Beyond the Standard Model

Theory Status

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(ICHEP 2016, Chicago)

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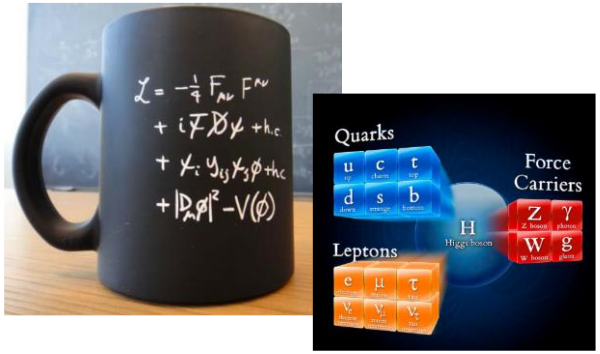
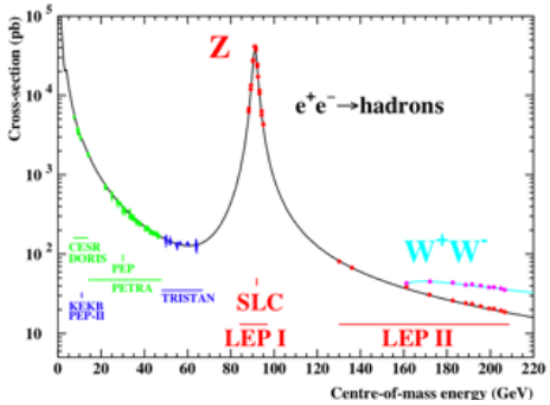
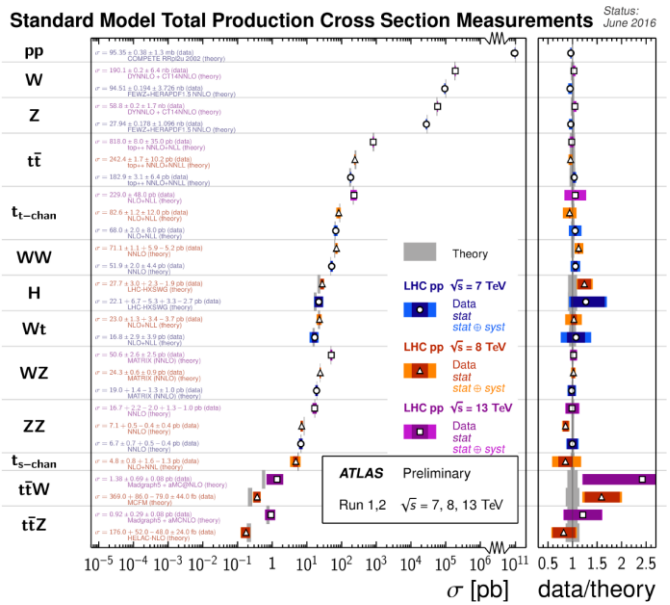
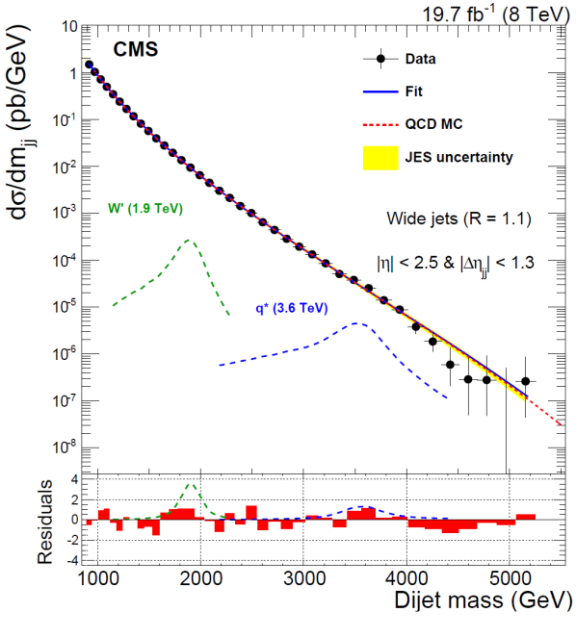
SM is simple enough to be summarized on a small coffee mug, yet it is amazingly successful!









Even with this great success, we have many reasons to speculate about physics beyond the SM (BSM):

* **BSM with observational evidence**

  Neutrino mass, Dark matter,

  Matter-antimatter asymmetry, Inflation

* **BSM to explain the naturalness problems of the SM**

  Hierarchy problem: SUSY, Extra Dim, Composite Higgs, Relaxion, ..

  Strong CP problem: Axions, Spontaneously broken CP, ...

* **BSM for theoretical completeness**

  Quantum gravity, Unification, ...

* **Why not?**

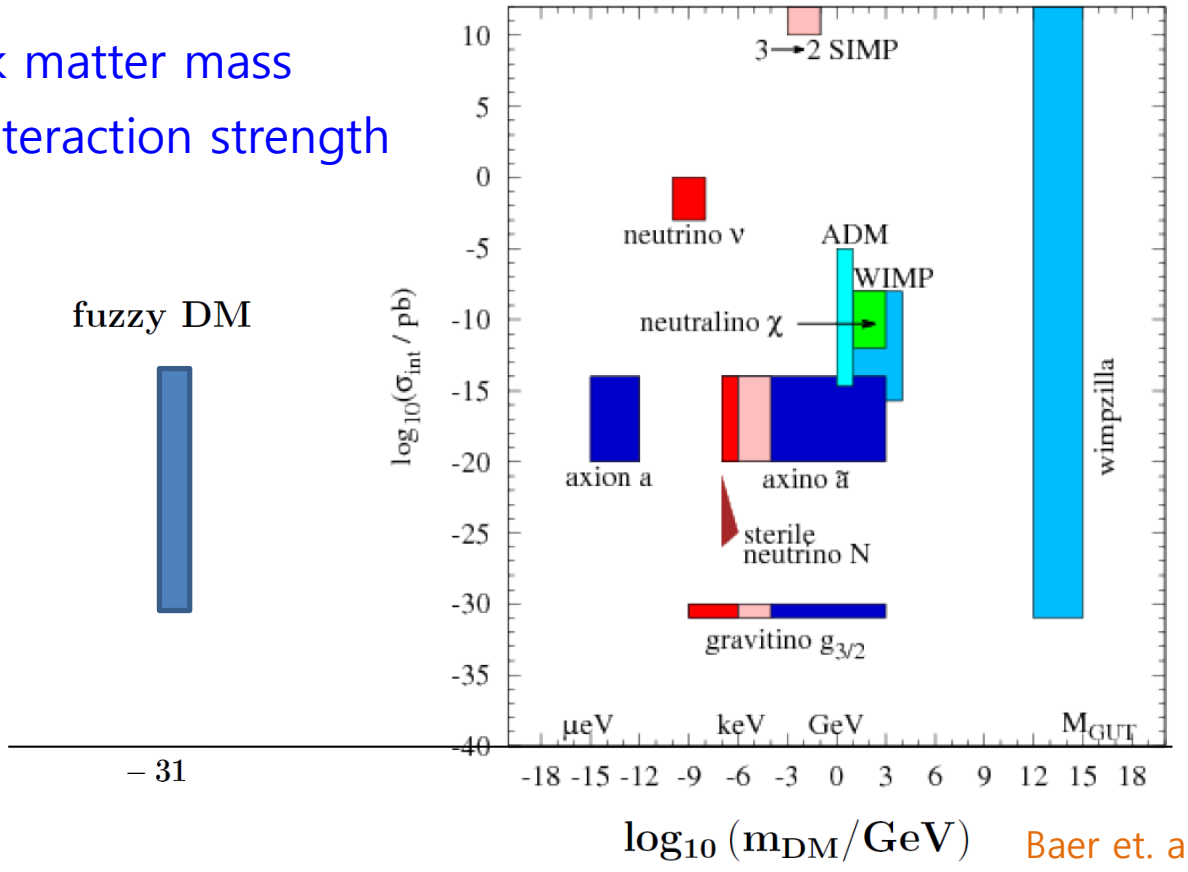
  Z-prime, W-prime, extra Higgs, vector-like quarks/leptons, leptoquarks, ...

We have a long list of possible BSM physics, but we don't know **where they are.**

After the discovery of the Higgs boson, we don't have anymore a convincing argument to pinpoint the next scale.

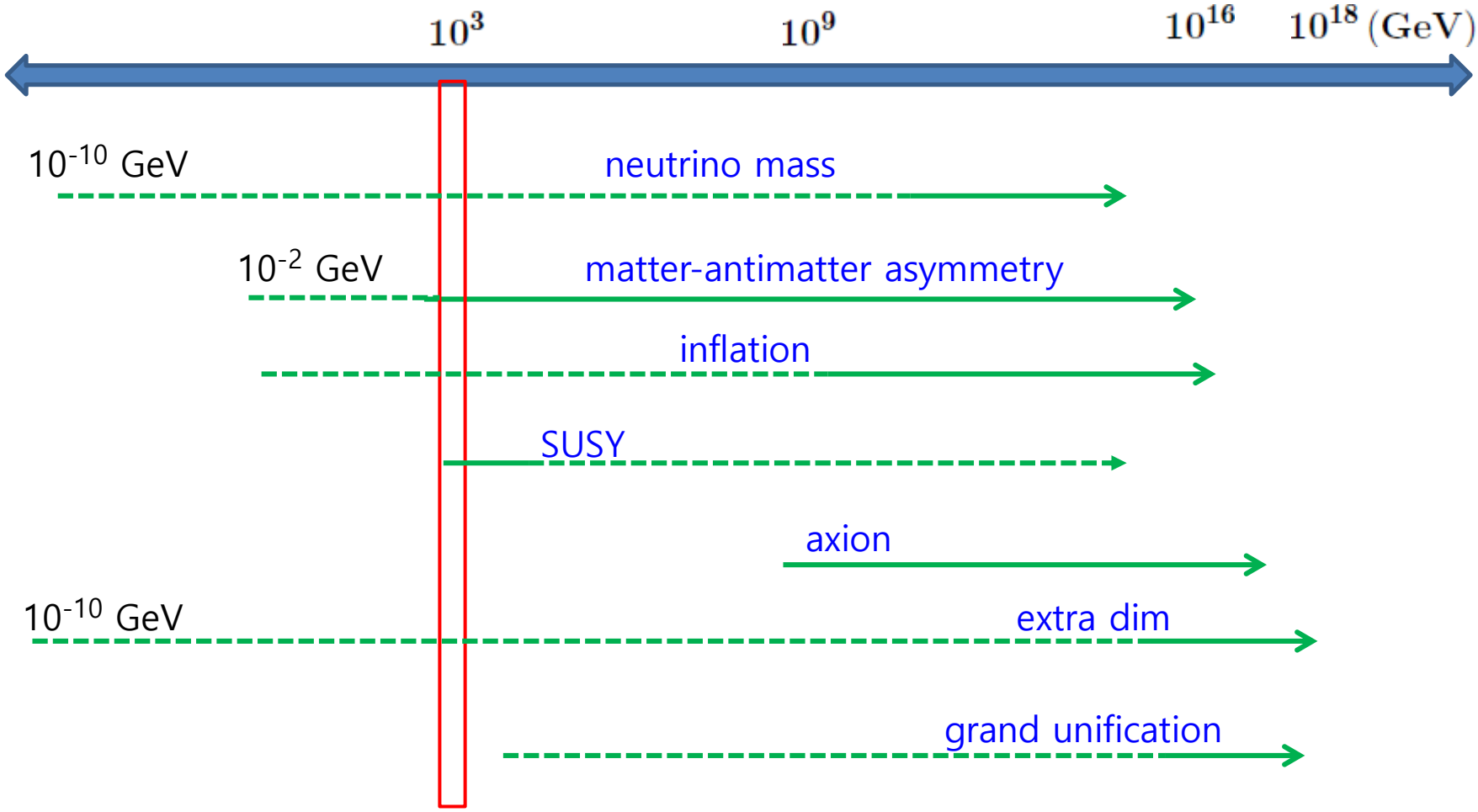
The scale of new physics is so ambiguous.

