier
9/9/2016-ICTP

THE MOST EXCITING LHC RESULT

THE HIGGS IS LIGHT AND

THERE IS NOTHING RELATED TO NATURALNESS

THE MOST EXCITING LHC RESULT

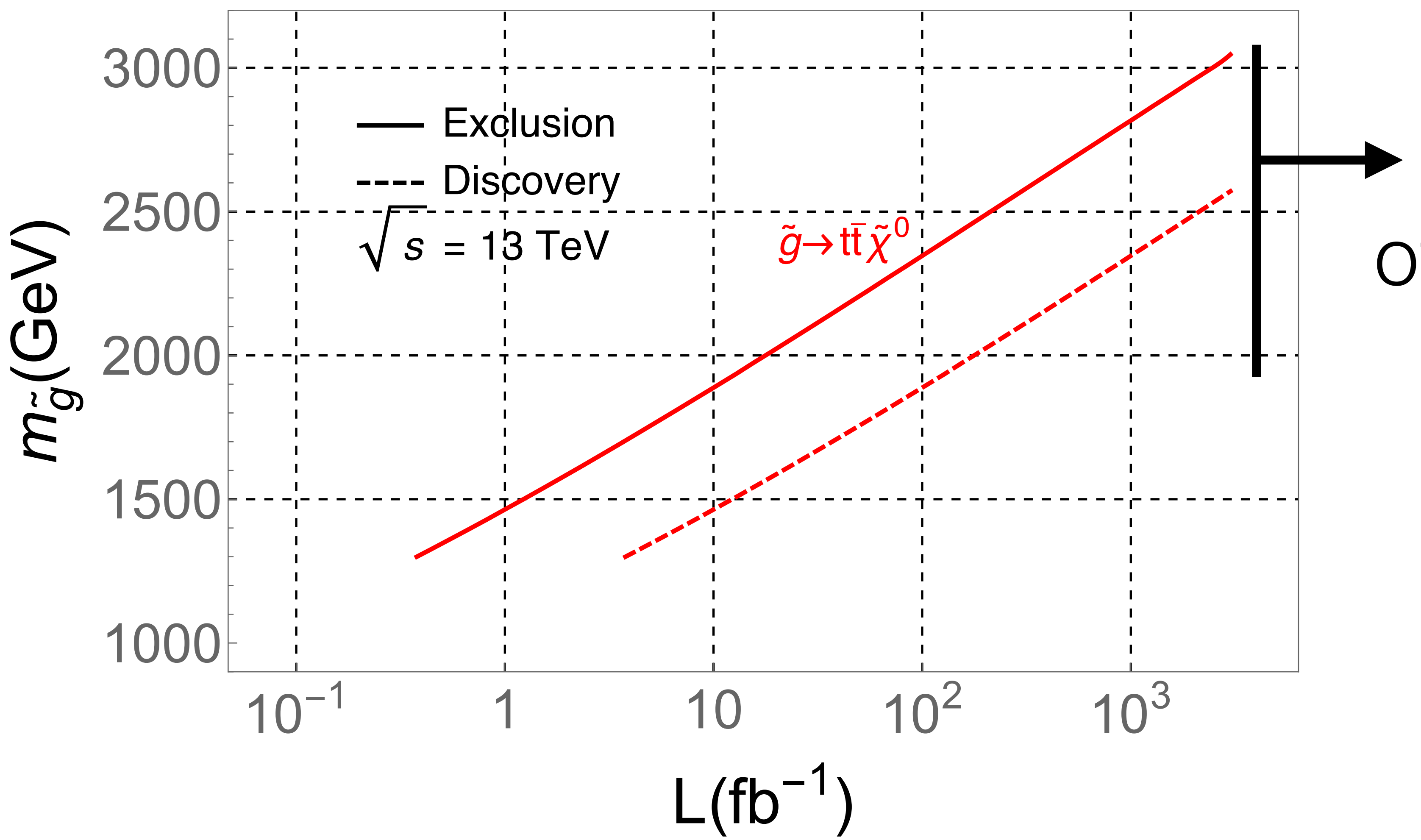
1. IS IT REASONABLE TO EXPECT NEW PARTICLES AT THE LHC?

2. WHAT ABOUT THE HIGGS MASS?

SOME PERSPECTIVE

1935		Never
π	vs	μ
1947		1936

SOME PERSPECTIVE



2-3 orders of magnitude in σ

SOME PERSPECTIVE

A general search for new phenomena with the ATLAS detector in pp collisions at $\sqrt{s} = 8$ TeV

