Les expériences du futur : potentiel de physique

Recherche de nouvelle physique

École de Gif 2019

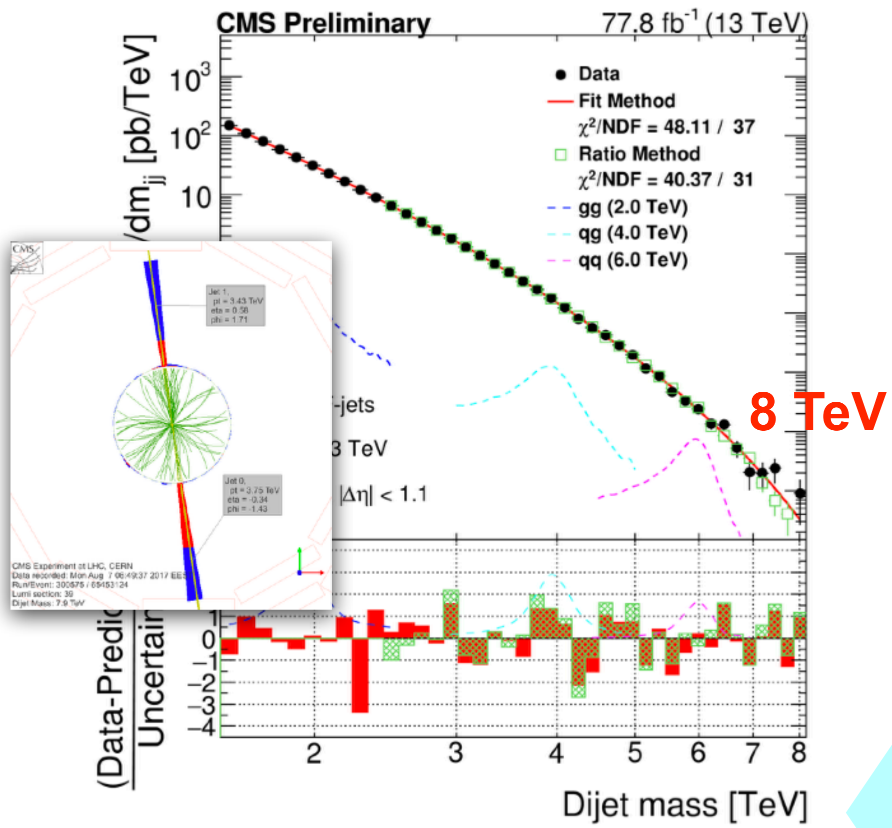
Questions ouvertes en physique des particules

2-6 septembre 2019

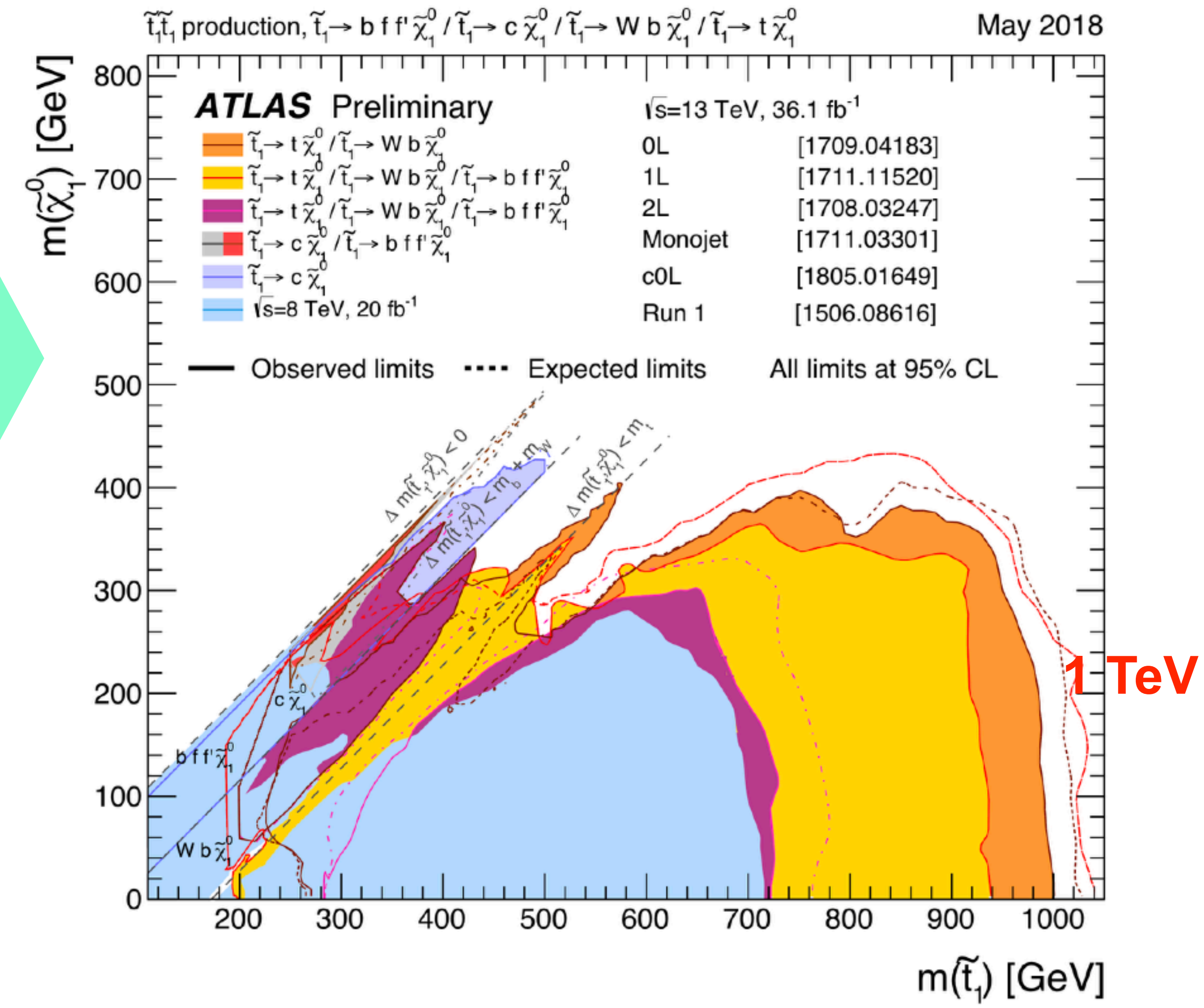
École polytechnique, Palaiseau

Gautier Hamel de Monchenault

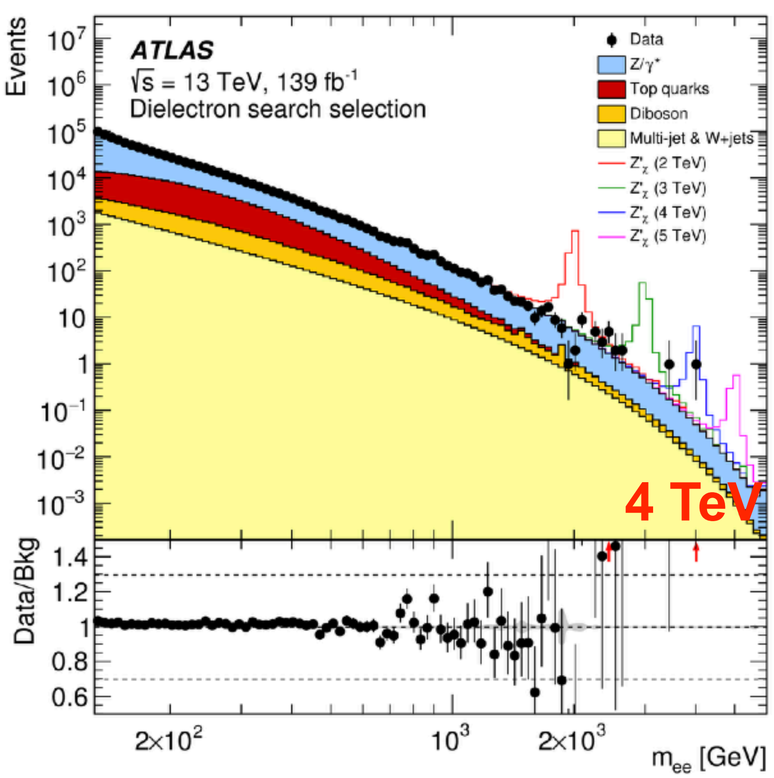
Search for Physics Beyond the SM (BSM)



search for Supersymmetry (here : *stops*)



search for new resonances



Résultat le plus marquant du LHC (après le Higgs)
☛ so far searches for new particles have not succeeded at unraveling new physics at the LHC

no evidence for SUSY at the TeV scale at the LHC

50% of the 900+ and 8 out of the last 10 CMS publications have title starting with "Search for" !

The Big Questions

For most physicists, search for New Physics (NP) is the most compelling motivation for future high-energy colliders, with the goal of providing elements of response to the big questions:

☛ Is the Higgs boson a portal to new physics?
- deviations from SM predictions (couplings, properties)
- Higgs potential and baryon asymmetry
- rare decay modes

☛ Is the Higgs boson fundamental or composite?
- composite Higgs
- new particles associated with EWK symmetry breaking
- heavy gauge bosons

☛ Are there new particles or interactions around at the TeV scale?
- supersymmetry (SUSY)
- extended Higgs sectors

☛ Can we close the search for thermal relic WIMPs at future colliders?
- Dark Matter (DM)

☛ Can we probe the feebly-interacting sector?
- feebly-interacting particles (axions, ALPs, dark photons)
- right-handed neutrinos

for these lectures, only a few chosen examples of searches at colliders, for illustration

Models with 1st Order Phase Transition

Question: is there BSM physics coupled to the Higgs capable of modifying the Higgs potential and allow for a 1st order EW phase transition as required for BAU?

Below, an example of minimal extension from the SM potential

☛ the SM Higgs potential

$$V_0^{\rm SM}(H) = -\mu^2|H|^2 + \lambda|H|^4$$

☛ the Real Scalar Singlet class of models

- add a single real singlet *S* (1 ddl) with coupling to the Higgs field (4 ddl)

$$V_0(H) = V_0^{\rm SM}(H) - \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 + \lambda_{HS}|H|^2 S^2$$

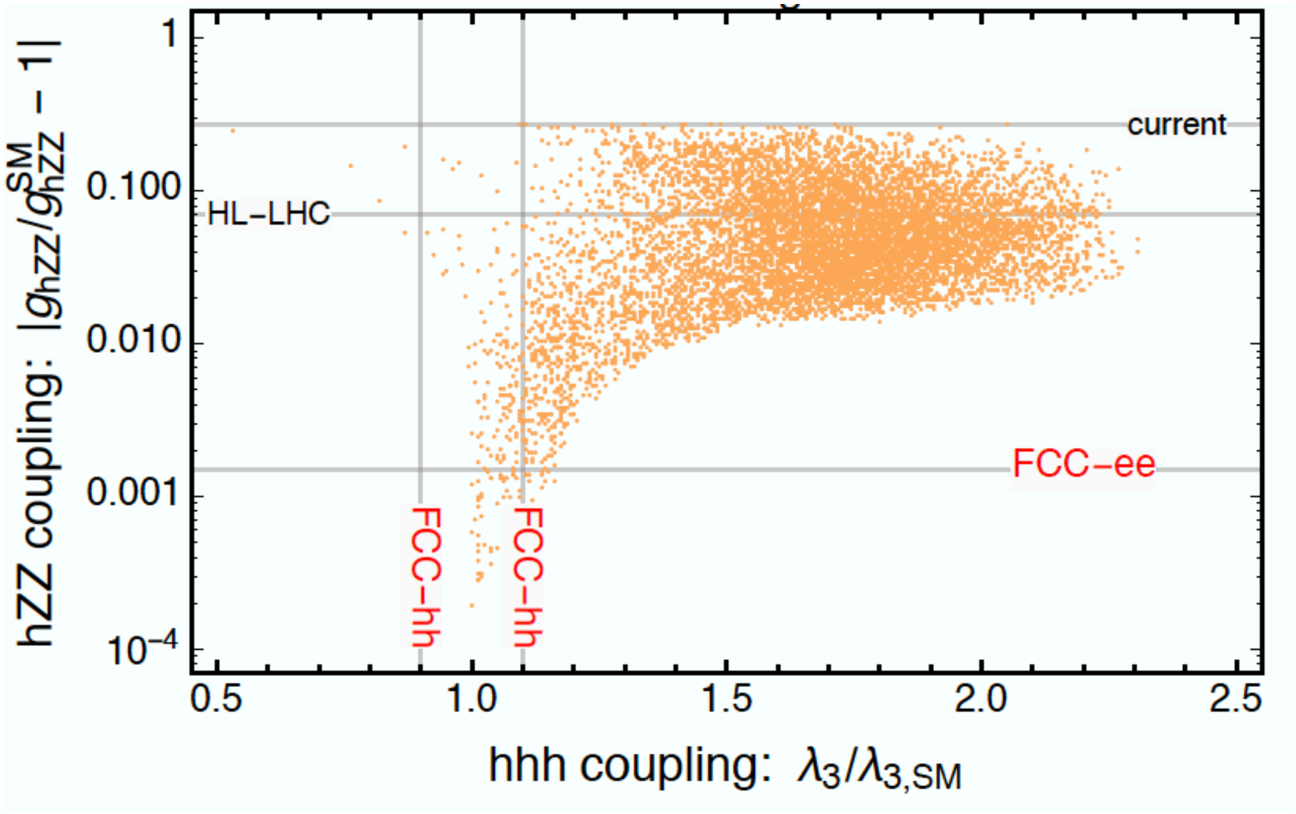
(simplified)

with
$$\begin{aligned} h &= h_0 \cos\gamma + S \sin\gamma \\ \phi &= -h_0 \sin\gamma + S \cos\gamma \end{aligned}$$

Equivalence theorem:
$B(\phi \to {\rm hh}) = B(\phi \to {\rm ZZ}) = 25\%$

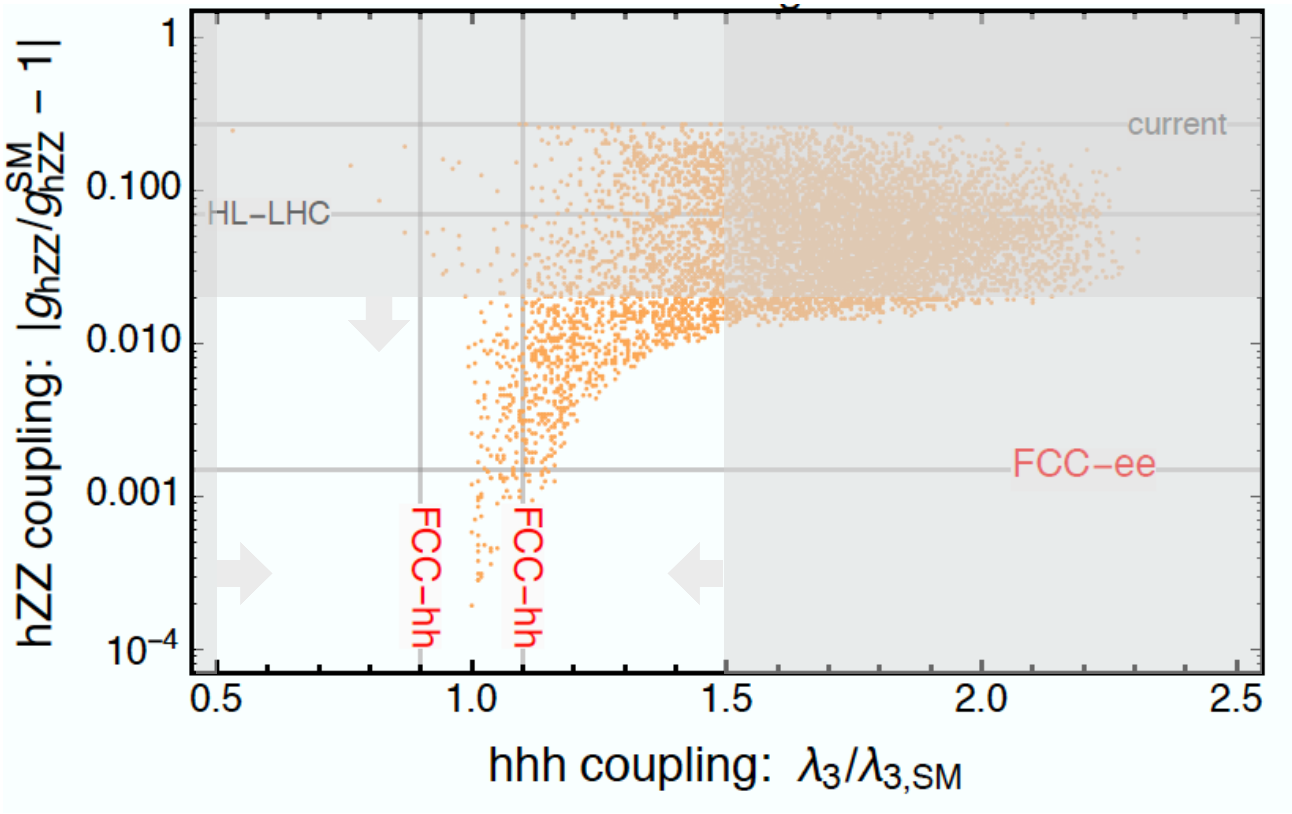
Real Scalar Singlet Model

Parameter space scan: the points indicate a first order phase transition



Real Scalar Singlet Model

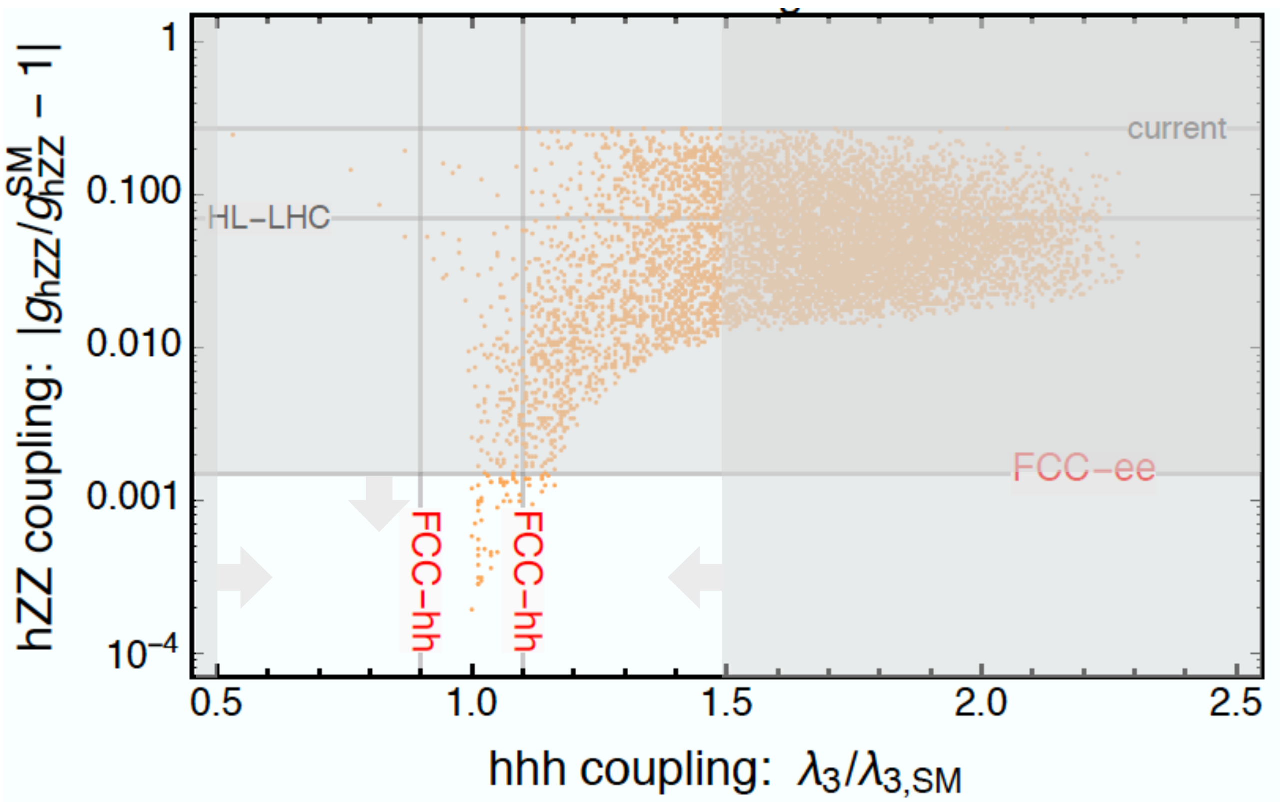
Parameter space scan: the points indicate a first order phase transition



HL-LHC
➠ g_{HZZ} to 0.02 and λ to 50% probe a good portion of parameter space, but not all

