EXOTIC SEARCHES AT LHC

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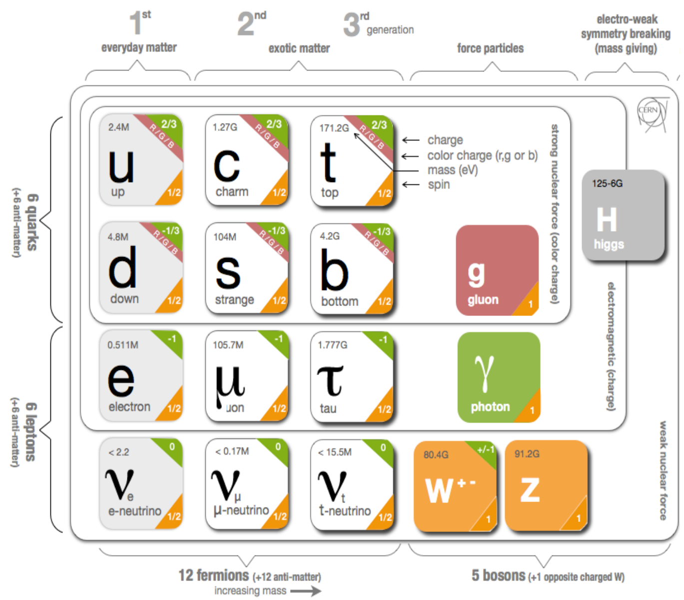
On behalf of the ATLAS, CMS & LHCb collaborations

PANIC2017 Conference, Beijing China
September 1 - 5, 2017

WHY SEARCH???

Standard Model has worked exceptionally well… Except it has Standard problems as well!!!

- ? Dark Matter
- ? Dark Energy
- ? Neutrino Oscillations
- ? Matter- Antimatter Symmetry



- ? Fermion mass hierarchy
- ? Higgs mass stability
- ? Gravity
- ? …

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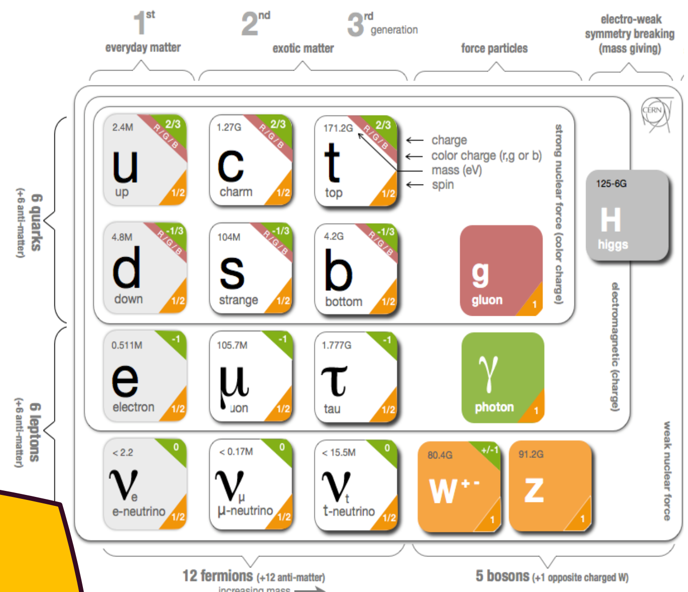

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Supersymmetry

- Several variants (MSSM, NMSSM, R-parity conservation or violation…)
- Heavy super-partners, prompt/long-lived, scalars
- Searches mostly theory motivated

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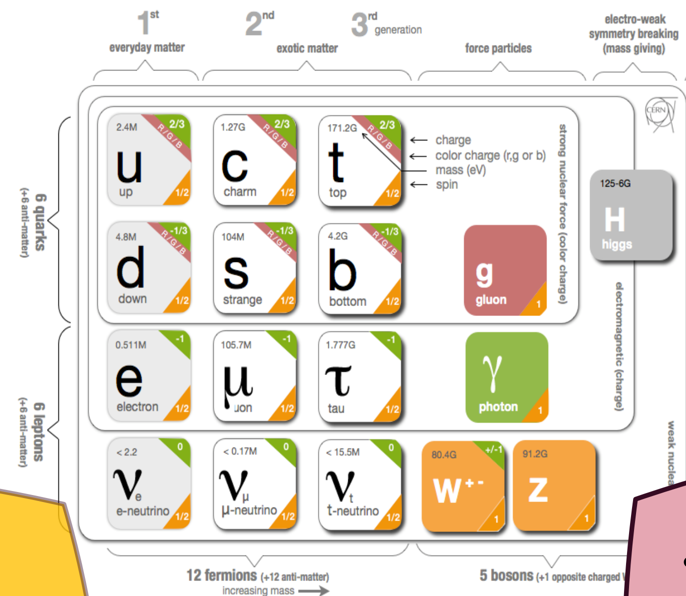

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Previous talk by Dr. Andrea Ventura

Exotics

- Variety of independent theories/models
- New particles & interactions
- Excited fermions, VLQs, Dark/Hidden sectors…
- Searches motivated by signatures in most cases.

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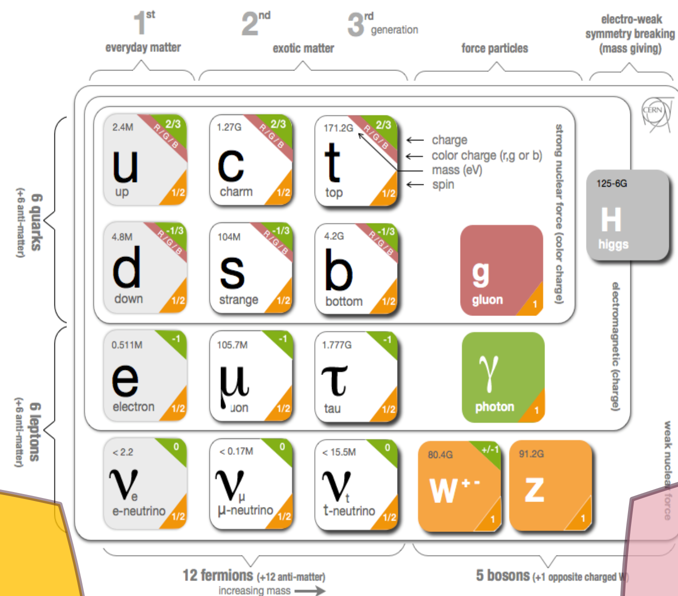

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Something New

Exotics

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Content of this talk

THE LHC MACHINE

7/8/13 TeV proton – proton collisions

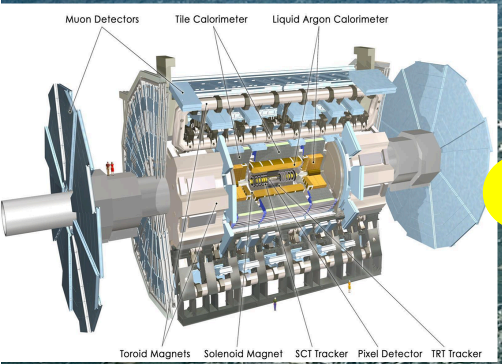
ATLAS/CMS

5 & 25 fb^{-1} per experiment (2011-12) @ 7 & 8 TeV

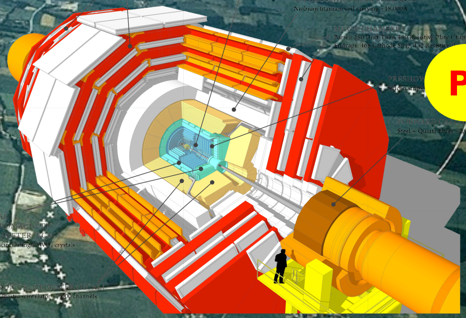
36 fb^{-1} (2015-16) & 19 fb^{-1} (2017)/exp @ 13 TeV

LHCb: 3 fb^{-1} @ 8 TeV

1.9 fb^{-1} (2015-16)/ 0.68 fb^{-1} (2017) @ 13 TeV



P1



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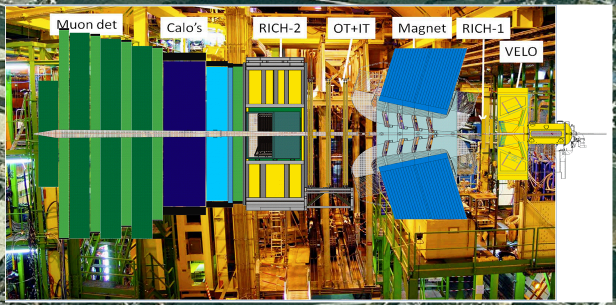
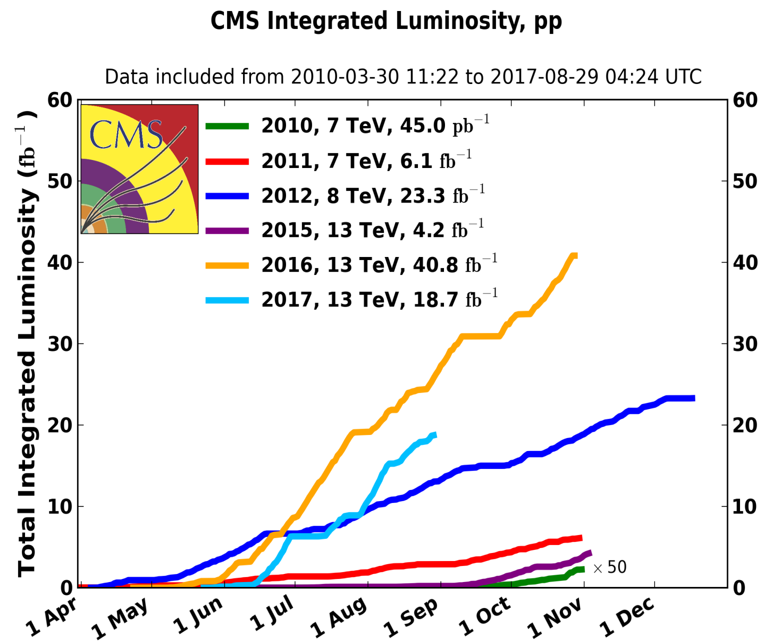
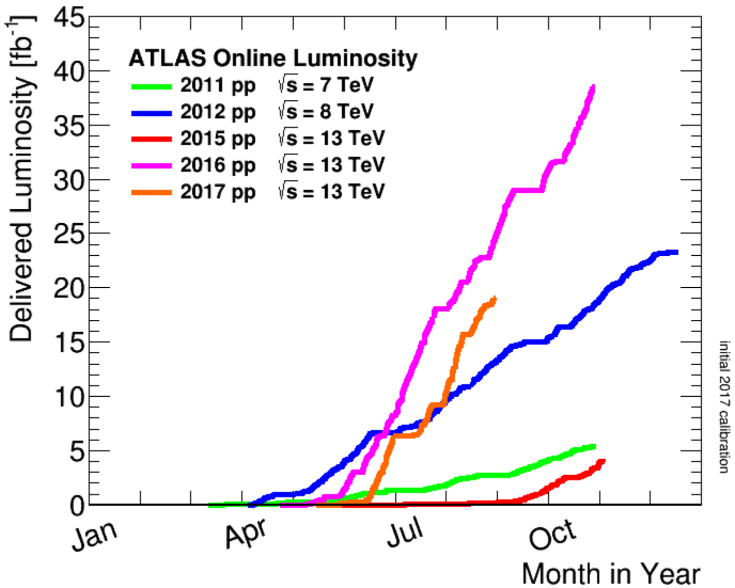
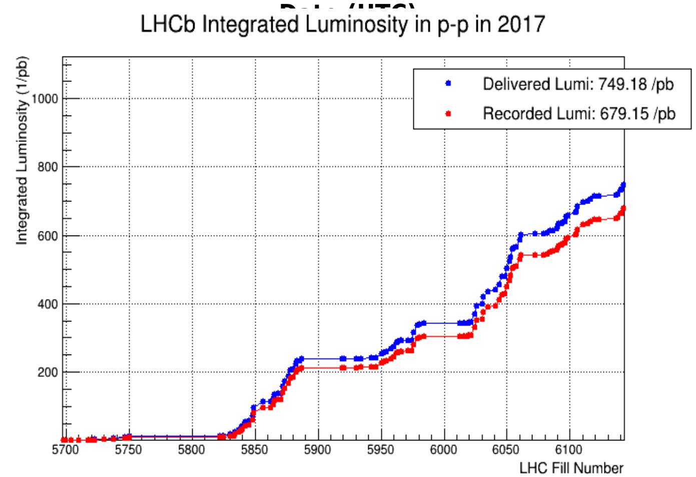


LHC RUN-II

- 2016 data taking in Run-II was commendable
- In 2017 as well LHC is delivering proton-proton data steadily
- Already delivered about 19 fb^{-1}



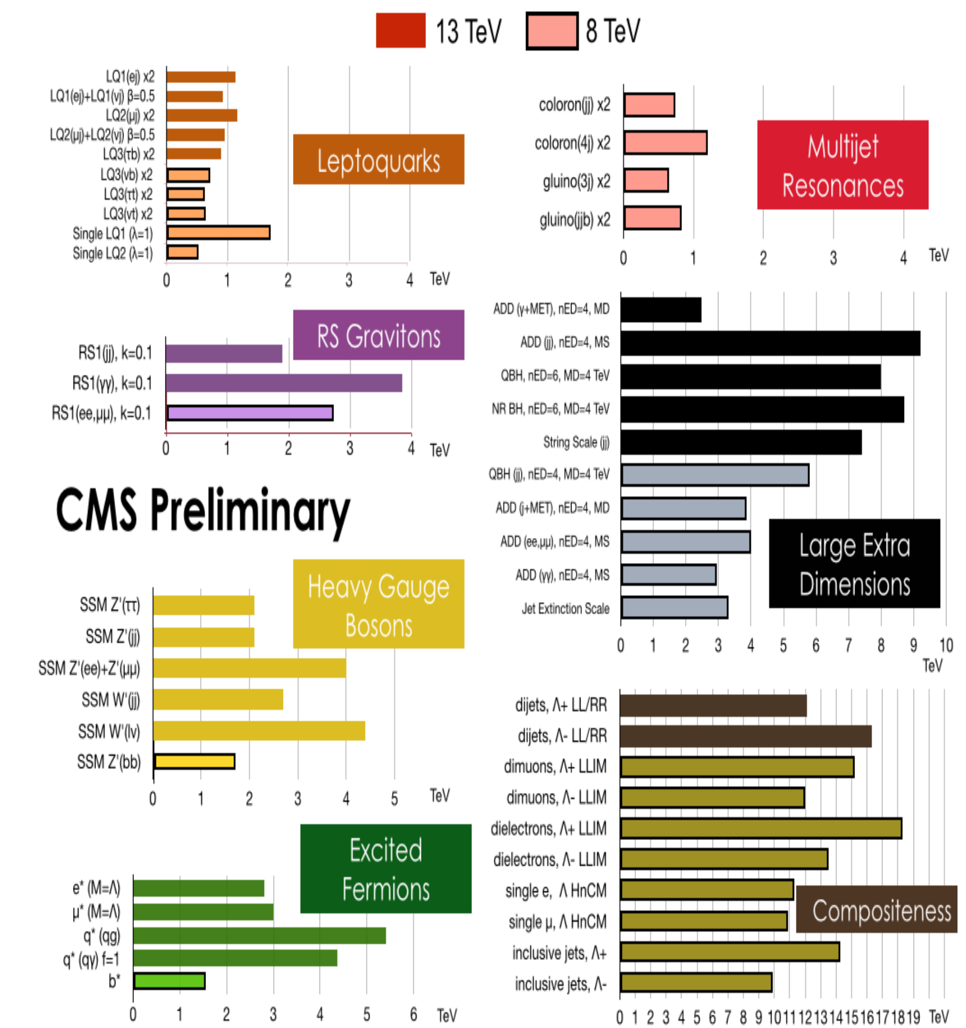




EXOTIC SEARCHES

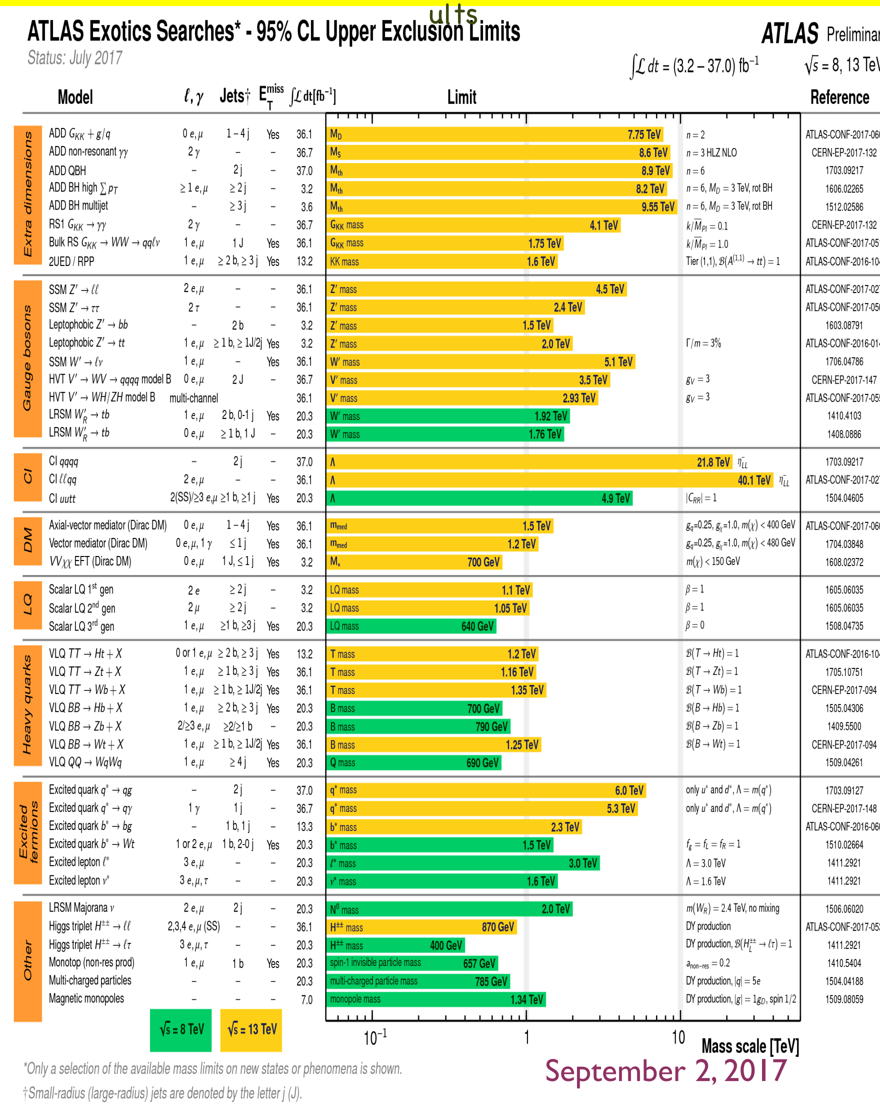
CMS Exotics Searches

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults



ATLAS Exotics Searches - 95% CL Upper Exclusion Limits

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults



THIS TALK

Only a small subset of representative analyses are presented

- ✓ This selection reflects my personal biases
- ✓ Apologies to other analyses I had to leave out

My aim is to give an overview of the latest results on:

- ✓ Resonance searches
- ✓ Vector-like quarks
- ✓ Dark matter (+extra dimensions and gravitons)
- ✓ Long-lived particles

Exotics

- Variety of independent theories/models
- New particles & interactions
- Excited fermions, VLQs, Dark/Hidden sectors…
- Searches motivated by signatures in most cases.

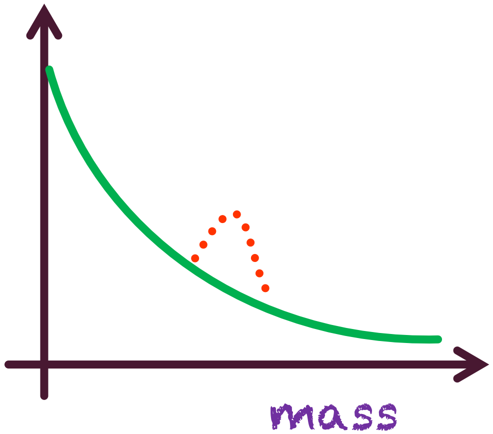
Content of this talk

Many related talks are being presented by others

Also, watch out for the poster session

Disclaimer: Most of the results from ATLAS & CMS with highlights from LHCb

RESONANCES



All relevant combinations of final state objects

jj, $\ell\ell$, VV, Vγ, $\gamma\gamma$, γ+j...

