HEP Perspectives from the Theory side after the LHC

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Content

- Introduction:

  (Our journey into the Energy frontier)

- Lessons from the LHC:

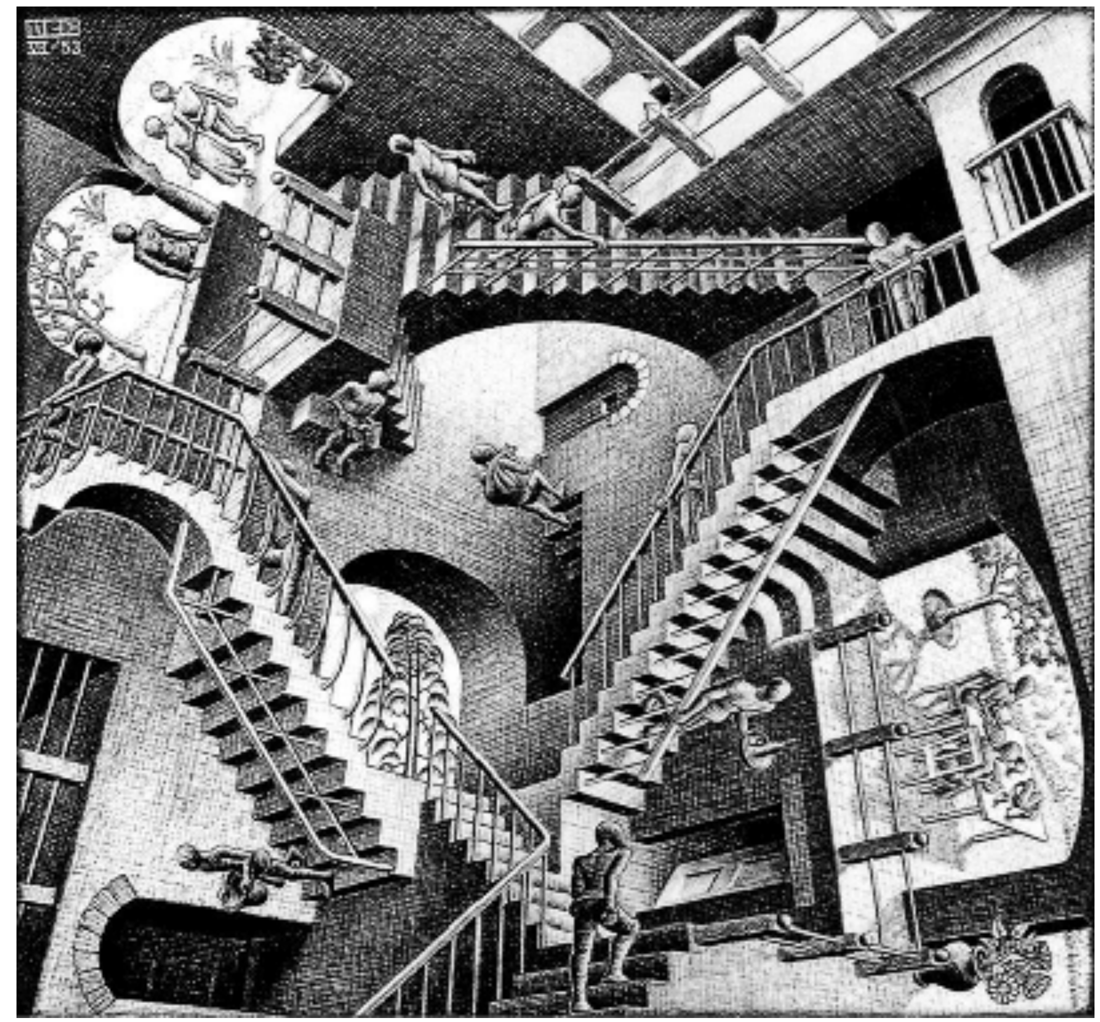
  - The present: Searches for Higgs, BSM and QFT

- Future of HEP-Theory

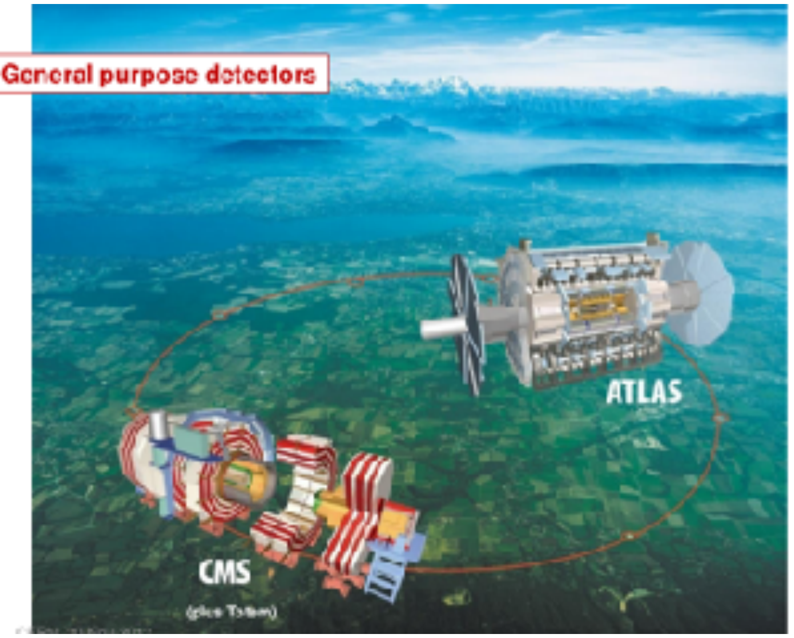
  - Phenomenology,

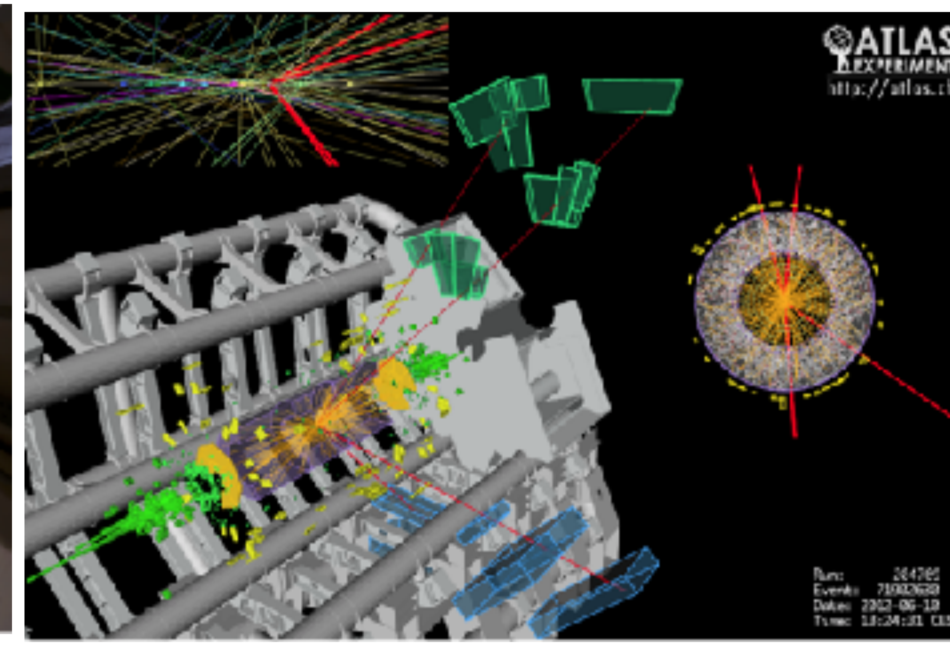
- Some remarks on Model building and theory,

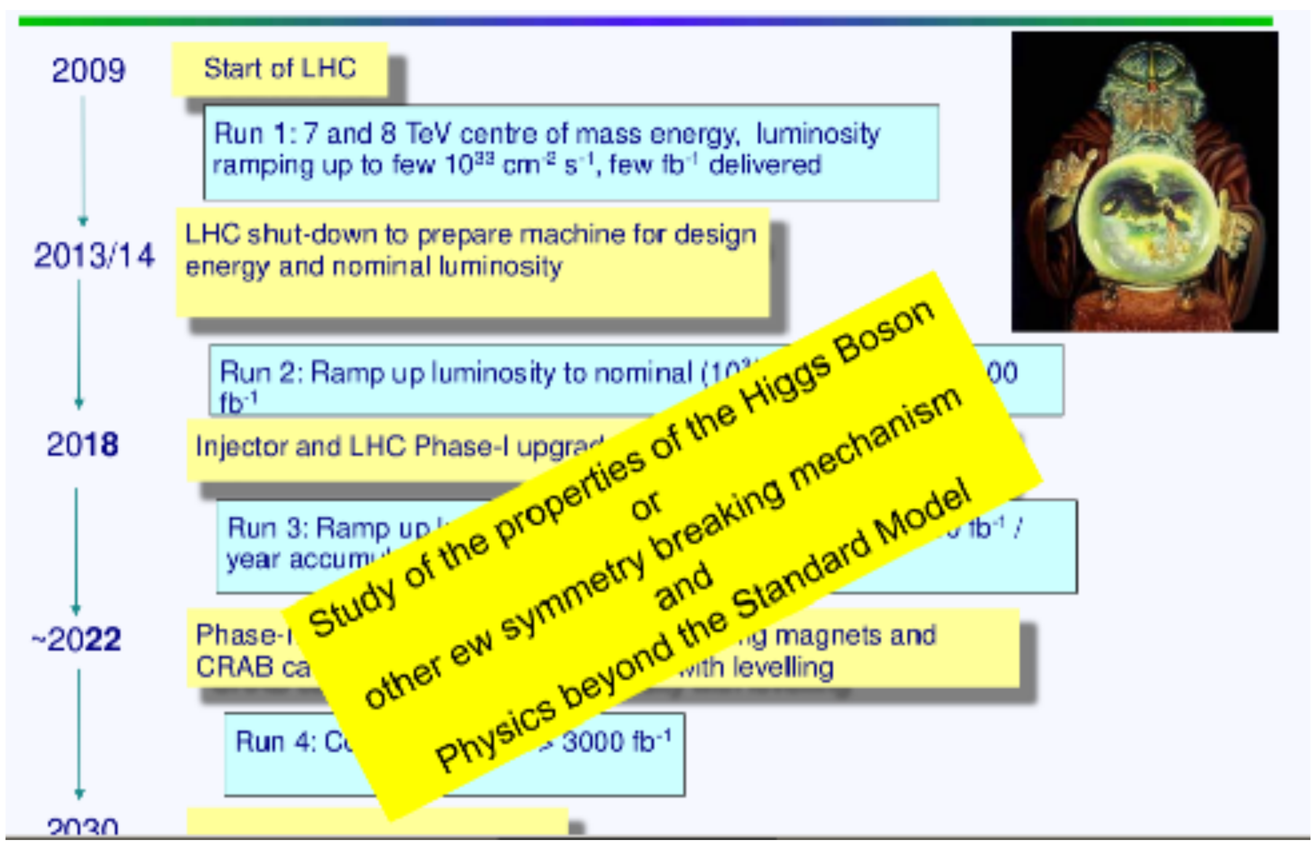
- Conclusions.



1. LHC: One fo the most successful experiments ever!

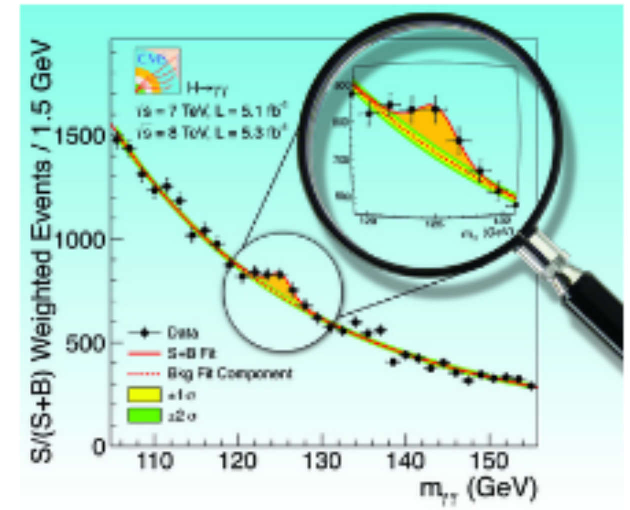


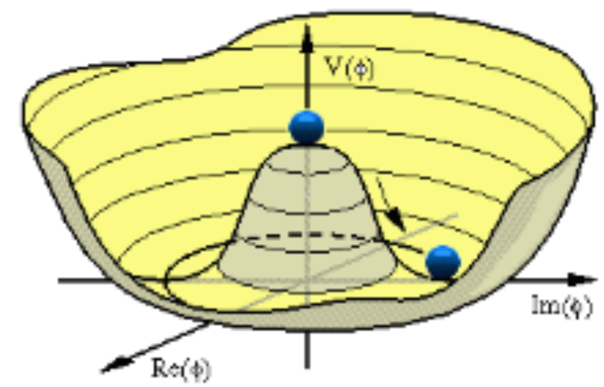




1.2 Lessons from LHC

- The SM is passing all tests at LHC -> The SM is great!
- The Higgs boson discovery remains as its greatest achievement,
- The absence of signals of Physics beyond the SM is intriguing,
- This means we need to keep improving experimental tools and think harder,
- But the evil is in the details …



