# Theoretical Perspectives on HEP


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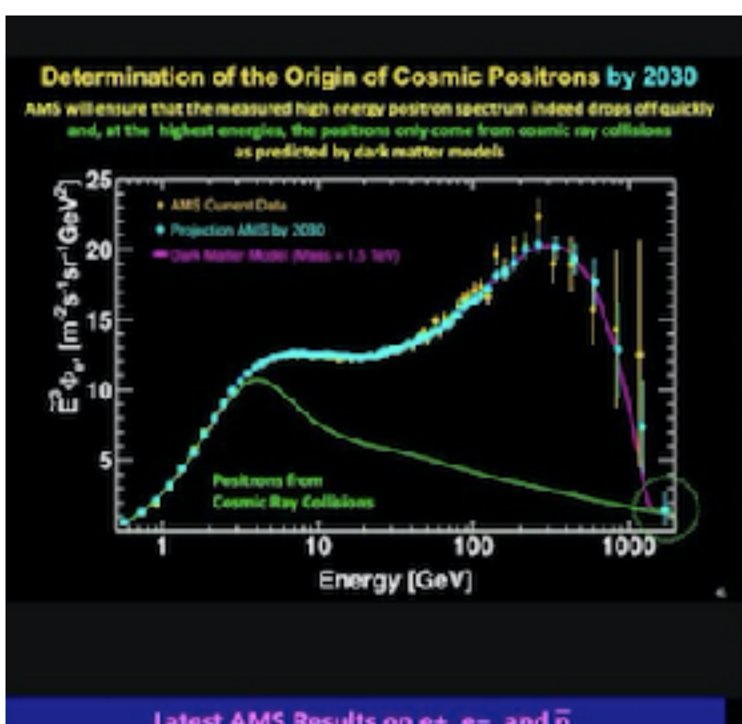
CINVESTAV-IPN

# Fundamental Physics Frontiers

- Precision Frontier: Measure particle properties with sensitive tools or high statistics,
- Energy Frontier: Explore sub-atomic world with accelerators (LHC, currently),
- Cosmic Frontier: Explore the cosmos to test fundamental physics laws,

  * Has DM with m=1.5 TeV, been detected?

- Computational Frontier? (Snowmass, IA, Quantum Comp.); Conceptual Frontier?




# Content:

- Introduction-

-Frontiers: Precision, Energy, Cosmic,

- Energy Frontier: Lessons from the LHC,

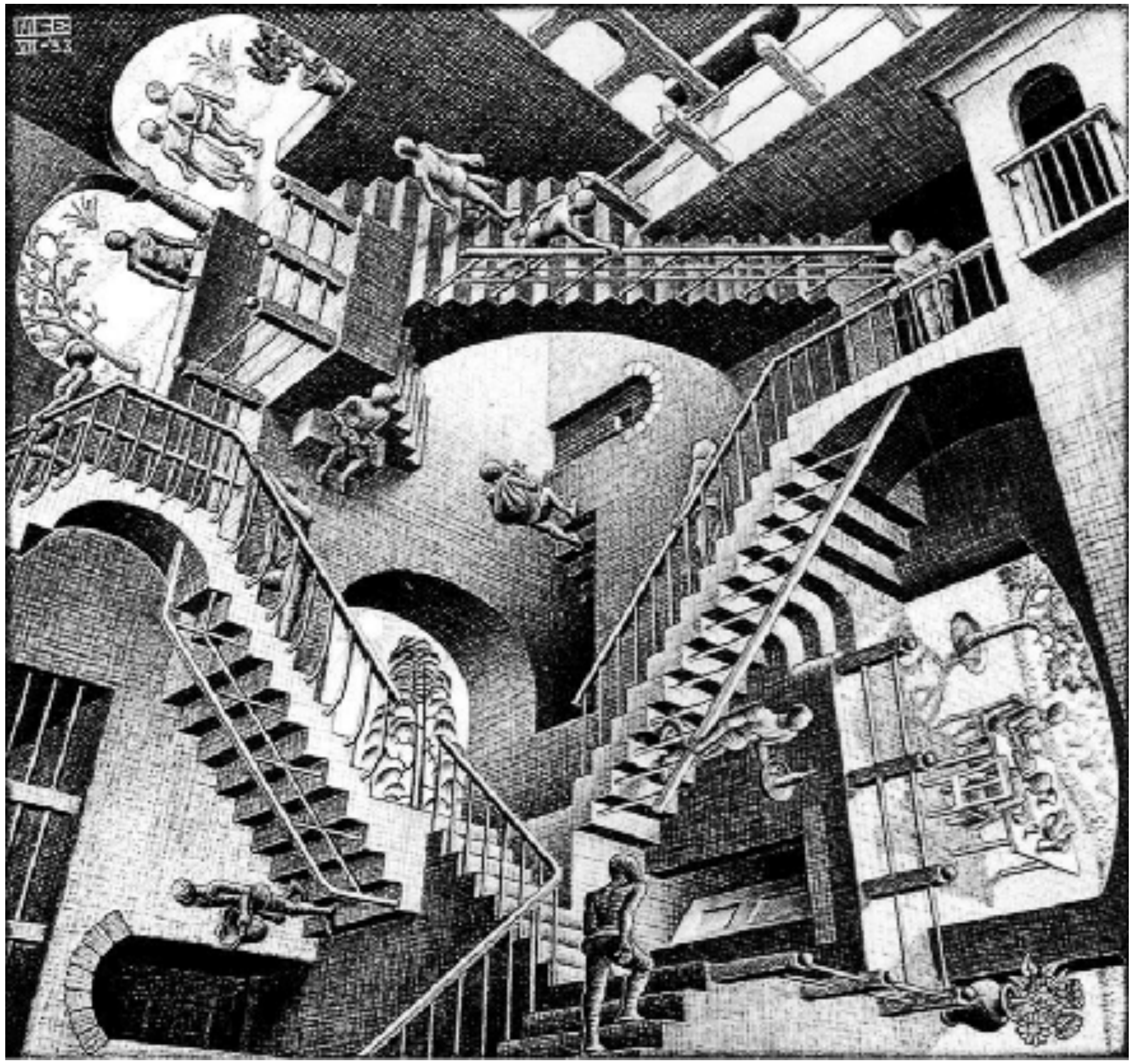
- Higgs: Yes,   BSM physics: No

- From LHC to QCD Amplitudes & Gravity

- Higgs as Master of the Universe?

- Hierachy problem & SMEFT,

- Conclusions.



# 1) Precision Frontier - Muon AMM

- Since early days of QED, AMM have been a great precision test,
- There seems to be a discrepancy between the SM prediction and experimental value for muon AMM (FNAL) (See P. Roig, RMF),
- At loop-levels there are hadronic contributions hard to calculate,
- Lattice calculations claim that SM is consistent with muon AMM,

$$a_\mu^{\text{Exp}} \times 10^{11} = 116592061(41)\,. \qquad (3)$$

This experimental average is $4.2\sigma$ away from the Standard Model (SM) prediction of $a_\mu$, as published in the White Paper (WP) [13][ii]

$$a_\mu^{\text{SM}} \times 10^{11} = 116591810(43)\,. \qquad (4)$$

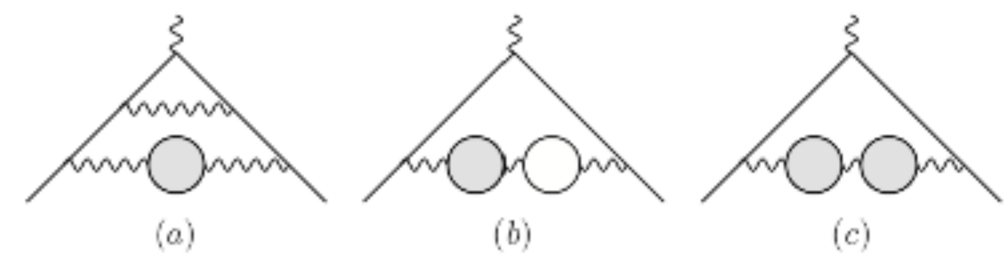


Figure 33: Higher order insertions of HVP at NLO. The gray blobs refer to HVP, the white one in diagram $(b)$ to leptonic VP.

| | FJ17 | HLMNT11 | KLMS14 | KNT19 |
|---|---|---|---|---|
| $a_\mu^{\text{HVP, NLO}} \times 10^{10}$ | −9.93(7) | −9.84(7) | −9.87(9) | −9.83(4) |

- However, there seems to be some controversy with the lattice result for the value of R,

**Consistency of hadronic vacuum polarization between lattice QCD and the R-ratio**

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(Dated: March 10, 2020)

There are emerging tensions for theory results of the hadronic vacuum polarization contribution to the muon anomalous magnetic moment both within recent lattice QCD calculations and between some lattice QCD calculations and R-ratio results. In this paper we work towards scruti-

- QCD is asymptotically free, i.e. it becomes weak in the UV, but non-pert. in the IR,

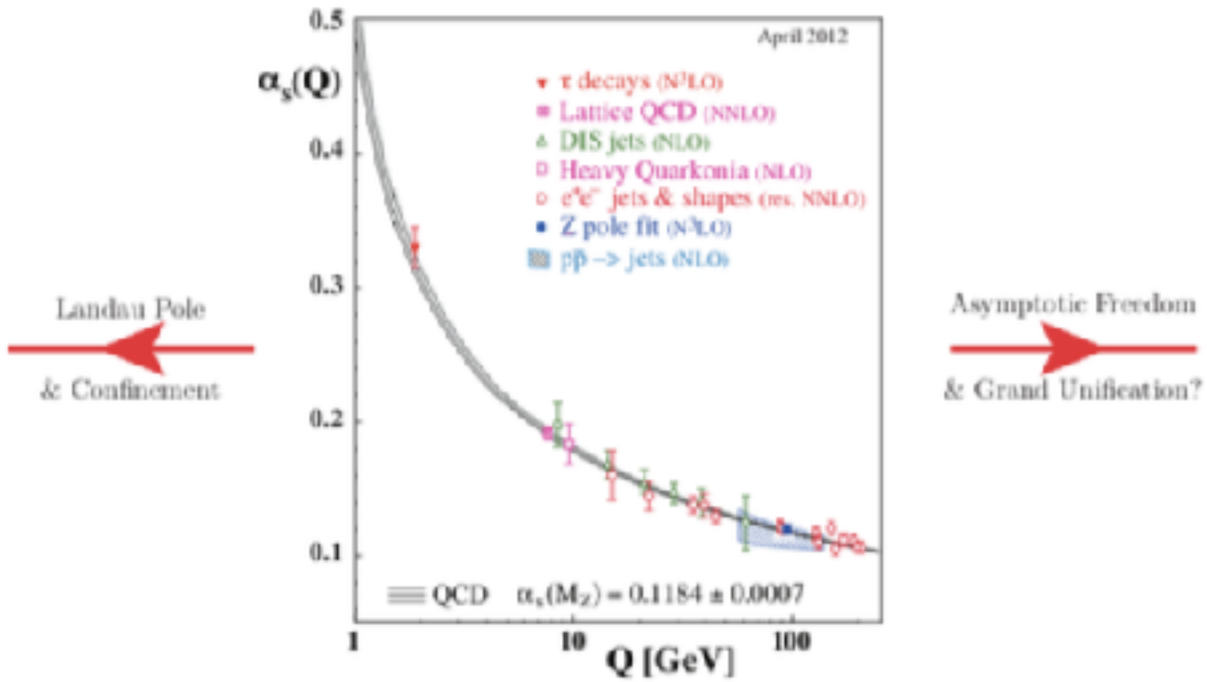
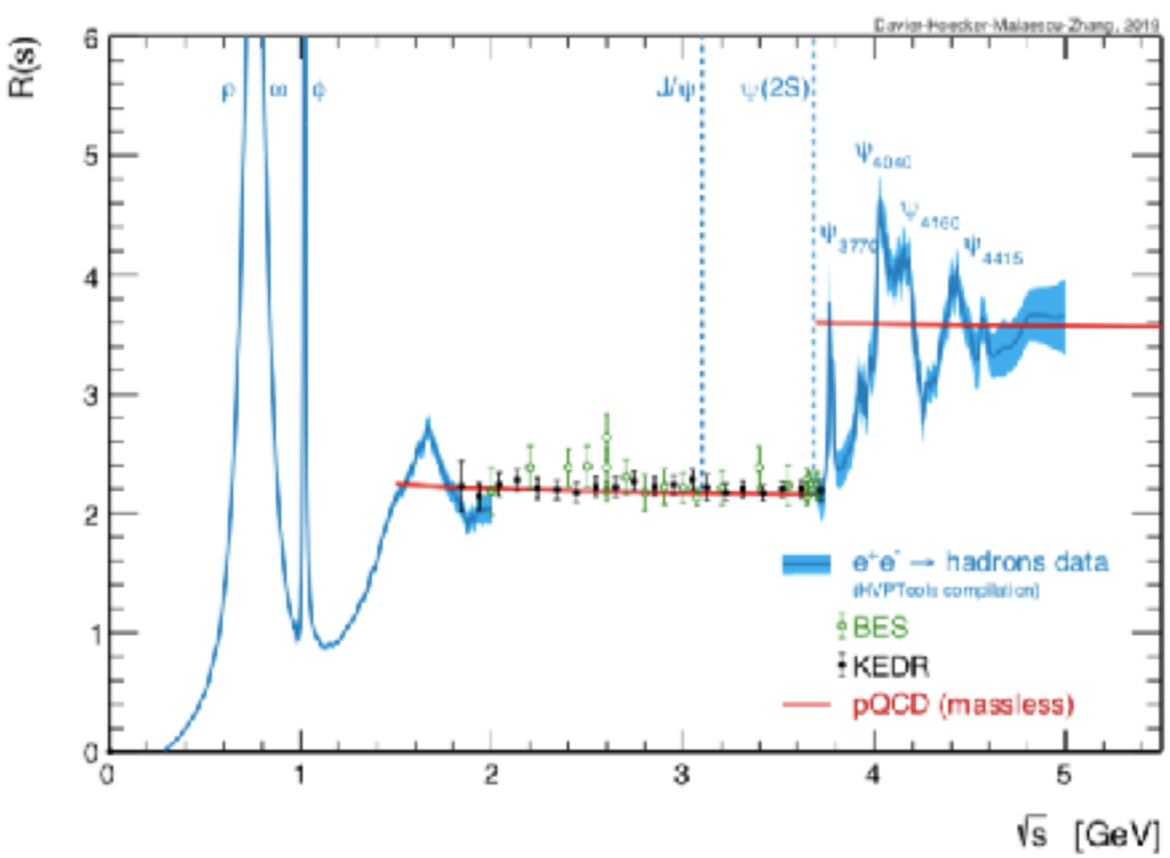



Figure 1.11: QCD running coupling at different energy scales, taken from [17, 18].



