Searches for Exotica with CMS

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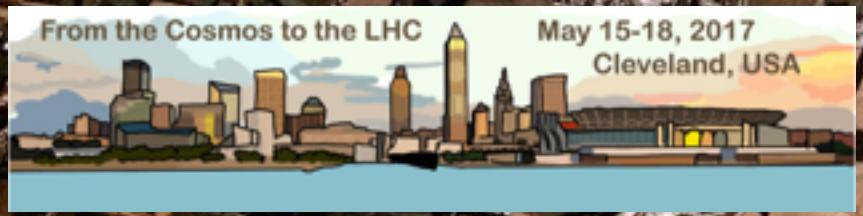
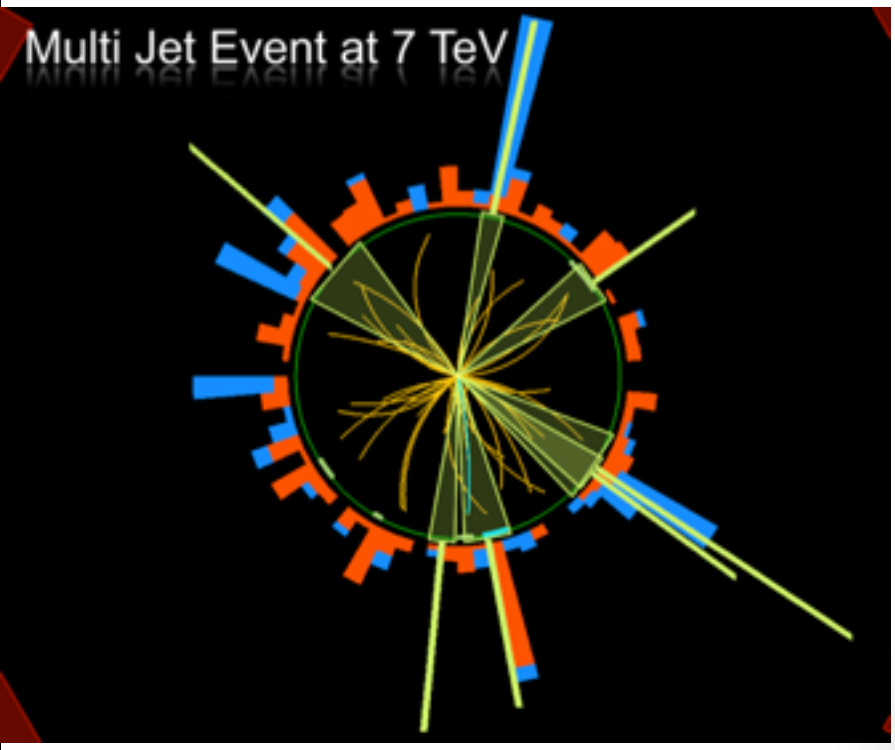
17th May 2017

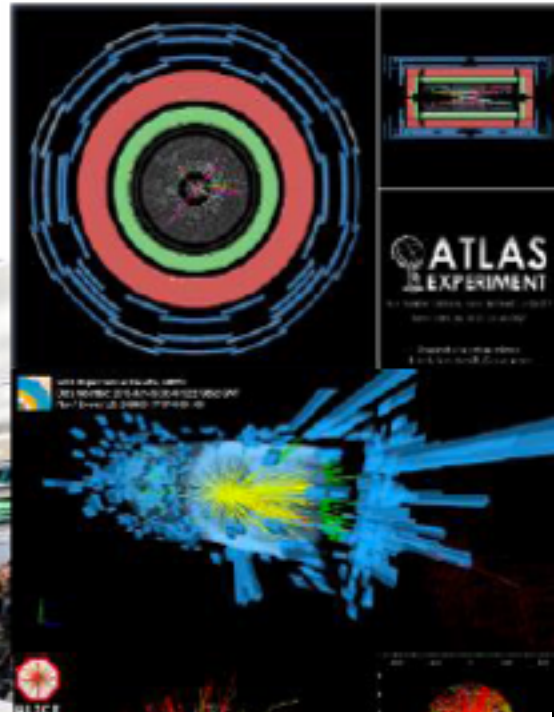


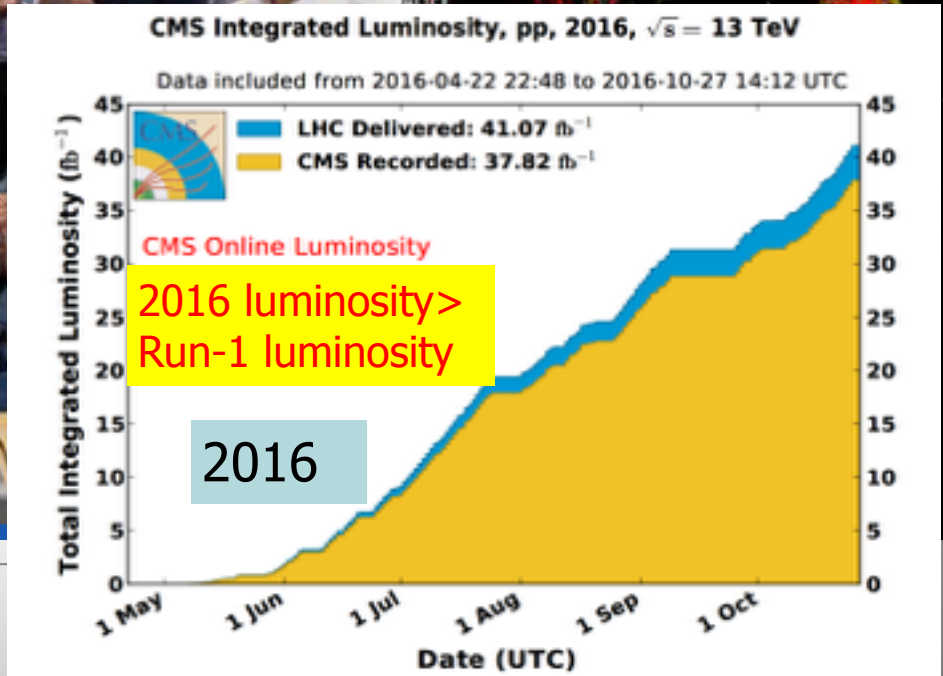


- Introduction to Searches
- Searches for New Physics
  - Searching SUSY (short)
  - Vector-like particles
  - Resonance searches
  - Dark Matter searches
  - Exotic new particles
  - Specific LFV Searches
- Summary

LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015 Run-2 starts

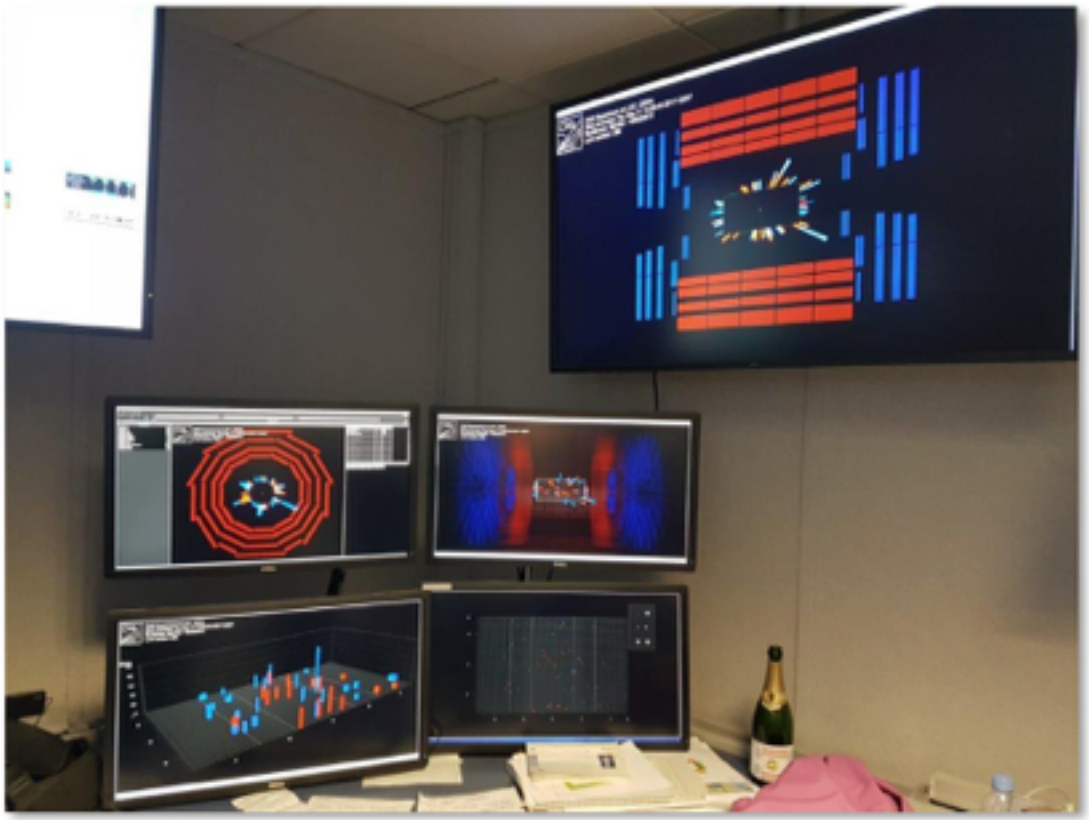




Many analysis presented today based on full 2016 data sample

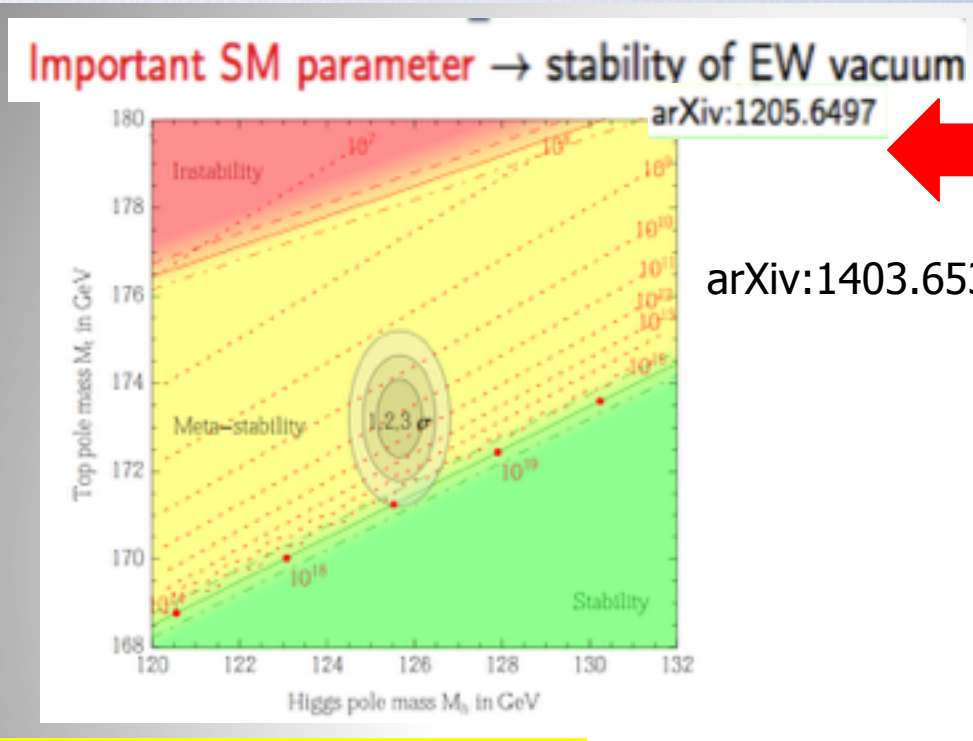
Recent LHC News: Beam is back

First test collisions in the experiments on Thursday last week



- Machine expected next week to start up with collisions (this weekend?)
- Expect to collect ~ 90 fb^{-1} in 2017-2018 -> around 130 fb^{-1} total in Run-2
- CMS is ready to collect data

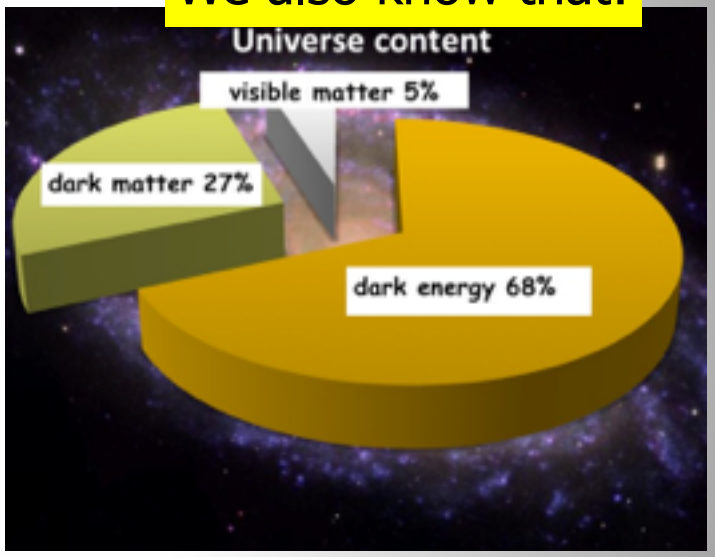
Physics Beyond the Standard Model?



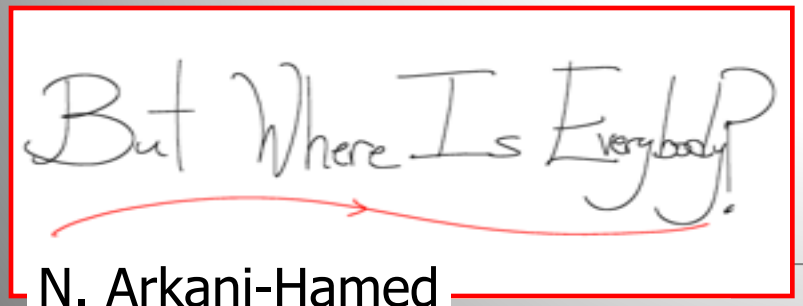
arXiv:1403.6535

A Higgs at 125 GeV
Precise measurements of the top quark and the Higgs mass

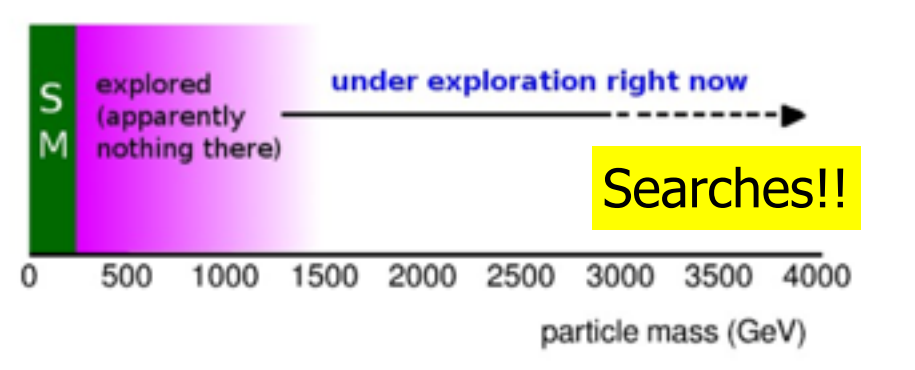
We also know that:



New Physics inevitable?
But at which scale/energy?

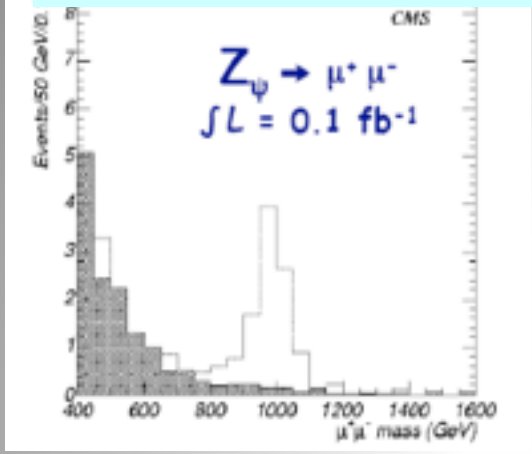


N. Arkani-Hamed

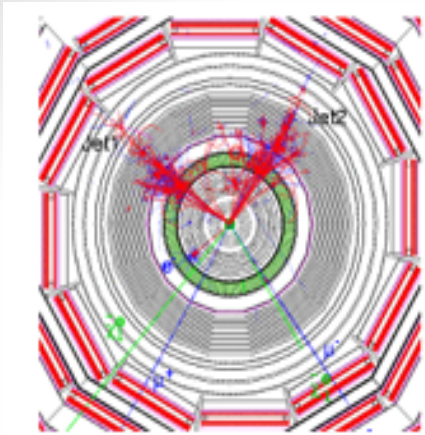


New Physics?

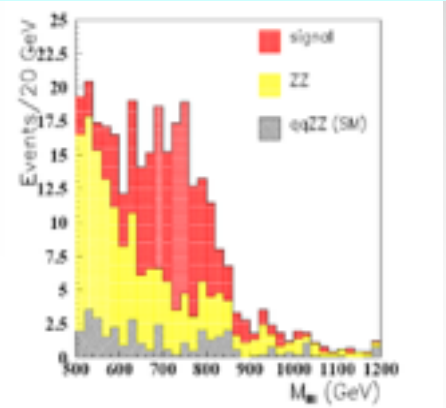
New Gauge Bosons?



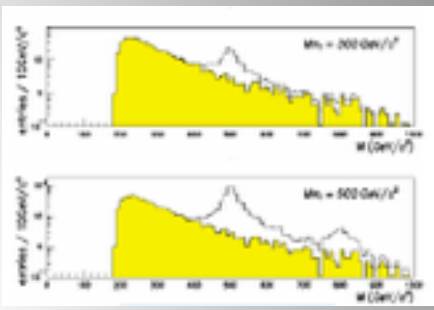
Supersymmetry



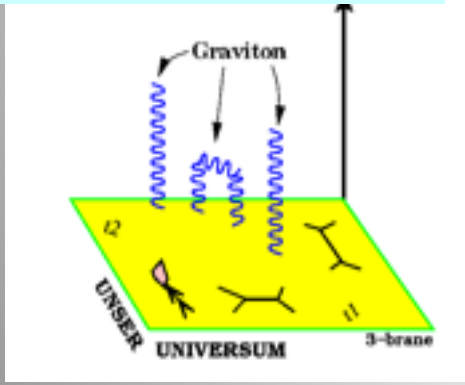
ZZ/WW resonances?



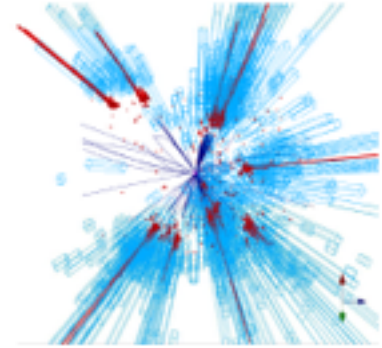
Technicolor?



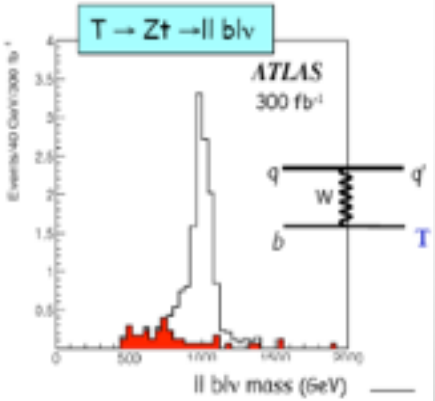
Extra Dimensions?