Real Scalar Singlet Model

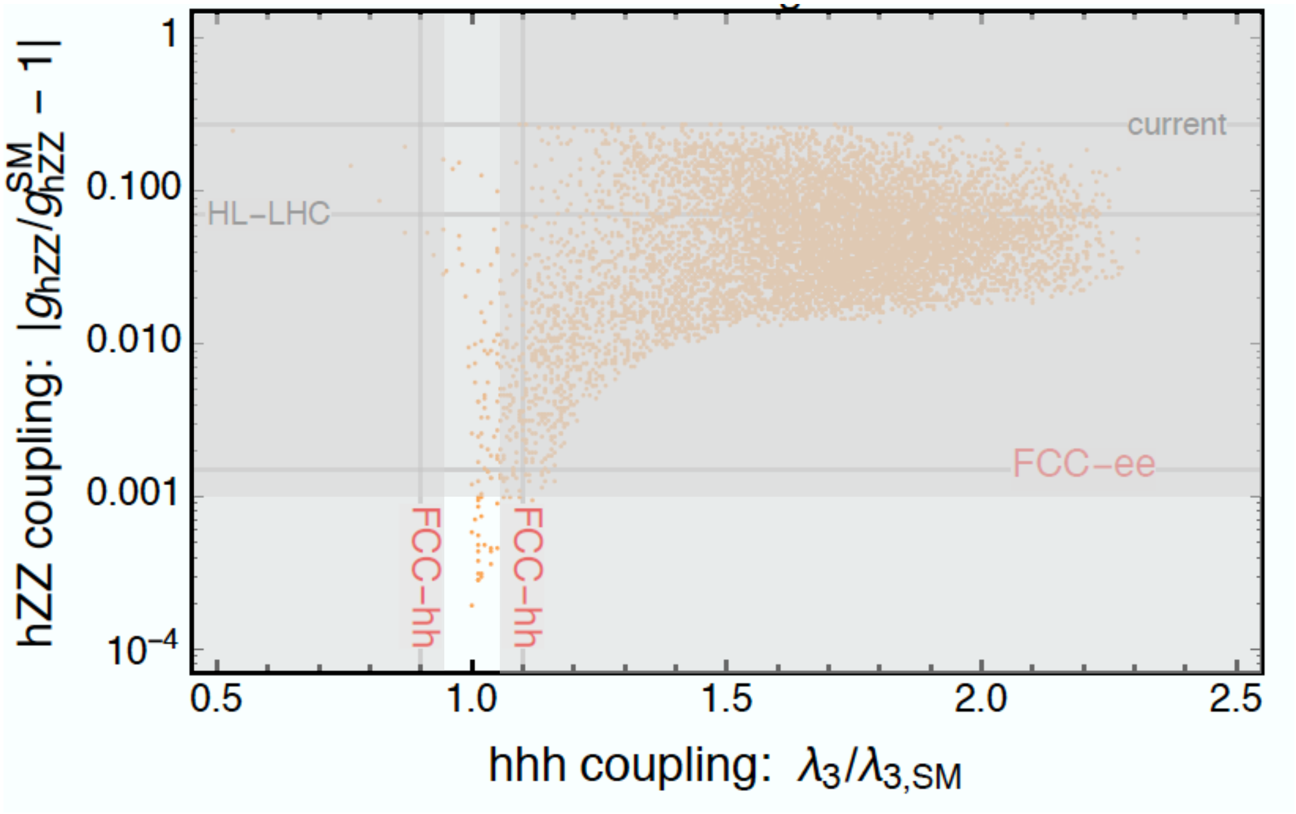
Parameter space scan: the points indicate a first order phase transition



FCC-ee
➟ g_{HZZ} to $1.5{\times}10^{-3}$ allows to probe most of the parameter space

Real Scalar Singlet Model

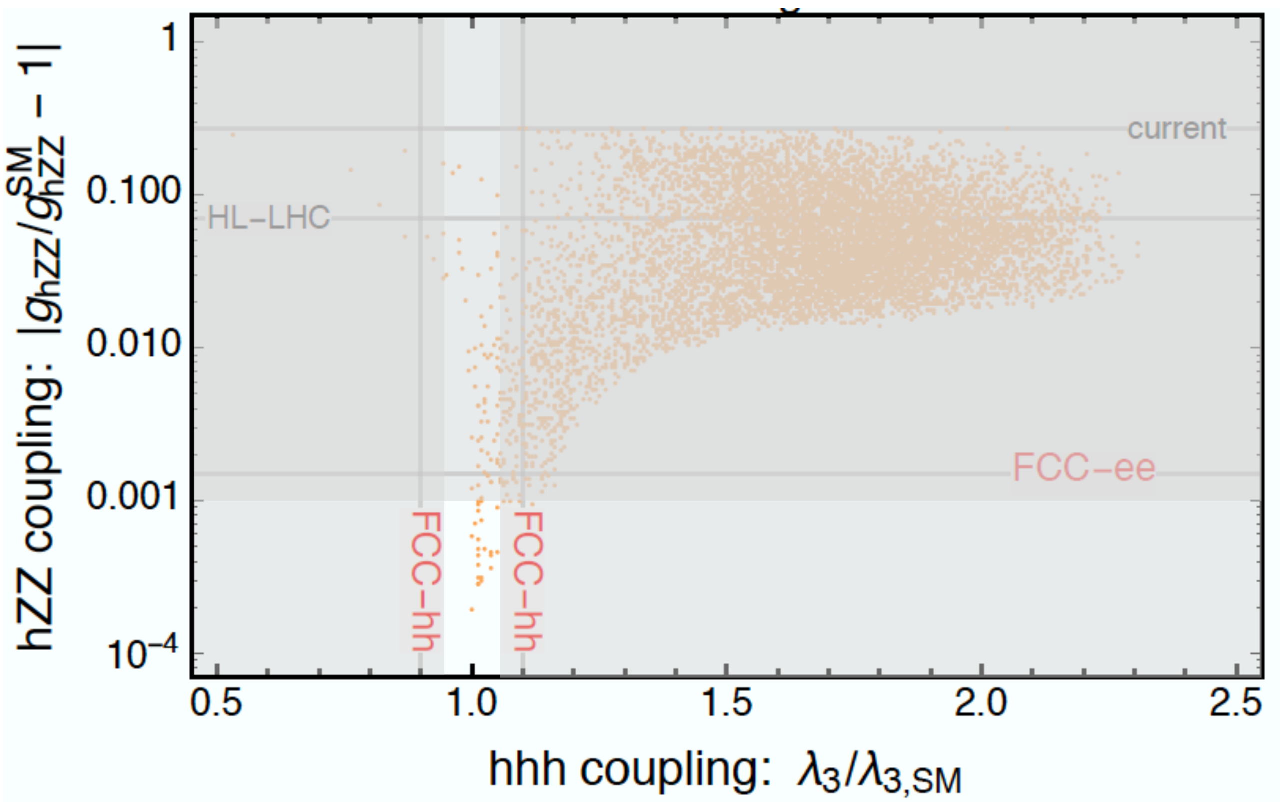
Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



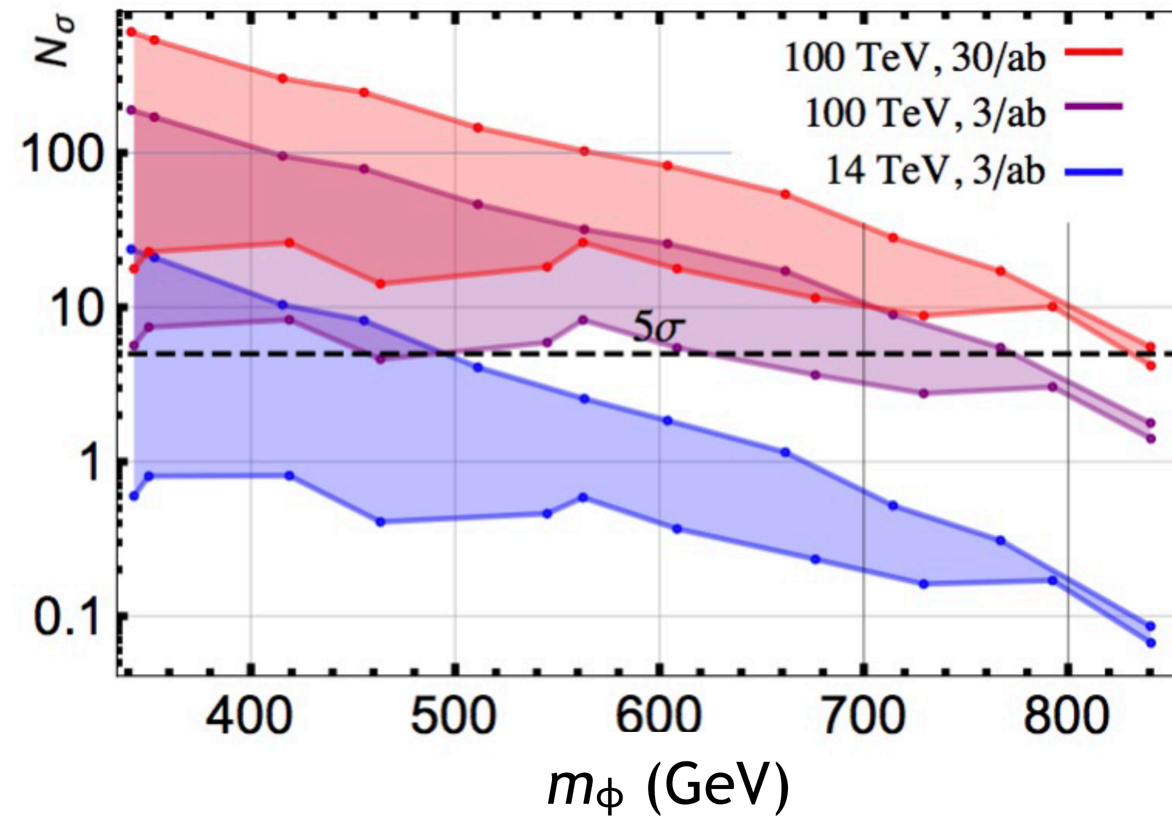
FCC-ee/hh
➠ g_{HZZ} to 1×10^{-3} and λ to 6% leaves only a very small portion of the parameter space

Real Scalar Singlet Model

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



Direct detection of extra heavy scalar states at FCC-hh



$$\phi \to hh \to b\bar{b}\gamma\gamma/\tau^+\tau^-$$

Operators that lead to visible deviations in the Higgs self coupling are likely to first manifest themselves through deviations of single-Higgs couplings to gauge bosons

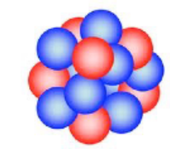
Self-coupling measurements remain important to interpret any SM departure in single-Higgs couplings to understand the origin of these deviations

M.L. Mangano @ HH 2019

Higgs Compositness

Question: is the Higgs point-like? If not, how big is it?

- can compositeness explain the smallness of the electroweak scale and solve the Naturalness problem?



Basic idea of Composite Higgs (CH) models

- all the degrees of freedom of the SM apart from the Higgs are elementary
- the Higgs instead arises as a bound state from a strong dynamics
- such dynamics is roughly described by two parameters:

  the overall mass scale m_* and its overall coupling strength g_*

$$\mathcal{L}_{\mathrm{U}}^{d=6} = c_{\mathrm{H}} \frac{g_\star^2}{m_\star^2} \mathcal{O}_{\mathrm{H}}$$

Scaling of Higgs couplings by a common factor

$$+ \frac{1}{g_\star^2 m_\star^2} \left[c_{2\mathrm{W}} g^2 \mathcal{O}_{2\mathrm{W}} + c_{2\mathrm{B}} g'^2 \mathcal{O}_{2\mathrm{B}} \right]$$

4-fermion contact interactions W', Z' resonances

$$+ \frac{1}{m_\star^2} \left[c_{\mathrm{W}} \mathcal{O}_{\mathrm{W}} + c_{\mathrm{B}} \mathcal{O}_{\mathrm{B}} \right]$$

2-fermion 2-boson contact interactions

$$+ c_{y_{\mathrm{t}}} \frac{g_\star^2}{m_\star^2} \mathcal{O}_{y_{\mathrm{t}}} + c_{y_{\mathrm{b}}} \frac{g_\star^2}{m_\star^2} \mathcal{O}_{y_{\mathrm{b}}}$$

Modified top and bottom Yukawa couplings

$$+ \ldots$$

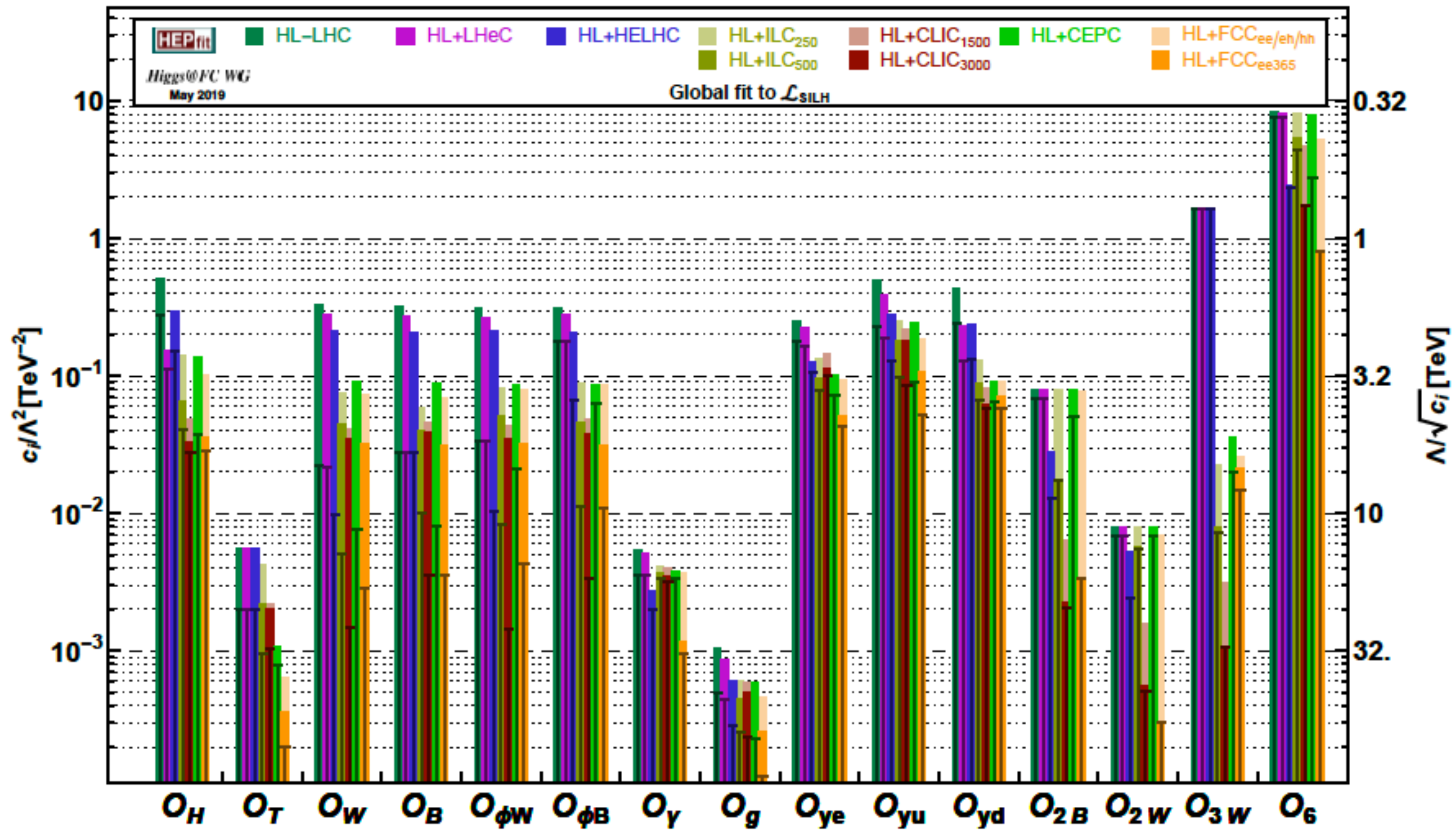
and more

this physics is encoded in Strongly-Interacting Light Higgs (SILH) dimension-6 operators

see backup

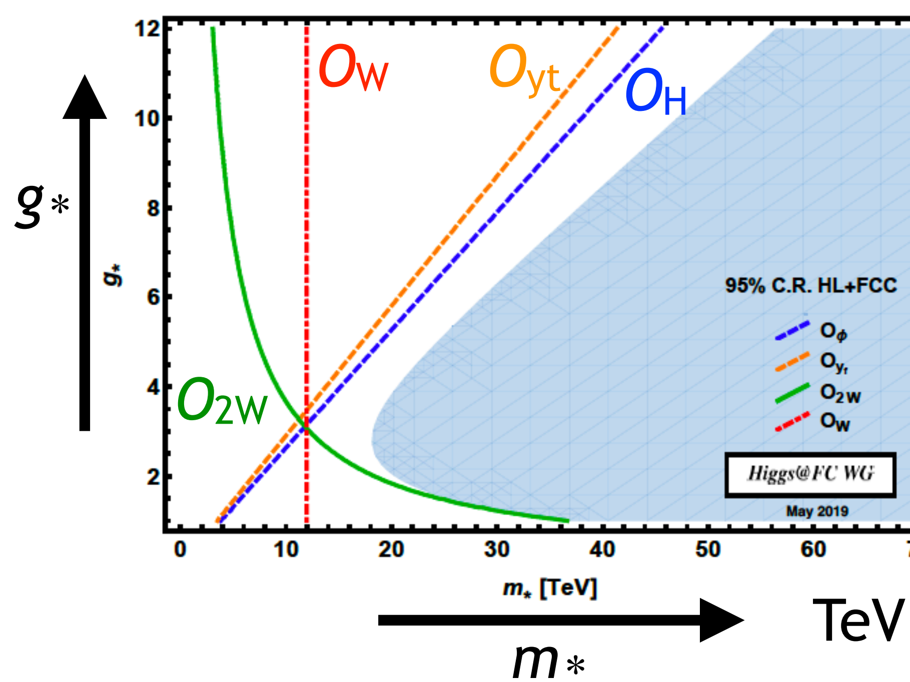
Bounds on SILH Lagrangian Interactions

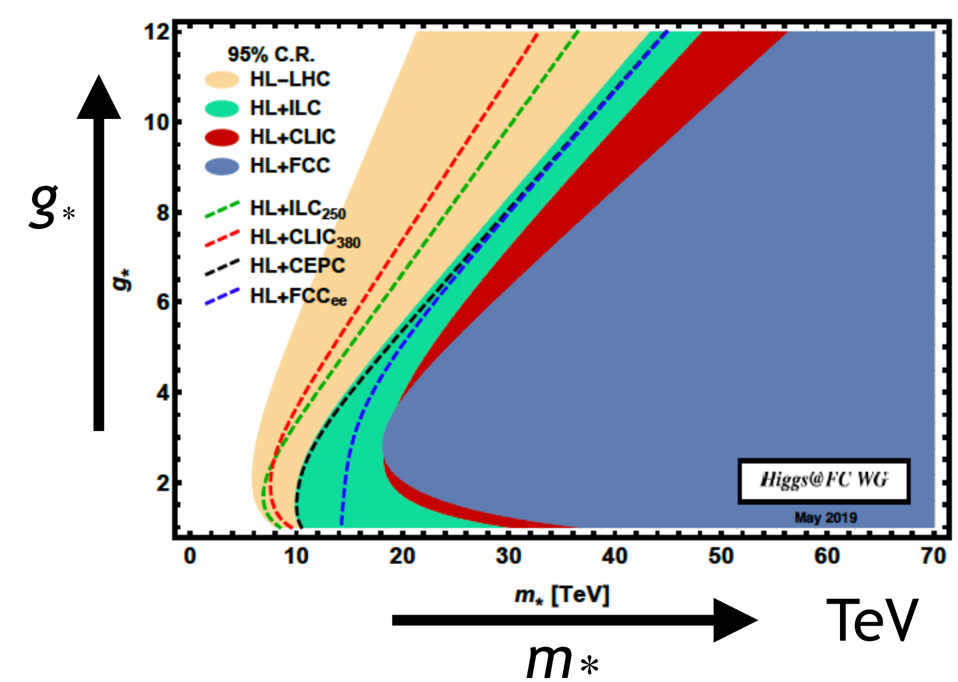
result of the SILH fit on Higgs and EW precision observables for various machines



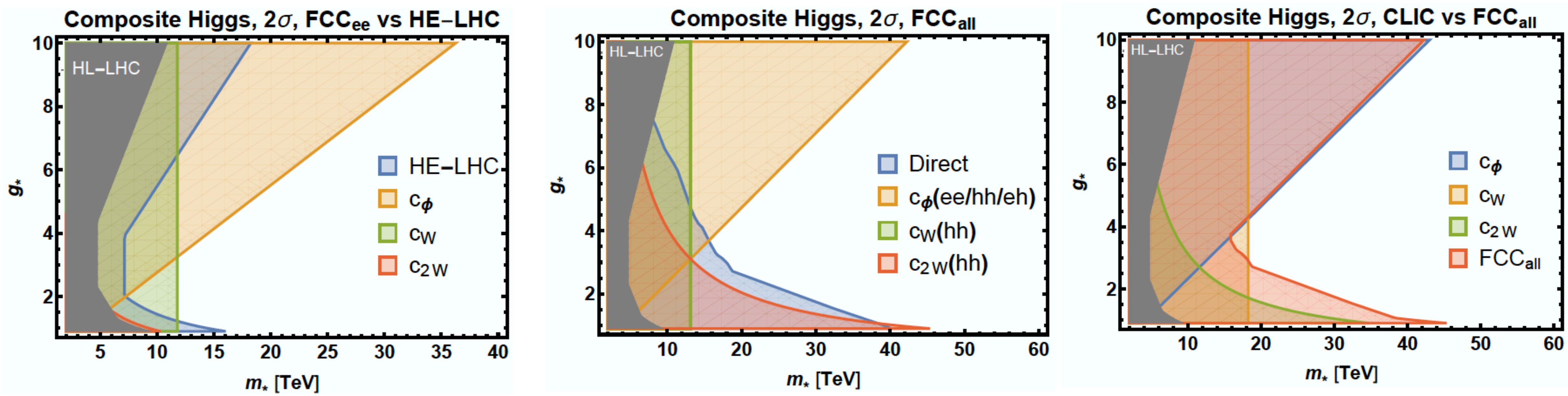
Bottom line: important BSM information from precision measurements