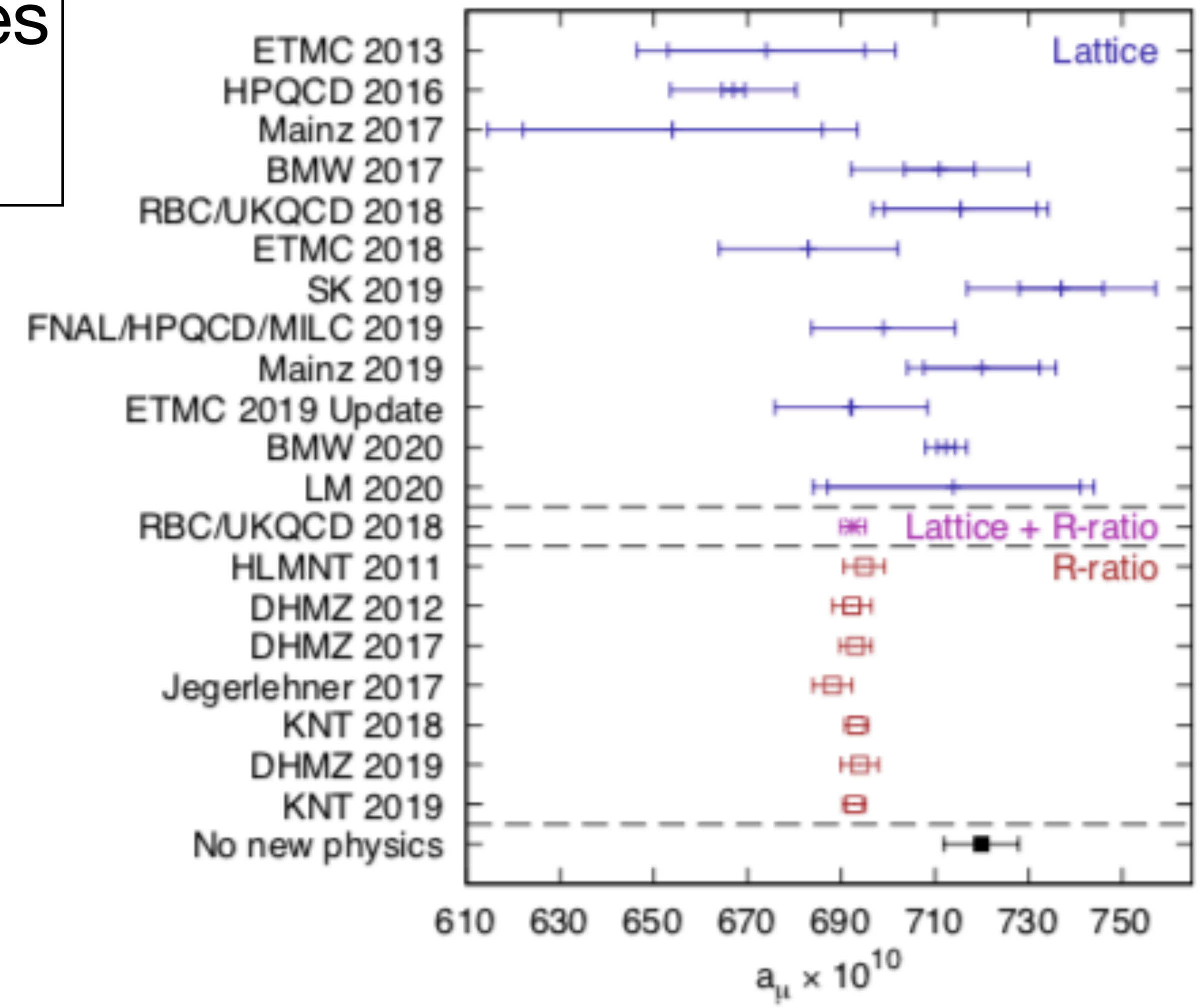
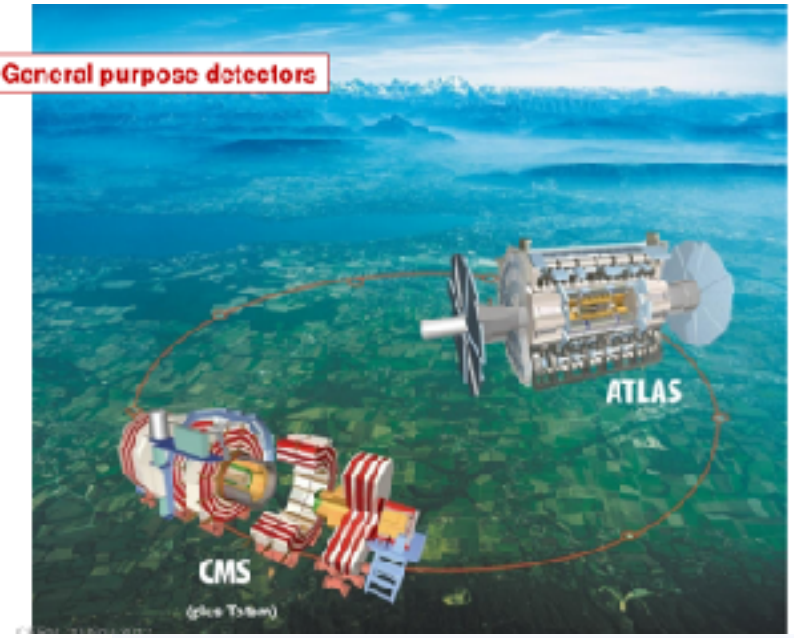
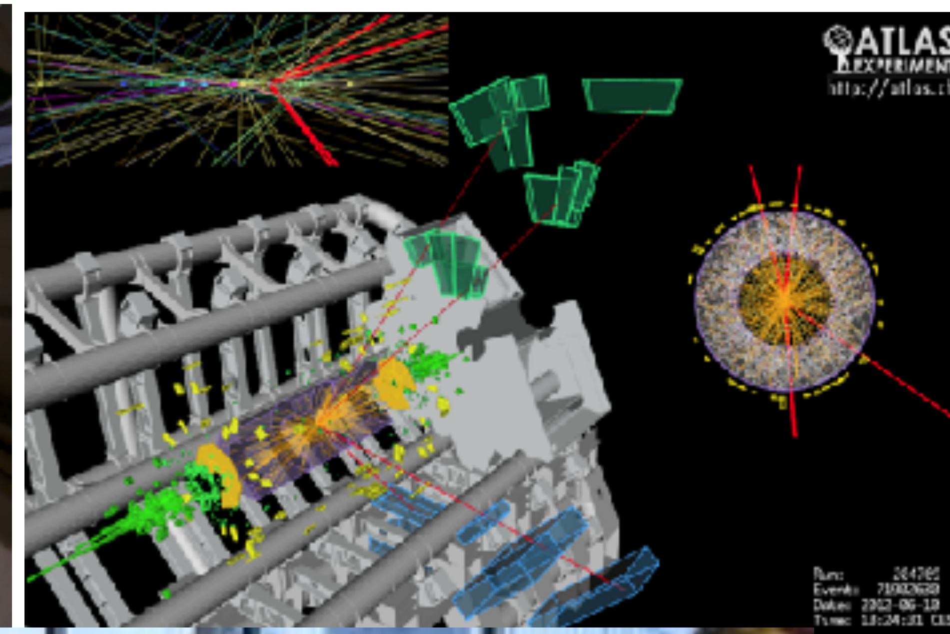



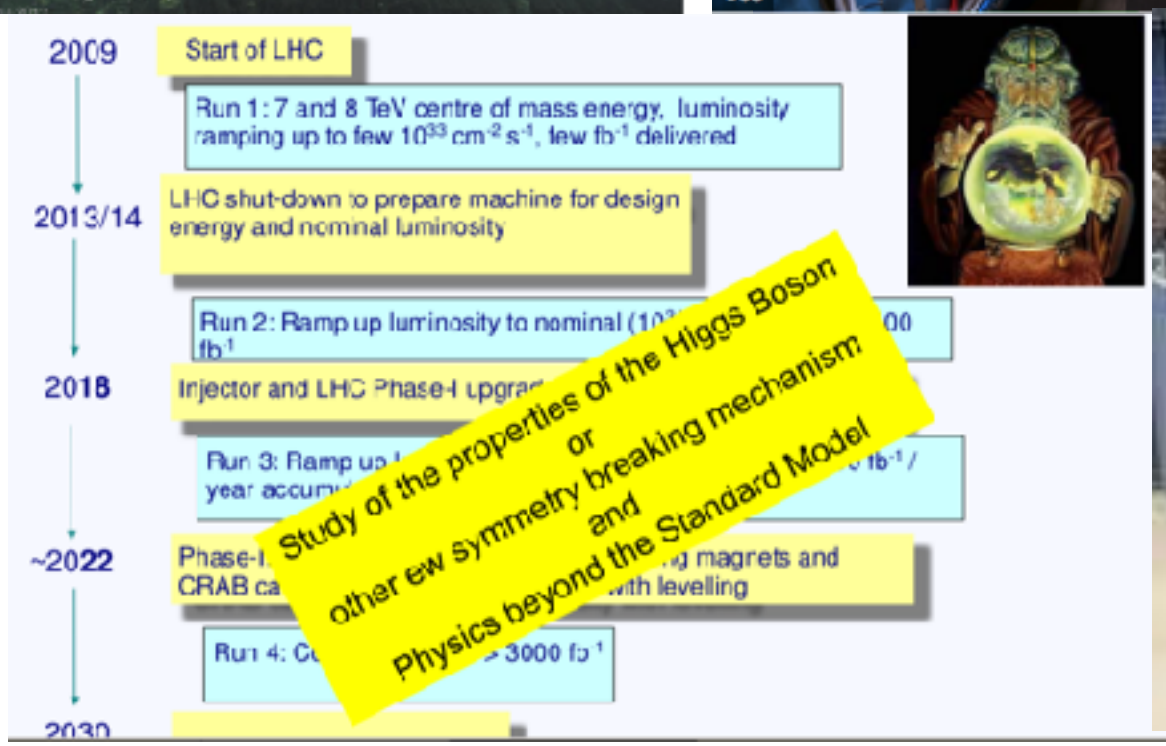

FIG. 14. Overview of total results for $a_\mu^{\rm HVP}$. The referenced contributions are: ETMC 2013 [11], HPQCD 2016 [14], Mainz 2017 [19], BMW 2017 [20], RBC/UKQCD 2018 [21], ETMC 2018 [22], SK 2019 [25], FNAL/HPQCD/MILC 2019 [24], Mainz 2019 [26], ETMC 2019 Update [30], BMW 2020 [27], HLMNT 2011 [6], DHMZ 2012 [7], DHMZ 2017 [8], Jegerlehner 2017 [9], KNT 2018 [10], DHMZ 2019 [1], and KNT 2019 [2]. The result of this work is labelled "LM 2020".

- Thus, more work needed to settle this issue, …, as far as I understand,

# 2. Energy Frontier: LHC is one fo the most successful experiments ever!

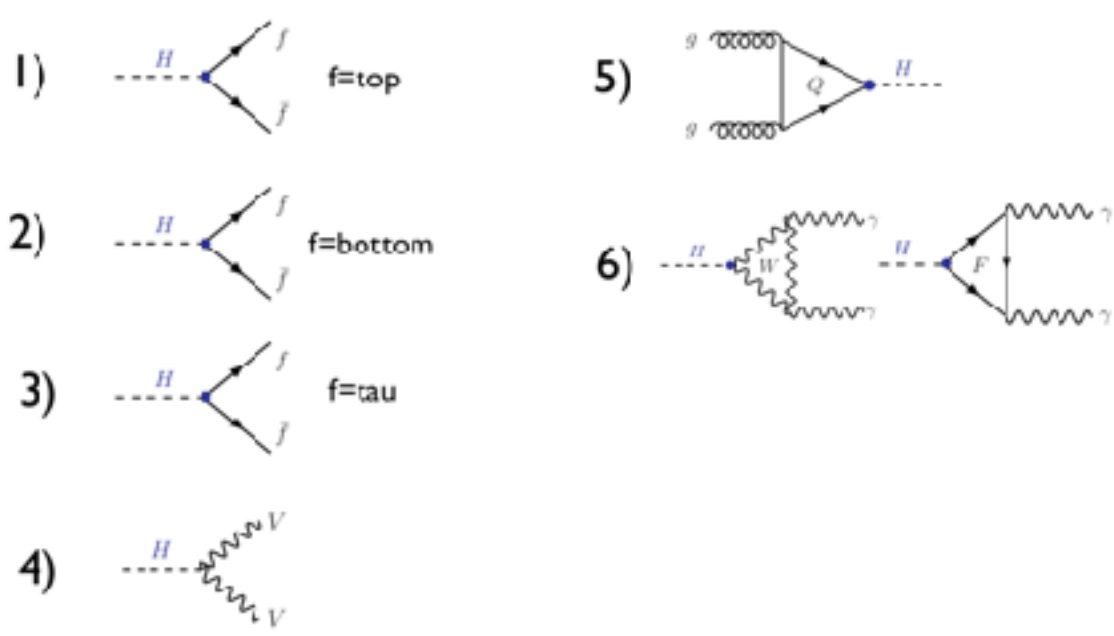


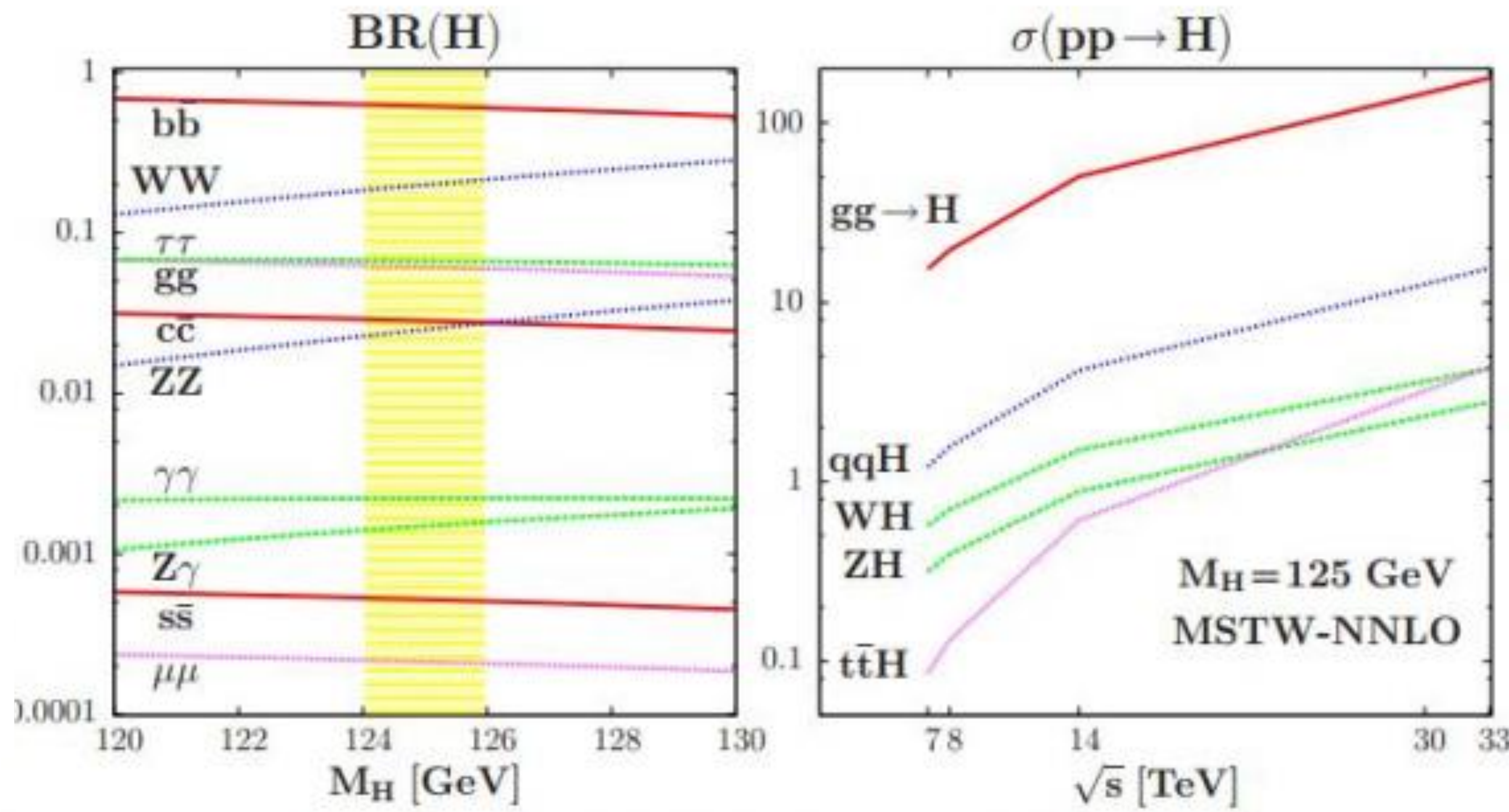



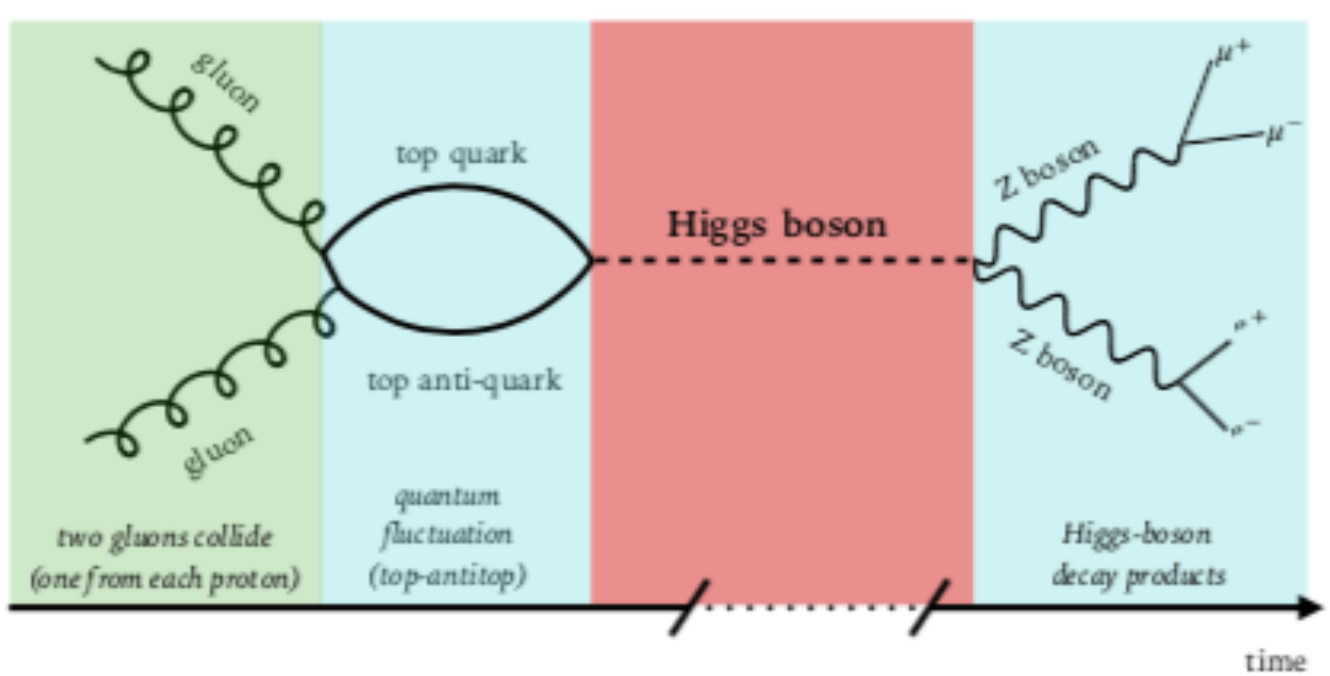



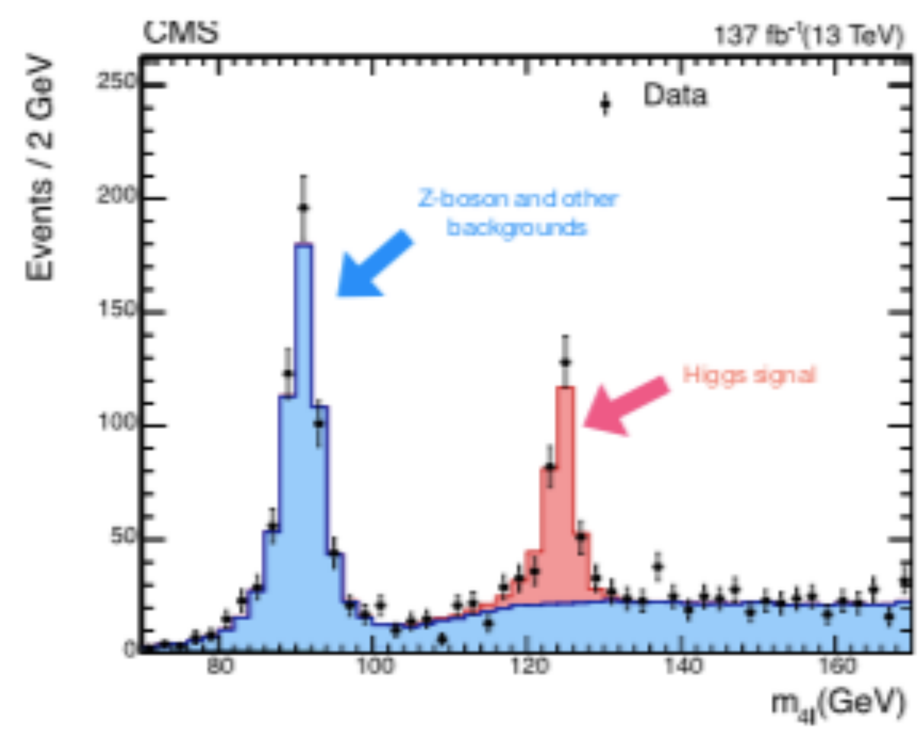

- One of the main goals of LHC was to detect and study the Higgs boson!

