HEAVY OR HIDDEN?

The experimental status of direct searches for exotic physics beyond the standard model at the Large Hadron Collider

Reviews in Physics 4 (2019) 100027

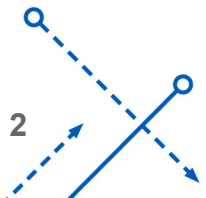
A man said to the universe:
“Sir, I exist!”
“However,” replied the universe,
“The fact has not created in me
A sense of obligation.”
– Stephen Crane

Salvatore Rappoccio

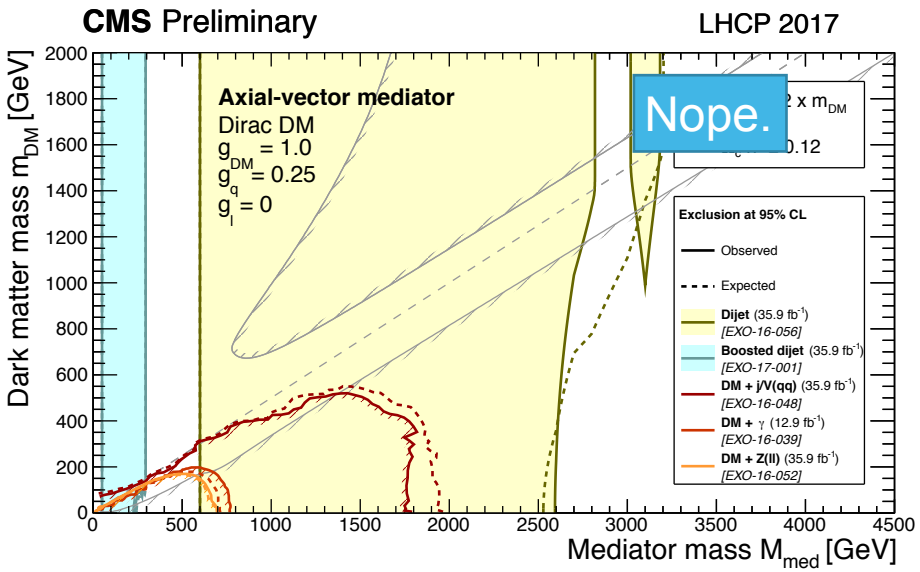
University at Buffalo The State University of New York

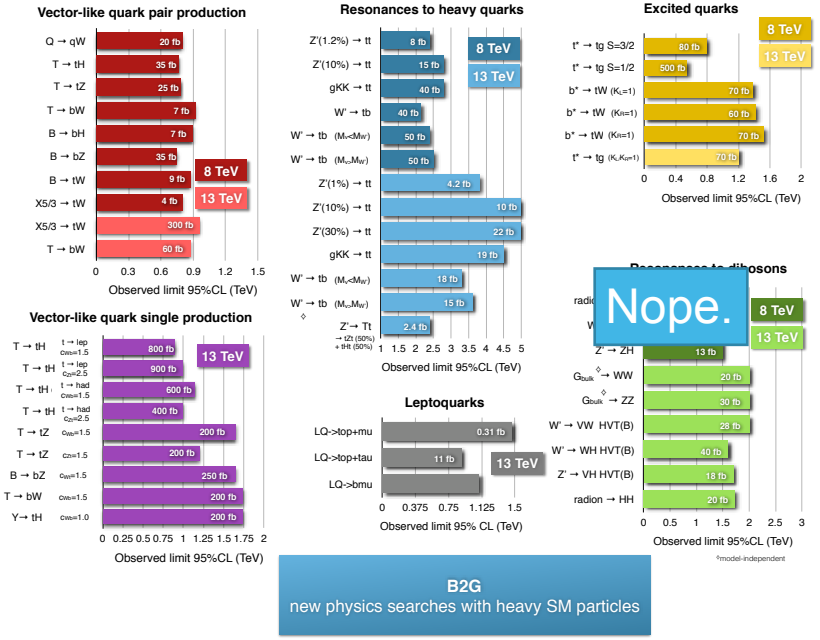
- **Kind invitation from Tommaso to write review article about the state of exotic searches at CMS, thanks very much!**

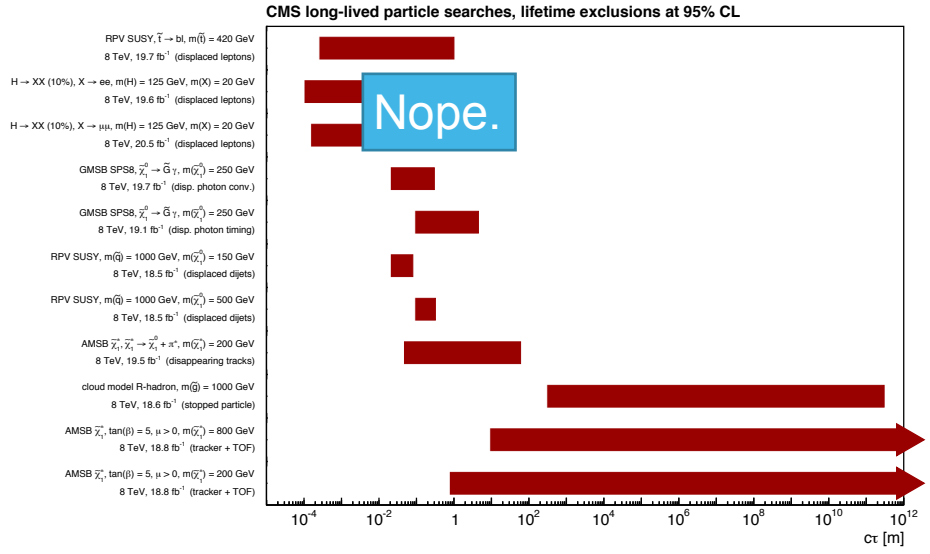
- **Me:**
  - Previous “Beyond Two Generations” (B2G) convener at CMS (Focused on boosted exotica)
  - Currently working on SM measurements in the SMP-HAD (hadronic measurements) group
  - Jets and substructure, tracking, software

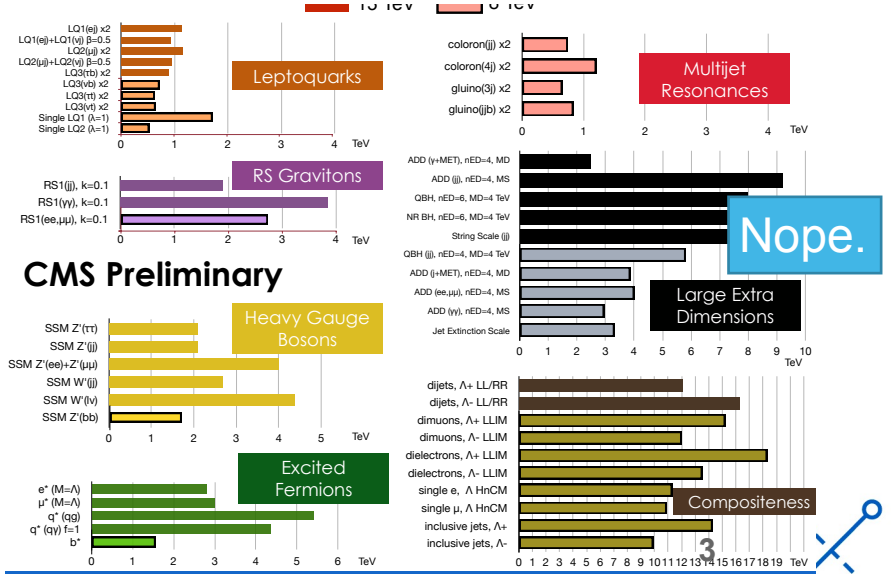


Spoiler Alert : No new physics yet.









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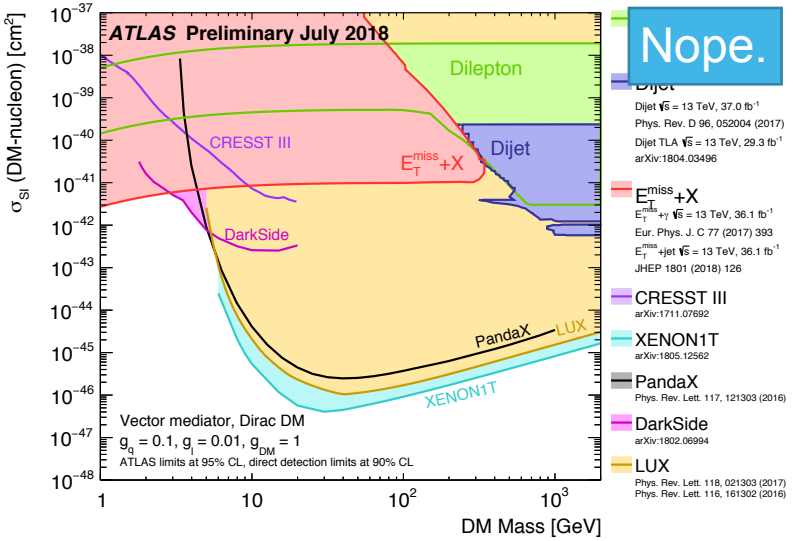
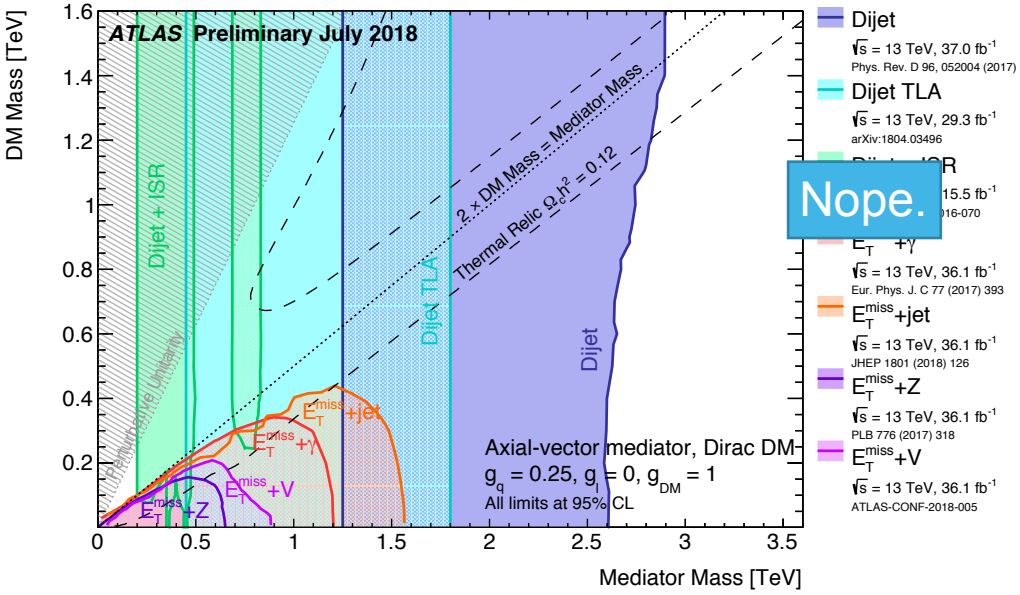
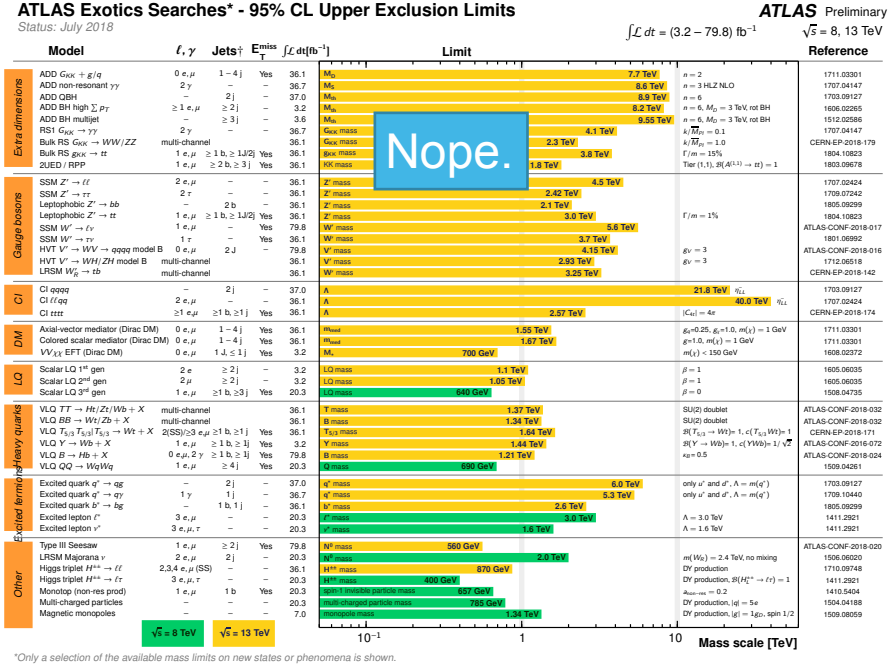
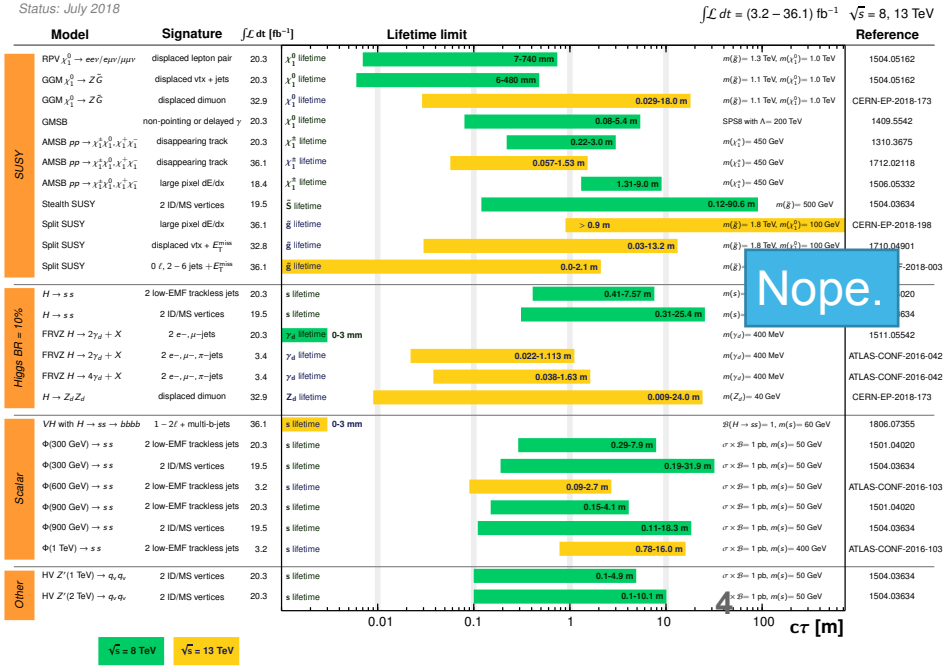