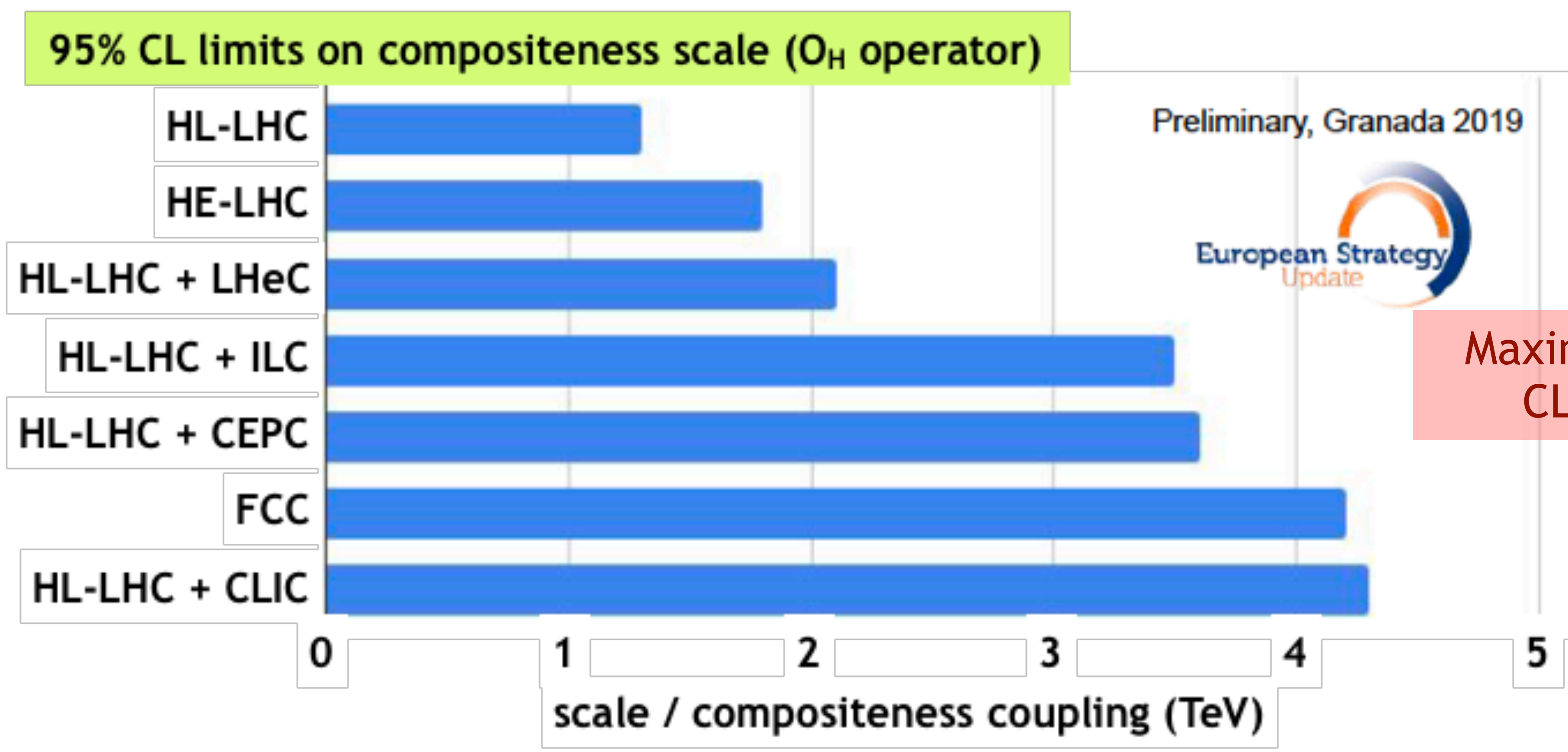
constraints on compositeness scale





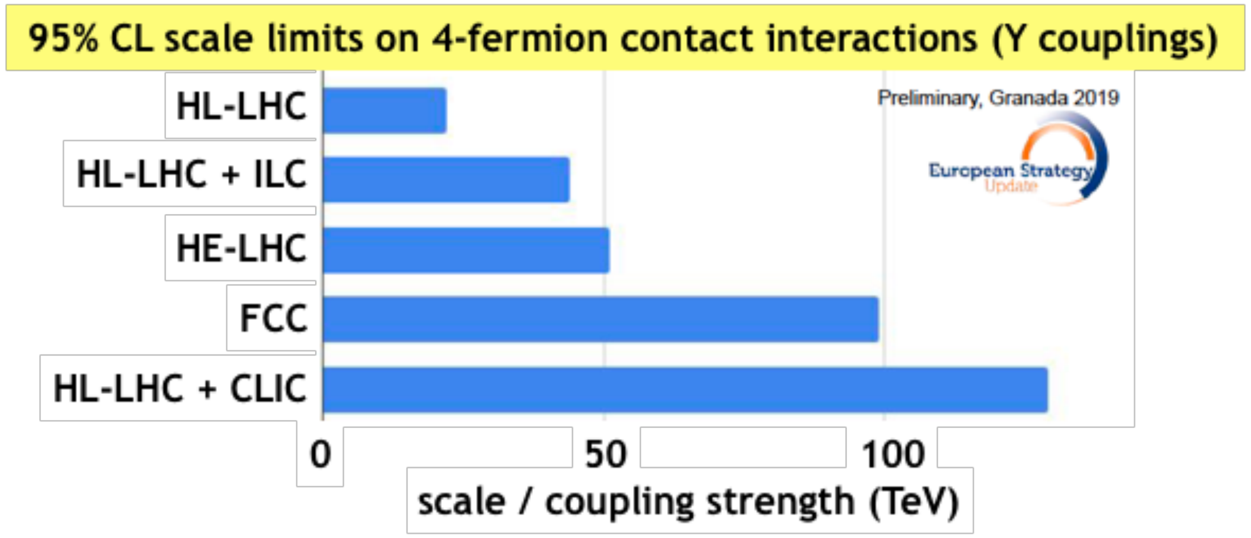
Higgs Compositness

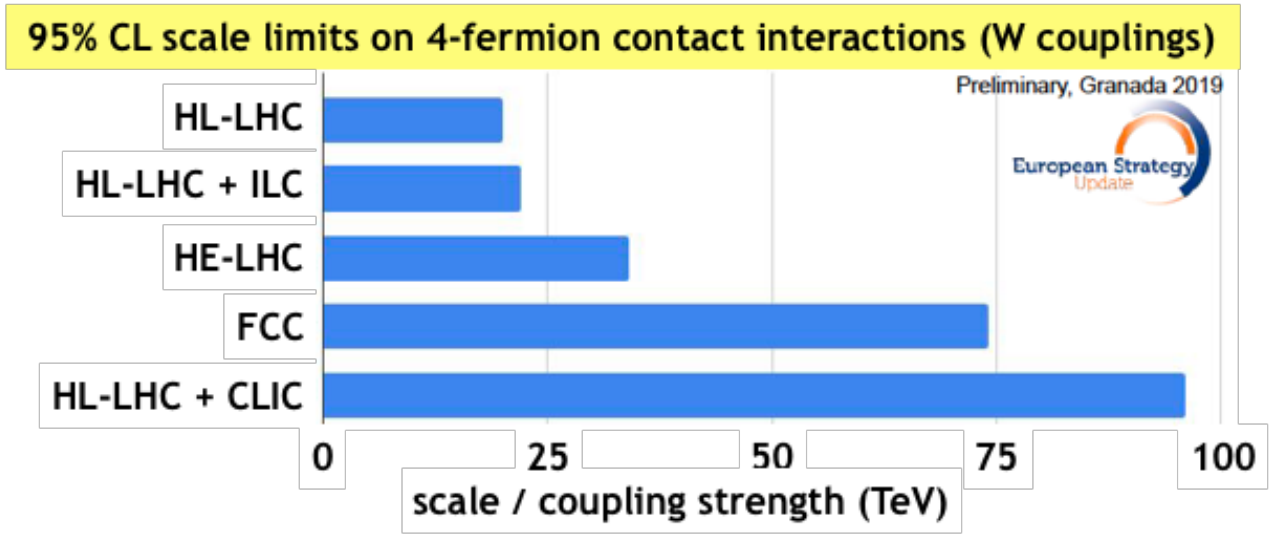


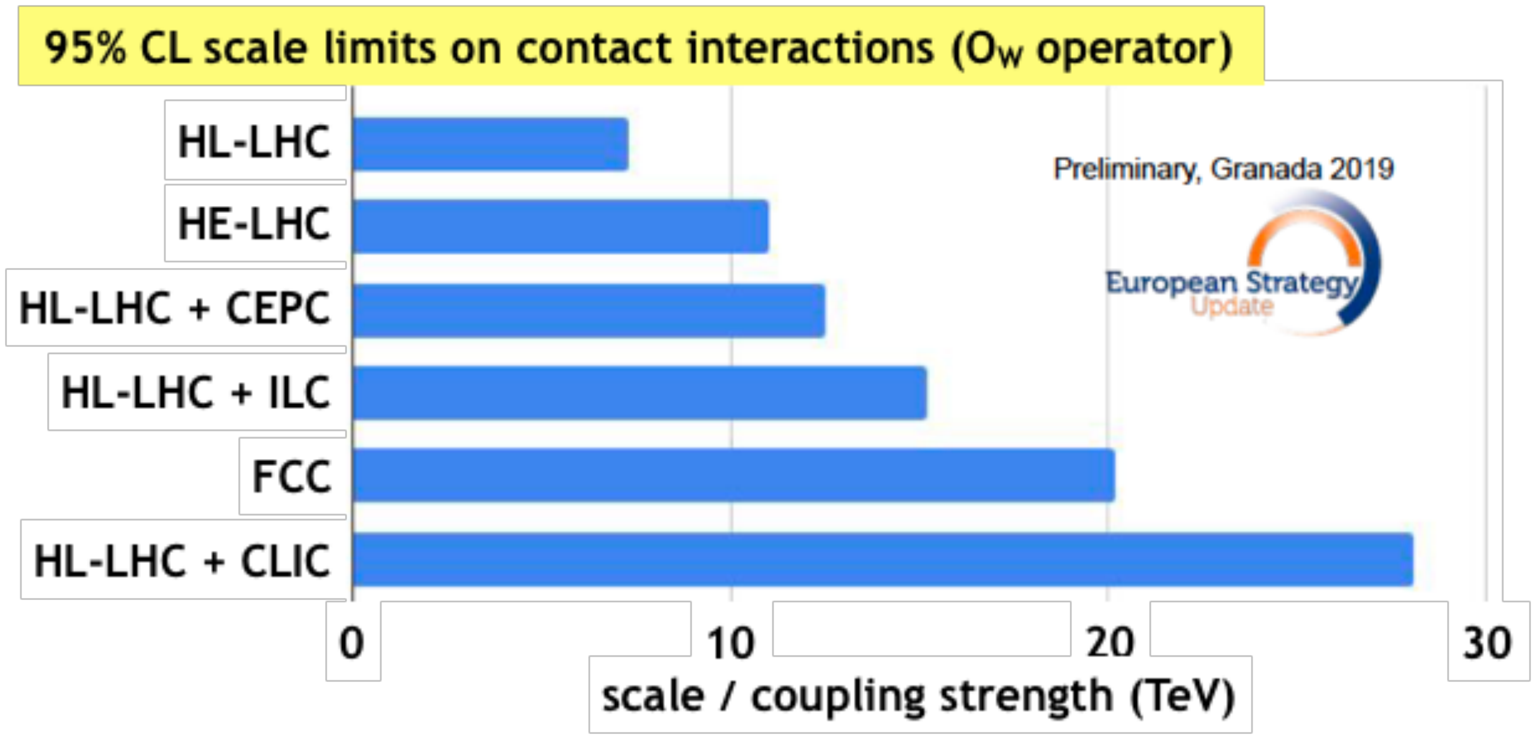


Maximum sensitivities from CLIC and FCC (ee+hh)

Compared SILH Reach at Future Colliders



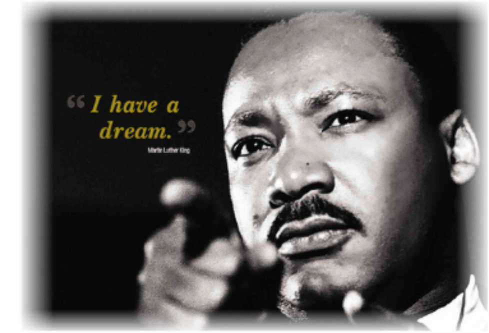




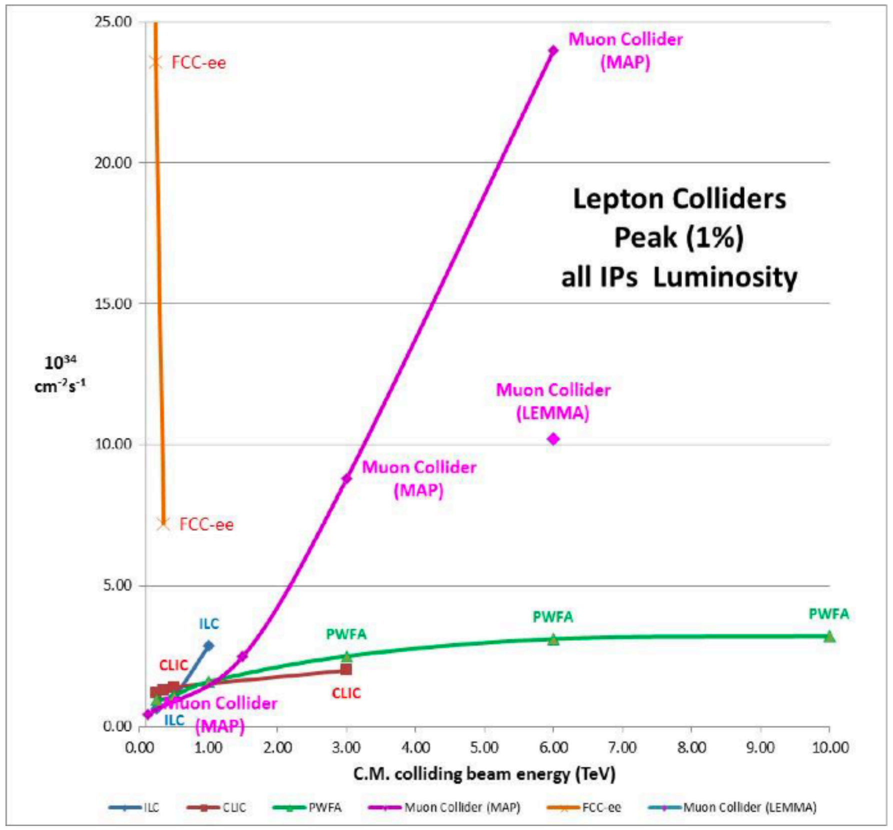
Bottom line:
FCC-hh and CLIC
always win…

What about muon colliders?

A Very High-Energy Muon Collider?

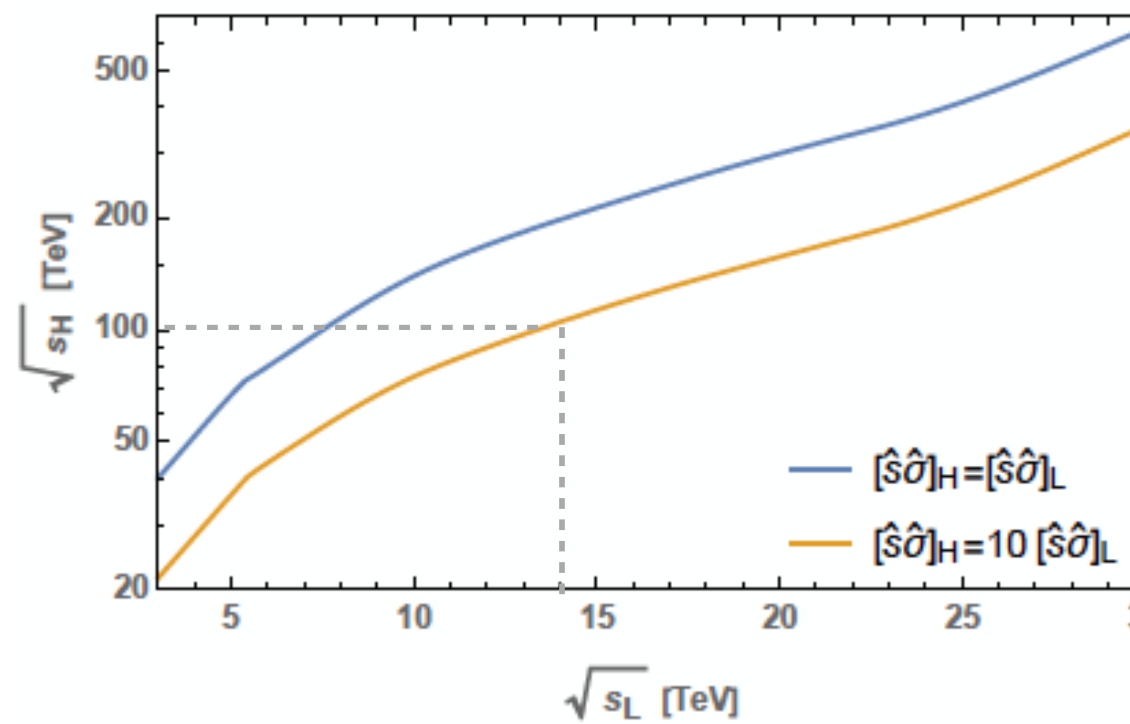


Let's have a dream…



J.P. Delahaye, DPhP seminar

★ … Imagine a muon collider at $\sqrt{s}$ = 14 TeV running for 5 years at $\mathscr{L} = 2\times10^{35}$ cm^{-2}s^{-1}

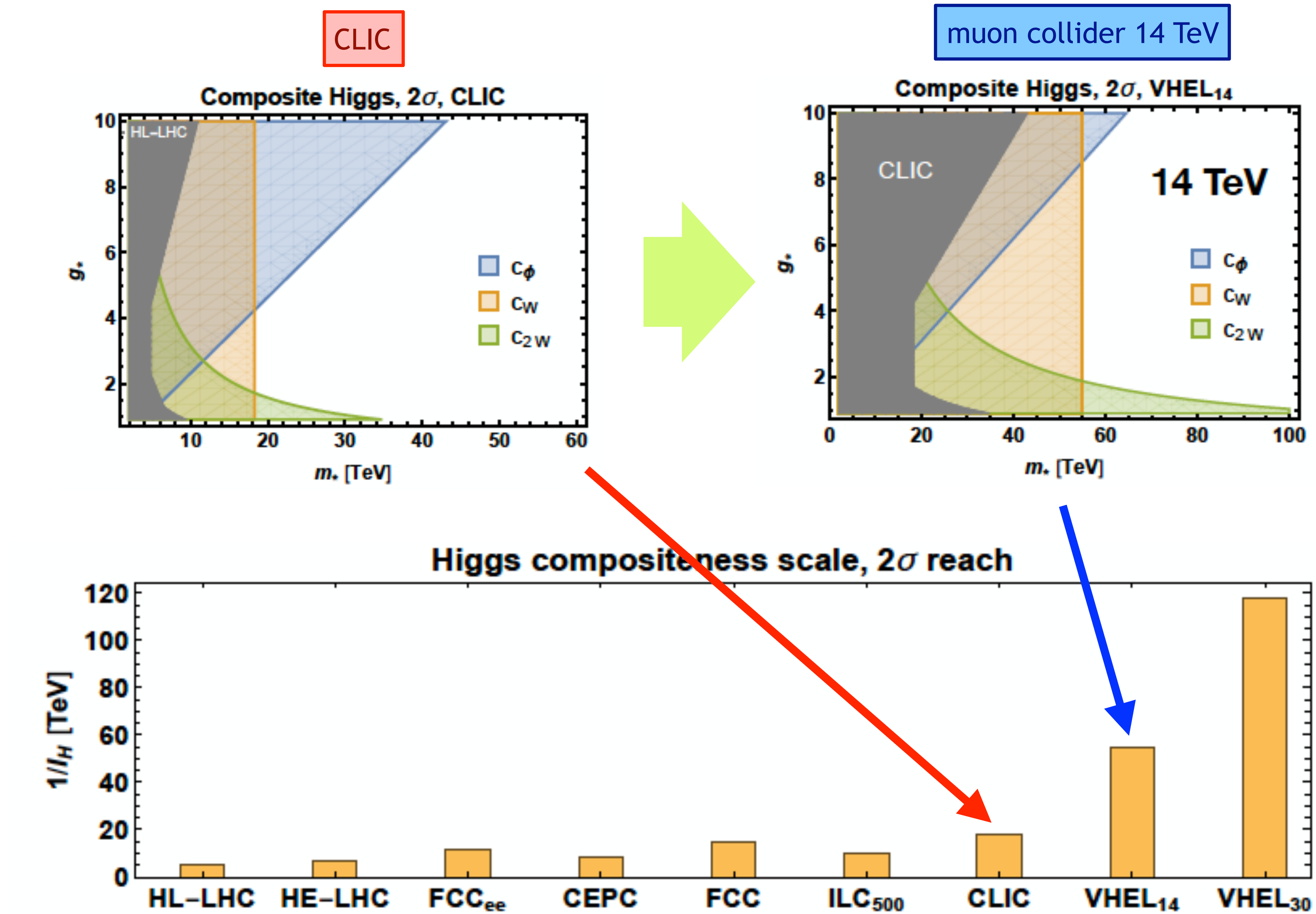


like CLIC… just ten times better!

A. Wulzer @ Granada EPPSU symposium 2019

- muon colliders are the only reasonable way to imagine high-energy high-luminosity lepton colliders
- in terms of BSM physics reach, a 14 TeV muon collider compares with a 100 TeV pp collider… but much cleaner!

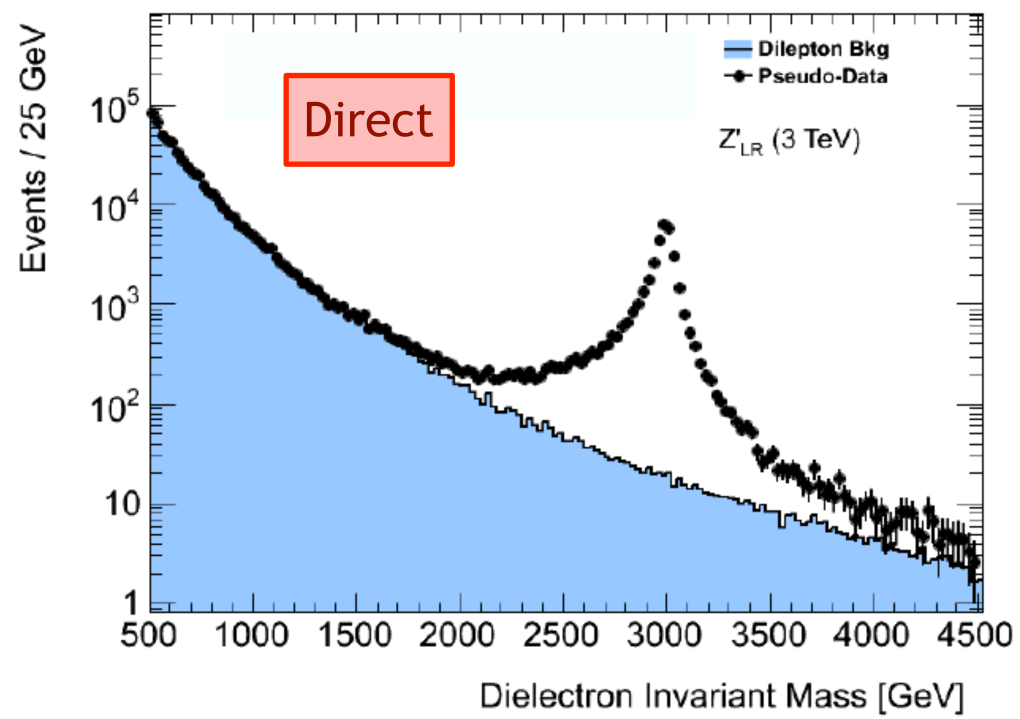
Higgs Compositness at Muon Collider



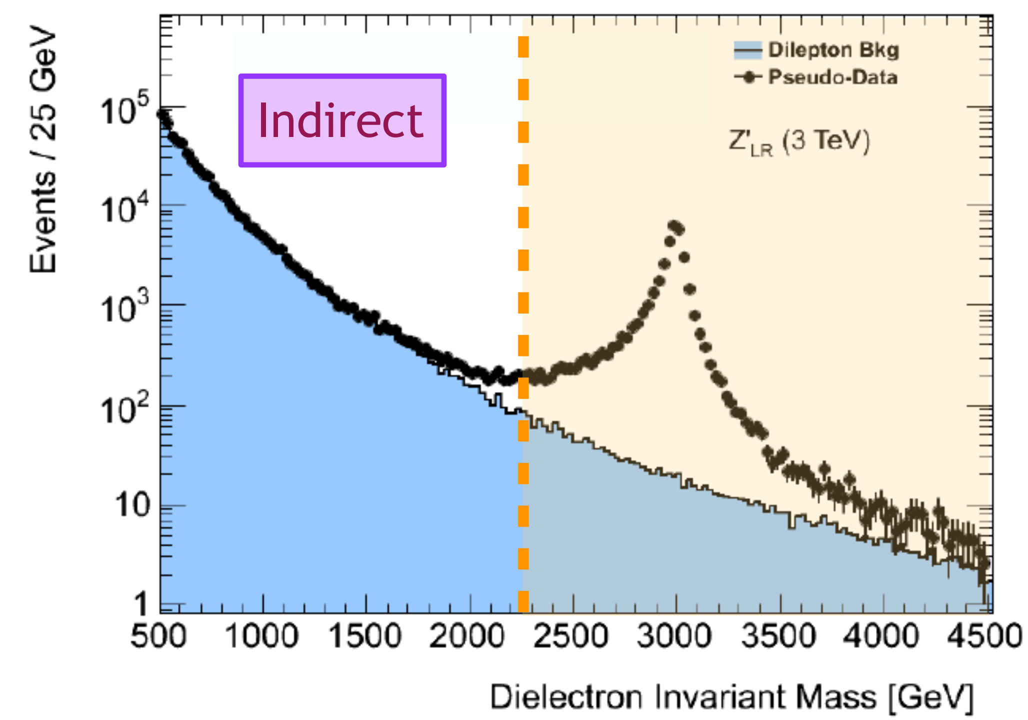
A. Wulzer @ Granada EPPSU symposium 2019

New Resonances, Particles or Forces

Question: is there a new very-short distance force on top of the electroweak and strong forces?



Z' resonance seen
in the dilepton spectrum



no resonance seen
but *deviations* wrt SM

Seeking a peak

- M < √s for lepton colliders
- M < 0.3-0.5 √s for hadron colliders, assuming "weak" couplings

Deviation in high-mass tails

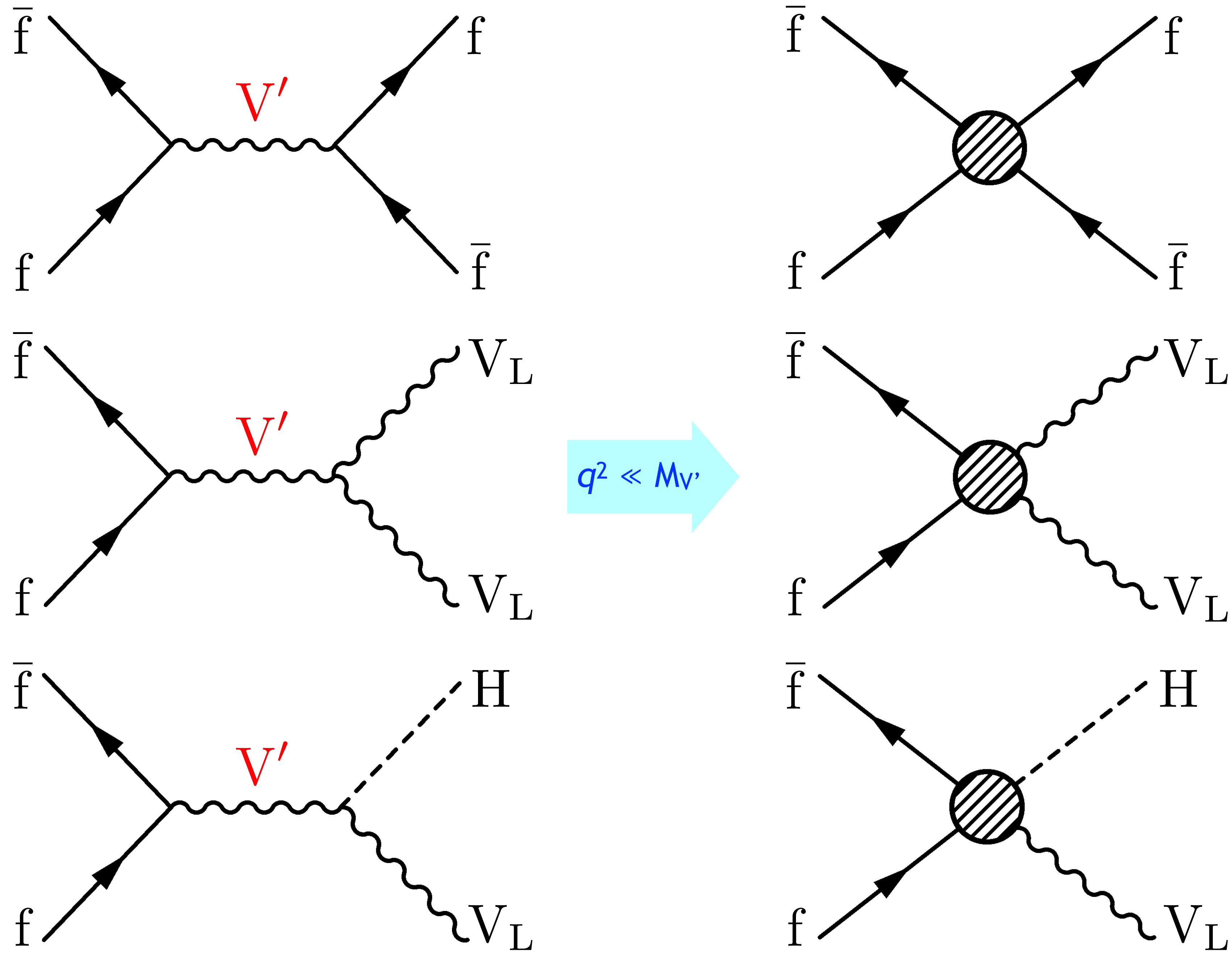
- lepton colliders: sensitive to ratio [mass/coupling] ≫ √s
- hadron colliders: only relevant if $g_{Z'} > g_{SM}$
  ➠ [mass/coupling] ≫ 0.5√s

J. de Blas @ EPPSU symposium, Granada 2019
J. Alcaraz @ EPPSU symposium, Granada 2019

High-Energy Probes

- ☛ example: new W', Z' vector bosons
- ☛ at low-energy typically accounted for by dimension-6 operators interfering with SM processes
- ☛ effects grow like center-of-mass energy squared of the collision

$$\propto \frac{s}{\Lambda^2}$$



➠ new resonance in the corresponding spectra

➠ excites the corresponding contact interaction operators in EFT fit

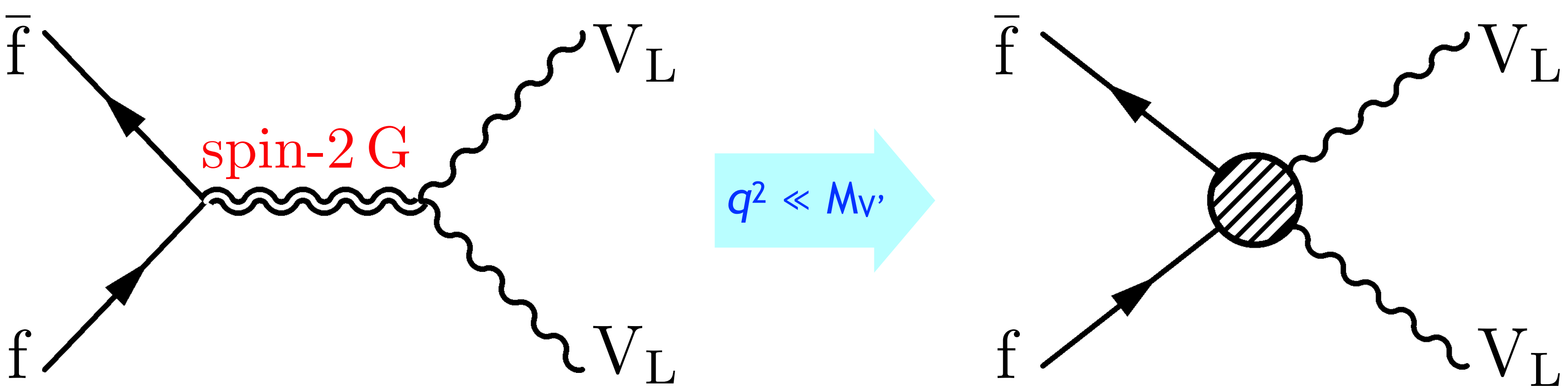
High-Energy Probes

- another example: spin-2 graviton

- at low-energy: dimension-8 operators

- grow with center-of-mass energy as

$$\propto \frac{s^2}{\Lambda^4}$$



due to huge growth with energy, can show up at high-energy colliders even in the absence of deviations at low energy

Heavy Bosons Benchmark Models

☛ **Sequential Standard Model (SSM)**

- simple model as benchmark to compare sensitivities of experiments
- massive W' and Z' bosons with couplings to fermions identical to SM W and Z bosons

☛ **Y-Universal Z' model**

- another "simple" model with a new Heavy Dark Photon Z'
- massive U(1) gauge symmetry
- charges equal to SM hypercharge

$$\mathscr{L} = -\frac{1}{4g_{Z'}^2}\left(Z'_{\mu\nu}\right)^2 - \frac{1}{4g'^2}\left(B_{\mu\nu} - Z'_{\mu\nu}\right)^2 + \frac{M_{Z'}^2}{2g_{Z'}^2}\left(Z'_{\mu}\right)^2$$

B field: generator of $U(1)_Y$ SM symmetry (coupling = g')

Direct searches at high-energy

- most sensitive: dilepton spectra

Indirect searches at low energy:

- one single ("universal") operator, known as Y-Universal

$$-\frac{g_{Z'}^2}{2g'^2 M_{Z'}^2}\left(\partial^\mu B_{\mu\nu}\right)^2$$

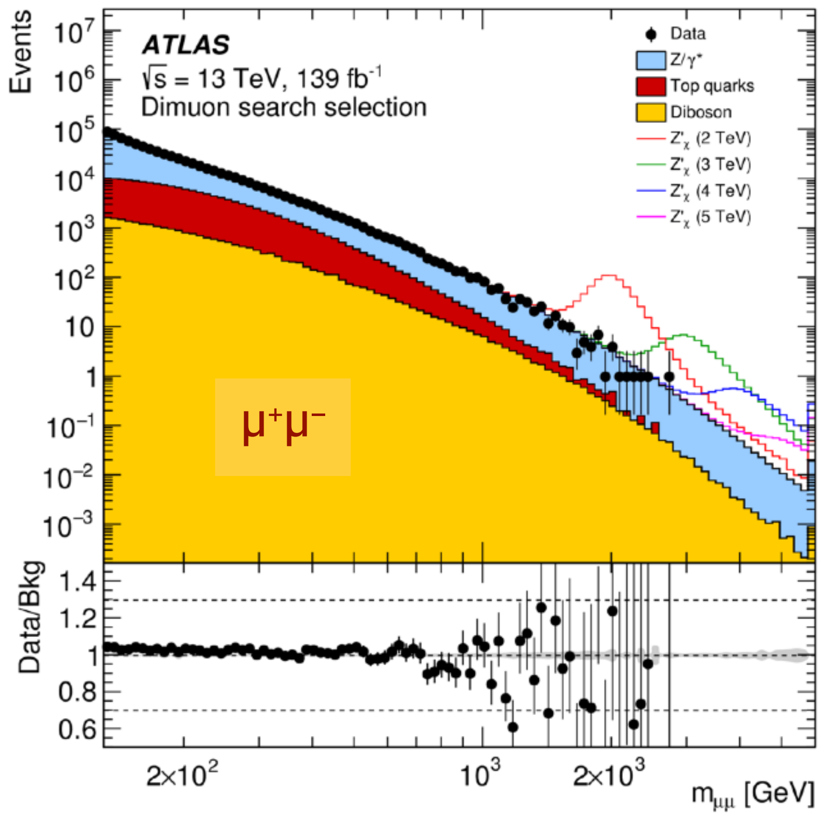
also known as c_{2B}

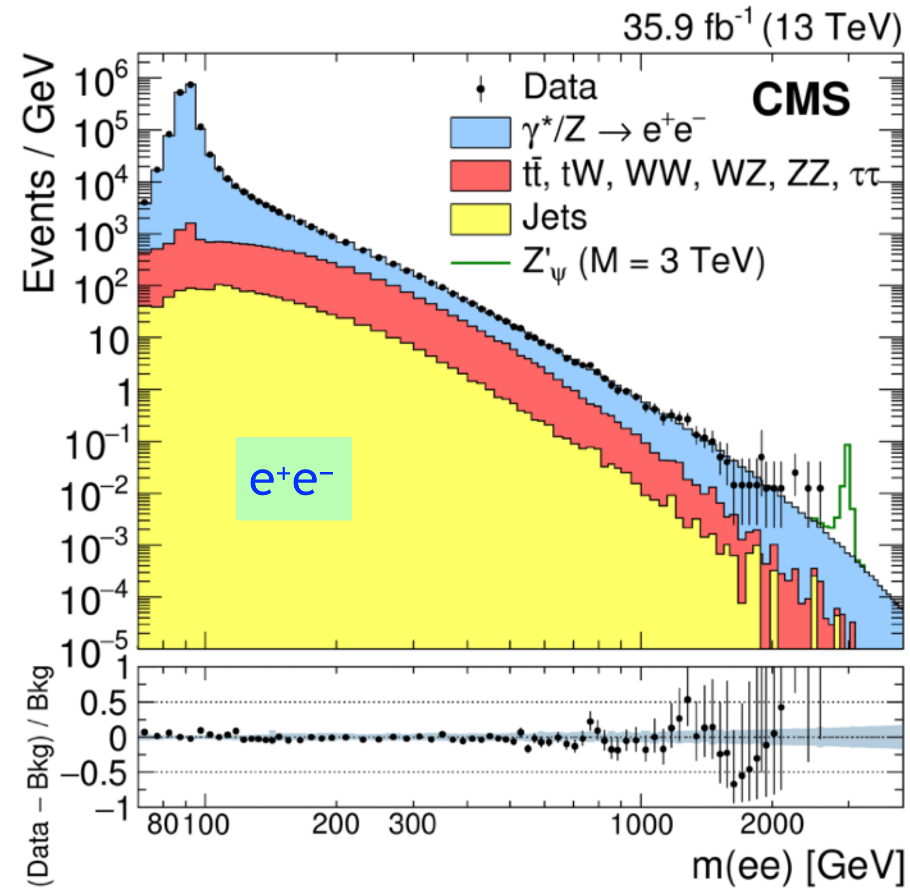
$$\frac{c_{2B}}{\Lambda^2} = \frac{g_{Z'}^2}{g'^4 M_{Z'}^2} = \frac{Y}{g'^2 m_W^2}$$

many other models with flavour dependence, etc.

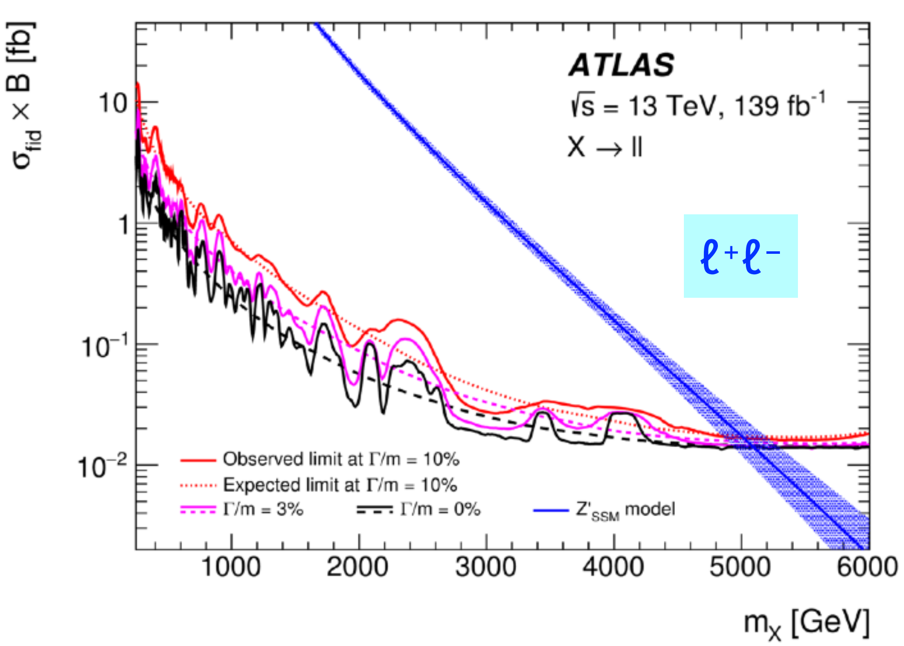
Direct Search for Resonances at LHC

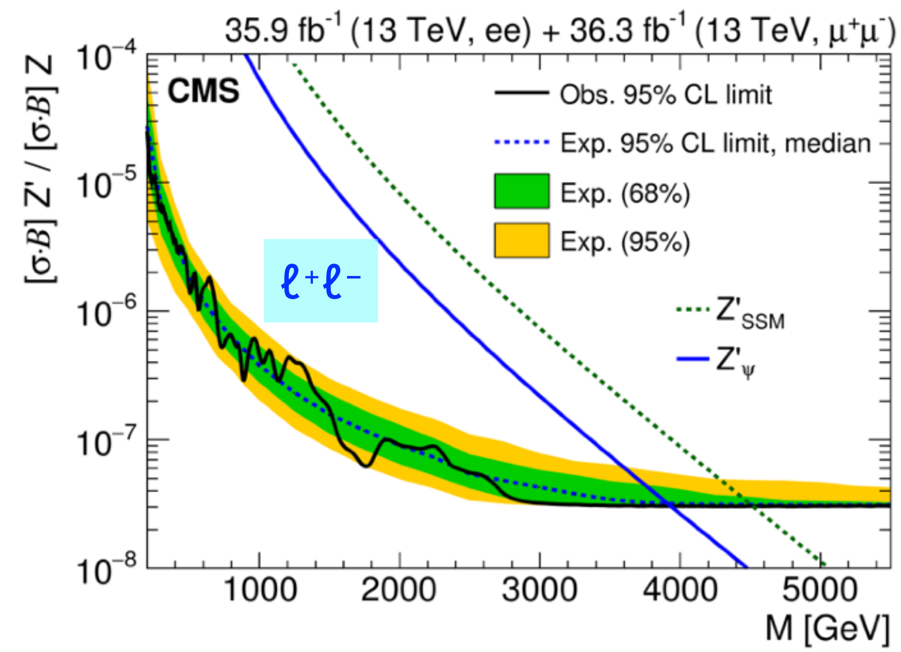
ATLAS Run-2
13 TeV
L = 139 fb^{-1}





CMS 2016
13 TeV
L = 36 fb^{-1}





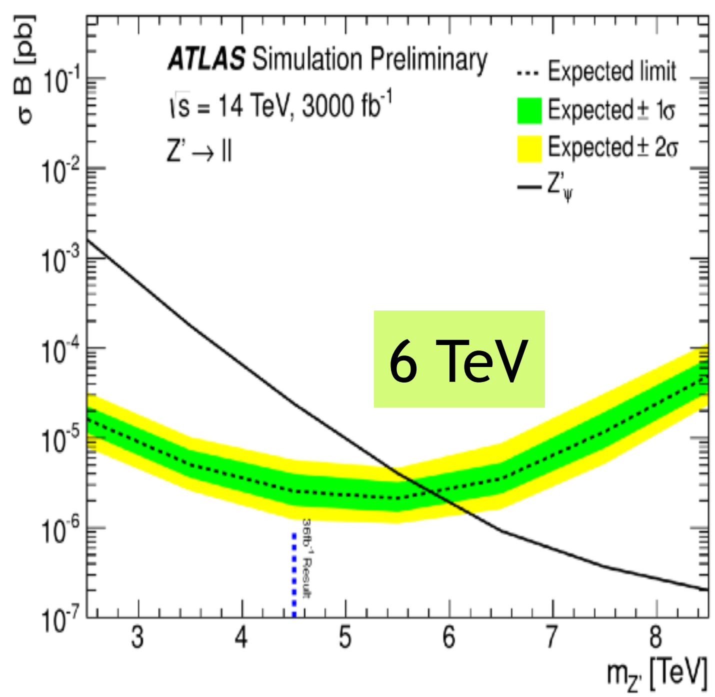
Typical
Run-2 limits
on Z' : 5 TeV

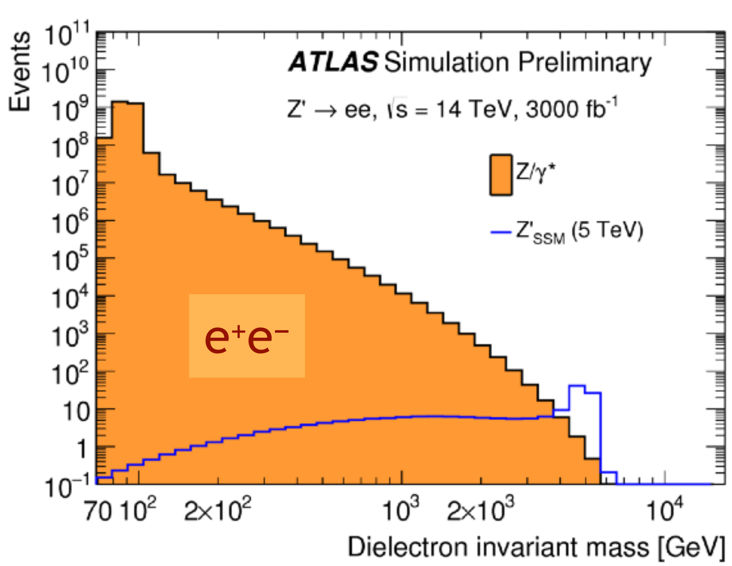
Phys. Lett. B 796 (2019) 68

JHEP 06 (2018) 120

Direct Search for Resonances LHC → FCC

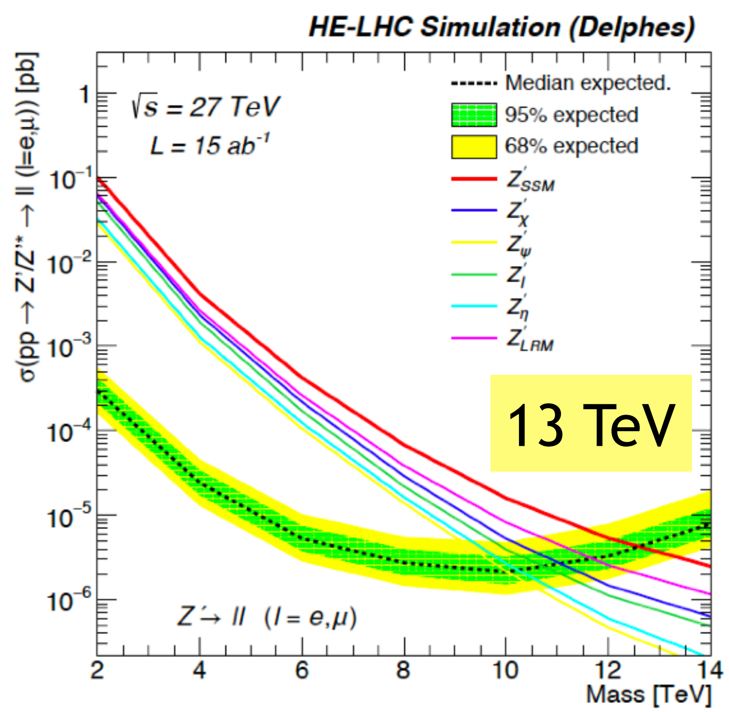
HL-LHC

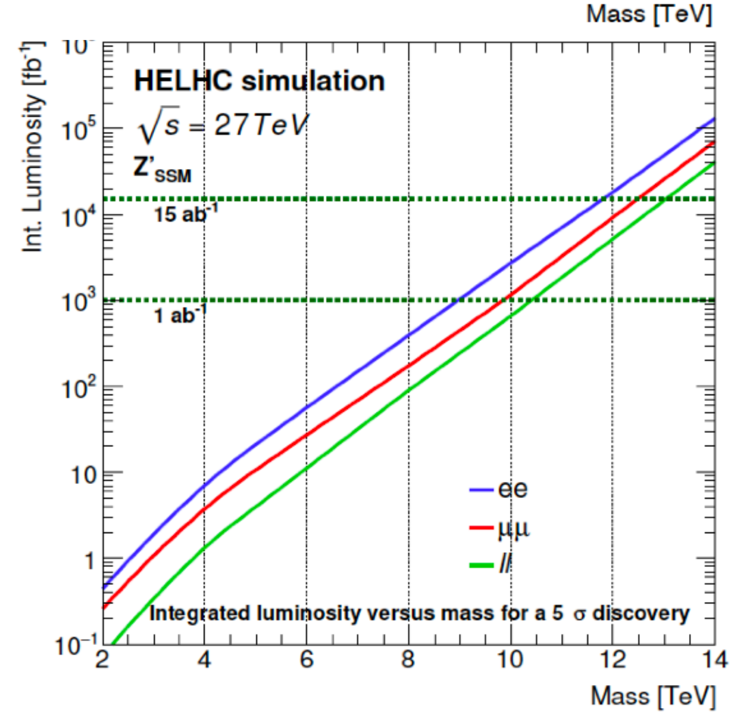




ATL-PHYS-PUB-2018-044

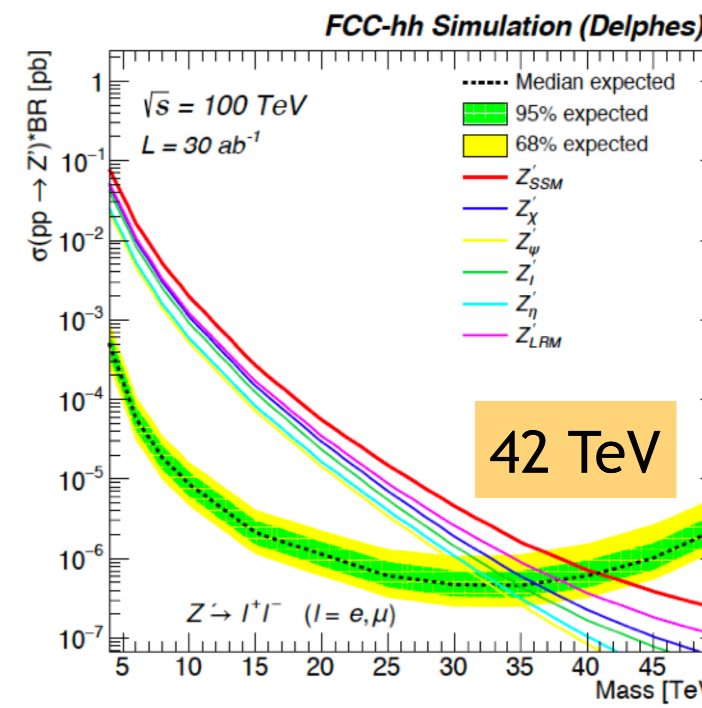
HE-LHC

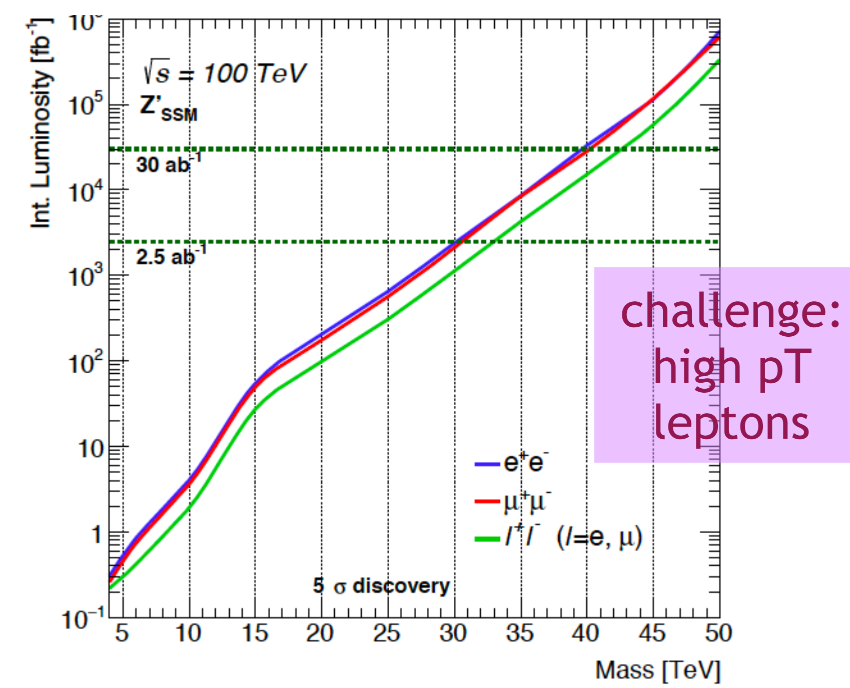




HL/HE-LHC (2018) BSM
arxiv:1812.07831

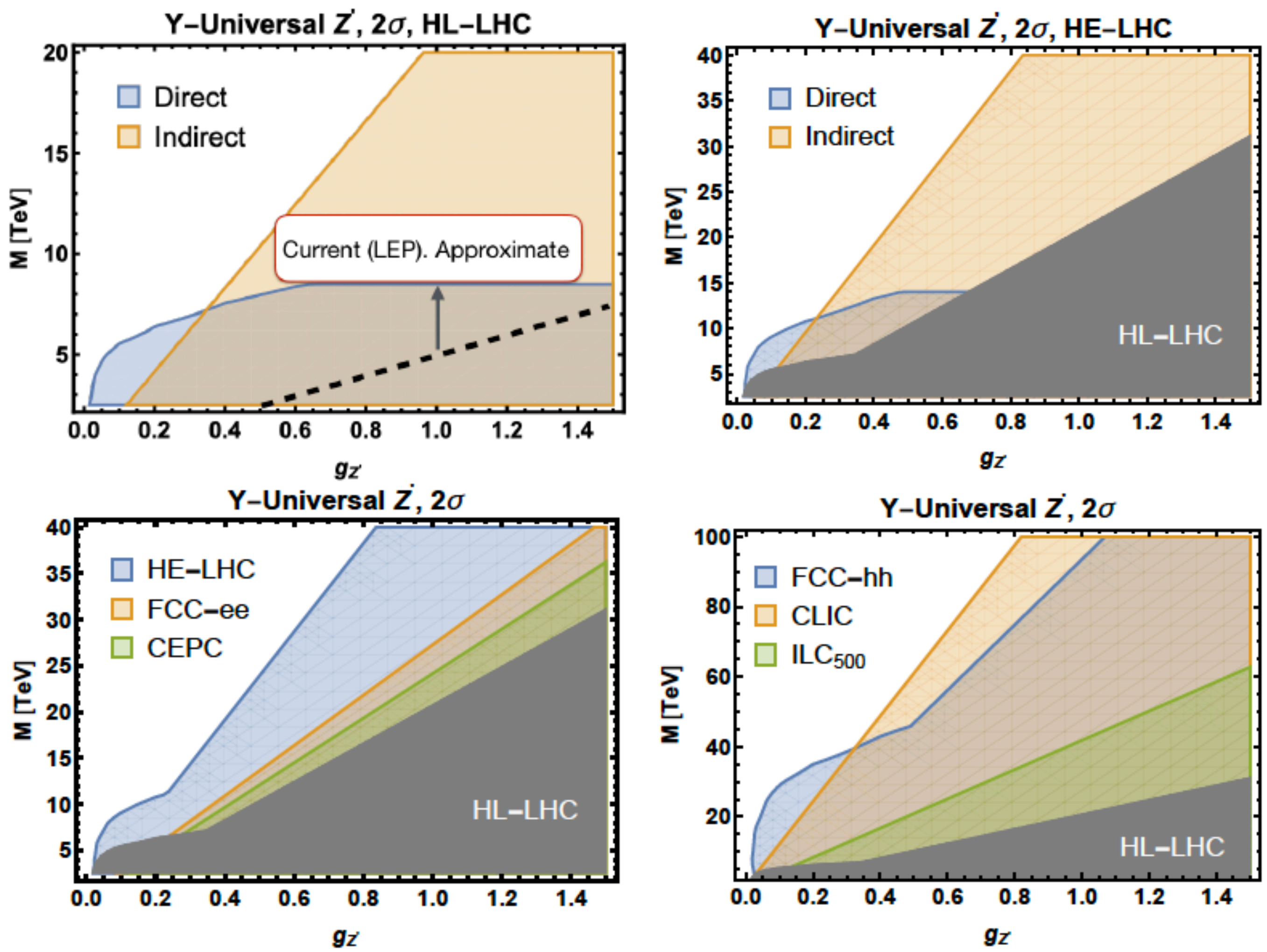
FCC-hh





C. Helsens et al. (2019)
arxiv:1902.11217

Z' Constraints at Future Colliders

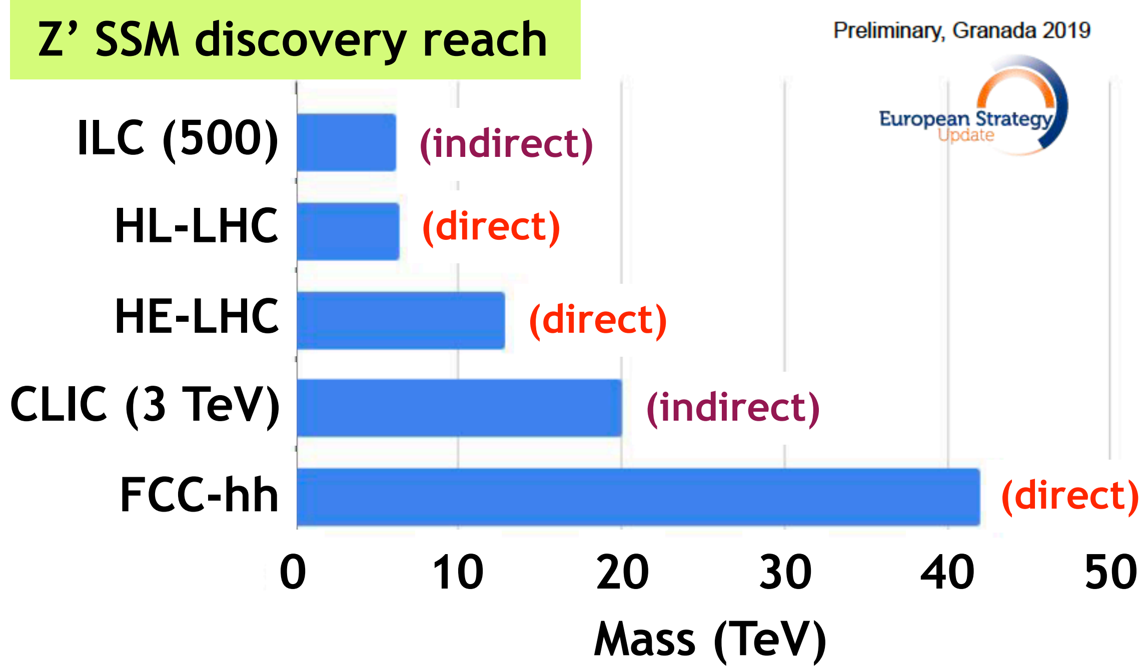


Best reach
- direct: FCC-hh
- indirect: CLIC 3-TeV

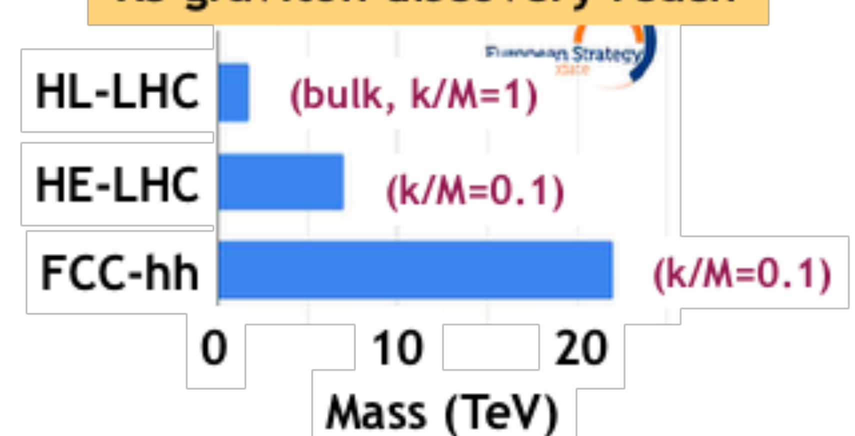
This is an example where high-energy makes a difference even for indirect constraints

- certain operators vary like v^2/Λ^2, precision probes large Λ (e.g. anomalous Higgs couplings)
- other operators vary like Q^2/Λ^2, those probe large Λ even with moderate precision

Z' SSM discovery reach



RS graviton discovery reach

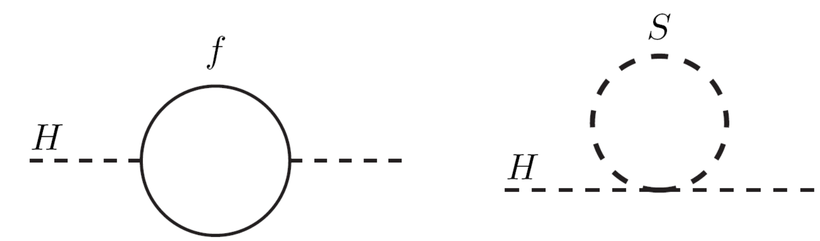


Supersymmetry

Supersymmetry: a family of weakly-coupled theoretical models that give solutions to the Naturalness problem, realise unification at the GUT scale, and, in certain realisations, provide a candidate of Dark Matter (R-parity conserving SUSY)

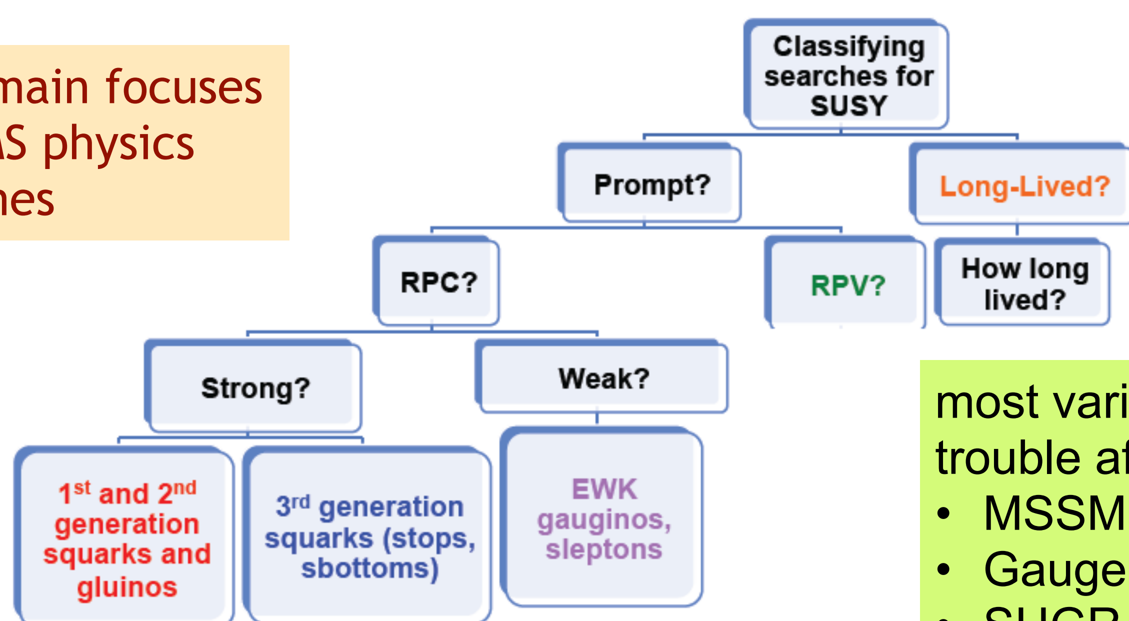
Spin 0	Spin 1/2	Spin 1	Spin 3/2	Spin 2
sleptons	leptons		gravitino	graviton
squarks	quarks			
Higgs	Higgsino			
	photino	photon		
	Zino	Z		
	Winos	W+ W-		
	gluinos	gluons		

SUSY is a fundamental space-time symmetry between fermions and bosons that regularises the Higgs boson mass



- each SM particle has a SUSY partner
- at which scale is SUSY broken?

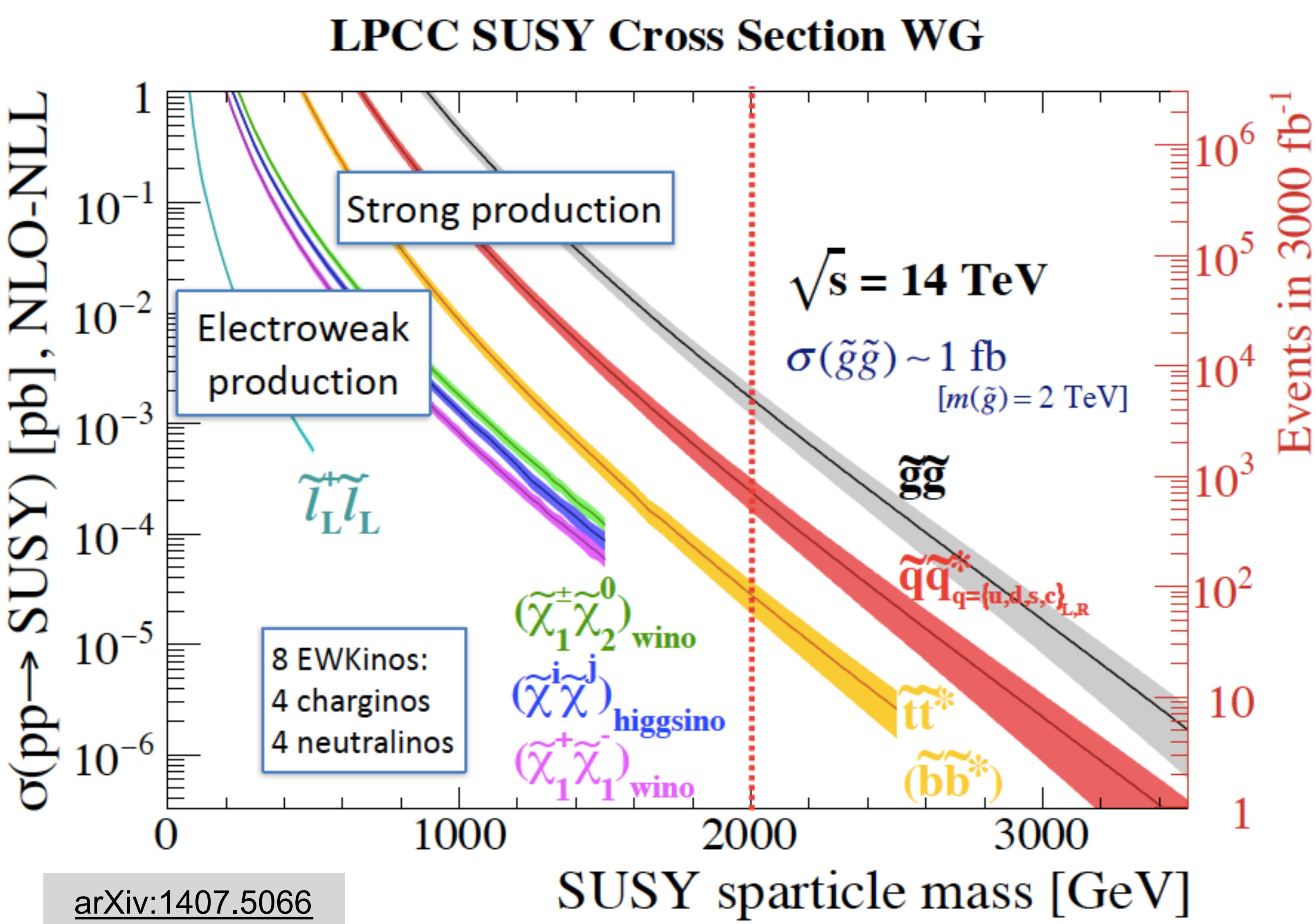
SUSY is one of the main focuses of ATLAS and CMS physics programmes



SUSY has an extended Higgs sector, for instance 2HDM as in MSSM
- CP even: h and H
- CP odd: A
- charged: H^+ and H^-

most variants of SUSY are in trouble after LHC Run-1 and-2
- MSSM, NMSSM, …
- Gauge Mediation
- SUGRA
- Stealth SUSY,
- etc.

SUSY Production



arXiv:1407.5066

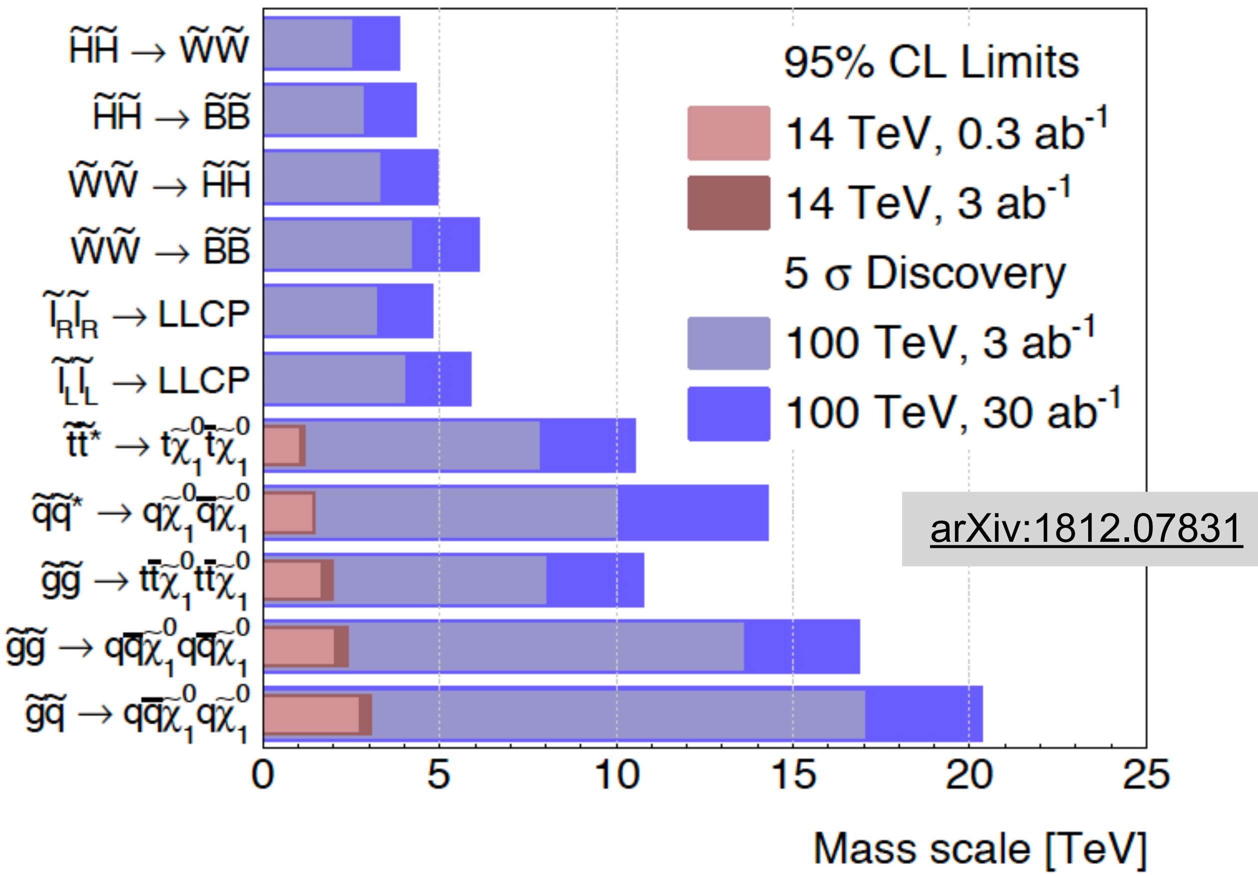
Strong production
- gluinos
- squarks of 1st and 2d generations
- top and bottom squarks

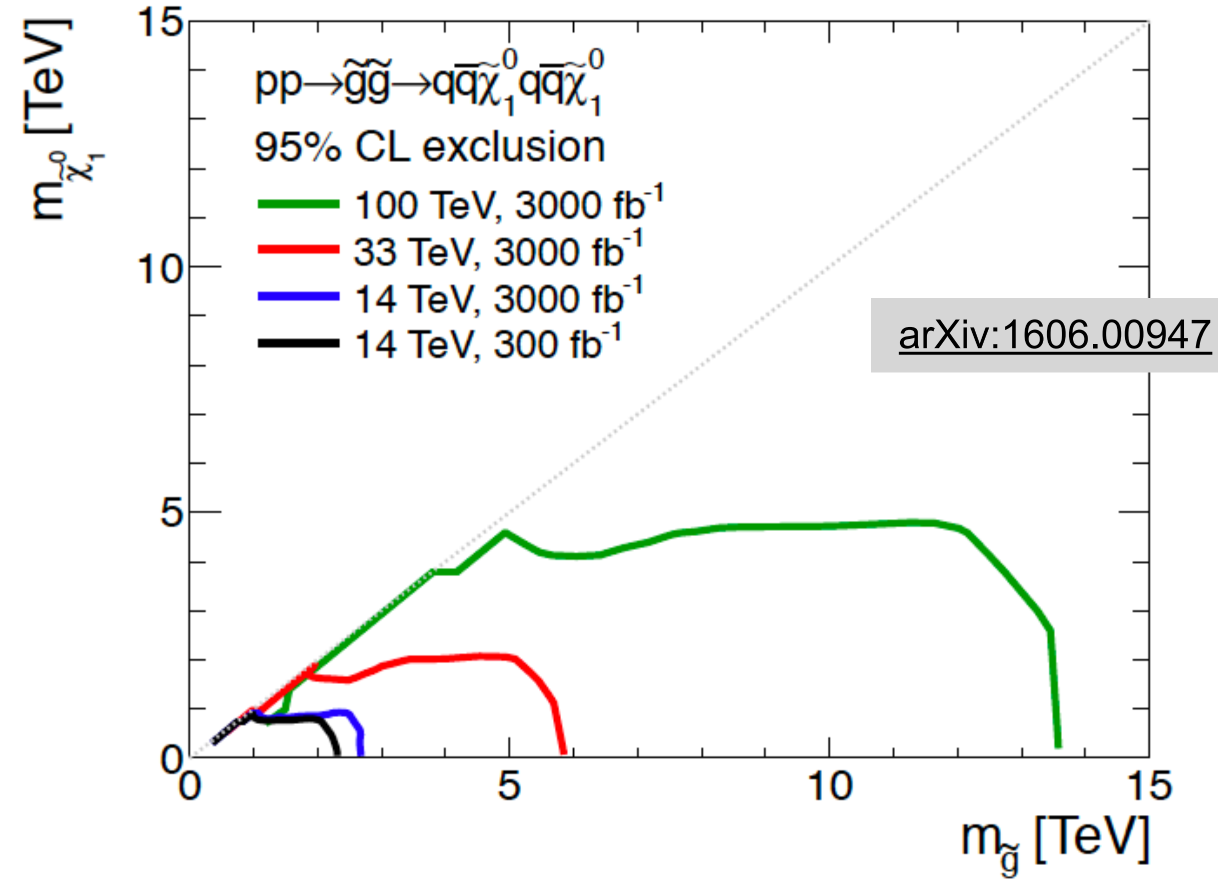
Electroweak production
- neutralinos
- charginos
- sleptons

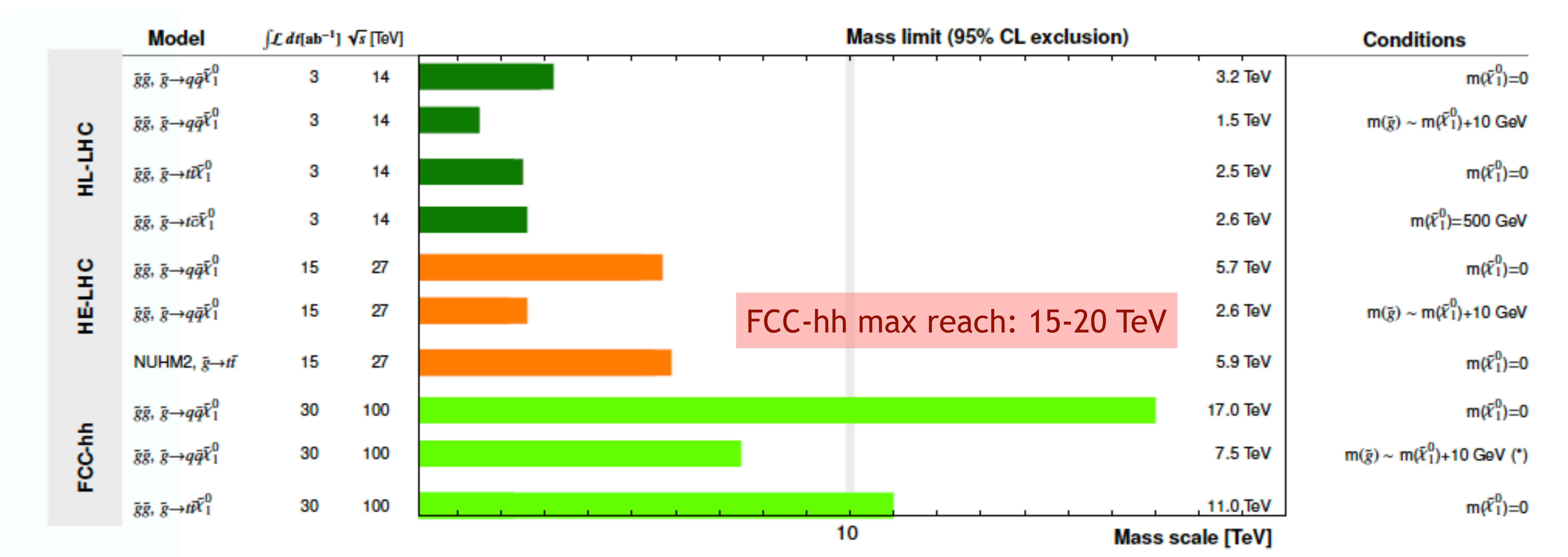
SUSY signatures
- R-parity conserving
  - large transverse missing energy
- R-parity violating
  - feebly interacting or non-prompt

If you believe in SUSY:
- direct searches are more powerful than precision constraints because SUSY is weakly coupled
- lepton colliders will provide limited improvement
- high-energy proton colliders bring significant improvement in direct coverage

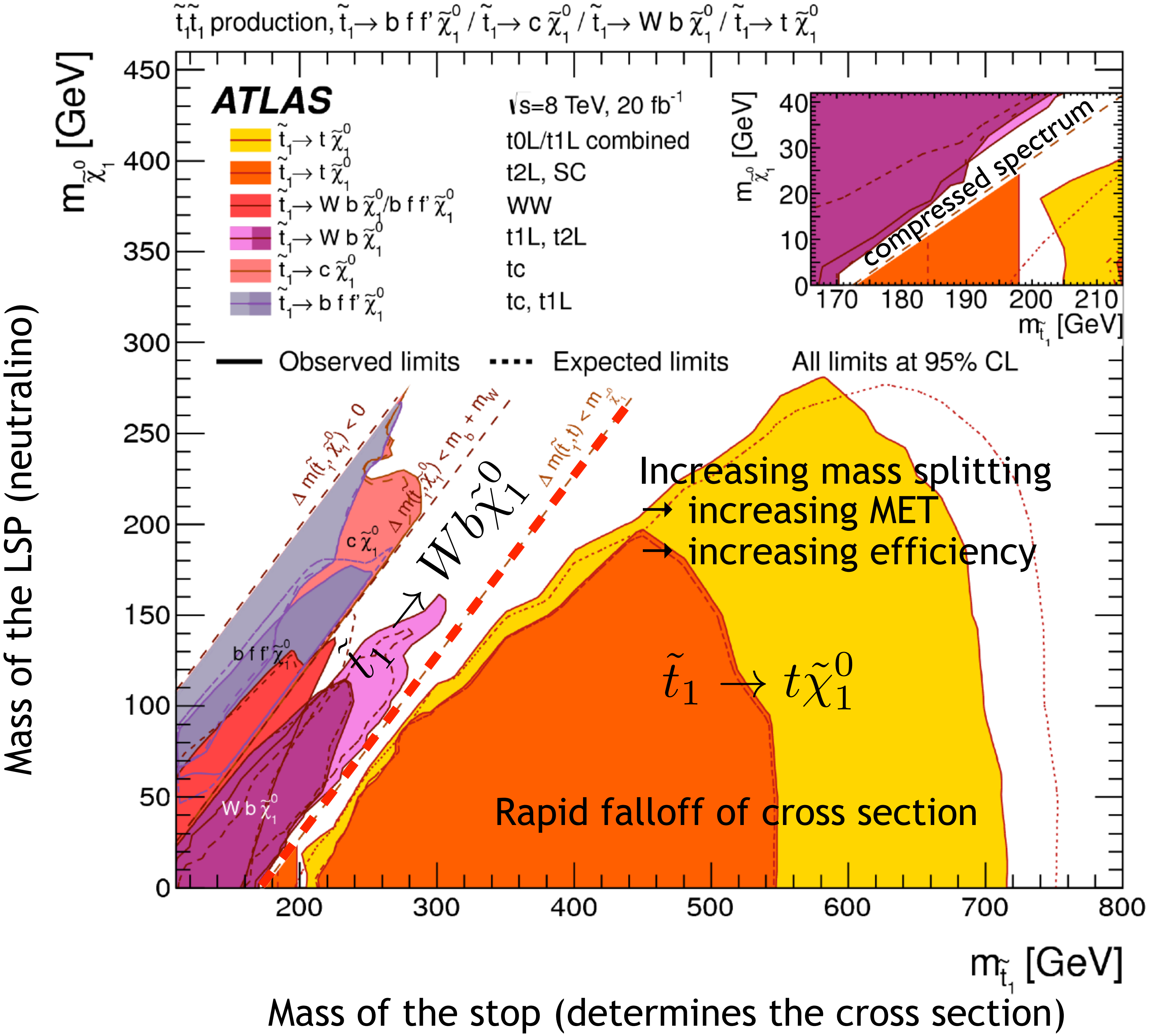
Gluino Searches



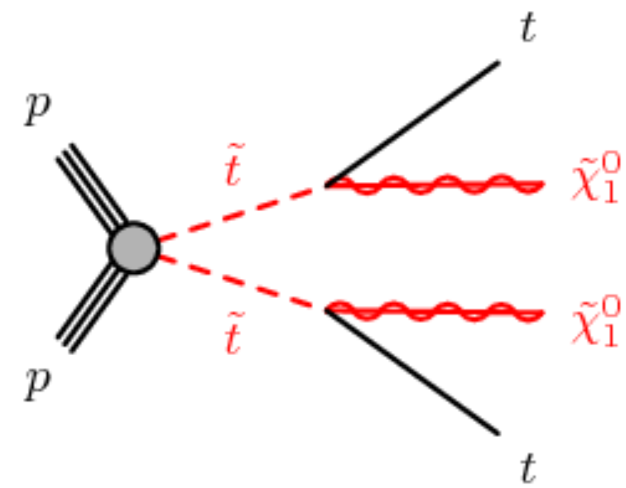




Example of Stop Exclusion Plot



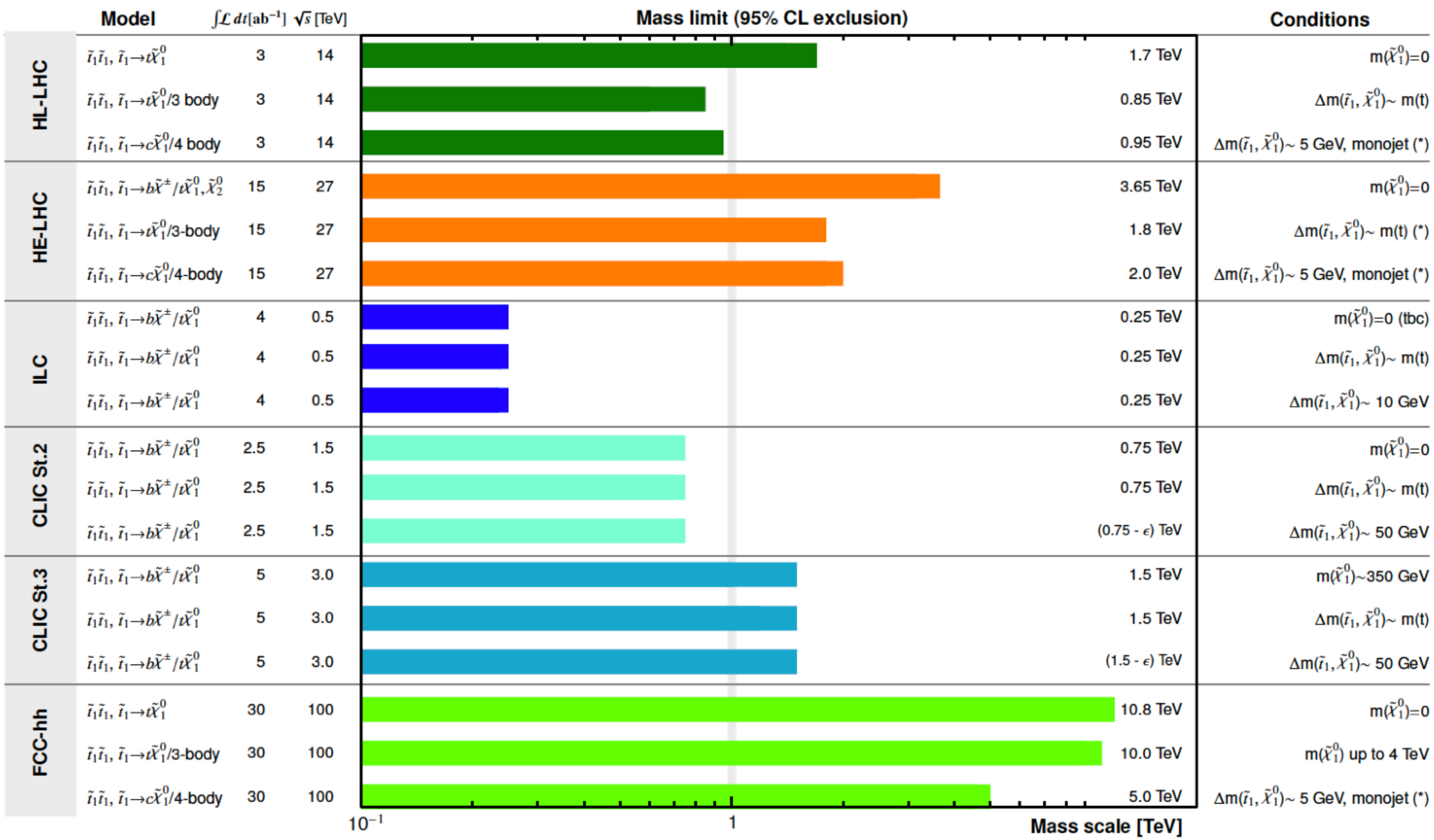
$$pp \to \tilde{t}_1\tilde{t}_1$$



Limits extend to m(stop) ≈ 700 GeV for low-mass LSP

No limit on m(stop) for m(LSP) > 275 GeV

Stop Searches



discovery potential

HL/HE-LHC
up to 1.4/3.2 TeV

ILC/CLIC
up to √s/2

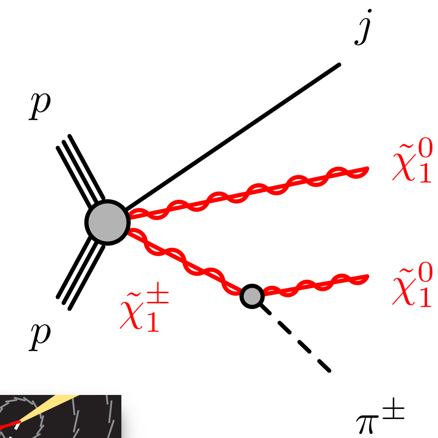
FCC-hh
up to 8 TeV

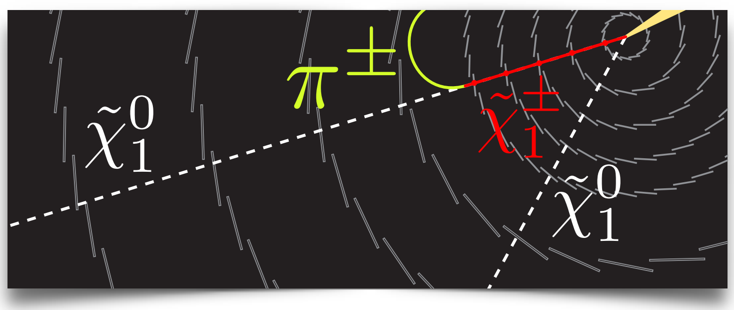
SUSY can/will never die... but if no stop is found at future colliders, SUSY cannot serve its main purpose, which is to solve the Naturalness problem

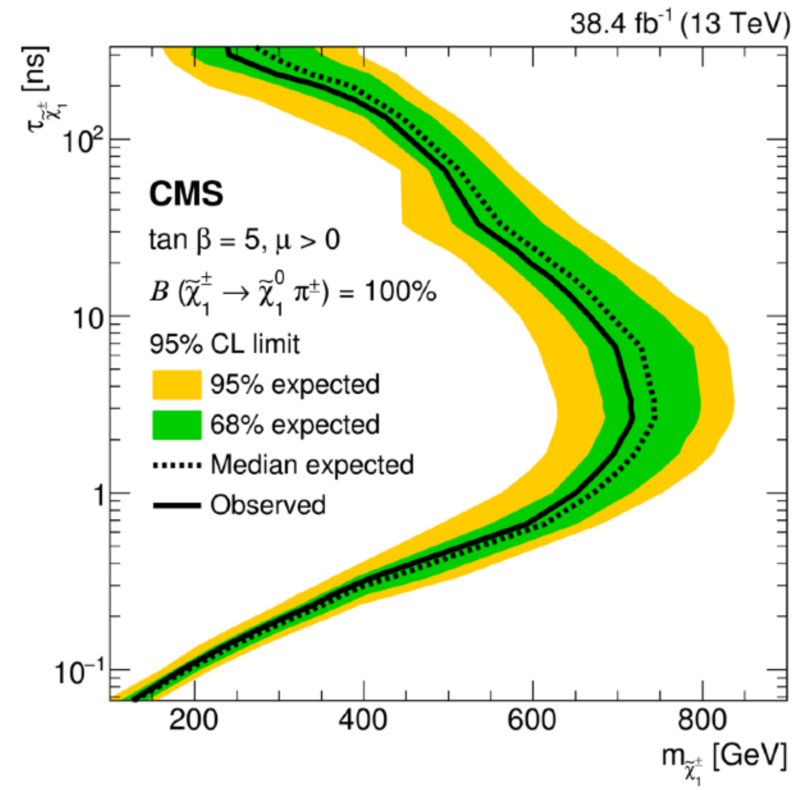
Disappearing Tracks

Example: Wino-like DM

$$\chi = \begin{pmatrix} \chi^+ \\ \chi^0 \\ \chi^- \end{pmatrix}$$ dark matter

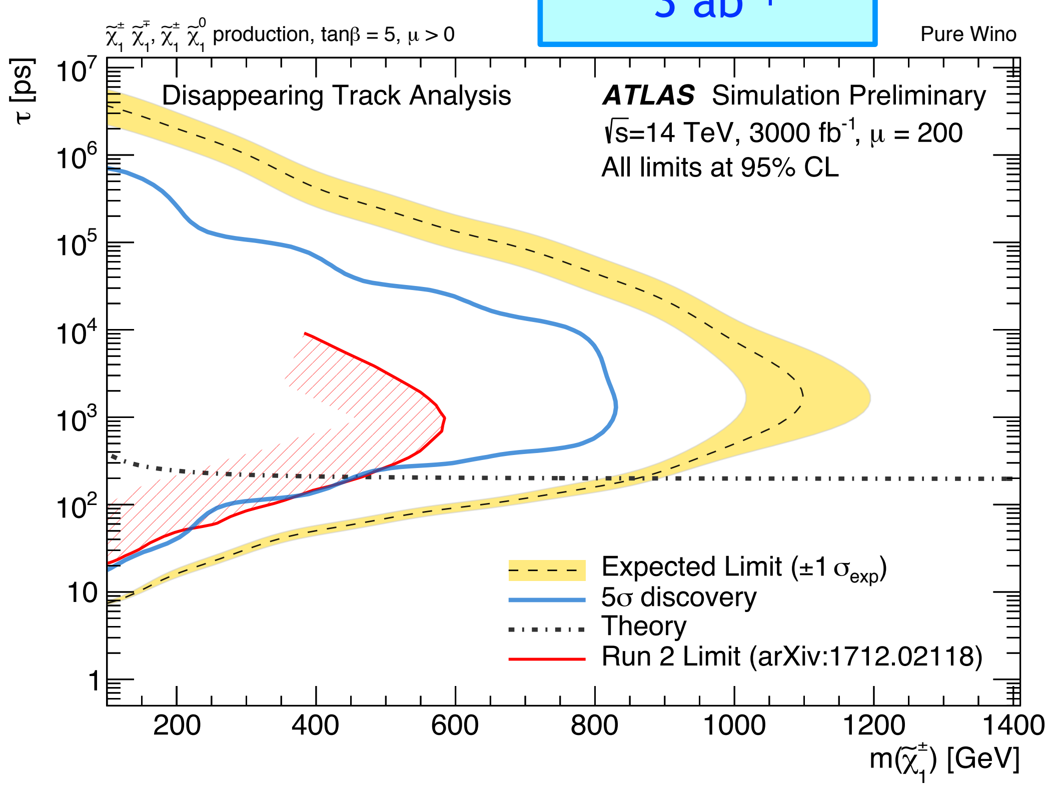


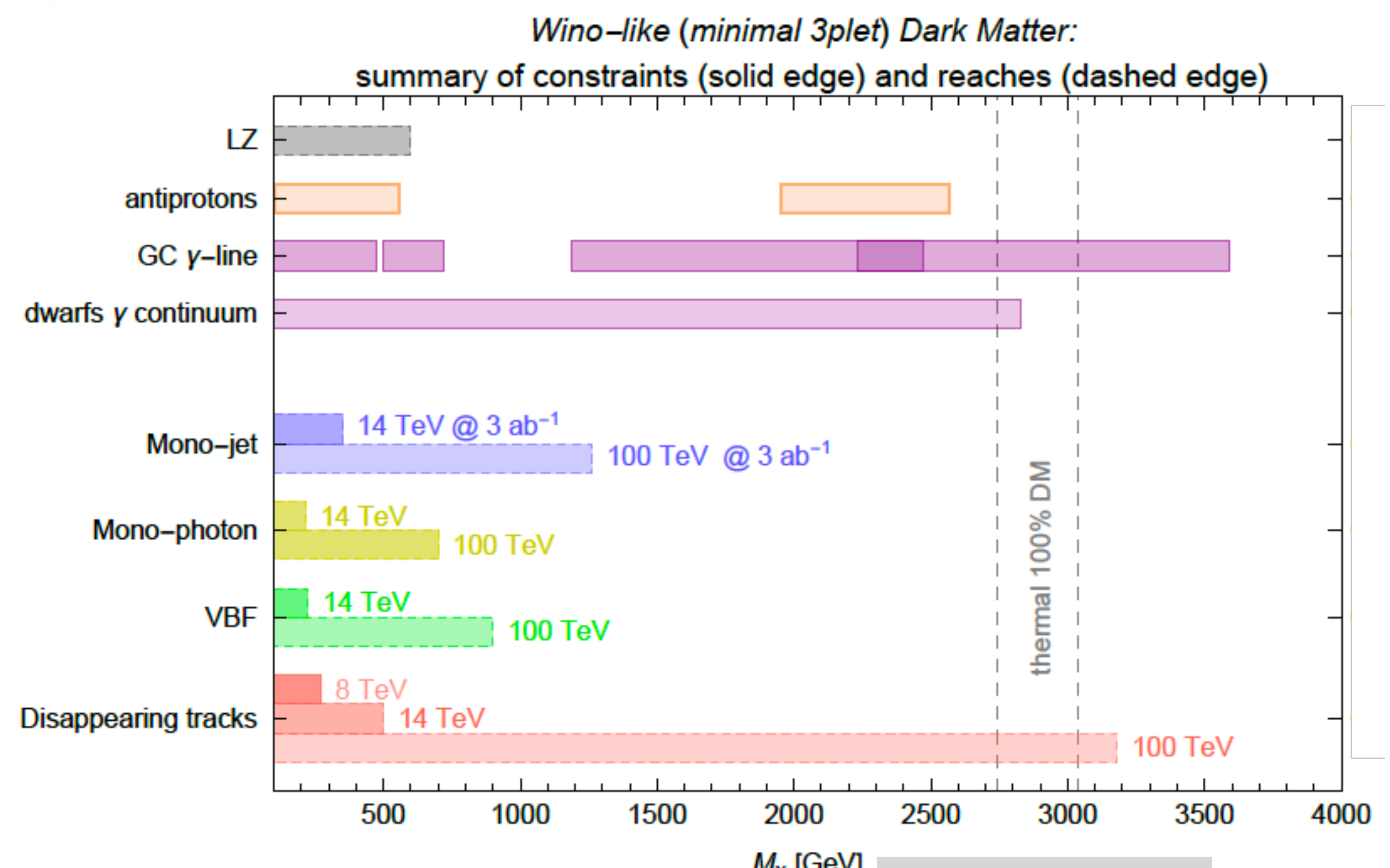




CMS 2016
13 TeV
L = 36 fb^{-1}

ATLAS HL-LHC
3 ab^{-1}

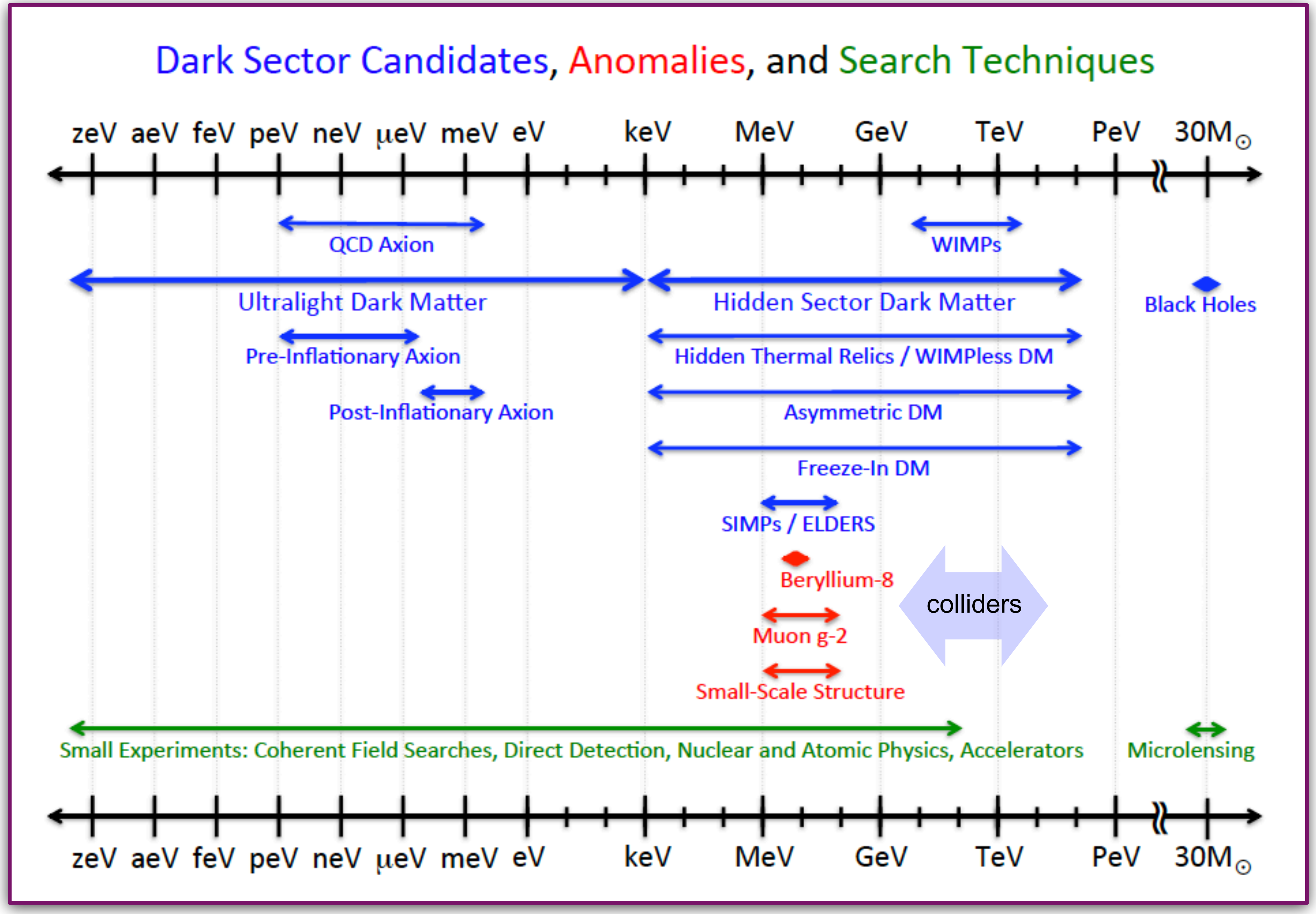




M. Cirelli et al.
arXiv:1407.7058

Dark Matter: The Log Crisis

Our ignorance of Dark Matter is logarithmic!



Mass ranges for dark matter and mediator particle candidates, experimental anomalies, and search techniques

arXiv:1707.04591

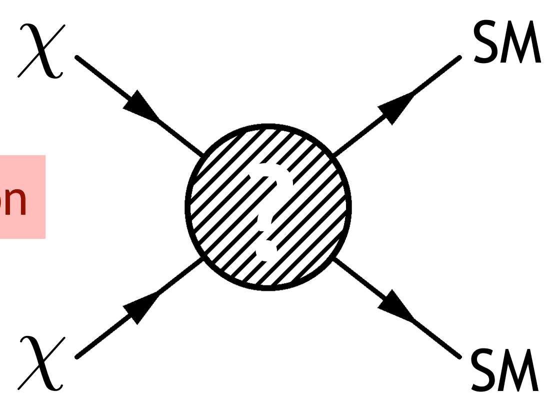
Thermal WIMPs

WIMP = weakly-interacting massive particle

WIMP scenario: the relic density of Dark Matter is set by non-relativistic annihilation (freeze-out) to SM particles, either through

- a SM portal (e.g., the Higgs boson)
- a new mediator (consider scalar, pseudoscalar, vector or axialvector mediators)

co-annihilation



the WIMP miracle?

g_{eff} = effective coupling strength

$$<\sigma v> \sim g_{\mathrm{eff}}^4 / M_{\mathrm{DM}}^2$$

arXiv:1606.00947

From cosmology: thermal freeze-out

$$\Omega_{\mathrm{DM}} h^2 \sim 0.12 \times \left(\frac{M_{\mathrm{DM}}}{2\,\mathrm{TeV}}\right)^2 \left(\frac{0.3}{g_{\mathrm{eff}}}\right)^4$$

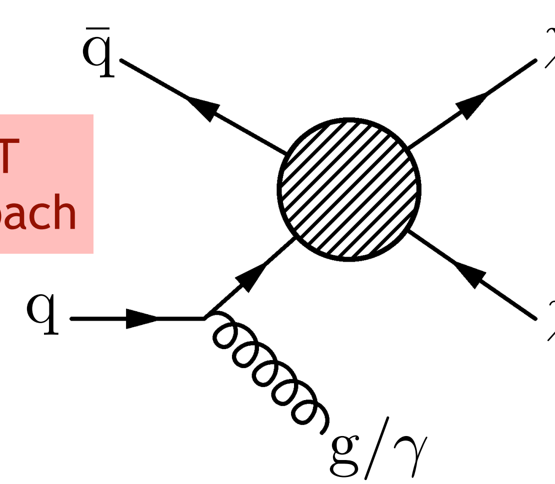
WIMPs can account for relic abundance for masses in the few GeV to few TeV range

At colliders: the recoil method

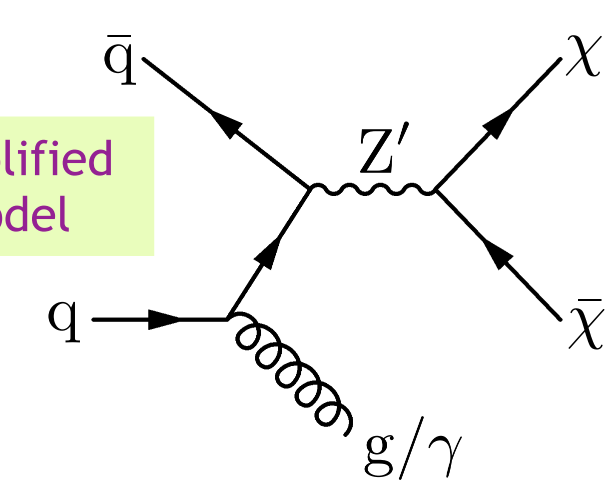
- the DM particle are pair-produced with a radiated SM particle
- main background: $Z \to \nu\bar{\nu}$

and 2 approaches

EFT approach



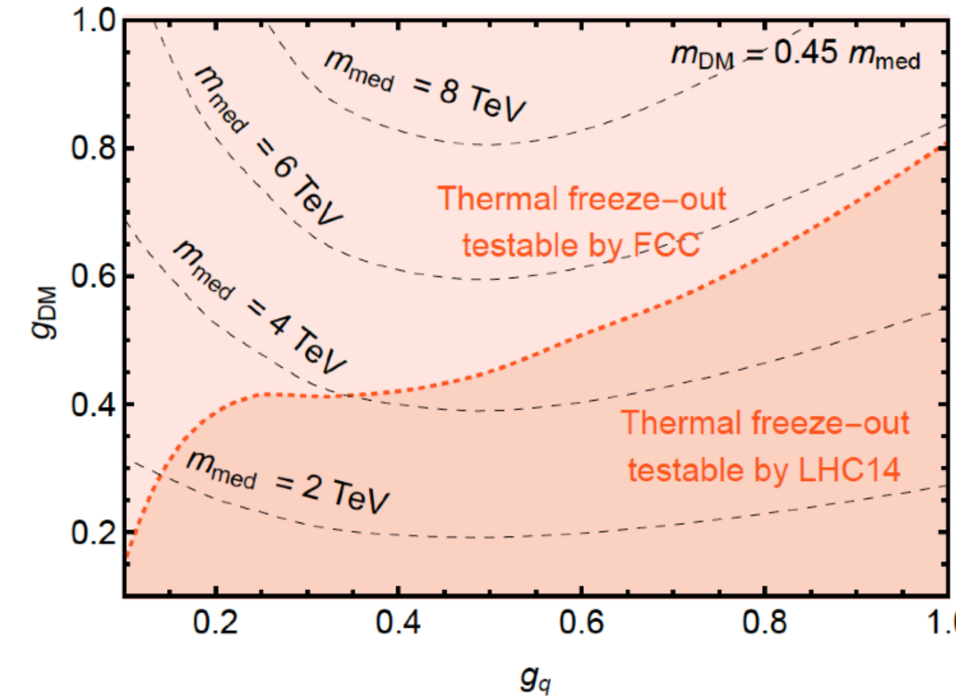
Simplified Model



A Simplified Dark Matter Model

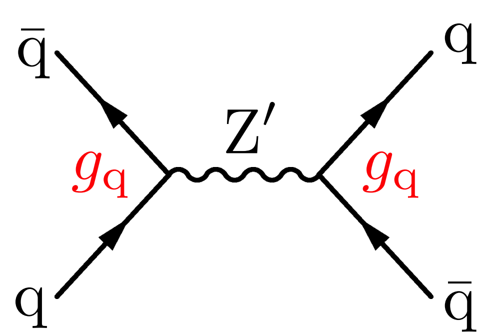
Consider a simple model where Dark Matter interacts via a new Z' boson

- the WIMP is a Majorana fermion
- the mediator Z' has only vector couplings to the SM quarks

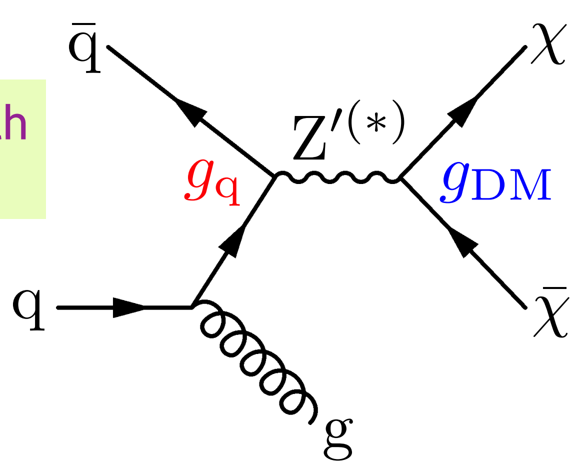


➠ no constraints from EWPO & dilepton resonance searches
➠ only relevant if no direct DM detection

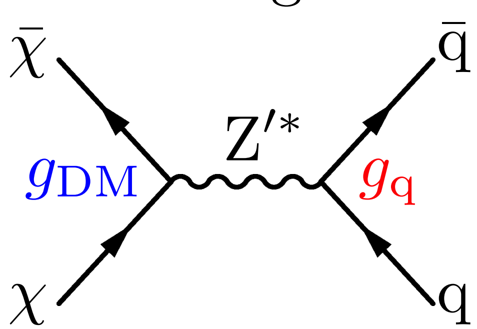
di-jet resonance

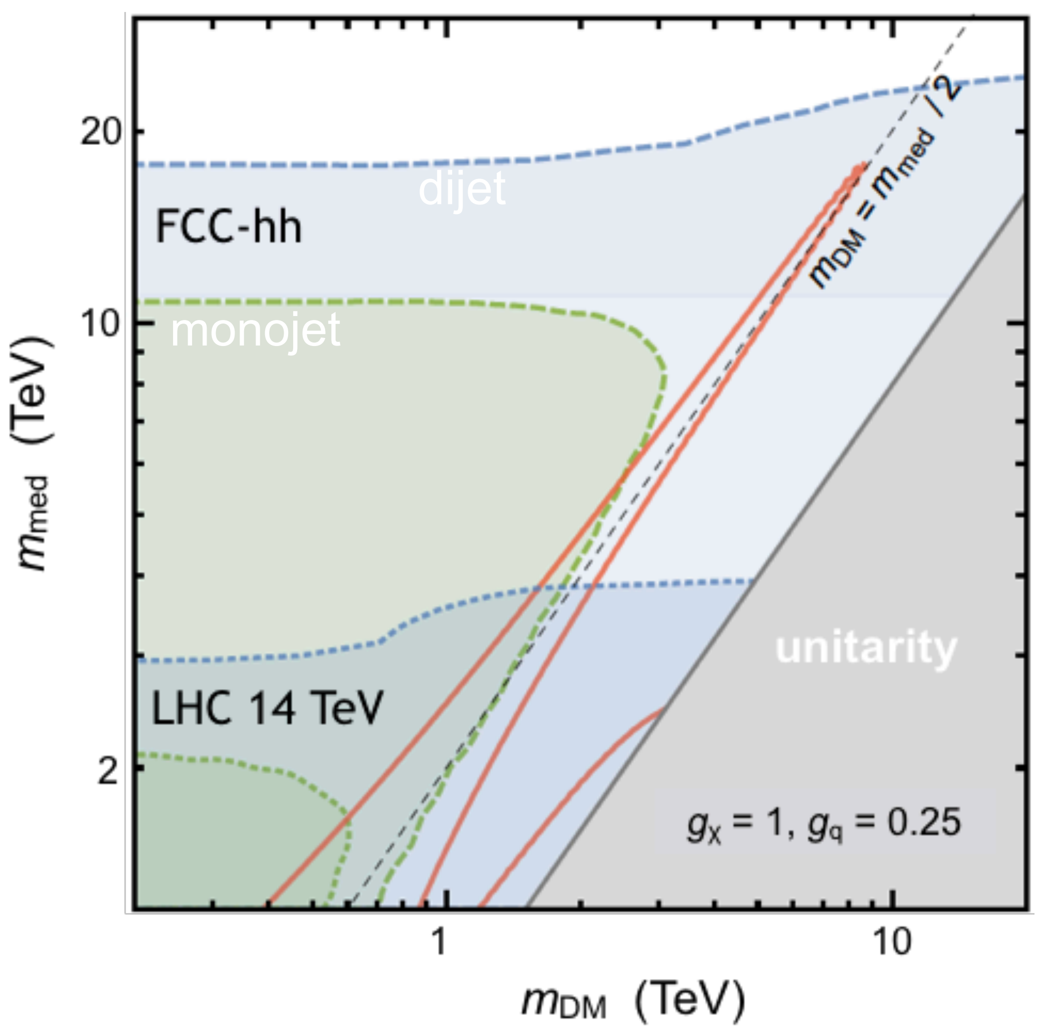


mono-jet with large E_T^{miss}



relic density





for illustration, fix the ratio between DM and mediator mass and pick mass that gives the right relic density

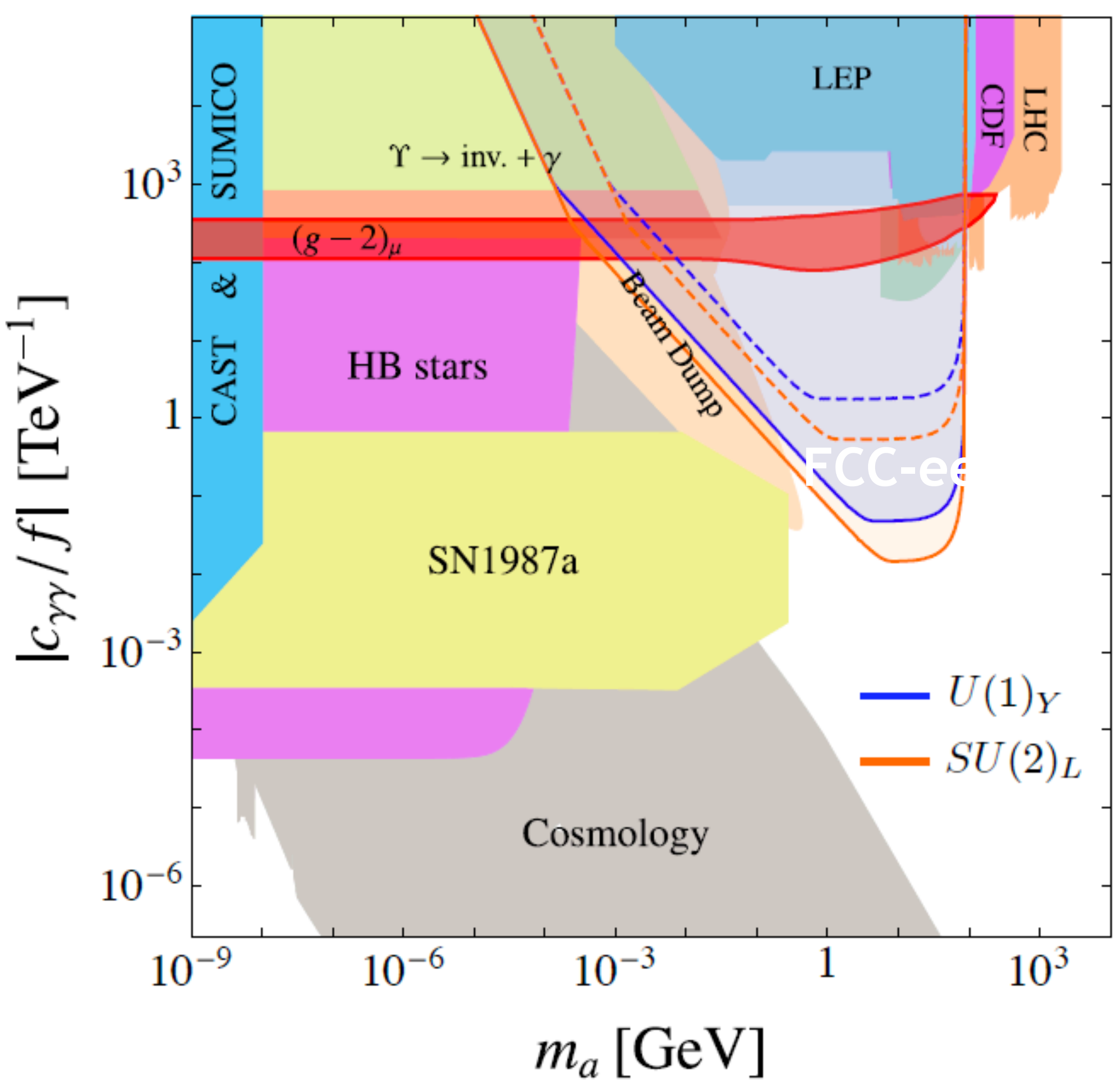
FCC-hh covers a much larger parameter space with reasonable couplings

arXiv:1606.00947

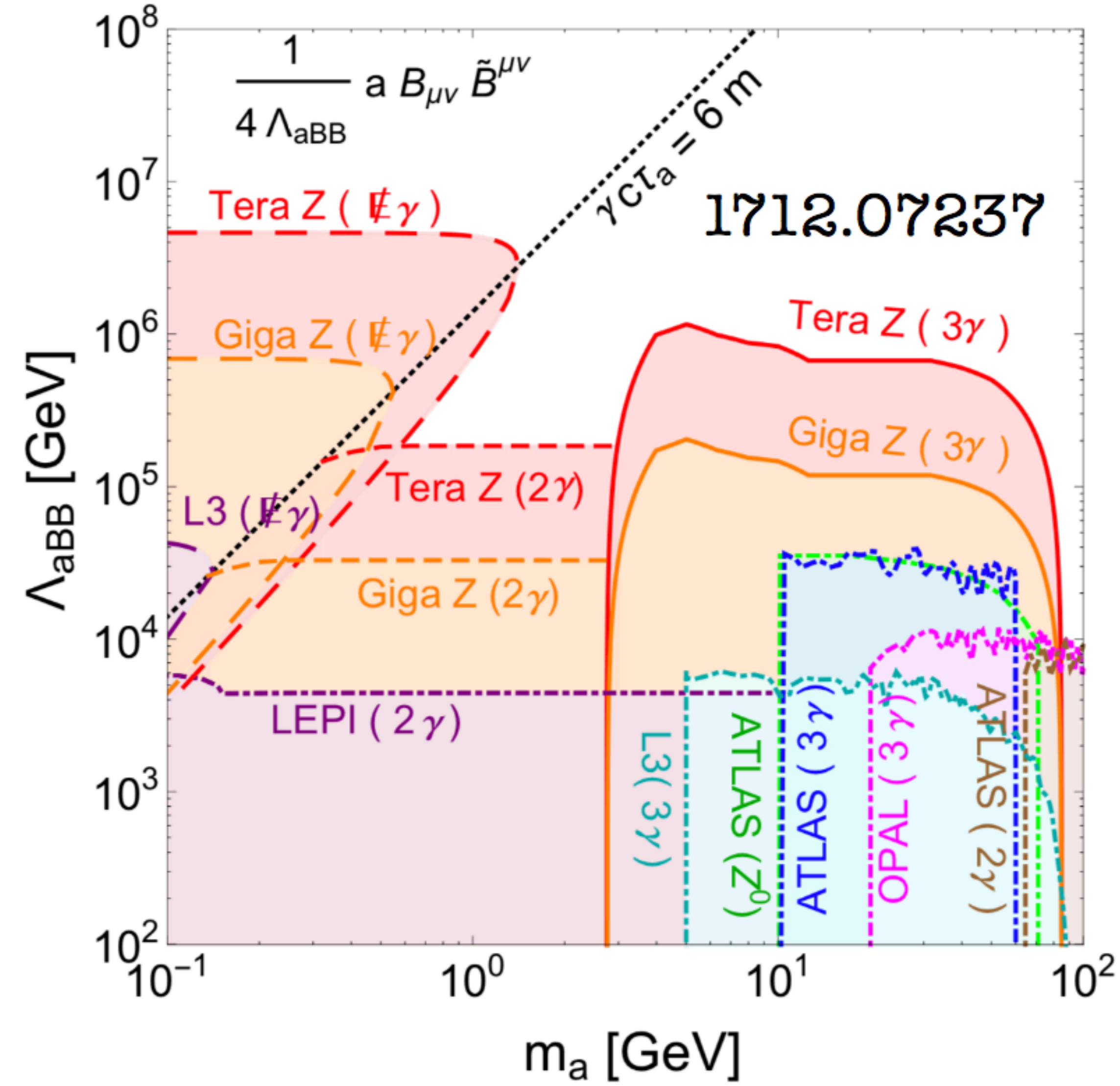
New Physics at the Z-Pole

A weekly coupled window on the Dark Sector

Search axion-like particles (ALP)



$Z \to \gamma a$, $a \to \gamma\gamma$

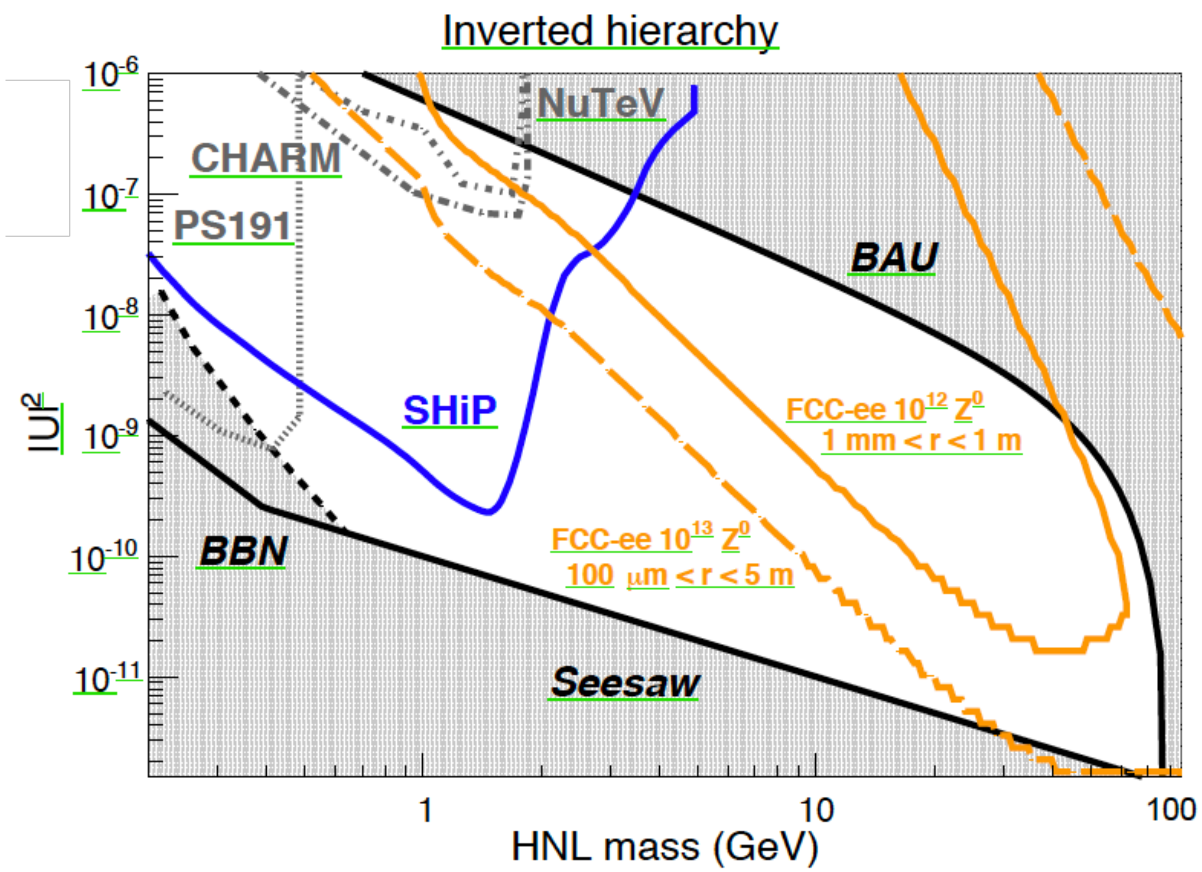


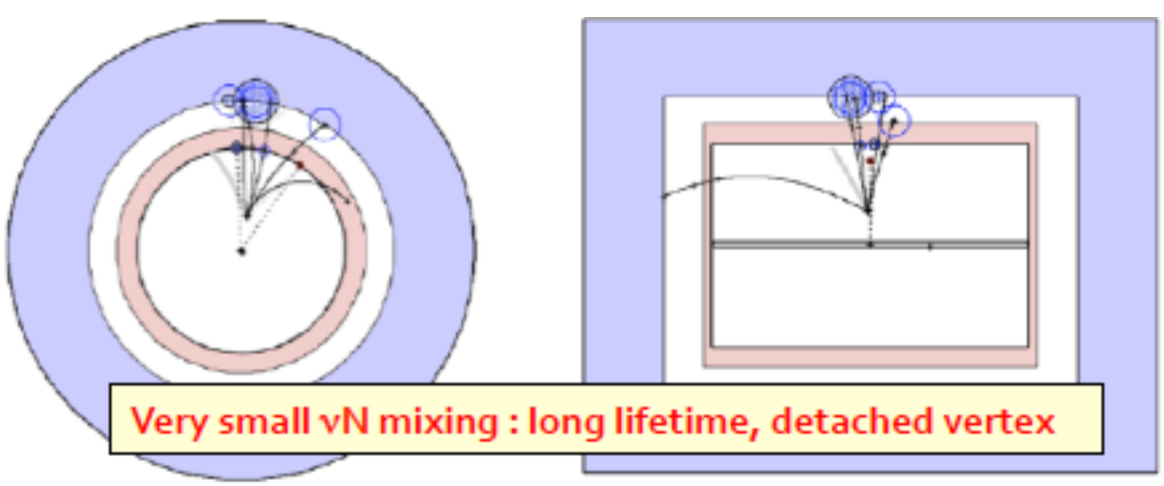
- very light: $Z \to \gamma$ + missing energy
- light: $Z \to \gamma\gamma$
- heavier: $Z \to \gamma\gamma\gamma$

New Physics at the Z-Pole

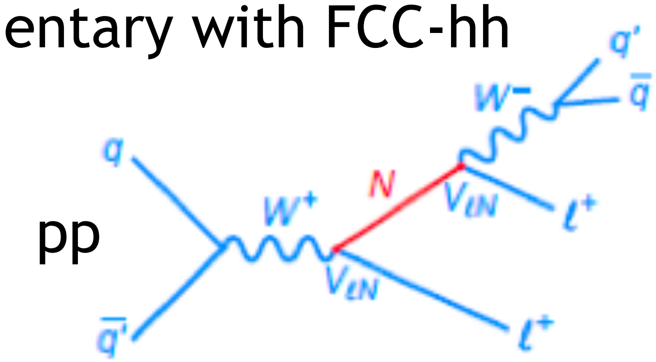
Huge production of neutrinos: $2 \times n_Z \times 20\%$!

Search for $Z \rightarrow \nu N$, $N \rightarrow W\ell / Z\nu$

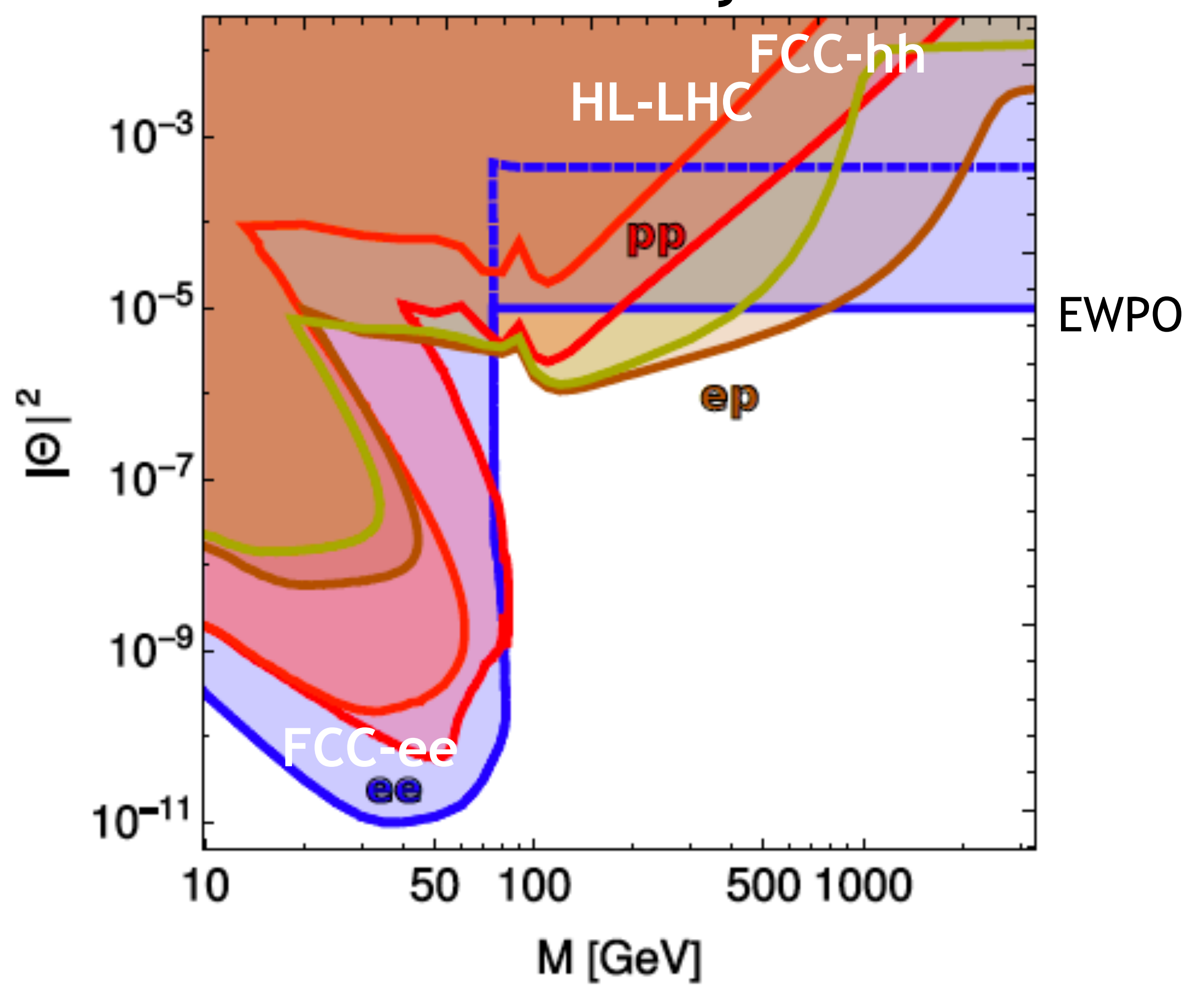


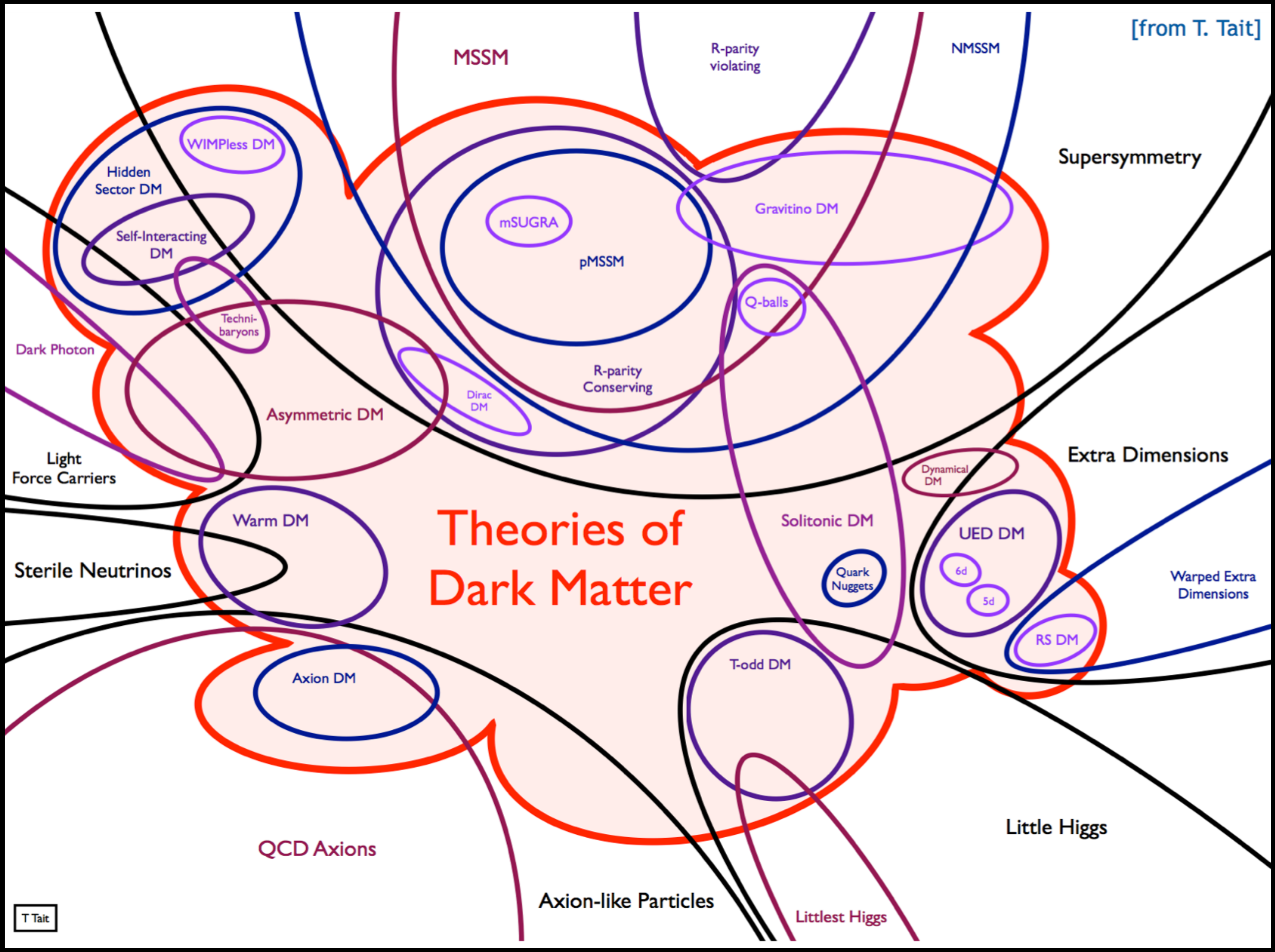


☛ complementary with FCC-hh



Search for heavy neutrinos





Gautier Hamel de Monchenault