Beyond Standard Model Theory

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BSM Theory before LHC

Minimal SUSY

Main actors related to naturalness:

stops and **gluinos**

- They control the corrections to the Higgs mass and the amount of tuning

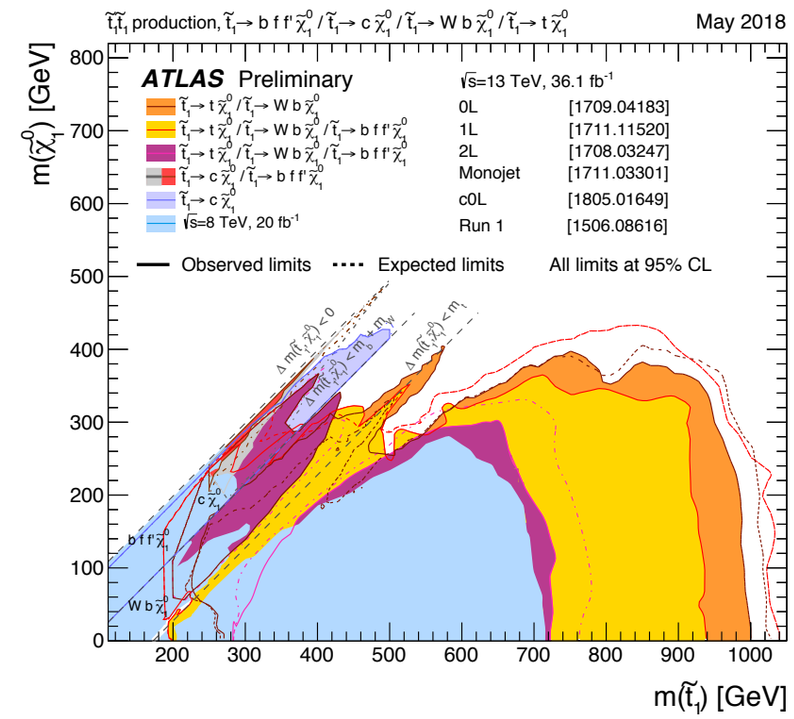
$$\delta m_H^2 \sim \frac{3y_t^2}{8\pi^2} m_{\tilde{t}}^2 \log(\Lambda/m_{\tilde{t}})$$

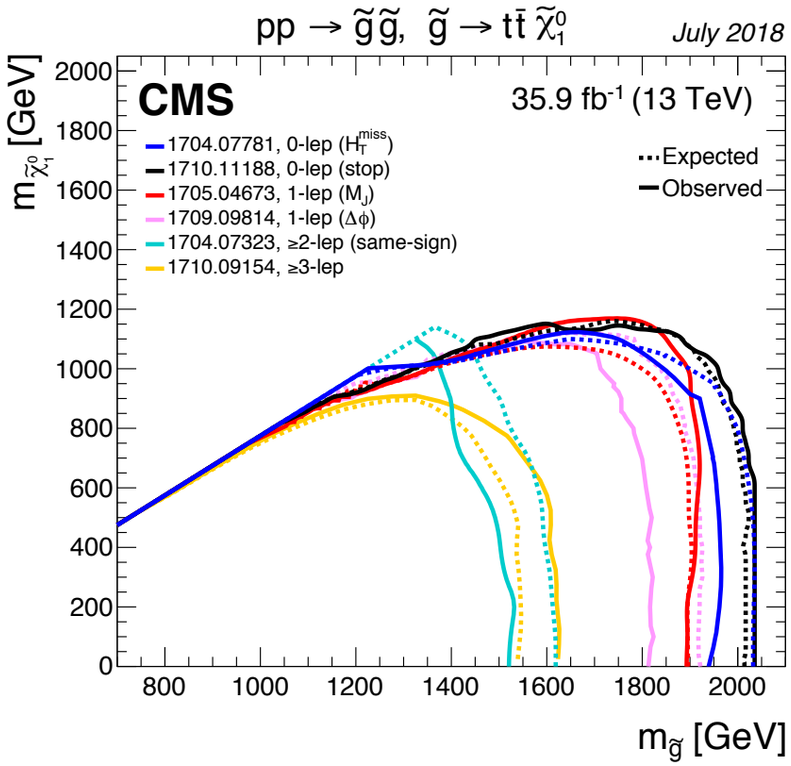
$$\delta m_H^2 \sim \frac{\alpha_S y_t^2}{\pi^3} m_{\tilde{g}}^2 \log^2(\Lambda/m_{\tilde{g}})$$

- Current exclusions

$$m_{\tilde{t}} \gtrsim 1\,\mathrm{TeV} \qquad m_{\tilde{g}} \gtrsim 2\,\mathrm{TeV}$$

imply a minimal tuning $1/\Delta \equiv \frac{m_H^2}{\delta m_H^2} \sim few\,\%$

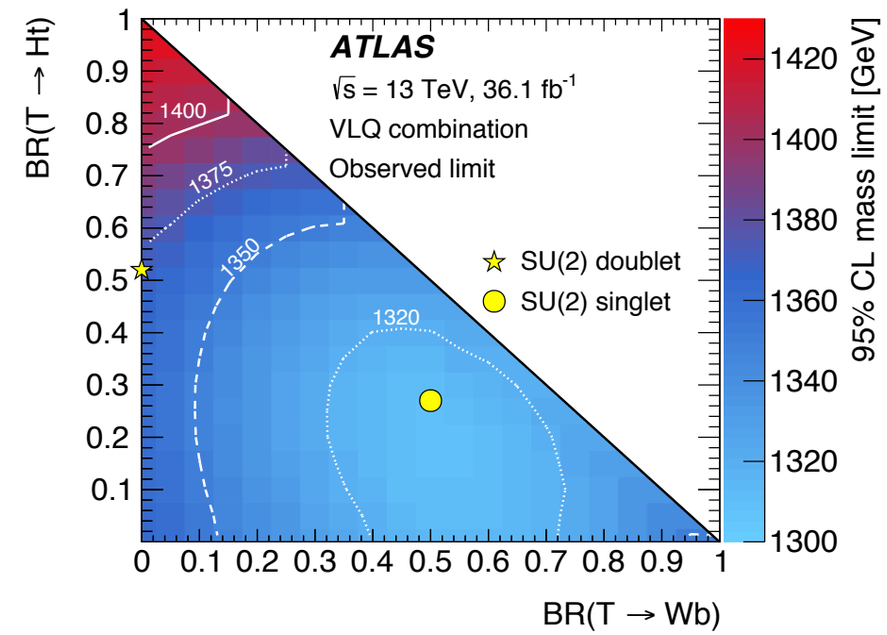




Minimal Compositeness

Main actors related to naturalness:

fermionic top partners



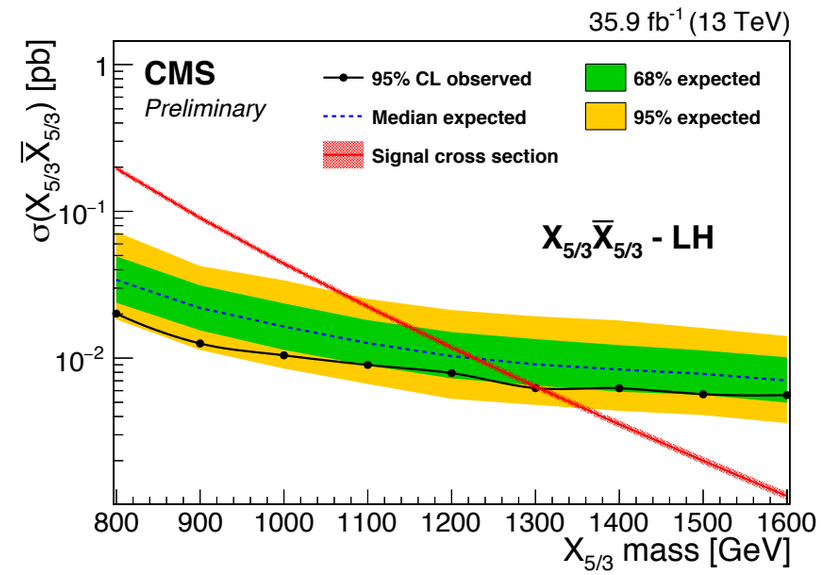
- They control the generation of the Higgs potential

$$\delta m_H^2 \sim \frac{3}{16\pi^2} y_t g_* m_*^2$$

- Current exclusions

$$m_{X_{5/3},T,B} \gtrsim 1.3\,\mathrm{TeV}$$

imply a minimal tuning $\quad 1/\Delta \equiv \frac{m_H^2}{\delta m_H^2} \sim few\,\%$



Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3} \mid T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e,μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e,μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261

A Change of Attitude

LHC results stimulated a healthy change of attitude in the particle theory community

- explore alternative theory paradigms (eg. alternatives to classical naturalness)
- abandon unmotivated prejudices (eg. minimality)
- enlarge the set of signatures to look for at colliders
- theory work closer to experiments
  (eg. working on strategies for data analysis, proposing new experiments)
- look for BSM physics in non-colliders experiments
  (eg. table-top, cosmological tests, …)

BSM Theory after LHC Run II

BSM Theory after LHC Run II

Is Theory still important?

Theory continues to play an important role in BSM exploration

- *naturalness* is still an important question to answer (although maybe no more the strongest guideline)
- *models* are useful to explore signatures and provide a framework for searches
- theory is needed to devise effective *model-independent search strategies* (blind search likely to miss crucial observables to look at)
- theory is needed for an *interpretation* of the experimental results

Naturalness and Predictivity

Naturalness and Predictivity

Naturalness is a very deep question:

what we want to know is whether the value of the **Higgs mass** can be **explained** by the UV theory

- in the presence of high tuning, even measuring with very good precision the fundamental parameters, we can not determine the Higgs mass

↓

<u>loss of predictivity</u>

Naturalness and Predictivity

Two opposite possibilities

Full Predictivity

Higgs mass and EW scale linked to *new dynamics at the TeV*

New symmetry ensures stability of Higgs potential
(SUSY, spontan. broken global symmetry,…)

Main signatures:
partners of top quark
(stops, fermionic top partners,…)

- low-energy SUSY (eg. MSSM)
- composite Higgs

No Predictivity

Higgs mass as a *free parameter*, can only be measured experimentally but not explained

No specific (low-energy) *signatures*

- landscape & anthropic
- UV-naturalness (no high-energy thresholds destabilize Higgs mass)

Naturalness and Predictivity

Two opposite possibilities … and a third way in between

Full Predictivity

Higgs mass and EV
to *new dynamics*

New symmetry ens
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Main signat
partners of to
(stops, fermionic top

- low-energy SUSY
- composite Higgs

Semi-Predictivity

Higgs mass *determined dynamically*,
only overall size explained
but not exact value

New *axion-like particle*

- relaxion

No Predictivity

s a *free parameter*,
sured experimentally
t explained

v-energy) *signatures*

anthropic
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bilize Higgs mass)

Modifying classical scenarios

Classical scenarios "rescued" by modified (typically non-minimal) constructions

Example: **Maximally symmetric composite Higgs** [Csáki, Ma, Shu '17]

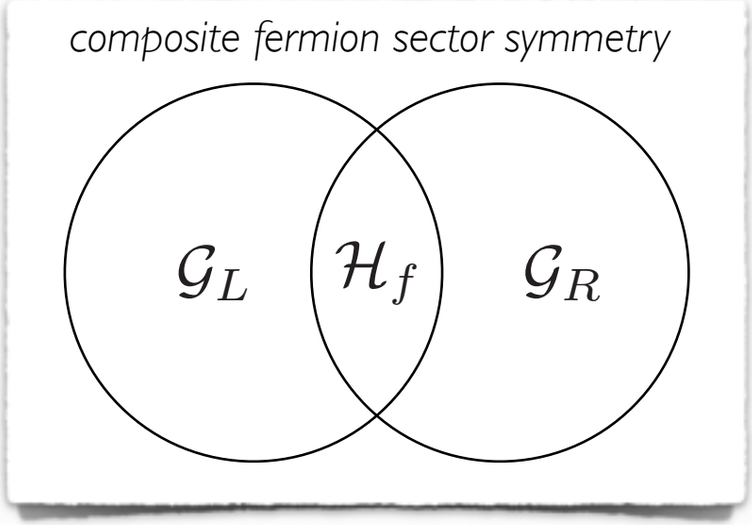
- standard symmetry pattern

$$\mathrm{SO}(5)_L \times \mathrm{SO}(5)_R \to \mathrm{SO}(4)$$

- maximal symmetry pattern

non-diagonal subgroup

$$\mathrm{SO}(5)_L \times \mathrm{SO}(5)_R \to \mathrm{SO}'(5)$$



- maximal symmetry reduces radiative contributions to Higgs mass term
- minimal tuning can be realized (analogy with old little Higgs idea)
- top partners can have larger masses ($\sim$ *few* TeV) with acceptable amount of tuning

Elusive new-physics

Strong collider constraints come from the fact that top partners are *charged* under QCD and therefore easily detectable

What if partners are *neutral* under QCD?