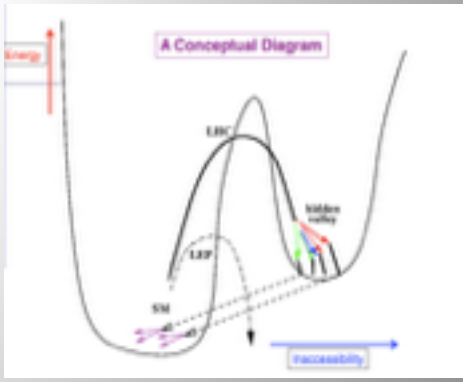
Black Holes???



Little Higgs?



Hidden Valleys?



What stabelizes the Higgs Mass? Many ideas, not all viable any more

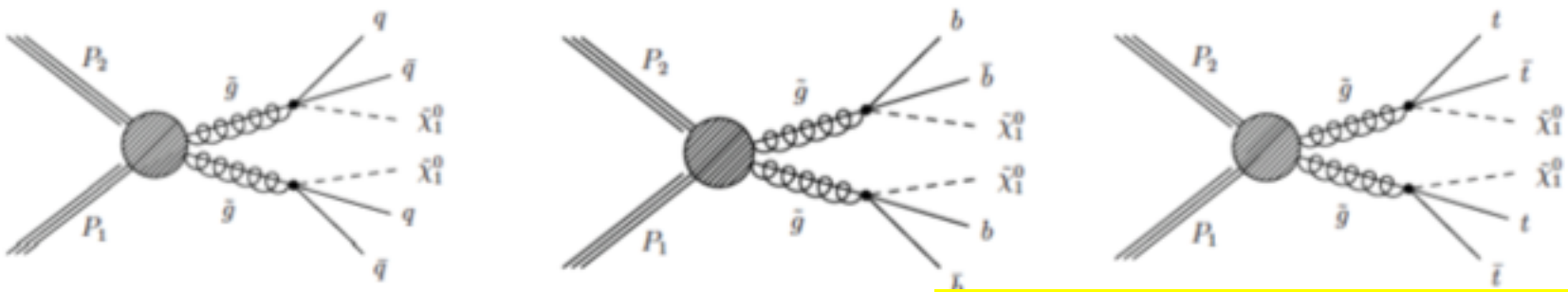
A large variety of possible signals. We have to be ready for that

Searches for BSM Physics

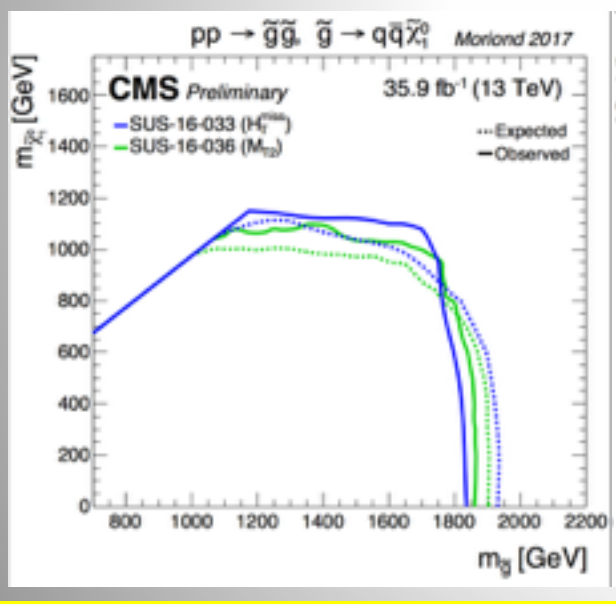
- First Searches at the LHC (2010-2012)
  - Supersymmetry with MET plus jets, lepton(s), photons
  - Extra Dimensions and black holes, heavy resonances (in electrons, muons, taus, jets), leptoquarks, excited leptons and quarks, 4th generation, a few very exotic signatures (R-hadrons)…
- Evolved Searches (2013-…)
  - Supersymmetry on third generation squarks, compressed spectra, stealth SUSY, EWKinos, VBF processes…
  - Higgs in decays or as study object, vector-like quarks, boosted objects, long lived particles, fractional charges…
  - More dedicated Dark Matter searches!
- We are now fully engaged in the analyses at 13 TeV…

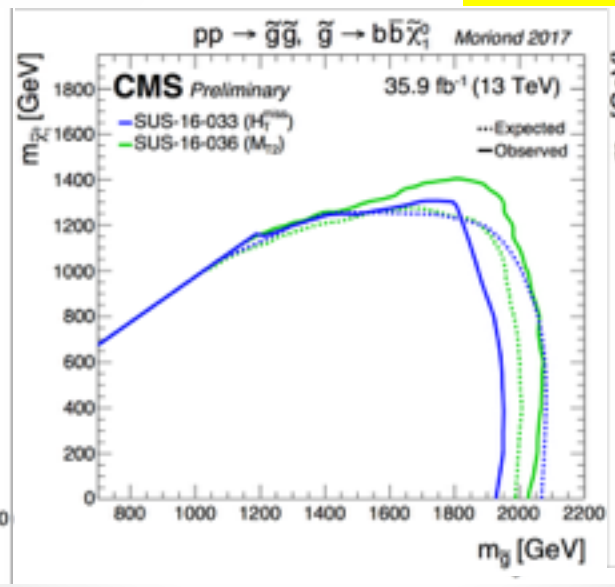
  Strategy is a combination of the above!

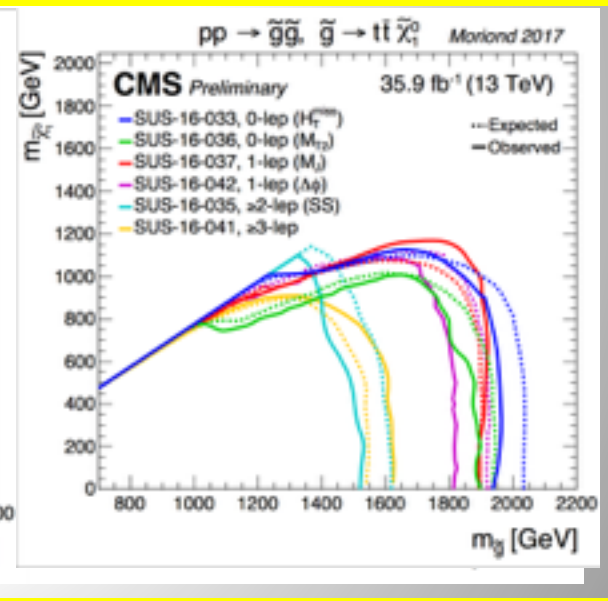
Supersymmetry? Examples:



Interpretation in simplified models







No significant signal to date

Within the context of the SMS:

Exclude with gluino masses ~ 2100 GeV for neutralino masses up to 800 GeV

SUSY Summary

November ’16 on the web page of The Economist (!?!):

Moriond '17

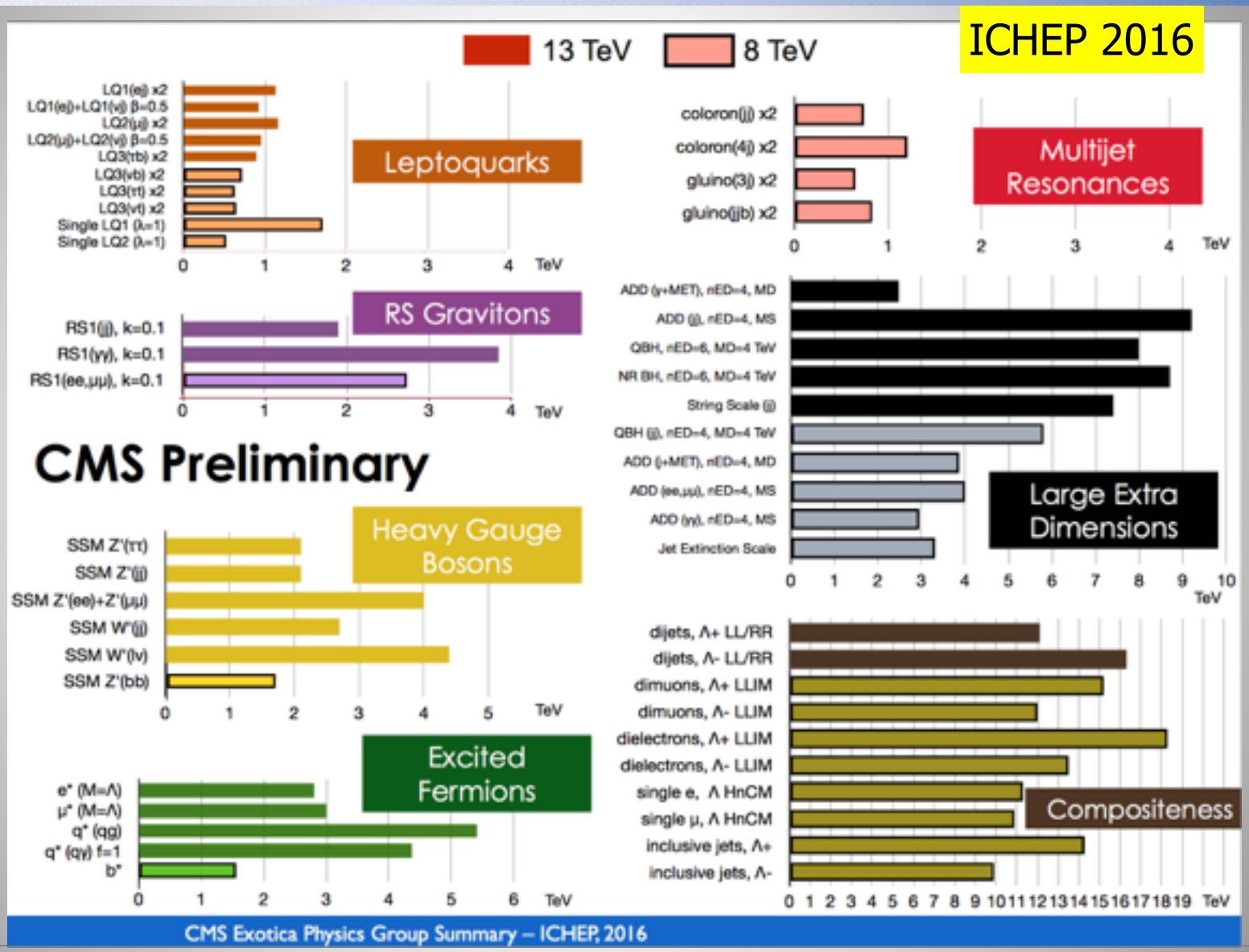
Observed limits at 95% C.L. - theory uncertainties not included

Mass Scale [GeV]

Only a selection of available mass limits. Probe "up to" the quoted mass limit for m_{LSP} ~0 GeV unless stated otherwise

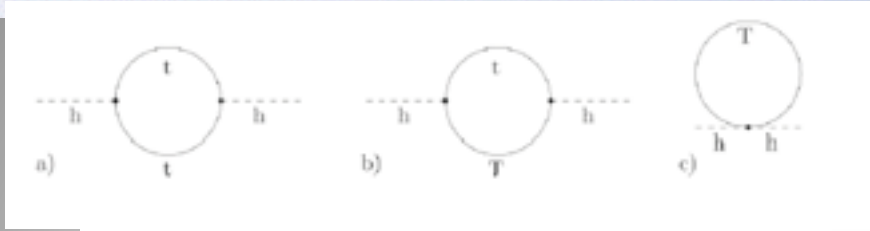
http://www.economist.com/news/science-and-technology/21709946-supersymmetry-beautiful-idea-there-still-no-evidence-support-it

Exotica Searches so far



Next: New analyses since March 2017

Vector-like Quark Pair Production

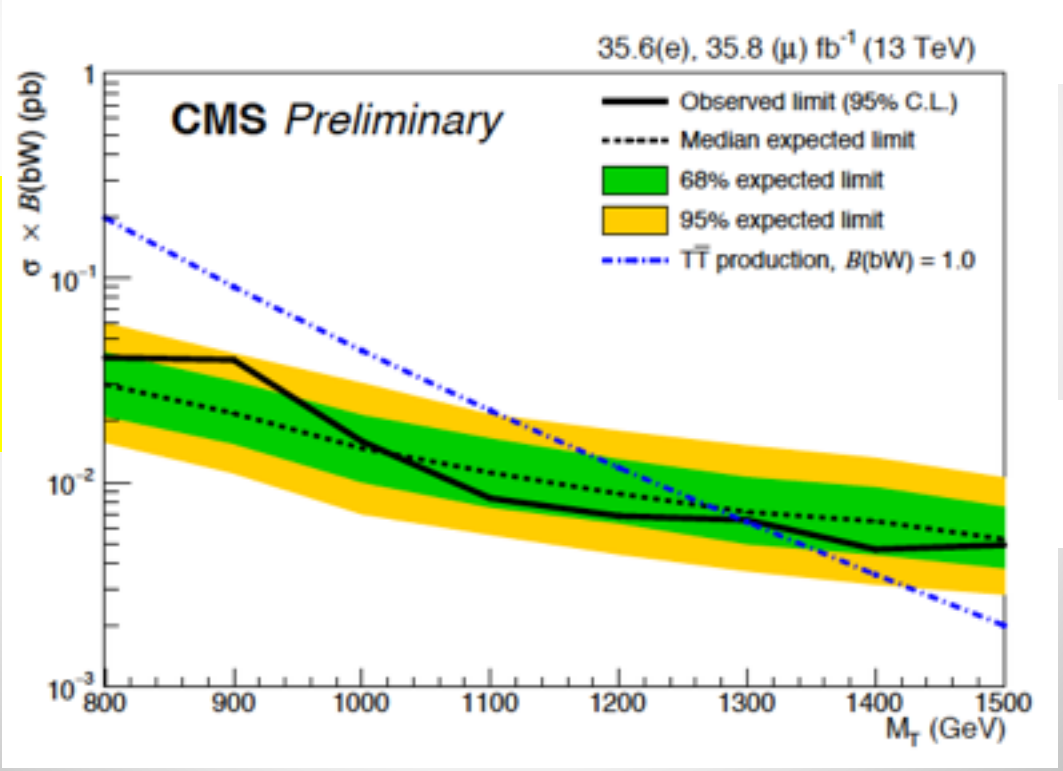


$$T\bar{T}(Y\bar{Y}) \rightarrow bW\bar{b}W \rightarrow b\ell\nu\bar{b}q\bar{q}'$$

Cancelling quadratic divergences to the Higgs mass… Hierarchy problem

Using kinematic reconstruction in lepton+jets final states

B2G-17-003



Vector-like quarks
Relevant eg in composite Higgs models

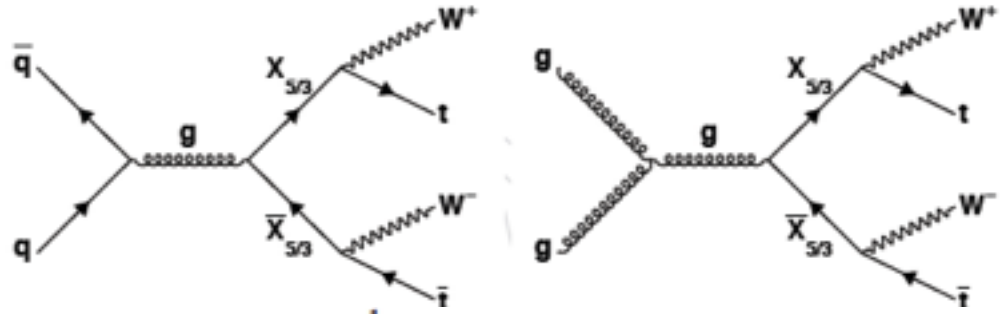
T charge 2/3
Y charge -4/3

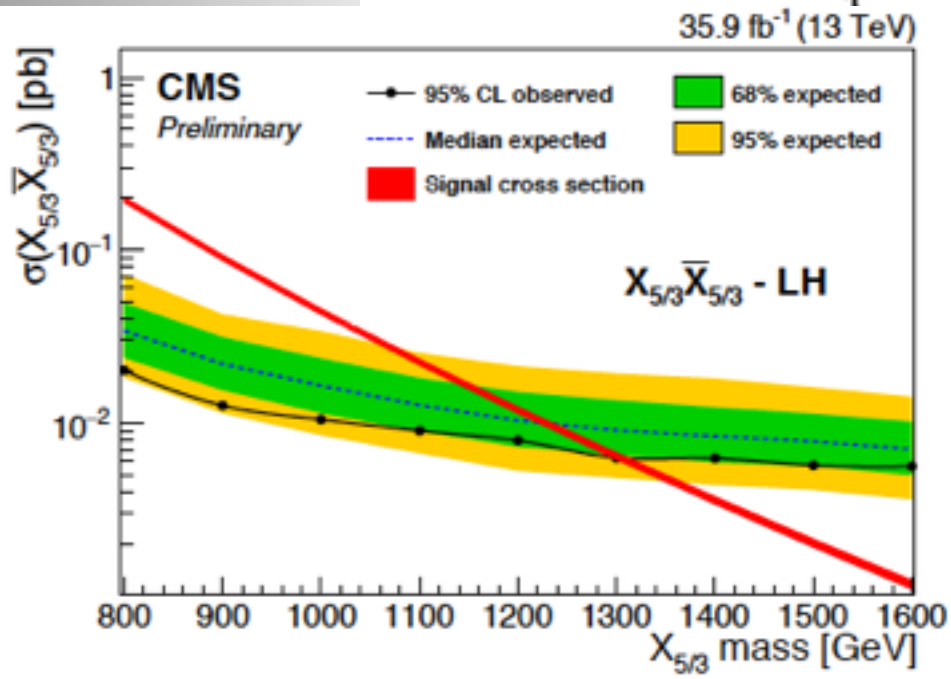
Mass limits of 1295 (1275) GeV excluded at 95% for T (Y)