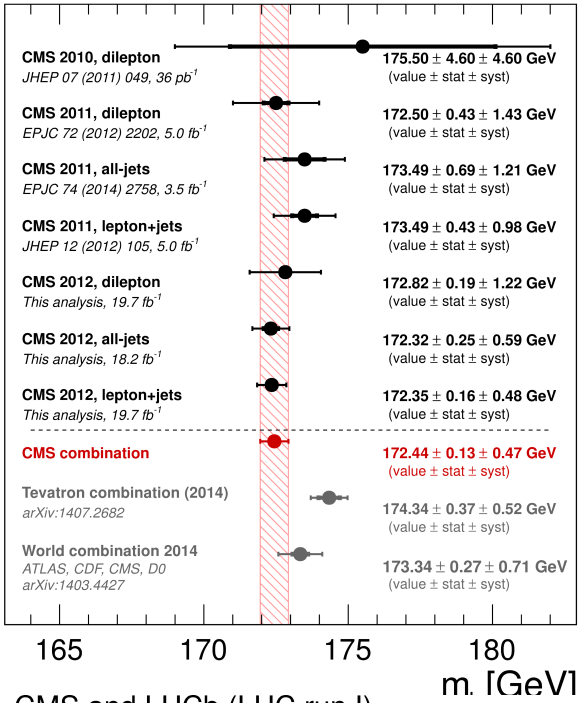


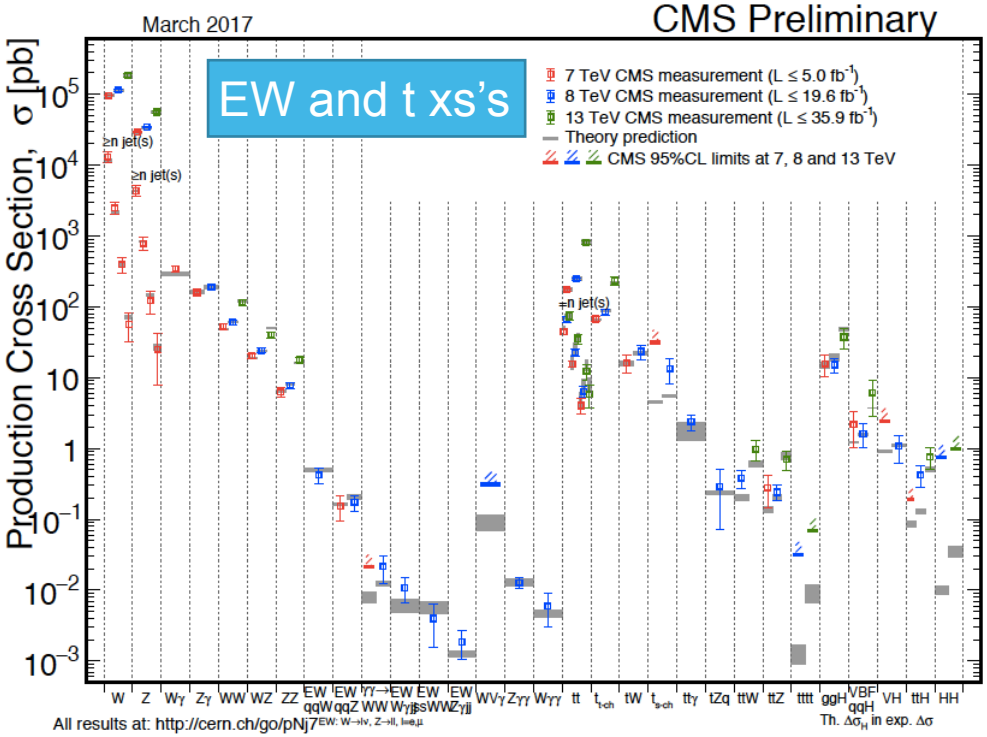


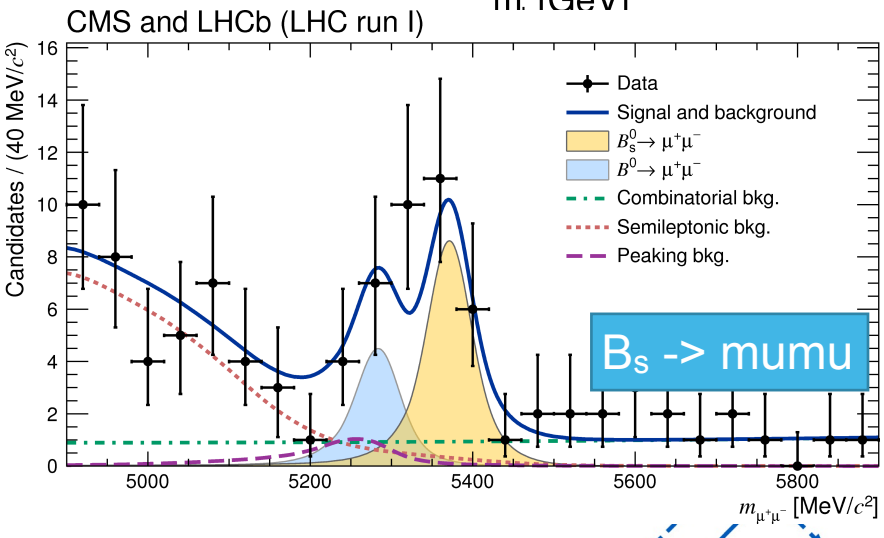


Extensive understanding of the SM

- Higgs
- W, Z
- Jets
- Top quark
- Bottom quark
- Forward physics



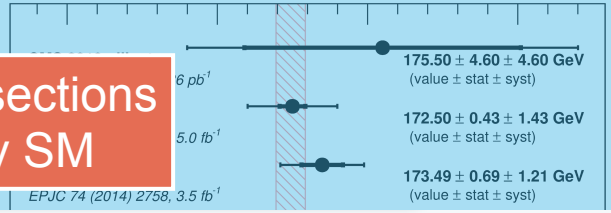




Extensive understanding of the SM

- Higgs
- W, Z
- Jets
- Top quark
- Bottom quark
- Forward physics

~10 orders of magnitude of cross sections measured at the LHC, predicted by SM



m_{top}

Smug Standard Model

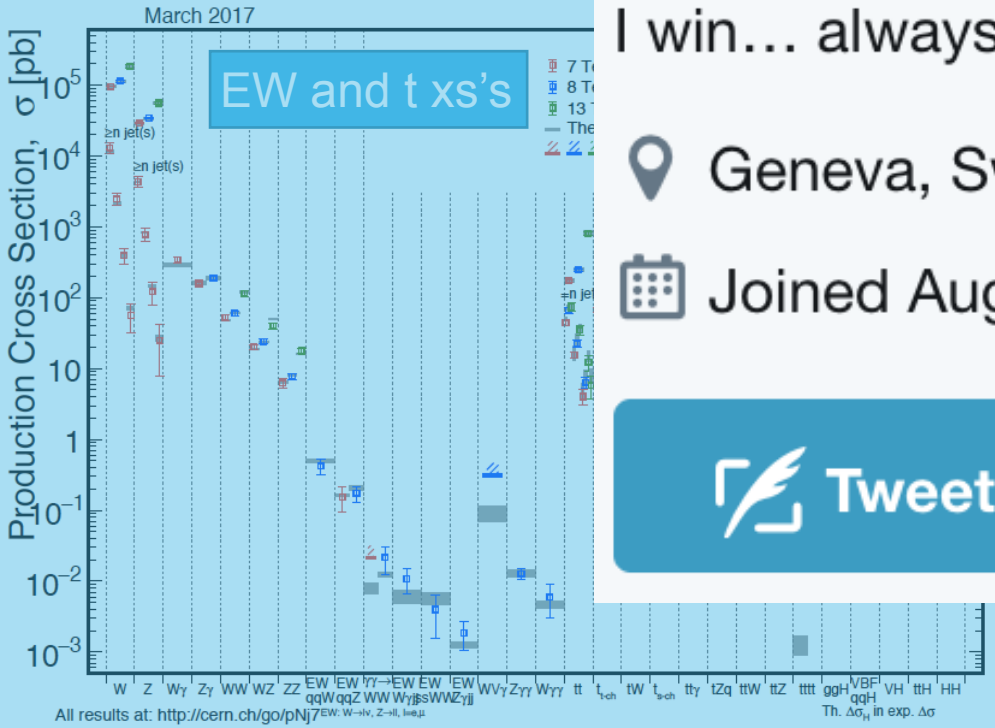
@smugsmphys

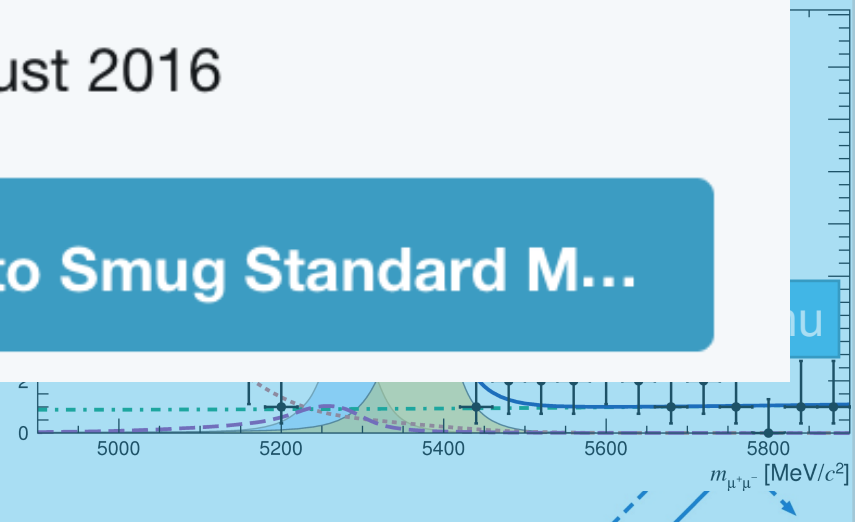
I win… always.

Geneva, Switzerland

Joined August 2016

Tweet to Smug Standard M…





The end of particle physics?

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Thursday, December 27, 2018

How the LHC may spell the end of particle physics

The Large Hadron Collider (LHC) recently completed its second experimental run. It now undergoes a scheduled upgrade to somewhat higher energies, at which more data will be collected. Besides the Higgs-boson, the LHC has not found any new elementary particle.

It is possible that in the data yet to come some new particle eventually shows up. But particle physicists are nervous. It's not looking good – besides a few anomalies that are not statistically significant, there is no evidence for anything out of the normal. And if the LHC finds nothing new, there is no reason to think the next larger collider will. In which case, why build one?

IFLSCIENCE!

Is This The End Of Particle Physics As We Know It? Let's Hope Not

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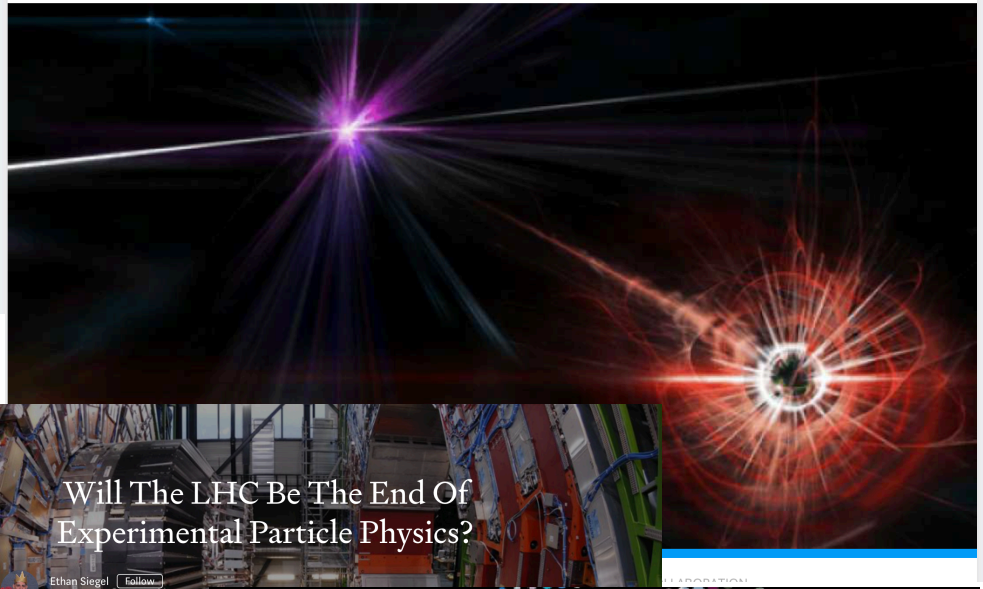
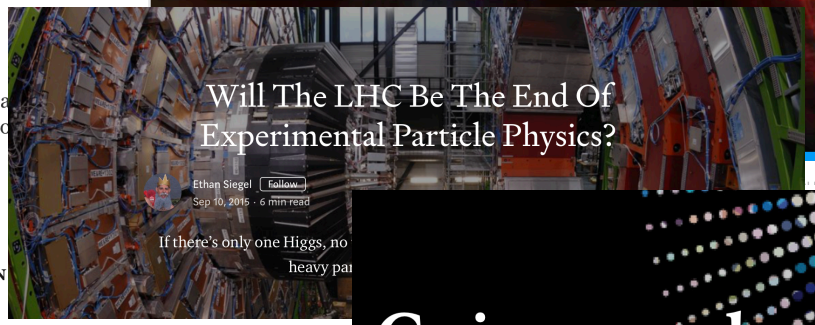


THE SCIENCES

Could the Higgs Nobel Be the End of Particle Physics?

Many physicists had hoped that the Large Hadron Collider would also yield a
directions for physics to take, not just a new particle, but that has yet to

By Harry Cliff, The Conversation on October 8, 2013



Will The LHC Be The End Of Experimental Particle Physics?

Ethan Siegel Follow
Sep 10, 2015 · 6 min read

If there's only one Higgs, no
heavy par

LATEST N

Physicists La
a New Super

Hollywood's
Science and
Ridiculous

Going nowhere fast

After the success of the Standard Model, experiments have stopped answering to grand theories. Is particle physics in crisis?

Collider physics answers

science 2.0
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Why We Need A New Collider

By Tommaso Dorigo | December 31st 2018 02:05 AM | Print | E-mail

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Tommaso Dorigo

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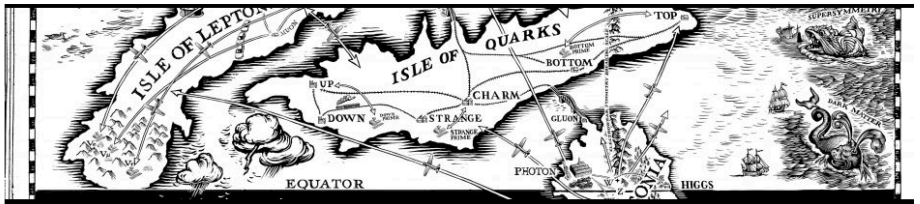
[**Update**: *I found the time to add a few links to the post below, which I had previously omitted for lack of time (hey I'm on vacation!), and I also updated it to add some commentary of Sabine Hossenfelder's latest post on "the end of particle physics".*]

In this age of short-term reward strategies (in politics, in society, and in individual behaviour) planning huge endeavours 20 years ahead is harder than it used to be. In the late eighties, when the Large Hadron Collider (LHC) was conceived and argued to be doable by a few visionaries, it immediately looked like a great idea to all.

The only other "high-energy" particle physics project on the board, the Superconducting Super Collider (SSC), promised to deliver everything a physicist could dream of: an assured discovery of the Higgs boson, plus a thorough investigation of new physics across the board and up to effective invariant mass of new resonances in the tens of TeV range.

Life and Physics



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← 2018 Highlights? Seriously? | Mile End Road →

Theory, experiment and supersymmetry

Posted on 29/12/2018 by Jon Butterworth

I am dismayed by the plethora of null results coming out of my experiment, as well as from our friendly rivals, at the Large Hadron Collider.

A science is any discipline in which the fool of this generation can go beyond the point reached by the genius of the last generation
Max Gluckman

Topics

- Arts
  - Education
  - History
  - Philosophy
  - Writing
- Politics
  - Science Policy
- Rambling
  - Physics Stories
- Science
  - Climate Change
  - Mathematics
  - Physics
    - Astrophysics
    - Particle Physics
      - My Favourite Particle
- Silly
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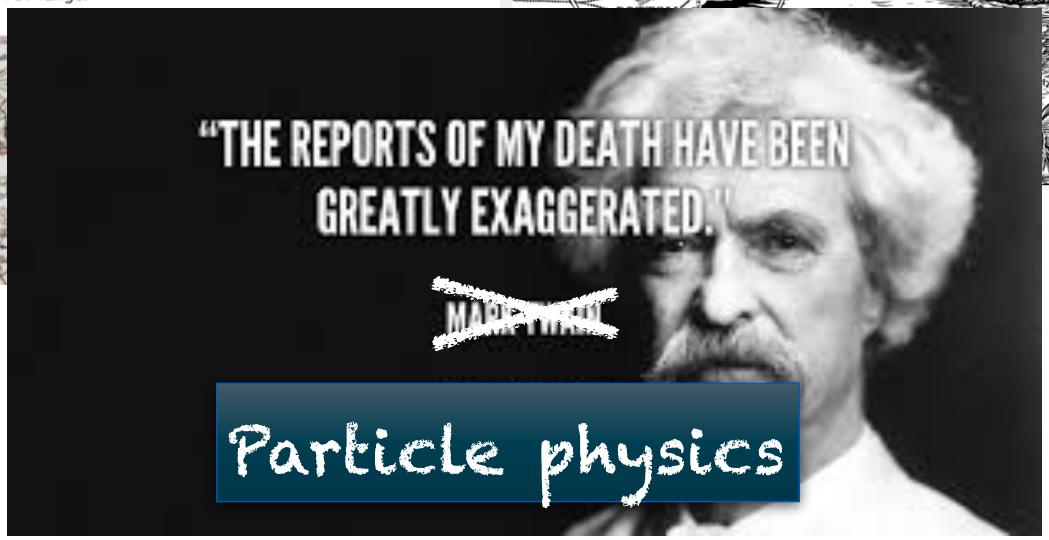
- Travel

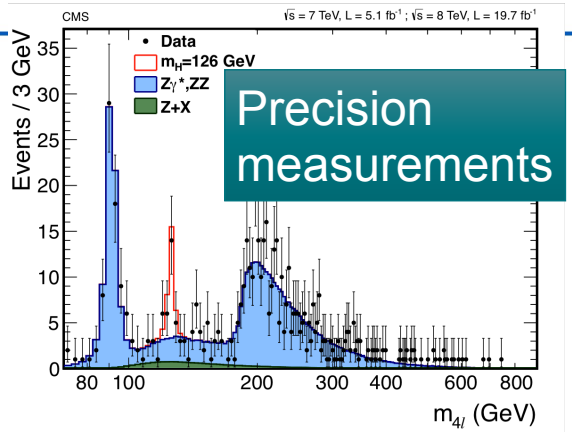
Tags



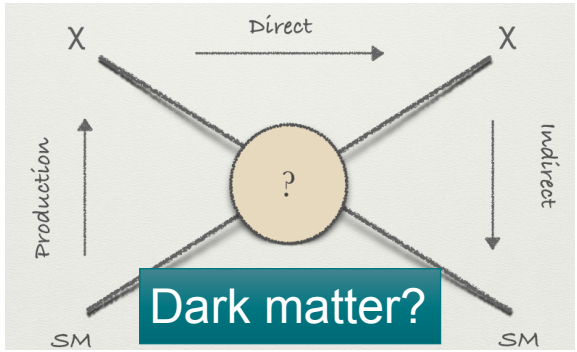
Why (still) the LHC?

More Higgses?

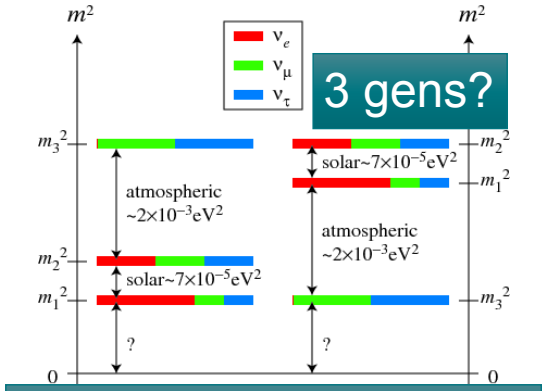
Hierarchy problem?



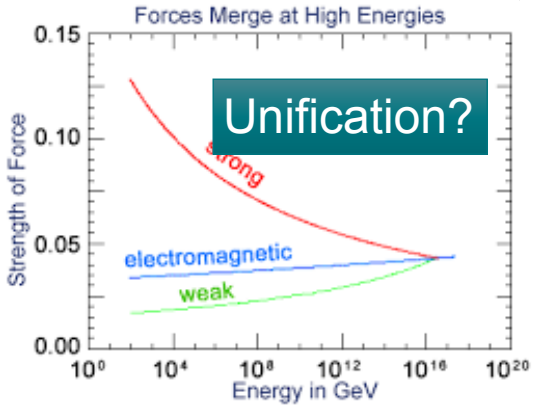
Precision measurements



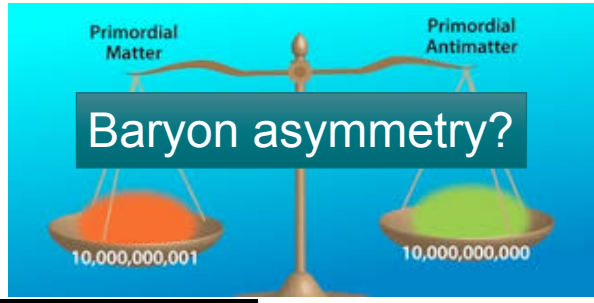
Dark matter?



3 gens?



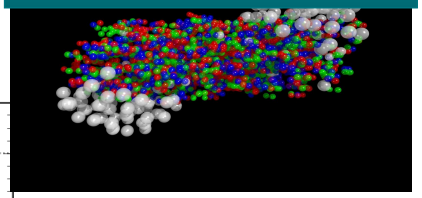
Unification?



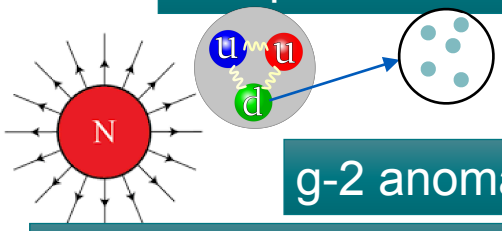
Baryon asymmetry?

Why mass hierarchies? Neutrinos? Quarks?

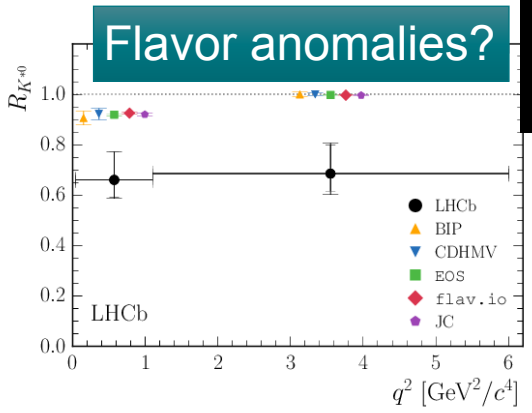
Behavior of QGP?



Compositeness?



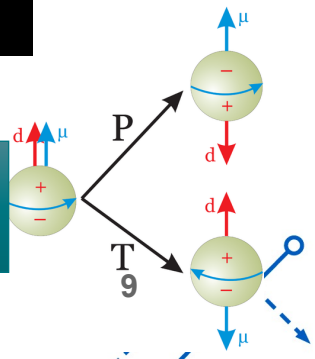
Flavor anomalies?



g-2 anomaly?

Magnetic monopoles?

Strong CP problem?



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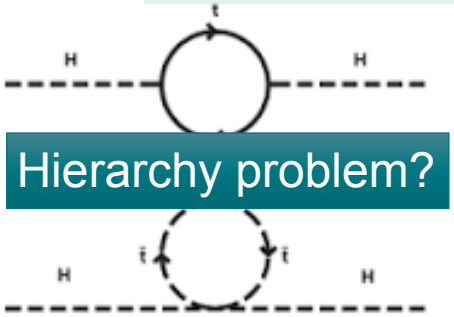
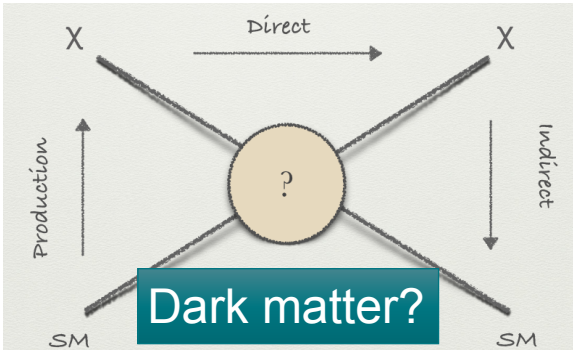


Hierarchy problem?

Precision measurements



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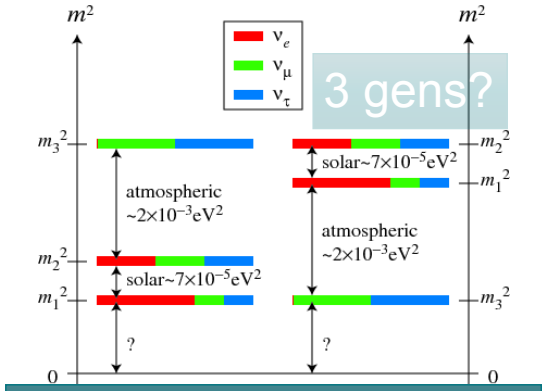

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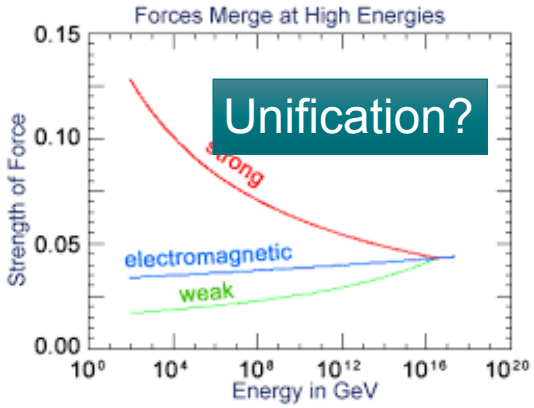

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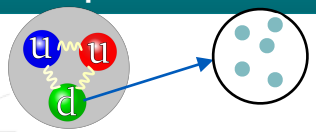


Behavior of QGP?

g-2 anomaly?

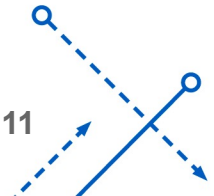
Magnetic monopoles?

This talk:

Non-SUSY exotic signatures of BSM physics

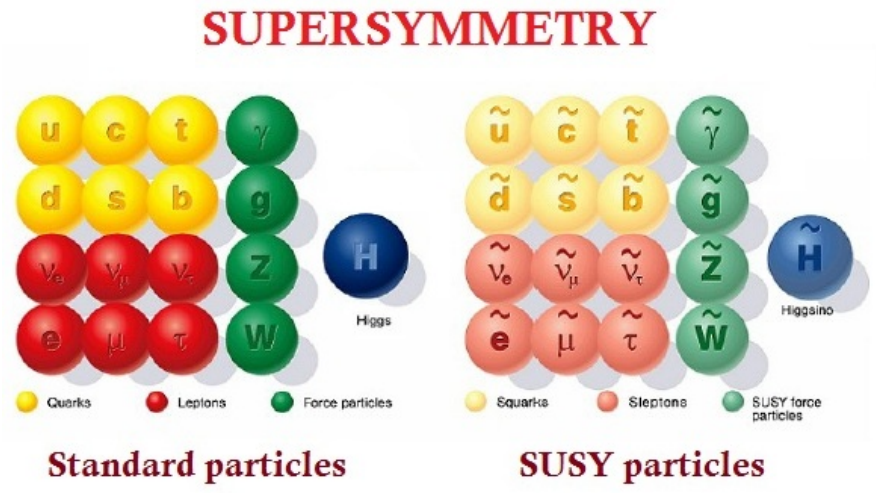
Outline

- **Why we still need particle physics**
- **Exotic physics introduction**
- **Search techniques**
- **Selected analyses**
- **Final thoughts**



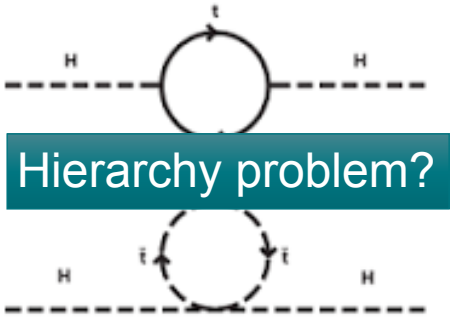
SUSY?

- **Very attractive:**
  - Solves the hierarchy problem
  - Provides DM candidate
  - Unification of forces
  - Points to string theory
  - Nice theoretical structure
- **But:**
  - No reason to think that all of these questions are linked
  - We haven't found any



Will investigate other solutions to these open questions

Question: Hierarchy problem?



- **Higgs potential:**

$$V = m_H^2 |H|^2 + \lambda |H|^4$$

pole mass

from v.e.v

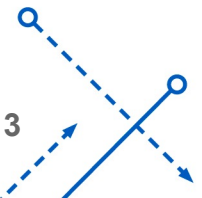
- **Higher-order corrections:**

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \ldots,$$

Yukawa coupling

Cutoff

- **If cutoff is Planck scale:**
  - Yukawa couplings of particles cancel to very high precision
- **Or:**
  - there is a scale between EW and Planck scales



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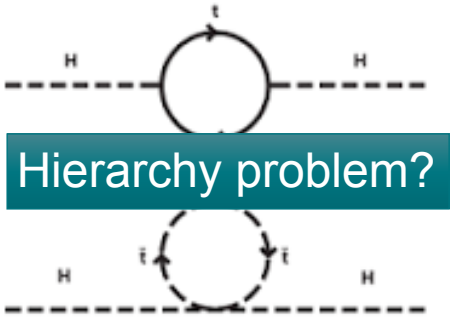
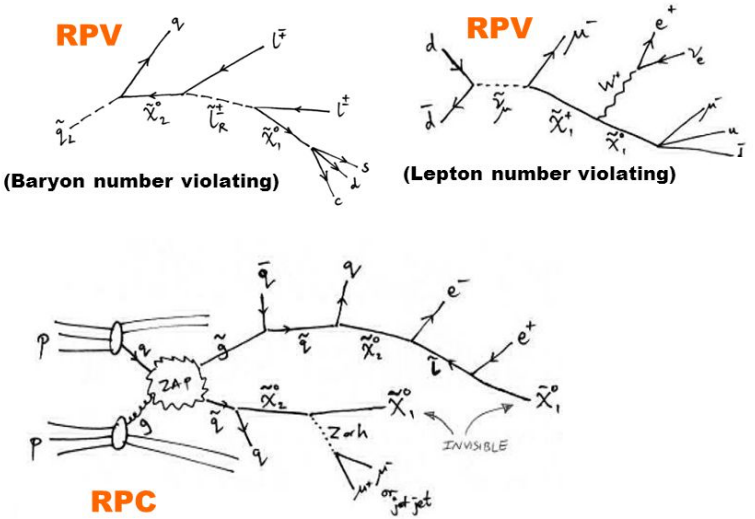


- **SUSY:**
  - Spin-zero particles cancel divergences
  - R parity conserving:
    - Has a DM candidate (lightes SUSY particle, LSP)
  - R parity violating:
    - Usually no DM candidate
    - Can lead to long-lived particles, heavy states decaying to SM particles
    - Violates Baryon or Lepton number



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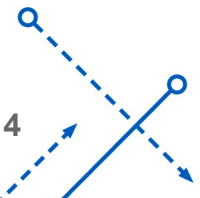

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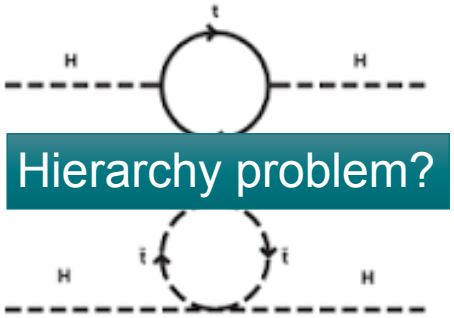
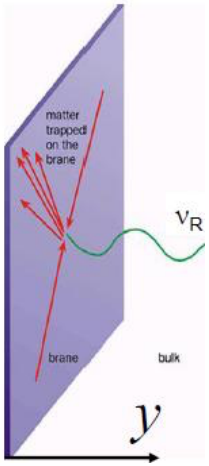
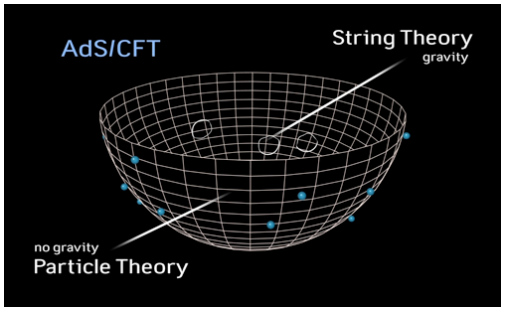


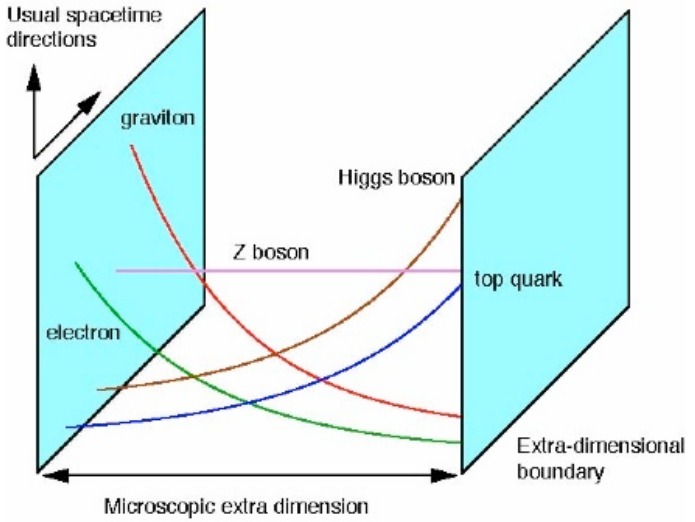
- **Extra dimensions / strong dynamics**
  - "Brings down" the Planck scale
- **Large: graviton propagates through bulk**
  - Creates quantum black holes
  - QM decays: ~2 particles
  - Thermally: many
- **Warped: SM constrained to one brane, Planck scale at another**
  - Creates Kaluza-Klein tower of particles
  - Decays to SM particles
- **AdS/CFT correspondence, strong dynamics can be represented as extra dimensional models**
  - Alternative way of thinking: CFT manifestations of AdS theory cancel divergence of Higgs



https://www.science20.com/quantum_diaries_survivor/large_extra_dimensions_reach_next_year



https://www.learner.org/courses/physics/visual/visual.html?shortname=AdSCFT



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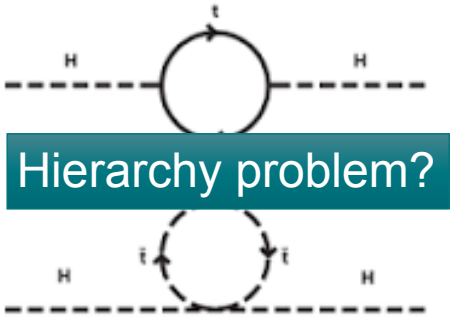

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Distinct signatures!

https://www.science20.com/quantum_diaries_survivor/large_extra_dimensions_reach_next_year

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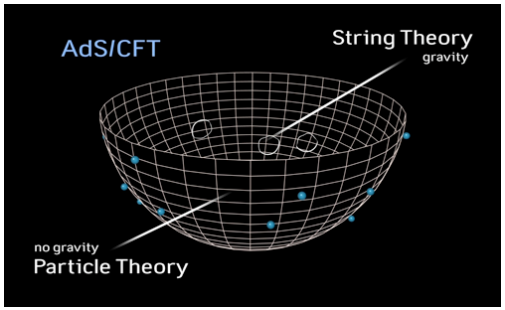
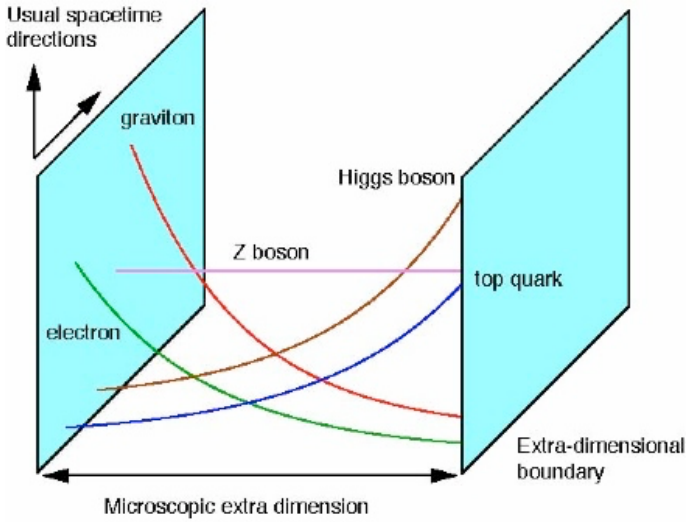
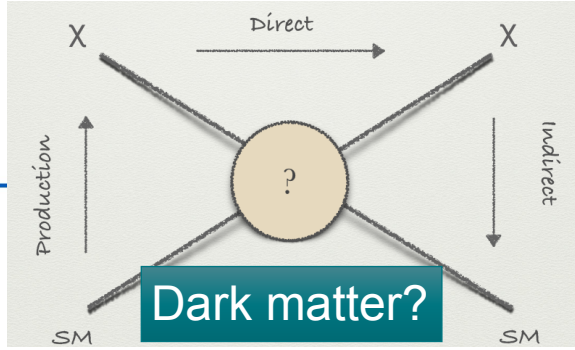
- **AdS/CFT correspondence, strong dynamics can be represented as extra dimensional models**
  - Alternative way of thinking: CFT manifestations of AdS theory cancel divergence of Higgs



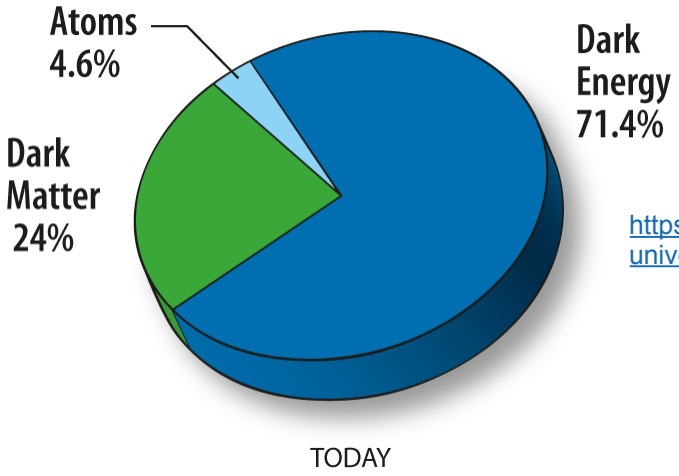
https://www.learner.org/courses/physics/visual/visual.html?shortname=AdSCFT



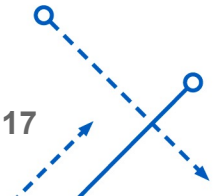
Question: Dark matter?



Our universe:



https://wmap.gsfc.nasa.gov/universe/uni_matter.html



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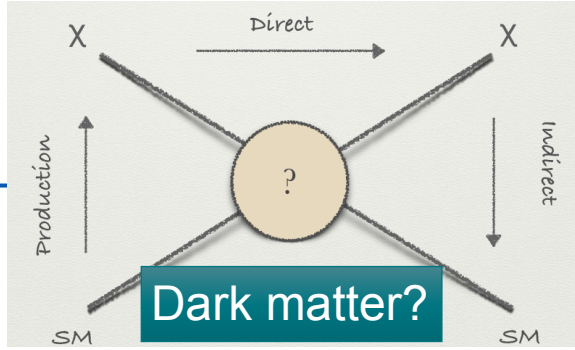
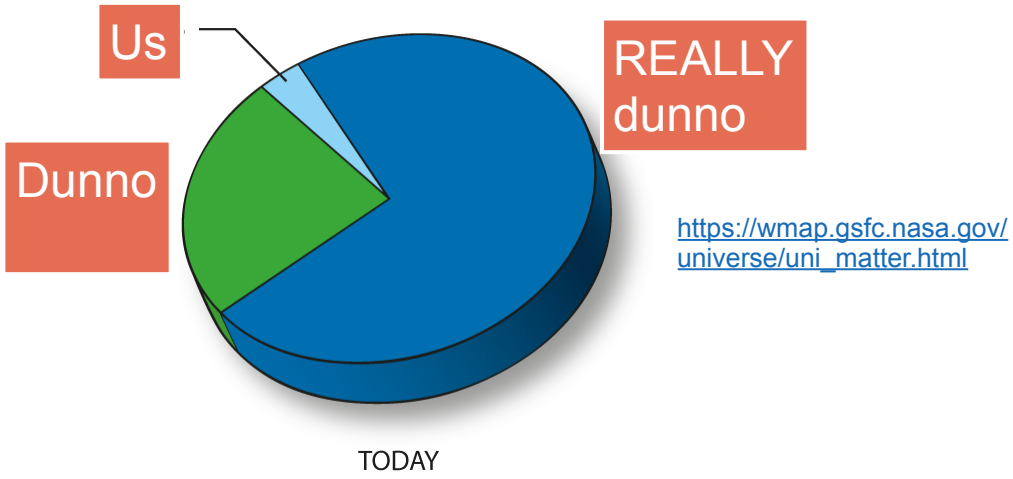
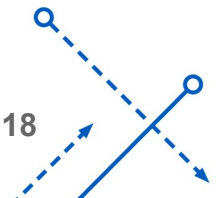


Our universe:



https://wmap.gsfc.nasa.gov/universe/uni_matter.html

- **Is it a particle?**
  - Probably yes. Modified gravity scenarios don't describe all of the observations.
- **How to search?**
  - Direct detection, indirect detection, or produced at colliders
  - Which is best? Depends on the nature of DM. We have a collider, let's use that.



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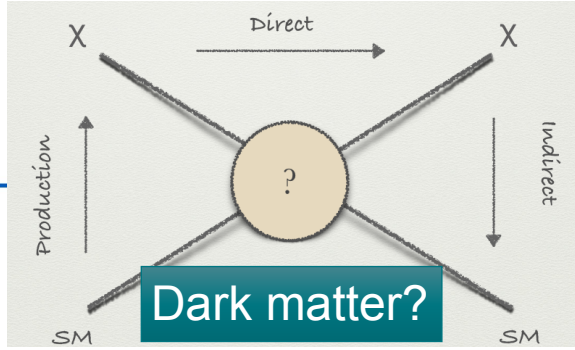
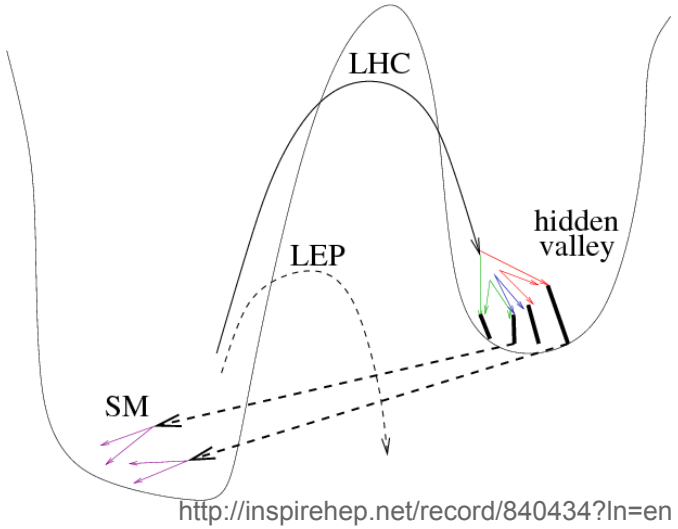
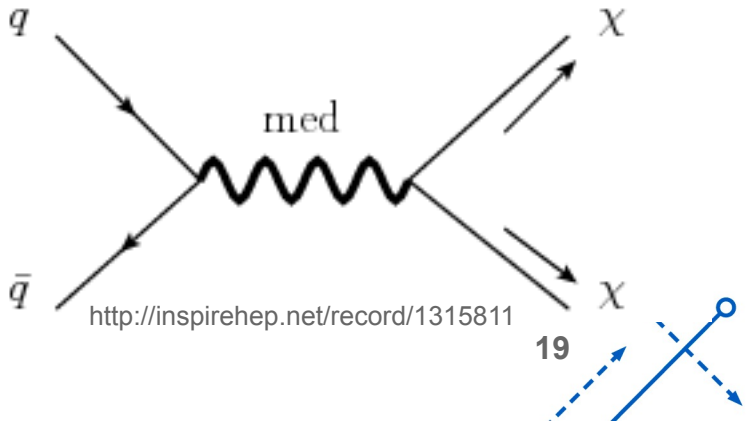


- **R-parity conserving SUSY**
  - Won't cover
- **Hidden sectors**
  - Entire "dark" universe, but interacts weakly with SM
- **Agnostic / parametric solutions**
  - Effective field theories (very heavy mediator)
  - Simplified models (finite mass mediator)

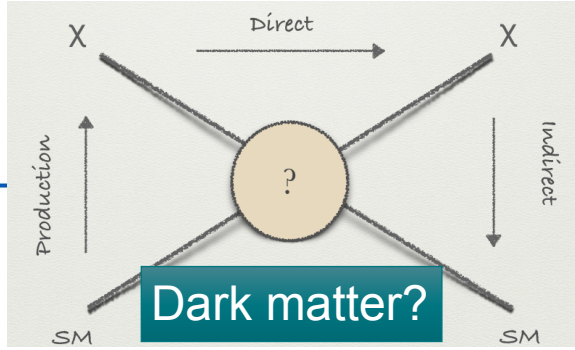


http://inspirehep.net/record/840434?ln=en



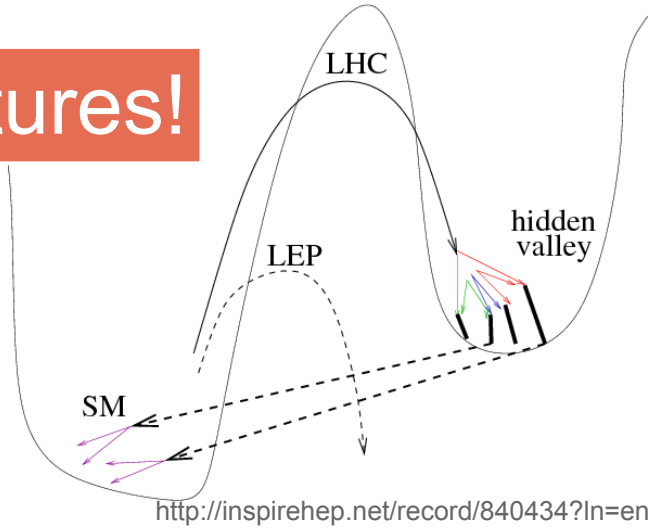
http://inspirehep.net/record/1315811

Question: Dark matter?



