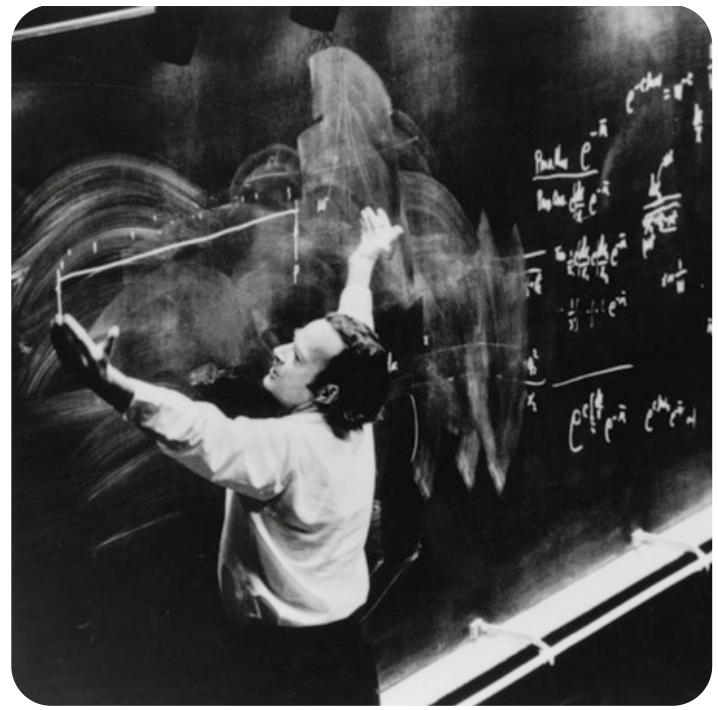
Beyond the SM 3/4

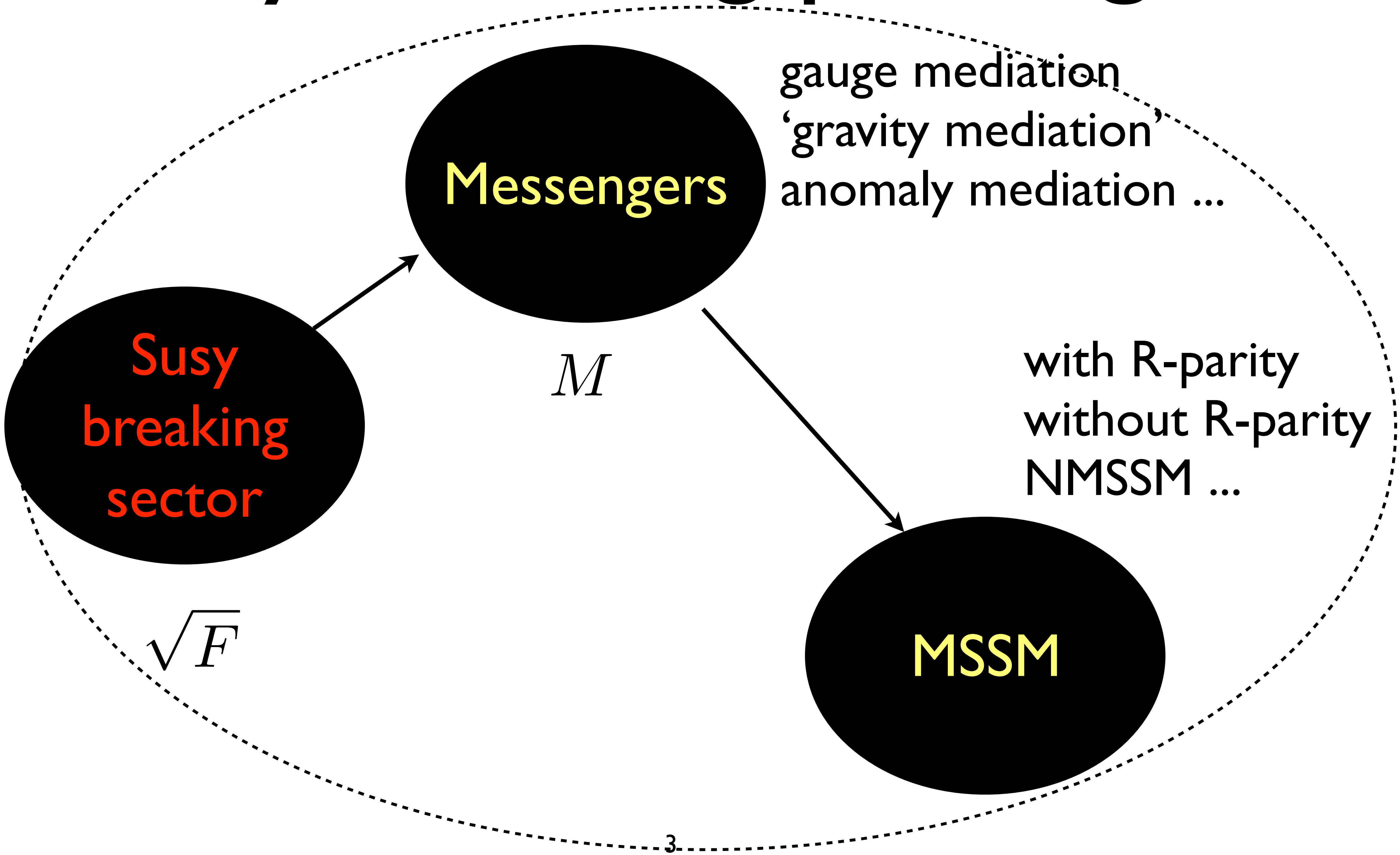


Andreas Weiler
(TU Munich)

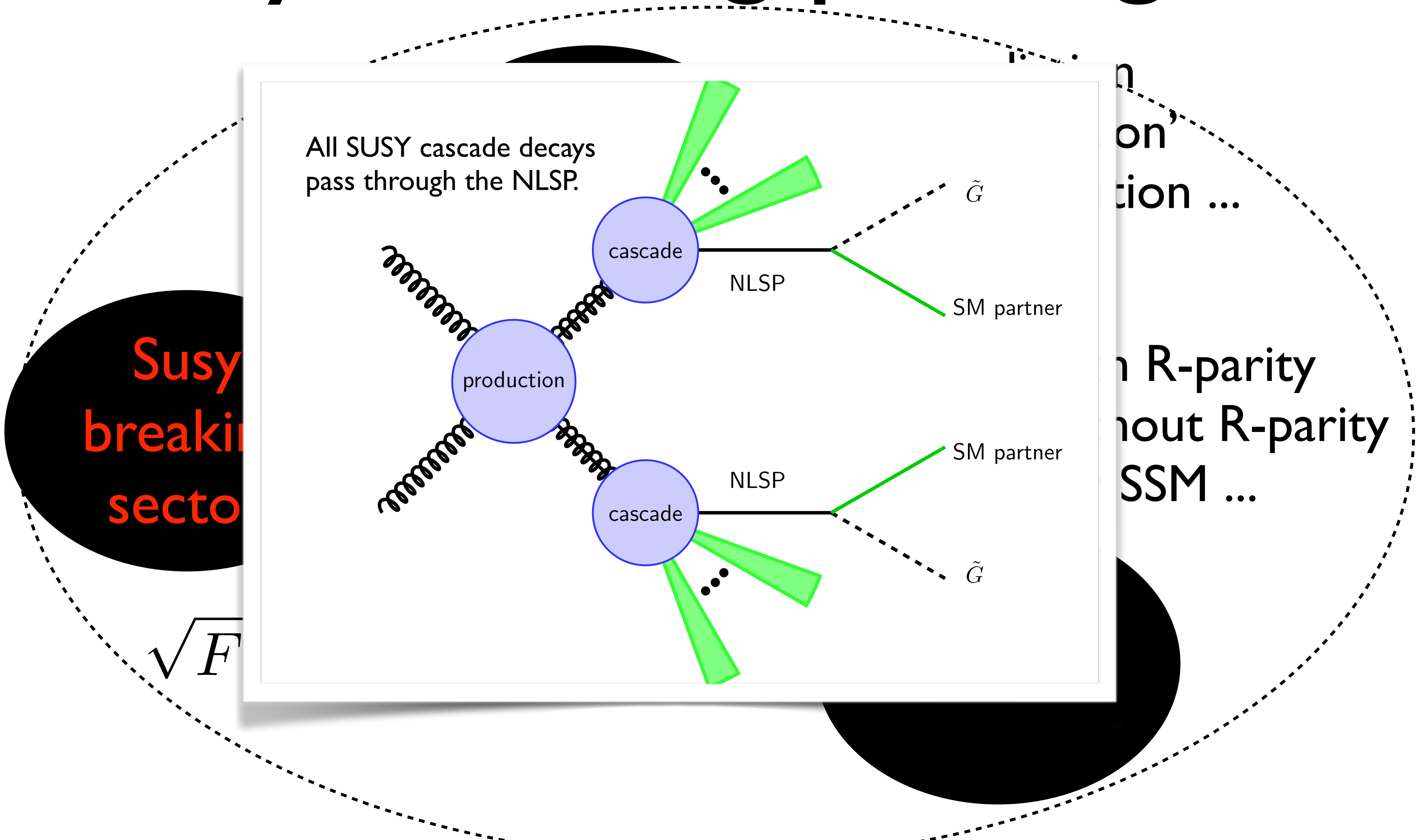
Summer school Slovenia
2019-26-8

recap…

Susy breaking paradigm

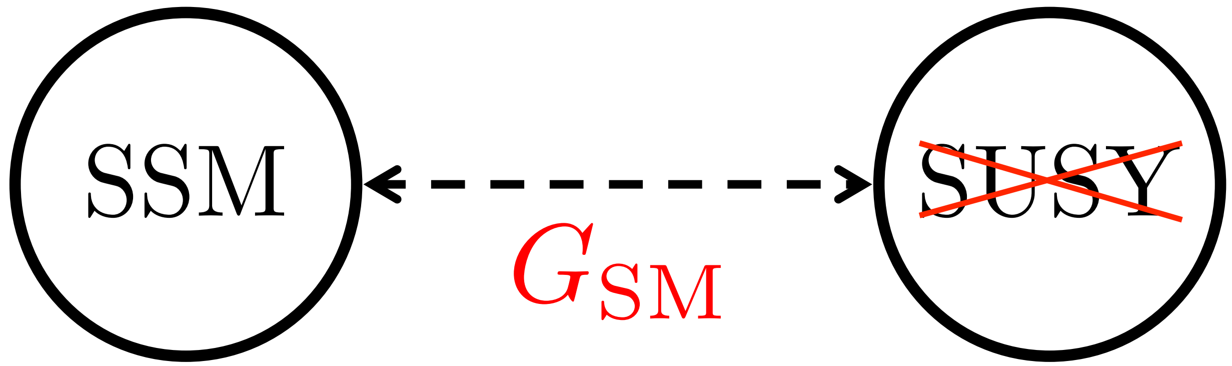


Susy breaking paradigm



Gauge Mediation

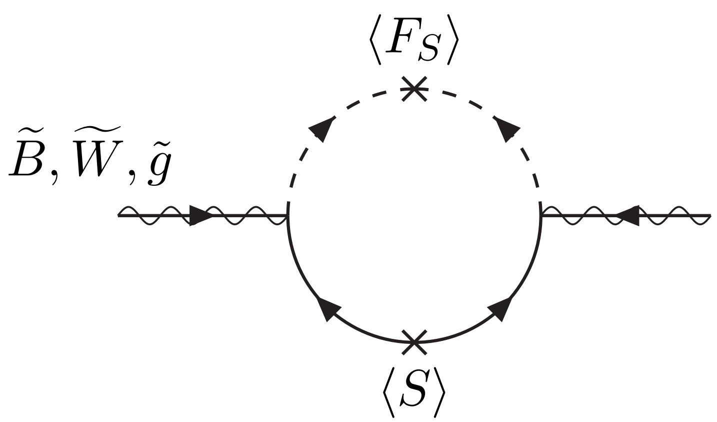
see e.g. Giudice/Rattazzi review



$$G_{\rm SM} = SU(3) \times SU(2) \times U(1)$$

Degenerate quarks at the messenger scale, no flavor problem.

Gauge mediation



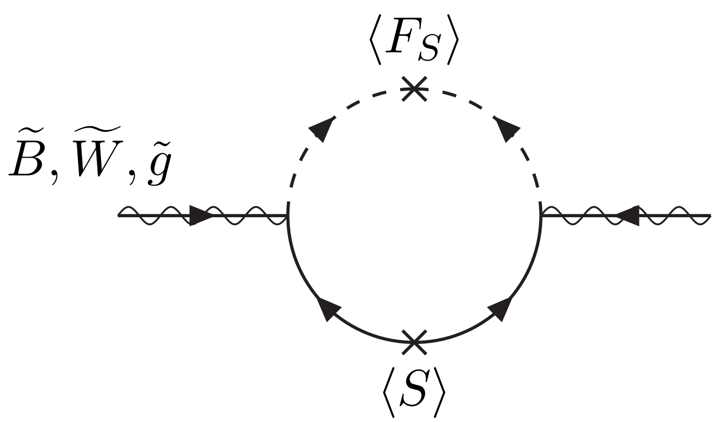
1 loop gaugino masses

$$M_a = \frac{\alpha_a}{4\pi} M_S, \quad M_S = \frac{\langle F_S \rangle}{\langle S \rangle}$$

Messengers (S) feel SUSY breaking, charged under SM gauge symmetries.

$\sqrt{F}$ Susy breaking order parameter

Gauge mediation



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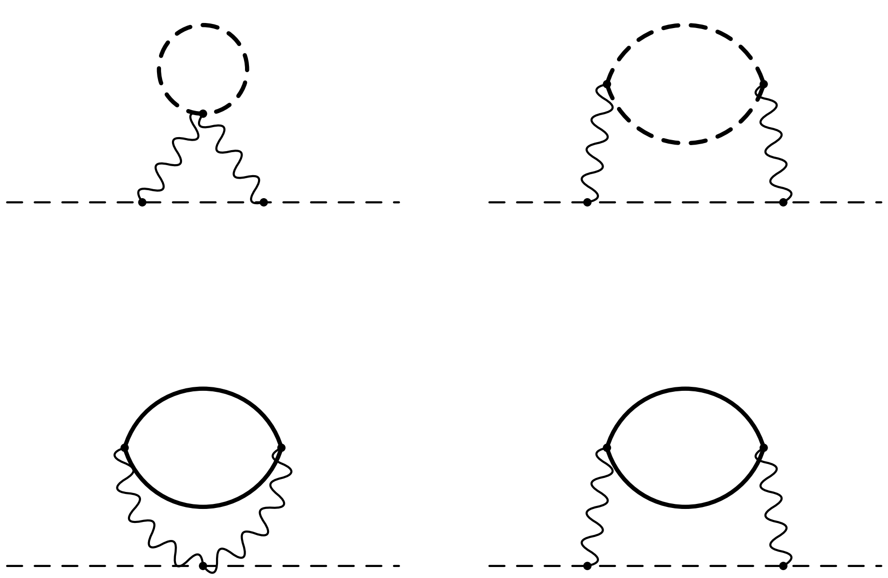


+ ....

2loop squark masses

$$m^2_{\rm scalar} = \left(\frac{\alpha}{4\pi}\right)^2 M_S^2$$

Gravitino

- SUSY spontaneously broken: goldstino
- Fermionic component of super-field w/ vev
- Becomes longitudinal component of gravitino (spin 3/2)
- If <F> << M_{pl} (e.g gauge med., gravitino LSP): gravitino LSP & NLSP can be long lived

sparticle particle gravitino

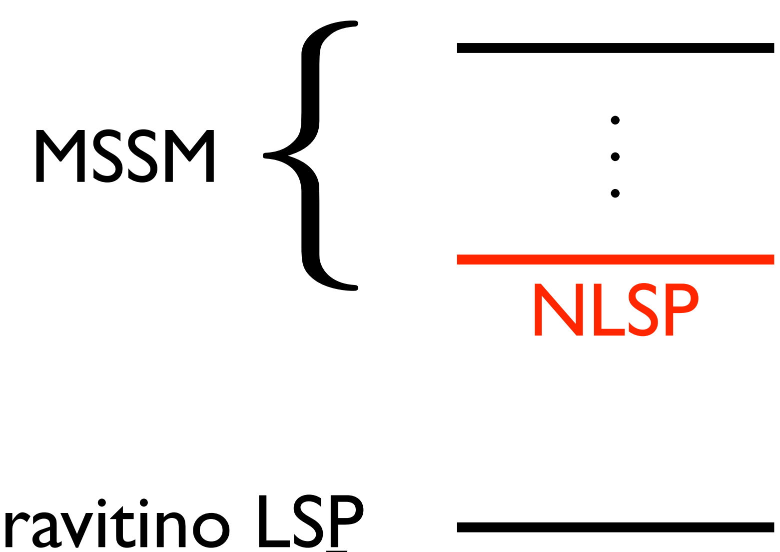
$$\Gamma(\tilde{X} \to X\tilde{G}) = \frac{m_{\tilde{X}}^5}{16\pi\langle F\rangle^2}\left(1 - \frac{m_X^2}{m_{\tilde{X}}^2}\right)^4$$

Gauge mediation

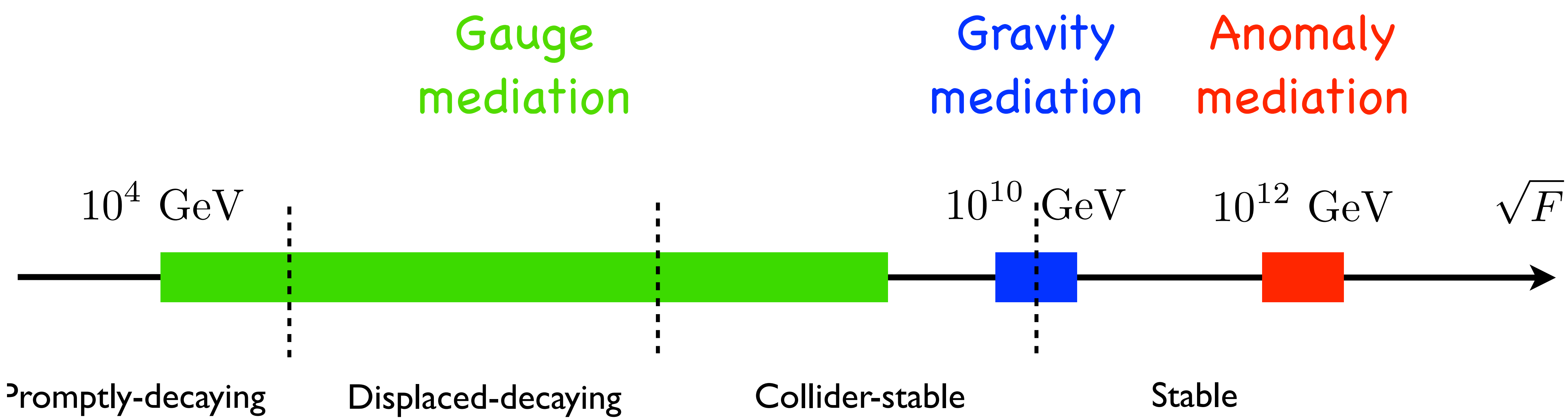
- Gravitino LSP is a universal prediction of gauge mediation models:

$$m_{3/2} = \frac{F}{\sqrt{3} M_{pl}} \quad (\sim \mathrm{eV} - \mathrm{GeV})$$

- Lightest MSSM sparticle becomes the next-to-lightest superpartner (NLSP).

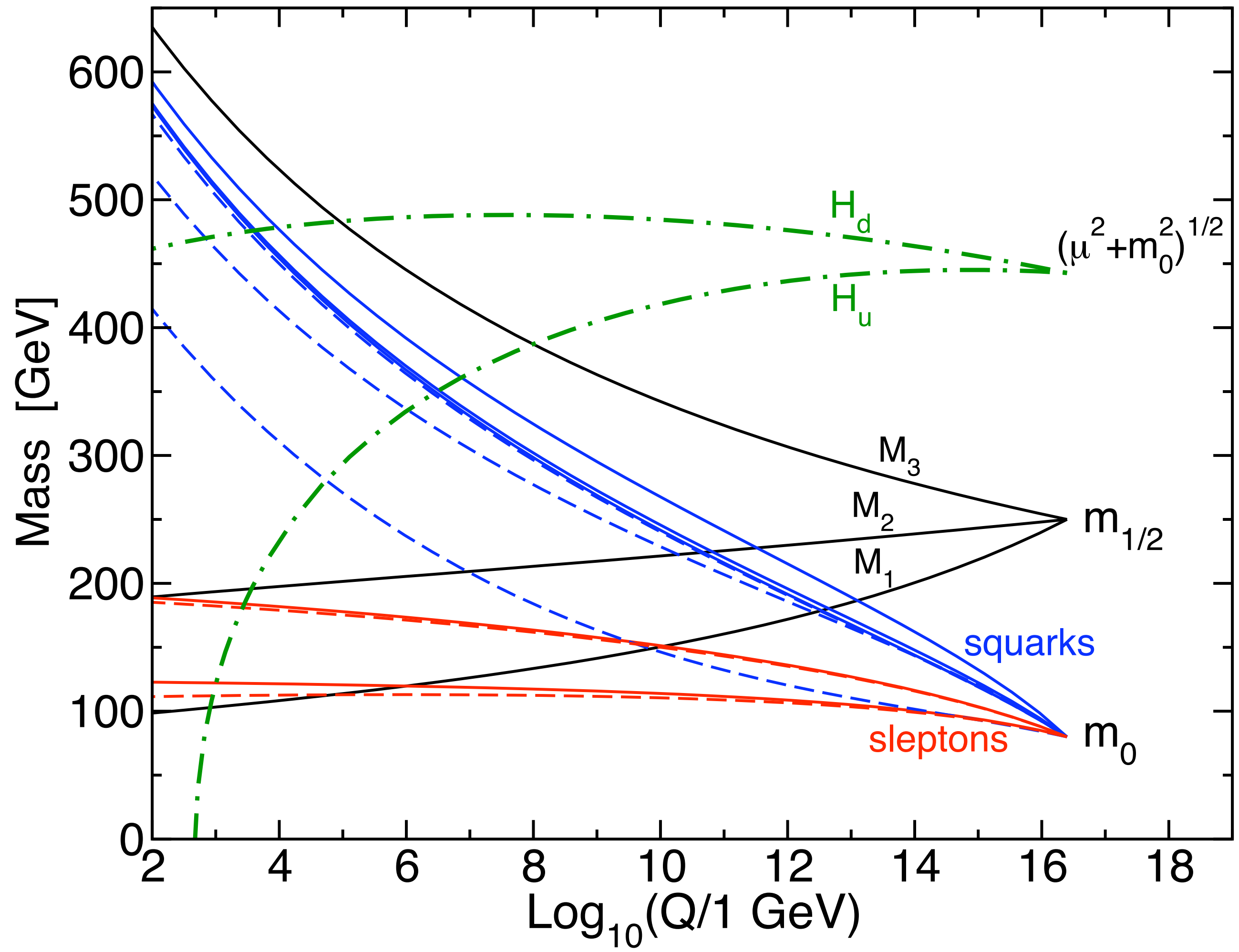


The scale of SUSY breaking determines the mediation mechanism.



It also determines the behavior of the lightest MSSM superpartner.

RGE evolution



radiative
EWSB

RGE evolution: masses evolve with scale

colored particles 'run' faster, large $\mathcal{O}(\text{several})$ corrections

Higgs potential

$$V_H = (\mu^2 + m_{H_u}^2)|H_u|^2 + (\mu^2 + m_{H_d}^2)|H_d|^2$$

$$- B_\mu H_u \cdot H_d + h.c. \boxed{+ \frac{1}{2} g^2 |H_u^\dagger H_d|^2}$$

$$\boxed{+ \frac{1}{8} (g^2 + g'^2) \left(|H_u|^2 - |H_d|^2\right)^2}$$

Neutral Higgs potential

$$V = \left(|\mu|^2 + m_{H_u}^2\right)|H_u^0|^2 + \left(|\mu|^2 + m_{H_d}^2\right)|H_d^0|^2$$

$$- B_\mu \left(H_u^0 H_d^0 + h.c.\right) \boxed{+\frac{1}{8}\left(g^2 + g'^2\right)\left(|H_u^0|^2 - |H_d^0|^2\right)^2}$$

quartic fixed by gauge interactions!

short digression →

Super YM

So full Lagrangian:

gauge trace

$$\mathcal{L} = -\frac{1}{4g^2}\,\mathrm{Tr}\left(W^\alpha W_\alpha\big|_{\theta^2} + \bar{W}_{\dot\alpha}\bar{W}^{\dot\alpha}\big|_{\bar\theta^2}\right)$$

$$+\,\Phi^\dagger e^V \Phi\big|_{\theta^2\bar\theta^2} + W(\Phi)\big|_{\theta^2} + h.c.$$

Super YM

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$$\mathcal{L} = \frac{1}{4g^2} \left(W^{a\alpha} W^a_\alpha \big|_{\theta^2} + \bar{W}^a_{\dot\alpha} \bar{W}^{a\dot\alpha} \big|_{\bar\theta^2} \right)$$

$$= -1/4 \, F^a_{\mu\nu} F^{a\mu\nu} + i \bar\lambda^a D_\mu \bar\sigma^\mu \lambda^a + \frac{1}{2} D^a D^a$$

Super YM

So full Lagrangian:

gauge trace

$$\mathcal{L} = -\frac{1}{4g^2} \mathrm{Tr}\left(W^\alpha W_\alpha \big|_{\theta^2} + \bar{W}_{\dot\alpha} \bar{W}^{\dot\alpha} \big|_{\bar\theta^2} \right)$$

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$$\Phi^\dagger e^V \Phi \big|_{\theta^2\bar\theta^2} = |D_\mu \varphi|^2$$

$$+ i \bar\Psi D_\mu \bar\sigma^\mu \Psi + F^* F$$

$$+ i\sqrt{2} \left(\varphi^* T^a \lambda^a \Psi + h.c. \right)$$

$$+ \varphi^* T^a D^a \varphi$$

Need to integrate out D^a $\downarrow$ new source for scalar potential.

Full scalar potential

$$V_D = \frac{1}{2} g^2 \sum_a \left| \sum_\varphi \varphi_i^* T^a \varphi_i \right|^2$$

$$V_F = \sum_i \left| \frac{\partial W}{\partial \varphi_i} \right|^2$$

$V(\varphi) \geq 0$ as expected...

Neutral Higgs potential

$$V = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - B_\mu (H_u^0 H_d^0 + h.c.) \boxed{+\frac{1}{8}(g^2+g'^2)\left(|H_u^0|^2 - |H_d^0|^2\right)^2}$$

quartic fixed by gauge interactions!

Higgs spectrum

$$\begin{aligned} V(H_u^0, H_d^0) &= (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b\, H_u^0 H_d^0 + h.c.) \\ &\quad + \tfrac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2. \end{aligned}$$

- Supersymmetry: gauge interactions always come with quartic scalar interactions (*D*-term potential)

$$\frac{1}{8}\left(g^2 + g'^2\right)\left(\left|H_u^0\right|^2 - \left|H_d^0\right|^2\right)^2$$

- Implication: Higgs quartic related to gauge couplings, which also determine *W*, *Z* masses: tree-level bound

$$m_h \leq m_Z \cos(2\beta)$$

Higgs spectrum

$$V(H_u^0, H_d^0) = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b\, H_u^0 H_d^0 + h.c.) + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2.$$

- Supersymmetry: gauge interactions always come with quartic scalar interactions (*D*-term potential)

$$\frac{1}{8}\left(g^2 + g'^2\right)\left(\left|H_u^0\right|^2 - \left|H_d^0\right|^2\right)^2$$

- Implication: Higgs
also determine *W*,

Higgs mass maximized at *large* tan beta.

$$m_h \leq m_Z \cos(2\beta)$$

Susy and the 125 GeV Higgs

MSSM:

$$m_h^2 = \boxed{m_Z^2 c_{2\beta}^2} + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

Haber, Hempfling '91

Susy and the 125 GeV Higgs

MSSM:

tree-level bound < M_Z

Haber, Hempfling '91

$$m_h^2 = \boxed{m_Z^2 c_{2\beta}^2} + \frac{3 m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right)$$

Susy and the 125 GeV Higgs

MSSM:

Logarithmic growth with M_{SUSY}

91

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\boxed{\log\left(\frac{M_S^2}{m_t^2}\right)} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

Susy and the 125 GeV Higgs

MSSM:

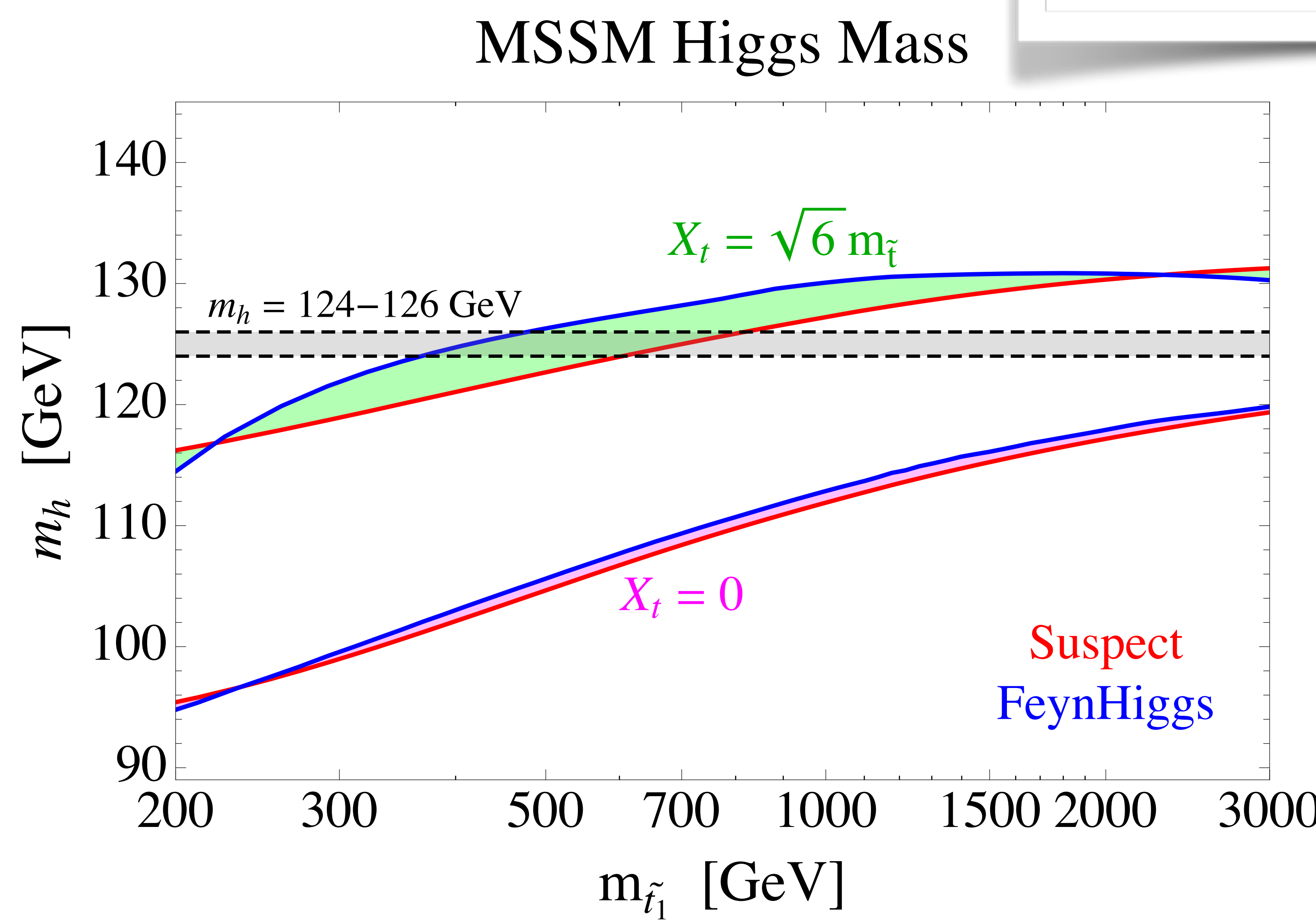
Quadratic term from stop mixing

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \boxed{\frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)}\right)$$

more: Haber, Hempfling, Hoang, Ellis, Ridolfi, Zwirner, Casas, Espinosa, Quiros, Riotto, Carena, Wagner, Degrassi, Heinemeyer, Hollik, Slavich, Weiglein

MSSM vs. the 125 GeV Higgs

$$X_t = A_t - \mu \cot \beta$$



$$\mathcal{L} \supset A_t Q \bar{u} H_u + c.c.$$

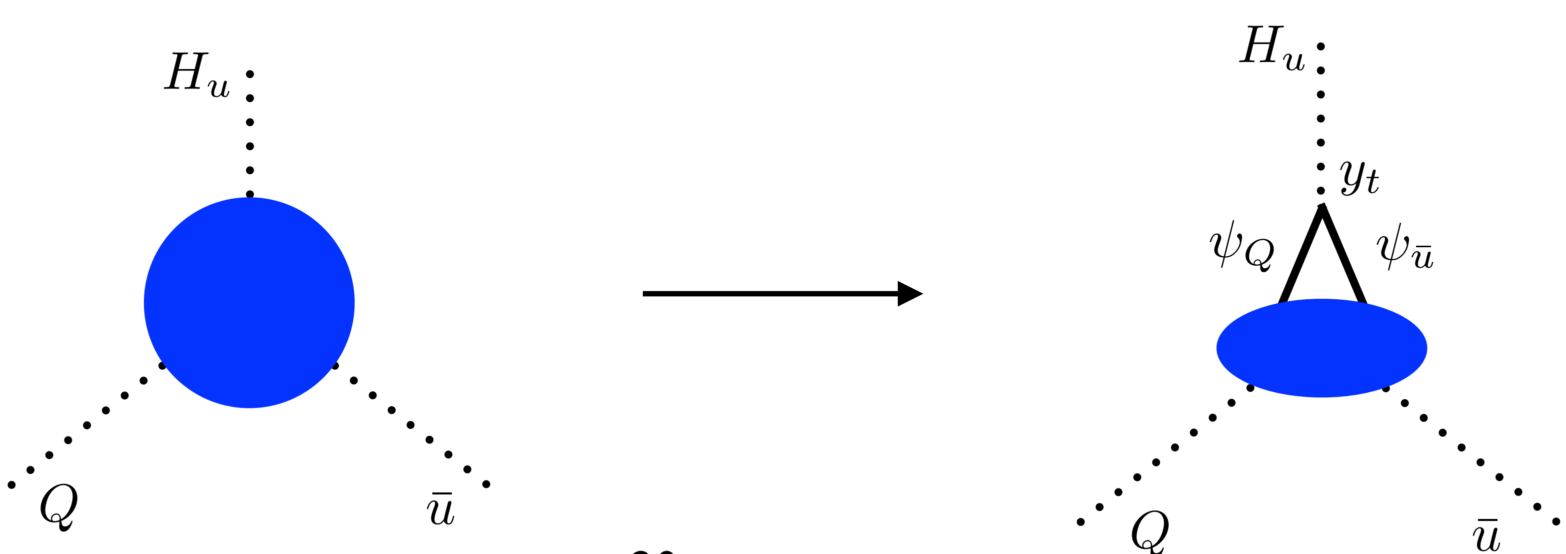
Hall, Pinner, Rudermann

A terms in gauge mediation?

$$\mathcal{L} \supset A_t Q \bar{u} H_u + c.c.$$

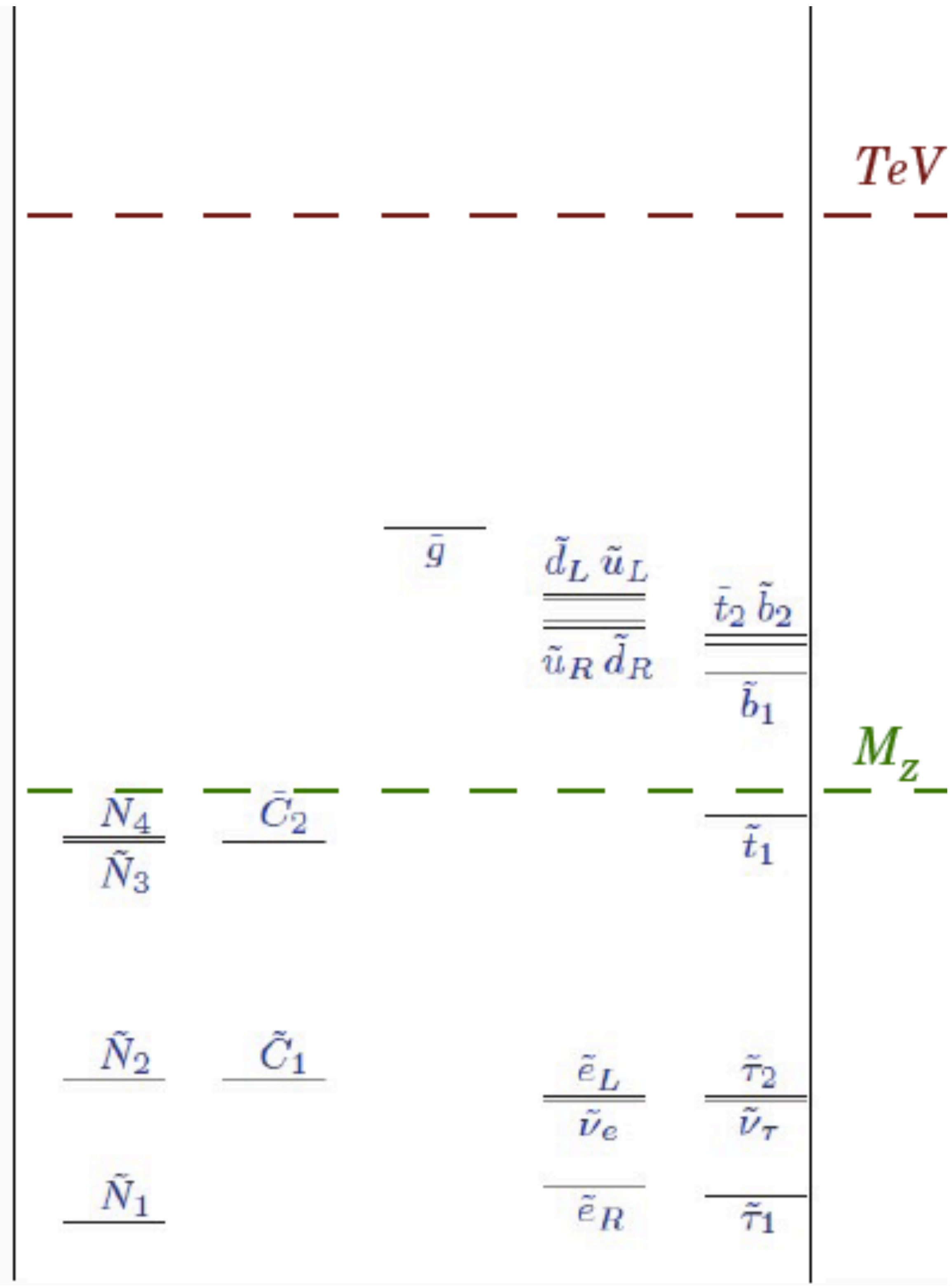
Like Yukawa couplings, break chiral (flavor) symmetries

