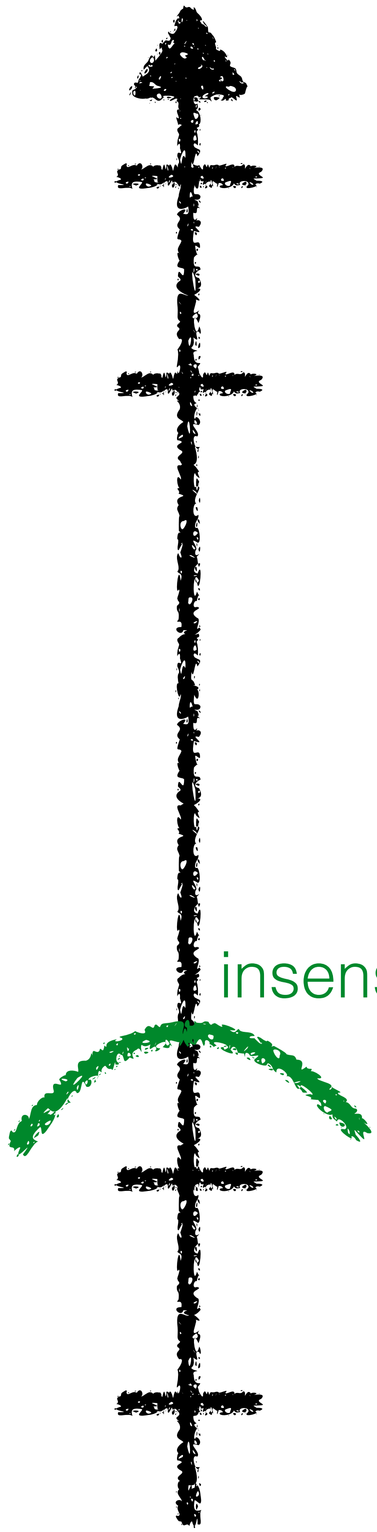
Natural Alternatives

Andreas Weiler
(TU Munich)

DESY Theory workshop 2015
1/10/2015

The long dream

Energy



Supergravity -> String theory

gauge couplings unify, GUT

insensitivity to UV scales

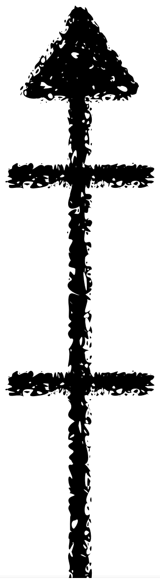
< TeV scale supersymmetry

m_{Higgs}

Abundance of coloured superparters, flavor signatures, dark matter explained

Energy

The long dream



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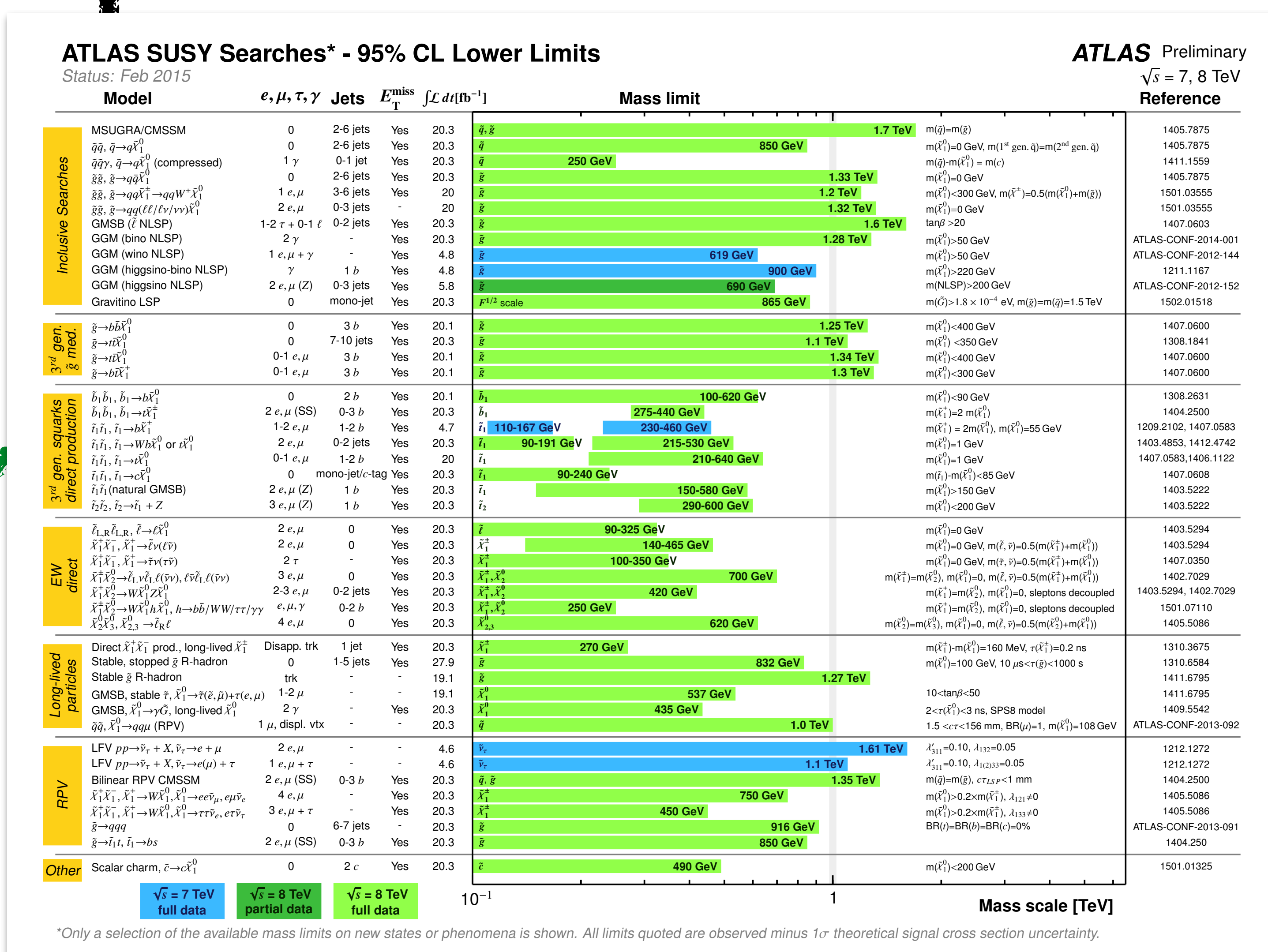

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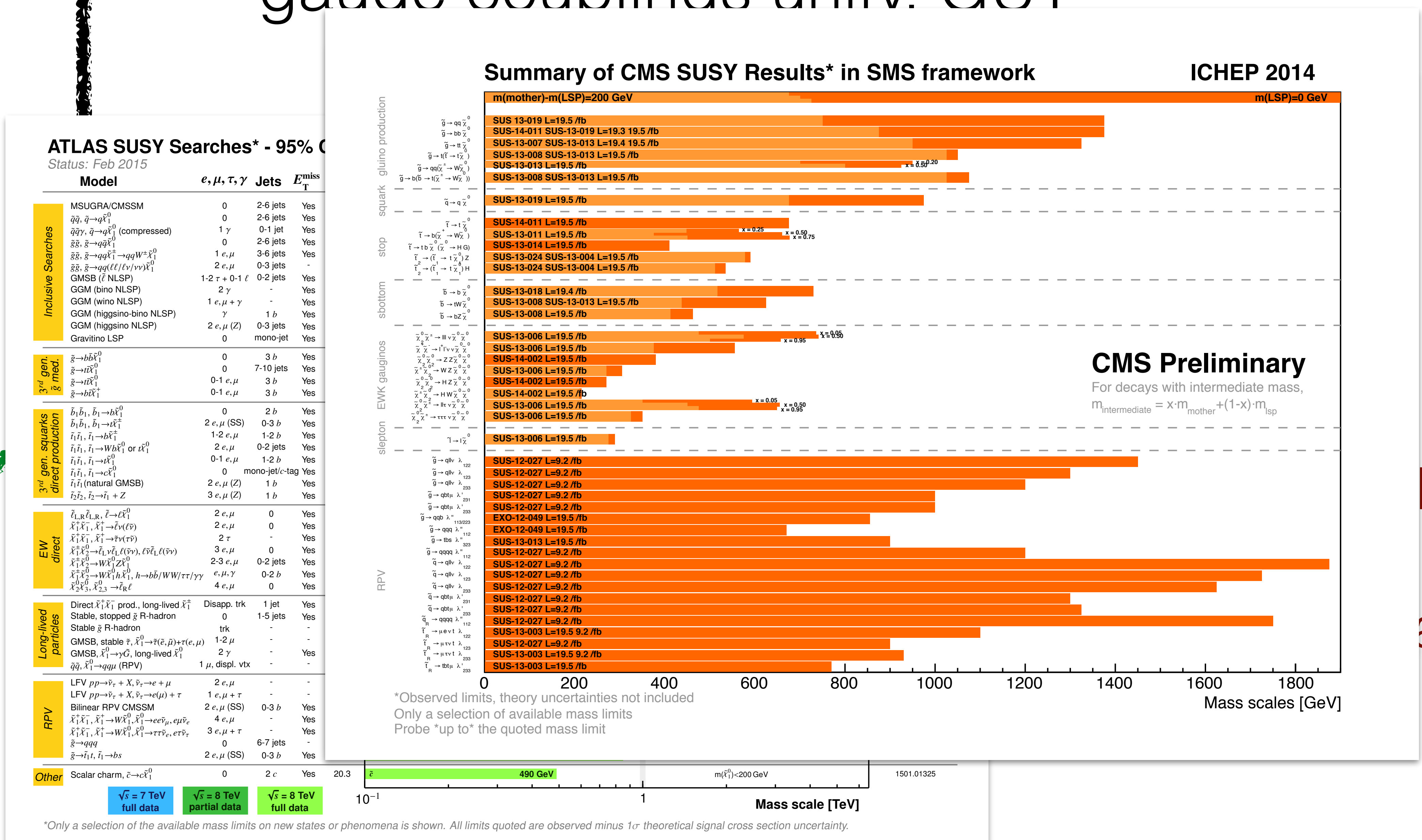

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ignatures,

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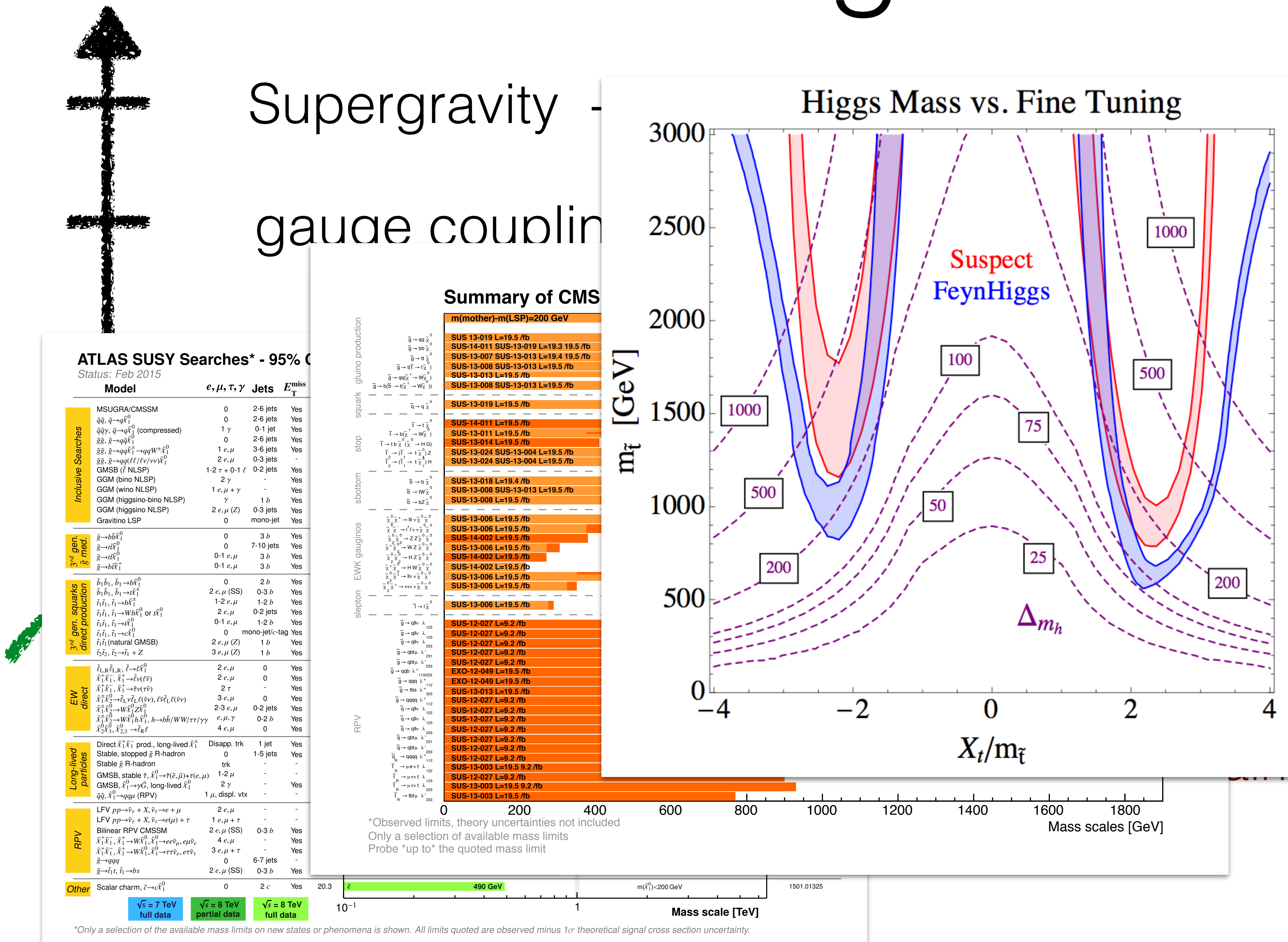
The long dream

Energy

Supergravity -

gauge couplin



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< 1% tuning in simplest models

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~~Abundance of coloured superparters, flavor signatures, dark matter detected~~

The long dream

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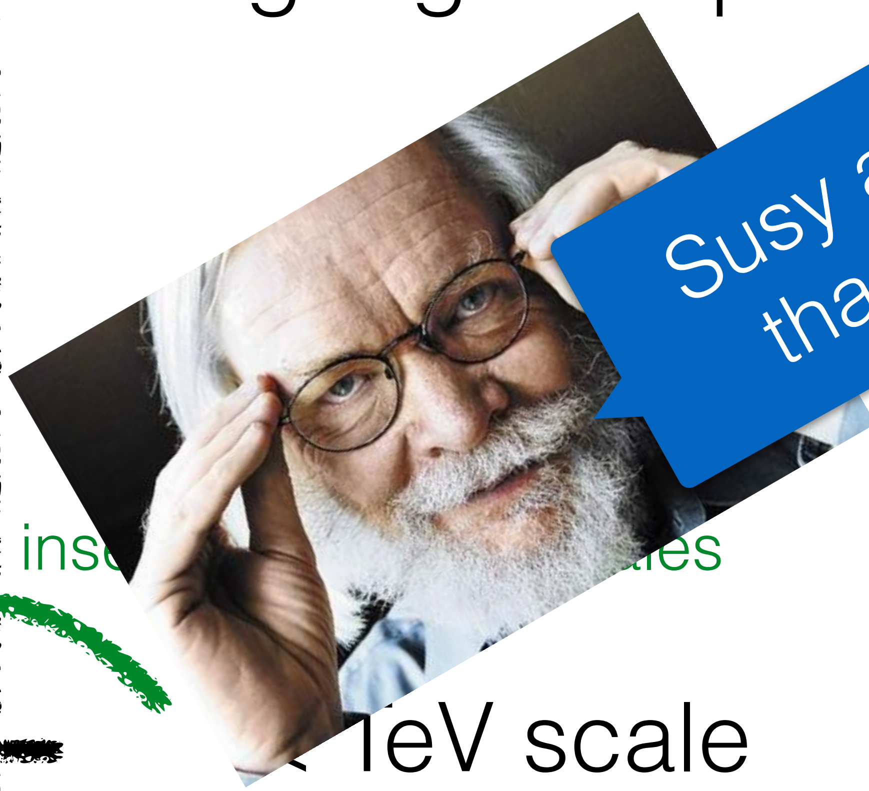
gauge couplings u