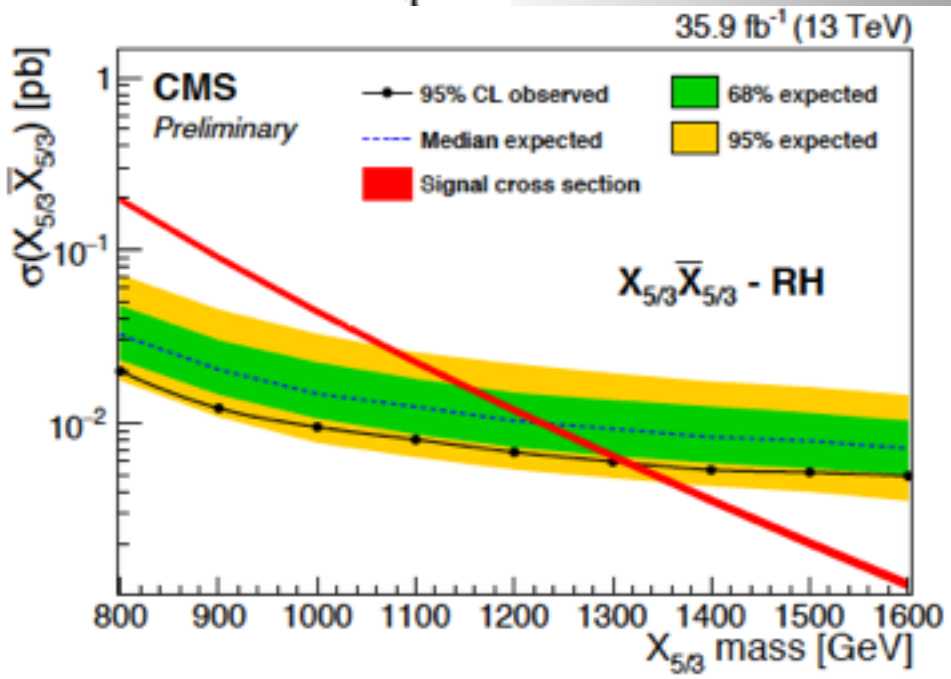
Search for Top Quark Partners

B2G-17-008

Top quark partners with charge 5/3

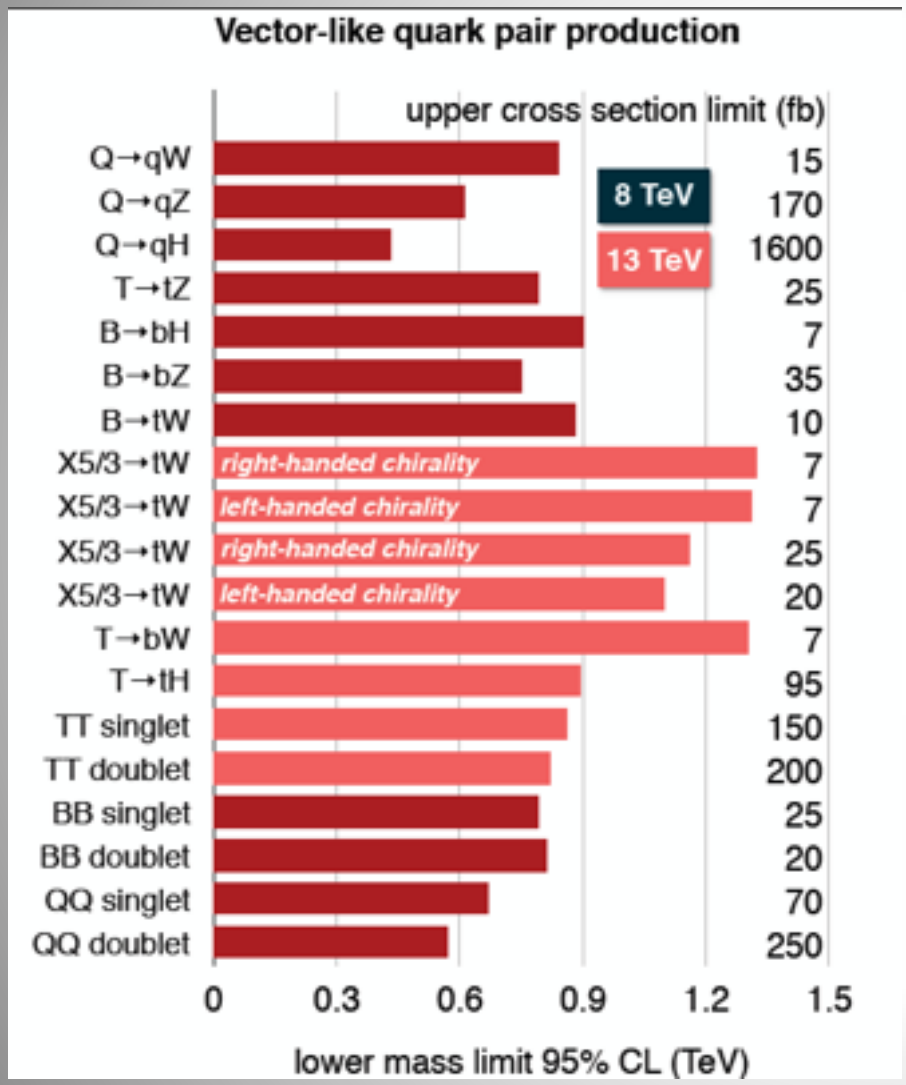


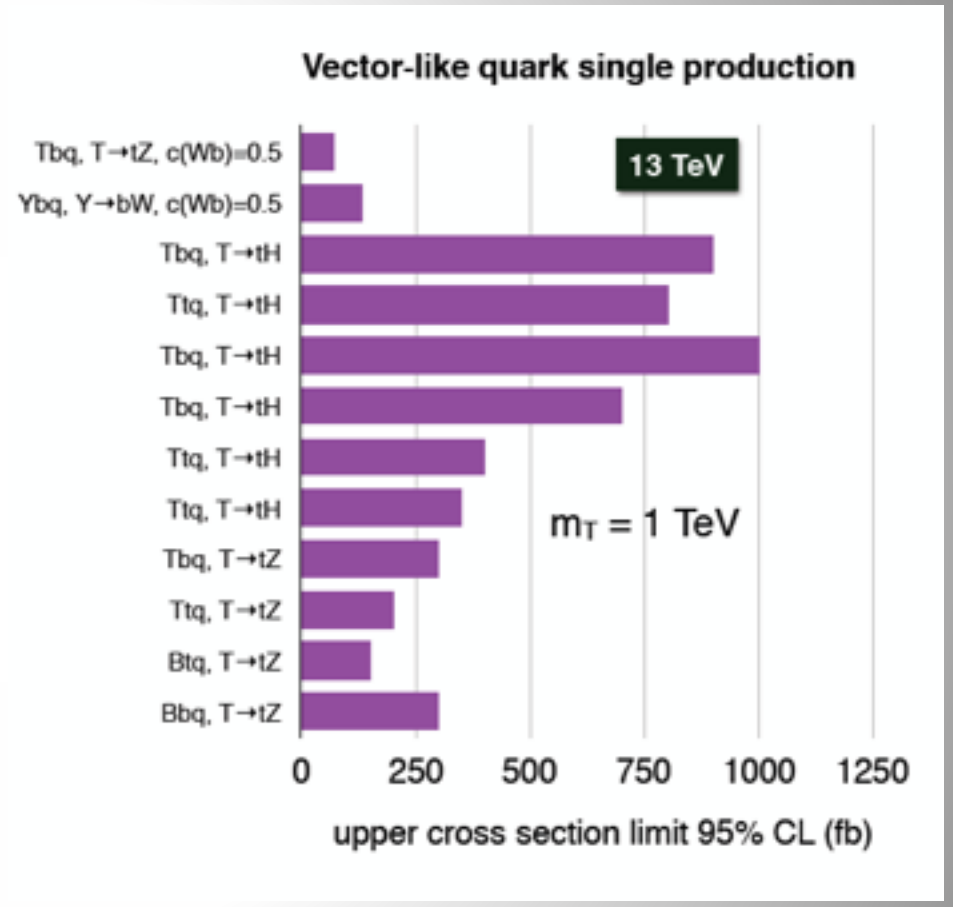




Mass Limits of 1.30 (1.32) TeV excluded at 95% for left (right)-handed couplings

Vector-like Quark Production Overview



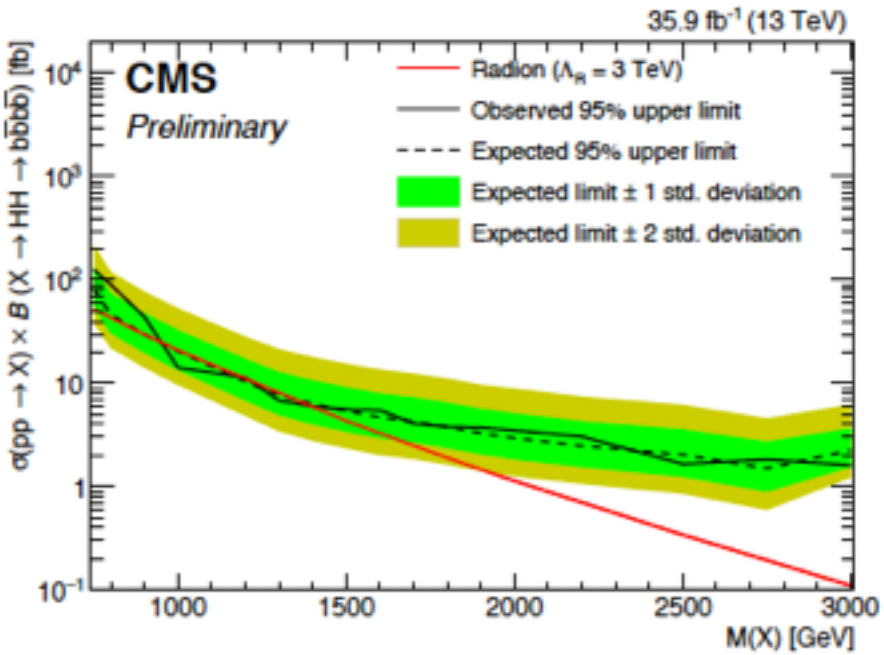


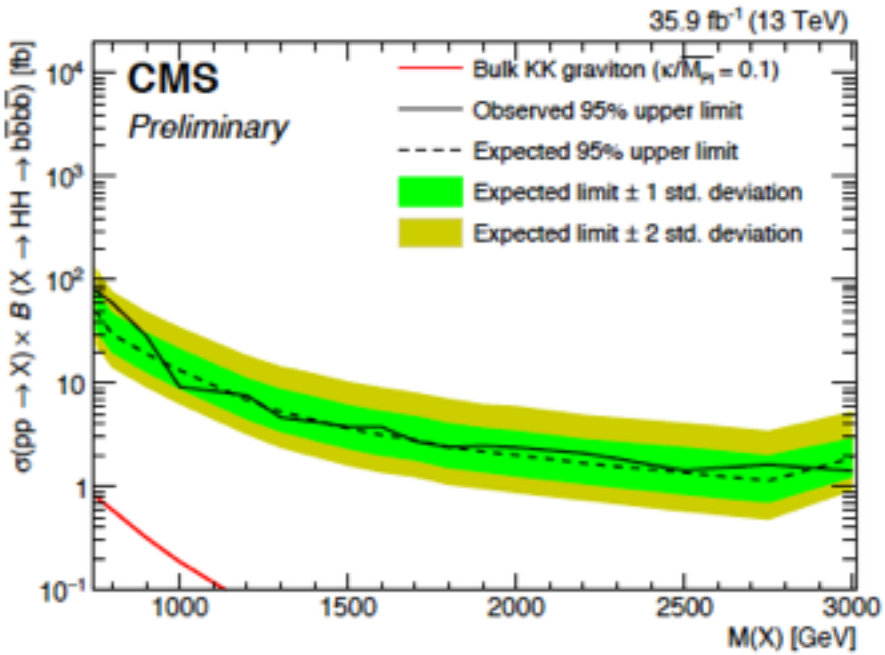
Updated summary plots on mass and cross section limits

Search for X->HH -> 4b

B2G-16-026

- Higgs produced with p_T> 1 TeV: boosted regime
- Search for double b-tagged "fat" dijets resonance



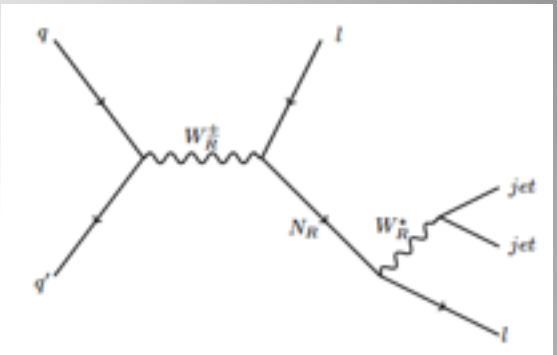


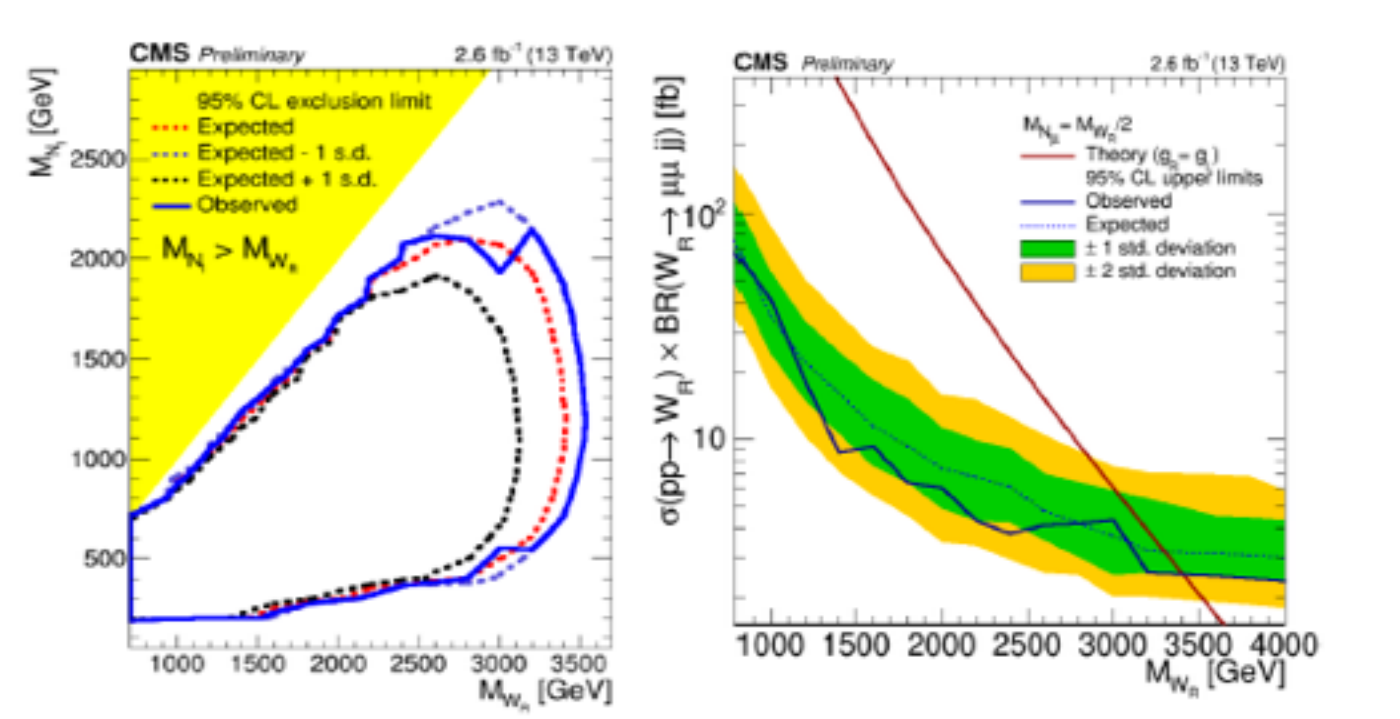
Limits on bulk gravitons and radions (RS model)
Eg for a mass scale Λ_R of 3 TeV, exclude radions 970-1450 at 95% CL

Right Handed Heavy Neutrinos and W Bosons

EXO-16-045

Search in 2 jets and 2 lepton final states



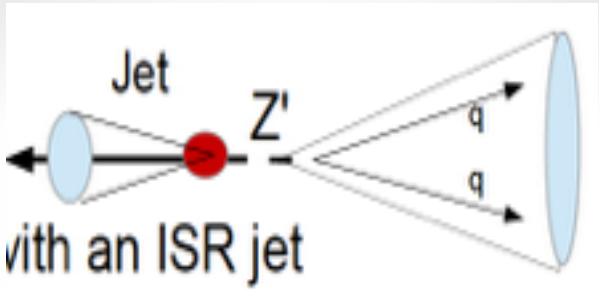


Similar for the electron final state channel

Limits on M_{WR} extend to 3.5 (3.3) TeV in the muon (electron channel)

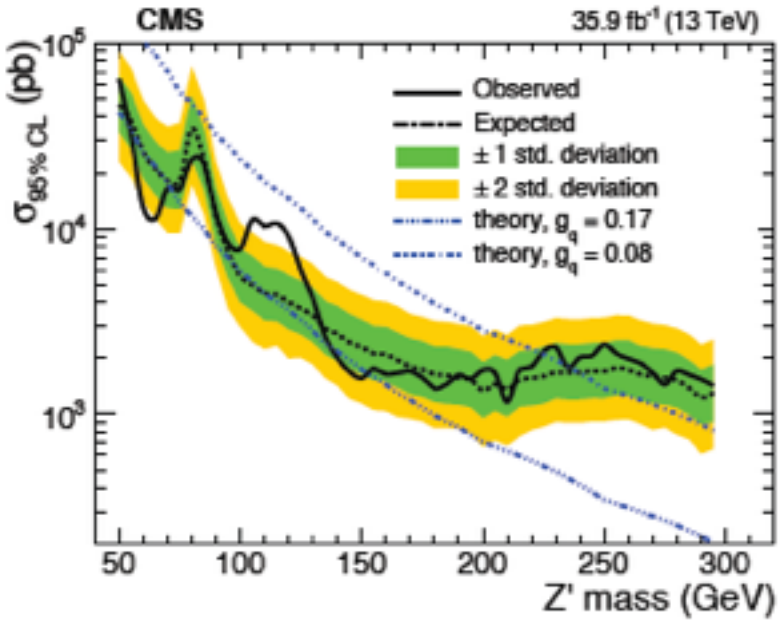
Search for Light Vector Resonances

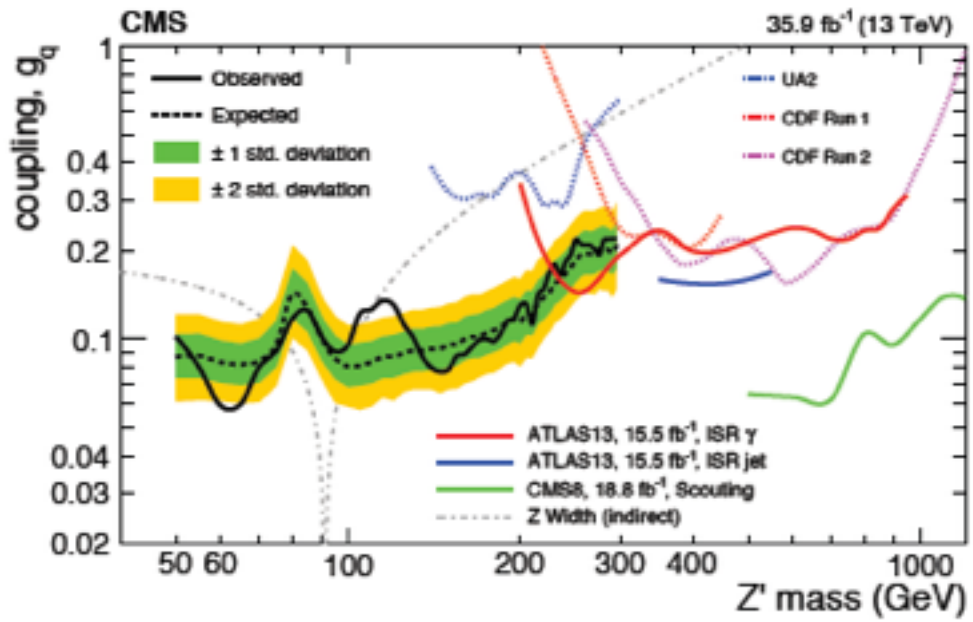
Bump hunting in dijets produced with an ISR jet or high p_T jet to give the trigger



