BSM Theory: The SM and Beyond

Patrick “PaDDy” Fox

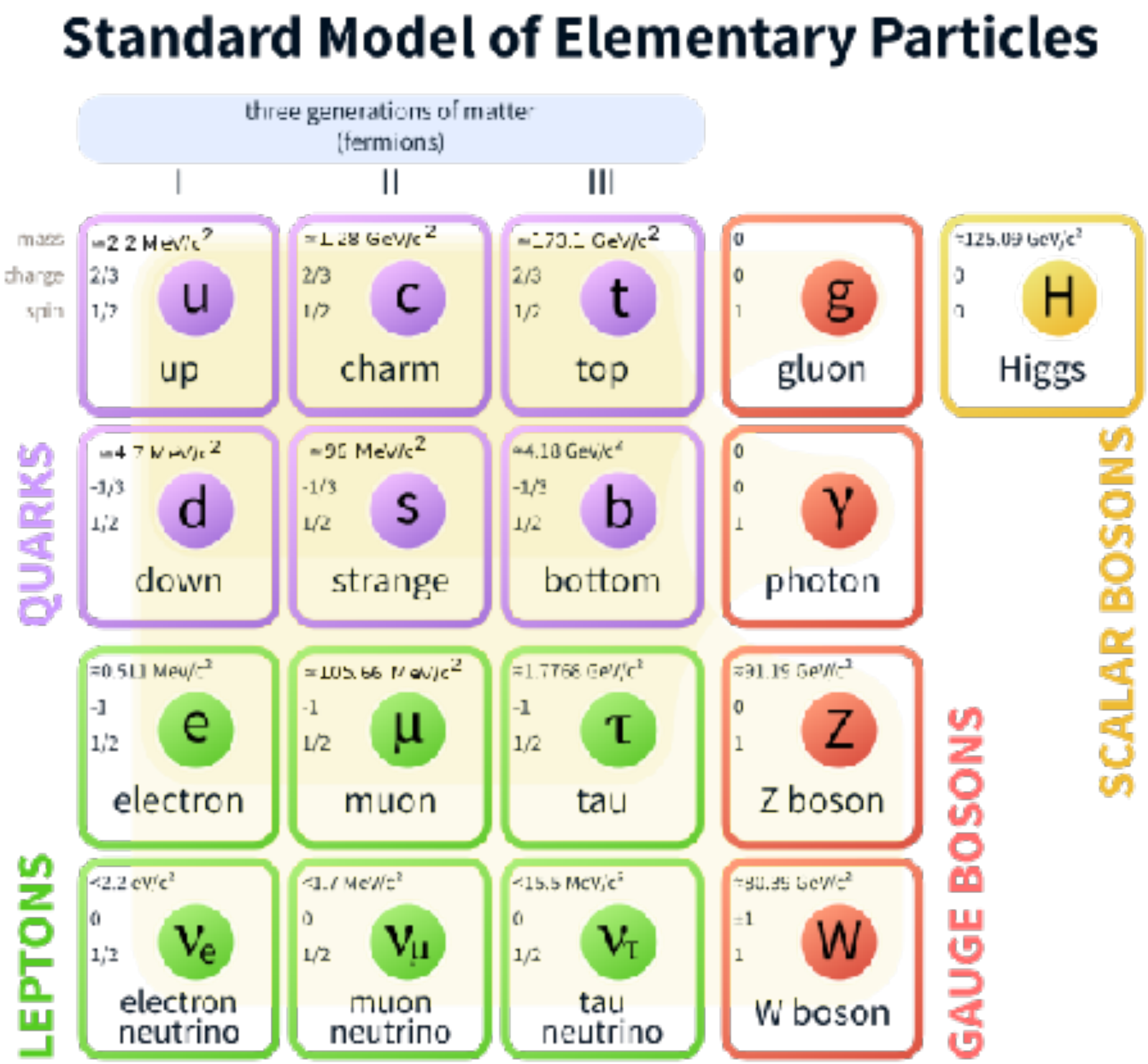
Fermilab

Topics to (try to) cover

- Review of the SM its “Bugs and Features”
- Case study in BSM: SUSY
- General BSM
- Dark Matter at Colliders and in the Cosmos
- Model Building in the LHC era
- Conclusions

“In theory there is no difference between theory and practice. But in practice there is.--Yogi Berra”

The Standard Model



	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
Q	3	2	1/6
u^c	$\bar{3}$	1	$-2/3$
D^c	$\bar{3}$	1	$+1/3$
L	1	2	$-1/2$
E^c	1	1	$+1$
H	1	2	1/2

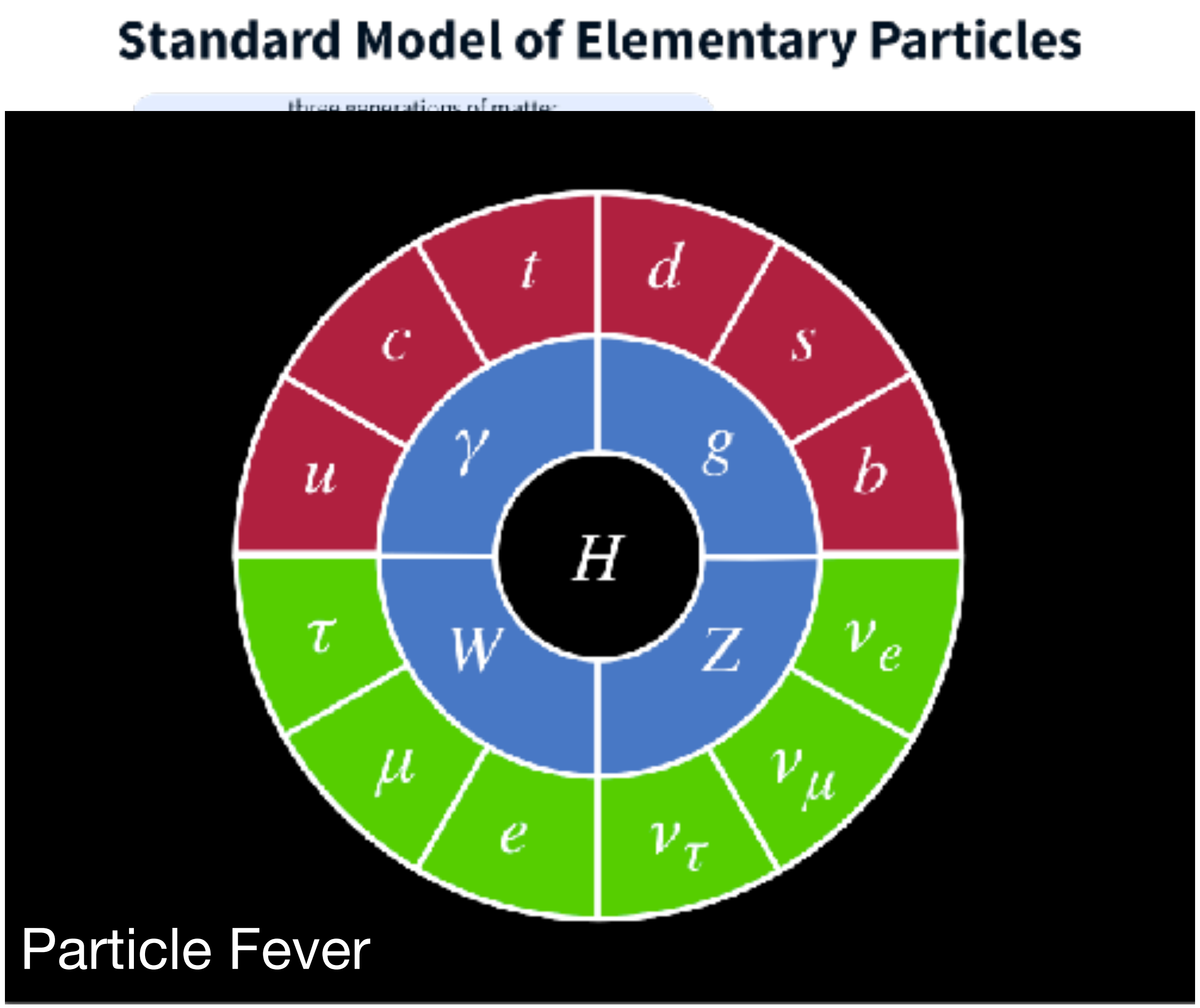
$Q \sim P_L \psi_0$

$u^c \sim (P_R \psi_0)^c$

+ Gauge principle

$$D_\mu = \partial_\mu + i g_s T^a A^a_\mu + i g_2 \frac{\sigma^j}{2} W^j_\mu + i g_1 Y B_\mu$$

The Standard Model



	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
Q	3	2	$1/6$
U^c	$\bar{3}$	1	$-2/3$
D^c	$\bar{3}$	1	$+1/3$
L	1	2	$-1/2$
E^c	1	1	$+1$
H	1	2	$1/2$

$Q \sim P_L \psi_0$

$U^c \sim (P_R \psi_0)^c$

+ Gauge principle

$$D_\mu = \partial_\mu + i g_s T^a A^a_\mu + i g_2 \frac{\sigma^j}{2} W^j_\mu + i g_1 Y B_\mu$$

The Standard Model

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_1 + \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \ldots$$

$\mathcal{L}_0 = \Lambda^4$ The cosmological constant...hard to measure @LHC

$\mathcal{L}_1 = \mu^3 \Phi$ Need a gauge singlet scalar, none in SM.

$\mathcal{L}_2 = \pm\mu^2 |H|^2$ Mass term of SM Higgs

$\mathcal{L}_3 = \mu\, \xi\eta$ Fermion mass term. Sterile neutrinos?

$$\mathcal{L}_4 = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{Q} \not{D} Q + |D_\mu H|^2 - \lambda |H|^4 + y H Q U^c + \ldots$$

Gauge kinetic terms, fermion kinetic terms, Higgs self-coupling, Yukawa couplings

The Standard Model

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_1 + \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \ldots$$

Come back to these later

$$\mathcal{L}_0 = \Lambda^4$$

The cosmological constant...hard to measure @LHC

$$\mathcal{L}_1 = \mu^3 \Phi$$

Need a gauge singlet scalar, none in SM.

$$\mathcal{L}_2 = \pm\mu^2 |H|^2$$

Mass term of SM Higgs

$$\mathcal{L}_3 = \mu\,\xi\eta$$

Fermion mass term. Sterile neutrinos?

$$\mathcal{L}_4 = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{Q} \not{D} Q + |D_\mu H|^2 - \lambda |H|^4 + y H Q U^c + \ldots$$

Gauge kinetic terms, fermion kinetic terms, Higgs self-coupling, Yukawa couplings

The Standard Model

The SM contains 18 **physical** parameters, the Lagrangian contains many more e.g.

$$Y_u^{ij} Q_i U_j^c H + Y_d^{ij} Q_i D_j^c \widetilde{H}$$

$$Y_{u,d} : 3 \times 3\, \mathbb{C} \text{ matrix} \Rightarrow 2 \times 18 \text{ params}$$

The quark kinetic terms ($\bar{Q} \not{D} Q$ etc.) have $U(3)^3$ broken to $U(1)_B$

Can make 26 field redefinitions to alter parameters

$$27 \text{ gens.} \not\to 1 \text{ gens}$$

$$36 - 26 = 10$$

6 quark masses, 3 angles and 1 phase of CKM

The Standard Model

What are the 18 **physical** parameters?
How do we explain them?

$$g_1, g_2, g_3 \quad (\alpha, \sin\theta_W, \alpha_S)$$ **3**

$$\langle H \rangle \equiv v, \lambda_h$$ **2**

$$m_{e,\mu,\tau}$$ **3** $= 18$

$$m_{u,d,c,s,b,t}$$ **6**

$$V_{CKM} \quad \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$ **4**

$$\theta_{QCD}, m_{\nu_e,\nu_\mu,\nu_\tau}, V_{PMNS}$$ **1+3+4**

(Depends on neutrino mass model)

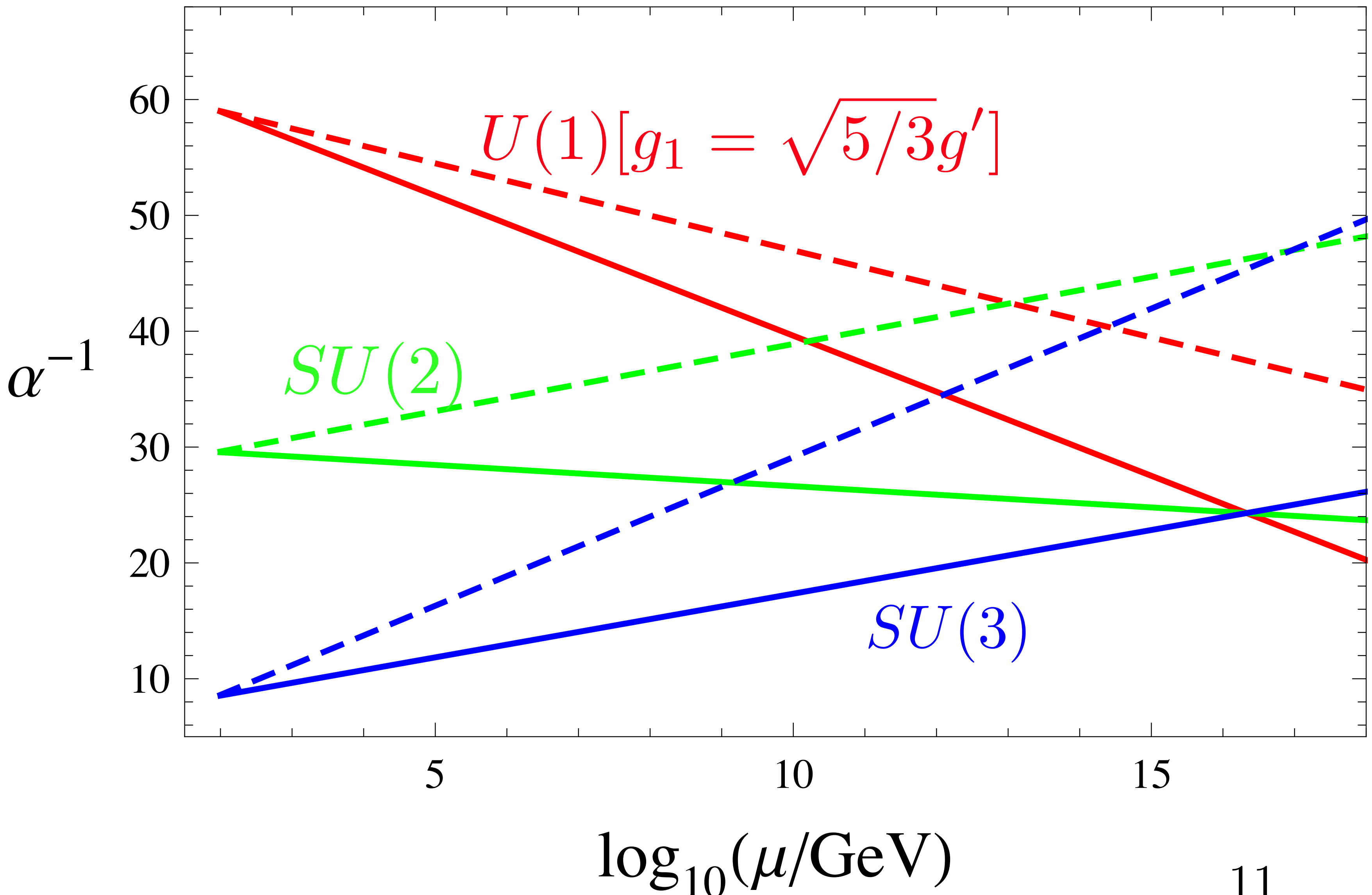
Bugs and Features

<u>Gauge coupling unification</u>

1 generation of SM matter fits into $\bar{\mathbf{5}}, \mathbf{10}$ of SU(5)