Can not be induced by gauge interactions alone (those leave chiral symmetries intact)→

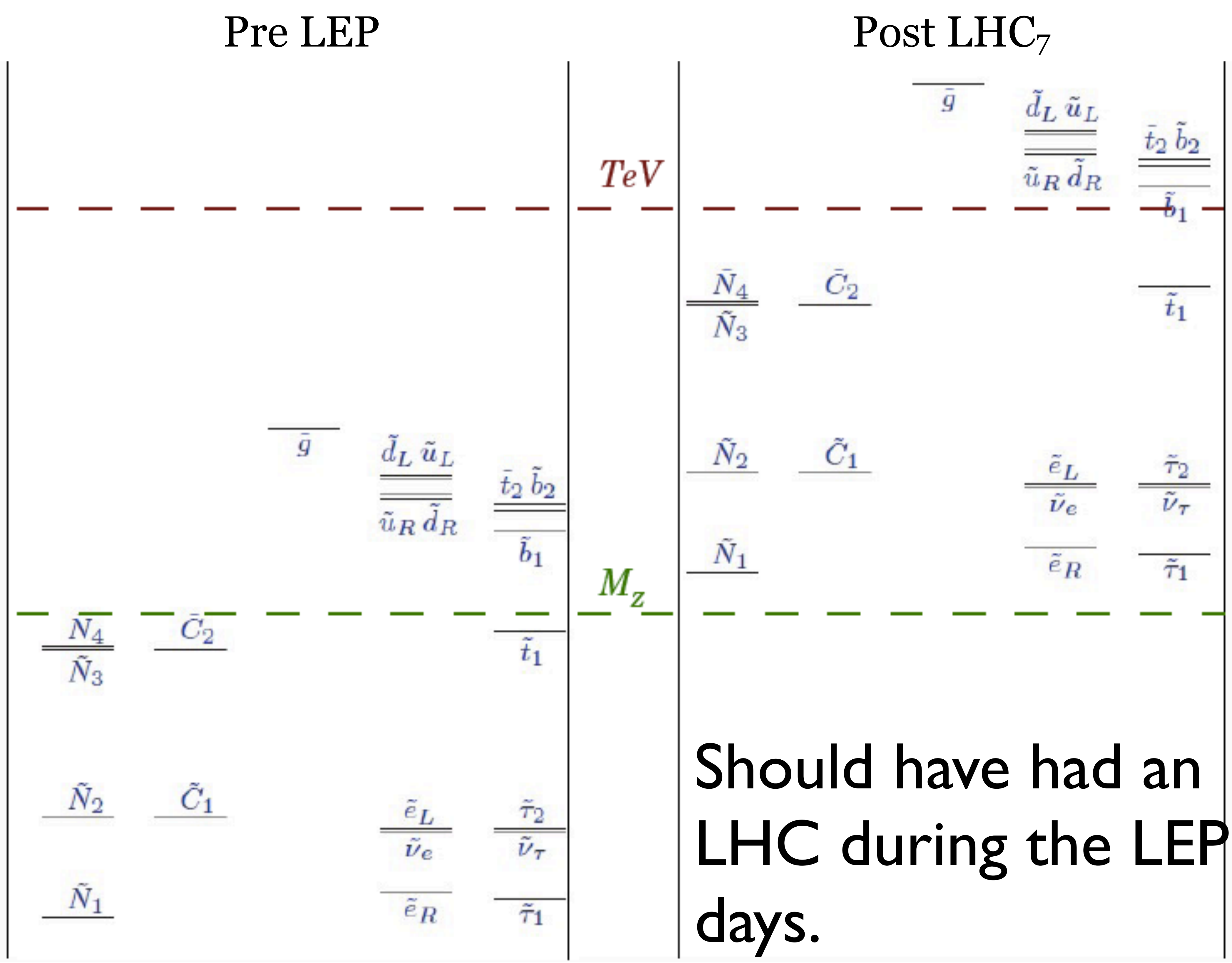


Direct Searches for Supersymmetry

Pre LEP

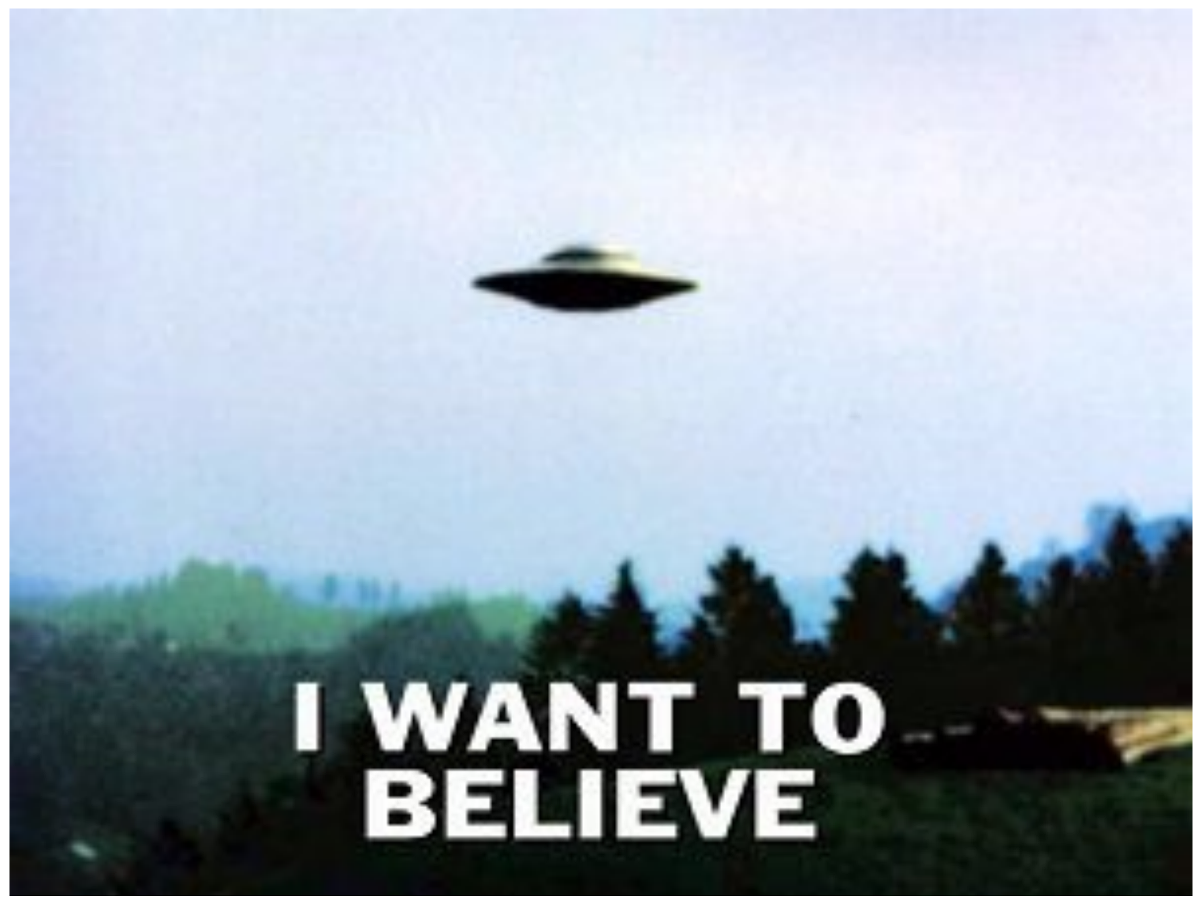


TeV
$\tilde{g}$
$\tilde{d}_L\ \tilde{u}_L$
$\tilde{t}_2\ \tilde{b}_2$
$\tilde{u}_R\ \tilde{d}_R$
$\tilde{b}_1$
M_Z
$\tilde{N}_4$
$\tilde{C}_2$
$\tilde{t}_1$
$\tilde{N}_3$
$\tilde{N}_2$
$\tilde{C}_1$
$\tilde{e}_L$
$\tilde{\tau}_2$
$\tilde{\nu}_e$
$\tilde{\nu}_\tau$
$\tilde{N}_1$
$\tilde{e}_R$
$\tilde{\tau}_1$



Should have had an LHC during the LEP days.

Where is everybody?



ATLAS SUSY Searches* - 95% CL Lower Limits

July 2019

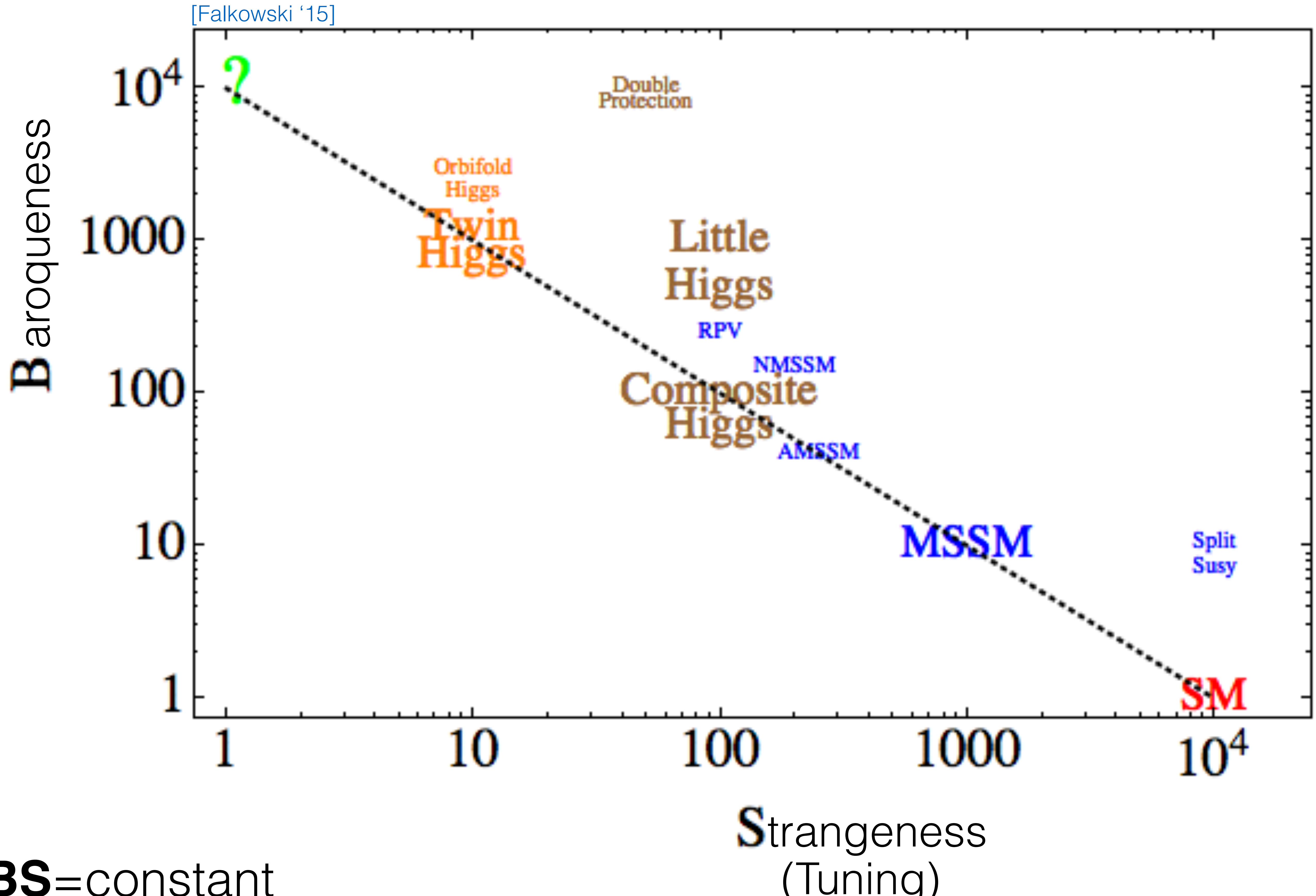
ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt\ [\mathrm{fb}^{-1}]$	Mass limit		Conditions	Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	$0\ e,\mu$	2-6 jets	E_T^{miss}	36.1	$\tilde{q}$ [2×, 8× Degen.]	0.9, 1.55	$m(\tilde{\chi}_1^0)$<100 GeV	1712.02332
		mono-jet	1-3 jets	E_T^{miss}	36.1	$\tilde{q}$ [1×, 8× Degen.]	0.43, 0.71	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	$0\ e,\mu$	2-6 jets	E_T^{miss}	36.1	$\tilde{g}$	2.0	$m(\tilde{\chi}_1^0)$<200 GeV	1712.02332
						$\tilde{g}$	Forbidden 0.95-1.6	$m(\tilde{\chi}_1^0)$=900 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$3\ e,\mu$	4 jets		36.1	$\tilde{g}$	1.85	$m(\tilde{\chi}_1^0)$<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	E_T^{miss}	36.1	$\tilde{g}$	1.2	$m(\tilde{g})$-$m(\tilde{\chi}_1^0)$=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	$0\ e,\mu$	7-11 jets	E_T^{miss}	36.1	$\tilde{g}$	1.8	$m(\tilde{\chi}_1^0)$ <400 GeV	1708.02794
		SS e,μ	6 jets		139	$\tilde{g}$	1.15	$m(\tilde{g})$-$m(\tilde{\chi}_1^0)$=200 GeV	ATLAS-CONF-2019-015
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	$3\ b$	E_T^{miss}	79.8	$\tilde{g}$	2.25	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$	1.25	$m(\tilde{g})$-$m(\tilde{\chi}_1^0)$=300 GeV	ATLAS-CONF-2019-015
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$	Forbidden 0.9	$m(\tilde{\chi}_1^0)$=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.58-0.82	$m(\tilde{\chi}_1^0)$=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5	1708.09266
			Multiple		139	$\tilde{b}_1$	Forbidden 0.74	$m(\tilde{\chi}_1^0)$=200 GeV, $m(\tilde{\chi}_1^\pm)$=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	ATLAS-CONF-2019-015
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	$0\ e,\mu$	$6\ b$	E_T^{miss}	139	$\tilde{b}_1$	Forbidden 0.23-1.35	$\Delta m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=130 GeV, $m(\tilde{\chi}_1^0)$=100 GeV	SUSY-2018-31
						$\tilde{b}_1$	0.23-0.48	$\Delta m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=130 GeV, $m(\tilde{\chi}_1^0)$=0 GeV	SUSY-2018-31
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	E_T^{miss}	36.1	$\tilde{t}_1$	1.0	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$	$1\ e,\mu$	3 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$	0.44-0.59	$m(\tilde{\chi}_1^0)$=400 GeV	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 b\nu, \tilde{\tau}_1\to\tau\tilde{G}$	$1\ \tau + 1\ e,\mu,\tau$	2 jets/1 b	E_T^{miss}	36.1	$\tilde{t}_1$	1.16	$m(\tilde{\tau}_1)$=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$	$0\ e,\mu$	$2\ c$	E_T^{miss}	36.1	$\tilde{c}$	0.85	$m(\tilde{\chi}_1^0)$=0 GeV	1805.01649
						$\tilde{t}_1$	0.46	$m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}_1^0)$=50 GeV	1805.01649
		$0\ e,\mu$	mono-jet	E_T^{miss}	36.1	$\tilde{t}_1$	0.43	$m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}_1^0)$=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e,μ	$4\ b$	E_T^{miss}	36.1	$\tilde{t}_2$	0.32-0.88	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$= 180 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	$3\ e,\mu$	$1\ b$	E_T^{miss}	139	$\tilde{t}_2$	Forbidden 0.86	$m(\tilde{\chi}_1^0)$=360 GeV, $m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$= 40 GeV	ATLAS-CONF-2019-016
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e,μ		E_T^{miss}	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.6	$m(\tilde{\chi}_1^0)$=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.205	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=5 GeV	ATLAS-CONF-2019-014
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	$2\ e,\mu$		E_T^{miss}	139	$\tilde{\chi}_1^\pm$	0.42	$m(\tilde{\chi}_1^0)$=0	ATLAS-CONF-2019-008
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	0-1 e,μ	$2\ b/2\ \gamma$	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	Forbidden 0.74	$m(\tilde{\chi}_1^0)$=70 GeV	ATLAS-CONF-2019-019, ATLAS-CONF-2019-XYZ
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	$2\ e,\mu$		E_T^{miss}	139	$\tilde{\chi}_1^\pm$	1.0	$m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2019-008
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau}\to\tau\tilde{\chi}_1^0$	$2\ \tau$		E_T^{miss}	139	$\tilde{\tau}$ [$\tilde{\tau}_L, \tilde{\tau}_{R,L}$]	0.16-0.3, 0.12-0.39	$m(\tilde{\chi}_1^0)$=0	ATLAS-CONF-2019-018
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	$2\ e,\mu$	0 jets	E_T^{miss}	139	$\tilde{\ell}$	0.7	$m(\tilde{\chi}_1^0)$=0	ATLAS-CONF-2019-008
		$2\ e,\mu$	≥ 1	E_T^{miss}	139	$\tilde{\ell}$	0.256	$m(\tilde{\ell})$-$m(\tilde{\chi}_1^0)$=10 GeV	ATLAS-CONF-2019-014
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	$0\ e,\mu$	$\geq 3\ b$	E_T^{miss}	36.1	$\tilde{H}$	0.13-0.23, 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		$4\ e,\mu$	0 jets	E_T^{miss}	36.1	$\tilde{H}$	0.3	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	E_T^{miss}	36.1	$\tilde{\chi}_1^\pm$	0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$	0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$	2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns]	2.05, 2.4	$m(\tilde{\chi}_1^0)$=100 GeV	1710.04901,1808.04095
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	$\tilde{\nu}_\tau$	1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	$4\ e,\mu$	0 jets	E_T^{miss}	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$]	0.82, 1.33	$m(\tilde{\chi}_1^0)$=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [$m(\tilde{\chi}_1^0)$=200 GeV, 1100 GeV]	1.3, 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5]	1.05, 2.0	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2]	0.55, 1.05	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs]	0.42, 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to q\ell$	$2\ e,\mu$	$2\ b$		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		$1\ \mu$	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0, 1.6	BR($\tilde{t}_1\to q\mu$)=100%, $\cos\theta_t$=1	ATLAS-CONF-2019-006

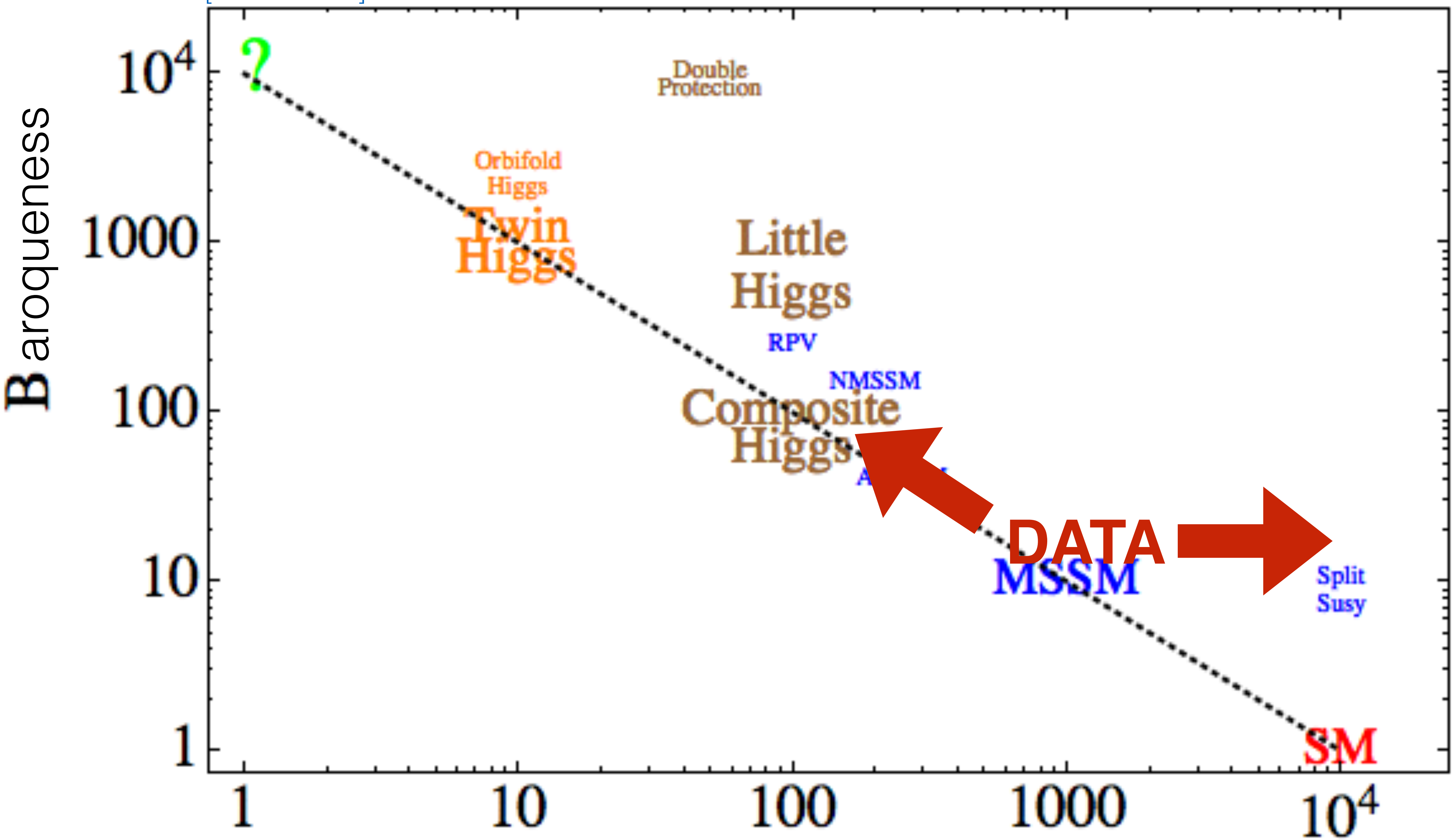
10^{-1} — 1 — **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.


[Falkowski '15]
Baroqueness
Strangeness
(Tuning)
?
Double
Protection
Orbifold
Higgs
Twin
Higgs
Little
Higgs
RPV
NMSSM
Composite
Higgs
AMSSM
MSSM
Split
Susy
SM
10^4
1000
100
10
1
1
10
100
1000
10^4

BS=constant

[Falkowski ‘15]



BS=constant

Comment on ‘beauty’

- We adapt our notation to make established physics as simple as possible, the SM is economical but not minimal

original form (1865)

$e+\frac{df}{dx}+\frac{dg}{dy}+\frac{dh}{dz}=0$	(1)	Gauss’ Law
$\mu\alpha=\frac{dH}{dy}-\frac{dG}{dz}$ $\mu\beta=\frac{dF}{dz}-\frac{dH}{dx}$ $\mu\gamma=\frac{dG}{dx}-\frac{dF}{dy}$	(2)	Equivalent to Gauss’ Law for magnetism
$P=\mu\left(\gamma\frac{dy}{dt}-\beta\frac{dz}{dt}\right)-\frac{dF}{dt}-\frac{d\Psi}{dz}$ $Q=\mu\left(\alpha\frac{dz}{dt}-\gamma\frac{dx}{dt}\right)-\frac{dG}{dt}-\frac{d\Psi}{dy}$ $R=\mu\left(\beta\frac{dx}{dt}-\alpha\frac{dy}{dt}\right)-\frac{dH}{dt}-\frac{d\Psi}{dz}$	(3)	Faraday’s Law (with the Lorentz Force and Poisson’s Law)
$\frac{d\gamma}{dy}-\frac{d\beta}{dz}=4\pi p'$ $\quad p'=p+\frac{df}{dt}$ $\frac{d\alpha}{dz}-\frac{d\gamma}{dx}=4\pi q'$ $\quad q'=q+\frac{dg}{dt}$ $\frac{d\beta}{dx}-\frac{d\alpha}{dy}=4\pi r'$ $\quad r'=r+\frac{dh}{dt}$	(4)	Ampère-Maxwell Law
$P=-\xi p \quad Q=-\xi q \quad R=-\xi r$		Ohm’s Law
$P=kf \quad Q=kg \quad R=kh$		The electric elasticity equation (**E** = **D**/ε)
$\frac{de}{dt}+\frac{dp}{dx}+\frac{dq}{dy}+\frac{dr}{dz}=0$		Continuity of charge

covariant form

$$\partial_\mu F^{\mu\nu}=\frac{1}{c}J^\nu \quad \text{and} \quad \partial_\mu {}^*F^{\mu\nu}=0,$$

http://ethw.org/Maxwell's_Equations

An analogy

An analogy

- Problem: Weak interactions

An analogy

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- Framework: Gauge theory

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- Simple theory: O(3) Schwinger Model (1957)

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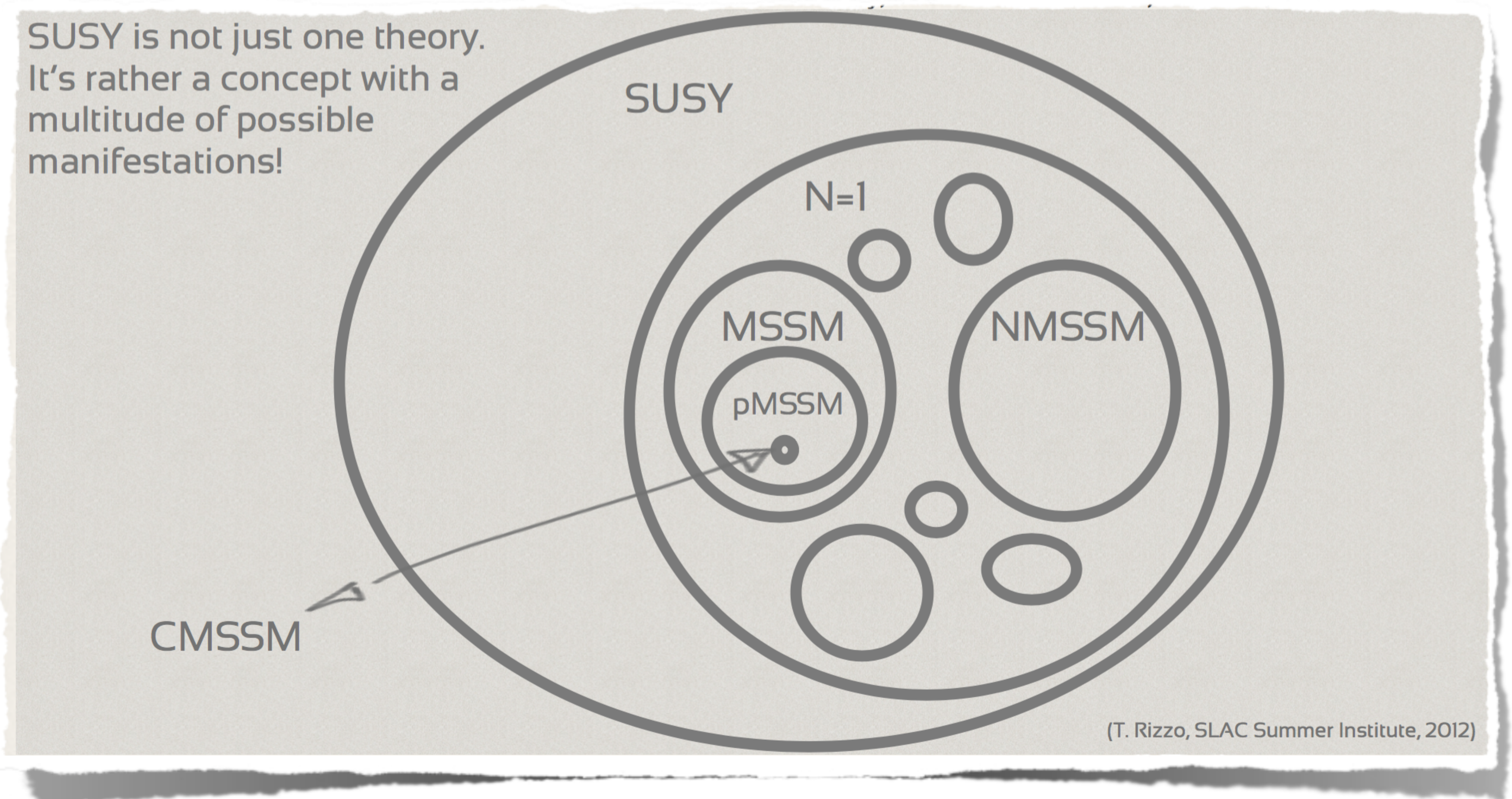
- *Framework correct! Actual realization in nature not really minimal.*

SUSY contains multitudes!



Natural EWSB & MSSM

Fine-tuning of (Higgs mass)^2

$$\frac{m_Z^2}{2} = -|\mu|^2 - \frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{\tan^2\beta - 1}$$

$$\approx -|\mu|^2 - m_{H_u}^2 - \delta m_{H_u}^2$$

Natural EWSB & SUSY

Fine-tuning of (Higgs mass)^2

$$\frac{m^2_{Higgs}}{2} = -|\mu|^2 + \ldots + \delta m^2_H$$

Natural EWSB & SUSY

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Higgsinos

Natural EWSB & SUSY

Fine-tuning of (Higgs mass)^2

$$\frac{m^2_{Higgs}}{2} = -\boxed{|\mu|^2} + \ldots + \boxed{\delta m^2_H}$$

Higgsinos

1loop $$\boxed{\delta m^2_H|_{stop}} = -\frac{3}{8\pi^2} y_t^2 \left(\underline{m^2_{U_3} + m^2_{Q_3} + |A_t|^2}\right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$$

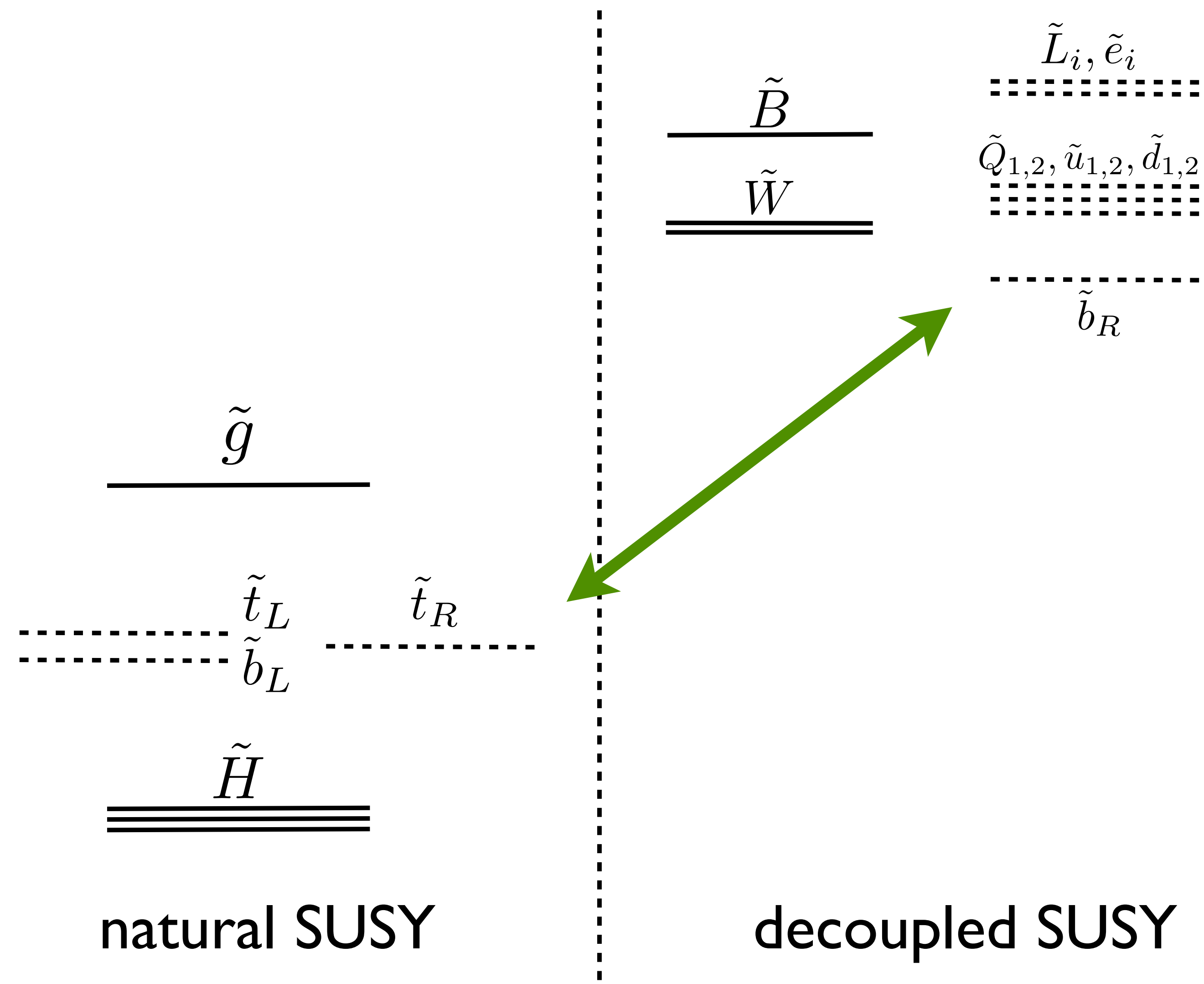
stops, sbottom$_L$

2loop $$\boxed{\delta m^2_H|_{gluino}} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) \underline{|M_3|^2} \log^2\left(\frac{\Lambda}{\text{TeV}}\right)$$

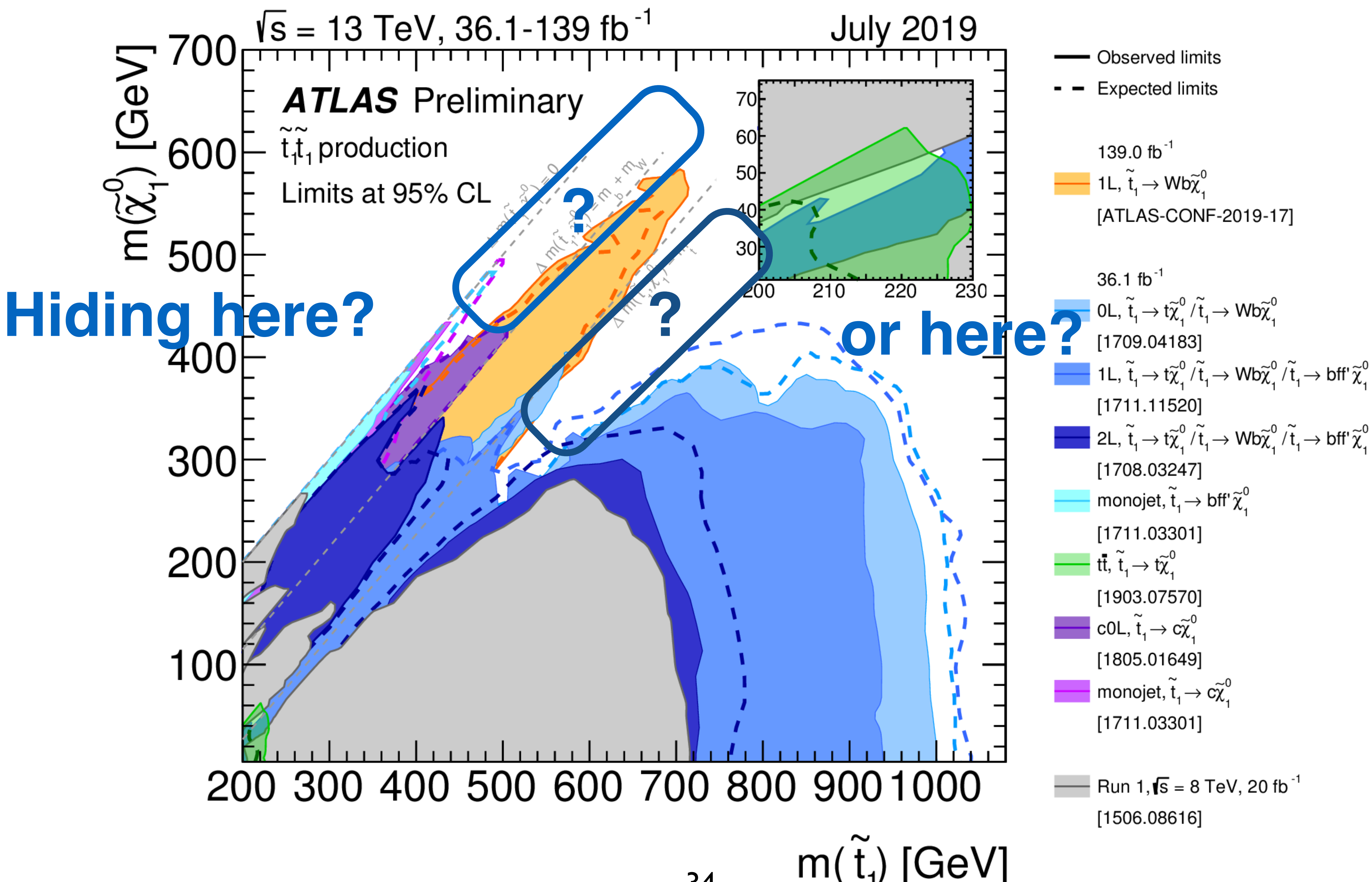
gluino

Reason for some optimism: natural susy

Scale	δm_H^2
multi TeV	<<
$\approx 1000\,\mathrm{GeV}$	2loop
$\approx 500\,\mathrm{GeV}$	1loop
$\approx 250\,\mathrm{GeV}$	tree



Stop searches



The other symmetric approach

Composite/Goldstone Higgs

Supersymmetry is a weakly coupled solution to the hierarchy problem. We can extrapolate physics to the Planck scale, complete the MSSM into a GUT.

