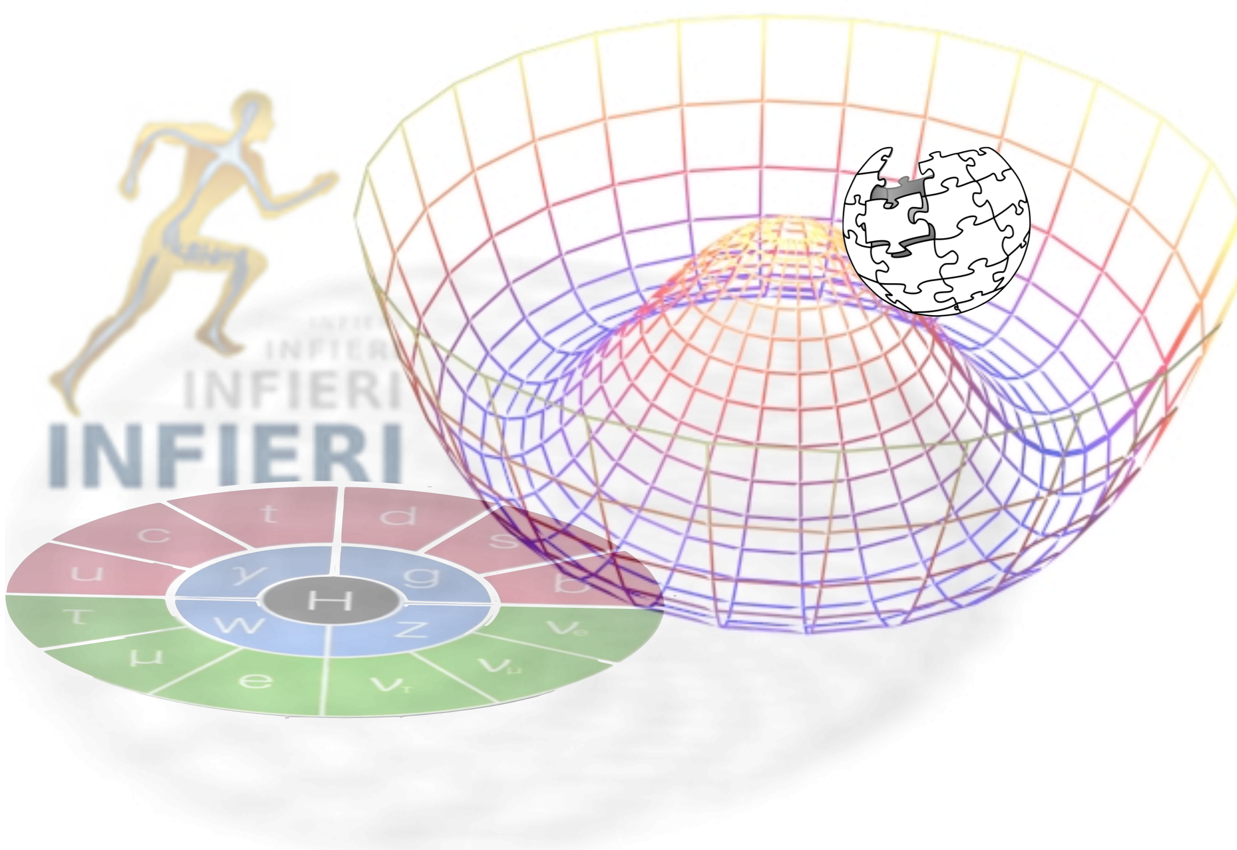
Higgs and Beyond

what will we learn at the future accelerators

International Summer School series on

" Intelligent Signal Processing for Frontier Research and Industry "

UAM, April 22, 2021



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Citius, Altius, Fortius
(was S. Bubka cheating?)

Often, the athletes, as the physicists, push the frontiers/break the records.
How high can a human jump with a pole?
Physics (energy conservation) tells us that longer and longer poles don't help!

$$\Delta h = \frac{v^2}{2g}$$

footspeed: 44.72km/h
(Usain Bolt, Berlin, August 2009, between 60m and 80m)

$$\Delta h = 7.62\,\mathrm{m}$$

Over the years, we have learnt a few other conservation laws
that tell us what an athlete/a particle can do or cannot do.
— Remarkable breakthrough in the understanding of Nature: —
forces among particles are associated to symmetries
conservation of E → invariance by (time)-translation
electro-magnetic forces → (local) invariance by phase rotation of particle wavefunctions

The Standard Model of Particle Physics
Lorentz symmetry + internal SU(3)xSU(2)xU(1) symmetry

SM Chirality

SM = S(R+Q)M
triumph of Special Relativity + Quantum Mechanics

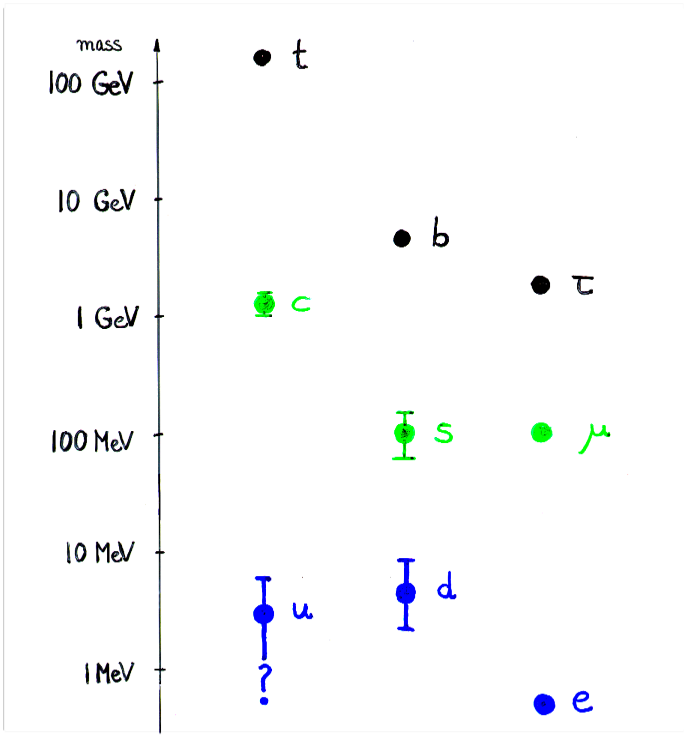
Particles = representations of Poincaré group, labelled by
(according to Coleman-Mandula)

(spin, mass) ⊗ internal quantum numbers

quantised continuous at least SU(3)xSU(2)xU(1)

A priori in agreement with data

BUT
spectrum is incompatible
with **chiral** nature of (gauge) symmetries
chiral fermion ⇛ m=0 only
gauge boson ⇛ m=0 only



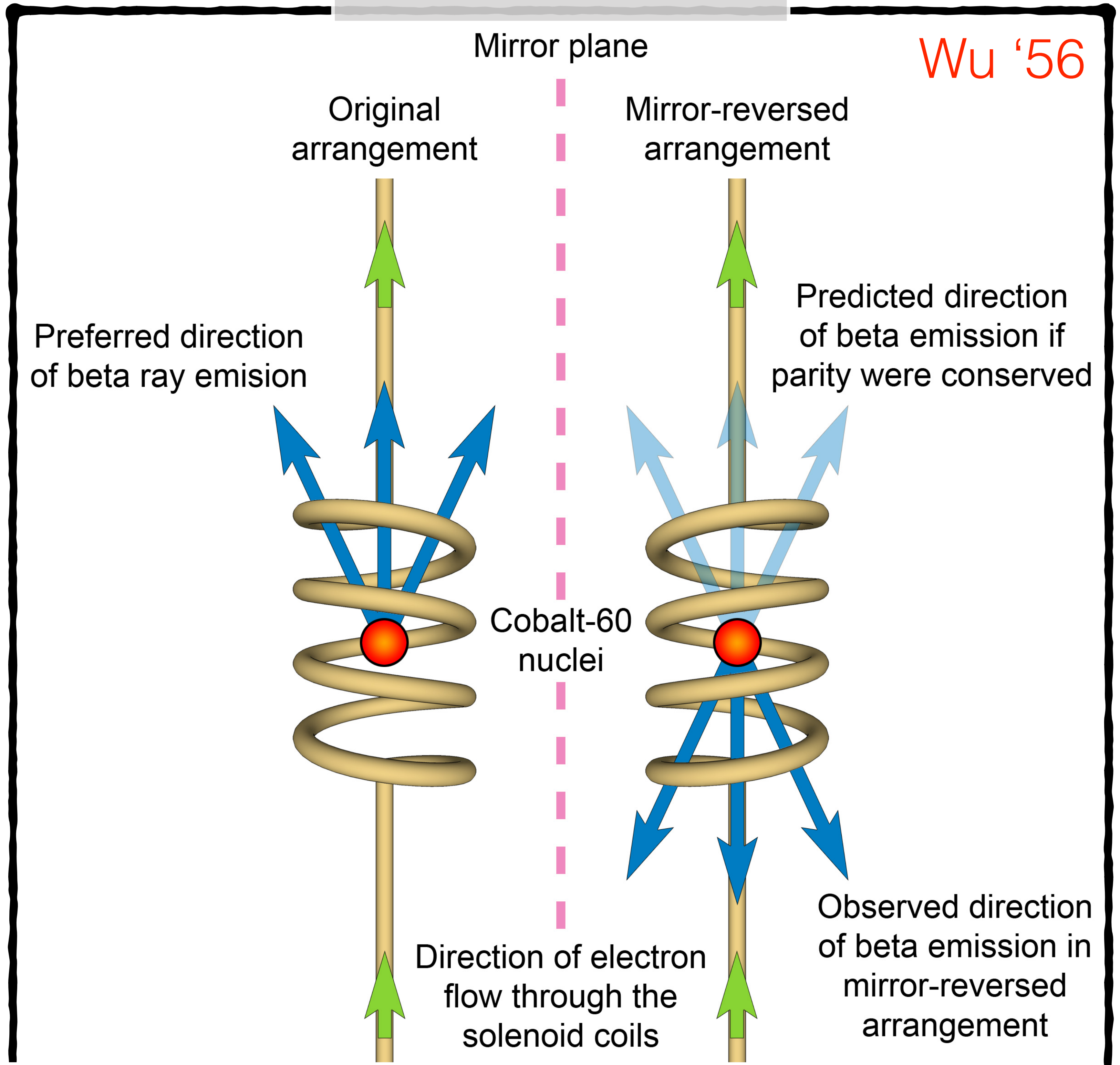
(picture: courtesy of A. Weiler)

Chirality of Weak Interactions

$${}^{60}_{27}\mathrm{Co} \to {}^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e$$

Weak interaction
(force responsible for
neutron decay)
is chiral!

[e_L and e_R are fundamentally
two different particles
Only an accident of the history of
physics that they are both called
electron]



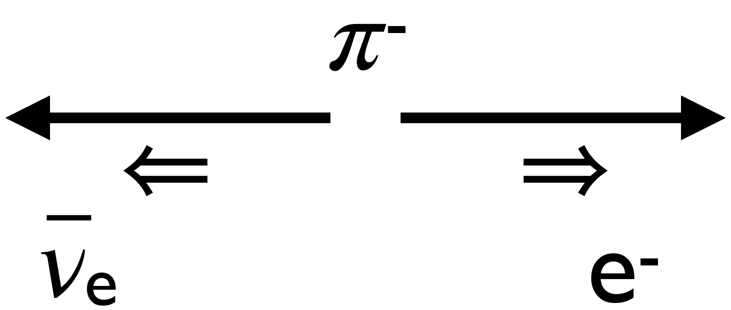
In **molecular biology**, chirality seems an **emergent** property.
Are the chiral nature of the **weak** interactions **emergent** too?

SM is a Chiral Theory

Weak interactions maximally violates P
This explains the peculiar decay pattern of the pions

Naively $\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} \sim \frac{(m_\pi - m_e)^5}{(m_\pi - m_\mu)^5} \sim 500$ But $\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} \sim 10^{-4}$

Different forces for e and μ?
No: selection rule due to EW chirality!



Conservation of momentum and spin imposes to have a RH e^-

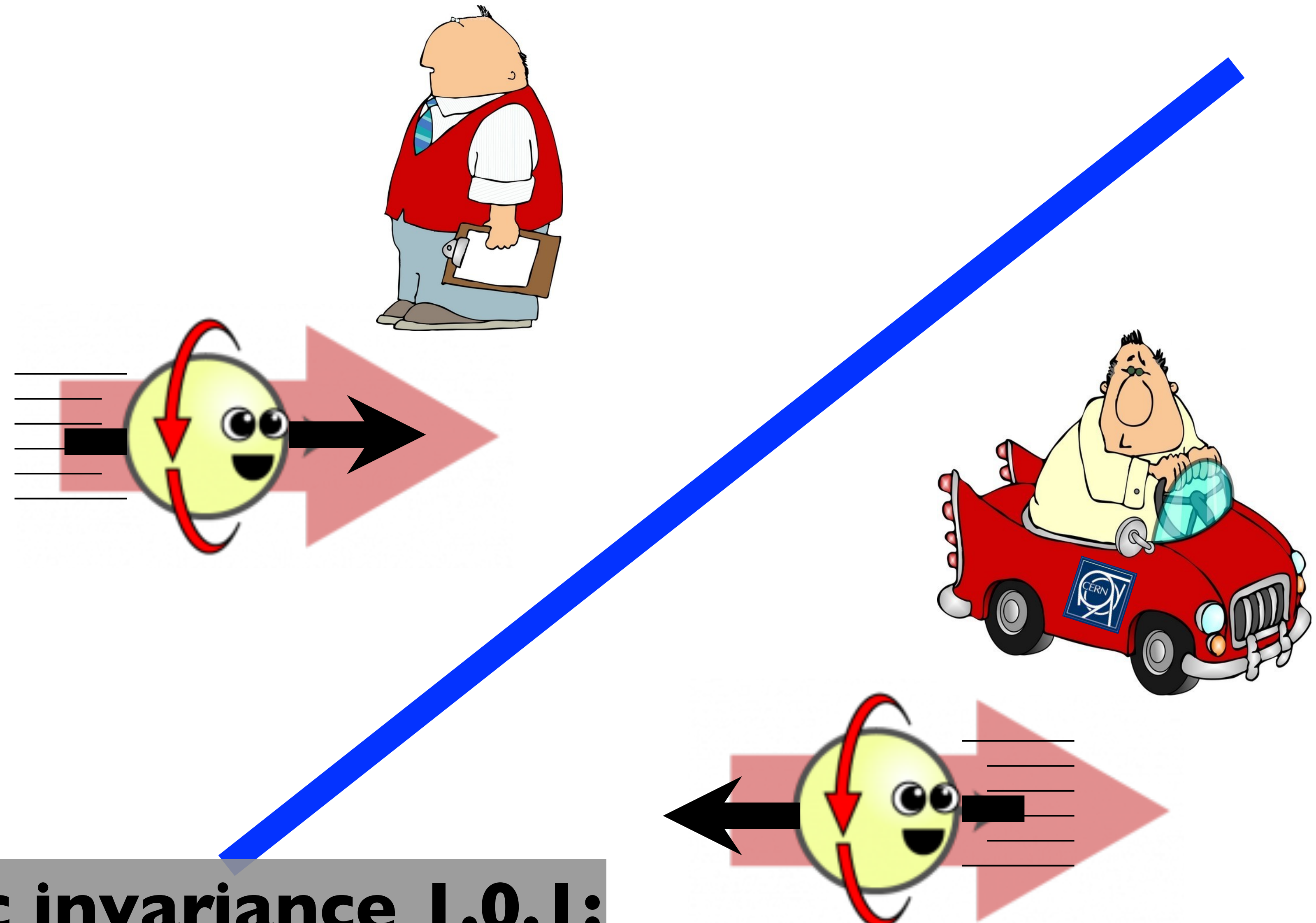
Weak decays proceed only w/ LH e^-
Needs a chirality flip to end up with RH e^-
So the amplitude is prop. to m_e

$$\mathcal{L}_{\rm Dirac} = \bar\psi_L \gamma^\mu \partial_\mu \psi_L + \bar\psi_R \gamma^\mu \partial_\mu \psi_R + m\left(\bar\psi_L \psi_R + \bar\psi_R \psi_L\right)$$

$$\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} \propto \frac{m_e^2}{m_\mu^2} \sim 2 \times 10^{-5} \sim 10^{-4}_{\rm obs}$$

↑ Extra phase-space factor

Chirality & Masslessness



Picture courtesy to G. Giudice

Relativistic invariance 1.0.1:

there must be no distinction between *massive* electrons spinning clockwise or anti-clockwise

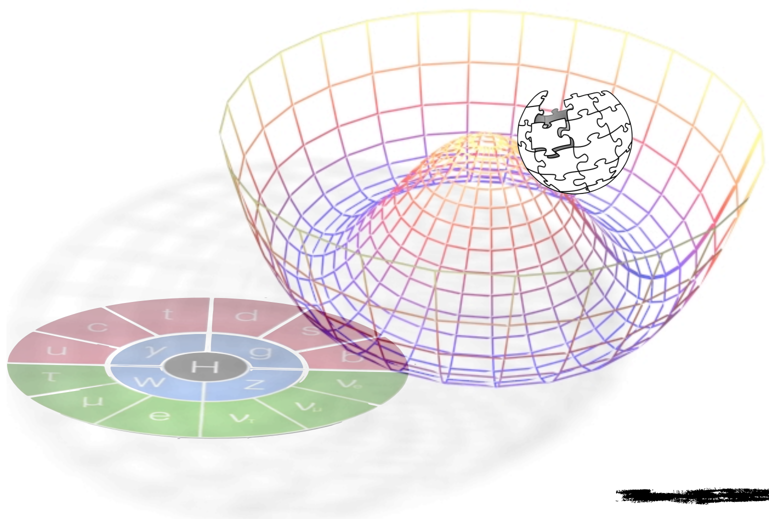
[chirality operator doesn't commute with the Hamiltonian]

If your theory sees a difference between e_L and e_R, either your theory is wrong or m_e=0

Spontaneous Symmetry Breaking

Short-distance interactions ≠ Long-distance interactions

The masses are emergent due to a non-trivial structure of the vacuum



~~**vacuum** = a space entirely devoid of matter~~

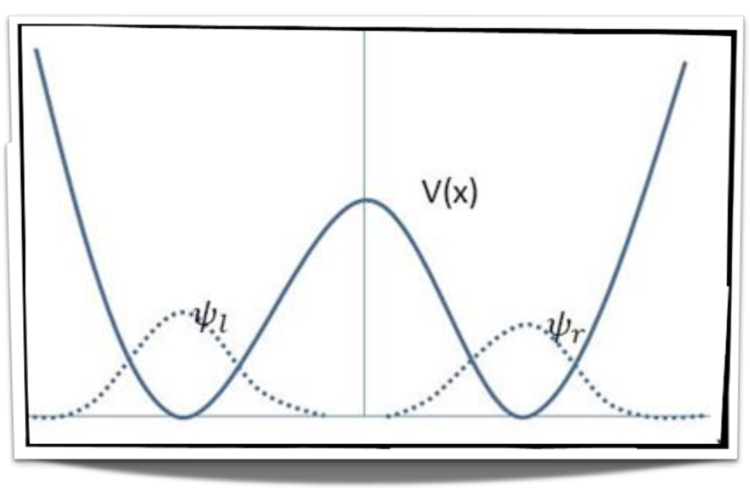
Oxford English

vacuum = a space filled with Higgs substance

Physics English

QM vs QFT

(courtesy of J. Lykken@Aspen2014)



Ground state of QM double well potential
is a superposition of two states each localised on one minimum,
and this superposition preserves the Z_2 symmetry of the potential

In QFT, it is more difficult to transition between degenerate vacua
and spontaneous symmetry breaking can occur
(or more correctly, the symmetry is non-linearly realised in Hilbert space)

The vacuum of the SM breaks SU(2)xU(1) to $U(1)_{em}$
via the dynamics of an elementary scalar field

The Higgs Boson

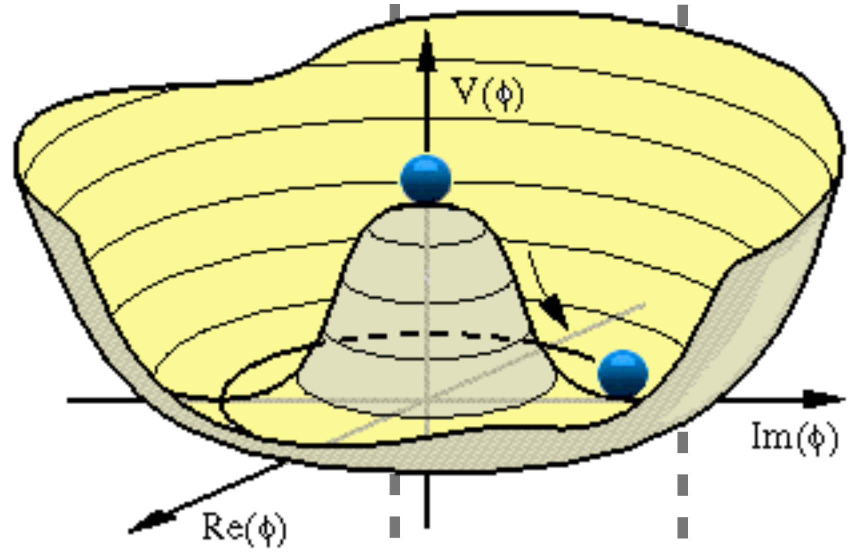
Spontaneous Symmetry Breaking

Symmetry of the Lagrangian

$$SU(2)_L \times U(1)_Y$$

Higgs Doublet

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$



Symmetry of the Vacuum

$$U(1)_{e.m.}$$

Vacuum Expectation Value

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad \text{with} \quad v \approx 246 \text{ GeV}$$

Most general (renormalisable) Higgs potential

$$V(H) = \lambda \left(|H|^2 - v^2/2 \right)^2$$

$v^2>0$ EW symmetry breaking, $v^2<0$ no breaking

Why Nature has decided that v2>0? No dynamics explains it!

$$\delta_{SU(2)} \langle H \rangle = \frac{i}{2} \left(\theta^1 \begin{pmatrix} & 1 \\ 1 & \end{pmatrix} + \theta^2 \begin{pmatrix} & -I \\ I & \end{pmatrix} + \theta^3 \begin{pmatrix} 1 & \\ & -1 \end{pmatrix} \right) \langle H \rangle \neq 0$$

$$\delta_Y \langle H \rangle = i\theta_Y \begin{pmatrix} 1/2 & \\ & 1/2 \end{pmatrix} \langle H \rangle \neq 0$$

$$\delta_Q \langle H \rangle = i\theta_{QED} \begin{pmatrix} 1 & \\ & 0 \end{pmatrix} \langle H \rangle = 0 \qquad \theta_{QED} = \theta_Y = \theta_3 \qquad Q = Y + T_{3L}$$

Higgs Boson

Before EW symmetry breaking

- 4 massless gauge bosons for SU(2)x(1): 4 x 2 = 8 dofs
- Complex scalar doublet: 4 dofs

After EW symmetry breaking

- 1 massless gauge boson, photon: 2 dofs
- 3 massive gauge bosons, $W^\pm$ and Z: 3 x 3 = 9 dofs
- 1 real scalar: 1 dof

$$H = \begin{pmatrix} 0 \\ \frac{v+h(x)}{\sqrt{2}} \end{pmatrix}$$

h(x) describes the **Higgs boson**
(the fluctuation above the VEV).
The other components of the Higgs doublet H become the longitudinal polarisations of the $W^\pm$ and Z.

Fermion Masses

SM is a chiral theory (≠ QED that is vector-like)

$$m_e \bar{e}_L e_R + h.c.$$ is not gauge invariant

($\bar{e}_L$: Y=1/2; e_R: Y=-1)

The SM Lagrangian cannot contain fermion mass term.
Fermion masses are emergent quantities
that originate from interactions with Higgs VEV:

$$\mathcal{L} = y_e \begin{pmatrix} \bar{\nu}_L \\ \bar{e}_L \end{pmatrix} \cdot \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} e_R = \frac{y_e\, v}{\sqrt{2}} \left(\bar{e}_L e_R + \frac{1}{v} \bar{e}_L e_R h \right)$$

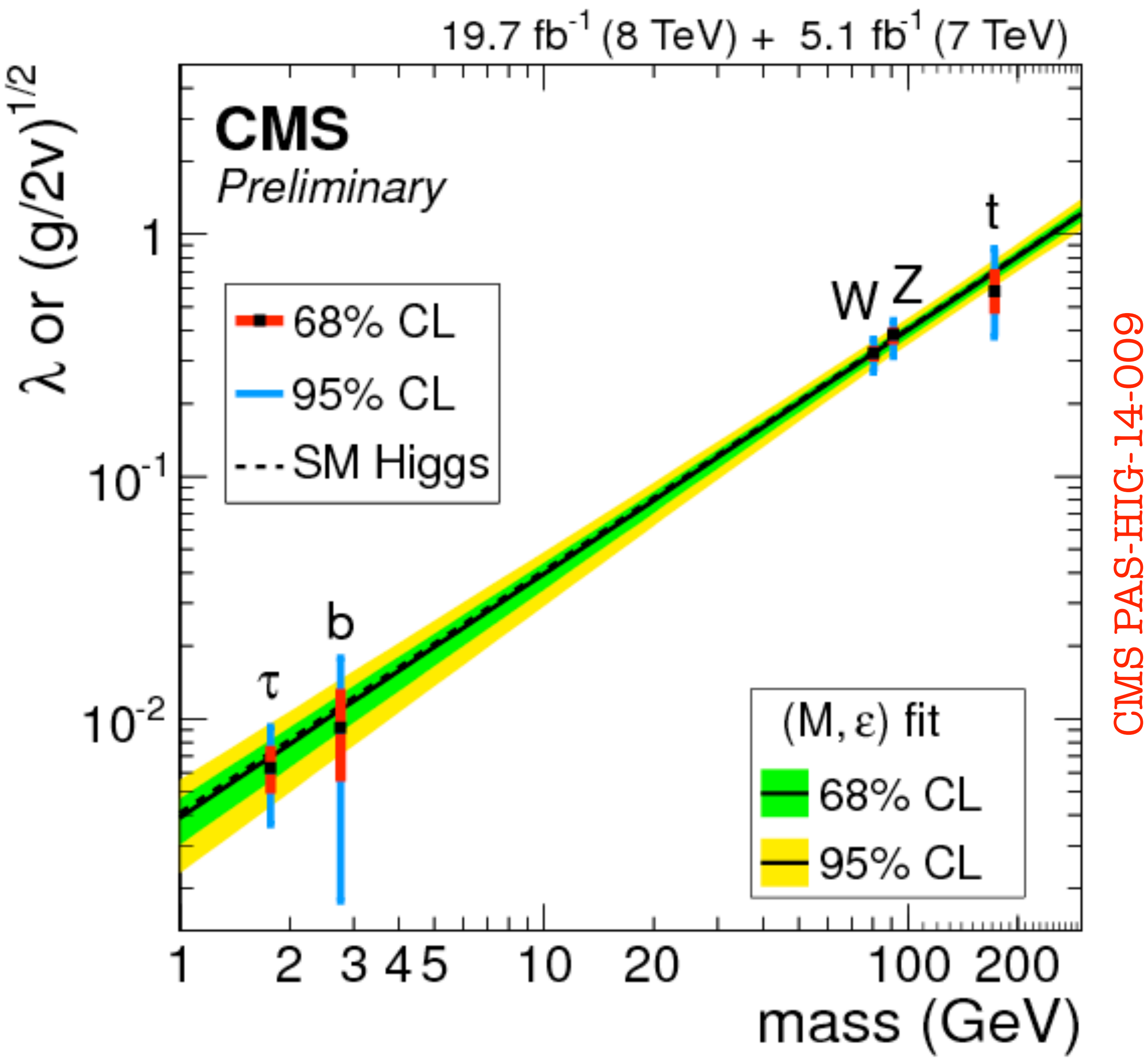
(Y=1/2, Y=1/2, Y=-1)

After EWSB: $H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$

h: Higgs Boson

Higgs couplings proportional to the mass of particles

The Higgs PR plot



Higgs couplings
are proportional
to the masses of the particles

$$\lambda_\psi \propto \frac{m_\psi}{v}\,, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

Fermion Masses

A mass term corresponds in the Lagrangian to an operator that is quadratic in the field. in QFT, this operator needs to be Lorentz invariant and invariant under the local/gauge symmetries. For spin-1/2 field, there are two types of mass terms:

- a **Dirac** mass (conserves Fermion number):

$$m\bar{\psi}\psi = m\left(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L\right) \quad \text{where} \quad \bar{\psi} = \psi^\dagger\gamma^0$$

- a **Majorana** mass (changes Fermion number by two units):

$$m\bar{\psi}_C\,\psi = m\left(\bar{\psi}_{L_C}\psi_L + \bar{\psi}_{R_C}\psi_R\right) \quad \text{where} \quad \psi_C = i\gamma^2\psi^* \quad \text{is the charge conjugated spinor}$$

A chiral fermion can have a **Majorana** mass
A **Dirac** mass requires spinors of opposite chirality

Whether or not a Dirac or a Majorana mass can be included in the Lagrangian depends on the charges of the fermion under the gauge transformations

Within the SM (with the Higgs field), a Dirac mass can written for the charged leptons and the quarks while a Majorana mass can be written only for the neutrinos.

One cannot write a Majorana mass for the electron since it would violate $U(1)_{em}$

Neutrino Masses

The same construction doesn't work for neutrinos
since in the SM there are only Left Handed neutrinos

For a uncharged particle, it is possible to write a Majorana mass

$$\mathcal{L}_{\text{Majorana}} = m\bar{\psi}_C\,\psi = m\left(\bar{\psi}_{L_C}\psi_L + \bar{\psi}_{R_C}\psi_R\right)$$

can build such a term with LH field only

$$\mathcal{L} = \frac{y_\nu}{\Lambda}\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}_C \cdot \begin{pmatrix}H^+\\ H^0\end{pmatrix}\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} \cdot \begin{pmatrix}H^+\\ H^0\end{pmatrix} = \frac{y_\nu\, v^2}{\Lambda}\nu_{LC}\nu_L$$

mass$^{3/2}$ mass mass$^{3/2}$ mass

non-renormalisable operator
(that's why it is often said that neutrinos are massless within the SM)

Seesaw: $m_\nu = \frac{y_\nu v^2}{\Lambda}$

Order eV
for y_ν~1 and Λ~10^{14}GeV

The Higgs Boson is Special

The Higgs discovery in 2012 has been an important milestone for HEP.
And many of us are still excited about it.

Higgs = **new forces** of different nature than the interactions known so far

- No underlying local symmetry
- No quantised charges
- Deeply connected to the space-time vacuum structure

The knowledge of the values of the **Higgs couplings** is essential to understand the deep structure of matter/Universe

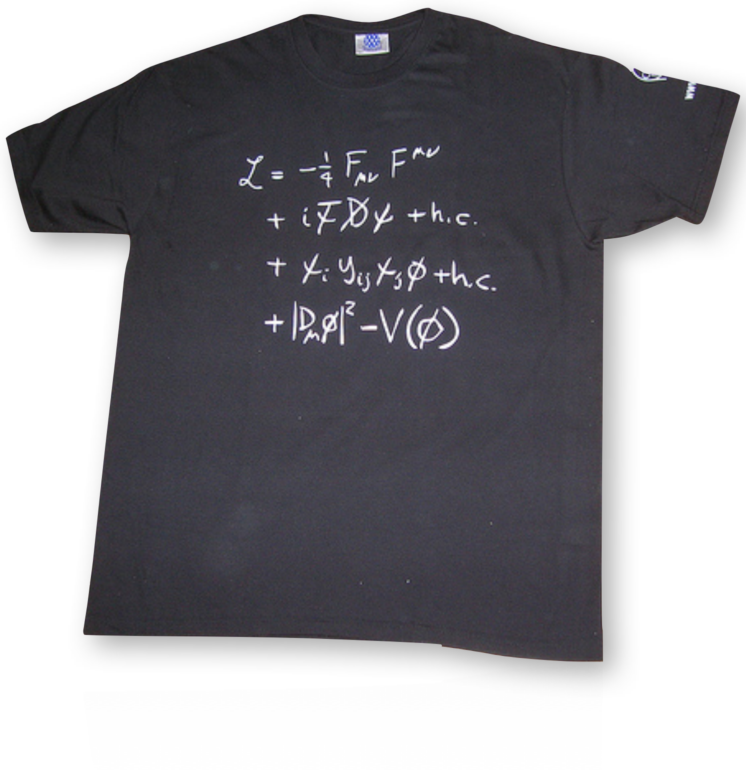
m_W, m_Z ↔ Higgs couplings ✓
↑
lifetime of stars
(why $t_{Sun} \sim t_{life\ evolution}$?)

m_e, m_u, m_d ↔ Higgs couplings ?
size of atoms (m_e) — nuclei stability (m_u, m_d)

EW @ $t \sim 10^{-10}$s ↔ Higgs self-coupling ?

matter/anti-matter ↔ CPV in Higgs sector ?