SM + N fits into $\mathbf{16}$ of SO(10)

$$\frac{d}{dt}\alpha_i^{-1} = -\frac{b_i}{2\pi}$$



SM

$b_i = (-41/10, 19/6, 7)$

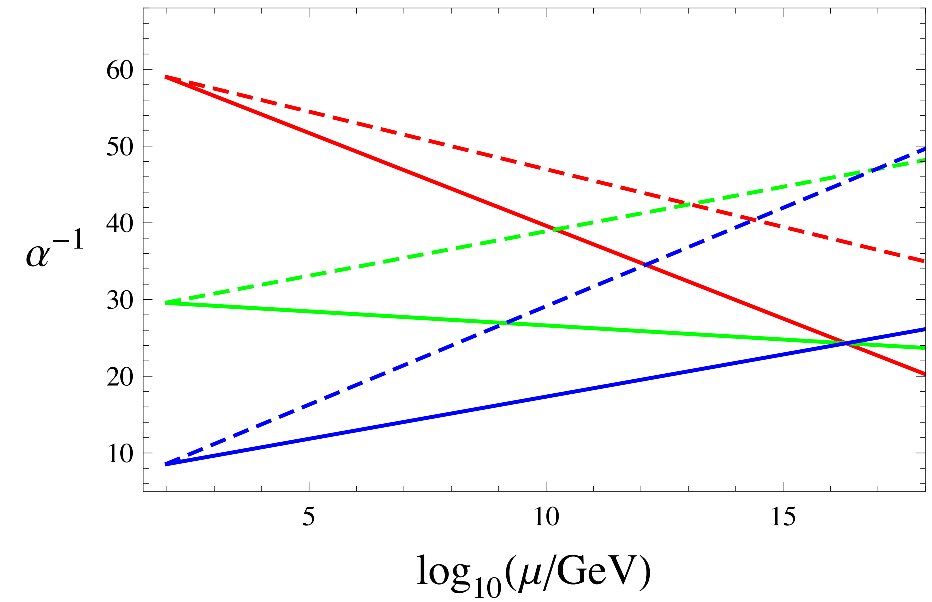
MSSM

$(b_1, b_2, b_3) = (-33/5, -1, 3)$

$$b = \frac{11}{3}N - \frac{2}{3}\sum_{fermions} C(r_f) - \frac{1}{3}\sum_{bosons} C(r_b)$$

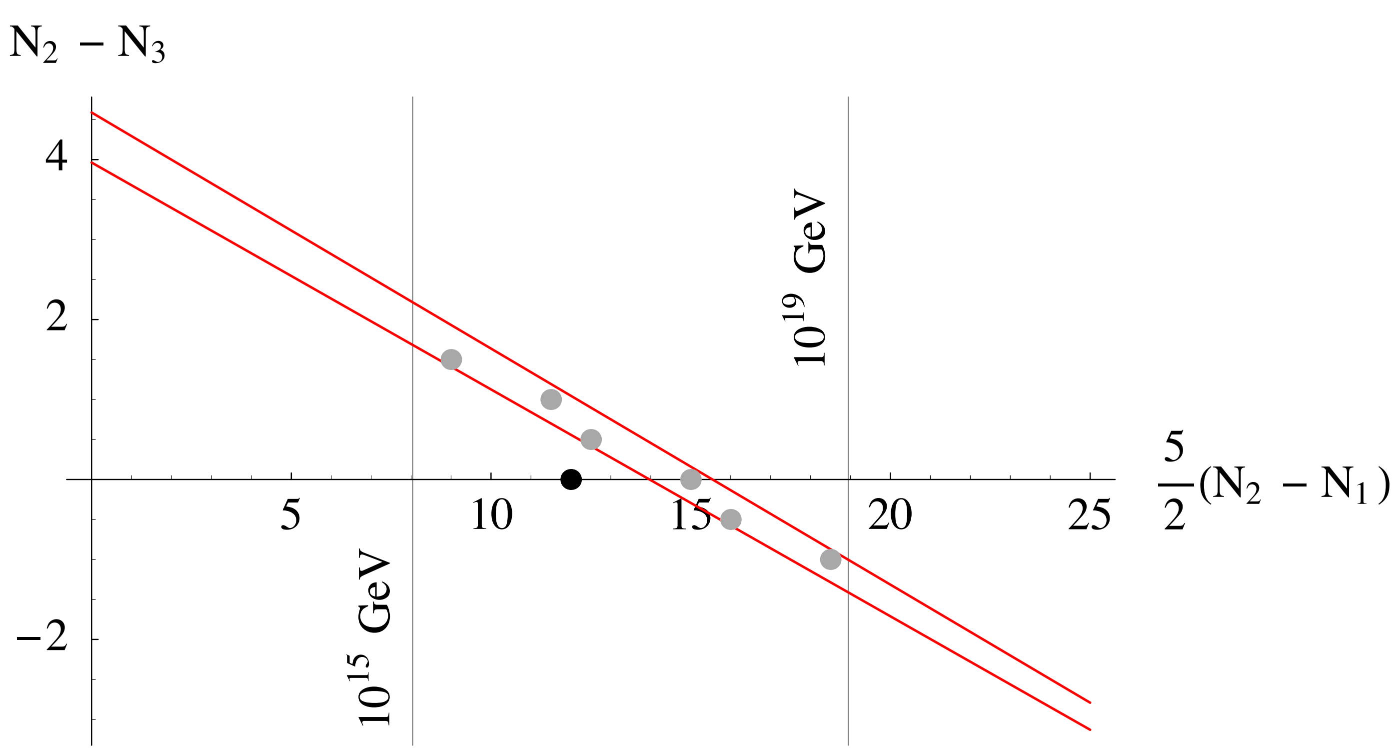
Bugs and Features

<u>Gauge coupling unification</u>



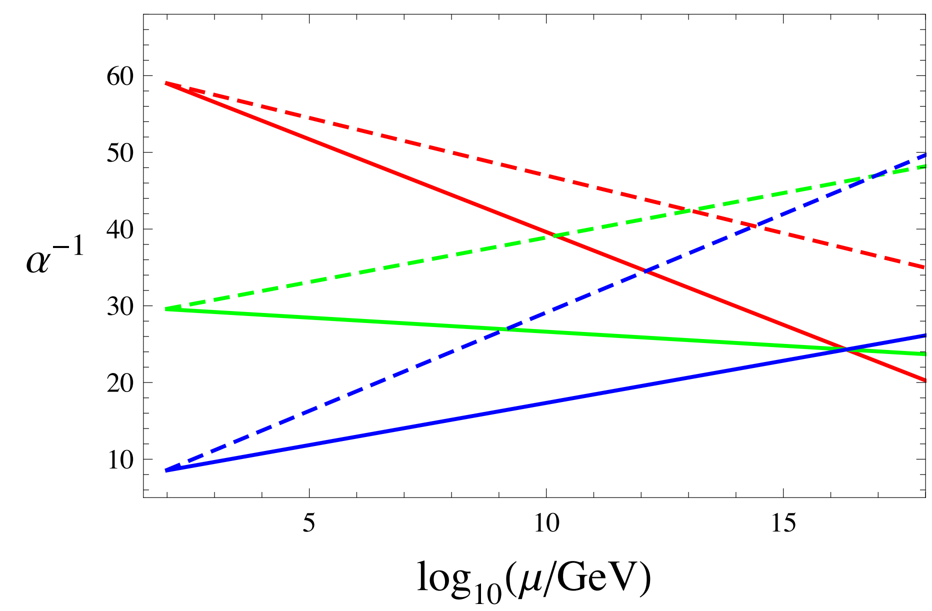
Hint for what new physics?

Many possible combinations of weak scale states give good unification e.g. MSSM, NMSSM, 6 Higgs doublets,



[Giudice, Romanino, ph/0406088]

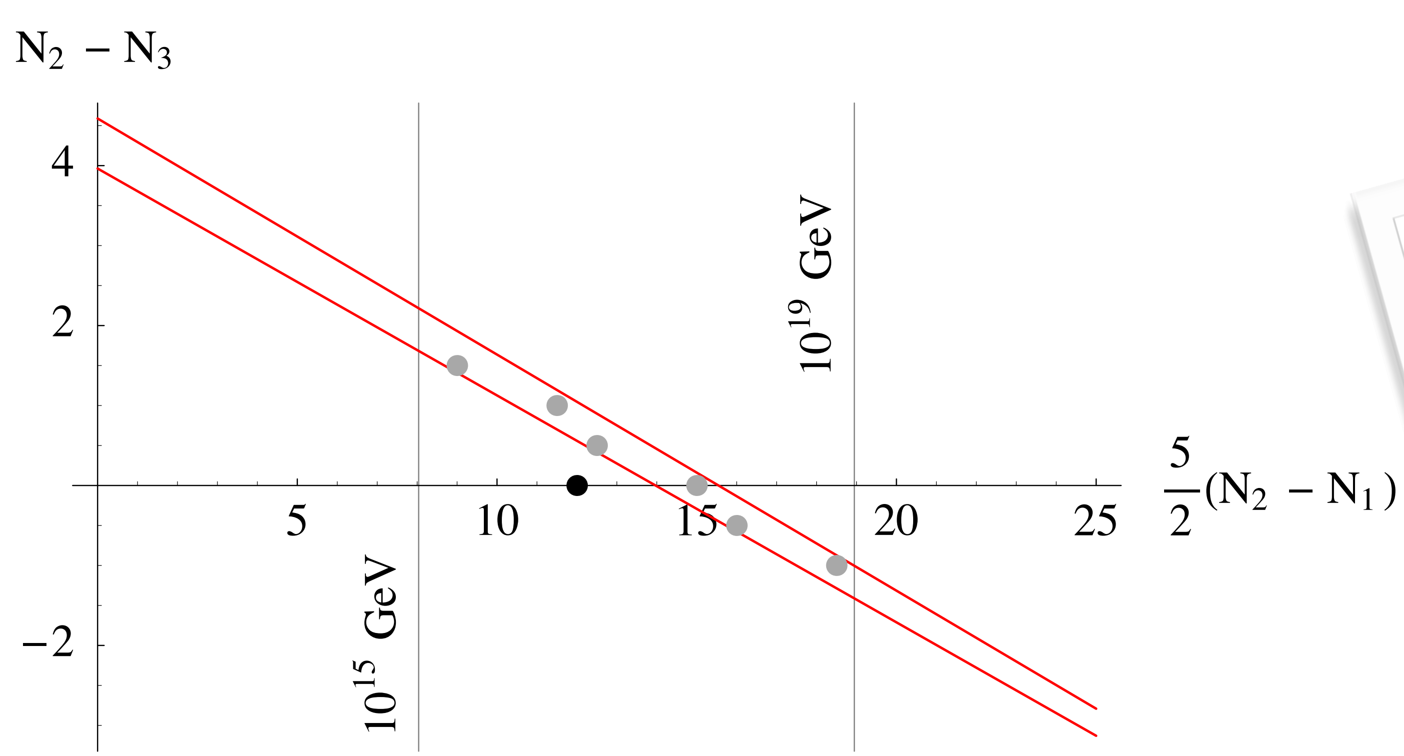
Bugs and Features



<u>Gauge coupling unification</u>

Hint for what new physics?

Many possible combinations of weak scale states give good unification e.g. MSSM, NMSSM, 6 Higgs doublets,



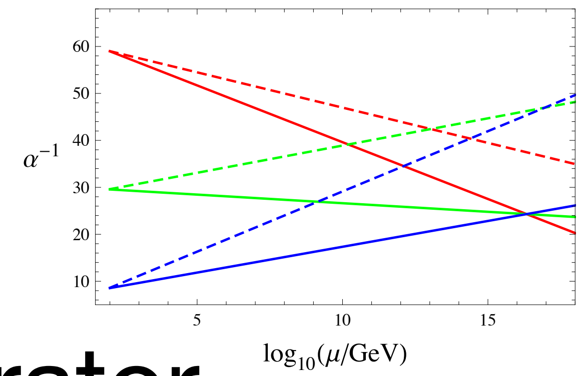
[Giudice, Romanino, ph/0406088]

Predictions?

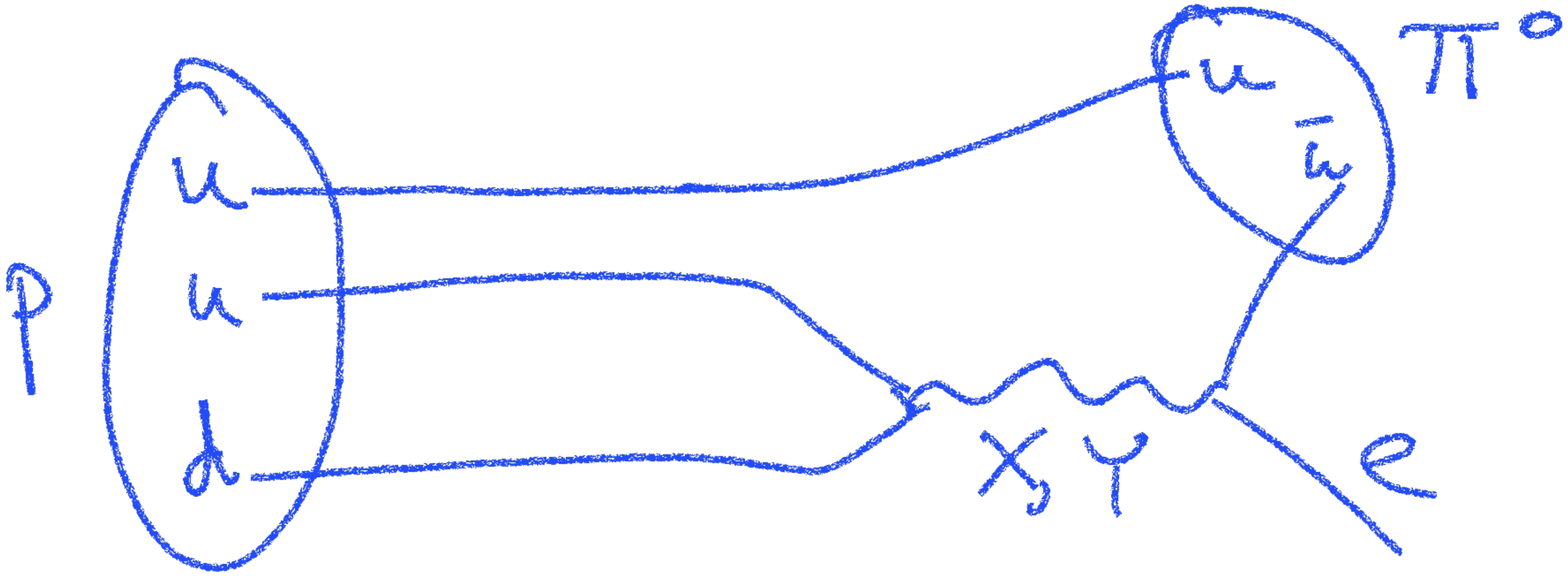
New states at weak scale with SM charge

New states at GUT scale —proton decay!

Gauge coupling unification



X,Y lead to proton decay, generate dim-6 operator



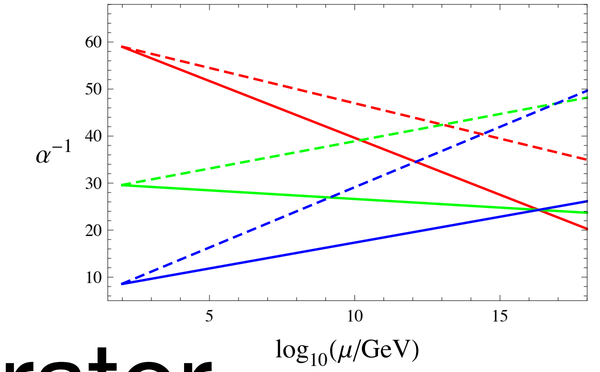
$$\frac{g_X^2}{M_X^2}\left(\bar{u}\gamma_\mu d\right)\left(\bar{e}\gamma^\mu u\right)$$