- **R-parity conserving SUSY**
  - Won't cover
- **Hidden sectors**
  - Entire "dark" universe, but interacts weakly with SM

Distinct signatures!



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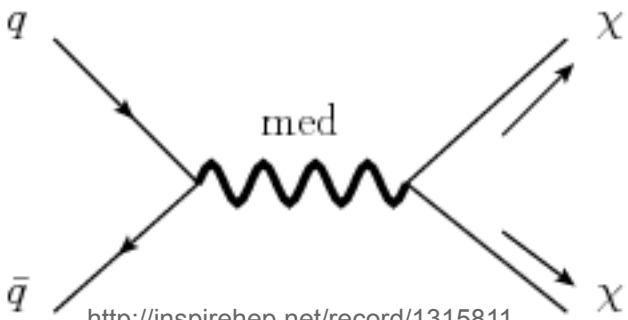
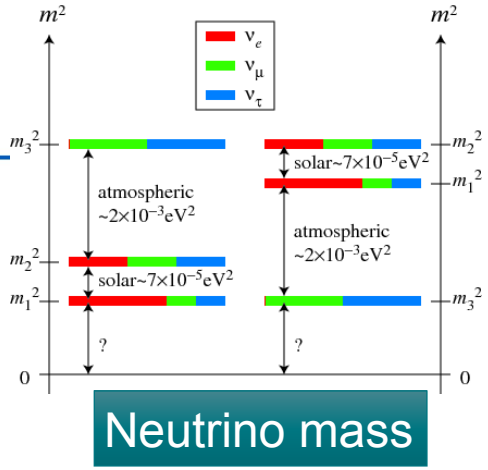
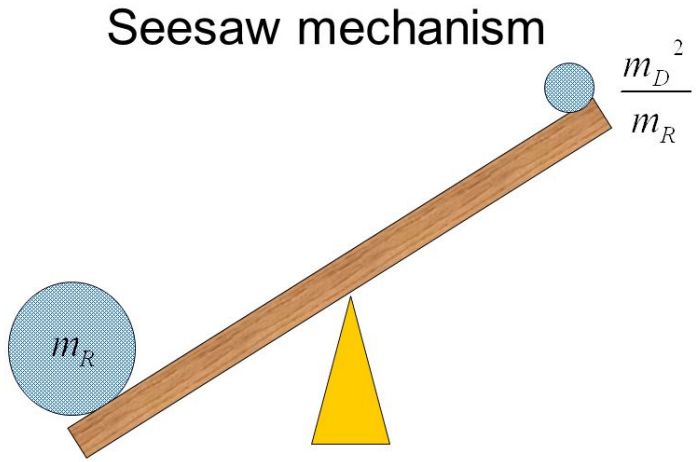


http://inspirehep.net/record/1315811

Question: Neutrino Mass?



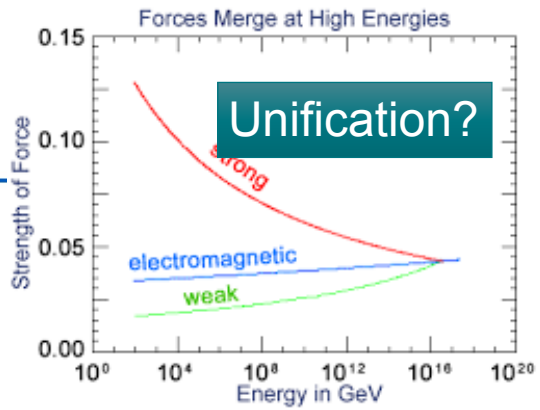
- **Neutrinos are massive**
  - That's not in the SM (i.e., this is BSM)
  - "Simple" to add mathematically, but profound implications
- **Not predicted by SUSY, which predicts, like, everything**
  - Hint that nature has other plans???
- **Why is this?**
  - "See-saw" mechanism?
  - Need colliders to check this!



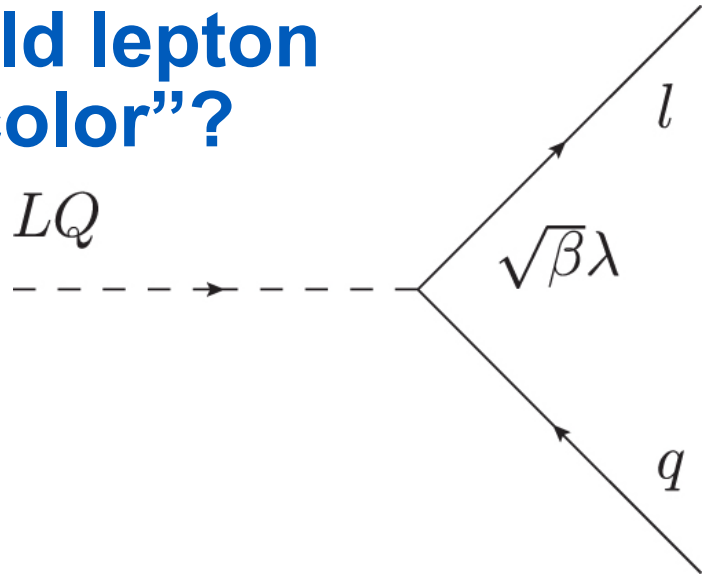
m_D	Dirac mass will be the same order as the others. (0.1~10 GeV)
m_R	Right handed Majorana mass will be at GUT scale 10^{15} GeV

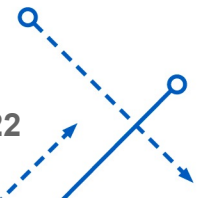
https://slideplayer.com/slide/7939689/

Question: Unification?

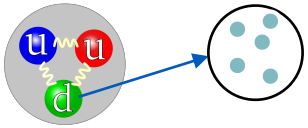


- **IS predicted by SUSY**
- **Strongly limited by proton decay**
- **More generally: could lepton flavor be a "fourth color"?**
  - Leptoquarks!

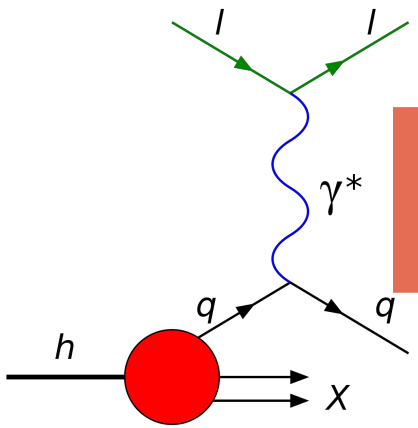




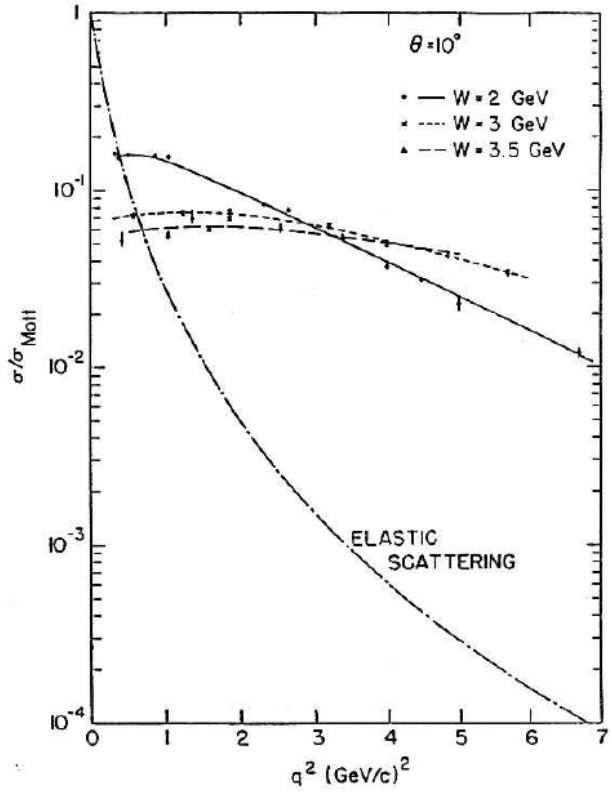
Question: Compositeness?



- **Not required, but sometimes a consequence of unification**
- **We know what to do! Rutherford / deep inelastic scattering!**



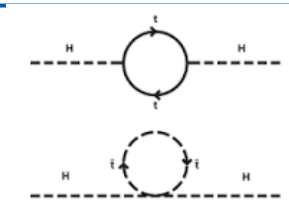
Except now we use protons on protons!

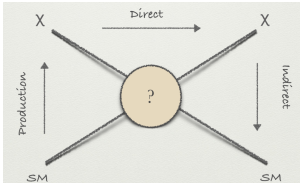


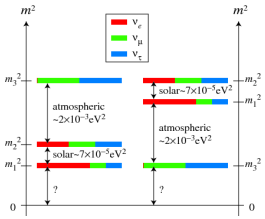
https://www.researchgate.net/figure/Inelastic-electron-scattering-data-versus-Q-2-at-fixed-W_fig6_2041350

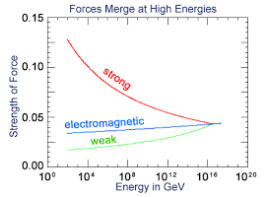
General Considerations

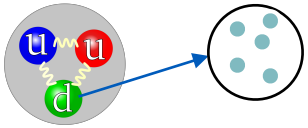
- **Hierarchy problem:**
  - Somehow bridges gap between EW and Planck scales
- **Dark matter**
  - Somehow interacts weakly with SM particles
- **Neutrino masses**
  - Somehow very tiny, but not zero
- **Unification**
  - Somehow leptons and quarks talk to each other outside of QED
- **Compositeness**
  - Somehow fundamental particles are made of something else



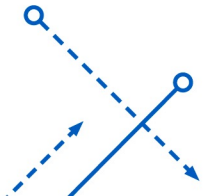






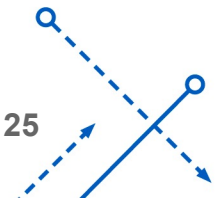


Several distinct signatures!



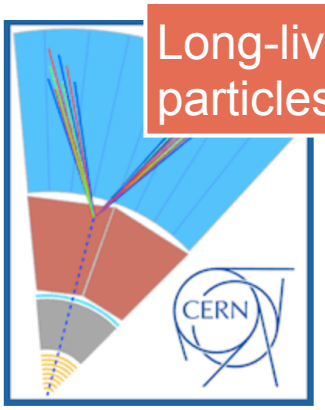
Outline

- **Why we still need particle physics**
- **Exotic physics introduction**
- **Search techniques**
- **Selected analyses**
- **Final thoughts**

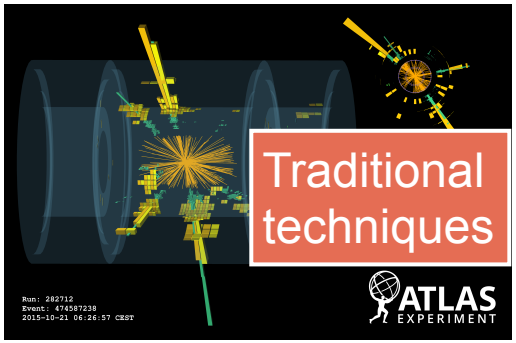


Distinct signatures

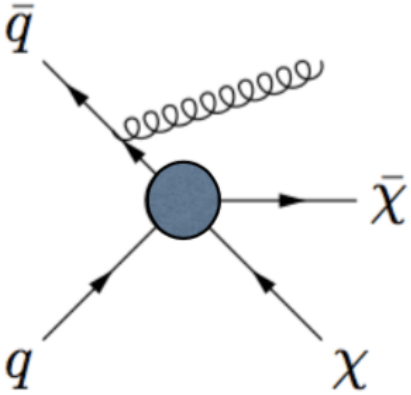
- **Can include our "traditional" techniques**
- **But non-traditional signatures require non-traditional techniques**



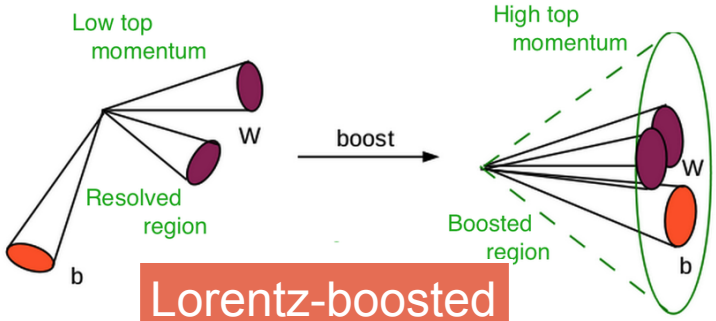
Long-lived particles



Traditional techniques



ISR-boosted particles

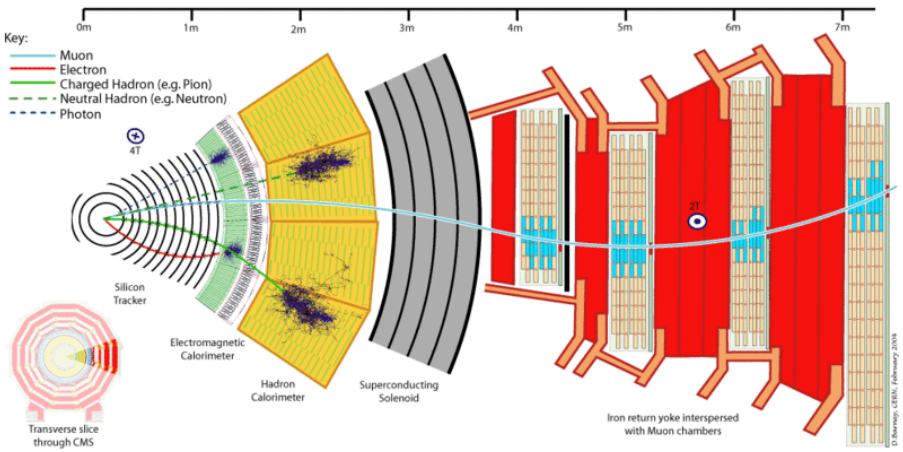


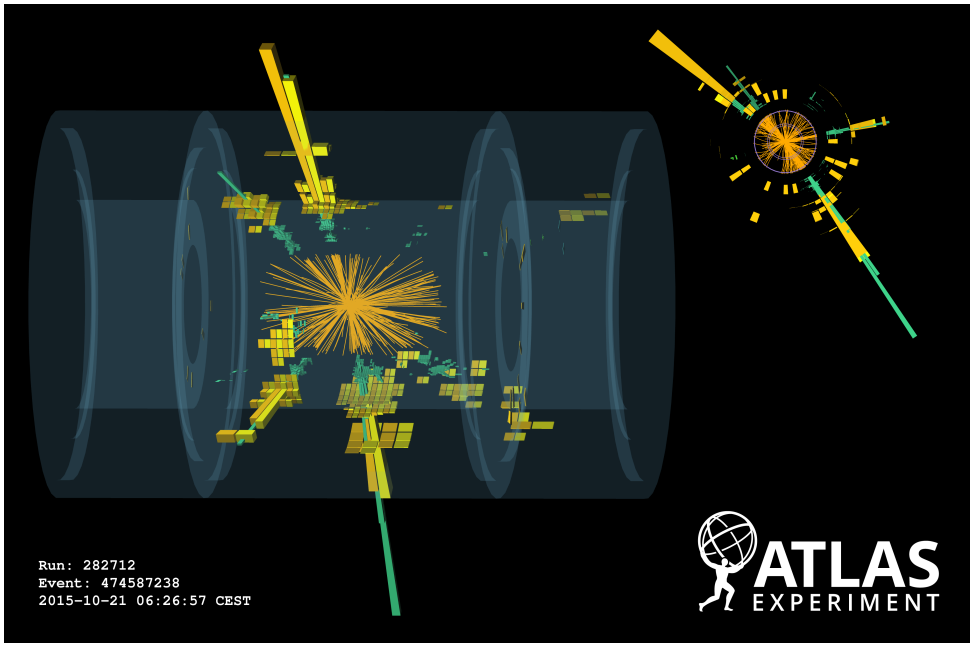
Lorentz-boosted particles

Tools : Traditional signatures

- **Many searches result in signatures similar to the SM**
  - Different in the kinematics

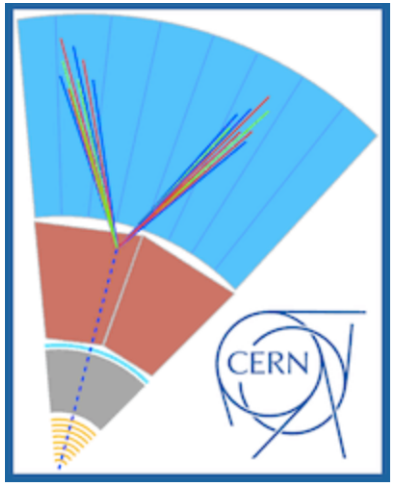
- **Still involves traditional jets, leptons, photons, missing pt.**



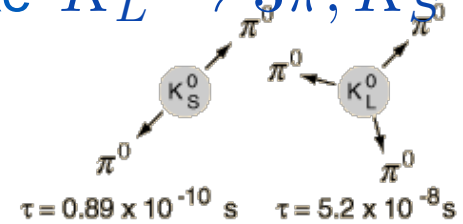


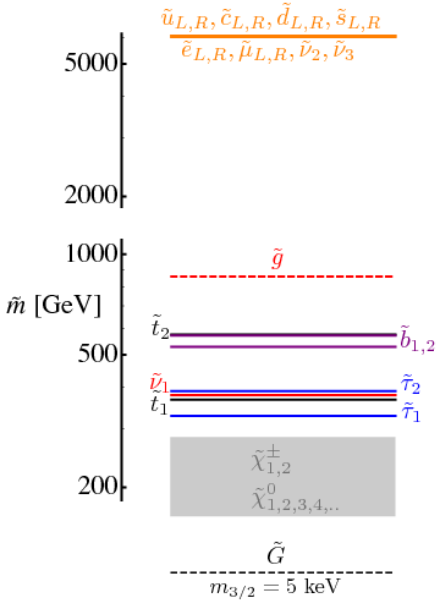
Tools : Long-lived particles

- **Particles may decay some time after collisions**

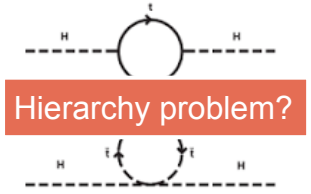


- **Options:**
  - Heavy mediator suppresses rate
    - (like $\pi \rightarrow \mu\nu$)
  - Small mass splittings, restricted phase space for decays
    - (like $K_L \rightarrow 3\pi, K_S \rightarrow 2\pi$)

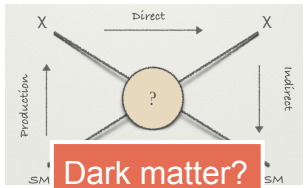




Applies to:



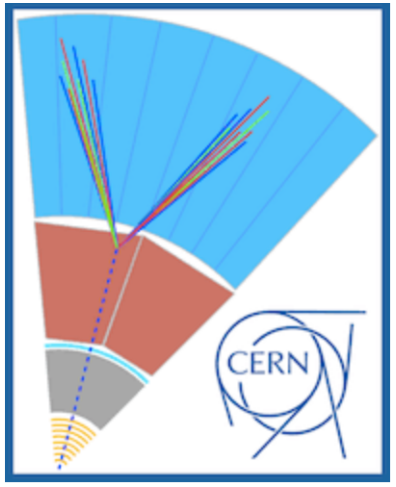
Hierarchy problem?



