BSM PHYSICS

Where will we go to?

PHYSICS AT THE TERA SCALE

Helmholtz Alliance

Eleventh Annual meeting
DESY, Nov. 29, 2017

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DESY

HELMHOLTZ GEMEINSCHAFT

HUMBOLDT-UNIVERSITÄT ZU BERLIN

What is physics beyond the Standard Model?

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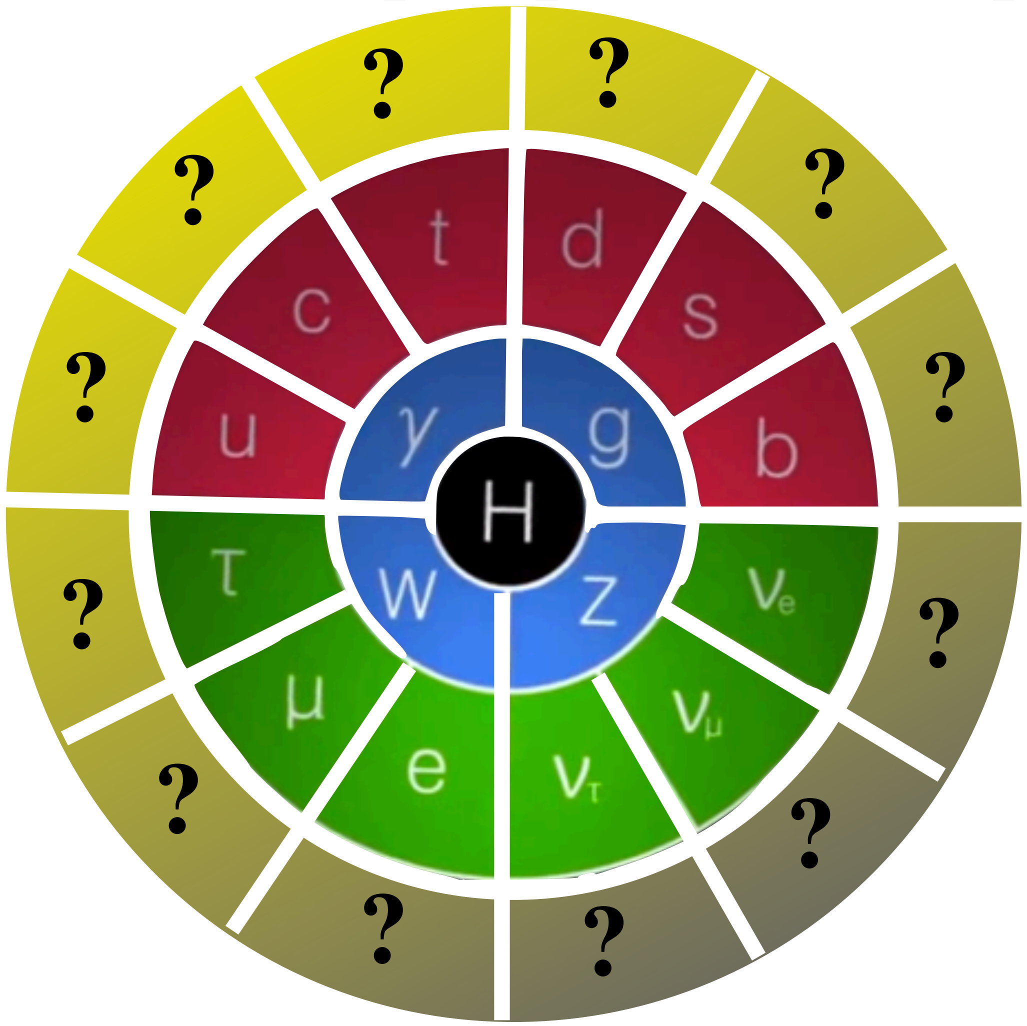

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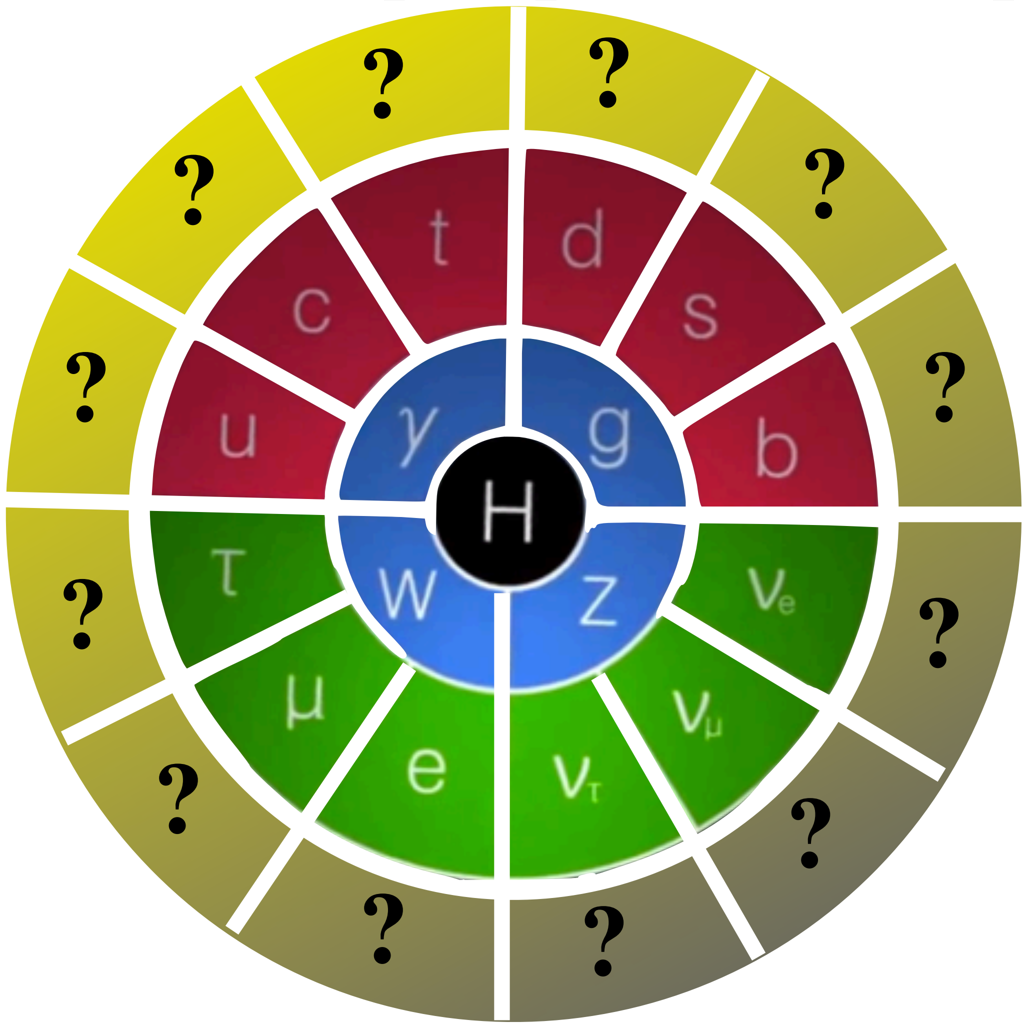
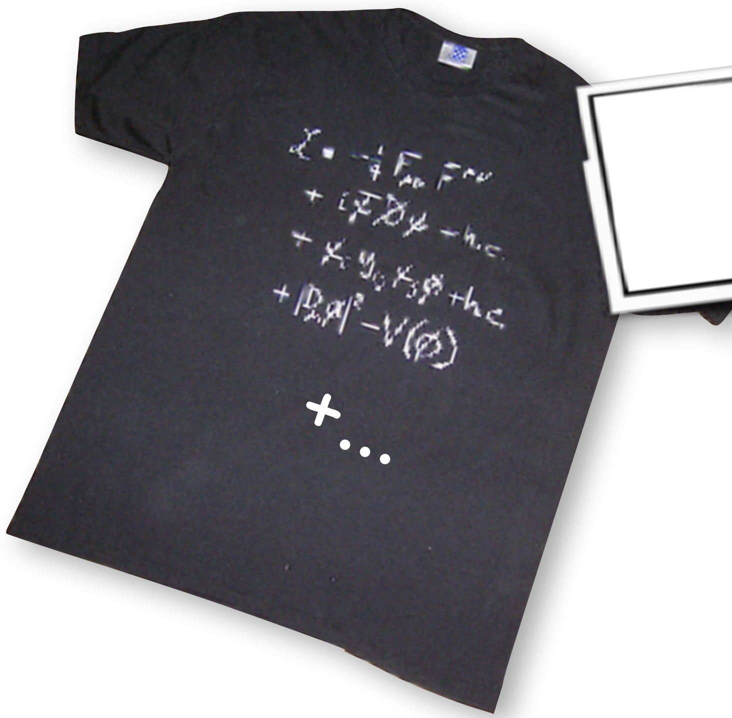


I don't know. Nobody knows [If it were known, it would be part of the SM!]
Many evidences that BSM exist
We just don't know what it is
We have plenty of good ideas and there are rich opportunities
But no guarantee we are on the right track
We should stay open-minded and also learn from our failures

" Looking and not finding is different than not looking "

Why BSM?



is not enough

[and HEP practitioners have to return SM royalties!]

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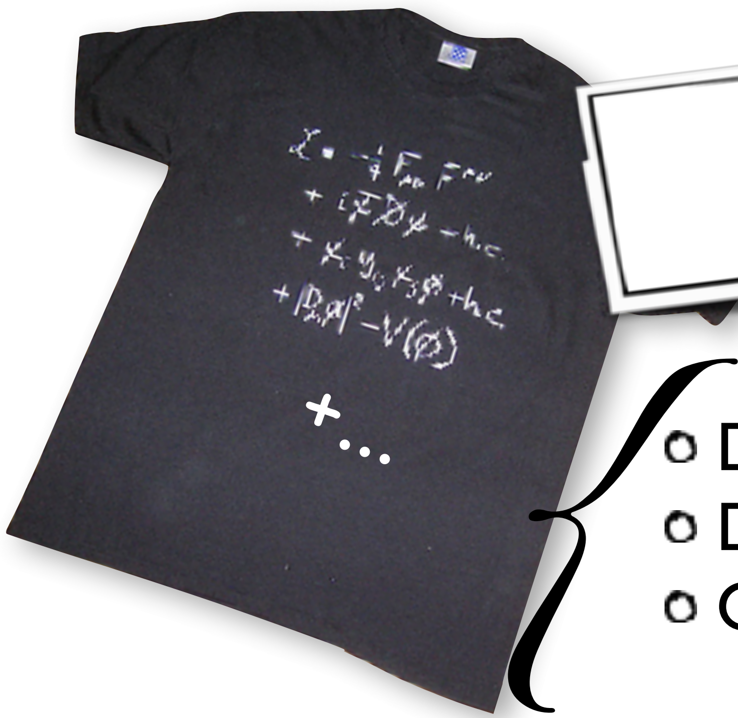

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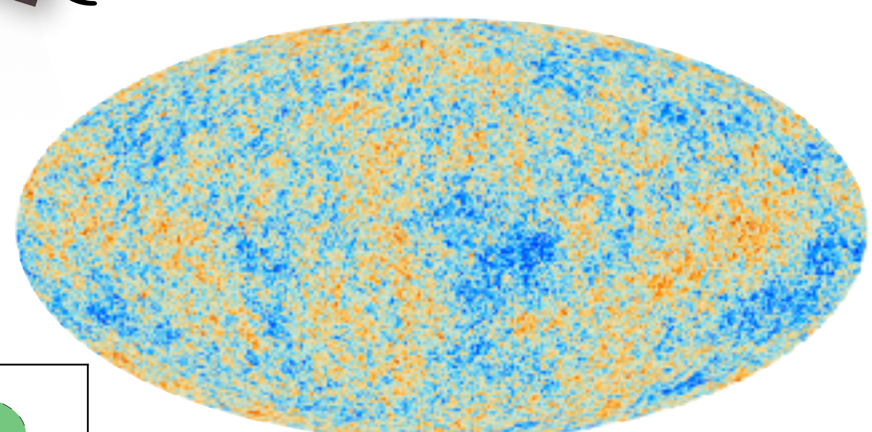
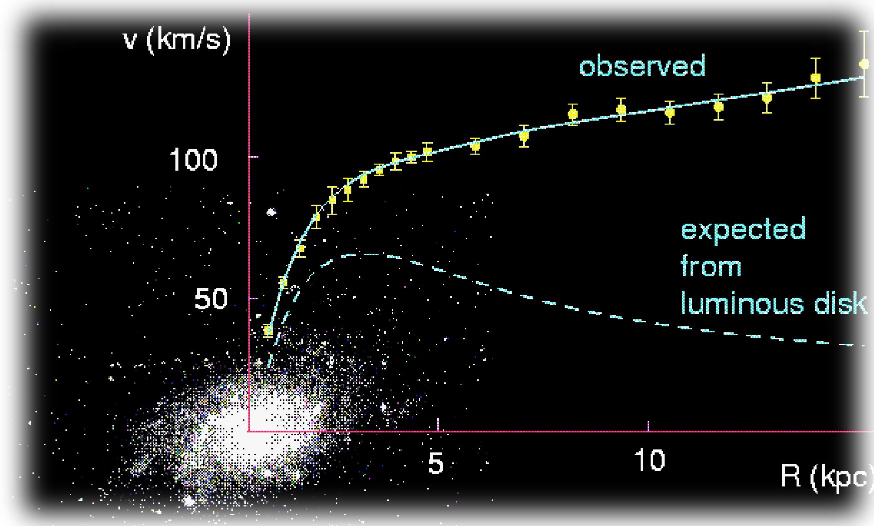
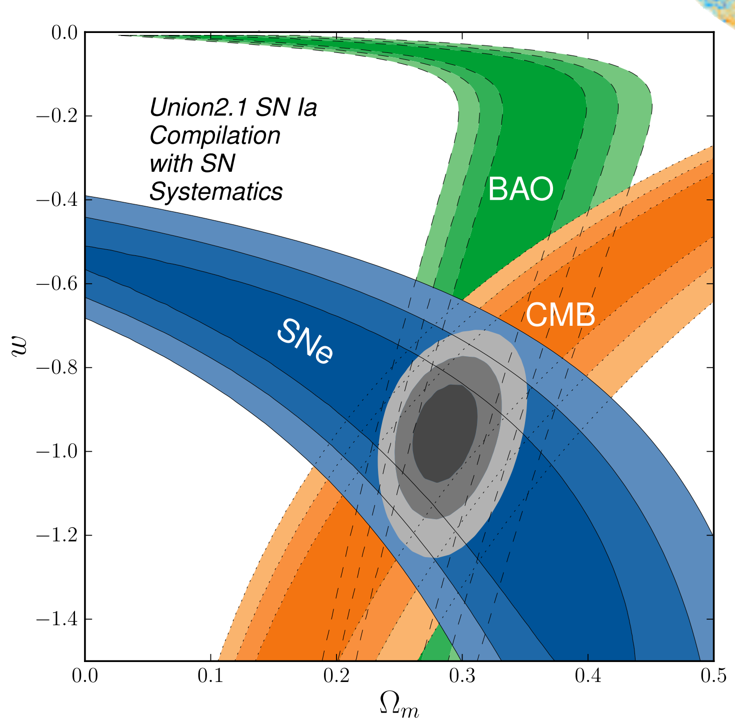
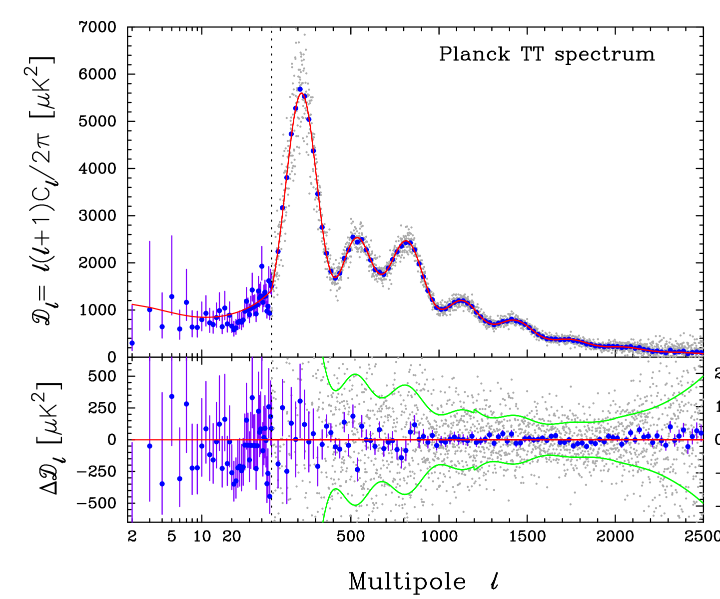
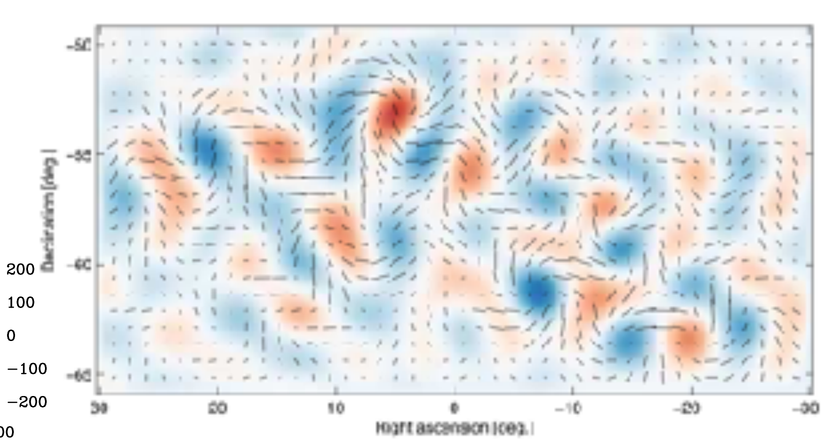
- Dark Matter
- Dark Energy
- Quantum gravity











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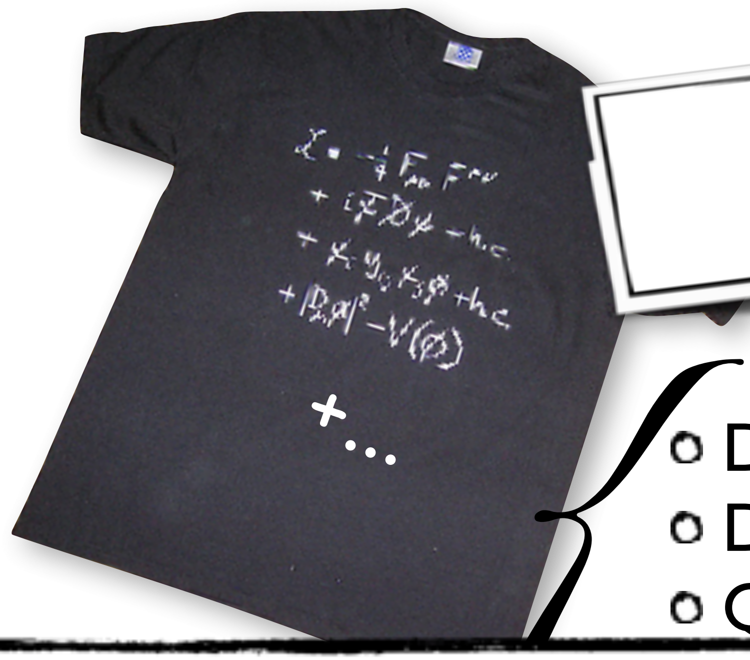

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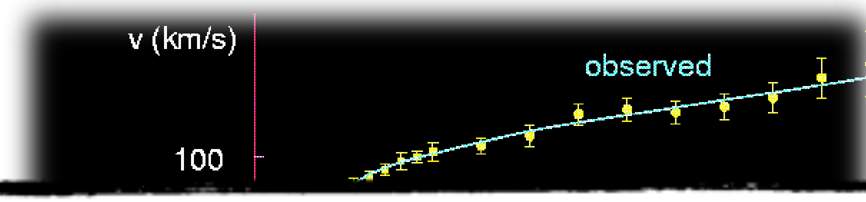