EXO-17-001

- Jet with p_T>360 GeV
- H_T > 800/900 GeV

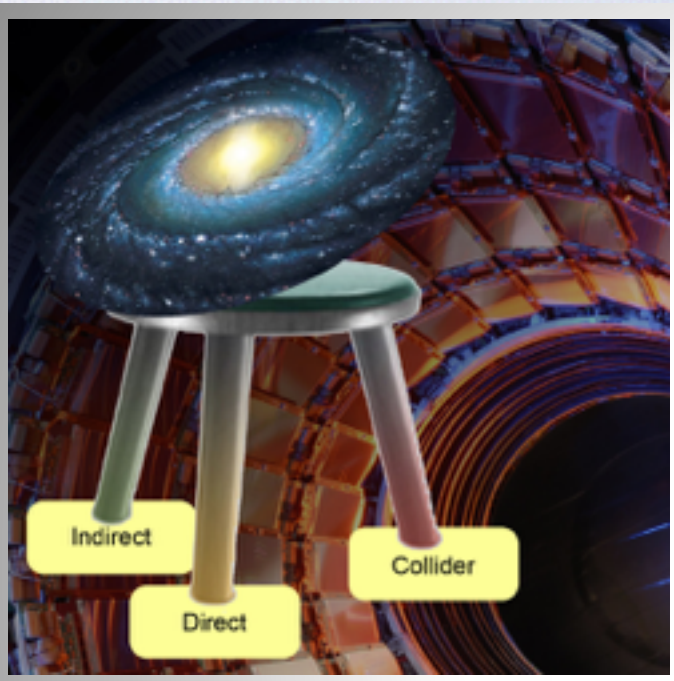


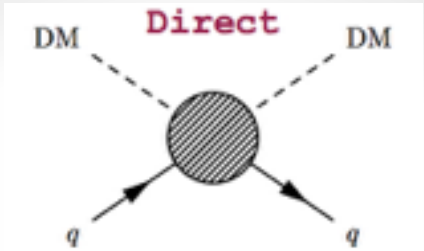


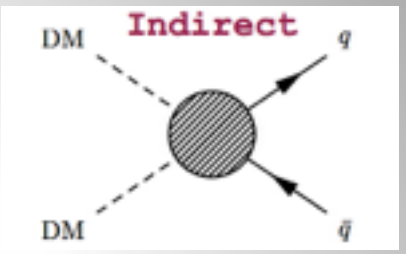
Sensitivity 'beats' the old UA2 result, going now below 140 GeV

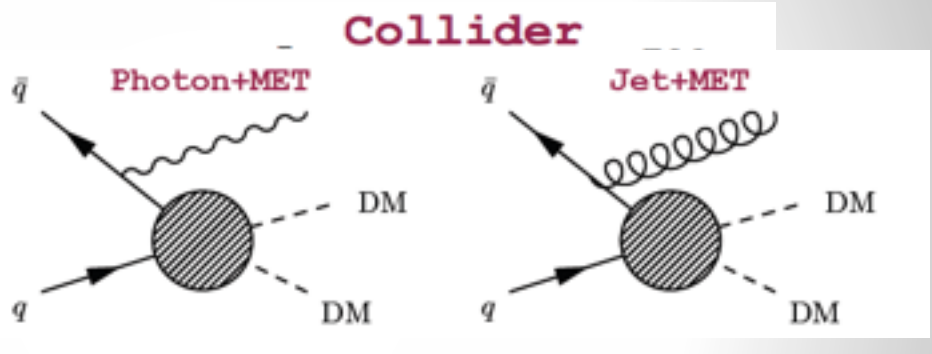
Mild excess around 115 GeV observed: 2.9σ (2.2σ) global (local) significance

The Generic Dark Matter Connection









Use effective theory or better simplified models to relate measurements to Dark Matter studies

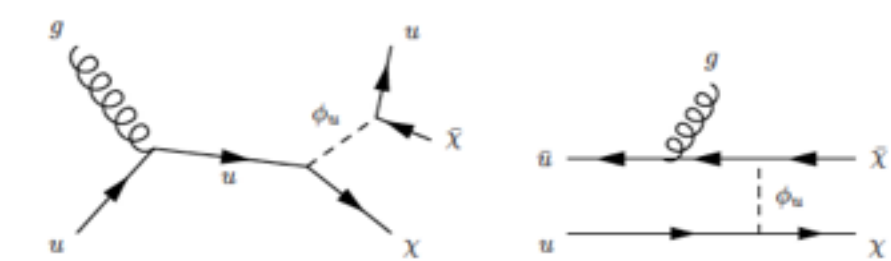
arXiv:1407.8257
arXiv:1411.0535

- Mono-jets: Generally very powerful
- Mono-photons: First used for dark matter searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs-portals

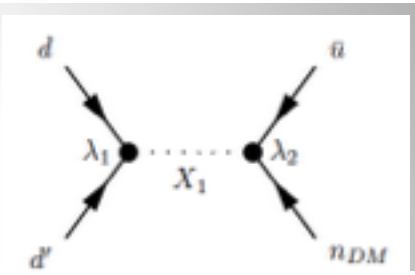
‘Mono-jets’ for ED and Dark Matter Searches

EXO-16-048

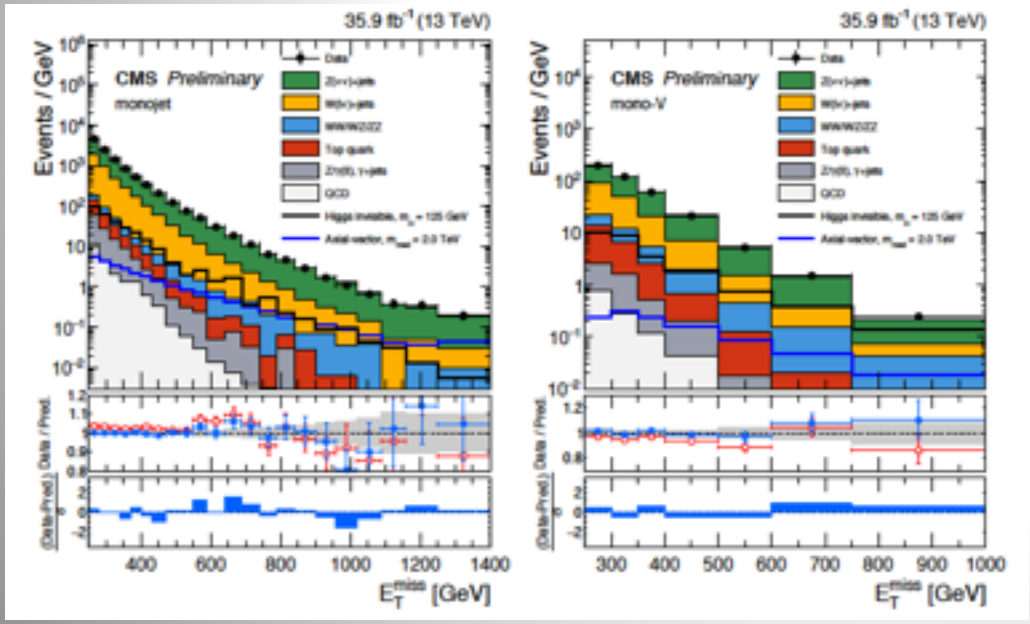
Search for new physics in final states with an energetic jet or boosted hadronically decaying vector bosons

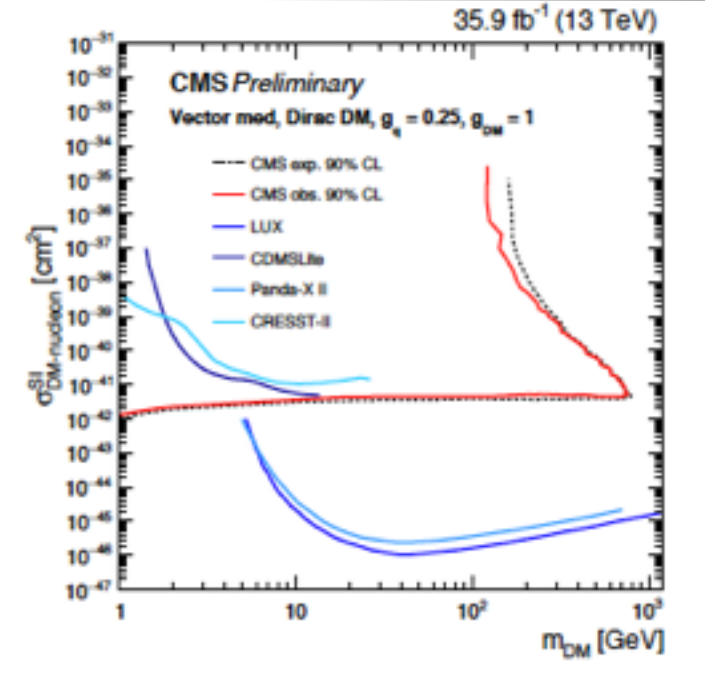


Dark matter in Fermion portal model



Dark matter in non-thermal model





More DM limits given in the summary plots

Search for Large Extra Dimensions

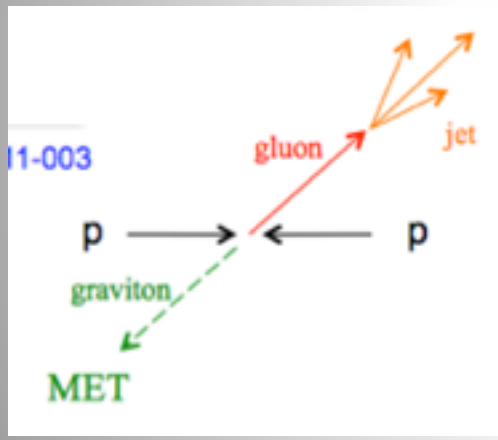
Mono-jet final state +Missing E_T (ADD)

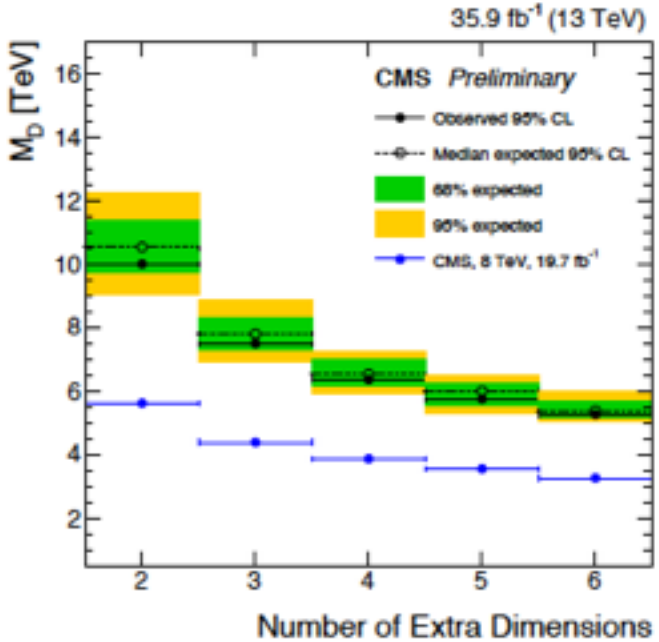
EXO-16-048

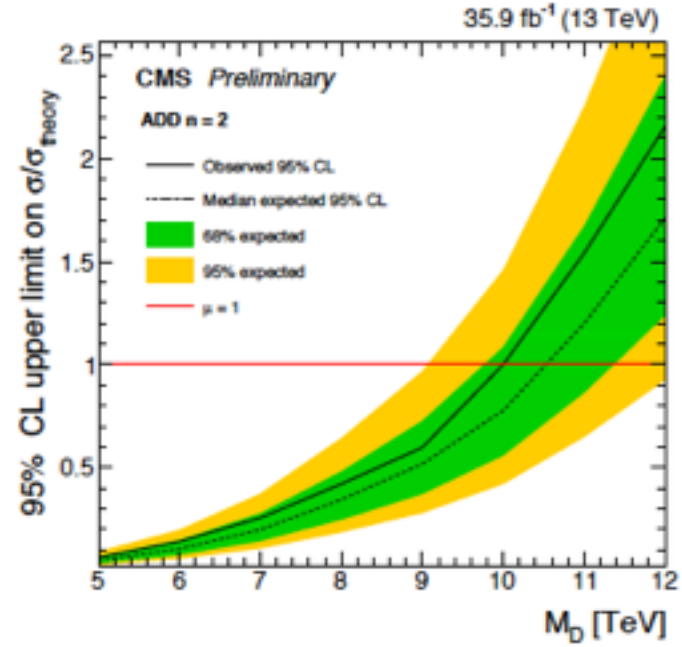
p_T jet > 100/250 GeV
MET > 250 GeV

Limits on M_D between 6 and 10 TeV

Lower limit on the Planck Scale versus number of extra dimensions





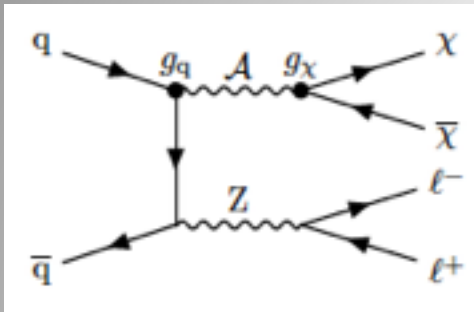


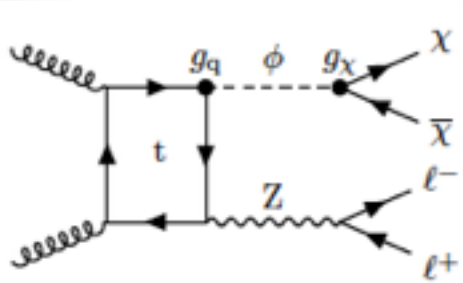
Monojets searches are typically the among the most sensitive ones