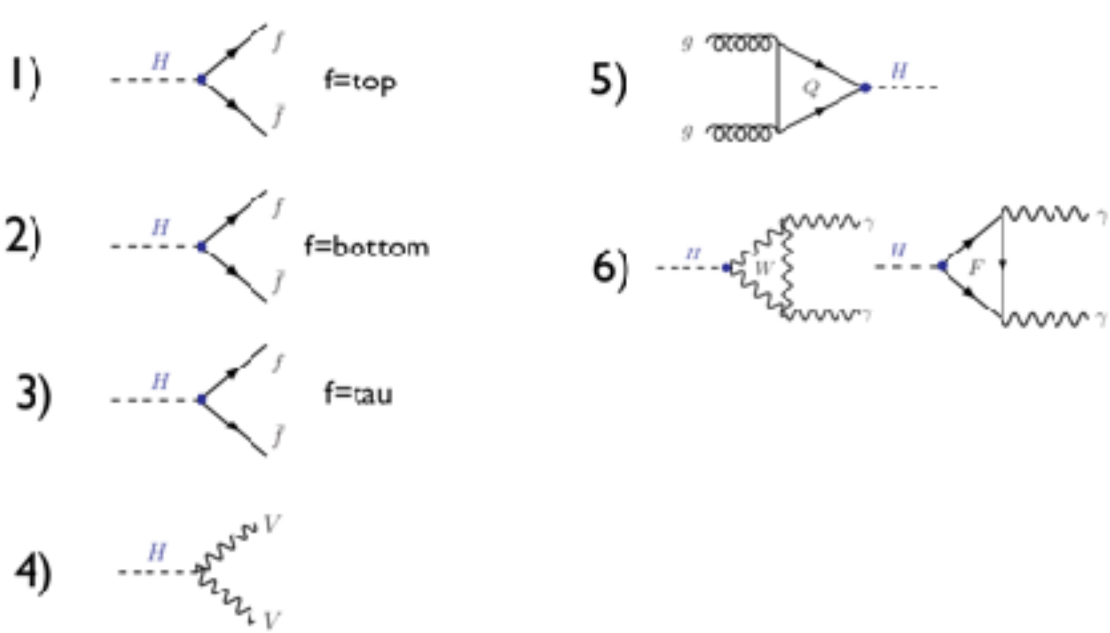


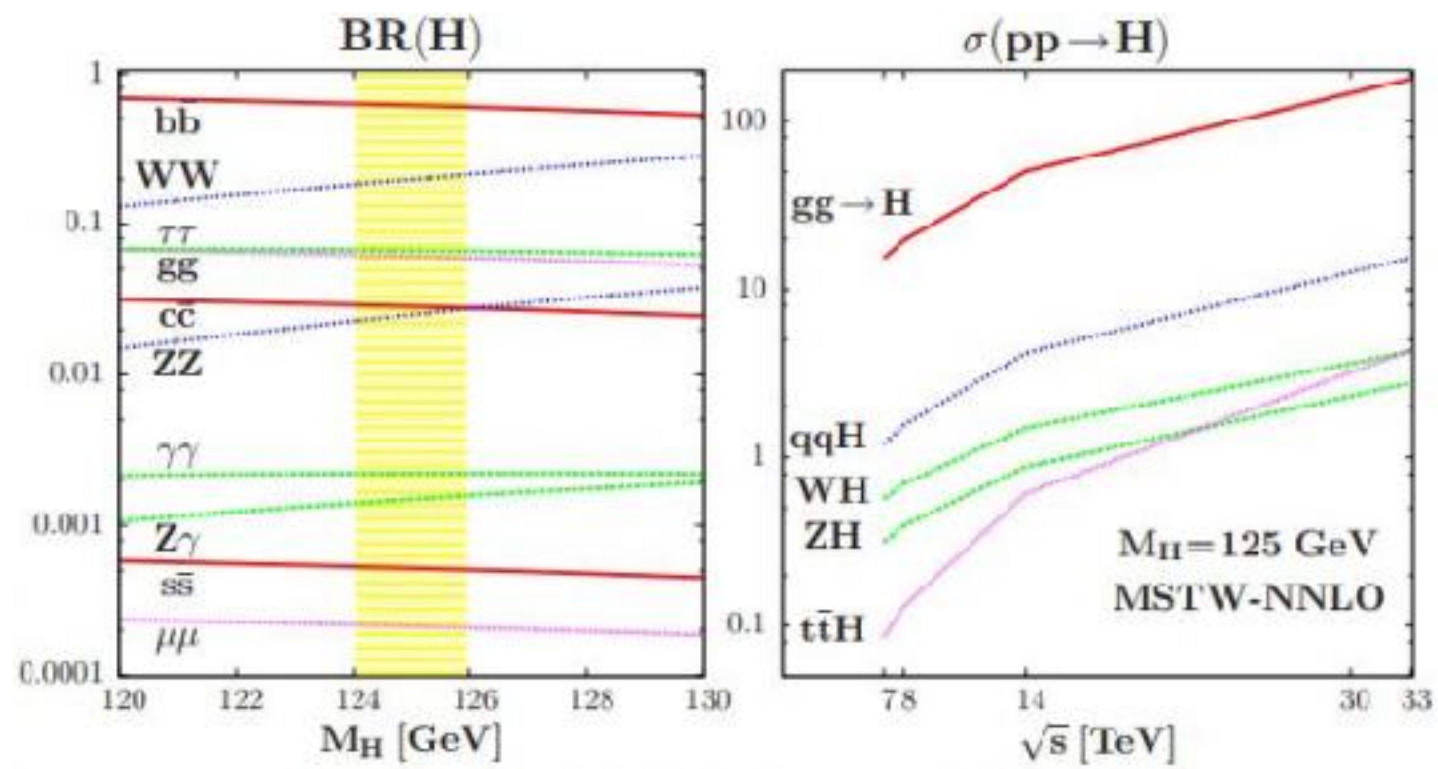
2. LHC lessons- EWSB and Higgs boson

- SM is a renormalizable gauge theory with SSB,
- The Higgs boson couples to the mass,
- SM Higgs couplings -> decays, prod. and signals,

The essential property of the Higgs:

$$\begin{aligned} L &= Y_f\,\bar{\psi}\psi\phi + \ldots \\ &= Y_f\,\bar{\psi}\psi(v+h) + \ldots \\ &= (Y_f v)\bar{\psi}\psi + Y_f\bar{\psi}\psi h + \ldots \\ &= m_f\bar{\psi}\psi + \frac{m_f}{v}\bar{\psi}\psi h + \ldots \end{aligned}$$



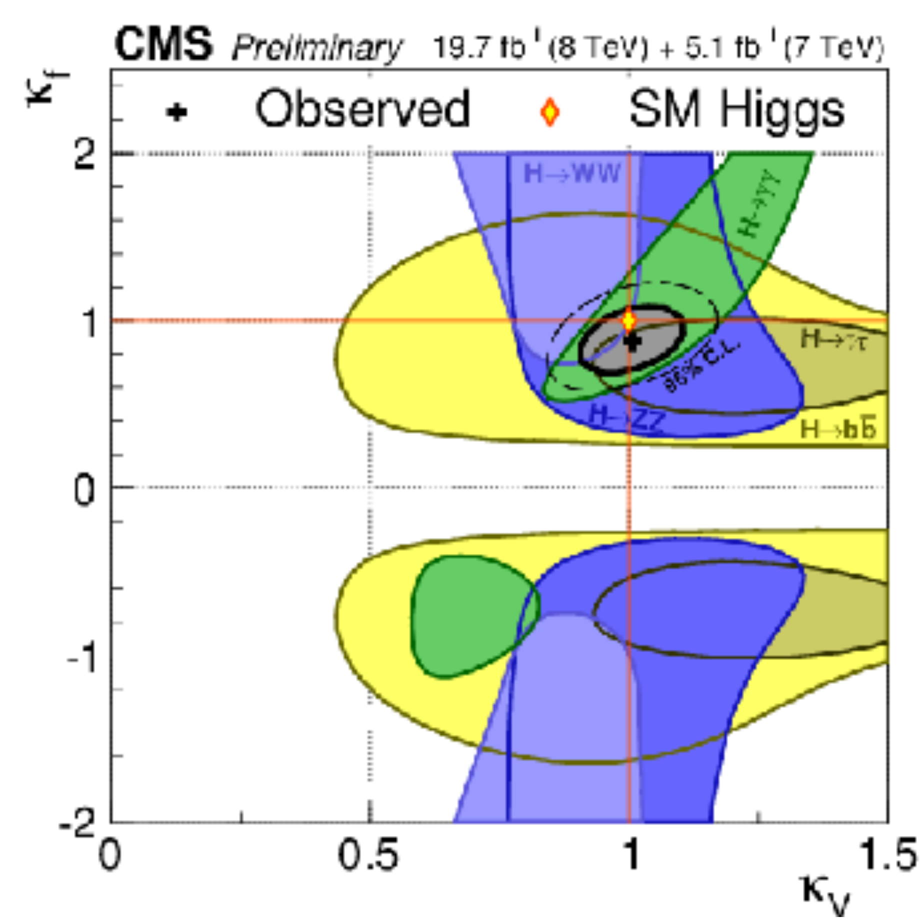


2.1 Higgs properties from LHC-7,8

- Signals at LHC7,8: ZZ*, WW*, gg, gaga, bb, ta ta
- Higgs mass: mh=125-126 GeV
- Spin-0 (Yang theorem),
- CP-even (hVV coupling),
- Initially some deviations from SM for gamma mode, but later gone …

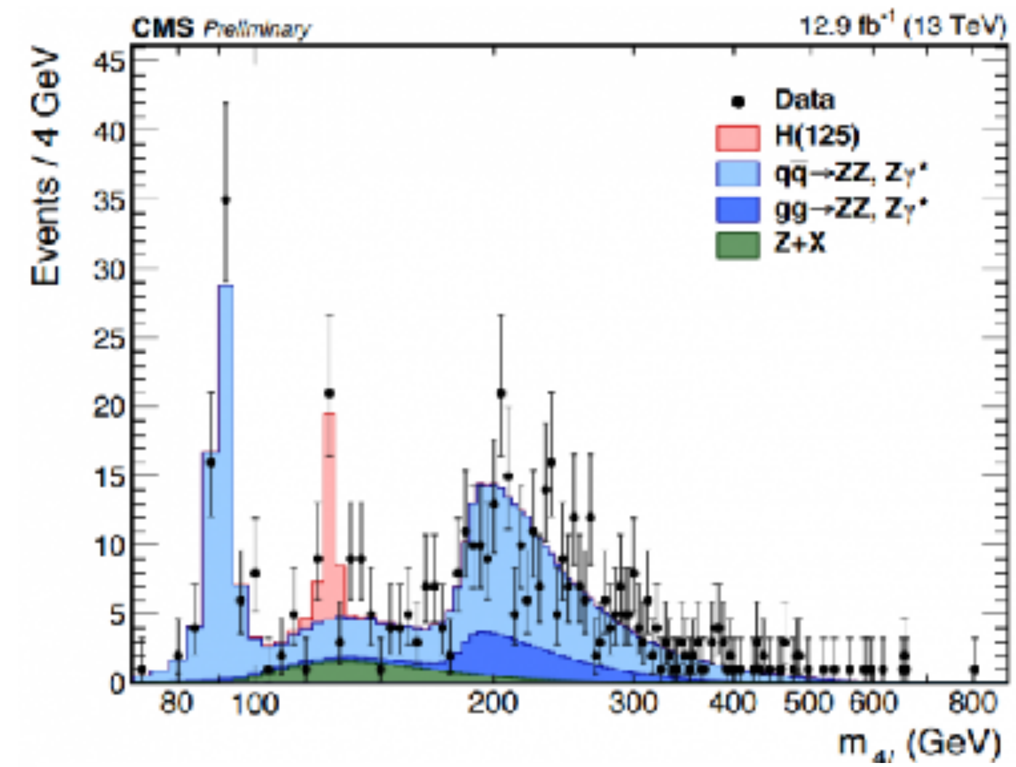
Channel	Production	Run-I	Channel	Production	Run-I
$\gamma\gamma$	ggh	$1.10^{+0.23}_{-0.22}$	$\tau^+\tau^-$	ggh	$1.0^{+0.6}_{-0.6}$
	VBF	$1.3^{+0.5}_{-0.5}$		VBF	$1.3^{+0.4}_{-0.4}$
	Wh	$0.5^{+1.3}_{-1.2}$		Wh	$-1.4^{+1.4}_{-1.4}$
	Zh	$0.5^{+3.0}_{-2.5}$		Zh	$2.2^{+2.2}_{-1.8}$
	$t\bar{t}h$	$2.2^{+1.6}_{-1.3}$		$t\bar{t}h$	$-1.9^{+3.7}_{-3.3}$
WW^*	ggh	$0.84^{+0.17}_{-0.17}$	$b\bar{b}$	Wh	$1.0^{+0.5}_{-0.5}$
	VBF	$1.2^{+0.4}_{-0.4}$		Zh	$0.4^{+0.4}_{-0.4}$
	Wh	$1.6^{+1.2}_{-1.0}$		$t\bar{t}h$	$1.15^{+0.99}_{-0.94}$
	Zh	$5.9^{+2.6}_{-2.2}$	ZZ^*	ggh	$1.13^{+0.31}_{-0.31}$
	$t\bar{t}h$	$5.0^{+1.8}_{-1.7}$		VBF	$0.1^{+1.1}_{-0.6}$

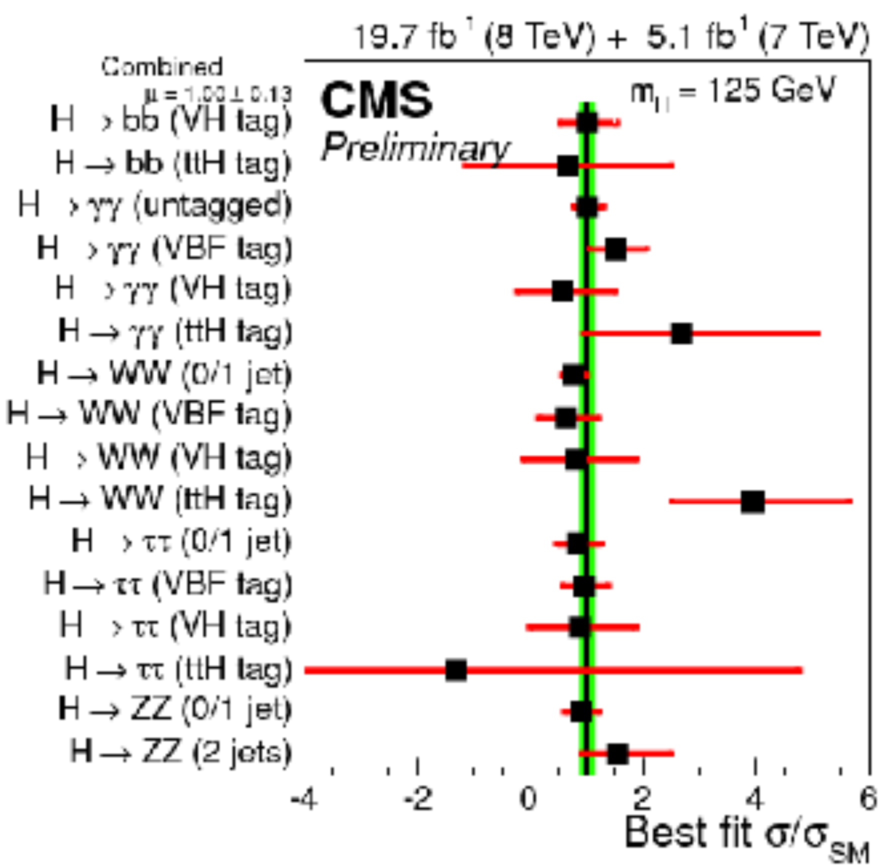
Table 8. The Higgs signal strength in various channels measured at the LHC Run-I [47]. Correlations between different Run I measurements quoted in Fig. 27 of Ref. [47] are taken into account.

