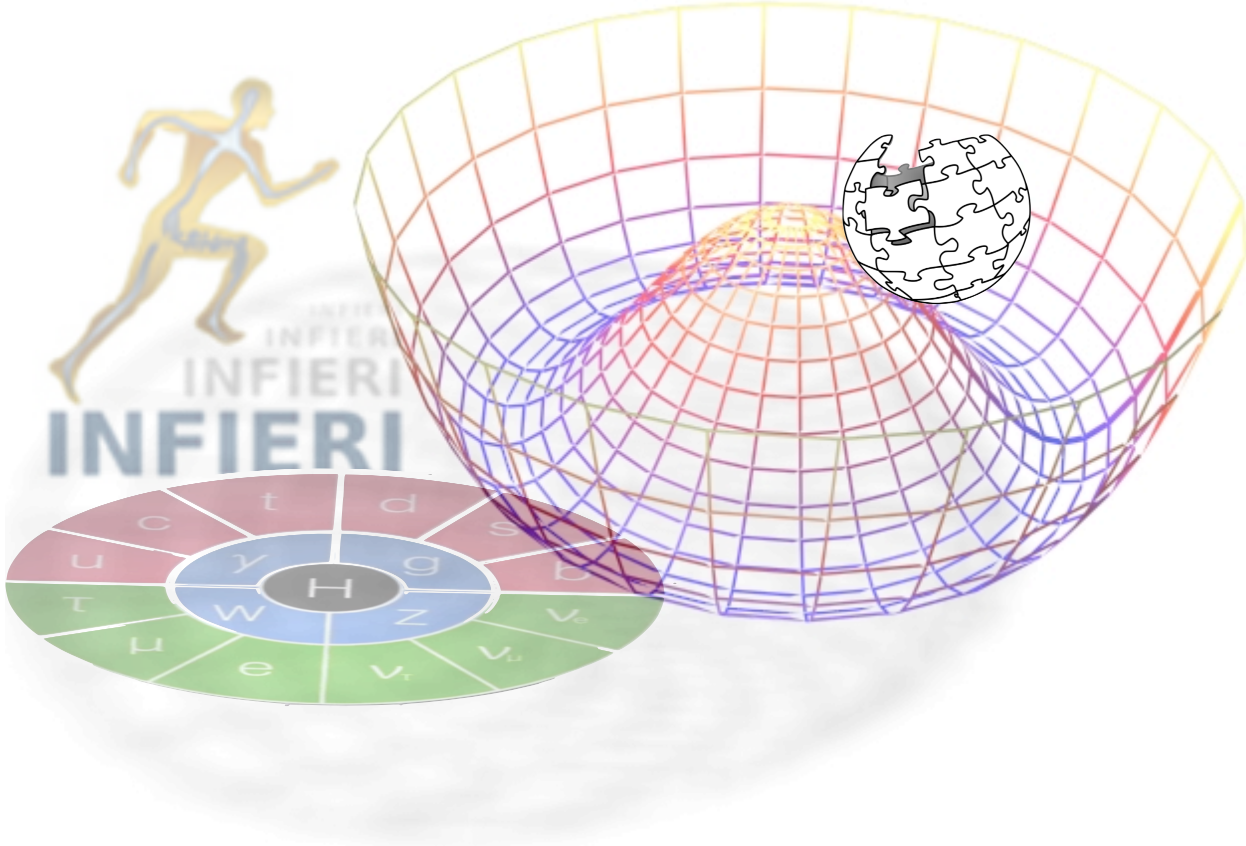
Physics Potential
at High-Energy (Hadron) Colliders

International Summer School series on

" Intelligent Signal Processing for Frontier Research and Industry "

UAM, August 27, 2021



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Humboldt University (Berlin)

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LHC Status After ~10 years

M. Mangano, CERN Courier ‘20

The Higgs exists… and nothing else Beyond the Standard Model showed up!

But we have learnt a lot (the biggest discovery is that supersymmetry was not discovered) and the spectrum of physics emerged from the LHC is far richer than expected !

The future is bright and promising.

Which Machine(s)?

Hadrons

- large mass reach ⇛ exploration?
- ▹ S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors
  (w/ optimised design)
- ▹ only pdf access to $\sqrt{\hat{s}}$
- ⇛ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇛ measurement?
- polarized beams
  (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇛ EW couplings

Circular

- higher luminosity + same tunnel for ee/hh
- several interaction points
- "greener"*: less power consumption at low E
- precise E-beam measurement
  (O(0.1MeV) via resonant (transverse) depolarization)
- ▹ $\sqrt{s}$ limited by synchroton radiation

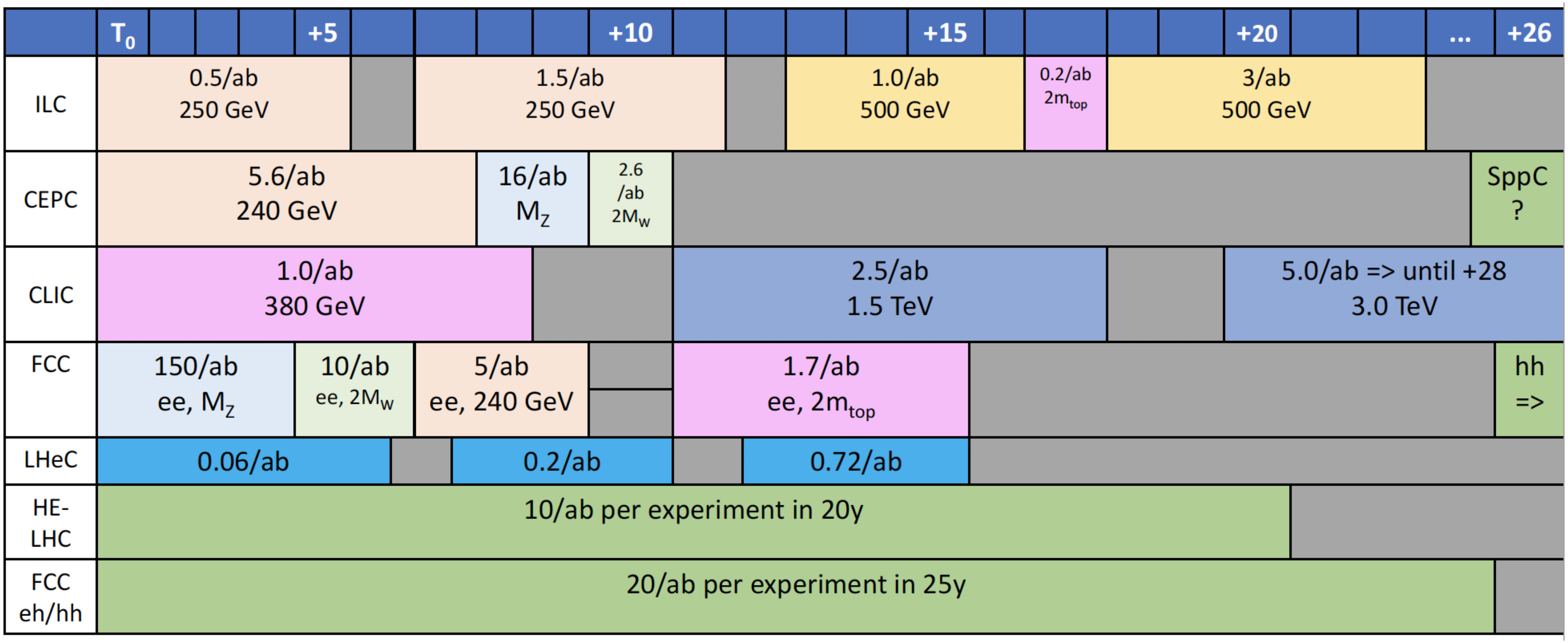
Linear

- easier to upgrade in energy
- easier to polarize beams
- "greener"*: less power consumption at high E
- ▹ large beamsthralung
- ▹ one IP only

*energy consumption per integrated luminosity (and Higgs produced) is lower at circular colliders but the energy consumption per GeV is lower at linear colliders; cross-over at ~ 365 GeV(running costs: 255 EUR/Higgs at FCC-ee240, >7'000 EUR/Higgs at ILC250)

Future of HEP

ECFA Higgs study group '19



	T_0				+5					+10					+15					+20			...	+26
ILC	0.5/ab 250 GeV						1.5/ab 250 GeV						1.0/ab 500 GeV				0.2/ab $2m_{top}$	3/ab 500 GeV						
CEPC	5.6/ab 240 GeV							16/ab M_Z		2.6 /ab $2M_W$													SppC ?	
CLIC	1.0/ab 380 GeV										2.5/ab 1.5 TeV									5.0/ab => until +28 3.0 TeV				
FCC	150/ab ee, M_Z				10/ab ee, $2M_W$		5/ab ee, 240 GeV				1.7/ab ee, $2m_{top}$													hh =>
LHeC	0.06/ab						0.2/ab					0.72/ab												
HE-LHC	10/ab per experiment in 20y																							
FCC eh/hh	20/ab per experiment in 25y																							

Future of HEP

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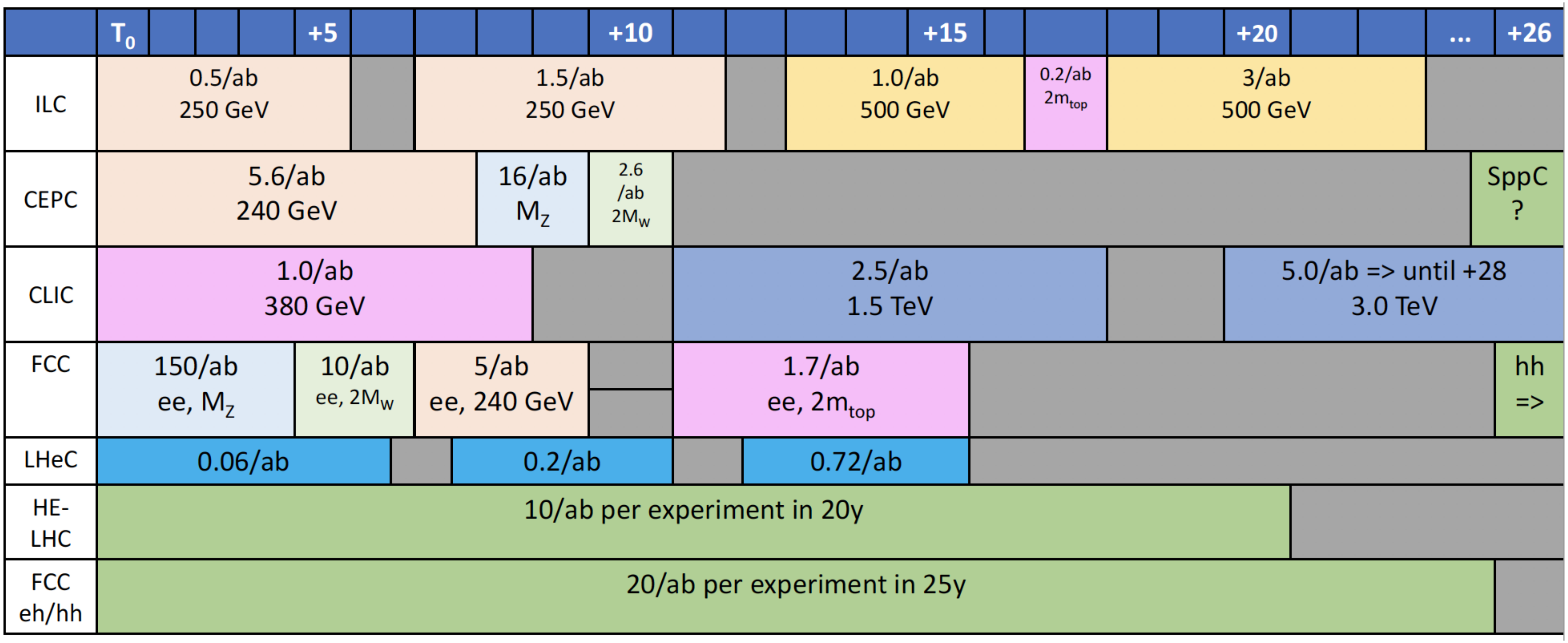
Subject to large uncertainty
1) need a scientific consensus
2) political approval



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LHeC	0.06/ab						0.2/ab					0.72/ab													2030
HE-LHC	10/ab per experiment in 20y																								2040
FCC eh/hh	20/ab per experiment in 25y																								2045

What is the scale of New Physics?

— Simplicity —

High Scale Wishes

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

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

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

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⟺

QM+SR basic rules
are such that models with heavy scale
cannot accommodate
a light Higgs boson nor a small vacuum energy.
Need to have additional structures/selection rules
for it to happen

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small EDMs: $\mathrm{arg det Y} \leq 10^{-10}$

↪ 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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⤷ light susy?

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 ◀

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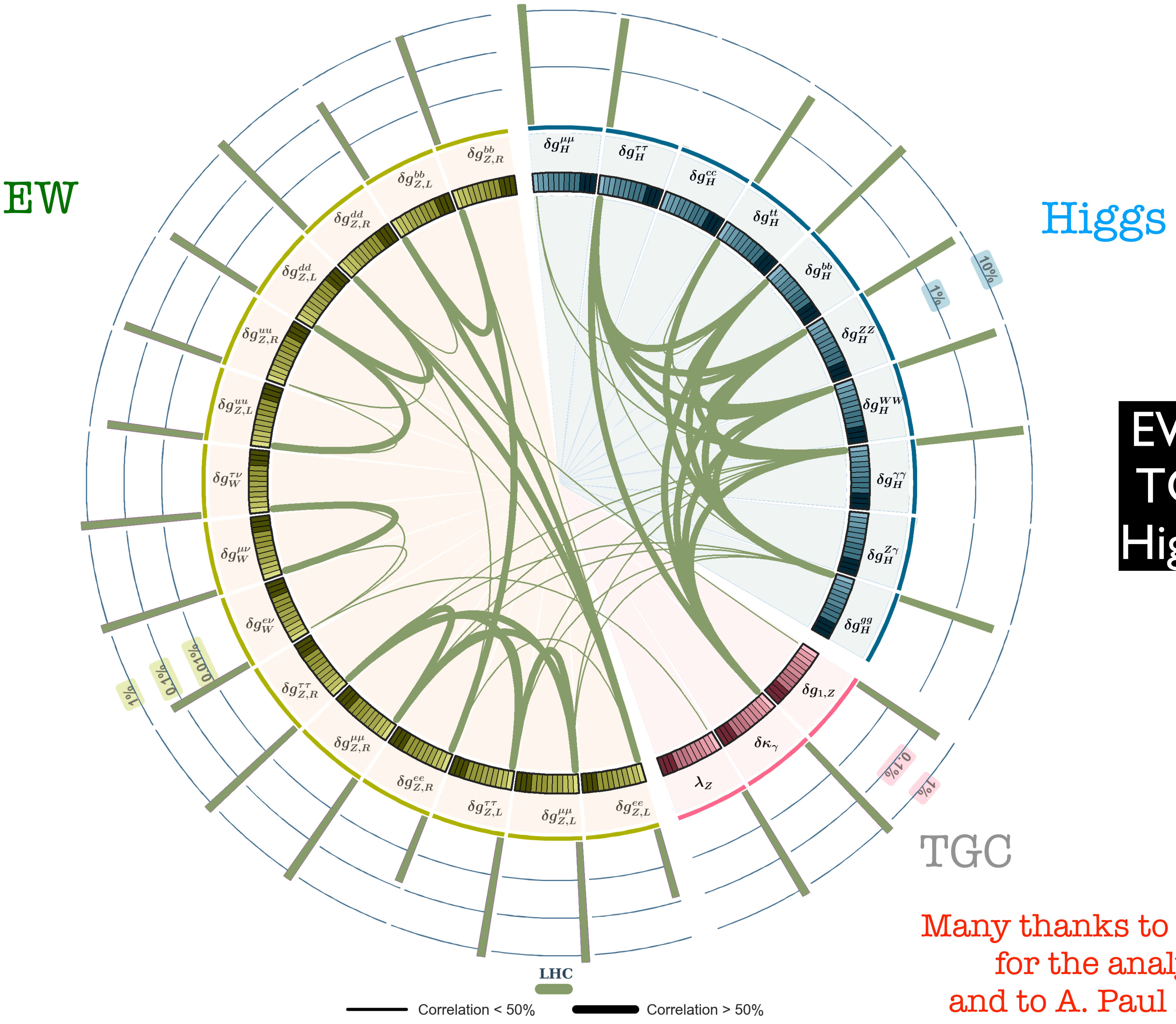
need for a versatile machine
capable to adjust to very different new physics scenario
(i) guaranteed deliverables
(ii) exploration potential

(i) Guaranteed Deliverables

— Exploration of the Higgs Sector —

SM: Once-Now



EW known at 0.1%
TGC known at 1%
Higgs known at 10%

Many thanks to J. De Blas et al. (HEPfit)
for the analysis of current data
and to A. Paul for plotting the results

Higgs programme at Future Colliders

more energy + more luminosity = more Higgses

\# of Higgses in 3 ab^{-1}

100 TeV > 2 billion

33 TeV > 500 million

14 TeV > 150 million

In comparison, O(million) Higgs at Higgs factories

@ 100 TeV

	σ	N / $10ab^{-1}$
gg→H	740 pb	7.4 G
VBF	82 pb	0.8 G
WH	16 pb	160 M
ZH	11 pb	110 M
ttH	38 pb	380 M
gg→HH	1.4 pb	14 M

M. Mangano, HXSWG '15

Statistical precision:

- O(100 - 500) better w.r.t Run 1
- O(10 - 20) better w.r.t HL-LHC

- ◉ better measurements of Higgs properties: mass, width
- ◉ precision measurements of Higgs couplings
- ◉ access to rare decay modes
- ◉ access at rare production modes/kinematical distributions
- ◉ discovery of extended Higgs sectors

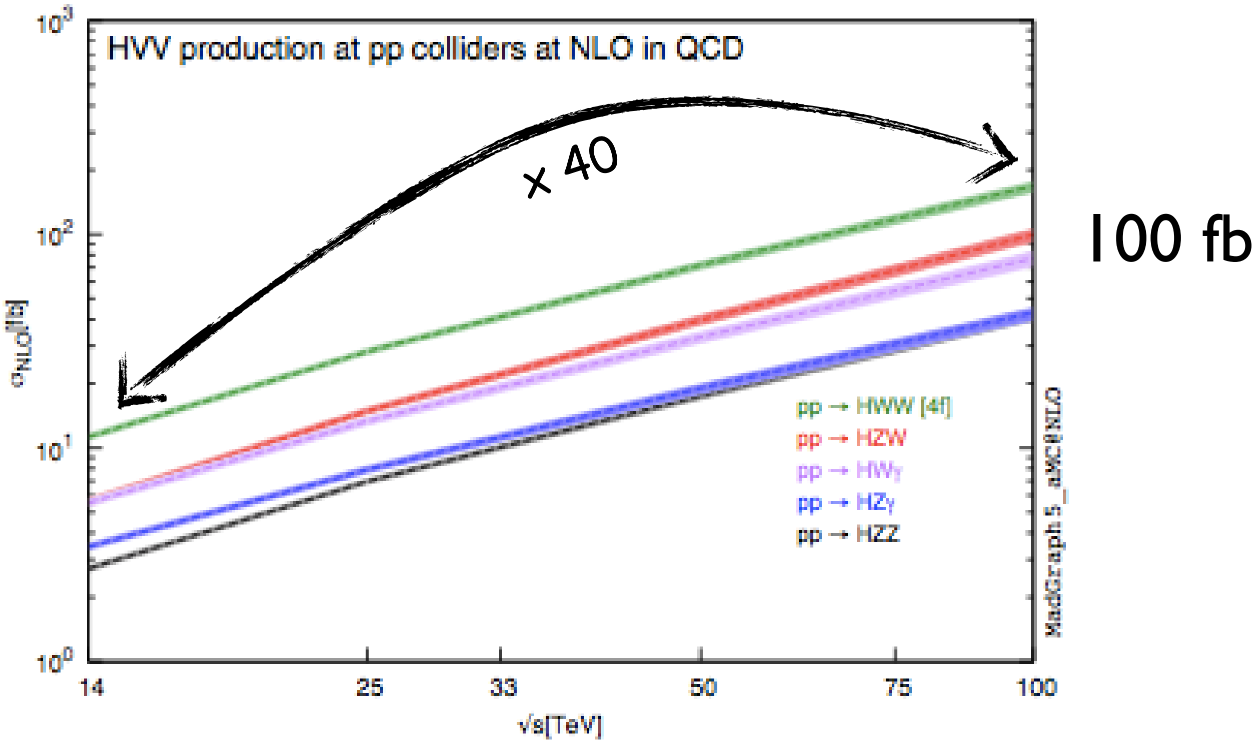
H production @ FCC-hh

	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

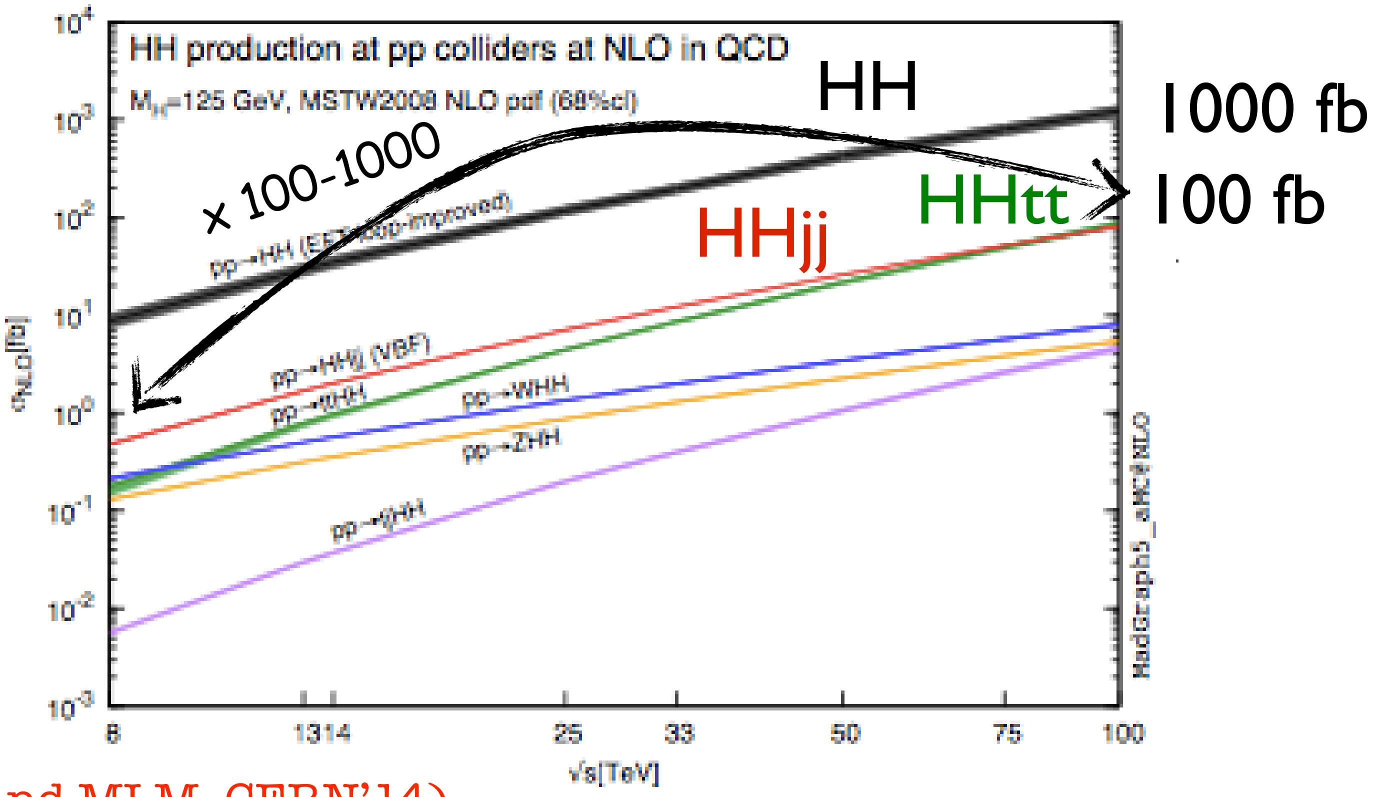
relative importance of production modes modified in favor of VBF and ttH

FCC-hh = H+X factory

Higgs-diboson associated production



Higgs-pair associated production



(Plots from P. Torrielli and MLM, CERN'14)

Higgs Programme at Future Colliders

Producing one Higgs is good. Producing H+X is better

@ 14 TeV

Higgs multiplicty →

Jet multiplicty ↓

Single h	Double h	Triple H
h $\sim 50\ \mathrm{pb}^{gg}$	hh $\sim 34\ \mathrm{fb}^{gg}$	hhh $\sim 44\ \mathrm{ab}^{gg}$
h+j $\sim 2\ \mathrm{pb}^{p_T(j)>100}$	hh+j	
h+jj $\sim 4.2\ \mathrm{pb}^{VBF}$	hh+jj $\sim 2\ \mathrm{fb}^{VBF}$	

- also roughly indicates possible initial states/related kinematics
- Jet multiplicity might be replaced with V=W,Z, top, etc...

(adapted from M. Son@Planck2014)

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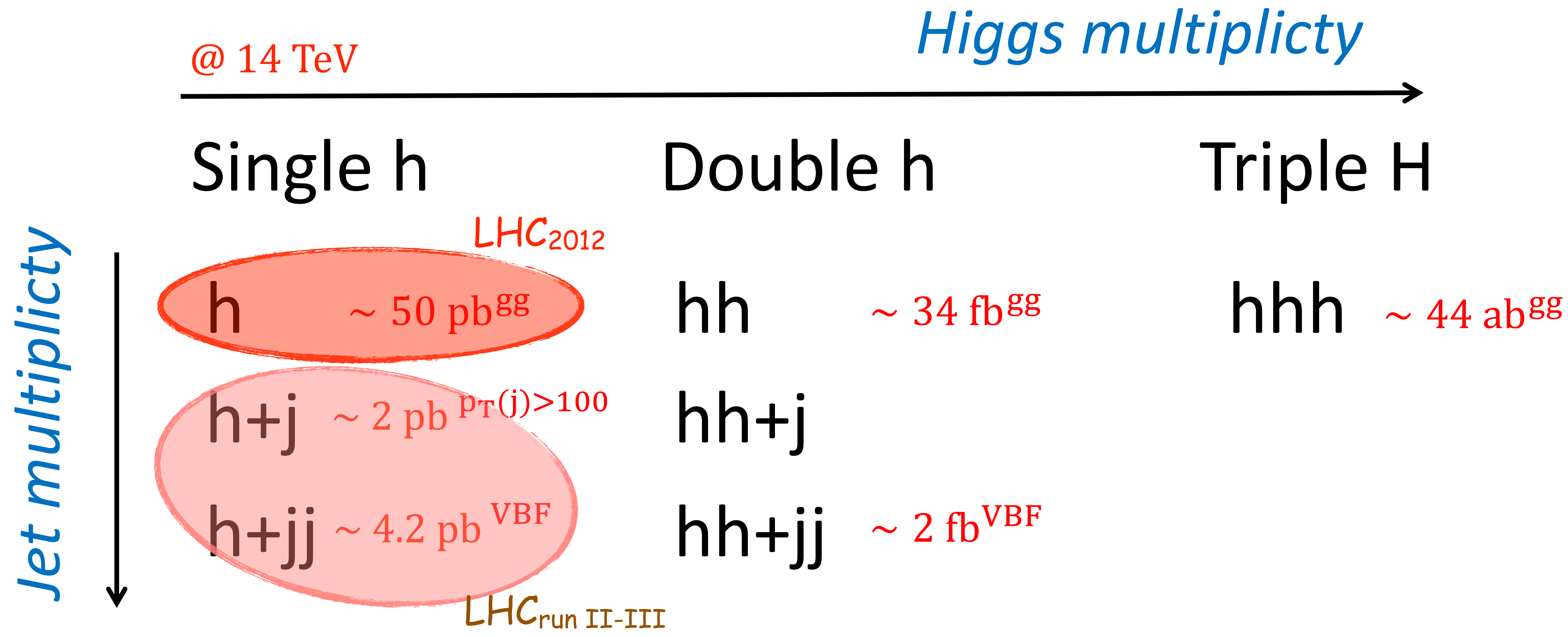

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LHC_{2012}

$\mathrm{LHC}_{\text{run II-III}}$

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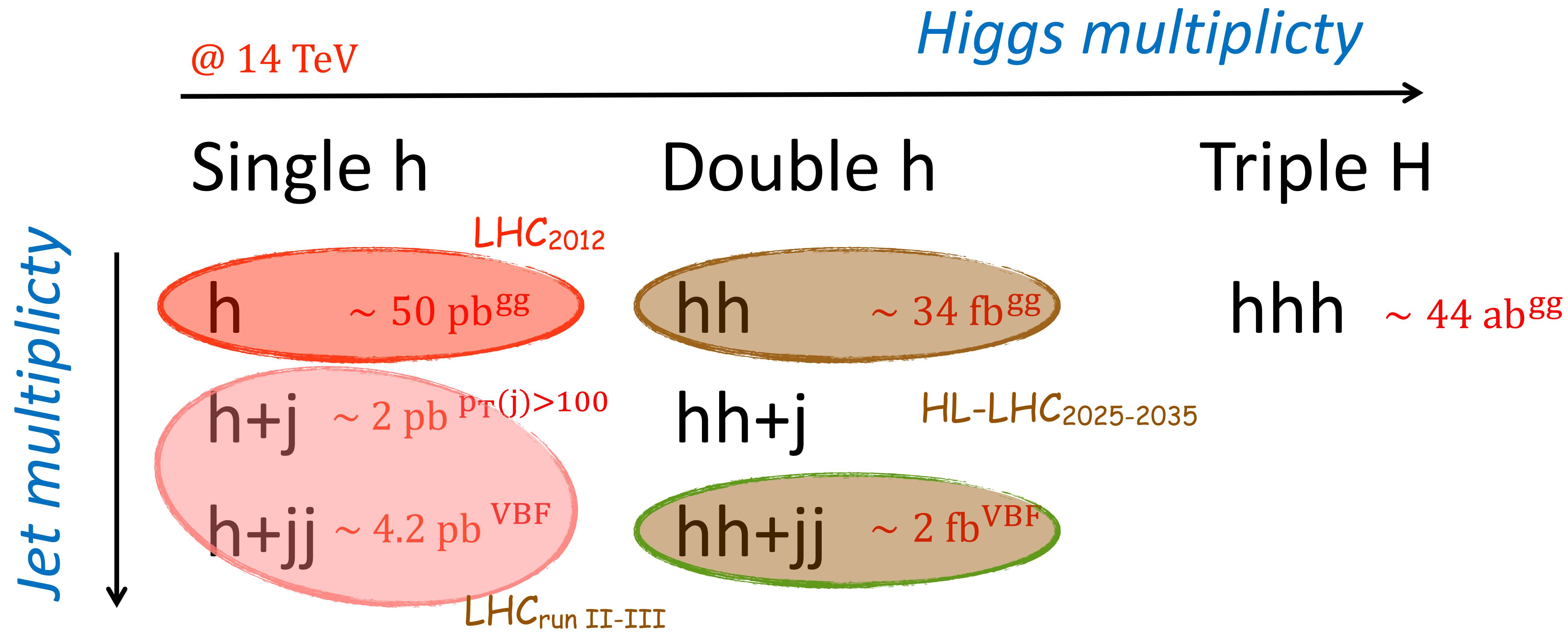

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HL-LHC$_{2025\text{-}2035}$

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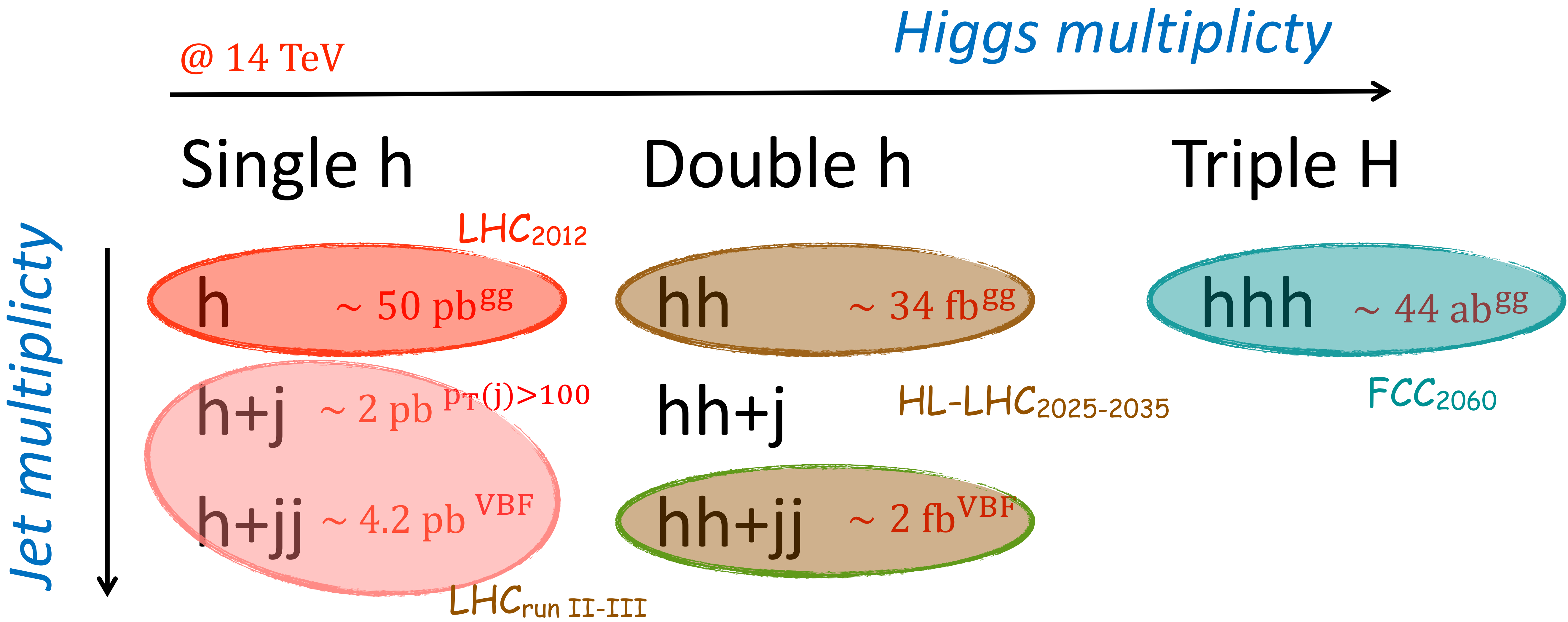

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hh+j

$\mathrm{HL\text{-}LHC}_{2025\text{-}2035}$

FCC_{2060}

h+jj $\sim 4.2\ \mathrm{pb}^{VBF}$

hh+jj $\sim 2\ \mathrm{fb}^{VBF}$

$\mathrm{LHC}_{\text{run II-III}}$

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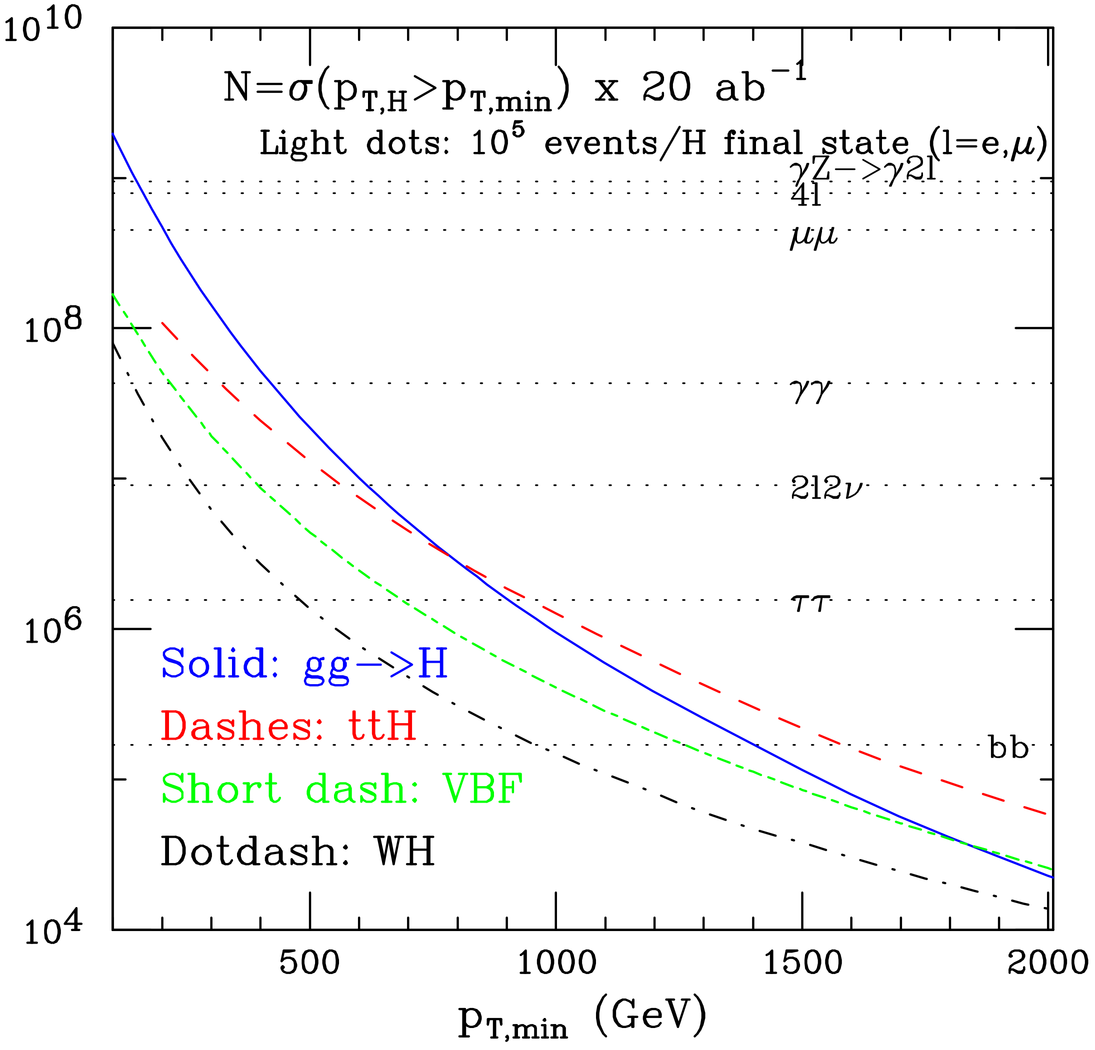
(adapted from M. Son@Planck2014)

Rare Higgs production/decay

two important handles to access rare/exotic channels

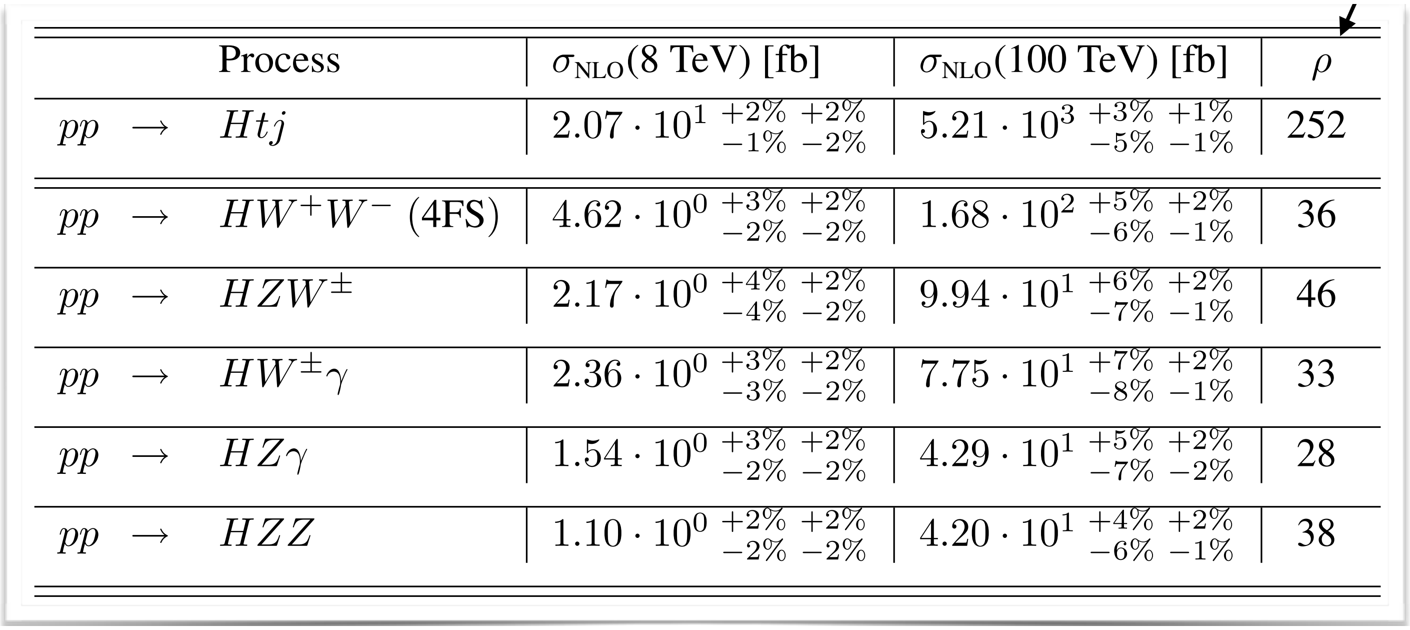
FCC-hh =
probe extreme kinematic regimes

FCC-hh = H+X factory



Lesson: Hierarchy of production channels changes at large $p_T(H)$:

- σ(ttH) > σ(gg→H) above 800 GeV
- σ(VBF) > σ(gg→H) above 1800 GeV



Process	σ_{NLO}(8 TeV) [fb]	σ_{NLO}(100 TeV) [fb]	ρ
$pp \to Htj$	$2.07\cdot 10^1\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$5.21\cdot 10^3\ ^{+3\%}_{-5\%}\ ^{+1\%}_{-1\%}$	252
$pp \to HW^+W^-$ (4FS)	$4.62\cdot 10^0\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$1.68\cdot 10^2\ ^{+5\%}_{-6\%}\ ^{+2\%}_{-1\%}$	36
$pp \to HZW^\pm$	$2.17\cdot 10^0\ ^{+4\%}_{-4\%}\ ^{+2\%}_{-2\%}$	$9.94\cdot 10^1\ ^{+6\%}_{-7\%}\ ^{+2\%}_{-1\%}$	46
$pp \to HW^\pm\gamma$	$2.36\cdot 10^0\ ^{+3\%}_{-3\%}\ ^{+2\%}_{-2\%}$	$7.75\cdot 10^1\ ^{+7\%}_{-8\%}\ ^{+2\%}_{-1\%}$	33
$pp \to HZ\gamma$	$1.54\cdot 10^0\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$4.29\cdot 10^1\ ^{+5\%}_{-7\%}\ ^{+2\%}_{-2\%}$	28
$pp \to HZZ$	$1.10\cdot 10^0\ ^{+2\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$4.20\cdot 10^1\ ^{+4\%}_{-6\%}\ ^{+2\%}_{-1\%}$	38

e.g.
h → Z_DZ_D → 4l

e.g.
h → 2a → 4b
or even h → jets

	E (Tev)	lumi (/fb)	N_{higgs} (all)	N_{higgs} (clean)	Br sensitivity for very **conspicuous** decays	Br sensitivity for very **difficult** decays
LHC run 1	7,8	25	500k	0	10^{-4}	O(1) or worse
LHC run 2	14	300	10 million	0	10^{-5}	O(0.1) - O(1)
HL-LHC	14	3000	100 million	0	10^{-6}	?
ILC	0.25 - 1	7000	1 million	40k	10^{-4} - 10^{-5}	10^{-2}
TLEP	0.25ish	10000	3 million	300k	10^{-5}	10^{-3}
100 TeV	100	3000	few billion	0	10^{-7} - 10^{-8}	10^{-2} ????

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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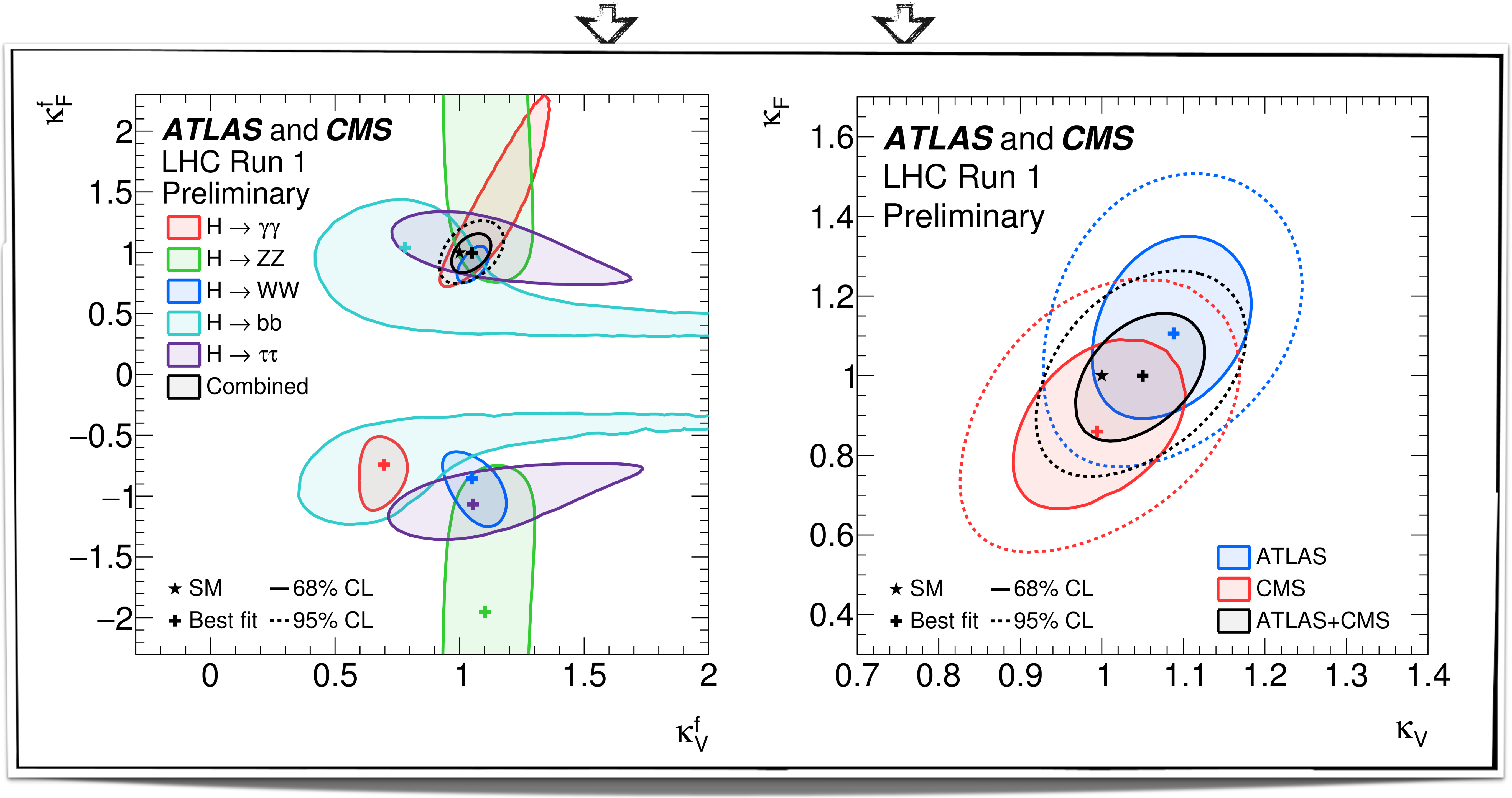

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So far the LHC has mostly produced Higgses on-shell
in processes with a characteristic scale $\mu \approx m_H$

access to Higgs couplings @ m_H

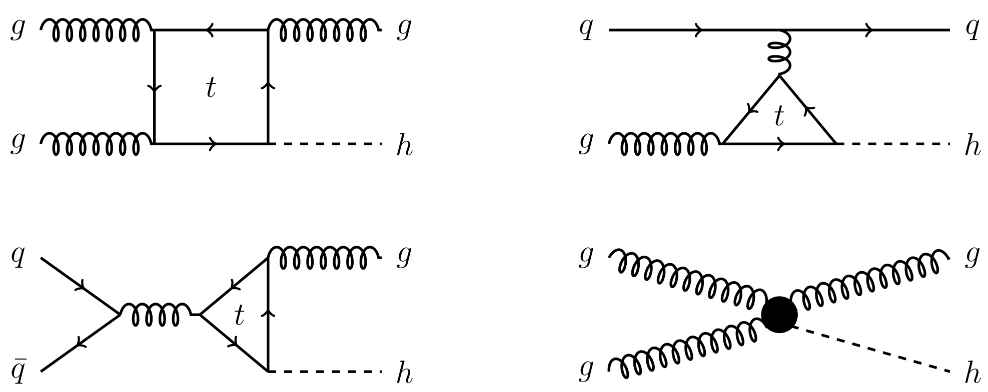
Producing a Higgs with boosted additional particle(s)
probe the Higgs couplings @ large energy
(important to check that the Higgs boson ensures perturbative unitarity)

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

Grojean, Salvioni, Schlaffer, Weiler '13



$$\frac{\sigma_{p_T^{\min}}(\kappa_t,\kappa_g)}{\sigma^{\rm SM}_{p_T^{\min}}} = (\kappa_t+\kappa_g)^2 + \delta\,\kappa_t\,\kappa_g + \epsilon\,\kappa_g^2$$

large pT, small rates

need to focus on dominant decay modes

$$h \to b\bar{b}, WW, \tau\tau$$

non-isolated "ditau-jets"

(separation between the 2 tau's: $\Delta R \sim 2m_h/p_T \lesssim 0.5$)

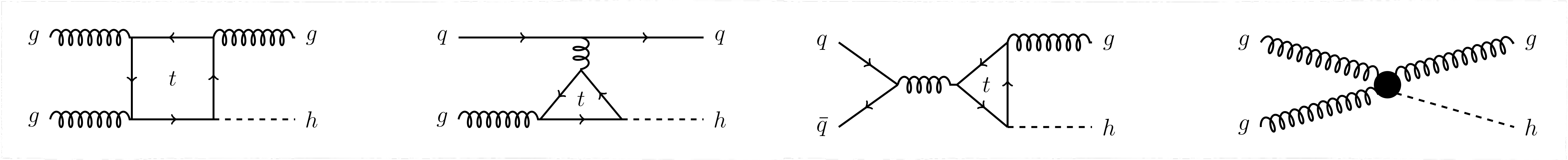
$$\epsilon_{\rm tot} = {\rm BR}(h\to\tau\tau)\left(\sum_{i=\tau_\ell\tau_\ell,\,\tau_\ell\tau_h,\,\tau_h\tau_h} {\rm BR}(\tau\tau\to i)\,\epsilon_i\right) \simeq 2\times 10^{-2}$$

$\sqrt{s}$ [TeV]	$p_T^{\min}$ [GeV]	$\sigma^{\rm SM}_{p_T^{\min}}$ [fb]	δ	ϵ	gg, qg [%]
14	100	2200	0.016	0.023	67, 31
	150	830	0.069	0.13	66, 32
	200	350	0.20	0.31	65, 34
	250	160	0.39	0.56	63, 36
	300	75	0.61	0.89	61, 38
	350	38	0.86	1.3	58, 41
	400	20	1.1	1.8	56, 43
	450	11	1.4	2.3	54, 45
	500	6.3	1.7	2.9	52, 47
	550	3.7	2.0	3.6	50, 49
	600	2.2	2.3	4.4	48, 51
	650	1.4	2.6	5.2	46, 53
	700	0.87	3.0	6.2	45, 54
	750	0.56	3.3	7.2	43, 56
	800	0.37	3.7	8.4	42, 57
100	500	970	1.8	3.1	72, 28
	2000	1.0	14	78	56, 43