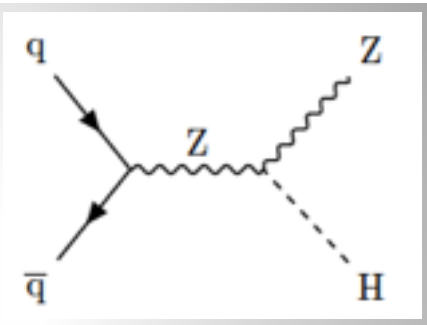
Search using Z + MET final states

EXO-16-052

Search for Dark Matter, Extra Dimensions, Invisible Higgs



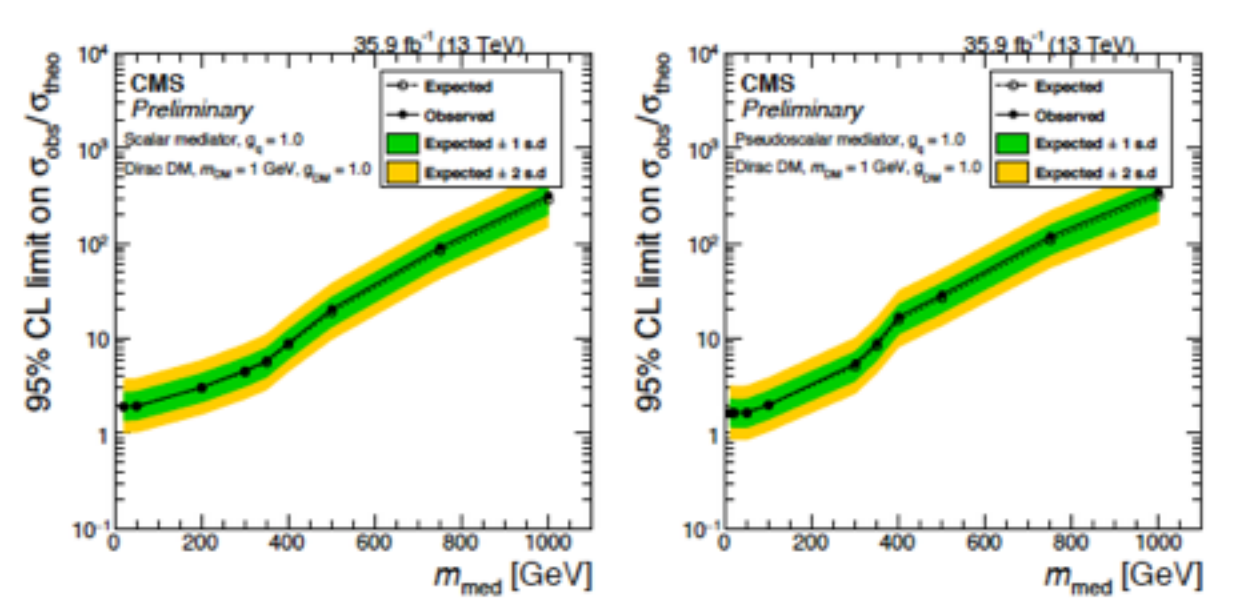


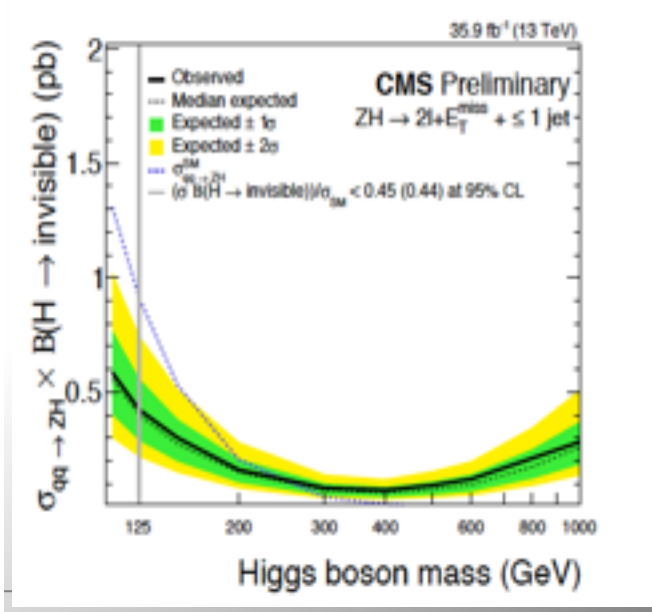


Dark Matter

Search: ETmiss > 100 GeV + Z boson

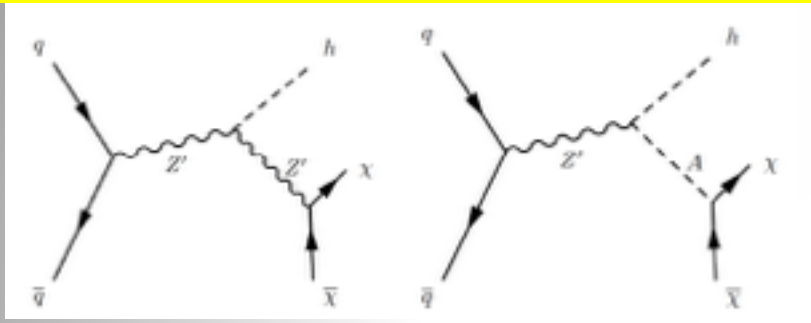
Invisible Higgs



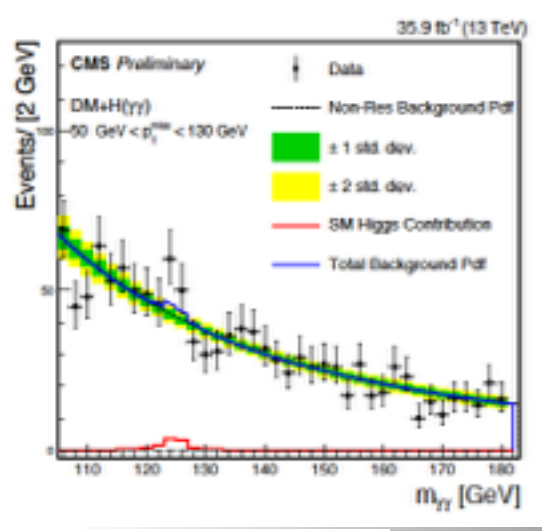


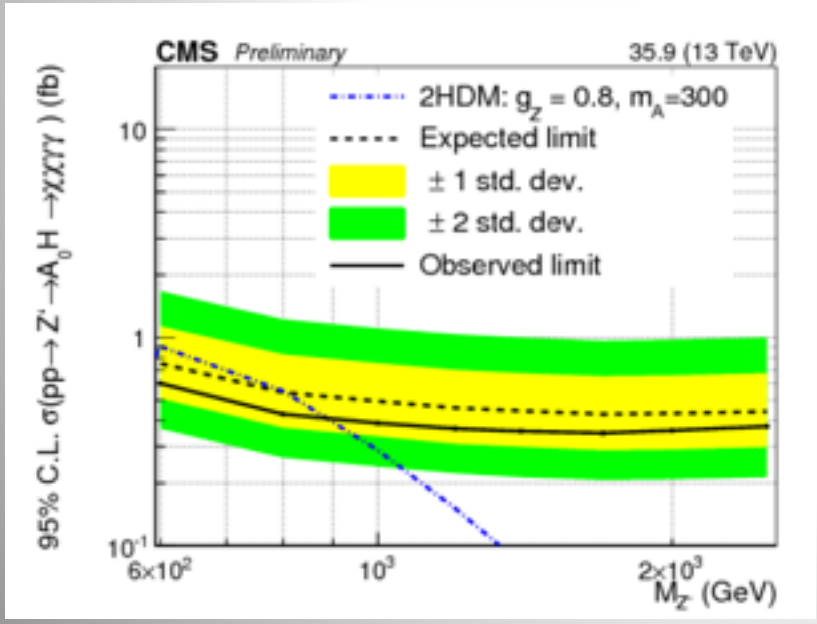
Search with MET + Higgs->γγ

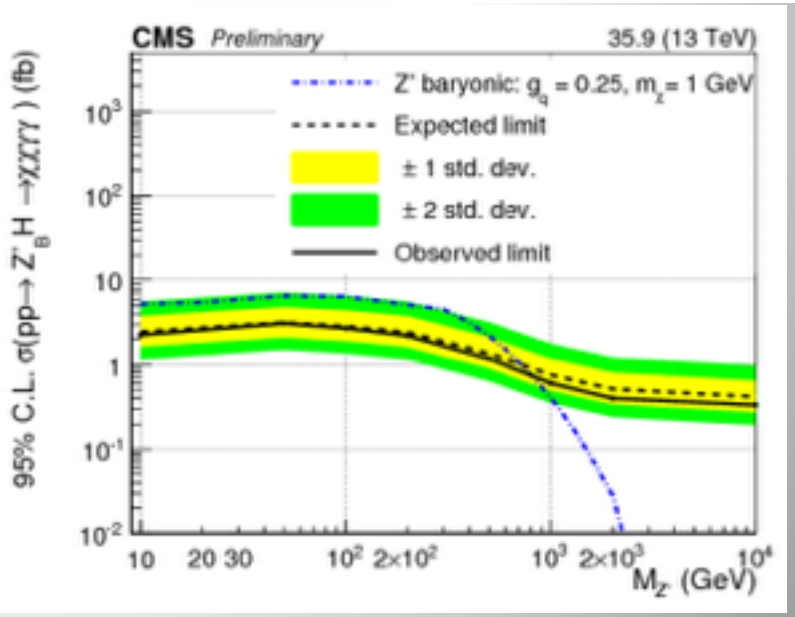
Search for dark matter produced in association with a Higgs boson decaying in two photons



EXO-16-054



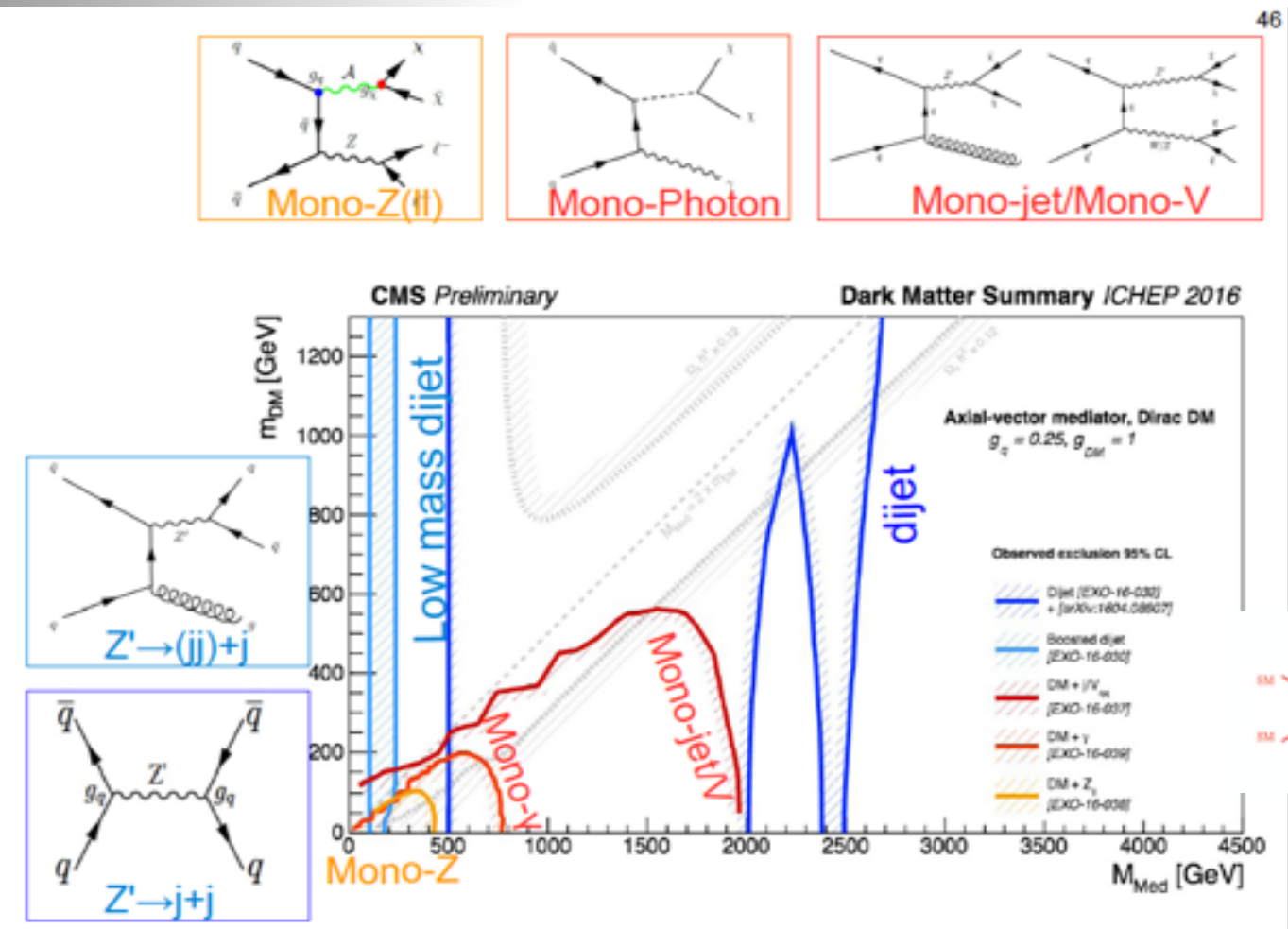




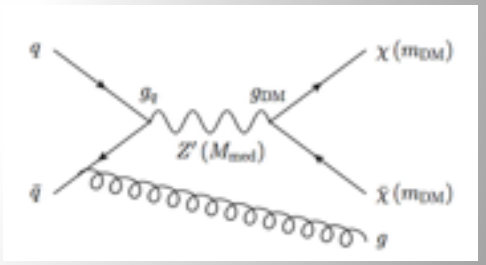
Limits on Two-Higgs Doublet Z' signals 900 GeV Baryonic Z' signals 800 GeV

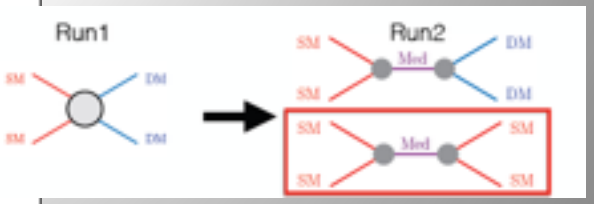
Dark Matter Searches: Evolution

- Dark Matter hunt is one of the new main physics goals for the LHC!
- New developments with Simplified Models, allow including many more search channels such as dijets (aka "In Search for the Mediator")



A promise for future studies

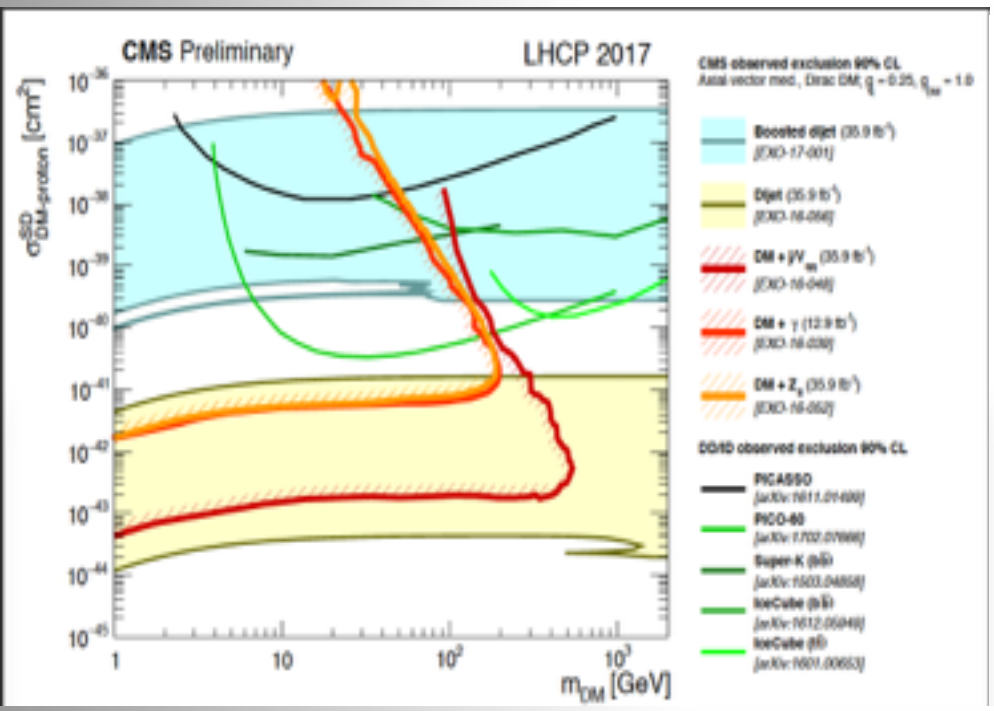


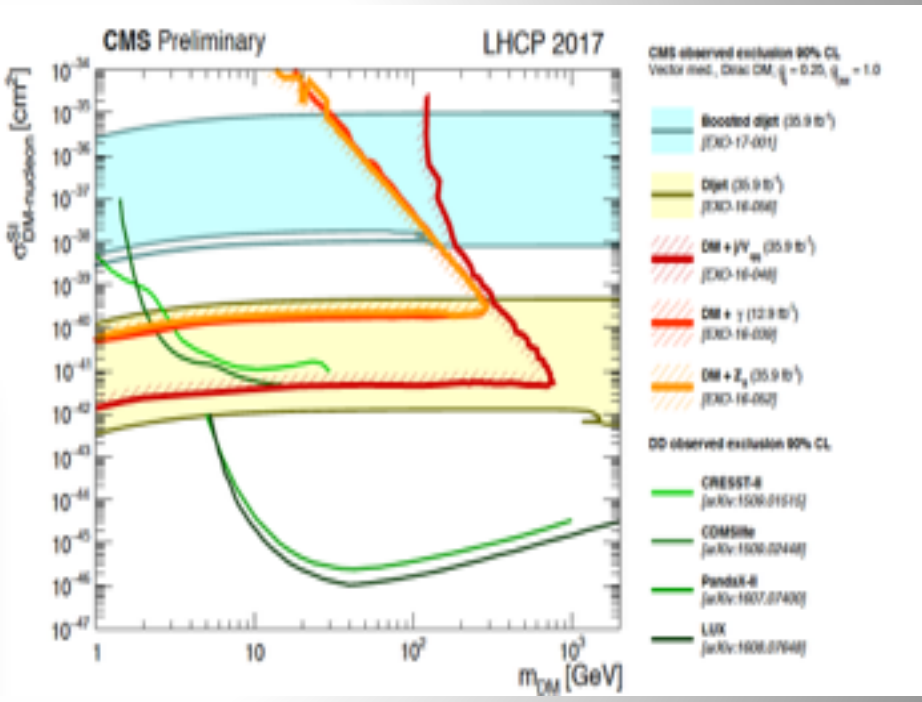


Comparison with Direct Detection

Axial-vector mediator and
Spin dependent direct limits

Vector mediator and
Spin independent direct limits



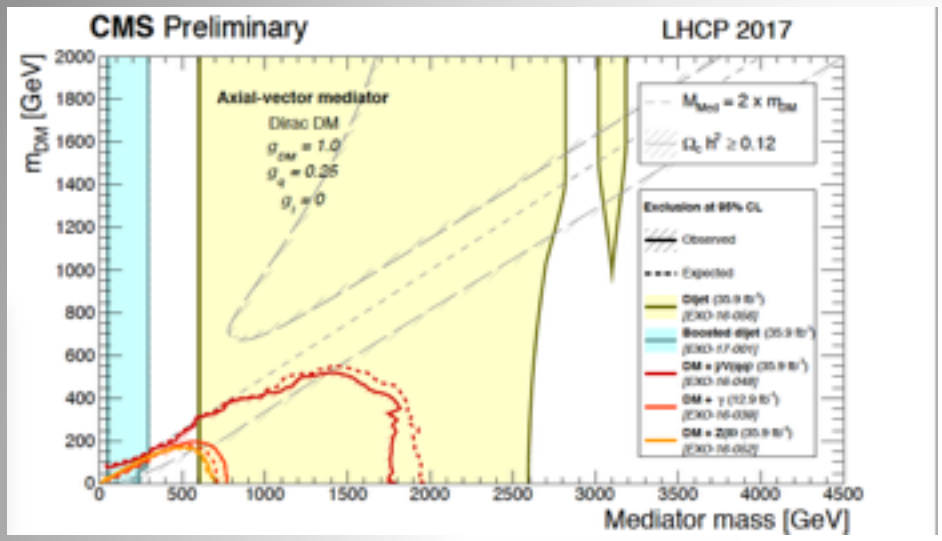


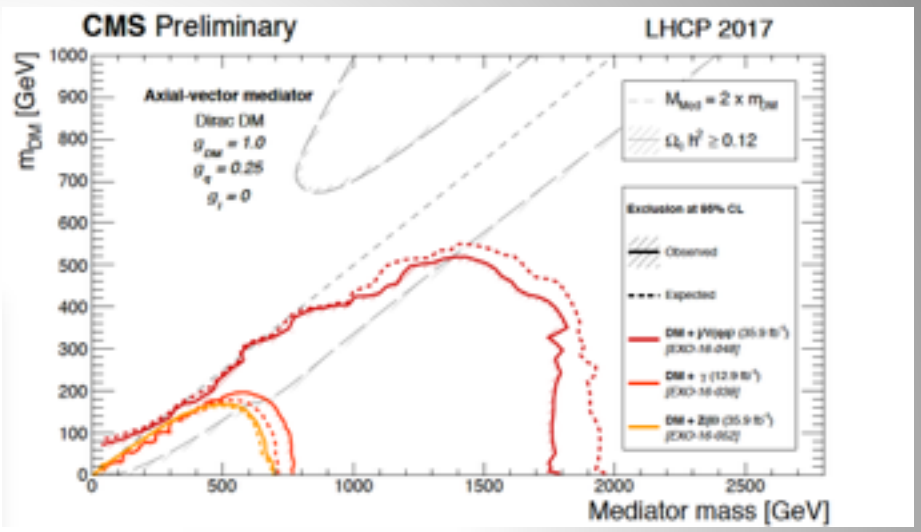
90% CL limits

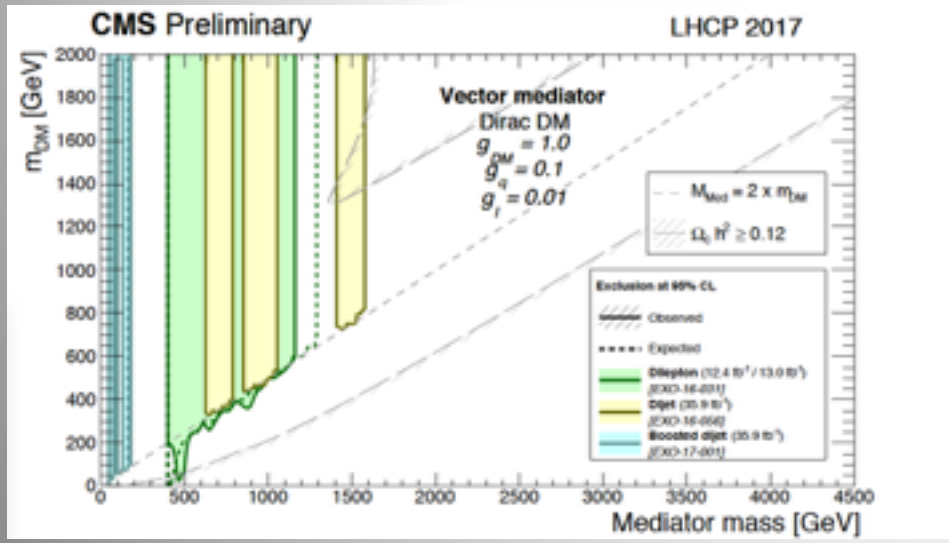
LHCP 2017

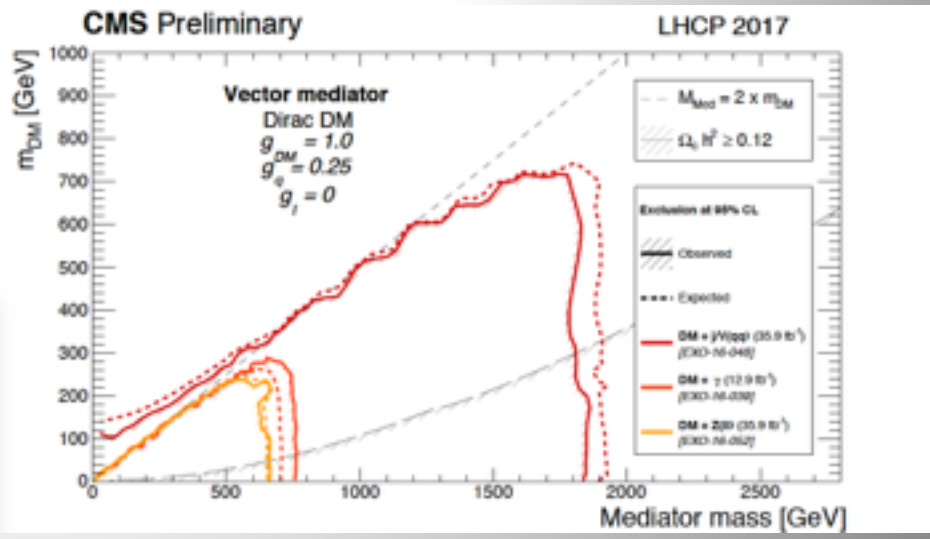
More reliable comparisons with direct detection results now possible via the SMS method

Dark Matter Search Summary Plots









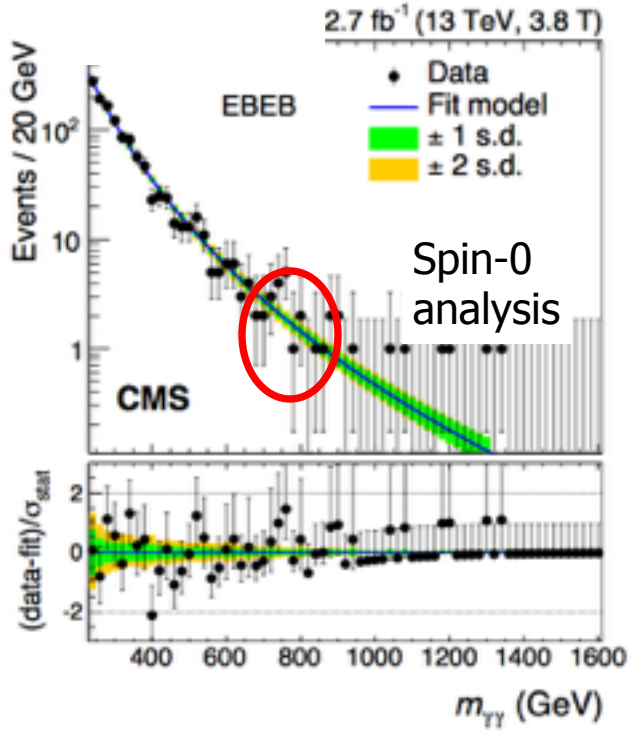
LHCP 2017

December2015: X → γγ 750 GeV?