$$\Gamma \sim \left(\frac{g_X}{M_X^2}\right)^2 m_p^5 \times \text{NP}$$

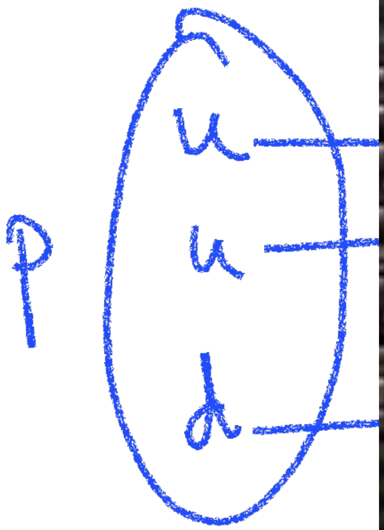
$$\tau \sim 10^{32(24)}\text{yr}$$

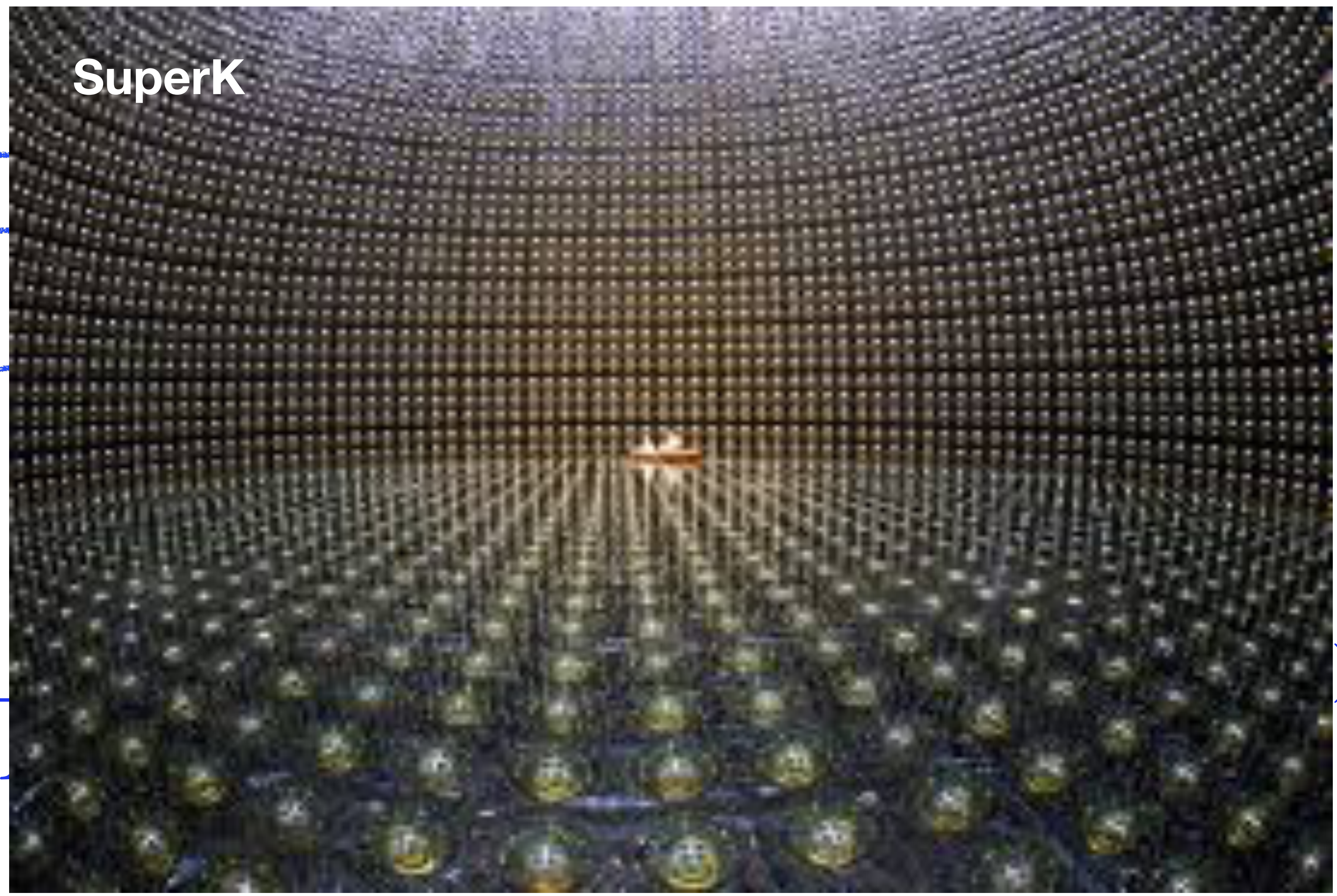
Use Avogadro's number to our advantage

Gauge coupling unification



X,Y lead to proton decay, generate dim-6 operator





$d)\,(\bar{e}\gamma^{\mu}u)$

$\Gamma \sim \Big($ … $\Big)\,\mathrm{yr}$

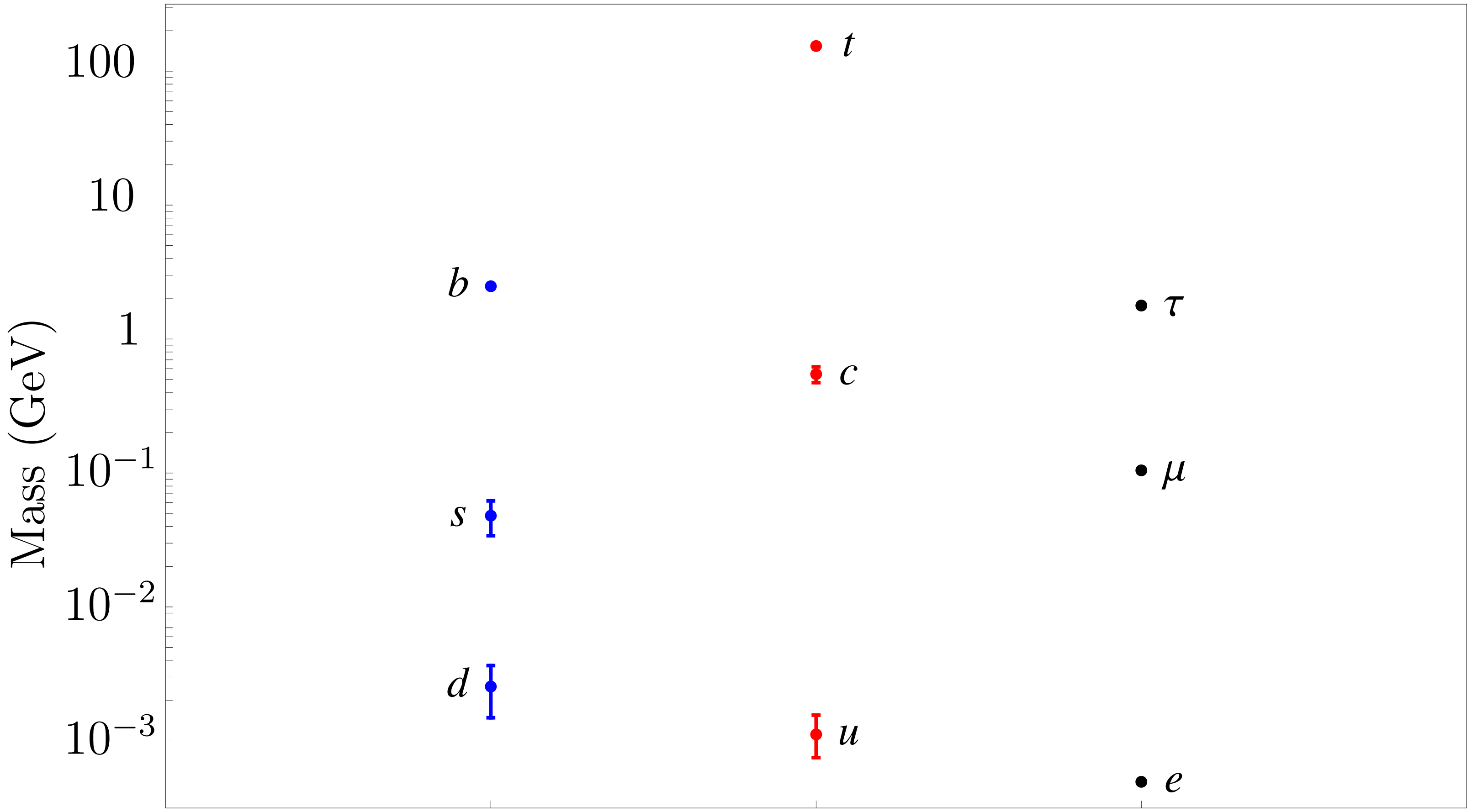
Use Avogadro’s number to our advantage

Bugs and Features

See Jure Zupan's lectures

Fermion masses, and mixings

What explains this hierarchy?



Technically natural

$$\delta m_f \sim \frac{g^2}{16\pi^2} m_f \log\left(\frac{\Lambda}{m_f}\right)$$

chiral symmetry

SM has no tree-level FCNC's

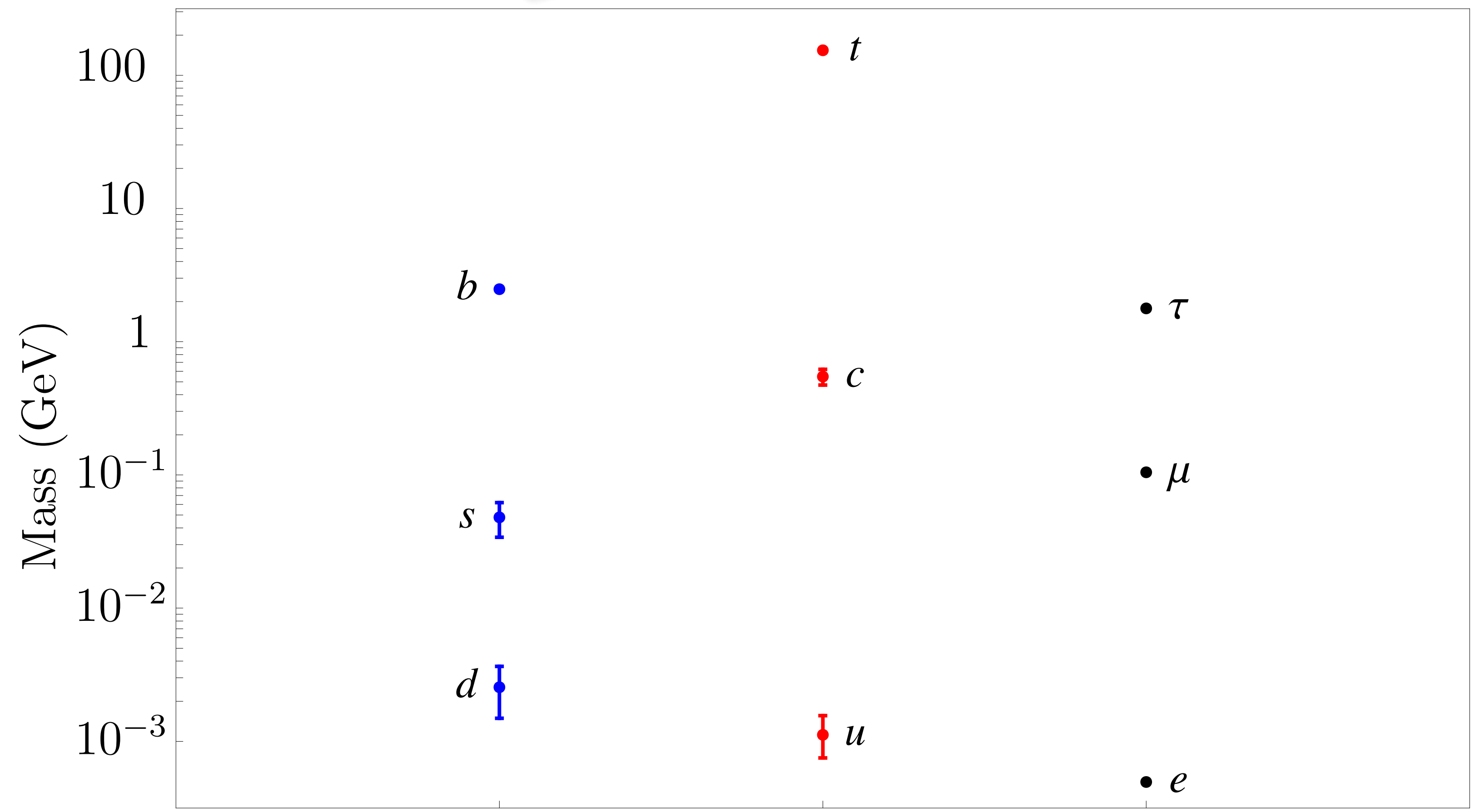
BSM physics probed indirectly for FCNC searches

Bugs and Features

Fermion masses, and mixings

See Jure Zupan's lectures

What explains this hierarchy?



Technically natural

$$\delta m_f \sim \frac{g^2}{16\pi^2} m_f \log\left(\frac{\Lambda}{m_f}\right)$$

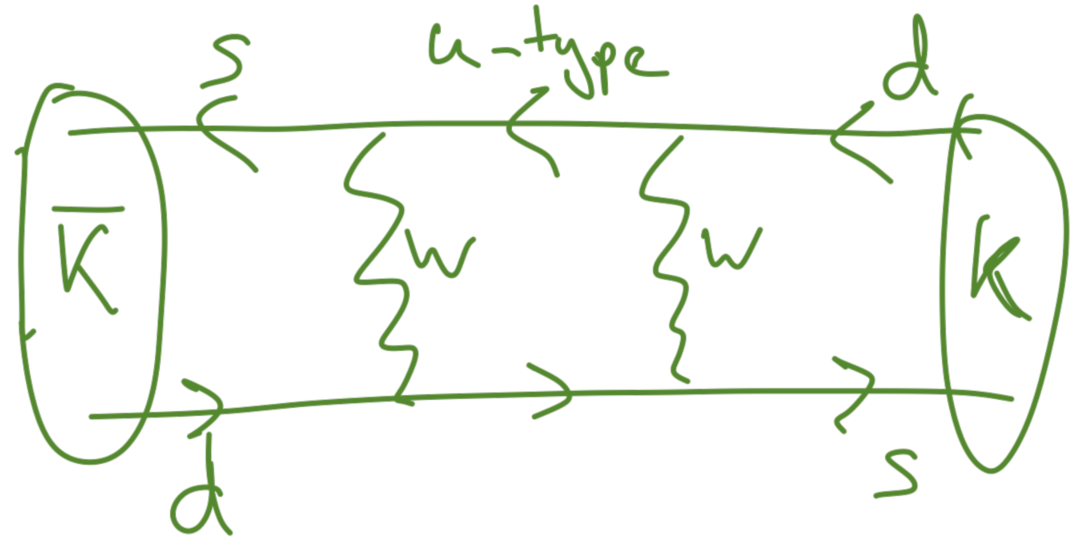
chiral symmetry

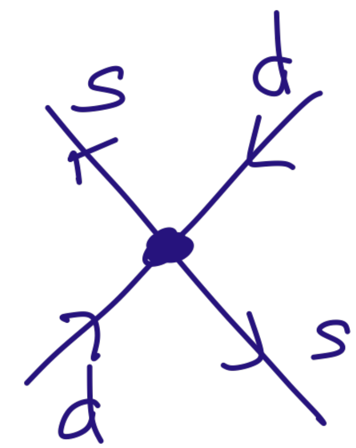
SM has no tree-level FCNC's

BSM physics probed indirectly for FCNC searches

Neutrinos?

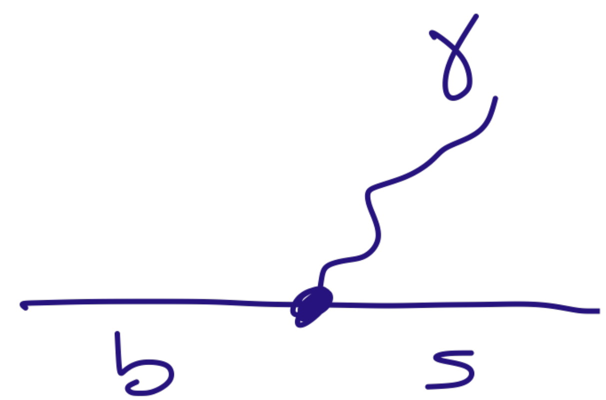
Fermion masses, and mixings





$$\frac{1}{\Lambda^2}(\bar{d}\,\Gamma s)(\bar{d}\,\Gamma s)$$

$$\Lambda \geq 1000 - 10000 \text{ TeV}$$



$$\frac{1}{\Lambda^2} H \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$$

$$\Lambda \geq 100 \text{ TeV}$$

BSM physics must have a carefully controlled flavour structure e.g. MFV

Bugs and Features

(see A. Shukraft lectures)

<u>Neutrino masses-another window to high scales?</u>

Not present in the SM, but observed in Nature

Dirac? $yLHN$ $y \sim 10^{-12}$ Lepton number ✔

Majorana? $\mathcal{L}_5 = \frac{1}{\Lambda}(LH)(LH)$ $\Lambda \sim 10^{14}\ \mathrm{GeV}$

Lepton number ✘

Only dim-5 op....already observed?

Neutrino model building

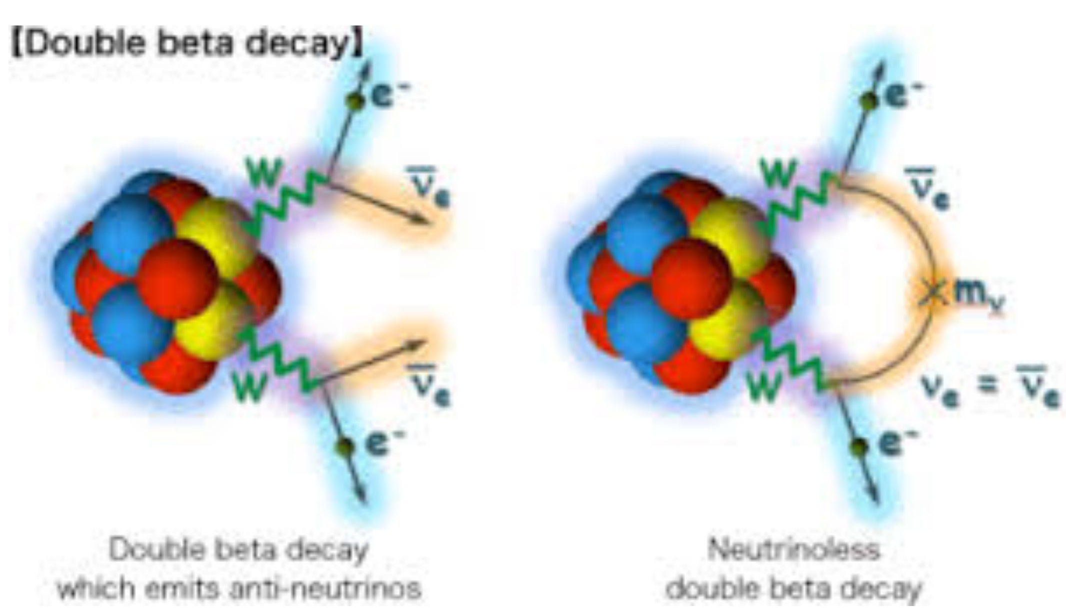
Dial “N” for neutrino

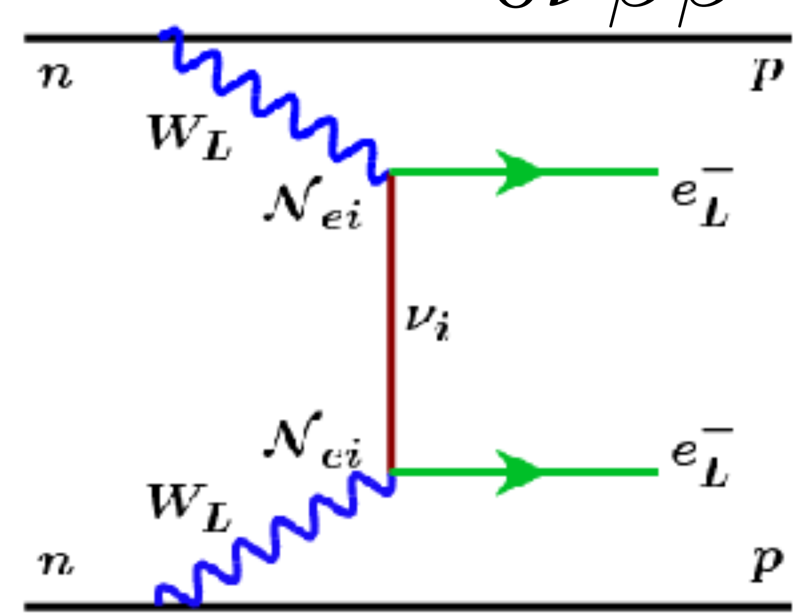
See-saw mechanism, new states at high scale

Low energy observable

$$yLHN + MNN \rightarrow \frac{y^2}{M}(LH)(LH)$$

$0\nu\beta\beta$



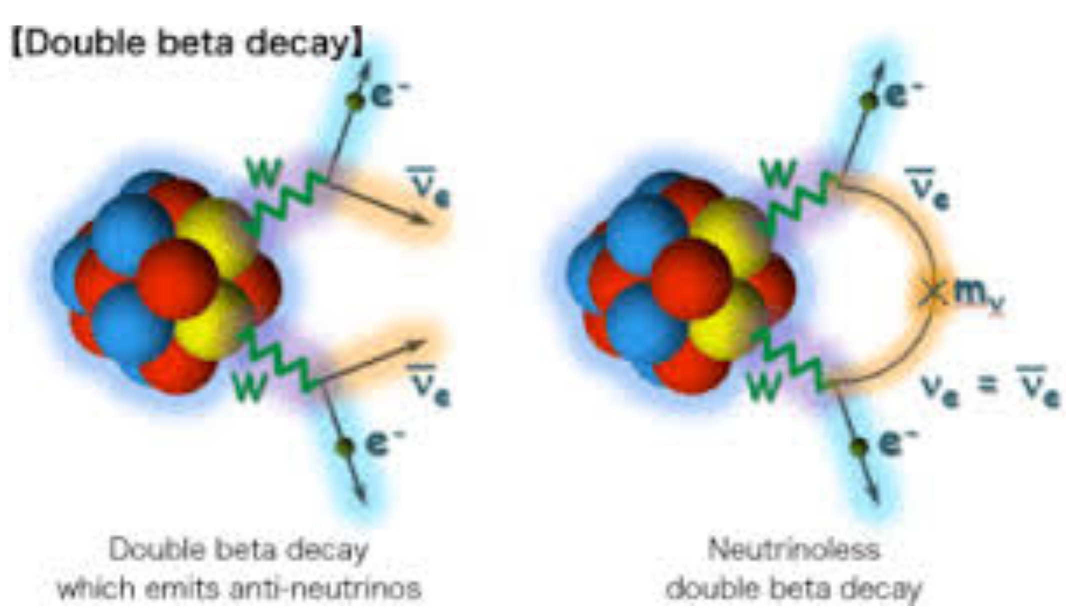


Dial “N” for neutrino

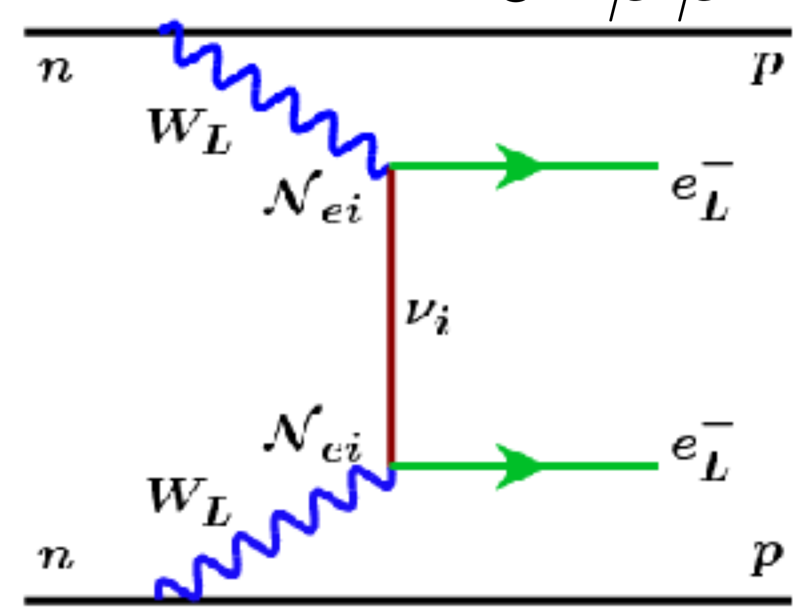
See-saw mechanism, new states at high scale

Low energy observable

$$yLHN + \underbrace{MNN}_{\mathcal{L}_3} \to \frac{y^2}{M}\,\underbrace{(LH)\,(LH)}_{\mathcal{L}_5}$$



$0\nu\beta\beta$



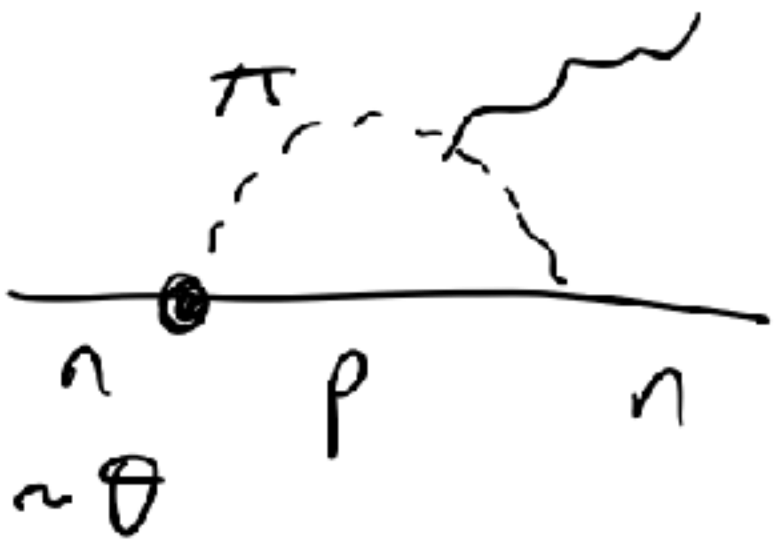
Bugs and Features

<u>Strong CP problem</u>

$$\mathcal{L}_4 \supset \theta_{QCD} G^a_{\mu\nu} G^a_{\alpha\beta} \epsilon^{\mu\nu\alpha\beta}$$

Dim-4 term violates CP (like E.B)
Leads to neutron electric dipole moment

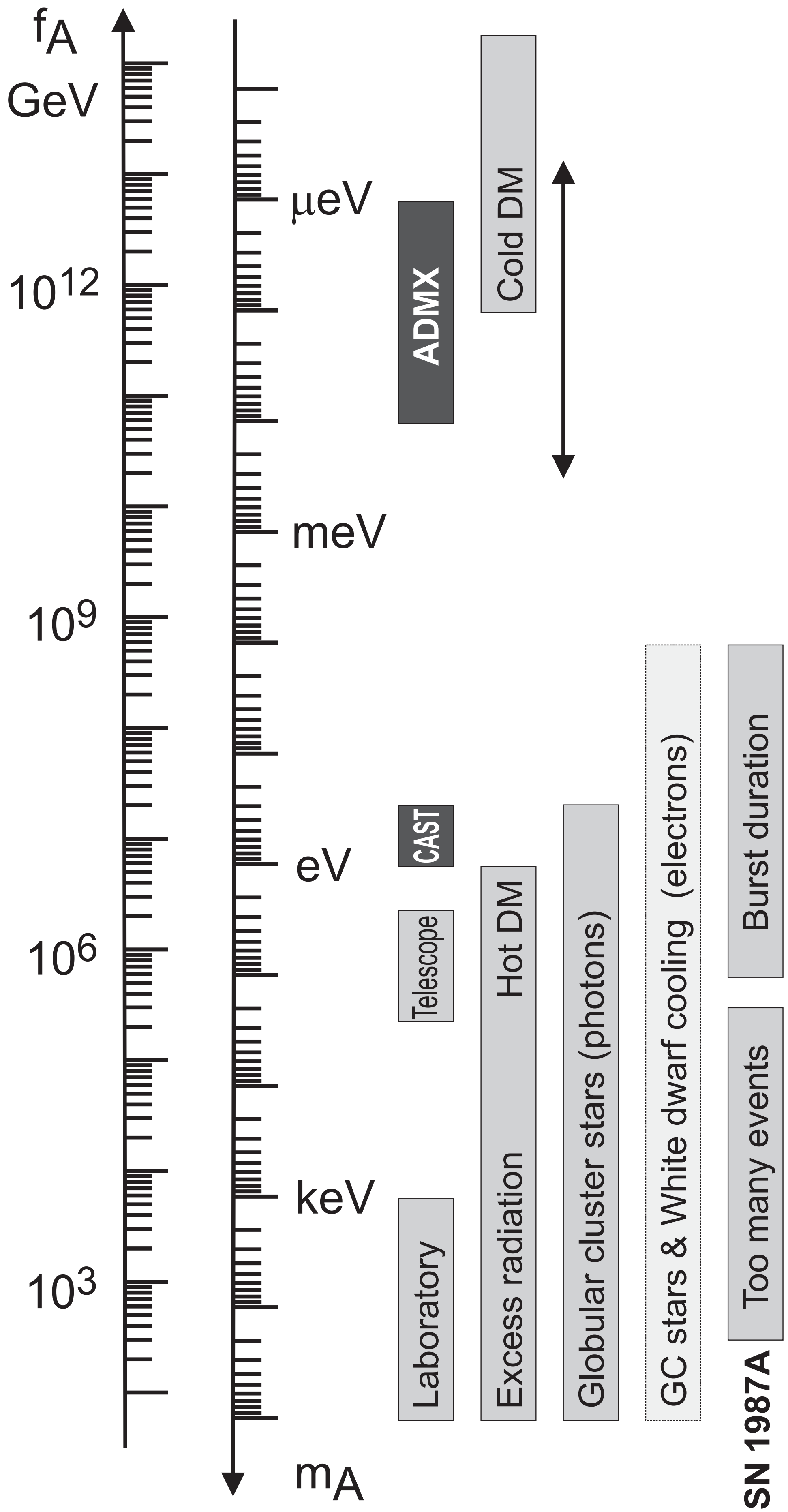
$$d_n \leq 10^{-26} e\, cm$$

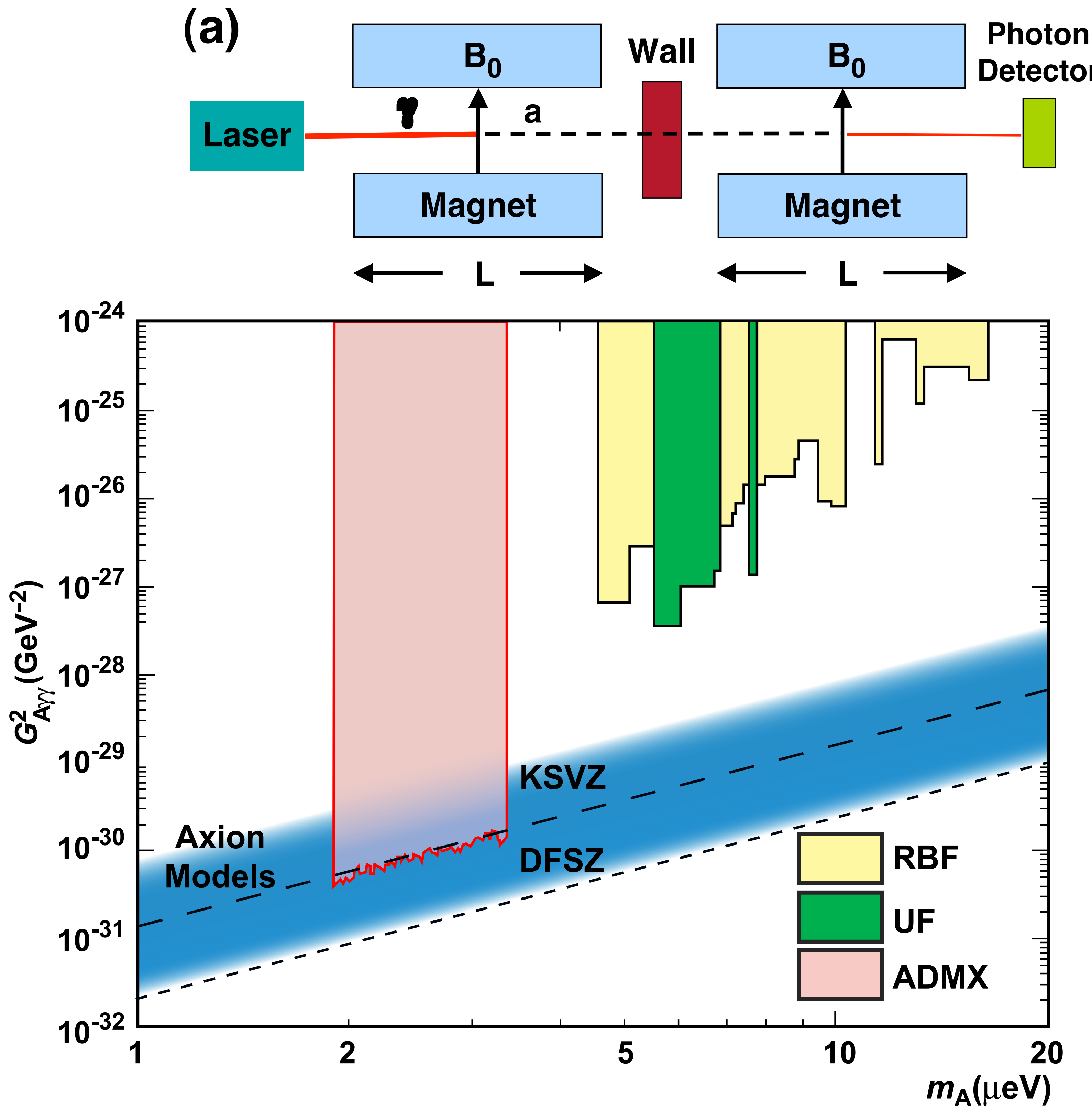


$$d_n \sim \theta \frac{e g_A}{(4\pi f_\pi)^2} \frac{m_u m_d}{m_u + m_d} \log \frac{m_n^2}{m_\pi^2}$$

$$\sim \theta \times 10^{-16} e\, cm$$

Massless up quark? (probably not)
Symmetry protection? e.g. Peccei-Quinn, Nelson-Barr


fA
GeV
10^12
10^9
10^6
10^3
μeV
meV
eV
keV
mA
ADMX
Cold DM
CAST
Telescope
Laboratory
Hot DM
Excess radiation
Globular cluster stars (photons)
GC stars & White dwarf cooling (electrons)
Burst duration
Too many events
SN 1987A


(a)
B0
Wall
B0
Photon Detector
Laser
a
Magnet
Magnet
L
L
10^-24
10^-25
10^-26
10^-27
10^-28
10^-29
10^-30
10^-31
10^-32
G²Aγγ (GeV⁻²)
KSVZ
DFSZ
Axion Models
RBF
UF
ADMX
1
2
5
10
20
mA(μeV)

Bugs and Features

Hierarchy (Naturalness) problem

$$\mathcal{L}_2 = \pm\mu^2|H|^2$$

Why is μ so much smaller than M_{GUT}, M_{Pl}?

Unlike fermions (and gauge bosons) no symmetry protects scalar mass parameter

1. Nature is fine-tuned (anthropics?)
2. The SM has no high scales (gravity?, unification?)
3. New dynamics/symmetries keeps mass scale low

Bugs and Features

Hierarchy (Naturalness) problem

$$\mathcal{L}_2 = \pm\mu^2|F$$

Why is μ sc

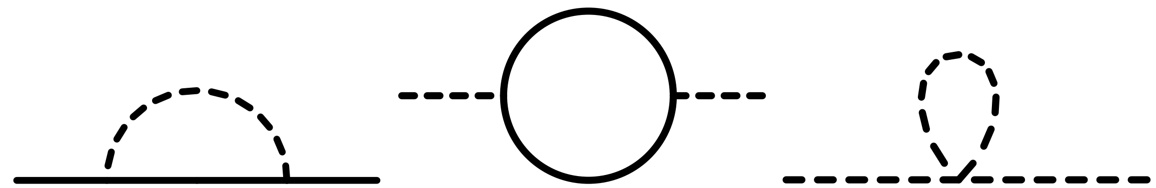
> There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact.
>
> —Mark Twain

Unlike fermions (and gauge bosons) no symmetry protects scalar mass parameter

1. Nature is fine-tuned (anthropics?)
2. The SM has no high scales (gravity?, unification?)
3. New dynamics/symmetries keeps mass scale low

Hierarchy (Naturalness) problem

$$\mathcal{L} = |\partial_\mu \phi|^2 + \overline{\psi} i \not{\partial} \psi - m_f \overline{\psi}\psi - y\phi\overline{\psi}\psi - \mu^2 |\phi|^2 - \lambda |\phi|^4$$



etc

$$\Delta m_f \sim -\frac{y^2}{16\pi^2} m_f \log\left(\frac{\Lambda}{m_f}\right)$$

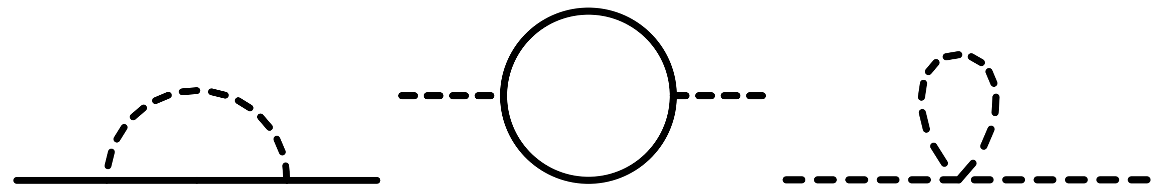
$$\Delta \mu^2 \sim \frac{\lambda - y^2}{16\pi^2}\Lambda^2 - \frac{y^2}{16\pi^2} m_f^2 \log\frac{\Lambda}{m_f}$$

Scalars are sensitive to the highest scale in the theory!

Expect new physics (Λ) at $\frac{4\pi}{g} m_h$

Hierarchy (Naturalness) problem

$$\mathcal{L} = |\partial_\mu \phi|^2 + \overline{\psi} i \partial\!\!\!/ \psi - m_f \overline{\psi}\psi - y\phi\overline{\psi}\psi - \mu^2 |\phi|^2 - \lambda |\phi|^4$$



etc

$$\Delta m_f \sim -\frac{y^2}{16\pi^2} m_f \log\left(\frac{\Lambda}{m_f}\right)$$

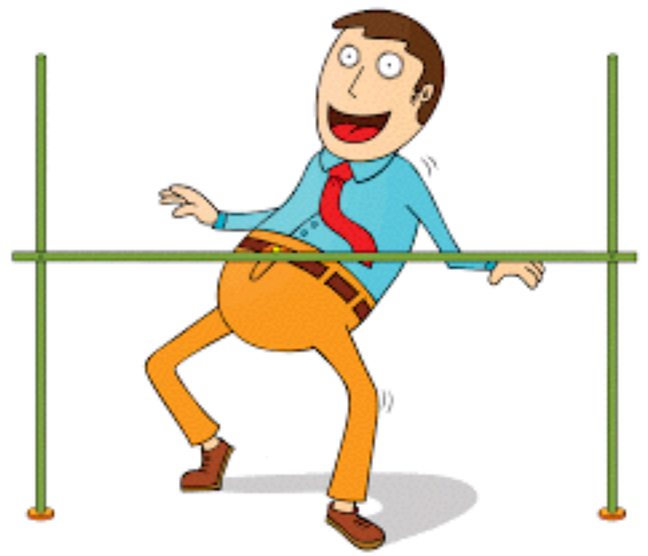
$$\Delta \mu^2 \sim \frac{\lambda - y^2}{16\pi^2}\Lambda^2 - \frac{y^2}{16\pi^2} m_f^2 \log\frac{\Lambda}{m_f}$$

Possible solution?

Scalars are sensitive to the highest scale in the theory!

Expect new physics (Λ) at $\frac{4\pi}{g} m_h$

Hierarchy (Naturalness) problem



SM Higgs sensitivity (how low ~~can you~~ go)

$$\delta m_h^2 = \alpha_t \Lambda_t^2 + \alpha_g \Lambda_g^2 + \alpha_h \Lambda_h^2$$

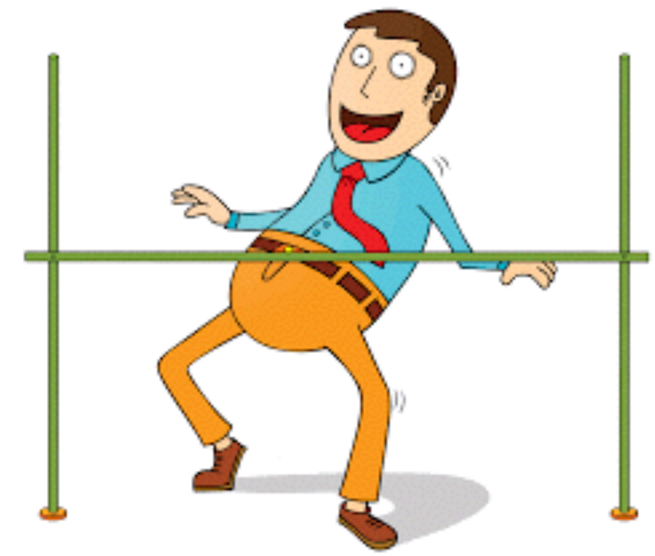
$$\alpha_t = \frac{3m_t^2}{4\pi^2 v^2}, \quad \alpha_g = -\frac{6m_W^2 + 3m_Z^2}{16\pi^2 v^2}, \quad \alpha_h = -\frac{3m_h^2}{16\pi^2 v^2}$$

(One) Measure of fine tuning: $D_i(m_h) \equiv \left| \frac{\partial \log m_h^2}{\partial \log \Lambda_i^2} \right| = \frac{|\alpha_i| \Lambda_i^2}{m_h^2}$

No guaranteed discovery, unlike Higgs mechanism

Should not stop us looking!!

Hierarchy (Naturalness) problem



SM Higgs sensitivity (how low does Nature go)

$$\delta m_h^2 = \alpha_t \Lambda_t^2 + \alpha_g \Lambda_g^2 + \alpha_h \Lambda_h^2$$

$$\alpha_t = \frac{3m_t^2}{4\pi^2 v^2}, \quad \alpha_g = -\frac{6m_W^2 + 3m_Z^2}{16\pi^2 v^2}, \quad \alpha_h = -\frac{3m_h^2}{16\pi^2 v^2}$$

(One) Measure of fine tuning: $D_i(m_h) \equiv \left| \frac{\partial \log m_h^2}{\partial \log \Lambda_i^2} \right| = \frac{|\alpha_i| \Lambda_i^2}{m_h^2}$

No guaranteed discovery, unlike Higgs mechanism

Should not stop us looking!!

Supersymmetry…a BSM case study

Bosons ⟷ Fermions

(more than) Doubling of the spectrum

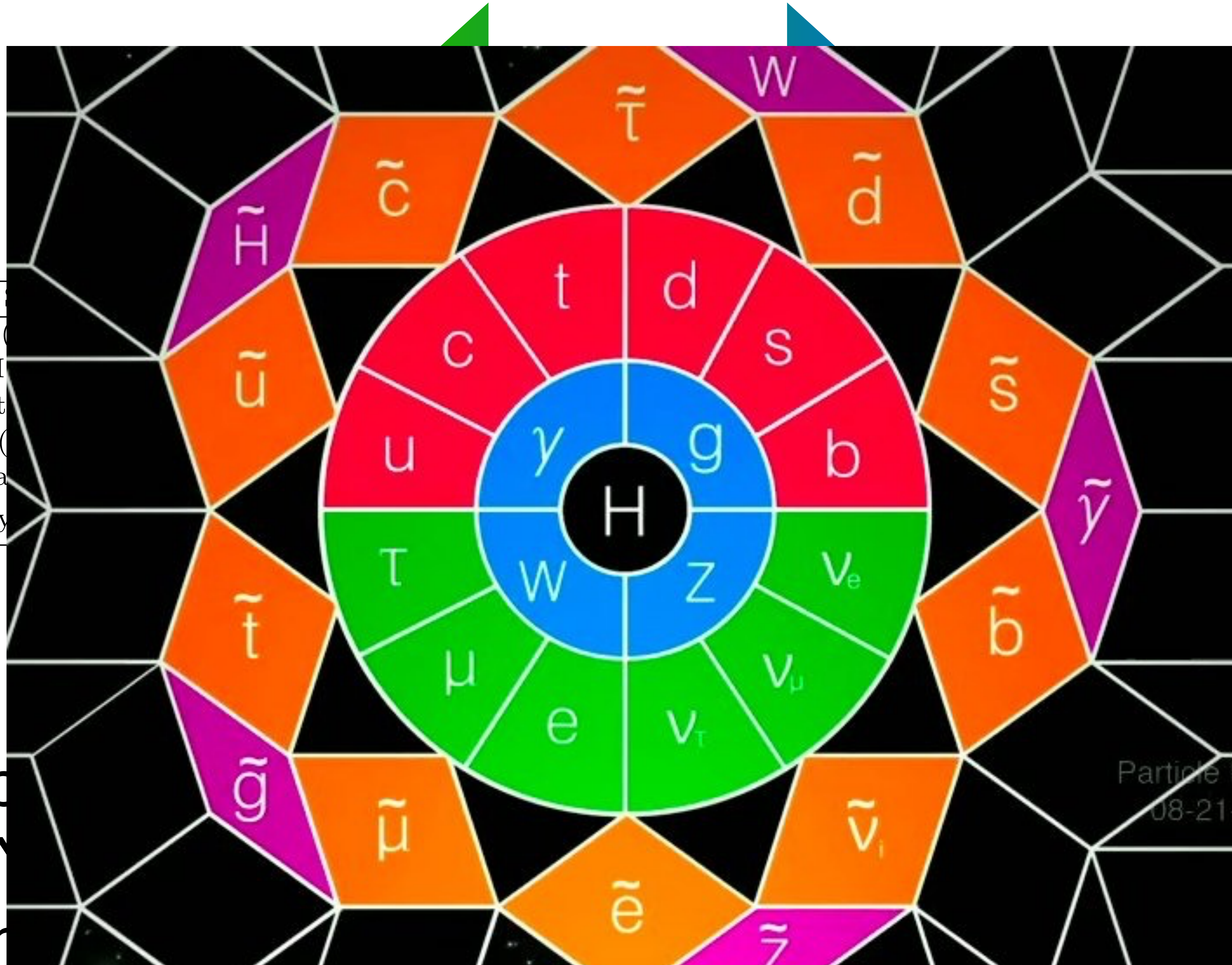
SM Field	$SU(3)$	$SU(2)$	$U(1)$	MSSM partner	Superfield
q_i (LH quarks)	3	2	$\frac{1}{6}$	$\tilde{q}_i$ (LH squarks)	Q_i
u_i^c (RH top, charm, up)	$\bar{3}$	1	$-\frac{2}{3}$	$\tilde{u}_i^c$ (RH stop, scharm, sup)	U_i^c
d_i^c (RH bottom, strange, down)	$\bar{3}$	1	$\frac{1}{3}$	$\tilde{d}_i^c$ (RH sbottom, sstrange, sdown)	D_i^c
ℓ_i (LH leptons)	1	2	$-\frac{1}{2}$	$\tilde{\ell}_i$ (LH sleptons)	L_i
e_i^c (RH tau, muon, electron)	1	1	1	$\tilde{e}_i^c$ (RH stau, smuon, selectron)	E_i^c
h_u (h_d) (up-type (down-type) Higgs)	1	2	$\frac{1}{2}$ $(-\frac{1}{2})$	$\tilde{h}_u$ $\left(\tilde{h}_d\right)$ (up-type (down-type) higgsino)	H_u (H_d)
gluino	8	1	0	gluino	
W/Z	1	3	0	Wino/Zino	
B/photon	1	1	0	bino/photino	

Superpartners have the same couplings as SM partners
If SUSY (softly) broken they have different masses
Many new interactions…>100 new parameters!

Many constrained by flavour, CP-violation
SUSY breaking models (GMSB, AMSB ,….) predict relations

Supersymmetry…a BSM case study

S	…	Superfield
q_i (		Q_i
u_i^c (RH		U_i^c
d_i^c (RH bot		D_i^c
ℓ_i (		L_i
e_i^c (RH ta		E_i^c
h_u (h_d) (up-ty	)	H_u (H_d)



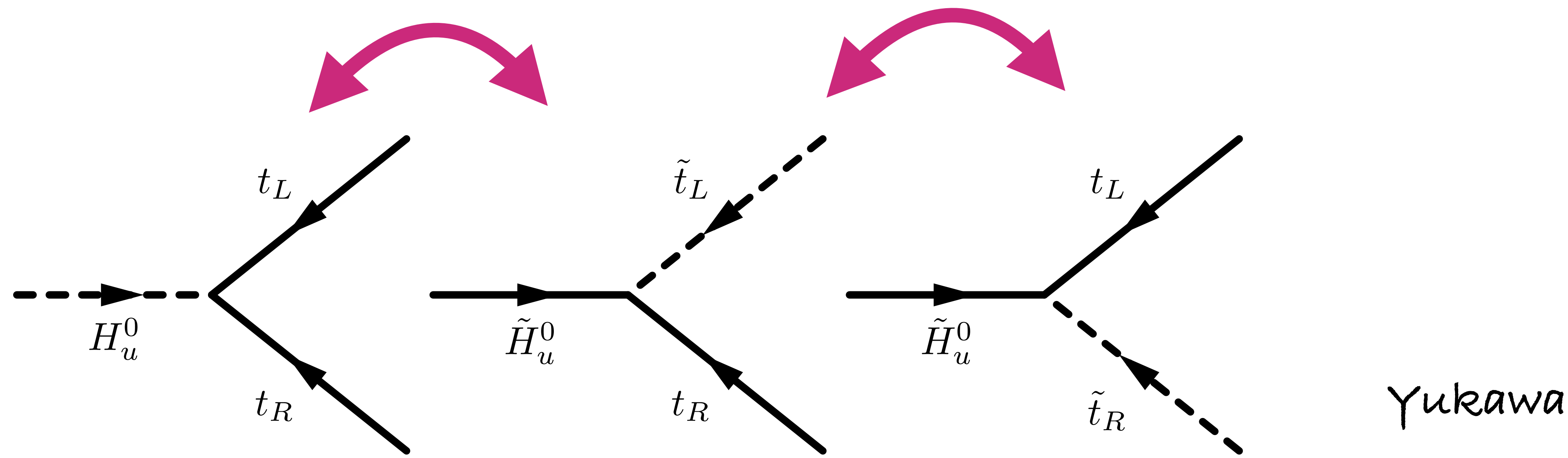
Superp … artners
If SUSY … s
Many r …

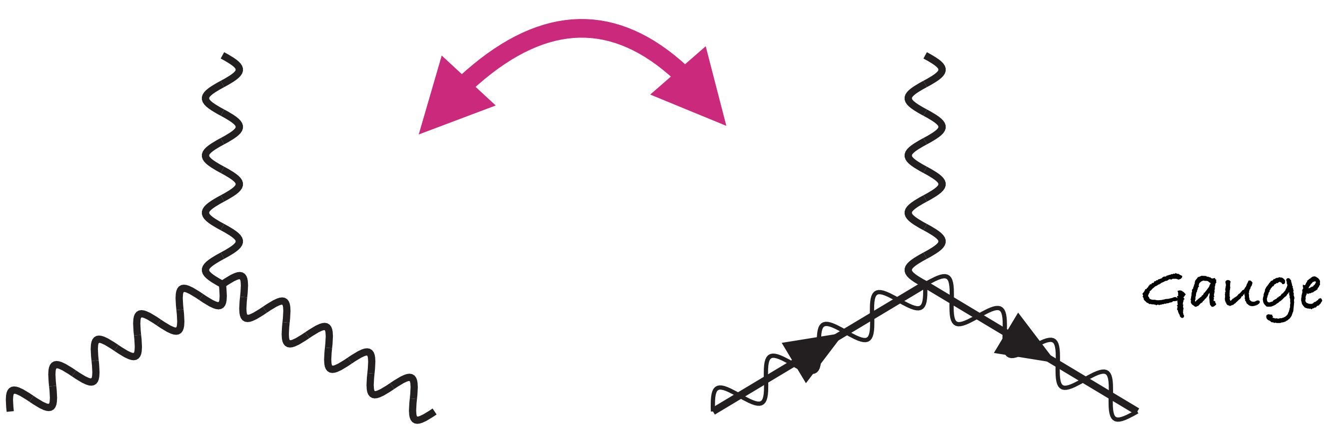
Many constrained by flavour, CP-violation
SUSY breaking models (GMSB, AMSB ,….) predict relations

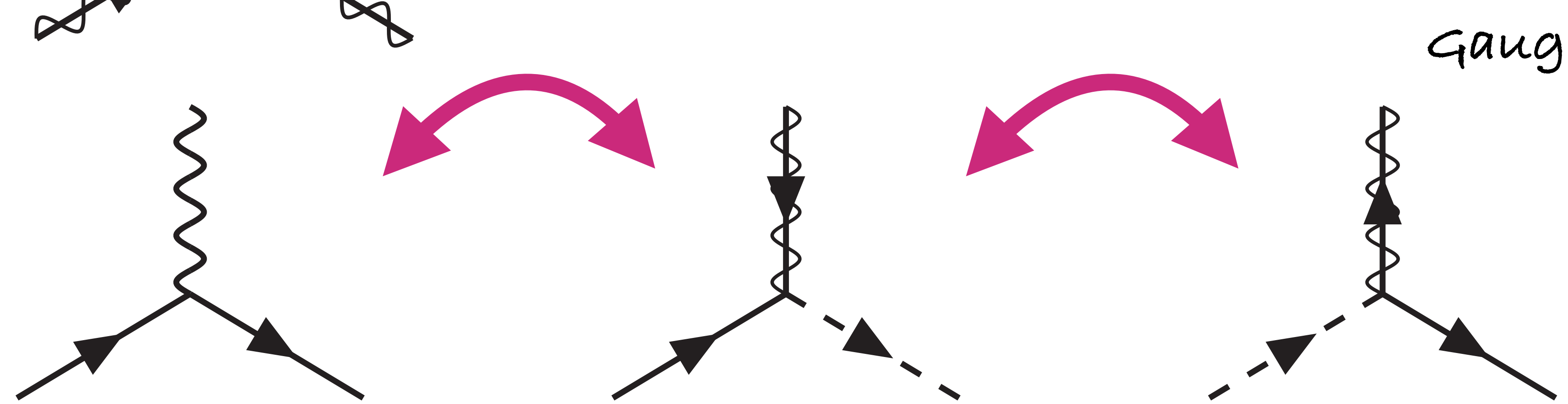
Supersymmetry

$$W_{MSSM} = \mathbf{Y_U} U^c Q H_u - \mathbf{Y_D} D^c Q H_d - \mathbf{Y_E} E^c L H_d + \mu H_u H_d$$

Flip two





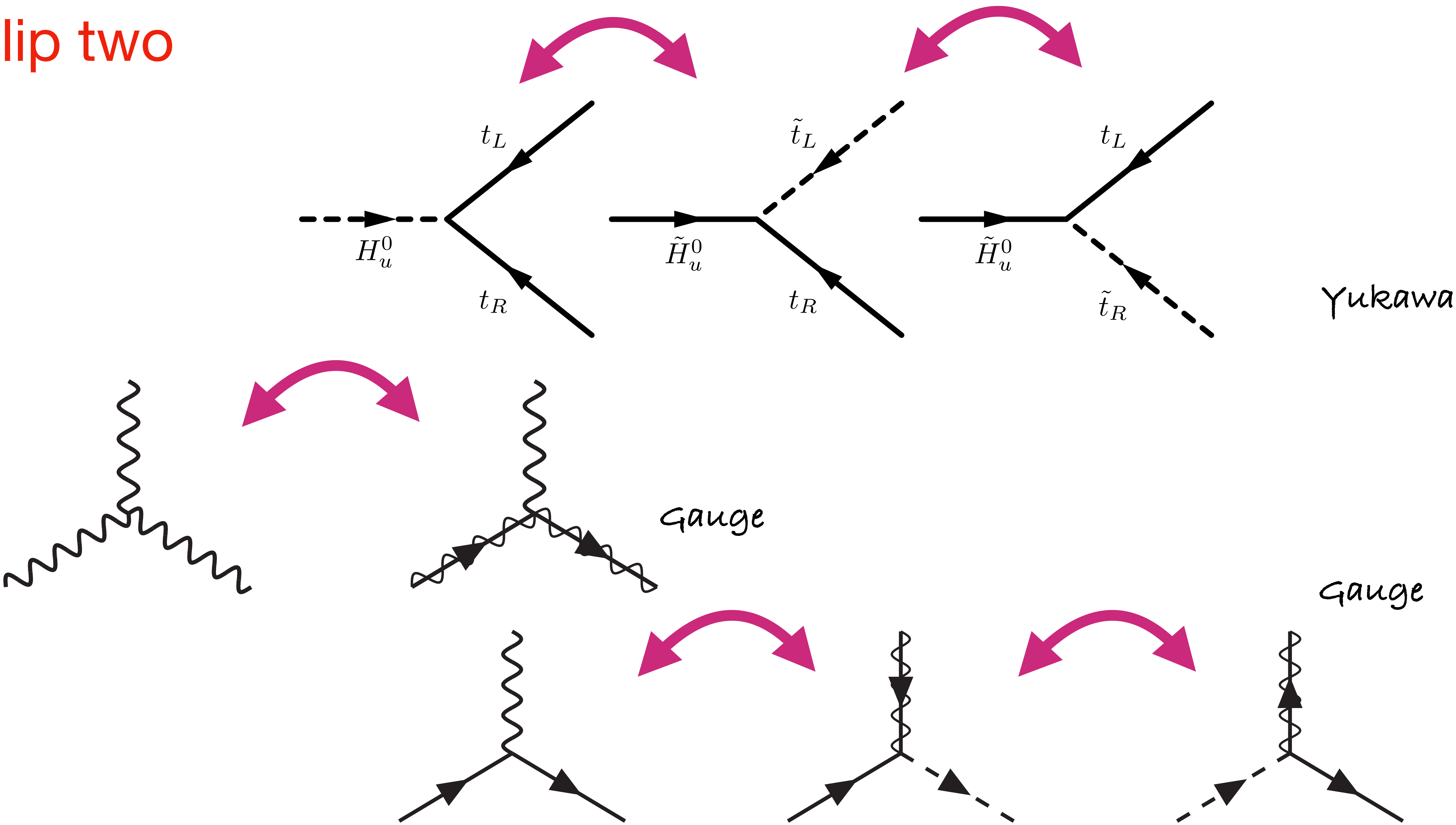


Supersymmetry

Extended Higgs sector
Higgs modifications

$$W_{MSSM} = \mathbf{Y_U} U^c Q H_u - \mathbf{Y_D} D^c Q H_d - \mathbf{Y_E} E^c L H_d + \mu H_u H_d$$

Flip two

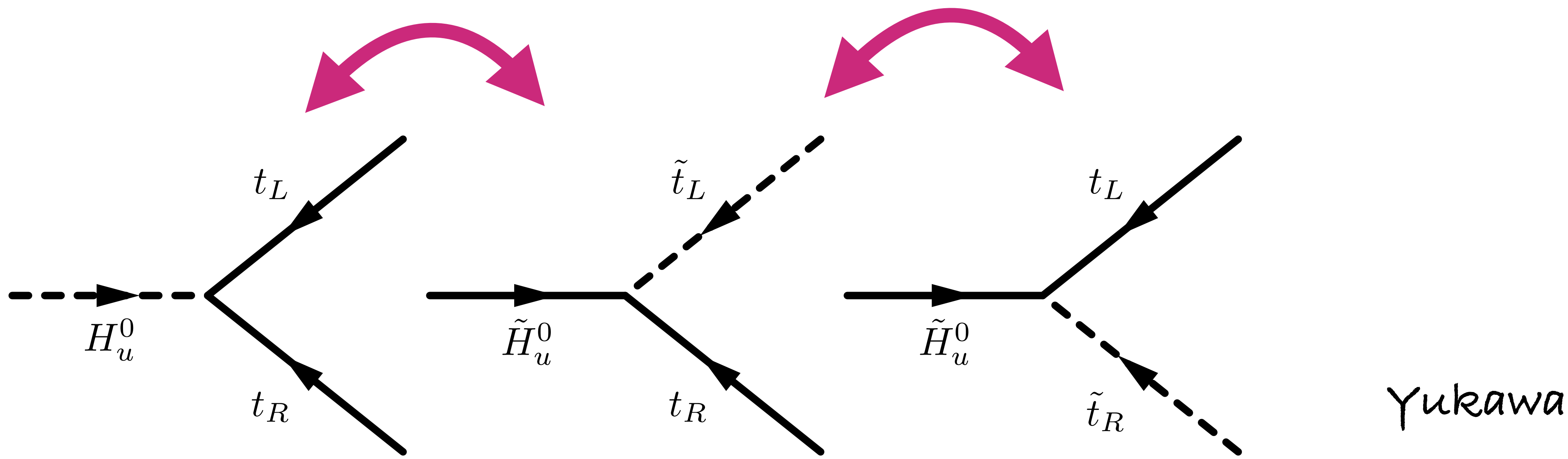


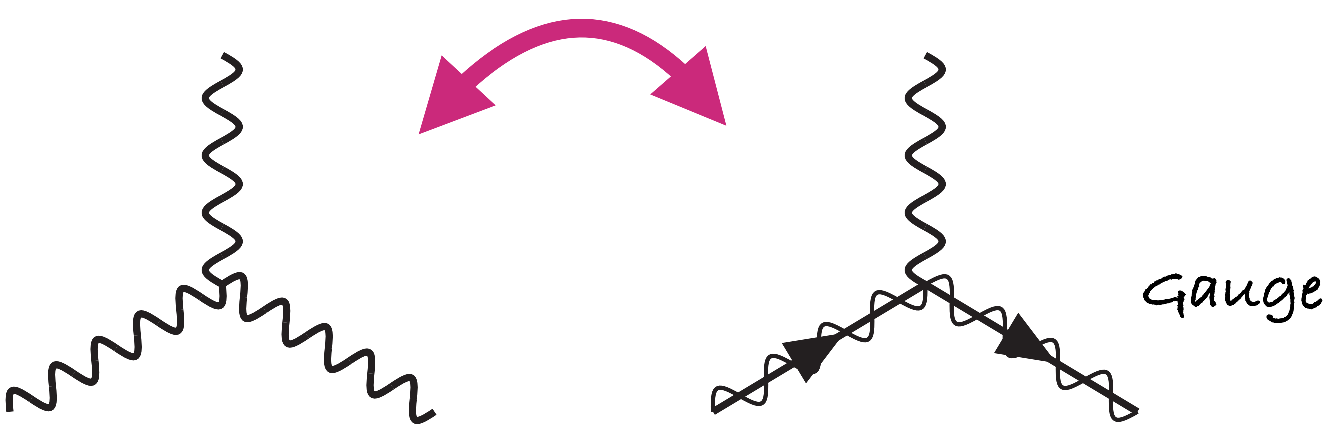
Supersymmetry

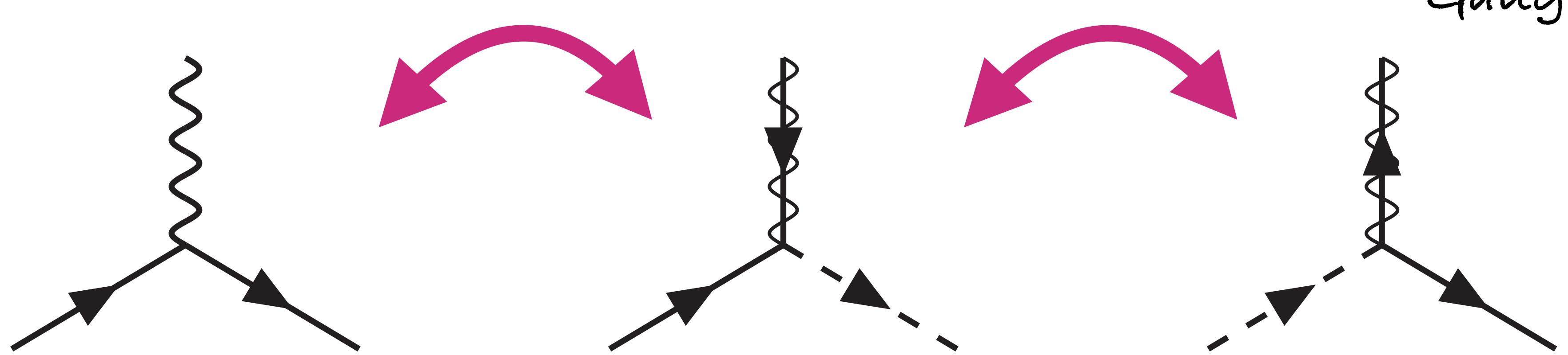
Extended Higgs sector
Higgs modifications

$$W_{MSSM} = \mathbf{Y_U} U^c Q H_u - \mathbf{Y_D} D^c Q H_d - \mathbf{Y_E} E^c L H_d + \mu H_u H_d$$

Flip two







Supersymmetry

New fields allow for new interactions (EFT philosophy)

$$\Delta L = 1 \quad \Delta L = 1 \quad \Delta L = 1 \quad \Delta B = 1$$

$$W_{\Delta B,L} = \kappa_1^{ijk} Q_i L_j D_k^c + \kappa_2^{ijk} L_i L_j E_k^c + \kappa_3^{i} L^i H_u + \kappa_4^{ijk} D_i^c D_j^c U_k^c$$

Proton lifetime: $\Gamma \sim \frac{\kappa_1 \kappa_4}{16\pi} \frac{m_p^5}{m_{\tilde{q}}^4}$ $\qquad \kappa < 10^{-12}!$

Forbid these (RPV) operators with a parity (R-parity)

$$SM \to SM \qquad BSM \to -BSM$$

LPOP

1. SM and partners don't mix
2. SUSY states pair produced
3. Lightest parity odd particle stable (DM?)

Supersymmetry

New fields allow for new interactions (EFT philosophy)

$$\Delta L = 1 \qquad \Delta L = 1 \qquad \Delta L = 1 \qquad \Delta B = 1$$

$$W_{\Delta B, L} = \kappa_1^{ijk} Q_i L_j D_k^c + \kappa_2^{ijk} L_i L_j E_k^c + \kappa_3^i L^i H_u + \kappa_4^{ijk} D_i^c D_j^c U_k^c$$

Proton lifetime: $\Gamma \sim \dfrac{\kappa_1 \kappa_4}{16\pi} \dfrac{m_p^5}{m_{\tilde{q}}^4}$ $\qquad \kappa < 10^{-12}!$

Forbid these (RPV) operators with a parity (R-parity)

$$SM \to SM \qquad BSM \to -BSM$$

LPOP

1. SM and partners don't mix
2. SUSY states pair produced
3. Lightest parity odd particle stable (DM?)

More later....

Supersymmetry

Complicated spectrum, details depend on model

GMSB, Effective/Natural SUSY, Dirac gauginos….

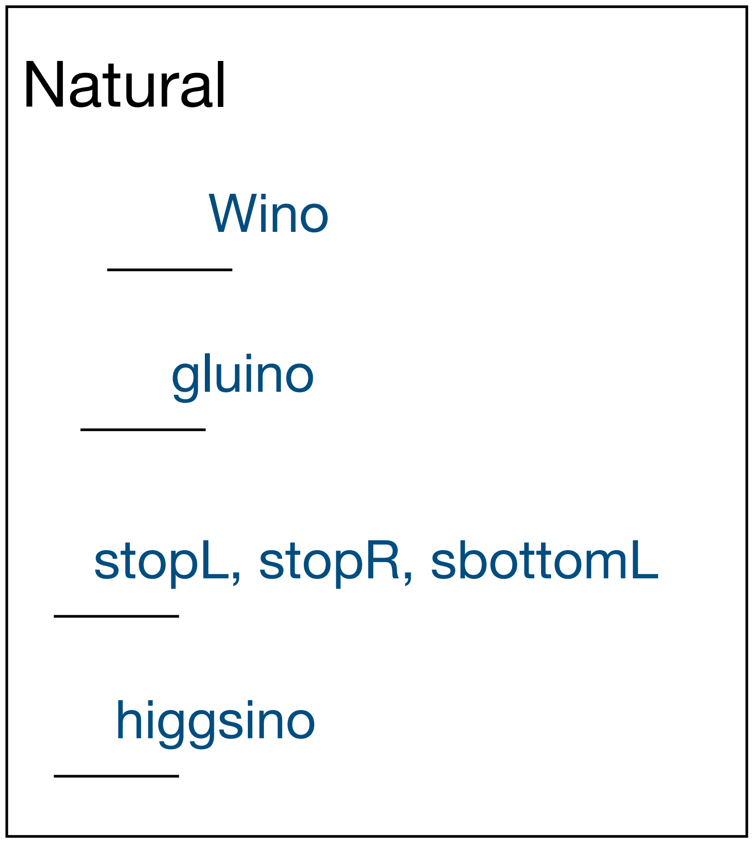
Many, many interesting collider signatures

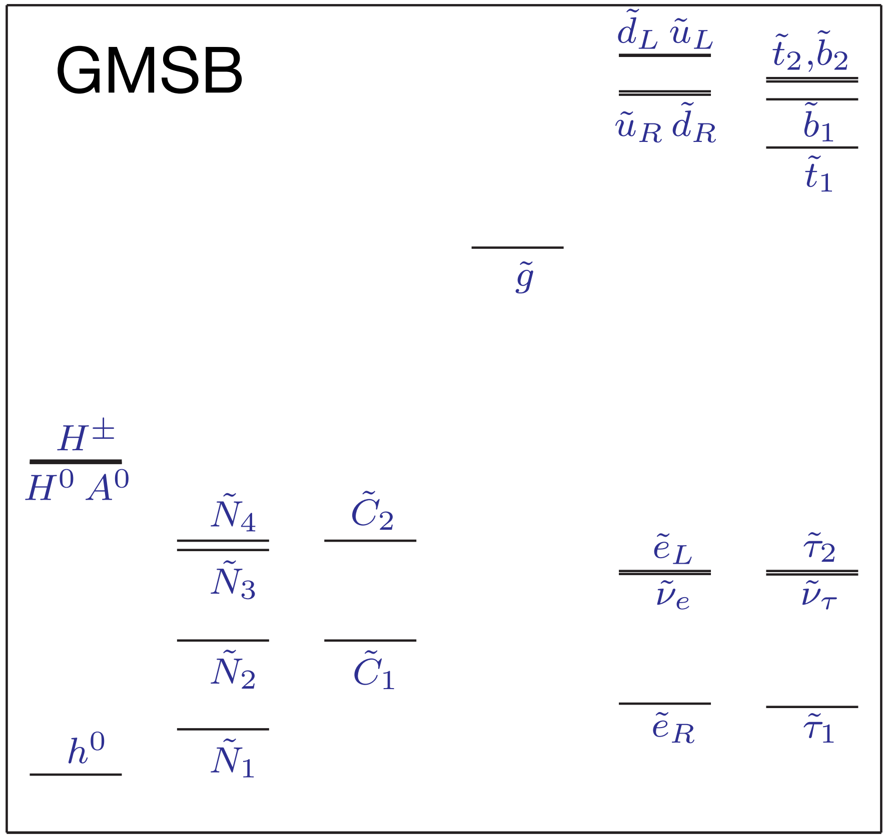
Lightest coloured states made first, decays involve MET

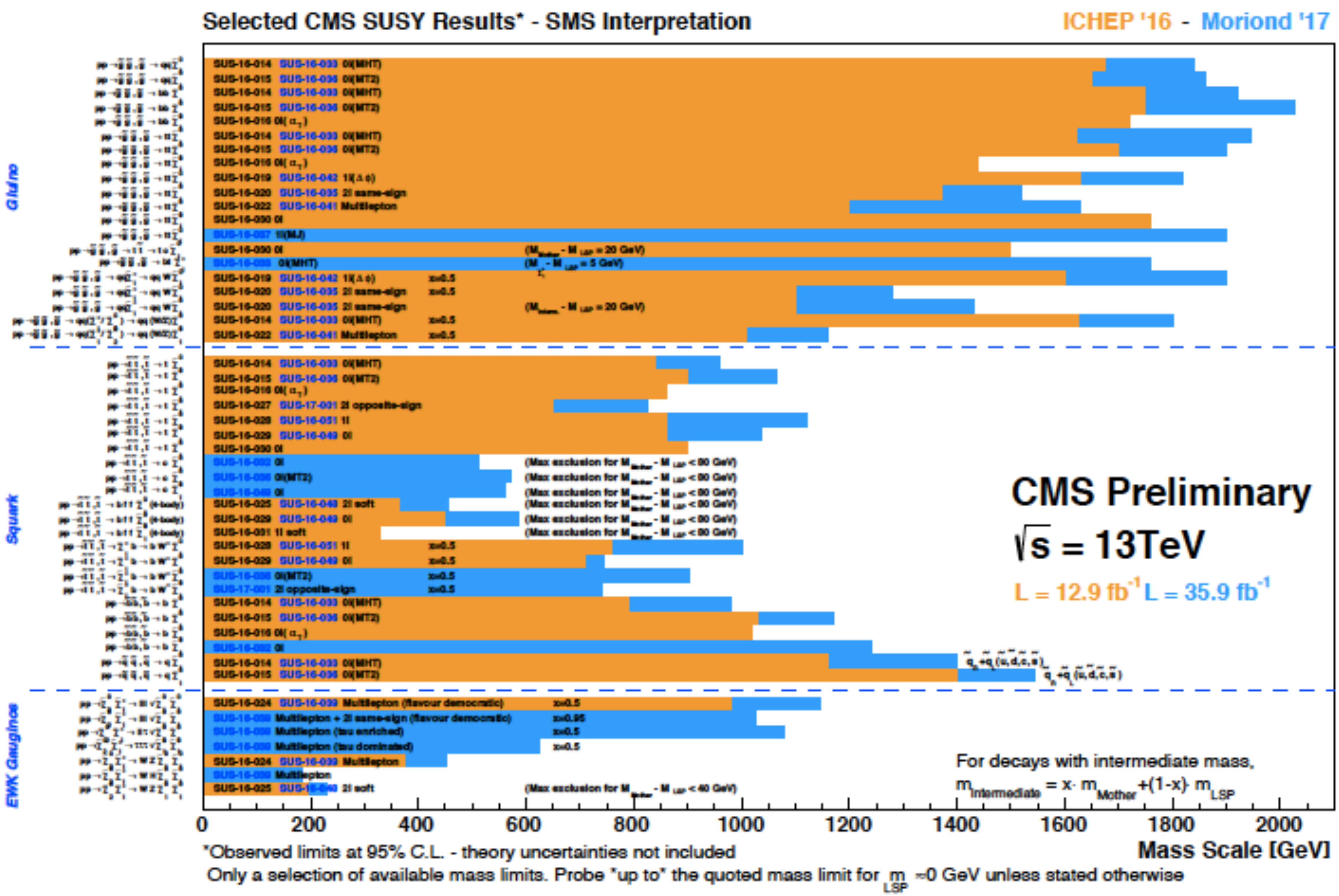
Compressed/Stealth spectra can hide SUSY (a little)

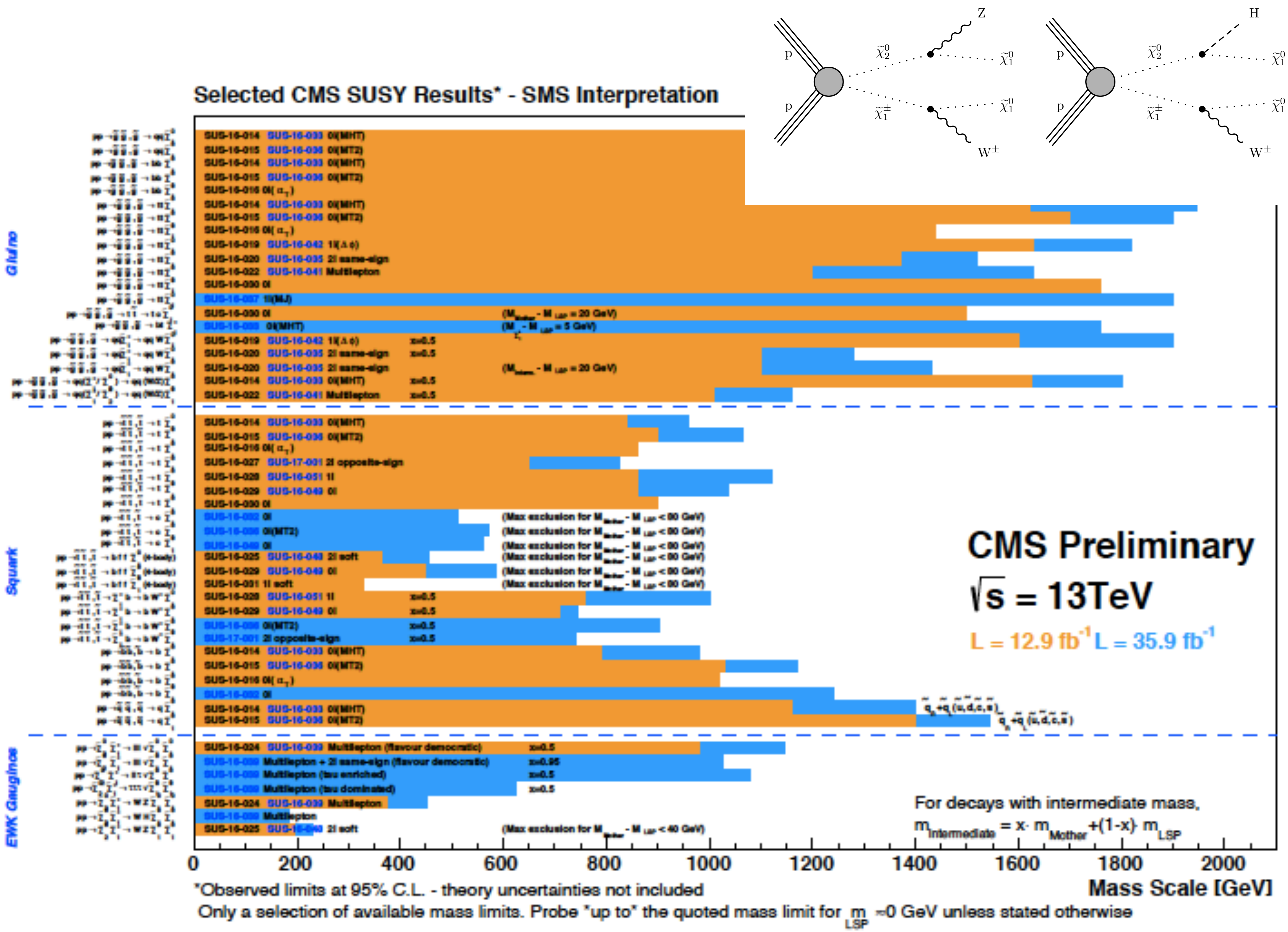
Electroweakino sector starting to be probed (DM)

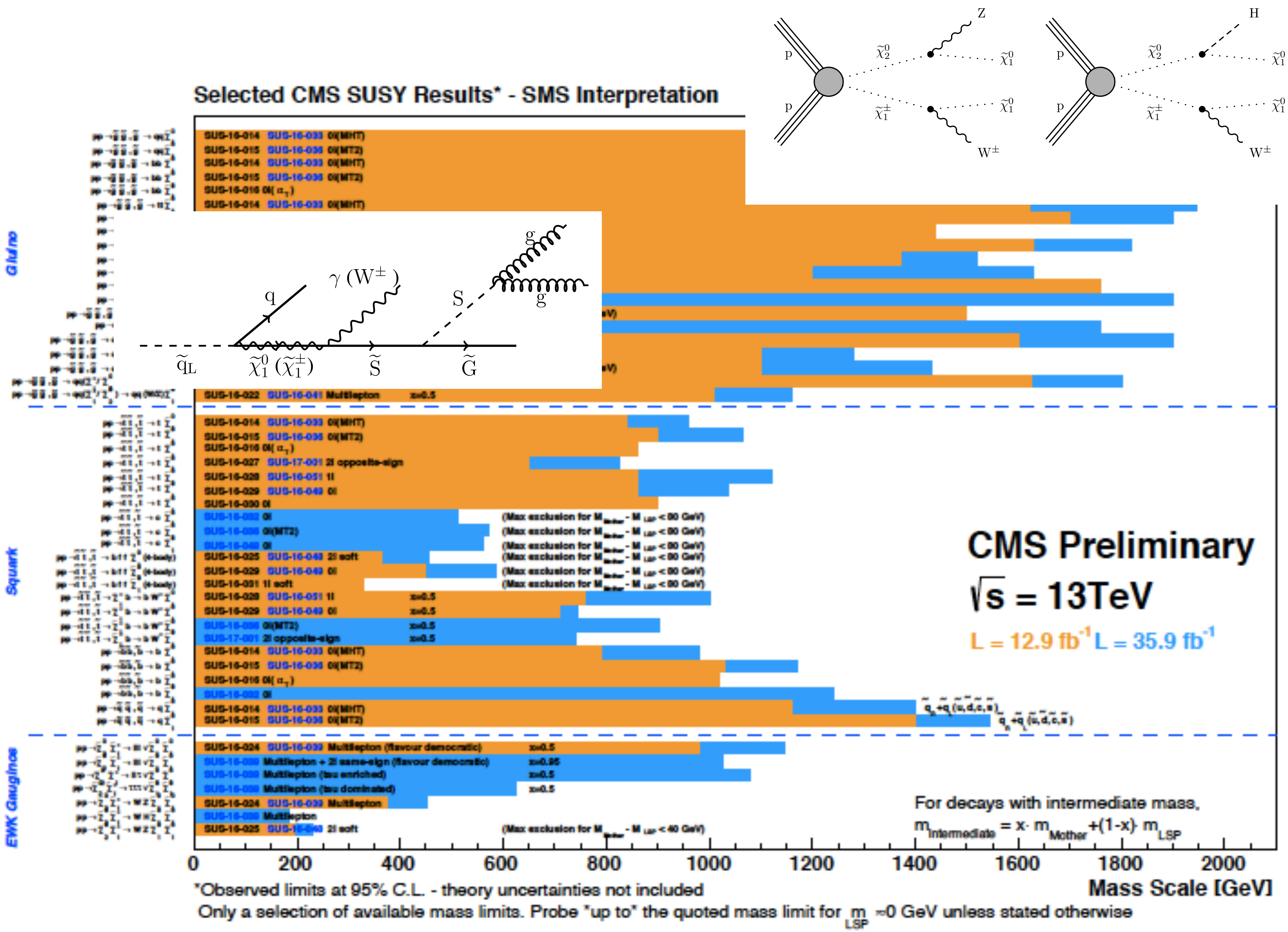
SUSY is a great signal generator

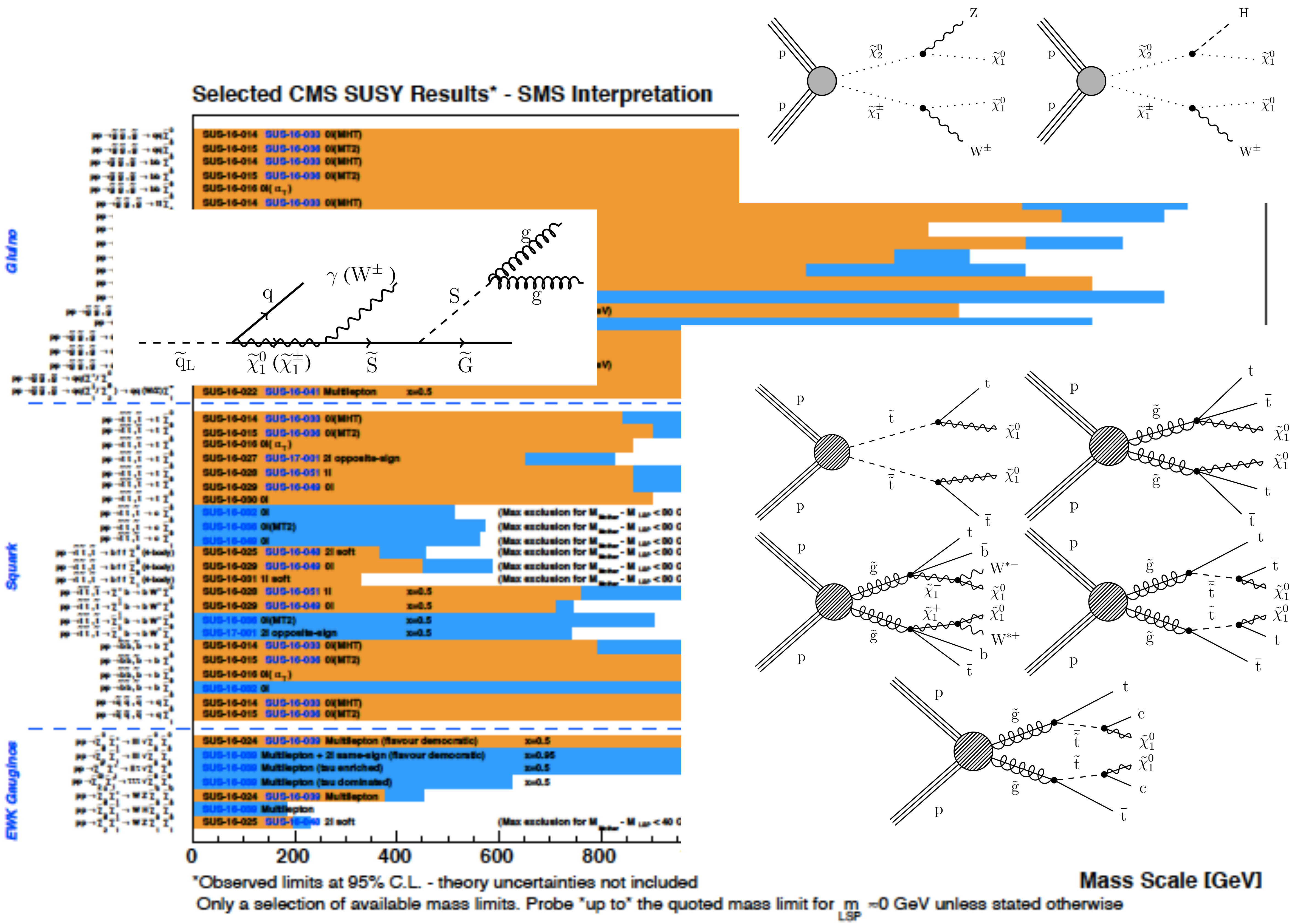





Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
CMS Preliminary
√s = 13TeV
L = 12.9 fb-1 L = 35.9 fb-1
For decays with intermediate mass,
m_Intermediate = x· m_Mother +(1-x)· m_LSP
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe "up to" the quoted mass limit for m_LSP ≈0 GeV unless stated otherwise


Z
H
p
p
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^\pm$
$W^\pm$
Selected CMS SUSY Results* - SMS Interpretation
Gluino
Squark
EWK Gauginos
CMS Preliminary
$\sqrt{s}$ = 13TeV
L = 12.9 fb^{-1} L = 35.9 fb^{-1}
For decays with intermediate mass,
$m_{Intermediate} = x \cdot m_{Mother} + (1-x) \cdot m_{LSP}$
0 200 400 600 800 1000 1200 1400 1600 1800 2000
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe "up to" the quoted mass limit for $m_{LSP} \approx 0$ GeV unless stated otherwise


Selected CMS SUSY Results* - SMS Interpretation
Gluino
Squark
EWK Gauginos
CMS Preliminary
$\sqrt{s}$ = 13TeV
L = 12.9 fb^{-1} L = 35.9 fb^{-1}
For decays with intermediate mass,
$m_{Intermediate} = x \cdot m_{Mother} + (1-x) \cdot m_{LSP}$
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe "up to" the quoted mass limit for m_{LSP} ≈0 GeV unless stated otherwise
p
p
Z
$\widetilde{\chi}^0_2$
$\widetilde{\chi}^0_1$
$\widetilde{\chi}^\pm_1$
$W^\pm$
H
q
γ ($W^\pm$)
S
g
$\widetilde{q}_L$
$\widetilde{\chi}^0_1$ ($\widetilde{\chi}^\pm_1$)
$\widetilde{S}$
$\widetilde{G}$


Selected CMS SUSY Results* - SMS Interpretation
Gluino
Squark
EWK Gauginos
0
200
400
600
800
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe "up to" the quoted mass limit for m LSP =0 GeV unless stated otherwise
q
γ (W±)
S
g
g
q̃L
χ̃01 (χ̃±1)
S̃
G̃
p
p
Z
H
W±
t
t̄
t̃
g̃
b
b̄
c
c̄
W*−
W*+

General BSM lessons

Top partners (fermions/bosons)
Higgs sector modifications
LPOPs, parity, DM, MET
Extra matter in fundamental and adjoint reps.

New gauge groups?
Lighter, more weakly coupled particles?
Resonances?

General BSM lessons

Composite Higgs

Top partners (fermions/bosons)
Higgs sector modifications
LPOPs, parity, DM, MET
Extra matter in fundamental and adjoint reps.

New gauge groups?
Lighter, more weakly coupled particles?
Resonances?

General BSM lessons

Composite Higgs

Top partners (fermions/bosons)
Higgs sector modifications
LPOPs, parity, DM, MET
Extra matter in fundamental and adj

Randall Sundrum

New gauge groups?
Lighter, more weakly coupled particles?
Resonances?

General BSM lessons

Top partners (fermions/bosons)
Higgs sector modifications
LPOPs, parity, DM, MET
Extra matter in fundamental and adj

Composite Higgs

Randall Sundrum

Little Higgs

New gauge groups?
Lighter, more weakly coupled particles?
Resonances?

Twin Higgs

[Chacko, Goh, Harnik]

$$\mathrm{SM}_A \times \mathrm{SM}_B \times \mathbb{Z}_2$$

$$\mathcal{L} \supset y\, Q_A H_A U_A^c + y\, Q_B H_B U_B^c$$

Higgs is a PNGB, and Higgs potential is O(8) symmetric

$$V = -m^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$$

$O(8) \to O(7)$:7 Goldstone bosons, 3 eaten by B gauge bosons

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} = e^{i h^a t^a / f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

Twin Higgs

[Chacko, Goh, Harnik]

$\mathrm{SM}_A \times \mathrm{SM}_B \times \mathbb{Z}_2$

$$\mathcal{L} \supset y\, Q_A H_A U_A^c + y\, Q_B H_B U_B^c$$

Higgs is a PNGB, and Higgs potential is O(8) symmetric

$$V = -m^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$$

$O(8) \to O(7)$:7 Goldstone bosons, 3 eaten by B gauge bosons

SM Higgs

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} = e^{i h^a t^a / f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

Twin Higgs

Gauge and Yukawa interactions explicitly break the O(8)

Mass for Higgs?

$$\frac{3}{8\pi^2}\Lambda^2\left(y_A^2 H_A^\dagger H_A + y_B^2 H_B^\dagger H_B\right)$$

↖ ↗

$$Z_2 \Rightarrow y_A = y_B$$

↓

$$\frac{3}{8\pi^2}\Lambda^2 y^2 H^\dagger H$$

Loop corrections to mass is O(8) symmetric, does not lead to *quadratically divergent* Higgs mass

EFT aside

Low energy degrees of freedom, non-linearly realized symm.

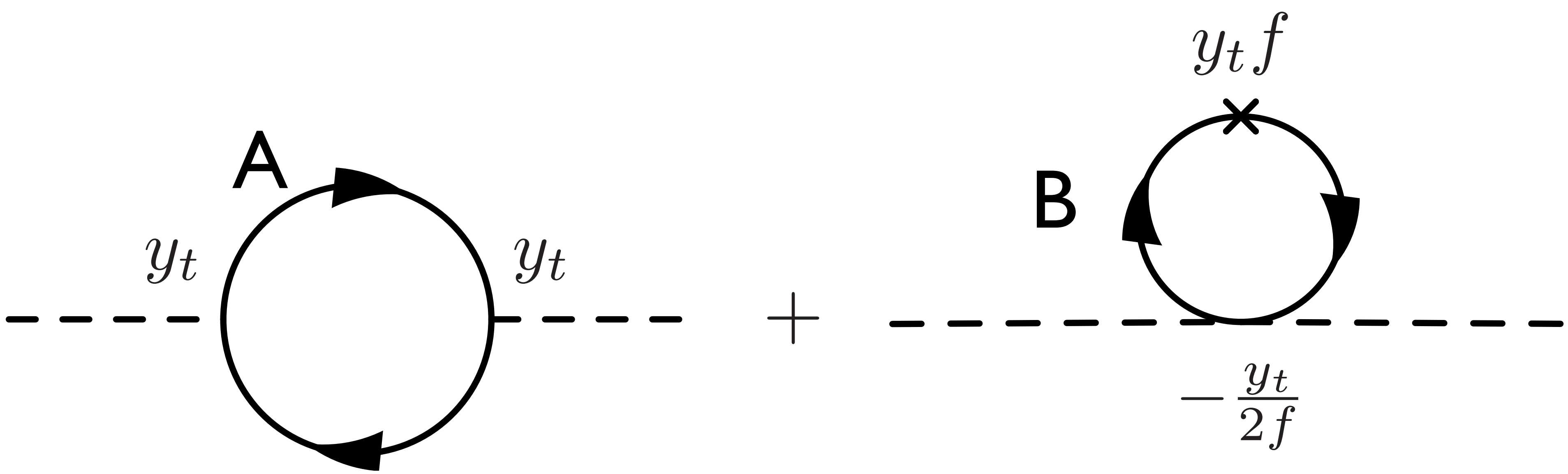
$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} = e^{i h^a t^a / f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

$$\vdots$$

$$H = \begin{pmatrix} \mathbf{h} \frac{i f}{\sqrt{\mathbf{h}^\dagger \mathbf{h}}} \sin \frac{\sqrt{\mathbf{h}^\dagger \mathbf{h}}}{f} \\ 0 \\ f \cos \frac{\sqrt{\mathbf{h}^\dagger \mathbf{h}}}{f} \end{pmatrix} = \begin{pmatrix} i\mathbf{h} \\ 0 \\ f - \frac{1}{2f} \sqrt{\mathbf{h}^\dagger \mathbf{h}} \end{pmatrix} + \ldots$$

Top sector

$$\mathcal{L} \sim y\, Q_A H U_A^c + y\, Q_B \left(f - \frac{|H|^2}{2f^2} \right) U_B^c$$



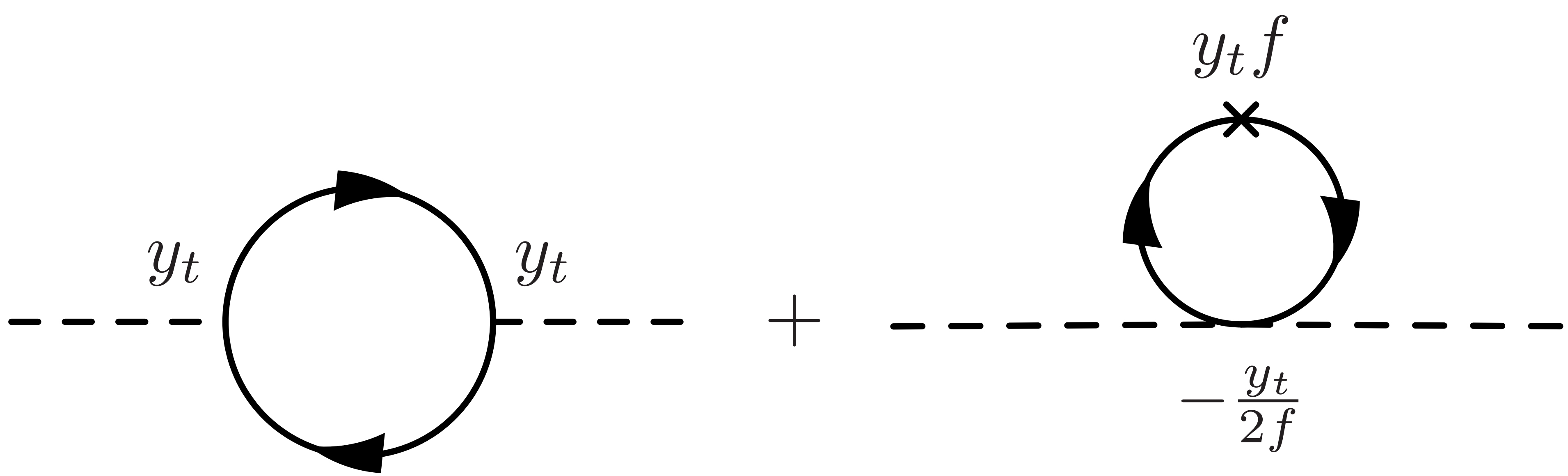
Quadratic divergences cancel, states running in loop have no SM charge, same spin

(3 is just a number)

Cancelling states not coloured: small production x-sec at LHC

To separate v and f and make the SM Higgs lie mostly in A introduce soft breaking $\mu_A^2 |H_A|^2$

$$\langle H_A \rangle = v_{SM} \ll \langle H_B \rangle = f \sim 1\,\mathrm{TeV}$$



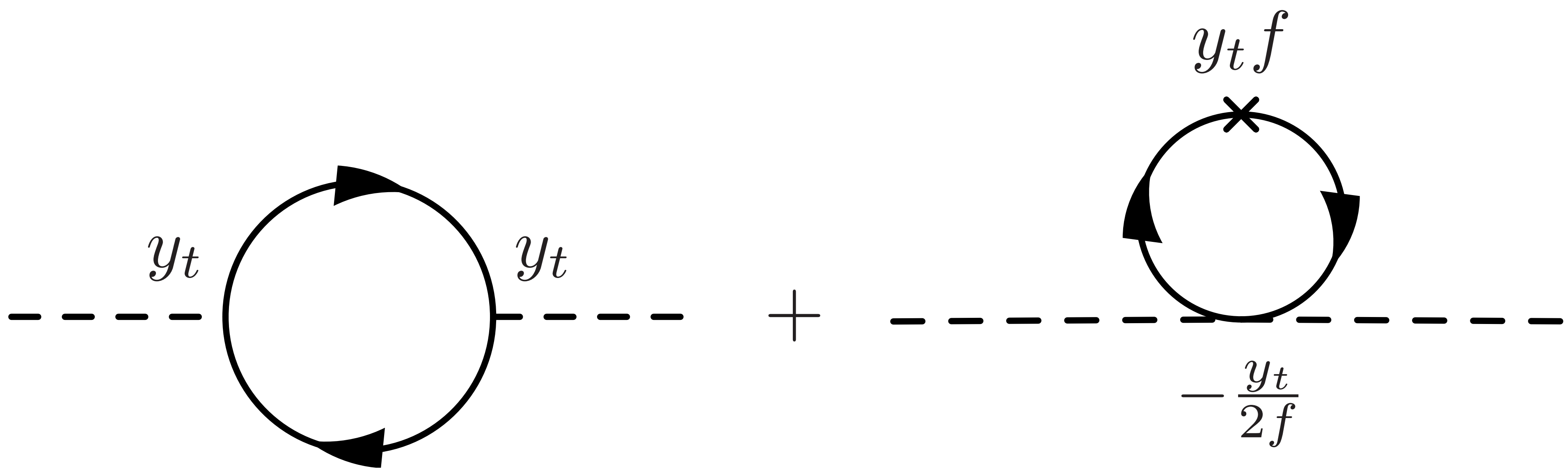
Tuning grows with f/v

$$\delta m_h^2 \sim \frac{3 y_t m_t^2}{4\pi^2} \left(\frac{f}{v}\right)^2 \log \frac{\Lambda v}{m_t f}$$

$$\Delta = \left| \frac{2\delta m_h^2}{m_h^2} \right|^{-1}$$

To separate v and f and make the SM Higgs lie mostly in A introduce soft breaking $\mu_A^2 |H_A|^2$

$$\langle H_A \rangle = v_{SM} \ll \langle H_B \rangle = f \sim 1\,\mathrm{TeV}$$



Tuning grows with f/v

$$\delta m_h^2 \sim \frac{3 y_t m_t^2}{4\pi^2} \left(\frac{f}{v}\right)^2 \log \frac{\Lambda v}{m_t f}$$

$$\Delta = \left| \frac{2\delta m_h^2}{m_h^2} \right|^{-1}$$

f/v~3-5

$$V = -m^2 \left(H_A^\dagger H_A + H_B^\dagger H_B \right) + \lambda \left(H_A^\dagger H_A + H_B^\dagger H_B \right)^2$$

Higgs portal between A and B sectors

- Higgs mixing and corrections to Higgs pheno at $\frac{v^2}{f^2}$
- Higgs invisible decay width, to light B sector stuff