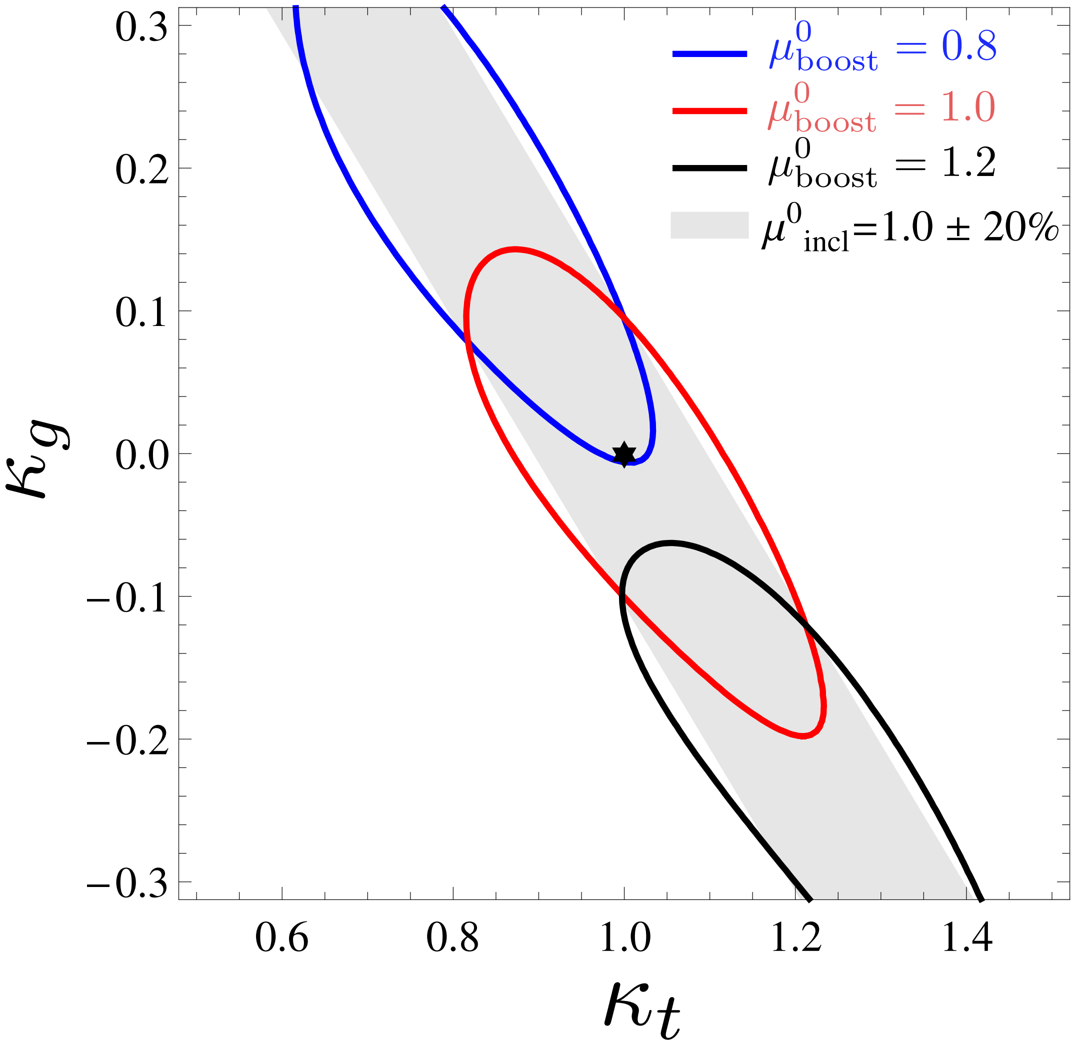
x 150 enhancement

FCC-hh is the machine
to decipher the gg→h process

Boosted Higgs+jet



Grojean, Salvioni, Schlaffer, Weiler '13
see also Azatov, Paul '13



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

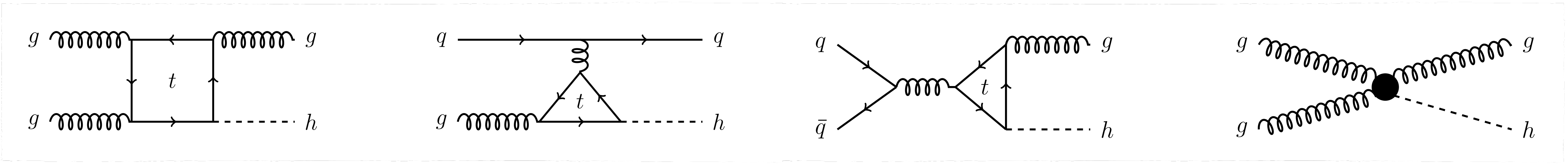
10-20% precision on κ_t

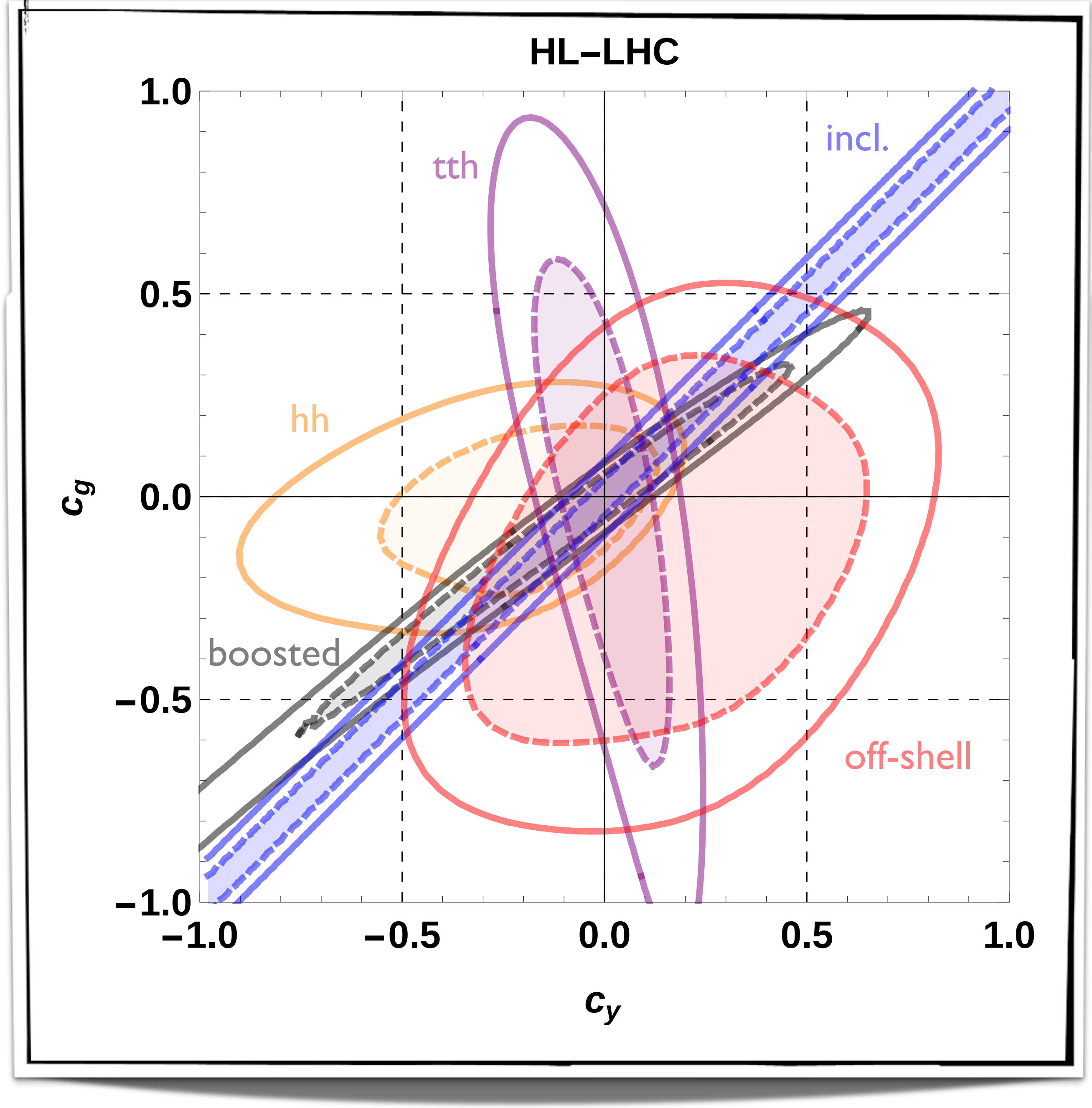
⇓ ⇓

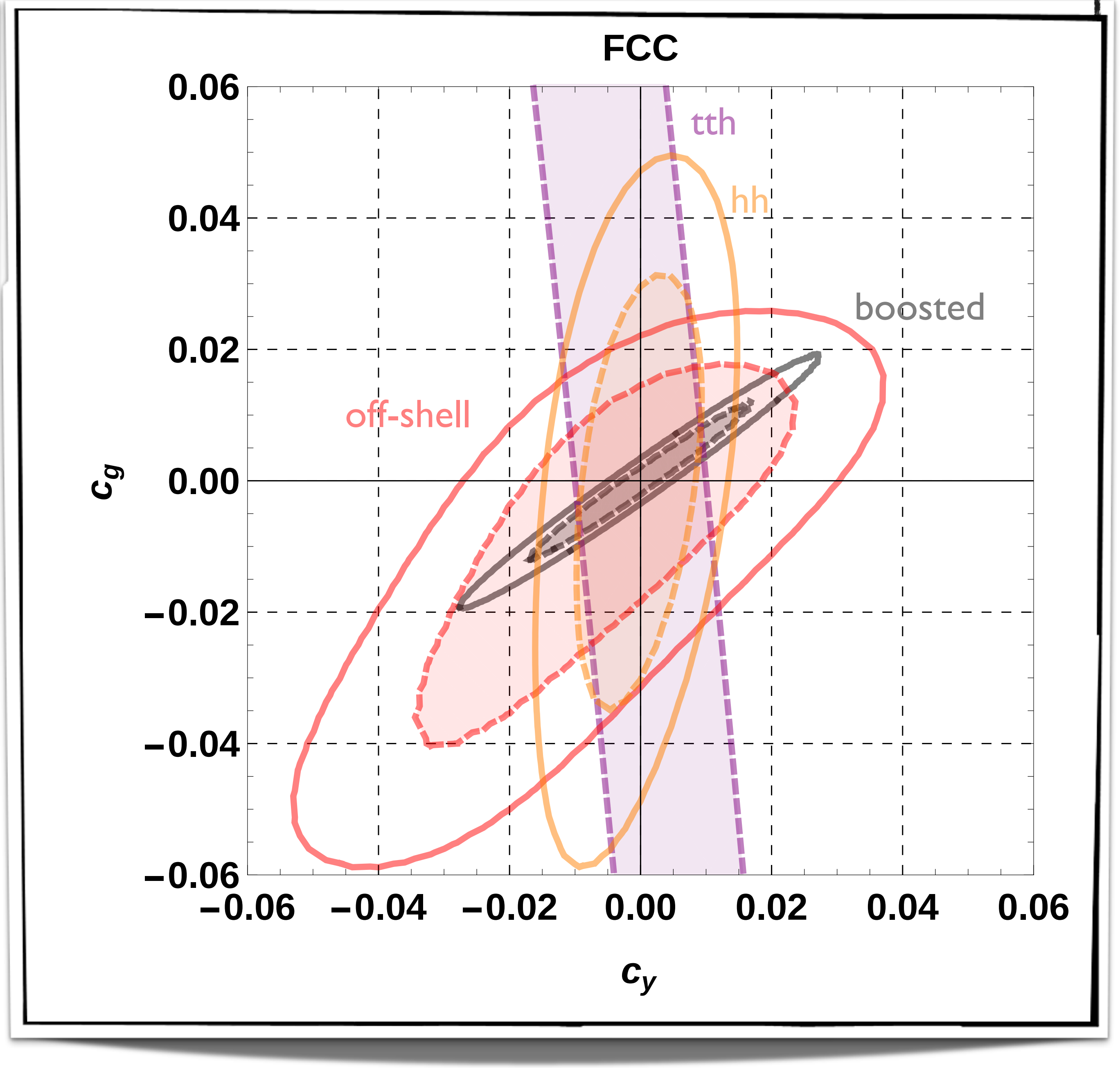
competitive/complementary to htt channel
for the measure the top-Higgs coupling

Are the NLO_m QCD corrections (not known) going to destroy all the sensitivity?
Frontier priority: $\text{N}^3\text{LO}_\infty$ for inclusive xs & NLO_mt for pT spectrum?

Boosted Higgs+jet







Azatov, Grojean, Paul, Salvioni '16

Light stop searches from Higgs+jet

Natural susy calls for **light stop(s)**

One good example where large statistics opens up new search strategy

Light stop searches from Higgs+jet

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

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

One good example where large statistics opens up new search strategy

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... or not if $\Delta_t \approx 0 \Rightarrow$ **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, $B \to X_s + \gamma$)
- ✦ RG evolution
- ✦ DM

Delgado et al ’12

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Inclusive Higgs measurements cannot rule out light stop

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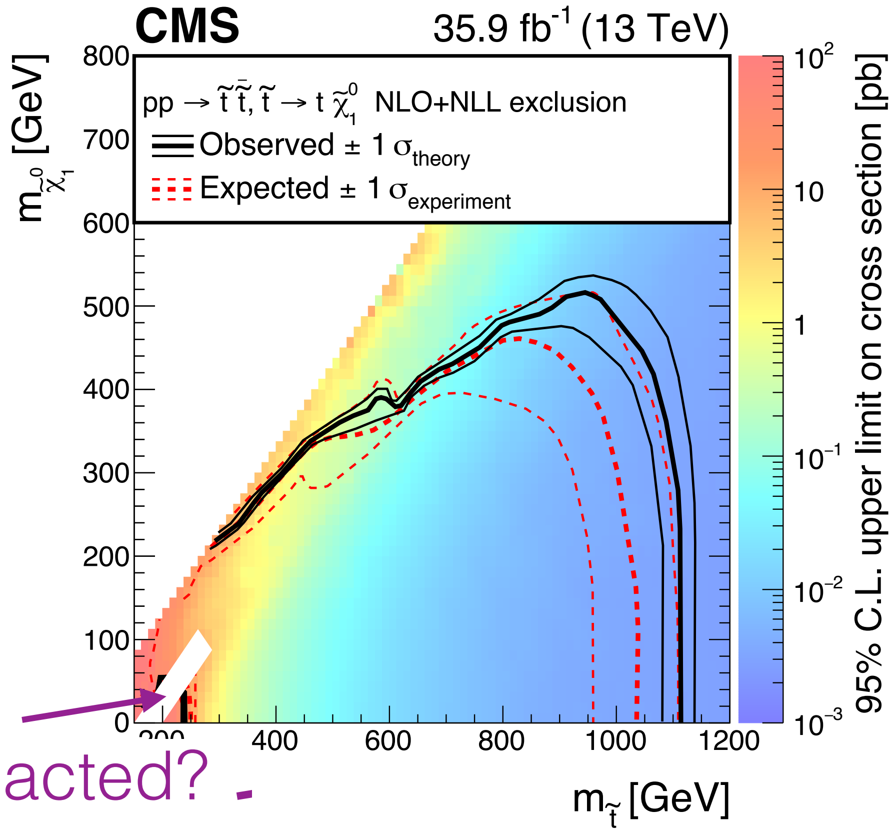


redacted?
(stealth stop)

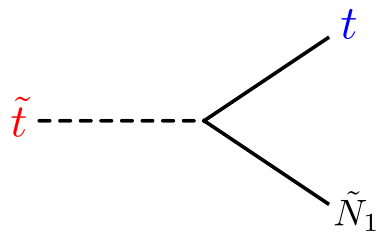
Inclusive Higgs measurements cannot rule out light stop

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

Difficult direct searches (trigger on stop+extra jet)



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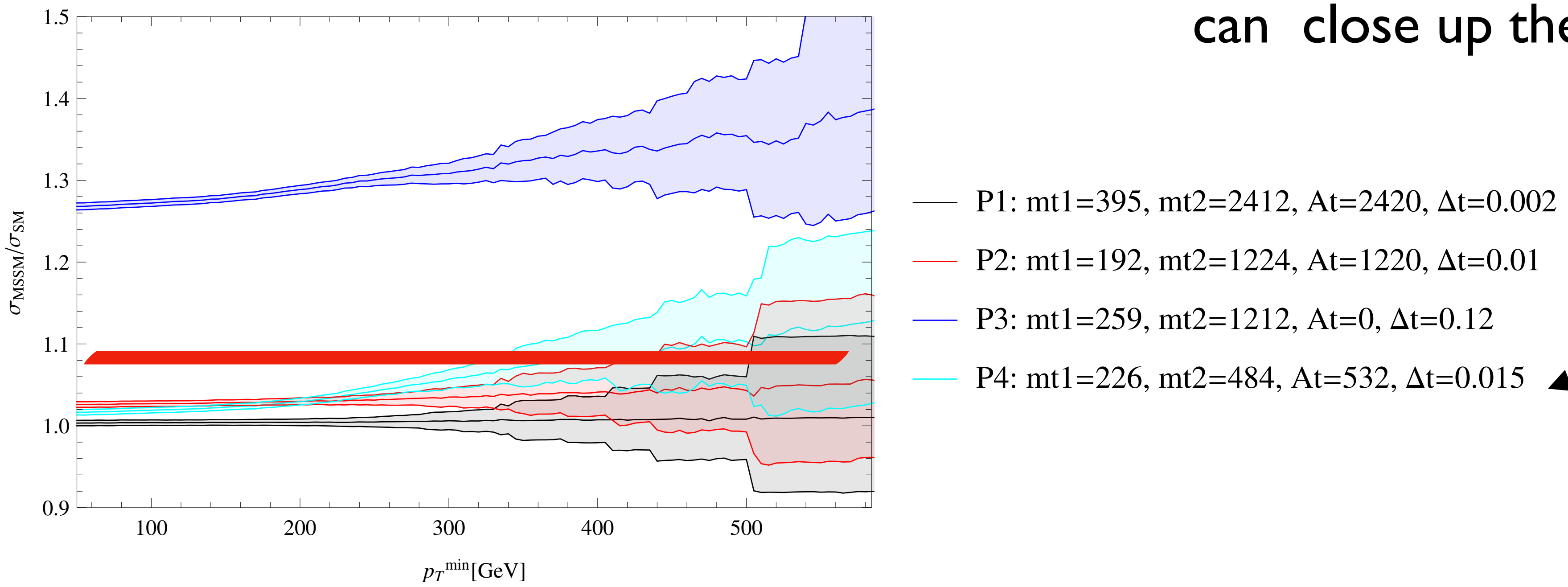
Inclusive Higgs measurements cannot rule out light stop

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



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

Grojean, Salvioni, Schlaffer, Weiler '13

One good example where large statistics opens up new search strategy

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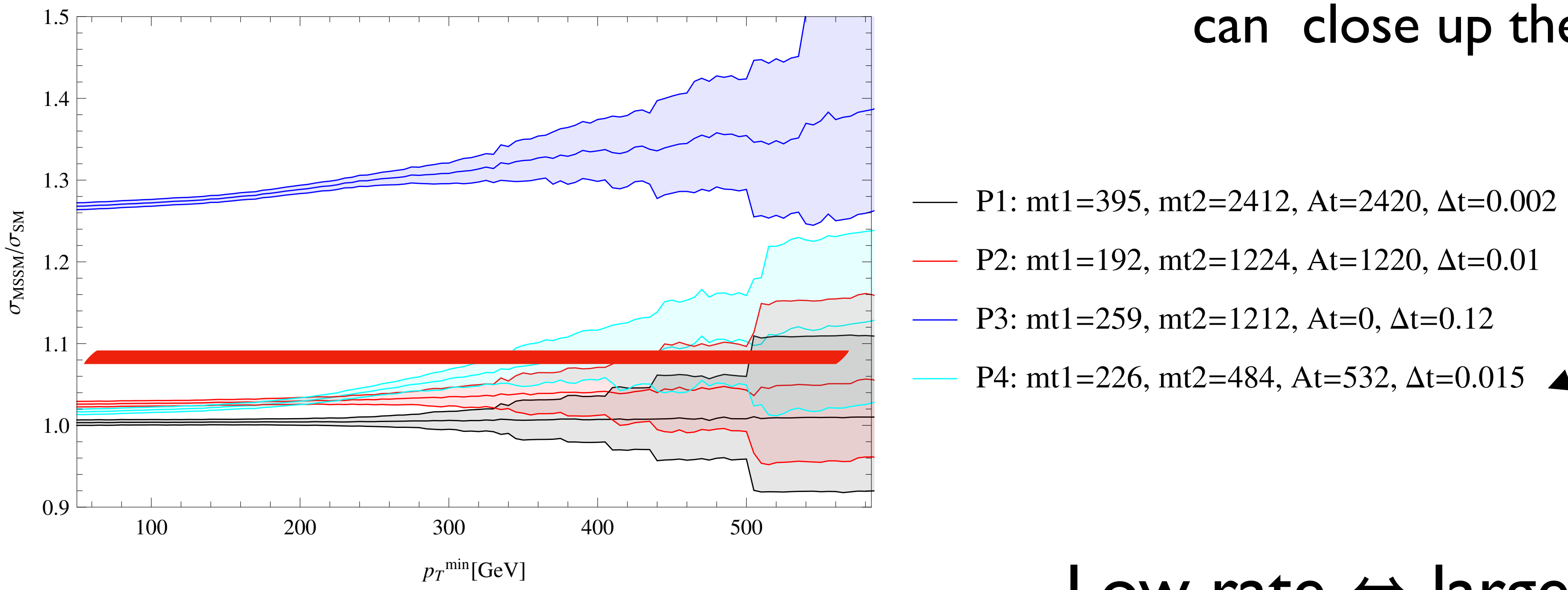

Light stop benchmark
that leaves no signal in inclusive rate
but predicts different tail in p_T
distribution

Grojean, Salvioni, Schlaffer, Weiler '13

Low rate ⇔ large luminosity needed

One good example where large statistics opens up new search strategy

The missing beast: Higgs self-coupling

The Higgs self-coupling plays important roles

1) is tight to the Hierarchy problem, i.e. stress-test basic principles of QFT/EFT
2) dictates the dynamics of EW phase transition and potentially conditions the generation of a matter-antimatter asymmetry via EW baryogenesis

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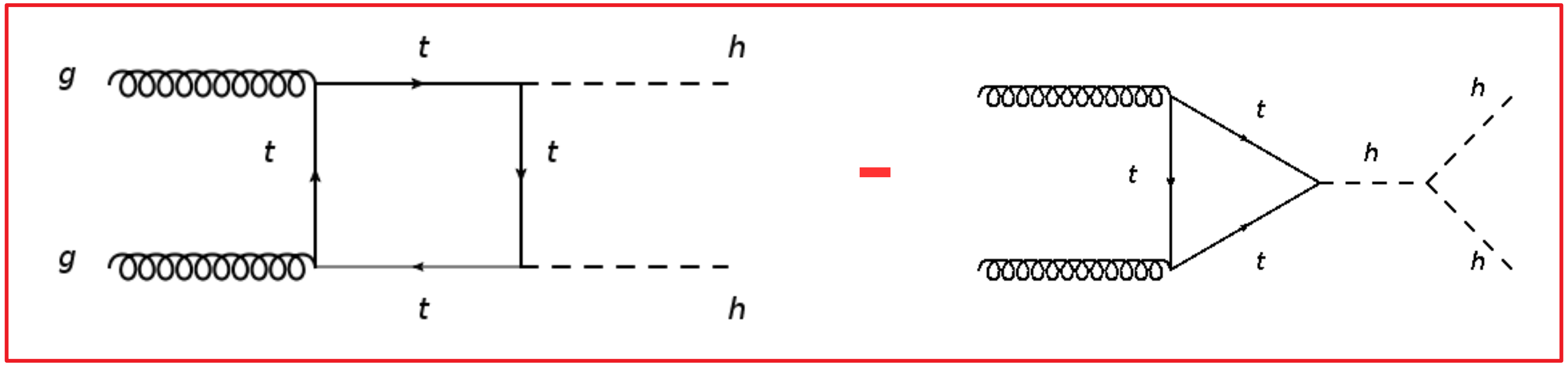
Does it need to be measured with high accuracy?

difficult to design new physics scenarios that dominantly affect the Higgs self-couplings and leave the other Higgs coupling deviations undetectable



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

The missing beast: Higgs self-coupling

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Under the assumption of heavy/decoupling new physics (i.e. analytic EFT Lagrangian)

deviation of Higgs cubic self-coupling can be a priori large

Perturbativity: $\kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} - 1 < 600\,\xi$ where ξ is the typical deviation in single Higgs couplings

Stability of EW vacuum: $\kappa_3 < 70\,\xi$

O(1) sensitivity in Higgs self-coupling is competitive to **5%** sensitivity in single Higgs couplings

Relevant for particular models, e.g. Higgs DM-portal models, not for composite/susy

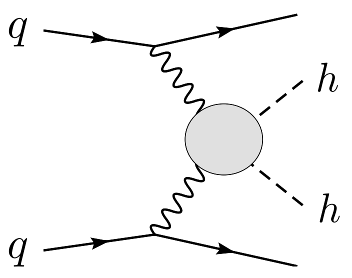
DiVita et al,: 1704.01953

Falkowski, Rattazzi: 1902.05936

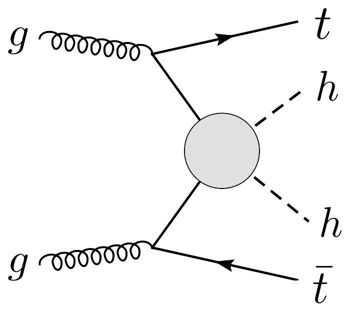
HH@FCC-hh

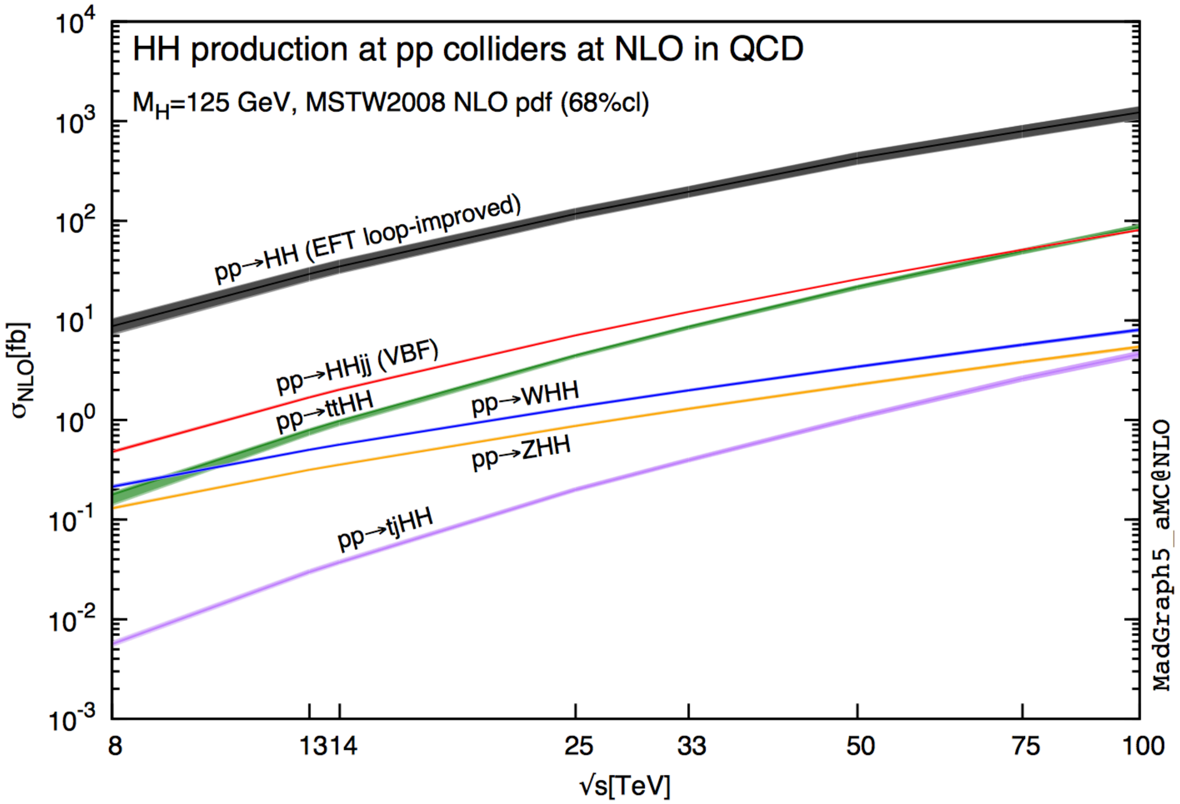
Gluon Fusion (GF)

Vector Boson Fusion (VBF)



tthh associated production

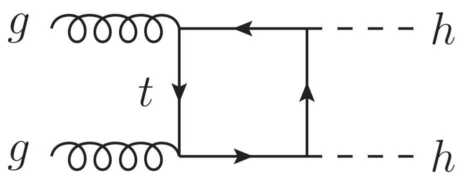




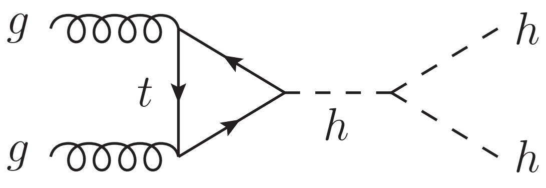
increase of xs by O(40)

process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

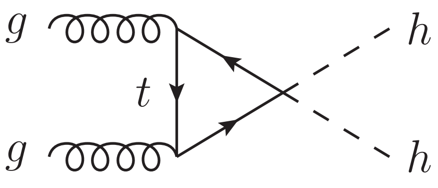
HH@FCC-hh: probe of HE couplings



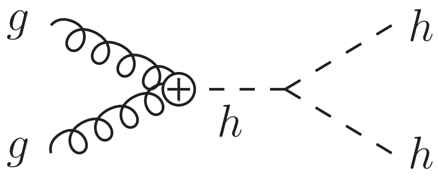
$\sim c_t^2 \times const.$



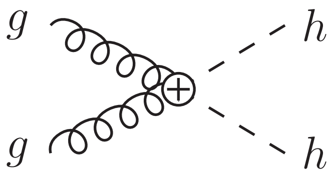
$\sim c_t c_3 \times \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$



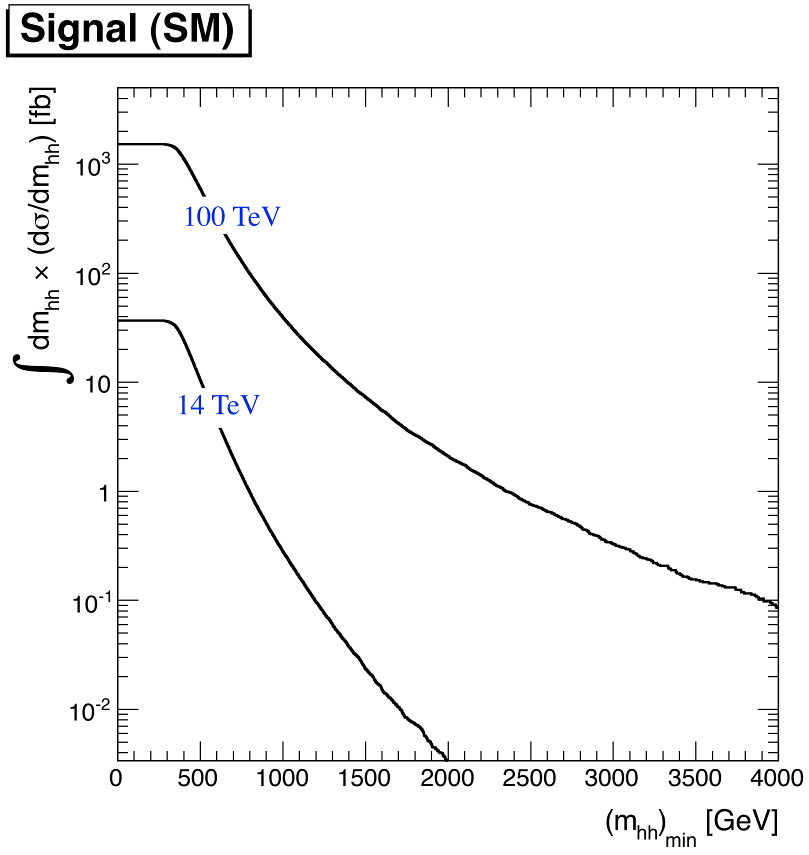
$\sim c_{2t} \times \log^2\left(\frac{m_t^2}{\hat{s}}\right)$

