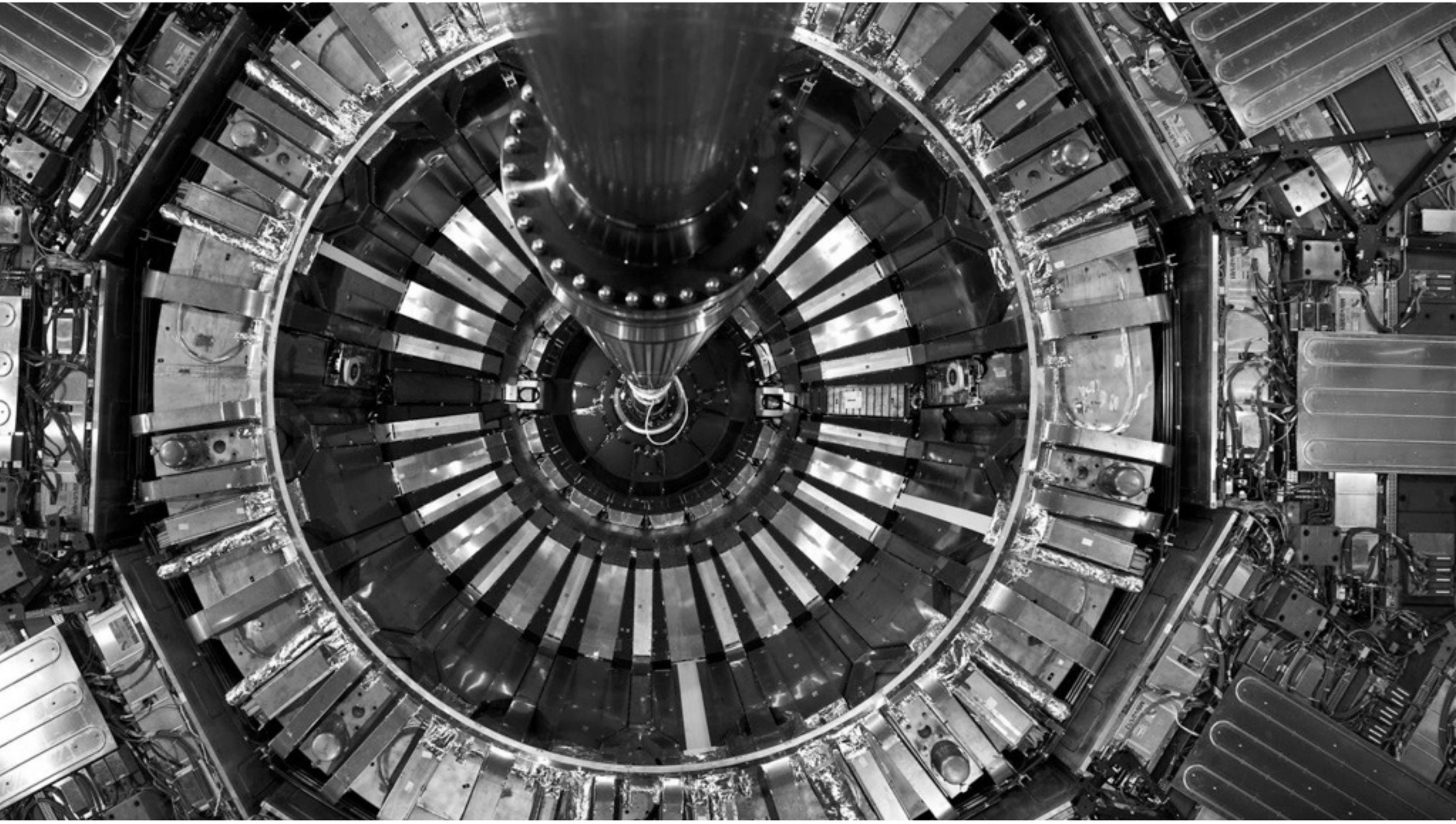
Beyond The SM Searches with CMS



Francisco Yumiceva

Florida Institute of Technology

Guatemala, SILAFAE 2016 — Nov. 18, 2016

Introduction

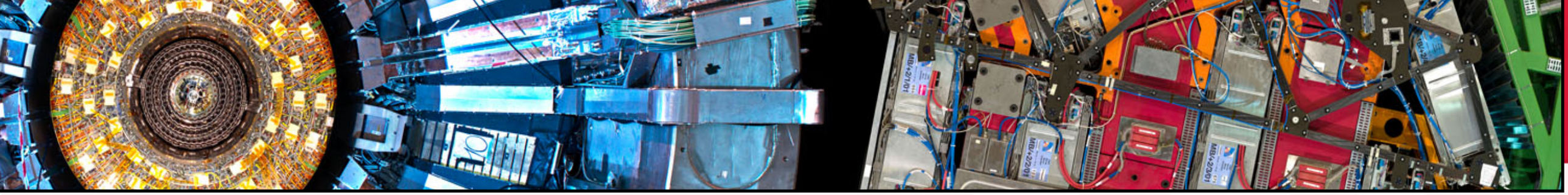
- I will present a brief summary of resent BSM searches with the CMS detector.

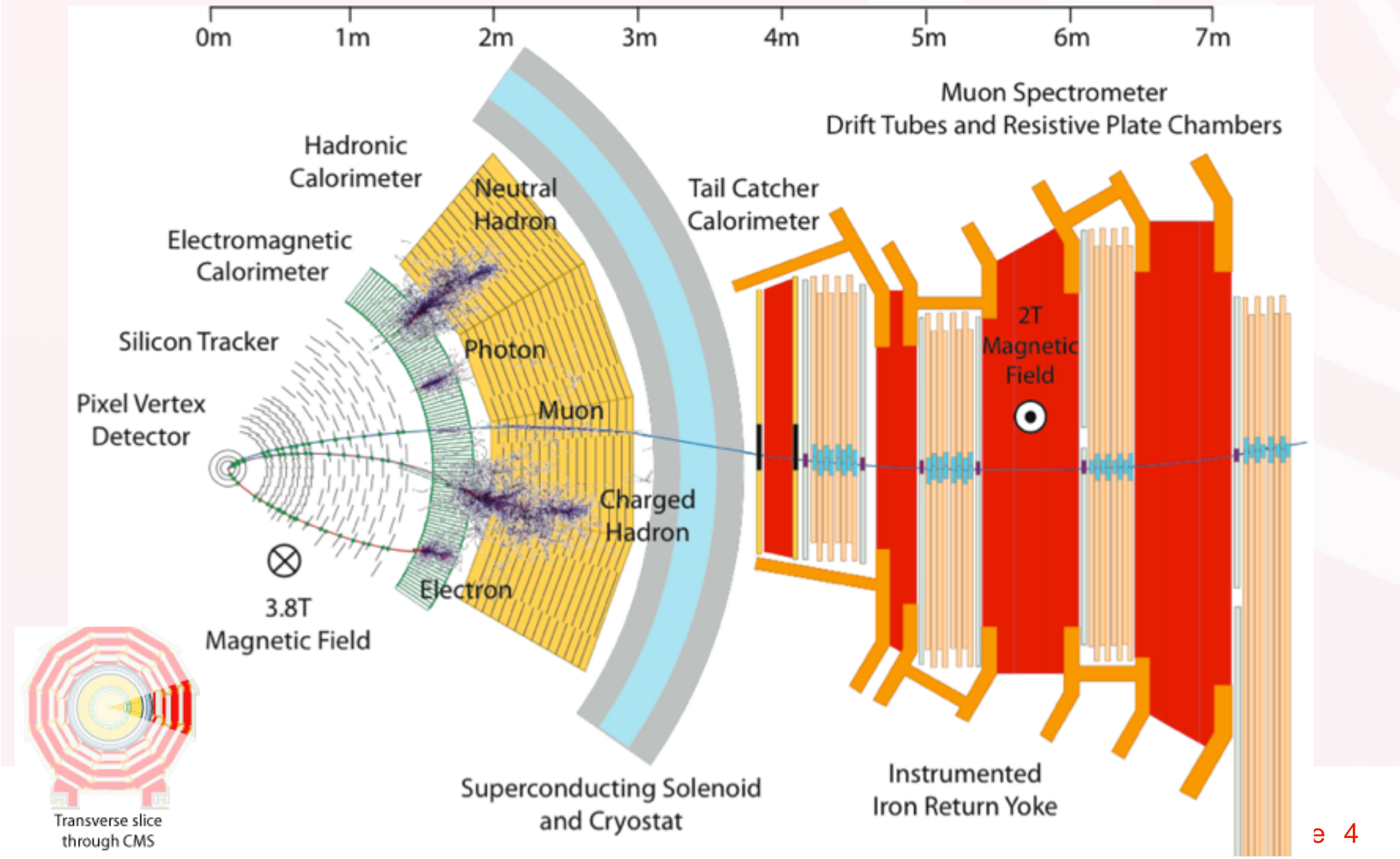
- Other results from CMS/Atlas shown in SILAFAE by:
  - Oscar Gonzalez on Higgs results.
  - Sudhir Malik on SUSY searches
  - Leonid Serkin Atlas results

- List of public results on CMS Exotica results at
  - http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html

- List of public results on CMS Beyond Two Generations (B2G) results at
  - http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G/index.html

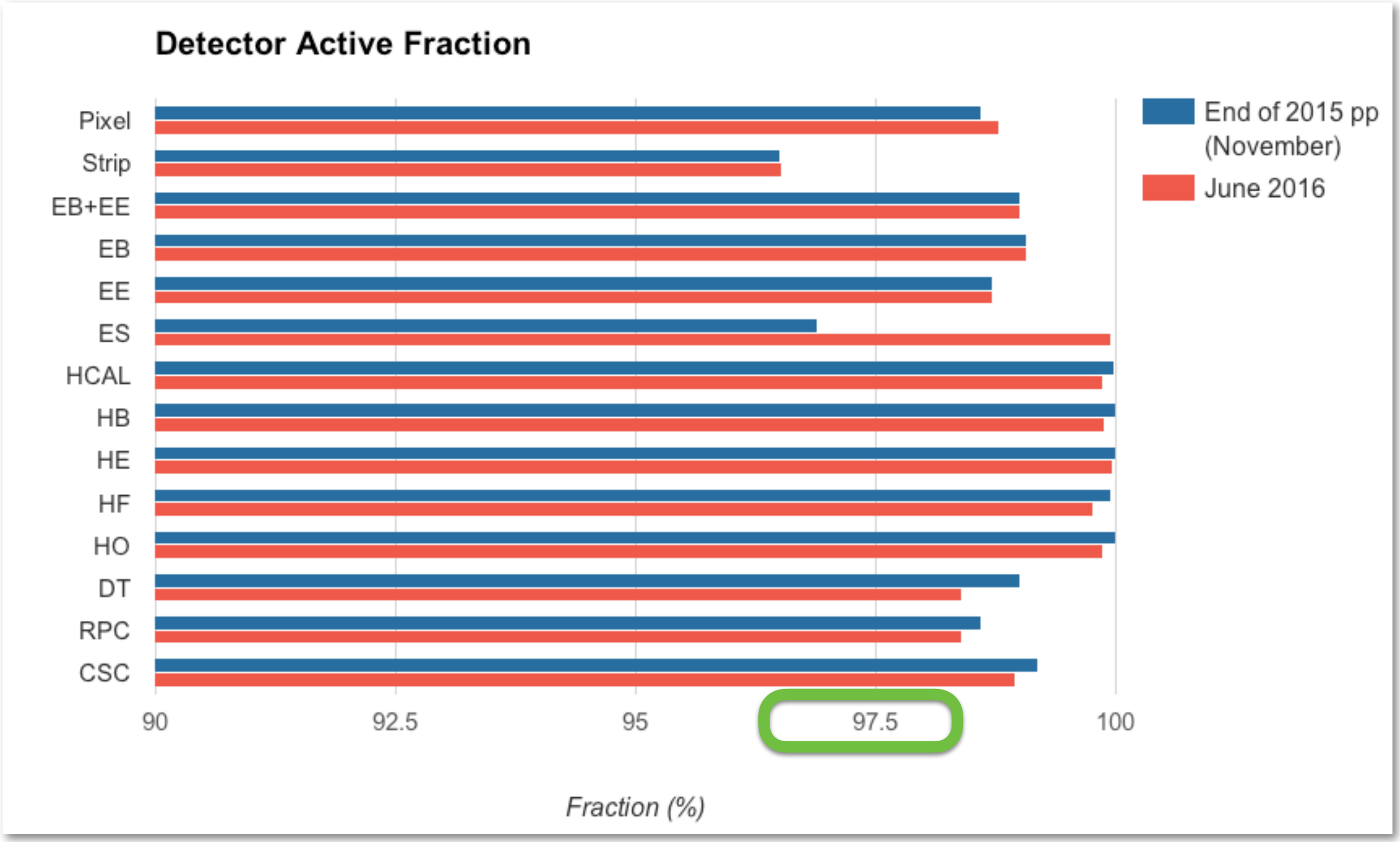
First, our tool ….



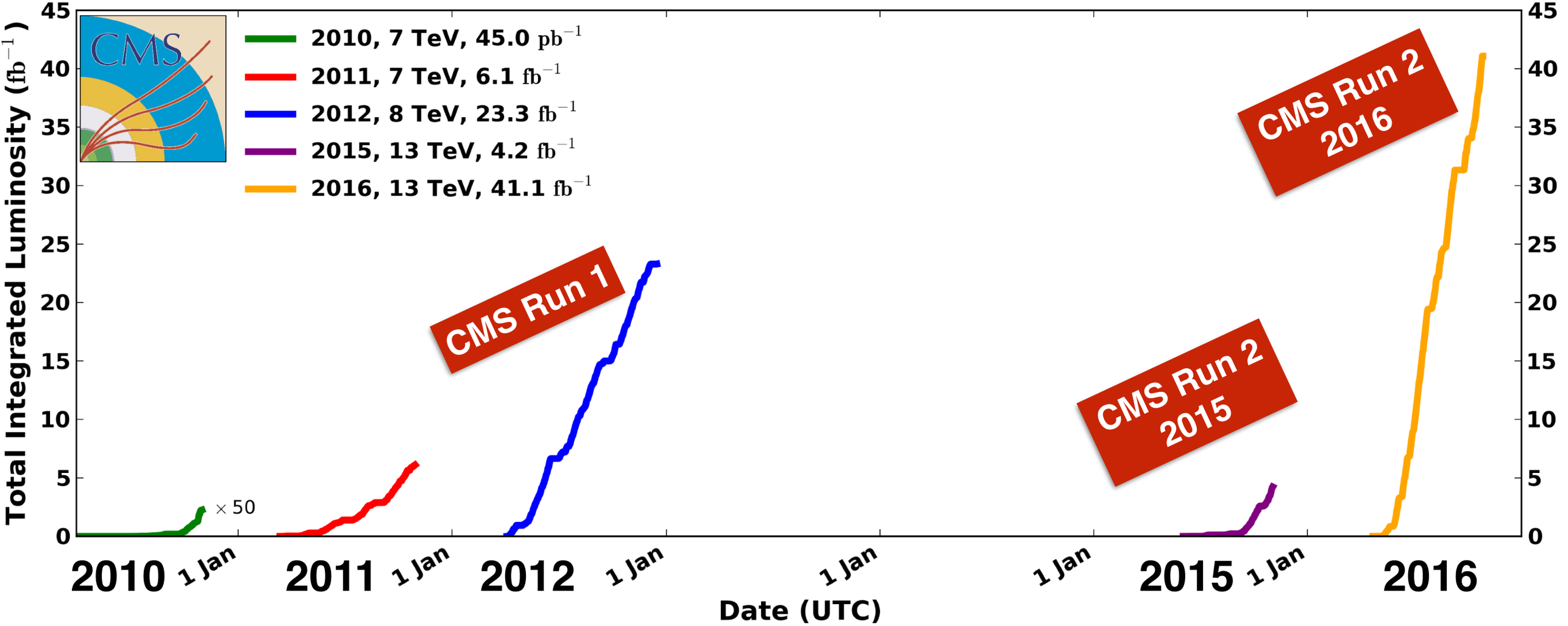

0m
1m
2m
3m
4m
5m
6m
7m
Muon Spectrometer
Drift Tubes and Resistive Plate Chambers
Hadronic Calorimeter
Neutral Hadron
Tail Catcher Calorimeter
Electromagnetic Calorimeter
Silicon Tracker
Photon
2T Magnetic Field
Pixel Vertex Detector
Muon
Charged Hadron
Electron
3.8T Magnetic Field
Transverse slice through CMS
Superconducting Solenoid and Cryostat
Instrumented Iron Return Yoke

Excellent Detector Performance

Status of CMS as on June 2016 (%)



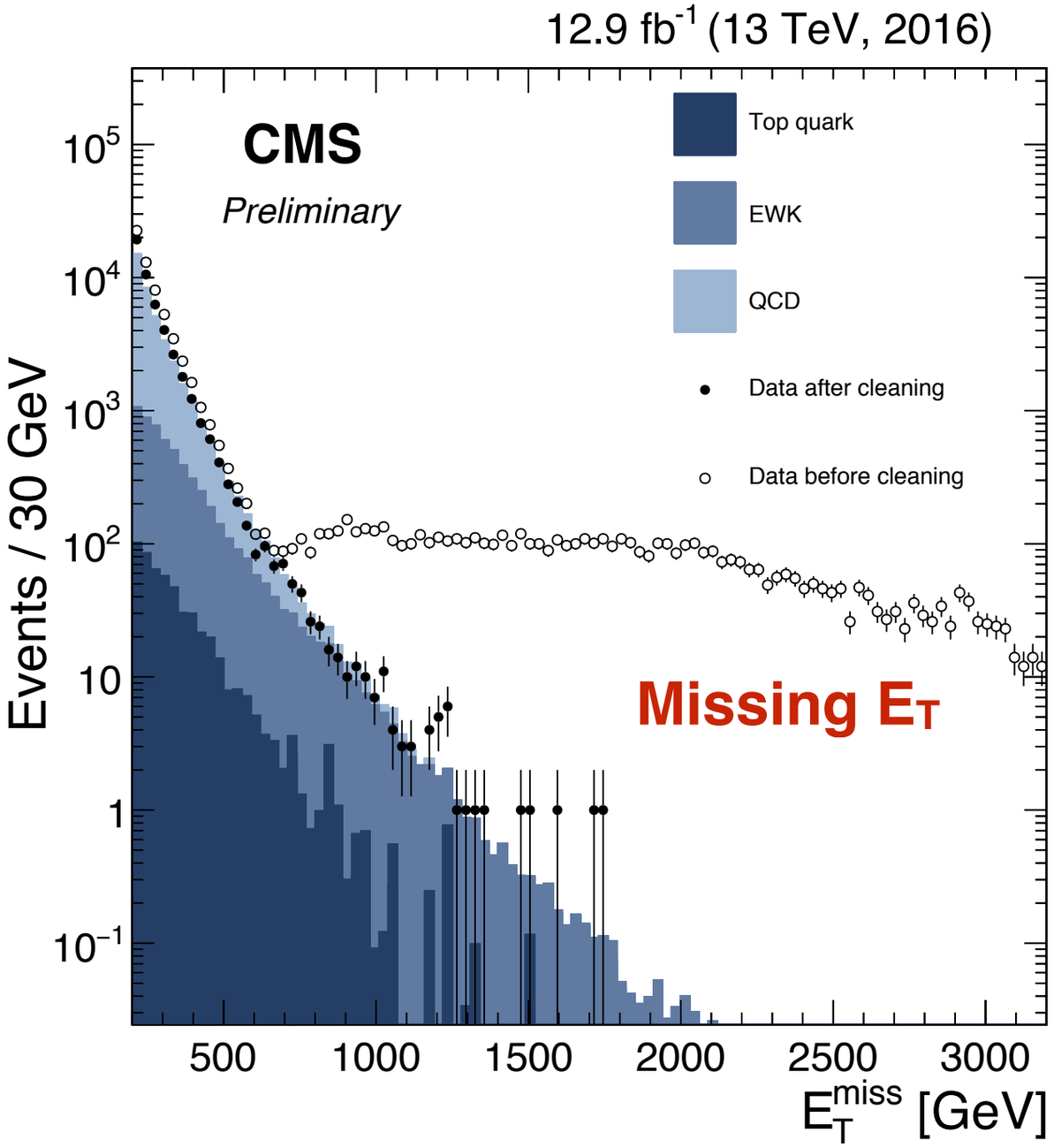
Data Collected by CMS



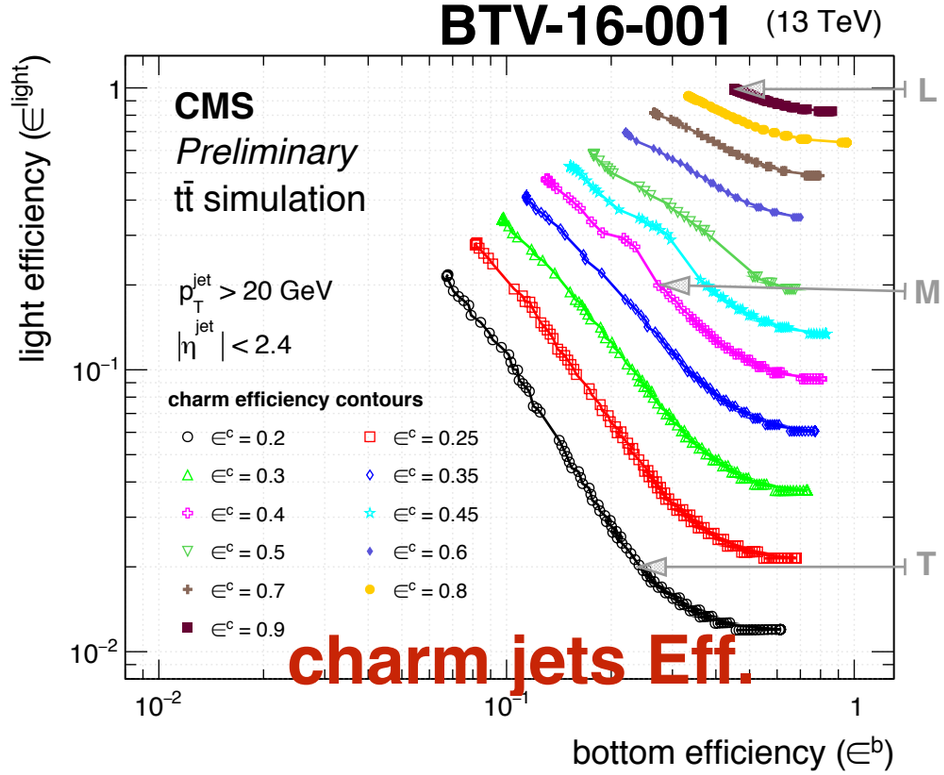
- Excellent and smooth performance by LHC operations
- Data collection efficiency 93%

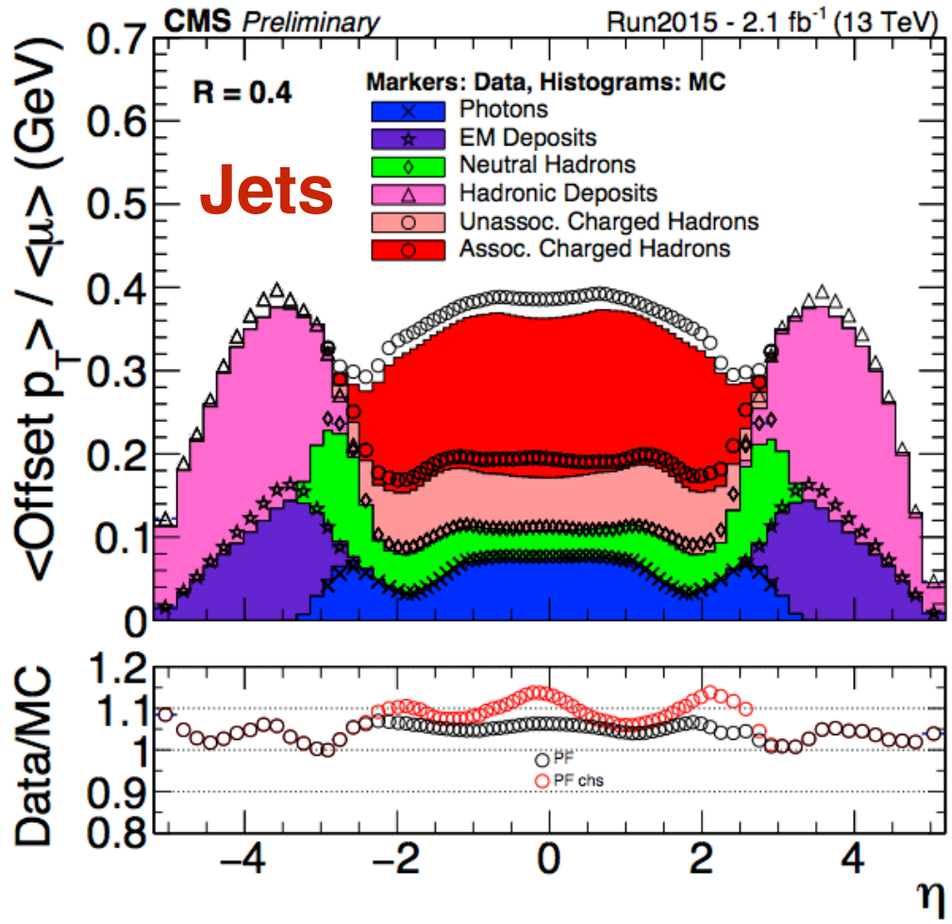
A few Examples of The Excellent Object Reconstruction

JME-16-004

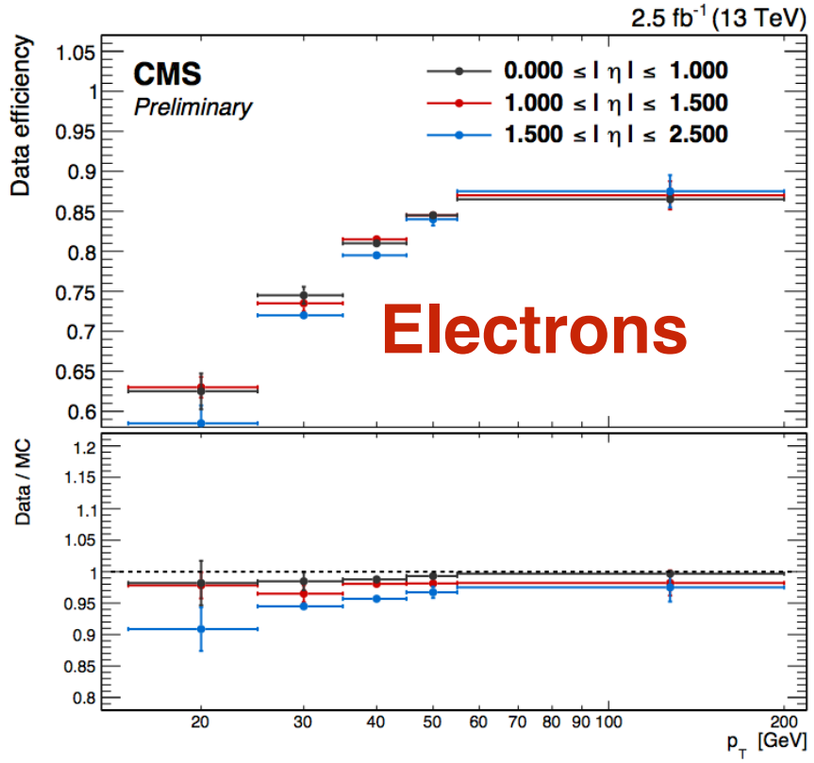


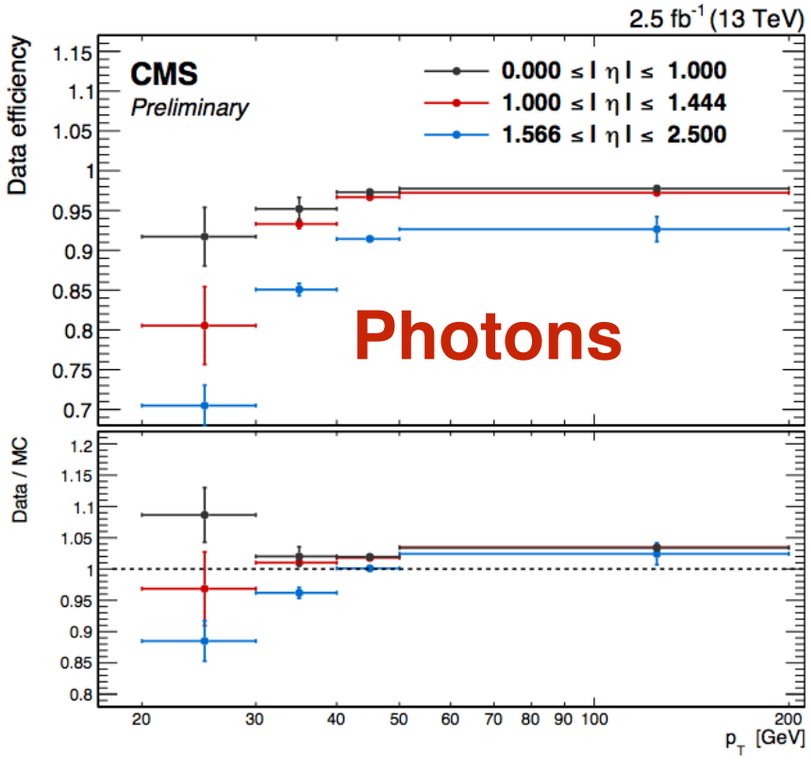
BTV-16-001 (13 TeV)

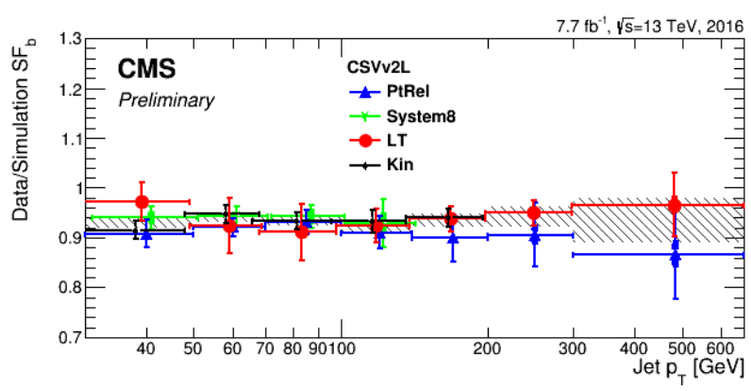


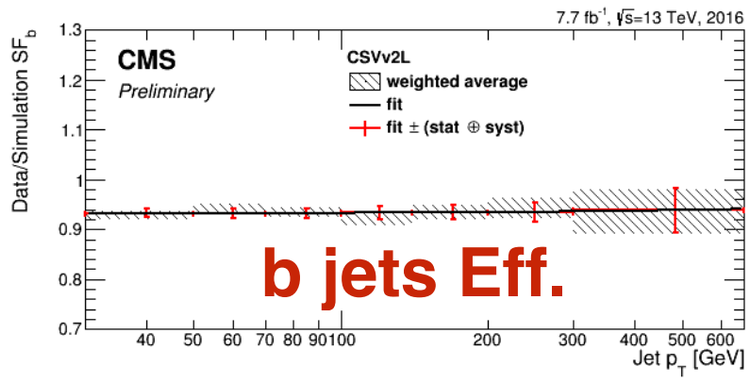


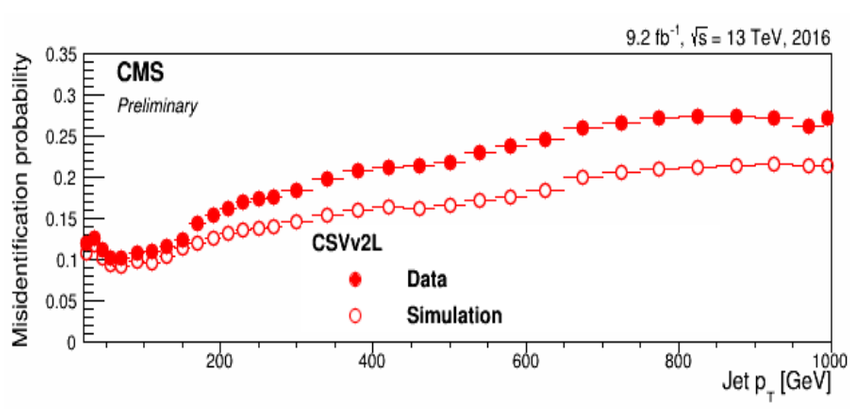
A few Examples of The Excellent Object Reconstruction