There is another way. Nature already employs a strongly coupled mechanism to explain:

$$\Lambda_{\mathrm{QCD}} \ll M_{\mathrm{Planck}}$$

$$\sim 1\,\mathrm{GeV} \qquad 10^{19}\,\mathrm{GeV}$$

QCD

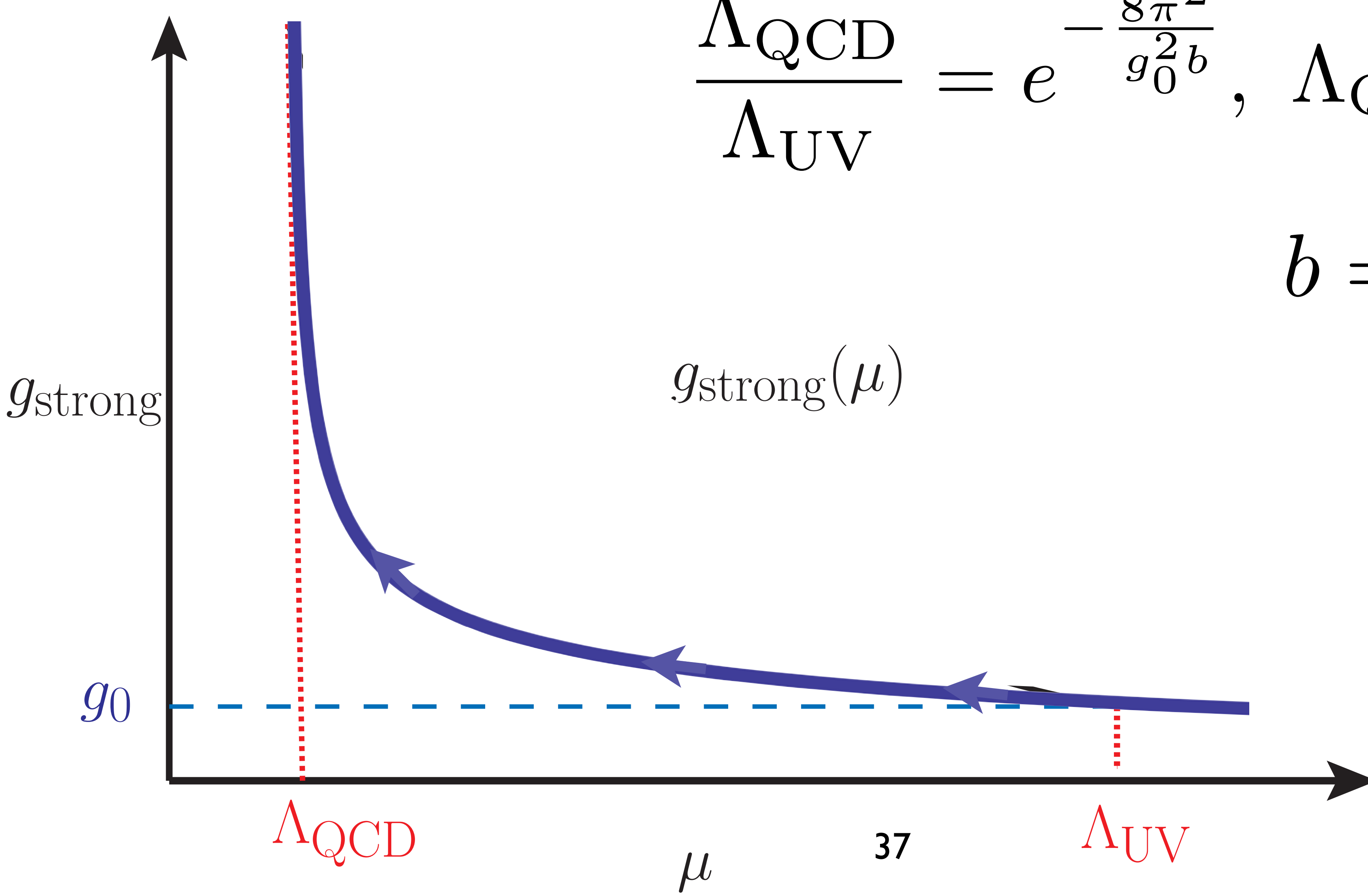
David J. Gross H. David Politzer Frank Wilczek

Fix QCD coupling at some high scale

→ exponential hierarchy generated dynamically

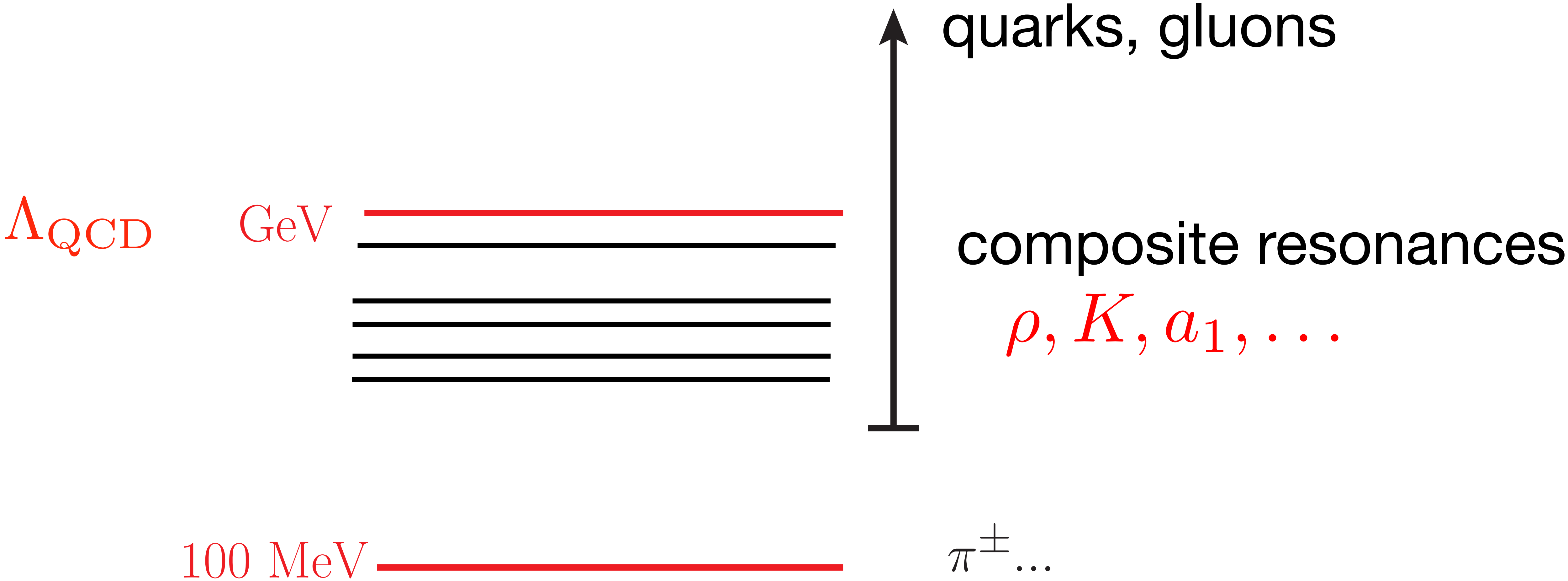
$$\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm UV}} = e^{-\frac{8\pi^2}{g_0^2 b}}, \quad \Lambda_{\rm QCD} \leq \ \text{GeV}$$

$$b = 7$$



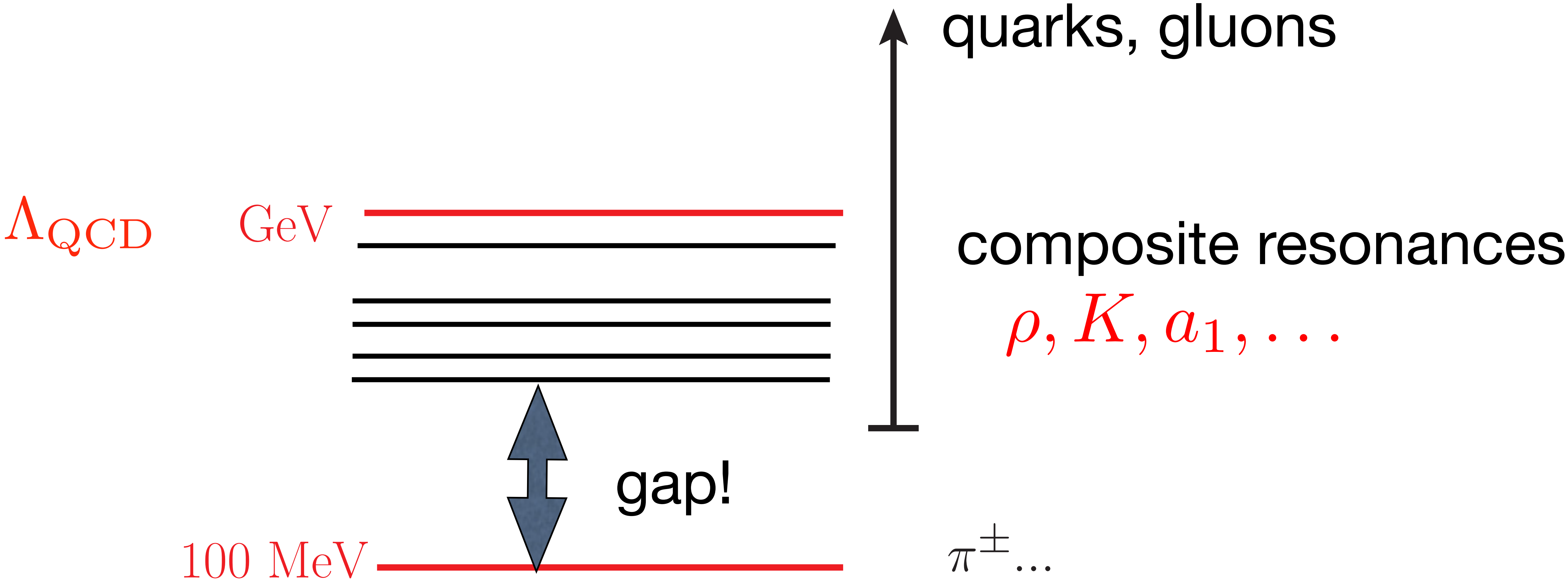
Asymptotic freedom

QCD: composite bound states



At strong coupling, new resonances are generated

QCD: composite bound states



At strong coupling, new resonances are generated

QCD vs. EWSB

QCD dynamically breaks SM gauge symmetry

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

$$\boxed{\langle \bar{q}_L q_R \rangle} \simeq \Lambda^3_{\mathrm{QCD}} \sim \ (\mathrm{GeV})^3$$

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$$\langle \bar{q}_L q_R \rangle \simeq \Lambda^3_{\mathrm{QCD}} \sim \ (\mathrm{GeV})^3$$

The QCD masses of W/Z are small

$$m_{\mathrm{W,Z}} \sim \frac{g}{4\pi} \Lambda_{\mathrm{QCD}} \sim 100 \ \mathrm{MeV}$$

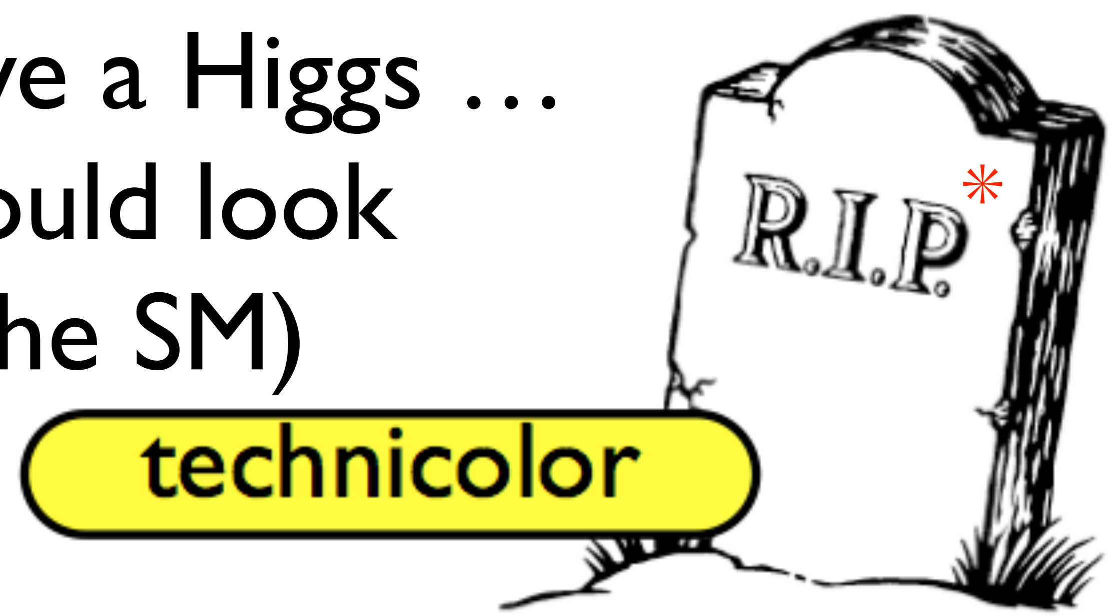
Longitudinal components of W & Z have tiny admixture of pions…

Technicolor

Scaled up version of QCD mechanism

$$\langle \bar{q}'_L q'_R \rangle \sim \Lambda^3_{\mathrm{TC}}, \quad \Lambda_{\mathrm{TC}} \sim \ \mathrm{TeV}$$

Technicolor, doesn't have a Higgs …
(or if there is one, it would look
very different from the SM)



* the Higgs as the dilaton
as the last bastion …

Composite Higgs

- Want to copy QCD, but extend pion sector (QCD: $\pi^0, \pi^\pm$)
- Higgs as a (pseudo) Goldstone boson

Goal

SUPERSYMMETRY

$$\phi \to \phi + \epsilon\psi$$
$$\psi \to \psi - i(\sigma^\nu \epsilon^\dagger)_\alpha \, \partial_\nu \phi$$

OPPOSITE-STATISTICS PARTNER
FOR EVERY SM PARTICLE

GLOBAL SYMMETRY

$$\Phi \to (1 + i\alpha T)\Phi$$

SAME-STATISTICS PARTNER
FOR EVERY SM PARTICLE

CONTRIBUTE TO THE HIGGS MASS:

$$m_h^2 \sim \frac{3y_t^2}{4\pi^2}\tilde{m}^2 \log(\Lambda^2/\tilde{m}^2)$$

adapted from N. Craig

Need to learn about goldstone bosons…

Quantum Protection

Symmetries can soften quantum behaviour

$$\mathcal{L} = |\partial_\mu \phi|^2 + \boxed{\mu^2 |\phi|^2} - \lambda |\phi|^4 + \ldots$$

breaks susy → corrections must be proportional to susy breaking

Shift symmetry

Higgs mass term can be forbidden

$$\mathcal{L} = |\partial_\mu \phi|^2 + \boxed{\mu^2 |\phi|^2} - \lambda |\phi|^4 + \ldots$$

$$\phi \to e^{i\alpha}\phi$$

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$\phi \to \phi + \alpha$ works!

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$\phi \to \phi + \alpha$ works!

Can we make the Higgs transform this way?

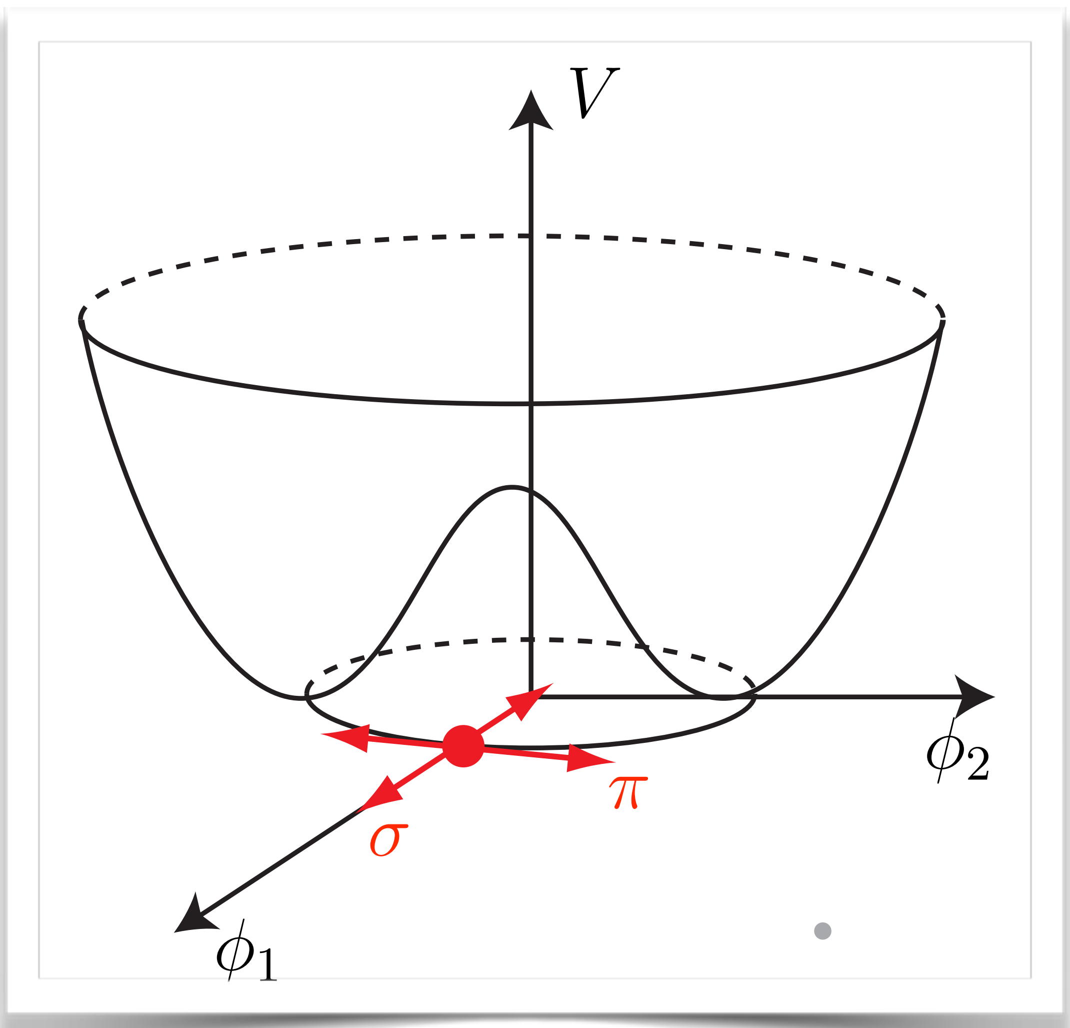
Spontaneous breaking of U(1)

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}}$$

Instead using complex field

$$\mathcal{L} = |\partial_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \dots$$

$$\phi = \phi_1 + i\phi_2$$



'phase' 'modulos'

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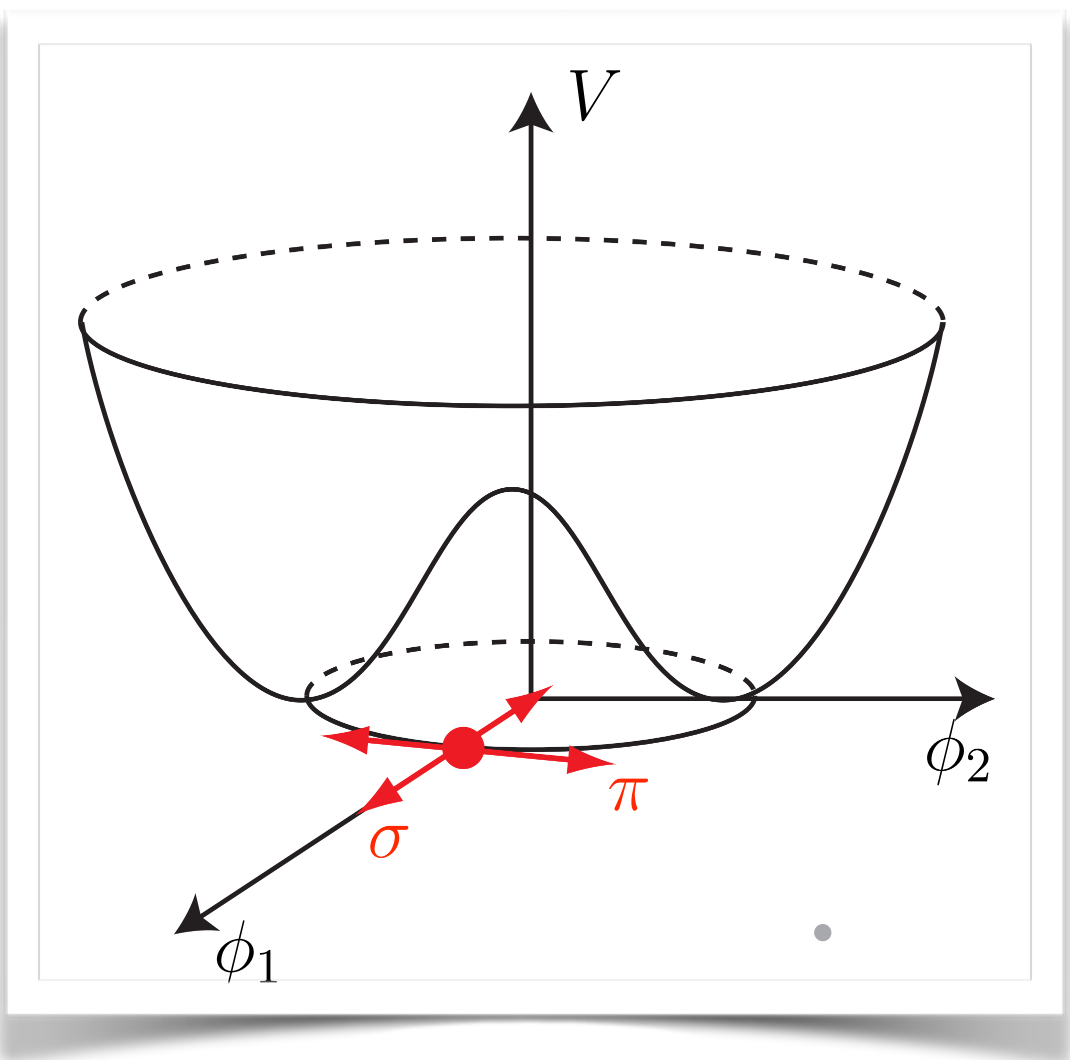

Instead using complex field

$$\phi = \phi_1 + i\phi_2$$

use real parametrisation

$$\phi(x) = \frac{1}{2} e^{i\pi(x)/f} (f + \sigma(x))$$

'phase' 'modulos'

$$\mathcal{L} = |\partial_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \ldots$$

use $$\phi(x) = \frac{1}{2} e^{i\pi(x)/f} (f + \sigma(x))$$

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use $\phi(x) = \frac{1}{2} e^{i\pi(x)/f} (f + \sigma(x))$

$$\partial^\mu \phi^\dagger \partial_\mu \phi = \frac{1}{2} \partial^\mu \sigma \partial_\mu \sigma + \frac{1}{2} (1 + \sigma/f)^2 \frac{1}{2} \partial^\mu \pi \partial_\mu \pi$$

$$\mathcal{L} = |\partial_\mu \phi|^2 + \boxed{\mu^2|\phi|^2 - \lambda|\phi|^4 + \ldots} \quad V(|\phi(x)|^2)$$

use $\quad \phi(x) = \frac{1}{2} e^{i\pi(x)/f}(f + \sigma(x))$

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$$V(|\phi(x)|^2) = V(\sigma(x))$$

no dependence on $\pi(x)$

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no mass term

$$V(|\phi(x)|^2) = V(\sigma(x))$$

no dependence on $\pi(x)$

$$\frac{1}{2}\left(1+\sigma(x)/f\right)^2\frac{1}{2}\partial^\mu\pi\partial_\mu\pi+\frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma-V(\sigma(x))$$

Using this parameterization a new symmetry is visible:

$$\pi(x)\to\pi(x)+\alpha$$

because $\pi(x)$ has only 'derivative interactions'

$$\partial_\mu(\pi(x)+\alpha)=\partial_\mu\pi(x)$$

$$\pi(x),\sigma(x)$$

$$\frac{1}{2}\left(1+\sigma(x)/f\right)^2 \frac{1}{2}\partial^\mu \pi \partial_\mu \pi + \frac{1}{2}\partial^\mu \sigma \partial_\mu \sigma - V(\sigma(x))$$

Using this parameterization a new symmetry is visible:

$$\pi(x) \to \pi(x) + \alpha$$

because $\pi(x)$ has only 'derivative interactions'

$$\partial_\mu(\pi(x) + \alpha) = \partial_\mu \pi(x)$$

But what happened to the U(1) symmetry ?

$\pi(x), \sigma(x)$ are real...

But what happened to the U(1) symmetry ?

$$\phi \to e^{i\alpha}\phi$$

$$e^{i\pi(x)/f}(f+\sigma(x)) \to e^{i\alpha}e^{i\pi(x)/f}(f+\sigma(x))$$

$$\boxed{\begin{aligned} \sigma(x) &\to \sigma(x) \\ \pi(x) &\to \pi(x) + \alpha \end{aligned}}$$

Phase rotation becomes shift symmetry

But what happened to the U(1) symmetry ?

$$\phi \to e^{i\alpha}\phi$$

$$e^{i\pi(x)/f}(f+\sigma(x)) \to e^{i\alpha}e^{i\pi(x)/f}(f+\sigma(x))$$

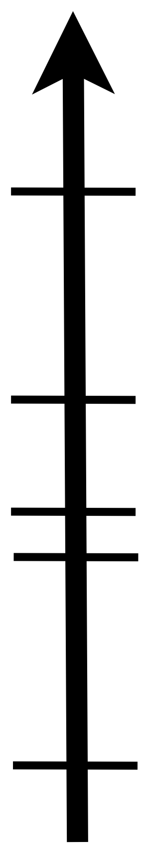
$$\Rightarrow \quad \boxed{\begin{aligned}\sigma(x) &\to \sigma(x)\\ \pi(x) &\to \pi(x)+\alpha\end{aligned}}$$

Phase rotation becomes shift symmetry

$\pi(x)$ is massless **but** also no

- gauge couplings
- potential
- yukawas

Semi-realistic model



$\Lambda = 4\pi f$ UV completion

$m_\rho = g_\rho f$ resonances

$v = 246\,\mathrm{GeV}$ EW scale

pGB Higgs

$SU(3) \to SU(2)$

Break symmetry using $\langle \Phi \rangle = \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}$

\# Goldstone bosons = # broken generators

$$\Phi = \frac{1}{\sqrt{2}} e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ f + \sigma \end{pmatrix} \qquad \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta/\sqrt{3} & 0 & H_1 \\ 0 & \eta/\sqrt{3} & H_2 \\ H_1^* & H_2^* & -2\eta/\sqrt{3} \end{pmatrix}$$

$$\Phi = \frac{1}{\sqrt{2}} e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ f+\sigma \end{pmatrix} \qquad \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta/\sqrt{3} & 0 & H_1 \\ 0 & \eta/\sqrt{3} & H_2 \\ H_1^* & H_2^* & -2\eta/\sqrt{3} \end{pmatrix}$$

Expand

$$\Phi(x) = \begin{pmatrix} H_1(x) \\ H_2(x) \\ -\frac{2}{\sqrt{2}}\eta(x) \end{pmatrix} + \ldots$$

Contains a Higgs: $H = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = SU(2)$ doublet

kinetic term:

$$\partial_\mu \Phi \partial^\mu \Phi^\dagger = \partial_\mu H \partial^\mu H^\dagger + \frac{(\partial_\mu H \partial^\mu H^\dagger) H^\dagger H}{f^2} + \ldots$$

Nonlinear corrections

$SU(3) \to SU(2)$

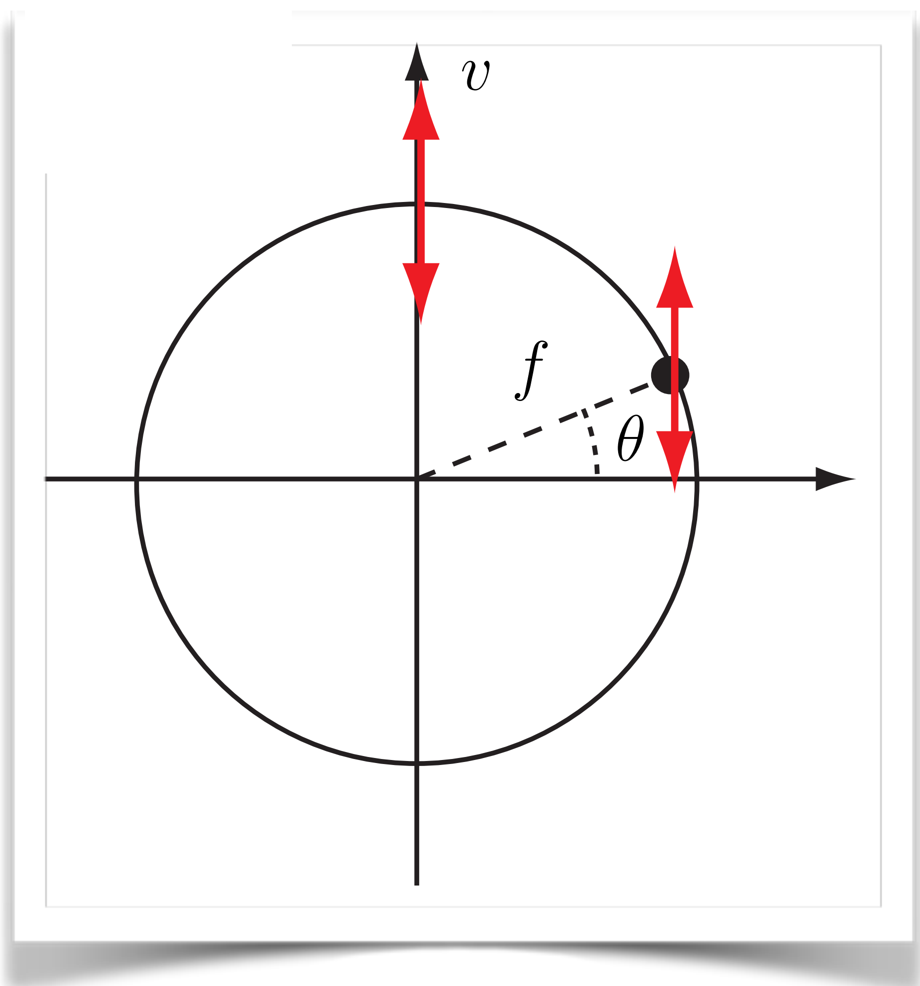
pGB Higgs

Unbroken gauge symmetry in global SU(2), dynamics generates ‘vacuum misalignment’

SU(2)$_L$ vs. SU(2)

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}} \begin{pmatrix} \boxed{\begin{matrix} 0 \\ \sin\theta \end{matrix}} \\ \cos\theta \end{pmatrix}$$ SU(2)$_L$

EW symmetry broken



pGB Higgs

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}} \begin{pmatrix} \boxed{\begin{matrix} 0 \\ \sin\theta \end{matrix}} \\ \cos\theta \end{pmatrix}$$ SU(2)$_L$

Electro-weak scale $v = f \sin\theta$

$f \sim$ scale of new physics

$\sin\theta \ll 1 \Leftrightarrow f \gg v$ (SM limit)

$$\Rightarrow \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Collective Breaking

We now want to add a yukawa coupling to give mass to the top quark

$$\lambda_t \bar{Q}_i H_i^c t_R \qquad \text{i: sum over SU(2)}$$

Fundamental field is a triplet

$$\phi = \exp\left\{ i \begin{pmatrix} & & h_1 \\ & & h_2 \\ h_1^* & h_2^* & \end{pmatrix} \right\} \begin{pmatrix} \\ \\ f \end{pmatrix}$$

Top yukawa: 1st try

$$\sum_i^2 \lambda_t \phi_i^c \bar{Q}_i t_R$$ works, gives mass to the top

… but breaks SU(3) structure explicitly, does not respect Goldstone symmetry protecting the Higgs mass:

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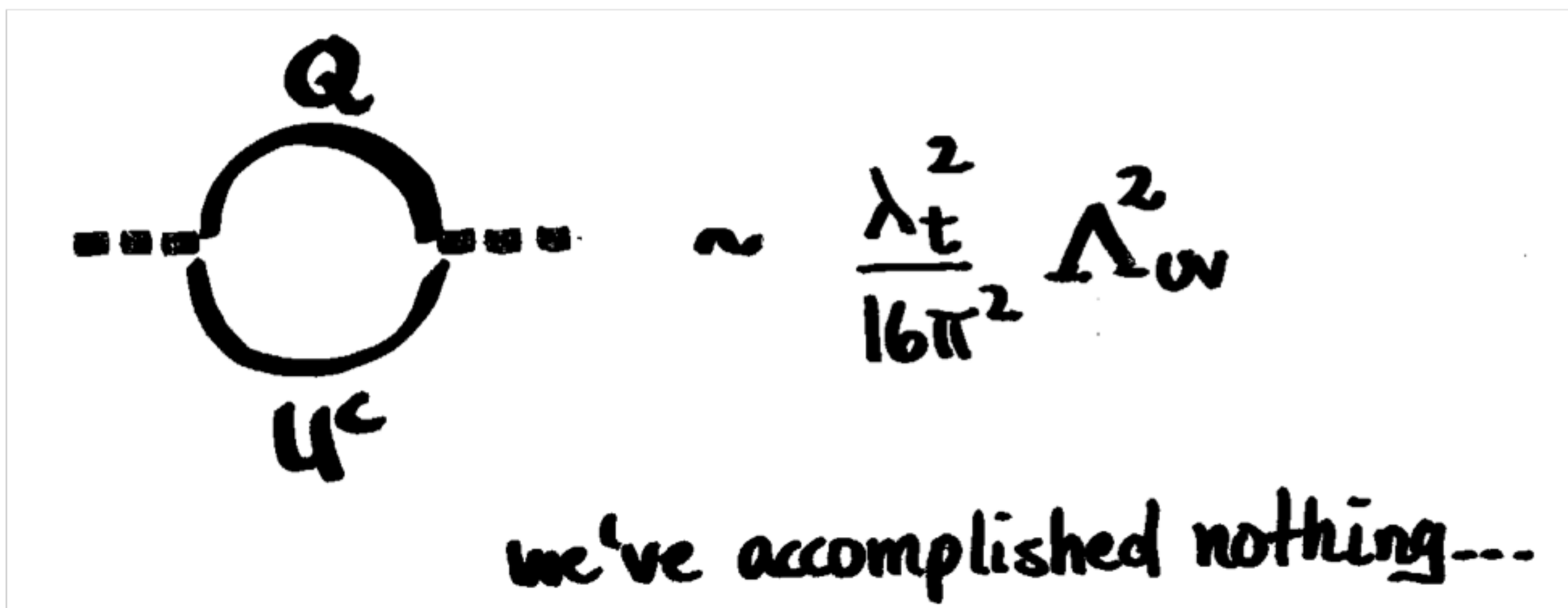

2nd try: "collective breaking"

Example: $SU(3) \to SU(2)$ (ignore $U(1)_Y$ again)

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ f_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ f_2 \end{pmatrix}$$

two scalar fields!

Gauge full $SU(3)$ ⇒ exact symmetry

$$\Psi_L = \begin{pmatrix} t_L \\ b_L \\ T_L \end{pmatrix} \qquad t_{1R},\ t_{2R},\ b_R$$

Global rotations ($SU(3)_1$ x $SU(3)_2$):

$$\Phi_1 \to U_1 \Phi_1$$

$$\Phi_2 \to U_2 \Phi_2$$

Gauge symmetry ($SU(3)_{1+2}$):

$$\Psi_L \to U_{1+2}(x) \Psi_L$$

$y_1 = 0, \ y_2 \neq 0$	$SU(3)_{1+2}$	$SU(3)_2$
$y_1 \neq 0, \ y_2 = 0$	$SU(3)_1$	$SU(3)_{1+2}$
$y_1 \neq 0, \ y_2 \neq 0$	$SU(3)_{1+2}$	

If only one y_1 or y_2 is present, then two SU(3)'s survive, one for the gauge bosons (eating the goldstones of one Φ_i) and one global SU(3) guaranteeing that the Yukawa does not contribute to Goldstone mass.

If both y_1 and y_2 present, then only one SU(3) present, and the goldstones of one combination of Φ_1 and Φ_2 are eaten, the other combination gets a mass from the Yukawa.

$$\mathcal{L}_{\text{Yukawa}} = y_1 \bar{\Psi}_L \Phi_1 t_{1R} + y_2 \bar{\Psi}_L \Phi_2 t_{2R}$$

$y_1 = 0,\ y_2 \neq 0$	$SU(3)_{1+2}$	$SU(3)_2$
$y_1 \neq 0,\ y_2 = 0$	$SU(3)_1$	$SU(3)_{1+2}$
$y_1 \neq 0,\ y_2 \neq 0$	$SU(3)_{1+2}$	

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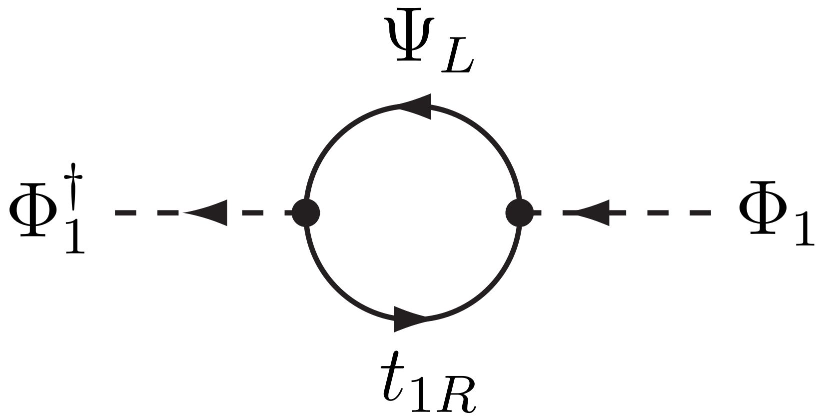
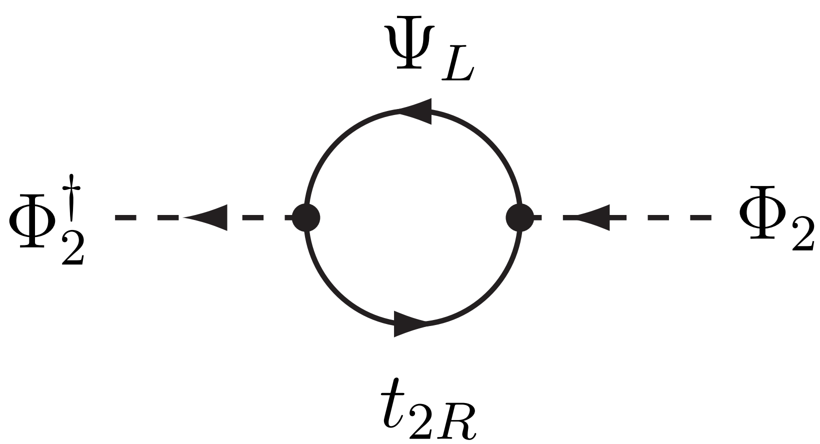


$$\sim \underbrace{\frac{y_1^2}{16\pi^2}\Lambda^2}$$

preserves $SU(3)_2 \to SU(2)_2$

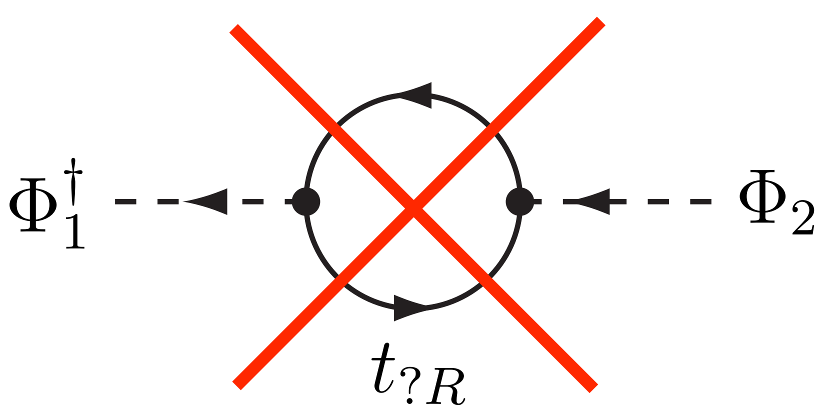
$\Rightarrow$ no PNGB Higgs mass



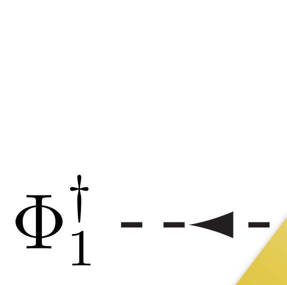
$$\sim \underbrace{\frac{y_2^2}{16\pi^2}\Lambda^2}$$

preserves $SU(3)_1 \to SU(2)_1$

$\Rightarrow$ no PNGB Higgs mass



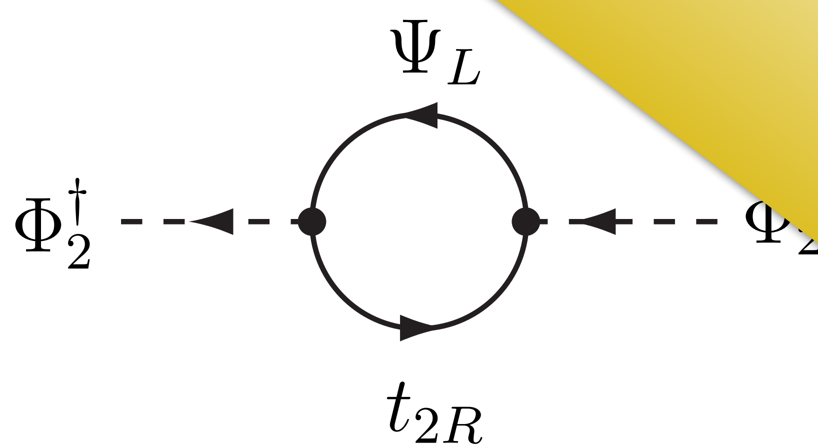
Not allowed



$$\sim \underbrace{\frac{y_1^2}{16\pi^2}\Lambda^2}$$

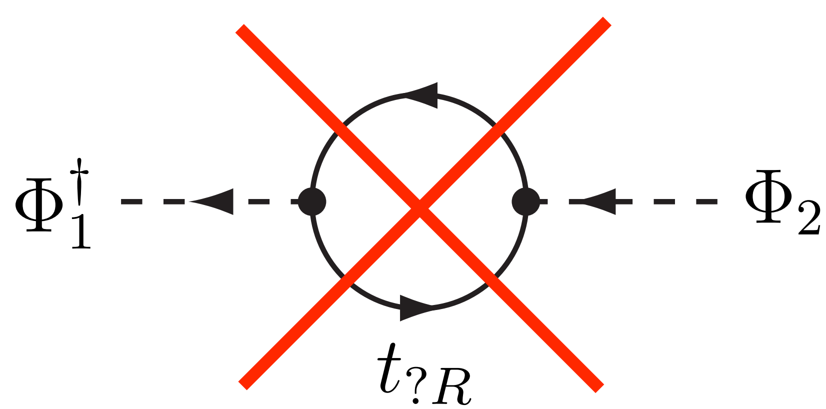
erves $SU(3)_2 \rightarrow SU(2)_2$

GB Higgs mass



pr $\rightarrow SU(2)_1$

$\Rightarrow$ no gs mass

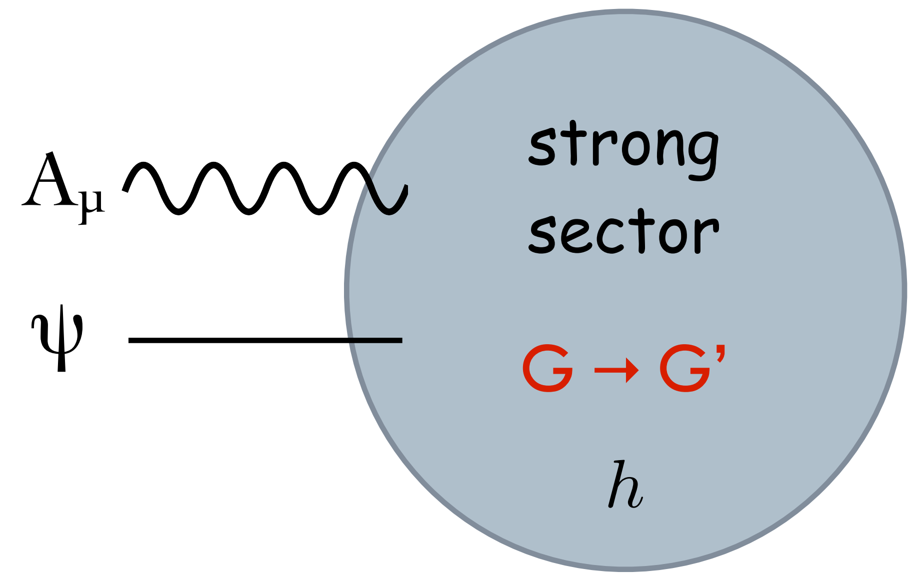


Not allowed

Predicts top-partners

Minimal composite Higgs

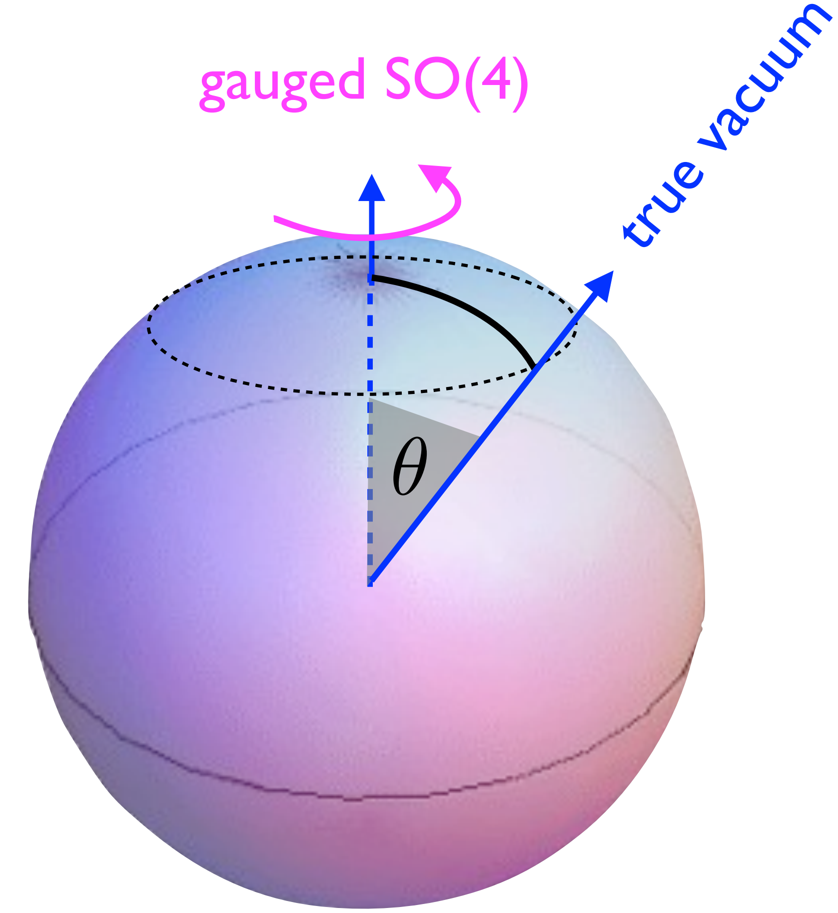
Agashe et. al



Minimal bottom up construction

$$SO(5) \to SO(4) \sim SU(2)_L \times SU(2)_R$$

$SO(5)/SO(4)$



Tree level: gauge SO(4) aligned

Higgs

$$\phi = e^{i\pi^{\hat{a}}T^{\hat{a}}/f}\begin{pmatrix}0\\0\\0\\0\\1\end{pmatrix} = \begin{pmatrix}\sin(\pi/f)\times\begin{pmatrix}\hat{\pi}^1\\\hat{\pi}^2\\\hat{\pi}^3\\\hat{\pi}^4\end{pmatrix}\\ \cos(\pi/f)\end{pmatrix} = \begin{pmatrix}\sin(\theta+h(x)/f)\;\; e^{i\chi^i(x)A^i/v}\begin{pmatrix}0\\0\\0\\1\end{pmatrix}\\ \cos(\theta+h(x)/f)\end{pmatrix}$$

1-loop $\langle\phi(x)\rangle = \theta\cdot f$

eaten by W_L, Z_L

Implications of m$_H$ = 125 GeV

Agashe et. al

Potential is fully radiatively generated

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

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

Implications of m_H = 125 GeV

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

Higgs dependent term
UV finite

Implications of m_H = 125 GeV

Agashe et. al

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

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

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

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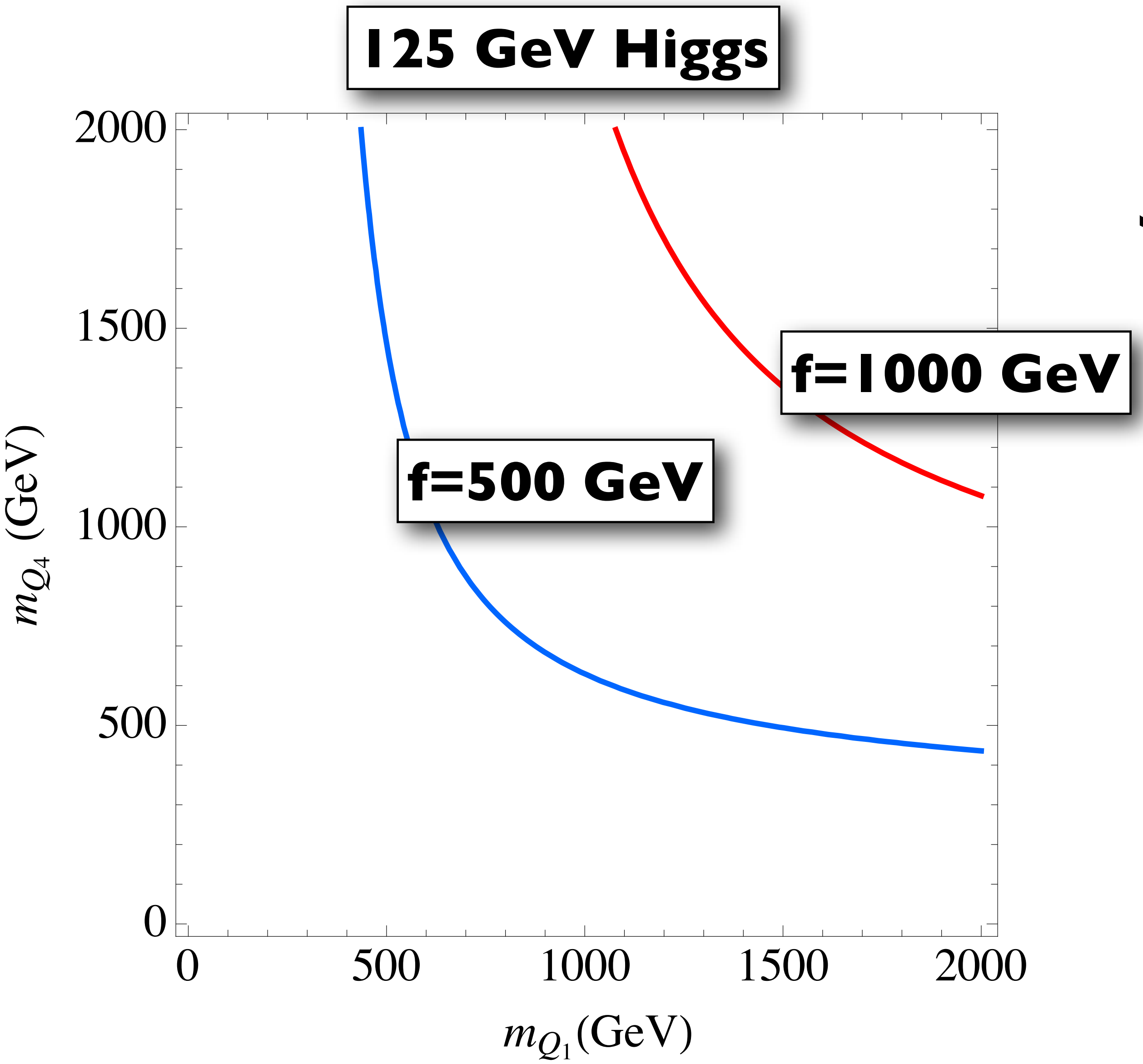
Pomarol et al; Marzocca



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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;

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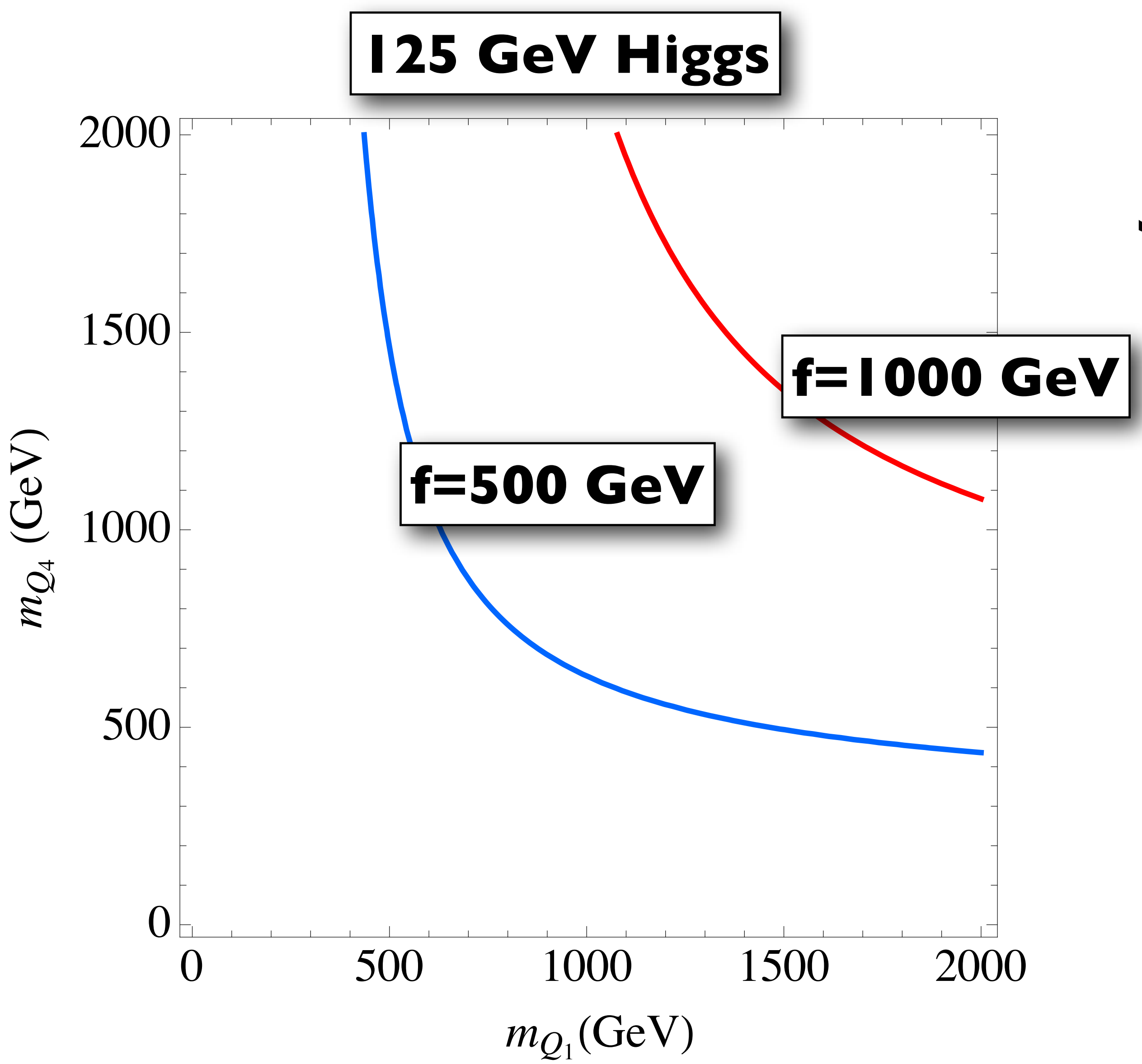

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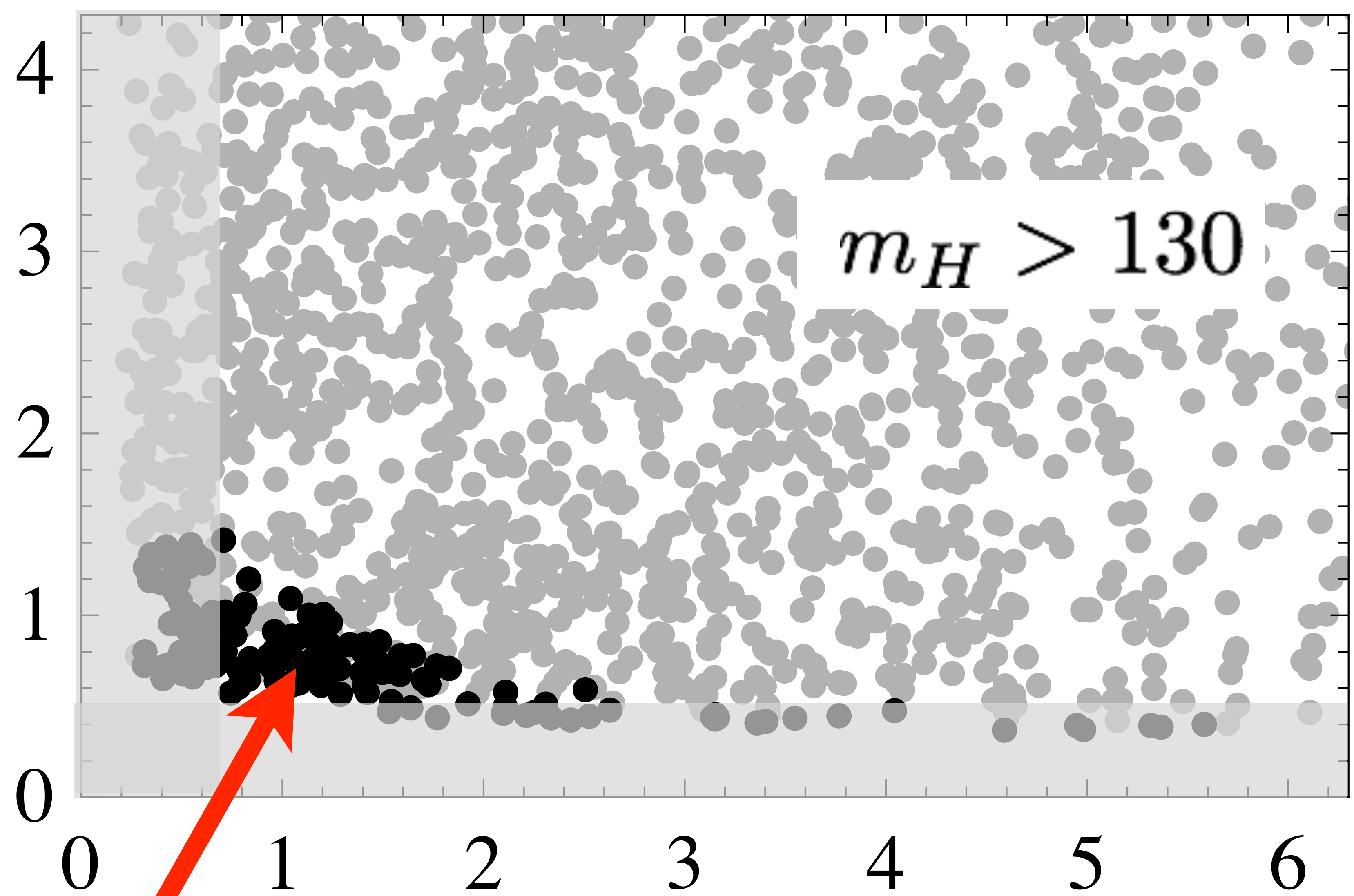
Contino et al; Pomarol, Riva; Matsedonskyi,Panico,Wulzer; Redi,Tesi; Marzocca,Serone,Shu;

Scan over composite Higgs parameter space

$\xi = 0.2$

from 1204.6333

$Q = 2/3$



$Q = 5/3$

m_H = 115 … 130 GeV

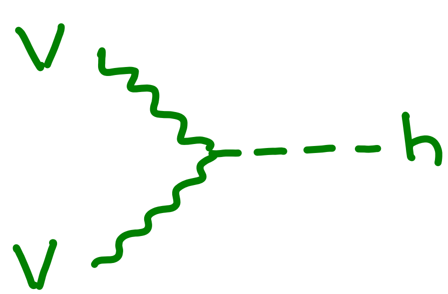
see e.g. ATLAS-CONF-2013-051

Deviations from SM Higgs

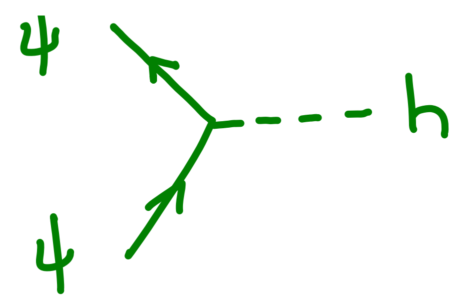
Goldstone boson nature

$$f^2 \left|\partial_\mu \, e^{i\pi/f}\right|^2 = |D_\mu H|^2 + \frac{c_H}{2f^2}\left[\partial_\mu (H^\dagger H)\right]^2 + \frac{c'_H}{2f^4}(H^\dagger H)\left[\partial_\mu (H^\dagger H)\right]^2 + \ldots$$

Giudice et al. JHEP 0706 (2007) 045

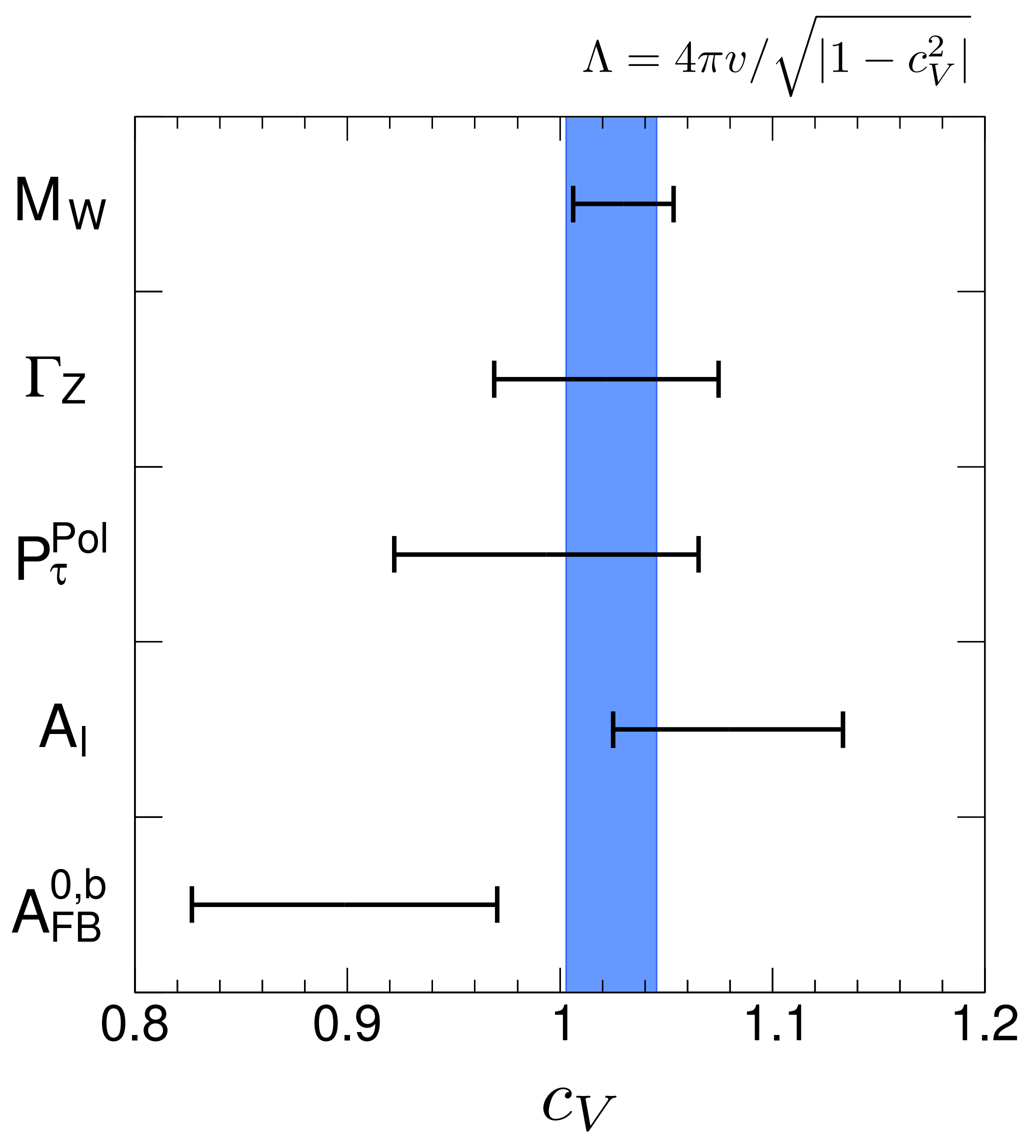


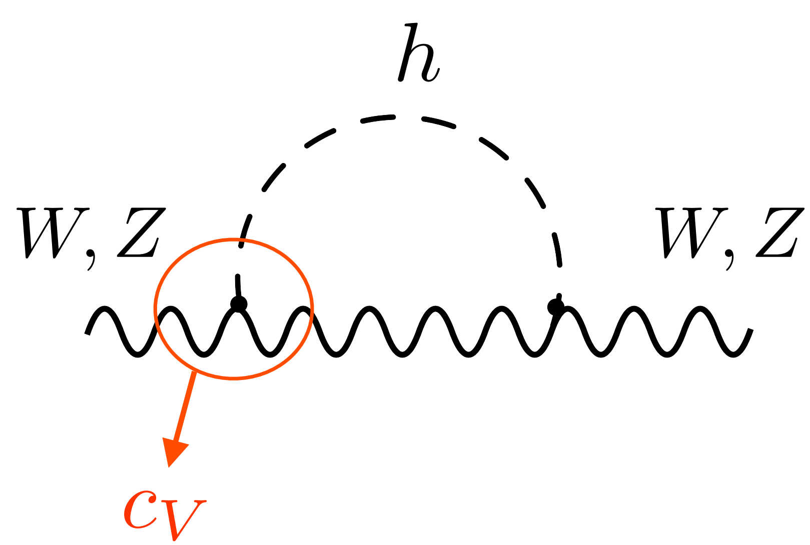
$a \, g^{SM}_{hVV}$



$c \, h^{SM}_{\psi\psi h}$

EW precision tests

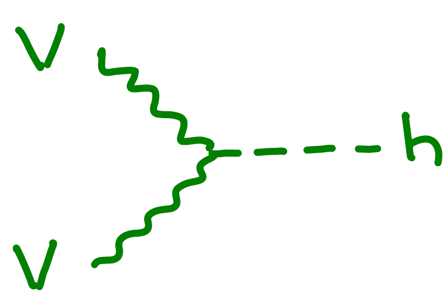




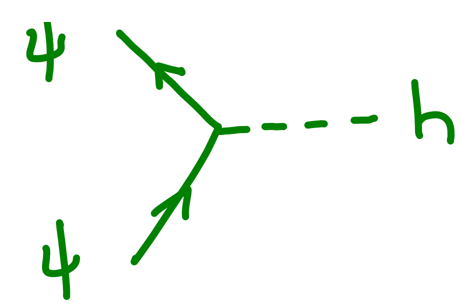
Ciuchini, Franco, Silvestrini, Mishima, arXiv:1306.4644

Higgs couplings

Have been measured to 20-30% precision



$a\, g_{hVV}^{SM}$



$c\, h_{\psi\psi h}^{SM}$

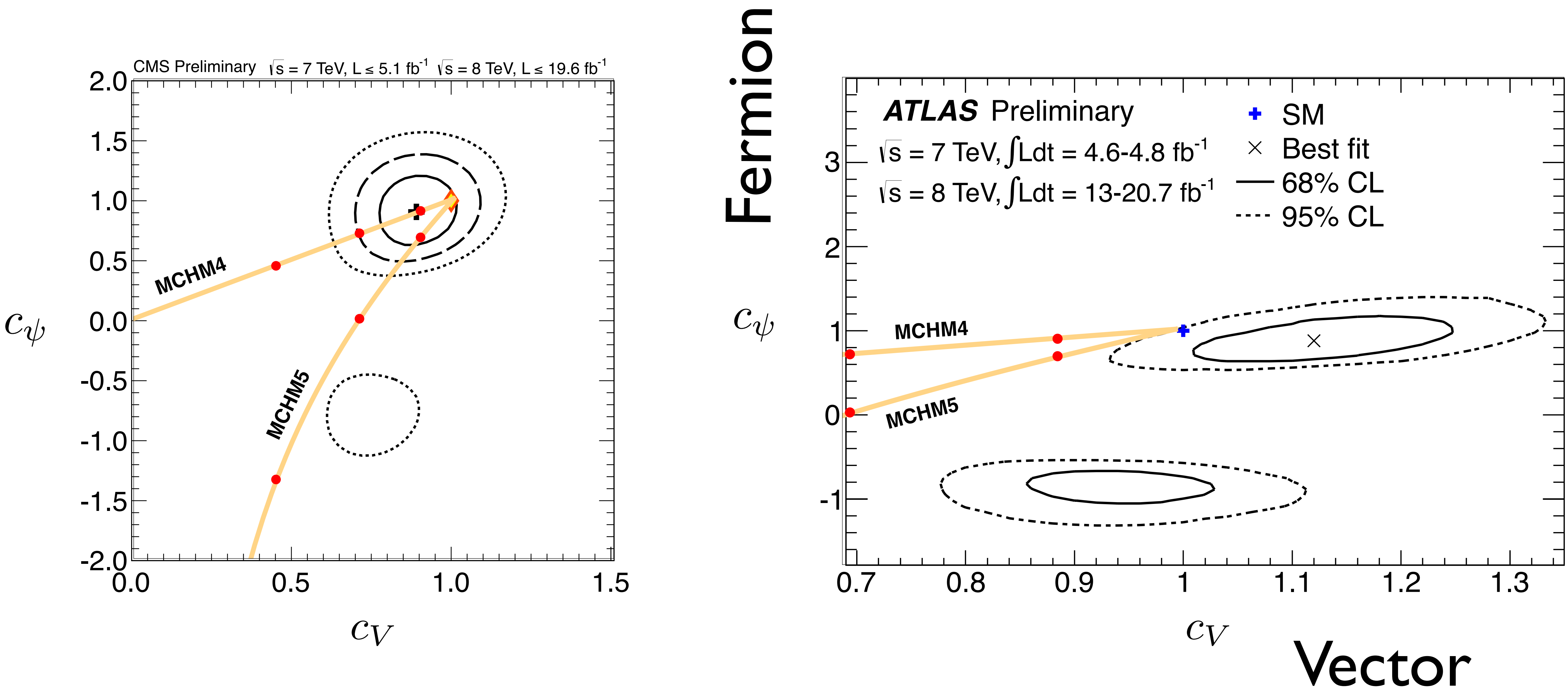
Expect deviations ~ $(v/f)^2$

$$a = \sqrt{1-\xi}$$

$$\xi \equiv \frac{v^2}{f^2}$$

$$c_f = \frac{1-(1+n)\xi}{1-\xi}$$

Higgs couplings



Red points at $\xi \equiv (v/f)^2 = 0.2,\ 0.5,\ 0.8$

New physics & naturalness

Light Higgs

?

light stops$_{1,2}$, sbottom$_L$, higgsinos, gluinos, …

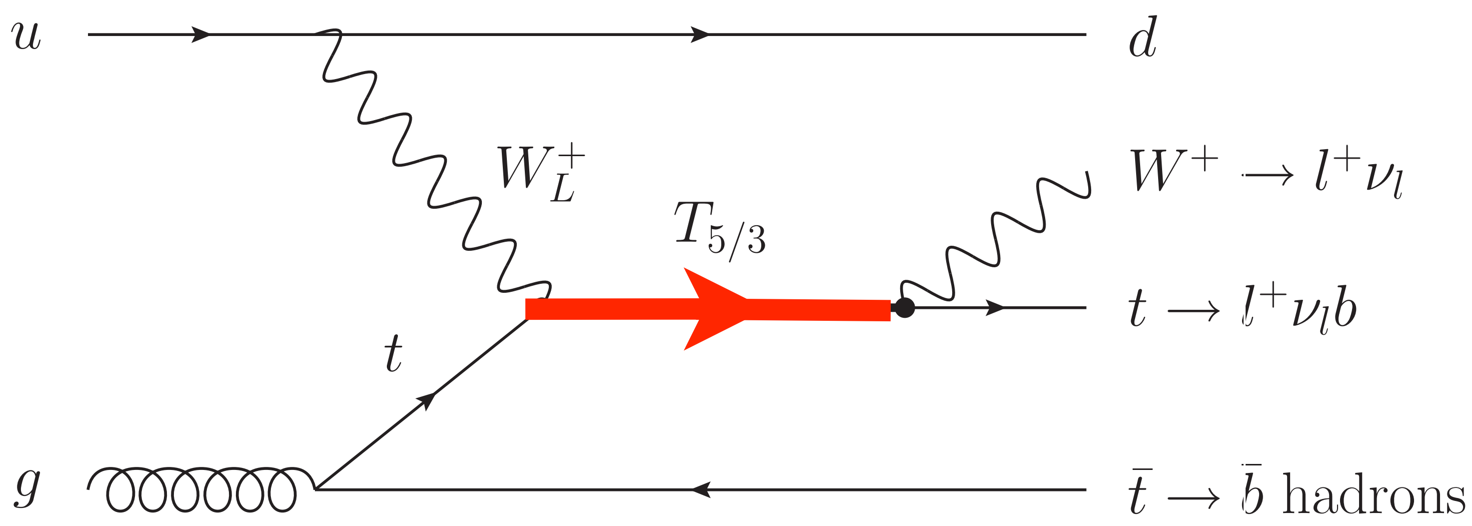
supersymmetry

light top partners (Q=5/3,2/3,1/3), anything else ?