The ATLAS Collaboration

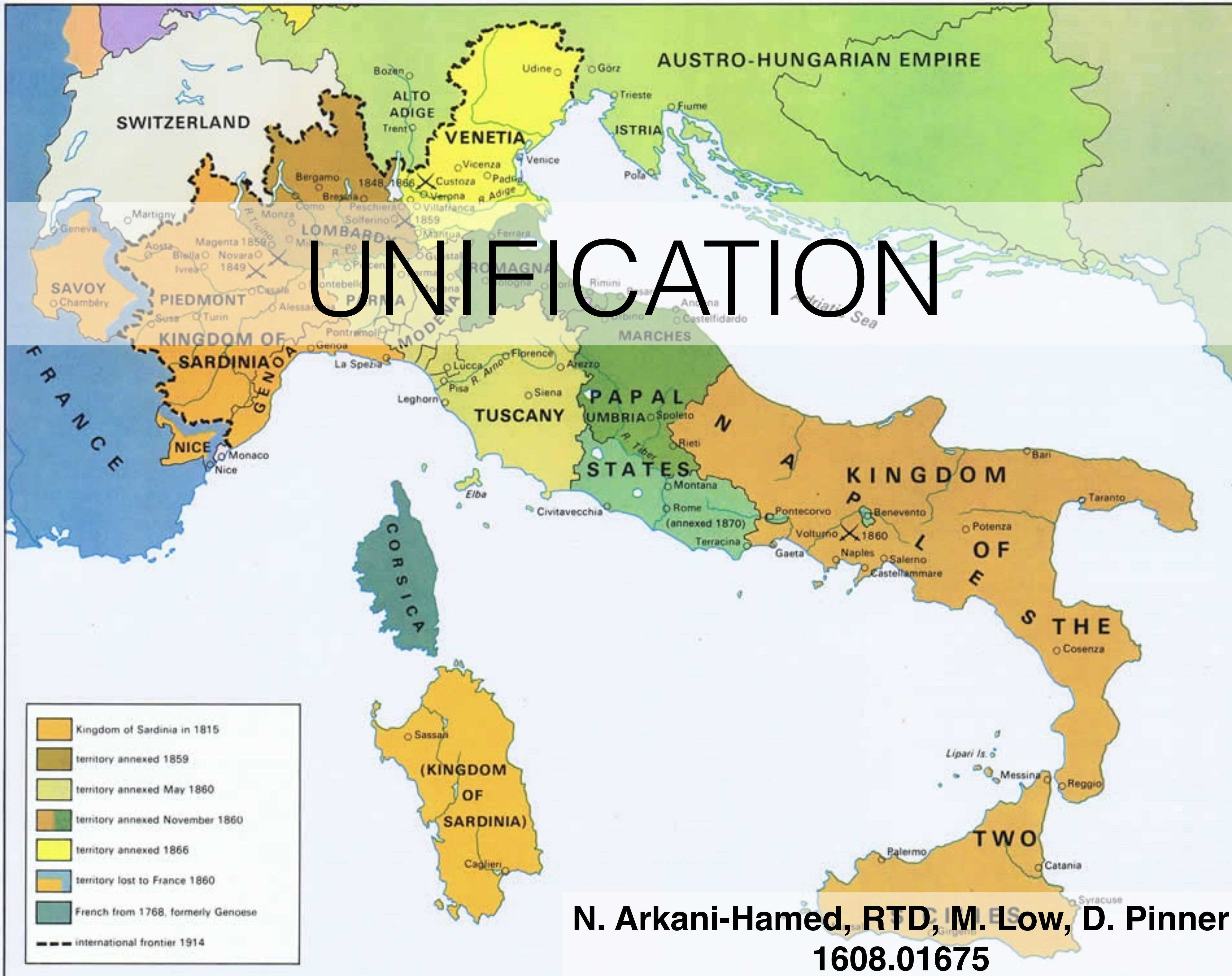
Abstract

This note presents a model-independent general search for new phenomena in proton-proton collisions at a centre-of-mass energy of 8 TeV with the ATLAS detector at the LHC. The data set corresponds to a total integrated luminosity of 20.3 fb^{-1}. Event topologies involving isolated electrons, photons and muons, as well as jets, including those identified as originating from b-quarks (b-jets) and missing transverse momentum are investigated. The events are subdivided according to their final states into exclusive event classes. For the 697 classes with a Standard Model expectation greater than 0.1 events, a search algorithm tests the compatibility of data against the Monte Carlo simulated background in three kinematic variables sensitive to new physics effects. Although this search approach is less sensitive than optimized searches for specific models, it provides a more comprehensive investigation for new physics signals. No significant deviation is found in data. The number and size of the observed deviations follow the Standard Model expectation obtained from simulated pseudo-experiments.