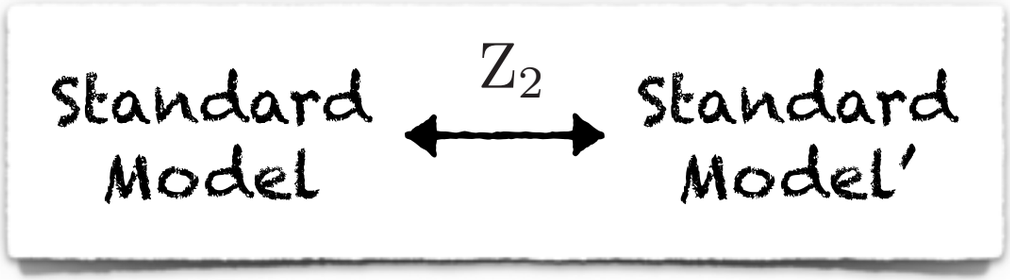
→ **Neutral naturalness** models implement this idea through symmetries

The Twin Higgs construction

[Chacko, Goh, Harnik '05]

- discrete Z_2 symmetry ensures stability of Higgs mass (thanks to enhanced $\mathrm{SU}(4)$ symmetry in Higgs mass term)

$$V(H,H') \sim \frac{\Lambda^2}{16\pi^2} y_t^2 (|H|^2 + |H'|^2)$$



- top partners are neutral under ordinary QCD, more difficult to be produced at colliders
- many implementations of this idea in different frameworks

Semi-Predictivity: Relaxion

Higgs mass is dynamically selected through a *backreaction mechanism*

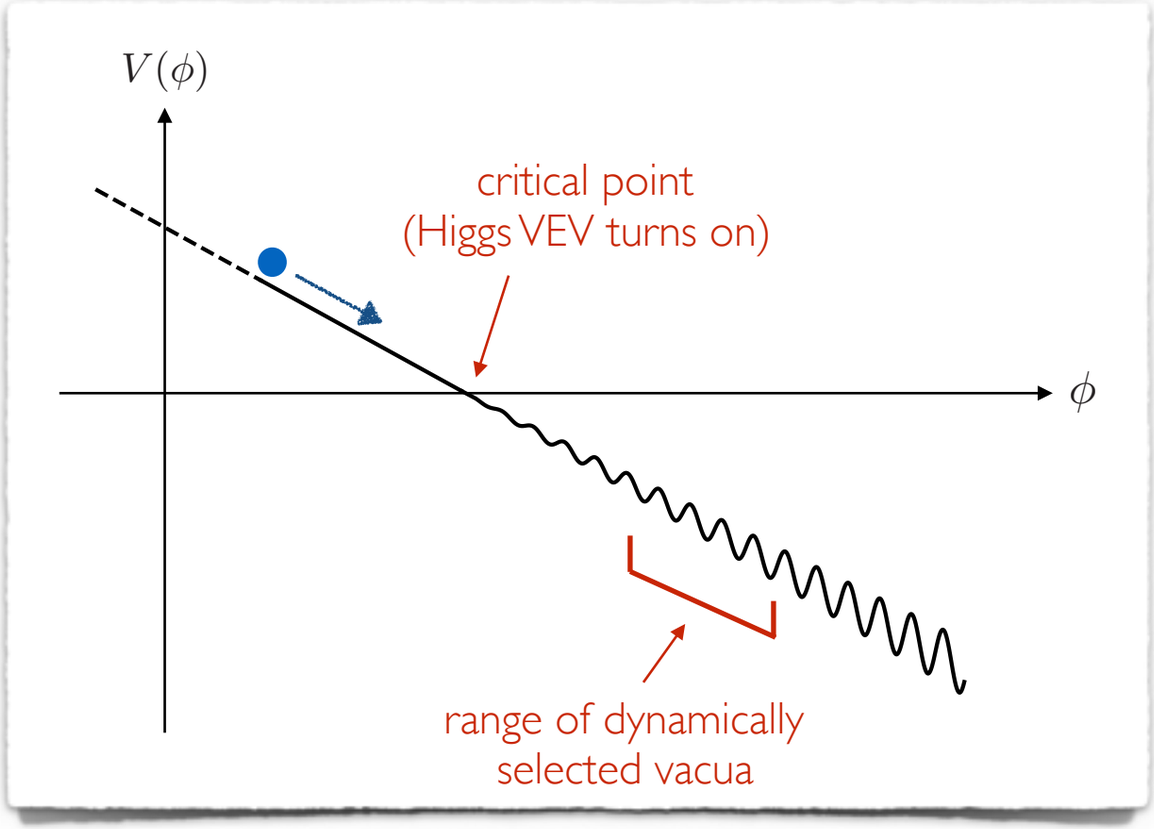
[Graham, Kaplan, Rajendran '15]

axion-like field

i) rolling *relaxion* field controls Higgs mass

ii) when Higgs VEV turns on a backreaction potential is induced

iii) evolution of relaxion is stopped



- vacuum is not uniquely selected: range of vacua possible
  - quantum corrections do not allow to determine stopping vacuum
  - many vacua with similar properties
  - UV parameters determine only overall size of Higgs mass

Semi-Predictivity: Relaxion

Many open questions:

- source of friction (needed to dissipate kinetic energy)
  (inflation? particle production? …)
- origin of relaxion field
  (difficulties in identifying with QCD axion, new dark sector needed)
- complete implementation still missing

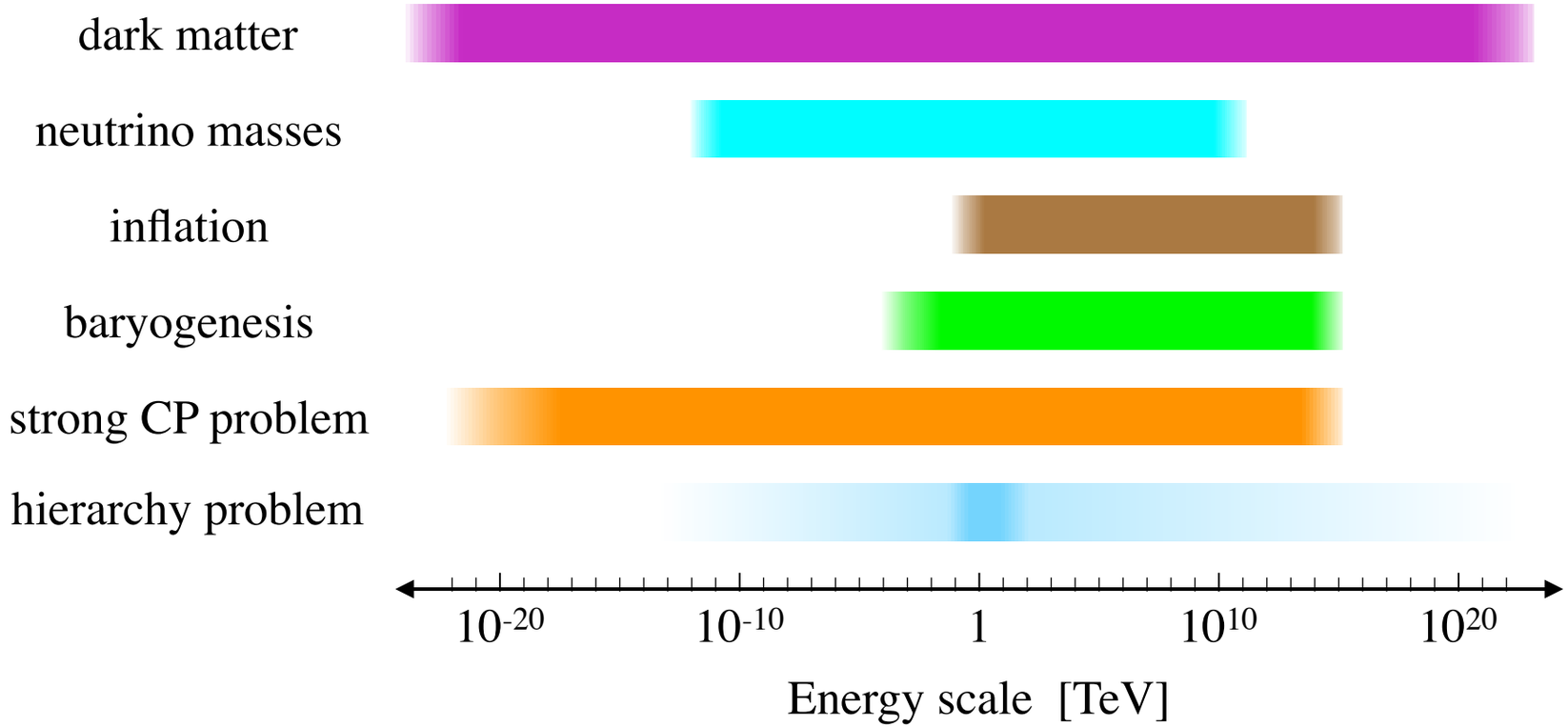
Interesting phenomenology:

- new physics not necessarily at the TeV scale
- relaxion field typically light and very weakly coupled
  (difficult to test at colliders)
- non-collider searches typically necessary to test models
  (table-top axion experiments, cosmological consequences,…)

Beyond Naturalness

BSM is not just naturalness

Many open questions imply physics beyond the Standard Model



Only naturalness (assuming full predictivity) seems to point towards a sharp range close to LHC energy…

… but different kinds of new physics can show up at other experiments and even (accidentally) at LHC

[image adapted from N. Craig EPS-HEP 2017]

EW baryogenesis and Higgs sector

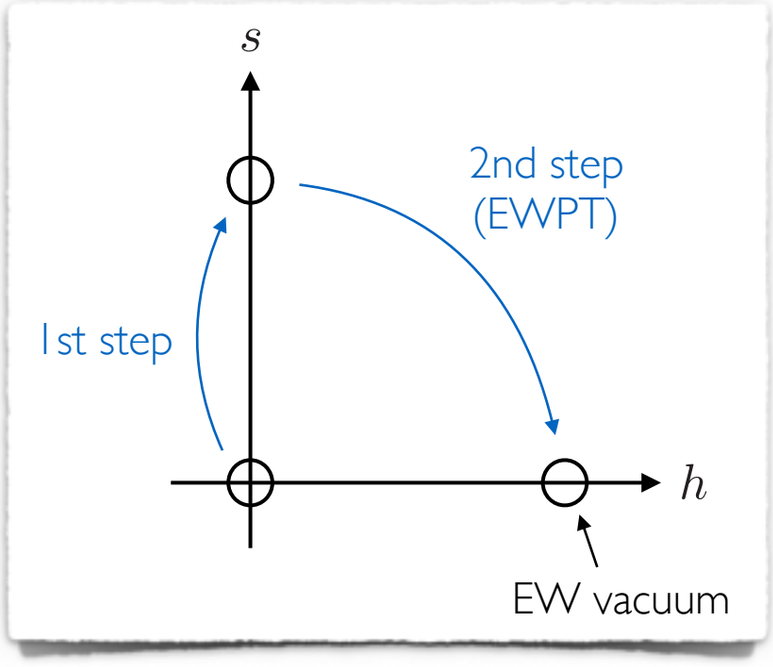
Interesting way to realize baryogenesis is via a strong *EW phase transition*

- modification/extension of Higgs sector
  (SM EW phase transition is cross over → not enough breaking of thermal equilibrium)
- new sources of CP violation (too weak in SM)

Example: **Higgs sector extended with additional singlet**

[Anderson, Hall '92; Choi, Volkas '93; Espinosa, Quiros '93; Profumo, Ramsey-Musolf, Shaughnessy '07, …]

- a two-step transition can give a strong 1st-order EW phase transition
- in the presence of additional CP violation baryogenesis can be achieved



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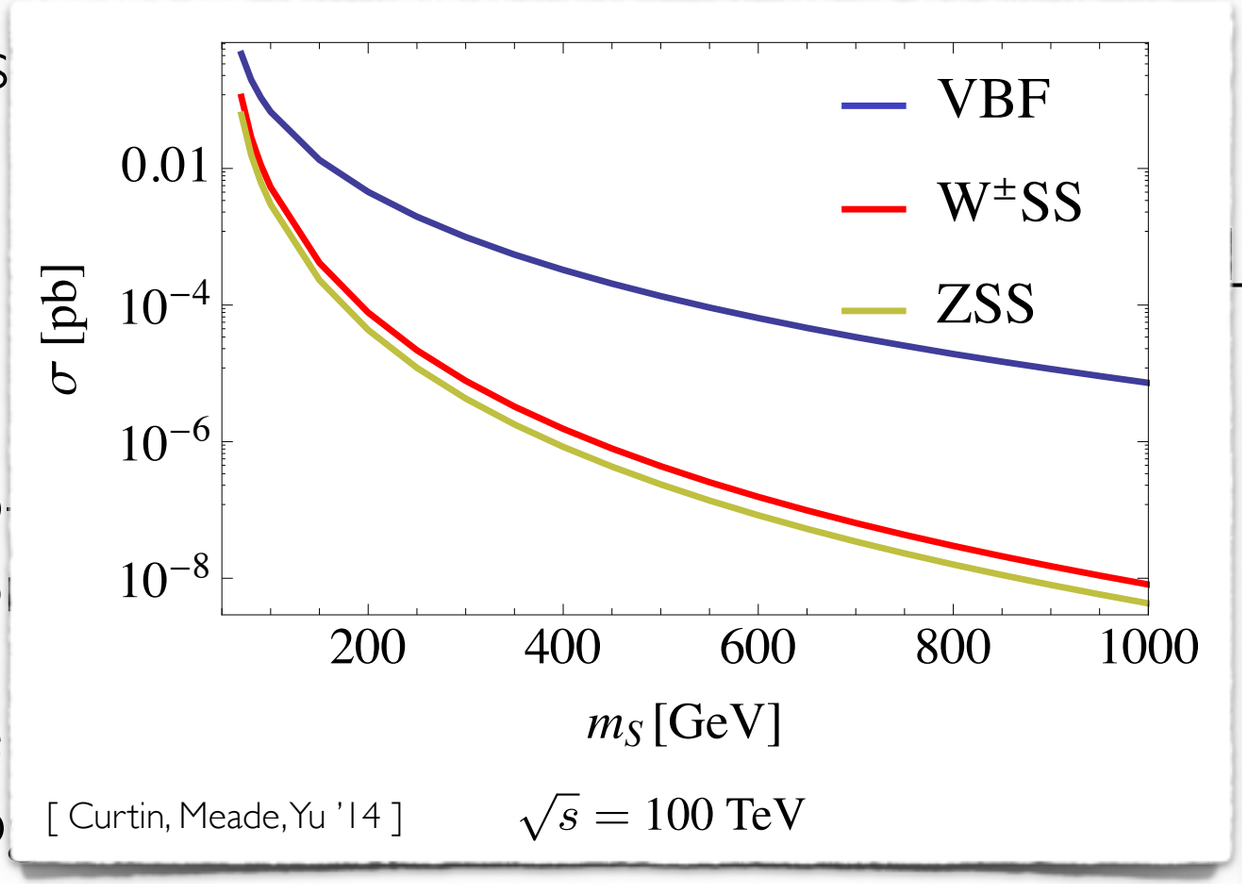