Dark matter mass
& interaction strength

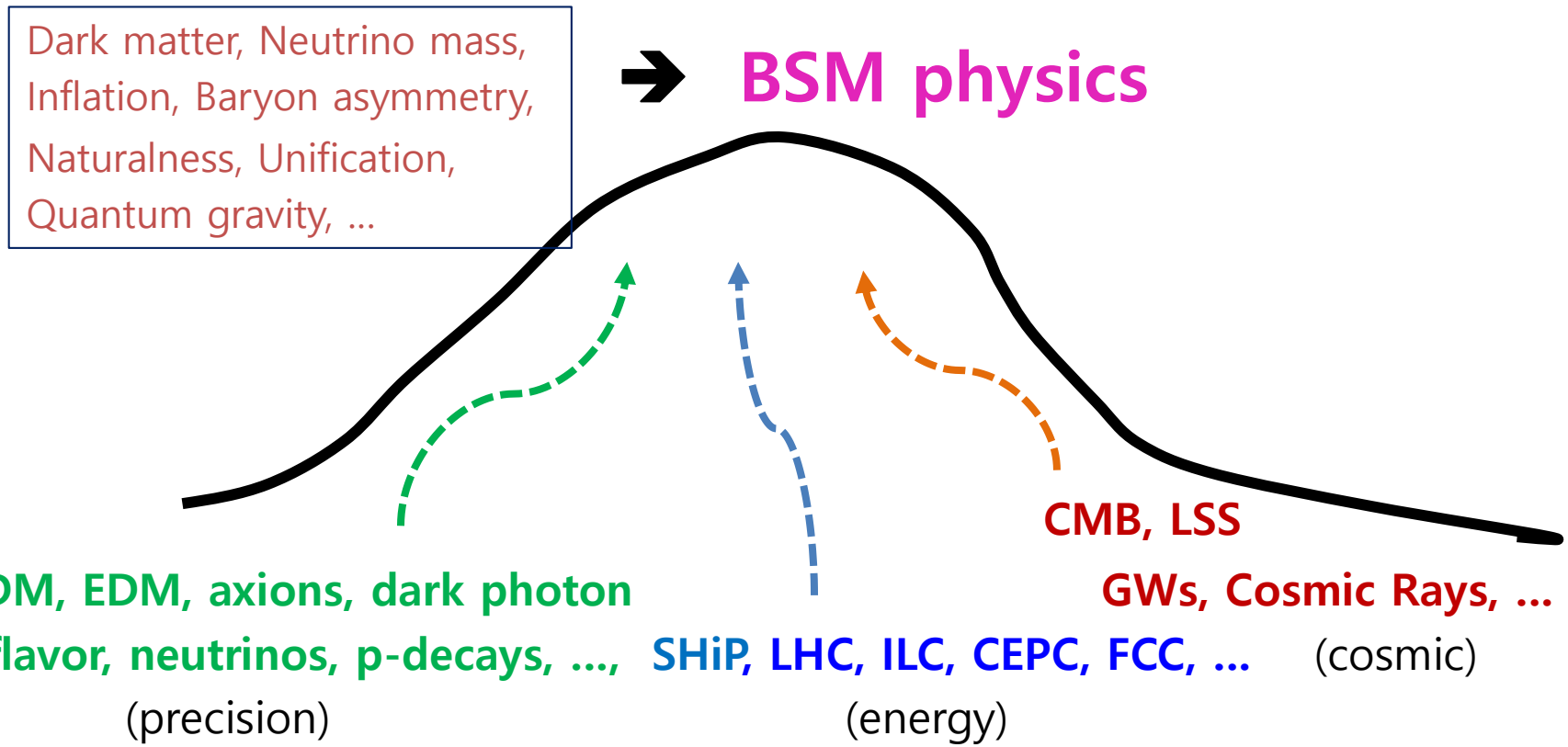


Baer et. al, 2014

Scales of new physics



This is why we need to explore BSM physics from all possible perspectives:



Anybody in this exciting adventure can be the hero of the next big discovery!

Although not convincing enough, we have had long-standing arguments suggesting BSM physics around the weak scale:

* Hierarchy problem: $m_{\rm Higgs}^2 \ll M_{\rm Planck}^2$

* WIMP miracle: $\Omega_{\rm WIMP} \sim 0.2 \left(\frac{m_\chi}{200\,{\rm GeV}}\right)^2 \left(\frac{0.1}{g^2}\right)^2$

These arguments are still alive as many talks in the BSM session are about the subjects motivated by those arguments.

Topics discussed in the BSM session

* SUSY, Composite Higgs, Extra Dim, Relaxion, Little conformal symmetry, …
* Dark sector involving dark matter, dark gauge bosons, hidden valley …
* 750 GeV diphoton excess (fluctuation)
* Others: W-prime, Z-prime, heavy Higgs, vector-like quarks, leptoquarks, GAMBIT, CheckMATE, …

Subjects to be discussed in the rest of this talk:

* SUSY
  (most frequently discussed and still appealing)

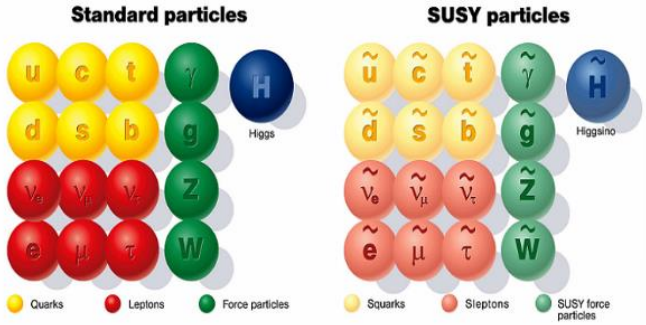
* 750 GeV diphoton excess
  (hottest subject over the last 8 months)

* Relaxion
  (new approach to the hierarchy problem)

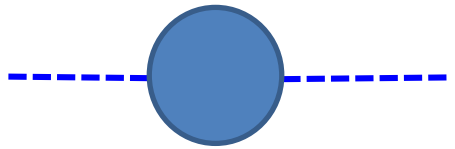
For other subjects of BSM physics related to neutrinos, Higgs boson, dark matter, flavor, see the talks by A. d. Gouvea, H. Logan, M. Nojiri, S. Khalil.

SUSY

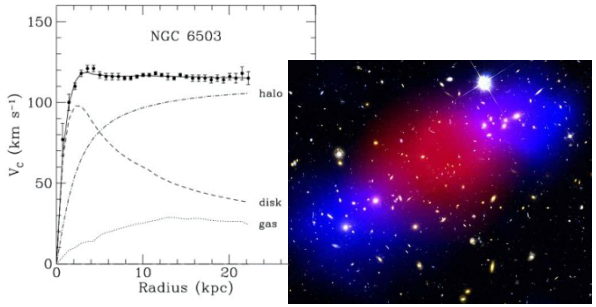
SUSY has been the prime candidate for BSM physics near the TeV scale.



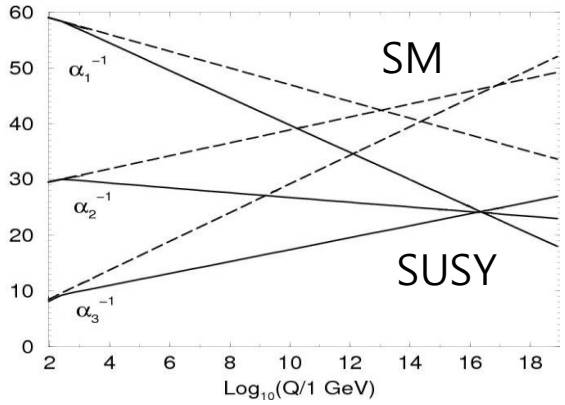
Hierarchy problem



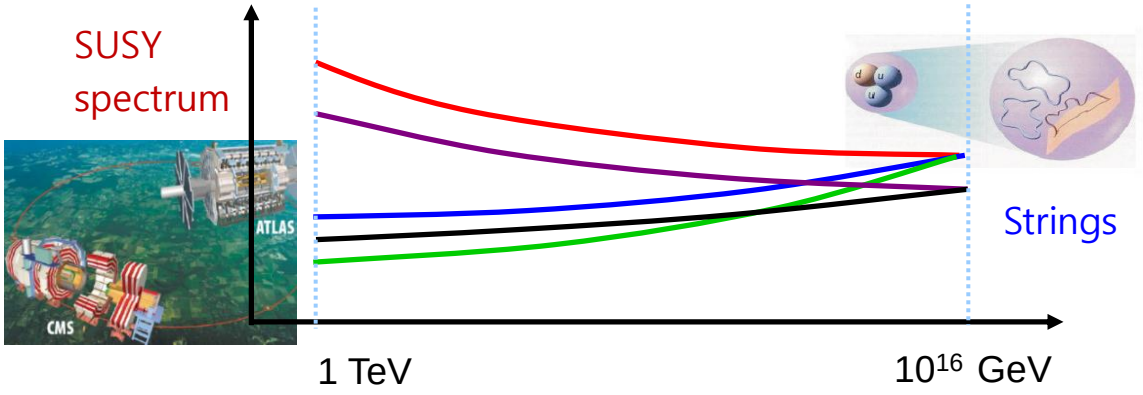
$$\delta m_H^2 \sim M_{\text{Planck}}^2 \Rightarrow m_{\text{SUSY}}^2$$



Dark matter



Gauge coupling unification



SUSY signatures at LHC:

Multi-jets (possibly with leptons or photons) + MET,

Displaced vertices, Long-lived particle (disappearing) tracks, ...

Details of SUSY signatures depend on

* What is the LSP?

  Higgsino, Bino/Wino, axino, gravitino, ...?

* SUSY spectrum: compressed or split?

  colored vs EW, squarks/sleptons vs Higgsino/gauginos, ...

* R-parity: conserved or broken?

* Extra singlet or U(1)?, ...

SUSY theory space is big & rich!

Theory of SUSY spectrum
= Mediation of SUSY breaking

Gravity, Gauge, Anomaly,
Dilaton/Moduli, Mirage,
Gaugino, D-term, Z-prime, ...
Mediations

Extra matters?

Extra gauge bosons?

Various types of LSP

Higsino, Gaugino,
Gravitino, Axino, ...