$\sqrt{s} = 13$ TeV

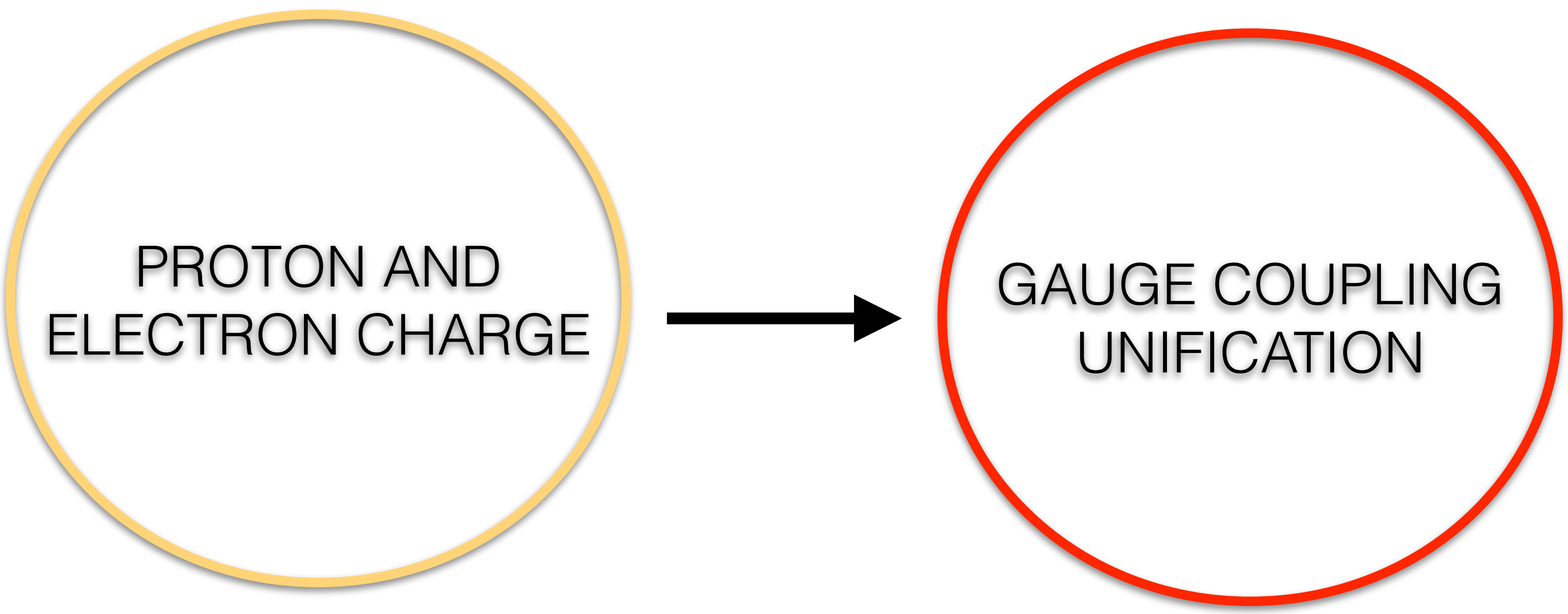
$< 10\%$

UNIFICATION

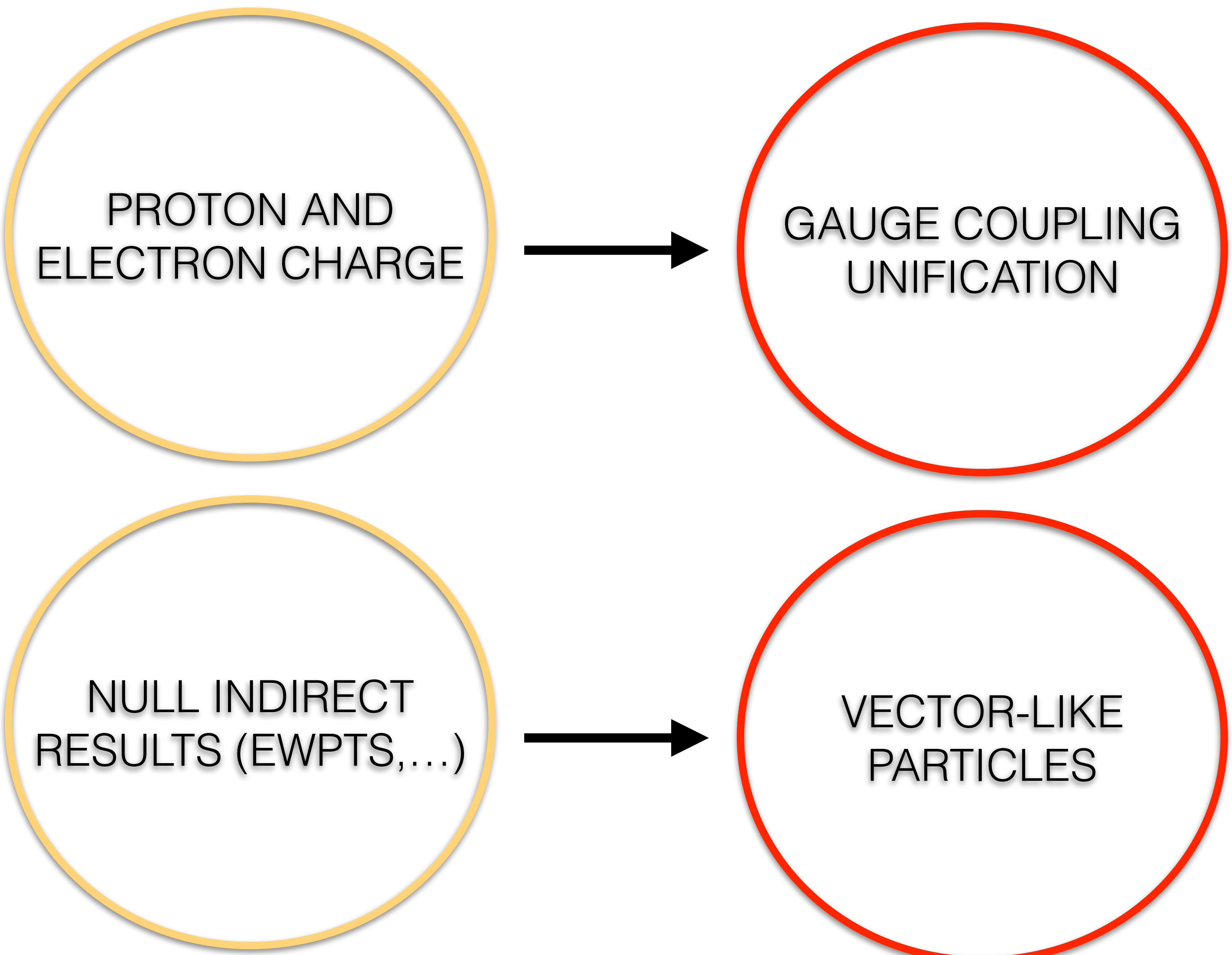


N. Arkani-Hamed, RTD, M. Low, D. Pinner
1608.01675

EXPERIMENTAL HINTS



EXPERIMENTAL HINTS



MATTER CONTENT

- **(PERTURBATIVE)** GAUGE COUPLING UNIFICATION
- VECTOR-LIKE **FERMIONS**

$$\lesssim 4 \times (\mathbf{5} + \bar{\mathbf{5}})$$

AT THE WEAK SCALE

$$\lesssim (\mathbf{5} + \bar{\mathbf{5}}) + \left(\mathbf{10} + \overline{\mathbf{10}}\right)$$

MATTER CONTENT

WEAKLY COUPLED

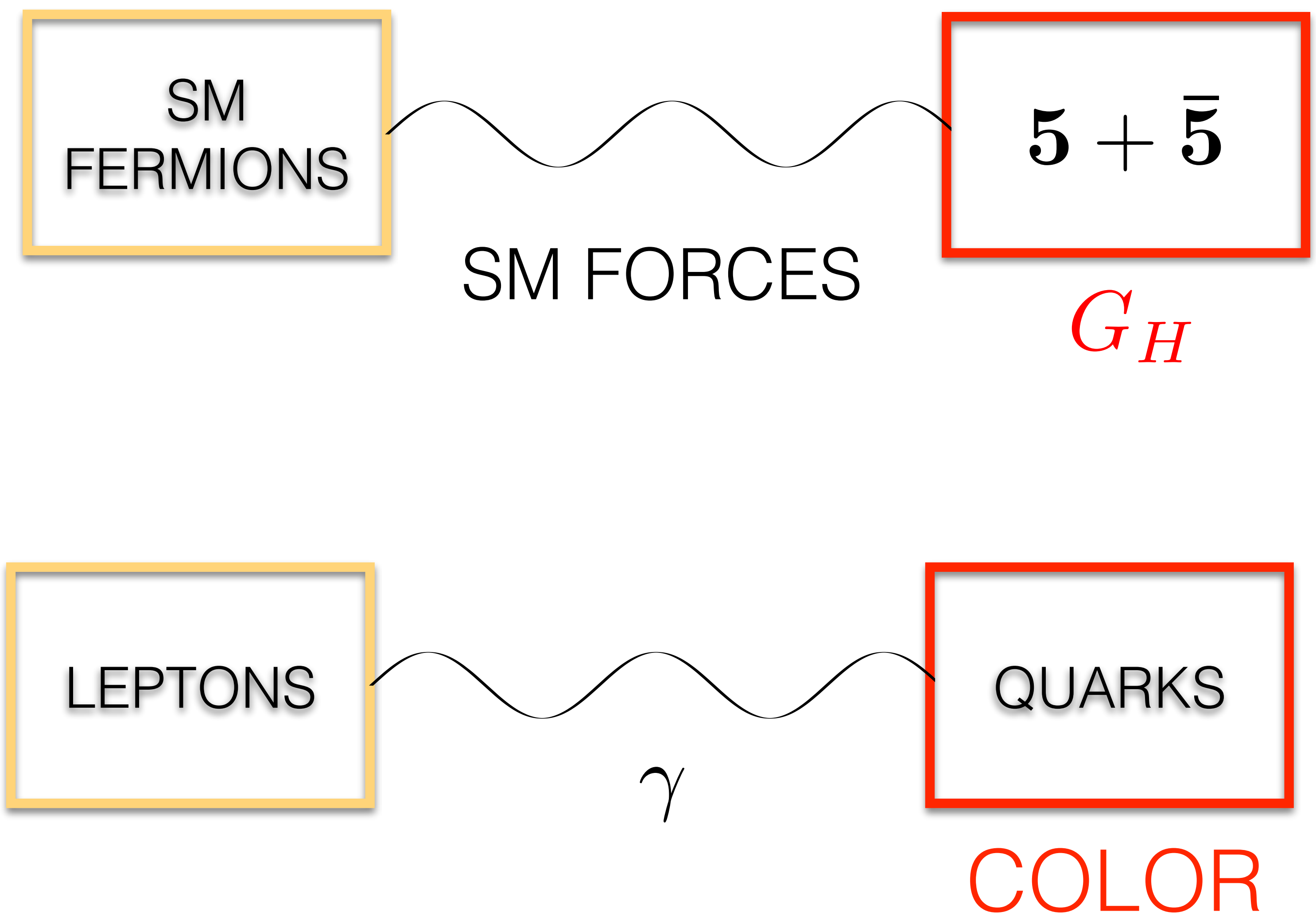
$$\mathbf{5} = (D, L^c)$$

$$\mathbf{10} = (Q^c, E, U^c)$$

WELL KNOWN PHENOMENOLOGY

NO REASON TO BE NEAR THE WEAK SCALE

VECTOR-LIKE CONFINEMENT



CONFINING GROUPS

G_H	N_F
SU(2)	≤ 6
SU(3)	≤ 9
SU(4)	≤ 12
Sp(4)	≤ 9

N.B. Only their fundamental representations are asymptotically free ($N_F \geq 5$)

