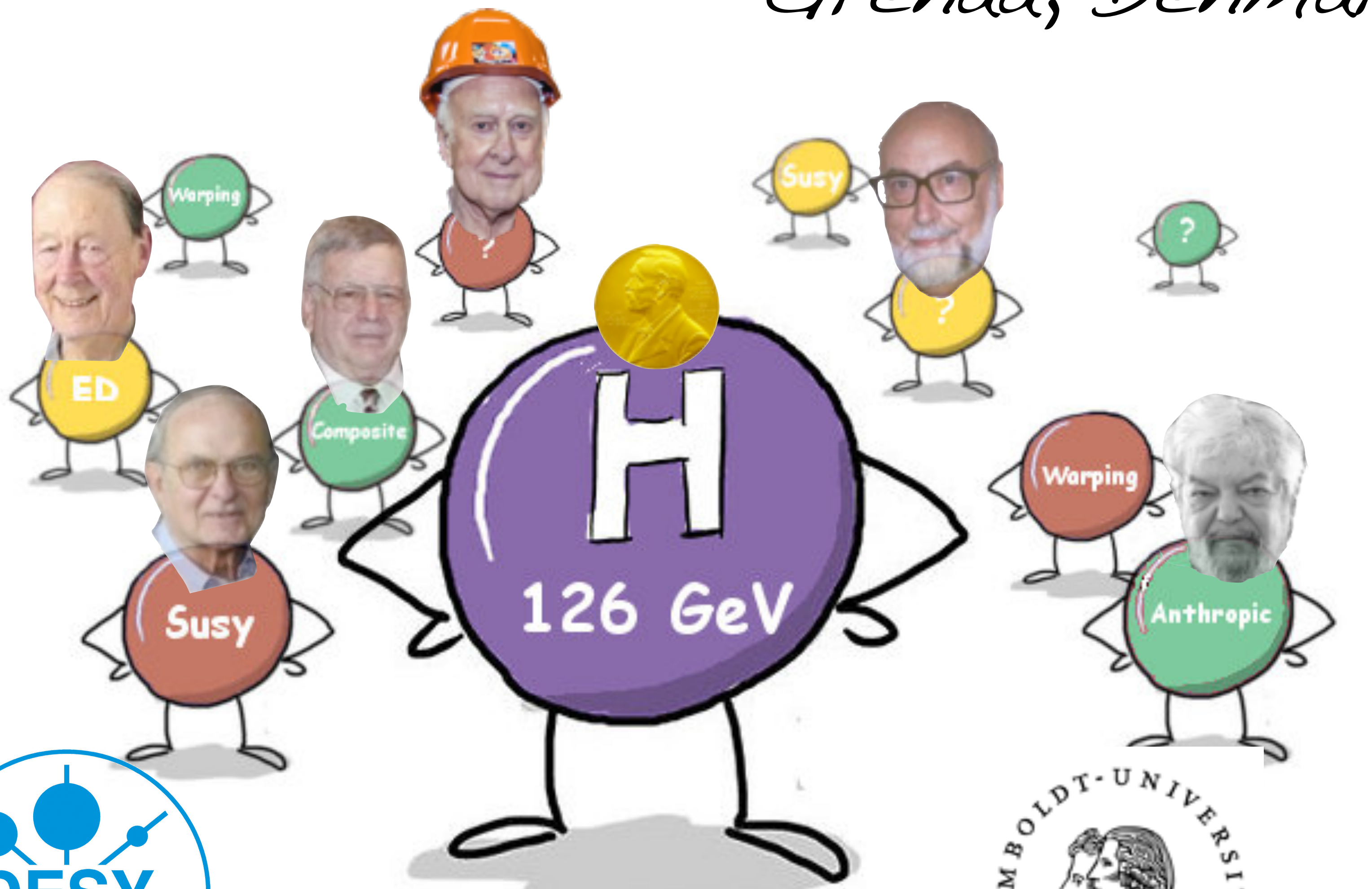
Higgs and Beyond

ESHEP 2023

Grenaa, Denmark

Lecture 3/4



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Outline

☐ Lecture #1

- Symmetries, Fields, Lagrangians
- From Fermi theory to the Standard Model
- Chirality and mass problem

☐ Lecture #2

- Spontaneous symmetry breaking, aka Higgs mechanism
- Particles masses, unitarity and the Higgs boson
- Higgs phenomenology (decay and production at colliders)
- Higgs quantum potential (vacuum (meta)stability, naturalness)
- Hierarchy problem

☐ Lecture #3

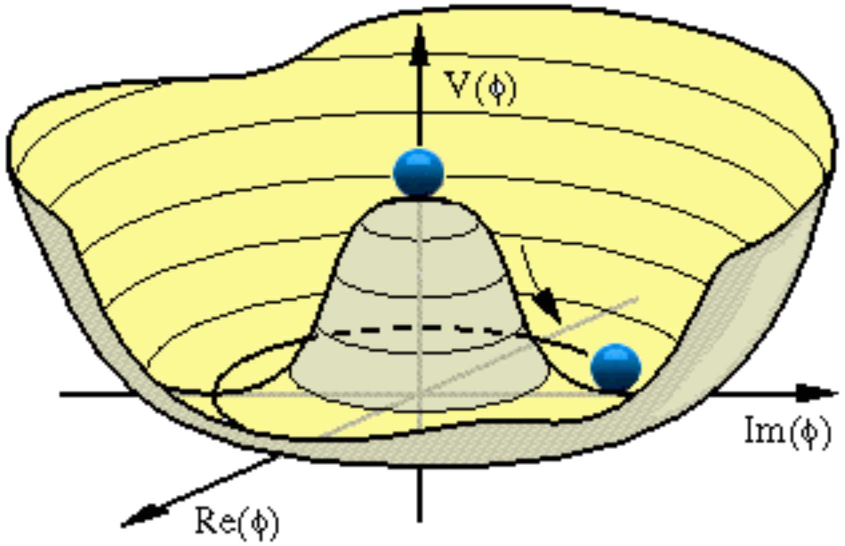
- Supersymmetry
- Composite Higgs
- Extra dimensions

☐ Lecture #4

- Connections particle physics-cosmology
- Quantum gravity: landscape vs swampland
- BSM searches beyond colliders

Quantum corrections to the Higgs potential

Quantum Stability of Higgs Potential



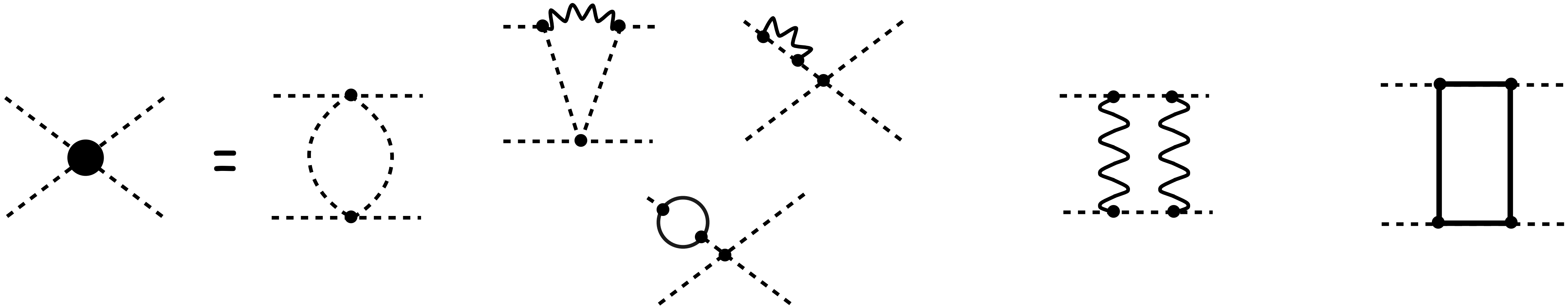
$$V(h) = -\tfrac{1}{2}\mu^2 h^2 + \tfrac{1}{4}\lambda h^4$$

$$\text{vev: } v^2 = \mu^2/\lambda \qquad \text{mass: } m_H^2 = 2\lambda v^2$$

How is Quantum Mechanics changing the picture?

The parameters of the Higgs potential, like any couplings in QFT, run with the energy:

Renormalisation Group Equation (RGE)



$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \tfrac{3}{8}g'^4 + \tfrac{3}{4}g'^2 g^2 + \tfrac{9}{8}g^4 - 6y_t^4 +$$

Higher loops
Small Yukawa

let's try to solve this equation in particular limits of small and large Higgs mass

Quantum Stability of Higgs Potential

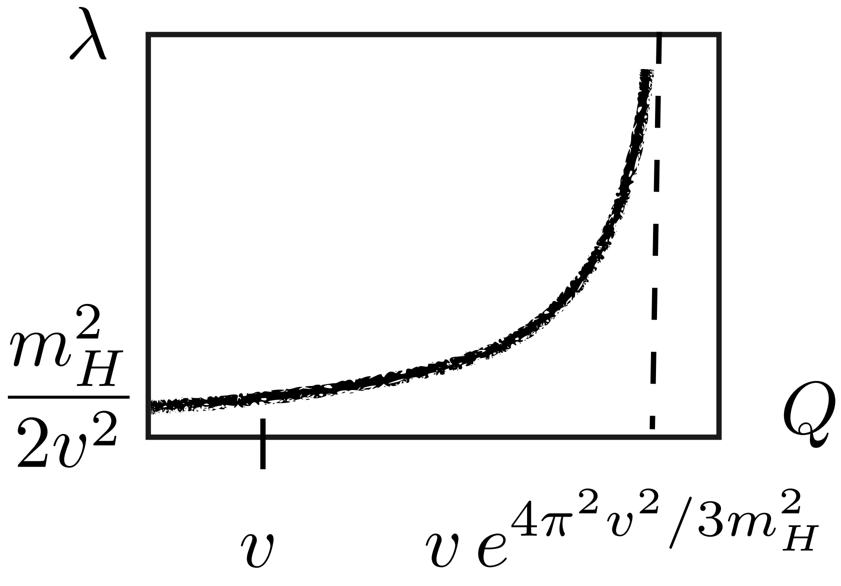
Large mass (λ dominated RGE)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2$$

λ increases with Q: IR-free coupling

$$\boxed{\lambda(Q) = \frac{m_H^2}{2v^2 - \frac{3}{2\pi^2} m_H^2 \ln(Q/v)}}$$

Wilson '71
Wilson, Kogut '74



theory develops a **Landau pole** (coupling blows up) at finite energy scale

New physics should appear
and change the running behaviour
before the Landau pole develops

⇛ upper bound on the scale of new physics

$$\boxed{\Lambda \leq v\, e^{4\pi^2 v^2/3m_H^2}}$$

This bound is often referred as the **triviality** bound:
the only way to get a microscopic theory valid up to arbitrarily high energy, i.e. Λ→∞, is to have the quartic coupling at low energy to vanish (λ(v)=0), i.e. to switch off the self-interactions.
Only a free/trivial theory is well behaved at high-energy.

Quantum Stability of Higgs Potential

Small mass (y_t dominated RGE)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = -6 y_t^4$$

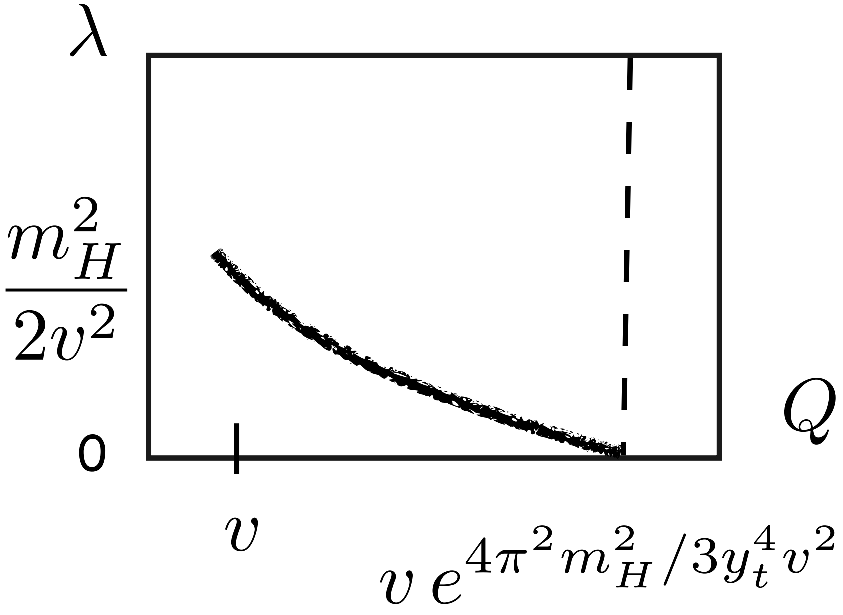
$$16\pi^2 \frac{d y_t}{d\ln Q} = \frac{9}{2}\, y_t^3$$

$$\boxed{\lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln\frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln\frac{Q}{Q_0}}}$$

$$y_0 = \frac{\sqrt{2} m_t}{v}$$

$$\lambda_0 = \frac{m_H^2}{2v^2}$$

Linde '76, '80
Weinberg '76
Maini et al '78, '79
Politzer, Wolfram '79



λ decreases with energy and can become negative

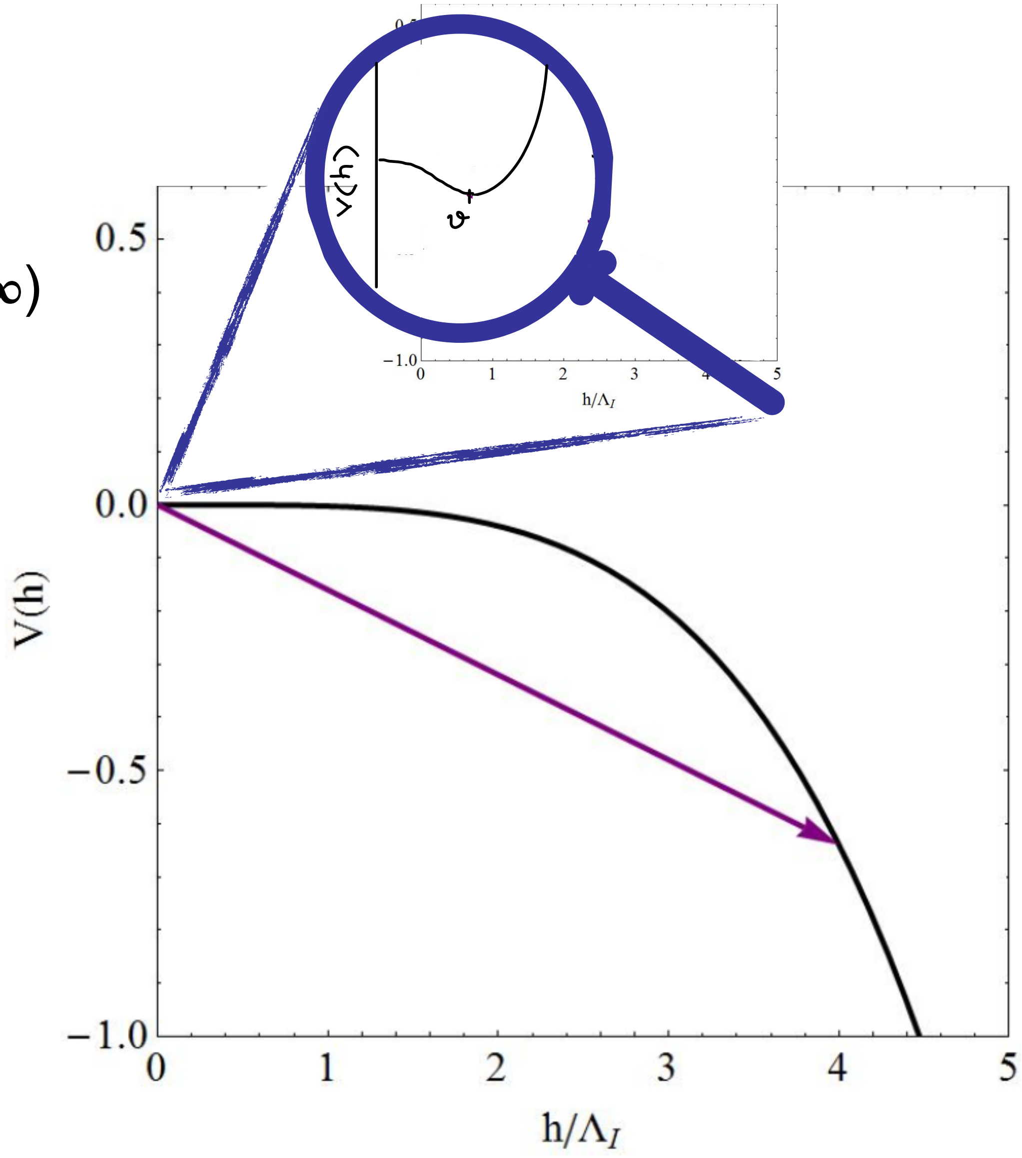
(potential unbounded from below, true minimum at v=∞)

New physics should appear
and change the running behaviour
before λ turns negative

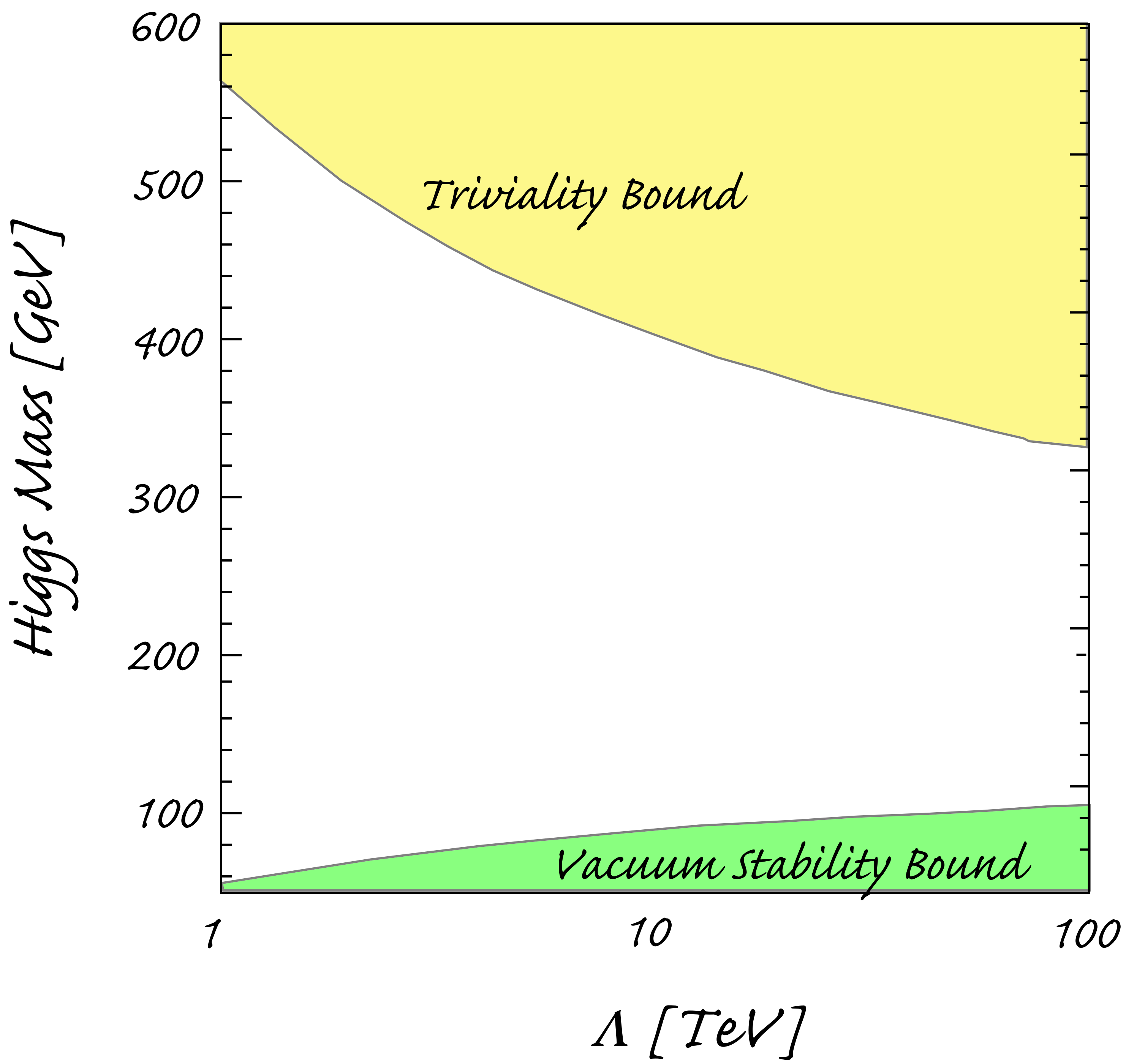
⇒ upper bound on the scale of new physics

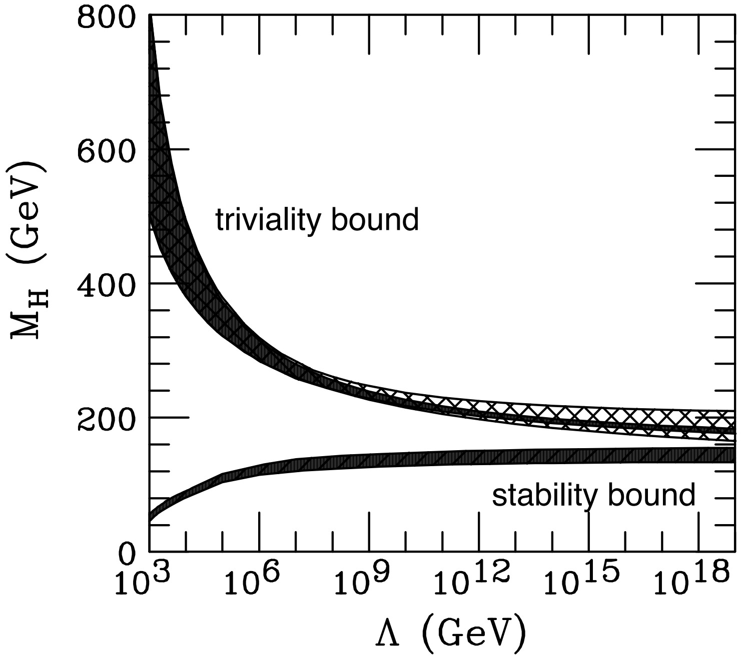
$$\Lambda \leq v\, e^{4\pi^2 m_H^2/3y_t^4 v^2}$$

This bound is often referred as the **stability** bound.



Quantum Stability of Higgs Potential





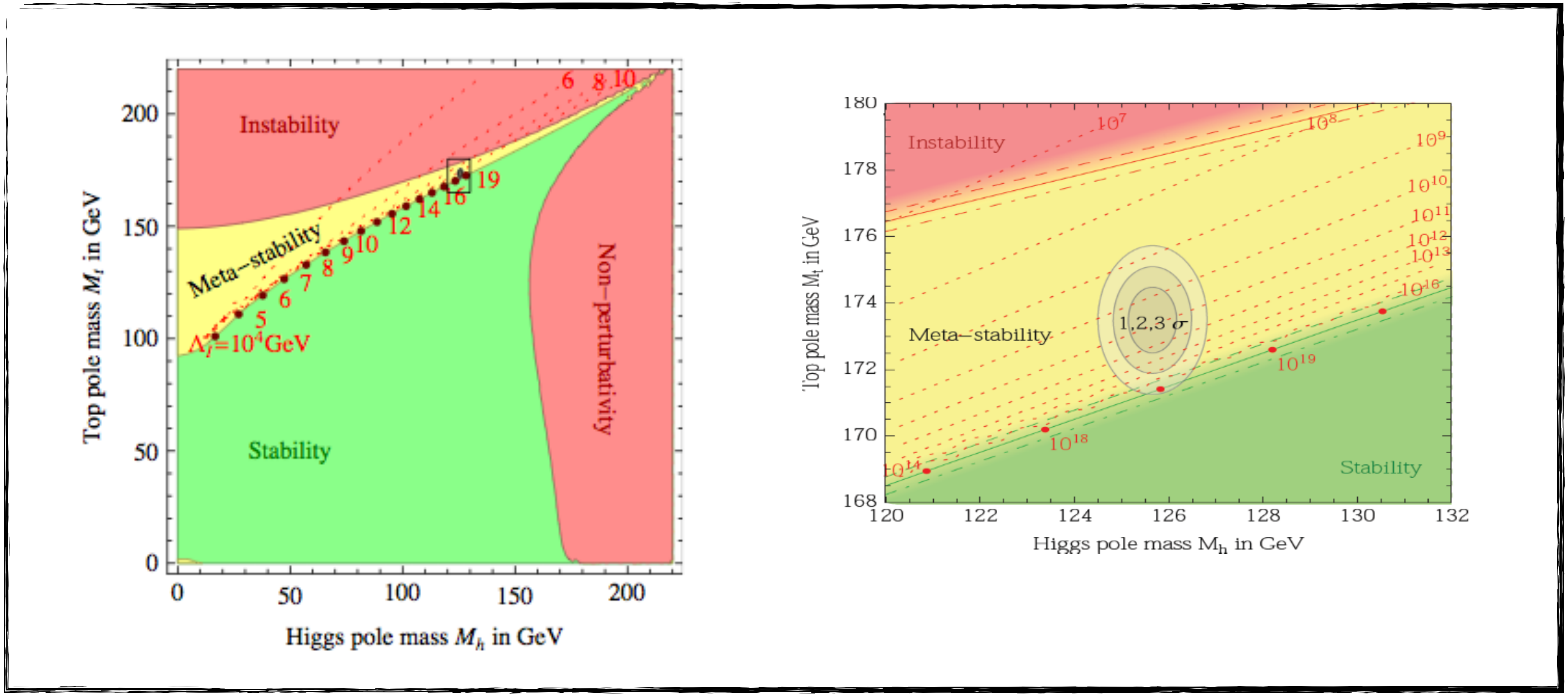
Hambye, Riesselmann '97

Only a light Higgs (120GeV<m_H<200GeV) allows for the absence of New Physics at low energy

Higgs and EW vacuum Stability

Only for restricted values of the Higgs and top masses,
does the SM Higgs potential have a well-behaved evolution under quantum corrections!

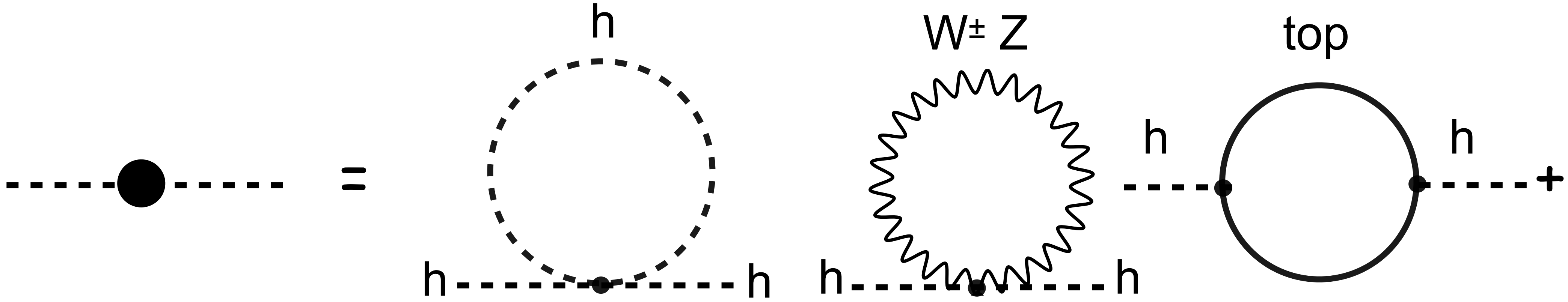
For the experimentally measured masses, the **EW vacuum** as we know it seems to be **metastable** (i.e. could tunnel to another totally different vacuum) unless **new physics** appears below $10^{10\text{-}12}$ GeV



Buttazzo et al '13

Quantum Instability of the Higgs Mass

so far we looked only at the RG evolution of the Higgs quartic coupling (dimensionless parameter). The Higgs mass has a totally different behaviour: it is highly dependent on the UV physics, which leads to the so called *hierarchy problem!*



Higher loops
smaller Yukawa

$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4}\frac{k^2}{(k^2-m^2)^2} \propto \Lambda^2$$

Weisskopf '39
't hooft '79

$$\delta m_H^2 = \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\frac{3G_F\Lambda^2}{8\sqrt{2}\pi^2}$$

$$m_H^2 \sim m_0^2 - (115\ \mathrm{GeV})^2\left(\frac{\Lambda}{700\ \mathrm{GeV}}\right)^2$$

Meaning of Quadratic Divergences

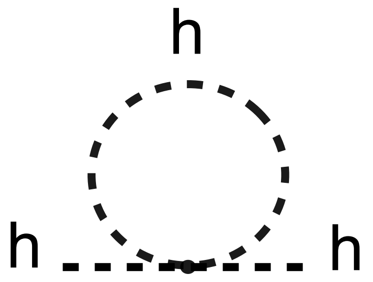
Are these divergences meaningful?

(quadratic divergences in dimensional regularisation are thrown away)

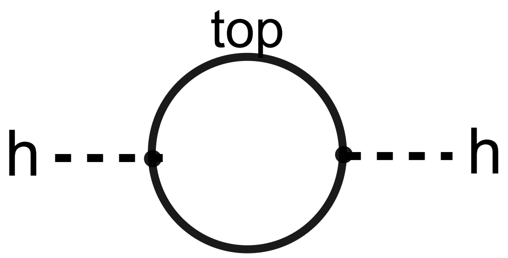
First, you can check whether they are even **gauge-independent**.

The computation on the previous slide, as in all textbooks/reviews, use propagators in unitary gauge.