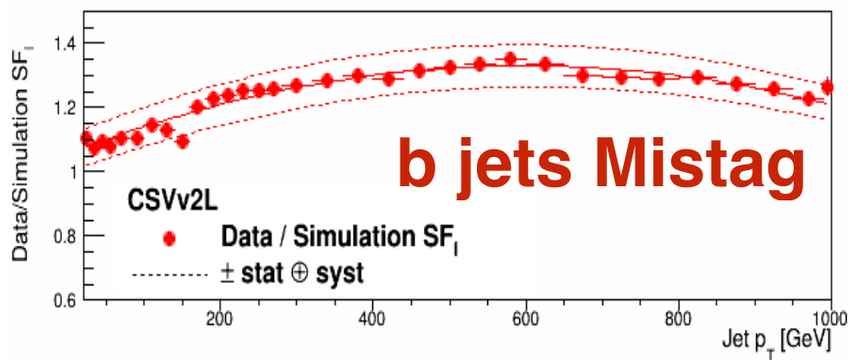












Looking for “bumps”

Reconstructing a Mass = X + Y

X

Jet(q,g,b)

Photon

Muon

Electron

Tau

Missing E_T

Boosted:
W/Z→qq

H→bb

top

+

Y

Jet(q,g,b)

Photon

Muon

Electron

Tau

Missing E_T

Boosted:
W/Z→qq

H→bb

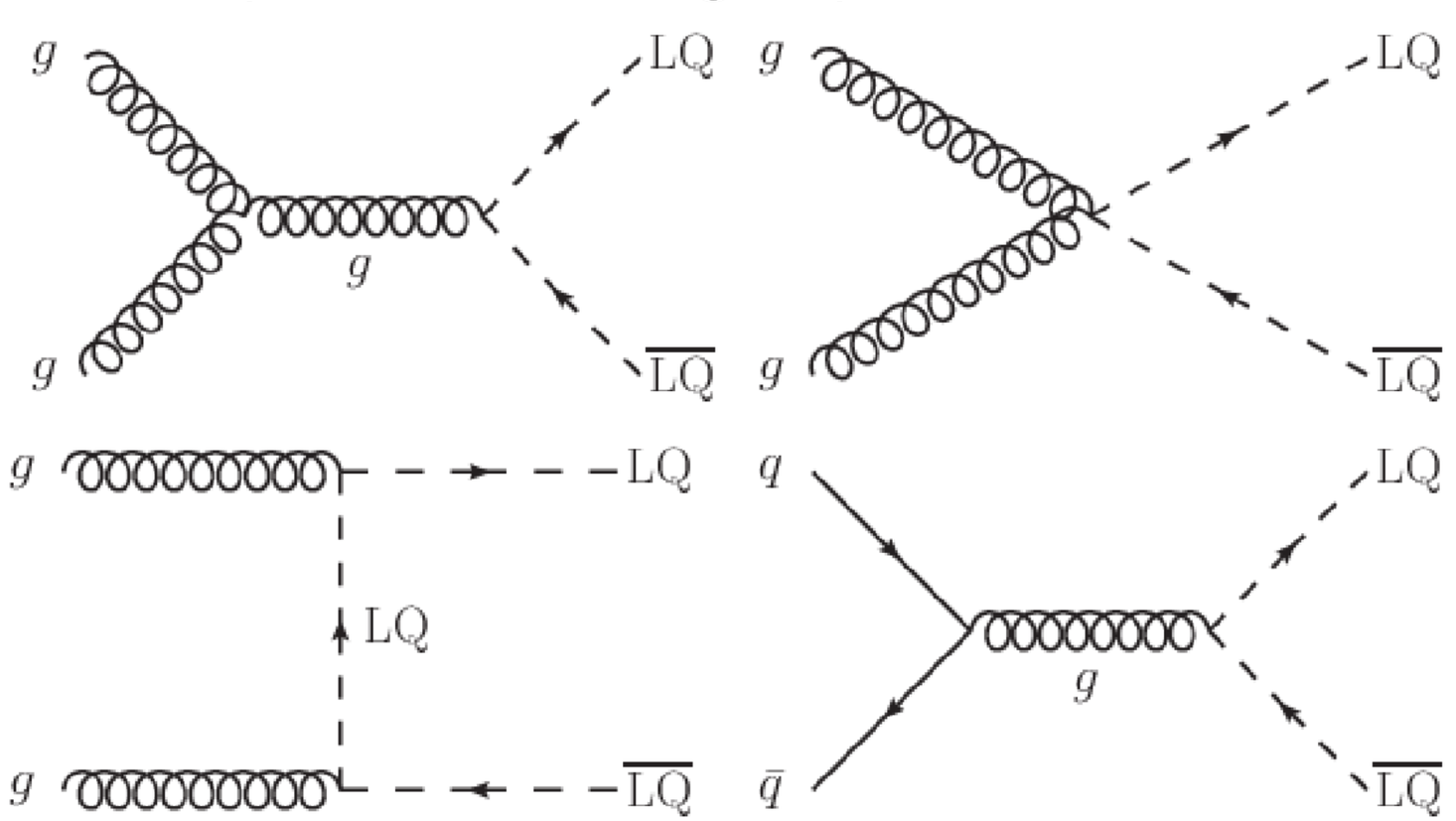
top

More than 150 ways to make a mass!

Run-1 Analysis with a slight excess

Leptoquarks (LQ)

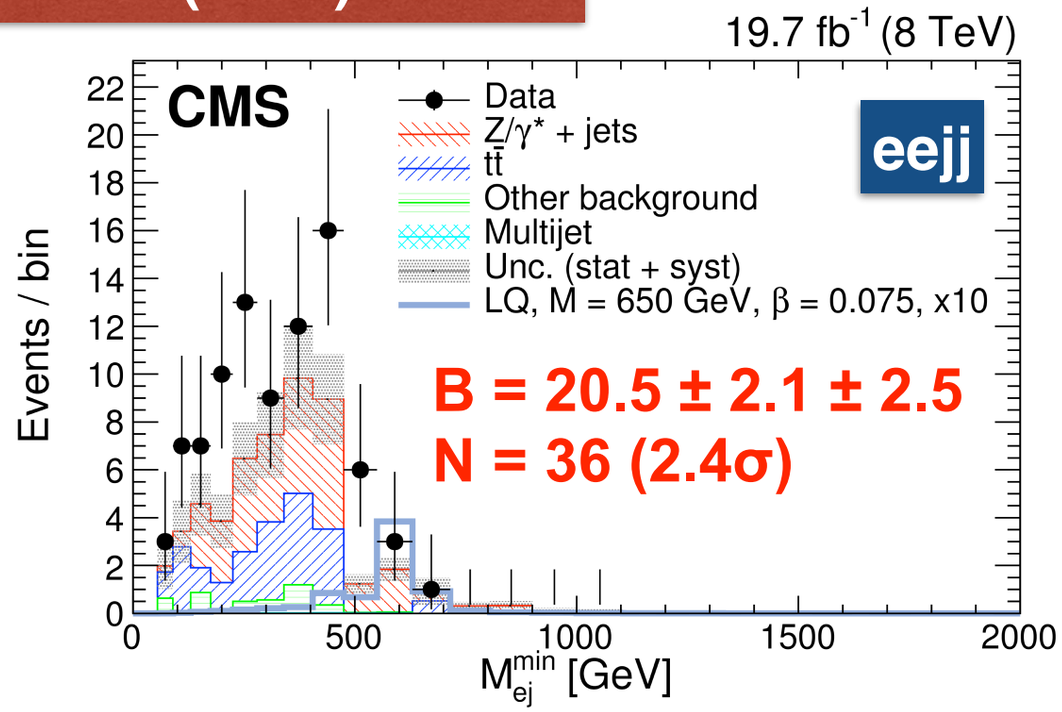
- Leptoquarks are hypothetical particles carrying both baryon and lepton number.
- LQ states are expected to exist in various extensions of SM e.g. GUT, SUSY with R-parity violation, technicolor, compositeness.
- The spin of the LQ state is taken to be 1 (vector LQ) or 0 (scalar LQ)
- Direct searches for LQ include pair and single productions:
  - $g + g \rightarrow LQ + \overline{LQ}$
  - $q + \bar{q} \rightarrow LQ + \overline{LQ}$
  - $g + q \rightarrow LQ + \ell$

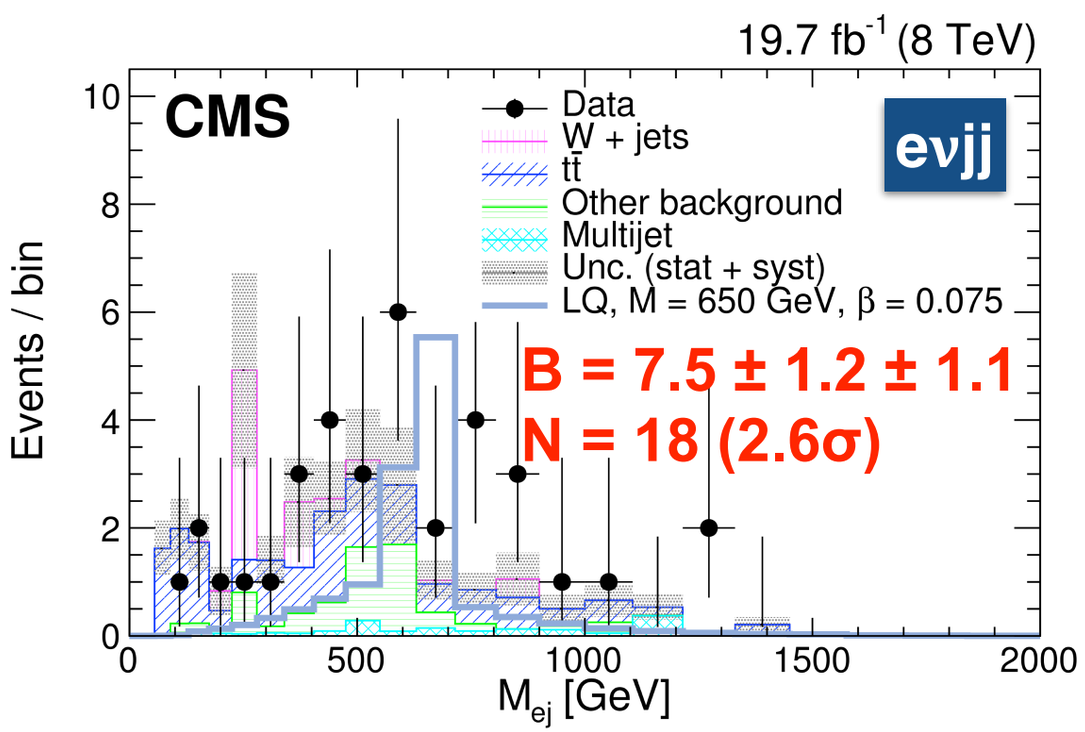


First Generation Leptoquarks (ee) at 8TeV

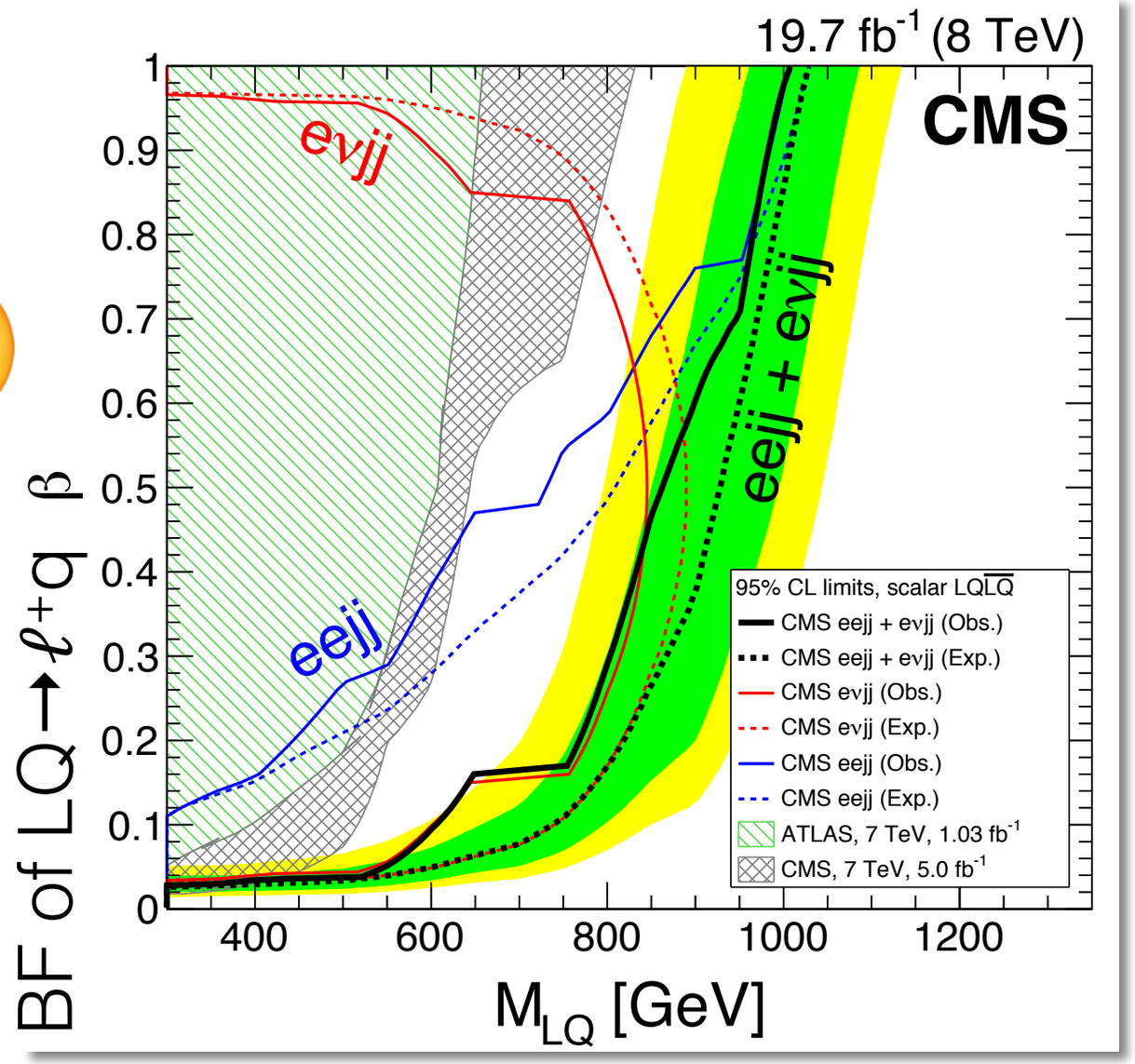
CMS Run 1

PRD 93 (2016) 032004



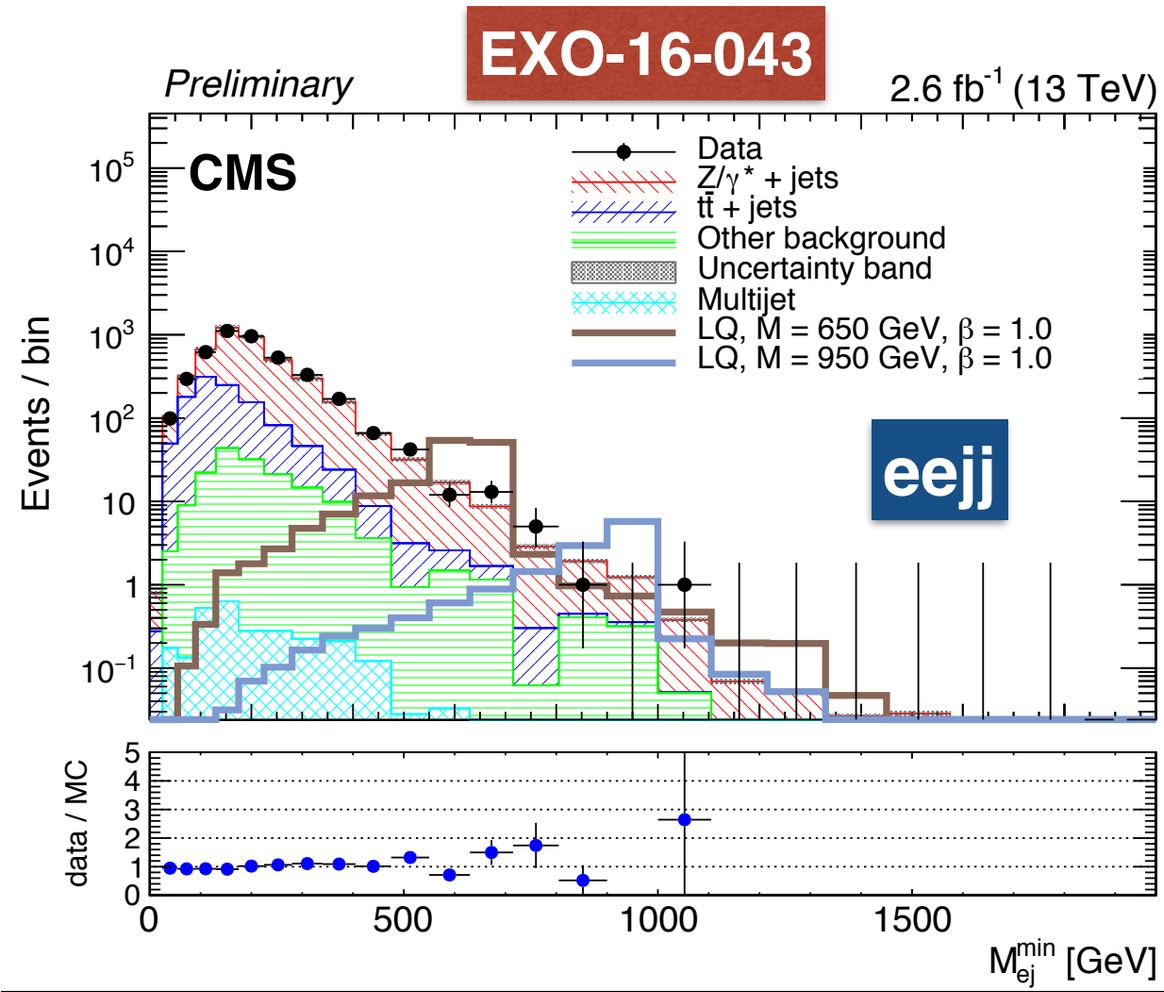


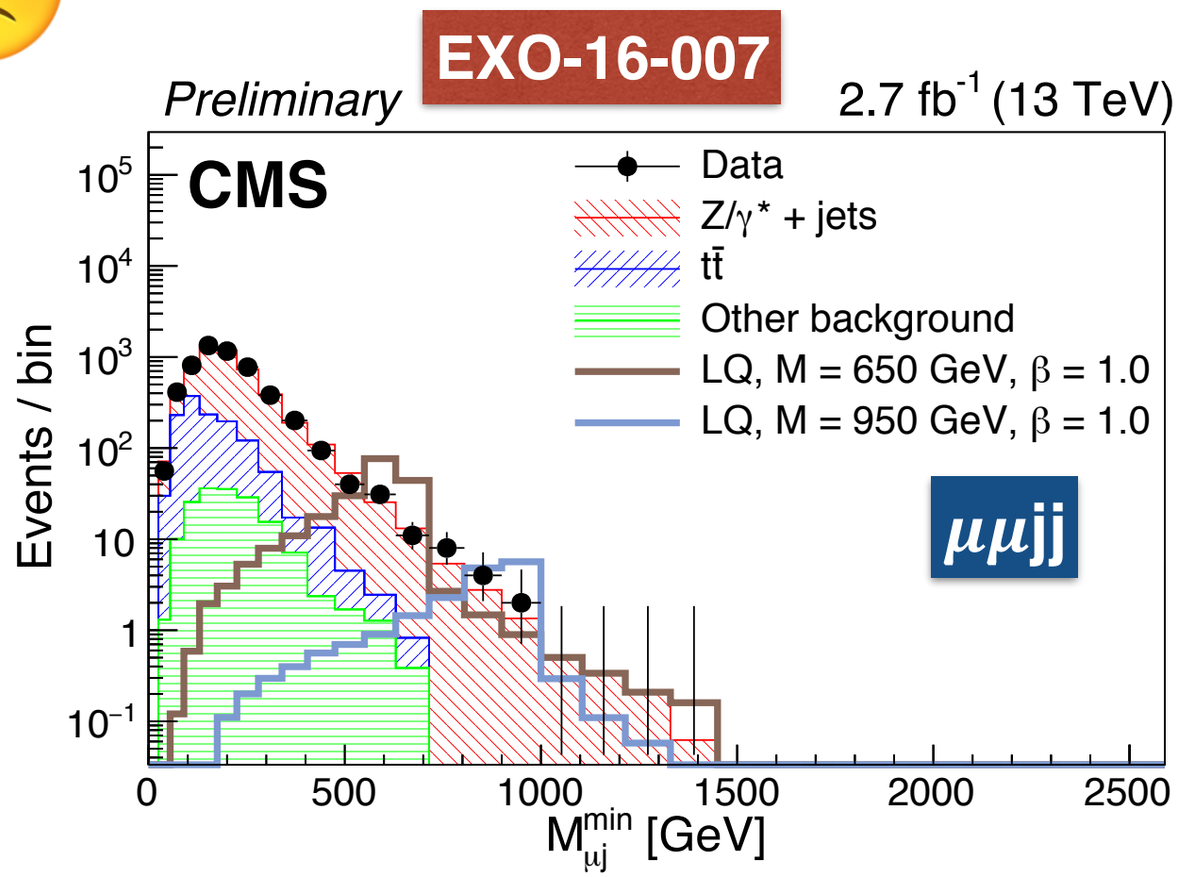
- Small **excess** seen in both eejj and ejj channels for the M(LQ)=650 GeV selection.
- Majorana neutrino search also observes small excess in same state.
- Many cross-checks have been done.



Leptoquark Search at 13 TeV

- Analysis followed up with 13 TeV 2015 data.
- No excess is seen in the eejj channel.
- First generation limits 1130 GeV (920 GeV) excluded for β=1 (β=0.5)
- Second generation limits at 1165 GeV (960 GeV) for β=1 (β=0.5)

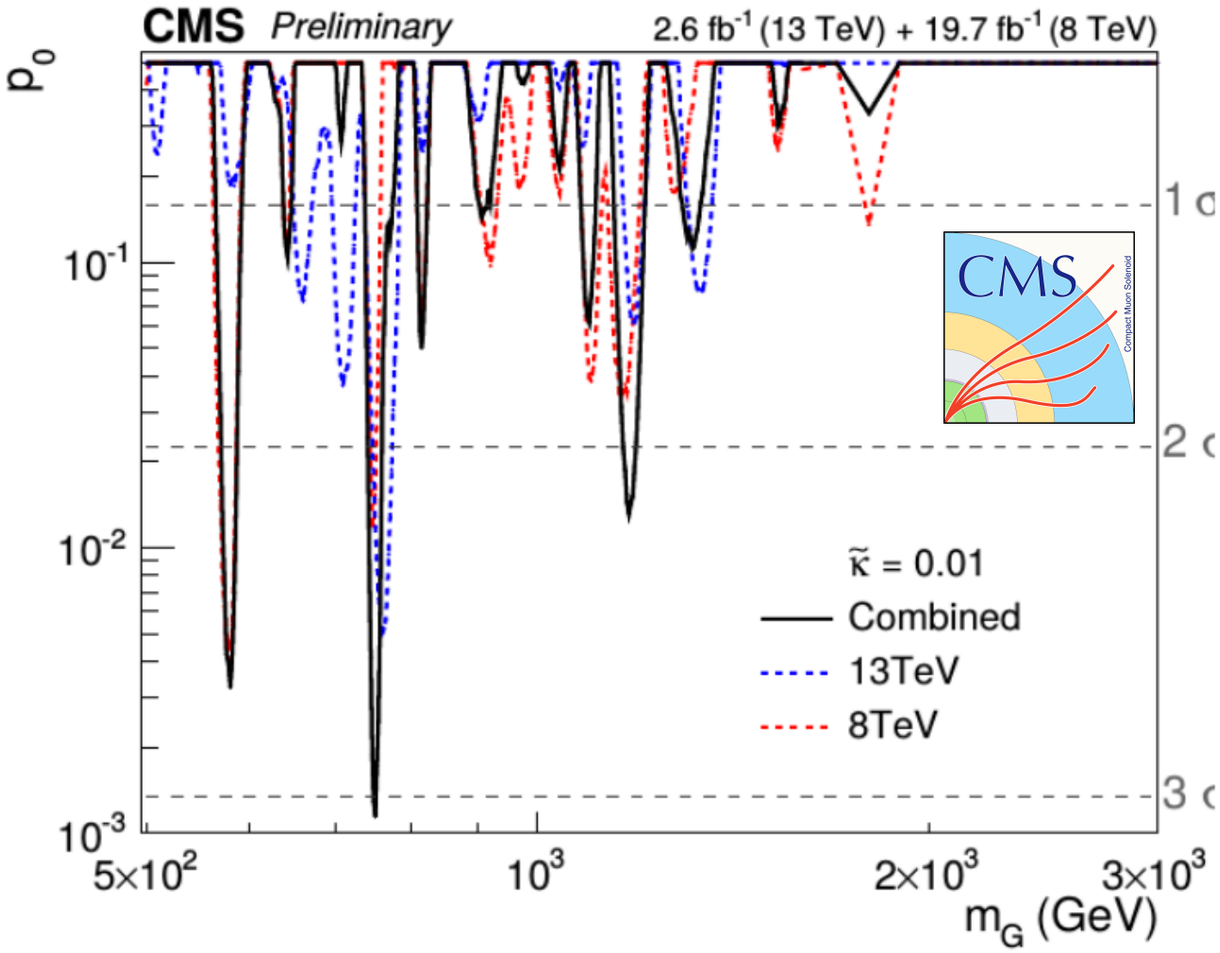




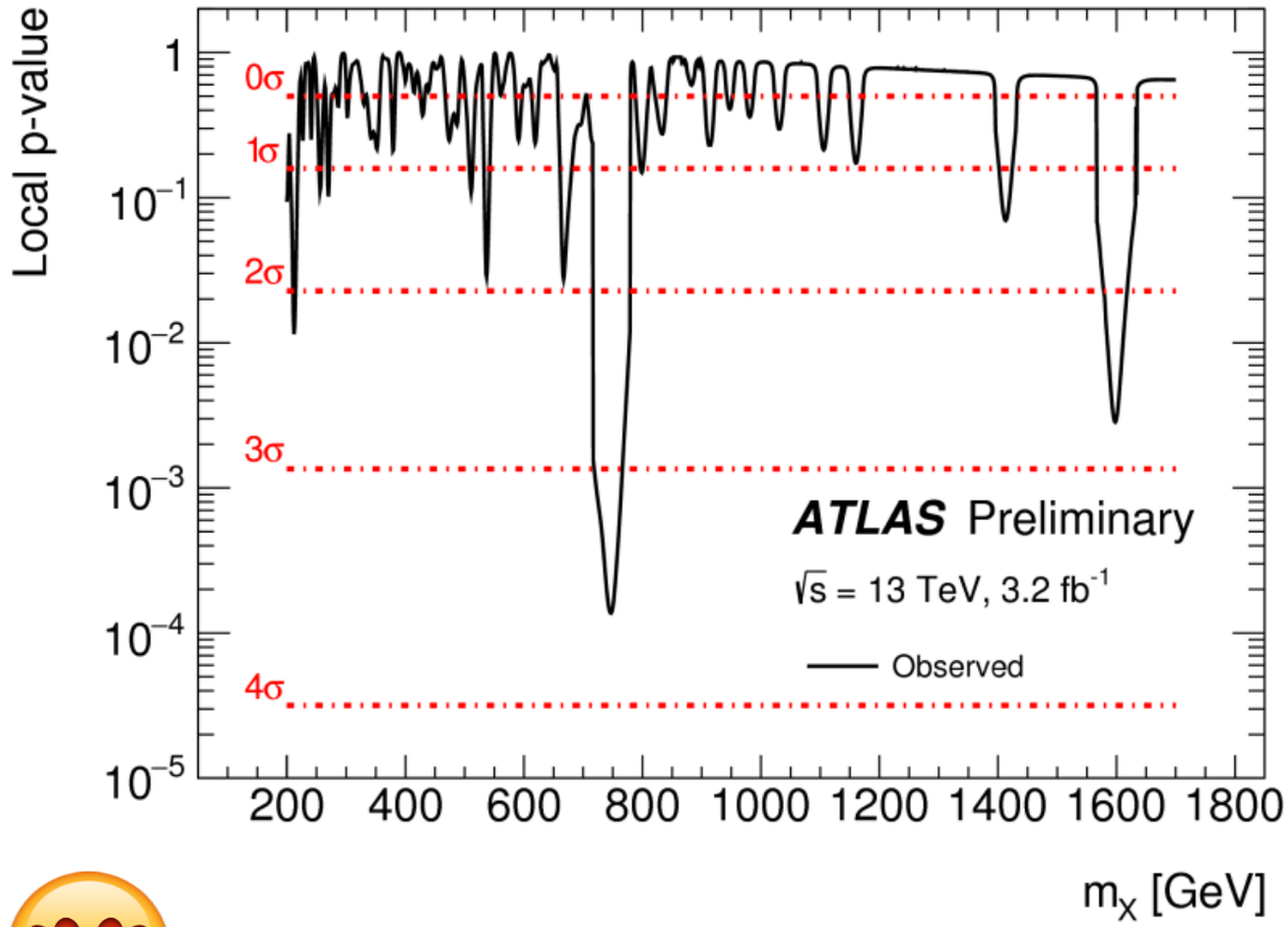
The Diphoton "excess"

CMS Run 1
Run 2 2015

- Search for resonances with mass above 500 GeV.
- Recall in 2015, Atlas and CMS reported slight excess of events at ~750 GeV using 3fb-1 at 13 TeV.
- Huge excitement in the theory community >450 papers.