CONFINING GROUPS

Gauge Group	N_F
SU(2)	≤ 6
SU(3)	≤ 9
SU(4)	≤ 12
Sp(4)	≤ 9

Example

$$3 \times (\mathbf{5} + \bar{\mathbf{5}})$$

$$N_F = 5$$

CONFORMAL WINDOW

ONE MORE INGREDIENT: SUSY IN THE UV

↓

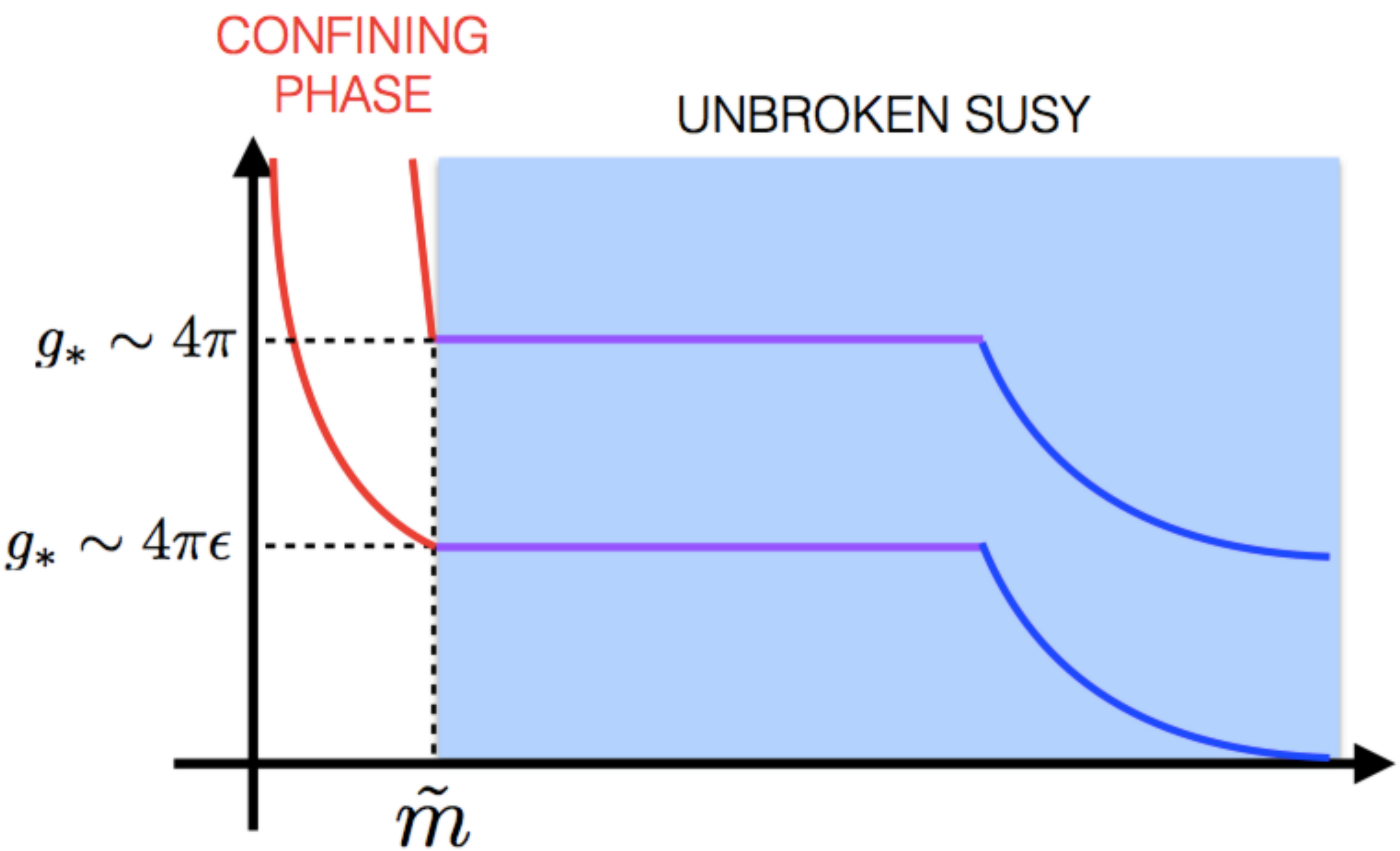
ALL(*) OUR THEORIES ARE IN THE CONFORMAL WINDOW

$$3N_c/2 < N_F < 3N_c \quad \mathrm{SU(N_c)}$$

$$3(N_c+1)/2 < N_F < 3(N_c+1) \quad \mathrm{Sp(N_c)}$$

(*) $\mathrm{SU}(4) \quad N_F \geq 7$

CONFORMAL WINDOW



$$\Lambda \sim \text{TeV} - 100 \text{ TeV}$$

SIGNALS

CHIRAL SYMMETRY

$\mathrm{SU}(3)_\mathrm{H}, \mathrm{SU}(4)_\mathrm{H}$ → $SU(N_F) \times SU(N_F)$ ↓ $SU(N_F)$

$N_F \geq 5$

$\mathrm{SU}(2)_\mathrm{H}, \mathrm{Sp}(4)_\mathrm{H}$ → $SU(2N_F)$ ↓ $Sp(2N_F)$

PIONS

$\mathrm{SU}(3)_{\mathrm{H}}, \mathrm{SU}(4)_{\mathrm{H}} \longrightarrow \mathbf{24} + \Delta(\mathbf{5} + \overline{\mathbf{5}}) + \Delta^2 \mathbf{1}$

$$\Delta = N_F - 5$$

$\mathrm{SU}(2)_{\mathrm{H}}, \mathrm{Sp}(4)_{\mathrm{H}} \longrightarrow \mathbf{24} + \mathbf{10} + \overline{\mathbf{10}} + 2\Delta(\mathbf{5} + \overline{\mathbf{5}}) + \Delta(2\Delta - 1)\mathbf{1}$

PIONS

EXAMPLE: $\mathbf{24}$ of SU(5)

meson	constituents	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
π_8	$D^c D$	$(\mathbf{8}, \mathbf{1})_0$
π_3	$L L^c$	$(\mathbf{1}, \mathbf{3})_0$
π_1	$2D^c D - 3LL^c$	$(\mathbf{1}, \mathbf{1})_0$
$Q_X = (X_{-1/3}, X_{-4/3})$	LD	$(\mathbf{3}, \mathbf{2})_{-5/6}$
$Q_X^* = (X_{4/3}, X_{1/3})$	$D^c L^c$	$(\bar{\mathbf{3}}, \mathbf{2})_{5/6}$

INTERACTIONS

meson	constituents	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
π_8	$D^c D$	$(\mathbf{8}, \mathbf{1})_0$
π_3	$L L^c$	$(\mathbf{1}, \mathbf{3})_0$
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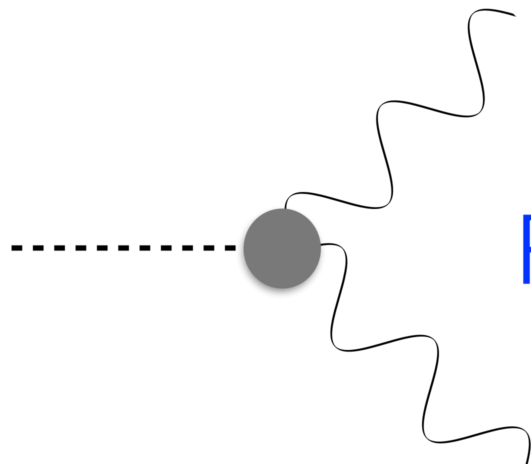