# SM Higgs boson decays and Csx



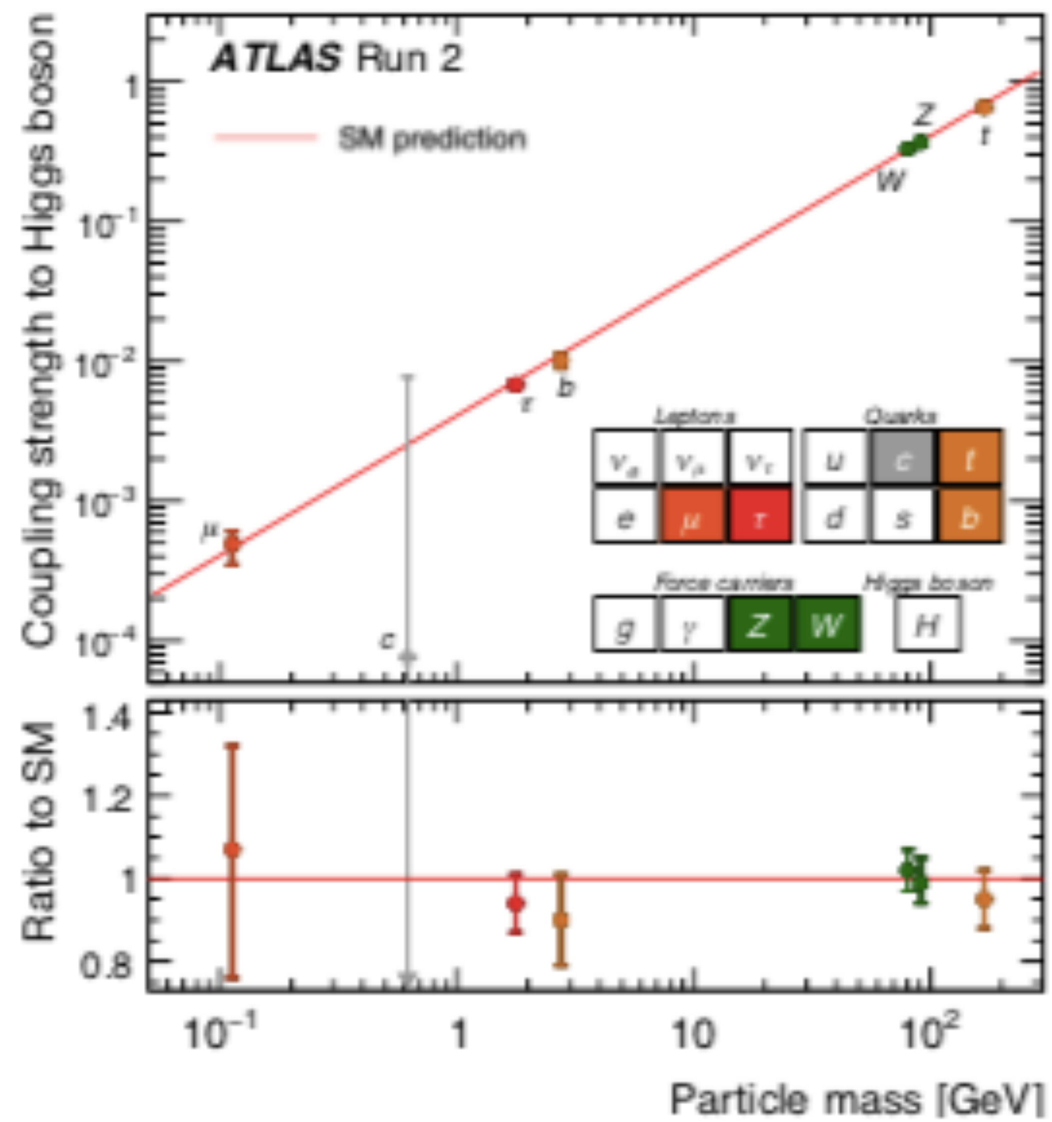



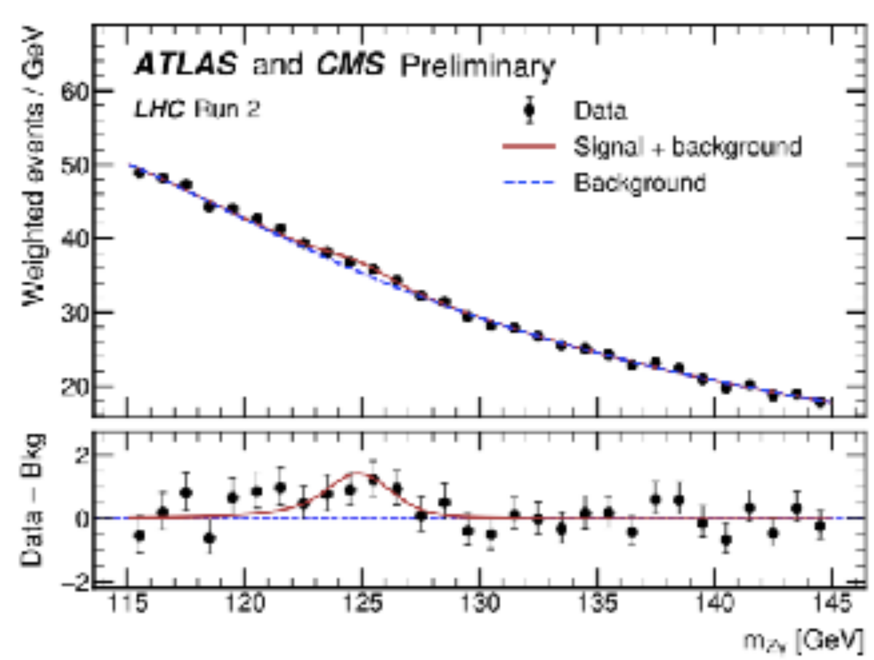



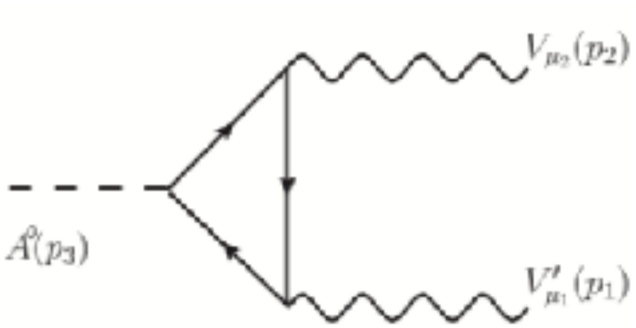



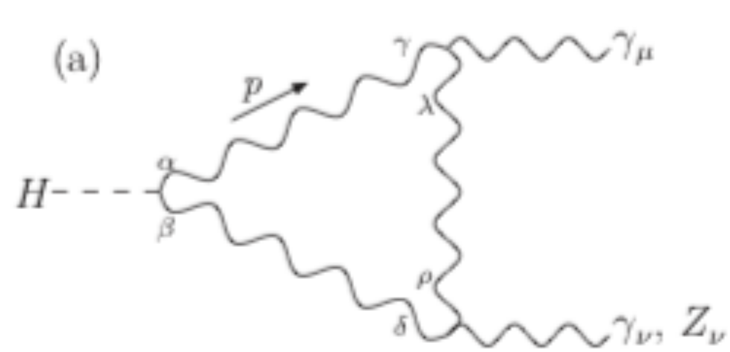
# 2.2) Lessons from LHC for Higgs signals

- The Higgs boson discovery is one of its greatest achievement,
- Many modes have been measured
- Higgs profile is consistent with the SM, so far ..
- Recently, the decay h->ZA (one-loop mode) has been detected,
- Within SM: BR(h->ZA) = 10^(-3)





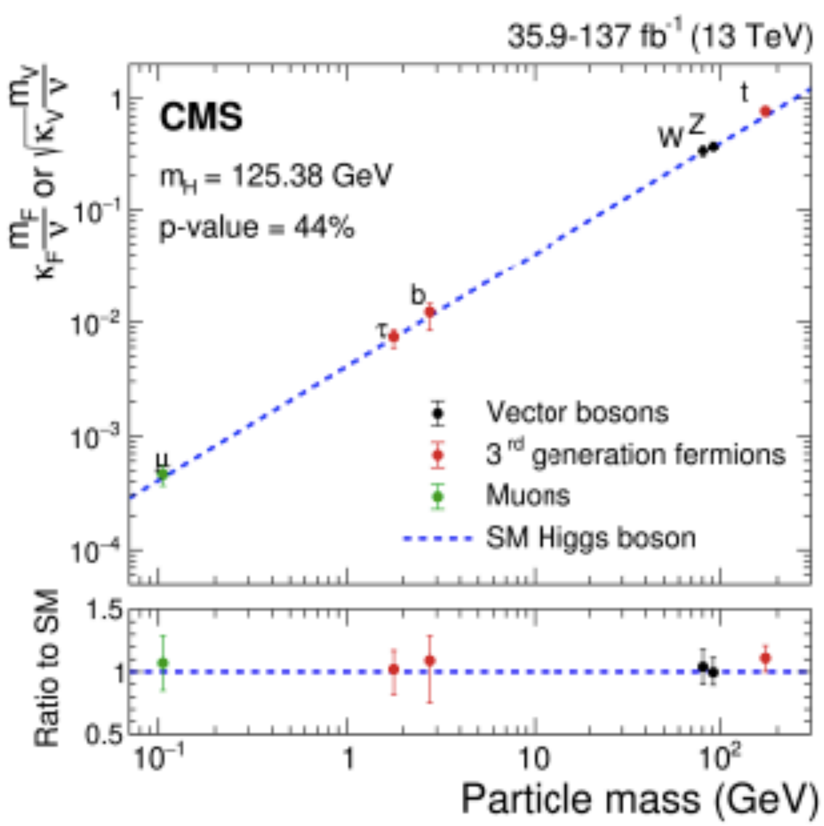
# All Higgs Couplings at LHC (FC case)

## Kappa Parametrization:

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

$$\mathcal{L}_F = \kappa_f \, y^{sm}_{hff} \, \bar{f} f h \qquad \kappa_f = \frac{y_{hff}}{y^{sm}_{hff}} \qquad \kappa_V = \frac{y_{hVV}}{y^{sm}_{hVV}} \qquad y^{sm}_{hff} = \frac{\sqrt{2}\, m_f}{v}$$

## Fit for couplings modifiers




Event rate for $ii \to H \to ff$: $\sigma_i \mathcal{B}^f = \frac{\sigma_i(\vec{\kappa})\Gamma^f(\vec{\kappa})}{\Gamma_H(\vec{\kappa})}$

**Fit for six Higgs coupling modifiers: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$**

**Assuming:**

- no "new physics" in loop-driven couplings ($H \to \gamma\gamma$, gg→ $H$)
- no BSM decays (invisible, not observed)
- couplings to the 1$^{st}$/2$^{nd}$–gen. quarks and electrons are SM-like (i.e., small and hence having a negligible effect on the fit)

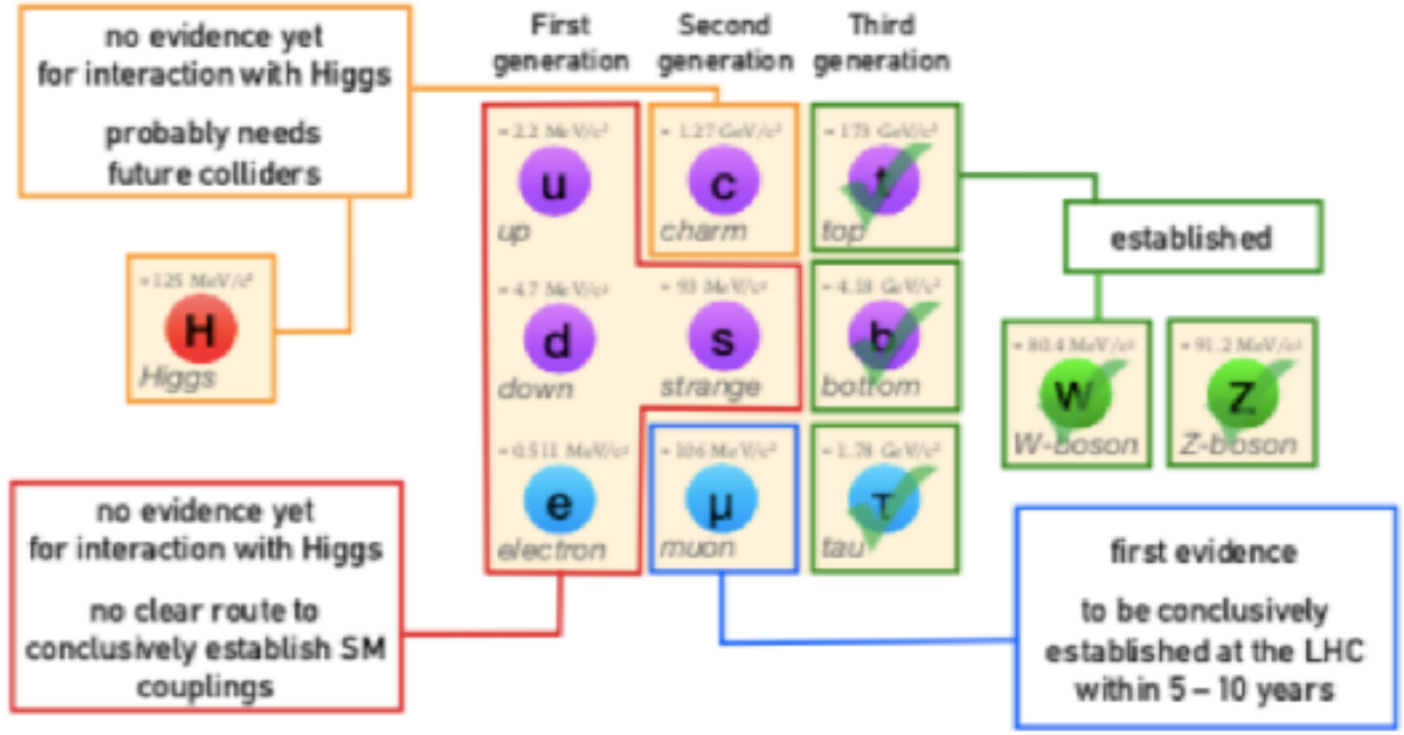
**Impressive agreement with SM over three orders of magnitude of couplings** (note: ±5% for ttH coupling)

# Couplings with light quarks and self-coupling

- In summary: Higgs couplings with 3rd generation (evidence of coupling with muons) has been detected at LHC,

- Higgs coupling with charm may be done at HL-LHC,

- But not clear with up, down and strange quark, & electron,



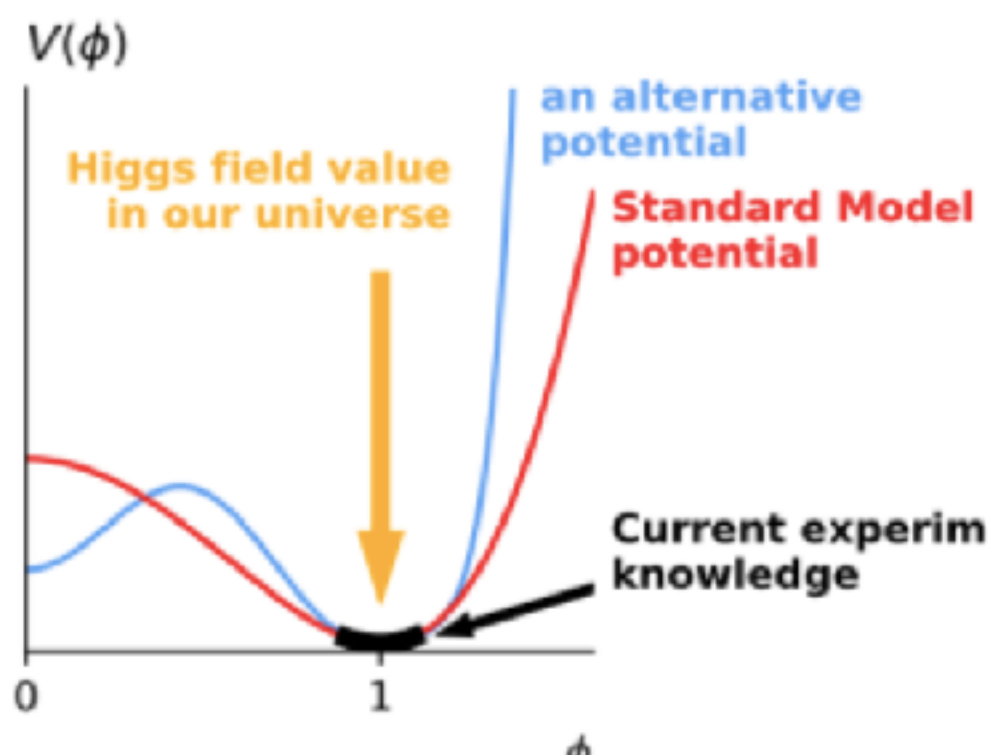

G. Salam et al, Arxive: 2207.00478 [hep-ph]

- Other properties needed to confirm the Higgs profile:

 - Higgs self-coupling (hhh): Higgs pair production,

 - Four-point interactions (hhVV, hhhh)

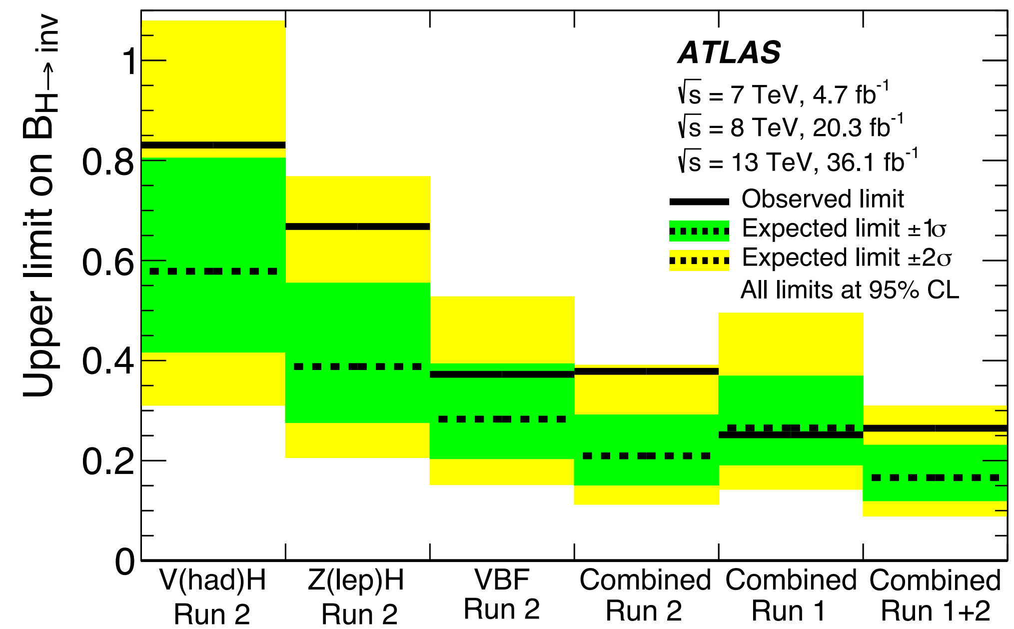
- More recently, Higgs pair production has been considered to probe light Higgs couplings.