The Unknowns of the Higgs Sector



If one assumes the SM is fully describing Nature,
then all parameters of the SM Lagrangian can be fixed
from experimental inputs

Higgs mass
Fermi constant
→
2 parameters
of the Higgs potential

Fermion masses
& mixing
→
All Yukawa couplings

But the SM *cannot* be the ultimate description of nature !

For instance, fermions masses *could* be generated by $y_{ij}|H|^{2n_{ij}}\bar{F}_i H F_j$ instead of $y_{ij}\bar{F}_i H F_j$

This could even offer an explanation to the fermion mass hierarchy.

It would predict Higgs-fermion interactions different than in SM

Most of them haven't been measured and will wait a long time:

— Higgs-muon coupling needs full HL-LHC luminosity —

— Higgs-electron coupling is unlikely to be measured in next 50 years —

The Unknowns of the Higgs Sector

$y_{ij}|H|^{2n_{ij}}\bar{F}_i H F_j$, as a solution to the mass hierarchy, is actually ruled out

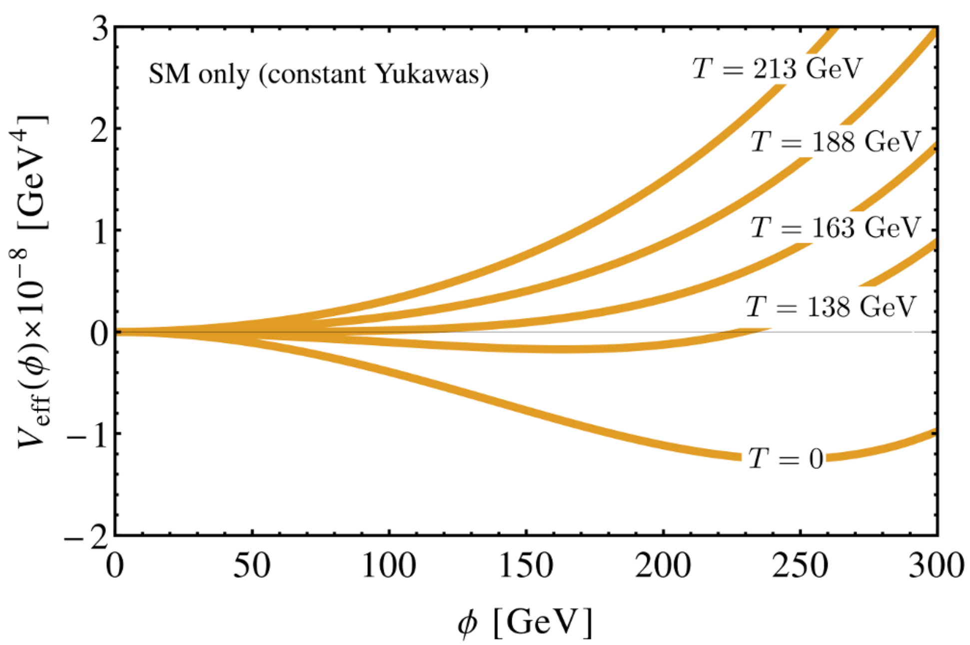
But one can rely on extra scalar who also develops a vacuum expectation value around the weak scale

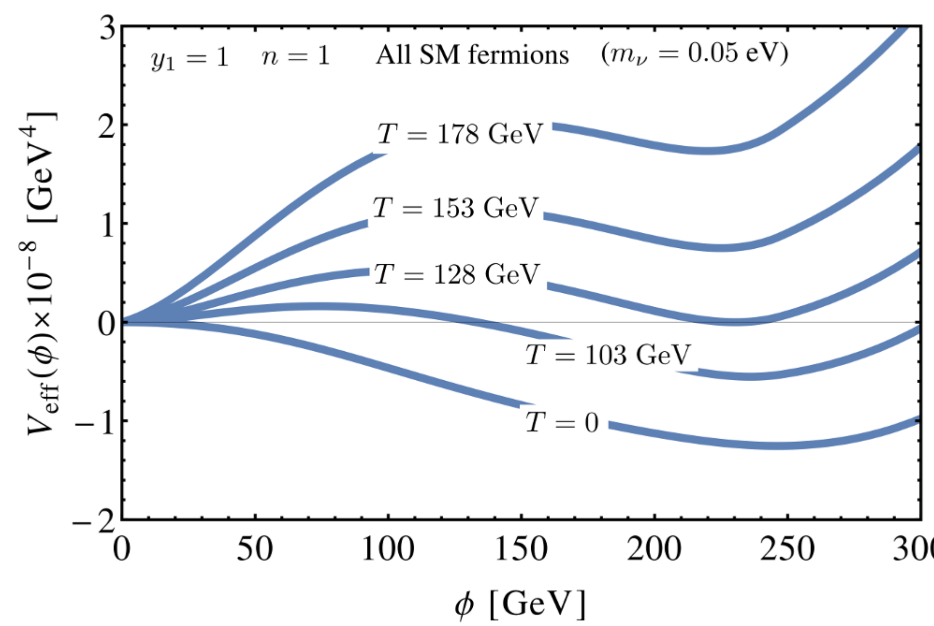
$$y_{ij}S^{n_{ij}}\bar{F}_i H F_j$$

Varying Yukawa's during the cosmological evolution of the Universe
Much larger at early time — Hierarchical values only at late time

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

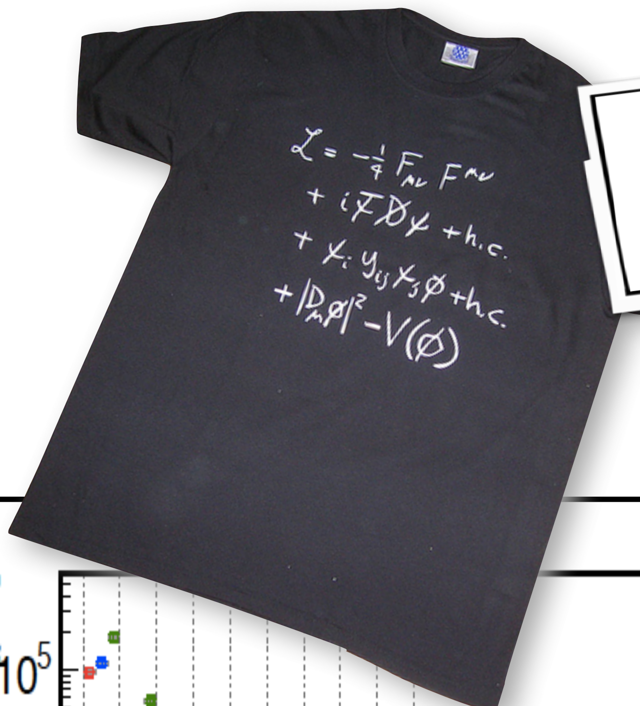
Baldes, Konstandin, Servant '16





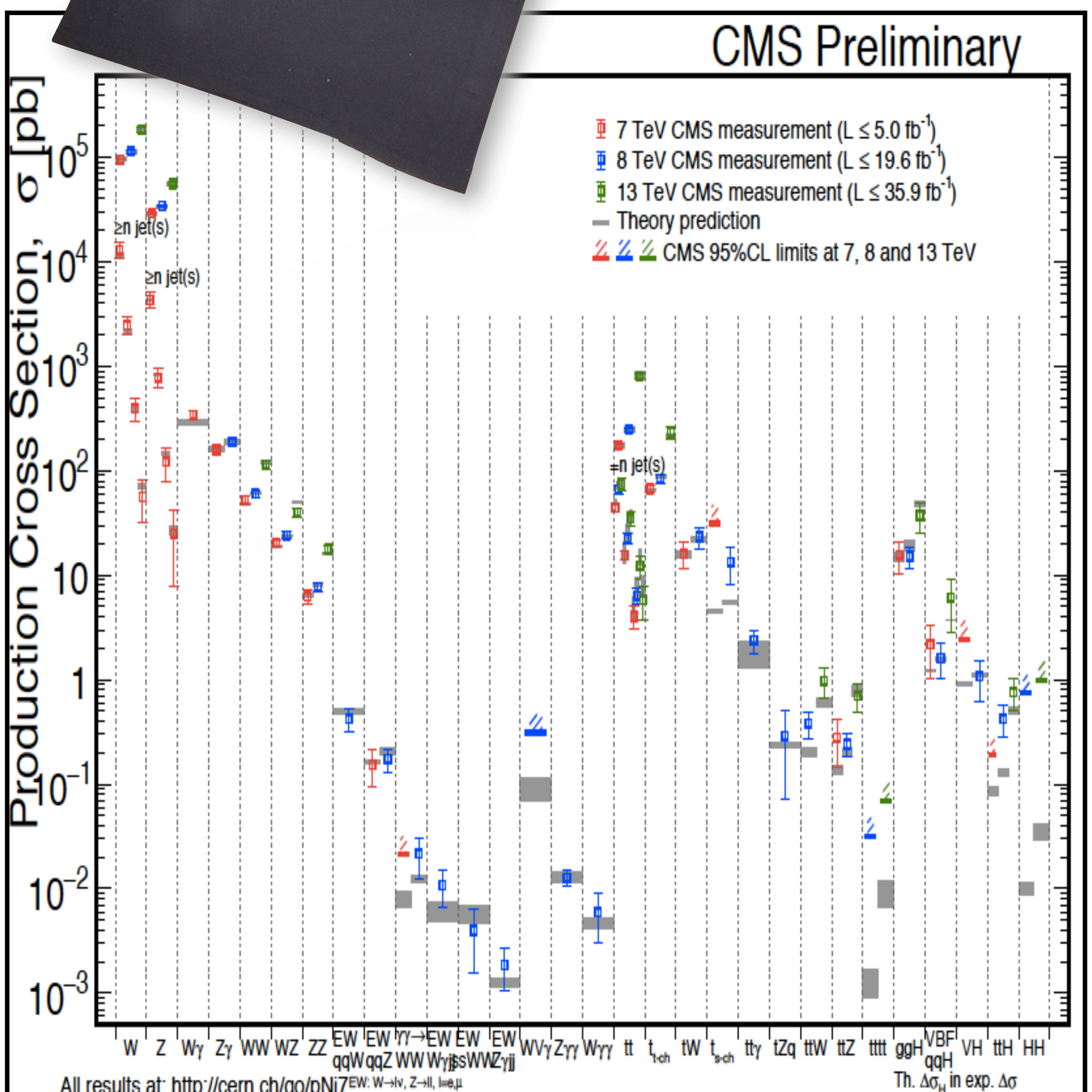
1st order phase transition + enhanced source of CP
All what you need for create matter/antimatter imbalance!

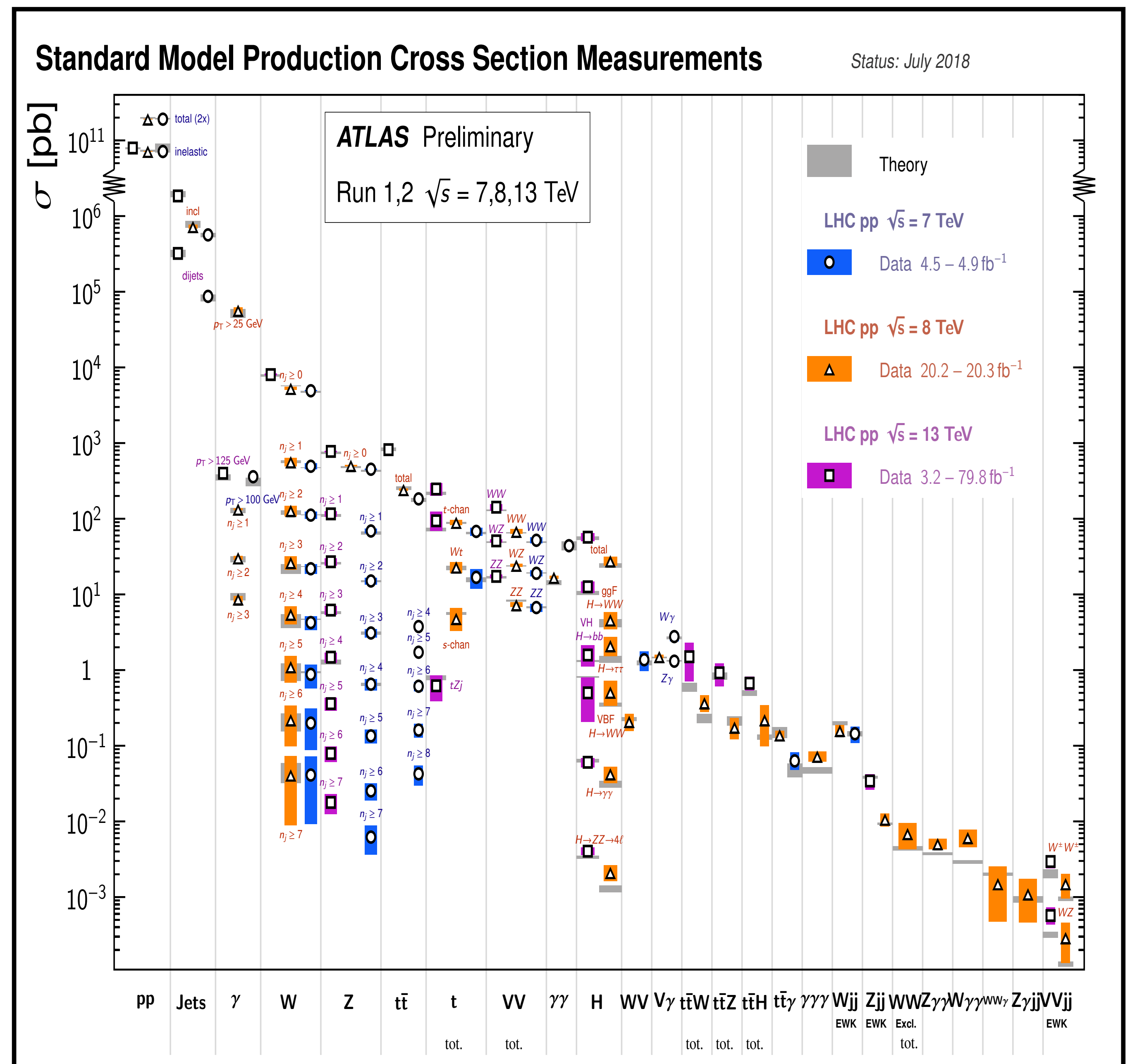
The SM and... the LHC data so far



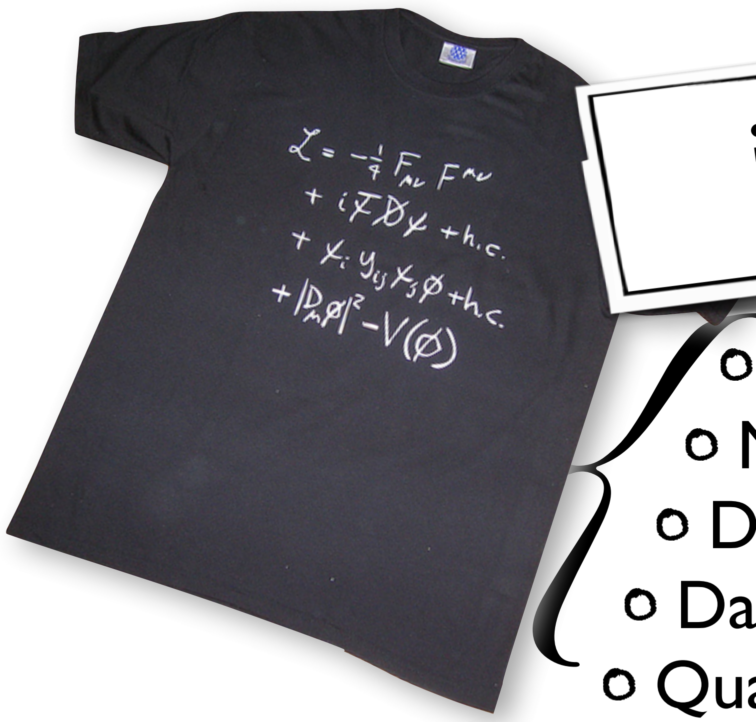
rules the world!

[and we, HEP practitioners, are all entitled for some royalties!]





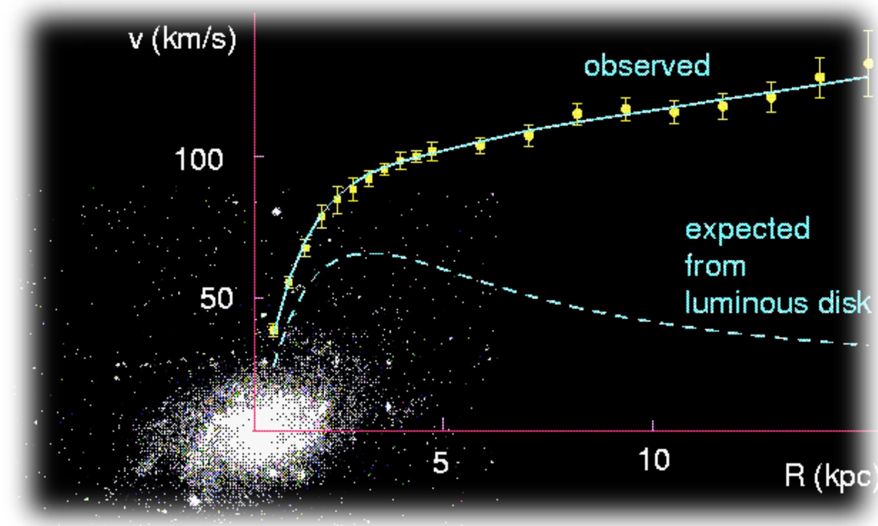
The SM and... the Universe

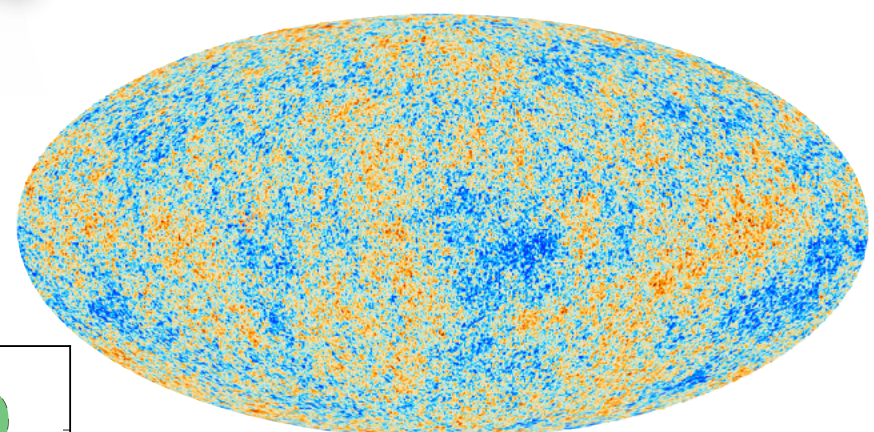


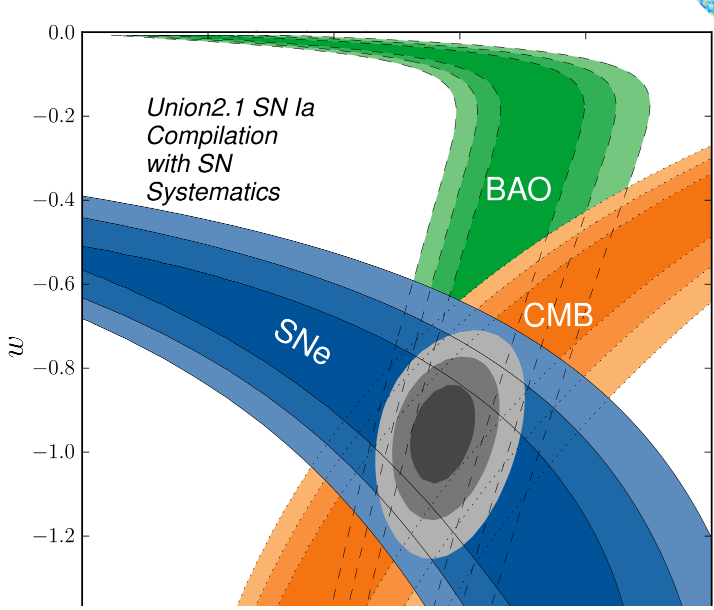
is not enough

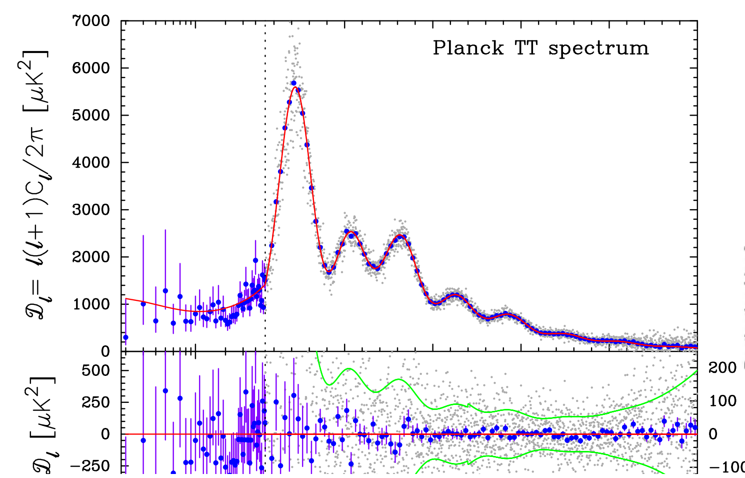
[and we all have to return our royalties!]

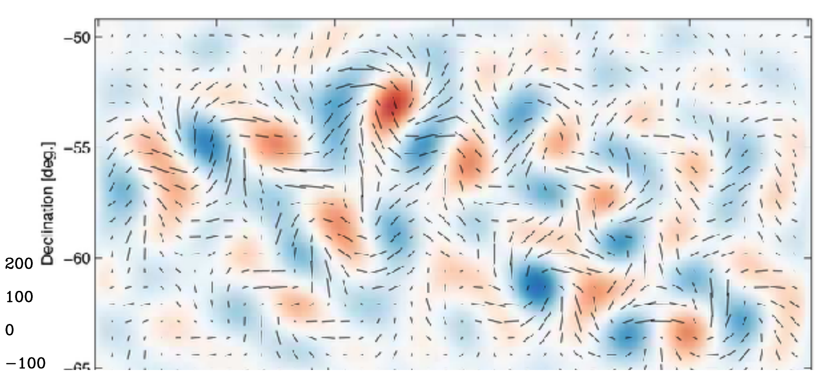
- Neutrino masses
- Matter-antimatter asymmetry
- Dark Matter
- Dark Energy
- Quantum gravity





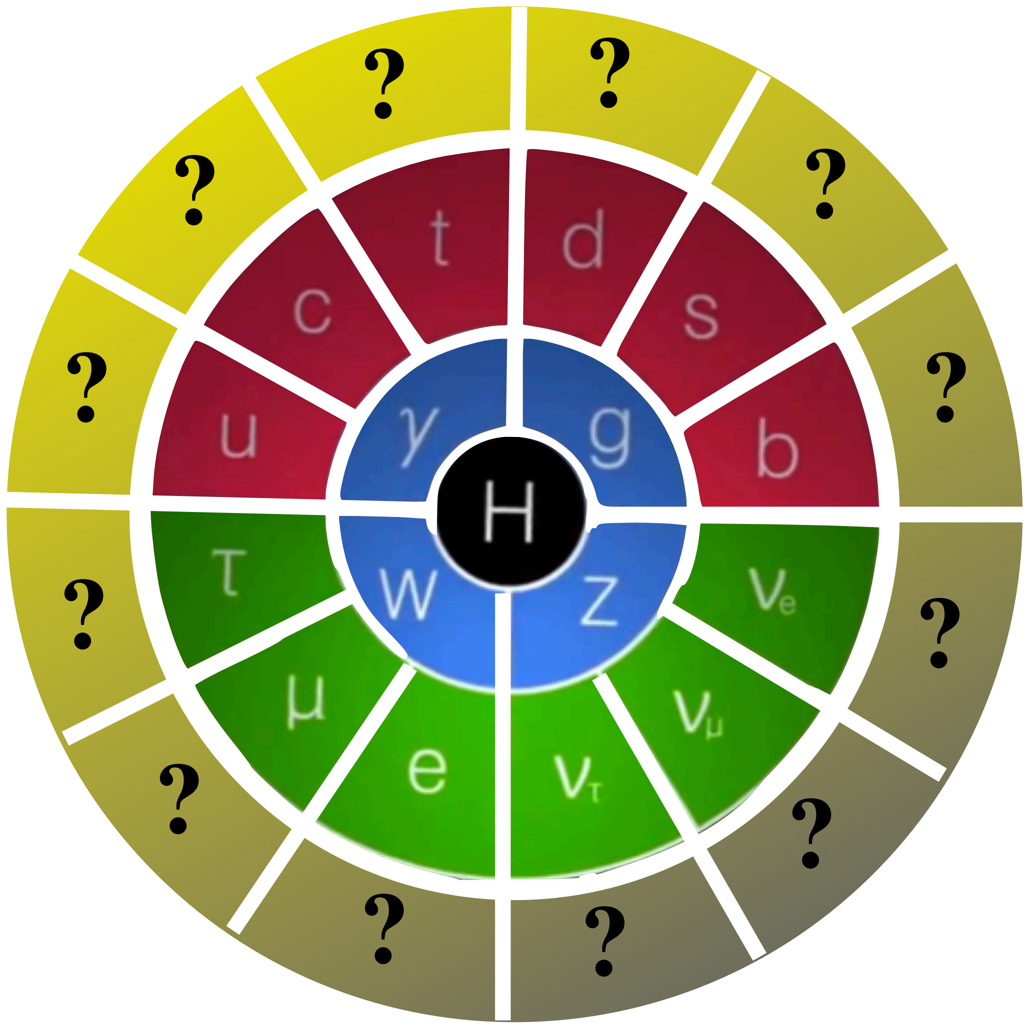






we do not understand the Matter the Universe is made from

What is Beyond Standard Model?



I don't know. Nobody knows [If it were known, it would be part of the SM!]

Many evidences that BSM exist

We have plenty of good ideas and there are rich opportunities

But no guarantee we are on the right track

We should stay open-minded and also learn from our failures

" Looking and not finding is different than not looking "

What is Beyond Standard Model?

Where and how does the SM break down?
Which machine(s) will reveal (best) this breakdown?

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

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)

Which Machine(s)?

The technical challenges of big colliders:

- energy: 10^{13} larger than everyday life batteries.

- magnetic field: 10^{4} larger than everyday life magnets.

Currents needed in 16T magnets ~ intramolecular fields (100 MV/m).

Going higher will imply a reorganisation of matter!

Plasma wakefield acceleration

Which Machine(s)?

Choice between different options: delicate balance between physics return, technological challenges and feasibility, time scales for completion and exploitation, financial and political realities

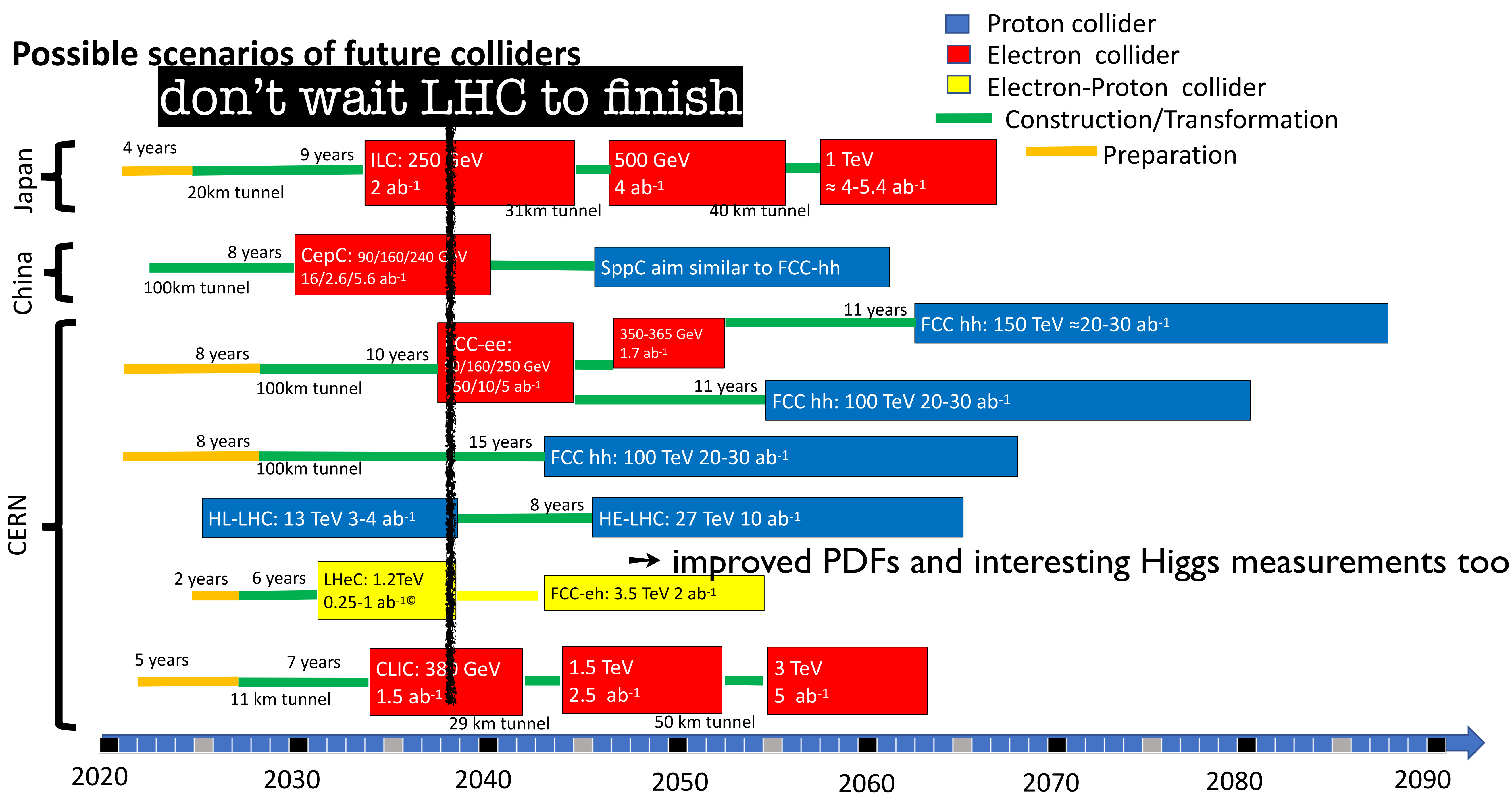
Exploration machines are at the heart of HEP.
Current consensus towards European Strategy Update: the best way to go to "energy frontier" is to start with an **e^+e^- Higgs factory**

Linear or Circular?