REAL

COMPLEX

MASSES

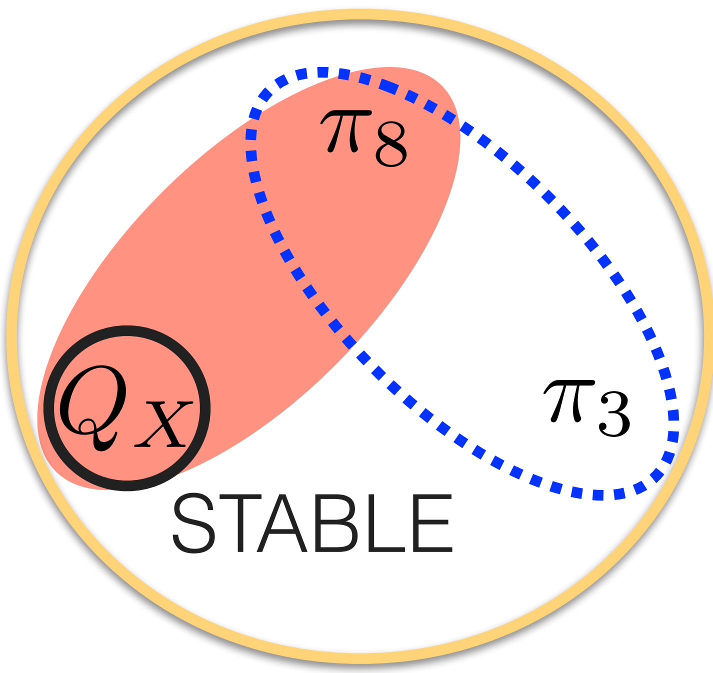
SIMPLEST SCENARIO: ONLY SM GAUGE INTERACTIONS BREAK THE FLAVOR SYMMETRY EXPLICITLY

meson	constituents	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$	
π_8	D^cD	$(\mathbf{8},\mathbf{1})_0$	$m^2 \sim (\alpha_s/4\pi)\Lambda^2$
π_3	LL^c	$(\mathbf{1},\mathbf{3})_0$	$m^2 \sim (\alpha_w/4\pi)\Lambda^2$
π_1	$2D^cD - 3LL^c$	$(\mathbf{1},\mathbf{1})_0$	$m \sim 50$ keV
$Q_X = (X_{-1/3}, X_{-4/3})$	LD	$(\mathbf{3},\mathbf{2})_{-5/6}$	$m^2 \sim (\alpha_s/4\pi)\Lambda^2$
$Q_X^* = (X_{4/3}, X_{1/3})$	D^cL^c	$(\bar{\mathbf{3}},\mathbf{2})_{5/6}$	

SUMMARY

WEAK SCALE MASSES

NEARLY MASSLESS



COLORED

PROMPT DECAYS TO VV

π_1

A HANDFUL OF PARAMETERS DETERMINES ALL THEIR PHENOMENOLOGY

SUMMARY, PART II

———	COLORED	$m \sim \text{TeV}$ $\sigma \sim 0.1\ \text{pb}$	DIJETS,MULTIJETS, SQUARKS, LEPTOQUARKS
———	EW CHARGED	$m \sim 400\ \text{GeV}$ $\sigma \sim \text{few fb}$	MULTI-W,Z,γ, SLEPTONS
———	ALPs, LIGHT HIGGSES	$f_a \sim \text{TeV}$ $s_\theta \lesssim 1\%$	SN1987A, BEAM DUMPS, LHCb, Belle, …

POSSIBLE DEDICATED SEARCHES

- SPECTACULAR CASCADES

$$[jl^+(l^-\bar{\nu})][jl^-(l^+\nu)]$$

- jZ RESONANCES

$$(jZ),(jZ)(jj),(jZ)(j\gamma)$$

- FOUR WEAK GAUGE BOSONS

- EXOTIC LEPTOQUARKS

$$tl,\tau j$$

N. Arkani-Hamed, RTD, A.Hook, H.D. Kim,M. Low
Very Preliminary

LOW ENERGY LANDSCAPES

IDEAL OUTCOME

MAKE THE HIGGS LIGHT BY TUNING ONLY

$$\Lambda$$

BONUS

SIGNALS OF
LOW ENERGY LANDSCAPES

SETUP

- WE IMAGINE THAT ANTHROPIC TUNING OR SUSY BRINGS THE CC DOWN TO SOME INTERMEDIATE VALUE $(\mathrm{meV})^4 \ll \Lambda_* \ll M_{Pl}^4$

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- AT LOW ENERGY WE INCLUDE 2^N ADDITIONAL DEGENERATE VACUA

$$V \supset -m^2 \sum_i \frac{\phi_i^2}{2} + \lambda \sum_i \frac{\phi_i^4}{4}$$

N.B. $\langle \phi_i \rangle \sim M_{Pl}$

SETUP

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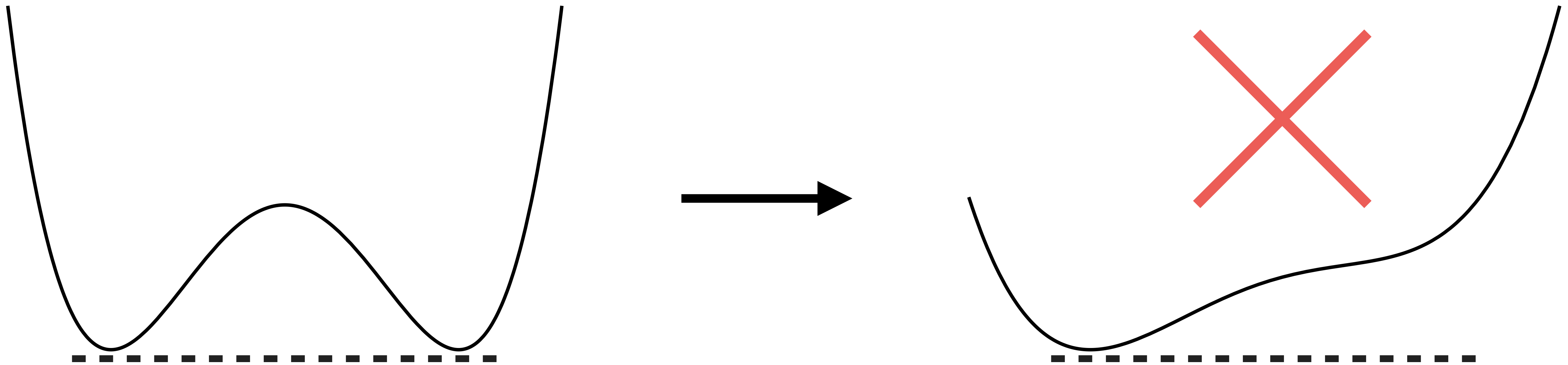
- AT LOW ENERGY WE INCLUDE 2^N ADDITIONAL DEGENERATE VACUA