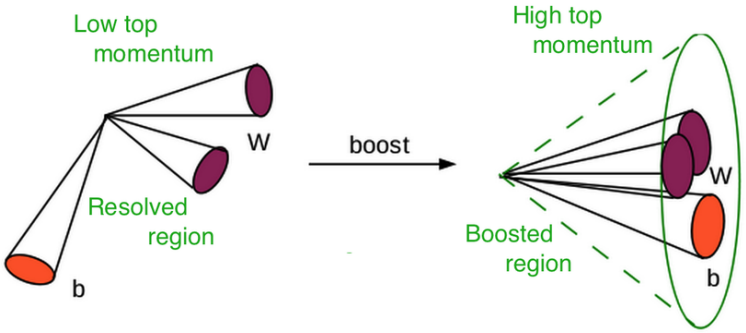
Dark matter?

Tools : Long-lived particles

- **Detection techniques:**
  - Displaced tracks
  - Signals in calorimeters
    - Sometimes far after collision!
  - Disappearing jets
  - Future: Signals far outside collision hall!

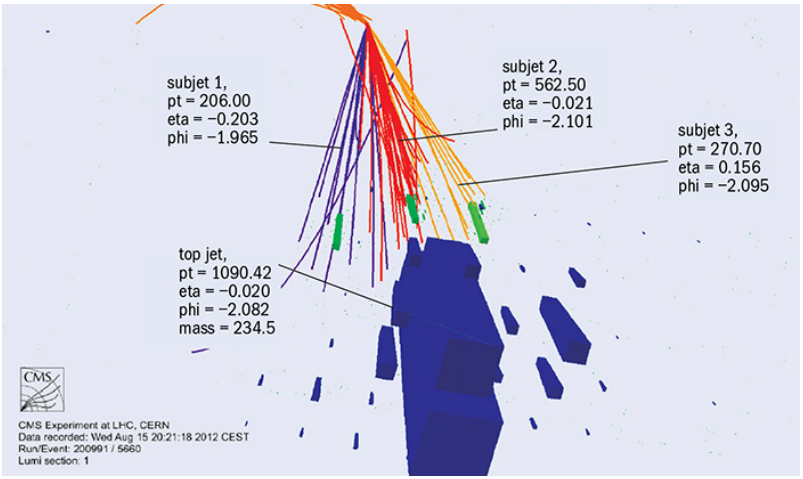


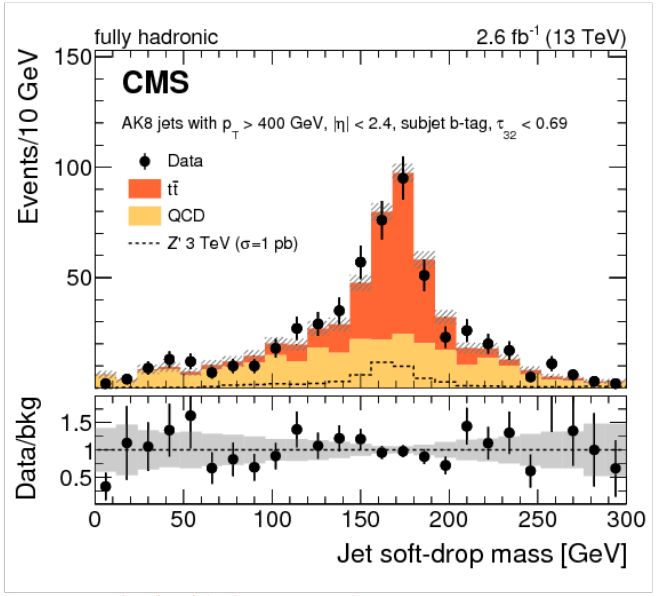
Tools : Lorentz-boosted particles



- **Heavy particle —> W/Z/H/t:**
  - can be Lorentz-boosted in lab frame!

- **Reconstruct particles within a single jet: substructure**





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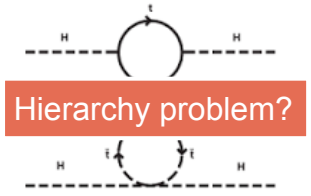

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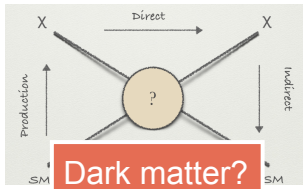
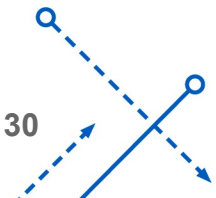
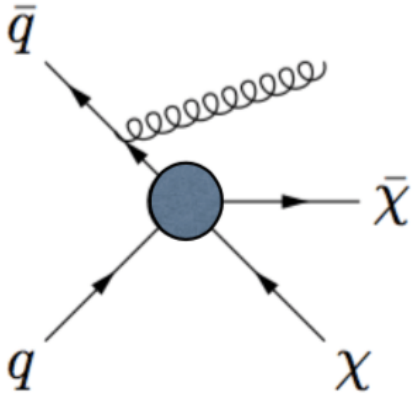


Dark matter?



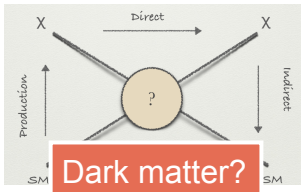
Tools : ISR-boosted particles

- **Particles that only interact weakly will not leave a detector signature**
  - Neutrinos, dark matter, other weird things

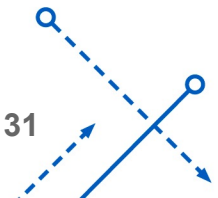


- **Only hope: use ISR + nothing else to identify the event**
  - Relies extensively on missing pt

Applies to:



Dark matter?



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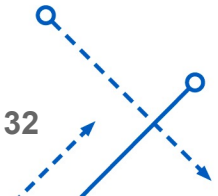
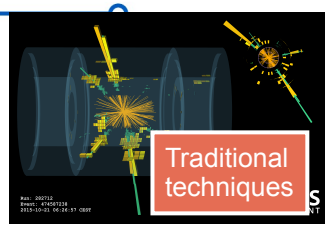
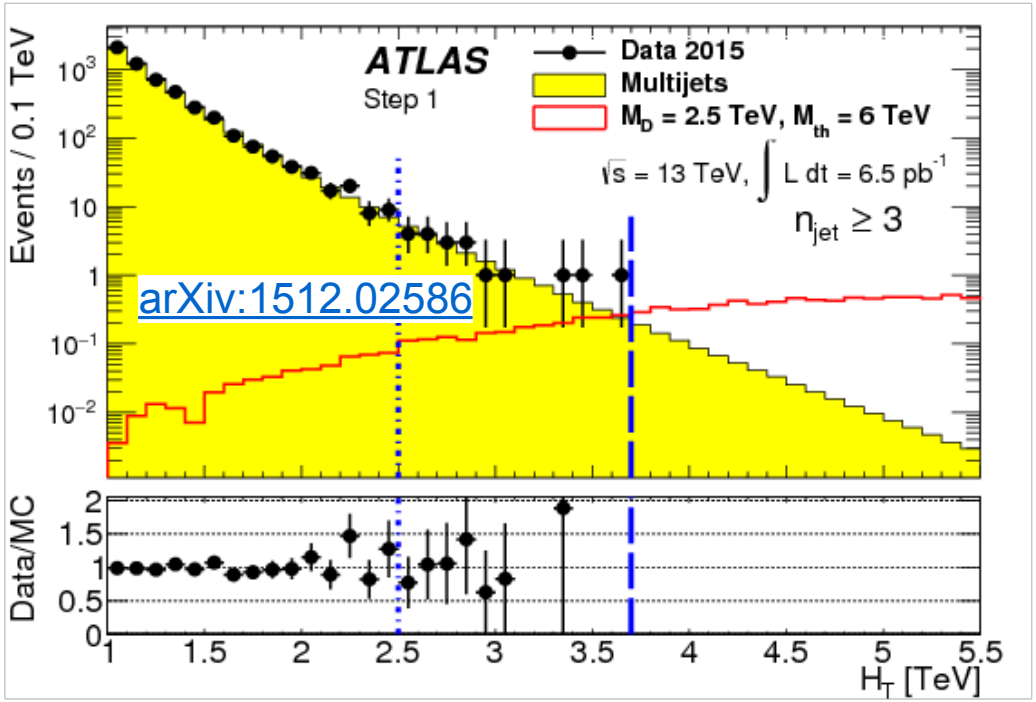
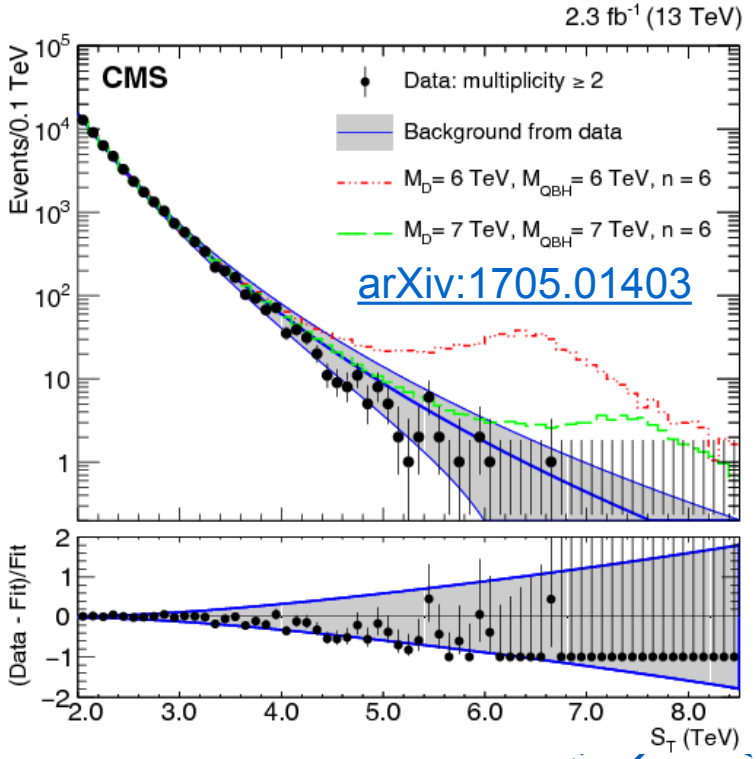


Search: Thermal Black Holes

- **Decays to many particles via Hawking radiation**
- **Signature is a large number of particles in the event**
- **Search for high summed pt**

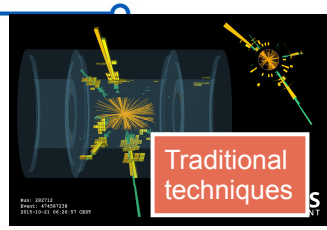


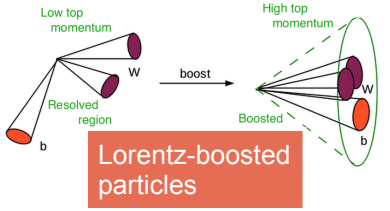




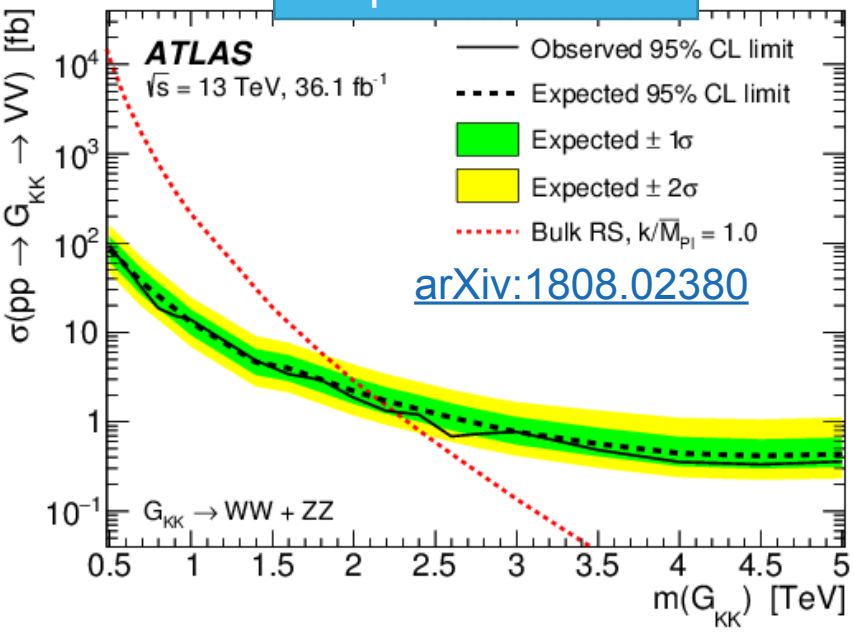
Search: Heavy resonances

- **Interpretations:**
  - Kaluza-Klein particles (graviton, gluon)
  - Extra gauge bosons
  - Quantum black holes
- **Signature:**
  - Di-everything
  - Jets, leptons, photons, W/Z, t, b, H
  - Extensive use of boosted topologies!

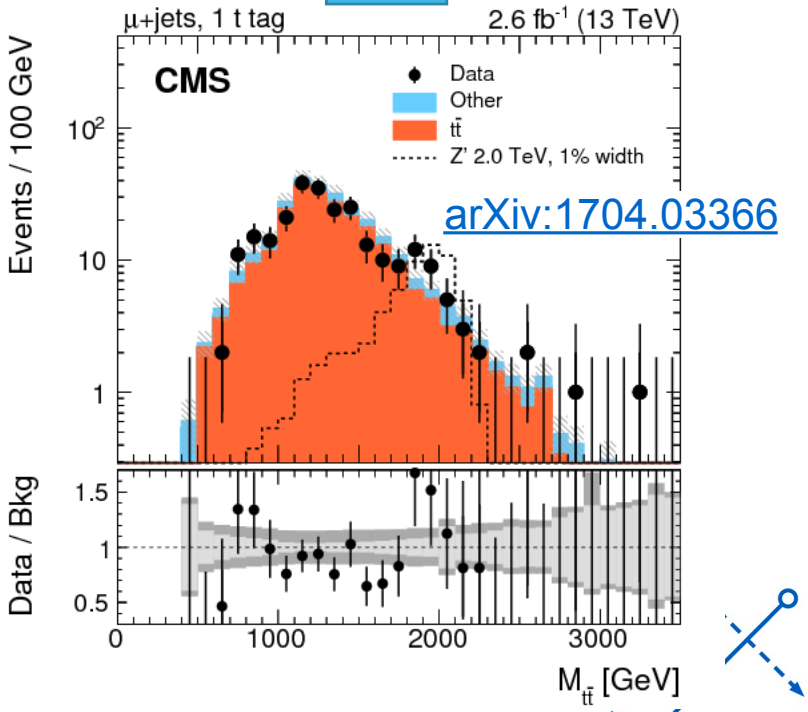




Dilepton + diboson

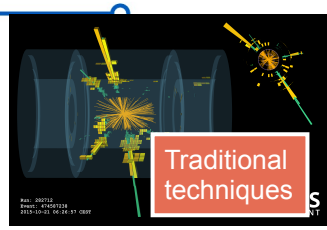


ttbar

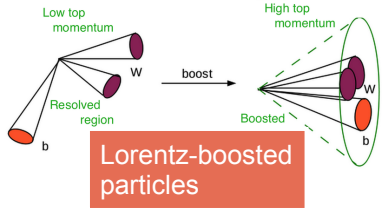


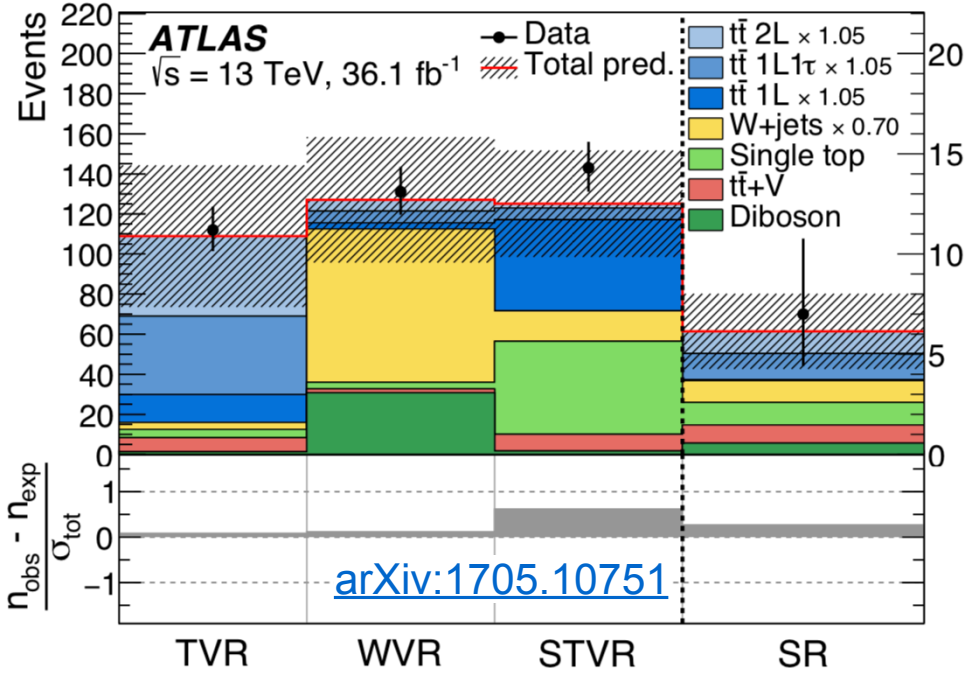
Search: Heavy fermion partners

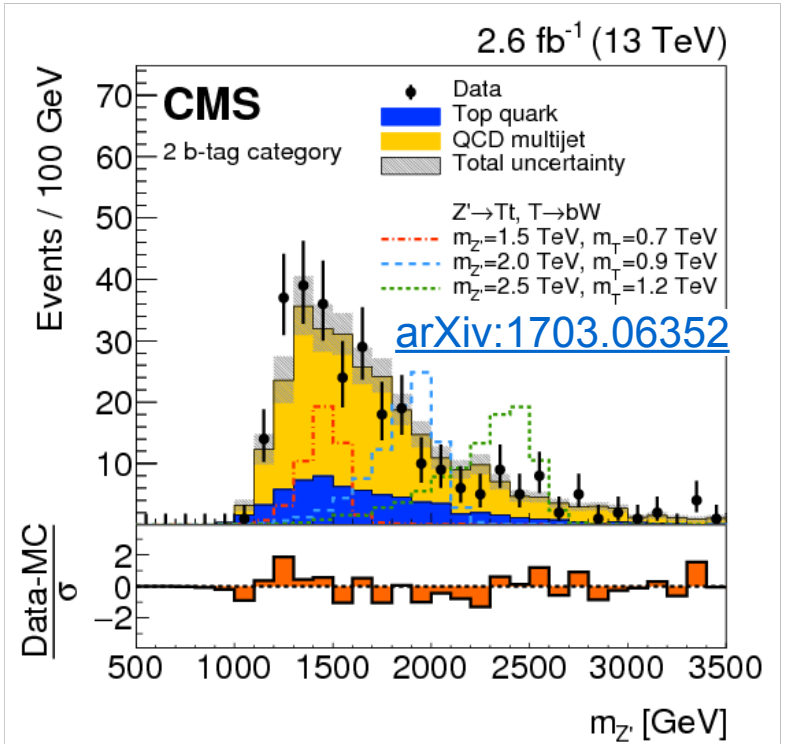
- **Interpretations:**
  - Vector-like fermions (extra dimensional theories)