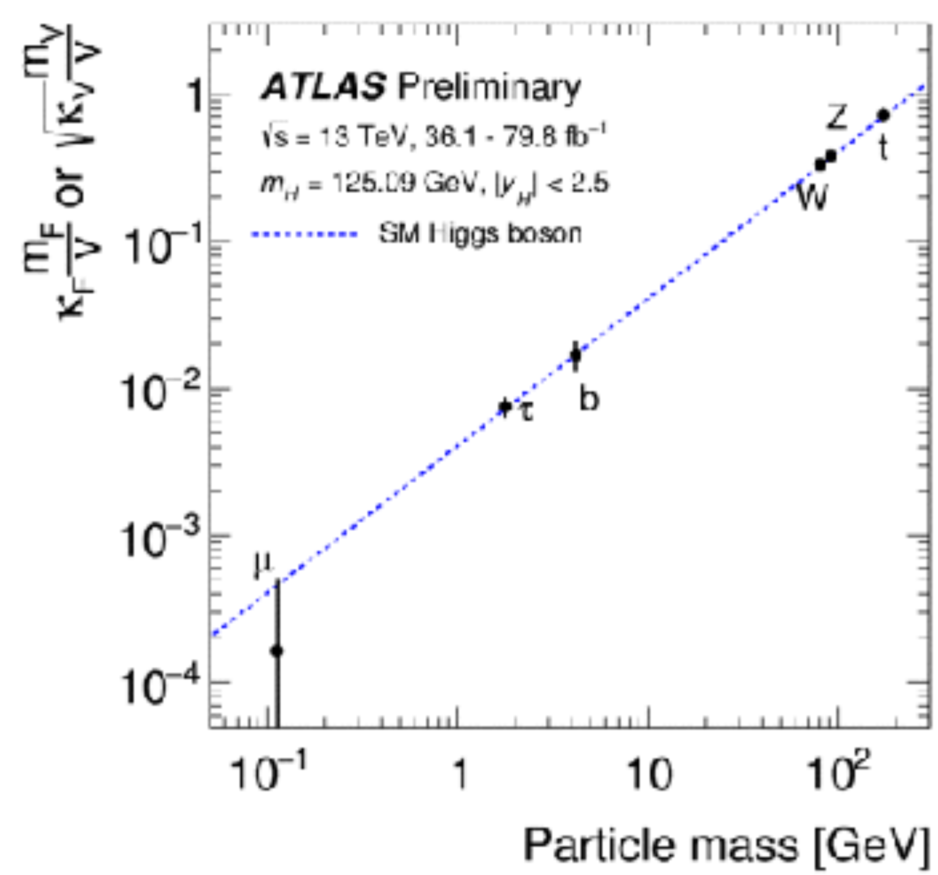


2.2 New SM signals studied at LHC13:

- New SM channels detected at LHC13: tth, Vh (->bb),
- Bounds on SM rare signals (h->mumu)
- Plenty of modes, ok with SM
- Lesson: Higgs couples with mass linearly,







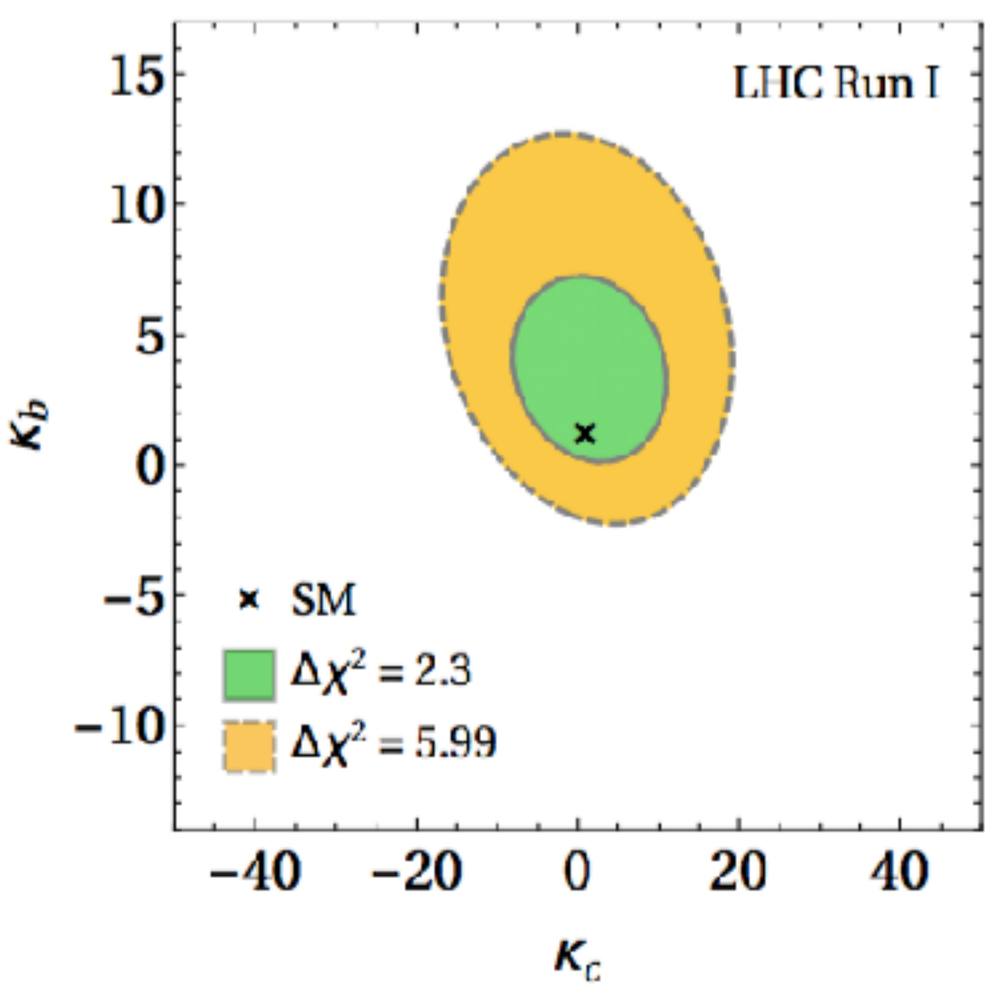
Higgs Couplings from LHC

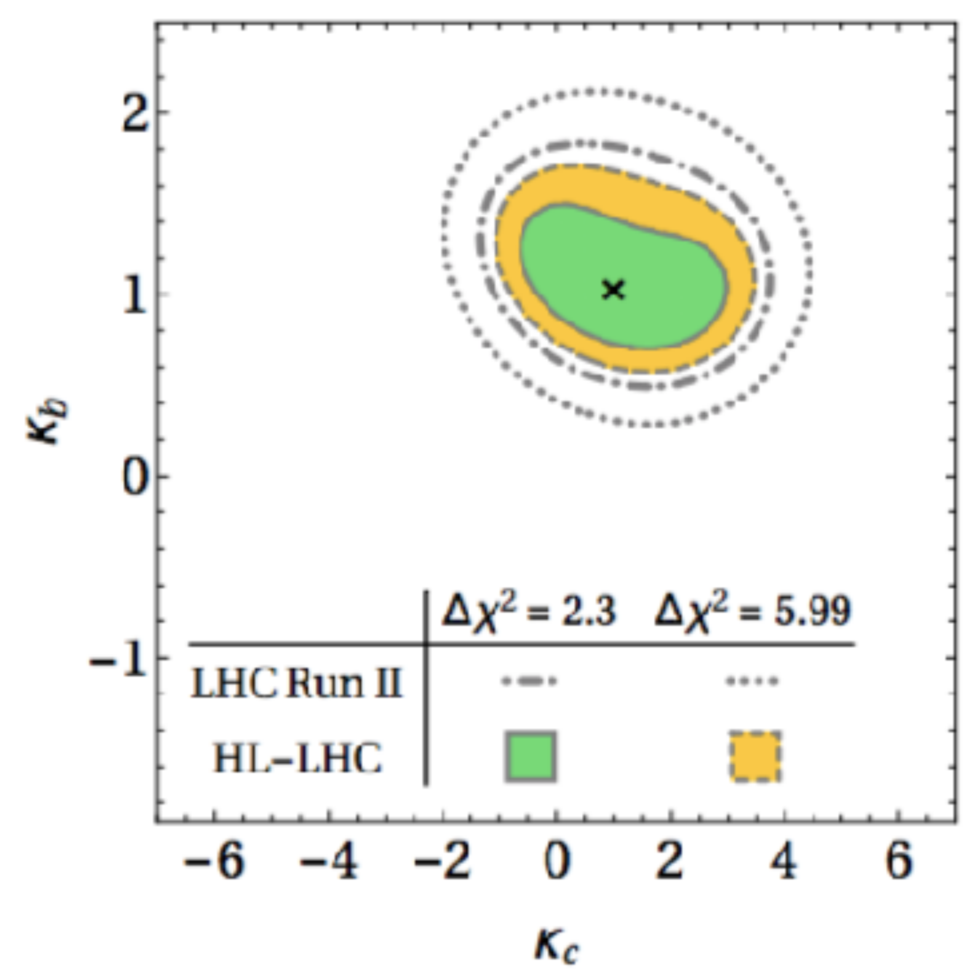
Kappa-formalism

$$\mathcal{L}_V = \kappa_W g m_W h W^{+\mu} W^-_\mu + \kappa_Z \frac{g m_Z}{2 c_W} h Z^\mu Z_\mu$$

TABLE I. Fit results for Higgs boson coupling modifiers κ_X reported by ATLAS and CMS collaborations and the expected results at HL-LHC.

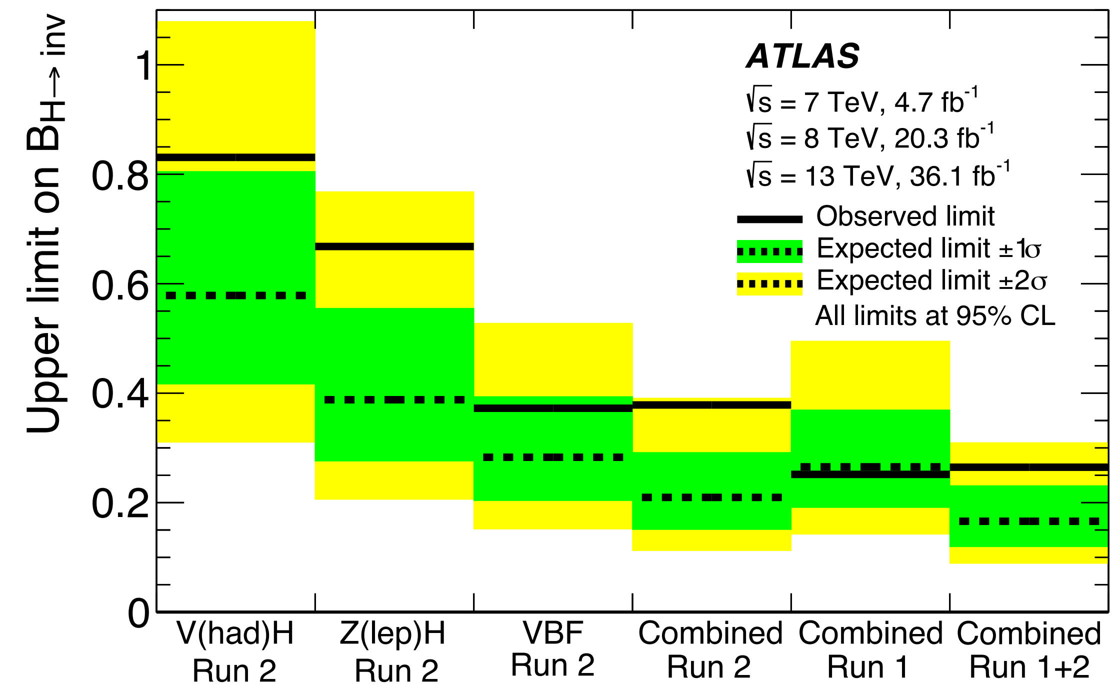
κ_X	ATLAS [16]	CMS [17]	HL-LHC [18]
κ_t	$1.03^{+0.12}_{-0.11}$	0.98 ± 0.14	1.04 ± 0.025
κ_b	$1.00^{+0.24}_{-0.22}$	$1.17^{+0.27}_{-0.31}$	0.94 ± 0.028
κ_τ	$1.04^{+0.17}_{-0.16}$	1.02 ± 0.17	1.0 ± 0.17
κ_Z	$1.07^{+0.11}_{-0.10}$	1.00 ± 0.11	1.01 ± 0.011
κ_W	1.04 ± 0.10	$-1.13^{+0.16}_{-0.13}$	1.01 ± 0.011
κ_μ	< 1.63	$0.80^{+0.59}_{-0.80}$	0.58 ± 0.042