DI-JET

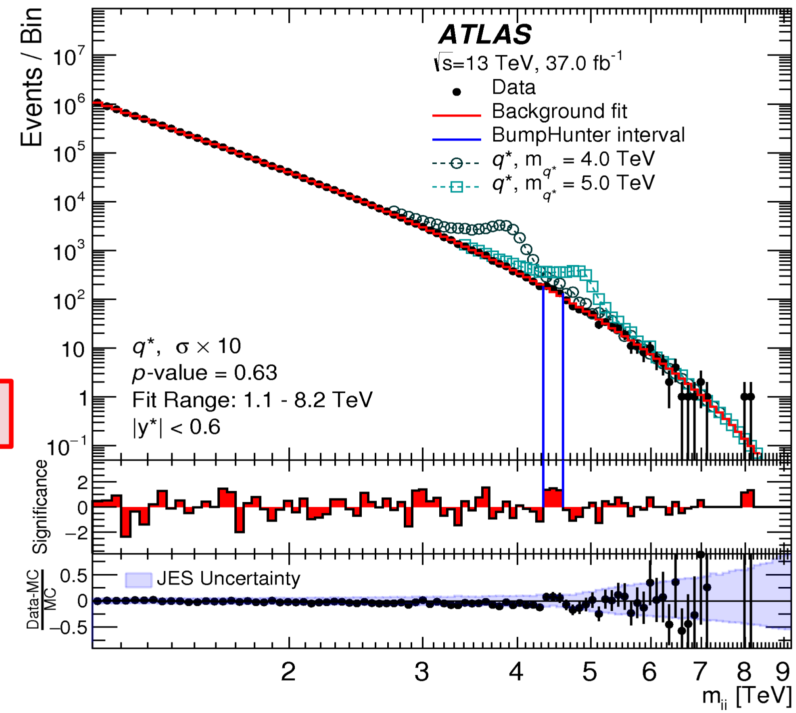
ATLAS – arXiv:1703.09127

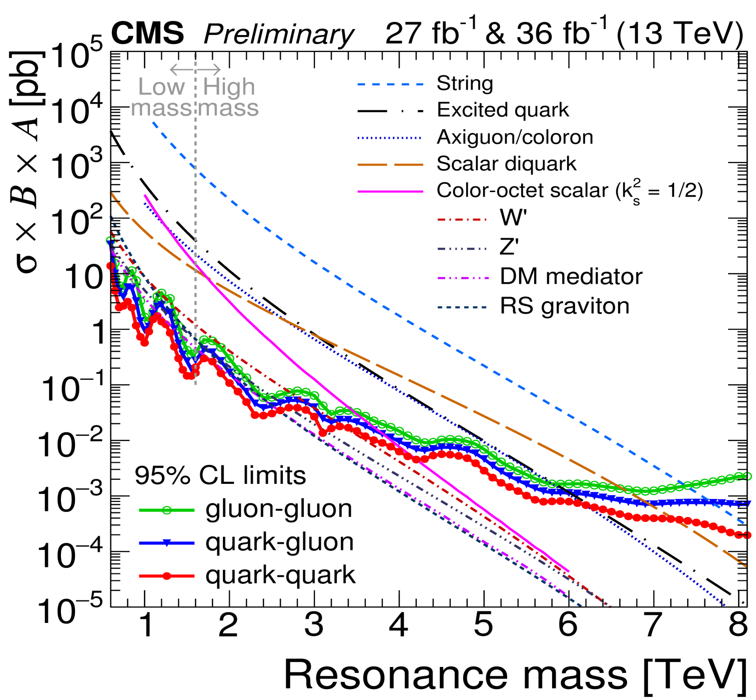
CMS – PAS-EXO-16-056

Classic signature to search for new physics with strong interactions

- Challenge: High background & trigger limitation
  - Excited quarks, W′, Z′, W*
  - Quantum black holes

No significant excess observed





Model	95% CL exclusion limit	
ATLAS	Observed	Expected
Quantum black hole	8.9 TeV	8.9 TeV
W'	3.6 TeV	3.7 TeV
W^*	3.4 TeV 3.77 TeV – 3.85 TeV	3.6 TeV
Excited quark	6.0 TeV	5.8 TeV
Z' $(g_q = 0.1)$	2.1 TeV	2.1 TeV
Z' $(g_q = 0.2)$	2.9 TeV	3.3 TeV
Contact interaction $(\eta_{LL} = -1)$	21.8 TeV	28.3 TeV
Contact interaction $(\eta_{LL} = +1)$	13.1 TeV 17.4 TeV – 29.5 TeV	15.0 TeV

DI-JET

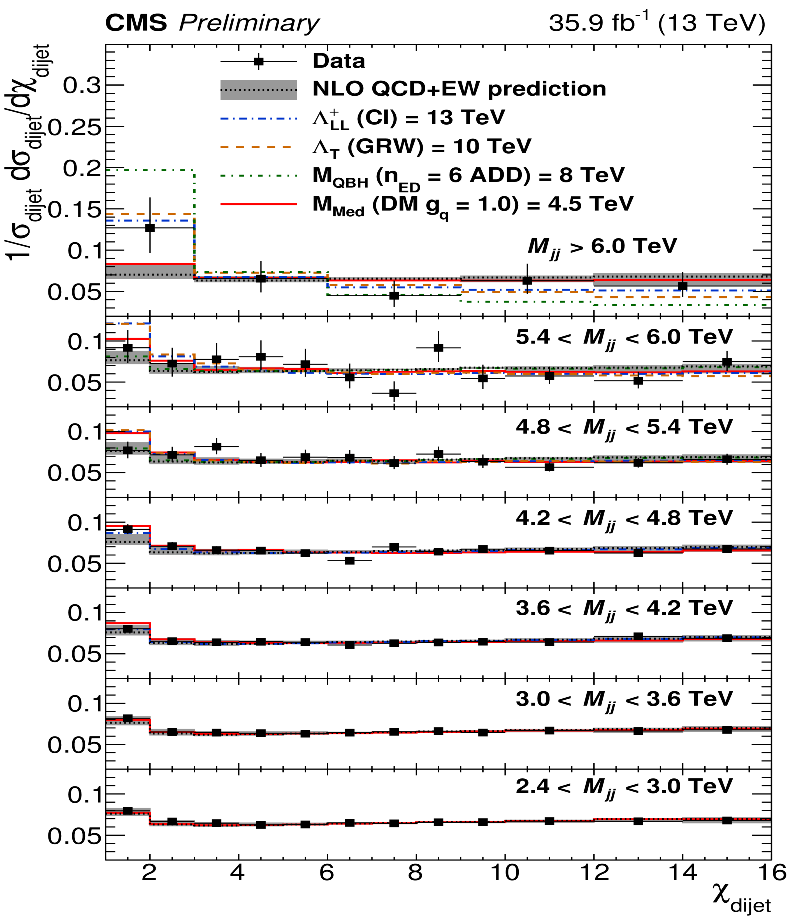
ATLAS - arXiv1703.09127

CMS - PAS-EXO-16-046

Measurements of dijet angular distributions.

Constraining models of quark contact interactions, extra spatial dimensions, quantum black holes, and dark matter.

$$\chi = e^{2|y^*|} \sim \frac{1-\cos\theta^*}{1-\cos\theta^*}$$



CMS

Model	Observed lower limit (TeV)	Expected lower limit (TeV)
$\Lambda^+_{LL/RR}$ (NLO)	13.1	15.2 ± 0.9
$\Lambda^-_{LL/RR}$ (NLO)	17.4	23.9 ± 3.0
Λ^+_{VV} (NLO)	15.1	17.3 ± 1.0
Λ^-_{VV} (NLO)	22.2	31.2 ± 3.8
Λ^+_{AA} (NLO)	15.2	17.3 ± 1.0
Λ^-_{AA} (NLO)	22.1	31.0 ± 3.8
$\Lambda^+_{(V-A)}$ (NLO)	9.1	11.7 ± 1.0
$\Lambda^-_{(V-A)}$ (NLO)	9.3	11.9 ± 1.1
ADD Λ_T (GRW)	10.6	12.1 ± 0.9
ADD M_S (HLZ) $n_{ED} = 2$	11.4	13.3 ± 1.0
ADD M_S (HLZ) $n_{ED} = 3$	12.6	14.4 ± 1.1
ADD M_S (HLZ) $n_{ED} = 4$	10.6	12.1 ± 0.9
ADD M_S (HLZ) $n_{ED} = 5$	9.6	10.9 ± 0.8
ADD M_S (HLZ) $n_{ED} = 6$	8.9	10.2 ± 0.8
QBH M_{QBH} (ADD $n_{ED} = 6$)	8.3	8.7 ± 0.3
QBH M_{QBH} (RS $n_{ED} = 1$)	6.0	6.5 ± 0.4
DM Vector/Axial-Vector M_{Med}	2.5–5.0	2.5–5.2

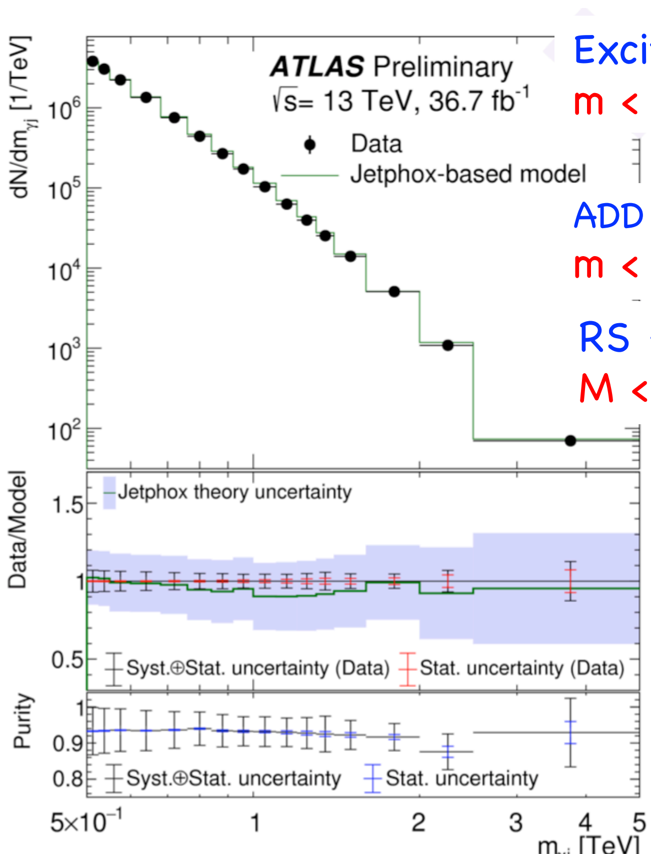
PHOTON + JET

ATLAS - to appear

CMS - PAS-EXO-17-002

Searches in the photon + jet final state

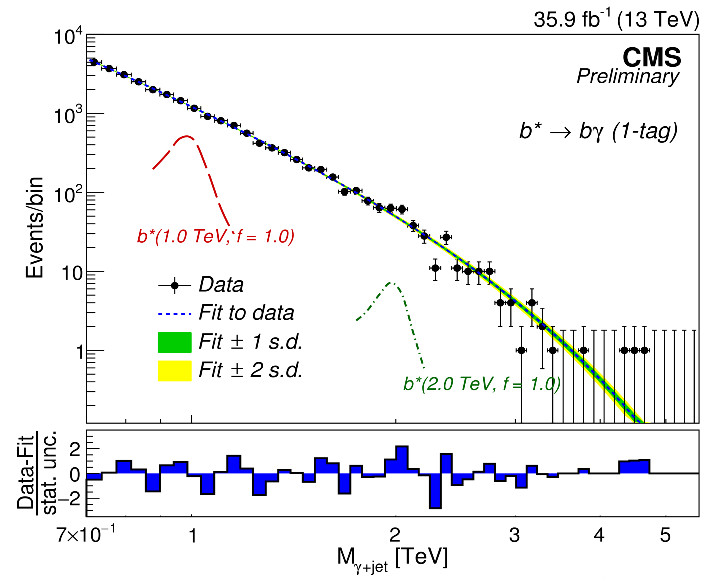
Exclusions: Excited quarks(q*, b*), ADD and RS Quantum blackholes

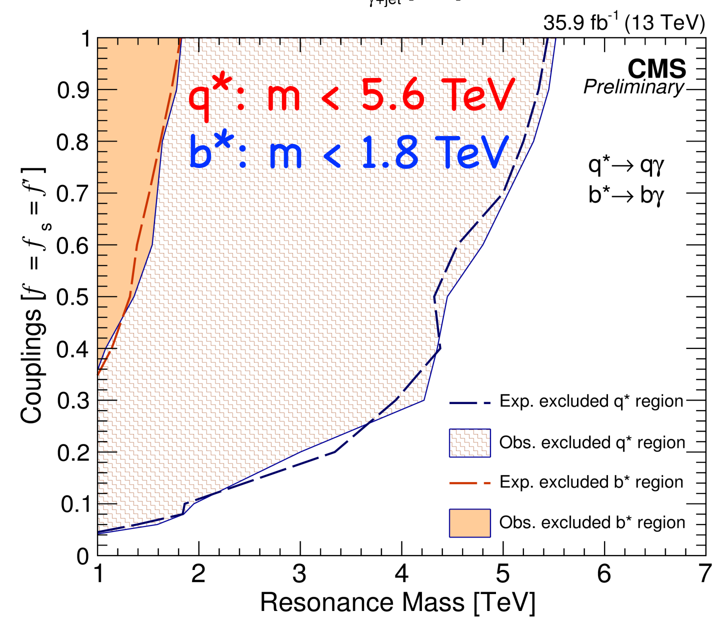


Excited quarks:
m < 5.3 TeV

ADD – QBH
m < 7.1 TeV

RS – QBH
M < 4.4 TeV

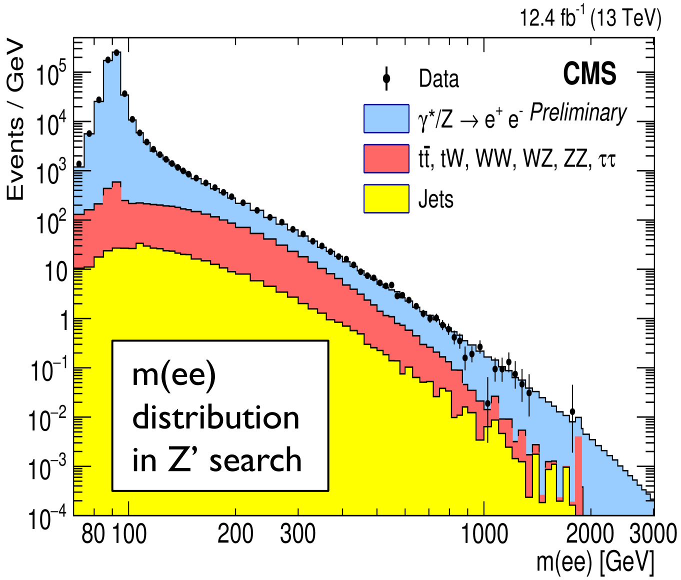




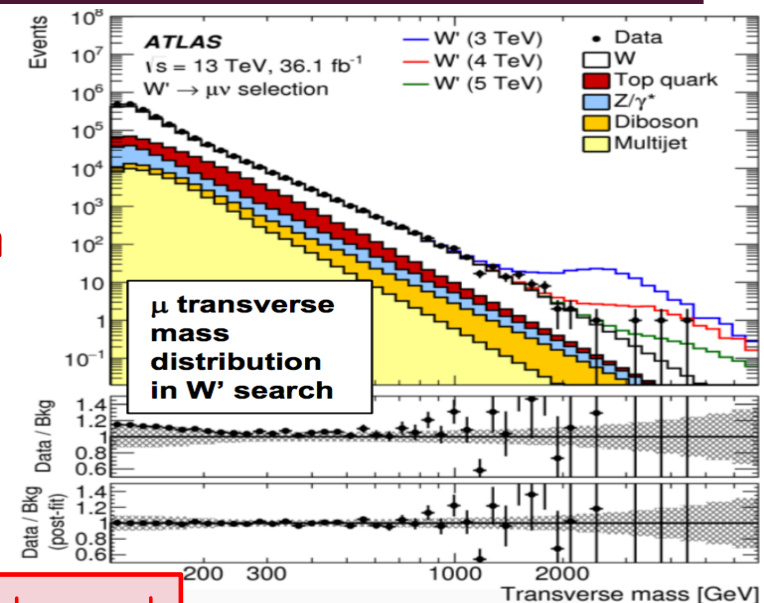
DI-LEPTONS

ATLAS – arXiv:1707.02424

CMS – arXiv:1612.09274 and PAS-EXO-16-031

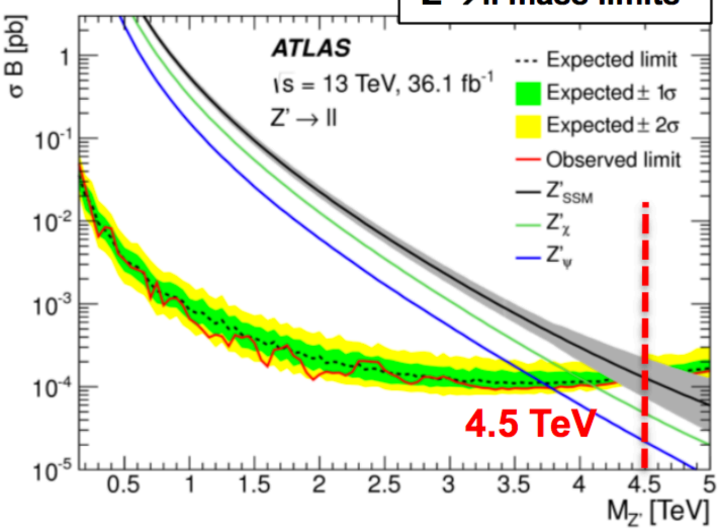


Resonances decaying to lepton pairs (Z′) and lepton+MET (W′)



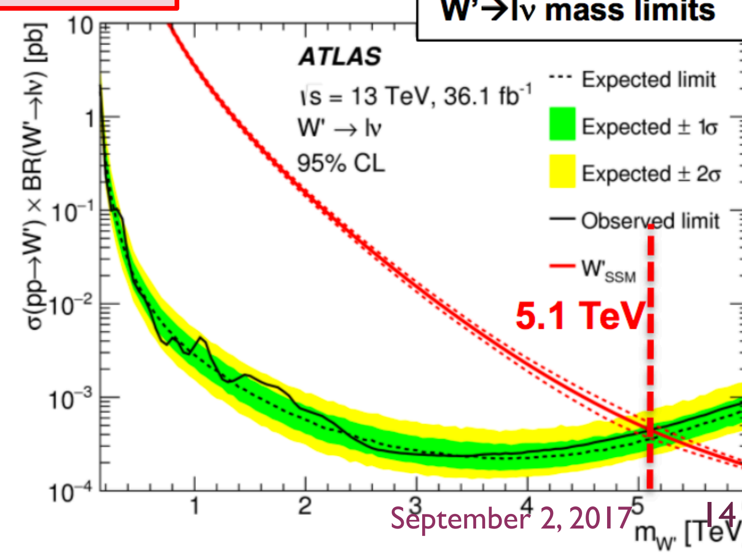
No significant excess observed

Z'→ll mass limits



Exclusion limits extracted in various new physics Z′ and W′ scenarios eg. Sequential Standard Model (SSM)

W'→lν mass limits



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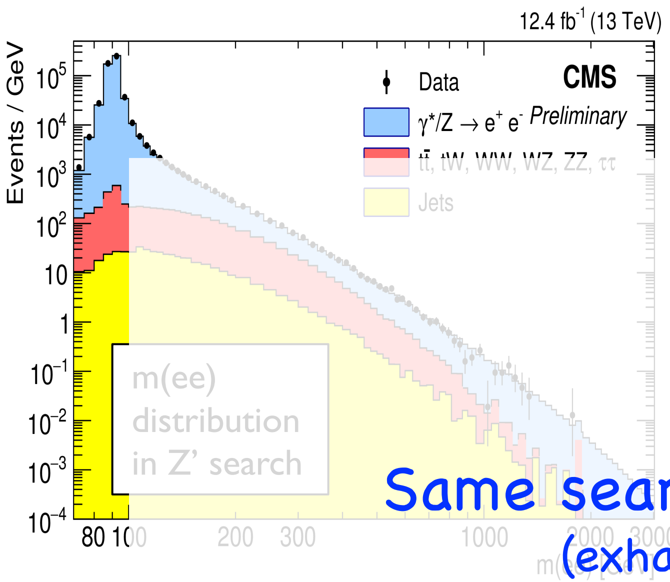
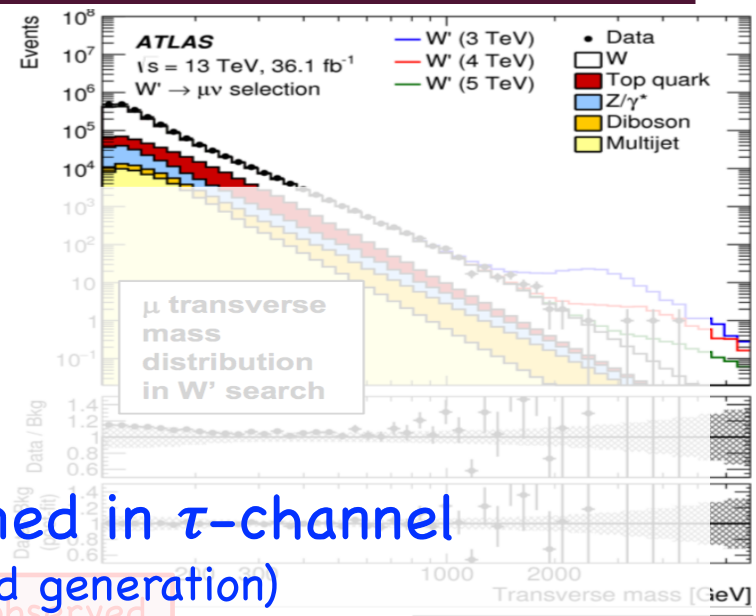
ATLAS – arXiv:1707.02424

CMS – arXiv:1612.09274 and PAS-EXO-16-031



m(ee) distribution in Z' search

Resonances decaying to lepton pairs (Z') and lepton+MET (W')



μ transverse mass distribution in W' search

No significant excess observed

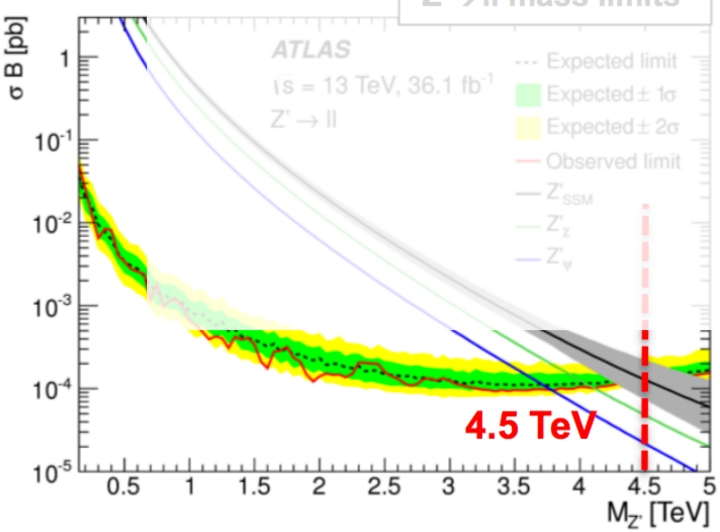
Same search also performed in τ-channel

(exhanced coupling to third generation)

CMS: JHEP 02 (2017) 048 [2015 data]

ATLAS: EXOT-2015-05 [2012 data]

Z'→ll mass limits



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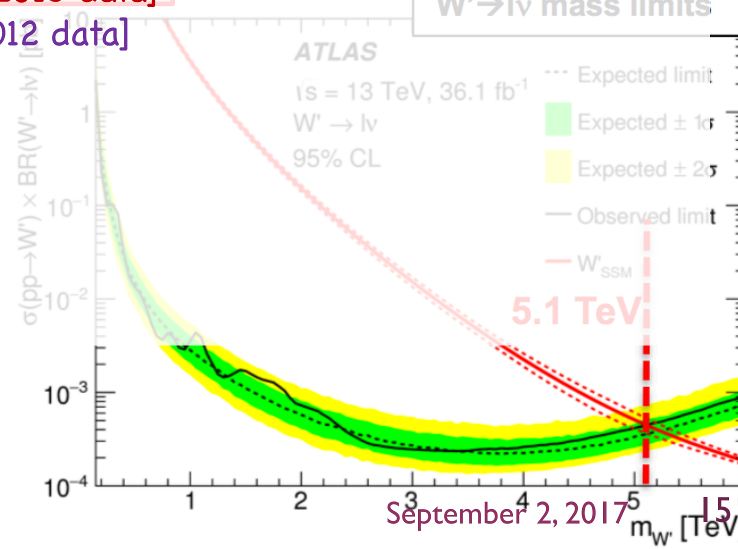
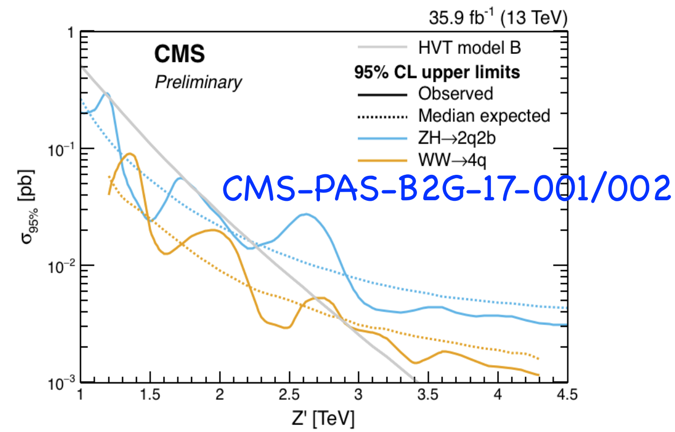
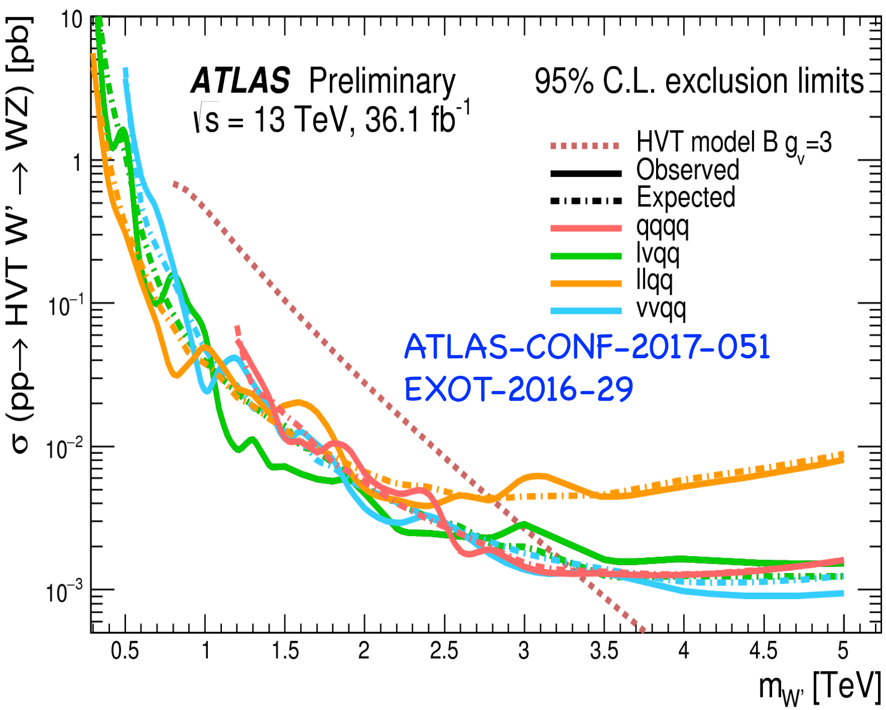


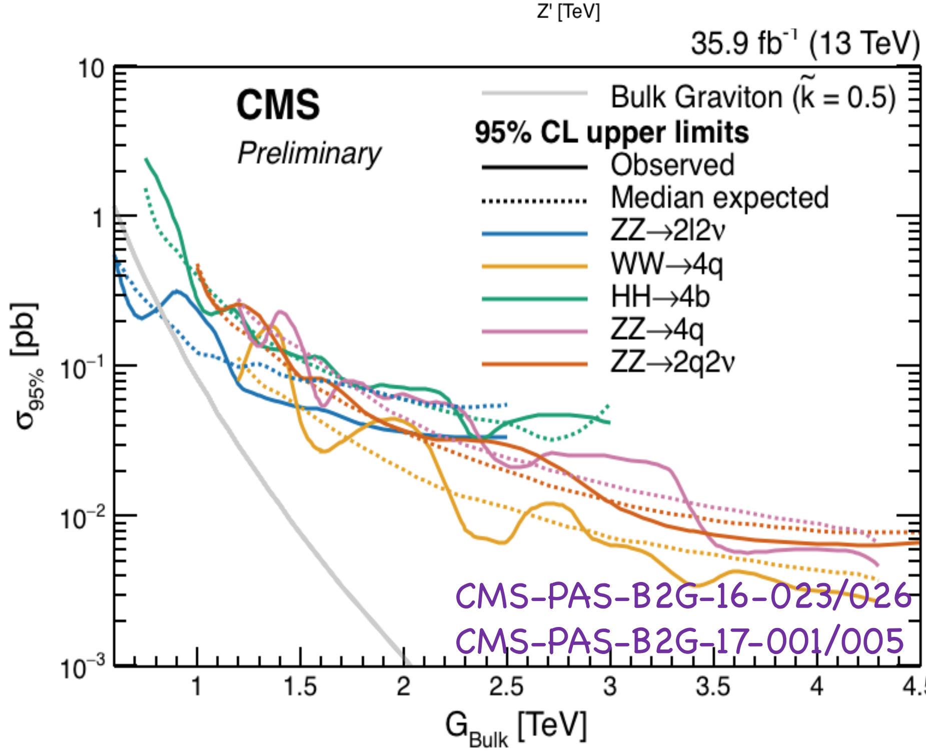
DI-BOSON

ATLAS – arXiv:1708.04445
CMS PAS-B2G-16-023/026
CMS PAS-B2G-17-001/002/005

- ✓ Benchmark models:
  - Heavy weakly coupled Vector Triplet (HVT) (Spin-1)
  - RS Graviton (Spin-2)
  - Final states probed: WW, WZ, ZZ
- ✓ Several control regions (CRs) and signal regions (SRs) per search, to estimate SM backgrounds
- ✓ Exploit gluon-fusion and VBF-production.



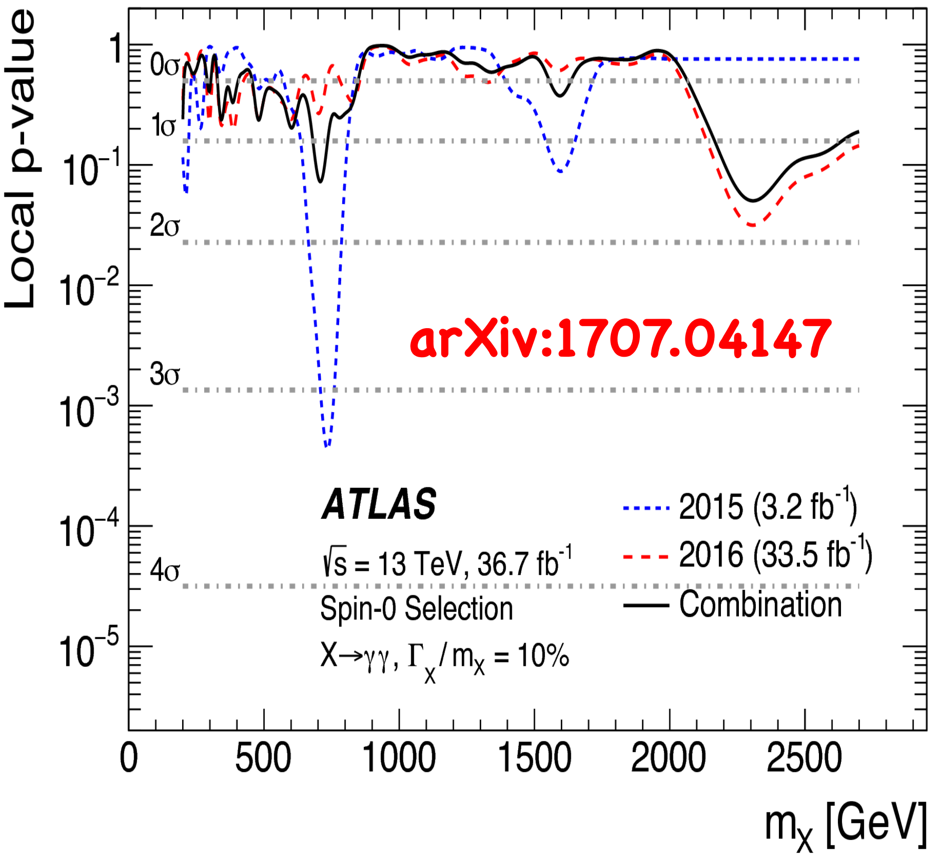


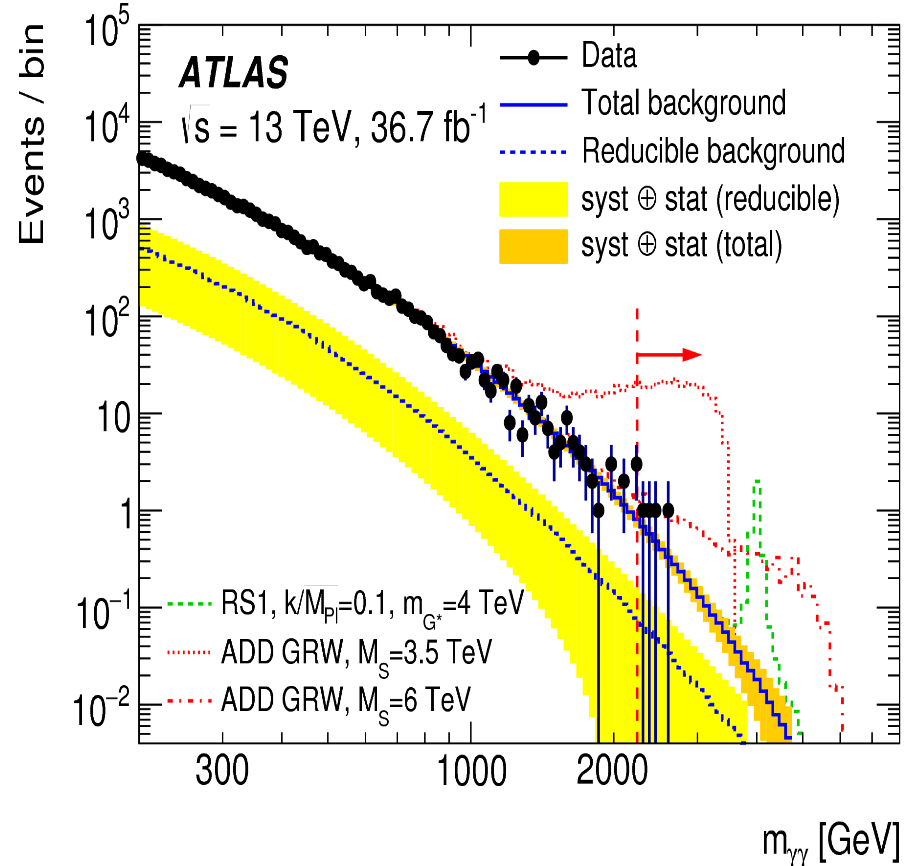


ATLAS – arXiv:1707.04147

DI-PHOTONS

CMS – PLB 767 (2017) 147





Sizeable excess observed by CMS and ATLAS at 750 GeV in 2015 data.

No excess with 10 times more data in 2016

No significant deviation from the Standard Model is observed

CMS – Phys. Lett. B 767 (2017) 147 (19.7 (2012@8TeV) and 3.3(2015@13TeV)

ZGAMMA

CMS – PAS-EXO-17-005

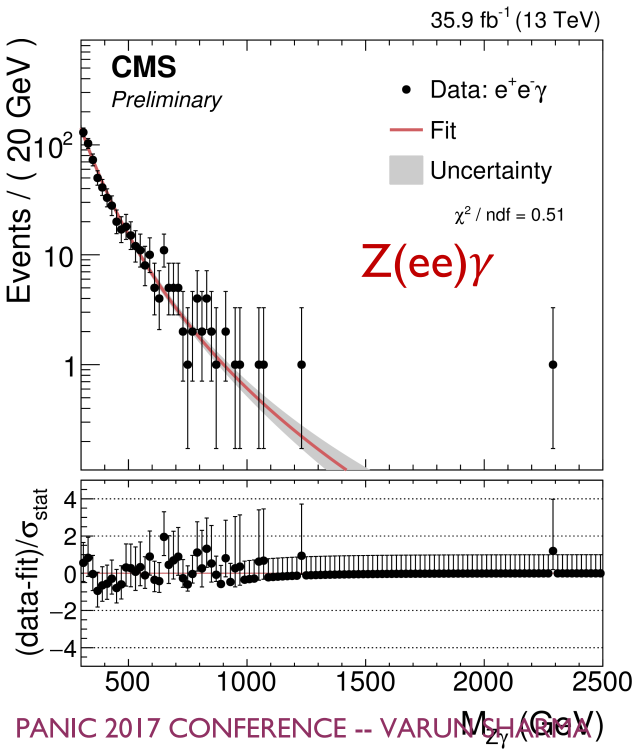
Bump hunt in M($Z\gamma$) spectrum: Both Z($\ell\ell$)γ and Z(qq)γ

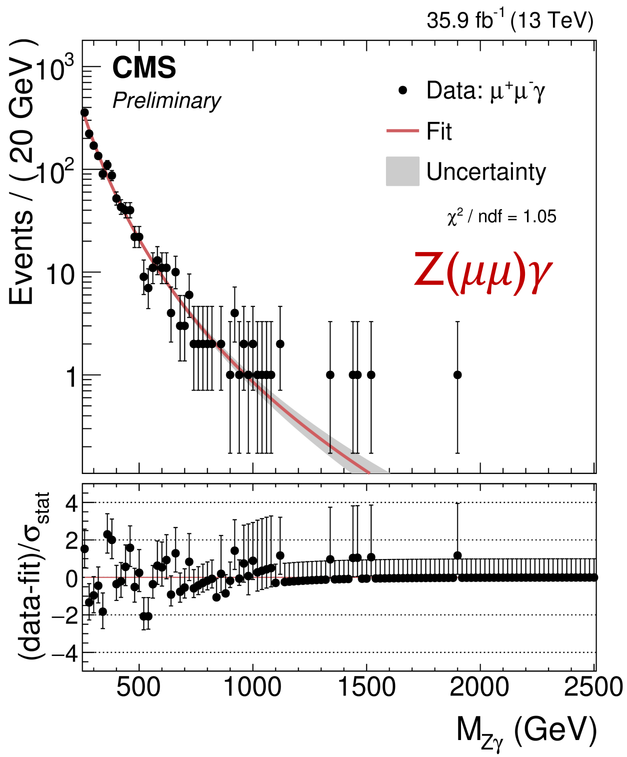
Z(qq)γ: Higher BR $\Rightarrow$ Good at high mass

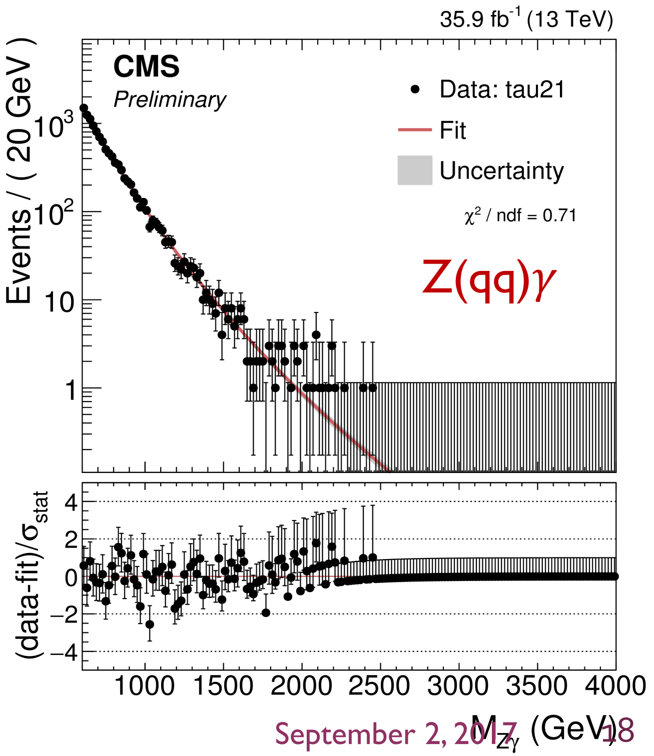
Z($\ell\ell$)γ: Lower trigger thresholds, low background $\Rightarrow$ Good at low mass

Z(qq)γ event categorization

- b tagged: Two b tagged subjet
- Anti-b tagged: Further divided by τ_{12} (Jet substructure techniques)