- **Signature:**
  - Strongly produced heavy quarks to SM quarks
  - Extensive use of boosted topologies

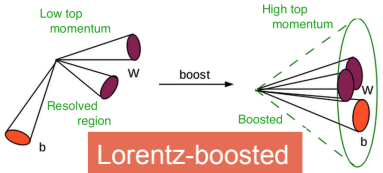




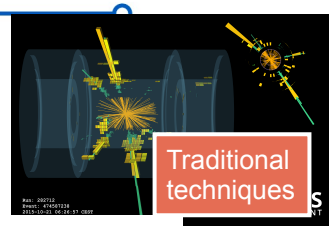


Search: Mono-mania

- **Interpretations:**
  - Dark matter
  - Large extra dimensions

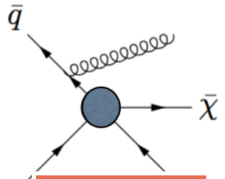


Lorentz-boosted particles

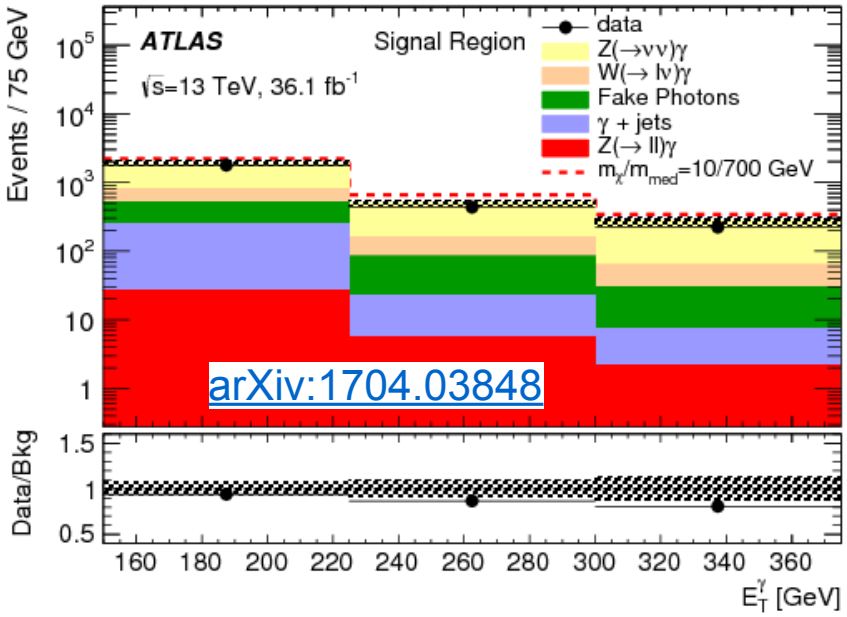


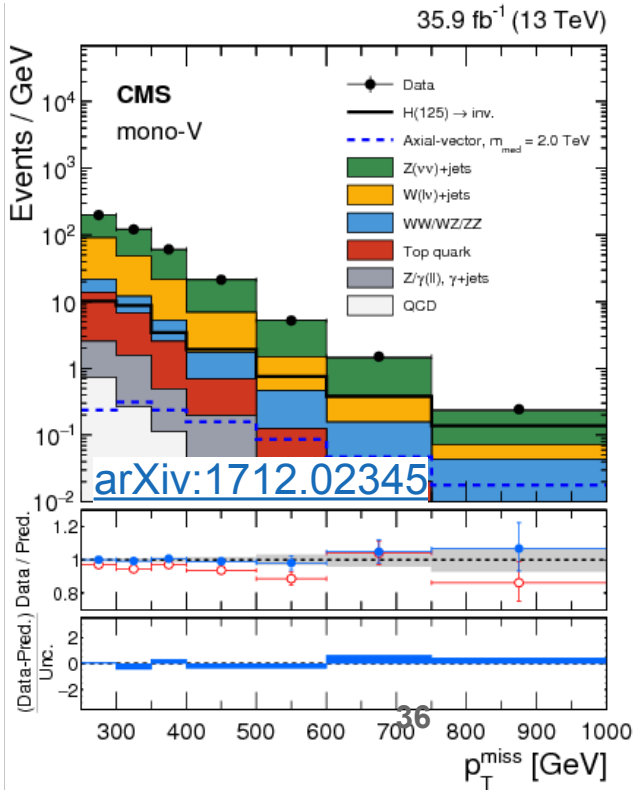
Traditional techniques

- **Signature:**
  - (1 of anything) + missing pt
  - Jet, lepton, gamma, W/Z/H, t, b



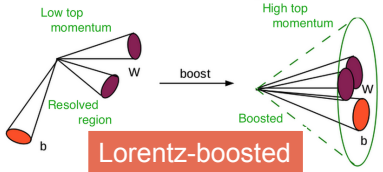
ISR-boosted particles



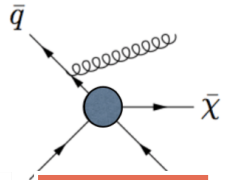


Search: Mono-mania revisited

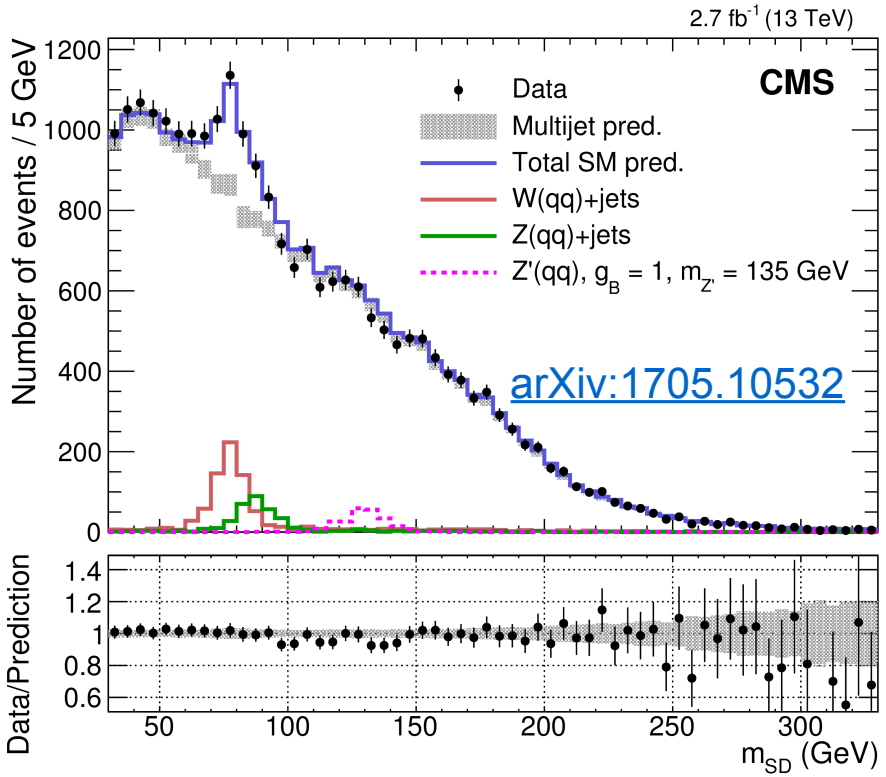
- **Example: mono-jet with substructure can be a search for lighter resonances!**
  - No DM candidate, just boost via ISR!



Lorentz-boosted particles

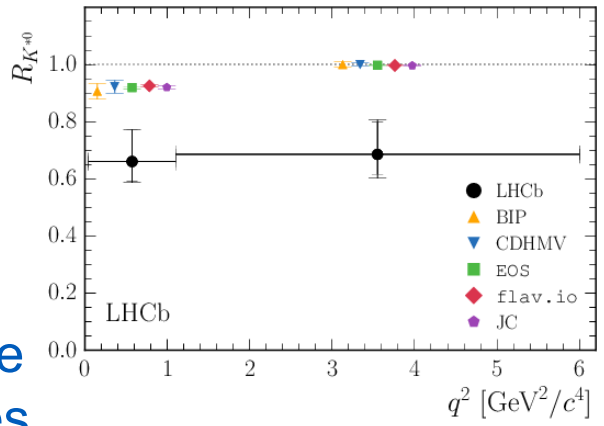


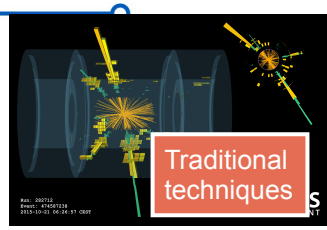
ISR-boosted particles

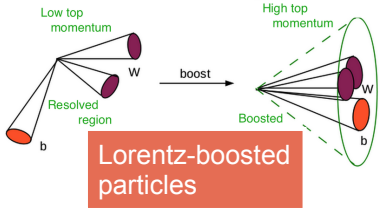


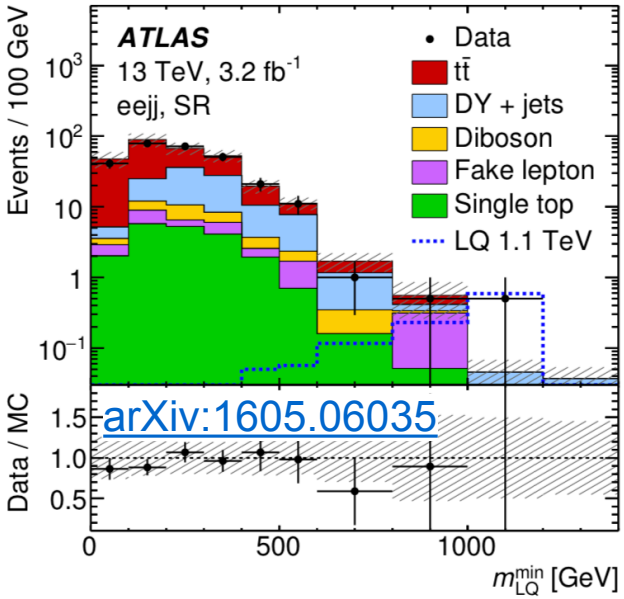
Search: Leptoquarks

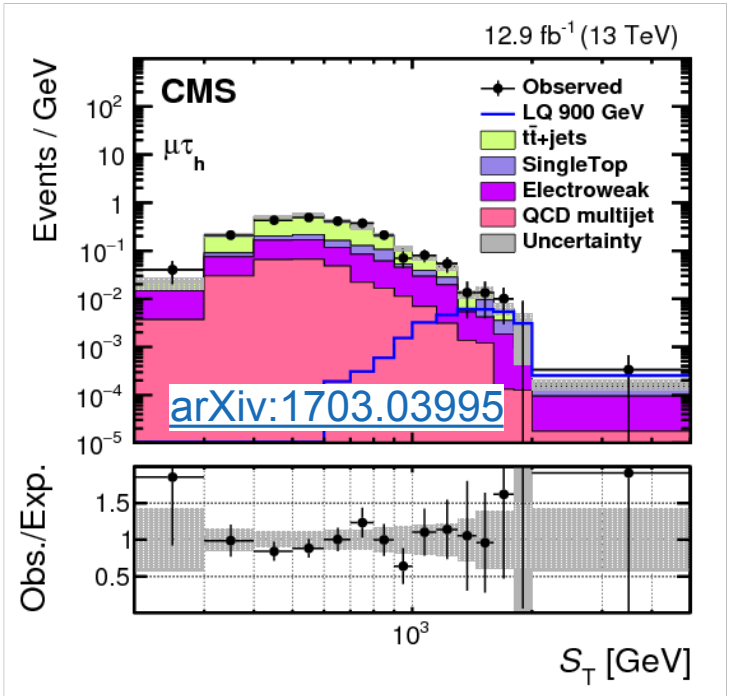
- **Interpretation:**
  - Unification
  - Explanation for lepton flavor violating anomalies in B sector
- **Signature:**
  - Leptons and quarks in final state
  - Can be low or high pt final states (traditional or boosted)





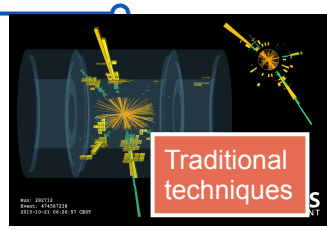




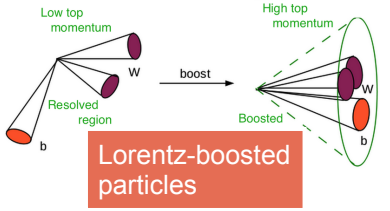


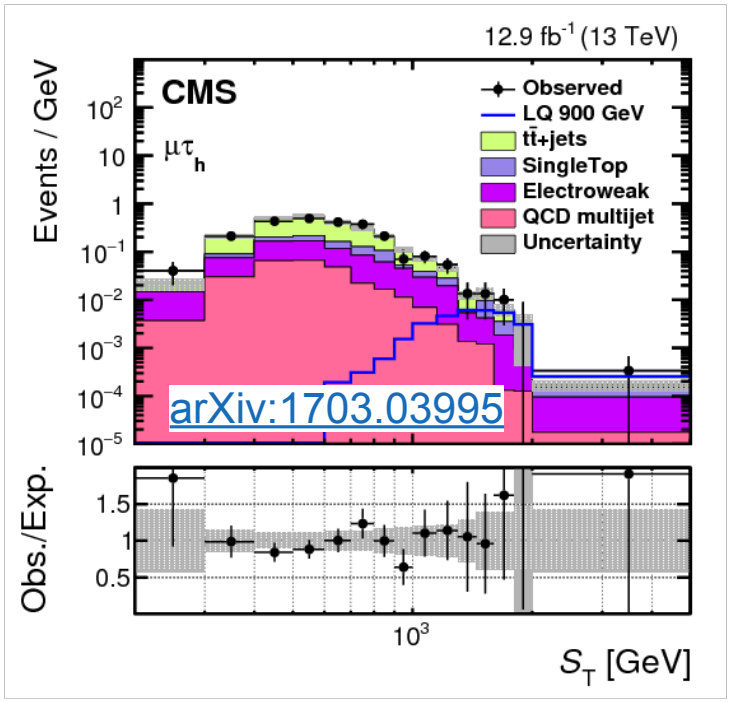
Search: Heavy Neutrinos

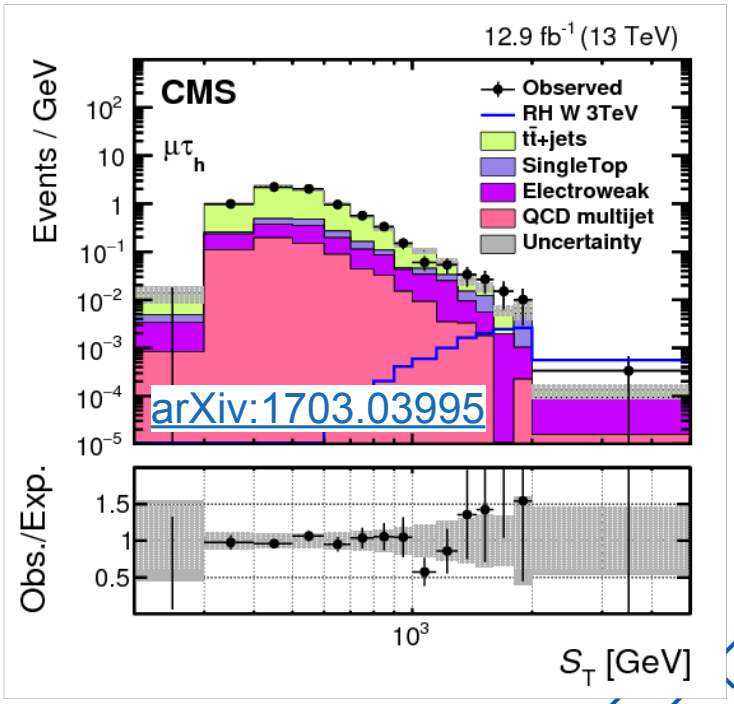
- **Interpretation:**
  - Seesaw mechanism



- **Signature:**
  - Similar final state to leptoquarks, so often a two-for-one deal!
  - Differs in the kinematics

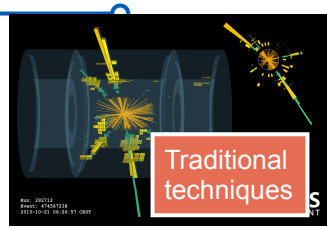


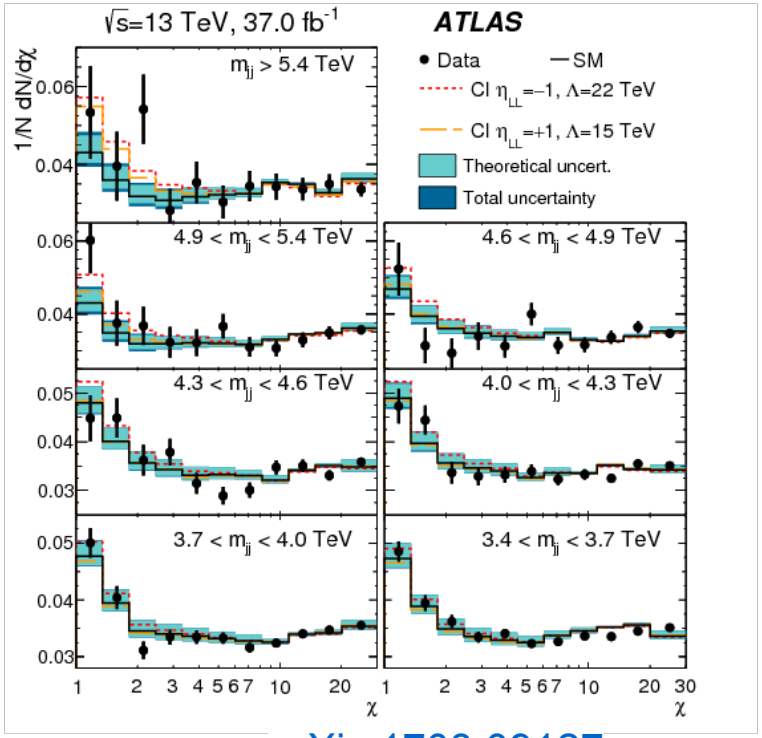




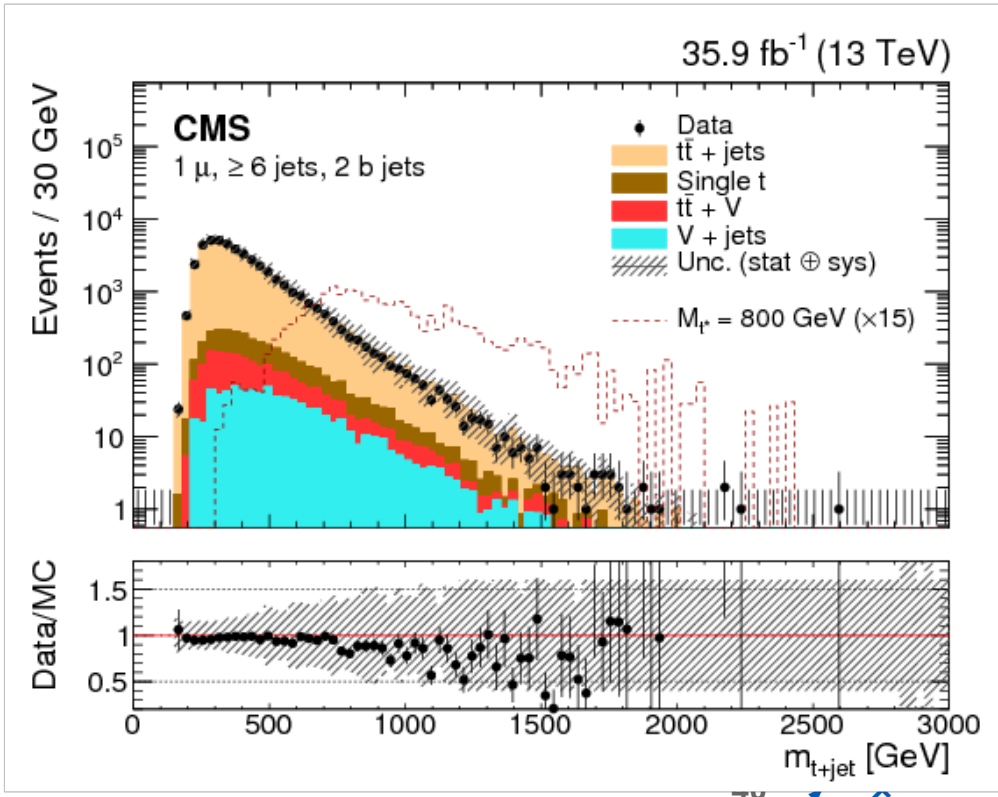
Search: Compositeness

- **Interpretation:**
  - Compositeness
- **Signatures:**
  - Different scattering spectra than elastic
  - Quark + gluon or photon resonances