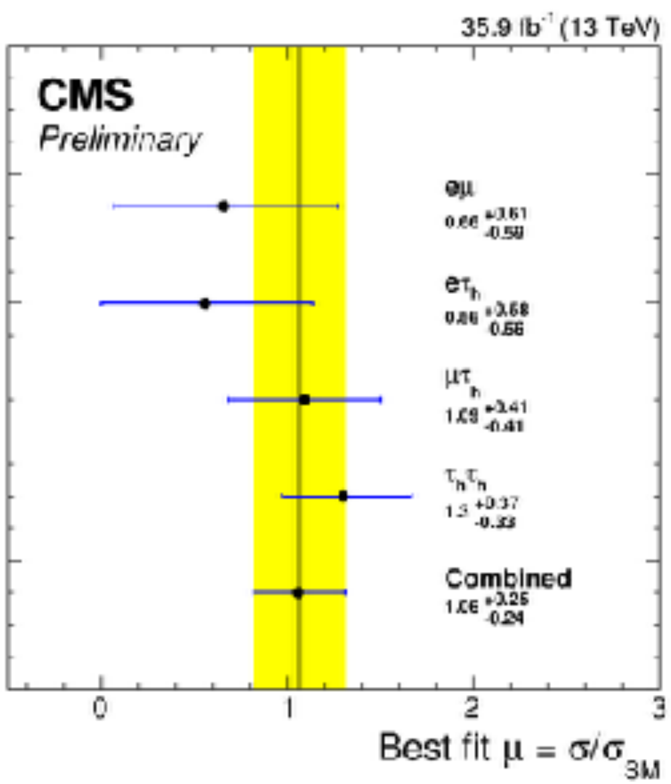


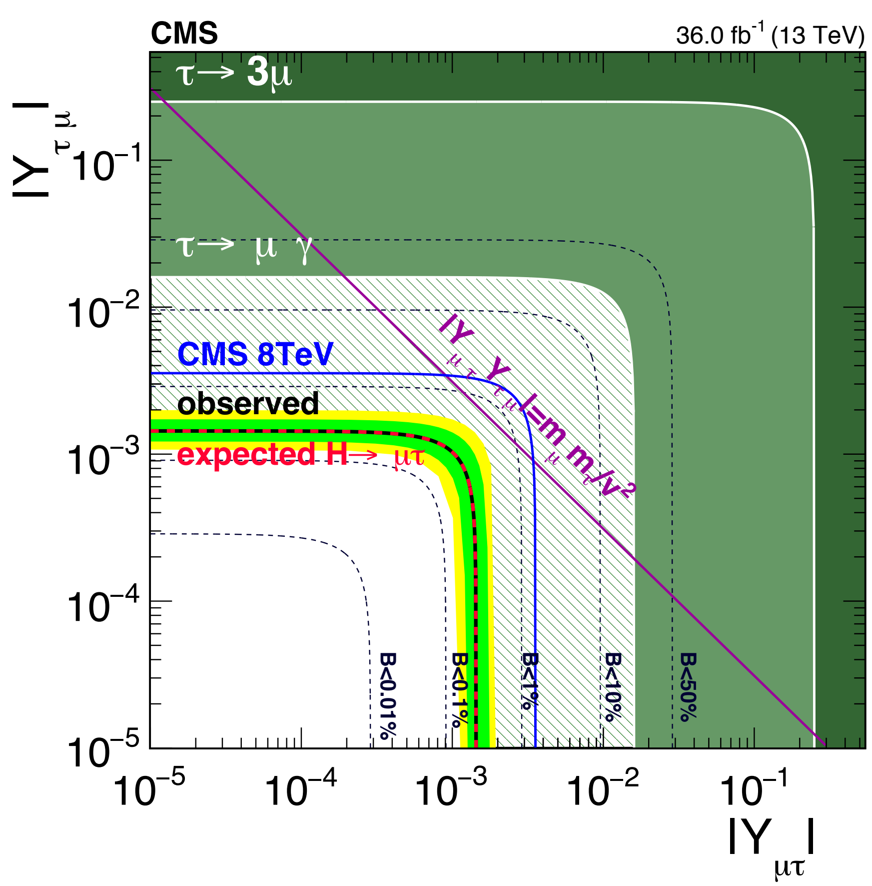


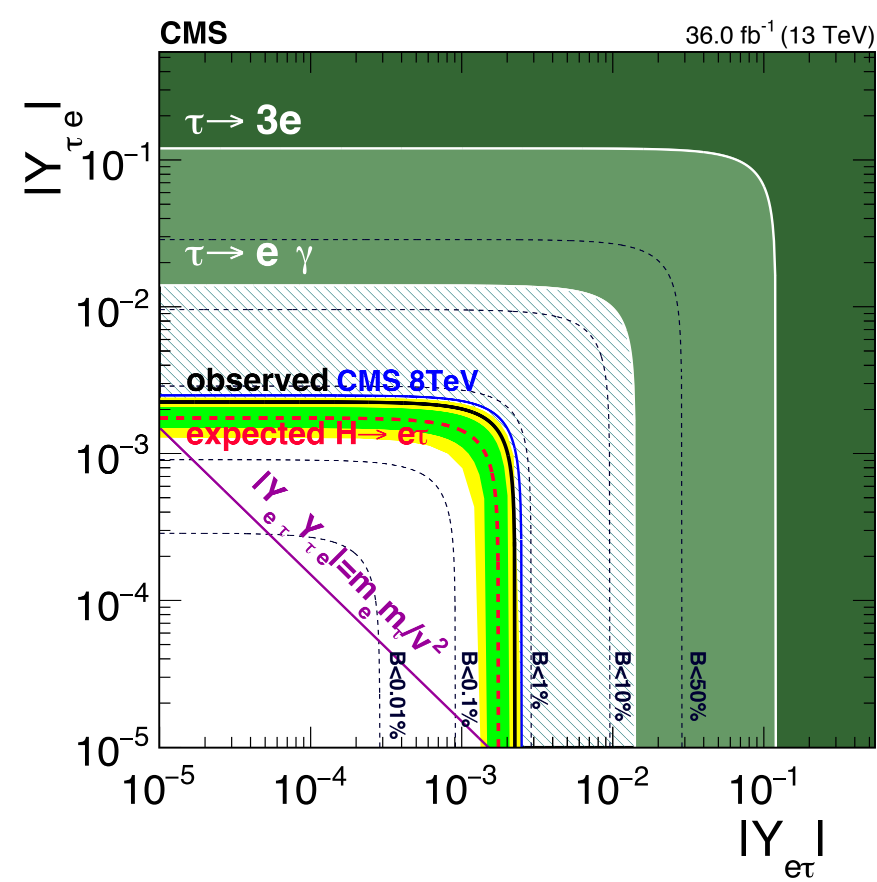
2.3) BSM Higgs signals studied at LHC13

- Invisible Higgs decay,
- LFV Higgs decays (h -> tau mu),
- Exotics (h->gravitinos+gammas)
- No BSM Higgs signal at LHC, yet …









BSM Physics

- The SM is great, but there are open issues:

  - Neutrino masses, DM, DE, BAU, …

  - Why the SM parameters?, why 3 families?,

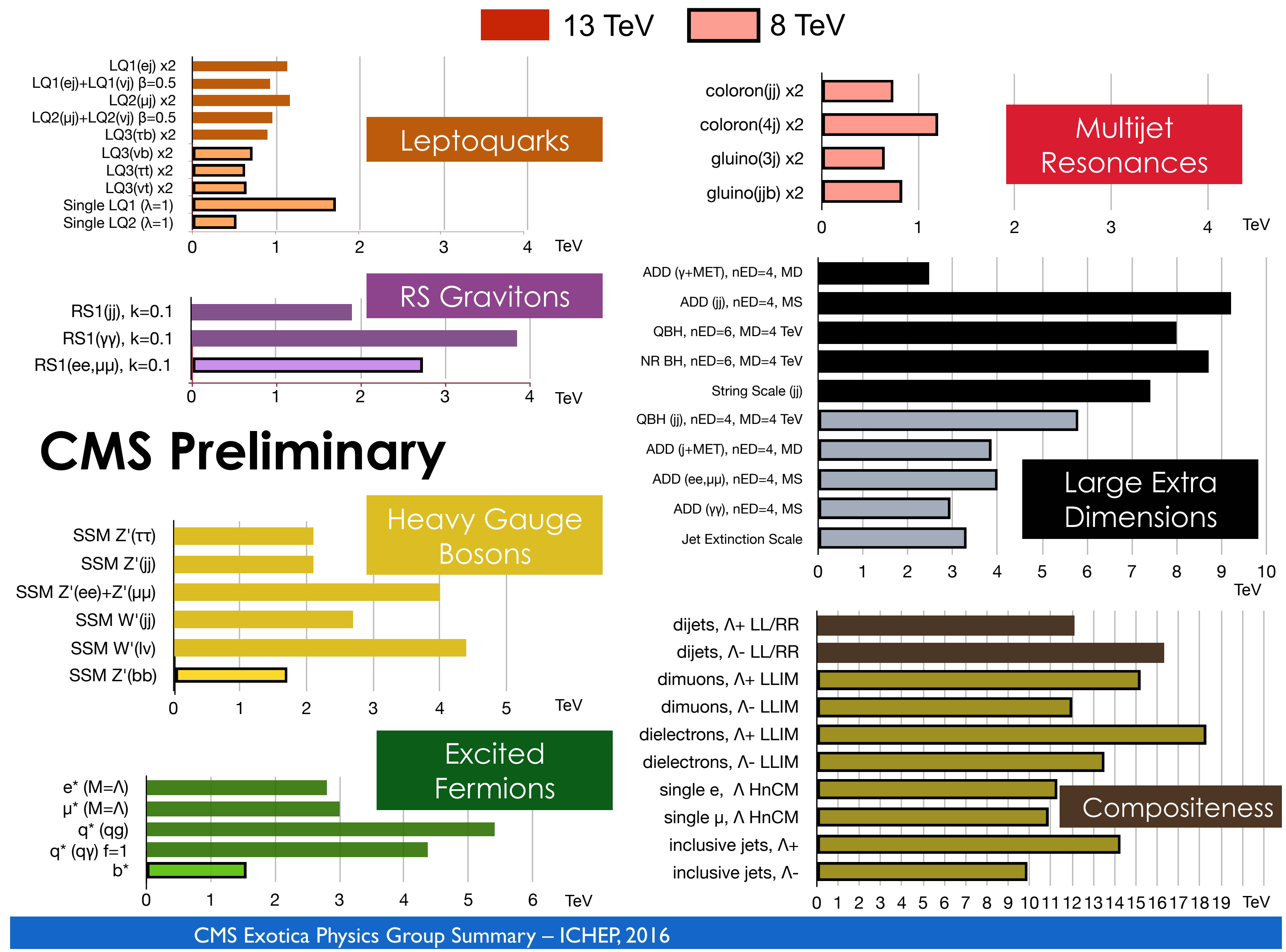
  - How to include gravity (Q.G.?)

- Many extensions have been proposed [NHDM, extra gauge forces, more fermions, more dimensions (L, XL, Q), etc]

- SUSY, GUT´s and String theory,

2.4) SEARCH FOR NEW PHSICS AT LHC

- No BSM signal has been found,
- Should LHC be closed and theorist be fired?
- Even a “no signal” is teaching lessons,



What is the absence of BSM-signal-at-LHC teaching us?

- Arguments for E=O(1) TeV NP scale must be re-examined,
- But open problems of the SM remain,
- Is there new physics?
- Is it consistent with QM and relativity?
- How is SUSY realized in nature? Or not?

All izz well

- But wait a minute … the LHC is not done yet: High Luminosity phase is next,
- One should search for these and other signals with higher luminosity, or energy,
- Also go to the intensity & cosmic frontiers,
- Build next ILC, VLHC …
- Ask help from Mexican mothers!

HEP theory perspectives

- Phenomenology,
- Model building,
- Theory (formalism),

3.1 Phenomenology

- All right, so far there are no signals of BSM at LHC, but we must keep looking …

- Actually models just include nice ideas that need further experimental input,

- Many BSM models, can be seen as generators of signatures, ex.

  - mSUGRA & LSP -> missing ET, DM,

  - GMM -> missing Et + photons,

  - EW Gravitino DM -> long lived sparticles,

  - **2HDM** -> H, A, H^+,

- Need to look closer at patterns and events, surprises may be around the corner,

Basics of the 2HDM

$$L = Y_1^u \bar{Q}_L^0 \tilde{\Phi}_2 u_R^0 + Y_2^u \bar{Q}_L^0 \tilde{\Phi}_2 u_R^0 + Y_1^d \bar{Q}_L^0 \Phi_1 d_R^0 + Y_2^d \bar{Q}_L^0 \Phi_2 d_R^0 + h.c.$$

where the quark doublets, quark singlets and Higgs doublets are written as:

$$Q_L^0 = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad \overline{Q}_L^0 = (\overline{u}_L, \overline{d}_L),$$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix},$$

- Two Higgs Doublets -> 8 d. of f.
- Physical spectrum: h(125), H, A, H^+,
- Parameters include two vevs: v1, v2 -> v=(v1^2+ v2^2)^1/2 = 246 GeV, tan(B)=v2/v1,

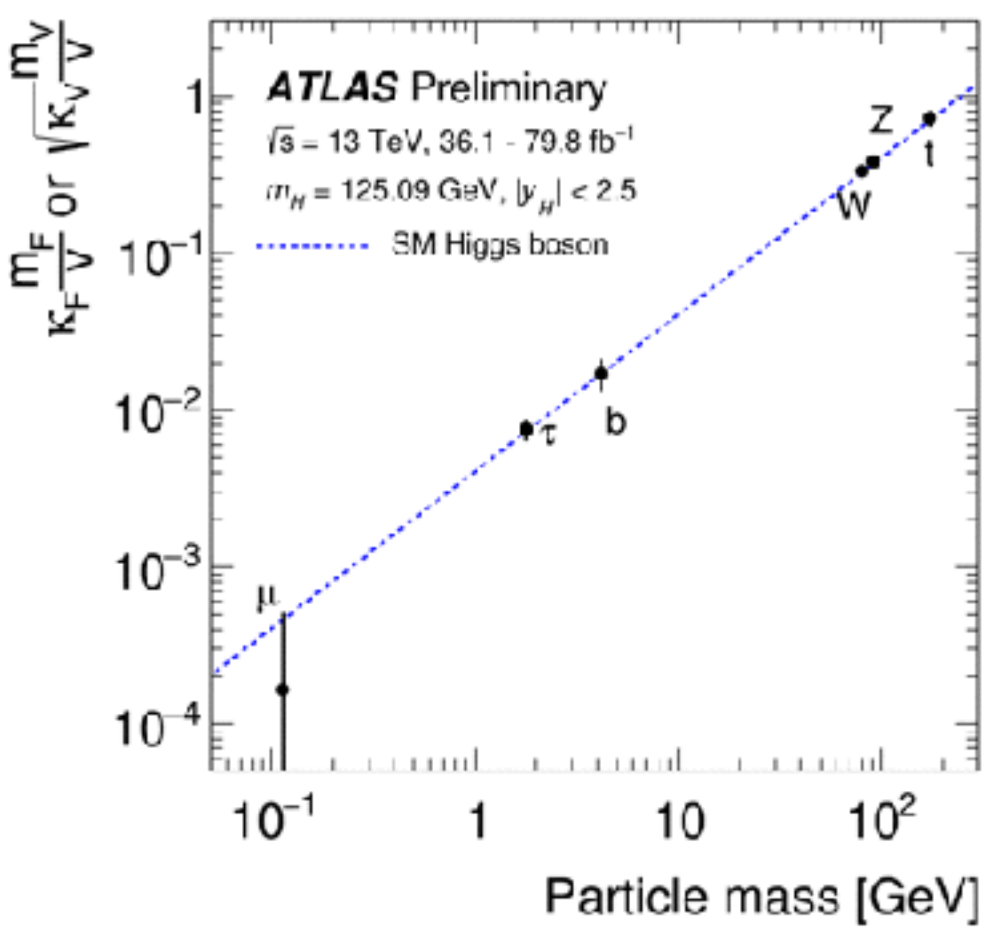
- Also the masses (M_Hi) and alpha (angle for diag. neutral Higgses)

Fermion-Higgs couplings and Yukawa Lines

Model type	Up quarks	Down quarks	Charged leptons
2HDM-I	Φ_1	Φ_1	Φ_1
2HDM-II	Φ_2	Φ_1	Φ_1
2HDM-X	Φ_2	Φ_2	Φ_1
2HDM-Y	Φ_2	Φ_1	Φ_2
2HDM-III	$\Phi_{1,2}$	$\Phi_{1,2}$	$\Phi_{1,2}$

TABLE I: Higgs interaction with fermions for the different 2HDM types.