Susy anywhere is better than susy nowhere…

< 1% tuning in simplest models

ins ies

< TeV scale

supersymmetry

m_{Higgs}

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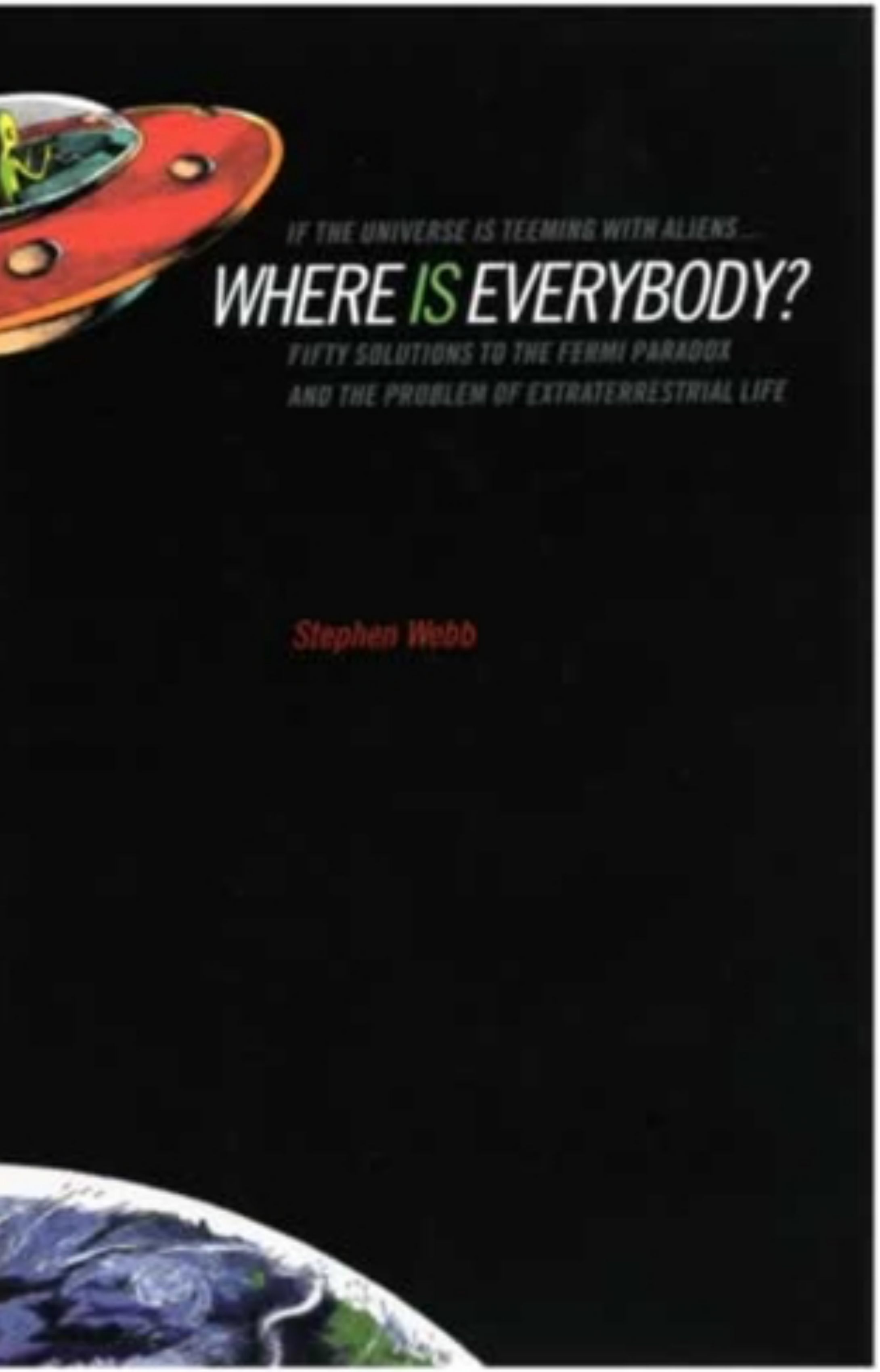


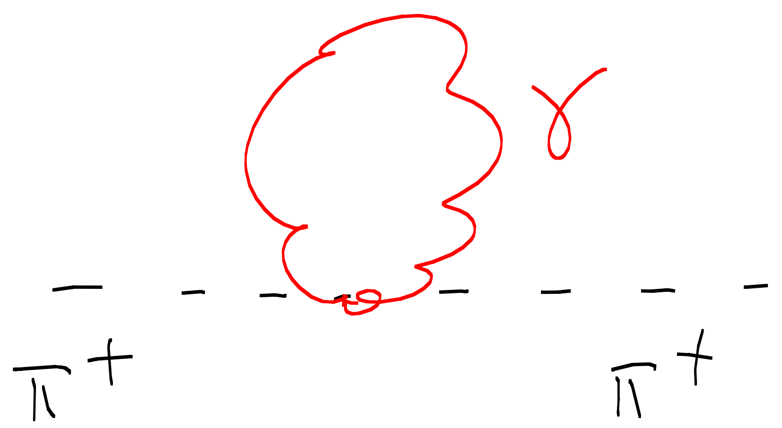
LHC run1: We have discovered the Higgs, nothing else.

We know that a SM-like Higgs is responsible for EW symmetry breaking.

Is the EW scale natural?

The naturalness strategy is not a no-lose theorem, but has been successful in the past.

Example: Pion mass



$$\delta m^2_{\pi^+} \sim \frac{3\alpha}{4\pi}\Lambda^2$$

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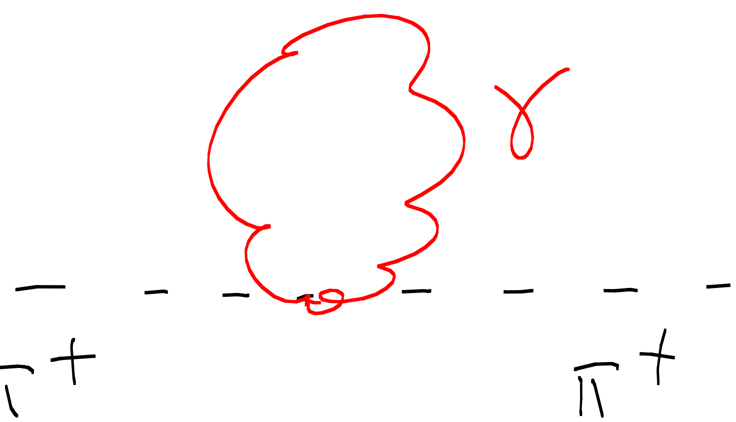

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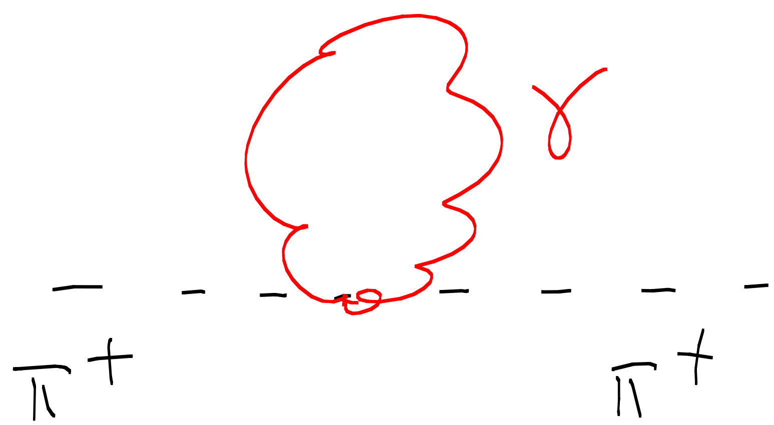

$$\delta m_{\pi^+}^2 \sim \frac{3\alpha}{4\pi}\Lambda^2 < (m_{\pi^+}^2 - m_{\pi^0}^2)_{\mathrm{exp}} \approx (4\,\mathrm{MeV})^2$$

Naturalness suggests $\rightarrow \Lambda < 850\,\mathrm{MeV}$

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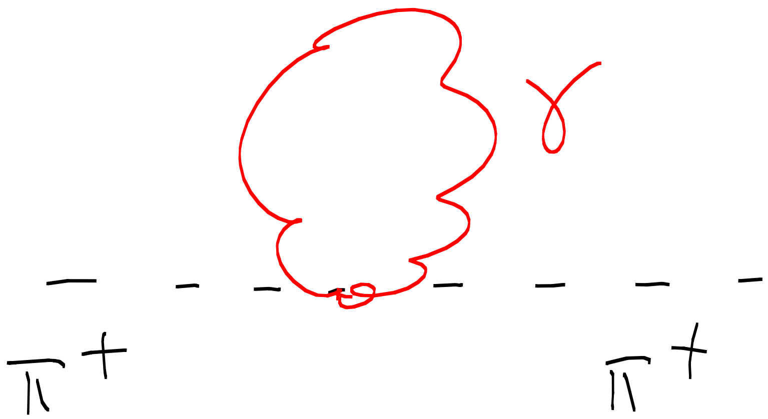

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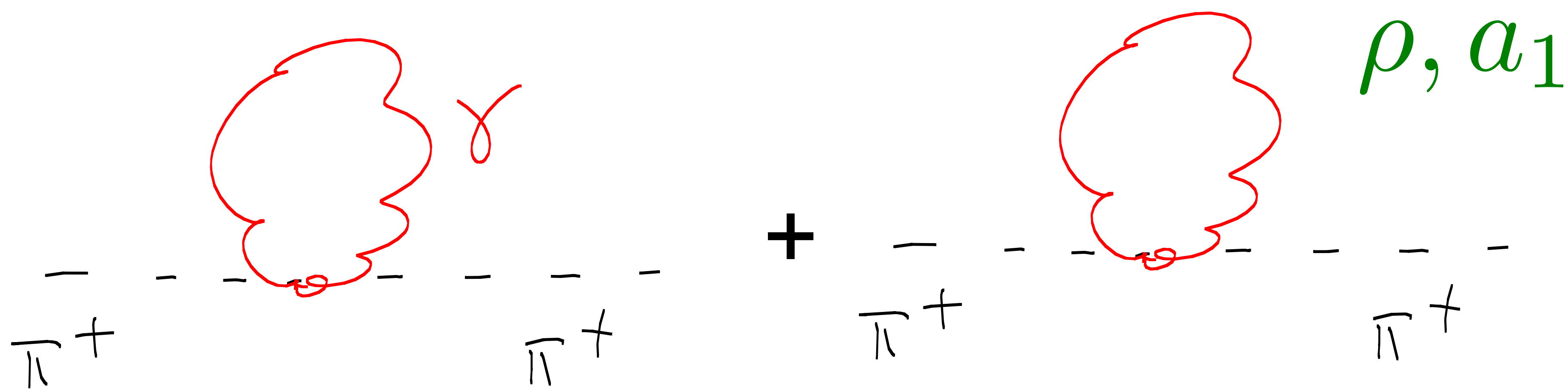

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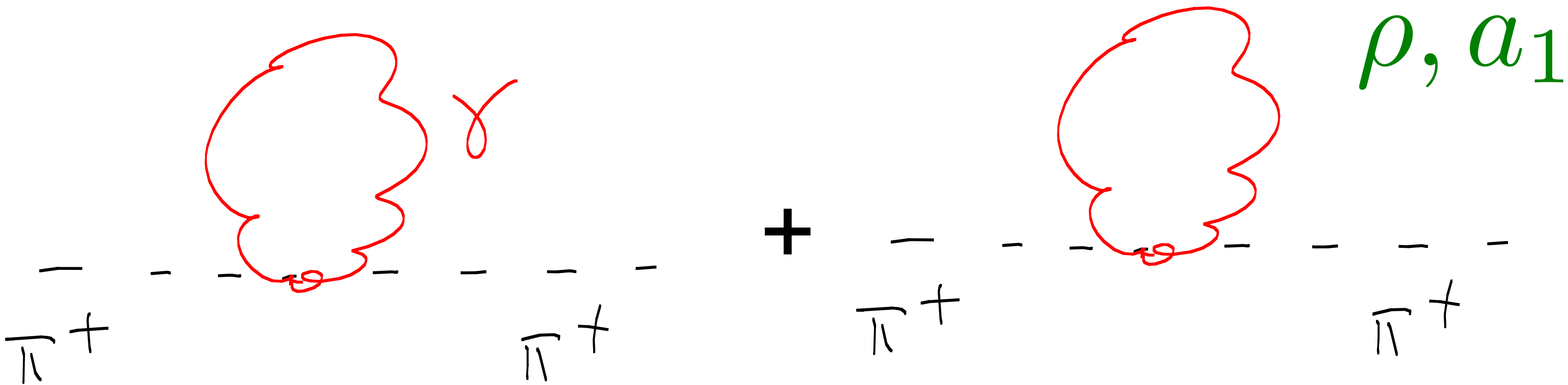

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'New physics': comes in at $m_\rho = 770\,{\rm MeV}$

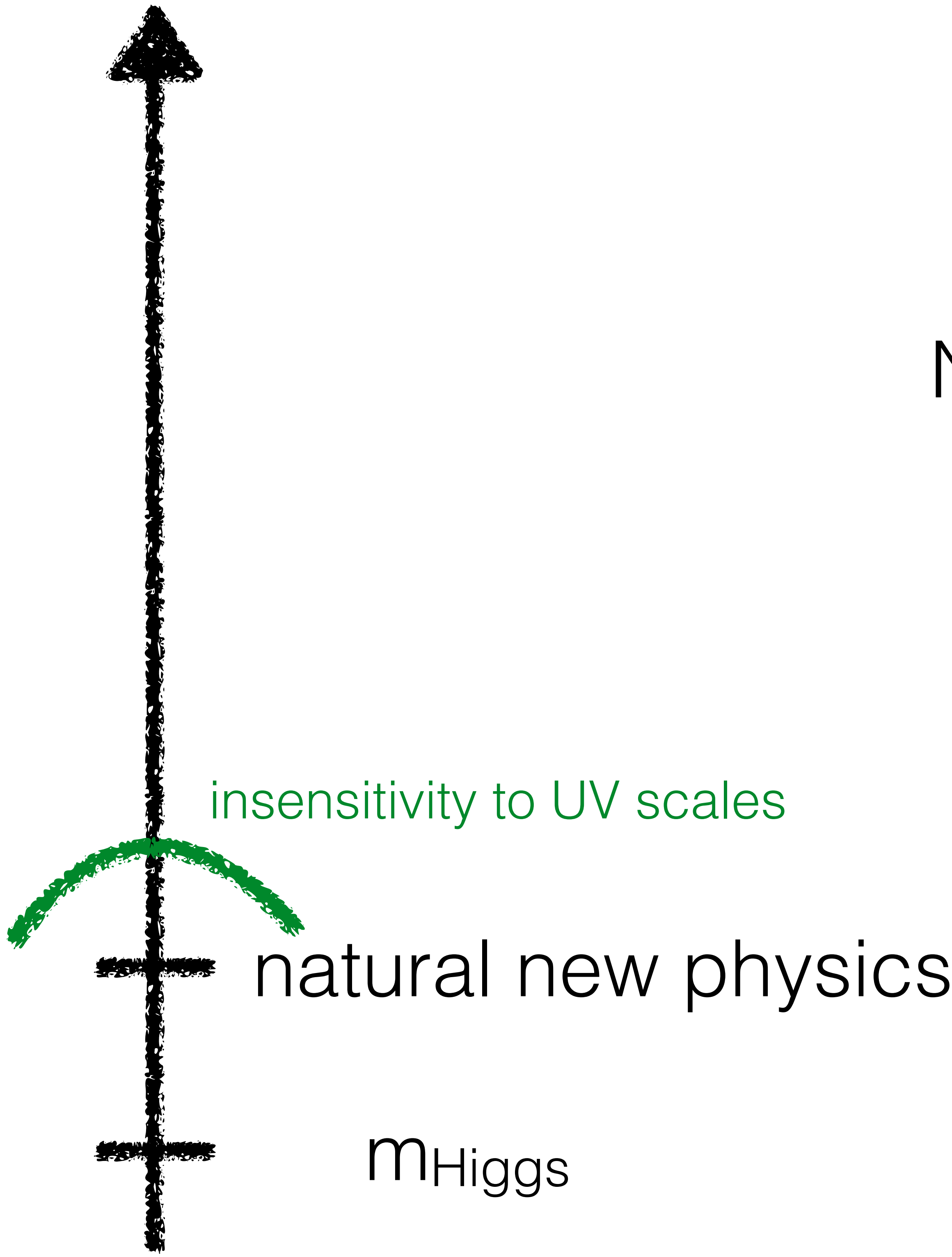
$$m^2_{\pi^\pm} - m^2_{\pi_0} \simeq \frac{3\,\alpha_{em}}{4\pi}\frac{m^2_\rho m^2_{a_1}}{m^2_{a_1} - m^2_\rho}\log\left(\frac{m^2_{a_1}}{m^2_\rho}\right)$$

Das et al '67

$$(m_{\pi^\pm} - m_{\pi_0})|_{\rm TH} \simeq 5.8\,{\rm MeV}\ !$$

Bottom-up naturalness

E



New physics cuts off quantum corrections above TeV

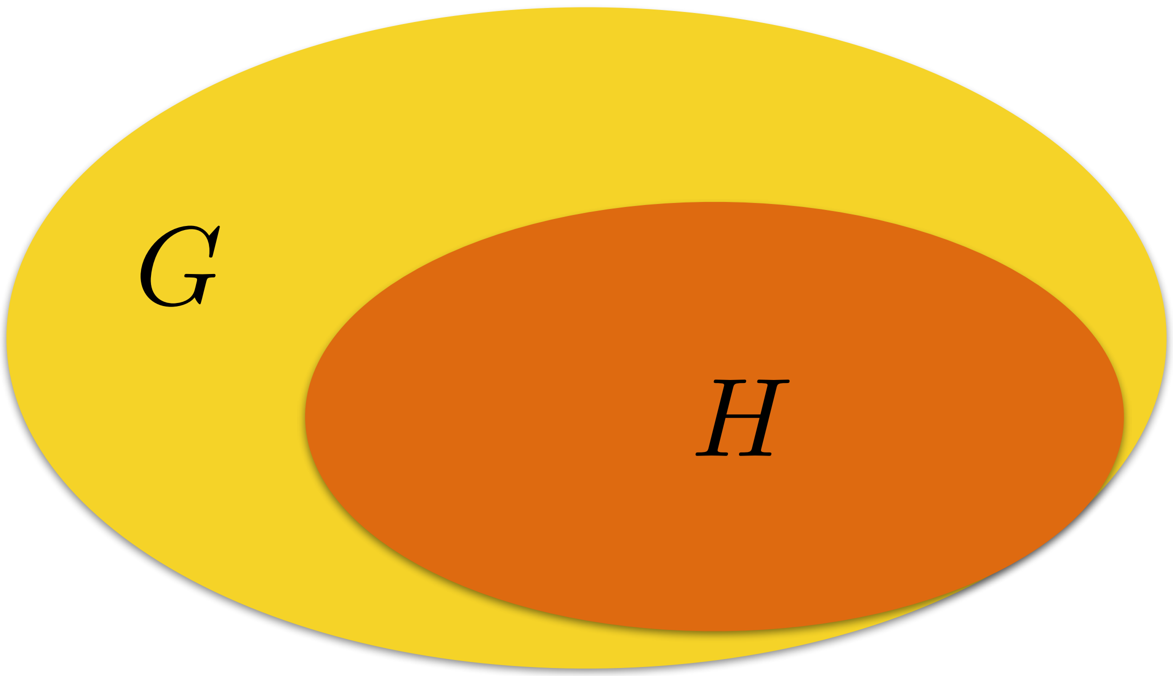
- Supersymmetry
- Composite Higgs
- Extra-dimensions
- Technicolor (RIP)

Naturalness under attack

* LHC direct bounds
* Higgs mass
* Higgs couplings
* Flavor & CP
* EW precision tests

Strong dynamics

$$< \bar{\Psi}^i_L \Psi^j_R >= \Lambda^3_{QCD}\, \delta_{ij} \longrightarrow \frac{SU(2)_L \otimes SU(2)_R}{SU(2)_{L+R}} \longrightarrow \mathcal{L} = f_\pi^2\, Tr\left[\partial_\mu U \partial^\mu U^\dagger\right]$$

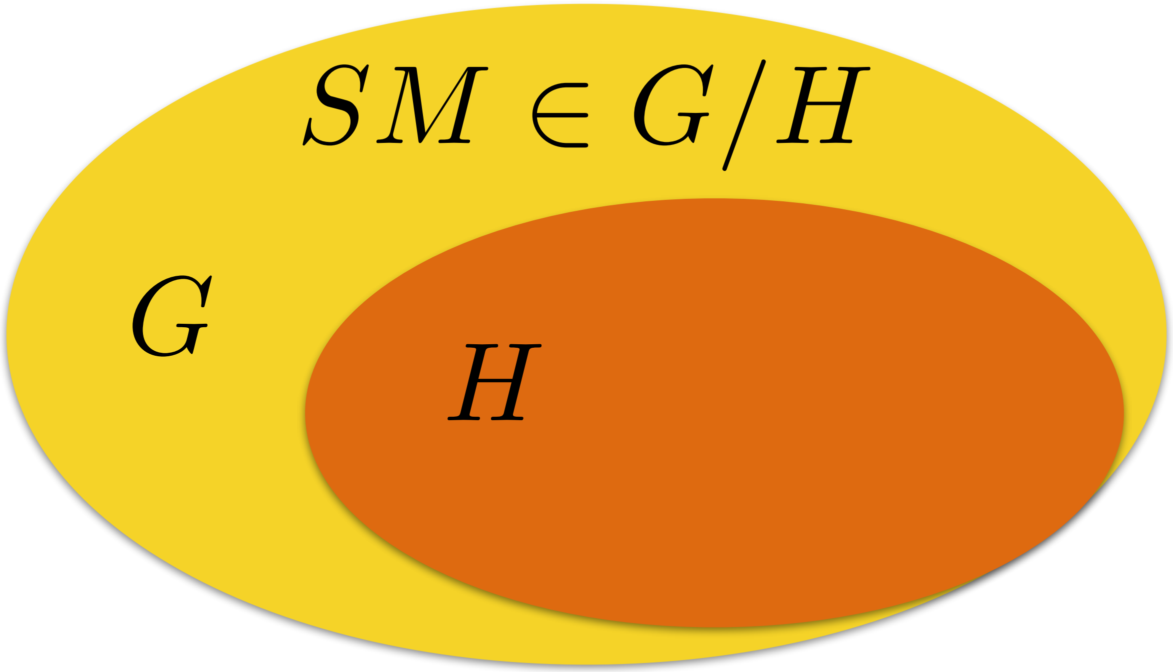


Spontaneous breaking of $G \to H$

QCD breaks EW symmetry, $f_\pi \ll v$

Technicolor

$f = v$



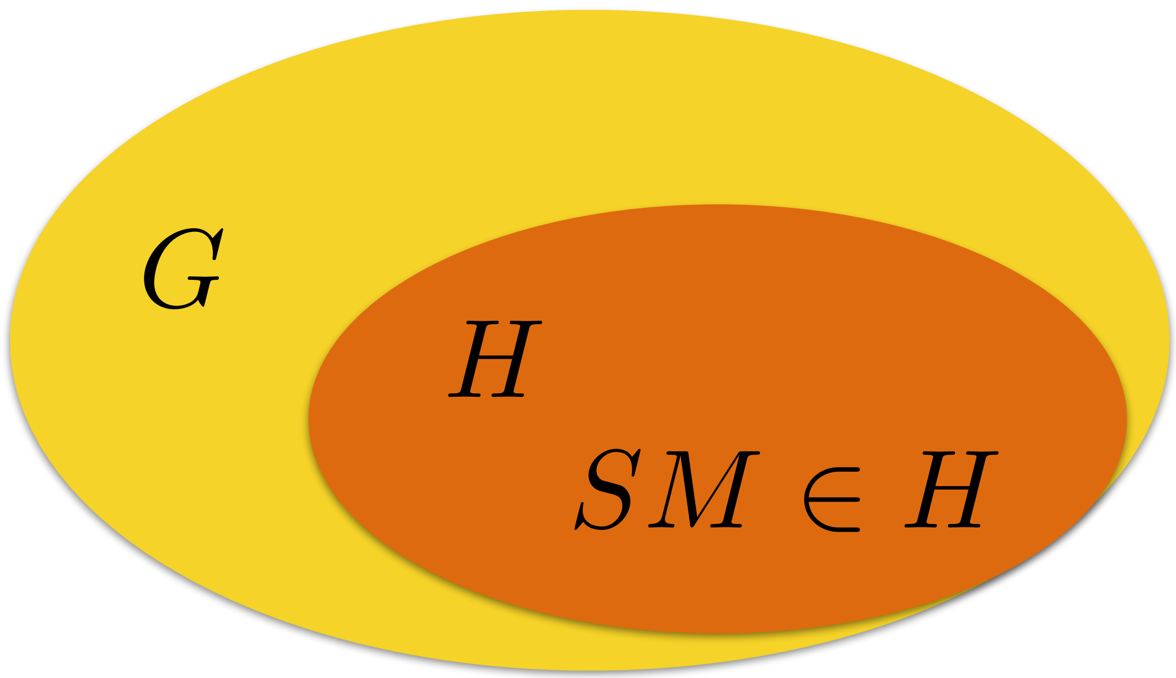
No need for a Higgs scalar, completely natural.

In trouble before LHC, now dead.

Composite Higgs

Georgi, Kaplan 80’s; Agashe, Contino, Pomarol ‘04

$f > v$

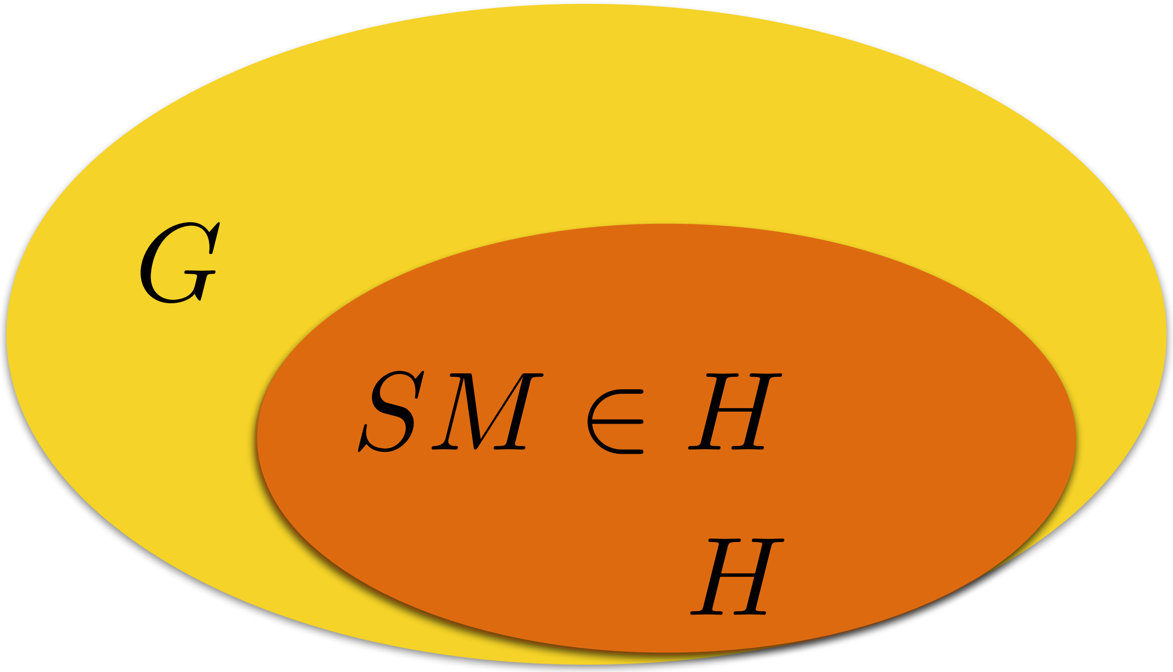


Higgs as an approximate pseudo Goldstone boson.

e.g. $SO(5)/SO(4)$ at scale f

$\rightarrow 4$ GB

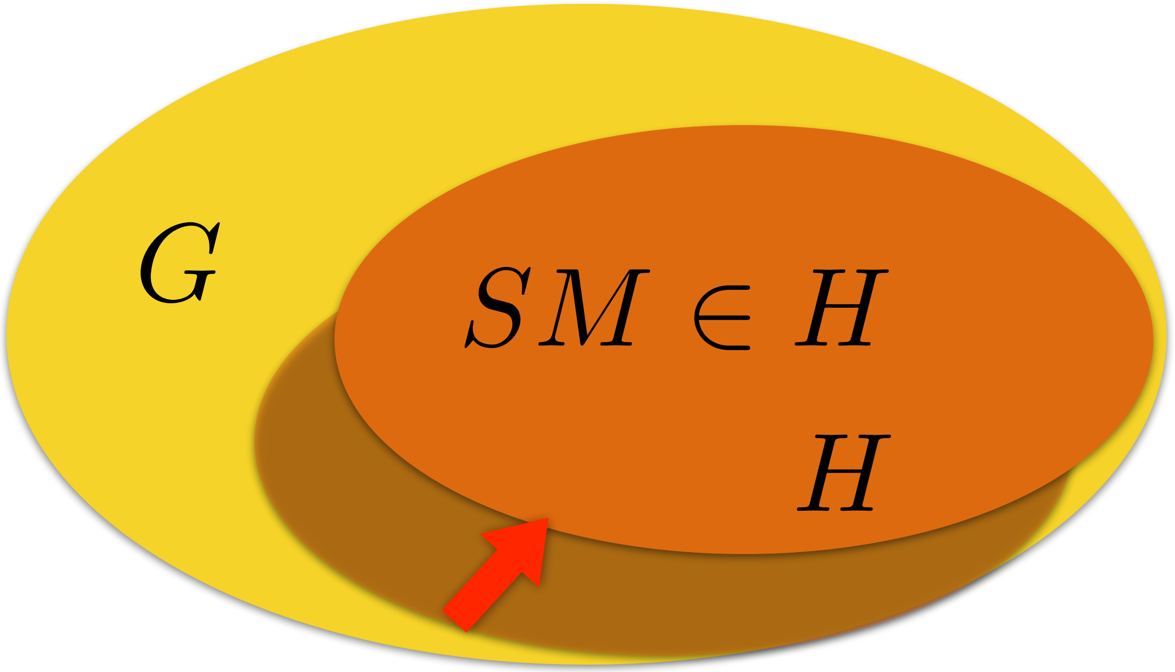
Composite Higgs



Higgs as an approximate pseudo Golstone boson.

Fermi-scale $v < f$ from vacuum-misalignment

Composite Higgs



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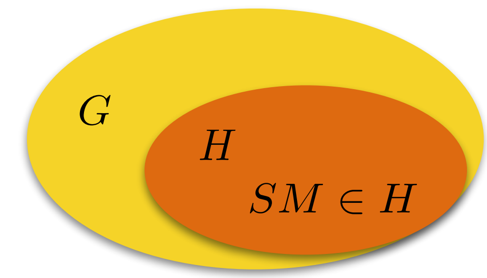
Next-to-minimal composite Higgs



Larger cosets with more scalars possible

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2) \times \mathrm{SU}(2)]$	
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$	[Agashe, Contino, Pomarol,…]
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$	[Gripaios, Pomarol, Riva, Serra 0902.1485]
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+2} + \bar{\mathbf{4}}_{-2} = 2 \times (\mathbf{2}, \mathbf{2})$	[Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer 1105.5403]
SO(7)	SO(6)	6	$\mathbf{6} = 2 \times (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$	
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$	[Chala 1210.6208]
SO(7)	SO(5) × SO(2)	10	$\mathbf{10}_{\mathbf{0}} = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$	
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \times (\mathbf{2}, \mathbf{2})$	
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4}, \mathbf{2}) = 2 \times (\mathbf{2}, \mathbf{2}), (\mathbf{2}, \mathbf{2}) + 2 \times (\mathbf{2}, \mathbf{1})$	[Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer 1105.5403]
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+\mathbf{5}} = 2 \times (\mathbf{2}, \mathbf{2})$	
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$	

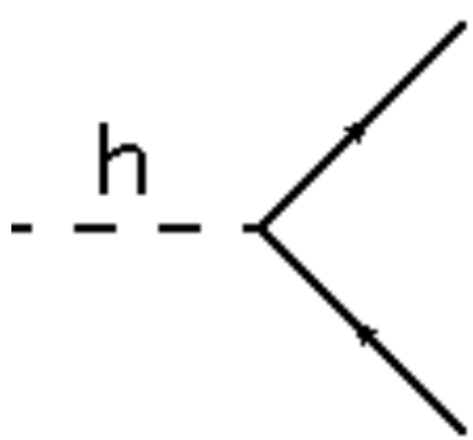
Higgs couplings

Low energy Higgs physics from **symmetries**

$$\mathcal{L}_\pi = \frac{f^2}{4} d_\mu^i d_i^\mu = \frac{1}{2}(\partial h)^2 + \frac{g^2}{4} f^2 \sin^2\frac{h}{f}\left(|W|^2 + \frac{1}{2c_w^2} Z^2\right)$$

$$g_{HVV} = i\,\frac{g^2}{4} v\sqrt{1-\xi} \qquad \xi \equiv \frac{v^2}{f^2} = \sin^2\frac{\langle h\rangle}{f}$$

Fermion couplings are less sharply predicted



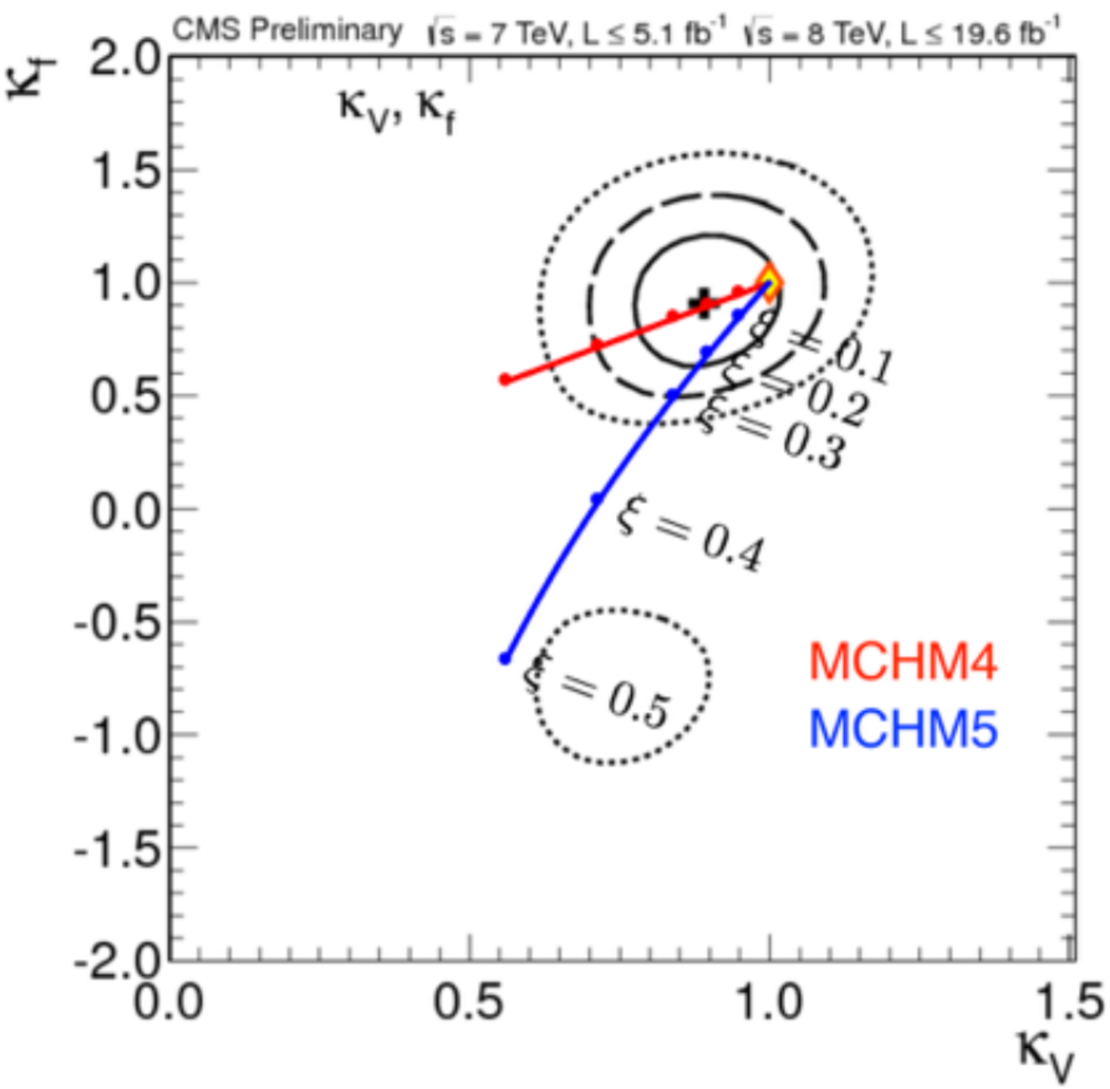
$$= i\,\frac{m_f}{v} c$$

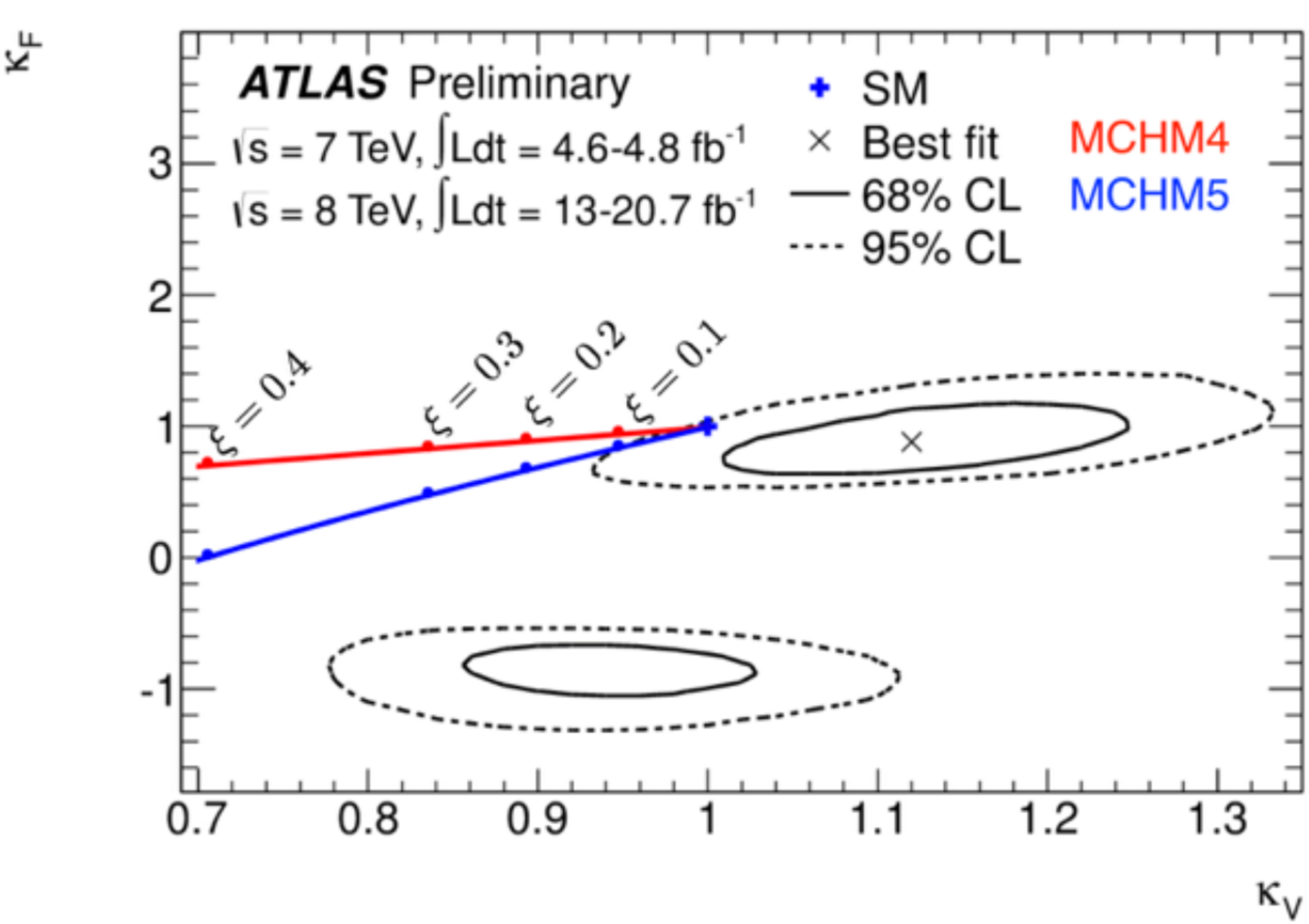
$$\mathrm{MCHM}_5 \qquad c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

$$\mathrm{MCHM}_4 \qquad c = \sqrt{1-\xi}$$

$$\mathrm{MCHM}_{10} \qquad \cdots$$

Higgs couplings





Indirect measurements

Collider	Energy	Luminosity	ξ $[1\sigma]$
LHC	$14\,\mathrm{TeV}$	$300\,\mathrm{fb}^{-1}$	$6.6 - 11.4 \times 10^{-2}$
LHC	$14\,\mathrm{TeV}$	$3\,\mathrm{ab}^{-1}$	$4 - 10 \times 10^{-2}$
ILC	$250\,\mathrm{GeV}$	$250\,\mathrm{fb}^{-1}$	$4.8\text{-}7.8 \times 10^{-3}$
	$+ 500\,\mathrm{GeV}$	$500\,\mathrm{fb}^{-1}$	
CLIC	$350\,\mathrm{GeV}$	$500\,\mathrm{fb}^{-1}$	2.2×10^{-3}
	$+ 1.4\,\mathrm{TeV}$	$1.5\,\mathrm{ab}^{-1}$	
	$+ 3.0\,\mathrm{TeV}$	$2\,\mathrm{ab}^{-1}$	
TLEP	$240\,\mathrm{GeV}$	$10\,\mathrm{ab}^{-1}$	2×10^{-3}
	$+ 350\,\mathrm{GeV}$	$2.6\,\mathrm{ab}^{-1}$	

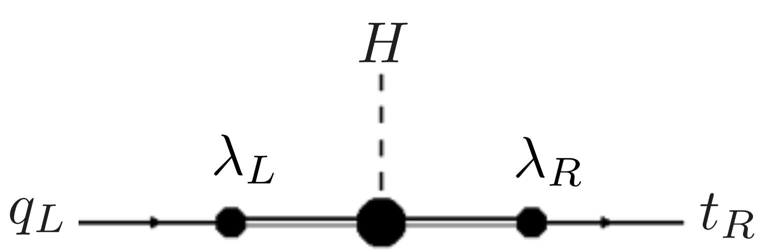
[CMS-NOTE-2012-006]
[ATL-PHYS-PUB-2013-014]
[Dawson et. al.1310.8361]
[CLIC 1307.5288]

Flavour

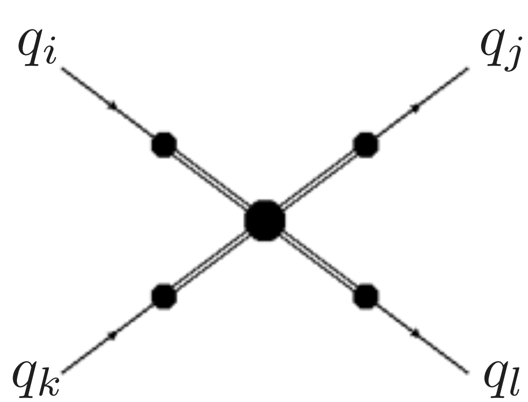
Csaki, Falkowski, Weiler, ’08, Neubert et.al, Buras et al

Linear mixing (partial compositeness)

$$\mathcal{L}_{\rm mix} = \lambda_L \, q_L \mathcal{O}_L^q + \lambda_R \, t_R \mathcal{O}_R^t + \text{h.c.} + g \, A_\mu \mathcal{J}^\mu$$



$$y_t \sim \frac{\lambda_L \lambda_R}{g_\psi} = \epsilon_L \epsilon_R g_\psi$$



$$\sim \epsilon^i \epsilon^j \epsilon^k \epsilon^l \, \frac{g_\psi^2}{m_\psi^2}$$

Flavor constraint ϵ_K

$$m_\rho > 10 - 30 \, \text{TeV}$$

Flavour

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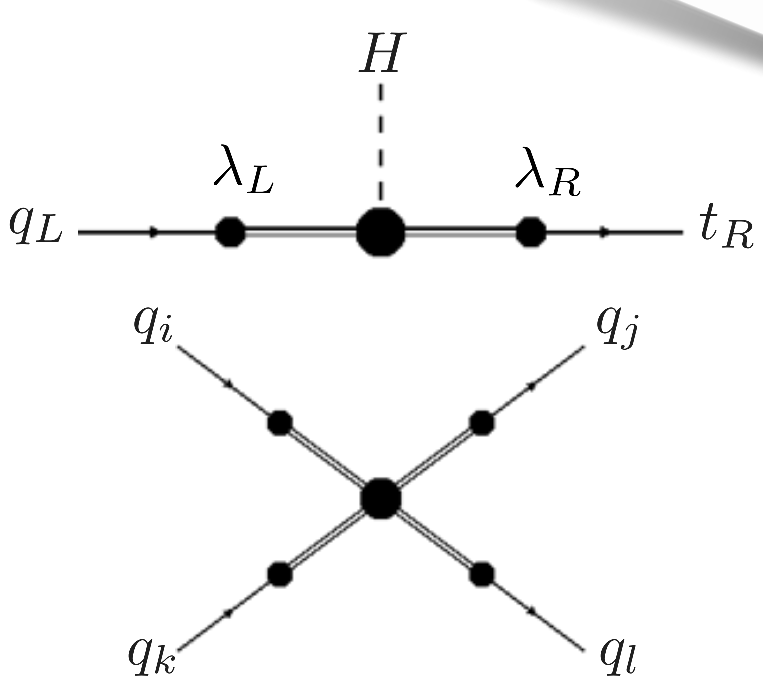
Linear mixing (…tial compositeness)

$$\mathcal{L}_{\rm mix} = \lambda_L\, q_L \mathcal{O} \ldots$$



y_t

$$\sim \epsilon^i \epsilon^j \epsilon^k \epsilon^l \,\frac{g_\psi^2}{m_\psi^2}$$

MFV scenario

$$\epsilon_R \propto Id$$

$$\epsilon_L \propto y_{SM}$$

Redi Weiler, '11

Implications of m_H = 125 GeV

Potential is fully radiatively generated

Agashe et. al

$$V_{gauge}(h) = \frac{9}{2}\int \frac{d^4p}{(2\pi)^4} \log\left(\Pi_0(p) + \frac{s_h^2}{4}\Pi_1(p)\right) \qquad s_h \equiv \sin h/f$$

$$\Pi_0(p) = \frac{p^2}{g^2} + \Pi_a(p)\ , \qquad \Pi_1(p) = 2\left[\Pi_{\hat{a}}(p) - \Pi_a(p)\right]$$

