Precision -- Higgs and SM

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SLAC NATIONAL ACCELERATOR LABORATORY

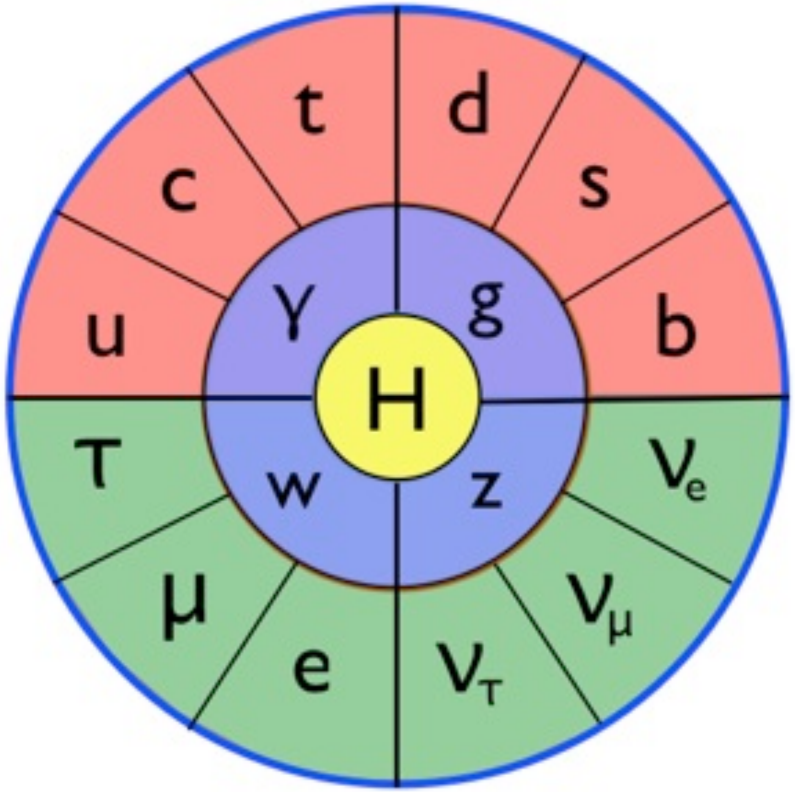
West Coast LHC Jamboree

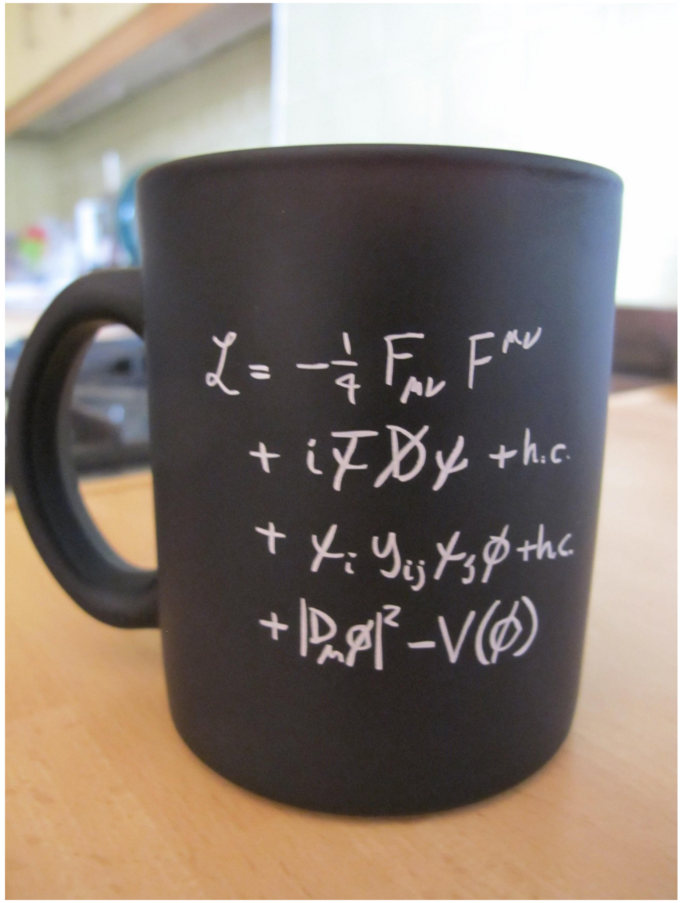
Disclaimer

- Impossible to cover everything and give much detail.

- Will try to give some broad context and cherry-pick a few topics.

The Standard Model is self-consistent after the discovery of the Higgs:





Self-consistent = Complete ?

(UV complete) (No BSM)

Self-consistent $\neq$ Complete

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This is a fallacy that has been refuted through out the course of history:

Self-consistent ≠ Complete

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- QED (photons+electrons) is UV-complete. But physics didn't stop there.
- QCD (gluons+quarks) is UV-complete. Again it didn't stop there.
- SM with one generation of fermion is UV-complete. "WHO ORDERED THAT?"

Not to mention the empirical evidence for BSM physics:
dark matter, dark energy, baryon asymmetry and etc.

The New York Times

Opinion

GRAY MATTER

A Crisis at the Edge of Physics

By Adam Frank and Marcelo Gleiser

June 5, 2015

“But the standard model, despite the glory of its vindication, is also a dead end. It offers no path forward […]”

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“But the standard model, despite the glory of its vindication, is also a dead end. It offers no path forward […]”

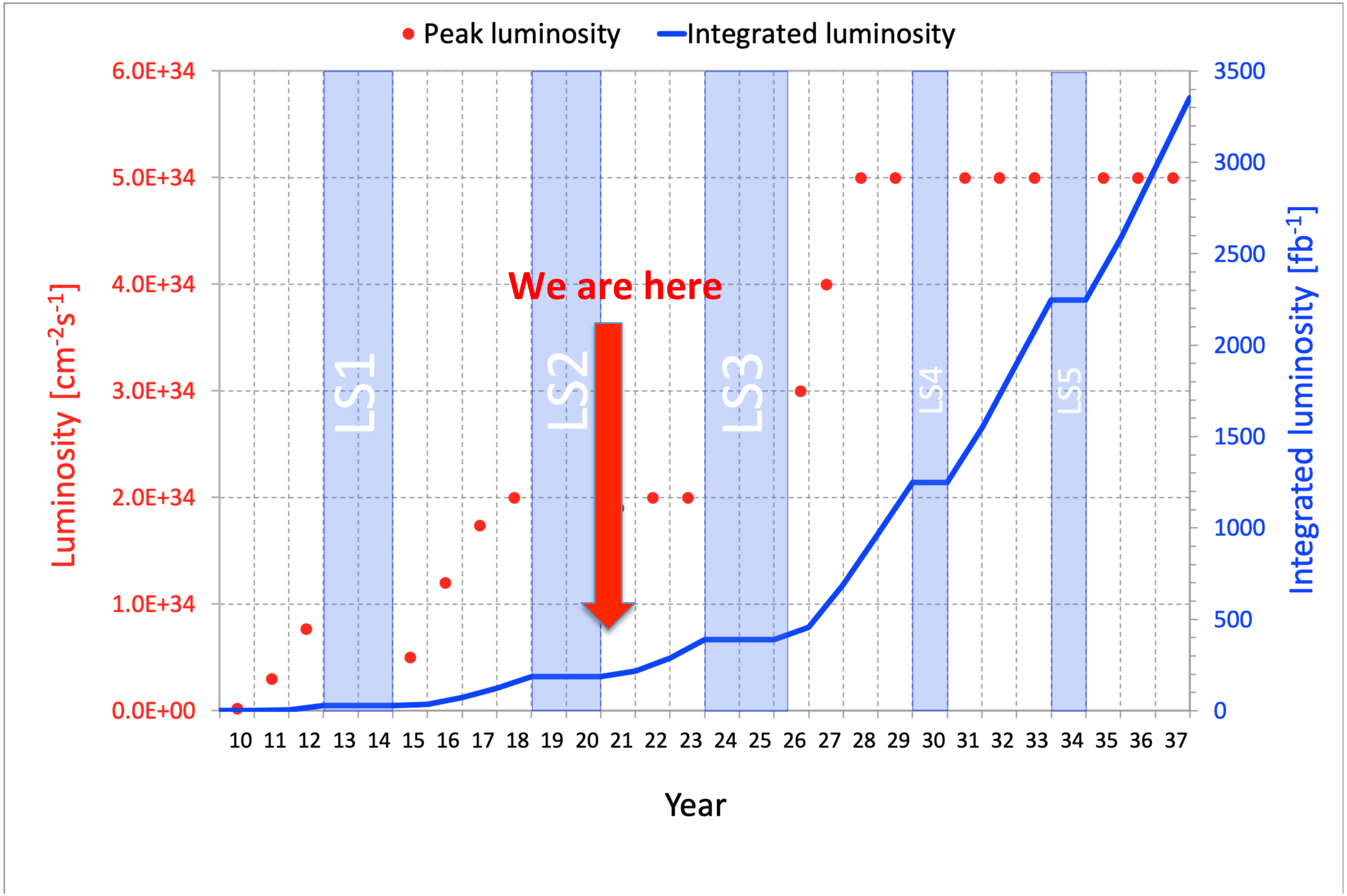
Yet another fallacy…

We find path forward by

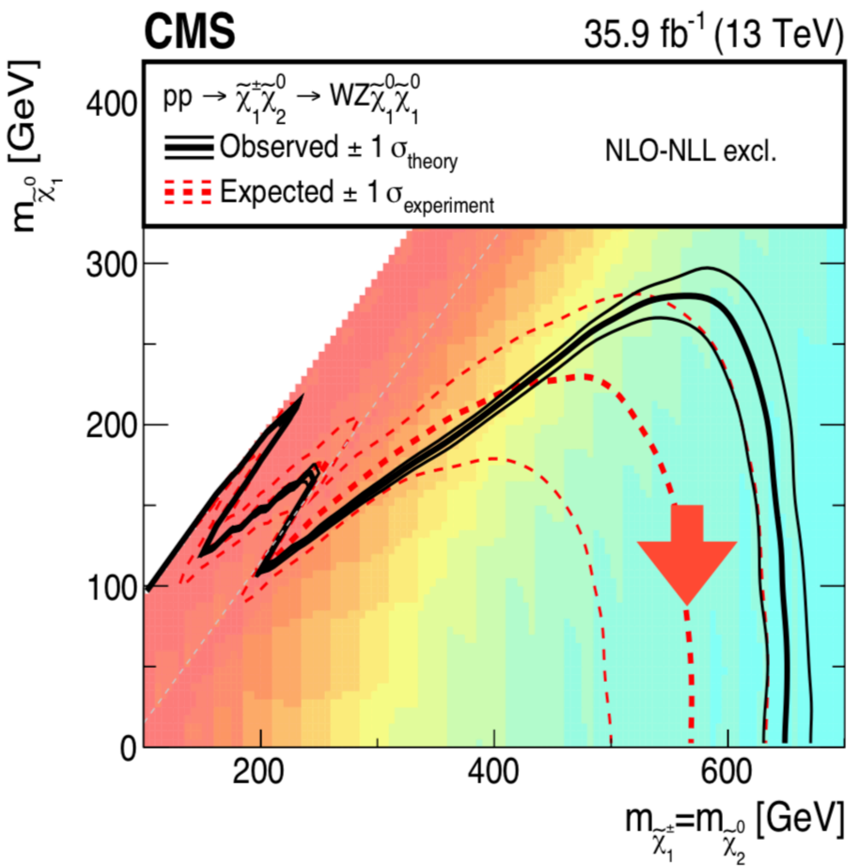
- Testing predictions of SM that have yet to be verified.

- Asking the right questions
  - conceptual and empirical questions that can’t be answered by the SM.

To move forward we will need data – LHC has only collected 5% of its designed luminosity:



The value of luminosity is often under-appreciated:

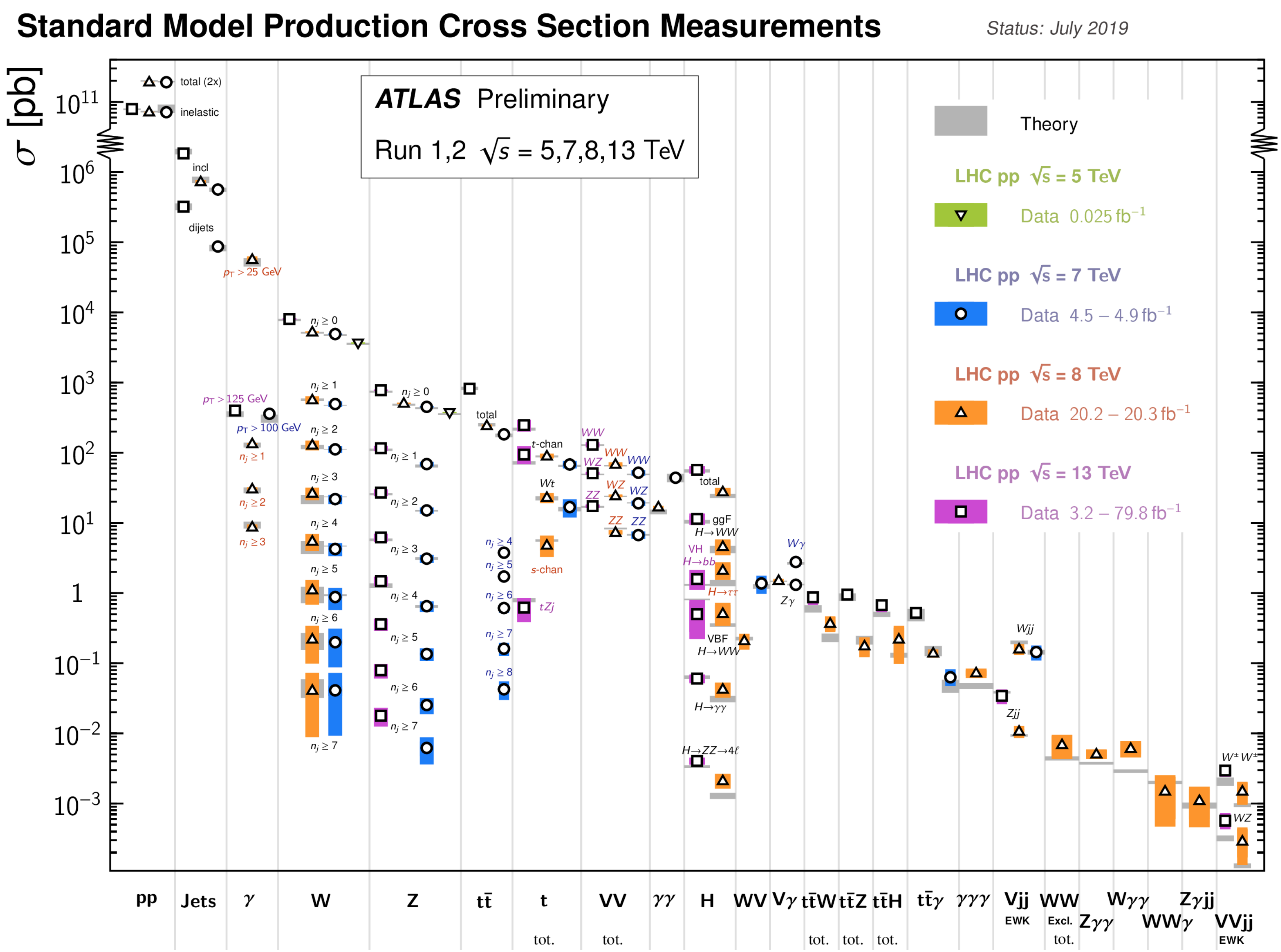


- Suppose we had a choice between
  - HL-LHC (14 TeV, $3ab^{-1}$)
  - or going to higher c.o.m. energy but limited to $80fb^{-1}$.
- How much energy would we need to equal the HL-LHC?

today's reach (13 TeV, $80fb^{-1}$)	HL-LHC reach (14 TeV $3ab^{-1}$)	energy needed for same reach with $80fb^{-1}$
4.7 TeV SSM Z'	6.7 TeV	20 TeV
2 TeV weakly coupled Z'	3.7 TeV	37 TeV
680 GeV chargino	1.4 TeV	54 TeV

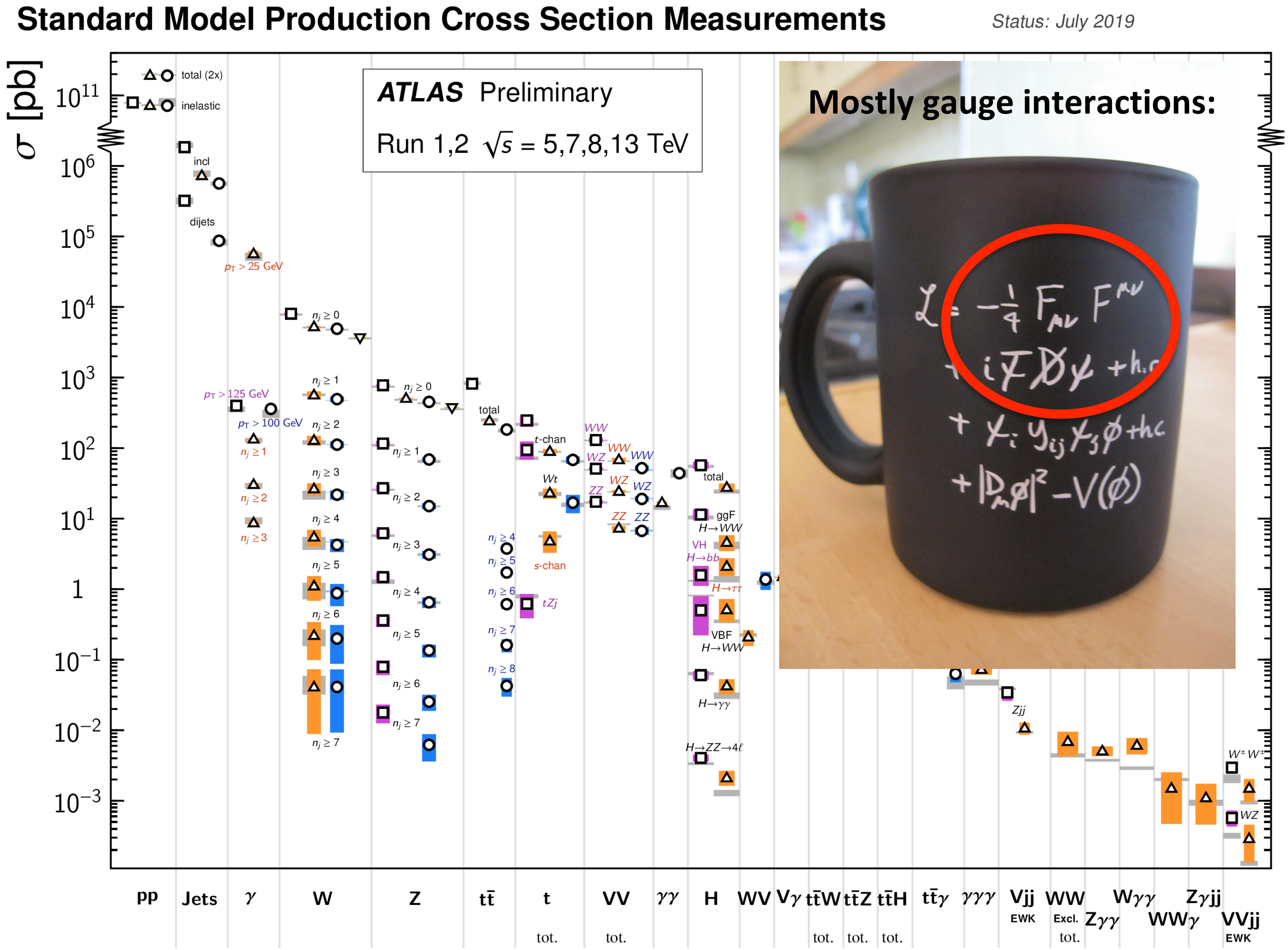
G. Salam @ LHCP 2018

Predictions of SM
(that have yet to be verified)

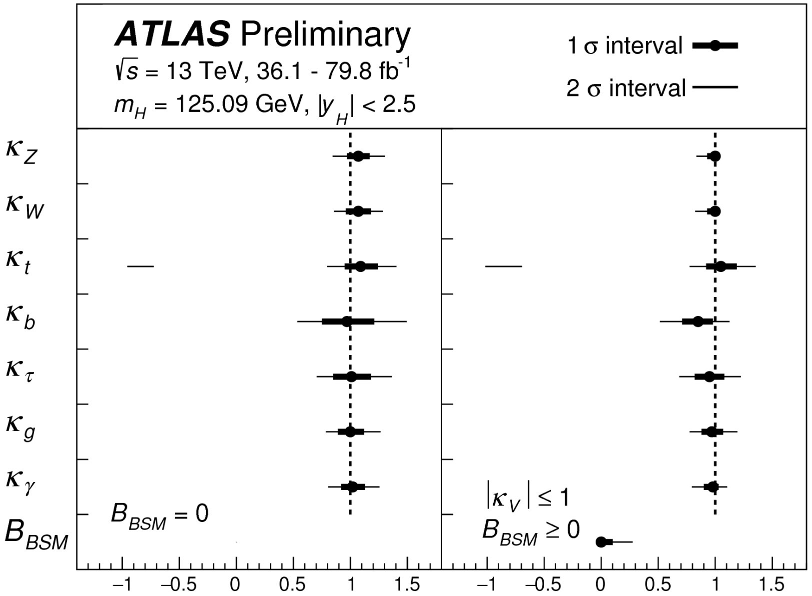


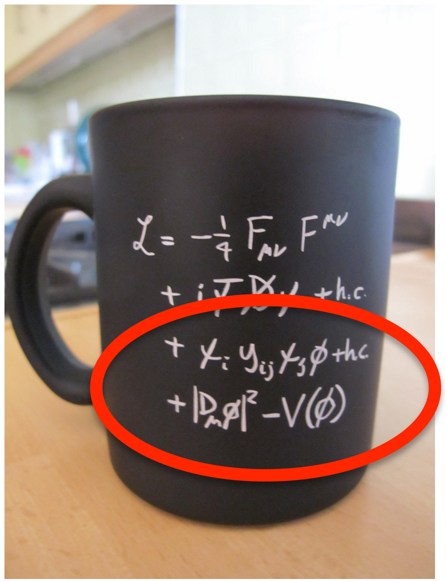
Standard Model Production Cross Section Measurements
Status: July 2019
ATLAS Preliminary
Run 1,2 √s = 5,7,8,13 TeV
Theory
LHC pp √s = 5 TeV
Data 0.025 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 79.8 fb⁻¹
σ [pb]
total (2x)
inelastic
incl
dijets
pT > 25 GeV
pT > 125 GeV
pT > 100 GeV
total
t-chan
Wt
s-chan
tZj
ggF
H→WW
VH
H→bb
H→ττ
VBF
H→γγ
H→ZZ→4ℓ
Wγ
Zγ
Wjj
Zjj
pp Jets γ W Z tt̄ t VV γγ H WV Vγ tt̄W tt̄Z tt̄H tt̄γ γγγ Vjj WW Zγγ Wγγ WWγ Zγjj VVjj

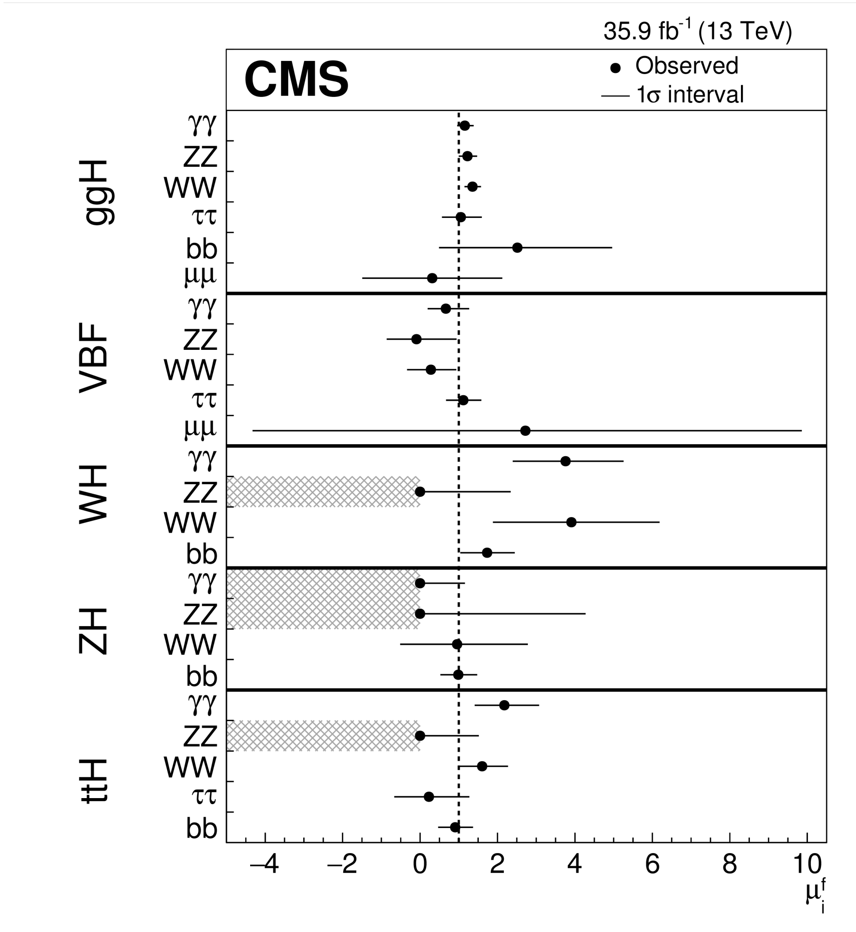
Mostly gauge interactions:



There is also the Higgs interaction:







Let me emphasize the Standard Model Higgs boson is a very special one!

In the Standard Model:

Couplings to massive gauge bosons →

$$\left(\frac{2m_W^2}{v}\,h\,W_\mu^+W^{-\,\mu} + \frac{m_Z^2}{v}\,h\,Z_\mu Z^\mu\right)$$

Couplings to massless gauge bosons →

$$+c_g\frac{\alpha_s}{12\pi v}h\,G^a_{\mu\nu}G^{a\,\mu\nu} + c_\gamma\frac{\alpha}{8\pi v}h\,F_{\mu\nu}F^{\mu\nu} + c_{Z\gamma}\frac{\alpha}{8\pi v s_w}\,h\,F_{\mu\nu}Z^{\mu\nu}$$

$$c_g^{(SM)}(125\text{ GeV}) = 1\ , \qquad c_\gamma^{(SM)}(125\text{ GeV}) = -6.48\ , \qquad c_{Z\gamma}^{(SM)}(125\text{ GeV}) = 5.48\ .$$

Couplings to fermions → $\sum_f \frac{m_f}{v}h\bar{f}f$

Self-couplings → $\frac{1}{2}m_h^2h^2 + \frac{m_h^2}{v}h^3 + \frac{2m_h^2}{v^2}h^4$

Once the mass is known, every single coupling is then determined!!

So far we have measured a subset of couplings with O(10-30%) uncertainty:

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$$\sum_f \frac{m_f}{v}\, h \bar{f} f$$

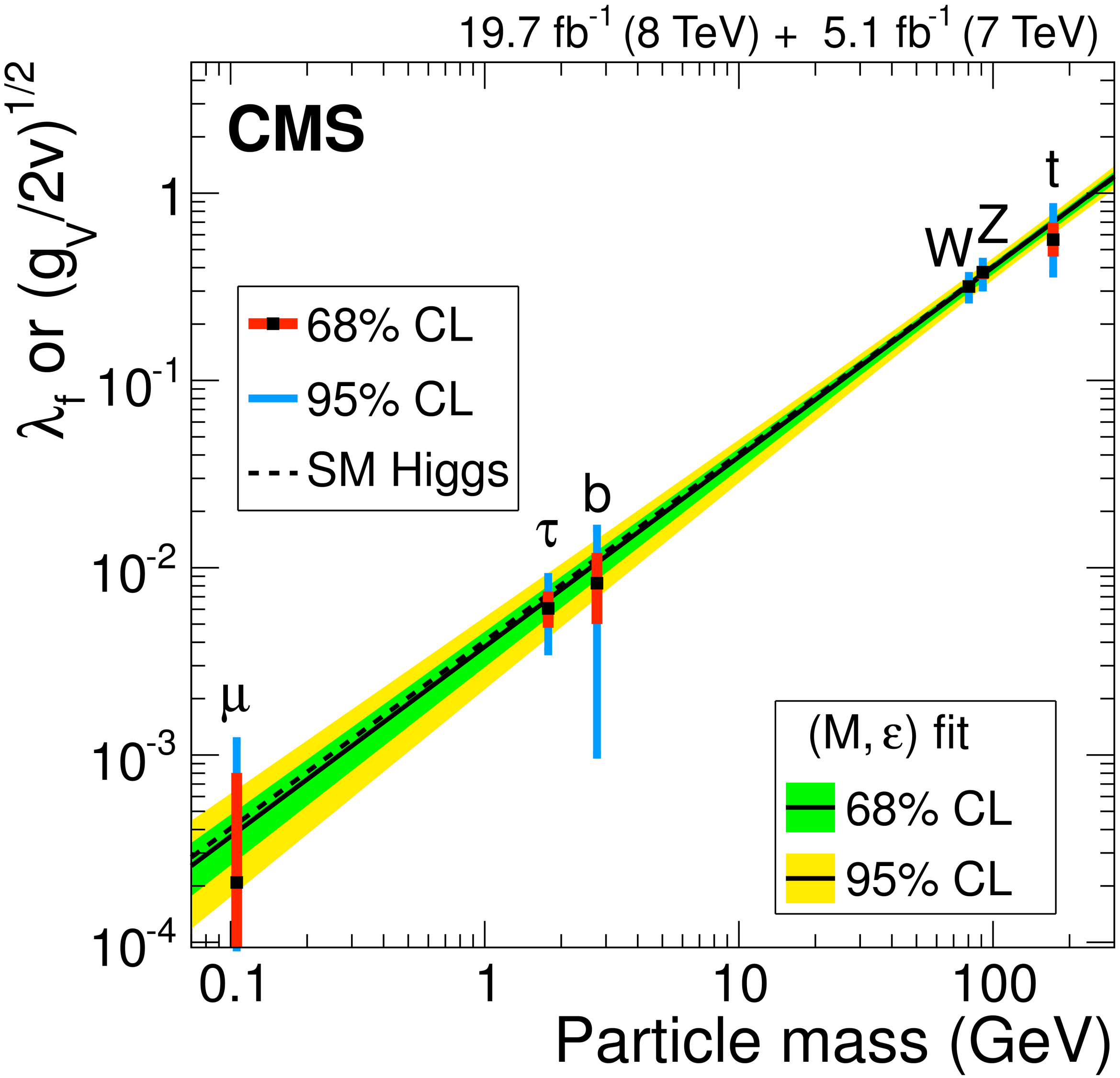
✔ for *bb*, *tt*, and *ττ* only!

Self-couplings →

$$\frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{v} h^3 + \frac{2m_h^2}{v^2} h^4$$

A “SM Higgs” is hardly vindicated!

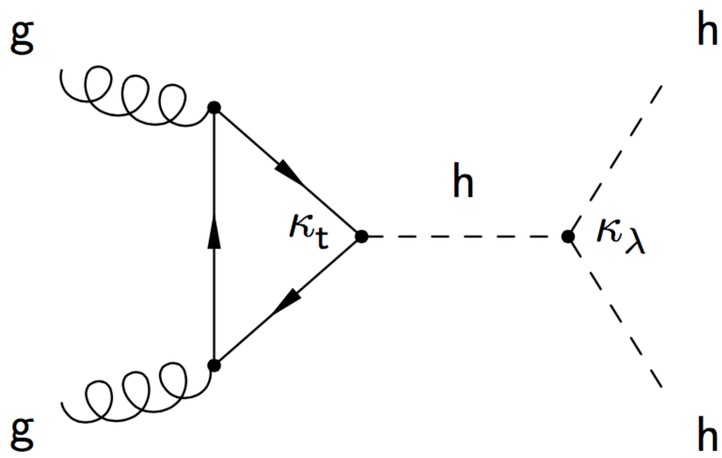
- We need to keep pursuing Yukawa couplings to 1st and 2nd generation fermions:



But there are two important classes of Higgs couplings that have yet to be established experimentally:

- Higgs self-couplings:

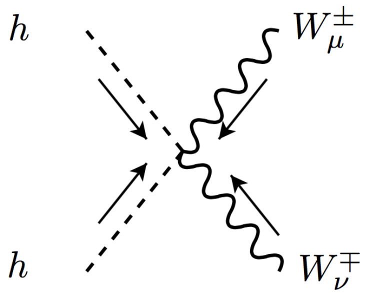
  This can be measured in the double-Higgs production



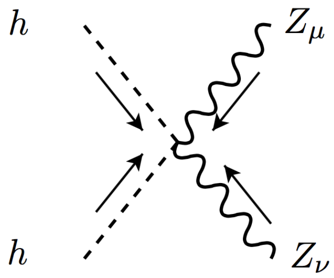
It is difficult to measure at the LHC, but experimental colleagues are making progress.

- The second class of coupling, however, is still largely missing from the picture -- the HHVV coupling

$$D_\mu H^\dagger D^\mu H \;\supset\; g^2 h^2 V_\mu V^\mu$$



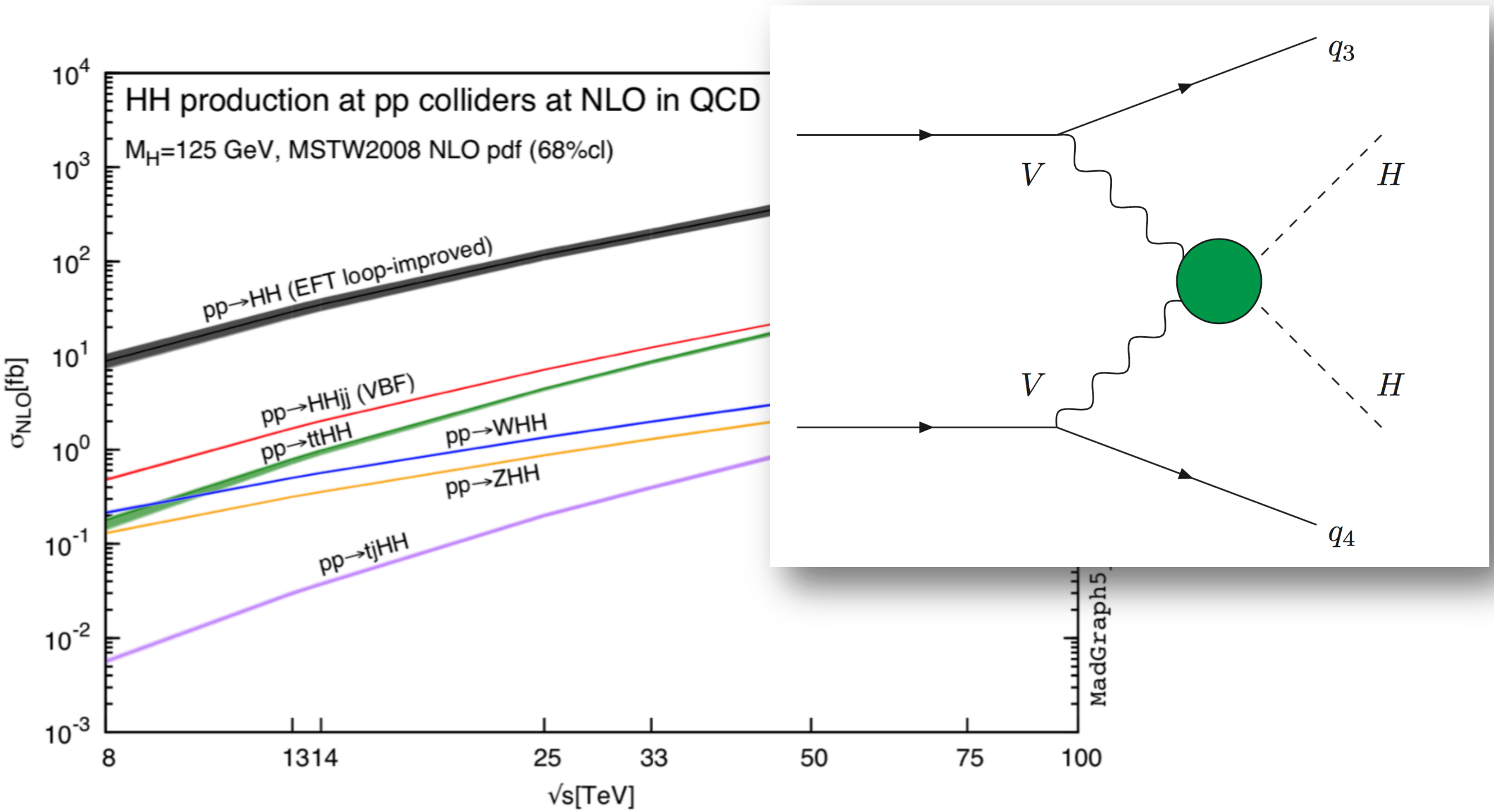
$$\frac{i}{2} g^2 g_{\mu\nu}$$



$$\frac{i}{2} \frac{g^2}{\cos^2\theta_W} g_{\mu\nu}$$

This is a hybrid Higgs-Gauge interaction.

This coupling can be probed in VBF HH production:



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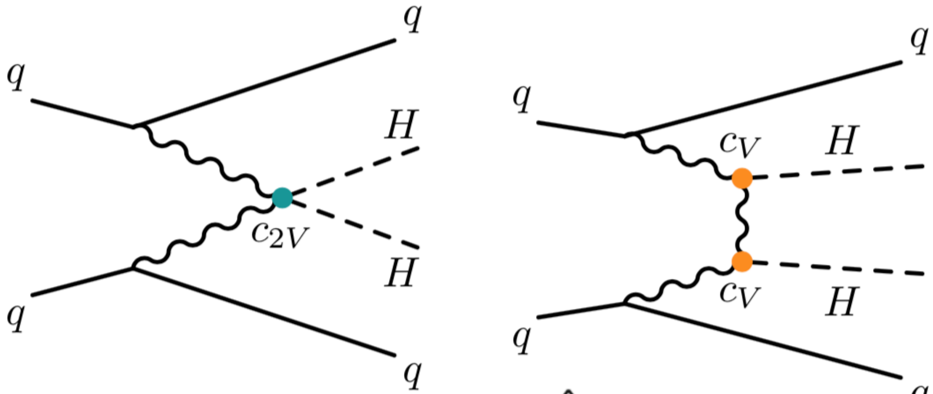
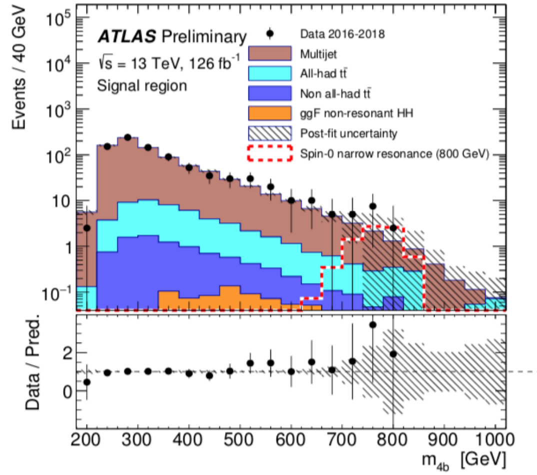
A first result from ATLAS on VVHH coupling:

Interference in other SM diagrams lead to similar vanishingly small x-sec

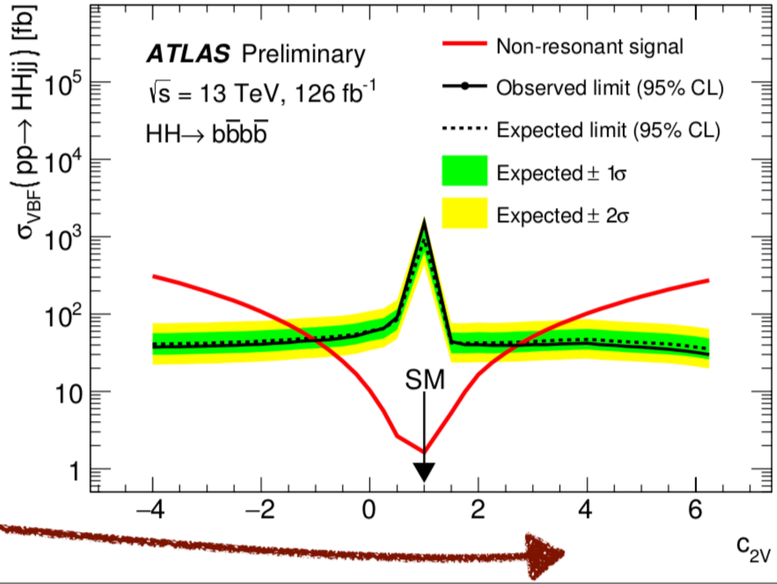


$$\mathscr{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)$$

ATLAS-CONF-2019-030



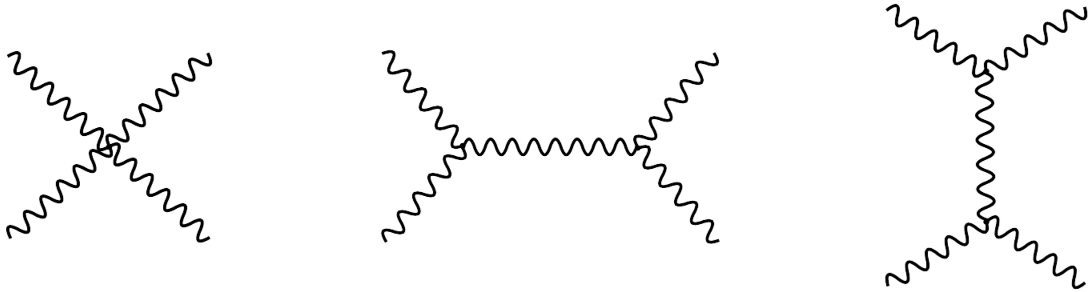
VBF di-Higgs production is one example!



First limits on the 4-point VVHH coupling

- One very important prediction of SM need to be pin-down precisely:

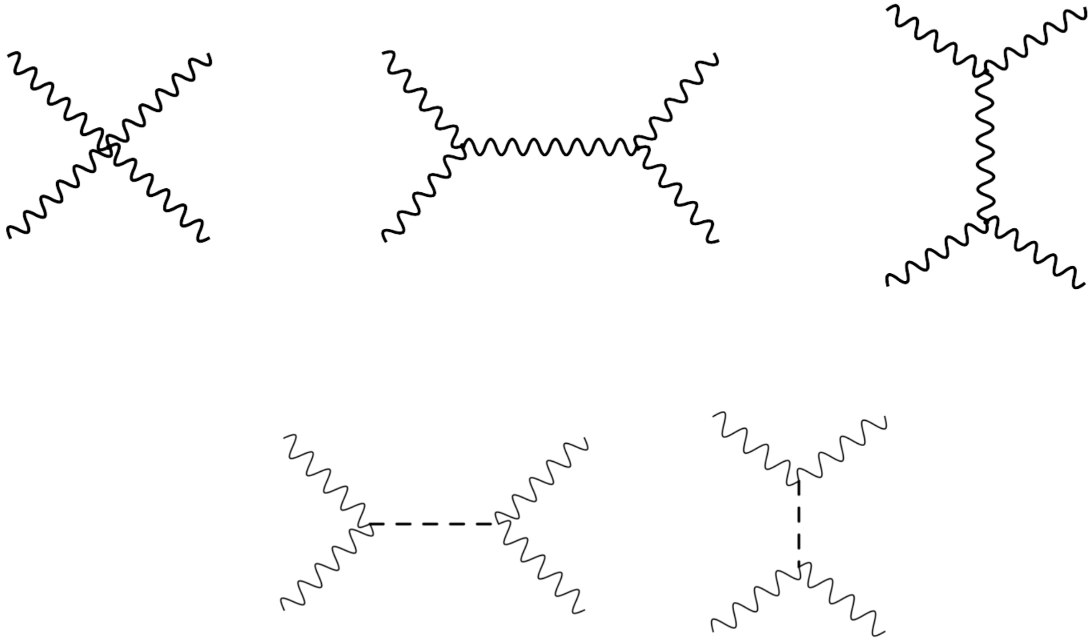
Without the Higgs, WW scattering amplitude violates unitarity:



$$\mathcal{A}(W_L^+W_L^- \to W_L^+W_L^-) \simeq \frac{g^2}{4m_W^2}(s+t) \ .$$

- One very important prediction of SM need to be pin-down precisely:

Including the Higgs contribution allows the growth to be cancelled completely,



provided the HWW coupling have precisely the form in the SM!

This is an extremely simple and economical solution, except…

Except that this is not how Nature *usually* deals with a situation like this.

(Recall we have NOT observed a fundamental scalar previously!)

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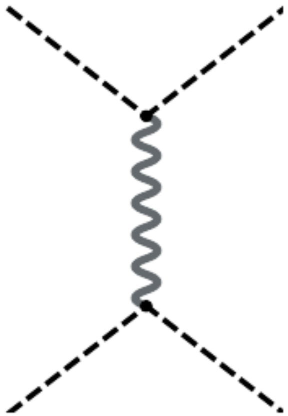
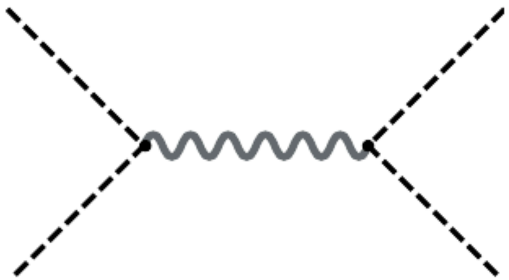
(Recall we have NOT observed a fundamental scalar previously!)

For example, pi-pi scattering is unitarized by a series of heavy resonances, including the spin-1 rho meson:





Each resonance only partially unitarizes the pi-pi scattering.

If the 125 GeV Higgs does NOT unitarize the VV scattering

→ the HVV coupling will be reduced from the SM expectation!!

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→ the HVV coupling will be reduced from the SM expectation!!

Unitarization in VV scattering is only tested with O(10%) uncertainty.

→ Clearly not sufficient!

To test this prediction we need to

- More precise measurements of HVV couplings.
- Direct measurements of VV scatterings.

Higgs coupling is a mature field of experimental physics at the LHC:

$$\delta_{hWW} \sim \frac{v^2}{f^2} \sim 10\% \quad \Rightarrow \quad f \sim 500 \text{ GeV}$$

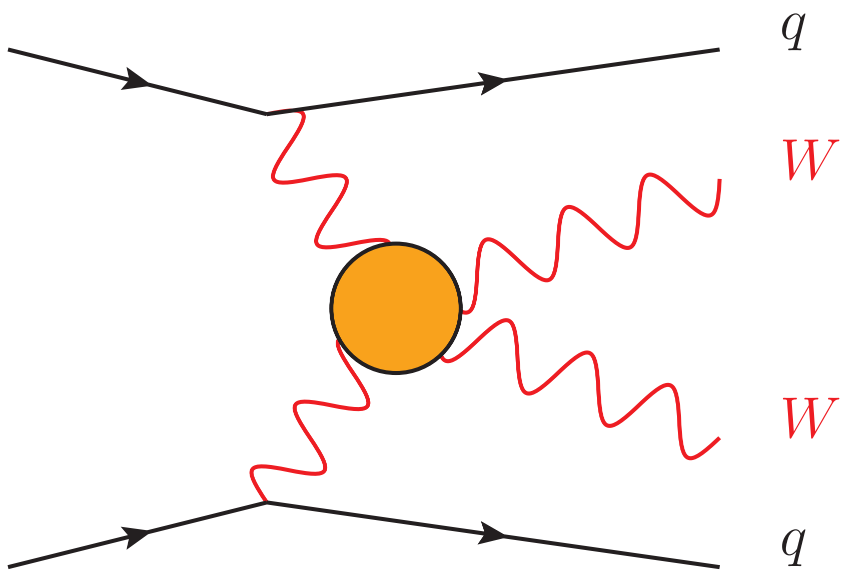
If the precision is improved,

ECFA 1905.03764

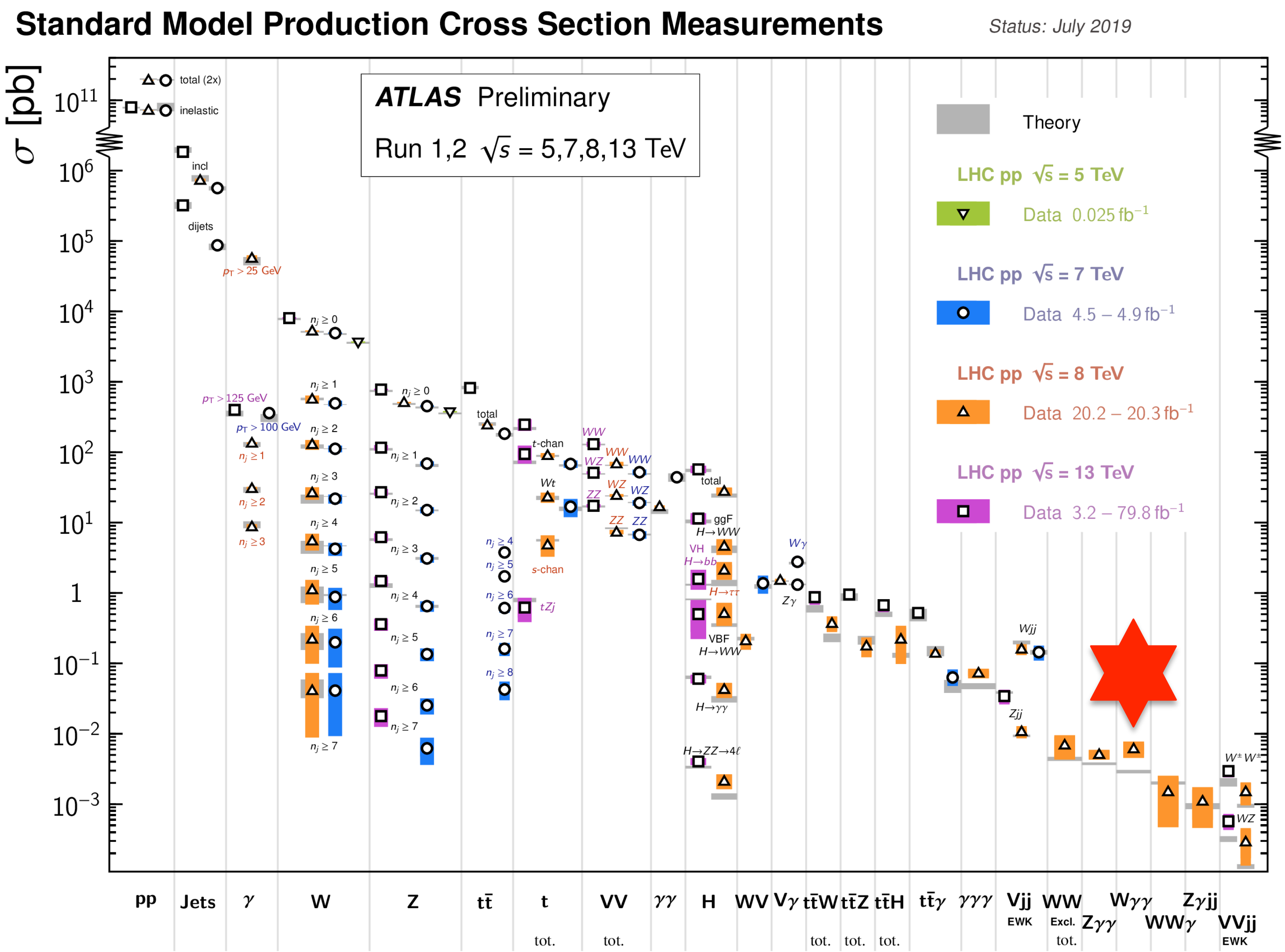
	HL-LHC	ILC250	ILC500	CLIC380	CLIC1500	CEPC	FCCee240	FCCee350
hZZ	3.6	0.47	0.22	0.66	0.27	0.52	0.47	0.26
hWW	3.2	0.48	0.23	0.65	0.24	0.51	0.46	0.27
hbb	5.1	0.83	0.52	1.0	0.47	0.67	0.70	0.56
hcc	-	1.8	1.2	4.0	1.9	1.9	1.4	1.3
$h\tau\tau$	3.5	0.85	0.60	1.3	0.93	0.70	0.70	0.57
hgg	2.2	1.1	0.79	1.3	0.97	0.79	0.95	0.82
$h\gamma\gamma$	3.7	1.3	1.1	1.4	1.2	1.2	1.2	1.2

$$\delta_{hWW} \sim 1\% \quad \Rightarrow \quad f \sim 1.7 \text{ TeV}$$
$$\delta_{hWW} \sim 0.1\% \quad \Rightarrow \quad f \sim 5.5 \text{ TeV}$$

Direct measurements of VV scatterings rely on VBF topology:



This is a difficult channel due to small rates:



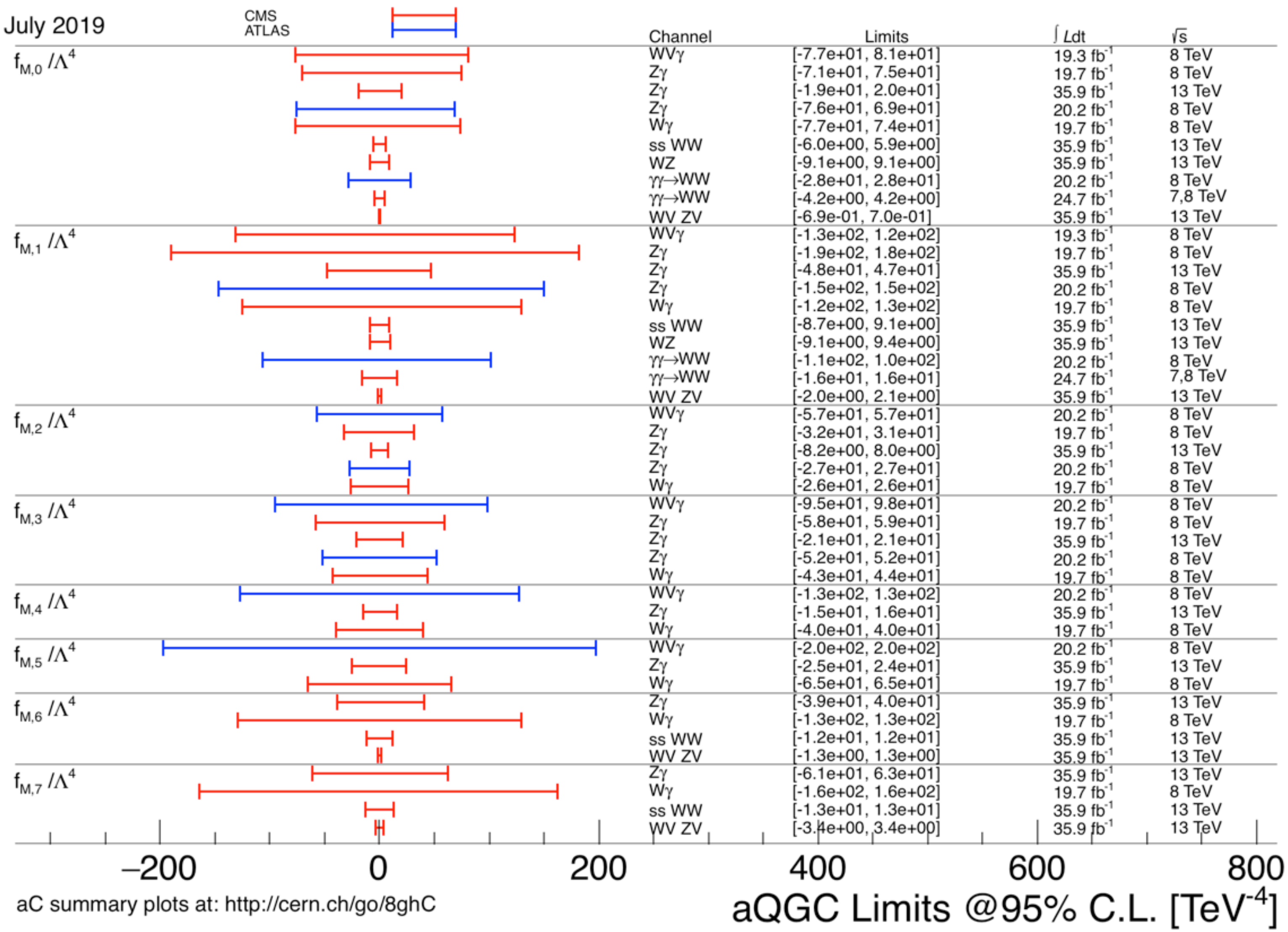
Experimental results are beginning to show up:

Channel	$\sqrt{s}$		Luminosity [fb^{-1}]		Observed (expected) significance	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$Z(\ell\ell)\gamma$	8 TeV	8 TeV	20.2	19.7	2.0σ (1.8σ)[82]	3.0σ (2.1σ)[83]
$Z(\nu\nu)\gamma$	8 TeV	–	20.2	–	Only aQGC lim. [82]	–
$W^{\pm}W^{\pm}$	8 TeV	8 TeV	20.3	19.4	3.6σ (2.3σ)[5],[4]	2.0σ (3.1σ)[6]
$W^{\pm}W^{\pm}$	–	13 TeV	–	35.9	–	5.5σ (5.7σ)[7]
$W(\ell\nu)\gamma$	–	8 TeV	–	19.7	–	2.7σ (1.5σ) [84]
$Z(\ell\ell)Z(\ell\ell)$	–	13 TeV	–	35.9	–	2.7σ (1.6σ) [85]
$W(\ell\nu)Z(\ell\ell)$	8 TeV	8 TeV	20.2	19.4	Only aQGC lim. [86]	N/A [6]
$W(\ell\nu)V(qq)$	8 TeV	–	20.2	–	Only aQGC lim. [87]	–
$\gamma\gamma \to WW$	–	7 TeV	–	5.05	–	$\sim 1\sigma$ [88]
$\gamma\gamma \to WW$	8 TeV	7+8 TeV	20.2	24.8	3.0σ [89]	3.4σ (2.8σ) [90]

Table 6: Summary of all published experimental results on VBS processes by final state with the details on luminosity and energy at the center of mass $\sqrt{s}$ used for the measurements. When available both expected and observed significances are provided. Channels for which "Only aQGC limits" were studied are indicated in the significance column.

1801.04203

With the EFT approach a large number of higher dimensional operators contribute:



The challenge:

Complicated final states + the need to disentangle effects from many different EFT operators.

How do we achieve precision?

Can machine learning help?

Inference Techniques

Traditional

- use summary statistics
  * hand-picked observables x'
  * estimate p(x'|θ)
- information loss
- problem dependent

Examples:

- rate only (cut and count)
- histograms
- Approximate Bayesian Computation
- STXS

Machine Learning

- multivariate analysis
- works great for S vs BG
- struggles with S' vs S
  * large number of S'
  * very similar S', S

Examples:

- Neural Density Estimator
- ML Classifier

Matrix Element Based

- multivariate analysis
- uses $p(x|\theta) \sim |M(x|\theta)|^2$
- works great at parton level
  * S' vs S is easy
- requires approximations in reality
  * S vs BG can be hard

Examples:

- Matrix Element Method
- Optimal Observables

power of machine learning → **MadMiner** ← physics insight of matrix element information

[J. Brehmer, K. Cranmer, G. Louppe, J. Pavez 1805.00013, 1805.00020, 1805.12244]

[J. Brehmer, FK, I. Espejo, K. Cranmer 1907.10621]

F. Kling @ SMEFT workshop at Argonne

Asking the right conceptual questions

A few years ago my (then) 7-year-old asked one such question:

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What is the Higgs boson made of?

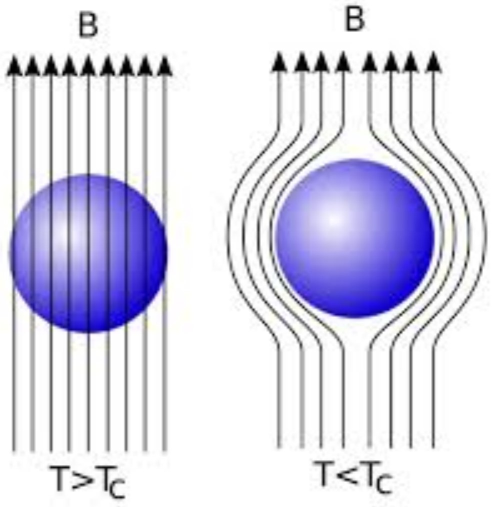
A physics Ph.D. could rephrase slightly:

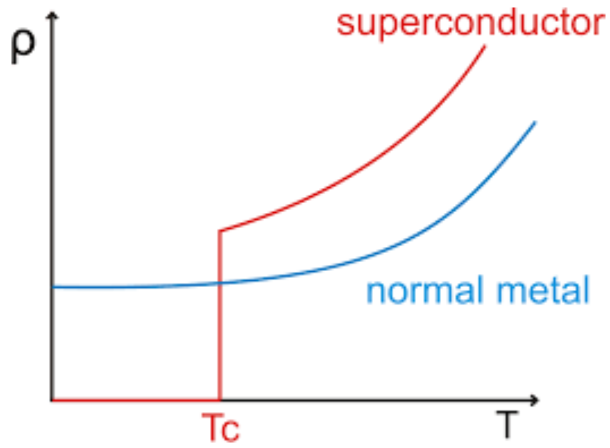
What is the microscopic theory that gives rise to the Higgs boson and its potential?

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

Our colleagues in condensed matter physics are very used to asking, and studying, this kind of questions.

One of the most beautiful examples is the superconductivity discovered in 1911:





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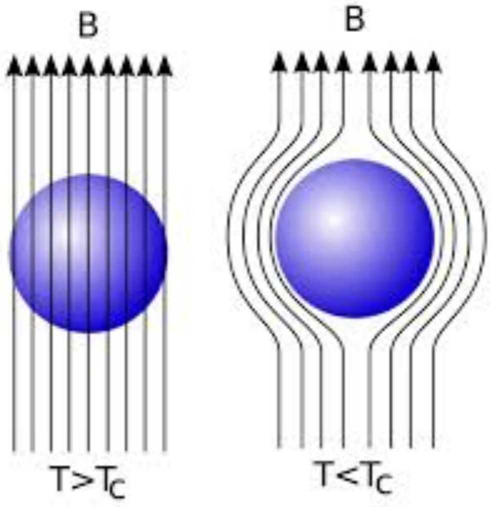

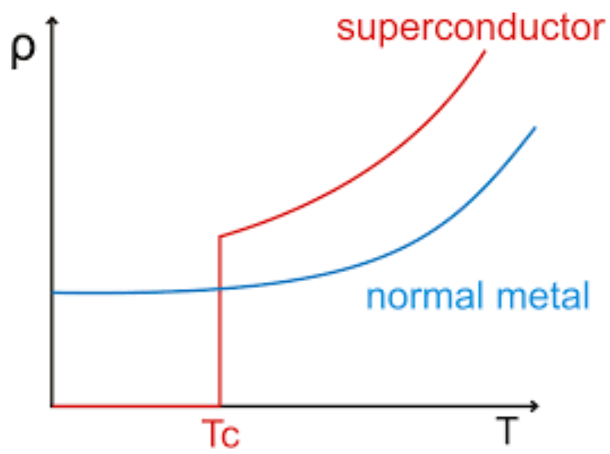

Ginzburg-Landau theory from 1950 offered a **macroscopic** (ie effective) theory for conventional superconductivity,

$$V(\Psi) = \alpha(T)|\Psi|^2 + \beta(T)|\Psi|^4 \qquad \alpha(T) \approx a^2(T - T_c) \qquad \text{and} \qquad \beta(T) \approx b^2$$

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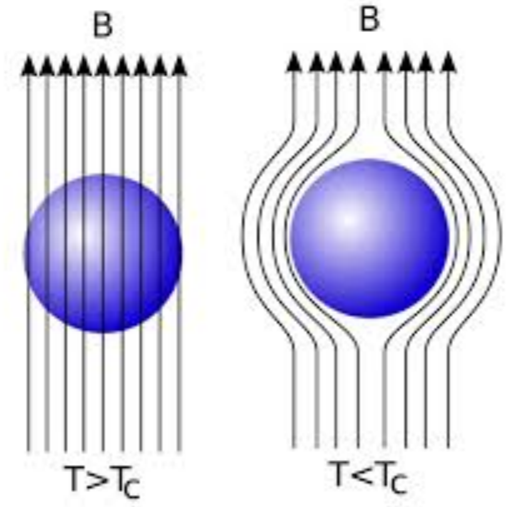

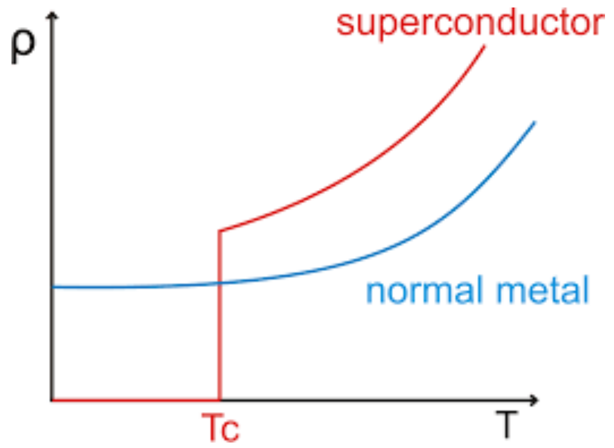

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What is the **microscopic** origin of the Ginzburg-Landau potential for superconductivity?

In 1957 Bardeen, Cooper and Schrieffer provided the **microscopic** (fundamental) theory that allows one to

1) interpret $|\Psi|^2$ as the number density of Cooper pairs

2) calculate coefficients of $|\Psi|^2$ and $|\Psi|^4$ in the potential.

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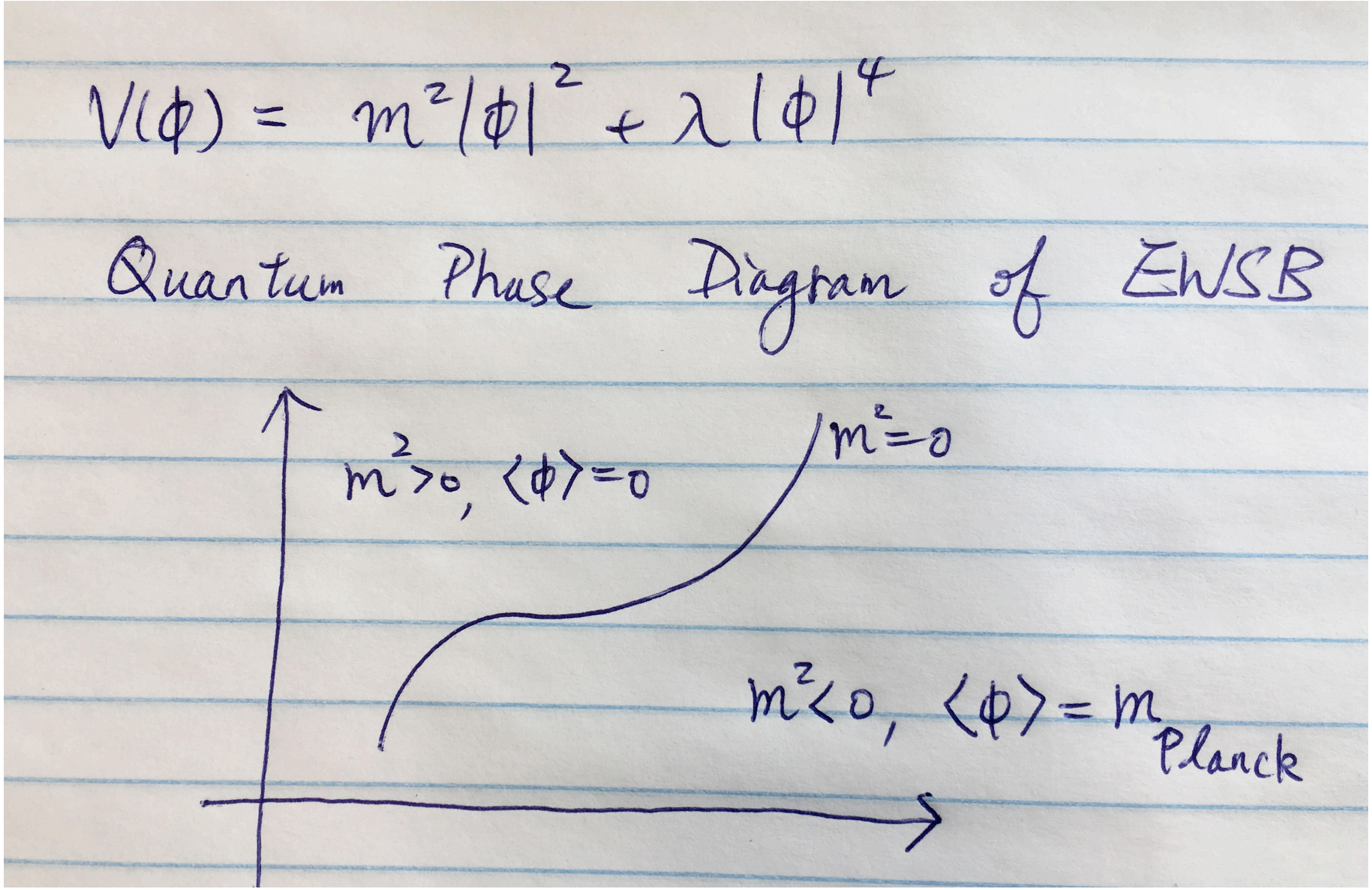
1) interpret $|\Psi|^2$ as the number density of Cooper pairs

2) calculate coefficients of $|\Psi|^2$ and $|\Psi|^4$ in the potential.

We do not have the corresponding **microscopic** theory for the Higgs boson.

In fact, we have NOT even measured the Ginzburg-Landau potential of the Higgs!

The question can be reformulated in terms of **Quantum Criticality**:



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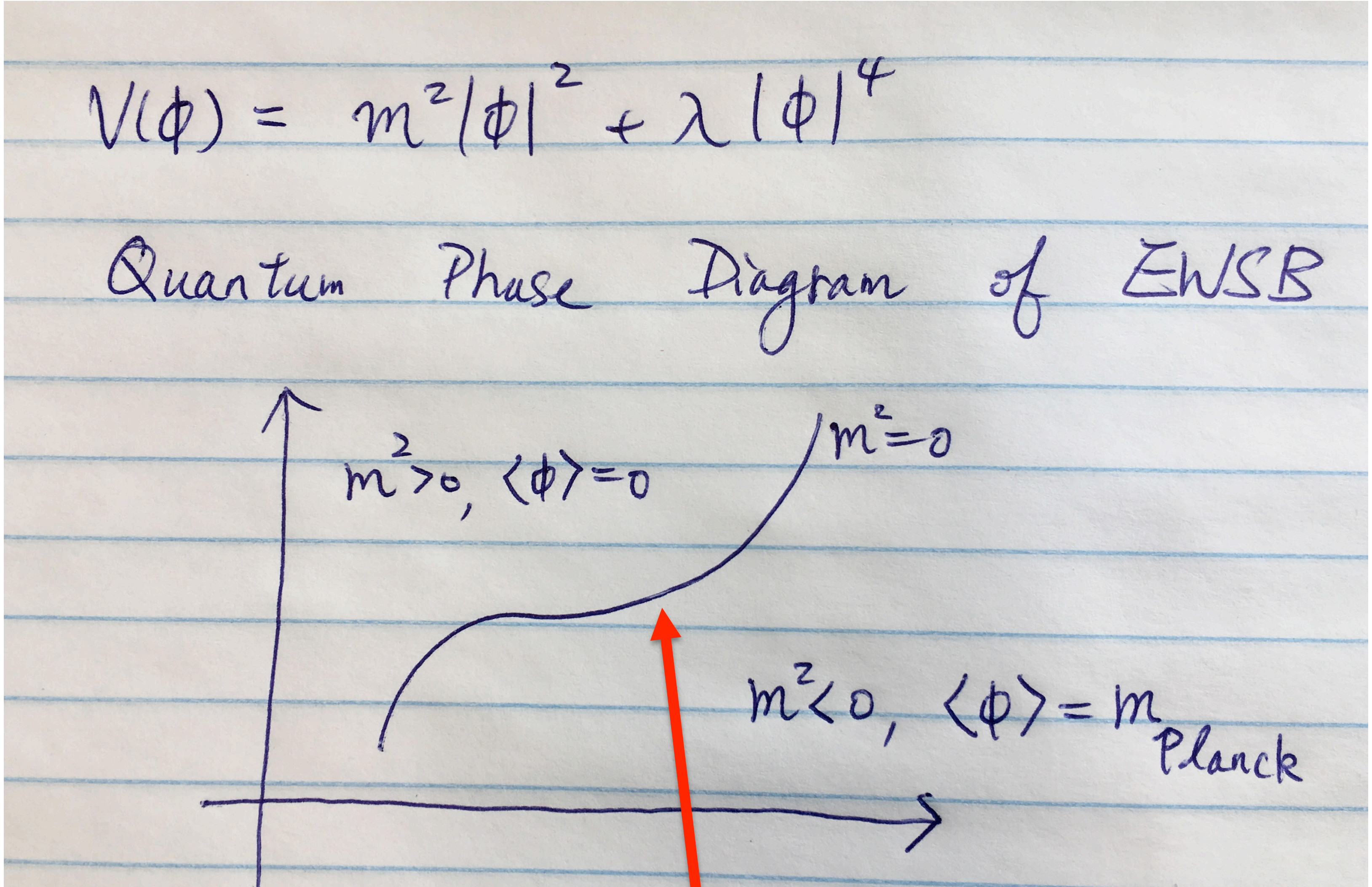

Mh=125 GeV. We are sitting extremely close to the criticality. **WHY??**

One appealing possibility – the critical line is selected dynamically.

This is the analogy of BCS theory for electroweak symmetry breaking. It goes by the name of “technicolor,” which is strongly disfavored experimentally.

The fact that we have not seen signs of BSM physics only **deepens** the mystery, of why we are sitting close to the critical line of EWSB!

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"Our Universe is not a piece of crappy metal!"

-- Nima Arkani-Hamed @ the Chicago workshop on CEPC

The Higgs boson really is the most exotic state of matter!

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In order to understand the *microscopic* nature of the Higgs, we can measure:

- Deviations in H(125) coupling structure.
- Rare and new decay channels of H(125).
- Partners of the SM top quark that couple significantly to H(125).

In considering deviations in the couplings, it is useful to recall the generic expectation from decoupling:

$$\mathcal{O}\left(\frac{v^2}{M_{\rm new}^2}\right) \sim 5\% \times \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2$$

So any significant deviation necessarily implies the existence of “light” degrees of freedom below 1 TeV!

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Alternatively, to establish credible deviations would require a precision at the percent level!

No need to feel distressed that no credible deviation is showing up yet (although it’d be nice to be surprised!)

In particular, simultaneous measurements on HVV and HHVV coupling structures allows to detect the presence of possible new symmetry in the Higgs sector.

If the Higgs is a (psuedo) Nambu-Goldstone boson like the pions, there will be a nonlinear symmetry relating multi-Higgs self-interactions.

→ This is a smoking gun signal!

Such a nonlinear symmetry also appears prominently in nuclear physics, relating the self-interactions of pions.

The effective Lagrangian of pions can be written as

$$\mathscr{L} = -\frac{1}{2}\frac{\partial_\mu \vec{\pi} \cdot \partial^\mu \vec{\pi}}{(1+\vec{\pi}^2/F^2)^2} \,. \qquad (19.5.18)$$

Weinberg QFT, Vol II

When expanding the two-derivative in “1/F”, all “multi-pion” vertices are controlled by one single parameter “F”.

For a pseudo-NGB Higgs boson, the analogous expression is:

$$\mathcal{L}^{(2)} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{g^2 f^2}{4}\sin^2(\theta + h/f)\left(W_\mu^+ W^{-\mu} + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu\right)$$

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One way to "detect" the presence of such disguised symmetry is to measure HVV and HHVV couplings to see if they are controlled by the same parameter.

→ Opens up a new experimental frontier

More concretely, we need to measure the anomalous HVV and HHVV couplings simultaneously

$$\mathcal{L}_{\rm NL} = \sum_i \frac{m_W^2}{m_\rho^2}\left(C_i^h \mathcal{I}_i^h + C_i^{2h}\mathcal{I}_i^{2h} + C_i^{3V}\mathcal{I}_i^{3V}\right)$$

$\mathcal{I}_i^h$
(1) $\frac{h}{v} Z_\mu \mathcal{D}^{\mu\nu} Z_\nu$
(2) $\frac{h}{v} Z_{\mu\nu} Z^{\mu\nu}$
(3) $\frac{h}{v} Z_\mu \mathcal{D}^{\mu\nu} A_\nu$
(4) $\frac{h}{v} Z_{\mu\nu} A^{\mu\nu}$

$\mathcal{I}_i^{2h}$
(1) $\frac{h^2}{v^2} Z_\mu \mathcal{D}^{\mu\nu} Z_\nu$
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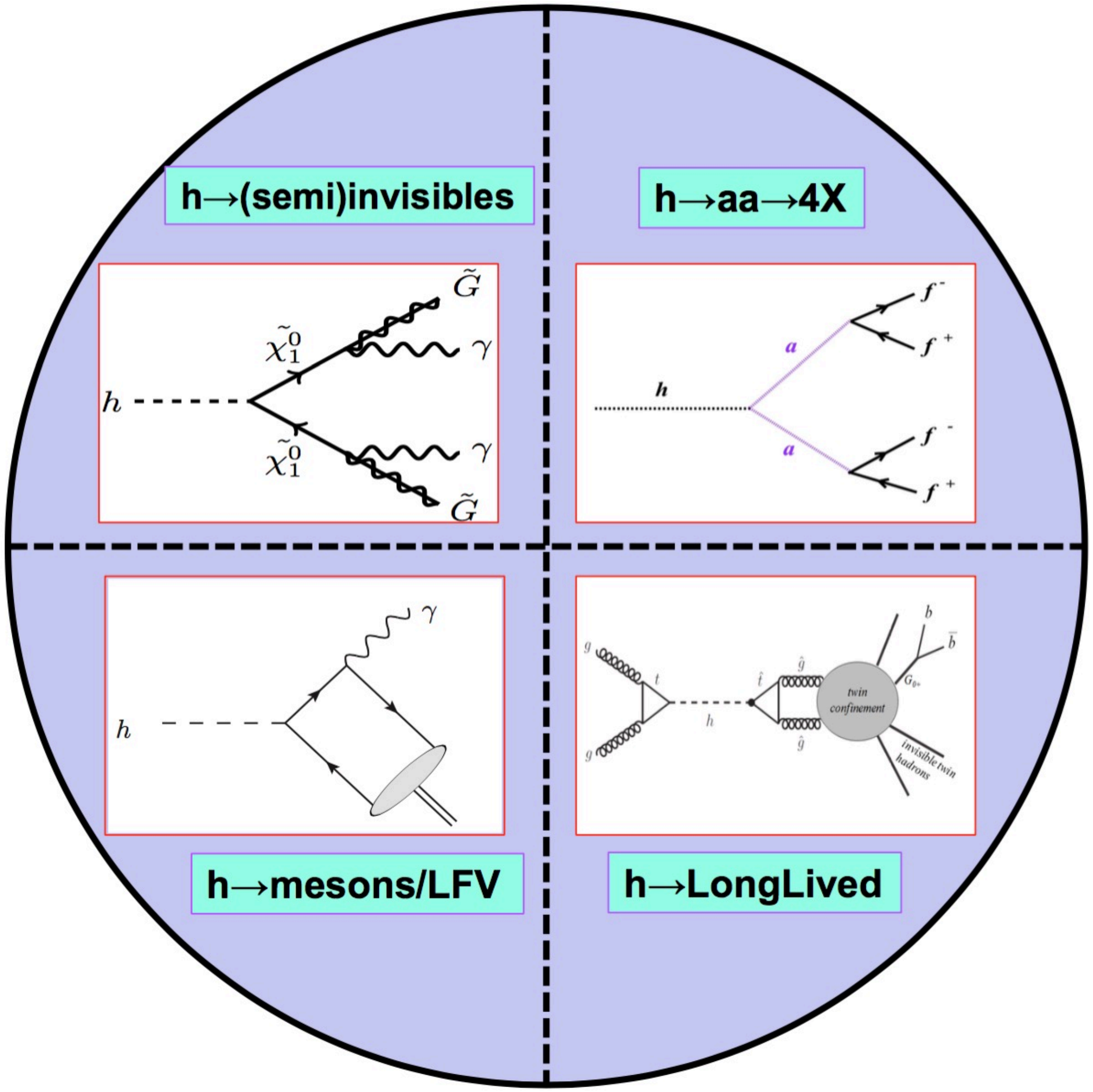
$$\frac{C_3^{2h}}{C_3^h} = \frac{C_4^{2h}}{C_4^h} = \frac{1}{2}\cos\theta \; = \frac{1}{2}\sqrt{1-\xi}$$

Z. Yin, D. Liu and IL: 1805.00489; 1809.09126

- Rare and new decay channels of H(125), a.k.a. "Exotic Higgs decays", are getting more attention lately.



HXWG Higgs EXO subgroup

There are several broad categories:

- Rare mesonic exclusive and flavor-violating decays:
  - Providing a unique window into the H(125) couplings to light quark flavors.
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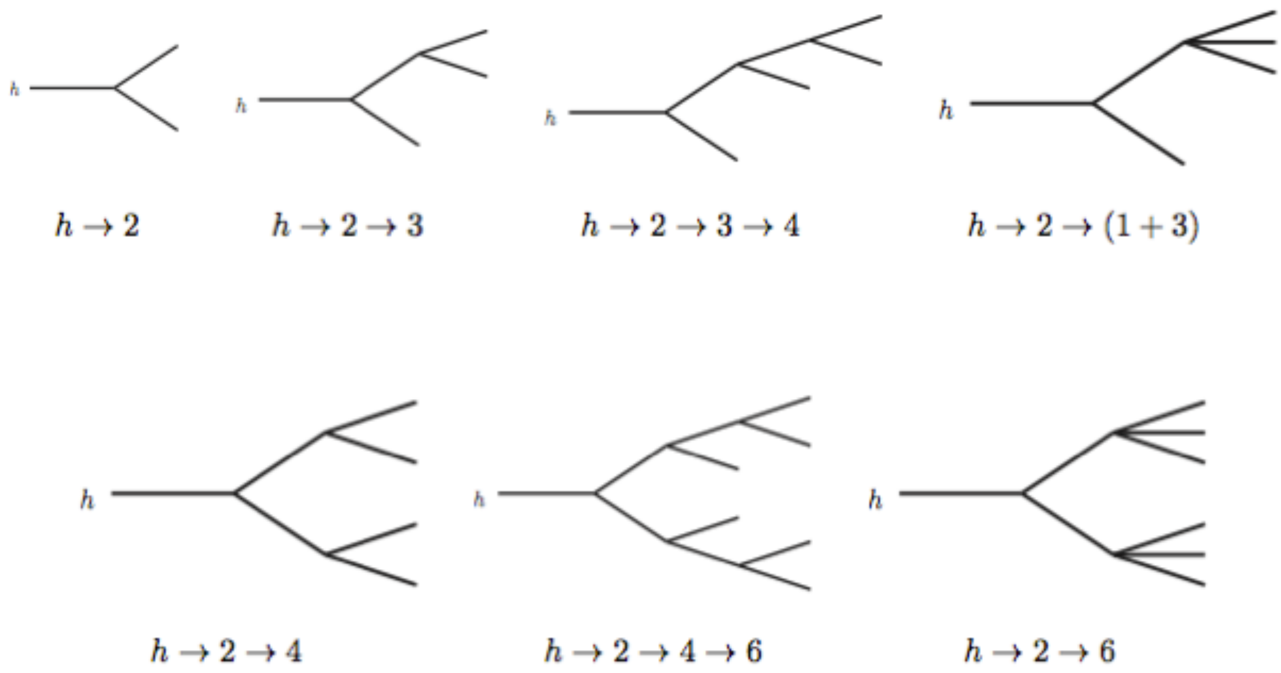
Mass of the Higgs is only 125 GeV, searches often face experimental challenges in triggering, detector response, MC simulations of signal samples, and etc.

→ Nice playground for theorists and experimentalists alike!

For example, theorists have proposed a comprehensive list of exotic Higgs decay signatures:



The exotic Higgs decay topologies we consider. Intermediate lines represent an *on-shell, neutral* particle, which is either a Z-boson or a BSM particle.

See 1312.4992

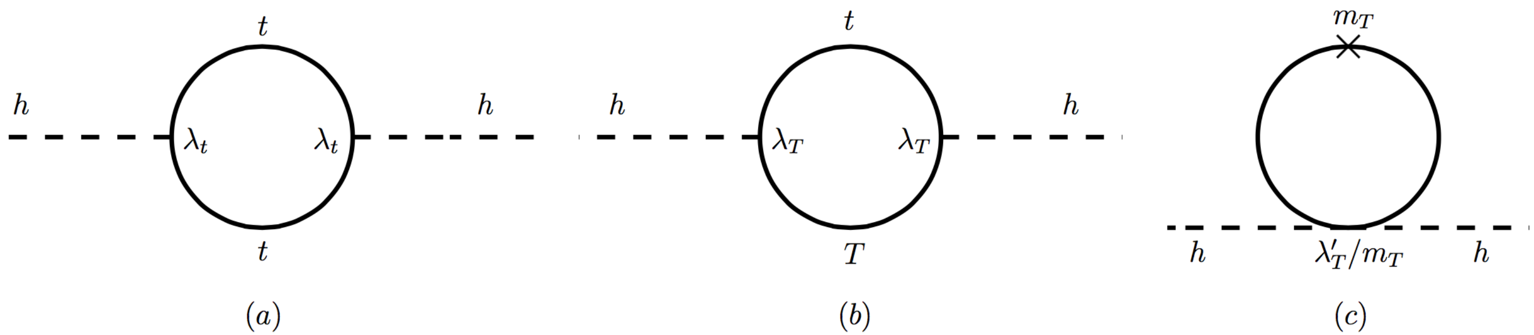
- Top partners can be either spin-0 in supersymmetry (the top squark) or spin-1/2 in composite Higgs models (the vector-like quark).

Their existence provides a "microscopic origin" for the special "minus sign" in the Higgs potential:

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

This sign could be generated by top partners at the loop-level through the celebrated Coleman-Weinberg mechanism.

In addition, the top partners are also responsible for cancelling the top quadratic divergences in the Higgs mass-squared:



They must have a significant coupling to the Higgs, but they are not necessarily colored!

The uncolored top partners (neutral naturalness) present special challenge for its discovery.

	Scalar Top Partner	Fermionic Top Partner
Colored Top Partner	Supersymmetry	Compositeness/Warped Extra Dimensions
EW-charged Top Partner	Folded SUSY [Chacko, Harnik, Goh, Burdman]	Quirky Little Higgs [Cai, Cheng, Terning]
Neutral Top Partner	Hyperbolic Higgs [Cohen, Craig, Giudice, McCullough] Tripled Top [Cheng, Li, Salvioni, Verhaaren]	Twin Higgs [Chacko, Harnik, Goh] [Barbieri, Gregoire, Hall]

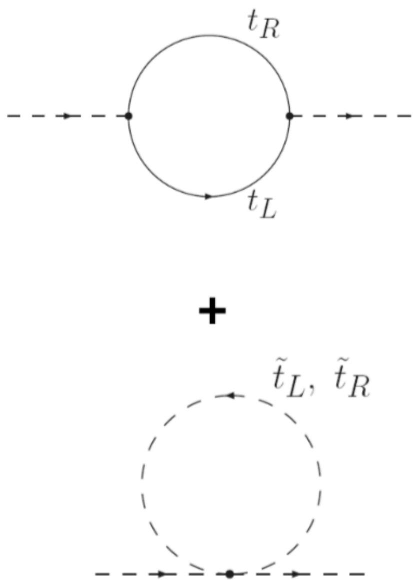


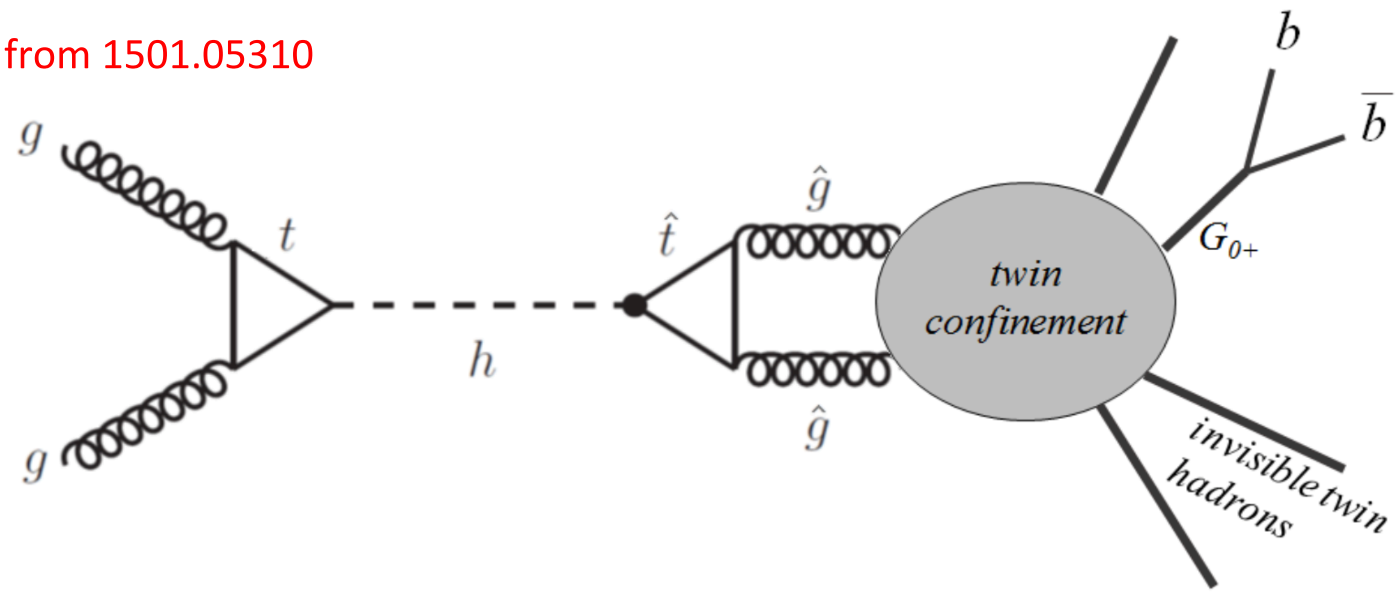
Table from B. Batell

[Table inspiration from Curtin, Verhaaren]

A. Martin @ DPF 2019

However, one might be able to infer neutral naturalness from exotic Higgs decays:

Figure from 1501.05310



This is the most salient feature common to popular models explaining the naturalness problem:

The existence of the symmetry-partner of the top!

Their presence often modifies the top Yukawa coupling.

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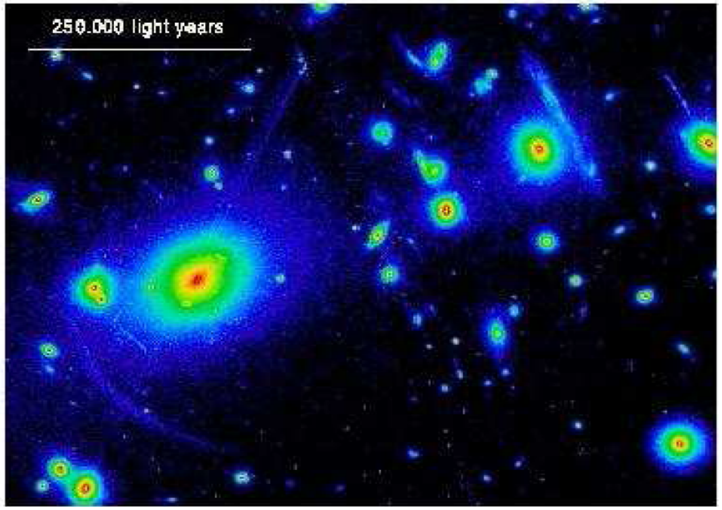
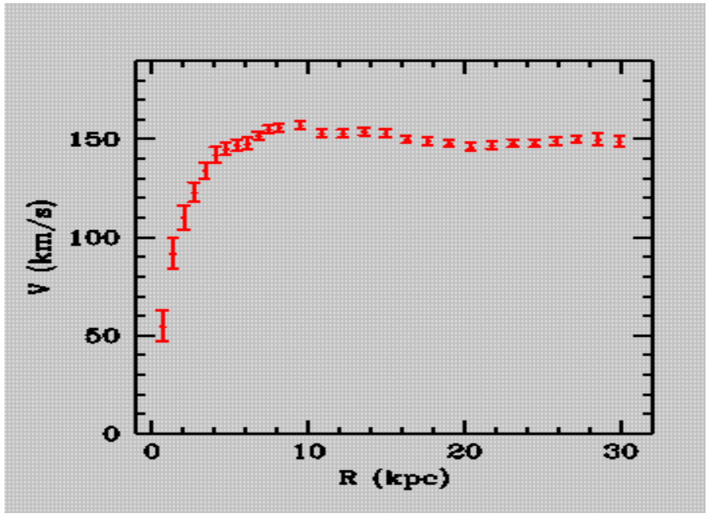
Three routes to measuring naturalness:

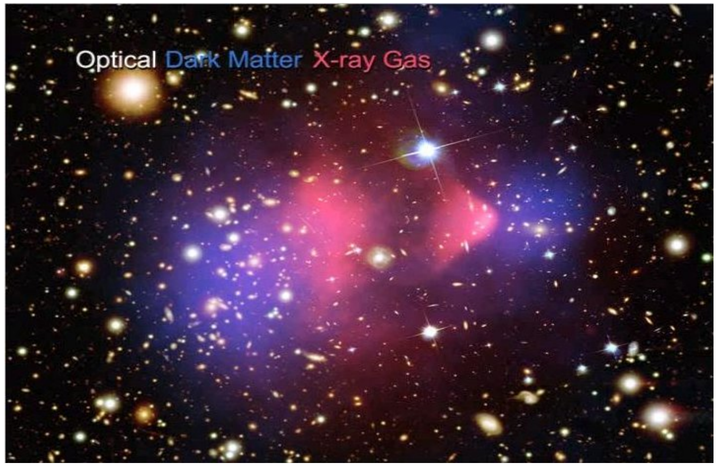
- Direct searches of the colored top partner.
- Indirect searches of the uncolored top partner through exotic decays of the 125 GeV Higgs.
- Precise measurements of the top Yukawa coupling.

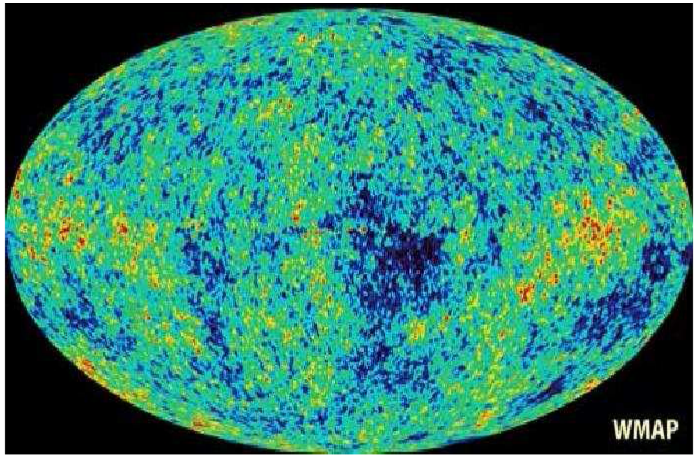
Asking the right empirical questions

We are all convinced about the existence of dark matter…



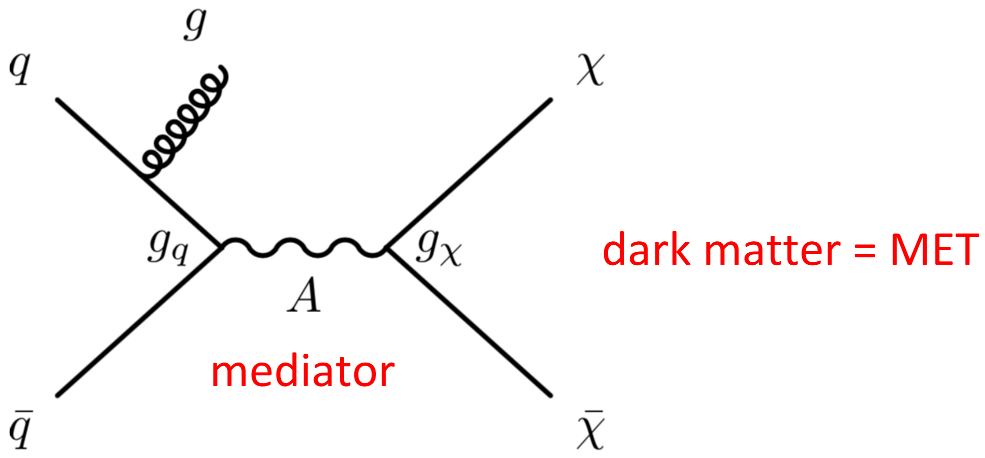






$$\Omega_b h^2 = 0.024 \pm 0.001 \qquad \Omega_m h^2 = 0.14 \pm 0.02$$

Collider searches typically rely on mono-X channels:

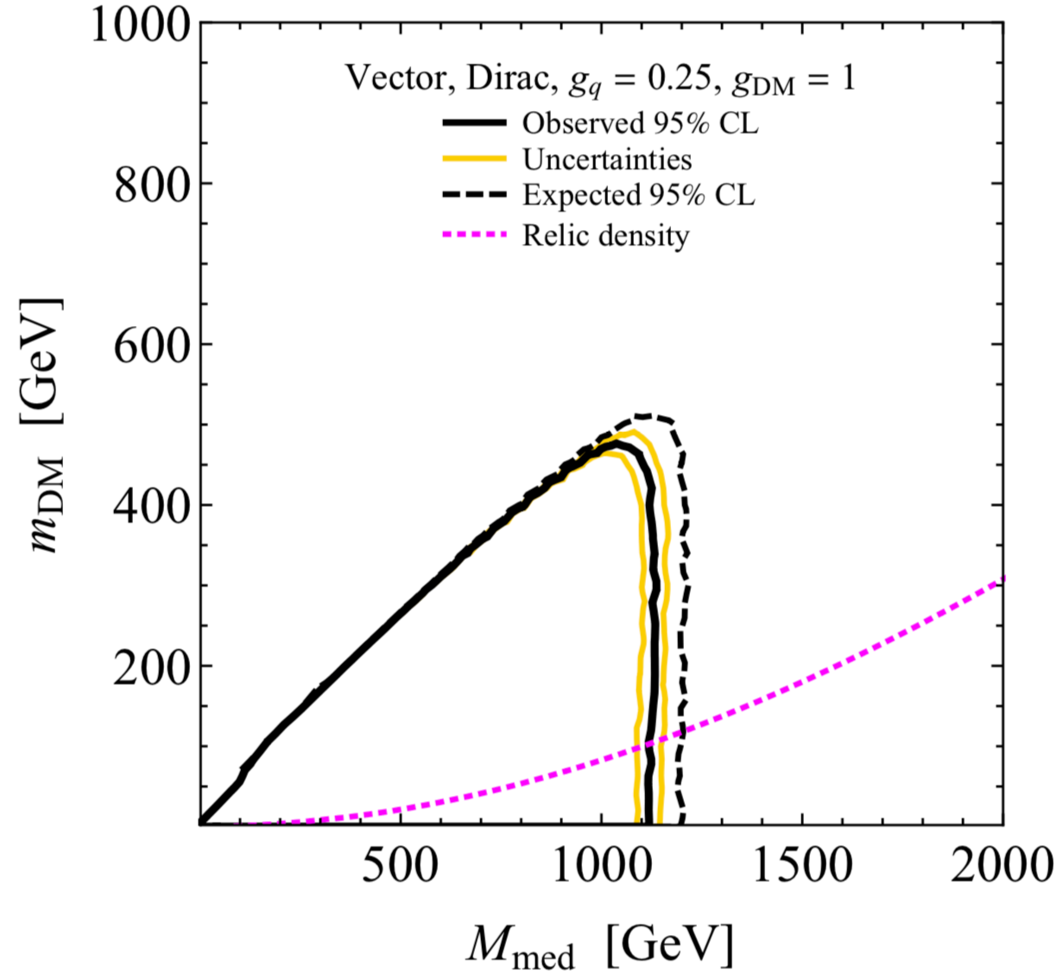


X = jet, W, Z, Higgs, photon, etc.

MET is a useful trigger and hard to produce in the SM (except for neutrinos.)

A typical LHC search limit is presented on the mass-mass plane:

1603.04156



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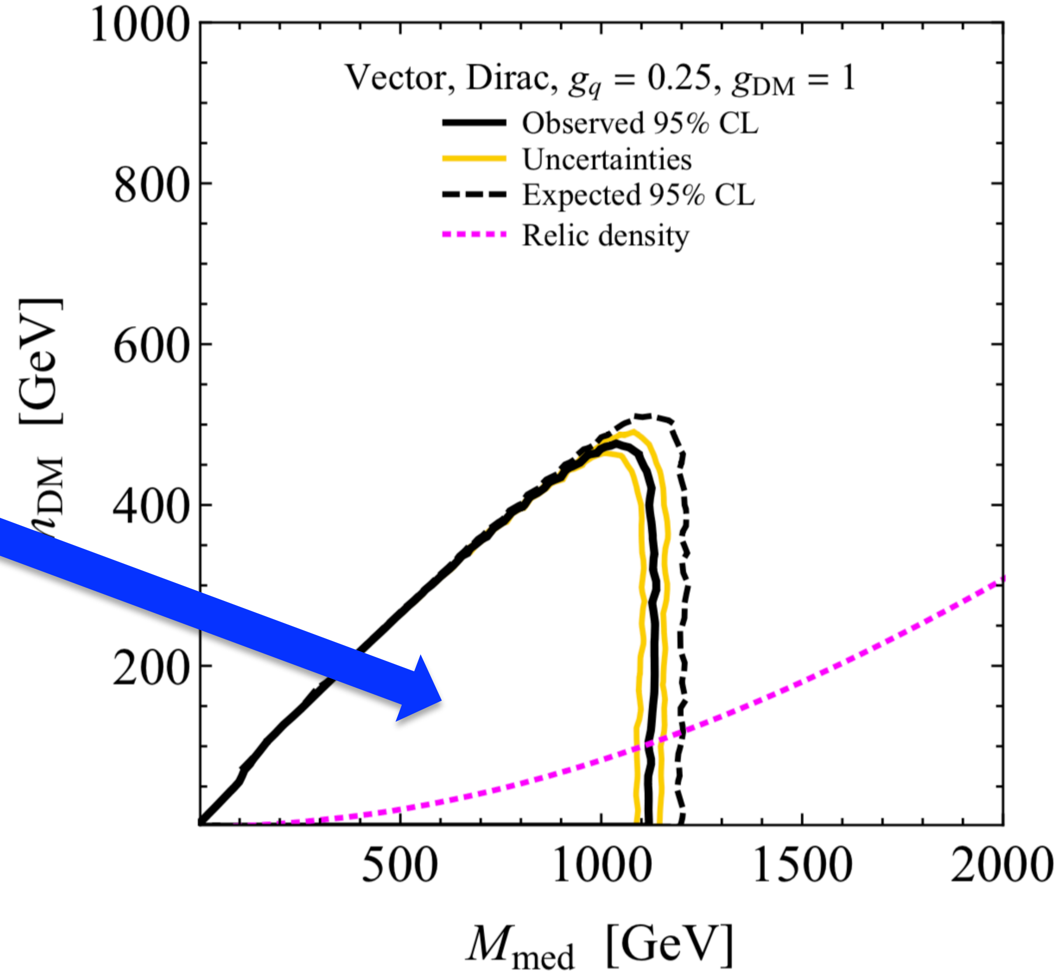

The search is most effective in the on-shell region:

$$M_{\rm med} > 2m_{\rm DM}$$

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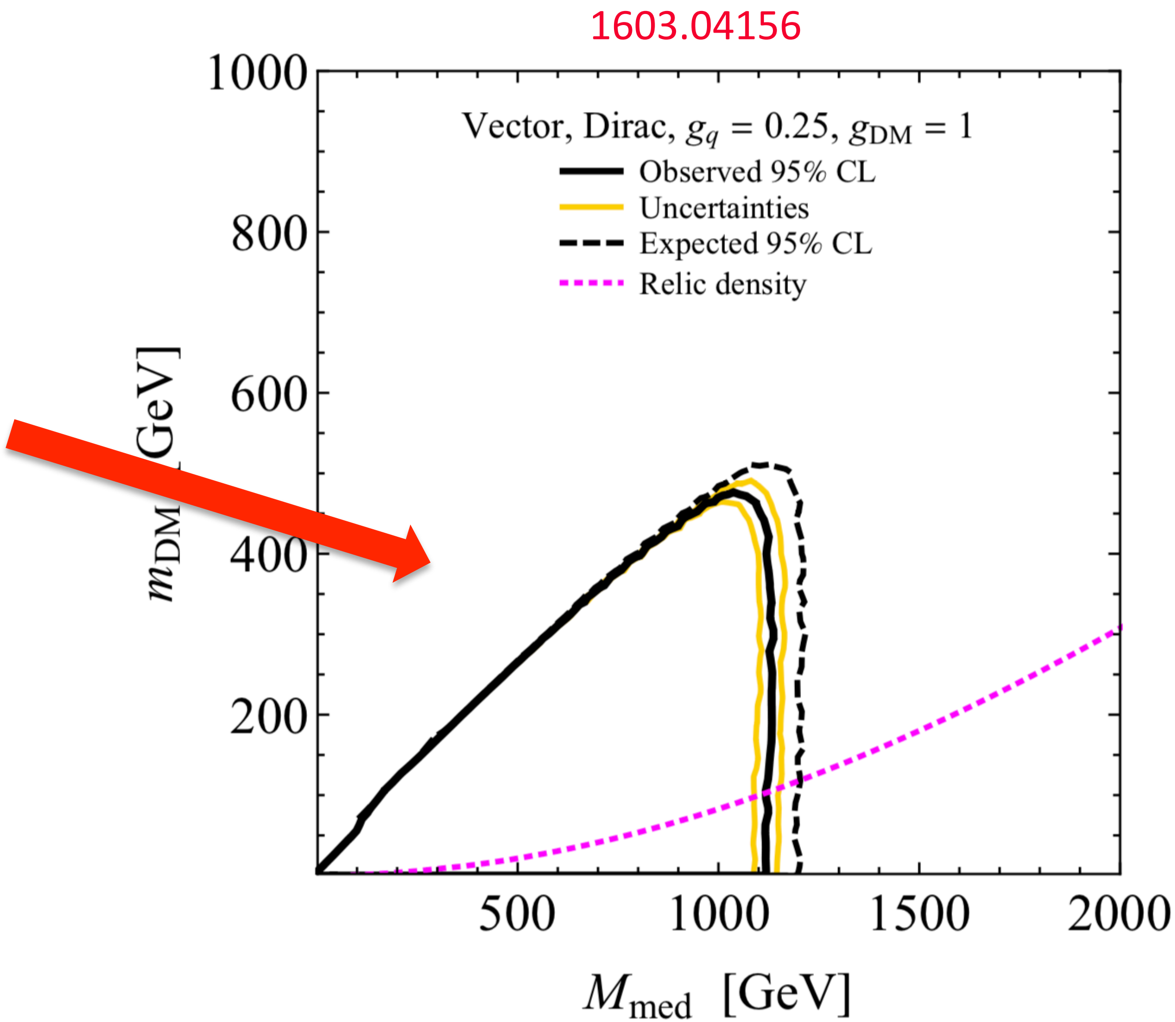
mono-X channels quickly lose steam…



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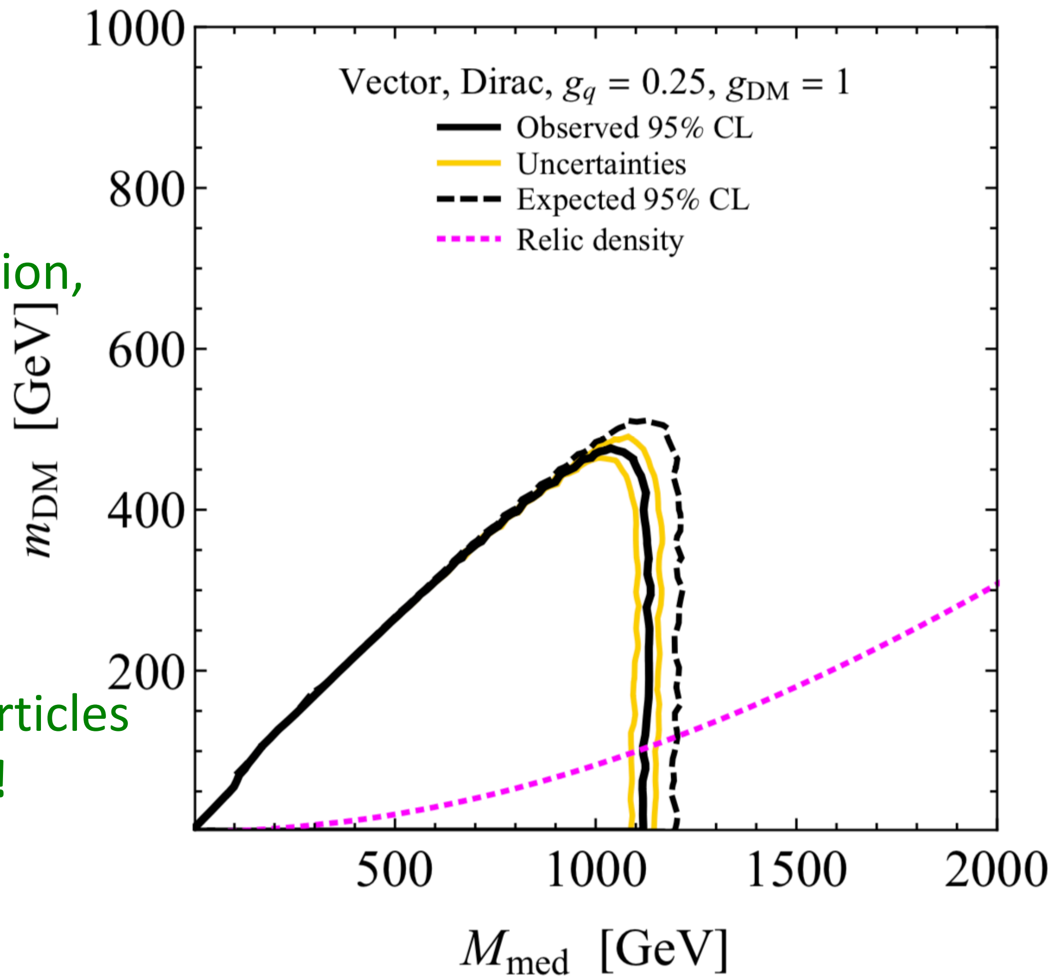


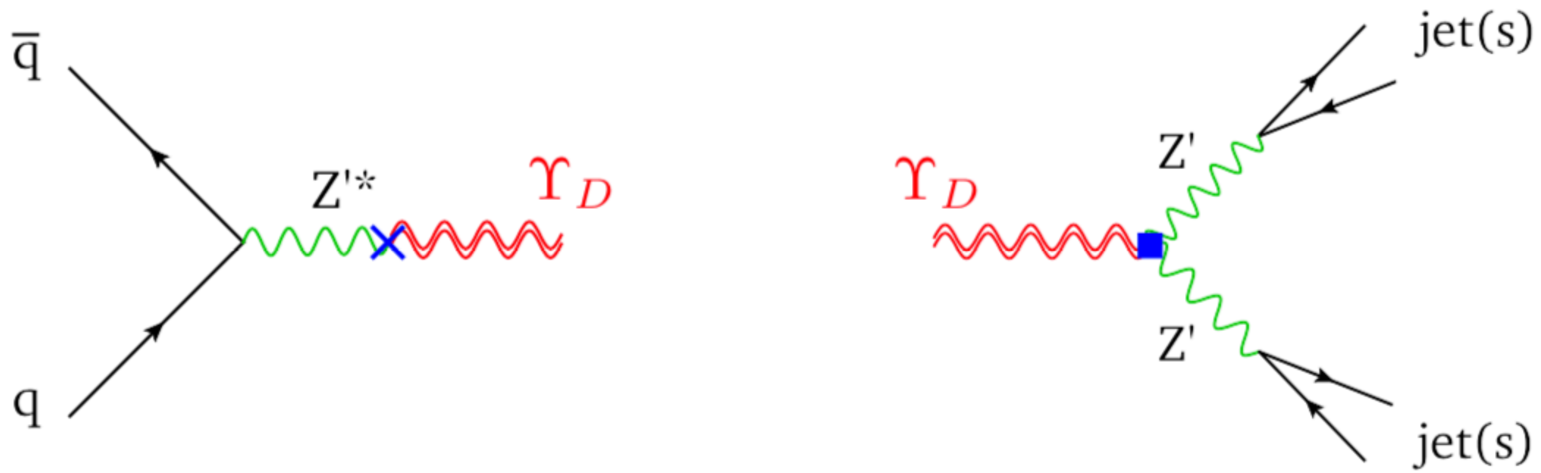
However, in the off-shell region,

$$M_{\rm med} < 2m_{\rm DM}$$

if the mediator mass is light enough, it could mediate an effective long-range force between the dark matter particles

→ **Formation of darkonium!**

- The darkonium can be produced singly and decay back to jets,



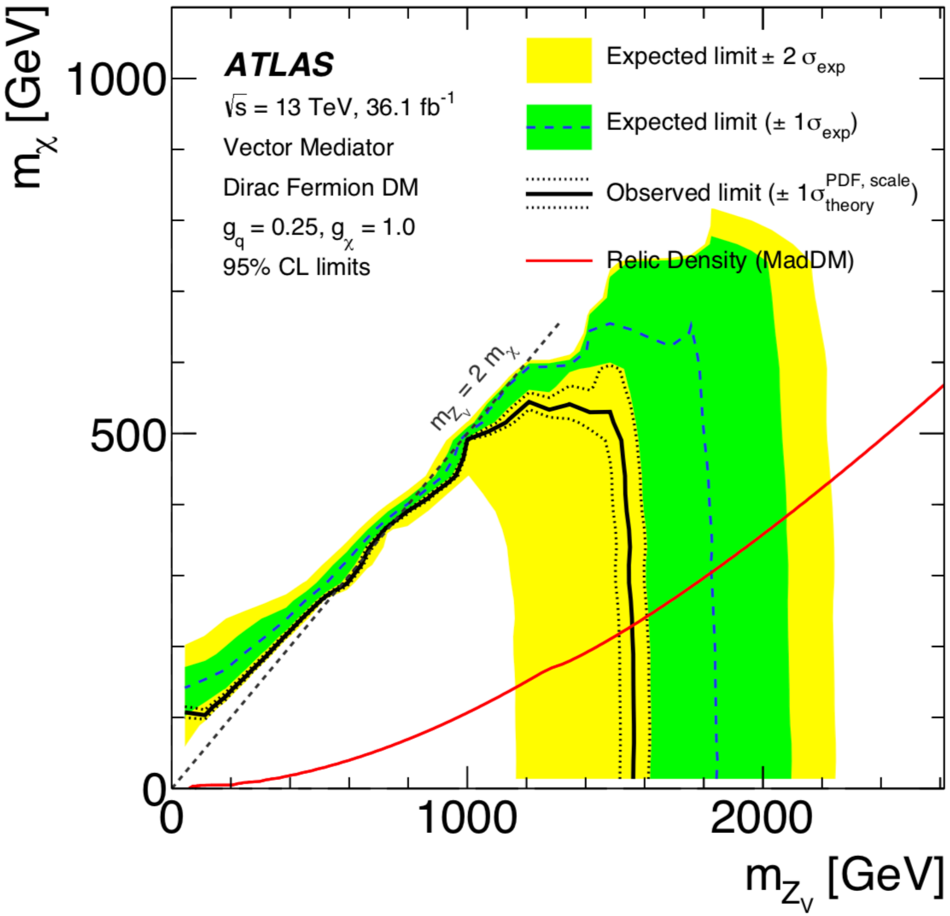
This is similar to the production of J/Psi!

We could be producing dark matter at the LHC without MET signatures!!

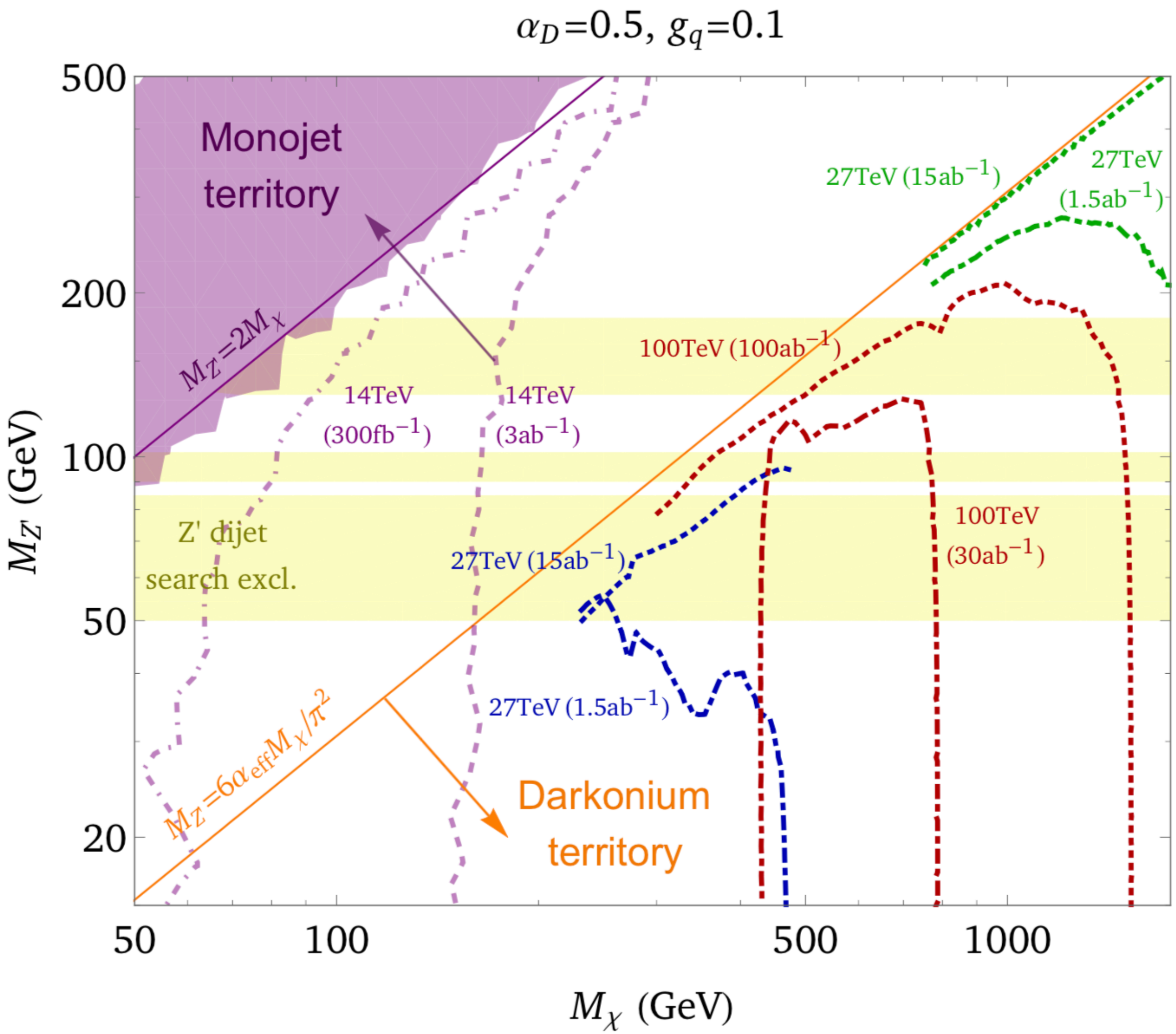
A. Krovi, IL and Y. Zhang: 1807.07972

A popular benchmark is the Z-prime mediator,

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + g_q \bar{q} \not{Z}' q - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} M_{Z'}^2 Z'_\mu Z'^\mu + \bar{\chi} \left(i\not{\partial} + \left(g_\chi + g'_\chi \gamma_5 \right) \not{Z}' - M_\chi \right) \chi$$

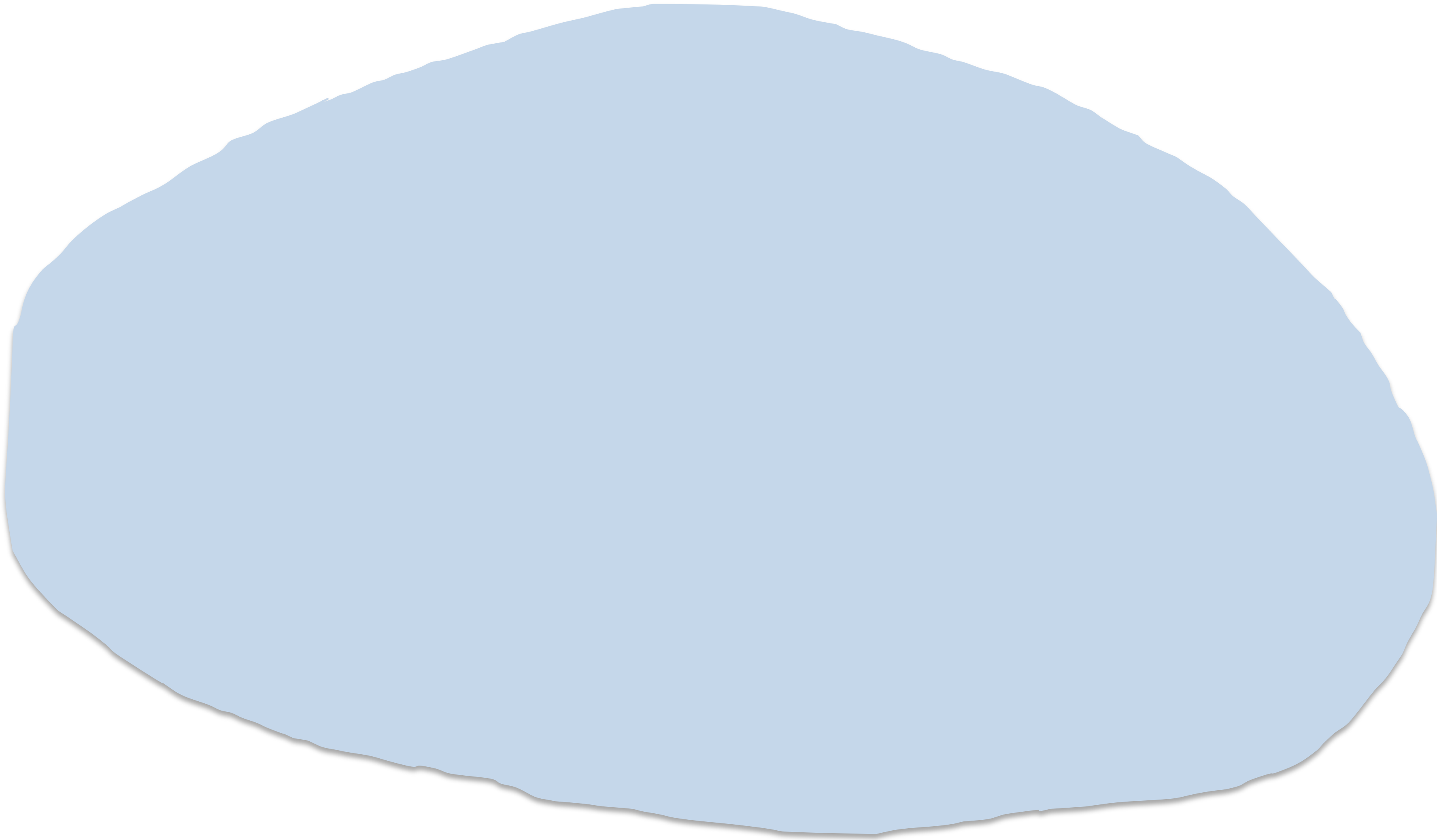


- The result relies on multijet final states
  → Need to the SM prediction very well!



What is the path forward?

Standard Model



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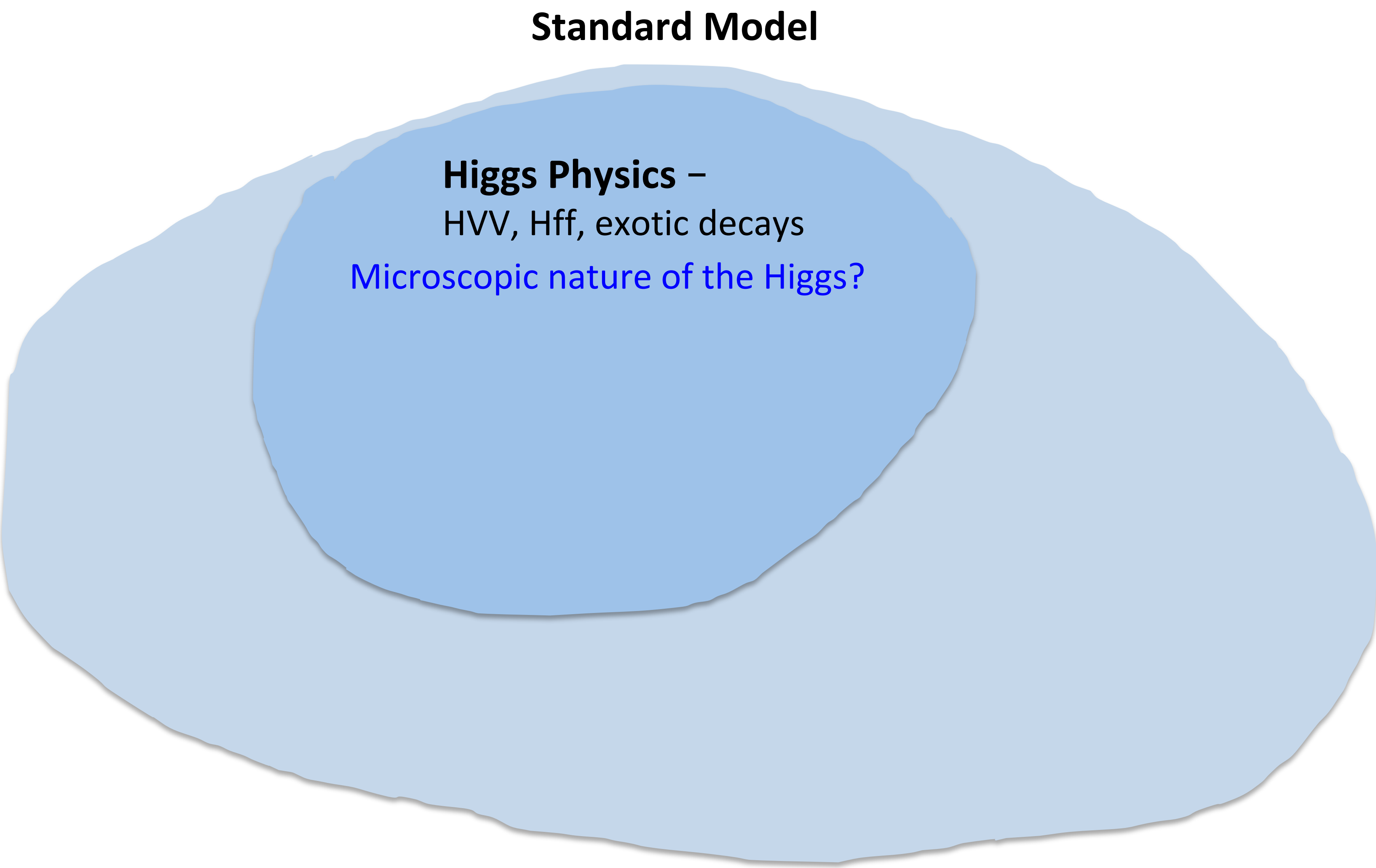

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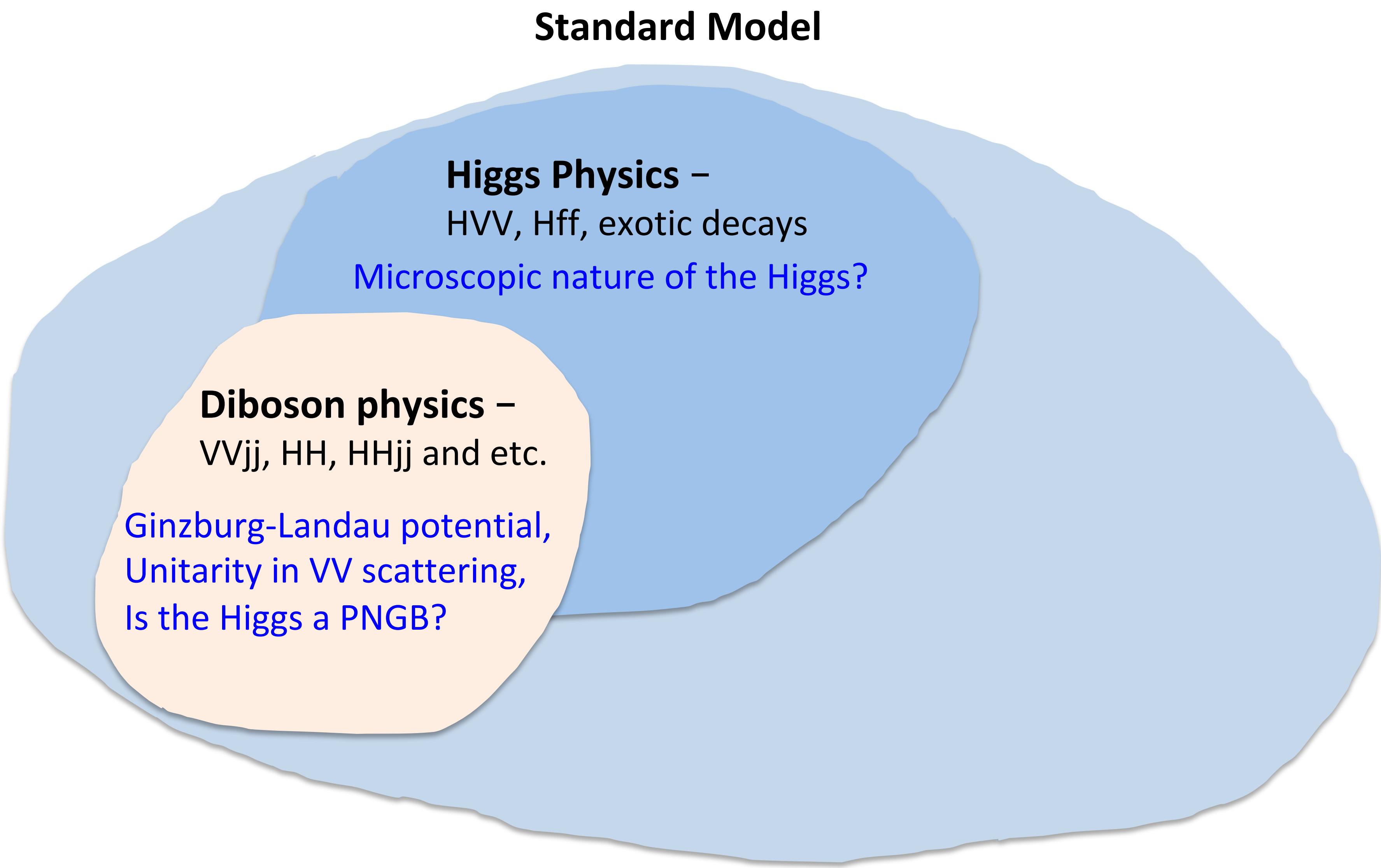

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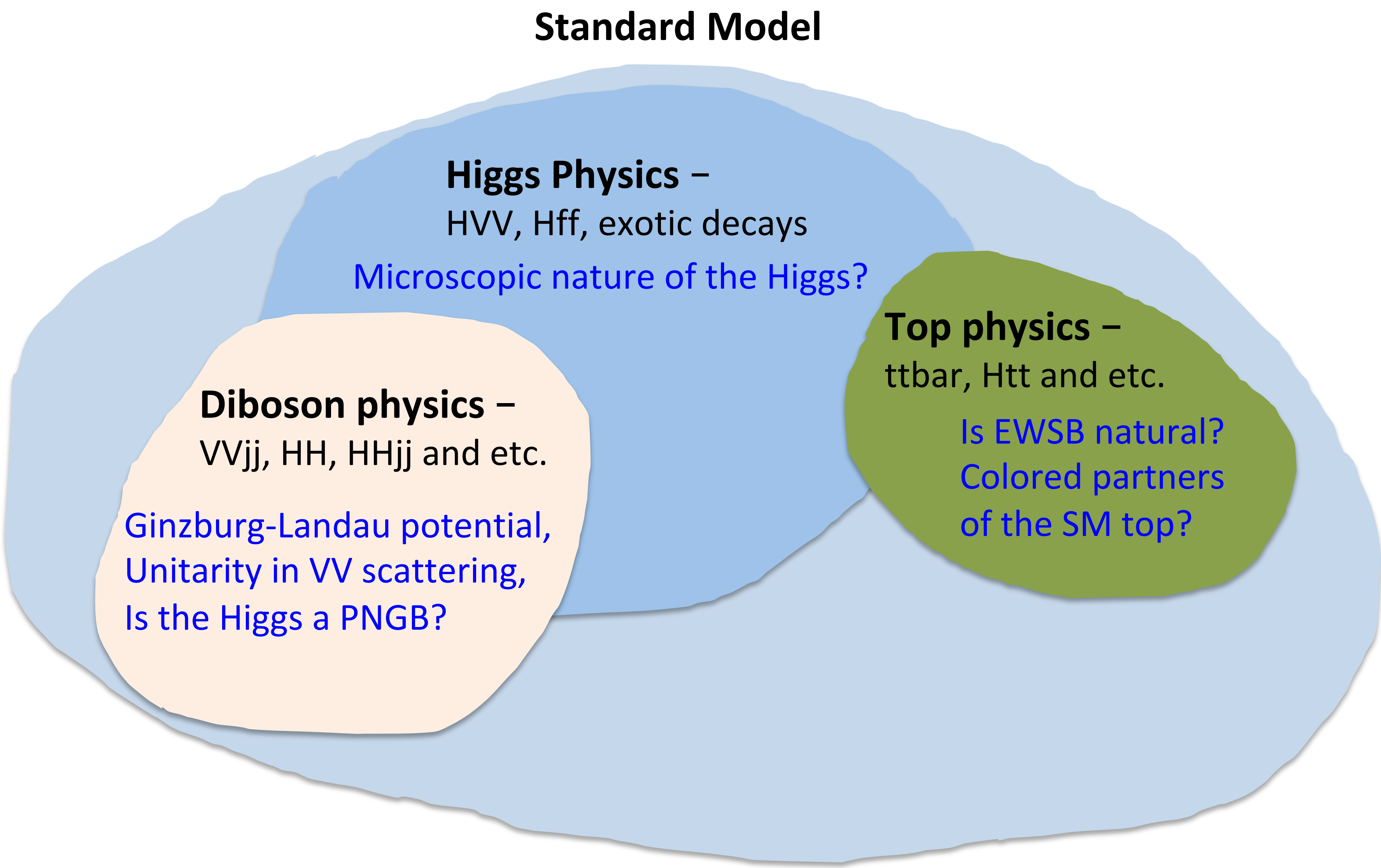

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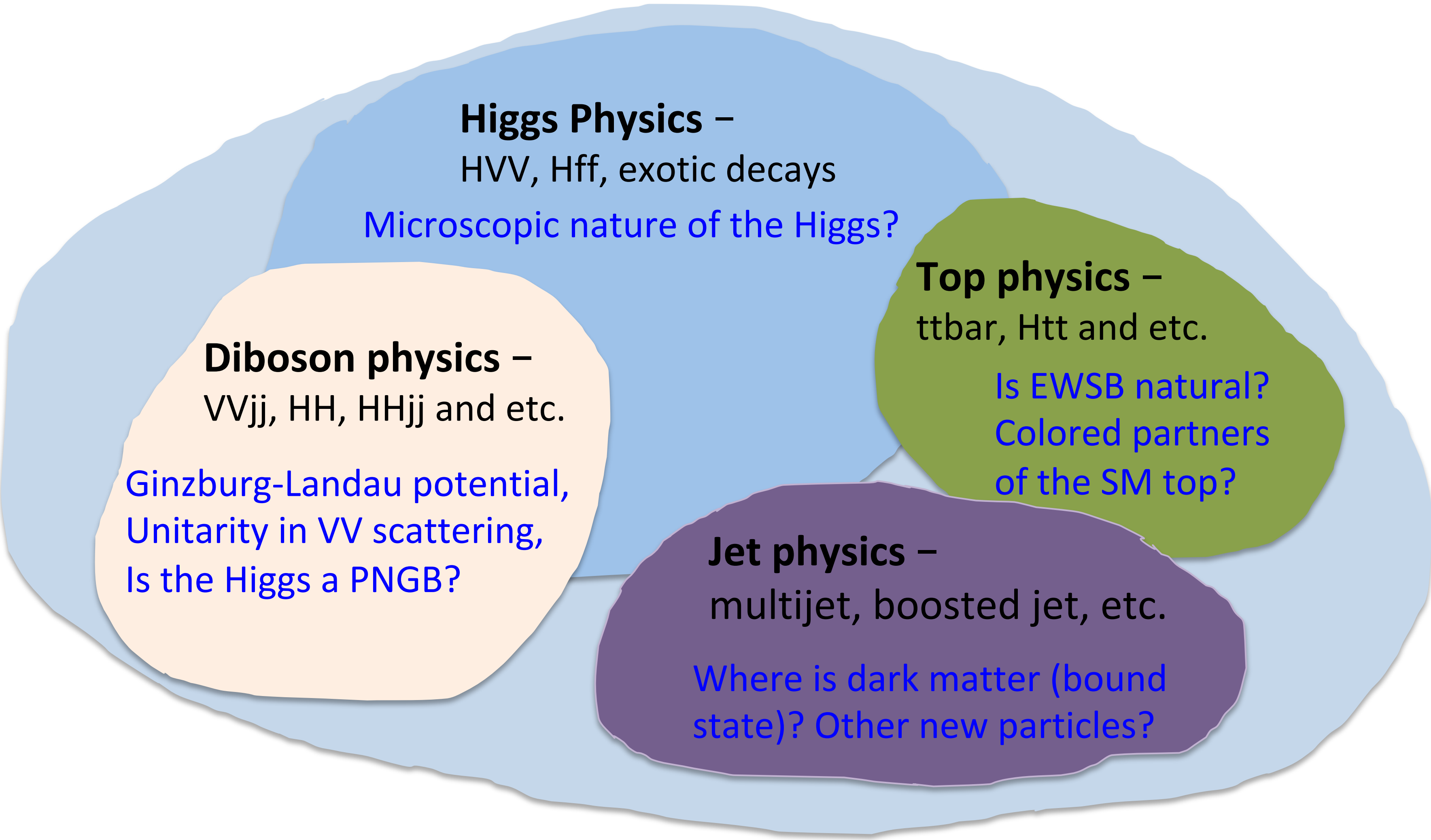
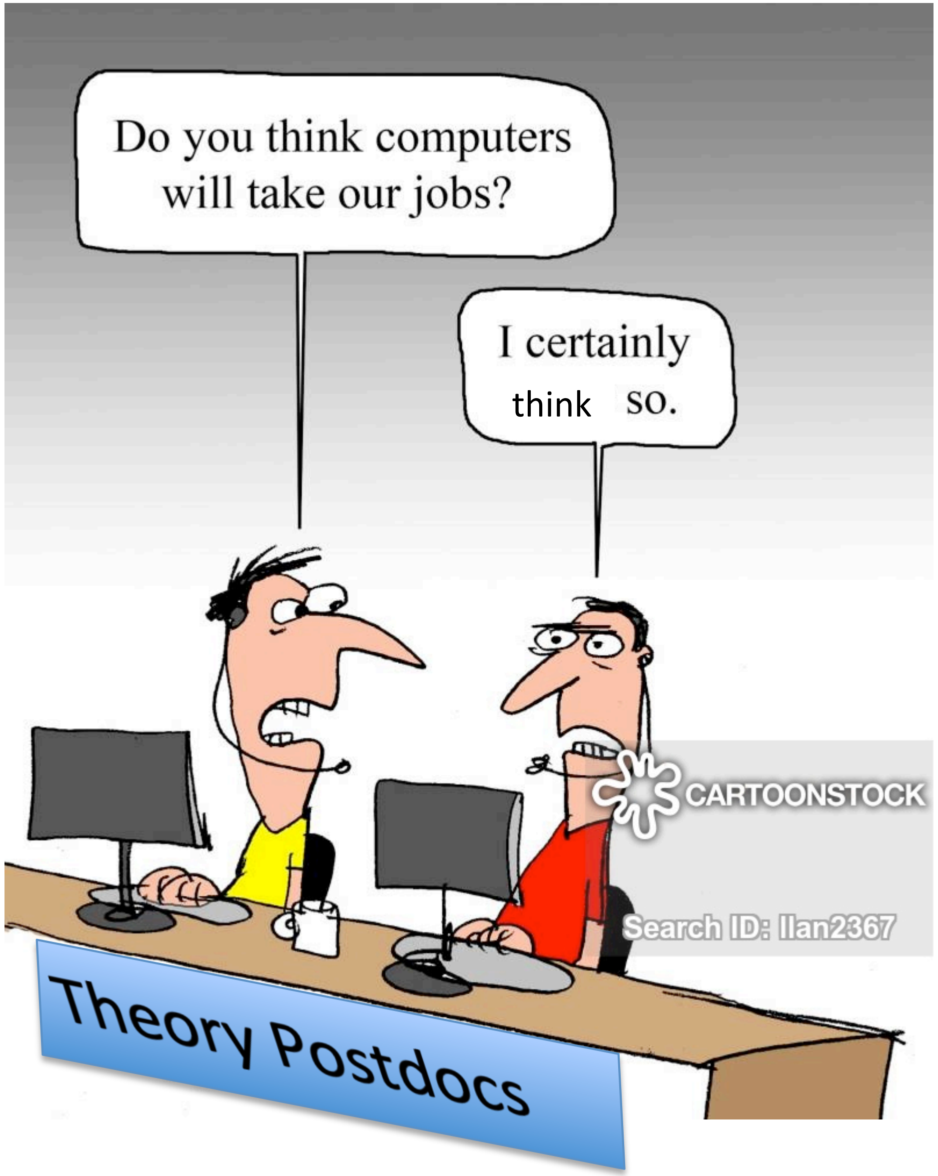


What is the path forward?

There are certainly many other possibilities, for example,

Unsupervised searching –
if a final state has not
been searched for, go for it!



Concluding Remarks:

- For the first time we are staring down the edge of the Standard Model.

  Anything we discover from this point on will be revolutionary.

- Standard Model is a self-consistent theory, but it is by no means a complete theory -- it cannot explain the existence of dark matter, nor the observed matter--anti-matter asymmetry, just to name a few.

  Something has to be out there!

- The Higgs boson is the most exotic state of matter in Nature.

- The electroweak criticality is the most bizarre type of quantum criticality.

- Our understanding is still preliminary, at the level of Ginzburg-Landau picture for the superconductivity.

  Need to pin down a microscopic picture.

The LHC has only collected 5% of its designed luminosity. The work has really just begun!