- In **NHDM´s**, Higgs couplings as function of the masses, could lay on one or more lines.
- For **2HDM-I**: fermions masses come from one doublets, say (Φ_1), then Yukawa couplings will lay on a single line. But it will not coincide with the SM one.
- In **2HDM-II:** Φ_1 gives mass to U-quarks, Φ_2 gives masses to D-quarks and leptons. Thus, there will be two HYL,

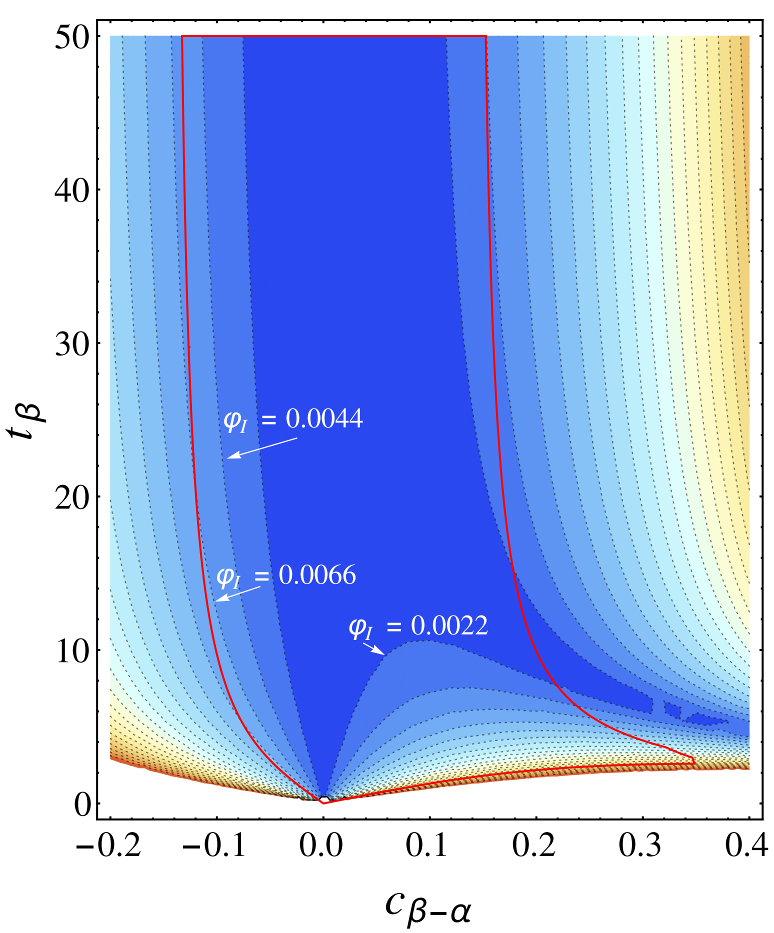


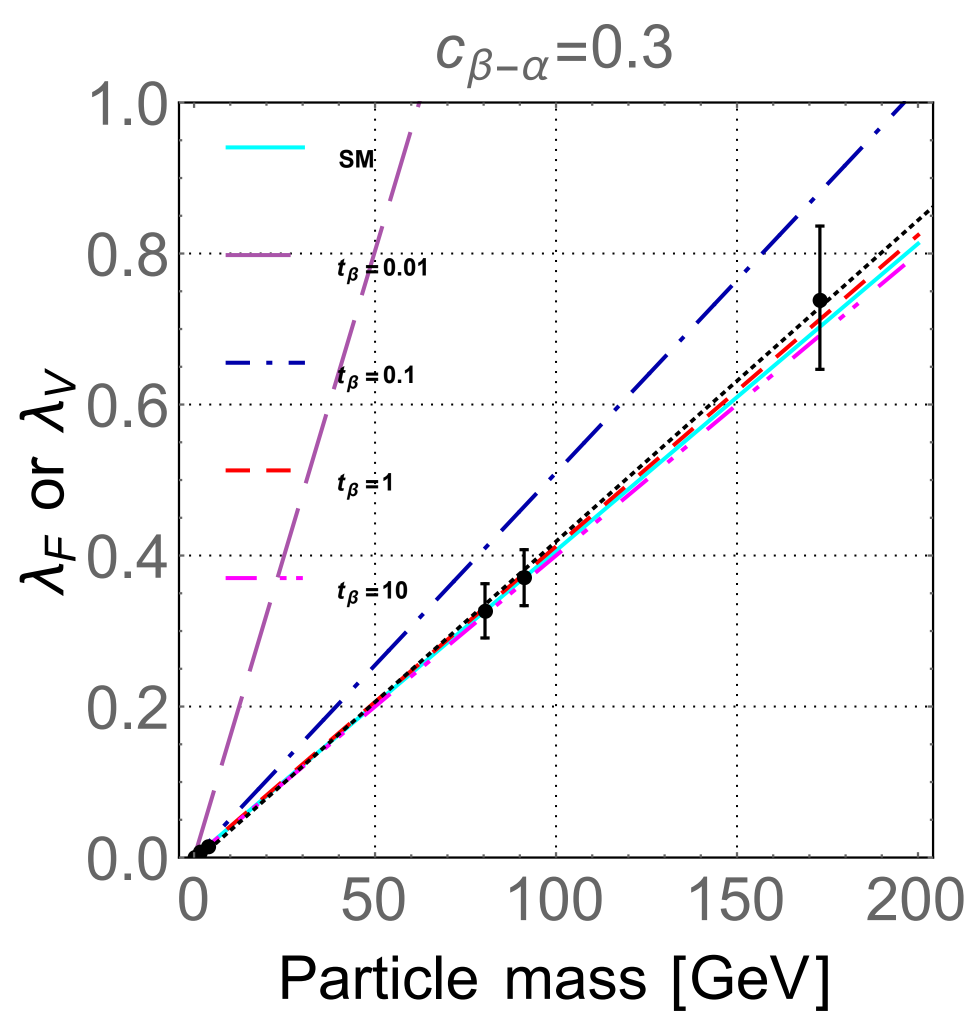
Hidden patterns in Higgs-Yukawa lines?

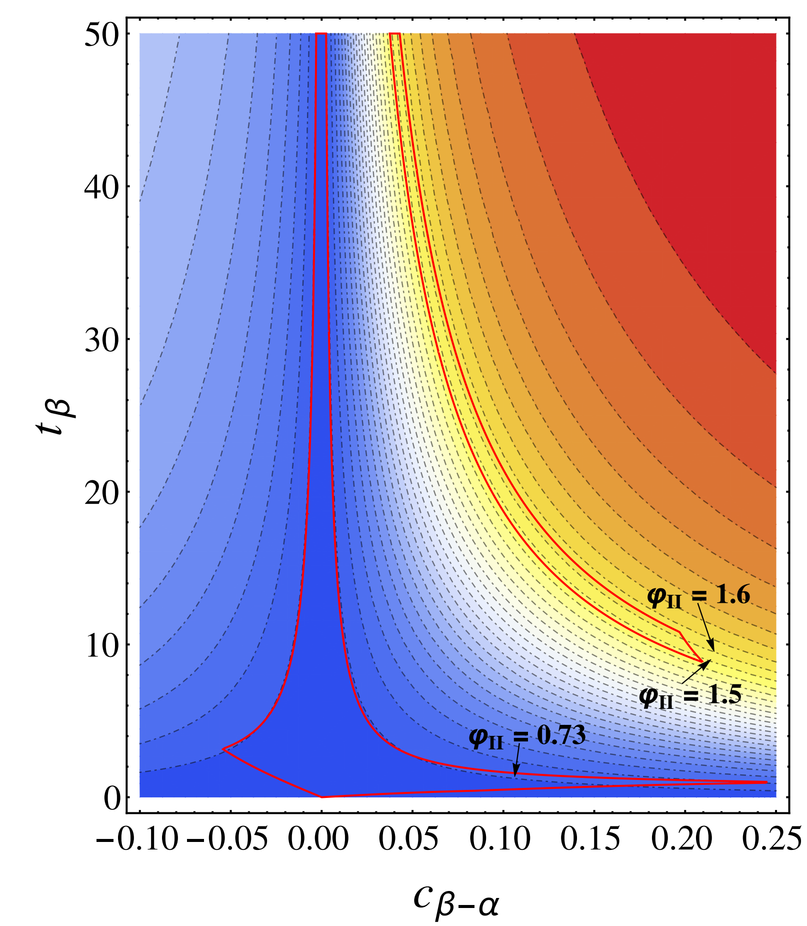
- Interesting to calculate the angle between Higgs Yukawa lines. In NHDM we find:

- Recent work with M.Arroyo, J.L. Diaz-Cruz (arXiv:2005.01153 [hep-ph])

$$\cos\psi_K = \frac{(\hat{m}_{fi} - \hat{m}_{fj})^2 + (y^K_{fi} - y^K_{fj})(y^{sm}_{fi} - y^{sm}_{fj}).}{[(\hat{m}_{fi} - \hat{m}_{fj})^2 + (y^K_{fi} - y^K_{fj})^2]^{1/2} * [(\hat{m}_{fi} - \hat{m}_{fj})^2 + (y^{sm}_{fi} - y^{sm}_{fj})^2]^{1/2}}$$





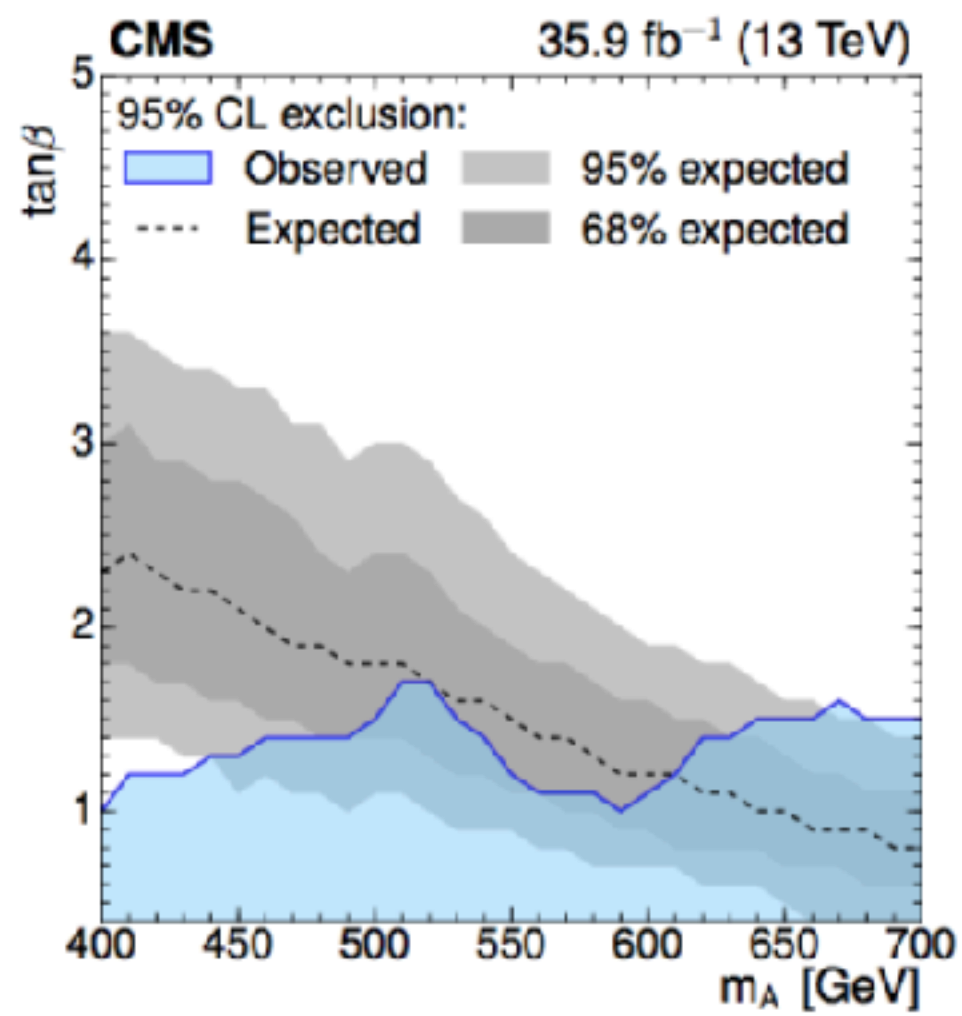


Search for heavy Higgs bosons decaying to a top quark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