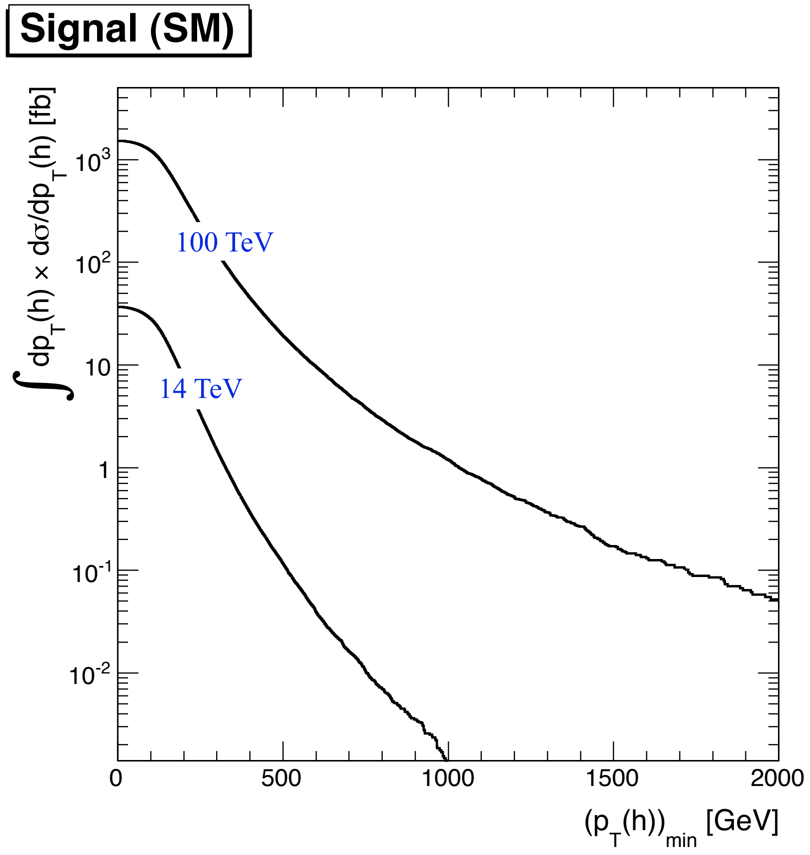


$\sim c_g c_3 \frac{\alpha_s}{4\pi} \times const.$



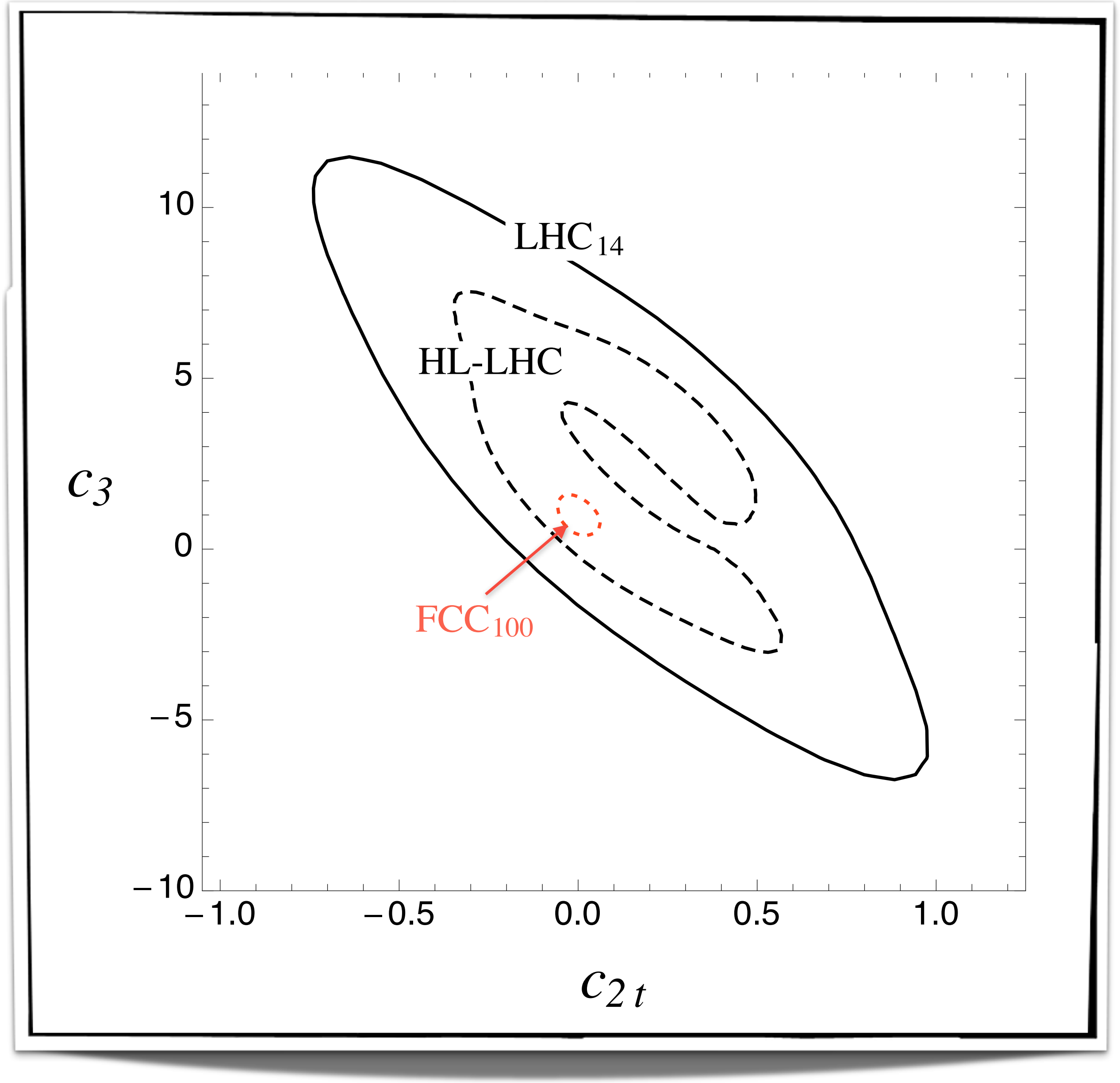
$\sim c_{2g} \frac{\alpha_s}{4\pi} \frac{\hat{s}}{v^2}$

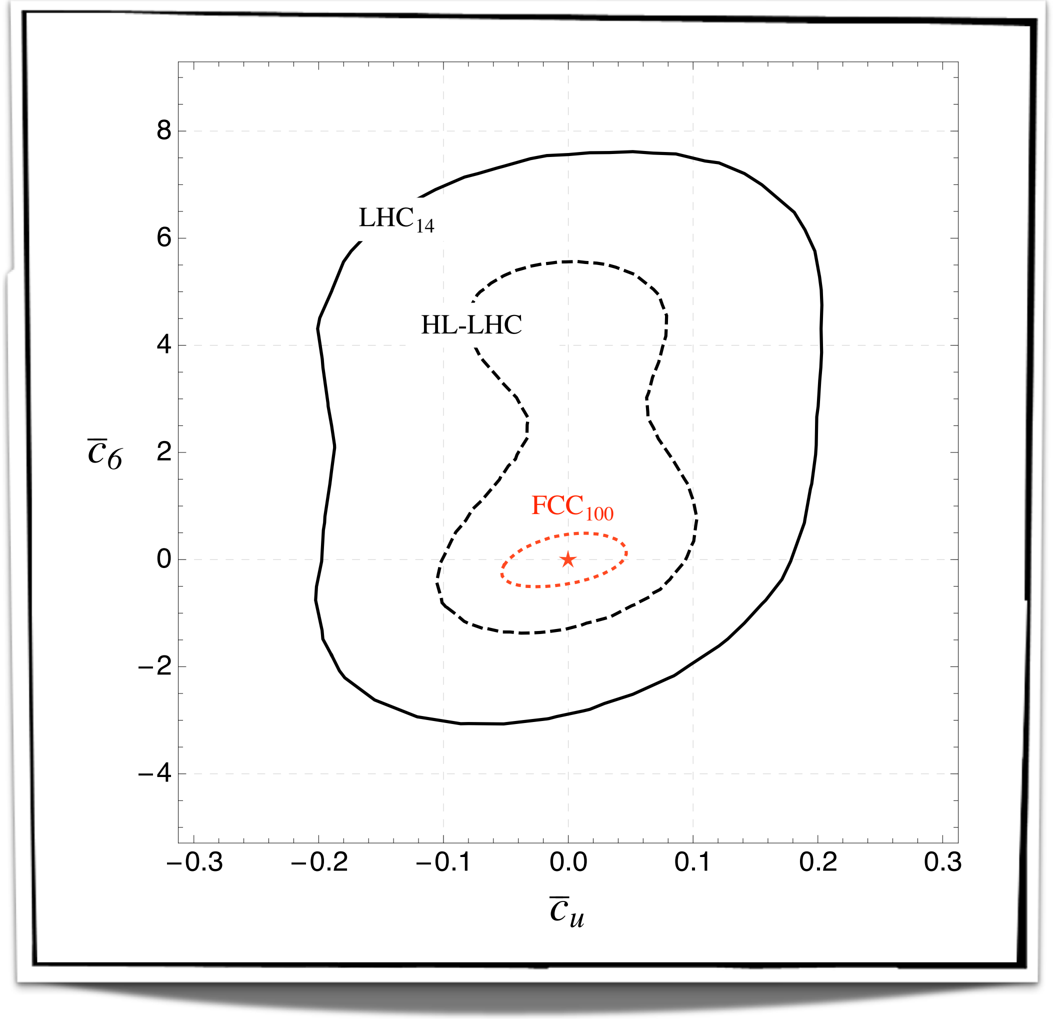




Azatov, Contino, Panico, Son ’15

HH@FCC-hh: probe of HE couplings





Azatov, Contino, Panico, Son ’15
see also Goertz, Papaefstathiou, Yang, Zurita ’14

Remarks:

- statistically limited @ HL-LHC, not at FCC-hh

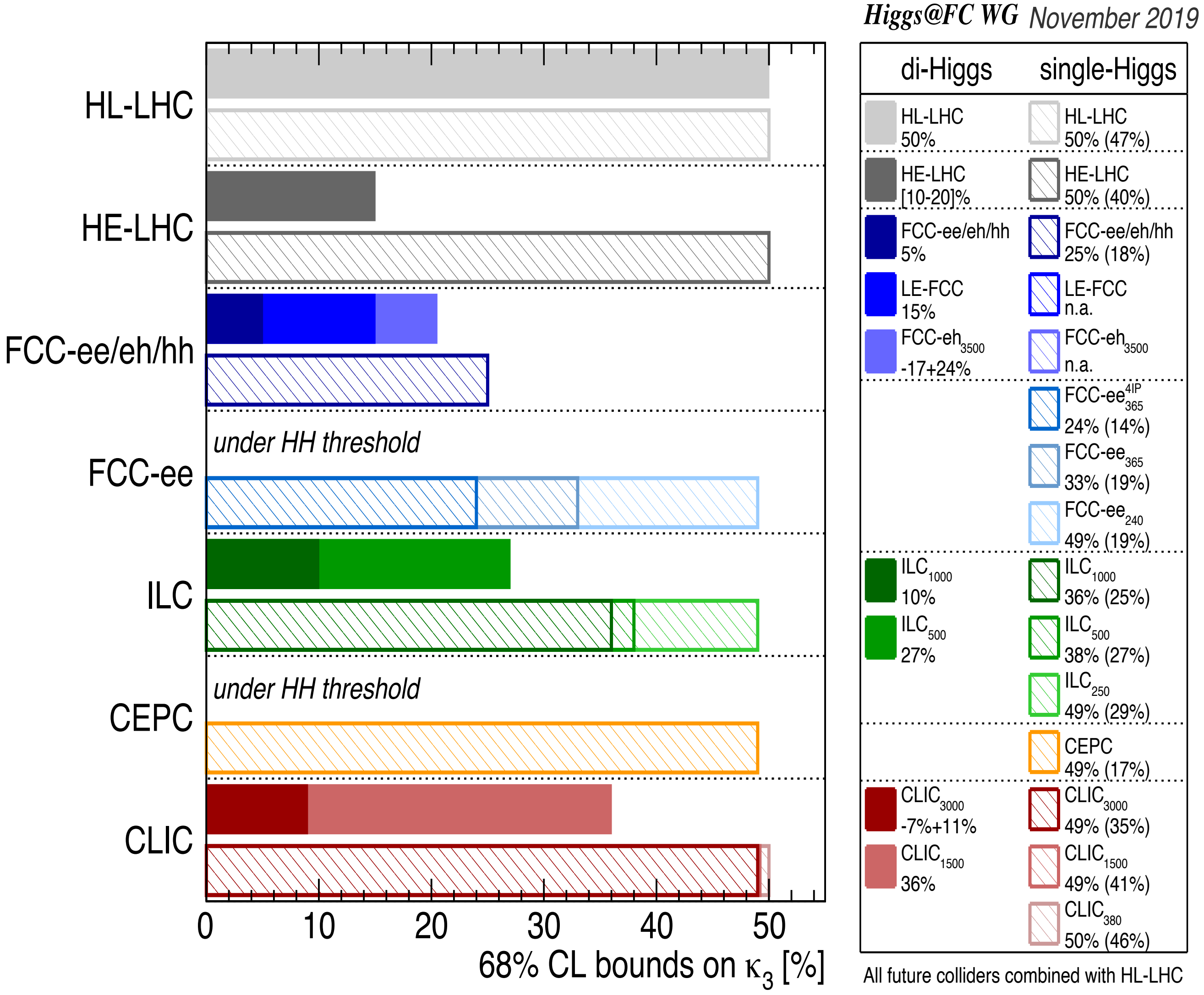
  ⇛ access to distribution (m_{hh})

  ⇛ discriminating power c_3 vs. c_{2t} vs c_g

Higgs Self-Coupling

ECFA Higgs study group '19

Higgs@FC WG November 2019



All future colliders combined with HL-LHC

1

Don't need to reach HH threshold
to have access to h^3.
Z-pole run is very important
if the HH threshold cannot be reached

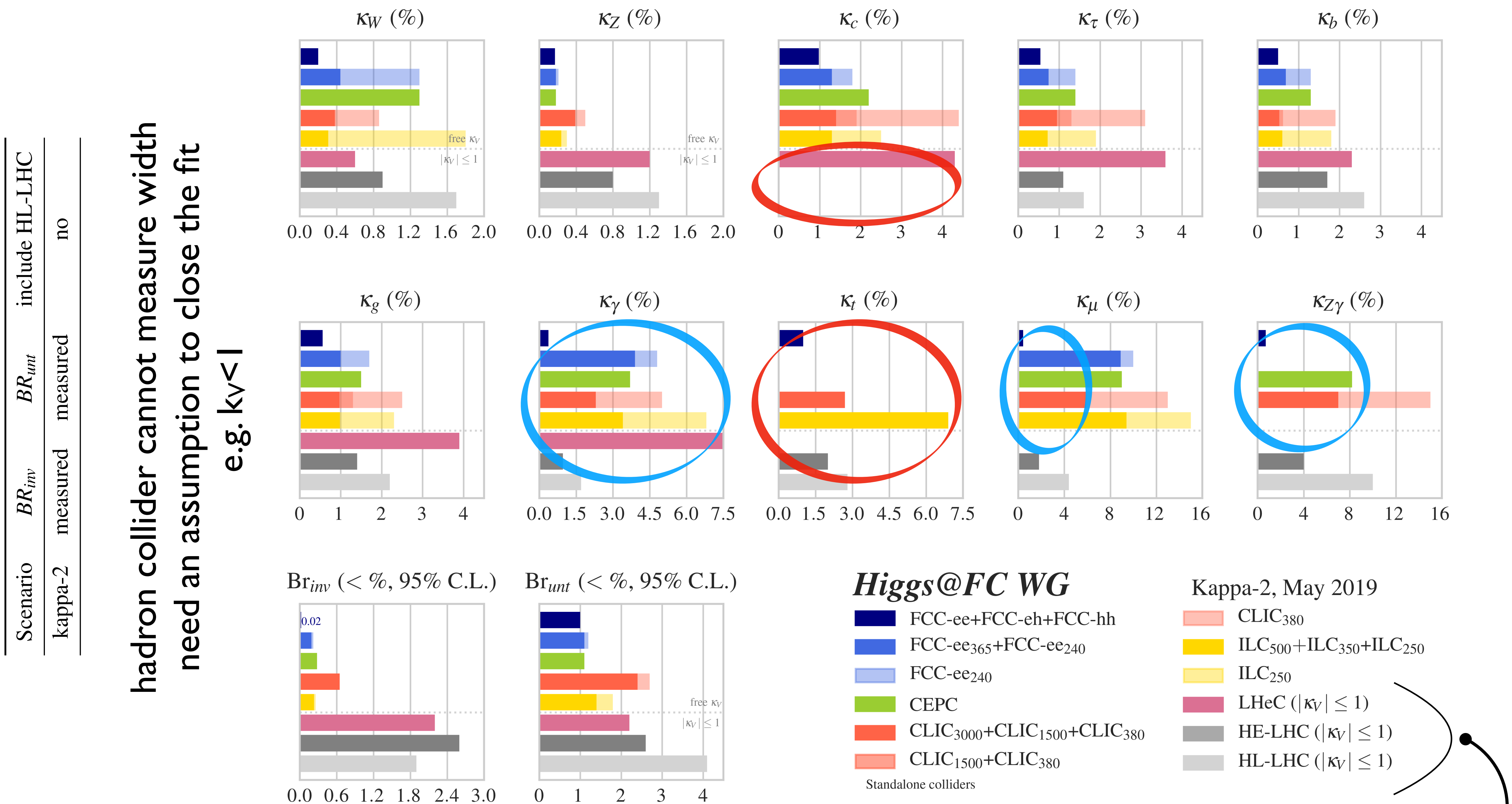
2

The determination of h^3 at FCC-hh
relies on HH channel,
for which FCC-ee is of little direct help.
But the extraction of h^3
requires precise knowledge of y_t.
1% $y_t \leftrightarrow$ 5% h^3
Precision measurement of y_t needs ee

50% sensitivity: establish that $h^3 \neq 0$ at 95%CL
20% sensitivity: 5σ discovery of the SM h^3 coupling
5% sensitivity: getting sensitive to quantum corrections to Higgs potential

Higgs Fit (Future Collider Alone)

ECFA Higgs study group ‘19

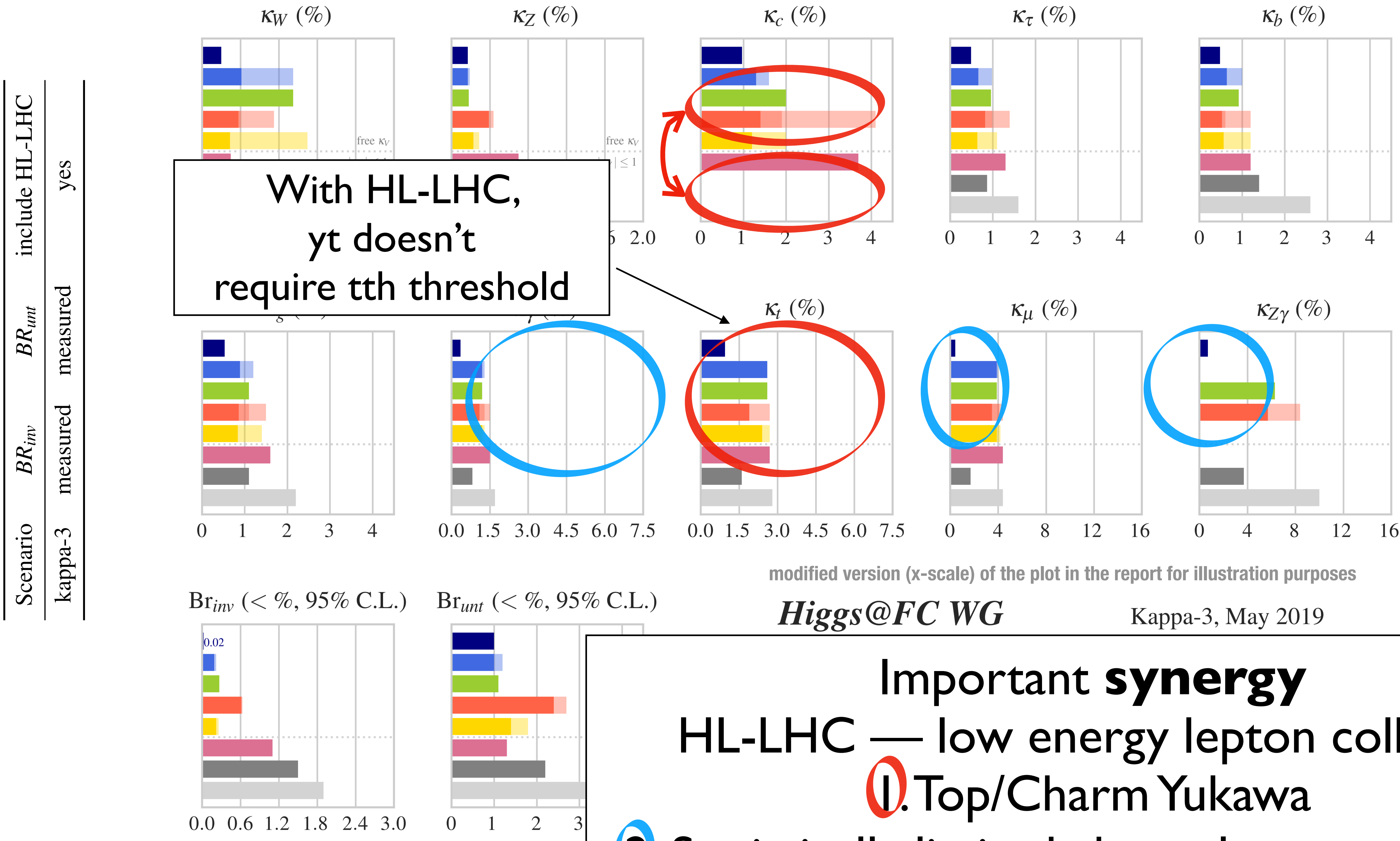


hadron collider cannot measure width
need an assumption to close the fit
e.g. κ_V<1

assumption needed for the fit to
close at hadron machines

Higgs Fit (HL-LHC+Future Collider)

ECFA Higgs study group '19



modified version (x-scale) of the plot in the report for illustration purposes

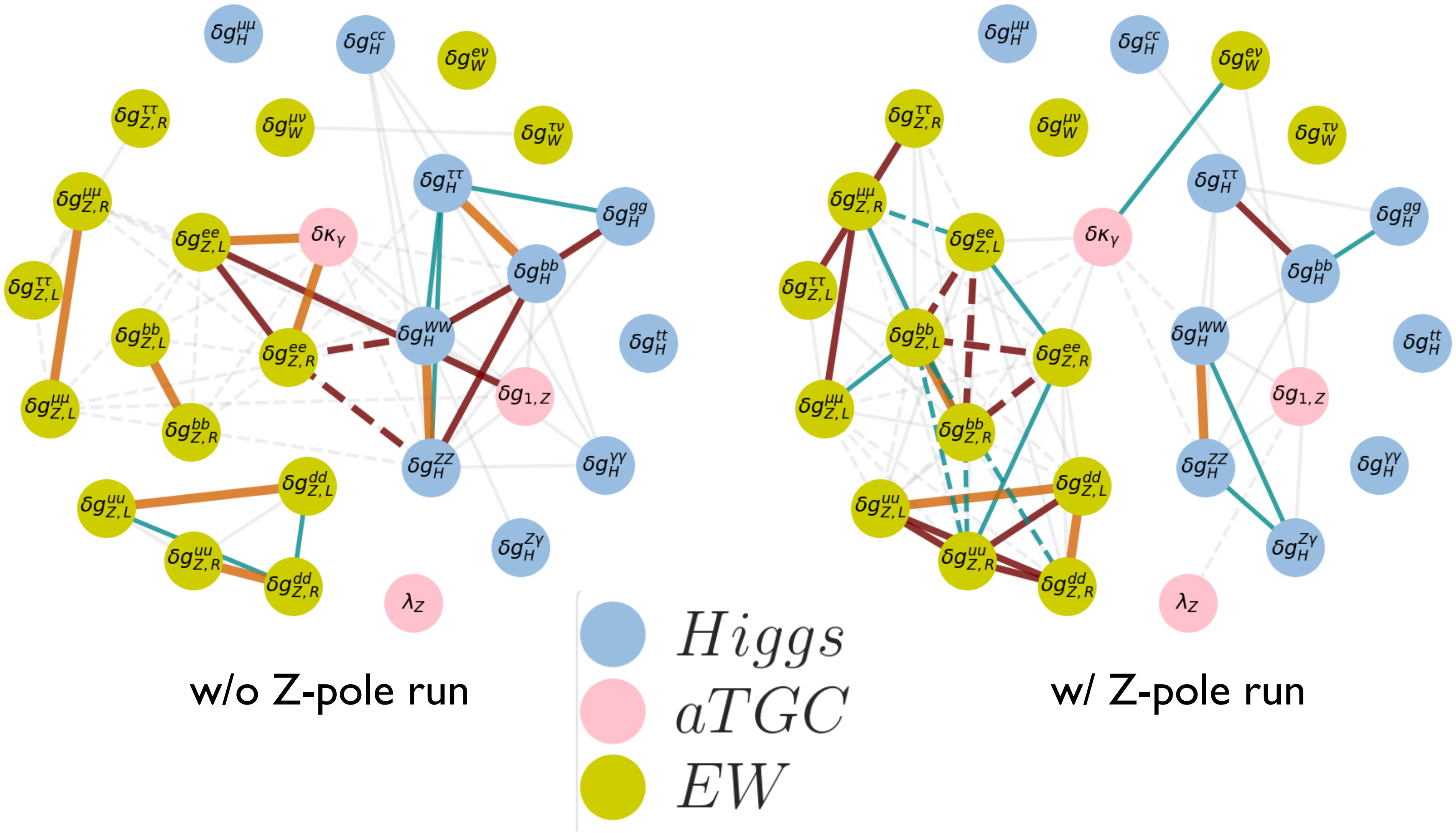
With HL-LHC,
yt doesn't
require tth threshold

Important **synergy**
HL-LHC — low energy lepton colliders
1. Top/Charm Yukawa
2. Statistically limited channels: γγ, mumu, Zγ

Synergy ee(M_Z)-ee(M_H)

J. De Blas et al. 1907.04311

interplay of runs at different energies change the correlation pattern



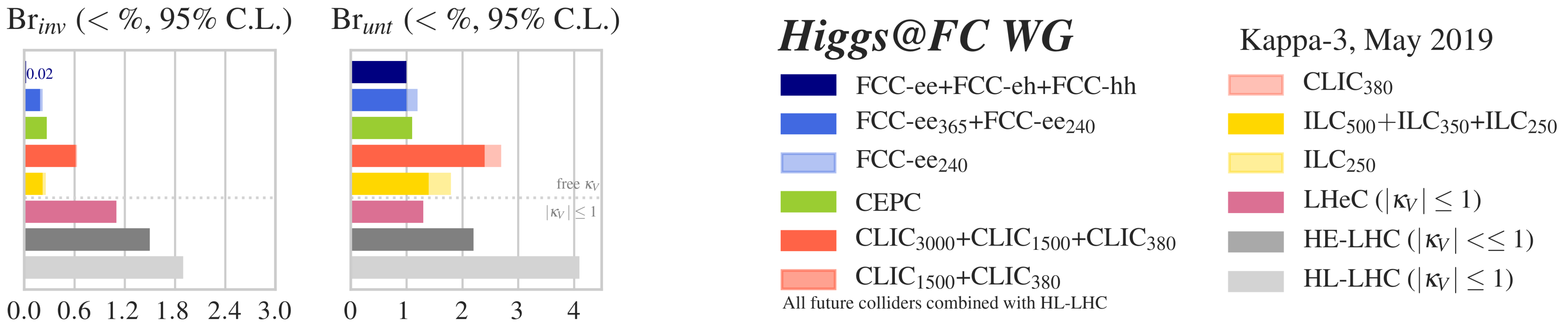
w/o Z-pole run

w/ Z-pole run

minimising correlations essential to lift flat directions in coupling fit
e.g. Higgs coupling sensitivity improves by 50% with new Z pole data

Synergy ee-hh-eh

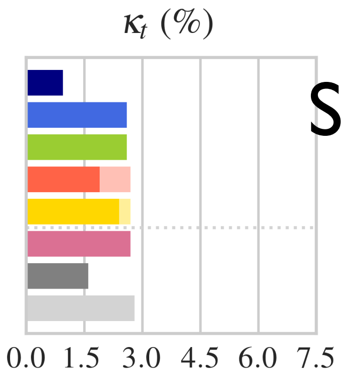
1



FCC-hh without ee could bound BR$_{inv}$ but it could say nothing about BR$_{unt}$

