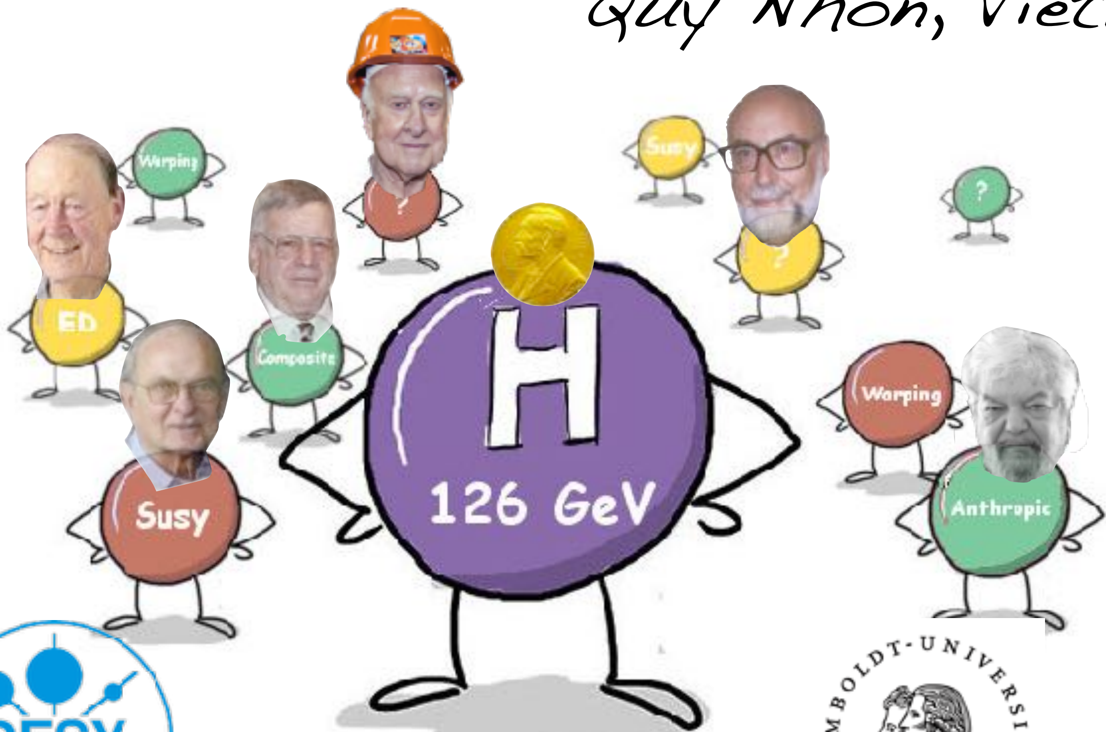
Higgs and BSM Physics

AEPSHEP 2018

Quy Nhon, Vietnam



Lecture 3/4

Christophe Grojean

DESY (Hamburg)

Humboldt University (Berlin)

(christophe.grojean@desy.de)

Outline

Lecture #1

- From Fermi theory to the Standard Model
- Chirality, fermion masses, spontaneous symmetry breaking
- Custodial symmetry
- Gauge boson masses, unitarity and the Higgs boson

Lecture #2

- 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: AMO, EDMs, nñ, GW, PBH

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:

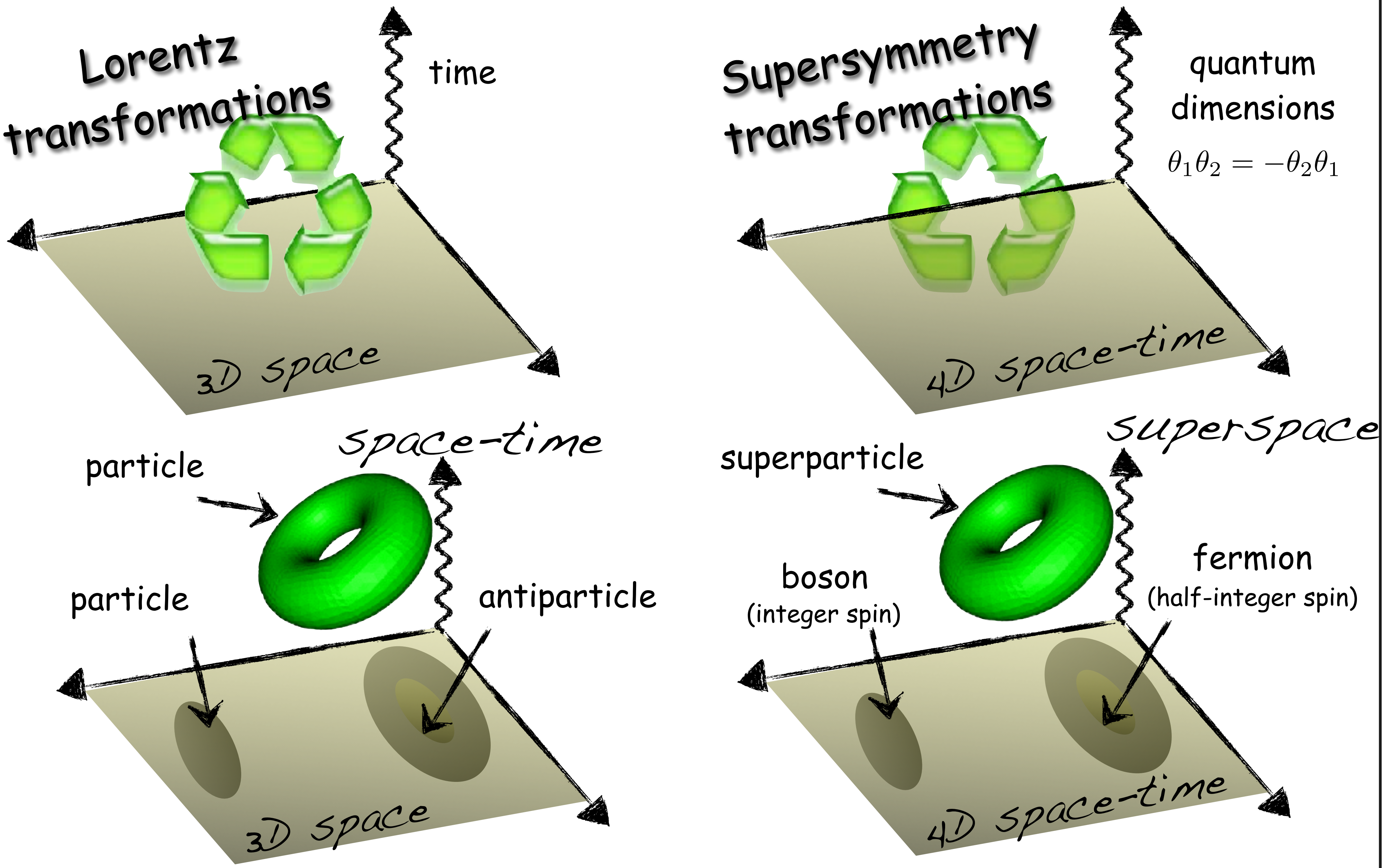
$$[\delta_{\epsilon_1}, \delta_{\epsilon_2}] \begin{pmatrix} \phi \\ \psi \end{pmatrix} = -i\left(\bar{\epsilon_2}\gamma^\mu \epsilon_1\right)\partial_\mu \begin{pmatrix} \phi \\ \psi \end{pmatrix}$$

susy² = 4D translation

How to introduce interactions?

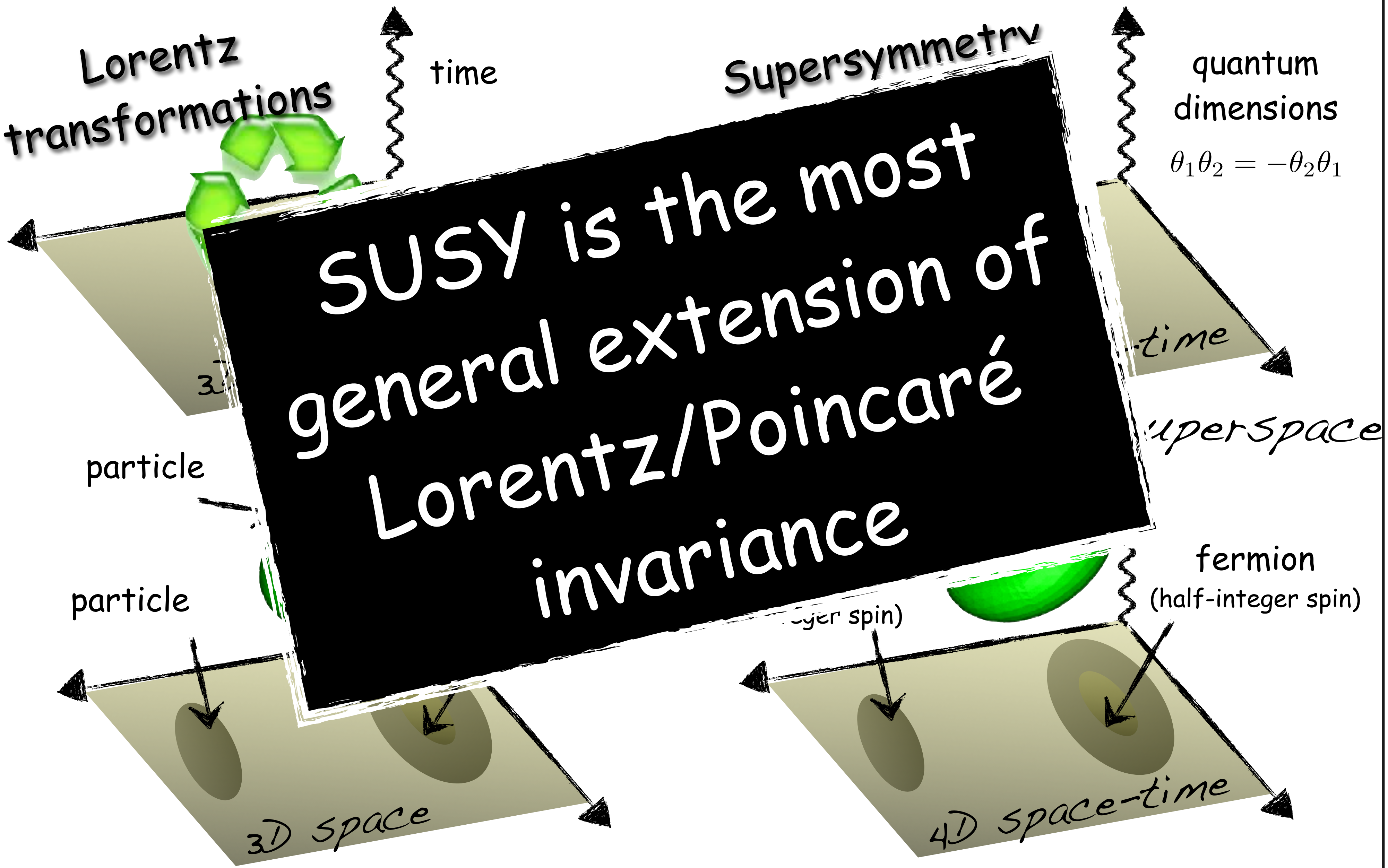
SUSY: a quantum space-time

(G. Giudice HCPSS'09)



SUSY: a quantum space-time

(G. Giudice HCPSS'09)



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 fields: $v_\mu(x)$ — 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
  ⇒

	$F = \phi(x)$	$+ \theta\psi(x)$	$+ \theta\theta f(x)$
off-shell dof	2	4	2
on-shell dof	2	2	0

chiral fermion!

- **Vector superfield** $F = F^\dagger$ ⇒

	$F = \theta\sigma^\mu\bar{\theta}v_\mu(x)$	$+ i\theta\theta\bar{\theta}\bar{\lambda}(x) - i\bar{\theta}\bar{\theta}\theta\lambda(x)$	$+ \frac{1}{2}\theta\theta\bar{\theta}\bar{\theta}d(x)$
off-shell dof	3	4	1
on-shell dof	2	2	0

massless gauge field

Superspace Integrals and SUSY

Any polynomial of superfields is a superfield itself

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

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

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

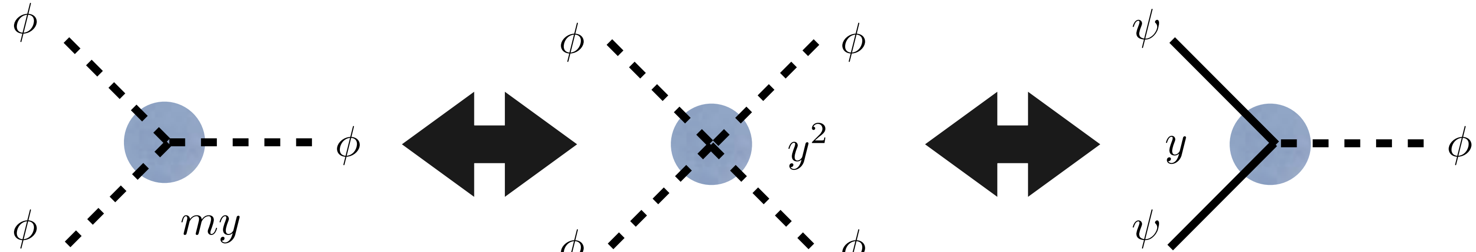
$$\mathcal{L} = \mathcal{L}_{\rm kin} - \left|\frac{\partial W}{\partial \phi}\right|^2_{|\theta=0} - \frac{1}{2}\frac{\partial^2 W}{\partial \phi^2}_{|\theta=0} \psi\psi + h.c.$$

is invariant under susy

example: susy Yukawa interaction

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

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

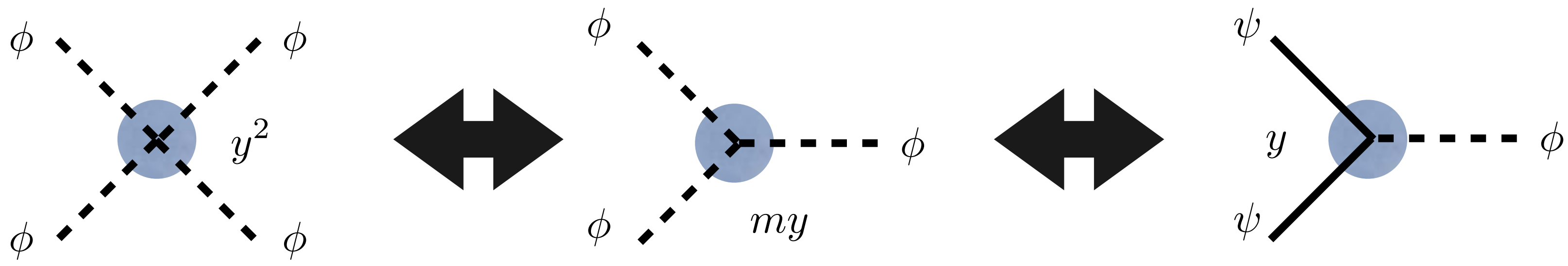


will be modified by soft susy breaking

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

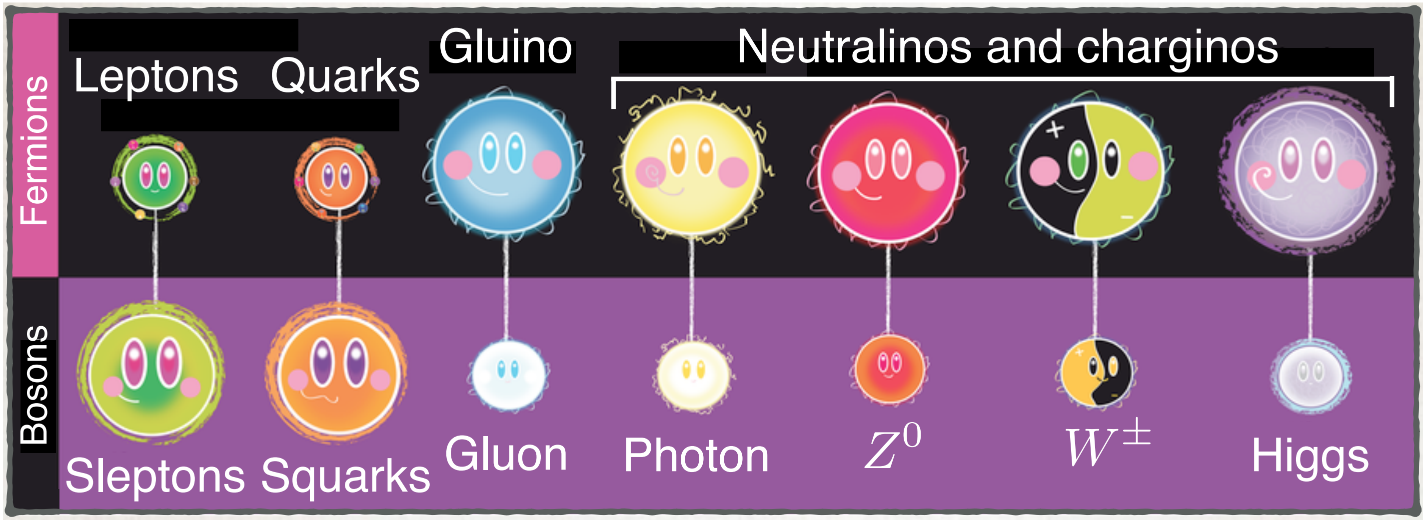
SUSY predictions

many new particles
many new interactions

MSSM - Matter Content

particles				Sparticles			
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	$\tilde{H}_1$ $\tilde{H}_2$		
	$W^{\pm}_\mu, W^3_\mu$			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)



MSSM Superpotential

the most general ("renormalizable") superpotential of the MSSM

$$W = H_u QD + H_u QU + H_d LE + \mu H_u H_d + LQD + UDD + LLE + \mu_L L H_u$$

$\not{B}, \not{L}$

lead to fast p decay

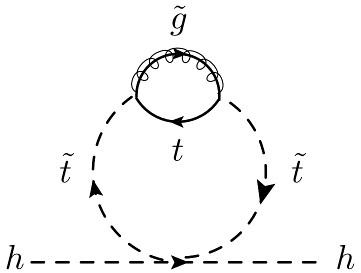
R parity forbids all the dangerous terms

superfields		R-parity		fields
$Q, D, U, L : -1$	⇒	doesn't commute with susy	⇒	$\phi_{\mathrm{SM}} : +1$
$H_u, H_d : +1$		$\theta : -1$		$\phi_{\mathrm{superpartner}} : -1$

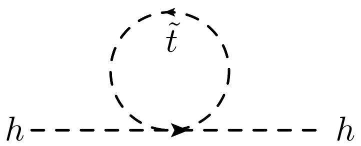
nice consequences:

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

Probing natural SUSY

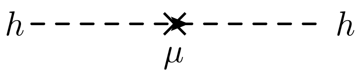


$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi} m_{gluino}^2 \left(\log\frac{\Lambda}{m_{gluino}}\right)^2$$



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

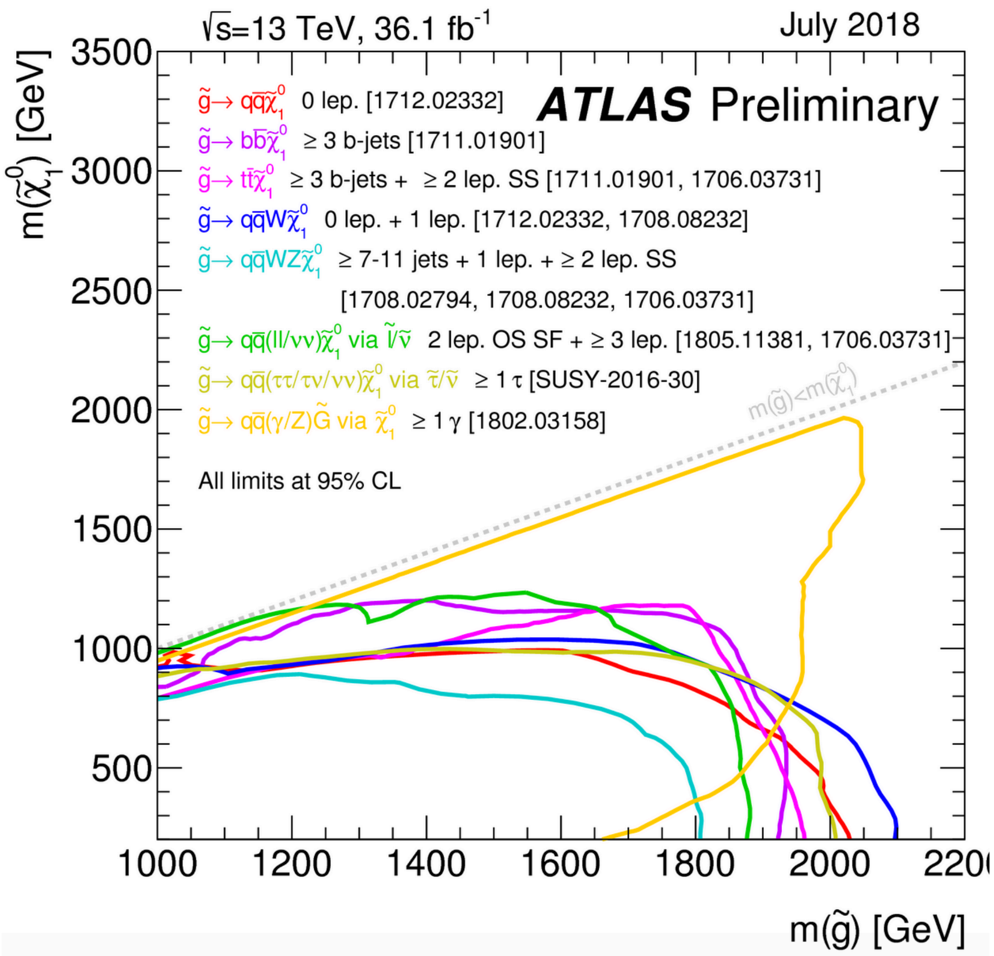
} **light stops, light gluinos!**
well tested @ LHC
but most questionable predictions
(RG effects)

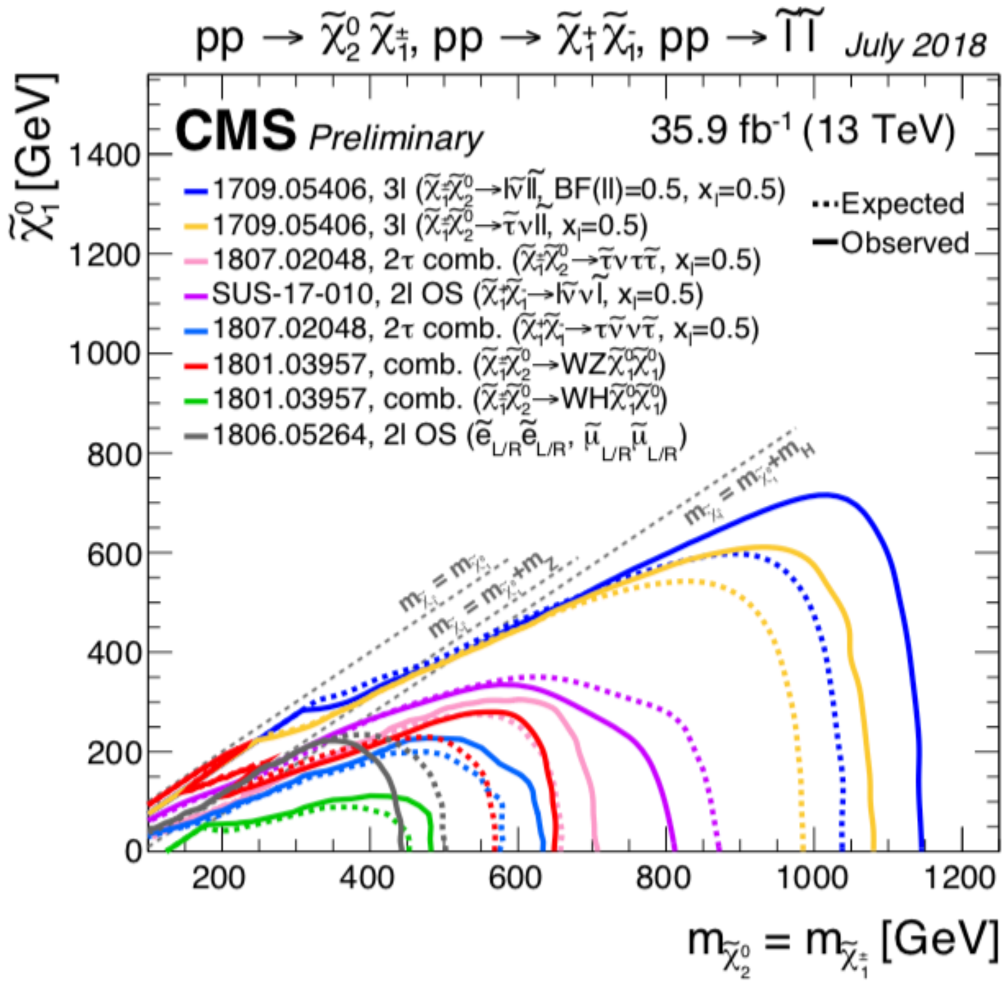


$$\delta m_H^2 \sim |\mu|^2$$

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

Probing natural SUSY





Probing natural SUSY

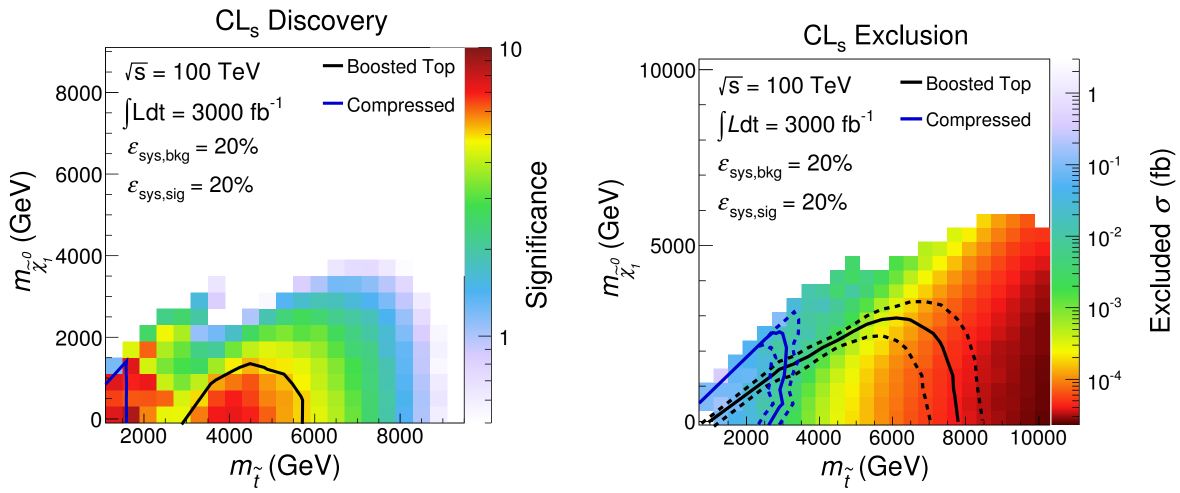


Fig. 12: Left: Discovery potential and Right: Projected exclusion limits for 3000 fb^{-1} of total integrated luminosity at $\sqrt{s} = 100$ TeV. The solid lines show the expected discovery or exclusion obtained from the boosted top (black) and compressed spectra (blue) searches. In the boosted regime 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

Probing natural SUSY

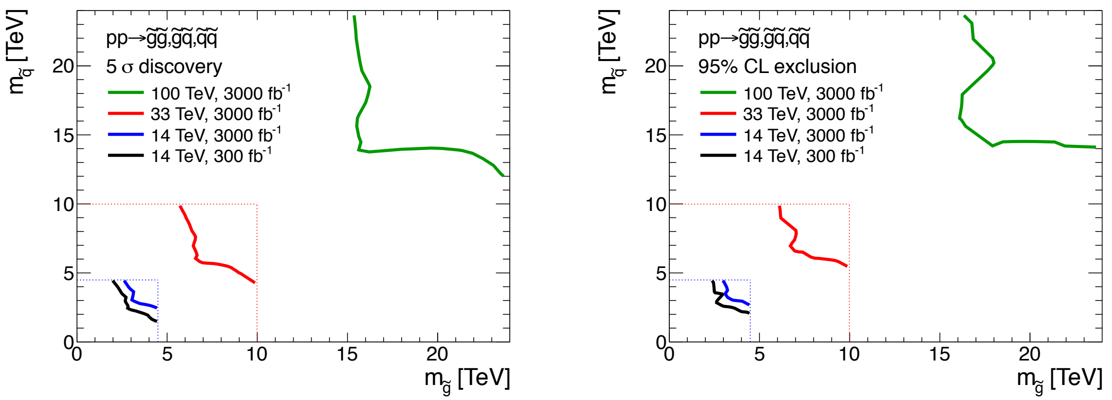
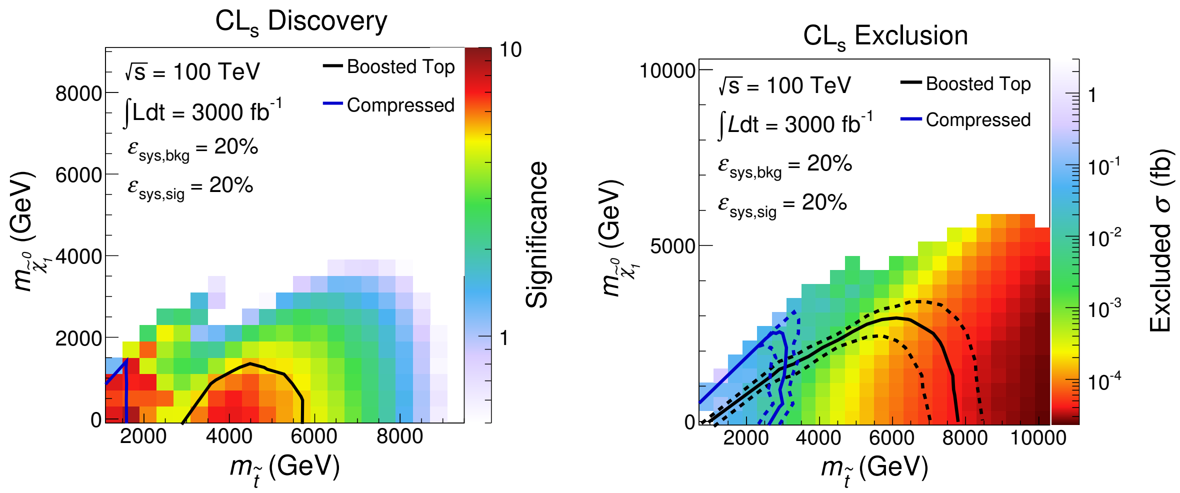


Fig. 16: Results for the gluino-squark-neutralino model. The neutralino mass is taken to be 1 GeV. The left [right] panel shows the $5\,\sigma$ discovery reach [95% CL exclusion] for the four collider scenarios studied here. A 20% systematic uncertainty is assumed and pile-up is not included.



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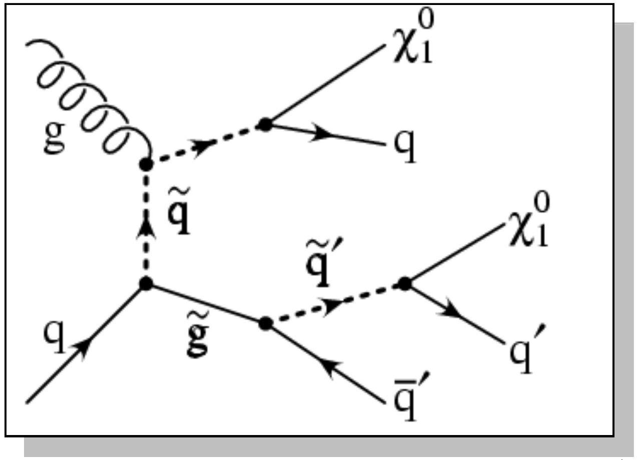
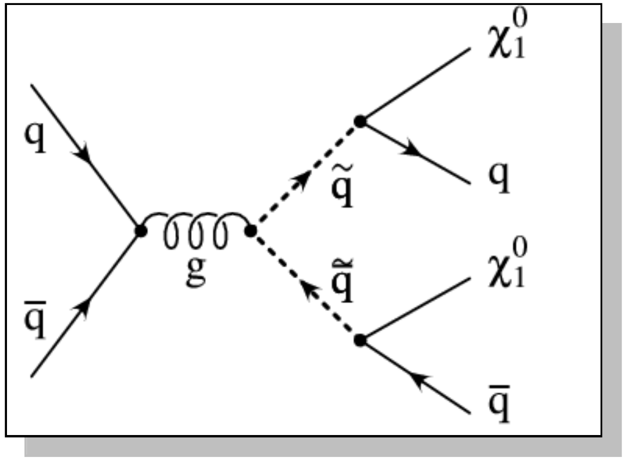
SUSY searches

gluinos and squarks are produced by QCD interactions





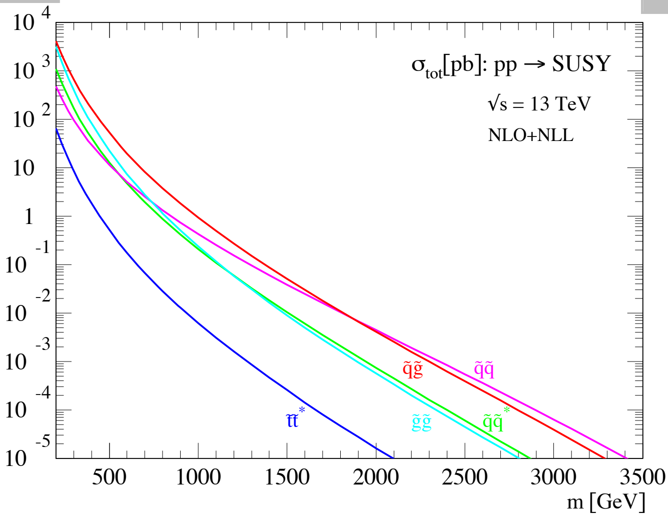
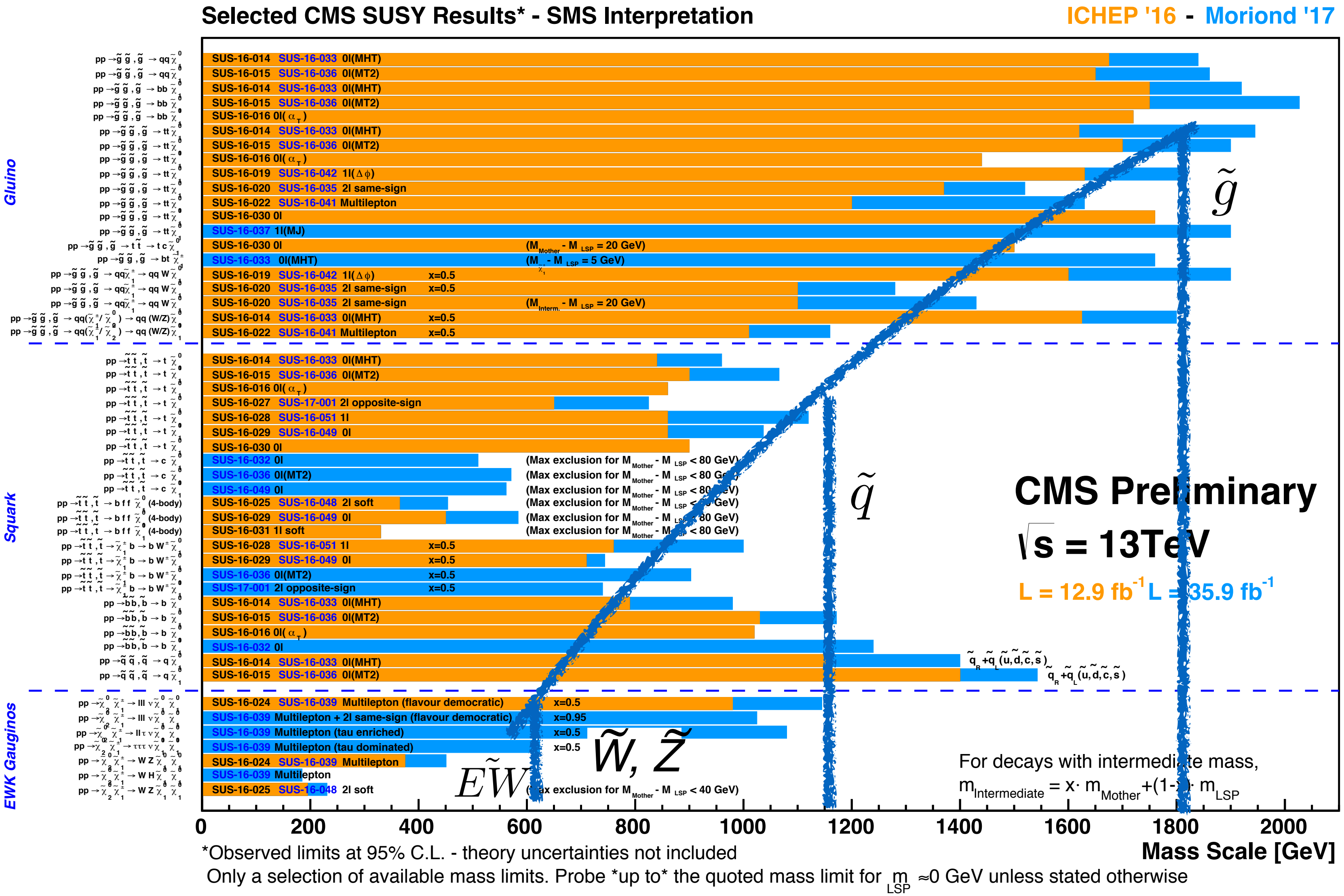


Figure 1: NLO+NLL production cross sections for the case of equal degenerate squark and gluino masses as a function of mass at $\sqrt{s} = 13$ TeV.

LSP (lightest supersymmetric particle) is stable ≈ Missing Energy

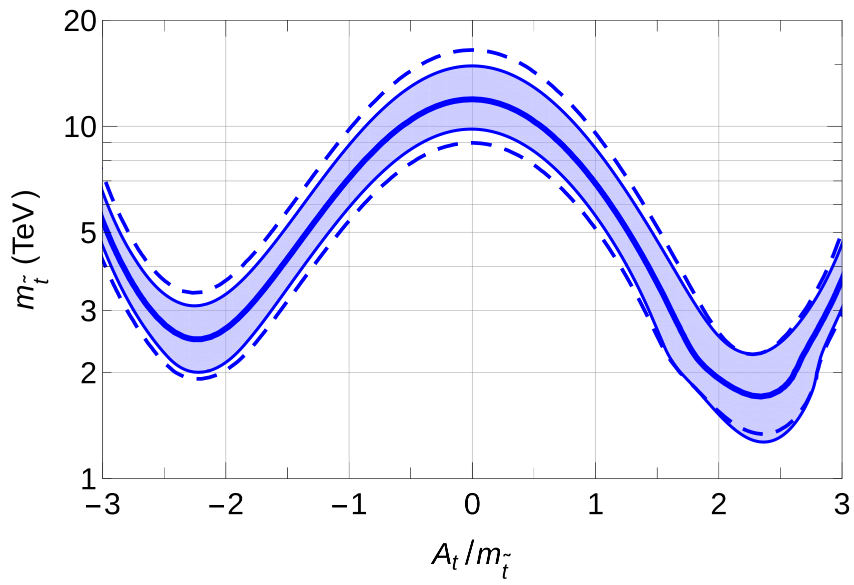
SUSY searches

gluinos and squarks are produced by QCD interactions



LSP (lightest supersymmetric particle) is stable ≈ Missing Energy

MSSM Higgs mass and stop searches



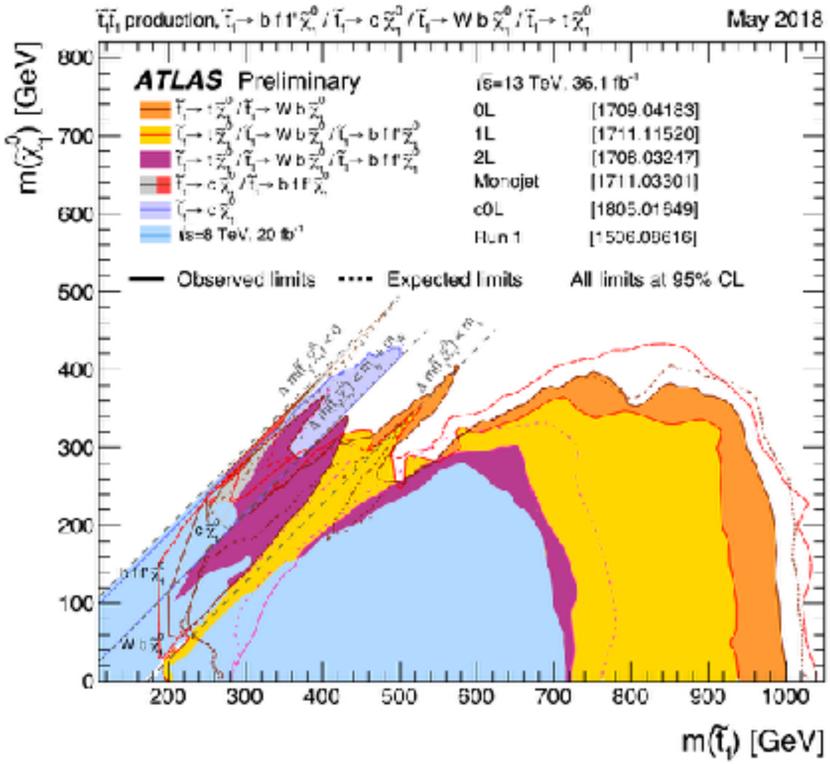
Pardo Vega, Villadoro '15 + many others

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

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 $M_3 + m_t$.*

Current and future bounds on stop mass

LHC (2018)



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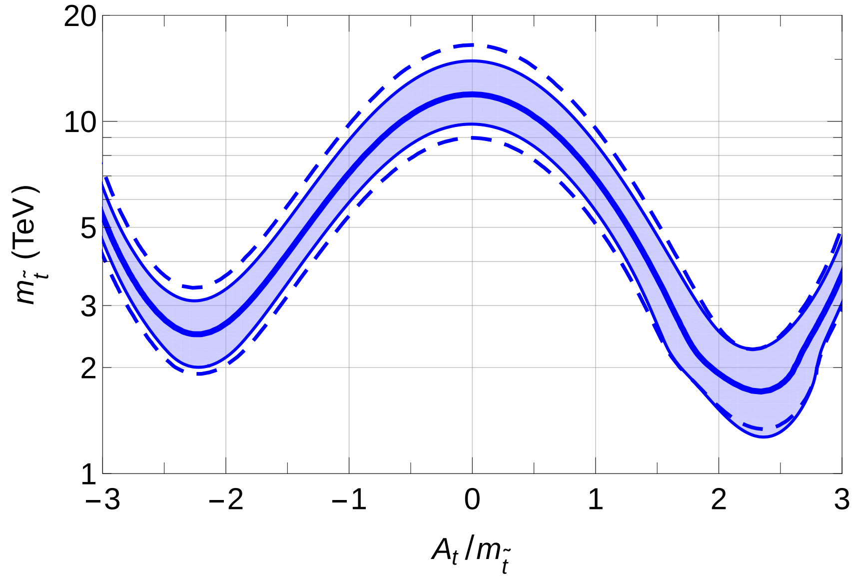

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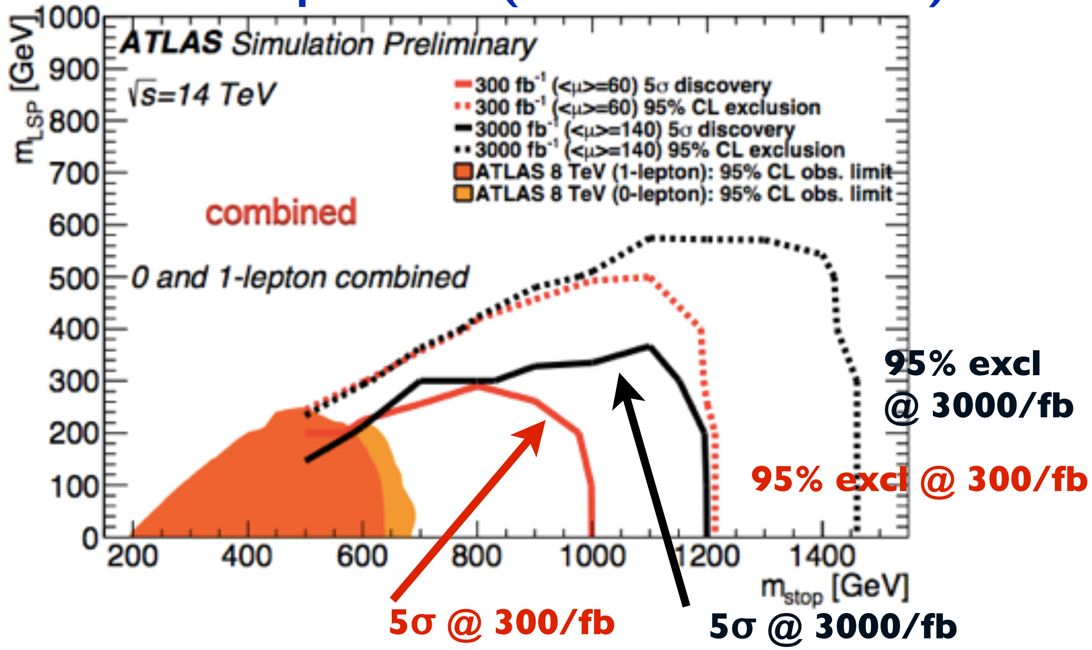
Current and future bounds on stop mass

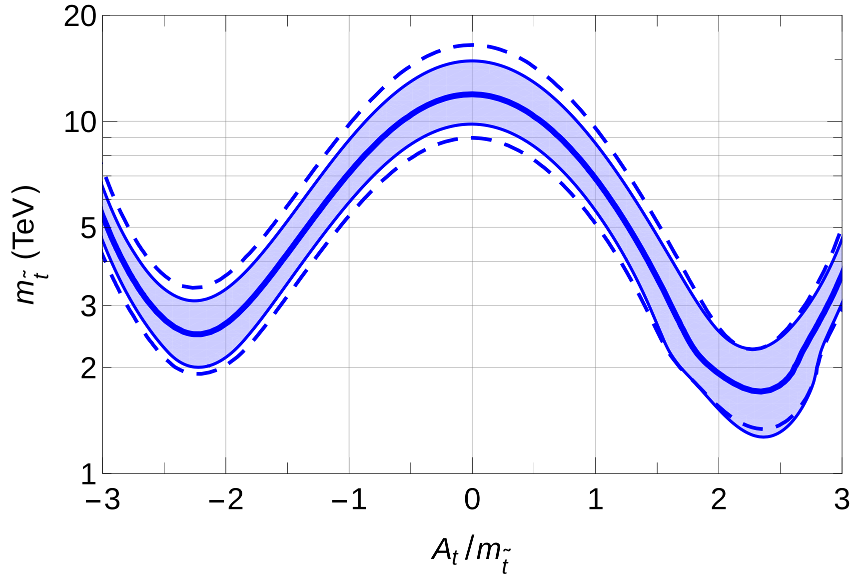
HL-LHC (2030)

Direct stop searches (ATLAS Snowmass doc)



MSSM Higgs mass and stop searches

Pardo Vega, Villadoro '15 + many others



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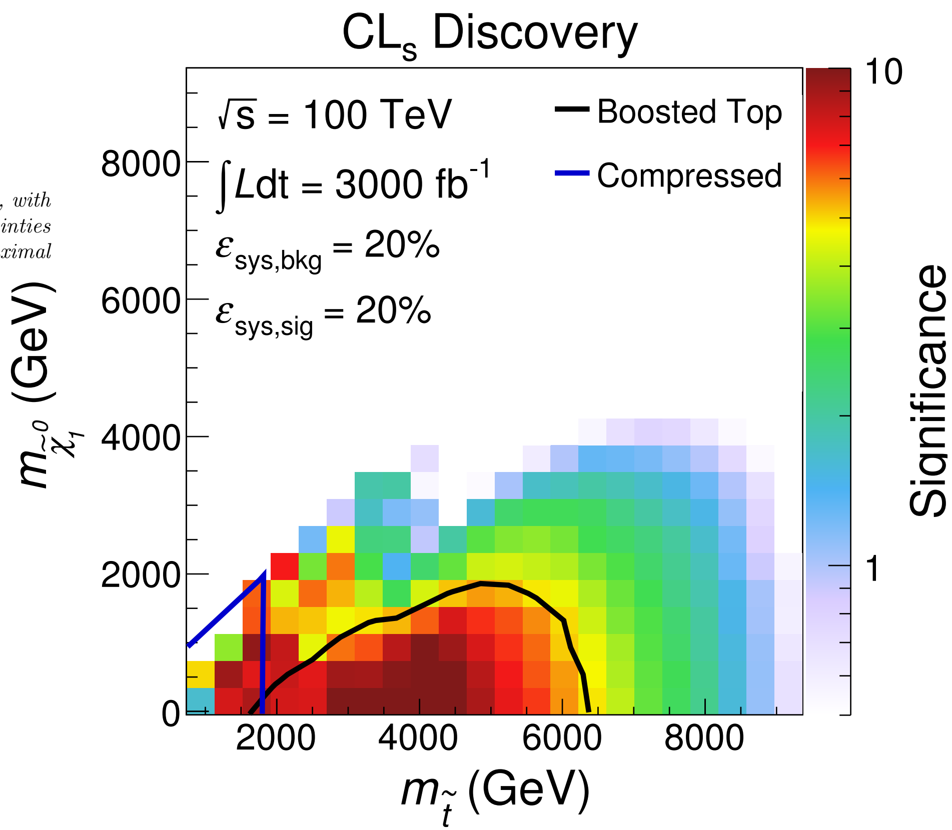
Current and future bounds on stop mass

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, Csaki et al compressed spectrum)
  - dilute MET (decay to invisible particles with more invisible particles)
  - soften MET (stealth susy, stop -top degeneracy) Fan et al

$LHC_{300(0)fb^{-1}}$ will tell!

Good coverage of

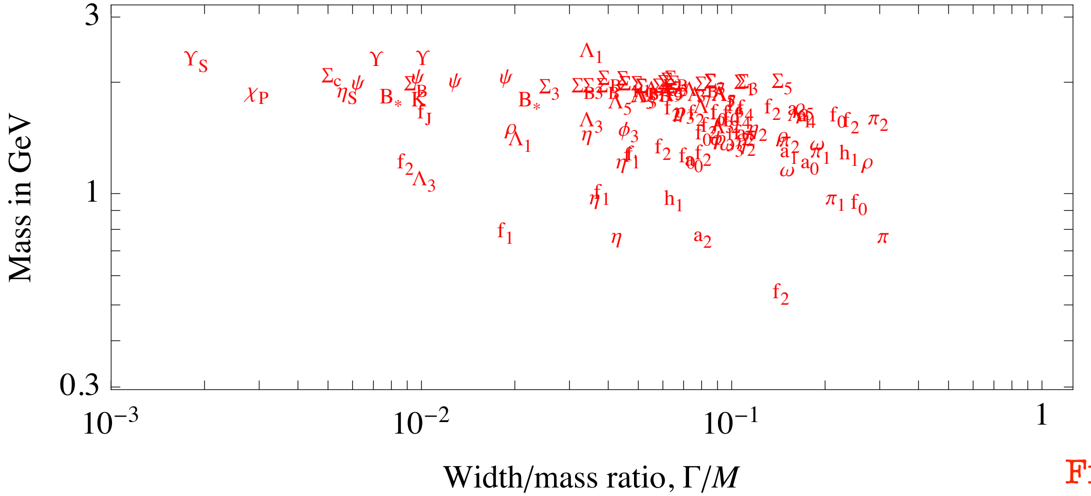
hidden natural susy

- mono-top searches (DM, flavored naturalness - mixing among different squark flavors-, 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

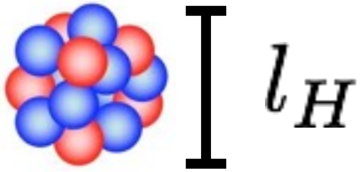
Composite Higgs

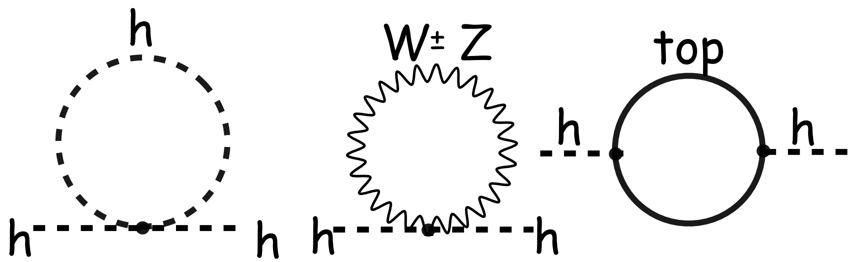
Light scalars exist in Nature but
all the ones observed before Higgs discovery were composite bounds states



Franceschini et al. ’15

Could the Higgs be a “hadron” of a new strong force?

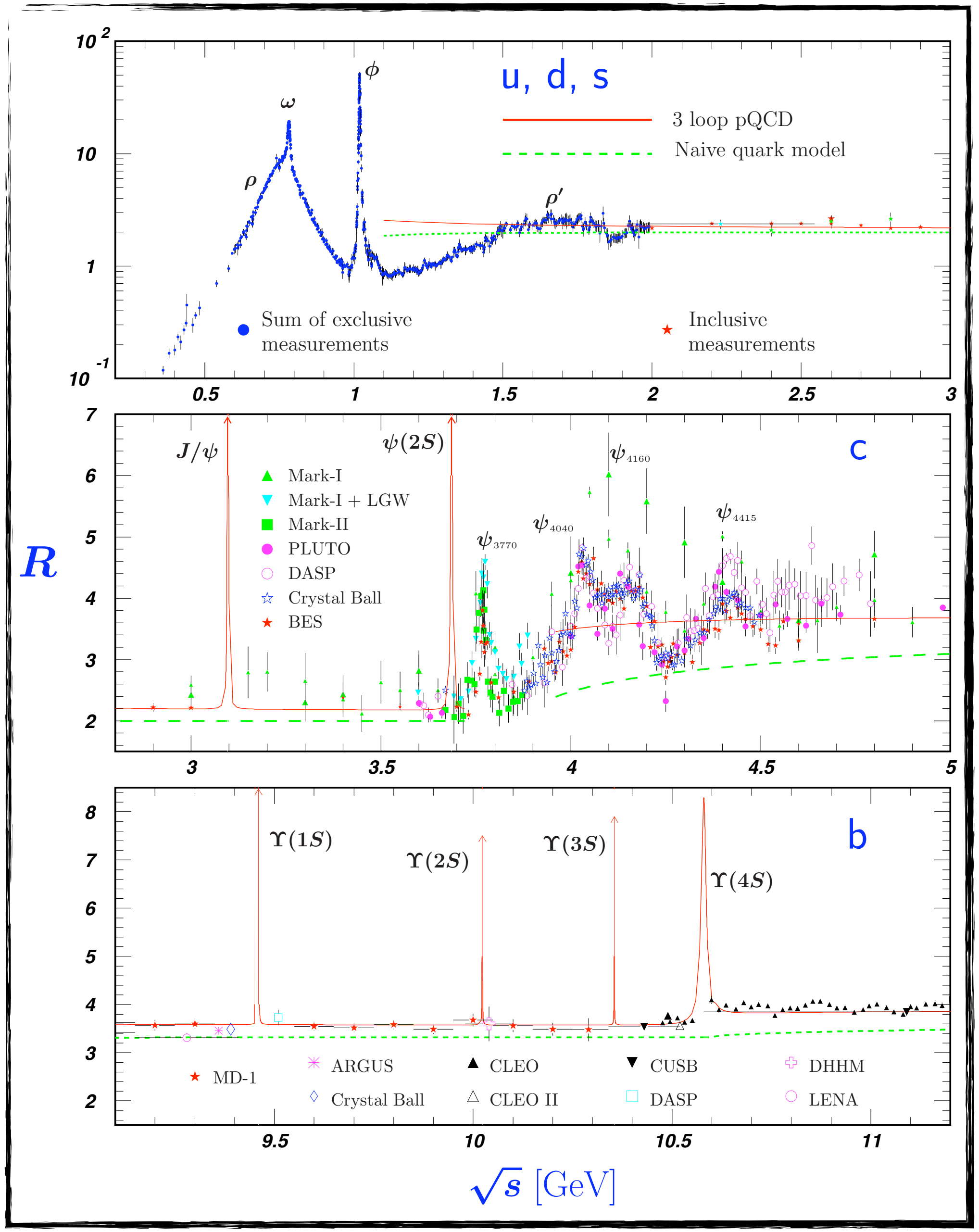




At energy above $1/\ell_H$, the Higgs dissolves, the integrals are smoothed out

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

Higgs as a bound state



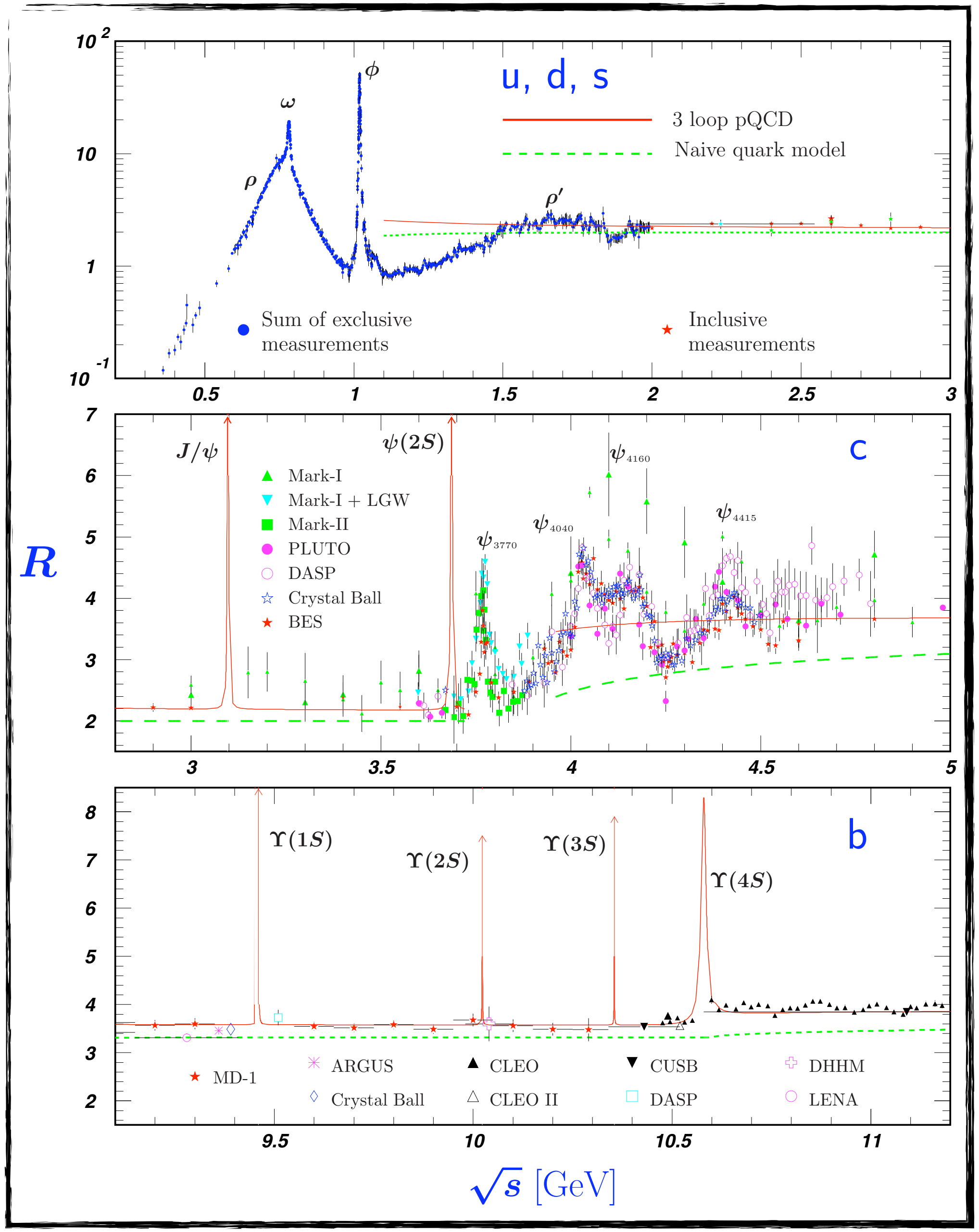
Structure of QCD was understood from inelastic scattering experiments

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

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

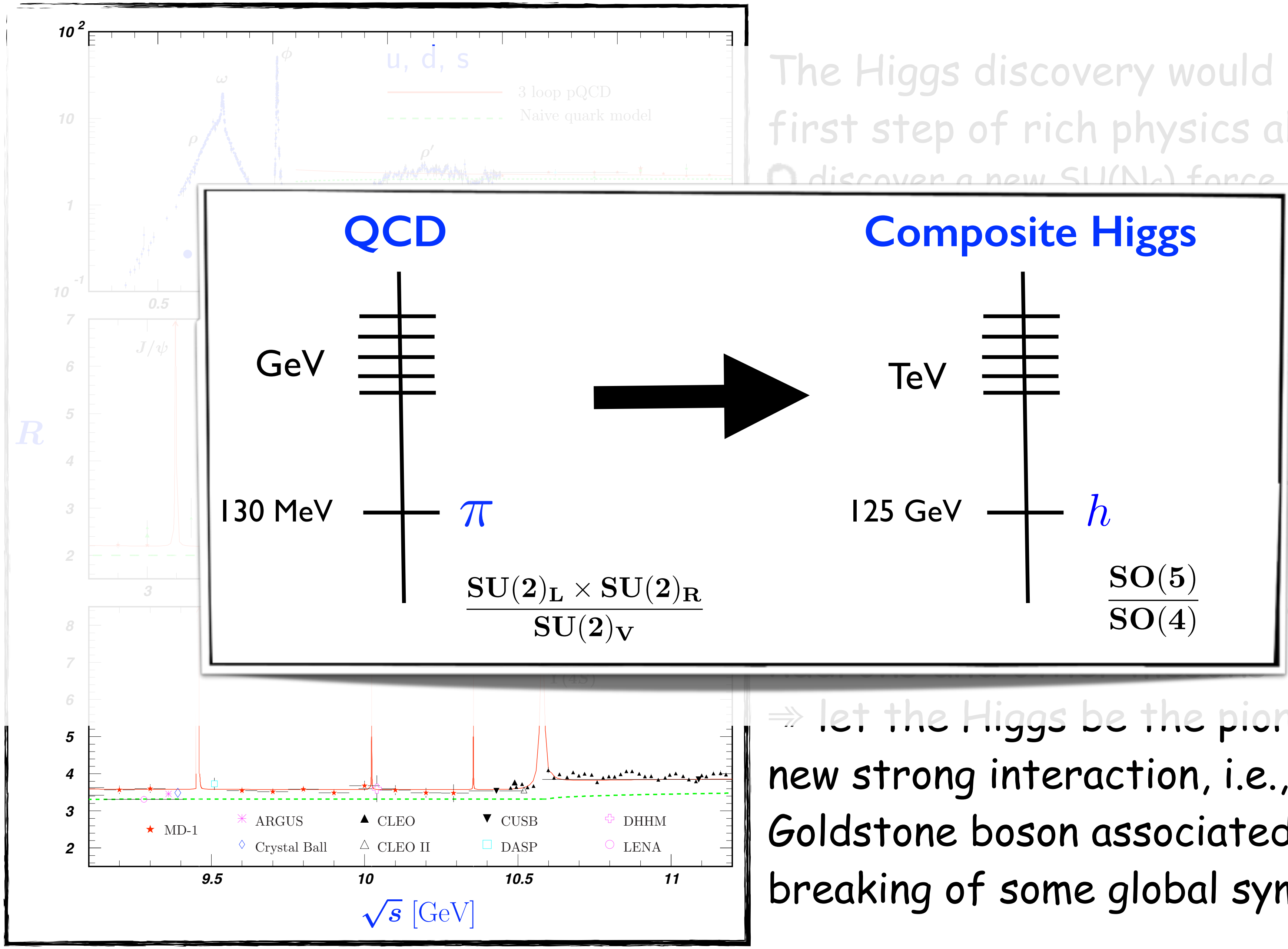
But how come we haven't seen anything of these yet?

⇛ 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



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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

SM: $SO(4)/SO(3)$ — $W^{\pm}_L$ & Z_L ⇒ BSM: G/H — $W^{\pm}_L$ & Z_L & h

Examples:

$SO(5)/SO(4)$: 4 PGBs=$W^{\pm}_L$, Z_L, h ⟵ Minimal Composite Higgs Model
(dim=10 / dim=6)

Agashe, Contino, Pomarol '04

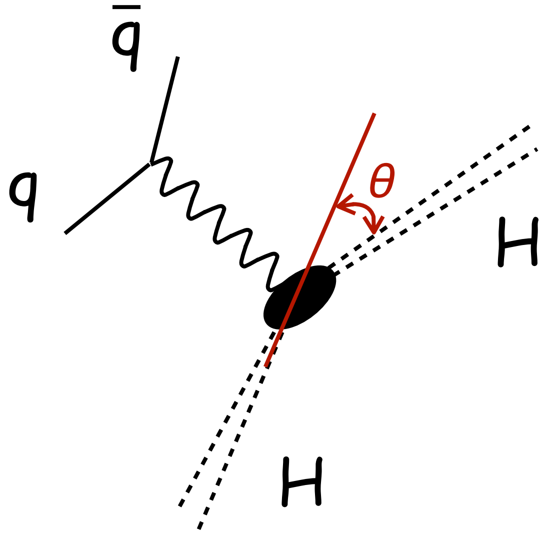
$SO(6)/SO(5)$: 5 PGBs=H, a ⟵ Next MCHM
(dim=15 / dim=10)

$SU(4)/Sp(4,\mathbb{C})$: 5 PGBs=H, s
(dim=15 / dim=10)

$SO(6)/SO(4)\times SO(2)$: 8 PGBs=H_1+H_2 ⟵ Minimal Composite Two Higgs Doublets
(dim=15 / dim=7)

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

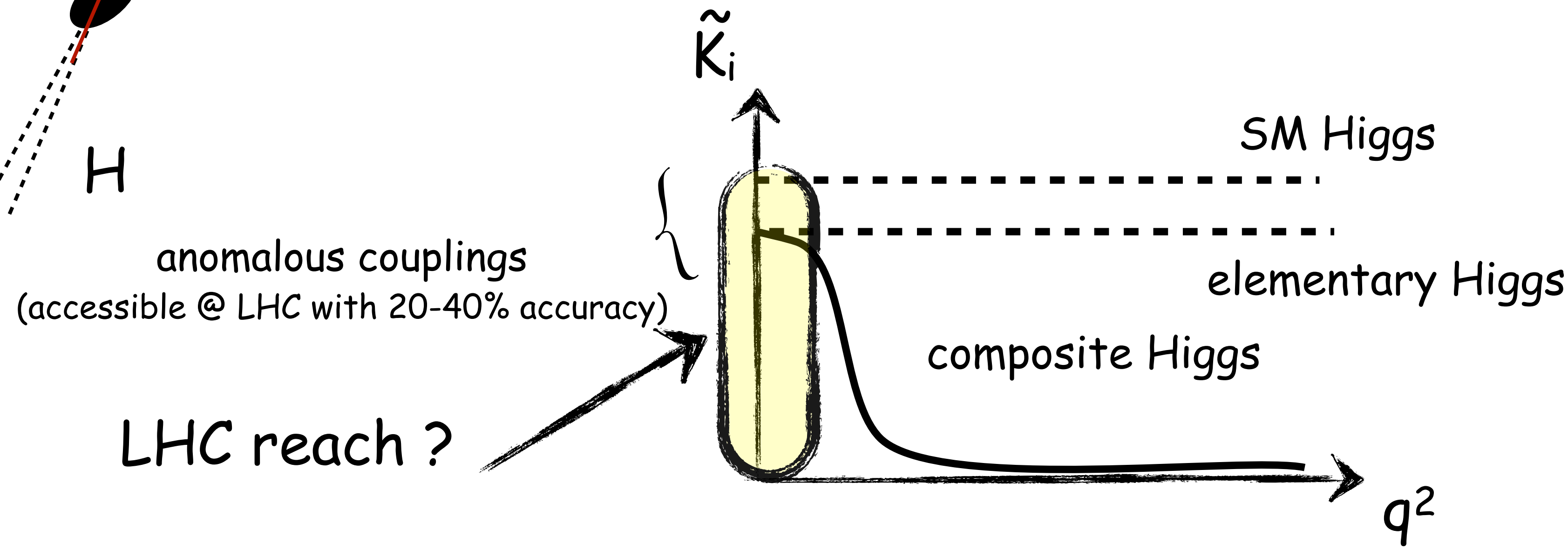
Probe the compositeness of the Higgs?



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

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

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 = √1-ξ ≈ 1-ξ/2

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

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

$$\mathcal{S} = \int d^4x \left(\mathcal{L}_0 + \hbar\mathcal{L}_1 + \hbar^2\mathcal{L}_2 + \ldots\right)$$

$$[\mathcal{L}_0]_\hbar = 1 \qquad [\mathcal{L}_1]_\hbar = 0 \qquad [\mathcal{L}_2]_\hbar = -1$$

$$[\mathcal{L}_0]_M = 4 \qquad [\mathcal{L}_1]_M = 4 \qquad [\mathcal{L}_2]_M = 4$$

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

$[\cdot]_\hbar = -1$ ↘ $[\cdot]_\hbar = 2$ ↙

$$\frac{1}{M^2} g_*^2 \left(\partial^\mu |H|^2\right)^2$$

$[\cdot]_\hbar = 1$ ↘ $[\cdot]_\hbar = 0$ ↙

$$\frac{i c_W}{2M^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right) \left(g\, D^\nu W_{\mu\nu}\right)^i$$

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

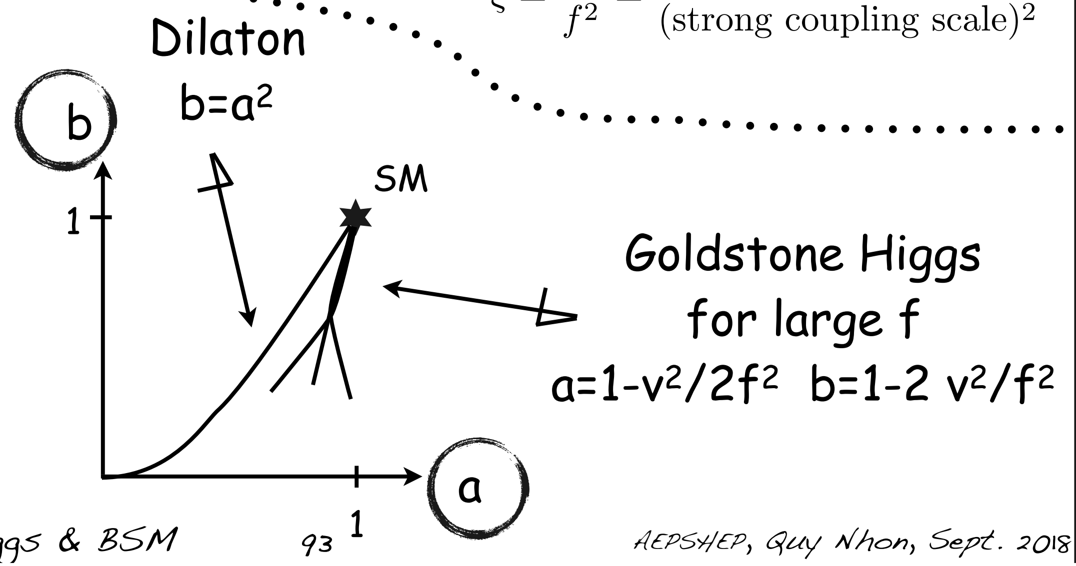
Minimal composite Higgs model (MCHM): SO(5)/SO(4)

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

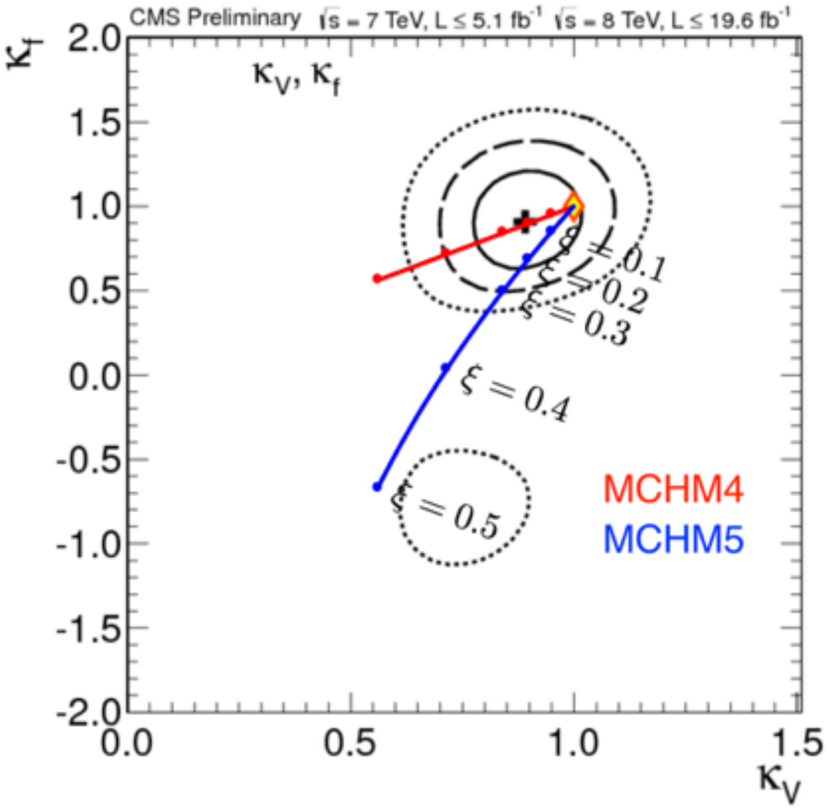
Uniqueness of Goldstone models
in the SM vicinity
(a single operator at dimension-6 level
controls the amplitudes)

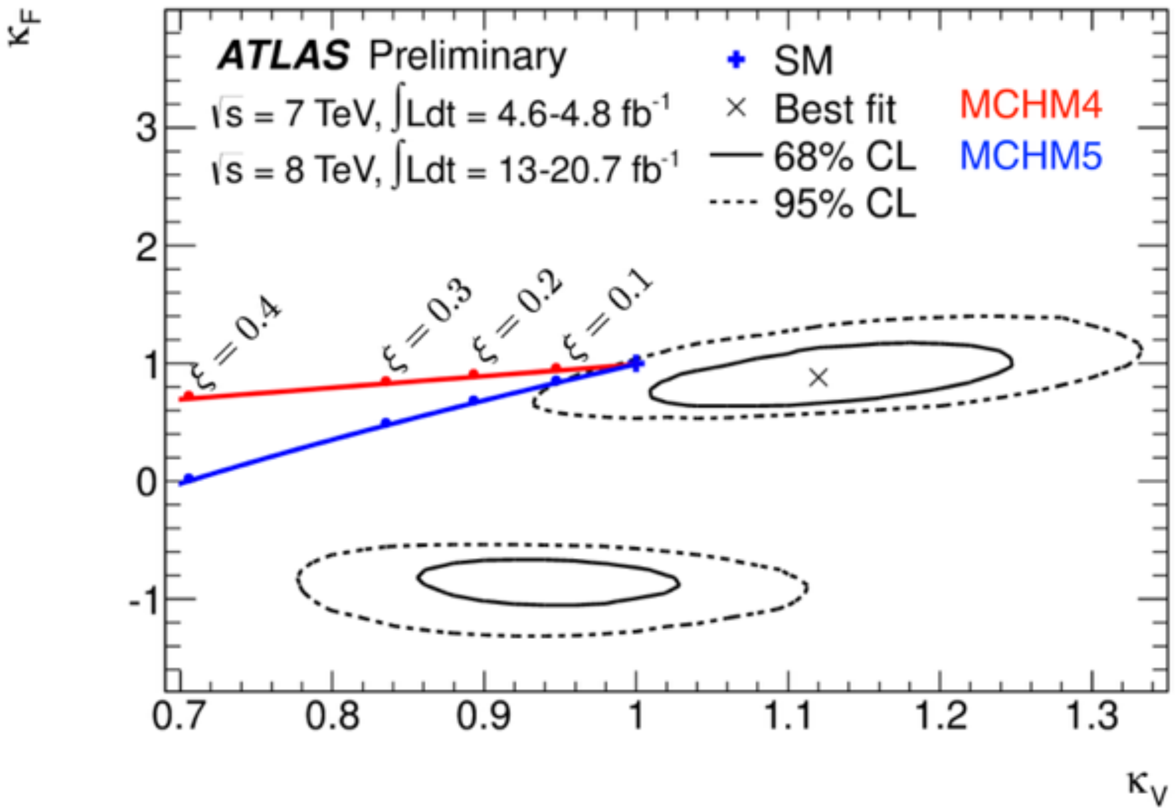
$$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$$

Composite Higgs
vs.
SM Higgs



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.:

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

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

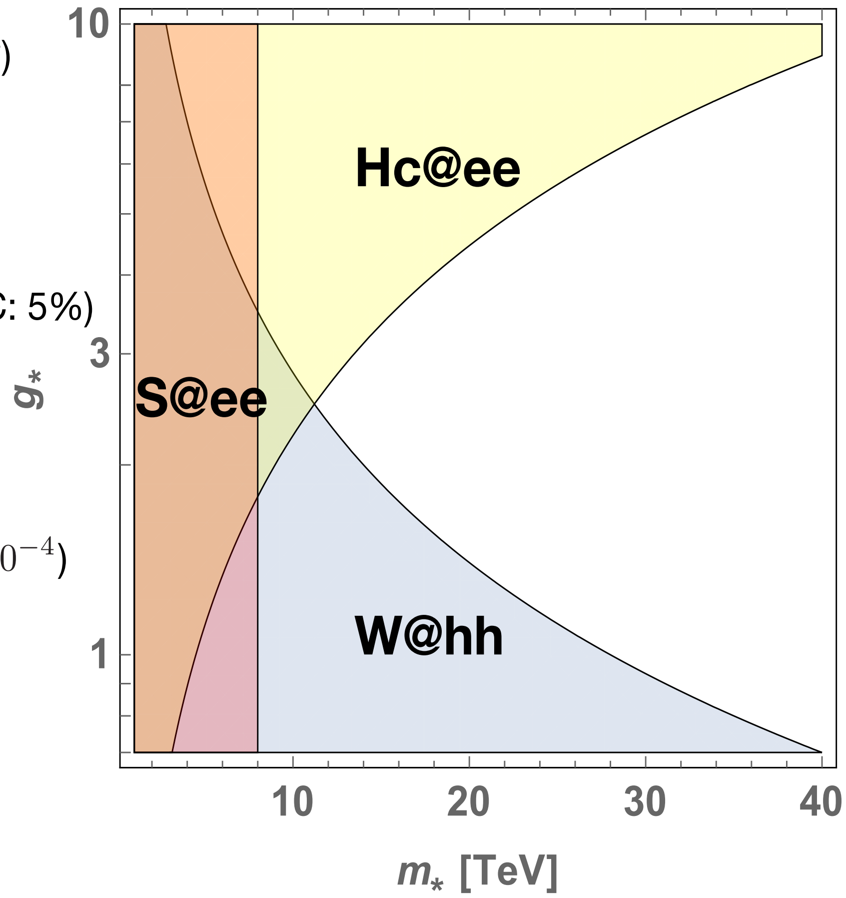
$$\frac{g_w g'}{m_*^2} H^\dagger \sigma_a H W^a_{\mu\nu} B^{\mu\nu} \;\Rightarrow\; \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}$$

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

Indirect composite signatures

Composite tR, comp. Higgs, **elementary tL** and gauge

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

ttH coupling @hh/ee: [Reports] (HL-LHC:10%)

$$\frac{y_t g_*^2}{m_*^2}|H|^2 \bar{q}_L H t_R \Rightarrow \frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2\,10^{-2}$$

Diff. oper.s comb. in ee and hh!!

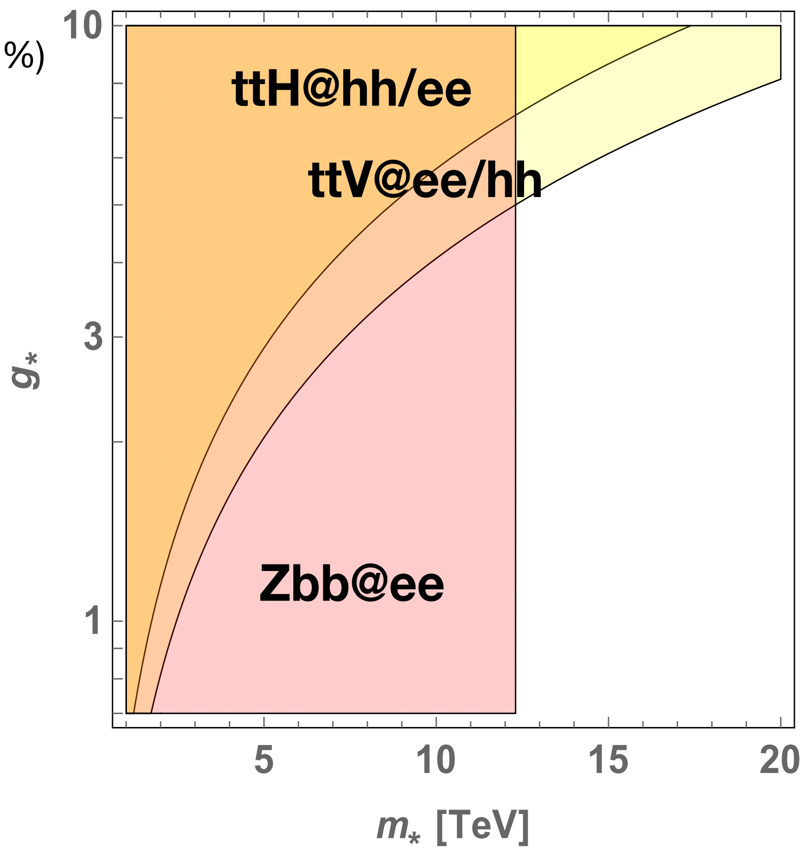
ttV coupling @ee/hh: [Janot / Farina et.al.]

$$\frac{g_*^2}{m_*^2} H^\dagger \overleftrightarrow{D}_\mu H\, \bar{t}_R \gamma^\mu t_R \Rightarrow \frac{\delta g_{tV}}{g_{tV}} = \frac{g_*^2 v^2}{m_*^2} < 10^{-2}$$

Same hh reach from en. + acc.?

Zbb coupling @ee: [ee Report] (LEP:10^{-3})

$$\frac{y_t^2}{m_*^2} H^\dagger \overleftrightarrow{D}_\mu H\, \bar{q}_L \gamma^\mu q_L + .. \Rightarrow \frac{\delta g_b}{g_b} = \frac{m_t^2}{m_*^2} < 2\,10^{-4}$$



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Composite tR, comp. Higgs, **elementary tL** and gauge

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

ttH coupling @hh/ee: [Reports] (HL-LHC:10%)

$$\frac{y_t g_*^2}{m_*^2}|H|^2\bar{q}_L H t_R \;\Rightarrow\; \frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2\,10^{-2}$$

Diff. oper.s comb. in ee and hh!!

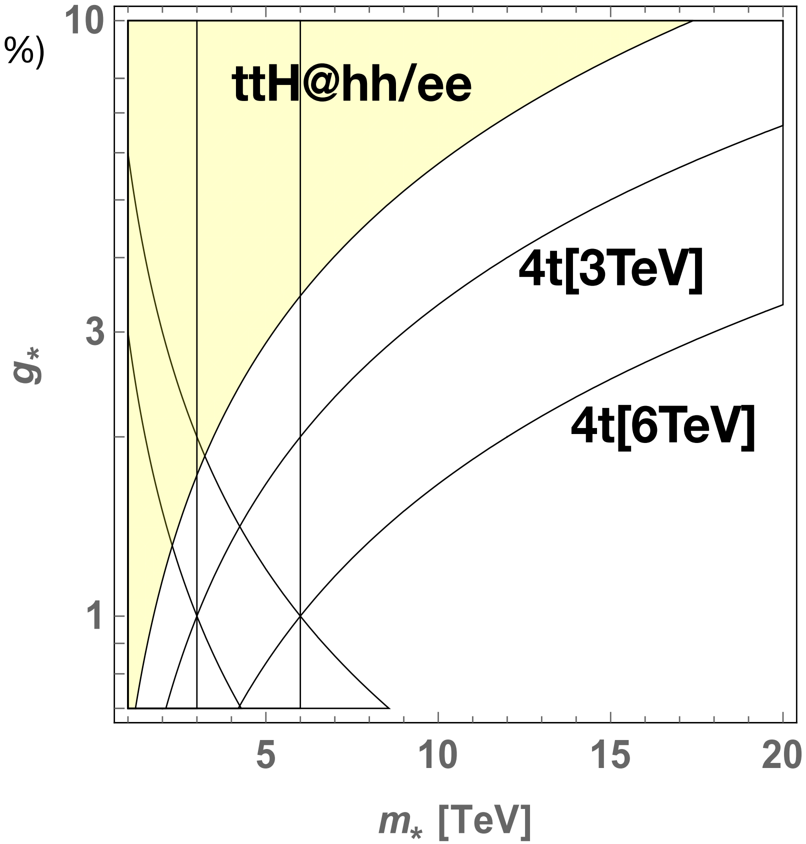
4-top contact interactions @hh:

$$\frac{g_*^2}{m_*^2}(\bar{t}_R\gamma_\mu t_R)^2 \;\Rightarrow\; \frac{g_*^2}{m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

$$\frac{y_t^2}{m_*^2}(\bar{q}_L\gamma_\mu q_L)(\bar{t}_R\gamma_\mu t_R) \;\Rightarrow\; \frac{y_t^2}{m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

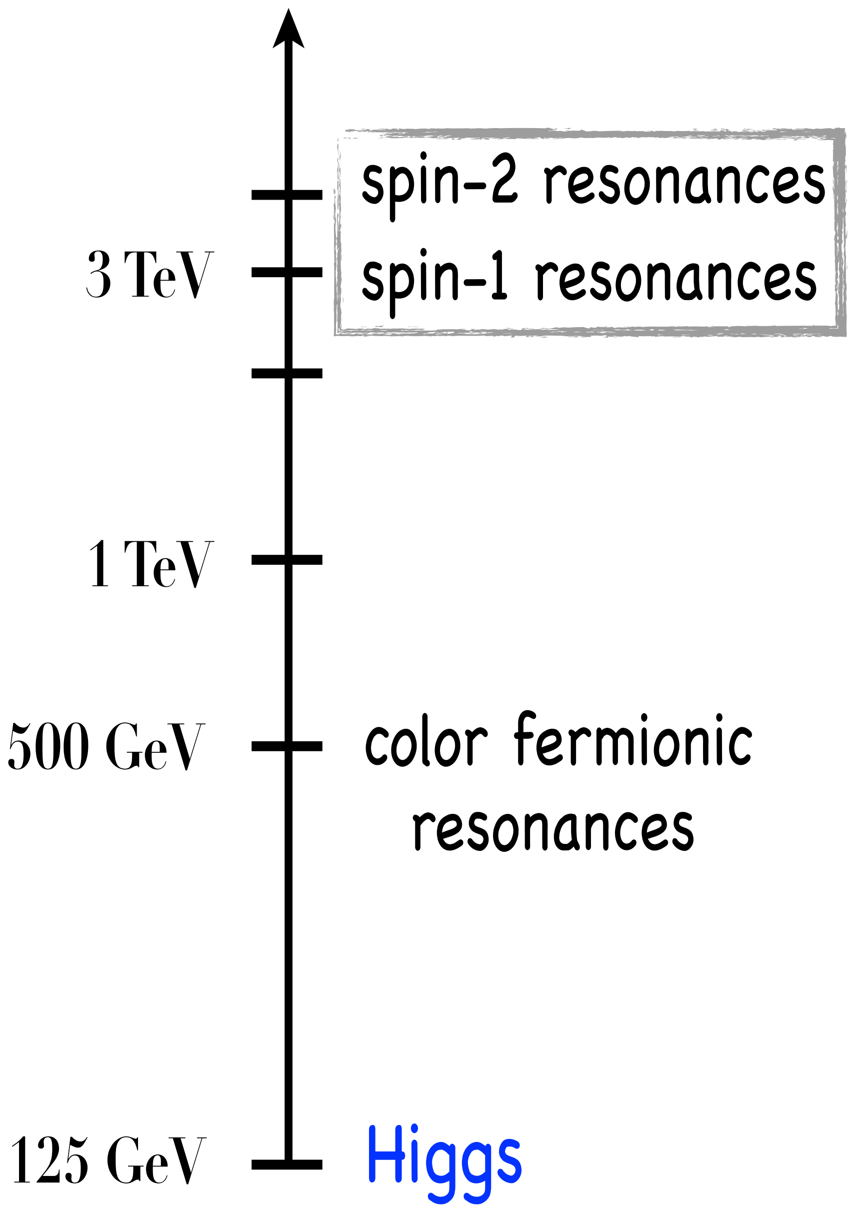
$$\frac{y_t^4}{g_*^2 m_*^2}(\bar{q}_L\gamma_\mu q_L)^2 \;\Rightarrow\; \frac{y_t^4}{g_*^2 m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

No study available (?)



Grojean-Wulzer @ FCC physics week '17

The other resonances



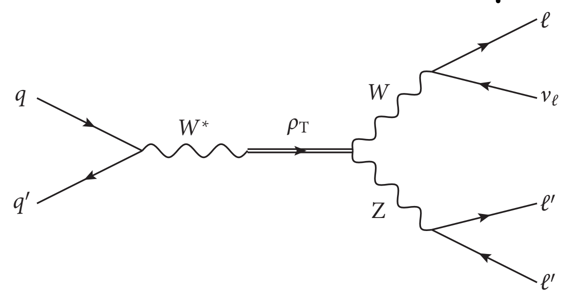
Dominant decays into longitudinal SM gauge bosons

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

Suppressed decays to SM quarks and leptons

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

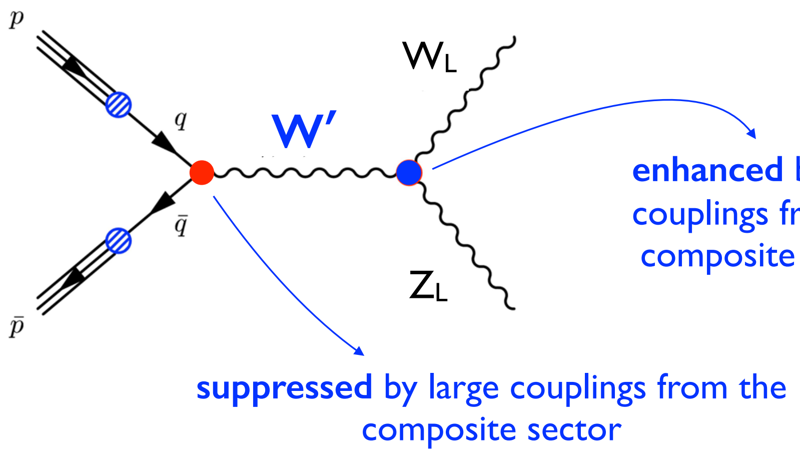
searches in WW, WZ channels in DY processes



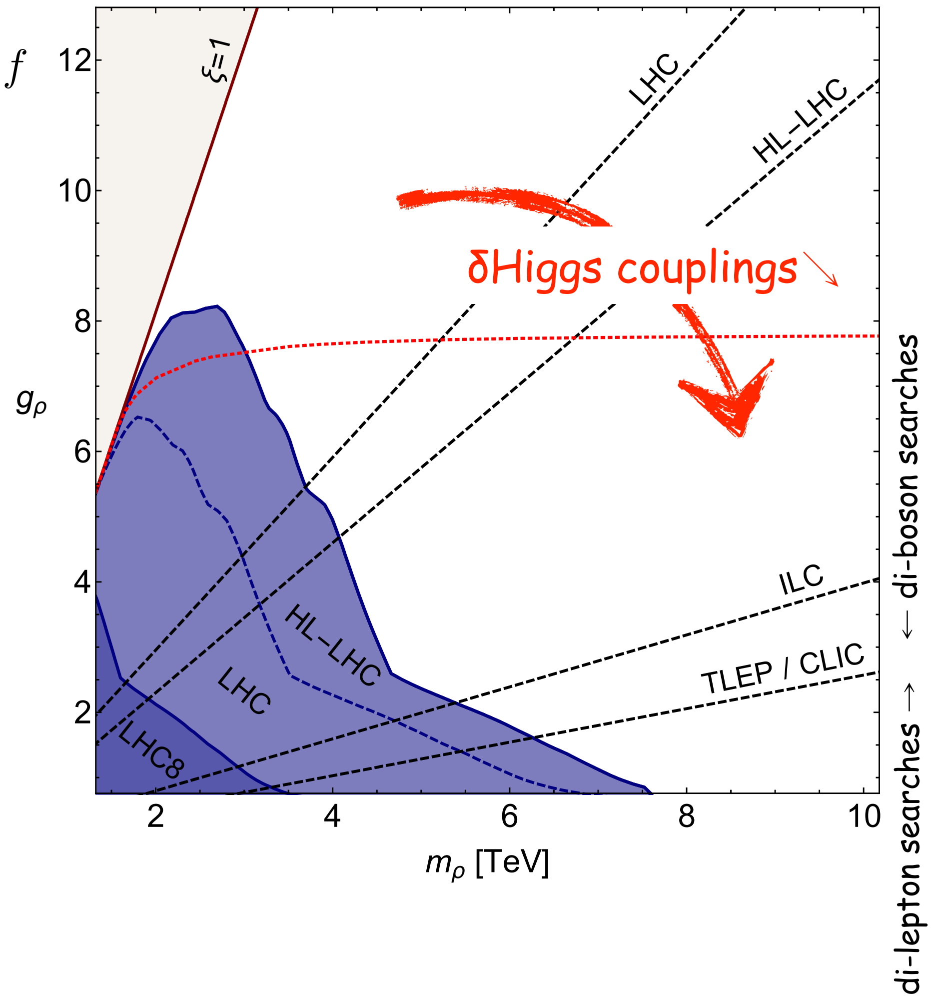
H couplings vs searches for vector resonances

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: $m_\rho \approx g_* f$



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



Torre, Thamm, Wulzer '15

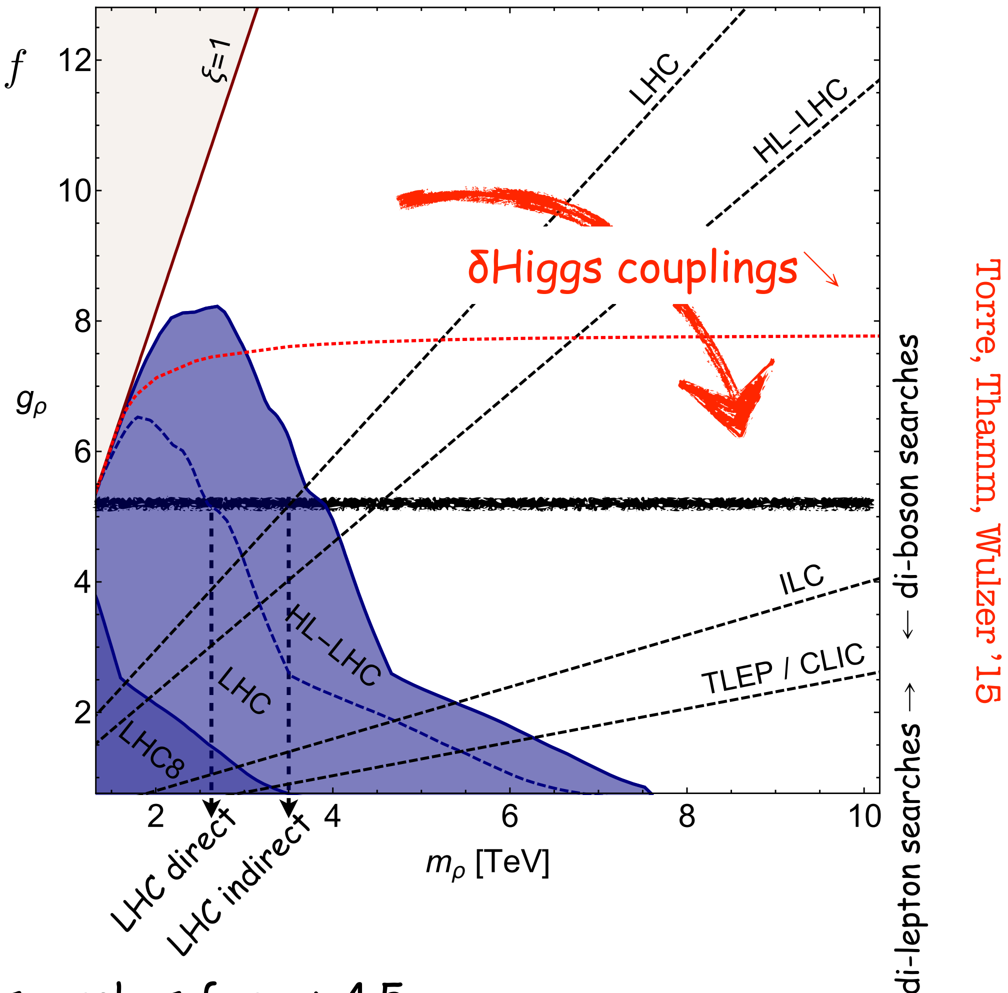
H couplings vs searches for vector resonances

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

- Precision Higgs study: $\xi \equiv \frac{\delta g}{g} = \frac{v^2}{f^2}$
- 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 $\times 10^{-3}$

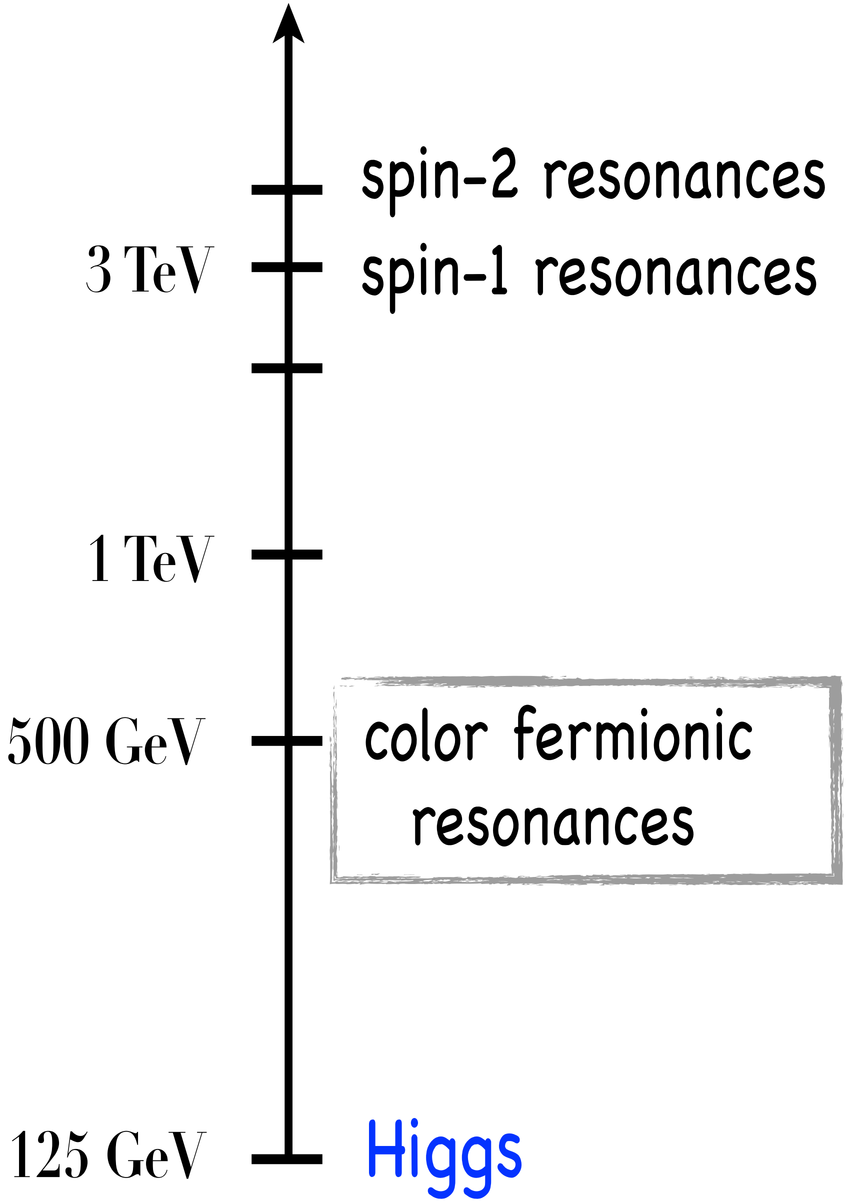
DY production xs of resonances decreases as $1/g_\rho^2$



- **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 $g > 4.5$
indirect searches at ILC over-perform direct searches at HL-LHC for $g > 2$