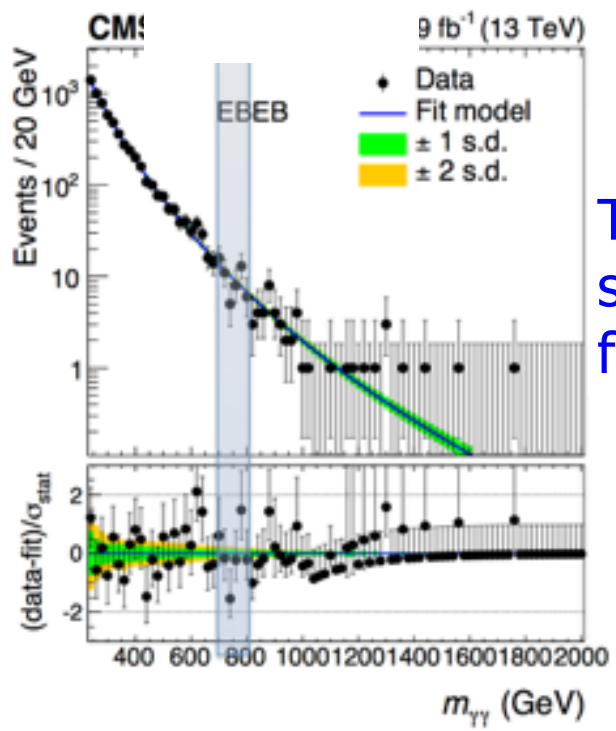
Excitement in December 2015: CMS & ATLAS
->Some excitement on an mild observed excess in both experiments for a diphoton mass of around 750 GeV
-> about 500 papers explaining a new particle ☺

A totally unexpected new particle???

EXO-15-004



EXO-16-027



August 2016:
The excess is NOT seen in the new data from 2016!

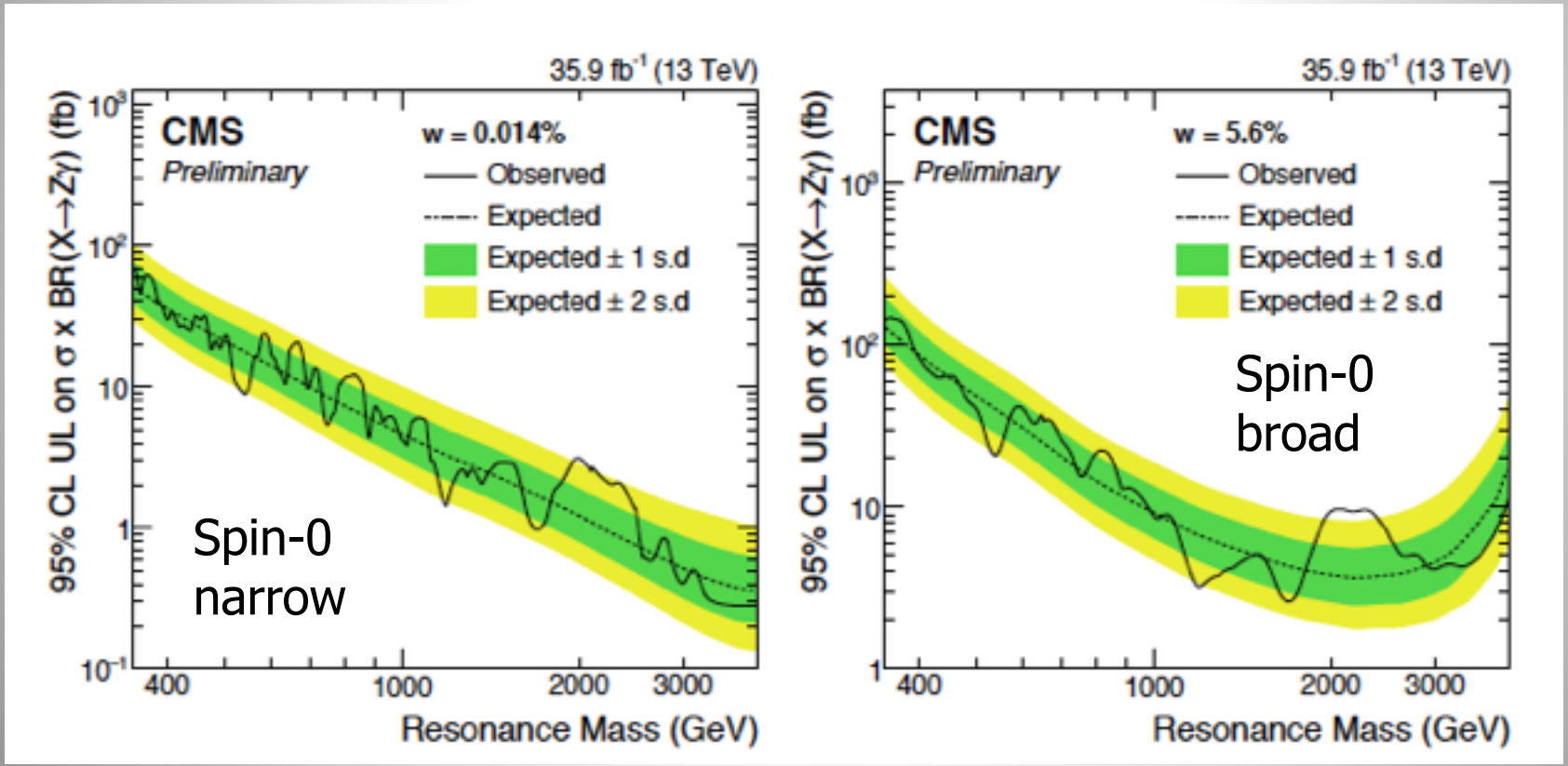
So, not for this time, but a sign of new physics can be found any time now
We need only one significant deviation of the Standard Model to show the way!

Search for high mass Zγ Resonances

EXO-17-005

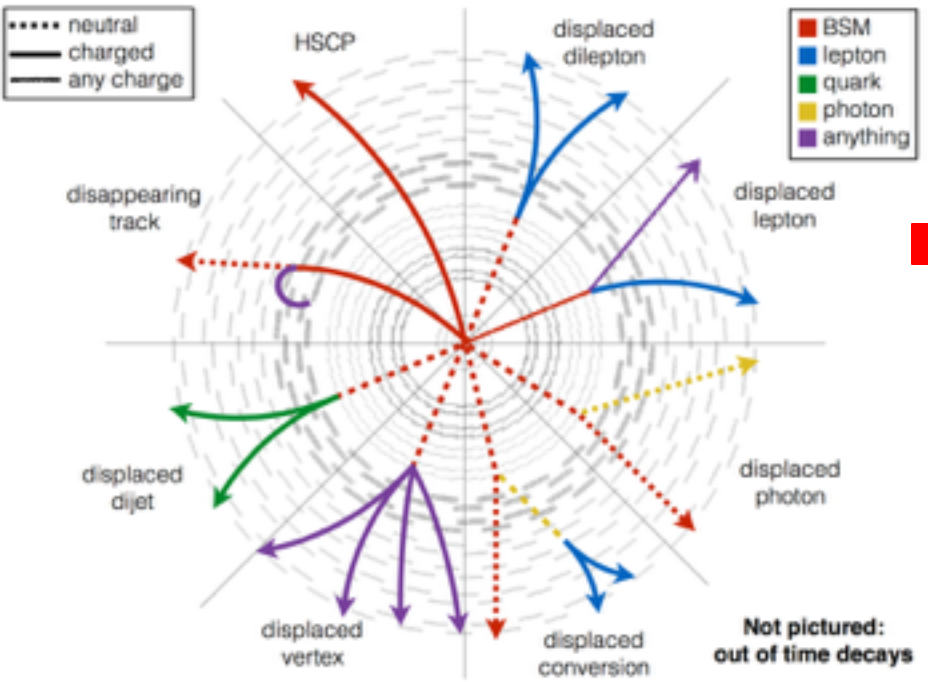
In the wake of the (mild) 750 GeV diphoton excess in 2015…
-> A search in the Zγ channel

Combining leptonics and hadronic Z decay channels



No sign of a new resonance – especially not at 750 GeV ☺

Searches for Long Lived Particles

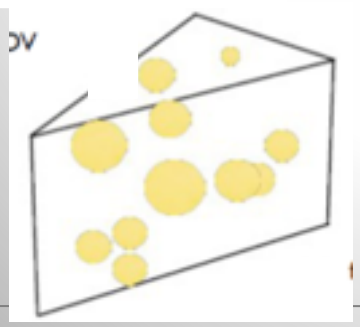


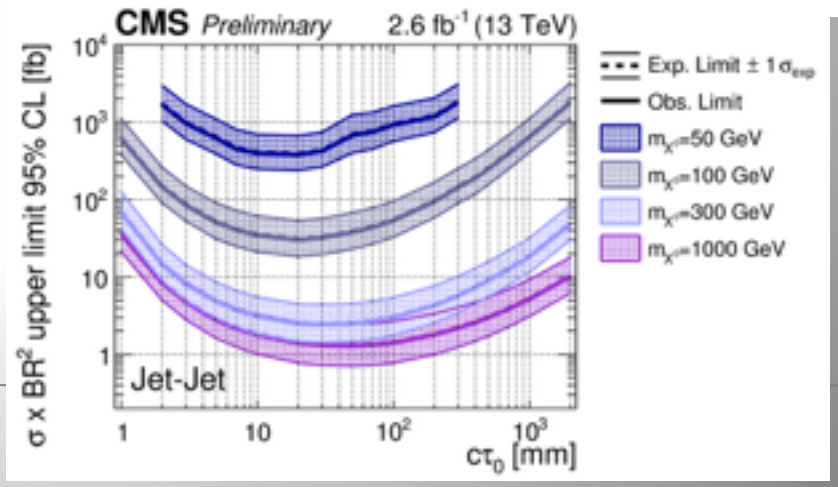
Increasing interest and effort:
Look for unusual signals in the detector from long-lived particles

- Example displaced Jets: search for pair-produced long-lived decays to four jet final states.

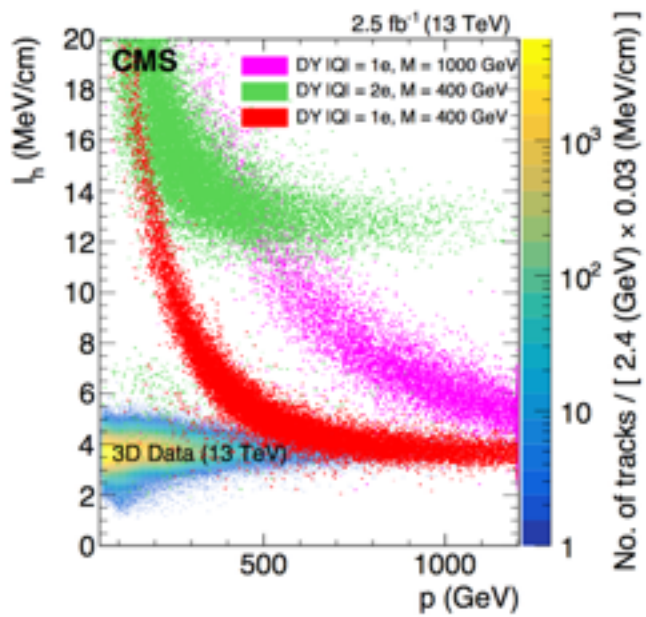
EXO-16-056

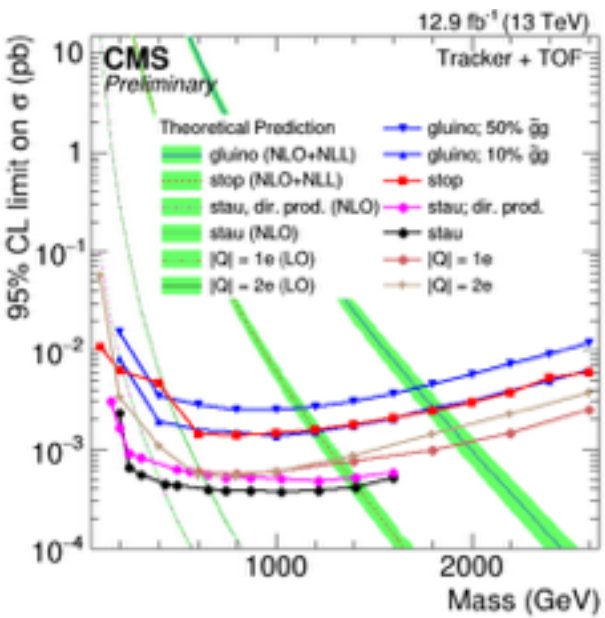
Present coverage?





Heavy Stable Ionizing Particles





Detection techniques used for (multiple/fractional) heavy stable charge particles

- Abnormal energy loss (de/dx)
- Slower than speed of light (lowβ) via time of flight measurements with the muon system

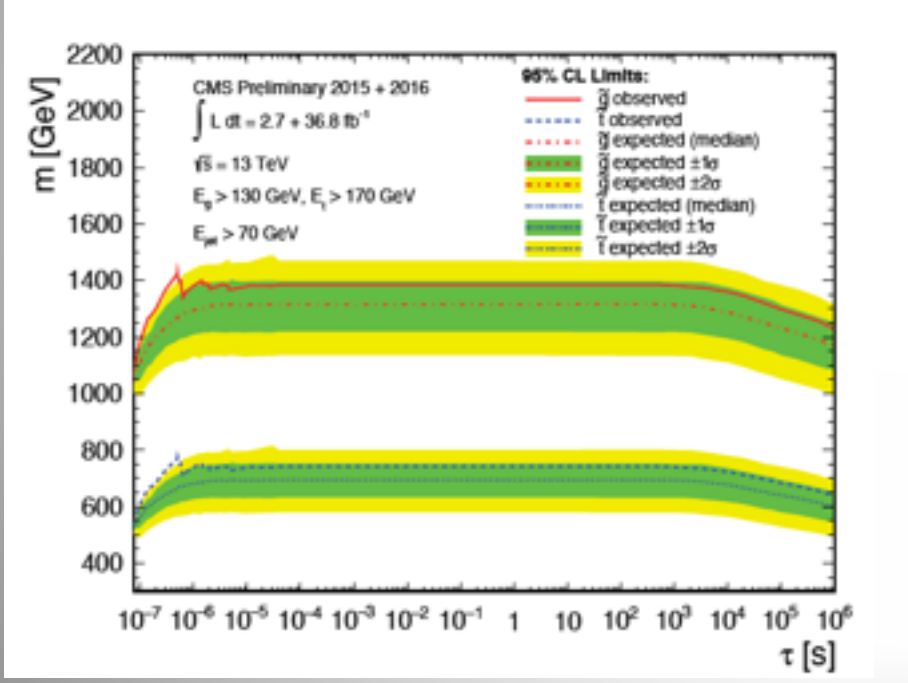
Time of flight $\frac{1}{\beta} = 1 + \frac{c\delta_t}{L}$ EXO-16-036

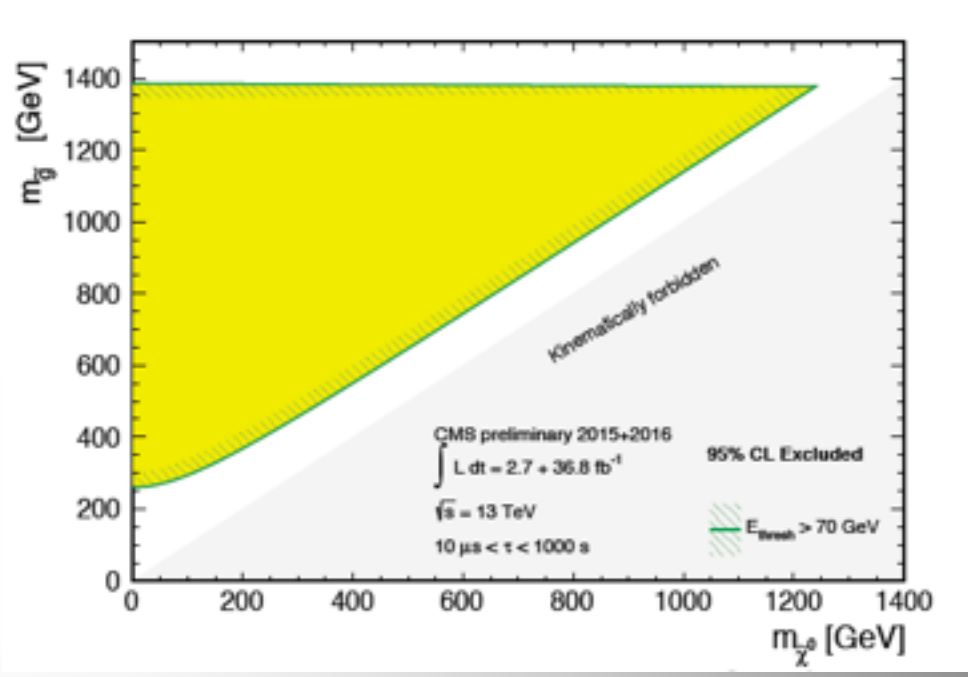
Model	Analysis	Mass Limits
Gluino $f = 0.1$	tracker-only tracker+TOF	$M > 1850(1850)$ GeV $M > 1810(1810)$ GeV
Gluino $f = 0.1$ CS	tracker-only	$M > 1840(1840)$ GeV
Gluino $f = 0.5$	tracker-only tracker+TOF	$M > 1760(1760)$ GeV $M > 1720(1720)$ GeV
Gluino $f = 0.5$ CS	tracker-only	$M > 1800(1800)$ GeV
Stop	tracker-only tracker+TOF	$M > 1250(1250)$ GeV $M > 1200(1200)$ GeV
Stop CS	tracker-only	$M > 1220(1220)$ GeV
GMSB Stau	tracker-only tracker+TOF	$M > 660(660)$ GeV $M > 660(660)$ GeV
Pair Prod. Stau	tracker-only tracker+TOF	$M > 170(170)$ GeV $M > 360(360)$ GeV
DY $Q = 1e$	tracker-only tracker+TOF	$M > 720(720)$ GeV $M > 730(730)$ GeV
DY $Q = 2e$	tracker-only tracker+TOF	$M > 670(750)$ GeV $M > 890(890)$ GeV