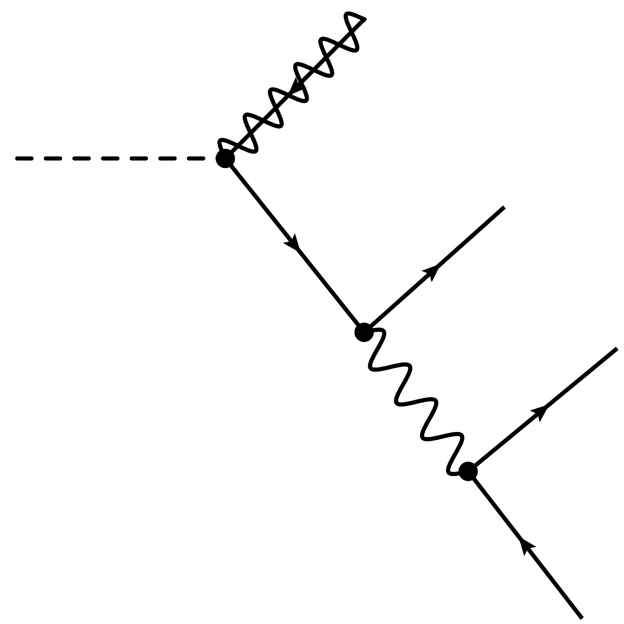
- CMS reported a moderate excess of events in tt production, for mA=400 GeV (1.9 sigmas):

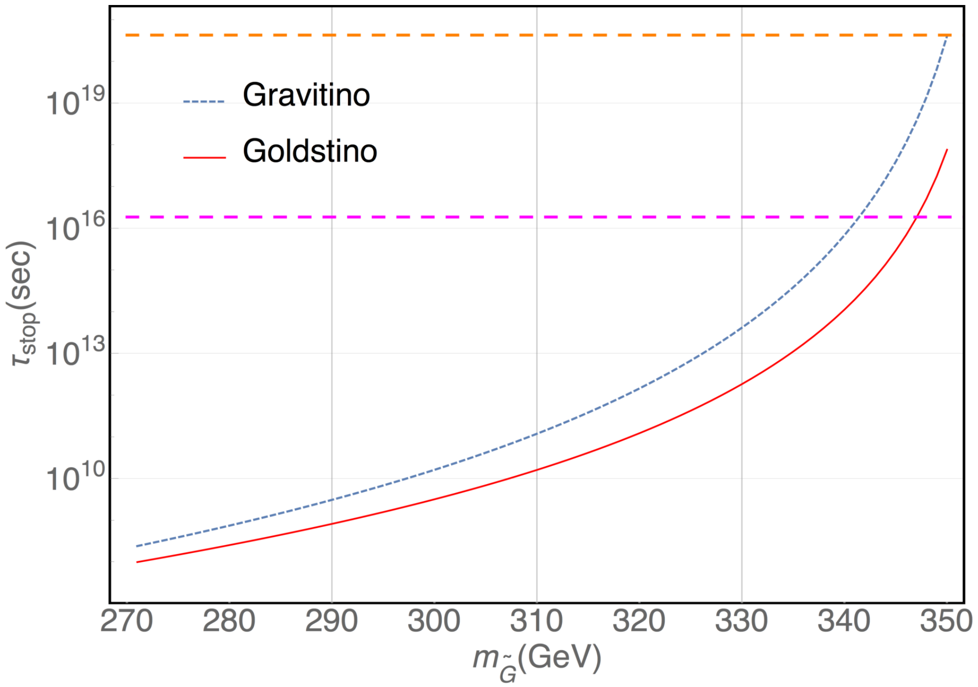


: 8. Exclusion in the $(m_A, \tan\beta)$ plane of the hMSSM. The inner (dark gray) band and light gray) band indicate the regions containing 68 and 95%, respectively, of the distribut straints expected under the background-only hypothesis. The observed excluded regior ed by the blue shaded area. Both H and A boson signals are included with masses that correspond to a given point in the plane.

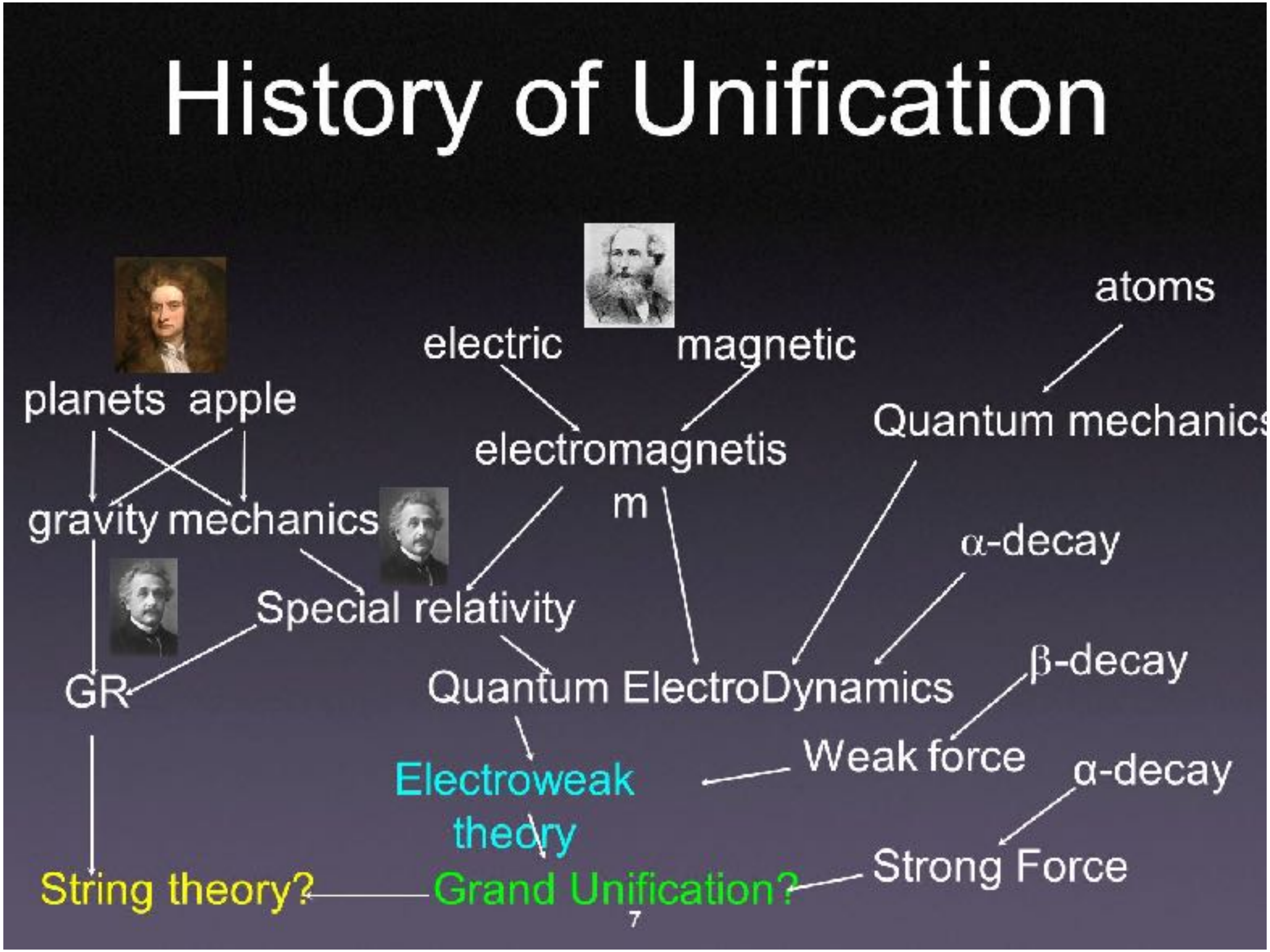
Search for signals from new SUSY scenarios - example: LLV stops

- LHC bounds on super partners in minimal SUSY are O(TeV),
- But most searches consider LSP=neutralino with R-Parity, it implies missing energy/transverse momentum signature,
- By considering LSP= EW gravitino, other types of signal : Long lived NLSP,
- Stop NLPS is very Long Lived (with B. Larios, ArXive:1901.06352)
- LHC detectors were not designed to search for such signals,





4.1) Lessons for Model building



A Model of Leptons

Steven Weinberg (MIT, LNS)
Nov, 1967

3 pages
Published in: *Phys.Rev.Lett.* 19 (1967) 1264-1266, Also in *Lichtenberg, D. B. (ed.), Rosen, S. P. (ed.): Developments In The Quark Theory Of Hadrons, Vol. 1*, 157-159, In *Lal, C. H. (ed.): Gauge Theory Of Weak and Electromagnetic Interactions*, 185-187, In *Rosner, J. L. (ed.): New Particles*, 26-28
DOI: 10.1103/PhysRevLett.19.1264
View in: OSTI Information Bridge Server, ADS Abstract Service

links cite

Citations per year

"Great scientists start new fields of science by making leaps in the dark. Nature decides which of the leaps is right and which is wrong."

–Freeman Dyson, IAS Professor

ias.edu/ideas

SU(3) x U(1) Gauge Theory of the Weak and Electromagnetic Interactions

Benjamin W. Lee (Fermilab), Steven Weinberg (Stanford U., ITP)
Mar 1, 1977

11 pages
Published in: *Phys.Rev.Lett.* 38 (1977) 1237
DOI: 10.1103/PhysRevLett.38.1237
Report number: FERMILAB-PUB-77-31-THY, FERMILAB-PUB-77-031-T
View in: OSTI Information Bridge Server, ADS Abstract Service

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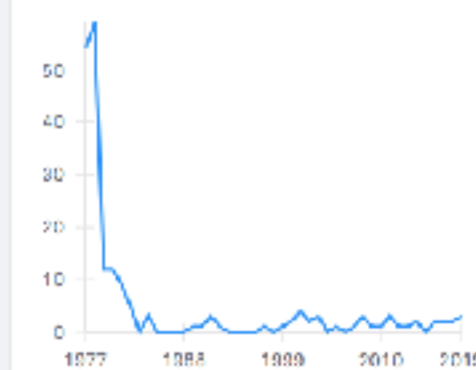
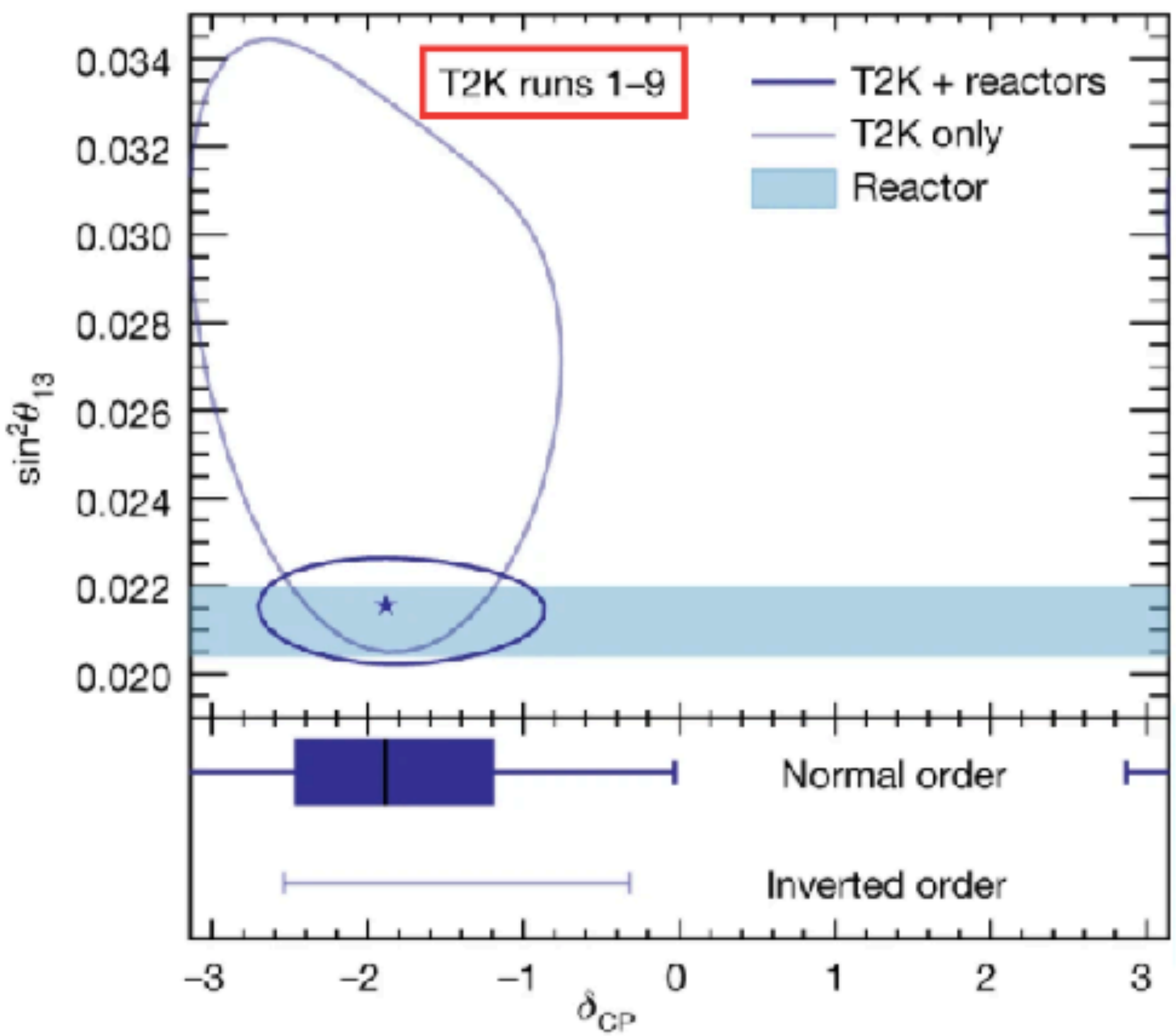


Abstract: (APS)
We describe an extension of the gauge theory of weak and electromagnetic interactions to SU(3) ⊗ U(1). The extended theory naturally insures universality, absence of right-handed currents in β and muon decay, flavor conservation in neutral currents, etc.; gives good quantitative agreement with observations of neutral currents; and accounts for recently observed trimuon events.