The other resonances



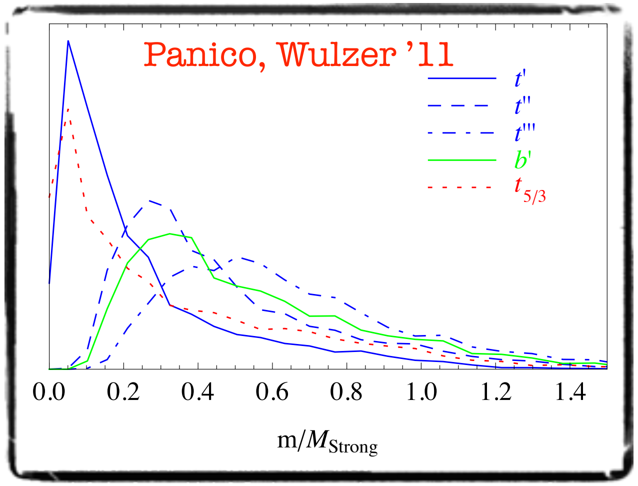
Top partners

SO(4)~SU(2)$_L$xSU(2)$_R$ embedding

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

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

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



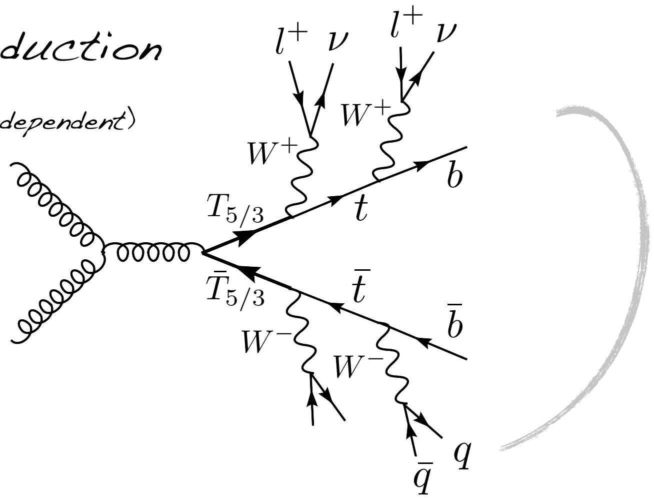
Searching for the top partners

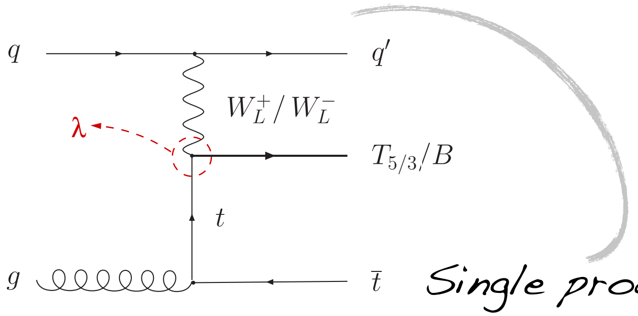
Search in same-sign dilepton events

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

Pair production

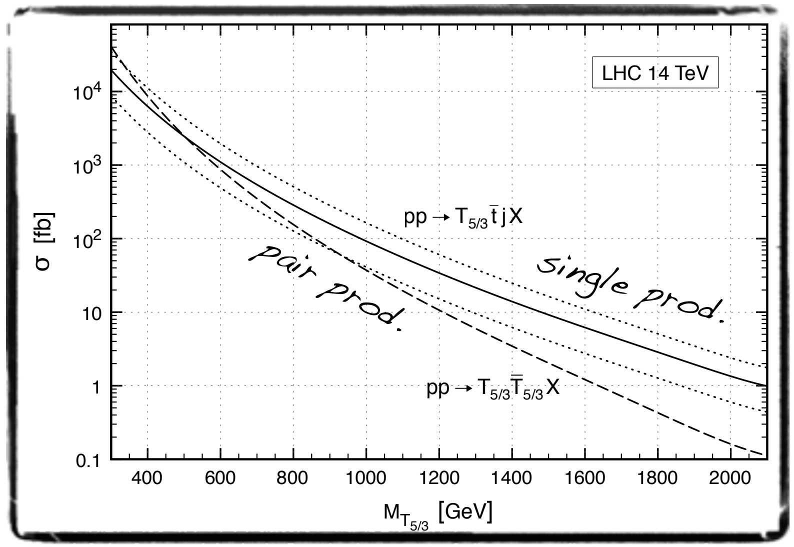
(model independent)





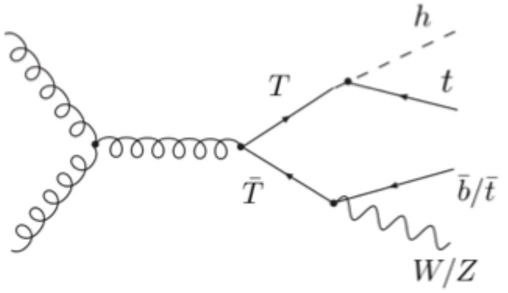
Single production

(model dependent)



[Contino, Servant '08]

Searching for the top partners



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

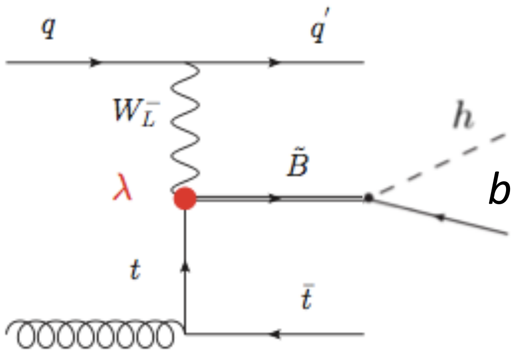
$$T\bar{T} \to HtW^-\bar{b} \to HW^+bW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}',$$
$$T\bar{T} \to HtV\bar{t} \to HW^+bVW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$$

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

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

- $\gamma\gamma$ final state Azatov et al '12

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

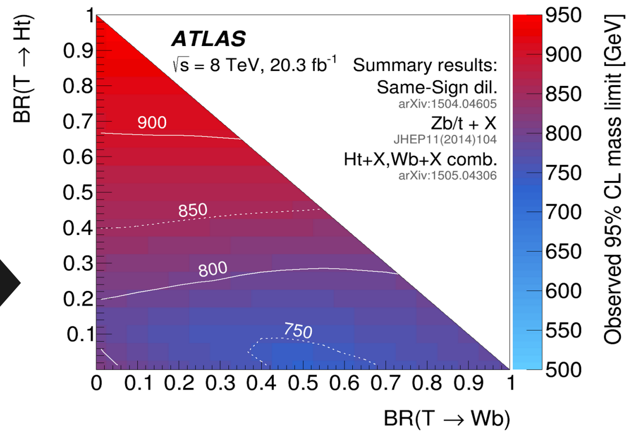


- $\ell^\pm$ + 4b final state Vignaroli '12

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

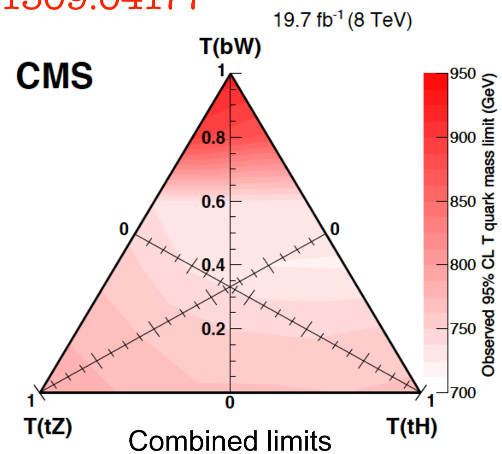
bounds on charge 2/3 states from pair production

1505.04306



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

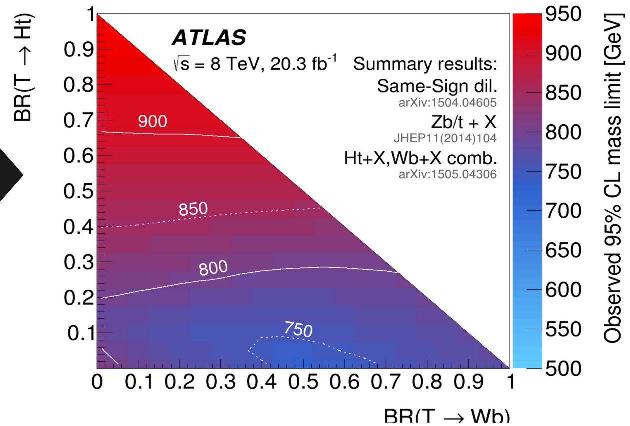
1509.04177



Searching for the top partners

bounds on
charge 2/3 states
from pair production

1505.04306



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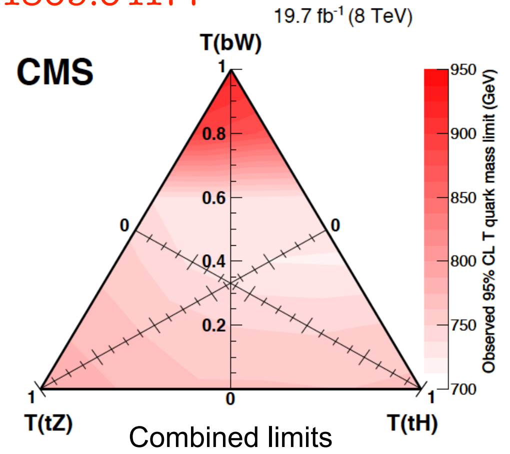
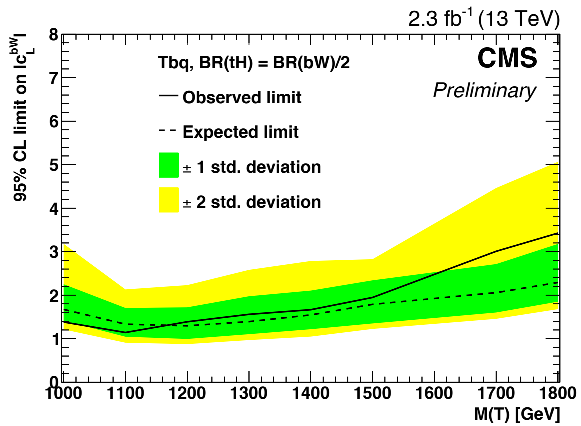
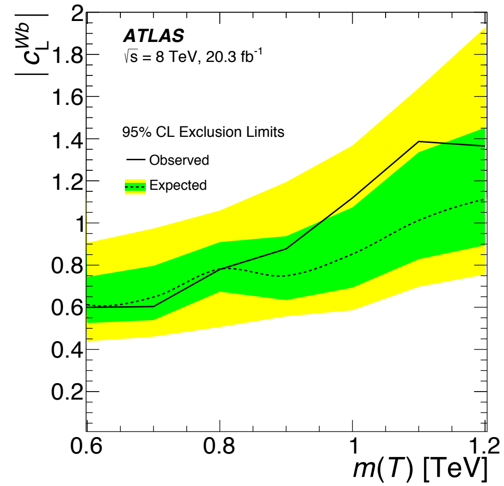
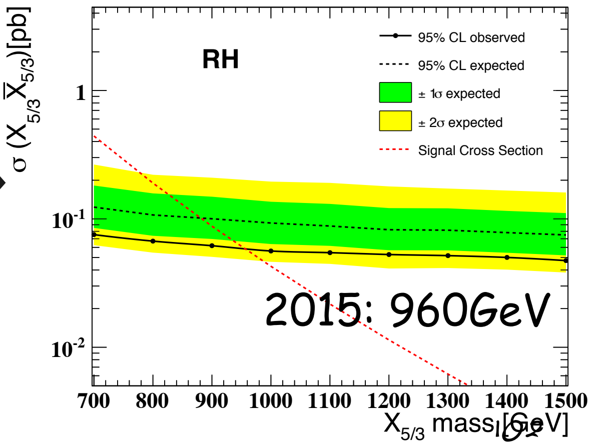


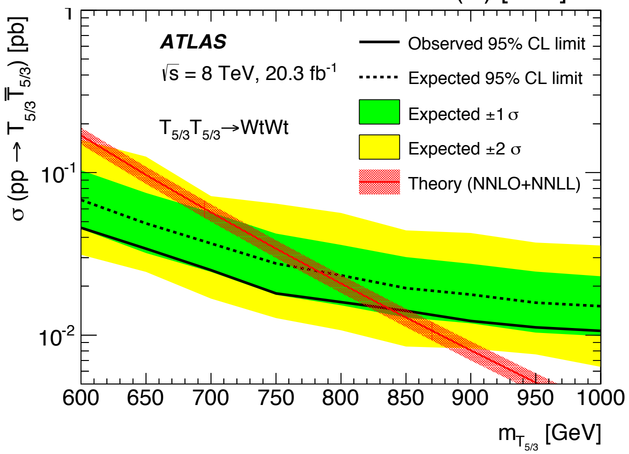
bounds on
charge 2/3 states
from single production





bounds on
charge 5/3 states
from single production

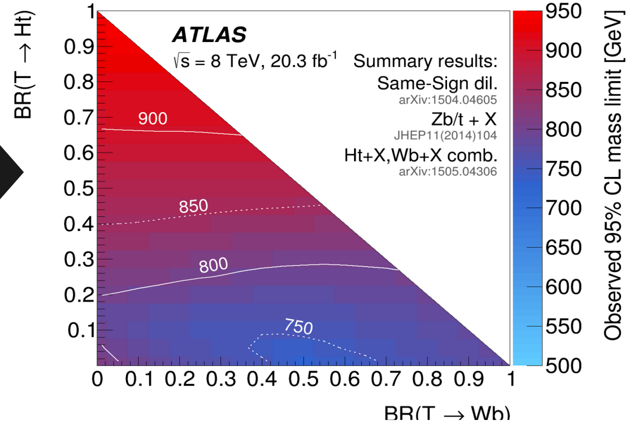




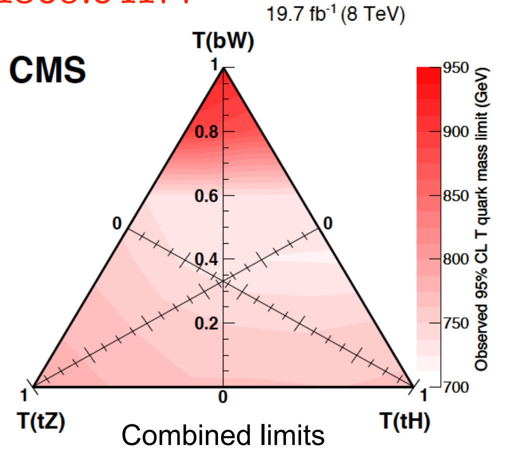
Searching for the top partners

bounds on
charge 2/3 states
from pair production

1505.04306



1509.04177



bounds on
charge 2/3 states
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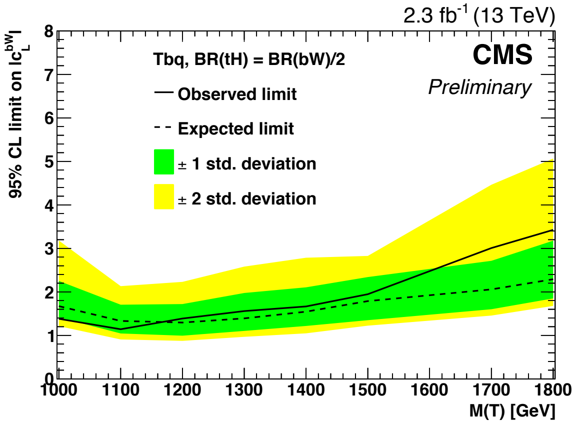
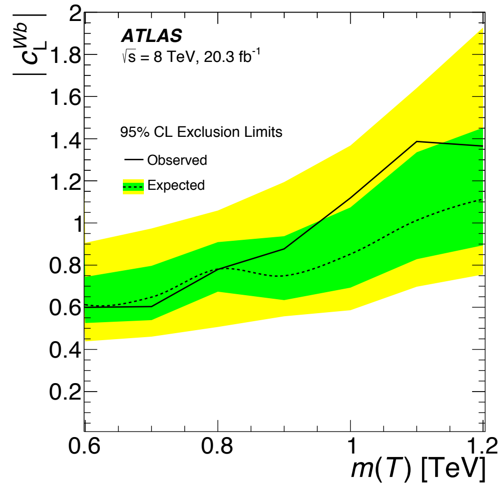
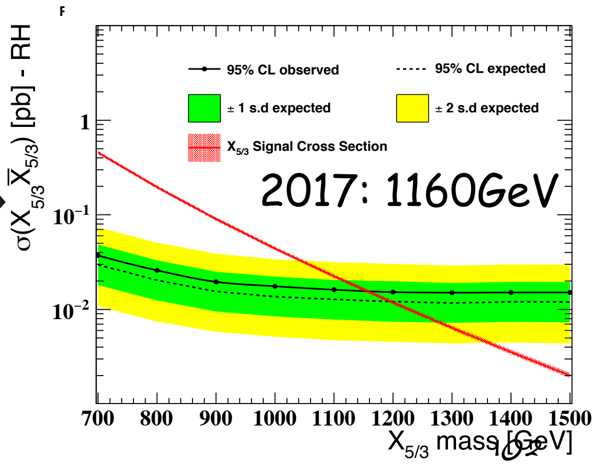
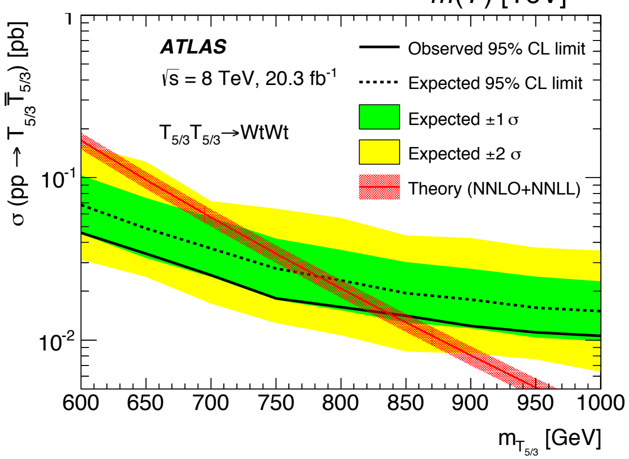




bounds on
charge 5/3 states
from single production



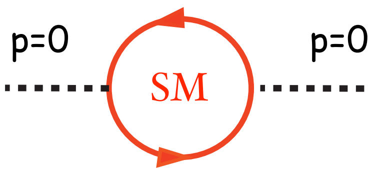
2017: 1160GeV

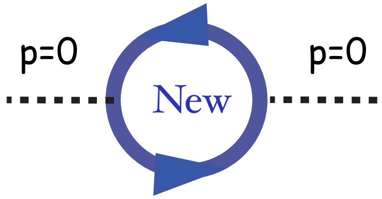


Neutral naturalness

Neutral Naturalness

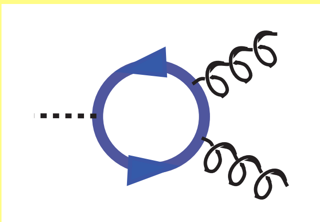
$$-(125\text{ GeV})^2\left(\frac{\Lambda}{600\text{ GeV}}\right)^2 \qquad\qquad \frac{g_*^2}{16\pi^2}\Lambda^2$$