Search for Stopped Long Lived Particles

EXO-16-004

- Search for long lived particles that stop in the detector and decay into jets after some time, non-coincident with pp collisions
- 586 hours trigger lifetime in 2016 included in this search.
- Searches for long lived gluinos and stops (R-hadrons)
- 13 events observed in 2016 -> consistent with background



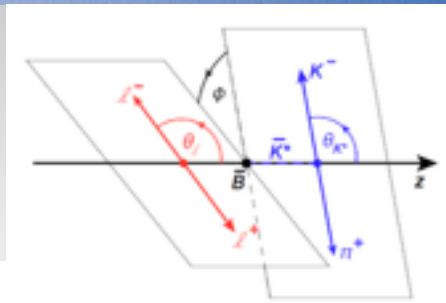


Limits on M_{stop} < 744 GeV and M_{gluino} <1385 GeV 95% CL for lifetimes from 10 μsec to 1000s

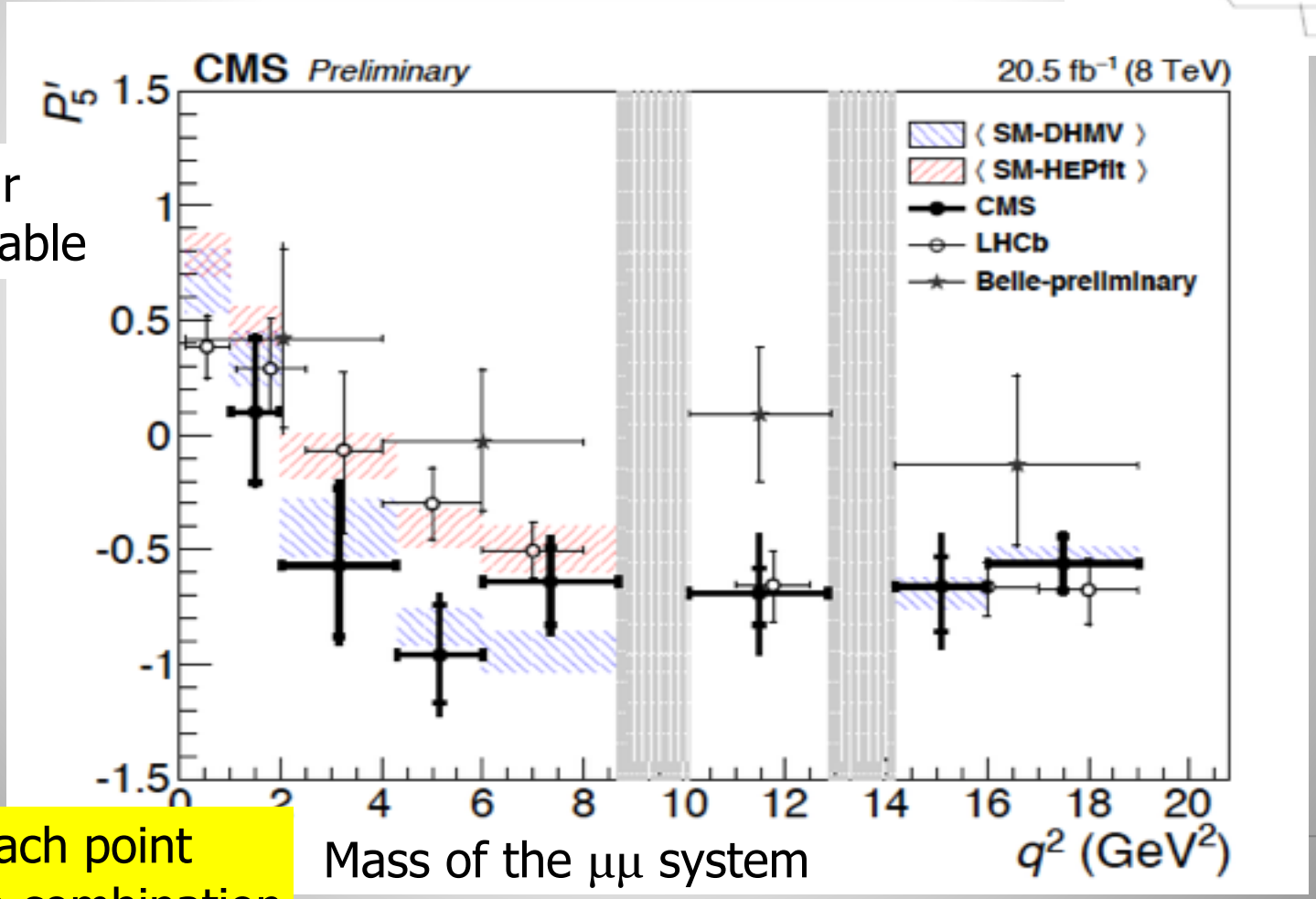
New Physics in Rare Decays?

Analysis of the B0→K*μ+μ- decay (LHCb)

LHCB: arXiv:1512.04442 CMS: BPH-15-008



Angular observable

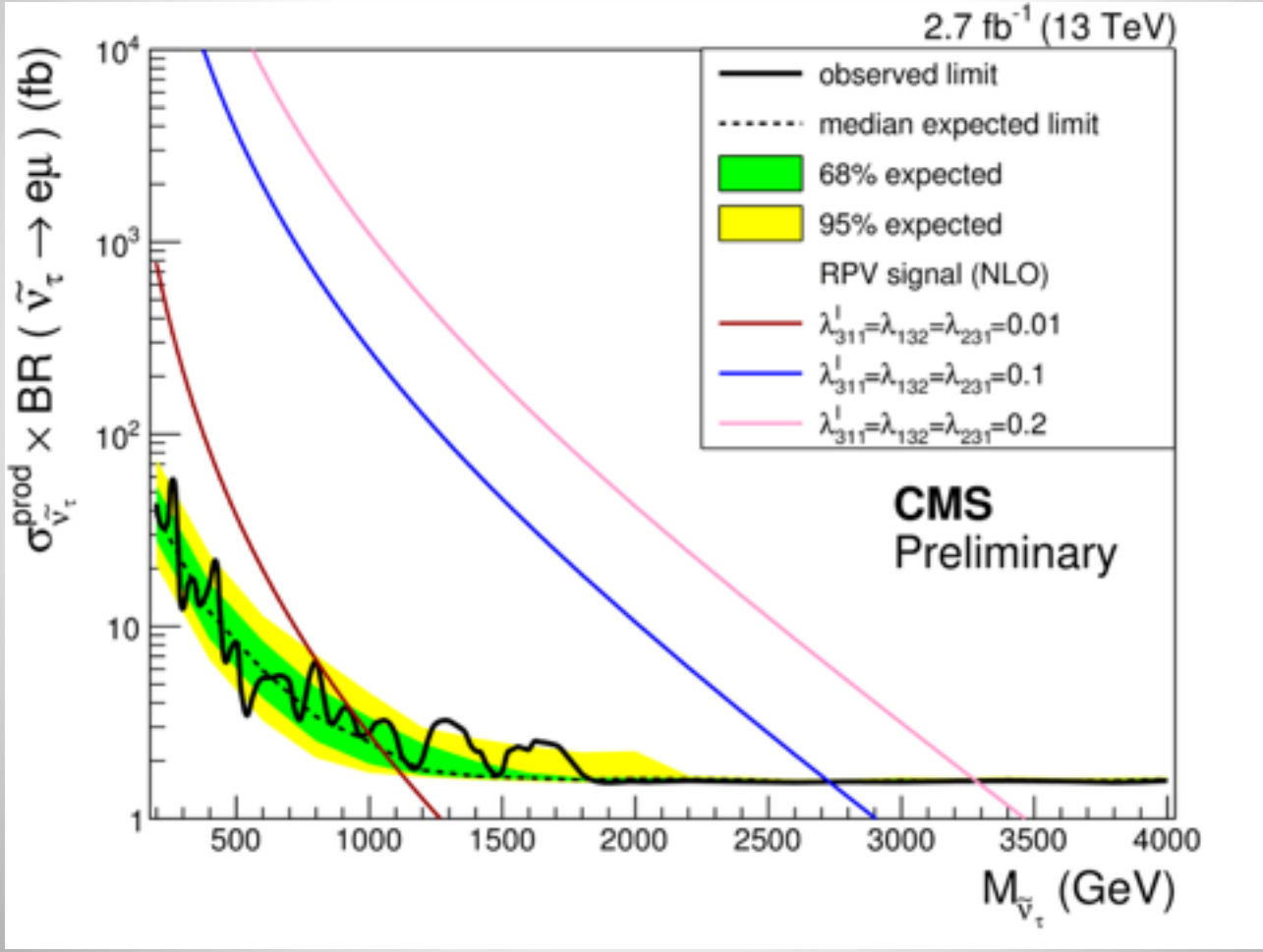


Mass of the μμ system

2.9σ for each point
3.7σ naive combination

Search for LFV Violating Decaying Resonances

- Search for high mass X-> eμ resonances
- No signal observed. Result interpreted in RPV SUSY



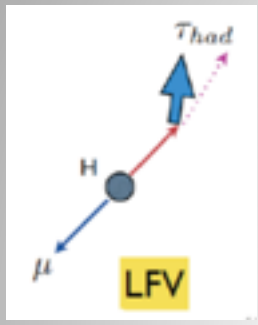
HIG-16-001

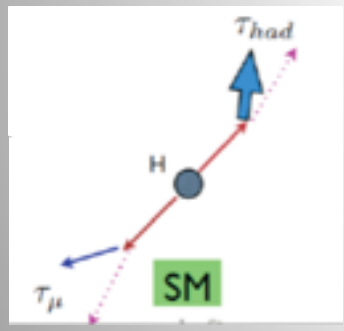
Limits range from 1.1 to 3.3 TeV, depending on mode parametersl

Search for LFV Decays: H →μτ

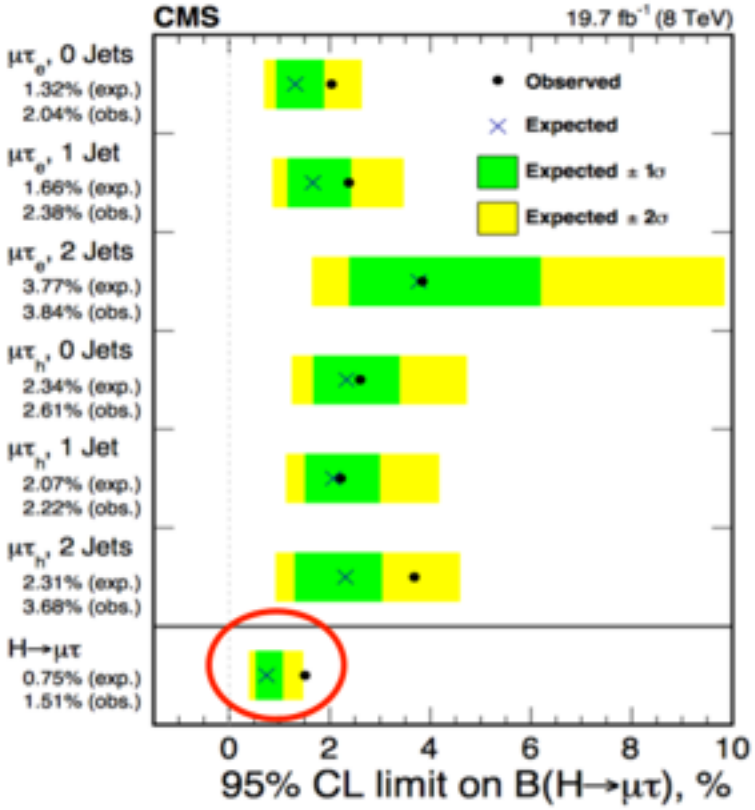
arXiv:1502.07400

Recall: Results from the 8 TeV





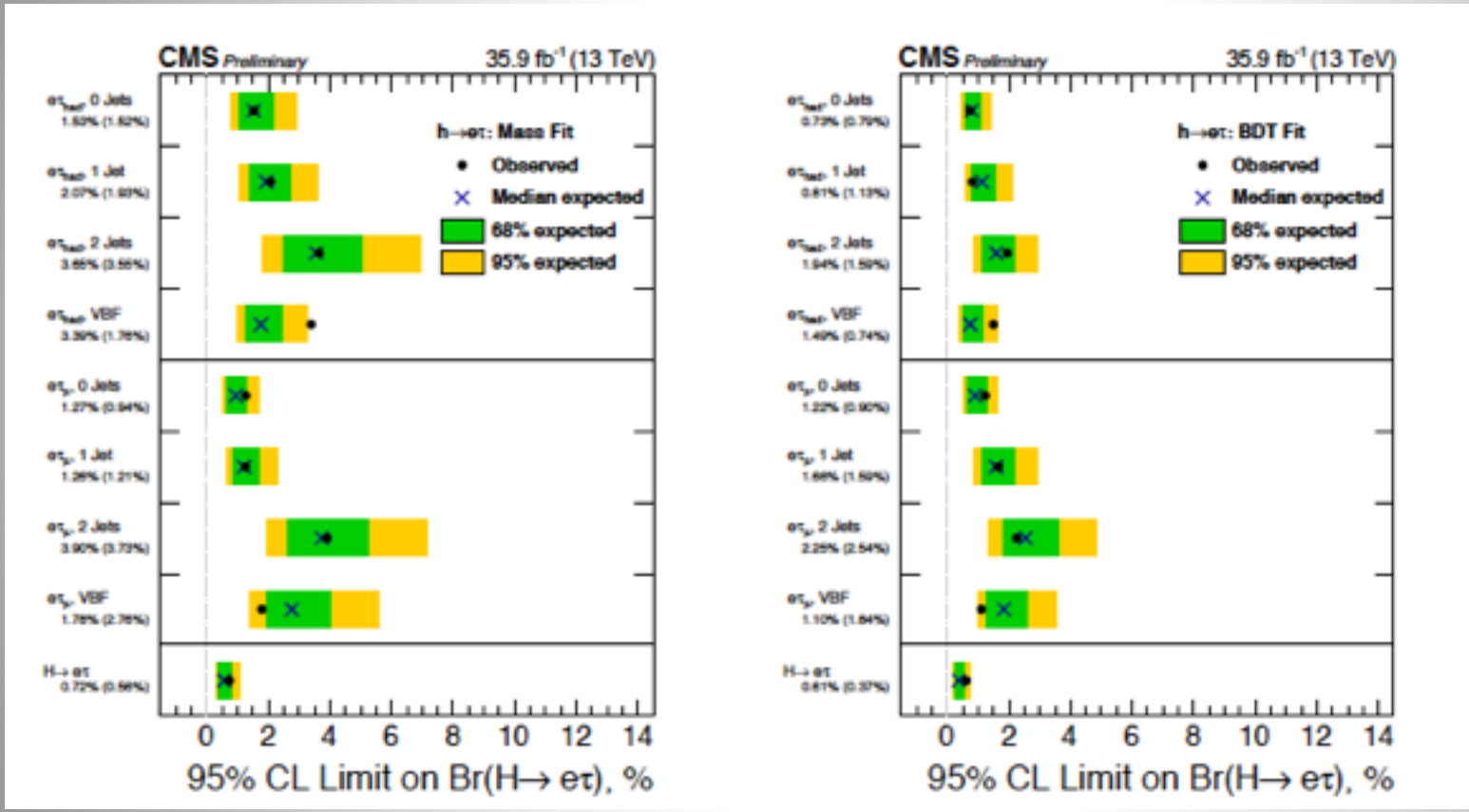
- Comparable sensitivity from all channels
- $\mathcal{B}(\mathrm{H} \to \mu\tau) < 1.51\%$ at 95%
- **Large improvement of previous limits**
- Background-only p-value of 0.010 (2.4 σ)
  - Best fit $\mathcal{B}(\mathrm{H} \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$.



Mild excess giving a 2.4σ effect in Run-1… What about 2016 data?