- Can be extended in energy
- Polarised (longitudinal) beams

- Higher luminosity
- Dedicated Z-pole run

Future of HEP: Flagship Projects



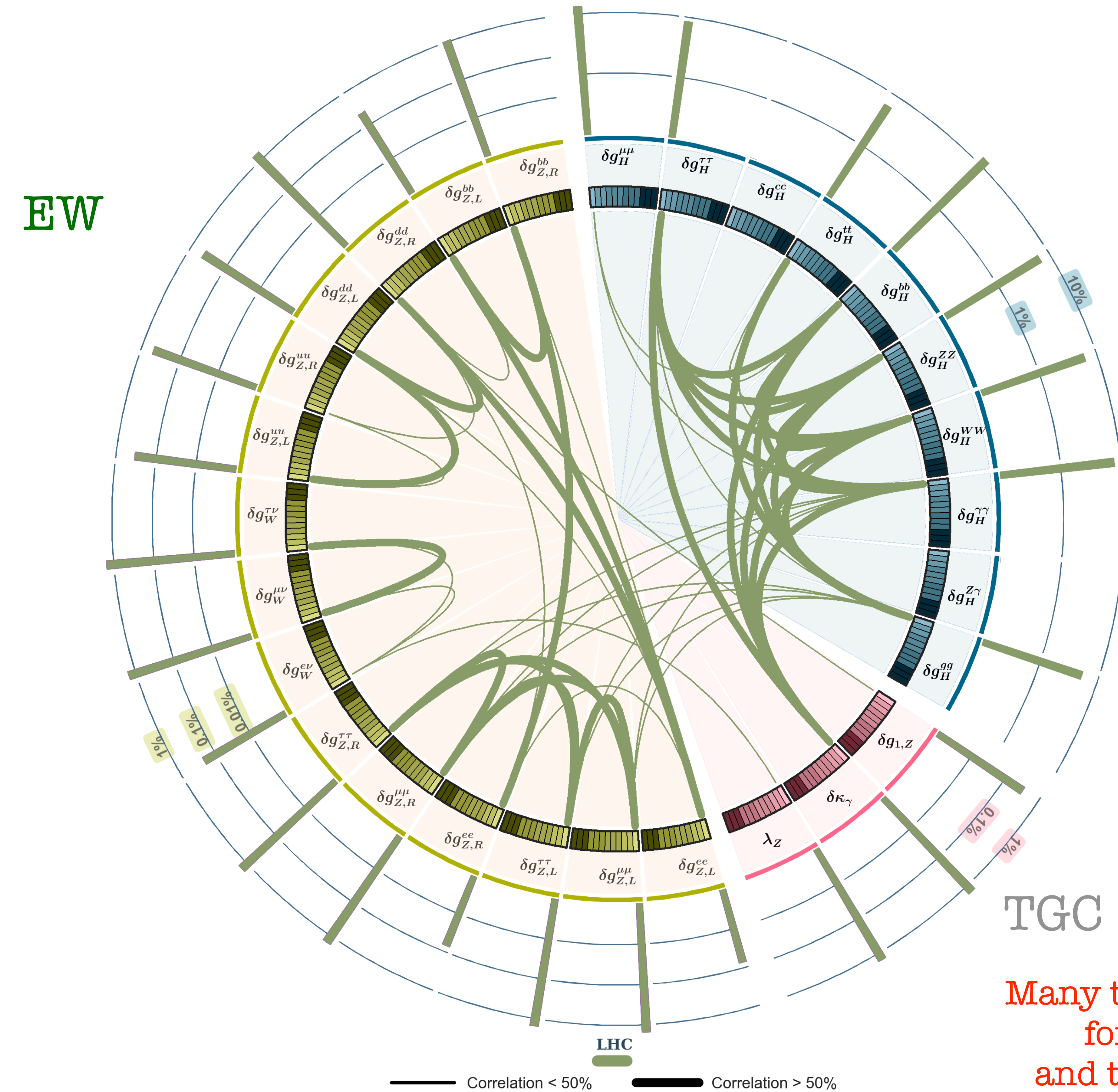
Ursula Bassler, Granada 13.05.2019

Future of HEP: Flagship Projects

Stay safe/healthy and live long!

(i) Exploration of the Higgs Sector

SM: Once-Now

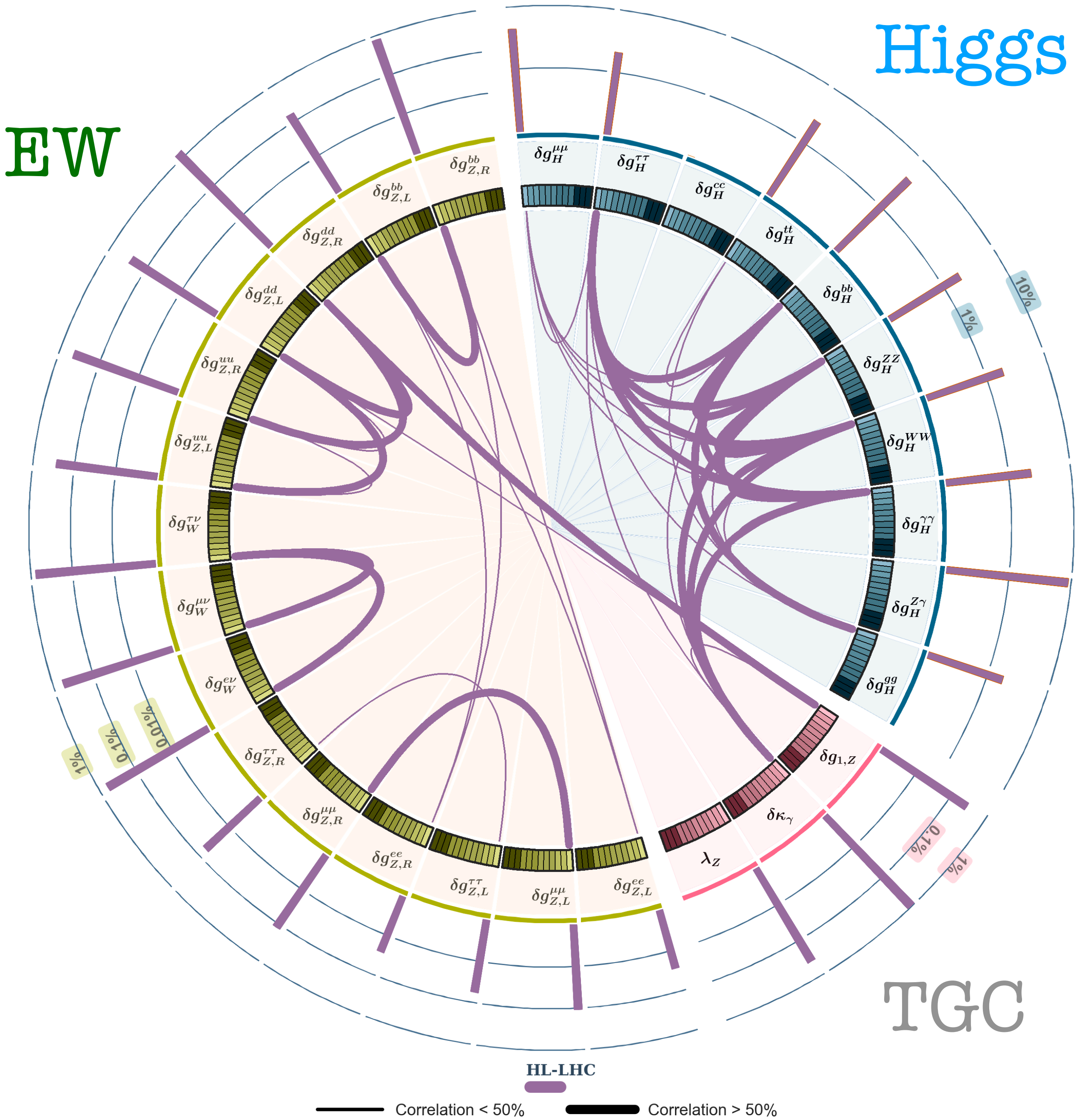


EW known at 0.1%
TGC known at 1%
Higgs known at 10%

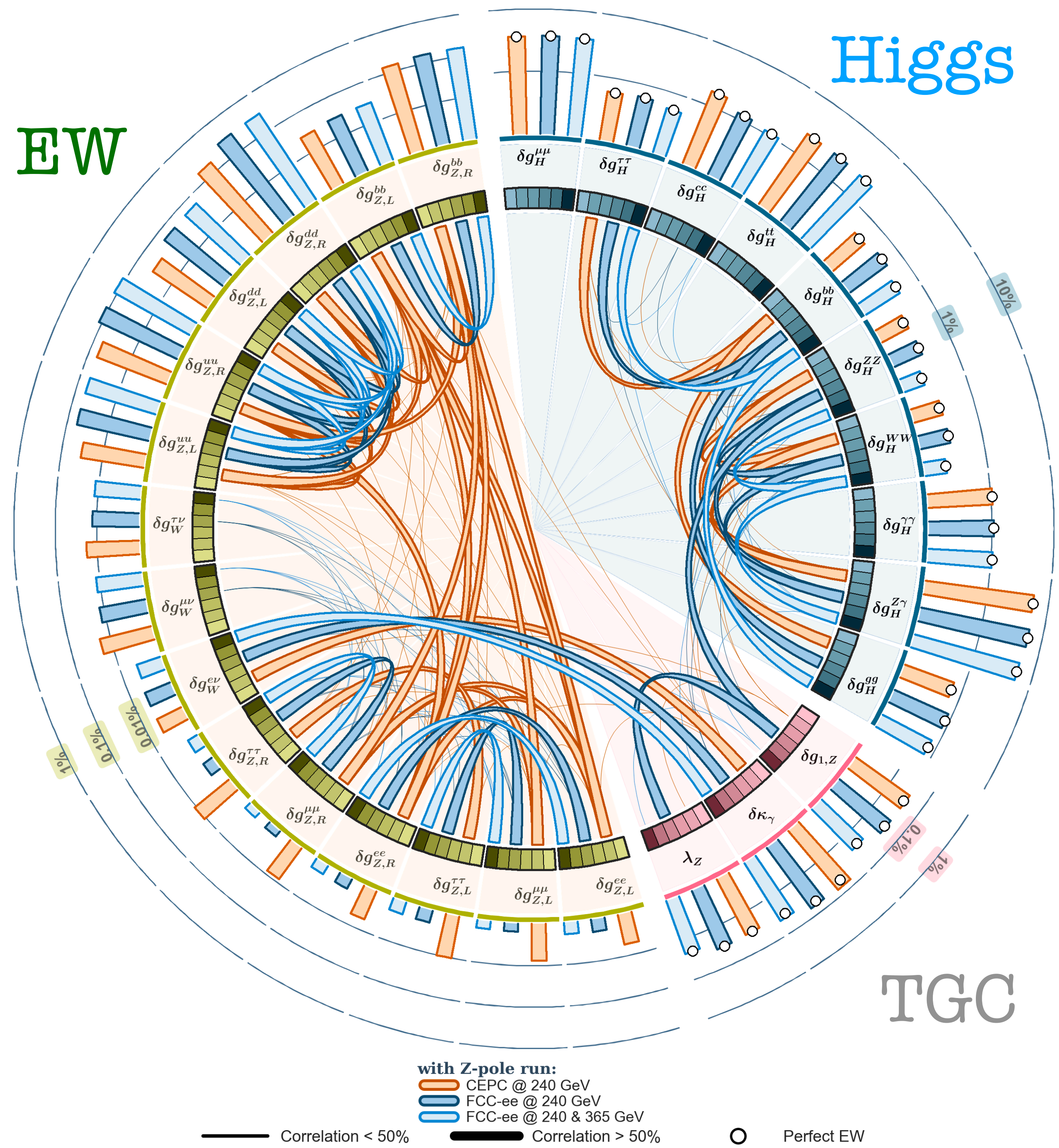
Many thanks to J. De Blas et al. (HEPfit) for the analysis of current data and to A. Paul for plotting the results

SM: Future

HL-LHC projection



Future Colliders



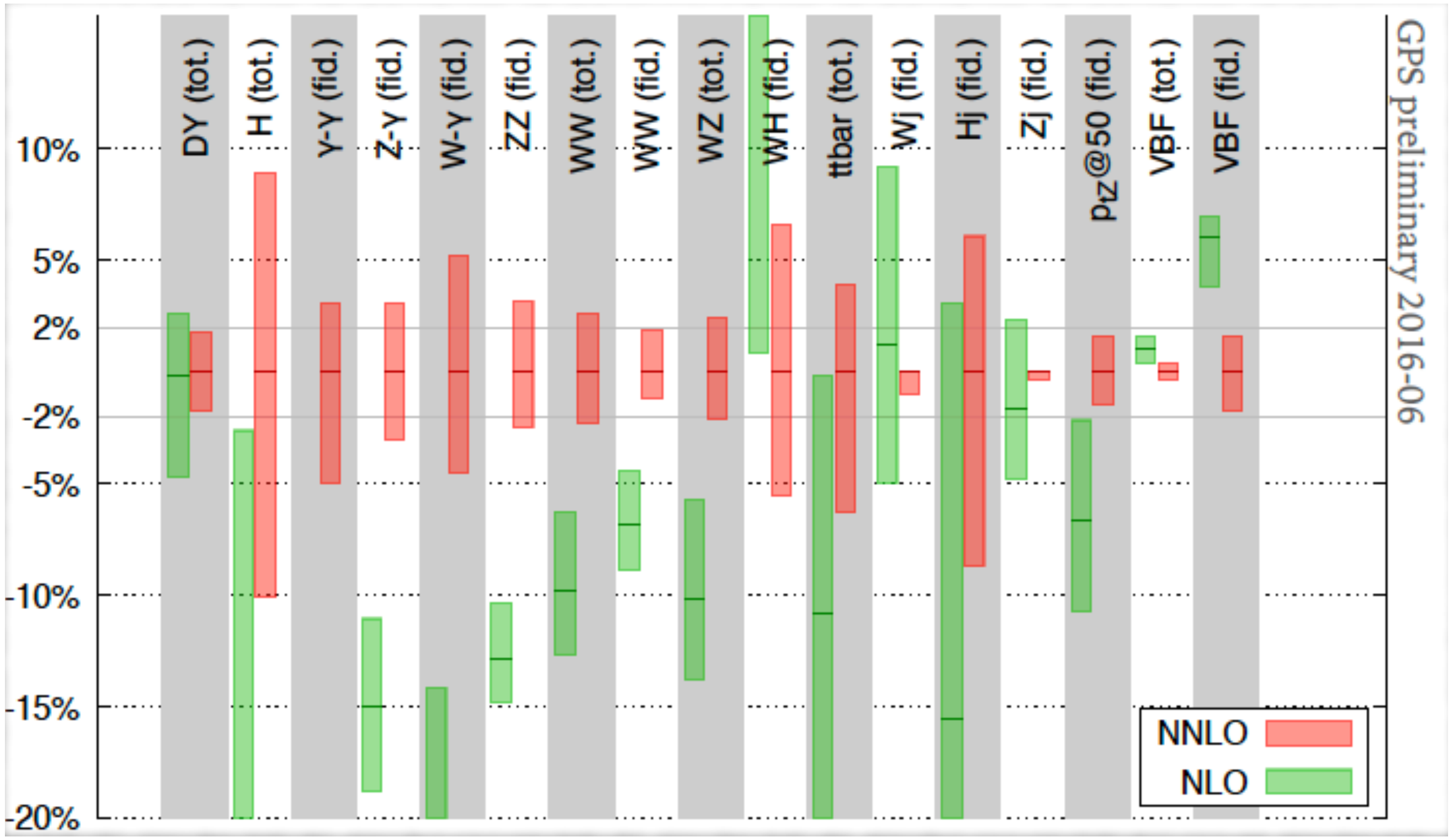
The SM Challenges to Further Progress

Early LHC days: fast progress followed from increased statistics

Statistics will be less and less important ↔ Systematics will be dominant

— Therefore progress requires —

- Better control of parametric uncertainties, e.g. PDFs, α_s, m_t, m_H
- Higher order theoretical computations, e.g. N…NLO
- Access to phase-space limited regions
- Understand correlations among different bins in diff. distributions



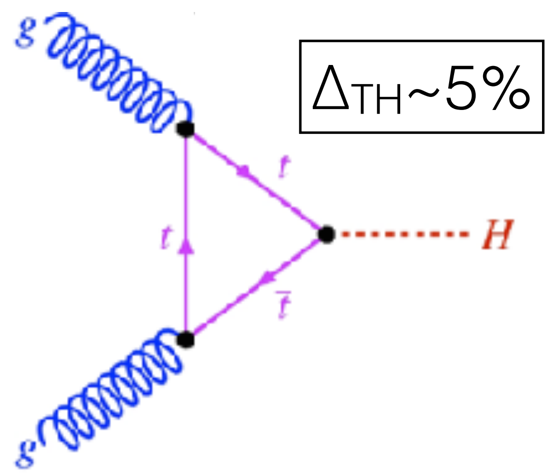
NNLO needed
to reach O(1%) precision

Don't think future HEP is only EXP-business. Theorists have to work harder too!

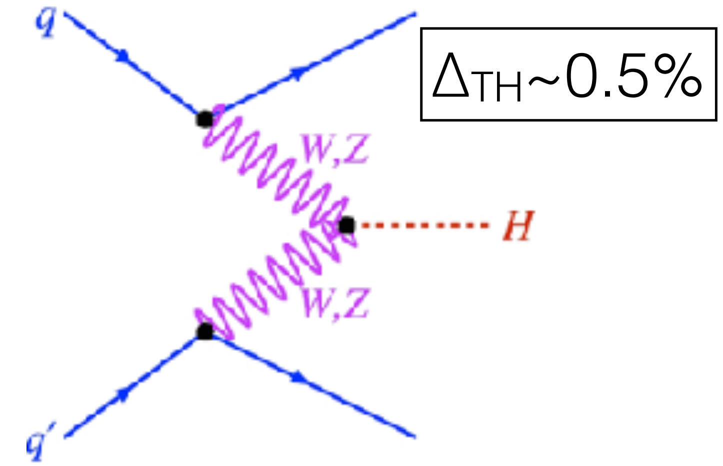
The SM Fast Progress

Sample of major SM computations in Higgs physics in the last few years

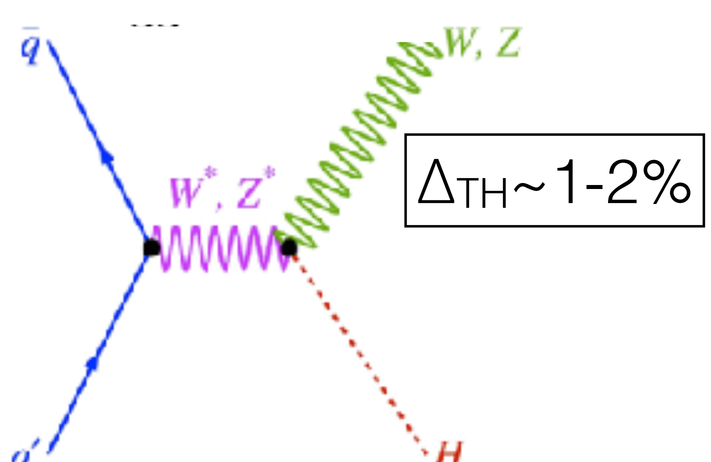
J. Lindert @ SM@LHC'18



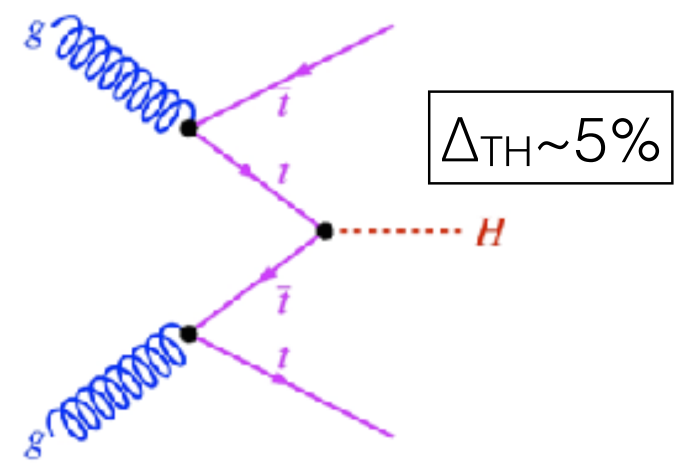
- H-inc: mixed QCD-EW *New!*
- H-pT: NNLO+N3LL *New!*
- H-pT: t & b NLO mass effects *New!*



- VBF-H: differential NNLO revised *New!*



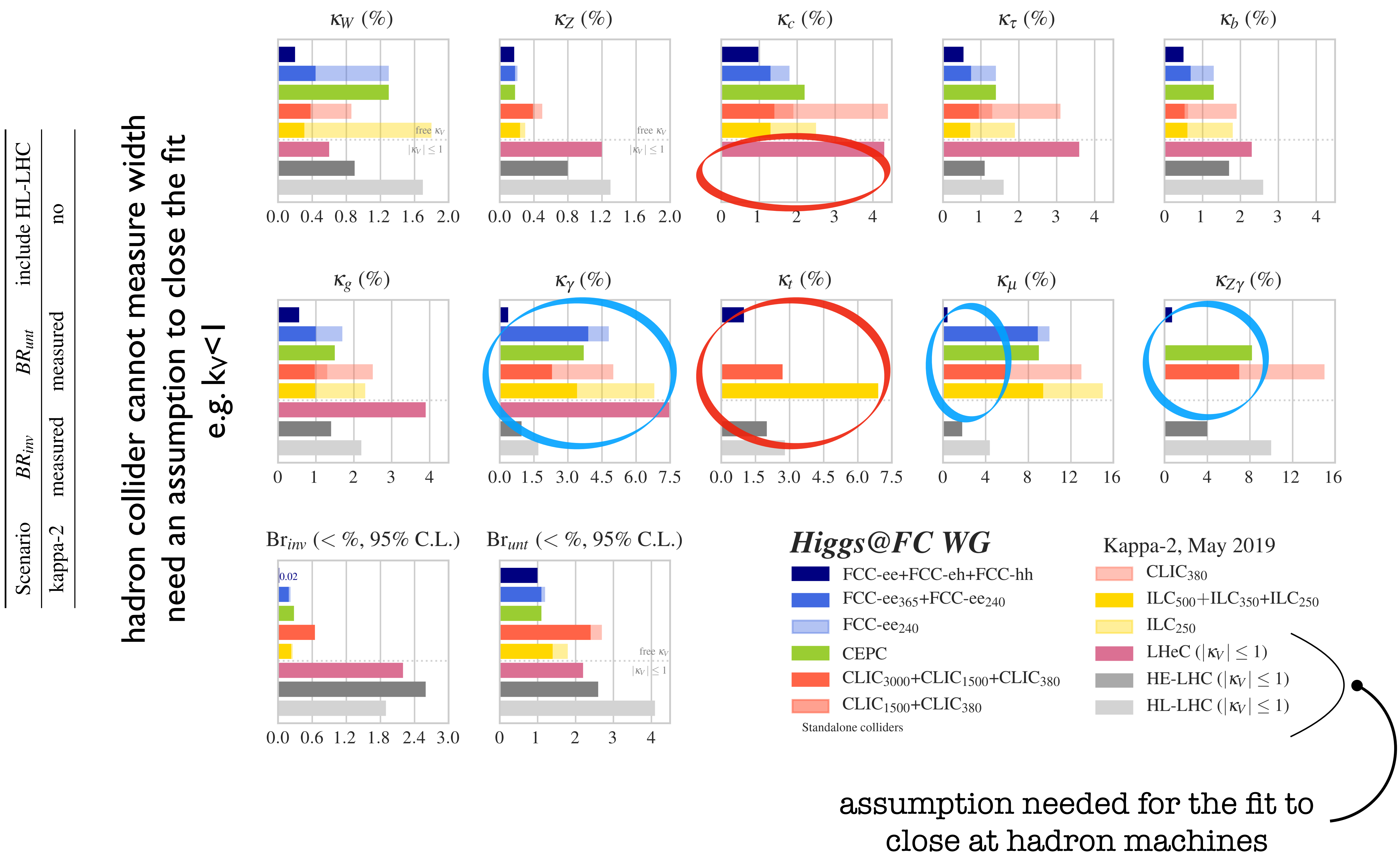
- VH(+jet) @ NLOPS QCD+EW *New!*



- ttH: ttbb background modelling *New!*

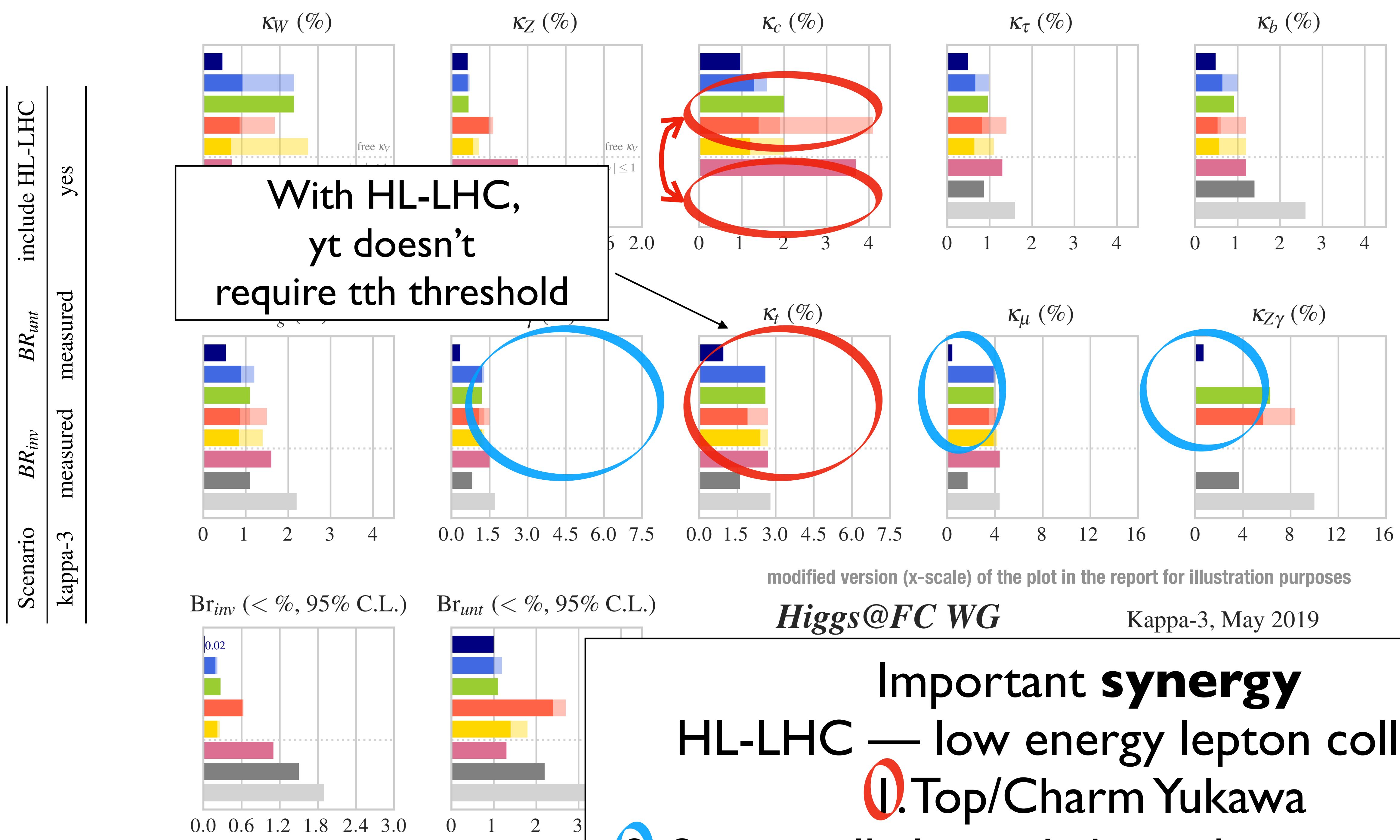
Higgs Fit (Future Collider Alone)

ECFA Higgs study group '19



Higgs Fit (HL-LHC+Future Collider)

ECFA Higgs study group '19



Important **synergy**

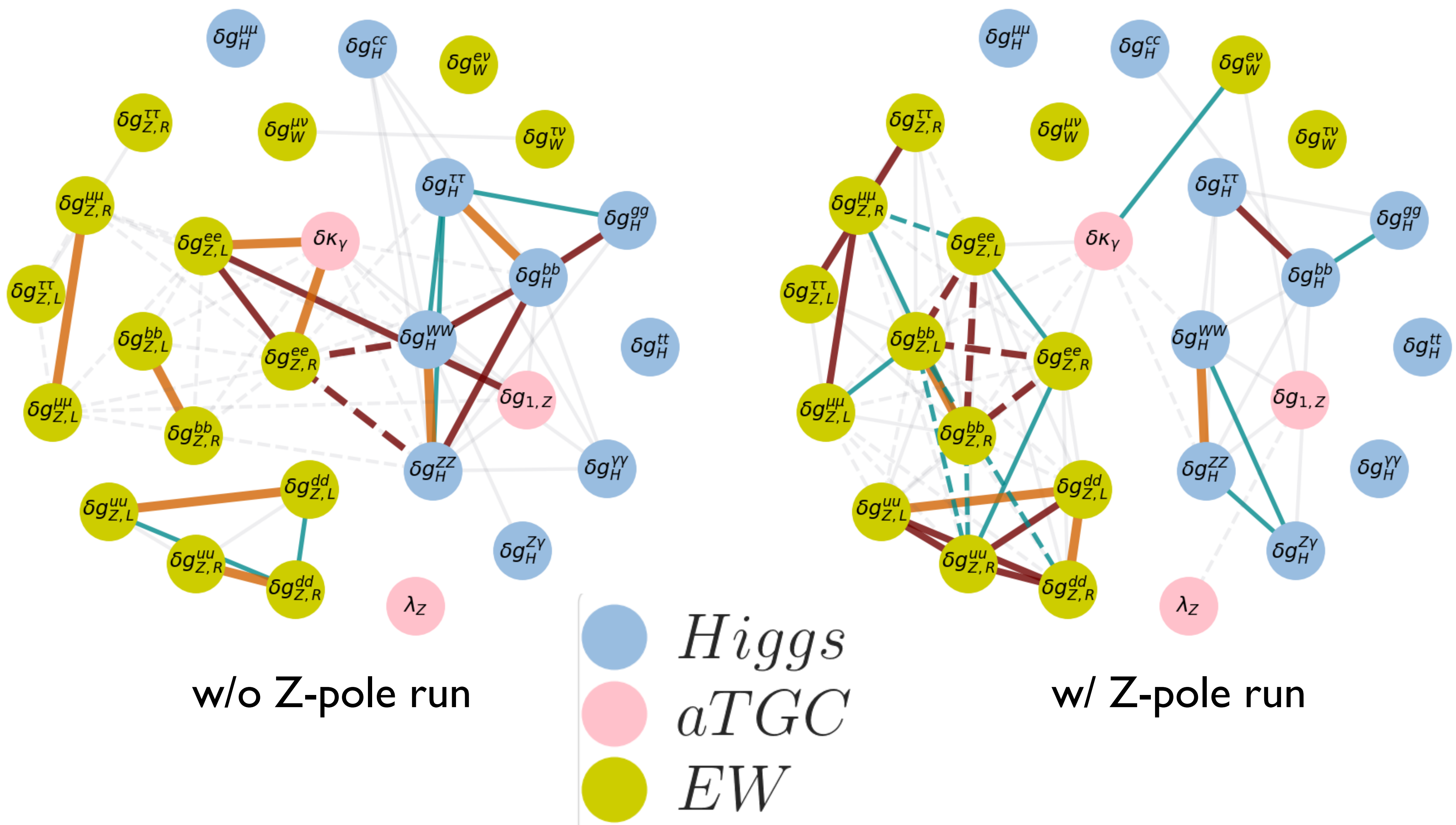
HL-LHC — low energy lepton colliders

1. Top/Charm Yukawa
2. Statistically limited channels: γγ, mumu, Zγ

Synergy ee(M_Z)-ee(M_H)