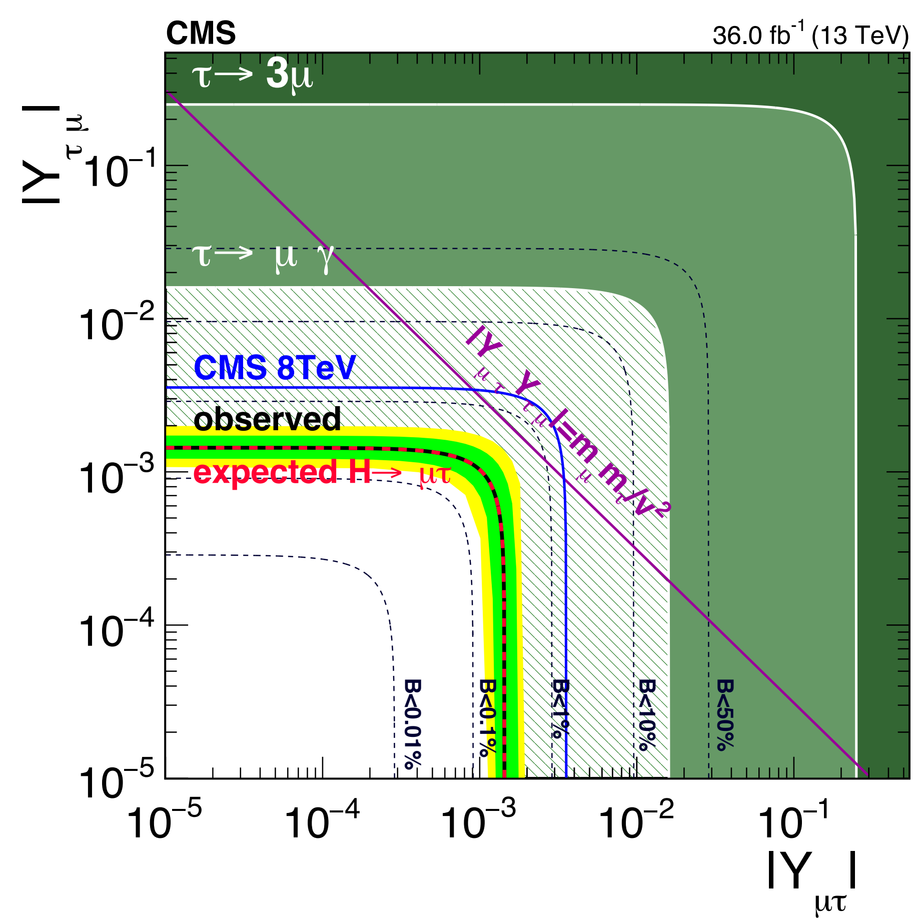


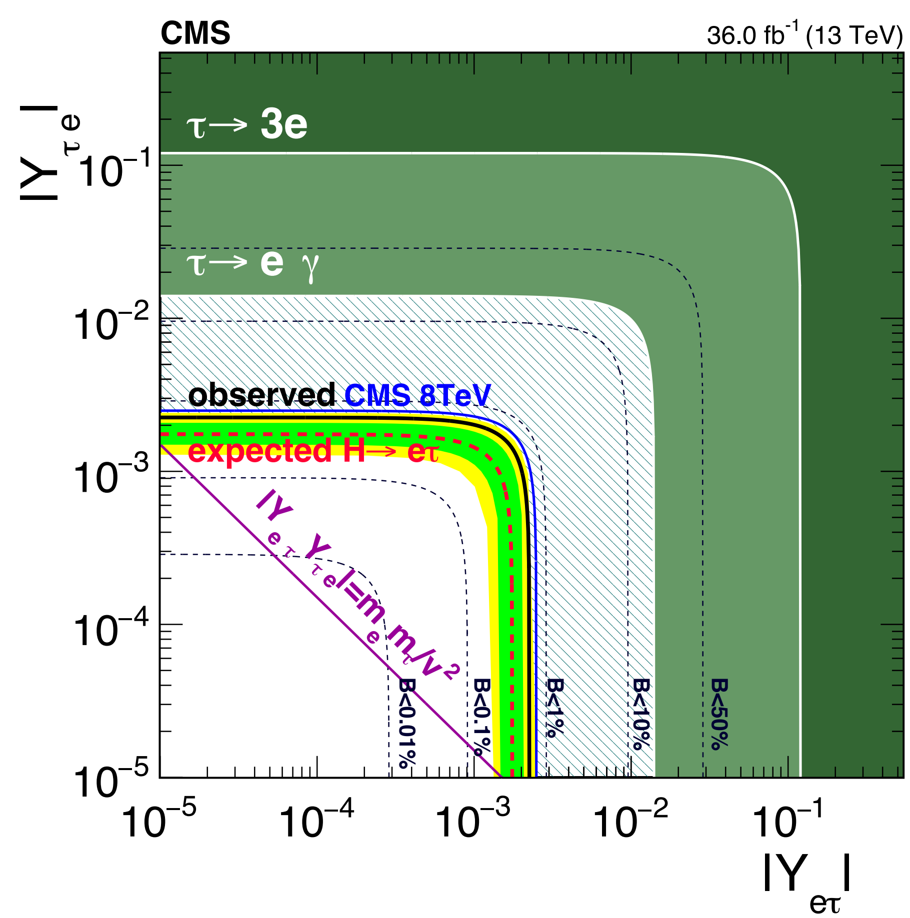

G. Salam et al. Arxive: 2207.00478 [hep-ph]

# 2c) Higgs signals Beyond the SM

- Invisible Higgs decay,
- Higgs decays into light scalars,
- Exotics (h->gravitinos+gammas),
- LFV Higgs decays,
- Higgs portal (DM), etc,

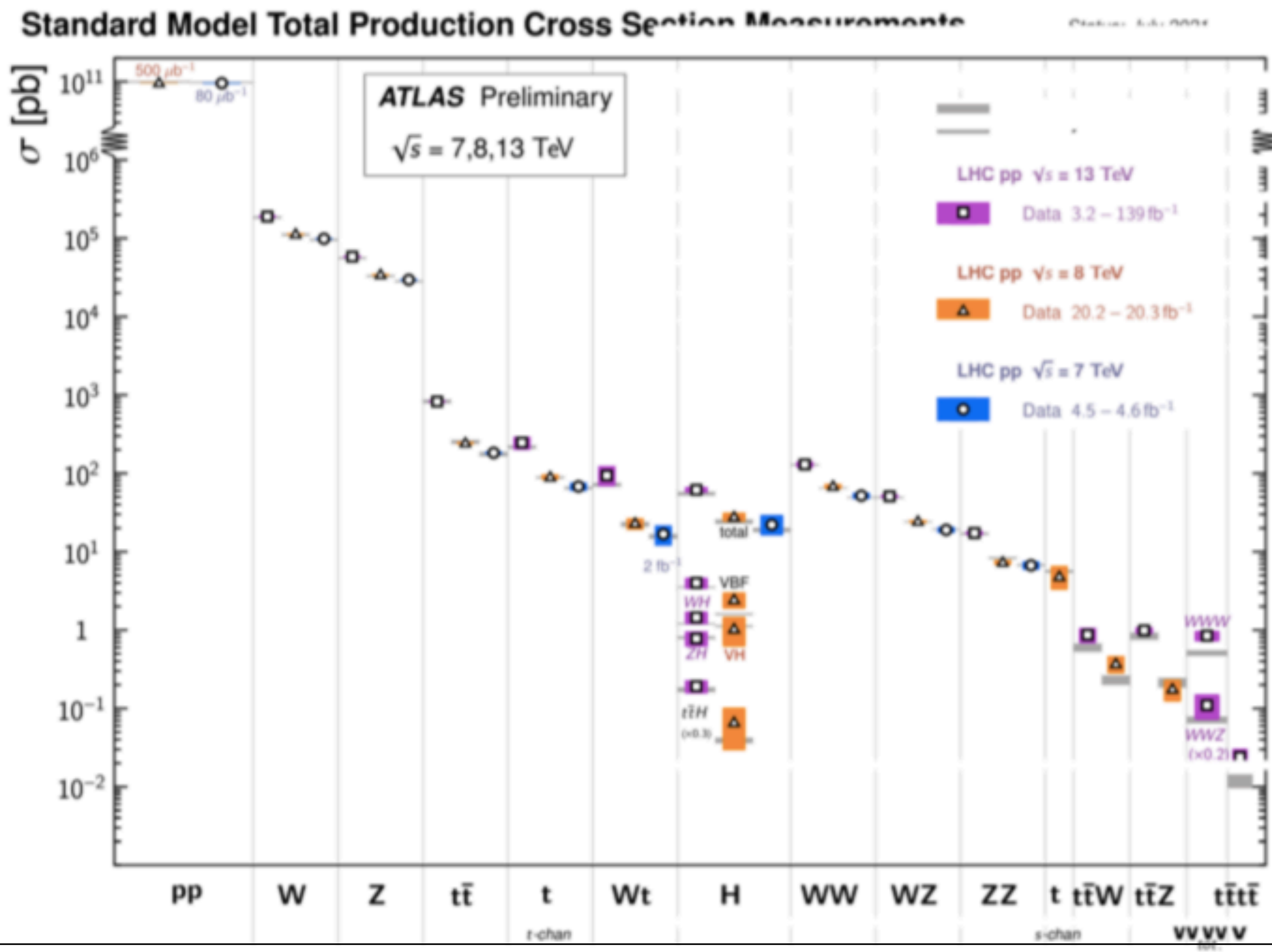



- So far, no new Higgs signal of this type has been detected at LHC …

- The SM is passing all tests at LHC —> The SM is great!




- But so much agreement between the SM with data is also intriguing,

# BSM - New Physics

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

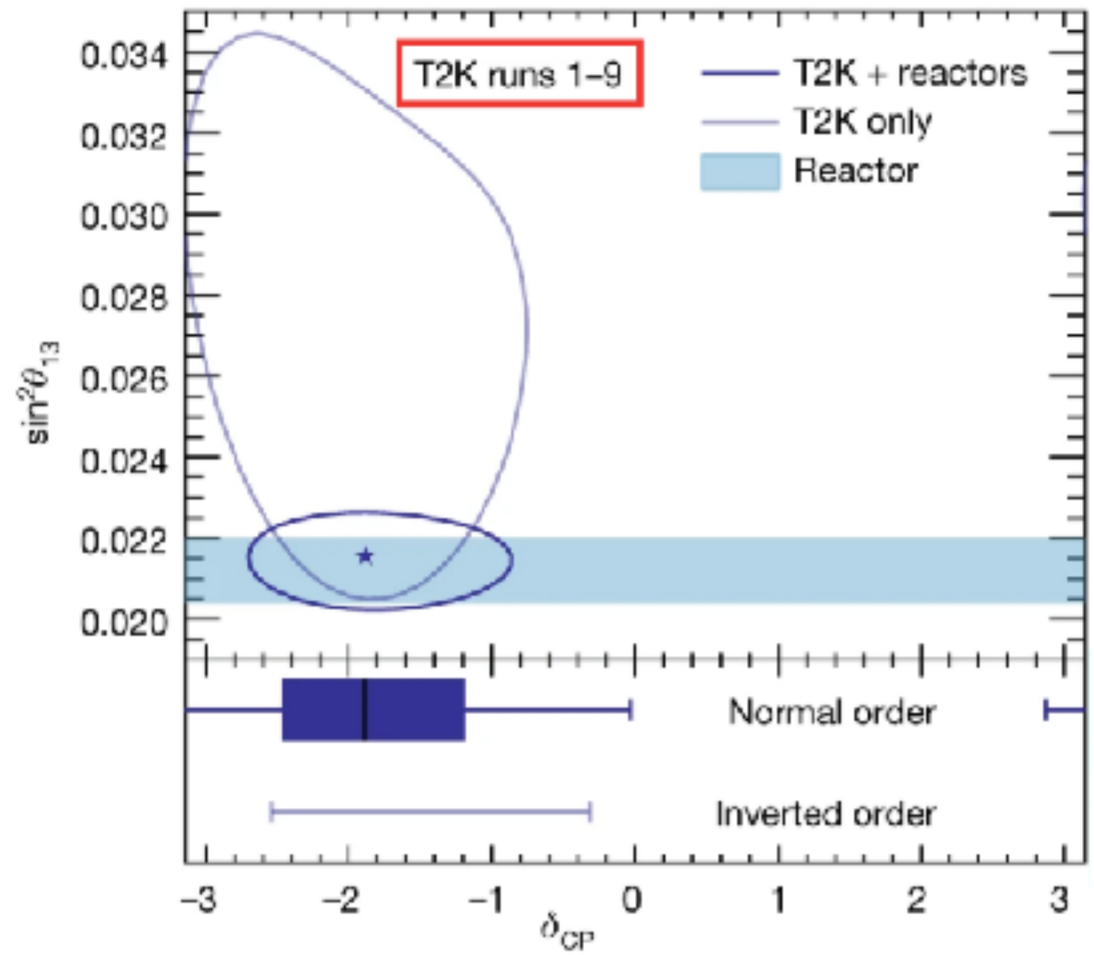
  - Why19 SM parameters?, why 3 families?,

  - How to include gravity?

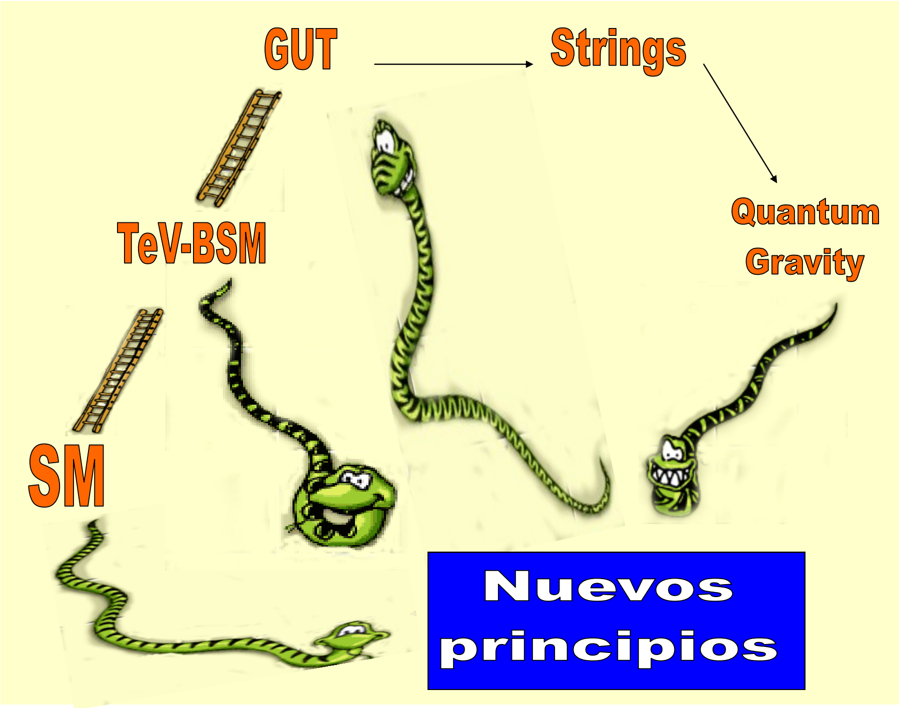
- Hints of New Physics: Neutrino masses and mixing, DM, DE, BAU, Bigbang,

- Many BSM extensions: NHDM, extra forces, more fermions, extra dims (L, XL), etc

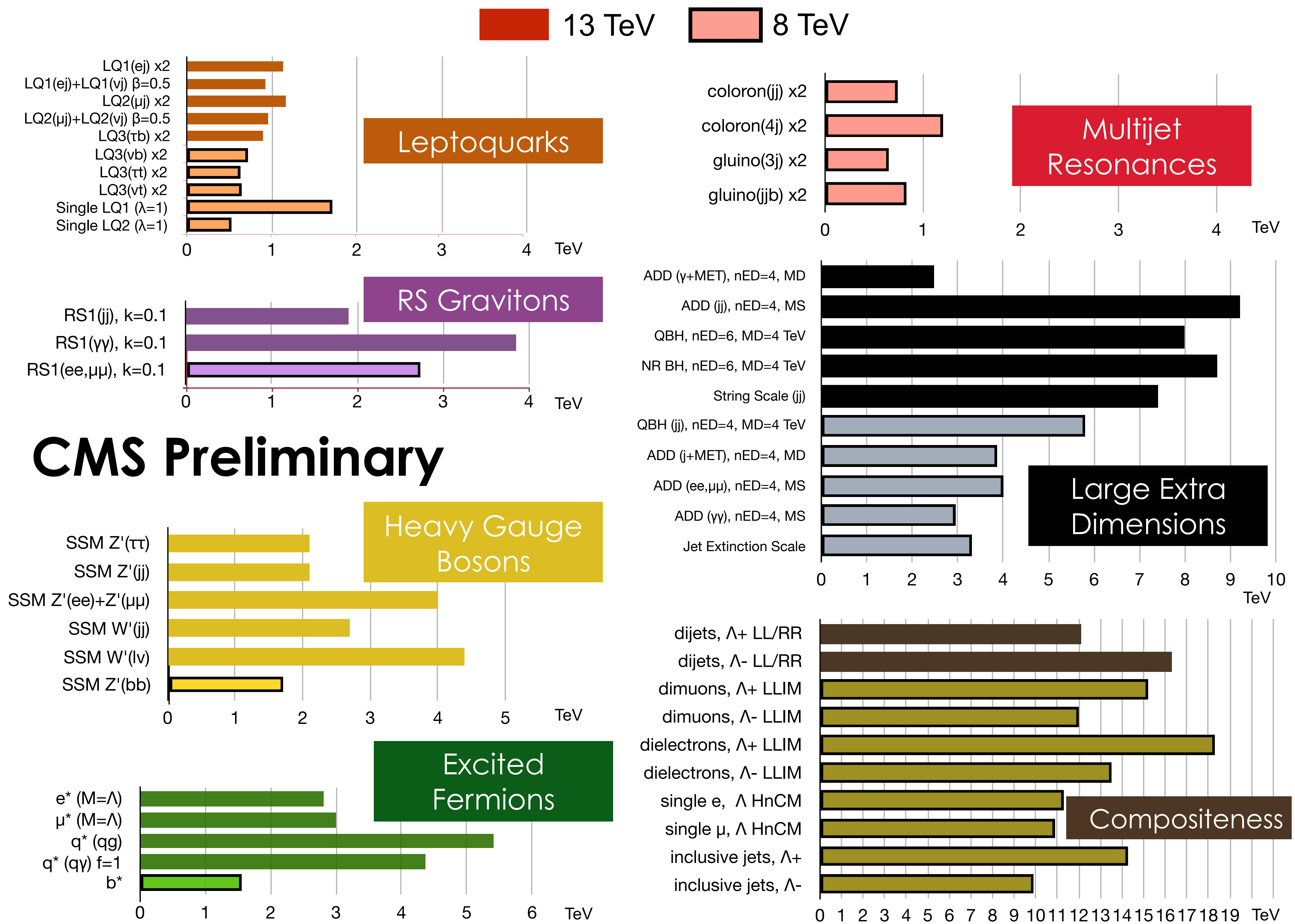
- SUSY, GUT´s and String theory,





# LHC SEARCH FOR NEW PHSICS: None




CMS Exotica Physics Group Summary – ICHEP, 2016

# So far, no signal of BSM; then what?

- 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 consider  as generators of signatures, ex.

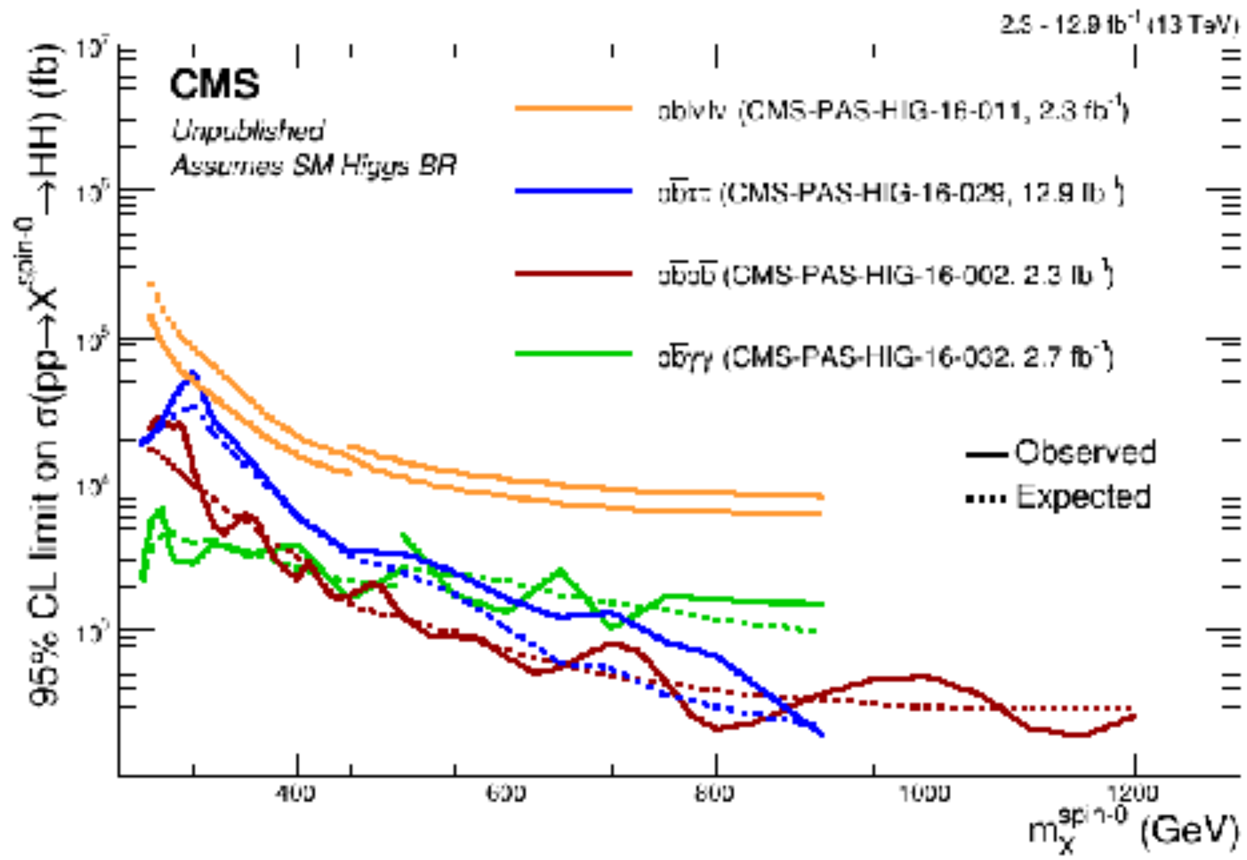
  - mSUGRA & LSP -> missing ET, DM,

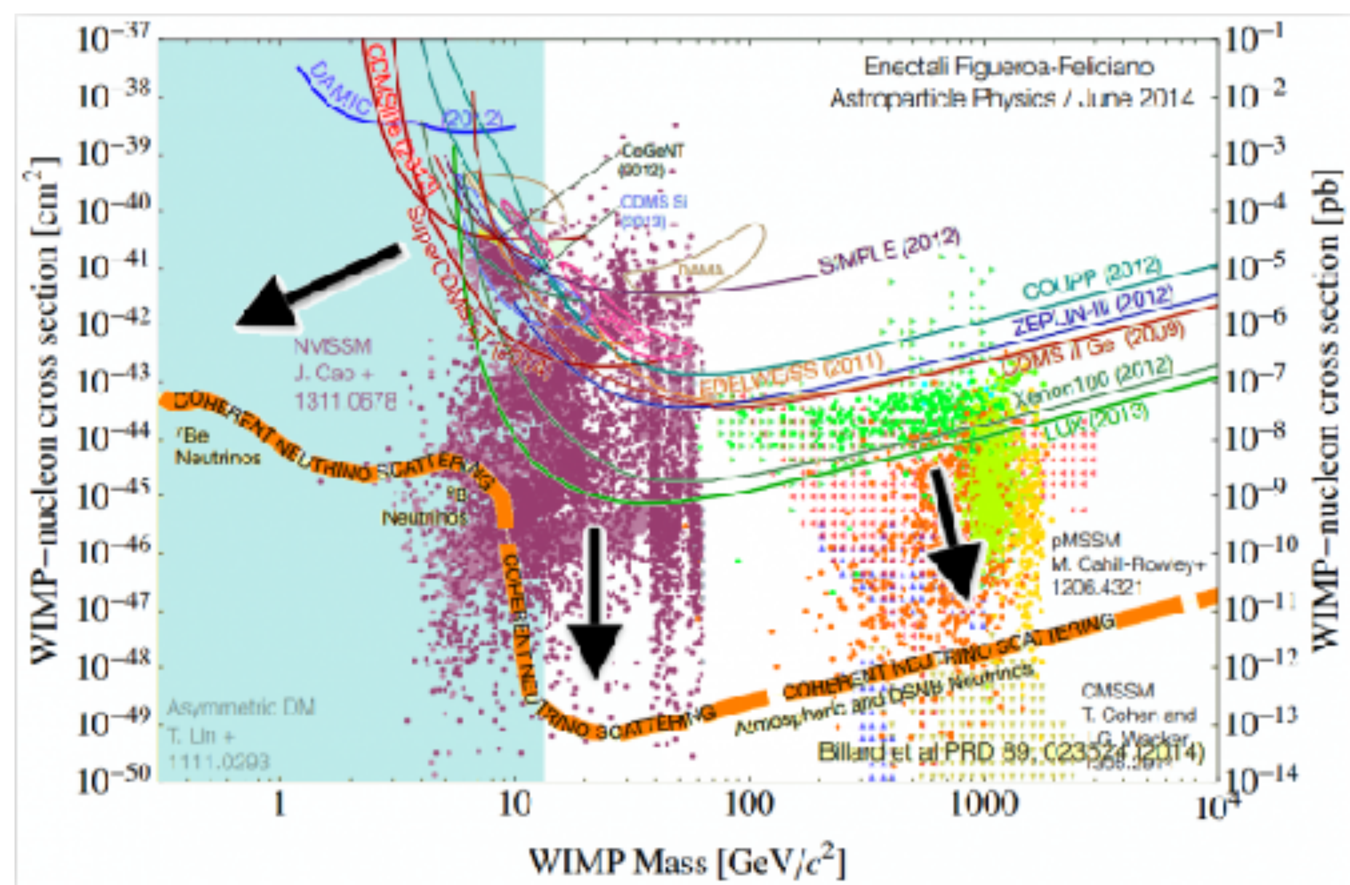
  - GMM -> missing Et + photons,

  - EW Gravitino DM -> long lived sparticles,

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

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



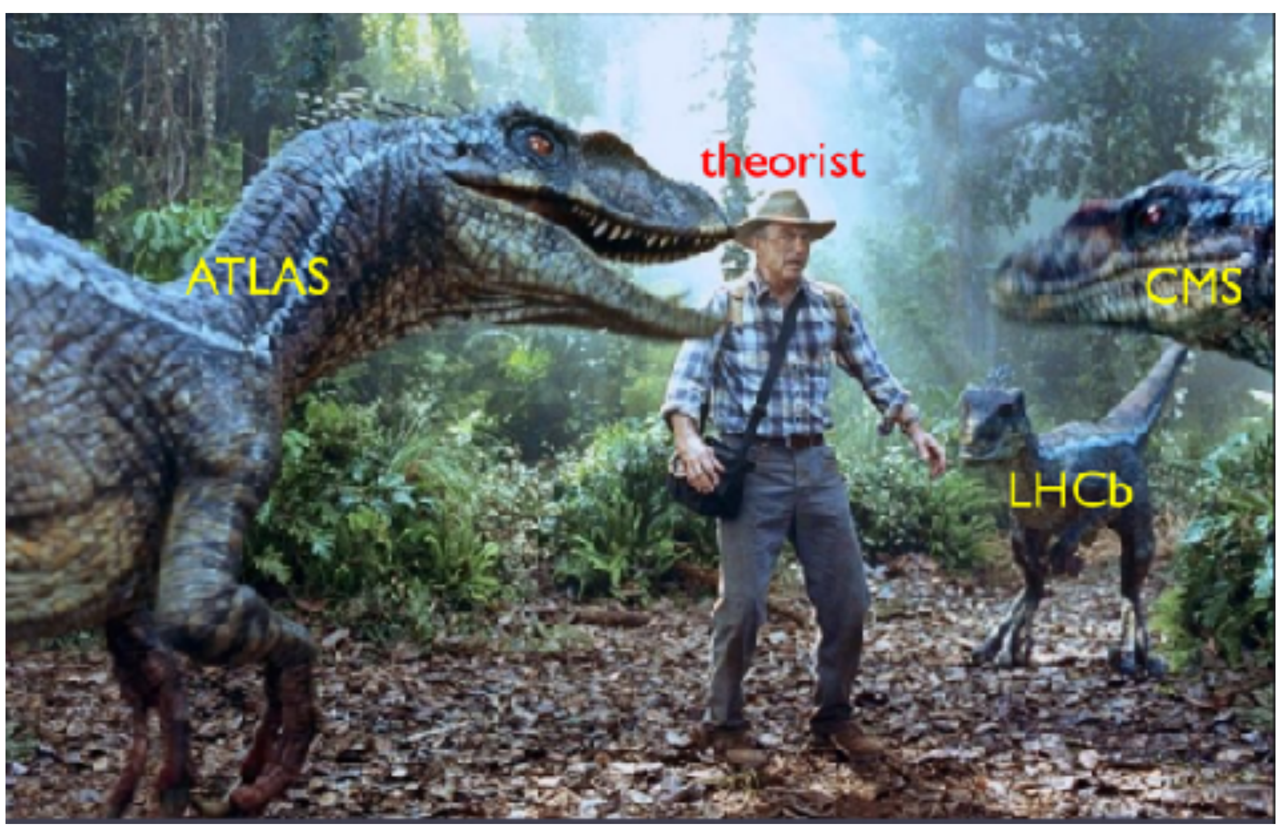
# 3. From LHC to QCD, Amplitudes and Gravity

What a humble theorist can do?

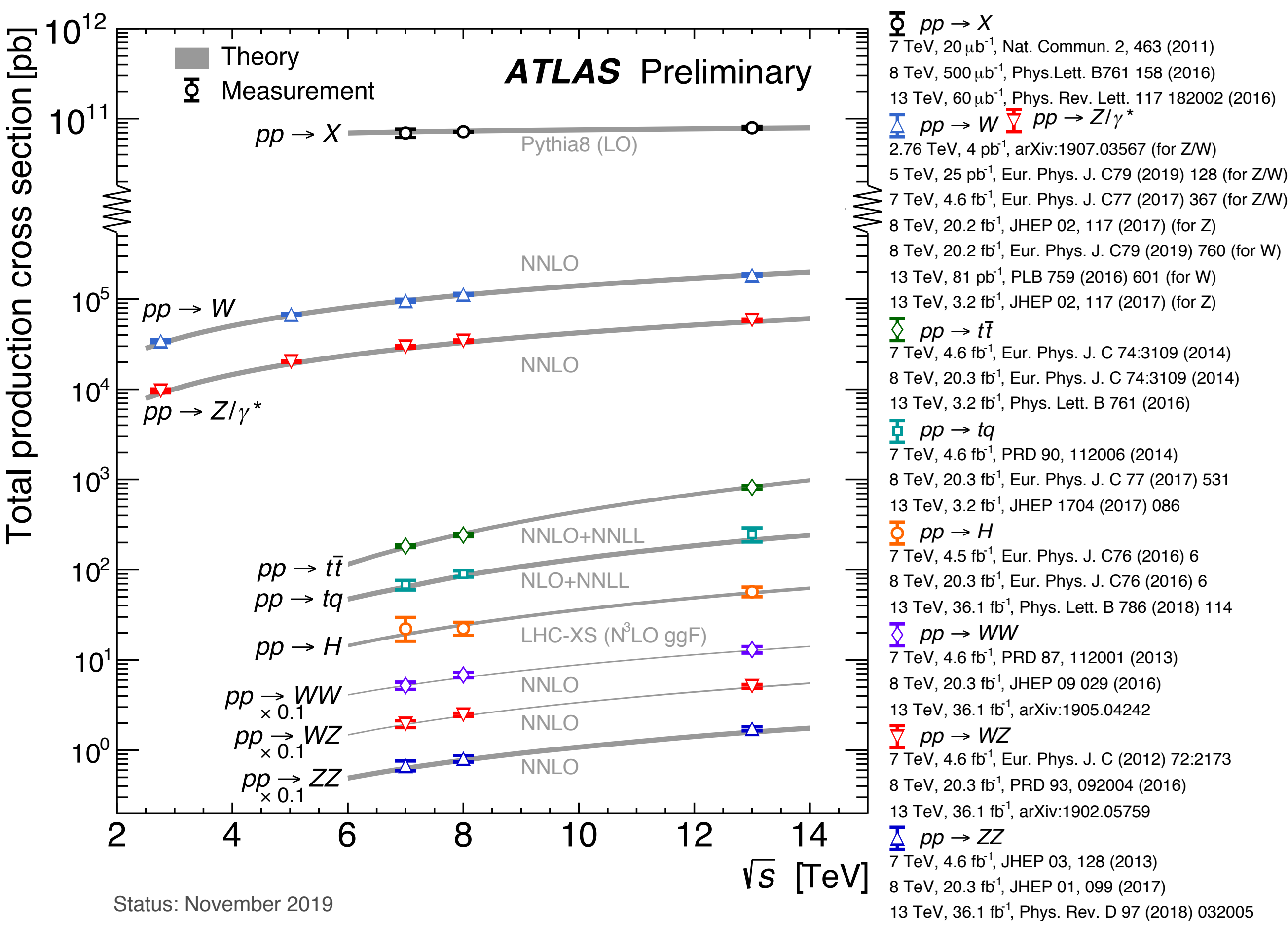
- Do complicated calculations (for real) !!