Search for LFV Decays: H →μτ, eτ

Breaking News: The 2016 data does NOT show an excess



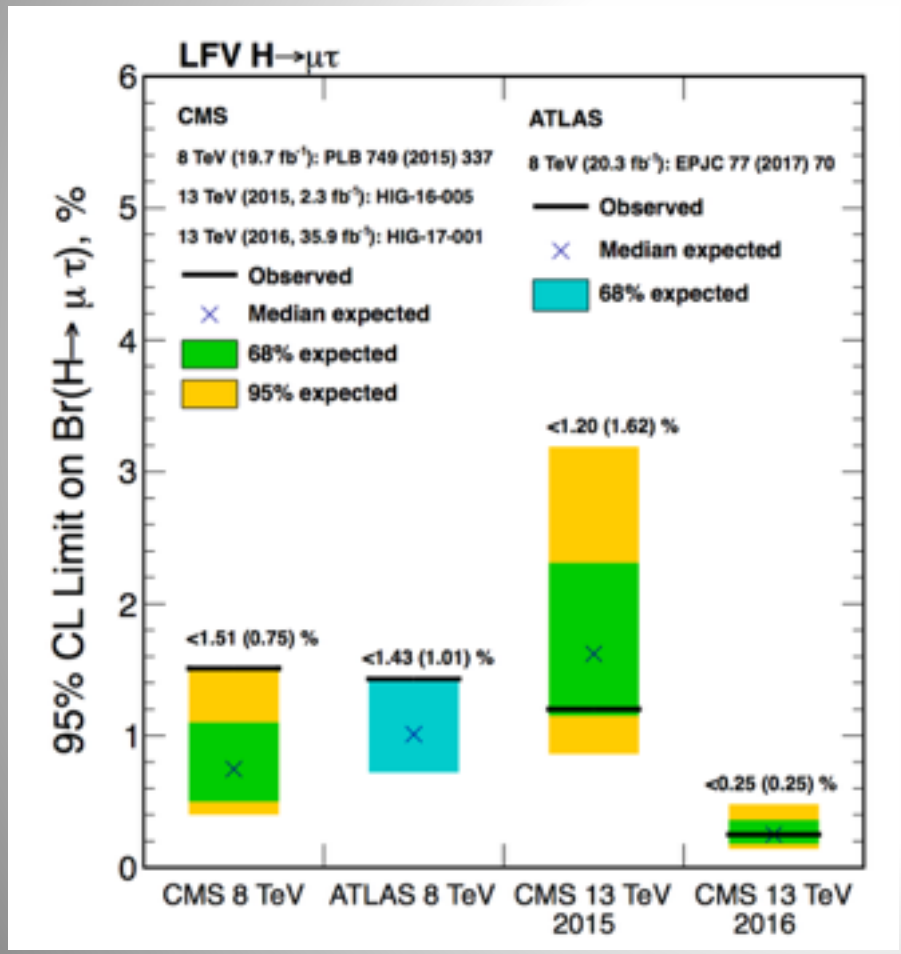
HIG-17-001

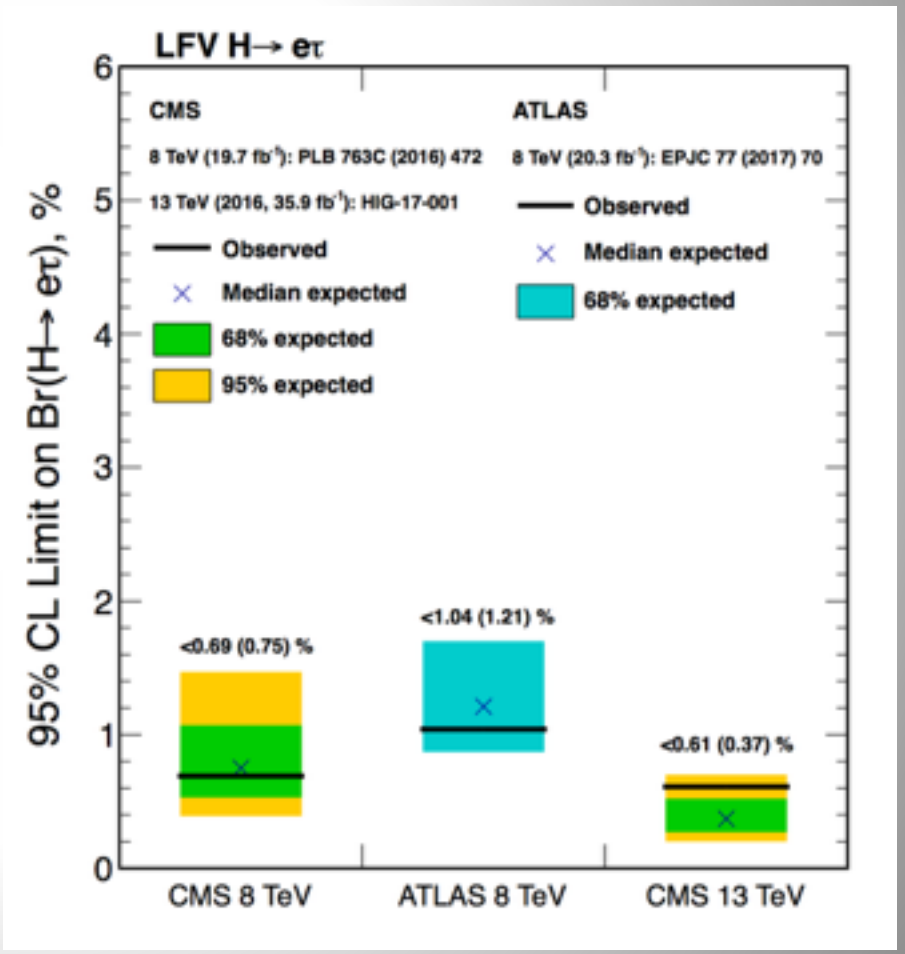
☹ It would Have been Nice…

	Observed(Expected) limits (%)		Best fit branching fraction (%)	
	M_{col}-fit	BDT-fit	M_{col}-fit	BDT-fit
$H \to \mu\tau$	<0.51 (0.49) %	<0.25 (0.25)%	$0.02 \pm 0.20\%$	0.00 ± 0.12 %
$H \to e\tau$	<0.72 (0.56) %	<0.61 (0.37) %	0.23 ± 0.24 %	0.30 ± 0.18 %

Search for LFV Decays: H →μτ, eτ

LHC measurements overview



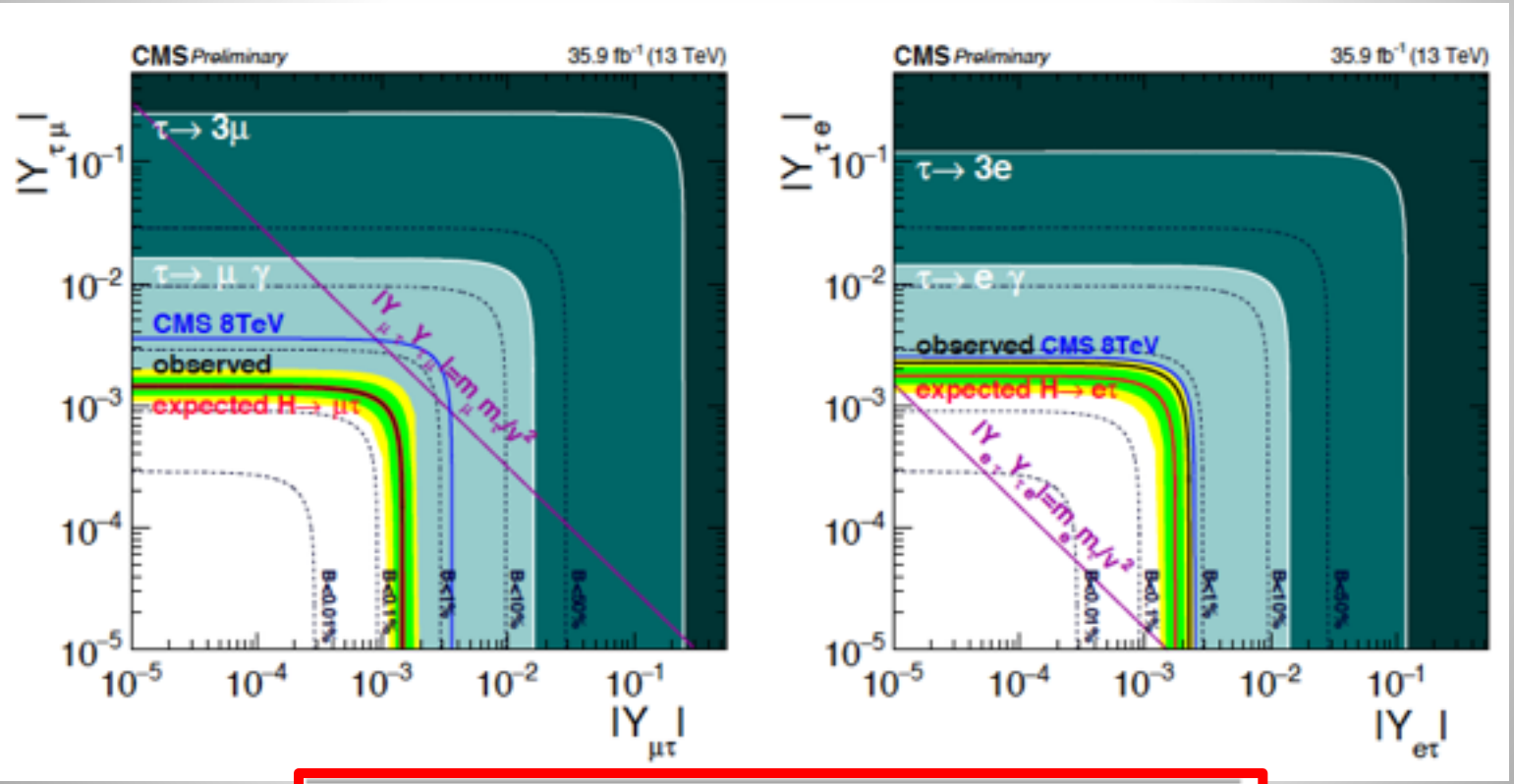


Probing the Yukawa Couplings

Interpreting these constraints in terms of LFV Yukawa coupling limits

$$\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{m_\mathrm{H}}{8\pi}\left(|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2\right)$$

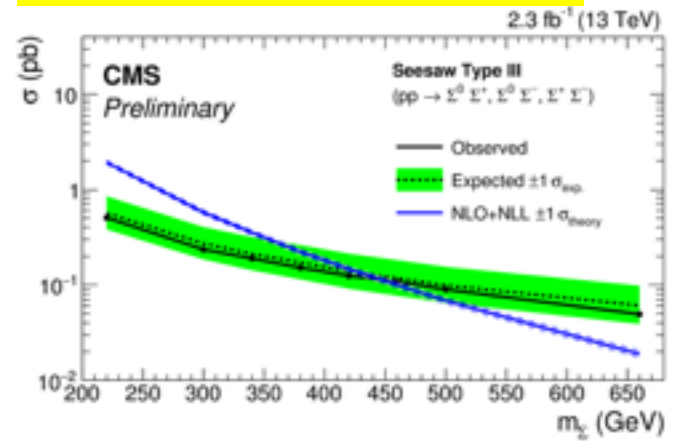
$$B(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta)}{\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) + \Gamma_{SM}}$$



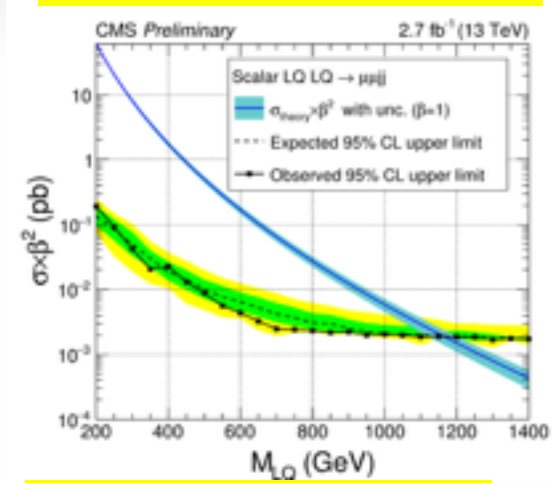
	M_{col}-fit	BDT-fit
$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	$< 2.05 \times 10^{-3}$	$< 1.43 \times 10^{-3}$
$\sqrt{\lvert Y_{e\tau}\rvert^2 + \lvert Y_{\tau e}\rvert^2}$	$< 2.45 \times 10^{-3}$	$< 2.26 \times 10^{-3}$

Many More Searches…

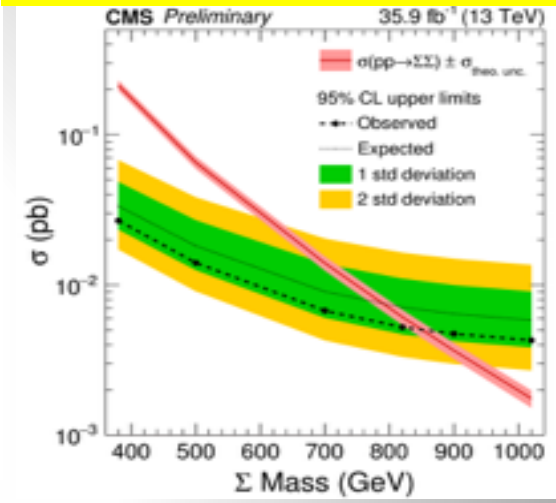
Heavy fermions EXO-16-001



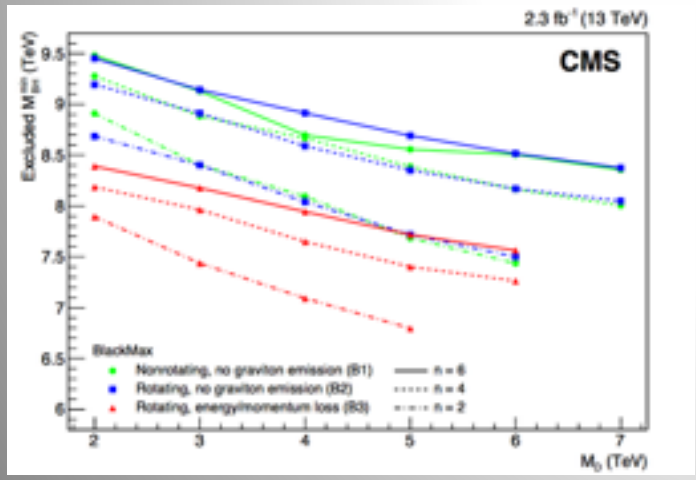
Leptoquarks EXO-16-007



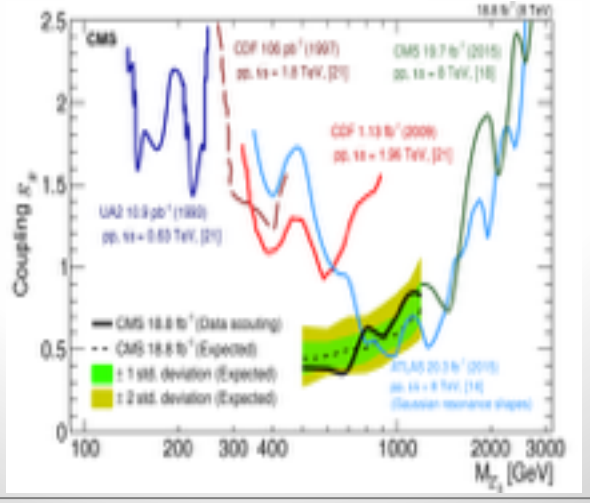
Seesaw type III EXO-17-006



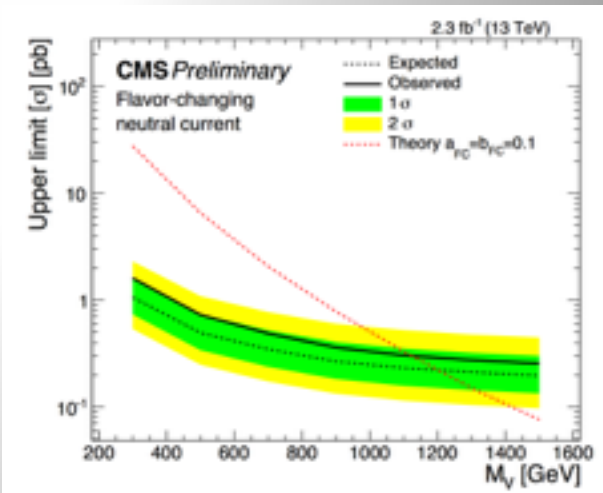
Black Holes: arXiv:1705.01403



Di-jets / data scouting EXO-14-005

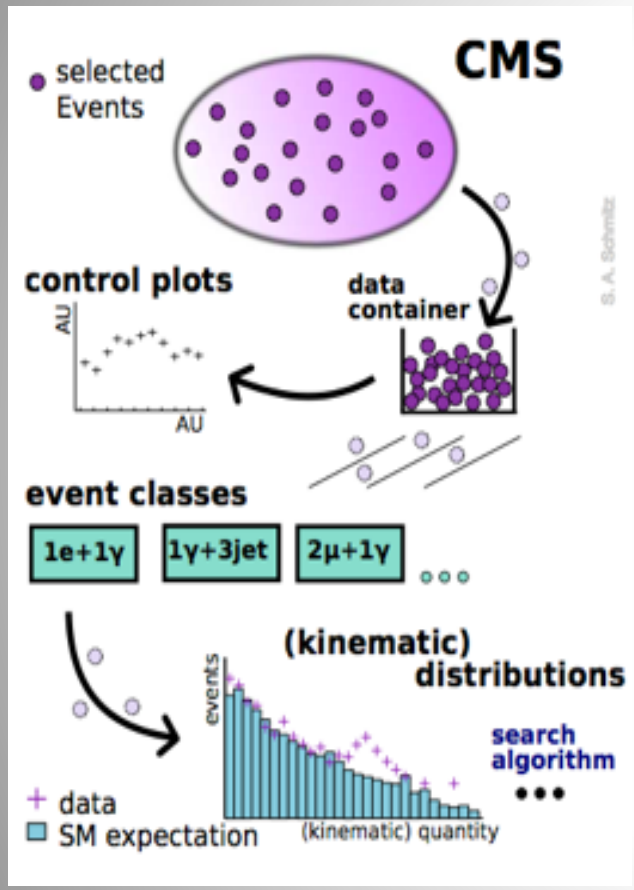


Mono-top EXO-16-017



A General Search View!

CMS-EXO-10-021

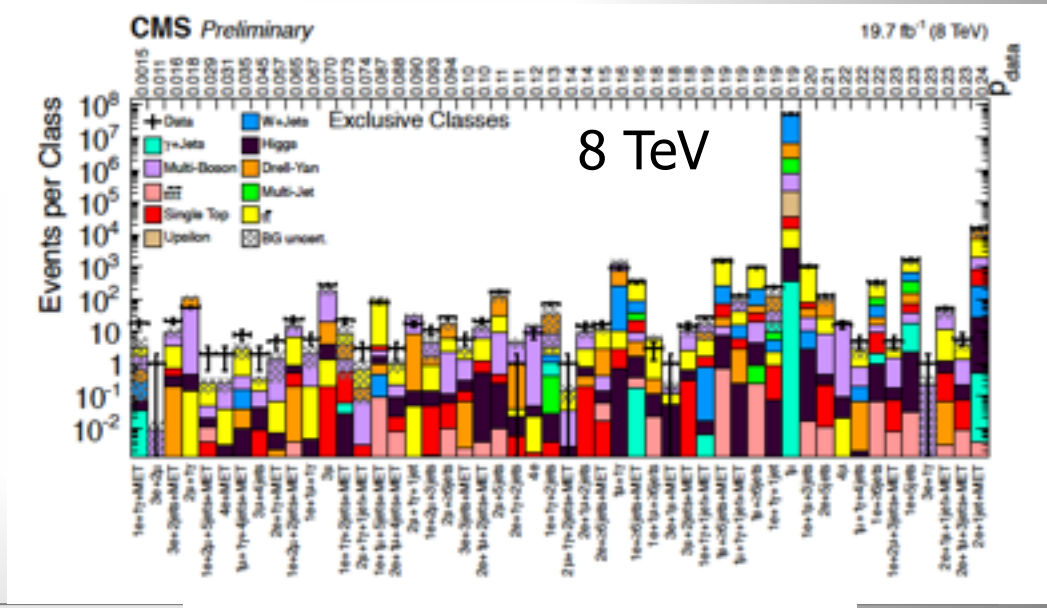


Model independent search

- Divide events into exclusive classes
- Study deviations from SM predictions in a statistical way

Distributions in each class

- $\sum p_T$ - Most general
- $M_{inv}^{(T)}$ - Good for resonances
- MET - Escaping particles



Rates (exclusive classes) as expected for 19.7 fb^{-1} for CMS

→muons, electrons, photons, MET

Analysis ongoing for 13 TeV

Summary: Searches at the LHC

- The LHC has entered a new territory. The experiments are heavily engaged in searches for new physics with the high statistics 13 TeV data samples
- No sign of new physics yet in these first analyses of the 13 TeV. Previous mild excesses have not been confirmed. No sign of LFV signals at present: $H \rightarrow \mu\tau$ not confirmed with 2016 data.
- Special efforts on Supersymmetry searches continuing and a more systematic covering of dark matter searches emerging.
- New exotic channels are being explored further: More systematic approach for eg long lived particle s
- The LHC is continuing to explore the Terascale data to look forward to: it will only take on signif show the way!!

And maybe one day soon: