Physics at HL-LHC (as seen after LHC-8 but before LHC-14)

Fabio Zwirner
University and INFN, Padova

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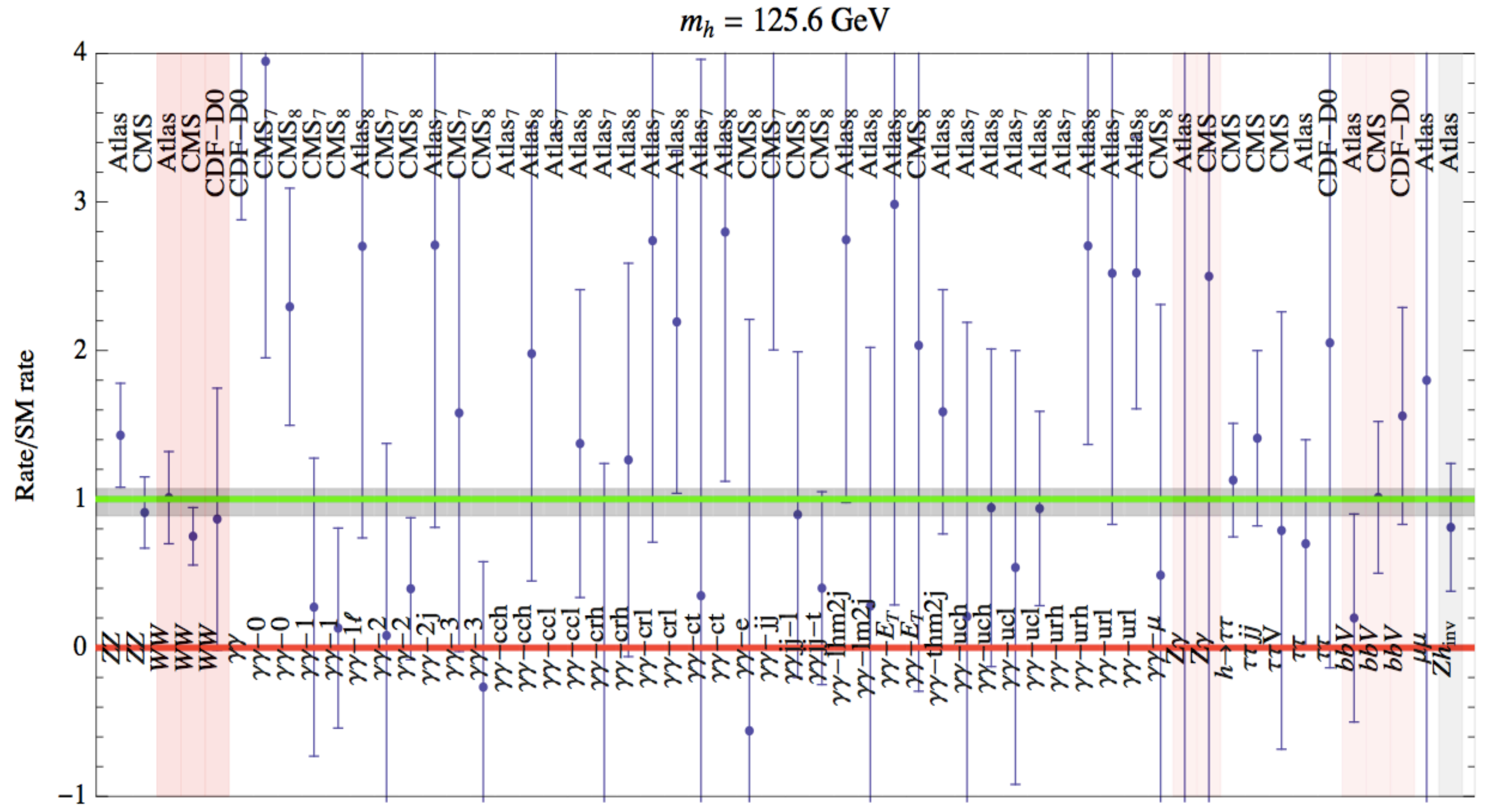
What have we been told by LHC-8?

Run 1
2009-2013
(most data in 2011-2)
$\sqrt{S}$ =7-8 TeV
< 30 fb^{-1}

The (Brout-Englert-) Higgs boson is there



Giardino-Kannike-Masina-Raidal-Strumia arXiv:1303.3570

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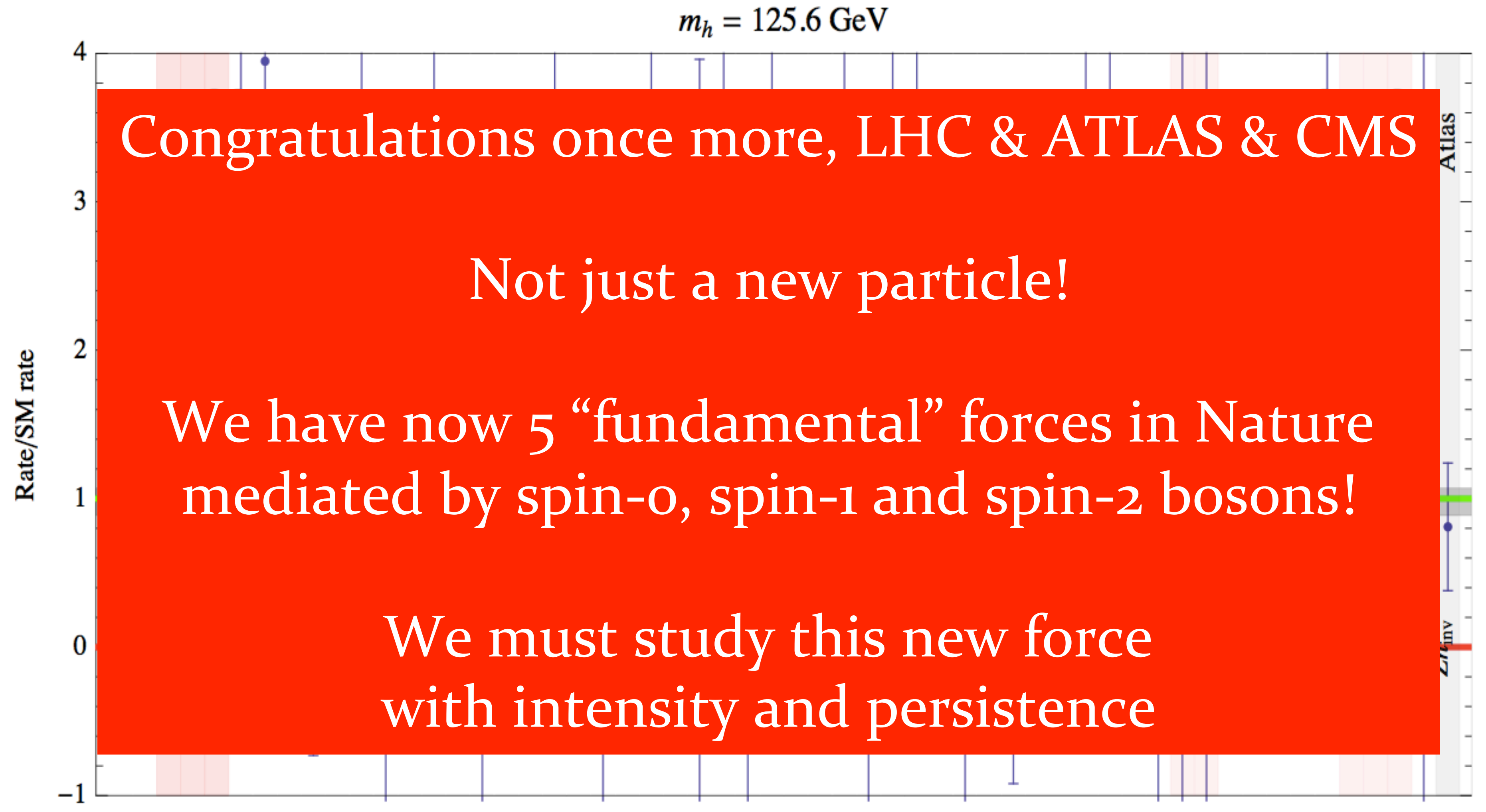


Congratulations once more, LHC & ATLAS & CMS

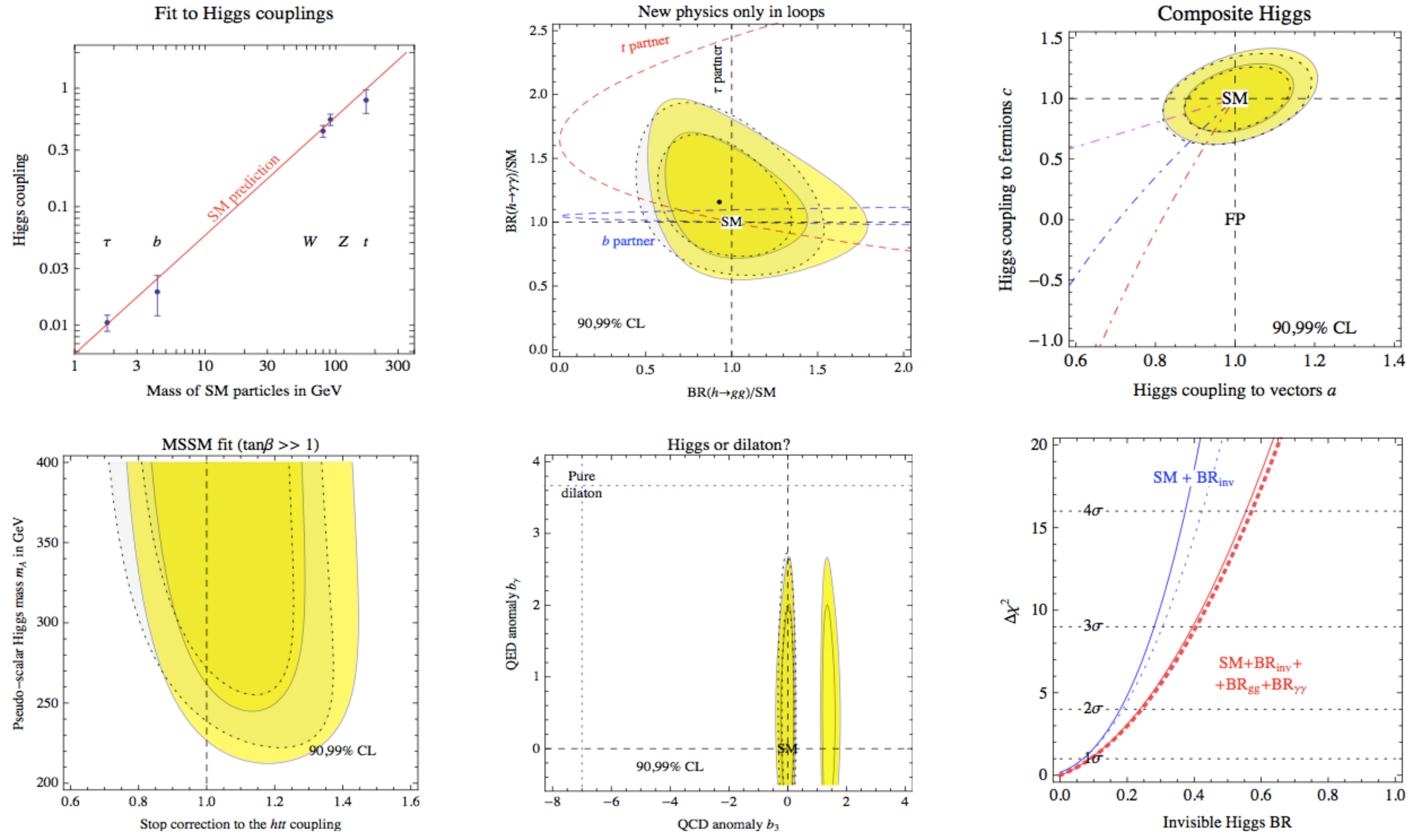
Not just a new particle!

We have now 5 “fundamental” forces in Nature
mediated by spin-0, spin-1 and spin-2 bosons!

We must study this new force
with intensity and persistence

Giardino-Kannike-Masina-Raidal-Strumia arXiv:1303.3570

Higgs boson looks *so far* SM-like



Fit to Higgs couplings

New physics only in loops

Composite Higgs

MSSM fit (tanβ >> 1)

Higgs or dilaton?

Giardino-Kannike-Masina-Raidal-Strumia arXiv:1303.3570

Higgs boson looks *so far* SM-like

- Mass where favoured by EW precision tests
- Couplings to vectors and fermions as in SM
- No signs of exotic states in γγ or gg loops
- No signs of mixing with other states
- No signs of invisible decay channels
- No signs of additional Higgs bosons

...all with still large errors...

Processes with 0, 1, 2, ... Higgses now *related*

Contino La Thuile 2014

Q: What is already constrained by experiments w/o Higgs ?

...but SM precision tests cannot be ignored...

In total: 59 dim-6 operators

Grzadkowski et al. JHEP 1010 (2010) 085

17 involve the Higgs

8 affect Higgs physics only

Elias-Miro, Espinosa, Masso, Pomarol
JHEP 1311 (2013) 066

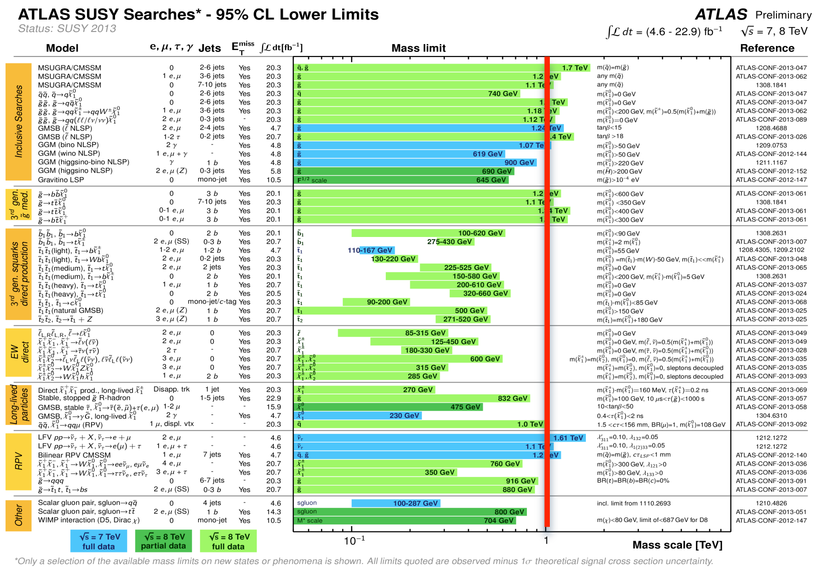
Pomarol, Riva JHEP 01 (2014) 151

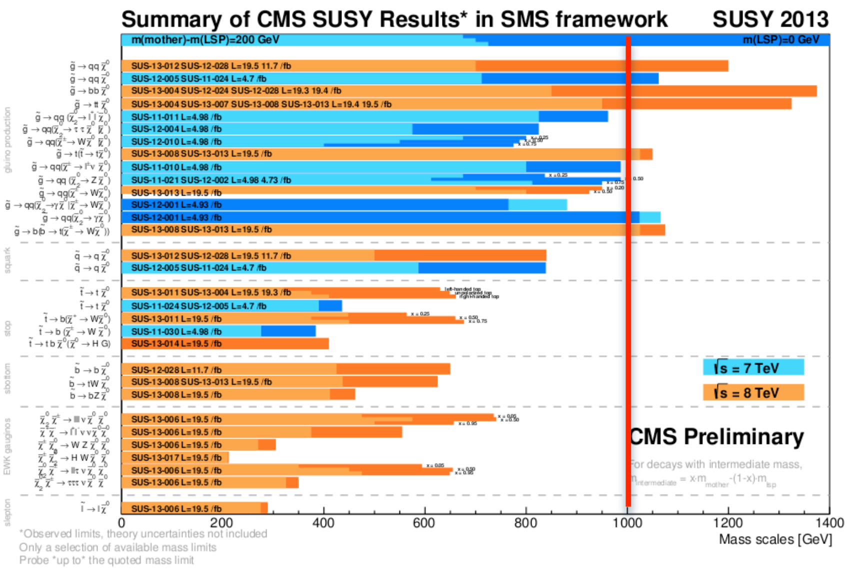
$O_H = (\partial_\mu \|H\|^2)^2$	shifts all couplings
$O_{BB} = g'^2 \|H\|^2 B_{\mu\nu} B^{\mu\nu}$	$h \to \gamma\gamma$
$O_{WW} = g^2 \|H\|^2 W_{\mu\nu} W^{\mu\nu}$	$h \to Z\gamma$
$O_{GG} = g_s^2 \|H\|^2 G_{\mu\nu} G^{\mu\nu}$	$gg \to h$
$O_{y_d} = y_d \|H\|^2 \bar{q}_L H d_R$	shift $h\psi\psi$
$O_{y_u} = y_u \|H\|^2 \bar{q}_L \tilde{H} u_R$	
$O_{y_e} = y_e \|H\|^2 \bar{L}_L H e_R$	
$O_6 = \lambda \|H\|^6$	$gg \to hh$

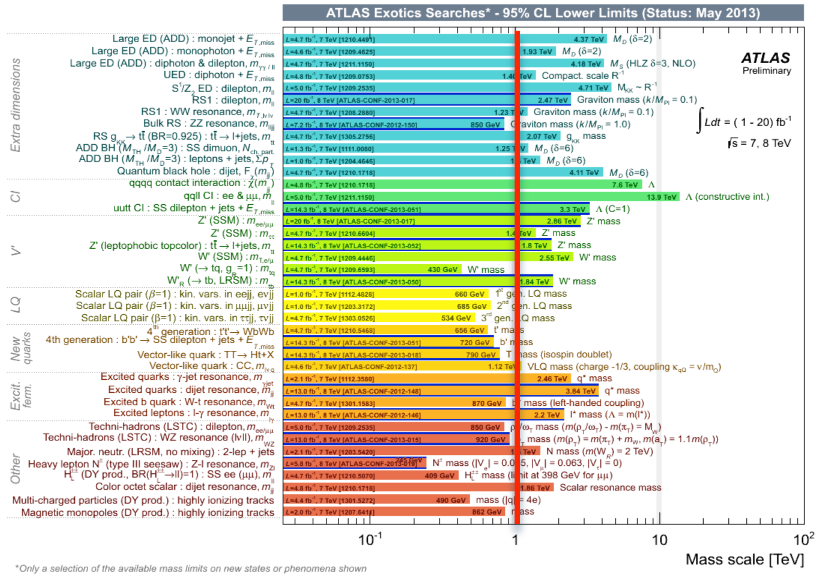
only 2 operators un-probed

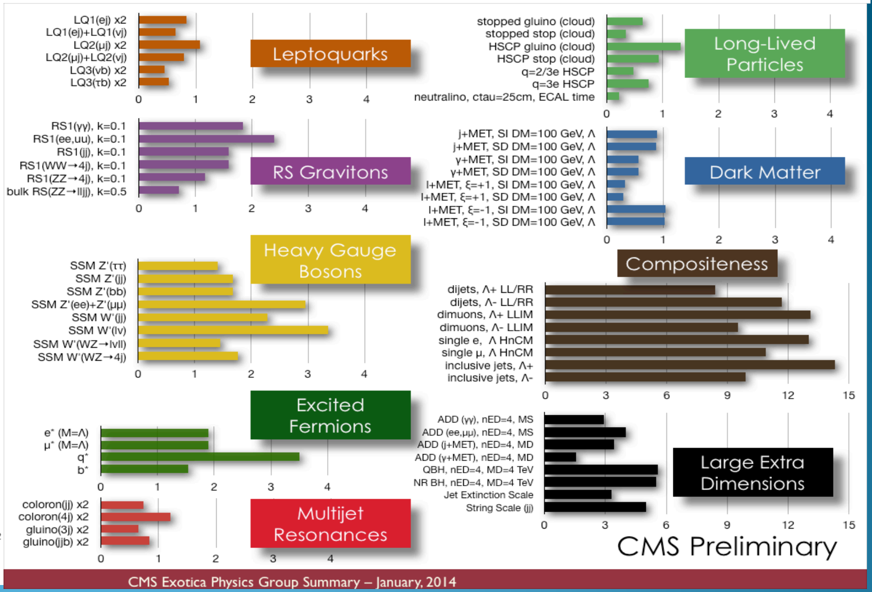
All other operators probed already by LEP + m_W + TGC

No new particle has *so far* been found

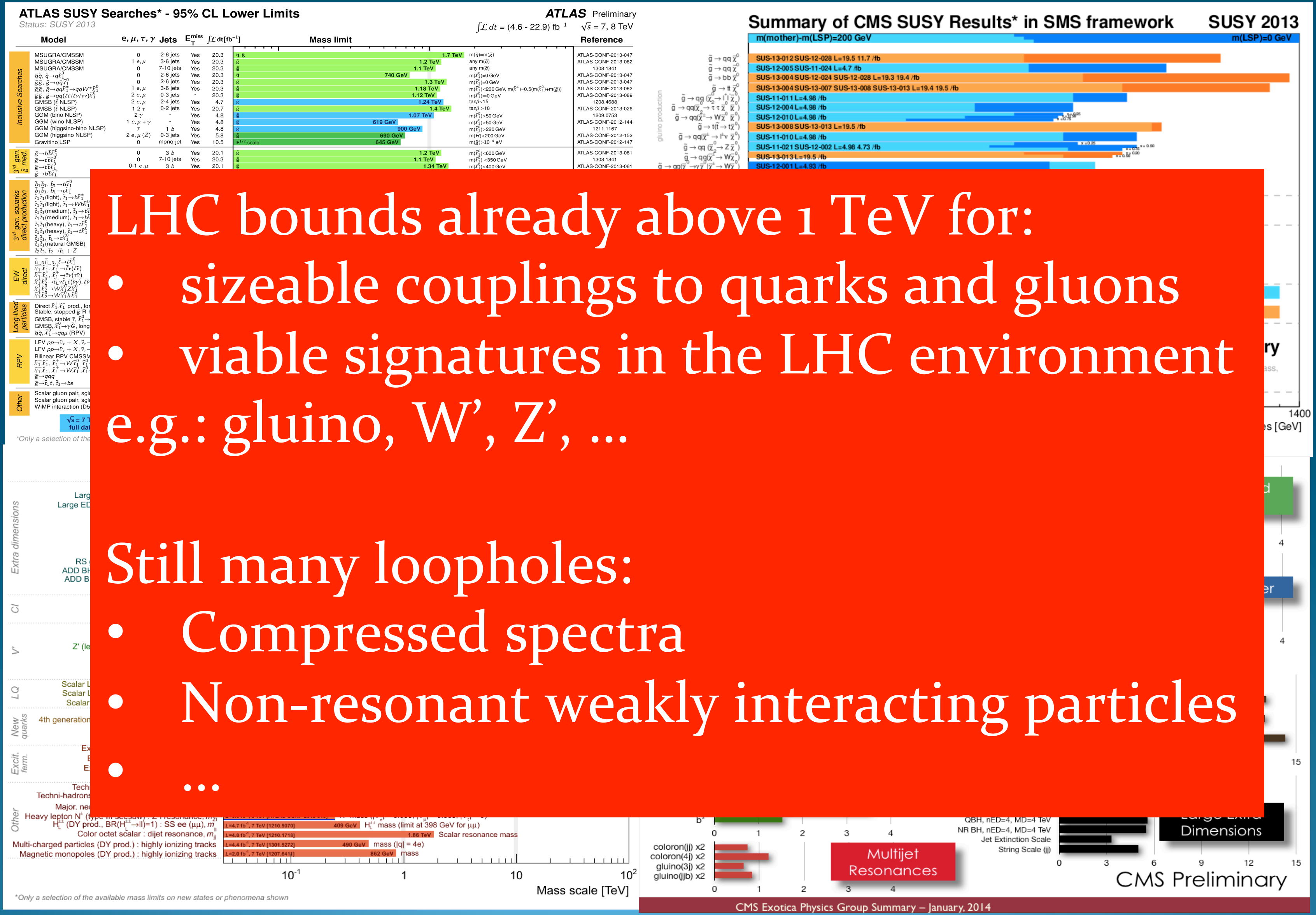








No new particle has *so far* been found



LHC bounds already above 1 TeV for:

- sizeable couplings to quarks and gluons
- viable signatures in the LHC environment

e.g.: gluino, W’, Z’, …

Still many loopholes:

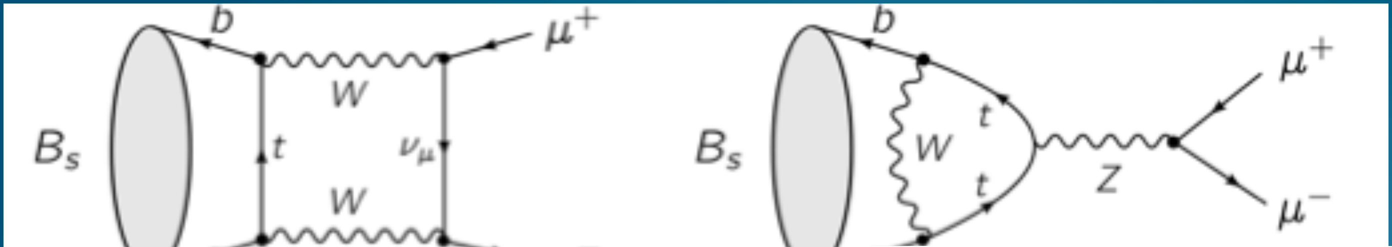
- Compressed spectra
- Non-resonant weakly interacting particles
- …

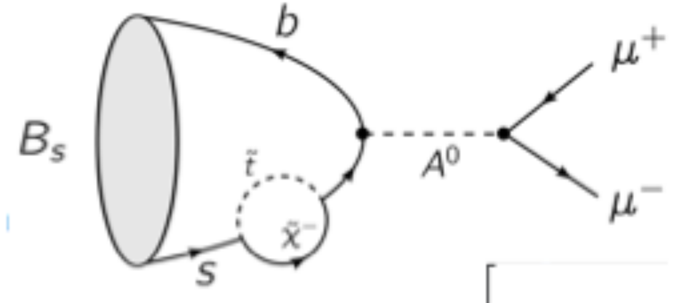
New precision tests in flavour physics have *so far* been passed with flying colors

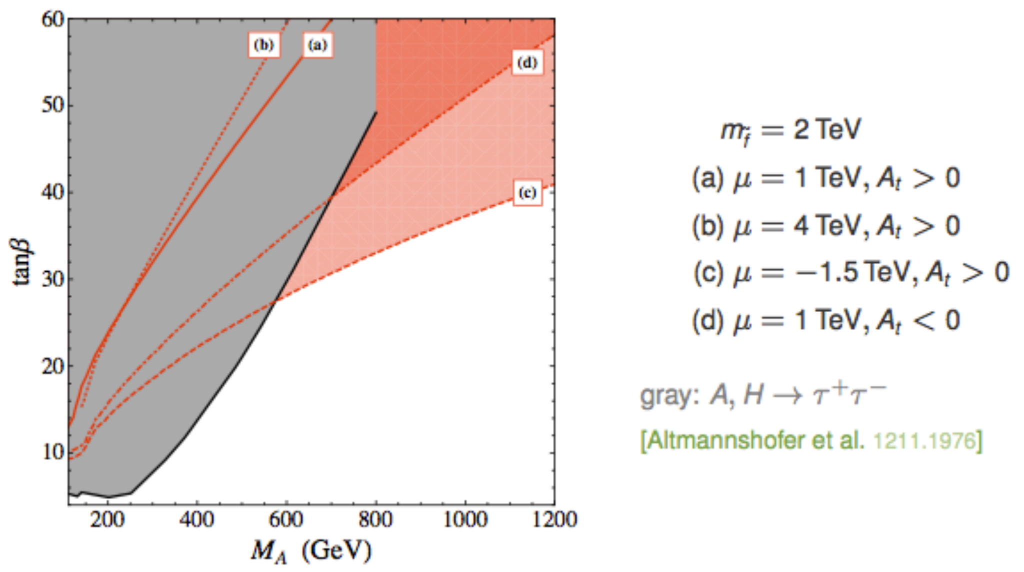
An example: $B_s \rightarrow \mu^+ \mu^-$

$BR_{LHCb+CMS}=(2.9\pm0.7)\times10^{-9}$ $BR_{SM}=(3.65\pm0.23)\times10^{-9}$

Can receive sizeable NP contribution, e.g.
MSSM @ large tan β and light CP-odd A^0







[Altmannshofer et al. 1211.1976]

What have we learnt *so far*?

so far:
4/7 of design energy
< 1/10 of design integrated luminosity
<1/100 of achievable integrated luminosity

↓

We are eager to learn more:
just the start of a major programme of work
may take several decades for completion
may need other machines beyond the LHC

The SM works TOO well

Naturalness seems *so far* to fail:

No quantum SM symmetry recovered for $m_H \rightarrow 0$
(scale invariance broken by quantum corrections)
SM unnatural unless New Physics at the TeV scale

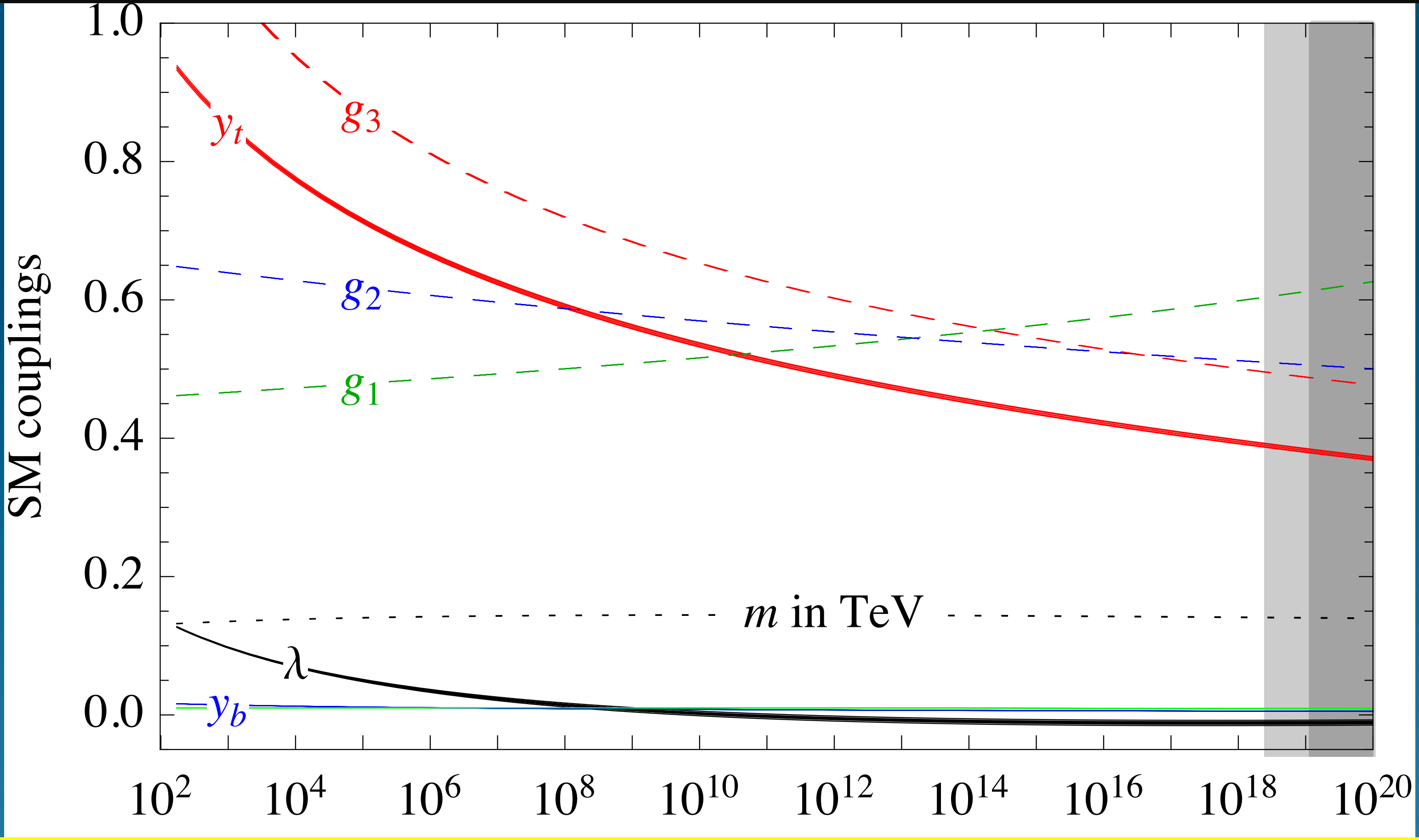
't Hooft Cargese 1979

Naively (too naively?):

$$\delta m_H^2 \sim -\frac{3\,h_t^2}{8\,\pi^2}\,\Lambda^2 < O(m_H^2) \quad \rightarrow \quad \Lambda < O(500)\ \mathrm{GeV}$$

We were expecting to see some new particle, and we have not seen it yet! EW and flavor precision tests are also pushing for Λ significantly above the TeV scale

Technically, there is nothing forcing us to extend the SM before 10^{10} GeV or so (perhaps even before M_P according to some models of ν masses, DM, BAU and inflation) [νMSM or "nightmare scenario" of Shaposhnikov et al.]



Buttazzo-Degrassi-Giardino-Giudice-Sala-Salvio-Strumia arXiv:1307.3536

[Linde, Weinberg, Cabibbo-Maiani-Parisi-Petronzio, Froggatt-Nielsen, Sher ...]

Naturalness puzzle: central question of particle physics for many years to come

Many other important questions:
Neutrino masses/Flavor/Unification
and, after including gravity:
Dark Matter/BAU/Inflation/Dark Energy/QG

Their solution may be put in perspective by what is found or excluded by the full (direct and indirect) exploration at the TeV scale

Ways out of the naturalness puzzle

Insist on naïve criterion: sub-TeV particles produced at LHC-8, they could hide so far

Relax naïve criterion: accidental cancellations at % level, must go beyond before giving up

More radical revisions of theory (still absent): Have we missed some more subtle naturalness (perhaps in connection with gravity and DE)? Puzzle might be solved only in the full theory (mysterious IR-UV connection missed by EFT)

[??environmental selection in landscape scenario??]

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[?envi onmental selection in landscape scenario?]

Having seen what happened in BSM particle theory before LHC-8, we desperately need all the experimental information that is at reach

As usual, ENERGY and PRECISION are the keys

A comment on Dark Matter

WIMP = Weakly Interacting Massive Particles
considered for long the leading DM candidates
because of the link with the naturalness problem

Still very plausible new physics at the TeV scale:
searching for WIMP dark matter is a
benchmark of the LHC-14 programme

not compelling if disconnected from naturalness:
DM could well be axions or keV neutrinos
or could be WIMPs out of reach for LHC-14

What will we learn from LHC-14?

Runs 2 (2015-8) and 3 (2020-2)
√S =13-14 TeV, > 300 fb^{-1}

and then from HL-LHC?

Runs 4 (2025-8) and 5 (2030-2)
and more (2034-…?)
√S =14 TeV, close to 3000 fb^{-1}

Conservative programme for HL-LHC

1. Study the Higgs boson properties with the highest possible precision
2. Keep searching directly for new particles at TeV scale (small visible σBR, challenging kinematics)
3. Even more precise tests in flavor/CPV physics
4. Heavy ion collisions and quark-gluon plasma

in addition, possible but not guaranteed:

?. Explore the properties of the new particles discovered in Run 2 and/or Run 3

Precision Higgs studies

- Increased precision on existing channels

Fit to couplings (w. assumptions), coupling ratios

- Study of rare Higgs processes:

H→μμ first window on 2nd generation fermions
H→Zγ large deviations possible in part. compos.

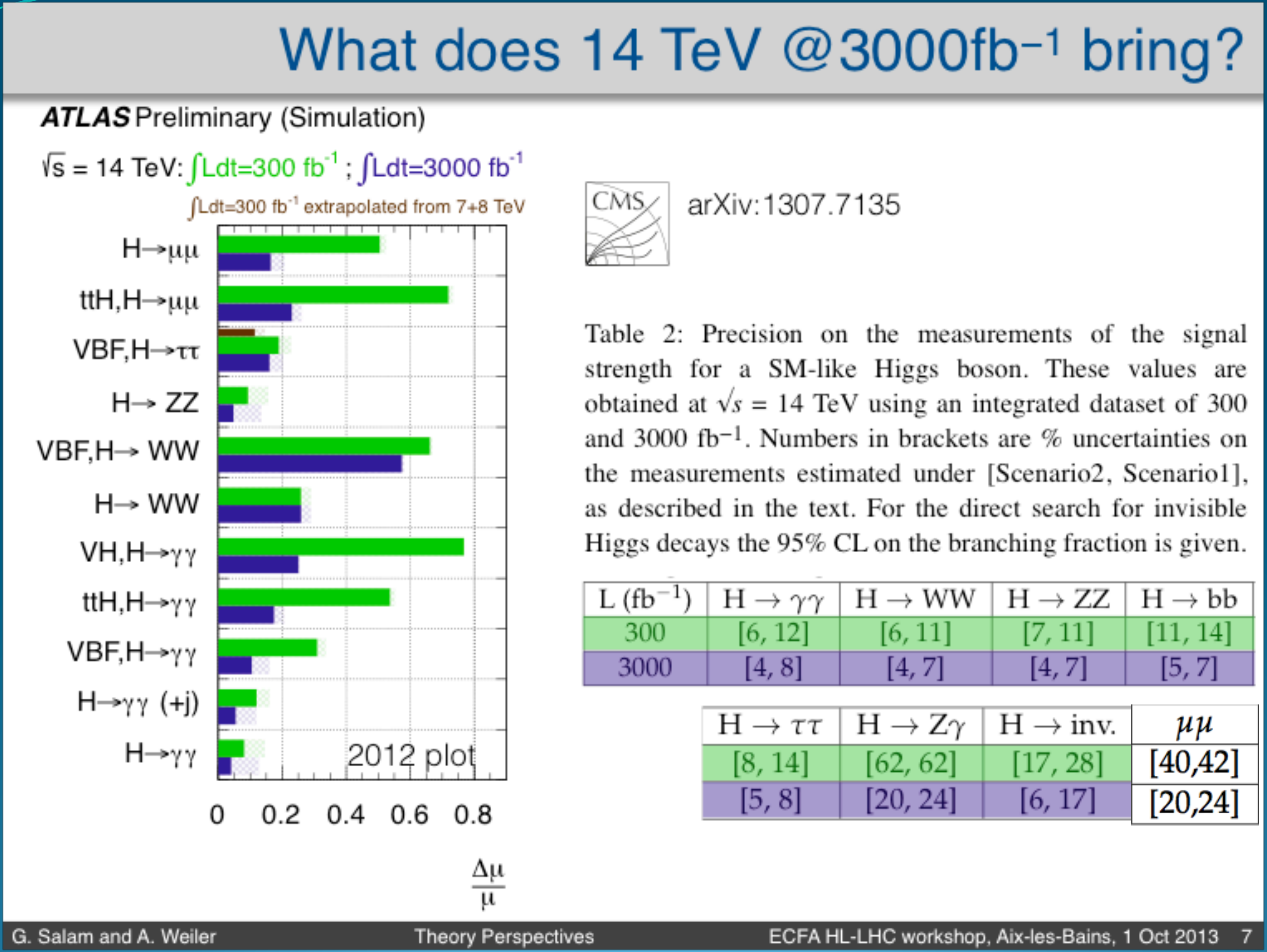
- Higgs boson pair production

First window on the Higgs self-coupling
Unconstrained operator in effective Lagrangians

- Longitudinal vector boson scattering

Higgs alone in unitarizing the SM?

Precision Higgs studies: signal strength



What does 14 TeV @3000fb^{-1} bring?

CMS

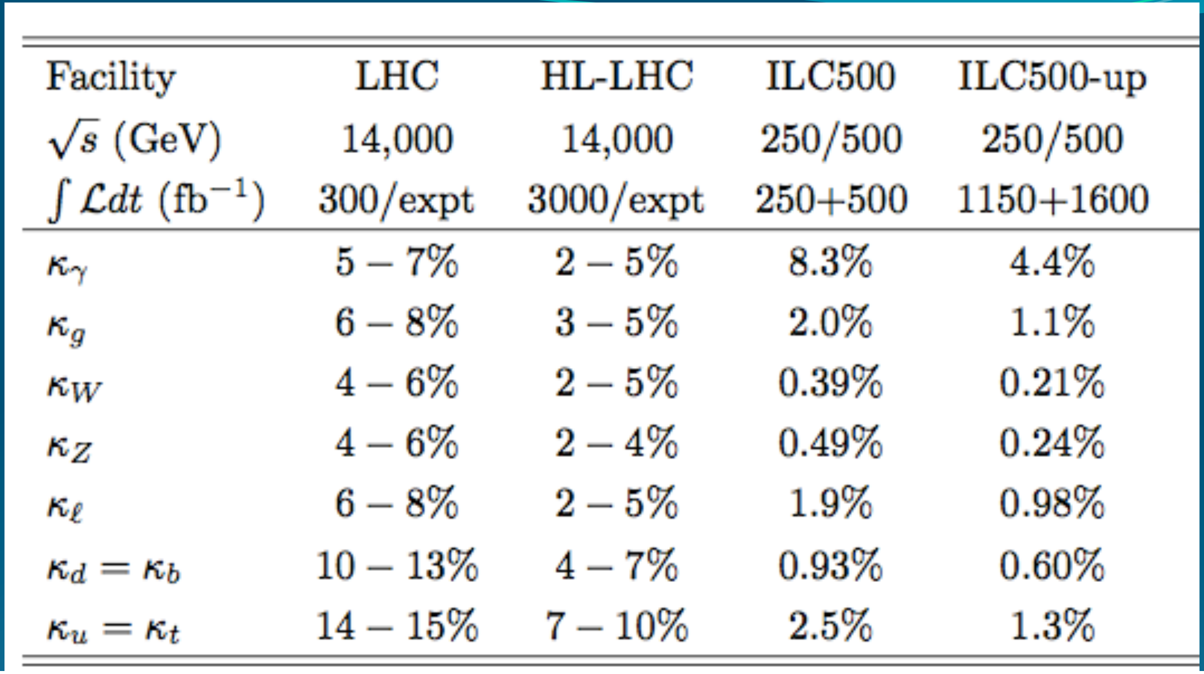
arXiv:1307.7135

Table 2: Precision on the measurements of the signal strength for a SM-like Higgs boson. These values are obtained at $\sqrt{s}$ = 14 TeV using an integrated dataset of 300 and 3000 fb^{-1}. Numbers in brackets are % uncertainties on the measurements estimated under [Scenario2, Scenario1], as described in the text. For the direct search for invisible Higgs decays the 95% CL on the branching fraction is given.

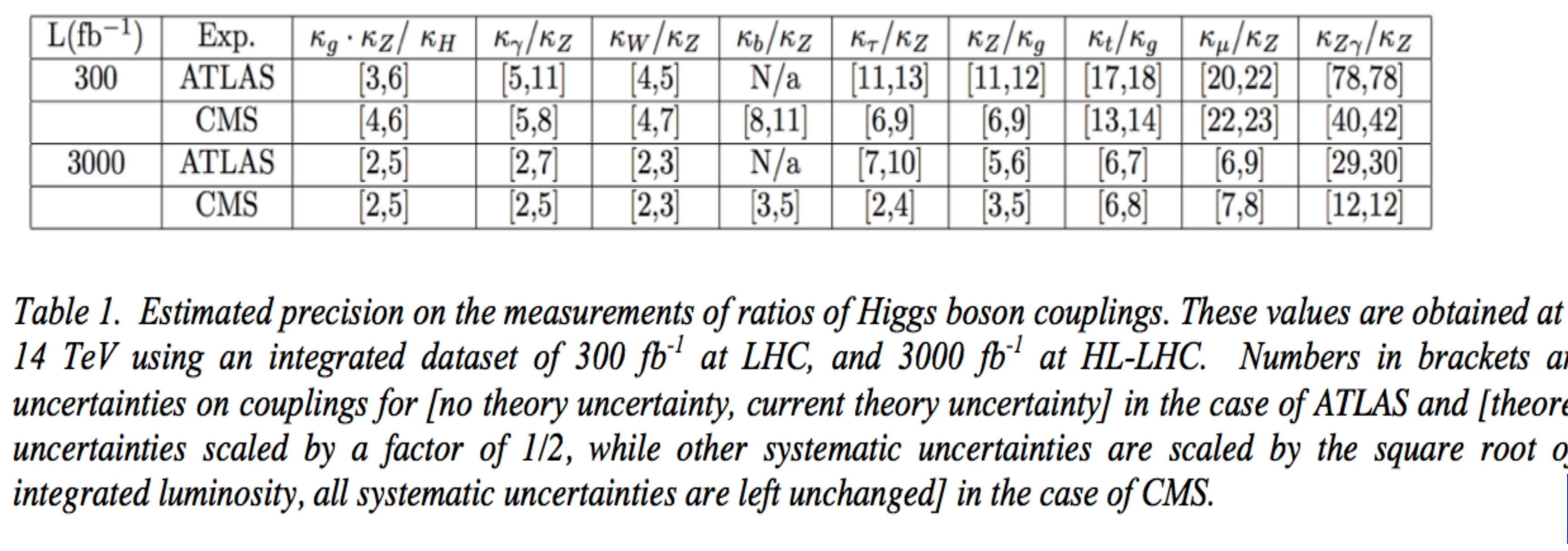
L (fb^{-1})	$H \to \gamma\gamma$	$H \to WW$	$H \to ZZ$	$H \to bb$
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]

$H \to \tau\tau$	$H \to Z\gamma$	$H \to$ inv.	$\mu\mu$
[8, 14]	[62, 62]	[17, 28]	[40,42]
[5, 8]	[20, 24]	[6, 17]	[20,24]

Precision Higgs studies: (ratios of) couplings



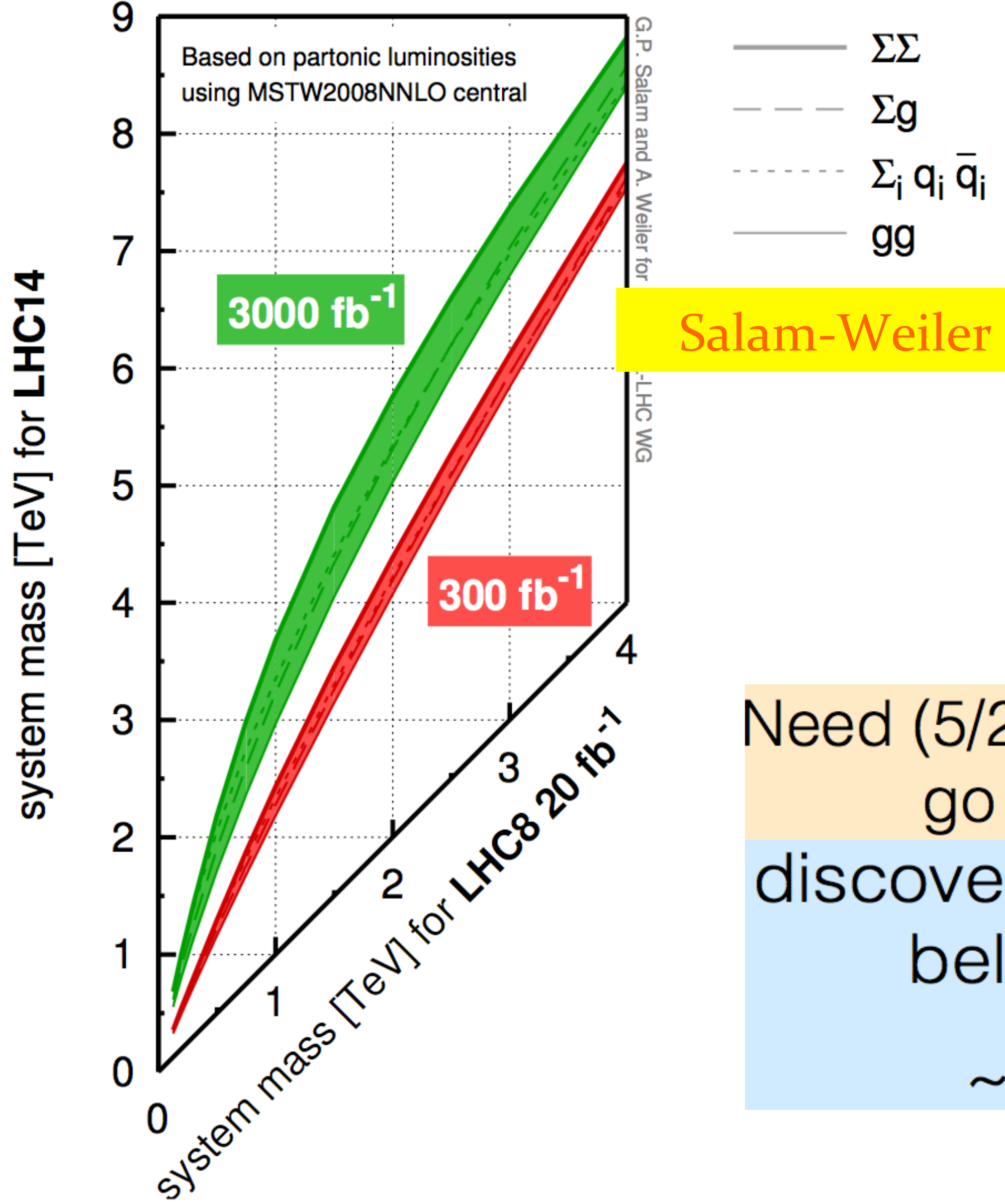
Facility	LHC	HL-LHC	ILC500	ILC500-up
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500
$\int \mathcal{L} dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%



L(fb^{-1})	Exp.	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ/κ_Z	κ_W/κ_Z	κ_b/κ_Z	κ_τ/κ_Z	κ_Z/κ_g	κ_t/κ_g	κ_μ/κ_Z	$\kappa_{Z\gamma}/\kappa_Z$
300	ATLAS	[3,6]	[5,11]	[4,5]	N/a	[11,13]	[11,12]	[17,18]	[20,22]	[78,78]
	CMS	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	ATLAS	[2,5]	[2,7]	[2,3]	N/a	[7,10]	[5,6]	[6,7]	[6,9]	[29,30]
	CMS	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

Table 1. Estimated precision on the measurements of ratios of Higgs boson couplings. These values are obtained at √s = 14 TeV using an integrated dataset of 300 fb^{-1} at LHC, and 3000 fb^{-1} at HL-LHC. Numbers in brackets are % uncertainties on couplings for [no theory uncertainty, current theory uncertainty] in the case of ATLAS and [theoretical uncertainties scaled by a factor of 1/2, while other systematic uncertainties are scaled by the square root of the integrated luminosity, all systematic uncertainties are left unchanged] in the case of CMS.

Push direct searches further



Salam-Weiler

Rule of thumb
(very very rough):

Increase luminosity by factor 10

→ reach increases by constant $\Delta m = 0.07\sqrt{s}$

i.e. for √s=14 TeV, reach goes by up 1 TeV

But 2σ to exclude
5σ to discover, then

Need $(5/2)^2 = 6.25$ increase in lumi to go from one to the other.

discovery reach is about $0.05\sqrt{s}$ below exclusion reach

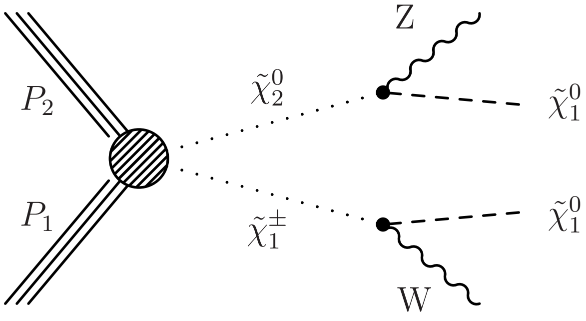
~ 0.8 TeV at 14 TeV

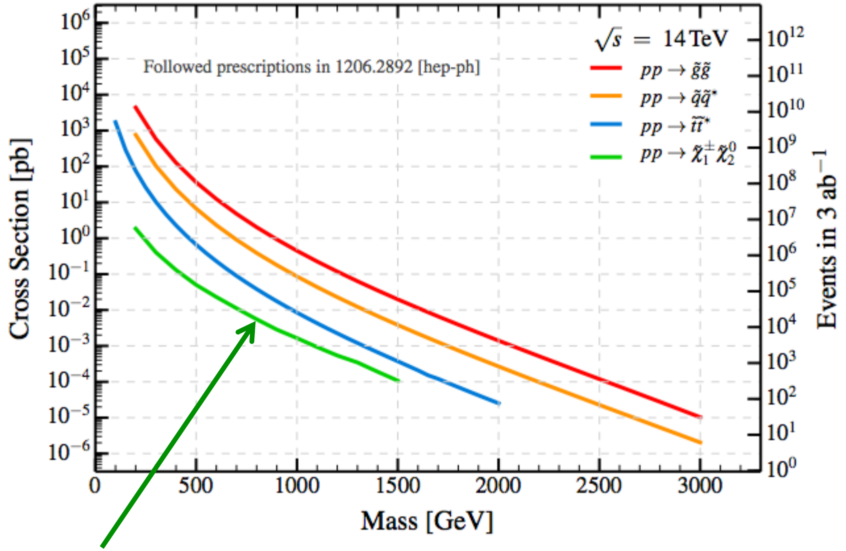
Hill's talk at ECFA workshop

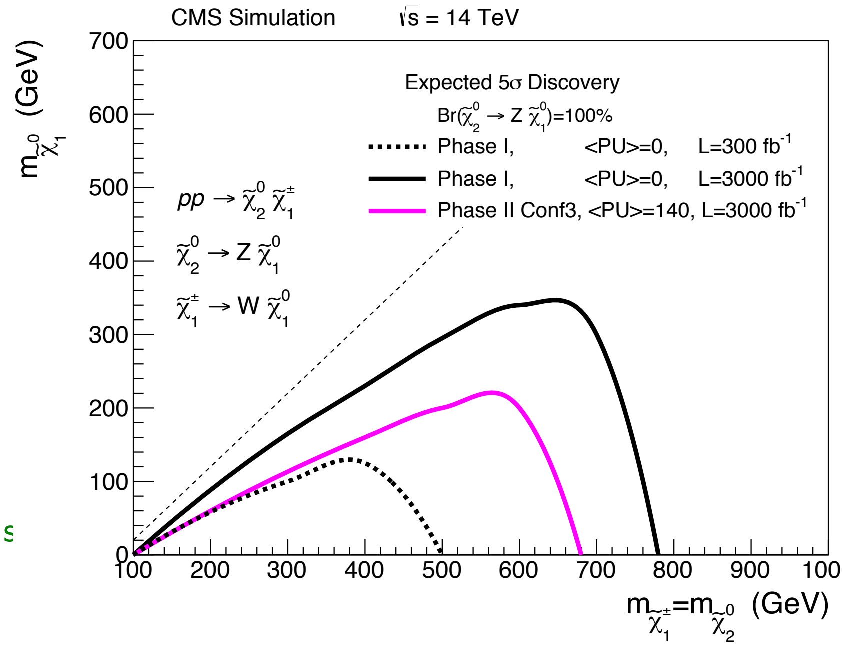
ECFA
European Committee for Future Accelerators

Direct Searches for BSM Particles

- HL-LHC luminosity needed to discover certain BSM scenarios
  - *E.g. SUSY through direct production of charginos/neutralinos*







Neutralino/chargino cross sections (here assuming Wino states) are very s

→ need high luminosity!!!

More precise flavor physics

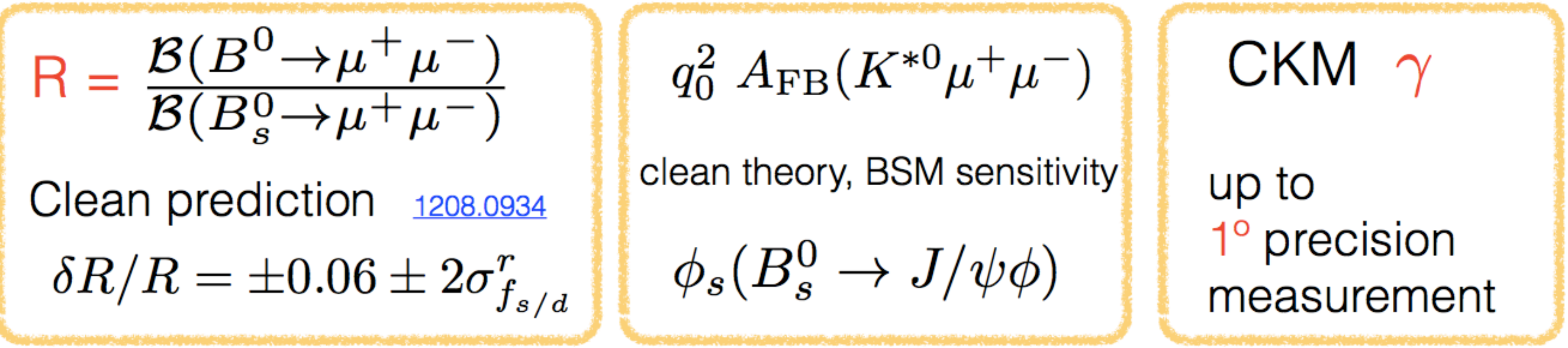
Precise studies of transitions between quarks of different flavours can be a window on new physics beyond the kinematical reach of direct searches

Historical examples:

K-meson mixing ➔ charm quark mass

B_d-meson mixing ➔ top quark mass

Some flavor measurements with high potential:



$$R = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}$$

Clean prediction 1208.0934

$$\delta R/R = \pm 0.06 \pm 2\sigma^r_{f_s/d}$$

$q_0^2 \; A_{\mathrm{FB}}(K^{*0}\mu^+\mu^-)$

clean theory, BSM sensitivity

$\phi_s(B_s^0 \to J/\psi\phi)$

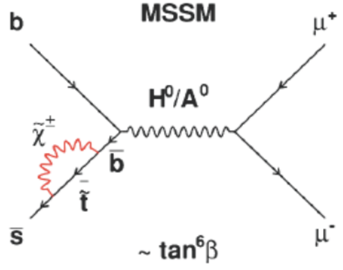
CKM γ

up to
1° precision
measurement

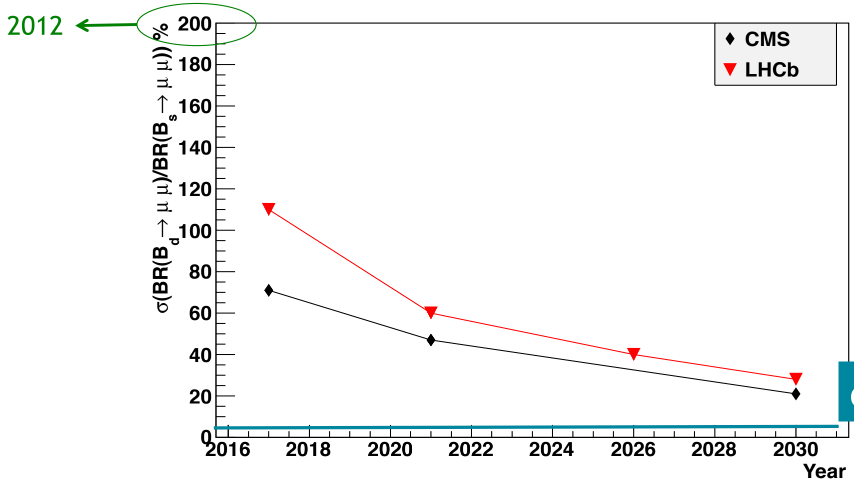
E.g. $B_{s,d}$ to $\mu^+\mu^-$

Hill/Schune

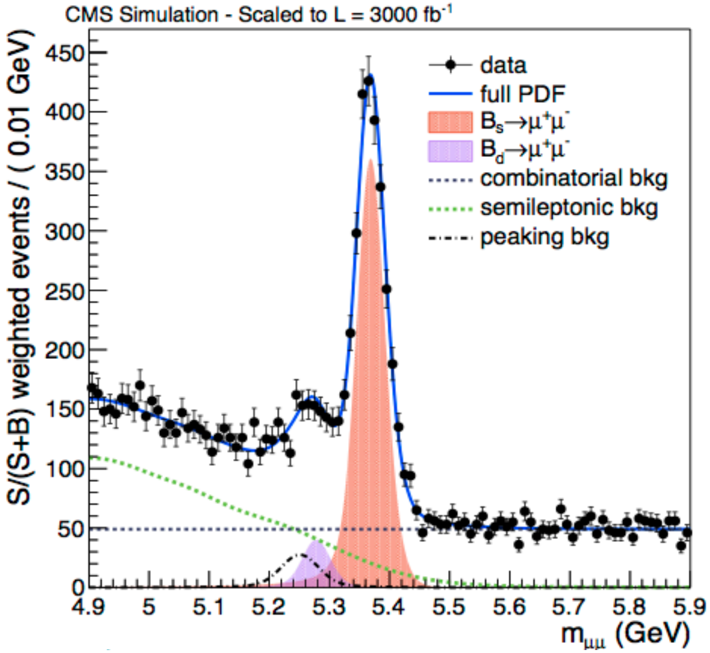
- Measure B_d and B_s
  - *NP effects can be different*
- CMS and LHCb can make precise measurements or BRs with HL-LHC



Expected precision on $BR(B_d \to \mu^+\mu^-)/BR(B_s \to \mu^+\mu^-)$



σ_{theory} ~5 %



Heavy ions and quark-gluon plasma

Factor 10 (triggerable probes) to 100 (minimum bias events) in statistics

↓

Exploration of rare probes of the QGP

New observables with low cross-sections (heavy-flavor baryons, b-jet correlations) or low ratio S/B (low-mass dileptons)

Key distributions as functions of several variables simultaneously

From the 2013 update of the European Strategy for Particle Physics

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.
Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.

Lessons from history: the Tevatron (1985-2011)

First collisions in 1985, first physics in 1988-9

Top discovery after 10 years (end of Run 1, 110 pb^{-1})

Still a lot of physics in Run 2 (2001-2011, 10 fb^{-1}):
m_{top} and m_W, B_S oscillations, CPV in $B \rightarrow \psi K_S$,
BSM and Higgs limits/evidence, QCD dynamics

Higgs (and $B_S \rightarrow \mu\mu$?) could come with more luminosity & upgraded detectors: 10 fb^{-1} @ 2 TeV as 500 fb^{-1} @ 14 TeV ?

Stopped in 2011 because of LHC (higher-energy, new detectors), will VHE-LHC play the same role one day?

A final comment

Run 1 exploited a powerful no-lose theorem

either the Higgs or New Physics at TeV scale

We won’t be again in such a condition for a long time

Diversify efforts to maximise chances
We must be patient and persistent!

Not obvious that next positive BSM input will come from the LHC, but a negative one equally important!

High-energy frontier essential for long-term progress