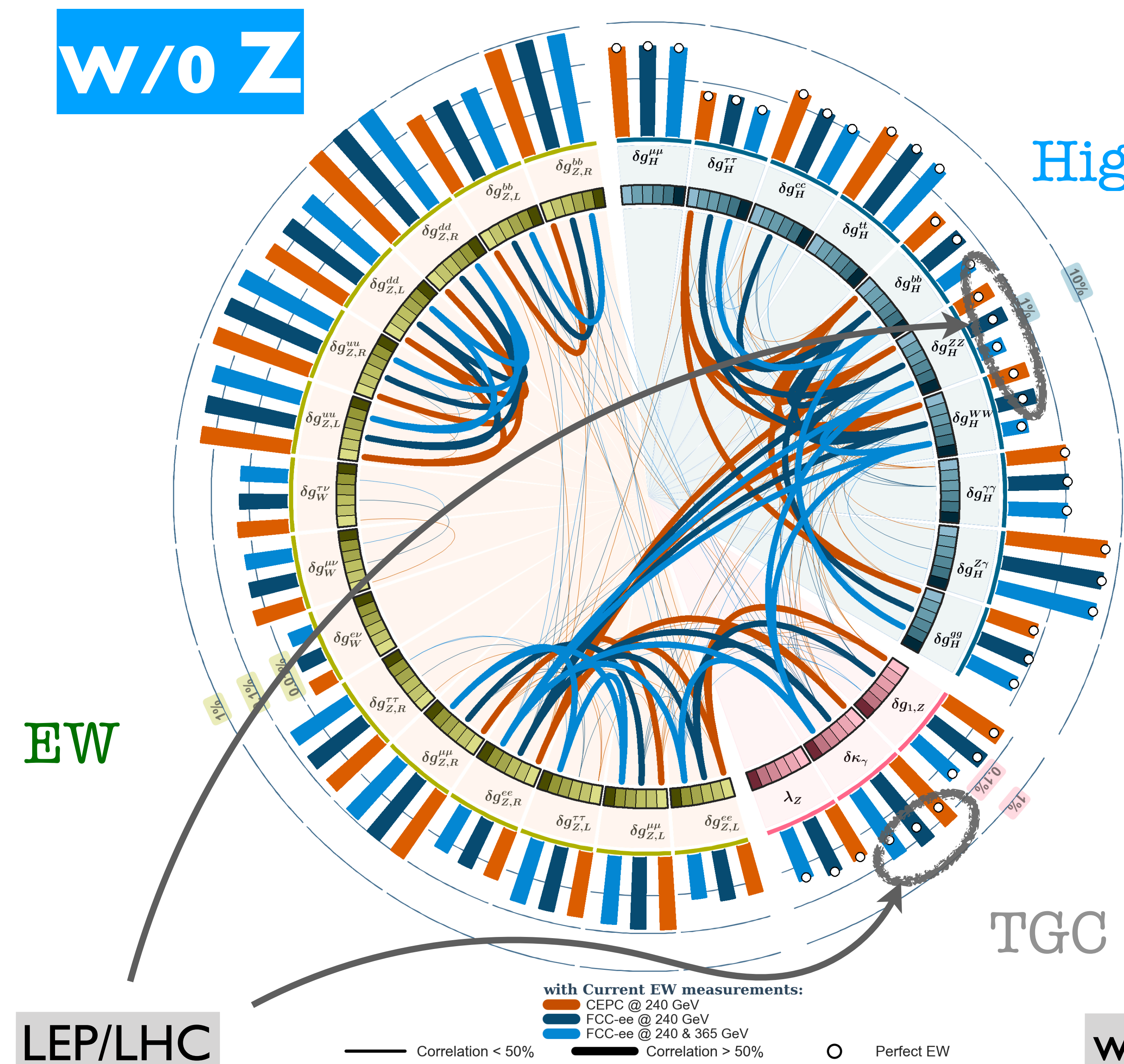
J. De Blas et al. 1907.04311

interplay of runs at different energies change the correlation pattern

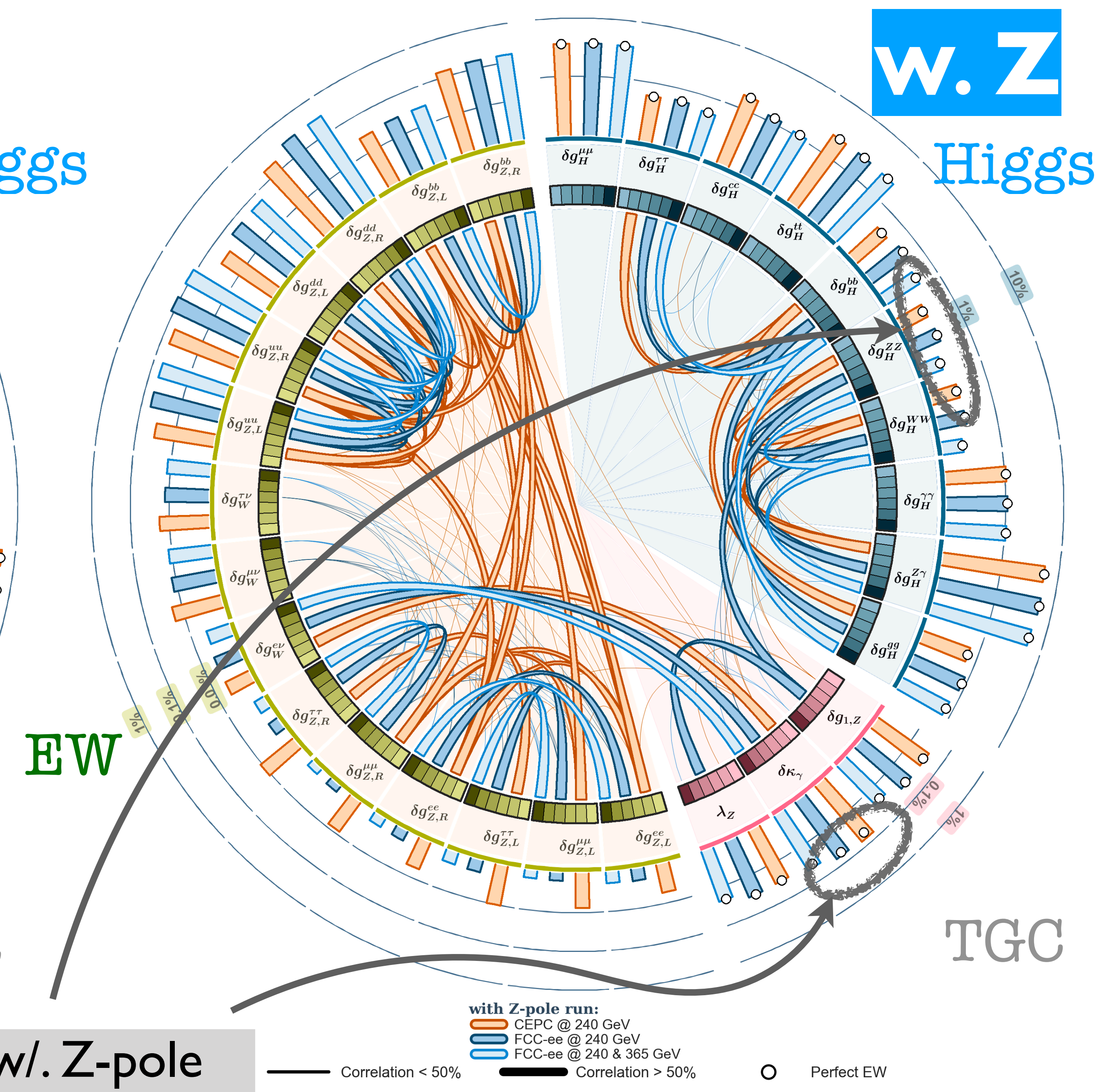


minimising correlations essential to lift flat directions in coupling fit
e.g. Higgs coupling sensitivity improves by 50% with new Z pole data

Synergy ee(M_Z)-ee(M_H)



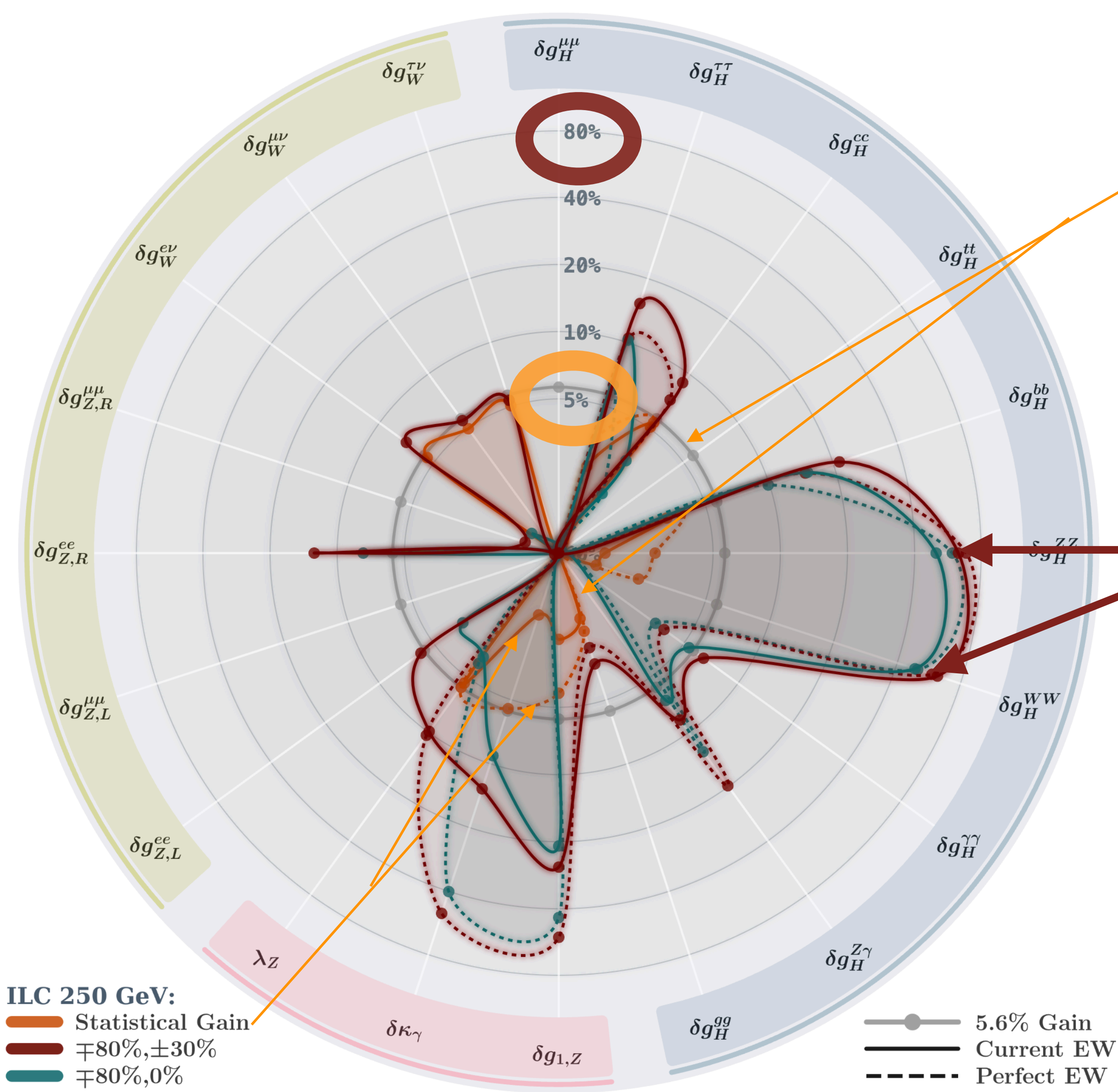
LEP/LHC EW measurements are a limiting factor to precision programme



w/. Z-pole EW uncertainties are not a limit to precision programme

Impact of Beam Polarisation (@250GeV)

J. De Blas et al. 1907.04311



Statistical gain from increased rates

$$\sigma_{P_{e^+}P_{e^-}} = \sigma_0(1 - P_{e^+}P_{e^-})\left[1 - A_{LR}\frac{P_{e^-} - P_{e^+}}{1 - P_{e^+}P_{e^-}}\right]$$

From ee→Zh, A_{LR}~0.15 so $\sigma_{-80,+30} \sim 1.4\,\sigma_0$
overall, one could expect
O(6%) increased coupling sensitivity

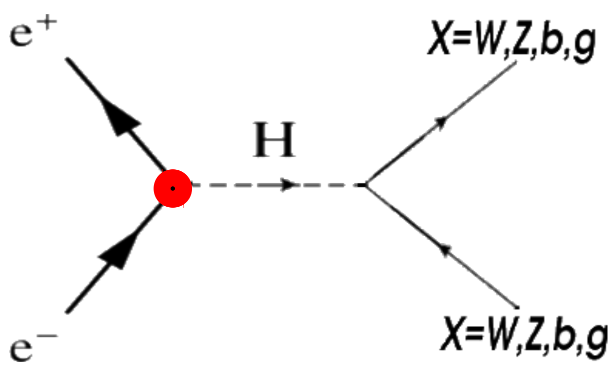
Gain reaches 80%

Gain is much higher in global EFT fit since polarisation removes degeneracies among operators

increased sensitivities Polarised vs. Unpolarised scenarios @ 250GeV

Polarisation benefit diminishes when other runs at higher energies are added and basically left only with statistical gain

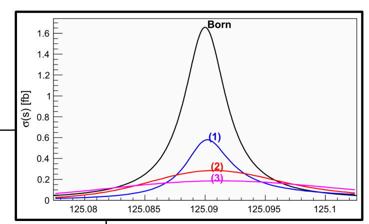
Access to e- Yukawa

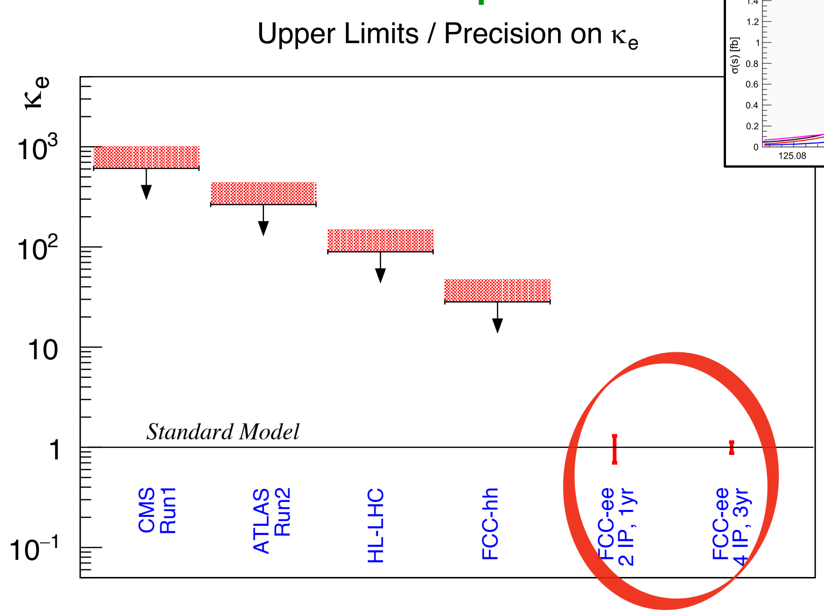


$\sigma(e^+e^- \to H) = 1.64$ fb

$\sigma_{spread+ISR}(e^+e^- \to H) = 0.17 \times \sigma(e^+e^- \to H) = 290$ ab

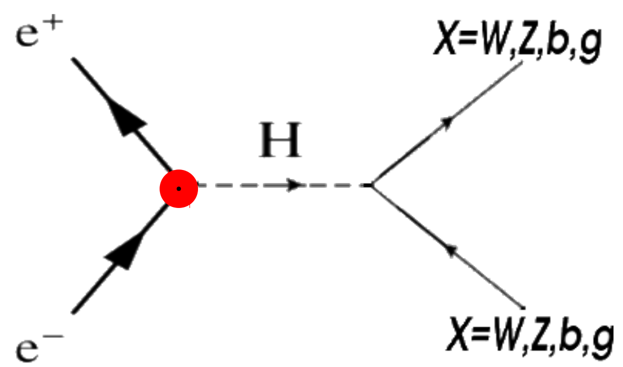
- **20 ab^{-1} / year at $\sqrt{s}$ = 125 GeV** *(not in baseline FCC-ee)*
- **Monochromatization $\sigma_{\sqrt{s}} \sim$ 1-2 × $\Gamma_H \sim$ 6 to 10 MeV**
  - **Resonant ee → H production**





  - **2σ excess in one year with 2 IP**
  - **±15% precion on κ_e in 3 years with 4 IP**
    - ➔ **Not feasible at ILC or CLIC**

Access to e- Yukawa



$\sigma(e^+e^- \to H)$ = 1.64 fb

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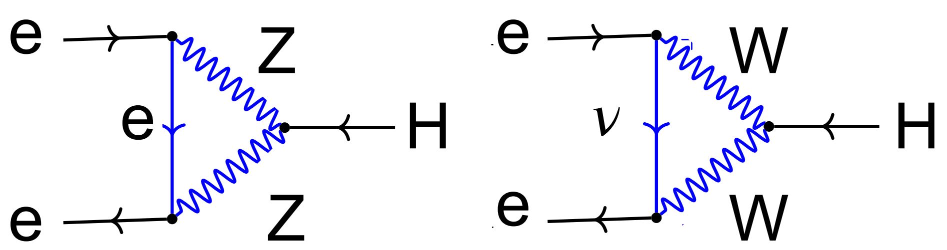
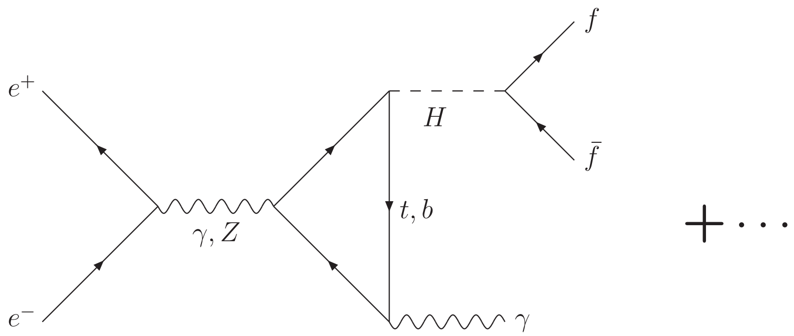
— Are theoretical inputs needed? —



chirality suppressed loops (propto to m_e)

~ 5% - 10% corrections

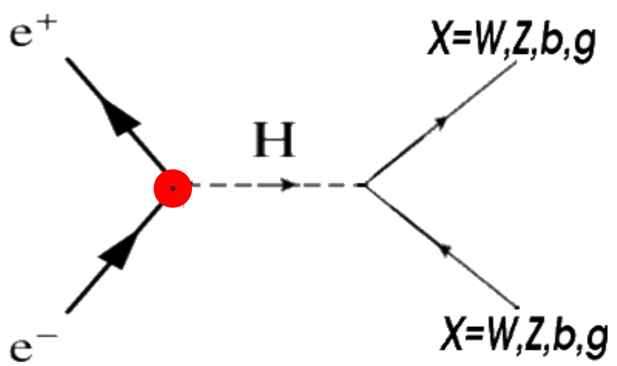
inverse Dalitz: no chirality suppression any longer



Dangerous background? Probably not

see M. Spira@Snowmass 09.20

Access to e- Yukawa



$\sigma(e^+e^-\to H)$ = 1.64 fb

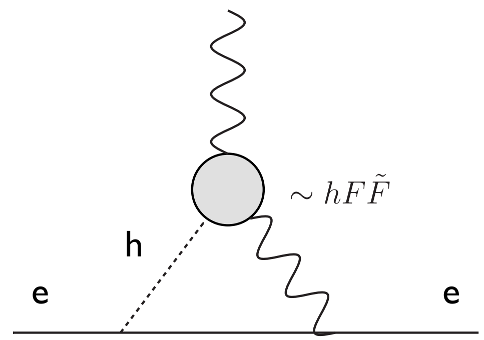
$\sigma_{spread+ISR}(e^+e^-\to H)=0.17\times\sigma(e^+e^-\to H)$=290 ab

Why this measurement is important?

Constraints on CPV from exquisite EDM

CPV bounds from EDM would vanish if hee is zero

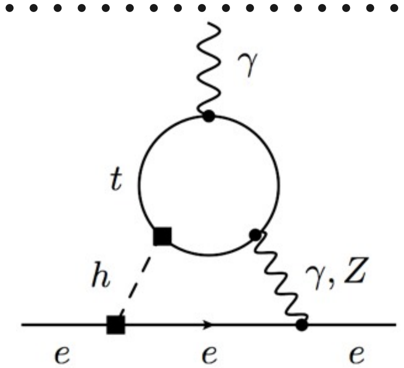
operators with γ McKeen+ '12



$\tilde{\kappa}_{\gamma\gamma} \sim \tilde{\kappa}_{\gamma Z} \leq 10^{-4}$

Λ_{CPV} > 25 TeV

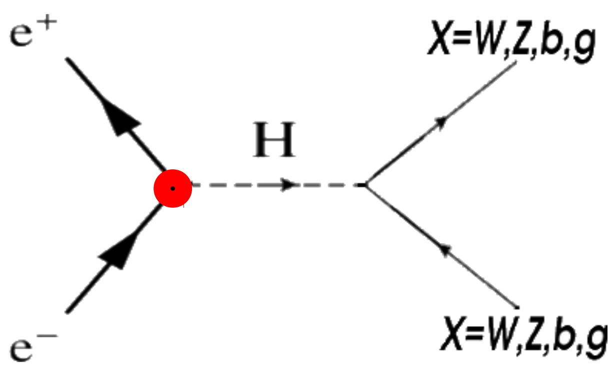
operators with top Brod+ '13



$\delta\tilde{g}_{htt} \leq 0.01$

Λ_{CPV} > 2.5 TeV

Access to e- Yukawa



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Constraints on CPV from exquisite EDM

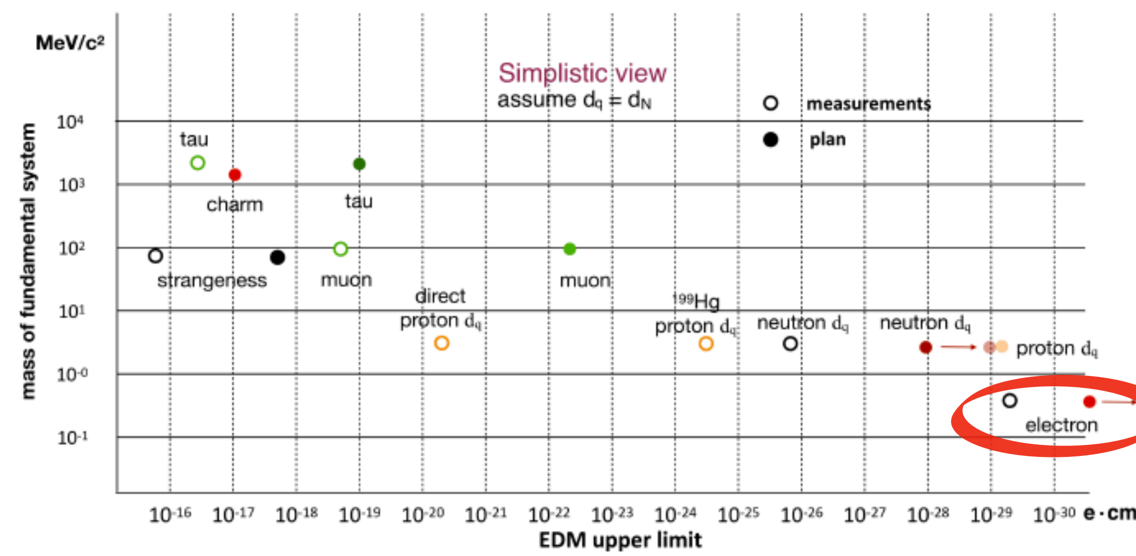
CPV bounds from EDM would vanish if hee is zero

current ACME 90%CL bound on e EDM

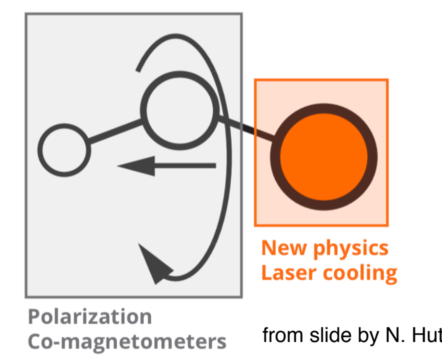
$$|d_e| < 1.1 \times 10^{-29}\, e\, \text{cm}.$$

(SM$_4$ value : 10^{-37}-10^{-44} e cm)

ESU, arXiv:1910.11775



Polyatomic EDM



from slide by N. Hutz

Time scale of 5-10 years:

$$|d_e| \lesssim 10^{-32}\, e\, \text{cm}$$

1-loop, PeV scale sensitivity

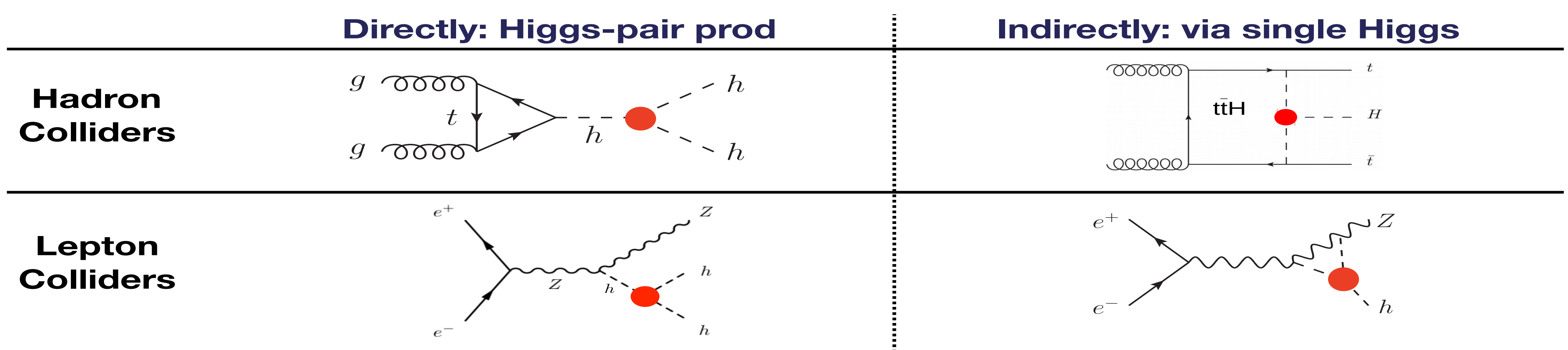
M. Reece @ Pheno2020

Snowmass LOI

Higgs Self-Coupling

Higgs self-couplings is very interesting for a multitude of reasons
(vacuum stability, hierarchy, baryogenesis, GW, EFT probe…).

How much different from the SM can it be
given the tight constraints on other Higgs couplings?
Do you need to reach HH production threshold to constrain h^3?

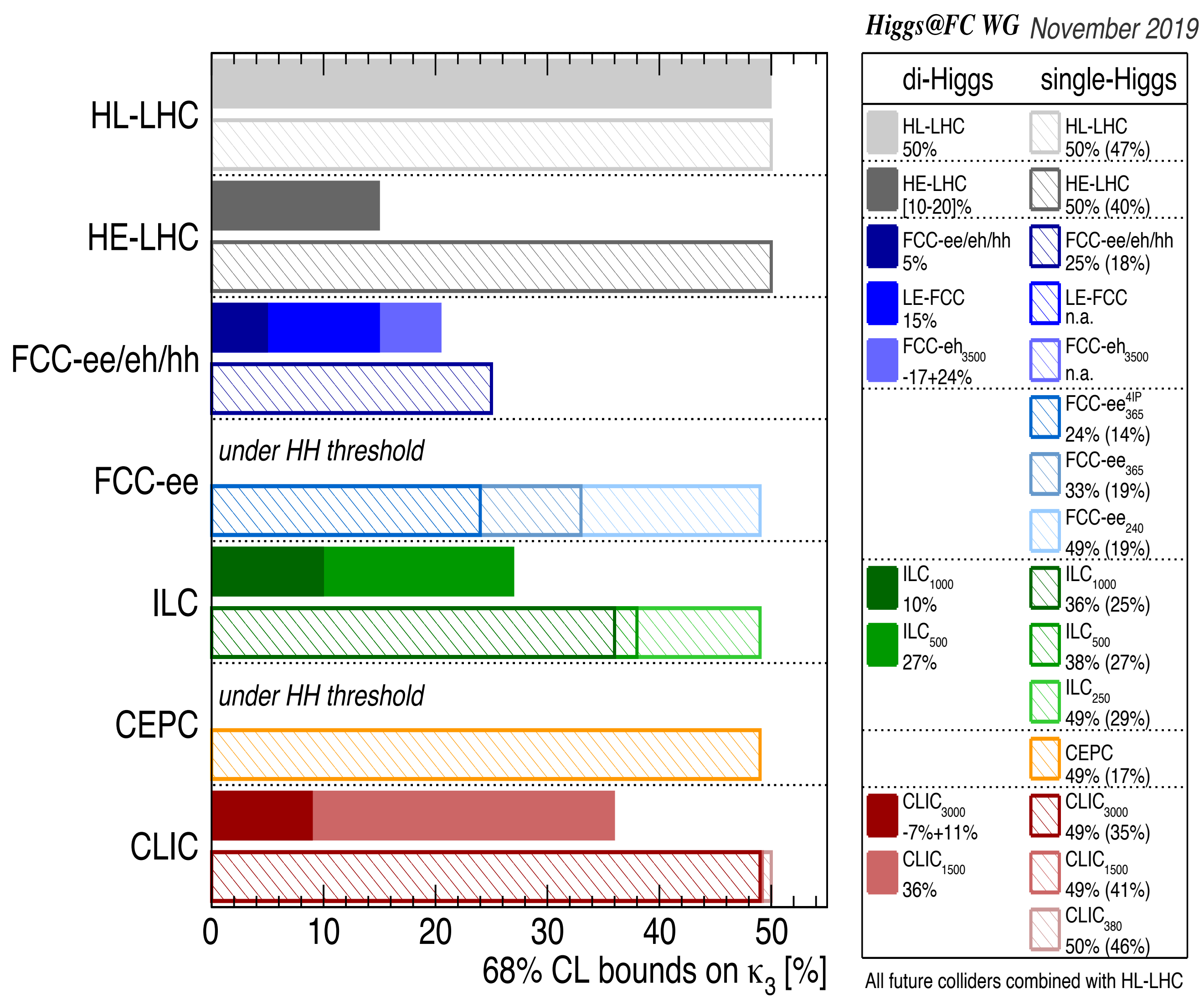


	di-Higgs	single-H
exclusive	**1. di-H, excl.** • Use of σ(HH) • only deformation of κλ	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of κλ
global	**2. di-H, glob.** • Use of σ(HH) • deformation of κλ + of the single-H couplings (a) do not consider the effects at higher order of κλ to single H production and decays (b) these higher order effects are included	**4. single-H, glob.** • single Higgs processes at higher order • deformation of κλ + of the single Higgs couplings

ECFA Higgs study group '19

Higgs Self-Coupling

ECFA Higgs study group '19



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

(ii) Exploration potential

New Physics

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

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

⇔

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

What is the scale of New Physics?

— Simplicity —

High Scale Wishes

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

— Complexity —

Low Scale Wishes

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

↪ axion?

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

↪ ?

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

↪ 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

What is the scale of New Physics?

— Simplicity —

High Scale Wishes

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

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

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— Complexity —

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↳ ?

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

↳ light susy?

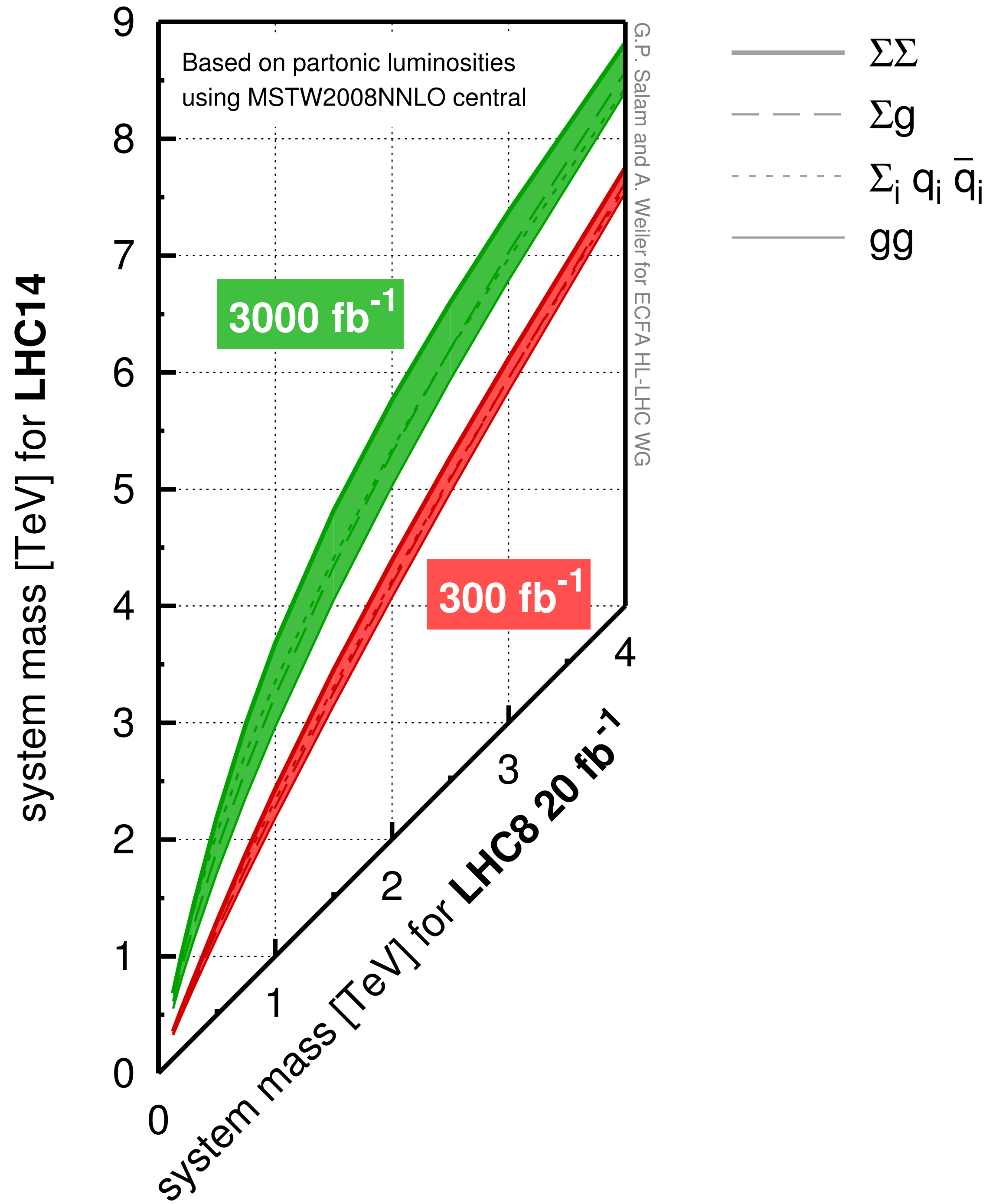
Where is everyone?