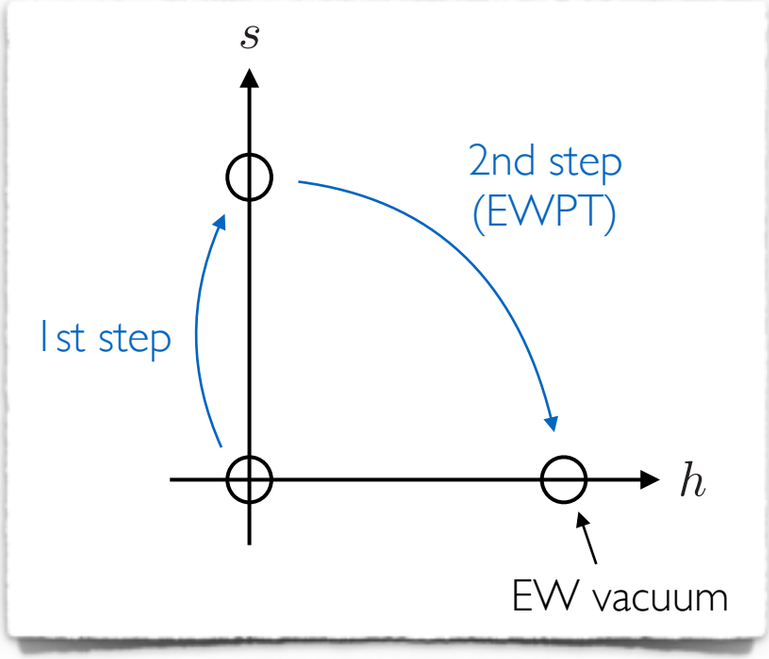

- can be probed at (future) *colliders* looking for the additional singlet

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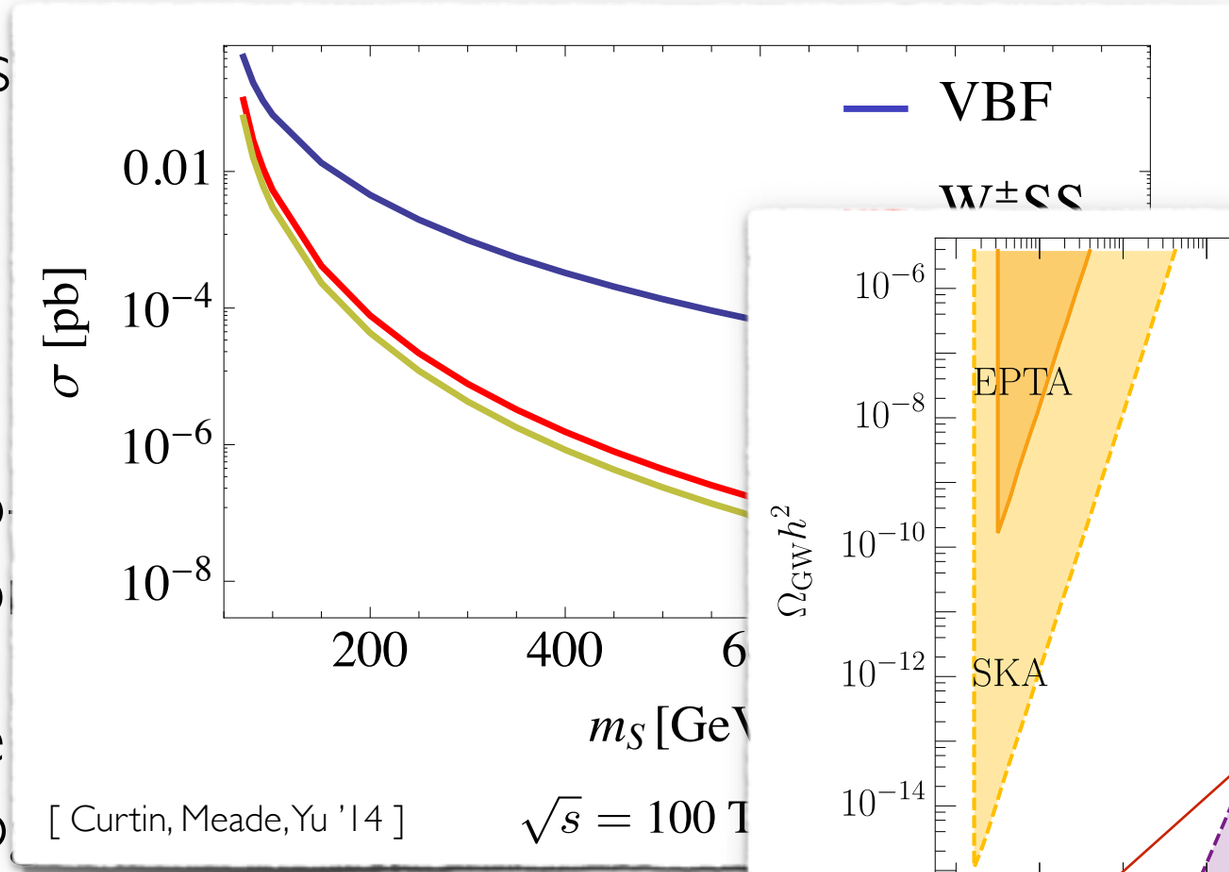