So, keep trying …

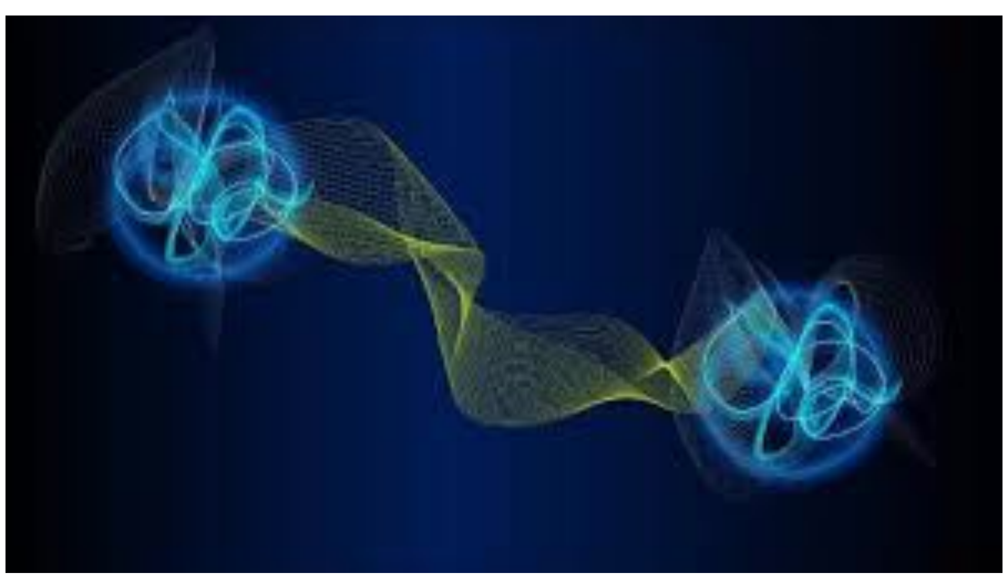
But we have already hints of BSM Physics

- Neutrino masses and mixing,
- Dark matter,
- BAU,
- Dark energy.



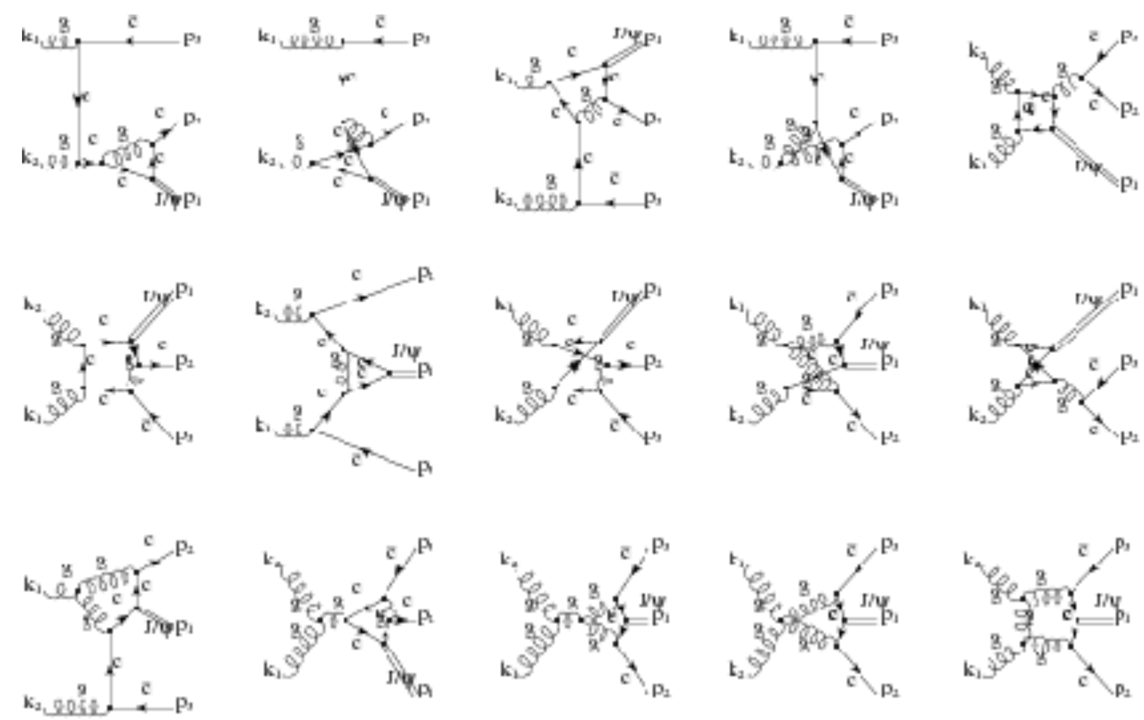
My hunch for BSM Physics: something in the interfase of Higgs, neutrinos & DM

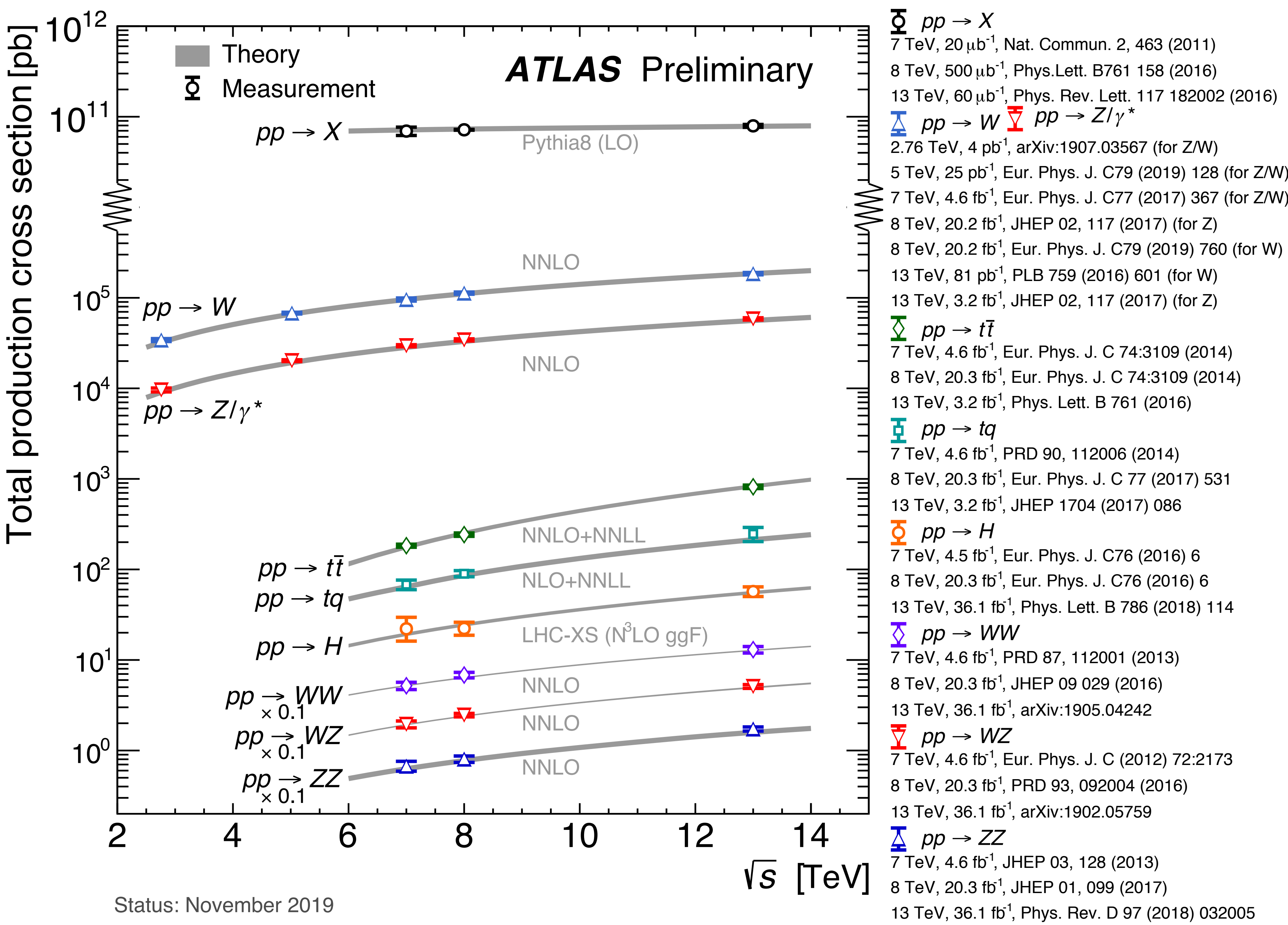
4.2 Theory - QFT at LHC



4.2a) QCD probes at LHC

- Do not forget that LHC test have relied on QFT (signal and backd.),
- In particular, heroic pert. QCD/SM calculations have been done for LHC,
- Lots of theory lessons have been obtained (more later)




ATLAS Preliminary
Theory
Measurement
Total production cross section [pb]
√s [TeV]
pp → X
Pythia8 (LO)
pp → W
NNLO
pp → Z/γ*
NNLO
pp → tt̄
NNLO+NNLL
pp → tq
NLO+NNLL
pp → H
LHC-XS (N3LO ggF)
pp → WW × 0.1
NNLO
pp → WZ × 0.1
NNLO
pp → ZZ × 0.1
NNLO
Status: November 2019
pp → X
7 TeV, 20 μb-1, Nat. Commun. 2, 463 (2011)
8 TeV, 500 μb-1, Phys.Lett. B761 158 (2016)
13 TeV, 60 μb-1, Phys. Rev. Lett. 117 182002 (2016)
pp → W pp → Z/γ*
2.76 TeV, 4 pb-1, arXiv:1907.03567 (for Z/W)
5 TeV, 25 pb-1, Eur. Phys. J. C79 (2019) 128 (for Z/W)
7 TeV, 4.6 fb-1, Eur. Phys. J. C77 (2017) 367 (for Z/W)
8 TeV, 20.2 fb-1, JHEP 02, 117 (2017) (for Z)
8 TeV, 20.2 fb-1, Eur. Phys. J. C79 (2019) 760 (for W)
13 TeV, 81 pb-1, PLB 759 (2016) 601 (for W)
13 TeV, 3.2 fb-1, JHEP 02, 117 (2017) (for Z)
pp → tt̄
7 TeV, 4.6 fb-1, Eur. Phys. J. C 74:3109 (2014)
8 TeV, 20.3 fb-1, Eur. Phys. J. C 74:3109 (2014)
13 TeV, 3.2 fb-1, Phys. Lett. B 761 (2016)
pp → tq
7 TeV, 4.6 fb-1, PRD 90, 112006 (2014)
8 TeV, 20.3 fb-1, Eur. Phys. J. C 77 (2017) 531
13 TeV, 3.2 fb-1, JHEP 1704 (2017) 086
pp → H
7 TeV, 4.5 fb-1, Eur. Phys. J. C76 (2016) 6
8 TeV, 20.3 fb-1, Eur. Phys. J. C76 (2016) 6
13 TeV, 36.1 fb-1, Phys. Lett. B 786 (2018) 114
pp → WW
7 TeV, 4.6 fb-1, PRD 87, 112001 (2013)
8 TeV, 20.3 fb-1, JHEP 09 029 (2016)
13 TeV, 36.1 fb-1, arXiv:1905.04242
pp → WZ
7 TeV, 4.6 fb-1, Eur. Phys. J. C (2012) 72:2173
8 TeV, 20.3 fb-1, PRD 93, 092004 (2016)
13 TeV, 36.1 fb-1, arXiv:1902.05759
pp → ZZ
7 TeV, 4.6 fb-1, JHEP 03, 128 (2013)
8 TeV, 20.3 fb-1, JHEP 01, 099 (2017)
13 TeV, 36.1 fb-1, Phys. Rev. D 97 (2018) 032005

4.3) Formal developments: Amplitudes, KLT, Double copy, BH, Constructible QFT´s

$$
\begin{aligned}
g+g &\rightarrow g+g && 4 \text{ diagrams} \\
g+g &\rightarrow g+g+g && 25 \text{ diagrams} \\
g+g &\rightarrow g+g+g+g && 220 \text{ diagrams}
\end{aligned}
\tag{1.3}
$$

The result for the 4-gluon amplitude is an example of the famous ***Parke-Taylor n-gluon tree amplitude***: for the case where gluons i and j have helicity -1 and all the $n-2$ other gluons have helicity $+1$, the tree amplitude is

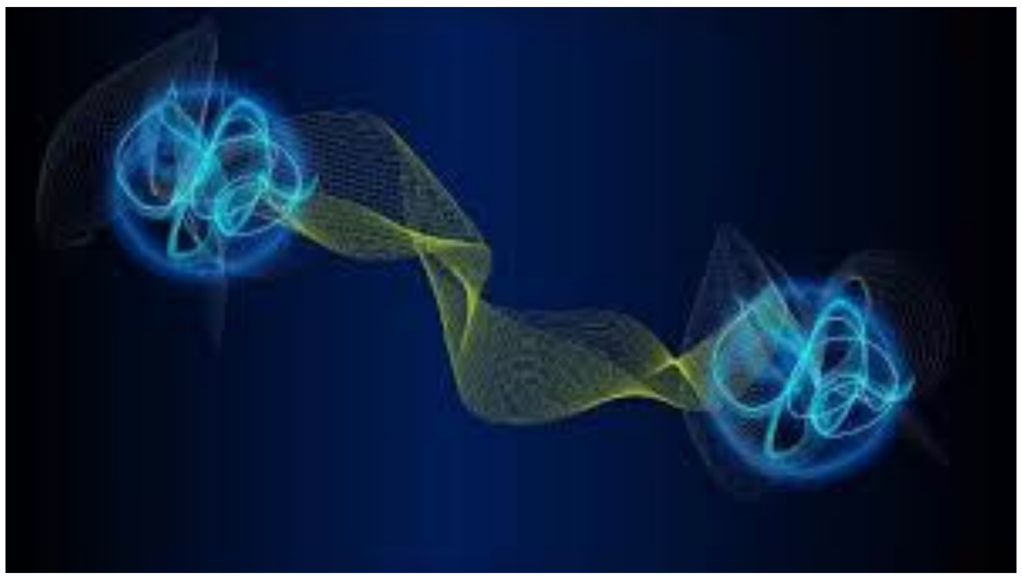
$$
A_n[1^+ \dots i^- \dots j^- \dots n^+] = \frac{\langle ij \rangle^4}{\langle 12 \rangle \langle 23 \rangle \cdots \langle n1 \rangle} \,. \tag{2.80}
$$

We prove this formula in Section 3. The number of Feynman diagrams that generically contribute to an n-gluon tree amplitude is[9]

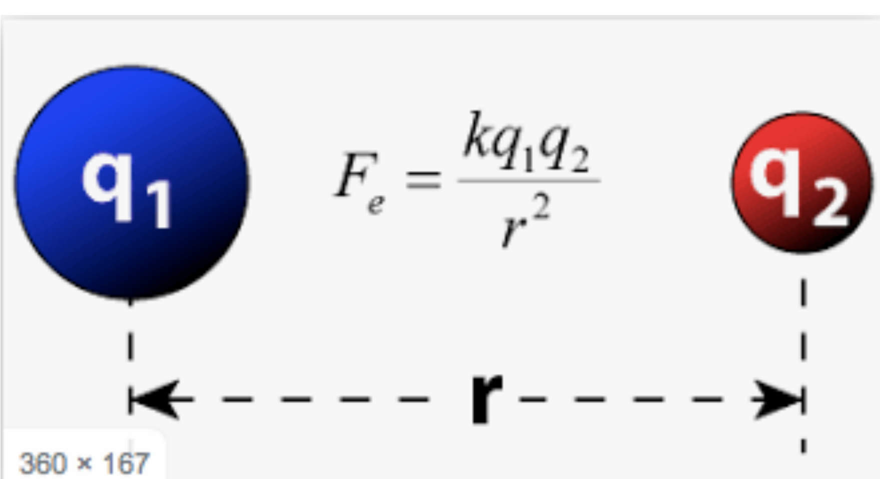
$n =$	3	4	5	6	7	...
#diagrams =	1	3	10	38	154	...