$$V \supset -m^2 \sum_i \frac{\phi_i^2}{2} + \lambda \sum_i \frac{\phi_i^4}{4}$$

- THE HIGGS VEV BREAKS THE DEGENERACY

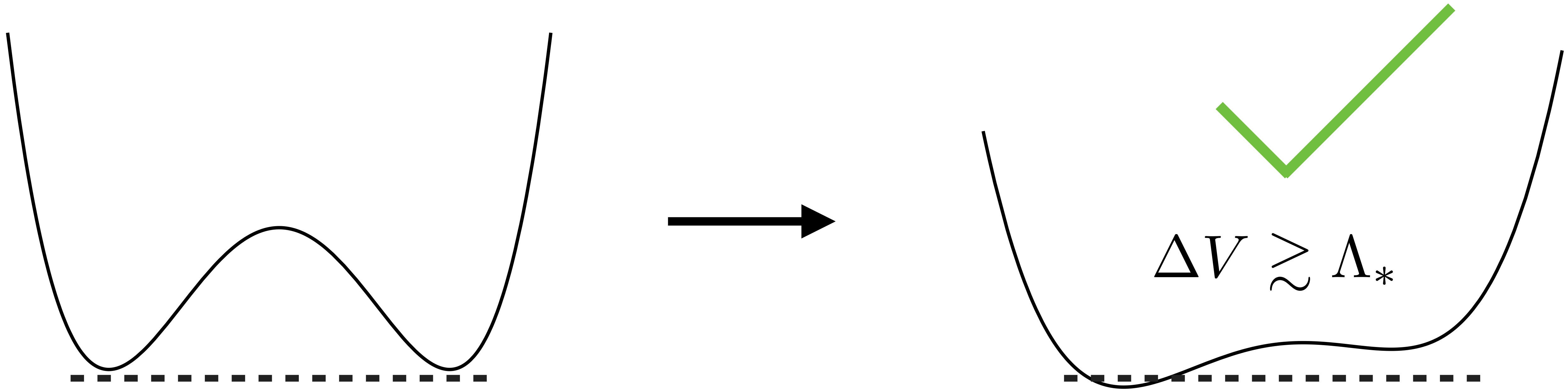
$$V \supset m H_1 H_2 \sum_i \epsilon_i \phi_i$$

BOUNDS ON THE HIGGS VEV



$$\langle H_1 H_2 \rangle \equiv v_*^2 \lesssim \frac{m M_{Pl}}{\epsilon}$$

BOUNDS ON THE HIGGS VEV



$$v_*^2 \gtrsim \frac{\Lambda_*}{\epsilon m M_{Pl}}$$

THE WEAK SCALE

$$\frac{\Lambda_*}{\epsilon m M_{Pl}} \lesssim v_*^2 \lesssim \frac{m M_{Pl}}{\epsilon}$$

$$\Lambda_* \sim v^4, \quad m \sim v^2/M_{Pl}$$

$$v_* \sim v$$

FOR SIMPLICITY
AT THE MOMENT
I AM TAKING

$$\epsilon = \mathcal{O}(1)$$

PHENOMENOLOGY

$$N \sim 6\log[v^4/(\mathrm{meV})^4] \sim 10^2$$

SCALARS

$$m \sim \frac{v^2}{M_{Pl}} \sim (\mathrm{few\ cm})^{-1}$$

$$\mathcal{L} \supset \frac{m_\psi}{M_{Pl}}\bar{\psi}\psi\sum_i \epsilon_i\phi_i$$

MEDIATING
LONG RANGE FORCES
WEAKER THAN GRAVITY

SOME WIGGLE ROOM

$$\epsilon \sim 1/\sqrt{N}$$

$$\frac{\Lambda_*}{\epsilon m M_{Pl}} \lesssim v_*^2 \lesssim \frac{m M_{Pl}}{\epsilon}$$

$$\Lambda_* \sim \epsilon^2 v^4$$

$$m \sim \epsilon \frac{v^2}{M_{Pl}}$$

$$v_* \sim v$$

$$m \sim \epsilon \times (\text{cm})^{-1}$$

$$G_N \times \epsilon$$

SOME WIGGLE ROOM

$$\epsilon \sim 1/\sqrt{N}$$

$$\frac{\Lambda_*}{\epsilon m M_{Pl}} \lesssim v_*^2 \lesssim \frac{m M_{Pl}}{\epsilon}$$

$$\Lambda_* \sim v^4$$

$$m \sim \frac{v^2}{\epsilon M_{Pl}}$$

$$v^2 \lesssim v_*^2 \lesssim v^2/\epsilon^2$$

$$m \sim (\epsilon \times \mathrm{cm})^{-1}$$

$$G_N \times \epsilon$$

SUPERSYMMETRIC CASE

$$\mathcal{W} \supset \mu H_u H_d + \kappa \sum_i \phi_i^3$$

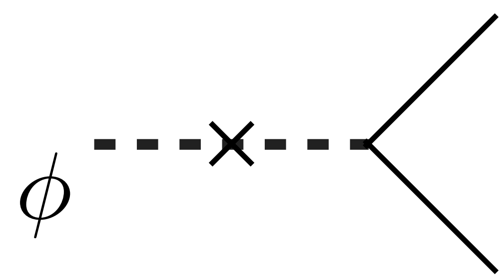
$$\mathcal{W} \supset \lambda \sum_i \phi_i H_u H_d + \kappa \sum_i \phi_i^3$$

…

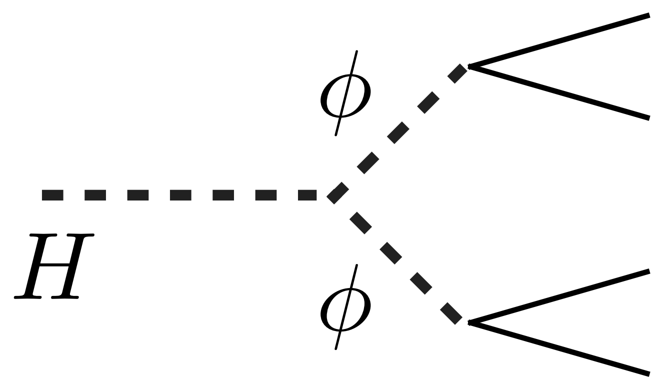
SAME IDEA, BUT THIS TIME $\langle \phi_i \rangle \sim \mathrm{TeV}$ IS NATURAL