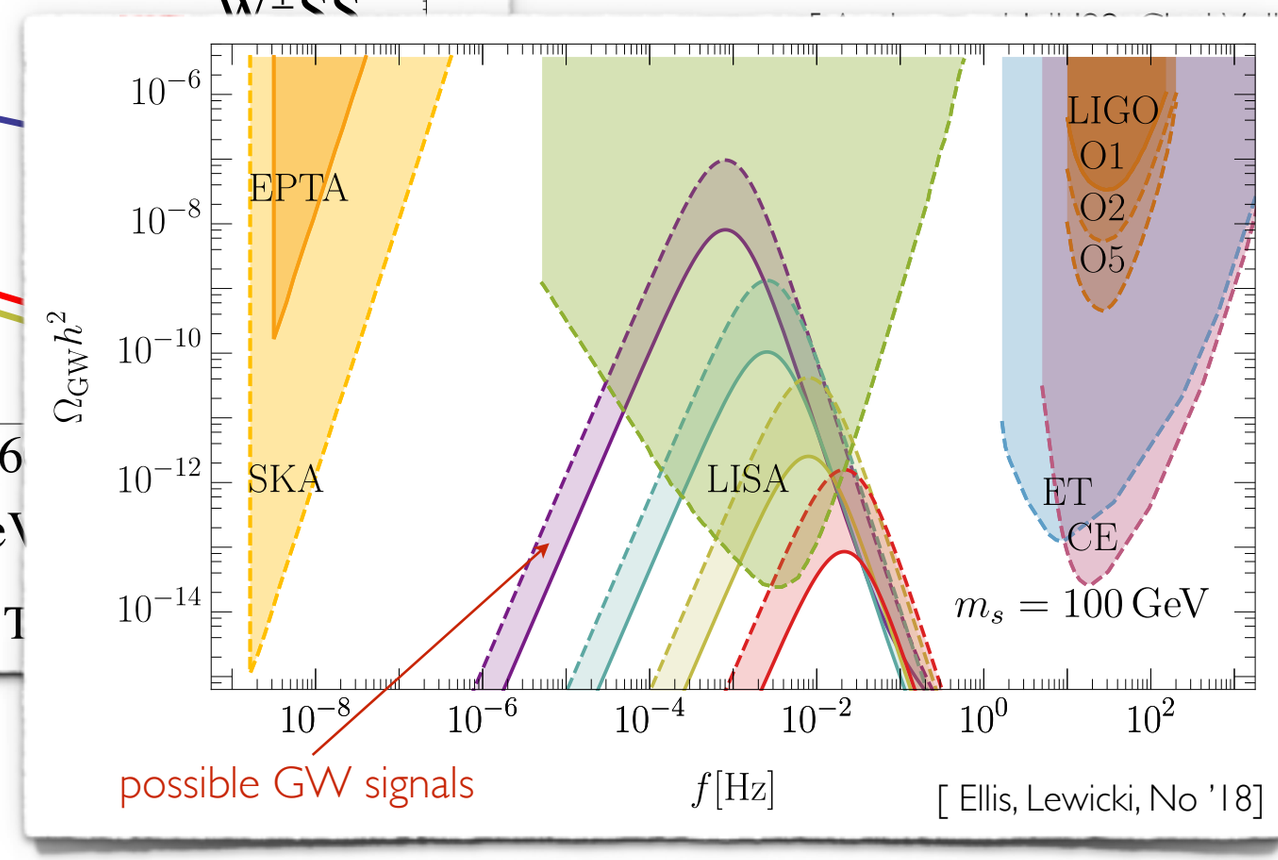

- can be probed at (future) *colliders* looking for the additional singlet
- possible tests through *gravitational waves*

The Flavor frontier

A viable flavor structure is an *essential* ingredient for all BSM scenarios

- many flavor *puzzles* still open
- high precision in new flavor data gives strong *indirect tests* for NP

Recent development: **Improved bound on electron EDM**

October 2018

ACME $|d_e| < 9.4 \cdot 10^{-29}\, e\,\mathrm{cm}$ → *ACME II* $|d_e| < 1.1 \cdot 10^{-29}\, e\,\mathrm{cm}$ → *ACME III* $|d_e| \lesssim 0.3 \cdot 10^{-30}\, e\,\mathrm{cm}$

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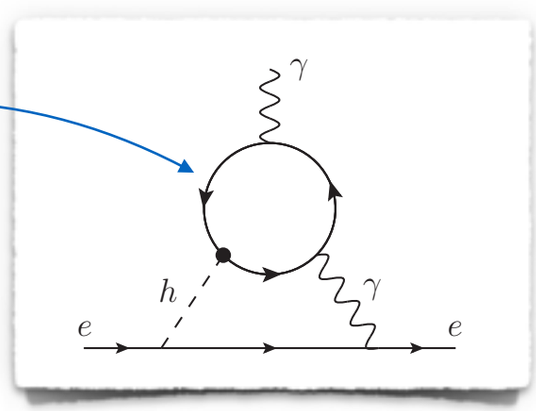
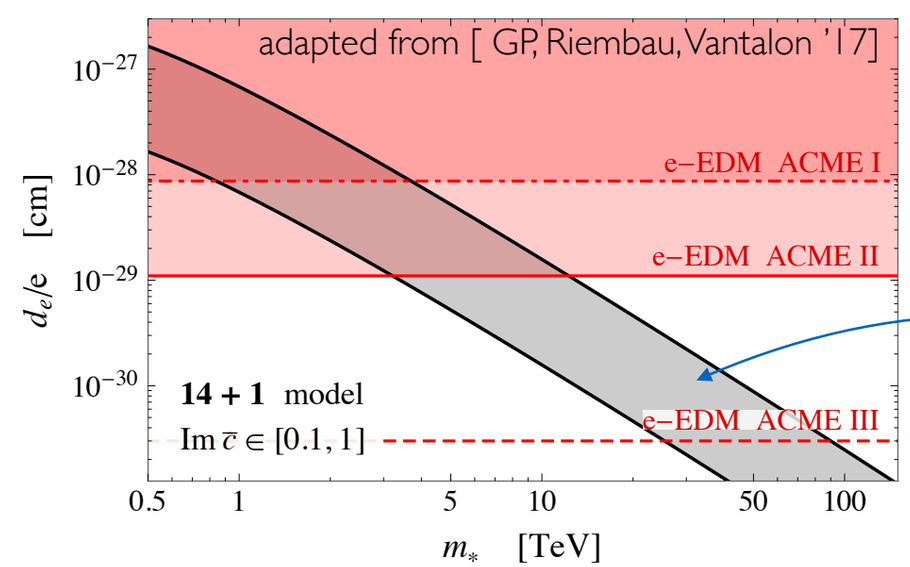
- can test NP in the 10 TeV range even through *two-loop effects*

fermionic top partners





e-EDM from fermionic top partners

- relevant implications also for *EW baryogenesis* models

Model-Independent Approaches

Testing NP without a Model

Model-independent approaches try to look for New Physics in a virtually *unbiased* way

Advantages:

- only relies on SM (+ minimal set of additional assumptions)
- can look for wider range (virtually any) NP model
- might discover unthought-for NP

Possible approaches:

- precision measurements (through Effective Field Theory formalism)
- anomaly detection

Precision Measurements

Even if NP is too heavy to be produced directly we can still look for **deviations from SM** in low-energy observables!

- NP parametrized in a model-independent way through extension of SM with higher-dimensional operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{dim-6} + \sum_i \frac{d_i}{\Lambda^4}\mathcal{O}_i^{dim-8} + \cdots$$

- precision EW and Higgs measurements can test possible deviations

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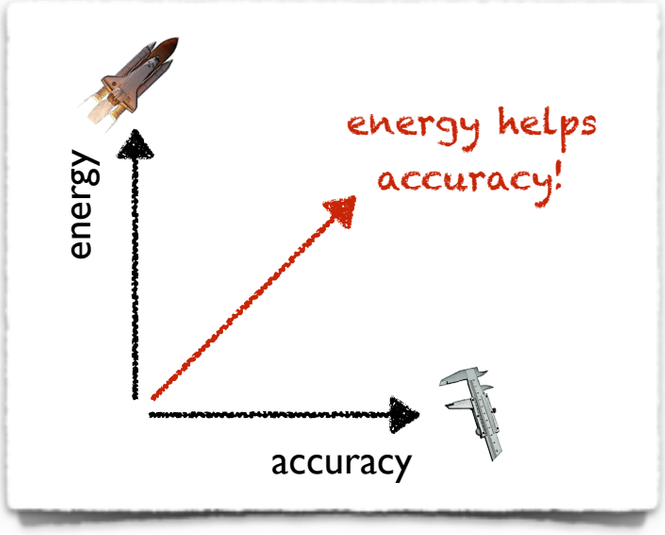
- precision EW and Higgs measurements can test possible deviations

Precision program effective also at *hadron colliders* (including LHC)

- new physics effects *grow with energy*

$$\Delta\mathcal{O}/\mathcal{O} \sim E^2/\Lambda^2$$

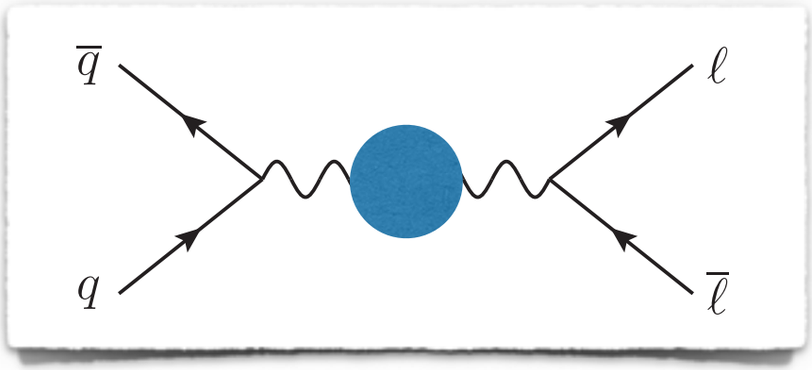
  - big boost with collider energy
  - steady improvement with luminosity



Precision Measurements

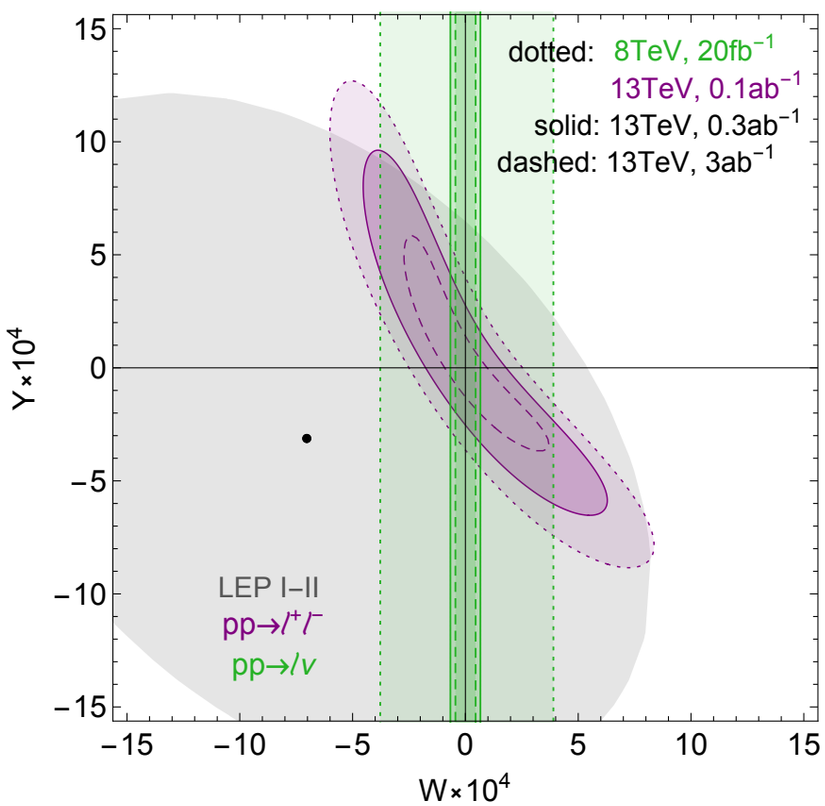
Simplest example: **Oblique parameters in di-lepton Drell-Yan**

[Farina, GP, Pappadopulo, Ruderman, Torre, Wulzer '16]



$$\Delta\mathcal{L} = -\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 - \frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

- LHC improves the LEP bounds by one order of magnitude



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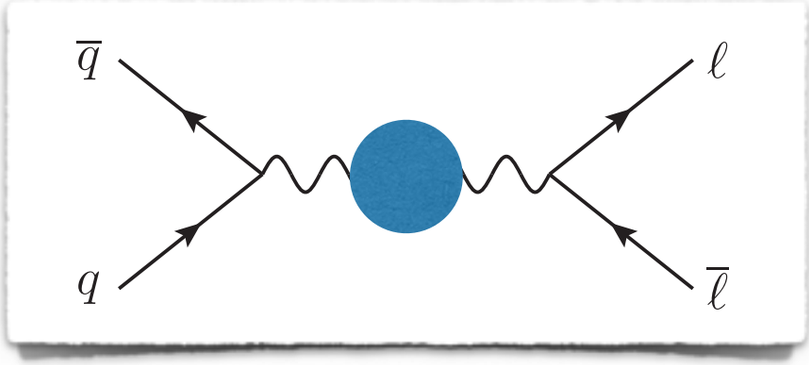