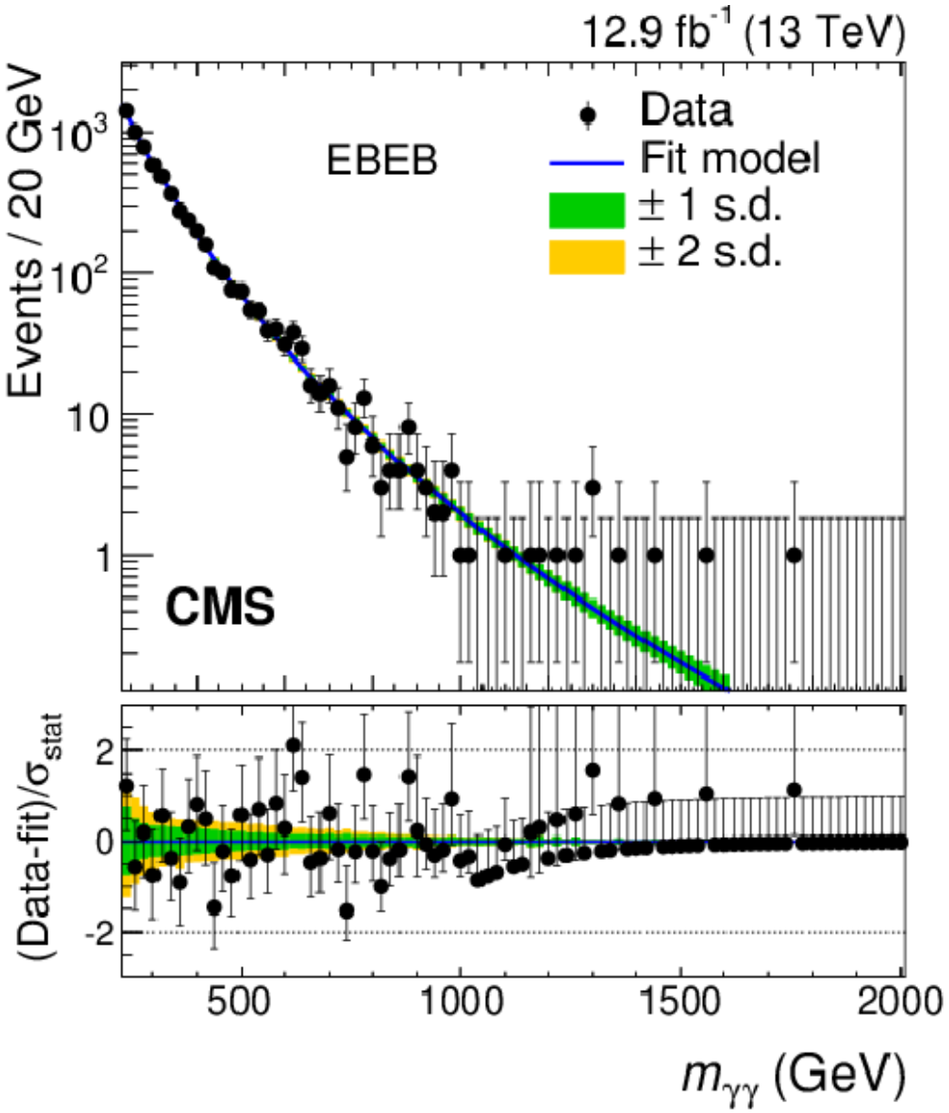
3σ local
1.7σ global

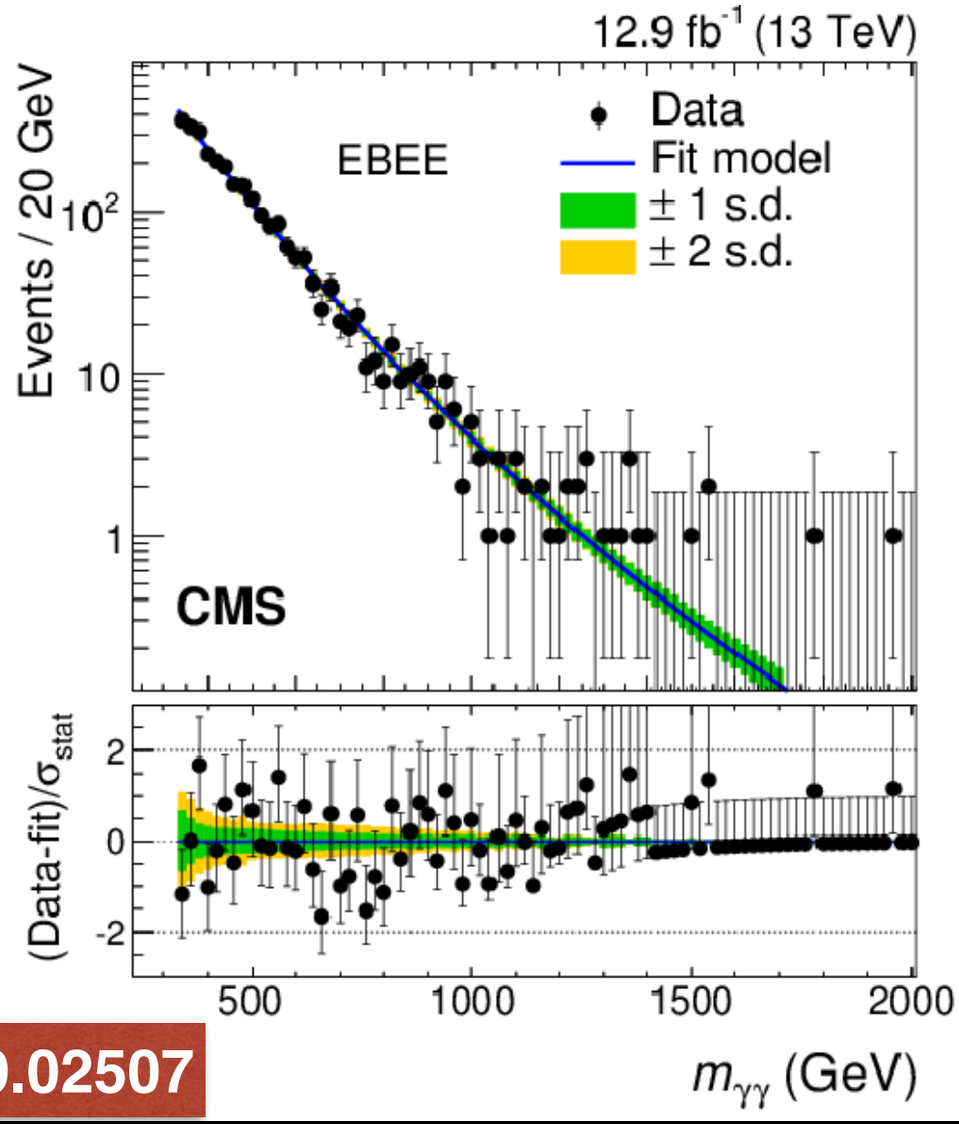


3.6σ local
2σ global

The Diphoton Search

- No hint of excess with 2016 data.
  - Local significance of 0.8σ with combined 2015-2016 data



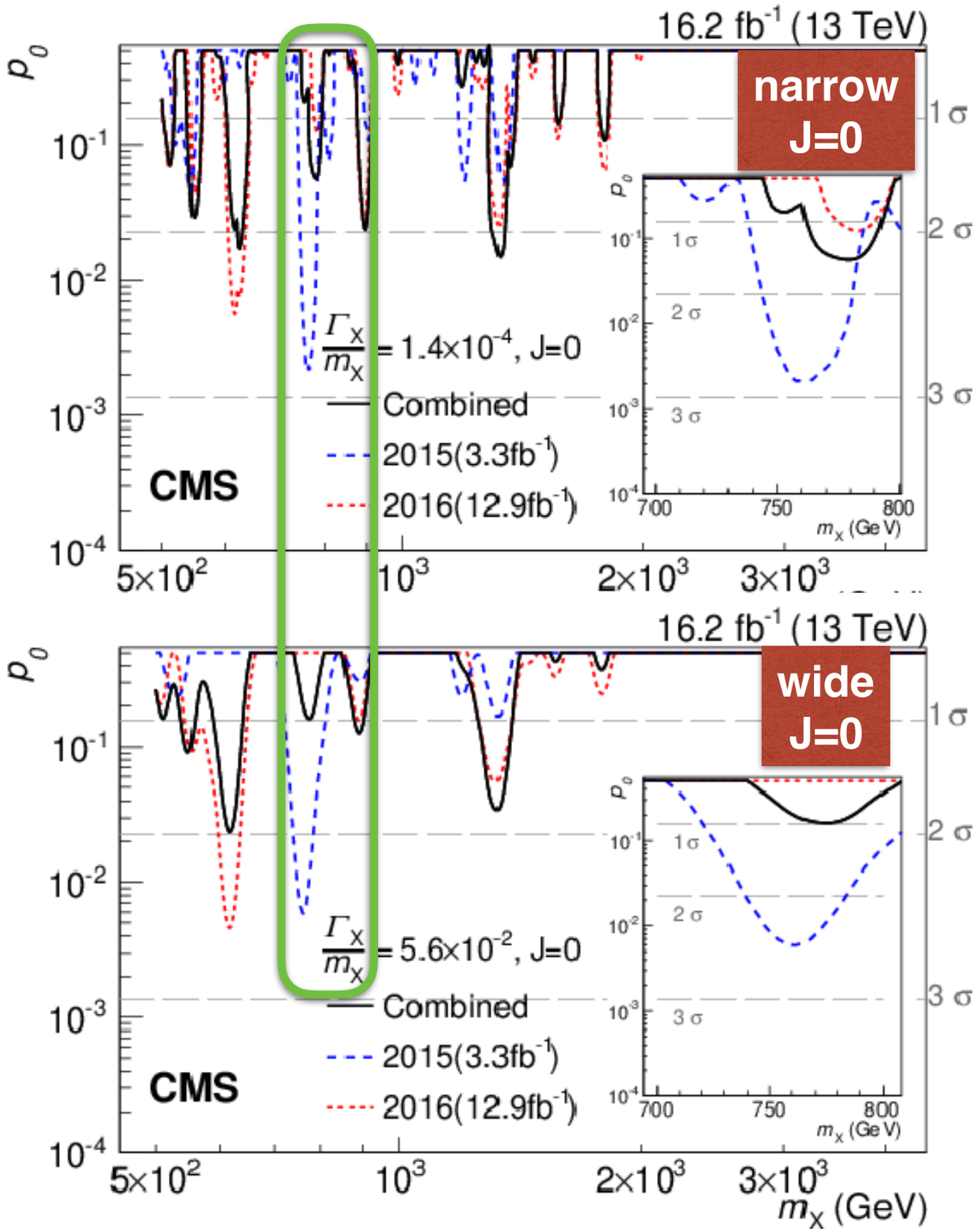


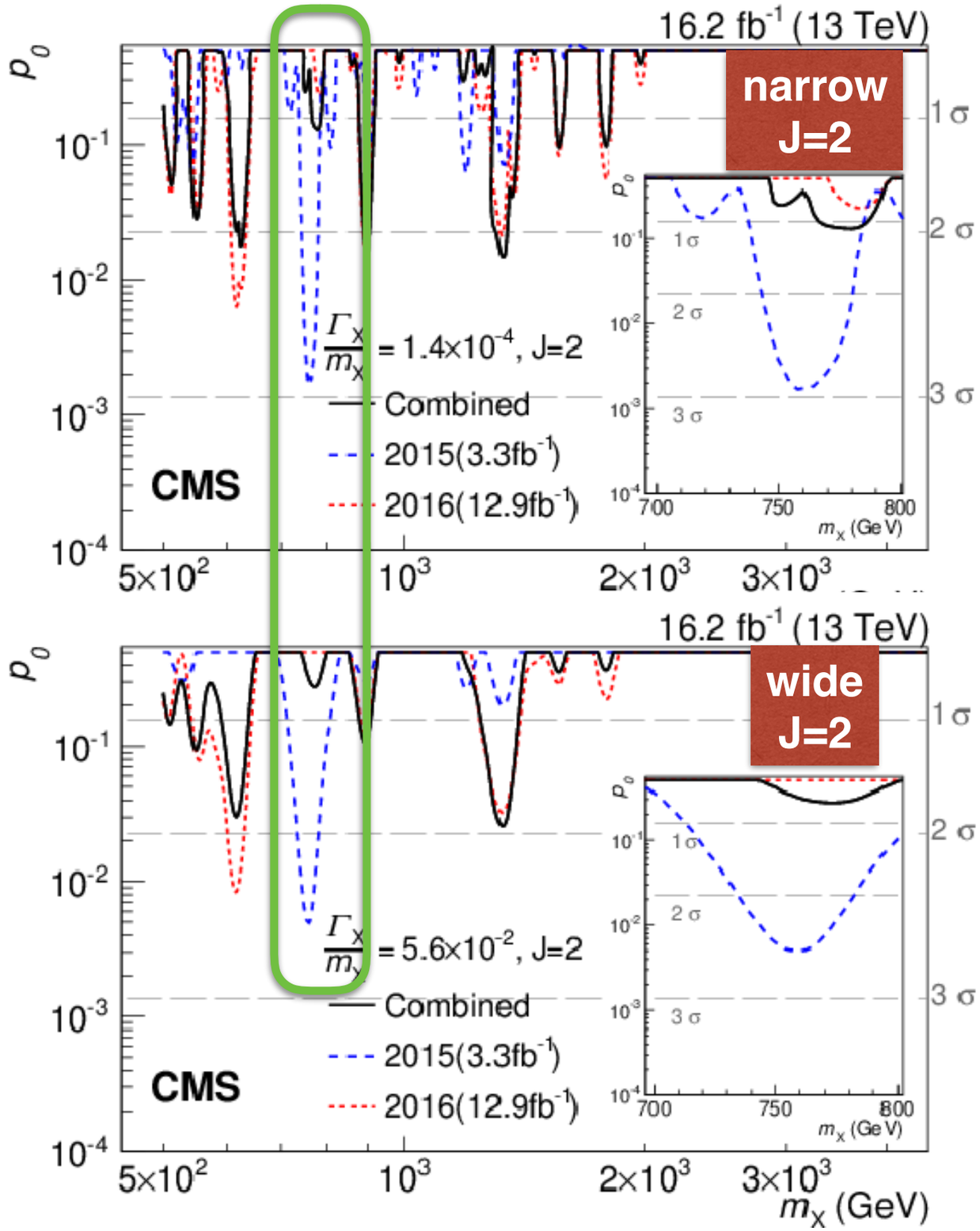
arXiv:1609.02507

The Diphoton Search

arXiv:1609.02507

- Local p-values for 2015, 2016, and combined datasets.



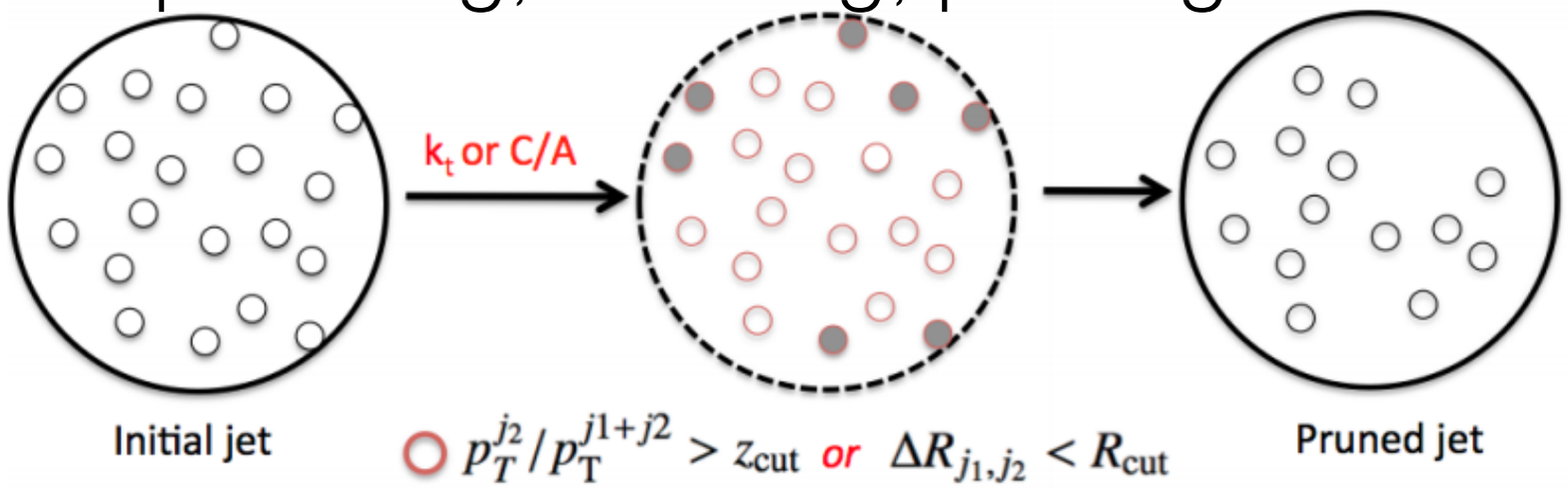


Jet Substructure Techniques

- Several methods for CA, anti-kt jets developed to find structure inside a wide jet.
- Usually applied to jets with p_T>300 GeV.
- Techniques take advantage of
  - Jet observables: jet mass, kT scale, N-subjettiness (τ_N)

$$\tau_N = \frac{1}{d_0}\sum_k p_{\mathrm{T}k} \times \min(\delta R_{1k}, \delta R_{2k}, ..., \delta R_{Nk}) \ , \quad \text{with} \quad d_0 \equiv \sum_k p_{\mathrm{T}k} \times R$$

    - τ_2/τ_1 (τ_3/τ_2) can be used as discriminators for boosted W/Z (top quarks)
- Jet grooming helps to improve the jet mass resolution and reduce sensitivity to multiple pp collisions:
  - mass-drop filtering, trimming, pruning

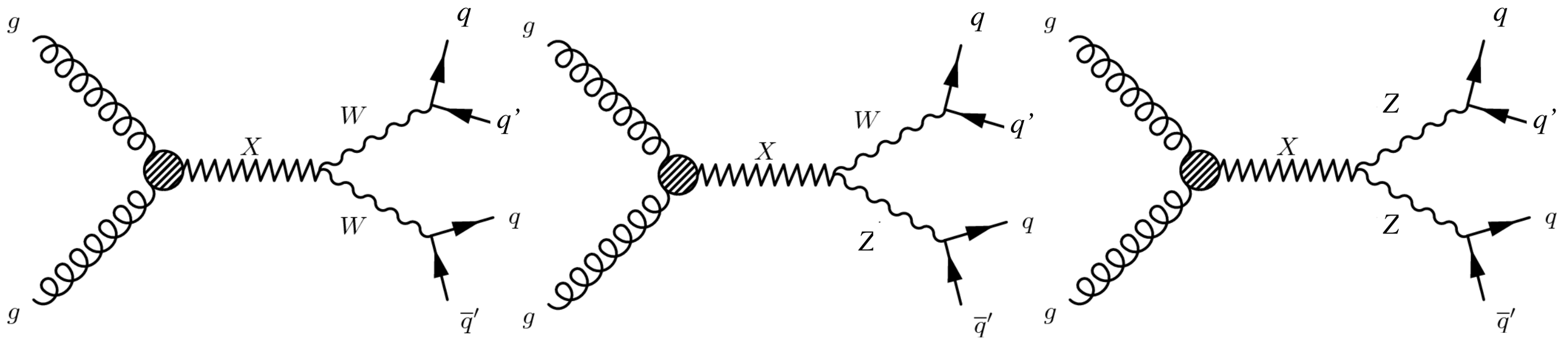


arXiv:1306.4945

CMS Run 1

WW/WZ/ZZ with tagged W/Z jets

- Massive resonance decaying to a pair of vector bosons.
- Limits on Randal-Sandrum (G_{RS}) and bulk (G_{bulk}) gravitons, and W heavy partner (W')
- Search using jet substructure techniques to tag W/Z jets.
- Small excess in fully hadronic channels but not in the lepton plus jets channel.
- Also excess observed by Atlas (~ same mass, larger excess)



CMS Run 1

WW/WZ/ZZ with tagged W/Z jets

- Tag CA (0.8) jets as W/Z jets using the mass of pruned jets between 70-100 GeV.
- Take advantage of N-subjettiness ratio τ_2/τ_1 to select signal-like candidates.
  - Tagging efficiency ~30%
- Slight excess seen around 2 TeV (similar in Atlas result). Excess only in the hadronic channel.

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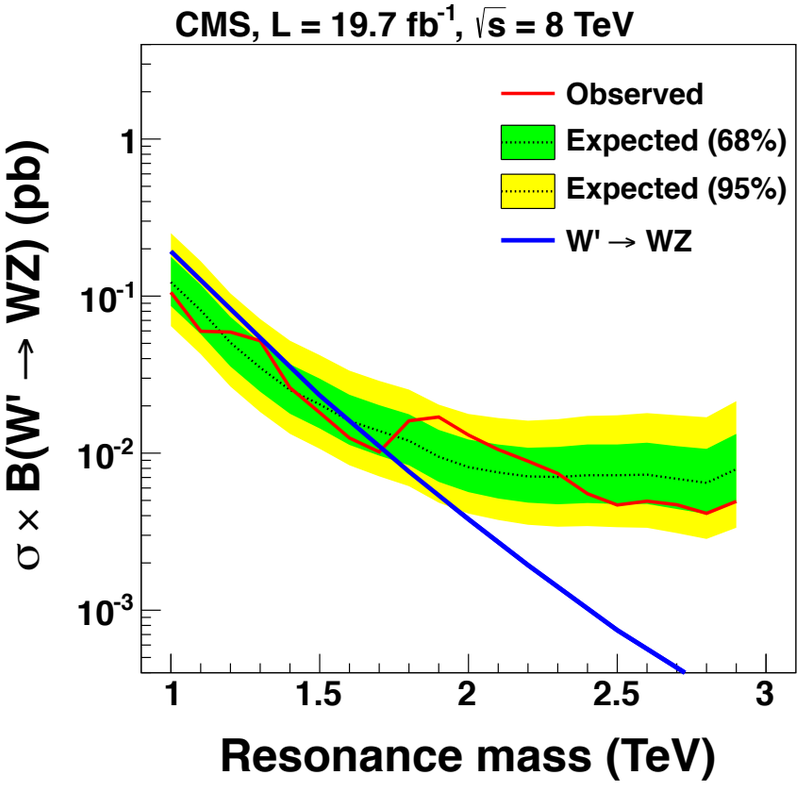
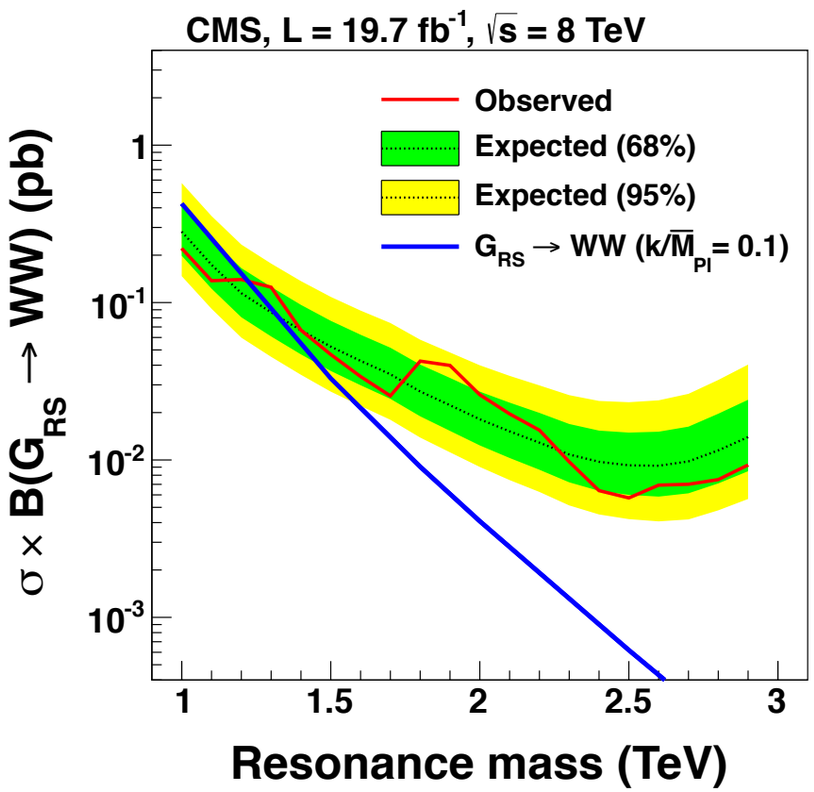
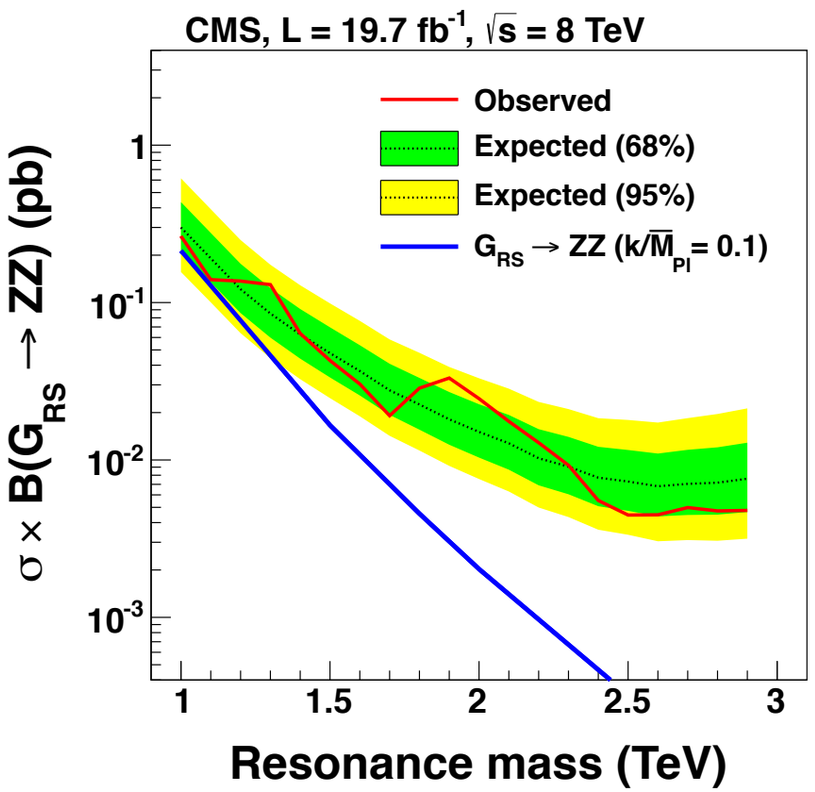


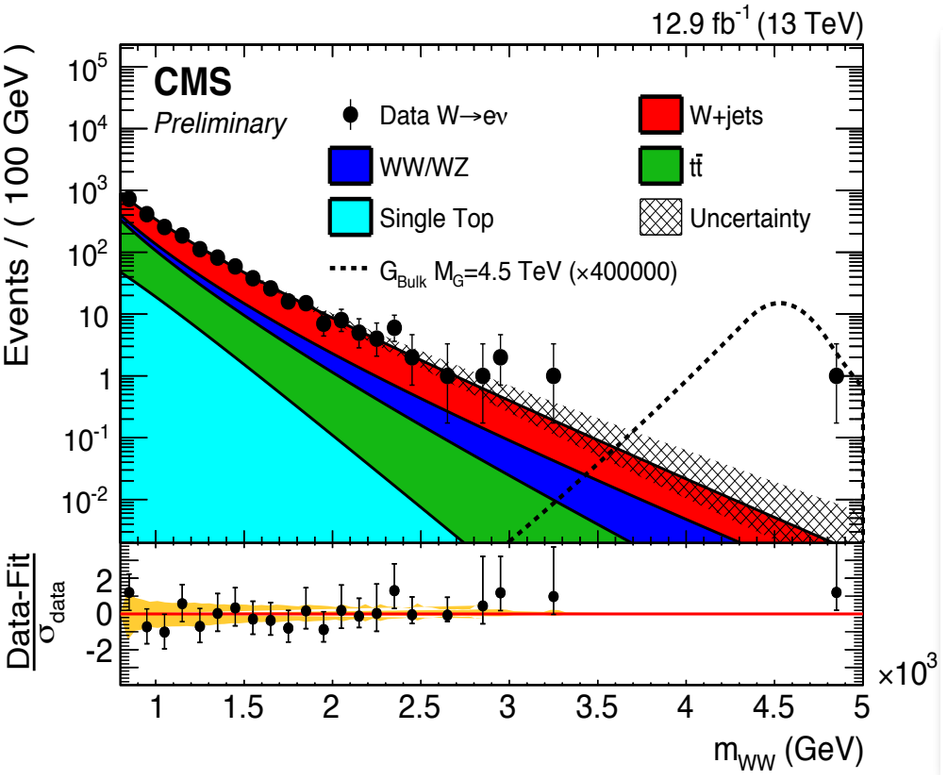


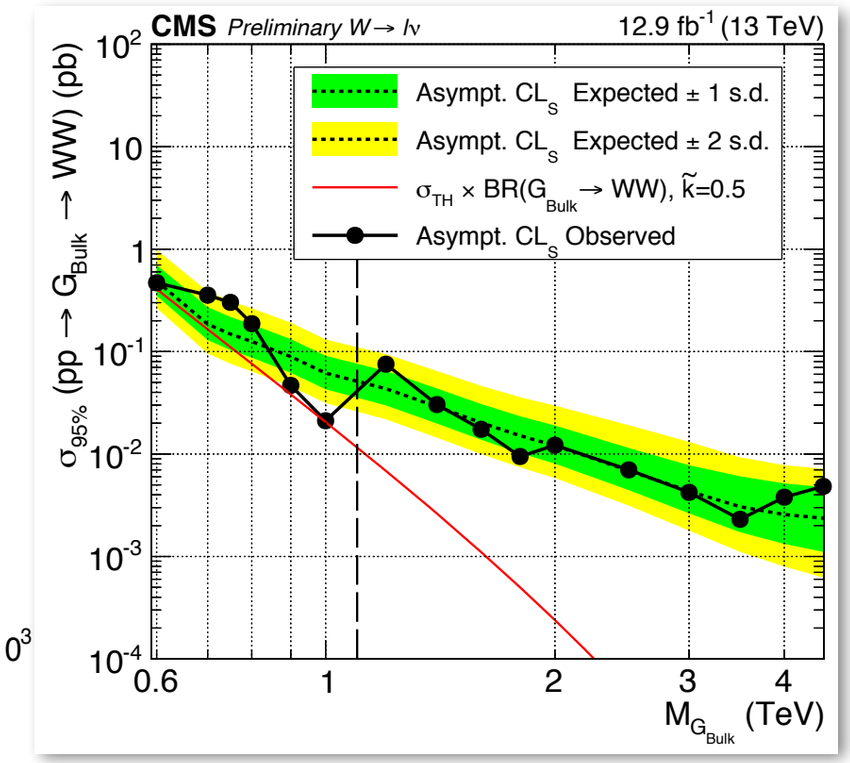


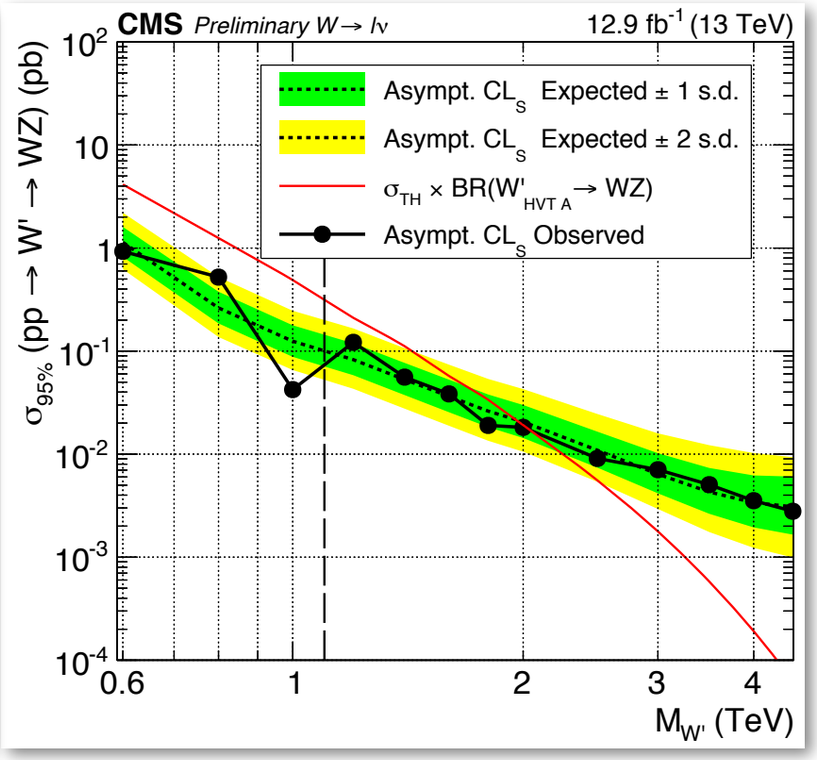
B2G-16-020

WW/WZ Search at 13 TeV

- Most recent analysis with 2016 data in the semileptonic channel (lνjj).
- The dijet system uses jet substructure.
- The WW and WZ analyses are not independent as the mass windows partially overlap.
- No evidence for statistically significance excess in the range 0.6 to 4.5 TeV.