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

need for a versatile machine
capable to adjust to very different new physics scenario

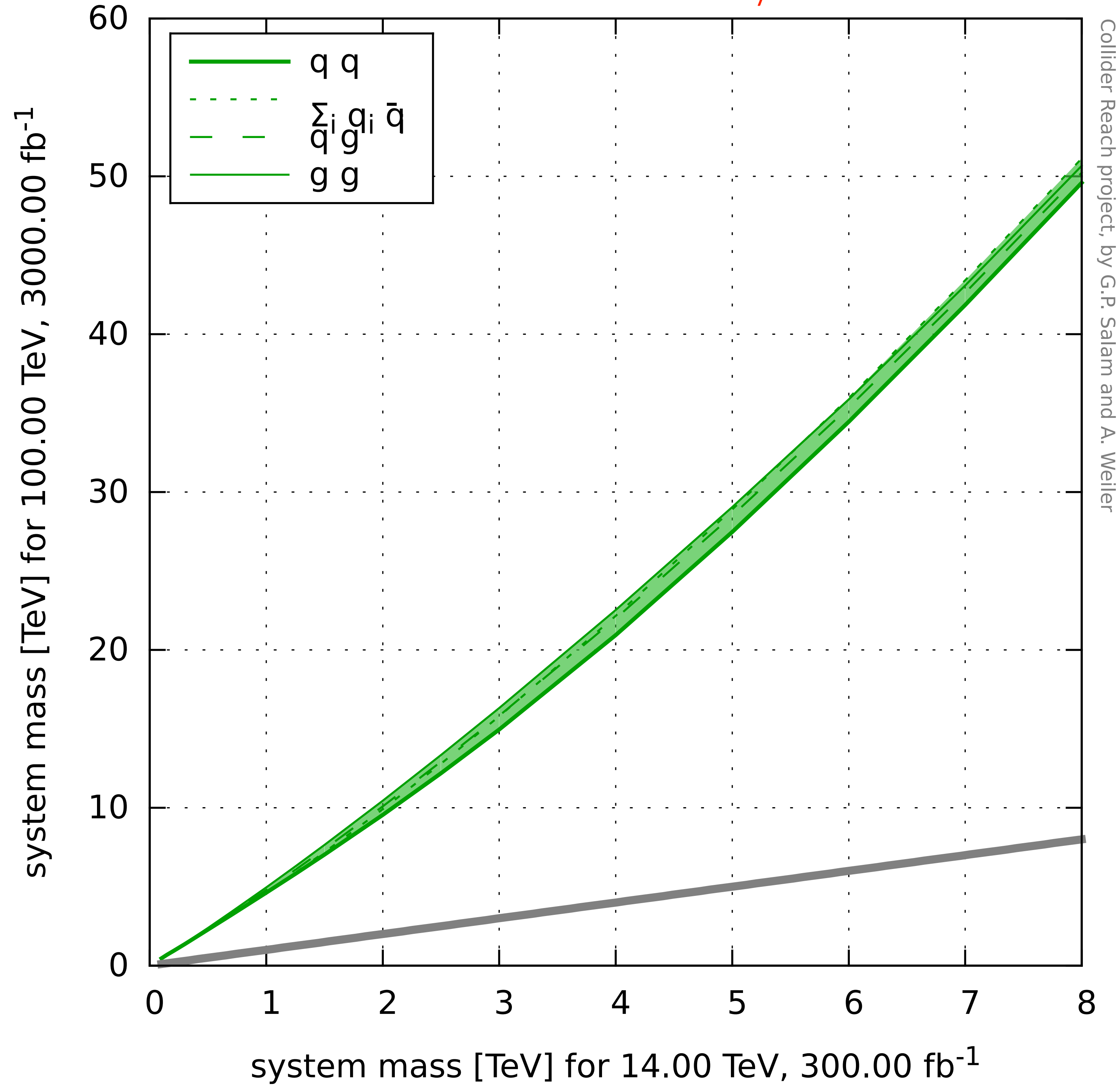
The power of PDF

Direct exploration of an unexplored energy territory



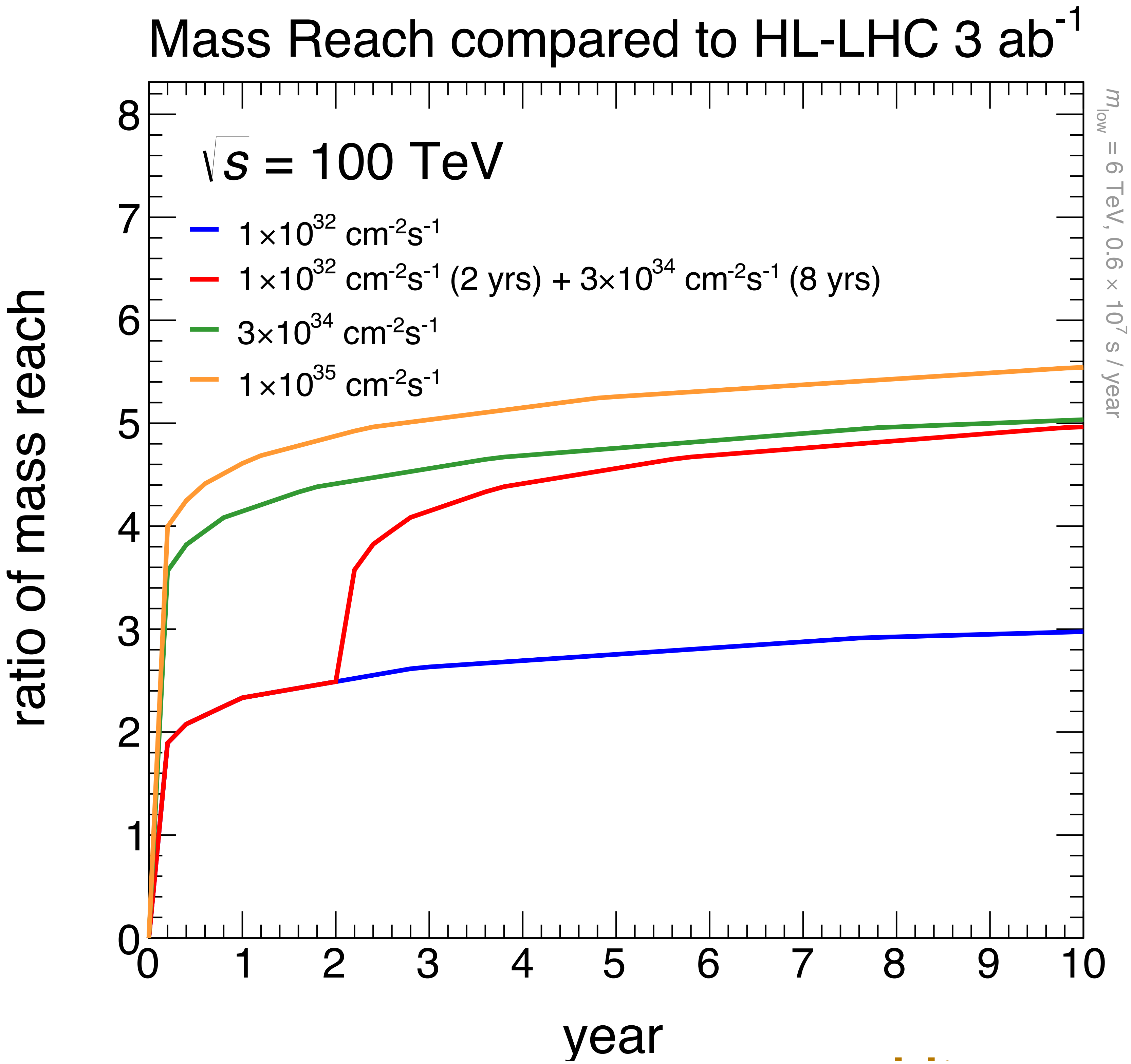
LHC14/LHC8:
mass reach x O(2)

Salam & Weiler "cern.ch/collider-reach" '14



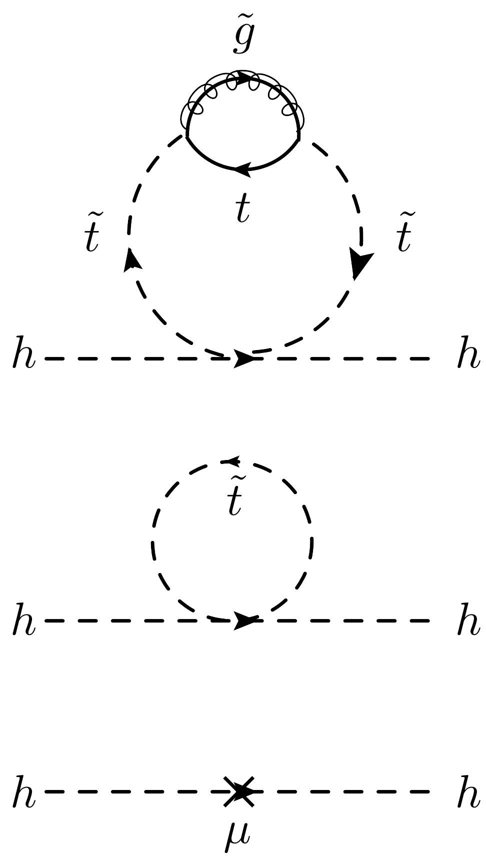
VHE-LHC100/LHC14:
mass reach x O(5)

The power of PDF



Hinchliffe, Kotwal, Mangano, Quigg, Wang '15

I. Probing natural SUSY



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

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

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

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

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

I. Probing natural SUSY

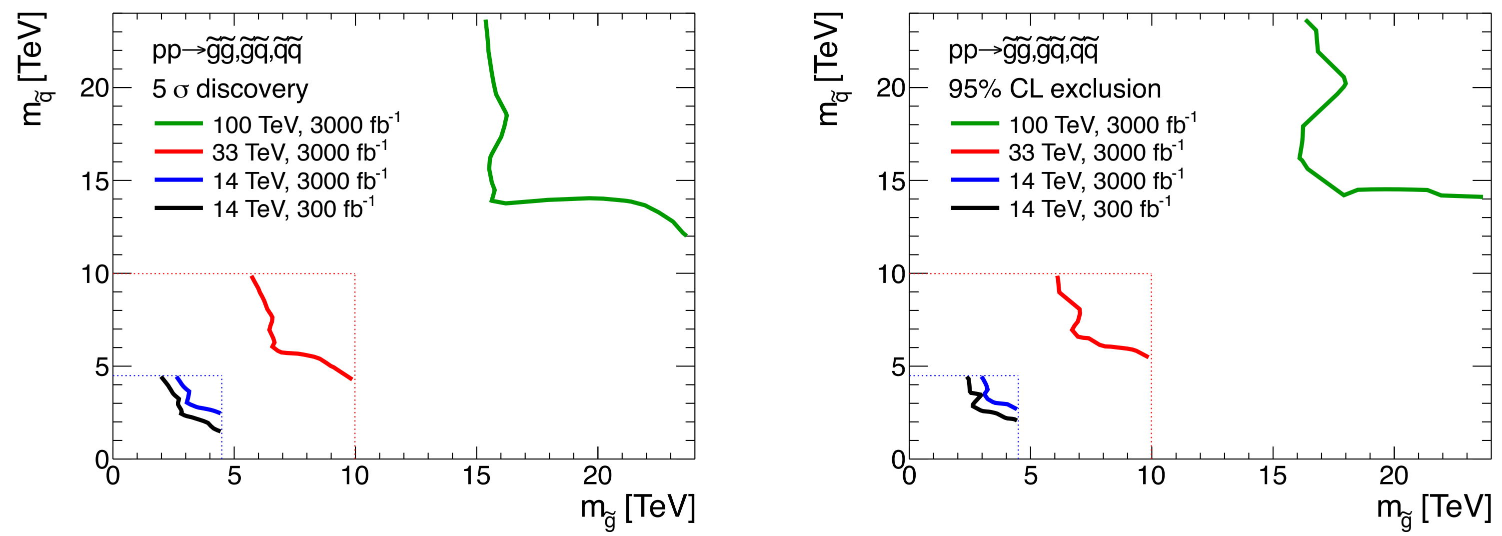


Fig. 16: Results for the gluino-squark-neutralino model. The neutralino mass is taken to be 1 GeV. The left [right] panel shows the $5\,\sigma$ discovery reach [95% CL exclusion] for the four collider scenarios studied here. A 20% systematic uncertainty is assumed and pile-up is not included.

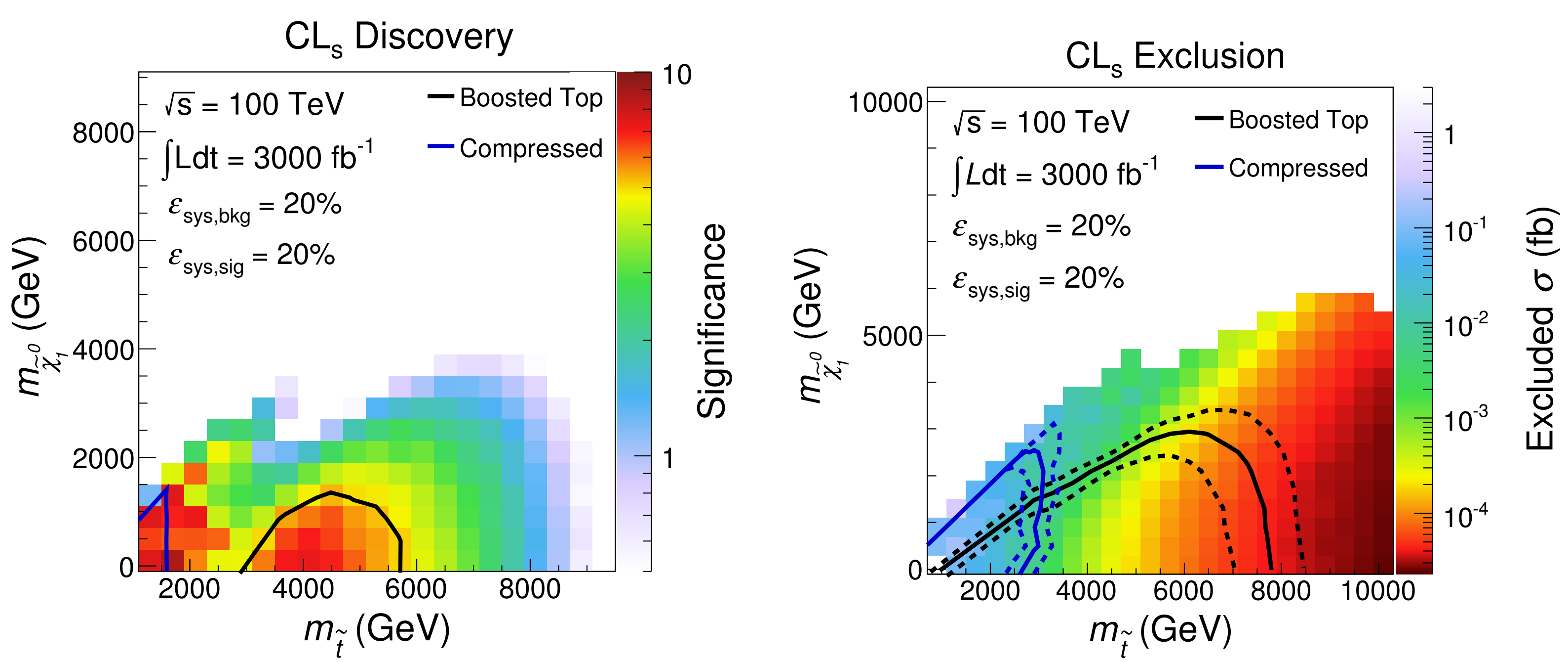


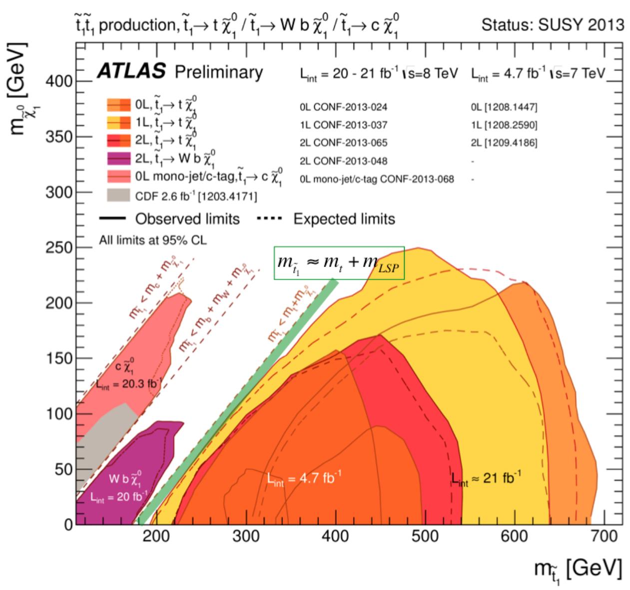
Fig. 12: Left: Discovery potential and Right: Projected exclusion limits for 3000 fb^{-1} of total integrated luminosity at $\sqrt{s} = 100$ TeV. The solid lines show the expected discovery or exclusion obtained from the boosted top (black) and compressed spectra (blue) searches. In the boosted regime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

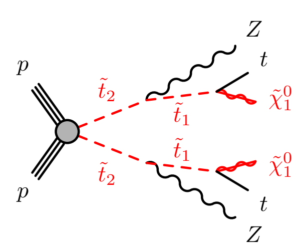
I. Natural SUSY: beyond standard searches

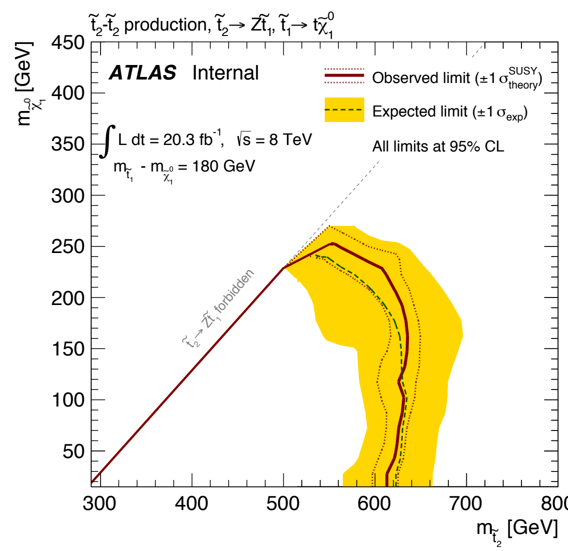
Searching for light stop from heavy stop decay

~ 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: $Z(\ell^+\ell^-)+\ell+b+E_T^{\text{miss}}$
- Eur. Phys. J. C **74** (2014) 2883 (20 fb^{-1})

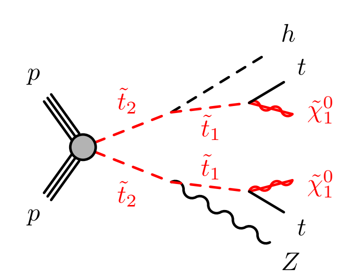


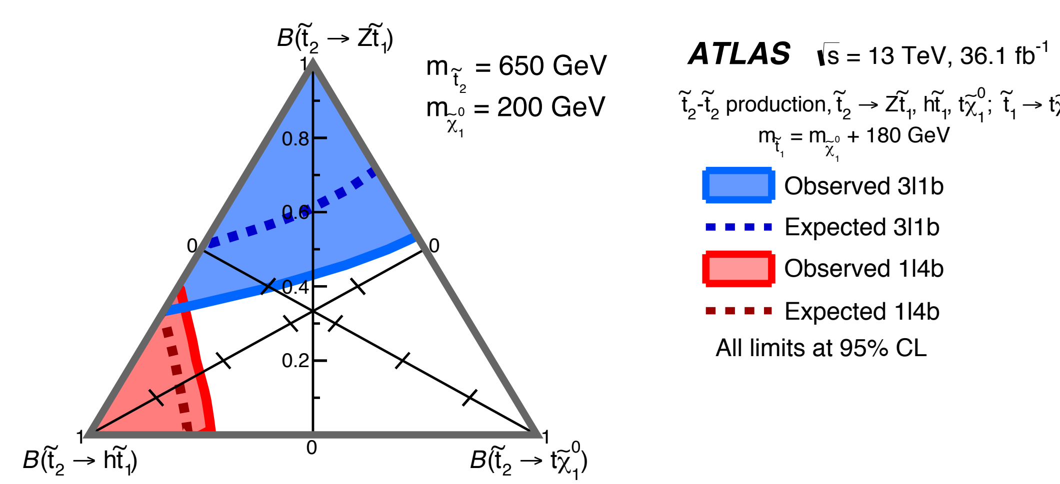


~ RUN 2 ~

- ATLAS-CONF-2016-038 (13 fb^{-1}): explore $\tilde{t}_2 \to Z\tilde{t}_1$ with $3\ell+b+E_T^{\text{miss}}$
- JHEP **1708** (2017) 006 (36 fb^{-1}): analysis extended to $\tilde{t}_2 \to h\tilde{t}_1$ with $1\ell+4b+E_T^{\text{miss}}$
- 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

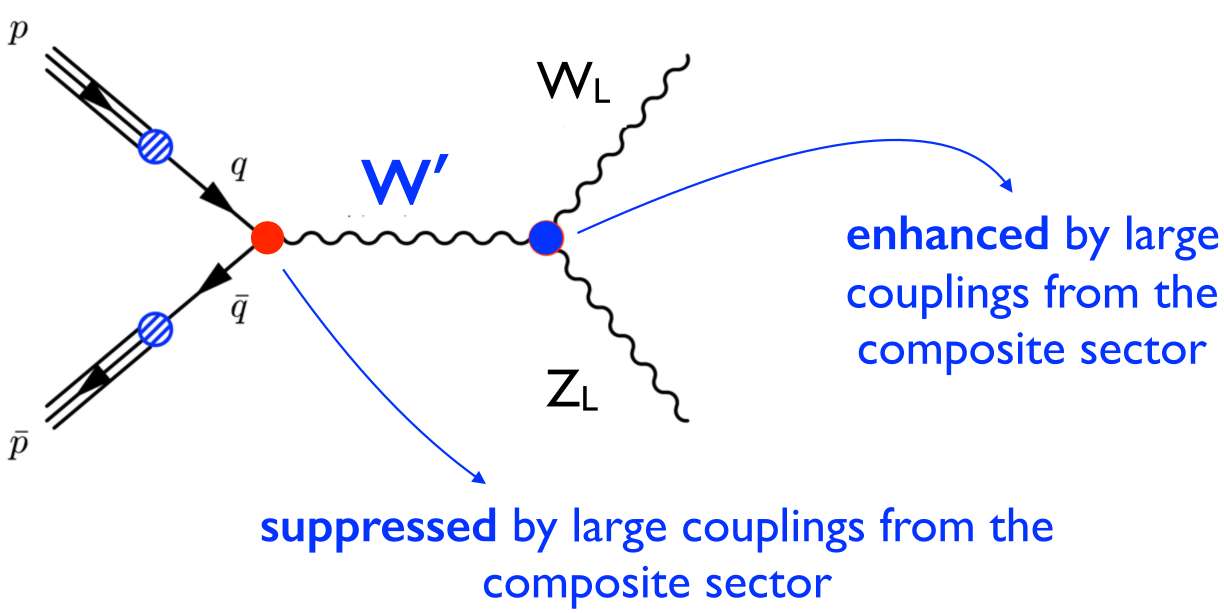




II. Vector resonances

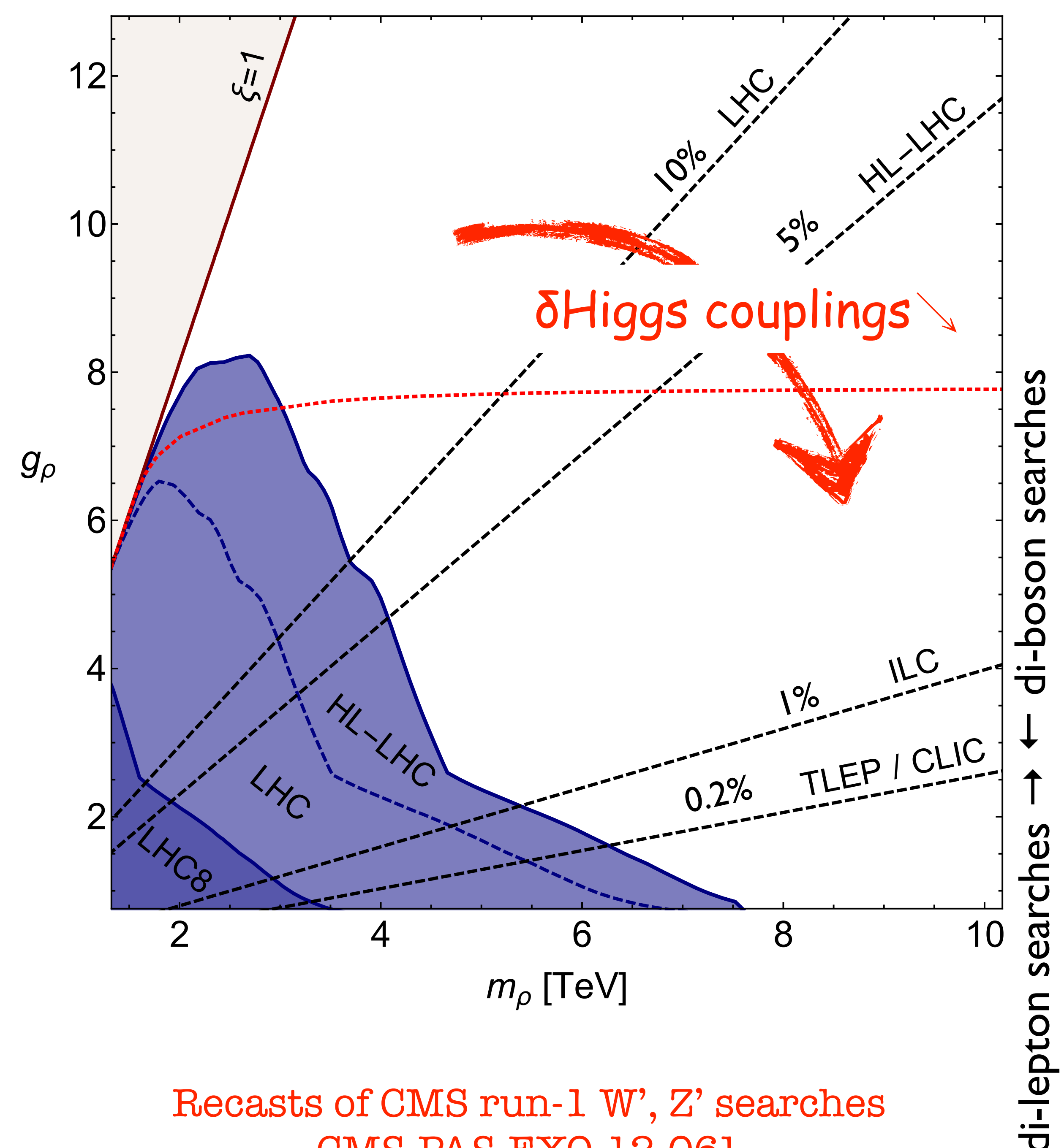
Precision /indirect searches (high lumi.) vs. direct searches (high energy)

Torre, Thamm, Wulzer '15



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

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



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

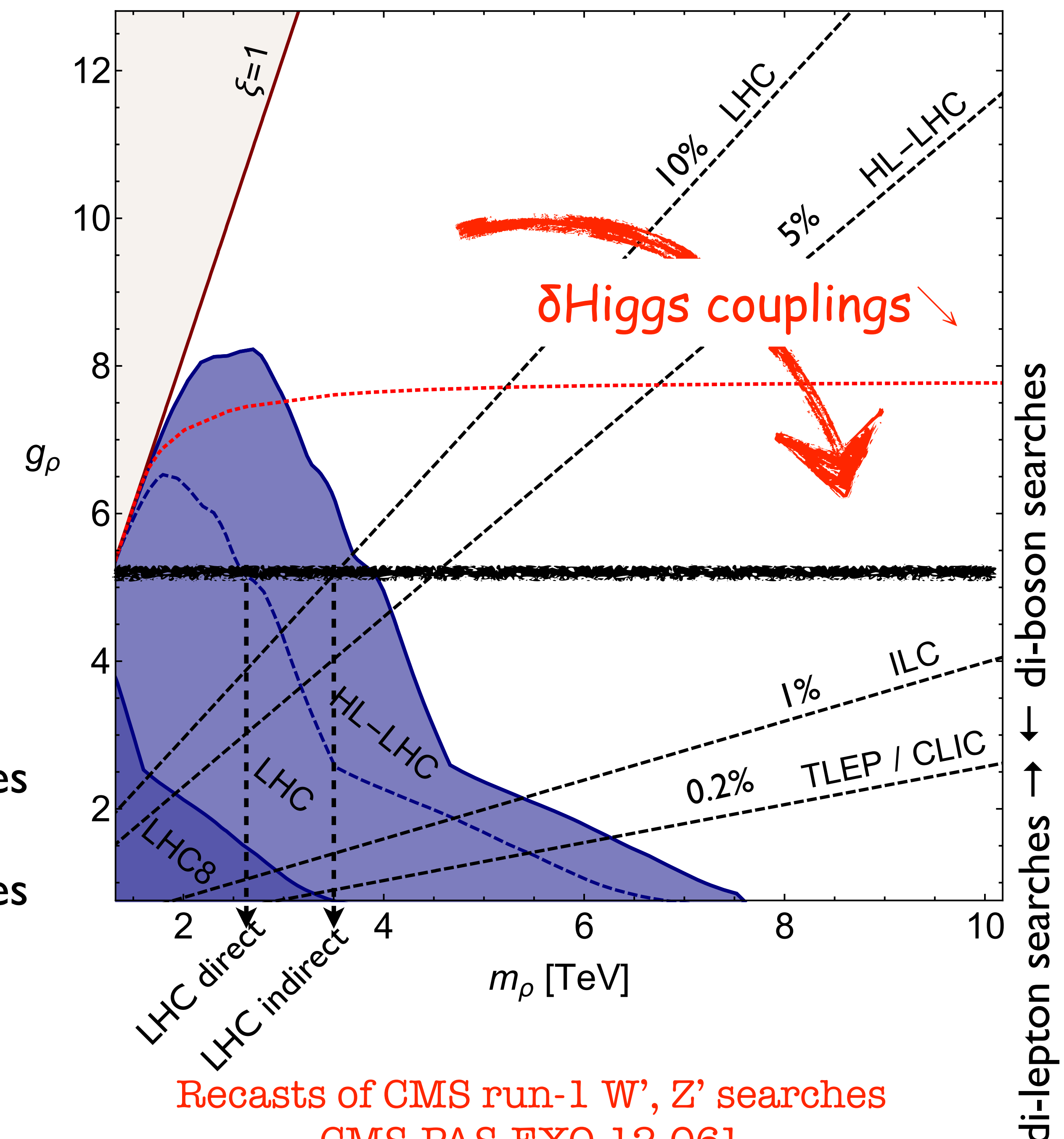
II. Vector resonances

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

Torre, Thamm, Wulzer '15

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

- **complementarity:**
  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling



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

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

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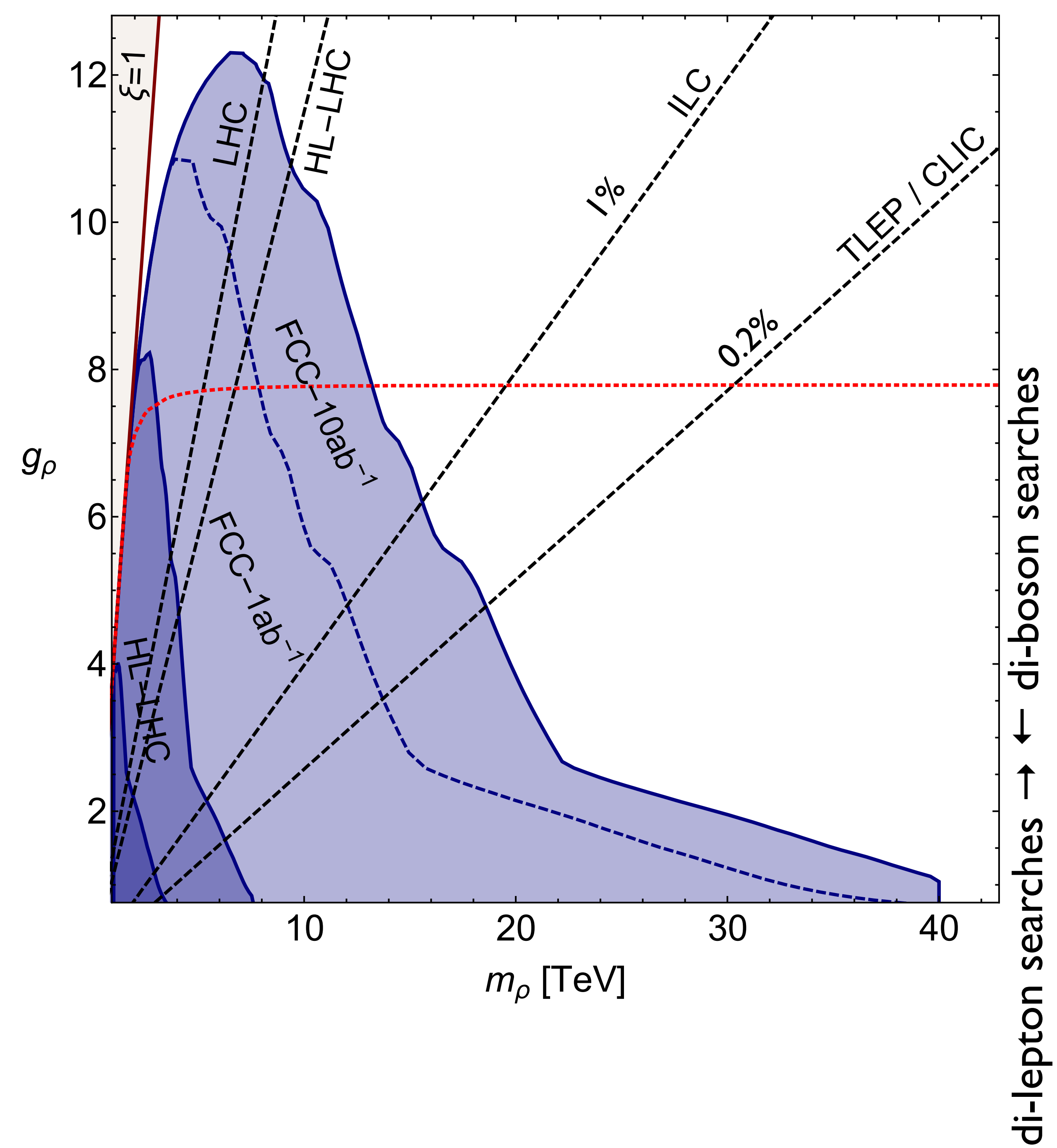

- **complementarity:**
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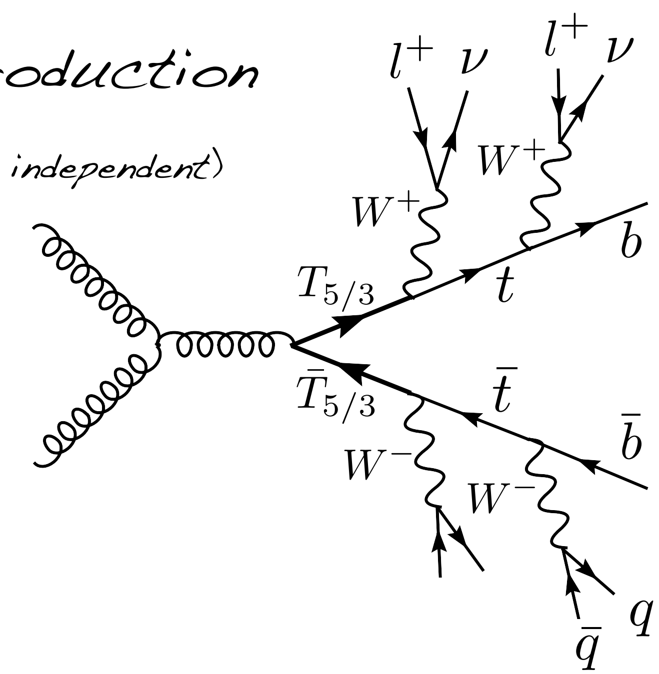
III. Fermionic top partners
(aka vector-like quarks)

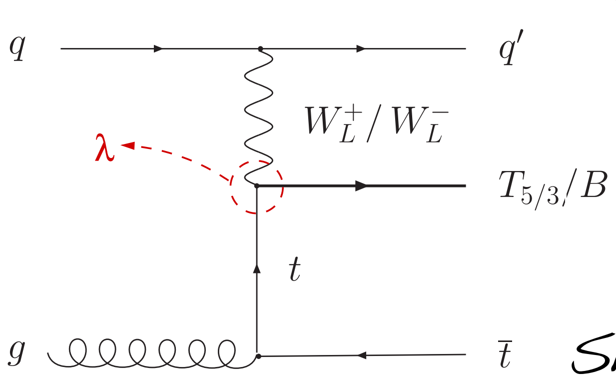
Search in same-sign dilepton events

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

Pair production

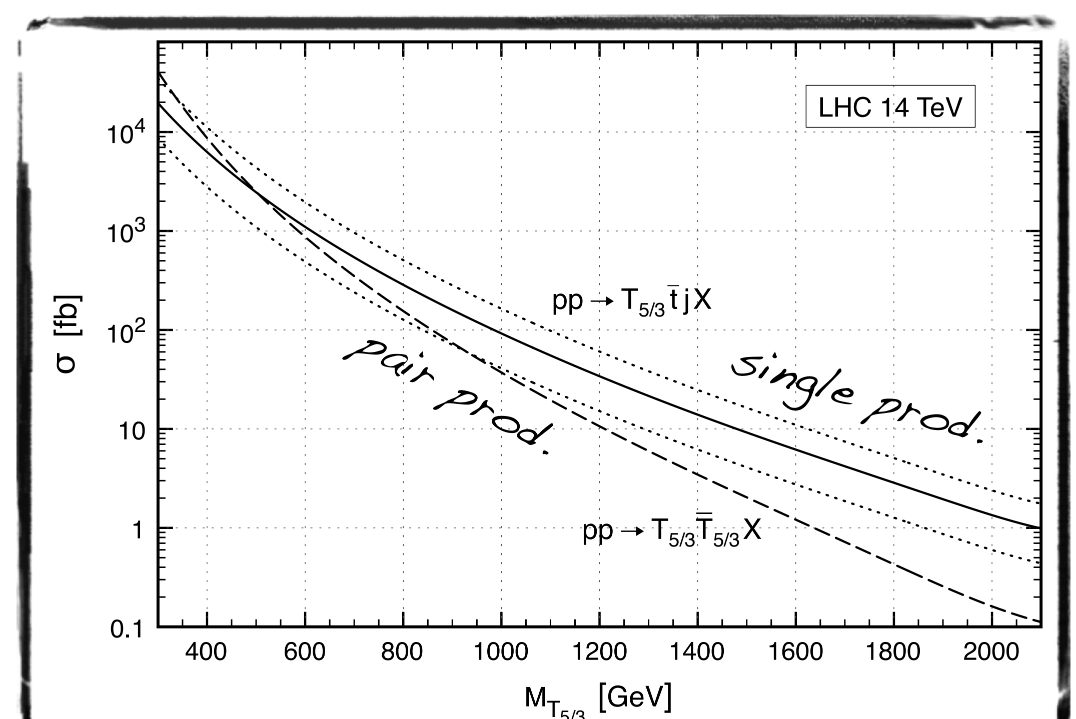
(model independent)





Single production

(model dependent)



[Contino, Servant '08]

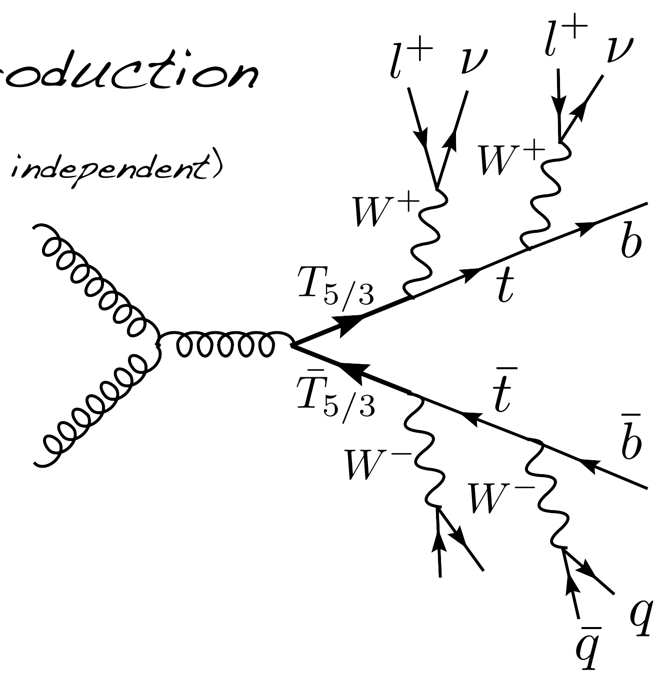
III. Fermionic top partners
(aka vector-like quarks)

Search in same-sign dilepton events

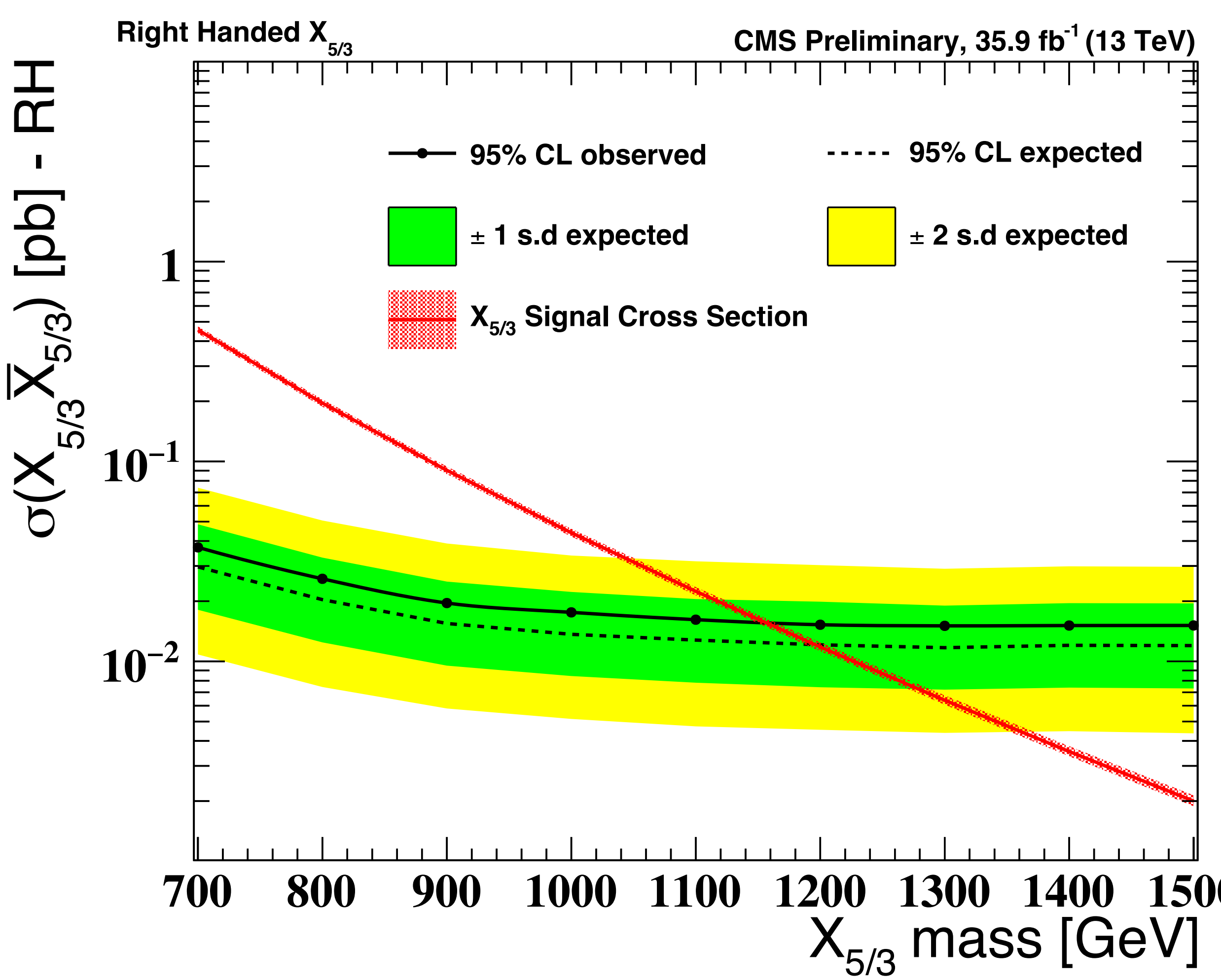
- *tt+jets* is not a background [except for charge mis-ID and fake e⁻]
- the resonant (tW) invariant mass can be reconstructed

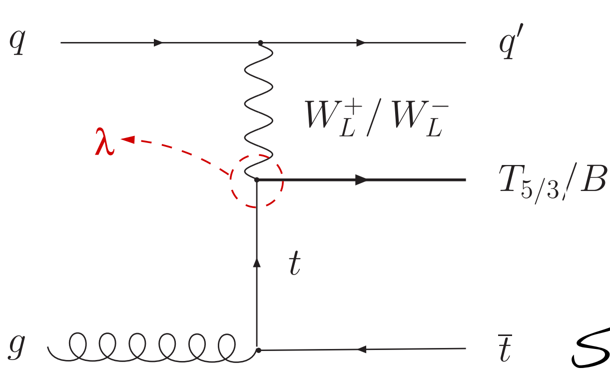
Pair production

(model independent)



Moriond'17 bound: 1160 GeV

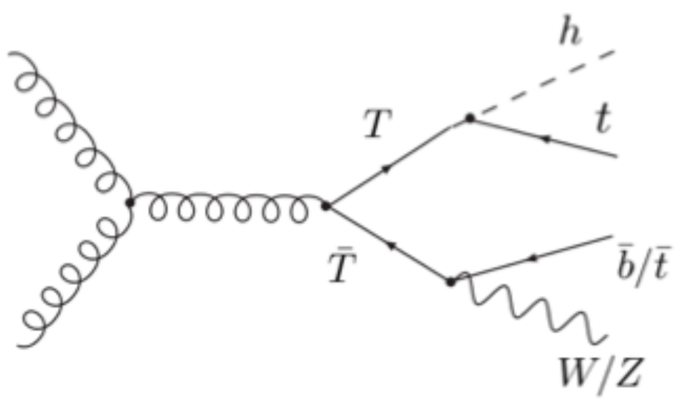




Single production

(model dependent)

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



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

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

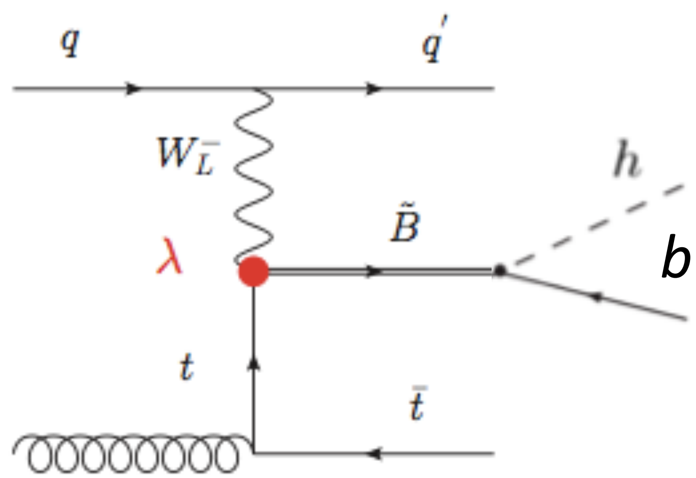
  $T\bar{T} \to HtV\bar{t} \to HW^+bVW^-\bar{b}$ $H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$

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

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

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

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

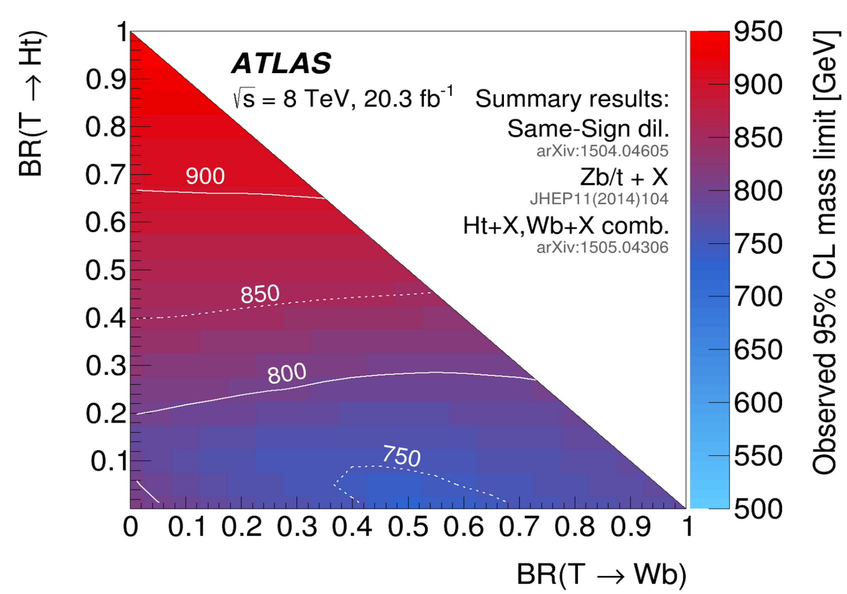


- $\ell^\pm$ + 4b final state Vignaroli '12

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

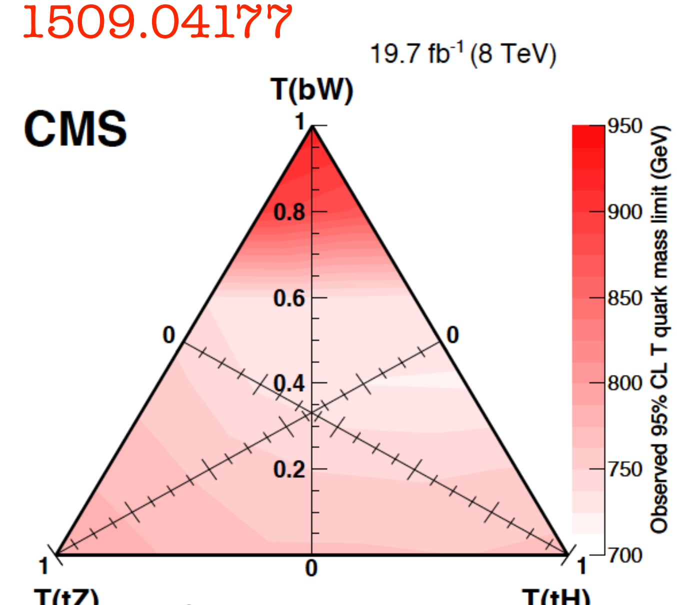
Moriond'17 update bounds above 1 TeV!

1505.04306



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

1509.04177



Combined limits

IV. Searches for extended Higgs sectors

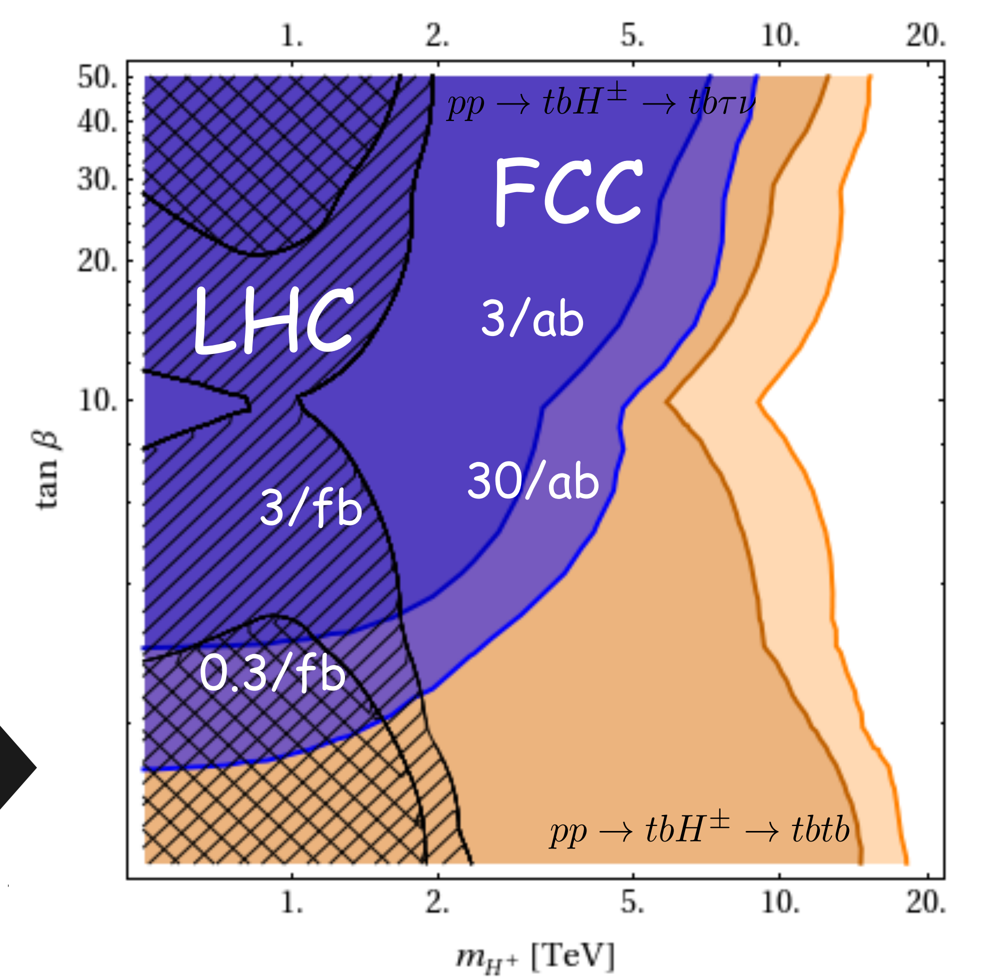
Extended Higgs sectors are a prediction of many BSM scenarios.
They may play a role in the following open questions:

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

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

Contino FCC@Rome '16

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



J. Hajer et al '15

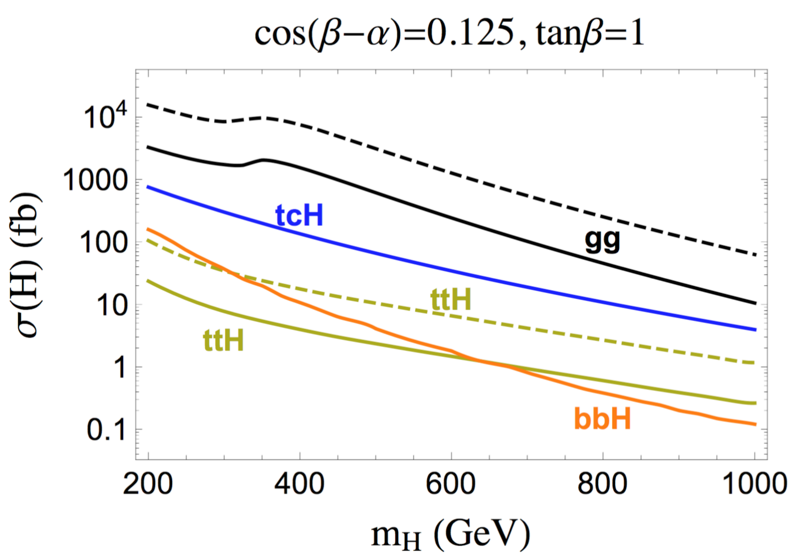
IV. Searches for extended Higgs sectors

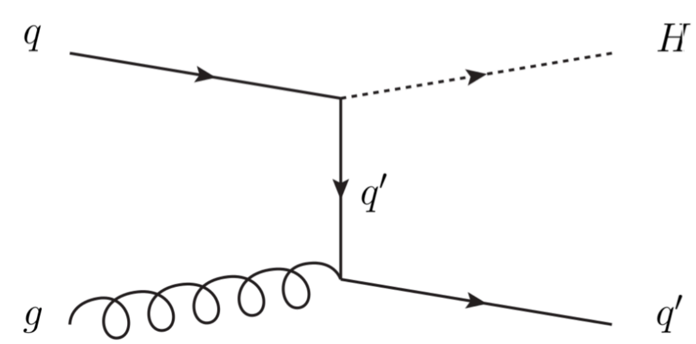
Going beyond type I-II:

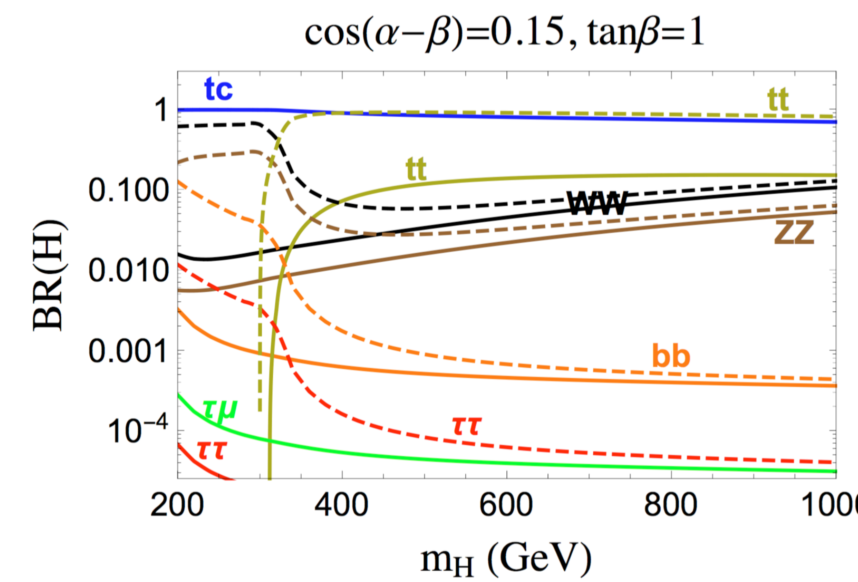
Loopholes in standard heavy Higgs searches

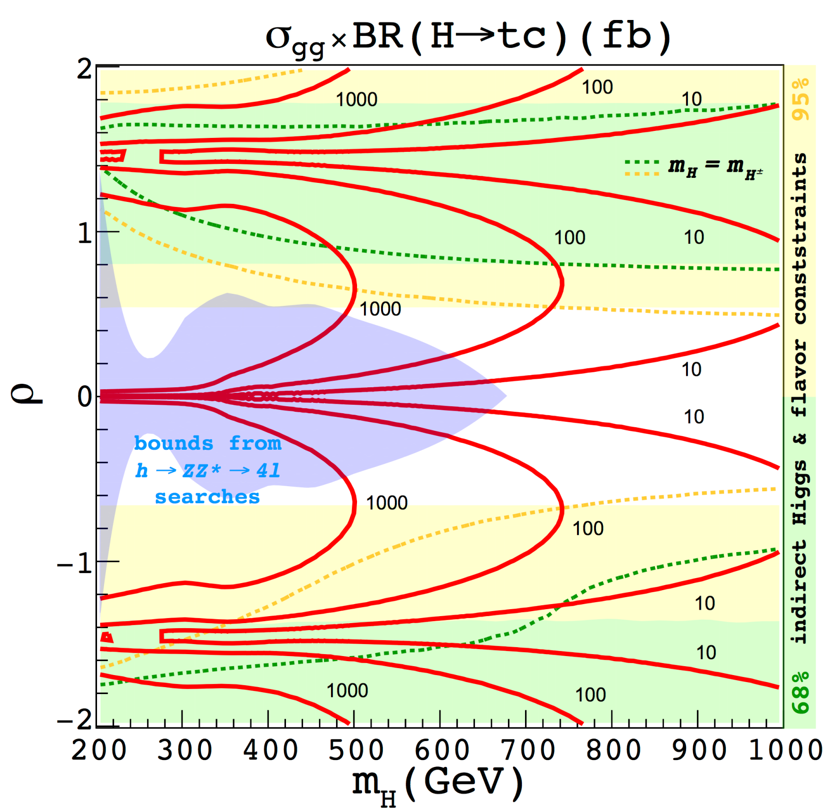
Nice opportunities for unexplored signatures

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









excluded by 13 TeV

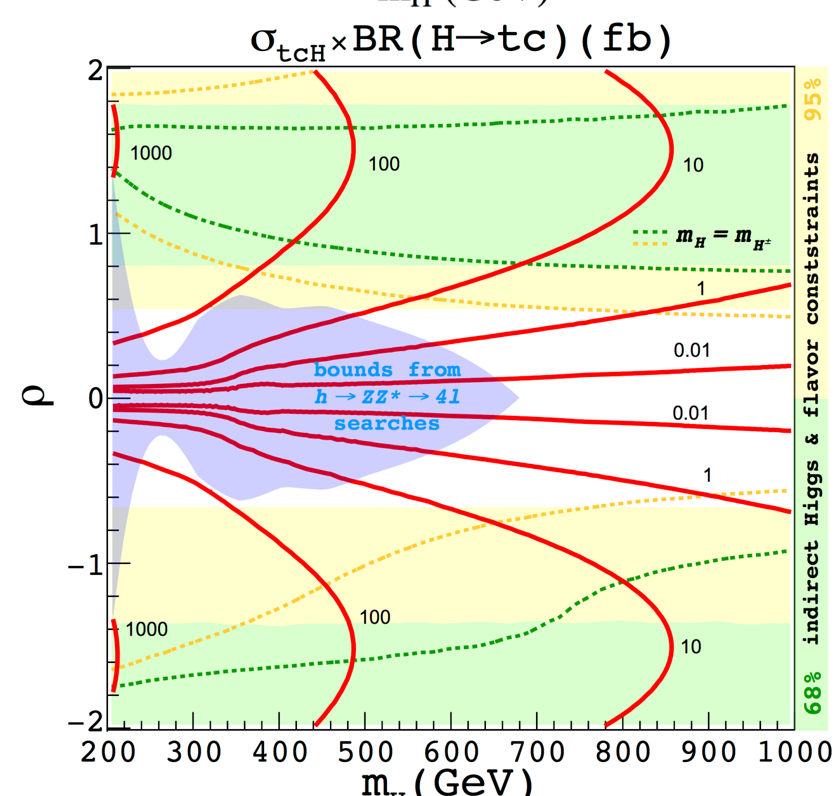
$gg \longrightarrow H \longrightarrow ZZ^* \longrightarrow 4l$

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

68.2 %

95.4 %

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



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

V. Particle or not Particle?

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

LHCP '2017

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

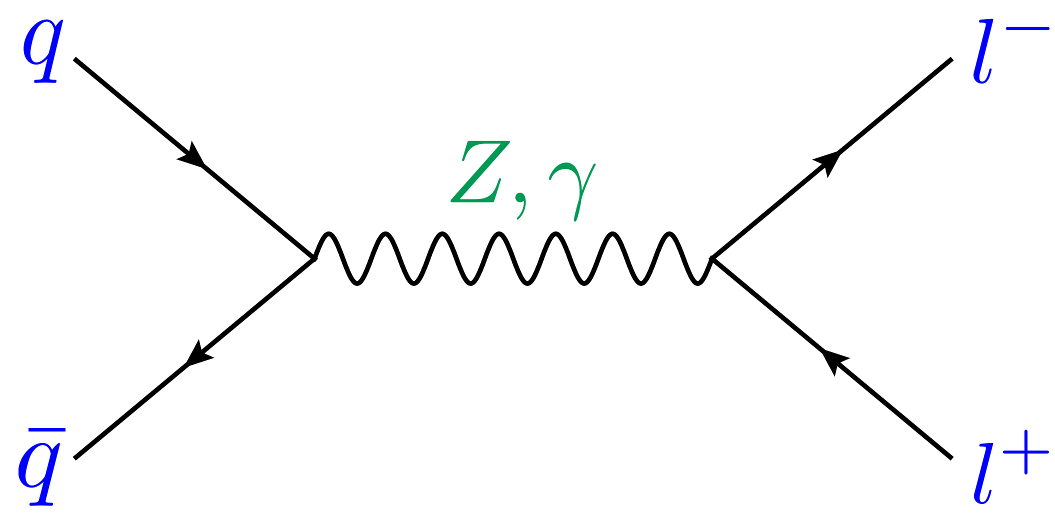
energy helps accuracy

Farina et al '16

$$\frac{\Delta\mathcal{O}}{\mathcal{O}} \propto E^2$$ ⬌ 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	$\sim \pm 0.5$	$\sim \pm 0.15$