PHENOMENOLOGY

NEW HIGGS-LIKE PARTICLES AT THE LHC



CASCADES



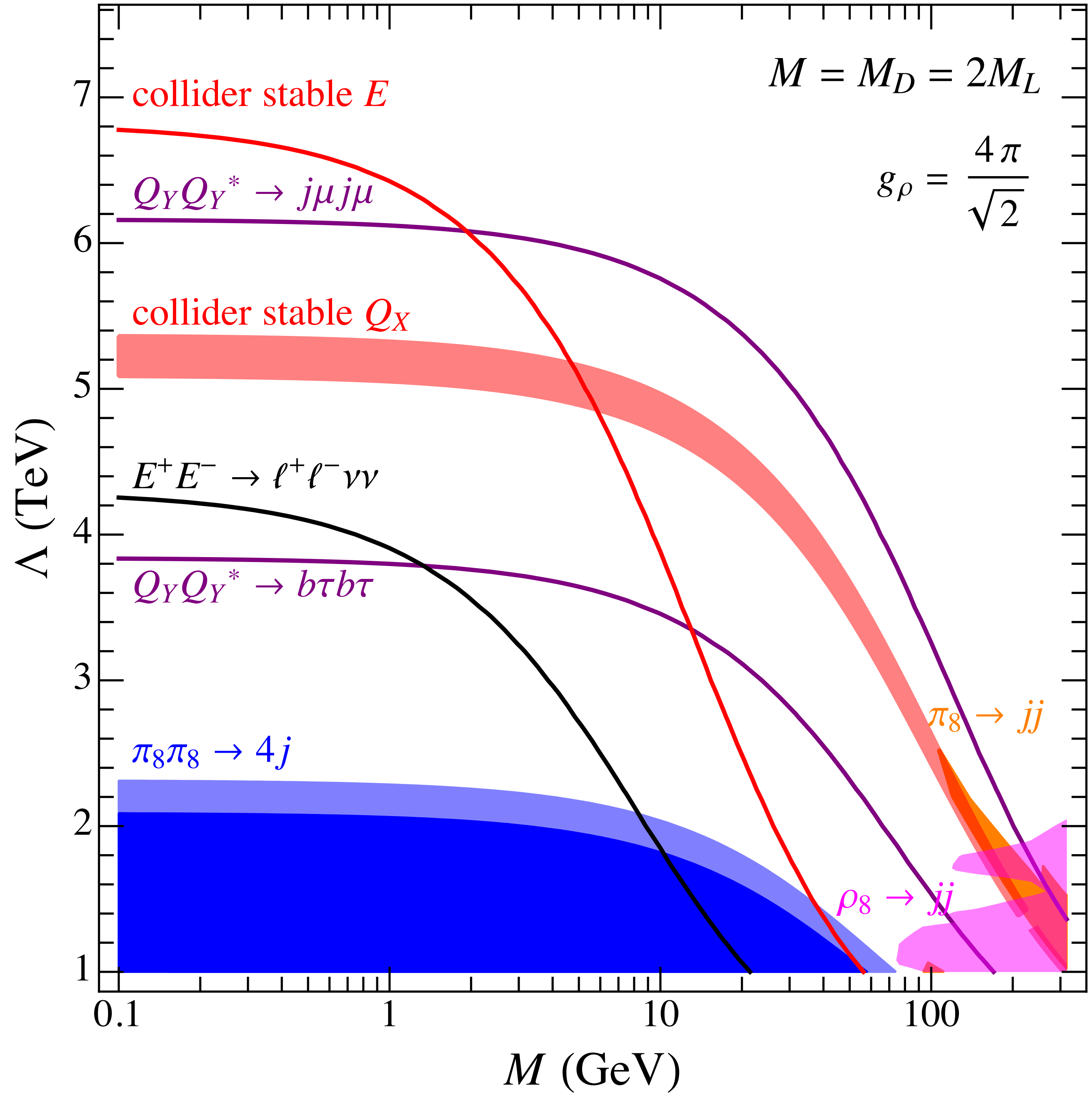
HIGGS COUPLING DEVIATIONS

CONCLUSION

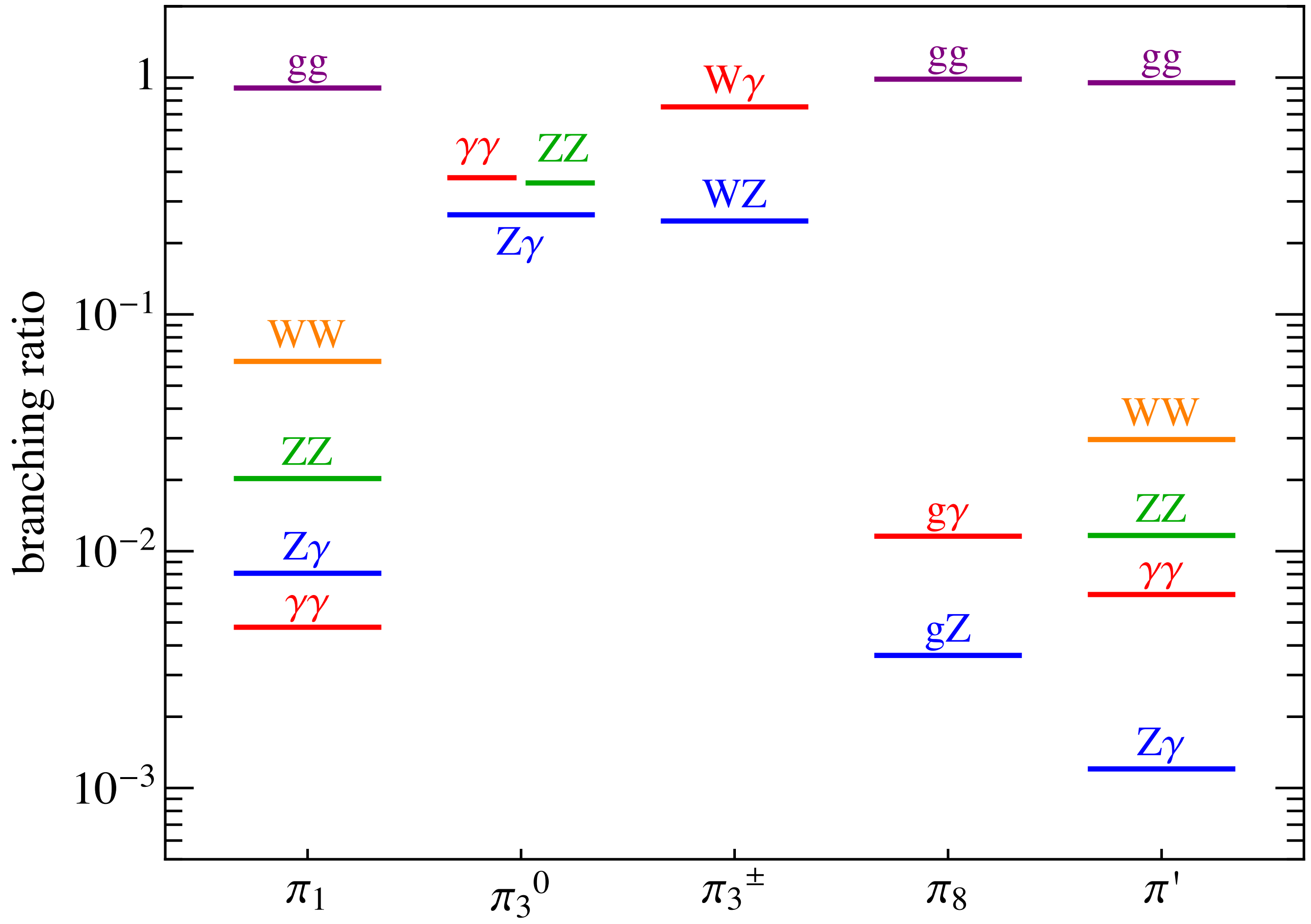
- SURPRISINGLY LEP AND LHC HAVE NOT YET UNVEILED THE SOLUTION TO THE HIERARCHY PROBLEM
- NONETHELESS THE LHC HAS STILL A HUGE PHYSICS POTENTIAL
- AND THERE ARE MANY OTHER REASONS TO EXPECT NEW PARTICLES OTHER THAN NATURALNESS, SOME OF WHICH UNEXPECTED:
  - LOW ENERGY LANDSCAPES
  - UNIFICATION + IR FIXED POINTS