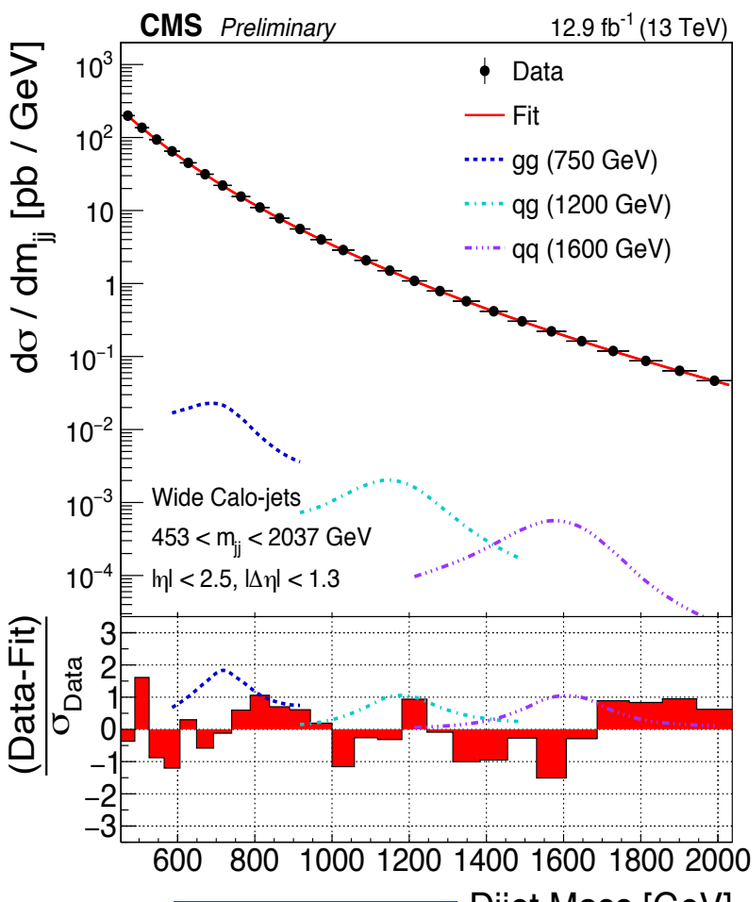
Run-2 Analysis: Dijet searches

Dijet Searches

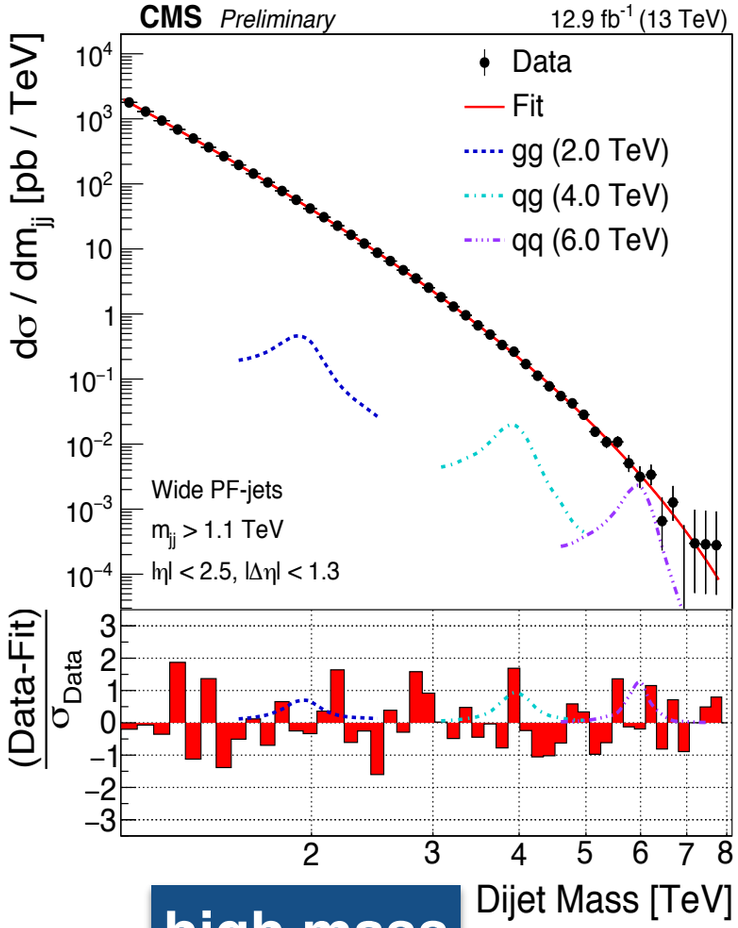
EXO-16-032

- Traditional dijet mass search using AK4 jets.
- High mass analysis combined leading jets using ΔR.
- Mass spectra fit with parametric function for background and signal shape from simulation.

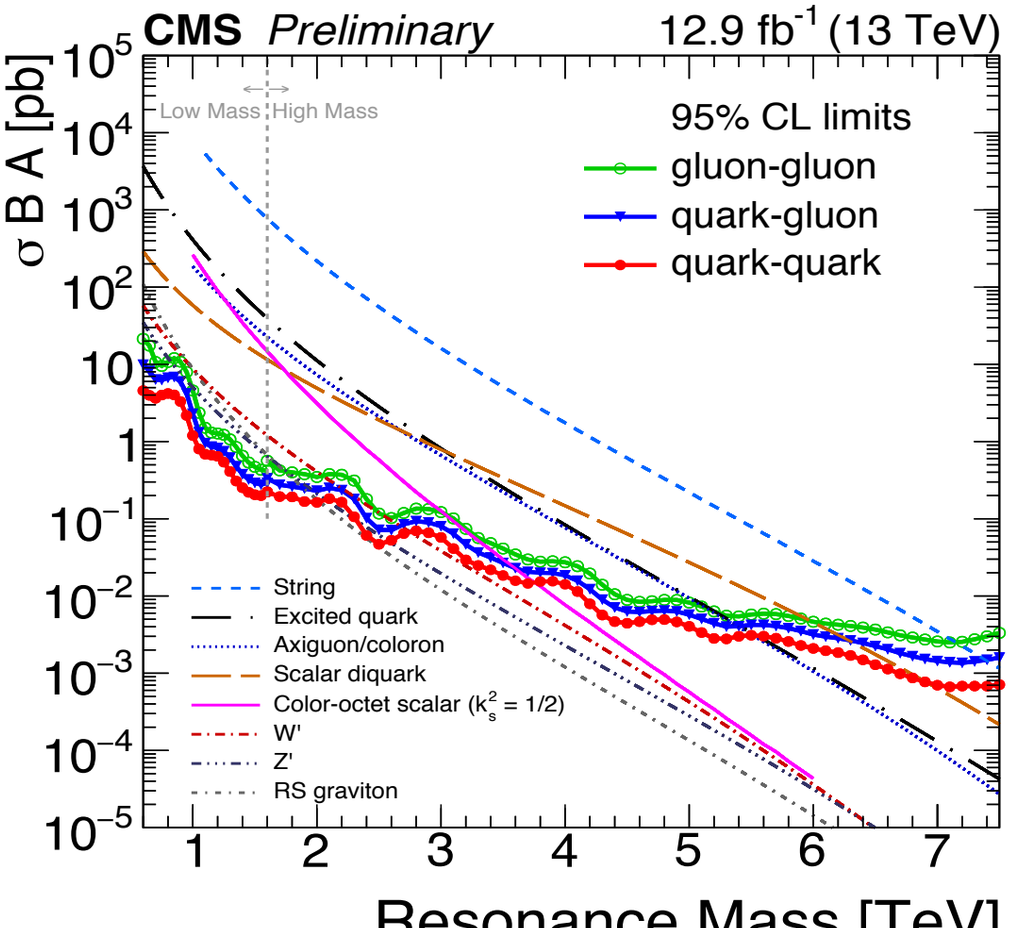
Model	Final State	Observed (expected) mass limit [TeV] 12.9 fb^{-1} 13 TeV	2.4 fb^{-1} 13 TeV	20 fb^{-1} 8 TeV
String	qg	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	$q\bar{q}$	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.0 (3.3)	—	—
W′	$q\bar{q}$	2.7 (3.1)	2.6 (2.3)	2.2 (2.2)
Z′	$q\bar{q}$	2.1 (2.3)	—	1.7 (1.8)
RS Graviton	$q\bar{q}$, gg	1.9 (1.8)	—	1.6 (1.3)

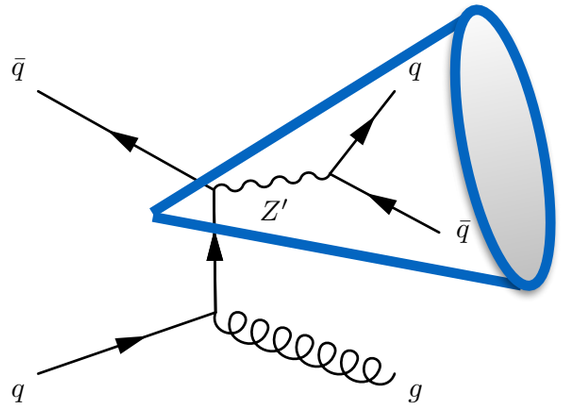


low mass



high mass

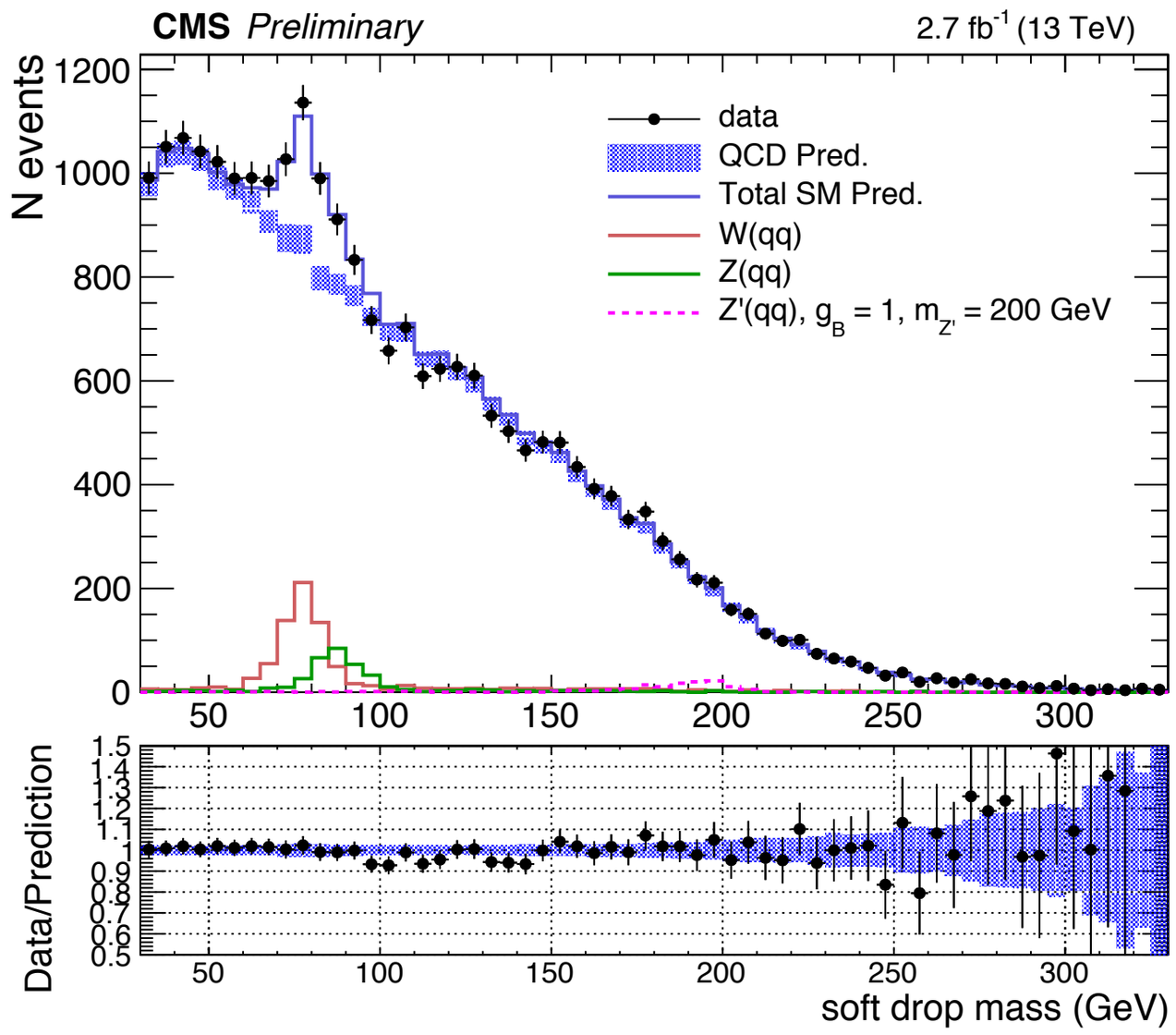


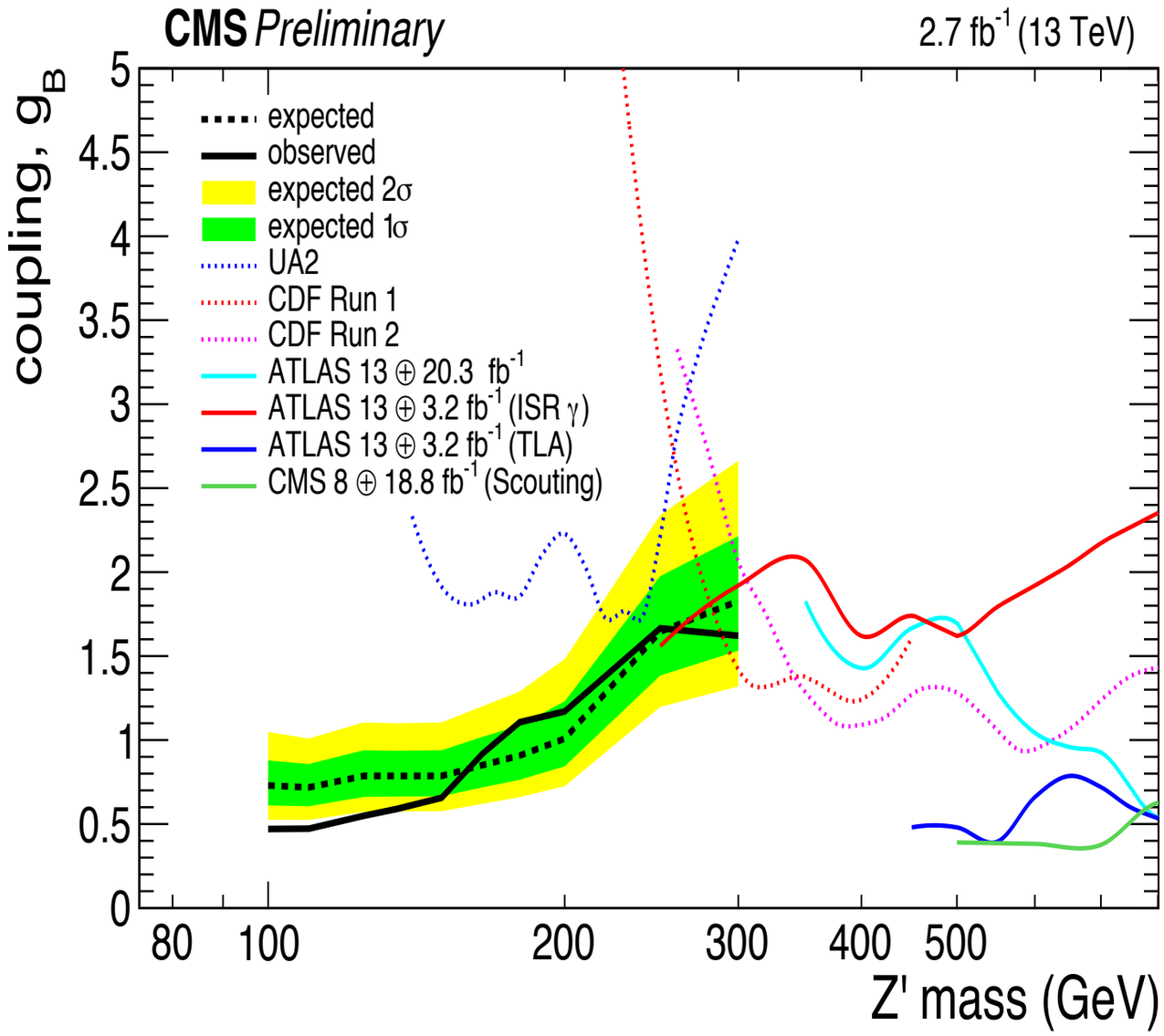


Light Vector Resonance

EXO-16-030

- Search in the region 100 GeV < m_{SD} < 300 GeV
- Use substructure techniques to reconstruct low mass wide jet.
- Multijet QCD background estimated from data in sidebands.
- Most stringent constraints for m(Z') < 300 GeV.

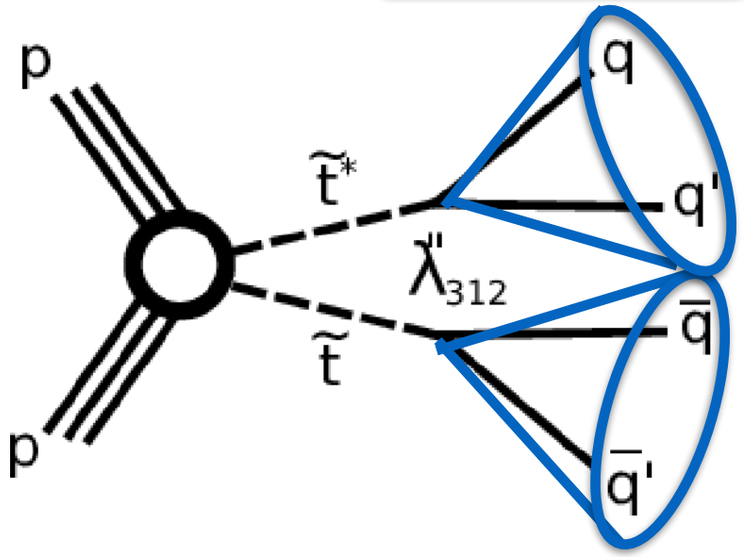


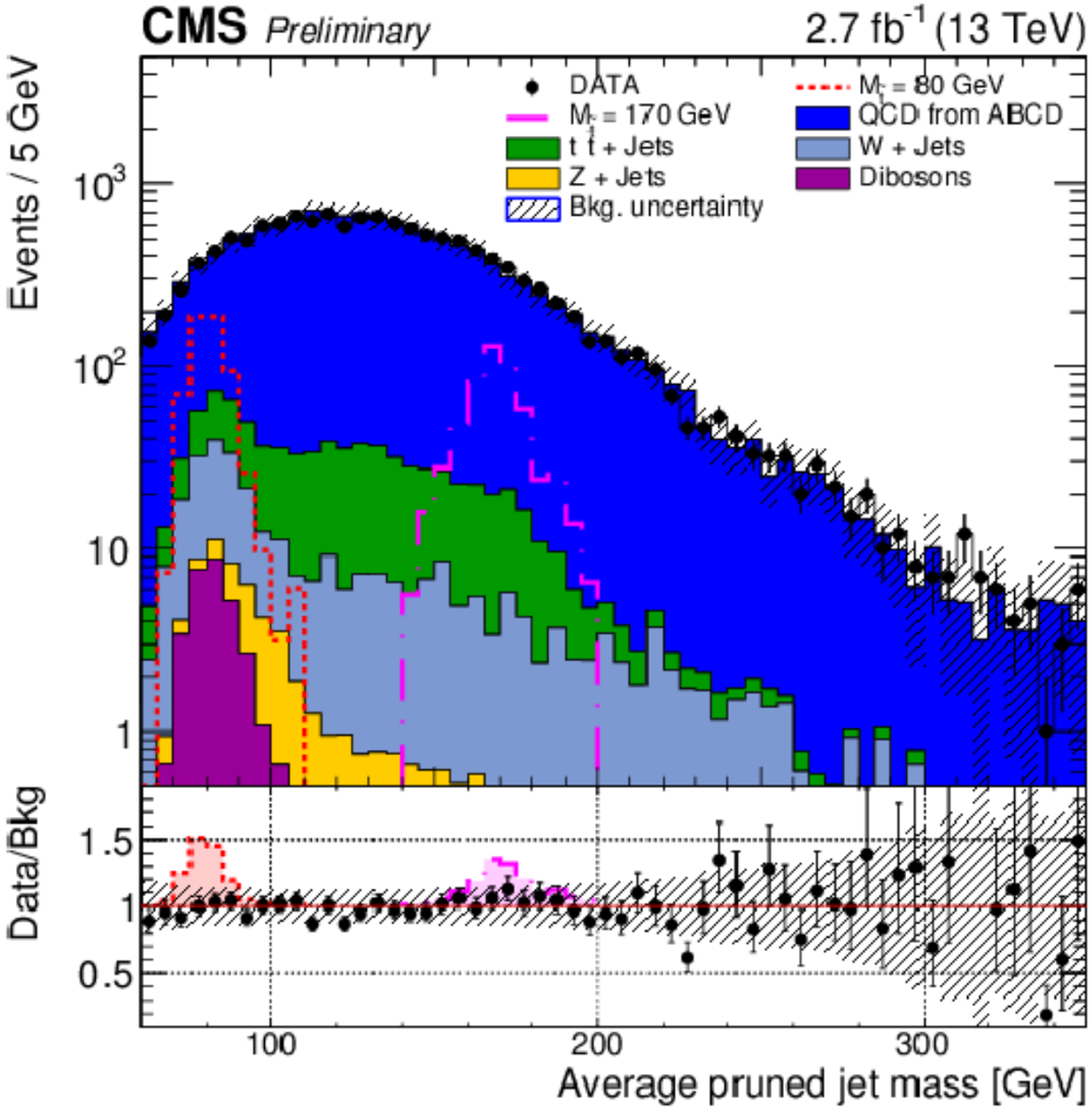


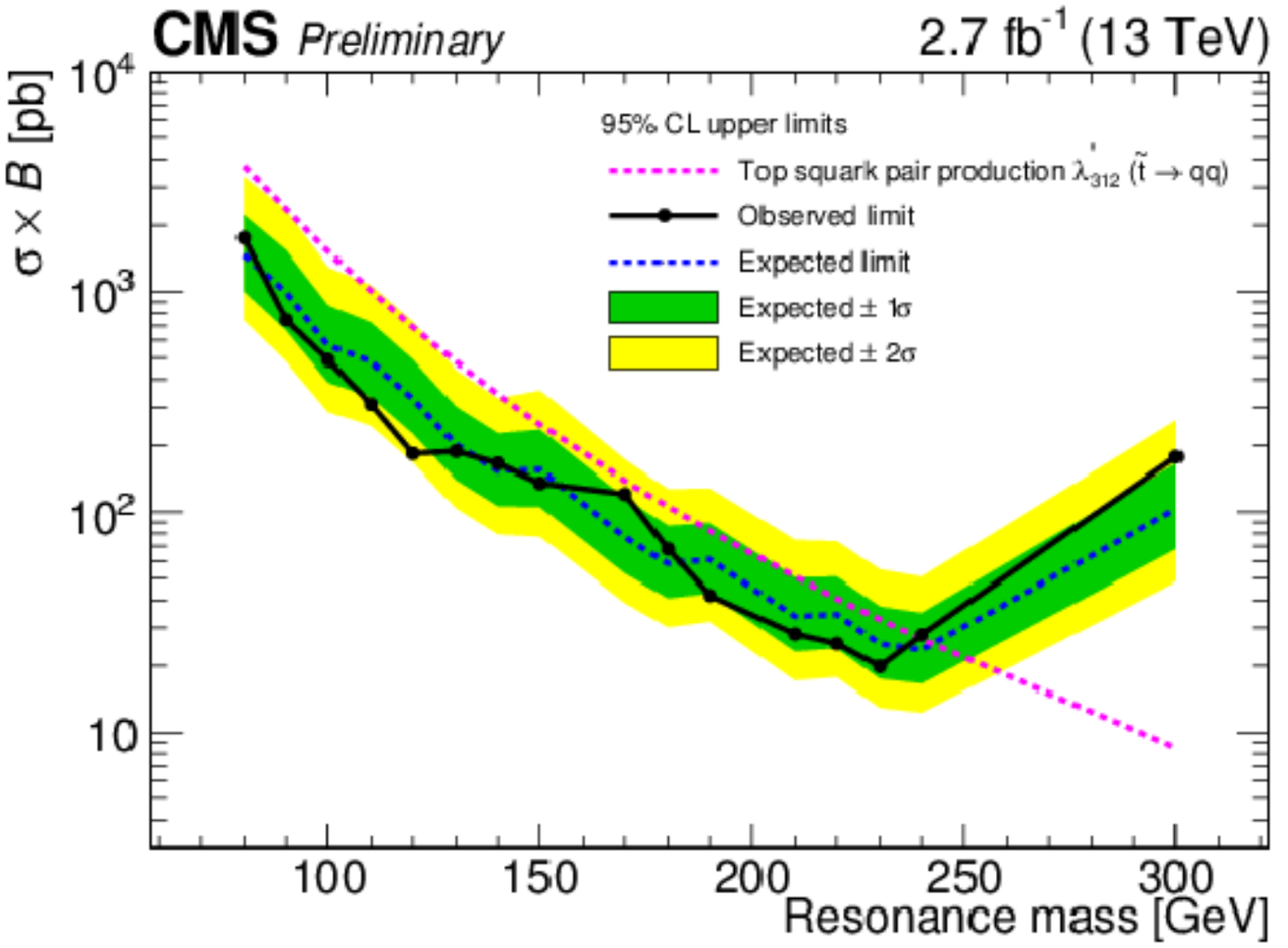
Low Mass Dijet with substructure

EXO-16-029

- RPV models of boosted stops decaying to light quarks.
- H_T>900 GeV. Pruning & N-subjettiness applied to jets.



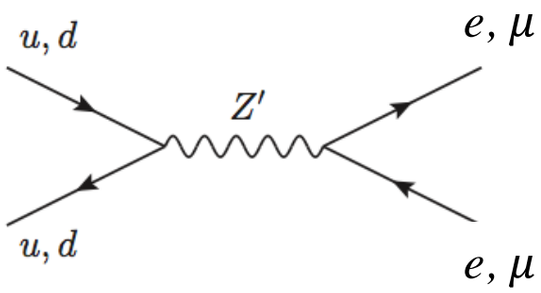


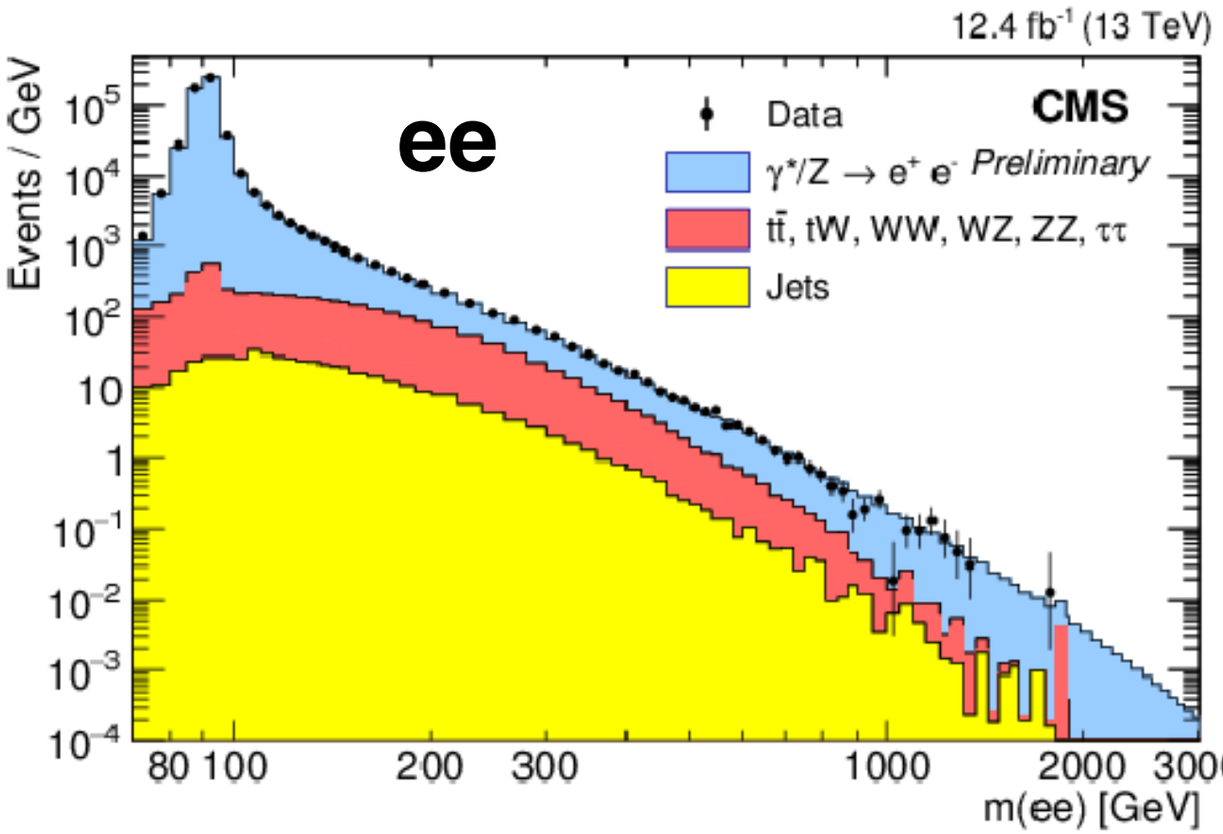


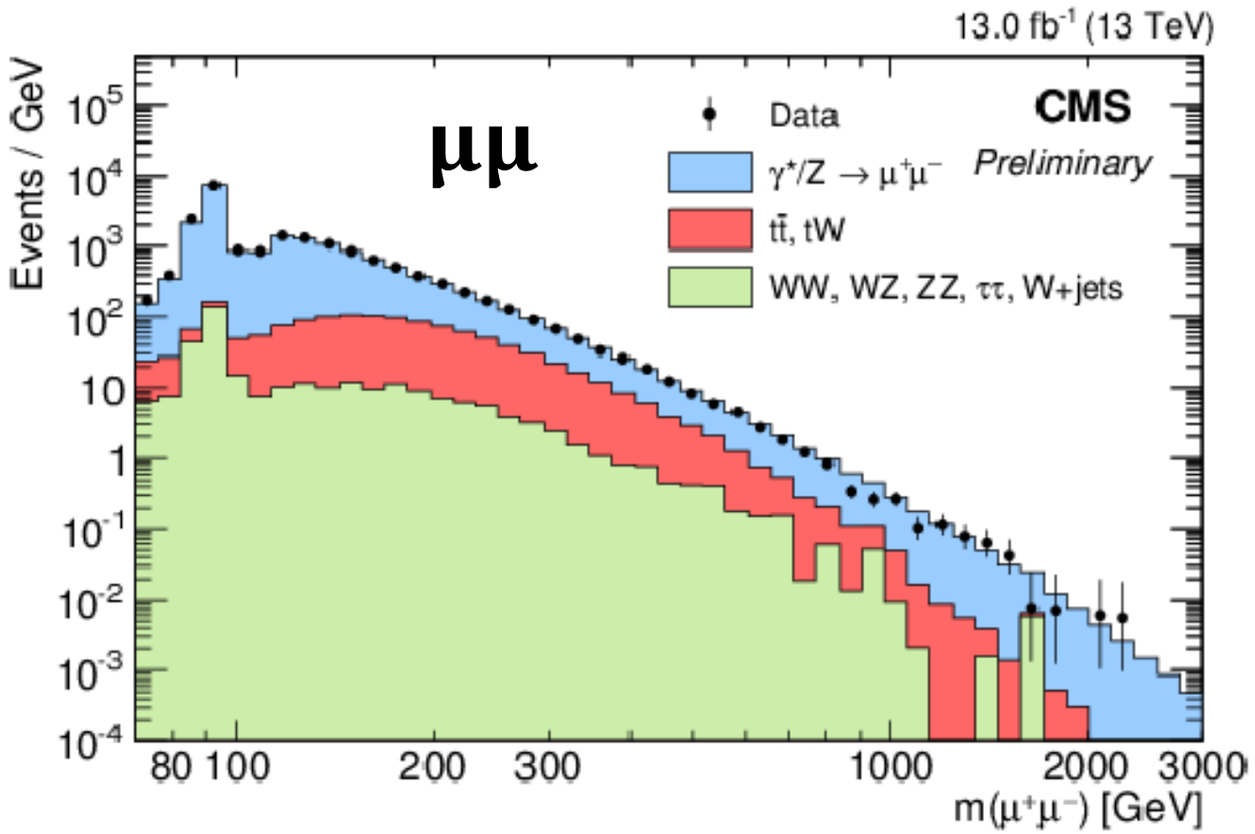
RPV stops excluded between masses 80-240 GeV

Run-2 Analysis: Z’ boson searches

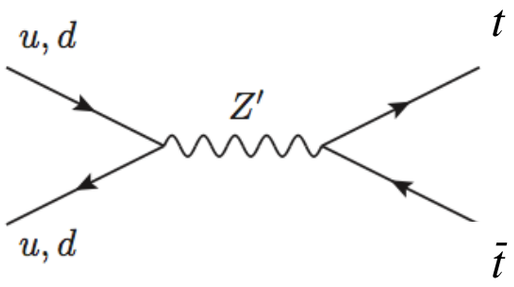
Z' to ee/μμ





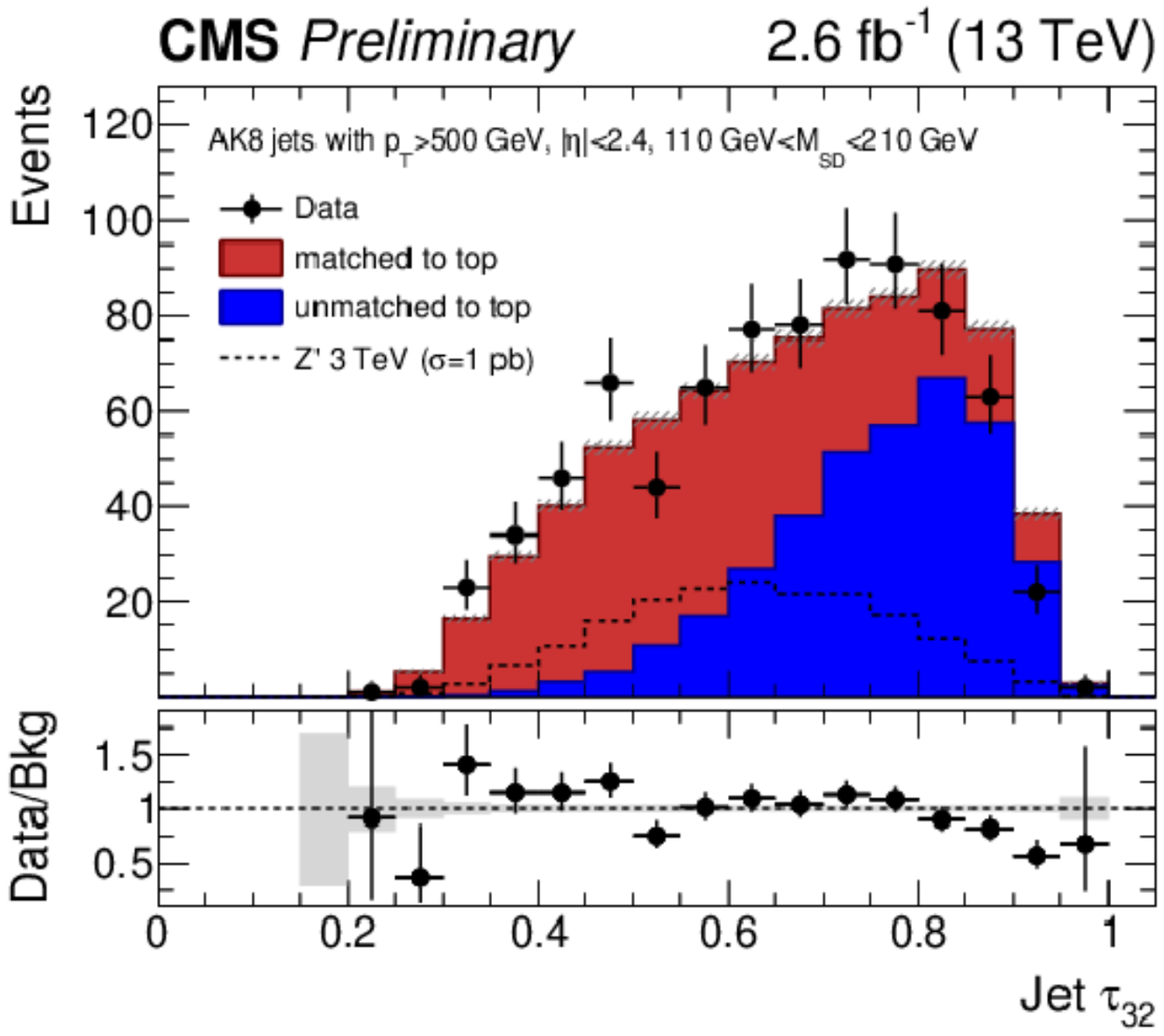


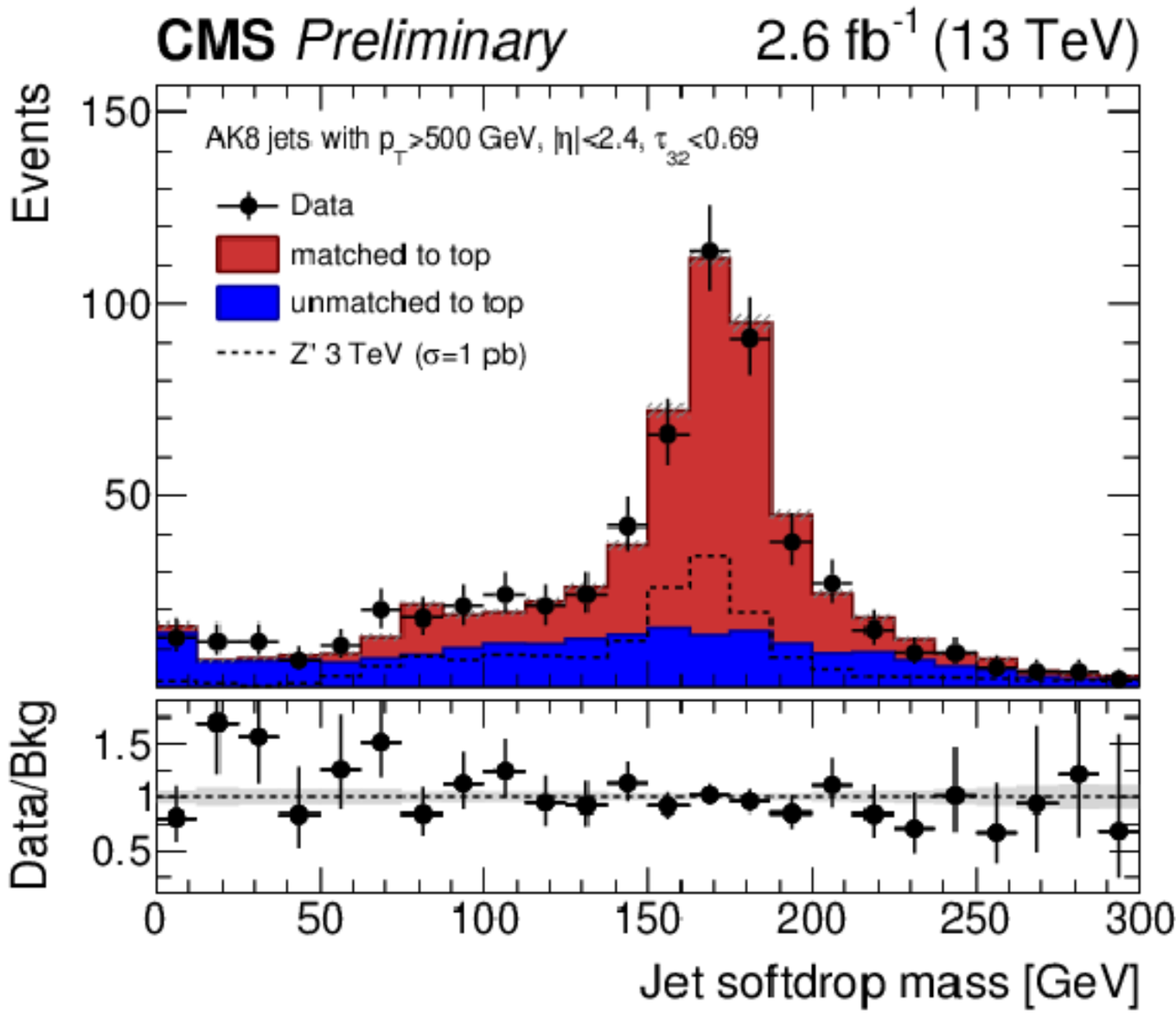
- Background fit using a parametric function.
- For a Sequential SM Z'_{SSM}, masses excluded < 4 TeV.
- For a GUT Z'_{ψ} model, masses excluded < 3.5 TeV.



Z' to tt̄ (semileptonic)

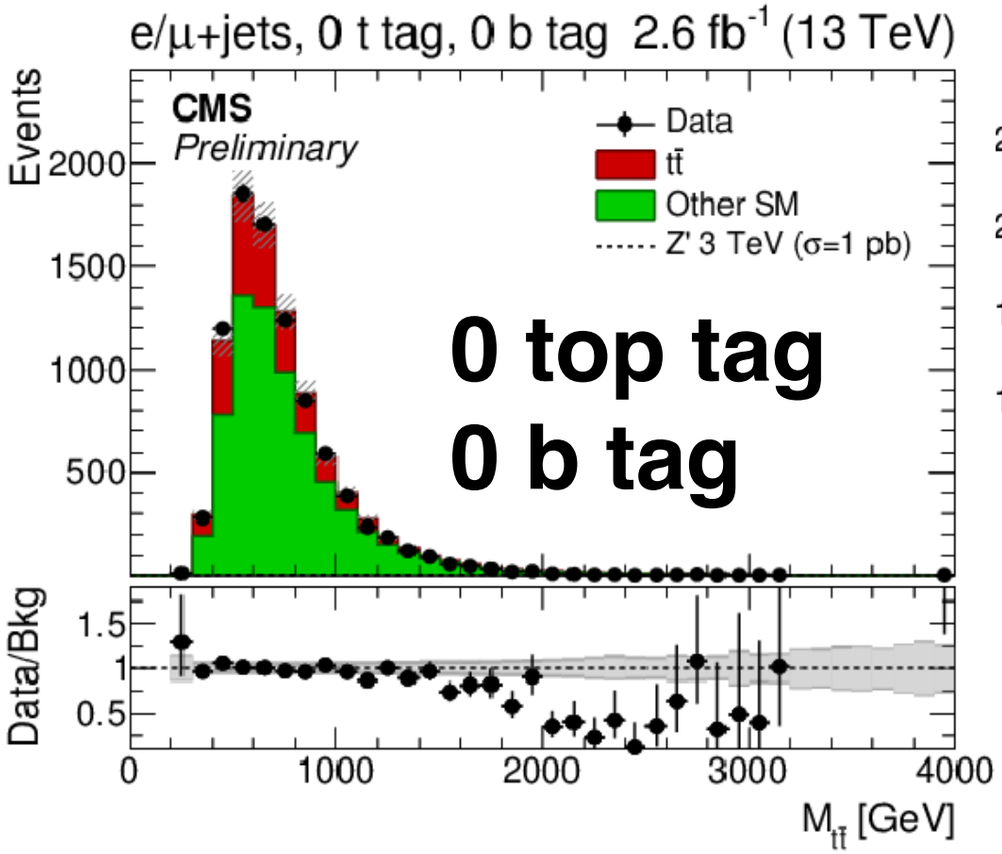
- Many extensions of the SM predicts a heavy Z' coupled to top quarks e.g. KK excitations of gluons and RS gravitons.
- Top-tagging is applied using $\tau_3/\tau_2<0.69$ and $110<M_{SD}<210$ GeV.

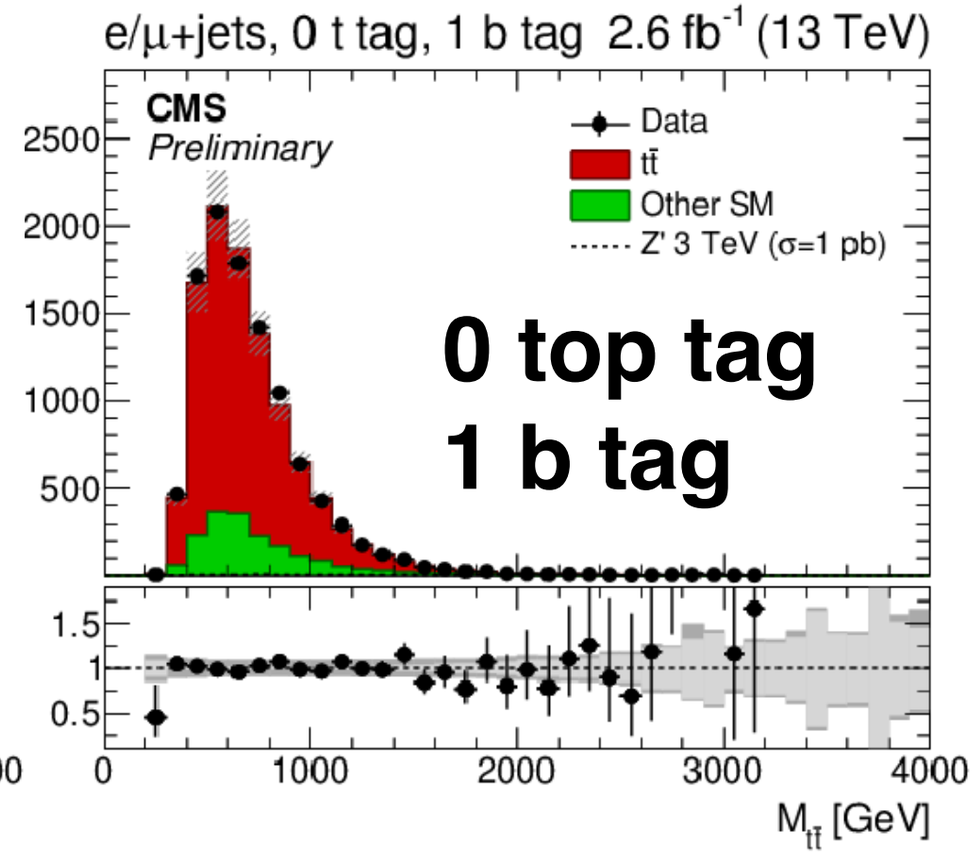




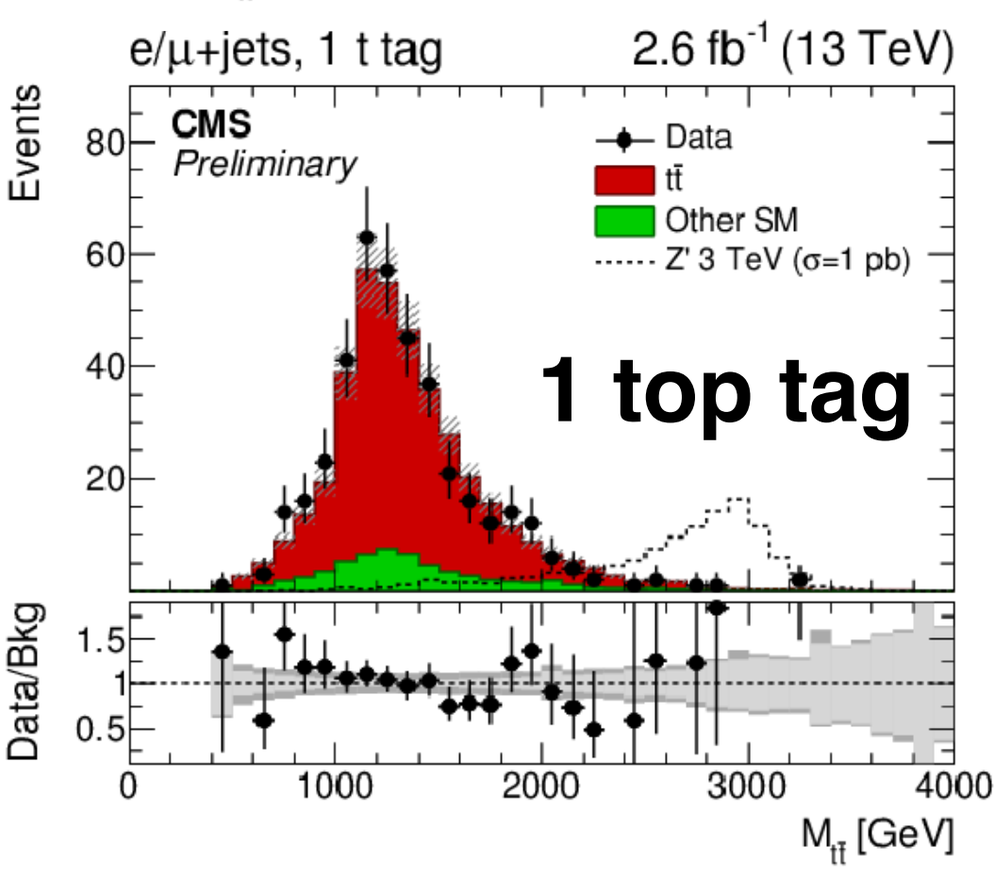
Z’ to $t\bar{t}$ (semileptonic)

B2G-15-002





signal	excluded mass regions [TeV]		
	μ + jets observed (expected)	e + jets observed (expected)	combination observed (expected)
Z' (1% width)	0.5 – 1.8 (0.6 – 1.9)	1.0 – 1.1, 1.3 – 2.2 (0.9 – 1.7)	0.6 – 2.3 (0.6 – 2.1)
Z' (10% width)	0.5 – 3.2 (0.5 – 3.3)	0.5 – 3.2 (0.5 – 3.2)	0.5 – 3.4 (0.5 – 3.5)
Z' (30% width)	0.5 – 3.9 (0.5 – 4.0)	0.5 – 3.8 (0.5 – 3.8)	0.5 – 4.0 (0.5 – 4.0)
KK gluon	0.5 – 2.7 (0.5 – 2.8)	0.6 – 2.7 (0.6 – 2.5)	0.5 – 2.9 (0.5 – 2.9)



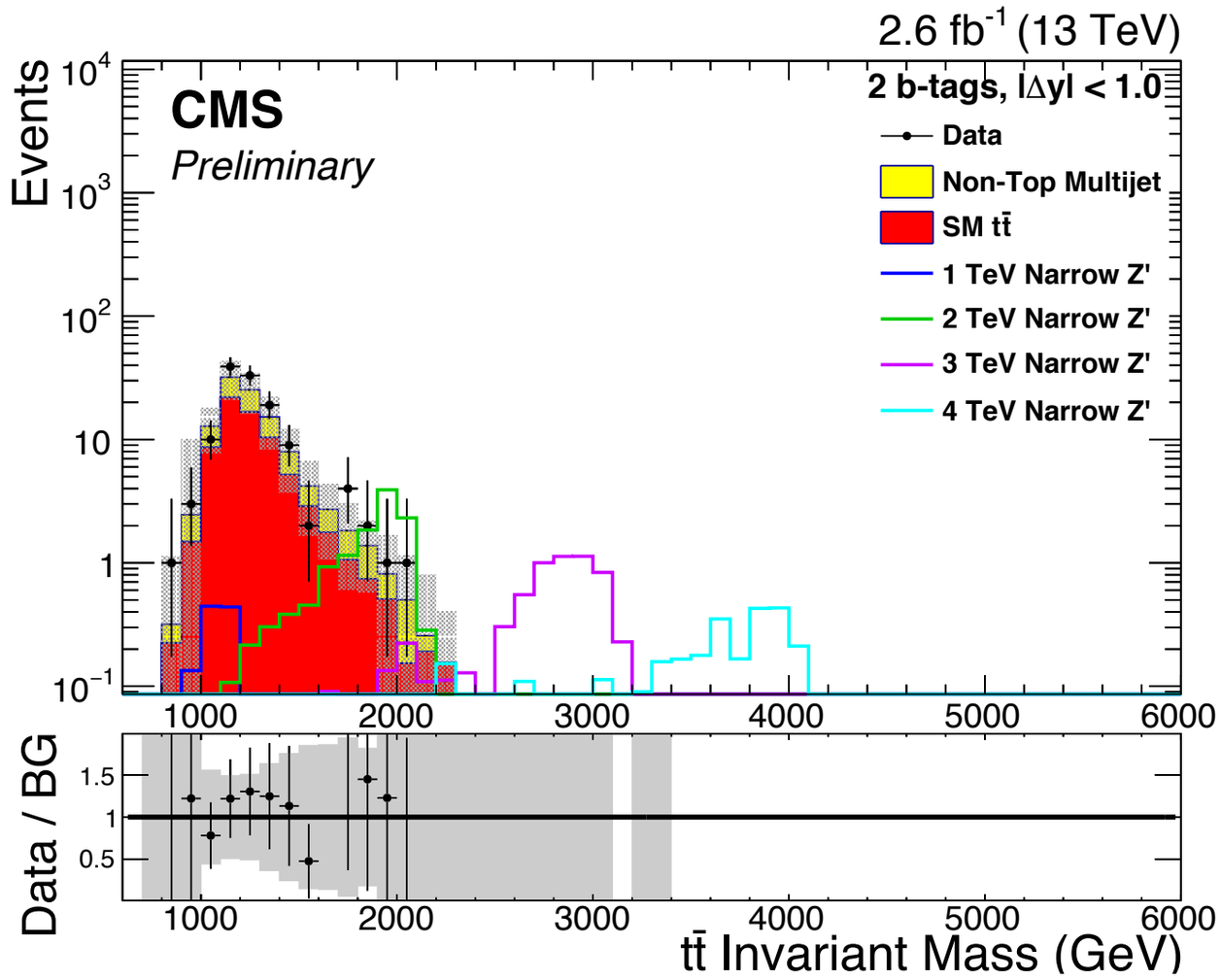
Z’ to $t\bar{t}$ (fully hadronic)

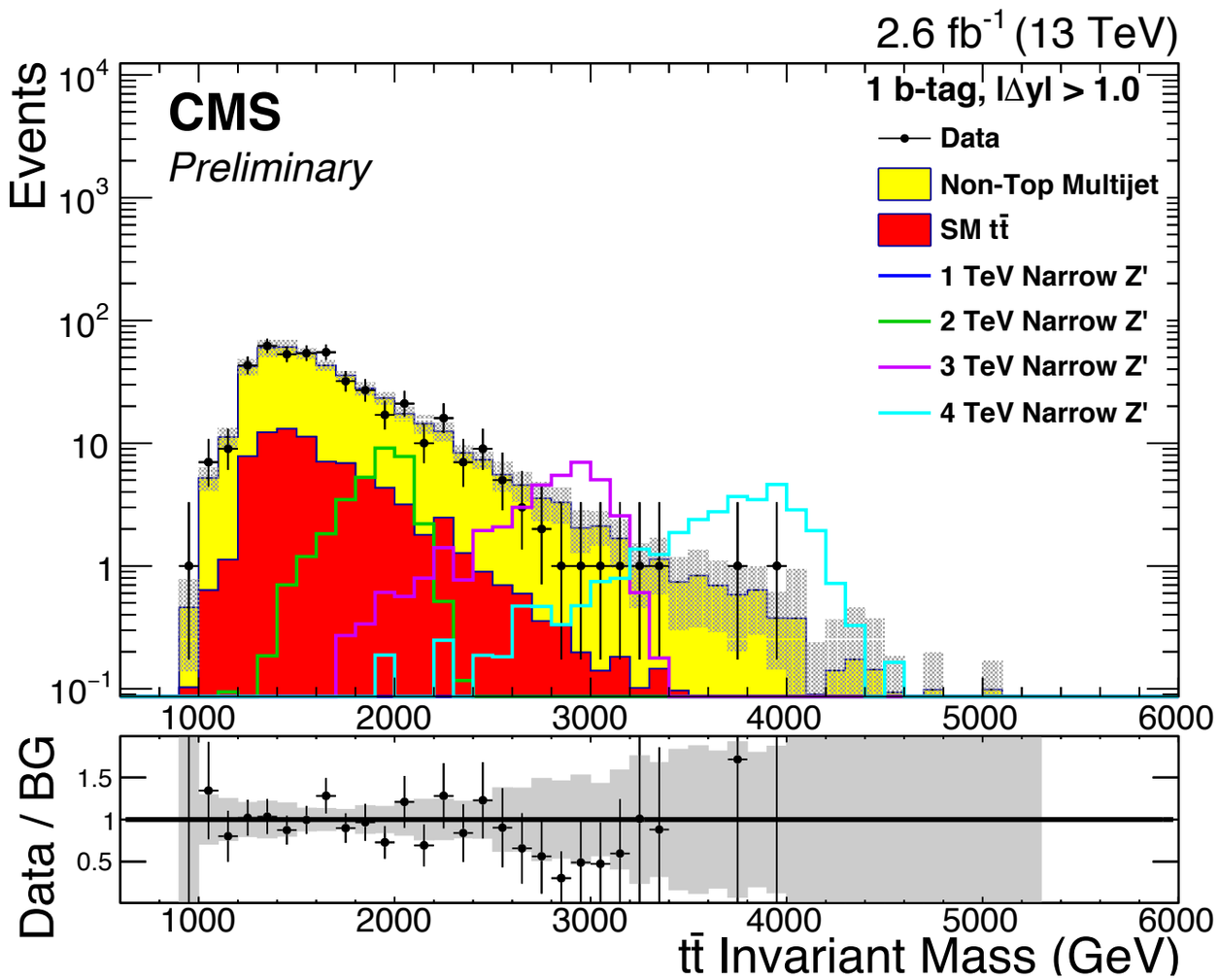
B2G-15-003

- Apply b-tagging algorithm to subjets.
- Use substructure to tag top jets.
- Analysis done in 6 samples: 0 b, 1 b, 2 b jets and rapidity difference $|\Delta y| < 1$ and $|\Delta y| > 1$.

Mass Exclusion Limits

Signal Model	Exclusion Ranges (TeV)	
	Expected	Observed
Z′ (1% Width)	1.2 – 1.6	1.4 – 1.6
Z′ (10% Width)	1.0 – 3.1	1.0 – 3.3
Z′ (30% Width)	1.0 – 3.7	1.0 – 3.8
RS Gluon	1.0 – 2.5	1 – 2.4

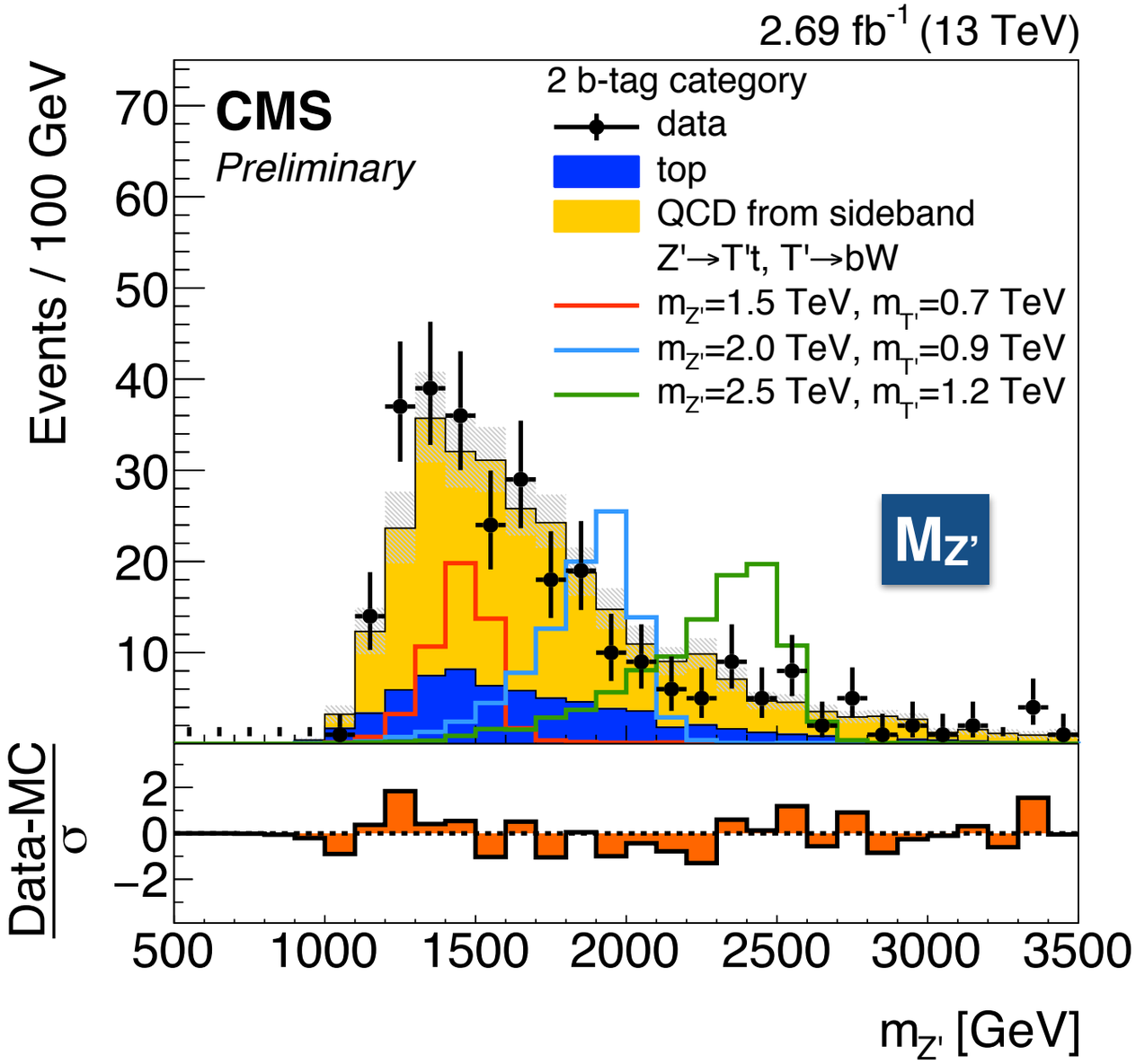


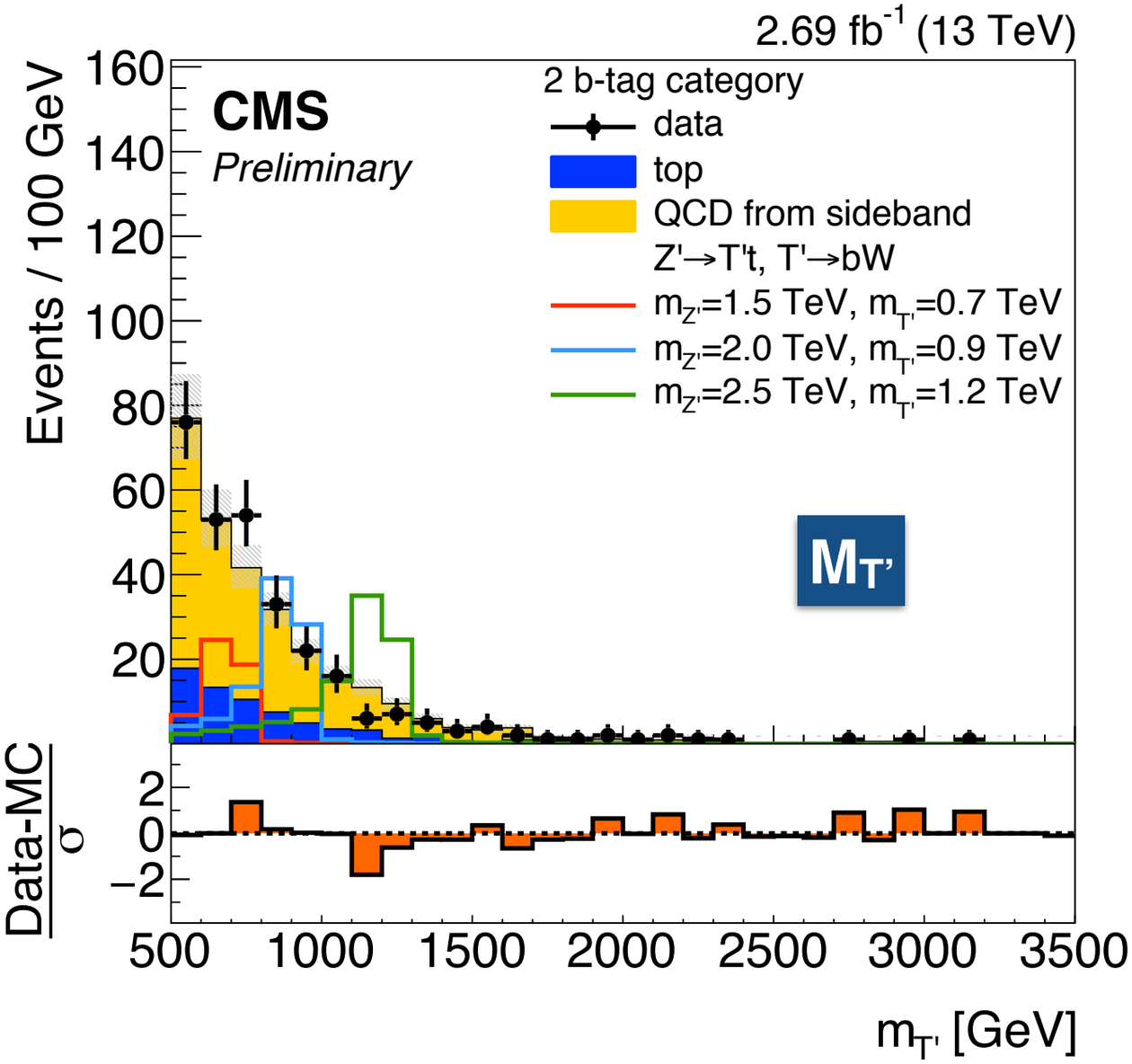


Z' to tT' (fully hadronic)

B2G-16-013

- Search for heavy spin-1 Z' decaying to a top quark and a heavy vector-like top partner T' decaying to Wb, and W to quarks.
- Substructure is used to tag a W and top jets.
- Z'(tT') is excluded with upper cross section limits ranging 0.13 to 11 pb.

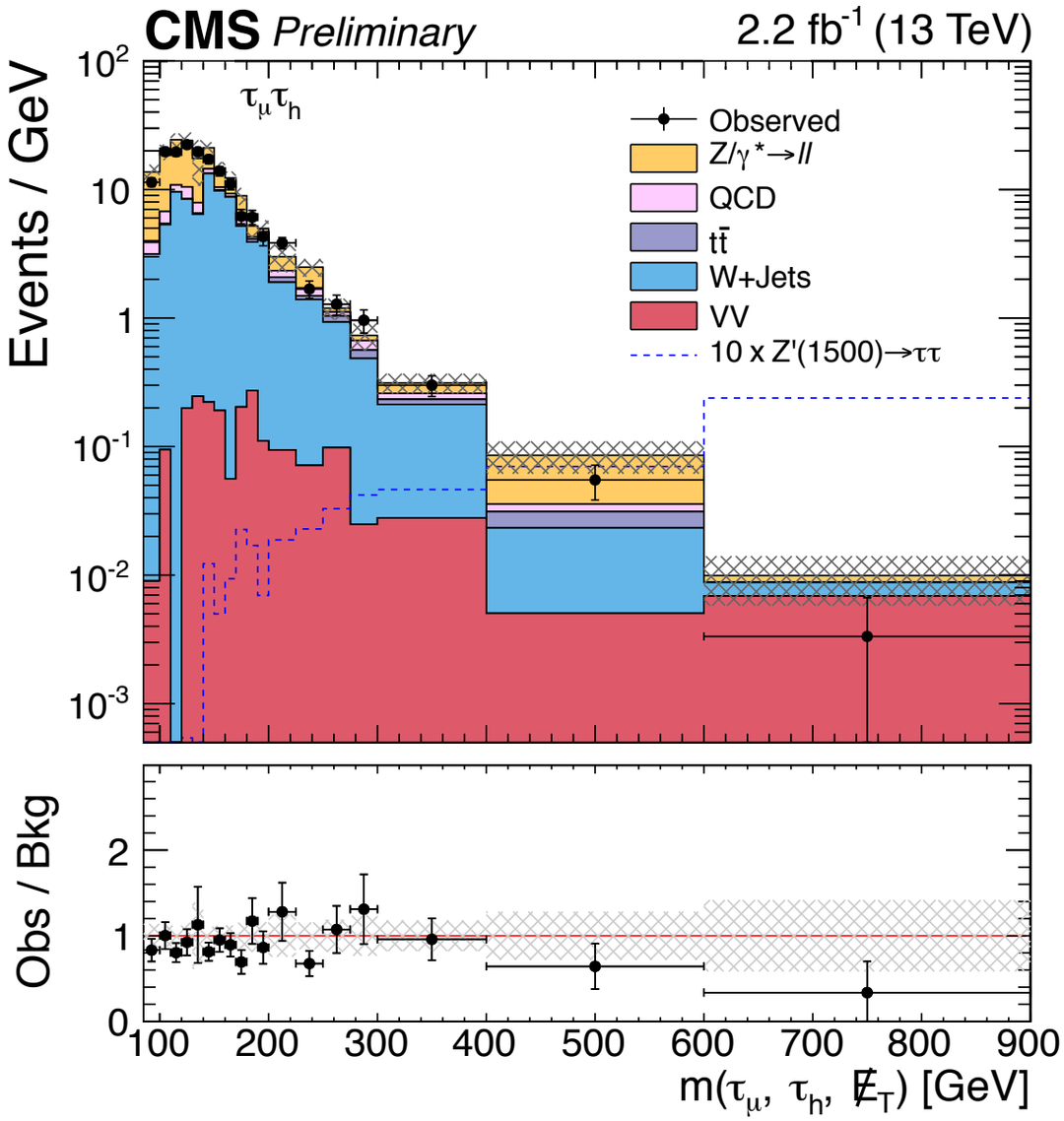


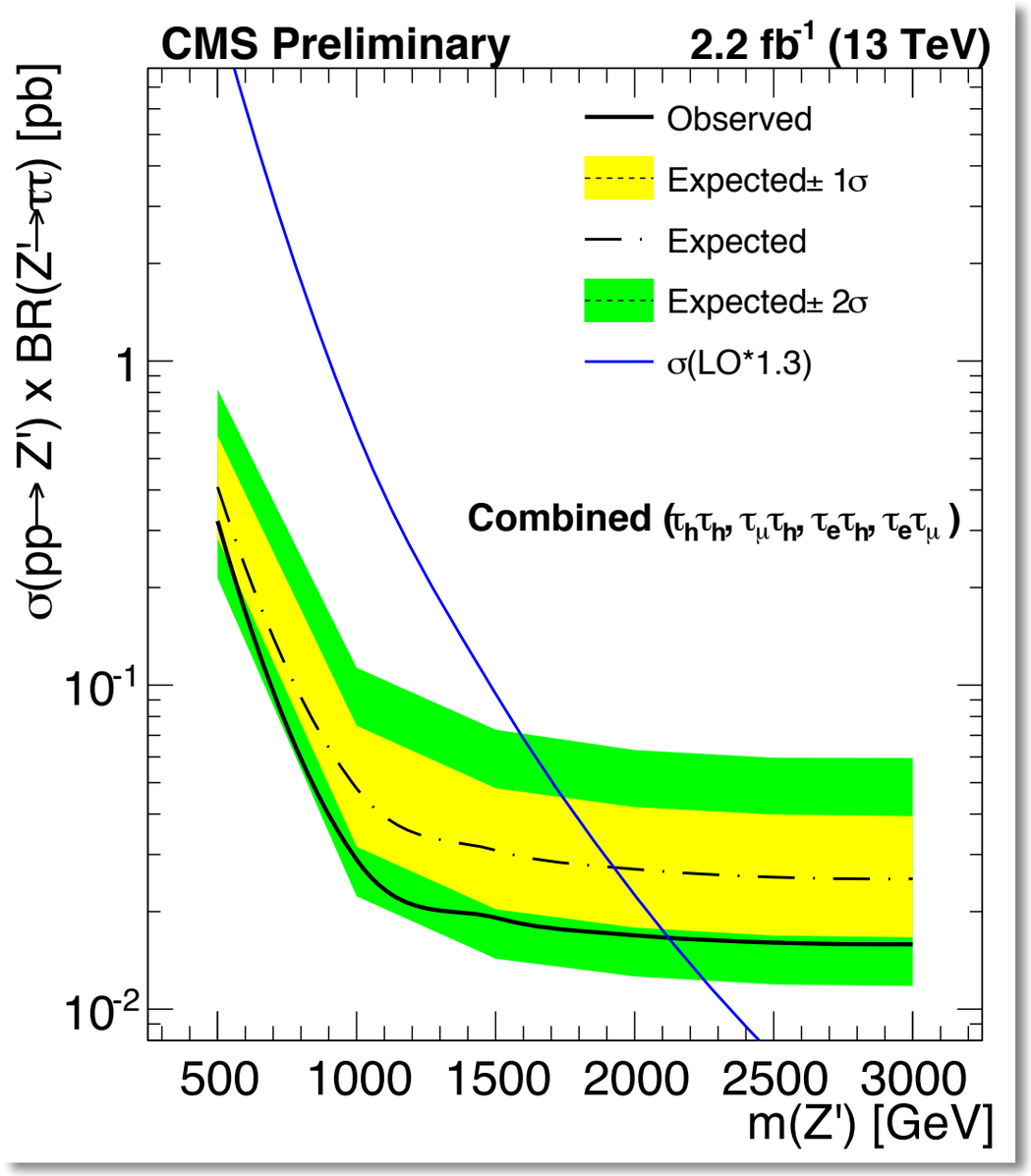


Z' to ττ

EXO-16-008

- Search for a Sequential SM Z' decaying to a pair of tau leptons.
- Four final states: $\tau_e\tau_\mu$, $\tau_e\tau_h$, $\tau_h\tau_\mu$, $\tau_h\tau_h$
- SSM Z' boson with masses < 2.1 TeV are excluded



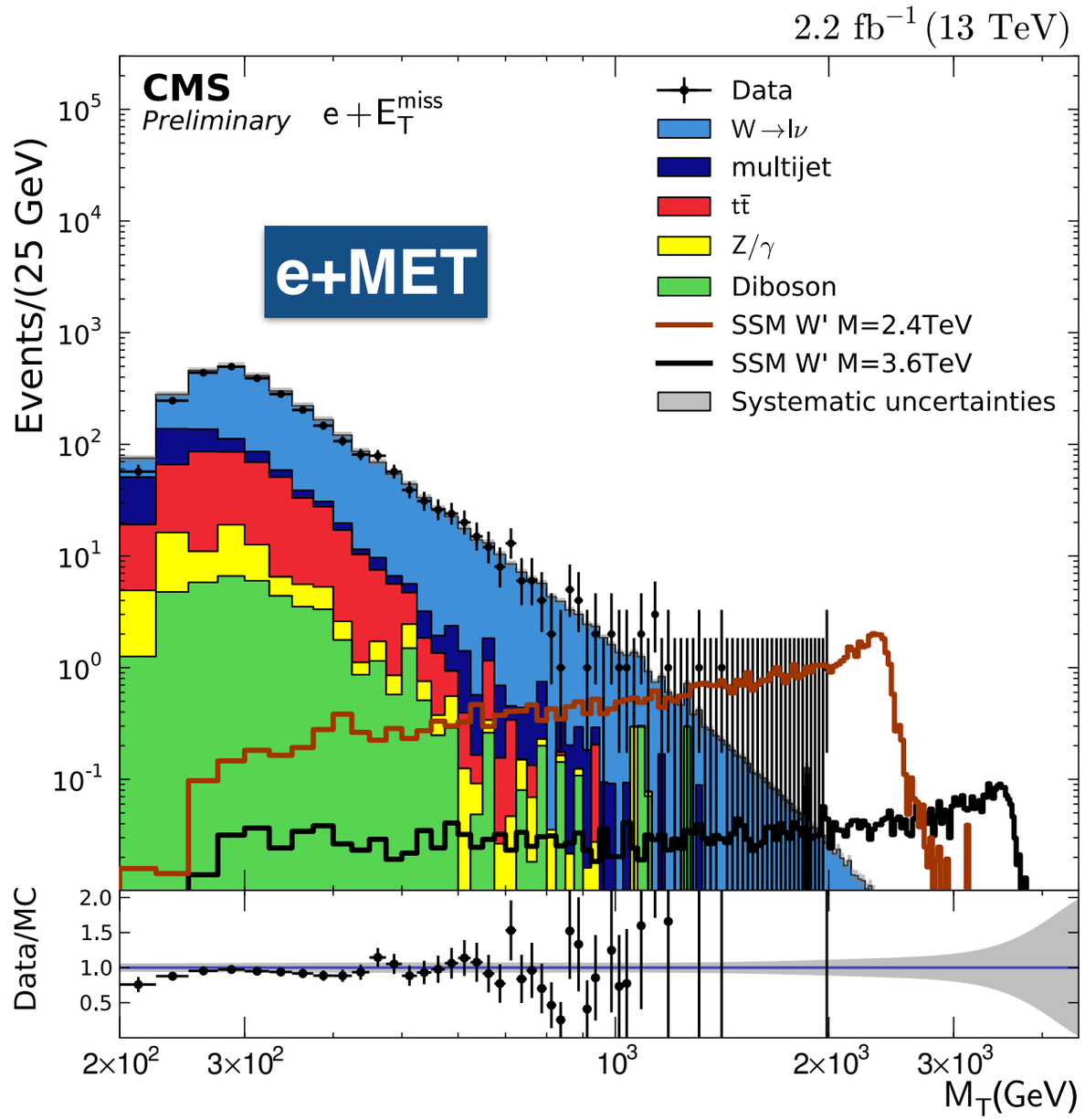


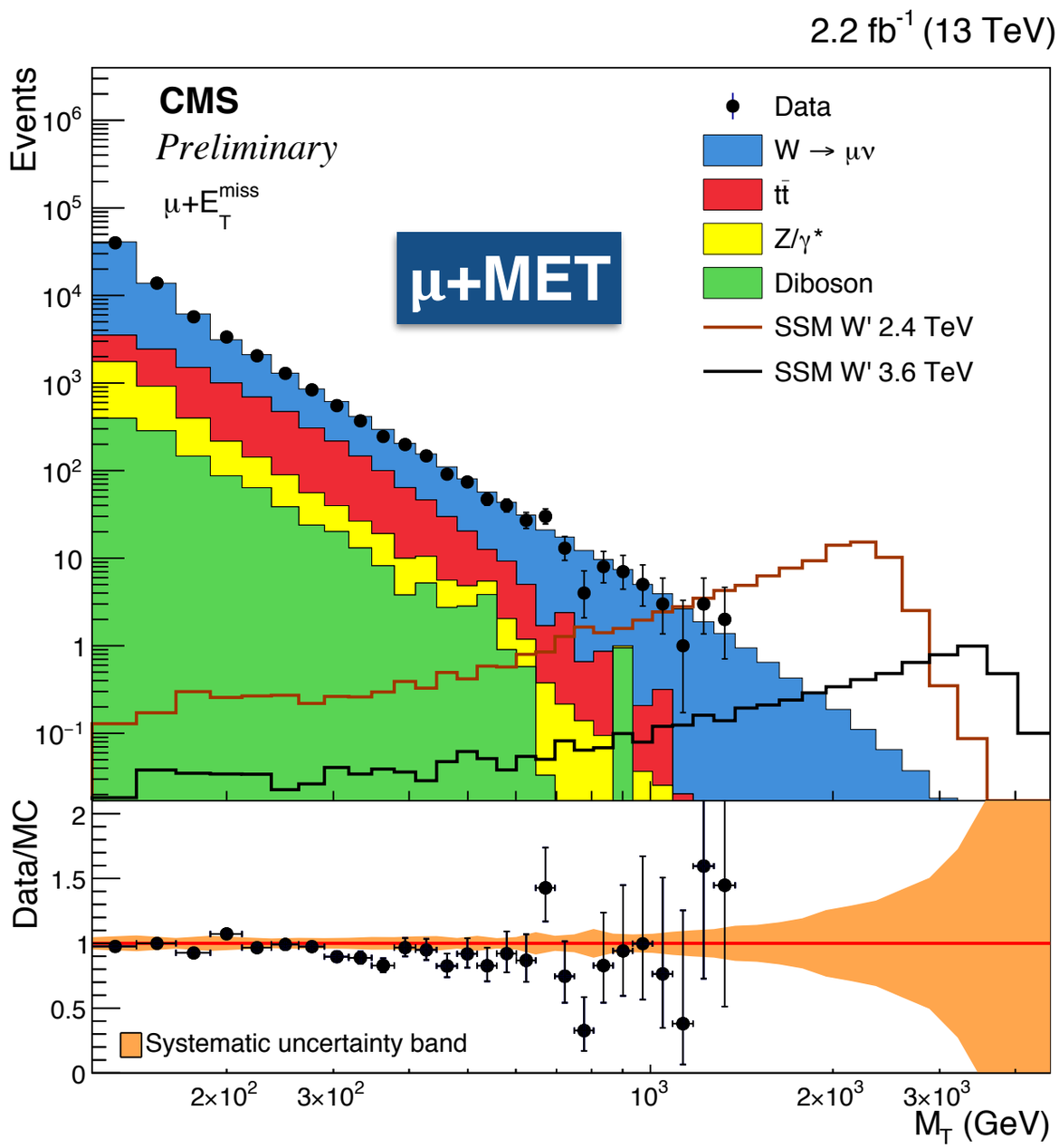
Run-2 Analysis: W’ searches

W' to lepton+ν

EXO-15-006

- SSM W' decaying to electron/muon + missing E_T is excluded below 4.4 TeV

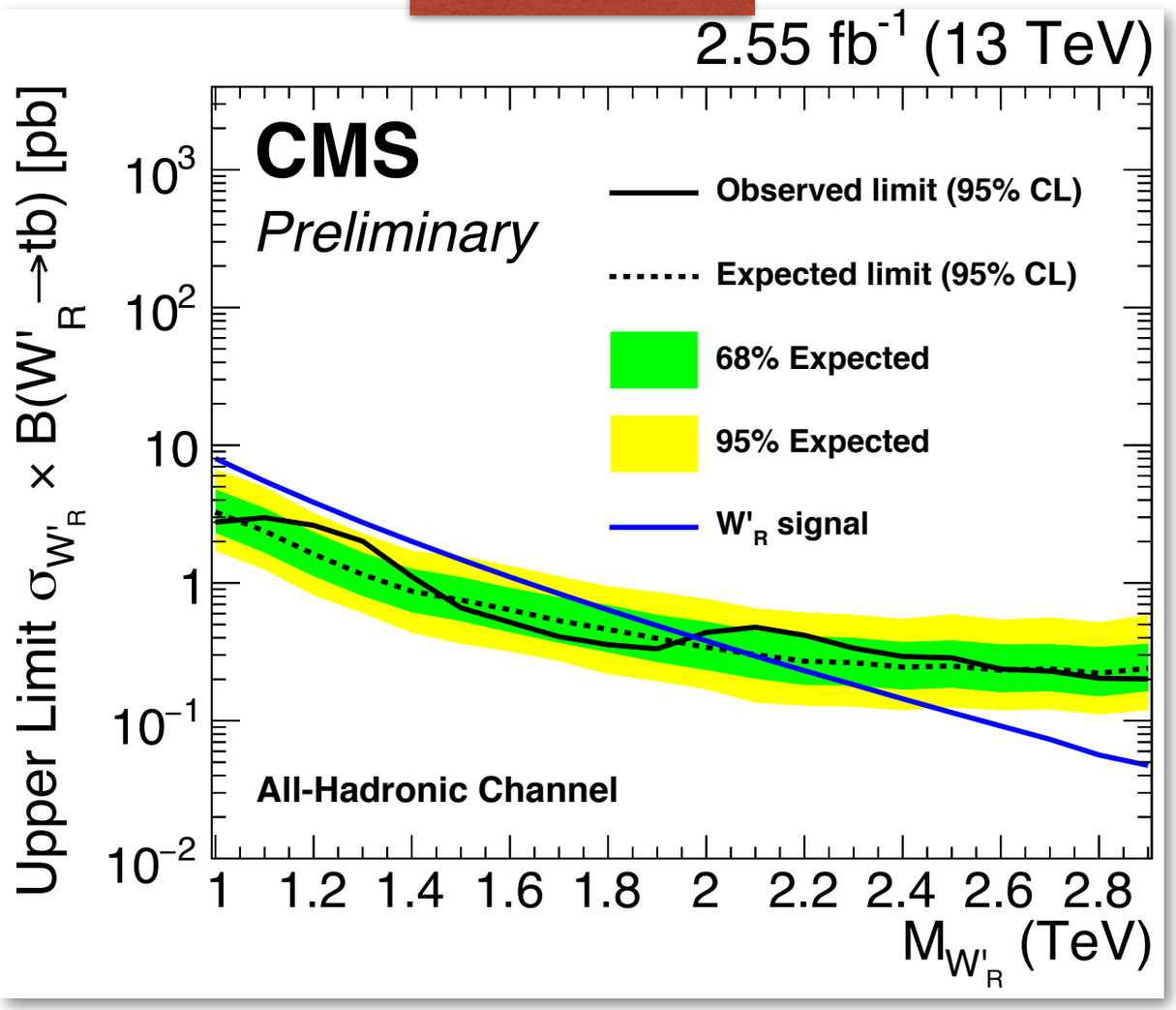




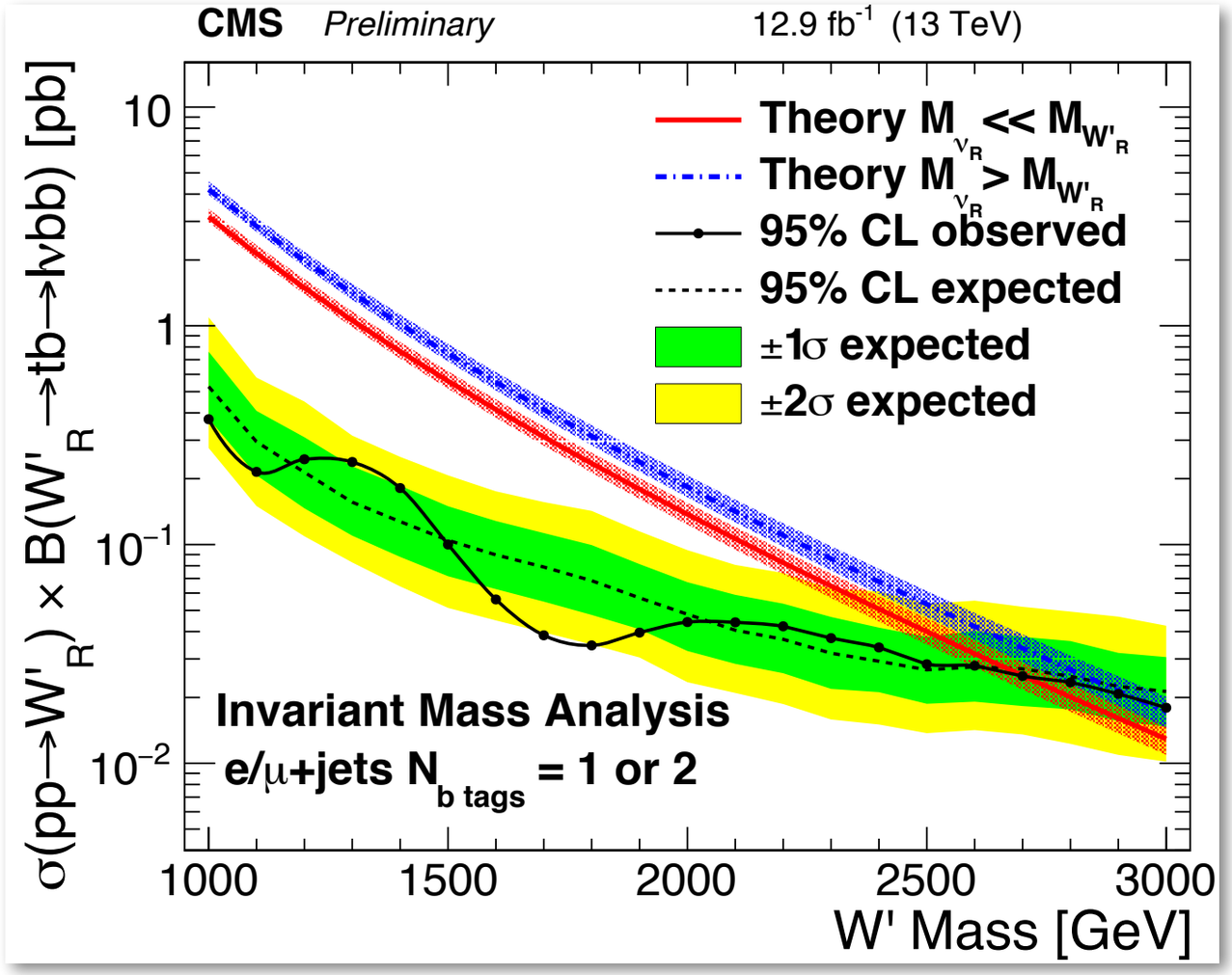
W'_R to tb

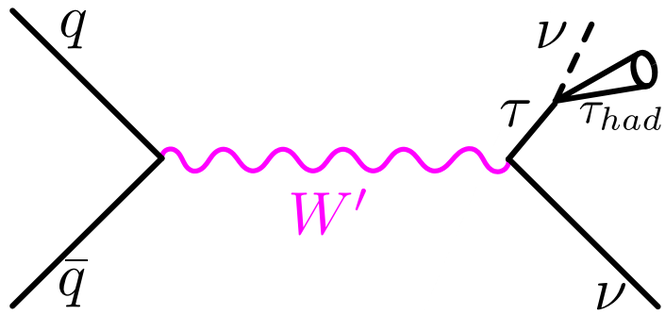
- Search for W' with purely right handed coupling. Two channels.
  - All hadronic channel uses jet substructure
  - Lepton+jets channels use reconstruction of top quark.
- Limits on W'_R are set between 2 and 2.7 TeV depending on the right handed neutrino mass

B2G-16-009



B2G-16-017

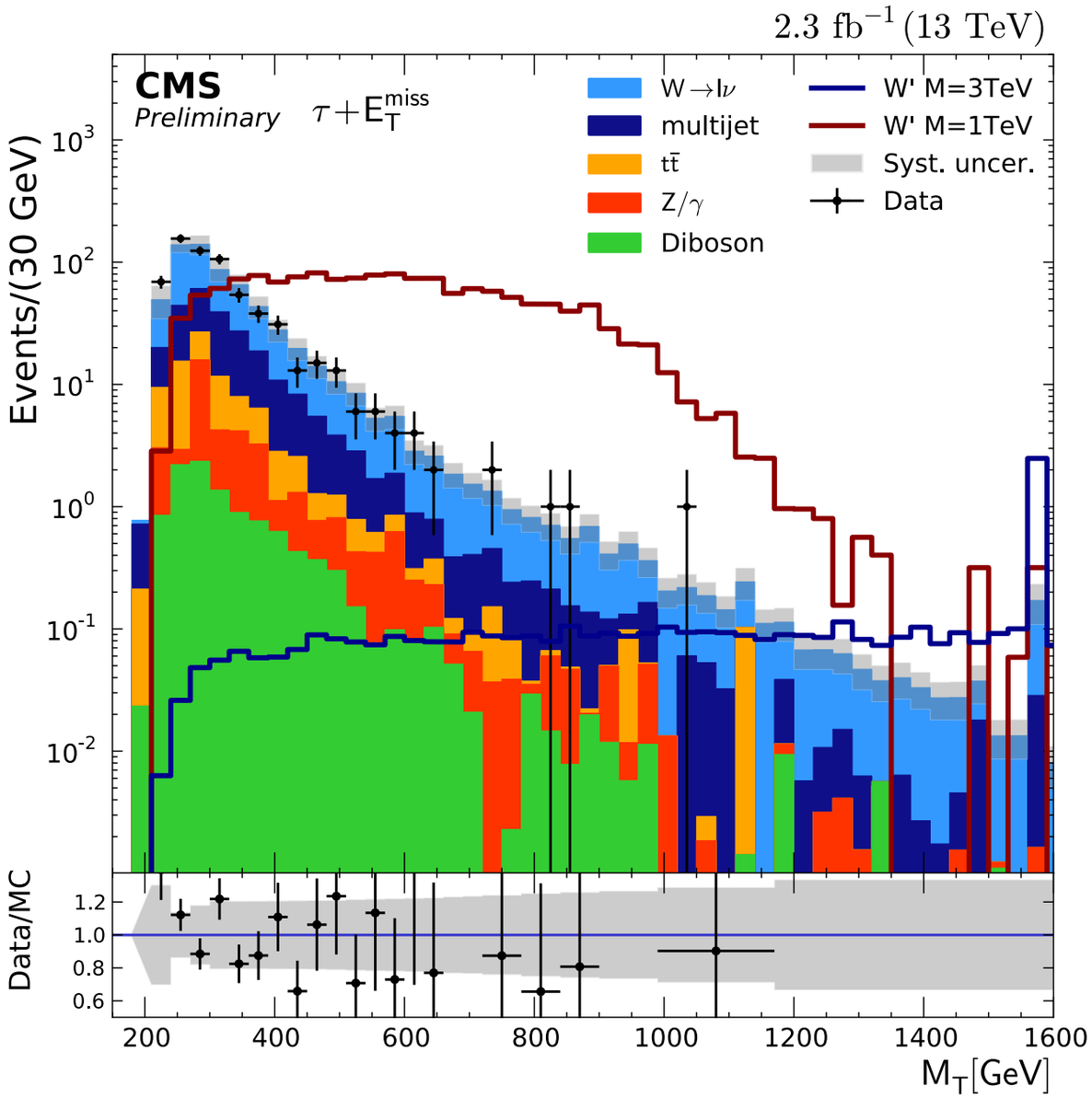


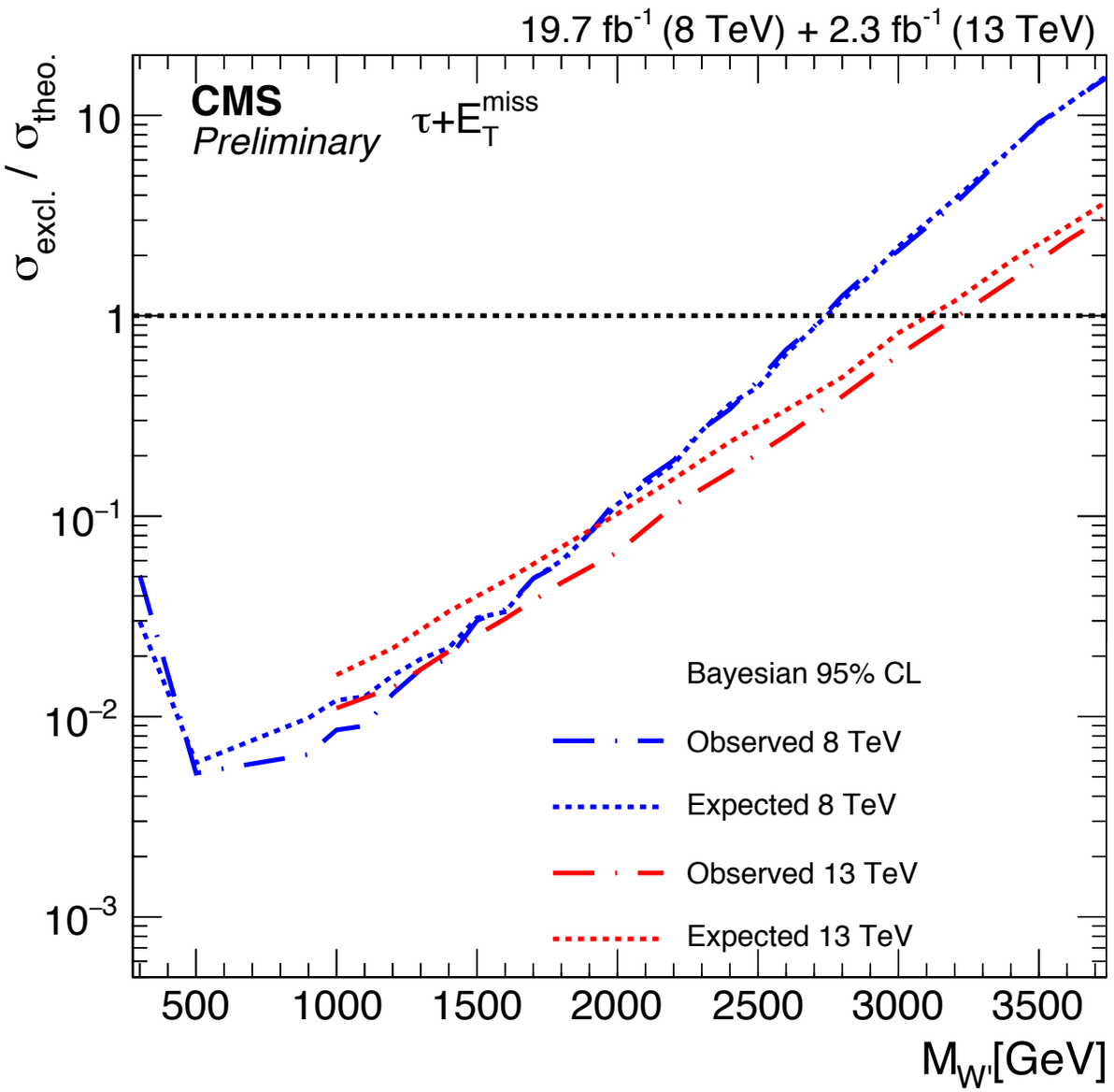


W' to τν

EXO-16-006

- W' decaying to tau (hadronic) and ν excluded from 1 to 3.3 TeV

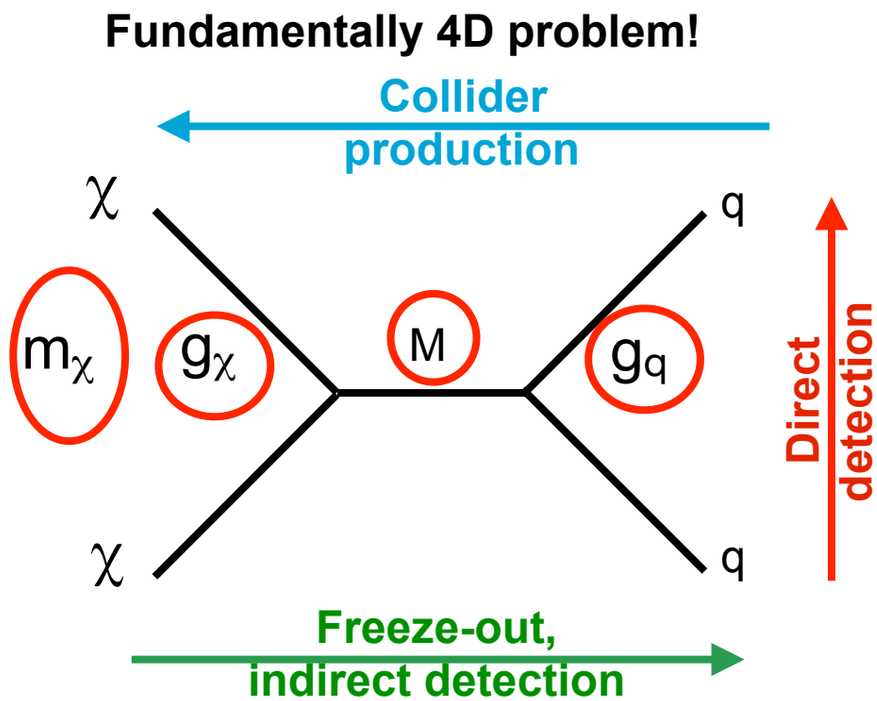




Run-2 Analysis: Dark Matter searches

Dark Matter Searches

- Three main processes to detect dark matter (DM):
  - DM nucleon scattering - direct detection (DD)
  - Indirect detection - annihilation (ID)
  - Pair production at colliders
- These processes are just permutations of the same Feynman diagram.
- DM particles can be observed at the LHC when they are produced in association with a SM particle (g, q, γ, Z, W, H).



- Each model is characterized by 4 parameters:
  - DM mass (m_χ), mediator mass (M_{med}), mediator coupling to quarks (g_q), and mediator coupling to DM (g_{DM})
  - Signal based on simplified models that allow a more fair comparison with DD results

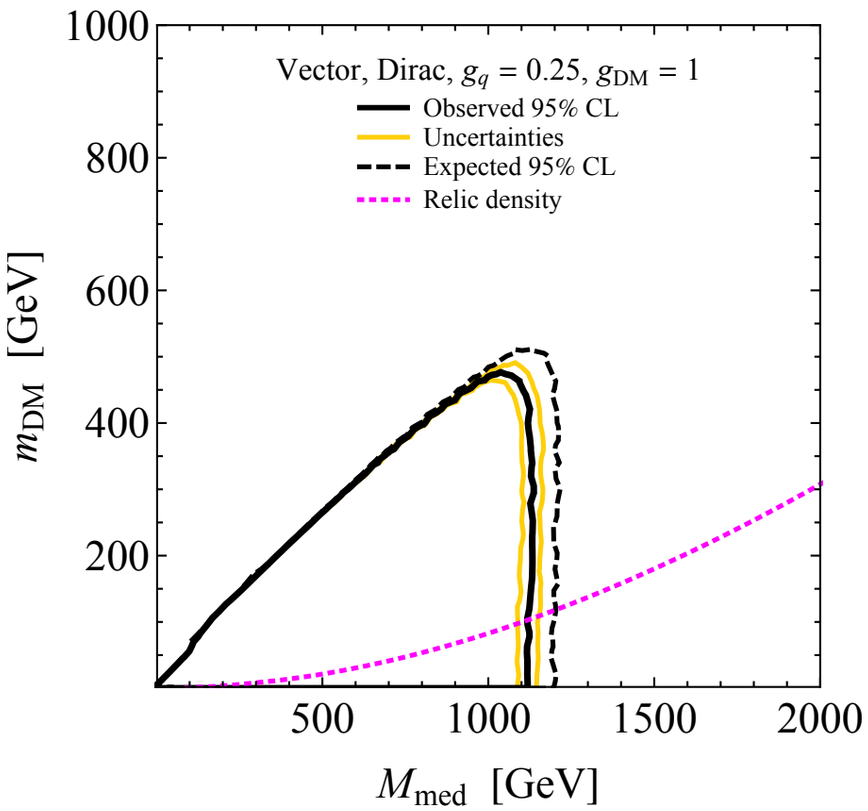
	Spin-1	
Vector		Axial
$g_{DM} Z'_\mu \bar{\chi} \gamma^\mu \chi$		$g_{DM} Z''_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$
EWK style coupling (equal to all leptons)		EWK style coupling (equal to all leptons)
Scalar	Spin-0	Pseudoscalar
$g_{DM} S \bar{\chi} \chi$		$g_{DM} P \bar{\chi} \gamma^5 \chi$
Yukawa style coupling (Mass based coupling)		Yukawa style coupling (Mass based coupling)

mono-business

Presentation of DM Search Results

- In 2015, the Atlas/CMS DM forum make recommendations for presentation of results from the LHC:
  - arXiv:1507.00966
  - arXiv:1603.04156
- Project full 4 dimensional parameter space to only 2 dimensions.
- Fix a set of coupling g_q and g_{DM} and produce a mass-mass plot:
  - g_{DM} =1, g_q = 0.25 for vector and axial cases
  - g_{DM} = g_q = 1 for scalar and pseudoscalar cases
  - Values motivated by requirements on the mediator width <10% of its mass, and current dijet constraints.

mass-mass contours



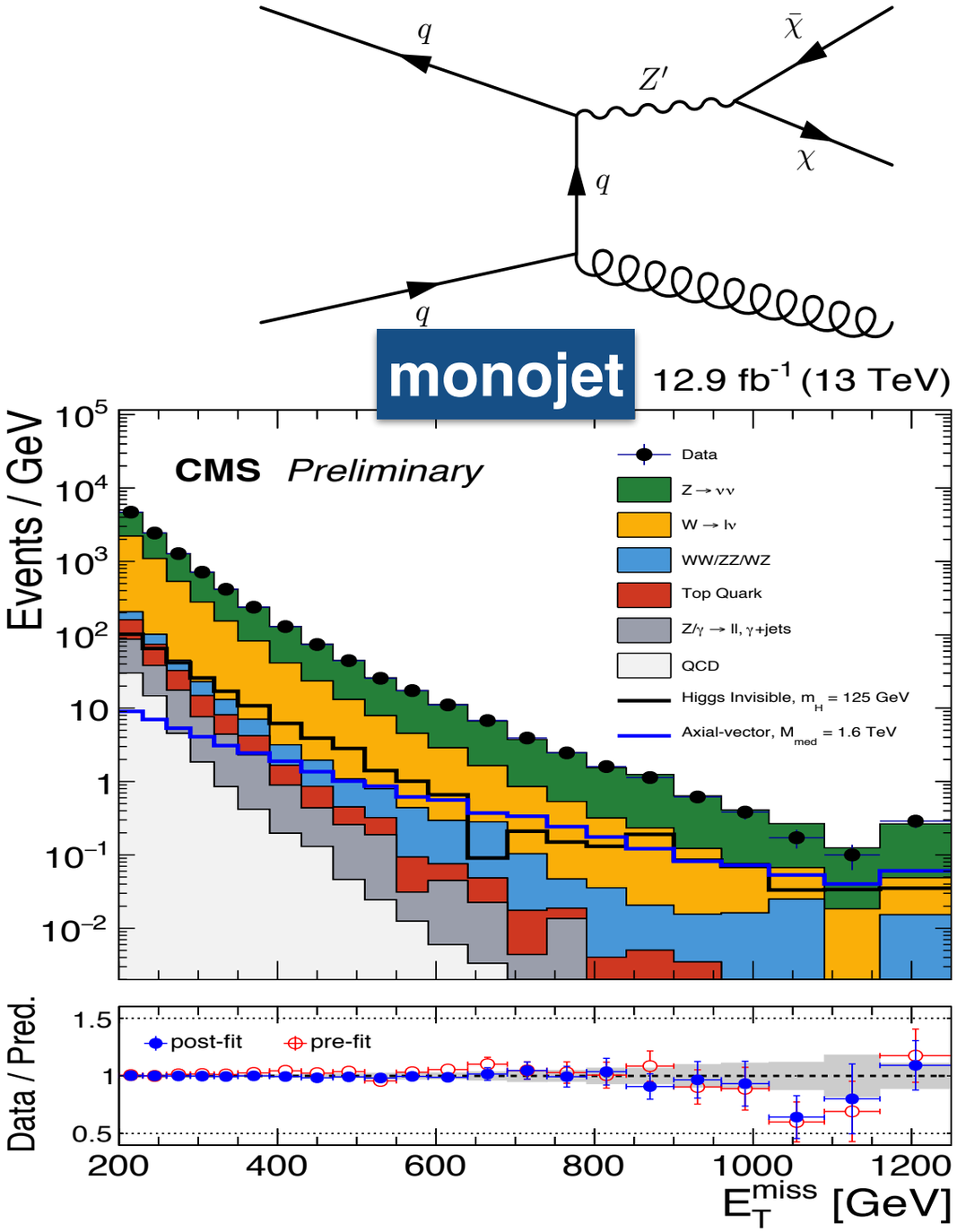
Relic Density:
DM density observed
by WMAP and Planck

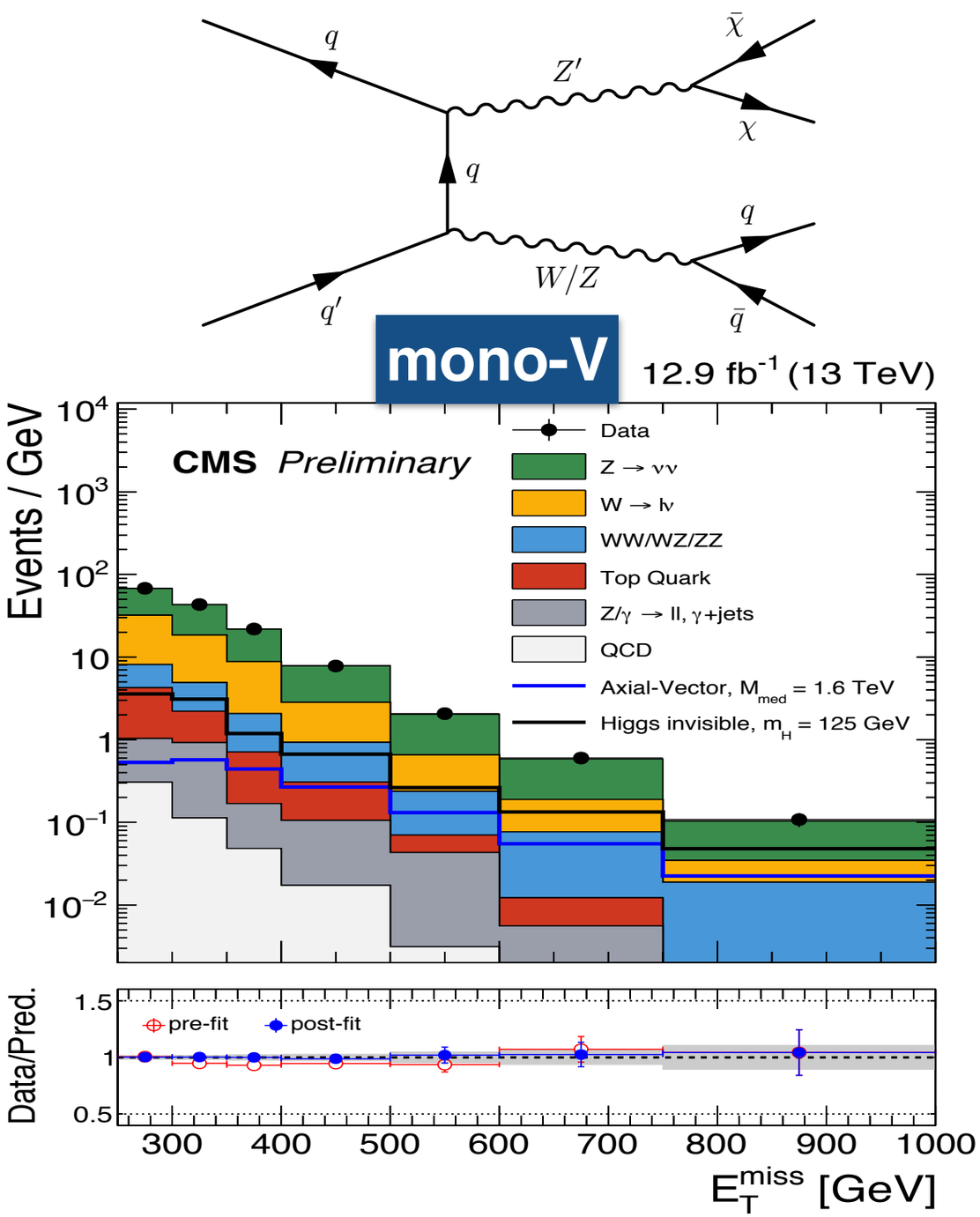
arXiv:1603.04156

DM: Monojet and Mono-V

EXO-16-037

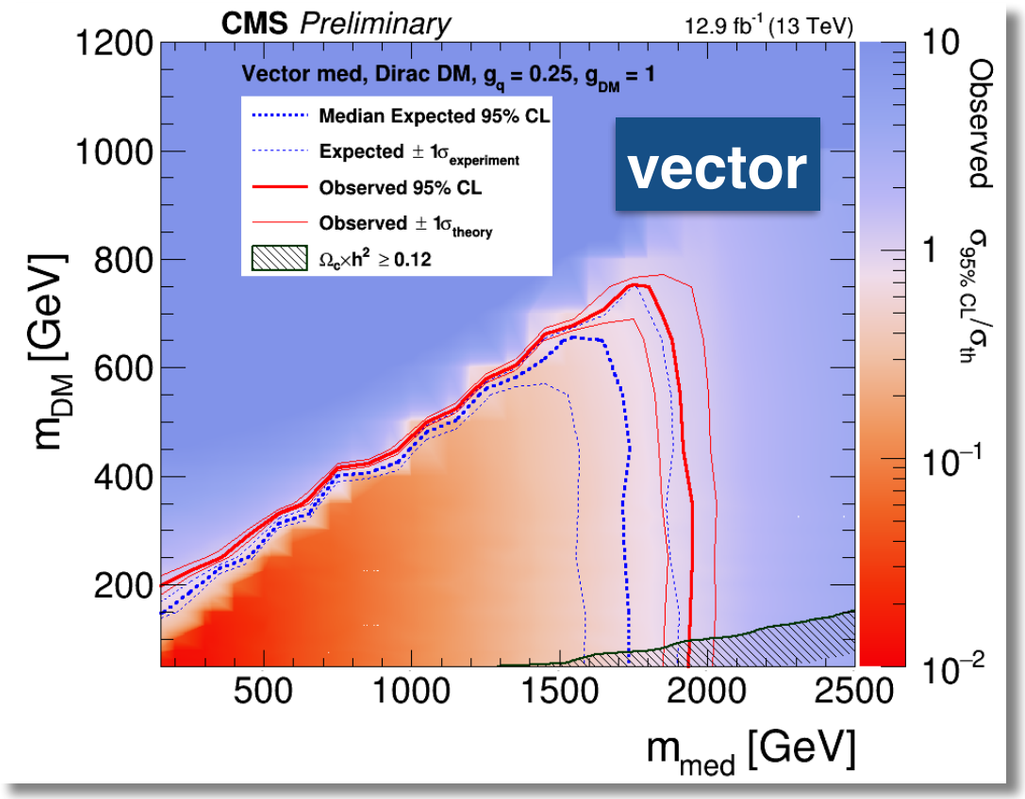
- Two event categories: monojets and mono-V boosted.
- Background estimated with a fit to control regions μμ/**ee**+jets, γ +jets, and μ/**e**+jets with "ME_T" defined ignoring the μ or γ.