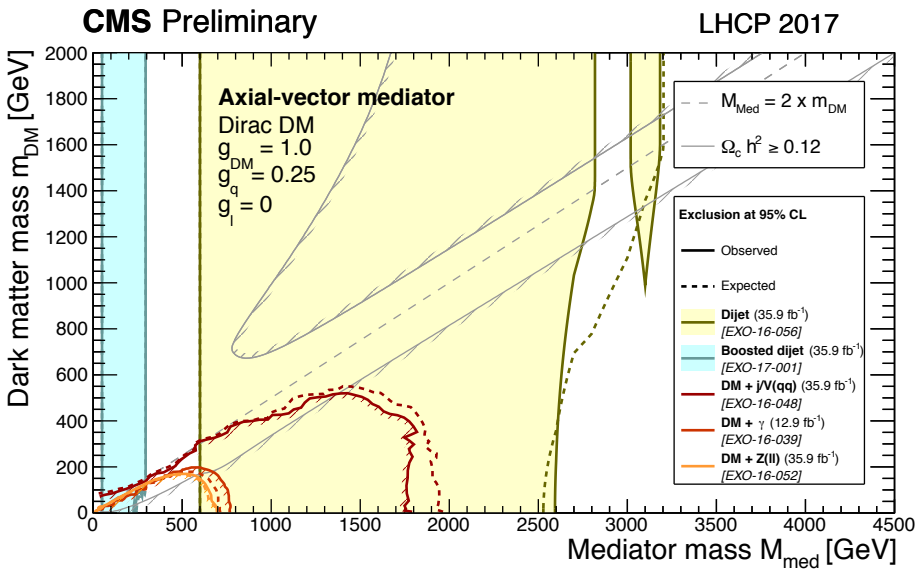


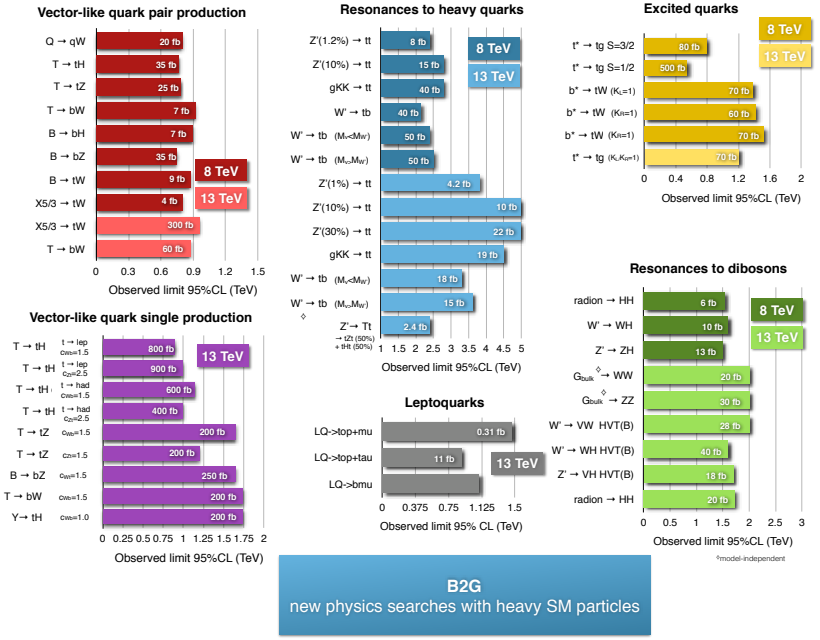
arXiv:1703.09127



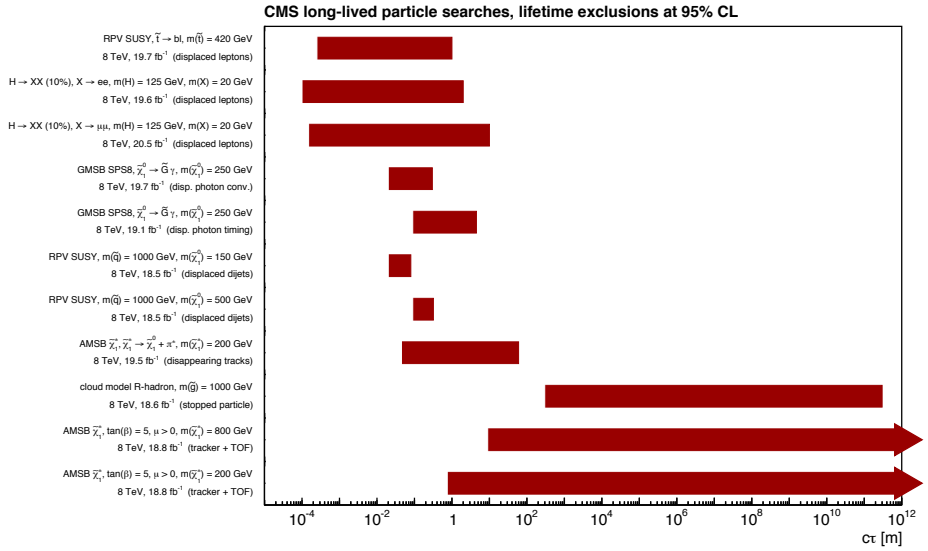
arXiv:1711.10949

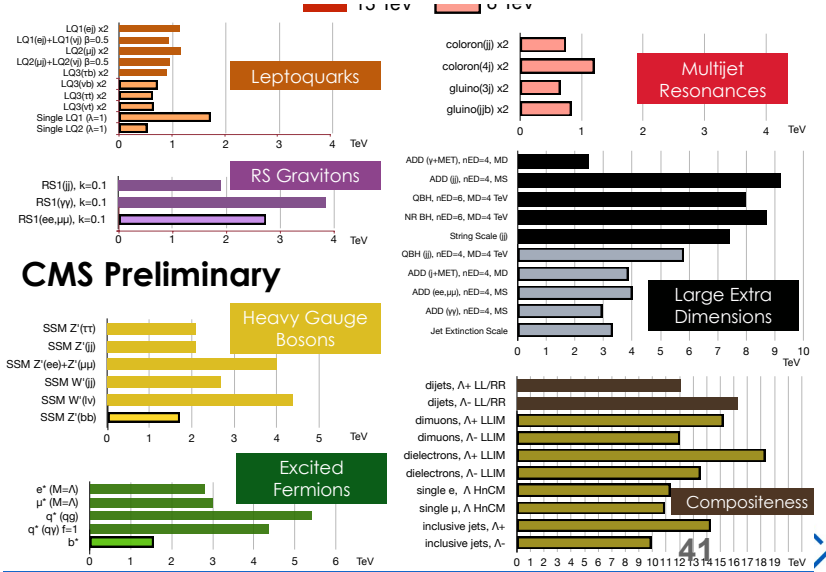
Once more:





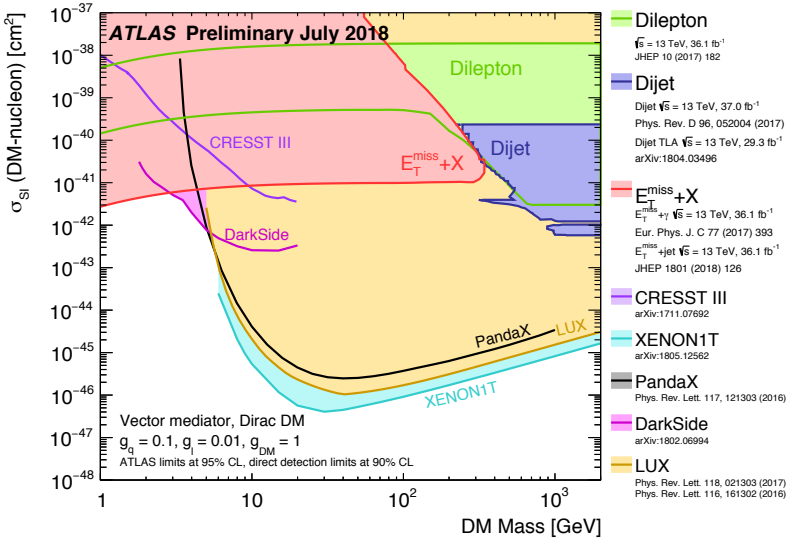
B2G
new physics searches with heavy SM particles

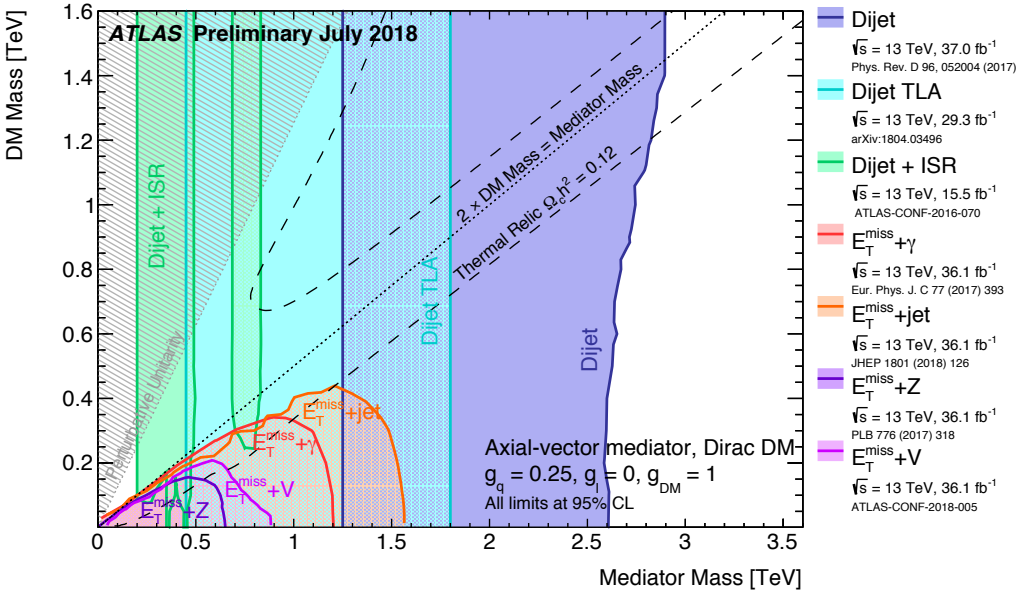


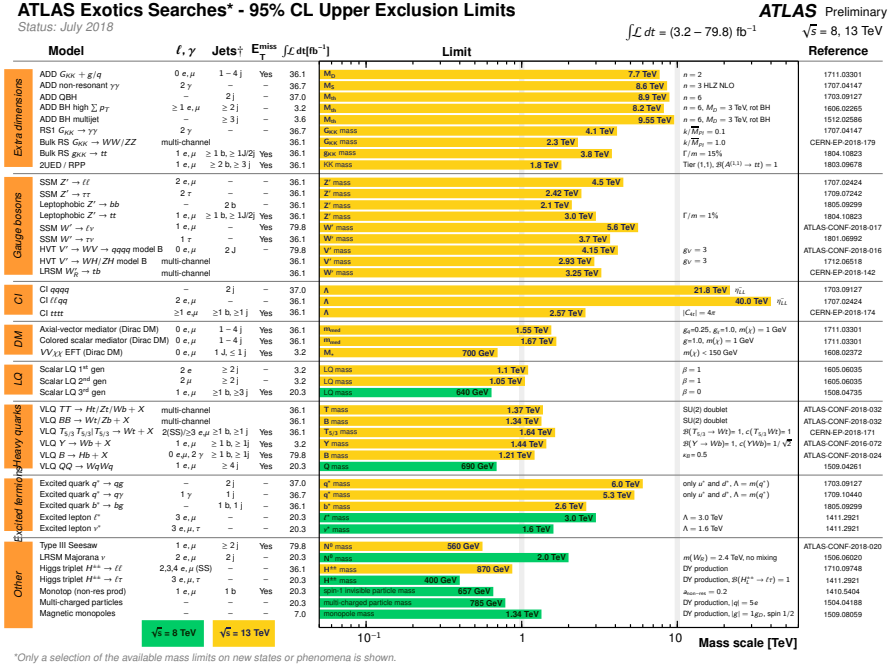


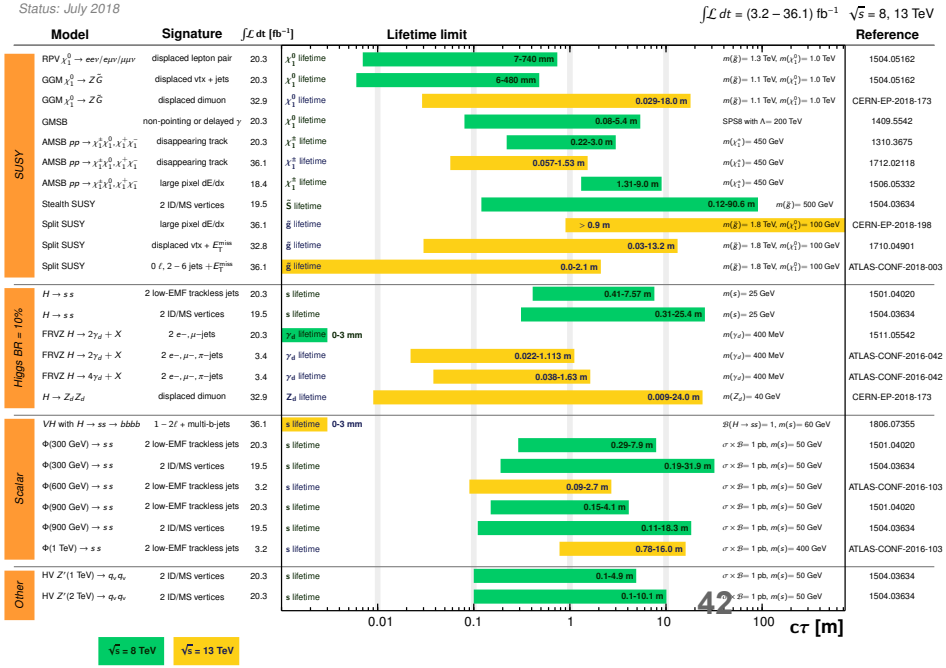
CMS Exotica Physics Group Summary – ICHEP 2016

Once more:


ATLAS Preliminary July 2018
Dilepton
Dijet
CRESST III
E_T^{miss}+X
DarkSide
PandaX
LUX
XENON1T
Vector mediator, Dirac DM
g_q = 0.1, g_l = 0.01, g_{DM} = 1
ATLAS limits at 95% CL, direct detection limits at 90% CL
σ_{SI} (DM-nucleon) [cm^2]
DM Mass [GeV]
Dilepton
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
JHEP 10 (2017) 182
Dijet
Dijet $\sqrt{s}$ = 13 TeV, 37.0 fb^{-1}
Phys. Rev. D 96, 052004 (2017)
Dijet TLA $\sqrt{s}$ = 13 TeV, 29.3 fb^{-1}
arXiv:1804.03496
E_T^{miss}+X
E_T^{miss}+γ $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C 77 (2017) 393
E_T^{miss}+jet $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
JHEP 1801 (2018) 126
CRESST III
arXiv:1711.07692
XENON1T
arXiv:1805.12562
PandaX
Phys. Rev. Lett. 117, 121303 (2016)
DarkSide
arXiv:1802.06994
LUX
Phys. Rev. Lett. 118, 021303 (2017)
Phys. Rev. Lett. 116, 161302 (2016)

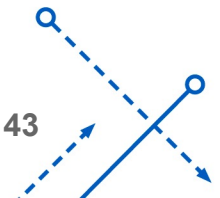

ATLAS Preliminary July 2018
Dijet + ISR
Perturbative Unitarity
Dijet TLA
Dijet
2 × DM Mass = Mediator Mass
Thermal Relic $\Omega_\chi h^2$ = 0.12
E_T^{miss}+jet
E_T^{miss}+γ
E_T^{miss}+V
E_T^{miss}+Z
Axial-vector mediator, Dirac DM
g_q = 0.25, g_l = 0, g_{DM} = 1
All limits at 95% CL
DM Mass [TeV]
Mediator Mass [TeV]
Dijet
$\sqrt{s}$ = 13 TeV, 37.0 fb^{-1}
Phys. Rev. D 96, 052004 (2017)
Dijet TLA
$\sqrt{s}$ = 13 TeV, 29.3 fb^{-1}
arXiv:1804.03496
Dijet + ISR
$\sqrt{s}$ = 13 TeV, 15.5 fb^{-1}
ATLAS-CONF-2016-070
E_T^{miss}+γ
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C 77 (2017) 393
E_T^{miss}+jet
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
JHEP 1801 (2018) 126
E_T^{miss}+Z
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
PLB 776 (2017) 318
E_T^{miss}+V
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2018-005


ATLAS Exotics Searches* - 95% CL Lower Exclusion Limits
ATLAS Preliminary
Status: July 2018
$\int \mathcal{L}\,dt$ = (3.2 – 79.8) fb^{-1}
$\sqrt{s}$ = 8, 13 TeV
Model
Limit
Reference
Extra dimensions
Gauge bosons
Contact Interactions
Dark Matter
Leptoquarks
Heavy quarks
Excited fermions
Other
$\sqrt{s}$ = 8 TeV
$\sqrt{s}$ = 13 TeV
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).


Status: July 2018
$\int \mathcal{L}\,dt$ = (3.2 – 36.1) fb^{-1}
$\sqrt{s}$ = 8, 13 TeV
Model
Signature
Lifetime limit
Reference
SUSY
Higgs BR = 10%
Scalar
Other
$c\tau$ [m]
$\sqrt{s}$ = 8 TeV
$\sqrt{s}$ = 13 TeV
*Only a selection of the available lifetime limits on new states is shown.

Outline

- **Why we still need particle physics**
- **Exotic physics introduction**
- **Search techniques**
- **Selected analyses**
- **Final thoughts**

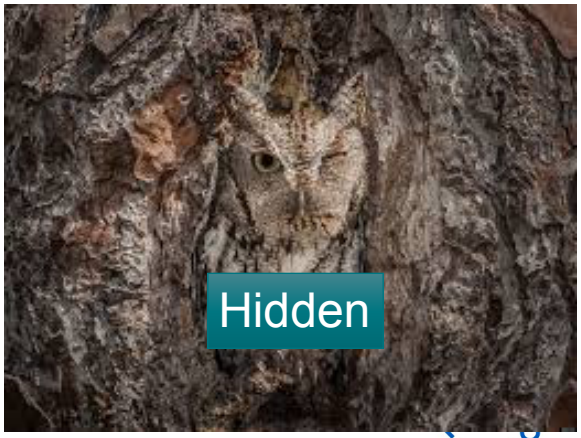


What's next?