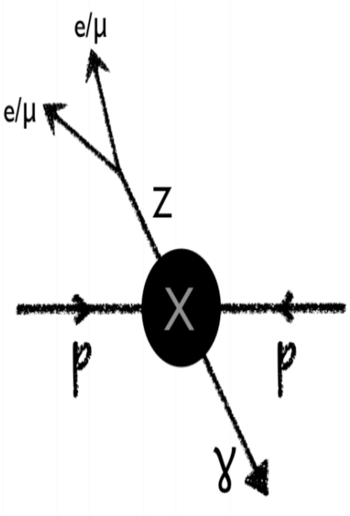


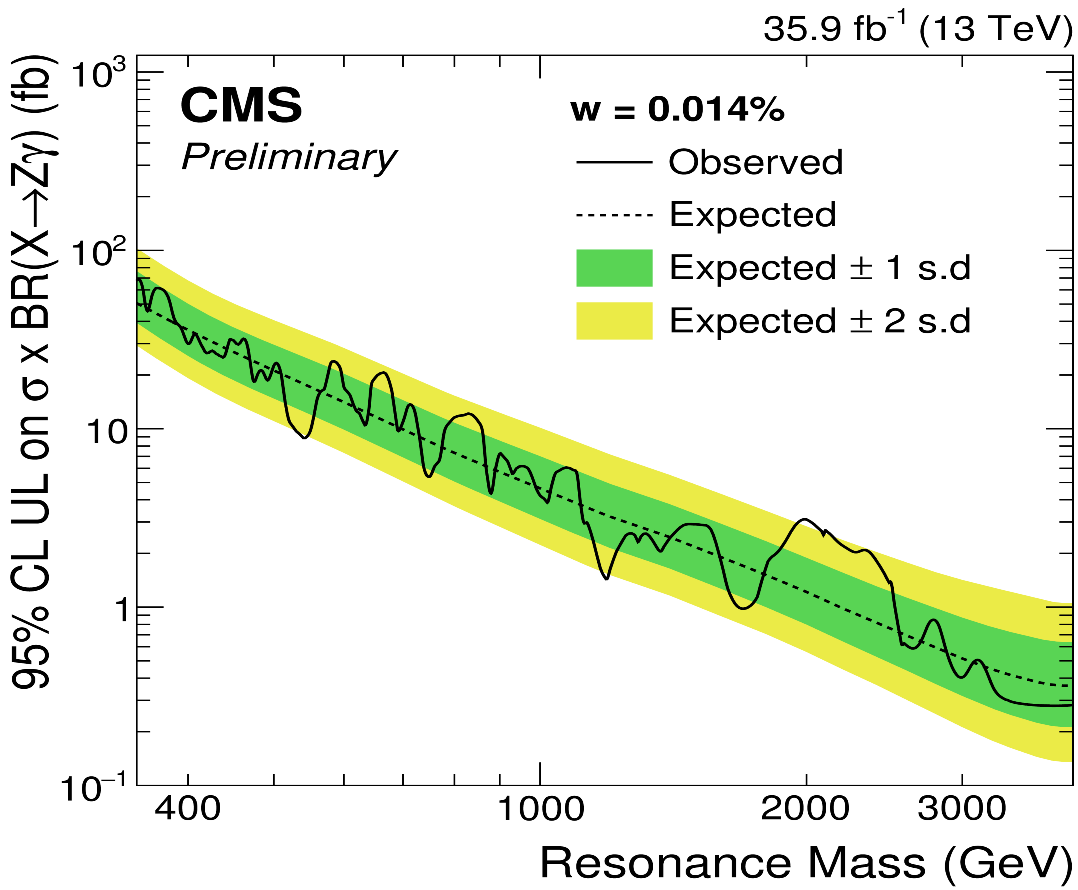


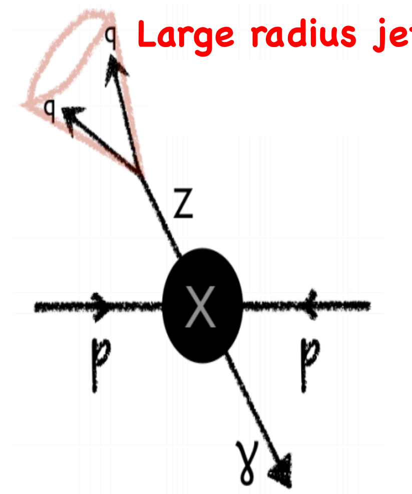


ZGAMMA

CMS – PAS-EXO-17-005

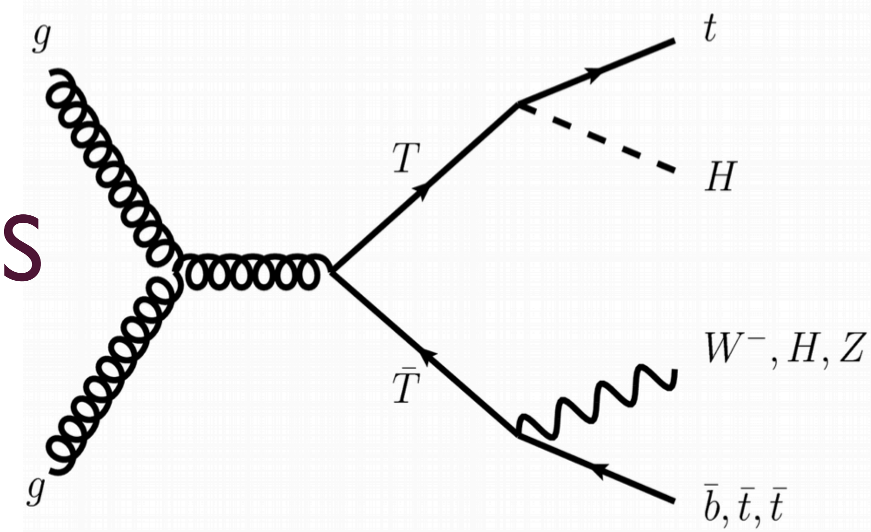






No significant excess observed

VECTOR LIKE QUARKS



VECTOR LIKE QUARKS

What are they?

- Colored spin-1/2 particles $\Rightarrow$ Quarks
- Don't get mass from Higgs $\Rightarrow$ "Vector-like"
- Both chiralities have the same representation under the EW group SU(2) x U(1)

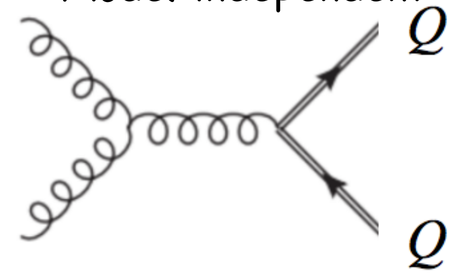
Why do we care for them?

- Potentially answer why Higgs has unnaturally small mass (the hierarchy problem)

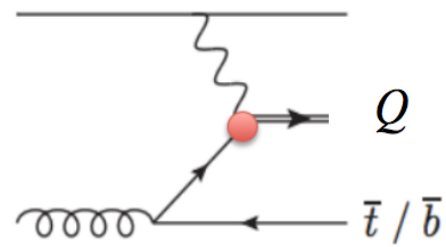
Where do we find them?

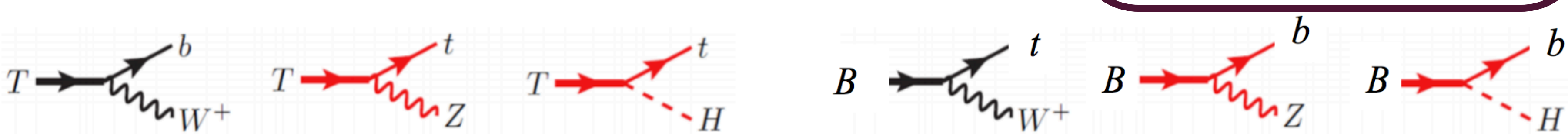
- Little/Composite Higgs
- Topcolor
- GUTs
- …

Pair production: Strong $\Rightarrow$ Model independent



Single production: EW $\Rightarrow$ Depends on SM quark mixing

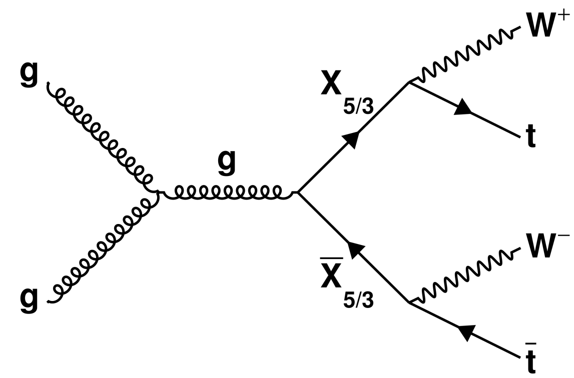




PAIR PRODUCTION

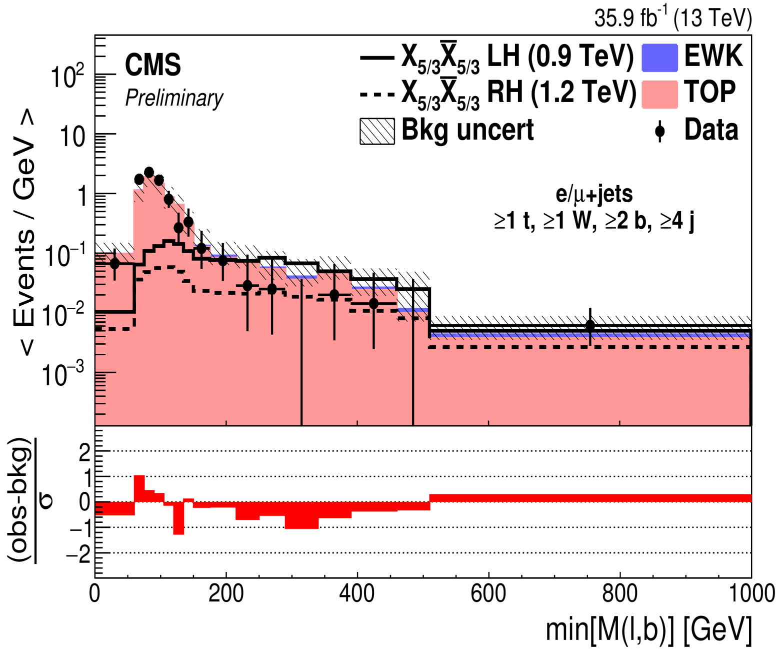
CMS - PAS-B2G-17-008

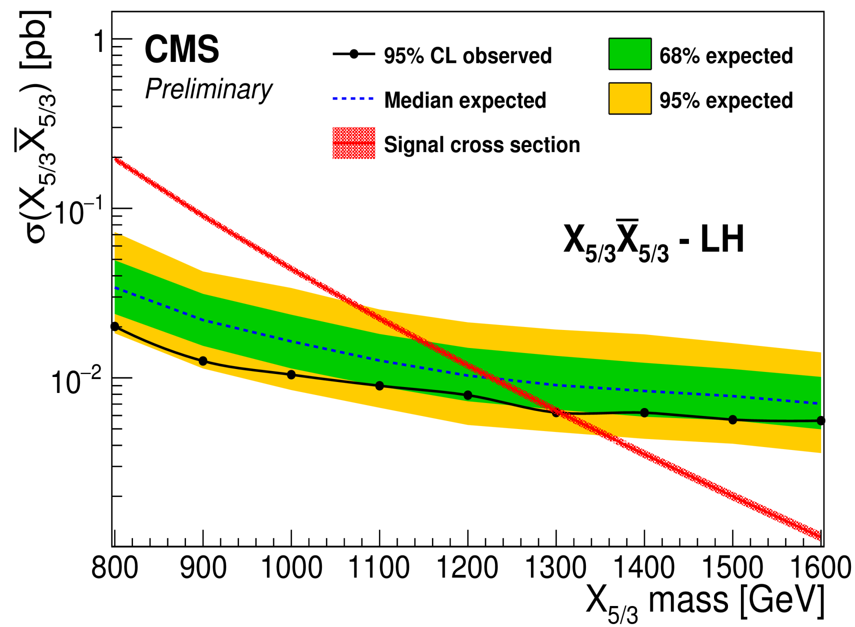
- Complex searches: many particles in final states (W, H, Z, t,…)
- Complicated dedicated variables.
- Several control and signal regions
- Exploitation of boosted decay products.



1lepton+jets+MET topology

Make use of W and top ``tagging”



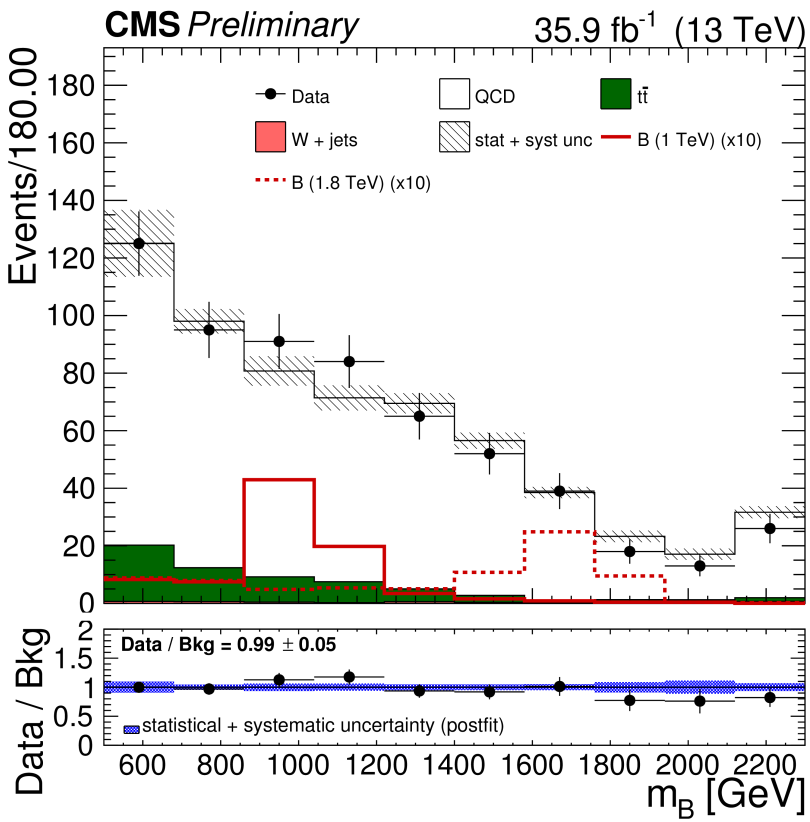


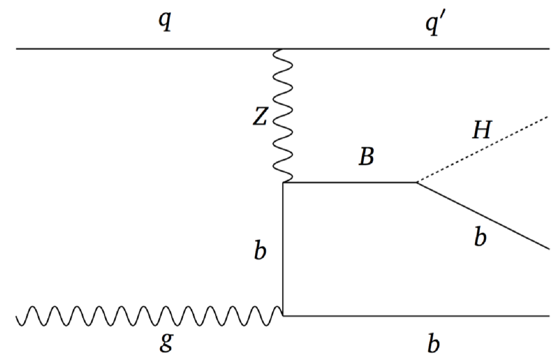
Similar constraints on Left- and Right- hand heavy quark partners

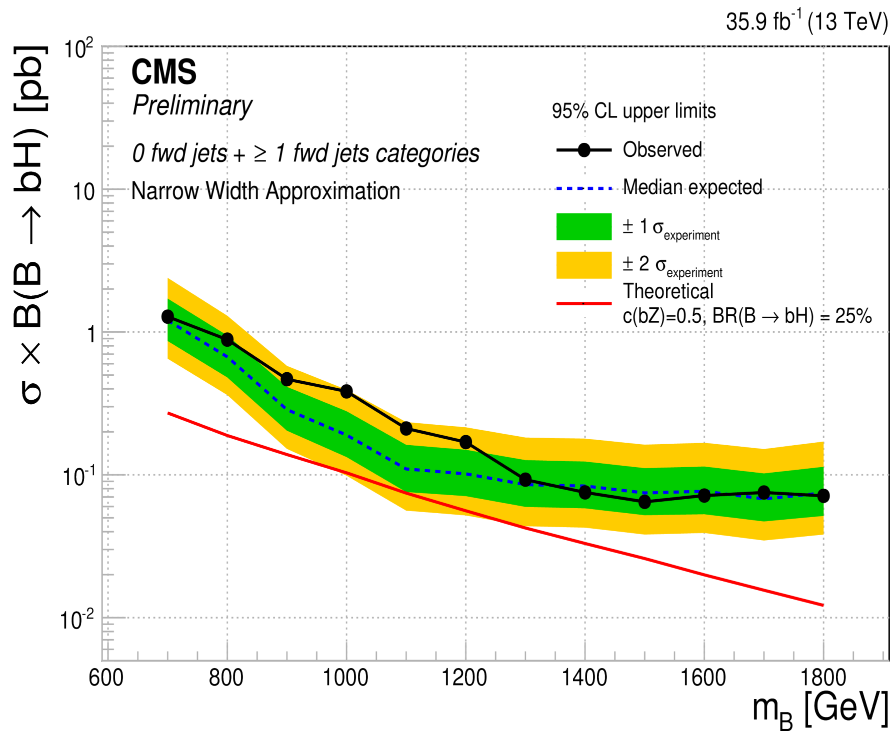
SINGLE PRODUCTION

CMS – PAS-B2G-17-009

B→bH (H→bb) + additional forward jets



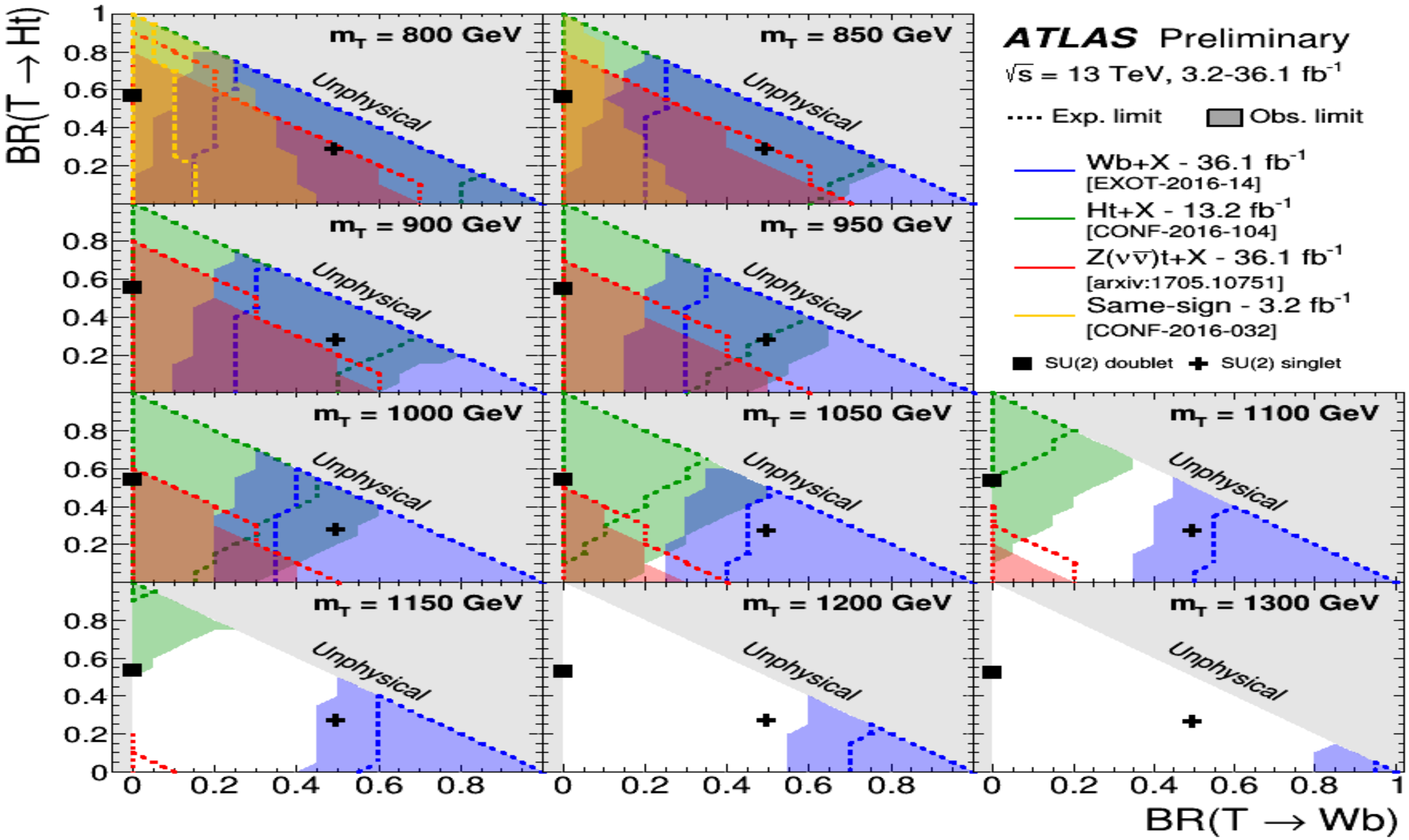




Limits vary between 0.07 pb and 1.28 pb

VECTOR LIKE TOP QUARKS

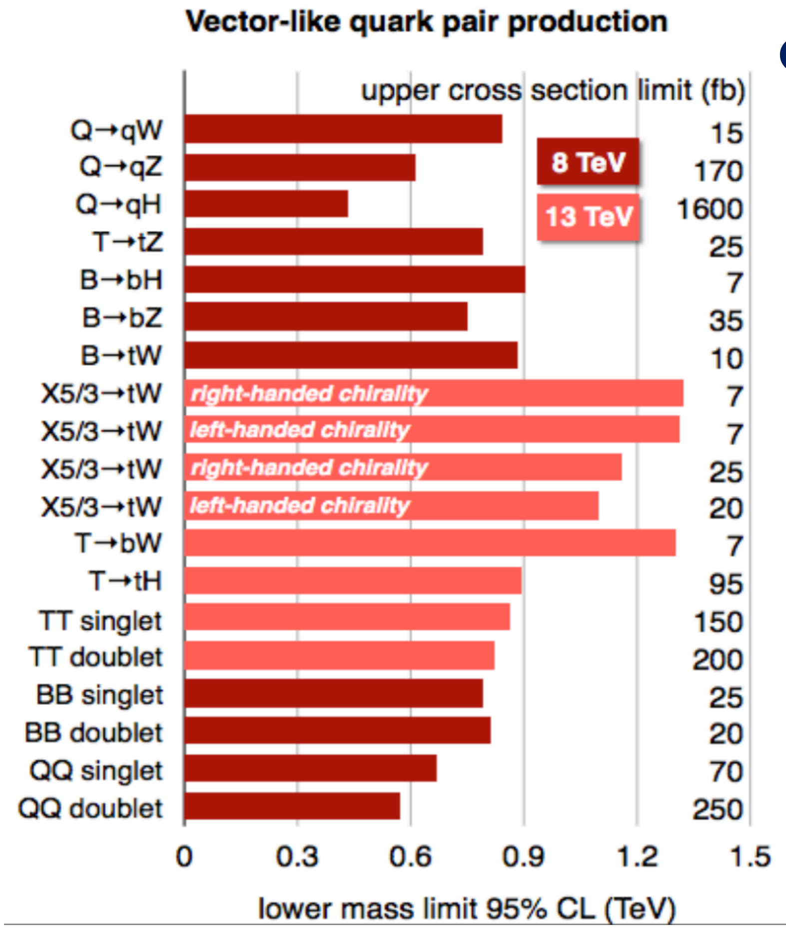
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html