FCC-ee needed for absolute normalisation of Higgs couplings

2



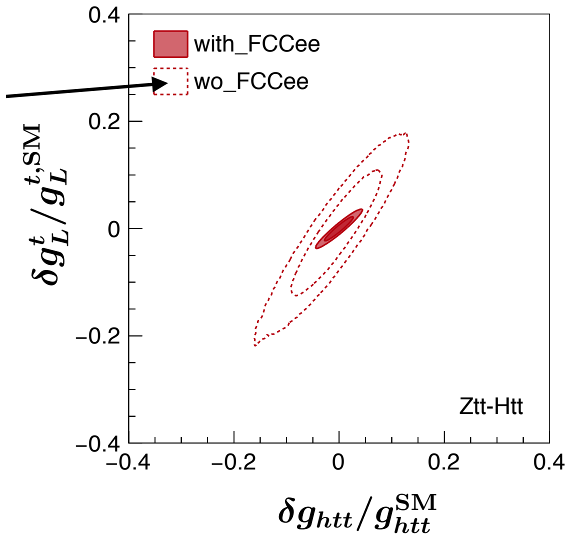
Mangano+ '15

FCC-hh is determining top Yukawa through ratio tth/ttZ

So extraction of top Yukawa relies on the knowledge of ttZ from FCC-ee

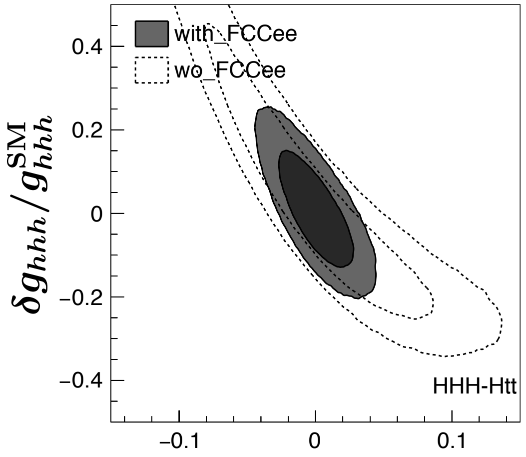
	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

uncertainty drops in ratio



3

Subsequently, the 1% sensitivity on tth is essential to determine h³ at O(5%) at FCC-hh



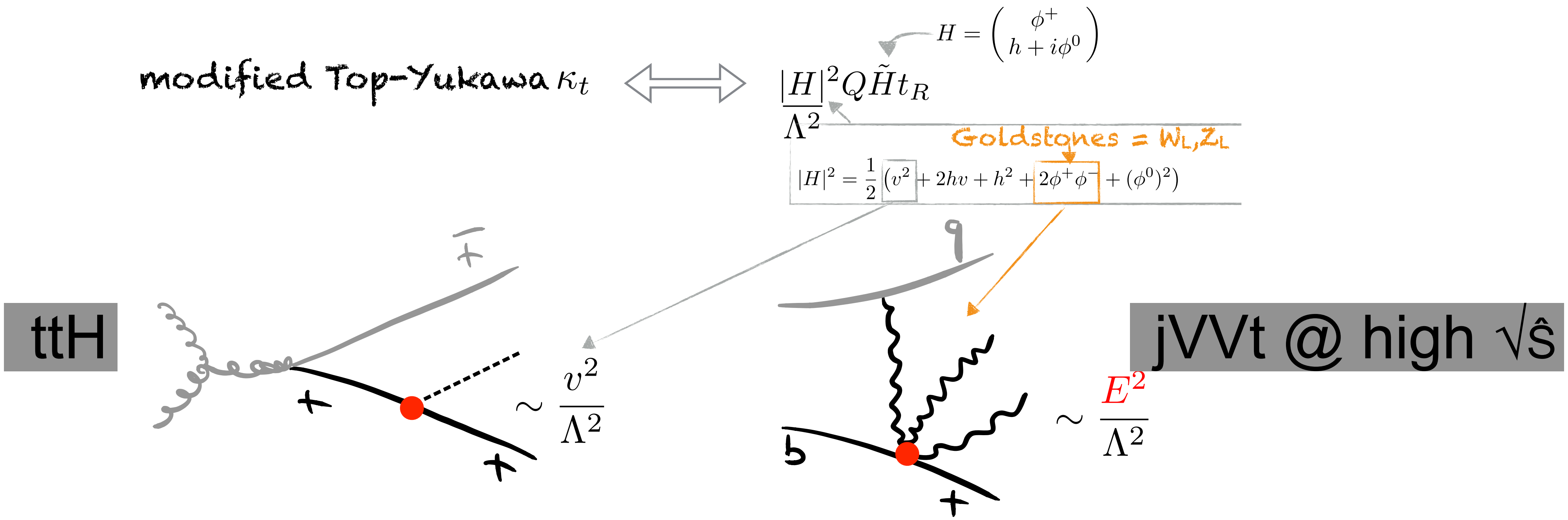
Plots by J. de Blas, '19

Synergy High-pT - Higgs Threshold

The global Higgs fit focused on inclusive measurements
They don't do justice to richness of kinematical distributions accessible
at high-energy hadronic machines

"Energy helps accuracy" — "Higgs couplings without the Higgs"

Riva @ Higgs
2020



Often the energy growth is cancelled in too inclusive observables.
Need to resurrect the interference by looking at angular and energy distributions

What are the measurements to perform at HL-LHC to be fully exploited later at HZ factory?

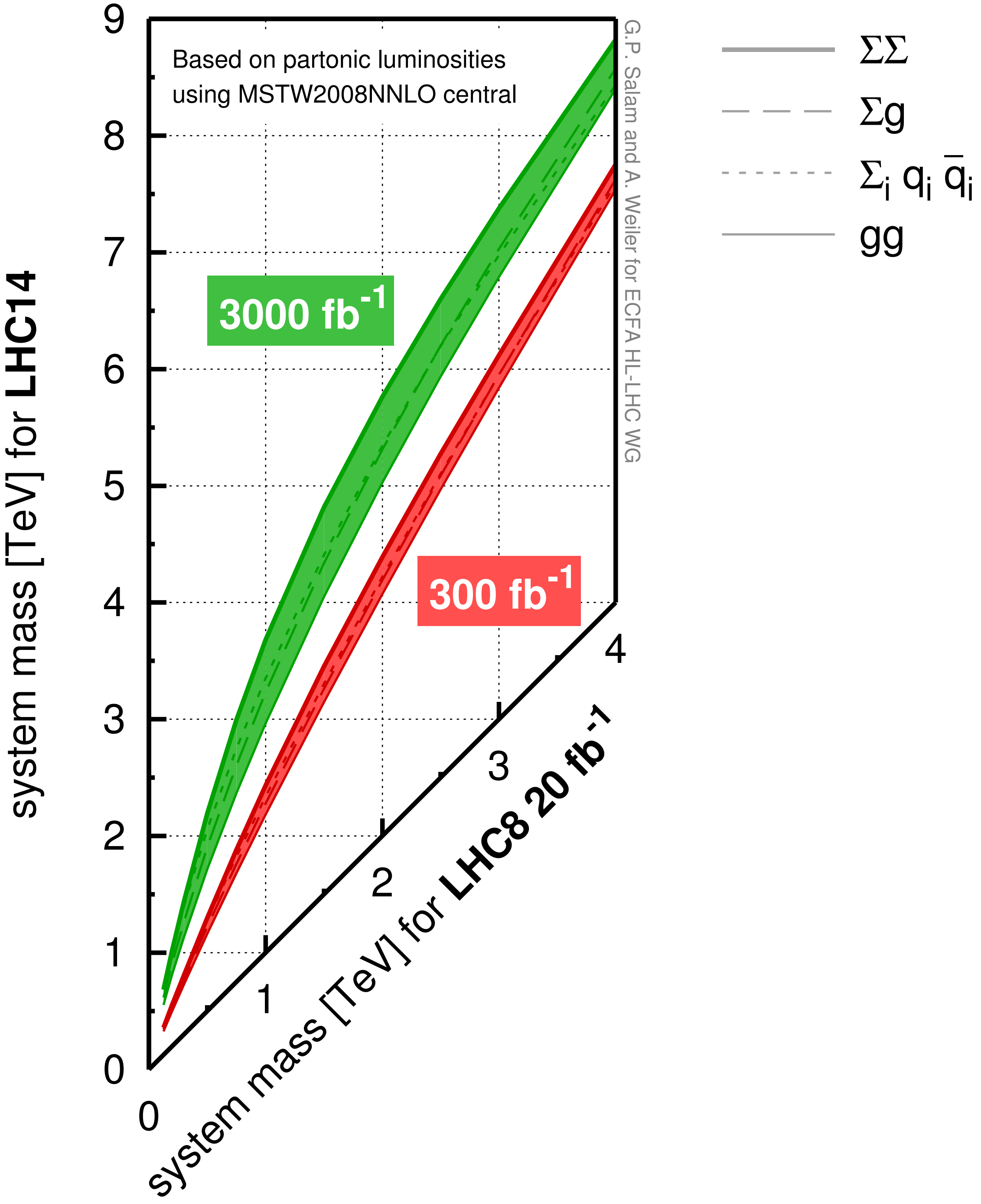
(ii) Exploration potential

— New Physics —

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

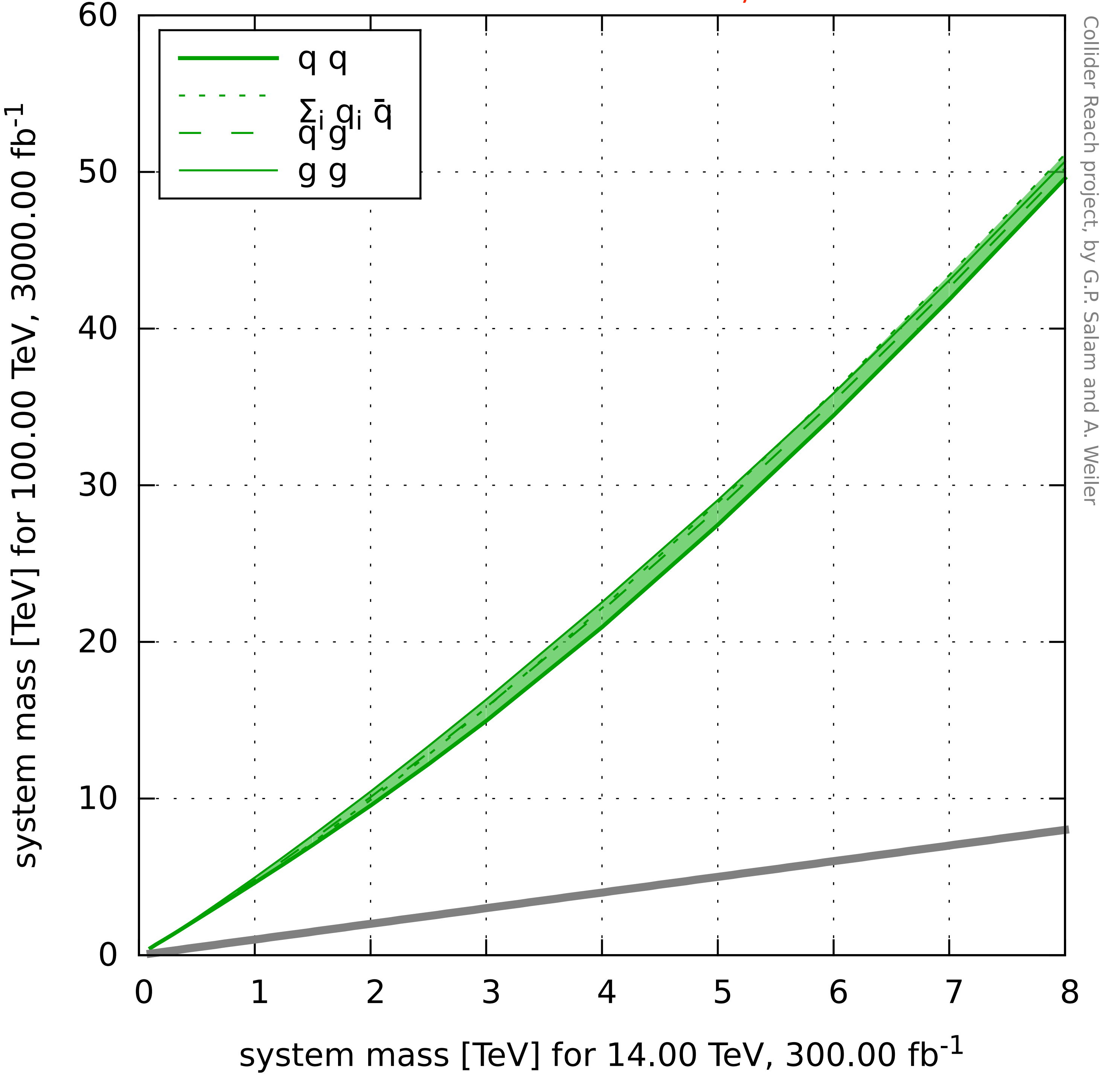
The power of PDF

Direct exploration of an unexplored energy territory



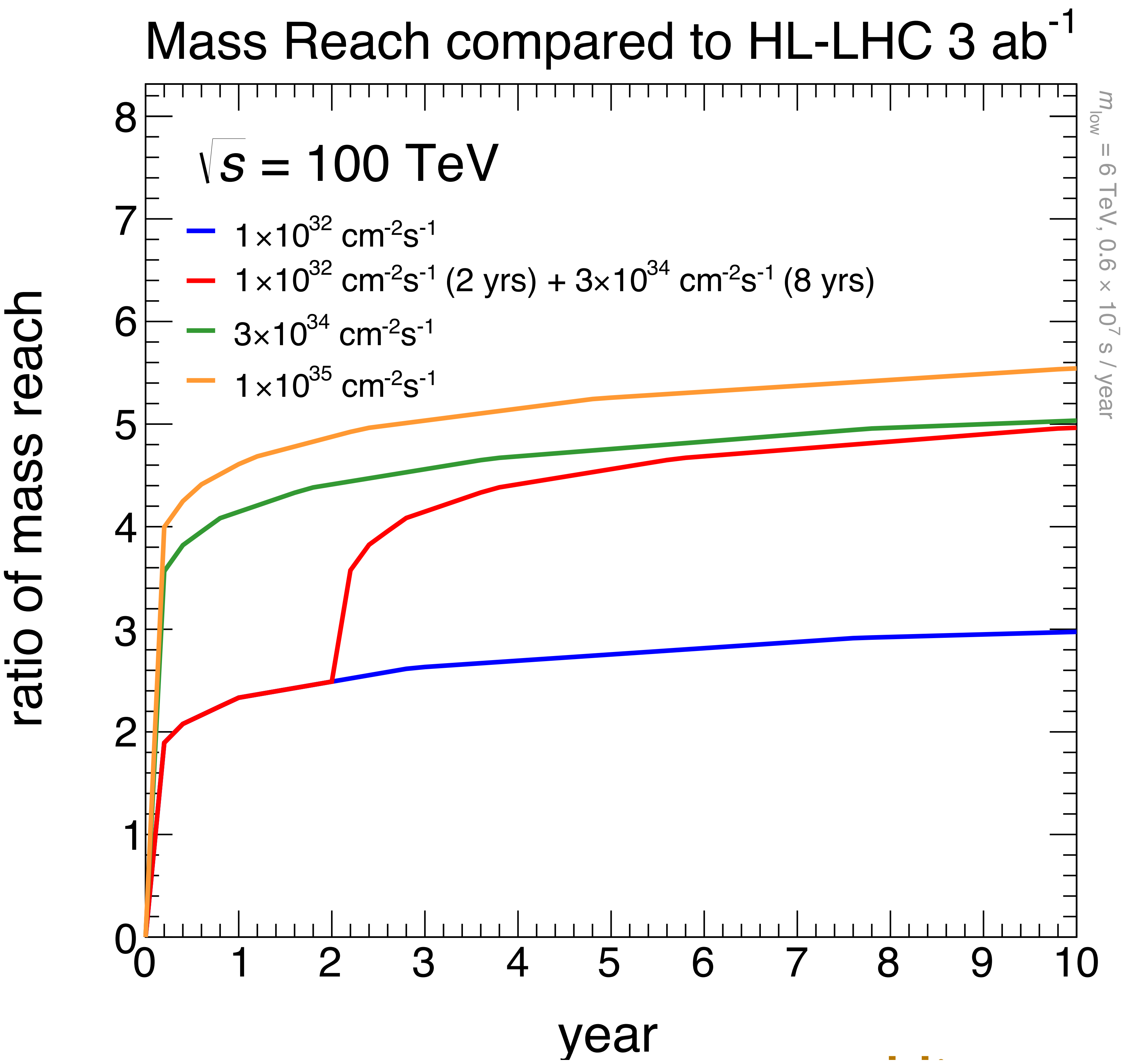
LHC$_{14}$/LHC$_8$:
mass reach x O(2)

Salam & Weiler “cern.ch/collider-reach” ’14



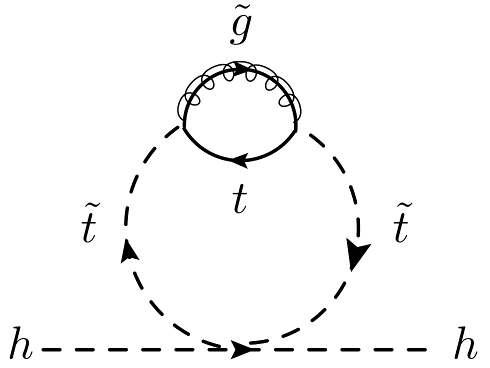
VHE-LHC$_{100}$/LHC$_{14}$:
mass reach x O(5)

The power of PDF

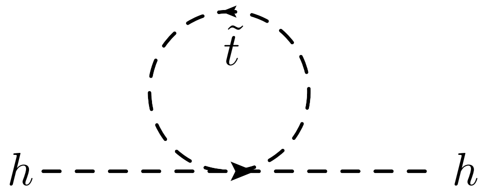


Hinchliffe, Kotwal, Mangano, Quigg, Wang ’15

I. Probing natural SUSY

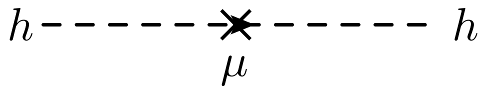


$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi} m_{gluino}^2 \left(\log \frac{\Lambda}{m_{gluino}}\right)^2$$



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

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

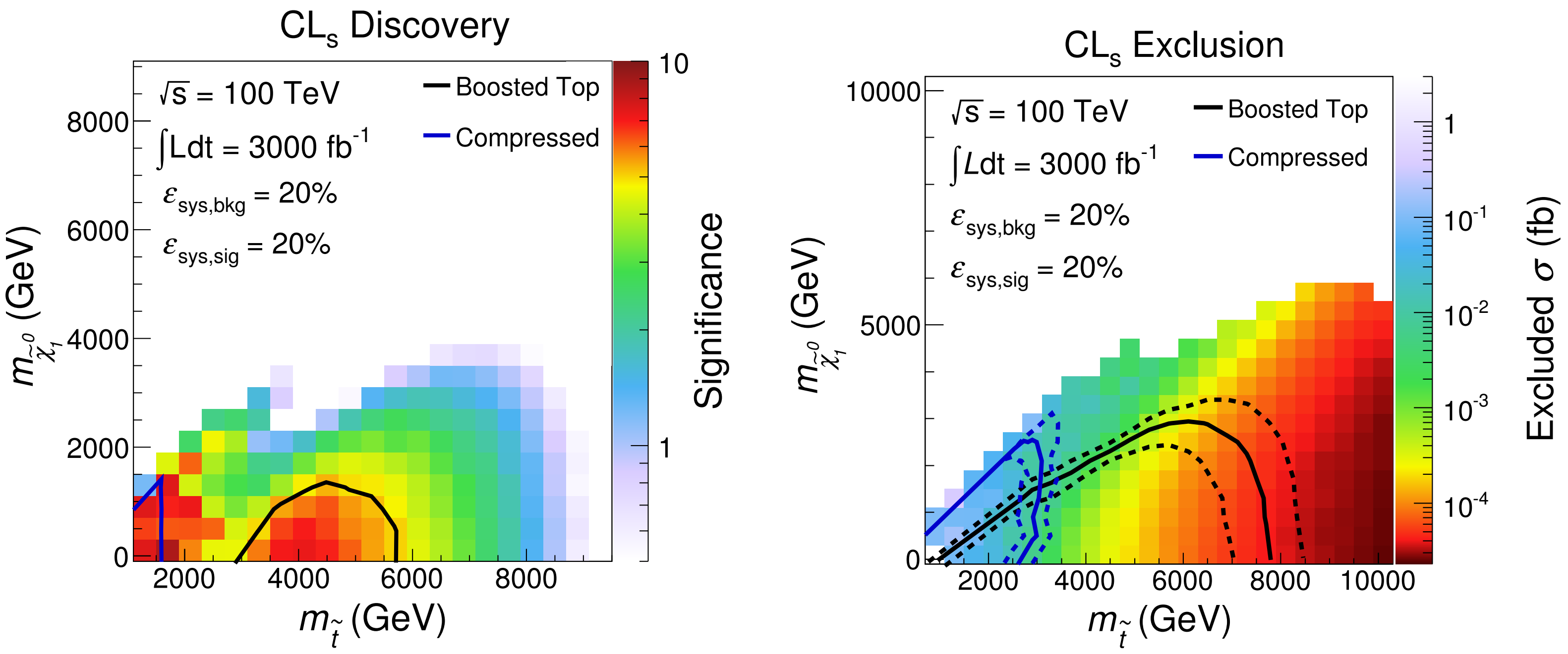


Fig. 12: Left: Discovery potential and Right: Projected exclusion limits for 3000 fb^{-1} of total integrated luminosity at $\sqrt{s} = 100$ TeV. The solid lines show the expected discovery or exclusion obtained from the boosted top (black) and compressed spectra (blue) searches. In the boosted regime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

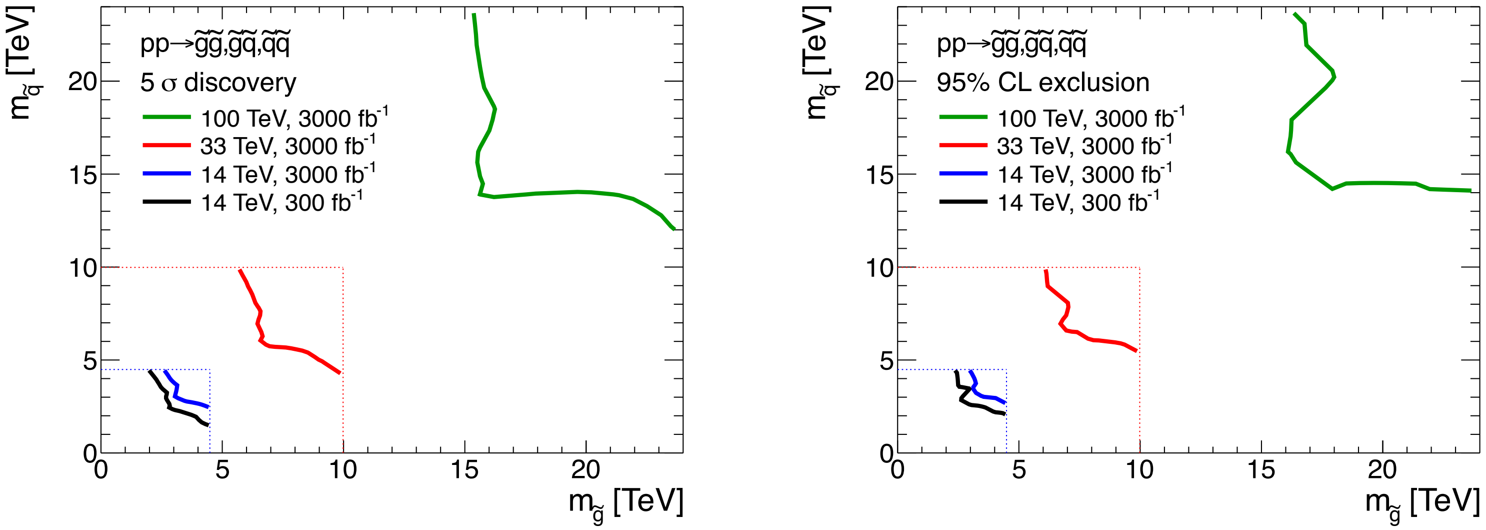


Fig. 16: Results for the gluino-squark-neutralino model. The neutralino mass is taken to be 1 GeV. The left [right] panel shows the $5\,\sigma$ discovery reach [95% CL exclusion] for the four collider scenarios studied here. A 20% systematic uncertainty is assumed and pile-up is not included.