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Farina et al '16

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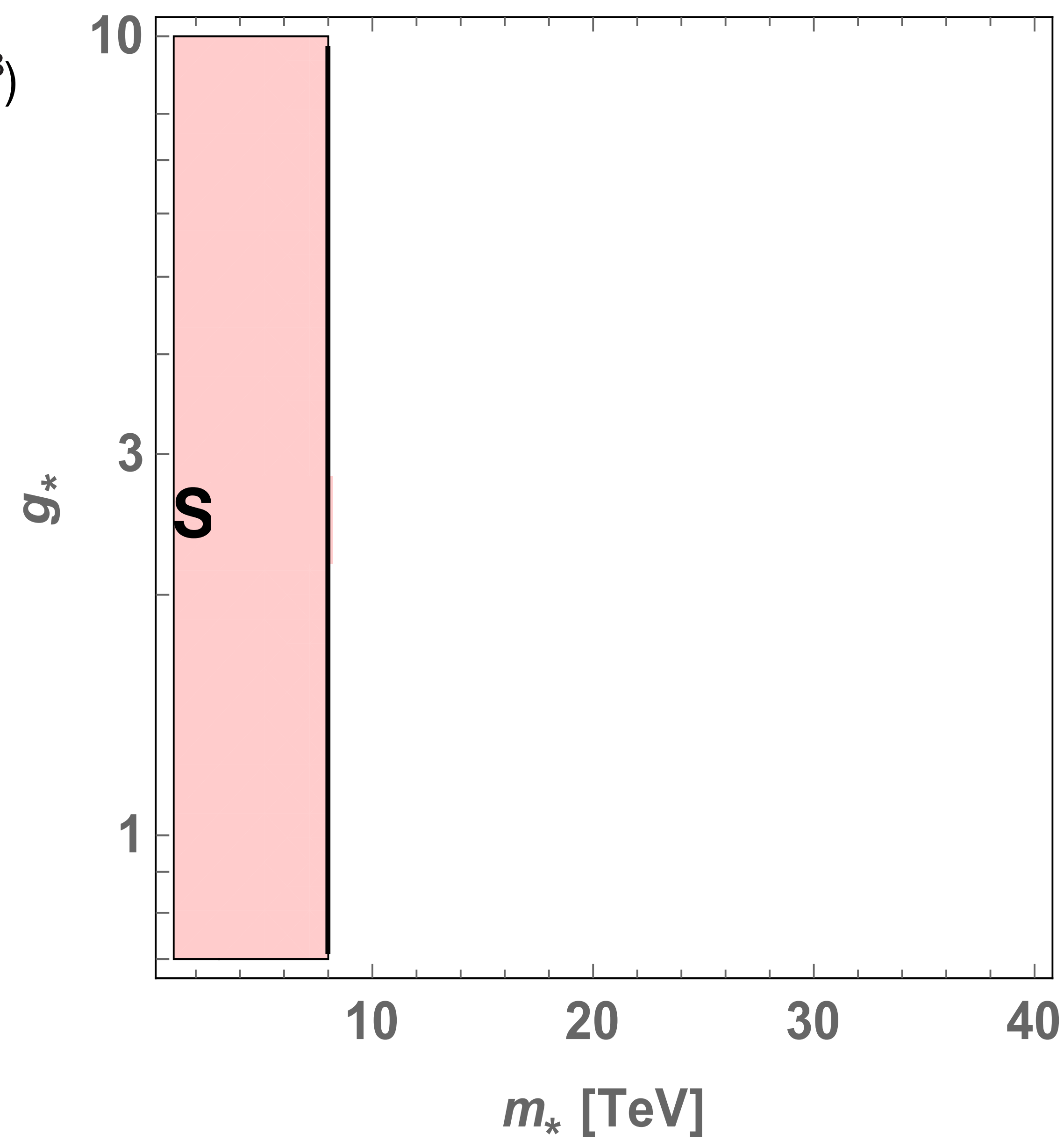
V. New force: Composite Higgs

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

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

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

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



Grojean-Wulzer @ FCC physics week '17

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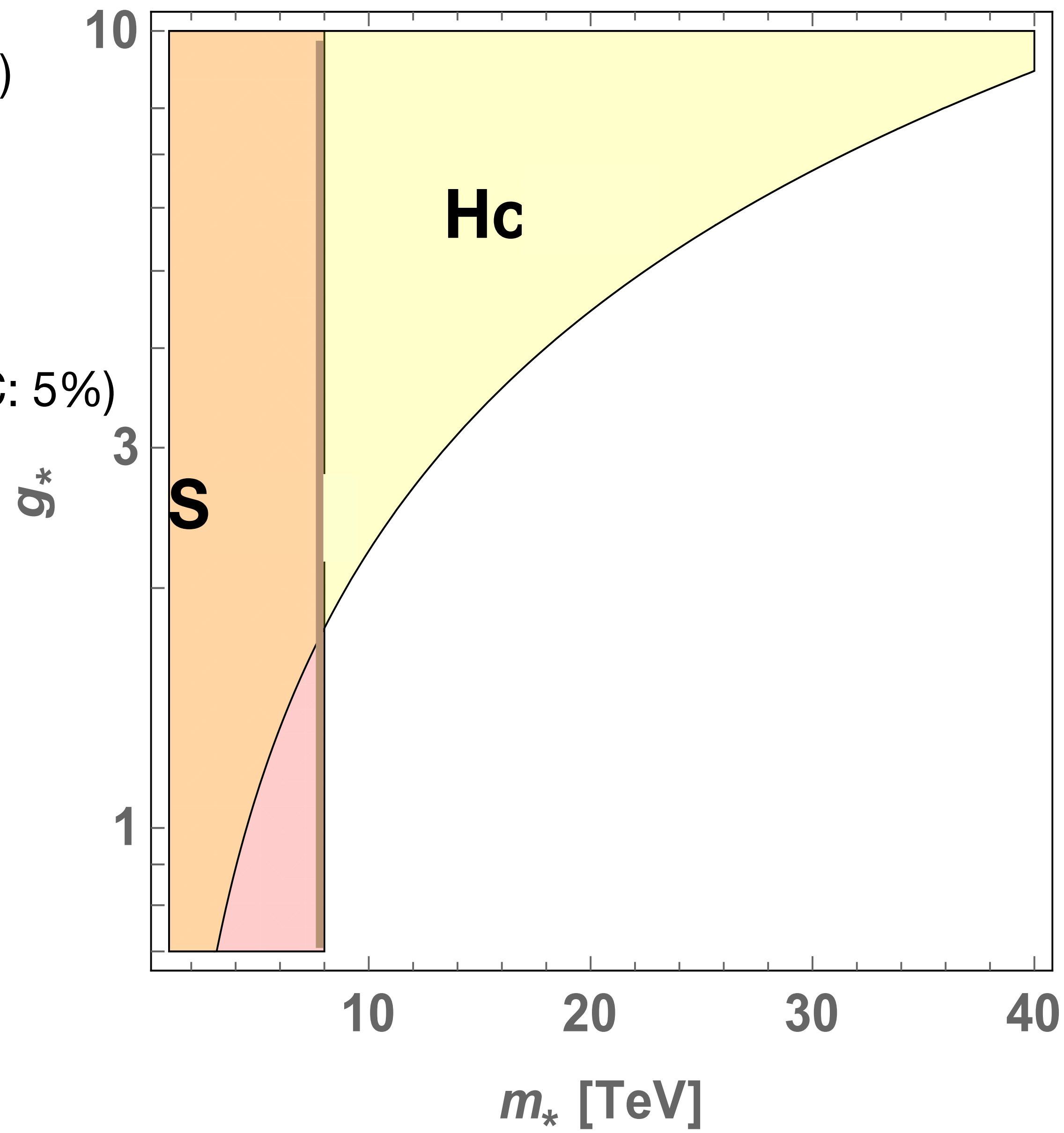
Higgs Couplings : [ee Report] (HL-LHC: 5%)

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



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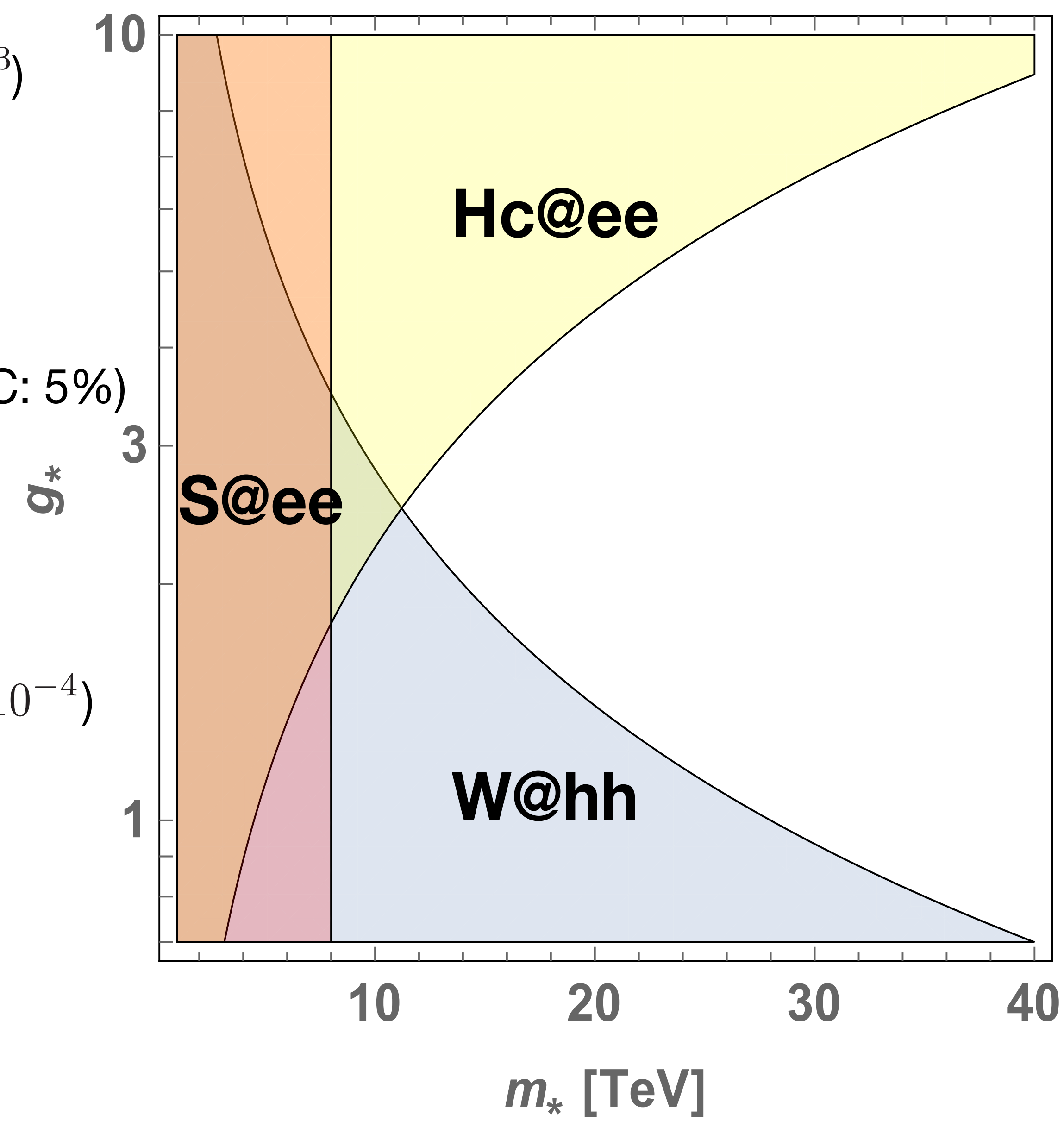
W @hh: (energy + accuracy) (HL-LHC< 10^{-4})

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



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V. New force: Composite Top

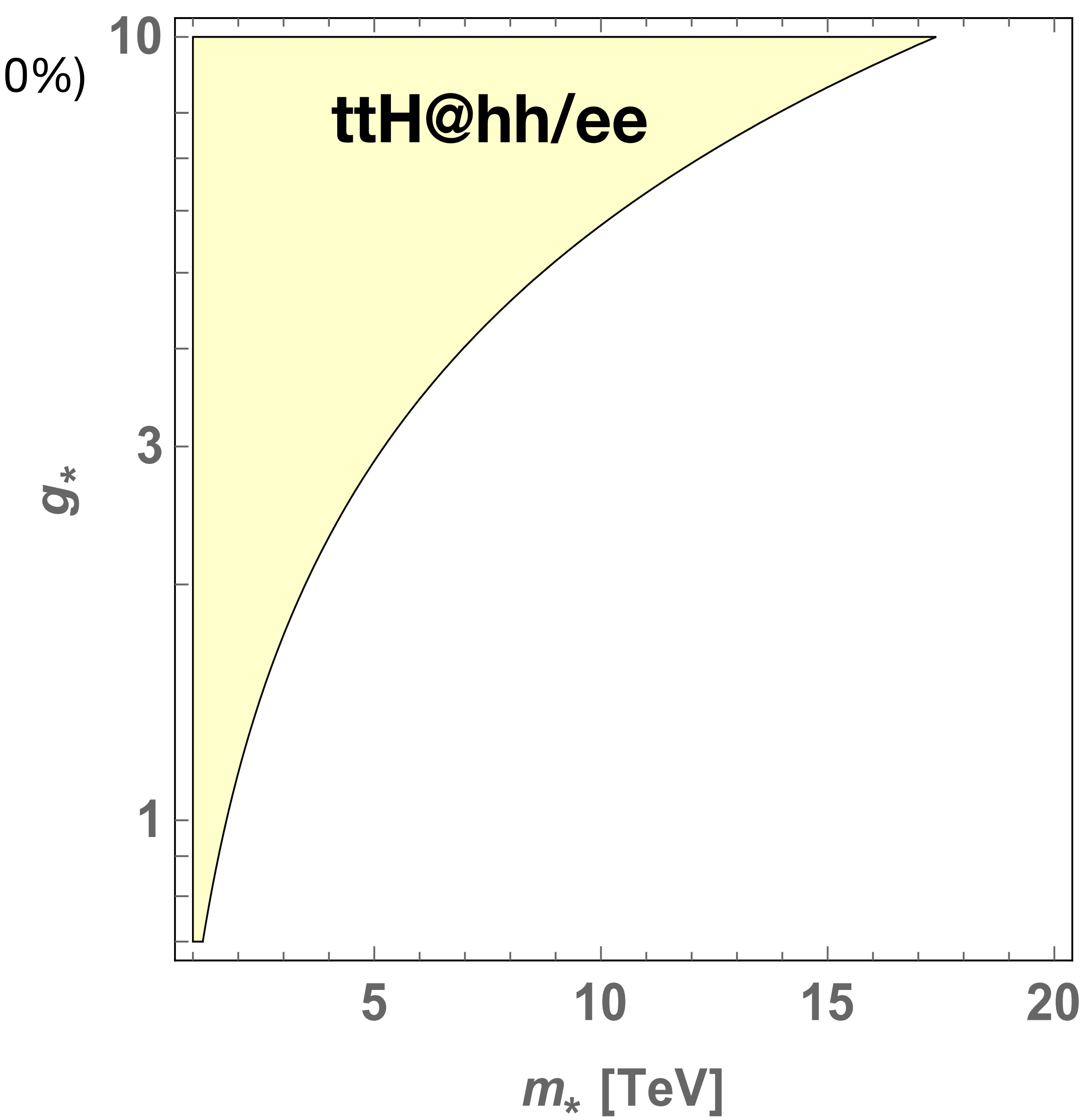
Composite tR, comp. Higgs, **elementary tL** and gauge

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

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!!



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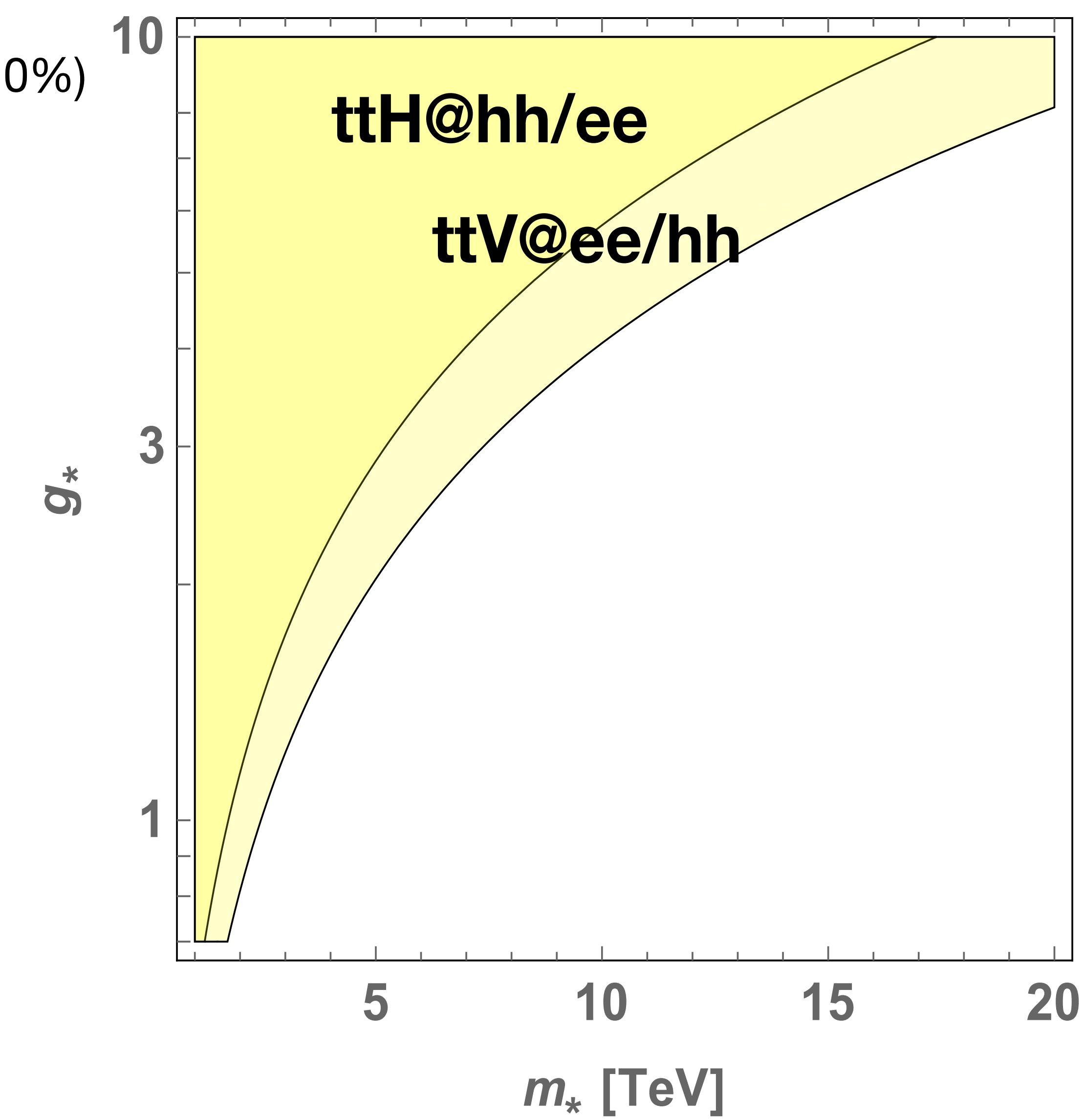
Diff. oper.s comb. in ee and hh!!

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

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

Same hh reach from en. + acc.?



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

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

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

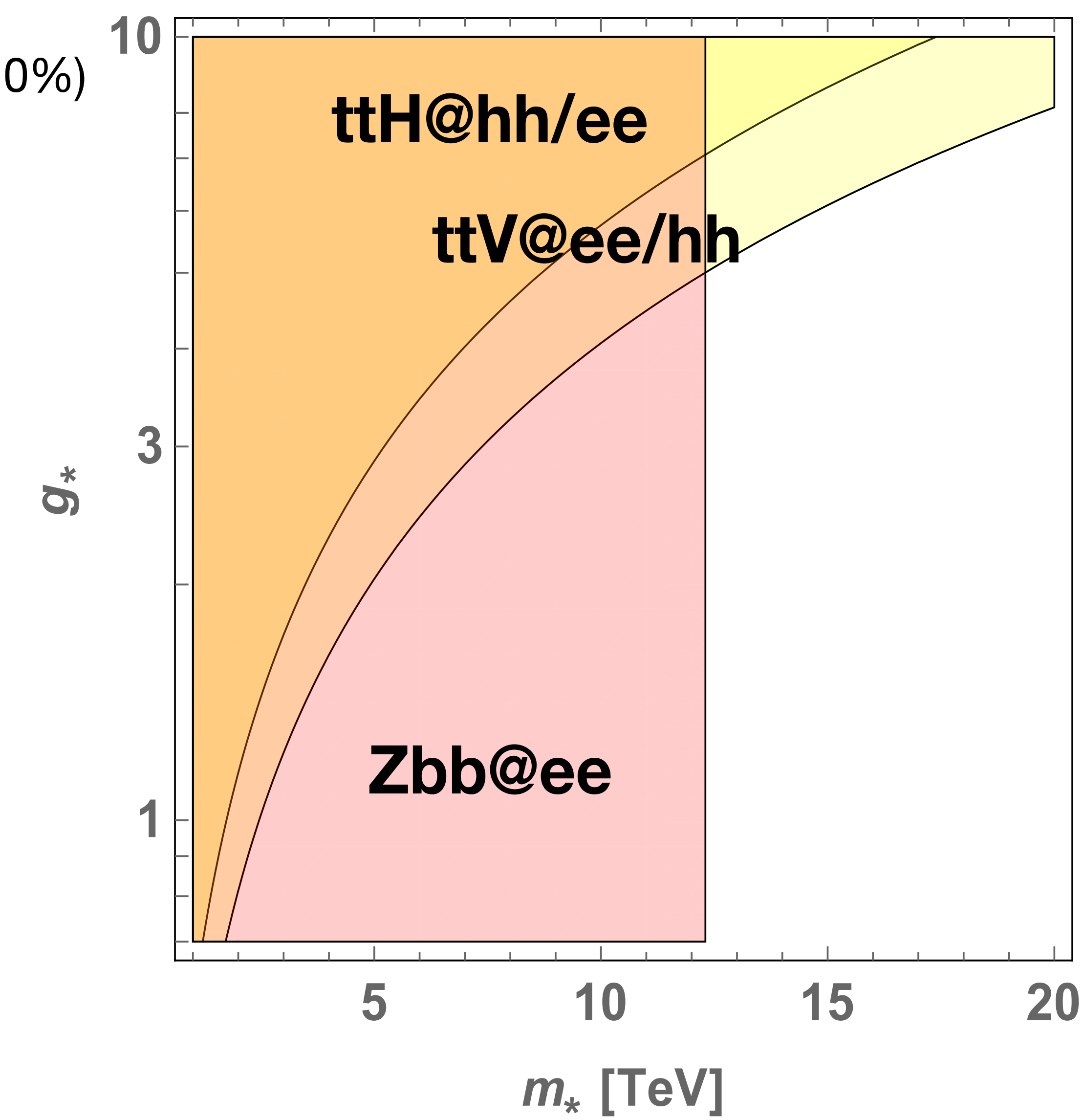
ttV coupling @ee/hh: [Janot / Farina et.al.]

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

Same hh reach from en. + acc.?

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

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



Grojean-Wulzer @ FCC physics week '17

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

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

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

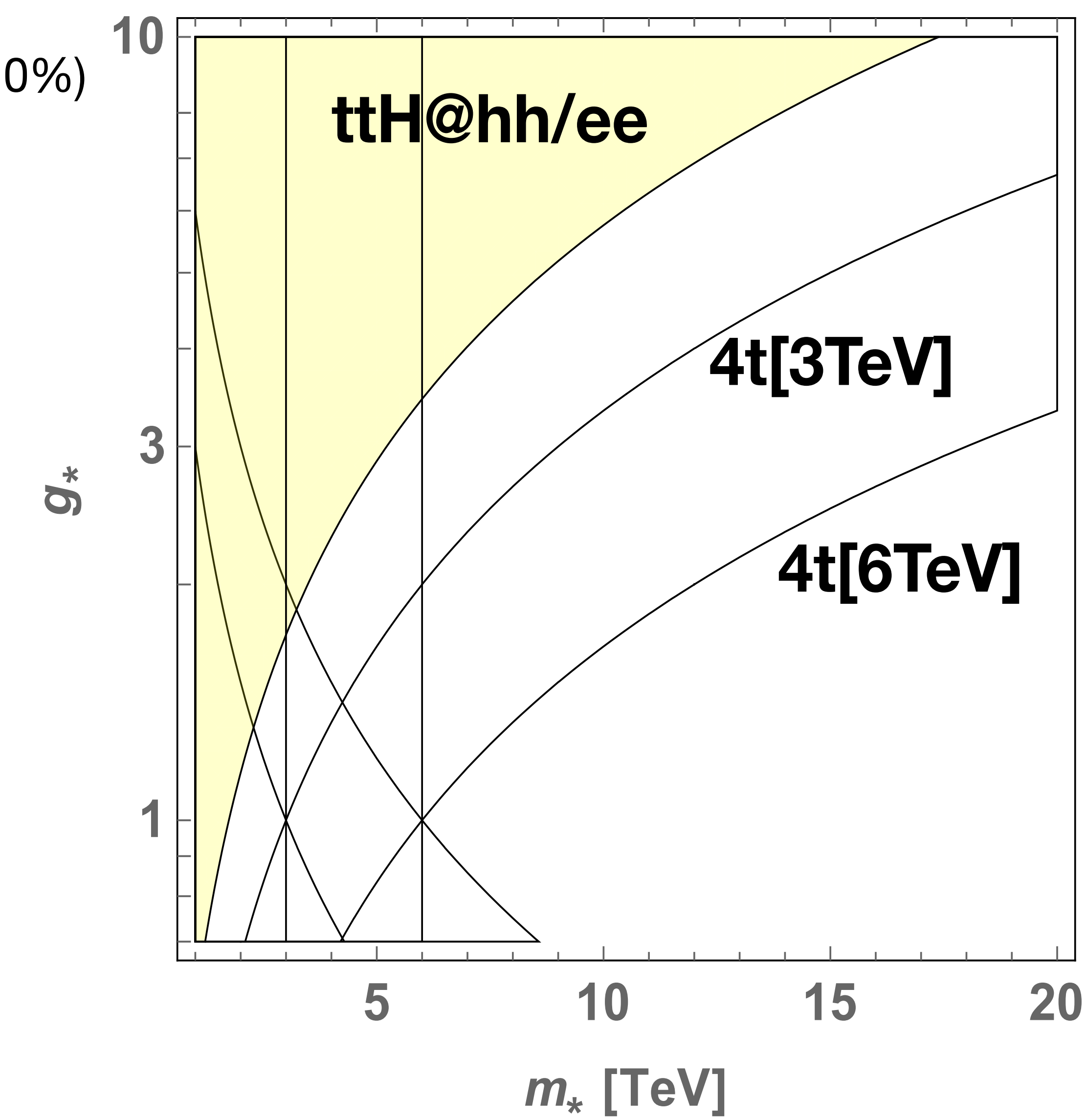
4-top contact interactions @hh:

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

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

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

No study available (?)