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$$\int d^4p\, \Pi_1(p)/\Pi_0(p) \quad < \infty$$

Higgs dependent term
UV finite

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Higgs dependent term
UV finite

→ 'Weinberg sum rules'

$$\lim_{p^2\to\infty} \Pi_1(p) = 0\ , \qquad \lim_{p^2\to\infty} p^2\Pi_1(p) = 0$$

UV finiteness requires at least two resonances

$$\Pi_1(p) = \frac{f^2 m_\rho^2 m_{a_1}^2}{(p^2+m_\rho^2)(p^2+m_{a_1}^2)}$$

spin1

UV finiteness requires at least two resonances

$$\Pi_1(p) = \frac{f^2 m_\rho^2 m_{a_1}^2}{(p^2+m_\rho^2)(p^2+m_{a_1}^2)}$$ **spin 1**

Similarly for SO(5) fermionic contribution

Pomarol et al; Marzocca

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

similar result in deconstruction:
Matsedonskyi et al; Redi et al

5 = 4 + 1 with EM charges 5/3, 2/3,-1/3

Q_4 Q_1

→ solve for m_h = 125 GeV

Light Higgs implies light fermionic top partners

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

Pomarol et al; Marzocca

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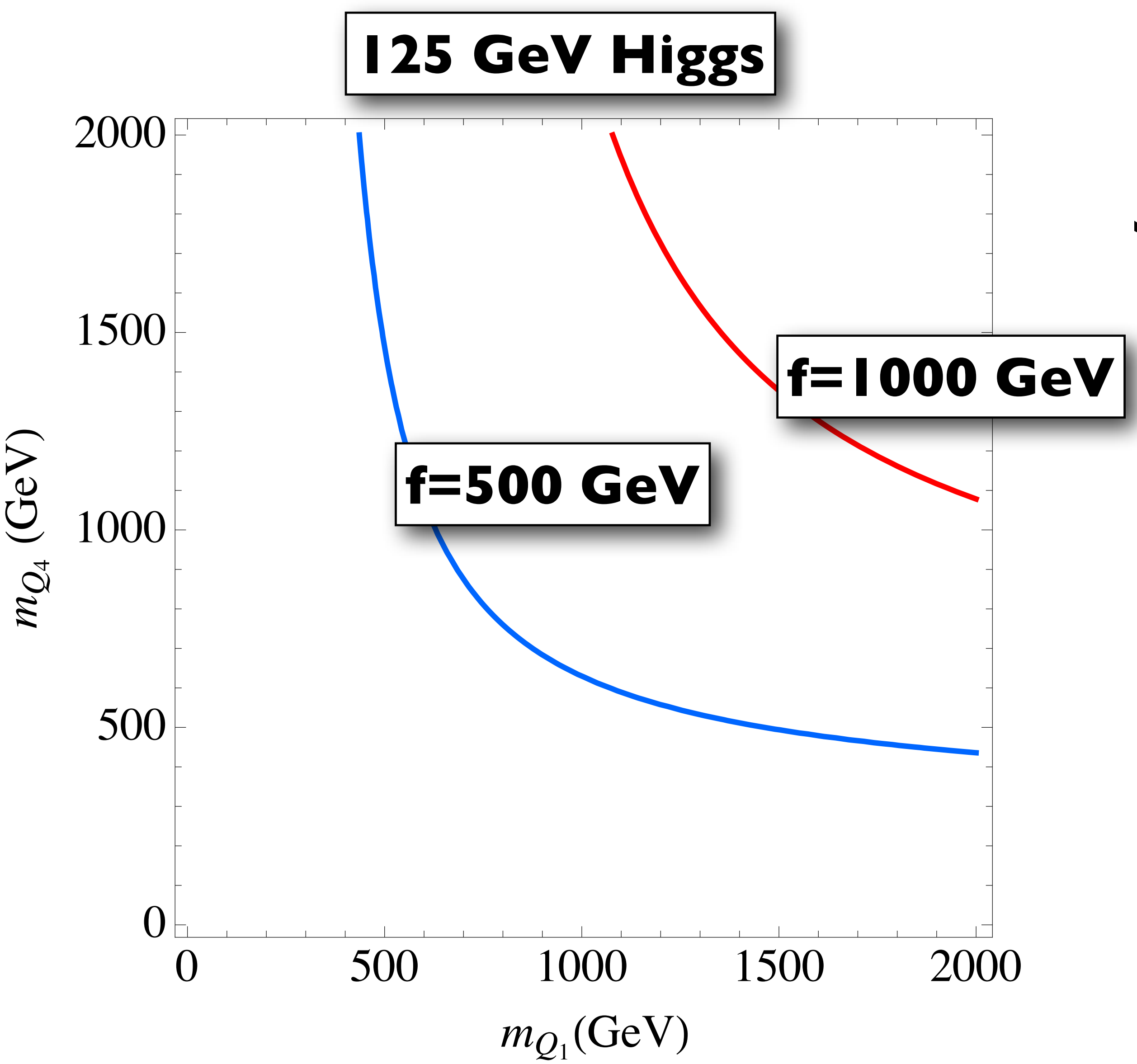


5 = 4 + 1

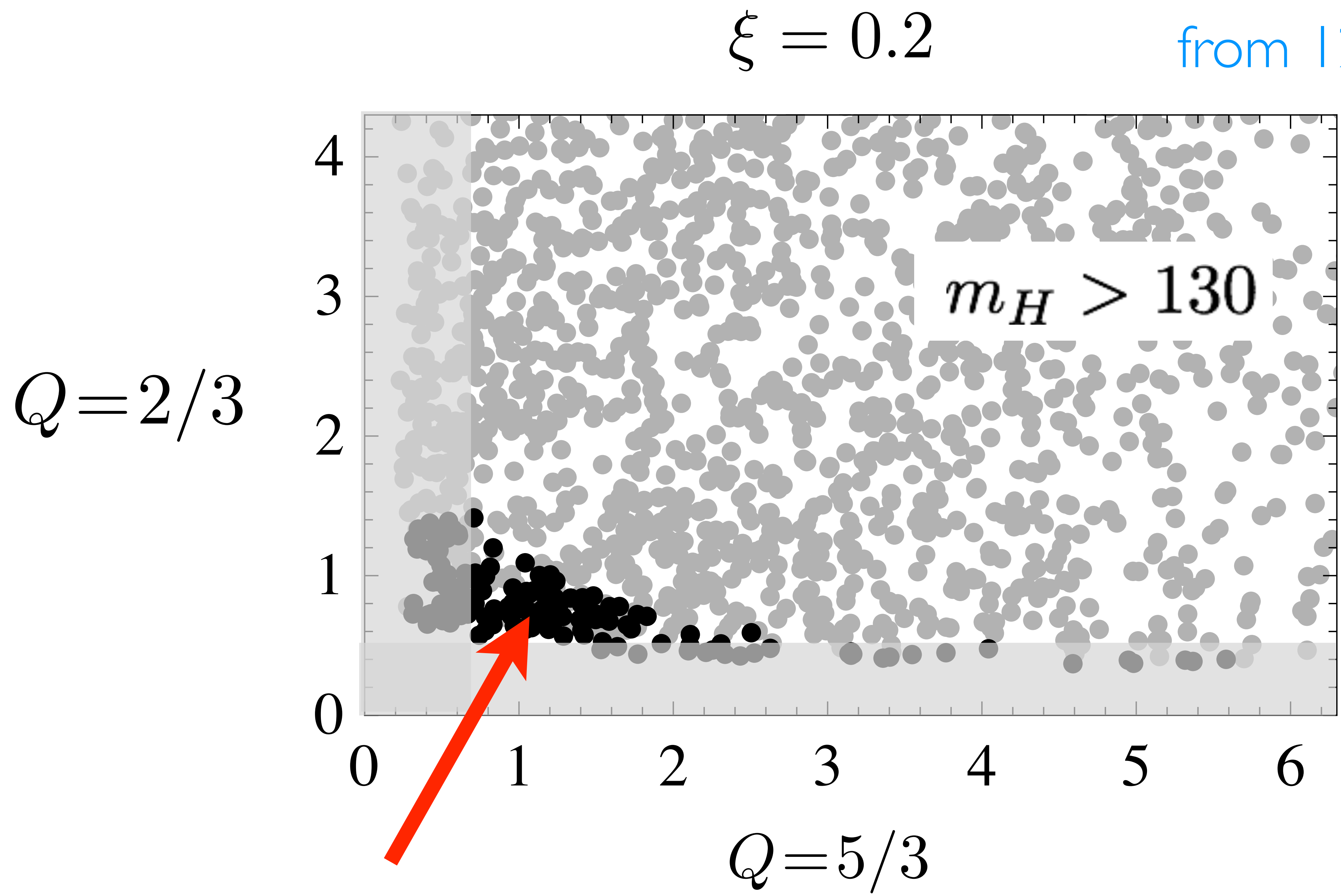
Q_4 Q_1

with EM charges 5/3, 2/3,-1/3

Contino et al; Pomarol, Riva; Matsedonskyi,Panico,Wulzer; Redi,Tesi; Marzocca,Serone,Shu;

Scan over composite Higgs parameter space

from 1204.6333

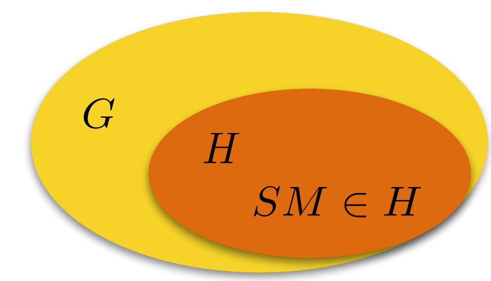


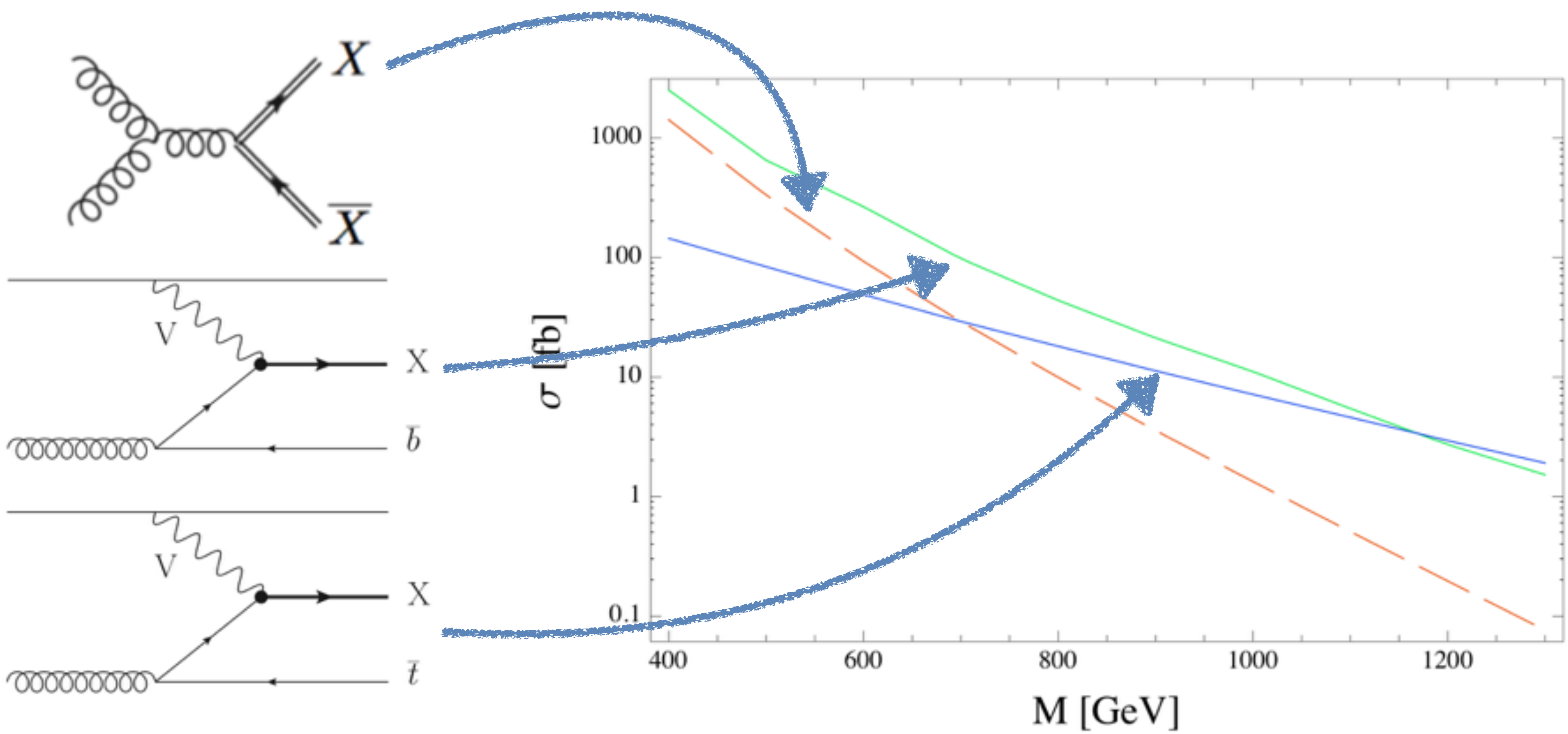
m_H = 115 … 130 GeV

see e.g. ATLAS-CONF-2013-051

Top partners

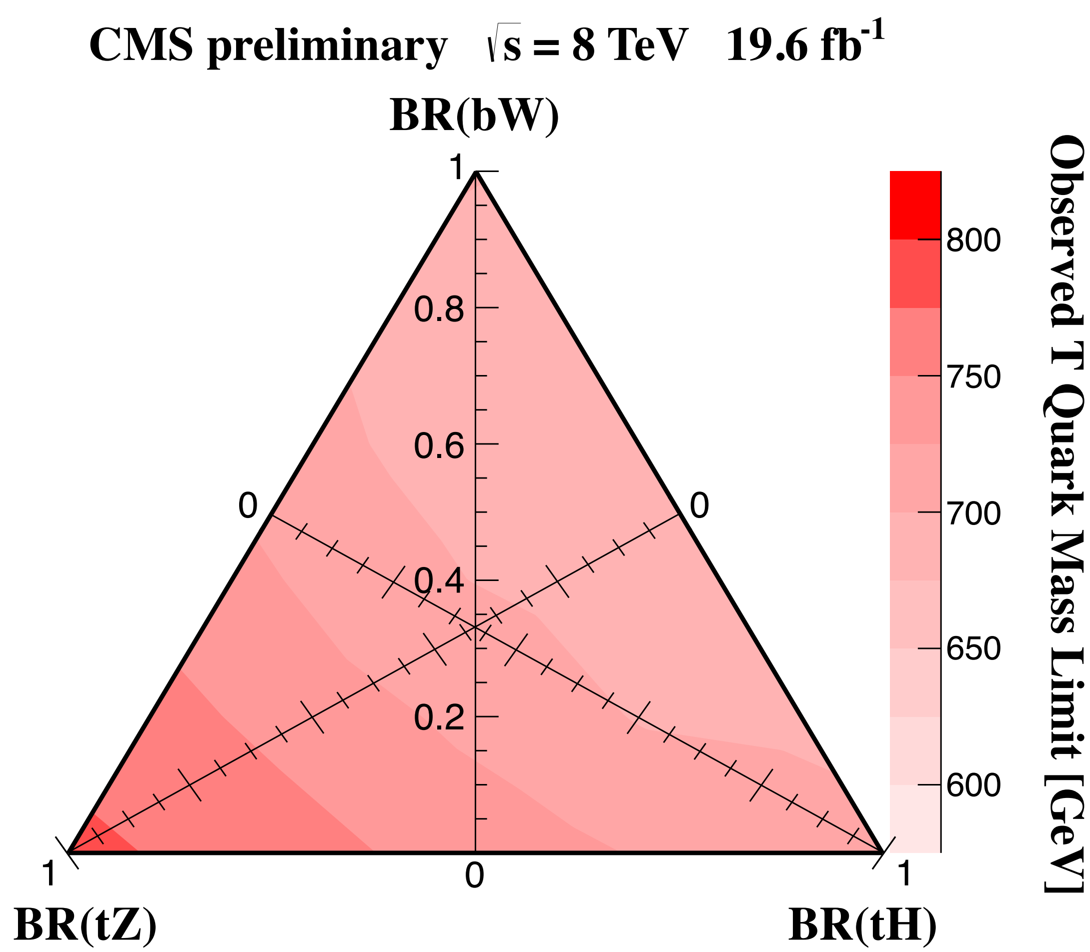
- expect new vector-like fermions at the TeV scale
- minimal case: top-like state and heavy charge 5/3 coloured state
- non-minimal cases: top-, bottom-like states, charge -4/3, 5/3, 8/3
- either pair production, or single production in association with a b or t

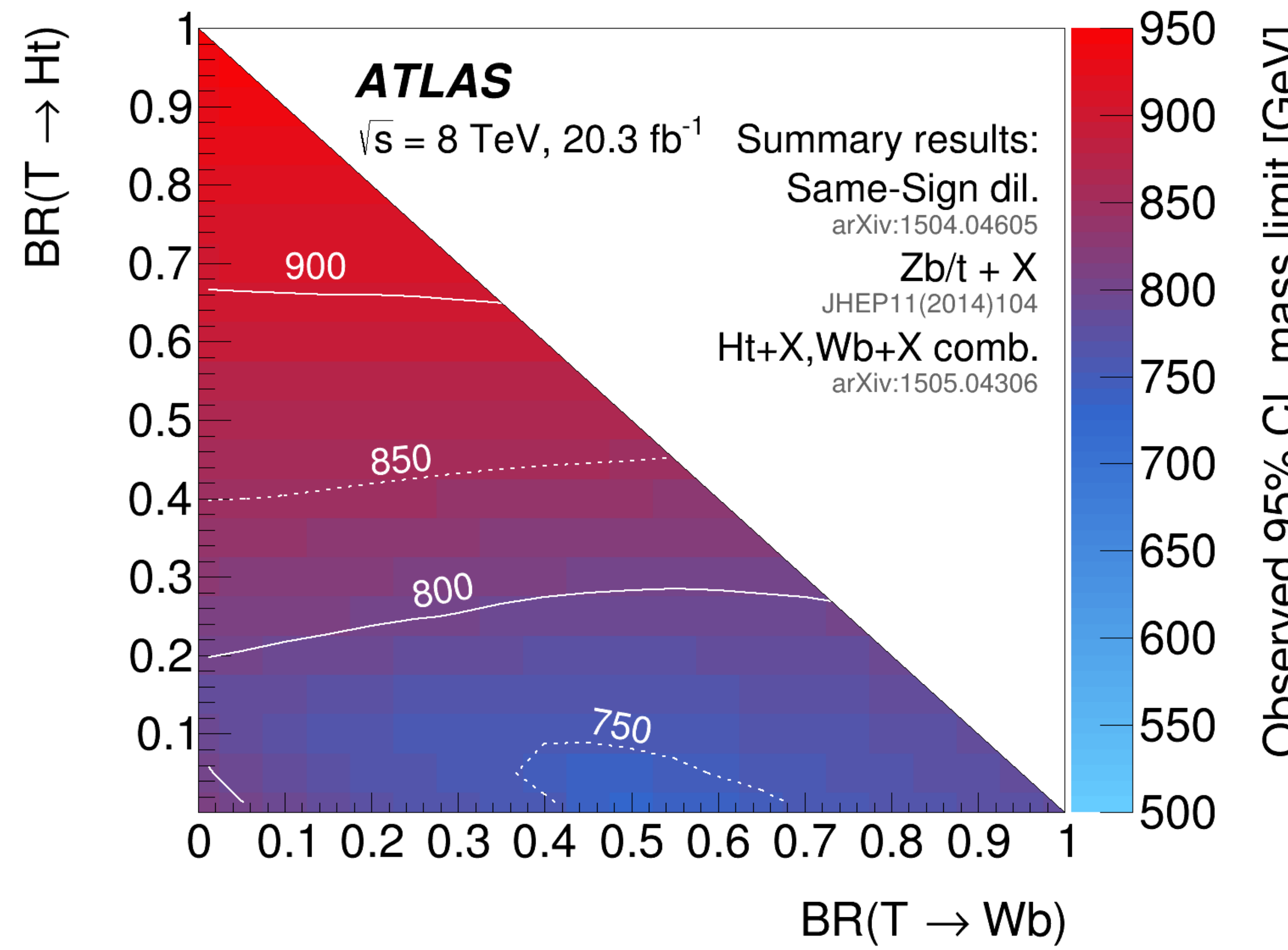




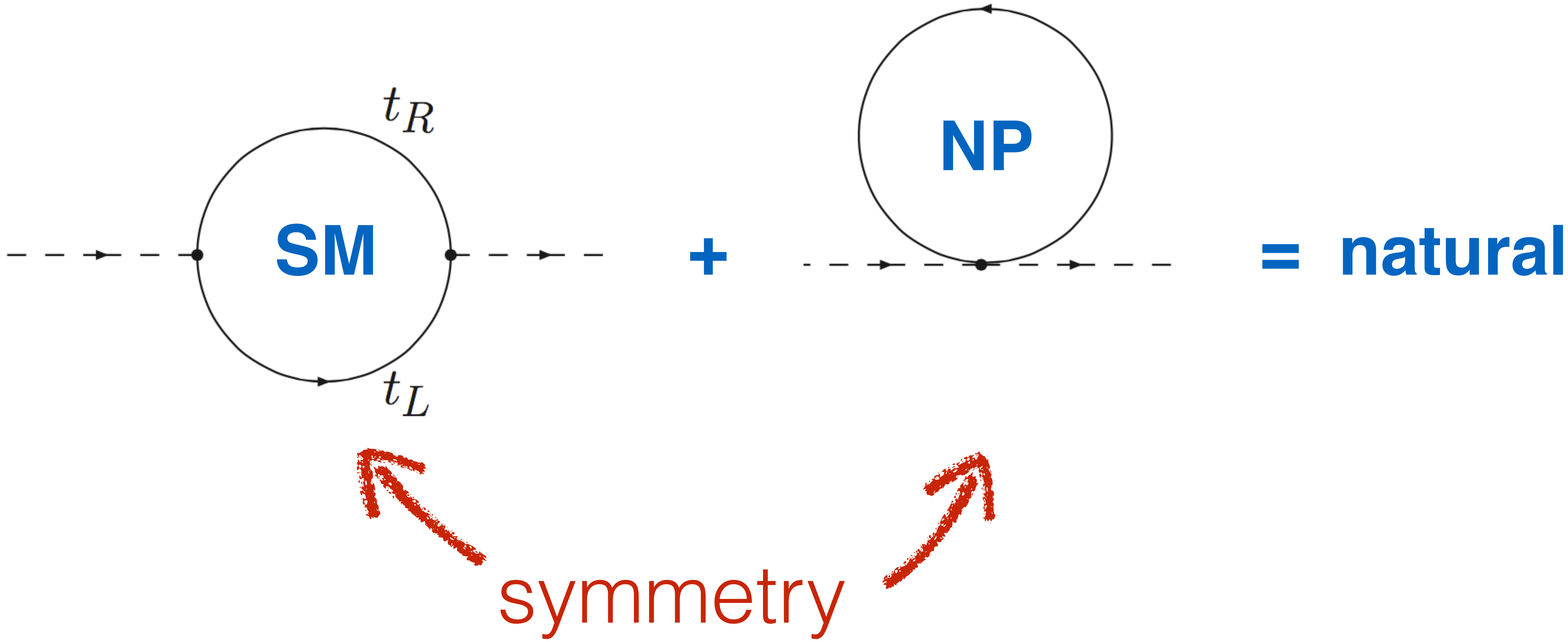
[De Simone, Matsedonskyi, Rattazzi, Wulzer 1211.5663]

LHC8 limits

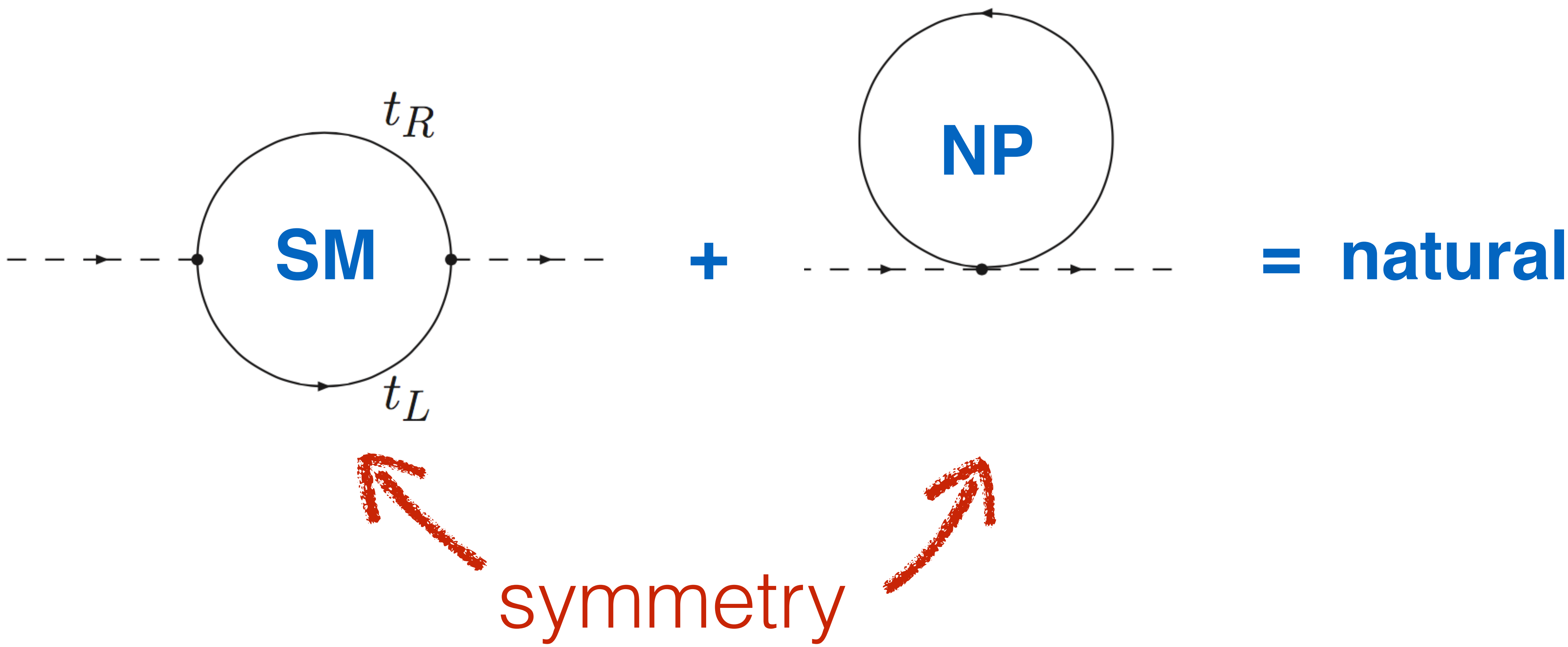

CMS preliminary √s = 8 TeV 19.6 fb-1
BR(bW)
BR(tZ)
BR(tH)
Observed T Quark Mass Limit [GeV]
800
750
700
650
600


ATLAS
√s = 8 TeV, 20.3 fb-1
Summary results:
Same-Sign dil.
arXiv:1504.04605
Zb/t + X
JHEP11(2014)104
Ht+X,Wb+X comb.
arXiv:1505.04306
900
850
800
750
BR(T → Ht)
BR(T → Wb)
Observed 95% CL mass limit [GeV]

No lose for naturalness?



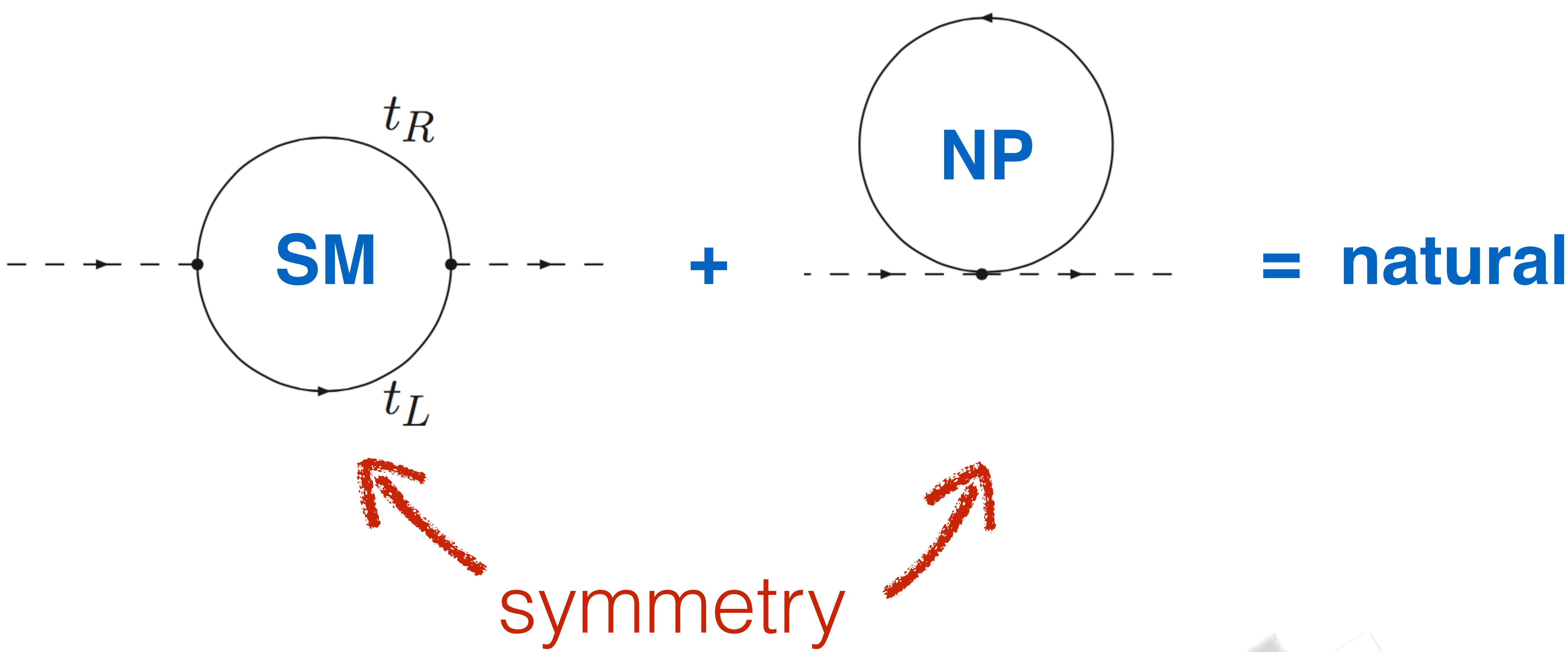
No lose for naturalness?



NP is related to the top by a symmetry, natural new particle mass around TeV

Symmetry commutes with color: will be produced copiously at the LHC!

No lose for naturalness?



NP is related to the top by a symmetry, natural new particle mass around TeV

Symmetry … s with color: … uced copious … he LHC!

Not true!