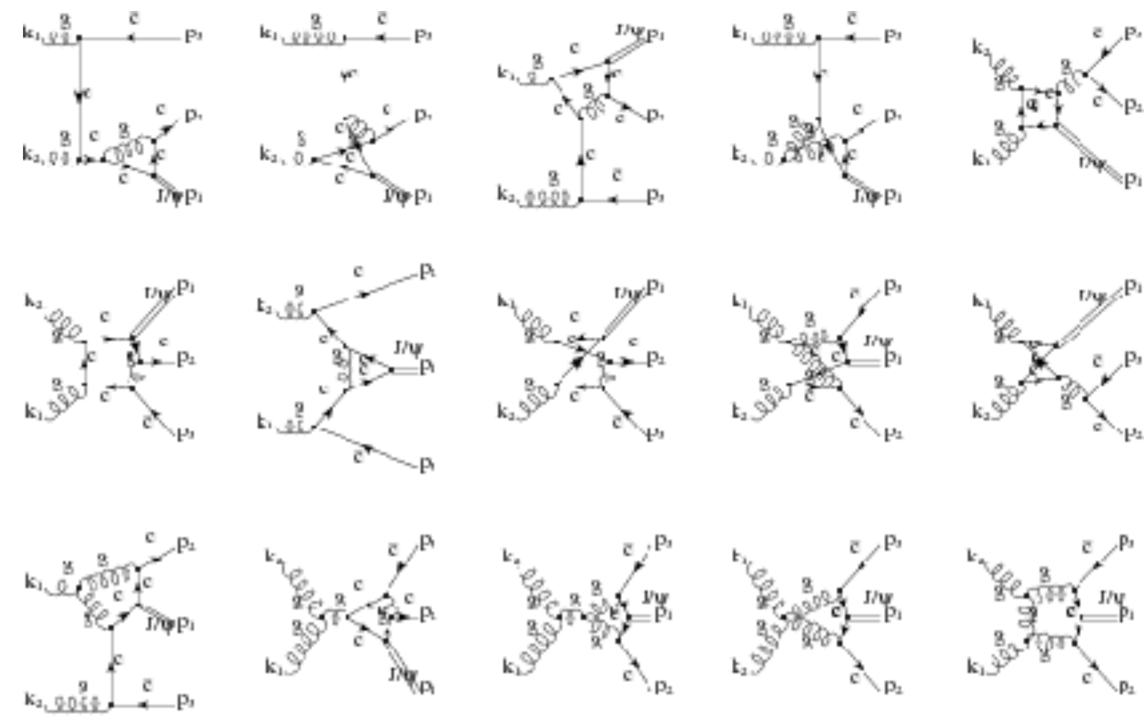
or …

- Have a great idea!




# 3.A) QCD probes at LHC - QFT in action!



- For instance, R-ratio can be evaluated with pert-QCD, but need to take care of IR and UV divergences, …

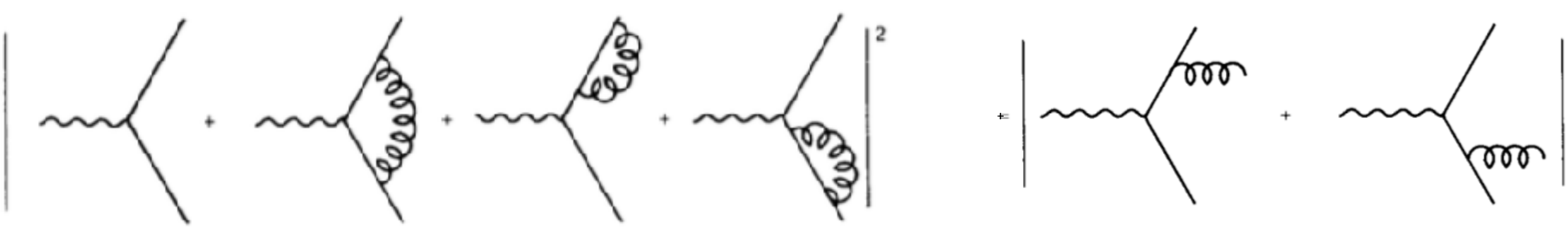


**Figure 2.7**: Representation of the first order virtual corrections to the $\gamma \to q\bar{q}$. The kinematics are the same than $\sigma(e^+e^- \to q\bar{q})$ Born level, given the loop nature of the radiated gluon.

# 3.3) Amplitudes & Constructible QFT´s

- But traditional methods, have its limitations,
- Amplitudes in QCD can be evaluated using Helicity Methods,
- Simple results suggested more efficient methods should be possible,
- Indeed: On-shell Constructible QFT,

| | | |
|---|---|---|
| $g+g \to g+g$ | | 4 diagrams |
| $g+g \to g+g+g$ | | 25 diagrams |
| $g+g \to g+g+g+g$ | | 220 diagrams |

$$p_{\alpha\dot{\alpha}} = p_\mu \sigma^\mu_{\alpha\dot{\alpha}} = \begin{pmatrix} p_0 + p_3 & p_1 - ip_2 \\ p_1 + ip_2 & p_0 - p_3 \end{pmatrix},$$

$$p_{\alpha,\dot{\alpha}} = \chi_\alpha \tilde{\chi}_{\dot{\alpha}}$$

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

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

$$< ij > = \chi_{i\alpha}\chi_{j\beta}\epsilon^{\alpha\beta}$$

$$< ij > [ij] = 2p_i \cdot p_j$$

$$[ij] = \tilde{\chi}_{i\dot{\alpha}}\tilde{\chi}_{j\dot{\beta}}\epsilon^{\dot{\alpha}\dot{\beta}}$$

- The master-equation for the 3-point amplitude:

$$A(1^{h_1}2^{h_2}3^{h_3}) = \begin{cases} \langle 12\rangle^{h_3-h_1-h_2}\langle 23\rangle^{h_1-h_2-h_3}\langle 31\rangle^{h_2-h_3-h_1}, & h \le 0 \\ [12]^{h_1+h_2-h_3}[23]^{h_2+h_3-h_1}[31]^{h_3+h_1-h_2}, & h \ge 0 \end{cases}$$

- For vector particles (gluons, with h=+-1) we obtain :

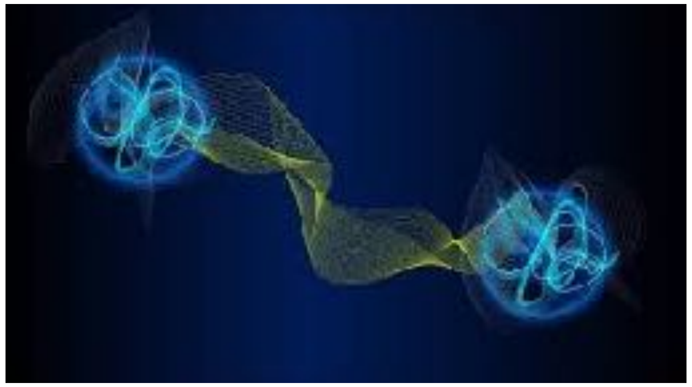
$$A(1_a^- 2_b^- 3_c^+) = f_{abc}\frac{\langle 12\rangle^3}{\langle 13\rangle\langle 32\rangle} \quad \text{and} \quad A(1_a^+ 2_b^+ 3_c^-) = f_{abc}\frac{[12]^3}{[13][32]}.$$

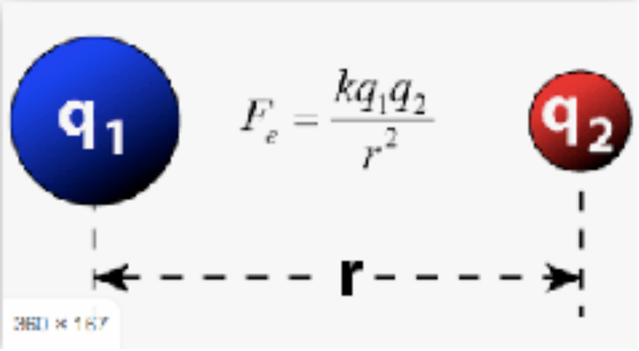
$$A(1_a^- 2_b^- 3_c^-) = f_{abc}\langle 12\rangle\langle 23\rangle\langle 31\rangle, \qquad A(1_a^+ 2_b^+ 3_c^+) = f_{abc}[12][23][31],$$

- For tensor particles (h=+-2), such as the graviton, we find:

$$A(1^{--}2^{--}3^{--}) = \langle 12\rangle^2\langle 23\rangle^2\langle 31\rangle^2, \qquad A(1^{++}2^{++}3^{++}) = [12]^2[23]^2[31]^2.$$

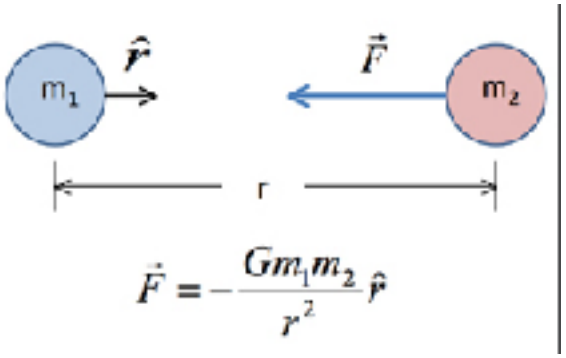
$$A(1^{--}2^{--}3^{++}) = \frac{\langle 12\rangle^6}{\langle 13\rangle^2\langle 32\rangle^2}, \qquad A(1^{++}2^{++}3^{--}) = \frac{[12]^6}{[13]^2[32]^2},$$






- Seems that:

GR= YM x YM !!

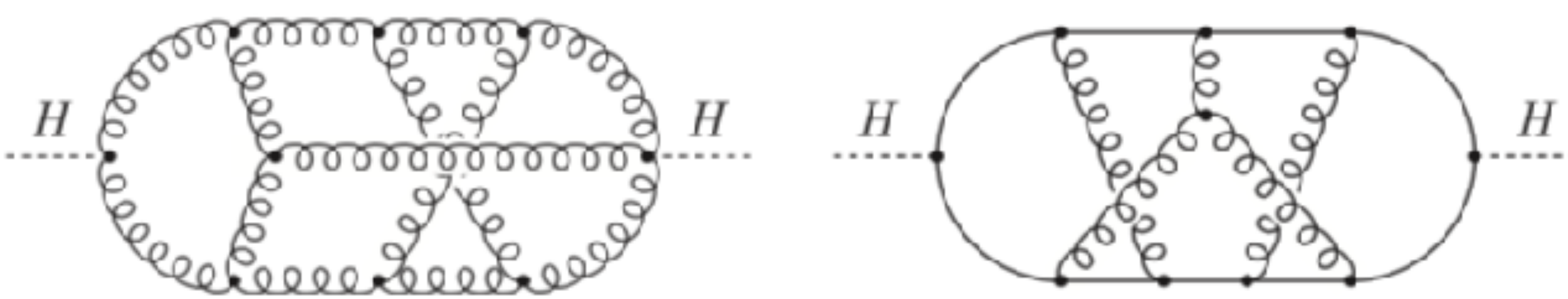


# 3.4) Non-Pert. Methods in QFT

- QCD Corrections to Higgs decay h-> bb: (Baikov et al, PRL96 (2006)

The decay rate of Higgs into $b\bar{b}$ is known up to fourth order ($\alpha_s^4$) in QCD for massless quarks [1] and is related to the imaginary part of the quark-antiquark scalar-current correlator $\Pi(s)$ as

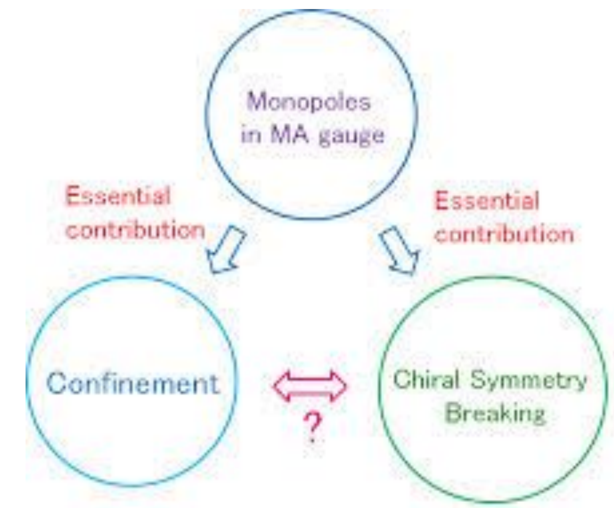
$$\Gamma(H \to b\bar{b}) = \frac{1}{v^2 m_H} \operatorname{Im} \Pi(m_H^2) = \frac{m_H}{v^2} \frac{N_c}{8\pi^2} m_b^2(m_H) \left[ 1 + \sum_{n=1}^{\infty} c_n a_s^n(m_H) \right] =$$
$$= \frac{m_H}{v^2} \frac{N_c}{8\pi^2} m_b^2(m_H) \left[ 1 + 5.667\, a_s + 29.15\, a_s^2 + 41.76\, a_s^3 - 825.7\, a_s^4 + \ldots \right], \quad (1)$$

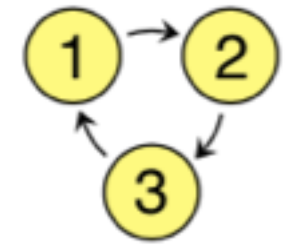


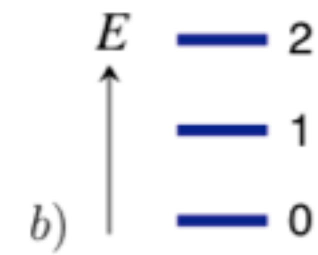

- The final result looks a lot simpler than the intermediate steps, so that one wonders if there be other ways to calculate amplitudes in QFT?

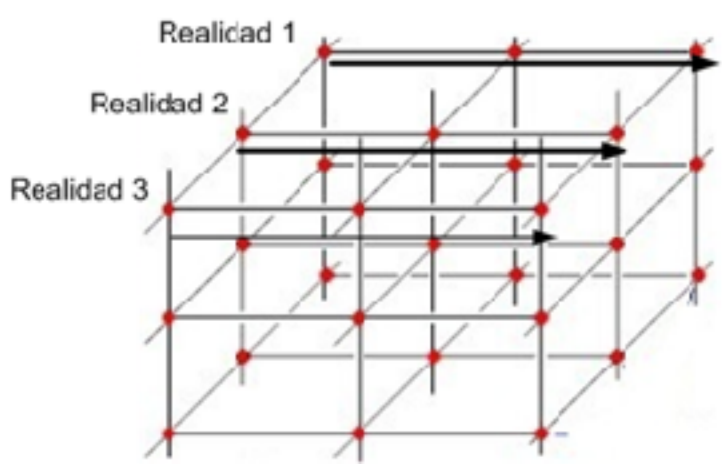
# • New Ideas? QFT in a new guise?

- Non-perturbative methods in QFT: Lattice QCD, Instantons, Solitons, …
- Could one calculate QFT Amplitudes, not only for Strong QCD, but also for weakly-interacting ones,
- Towards a non-perturbative definition of the S-matrix, Pade Approximants,
- Algorithms from quantum computers, Cellular Automaton (t Hooft)?,




**Towards a nonperturbative construction of the $S$-matrix**


Brian Henning,[1,2] Hitoshi Murayama,[3,4,5] Francesco Riva,[2]
Jedidiah O. Thompson,[6] and Matthew T. Walters[1,2]



Abstract

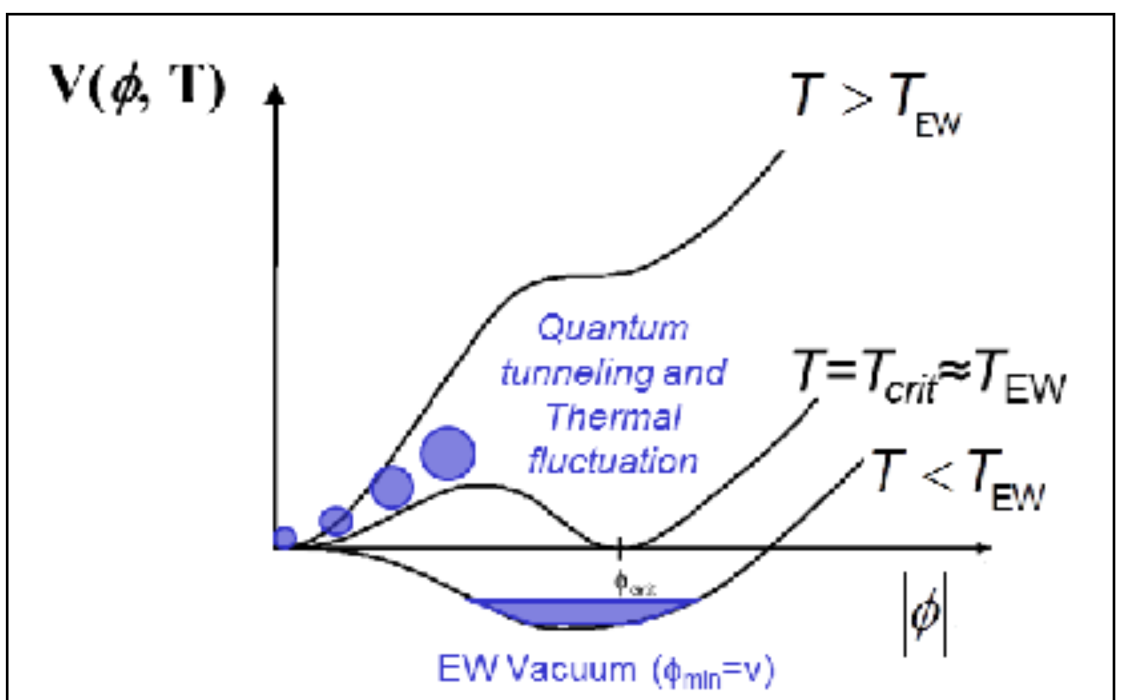
We present a nonperturbative recipe for directly computing the $S$-matrix in strongly-coupled QFTs. The method makes use of spectral data obtained in a Hamiltonian framework and can be applied to a wide range of theories, including potentially QCD. We demonstrate the utility

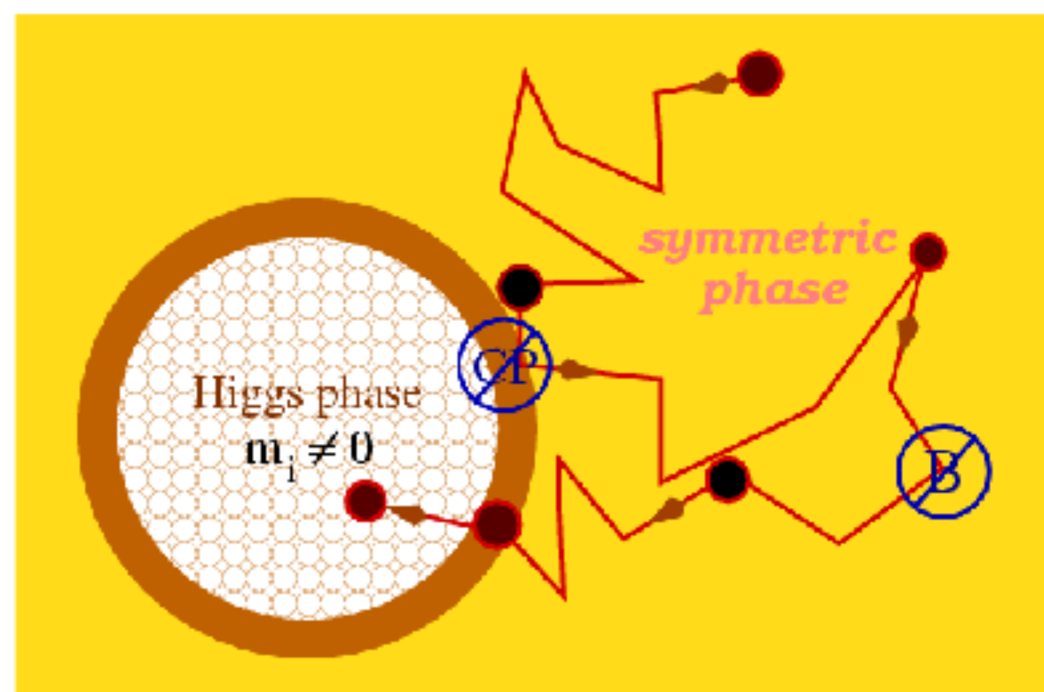

**Scattering Amplitude from Quantum Computing with Reduction Formula**


Tianyin Li,[1,2] Wai Kin Lai,[1,2,3,*] Enke Wang,[1,2,†] and Hongxi Xing[1,2,‡]
(QuNu Collaboration)

# 4. The Higgs boson as the Master of the Universe?

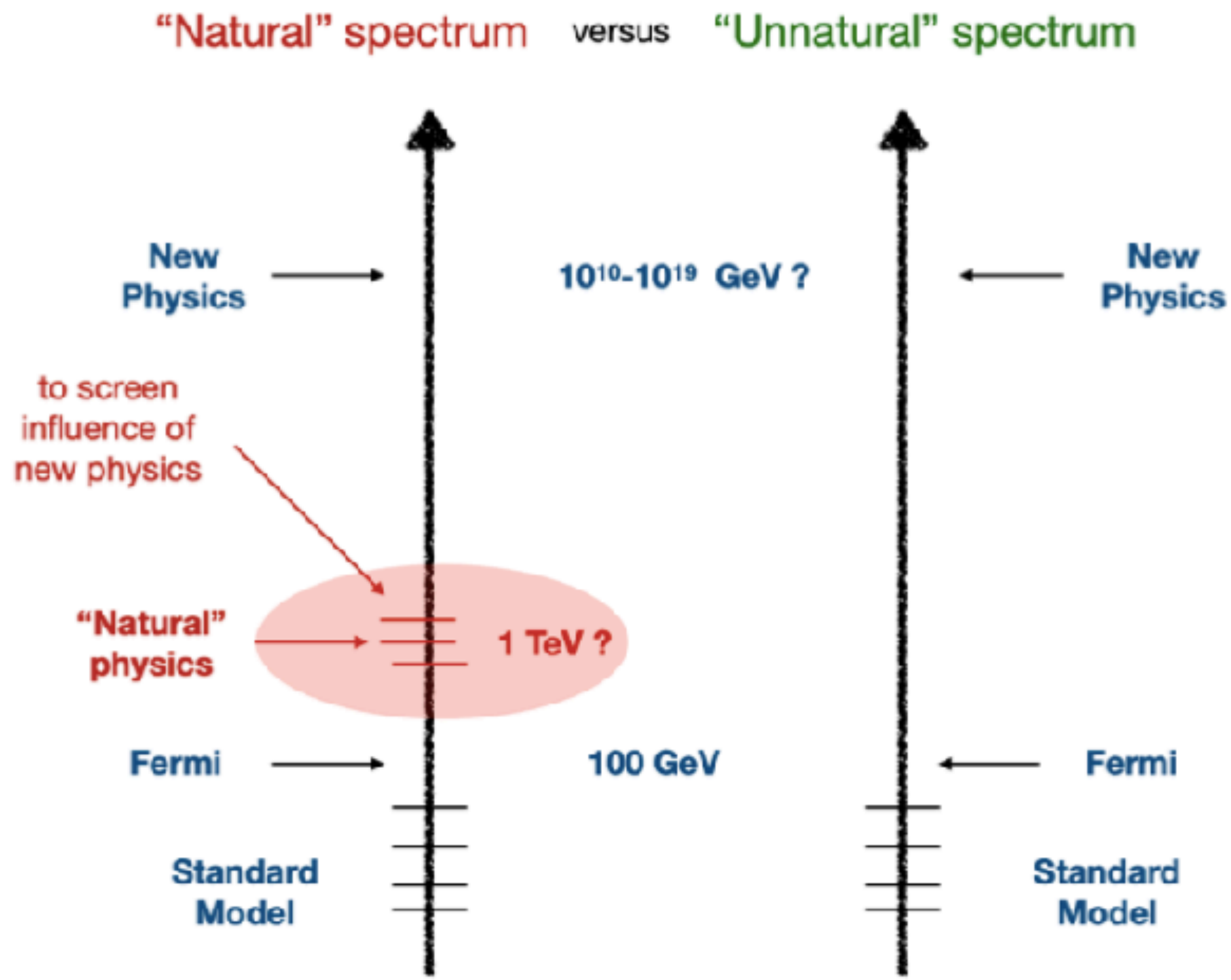
- Hierarchy Problem: Is nature fine-tuned? SMEFT
- The nature of Electro-Weak Phase Transition and its connection with BAU,
- Higgs and gravity - pQG,
- Deep issues about vacuum and CC, etc …

# 4.1) Is the SM a Natural Theory?

- Previous thoughts on natural vs-unnatural physics:
- Since no PBSM showed up, with M=O(1) TeV, is the SM valid up to: E >> O(1TeV);
- Is the SM still a Natural theory?




We understand better these questions, like what is QFT & renormalization, from a modern point of view -> Effective QFT (K. Wilson, 1970-80´s)

# 4.2) What is an Effective QFT?

- Suppose a QFT has a heavy and a light fields:

  (With masses: M & m)

- For E> M, the theory is described by:

- For E<M, QFT only includes light fields, and it is described by:

- The parameters (H&L) are different in general,

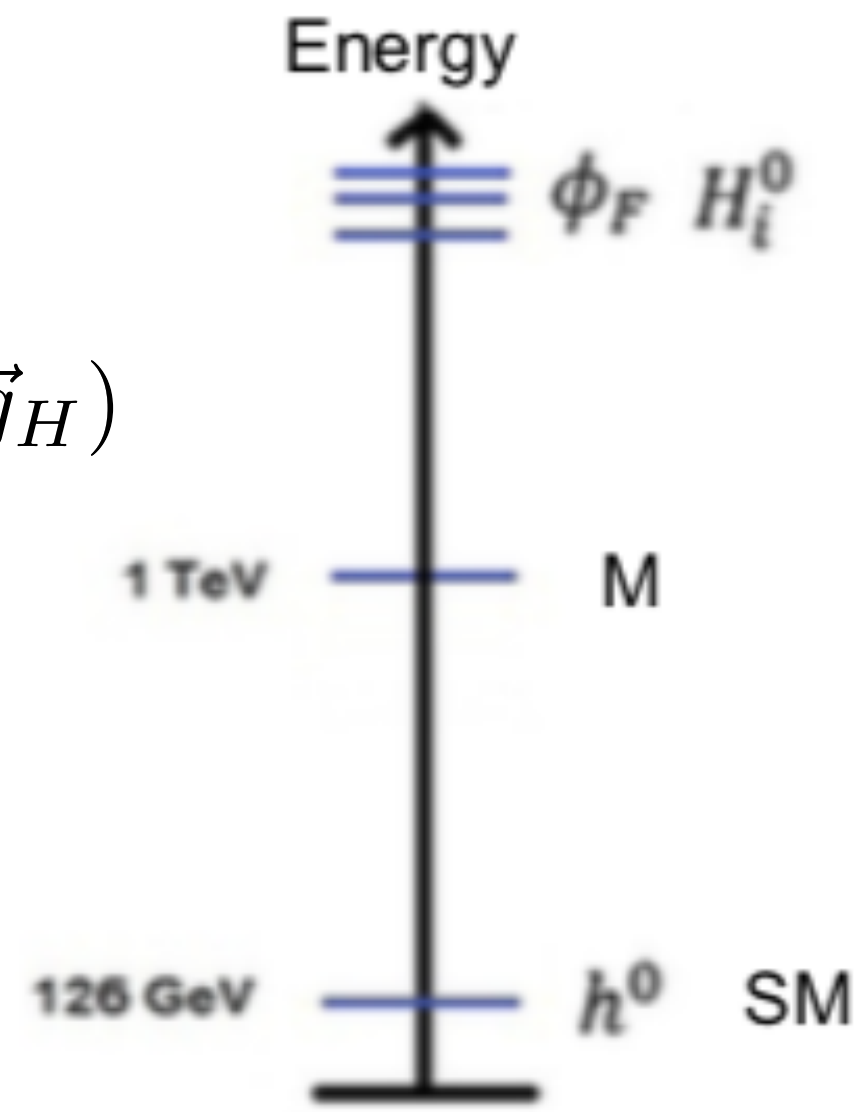
$$\Phi_H \text{ and } \phi_\mathrm{L}$$

$$\mathcal{L}_H = \mathcal{L}_H(\Phi_H, \phi_L; \vec{g}_H)$$

$$\downarrow$$

$$\mathcal{L}_L = \mathcal{L}_L(\phi_L; \vec{g}_L)$$

$$\vec{g}_H \neq \vec{g}_L$$




In the EFT, the heavy field is integrated out & the parameters change with Energy (Scale, RGE):

$$g_i = g_i(M)$$

# (Bottom-up) Effective SM (nu-masses & Gravity, J. Dognohue)

- The SM, as an EFT, includes all higher-dimensional terms:

- Renormalizability means that a theory is valid up to very high scales, while a non-renorm. theory is valid up to some scale:

$$\mathcal{L}_{eff} = \mathcal{L}_0 + \mathcal{L}_{d=5} + \mathcal{L}_{d=6} + \ldots ,$$

- For instance, the dim-5 terms include neutrino masses:

$$M \leq \Lambda \, (= M_{Pl})$$

$$\mathcal{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda} [\Phi \cdot \overline{L}_\ell^c] \, [L_{\ell'} \cdot \Phi], \qquad m_{\ell\ell'} = C_5^{\ell\ell'} v^2 / \Lambda,$$

- One often hears that the SM can not include gravity, or that there is not quantum theory of gravity …

- But GR can be considered as a quantum EFT (=pQG), and it works in the IR,

# Wilson Criteria for Naturalness & Fine-tuning (J.Wells)

- When a threshold (M) is crossed, heavy particles are integrated our,
- Then, the low-energy parameters have a dependency on the heavy masses,

- Thus, we can define the max. degree of fine-tuning, as follows:

$$\mathrm{FT}[g_{Li}\,|\,g_{Hj}] = \left|\frac{g_{Hj}}{g_{Li}}\frac{\partial g_{Li}}{\partial g_{Hj}}\right|_{\mu^2=M^2} \qquad \mathrm{FT}[g_{Li}] = \max_k\ \mathrm{FT}[g_{Li}\,|\,g_{Hk}]$$

- Within the SM, the max. fine-tuning, appears in the Higgs mass, as function of the top mass:

$$\mathrm{FT}[m^2] = 10^X \quad \longrightarrow \quad \text{Level-X finetuned theory.}$$

$$\mathcal{L}_{\mathrm{SM}} = -m^2 H^\dagger H + \cdots . \qquad \mathrm{FT}[m_h^2|m_t] \simeq \frac{3m_t^4}{\pi^2 v^2 m_h^2}$$

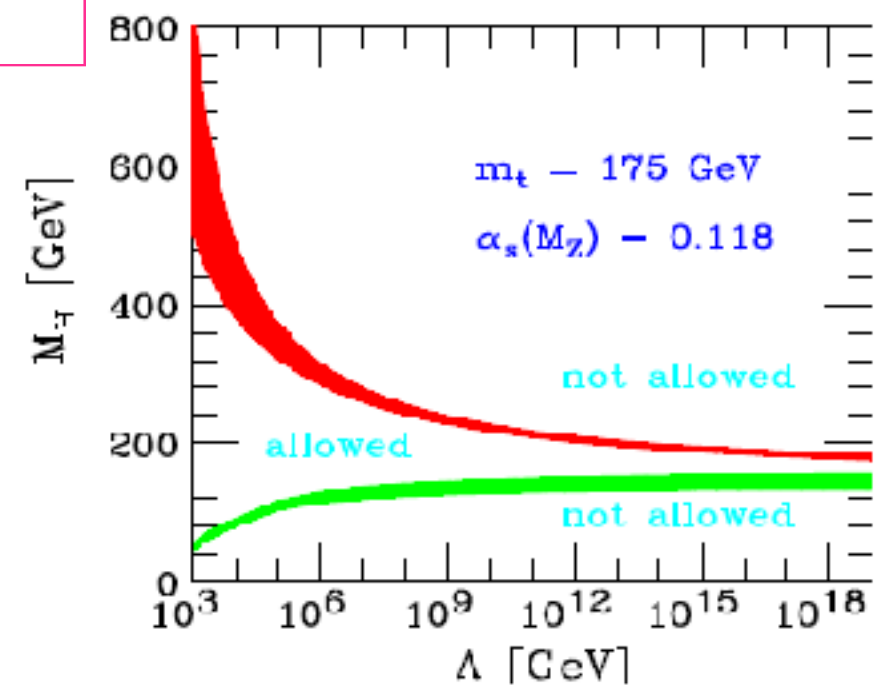
- But this fine-tuning is only of Level- 0.3,
- Thus, there is no problem in the SM!

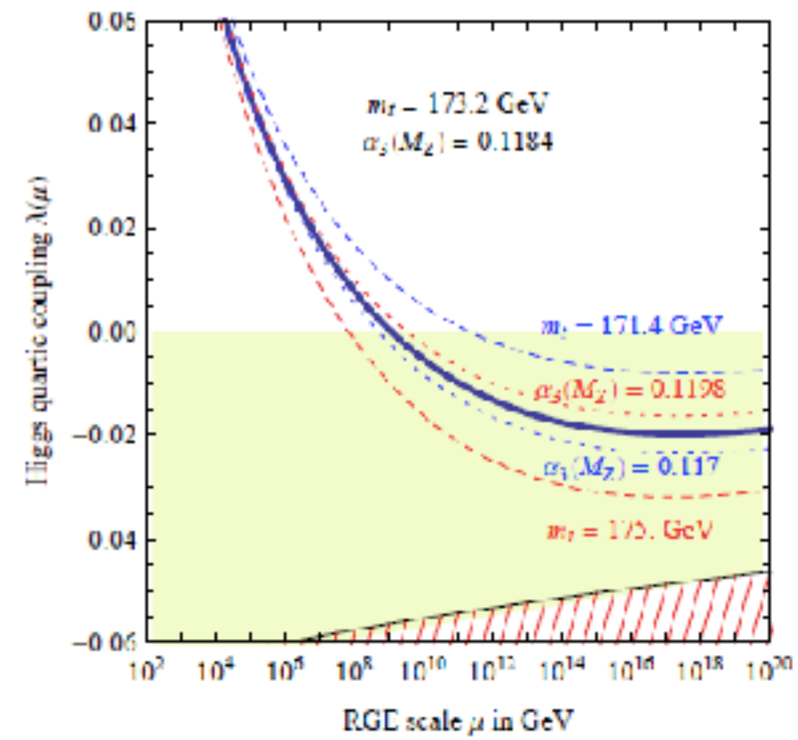
# Is the Higgs Boson the Master of the Universe?