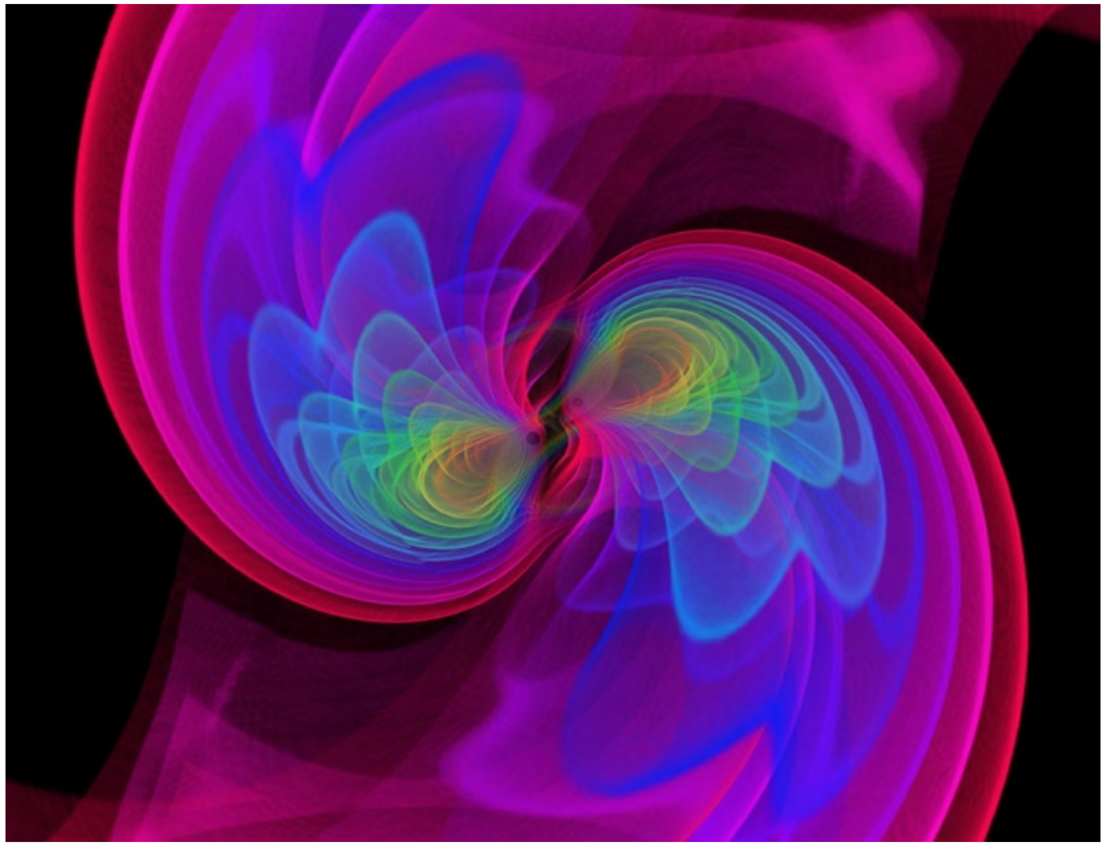
Grojean-Wulzer @ FCC physics week '17

(iii) Looking for BSM elsewhere

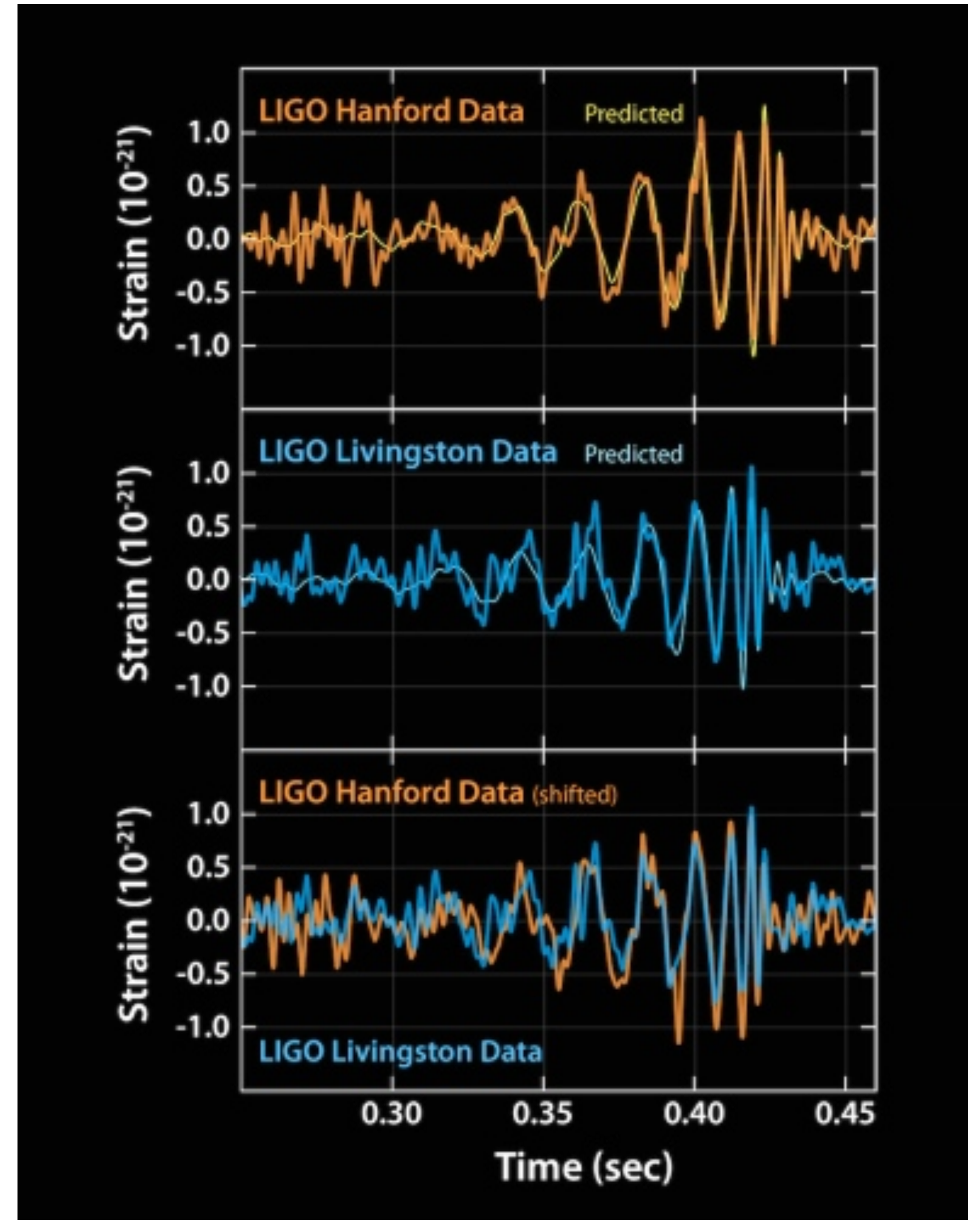
GW
Neutron-antineutron oscillations
Isotope shifts

The pictures of shook the Earth

GW150914



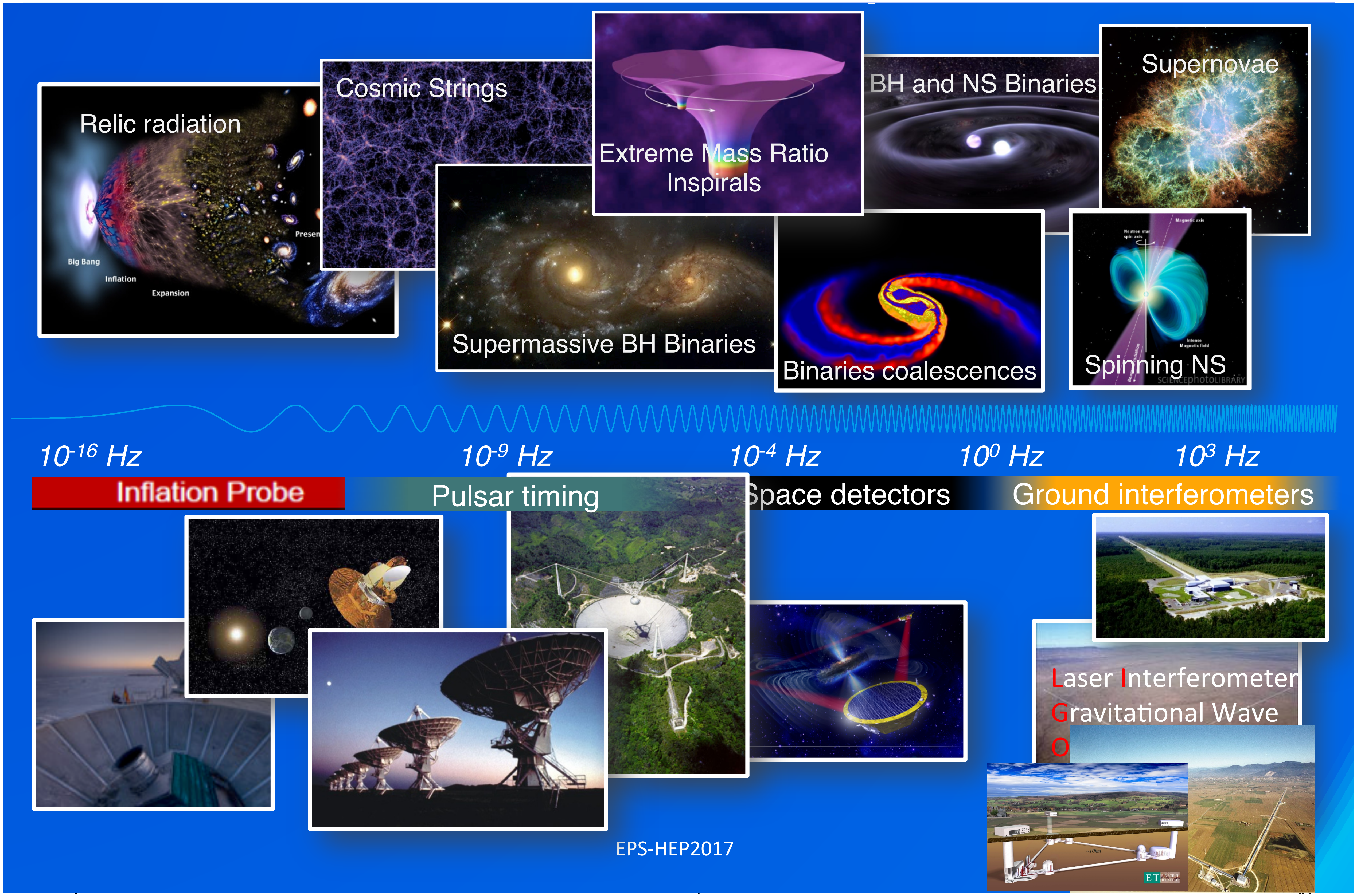
1.3 billion years later on earth



what did it teach us?

- never give up against strong background when you know you are right
- $m_g < 10^{-22}$ eV ($c_g - c_\gamma < 10^{-17}$ GRB observed together with GW with the same origin?)
- no spectral distortions: scale of quantum gravity > 100 keV

GW and astrophysics/cosmology



GW and the ElectroWeak Phase Transition

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 ~

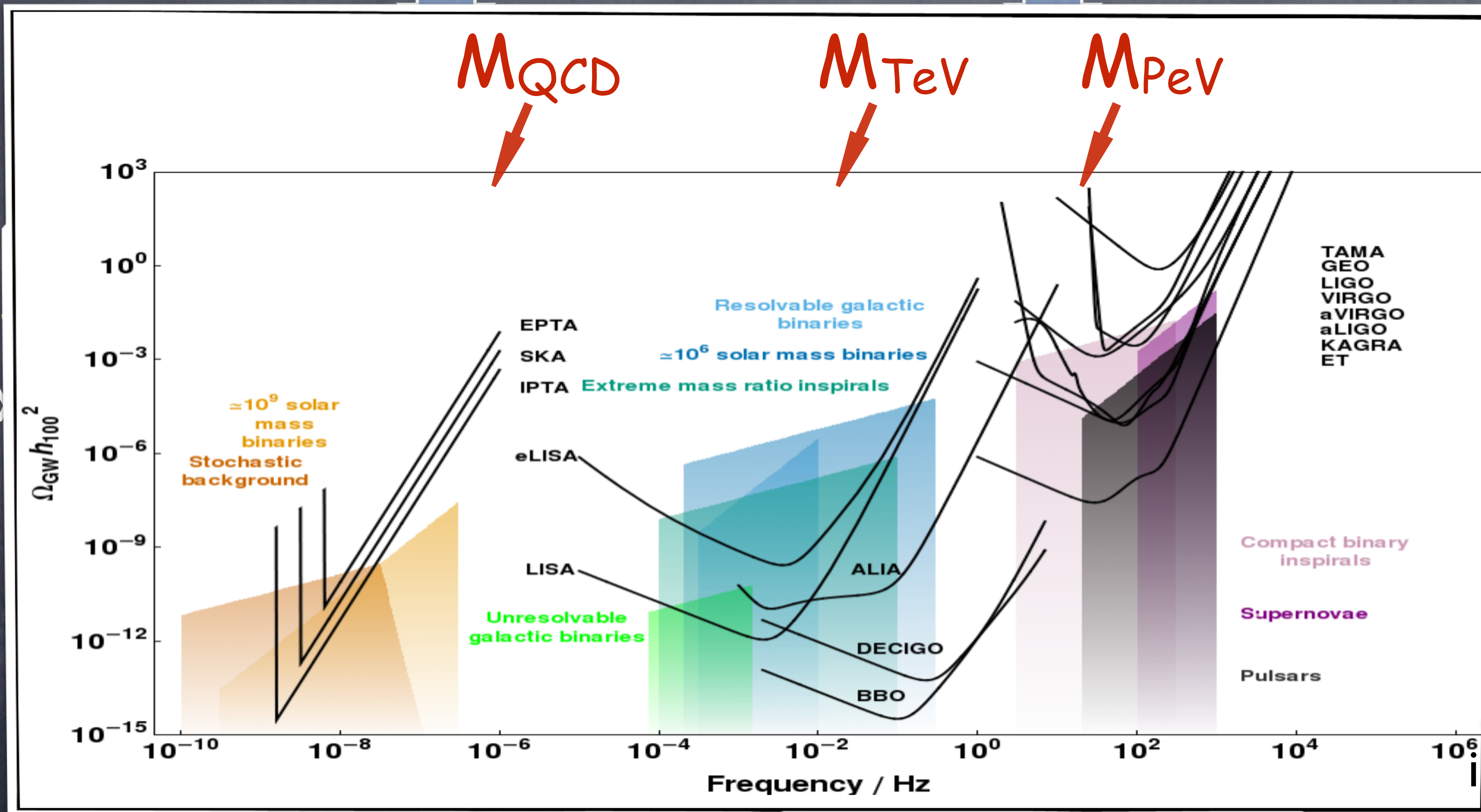
$$f \sim \# \frac{2\cdot 10^{-4}\ \text{eV}}{100\ \text{GeV}}\, 10^{-15}\ \text{GeV} \sim \# \, 10^{-5}\ \text{Hz}$$

Grojean, Servant '06

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

GW and the ElectroWeak Phase Transition

GW interact very weakly and are not absorbed



Grojean, Servant '06

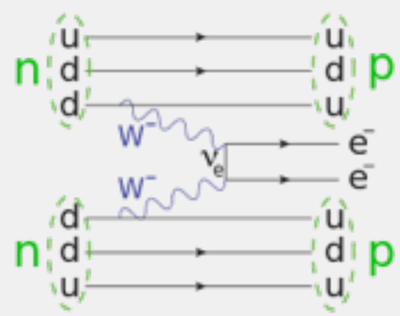
The GW spectrum from a 1st order electroweak PT
is peaked around the milliHertz frequency

Intensity Frontier: $n\bar{n}$ Oscillations

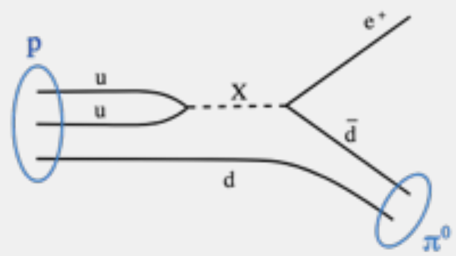
A. Kobach '16

$\mathcal{L}$ =	$\mathcal{L}_{SM}$	+ 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)

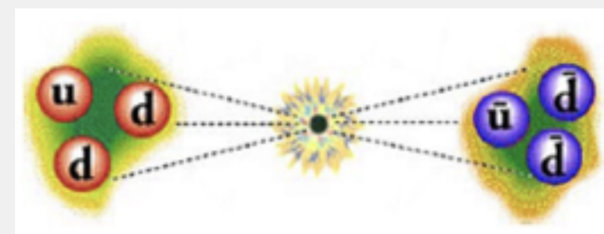
$0\nu\beta\beta$ decay



proton decays



neutron-antineutron oscillation



Slide stolen to Z. Zhang @ Pascos'18

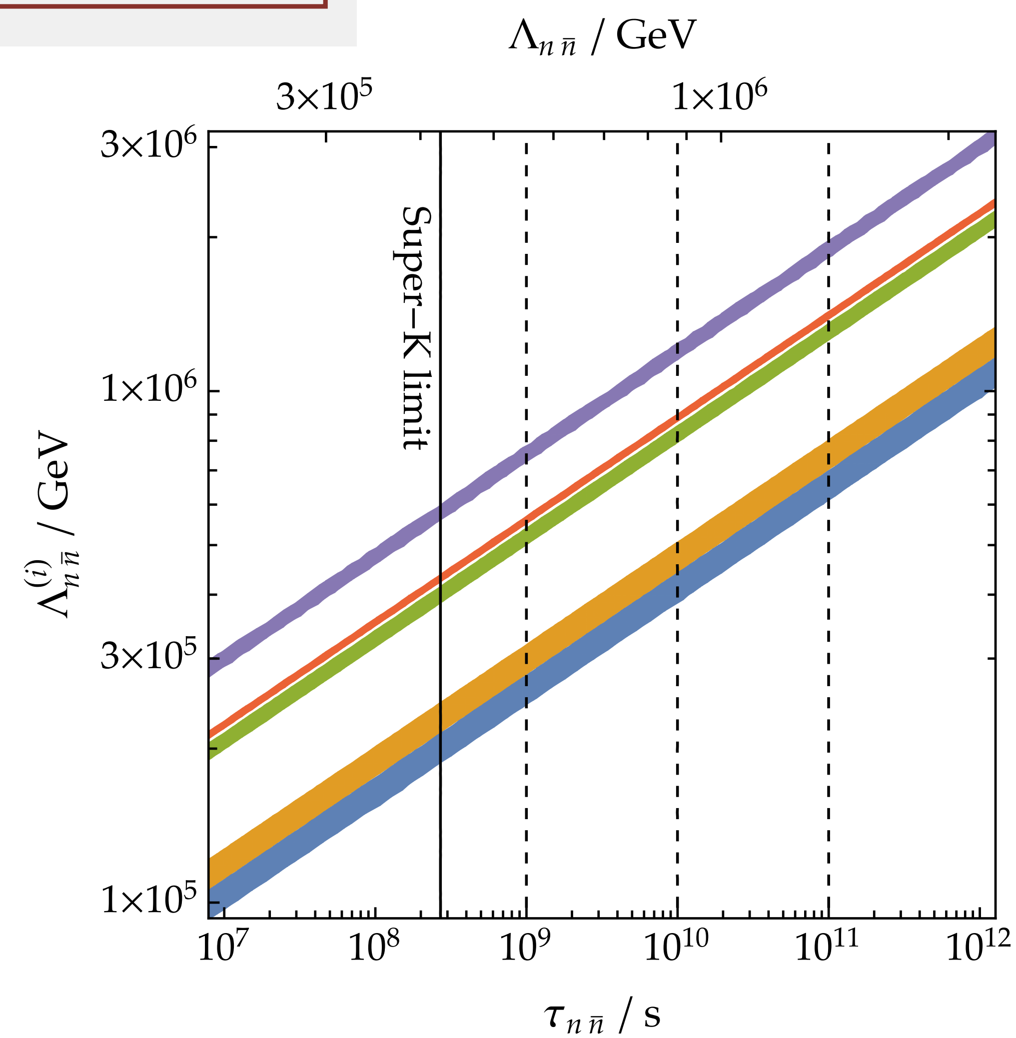
12 operators (of the type 'uudddd')

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

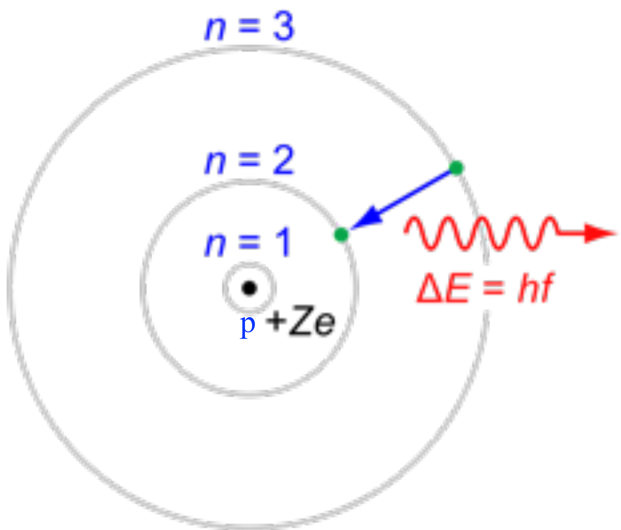
SuperK/ESS, DUNE is/will probe scales 10^5-10^6 GeV

models of high-scale baryogenesis (sphalerons are active ↔ violation of B-L)

Grojean, Shakya, Wells, Zhang '18



BSM with AMO



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.

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

fifth force ⟹ ?

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

(ms over one billon years)

Not all transitions can be used (yet) for BSM

frequency shifts O(1-100 Hz) over frequencies O(1THz): still a sensitivity O(10^{-9})

can be used to detect new (long range) forces

Isolating the signal: isotope shifts

Compare frequency of an atomic transition for two different isotopes

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

mass shift field shift

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

$m\nu_2^{AA'} = K_{21} + F_{21} m\nu_1^{AA'}$ King linearity (1963)

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:

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

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

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

Isolating the signal: isotope shifts

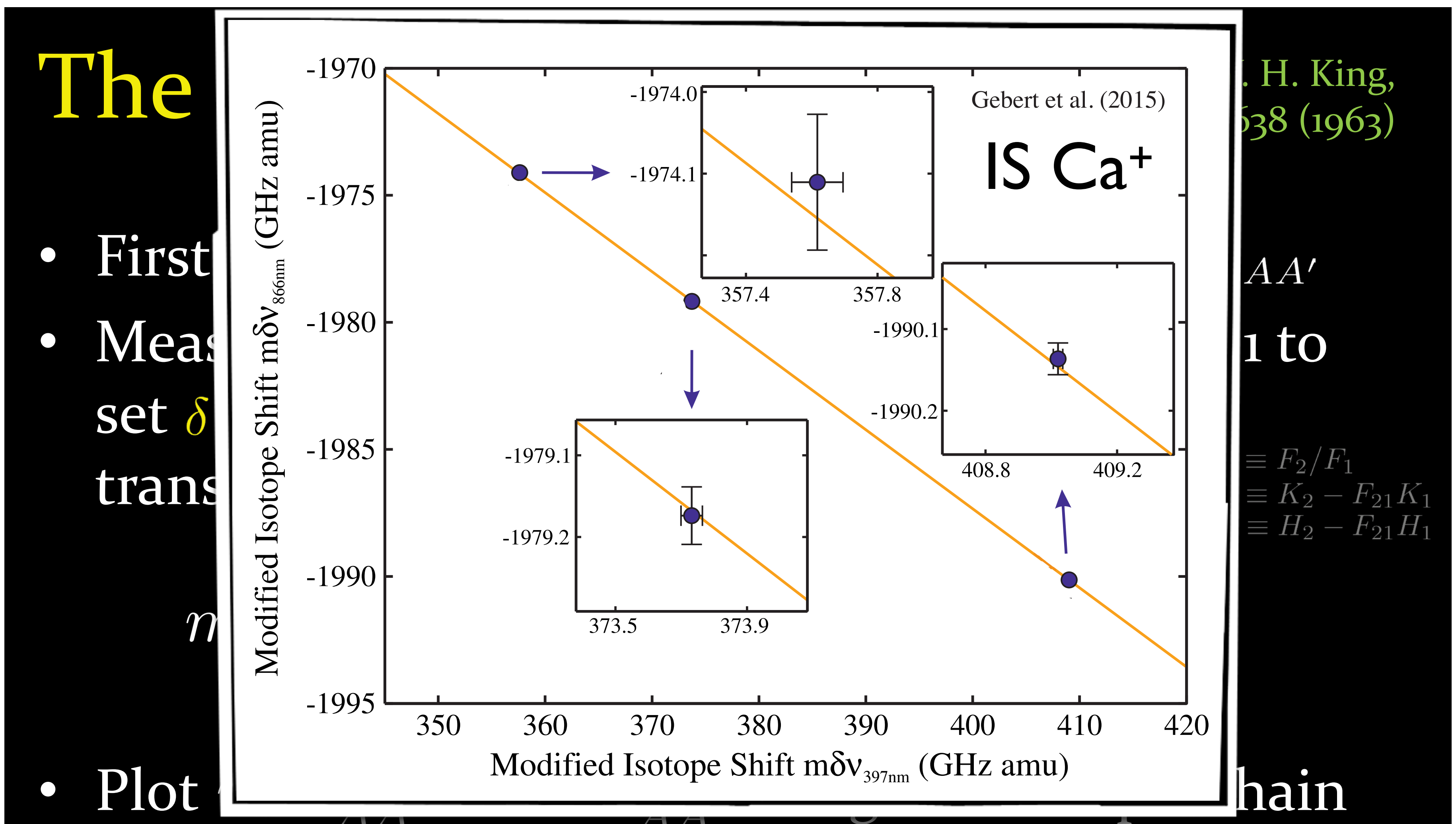
Compare frequency of an atomic transition for two different isotopes

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

mass shift field shift

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

$$m\nu_2^{AA'} = K_{21} + F_{21} m\nu_1^{AA'}$$ King linearity (1963)



Isolating the signal: isotope shifts

Compare frequency of an atomic transition for two different isotopes

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

mass shift   field shift   BSM or NLO SM/QED

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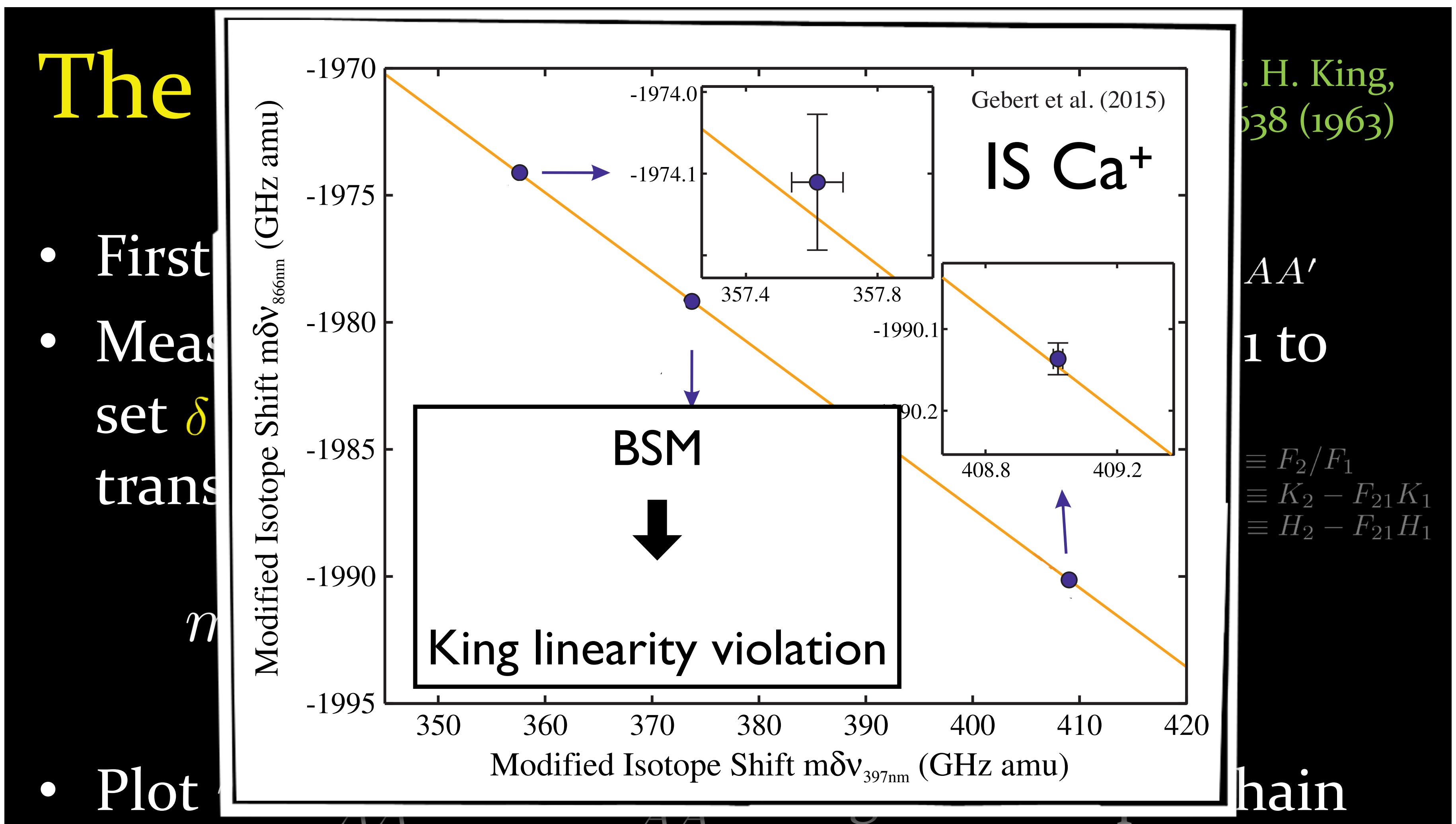
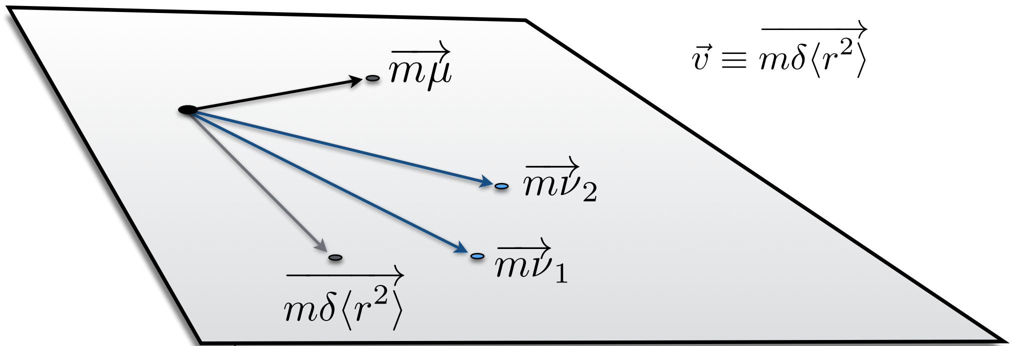
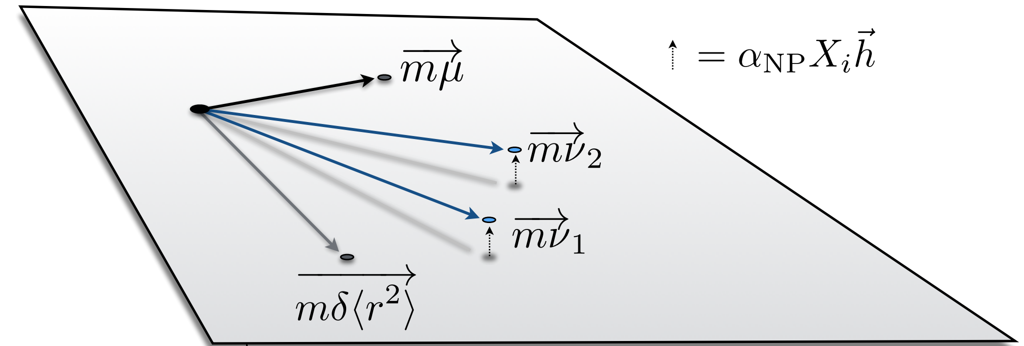


Constraining Light NP

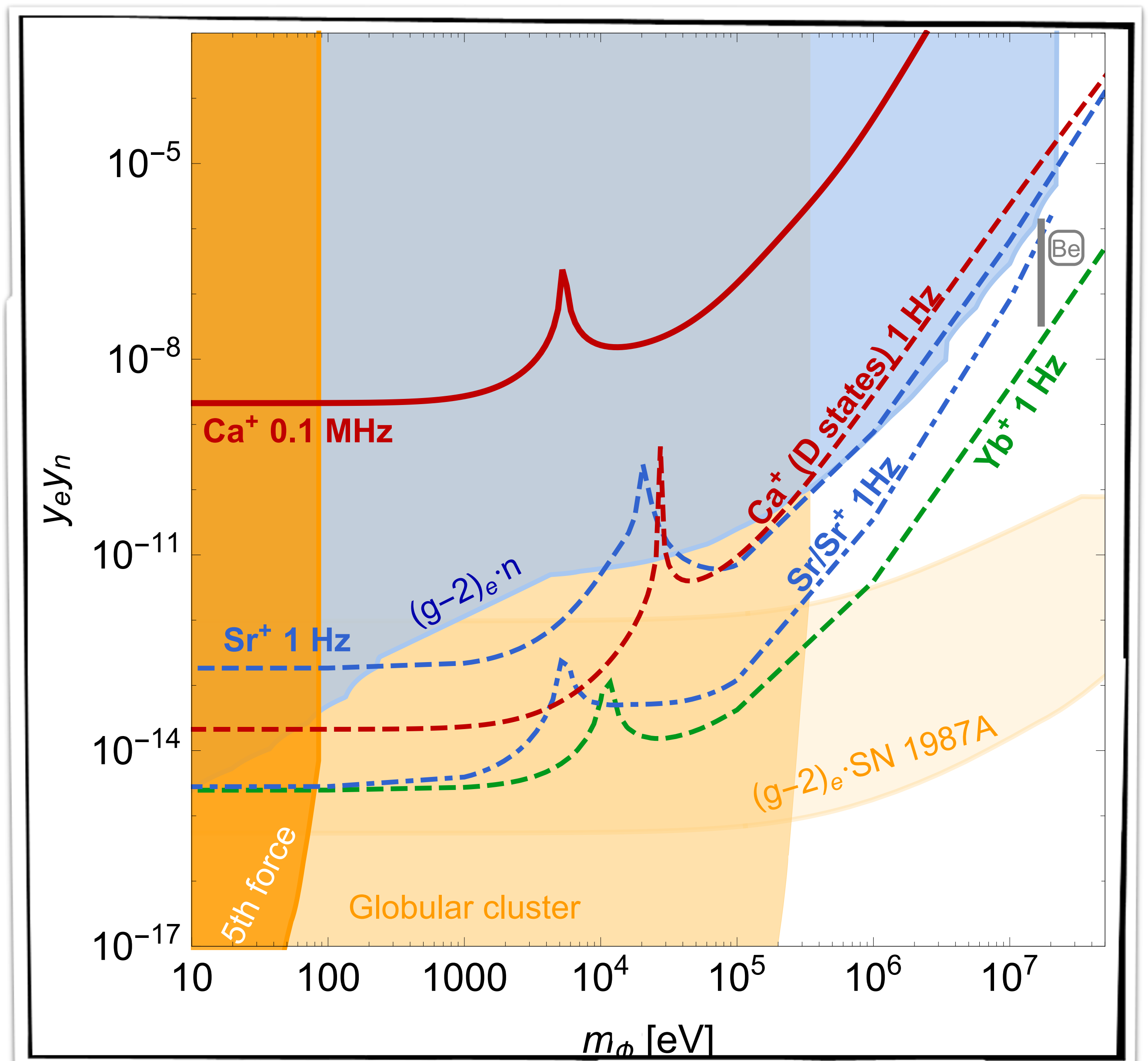


the plane spanned by $\overrightarrow{m\mu}$ and $\overrightarrow{m\delta\langle r^2\rangle}$



the plane spanned by $\overrightarrow{m\mu}$ and $\overrightarrow{m\delta\langle r^2\rangle}$

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



arXiv:1704.05068v1 [hep-ph]

Berengut+'17

Spectacular
experimental
progress
very recently

2004.11383
Yb+ King plot (300 Hz)

2005.00529
Ca+ King plot (20 Hz)

Conclusions

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

Conclusion

Once upon a time…

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His proposal was scientifically rejected twice (by Portuguese's & Salamanca U.) but fortunately the decision was overruled by Isabel ... and America became great (already)

Moral(s)

"if your proposal is rejected, submit it again"

"you need the right technology to beat your competitors"

"theorists don't need to be right!
but progress needs theoretical models to motivate exploration"

BSM search is an exploration

M. Zuckerberg created FaceMash before Facebook

J.K. Rowling got rejected 12 times by editors before she published Harry Potter

Beyonce wrote hundreds of songs before 'Halo'

... Physicists building new colliders ...

one doesn't have to succeed on the first try

"the success comes from the freedom to fail"

M. Zuckerberg, Harvard graduation ceremony speech, May 25, 2017

(… anticipating Cambridge Analytica scandal?…)

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

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