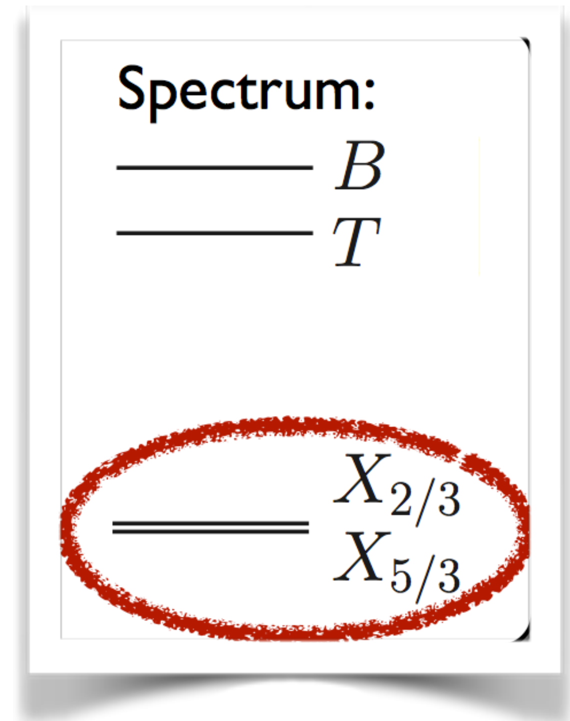
composite Higgs

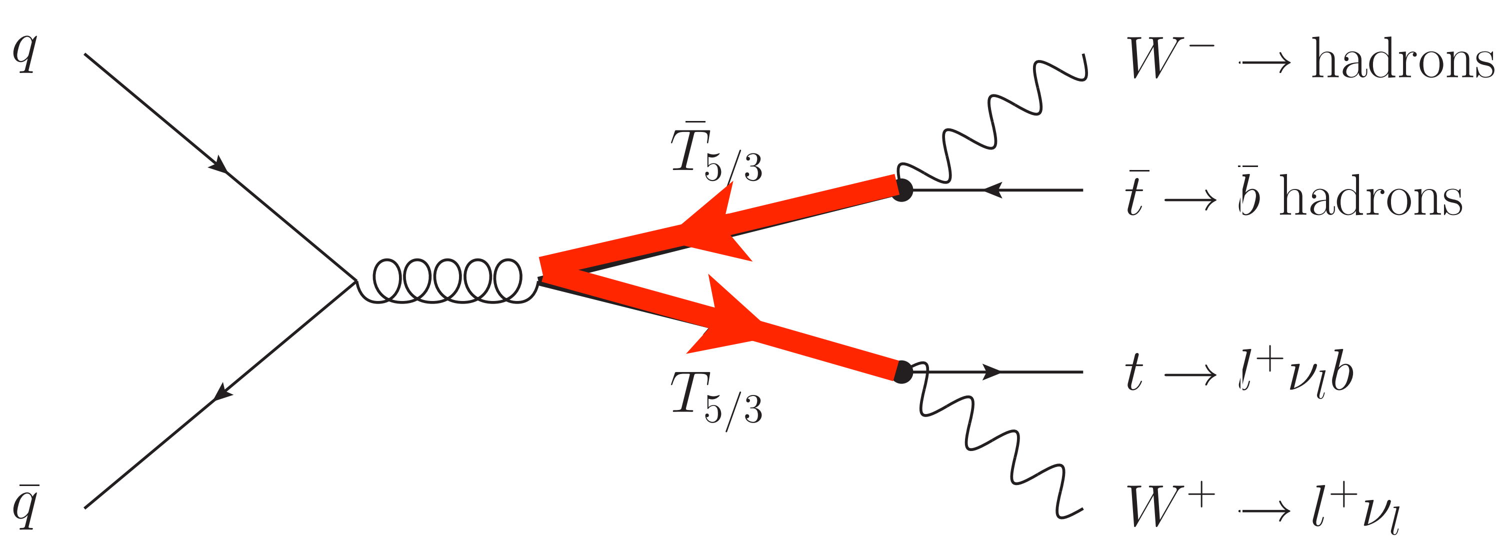
e.g. Perelstein, Pierce, Peskin
Contino, Servant; Mrazek, Wulzer;
De Simone, Matsedonkyi, Rattazzi, Wulzer

$T_{5/3}$



Single

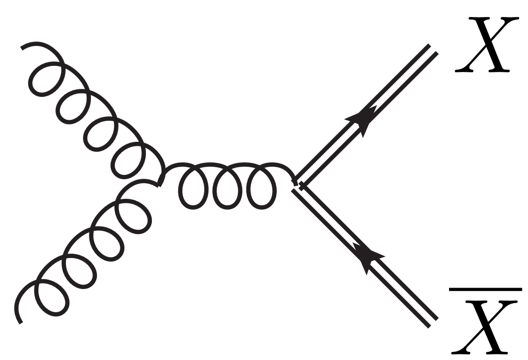




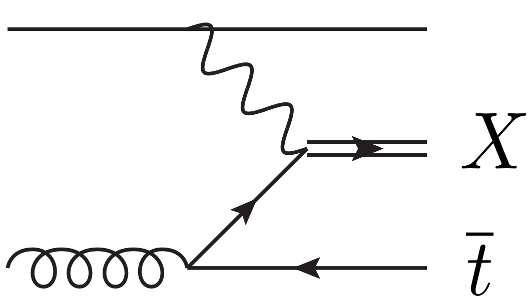
Double

Phenomenology

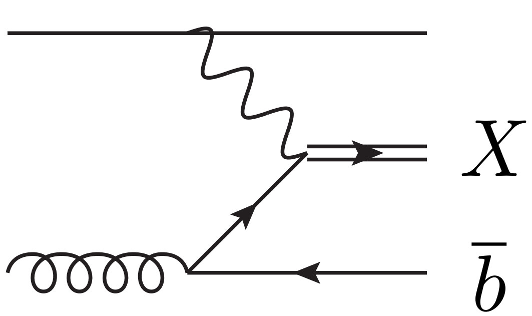
Three possible production mechanisms



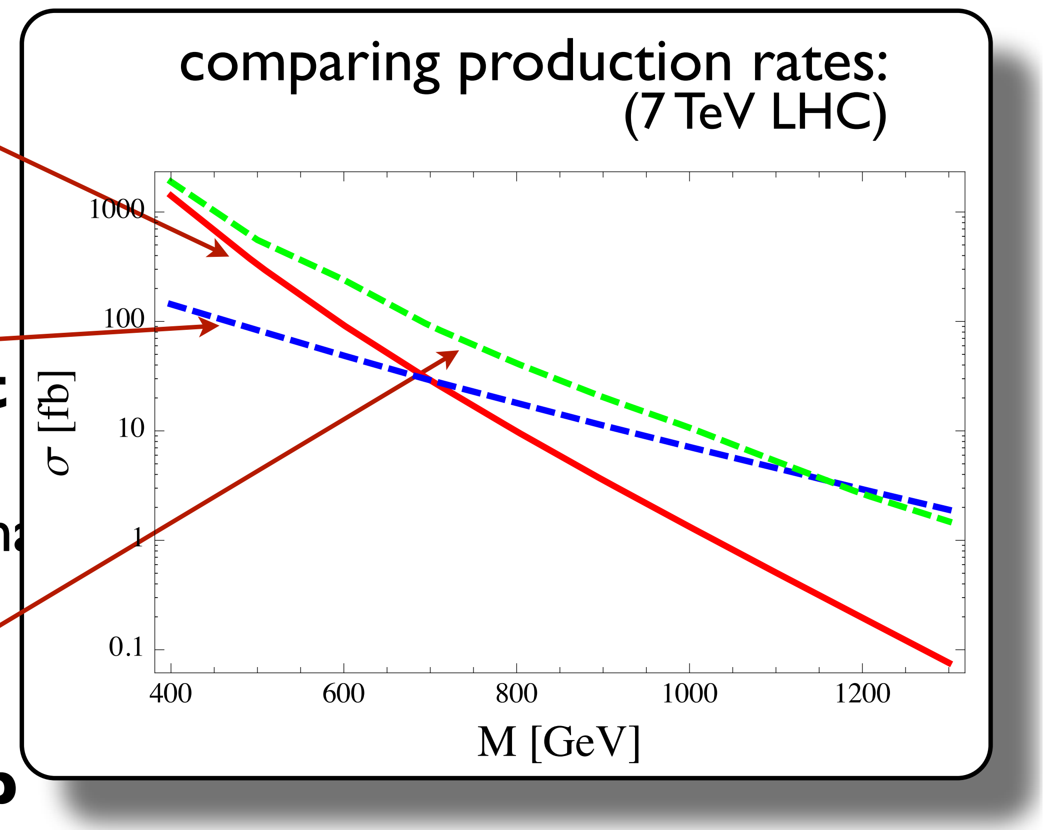
QCD **pair prod**.
model indep.,
relevant at low mass



single prod. with **t**
model dep. coupling
pdf-favored at high ma



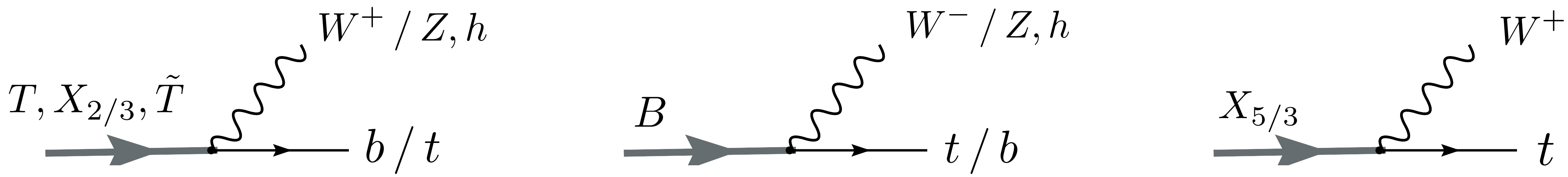
single prod. with **b**
favored by small b mass
dominant when allowed

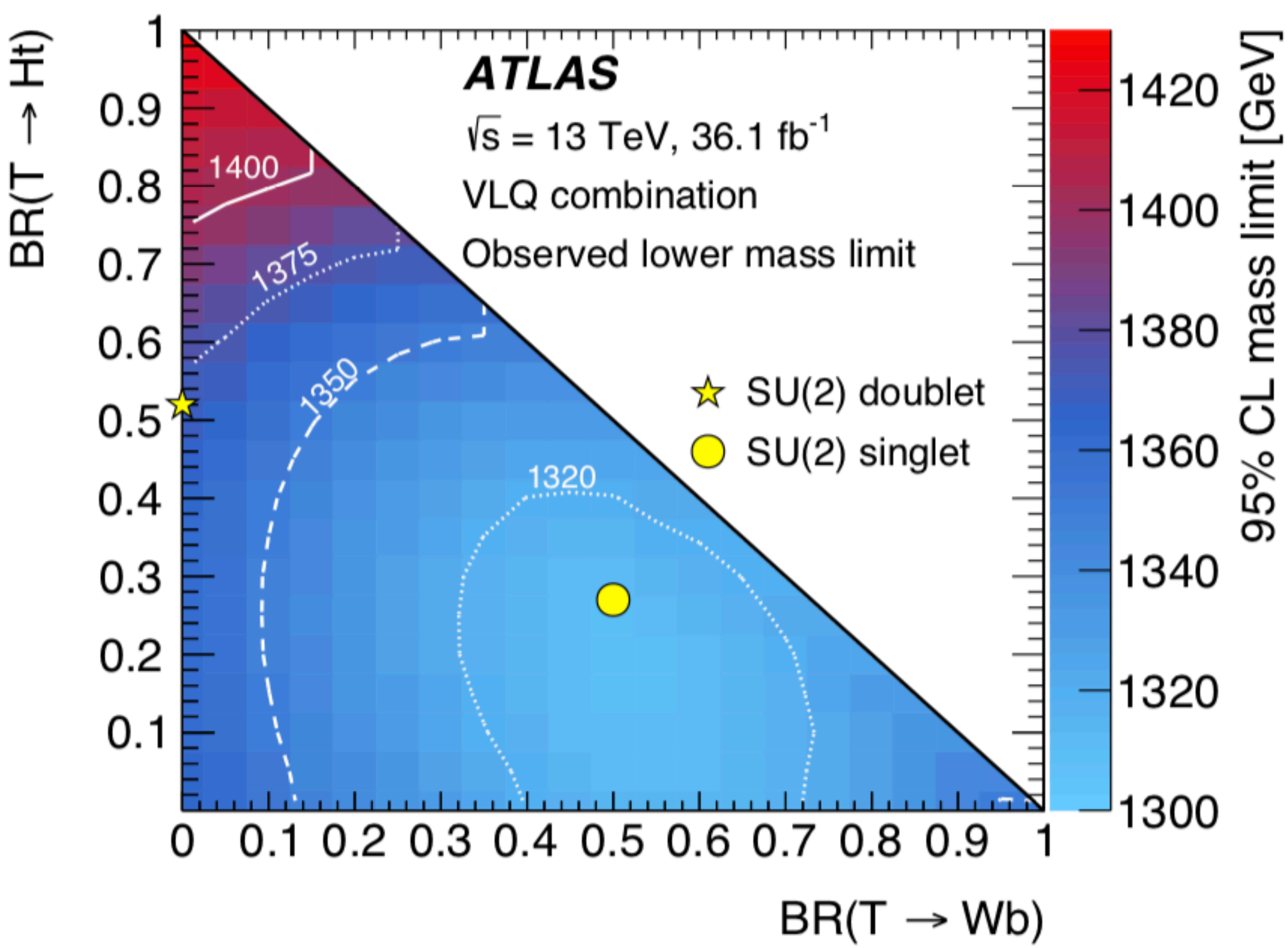


27

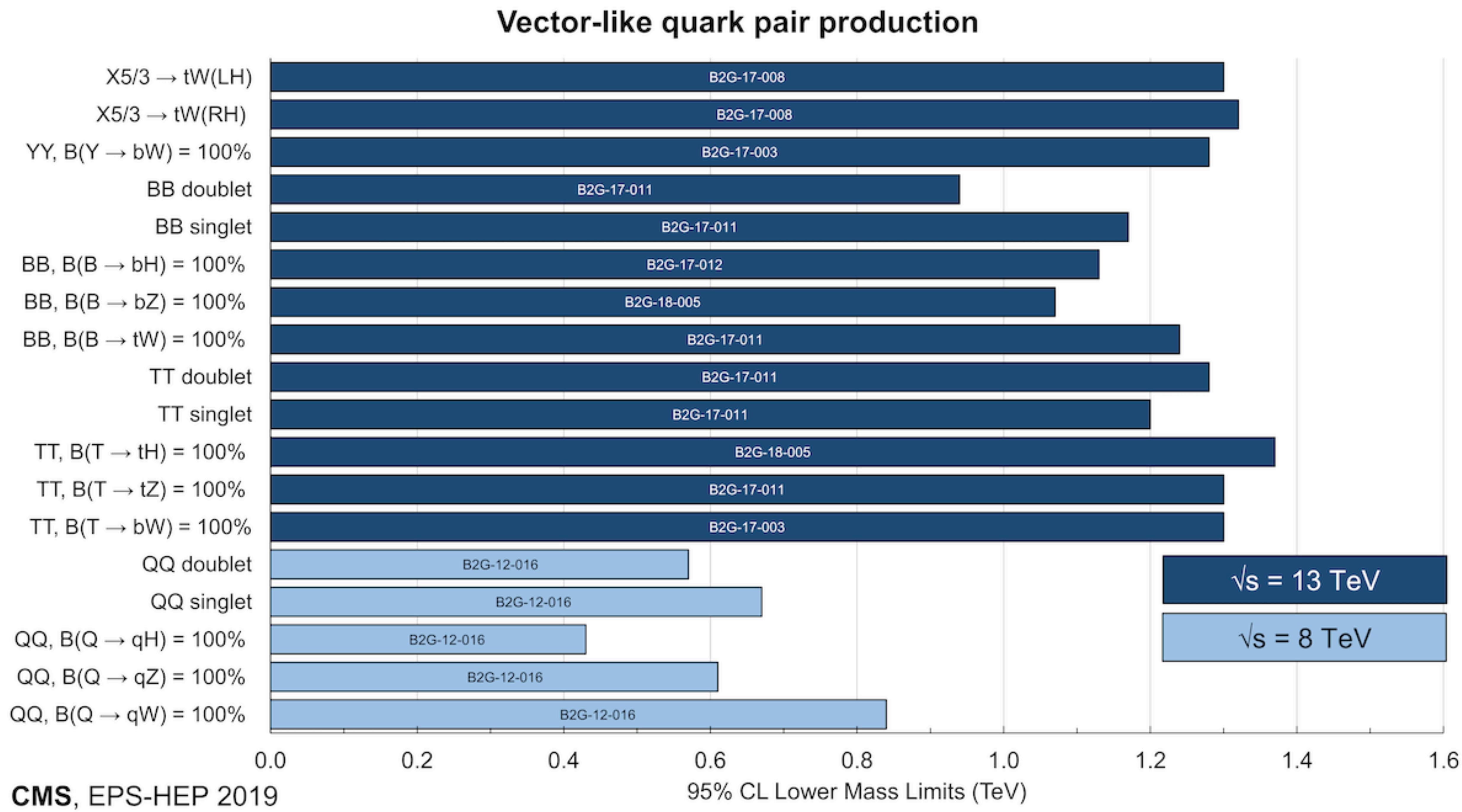
slide by A. Wulzer

Decay modes





Current limits
> 1300 GeV


Vector-like quark pair production
X5/3 → tW(LH)
X5/3 → tW(RH)
YY, B(Y → bW) = 100%
BB doublet
BB singlet
BB, B(B → bH) = 100%
BB, B(B → bZ) = 100%
BB, B(B → tW) = 100%
TT doublet
TT singlet
TT, B(T → tH) = 100%
TT, B(T → tZ) = 100%
TT, B(T → bW) = 100%
QQ doublet
QQ singlet
QQ, B(Q → qH) = 100%
QQ, B(Q → qZ) = 100%
QQ, B(Q → qW) = 100%
B2G-17-008
B2G-17-008
B2G-17-003
B2G-17-011
B2G-17-011
B2G-17-012
B2G-18-005
B2G-17-011
B2G-17-011
B2G-17-011
B2G-18-005
B2G-17-011
B2G-17-003
B2G-12-016
B2G-12-016
B2G-12-016
B2G-12-016
B2G-12-016
√s = 13 TeV
√s = 8 TeV
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
95% CL Lower Mass Limits (TeV)
CMS, EPS-HEP 2019

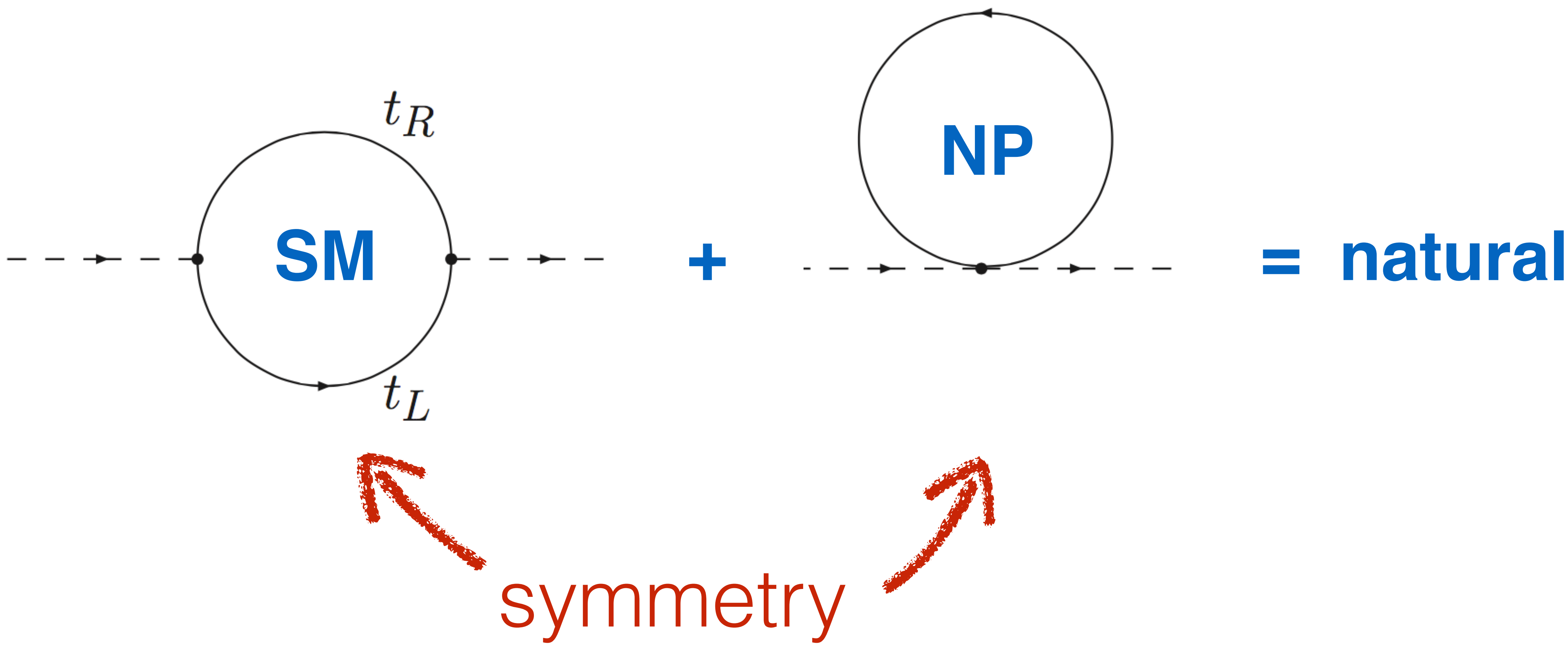
New ideas

twin Higgs

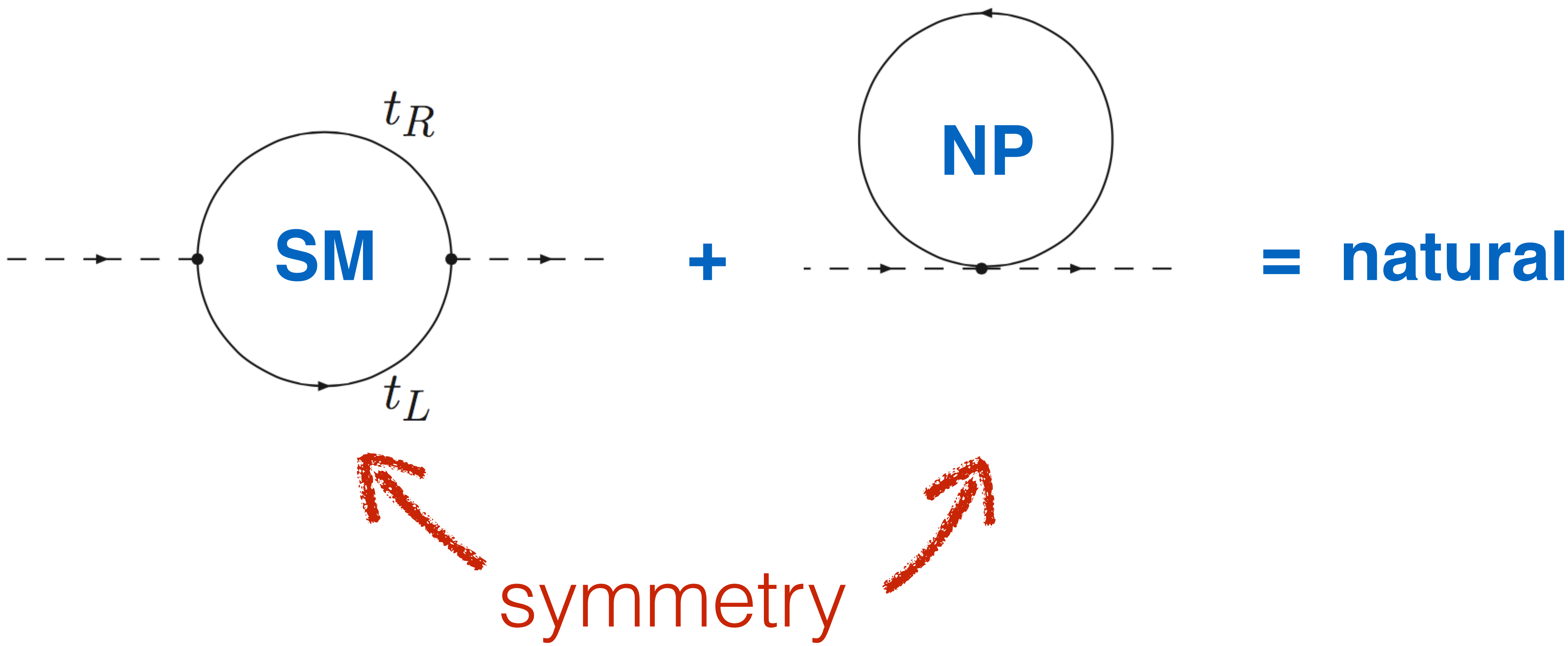
Relaxion

ION

No lose for naturalness?



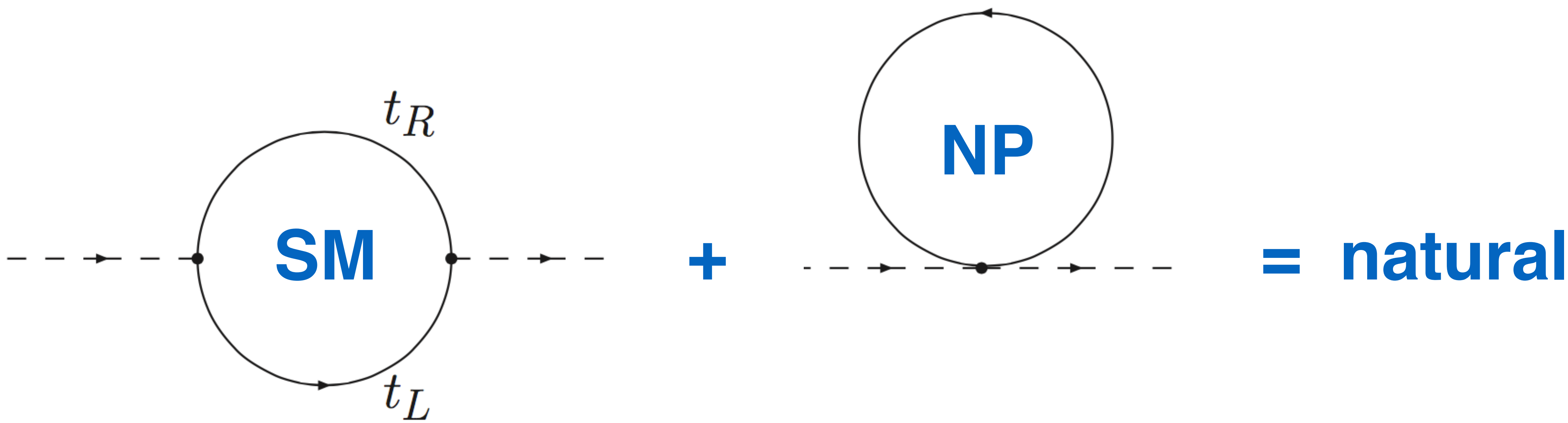
No lose for naturalness?



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?



symmetry

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

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

Not true!

Twin Higgs

Standard Model $\xleftrightarrow{Z_2}$ **Standard Model**

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

Quadratic divergences from SM top quark loops cancelled by loops of “Twin” top quarks.

Twin Higgs

Standard Model $\xleftrightarrow{Z_2}$ **Standard Model**

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

Quadratic divergences from SM top quark loops cancelled by loops of “Twin” top quarks.

Global Symmetry → Twin Higgs

Chacko
Goh
Harnik
2005

Super-Symmetry → Folded SUSY

Burdmann
Chacko
Goh
Harnik
2006

Under the gauge symmetry,

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

where H_A will eventually be identified with the Standard Model Higgs, while H_B is its `twin partner'.

Now the Higgs potential receives radiative corrections from gauge fields

$$\Delta V(H) = \frac{9g_A^2\Lambda^2}{64\pi^2} H_A^\dagger H_A + \frac{9g_B^2\Lambda^2}{64\pi^2} H_B^\dagger H_B$$

Impose a Z_2 `twin' symmetry under which A $\leftrightarrow$ B. Then $g_A = g_B = g$. Then the radiative corrections take the form

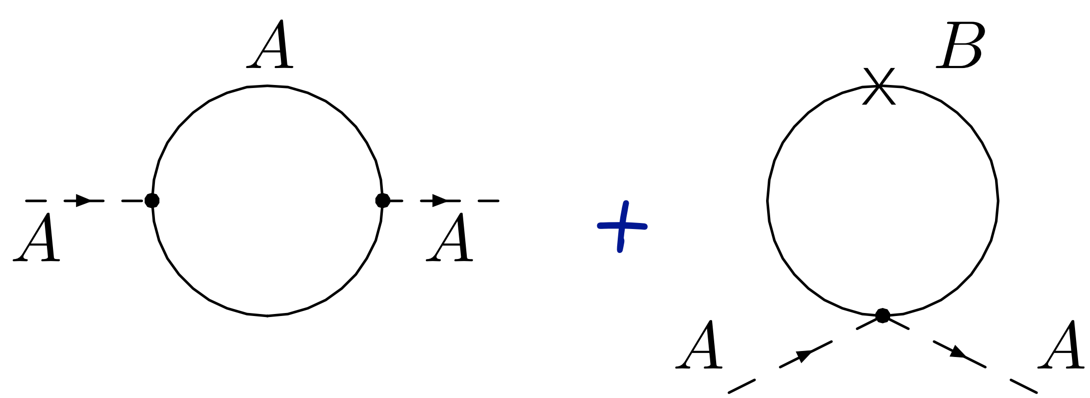
$$\Delta V = \frac{9g^2\Lambda^2}{64\pi^2}(H_A^\dagger H_A + H_B^\dagger H_B)$$

This is U(4) invariant and cannot give a mass to the Goldstones!

Parity symmetry enforces y_t same

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

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



Same coupling, but not same colour group for top and top partner! Still: little Higgs like cancellation.

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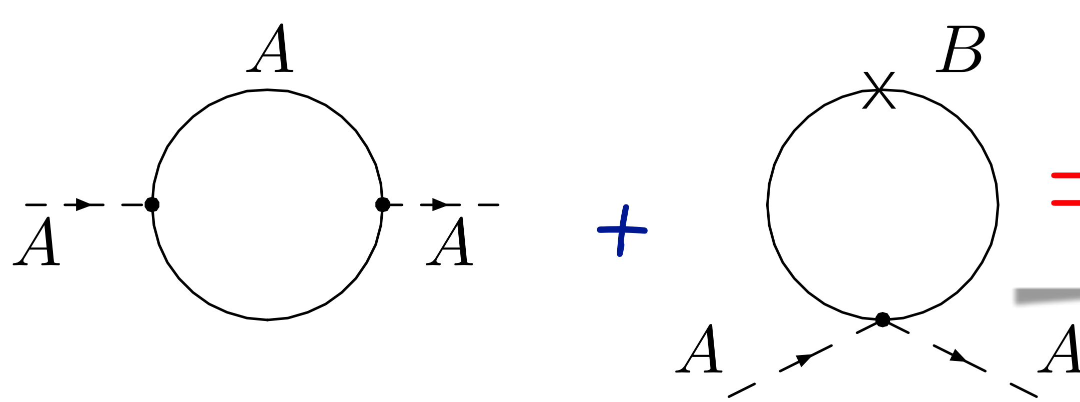
$$= y_t h\, \bar{t}_A t_A + y_t \left(f - \frac{|h|^2}{2f} \right) \bar{t}_B t_B + \dots$$



$$= 0 \times \Lambda^2$$

Same coupling, but not same colour group for top and top partner! Still: little Higgs like cancellation.

- Mirror sector is copy of SM, completely neutral under SM interactions

- Allowed interaction terms:

$$\lambda_{AB}|H_A|^2|H_B|^2$$ Higgs portal

$$\epsilon_{AB}F_{\mu\nu,A}F^{\mu\nu}_B$$ kinetic mixing portal

- Mirror sector is copy of SM, ~~completely neutral~~ under SM interactions

- Allowed interaction terms:

Hypercharged Naturalness

Javi Serra[a], Stefan Stelzl[a], Riccardo Torre[b,c], and Andreas Weiler[a]

[a] *Physik-Department, Technische Universität München, 85748 Garching, Germany*

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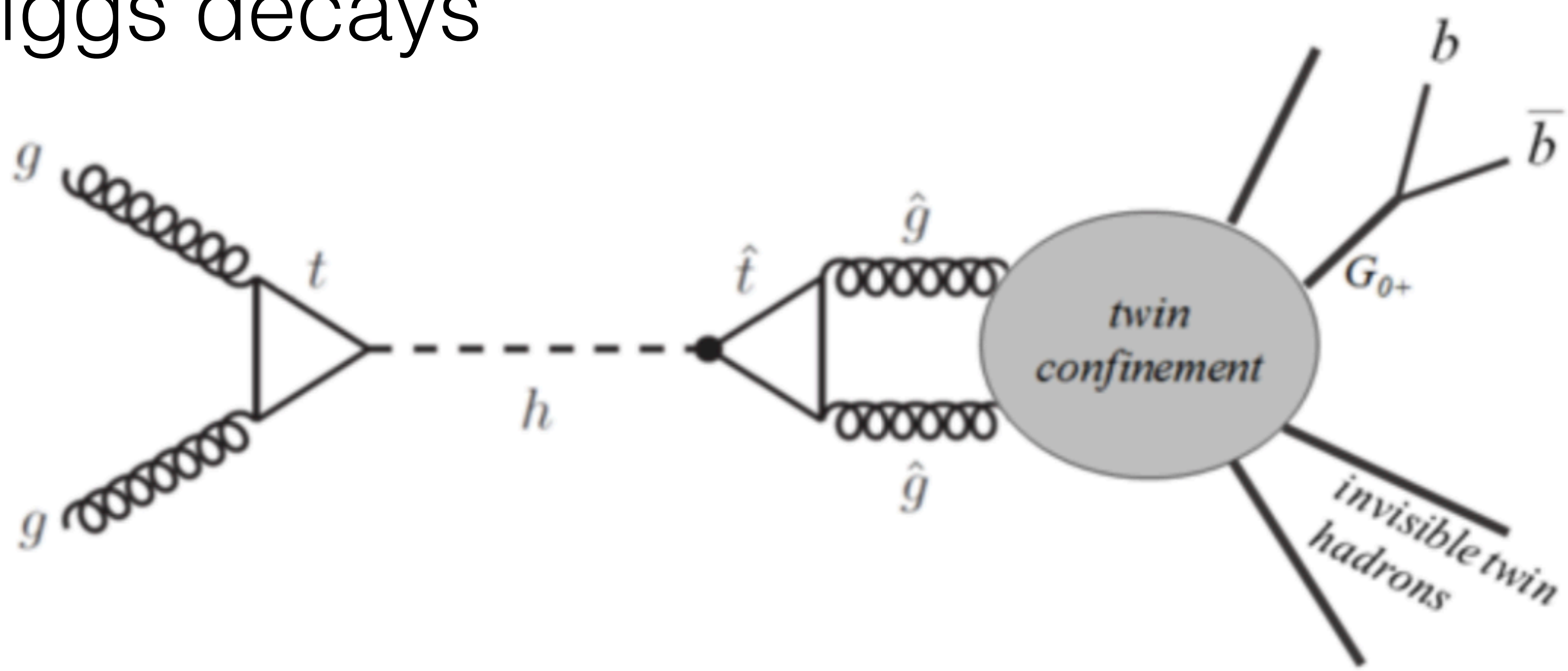
[c] *INFN, Sezione di Genova, Via Dodecaneso 33, 16146 Genova, Italy*

Abstract

We present an exceptional twin-Higgs model with the minimal symmetry structure for an exact implementation of twin parity along with custodial symmetry. Twin particles are mirrors of the Standard Model yet they carry hypercharge, while the photon is identified with its twin. We thoroughly explore the phenomenological signatures of hypercharged naturalness: long-lived charged particles, a colorless twin top with elec-

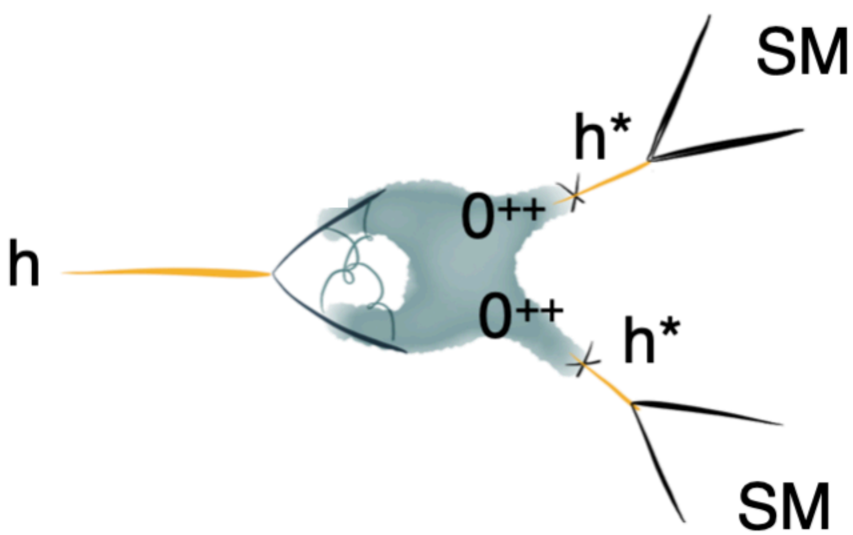
Twin Higgs consequences

- SU(3)B confines at $\Lambda_B > \Lambda_{\mathrm{QCD}}$
- Dark sector QCD-like with dark-pions, dark kaons, …
- Exotic Higgs decays



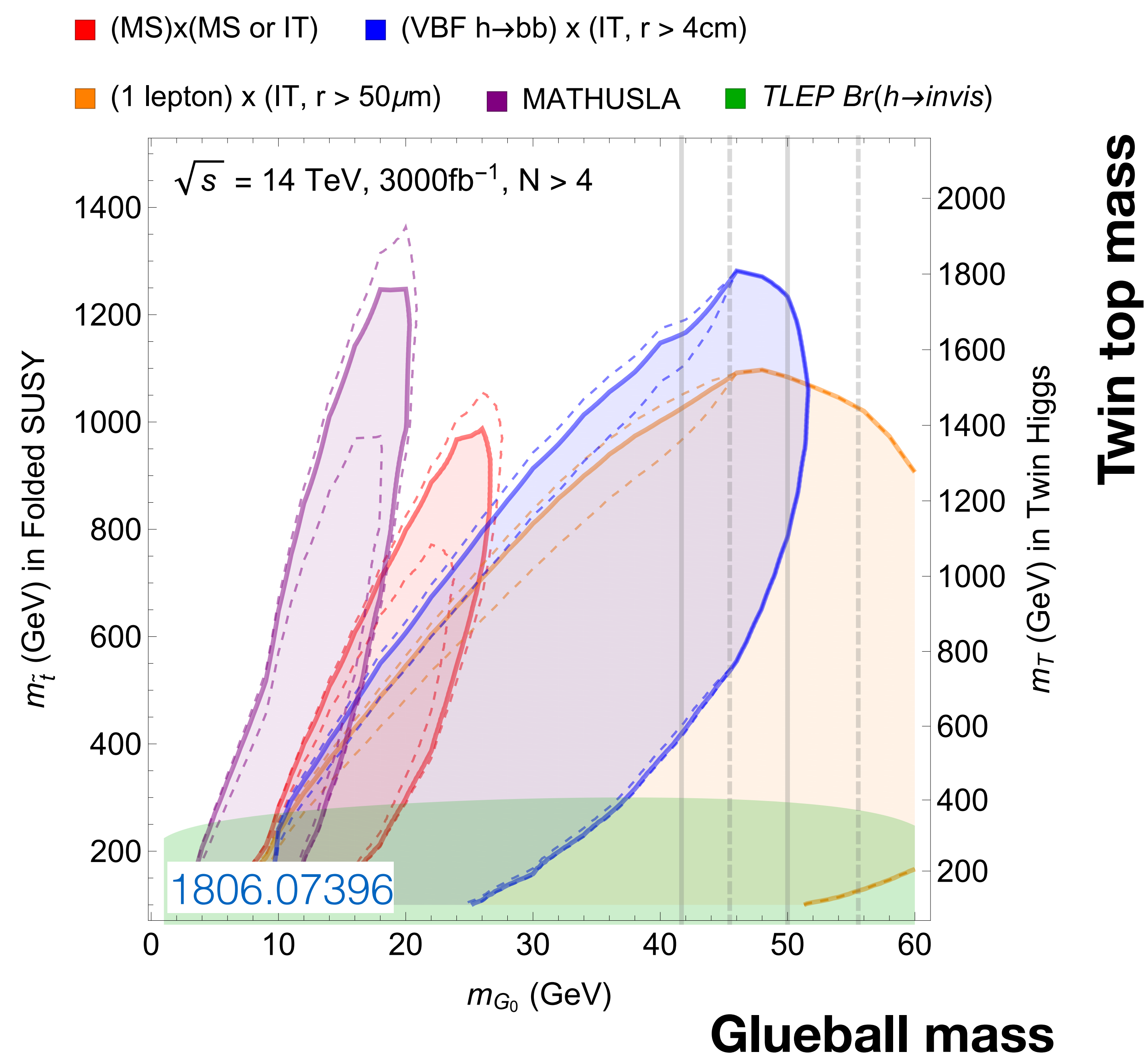
Craig, Katz, Sundrum, Strassler, 2015

New signature: exotic Higgs decays



Long-lived Glueballs; lightest have same quantum # as Higgs

$$\mathcal{L} \supset -\frac{\alpha_3'}{6\pi}\frac{v}{f}\frac{h}{f}G'^{\,a}_{\mu\nu}G'^{\,\mu\nu}_{a}$$



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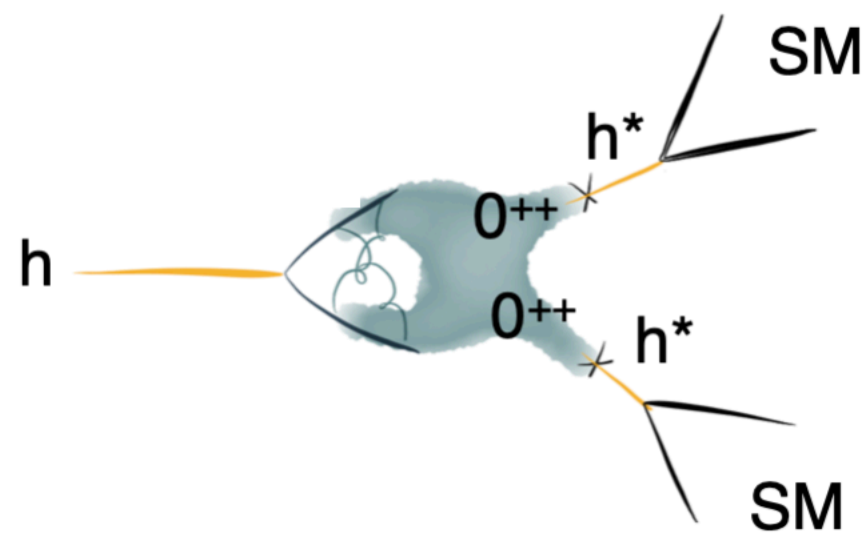

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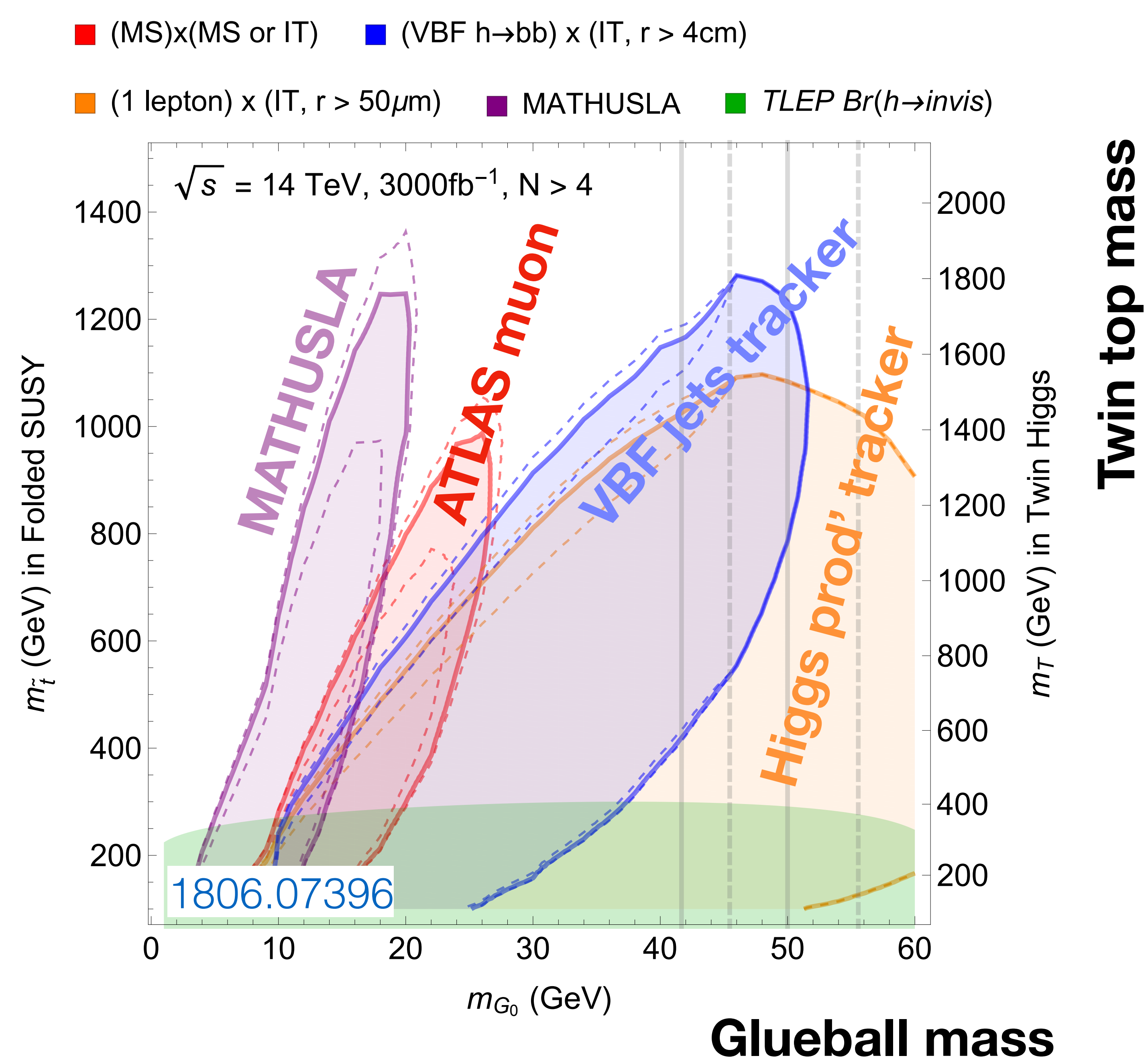
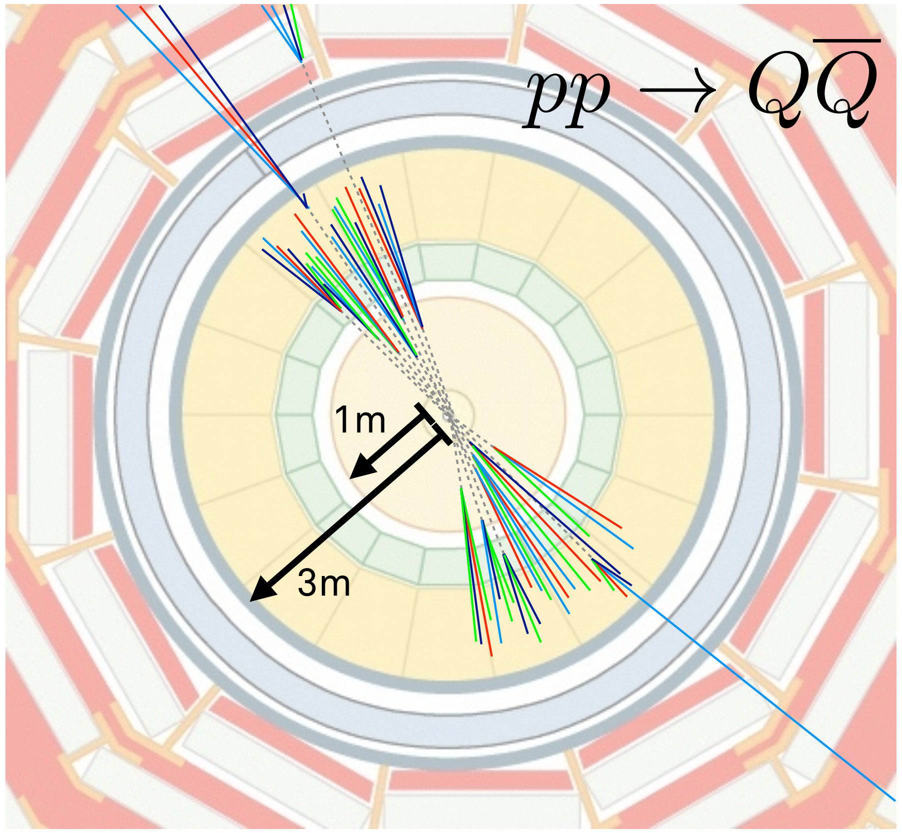
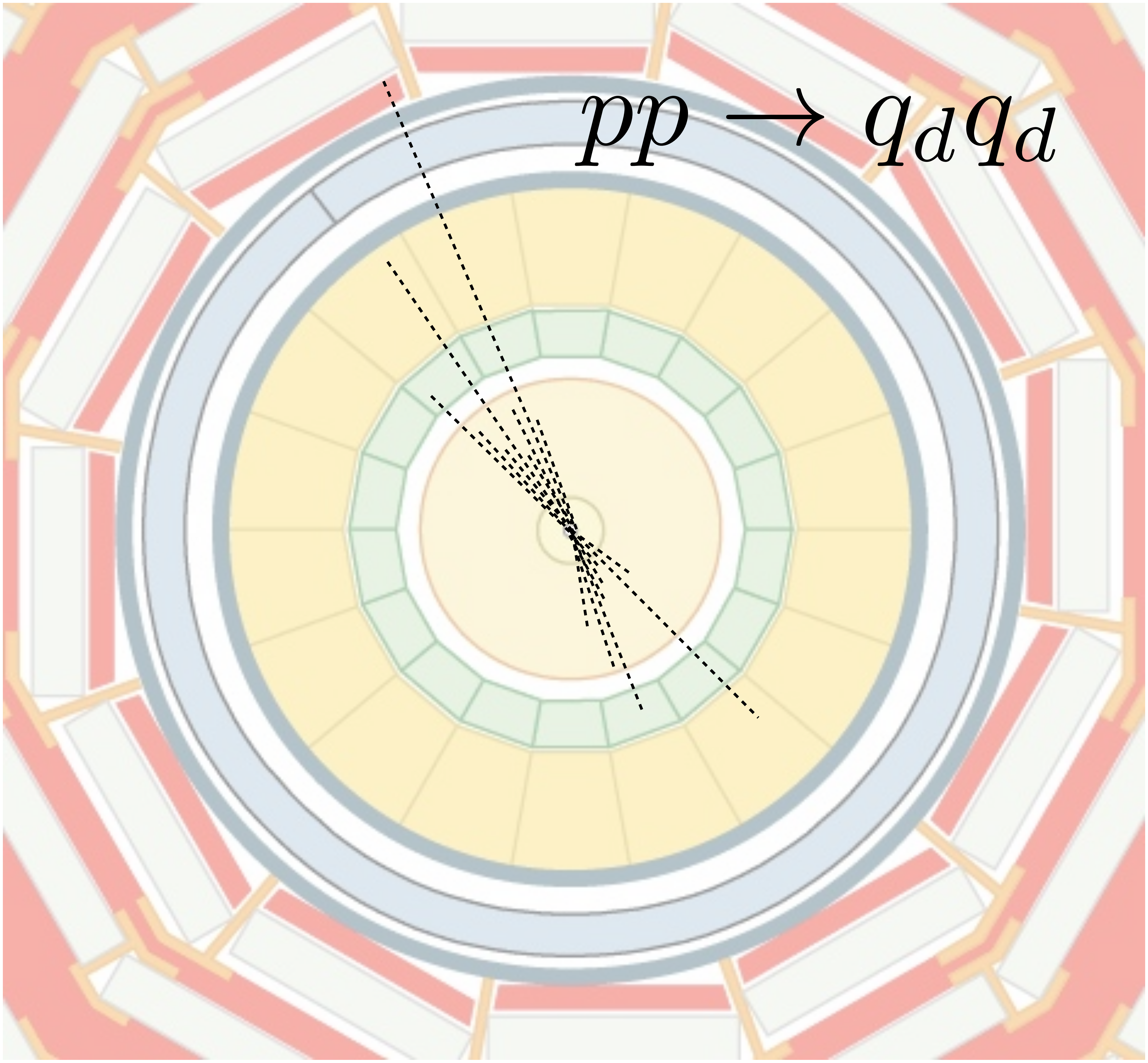


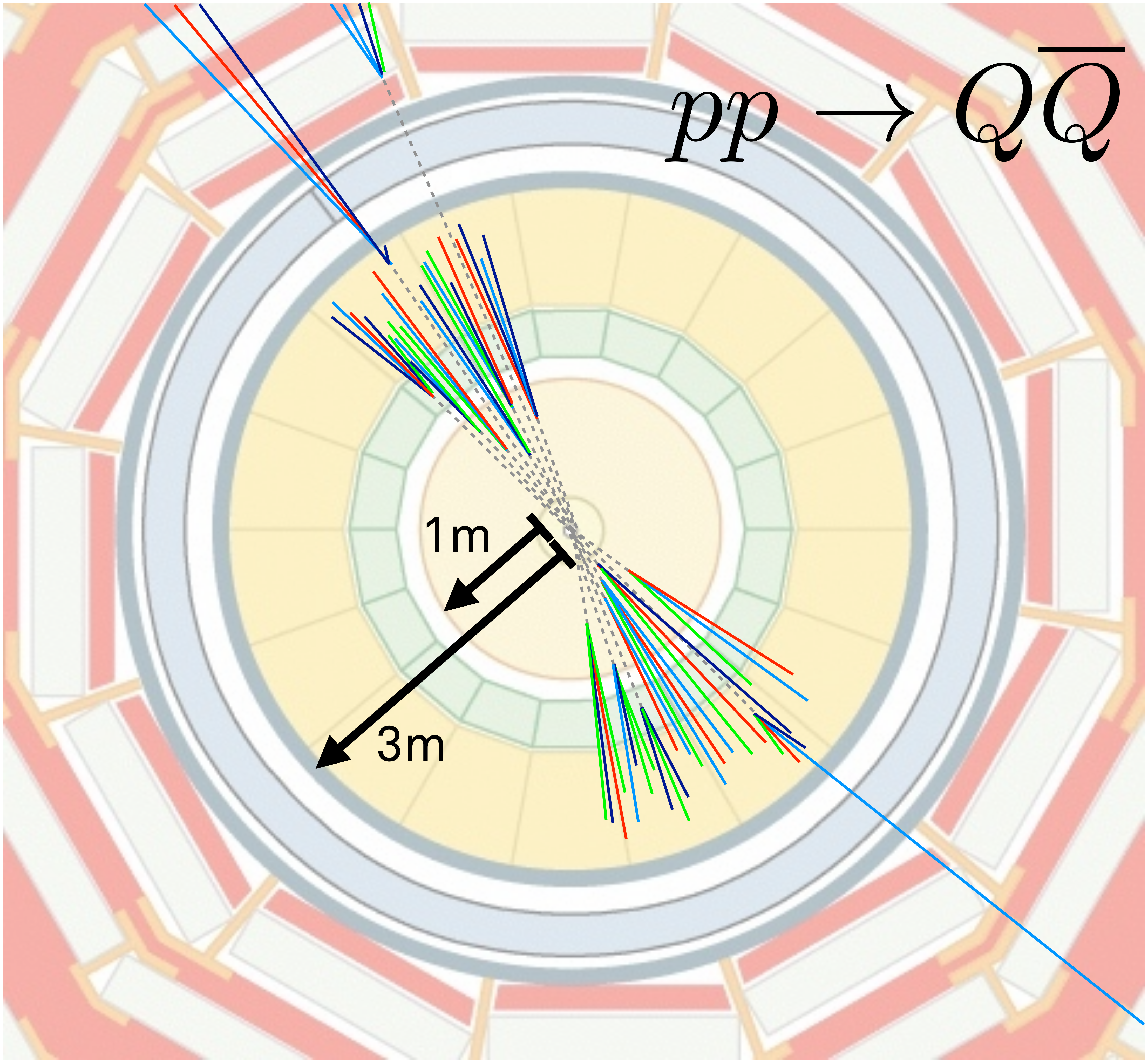
Twin Higgs pheno

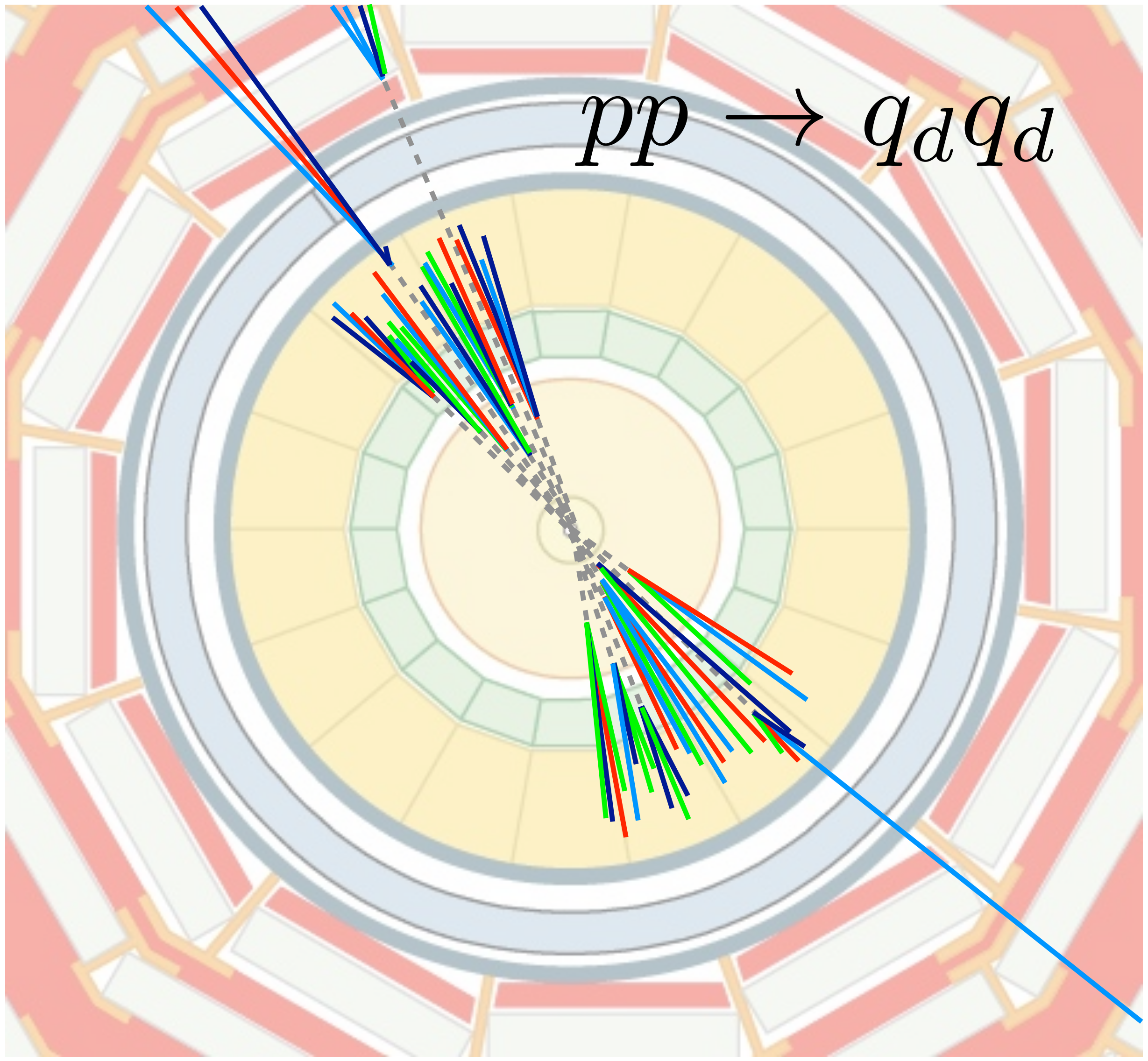
Schwaller, Stolarski, AW '15

- Twin parton shower -> Emerging Jets
- Signature of dark sector with long lived states




$pp \to q_d q_d$

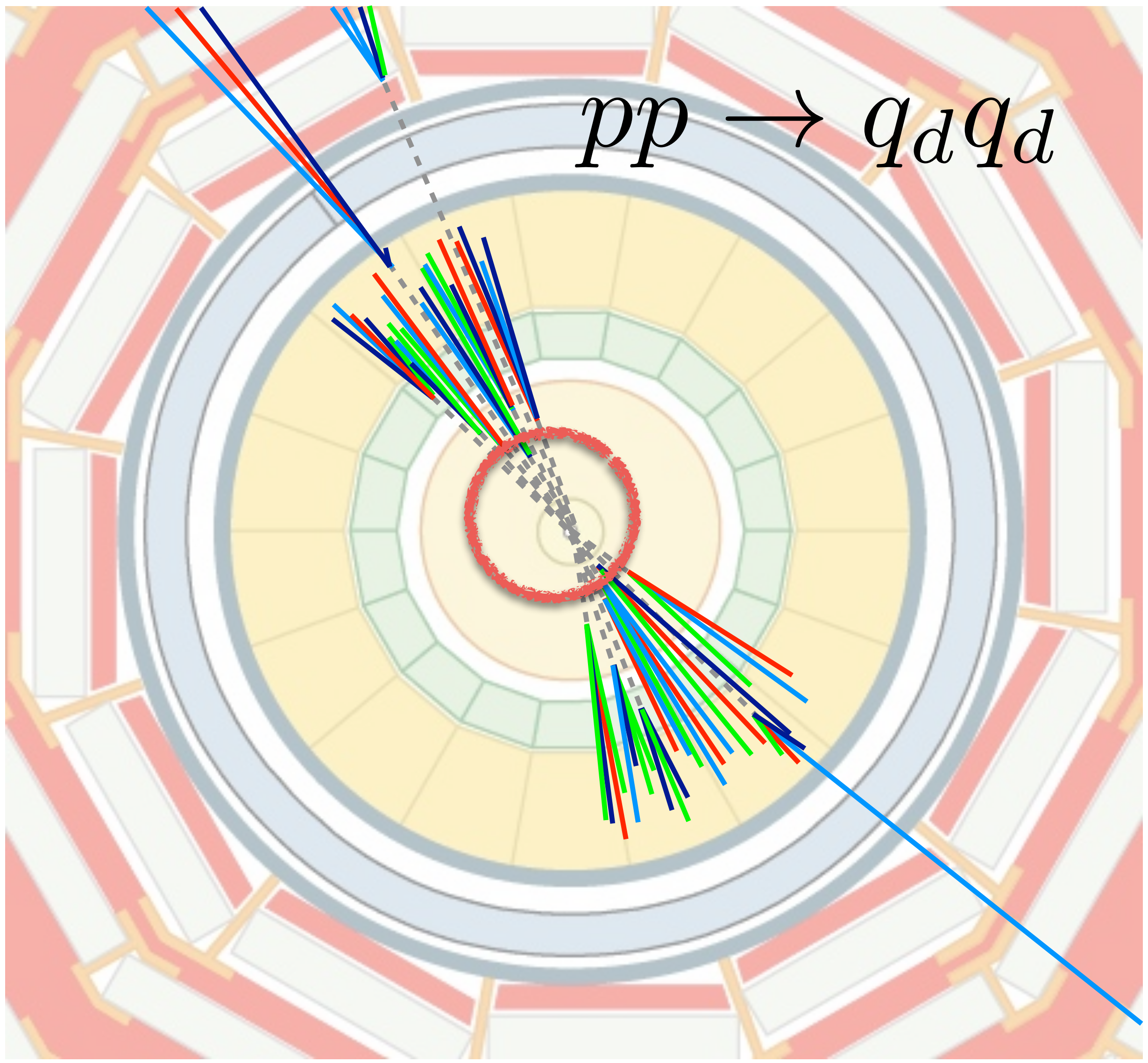

$pp \to Q\overline{Q}$
1m
3m



Decay lifetime of ~ cm

Exponential decay profile: Several displaced vertices inside a jet "cone" (or calo-jet)

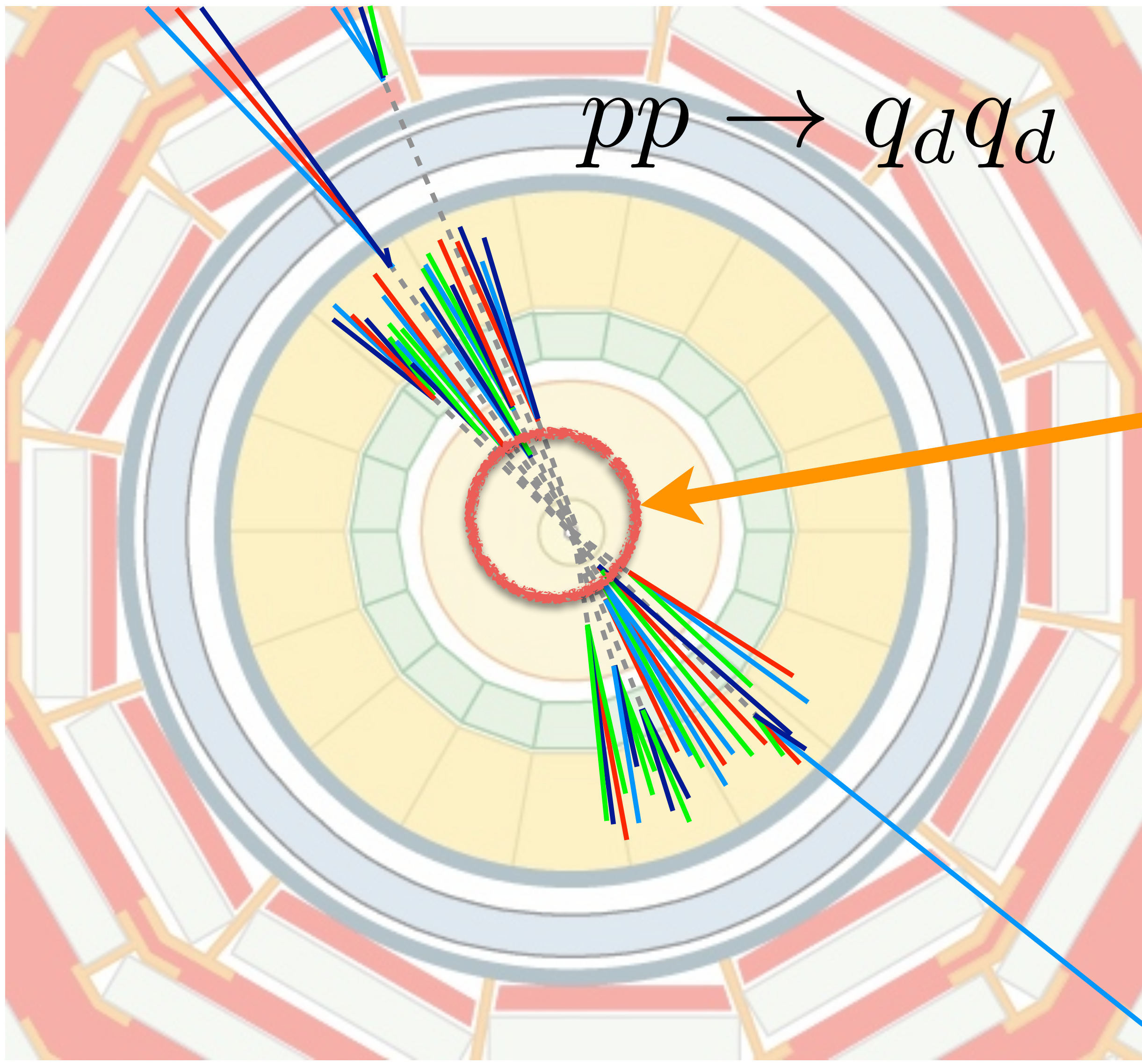
No/few tracks originating from interaction point



Look for Hcal-jets with no/few tracks below distance to inter-action point (inside circle)

New 'track-less' signature

Universal for a large class of displaced physics



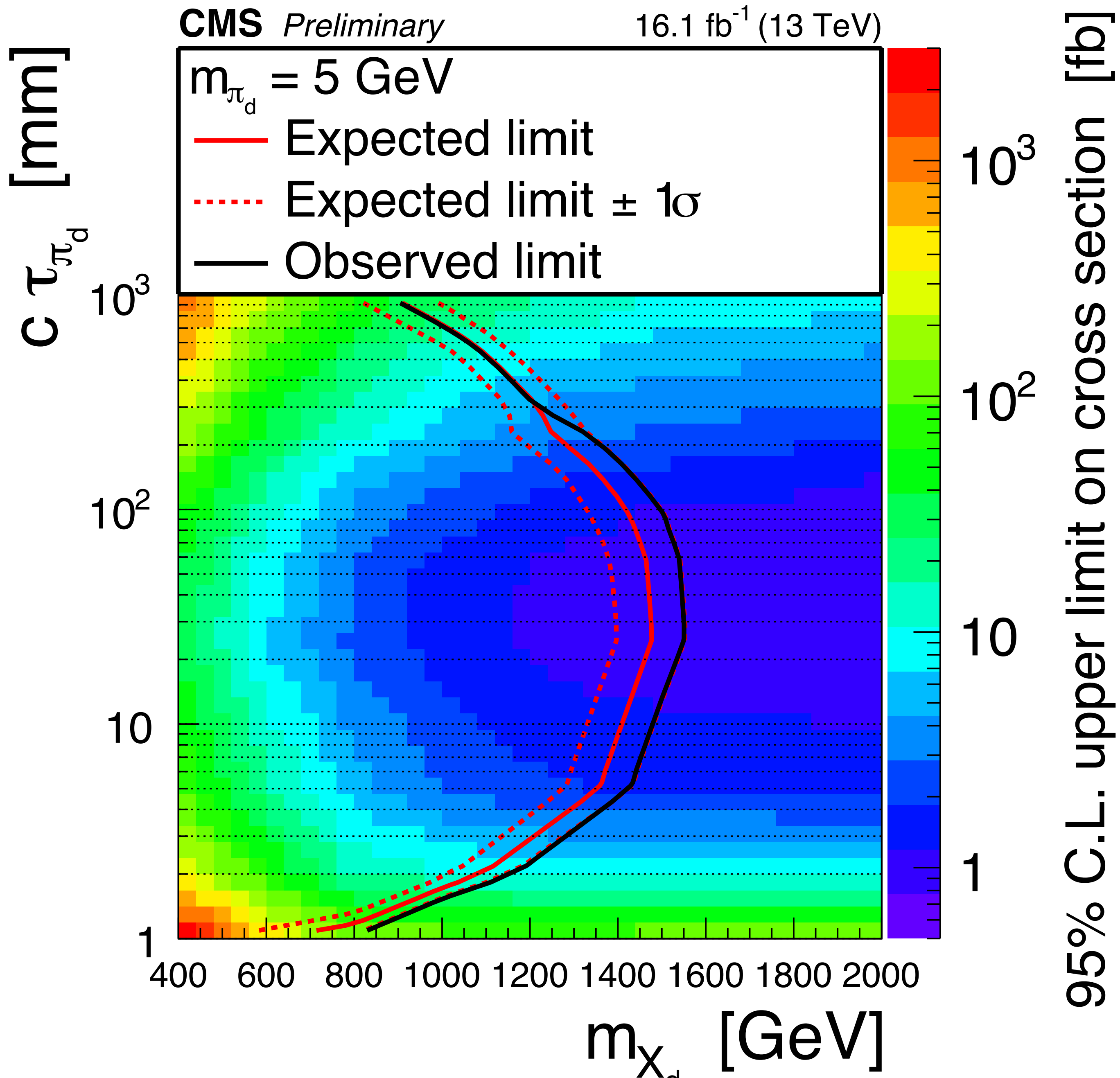
Look for Hcal-jets with no/few tracks below distance to inter-action point (inside circle)

New ‘track-less’ signature

Universal for a large class of displaced physics

Emerging jets search

"Mediator particles with masses between 400 and 1250 GeV are excluded for dark hadron decay lengths between 5 and 225 mm."



[CMS PAS EXO-18-001]

Amazing work by UMD CMS team (Belloni, Eno, Jeng, …)

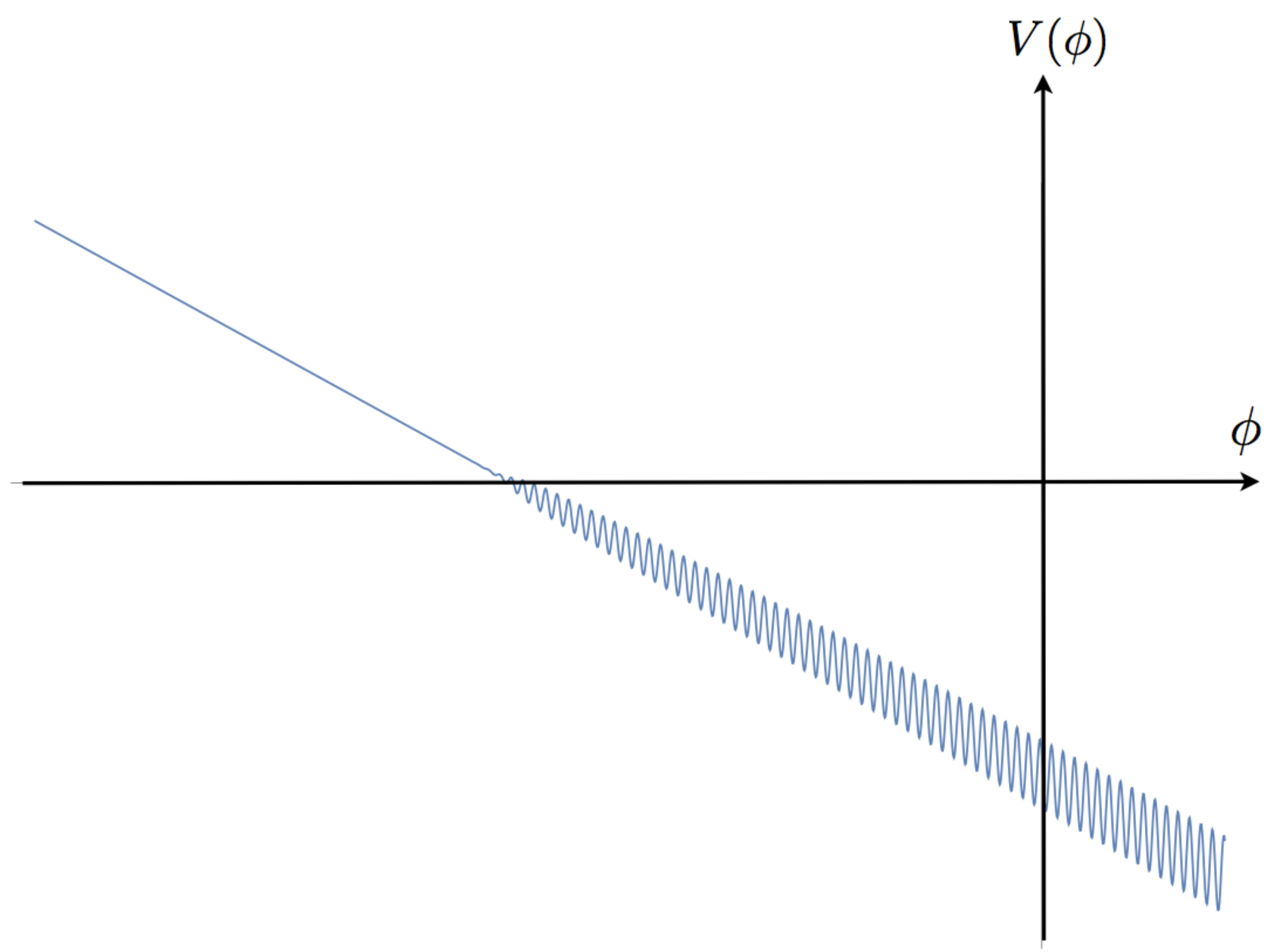
G. Giudice

“Is neutral naturalness the beautiful reason we haven’t seen anything, or the last desperate hope of theorists?”

Relaxion

Relaxing towards the Fermi scale

SM + axion + m_{Higgs}^2(axion-field) + driver



Relaxion paradigm

P.W. Graham, D.E. Kaplan, S.Rajendran ‘15
(earlier work by Abbott 85, G.Dvali,A.Vilenkin 04, G.Dvali 06)

A technically natural solution to the hierarchy problem

Uses dynamics, not symmetries

Still at the drafting stage, but a very interesting framework

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$$m^2|H|^2$$

Higgs mass

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$$= \Lambda^2 - g\phi$$

$$m^2|H|^2 \longrightarrow m^2(\phi)|H|^2$$

Higgs mass — axion-field dependent mass

Relaxion paradigm

P.W. Graham, D.E. Kaplan, S.Rajendran '15
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$$= \Lambda^2 - g\phi$$

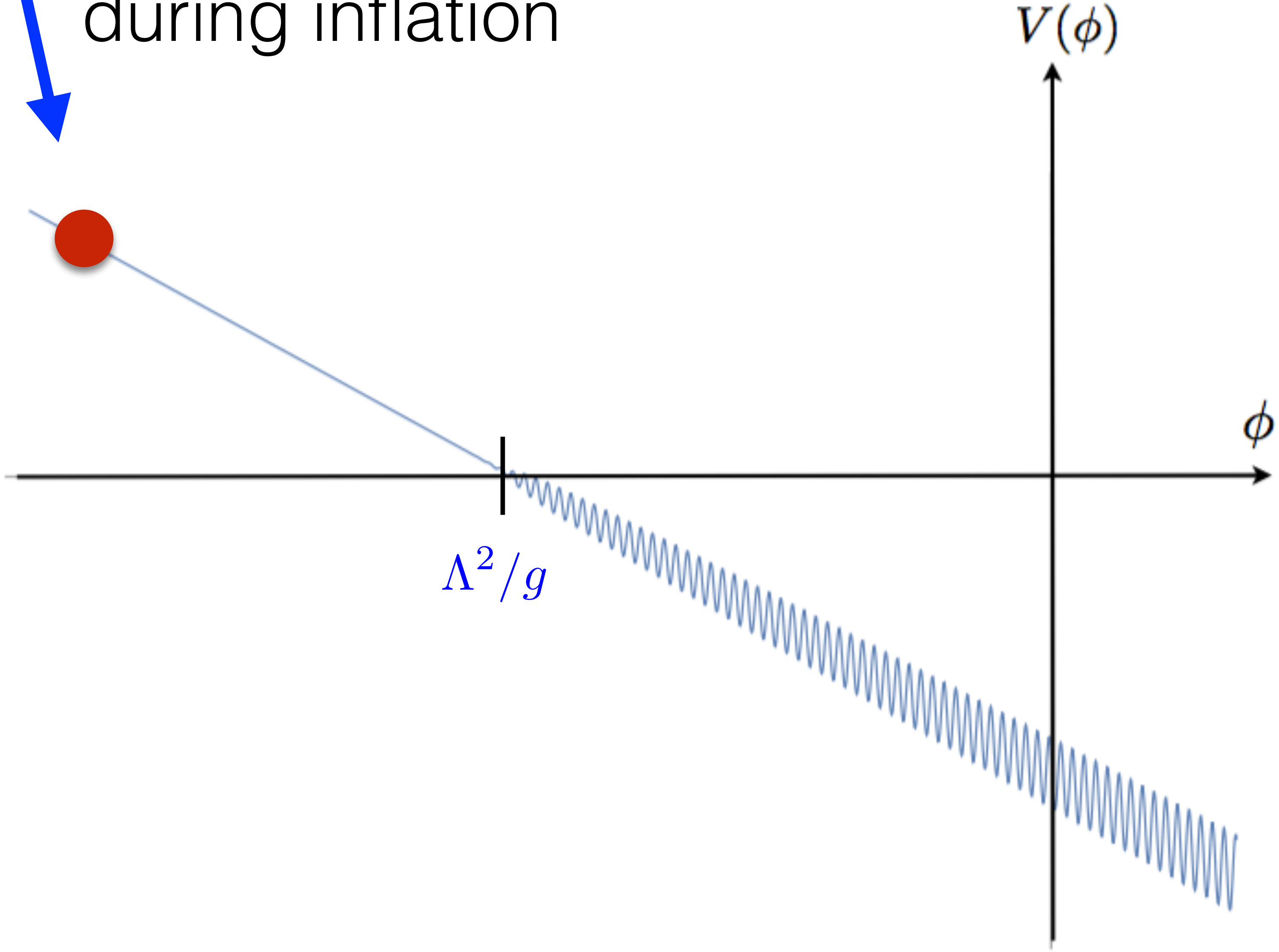
$$m^2|H|^2 \longrightarrow m^2(\phi)|H|^2$$

Higgs mass axion-field dependent mass

Clever dynamics stabilizes ϕ at values: $m^2(\phi) \ll \Lambda^2$

$$V(g\phi) + (\Lambda^2 - g\phi)|H|^2 + \epsilon\Lambda_{QCD}^3 h \cos\frac{\phi}{f}$$

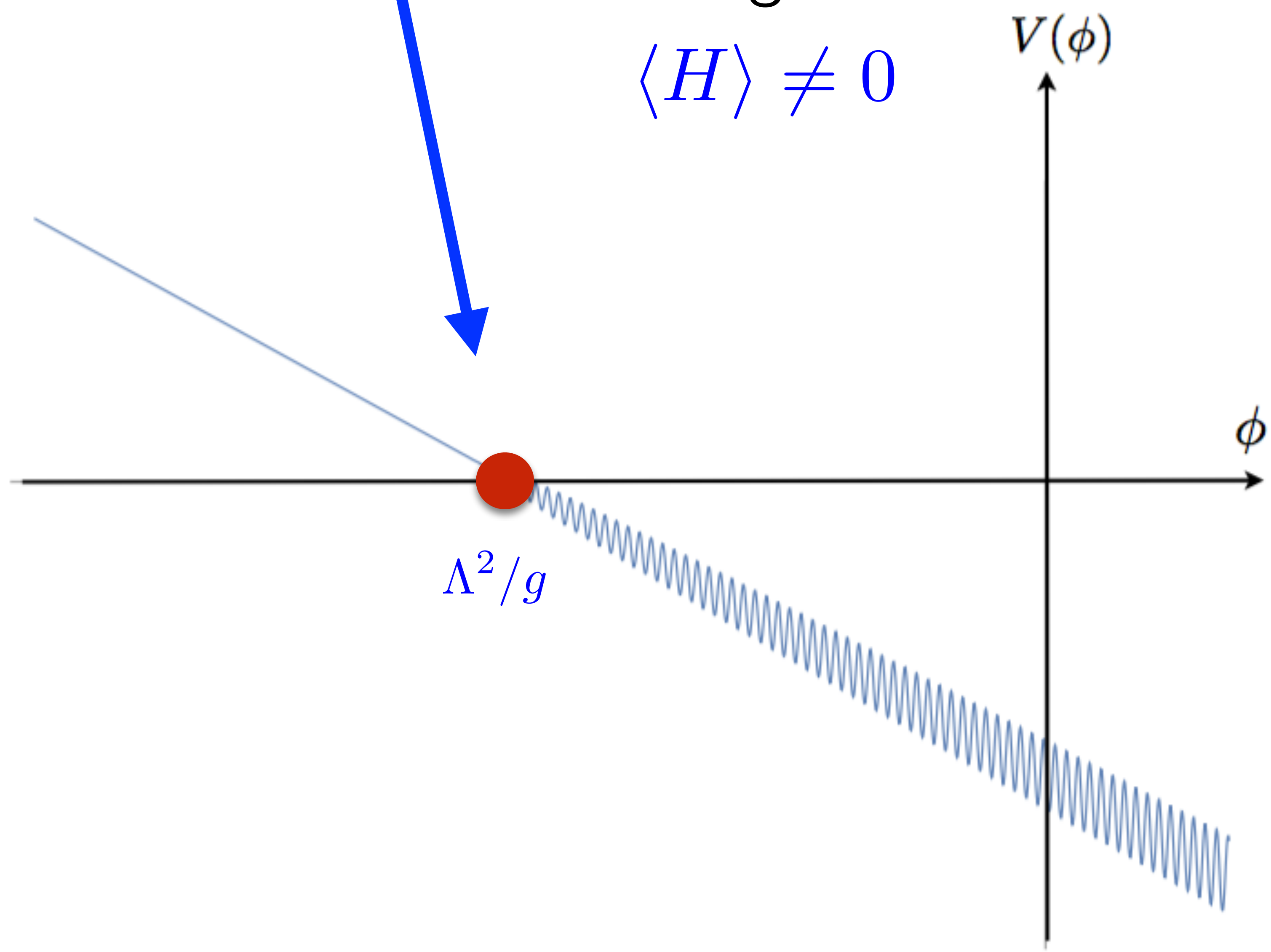
potential to slow-roll ϕ
during inflation



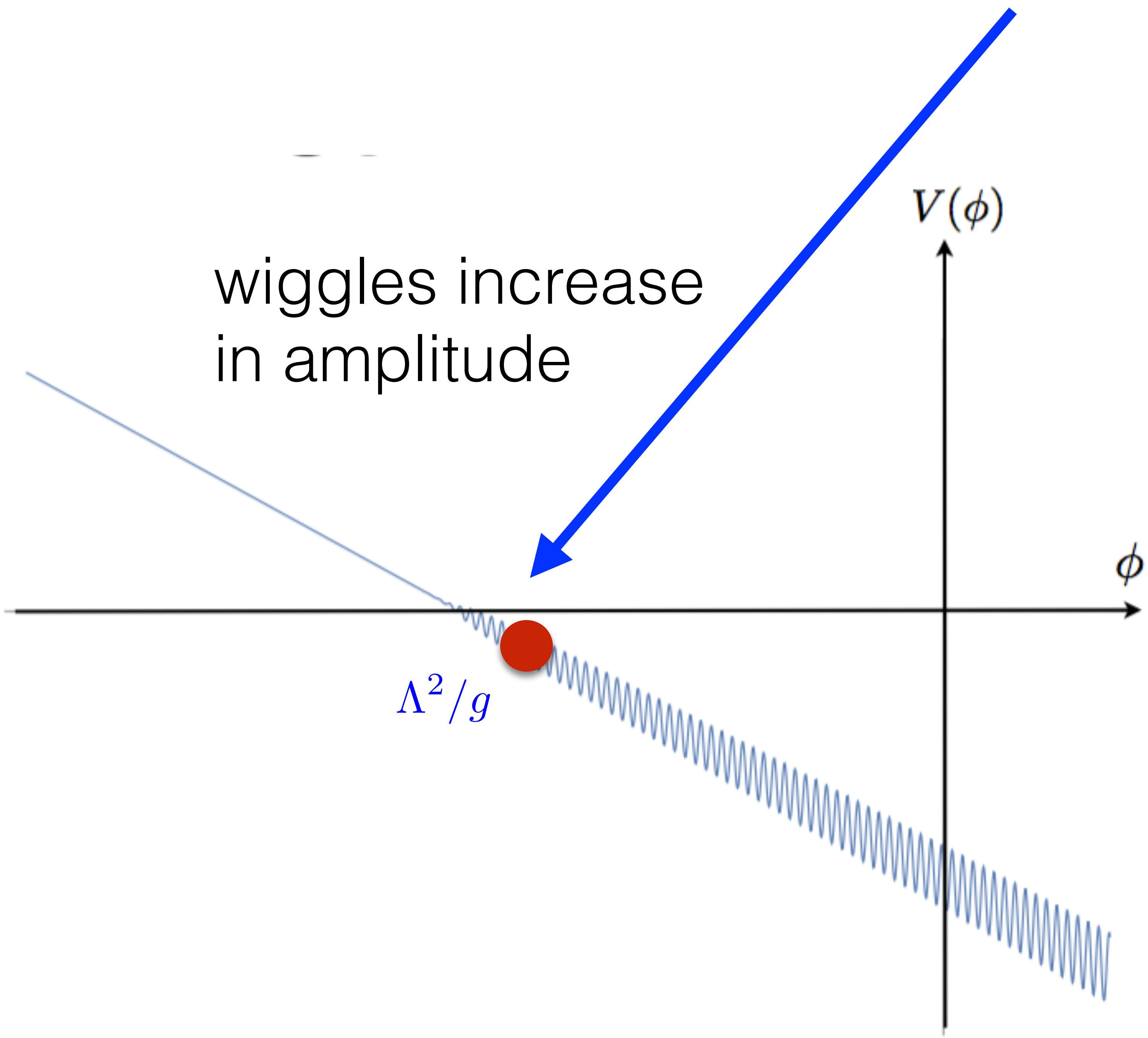
$$V(g\phi) + (\Lambda^2 - g\phi)|H|^2 + \epsilon \Lambda_{QCD}^3 h \cos\frac{\phi}{f}$$

Higgs mass squared
turns negative

$$\langle H \rangle \neq 0$$

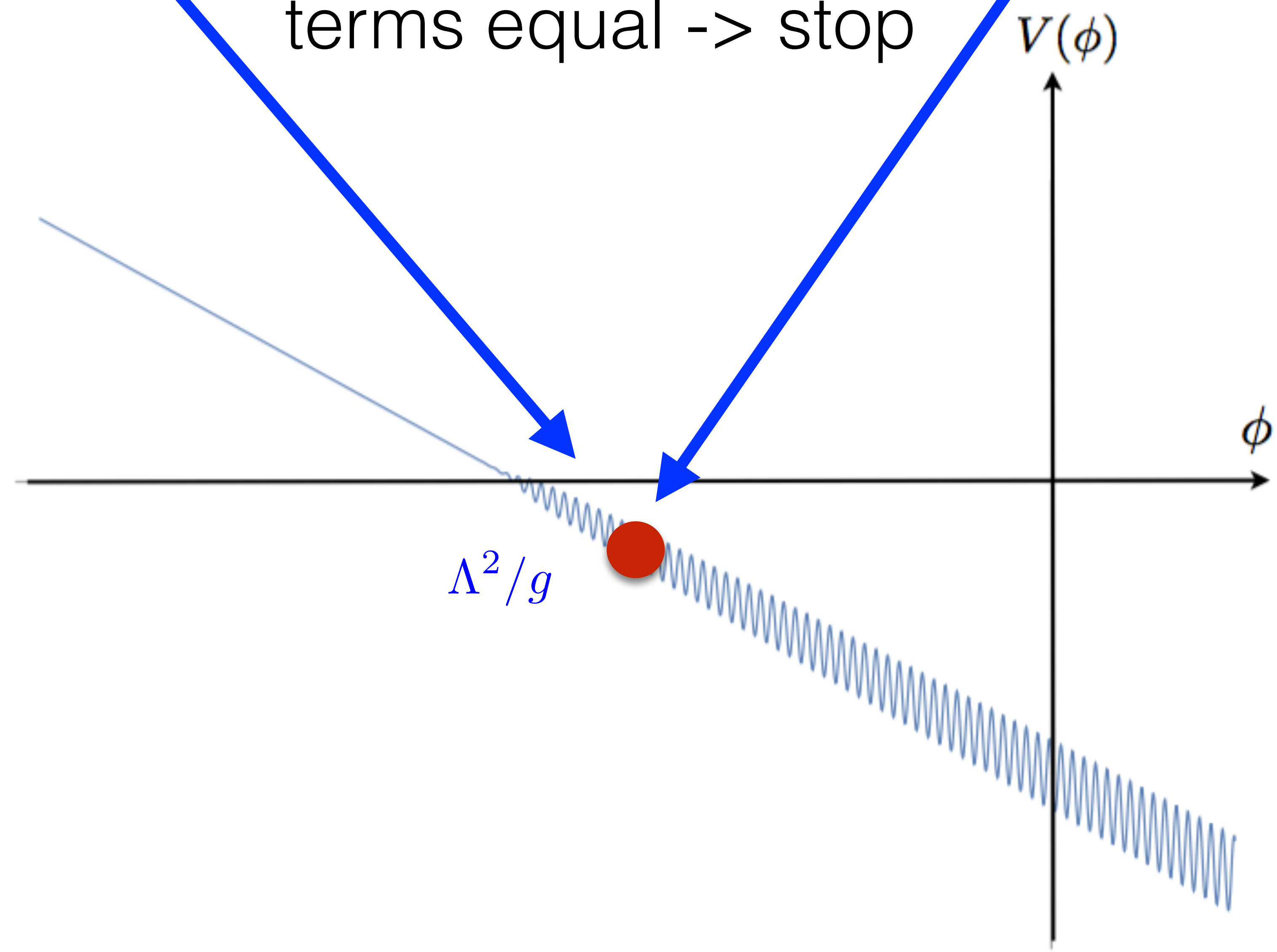


$$V(g\phi) + (\Lambda^2 - g\phi)|H|^2 + \epsilon\Lambda_{QCD}^3 h \cos\frac{\phi}{f}$$



$$V(g\phi) + (\Lambda^2 - g\phi)|H|^2 + \epsilon\Lambda_{QCD}^3 h \cos\frac{\phi}{f}$$

steepness of
terms equal -> stop



$$V(g\phi) + (\Lambda^2 - g\phi)|H|^2 + \epsilon\Lambda^3_{QCD}\, h \cos\frac{\phi}{f}$$

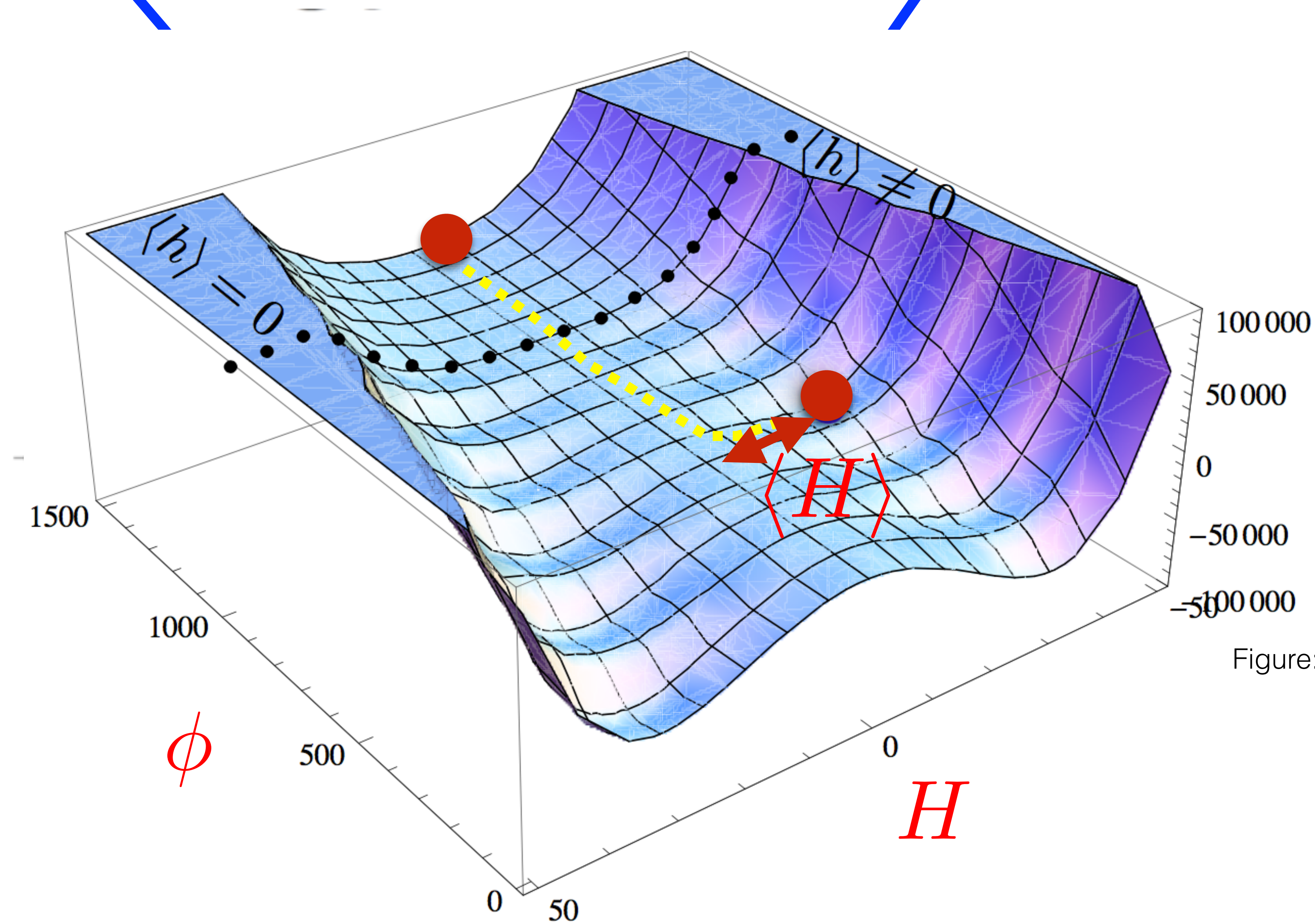


Figure: C. Grojean

* QCD axion doesn't work: $\theta_{QCD} \sim 1$ due to tilt
  * Add new QCD' group => new weak-scale signals!
  * Add additional scanning field => **no** collider signals! Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

Some points of concern:

$g \sim 10^{-27}\mathrm{GeV}$ UV completion ?

$N > H^2/g^2 \sim 10^{45}$ inflation ?

$\Delta\Phi \simeq 10^{41}\mathrm{GeV}$ large field excursions

The future

Or …


USS ENTERPRISE
BUD LIGHT

How far can we go?

Can I get an App for that?

Collider-Reach 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

Z’ example

$$\hat{\sigma}_0(\hat{s}) = C\,\frac{\hat{s}}{(\hat{s}-M_{Z'}^2)^2 + \Gamma_{Z'}^2 M_{Z'}^2}$$

$\mathcal{L}_{ij}$ narrow width approx.

$$\rightsquigarrow \frac{1}{M^2} \times \text{parton-luminosity}$$

Z' example

$$\frac{d\sigma}{dm^2} = \int dx_1 dx_2 \, [f_1(x_1) f_2(x_2)] \; \hat{\sigma}_0(\hat{s}) \delta(m^2 - \hat{s}^2), \qquad \hat{\sigma}_0(\hat{s}) = C \, \frac{\hat{s}}{(\hat{s} - M_{Z'}^2)^2 + \Gamma_{Z'}^2 M_{Z'}^2}$$

$$= \sum_{ij} \underbrace{\left[\tau \int \frac{dx}{x} f_i(x) f_j(\tau/x)\right]}_{\mathcal{L}_{ij}} \underbrace{\frac{C}{(m^2 - M_{Z'}^2)^2 + \Gamma_{Z'}^2 M_{Z'}^2}}_{\text{narrow width approx.}}$$

$$\rightsquigarrow \frac{1}{M^2} \times \text{parton-luminosity}$$

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$$\sigma \approx \int dm^2 \sum_{ij} \underbrace{\mathcal{L}_{ij}(m^2, s)}\, \underbrace{C \, \frac{\pi}{\Gamma_{Z'} M_{Z'}} \, \delta(m^2 - M_{Z'}^2)} \qquad \Gamma_{Z'} \propto M_{Z'}$$

$$= \frac{1}{M_{Z'}^2} \sum_{ij} C' \mathcal{L}_{ij}(M_{Z'}^2, s)$$

$$= N(M_{Z'}, s) \qquad \rightsquigarrow \frac{1}{M^2} \times \text{parton-luminosity}$$

Instead of cross section ratio, use **parton luminosity ratio**

Equation we solve to find M_{high} is then

$$\frac{\mathcal{L}_{ij}(M^2_{\text{high}}, s_{\text{high}})}{\mathcal{L}_{ij}(M^2_{\text{low}}, s_{\text{low}})} \times \frac{\text{lumi}_{\text{high}}}{\text{lumi}_{\text{low}}} = \frac{M^2_{\text{high}}}{M^2_{\text{low}}}$$

The tools we use for this are
LHAPDF and HOPPET
most plots with MSTW2008 NNLO PDFs

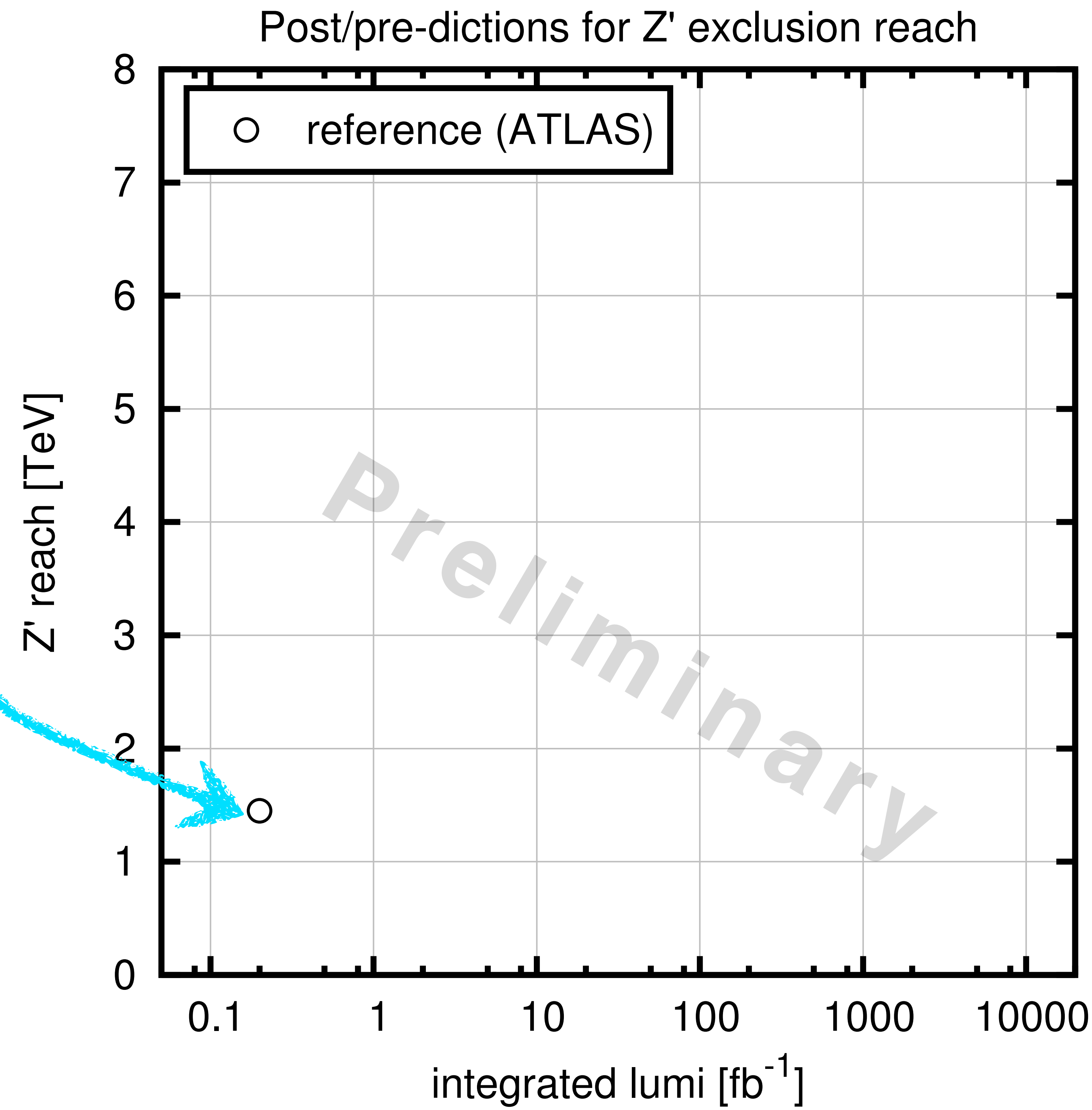
$$\mathcal{L}_{ij}(M^2, s) = \int_\tau^1 \frac{dx}{x} x f_i(x, M^2) \frac{\tau}{x} f_j\left(\frac{\tau}{x}, M^2\right) \qquad \tau \equiv \frac{M^2}{s}$$

i & j parton

Does it work?

Try a Z' search. Take a baseline analysis:

ATLAS,
0.2 fb^{-1} @ 7 TeV
excludes M < 1450 GeV



Try a Z' search. Take a baseline analysis:

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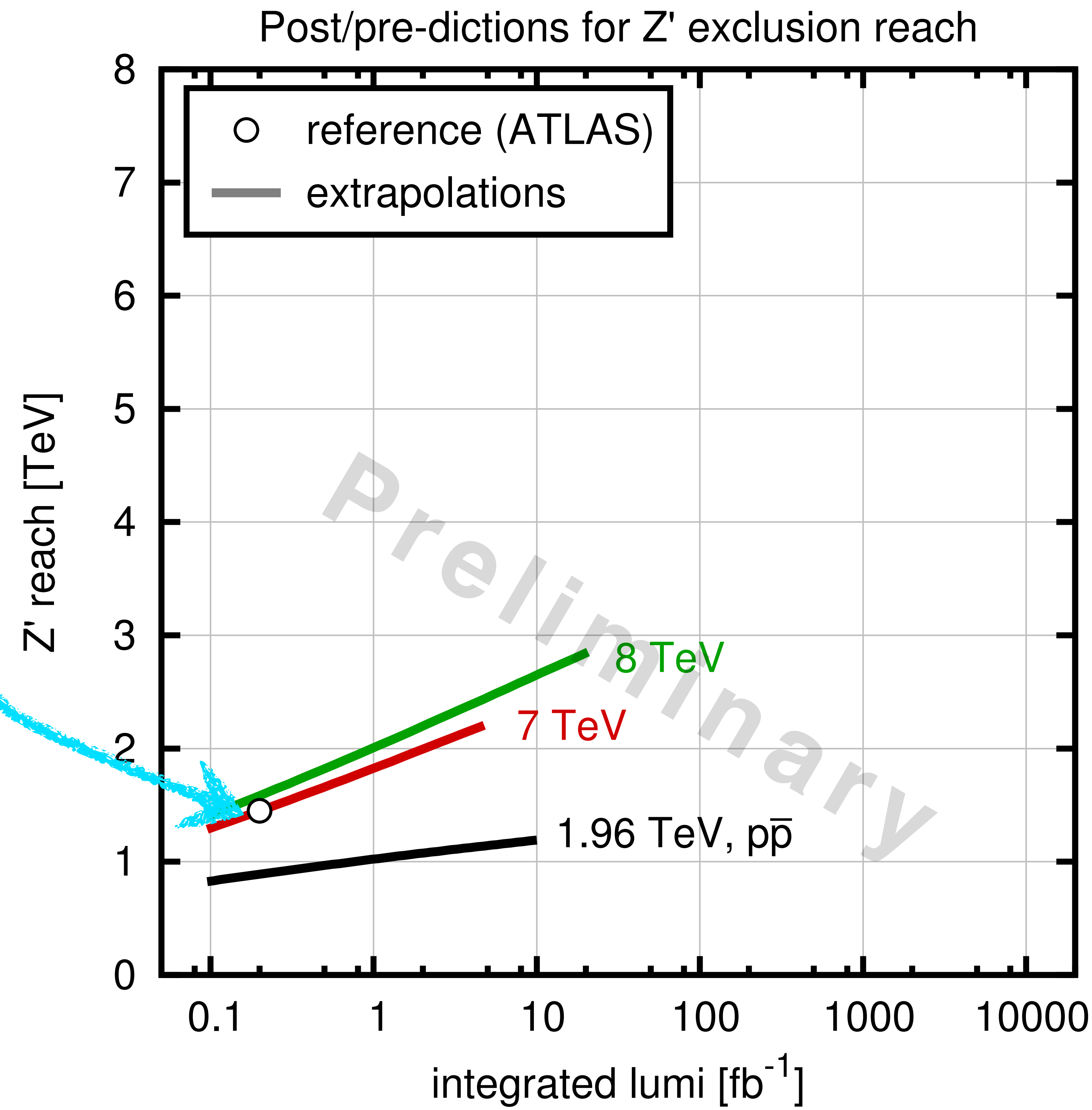
"Predict" exclusions at other lumis & energies (assume $q\bar{q}$)



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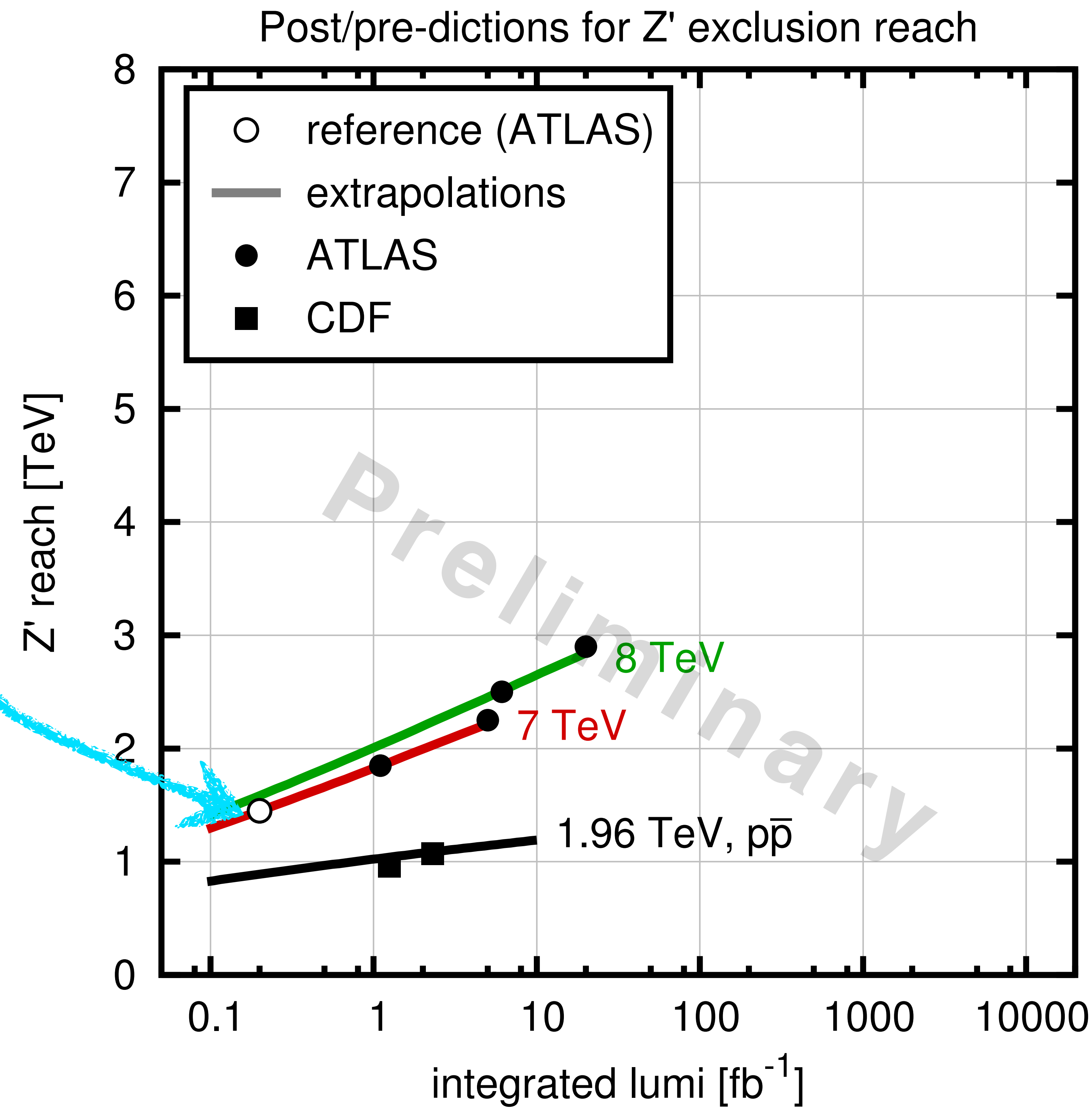
Compare to actual exclusions



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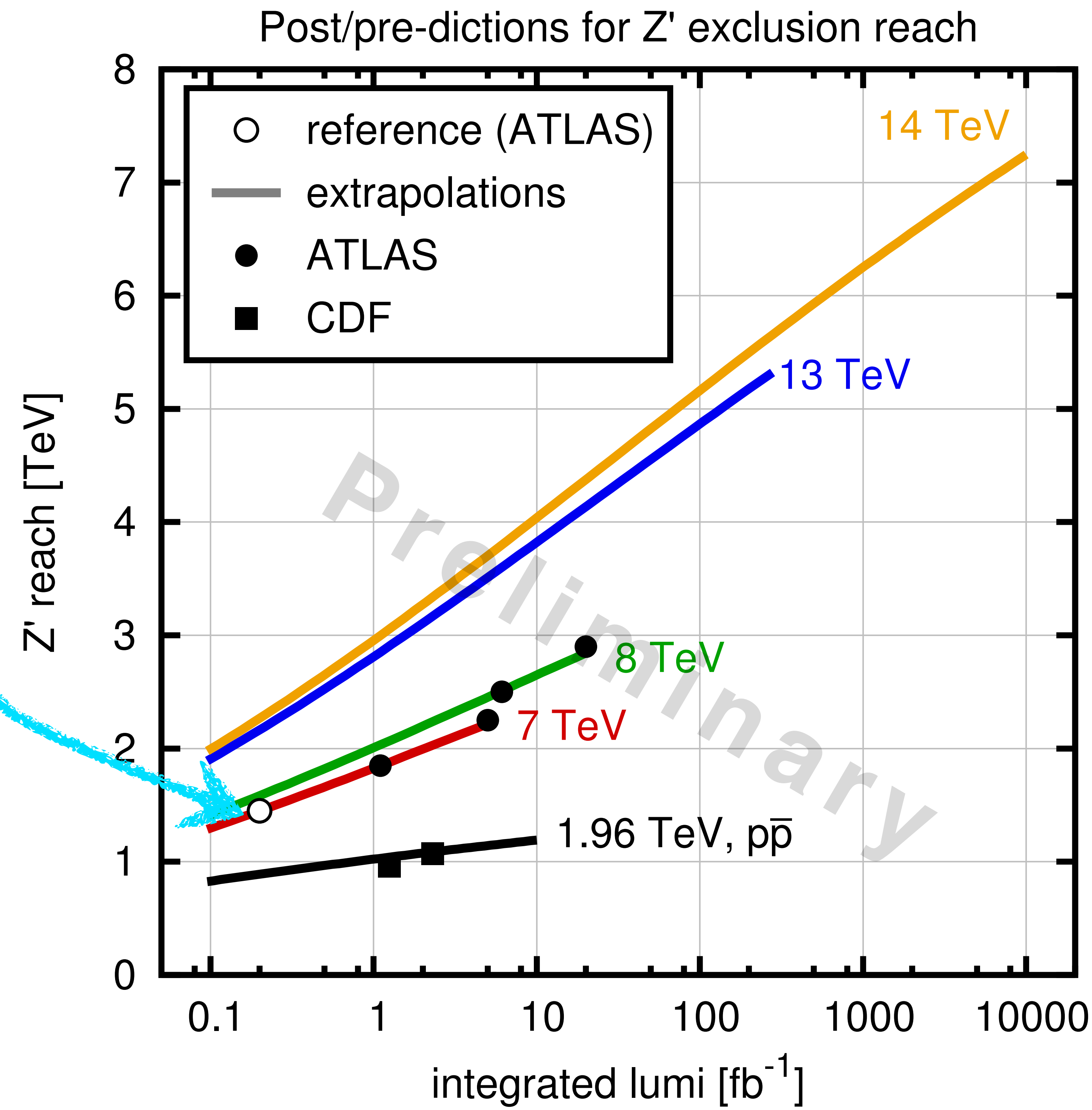
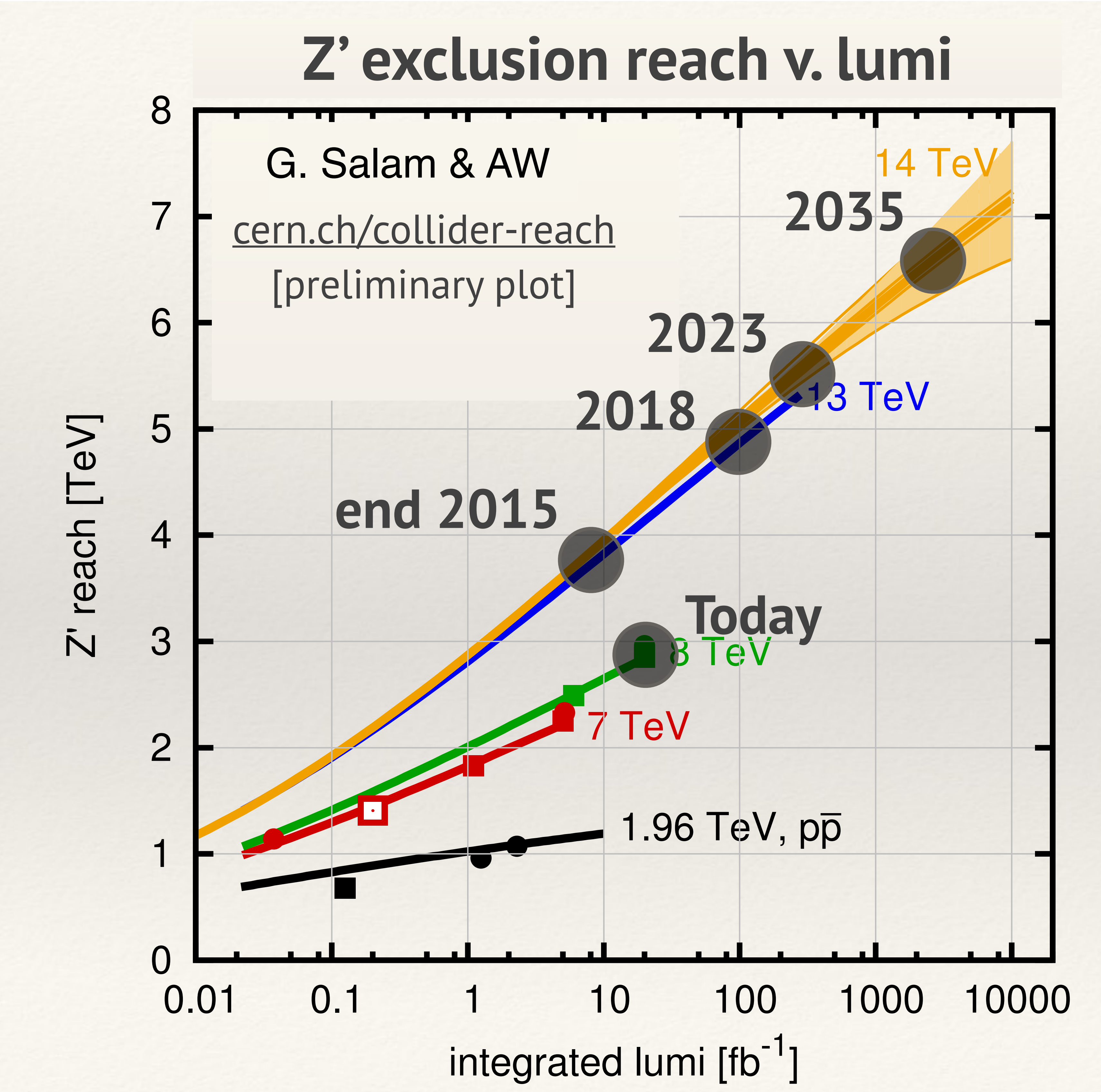
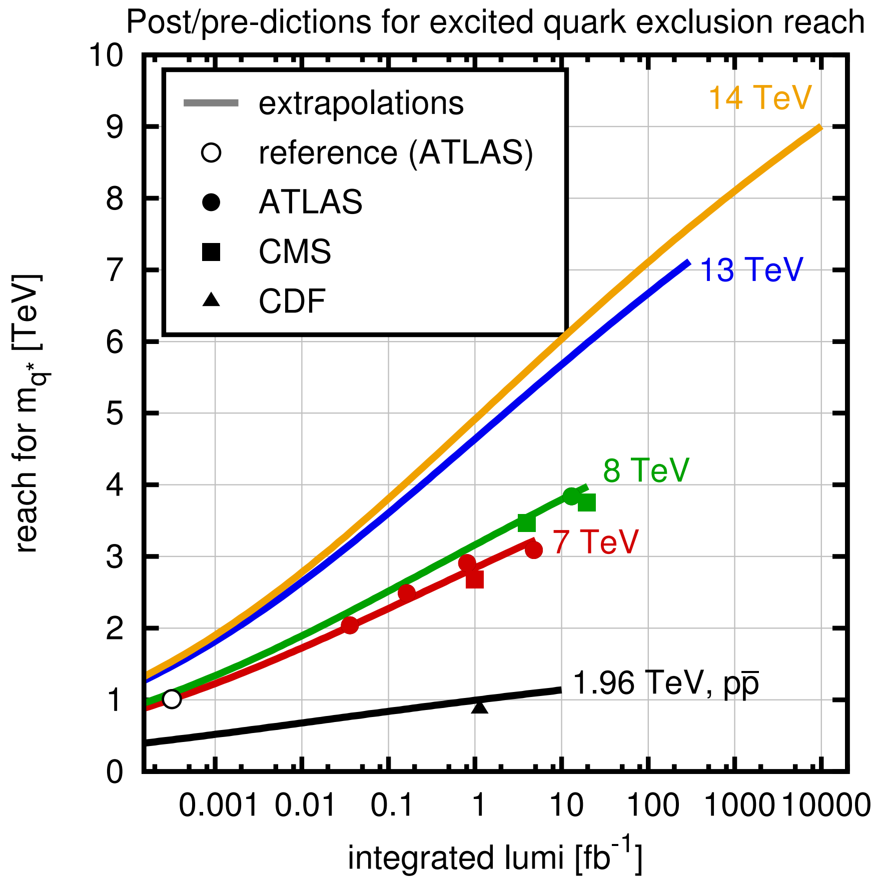


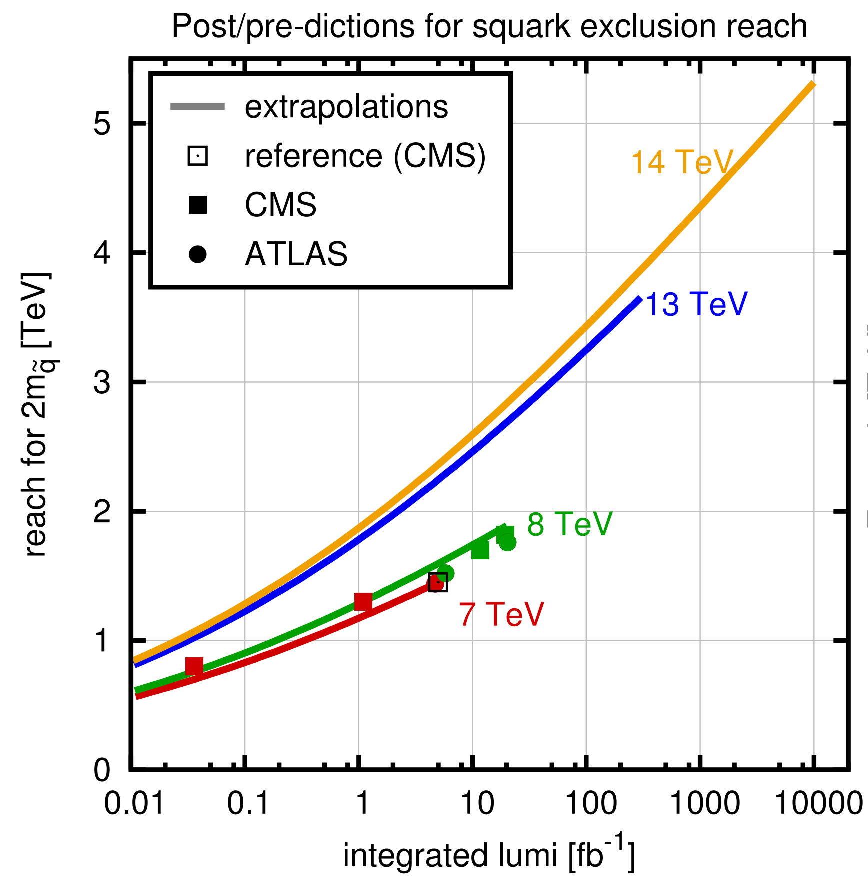
Maybe it only works so well because it's a simple search?
(Signal & Bkgd are both $q\bar{q}$ driven)

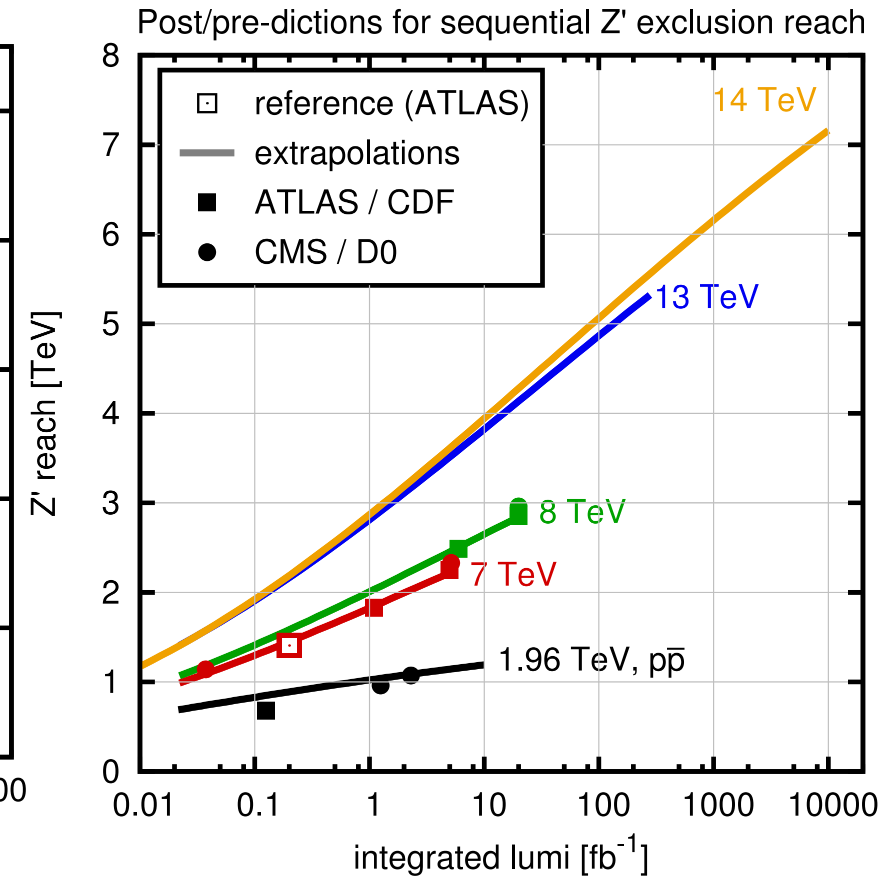


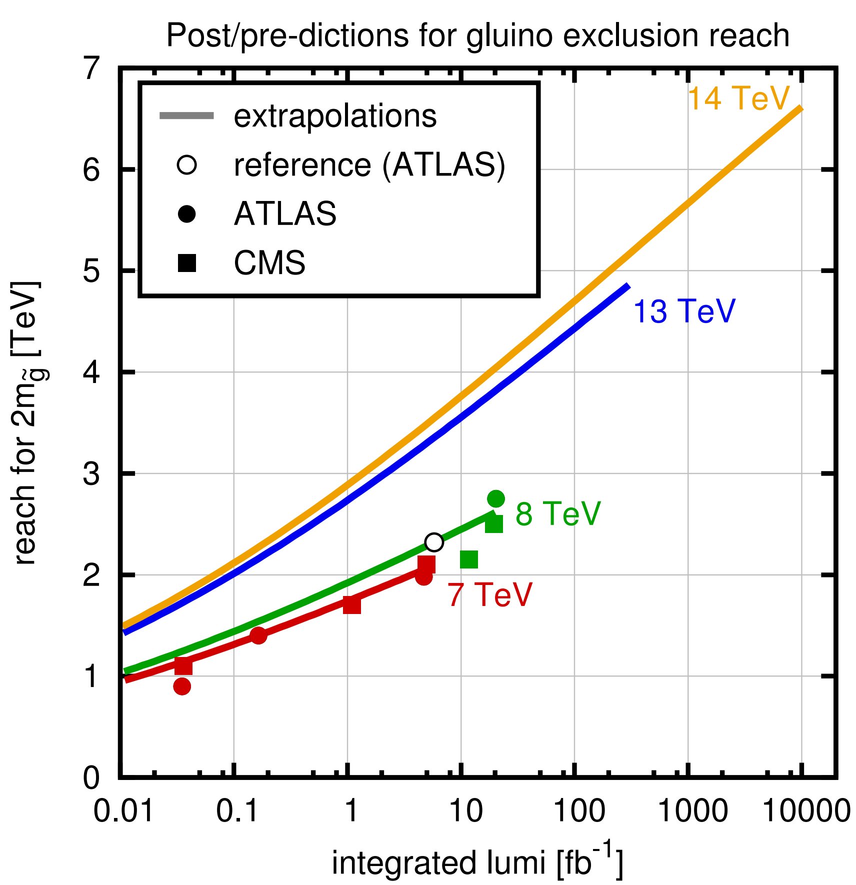
By the end of the year, most searches will beat 8 TeV results

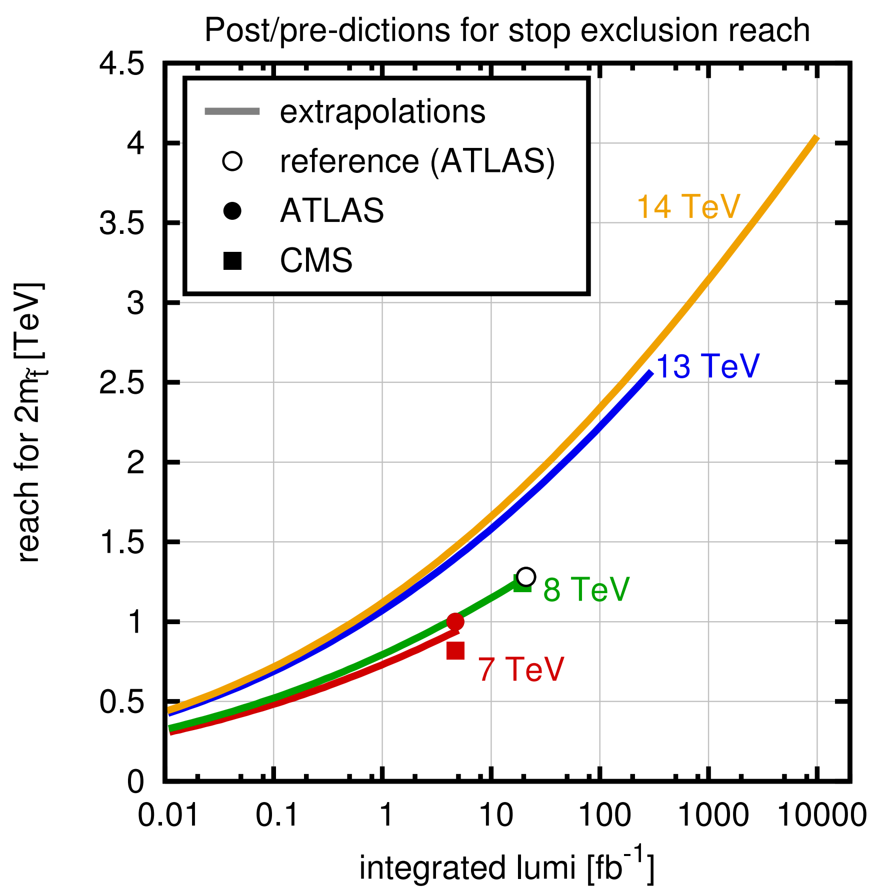
[Some, e.g. excited quarks, will surpass 8 TeV with just 0.2 fb^{-1}]

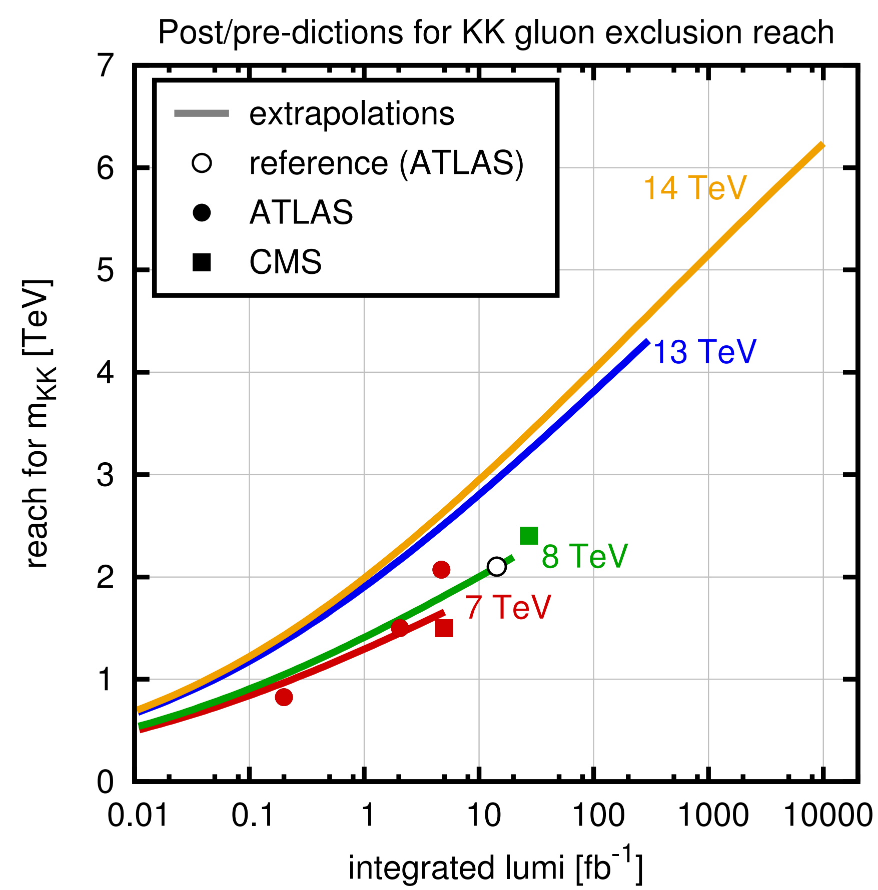












Salam, AW cern.ch/collider-reach

From your iPhone/Android

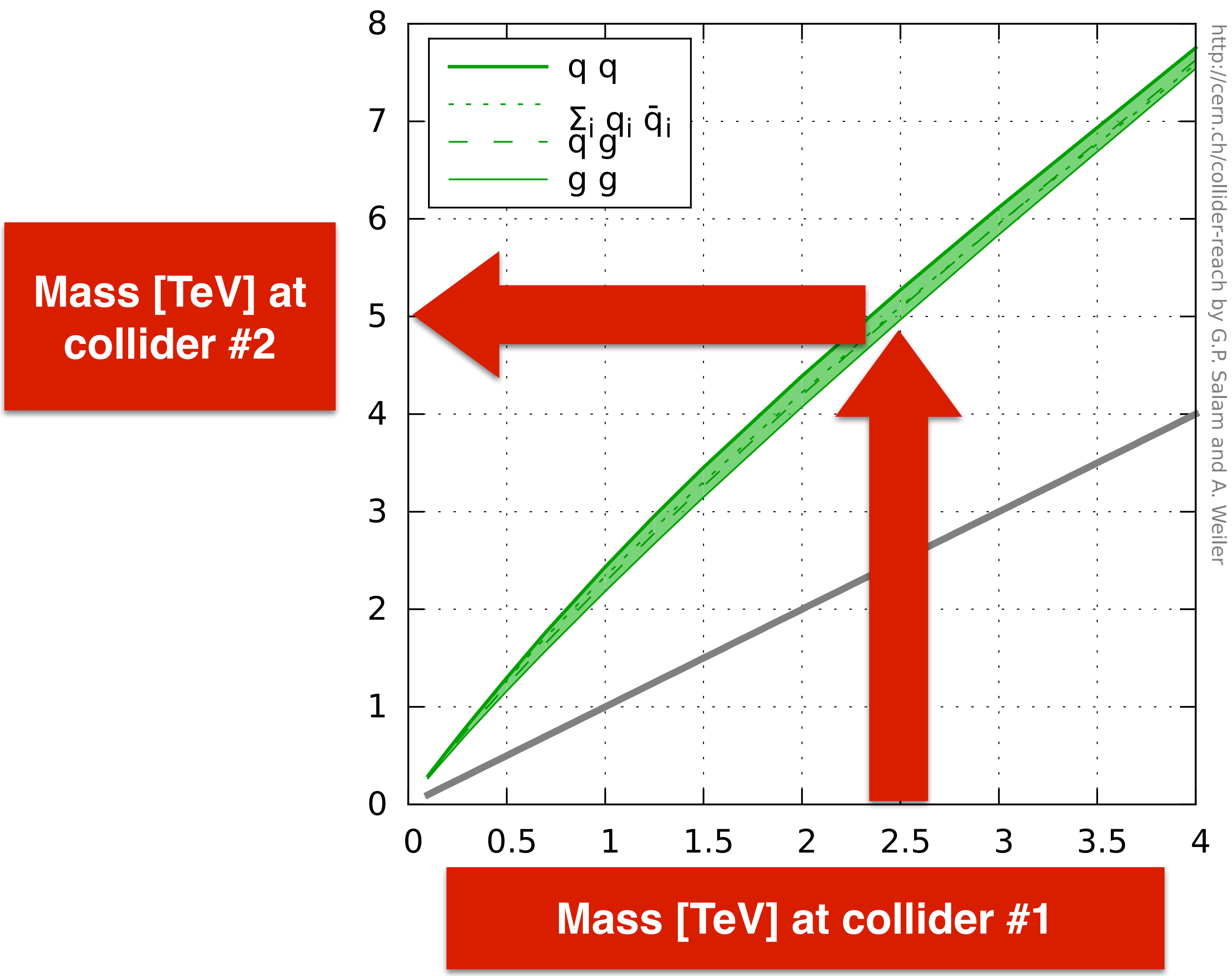
(or a generic browser)

cern.ch/collider-reach

Collider 1: CoM energy 8 TeV, integrated luminosity 20 fb^{-1}

Collider 2: CoM energy 14 TeV, integrated luminosity 300 fb^{-1}

PDF: MSTW2008nnlo68cl



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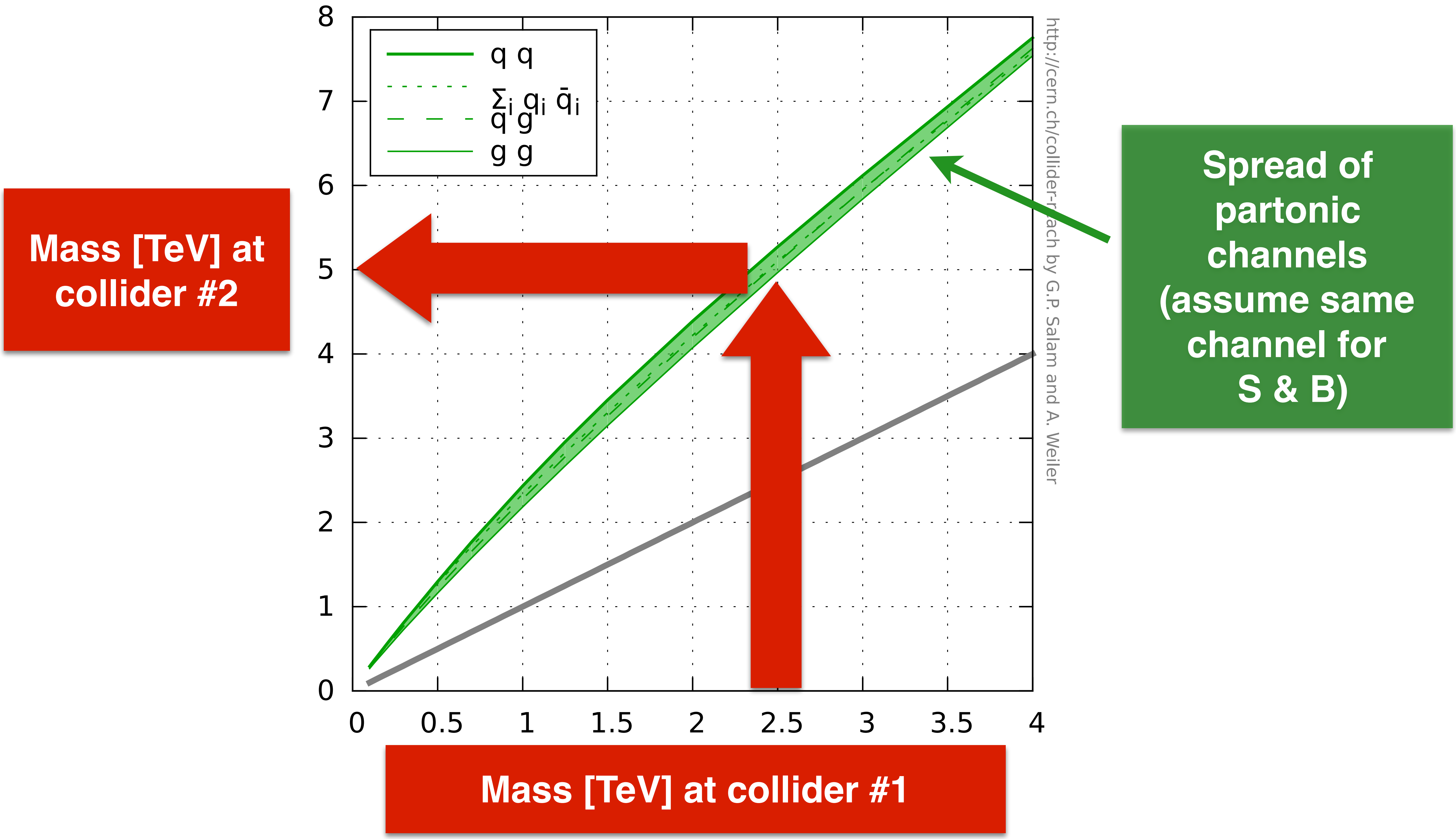


Collider Reach (β) | Home | Plots | About

cern.ch/collider-reach

The Collider Reach tool gives you a quick (and dirty) estimate of the relation between the mass reaches of different proton-proton collider setups.

Collider 1: CoM energy 14 TeV, integrated luminosity 300 fb^{-1}

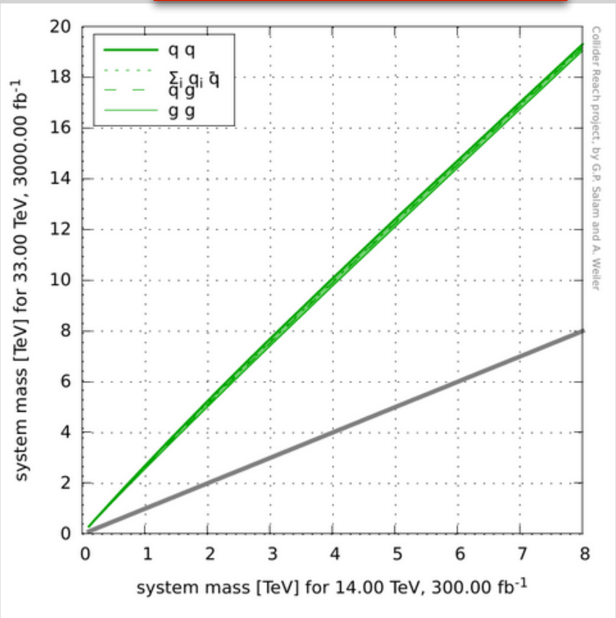
Collider 2: CoM energy 33 TeV, integrated luminosity 3000 fb^{-1}

PDF: CT10nlo

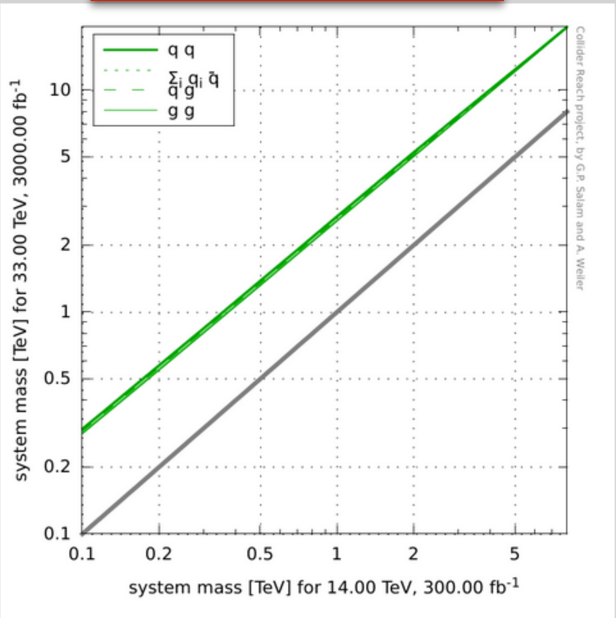
Submit

Plots

linear plot



log-log plot



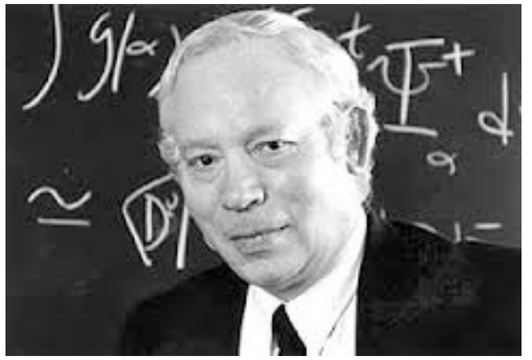
Download: collider.pdf, colliderloglog.pdf, plot generation log file

The PDF choice was CT10nlo.LHgrid

Original mass	gg	qg	allqq	qqbar
100.	283.	291.	298.	297.
125.	350.	359.	368.	367.
150.	416.	427.	438.	437.
200.	547.	562.	576.	575.
300.	806.	827.	848.	847.
500.	1317.	1350.	1386.	1382.
700.	1822.	1866.	1916.	1907.
1000.	2570.	2628.	2702.	2680.
1250.	3188.	3256.	3349.	3314.
1500.	3802.	3879.	3990.	3939.
2000.	5018.	5110.	5251.	5169.
2500.	6223.	6327.	6488.	6380.
3000.	7417.	7530.	7703.	7578.
4000.	9782.	9904.	10082.	9945.
5000.	12120.	12246.	12417.	12284.
6000.	14439.	14565.	14726.	14601.
7000.	16748.	16871.	17021.	16905.
8000.	19053.	19169.	19310.	19206.

the last word…

Four Lessons

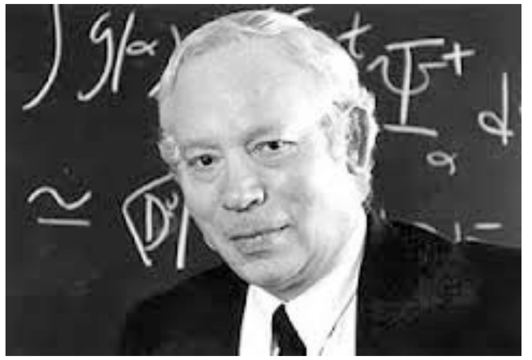


1) How could I do anything without knowing everything that had already been done? […] pick up what I needed to know as I went along. It was sink or swim. […] But I did learn one big thing: that no one knows everything, and you don't have to.

2) While you are swimming and not sinking you should aim for rough water. […] My advice is to go for the messes — that's where the action is.

Scientist: Four golden lessons
Steven Weinberg, Nature 426, 389 (27 November 2003)

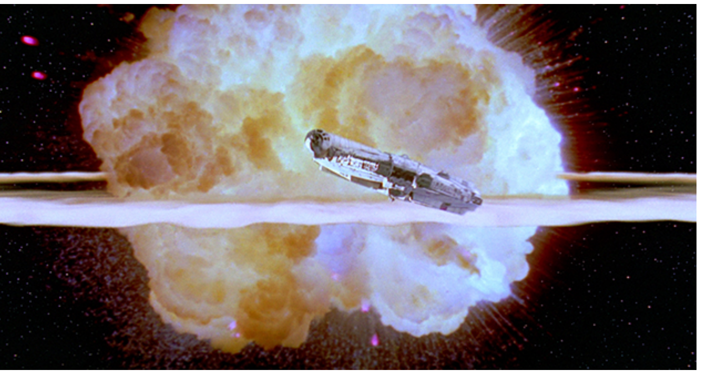
Four Lessons



3) Forgive yourself for wasting time. […] in the real world, it's very hard to know which problems are important, and you never know whether at a given moment in history a problem is solvable [...] get used […] to being becalmed on the ocean of scientific knowledge.

4) Learn something about the history of science […] As a scientist, you're probably not going to get rich. […] But you can get great satisfaction by recognizing that your work in science is a part of history.

Scientist: Four golden lessons
Steven Weinberg, Nature 426, 389 (27 November 2003)



- No signs of new physics have appeared so far.
- The Higgs fine-tuning puzzle is as puzzling as ever. Do we simply live in a (mildly?) fine-tuned universe? Or is there a subtle solution?
- Themes of recent years: search for electroweak or neutral new particles at colliders to exhaust possibilities; intriguing possibilities for connections of the weak scale with cosmology.
- Amazing landscape of experiments: LHC, dark matter, EDMs, flavor physics. New physics discovery could come at any time!