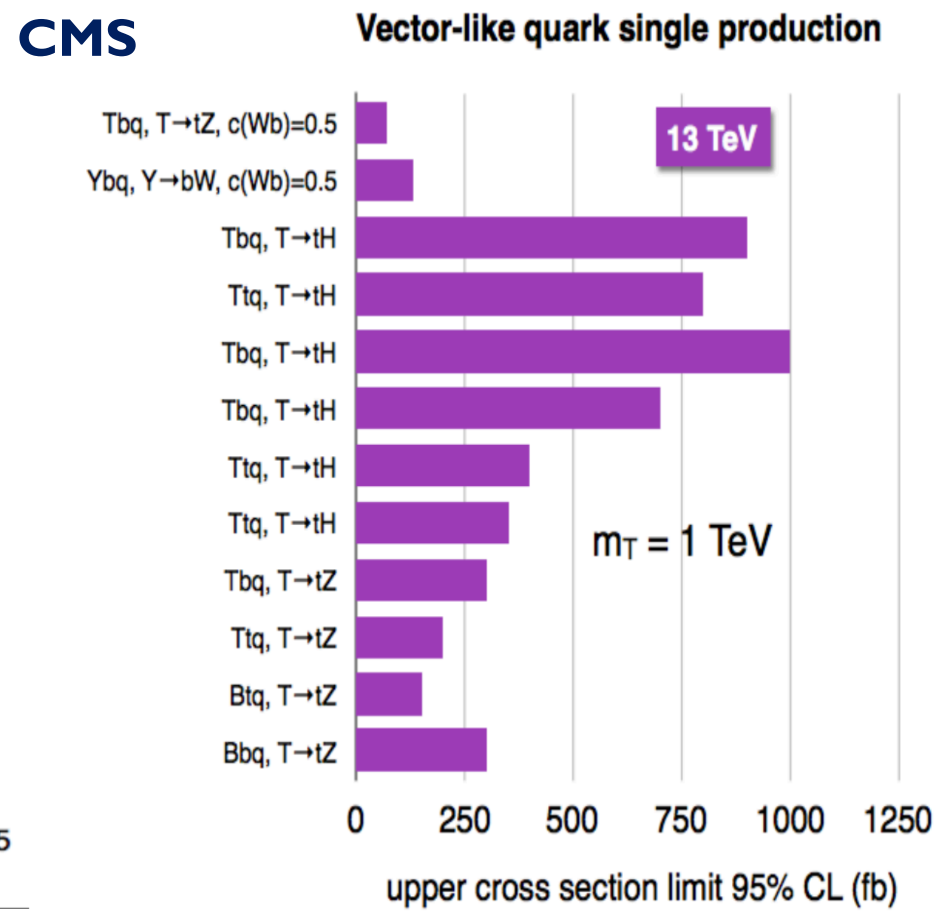


- T singlet excluded for m < 1170 GeV
- T in (T,B) Doublet excluded for m < 1155 GeV

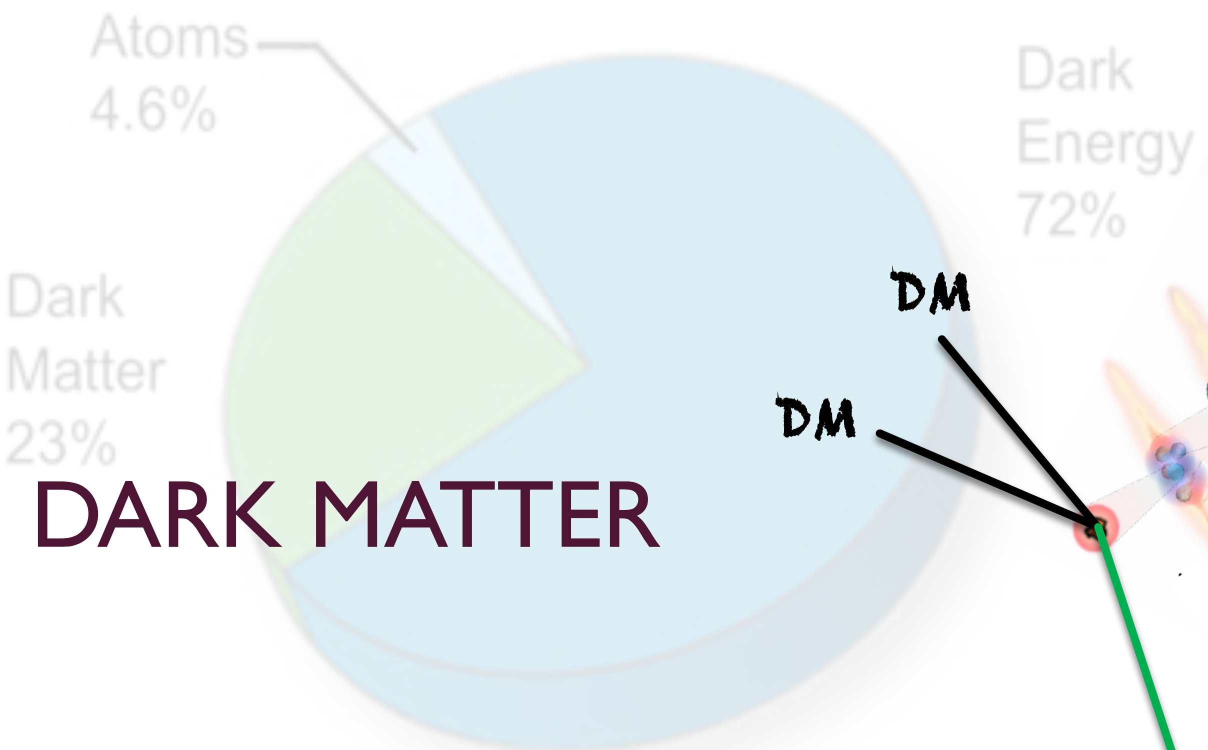
VECTOR LIKE QUARKS

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/index.html

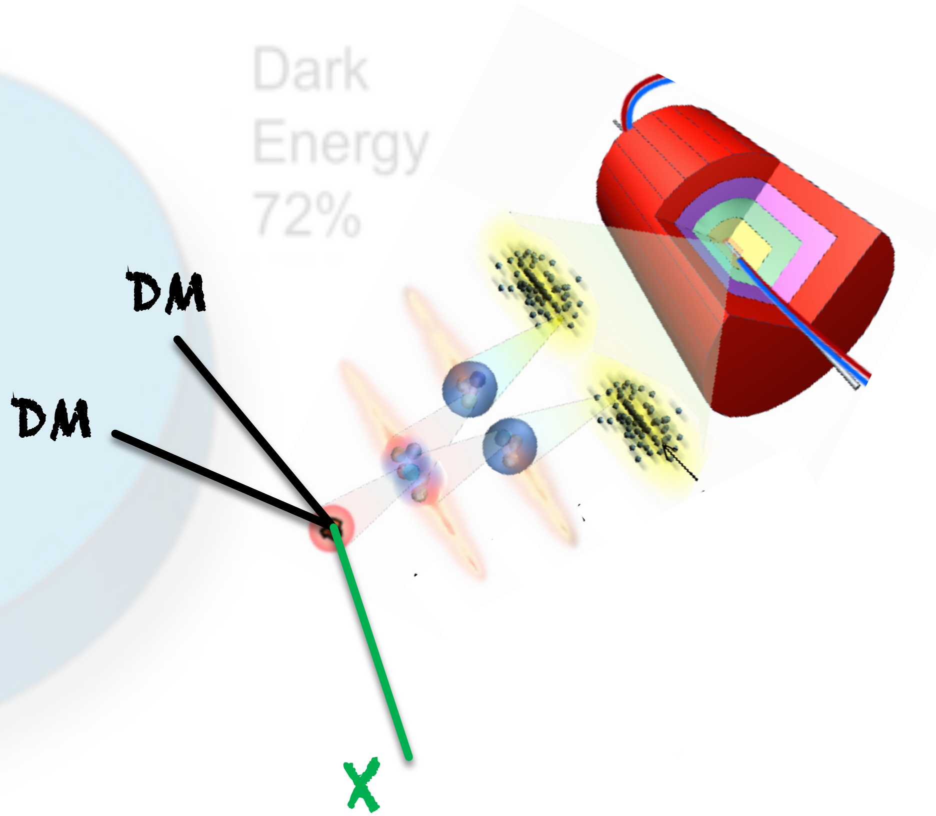


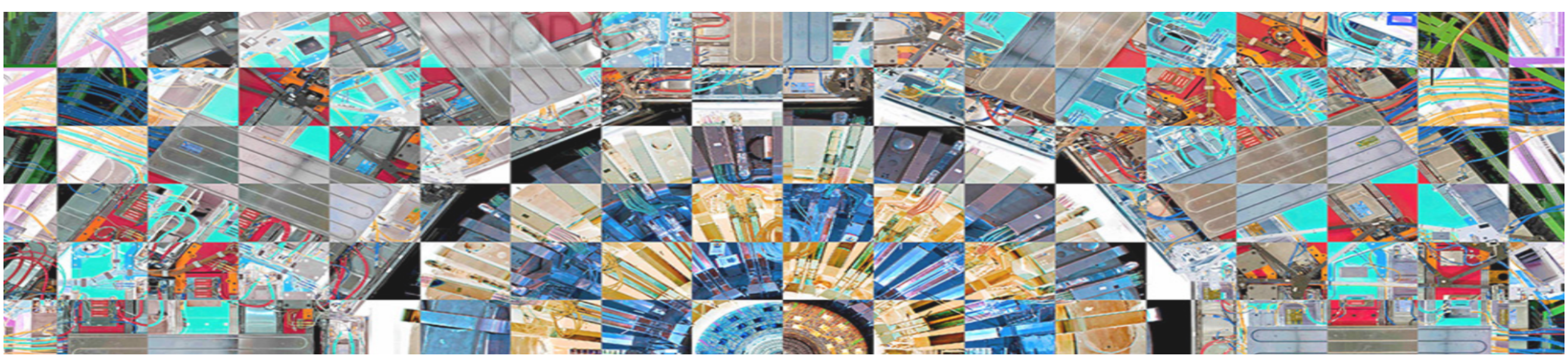


No significant excess observed



DARK MATTER





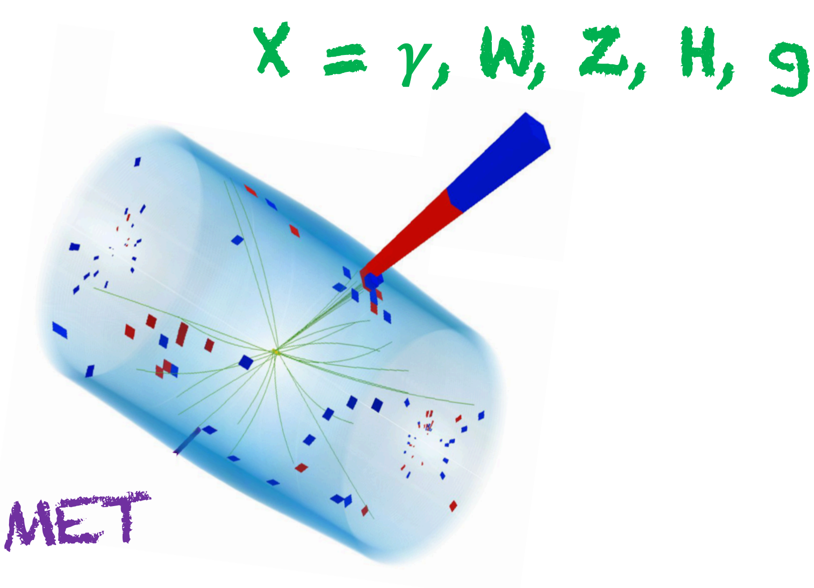
DARK MATTER

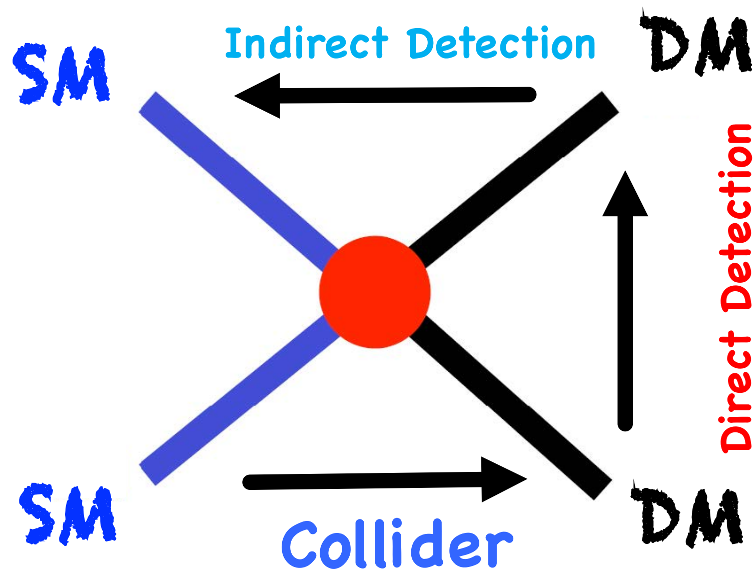
There is overwhelming evidence for the existence of dark matter from its gravtitational effects.

- Favourite collider candidate: WIMP
- Weakly interacting, massive, stable

➤ Should be able to produce at LHC

General collider strategy



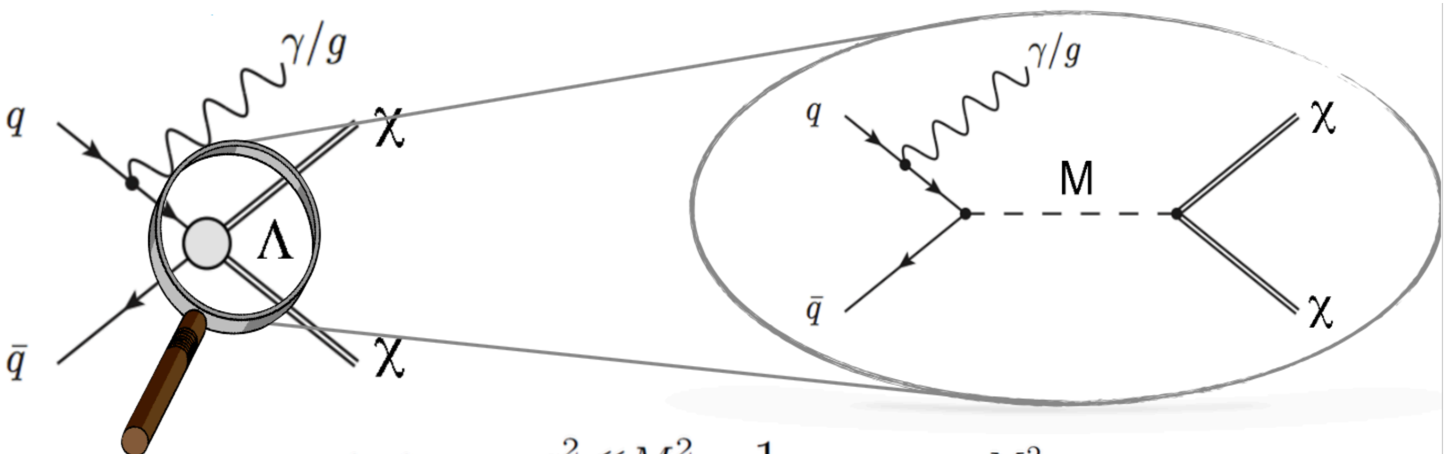


LHC DM FORUM: arXiv:1507.00966v1

INTERPRETING DM PRODUCTION

Effective Fiefld theory:
Heavy mediator integrated out

Simplified Model:
Explicit nature of the mediator



$$\frac{g_q g_\chi}{q^2 - M^2} \xleftrightarrow{q^2 \ll M^2} \frac{1}{\Lambda^2} \qquad \Lambda^2 = \frac{M^2}{g_q g_\chi}$$

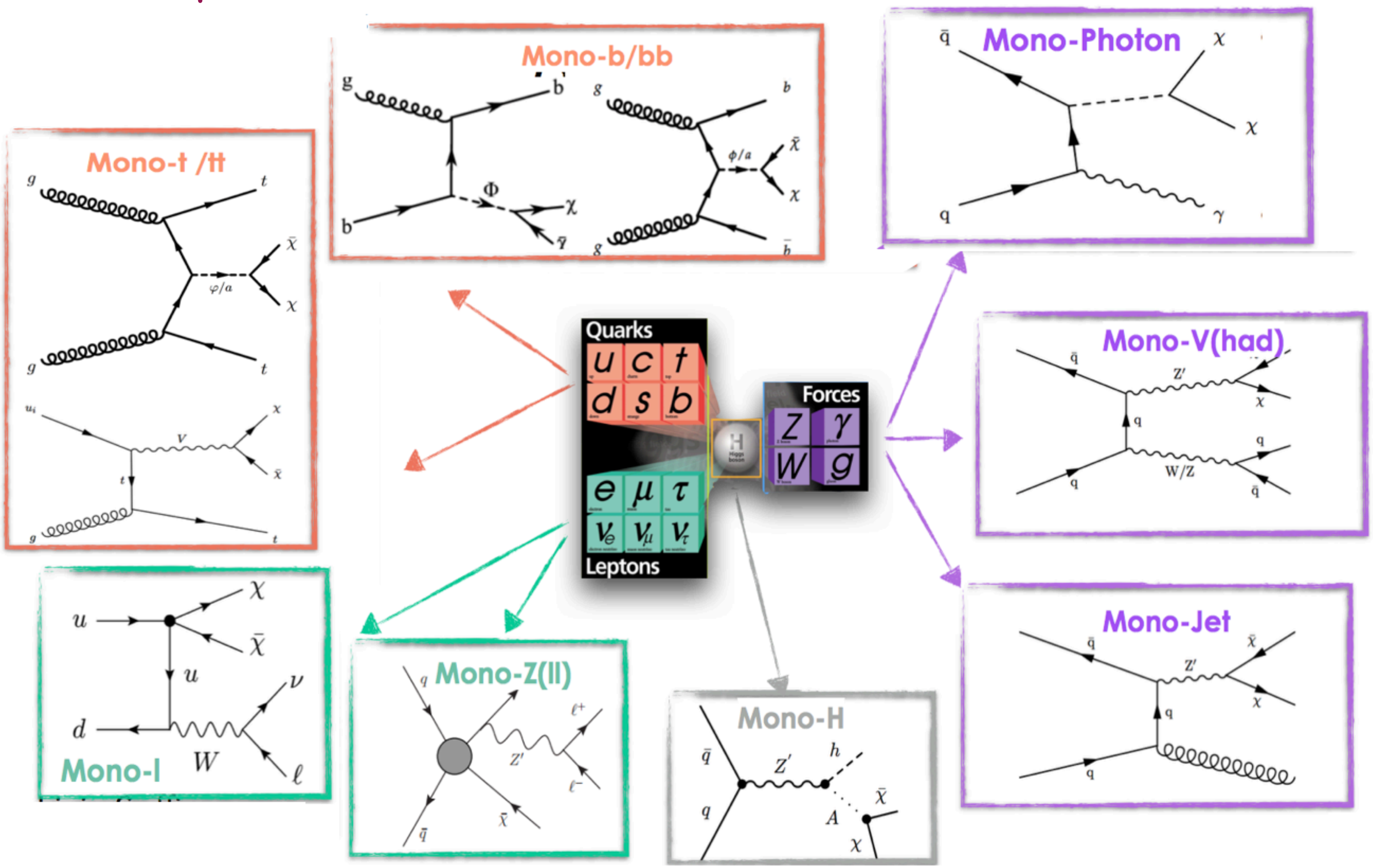
- Model independent
- Validity issues at LHC energies

$$Q_{\mathrm{transfer}} < M = \sqrt{g_\chi g_q}\Lambda < 4\pi\Lambda$$

- At least 4 parameters (M_{med}, M_{DM}, g_{SM} , g_{DM})
- Valid at all energies

WIDE RANGE AVAILABLE

A wide range of final states can be explored exploiting the full potential of the LHC experiment



MONO-JET

Generally most sensitive mono-X search

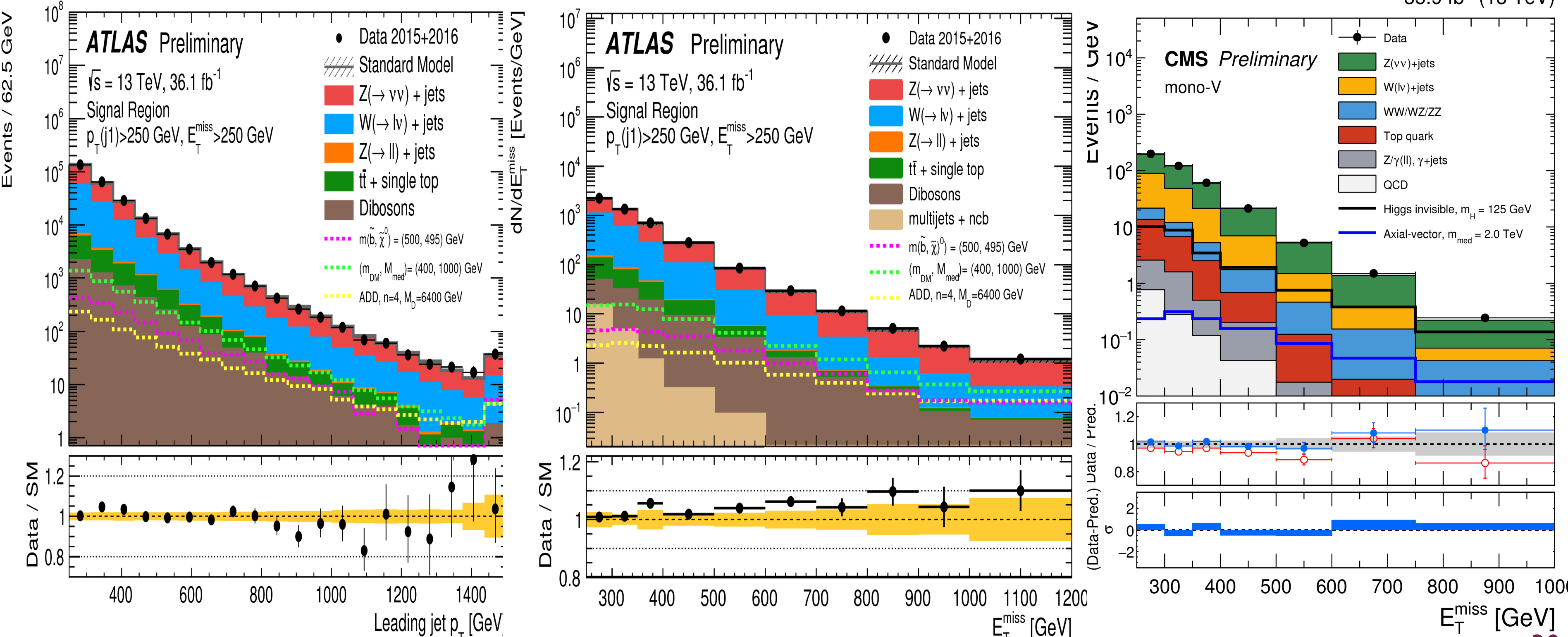
Selection:

- At least one high-p_T central jet
- Veto leptons & isolated tracks

Backgrounds:

- W/Z+jets, top, diboson, multijet
- Dominant backgrounds normalized in control regions

Signal region ⇒ high MET



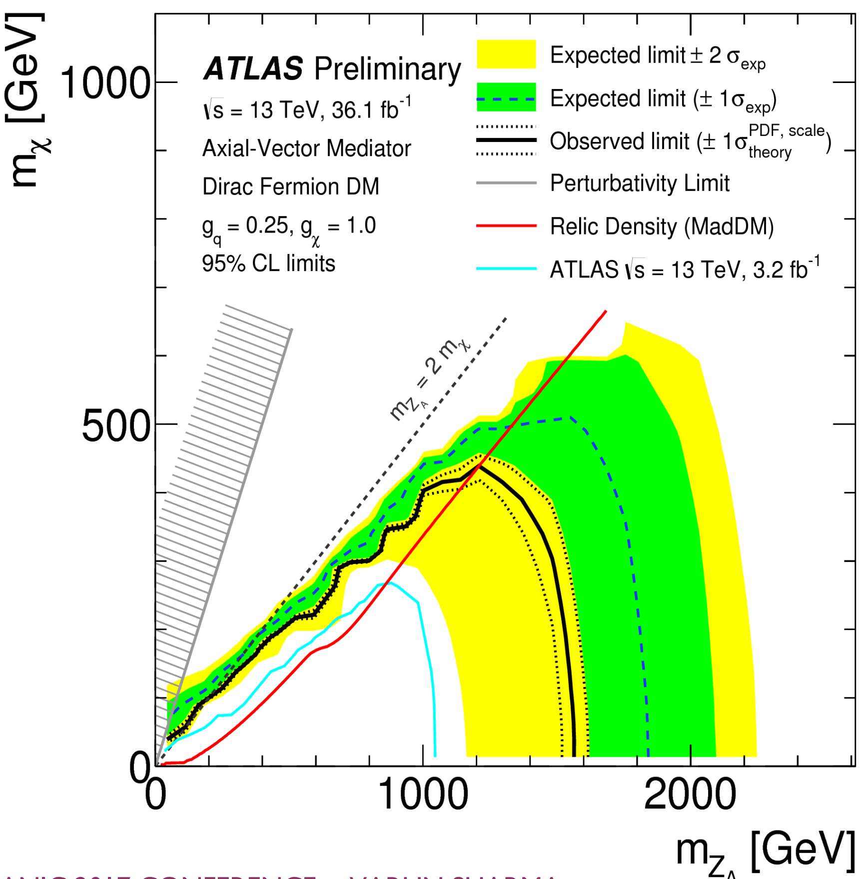
ATLAS-CONF-2017-060

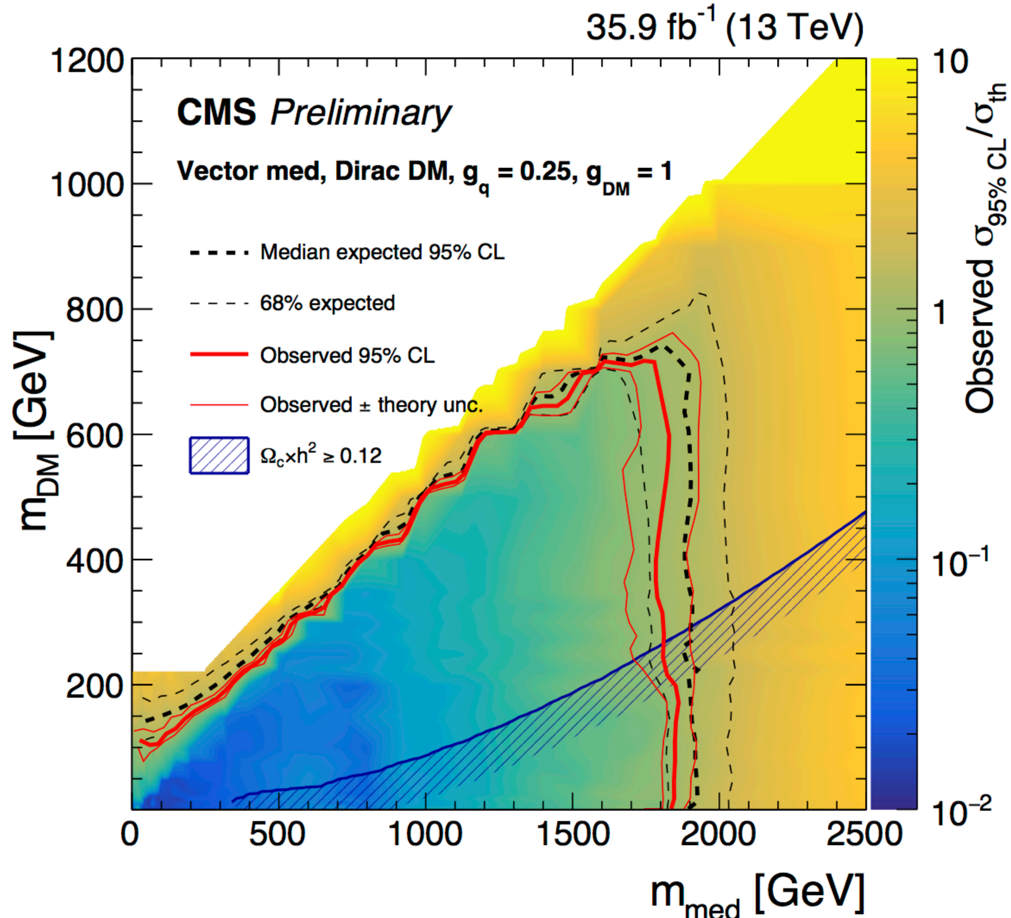
CMS PAS EXO-16-048

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-16-048/index.html

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2017-060/

Limits on mediator mass vs dark matter mass





MONO-JET - INTERPRETATIONS

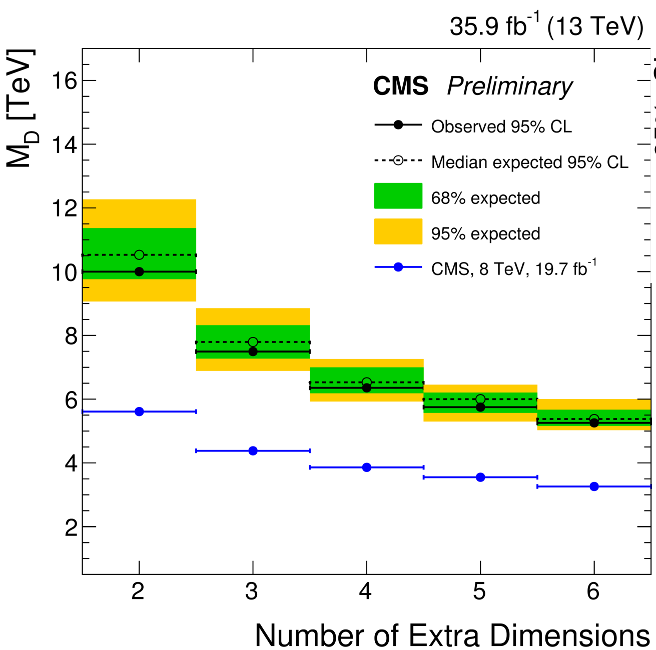
ATLAS-CONF-2017-060

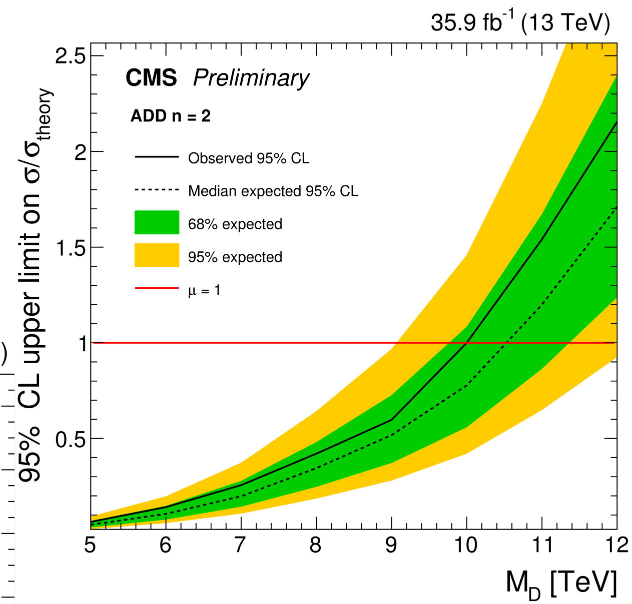
CMS PAS EXO-16-048

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-16-048/index.html

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2017-060/

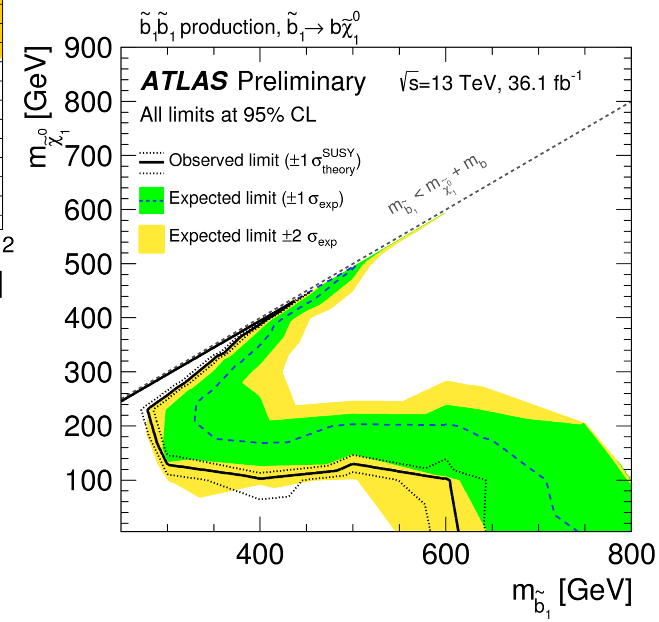
Extra Dimensions





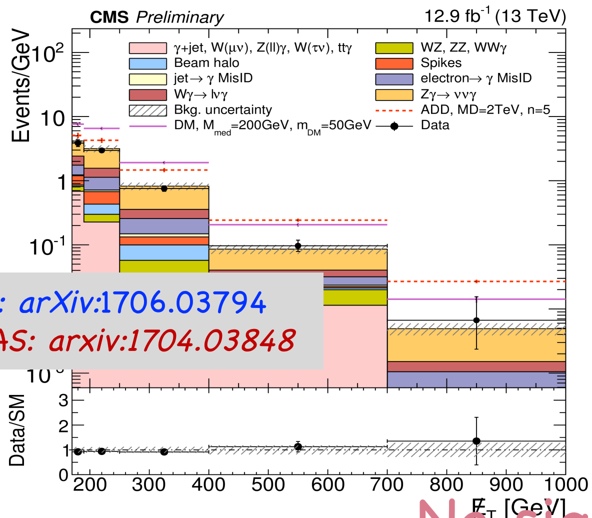
ADD Graviton

sbottom vs neutralino



MANY MORE MONO-X SEARCHES

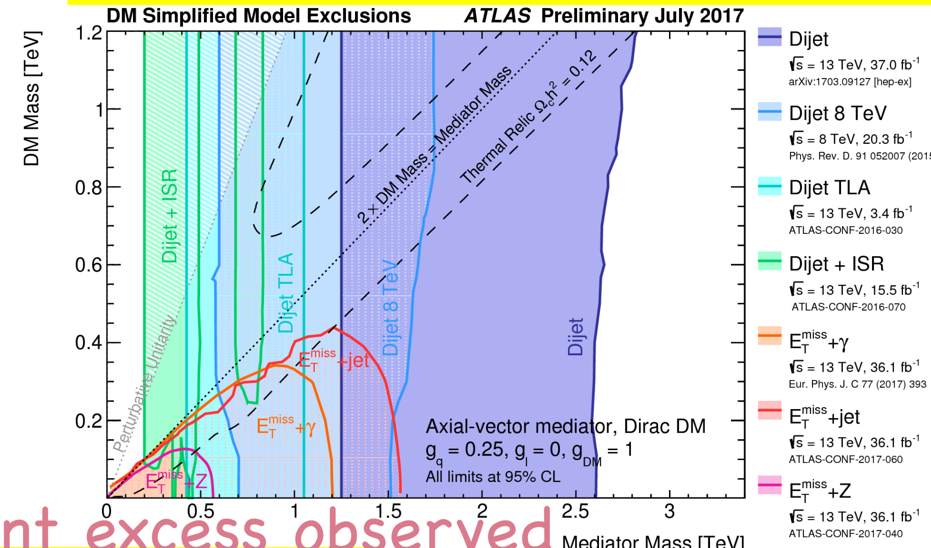
Mono-photon



CMS: arXiv:1706.03794

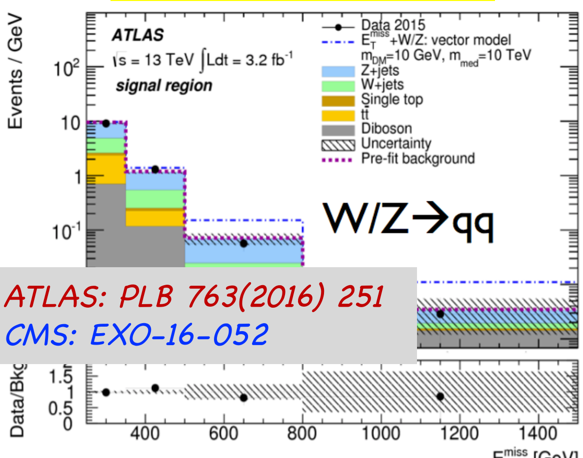
ATLAS: arxiv:1704.03848

A model-dependent summary of various searches



No significant excess observed

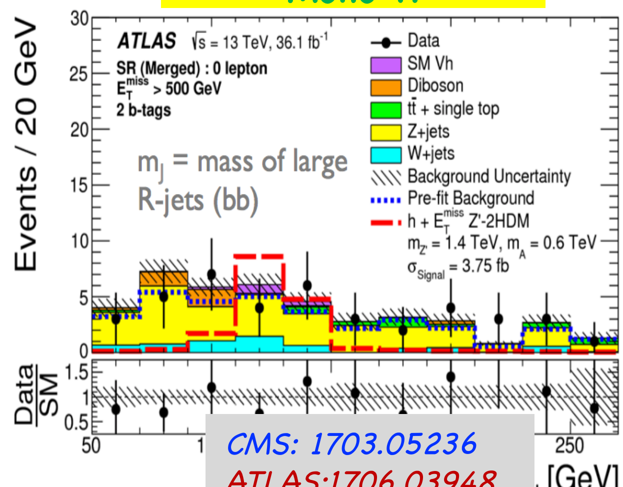
Mono-W/Z



ATLAS: PLB 763(2016) 251

CMS: EXO-16-052

Mono-H

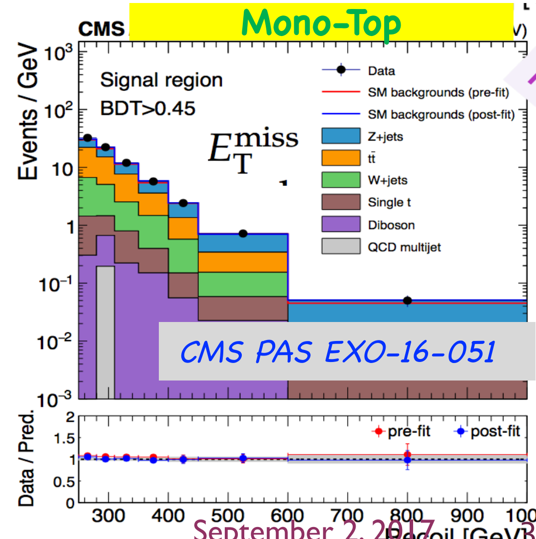


CMS: 1703.05236

ATLAS:1706.03948

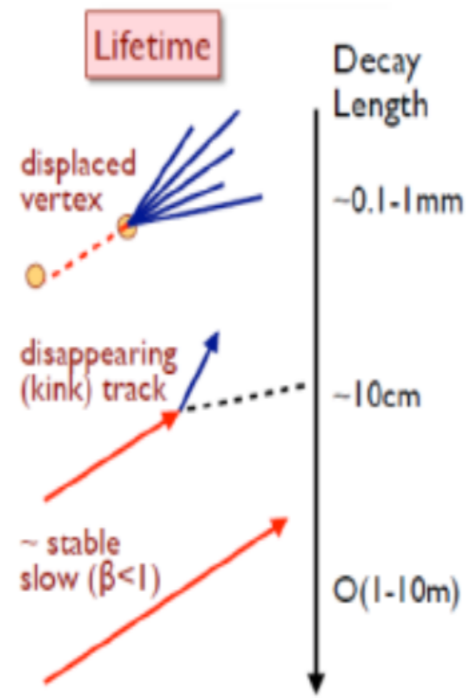
ATLAS:1707. 01302

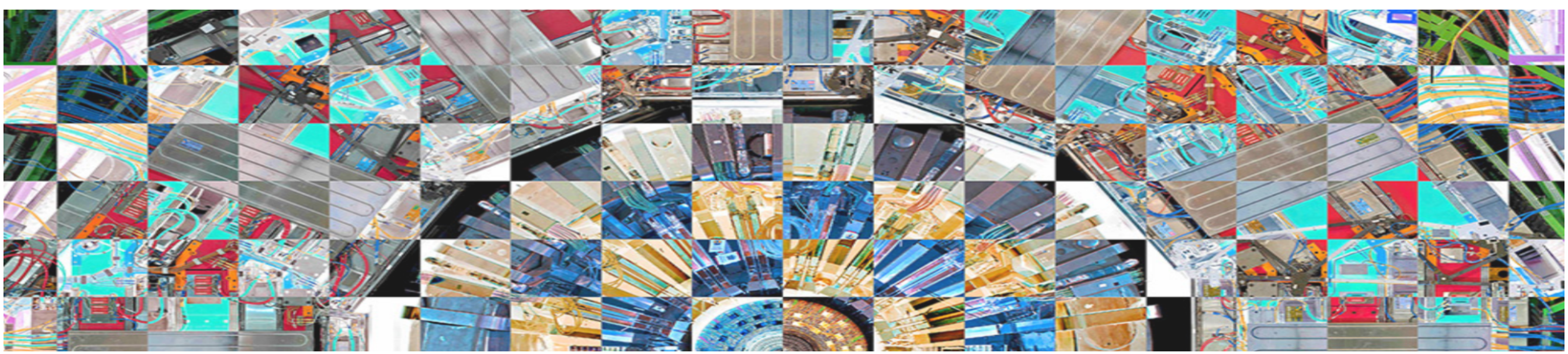
Mono-Top



CMS PAS EXO-16-051

LONG-LIVED PARTICLES



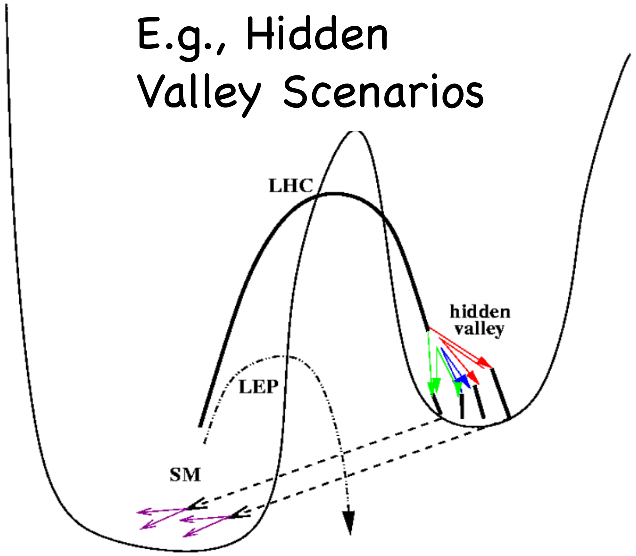


LONG-LIVED PARTICLES

What makes a particle long lived:

- Small coupling in decay chain
  - R-Parity Violating decays
- Small mass difference in decay chain
  - Split SUSY
- Hidden Valley

E.g., Hidden Valley Scenarios



Signatures depend on the lifetime

What to look for?

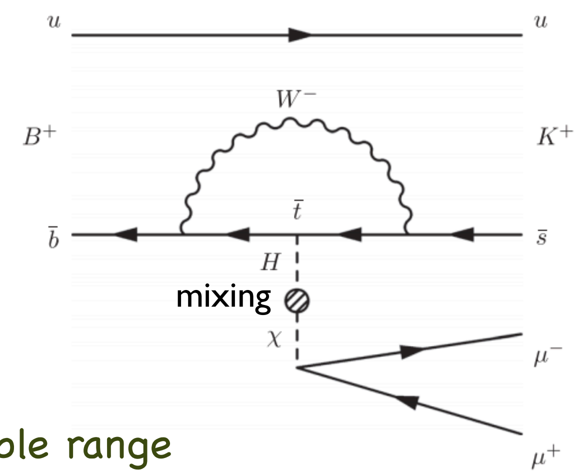
- Non-pointing or delayed photons
- Out-of-time decays
- Disappearing tracks
- Displaced jets or vertices
- Trackless jets

HIDDEN SECTOR IN B ➛ $K^*\chi(\mu\mu)$

PRD 95, 071101 (2017)

Search for new hidden-sector bosons in b⟶s penguin transistions.

- Can be Long-lived *inflatons* (or axions)
- Search for narrow peak in m($\mu\mu$), excluding QCD resonance.

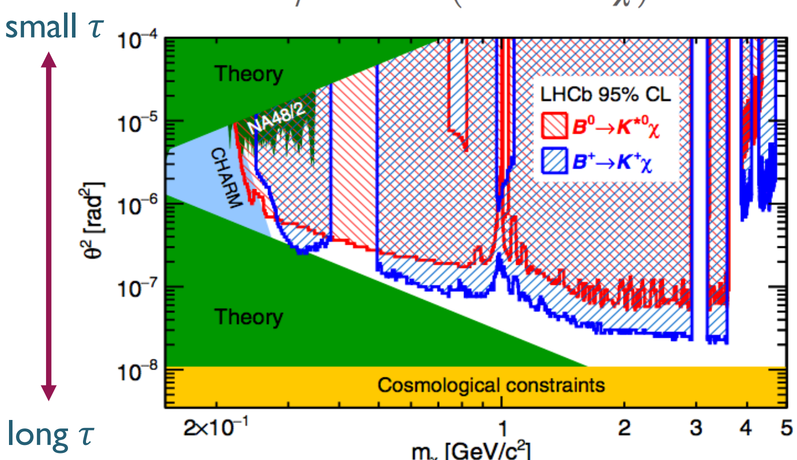


LHCb collected record samples of rare decays B⟶K$^*\mu\mu$

Constraints on new scalar mixing with Higgs

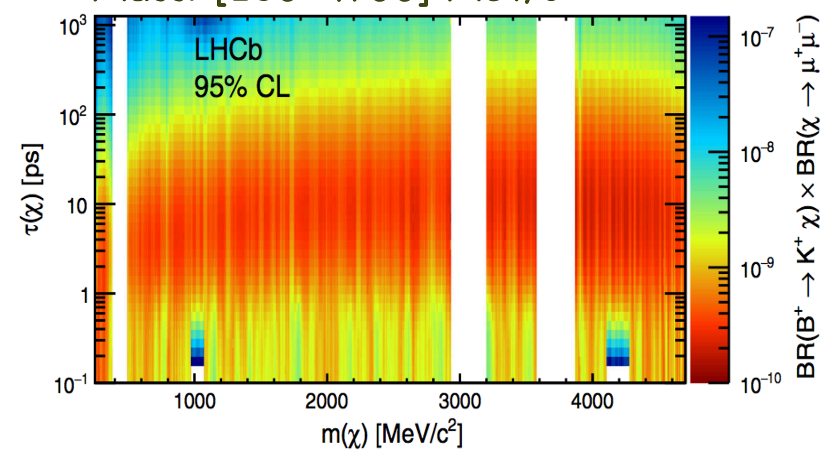
$$|\chi\rangle_{\text{phys}} = \cos\theta|\chi\rangle + \sin\theta|\text{Higgs}\rangle$$

$$\tau \propto 1/\theta^2 \qquad \mathcal{B}(B^+ \to K^+\chi) \propto \theta^2$$



Parameter space of the inflaton model: mixing angle vs mass

Accessible range
Lifetime: [0.1-1000]ps (30μm to 30cm)
Mass: [250-4700] MeV/c²



No significant excess observed

LLP ➝ μ + JETS

EPJC (2017) 77:224
arXiv:1612.00945

Signature

Single displaced vertex with several tracks and a high-p_T muon.

Model

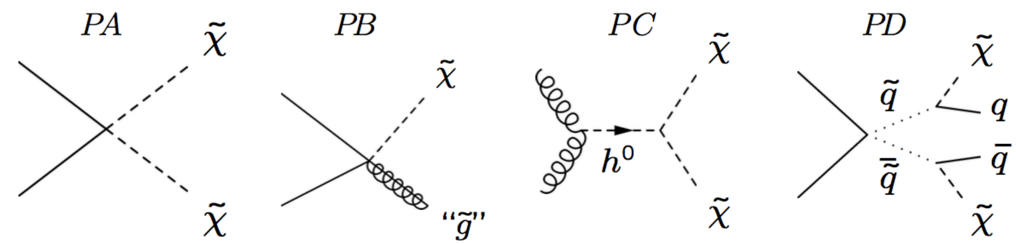
RPV mSuGRA neutralino (LLP) decaying to a muon & two jets

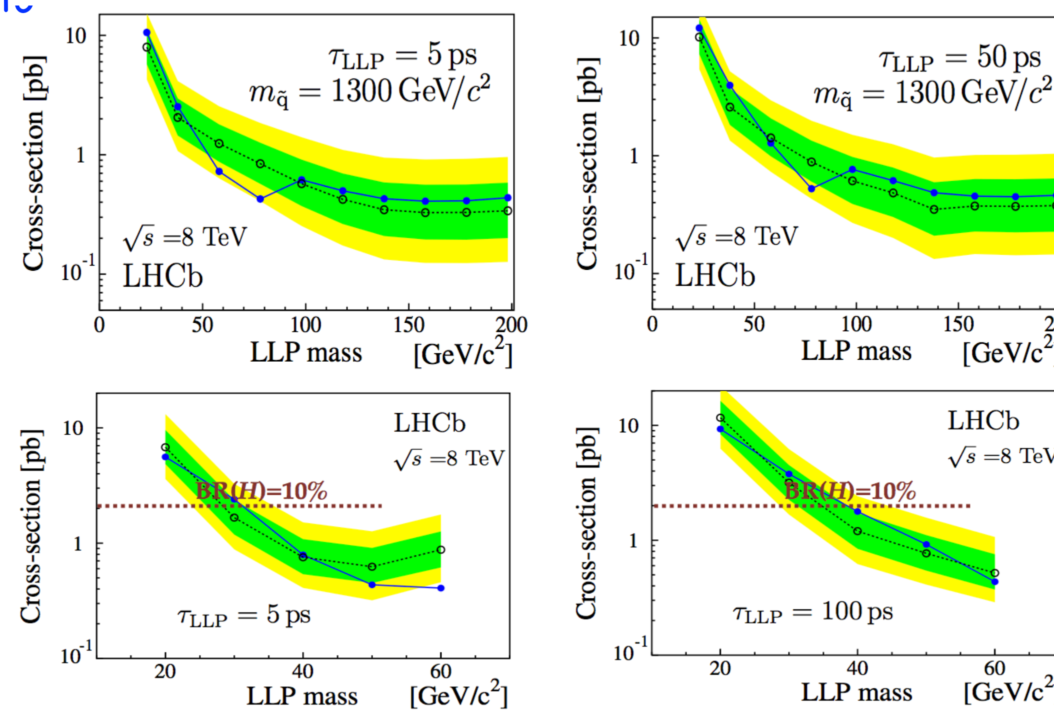
LLP: m[20-80] GeV/c^2; τ[5-100]ps

Larger than typical b-hadron lifetimes

Corresponds to an average lifetime dist. of up to 30cm (well inside LHCb vertex detector)

Production mechanisms





Interpretations

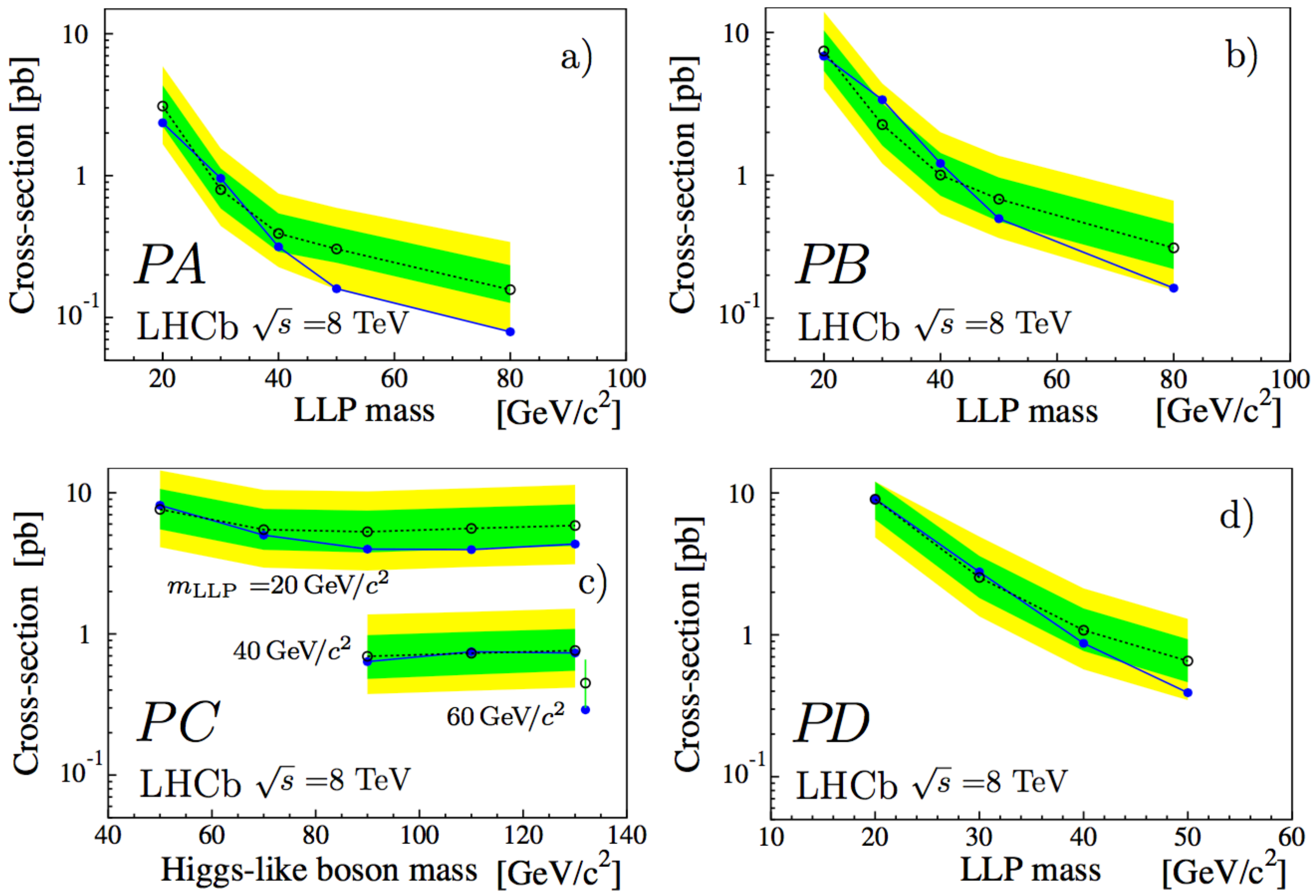
- RPV mSUGRA from Pythia6
- Simplified topologies: Higgs(125) decays

Rejected BR(H➝$\chi\chi$)>10% down to m_χ = 30 GeV; τ_χ =5ps

LLP → μ + JETS

EPJC (2017) 77:224
arXiv:1612.00945

Category wise results



No excess above background expectation observed

LLP ➛ JET + JET

EPJC (2017) 77:224
arXiv:1705.07332

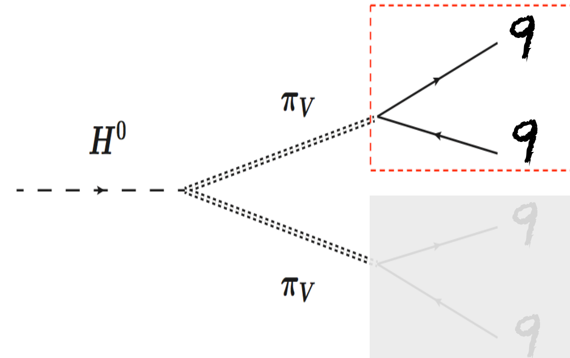
Signature
Single displaced vertex associated with two jets.

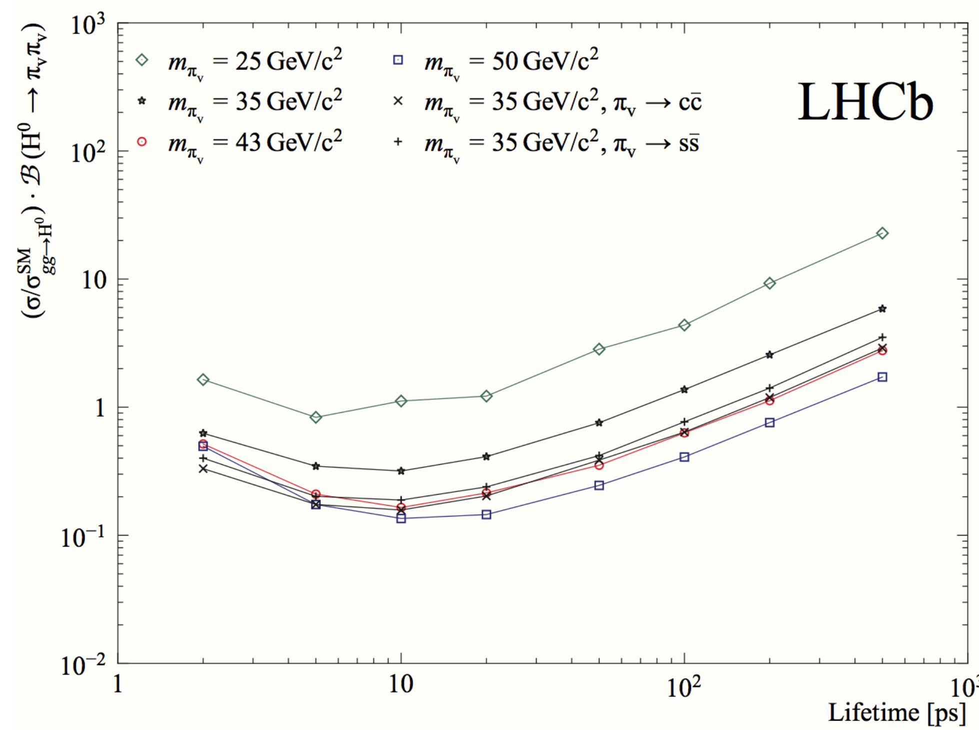
Model
Hidden Valley pions (π_V) from SM Higgs decay

LLP: m[20-50] GeV/c²; τ[2-500]ps

From simulation ➤ No more than one of the two π_V decays occur inside the LHCb acceptance

No evidence of unknown Long-lived particles





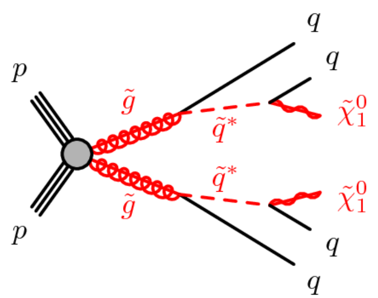
LONG-LIVED PARTICLES

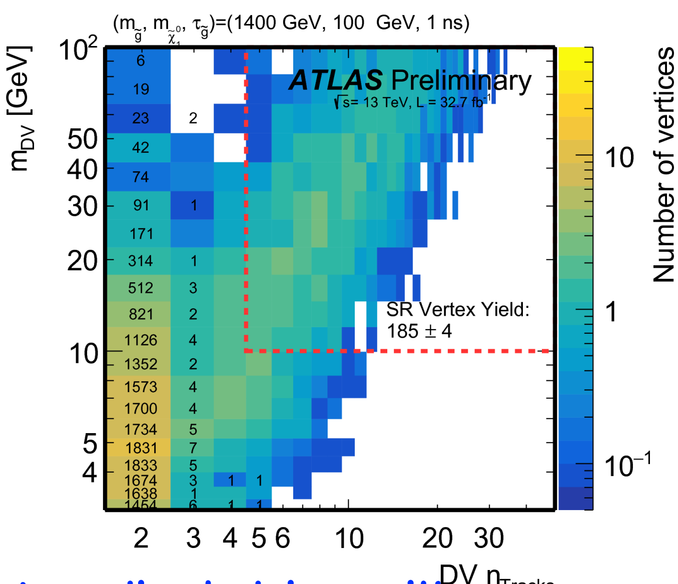
ATLAS-CONF-2017-026

CMS-PAS-EXO-17-004

Displaced vertices + MET

ATLAS-CONF-2017-026





Long-lived gluinos with masses up to 2.2 TeV in a simplified model inspired by split SUSY

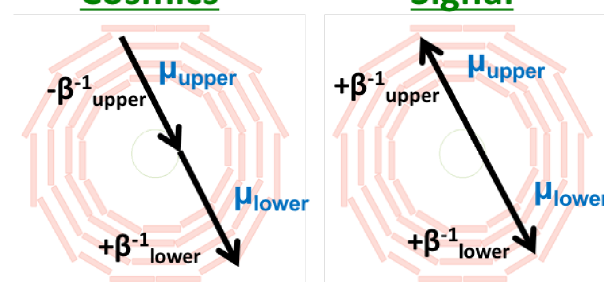
Stopped Objects ➢ Muons

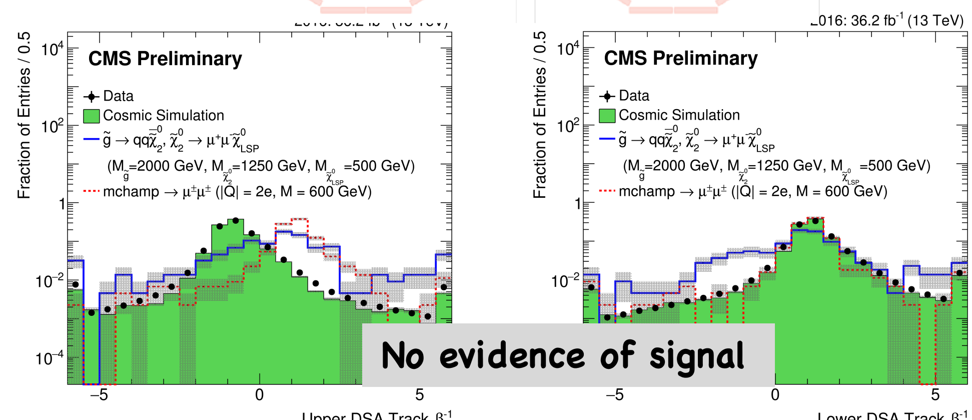
CMS-PAS-EXO-17-004 **FIRST RESULTS @LHC**

LLP that stop in the CMS detector and decay to muons

Trigger: Events out-of-time with collision

Dedicated algorithm: Delayed StandAlone muon track



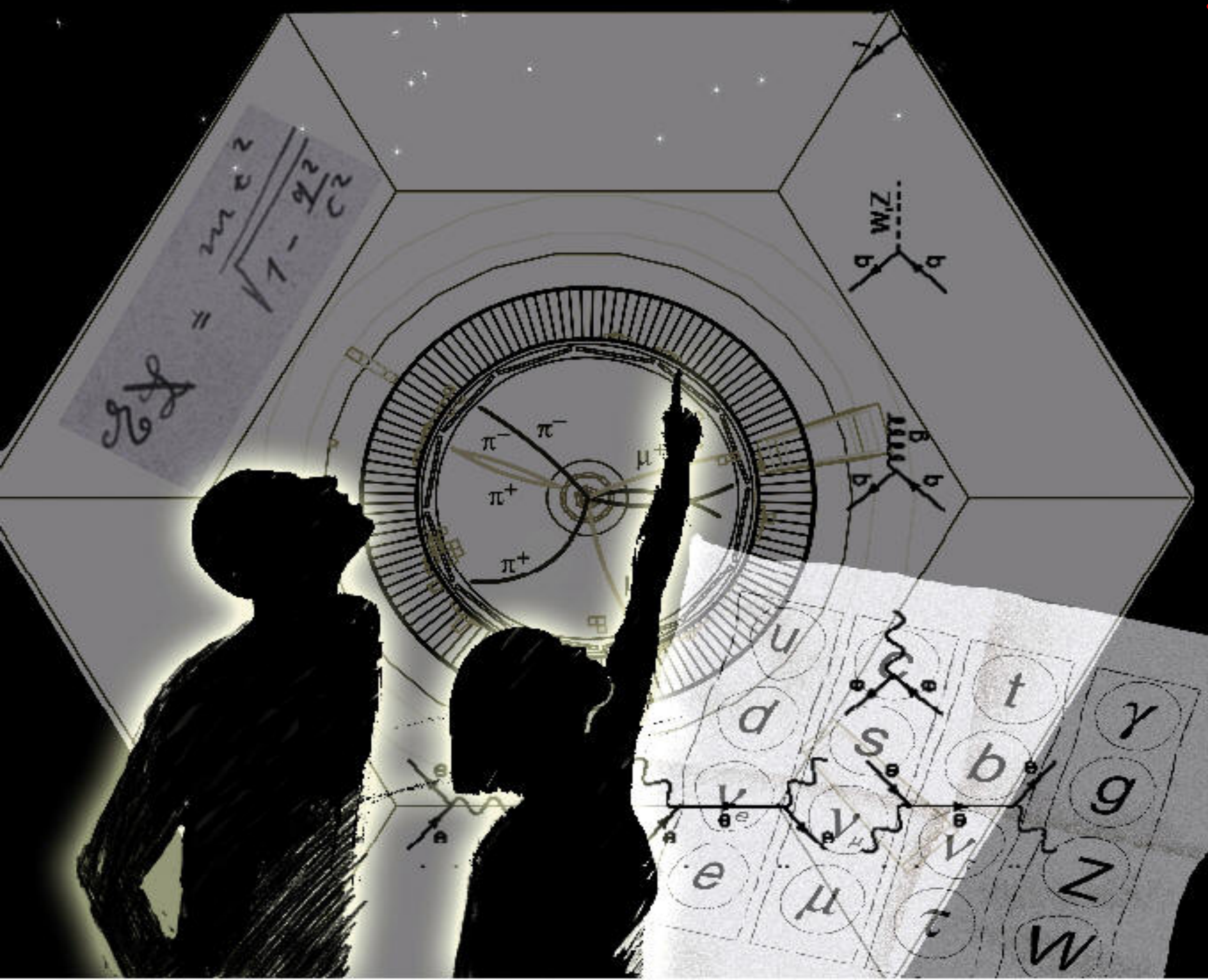


Cross section times BF limits were also set for each gluino and mchamp mass as a function of lifetime, for lifetimes between 100 ns and 10 day

SUMMARY

- ✓ An immense program of searches for new physics at the energy frontier (LHC) is being carried out.
- ✓ ATLAS, CMS and LHCb are making tremendous efforts to study the LHC data.
- ✓ Nothing has turned up yet!
- ✓ Stringent limits and contraints on most of the new physics scenarios
  - ✓ More sophisticated and ingenius techniques being employed to make full use of the LHC data.
  - ✓ All possible efforts being made to explore extreme region of phase space and a plethora of theories and models.
- ✓ Special thanks to theory community for reliable Monte Carlo simulation predictions and precise theoretical calculations.

The LHC Landscape



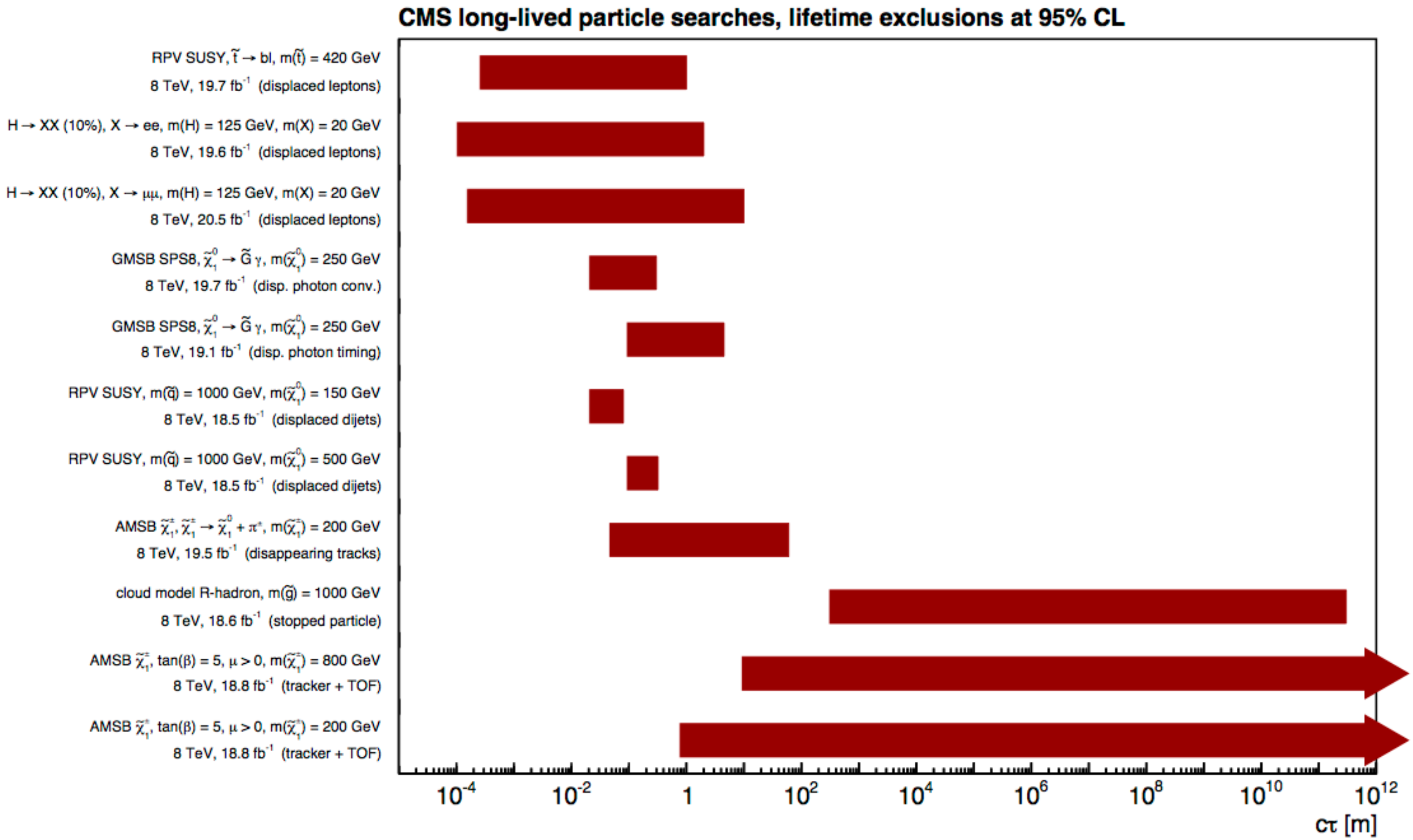
The game is on!

Stay Tuned!
Lot more to come

Thank You

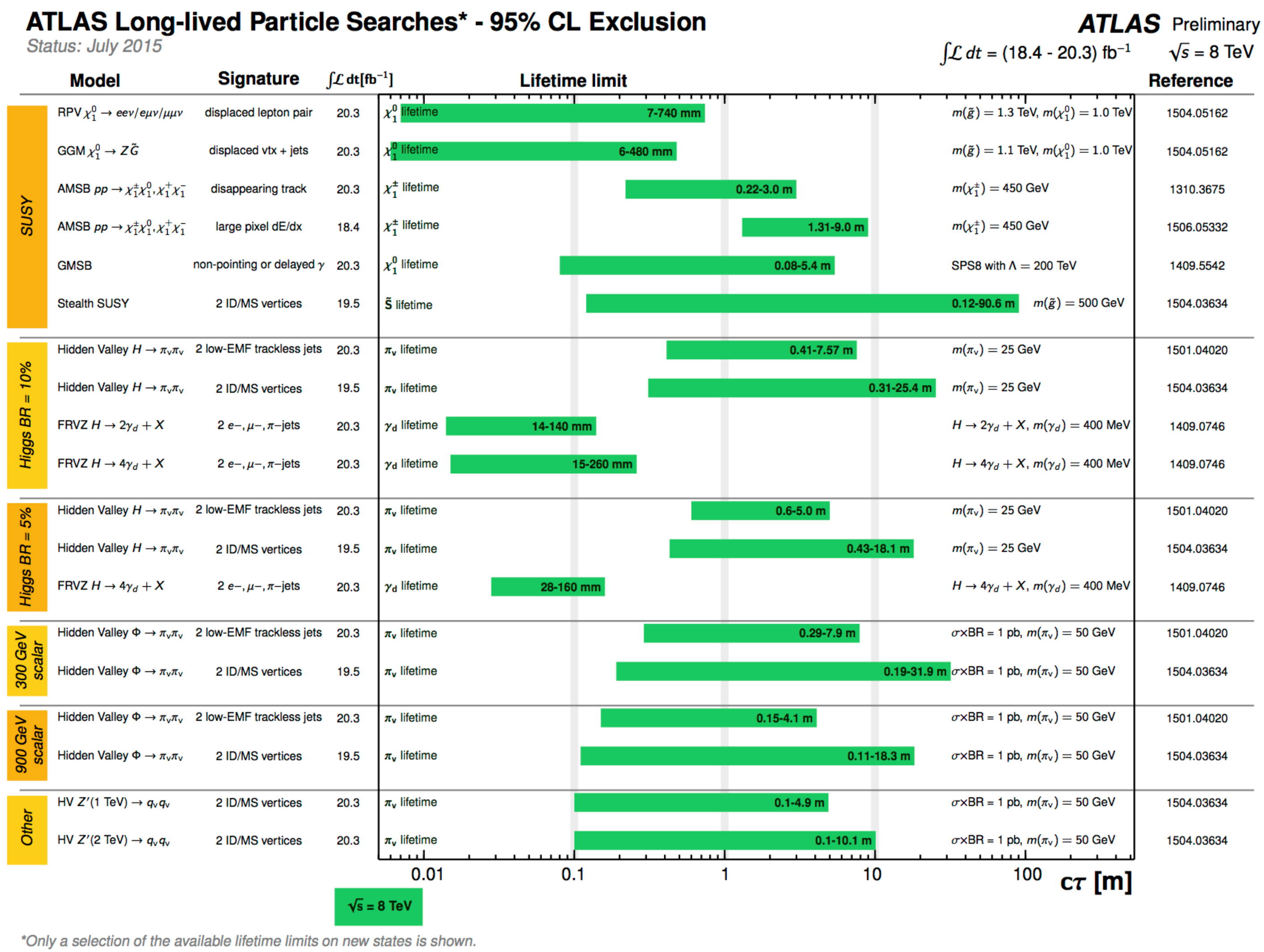
EXTRA MATERIAL

CMS LONG-LIVED PARTICLE SEARCHES



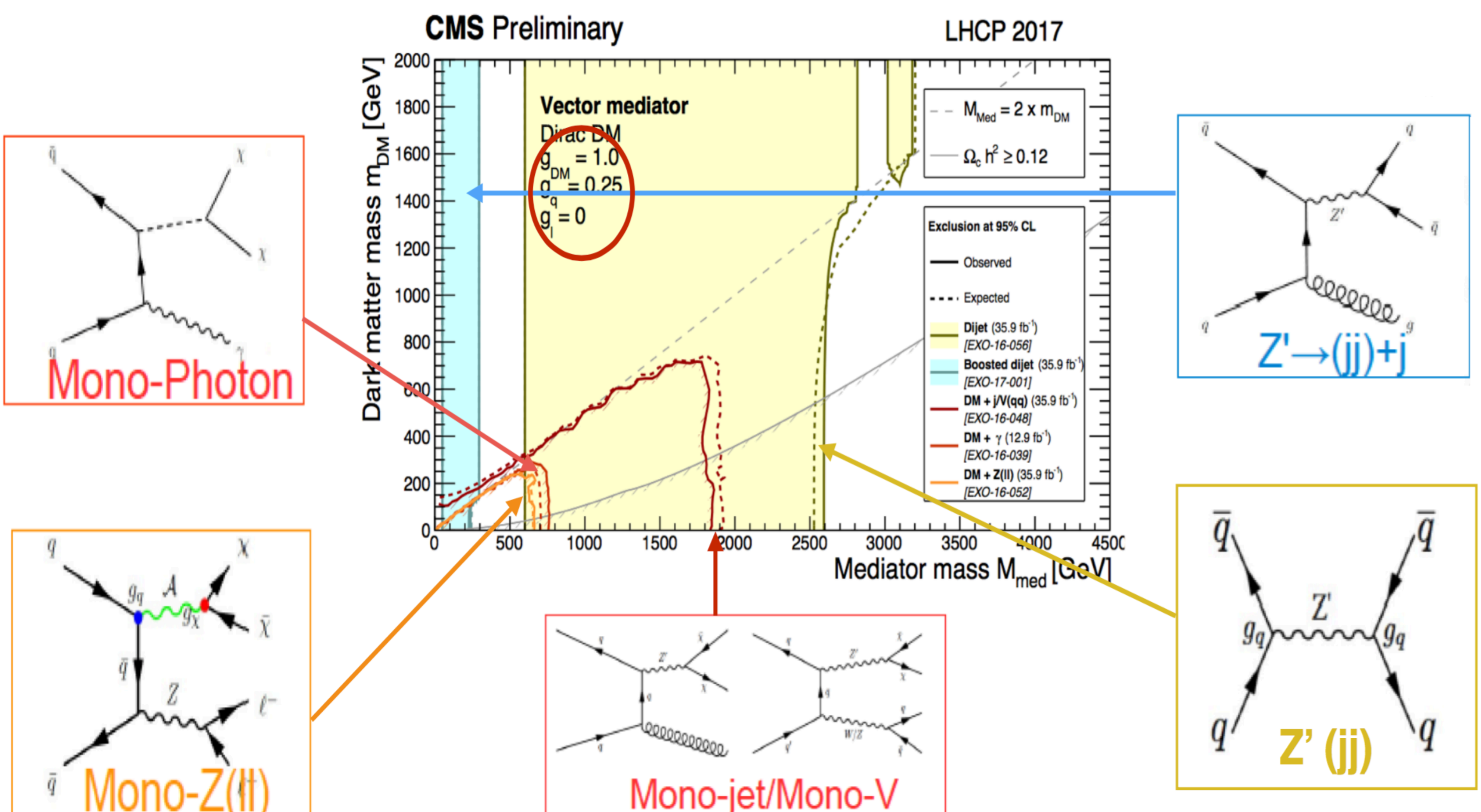
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

ATLAS LONG-LIVED PARTICLE SEARCHES



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

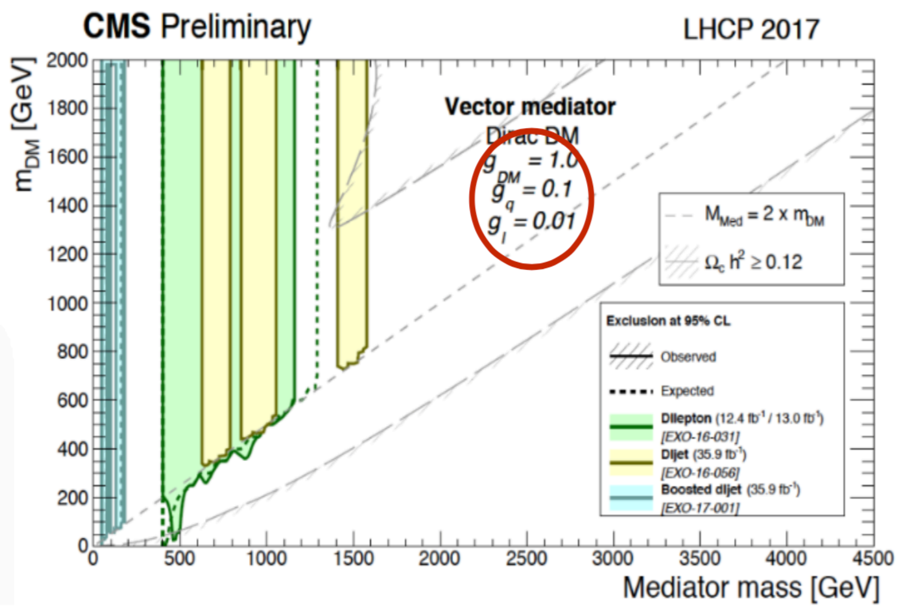
DARK MATTER @ CMS

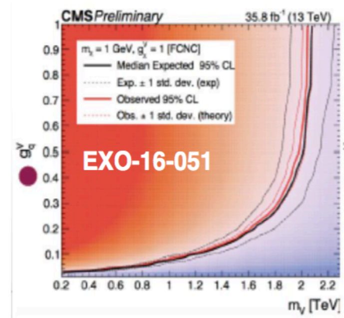


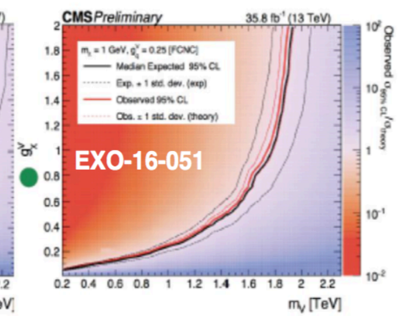
COUPLING STRENGTH MATTERS

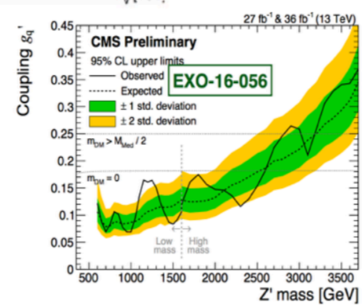
With a simple change of coupling strength ($g_q = 0.25 \longrightarrow 0.1$), the sensitivity is back to square one!

and we don't know what the coupling really is …





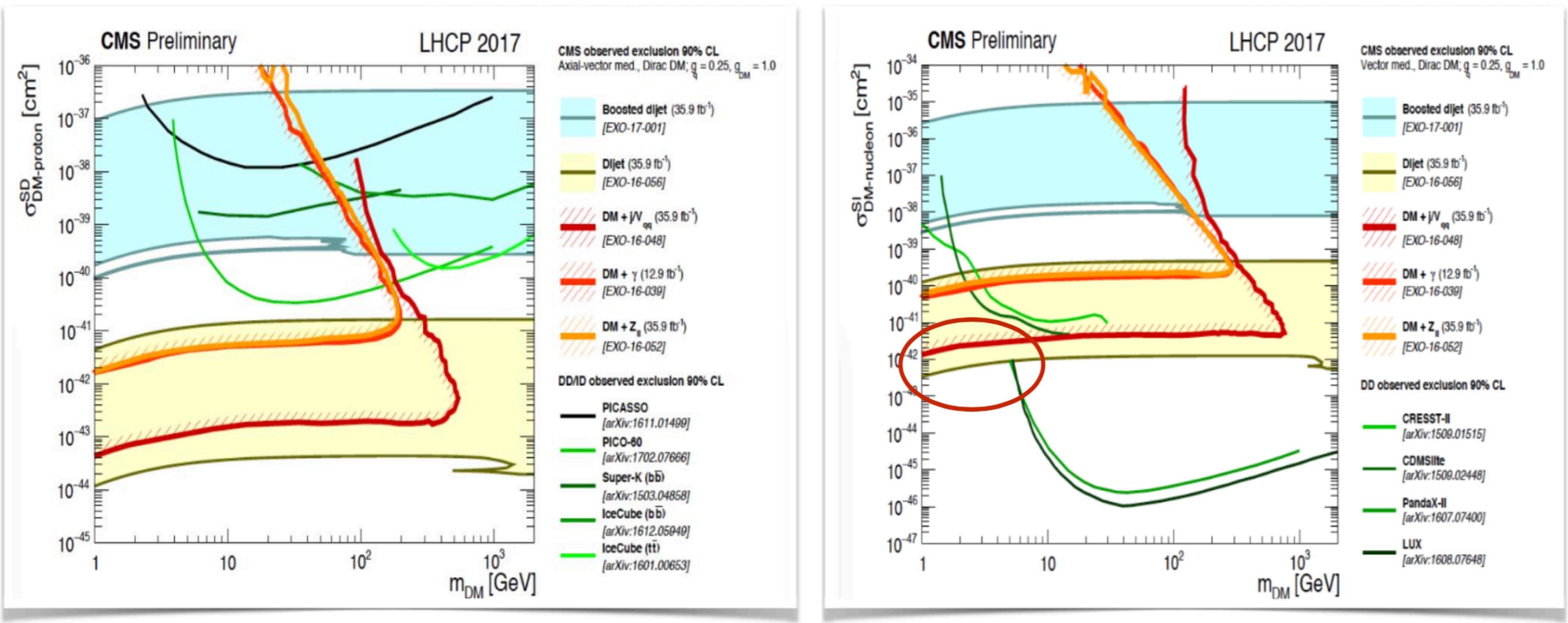




CMS has started presenting the results in terms of the coupling reach!

Discussions on going on the "next generation" of coupling plots

GLOBAL PICTURE : COMPARISON TO EVERYONE



<u>For light DM</u>, LHC has higher sensitivity.

At colliders, sensitivity is limited by threshold effects, resolution and background estimation.