$\delta m_H^2 =$ 

$+$ 

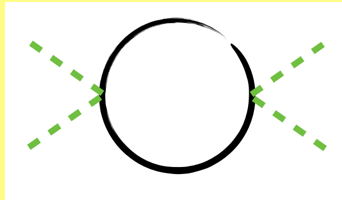
$\sim m_H^2$

charged particles — generically — neutral particles



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

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



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

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

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

nice to be able to measure Zh & Γ

Colorful naturalness probed @ LHC

Neutral naturalness (invisible?) @ LHC

Twin Higgs

[Chacko, Goh, Harnik '05]

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

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

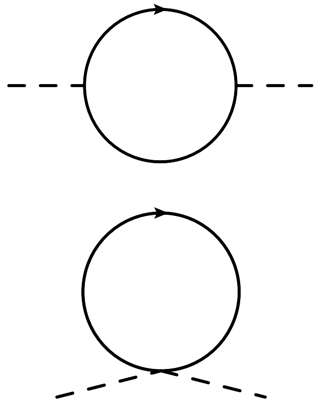
$$V(H) \supset \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + \frac{9}{4}g^2 + \ldots\right)\left(|H_A|^2 + |H_B|^2\right)$$

(N. Craig @ Paris'18)

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

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

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



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

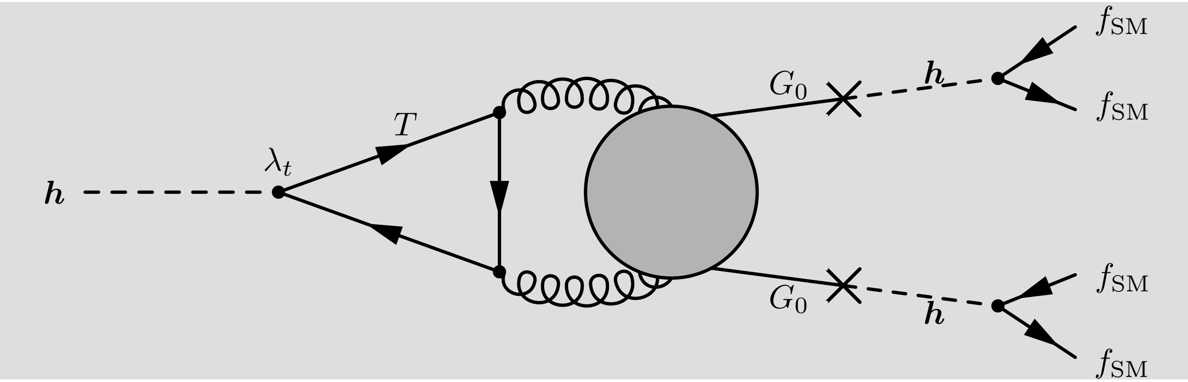
Curtin, Verhaaren ’1

⇒ 2) emerging jets

Schwaller, Stolarski, Weiler ’15

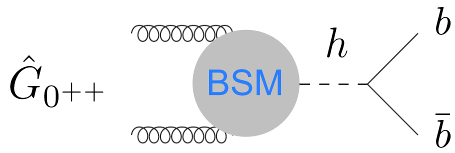
(C. Verhaaren@NIKPI’16)

Neutral Naturalness

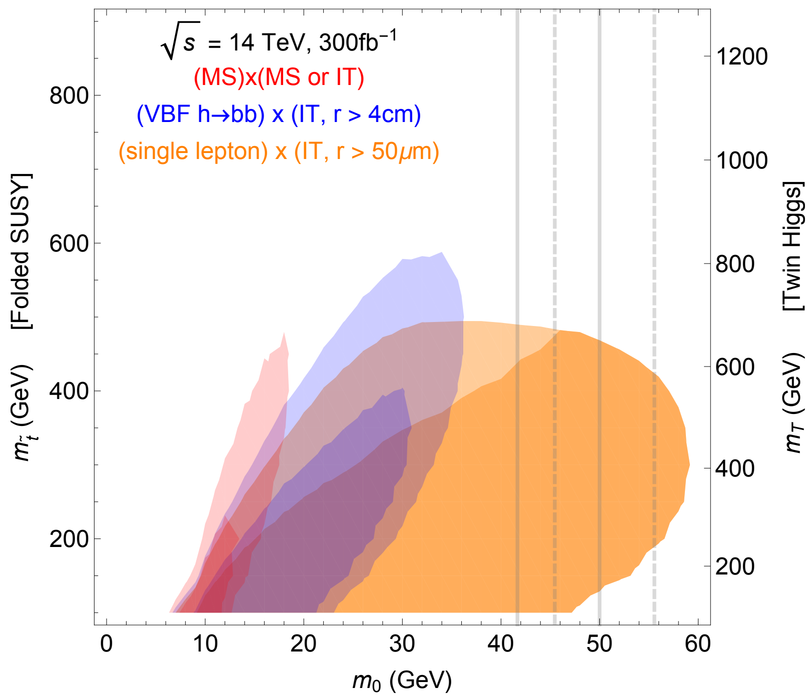


top parters are EW charged: m>100GeV (LEP)
Lightest hidden states are glueballs of QCD' that can mix with the Higgs boson

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

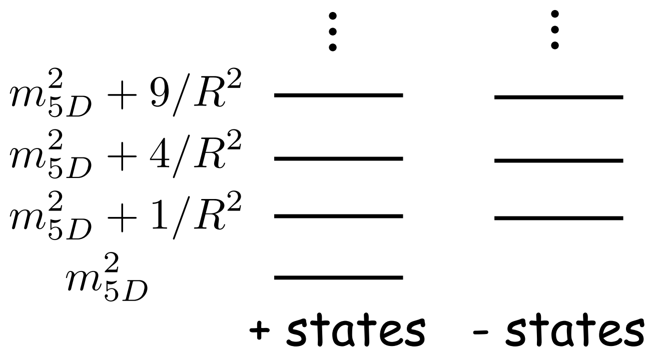
$$0^{++} \to h^* \to f\bar{f}$$

Long-lived, length scale ~ LHC detectors

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

Extra dimensions

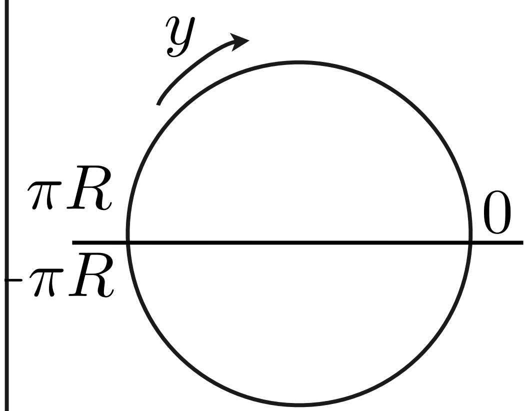
Extra dimensions



5D field=infinite tower of massive 4D fields

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

~~ Compactification on a Circle ~~



circle:
$$y \sim y + 2\pi R$$
$$\phi(y + 2\pi R) = \phi(y)$$

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

5D field

wavefunction = localization of KK mode along the xdim

4D Kaluza-Klein modes

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

Extra dimensions

	+ states	- states
⋮	⋮	⋮
$m_{5D}^2 + 9/R^2$	——	——
$m_{5D}^2 + 4/R^2$	——	——
$m_{5D}^2 + 1/R^2$	——	——
m_{5D}^2	——	

5D field=infinite tower of massive 4D fields

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

~~ Compactification on a Circle ~~

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

localization of KK mode
along the xdim

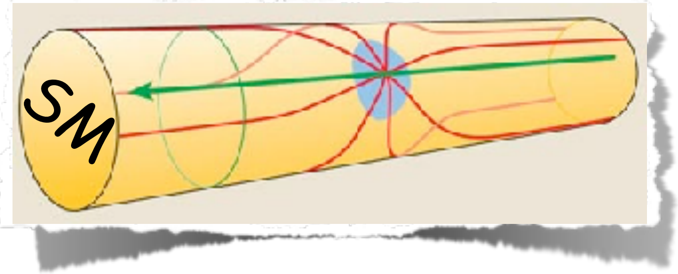
$$m_n = p_y^n = \frac{n}{R}$$

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



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

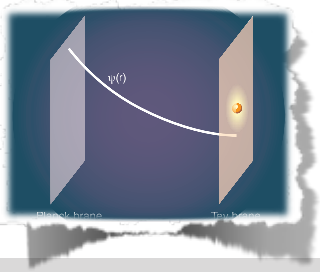
$$M_{Pl}^2 = V_n M_\star^{2+n}$$

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

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

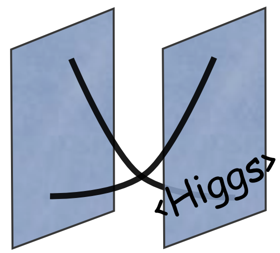
$M_* = 10^{19}$ GeV $\qquad v = 250$ GeV

$R \sim 11/M_*$

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

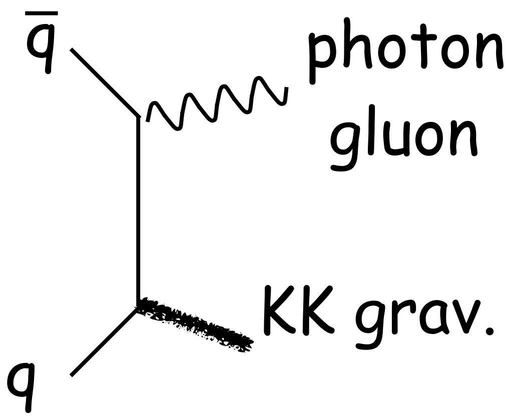
- orbifold breaking, Higgsless

Large volume xdim phenomenology

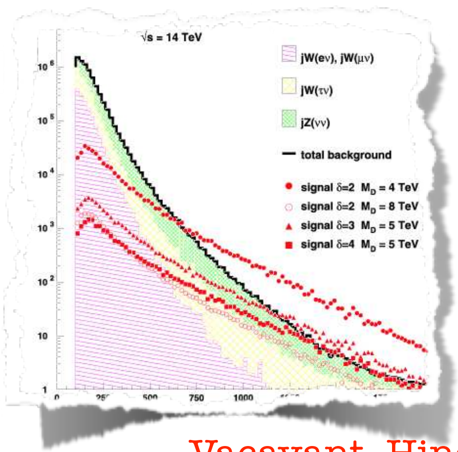
eV splitting between graviton KK modes

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

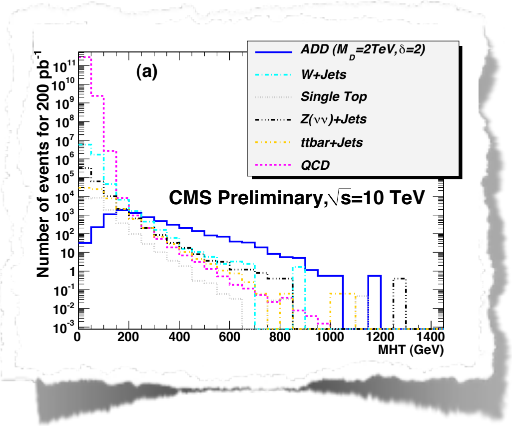
- Graviton production in colliders



monojet+$\not{E}_T$

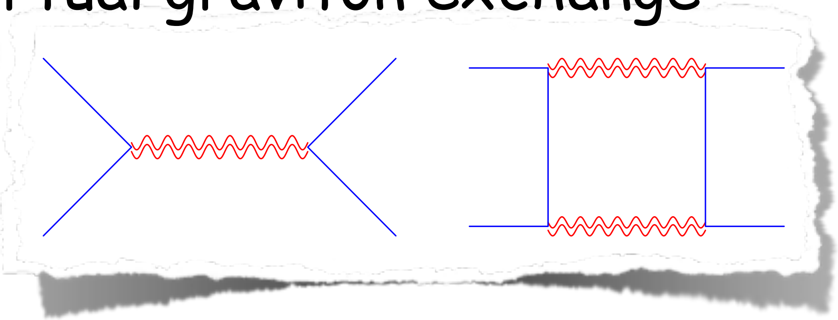


Vacavant, Hinchliffe '01



CMS PAS EXO 09-013

- Virtual graviton exchange

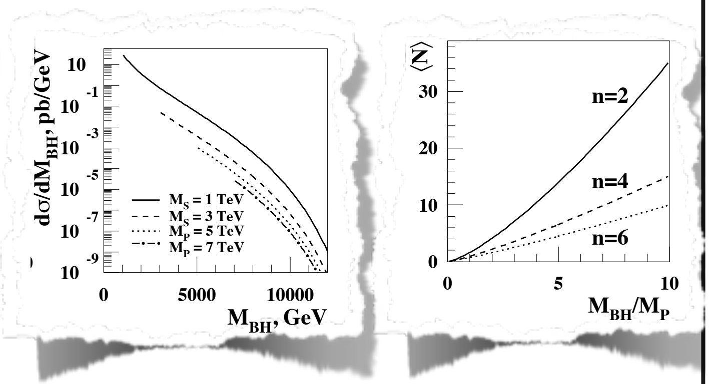


Large volume xdim phenomenology

- 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



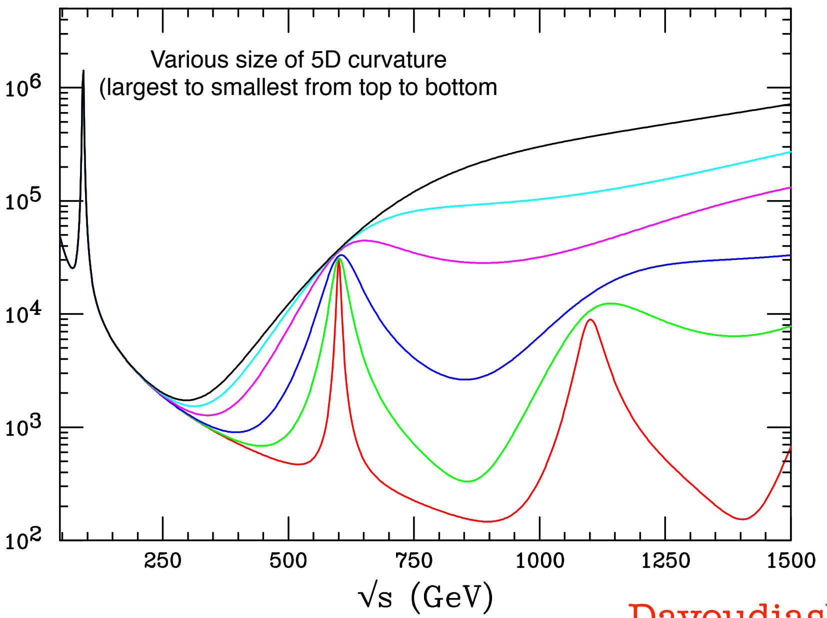
Dimopoulos, Landsberg, '01

- String resonances production

Curved xdim phenomenology

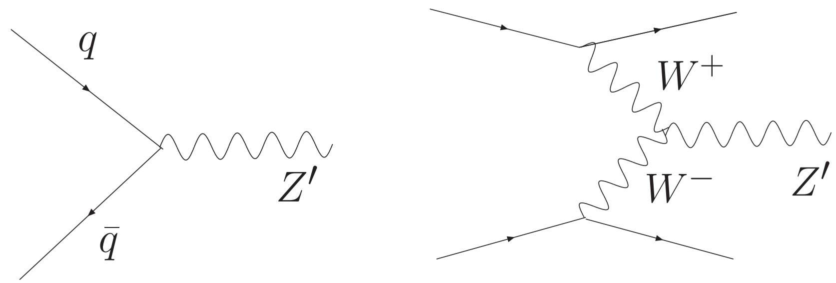
TeV splitting between gauge KK modes

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

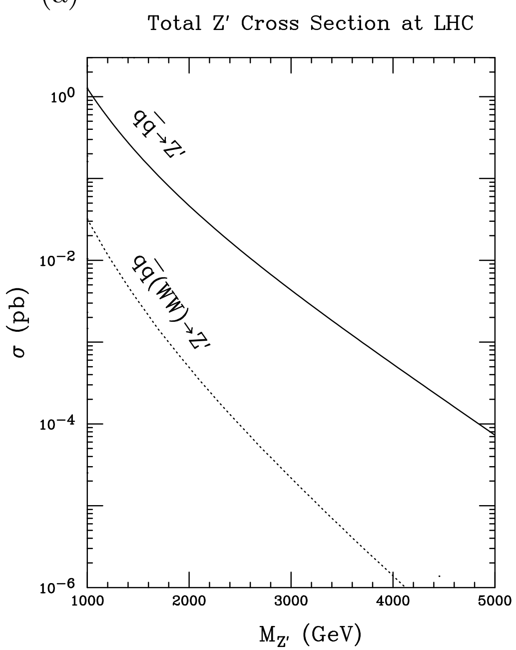


Davoudiasl et al '99

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



(a) (b)



Agashe et al '07

current LHC bounds on KK resonance
O(few) TeV