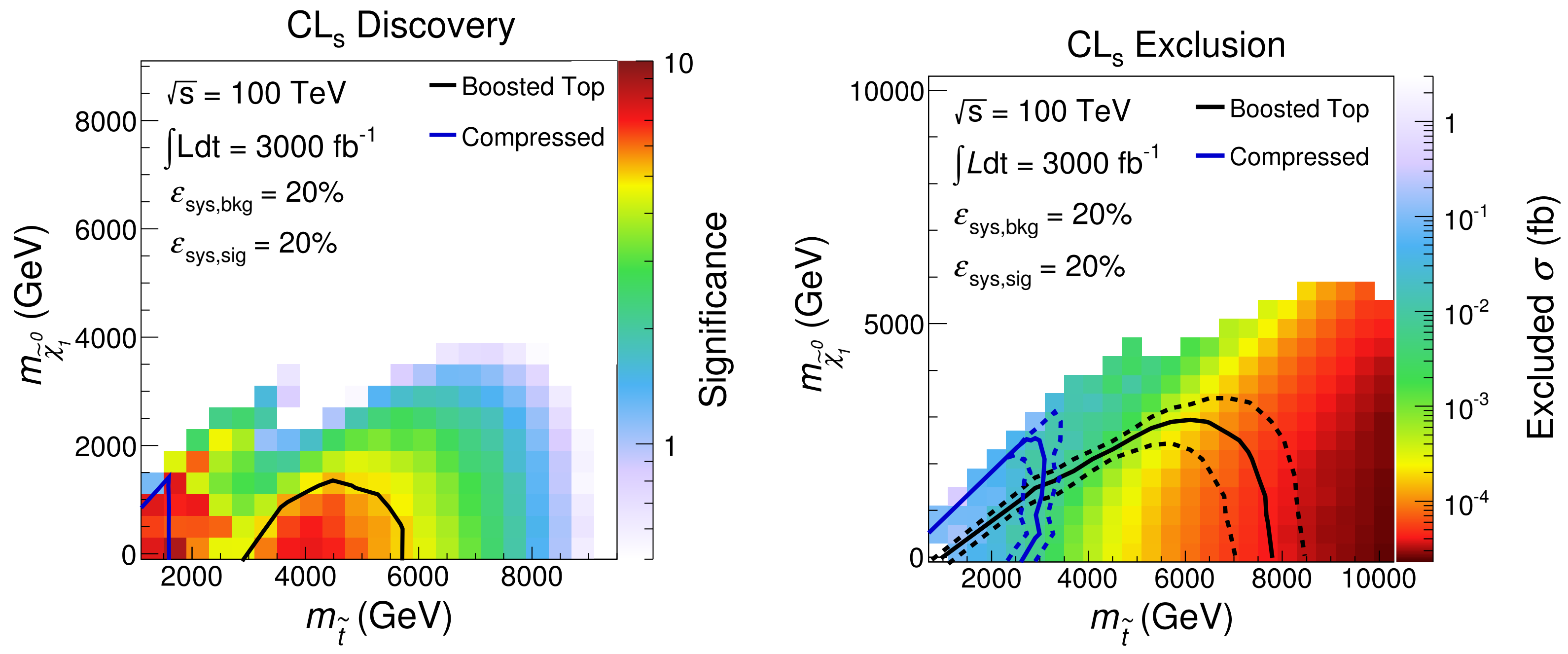


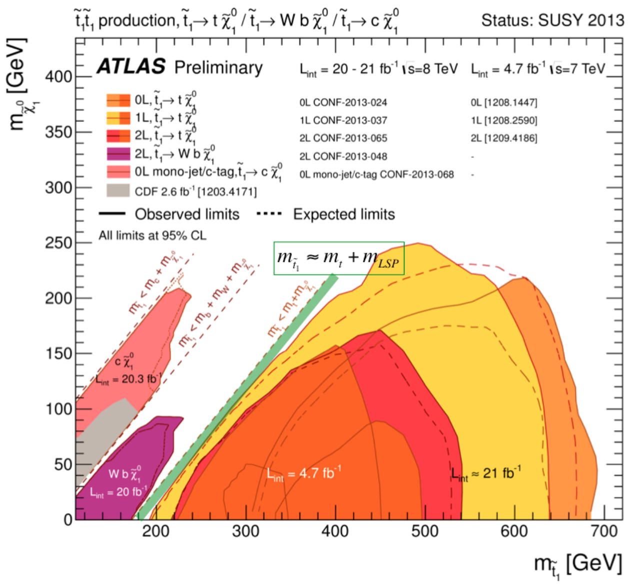
Fig. 12: Left: Discovery potential and Right: Projected exclusion limits for 3000 fb^{-1} of total integrated luminosity at $\sqrt{s} = 100$ TeV. The solid lines show the expected discovery or exclusion obtained from the boosted top (black) and compressed spectra (blue) searches. In the boosted regime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

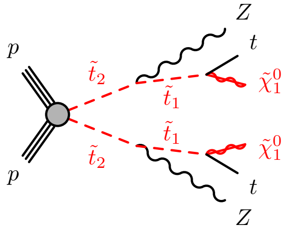
I. Natural SUSY: beyond standard searches

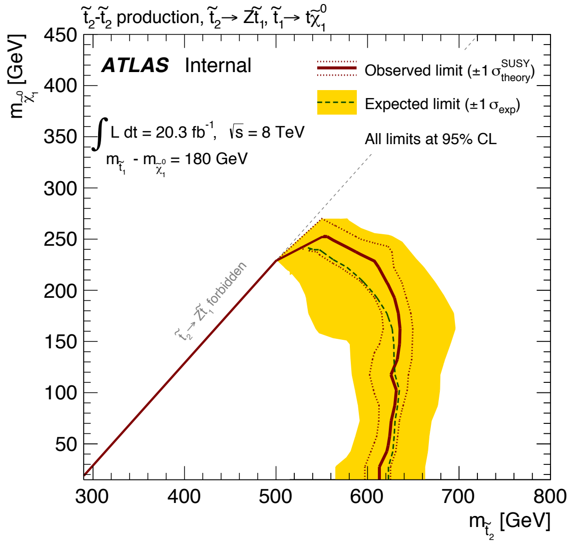
Searching for light stop from heavy stop decay

~ RUN 1 ~



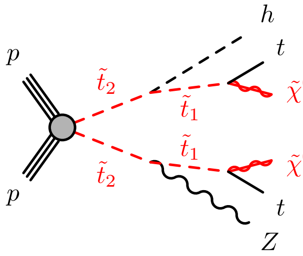
- 2012 (20 fb^{-1}): stops searches based on $\tilde{t}_1\tilde{t}_1$ production, with $\tilde{t}_1\to t\tilde{\chi}^0_1$ or $\tilde{t}_1\to b\tilde{\chi}^\pm_1$
- No sensitivity for $\tilde{t}_1\to t\tilde{\chi}^0_1$ with $m_{\tilde{t}_1}\gtrsim m_{\tilde{\chi}^0_1}+m_t$: very similar to SM $t\bar{t}$
- **[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})

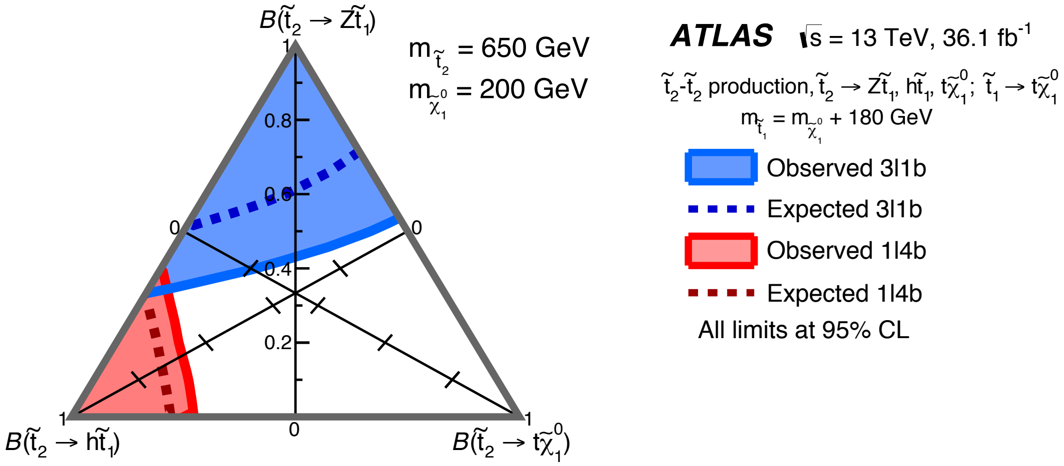




~ RUN 2 ~

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

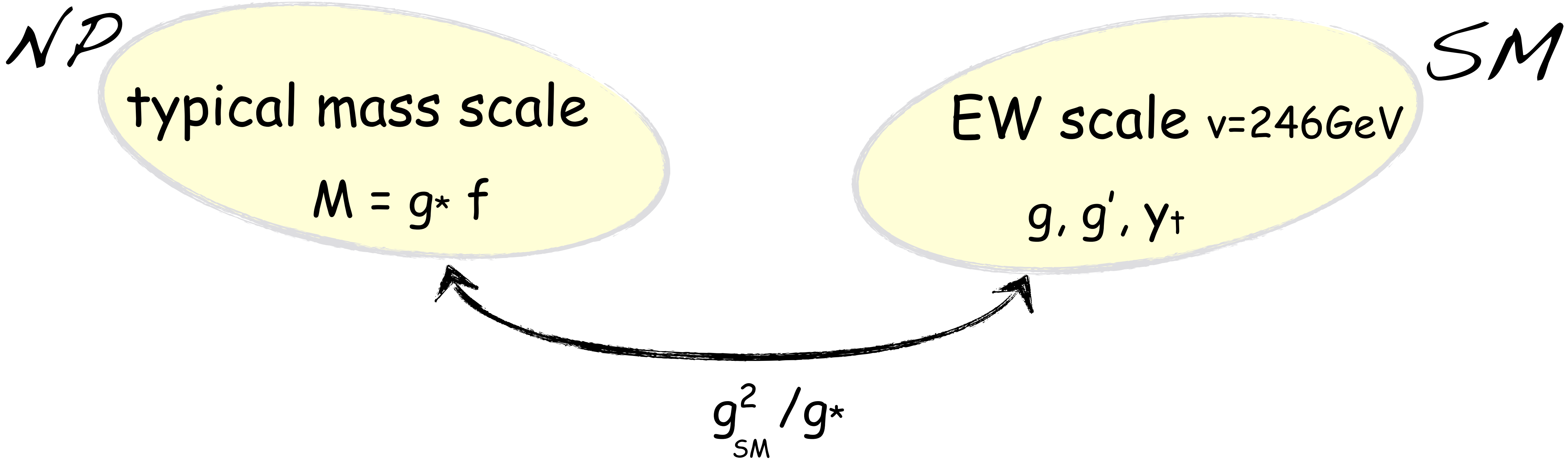




X. Poveda @ DESY'17

II. Vector resonances

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



NP

typical mass scale

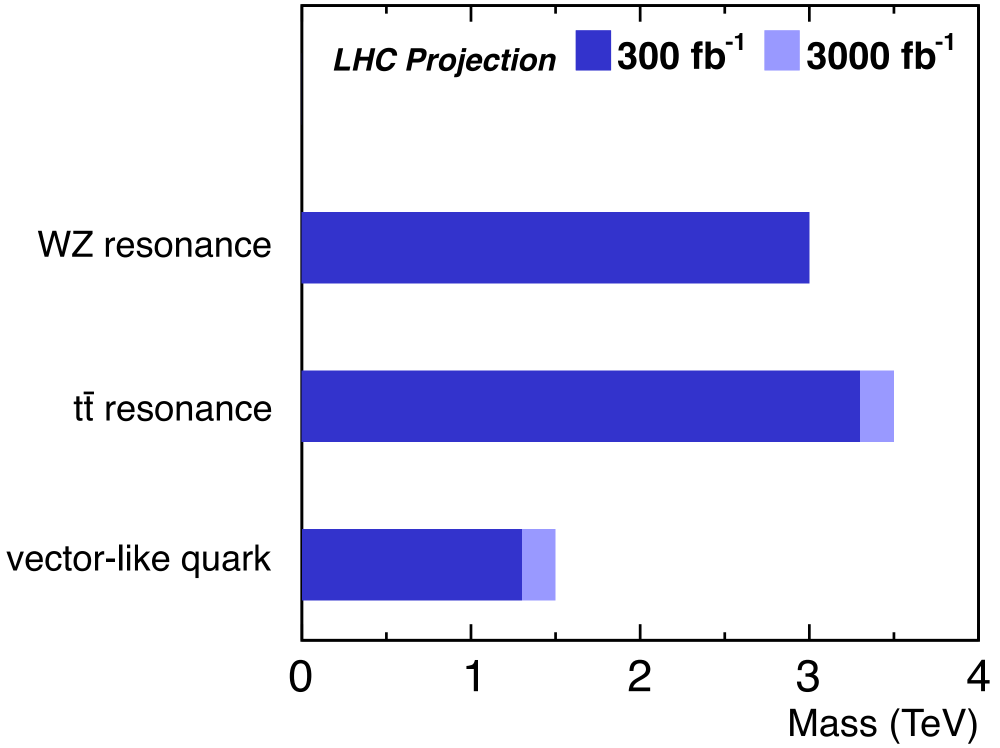
$M = g_* f$

SM

EW scale v=246GeV

g, g', y_t

g_{SM}^2/g_*



LHC direct search

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

Which one is doing best?
it depends on value of g_*

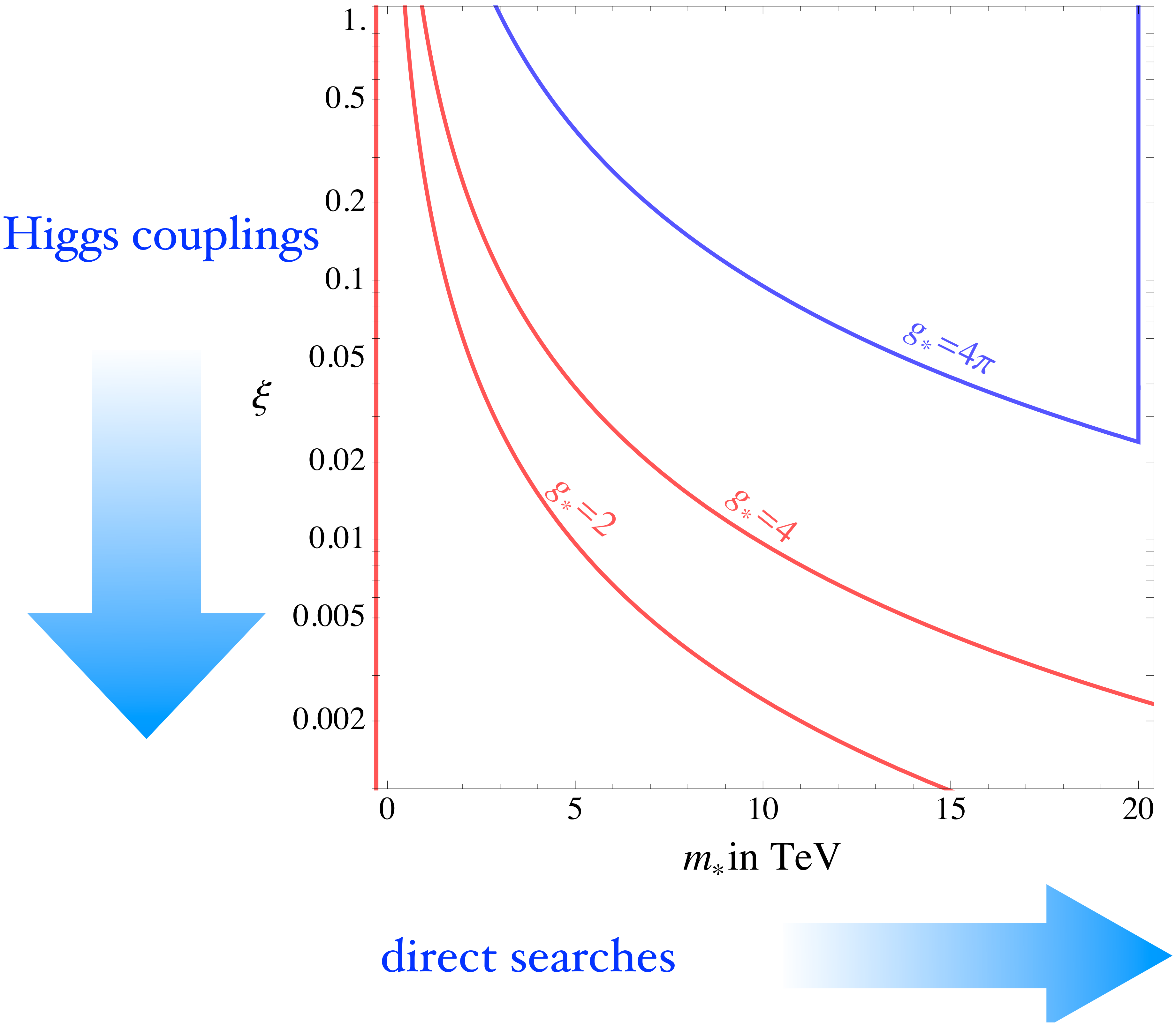
II. Vector resonances

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

Mass reach:

a deviation in Higgs couplings also teaches us on the maximum mass scale to search for!

e.g. 10% deviation ⇛ $m_V < 10$TeV i.e. resonance within the reach of FCC-hh



Rattazzi, BSM@100TeV, CERN '14

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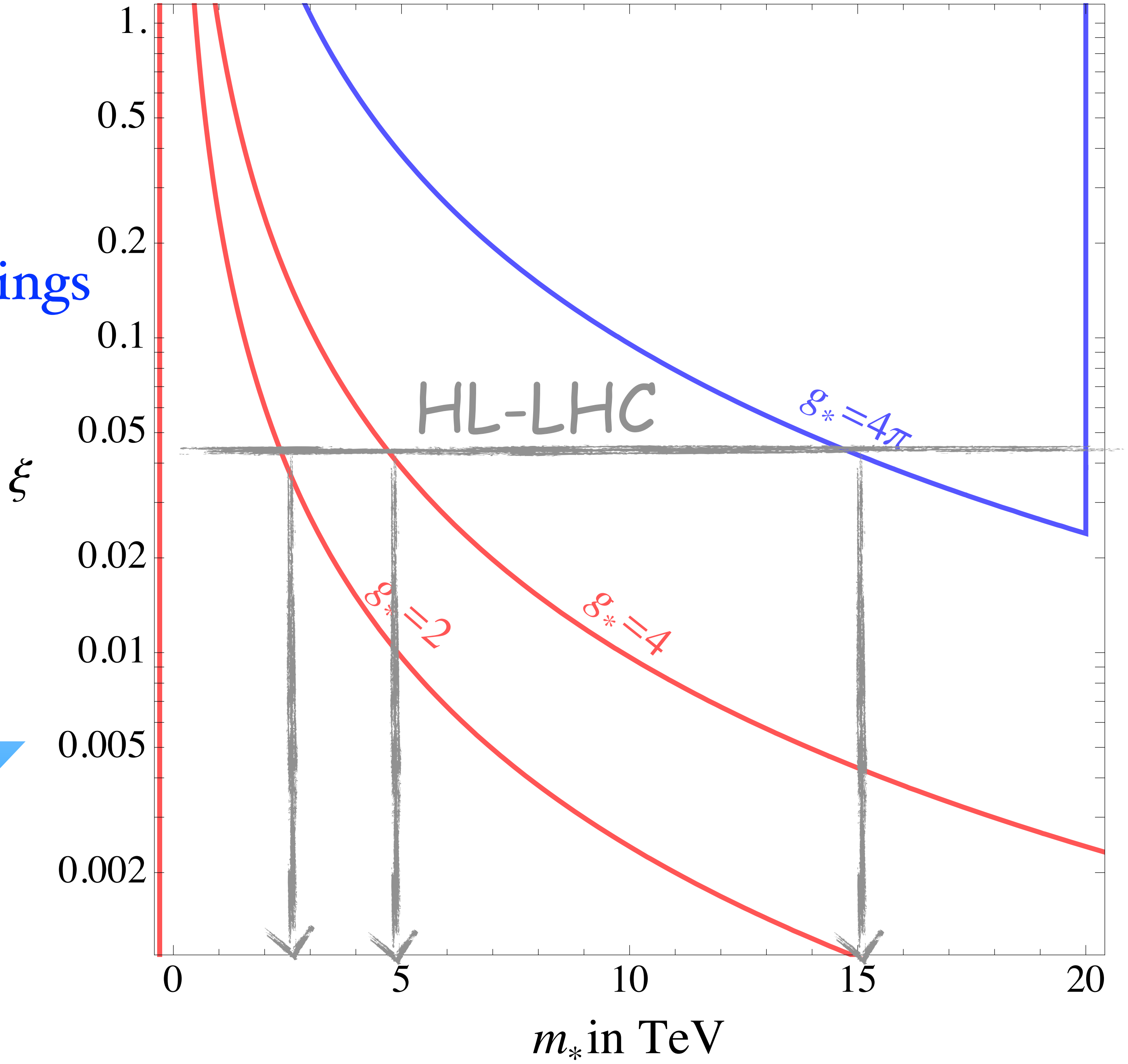
Higgs couplings



direct searches

Rattazzi, BSM@100TeV, CERN '14

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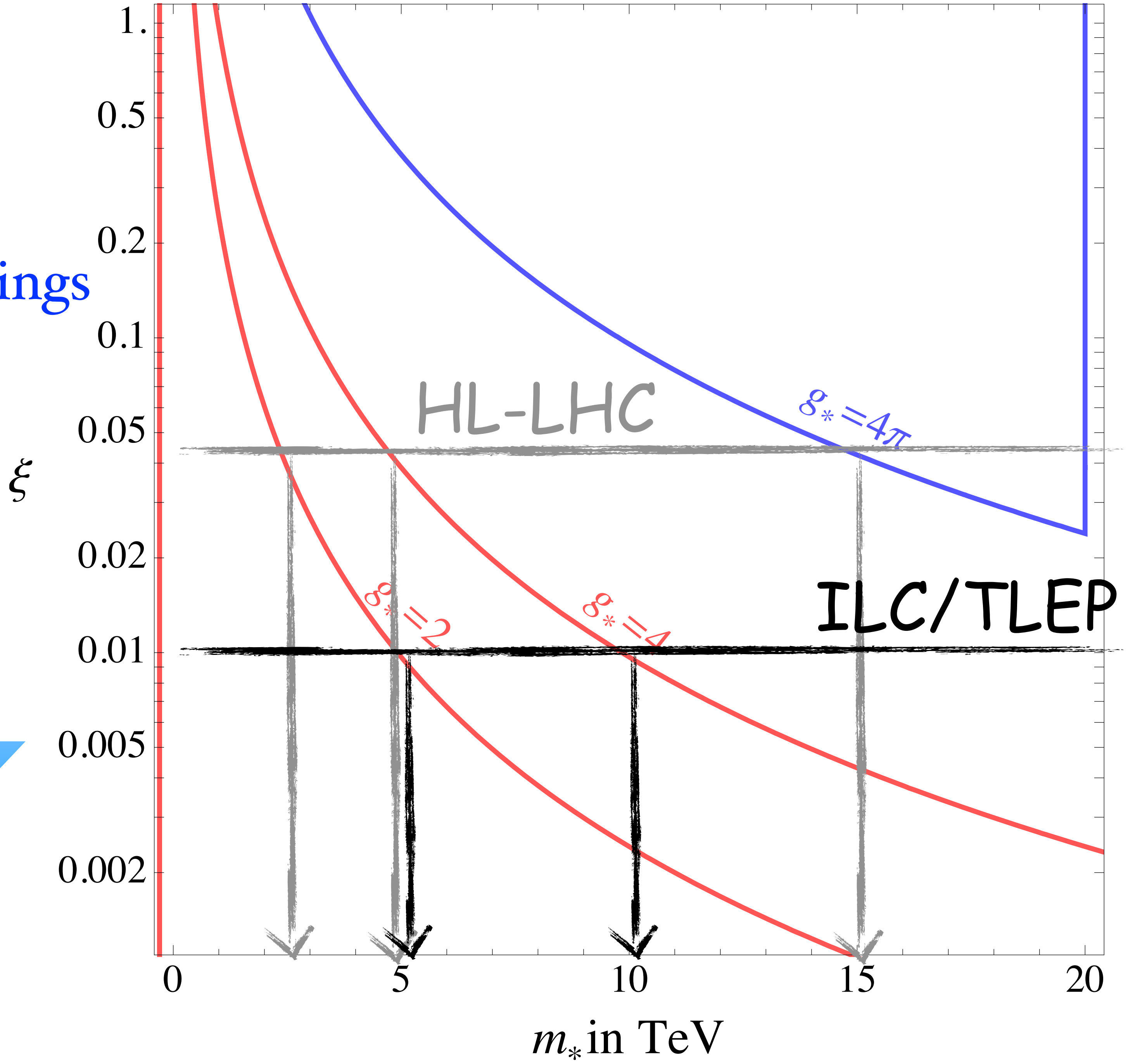

direct searches

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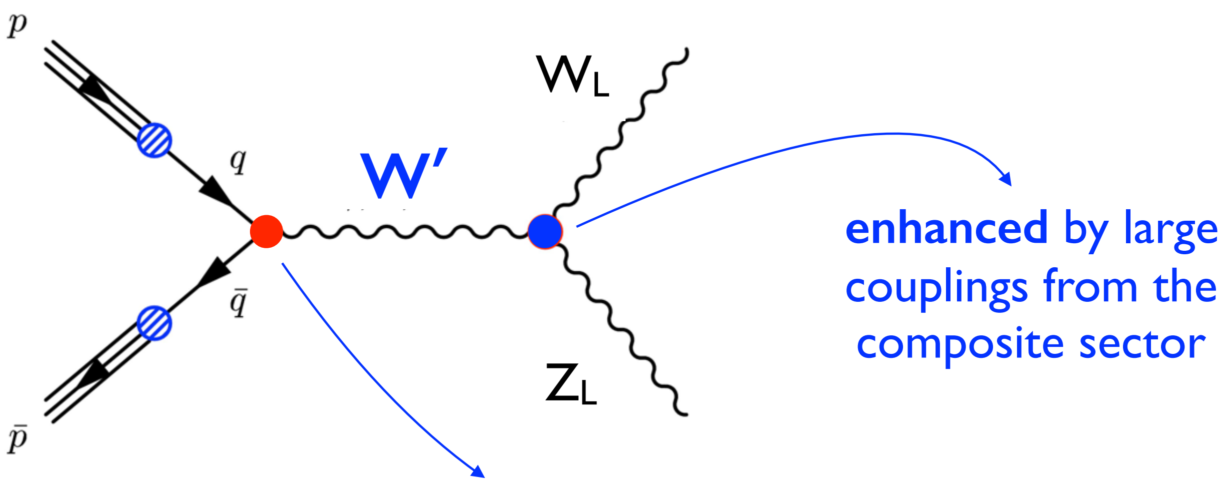
Torre, Thamm, Wulzer '15

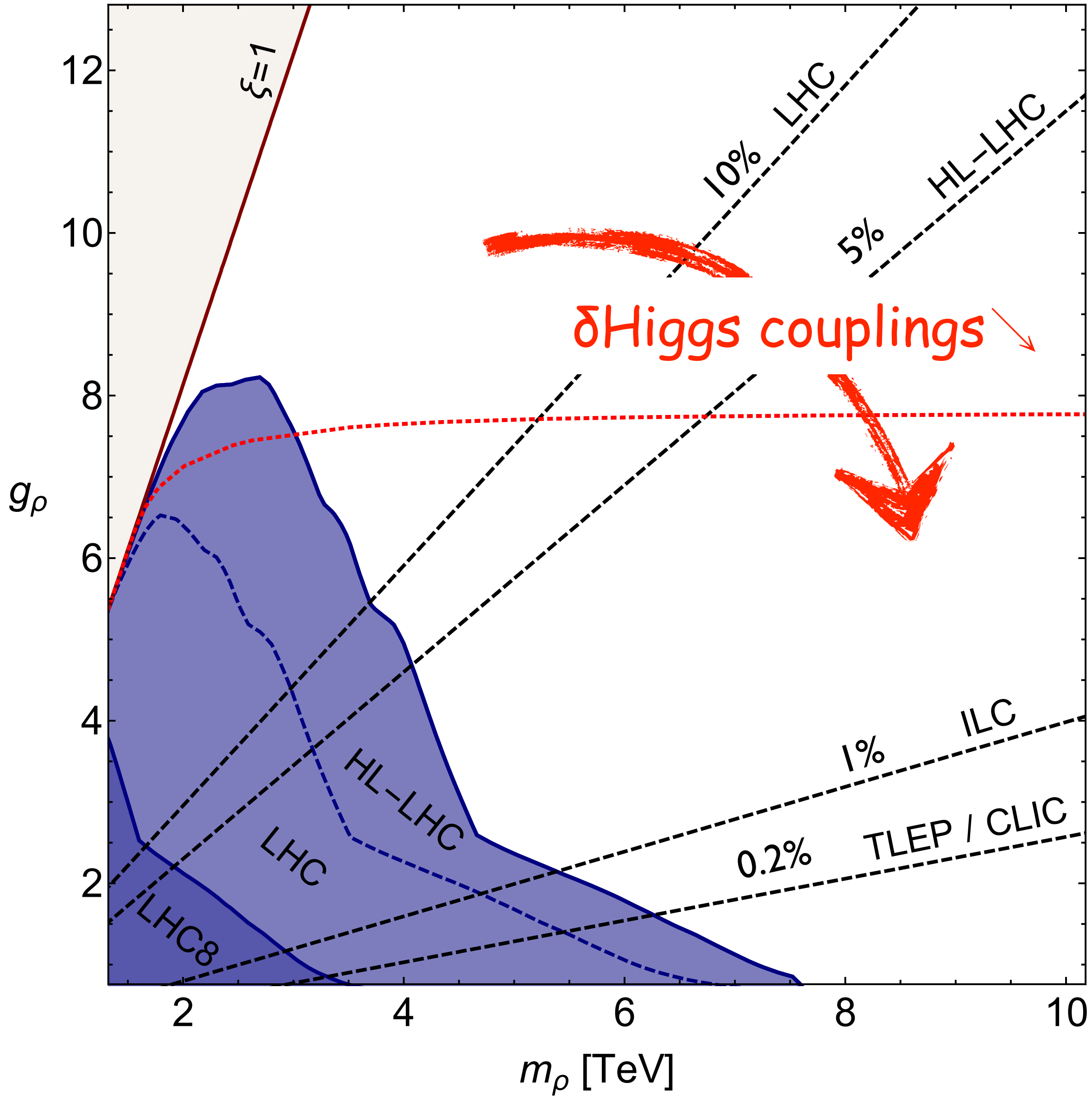


enhanced by large couplings from the composite sector

suppressed by large couplings from the composite sector

Collider	Energy	Luminosity	ξ $[1\sigma]$
LHC	14 TeV	300 fb^{-1}	$6.6-11.4\times10^{-2}$
LHC	14 TeV	3 ab^{-1}	$4-10\times10^{-2}$
ILC	250 GeV + 500 GeV	250 fb^{-1} 500 fb^{-1}	4.8-7.8 $\times10^{-3}$
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	500 fb^{-1} 1.5 ab^{-1} 2 ab^{-1}	2.2 $\times10^{-3}$
TLEP	240 GeV + 350 GeV	10 ab^{-1} 2.6 ab^{-1}	2 $\times10^{-3}$