Twin Higgs

Chacko, Goh, Harnik '05

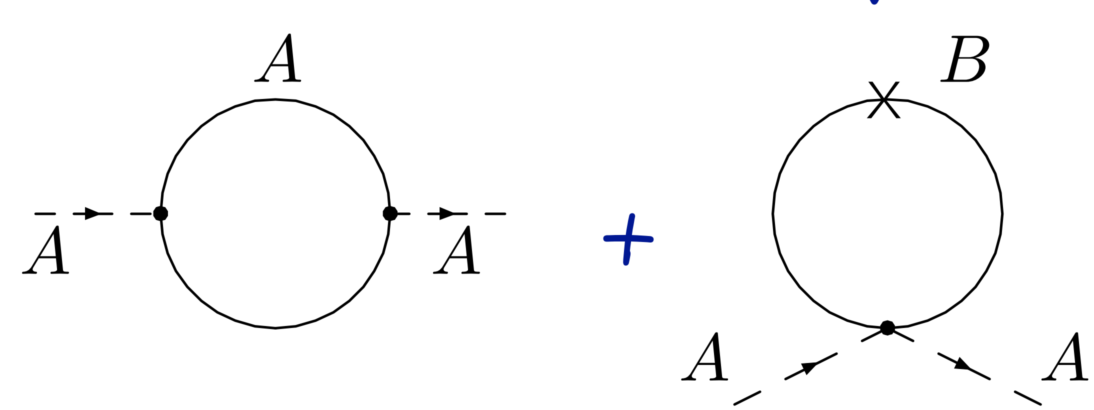
Standard Model $\overset{Z_2}{\longleftrightarrow}$ **Standard Model**

$SU(2)_L$ $\qquad\qquad$ $SU(2)_{\text{twin}}$

Higgs is a pseudoGoldstone boson of SU(4), top partner states are neutral under SM.

$$\mathcal{L} \supset y_t H_A \bar{t}_A t_A + y_t H_B \bar{t}_B t_B$$

$$= y_t h\, \bar{t}_A t_A + y_t \left(f - \frac{|h|^2}{2f} \right) \bar{t}_B t_B + \ldots$$



(Evil) Twin consequences

Higgs is protected by a symmetry.
All new particles below cut-off are SM singlets!

Craig,Knapen, Longhi ’14, Geller,Telem, ’14; Tesi et.al, ’15, Barbieri, et. al ’15

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What's the phenomenology?

* LHC finds Higgs and nothing else (check!)
* Higgs is pNGB: Higgs couplings $\propto \cos(v/f)$
* $\mathrm{Br}(h \to b_{\mathrm{twin}} b_{\mathrm{twin}}) = \mathrm{Br}(h \to \mathrm{inv.}) = \sin^2(v/f)$
* Can have displaced Higgs decays

Juknevich, Melnikov, Strassler;

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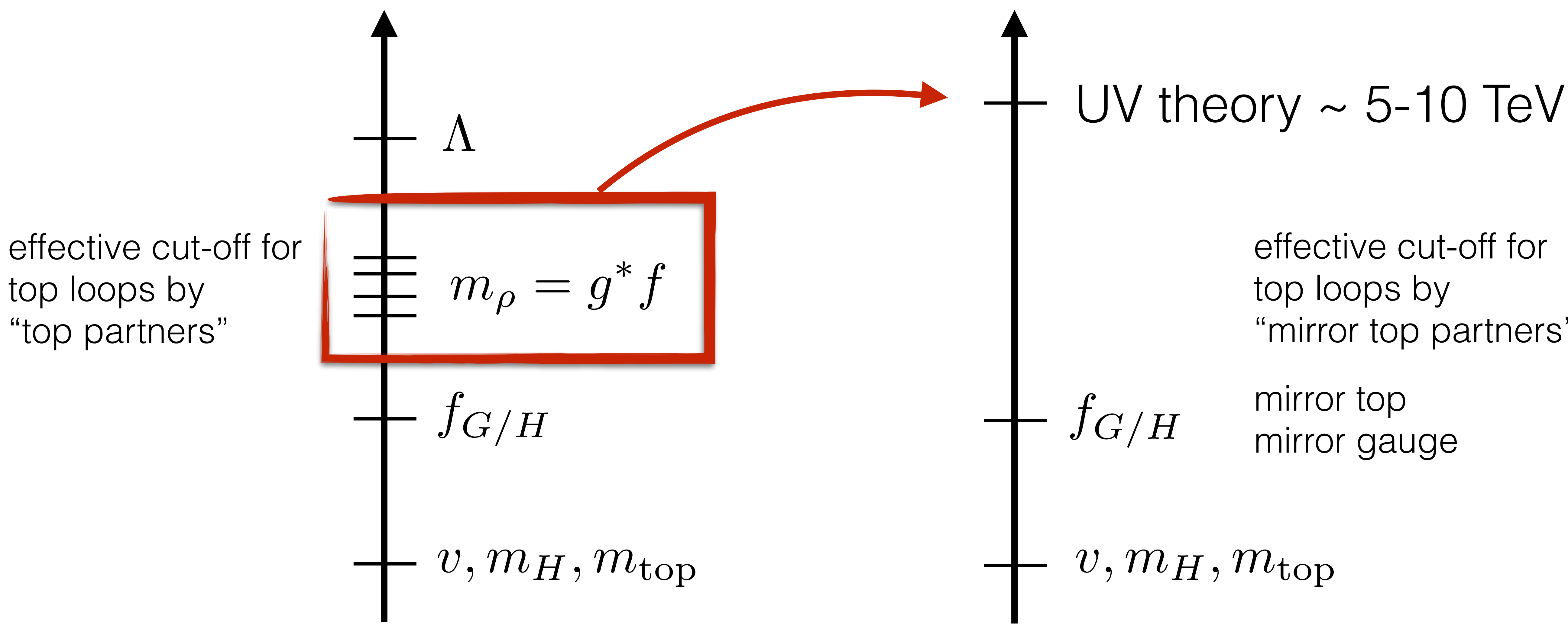
Juknevich, Melnikov, Strassler;

Craig, Katz, Strassler, Sundrum

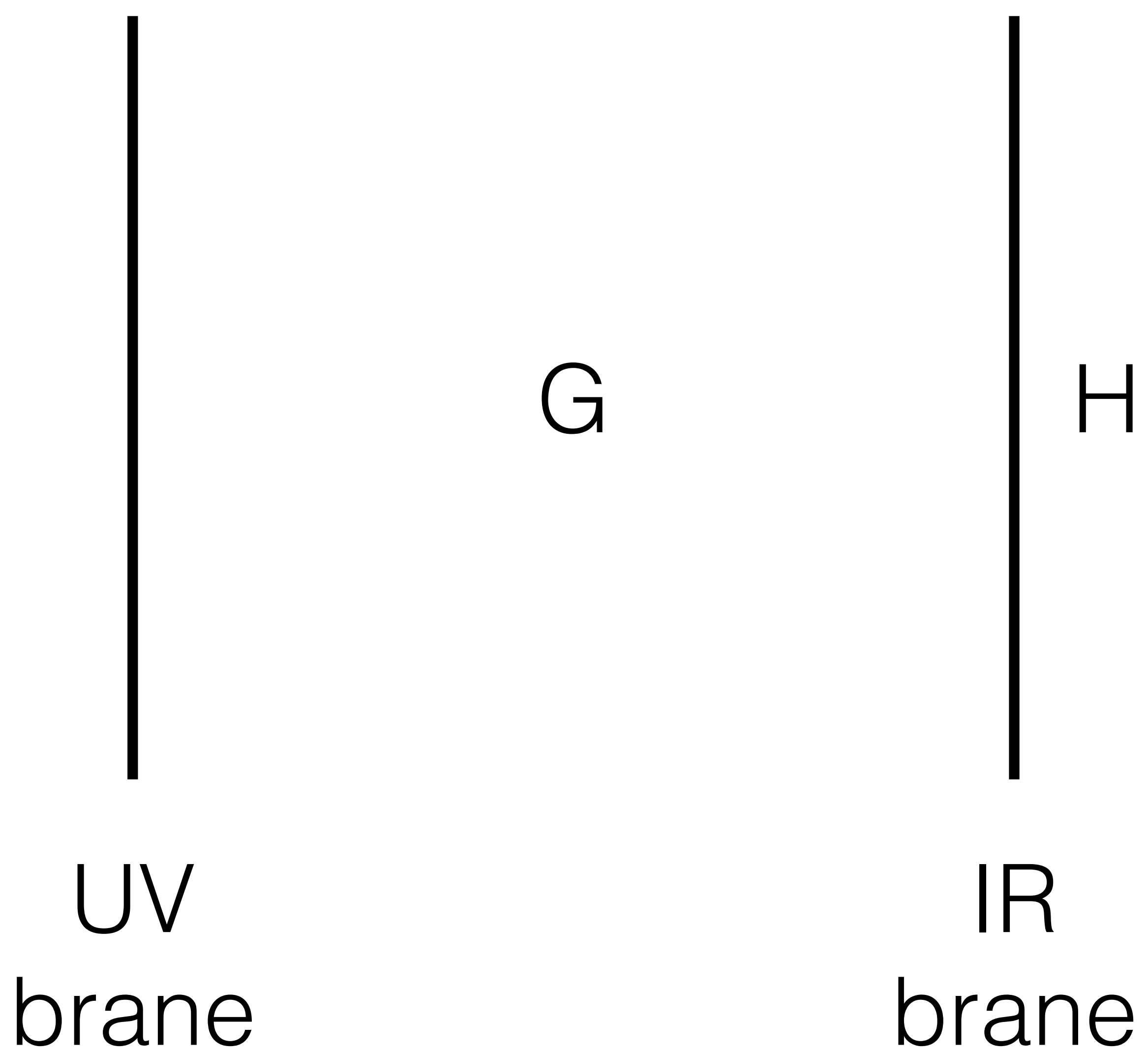
No meaningful constraints yet.
Naturalness potentially probed to ~20% level by end of LHC.

Twin Higgs and composite Higgs



UV completion

- Holographic dual, 5D theory in AdS



Higgs is fifth component of the G/H gauge field

$$A_5(z) = \sqrt{\frac{2}{R}}\frac{z}{R'}T^a_{G/h}h^a$$

Gauge higgs unification

- The Gauge-Higgs vev enters the fermion EOMs:

$$\Psi_q(z,v) = \Omega(z,v)\Psi_q(z) \qquad \Omega(\mathrm{z}) = e^{ig_5 \int A_5(z)}$$ - The Wilson line

- Coleman-Weinberg potential for Higgs potential

$$V(h) = \frac{N}{(4\pi)^2}\int dpp^3 \log\left(\rho[-p^2]\right)$$

Holographic twins

Geller, Telem; Csaki, Geller, Telem, AW

SM gauge
SM$^{\text{mirror}}$ gauge
Z_2

$$G : SO(8) \times U(1)_X \times U(1)_X^m \times Z_2$$

$$H : SO(7) \times U(1)_X \times U(1)_X^m \times Z_2$$

UV
brane

IR
brane

$$SO(8) \to SU(2)_L \times SU(2)_R \times SU(2)_L^m \times SU(2)_R^m$$

Top quark

	SO(8)	$SU(3)_c$	$U(1)_X$
Ψ_q	8	3	2/3
Ψ_t	1	3	2/3

$\xleftrightarrow{\text{bulk } Z_2\text{, 7 of SU(7)}}$

	SO(8)	$SU(3)_c^{\mathrm{m}}$	$U(1)_X^{\mathrm{m}}$
Ψ_q^m	8	3	2/3
Ψ_t^m	1	3	2/3

UV b.c. (+):

	$SU(2)_L$	$SU(3)_c$	$U(1)_Y$
Q_L	**2**	**3**	1/6
t_R	**1**	**3**	2/3

$\xleftrightarrow{UV\ Z_2}$

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t_R^m	**1**	**3**	2/3

IR b.c. (+):

	SO(7)	$SU(3)_c$	$U(1)_X$
Ψ_{qL}^7, Ψ_{qL}^1	7,1	3	2/3
Ψ_{tR}	1	3	2/3

IR masses: $m_t^1 \Psi_{qL}^1 \Psi_{tR}$

$\xleftrightarrow{IR\ Z_2\text{, 7 of SU(7)}}$

	SO(7)	$SU(3)_c^{\mathrm{m}}$	$U(1)_X^{\mathrm{m}}$
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IR masses: $m_t^1 \Psi_{qL}^{1m} \Psi_{tR}^m$

Higgs potential

$$V(h) \approx -\alpha_2 \sin^2(h/f) + \frac{\alpha}{2}\sin^4(h/f) - \alpha_2 \cos^2(h/f) + \frac{\alpha}{2}\cos^4(h/f) = \alpha \sin^2(h/f)\cos^2(h/f) + \mathrm{c}$$

top + gauge

mirror top + gauge

$$\alpha_2 \sim \frac{3}{32\pi^2} y_t^2 f^2 m_{KK}^2$$

$$\alpha \sim \frac{3}{64\pi^2} y_t^4 f^4 \log\frac{2M_{KK}^2}{y_t^2 f^2}$$

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Higgs potential

Csaki, Geller, Telem, AW

Naturalness without Top-partners

* KK tops do not enter tuning
* Tuning scales as f^2/v^2, Higgs data
* M_{KK} can be as high as $4\pi f$

Need Z_2 breaking

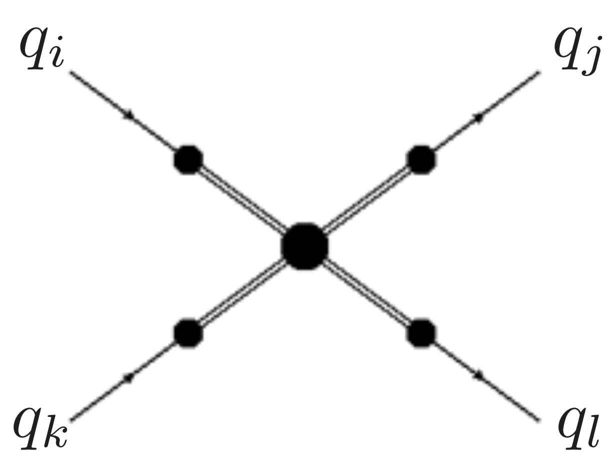
* Higgs potential $-\beta \sin^2(h/v)$
* $U(1)_X$ and mirror $U(1)_X$ mismatch

$$\beta \approx \frac{3}{128\pi^2}(g'^2 - g_m'^2) g_*^2 f^4$$

Flavour twist

Csaki, Geller, Telem, AW, in prep.