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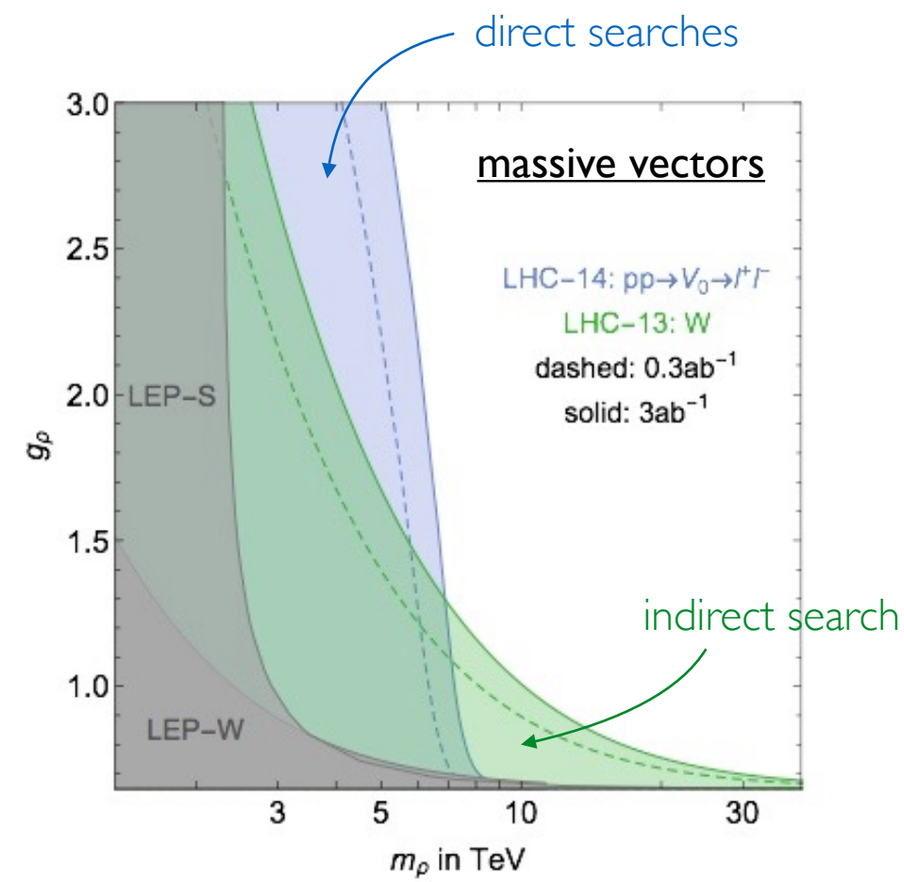


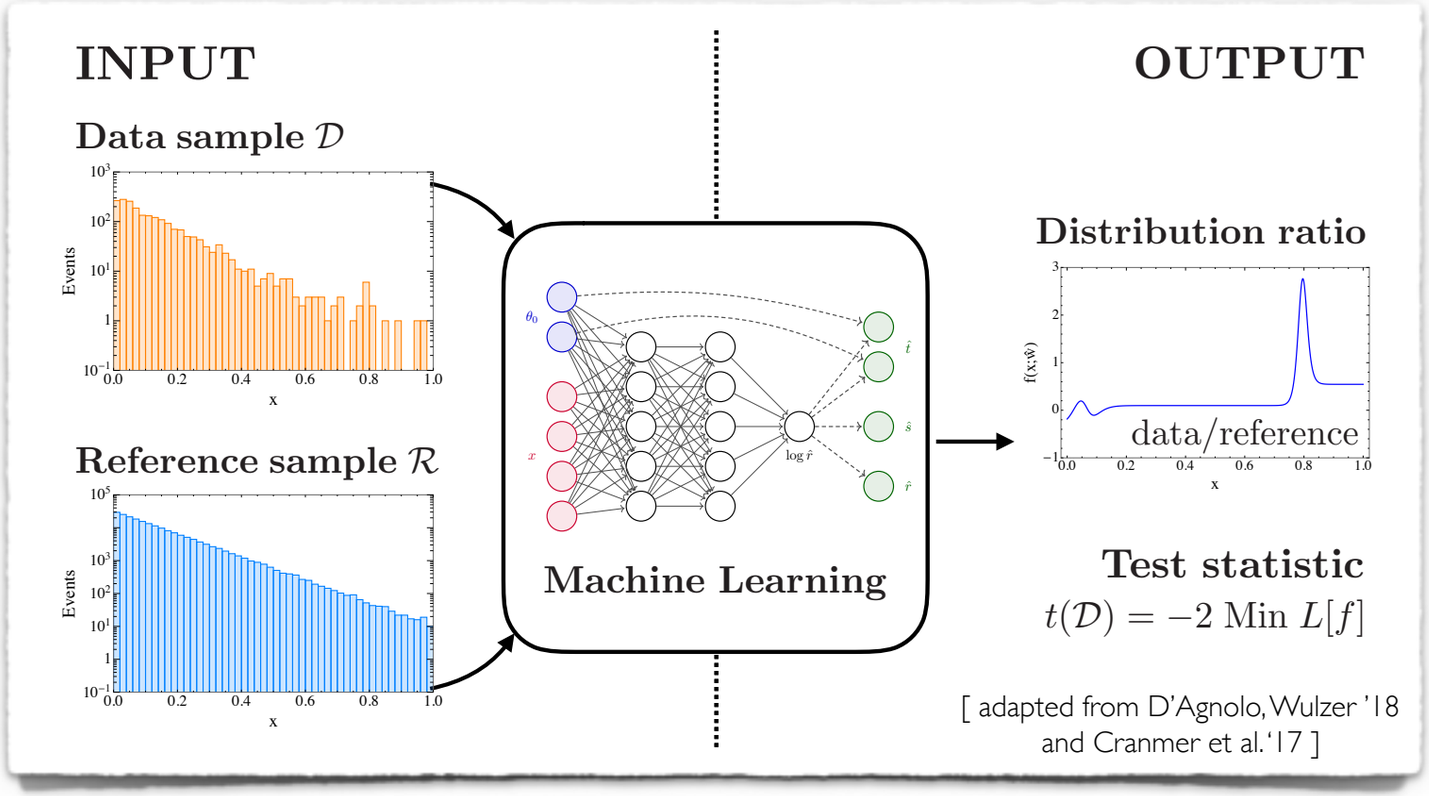
- LHC improves the LEP bounds by one order of magnitude
- can complement direct searches (eg. heavy resonances or difficult signals)

Anomaly Detection

Search for **departures** from a given **reference model** (in our case the SM) with no need to specify alternative theory

- ideally sensitive to *any* new-physics model

machine learning used to compare experimental data with reference model



[adapted from D'Agnolo, Wulzer '18 and Cranmer et al. '17]

- limitation: can not be used for exclusion (negative results are not informative)

Anomaly Detection

Still at an early-development level, but *many interesting directions*…

- CWoLa Hunting [Collins, Howe, Nachman '18]
- Novelty Detection [Hajer et al. '18; Pierini et al. in progress]
- Distribution Comparison [D'Agnolo, Wulzer '18]
- Non-QCD jets [Aguilar-Saavedra et al '17; Heimel et al. '18]
- Gaussian Mixture pdf [Kuusela et al. '11]
- Nearest-Neighbours pdf [De Simone, Jacques '18]

Conclusions

Conclusions

Last years saw *explosion* of research directions in BSM physics

Naturalness remains an important question and fruitful guideline…

- (minimal) classical scenarios under pressure
- several alternatives are being explored

… but a **broader search program** is clearly necessary

- many open questions in SM
- new search strategies at colliders (eg. model independent approach)
- beyond-collider probes