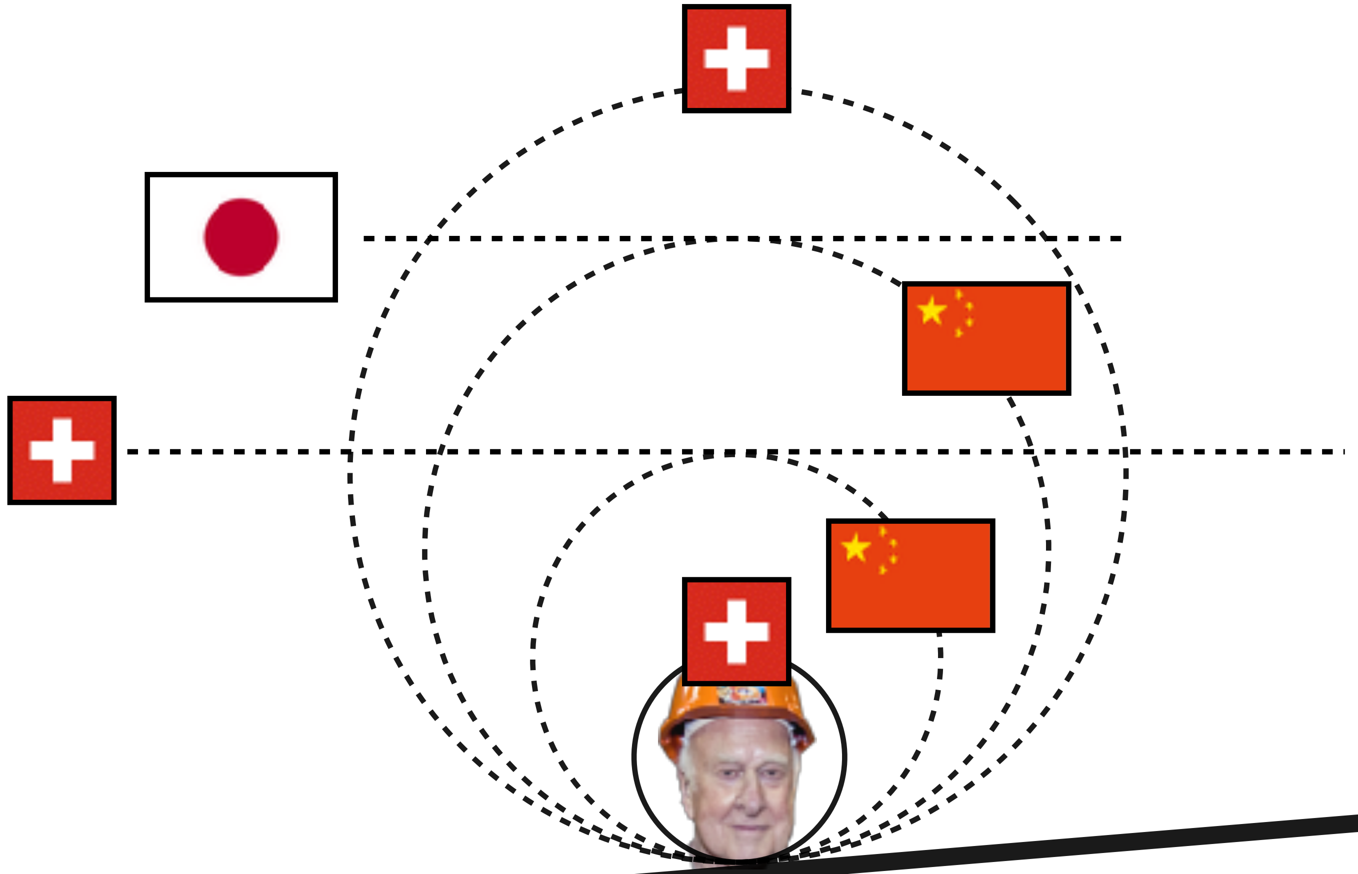
Future Colliders (3/3)

What the future colliders might how about the Higgs and BSM

Weihai High-Energy Physics School

August 26-28, 2019



Christophe Grojean

DESY (Hamburg)

Humboldt University (Berlin)

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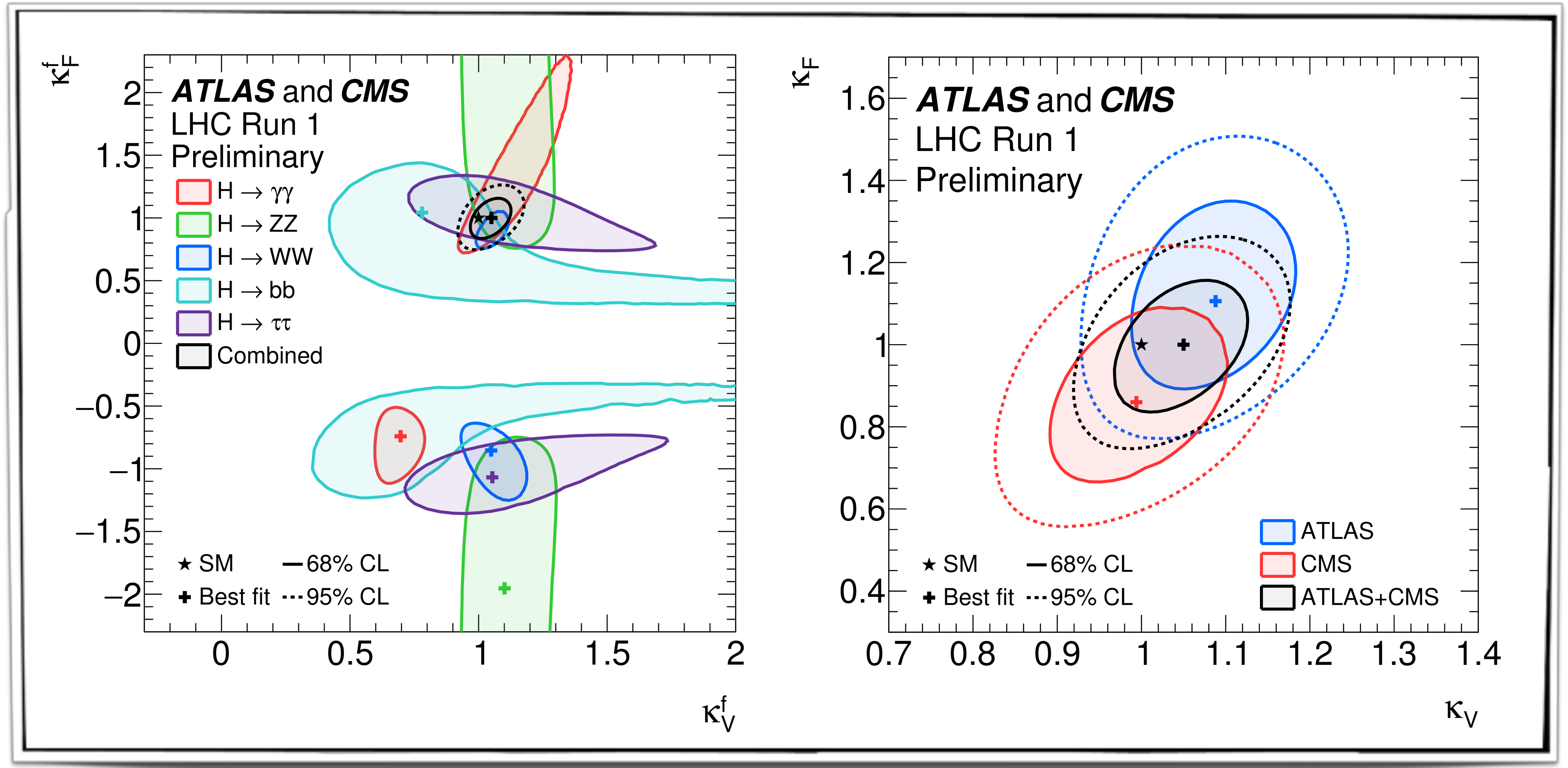
Beyond Inclusive Higgs analysis

one example

Why going beyond inclusive Higgs processes?

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

access to Higgs couplings @ m_H



Why going beyond inclusive Higgs processes?

So far the LHC has mostly produced Higgses on-shell
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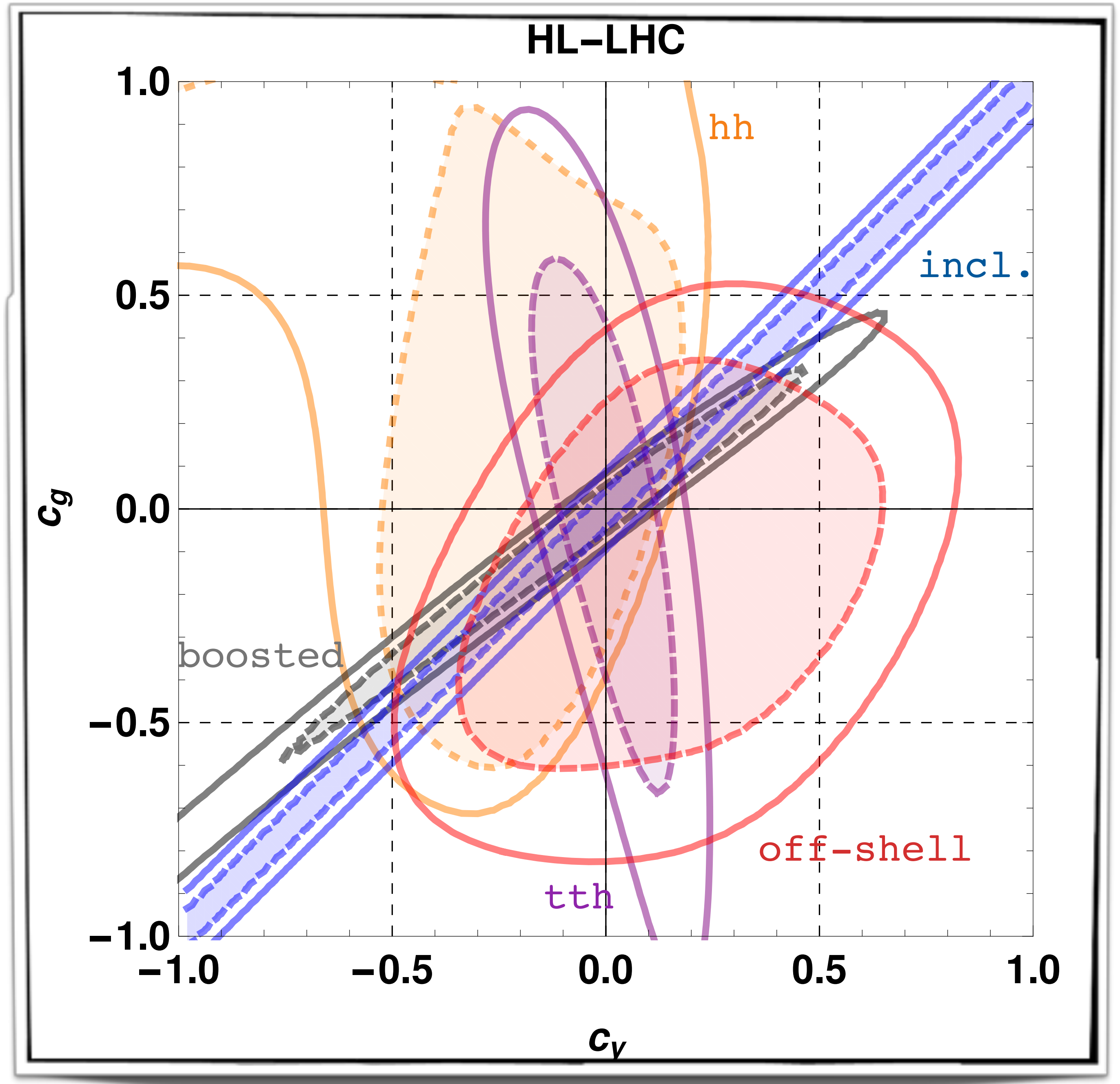
access to Higgs couplings @ m_H

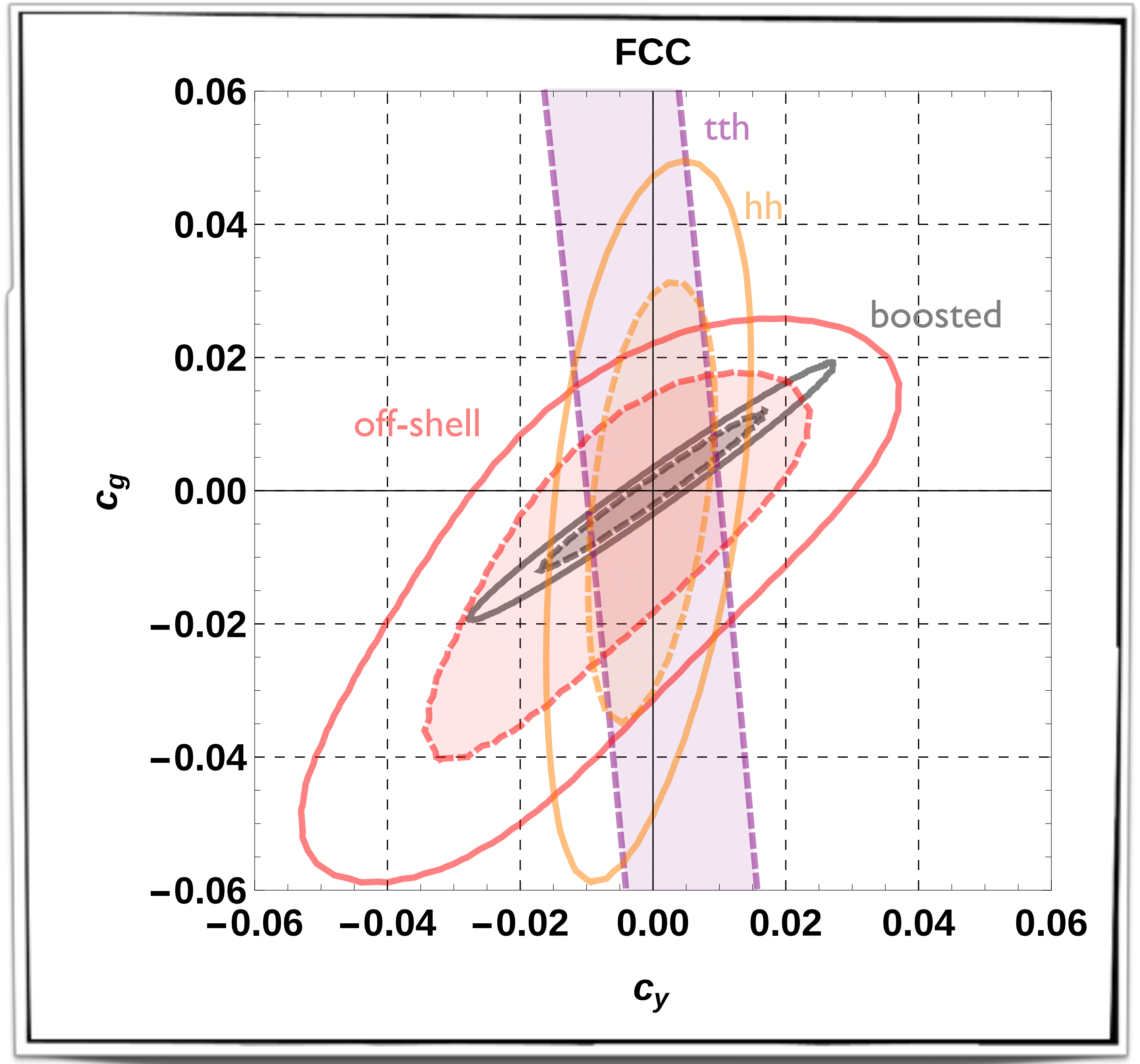
Producing a Higgs with boosted additional particle(s)
probe the Higgs couplings @ large energy
(important to check that the Higgs boson ensures perturbative unitarity)

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

Why going beyond inclusive Higgs processes?





Azatov, Grojean, Paul, Salvioni '16

Light stop searches from Higgs+jet

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

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

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

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

Inclusive Higgs measurements cannot rule out light stop

There are various arguments that favour this **light stop** region

- ✦ flavor constraints (ε_K, $B \to X_s + \gamma$)
- ✦ RG evolution
- ✦ DM

Delgado et al '12

Light stop searches from Higgs+jet

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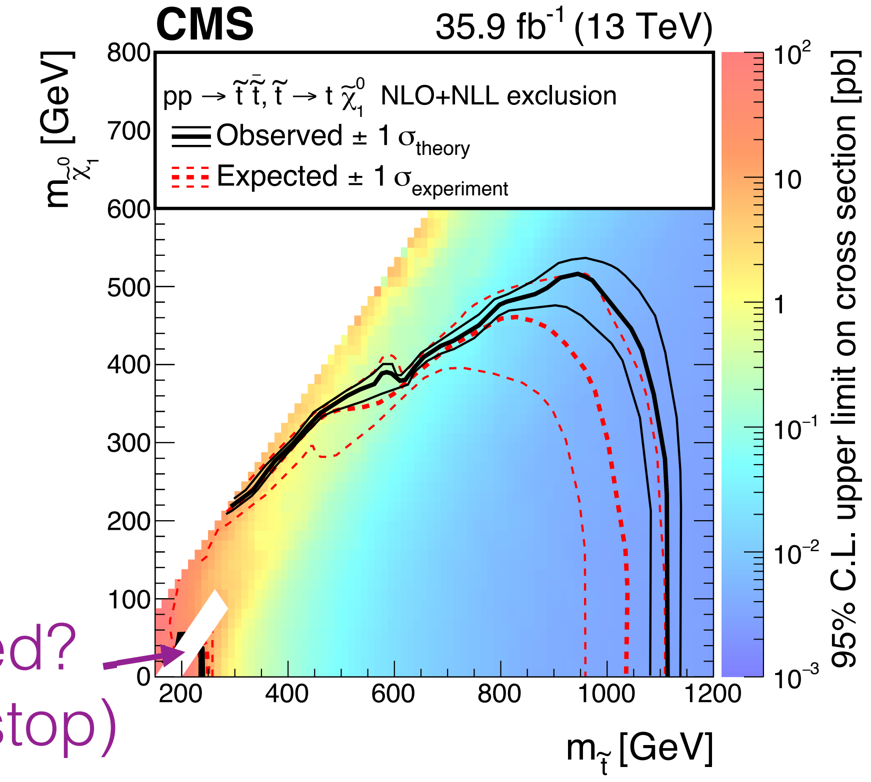
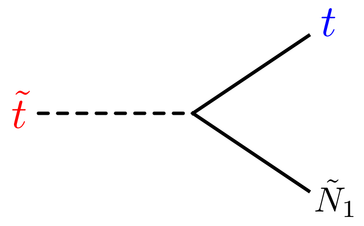


Difficult direct searches (trigger on stop+extra jet)



Light stop searches from Higgs+jet

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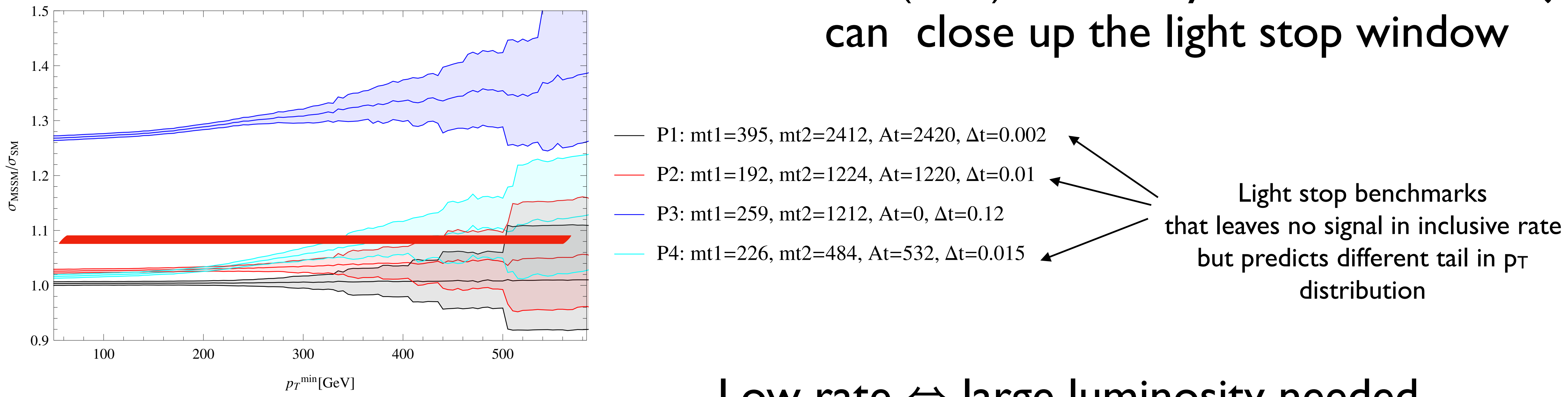
Inclusive Higgs measurements cannot rule out light stop

but O(10%) sensitivity on **boosted** h+j
can close up the light stop window



Grojean, Salvioni, Schlaffer, Weiler '13

Low rate ⇔ large luminosity needed

One good example where large statistics opens up new search strategy

One missing piece: The Higgs self-coupling

Do we need to reach HH threshold to learn about h^3?

One missing beast: h^3

The Higgs self-coupling plays important roles

1) linked to **naturalness/hierarchy** problem
2) controls the **stability** of the EW vacuum (… like many other BSM parameters)
3) dictates the dynamics of EW **phase transition** and potentially conditions the generation of a matter-antimatter imbalance via **EW baryogenesis**

Does it need to be measured with high accuracy?

Only a few new physics scenarios (but they exist) that will be revealed in the measurements of h^3
But this measurement is the only way to understand the dynamics of EWSB (Cooper pair or elementary scalar?)

M. McCullough, DESY'18

What sort of precision should we aim for?

- 95% confidence it exists: Around 50% accuracy
- 5σ discovery: Around 20 % accuracy.
- Quantum structure: Around 5% accuracy.

Higgs self-couplings and Naturalness

In the SM, $|H|^2$ is the only relevant operator
and it is the source of the hierarchy/naturalness/fine-tuning problem
It presence has never been tested!

Reconstructing the Higgs potential before EW symmetry breaking
from measurements around the vacuum is difficult in general
but we can easily test gross features, like the presence of the relevant operator(s)

Grojean, Servant, Wells '04

Goertz '15

SM

$$V = -\mu^2 |H|^2 + \lambda |H|^4 \quad \Rightarrow \quad V(h) = \frac{1}{2} m_h^2 h^2 + \frac{1}{6} \frac{3 m_h^2}{v} h^3 + \ldots$$

EWSB W/O H²

$$V = -\lambda |H|^4 + \frac{1}{\Lambda^2} |H|^6 \quad \Rightarrow \quad V(h) = \frac{1}{2} m_h^2 h^2 + \frac{1}{6} \frac{7 m_h^2}{v} h^3 + \ldots$$

200% correction to SM prediction

Possible 1st order phase transition

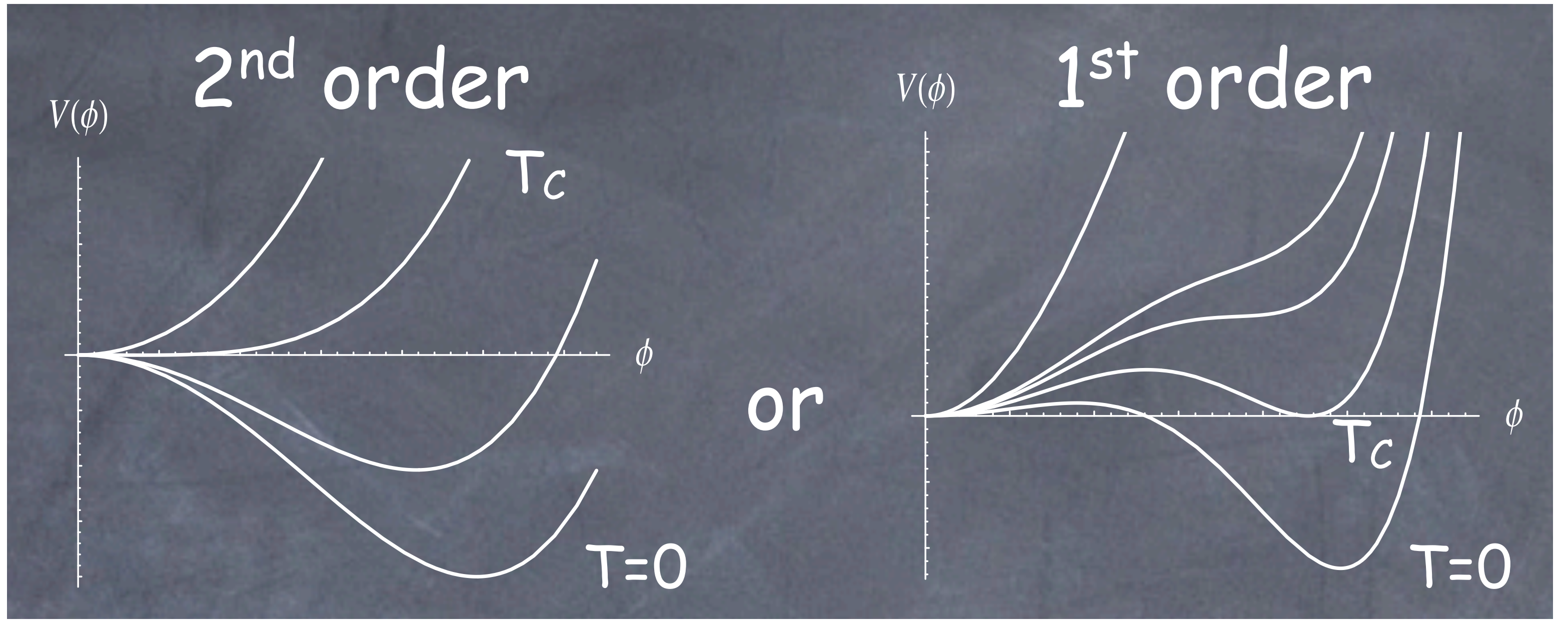
Coleman-Weinberg

$$V = C |H|^4 \left(-1/8 + \log(|H|^2/v^2)\right) \quad \Rightarrow \quad V(h) = \frac{1}{2} m_h^2 h^2 + \frac{1}{6} \frac{5 m_h^2}{v} h^3 + \ldots$$

Dynamics of EW phase transition

The asymmetry between matter-antimatter can be created dynamically
it requires an out-of-equilibrium phase in the cosmological history of the Universe

An appealing idea is EW baryogenesis associated to a first order EW phase transition
(not the only option but the only one that can be tested at colliders)



the dynamics of the phase transition is determined by Higgs effective potential at finite T
which we have no direct access at in colliders (LHC≠Big Bang machine)

finite T Higgs potential ⟺ Higgs couplings at T=0

SM: first order phase transition iff $m_H < 47$ GeV
BSM: first order phase transition needs some sizeable deviations in Higgs couplings

h³ and GW

GW interact very weakly and are not absorbed

direct probe of physical process of the very early universe

possible cosmological sources:

inflation, vibrations of topological defects, excitations of xdim modes, 1st order phase transitions...

ElectroWeak Phase Transition (if 1st order)

typical freq. ~ (size of the bubble)$^{-1}$ ~ (fraction of the horizon size)$^{-1}$

$$@\ T = 100\ \text{GeV}, \qquad H = \sqrt{\frac{8\pi^3}{45}}\frac{T^2}{M_{Pl}} \sim 10^{-15}\ \text{GeV}$$

redshifted freq.

~ today ~

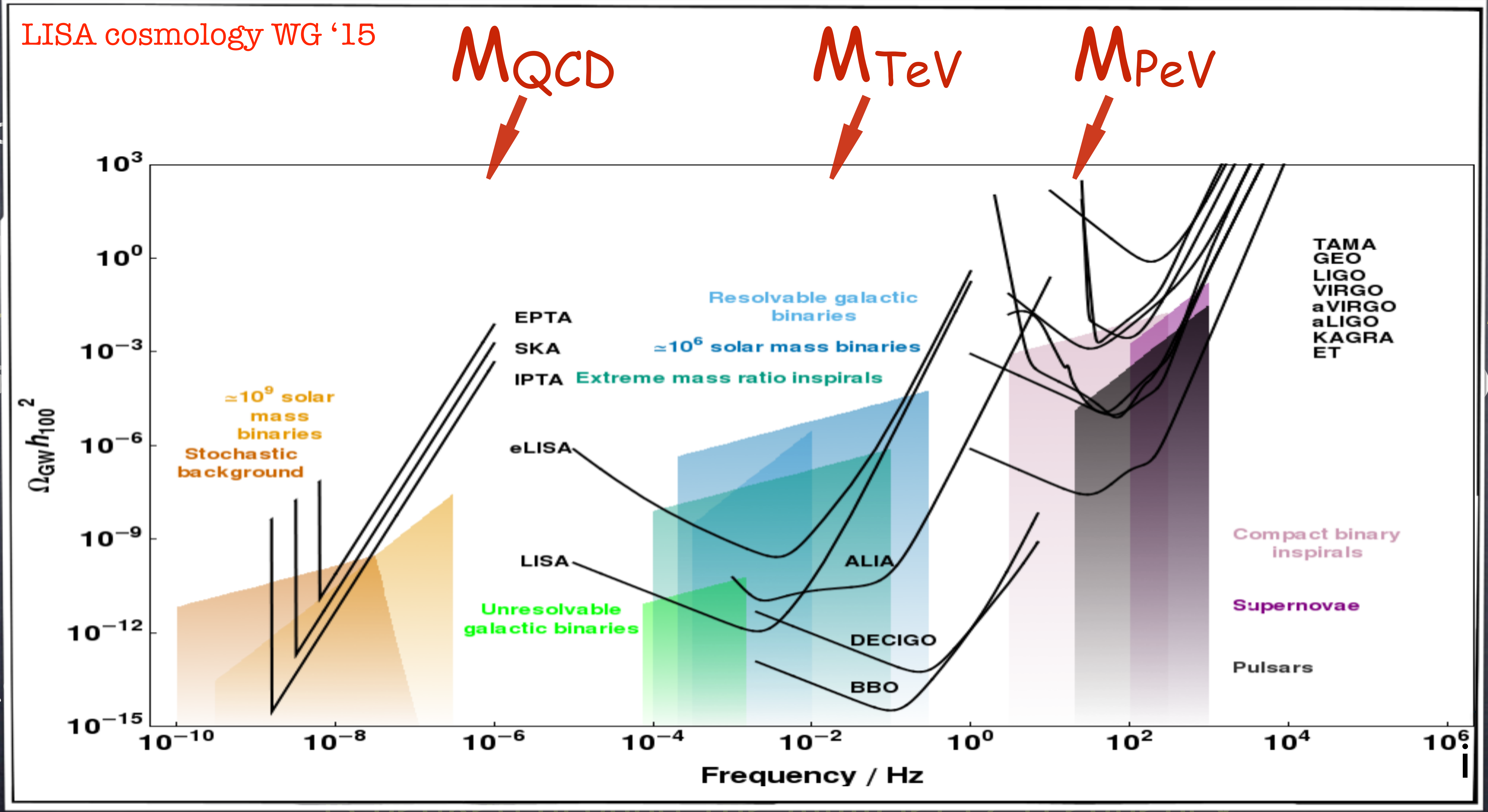
$$f \sim \# \frac{2\cdot 10^{-4}\ \text{eV}}{100\ \text{GeV}}\ 10^{-15}\ \text{GeV} \sim \# 10^{-5}\ \text{Hz}$$

Grojean, Servant '06

The GW spectrum from a 1st order electroweak PT is peaked around the milliHertz frequency

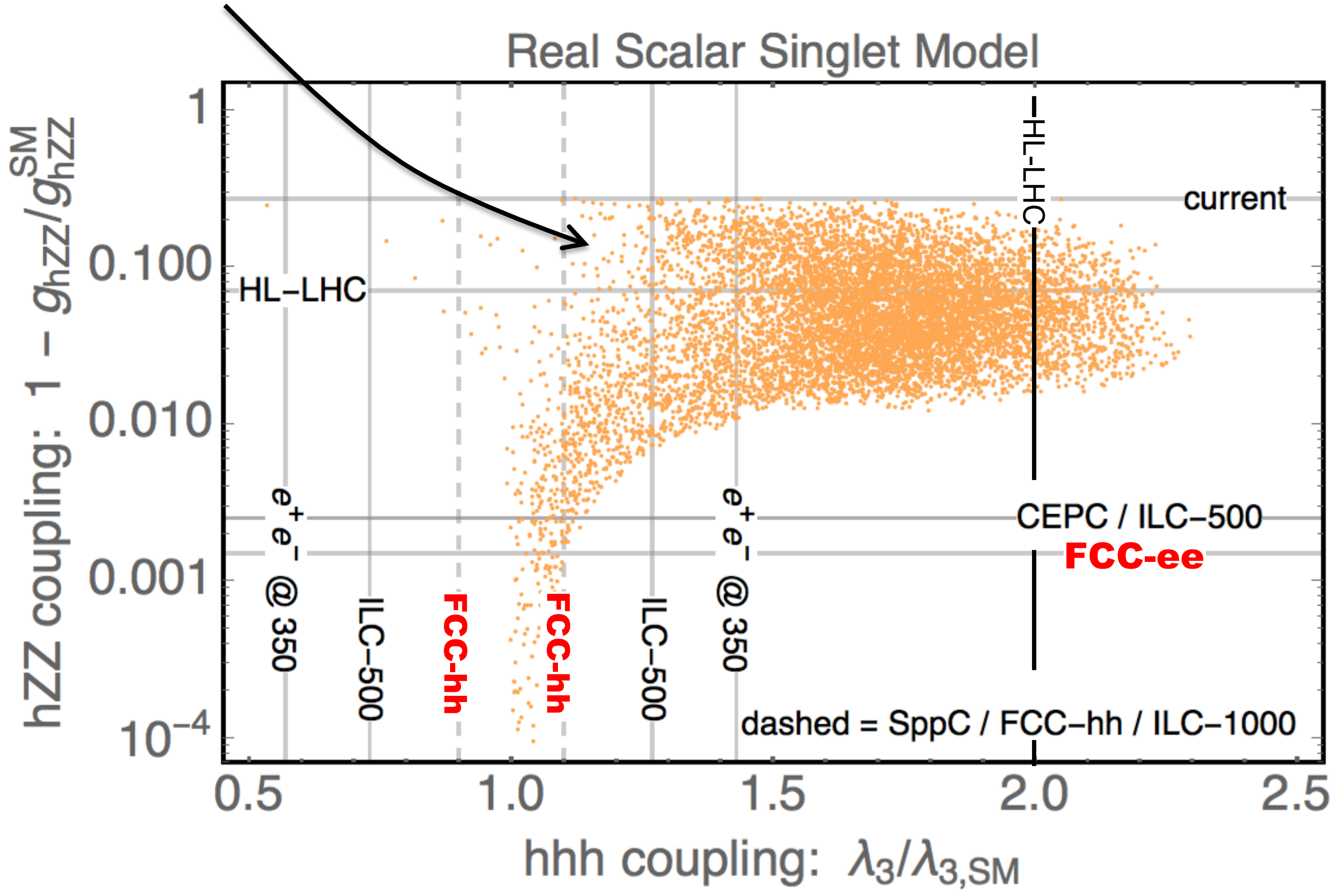
h^3 and GW

Grojean, Servant '06



Window to early universe complementary GW - Colliders

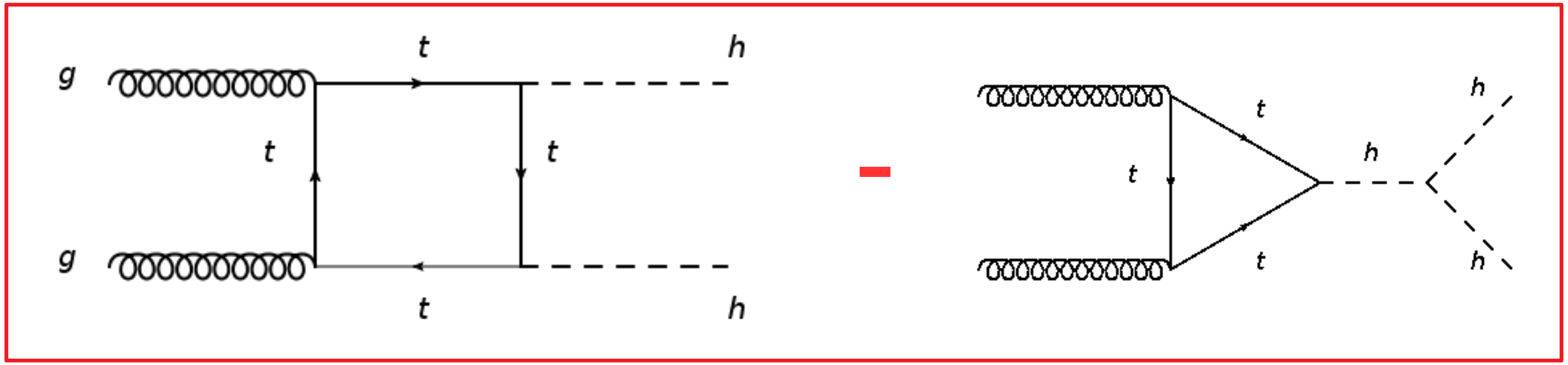
EWPT is 1st order giving rise to GW stochastic background



Huang, Long, Wang '16

h^3 Extraction @ LHC

Notoriously difficult



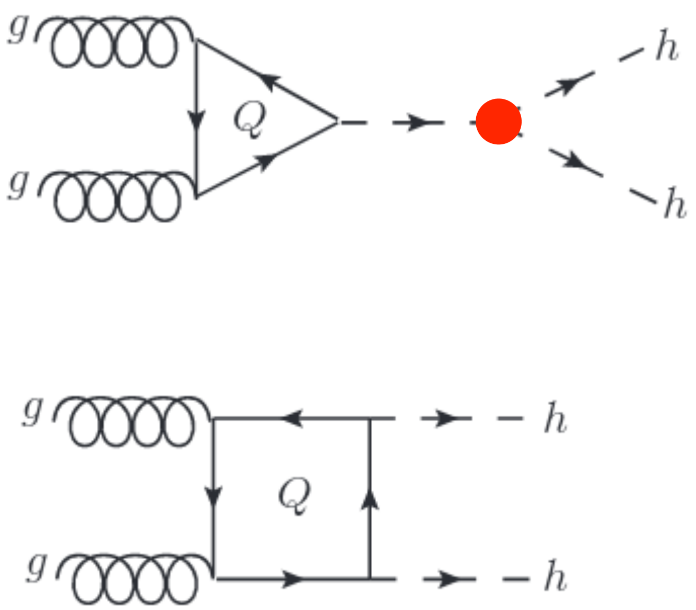
$$A_{\Box} = \frac{\alpha_s}{4\pi} y_t^2 \,, \qquad A_{\triangle} = \lambda_3 \frac{\alpha_s}{4\pi} y_t^2 \frac{m_h^2}{\hat{s}} \left(\log \frac{m_t^2}{\hat{s}} + i\pi \right)^2$$

$$\frac{\sigma(pp \to hh)}{\sigma(pp \to h)} \sim 10^{-3}$$

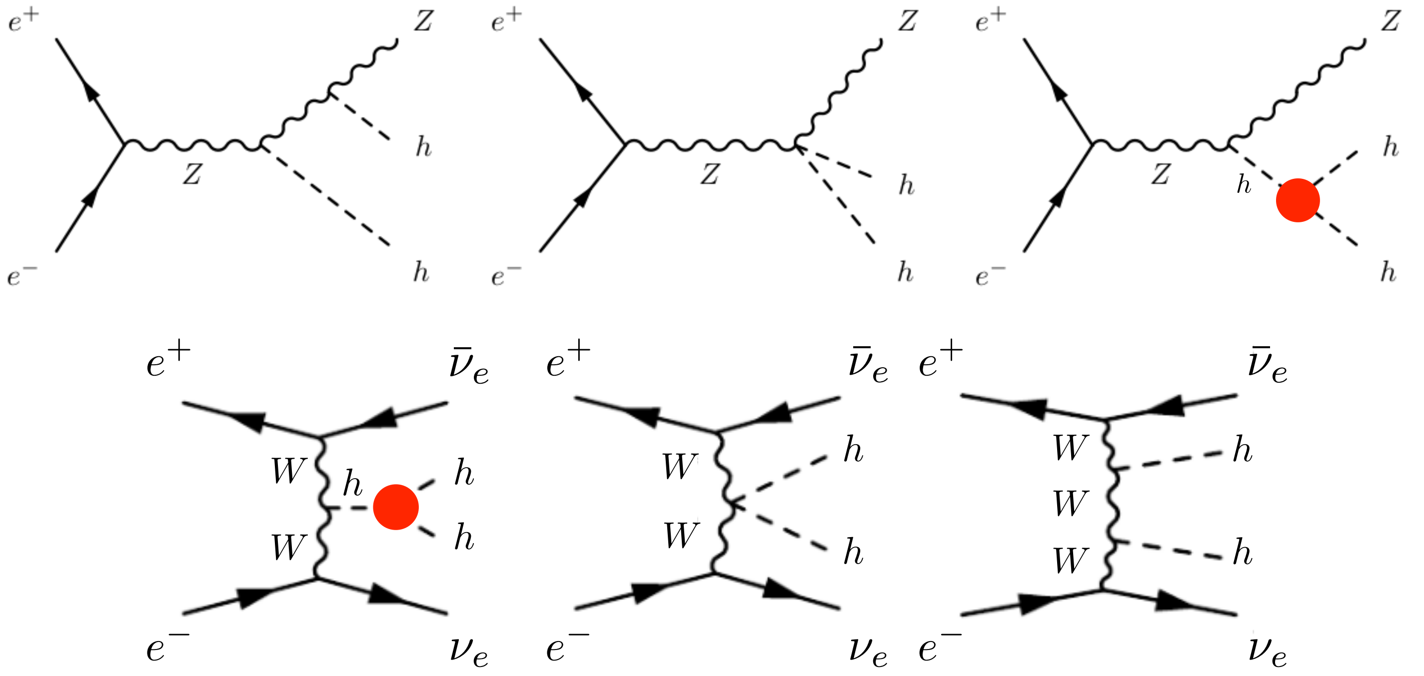
Note also: 2% uncertainty on tth → 5% uncertainty on h^3

h^3 from HH

pp colliders

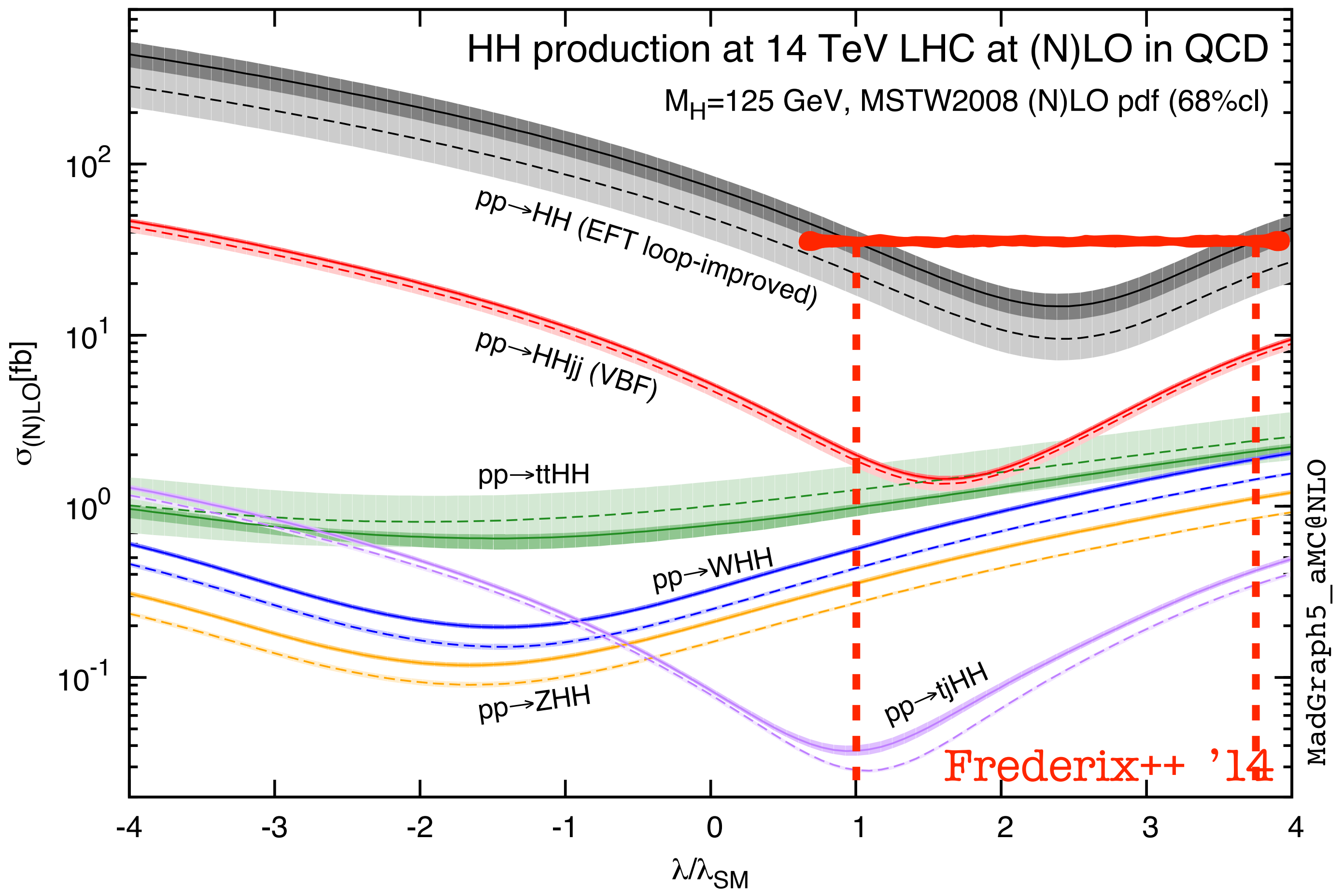


ee colliders



h^3 from HH: issue with second minimum

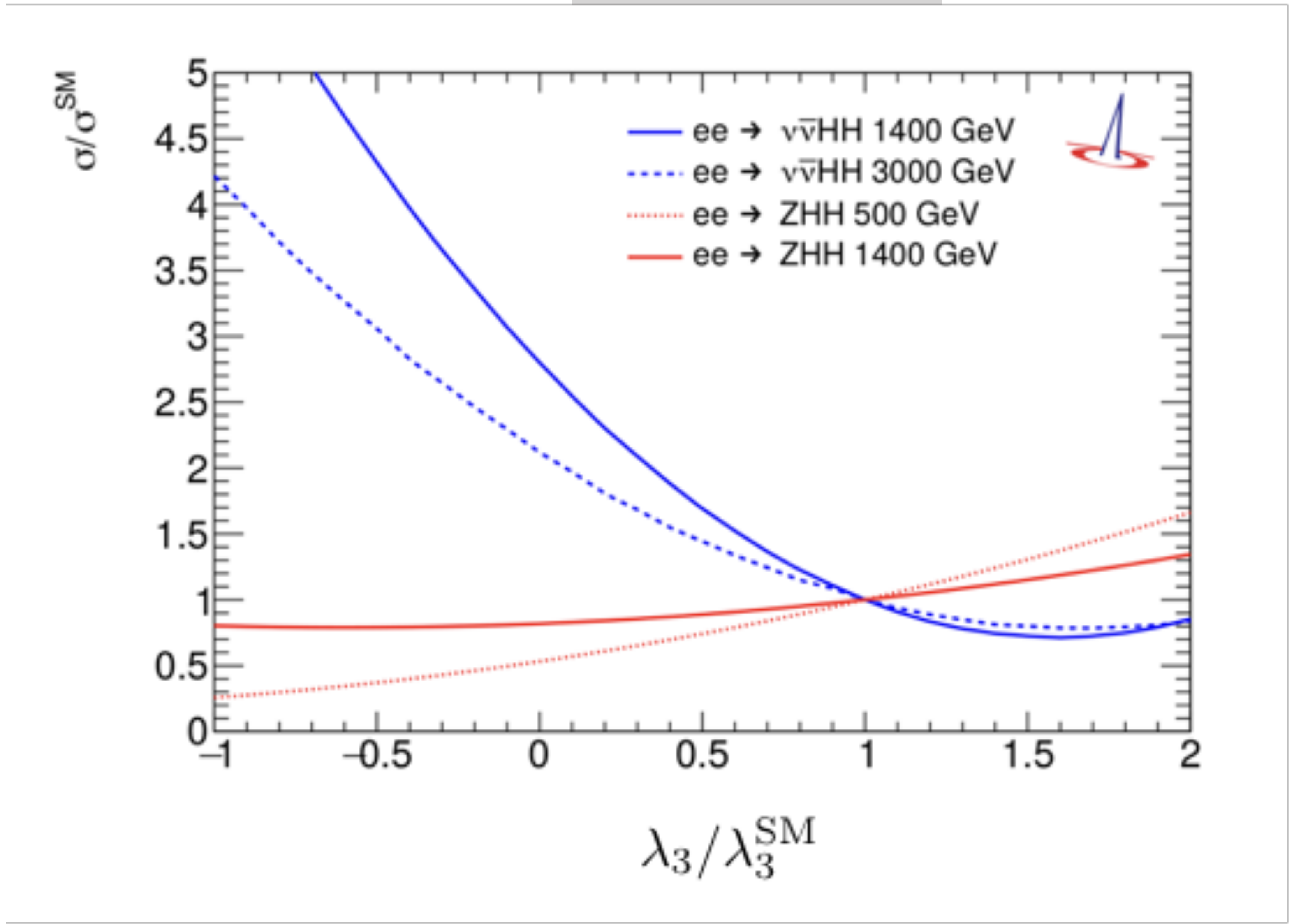
pp colliders



mhh distribution will help separate the two degenerate points

(larger h^3, m_{hh} more picked close to threshold)

ee colliders



ZHH gives stronger constraints on $\delta\kappa_\lambda > 0$

$\nu\bar{\nu}HH$ gives stronger constraints on $\delta\kappa_\lambda < 0$

h^3 from hh@LHC now

Current constraints:

Obs.(exp.) limit on σ_{hh}/σ_{SM}:

Final state	ATLAS	CMS
$b\bar{b}\gamma\gamma$	177 (162)	19 (16)
$b\bar{b}\tau\tau$		30 (25)
$b\bar{b}b\bar{b}$	29 (38)	342 (308)
$b\bar{b}WW^*$		79 (89)
$\gamma\gamma WW^*$	750 (386)	

- 2015 (2.3-3.2 fb^{-1})
- 2015+2016 (13.3 fb^{-1})
- 2016 (35.9 fb^{-1})

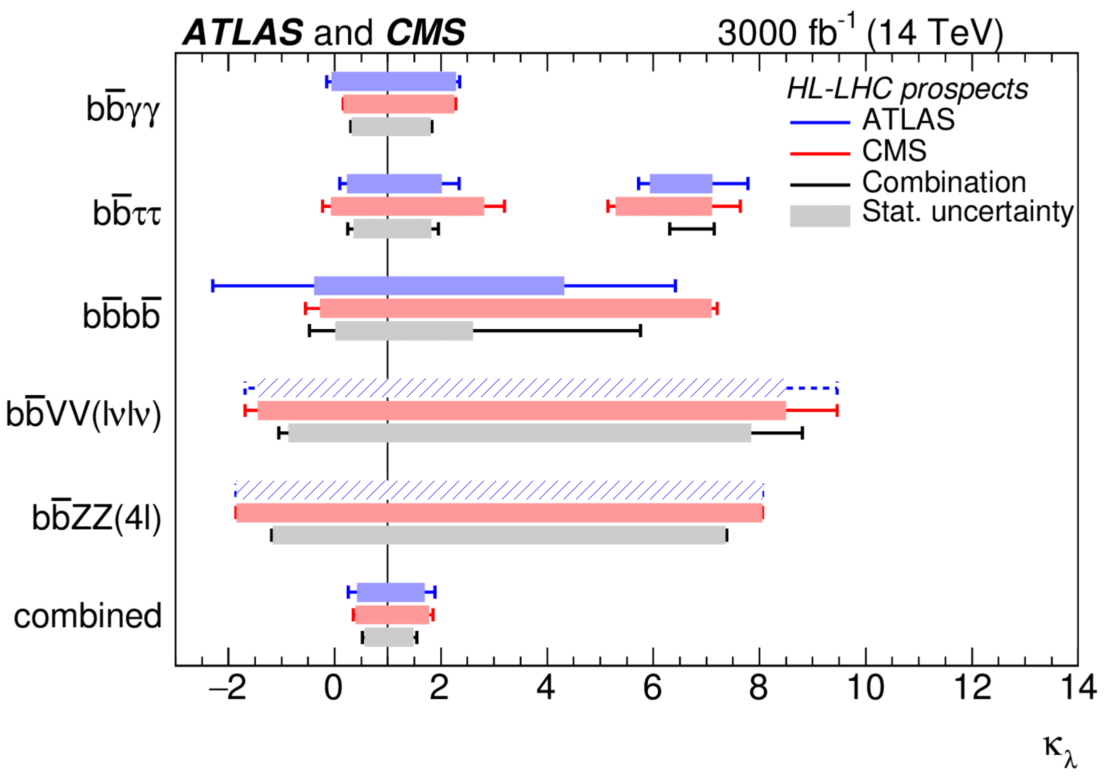
S. Wertz,

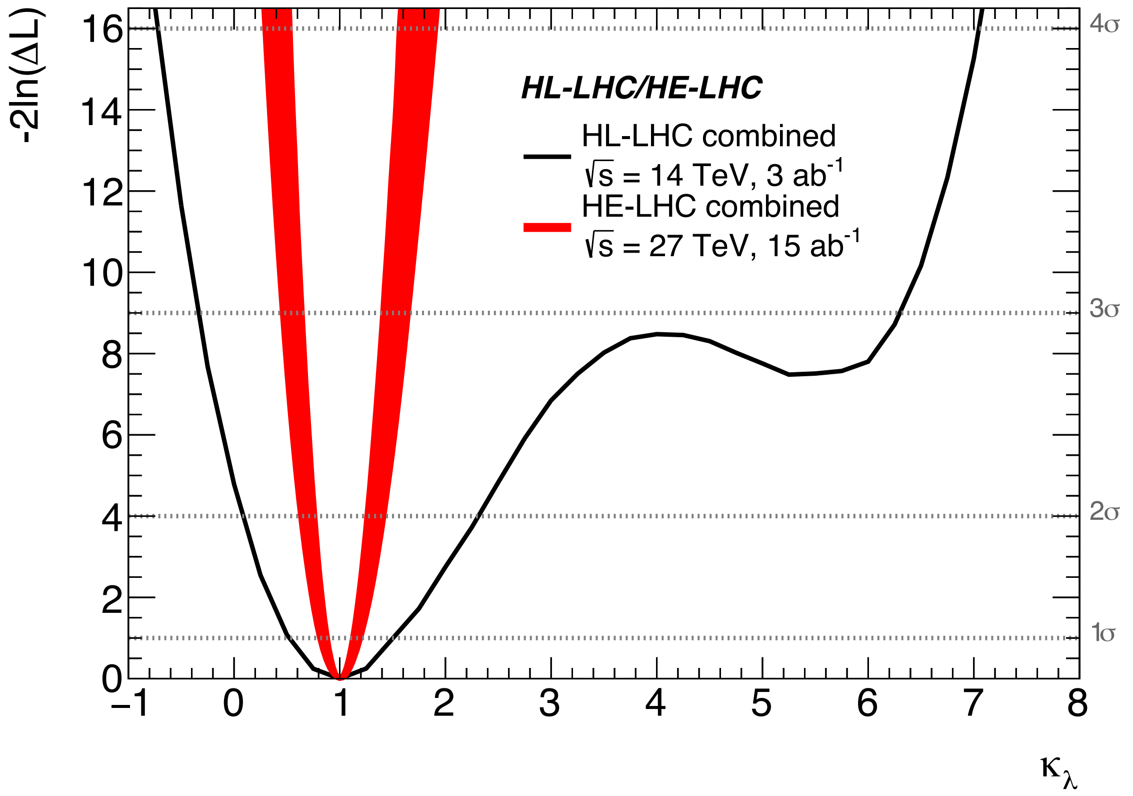
Higgs Couplings 2017

$$\longrightarrow \quad -8.8 < \kappa_\lambda < 15$$

h^3 from hh@HL/HE-LHC

HL/HE-LHC Higgs WG report





- ✦ HL-LHC can test the Higgs trilinear with O(50%) precision

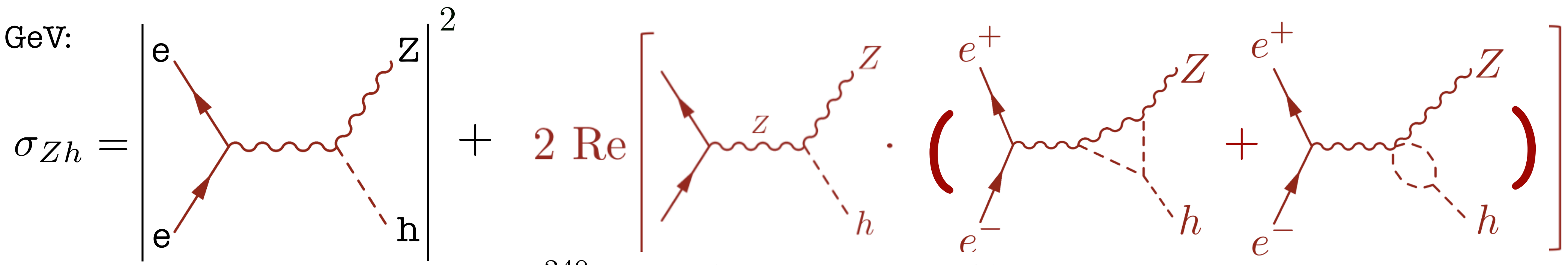
$$0.57 \leq \kappa_\lambda \leq 1.5 \quad \text{at} \quad 68\% \text{ C.L.}$$

- ✦ HE-LHC could test the Higgs trilinear with O(15-30%) precision
  (projections vary significantly between different analyses)

h^3 from h@NLO@HL-LHC

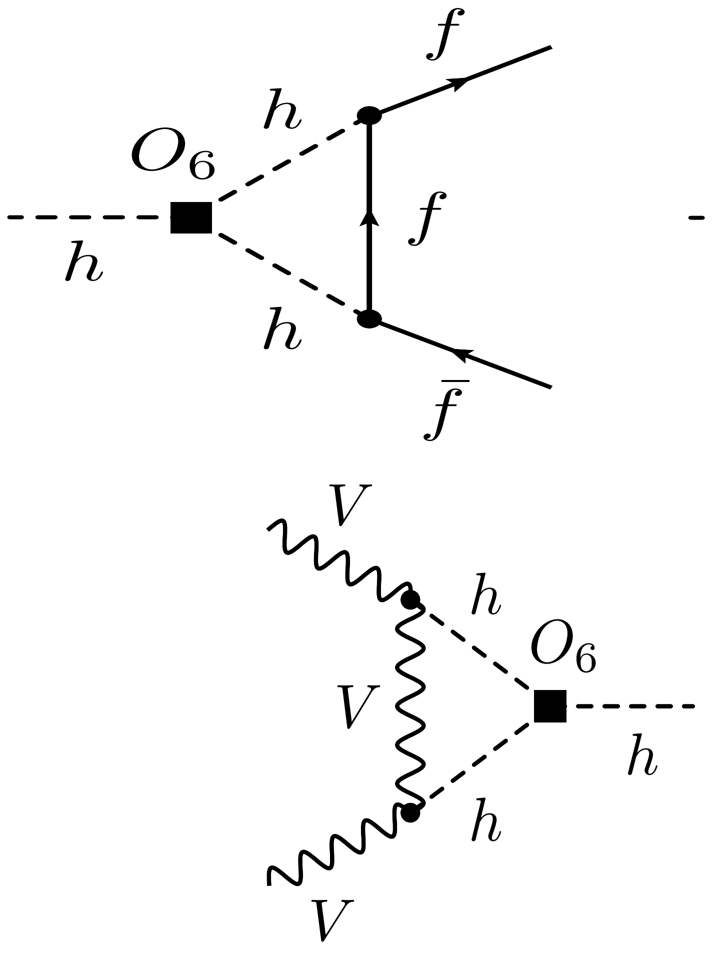
M. McCullough '14

At 240 GeV:

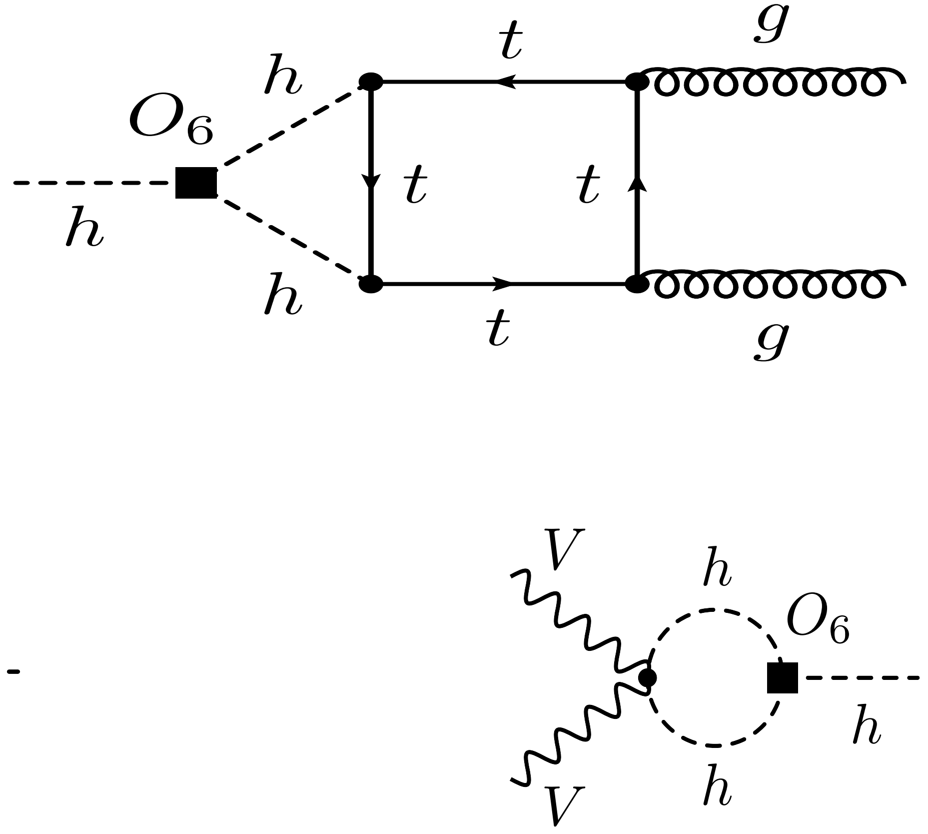


$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

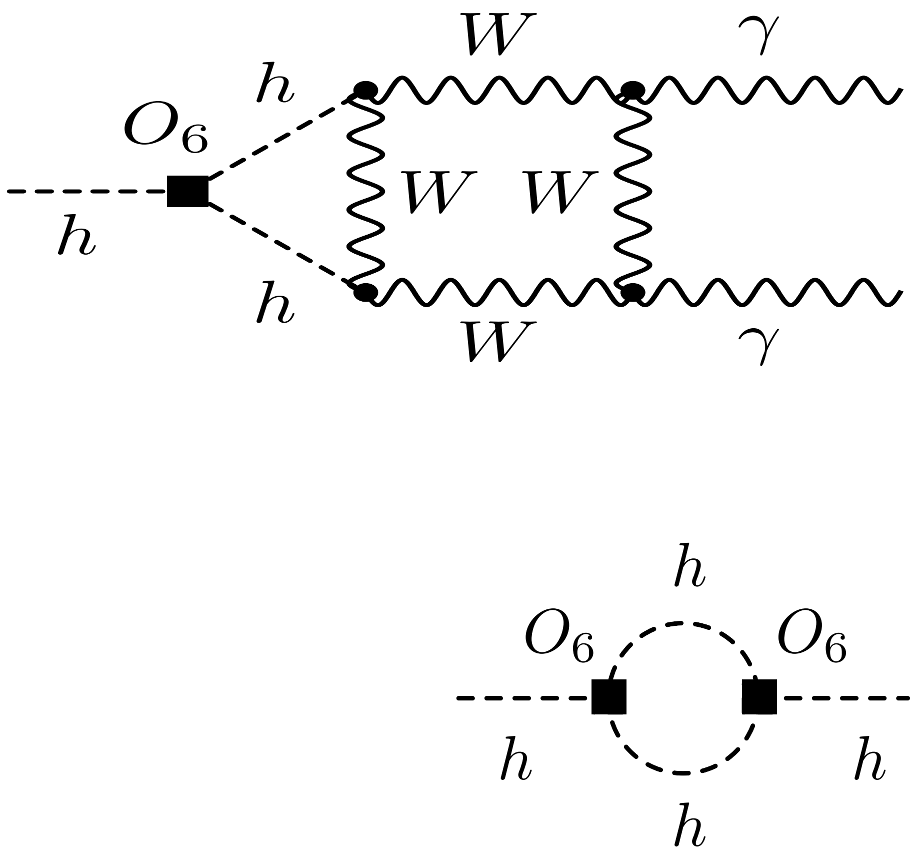
Gorbahn et al '16



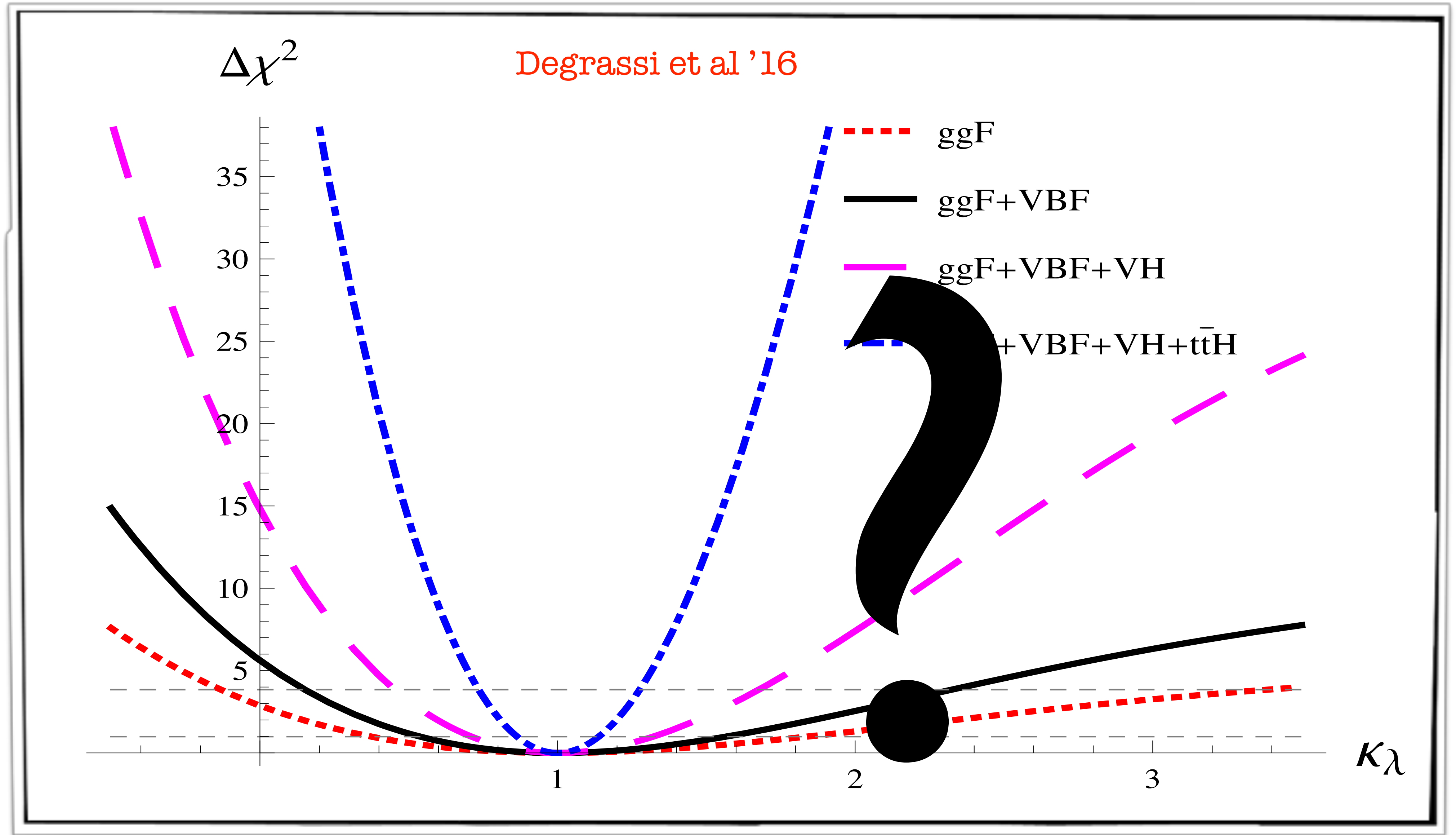
Degrassi et al '16



Bizon et al '16



h^3 from h@NLO@HL-LHC



$$\kappa_\lambda = \frac{g_{h^3}}{g_{h^3}^{\rm SM}}$$

$$\mathcal{L} \supset \frac{c_6}{\Lambda^2}|H|^6 \Longleftrightarrow \kappa_\lambda = 1 + \frac{c_6 G_F^{-2}}{m_H^2 \Lambda^2}$$

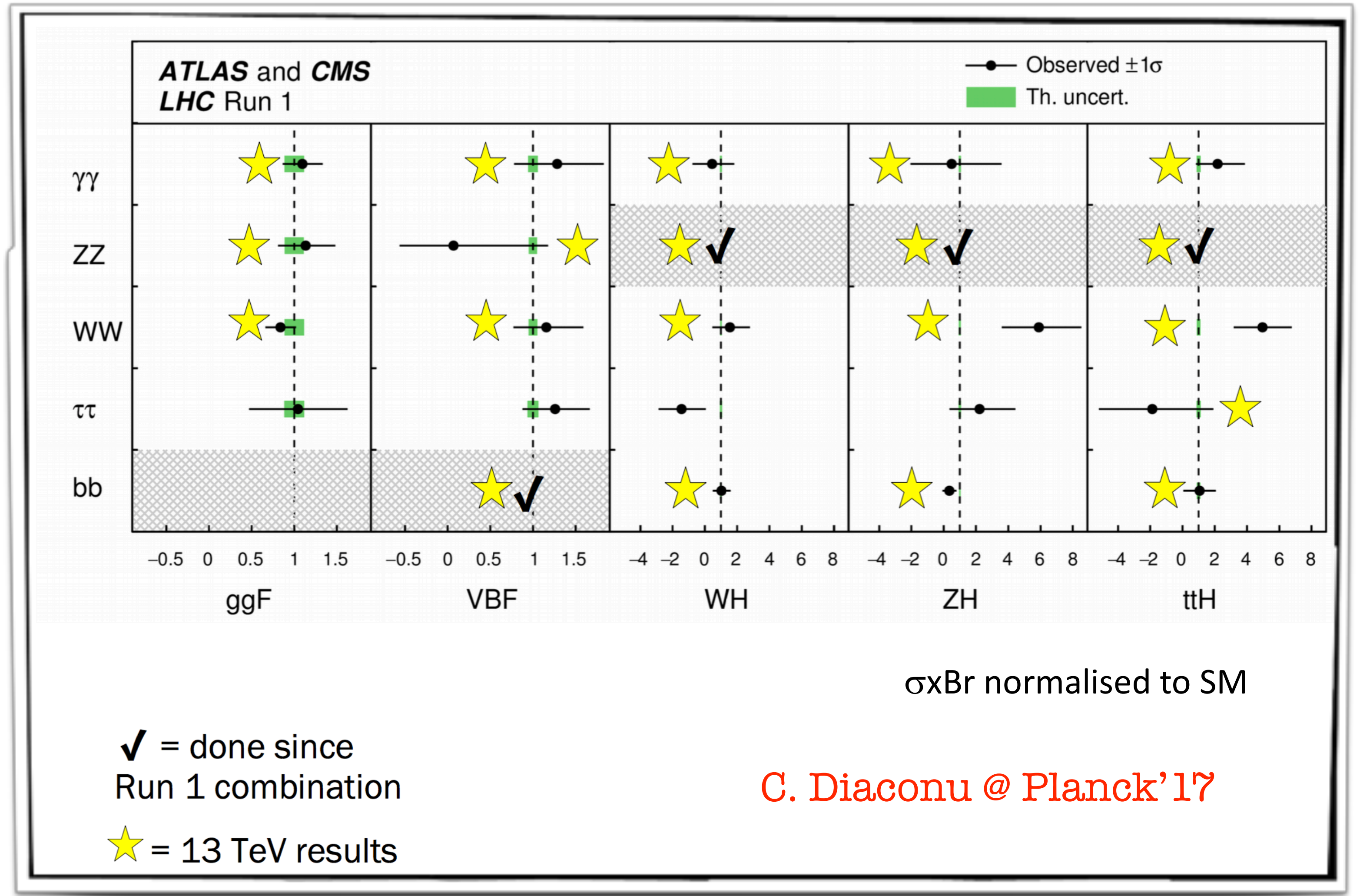
$$\kappa_\lambda \in [-0.7, 4.2]$$

Worse than direct determination via double Higgs production but different systematics and "easier" analysis

h^3 @NLO vs h @ LO in global fit

The fabulous 5^2 channels

5 main production modes: ggF, VBF, WH, ZH, ttH
5 main decay modes: ZZ, WW, γγ, ττ, bb



h^3 @NLO vs h @ LO in global fit

Good sensitivity (O(5-10-20)%) on 16 channels @ **HL-LHC**

Process		Combination	Theory	Experimental
$H \to \gamma\gamma$	ggF	0.07	0.05	0.05
	VBF	0.22	0.16	0.15
	$t\bar{t}H$	0.17	0.12	0.12
	WH	0.19	0.08	0.17
	ZH	0.28	0.07	0.27
$H \to ZZ$	ggF	0.06	0.05	0.04
	VBF	0.17	0.10	0.14
	$t\bar{t}H$	0.20	0.12	0.16
	WH	0.16	0.06	0.15
	ZH	0.21	0.08	0.20
$H \to WW$	ggF	0.07	0.05	0.05
	VBF	0.15	0.12	0.09
$H \to Z\gamma$	incl.	0.30	0.13	0.27
$H \to b\bar{b}$	WH	0.37	0.09	0.36
	ZH	0.14	0.05	0.13
$H \to \tau^+\tau^-$	VBF	0.19	0.12	0.15

Estimated relative uncertainties on the determination of single-Higgs production channels at the HL-LHC(14 TeV center of mass energy, 3/ab integrated luminosity and pile-up 140 events/bunch-crossing).

ATL-PHYS-PUB-2014-016 ATL-PHYS-PUB-2016-008 ATL-PHYS-PUB-2016-018

h^3 @NLO vs h @ LO in global fit

The fabulous 5^2 channels

5 main production modes: ggF, VBF, WH, ZH, ttH

5 main decay modes: ZZ, WW, γγ, ττ, bb

a priori up to **25** measurements

but for an on-shell particles, at most **10** physical quantities

since only products σxBR are measured ⇒ only **9** independent constraints

$$\mu_i^f = \mu_i \times \mu^f = \frac{\sigma_i}{(\sigma_i)_{\rm SM}} \times \frac{{\rm BR}[f]}{({\rm BR}[f])_{\rm SM}}$$

$$\mu_i^f \simeq 1 + \delta\mu_i + \delta\mu^f$$

linearized BSM perturbations

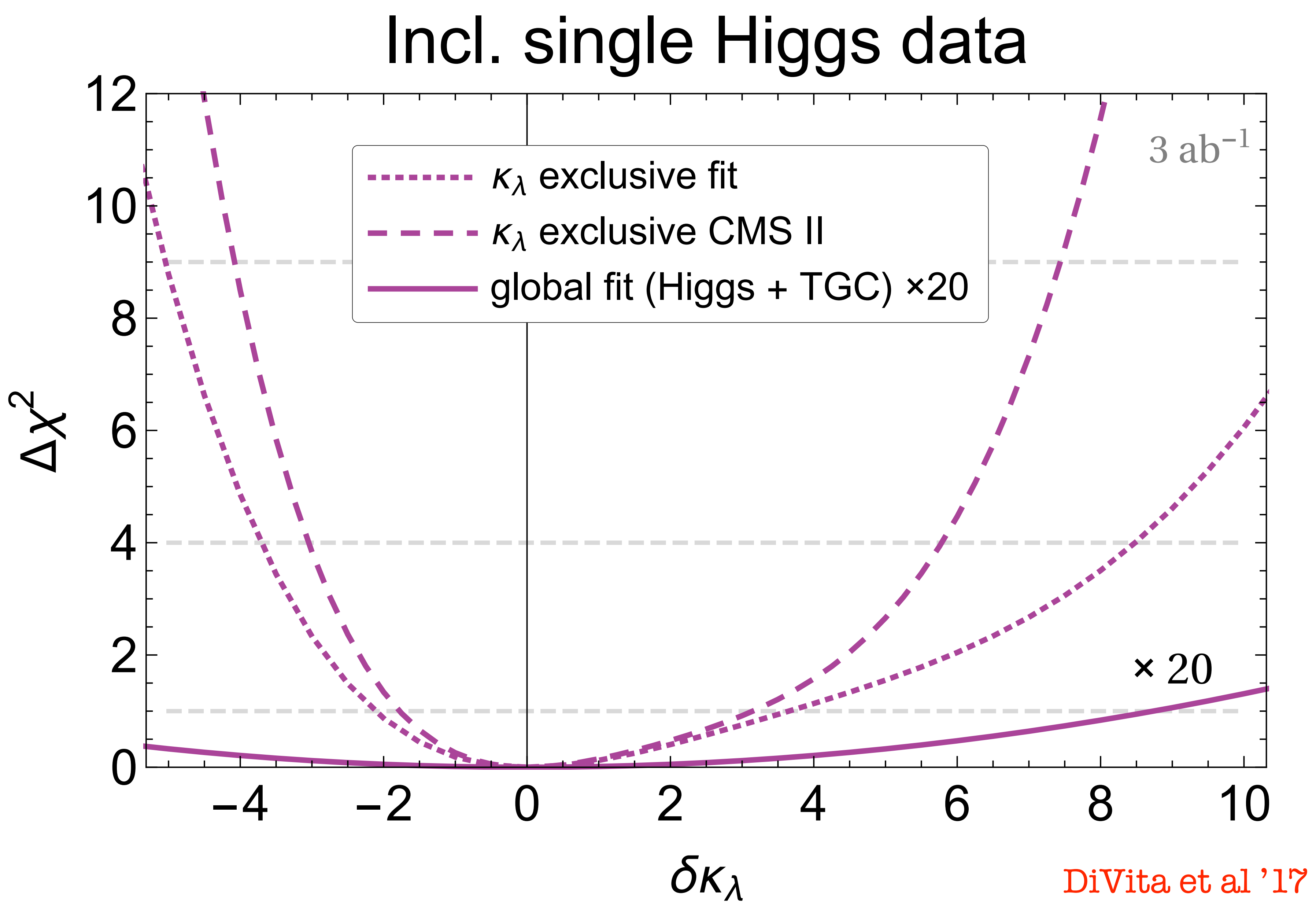
$$\mu_i \to \mu_i + \delta \qquad \mu^f \to \mu^f - \delta$$

cannot determine univocally 10 EFT parameters!

one flat direction is expected!

h^3 @NLO vs h @ LO in global fit

The fabulous 5^2 channels



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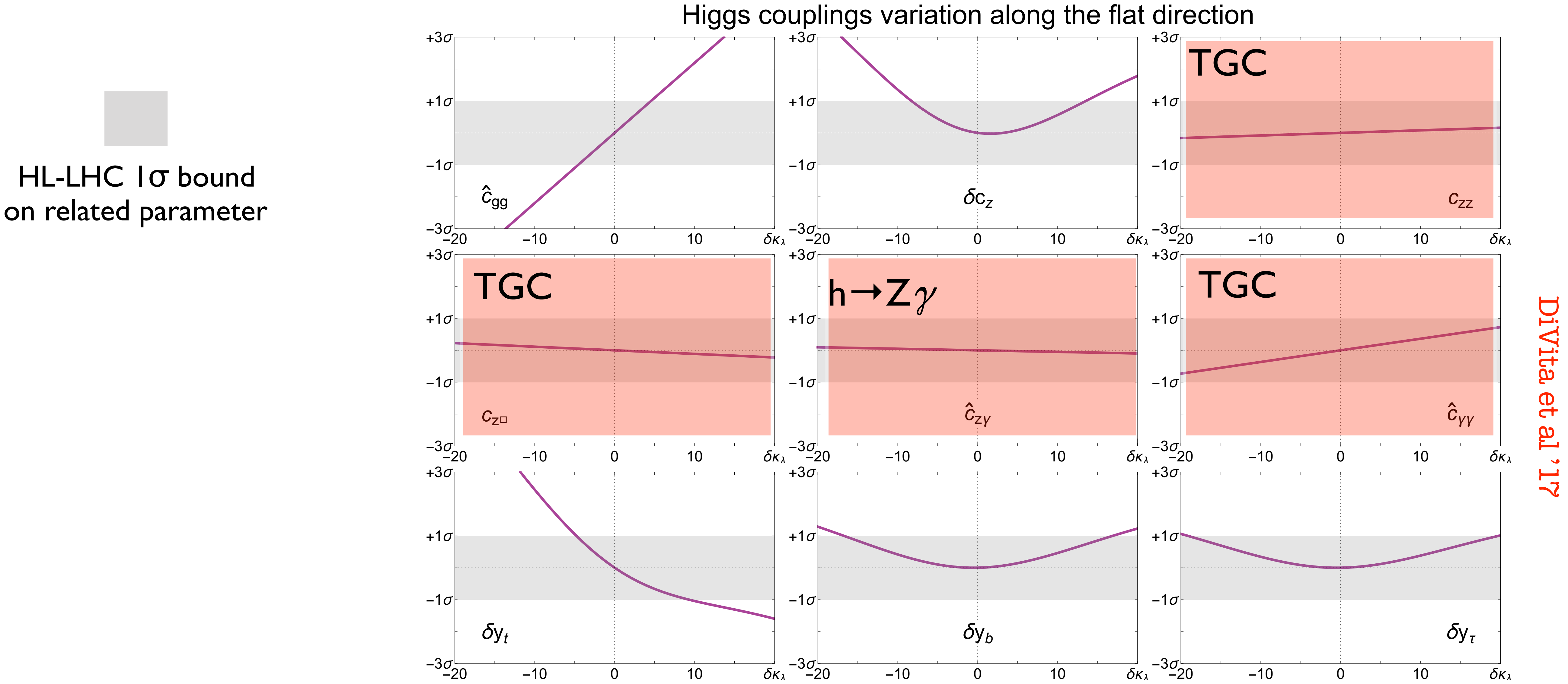
h³ @NLO vs h @ LO in global fit



The particular structure of this flat direction tells that adding new data on diboson or h→Zγ won't help much

cannot determine univocally 10 EFT parameters!

one flat direction is expected!

Does h³ modify the fit to other couplings?

DiVita et al '17

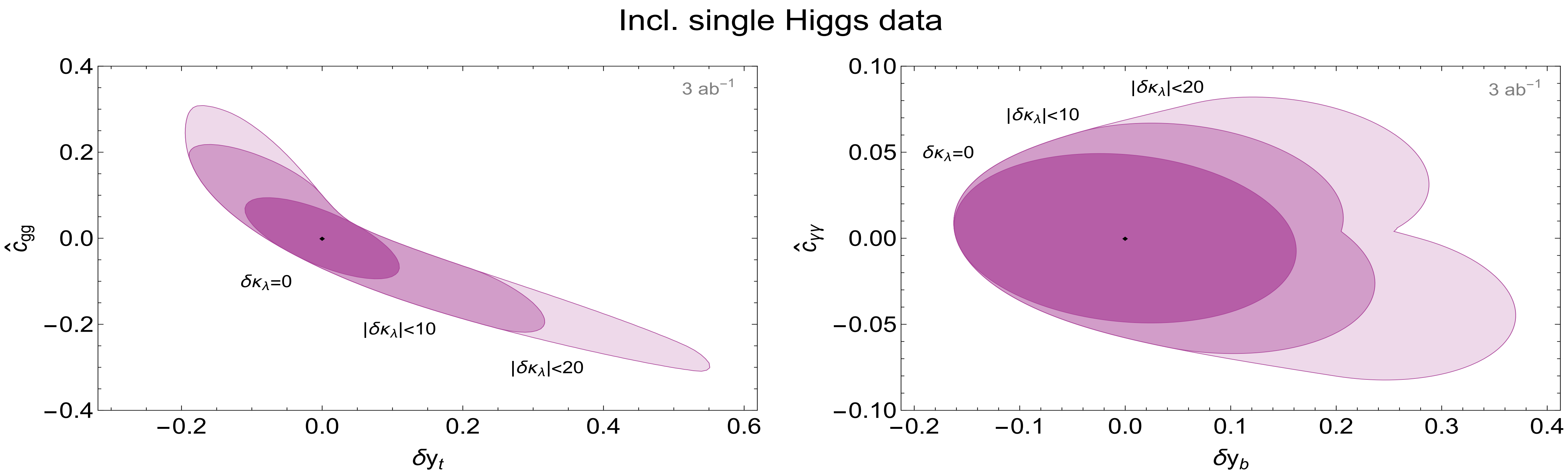


Figure 3. Constraints in the planes $(\delta y_t, \hat{c}_{gg})$ (left panel) and $(\delta y_b, \hat{c}_{\gamma\gamma})$ (right panel) obtained from a global fit on the single-Higgs processes. The darker regions are obtained by fixing the Higgs trilinear to the SM value $\kappa_\lambda = 1$, while the lighter ones are obtained through profiling by restricting $\delta\kappa_\lambda$ in the ranges $|\delta\kappa_\lambda| \leq 10$ and $|\delta\kappa_\lambda| \leq 20$ respectively. The regions correspond to 68% confidence level (defined in the Gaussian limit corresponding to $\Delta\chi^2 = 2.3$).

In models with parametrically large h³, fit with κ_λ @ NLO can differ from LO fit by a factor 2.

But this concerns only particular BSM models, in most models $\kappa_\lambda \sim \kappa_i$ and NLO effects are negligible.

Furthermore, HL-LHC will already measure h³ at 50%,

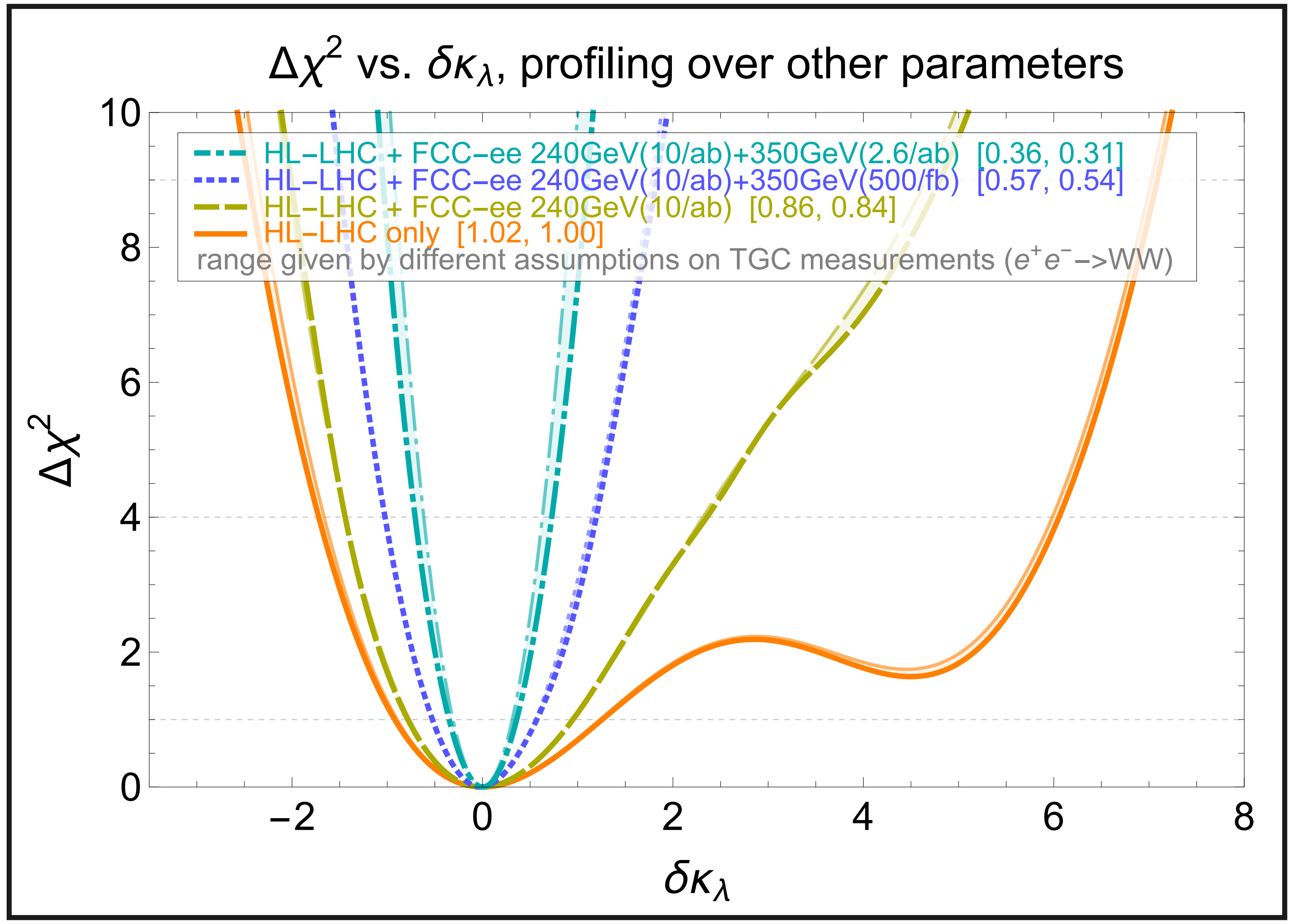
so even in the extreme case, the NLO effects are limited to 20-30%

What about (low energy) e^+e^- colliders?

1 main production mode (ZH) & 1 subdominant production (VBF)
+ access to full angular distributions (4) and/or beam polarizations (2)

7 (+2) accessible decay modes: ZZ, WW, $\gamma\gamma$, Zγ, $\tau\tau$, bb, gg, (cc, μμ)

no flat direction is expected!



Don't need high-energy ee to measure h³

1) with a run at 240 GeV only, bound starts to become meaningful only if perfect control of di-boson

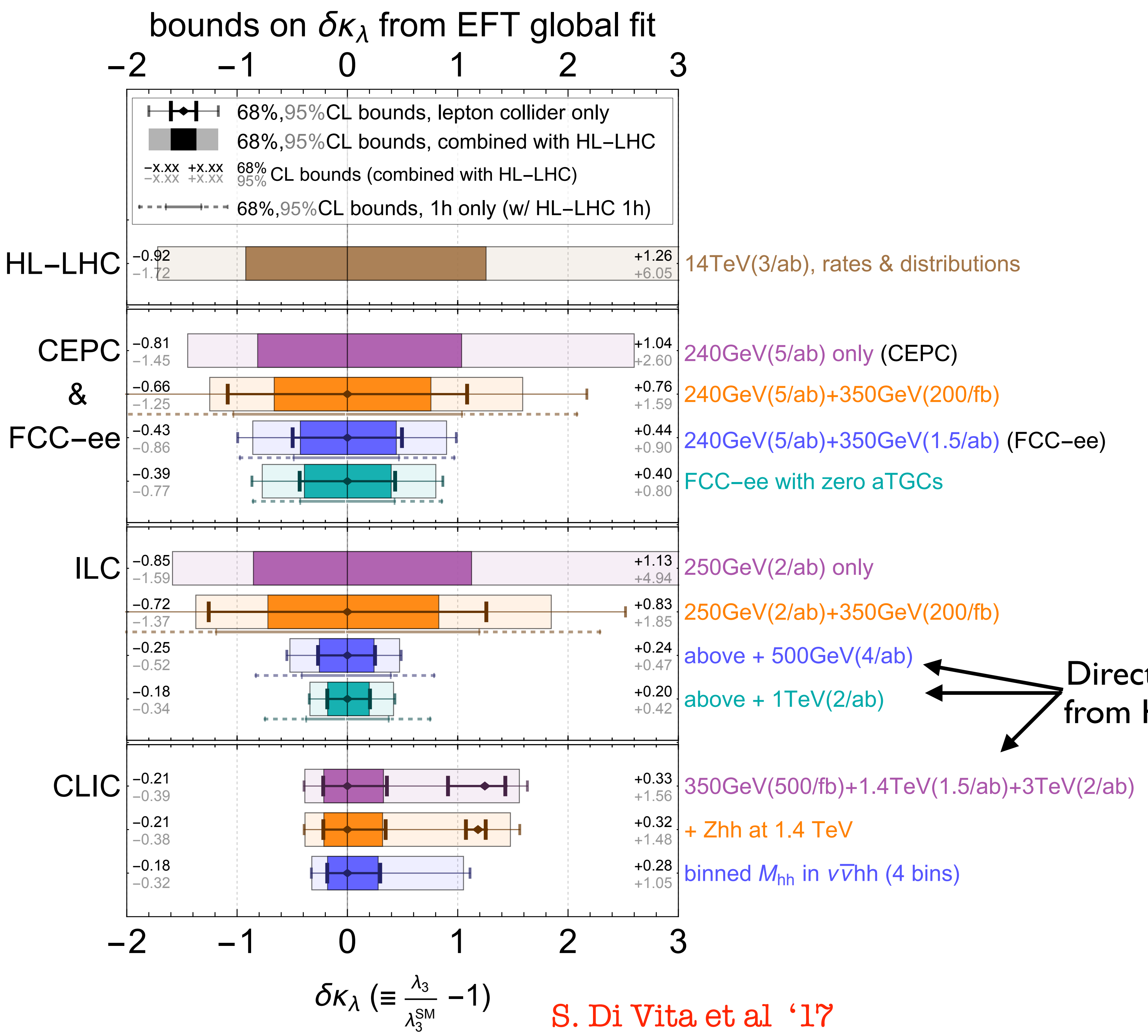
2) combining 240+350 improves significantly the bounds on h³

3) combination FCC-ee and HL-LHC is very powerful (especially if cannot afford FCC-ee @ 350GeV)

S. Di Vita, G. Durieux, C. Grojean, J. Gu, Z. Liu, G. Panico, M. Riembau, T. Vantalon '17

See also F. Maltoni, D. Pagani, X. Zhao '18

Future prospects for h^3 measurements



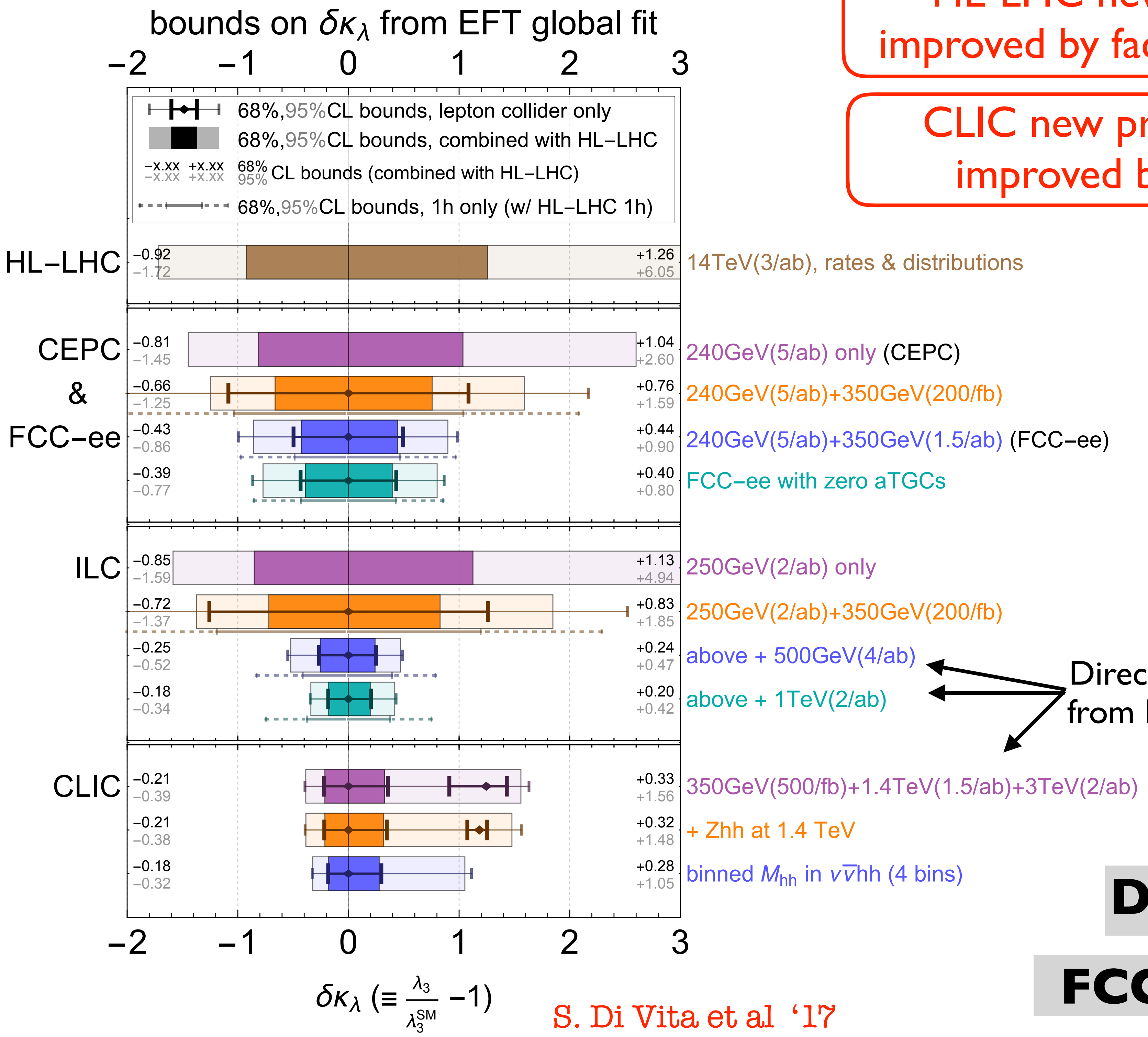
Direct measurement from HH production

S. Di Vita et al '17

Future prospects for h^3 measurements

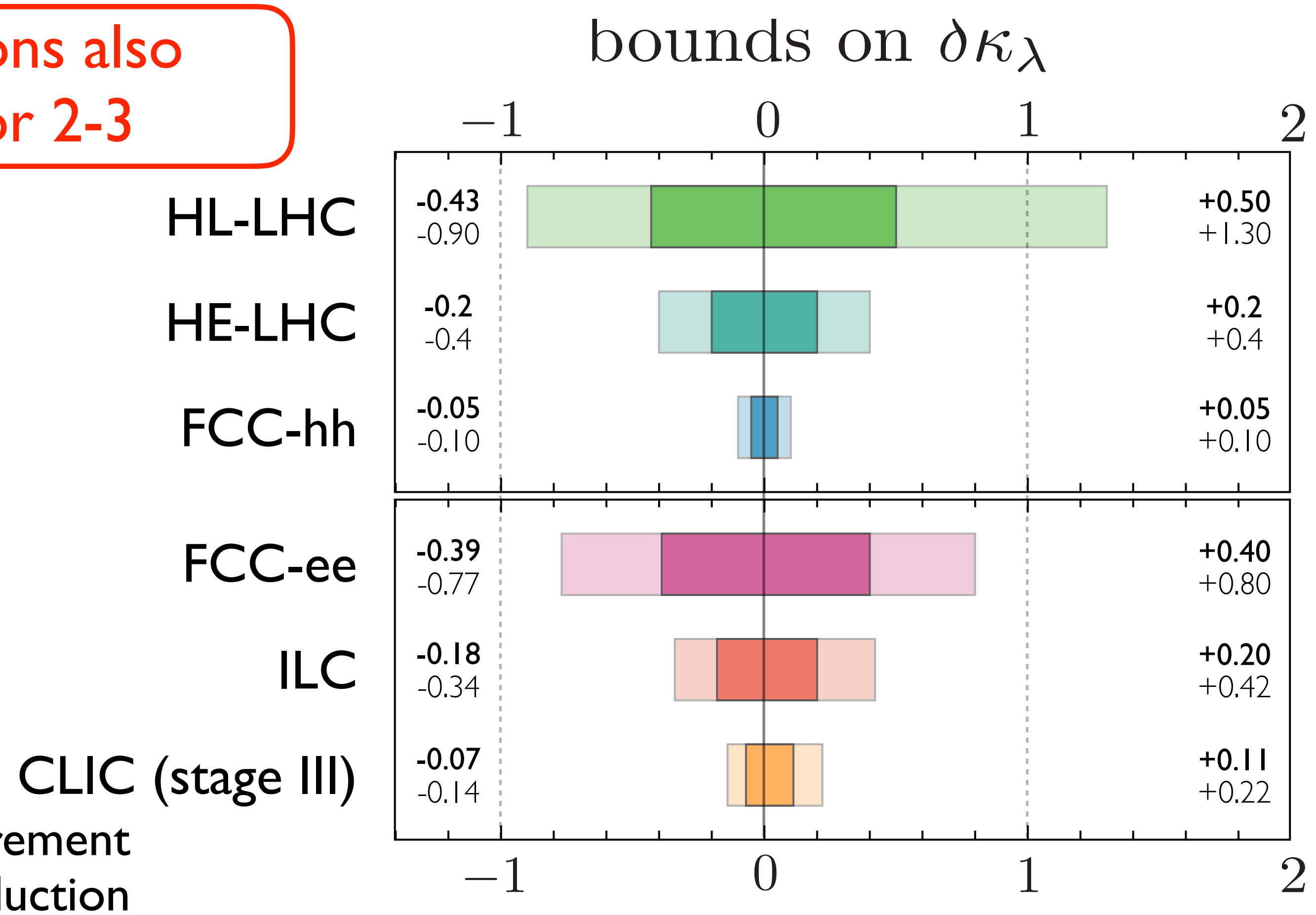
HL-LHC new projections improved by factor 2-3 vs 2013

CLIC new projections also improved by factor 2-3



Direct measurement from HH production

S. Di Vita et al '17



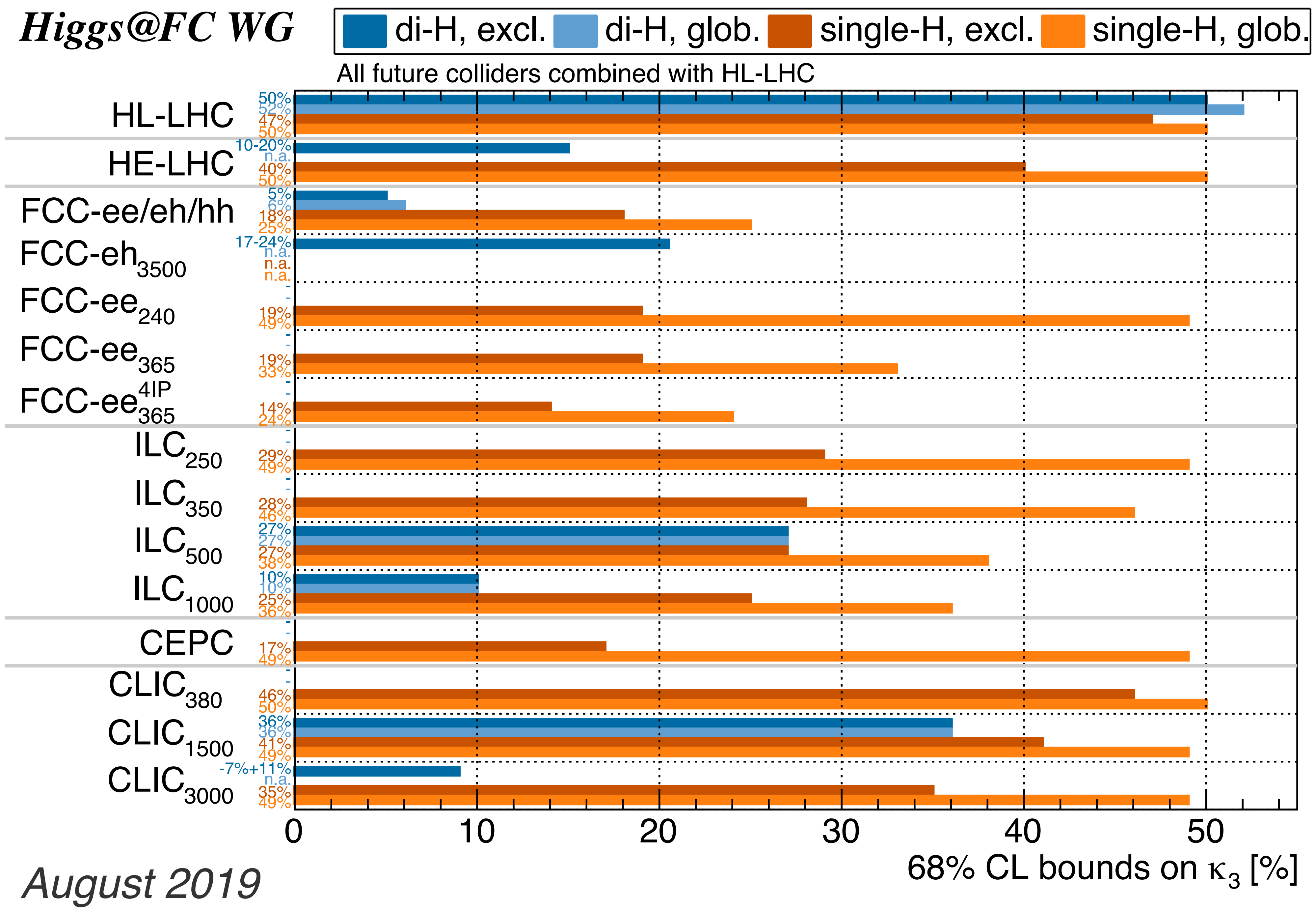
Jan. '19 Update

Don't need high-energy ee to measure h^3

FCC-hh can probe quantum corrections to h^3

Future prospects for h^3 measurements

ECFA Higgs study group '19



Don't need high-energy ee to establish the existence of h^3

What sort of precision should we aim for?

- 95% confidence it exists: Around 50% accuracy
- 5σ discovery: Around 20 % accuracy.
- Quantum structure: Around 5% accuracy.

Sensitivity from measurements at high E

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

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

$$m_* = g_* f_*$$

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

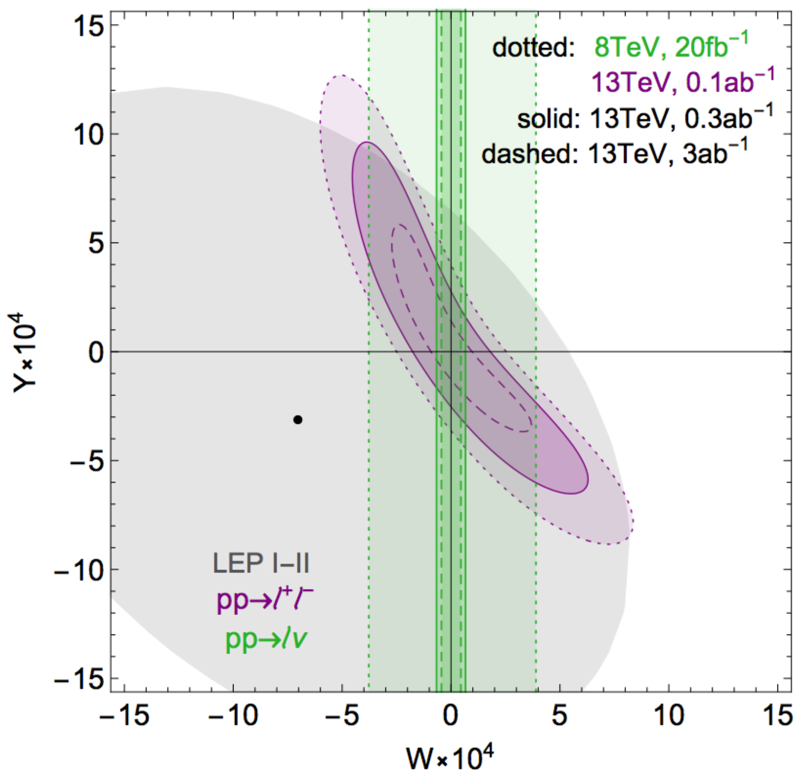
"energy helps accuracy"

Farina et al '16

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

CLIC: best accuracy from great sensitivity & large energy

Particle or not Particle?



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

	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

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

CLIC: best accuracy from great sensitivity & large energy

Composite Higgs

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

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

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

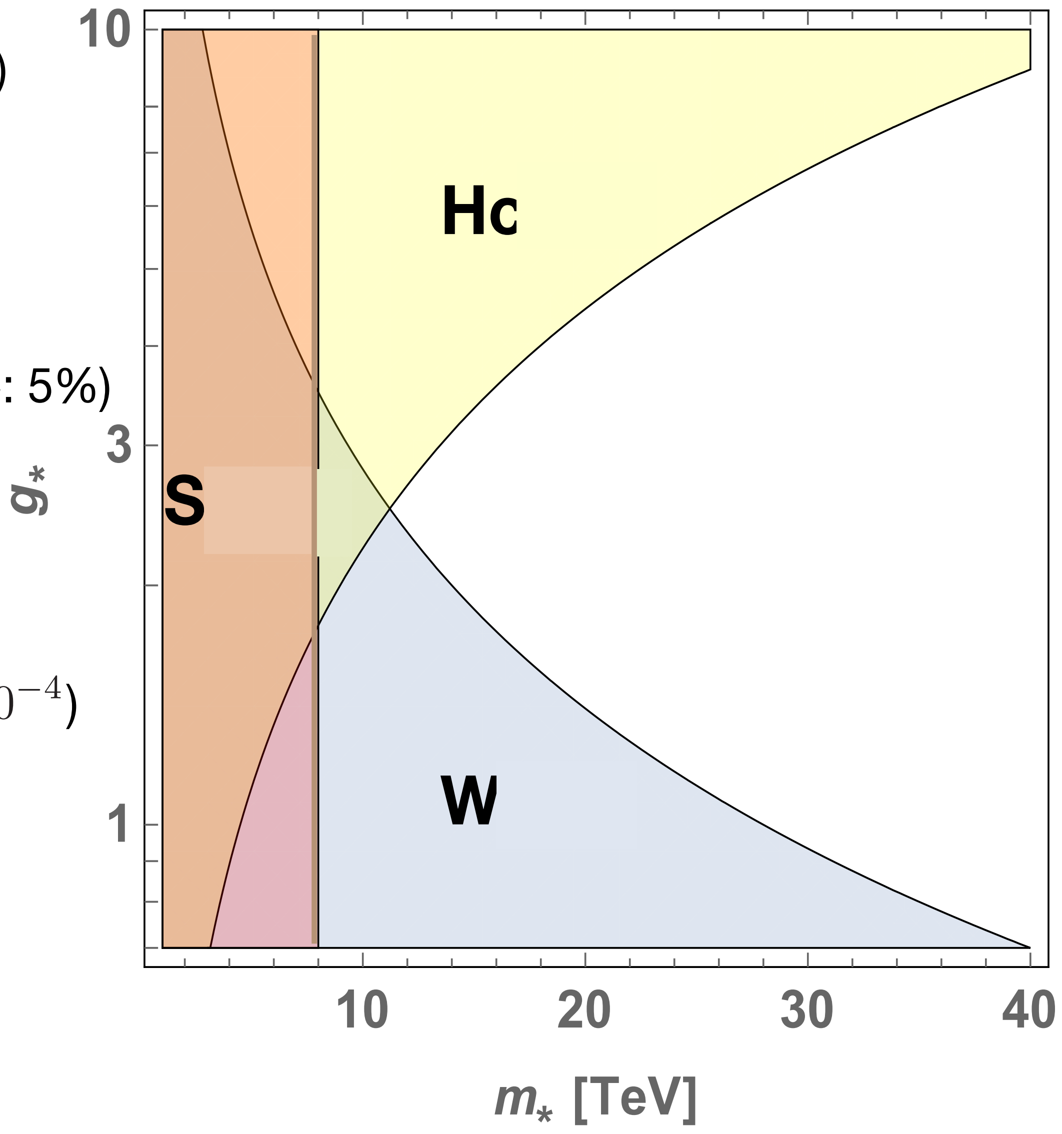
$$\frac{g_w g'}{m_*^2} H^\dagger \sigma_a H W^a_{\mu\nu} B^{\mu\nu} \Rightarrow \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}$$

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

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

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

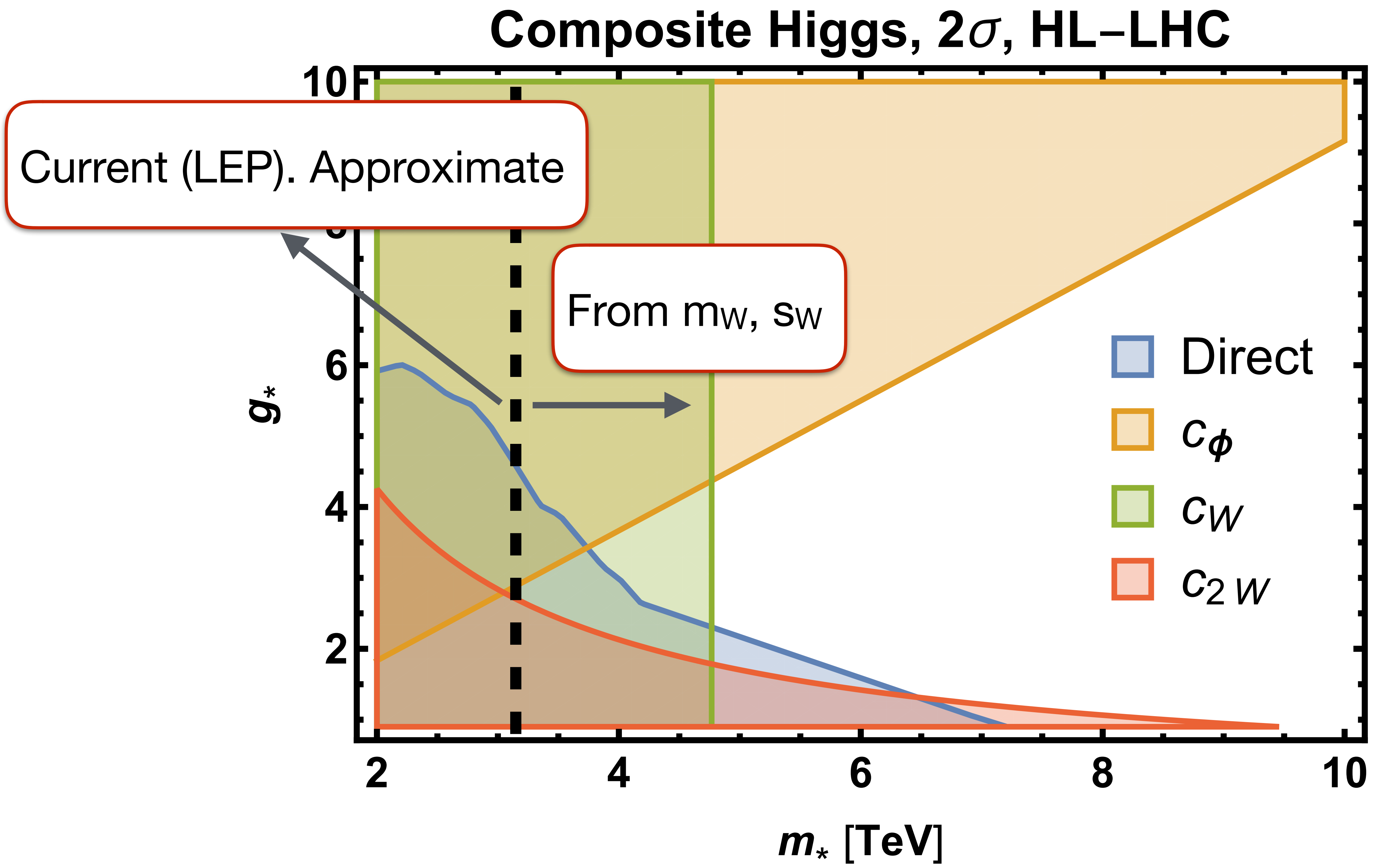
$$\frac{g_w^2}{g_*^2 m_*^2}(D_\mu W_{\nu\rho})^2 \Rightarrow W = \frac{g_w^2 m_w^2}{g_*^2 m_*^2} < \; 10^{-5}$$



Grojean-Wulzer @ FCC physics week '17

Composite Higgs

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



Wulzer @ Granada ESU 2019

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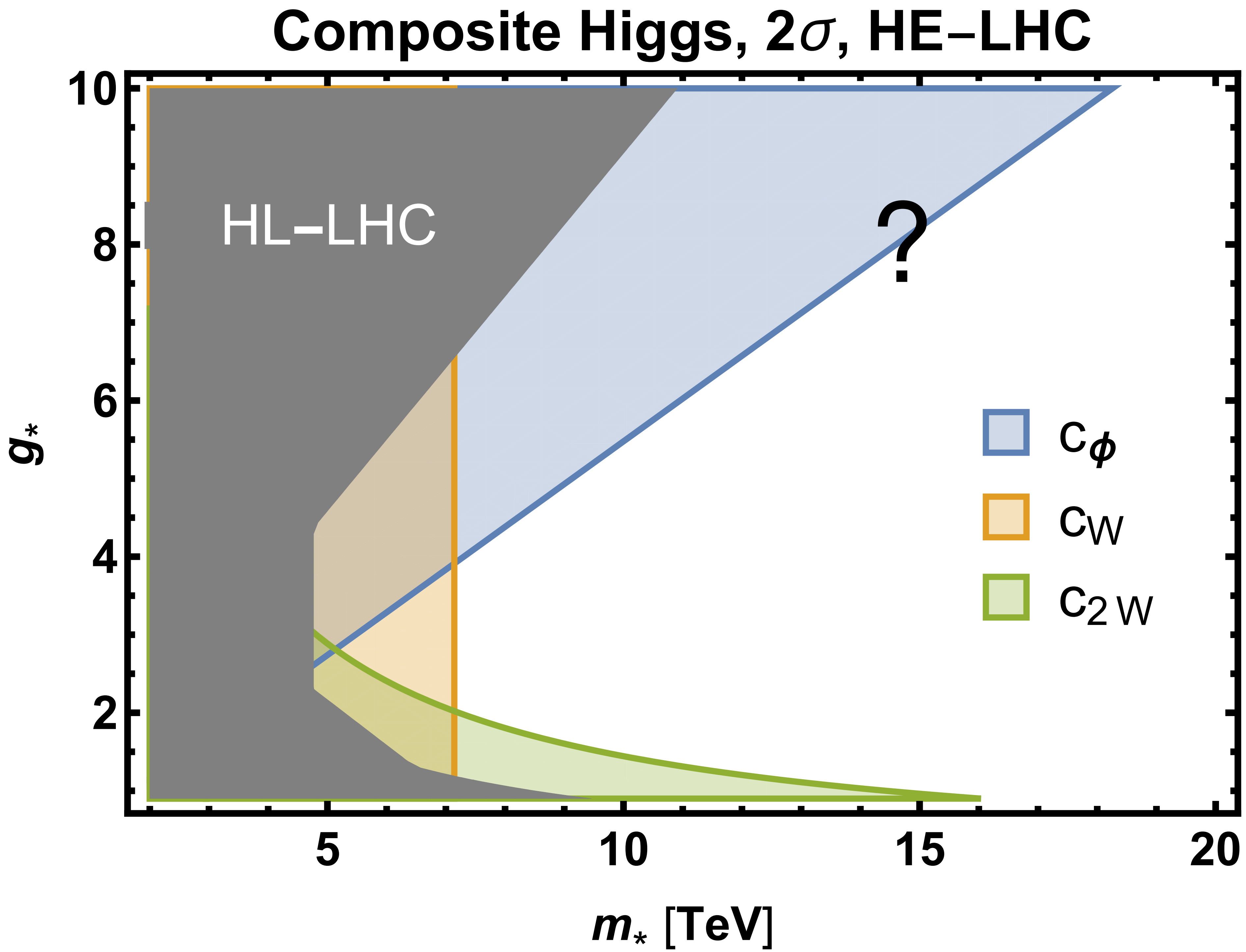

Wulzer @ Granada ESU 2019

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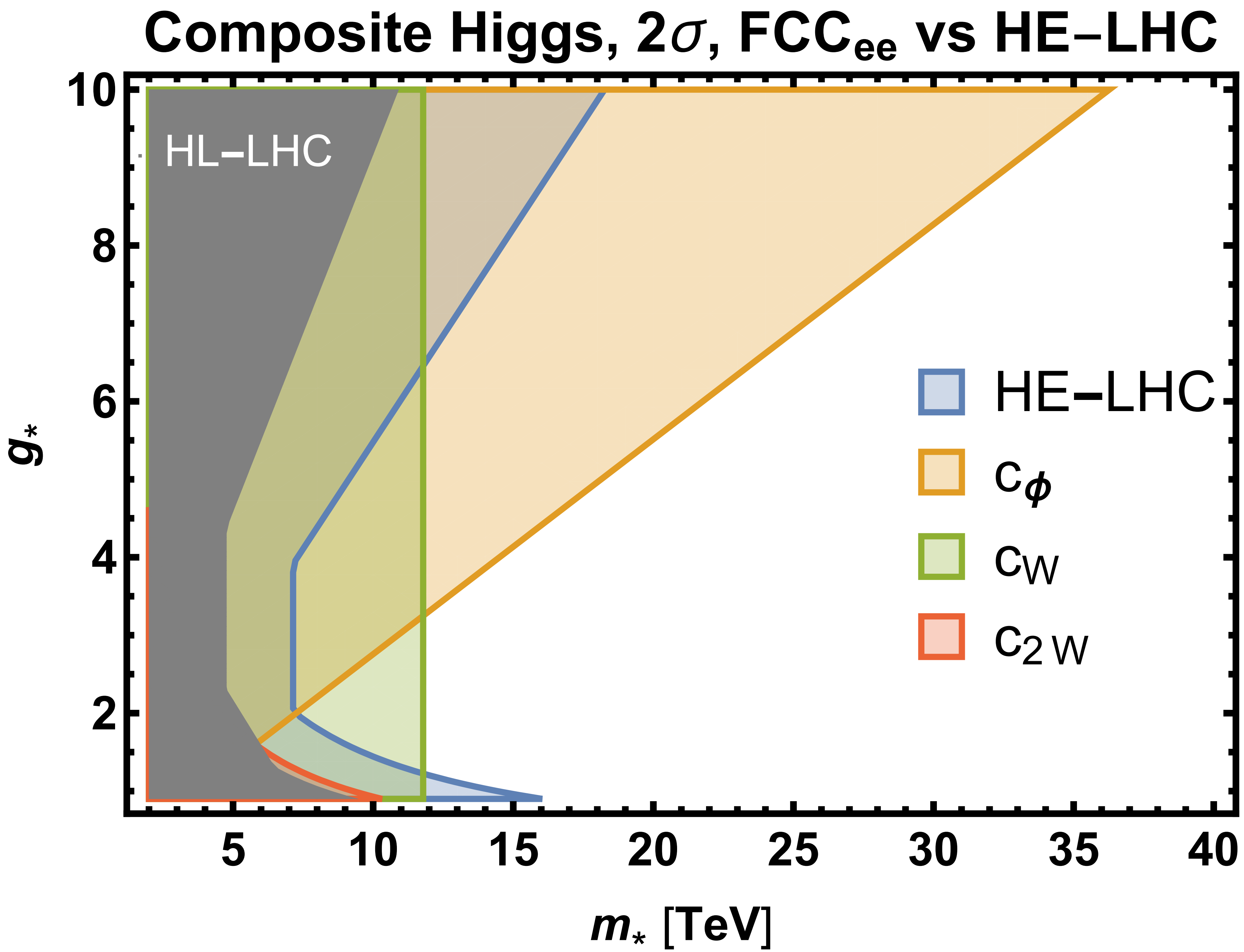

Wulzer @ Granada ESU 2019

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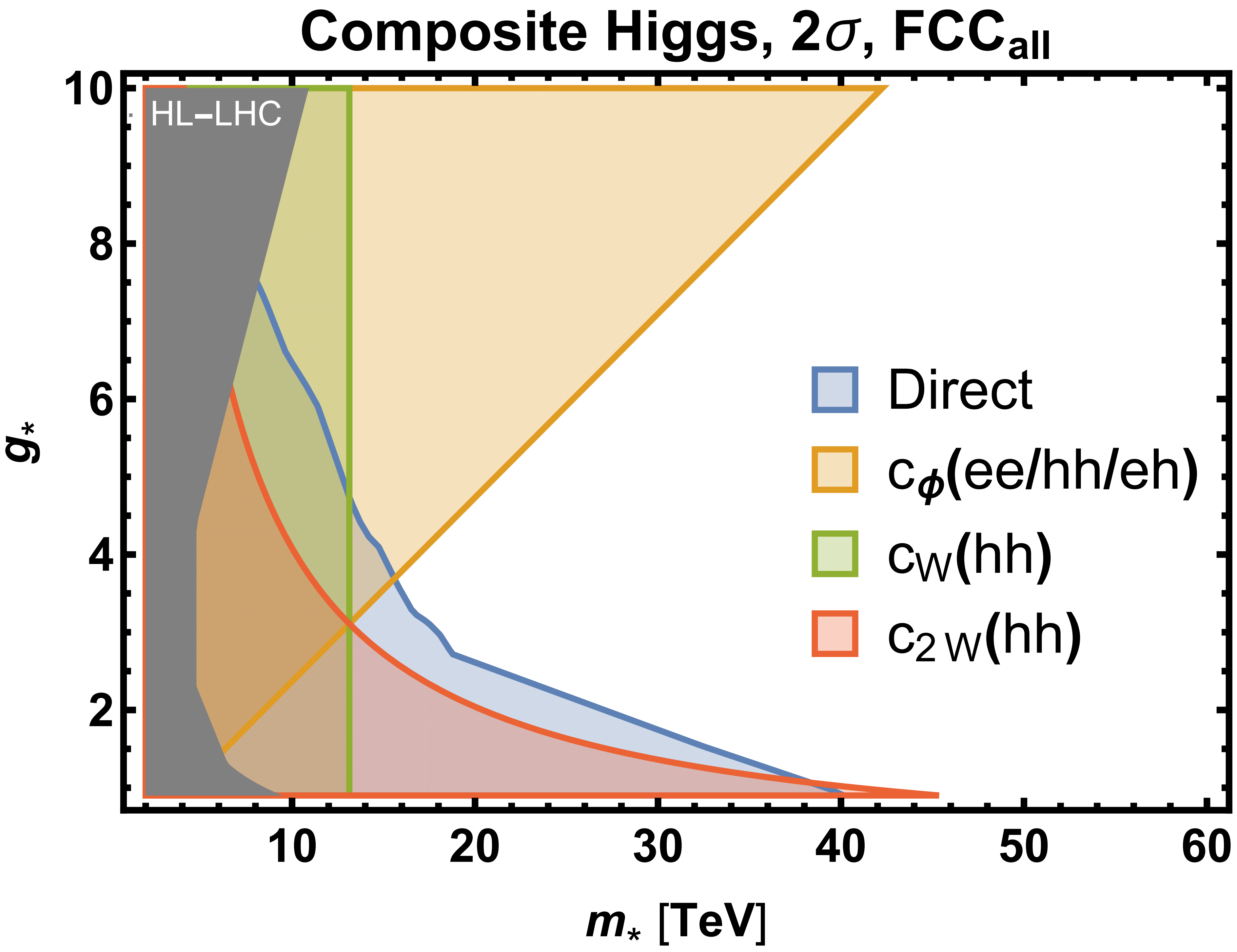


Wulzer @ Granada ESU 2019

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!!

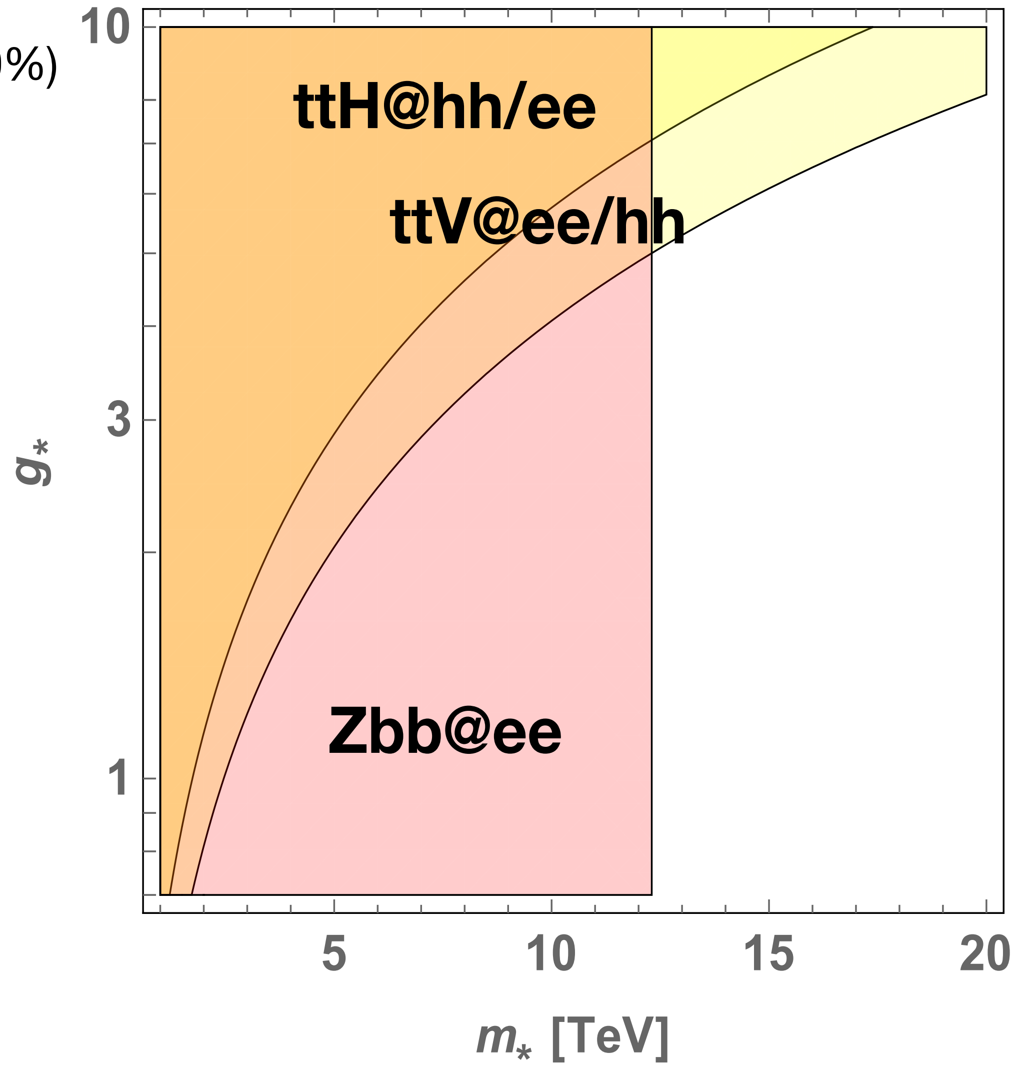
ttV coupling @ee/hh: [Janot / Farina et.al.]

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

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

Composite Top

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

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

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

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

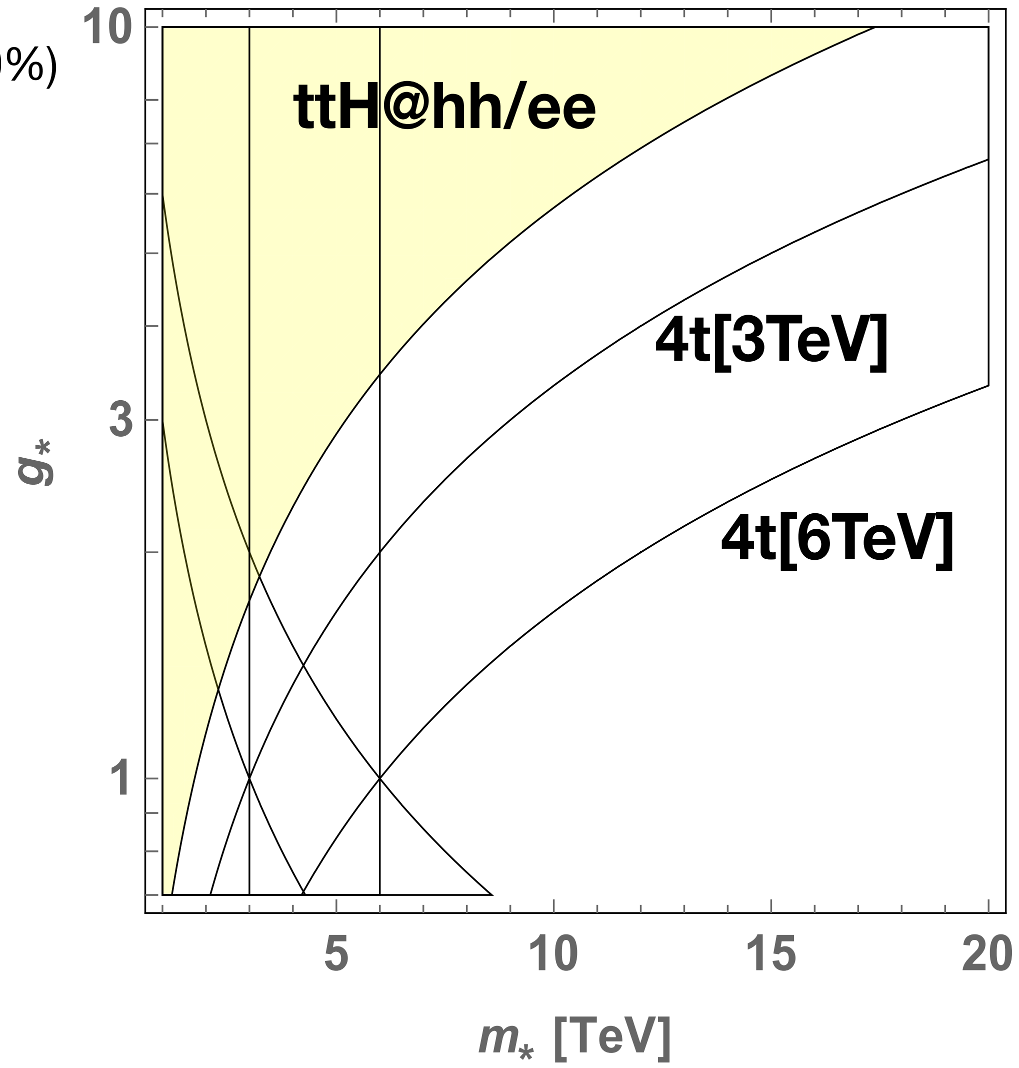
4-top contact interactions @hh:

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

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

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

No study available (?)

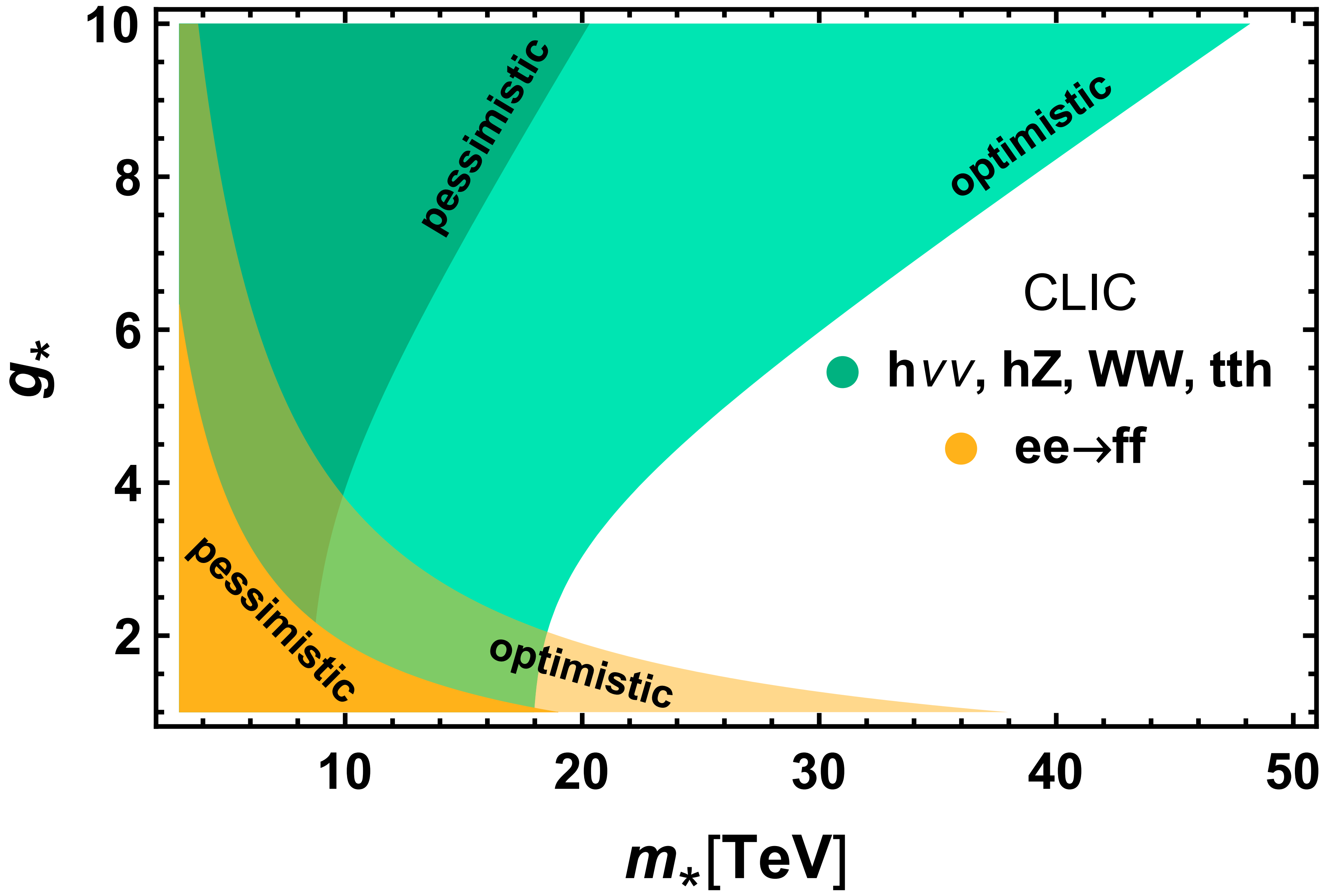


Grojean-Wulzer @ FCC physics week '17

Composite Top

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

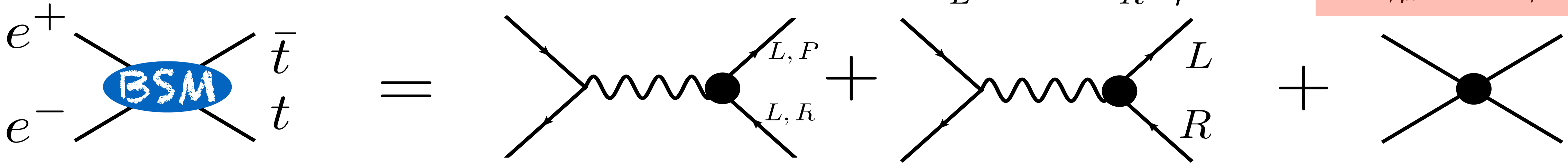
Durieux, Matsedonskyi '18



Composite Top @ CLIC

Riva @ Top@LC '17

$$H^\dagger \overleftrightarrow{D}_\mu H \bar\Psi^3 \gamma^\mu \Psi^3 \qquad \bar\Psi^3_L \sigma^{\mu\nu} H \Psi^3_R F_{\mu\nu} \qquad \bar\Psi^e \gamma_\mu \Psi^e \bar\Psi^3 \gamma^\mu \Psi^3$$



$$\sim c_{H\Psi^3} \frac{v^2}{M^2} \qquad \sim c_{F\Psi^3} \frac{vE}{M^2} \qquad \sim c_{(\Psi)^4} \frac{E^2}{M^2}$$

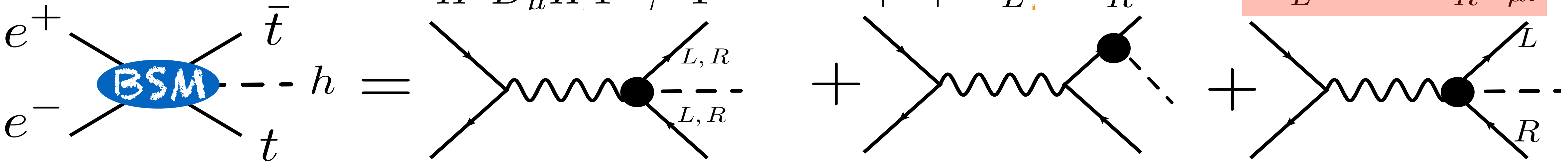
best measured @ threshold

$$M \gtrsim \sqrt{c_{H\Psi^3}}\ 8\,\mathrm{TeV}$$

best measured @ tail

$$M \sim 30 \frac{\sqrt{c_{(\Psi)^4}}}{g}\ \mathrm{TeV}$$

$$H^\dagger \overleftrightarrow{D}_\mu H \bar\Psi^3 \gamma^\mu \Psi^3 \qquad |H|^2 \bar\Psi^3_L H \Psi^3_R \qquad \bar\Psi^3_L \sigma^{\mu\nu} H \Psi^3_R F_{\mu\nu}$$



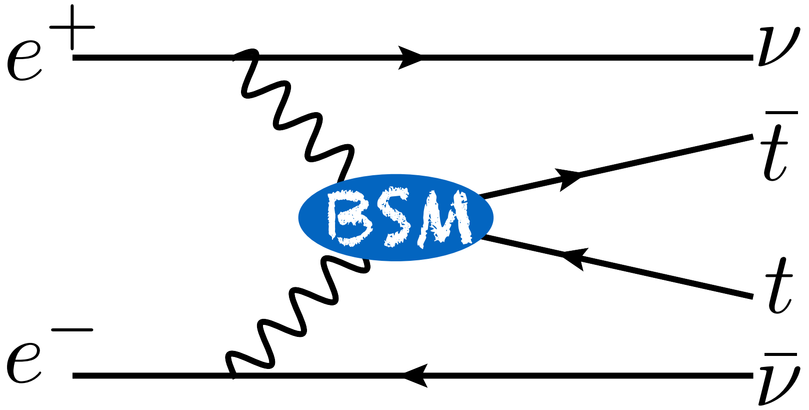
$$c_{H\Psi^3} \frac{vE}{M^2} \qquad \sim c_{y_t} \frac{v^2}{M^2} \qquad c_{F\Psi^3} \frac{E^2}{M^2}$$

$$M \gtrsim \sqrt{c_{y_t}/y_t}\ 1\,\mathrm{TeV} \qquad M \gtrsim 15 \sqrt{\frac{c_{F\Psi^3}}{gY_t}}\ \mathrm{TeV}$$

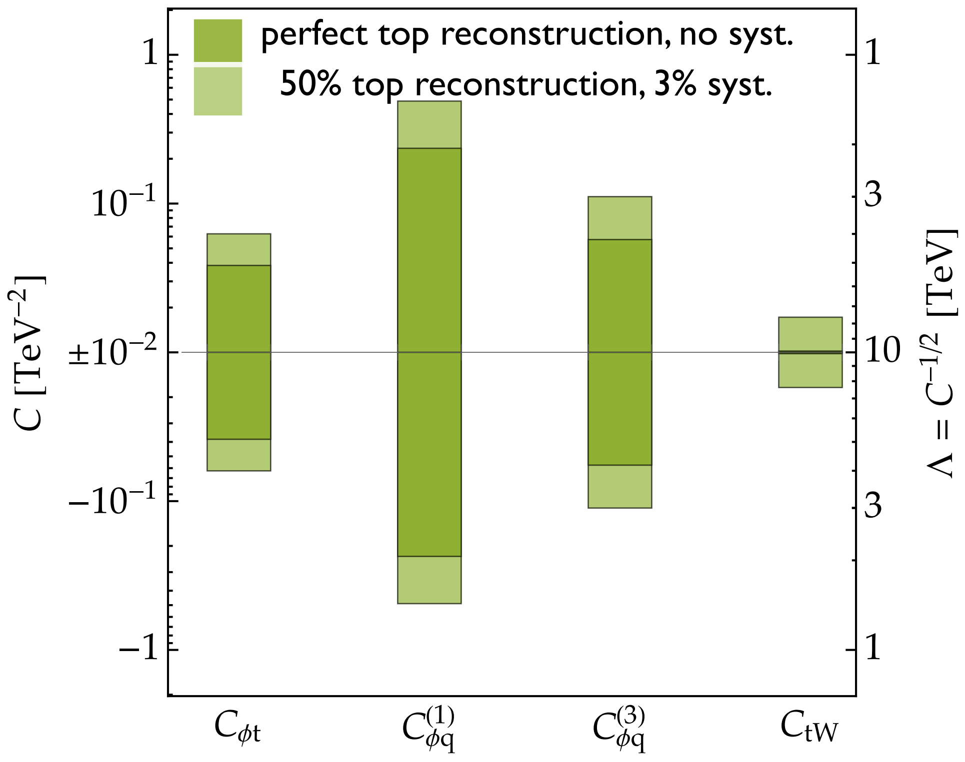
Composite Top @ CLIC

Riva @ Top@LC '17

$$H^\dagger \overleftrightarrow{D}_\mu H \bar{\Psi}^3 \gamma^\mu \Psi^3$$



$$\sim c_{H\Psi^3} \frac{E^2}{M^2}$$



Grojean, Wulzer, You and Zhang 'in progress

Composite Top @ LHC

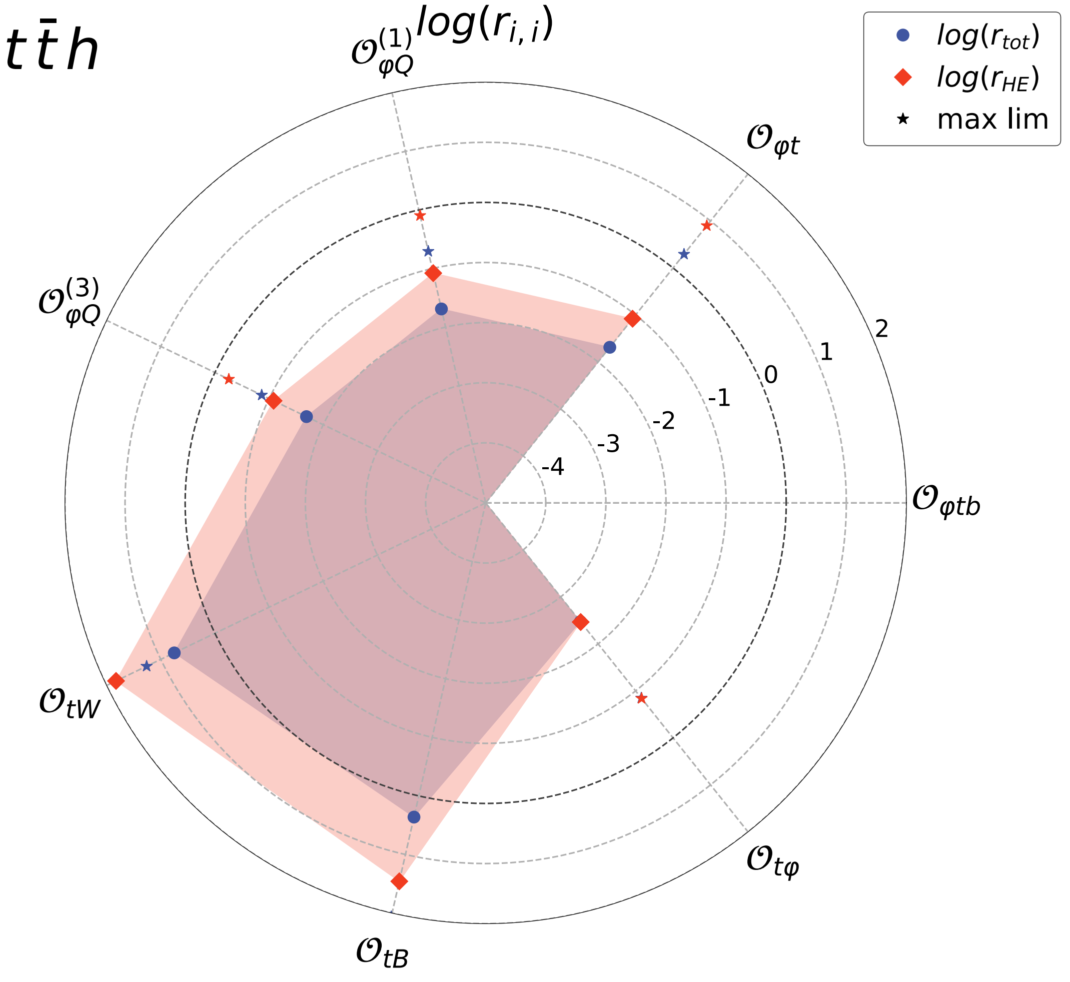
Exploration of energy growing processes at LHC

Maltoni, Mantani, Mimasu '19

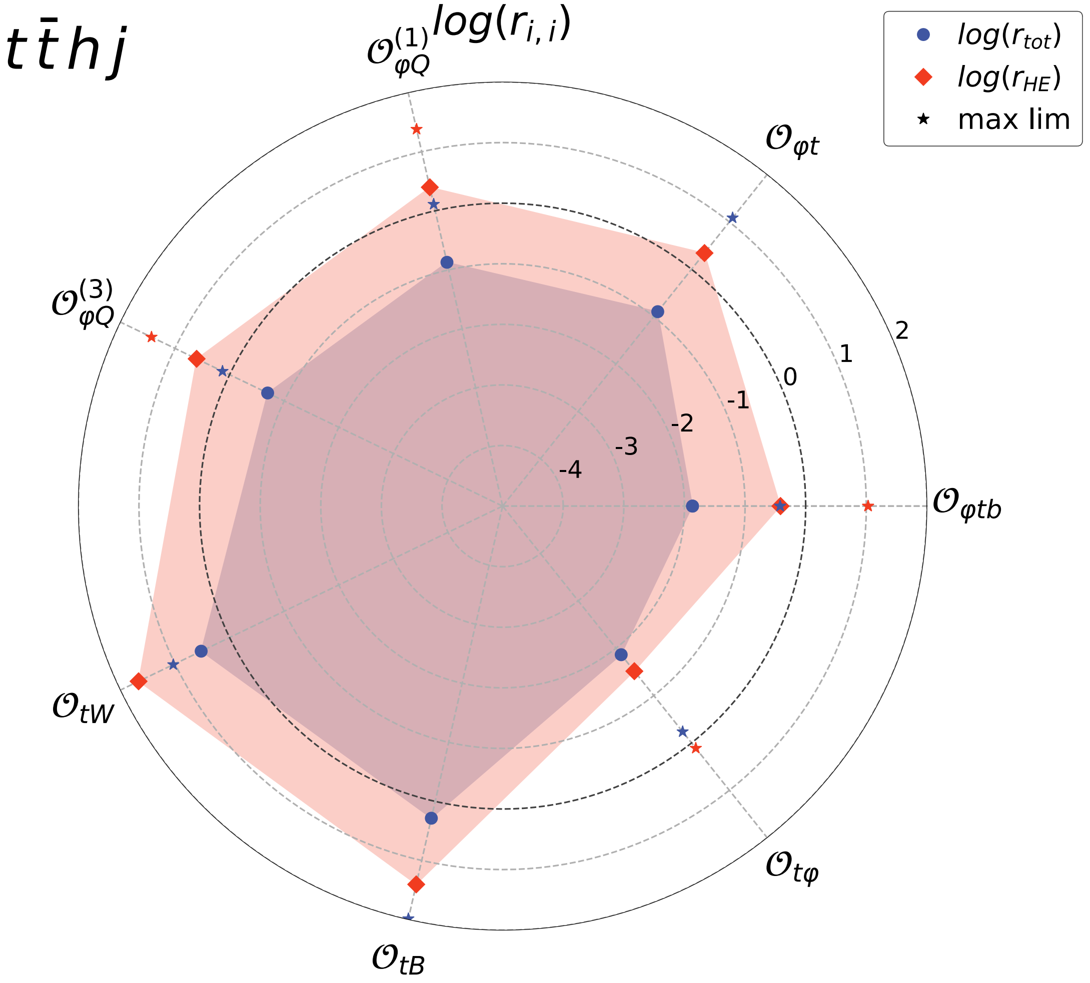
$$r = \frac{\sigma_{\rm BSM}}{\sigma_{\rm SM}}$$

Impact of operator vs. SM

$pp \to t\bar{t}h$



$pp \to t\bar{t}hj$



"inclusive" analysis

"high-E" analysis

can have a factor 10 effect for the operators that lead to an effect growing with E

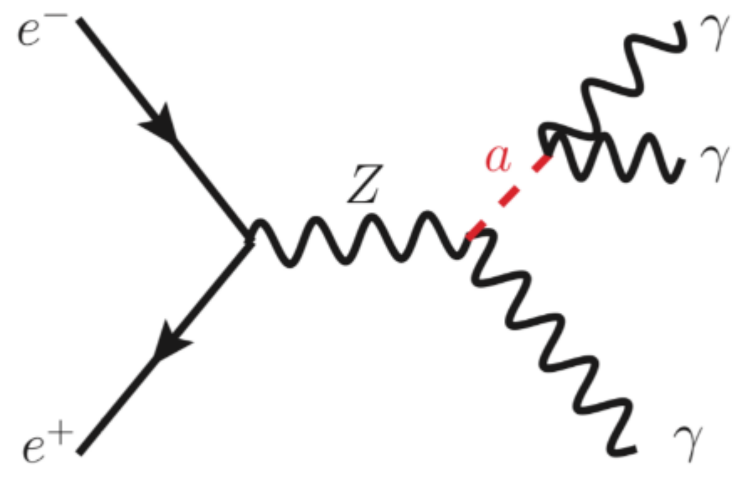
New interesting analyses to be done to maximise EFT sensitivity in top measurement!

Other BSM searches at future colliders

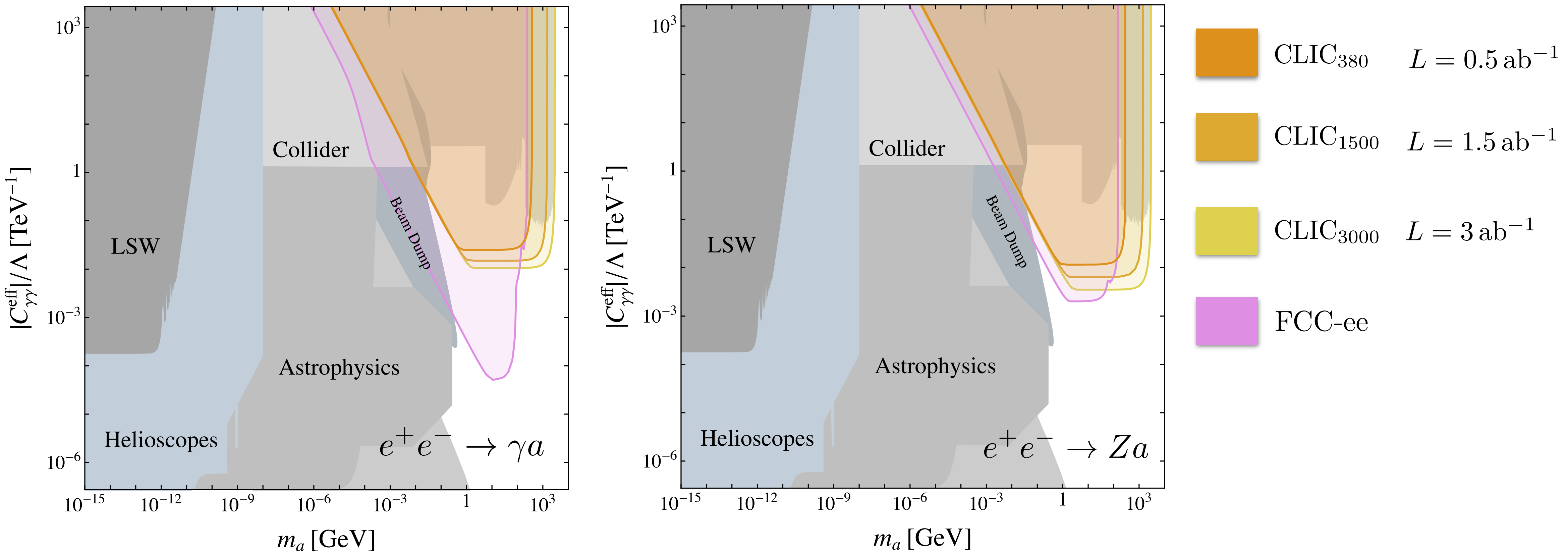
Axion Like Particles

Material from A. Thamm

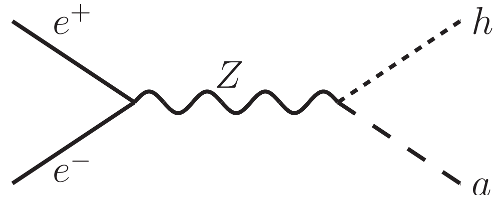
- ALP associated production with a photon or Z

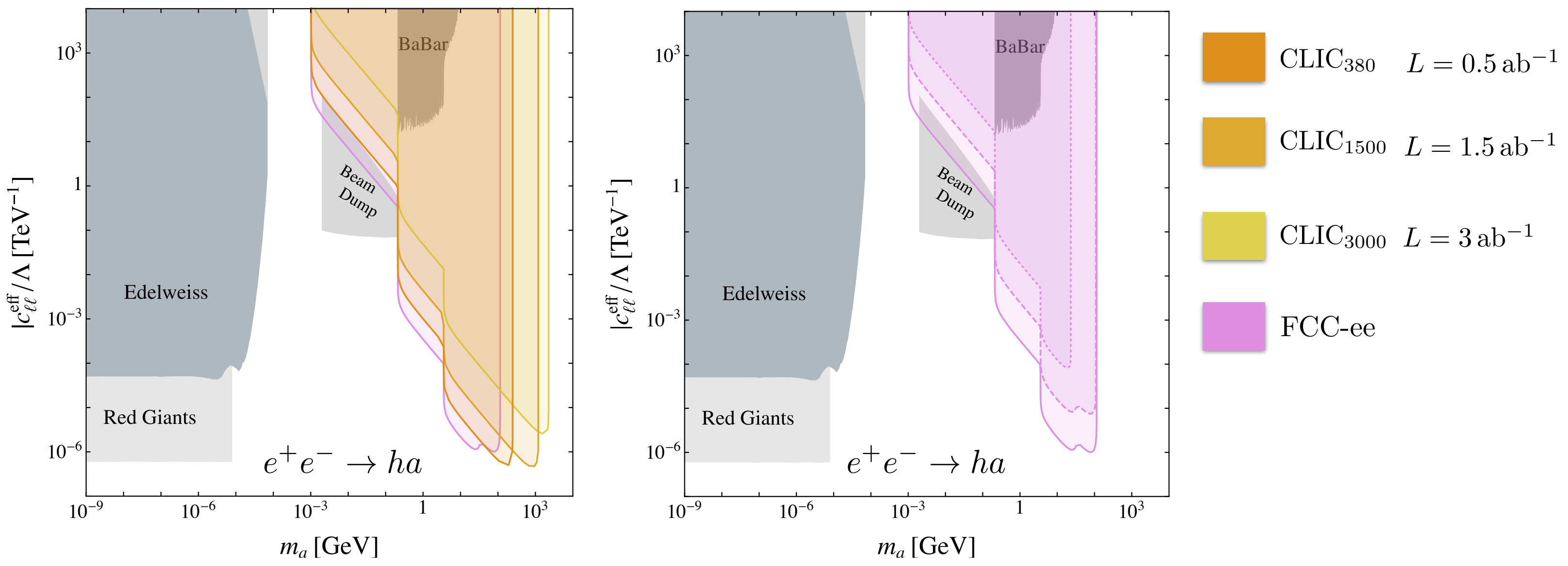


- ➡ $\gamma + E_{MISS}$ for very light a
- ➡ $\gamma\gamma$ for light a
- ➡ $\gamma\gamma\gamma$ for heavier a



- ALP associated production with a H

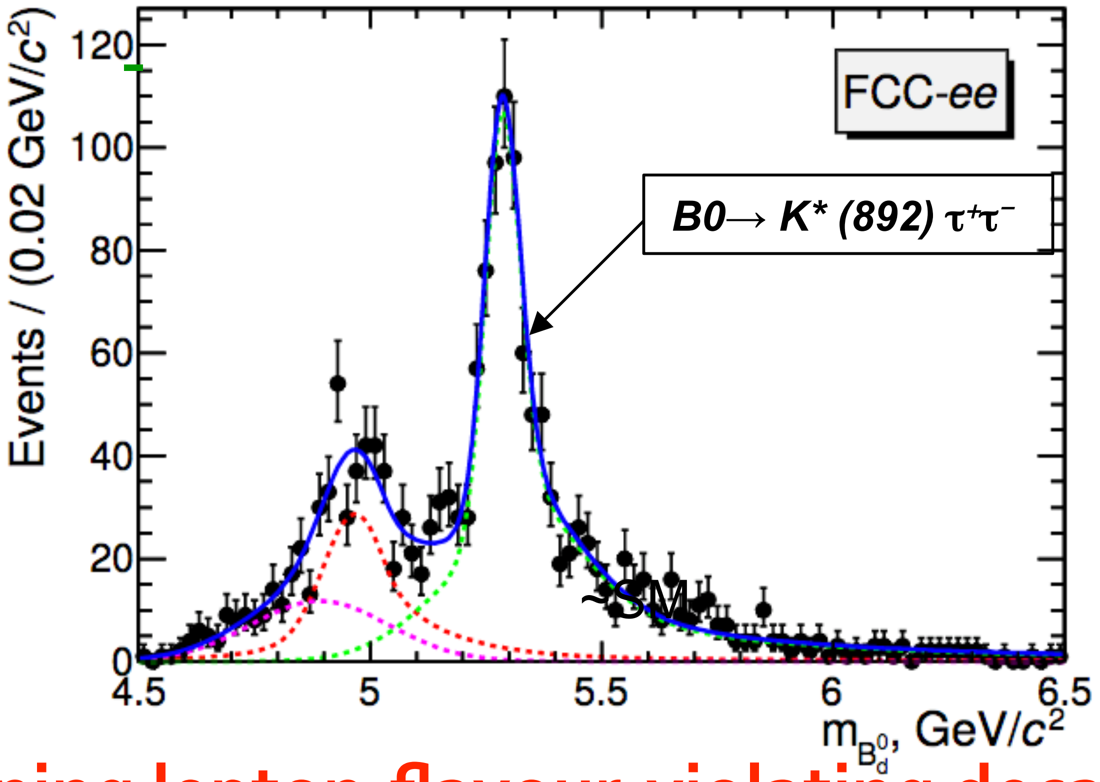




FCC is also a flavour factory

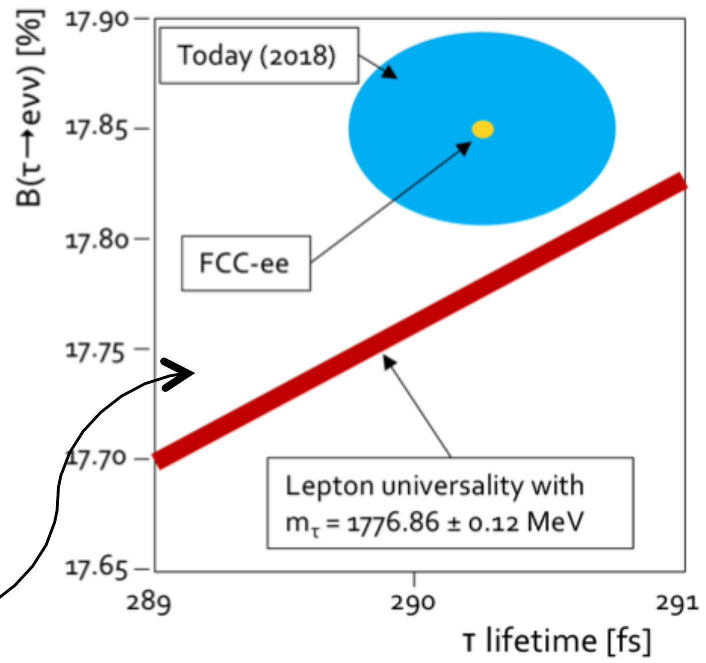
- Lepton flavour universality is challenged in $b \to s\, \ell^+\ell^-$ transitions @ LHCb
  - This effect, if real, could be enhanced for $\ell = \tau$, in $B \to K^{(*)} \tau^+\tau^-$
    - Extremely challenging in hadron colliders
    - With 10^{12} $Z \to bb$, FCC-ee is beyond any foreseeable competition
      - ➨ Decay can be fully reconstructed; full angular analysis possible

J.F. Kamenik et al.
arXiv:1705.11106



Also 100,000 $B_S \to \tau^+\tau^-$ @ FCC-ee
Reconstruction efficiency under study

- Not mentioning lepton-flavour-violating decays
  - BR($Z \to e\tau, \mu\tau$) down to 10^{-9} (improved by 10^4)
  - BR($\tau \to \mu\gamma, \mu\mu\mu$) down to a few 10^{-10}
  - τ lifetime vs BR($\tau \to e\nu_e\nu_\tau, \mu\nu_\mu\nu_\tau$) : lepton universality tests



Material from P. Janot

FCC is also a flavour factory

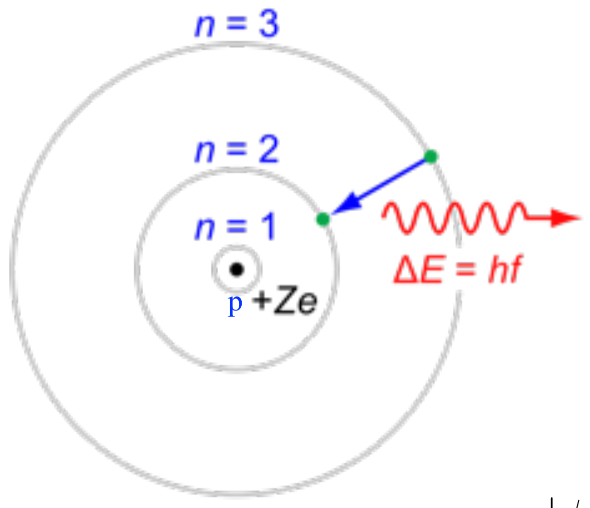
Material from CepC CDR

Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
$\mathrm{BR}(B_s \to ee)$	2.8×10^{-7} (CDF) [10]	$\sim 7 \times 10^{-10}$ (LHCb) [18]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \mu\mu)$	0.7×10^{-9} (LHCb) [8]	$\sim 1.6 \times 10^{-10}$ (LHCb) [18]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \tau\tau)$	5.2×10^{-3} (LHCb) [9]	$\sim 5 \times 10^{-4}$ (LHCb) [18]	$\sim 10^{-5}$
R_K, R_{K^*}	$\sim 10\%$ (LHCb) [5, 4]	$\sim$few% (LHCb/Belle II) [18, 40]	$\sim$few %
$\mathrm{BR}(B \to K^*\tau\tau)$	–	$\sim 10^{-5}$ (Belle II) [40]	$\sim 10^{-8}$
$\mathrm{BR}(B \to K^*\nu\nu)$	4.0×10^{-5} (Belle) [44]	$\sim 10^{-6}$ (Belle II) [40]	$\sim 10^{-6}$
$\mathrm{BR}(B_s \to \phi\nu\bar{\nu})$	1.0×10^{-3} (LEP) [15]	–	$\sim 10^{-6}$
$\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})$	–	–	$\sim 10^{-6}$
$\mathrm{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar) [24]	$\sim 10^{-9}$ (Belle II) [40]	$\sim 10^{-9}$
$\mathrm{BR}(\tau \to 3\mu)$	2.1×10^{-8} (Belle) [37]	$\sim$ few $\times 10^{-10}$ (Belle II) [40]	$\sim$ few $\times 10^{-10}$
$\frac{\mathrm{BR}(\tau\to\mu\nu\bar{\nu})}{\mathrm{BR}(\tau\to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar) [23]	$\sim 10^{-3}$ (Belle II) [40]	$\sim 10^{-4}$
$\mathrm{BR}(Z \to \mu e)$	7.5×10^{-7} (ATLAS) [3]	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9} - 10^{-11}$
$\mathrm{BR}(Z \to \tau e)$	9.8×10^{-6} (LEP) [17]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-11}$
$\mathrm{BR}(Z \to \tau\mu)$	1.2×10^{-5} (LEP) [13]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-10}$

BSM searches away from high-energy colliders

BSM and Atomic Physics

Atomic Clocks as a BSM probe



Physics beyond QED contributes to the frequency of the radiation

$$\frac{1}{\lambda} = R\,Z^2\left(\frac{1}{n^2} - \frac{1}{n'^2}\right)$$

$|\psi(0)|^2/n^3$ is the wave-function-density at the origin.

$$V_{\rm weak}(r) = -\frac{8G_{\rm F}m_{Z^0}^2}{\sqrt{2}}\frac{g_e g_A}{4\pi}\frac{e^{-rm_{Z^0}}}{r} \quad \Rightarrow \quad \delta E_{nlm}^{\rm weak} = -\frac{8G_F m_Z^2}{\sqrt{2}}\frac{g_e g_A}{4\pi m_Z^2}|\psi(0)|^2\frac{\delta_{l,0}}{n^3}$$

fifth force ⇒ ?

Exp sensitivity in atomic clock measurements O(10^{-18})

(ms over one billon years)

Can be used to detect new (long range) forces

Isolating the signal: isotope shifts

$$\nu_i^{AA'} = \nu_i^A - \nu_i^{A'}$$

$$\delta\nu^i_{AA'} = K_i\,\mu_{AA'} + F_i\delta\langle r^2\rangle_{AA'} + H_i(A - A')$$

mass shift — field shift — BSM or NLO SM/QED

K_i and F_i are difficult to compute to the accuracy needed
but they are the same for different isotopes

The King Plot

W. H. King,
J. Opt. Soc. Am. 53, 638 (1963)

- First, define modified IS as $m\delta\nu^i_{AA'} \equiv \delta\nu^i_{AA'}/\mu_{AA'}$
- Measure IS in two transitions. Use transition 1 to set $\delta\langle r^2\rangle_{AA'}/\mu_{AA'}$ and substitute back into transition 2:

$$F_{21} \equiv F_2/F_1$$
$$K_{21} \equiv K_2 - F_{21}K_1$$
$$H_{21} \equiv H_2 - F_{21}H_1$$

$$m\delta\nu^2_{AA'} = K_{21} + F_{21}m\delta\nu^1_{AA'} - AA'H_{21}$$

- Plot $m\delta\nu^1_{AA'}$ vs. $m\delta\nu^2_{AA'}$ along the isotopic chain

Needs to measure 2 atomic transitions with at least 4 isotopes

Isolating the signal: isotope shifts

$$\nu_i^{AA'} = \nu_i^A - \nu_i^{A'}$$

$$\delta\nu^i_{AA'} = K_i\,\mu_{AA'} + F_i\delta\langle r^2\rangle_{AA'} + H_i(A - A')$$

mass shift — field shift — BSM or NLO SM/QED

K_i and F_i are difficult to compute to the accuracy needed

b … s

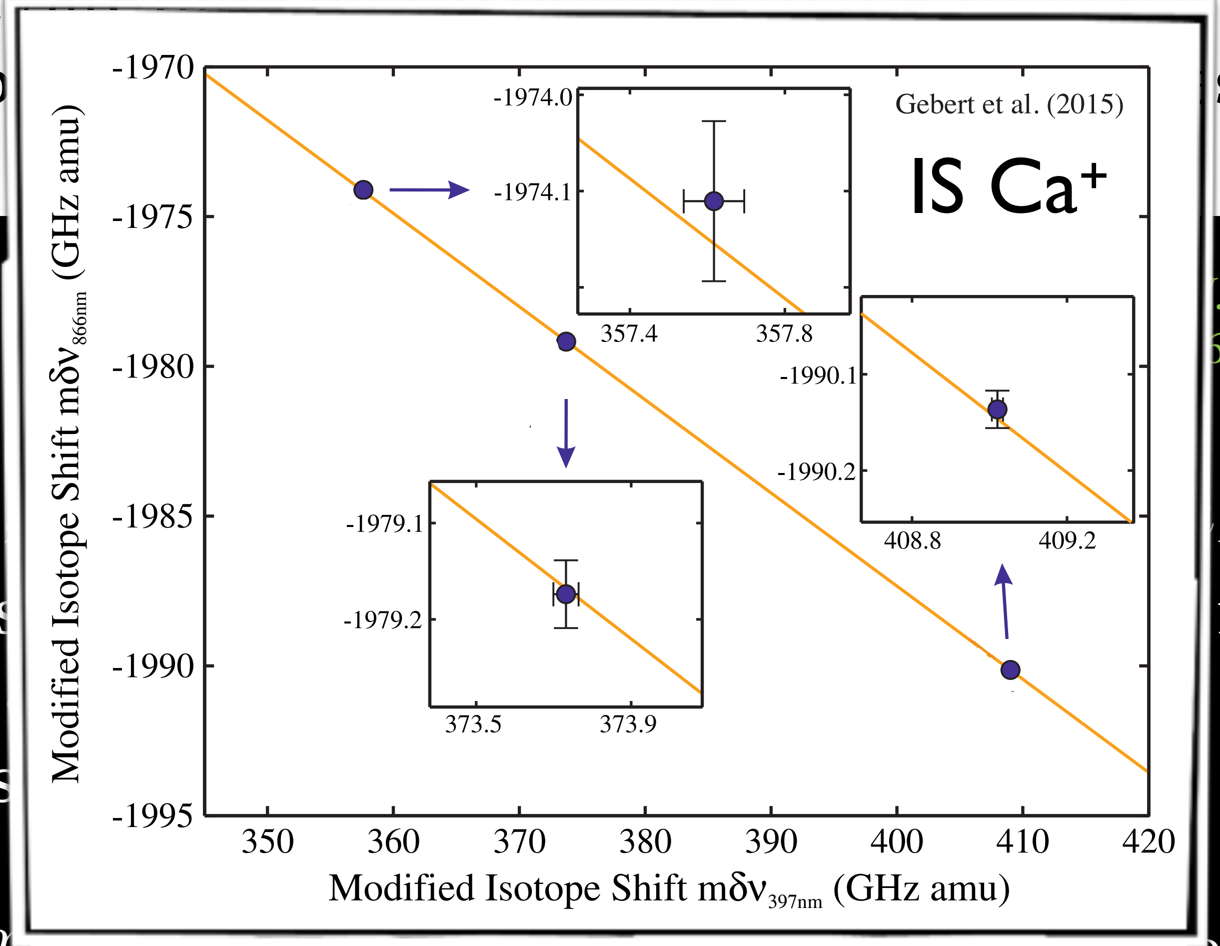
The … H. King, …638 (1963)

- First … $_{AA'}$
- Meas… n to set δ … trans…

$\equiv F_2/F_1$
$\equiv K_2 - F_{21}K_1$
$\equiv H_2 - F_{21}H_1$

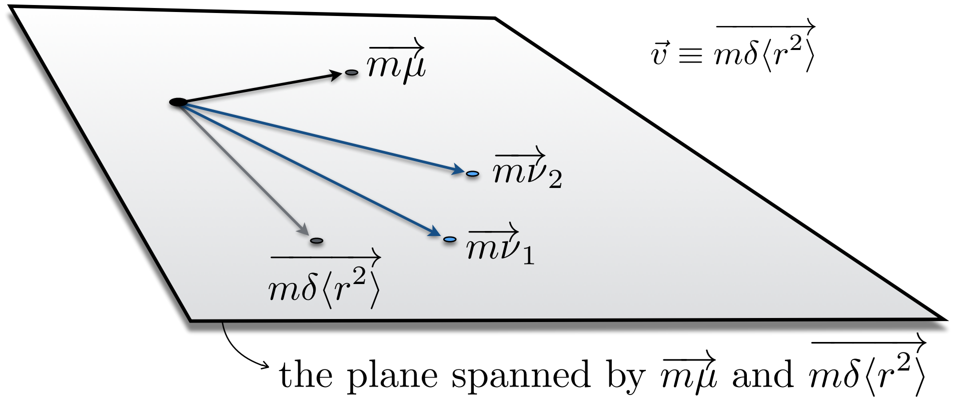
$$m\delta\nu_{AA'} = K_{21} + F_{21}\,m\delta\nu_{AA'} - AA'H_{21}$$

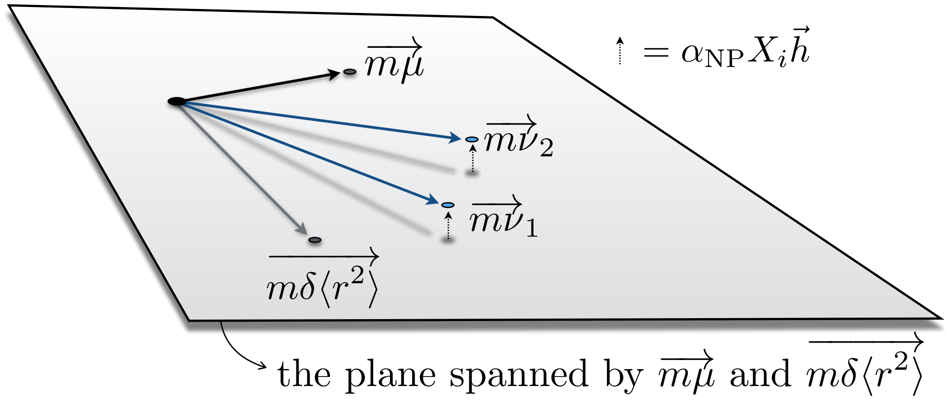
- Plot $m\delta\nu^1_{AA'}$ vs. $m\delta\nu^2_{AA'}$ along the isotopic chain



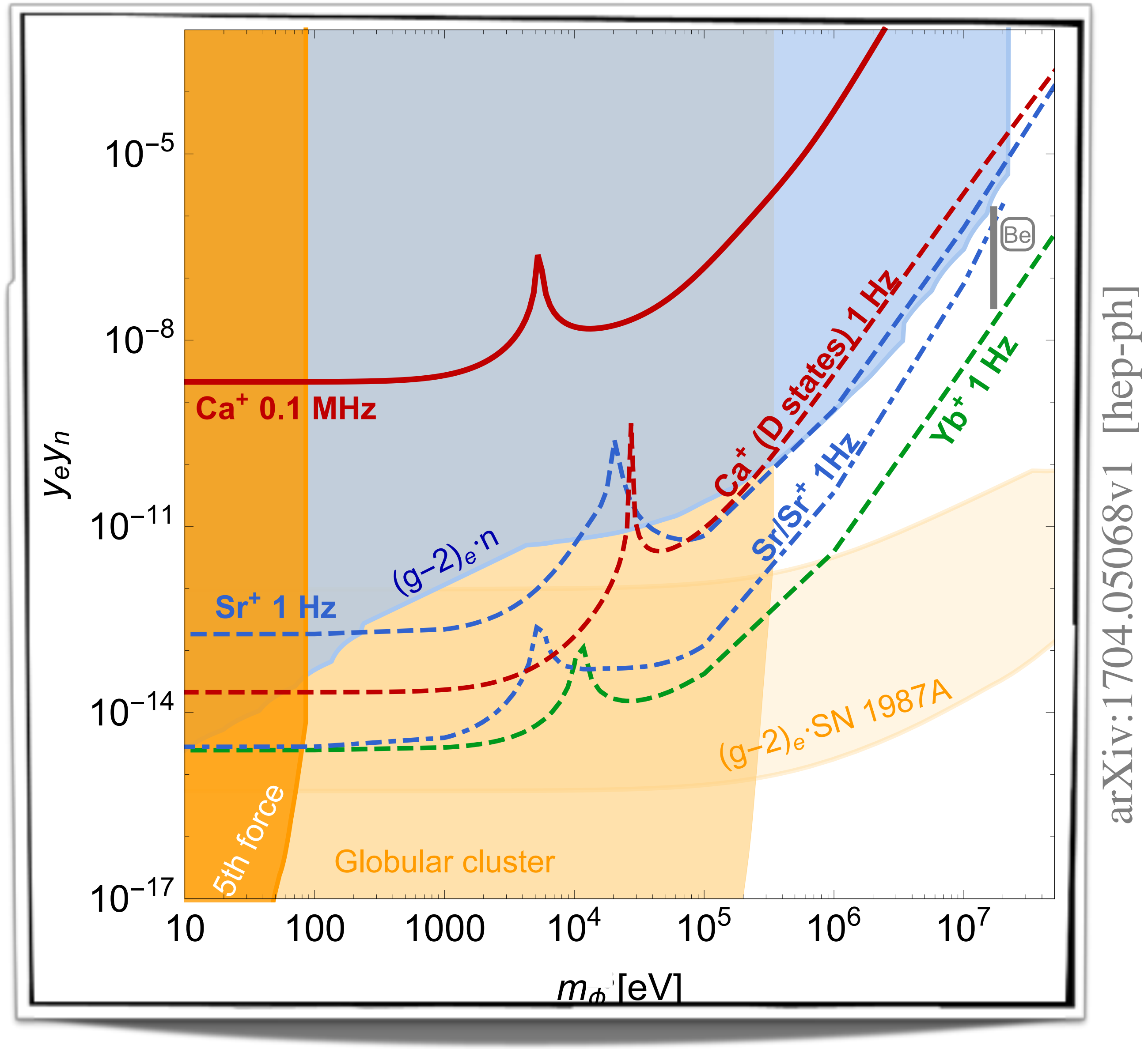
Needs to measure 2 atomic transitions with at least 4 isotopes

Constraining light NP





As long as
King linearity deviation is
not observed,
one can bound
new physics sources
More tricky to interpret
if a signal is observed



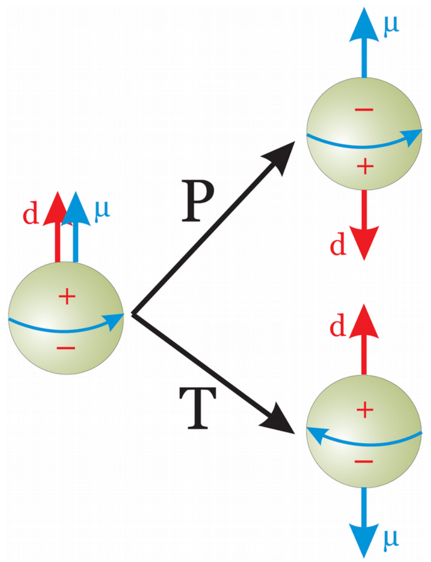
EDM

Electric Dipole Moment

$$\mathcal{L}_{dipole} = -\frac{\mu}{2}\bar{\Psi}\sigma^{\mu\nu}F_{\mu\nu}\Psi - \frac{d}{2}\bar{\Psi}\sigma^{\mu\nu}i\gamma^5 F_{\mu\nu}\Psi$$

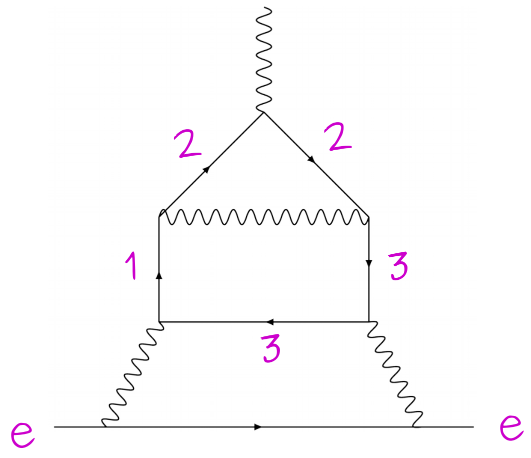
Non-relativistic limit

$$H = -\mu\,\vec{B}\cdot\frac{\vec{S}}{S} - d\,\vec{E}\cdot\frac{\vec{S}}{S}$$



Nonvanishing EDM breaks CP

SM predictions



$\rightarrow d_e/e \sim 10^{-40}\ cm$

SM contribution is ridiculously small
EDM is clear signal of New Physics

EDM - experimental status

Science 343, p. 269-272 (2014)

$$|d_e| < 9.4 \cdot 10^{-29}\, e\,\mathrm{cm} \qquad \text{at} \;\; 90\%\ \mathrm{CL}$$

$$|d_e| \lesssim 0.5 \cdot 10^{-29}\, e\,\mathrm{cm} \qquad (\mathrm{ACME\ II})$$

$$|d_e| \lesssim 0.3 \cdot 10^{-30}\, e\,\mathrm{cm} \qquad (\mathrm{ACME\ III})$$

$$|d_e| \lesssim 10^{-30}\; e\; cm$$ arXiv:1704.07928

$$|d_e| \lesssim 5 \cdot 10^{-30}\; e\; cm$$ arXiv:1804.10012

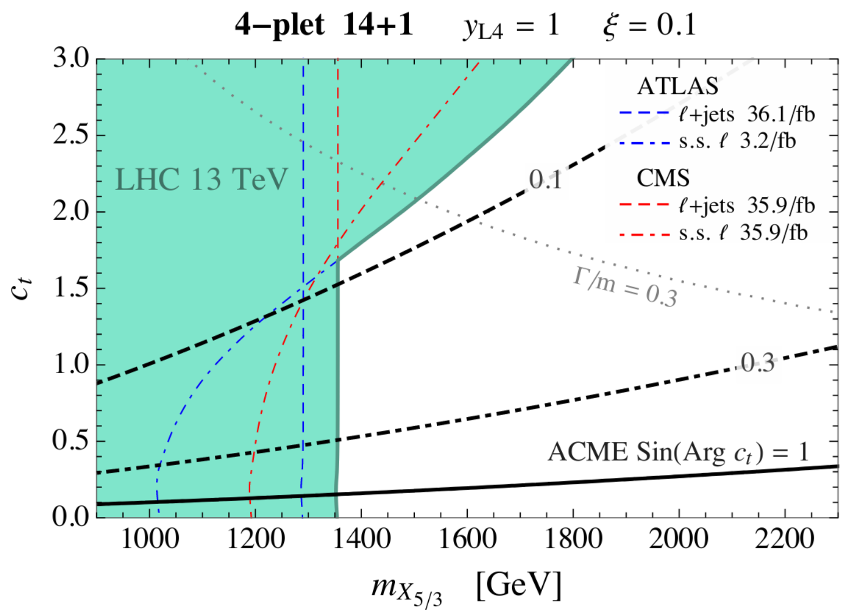
$$|d_e| \lesssim 10^{-35}\; e\; cm$$ arXiv:1710.08785

EDM as a BSM probe

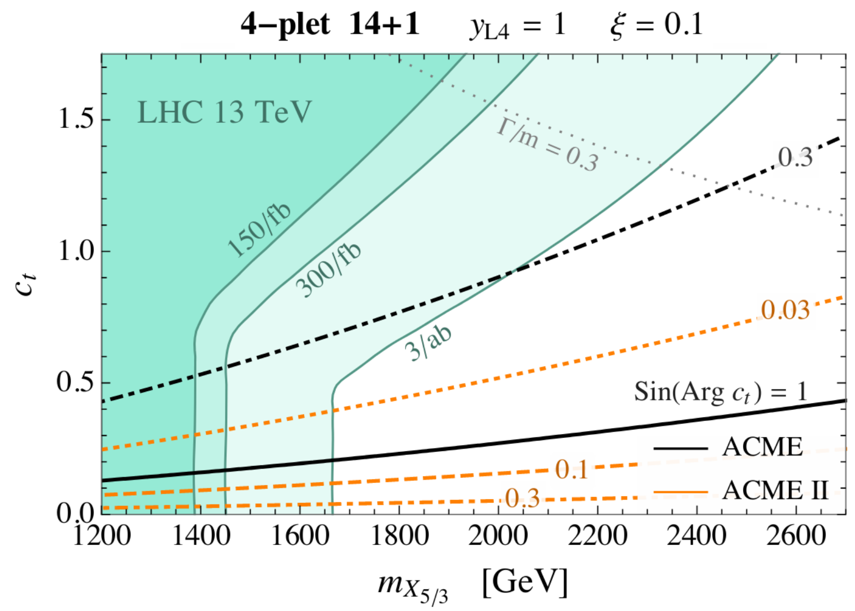
Panico, Riembau, Vantalon ‘17

e.g., EDM can help testing the presence of top partners in composite Higgs models

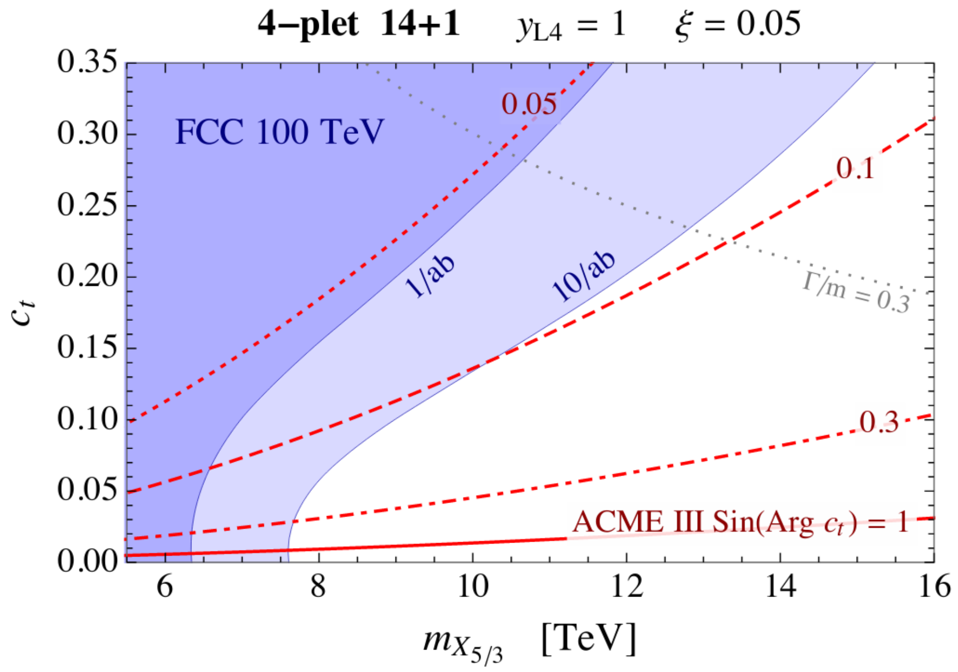
LHC



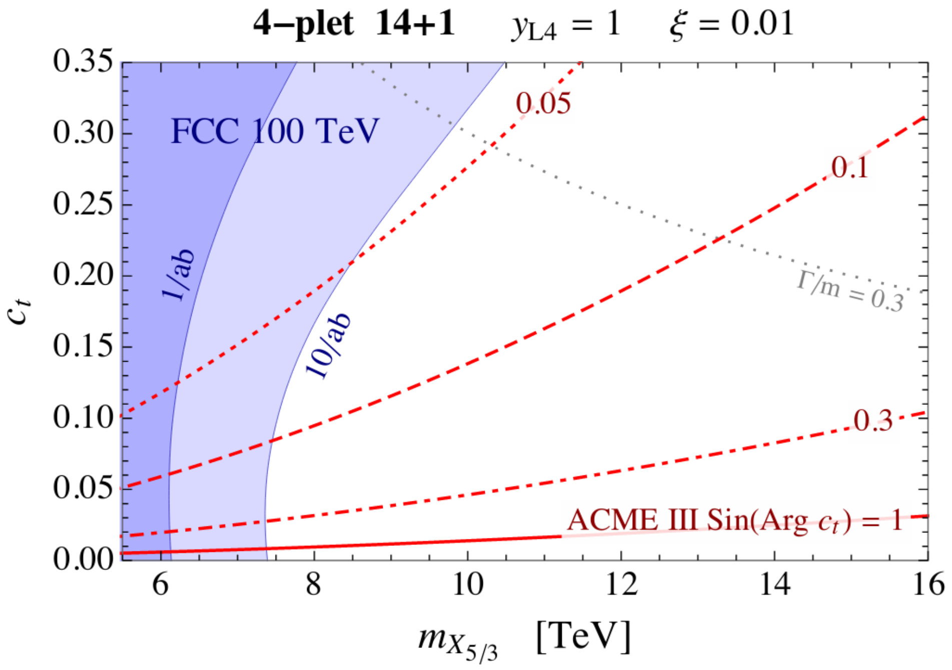
HL-LHC



FCC-hh



FCC-hh



Neutron-antineutron oscillations

Baryon number violation(s)

Why are we expecting B violation(s)?

1) Neutral meson oscillations, neutral lepton oscillations (very likely), why not neutral baryon oscillations?

2) Global symmetry are not consistent with quantum gravity

3) Need to generate matter-antimatter imbalance

Selection rule

conservation of angular momentum ⇒ spin of nucleon should be transferred to another fermion

1) $\Delta B = \Delta L$ (nucleon → antilepton)
2) $\Delta B = -\Delta L$ (nucleon → lepton)
3) $\Delta L = \pm 2$ ($0\nu\beta\beta$)
4) $\Delta B = \pm 2$ ($n\bar{n}$ oscillations, dinucleon decays)

Proton stability doesn't exclude baryogenesis!

If h^3 coupling is SM-like, unlikely that baryogenesis occurs at weak scale
Large scale baryogenesis requires B-L violation
otherwise any B asymmetry created above EWSB scale is wiped out by active EW sphalerons

Constraints on Baryon # violation

	Mode	Partial mean life (10^{30} years)	Confidence level
	Antilepton + meson		
τ_1	$N \to e^+\pi$	> 2000 (n), > 8200 (p)	90%
τ_2	$N \to \mu^+\pi$	> 1000 (n), > 6600 (p)	90%
τ_3	$N \to \nu\pi$	> 1100 (n), > 390 (p)	90%
τ_4	$p \to e^+\eta$	> 4200	90%
τ_5	$p \to \mu^+\eta$	> 1300	90%
τ_6	$n \to \nu\eta$	> 158	90%
τ_7	$N \to e^+\rho$	> 217 (n), > 710 (p)	90%
τ_8	$N \to \mu^+\rho$	> 228 (n), > 160 (p)	90%
τ_9	$N \to \nu\rho$	> 19 (n), > 162 (p)	90%
τ_{10}	$p \to e^+\omega$	> 320	90%
τ_{11}	$p \to \mu^+\omega$	> 780	90%
τ_{12}	$n \to \nu\omega$	> 108	90%
τ_{13}	$N \to e^+K$	> 17 (n), > 1000 (p)	90%
τ_{14}	$p \to e^+K^0_S$		
τ_{15}	$p \to e^+K^0_L$		
τ_{16}	$N \to \mu^+K$	> 26 (n), > 1600 (p)	90%
τ_{17}	$p \to \mu^+K^0_S$		
τ_{18}	$p \to \mu^+K^0_L$		
τ_{19}	$N \to \nu K$	> 86 (n), > 5900 (p)	90%
τ_{20}	$n \to \nu K^0_S$	> 260	90%
τ_{21}	$p \to e^+K^*(892)^0$	> 84	90%
τ_{22}	$N \to \nu K^*(892)$	> 78 (n), > 51 (p)	90%
	Antilepton + mesons		
τ_{23}	$p \to e^+\pi^+\pi^-$	> 82	90%
τ_{24}	$p \to e^+\pi^0\pi^0$	> 147	90%
τ_{25}	$n \to e^+\pi^-\pi^0$	> 52	90%
τ_{26}	$p \to \mu^+\pi^+\pi^-$	> 133	90%
τ_{27}	$p \to \mu^+\pi^0\pi^0$	> 101	90%
τ_{28}	$n \to \mu^+\pi^-\pi^0$	> 74	90%
τ_{29}	$n \to e^+K^0\pi^-$	> 18	90%

ΔB=ΔL=1 decay bounds

	Mode	Partial mean life (10^{30} years)	Confidence level
	Lepton + meson		
τ_{30}	$n \to e^-\pi^+$	> 65	90%
τ_{31}	$n \to \mu^-\pi^+$	> 49	90%
τ_{32}	$n \to e^-\rho^+$	> 62	90%
τ_{33}	$n \to \mu^-\rho^+$	> 7	90%
τ_{34}	$n \to e^-K^+$	> 32	90%
τ_{35}	$n \to \mu^-K^+$	> 57	90%
	Lepton + mesons		
τ_{36}	$p \to e^-\pi^+\pi^+$	> 30	90%
τ_{37}	$n \to e^-\pi^+\pi^0$	> 29	90%
τ_{38}	$p \to \mu^-\pi^+\pi^+$	> 17	90%
τ_{39}	$n \to \mu^-\pi^+\pi^0$	> 34	90%
τ_{40}	$p \to e^-\pi^+K^+$	> 75	90%
τ_{41}	$p \to \mu^-\pi^+K^+$	> 245	90%

ΔB=-ΔL=1 decay bounds

	Mode	Partial mean life (10^{30} years)	Confidence level
τ_{66}	$pp \to \pi^+\pi^+$	> 72.2	90%
τ_{67}	$pn \to \pi^+\pi^0$	> 170	90%
τ_{68}	$nn \to \pi^+\pi^-$	> 0.7	90%
τ_{69}	$nn \to \pi^0\pi^0$	> 404	90%
τ_{70}	$pp \to K^+K^+$	> 170	90%
τ_{71}	$pp \to e^+e^+$	> 5.8	90%
τ_{72}	$pp \to e^+\mu^+$	> 3.6	90%
τ_{73}	$pp \to \mu^+\mu^+$	> 1.7	90%
τ_{74}	$pn \to e^+\overline{\nu}$	> 260	90%
τ_{75}	$pn \to \mu^+\overline{\nu}$	> 200	90%
τ_{76}	$pn \to \tau^+\overline{\nu}_\tau$	> 29	90%
τ_{77}	$nn \to \nu_e\overline{\nu}_e$	> 1.4	90%
τ_{78}	$nn \to \nu_\mu\overline{\nu}_\mu$	> 1.4	90%
τ_{79}	$pn \to$ invisible	$> 2.1 \times 10^{-5}$	90%
τ_{80}	$pp \to$ invisible	$> 5 \times 10^{-5}$	90%

ΔB=2/ΔL=0 decay bounds*

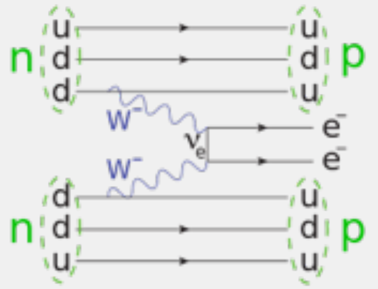
*For flavour universal models, nn gives the strongest constraints. For other flavour setups (e.g. MFV-RPV susy), dinucleon decays might be win

Pattern of B violation in SM(EFT)

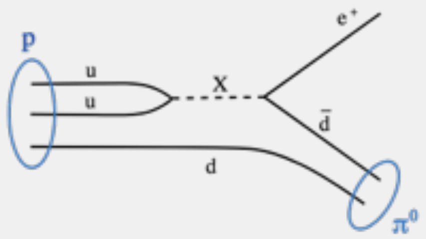
A. Kobach '16

$\mathcal{L}$ =	$\mathcal{L}_{SM}$	+ dim-5	+ dim-6	+ dim-7	+ dim-8	+ dim-9 + …
allowed (ΔB, ΔL)	(0, 0)	(0, 2)	(0, 0), (1, 1)	(0, 2), (1, -1)	(0, 0), (1, 1)	(2, 0), (1, -1), (0, 2), (1, 3)

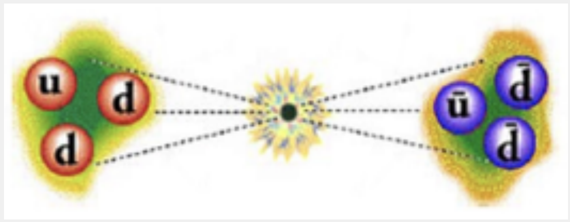
$0\nu\beta\beta$ decay



proton decays



neutron-antineutron oscillation

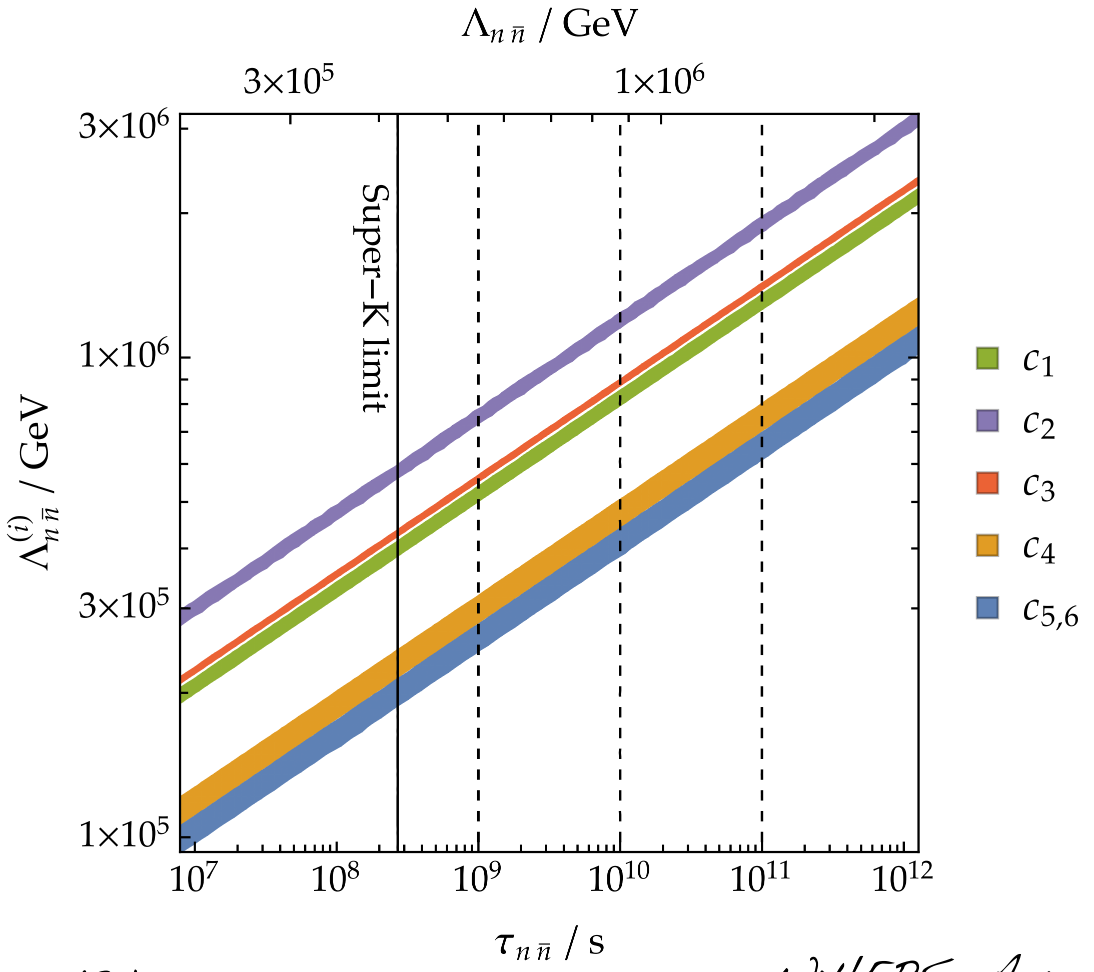


Slide stolen to Z. Zhang @ Pascos'18

12 operators (of the type 'uudddd')

$$\tau_{n\bar{n}}^{-1} = \left|\langle \bar{n}|\mathcal{H}_{\rm eff}|n\rangle\right|$$

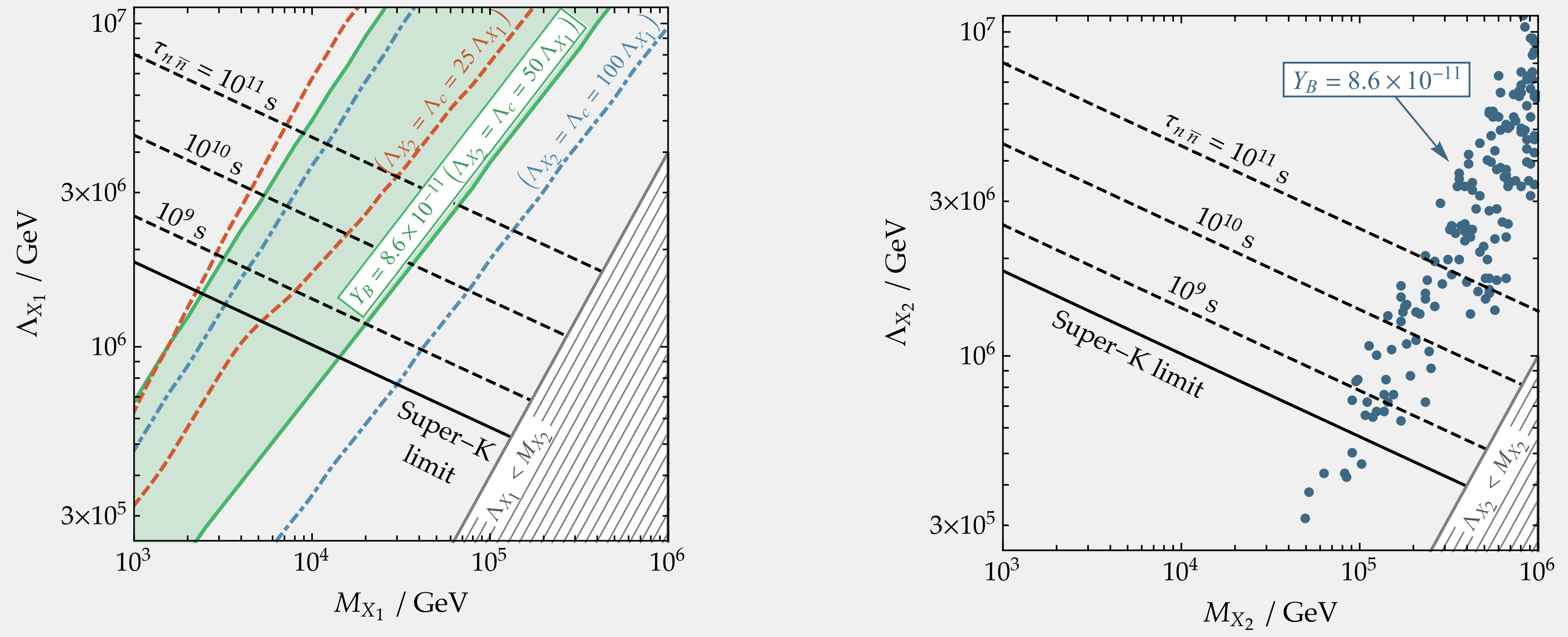
SuperK/ESS, DUNE is/will probe scales 10^5-10^6 GeV



Baryogenesis

Grojean, Shakya, Wells, Zhang '18

Late decay scenario	Early decay scenario
$\Lambda_{X_2} \sim \Lambda_c \gg \Lambda_{X_1}$	$\Lambda_{X_1} \gg \Lambda_{X_2} \gtrsim \Lambda_c$



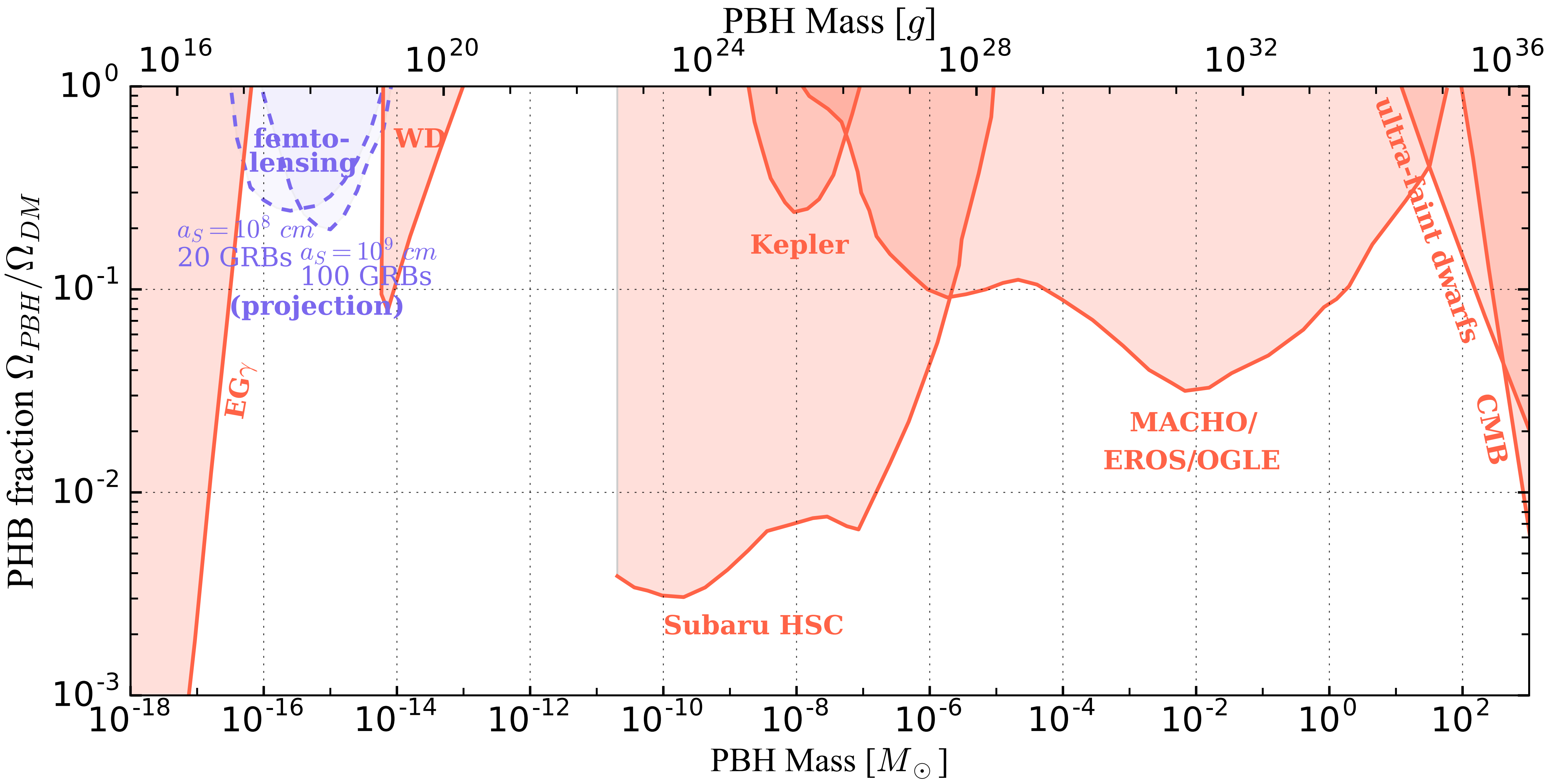
Explicit realisation of late decay scenario:
RPV SUSY with late decays of the bino in presence of a wino/gluino
[F.Rompineve, 1310.0840] [Y.Cui, 1309.2952] [G.Arcadi, L.Covi, M.Nardecchia, 1507.05584]

$n\bar{n}$ oscillations can probe direct baryogenesis scenarios @ $10^{5\text{-}6}$ GeV

Searching for a primordial blackhole with your cell phone

PBHs as DM

$$t_{\text{evaporation}} > 10^{64} \left(\frac{M_{BH}}{M_\odot}\right)^3 \text{ year} \quad \Rightarrow \quad M_{PBH} > 10^{-17} M_\odot$$



Katz+ 1807.11495

PBH abundance

Production of PBH is still subject to research and debates (gravitational collapse of large over-densities during inflation? Topological defects?...)

$$\rho_{DM} \sim 0.3\,\mathrm{GeV/cm^3} \sim 10^{-15} M_\odot / V_{\text{Solar system}}$$

So, if

$$M_{\text{PBH}} \sim 10^{-16} M_\odot, \text{ i.e., } R_{\text{Sch}} \sim 10^{-13}\,\mathrm{cm}$$

we expect a few in the Solar system

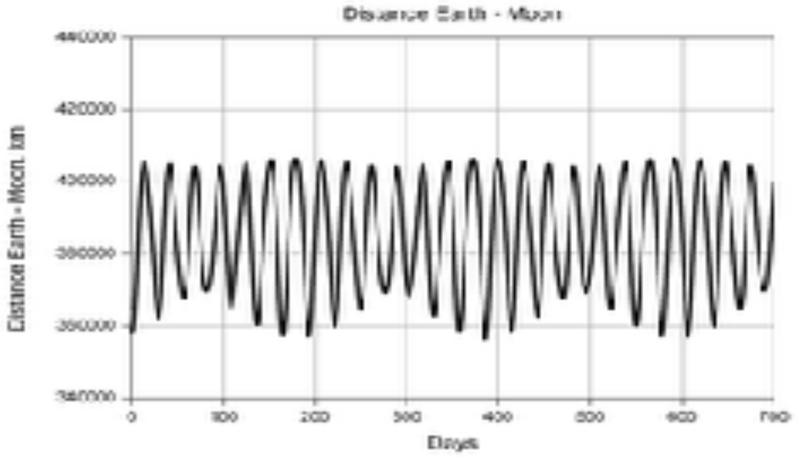
How can we detect such PBHs living in the Solar system?

A PBH orbiting around Earth

Grojean, Panico, Ruderman et al, in progress

Is there a black moon around Earth and interacting only gravitationally?

A black moon between the Earth and the Moon will induce a variation of the distance Earth-Moon, this distance is measured with an accuracy of 1mm (10^{-11} relative accuracy), even though there is large theoretical uncertainty.



$$\Delta d_{\oplus-\circ} = \frac{d_{\oplus-\mathrm{PBH}} M_{\mathrm{PBH}}}{M_\oplus}$$

numerically

$$1\,\mathrm{mm} = \frac{1000\,\mathrm{km} \times 10^{-16} M_\odot}{M_\oplus}$$

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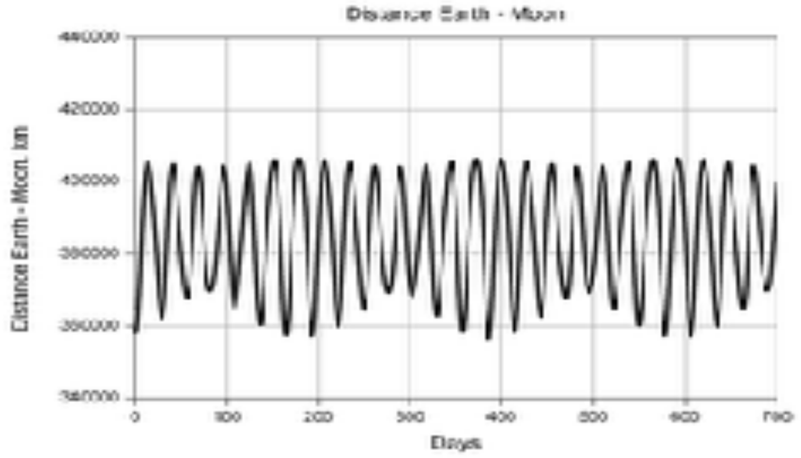

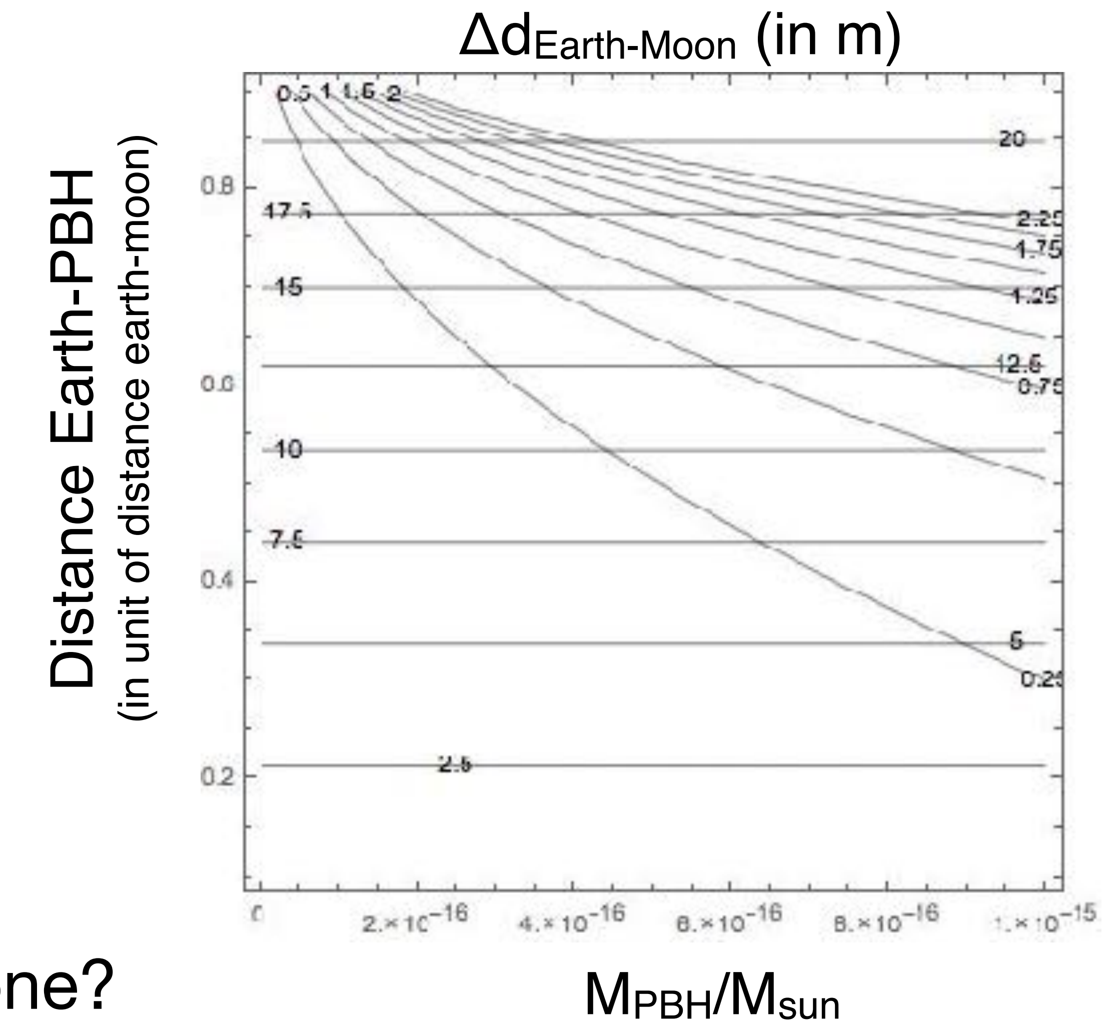

Can also use GPS measurements…
Looking for a black moon with your cell-phone?

Time to wrap up...

Executive summary on status of BSM

BAD NEWS

Experimentalists haven’t found (yet)
what theorists told them they will find

GOOD NEWS

There are rich opportunities
for mind-boggling signatures
@ colliders and beyond

Conclusion

Once upon a time… Columbus had a great proposal: "reaching India by sailing to the West"

He had a theoretical model

- the Earth is round,
- Eratosthenes of Cyrene first estimated its circumference to be 250'000 stadia
- other measurements later found smaller values ☞Toscanelli's map
- lost in unit-conversion or misled by post-truth statements, Columbus thought it was only 70'000 stadia, so he believed he could reach India in 4 weeks

He had the right technology

- Caravels were the only ships at that time to sail against the wind, necessary tool to fight the prevailing winds, aka Alizée. Actually, the Vikings had the right technology too but the knowledge was lost

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Moral(s)

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Moral(s)

“if your proposal is rejected, submit it again” J. Mnich

“you need the right technology to beat your competitors” J. Fuster

“theorists don’t need to be right!
but progress needs theoretical models to motivate exploration”

Breaking the HEP frontiers

new machines much wanted to

~~ open new horizons beyond LHC ~~

no lack of theoretical motivations

& plenty of physics issues outside the SM frame

from deep QFT questions ~~ to pressing phenomenological puzzles

* no BSM major discovery without a thorough understanding of SM background

* challenge: control theoretical uncertainty to the level of experimental sensitivity

* complementarity and synergy of electron and hadron machines

When thinking about any future big projects:

~~ 2 human characteristics to balance ~~

finite lifetime
(and awareness of it)

capacity of dreaming

Particle Physics is Exciting

B. Clinton, Davos 2011

ippog.web.cern.ch/resources/2011/bill-clinton-davos-2011

Final Homework:
imagine what the current US president could say about science and HEP

Thank you for your attention.
Good luck for your future career!

And thanks a lot to the organisers for setting up this nice event!

if you have question/want to know more

do not hesitate to send me an email

christophe.grojean@desy.de