BACKUP

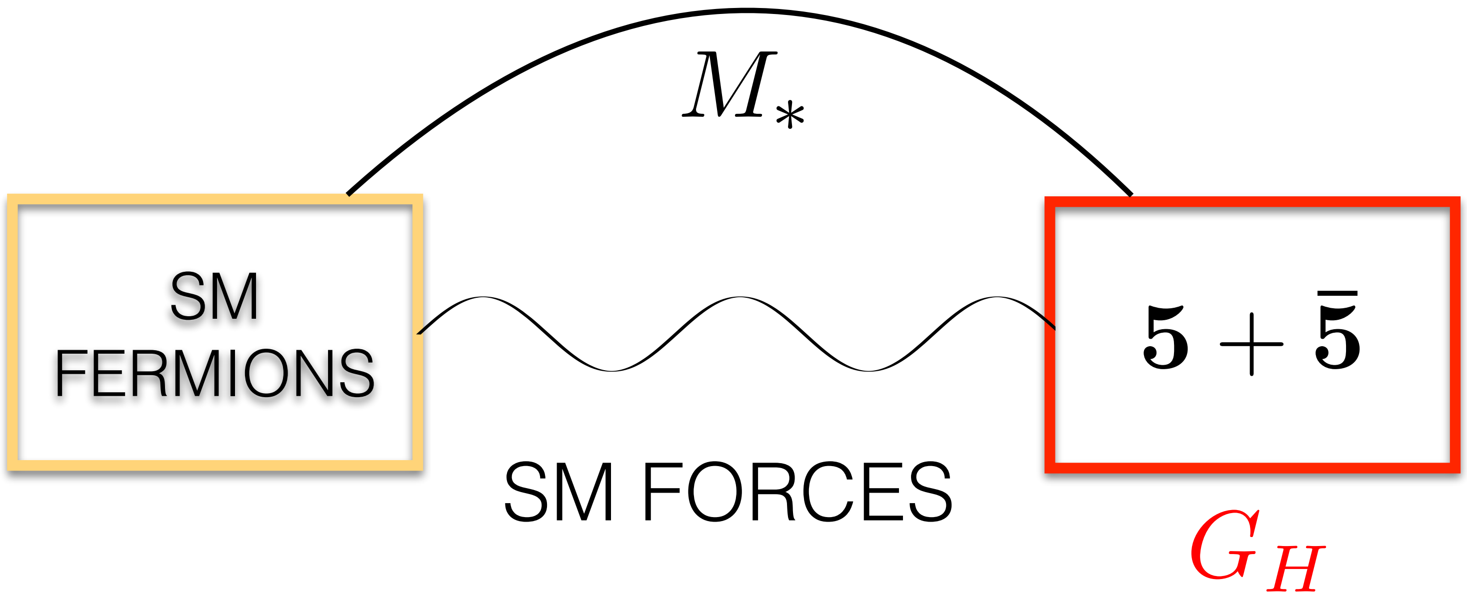
CONSTRAINTS

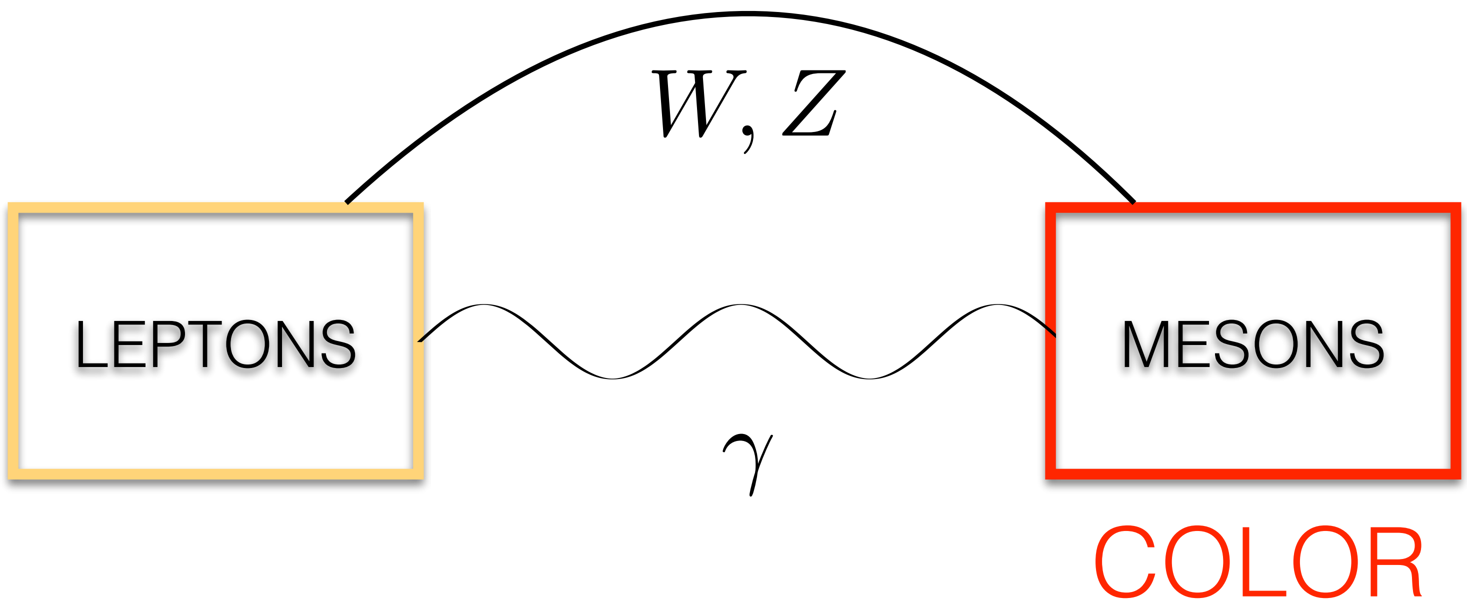


REAL PIONS BRs



"STABLE" PIONS





“STABLE” PIONS

$$\frac{f}{M_*^2}\partial_\mu Q_X \bar{\ell}\bar{\sigma}^\mu d^c$$

$$\tau \simeq 0.1 \text{ mm} \left(\frac{0.1}{c_i}\right)^2 \left(\frac{3 \text{ TeV}}{\Lambda}\right)^2 \left(\frac{M_*}{10 \text{ TeV}}\right)^4 \left(\frac{(1 \text{ GeV})^2}{m_a^2 + m_b^2}\right) \left(\frac{1 \text{ TeV}}{M_\pi}\right)$$

$$\frac{\Lambda f}{M_*^2} Q_X d^c \tilde{H}_u$$

$$\tau \simeq 10^{-11} \text{ m} \left(\frac{0.1}{c_i}\right)^2 \left(\frac{3 \text{ TeV}}{\Lambda}\right)^4 \left(\frac{M_*}{10 \text{ TeV}}\right)^4 \left(\frac{1 \text{ TeV}}{M_\pi}\right)$$

FLAVOR

$$W \supset M_\Phi \Phi \Phi^c + \lambda_{L,i} \Phi^c L^c \ell_i + \lambda_{D,i} \Phi^c D d_i^c + M_L L L^c + M_D D D^c$$

$$\mathcal{L} \supset \left(\frac{\lambda_{D,s} \lambda^*_{D,d}}{4\pi M_\Phi} \right)^2 (\bar{d}^c \bar{\sigma}^\mu s^c)^2 + \frac{\lambda_{L,e} \lambda^*_{L,\mu} e}{16\pi^2} \frac{m_\mu}{M_\Phi^2} (\mu^c \sigma^{\mu\nu} e_L) F_{\mu\nu} + \ldots$$

$$\mu \to e\gamma$$

$$M_\Phi^2 / (\lambda_{L,e} \lambda^*_{L,\mu}) \gtrsim (60 \text{ TeV})^2$$

$$K - \bar{K}$$

$$\Re(M_\Phi / (\lambda_{D,s} \lambda^*_{D,d})) \gtrsim 80 \text{ TeV}$$

$$\Im(M_\Phi / (\lambda_{D,s} \lambda^*_{D,d})) \gtrsim 1.3 \times 10^3 \text{ TeV}$$