Fred Jegerlehner[1,2]

e-Print: 2305.01326 [hep-ph]

- Higgs boson discovery and absence of BSM physics at O(1) TeV -> new paradigm,
- SM masses & couplings show amazingly deep conspiracy -> SM vacuum stable up to the Planck scale,
- At higher energy (below Planck scale), there is a phase transition from Higgs phase (SSB) to symmetric one,
- In the disordered phase, four physical Higgs scalars are very heavy -> provide enormous Dark Energy (DE).



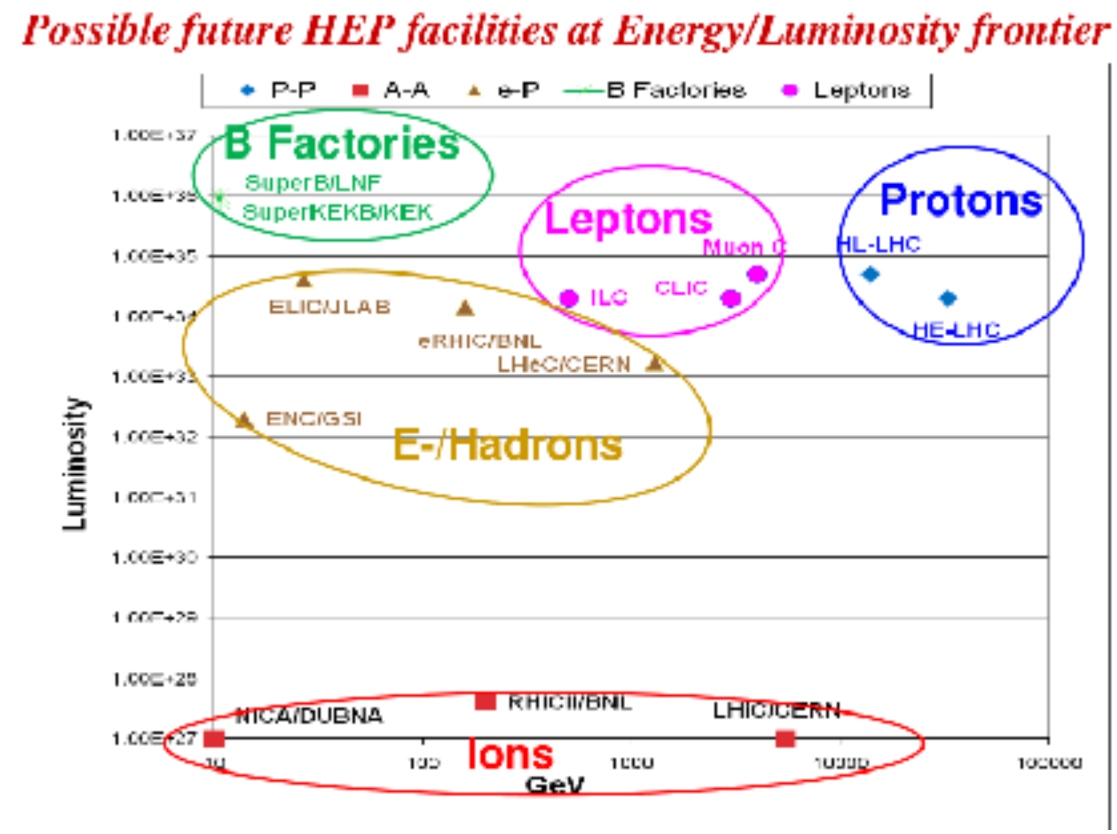



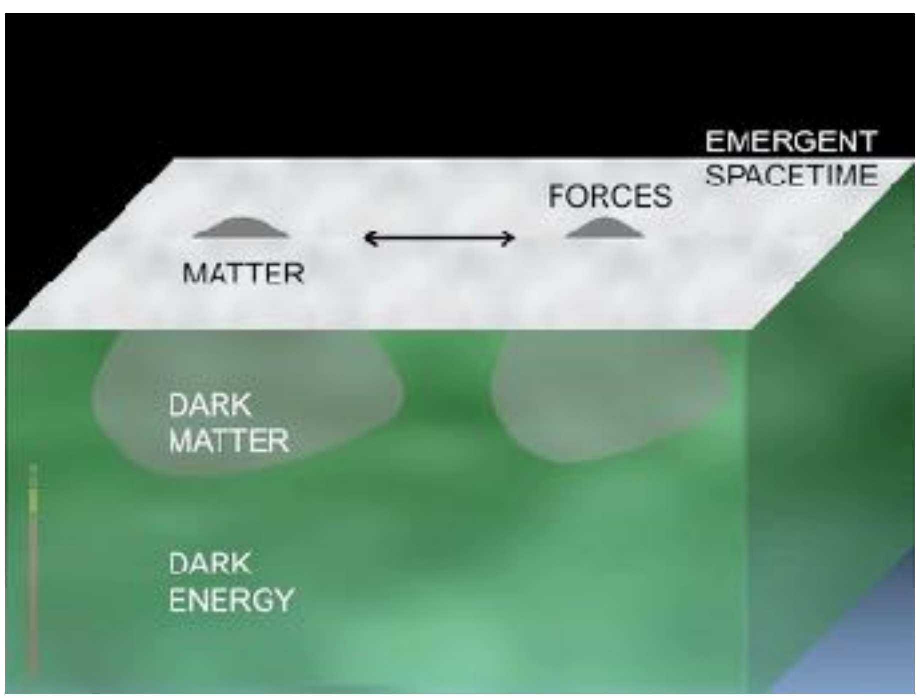

$$\delta m_H^2 = m_{H0}^2 - M_H^2 = C_1\,\Xi;\; C_1 = 2\lambda + 3/2\,g'^2 + 9/2\,g^2 - 12\,y_t^2$$

- C1 has a zero, at about E=10^(17) GeV, for mh=125 GeV.

# 5) Conclusions

- SM is not a theory of everything, but it could be more subtle than we thought,
- LHC has provided valuable data, in particular for Higgs physics,
- We must keep working towards completing the Higgs profile (LHC or ??),
- Surprises may be waiting for the one that looks for anything,




# What could come after the SM? (DiazCruz)

- Is the New Physics still consistent with QM & Relativity

$\xrightarrow{No}$ Holy ghost! We are in trouble …

$\downarrow$ Yes

Is it a consistente QFT?

$\xrightarrow{No}$ Try String Theory or LQG or …

$\downarrow$ Yes

Is there a new gauge boson?

$\xrightarrow{Yes}$ Try extra U(1) or LR or GUTs …

$\downarrow$ No

Is the same Repr. as in the SM?

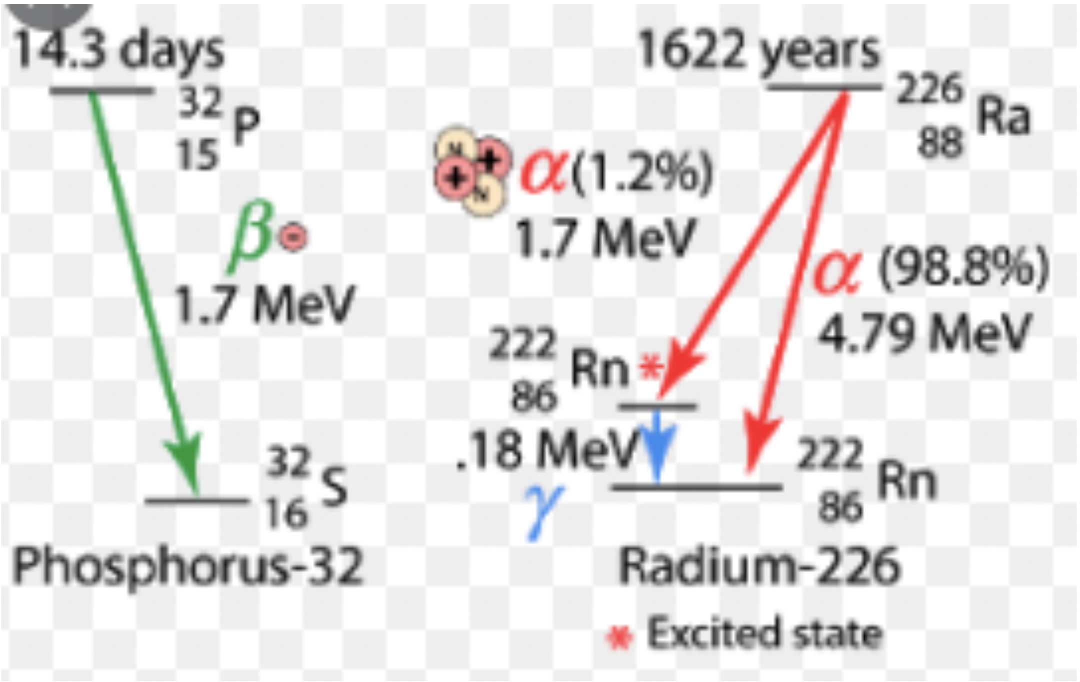
$\xrightarrow{No}$ Try extra U(1) or LR or SUSY or GUTs …

$\downarrow$ Yes

It is still Rock & Roll to me … keep calling it the SM-X

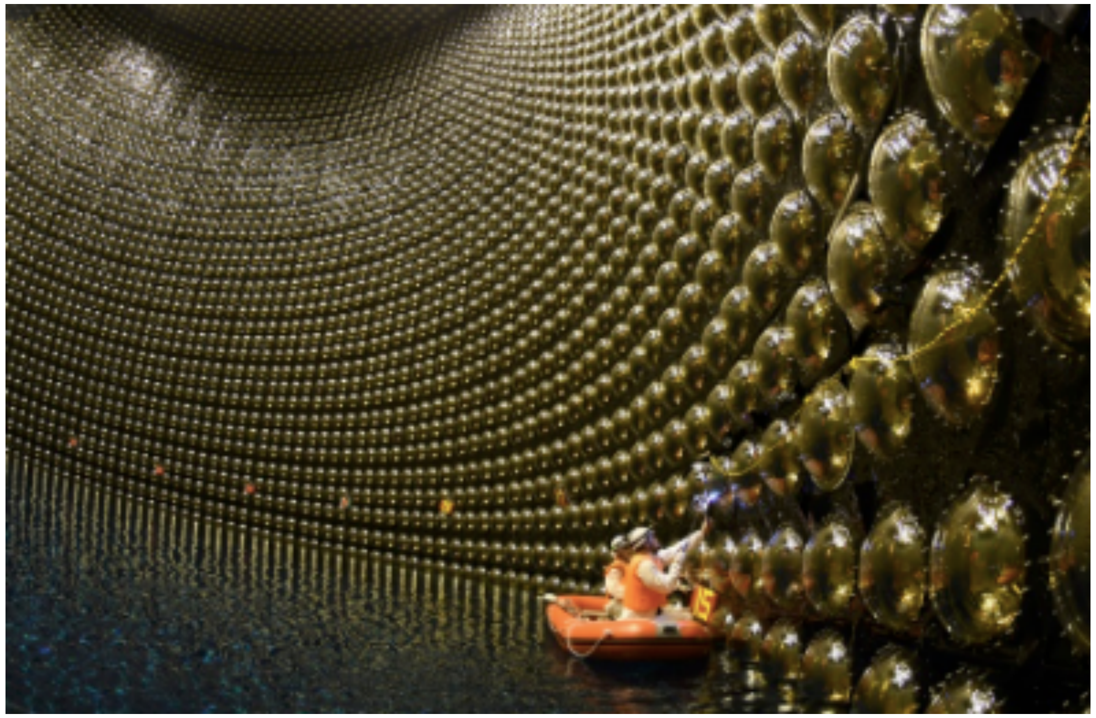
# 3.2 La Frontera de precisión

- Para observar un proceso muy raro, como un decaimiento de un núcleo radiactivo, se necesitan muchos núcleos, N = N_0 exp(-T/tau)




- Kamiokande, IMB: neutrinos, proton decay,

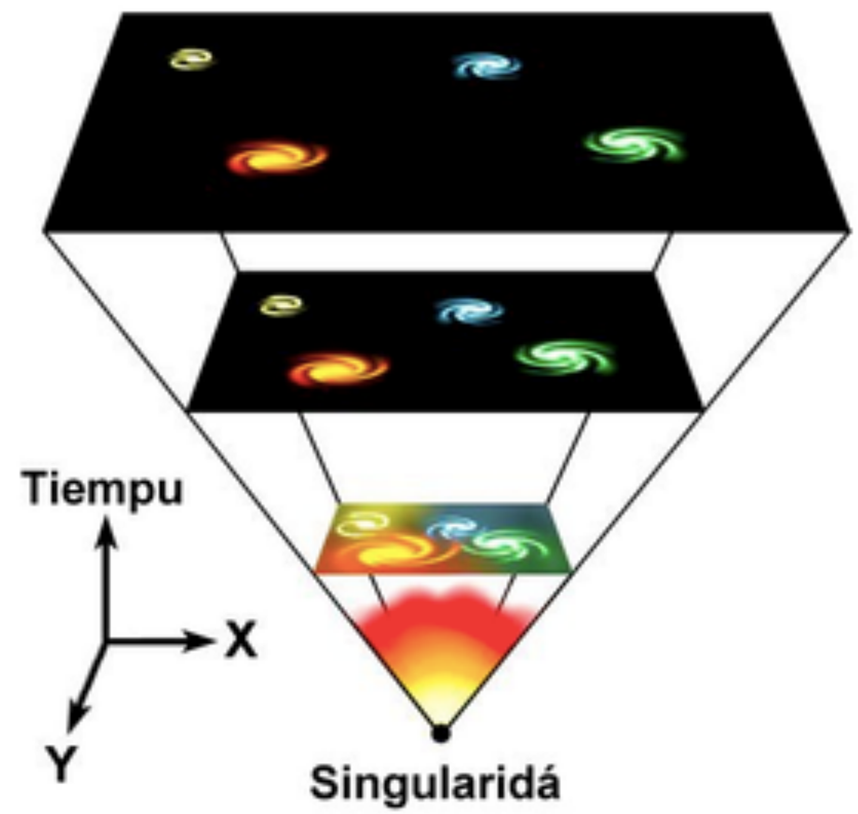
- Reactores nucleares: momentos eléctricos y magnéticos (neutrons, electrons, muons), neutrinos,

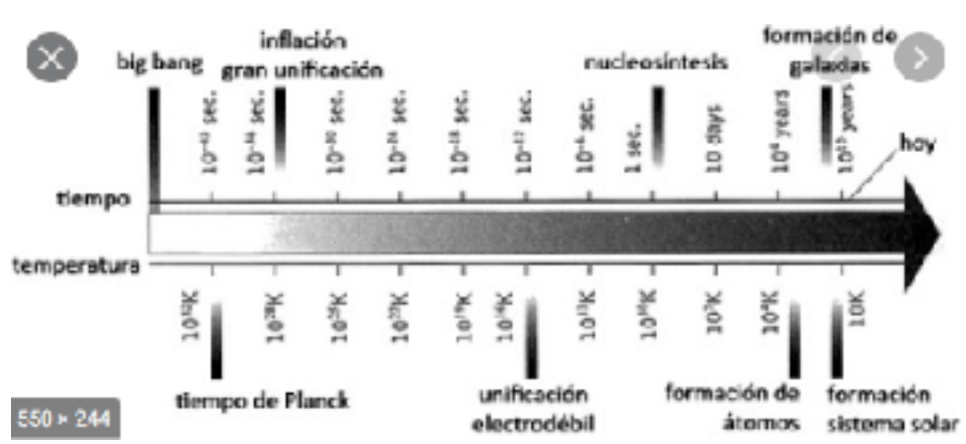


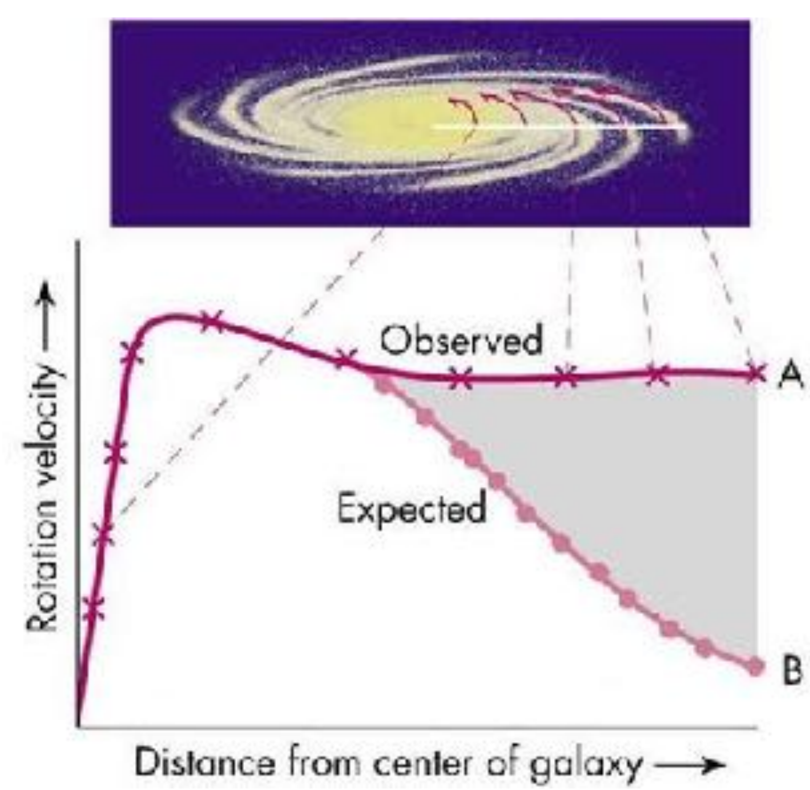
- Fuentes de b, taus, muon (Belle, …)

# 3.3 La Frontera Cósmica

- La exploración del universo nos ha permitido medir su edad, origen y composición,
- La expansión del universo nos permite inferir que su edad es de aprox. 13.8 mil millones de años  (Big-Bang)
- Ese origen dejó una huella: la Radiación cósmica de fondo (CMB),
- ¿Está el universo hecho de los mismo que nosotros? ¿Son las leyes físicas las mismas en la tierra que en el cielo?



# Gracias!