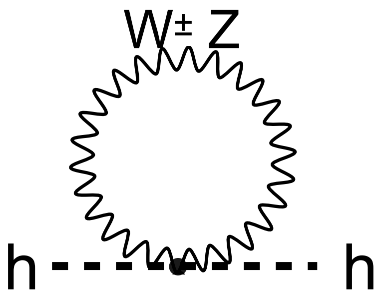
Let's redo computation in **R-ξ gauge**:



$$6\lambda\int\frac{d^4k}{(2\pi)^4}\frac{i}{k^2-m^2}\propto\frac{3m_h^2}{16\pi^2v^2}\Lambda^2$$

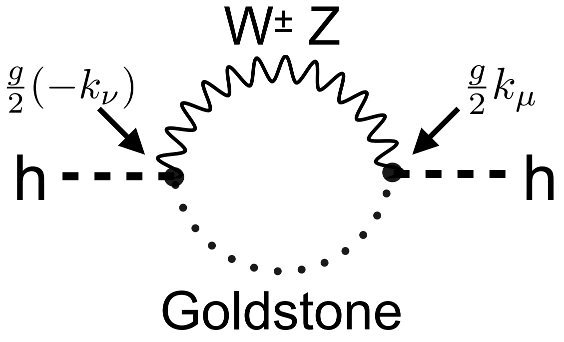


$$-i\frac{y_t^2}{2}\int\frac{d^4k}{(2\pi)^4}N_C\mathrm{Tr}\left(\frac{i}{\not k-m}\frac{i}{\not k-m}\right)\propto-\frac{3m_t^2}{4\pi^2v^2}\Lambda^2$$



$$\frac{3g^2}{4}\int\frac{d^4k}{(2\pi)^4}\frac{i}{k^2-m^2}\eta_{\mu\nu}\left(\eta^{\mu\nu}-(1-\xi)\frac{k^\mu k^\nu}{k^2-\xi m^2}\right)\propto\frac{(3-\xi)\left(2m_W^2+m_Z^2\right)}{16\pi^2v^2}\Lambda^2$$

Need a 4th divergent diagram (hardly mentioned anywhere) involving the Goldstone's mode:



$$i\frac{g^2}{4}\int\frac{d^4k}{(2\pi)^4}(k_\mu)(-k_\nu)\frac{i}{k^2-m^2}\left(\eta^{\mu\nu}-(1-\xi)\frac{k^\mu k^\nu}{k^2-\xi m^2}\right)3\frac{-i}{k^2-\xi m^2}\propto\frac{2m_W^2+m_Z^2}{16\pi^2v^2}\xi\Lambda^2$$

The quadratic divergences are gauge-independent!

Meaning of Quadratic Divergences

The quadratic divergences signal a sensitivity to high-scale physics

Maltoni ESHEP'22

Two scalars interacting through the potential

$$V(\varphi, \Phi) = \frac{m^2}{2}\varphi^2 + \frac{M^2}{2}\Phi^2 + \frac{\lambda}{4!}\varphi^4 + \frac{\sigma}{4!}\Phi^4 + \frac{\delta}{4}\varphi^2\Phi^2$$

which is the most general renormalizable potential, if we require the symmetry under $\varphi \to -\varphi$ and $\Phi \to -\Phi$. We assume that $M^2 \gg m^2$. Let's check if this hierarchy is conserved at the quantum level. Compute the one-loop radiative corrections to the pole mass m^2

$$m^2_{\text{pole}} = m^2(\mu^2) + \frac{\lambda m^2}{32\pi^2}\left(\log\frac{m^2}{\mu^2} - 1\right) + \frac{\delta M^2}{32\pi^2}\left(\log\frac{M^2}{\mu^2} - 1\right)$$

where the running mass $m^2(\mu^2)$ obeys the RGE

$$\frac{dm^2(\mu^2)}{d\log\mu^2} = \frac{1}{32\pi^2}\left(\lambda m^2 + \delta M^2\right)$$

Corrections to m^2 proportional to M^2 appear at one loop. One can choose $\mu^2 \approx M^2$ to get rid of them, but they reappear through the running of $m^2(\mu^2)$.

The only way to preserve the hierarchy $m^2 \ll M^2$ is carefully choosing the coupling constants $\lambda m^2 \approx \delta M^2$

and this requires fixing the renormalized coupling constants with and unnaturally high accuracy $\frac{\lambda}{\delta} \approx \frac{M^2}{m^2}$

This is what is usually called the fine tuning of the parameters.

Renormalisation mixes scalar mass scales

(contrary to fermions: quantum correction to m_e is proportional to m_e).

No enhanced symmetry when the mass of the scalar goes to zero

(while chiral symmetry is restored when $m_e \to 0$).

If new physics exists at high energy, it will give large corrections to the Higgs mass!

The Higgs hierarchy problem

The hierarchy problem made easy

only a few electrons are enough to lift your hair (~ 10^{25} mass of e^-)

the electric force between 2 e^- is 10^{43} times larger than their gravitational interaction

we don’t know why gravity is so weak?
we don’t know why the masses of particles are so small?

Several theoretical hypotheses
new dynamics? new symmetries? new space-time structure?
modification of special relativity? of quantum mechanics?

Naturalness principle @ work

Following the arguments of Wilson, ‘t Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections

Introduce new degrees of freedom to regulate the high-energy behaviour

Beautiful examples of naturalness to understand the need of “new” physics

see for instance Giudice ’13 (and refs. therein) for an account

- the need of the **positron** to screen the electron self-energy: $\Lambda < m_e/\alpha_{\rm em}$
- the **rho meson** to cutoff the EM contribution to the charged pion mass: $\Lambda < \delta m_\pi^2/\alpha_{\rm em}$
- the kaon mass difference regulated by the **charm** quark: $\Lambda^2 < \frac{\delta m_K}{m_K}\frac{6\pi^2}{G_F^2 f_K^2 \sin^2\theta_C}$
- the light **Higgs** boson to screen the EW corrections to gauge bosons self-energies
- ...
- **new physics** at the weak scale to cancel the UV sensitivity of the Higgs mass?

The different paths to Higgs naturalness

▷ Single vacuum ◁

the low Higgs mass is screened from
large quantum corrections by

1. a symmetry (Susy, PQ)
2. a form factor (composite Higgs)
3. a low UV scale (xdim, RS, large N…)
4. a combination of the above

see next slides

▷ Multiple vacua ◁

many metastable vacua
with a vast range of values for m_H
Dynamical (or anthropic selection) of $m_H \ll \Lambda$

1. anthropic multiverse
2. NNaturalness with 10^{16} copies of SM
3. relaxion and cosmological scanning with non-trivial back reaction

see tomorrow lecture

How to stabilize the Higgs potential?

The spin trick

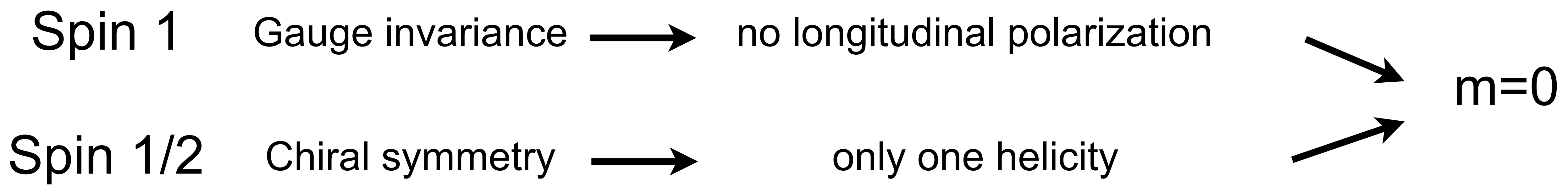
a particle of spin s:

2s+1 polarization states

...with the only exception of a particle moving at the speed of light, i.e., massless particle

... fewer polarization states

and the converse is also true!



Spin 1 Gauge invariance → no longitudinal polarization

Spin 1/2 Chiral symmetry → only one helicity

m=0

If the symmetries are broken, the radiative mass will be set by the scale of symmetry breaking, not the UV/Planck scale

... but the Higgs is a spin 0 particle

Symmetries to stabilize a scalar potential

Supersymmetry

fermion ~ boson

Higher Dimensional Lorentz invariance

⇚ gauge-Higgs unification models

[Manton '79, Fairlie 79, Hosotani '83 +...]

$$A_\mu \sim A_5$$

4D spin 1

4D spin 0

These symmetries cannot be exact symmetry of the Nature. They have to be broken. We want to look for a soft breaking in order to preserve the stabilization of the weak scale.

Other approaches to the hierarchy problem

the hierarchy problem can be reformulated as:
why the weak scale so much smaller than the Planck scale of quantum gravity?

$$M_{\mathrm{Pl}} = \sqrt{\frac{\hbar c}{G_{\mathrm{N}}}} \sim 10^{19}\,\mathrm{GeV}/c^2$$

✳ **large extra dimensions (~1mm)**: dilute gravitational interactions into large volume not accessible to other forces. Scale of quantum gravity around 1TeV. Black holes could be produced at the LHC.

✳ **many different species**: $M_* = M_{\mathrm{Pl}}/\sqrt{N}$, i.e. $M_* \sim 1\mathrm{TeV}$ if $N \sim 10^{32}$

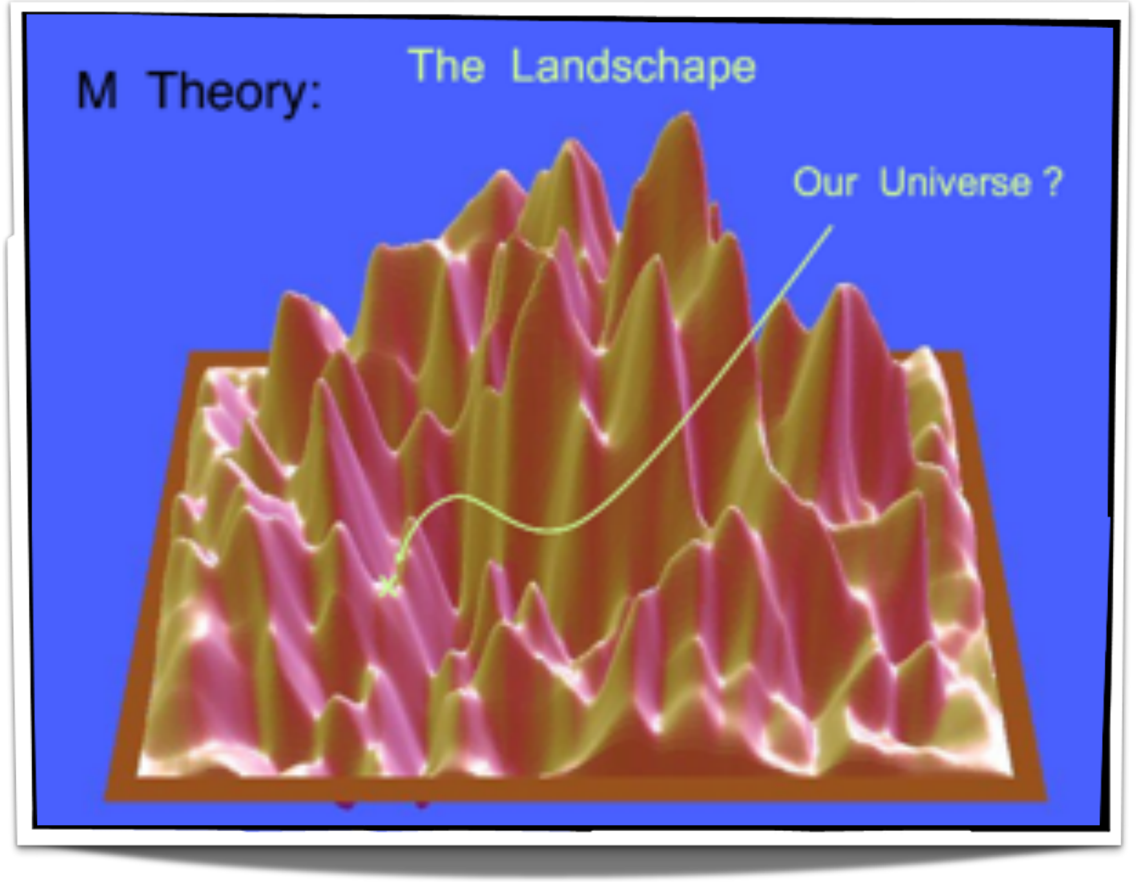
✳ **composite Higgs**: above the scale of compositeness, the Higgs boson dissolves into its fundamental constituents. Momentum-dependent form factors cut off the divergent integrals

✳ ~~break EW symmetry **without a Higgs boson**, aka technicolor models.~~
Ruled out by the Higgs boson discovery

Could the EW scale accidentally small?

The Sun and the Moon have the same angular size seen from Earth. Why?

- Dynamical explanation?
- Accident?
- Multiverse… there exist many (exo)planets with moons!
- Anthropic selection (probably not for the Moon, but maybe for the Higgs)



Number of string vacua: $10^{500 \pm 272\,000}$

Taylor, Wang ‘15

Supersymmetry

SUSY 1.0.1

Wess, Zumino '74

fermion ⇔ boson

$$\mathcal{L} = \partial^\mu \phi^\dagger \partial_\mu \phi + i\bar{\psi}\gamma^\mu \partial_\mu \psi$$

- susy transformations:

$$\delta\phi = \bar{\epsilon}\psi$$
$$\delta\psi = -i\left(\gamma^\mu \partial_\mu \phi\right)\epsilon$$

$$\delta\mathcal{L} = \text{total derivative}$$

- susy algebra:

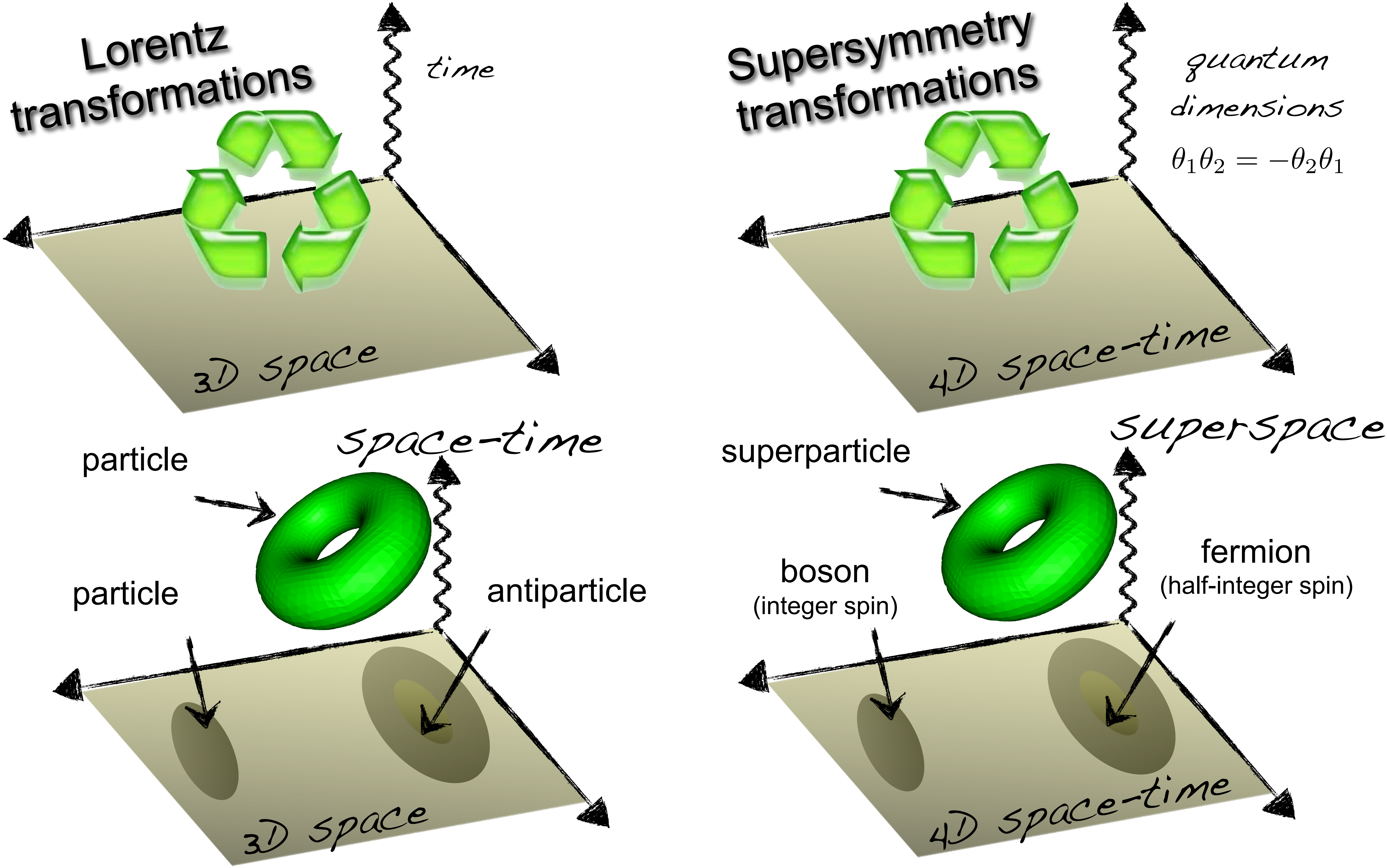
$$[\delta_{\epsilon_1}, \delta_{\epsilon_2}] \begin{pmatrix} \phi \\ \psi \end{pmatrix} = -i\left(\bar{\epsilon_2}\gamma^\mu \epsilon_1\right)\partial_\mu \begin{pmatrix} \phi \\ \psi \end{pmatrix}$$

susy^2 = 4D translation

How to introduce interactions?

SUSY: a quantum space-time

(G. Giudice HCPSS'09)



Lorentz transformations

Supersymmetry transformations

$$\theta_1\theta_2 = -\theta_2\theta_1$$

particle

particle

antiparticle

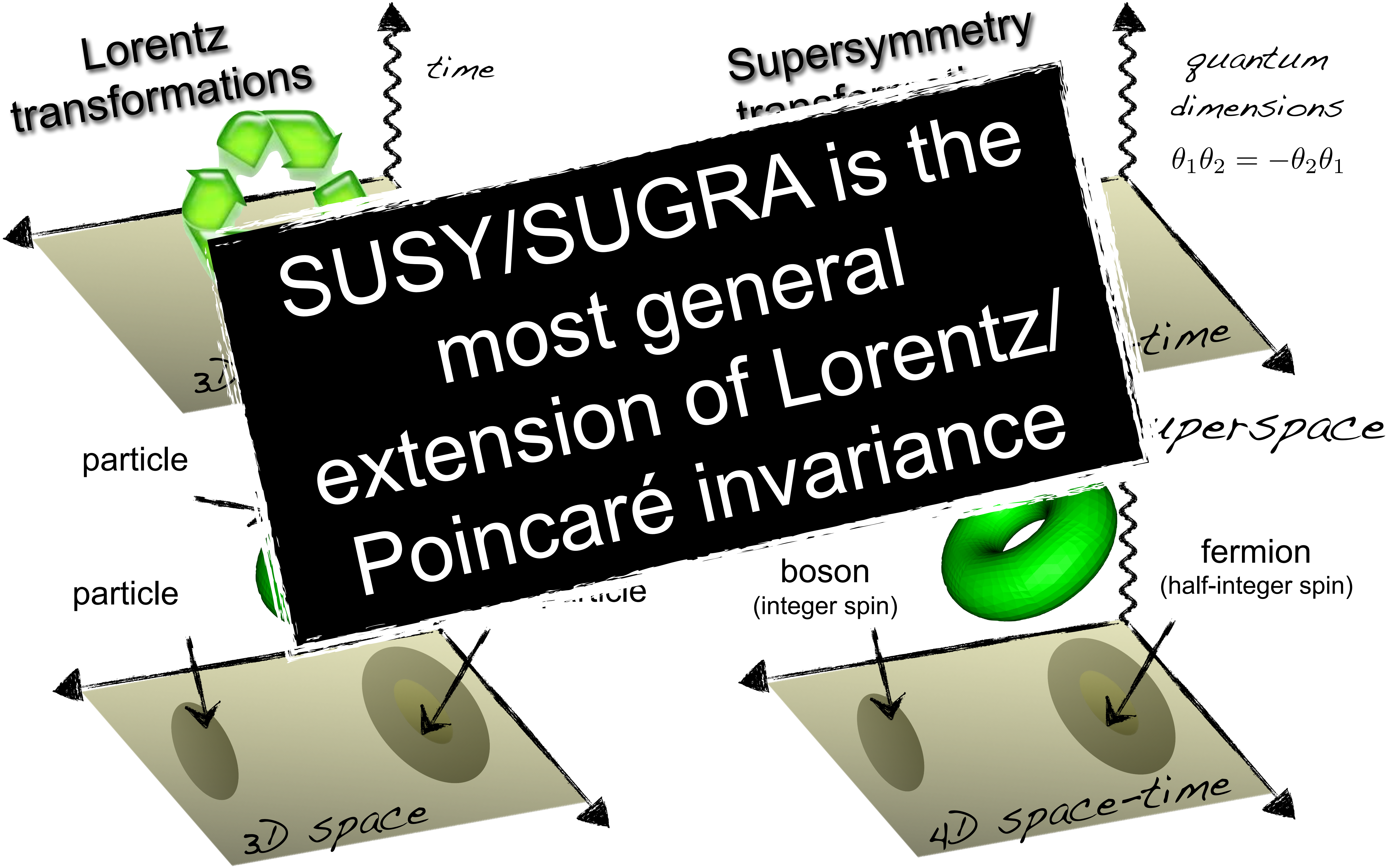
superparticle

boson (integer spin)

fermion (half-integer spin)

SUSY: a quantum space-time

(G. Giudice HCPSS'09)



SUSY/SUGRA is the most general extension of Lorentz/ Poincaré invariance

Superspace

$$\left(x^\mu, \theta, \bar{\theta}\right)$$

usual 4D
space-time coordinates

new fermionic/Grassmanian
coordinates

A general superfield can be Taylor-expanded in the superspace

$$F(x,\theta,\bar\theta) = f(x) + \theta\chi(x) + \bar\theta\bar\chi(x) + \theta\theta m(x) + \bar\theta\bar\theta\bar m(x) + \theta\sigma^\mu\bar\theta v_\mu(x) + i\theta\theta\bar\theta\bar\lambda(x) - i\bar\theta\bar\theta\theta\lambda(x) + \frac{1}{2}\theta\theta\bar\theta\bar\theta d(x)$$

complex spin-0 fields:	$f(x), m(x), \bar m(x), d(x)$	4x2=8 real off-shell degrees of freedom
complex spin-1 field:	$v_\mu(x)$	1x8=8 real off-shell degrees of freedom
Weyl spin-1/2 fields:	$\chi(x), \bar\chi, \lambda(x), \bar\lambda(x)$	4x4=16 real off-shell degrees of freedom

Chiral superfield

$$\bar{D}_{\dot\alpha} F = 0$$

covariant derivative
ie commute with supersymmetry

$\Rightarrow$

$$F = \phi(x) + \theta\psi(x) + \theta\theta f(x)$$

off-shell dof	2	4	2
on-shell dof	2	2	0
	complex scalar	chiral fermion	

Vector superfield

$$F = F^\dagger$$

$\Rightarrow$

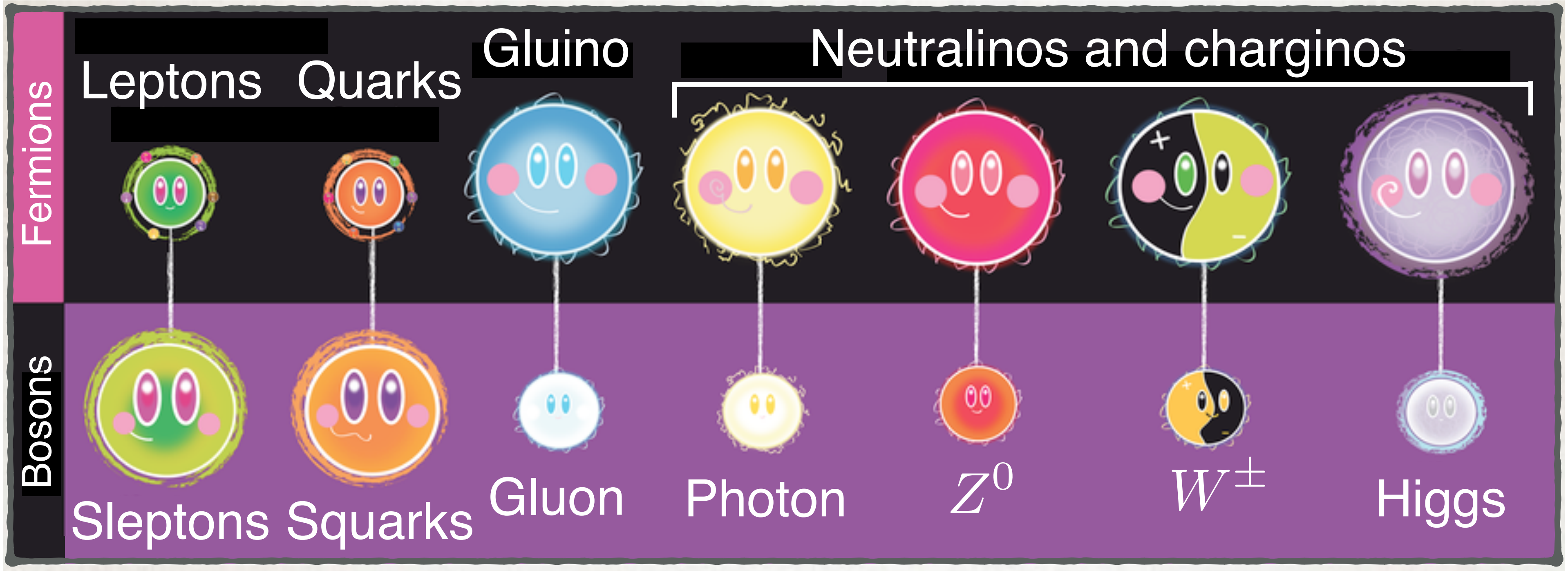
$$F = \theta\sigma^\mu\bar\theta v_\mu(x) + i\theta\theta\bar\theta\bar\lambda(x) - i\bar\theta\bar\theta\theta\lambda(x) + \frac{1}{2}\theta\theta\bar\theta\bar\theta d(x)$$

off-shell dof	3	4	1
on-shell dof	2	2	0
	massless gauge field	chiral fermion	

MSSM - Matter Content

		particles				Sparticles			
chiral superfields	quarks	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	u_R	d_R	squarks	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	$\tilde{u}_R$	$\tilde{d}_R$
	leptons	$\begin{pmatrix} e_L \\ \nu_L \end{pmatrix}$	e_R		sleptons	$\begin{pmatrix} \tilde{e}_L \\ \tilde{\nu}_L \end{pmatrix}$	$\tilde{e}_R$	
	Higgs doublets	H_1 (hypercharge $= -1$) H_2 (hypercharge $= +1$)			Higgsinos	$\tilde{H}_1$ $\tilde{H}_2$		
vector superfields		$W^{\pm}_{\mu}, W^{3}_{\mu}$			winos	$\tilde{\omega}^{\pm}, \tilde{\omega}^{3}$		
		B_{μ}			bino	$\tilde{b}$		
		G^{A}_{μ}	$A = 1, \ldots, 8$		gluinos	$\tilde{g}^{A}$		

(G. Giudice HCPSS'09)



Superspace Integrals and SUSY

Any polynomial of superfields is a superfield itself

$$\int d\theta\,\theta = 1$$

It can be proven that

$$\int d^2\theta d^2\bar{\theta}\, F(\theta,\bar{\theta}) \quad \text{and} \quad \int d^2\theta\, Q(\theta)$$

are two quantities invariant by supersymmetry

All particles are seen as superfields and using the results above, one can easily construct Lagrangians as polynomials of these superfields.
These Lagrangians are automatically invariant under supersymmetry.

SUSY Interactions - Superpotential

superpotential W = holomorphic fct of chiral superfields

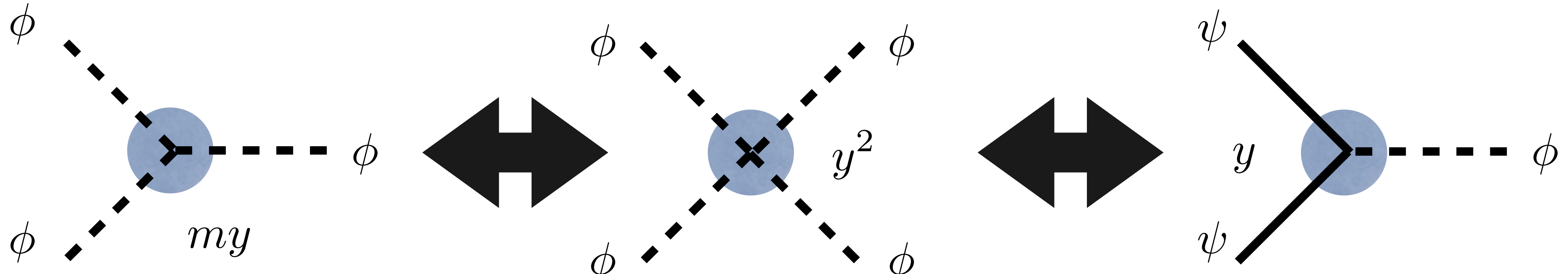
$$\mathcal{L} = \mathcal{L}_{\text{kin}} - \left|\frac{\partial W}{\partial \phi}\right|^2_{|\theta=0} - \frac{1}{2}\frac{\partial^2 W}{\partial \phi^2}_{|\theta=0} \psi\psi + h.c.$$

is invariant under susy

example: susy Yukawa interaction

$$W = \frac{1}{2}m\phi^2 + \frac{1}{3!}y\phi^3 \qquad \partial_\phi W = m\phi + \frac{1}{2}y\phi^2 \qquad \partial_\phi^2 W = m + y\phi$$

$$\mathcal{L} = \mathcal{L}_{\text{kin}} - \left|m\phi + \frac{1}{2}y\phi^2\right|^2 - \frac{1}{2}\left(m + y\phi\right)\psi\psi + h.c.$$

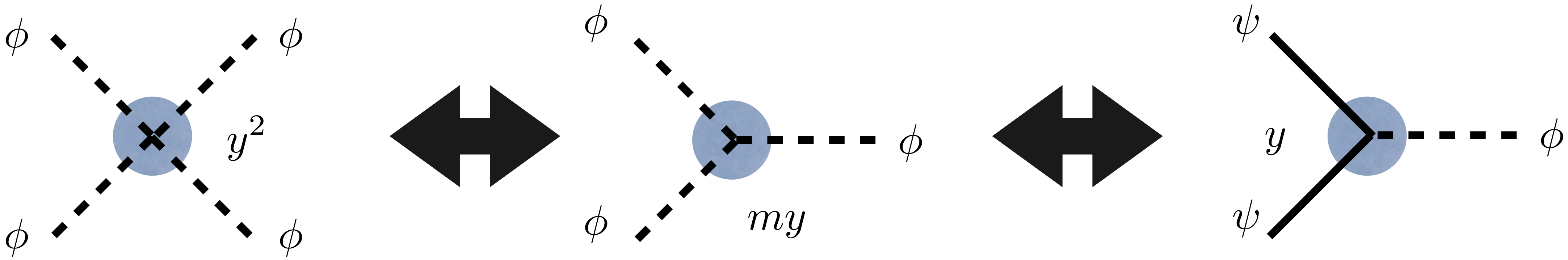


will be modified by
soft susy breaking

will survive soft susy breaking

SUSY Interactions

heuristic rule:
replace bosons with fermions in the interaction



Scalar potential is not arbitrary any longer:
dictated by gauge and Yukawa interactions.
One important consequence: upper bound on Higgs mass in simplest models

SUSY predictions

many new particles
many new interactions

MSSM Superpotential

the most general (“renormalizable”) superpotential of the MSSM

$$W = H_u Q D + H_u Q U + H_d L E + \mu H_u H_d + LQD + UDD + LLE + \mu_L L H_u$$

$\cancel{B}, \cancel{L}$

lead to fast p decay

R parity forbids all the dangerous terms

superfields

$$Q, D, U, L : -1$$

$$H_u, H_d : +1$$

⇨

R-parity

doesn’t commute with susy

$$\theta : -1$$

⇨

fields

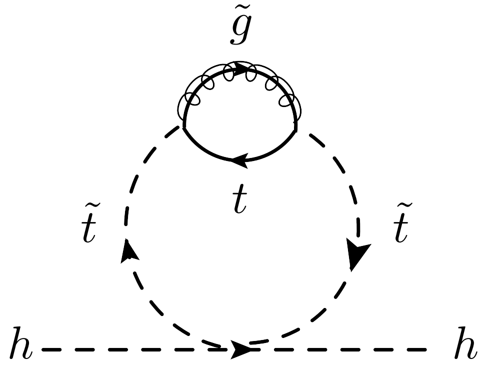
$$\phi_{\rm SM} : +1$$

$$\phi_{\rm superpartner} : -1$$

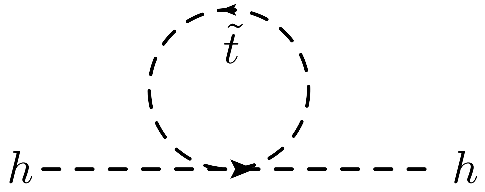
Nice consequences:

- superpartners are pair-produced
- Lightest Supersymmetric Particle is stable → DM?

Probing natural SUSY

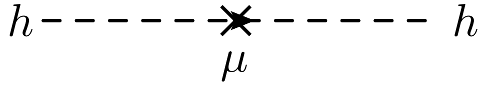


$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi}m_{gluino}^2\left(\log\frac{\Lambda}{m_{gluino}}\right)^2$$



$$\delta m_H^2 \sim -\frac{3}{8\pi^2}y_t^2 m_{stop}^2 \log\frac{\Lambda}{m_{stop}}$$

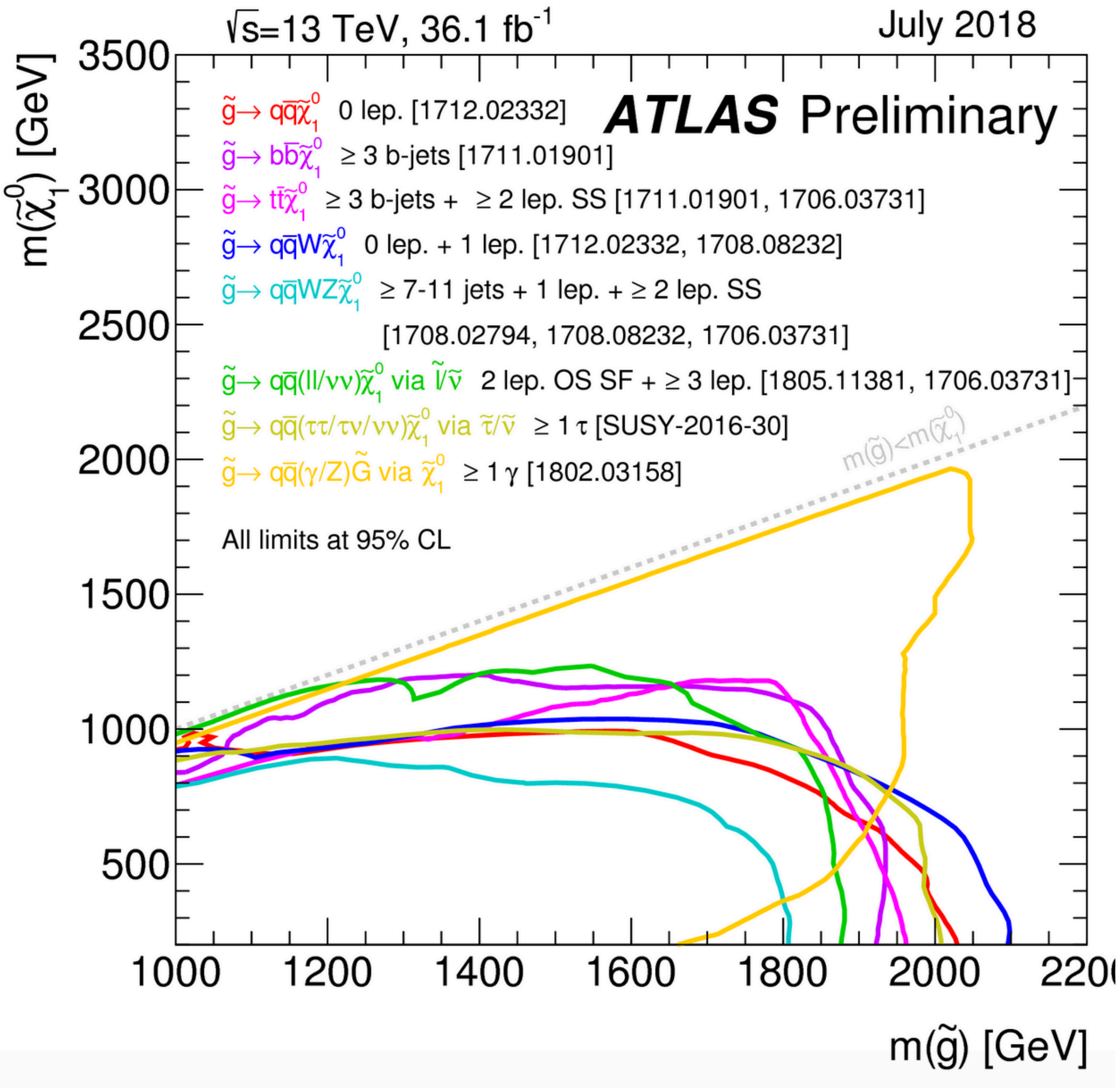
light stops, light gluinos!
well tested @ LHC
but most questionable predictions
(RG effects)

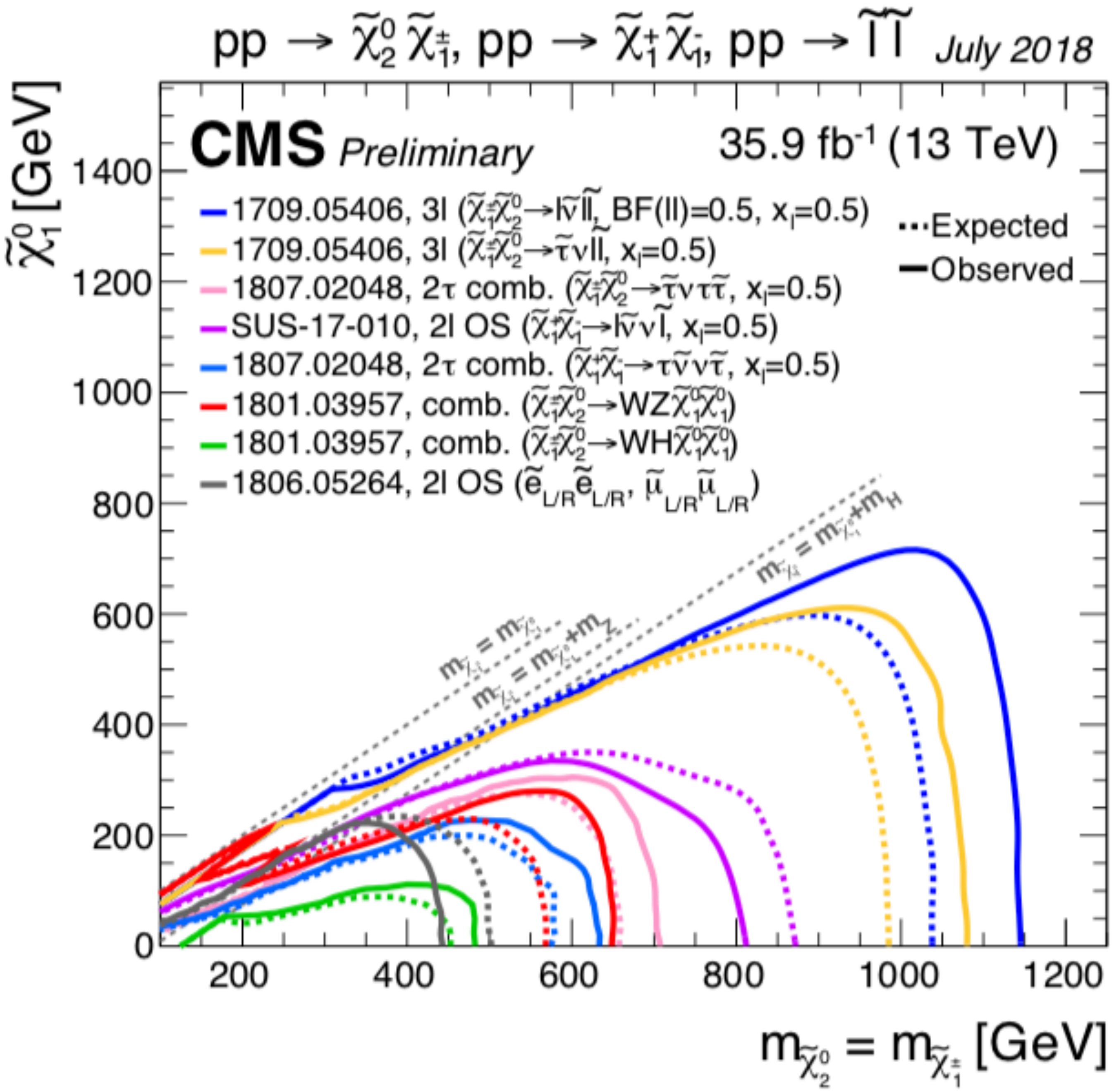


$$\delta m_H^2 \sim |\mu|^2$$

light Higgsinos!
very low sensitivity @ LHC
ILC needed to probe the other side

Probing natural SUSY





Probing natural SUSY

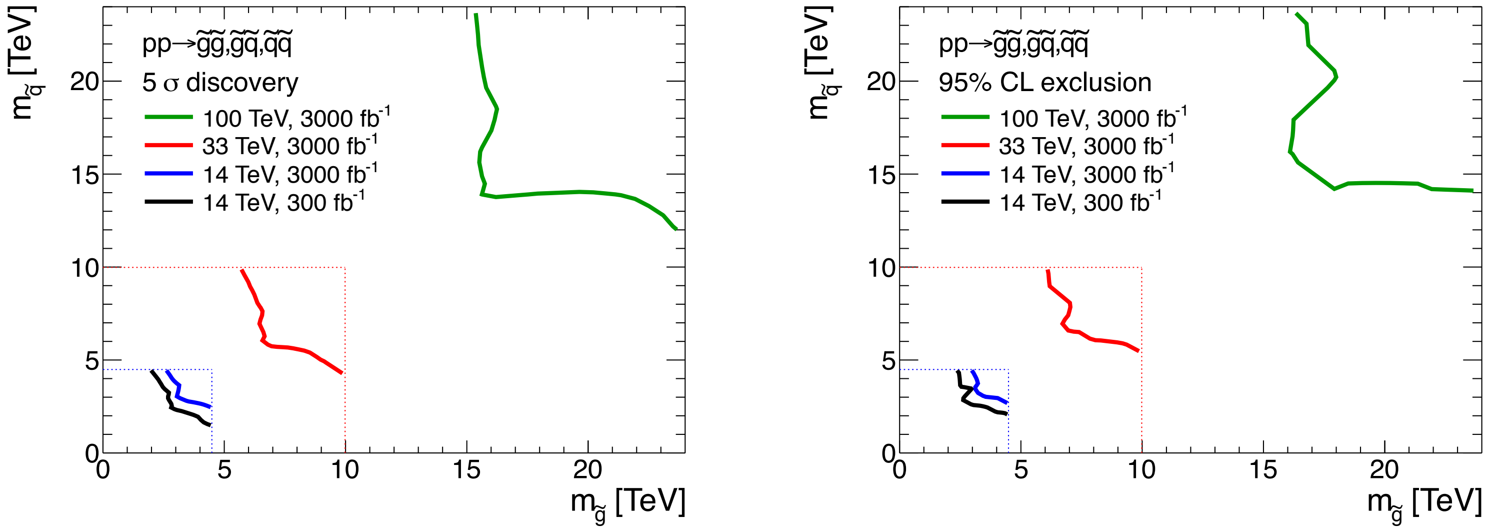


Fig. 16: Results for the gluino-squark-neutralino model. The neutralino mass is taken to be 1 GeV. The left [right] panel shows the $5\,\sigma$ discovery reach [95% CL exclusion] for the four collider scenarios studied here. A 20% systematic uncertainty is assumed and pile-up is not included.

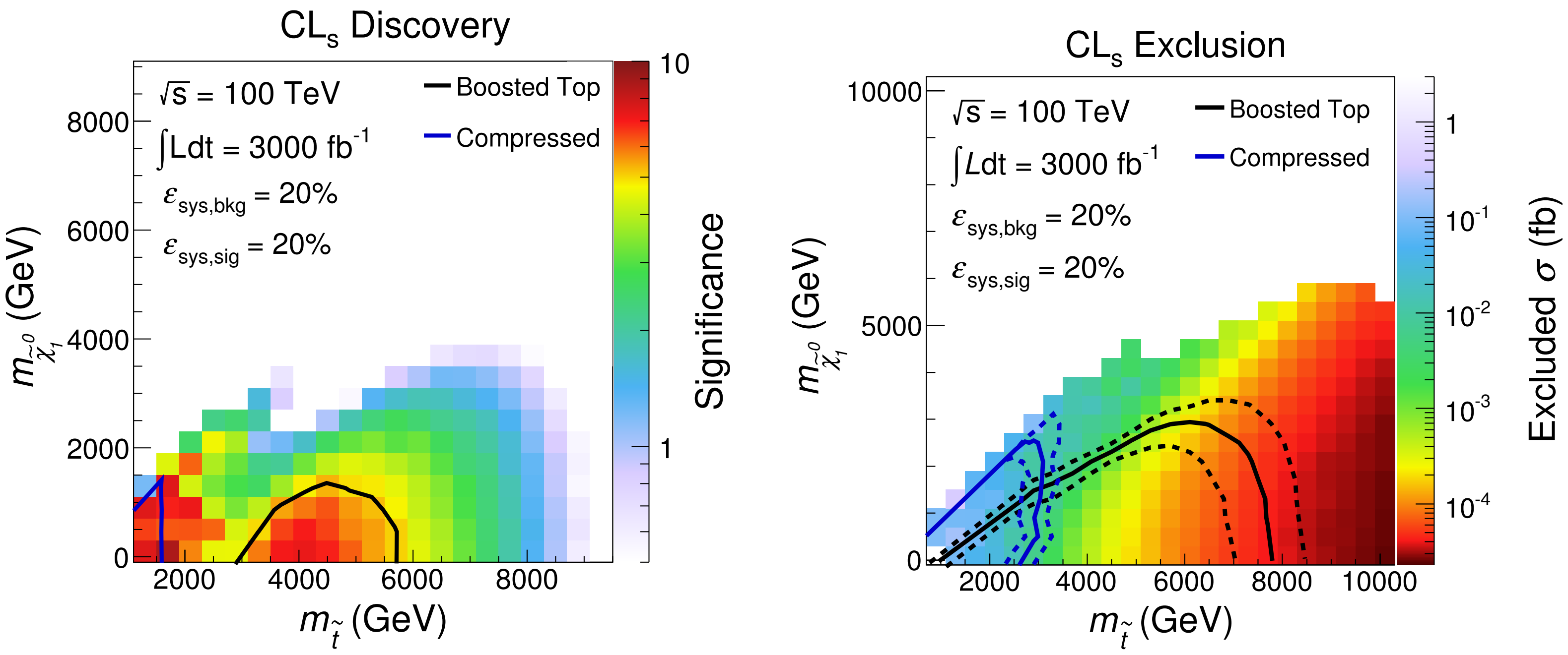
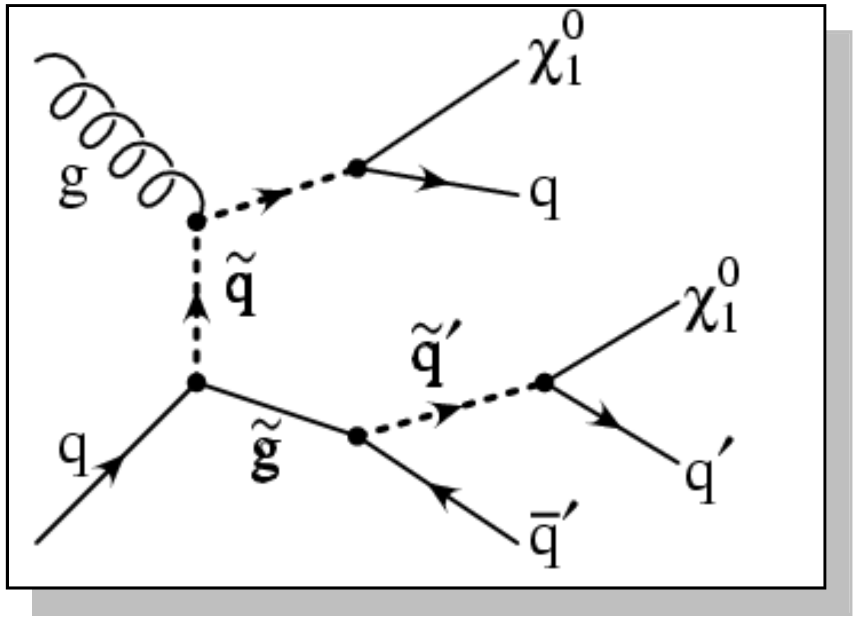


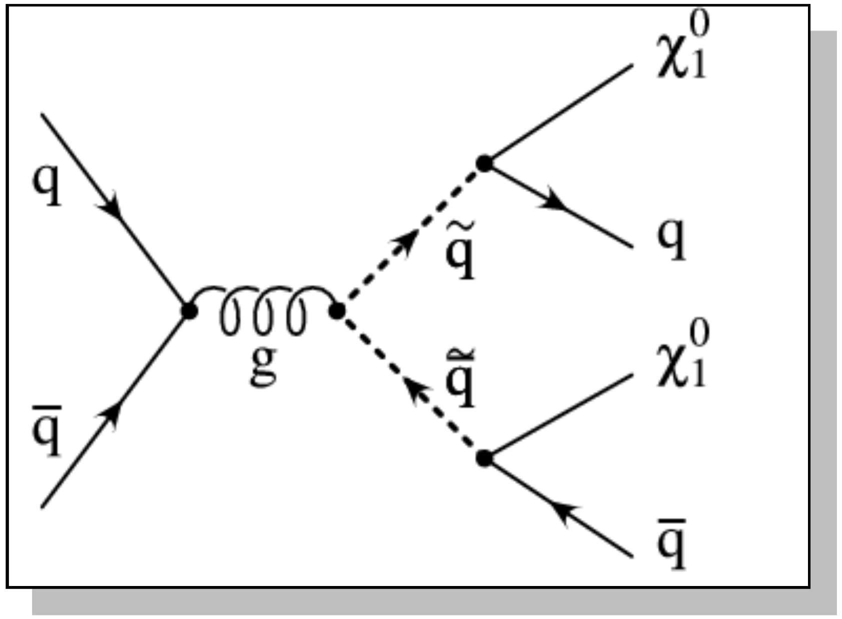
Fig. 12: Left: Discovery potential and Right: Projected exclusion limits for 3000 fb^{-1} of total integrated luminosity at $\sqrt{s} = 100$ TeV. The solid lines show the expected discovery or exclusion obtained from the boosted top (black) and compressed spectra (blue) searches. In the boosted regime we use the $\not{E}_T$ cut that gives the strongest exclusion for each point in the plane. The dotted lines in the left panel show the $\pm 1\sigma$ uncertainty band around the expected exclusion.

Collider	Energy	Luminosity	Cross Section	Mass
LHC8	8 TeV	20.5 fb^{-1}	10 fb	650 GeV
LHC	14 TeV	300 fb^{-1}	3.5 fb	1.0 TeV
HL LHC	14 TeV	3 ab^{-1}	1.1 fb	1.2 TeV
HE LHC	33 TeV	3 ab^{-1}	91 ab	3.0 TeV
FCC-hh	100 TeV	1 ab^{-1}	200 ab	5.7 TeV

SUSY searches

gluinos and squarks are produced by QCD interactions





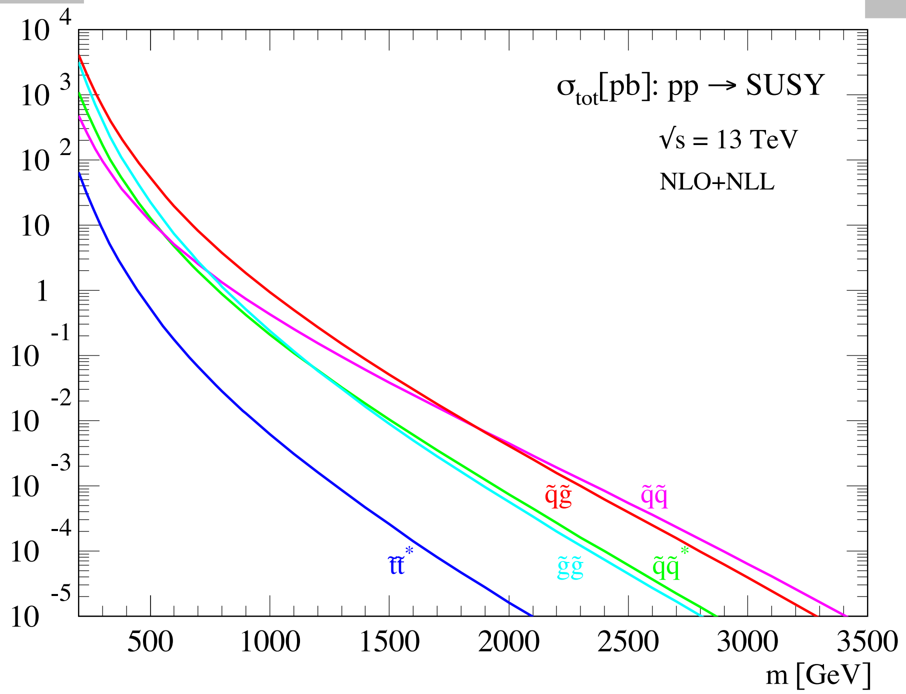
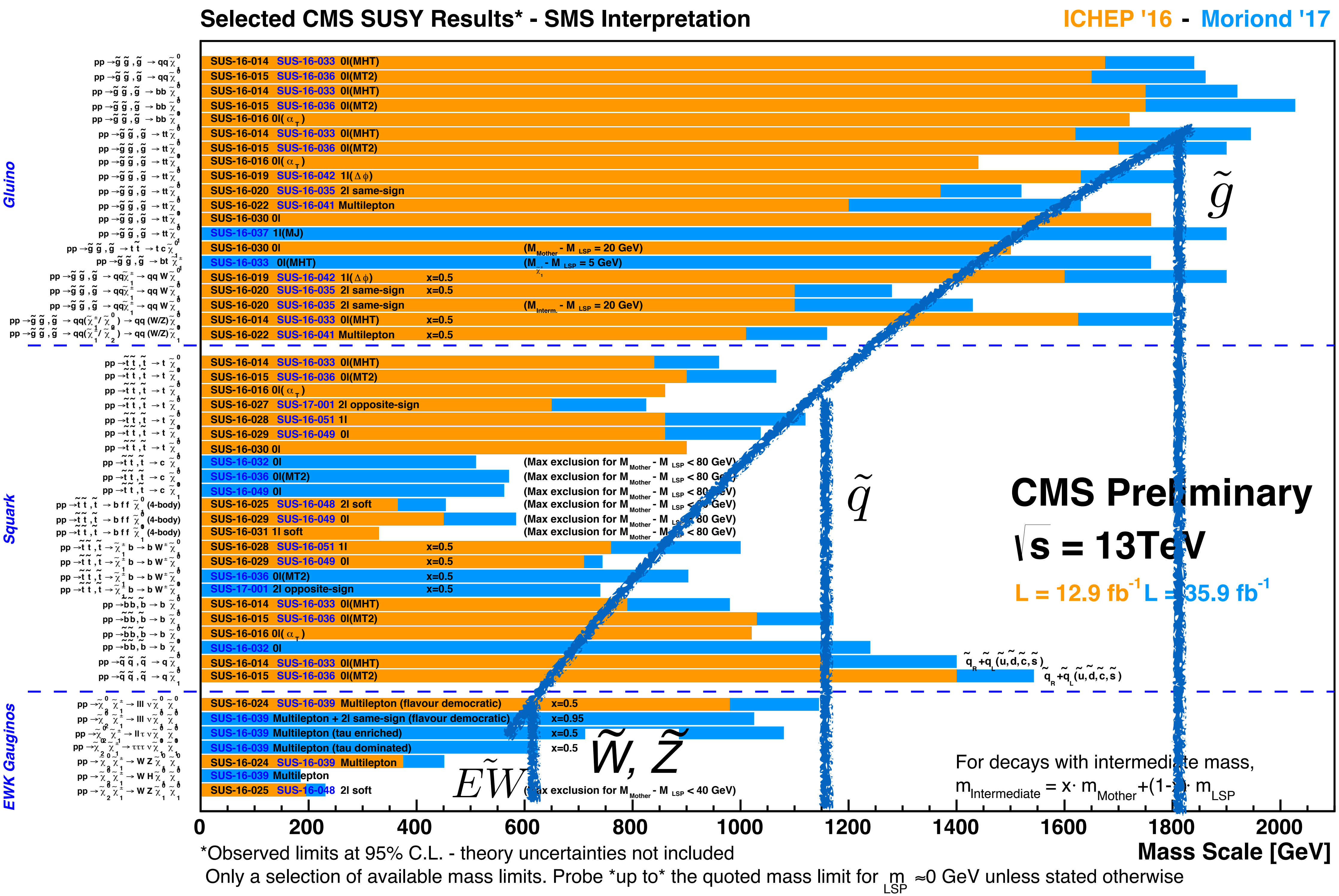


Figure 1: NLO+NLL production cross sections for the case of equal degenerate squark and gluino masses as a function of mass at $\sqrt{s} = 13$ TeV.

LSP (lightest supersymmetric particle) is stable ≈ Missing Energy

SUSY searches

gluinos and squarks are produced by QCD interactions



*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

LSP (lightest supersymmetric particle) is stable ≈ Missing Energy

MSSM Higgs mass and stop searches

Pardo Vega, Villadoro '15 + many others

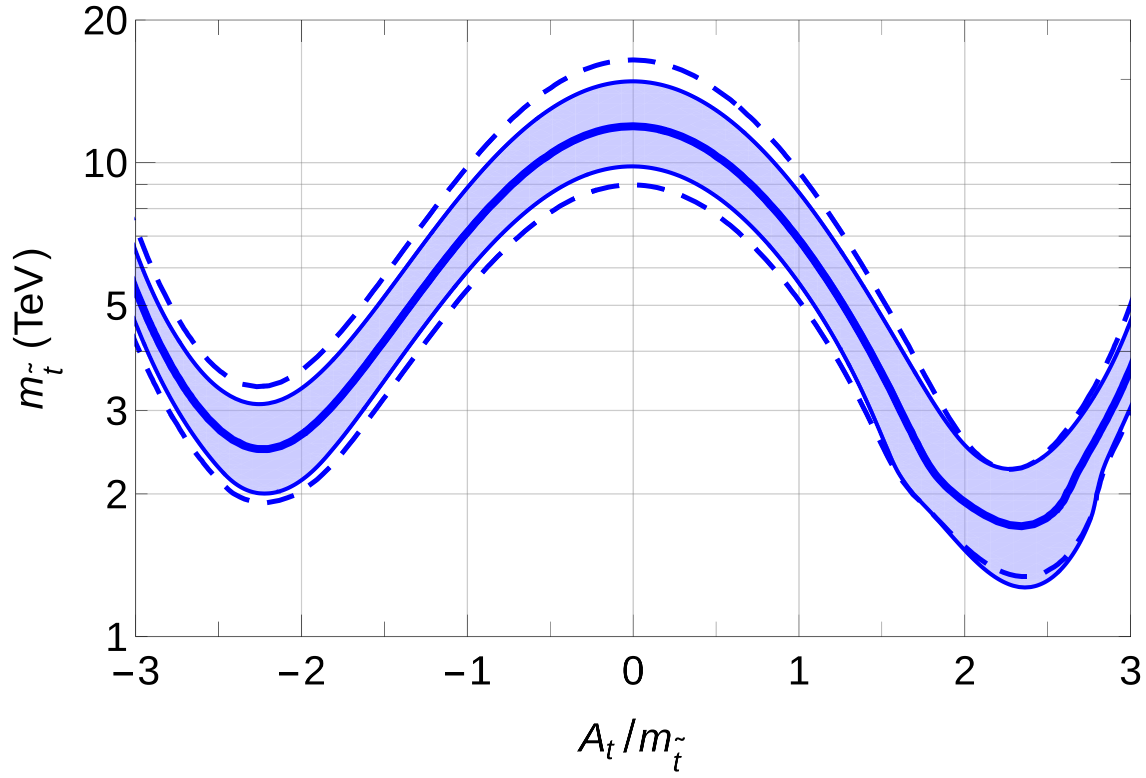
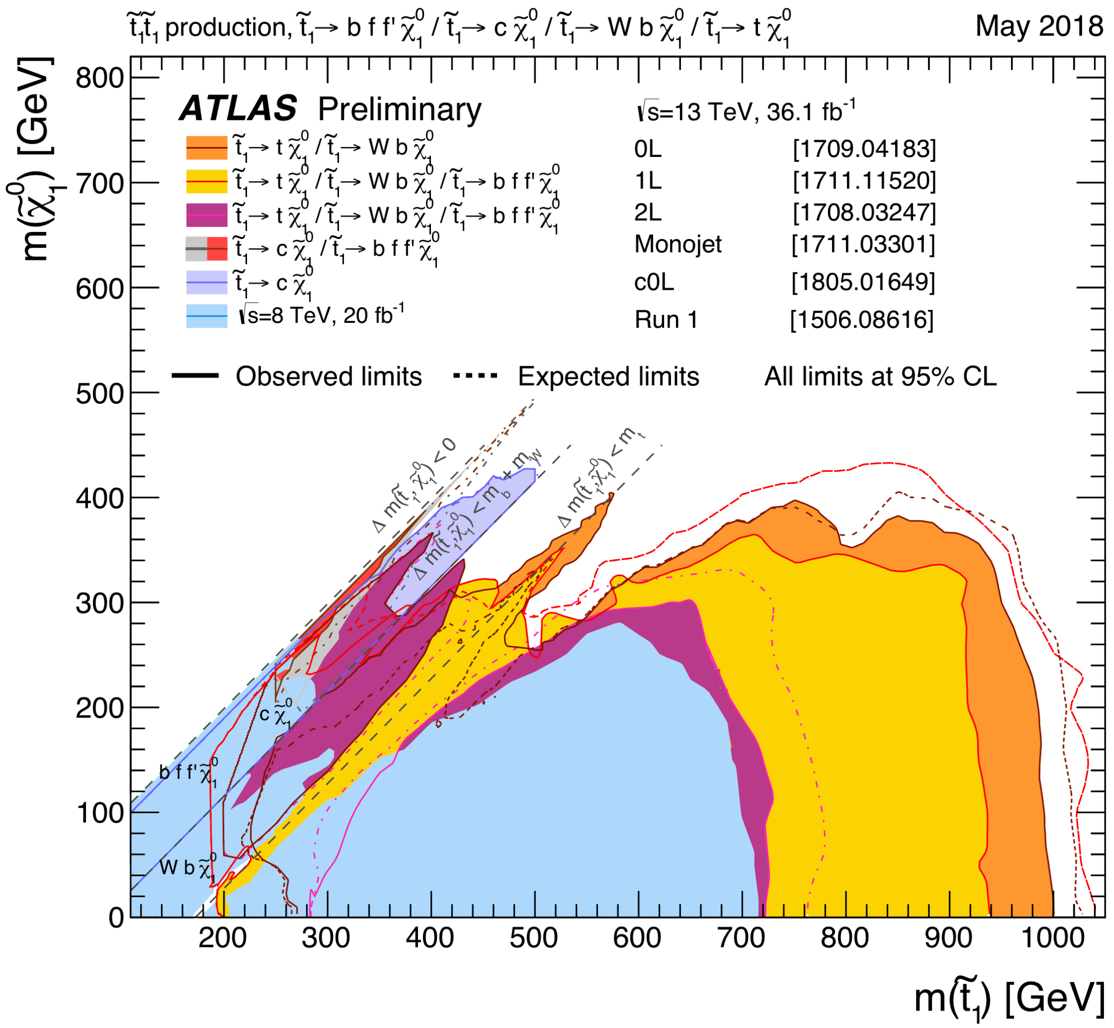


Figure 5: *Allowed values of the OS stop mass reproducing $m_h = 125$ GeV as a function of the stop mixing, with $\tan\beta = 20$, $\mu = 300$ GeV and all the other sparticles at 2 TeV. The band reproduce the theoretical uncertainties while the dashed line the 2σ experimental uncertainty from the top mass. The wiggle around the positive maximal mixing point is due to the physical threshold when $m_{\tilde t}$ crosses $M_3 + m_t$.*

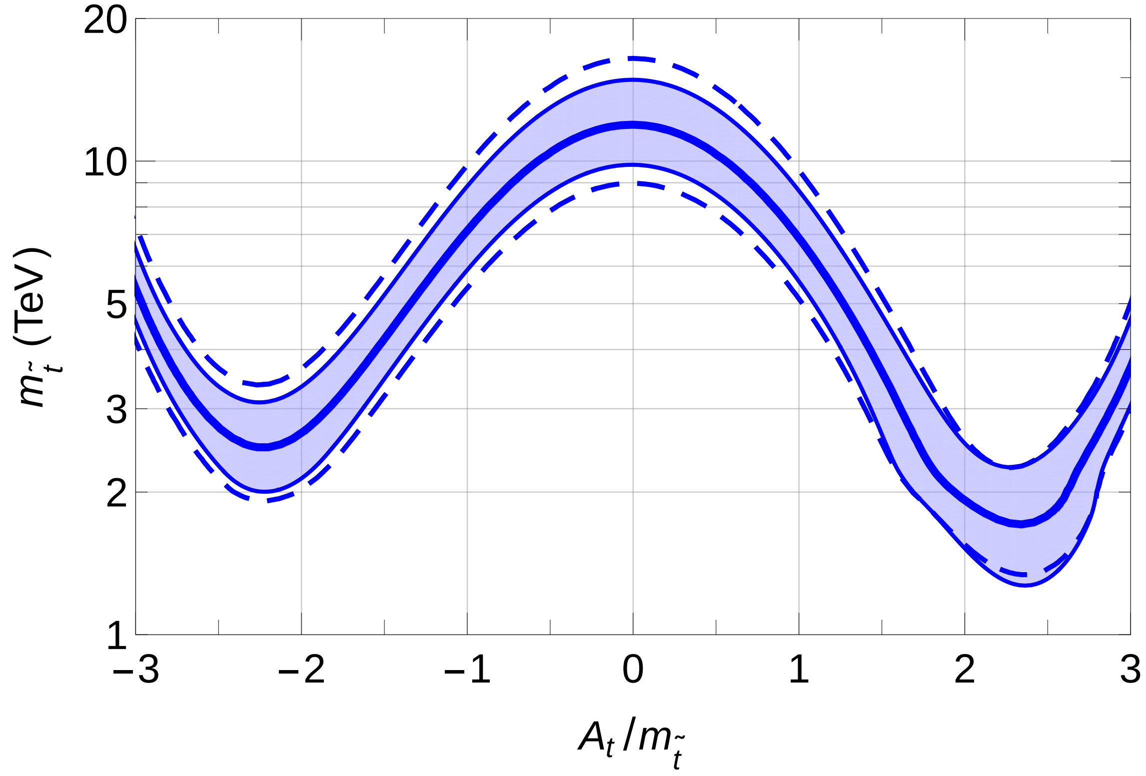
One needs heavy stop(s)
to obtain a 125GeV Higgs
(within the MSSM)

Current and future
bounds on stop mass

LHC (2018)



MSSM Higgs mass and stop searches



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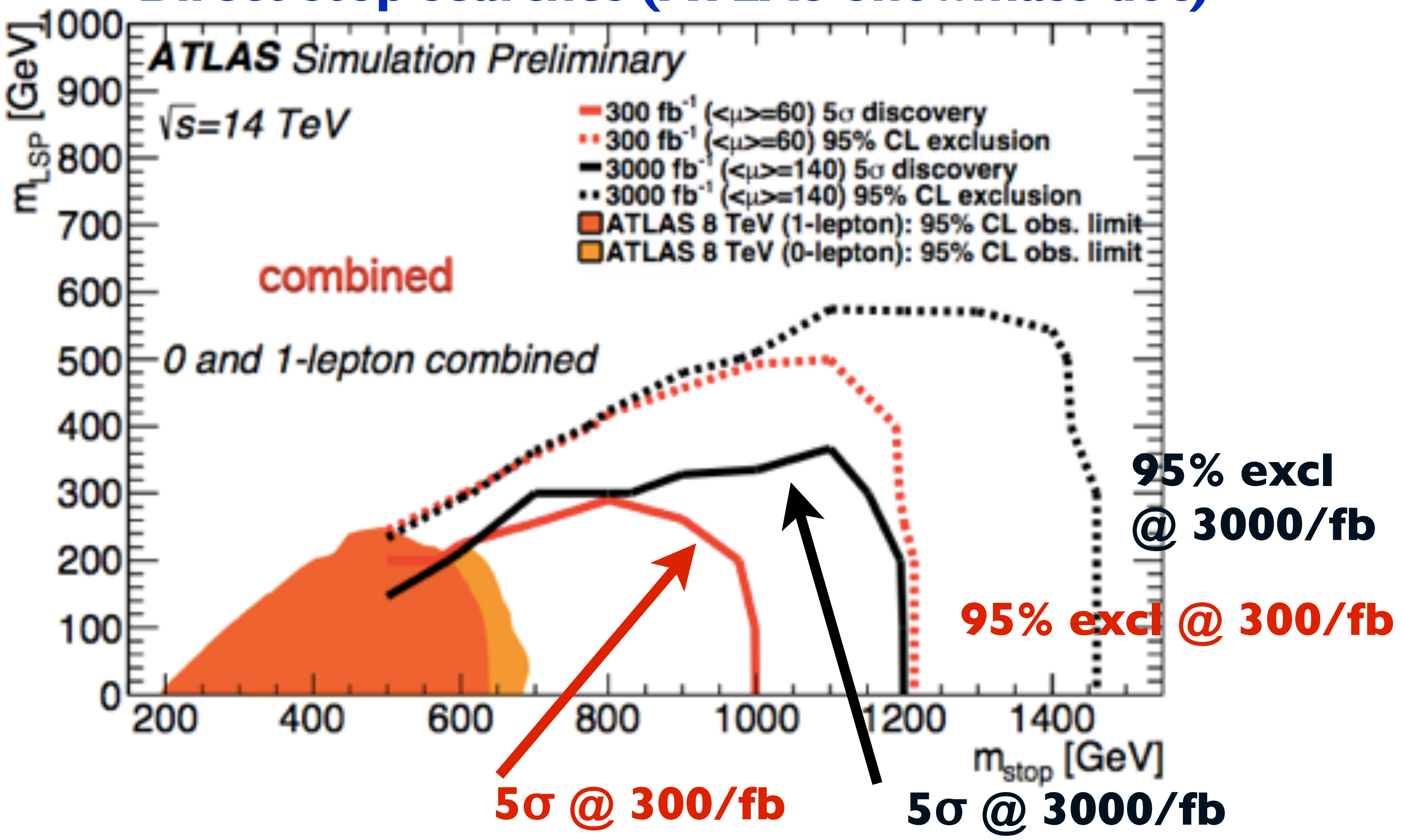
Pardo Vega, Villadoro '15 + many others

One needs heavy stop(s)
to obtain a 125GeV Higgs
(within the MSSM)

Current and future
bounds on stop mass

HL-LHC (2030)

Direct stop searches (ATLAS Snowmass doc)



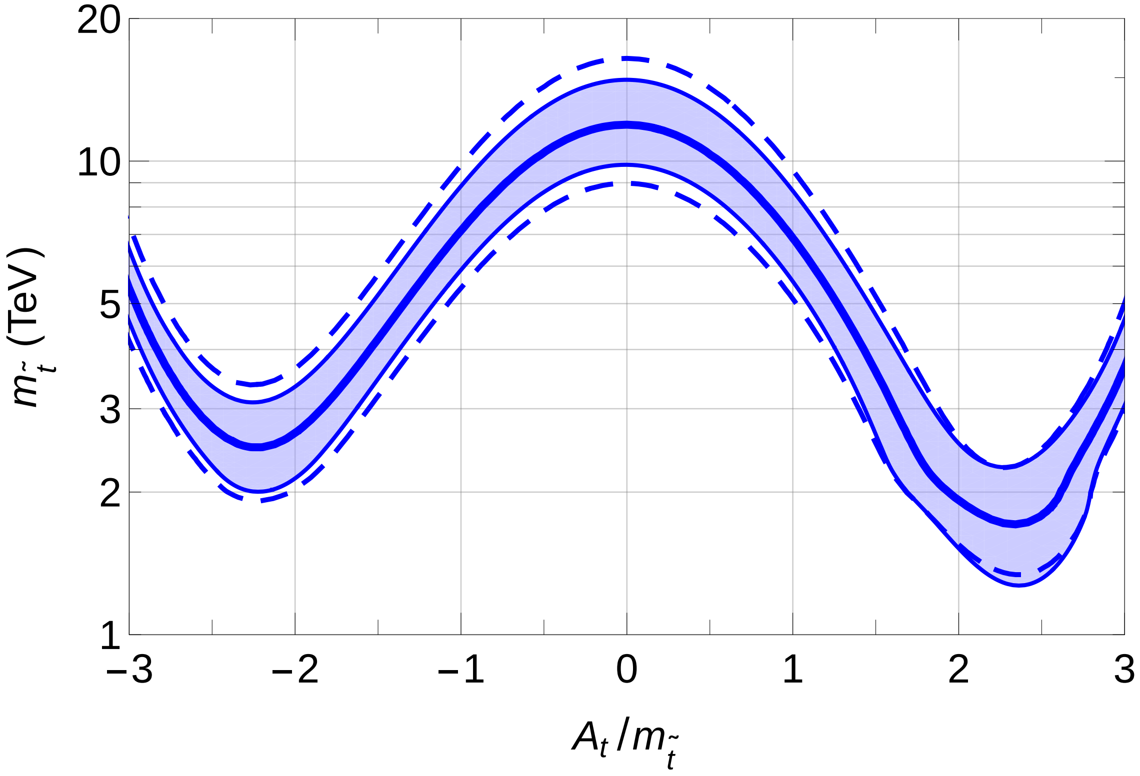
95% excl @ 3000/fb

95% excl @ 300/fb

5σ @ 300/fb

5σ @ 3000/fb

MSSM Higgs mass and stop searches



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Current and future
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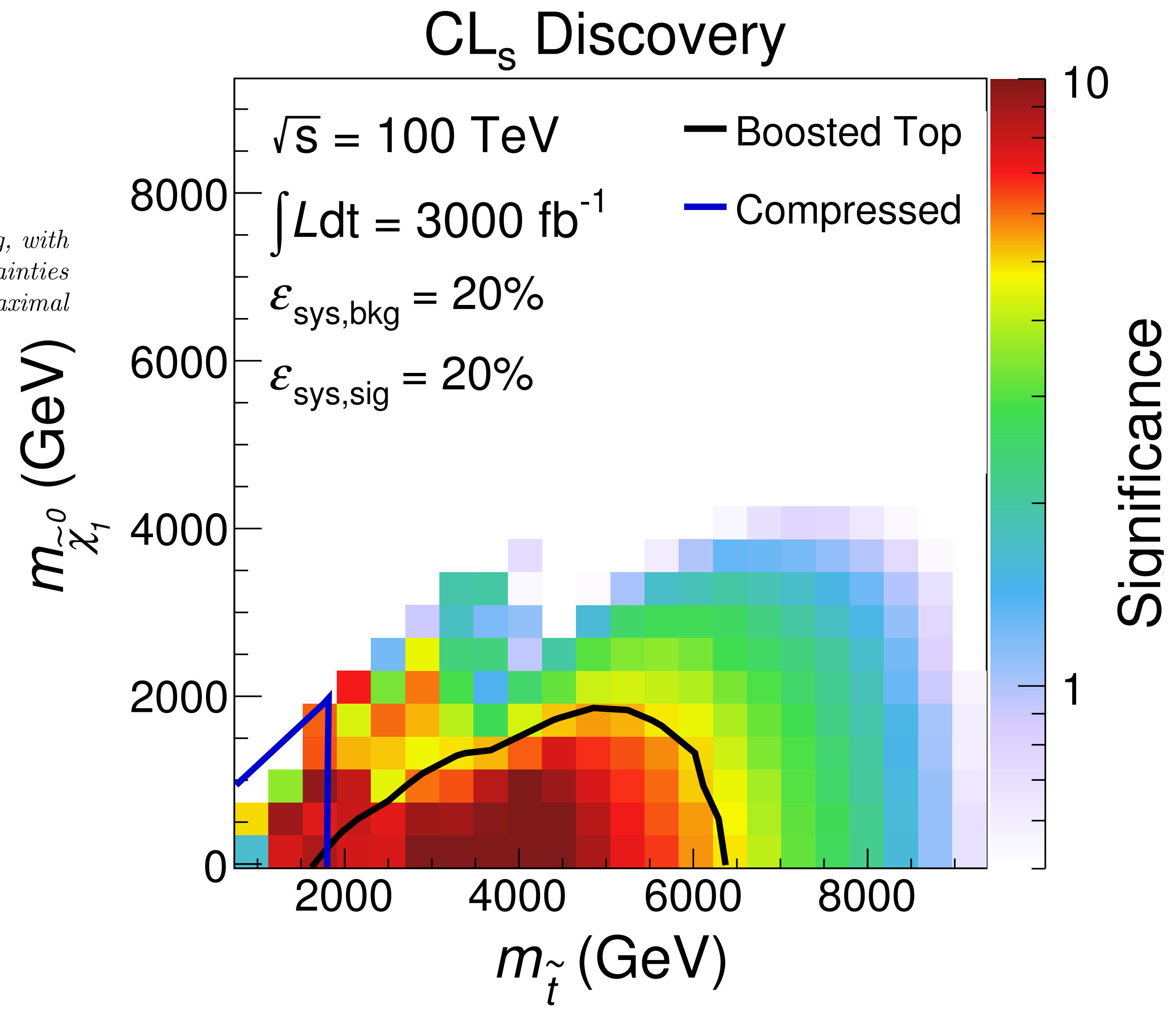


FCC-hh @ 100TeV (2060)

Saving SUSY

SUSY is Natural
but not plain vanilla

- ~~CMSSM~~
- ~~pMSSM~~
- NMSSM
- colorless stops (“folded susy”)
- Hide SUSY, e.g. smaller phase space
  - reduce production (eg. split families)
    Mahbubani et al
  - reduce MET (e.g. ~~R-parity~~, compressed spectrum)
    Csaki et al
  - dilute MET (decay to invisible particles with more invisible particles)
  - soften MET (stealth susy, stop -top degeneracy)
    Fan et al

LHC$_{3000\mathrm{fb}^{-1}}$ will tell!

Good coverage of

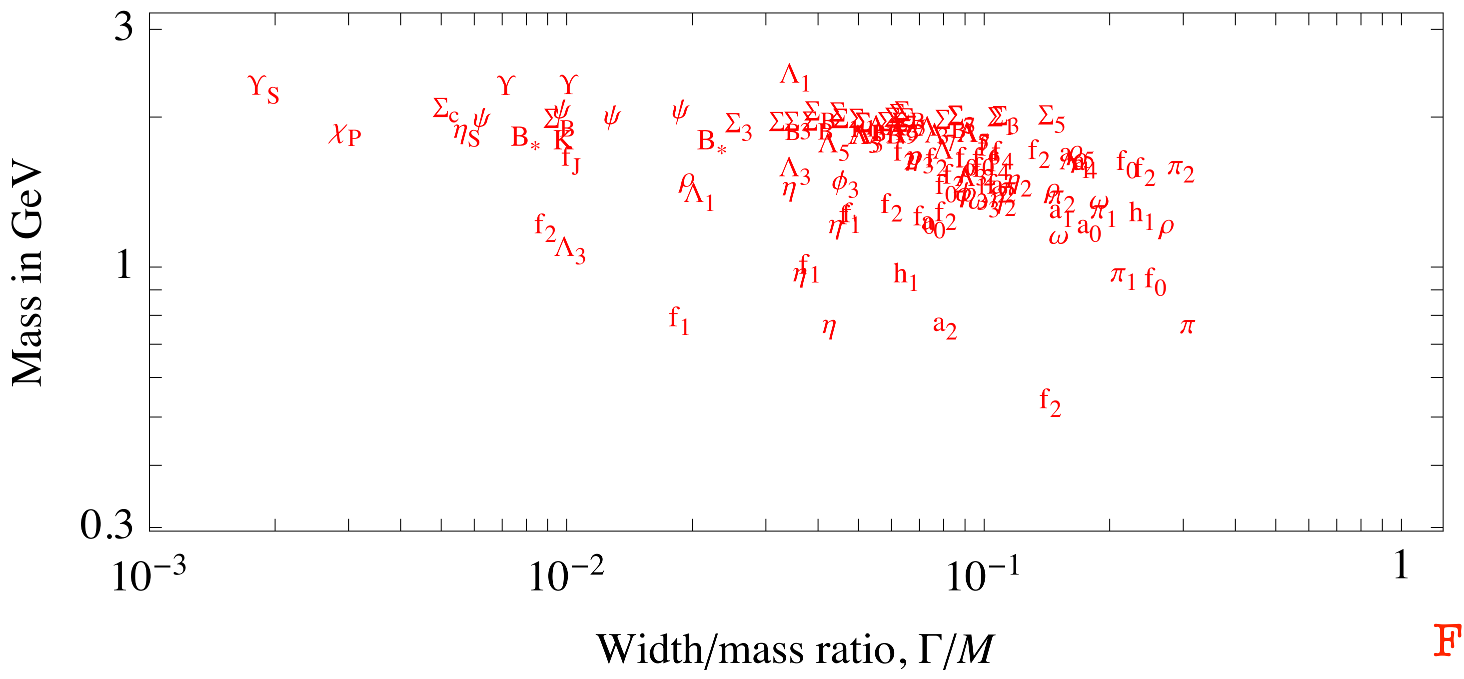
hidden natural susy

- **mono-top searches** (DM, flavoured naturalness i.e. mixing among different squark flavours, stop-higgsino mixings)
- **mono-jet searches with ISR recoil** (compressed spectra)
- **precise tt inclusive measurement + spin correlations**
  (stop → top + soft neutralino)
- **multi-hard-jets** (RPV, hidden valleys, long decay chains)

Composite Higgs Models

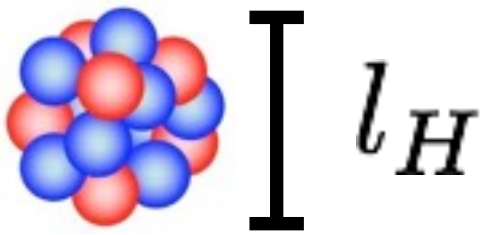
Composite Higgs

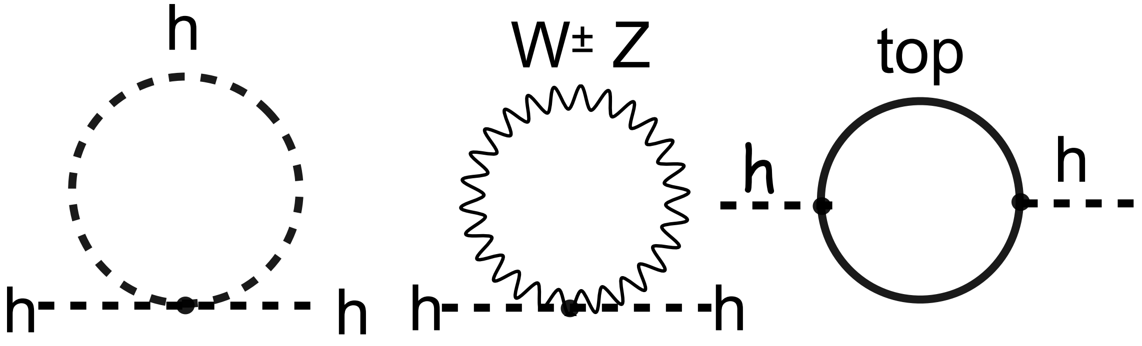
Light scalars exist in Nature but
all the ones observed before Higgs discovery were composite bounds states



Franceschini et al. '15

Could the Higgs be a "hadron" of a new strong force?

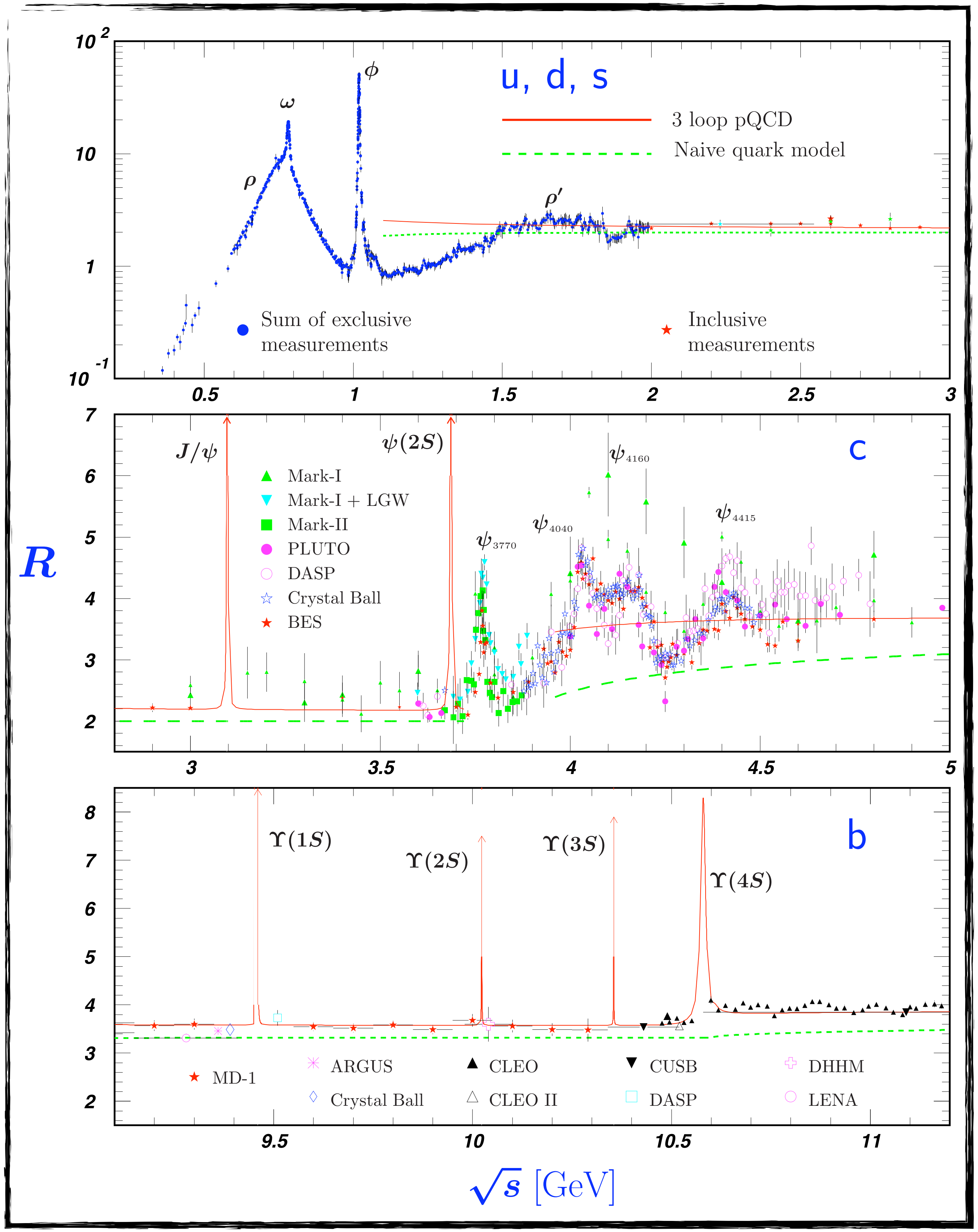




At energy above $1/\ell_H$, the Higgs dissolves, the integrals are smoothed out

$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2 \quad \Rightarrow \quad \int \frac{d^4k}{(2\pi)^4}\mathcal{F}_H(k)\frac{1}{k^2-m^2} \propto 1/l_H^2$$

Higgs as a bound state



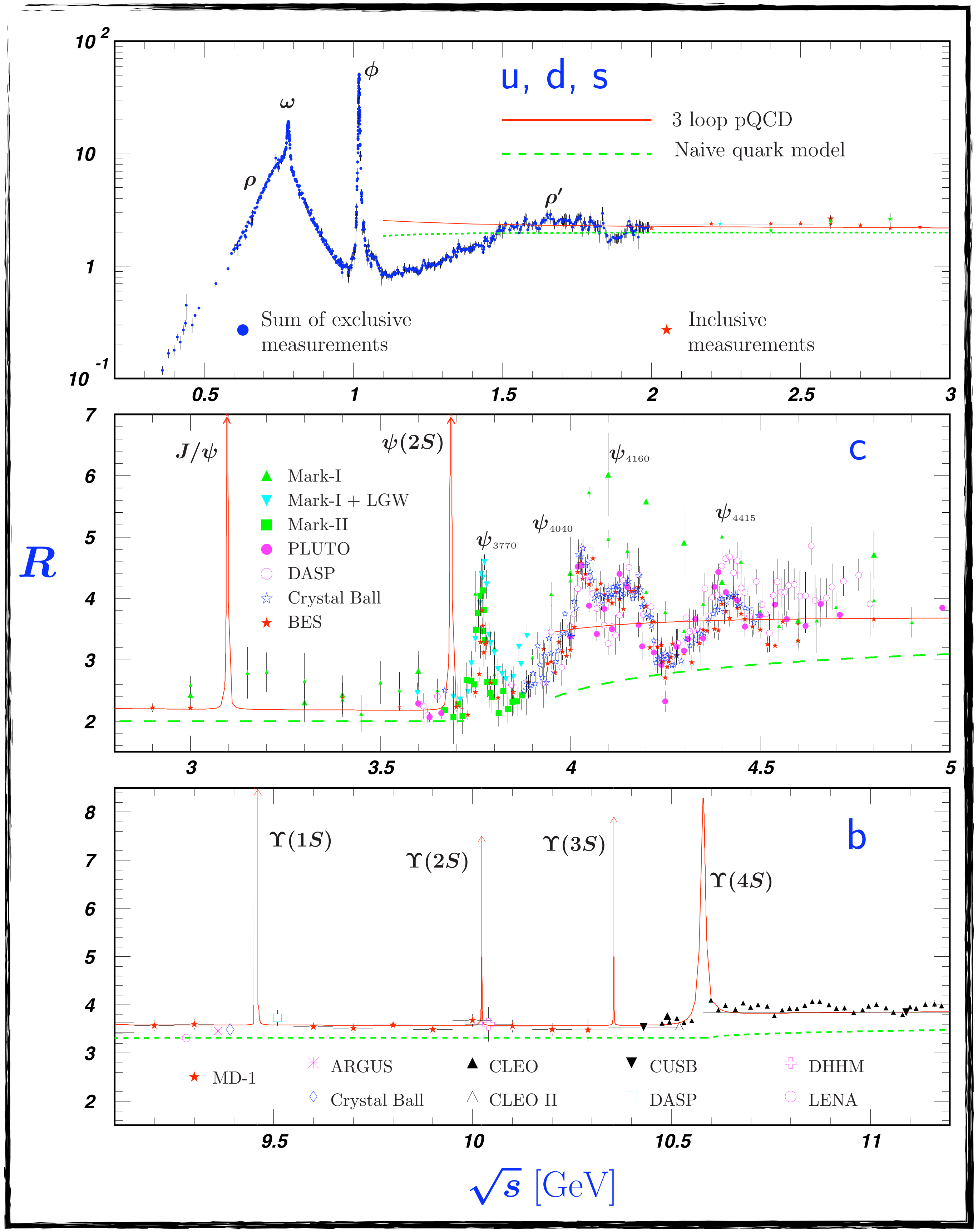
Structure of QCD was understood from inelastic scattering experiments

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Shows some peaks/resonances at each QCD bound states

Eventually the asymptotic value of R also tells the number of color of QCD

Higgs as a bound state



The Higgs discovery would be the first step of rich physics ahead of us:

- discover a new SU(N_C) force
- access to the fundamental constituents
- rich spectrum of bound states

But how come we haven’t seen anything of these yet?

⇛ The Higgs has to be lighter than the other bound states

⇛ pions are lighter than nucleons, hadrons and other mesons

⇛ let the Higgs be the pions of the new strong interaction, i.e., the Goldstone boson associated to the breaking of some global symmetry

Higgs as a bound state

The Higgs discovery would be the first step of rich physics ahead of us:

- discover a new SU(N_C) force
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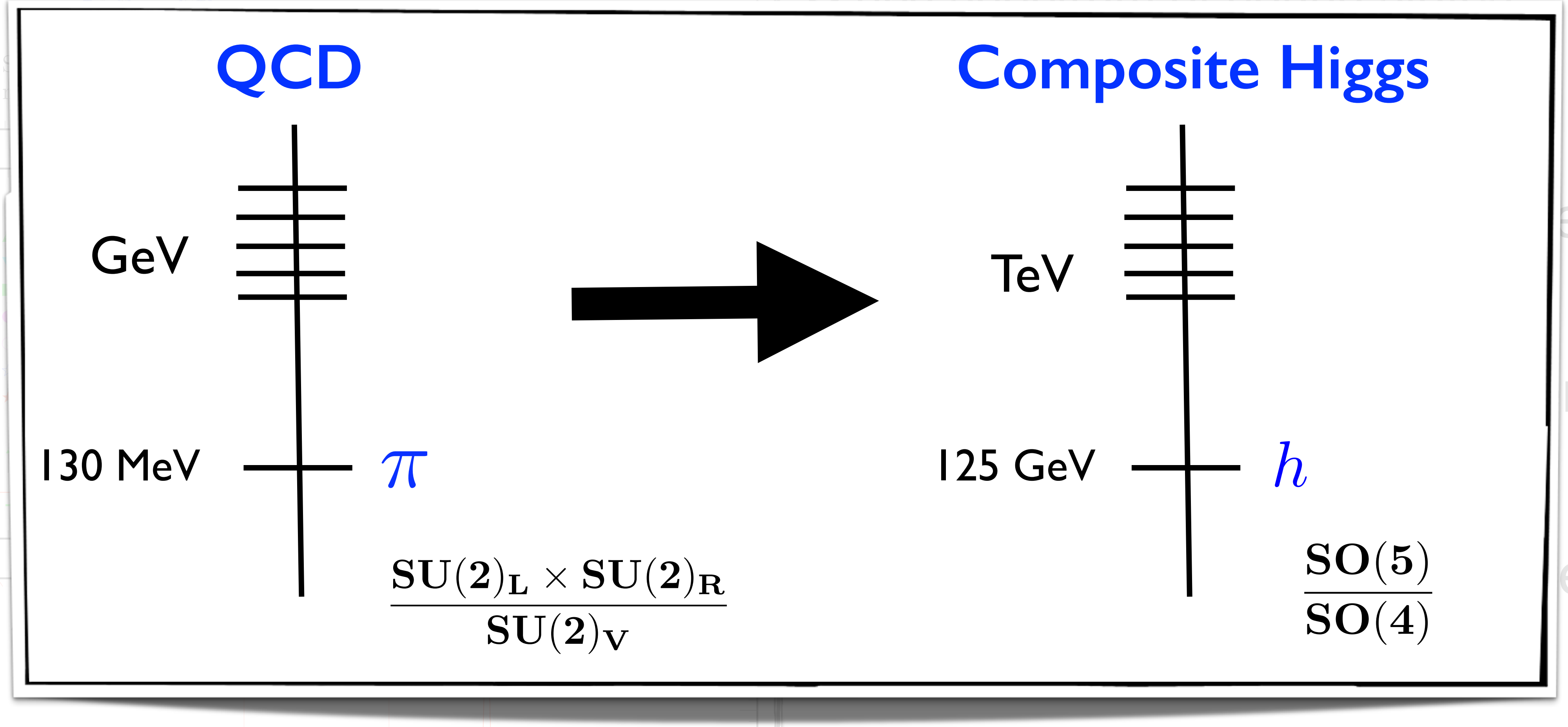
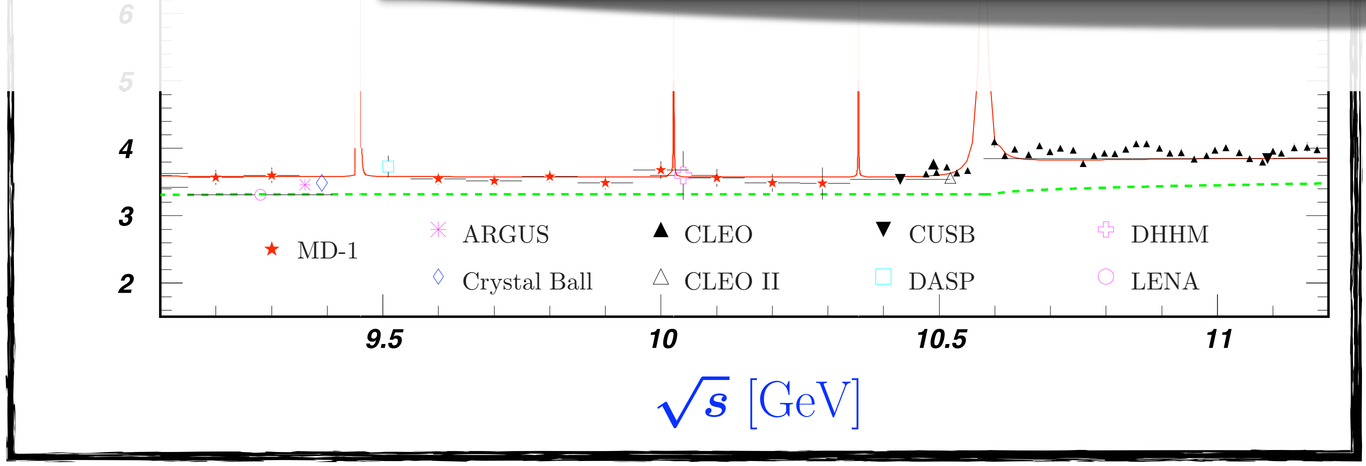
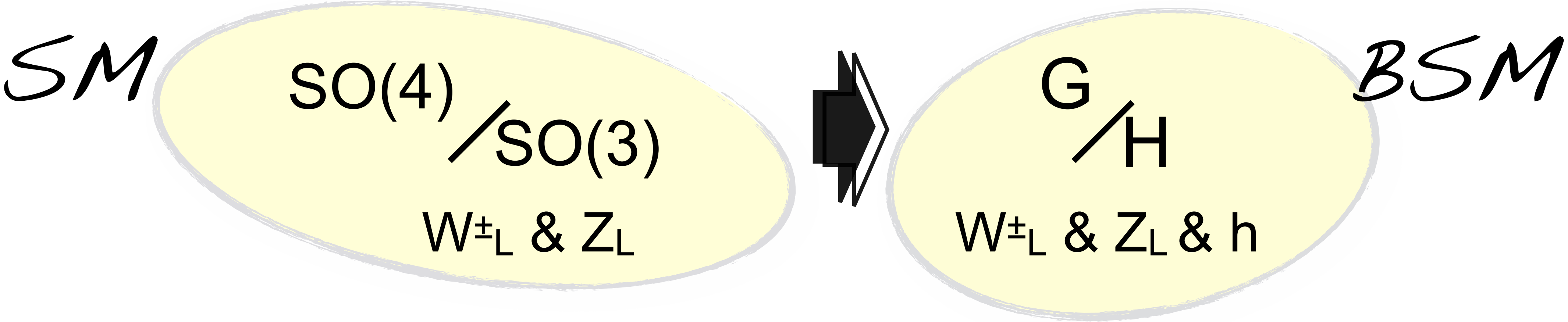




⇒ let the Higgs be the pions of the new strong interaction, i.e., the Goldstone boson associated to the breaking of some global symmetry

Higgs as a Goldstone boson



Examples: $SO(5)/SO(4)$: 4 PGBs=$W^\pm_L$, Z_L, h

dim=10 dim=6

← Minimal Composite Higgs Model

Agashe, Contino, Pomarol '04

$SO(6)/SO(5)$: 5 PGBs=H, a ← Next MCHM

dim=15 dim=10

$SU(4)/Sp(4,\mathbb{C})$: 5 PGBs=H, s

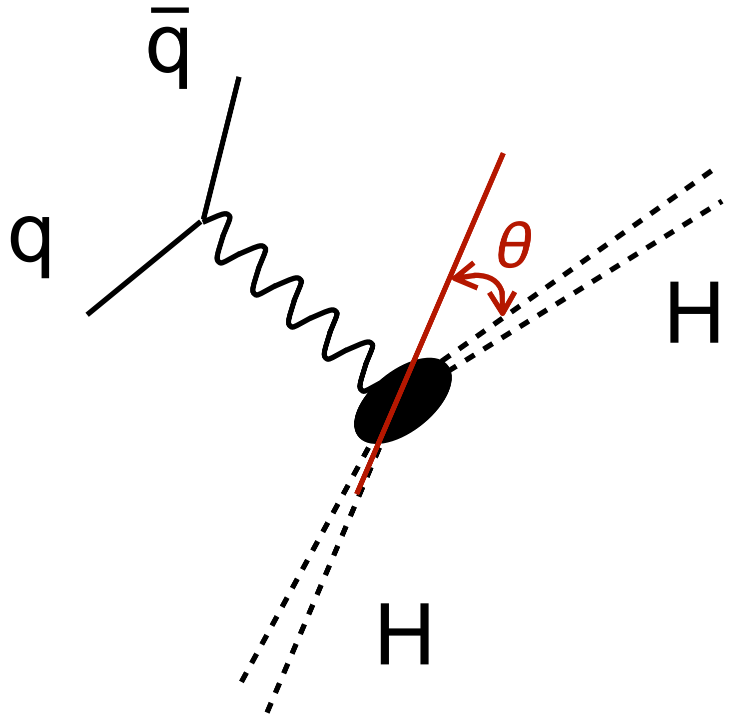
dim=15 dim=10

$SO(6)/SO(4)\mathrm{x}SO(2)$: 8 PGBs=$H_1+H_2$ ← Minimal Composite Two Higgs Doublets

dim=15 dim=7

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

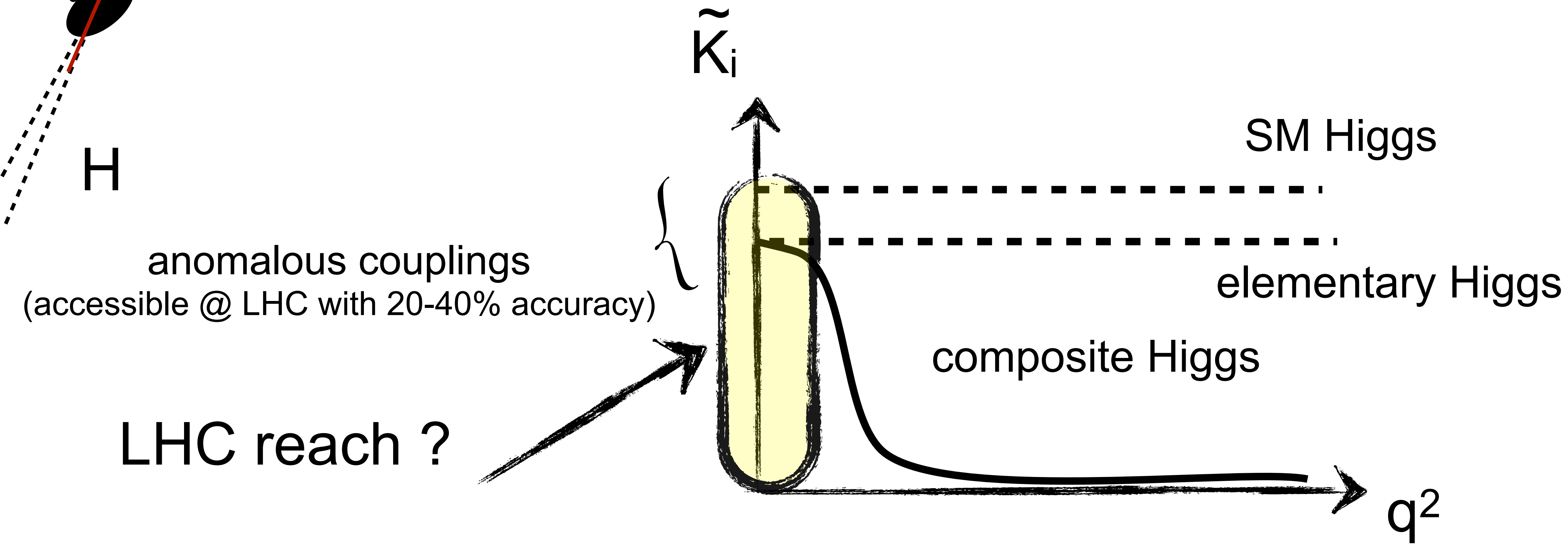
Probe the compositeness of the Higgs?



Rosenbluth-type cross-section

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16 m_H^2 \sin^4\theta/2}\,\frac{E'}{E^3}\left(2\tilde{K}_1 q^2 \sin^2\theta/2 + \tilde{K}_2 \cos^2\theta/2\right)$$

Constants factor for point-like target
Momentum-dependent when target has an internal structure



Need to develop tools to understand the physics of a composite Higgs

- ○ use effective theory approach
- ○ rely on symmetries of the problem

} identify interesting processes

Composite Higgs Anomalous Couplings

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L} \supset \frac{c_H}{2f^2}\partial^\mu\left(|H|^2\right)\partial_\mu\left(|H|^2\right) \qquad c_H \sim \mathcal{O}(1)$$

f=compositeness scale of the Higgs boson

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Longrightarrow \mathcal{L} = \frac{1}{2}\left(1 + c_H\frac{v^2}{f^2}\right)\left(\partial^\mu h\right)^2 + \ldots$$

Modified Higgs propagator ~ Higgs couplings rescaled by $\frac{1}{\sqrt{1+c_H\frac{v^2}{f^2}}} \sim 1 - c_H\frac{v^2}{2f^2} \equiv 1 - \xi/2$

Higgs anomalous coupling: $a = \sqrt{1-\xi} \approx 1-\xi/2$

$$\xi = v^2/f^2$$

Typical resonance mass: $m_\rho = g_\rho \times f$. Strong coupling: $m_\rho \gg f$

EFT = dimensional analysis

It is important to remember that couplings are not dimensionless

		M^n	$\hbar^n$
scalar field	ϕ	1	1/2
fermion field	ψ	3/2	1/2
vector field	A_μ	1	1/2
mass	m	1	0
gauge coupling	g	0	$-1/2$
quartic coupling	λ	0	-1
Yukawa coupling	y_f	0	$-1/2$

$$\mathcal{S} = \int d^4x \left(\underset{\substack{[\mathcal{L}_0]_\hbar = 1 \\ [\mathcal{L}_0]_M = 4}}{\mathcal{L}_0} + \hbar \underset{\substack{[\mathcal{L}_1]_\hbar = 0 \\ [\mathcal{L}_1]_M = 4}}{\mathcal{L}_1} + \hbar^2 \underset{\substack{[\mathcal{L}_2]_\hbar = -1 \\ [\mathcal{L}_2]_M = 4}}{\mathcal{L}_2} + \ldots \right)$$

v is not simply a mass scale but also a “coupling”

$$[v]_\hbar = 1/2$$

$$\mathcal{A}_{W_L W_L \to W_L W_L} = \frac{s}{v^2}$$ even when gauge coupling are zero

$$\frac{1}{M^2} \overset{[\cdot]_\hbar = -1}{g_*^2} \overset{[\cdot]_\hbar = 2}{\left(\partial^\mu |H|^2\right)^2}$$

$$\frac{ic_W}{2M^2} \overset{[\cdot]_\hbar = 1}{\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)} \overset{[\cdot]_\hbar = 0}{\left(g\, D^\nu W_{\mu\nu}\right)^i}$$

SILH Effective Lagrangian

(strongly-interacting light Higgs)

Giudice, Grojean, Pomarol, Rattazzi '07

- extra Higgs leg: H/f
- extra derivative: ∂/m_ρ

Genuine strong operators (sensitive to the scale f)

$$\frac{c_H}{2f^2}\left(\partial^\mu |H|^2\right)^2 \qquad \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2 \qquad \frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + \text{h.c.} \qquad \frac{c_6\lambda}{f^2}|H|^6$$

custodial breaking

Form factor operators (sensitive to the scale m_ρ)

$$\frac{ic_W}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i \qquad \frac{ic_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$\frac{ic_{HW}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} \qquad \frac{ic_{HB}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} \qquad \frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}$$

Goldstone sym.

Higgs anomalous couplings

$$\mathcal{L}_{\rm EWSB} = m_W^2 W_\mu^+ W_\mu^+ \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_\psi \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right)$$

The Higgs couplings deviates from SM ones (a=b=c=1)
and the deviations are controlled by c_H and c_y

Anomalous couplings are related to the coset symmetry and not the spectrum of resonances

Minimal composite Higgs model (MCHM): SO(5)/SO(4)

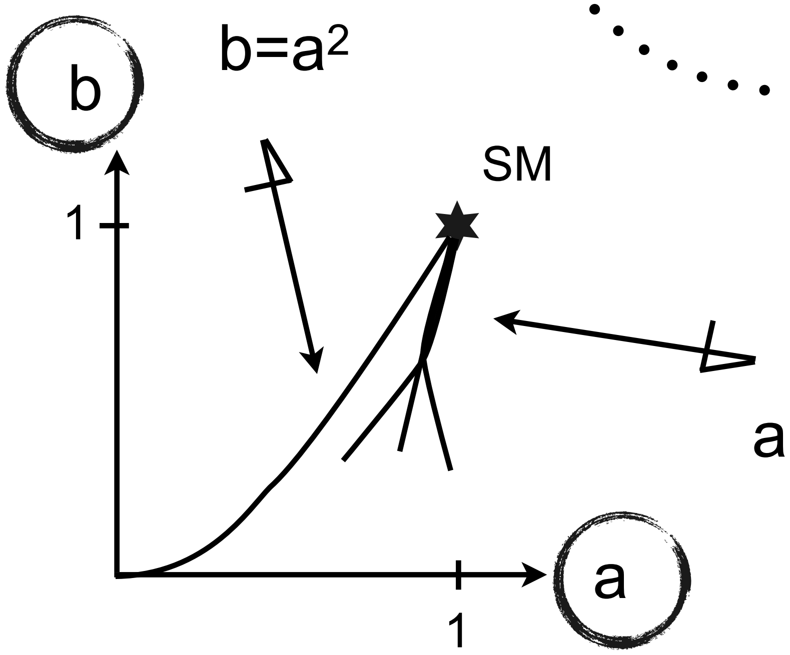
$$a = \sqrt{1-\xi} \qquad b = 1 - 2\xi \qquad b_3 = -\frac{4}{3}\xi\sqrt{1-\xi} \qquad c = \left(\sqrt{1-\xi}, \frac{1-2\xi}{\sqrt{1-\xi}}\right) \qquad c_2 = -(\xi, 4\xi)$$

Uniqueness of Goldstone models in the SM vicinity

— a single operator at dimension-6 level controls the amplitudes —

$$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$$

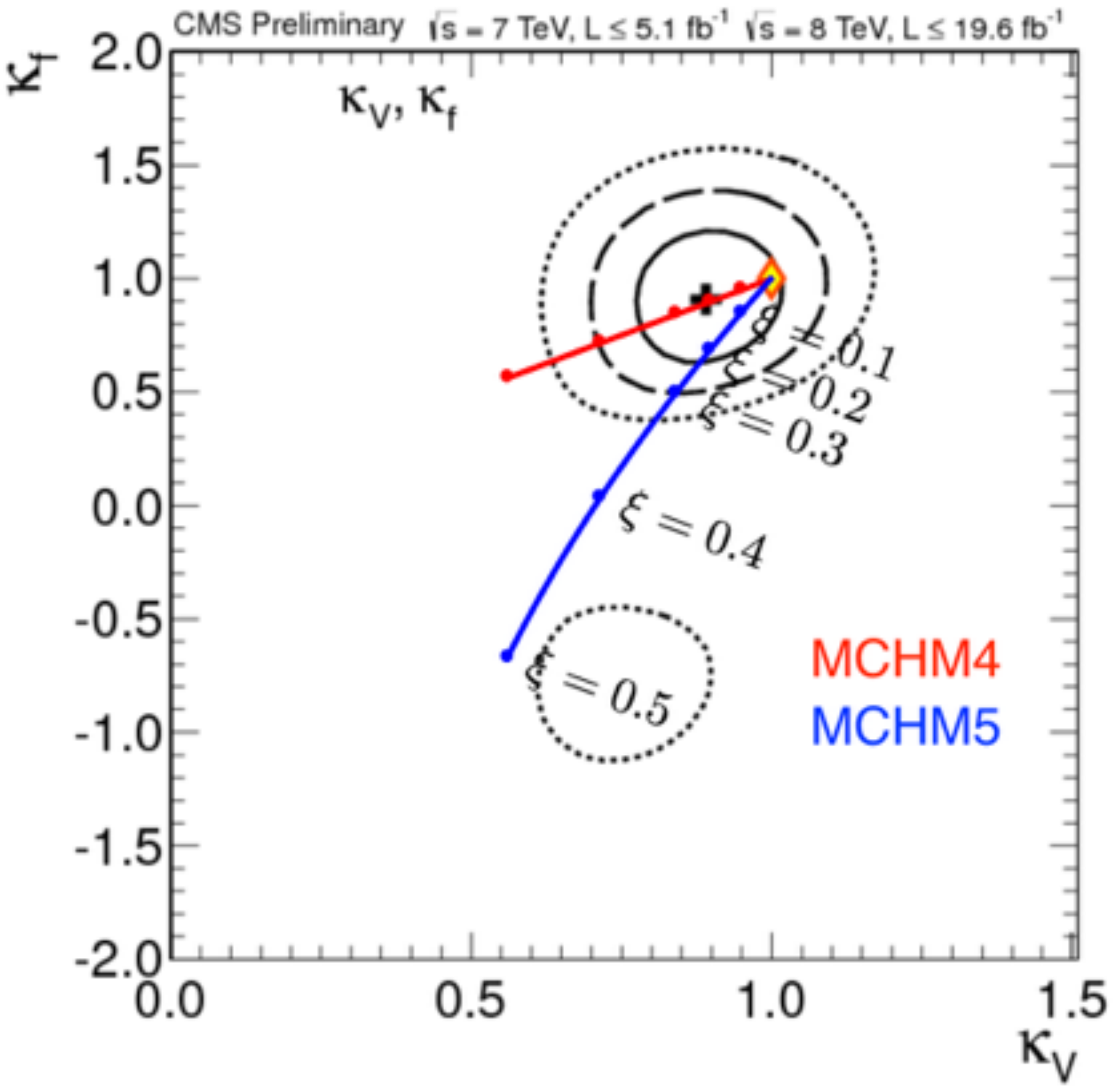
Composite Higgs
vs.
SM Higgs

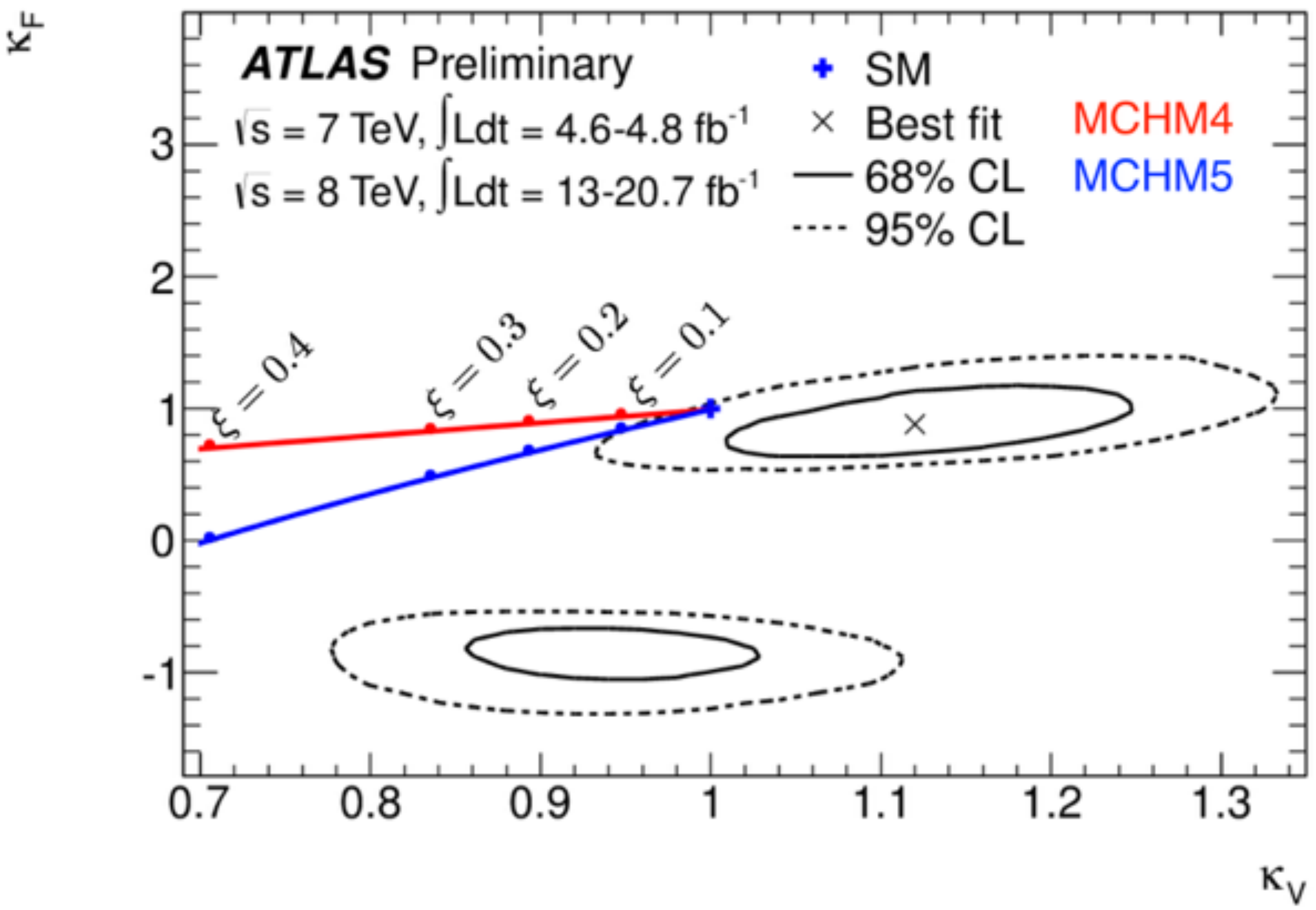


Dilaton
b=a²

Goldstone Higgs
for large f
$a=1-v^2/2f^2$ $b=1-2\,v^2/f^2$

Higgs couplings fit





- MCHM4

$$\xi < 0.12 \quad \text{at } 95\%\text{CL}$$

- MCHM5

$$\xi < 0.10 \quad \text{at } 95\%\text{CL}$$

Indirect composite signatures

Assuming **composite** Higgs, **elementary** gauge bos.:

$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* H, g_w V_\mu, \partial_\mu]$$

S-parameter @ee: [De Blas et. al.] (LEP: 10^{-3})

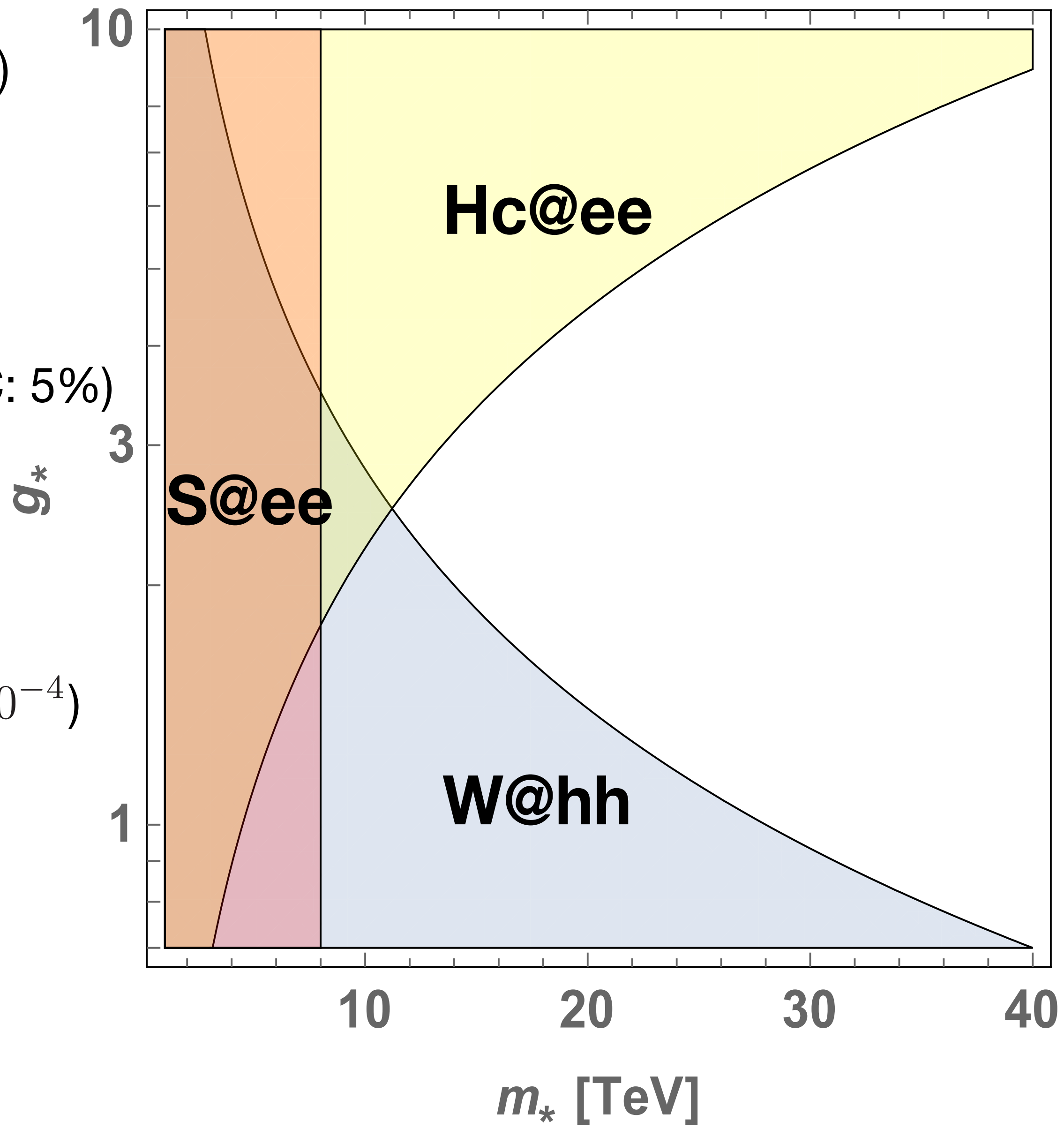
$$\frac{g_w g'}{m_*^2} H^\dagger \sigma_a H W^a_{\mu\nu} B^{\mu\nu} \Rightarrow \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}$$

Higgs Couplings @ee: [ee Report] (HL-LHC: 5%)

$$\frac{g_*^2}{m_*^2}\partial_\mu |H|^2 \partial^\mu |H|^2 \Rightarrow \delta\kappa_{V,F} = \frac{g_*^2 v^2}{m_*^2} < 3\,10^{-3}$$

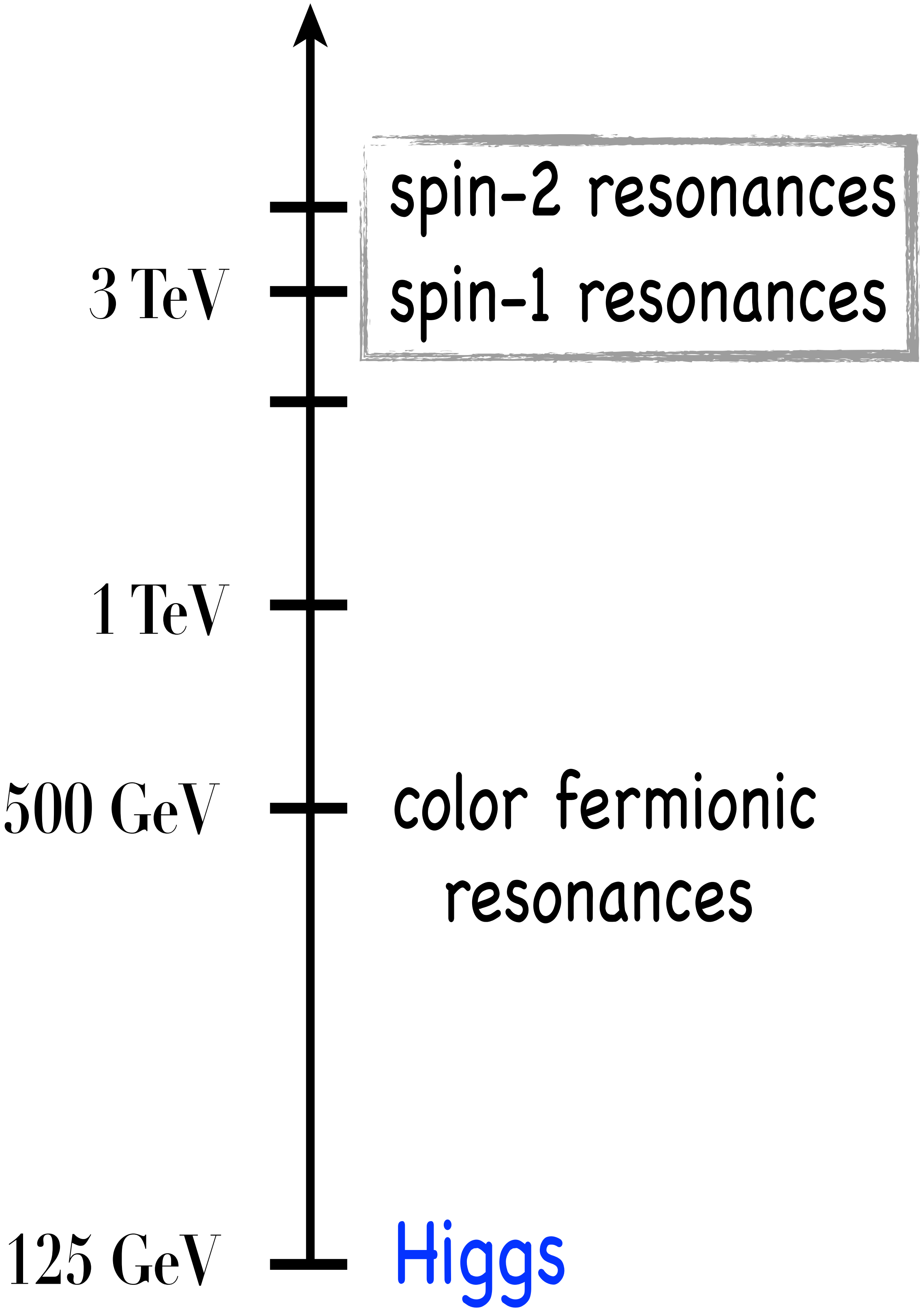
W @hh: (energy + accuracy) (HL-LHC< 10^{-4})

$$\frac{g_w^2}{g_*^2 m_*^2}(D_\mu W_{\nu\rho})^2 \Rightarrow W = \frac{g_w^2 m_w^2}{g_*^2 m_*^2} < \ 10^{-5}$$



Grojean-Wulzer @ FCC physics week '17

The other resonances



spin-2 resonances

spin-1 resonances

3 TeV

1 TeV

500 GeV

color fermionic resonances

125 GeV

Higgs

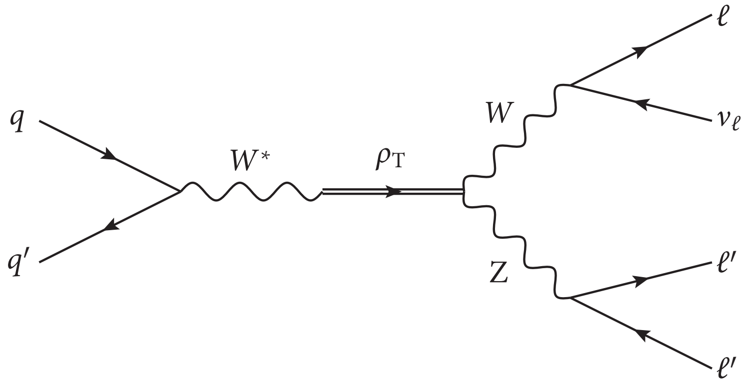
Dominant decays into longitudinal SM gauge bosons

$$\Gamma(\rho^0 \to W^+W^-) \approx \Gamma(\rho^\pm \to ZW^\pm) \approx \frac{m_\rho g^2_{\rho\pi\pi}}{48\pi} = \frac{m_\rho^5}{192\pi g_\rho^2 v^4}$$

Suppressed decays to SM quarks and leptons

$$\mathrm{Br}(\rho^\pm \to e^\pm \nu) \approx 2\mathrm{Br}(\rho^0 \to e^+e^-) \approx \frac{16 m_W^4}{m_\rho^4}$$

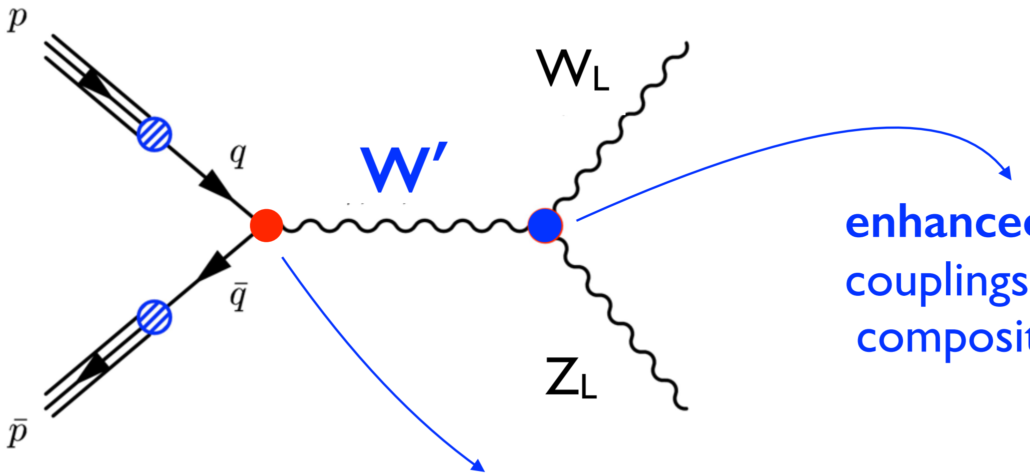
searches in WW, WZ channels in DY processes



H couplings vs searches for vector resonances

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

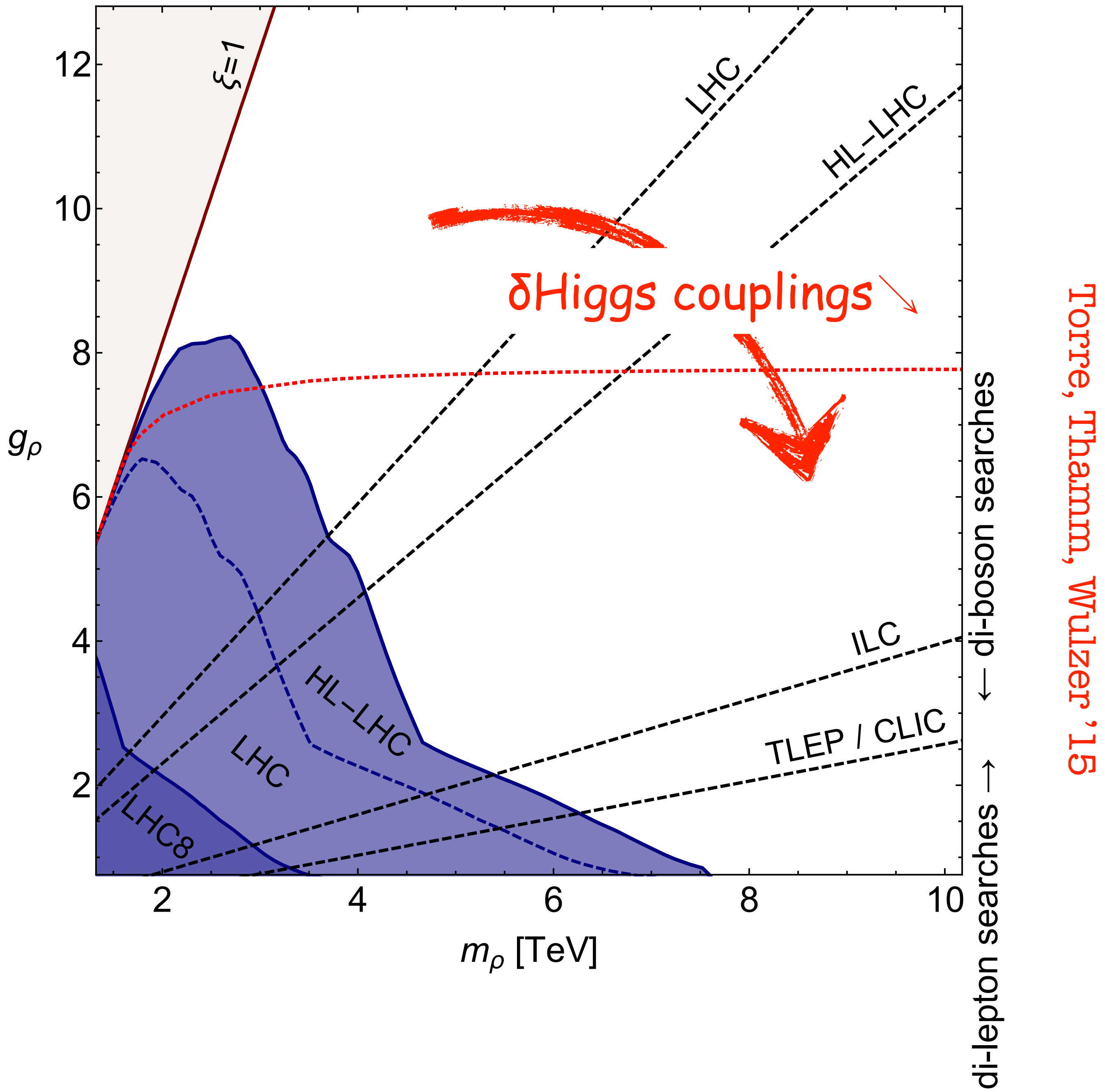
- Precision Higgs study: $\xi \equiv \frac{\delta g}{g} = \frac{v^2}{f^2}$
- Direct searches for resonances: $m_\rho \approx g_* f$



enhanced by large couplings from the composite sector

suppressed by large couplings from the composite sector

DY production xs of resonances decreases as $1/g_\rho^2$



Torre, Thamm, Wulzer '15

H couplings vs searches for vector resonances

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

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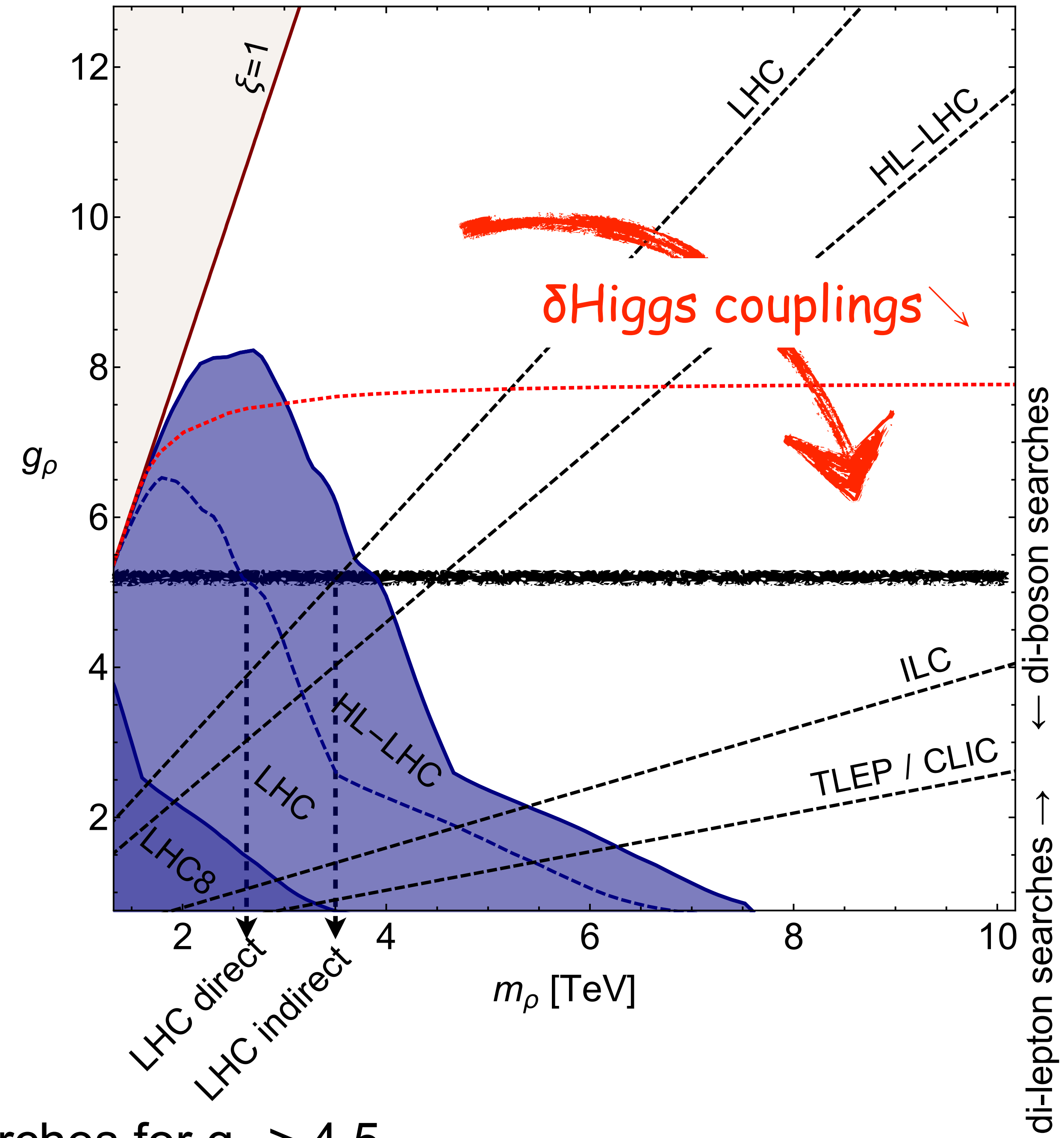
- Direct searches for resonances: $m_\rho \approx g_* f$

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

DY production xs of resonances decreases as $1/g_\rho^2$



Torre, Thamm, Wulzer '15

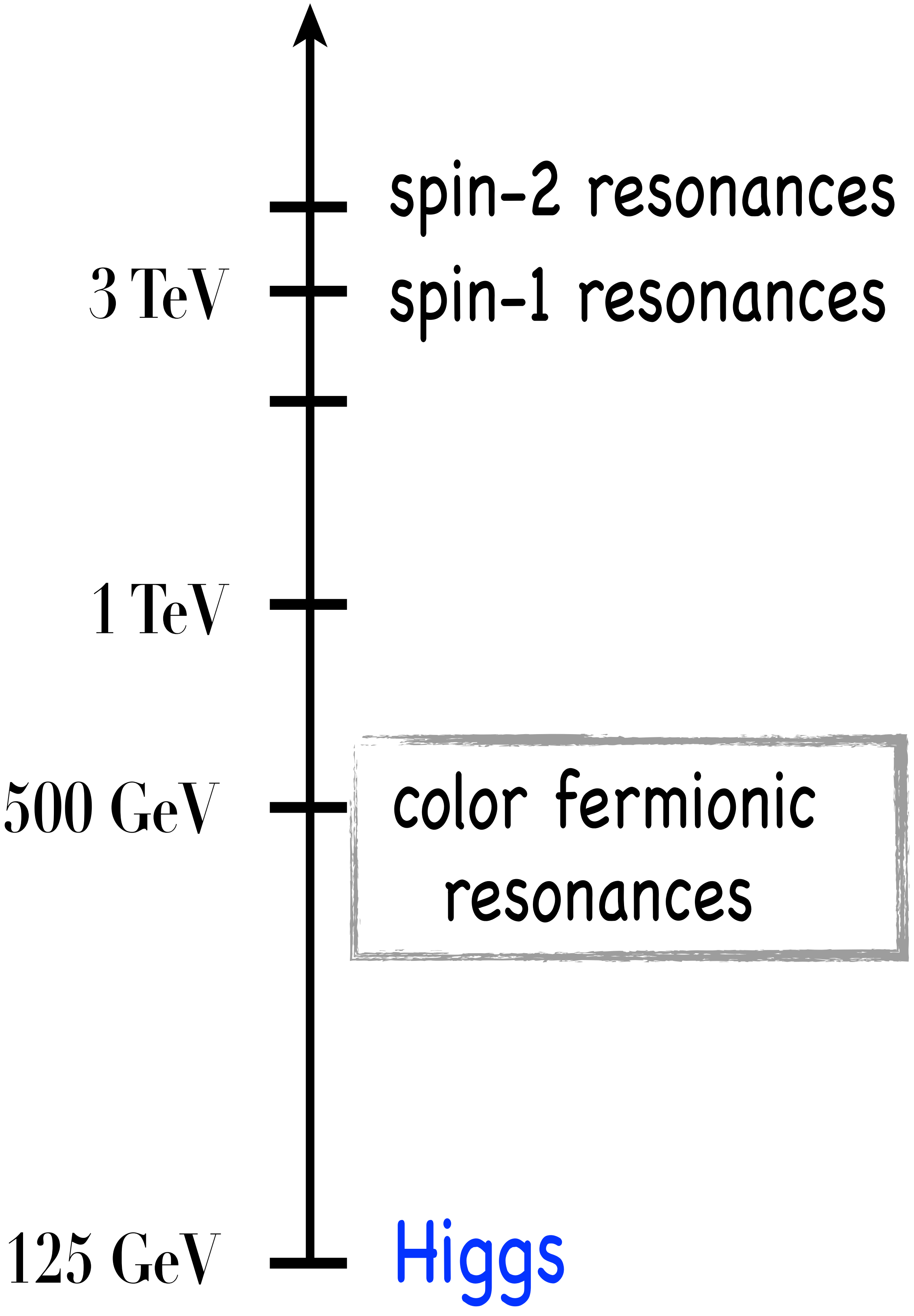
- **complementarity:**
  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling

e.g.

indirect searches at LHC over-perform direct searches for $g_\rho > 4.5$

indirect searches at ILC over-perform direct searches at HL-LHC for $g_\rho > 2$

The other resonances



spin-2 resonances

3 TeV

spin-1 resonances

1 TeV

500 GeV

color fermionic resonances

125 GeV

Higgs

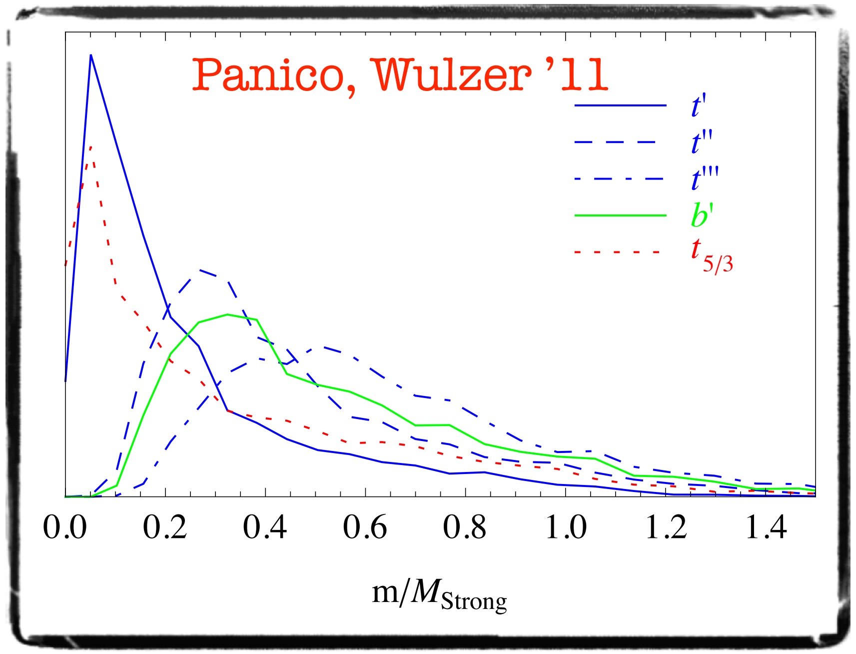
Top partners

SO(4)~SU(2)LxSU(2)R embedding

$$Q_L = \begin{pmatrix} t_L^{2/3} & t_L^{5/3} \\ b_L^{-1/3} & b_L^{2/3} \end{pmatrix} \equiv (2, \bar{2})_{2/3}$$

$$t_R \equiv (1,1)_{2/3}$$

$$b_R \equiv (1,1)_{-1/3}$$



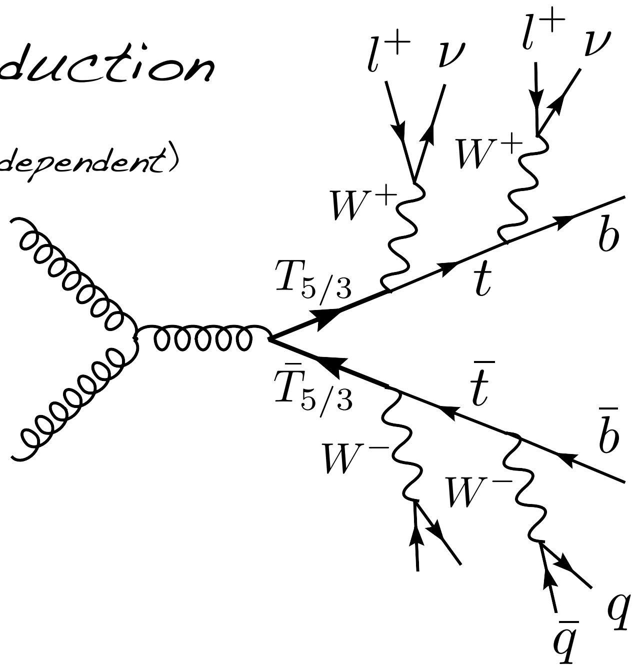
Searching for the top partners

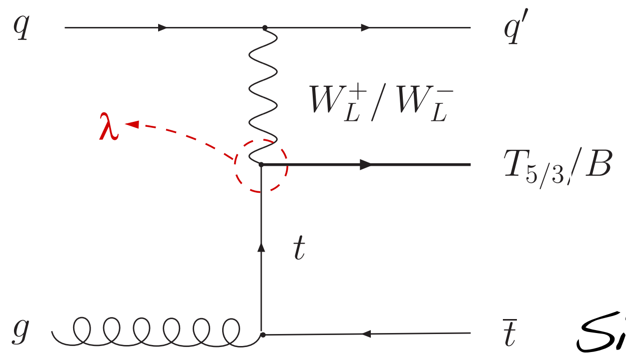
Search in same-sign dilepton events

- tt+jets is not a background [except for charge mis-ID and fake e-]
- the resonant (tW) invariant mass can be reconstructed

Pair production

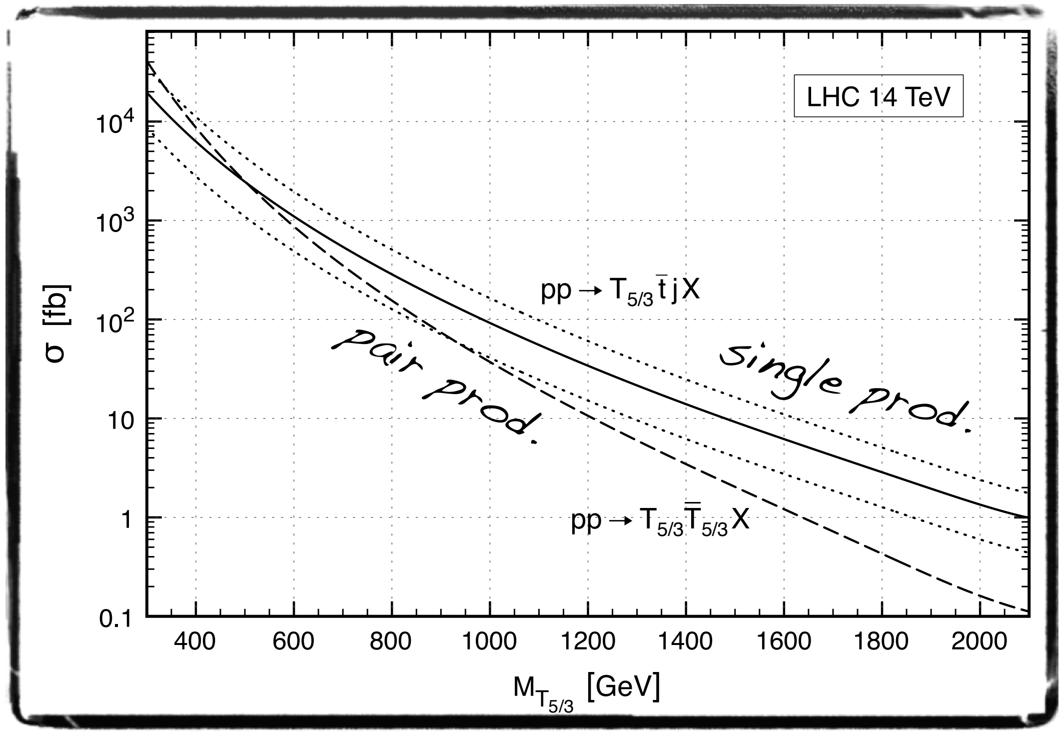
(model independent)





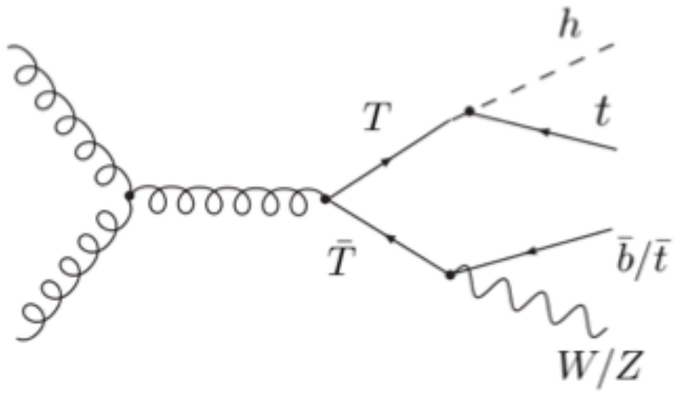
Single production

(model dependent)



[Contino, Servant '08]

Searching for the top partners



- ◉ $\ell^\pm$ + 4b final state Aguilar-Saavedra ’09

  $T\bar{T} \to HtW^-\bar{b} \to HW^+bW^-\bar{b}$ $\quad H \to b\bar{b}, WW \to \ell\nu q\bar{q}'$,

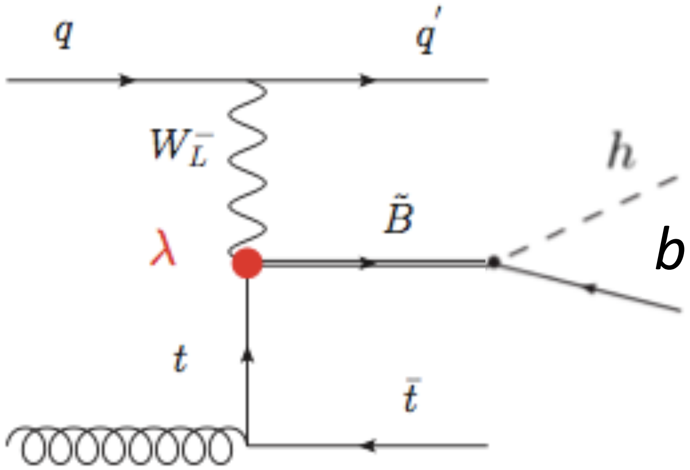
  $T\bar{T} \to HtV\bar{t} \to HW^+bVW^-\bar{b}$ $\quad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$

- ◉ $\ell^\pm$ + 6b final state Aguilar-Saavedra ’09

  $T\bar{T} \to HtH\bar{t} \to HW^+bHW^-\bar{b}$ $\quad H \to b\bar{b}, WW \to \ell\nu q\bar{q}'$

- ◉ $\gamma\gamma$ final state Azatov et al ’12

  $thbW/thtZ/thth,\ h \to \gamma\gamma$

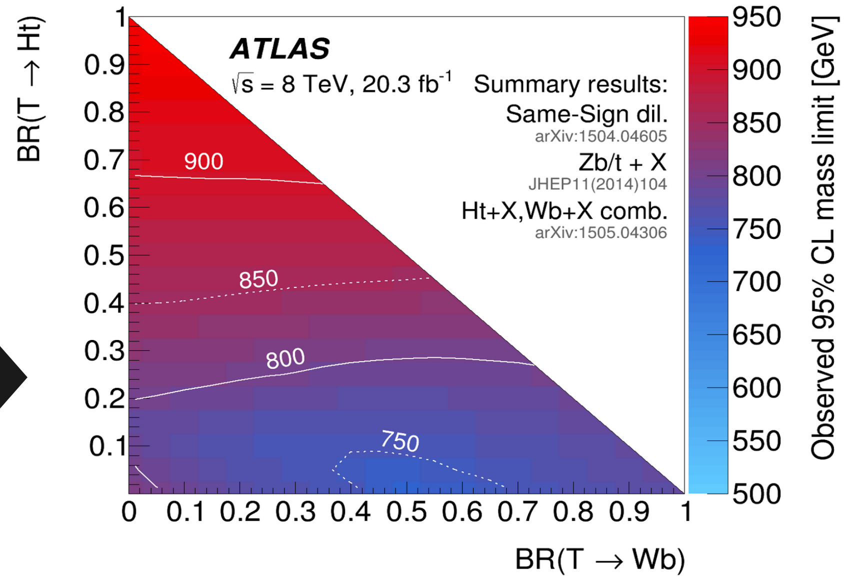


- ◉ $\ell^\pm$ + 4b final state Vignaroli ‘12

  $pp \to (\tilde{B} \to (h \to bb)b)t + X$

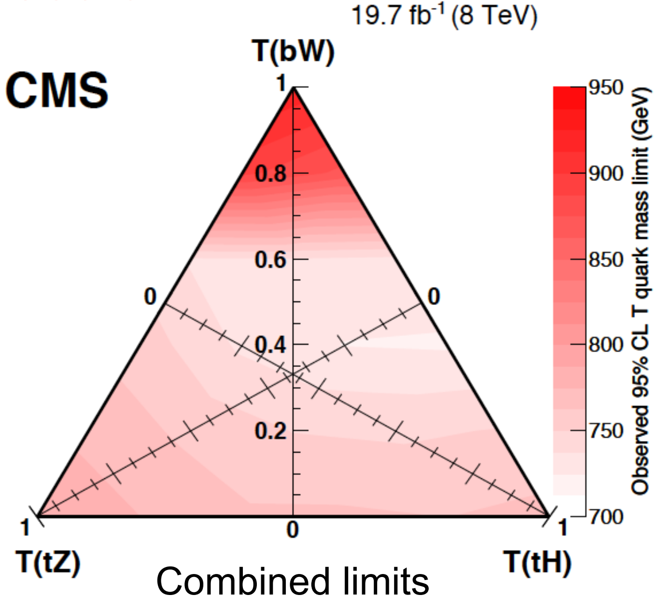
bounds on
charge 2/3 states
from pair production

1505.04306



(*) Not a combination. Only most restrictive individual bounds shown.

1509.04177

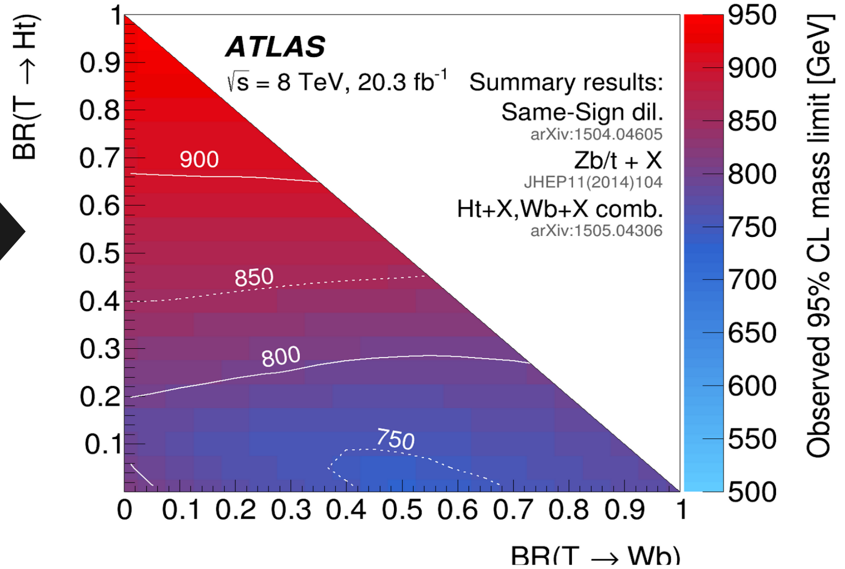


Combined limits

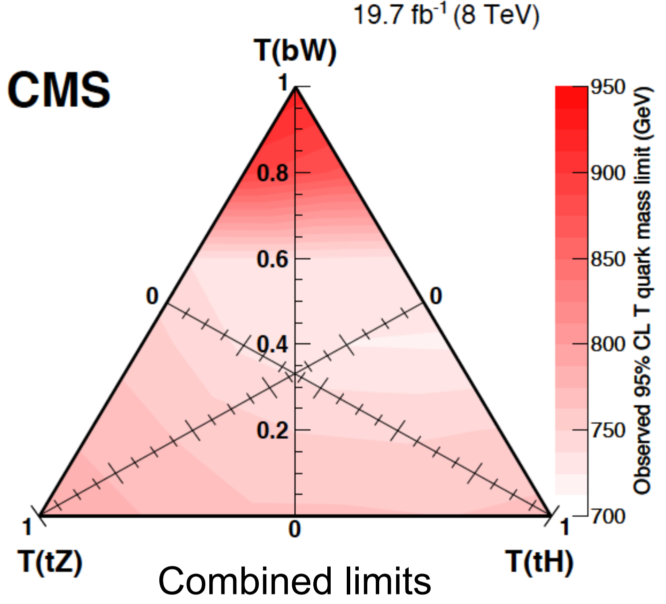
Searching for the top partners

bounds on
charge 2/3 states
from pair production

1505.04306

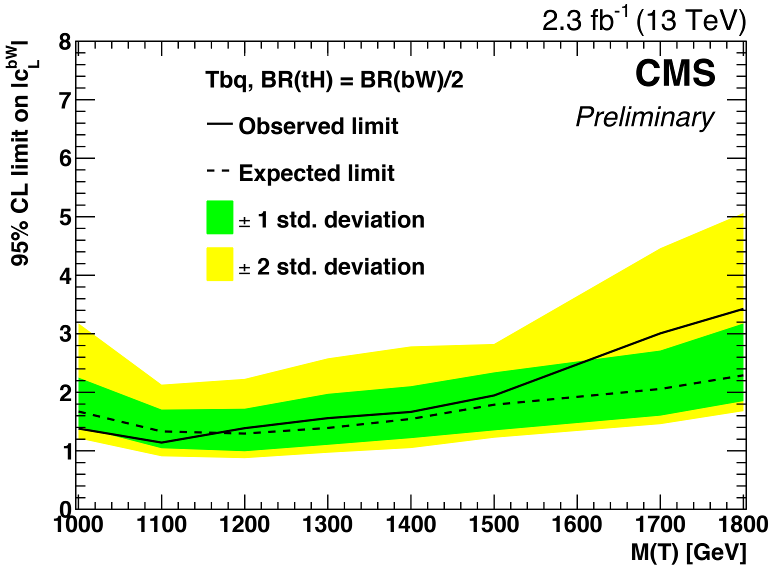


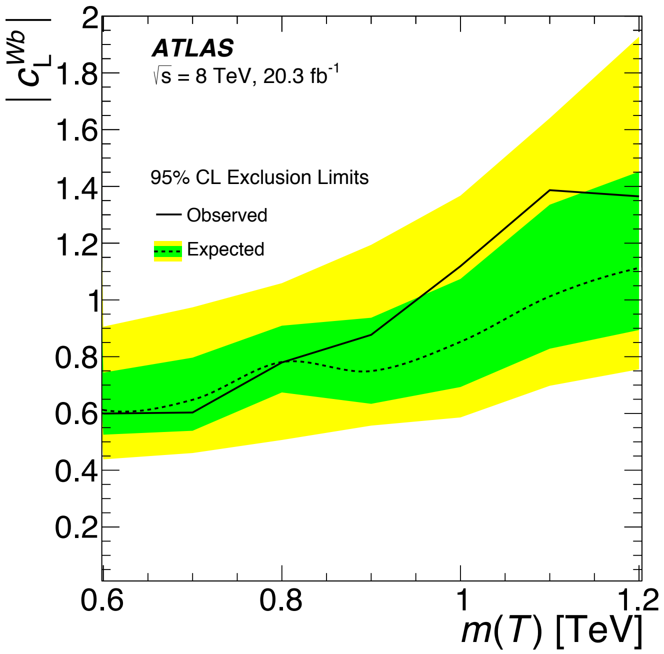
1509.04177



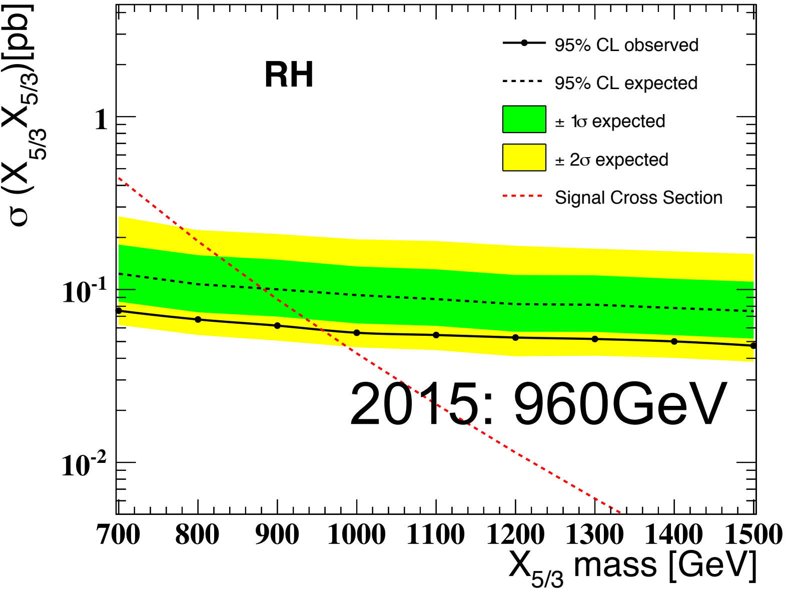
Combined limits

bounds on
charge 2/3 states
from single production

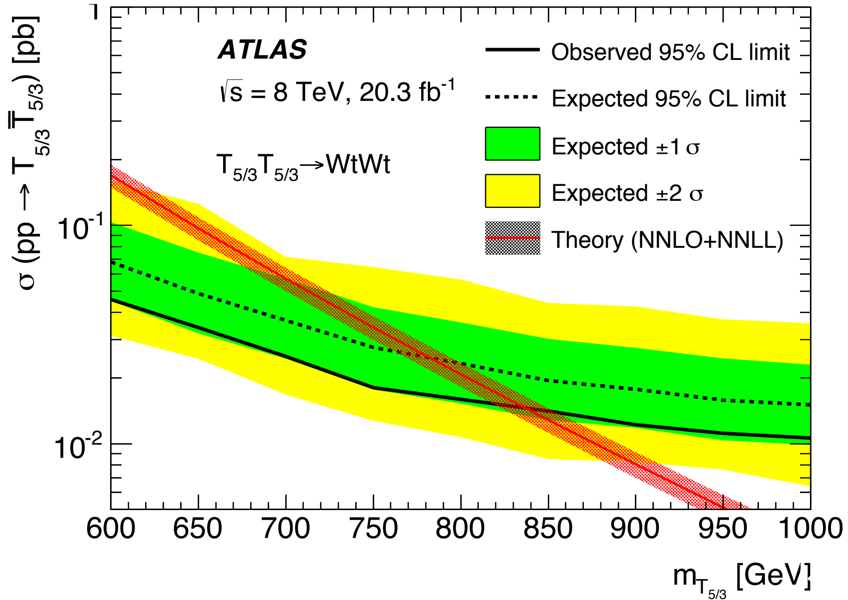




bounds on
charge 5/3 states
from single production



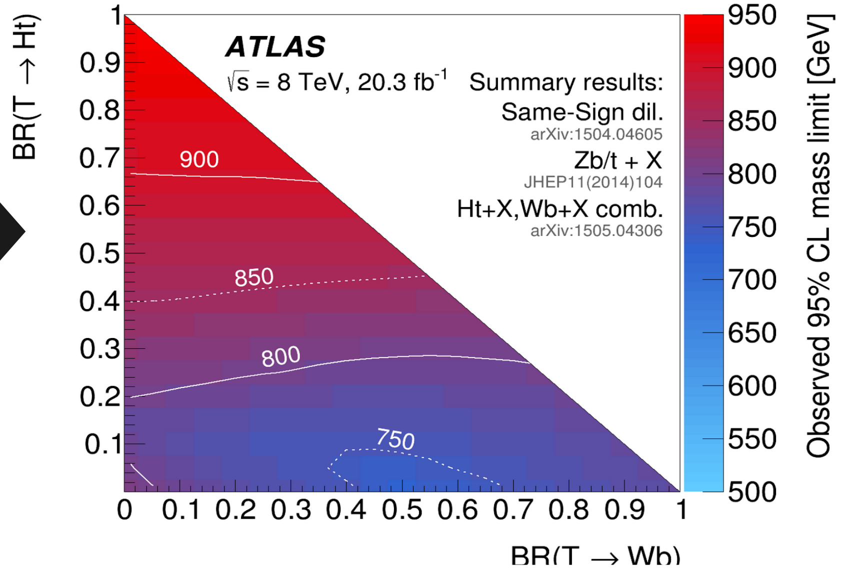
2015: 960GeV



Searching for the top partners

bounds on
charge 2/3 states
from pair production

1505.04306



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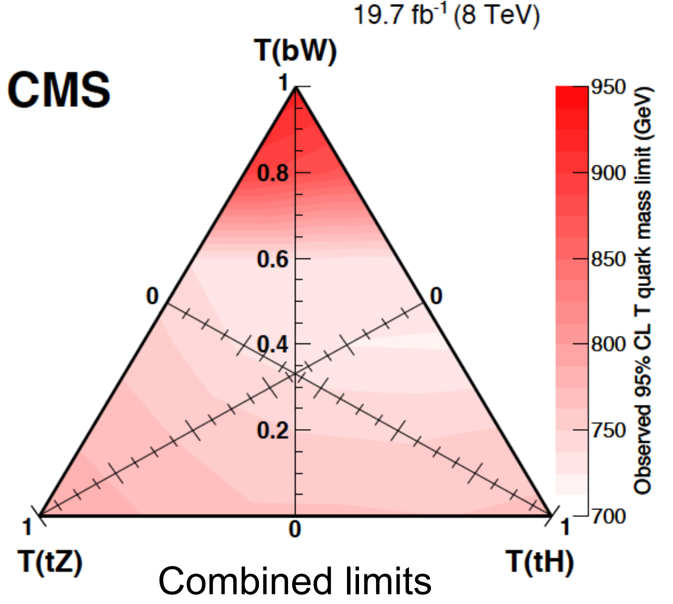
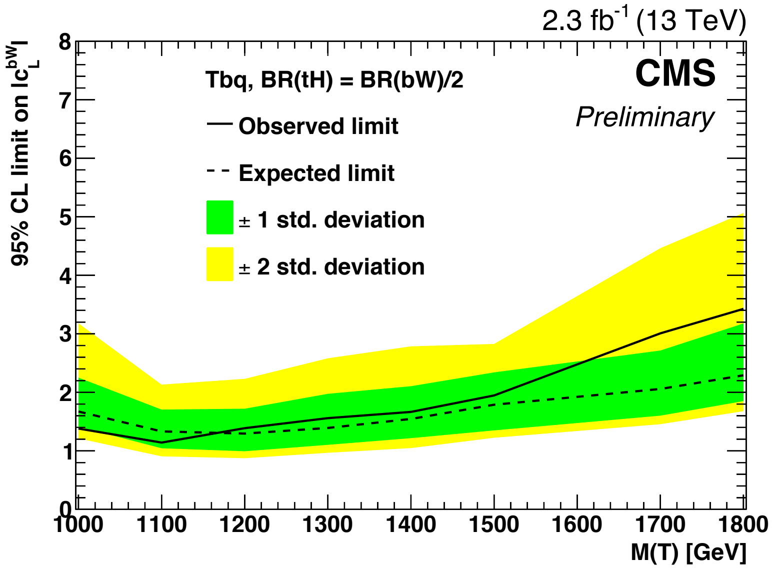
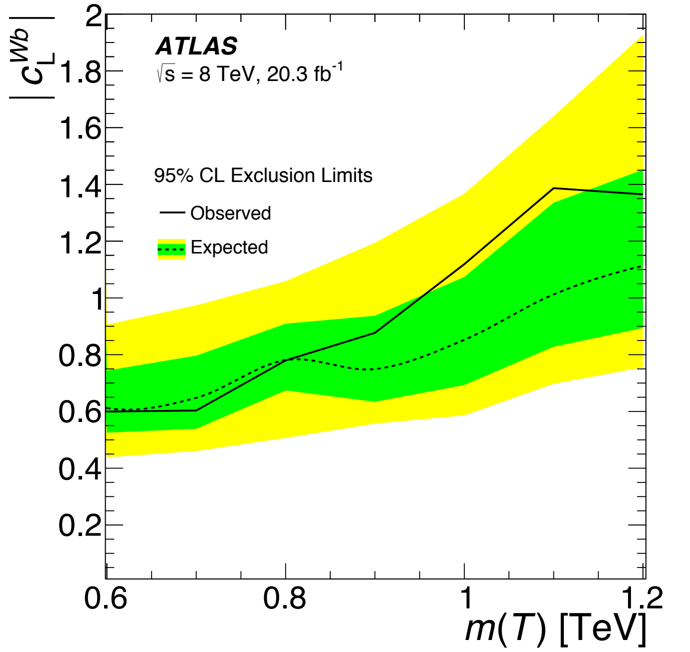
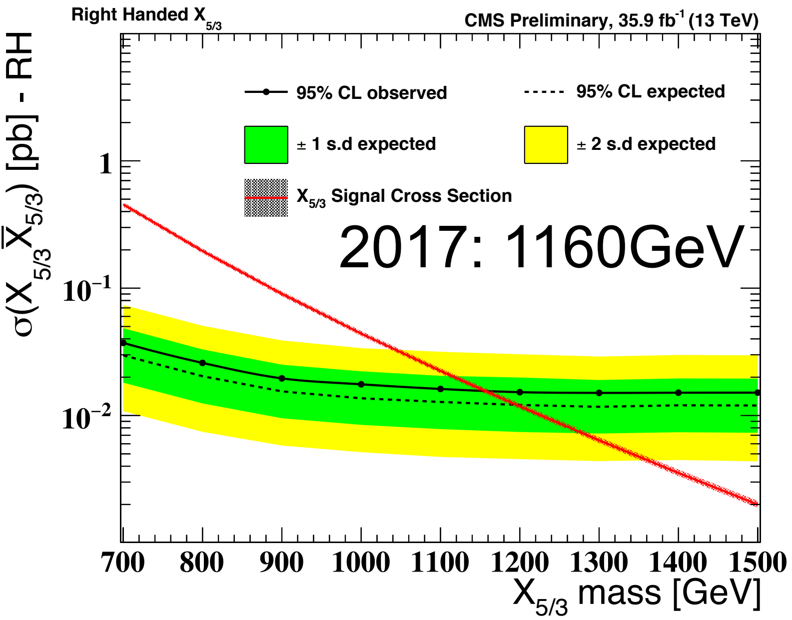


bounds on
charge 2/3 states
from single production

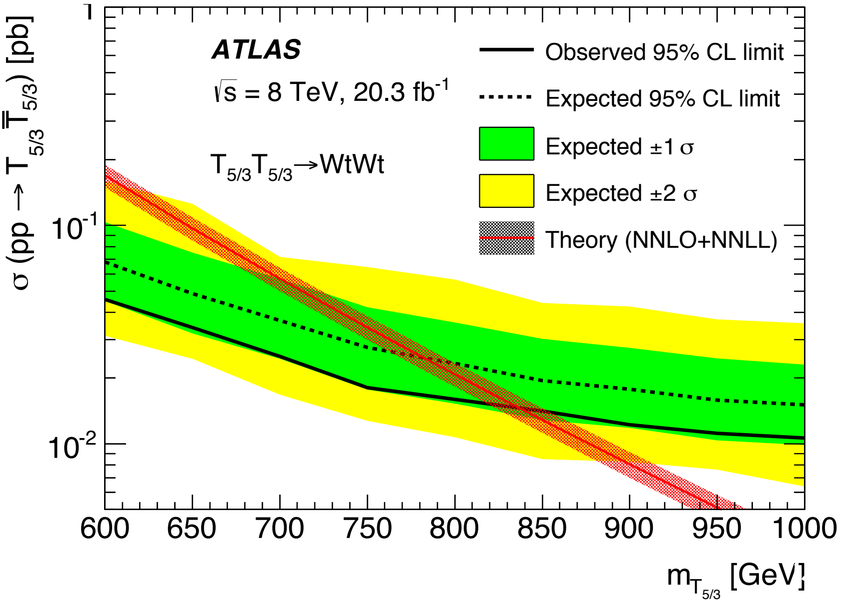




bounds on
charge 5/3 states
from single production



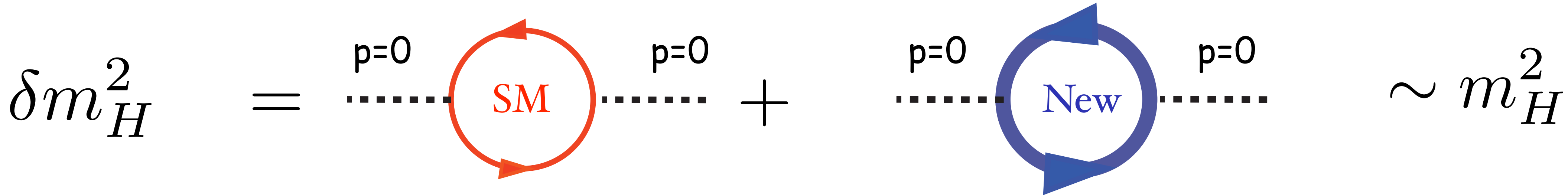
2017: 1160GeV



Neutral naturalness

Neutral Naturalness

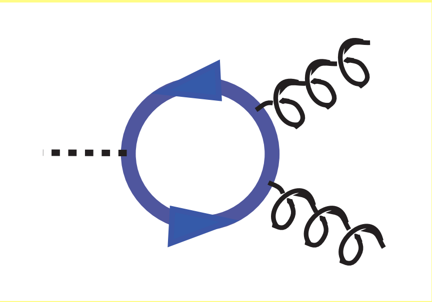
$$-(125\ \mathrm{GeV})^2\left(\frac{\Lambda}{600\ \mathrm{GeV}}\right)^2 \qquad\qquad \frac{g_*^2}{16\pi^2}\Lambda^2$$



$$\delta m_H^2 \quad = \quad [\mathrm{SM}] \quad + \quad [\mathrm{New}] \quad \sim m_H^2$$

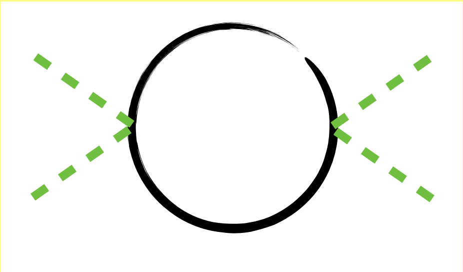
charged particles

neutral particles



$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2$$

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\mathrm{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$



$$\frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

$$BR(h\to ii) = BR_{\mathrm{SM}} \qquad \Gamma = \left(1-\frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\mathrm{SM}}$$

$$\delta\sigma_{Zh} = -\frac{g_\star^2}{8\pi^2}\frac{v^2}{m_\star^2}$$

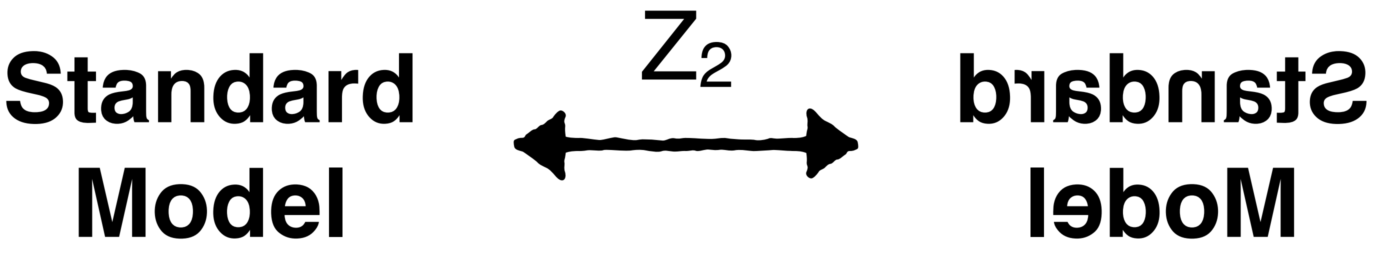
useful to be able to measure ZH & Γ_H

Colorful naturalness probed @ LHC

Neutral naturalness (invisible?) @ LHC

Twin Higgs

[Chacko, Goh, Harnik ‘05]



Radiative corrections to the Higgs mass are SU(4) symmetric thanks to Z_2:

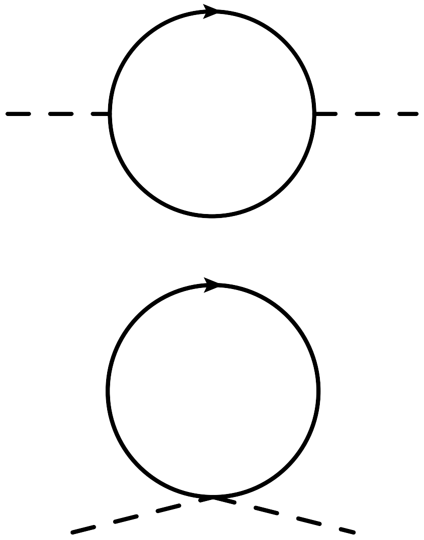
$$V(H) \supset \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + \frac{9}{4}g^2 + \ldots\right)\left(|H_A|^2 + |H_B|^2\right)$$

(N. Craig @ Paris’18)

Higgs is a PNGB of ~SU(4), but partner states neutral under SM.

$$\mathcal{L} \supset -y_t H_A Q_3^A \bar{u}_3^A - y_t H_B Q_3^B \bar{u}_3^B$$

$$H_A \downarrow \; h + \ldots \qquad H_B \downarrow \; f - \frac{h^2}{2f} + \ldots$$



Neutral Naturalness: new signatures

" Looking and not finding is different than not looking "

giving the null search results, the top partners should either be

- **heavy** (harder to produce because of phase space)
- **stealthy** (easy to produce but hard to distinguish from background, e.g. $m_{stop} \sim m_{top}$)
- **colorless** (hard to produce, unusual decay)

need to go beyond traditional searches

	Scalar Top Partner	Fermion Top Partner
All SM Charges	SUSY '70	pNGB/RS '00
EW Charges	Folded SUSY '05	Quirky Little Higgs '02
No SM Charges	Hyperbolic Higgs '18	Twin Higgs '05

only little corner of theory/model space has been explored so far

require **hidden QCD** with a higher confining scale:

⇒ 1) hidden glueball (0^{++}) that can mix with Higgs
$h \to G_0 G_0 \to 4l$ with displaced vertices

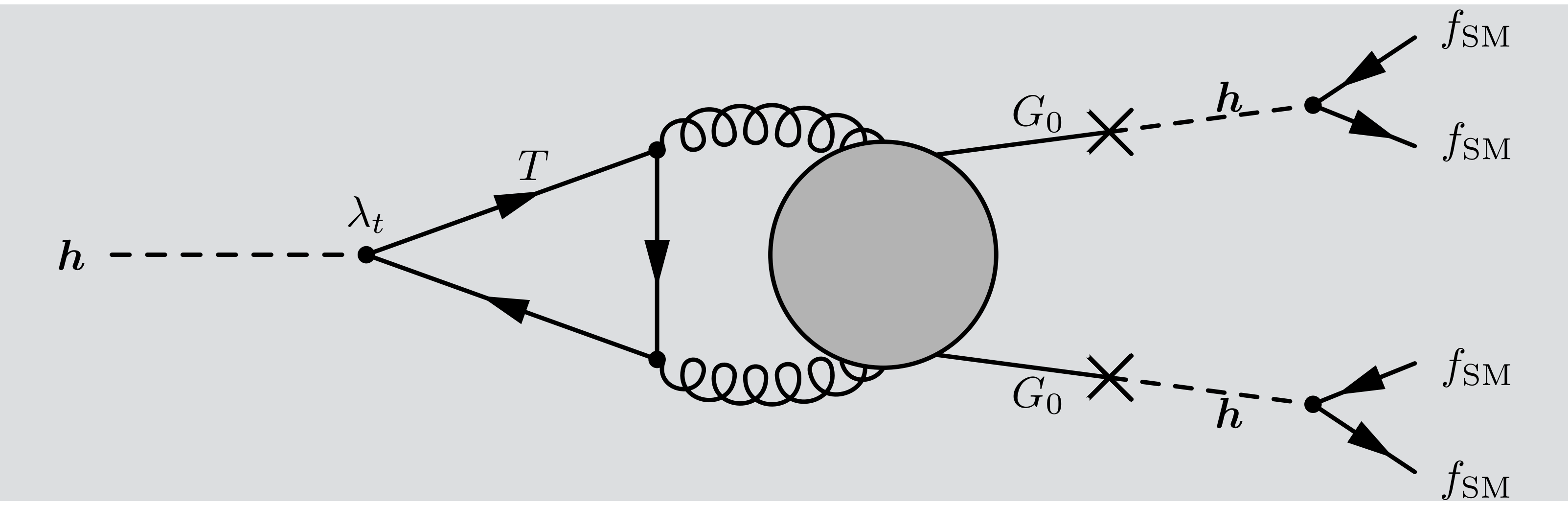
Curtin, Verhaaren '1

⇒ 2) emerging jets

Schwaller, Stolarski, Weiler '15

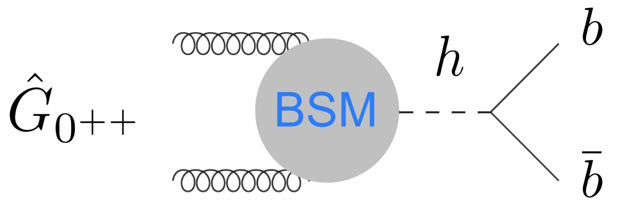
(C. Verhaaren@NKPI'16)

Neutral Naturalness

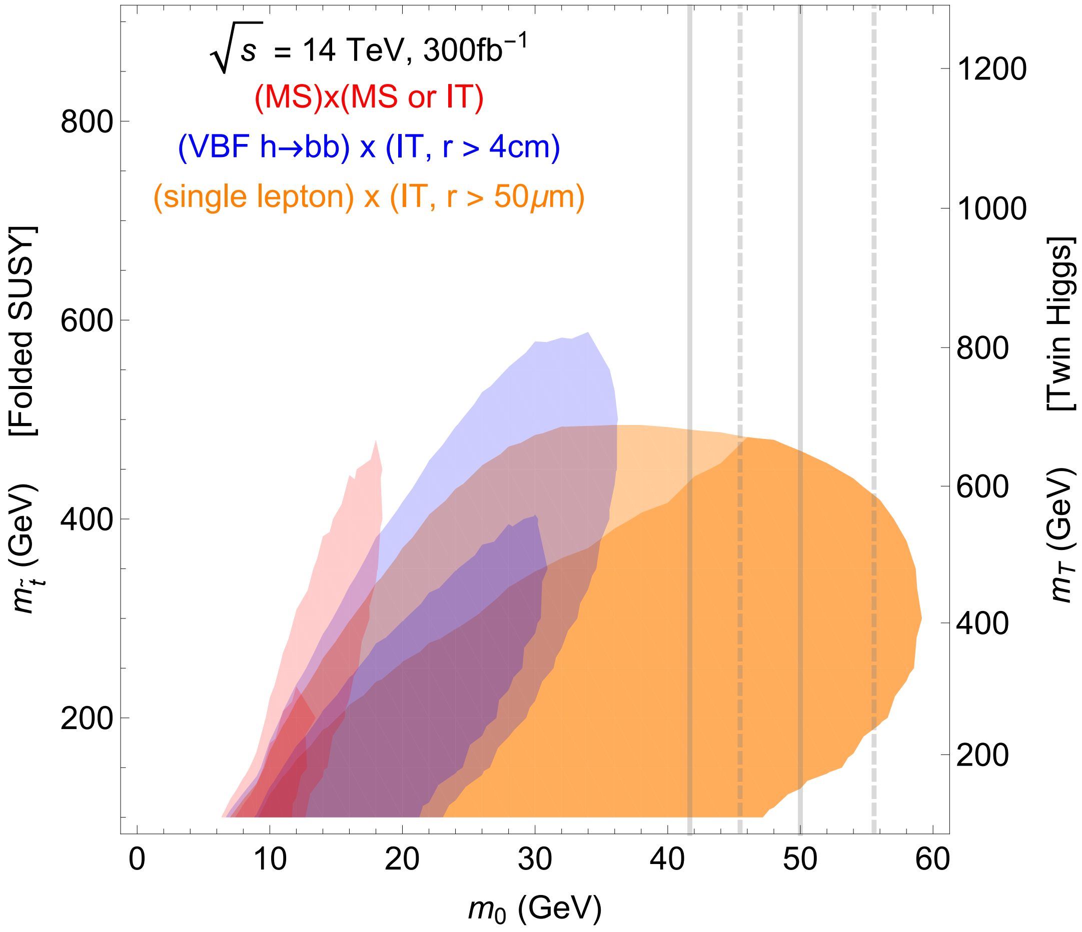


top parters are EW charged: m>100GeV (LEP)
Lightest hidden states are glueballs of QCD'
that can mix with the Higgs boson

Exotic Higgs decays with displaced vertices



Curtin, Verhaaren '15



Higgs couples to QCD' bound states

Produce in rare Higgs decays (BR~10^{-3}-10^{-4})

$$gg \to h \to 0^{++} + 0^{++} + \ldots$$

Decay back to SM via Higgs

$$0^{++} \to h^* \to f\bar{f}$$

Long-lived, length scale ~ LHC detectors

Mathusla to detect Long Lived Particles?
Precise timing within ATLAS/CMS detectors?

Extra dimensions

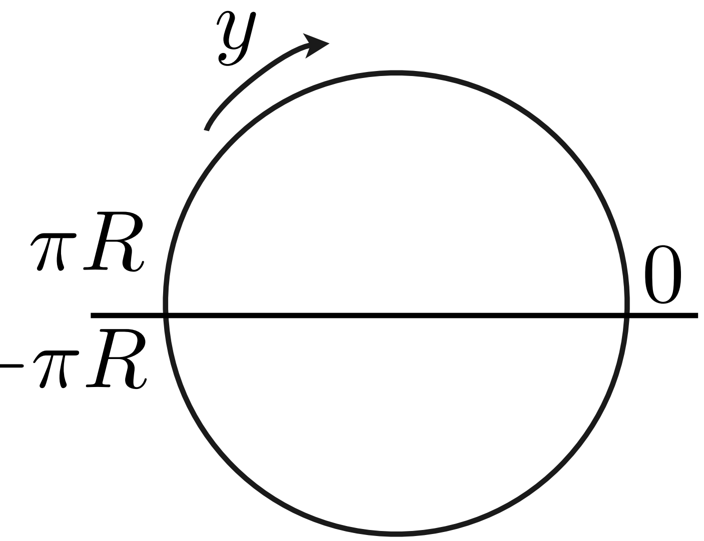
Extra dimensions

mass from motion in extra dimensions

$$m_D^2 = E^2 - \vec{p}_3{}^2 - \vec{p}_\perp{}^2 \quad \Rightarrow \quad m_D^2 + \vec{p}_\perp{}^2 = E^2 - \vec{p}_3{}^2 = m_4^2$$

momentum along extra dimensions ~ 4D mass

— Compactification on a Circle —



circle: $y \sim y + 2\pi R$

$$\phi(y + 2\pi R) = \phi(y)$$

$$\phi(x,y) = \sum_n \frac{1}{\sqrt{2^{\delta_{n0}}\pi R}} \left(\boxed{\cos\left(\frac{ny}{R}\right)} \phi_n^+(x) + \boxed{\sin\left(\frac{ny}{R}\right)} \phi_n^-(x) \right)$$

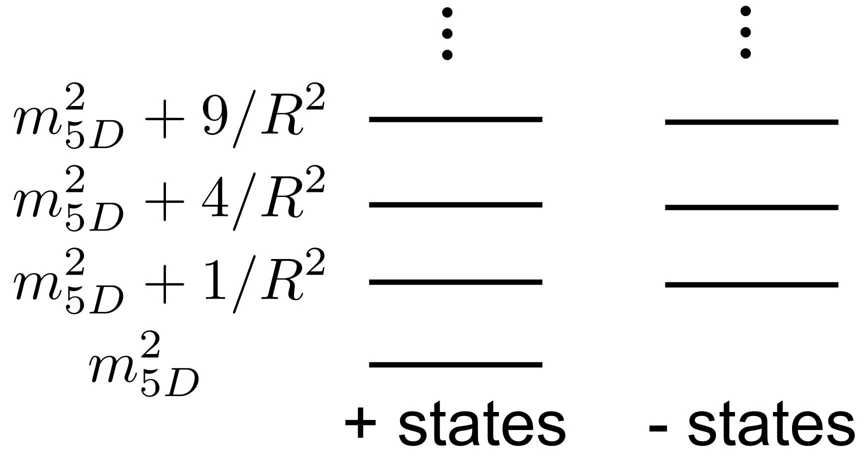
5D field

wavefunction = localization of KK mode along the xdim

4D Kaluza-Klein modes

$$m_n = p_y^n = \frac{n}{R}$$

Extra dimensions



5D field=infinite tower of massive 4D fields

depending of the energy available, you can probe
more and more of these KK modes

5D General relativity = 4D GR + U(1) gauge symmetry

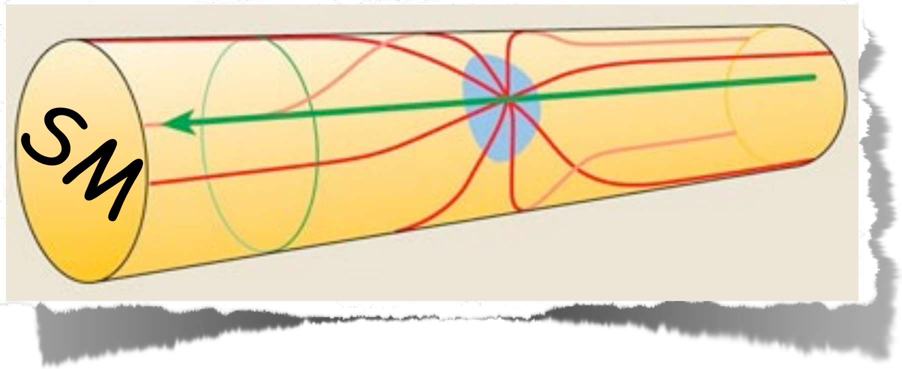
gauge symmetries are emerging from
gravitational interactions in extra dimensions?
beautiful idea of Kaluza & Klein
but
quantization? non-abelian structure? different gauge couplings?
no successful realization till now

Extra Dimensions for TeV/LHC Physics

1) Hierarchy problem

- large (mm size) flat extra dimensions (ADD)

  gravity is diluted into space while we are localized on a brane



$$\int d^{4+n}x\,\sqrt{|g_{4+n}|}M_\star^{2+n}\mathcal{R} = \int d^4x\,\sqrt{|g_4|}M_{Pl}^2\mathcal{R}$$

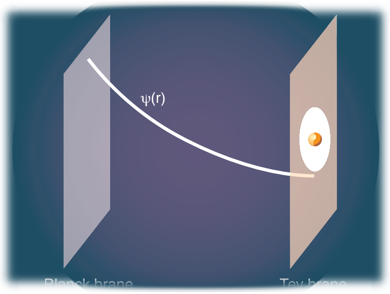
$$M_{Pl}^2 = V_n M_\star^{2+n}$$

$M_{Pl} = 10^{19}$ GeV $M_* = 1$ TeV

$V_2 = (2\,\mathrm{mm})^2 = (10^{-4}\,\mathrm{eV})^{-2}$

- warped/curved extra dimensions (RS)

  gravity is localized away from SM matter and we feel only the tail of the graviton



graviton wavefunction is exponentially localized away from SM brane

$$v = M_\star e^{-\pi R M_\star}$$

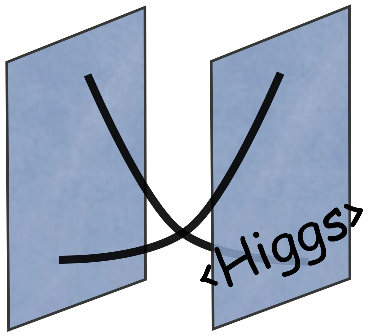
$M_* = 10^{19}$ GeV $v = 250$ GeV

$R \sim 11/M_*$

2) Fermion mass hierarchy & flavour structure

- fermion profiles:

  the bigger overlap with Higgs vev, the bigger the mass



3) EW symmetry breaking by boundary conditions

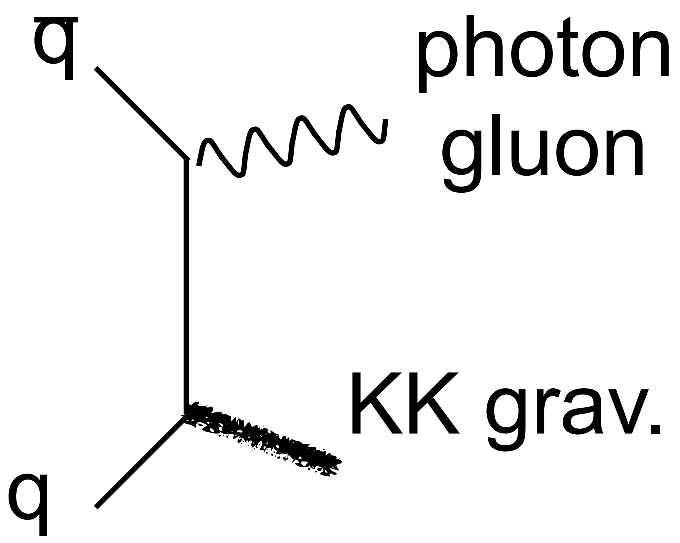
- orbifold breaking, Higgsless

Large volume xdim phenomenology

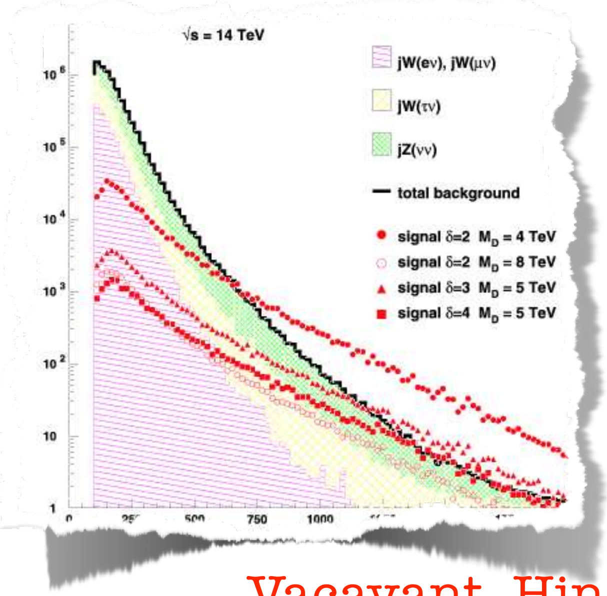
eV splitting between graviton KK modes

$1/M_{Pl}$ couplings of graviton KK modes to SM

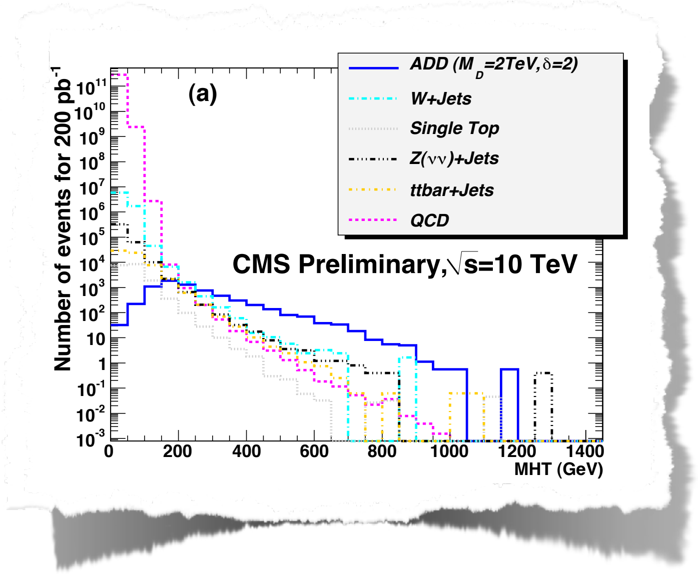
- Graviton production in colliders



monojet+$\not{E}_T$

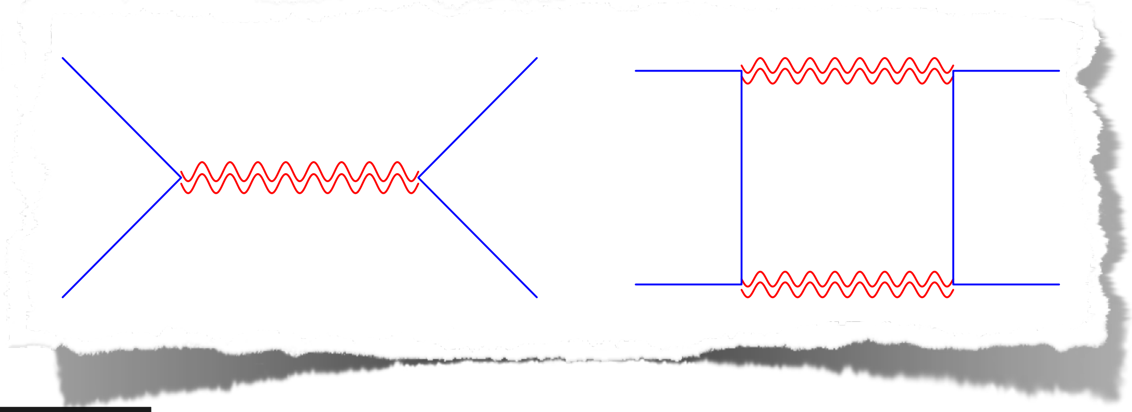


Vacavant, Hinchliffe '01



CMS PAS EXO 09-013

- Virtual graviton exchange

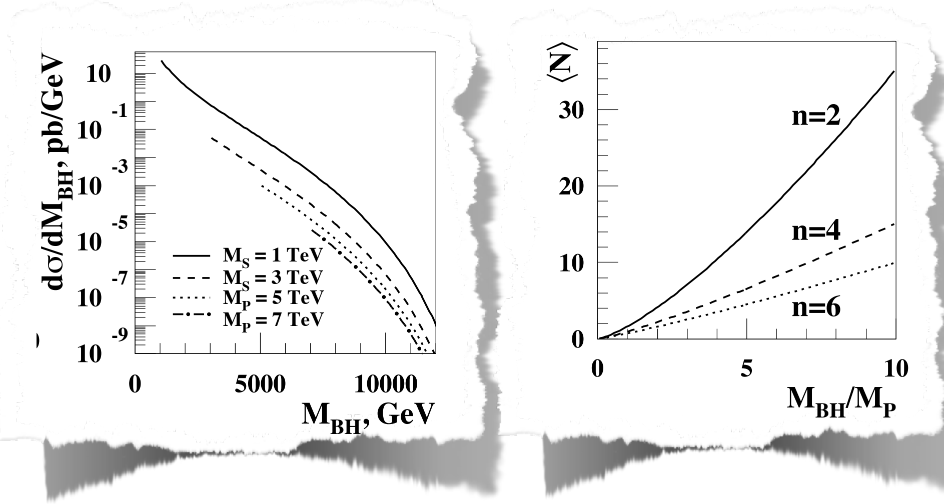


Large volume xdim phenomenology

- Supernova cooling: $M_* > 100$ TeV (for 2 xdim)

- Black Hole production

  classical production (can be very large $10^{3\text{-}4}$ pb),
  Hawking thermal decay, i.e., large decay multiplicity



Dimopoulos, Landsberg, ’01

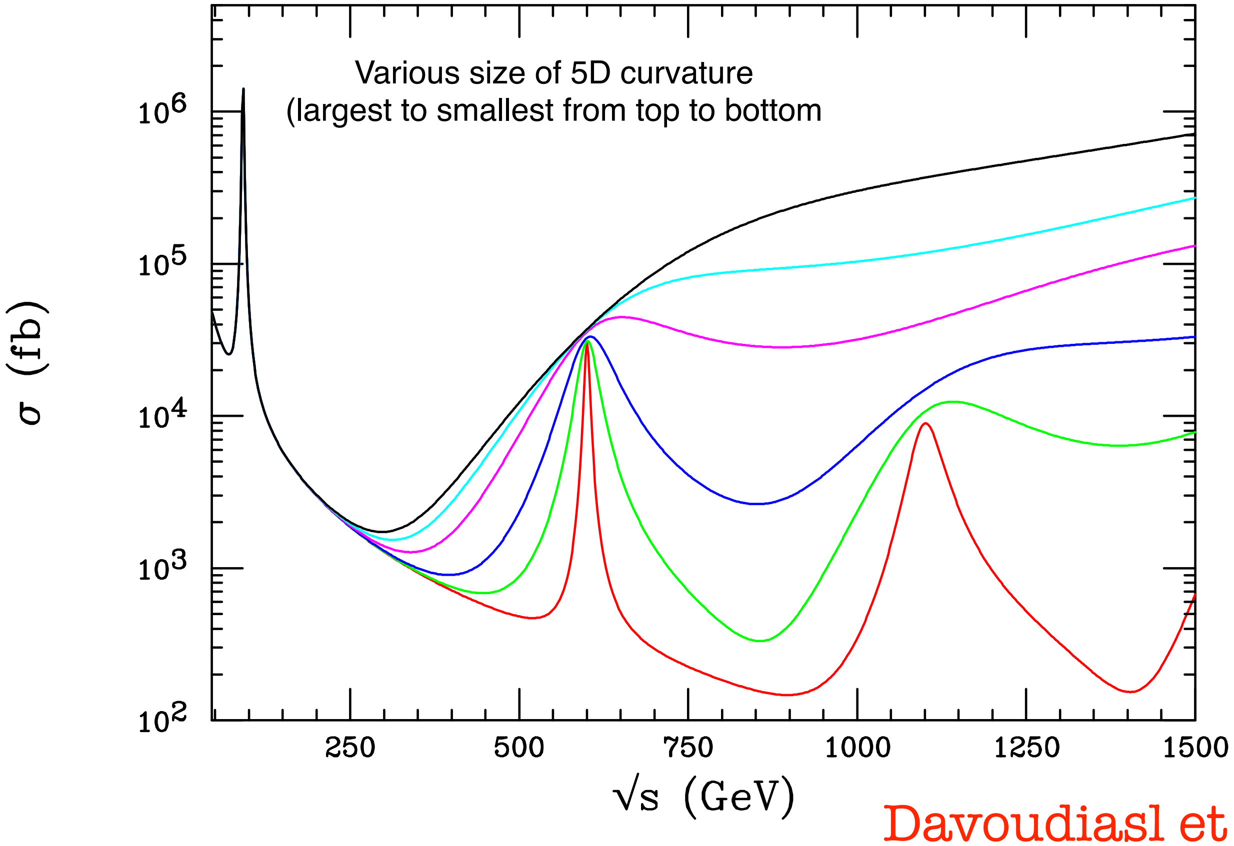
- String resonances production

Curved xdim phenomenology

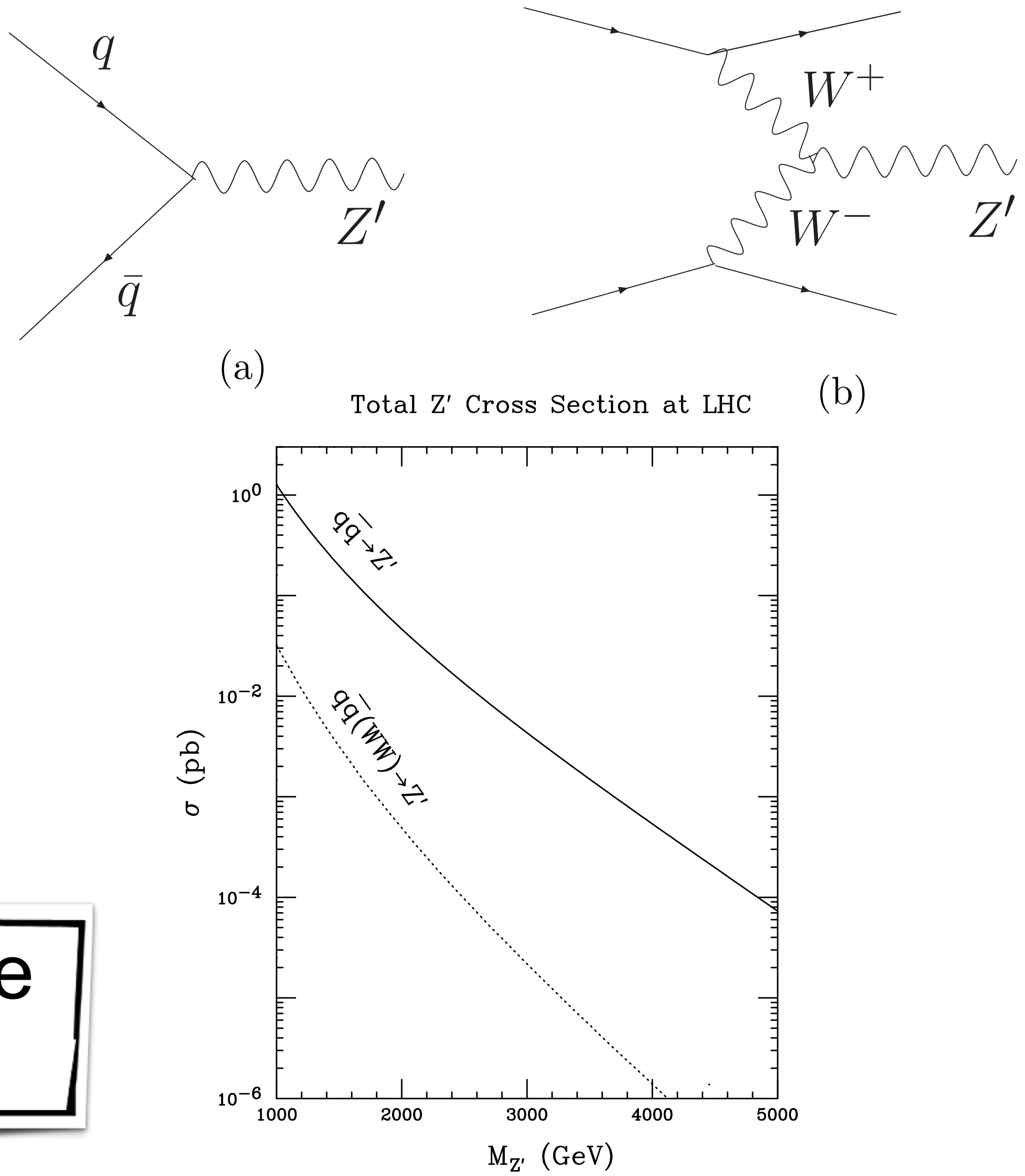
TeV splitting between gauge KK modes

$O(g_{SM})$ couplings of gauge KK modes to SM

$e^+e^- \to \mu^+\mu^-$



Davoudiasl et al ’99



Agashe et al ’07

current LHC bounds on KK resonance
O(few) TeV