Various forms of SUSY spectrum

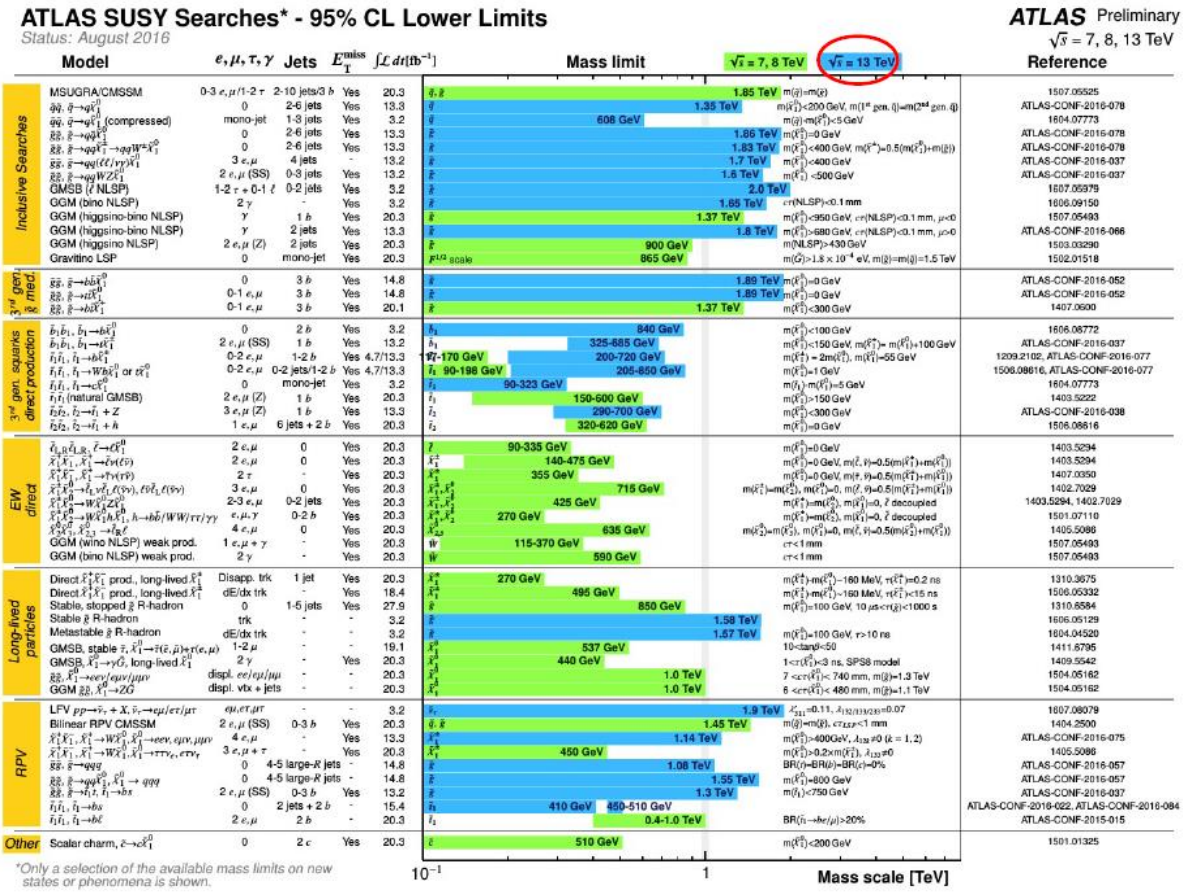
CMSSM, mSUGRA,
NUHM, More-minimal,
Natural, Split, Compressed,
Stealth, Spread, ...

SUSY models possibly with extra matter/gauge bosons

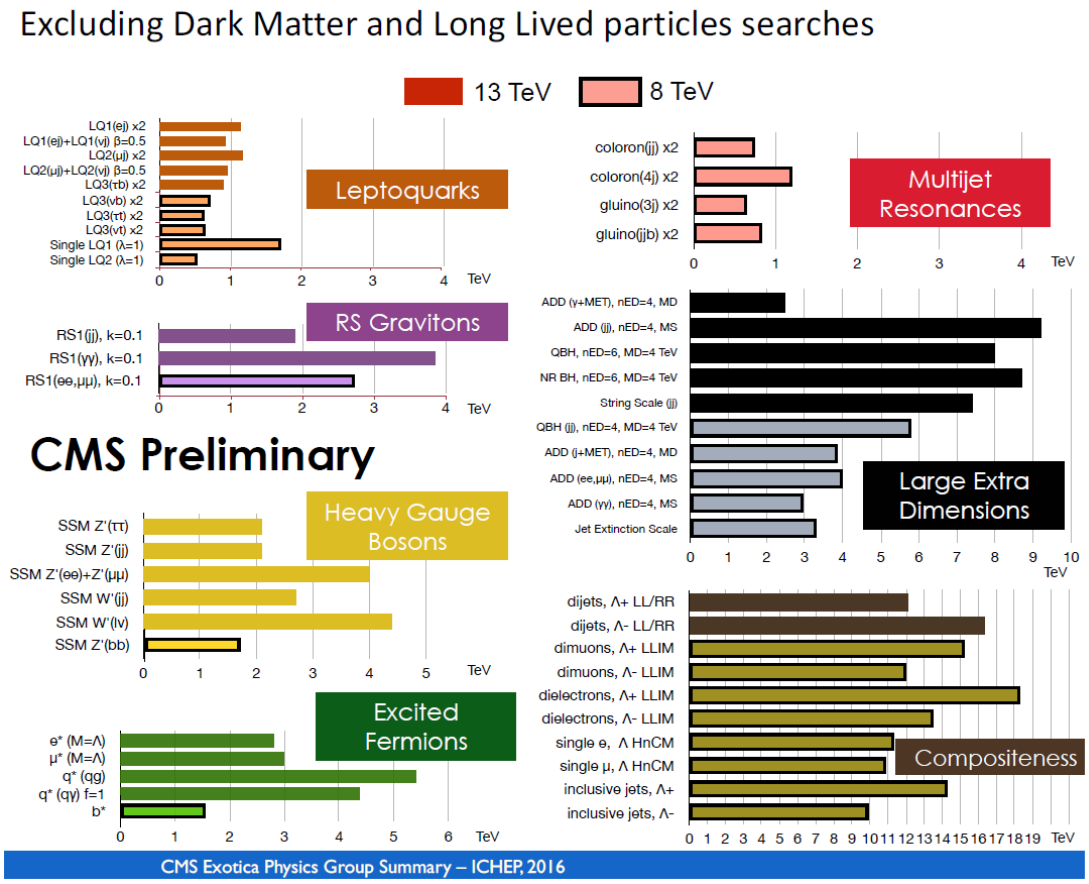
MSSM, NMSSM,
USSM, μνSSM,
E6SSM, PQNMSSM,
.....

Combined anomaly & Z-prime mediation, Talk by Roy

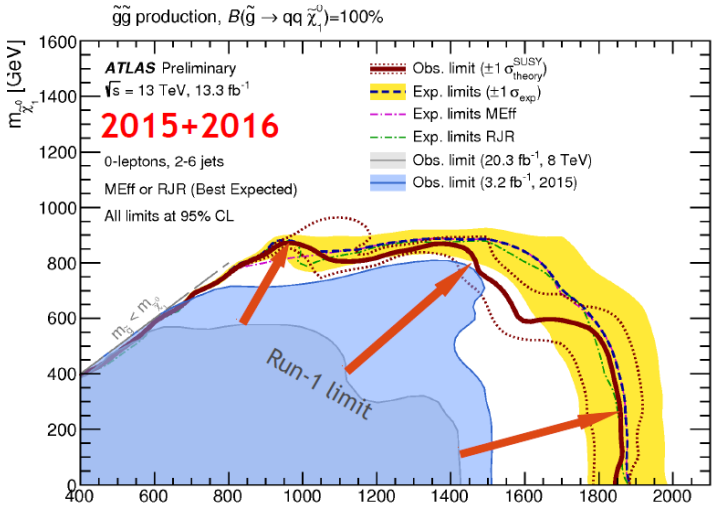
Theorists are ready well to interpret any SUSY signature at LHC, but there is no sign of SUSY yet!

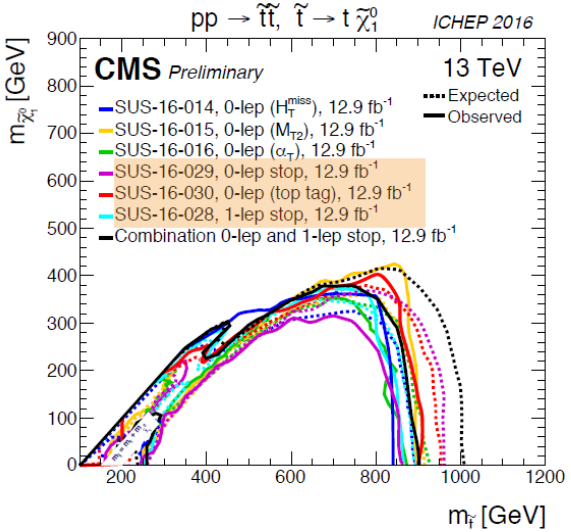


No sign of other BSM also!



- Significant improvement compared Run 1!

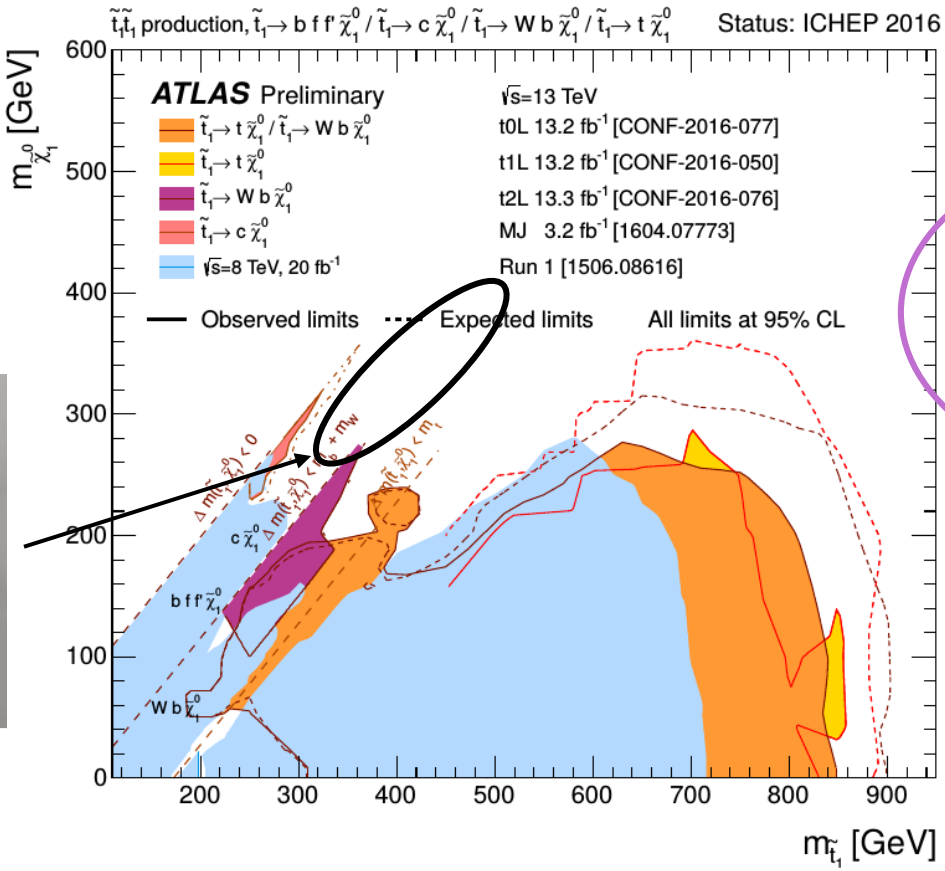


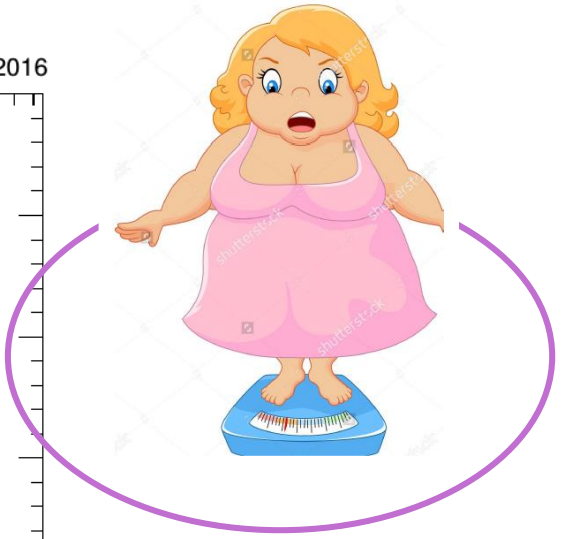


  - … but some excesses that will be interesting to follow as more data is recorded!

LHC is performing amazingly well, stay tuned for more results by the end of the year!

SUSY is either heavy or stealthy (compressed)!





Hints on SUSY scales:

* Naturalness:

$$\delta m_{H_u}^2 = m_{\text{higgsino}}^2 - \frac{3y_t^2}{4\pi^2}\left(m_{\text{stop}}^2 + \frac{g_s^2}{3\pi^2} m_{\text{gluino}}^2 \ln\left(\frac{\Lambda_{\text{mess}}}{m_{\text{gluino}}}\right)\right)\ln\left(\frac{\Lambda_{\text{mess}}}{m_{\text{stop}}}\right) + \ldots$$

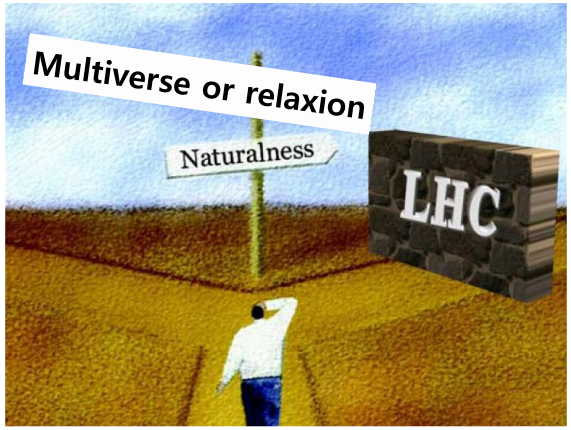
➔ Higgsino, stop and gluino are around the weak scale (Natural SUSY).

(cf: Radiatively-driven naturalness with stop and gluino around 1-4 TeV)

Baer et al

However there are some alternatives to the naturalness, which allow SUSY to be well above the weak scale:

$m_{SUSY} >> m_{Higgs}$
with anthropic selection
or relaxion?



G. Villadoro

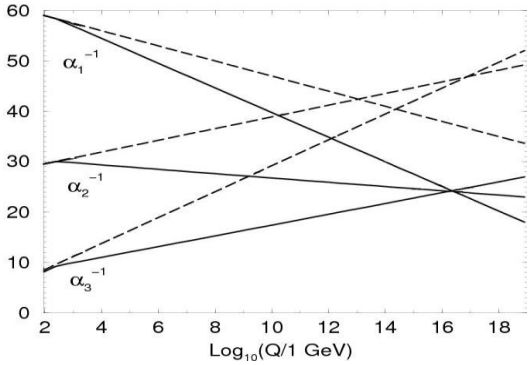
Even when we abandon the naturalness, still there are some indications that SUSY may not be too far away from the weak scale.

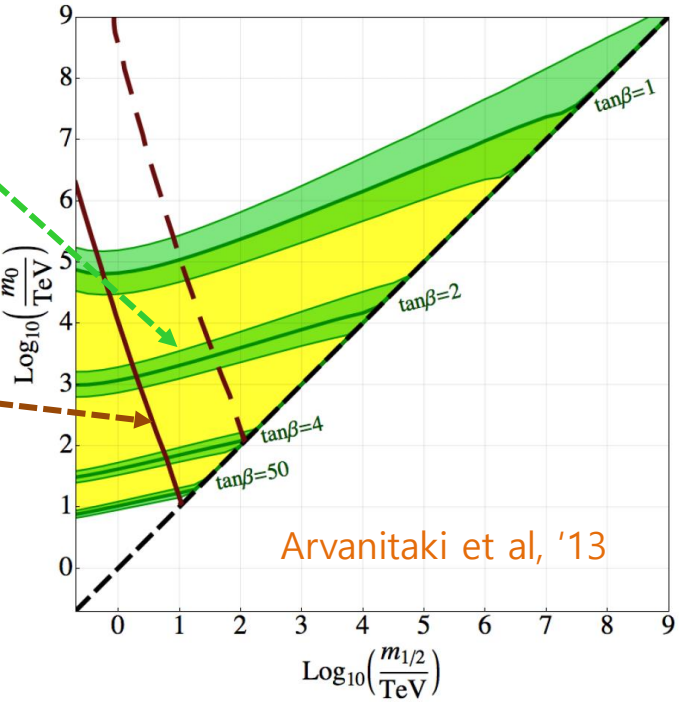
* Higgs mass = 125 GeV: $m_h^2 = M_Z^2 \cos^2 2\beta + \frac{3y_t^2 m_t^2}{4\pi^2} \ln\left(\frac{m_{\rm stop}}{m_t}\right) + \ldots$

➔ squark and slepton masses:

m_0 < 1000 TeV for tanβ > 2

* Gauge coupling unification:





➔ Higgsino and gaugino masses:

$m_{1/2}$ < 10 TeV

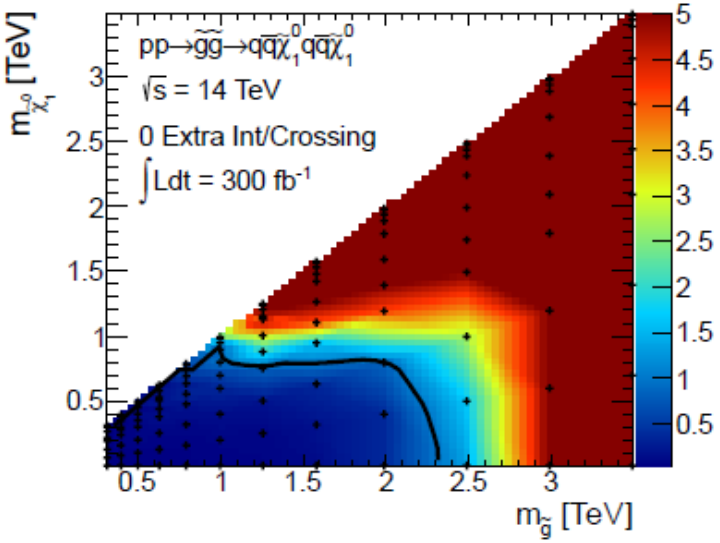
SUSY is certainly a compelling candidates of BSM physics, so we should keep searching for her without leaving any stone unturned.

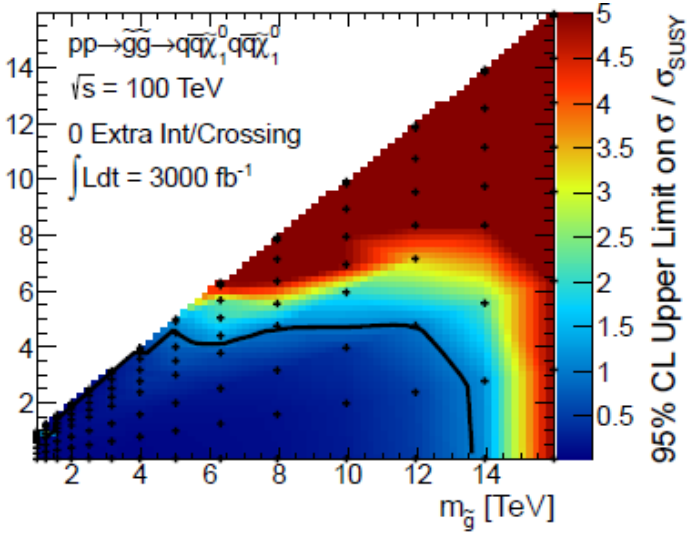
* Taking the gauge coupling unification seriously, SUSY may have some chance to be seen at LHC, and a good chance at the FCC:

High luminosity LHC

Cohen et al, '13

100 TeV collider



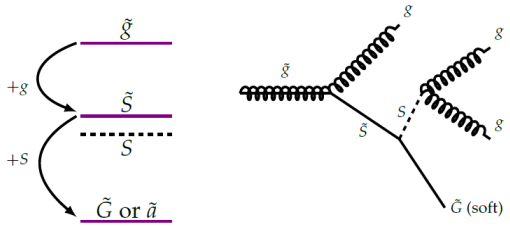


* An interesting possibility for relatively light SUSY:

Stealth SUSY

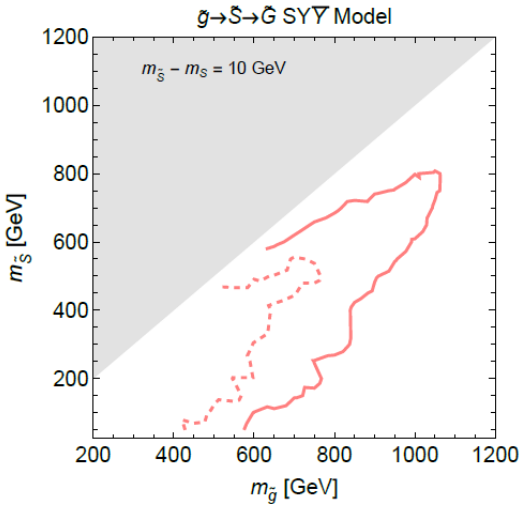
MSSM

Stealth sector



axino/gravitino LSP

J. Fan et al '11



arXiv:1512.05781

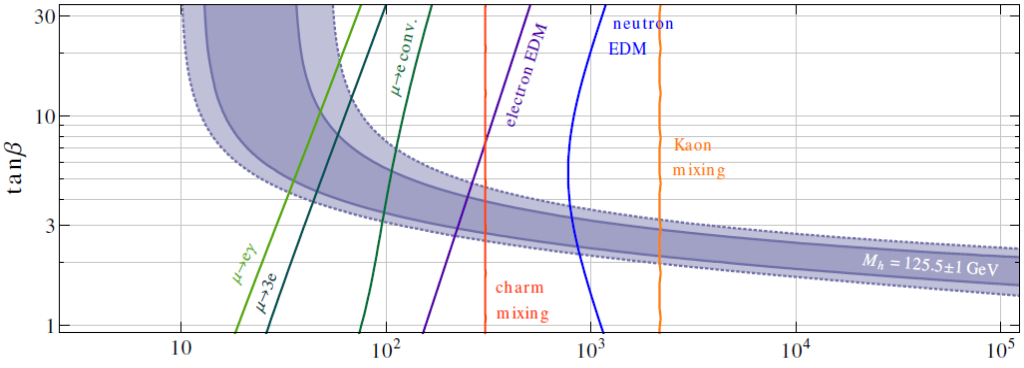
* EW SUSY may be much lighter than colored SUSY: (cf: $(g-2)_\mu$, DM, ...)

EWKinos or sleptons (or generic WIMP) search @ High luminosity LHC

(also @ ILC (Talks by Berggren, Habermehl, List/Baer), @ CLIC (Talk by Simonnielo))

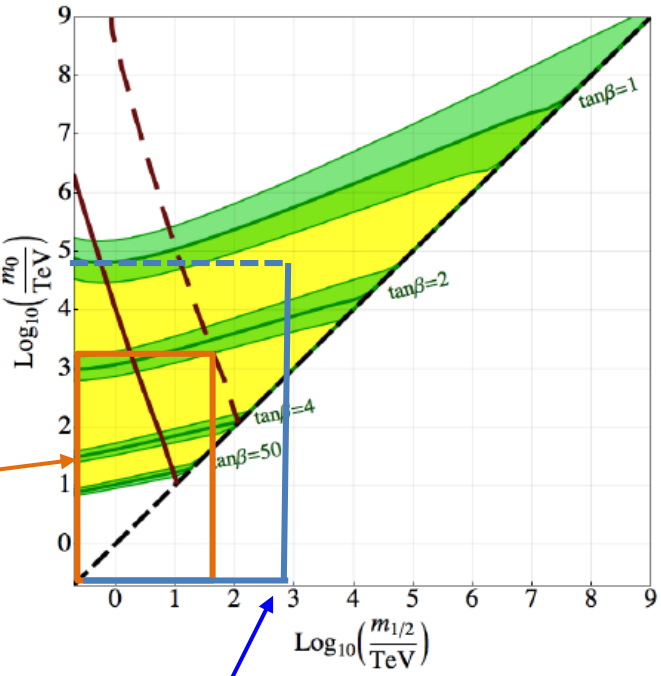
SUSY can leave an observable imprint in **flavor mixing** or **EDM** even when she is well above the weak scale: (Talk by S. Khalil)

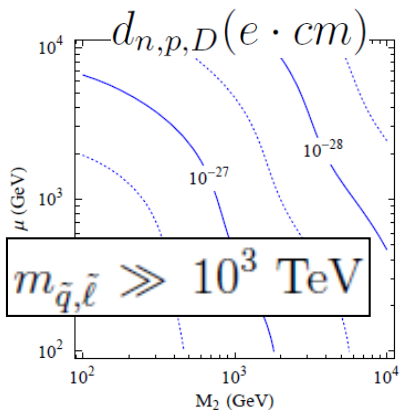
Altmannshofer et. al. '13



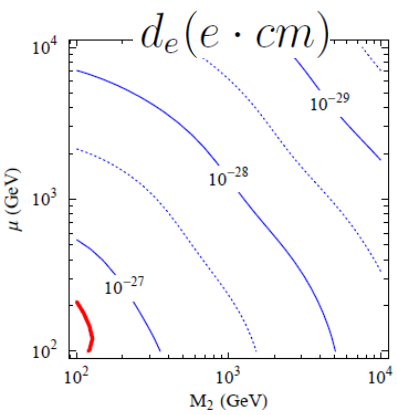
$$m_{\tilde{q}} = m_{\tilde{l}} = |\mu| \ \text{(TeV)}$$

Flavor mixing





$m_{\tilde{q},\tilde{\ell}} \gg 10^3$ TeV



Giudice, Romanino '05

squarks/sleptons $\gg 10^3$ TeV,

EWKinos $< 10^3$ TeV

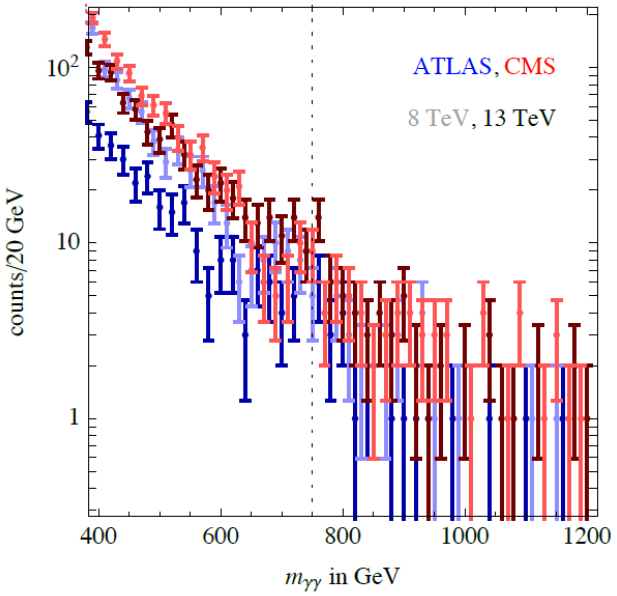
➔ Hadronic **EDMs** $> 10^{-30}$ e-cm

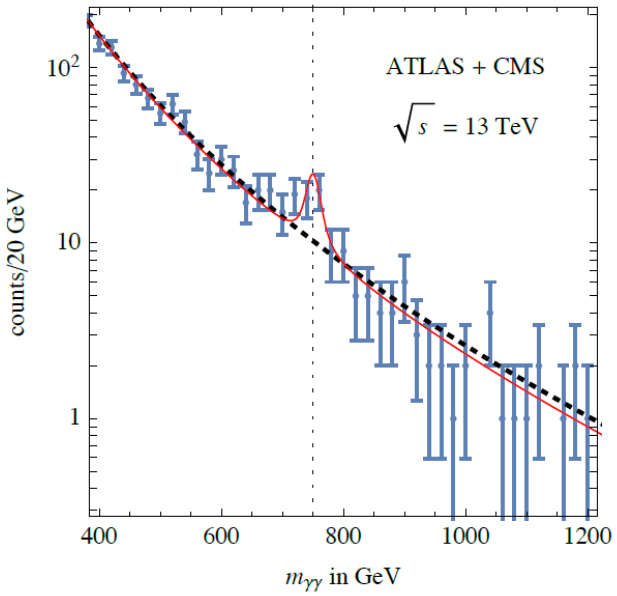
Storage-ring EDM experiment

Y. Semertzidis

750 GeV diphoton excess

ATLAS-CONF-2015-081, 2016-018; CMS PAS EXO-15-004, 16-018



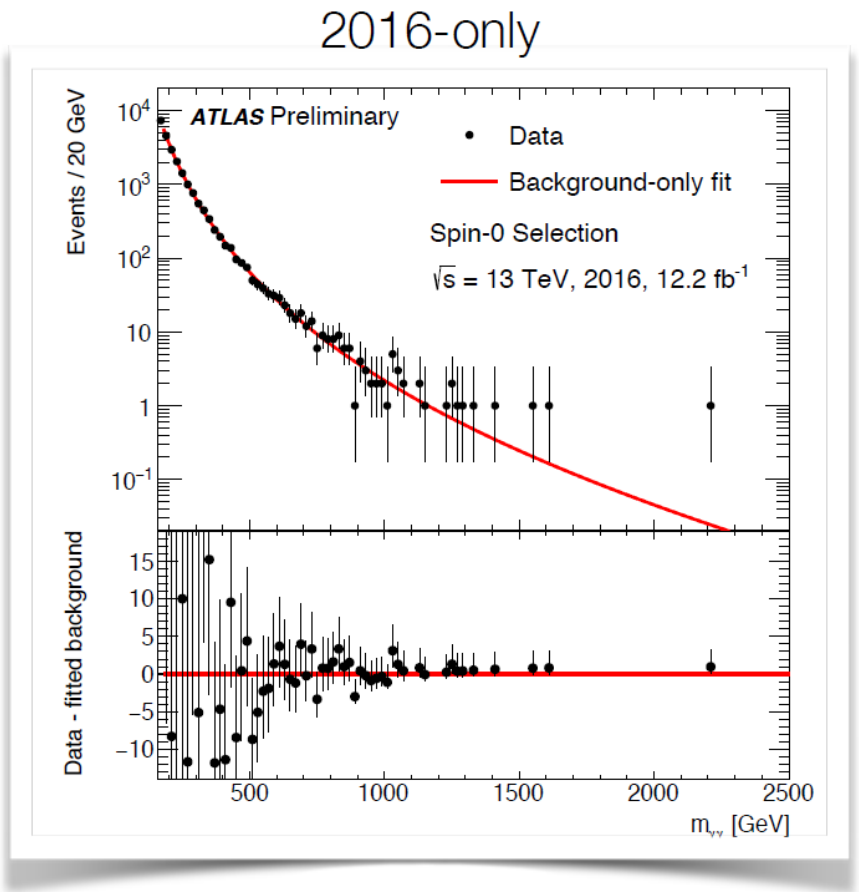


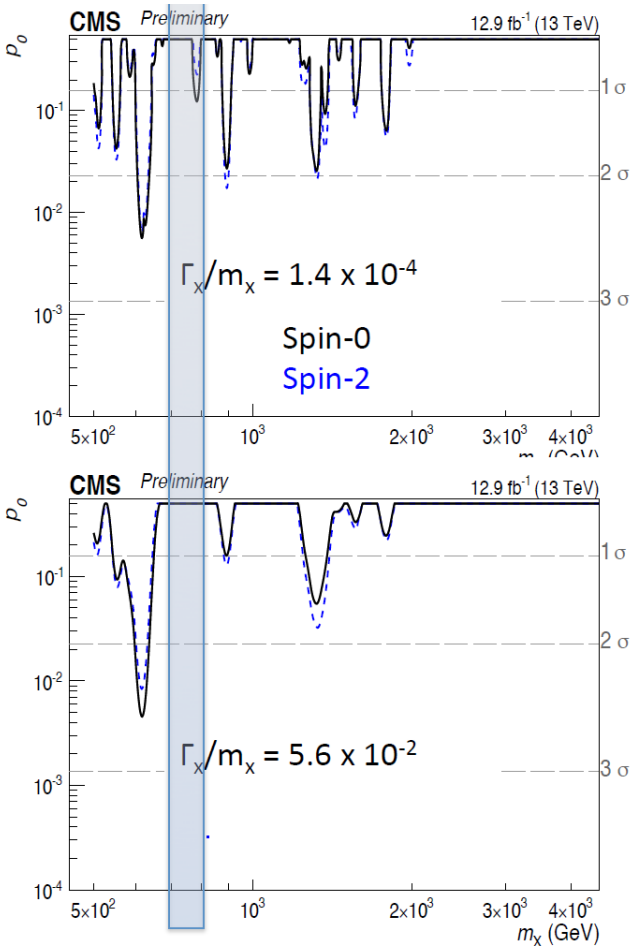
arXiv:1605.09401

What is it?

New resonance to revise the Particle Data Book?

New data @ ICHEP 2016:

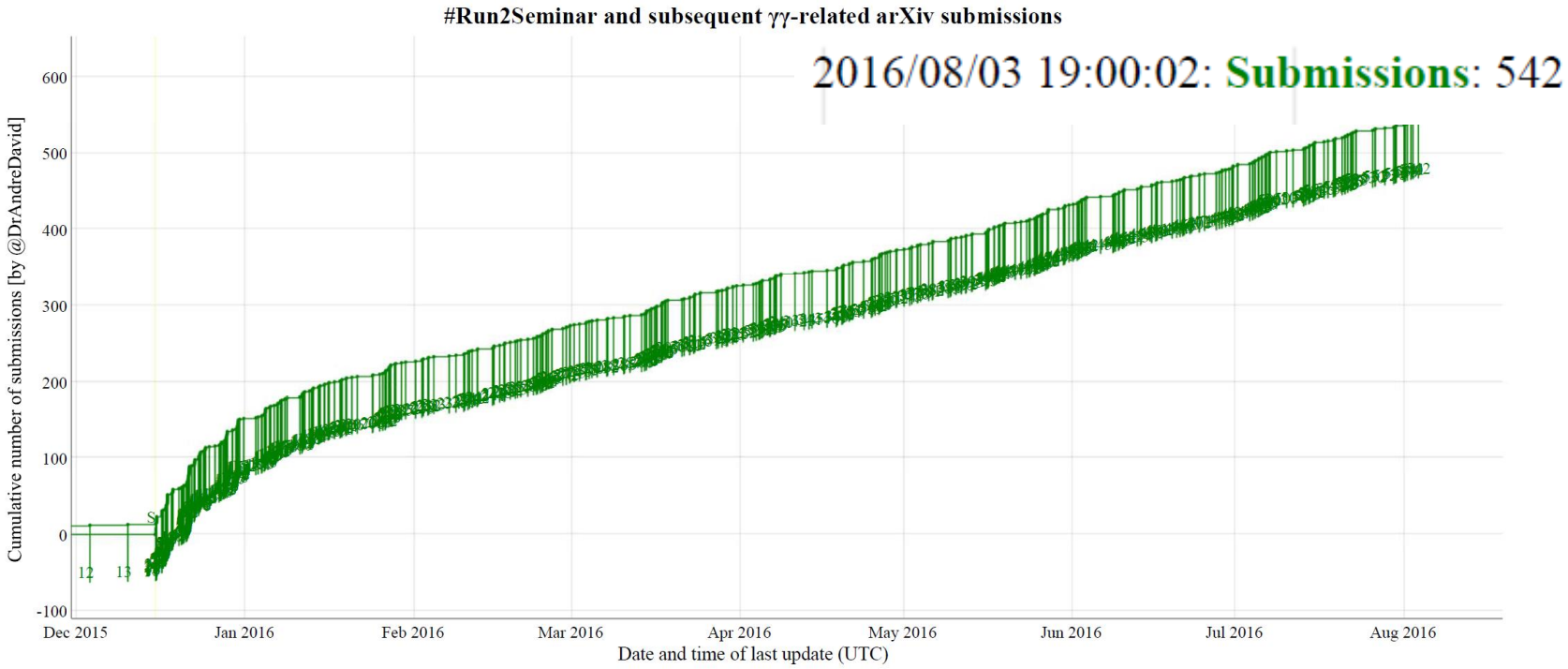




Signals are fading away, so does the excitement.

What have we learned?

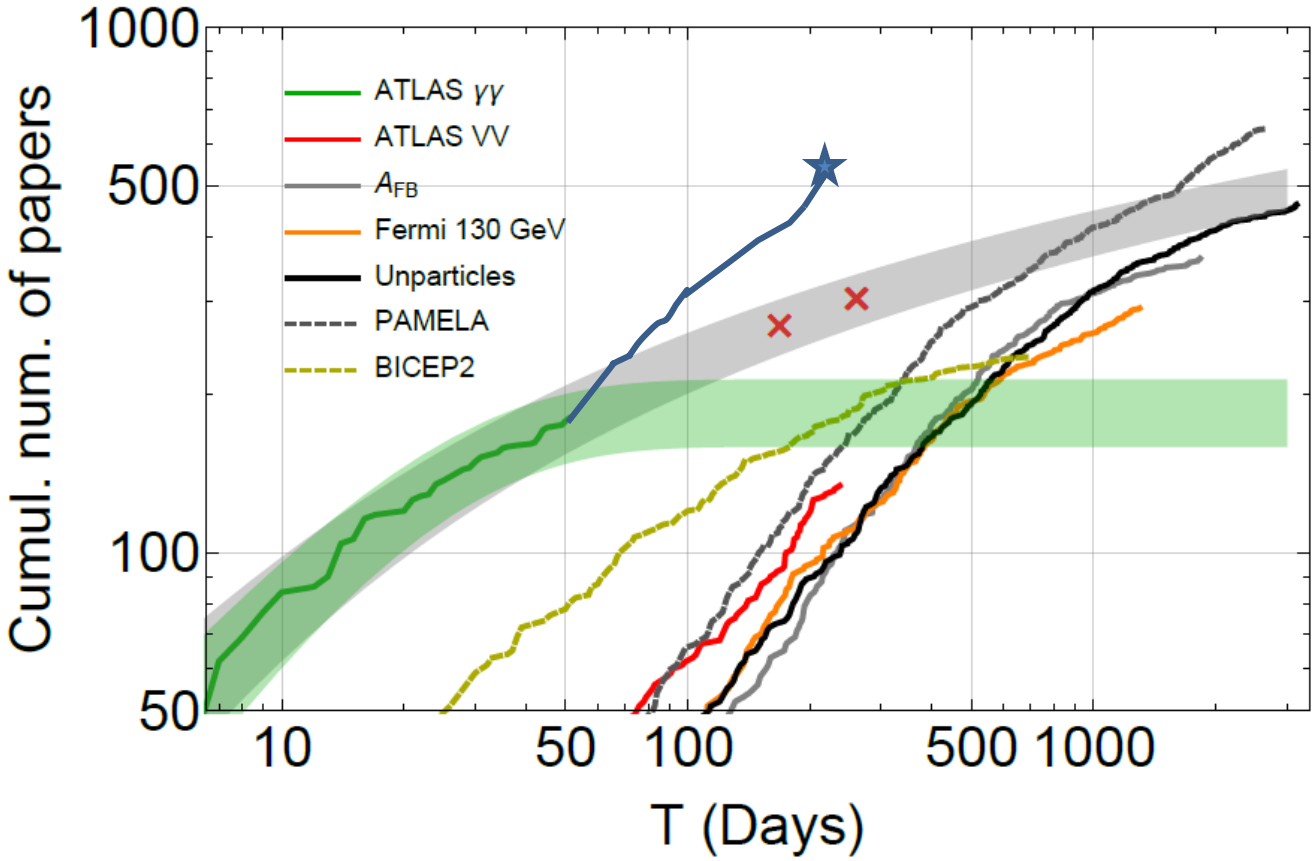
750 GeV flood! https://jsfiddle.net/adavid/bk2tmc2m/show/



Theorists have been so hungry for experimental discovery, a lot more than what we have thought.

It was indeed a big rush, even the theory of ambulance chasing does not work in this case:

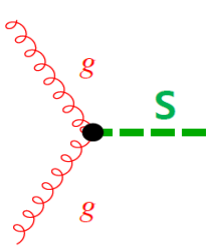
M. Backovic, 1603.01204 [physics.soc-ph]

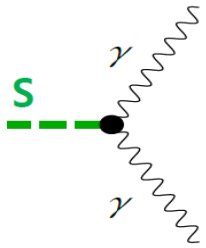


Most straightforward explanation for the diphoton excess:

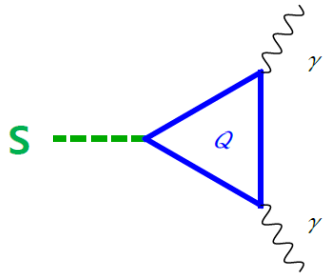
$$\mathcal{L}_{\rm eff} = \frac{S}{M_2}\left(G^{a\mu\nu}G^a_{\mu\nu} \text{ or } G^{a\mu\nu}\tilde{G}^a_{\mu\nu}\right) + \frac{S}{M_1}\left(F^{\mu\nu}F_{\mu\nu} \text{ or } F^{\mu\nu}\tilde{F}_{\mu\nu}\right)$$

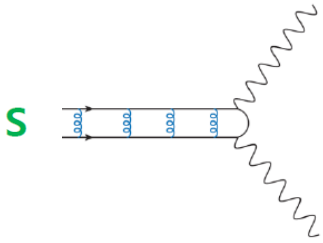
New physics communicating with the SM dominantly through the SM gauge bosons:



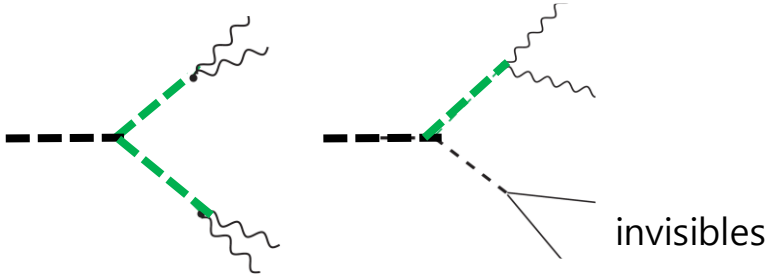


Elementary or composite?

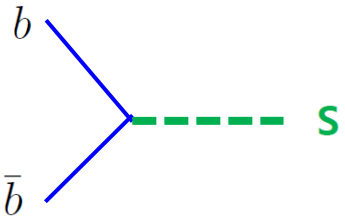




Different decay topologies?



Alternative production?



Models for 750 GeV excess discussed in the Higgs-BSM joint session:

Composite meson in relaxion model, M. Fedderke

Dark sector Higgs boson, P. Ko

NMSSM singlet decaying into light diaxions, K. Rolbiecki

Singlet in SUSY model with extra U(1) and vector-like quarks, Q. Shafi

Anomalous quartic photon coupling (induced by new resonance) in forward pp -> ppγγ, C. Royon

Some speakers changed the content of the talk, and one speaker even didn't show up.

Many different explanations:

Composite Pseudo-Nambu-Goldstone boson,

Quarkonium-like bound state, Sgoldstino, Heavy axion (axizilla),...

Interpreting the 750 GeV digamma excess: a review

arXiv:1605.09401

ALESSANDRO STRUMIA

CERN, INFN and Dipartimento di Fisica, Università di Pisa

References

1. ATLAS note, ATLAS-CONF-2015-081. CMS note, CMS PAS EXO-15-004. Talks by M. Delmastro (ATLAS) and P. Musella (CMS) at the Moriond 2016 conference. ATLAS note CONF-2016-018. CMS note PAS EXO-16-018.
2. K. Harigaya, Y. Nomura, *"Composite Models for the* 750 GeV *Diphoton Excess"*, Phys. Lett. B754 (2016) 151 [arXiv:1512.04850].

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314. S. Jain, F. Margaroli, S. Moretti, L. Panizzi, *"The* 750 GeV *threshold to a new particle world"* [arXiv:1605.08741].
315. B.A. Dobrescu, P.J. Fox, J. Kearney, *"Multi-step production of a diphoton resonance"* [arXiv:1605.08772].

This was not an waste of time!

We could learn more on many things related to BSM physics which communicate with the SM mainly through the SM gauge bosons:

Vector-like fermions,

EW symmetry preserving new strong forces,

Axion-like-particles,

Near threshold behavior of heavy particle loops,

Resonance-continuum interference,

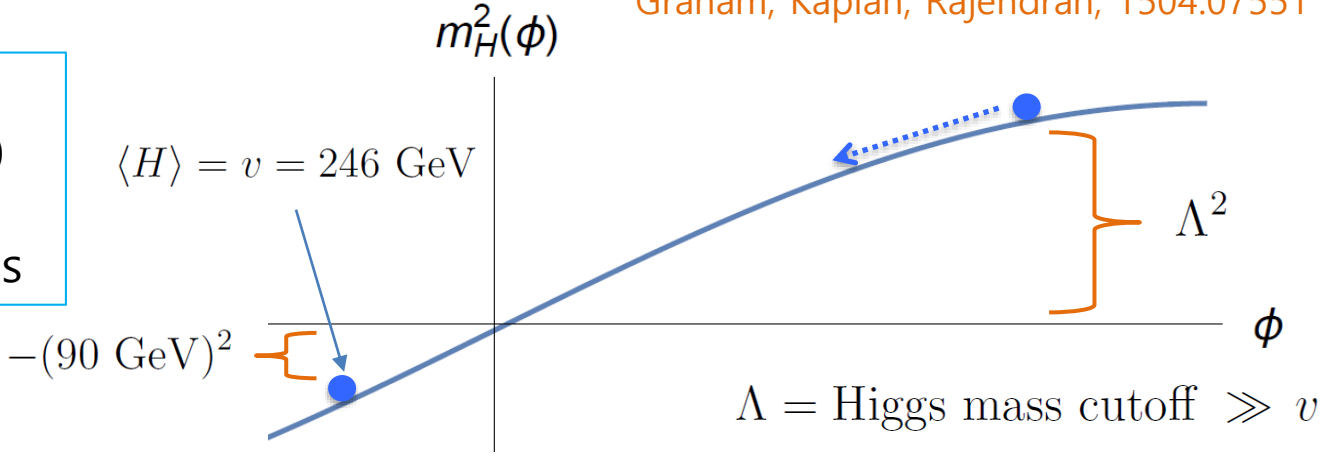
Single photon vs diphoton-jet,

.....

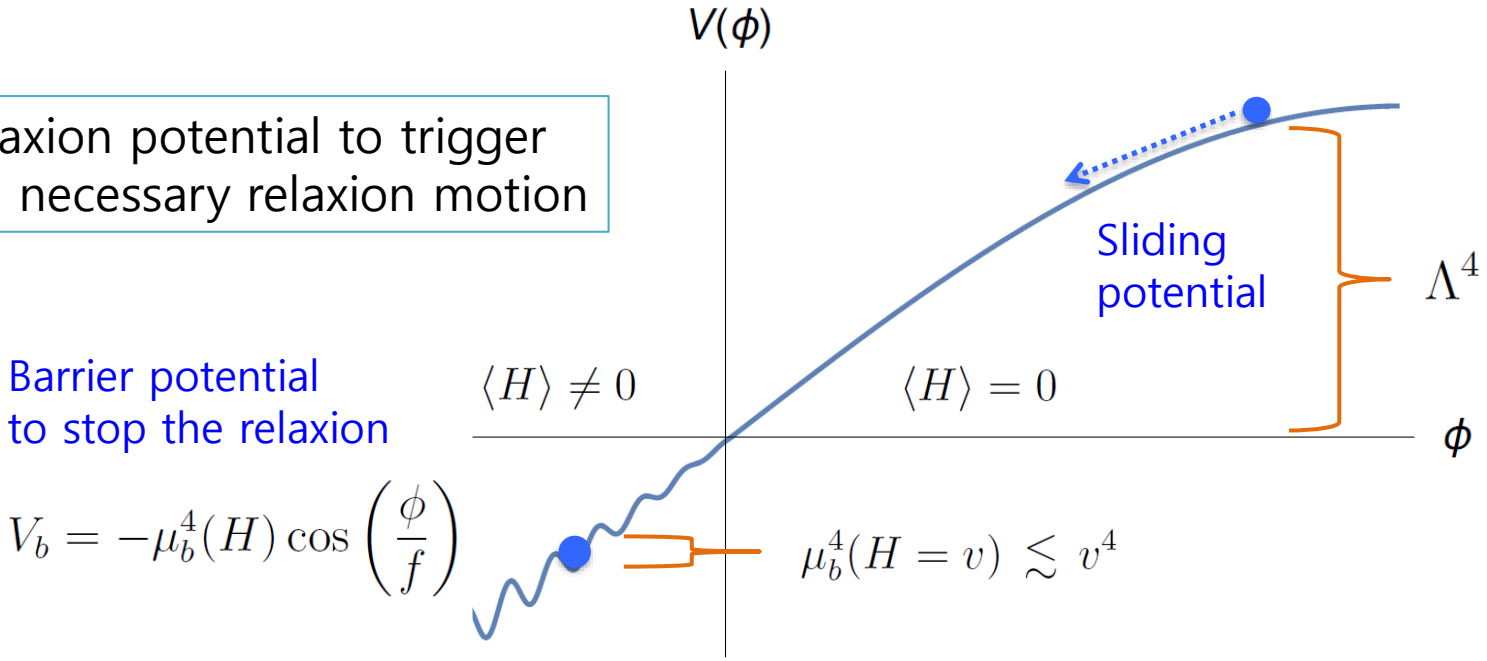
Relaxion: New approach to the weak scale hierarchy problem

Graham, Kaplan, Rajendran, 1504.07551

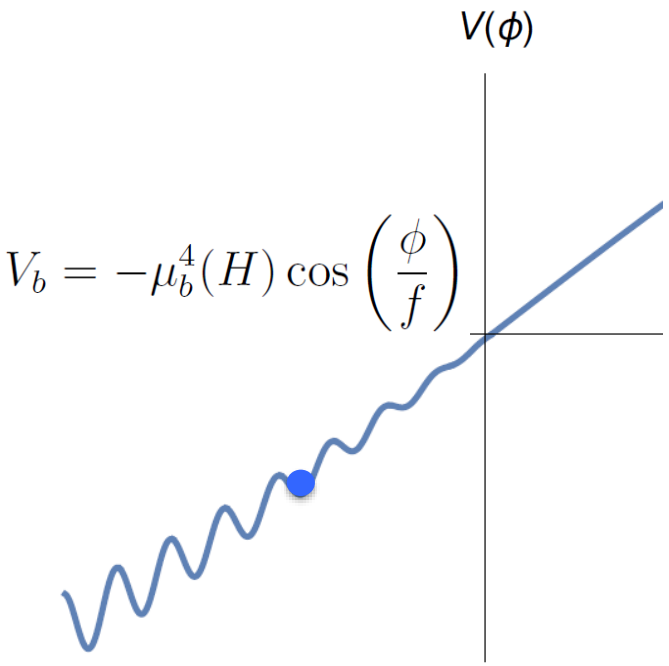
axion-like field
(=relaxion ϕ)
which scans
the Higgs mass



Relaxion potential to trigger
the necessary relaxion motion



Possible origin of the barrier potential:



* QCD: $\frac{1}{32\pi^2}\frac{\phi}{f}\left(G\tilde{G}\right)_{\rm QCD}$

➔ $\mu_b^4(H=v) \sim m_u \Lambda_{\rm QCD}^3 \sim \left(0.1\ {\rm GeV}\right)^4$

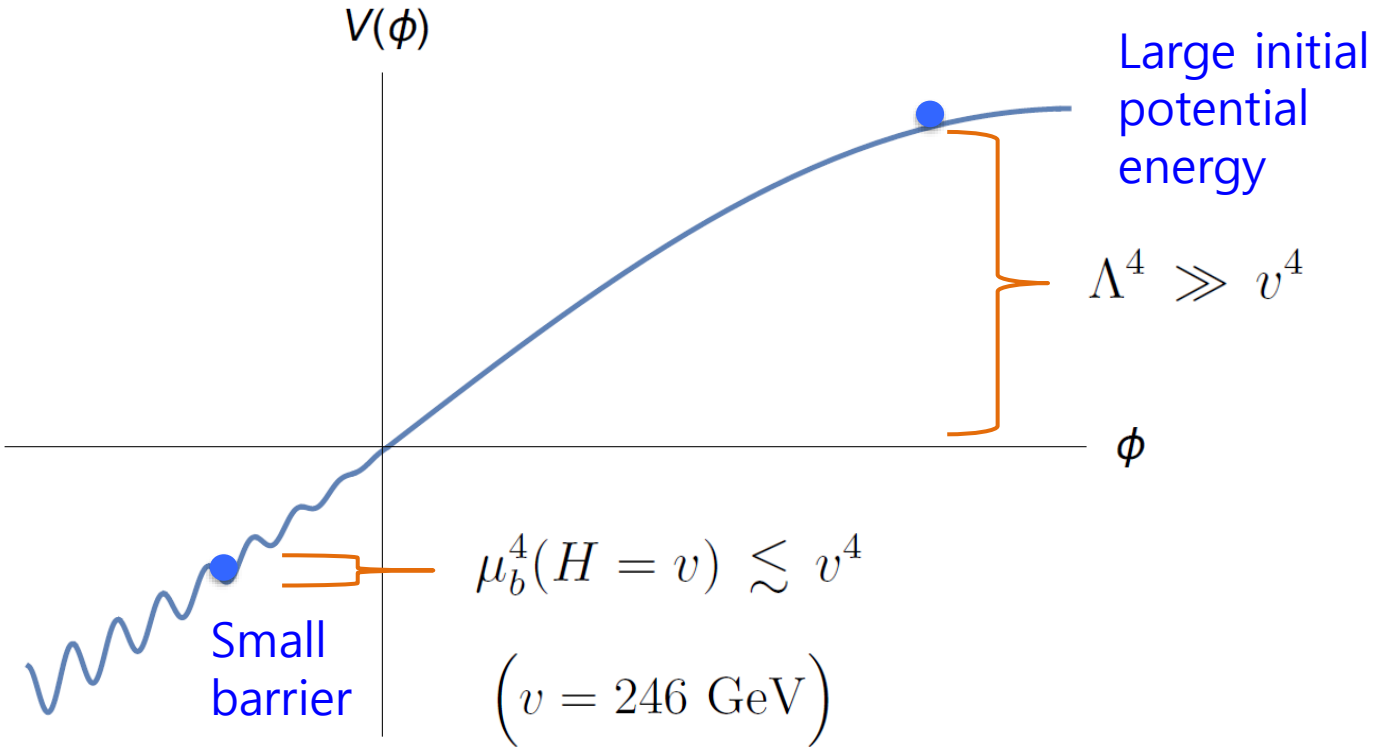
* QCD-like hidden-color dynamics confining around TeV:

➔ $\mu_b^4(H=v) \sim \left(200\ {\rm GeV}\right)^4$

(* Perturbative shift symmetry breaking yielding $\mu_b^4(H=v) \sim \left(200\ {\rm GeV}\right)^4$)

Gupta et al, 1509.0047

Price to pay:
(expensive?)



➔ Long time of energy dissipation and long field excursion

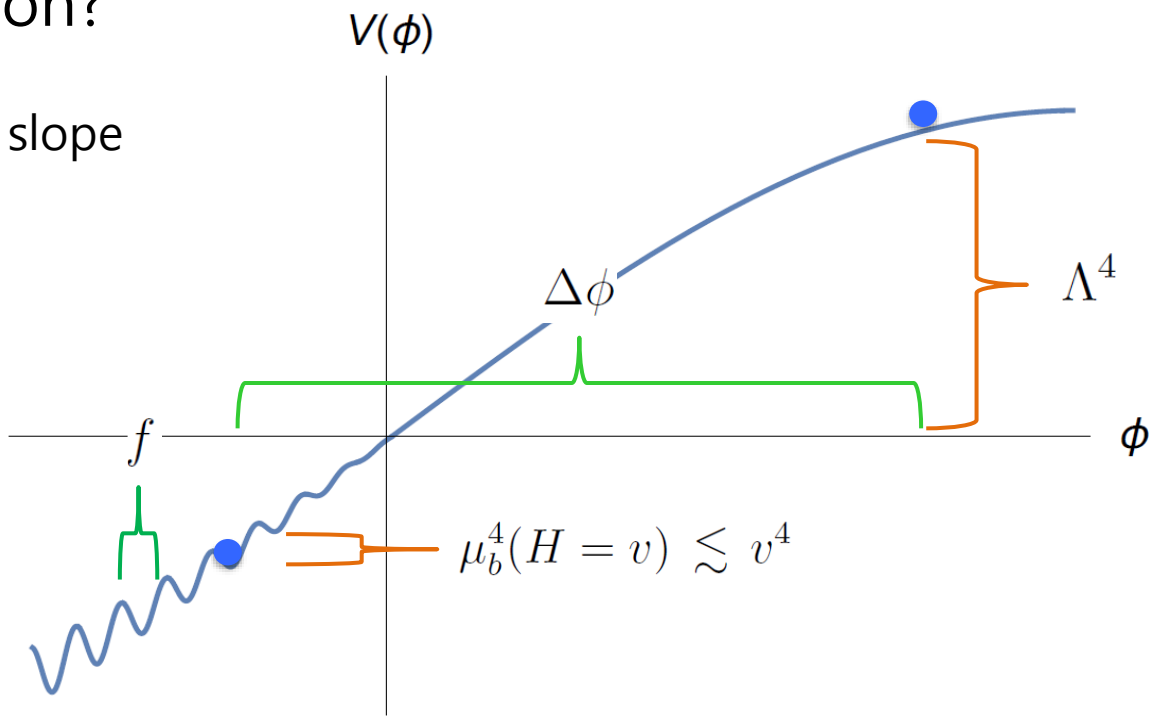
How long excursion?

Barrier slope ~ Sliding slope

$$\frac{\mu_b^4}{f} \sim \frac{\Lambda^4}{\Delta\phi}$$

➔ Relaxion excursion (in angle unit)

$$\frac{\Delta\phi}{f} \gtrsim \left(\frac{\Lambda^2}{v^2}\right)^2$$



Technically unnatural weak scale hierarchy

$$\Lambda^2 \gg v^2 = (246\,\mathrm{GeV})^2$$

relaxion ➔

Technically natural, but even bigger relaxion scale hierarchy

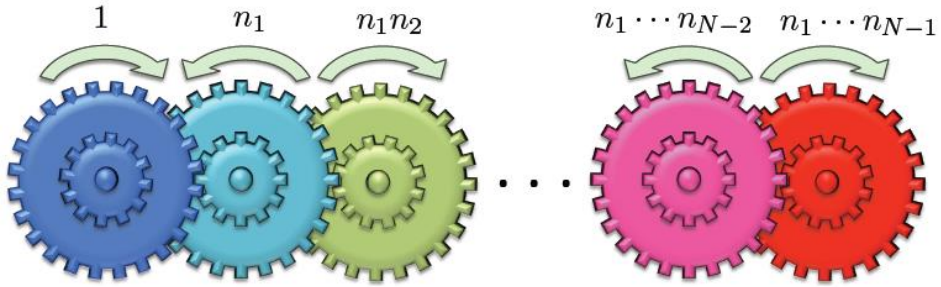
$$\frac{\Delta\phi}{f} \gtrsim \left(\frac{\Lambda^2}{v^2}\right)^2$$

Mechanism to generate long relaxion excursion:

(= big hierarchy in relaxion scales)

Clockwork mechanism with multiple axions

(=rotation angle of multiple wheels)



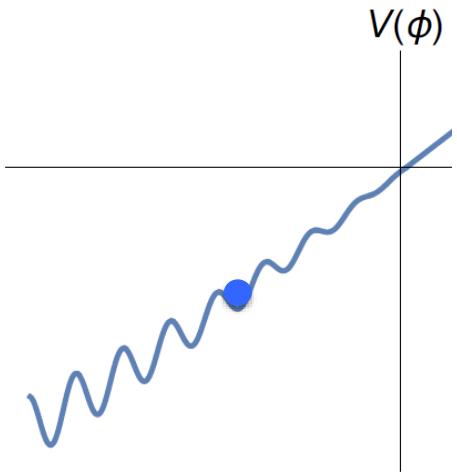
KC, Im, 1511.00132; Kaplan, Rattazzi, 1511.01827

Relaxion identified as the rotation angle of the last wheel:

$$\frac{\Delta\phi}{f} \sim n_1 n_2 n_3 ... n_{N-1} \sim e^N \quad (N = \text{Number of axions})$$

(Exponentially long relaxion excursion)

Observable consequences?



QCD-like hidden-color with vector-like fermions: L, L^c, N, N^c

Graham et al, 1504.07551; Antipin & Redi, 1508.01112; KC & Im, in preparation

$$\Delta\mathcal{L} = y_1 H L N + y_2 H^* L^c N^c + m_L e^{i\phi/f} L L^c + m_N N N^c$$

$$\Delta\mathcal{L}_{\text{eff}} = \mu_1^4 \cos\left(\frac{\eta_H}{f_H}\right) + \mu_2^2 |H|^2 \cos\left(\frac{\eta_H}{f_H} + \frac{\phi}{f}\right) + \frac{1}{16\pi^2}\left(\frac{\eta_H}{f_H} + \frac{\phi}{f}\right) F\tilde{F}$$

TeV scale composite mesons with a variety of observable consequences which may be probed at LHC & future collider

Talk by Fedderke

Axion-like relaxion with mass and couplings in the range probed by SHiP

EDMs from the relaxion-Higgs mixing

Relaxion is a new baby in town, so deserves more attention:

* UV completion? Talk by Evans

Supersymmetric UV completion:

Batell et al, 1509.00834; KC and Im, 1511.00132; Evans et al, 1602.04812

* Coincidence problem?

Espinosa et al, 1506.09217

* Relaxion energy dissipation other than the Hubble friction?

Hook & Marques-Tavares, 1607.01786

* Further collider signature and/or low energy observable?

Conclusion

* Long list of candidates for BSM physics, but scales are uncertain.

  BSM physics should be explored from all possible perspectives.

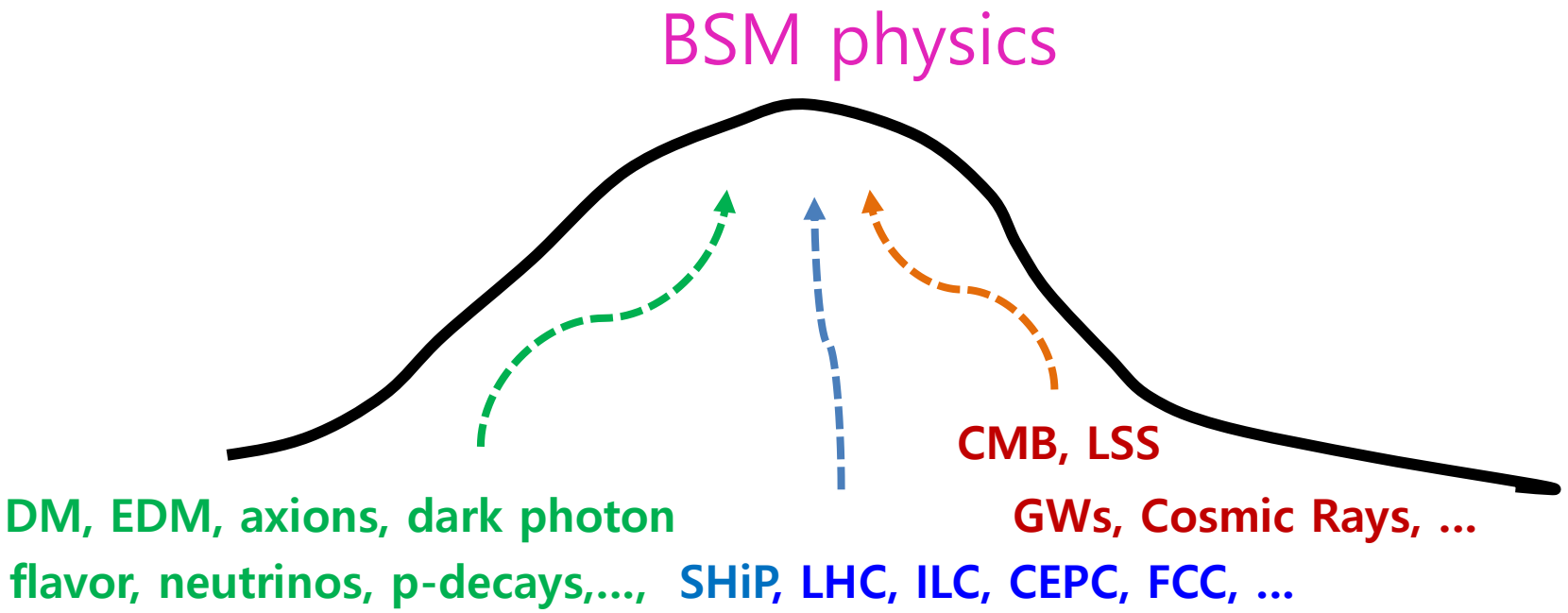
* Dark matter and hierarchy problem are yet the major driving engine of our search for BSM physics, and hopefully SUSY or WIMP DM may be just around the corner.

* From 750 GeV diphoton excess, we learned more on many things related to BSM physics communicating with the SM mainly through the SM gauge bosons.

* Relaxion is a new baby in town, so deserves further attention.

* To make a further progress, definitely we need a guide from experiments.

  Let's hope big discoveries come soon from some of the on-going (or planned) efforts to search for BSM physics:



Thank you for your attention!