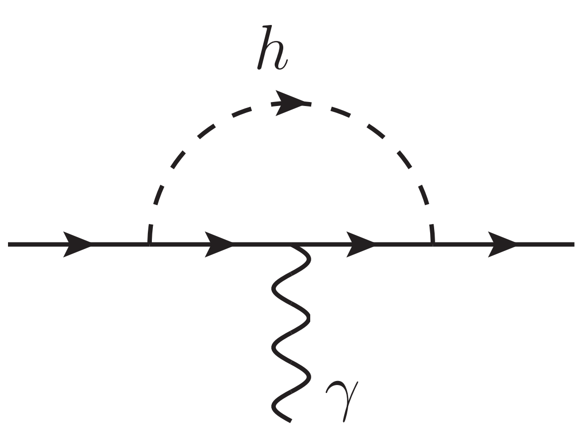
RS-GIM suppresses flavor violation



Flavor constraint ϵ_K

$$C_K^4 \sim \frac{1}{M_{KK}^2} \frac{g_{s*}^2}{g_*^2} \frac{8 m_d m_s}{v^2} \frac{1+\tilde{m}_d^2}{\tilde{m}_d^2} \qquad g_*^2 f \tilde{m}_d > 106 \text{ TeV}$$

EDM of neutron



$$\frac{c}{16\pi^2 f^2} m_d \bar{d}_L \sigma^{\mu\nu} e F_{\mu\nu} d_R$$

$$c \sim \frac{1}{g_*^2 m_d} \frac{v}{\sqrt{2}} \left[f_Q (Y_d Y_d^\dagger + Y_u Y_u^\dagger) Y_d f_{-d} \right] \sim \frac{1}{g_*^2} (Y^2) = \frac{\tilde{m}_d^2}{2}$$

$$\frac{2f}{\tilde{m}_d} > 7.29 \text{ TeV}$$

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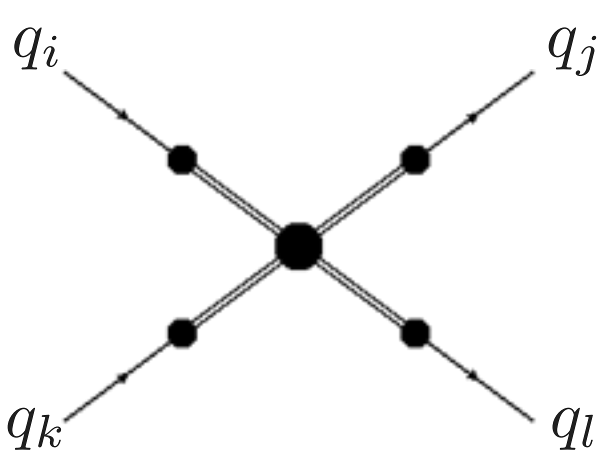

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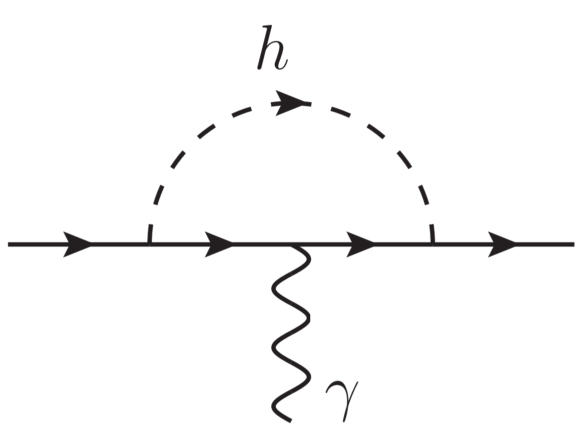

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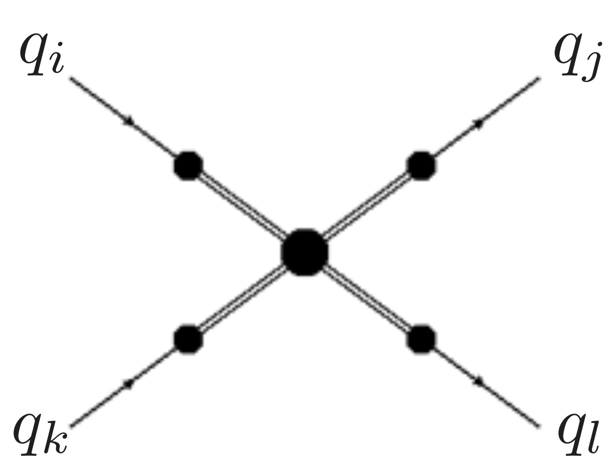

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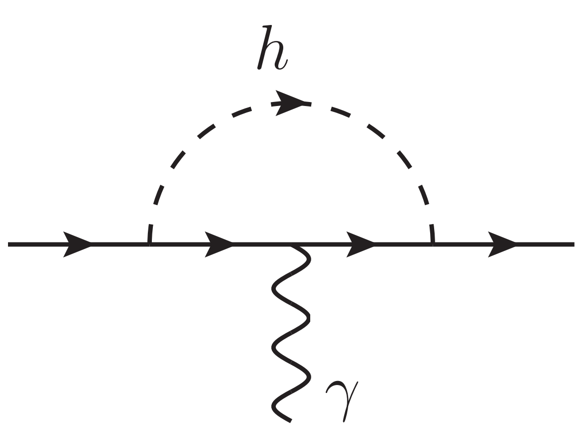

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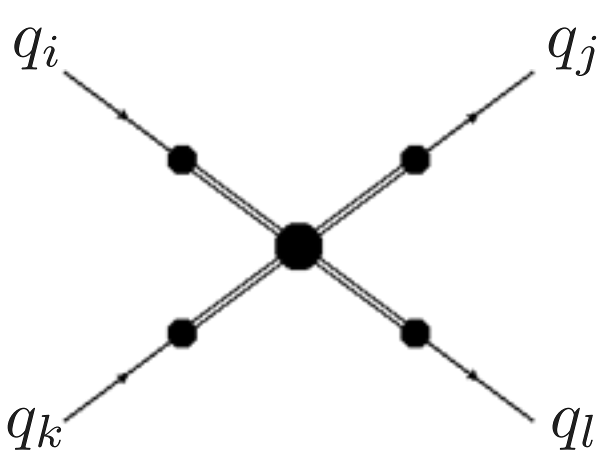

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$g_* f > 19.6 \text{ TeV}$

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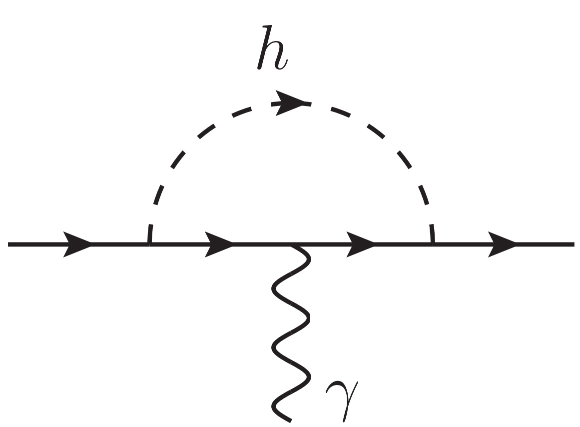

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$\frac{2f}{\tilde{m}_d} > 7.29 \text{ TeV}$

Flavour twist

Csaki, Geller, Telem, AW, in prep.

The two most stringent bounds combined

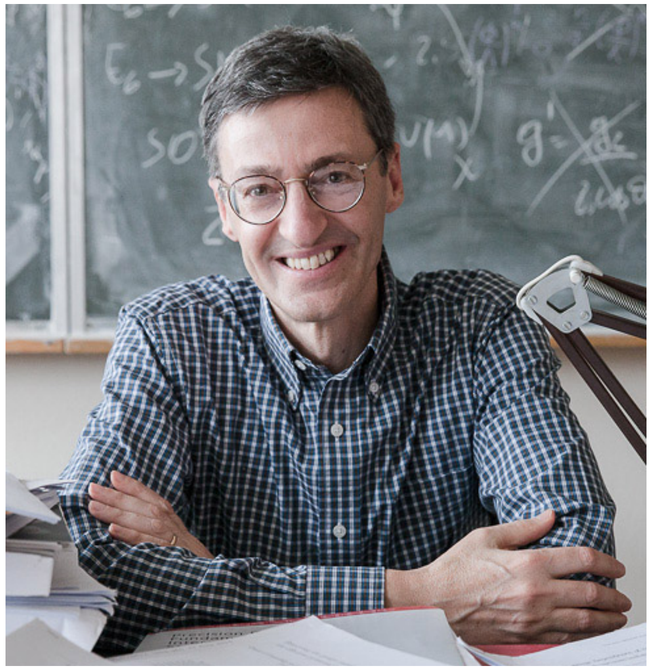
$$\boxed{g_* f > 19.6 \text{ TeV}}$$

We can live with large coupling without paying the price of tuning (twin protection)

At the limit of perturbative control

$$g_* \approx 4\pi \to f > 1.5\,\text{TeV}$$

which allows anarchic flavour with O(%) tuning.



G. Giudice

"Is neutral naturalness the beautiful reason we haven't seen anything, or the last desperate hope of theorists?"

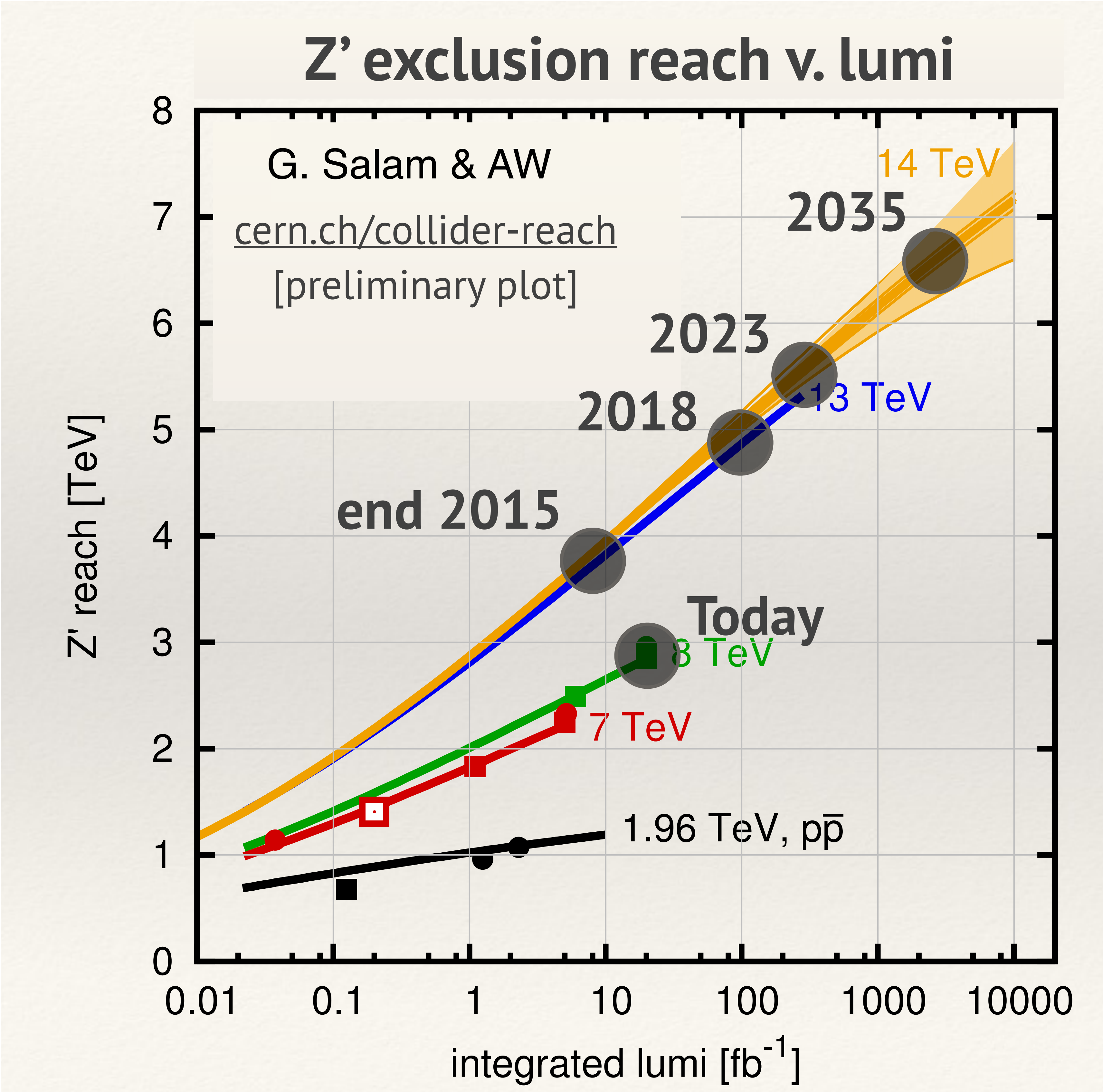
Run 2 projections

$$\frac{N_{\text{signal-events}}(M^2_{\text{high}}, 14\,\text{TeV}, \text{Lumi})}{N_{\text{signal-events}}(M^2_{\text{low}},\ 8\,\text{TeV},\ 19\text{fb}^{-1})} = 1$$

Coupling constants & other prefactors mostly cancel in the ratio.

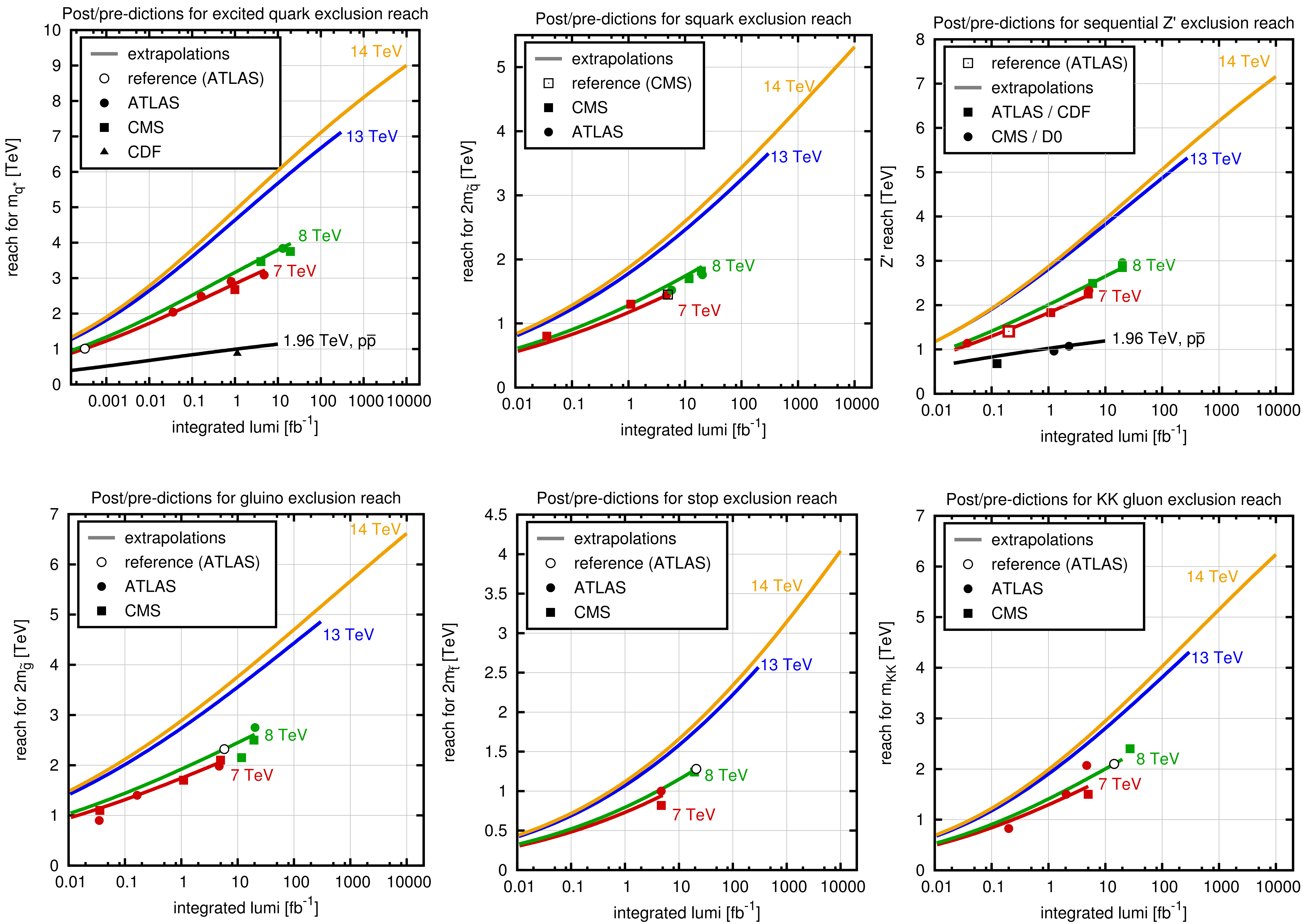
Dependence on *M* and on √s mostly comes about through parton distribution functions (PDFs) & simple dimensions.

G. Salam, AW cern.ch/collider-reach



By the end of the year, most searches will beat 8 TeV results

[Some, e.g. excited quarks, will surpass 8 TeV with just 0.2 fb^{-1}]



Salam, AW cern.ch/collider-reach

Conclusions

- Run1 left the most motivated natural models in a somewhat bruised state
- Run2 will be a big jump in sensitivity
- Direct searches will take over in the exploration of compositeness
- Twin models still natural, hard to find, can explain flavour

Fin