- **Nothing conclusive yet**
  - Hints abound in lepton sector (nu masses, LFV)
  - Dark matter is still there
  - Have to study the Higgs in detail

- **Three possibilities:**

Nothing new or 

or 

Perspective

1985 View of “The Future” (2017):

Styles of 2017

Multiple wristwatches… only tells time!

“Mr. Fusion” cold fusion reactor

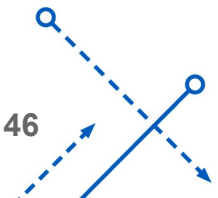
Flying car
(Delorean)

Perspective

Next run of LHC:

- Are we still looking for “Mr. Fusion” and flying cars? (extrapolation of present ideas of “the future”)
- There is nothing but our personal bias to motivate this, but nature does not care
- Or, is there a new deeper understanding we need to uncover?

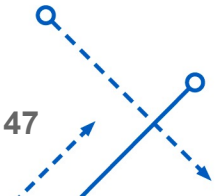
A man said to the universe:
“Sir, I exist!”
“However,” replied the universe,
“The fact has not created in me
A sense of obligation.”
– Stephen Crane



My personal take

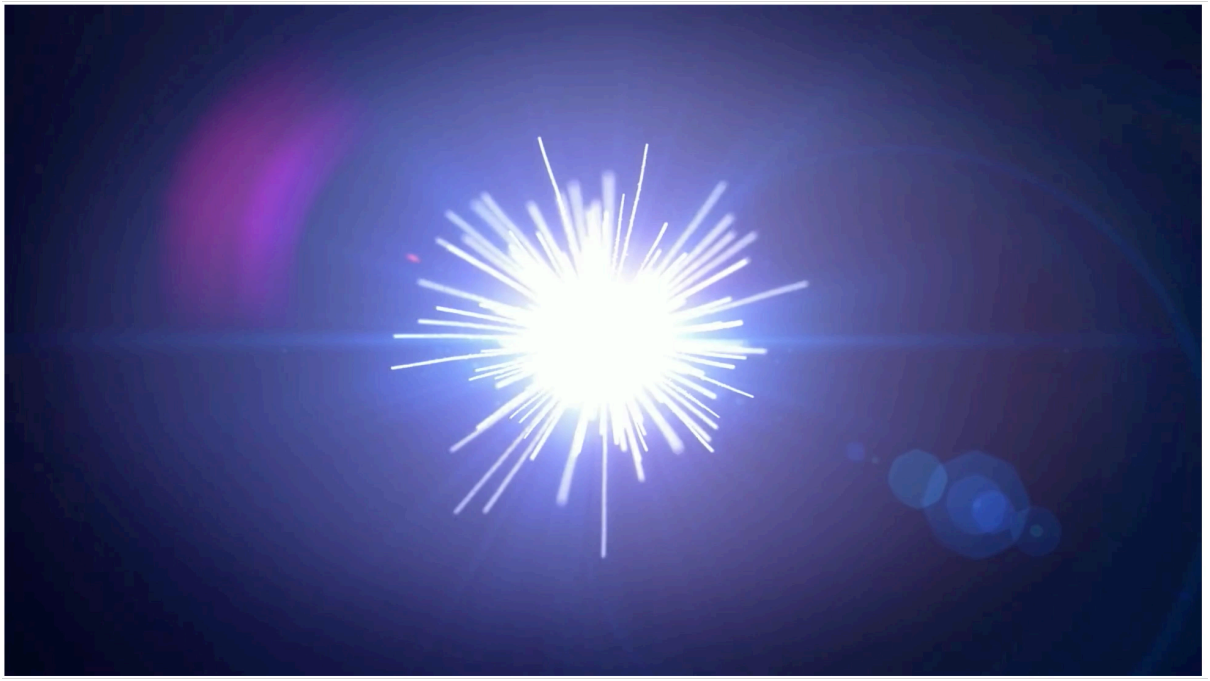
- **Dark matter is unknown…**
  - Probably non-negotiable. This is almost certainly a particle.
- **Higgs + QM is extremely weird…**
  - Problem with nature, or problem with us?
- **Lepton sector questions are very puzzling…**
  - “Who ordered THAT!?!” …I. I. Rabi, after discovery of the muon
  - 80 years later, still full of surprises

All need further investigation from particle physics!
Future colliders a necessity!



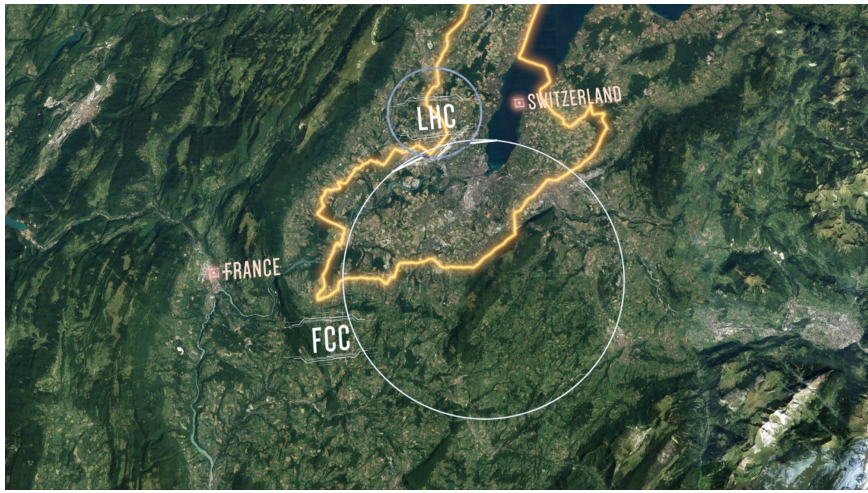
CERN's take

- **Hot off the press! 15-Jan-2019!**
- **Future Circular Collider (FCC) Conceptual Design Report (CDR)**
  - https://fcc-cdr.web.cern.ch



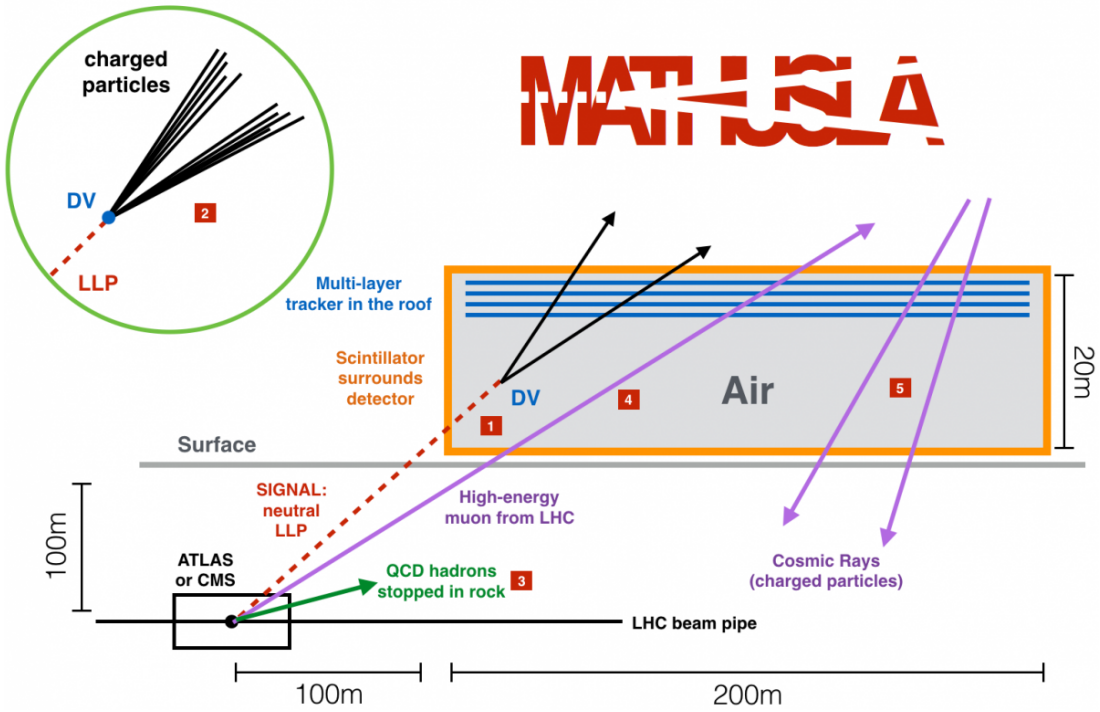
FCC CDR tl;dr

- **LHC tunnel (27 km)**
  - Timeline: **driven by accelerator R+D**
  - HE-LHC : 27 TeV
  - 7B CHF
- **New tunnel (100 km)**
  - FCC-ee :
    - Timeline: 2040
    - scan Z—>WW—>H—>ttbar
    - 10B CHF
  - FCC-hh :
    - Timeline: 2050
    - 100 TeV pp
    - 15B CHF



New directions

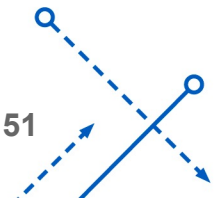
- **Aside from colliders, need BIGGER detectors!**
  - Put detectors far from interaction
  - MATHUSLA / FASER



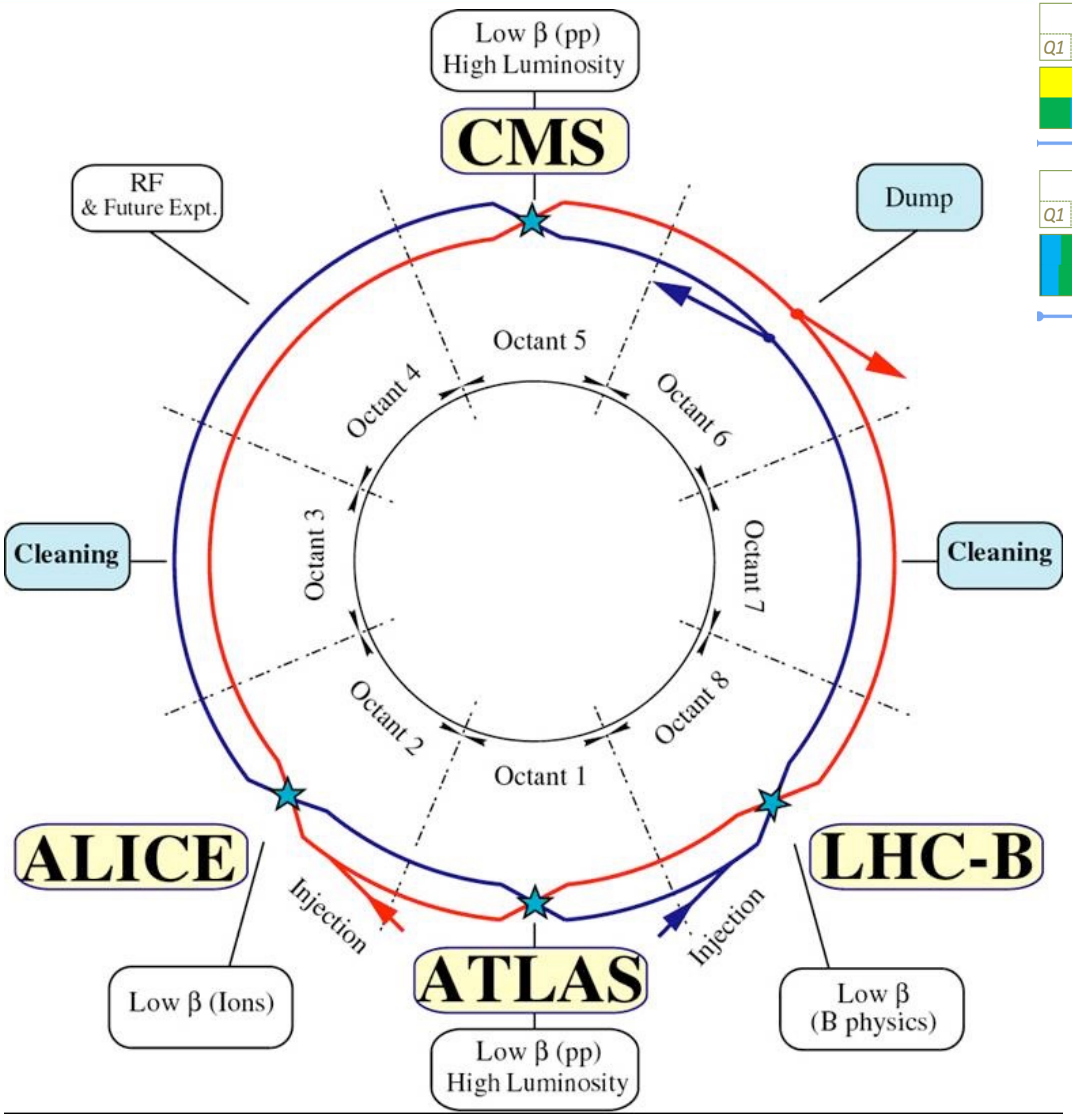
Summary

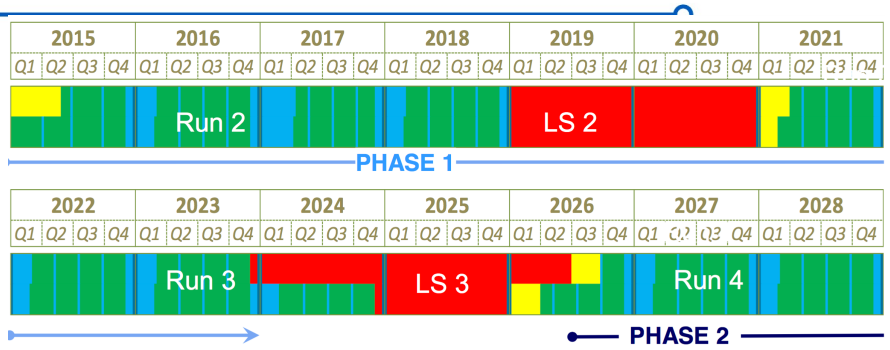
- **Plethora of open questions in particle physics**
- **Nearly guaranteed that we don't have the full picture**
- **LHC and future colliders are an important part of the scientific puzzle facing humanity**

Fin



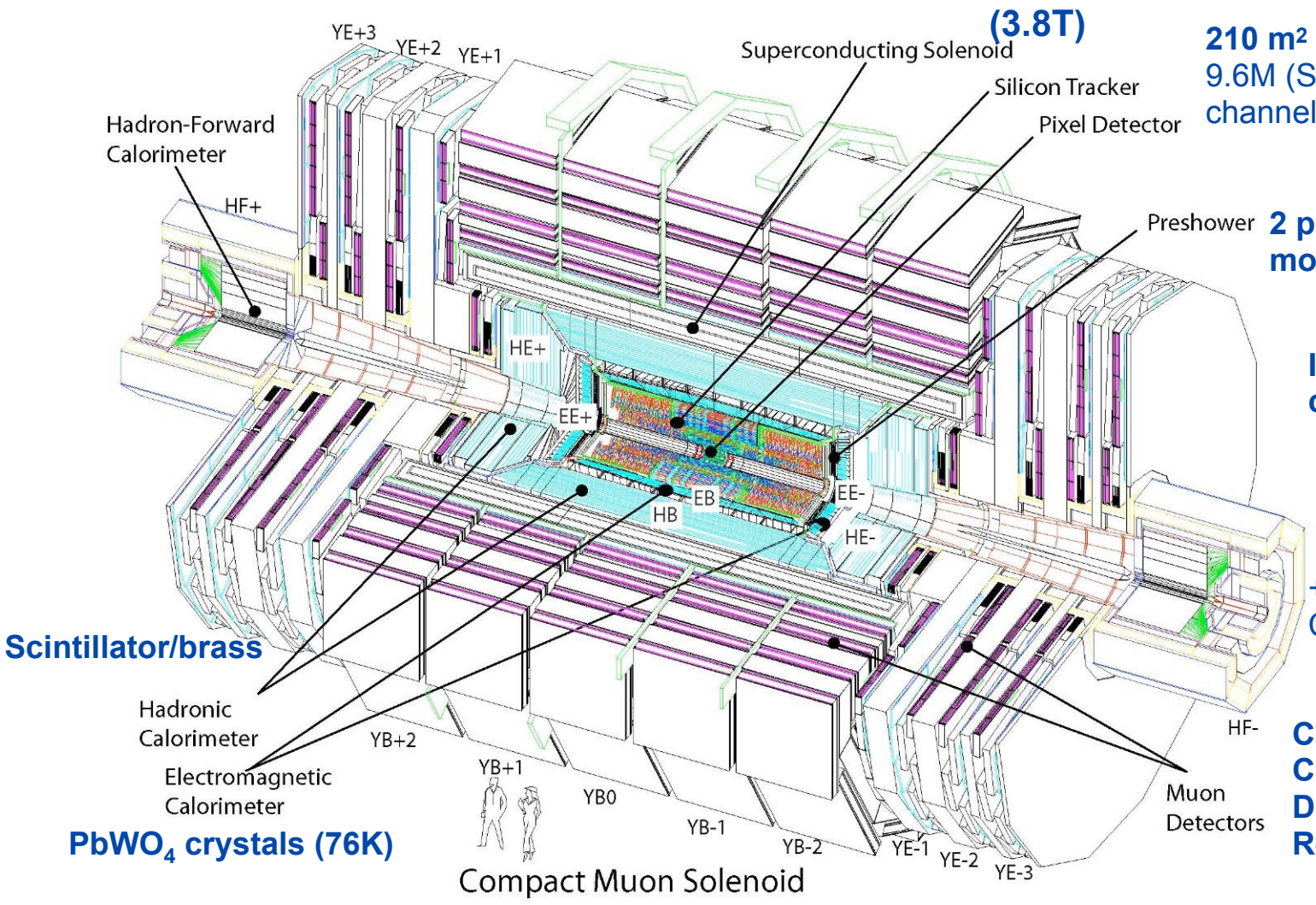
The Large Hadron Collider





- pp collider in Geneva, Switzerland and surrounding areas in France
- 27 km circumference
- 50-175 m underground
- Restarted May 23rd
- Ecom = 13 TeV
- Expect L > 1.7e34 / cm^2-s
- Plan on O(50) fb-1 integrated lumi this year

CMS



210 m² of silicon sensors: 9.6M (Str) & 66M (Pix) channels

2 planes of silicon modules for ECAL

Iron / Quartz fiber fwd calorimeter, $3<|\eta|<5$;

+ Castor, $5<|\eta|<6.55$

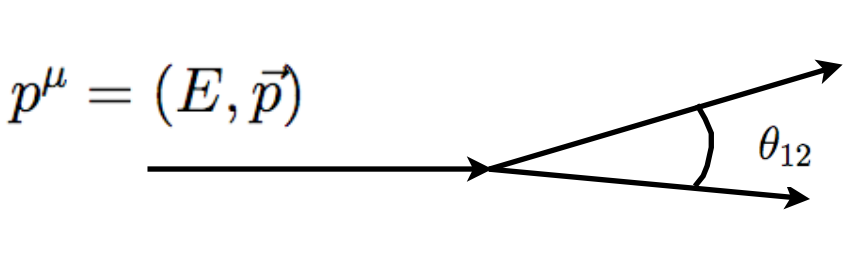
+ Zero Degree Calorimeter

Scintillator/brass

$PbWO_4$ crystals (76K)

Cathode Strip Chambers, Drift Tubes, Resistive Plates

Tools : Boosted hadronic jets



$$
\begin{aligned}
p^\mu p_\mu &= (p_1 + p_2)^\mu (p_1 + p_2)_\mu \\
m^2 &= (E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2}) \cdot (\vec{p_1} + \vec{p_2}) \\
m^2 &\approx 2E_1E_2(1 - \cos(\theta_{12}))
\end{aligned}
$$

Assume E1=E2 = E/2

$$
\begin{aligned}
m^2 &\approx E^2(1 - \cos(\theta_{12})) \\
\cos(\theta_{12}) &\approx 1 - \frac{m^2}{E^2} \approx 1 - \frac{1}{\gamma^2}
\end{aligned}
$$

$$\theta_{12} \approx \frac{2m}{E} = \frac{2}{\gamma}$$

Traditional jet clustering fixes theta, so is a de-facto a MAXIMUM energy selection (bad): Need substructure!