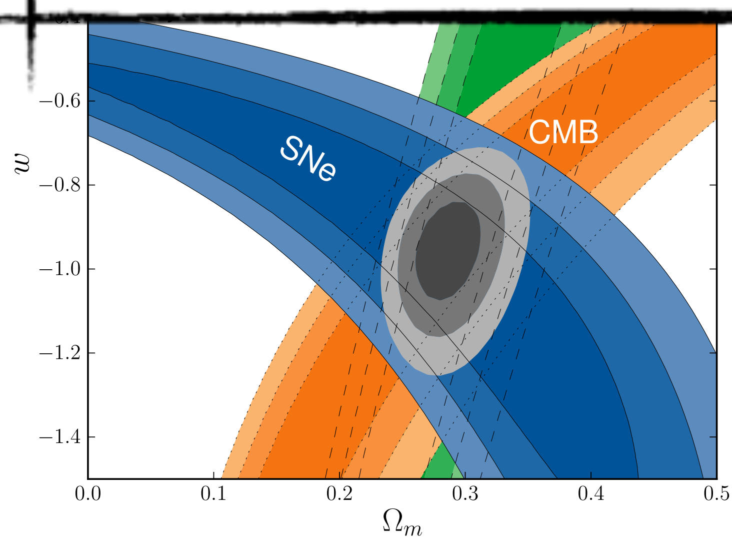
BSM searches have numerous spin-offs

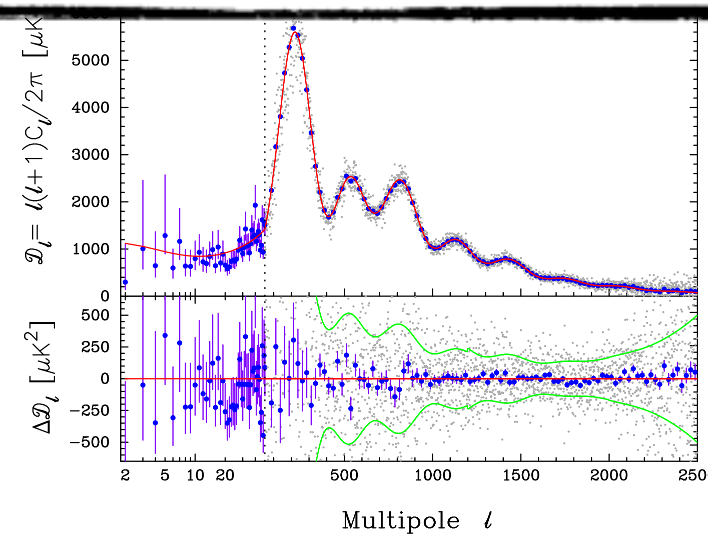
⦿ Force us to understand the SM thoroughly ⦿

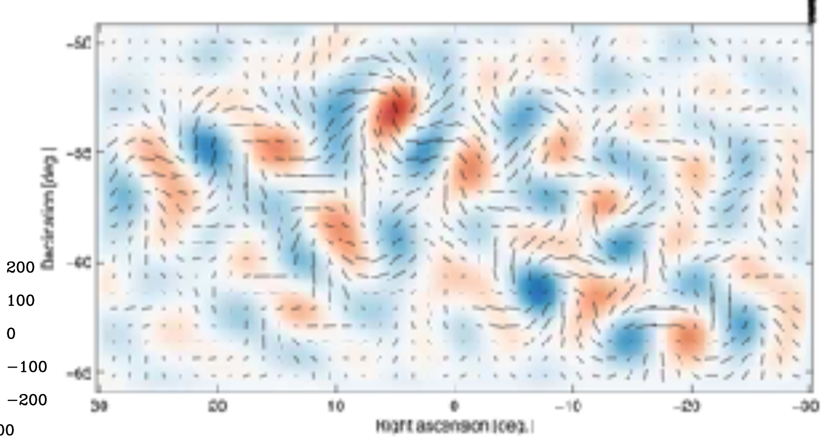
⦿ Boost creativity of theorists ⦿

⦿ Advance technological progress to cope with experimental challenges ⦿

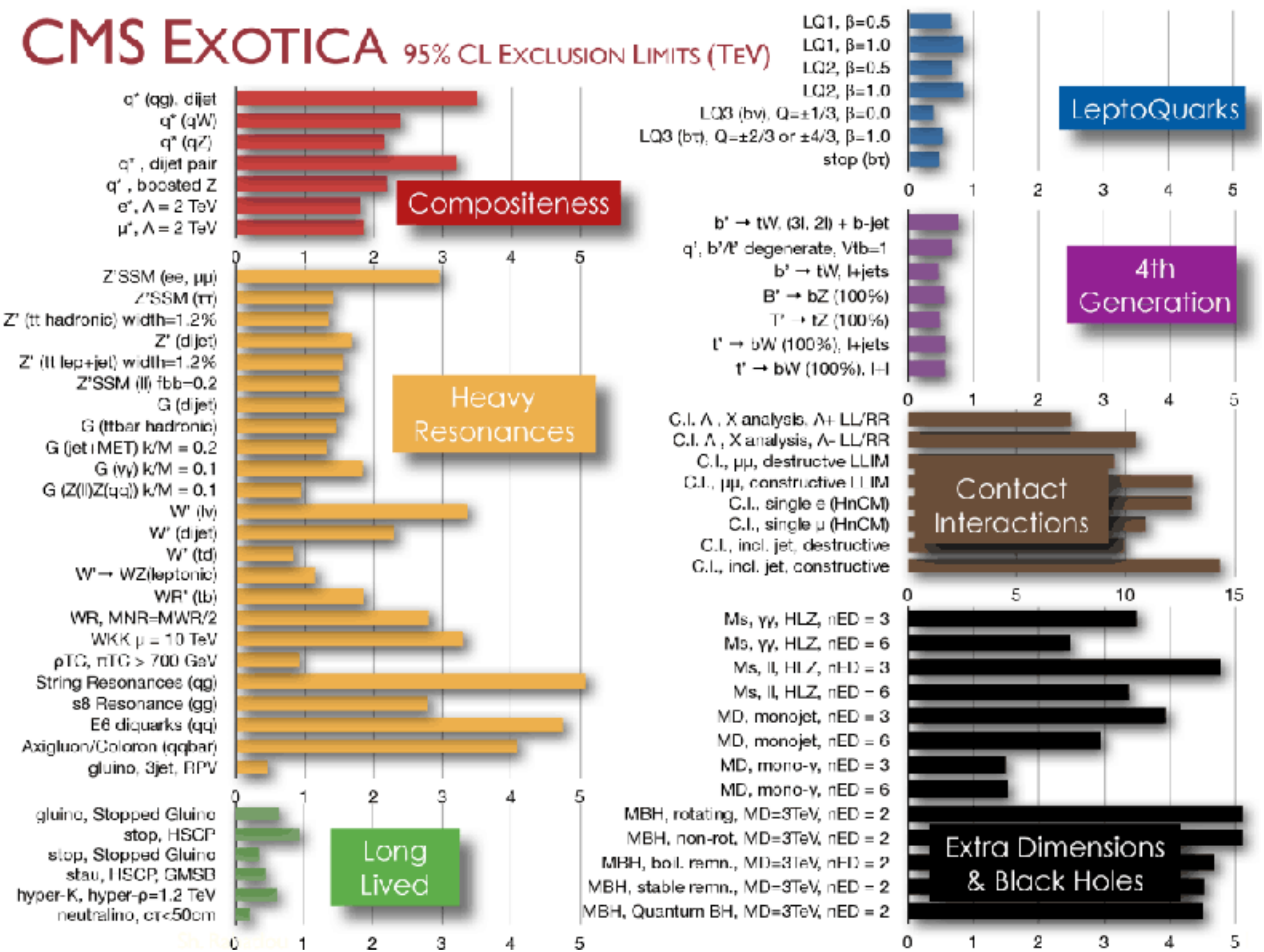
⦿ Keep us entertained ⦿







Current status of BSM searches



Current status of BSM searches

lost in translation: Babel tower!

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the ultimate goal

Current status of BSM searches

lost in translation: Babel tower!

the ultimate goal

theorists and experimentalists also need
to start speaking a common language

Discovering New Physics: the different paths

new discoveries can follow from

- **Disagreements between theory predictions and experimental data**
  - ↪ e.g. Newton mechanics and constant speed of light
- **Apparent fine-tunings**
  - ↪ charm quark to screen the Kaon mass difference
- **Theoretical inconsistencies**
  - ↪ W boson to regularize Fermi theory, Higgs boson to unitarize WW scattering
- **Serendipity**
  - ↪ CMB discovery
- **Surprises**
  - ↪ muon

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Post-Higgs discovery: SM has no (major) theoretical inconsistencies

apart maybe black hole information paradox which might require soft hairs i.e. massless particles with zero momentum located at the infinite future boundary of the horizon

(Hawking, Perry, Strominger '16)

Need powerful machines to explore the unknown* through the intensity and energy frontiers

What is the scale of New Physics?

High Scale Wishes

small FCNC: $\dfrac{gF_{\mu\nu}\bar{\psi}H\sigma^{\mu\nu}\psi}{M_{\rm NP}^2}$

tiny neutrino masses: $\dfrac{(LH)^2}{M_{\rm NP}}$

slow proton decay: $\dfrac{UUDE}{M_{\rm NP}^2}$

$\Longleftrightarrow$

Low Scale Wishes

small EDMs: $\mathrm{argdetY} \leq 10^{-10}$

↪ axion?

tiny vacuum energy: $\Lambda \approx M_{\rm NP}^4 \gg \left(10^{-3}\mathrm{eV}\right)^4$

↪ ?

light Higgs boson: $m_H^2 \approx M_{\rm NP}^2 \gg (125\mathrm{GeV})^2$

↪ light susy?

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Where is everyone?

even new physics at few hundreds of GeV might be difficult to see and could escape our detection

- **compressed spectra**
- **displaced vertices**
- **no MET, soft decay products, long decay chains**
- **uncoloured new physics**

- **$\not{R}$-susy**
- **Neutral naturalness** (twin Higgs, folded susy)
- **Relaxion**

BSM probes

in order to address the physics questions that dwell outside the SM boundaries the experimental physics program should be built around five key goals

1. Measurement of the properties of the newly-discovered **Higgs** boson with very high precision. ⇛ Is it elementary? Does it have siblings/relatives? What keeps it light? Why does it freeze in?

2. Measurement of the properties of the **top** quark with very high precision to indirectly constrain new physics

3. Precision measurements of the EW observable: the **Z** boson will be the atomic clock of High Energy Physics.

4. Direct searches for and studies of (uncolored) **new particles** expected in models of physics at the TeV energy scale. Complementary to LHC searches.

5. Provide **definitive answers** to broad physics questions: e.g. (i) new physics at TeV scale? (ii) TeV-scale solution to the hierarchy pb? (iii) DM=WIMP? (iv) electroweak baryogenesis?

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Exploration potential

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Physics answers

The way forward

- increased energy
- increased statistics

- increased precision
- increased sensitivity

- High rates allow the exploration of **rare** phenomena and **extreme** phase space configurations

- High rates also shift the **balance** between **systematic** and **statistical** uncertainties. It can be exploited to define different signal regions, with better S/B, better systematics, pushing the potential for better measurements beyond the "systematic wall" of low stat. measurements

HL-LHC will change the rules of the game
opening new search opportunities

(i) Guaranteed deliverables

Higgs

similar discussions can be done for top and EW gauge bosons
see different talks at this meeting for concrete examples

HEP with a Higgs boson

breathtaking successes

- in O(5) years, the Higgs mass has been measured to 0.2% (vs 0.5% for the 20-year old top)
- some of its couplings, e.g. κ_γ, have been measured with 1-loop sensitivity (as EW physics at LEP)

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Higgs agenda for the LHC-II, HL-LHC, ILC/CLIC, FCC, CepC, SppC

multiple independent, synergetic and complementary approaches to achieve **precision** (couplings), **sensitivity** (rare and forbidden decays) and **perspective** (role of Higgs dynamics in broad issues like EWSB and vacuum stability, baryogenesis, inflation, naturalness, etc)

M.L. Mangano, Washington '15

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- rare Higgs decays: $h\to\mu\mu$, $h\to\gamma Z$
- Higgs flavor violating couplings: $h\to\mu\tau$ and $t\to hc$
- Higgs CP violating couplings
- exclusive Higgs decays (e.g. $h\to J/\Psi+\gamma$) and measurement of couplings to light quarks
- exotic Higgs decay channels:

  $h\to \cancel{E}_T$, $h\to 4b$, $h\to 2b2\mu$, $h\to 4\tau, 2\tau 2\mu$, $h\to 4j$, $h\to 2\gamma 2j$, $h\to 4\gamma$, $h\to \gamma/2\gamma+\cancel{E}_T$,

  $h\to$ isolated leptons$+\cancel{E}_T$, $h\to 2l+\cancel{E}_T$, $h\to$ one/two lepton-jet(s)$+X$, $h\to bb+\cancel{E}_T$, $h\to \tau\tau+\cancel{E}_T$ ...
- searches for extended Higgs sectors ($H, A, H^\pm, H^{\pm\pm}$...)
- Higgs self-coupling(s)
- Higgs width
- Higgs/axion coupling?
- ...

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complementarity and synergy needed to achieve the full program

HEP with a Higgs boson

The Higgs discovery has been an important milestone for HEP
but it hasn't taught us much about **BSM** yet

typical Higgs coupling deformation: $\frac{\delta g_h}{g_h} \sim \frac{v^2}{f^2} = \frac{g_*^2\, v^2}{\Lambda_{\rm BSM}^2}$

current (and future) LHC sensitivity
O(10-20)% ⇔ Λ_{BSM} > 500(g_*/g_{SM}) GeV

not doing better than direct searches unless in the case of strongly coupled new physics
(notable exceptions: New Physics breaks some structural features of the SM
e.g. flavor number violation as in h→$\mu\tau$)

Higgs precision program is very much wanted
to probe BSM physics

...

Why going beyond inclusive Higgs processes?

So far the LHC has mostly produced Higgses on-shell
in processes with a characteristic scale $\mu \approx m_H$

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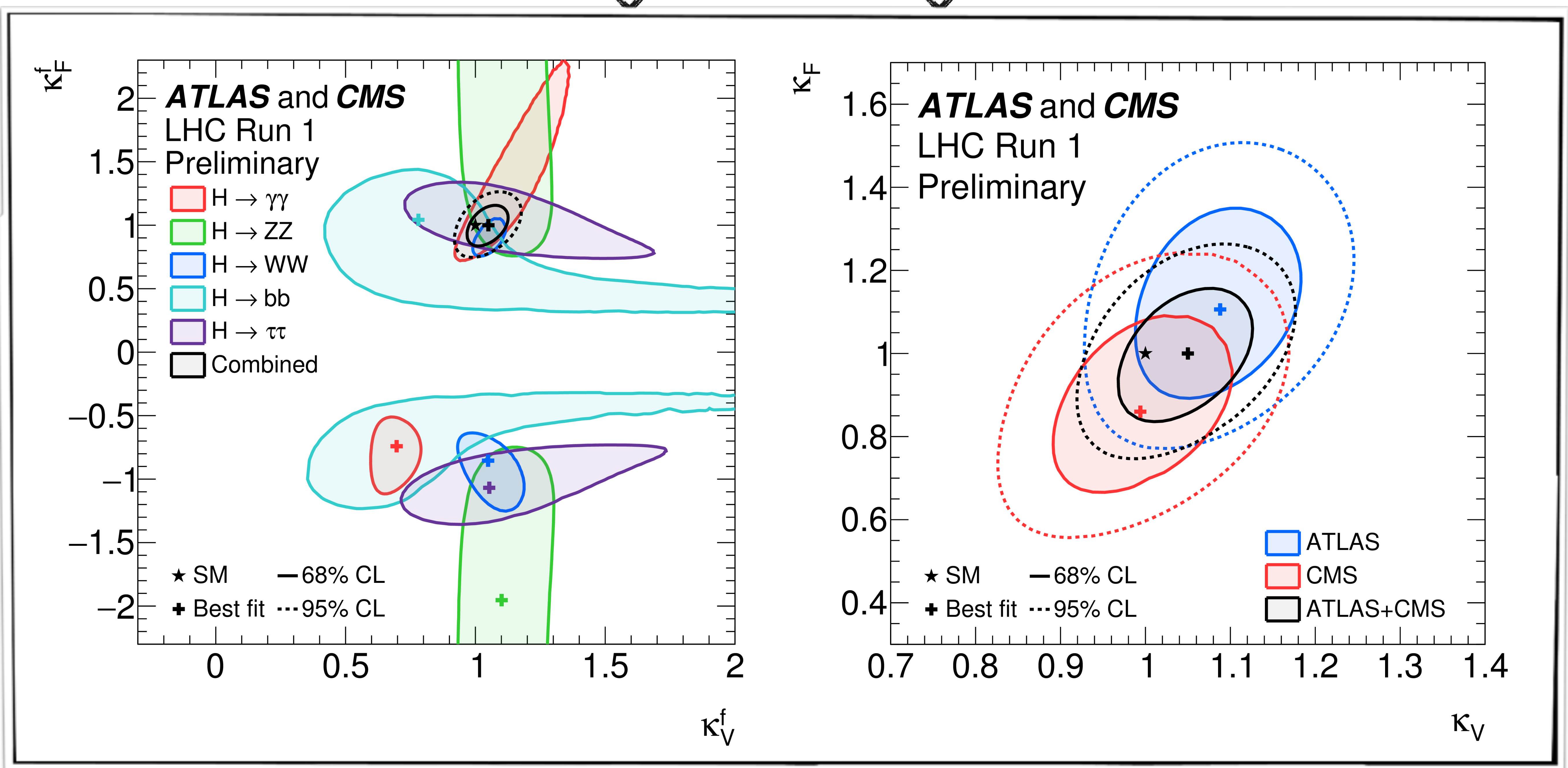

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$\Downarrow$ $\Downarrow$

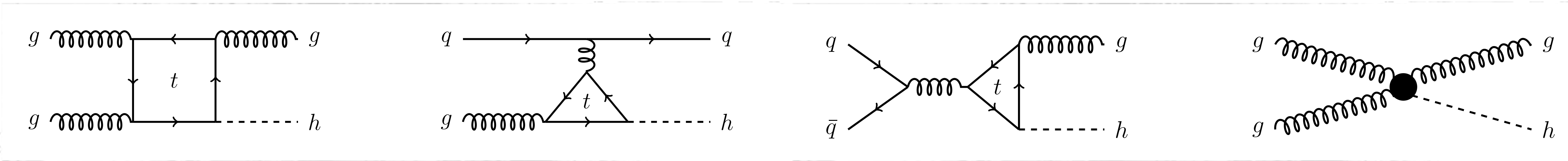
access to Higgs couplings @ m_H

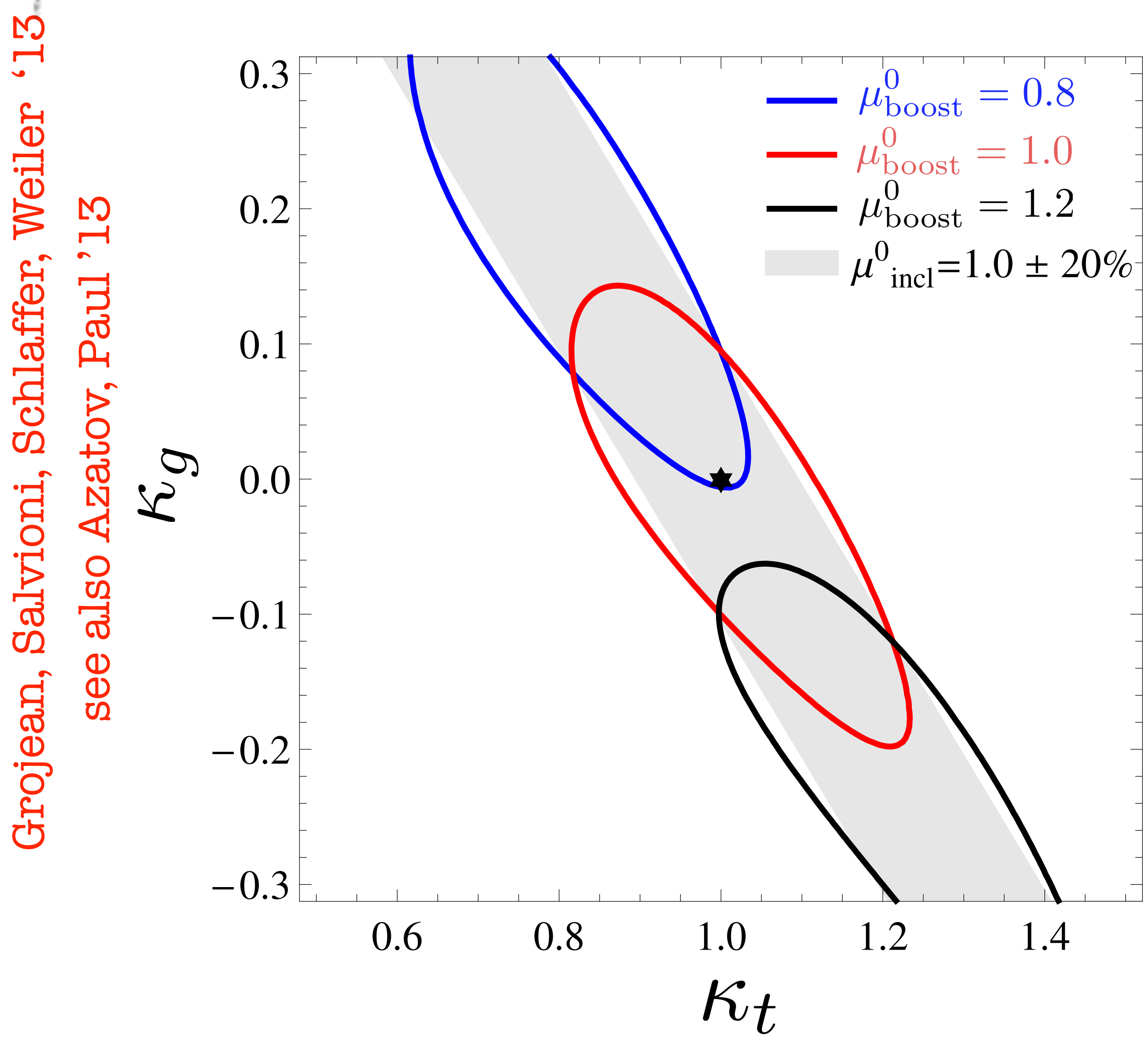
Producing a Higgs with boosted additional particle(s)
probe the Higgs couplings @ large energy
(important to check that the Higgs boson ensures perturbative unitarity)

Examples of interesting channels to explore further:

1. off-shell $gg \to h^* \to ZZ \to 4l$
2. boosted Higgs: Higgs+ high-p_T jet
3. double Higgs production

Boosted Higgs+jet





high p_T tail discriminates
short and long distance physics contribution to gg → h

$$\sqrt{s} = 14 \text{ TeV}, \int dt\, \mathcal{L} = 3\text{ab}^{-1}, p_T > 650 \text{ GeV}$$

(partonic analysis in the boosted "ditau-jets" channel)

see Schlaffer et al '14 for a more complete analysis including WW channel

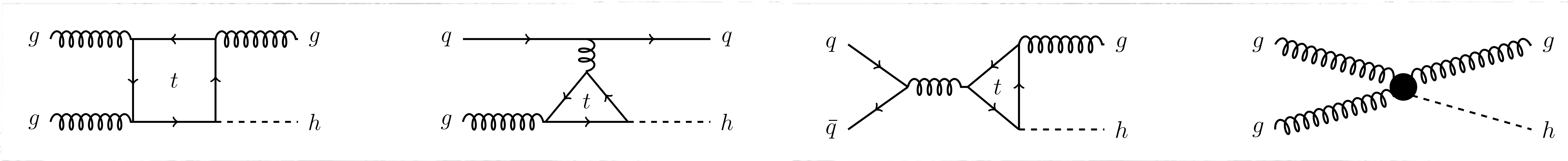
10-20% precision on κ_t

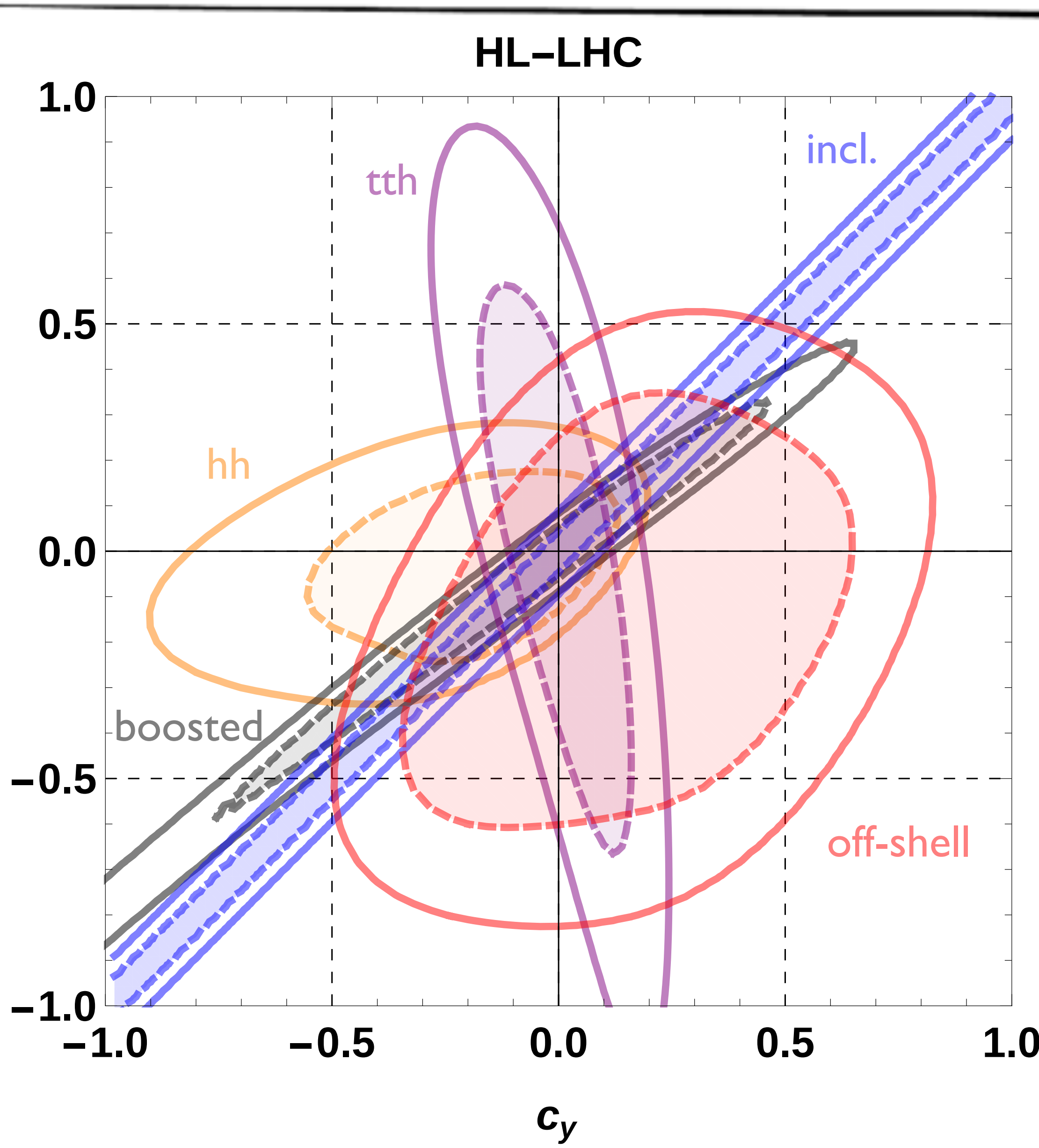
⇓ ⇓

competitive/complementary to htt channel for the measure the top-Higgs coupling

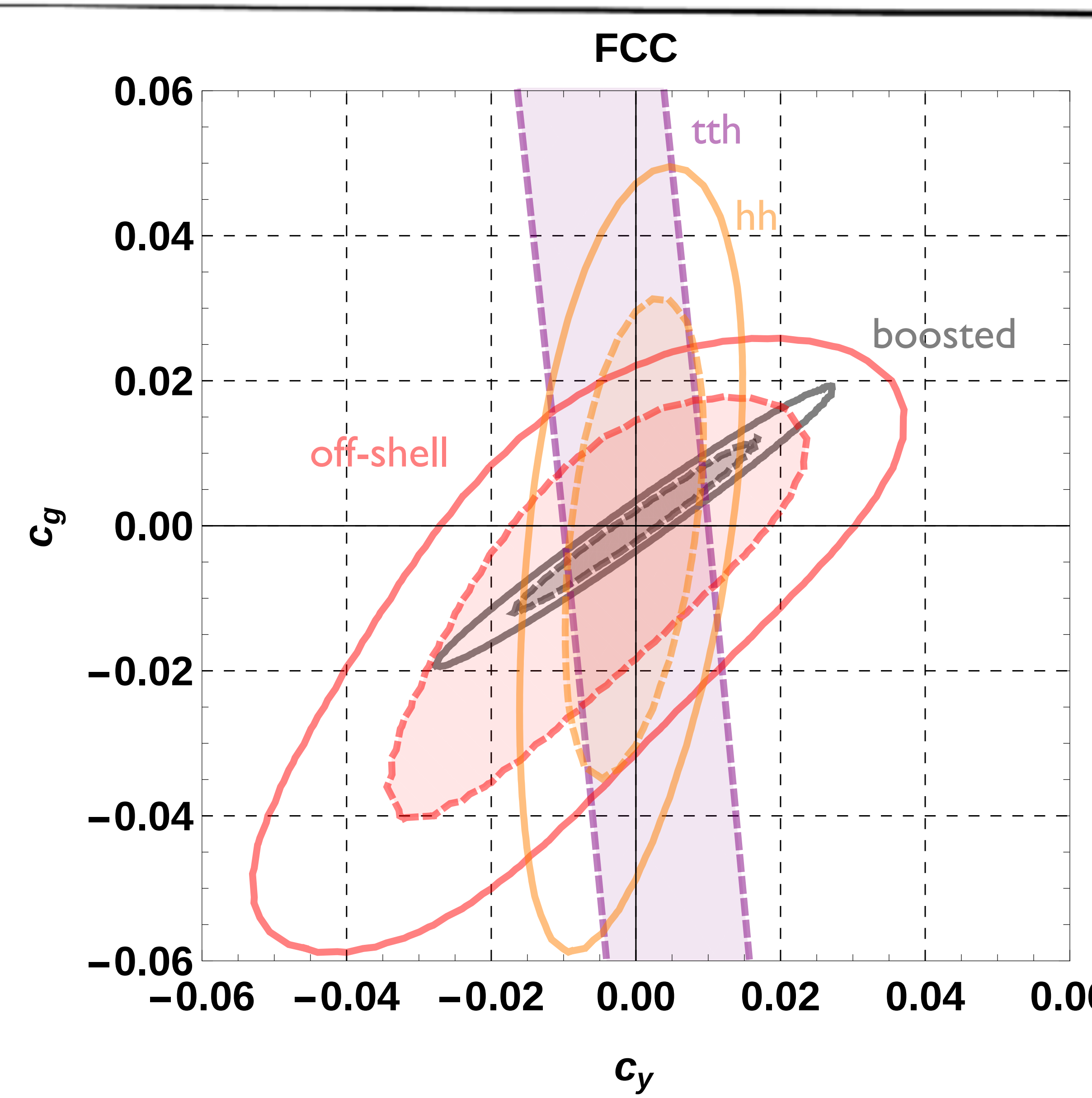
Are the NLO_m QCD corrections (not known) going to destroy all the sensitivity?
Frontier priority: N^3LO_∞ for inclusive xs or NLO_{mt} for pT spectrum?

Boosted Higgs+jet





see also Azatov, Paul '13



Azatov, Grojean, Paul, Salvioni '16

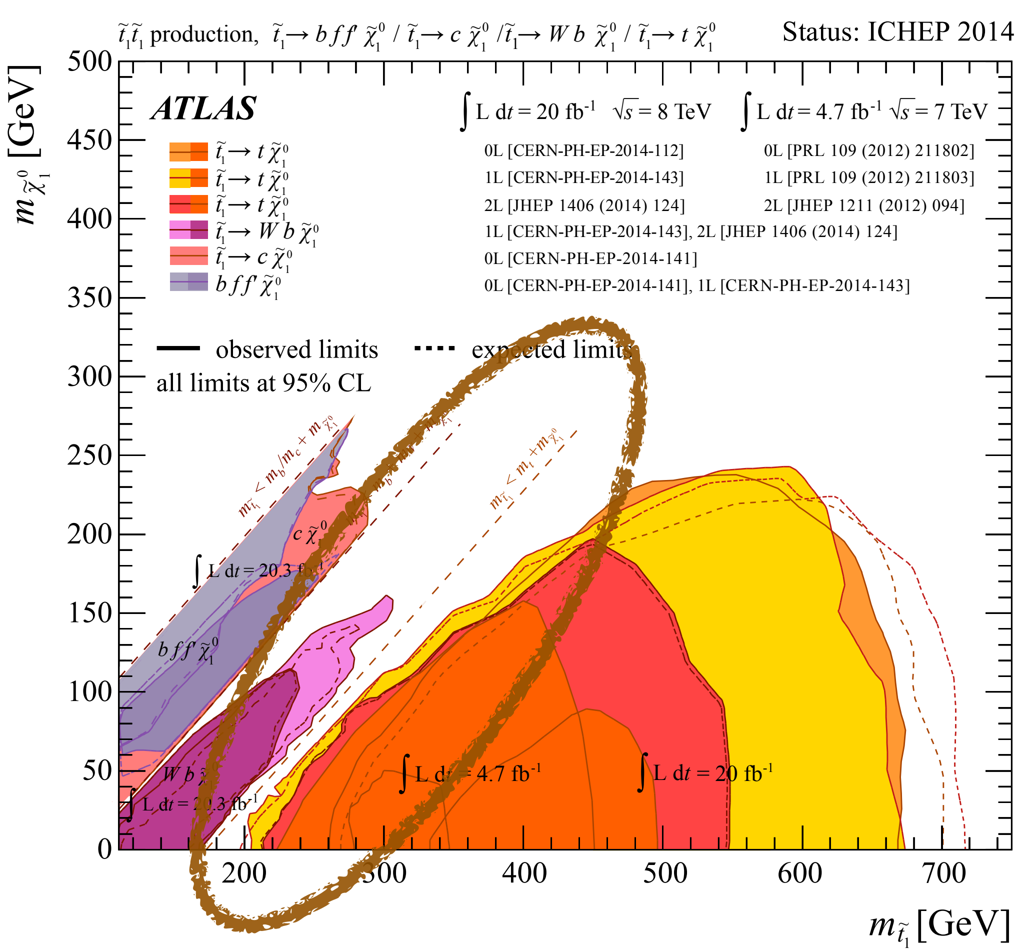
Light stop searches from Higgs+jet

natural susy calls for light stop(s) that can affect the Higgs physics

$$\frac{\Gamma(h \leftrightarrow gg)}{\Gamma(h \leftrightarrow gg)_{\rm SM}} = (1+\Delta_t)^2 \ , \qquad \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} = (1-0.28\Delta_t)^2 \qquad \text{with} \quad \Delta_t \approx \frac{m_t^2}{4}\left(\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)$$

... or not if $\Delta_t \approx 0$ ⇒ light stop window in the MSSM

(stop right ~200-400GeV ~ neutralino w/ gluino < 1.5 TeV)



There are various arguments that favour this light stop region

- ✦flavor constraints (ε_K, B→X_s+γ)
- ✦ RG evolution
- ✦ DM

Delgado et al '12

inclusive Higgs measurements cannot rule out light stop and difficult direct search (trigger on stop+extra jet)

One prime example where large statistics opens up new search strategy

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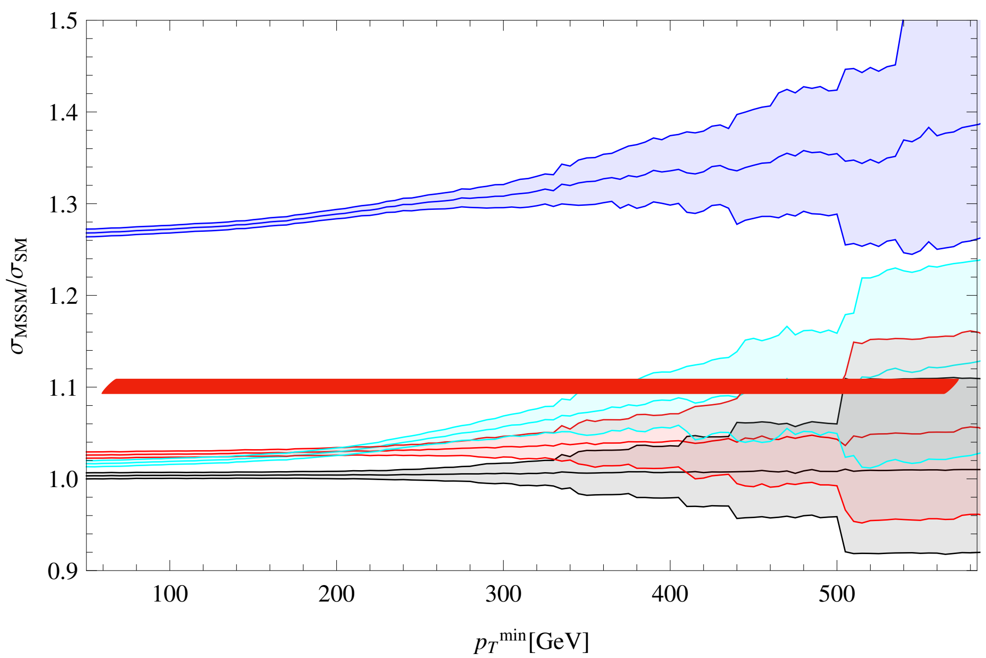


Grojean, Salvioni, Schlaffer, Weiler '13

There are various arguments that favour this light stop region

P1: mt1=395, mt2=2412, At=2420, Δt=0.002
P2: mt1=192, mt2=1224, At=1220, Δt=0.01
P3: mt1=259, mt2=1212, At=0, Δt=0.12
P4: mt1=226, mt2=484, At=532, Δt=0.015

Light stop benchmark
that leaves no signal in inclusive rate
but predicts different tail in p_T
distribution

inclusive Higgs measurements cannot rule out light stop

but O(10%) sensitivity on boosted h+j can
close up the light stop window
Low rate ⇔ large luminosity needed

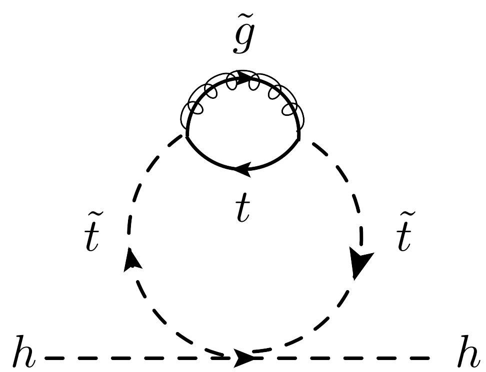
One prime example where large statistics opens up new search strategy

(ii) Exploration potential

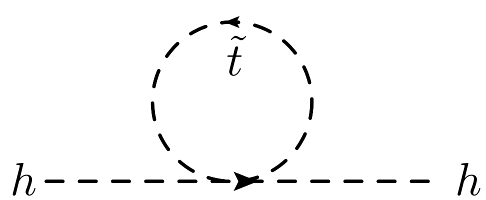
New Physics

e.g. susy searches, vector resonances, extended Higgs sectors, searches for new interactions

I. Probing natural SUSY

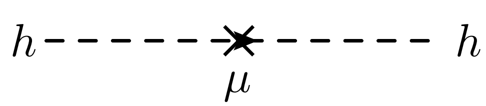


$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi} m_{gluino}^2 \left(\log \frac{\Lambda}{m_{gluino}}\right)^2$$



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

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

I. Probing natural SUSY

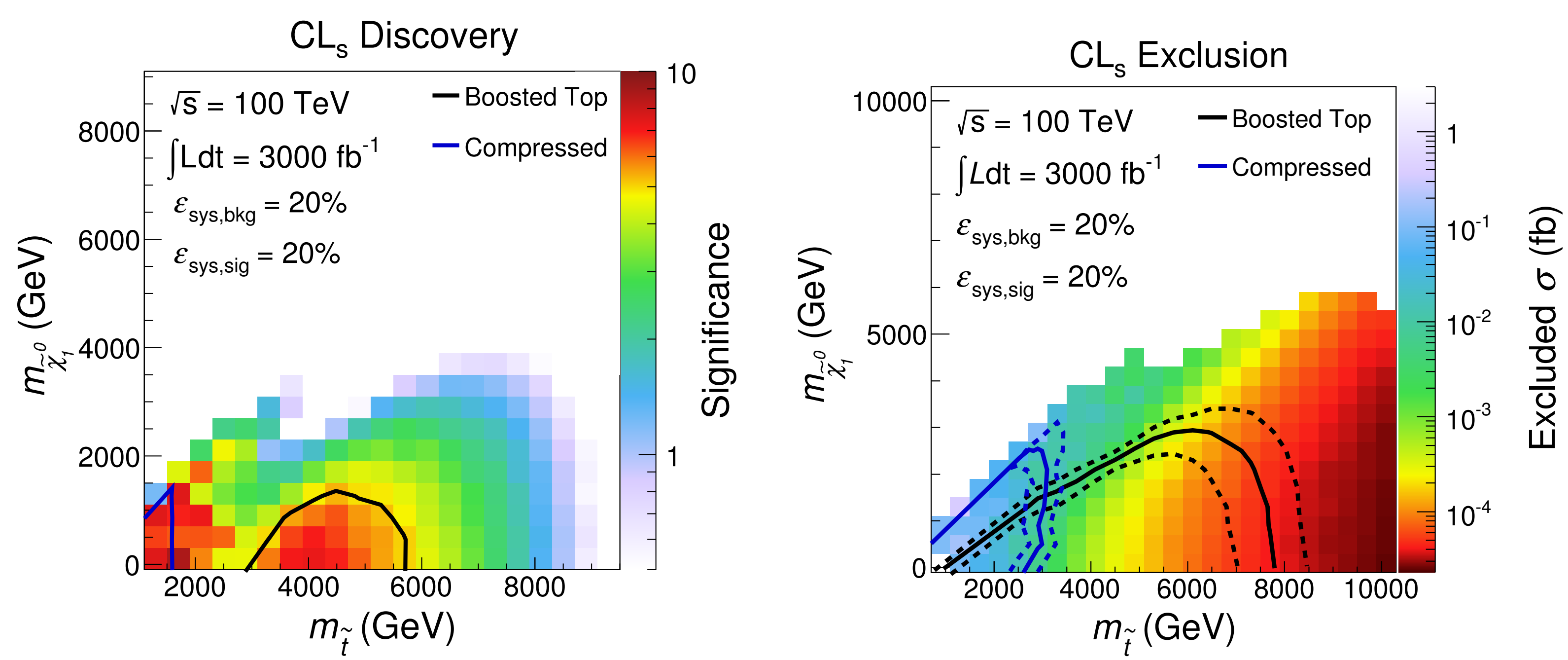


Fig. 12: Left: Discovery potential and Right: Projected exclusion limits for 3000 fb^{-1} of total integrated luminosity at $\sqrt{s} = 100$ TeV. The solid lines show the expected discovery or exclusion obtained from the boosted top (black) and compressed spectra (blue) searches. In the boosted regime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

I. Probing natural SUSY

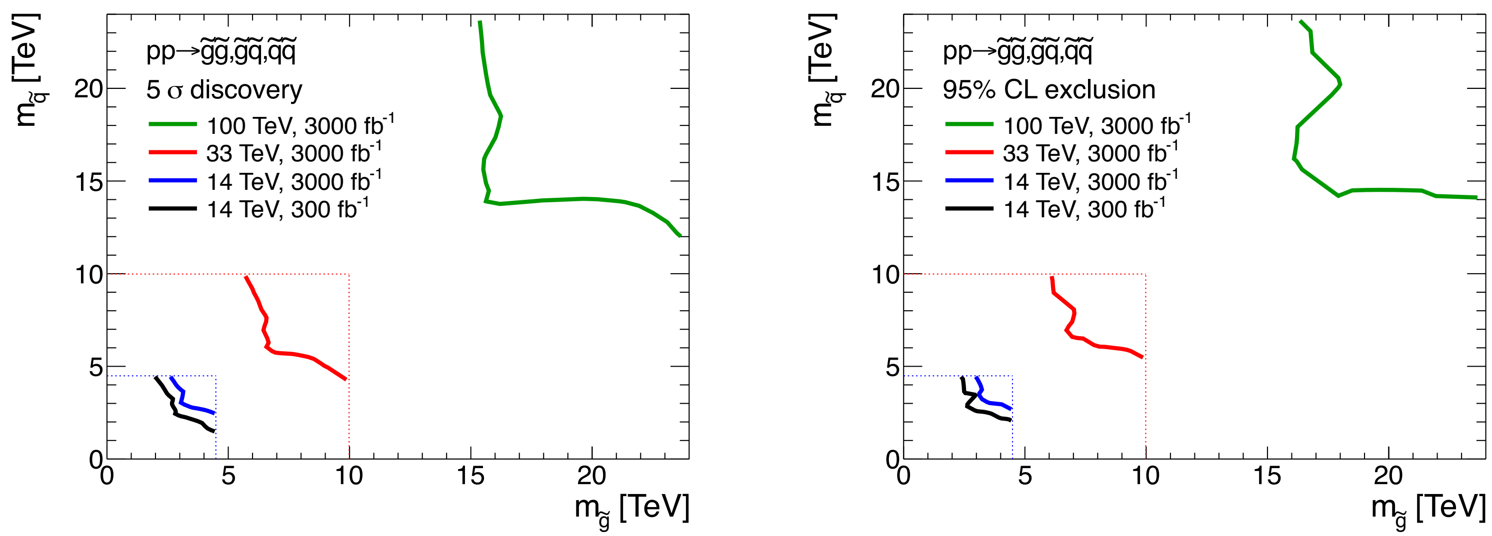
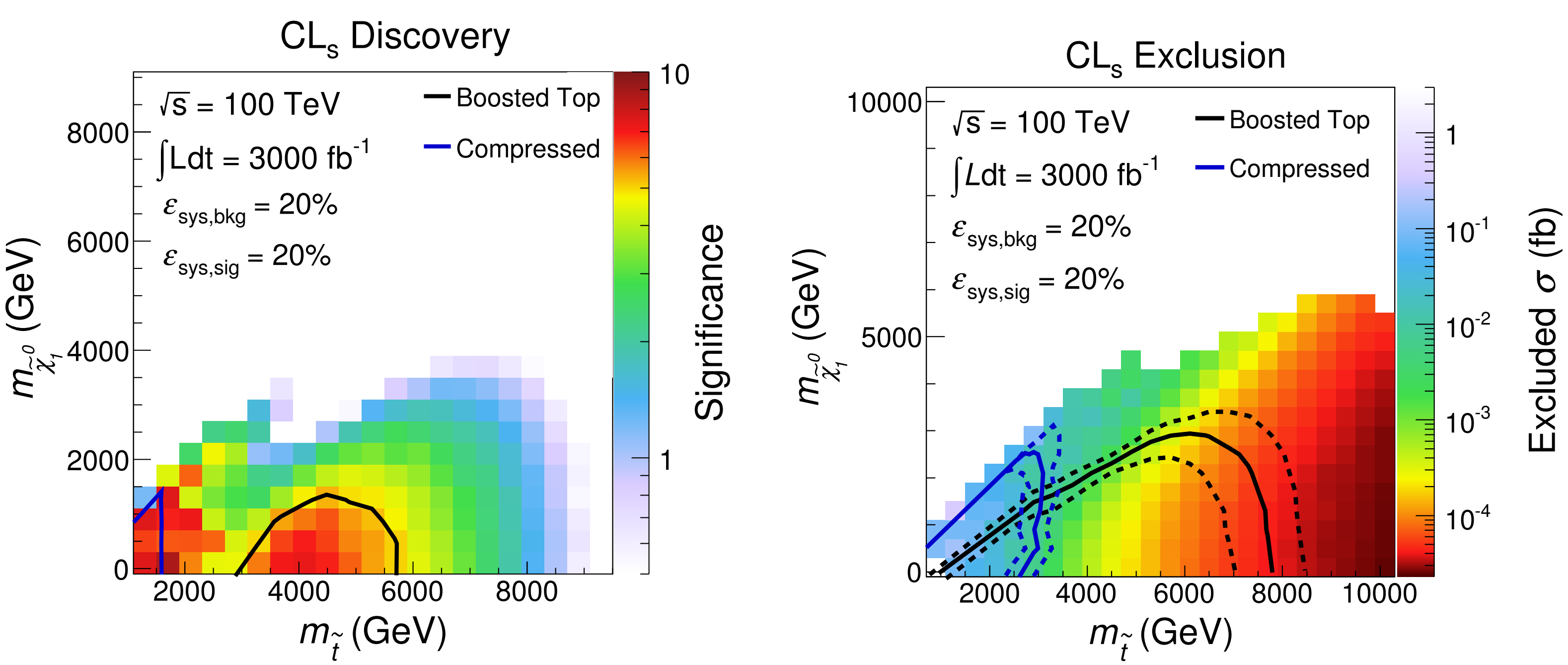


Fig. 16: Results for the gluino-squark-neutralino model. The neutralino mass is taken to be 1 GeV. The left [right] panel shows the $5\,\sigma$ discovery reach [95% CL exclusion] for the four collider scenarios studied here. A 20% systematic uncertainty is assumed and pile-up is not included.



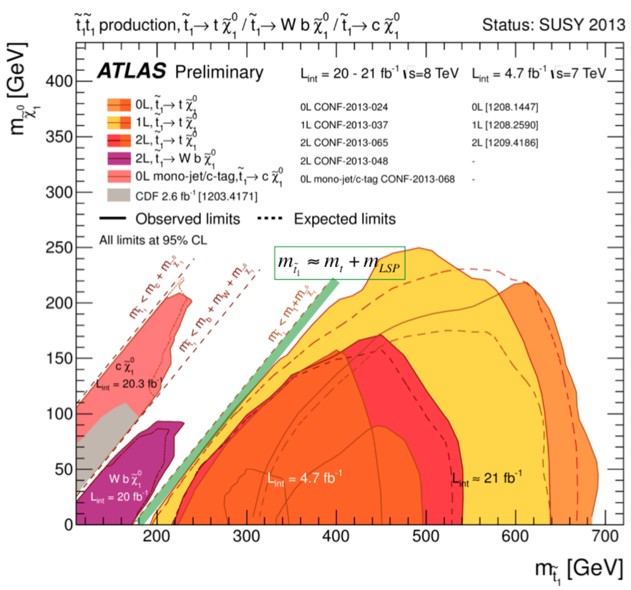
Collider	Energy	Luminosity	Cross Section	Mass
LHC8	8 TeV	20.5 fb^{-1}	10 fb	650 GeV
LHC	14 TeV	300 fb^{-1}	3.5 fb	1.0 TeV
HL LHC	14 TeV	3 ab^{-1}	1.1 fb	1.2 TeV
HE LHC	33 TeV	3 ab^{-1}	91 ab	3.0 TeV
FCC-hh	100 TeV	1 ab^{-1}	200 ab	5.7 TeV

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.

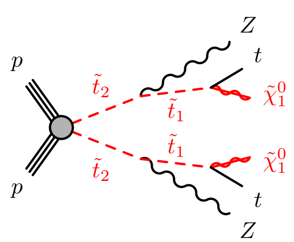
I. Natural SUSY: beyond standard searches

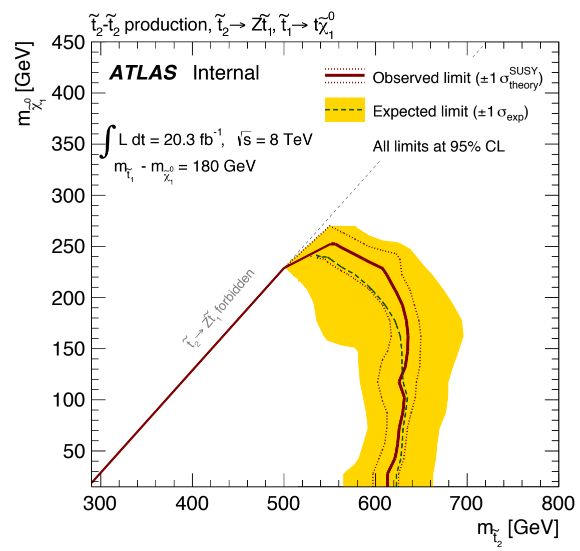
Searching for light stop from heavy stop decay

~ RUN 1 ~



- 2012 (20 fb^{-1}): stops searches based on $\tilde{t}_1\tilde{t}_1$ production, with $\tilde{t}_1 \to t\tilde{\chi}_1^0$ or $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$
- No sensitivity for $\tilde{t}_1 \to t\tilde{\chi}_1^0$ with $m_{\tilde{t}_1} \gtrsim m_{\tilde{\chi}_1^0} + m_t$: very similar to SM $t\bar{t}$
- [New at the LHC] Production of the heavier stop mass eigenstate ($\tilde{t}_2$) relying on the $\tilde{t}_2 \to Z\tilde{t}_1$ decay to reduce $t\bar{t}$ → Signature: $Z(\ell^+\ell^-)+\ell+b+E_T^{\rm miss}$
- Eur. Phys. J. C **74** (2014) 2883 (20 fb^{-1})

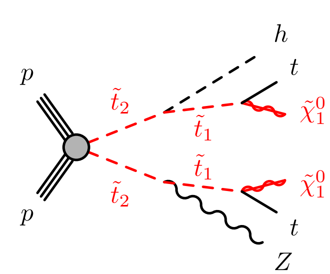


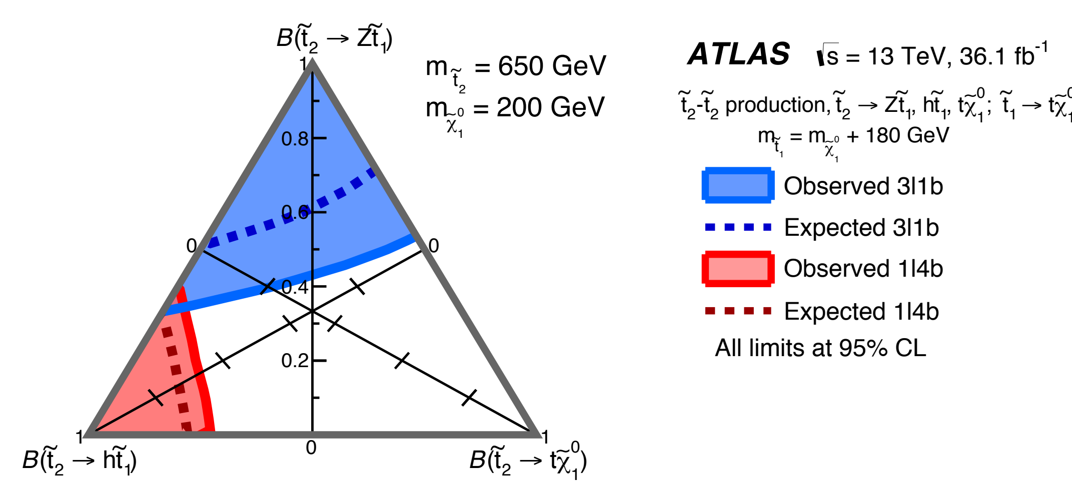


~ RUN 2 ~

- ATLAS-CONF-2016-038 (13 fb^{-1}): explore $\tilde{t}_2 \to Z\tilde{t}_1$ with $3\ell+b+E_T^{\rm miss}$
- JHEP **1708** (2017) 006 (36 fb^{-1}): analysis extended to $\tilde{t}_2 \to h\tilde{t}_1$ with $1\ell+4b+E_T^{\rm miss}$
- Interpretations for varying BRs in $\tilde{t}_2 \to h\tilde{t}_1/Z\tilde{t}_1$ and also for $\tilde{t}_1 \to t\chi_2^0$, $\chi_2^0 \to h/Z\tilde{\chi}_1^0$

X. Poveda @ DESY'17

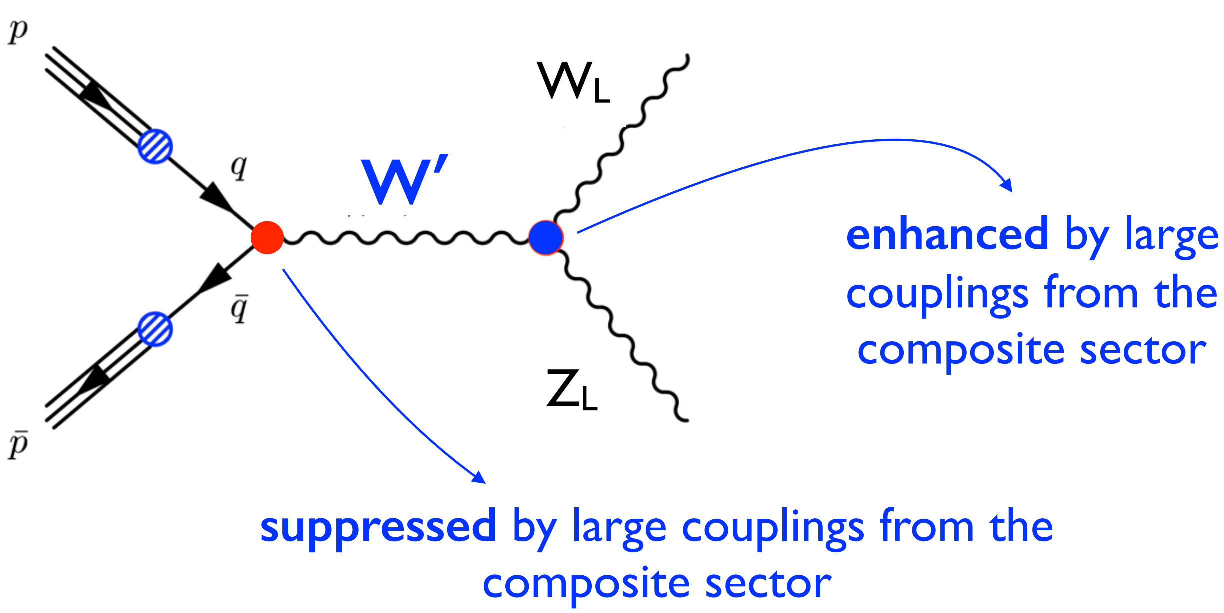




II. Vector resonances

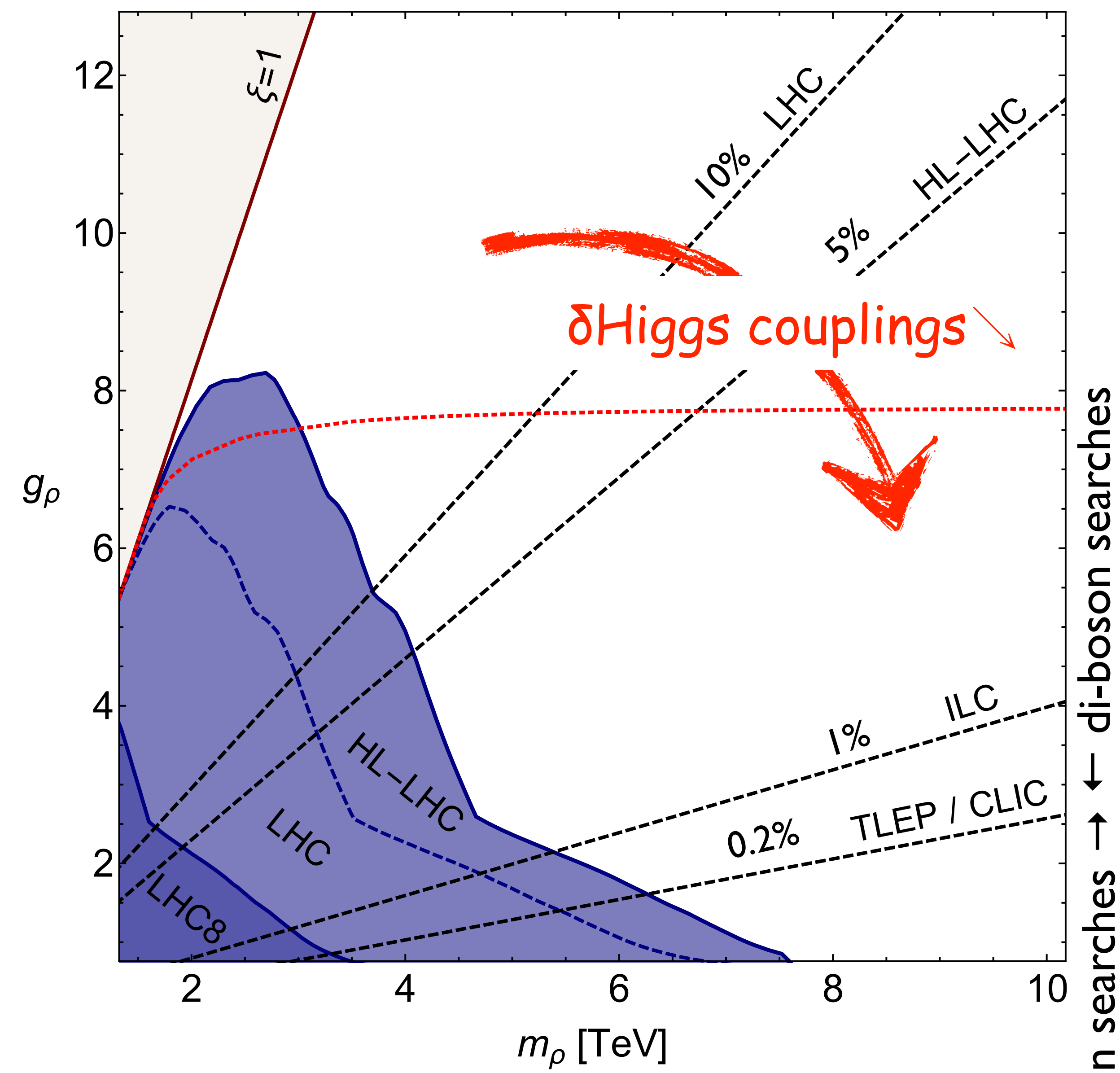
Precision /indirect searches (high lumi.) vs. direct searches (high energy)

Torre, Thamm, Wulzer '15



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 $1/g_\rho^2$



Recasts of CMS run-1 W', Z' searches
CMS-PAS-EXO-12-061
arXiv:1407.3476

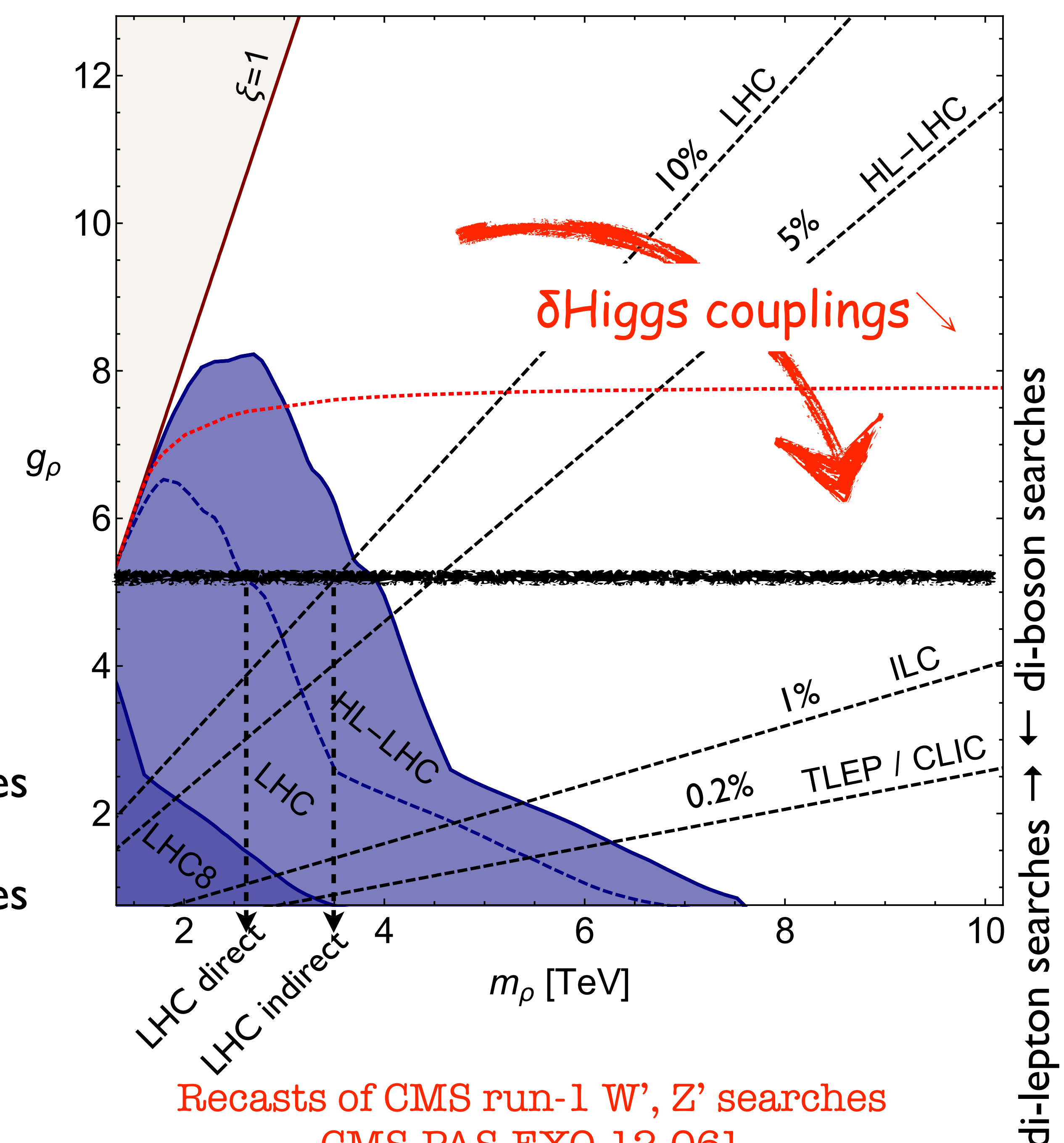
II. Vector resonances

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

Torre, Thamm, Wulzer '15

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



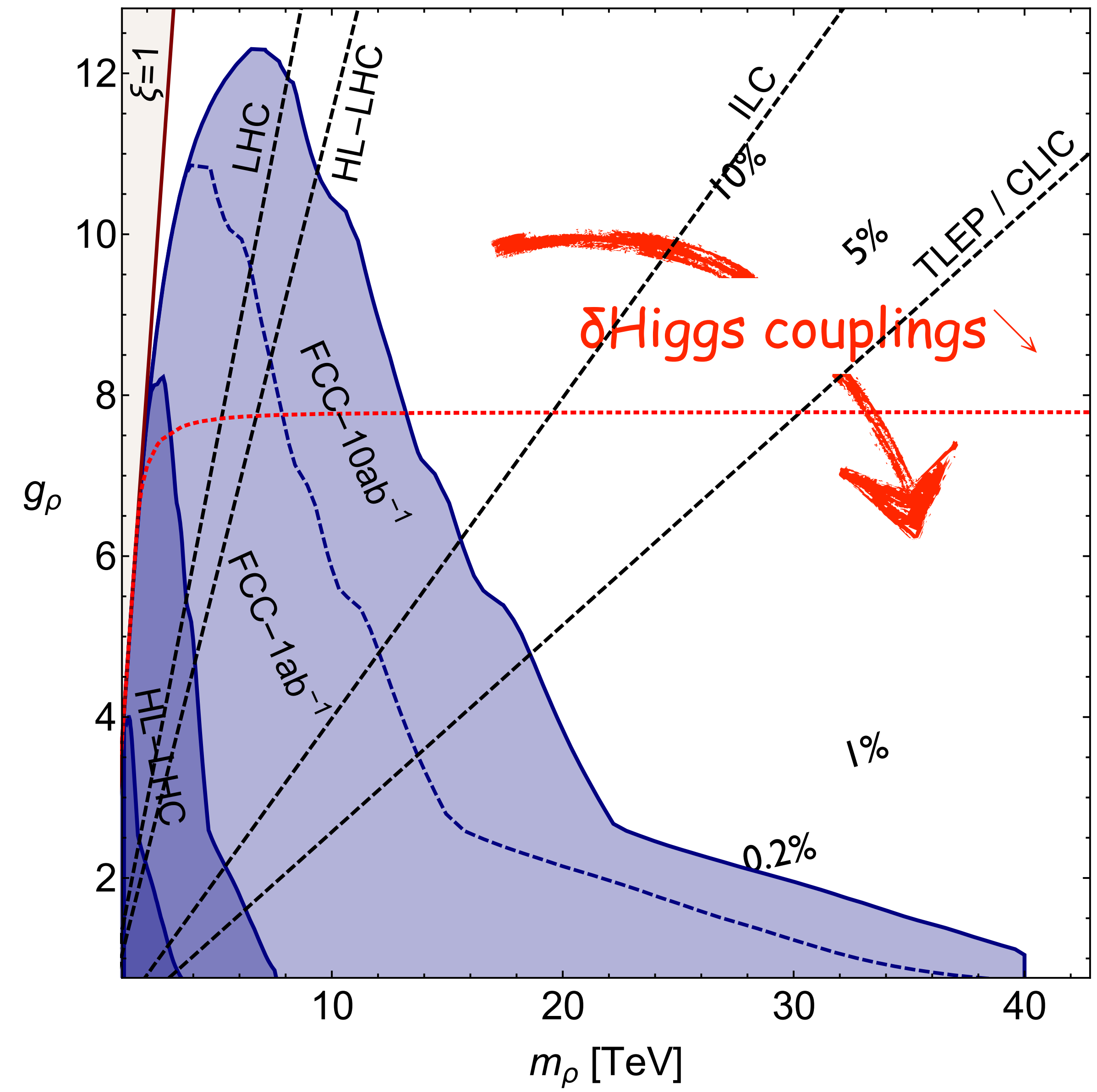
Recasts of CMS run-1 W', Z' searches
CMS-PAS-EXO-12-061
arXiv:1407.3476

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

II. Vector resonances

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

Torre, Thamm, Wulzer '15



Recasts of CMS run-1 W', Z' searches
CMS-PAS-EXO-12-061
arXiv:1407.3476

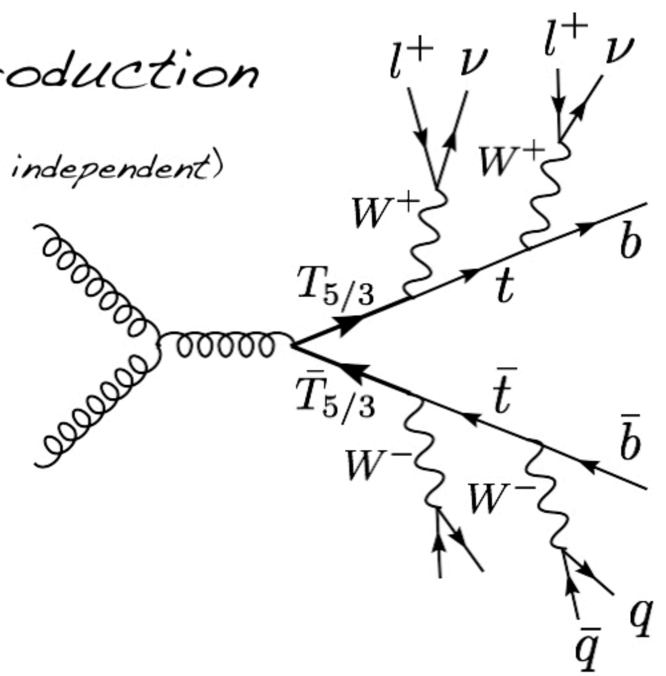
III. Fermionic top partners
(aka vector-like quarks)

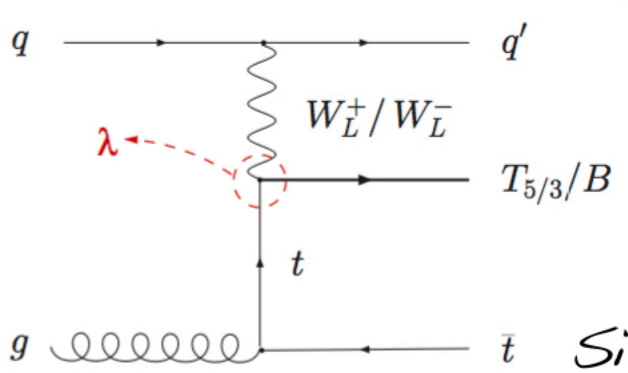
Search in same-sign dilepton events

- $t\bar{t}$+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)

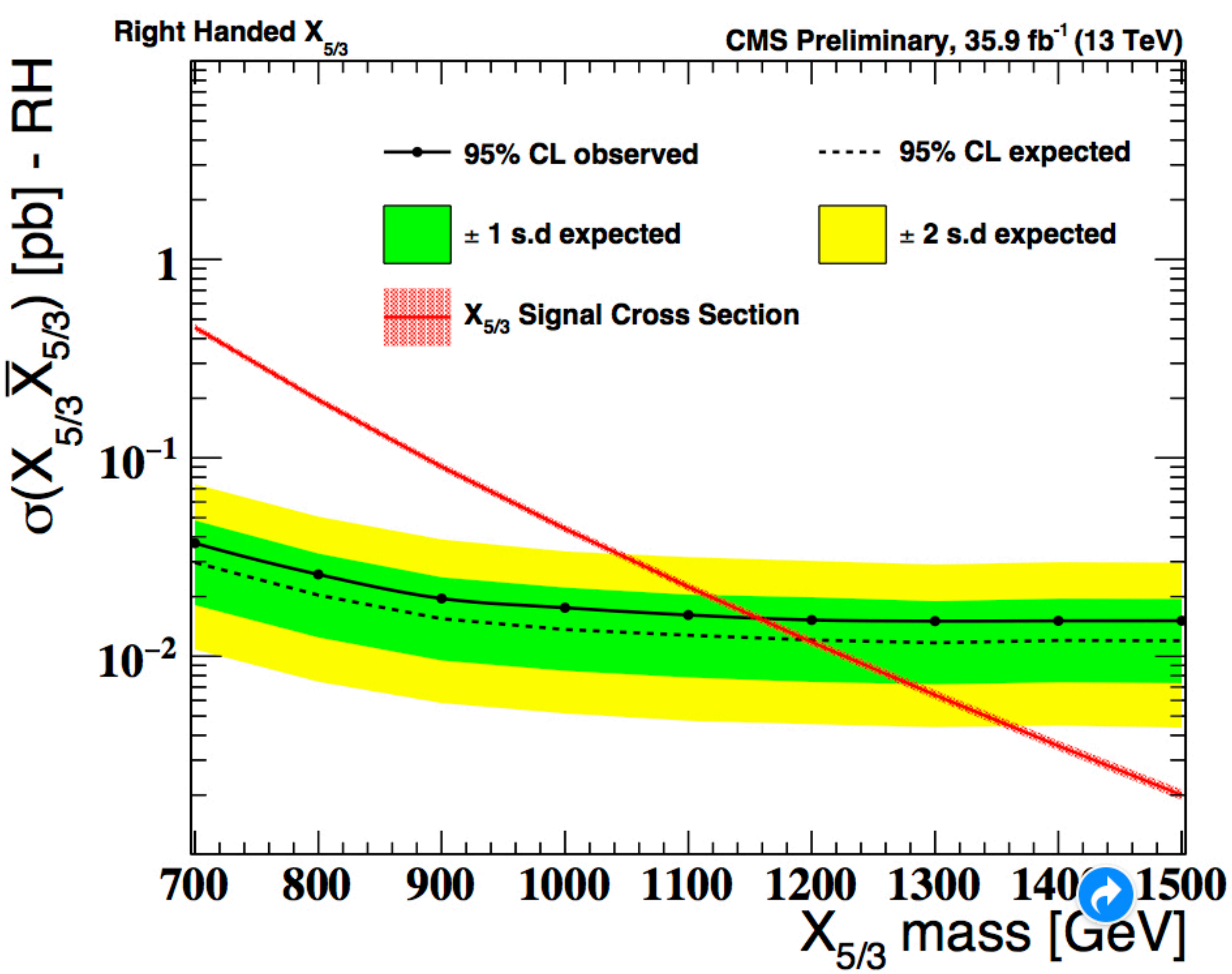




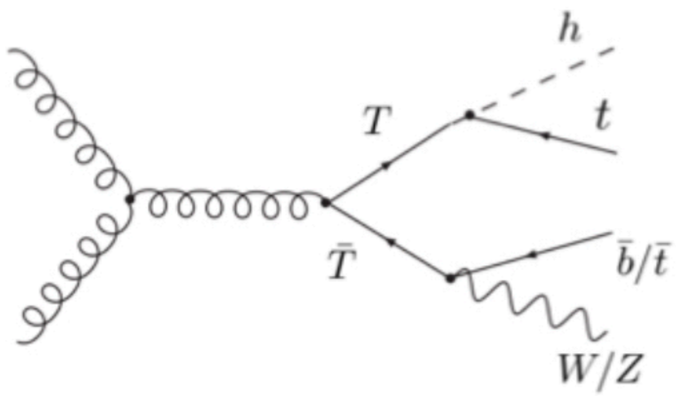
Single production

(model dependent)

Moriond'17 bound: 1160 GeV



III. Fermionic top partners
(aka vector-like quarks)



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

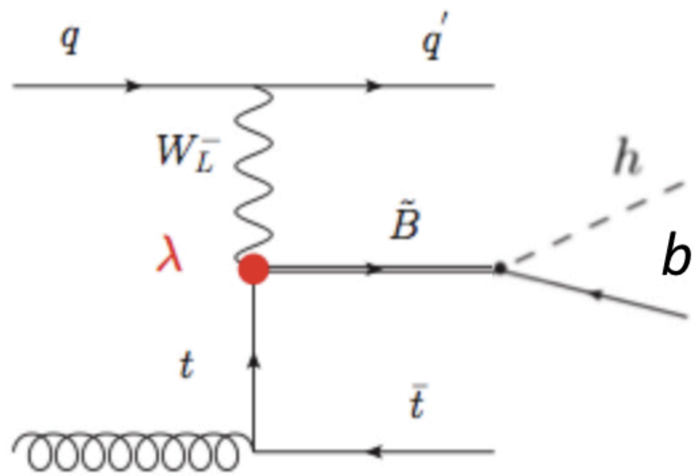
$$T\bar{T} \to HtW^-\bar{b} \to HW^+bW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}',$$
$$T\bar{T} \to HtV\bar{t} \to HW^+bVW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$$

- $\ell^\pm$ + 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

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

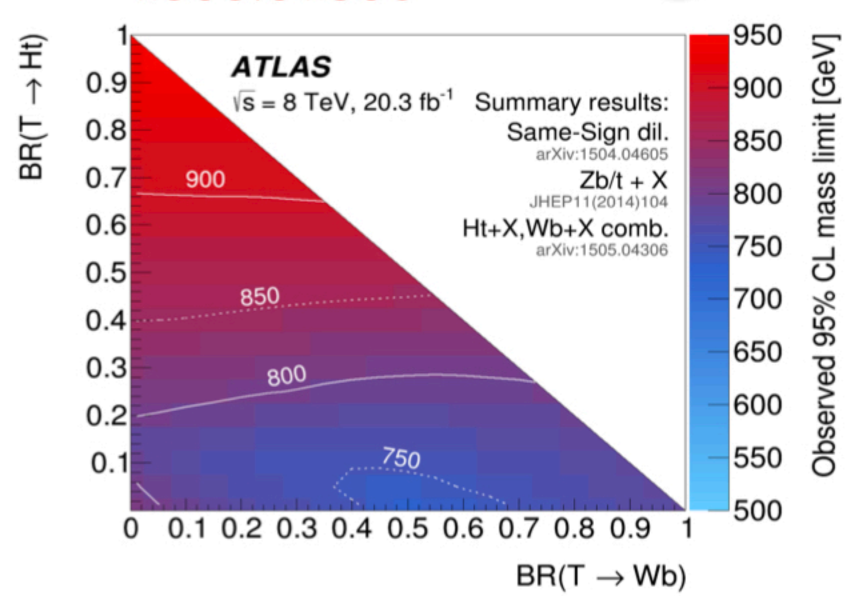


- $\ell^\pm$ + 4b final state Vignaroli '12

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

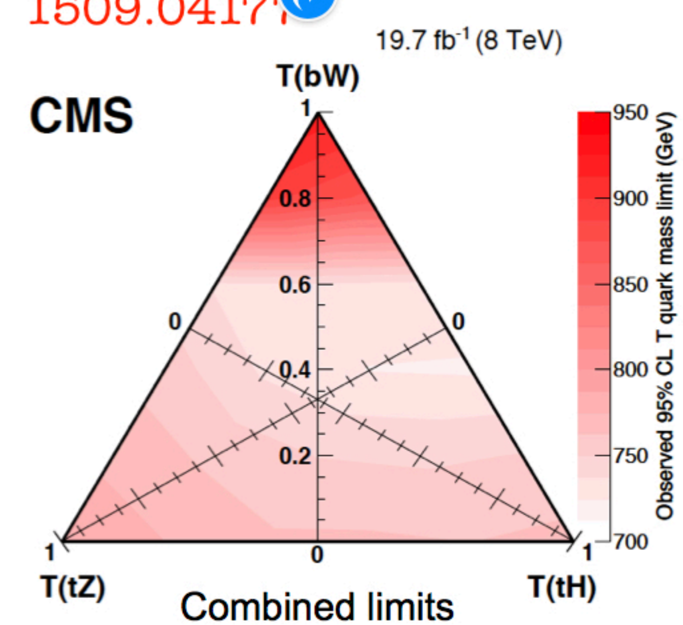
Moriond'17 update
bounds above 1 TeV!

1505.04306



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

1509.04177



IV. Searches for extended Higgs sectors

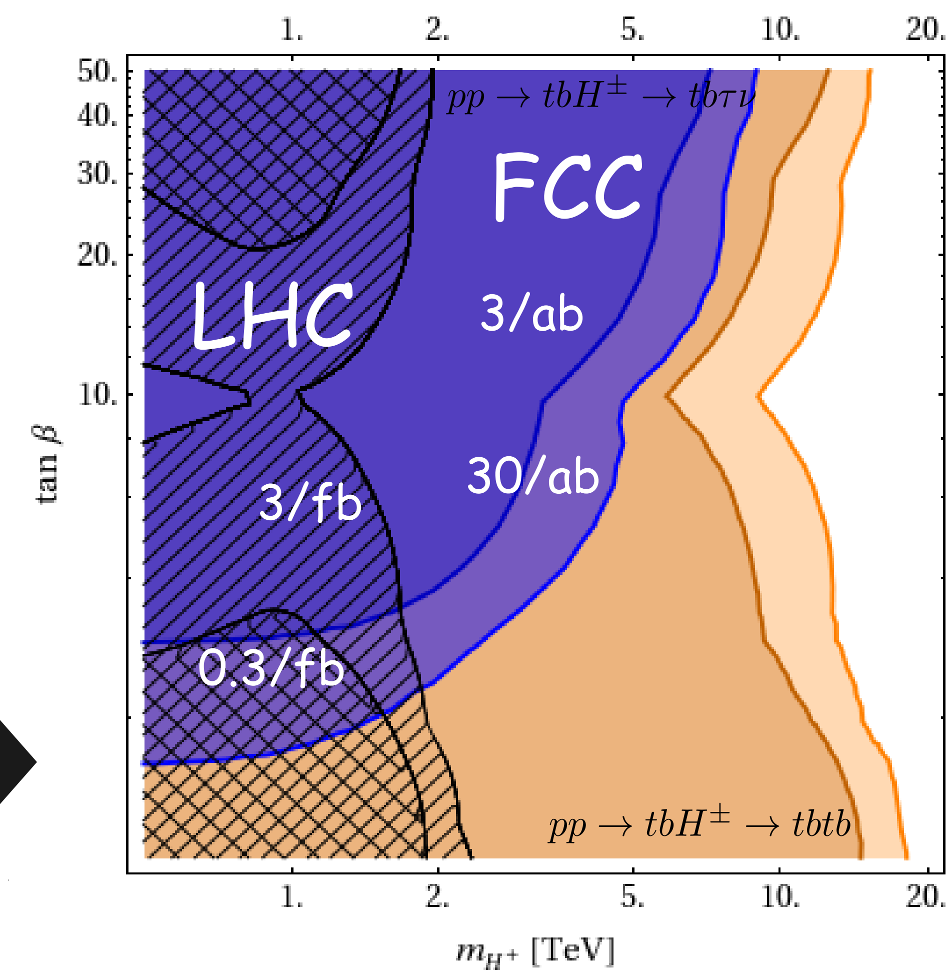
Extended Higgs sectors are a prediction of many BSM scenarios.
They may play a role in the following open questions:

- (EW) Baryogenesis → Modified scalar potential can lead to a 1st order EW phase transition
- Identity of Dark Matter → Scalar DM with TeV mass; Scalar mediators in hidden-sector DM coupled to Higgs portal
- Smallness of the neutrino masses → Type-II see-saw through extra scalars
- Naturalness of the EW scale → Extended scalar sectors follows in natural theories:
  i) SUSY
  ii) Neutral Naturalness

☞ A 100TeV pp collider offers the unique opportunity to discover EW-charged or SM-singlet scalars with a few TeV mass

Contino FCC@Rome '16

just one example for illustration:
charged Higgs 95%CL exclusion



J. Hajer et al '15

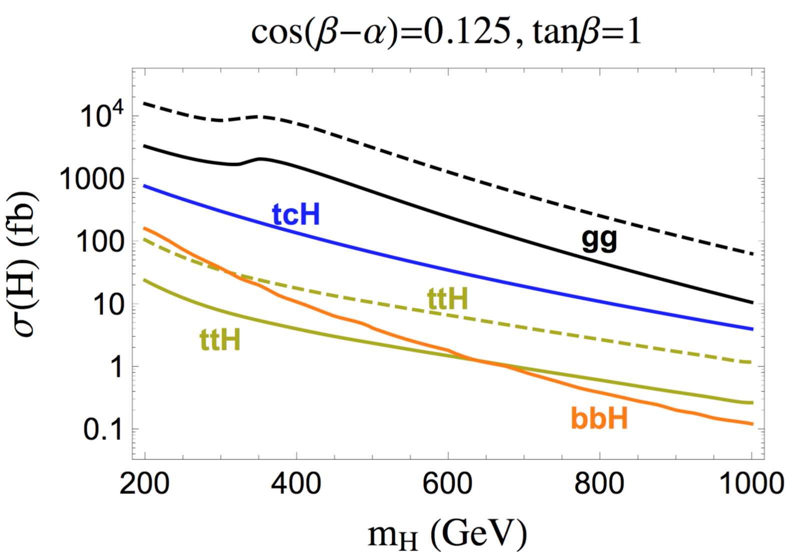
IV. Searches for extended Higgs sectors

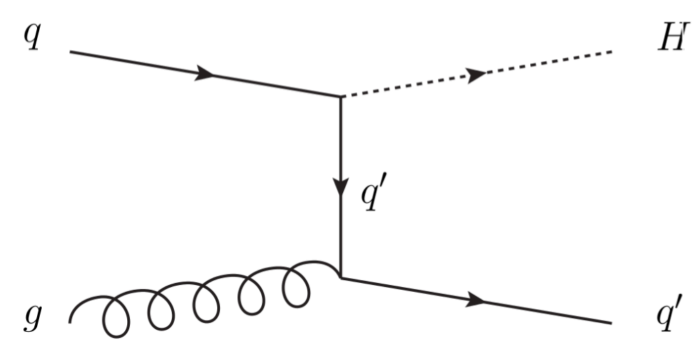
Going beyond type I-II:

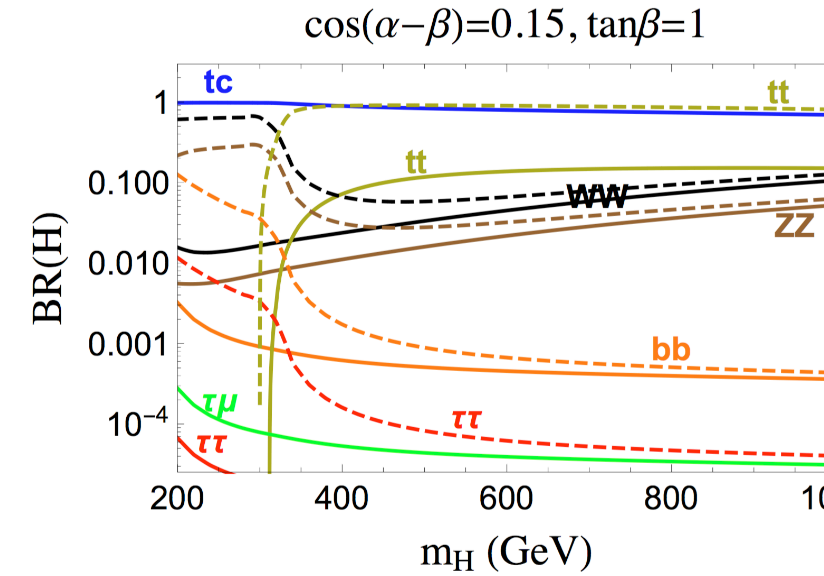
Loopholes in standard heavy Higgs searches

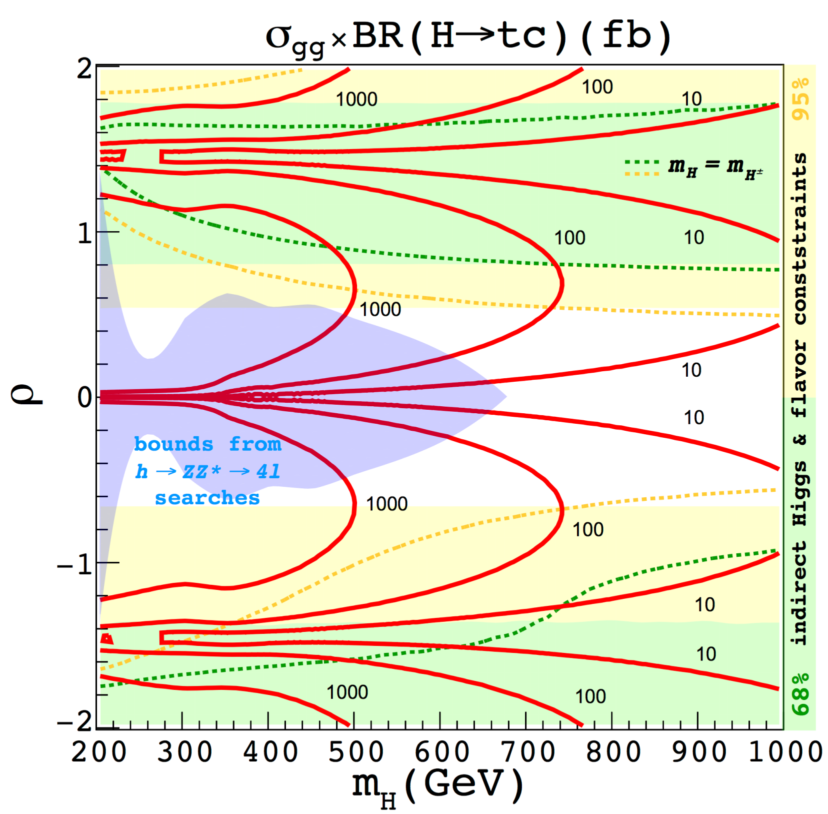
Nice opportunities for unexplored signatures

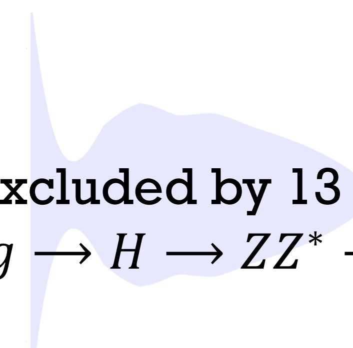
$pp \to H \to tc$	$pp \to tcH(\to tc)$
1 charged lepton	2 same-sign leptons
$E_T^{\rm miss}$	2 b-jets
1 b-jet	≥ 1 c-jet
1 c-jet	











excluded by 13 TeV

$gg \longrightarrow H \longrightarrow ZZ^* \longrightarrow 4l$

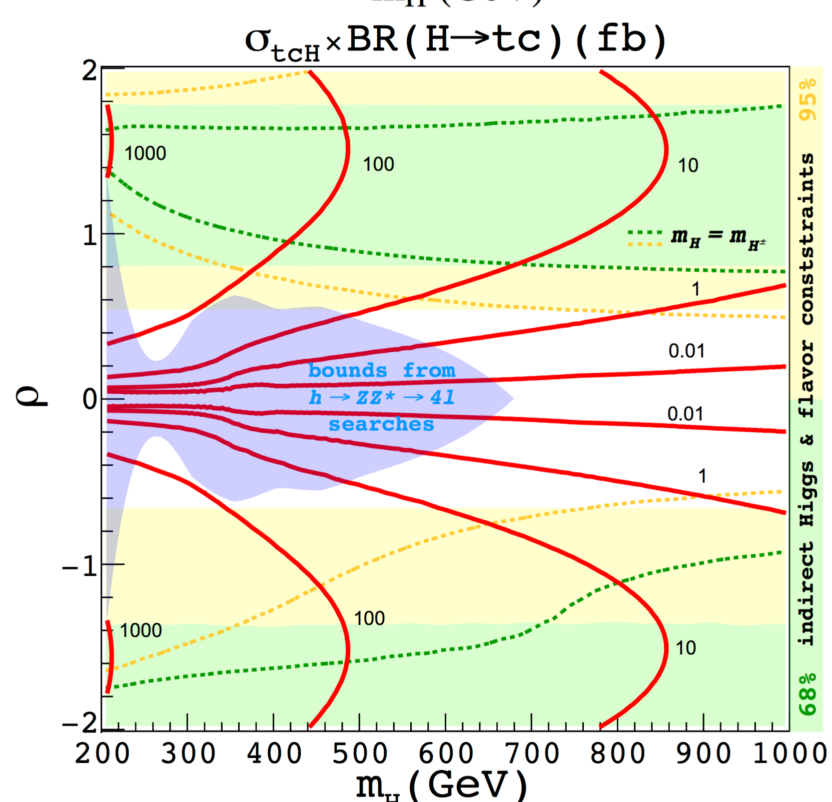
$\cos(\beta-\alpha) = 0.125$ and $\tan\beta = 1$

68.2 %

95.4 %

$m_{H^\pm} = m_{H^0}$

marginalized over $m_{H^\pm}$



11

S. Gori, C. Grojean, A. Juste, A. Paul '17

V. Particle or not Particle?

- Nima: "*If you do particle physics with the goal of discovering a new particle, better you think what to do with your life now.*" (in the context of "direct discovery" vs "indirect/precision physics" at future colliders)

LHCP '2017

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New physics doesn't necessarily mean new particle,
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And it could reveal through precision measurements

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$$m_* = g_* f_*$$

g_* weak:	g_* strong:
resonances before interactions	interactions before resonances

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energy helps accuracy

Farina et al '16

$$\frac{\Delta\mathcal{O}}{\mathcal{O}} \propto E^2$$ ⟺ precision of 0.1% @ 100GeV ≈ precision of 10% @ 1TeV
same sensitivity to new physics

at high energy, you can be sensitive without having to be precise

V. Particle or not Particle?

e.g. measurement of p^4 EW oblique parameters

	LEP	LHC 13		FCC 100	ILC	TLEP	CEPC	ILC 500	CLIC 1	CLIC 3
luminosity	$2 \times 10^7\ Z$	0.3/ab	3/ab	10/ab	$10^9\ Z$	$10^{12}\ Z$	$10^{10}\ Z$	3/ab	1/ab	1/ab
W $\times 10^4$	$[-19, 3]$	± 0.7	± 0.45	± 0.02	± 4.2	± 1.2	± 3.6	± 0.3	± 0.5	± 0.15
Y $\times 10^4$	$[-17, 4]$	± 2.3	± 1.2	± 0.06	± 1.8	± 1.5	± 3.1	± 0.2	$\sim \pm 0.5$	$\sim \pm 0.15$

energy helps accuracy

Farina et al '16

$$\frac{\Delta \mathcal{O}}{\mathcal{O}} \propto E^2$$ ⟺

precision of 0.1% @ 100GeV ≈ precision of 10% @ 1TeV
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V. New force: Composite Higgs

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

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

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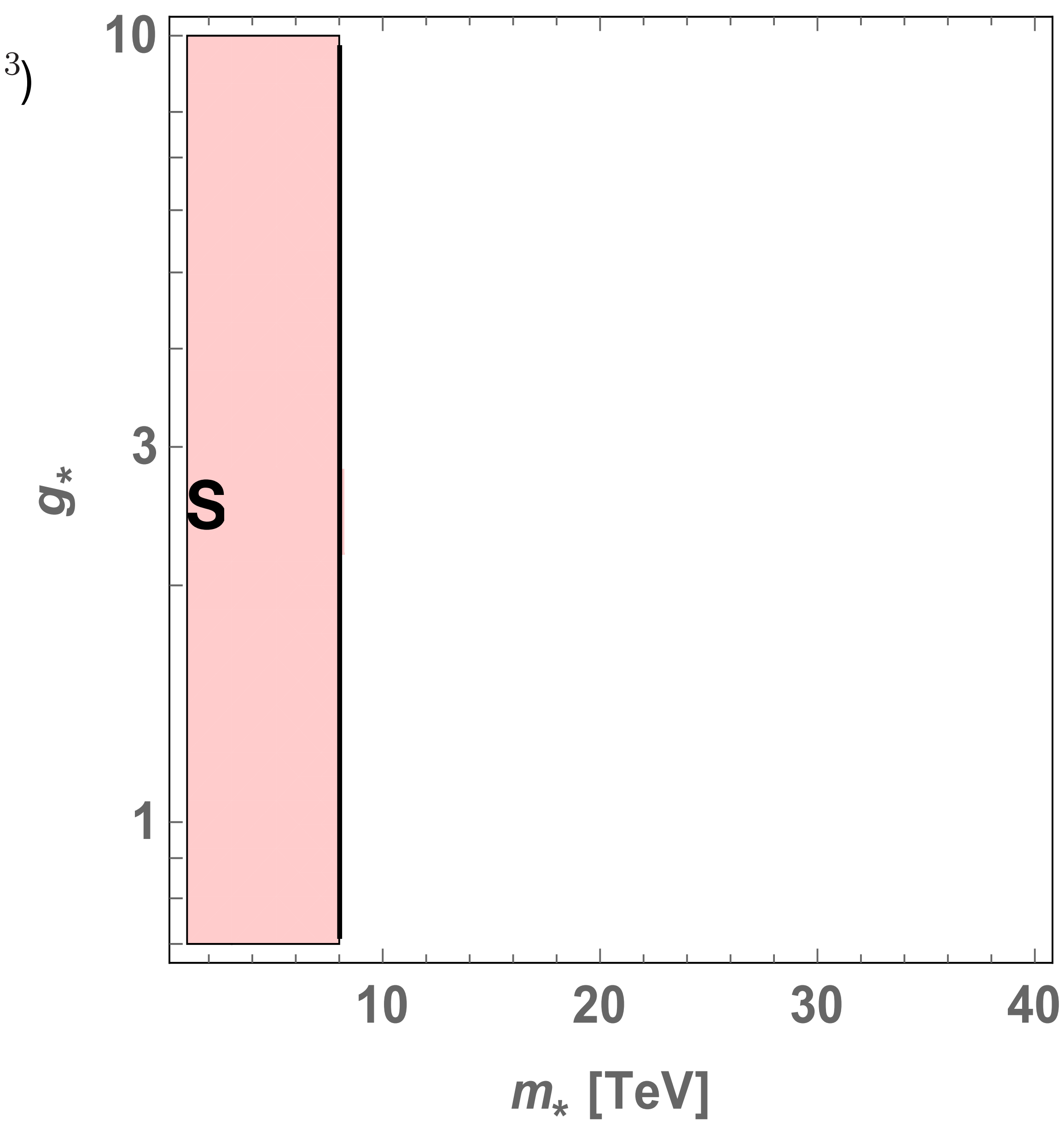
S-parameter : [De Blas et. al.] (LEP: 10^{-3})

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



Grojean-Wulzer @ FCC physics week '17

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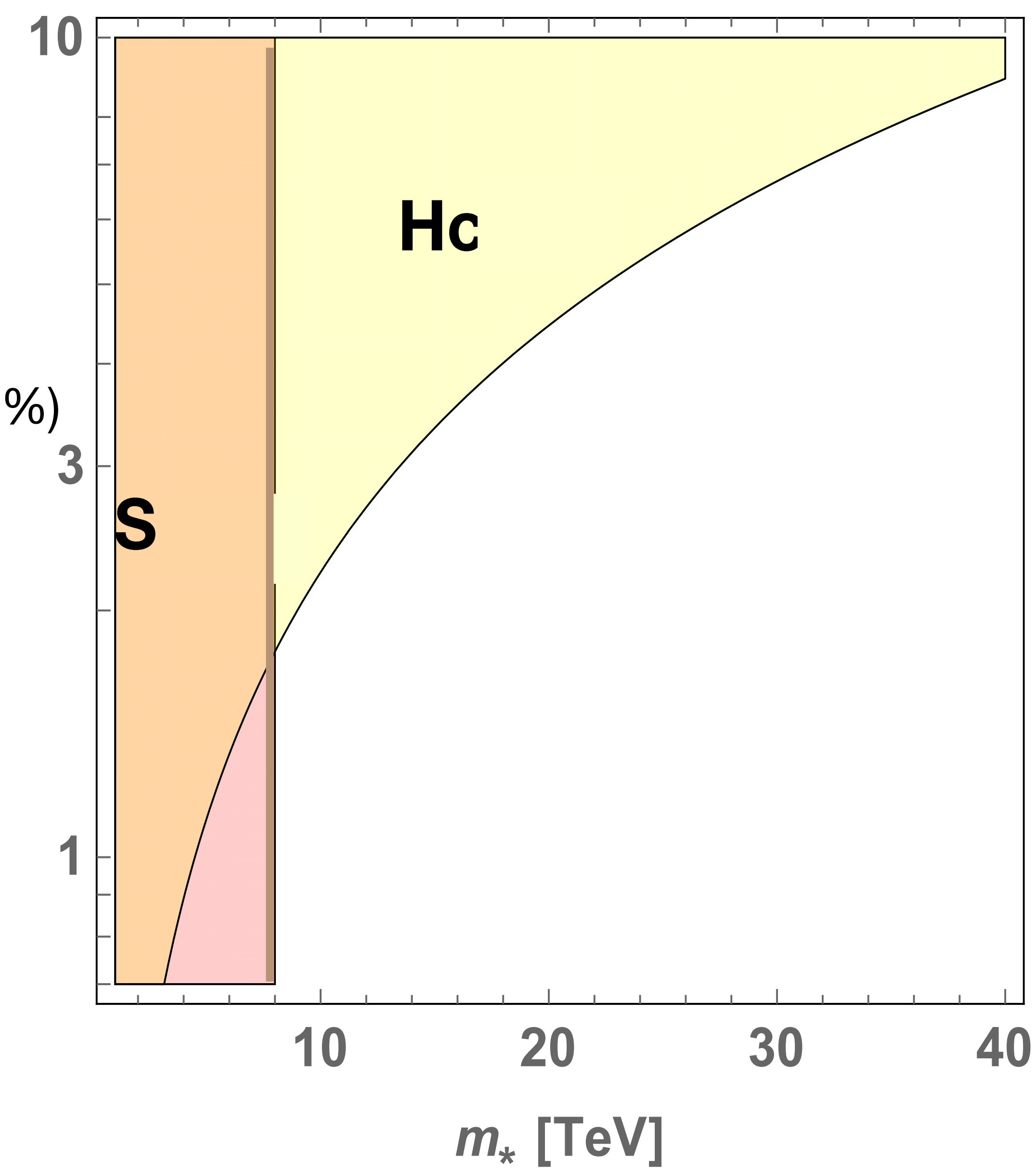
Higgs Couplings : [ee Report] (HL-LHC: 5%)

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



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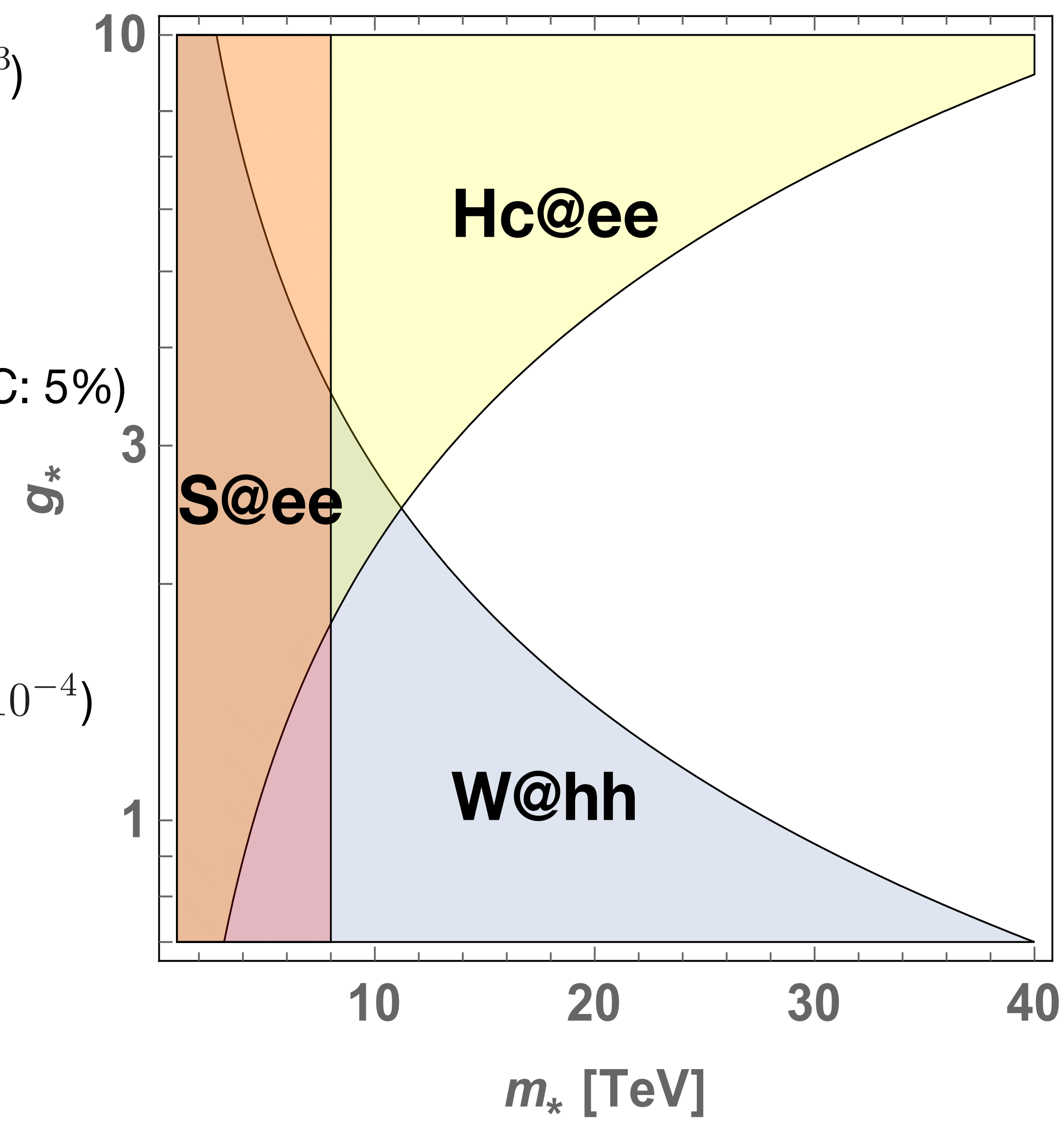
W @hh: (energy + accuracy) (HL-LHC< 10^{-4})

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



Grojean-Wulzer @ FCC physics week '17

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

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

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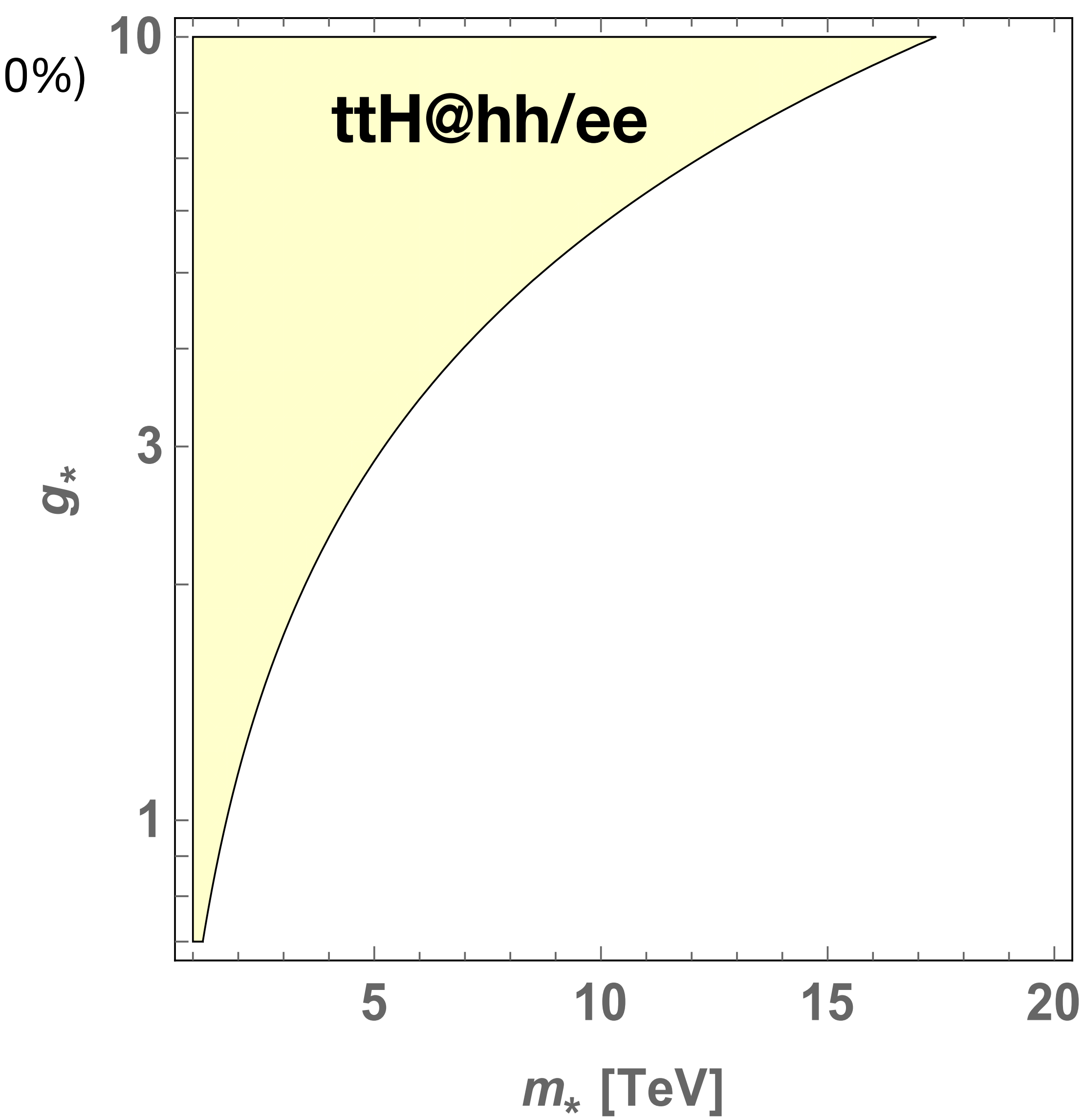
ttH coupling @hh/ee: [Reports] (HL-LHC:10%)

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

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



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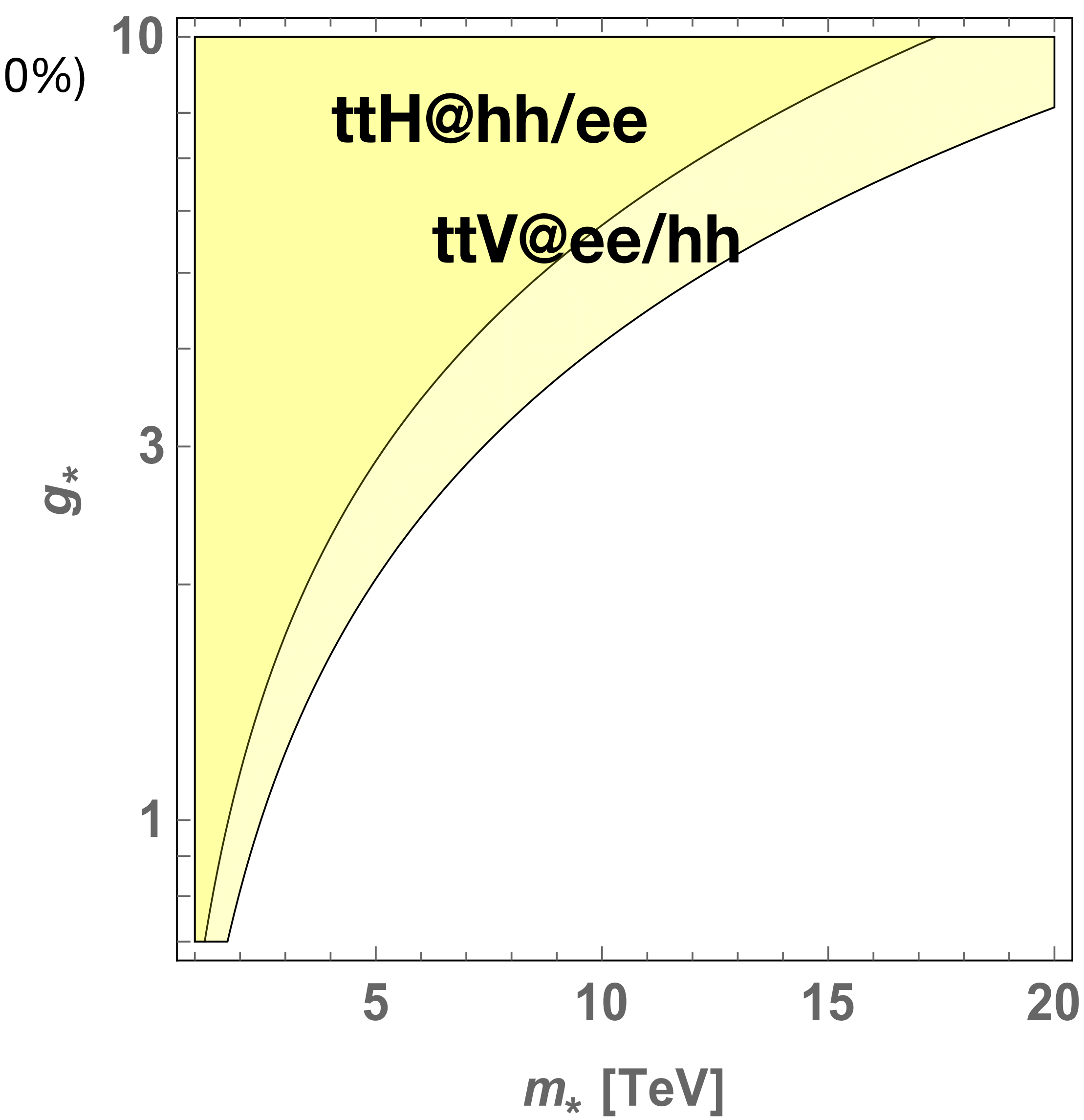
Diff. oper.s comb. in ee and hh!!

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.?



Grojean-Wulzer @ FCC physics week '17

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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!!

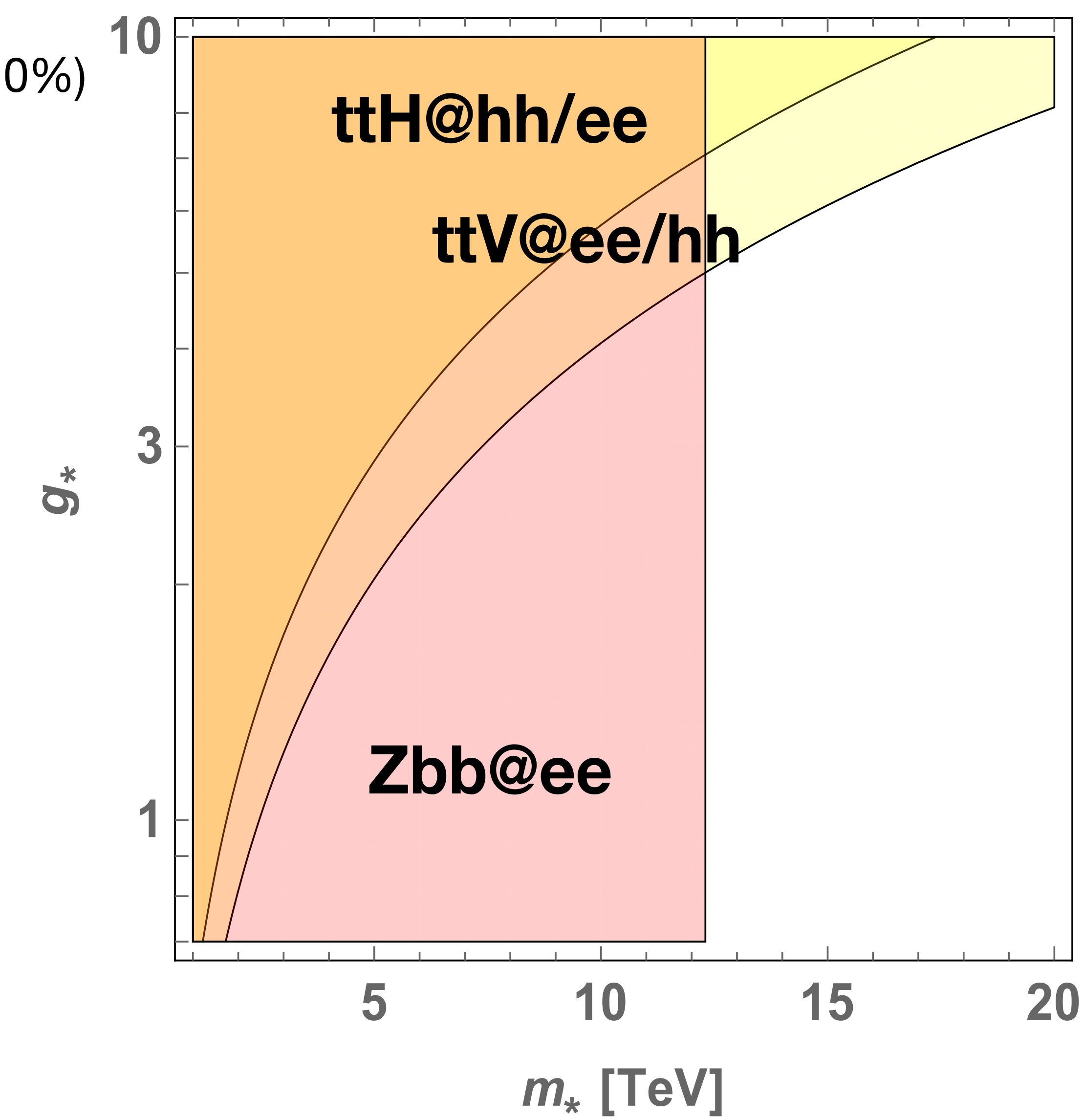
ttV coupling @ee/hh: [Janot / Farina et.al.]

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

Same hh reach from en. + acc.?

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

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



Grojean-Wulzer @ FCC physics week '17

V. New force: Composite Top

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!!

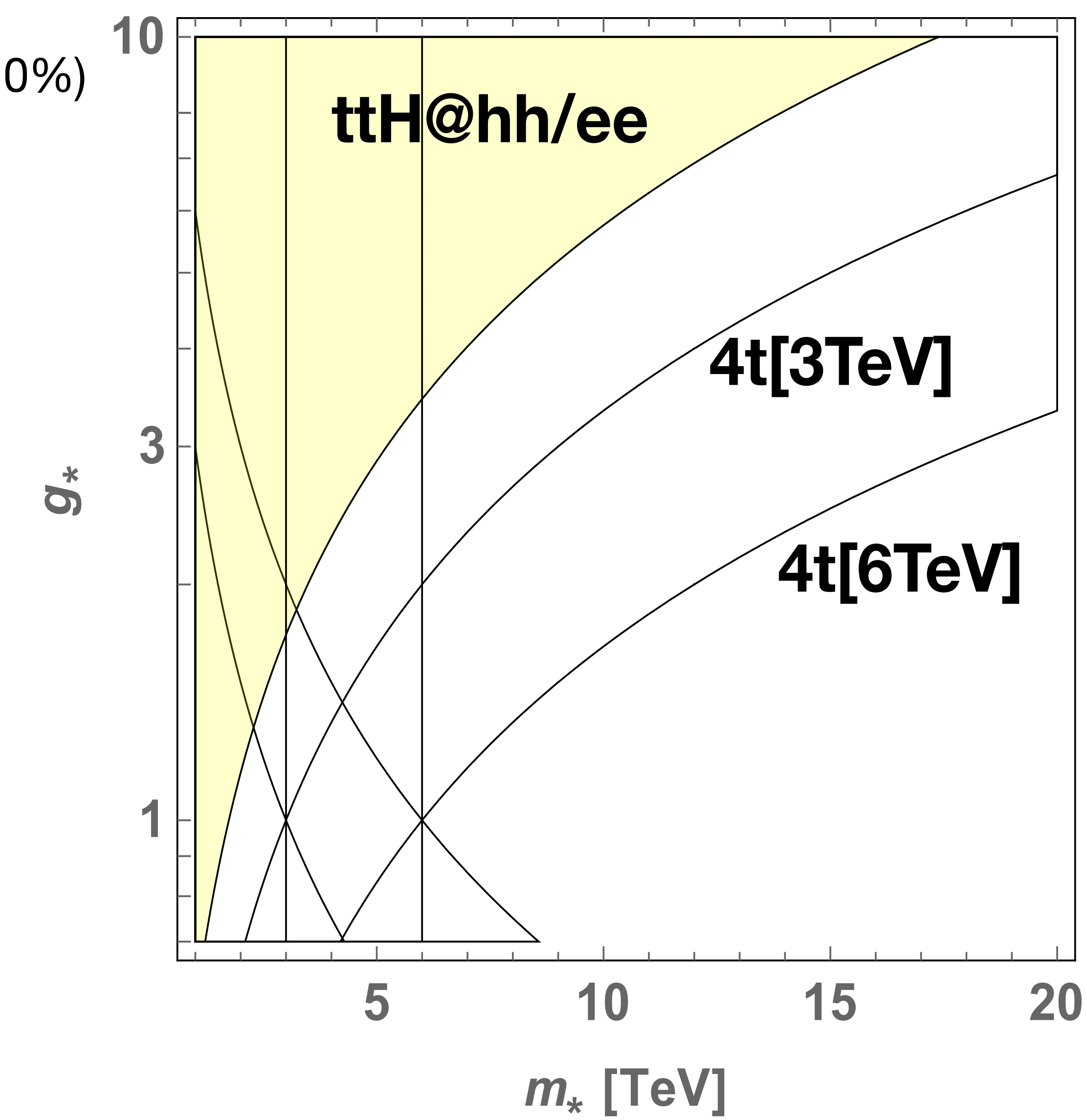
4-top contact interactions @hh:

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

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

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

No study available (?)



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(iii) Physics questions

e.g. naturalness, matter-antimatter asymmetry

The hierarchy problem made easy

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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

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

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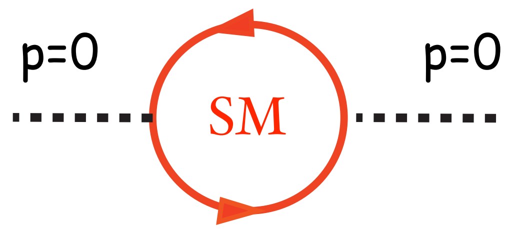
We need an experimental answer!

I. Neutral Naturalness

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

$\delta m_H^2 =$



$+$

$\sim m_H^2$

generically

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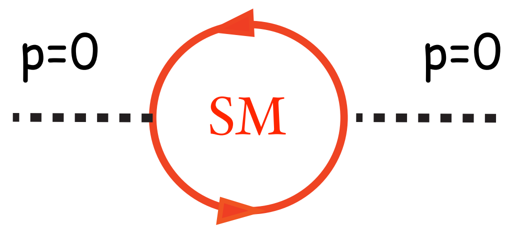
$\delta m_H^2 =$ 

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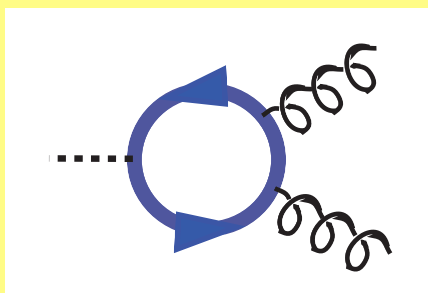
charged particles

generically



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

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

Colorful naturalness probed @ LHC

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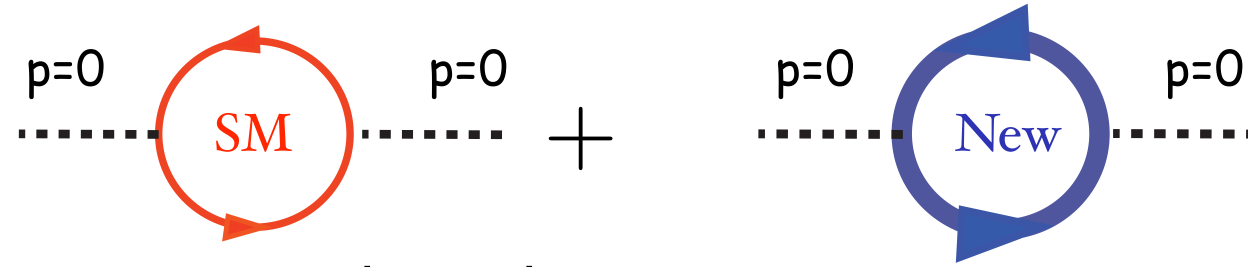

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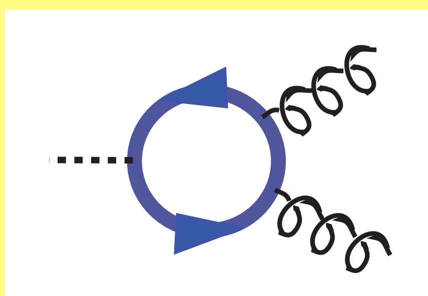

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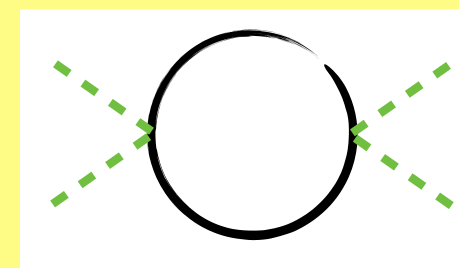


$$\frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

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

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

nice to be able to measure Zh & Γ

Colorful naturalness probed @ LHC

Neutral naturalness (invisible?) @ LHC

aka twin Higgs

I. Neutral Naturalness

" 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	pNGB/RS
EW Charges	Folded SUSY	Quirky Little Higgs
No SM Charges	???	Twin Higgs

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

(C. Verhaaren@NKPI'16)

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

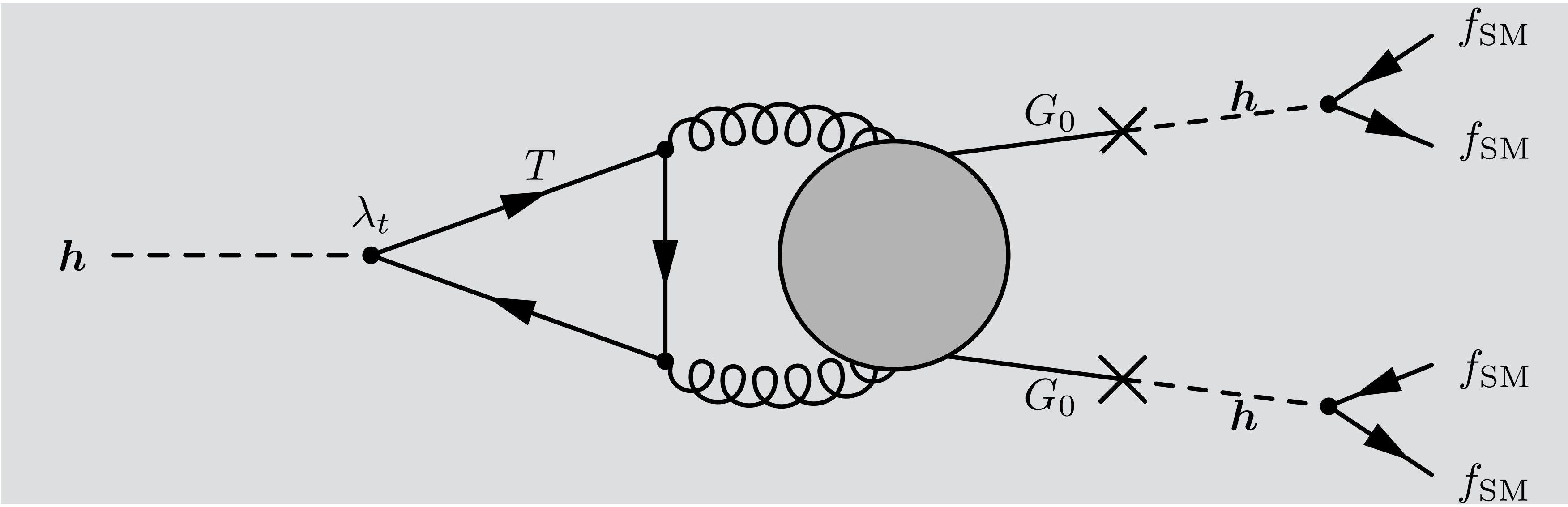
⇒ 1) hidden glueball (0^{++}) that can mix with Higgs
$h \to G_0 G_0 \to 4l$ with displaced vertices

Curtin, Verhaaren '1

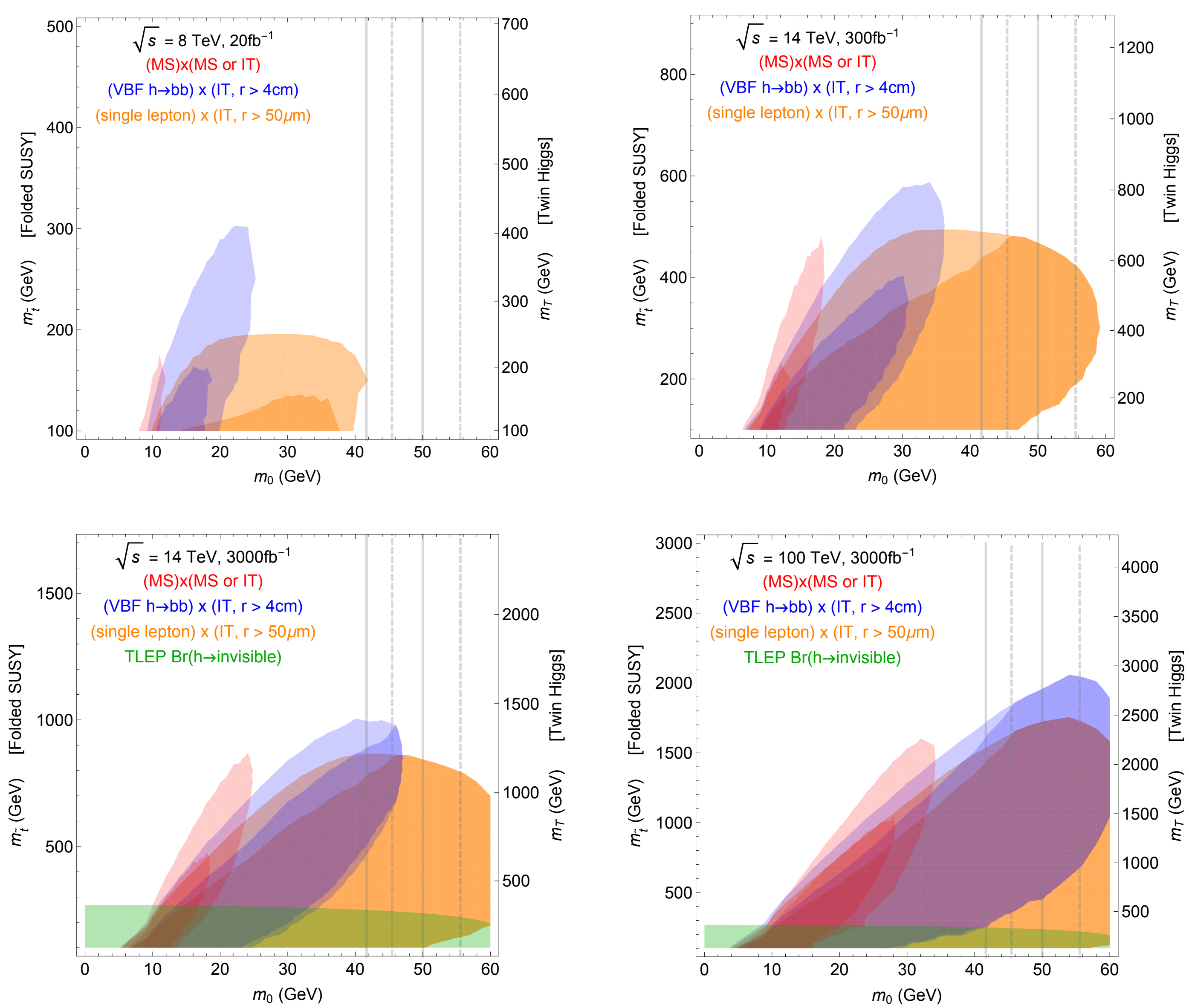
⇒ 2) emerging jets

Schwaller, Stolarski, Weiler '15

I. Neutral Naturalness



displaced vertices



Curtin, Verhaaren '15

II. Matter-antimatter asymmetry

Baldes, Konstandin, Servant '16

Electroweak baryogenesis requires:

- A strong first order phase transition
- Sufficient CP violation

However in the SM:

- The Higgs mass is too large
- Quark masses are too small

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These negative results are tied to the fact that
Yukawa couplings during EW phase transition are identical the ones afterwards
What if they were larger?
E.g. flavor structure emerges during the EW transition

$$y_{ij}\bar{f}_L^i H f_R^j \quad \Rrightarrow \quad y_{ij}\left(\frac{\chi}{M}\right)^{q_H+q_j-q_i} \bar{f}_L^i H f_R^j$$

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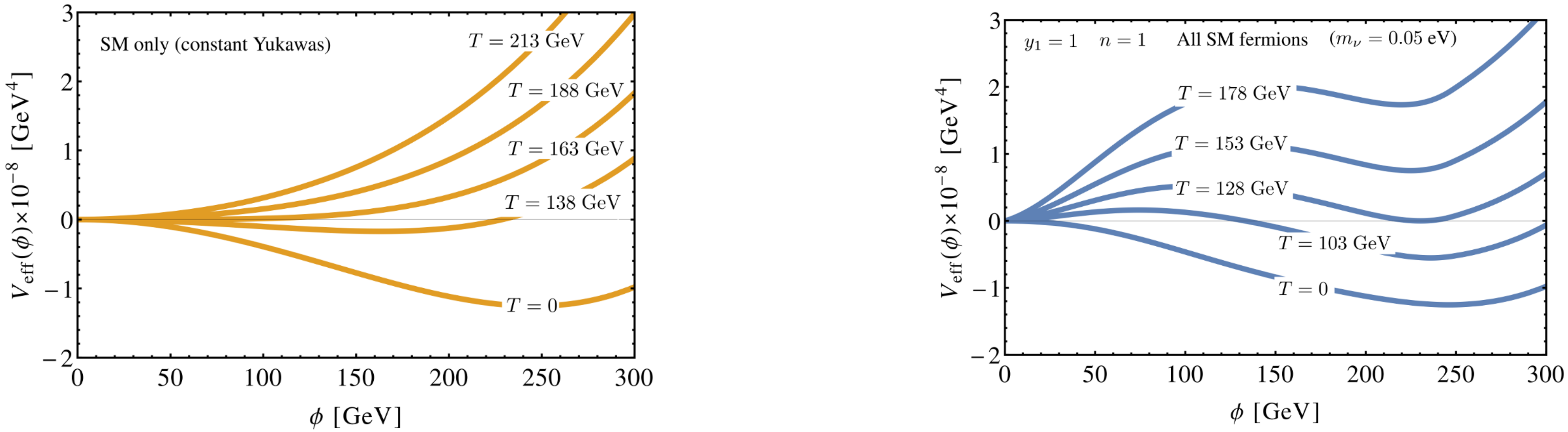
traditionally, M ≫ v and χ is frozen during EWSB

lowering M and allowing χ to vary leads to totally different phenomenology

EW scale flavons for EW baryogenesis

Baldes, Konstandin, Servant '16

$$y(\phi) = \begin{cases} y_1 \left(1 - \left[\frac{\phi}{v}\right]^n\right) + y_0 & \text{for} \quad \phi \le v, \\ y_0 & \text{for} \quad \phi \ge v. \end{cases}$$



The evolution of the effective potential with temperature in the SM (left) and with varying Yukawas (right) The varying Yukawa calculation includes all SM fermions with y1=1, n=1 and their respective y0, chosen to return the observed fermion masses today (the neutrinos are assumed to have a Dirac m=0.05eV).

In the varying Yukawa case, there is a first-order phase transition with ϕ_c=230GeV and T_C=128GeV (vs. second order transition at T_C=163GeV for the constant Yukawa case).

1st order phase transition + enhanced source of CP

Signatures at colliders

Nice interplay with Gravitational Waves searches

Conclusions: breaking the HEP frontiers

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rich experimental program to

~ open new horizons beyond
our current understanding of matter~

no lack of theoretical motivations

& plenty of physics issues outside the SM frame

from deep QFT questions ~~ to pressing phenomenological puzzles

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~~ 2 human characteristics to remember ~~

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finite lifetime
(and awareness of it)

capacity of dreaming

hoping that the (physics) humanity will learn to speak Esperanto!

Esperanto for New Physics: parametrisation of the unknown