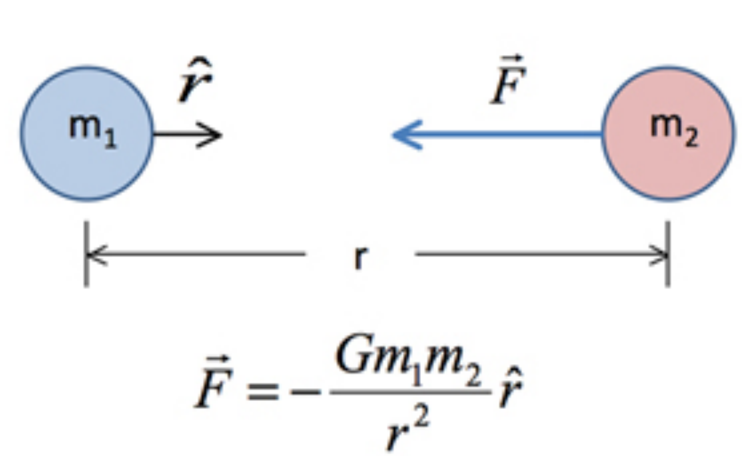
- Graviton scattering: KLT Relations -> GR= YM x YM

$$
\begin{aligned}
M_4^{\text{tree}}(1234) &= -\, s_{12}\, A_4^{\text{tree}}[1234]\, A_4^{\text{tree}}[1243]\,, \\
M_5^{\text{tree}}(12345) &= s_{23}s_{45}\, A_5^{\text{tree}}[12345]\, A_5^{\text{tree}}[13254] + (3 \leftrightarrow 4)\,, \\
M_6^{\text{tree}}(123456) &= -\, s_{12}s_{45}A_6^{\text{tree}}[123456]\Big(s_{35}A_6^{\text{tree}}[153462] + (s_{34}+s_{35})A_6^{\text{tree}}[154362]\Big) \\
&\quad + \mathcal{P}(2,3,4)\,.
\end{aligned}
$$

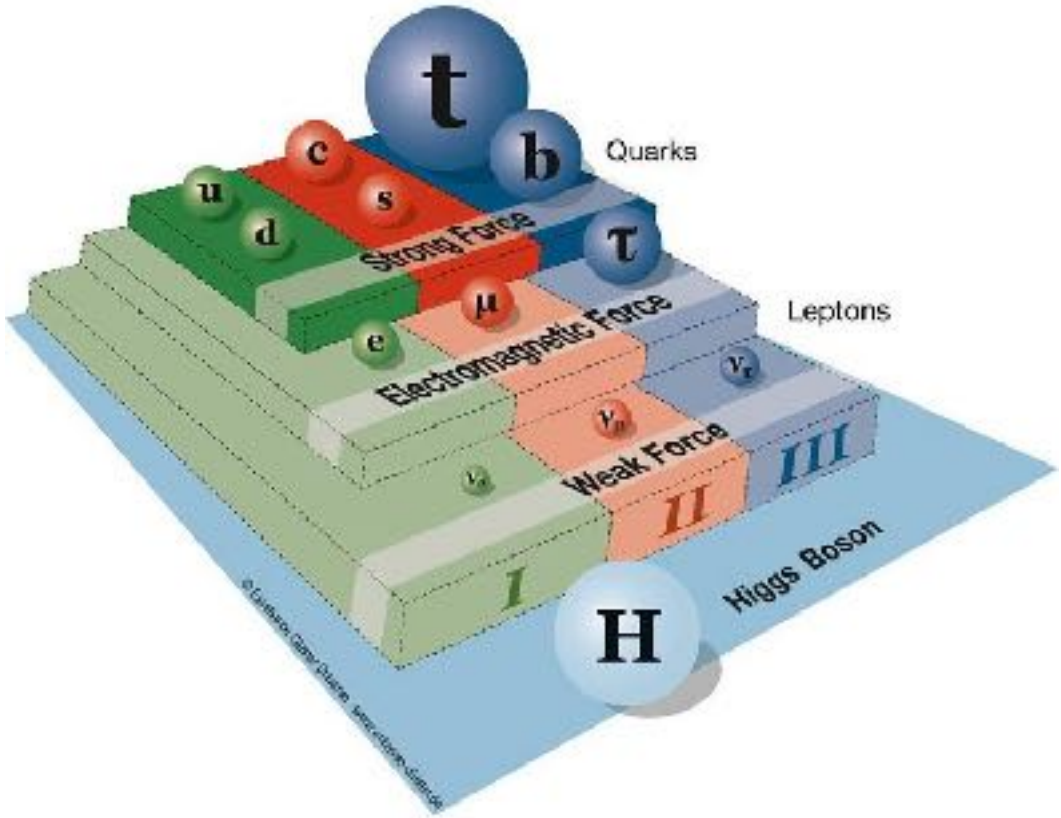


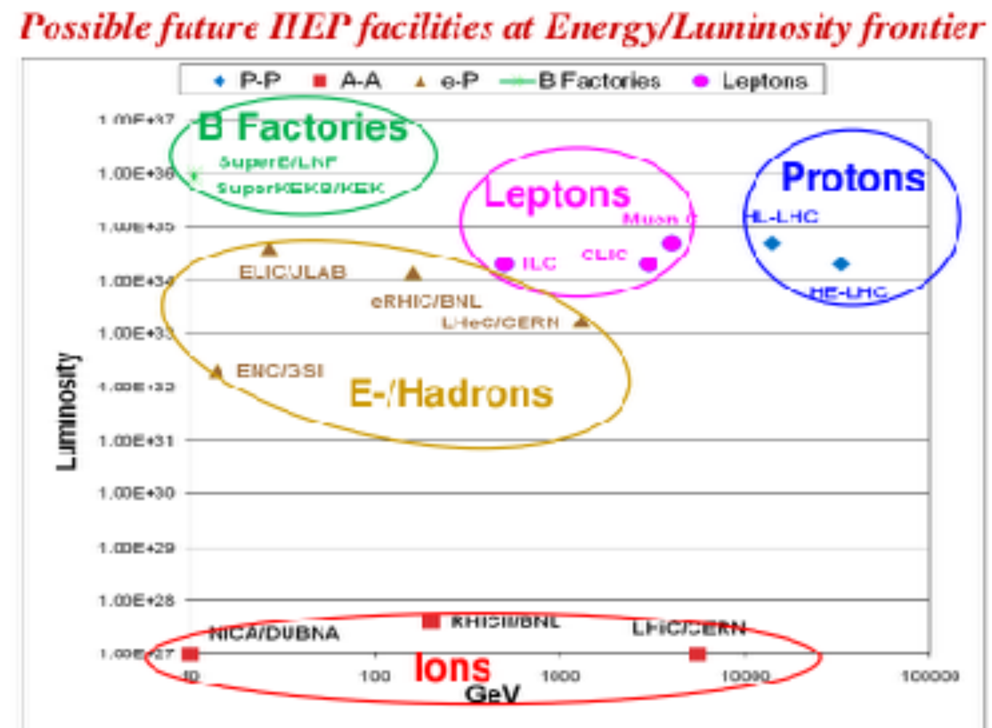
$$
M_4^{\text{tree}}(1^-2^-3^+4^+) = \frac{\langle 12\rangle^7[12]}{\langle 13\rangle\langle 14\rangle\langle 23\rangle\langle 24\rangle\langle 34\rangle^2} = \frac{\langle 12\rangle^4[34]^4}{stu}\,.
$$

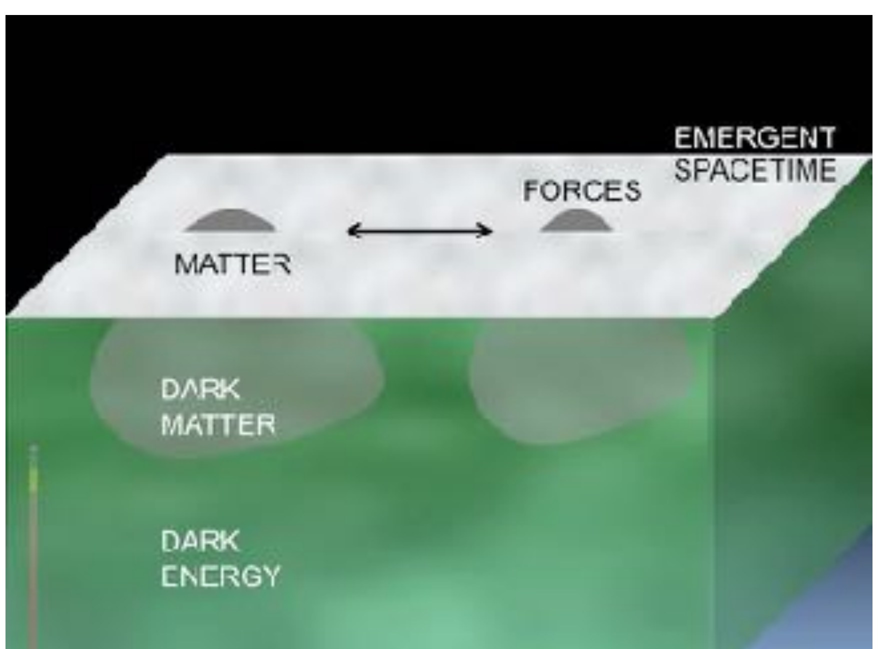




4) Conclusions







Gracias!

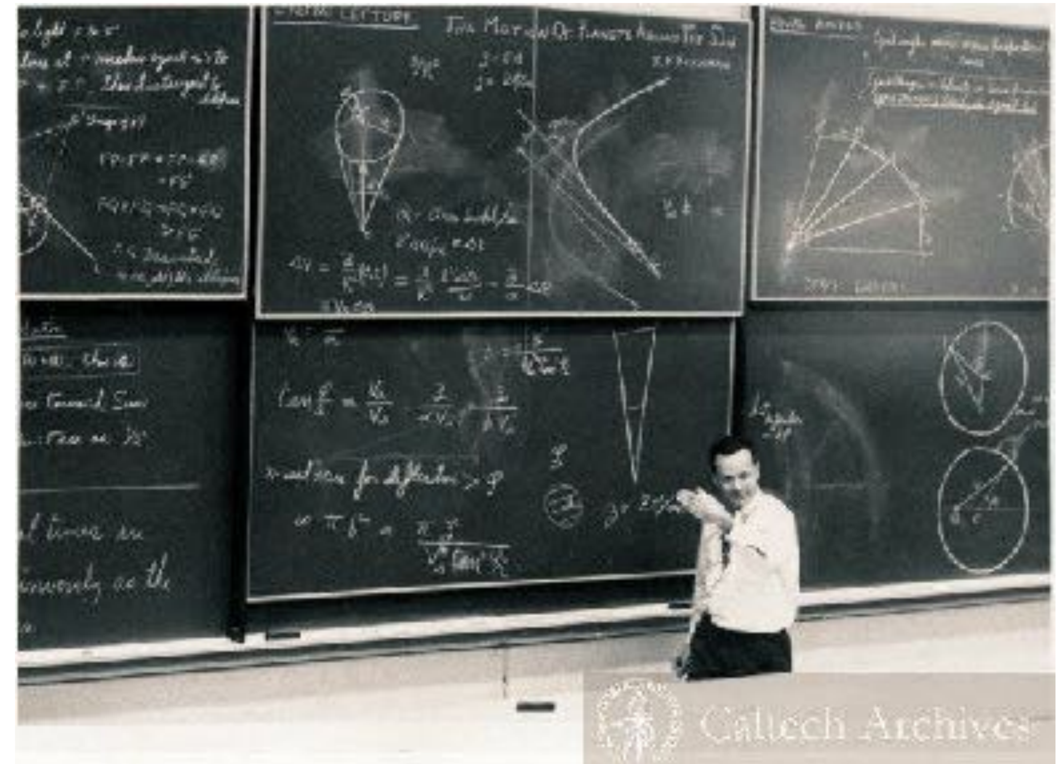
Conceptos sí, ecuaciones no (Física introductoria)

- La física es apasionante, hermosa, importante, trascendente,

- Pero poco de eso se ve en los cursos de secundaria y prepa,

- Parte de los problemas de los estudiantes para aprender Física, es que deben aprender física y matemáticas al mismo tiempo,

- ¿Es posible estudiar los conceptos de Física con un mínimo de matemáticas?



¿Como enseñar ciencias en la educación básica de una manera efectiva, moderna, atractiva?

- Efectiva: Que logre transmitir un conocimiento que forme, informe y sirva para la vida diaria,
- Moderna: Que incluya nuevos resultados científicos, tendencias recientes en enseñanza,
- Atractiva: Que anime la curiosidad de los niños y jóvenes, desarrolle su aprecio por la ciencia, incluya nuevas tecnologías (redes, videos, animaciones),
- ¿Porqué nosotros? (Profesores-Investigadores) La educación de un país es tan importante que los diferentes sectores del sistema educativo debemos participar y proponer mejoras.