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



di-lepton searches ← → di-boson searches

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

II. Vector resonances

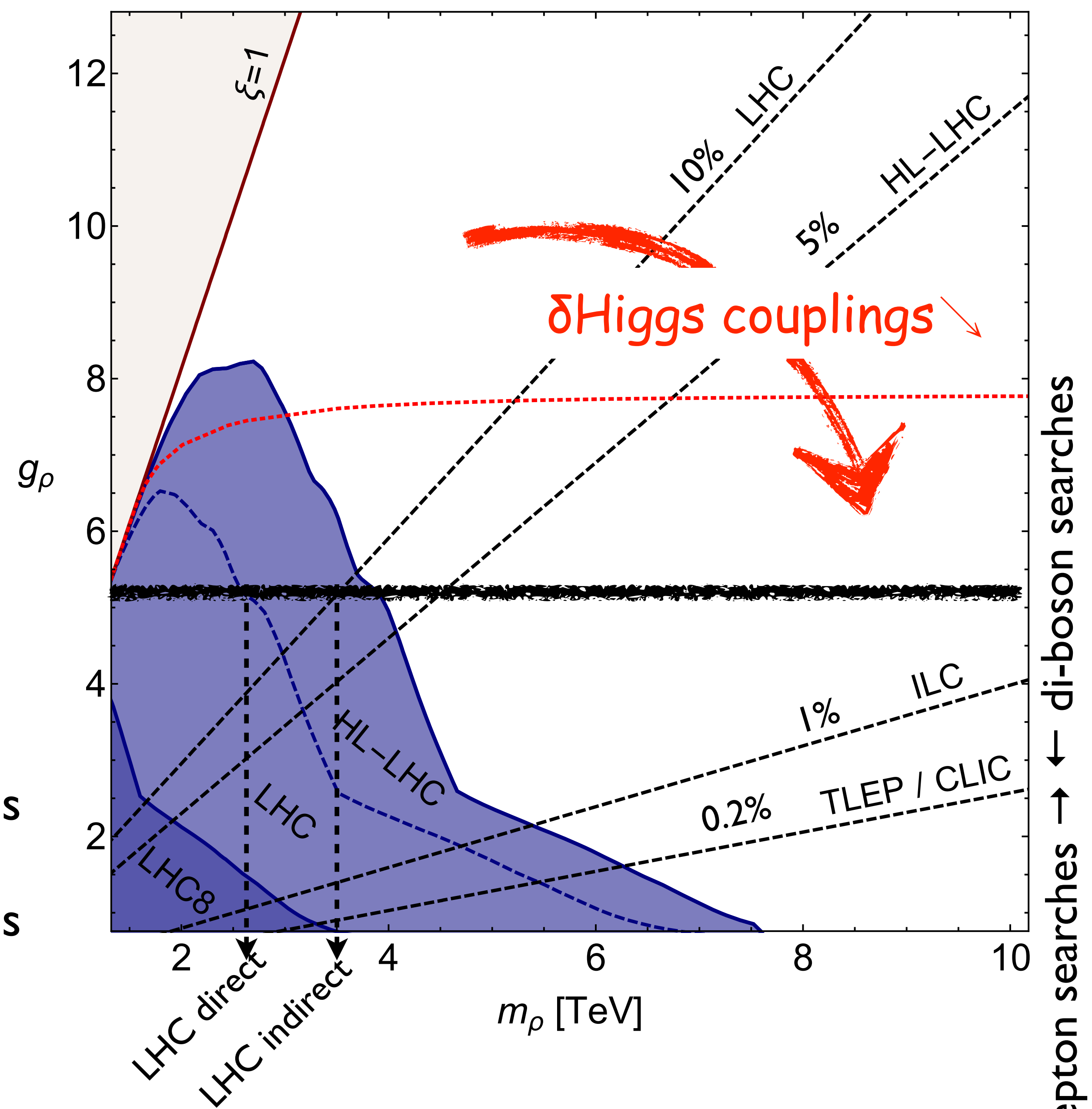
Precision /indirect searches (high lumi.) vs. direct searches (high energy)

Torre, Thamm, Wulzer ’15

- **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

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



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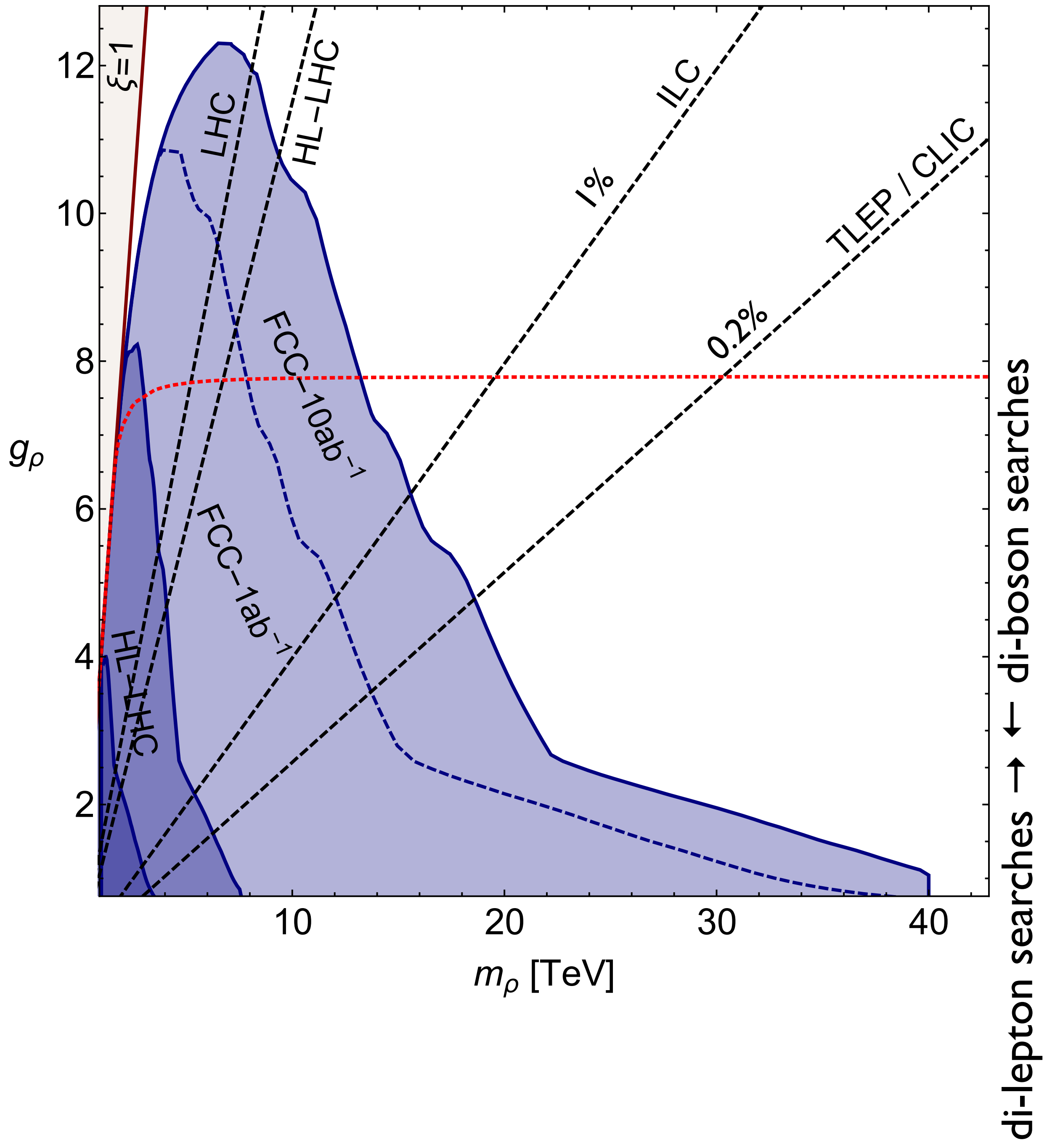

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III. Fermionic top partners

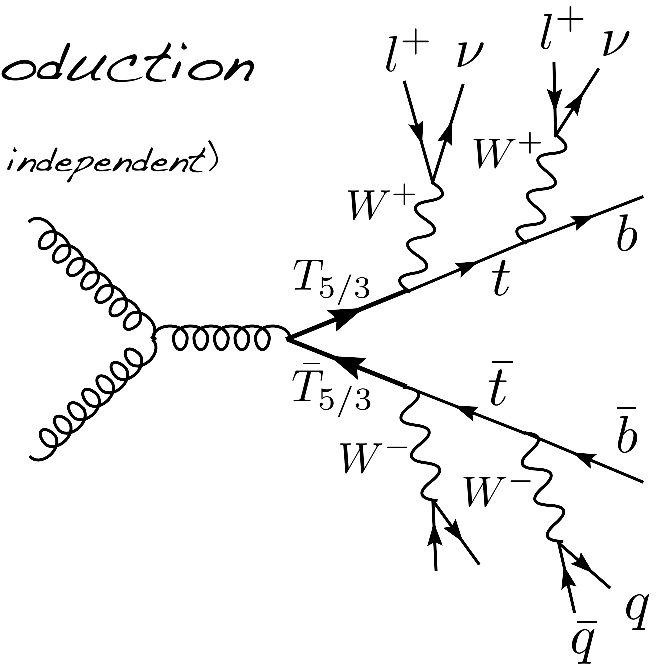
(aka vector-like quarks)

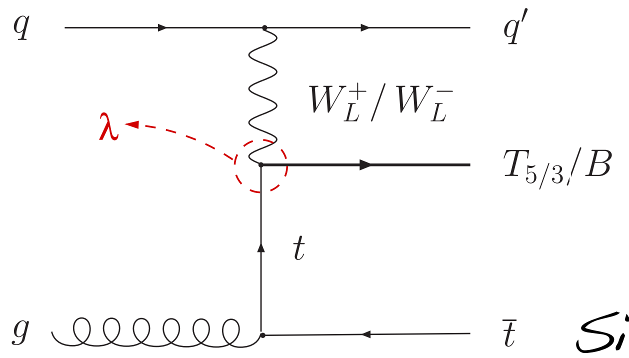
Search in same-sign dilepton events

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

Pair production

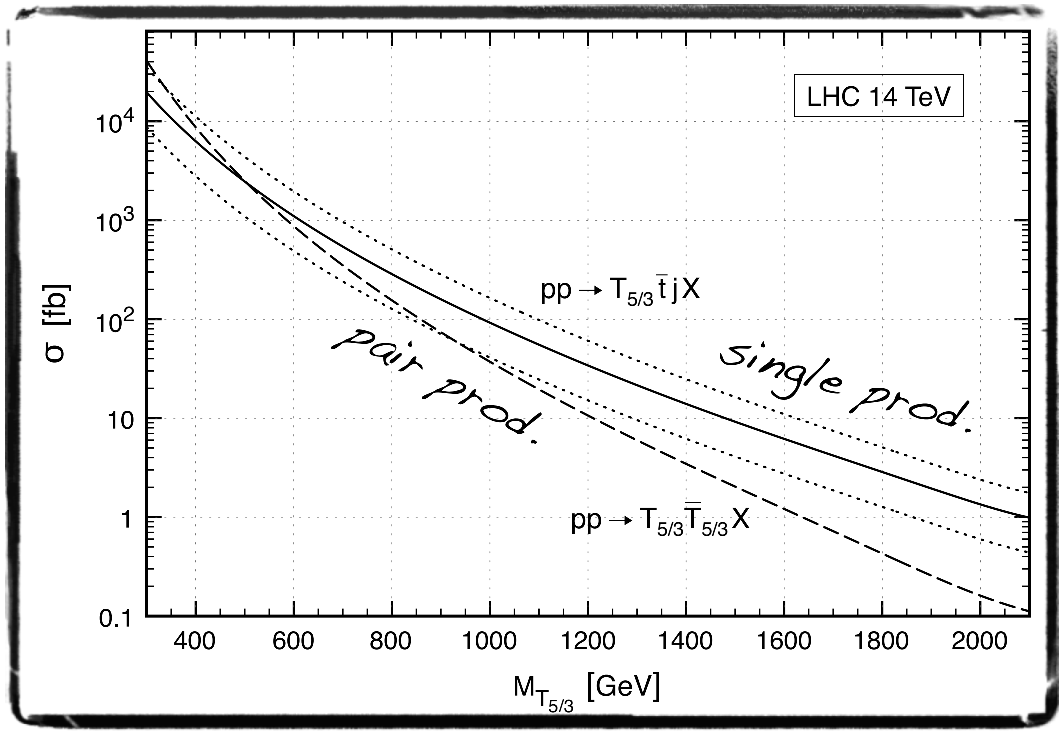
(model independent)





Single production

(model dependent)



[Contino, Servant '08]

III. Fermionic top partners

(aka vector-like quarks)

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

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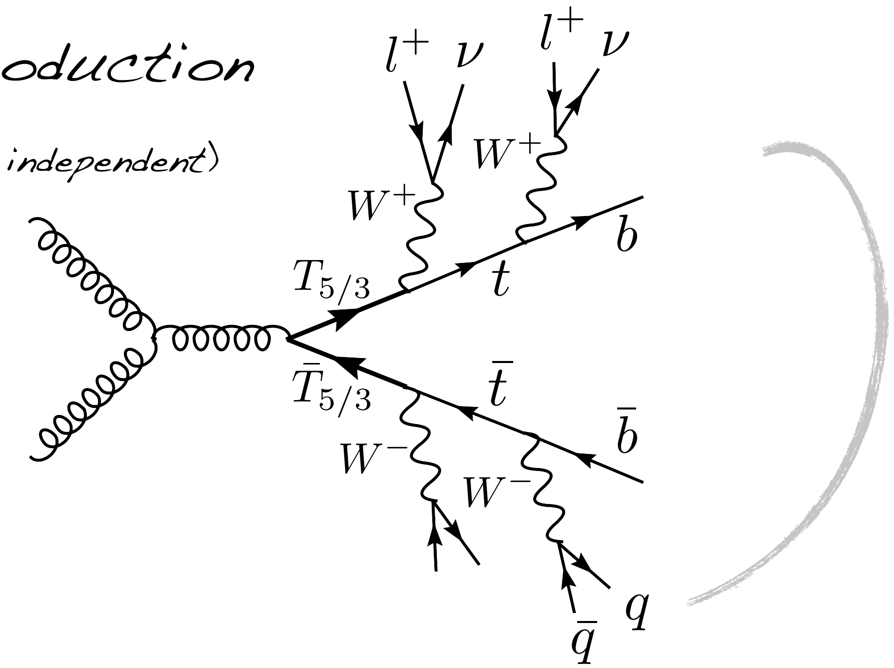
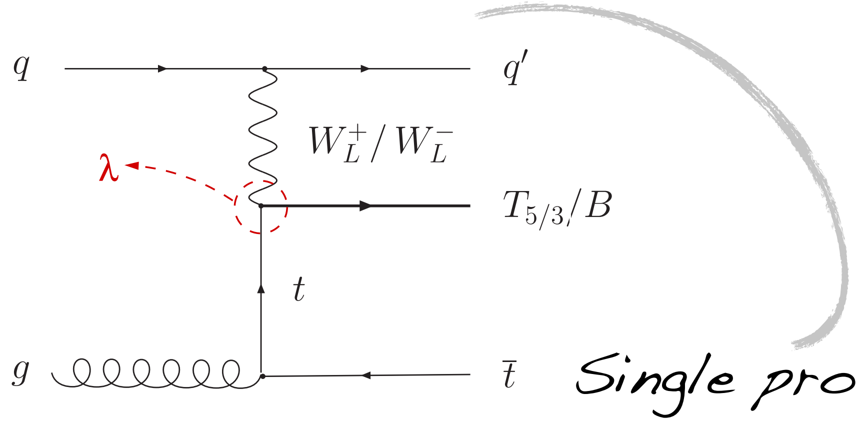
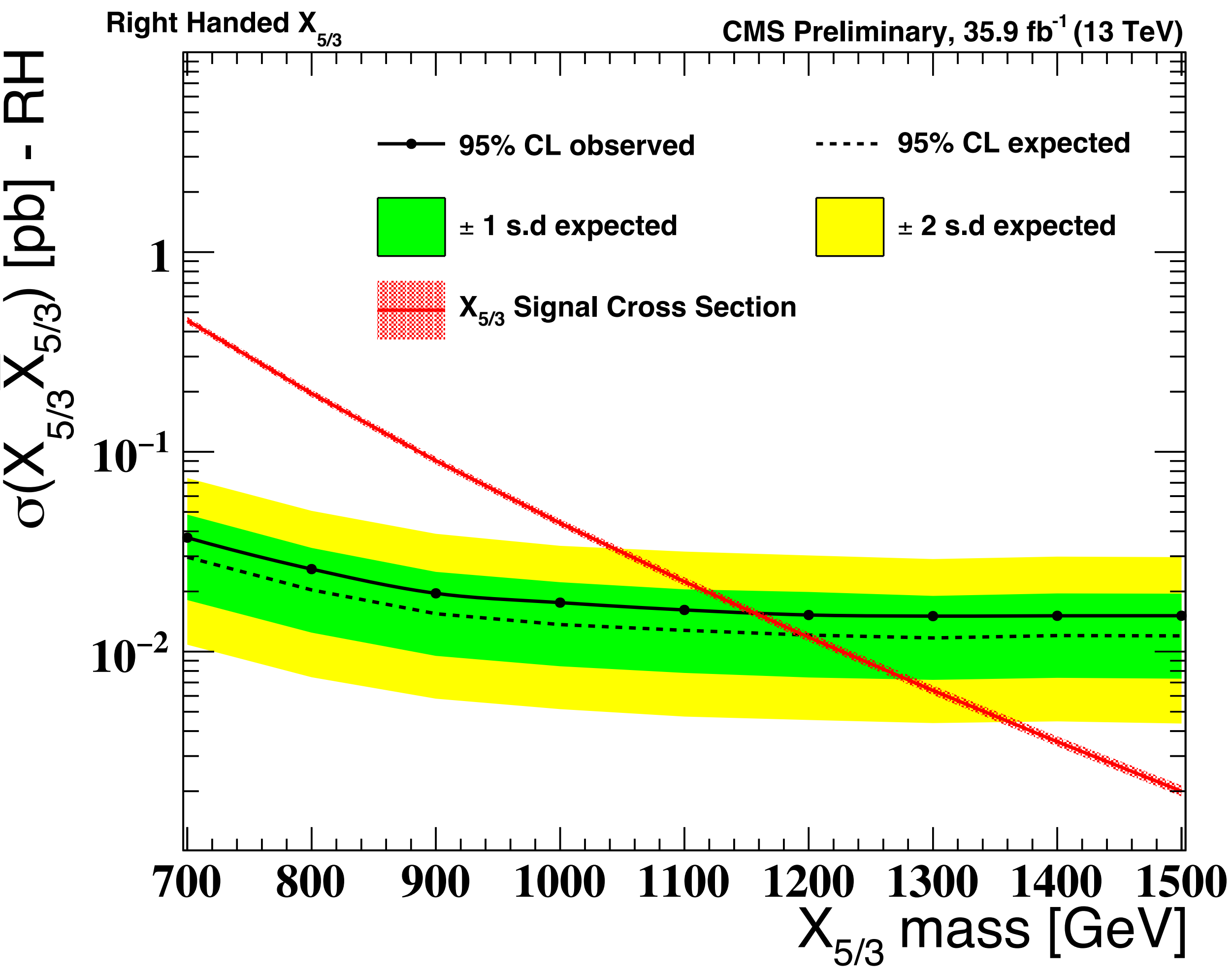




Single production

(model dependent)

Moriond'17 bound: 1160 GeV



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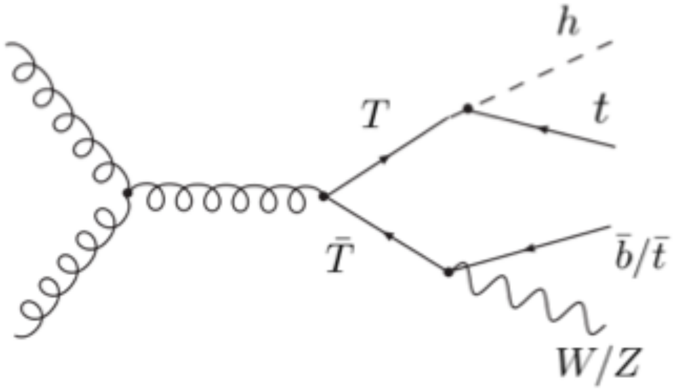


- $\ell^\pm$ + 4b final state Aguilar-Saavedra '09

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

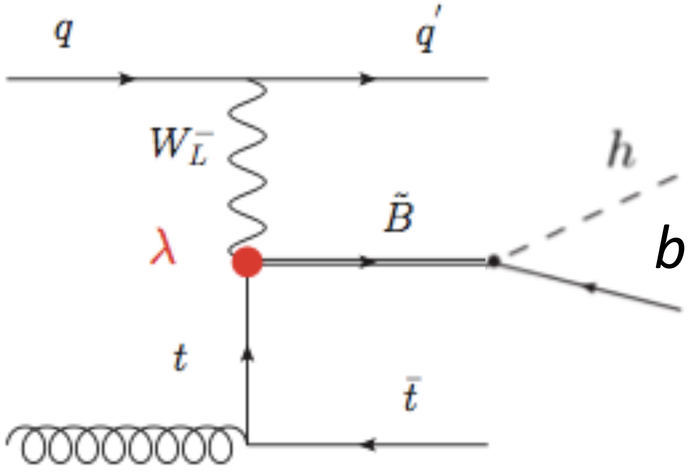
$$T\bar{T} \to HtV\bar{t} \to HW^+bVW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$$

- $\ell^\pm$ + 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

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

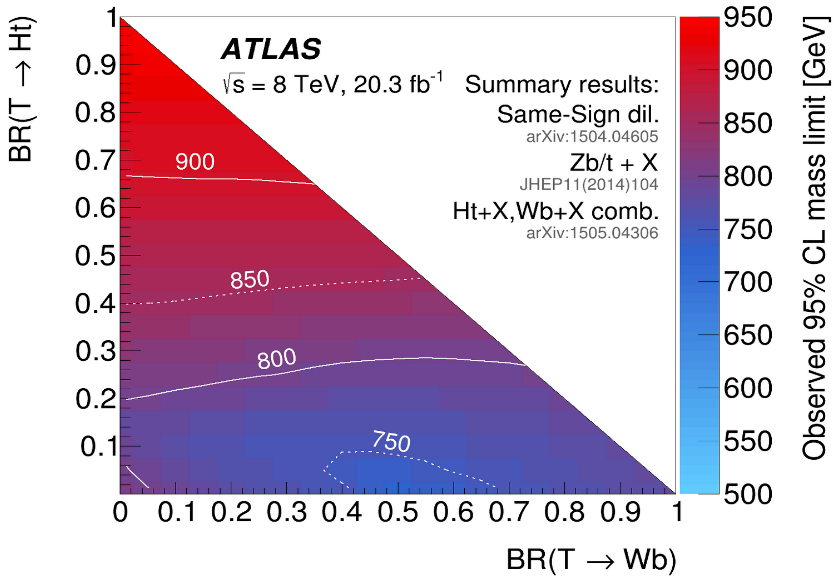


- $\ell^\pm$ + 4b final state Vignaroli '12

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

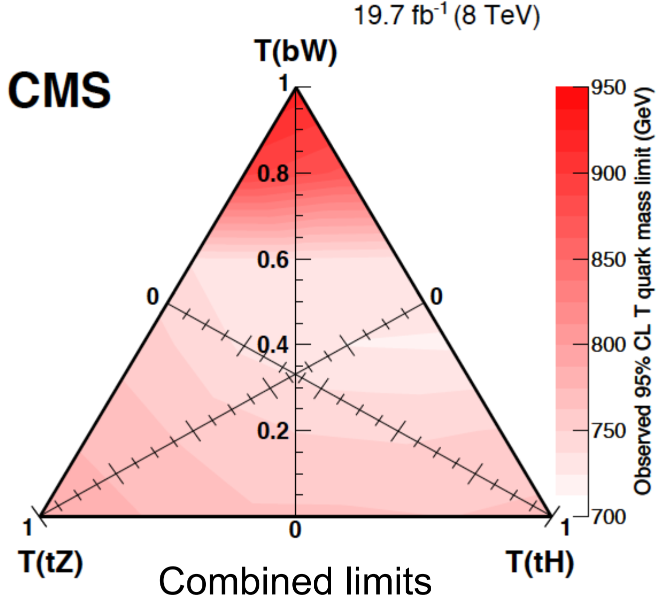
Moriond'17 update
bounds above 1 TeV!

1505.04306



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

1509.04177



IV. Searches for extended Higgs sectors

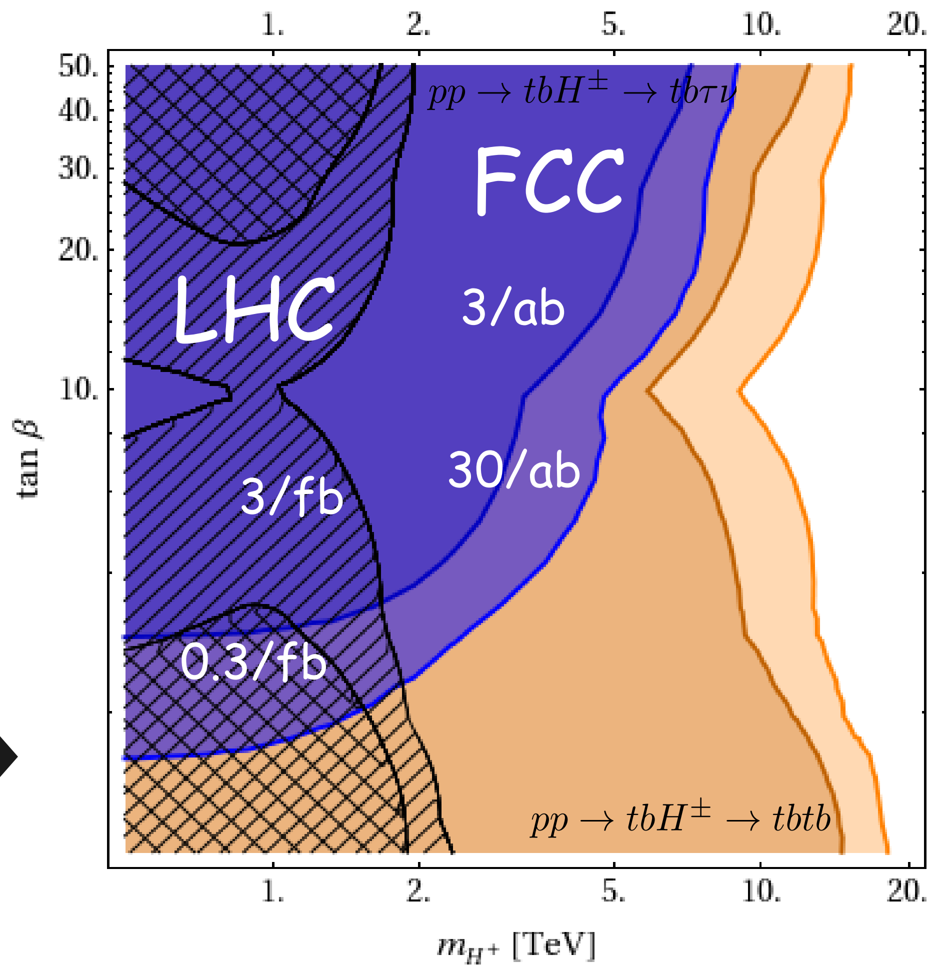
Extended Higgs sectors are a prediction of many BSM scenarios.
They may play a role in the following open questions:

- (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

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,
it could also mean new dynamics.
And it could reveal through precision measurements

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LHCP ‘2017

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$$m_* = g_* f_*$$

g* weak:

resonances before interactions

g* strong:

interactions before resonances

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

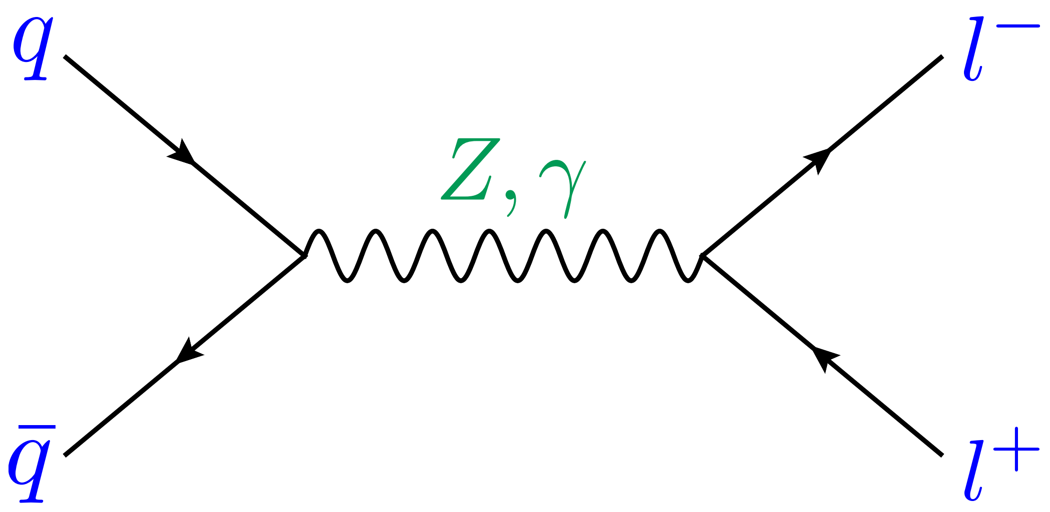
energy helps accuracy

Farina et al '16

$\frac{\Delta\mathcal{O}}{\mathcal{O}} \propto E^2$ ⬌ 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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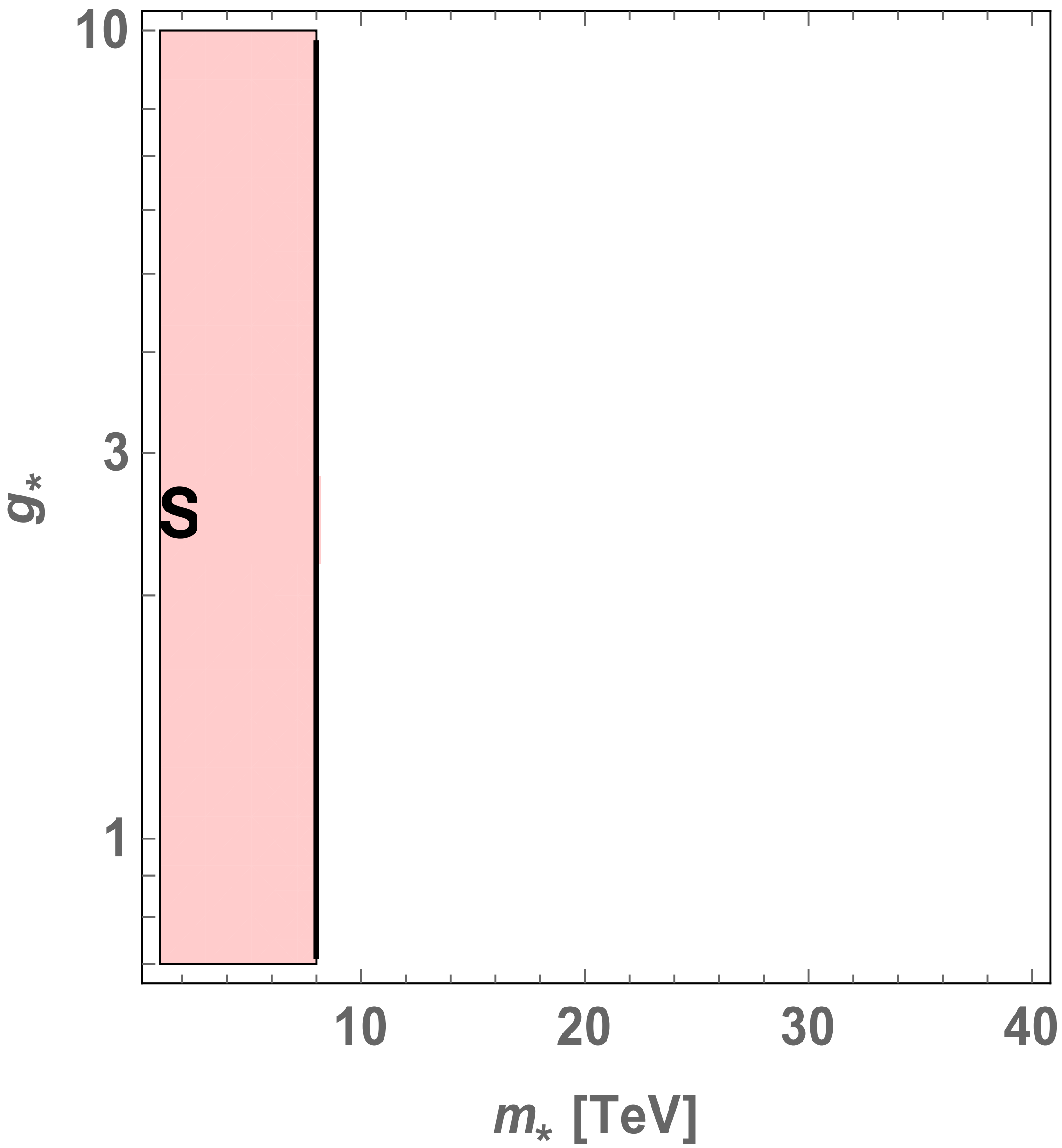
S-parameter : [De Blas et. al.] (LEP: 10^{-3})

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



Grojean-Wulzer @ FCC physics week '17

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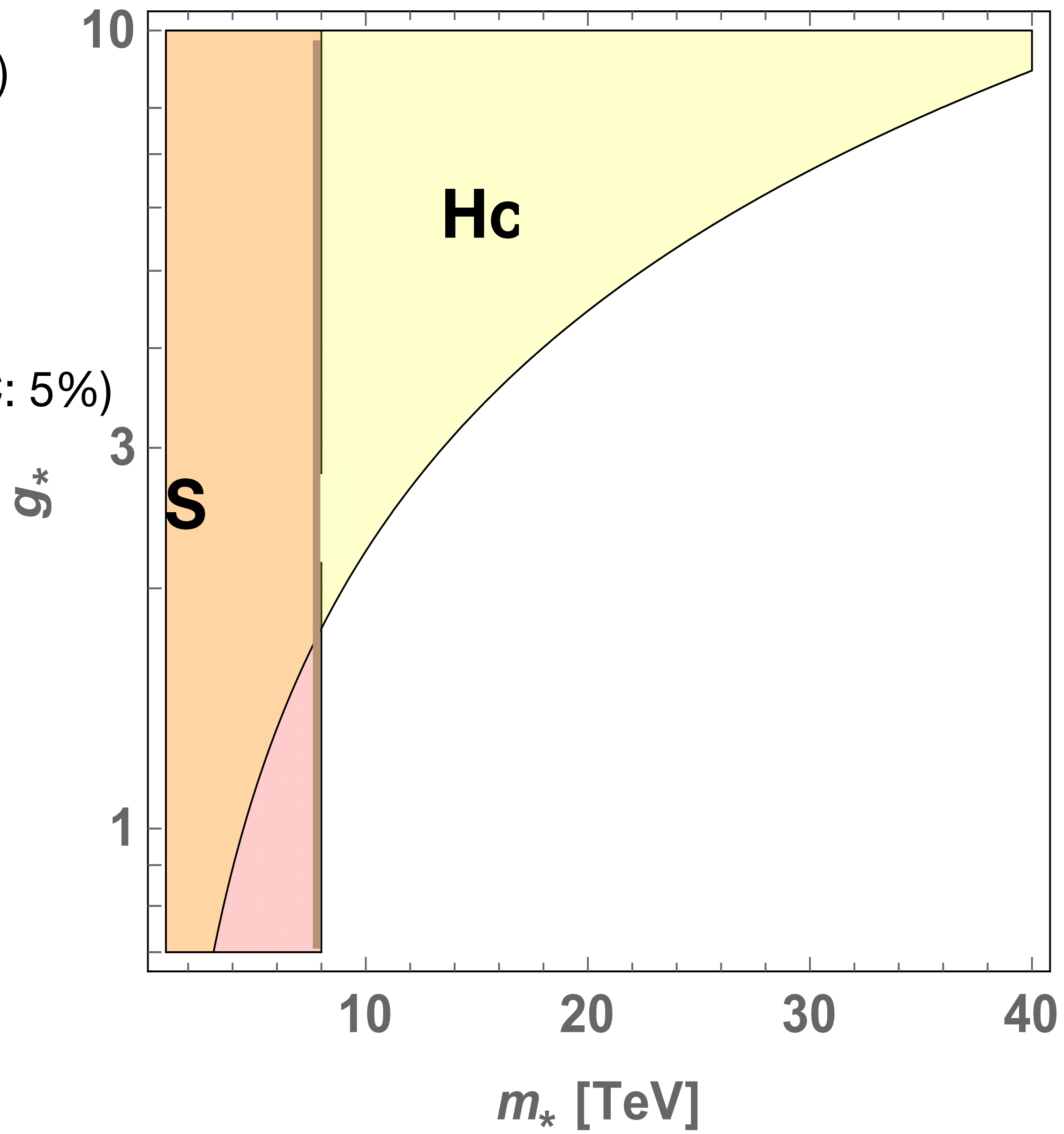
Higgs Couplings : [ee Report] (HL-LHC: 5%)

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



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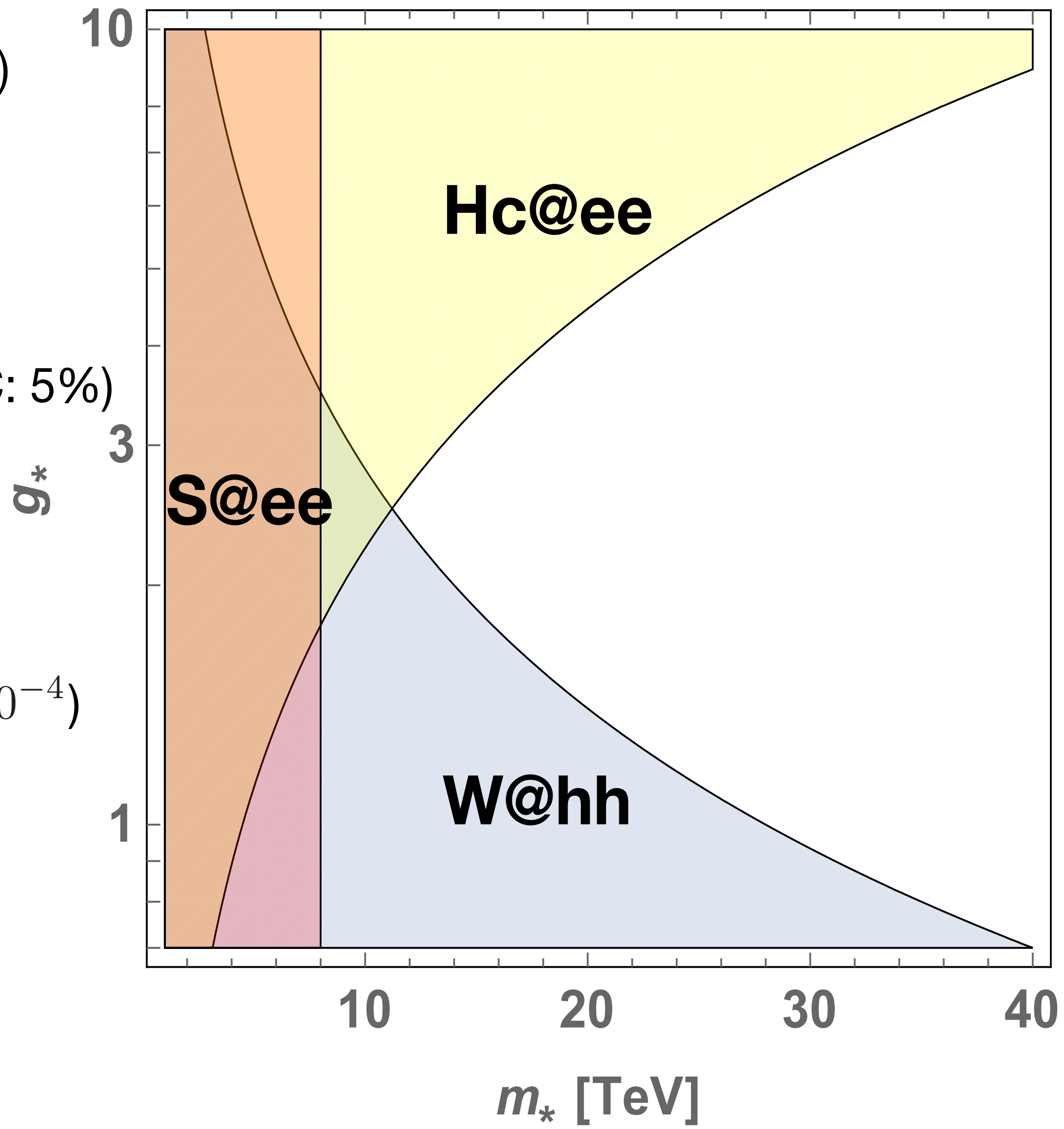
W @hh: (energy + accuracy) (HL-LHC< 10^{-4})

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



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

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V. New force: Composite Top

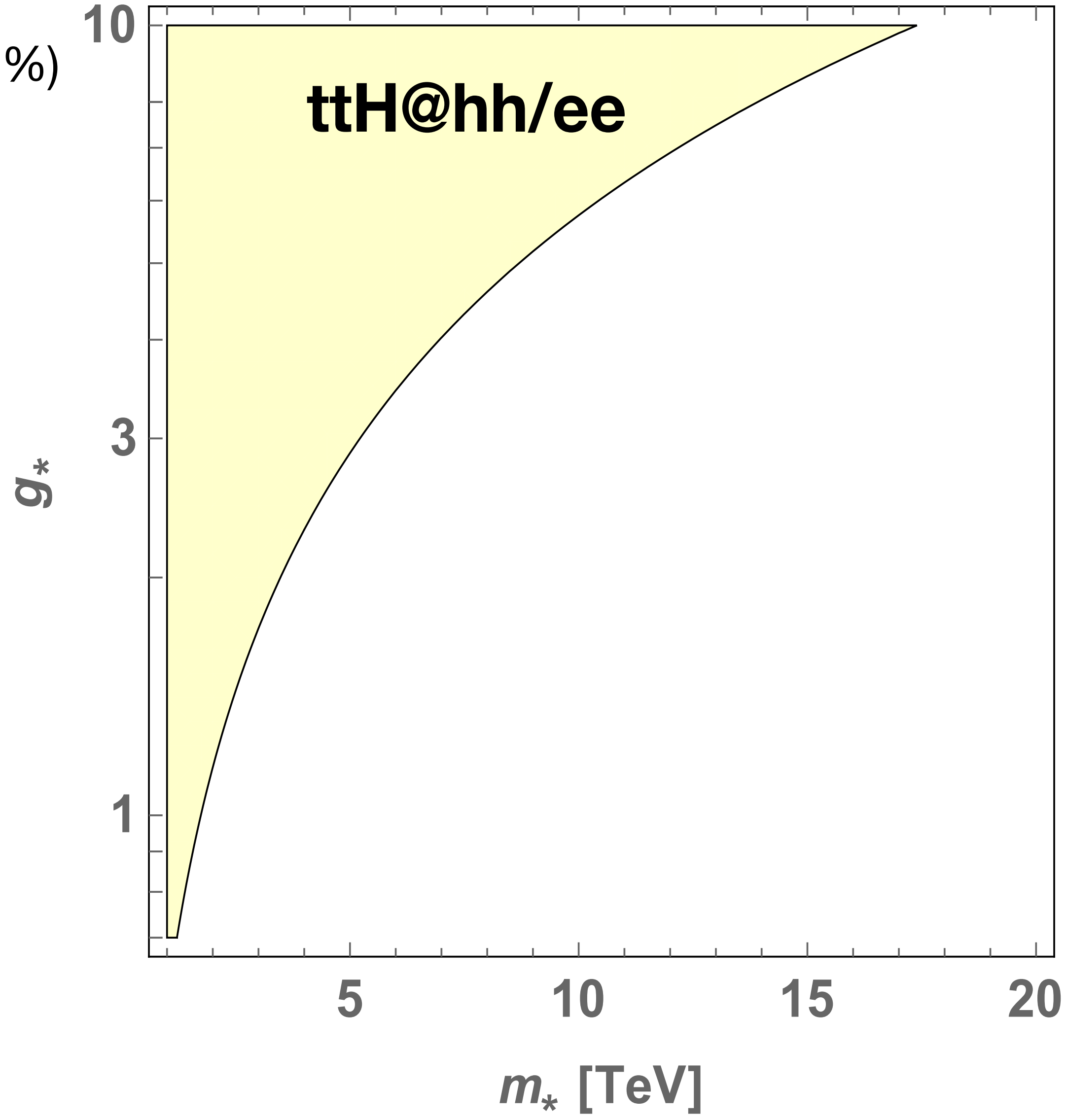
Composite tR, comp. Higgs, **elementary tL** and gauge

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

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

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

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



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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%)

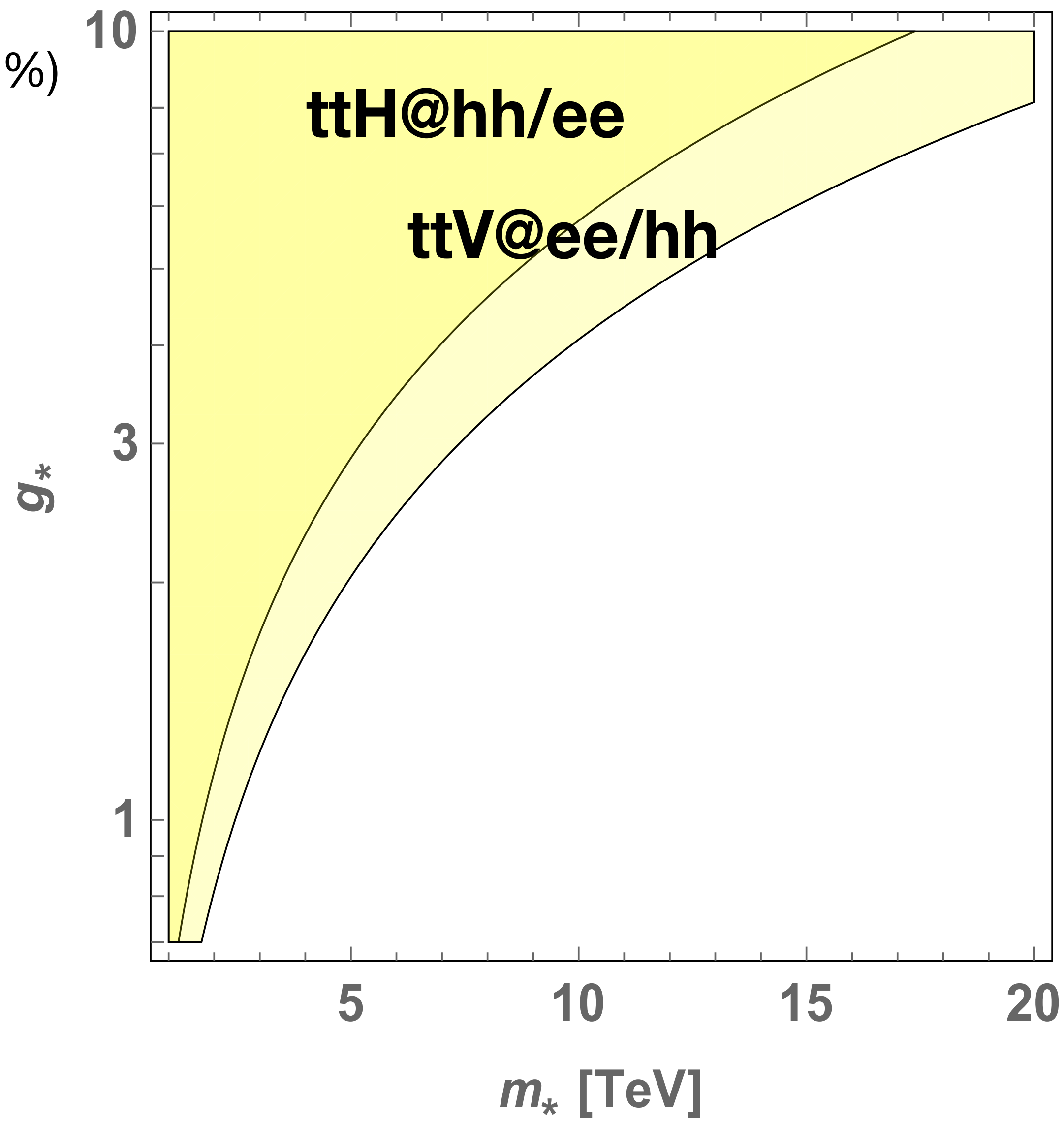
$$\frac{y_t g_*^2}{m_*^2}|H|^2 \bar{q}_L H t_R \quad ➡ \quad \frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2\,10^{-2}$$

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

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

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

Same hh reach from en. + acc.?



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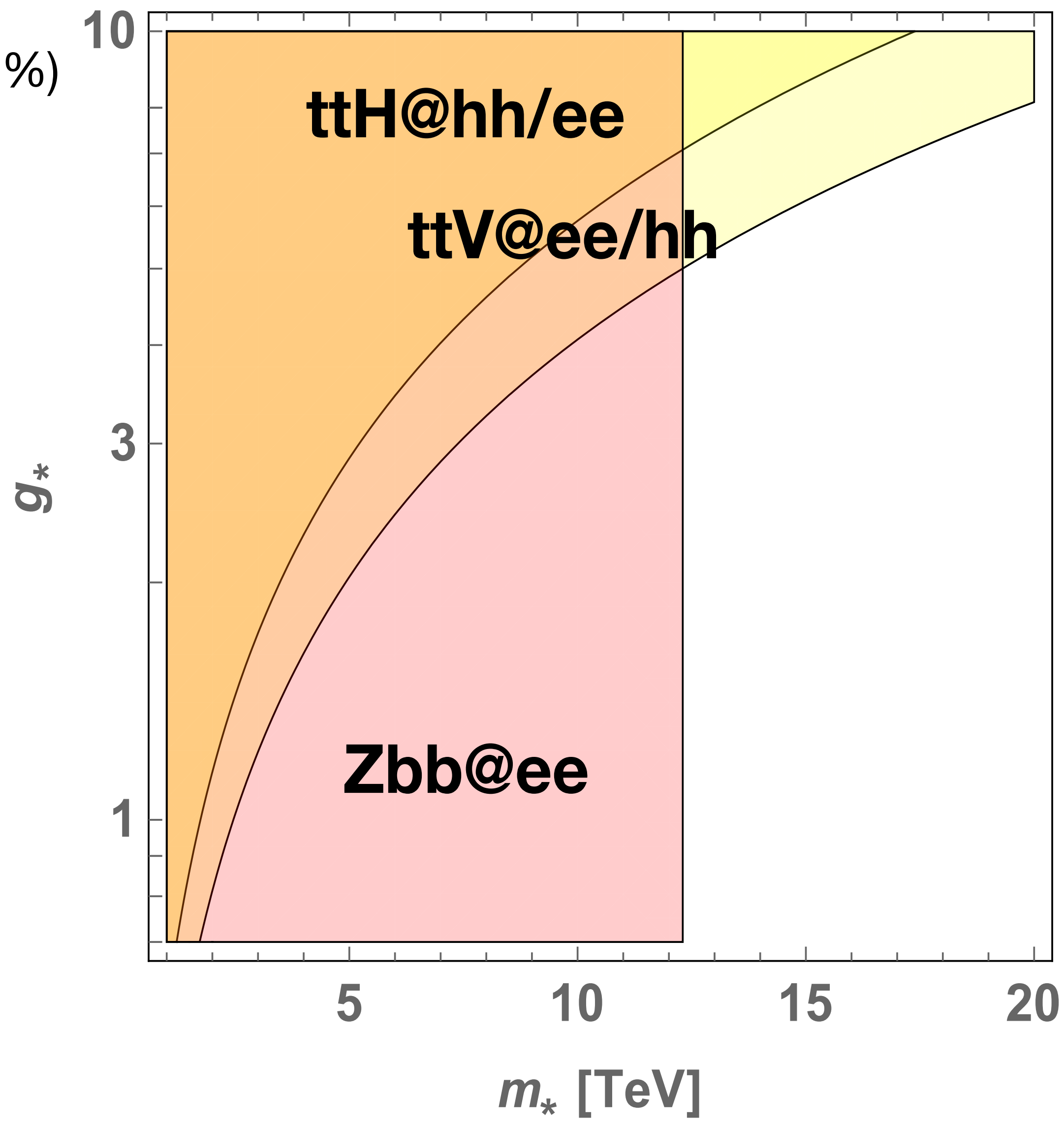
Zbb coupling @ee: [ee Report] (LEP:10^{-3})

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



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

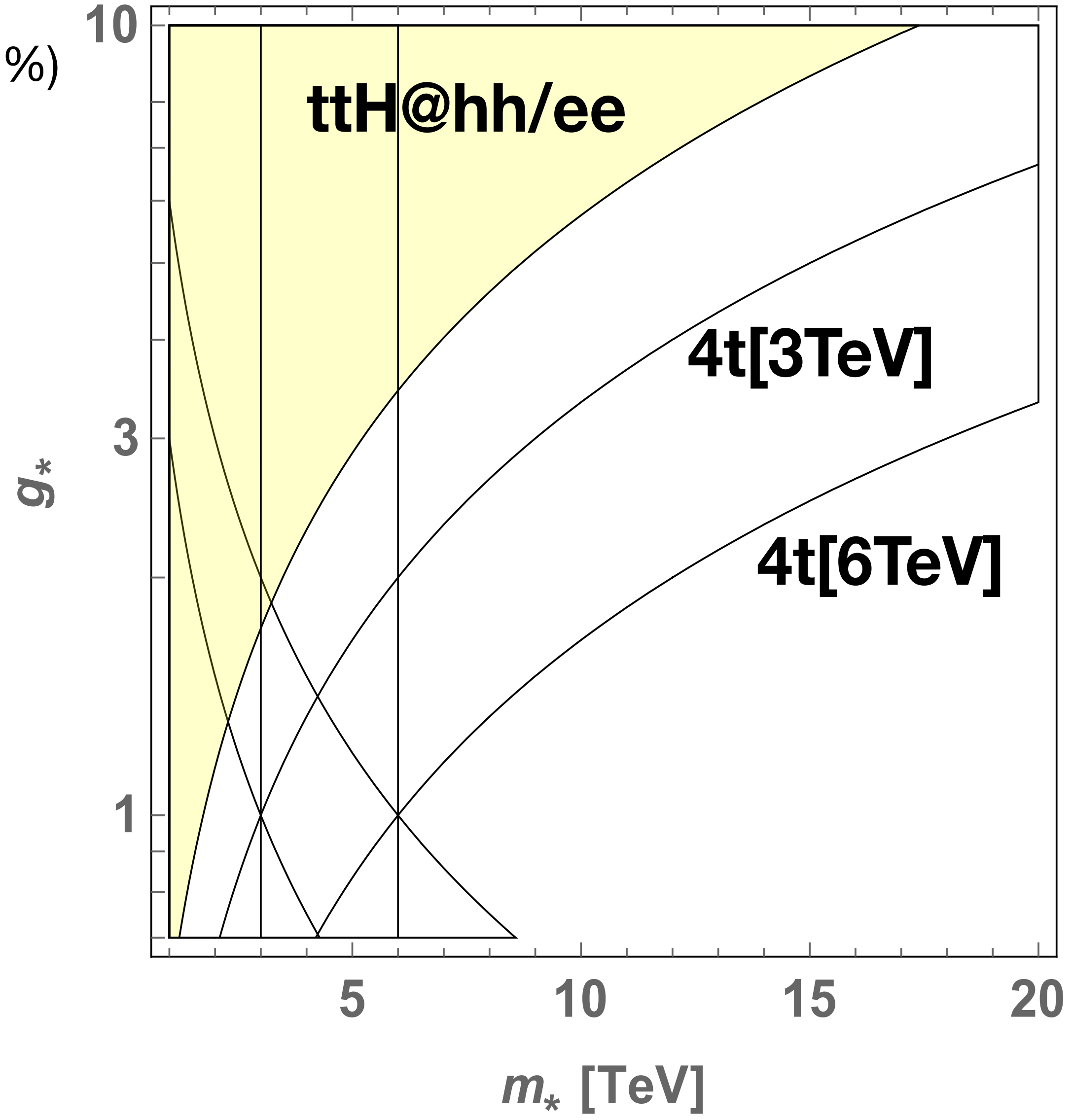
4-top contact interactions @hh:

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

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

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

No study available (?)



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Conclusions

Discovering New Physics: the way forward

so far new discoveries followed 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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Need powerful machines to explore the unknown through the intensity and energy frontiers.

Data always bring new understanding.
We need facts and data: physics is a natural science!

We have profound questions and we need create opportunities to answer them!

Thank you for your attention.
Good luck for your studies!

if you have question/want to know more

do not hesitate to send me an email

christophe.grojean@desy.de