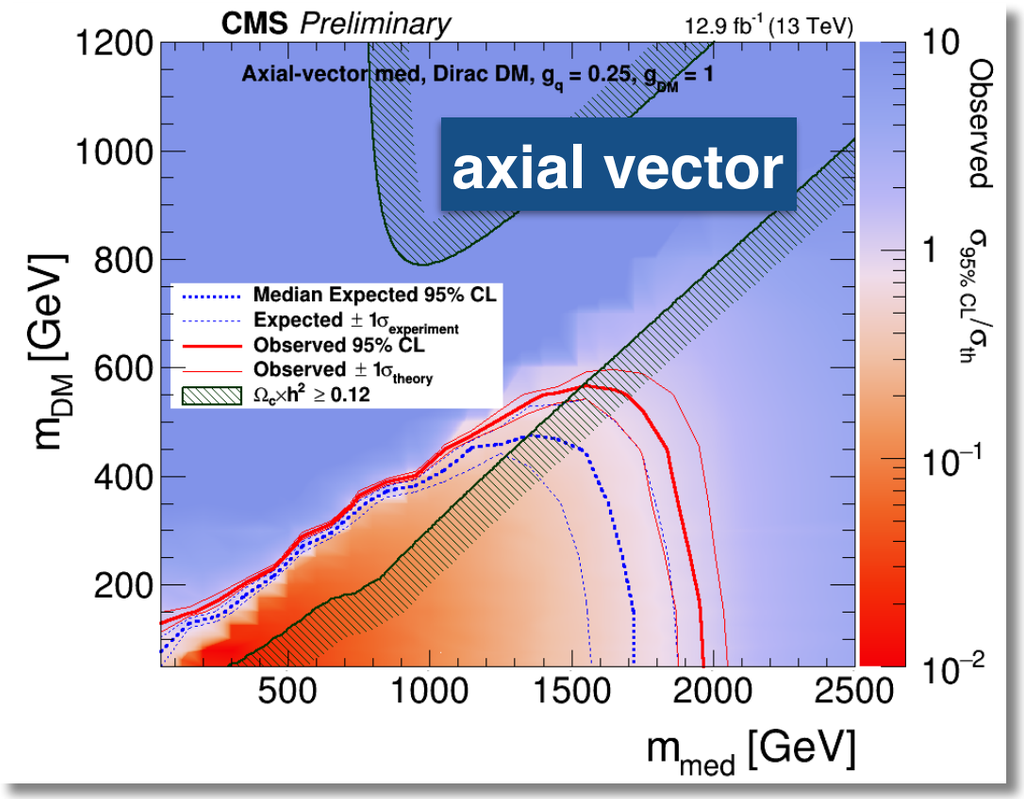


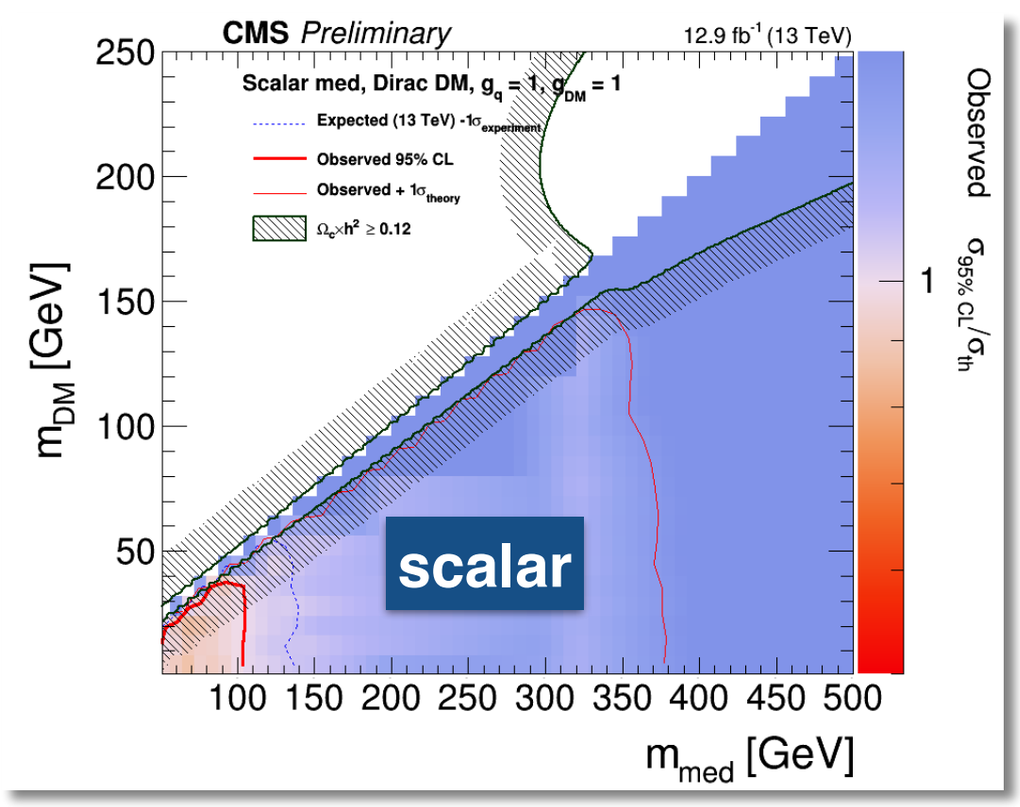


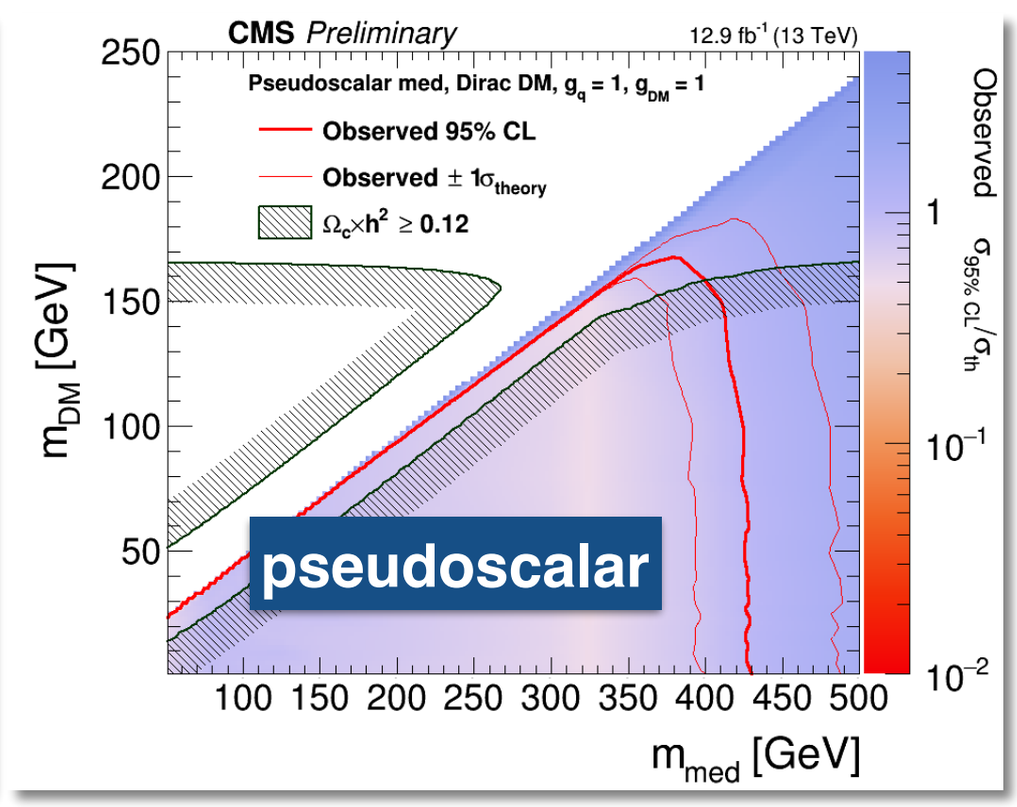
Monojet and Mono-V Searches

EXO-16-037







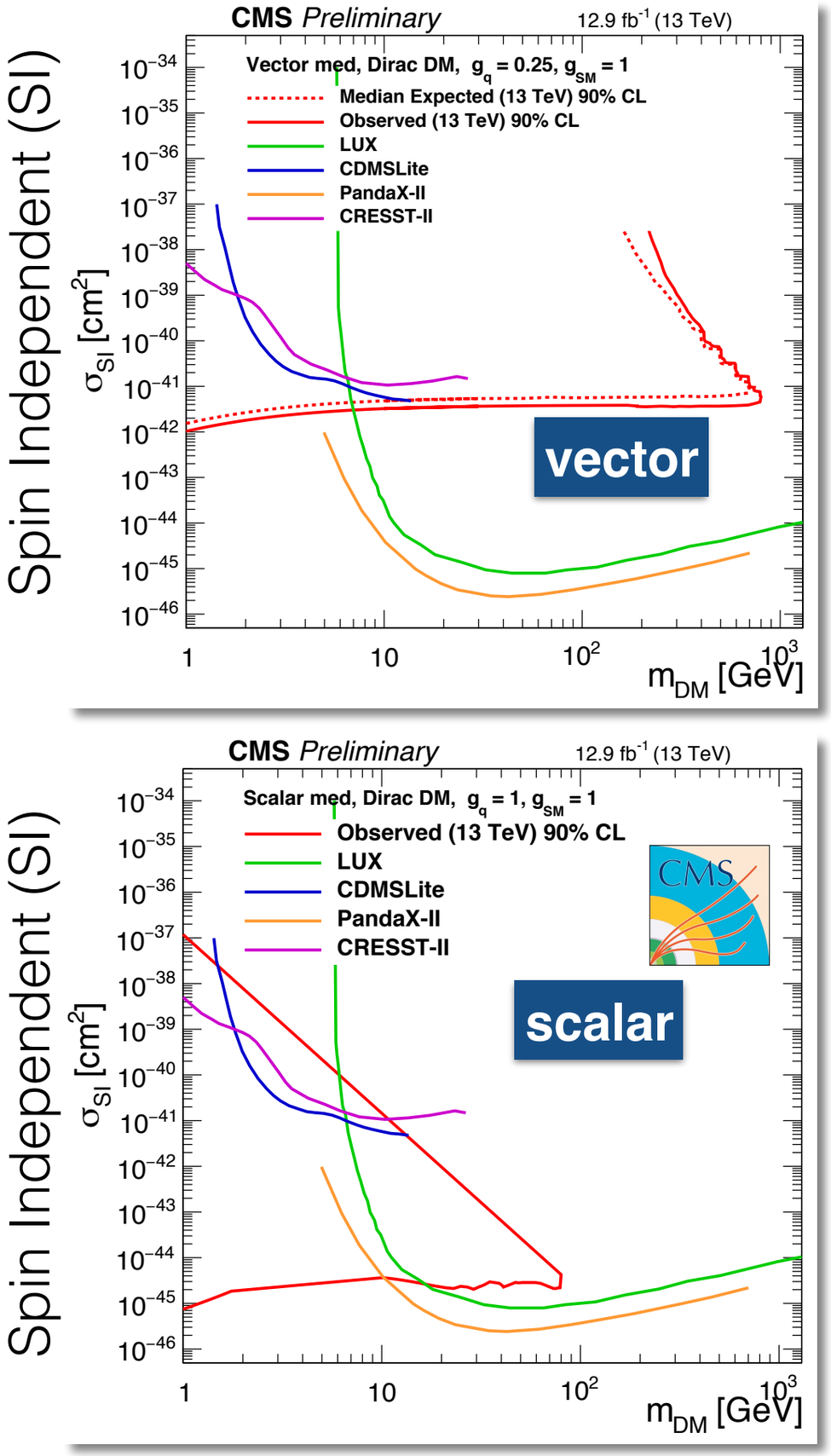


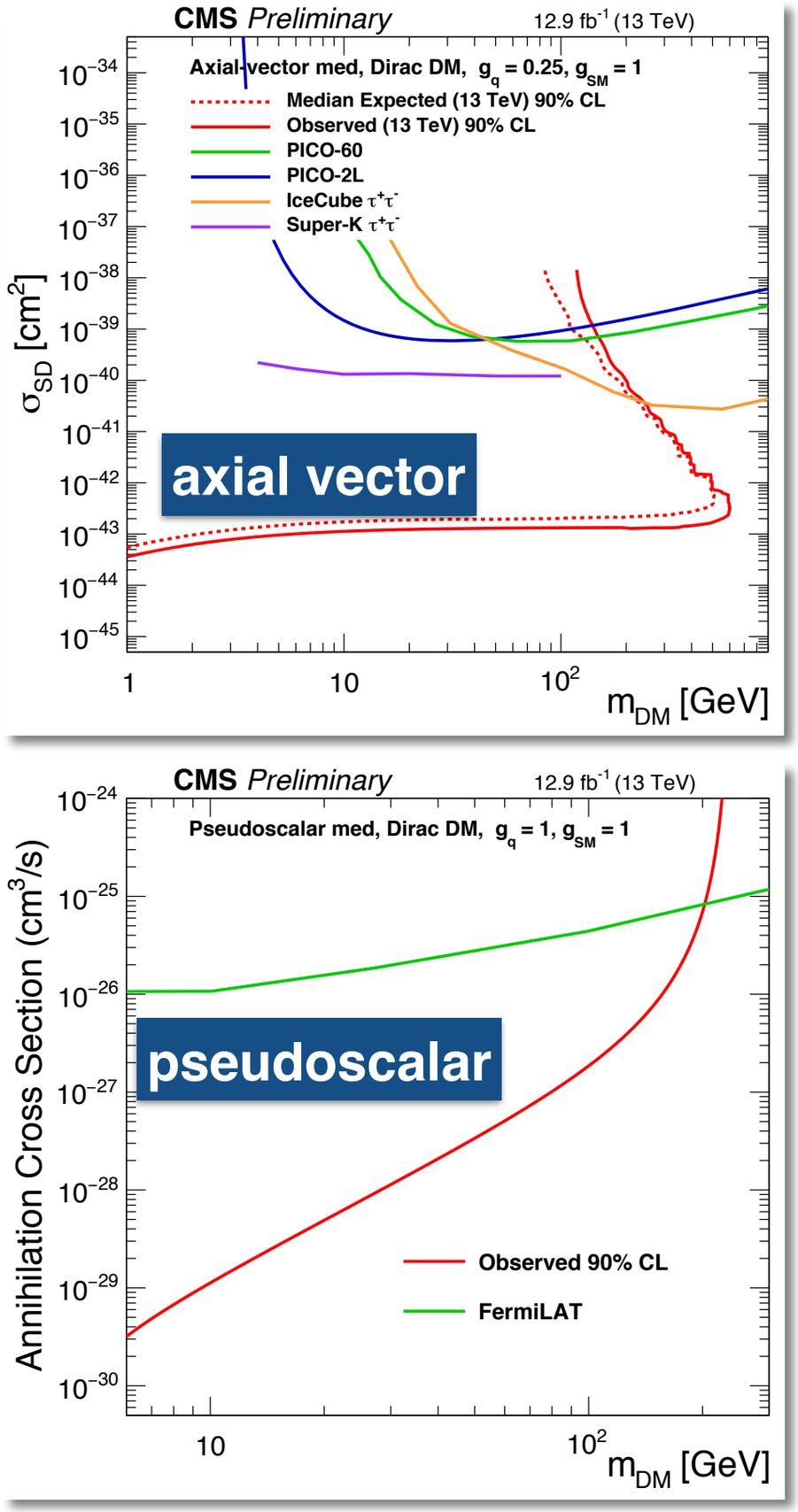
Exclusions:

- **Vector and axial-vector at <1.95 TeV**
- **pseudo scalar < 430 GeV and**
- **scalar <100 GeV**

Comparison with ID and DD Results

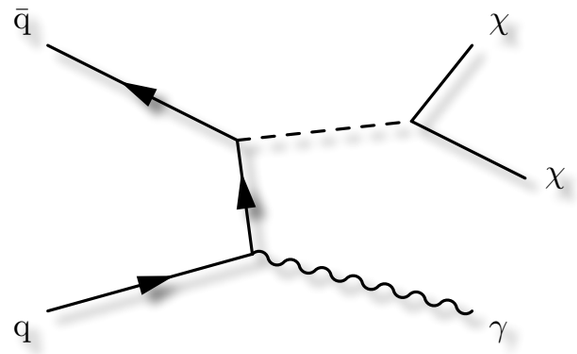
EXO-16-037



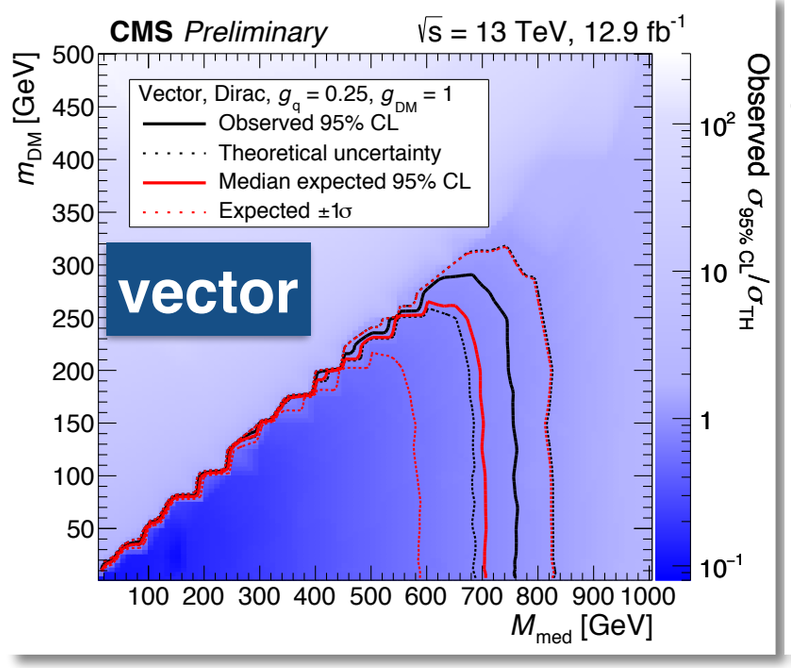


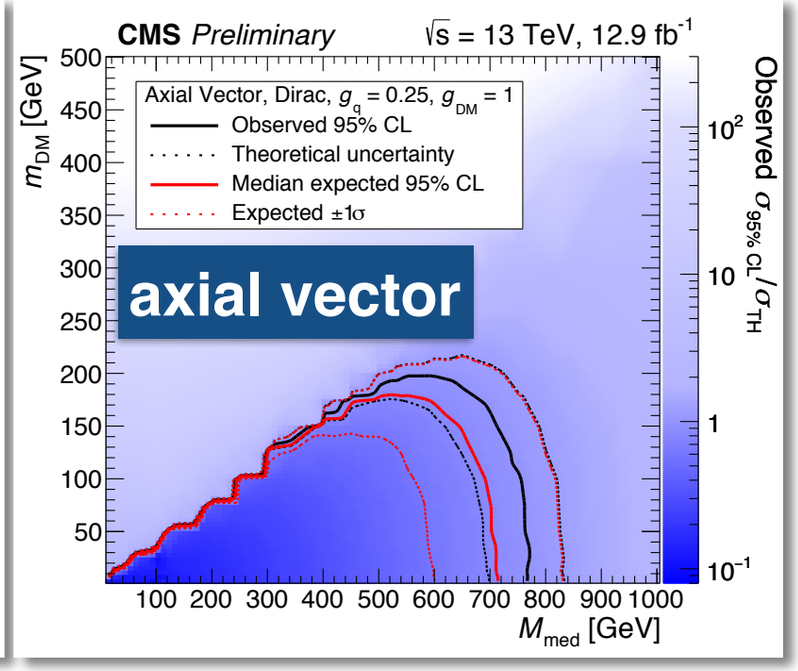
EXO-16-039

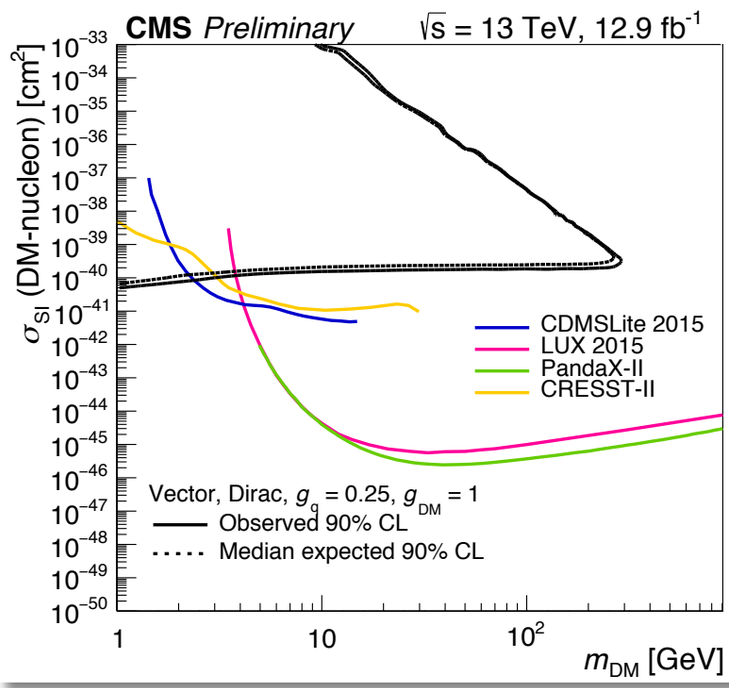
Mono-photon

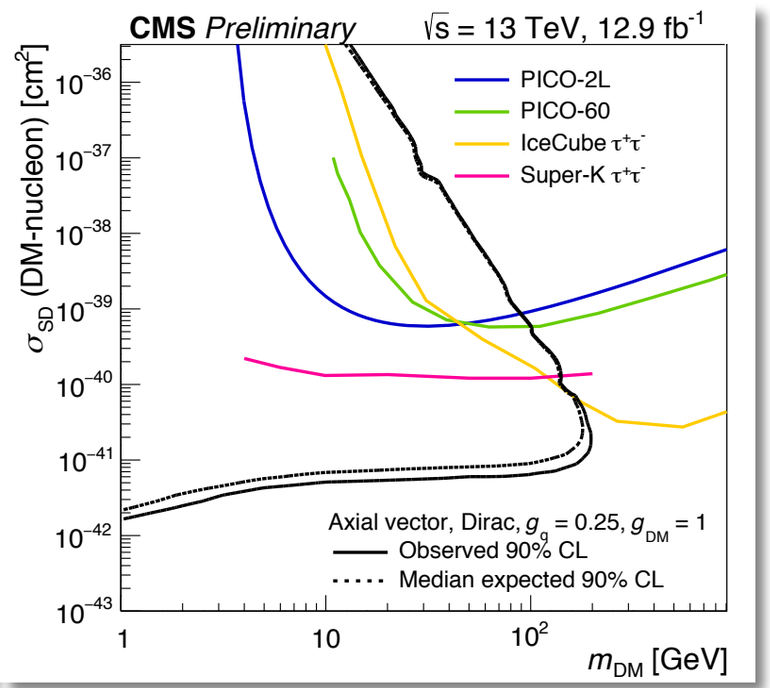


- Photon E_T > 175 GeV
- Missing E_T > 170 GeV
- Dominant background are Z(nunu)+gamma and W(lnu)+gamma





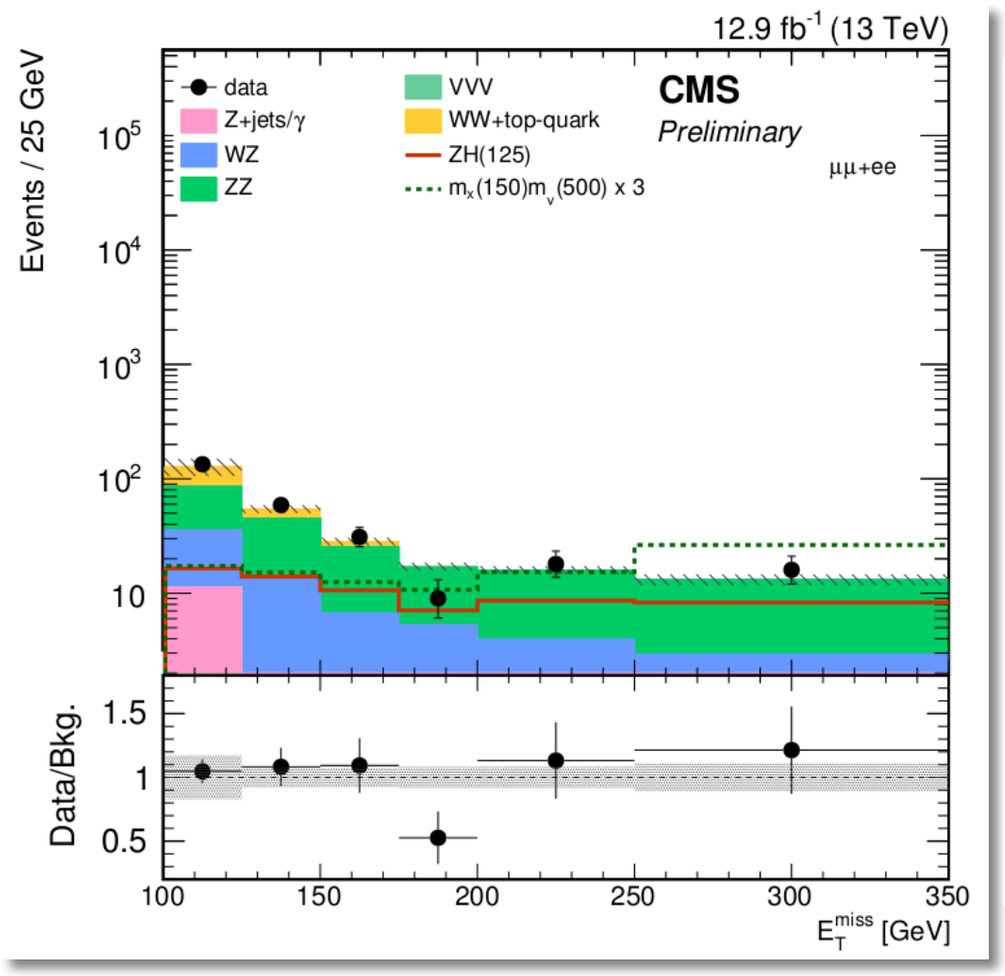


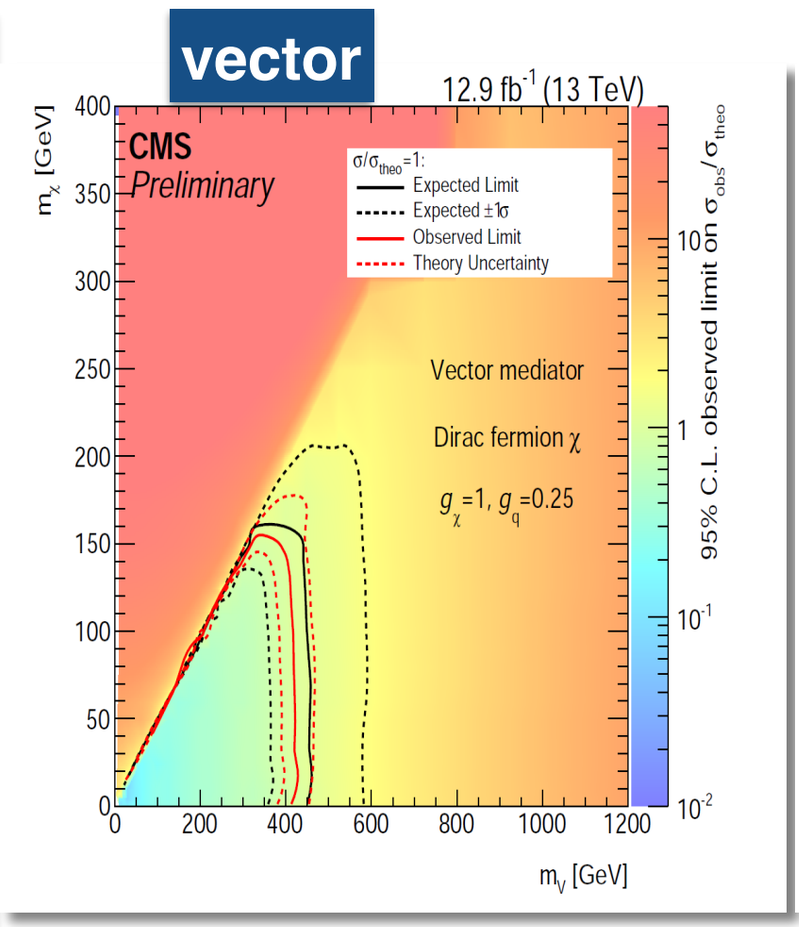


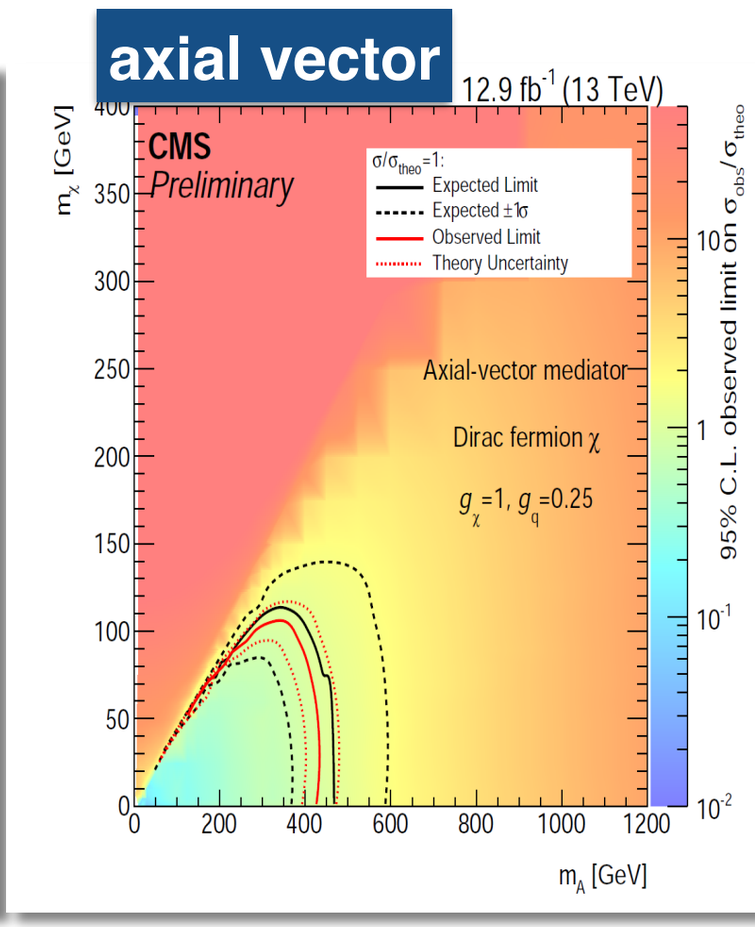
Mono-Z($\ell^+\ell^-$)

EXO-16-038

- Missing E_T + Z(dilepton) signature:
  - Select dilepton around Z mass window
  - Missing E_T > 100 GeV
- Dominant background are Z($\ell\ell$)Z($\nu\nu$) and Z($\ell\ell$)W($\ell\nu$)
- Missing E_T shape analysis

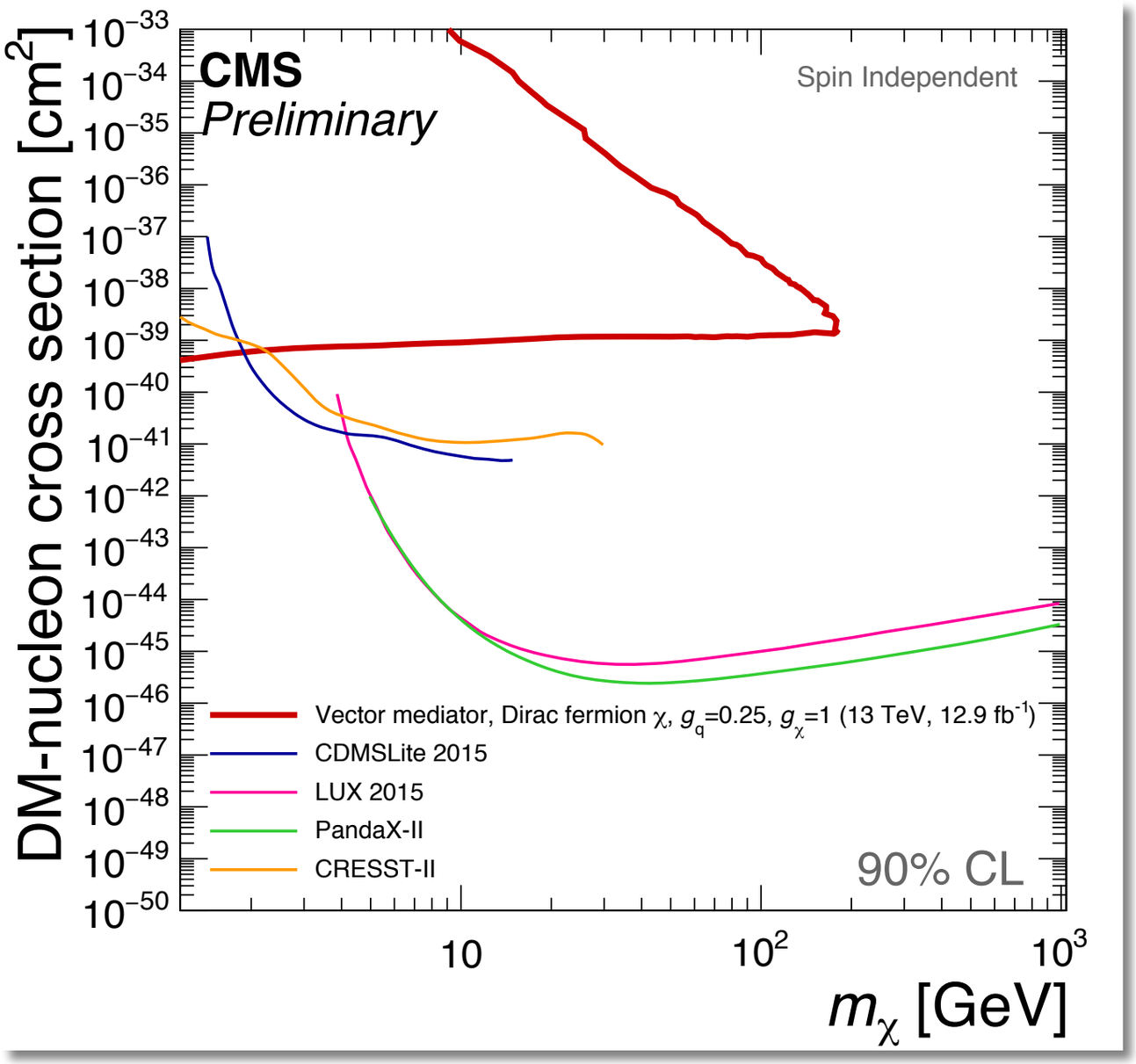


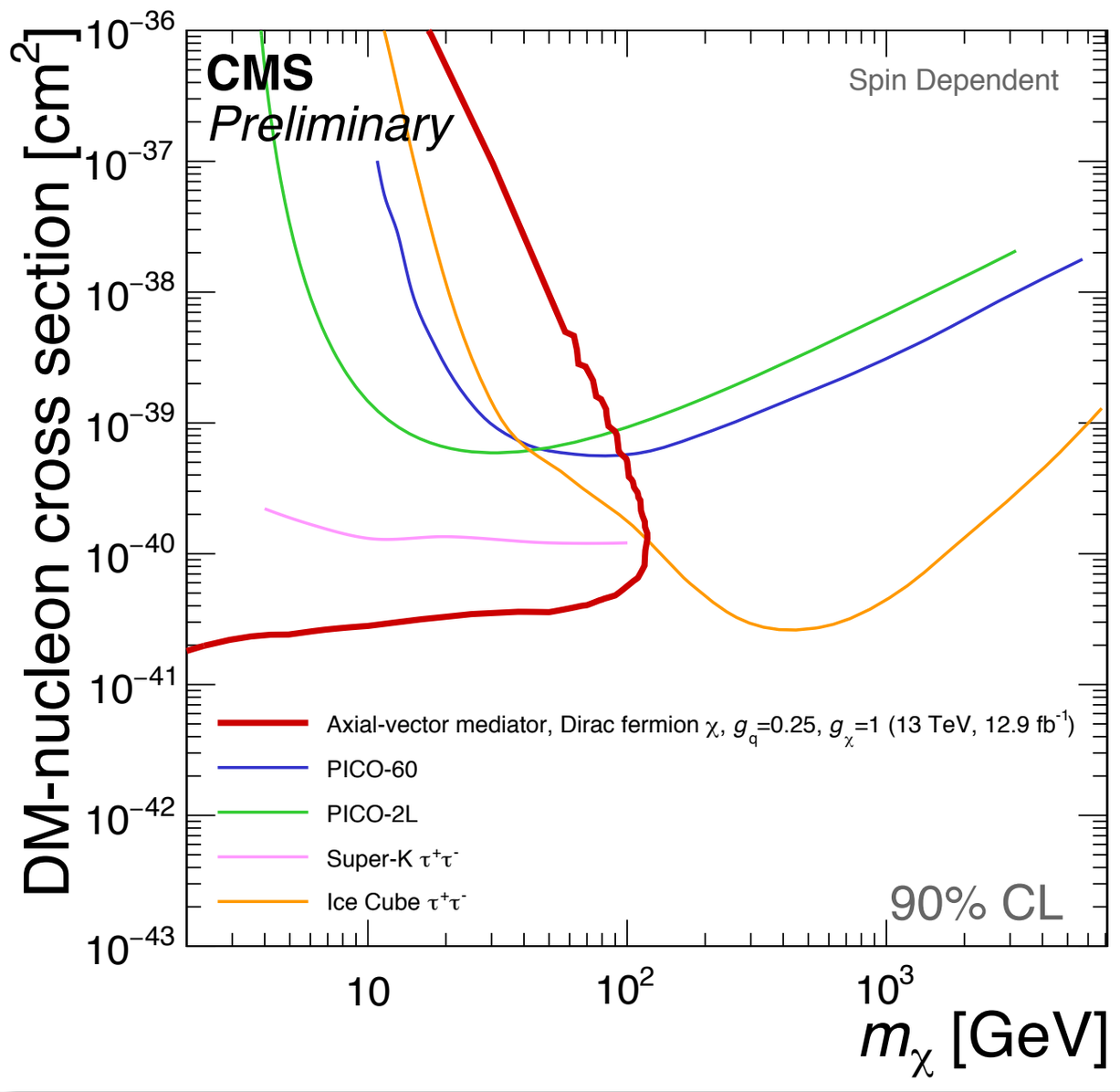




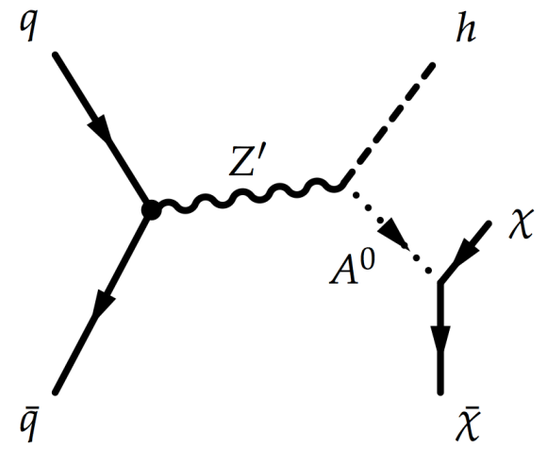
Mono-Z($\ell^+\ell^-$)
Comparison with (I)DD

EXO-16-038

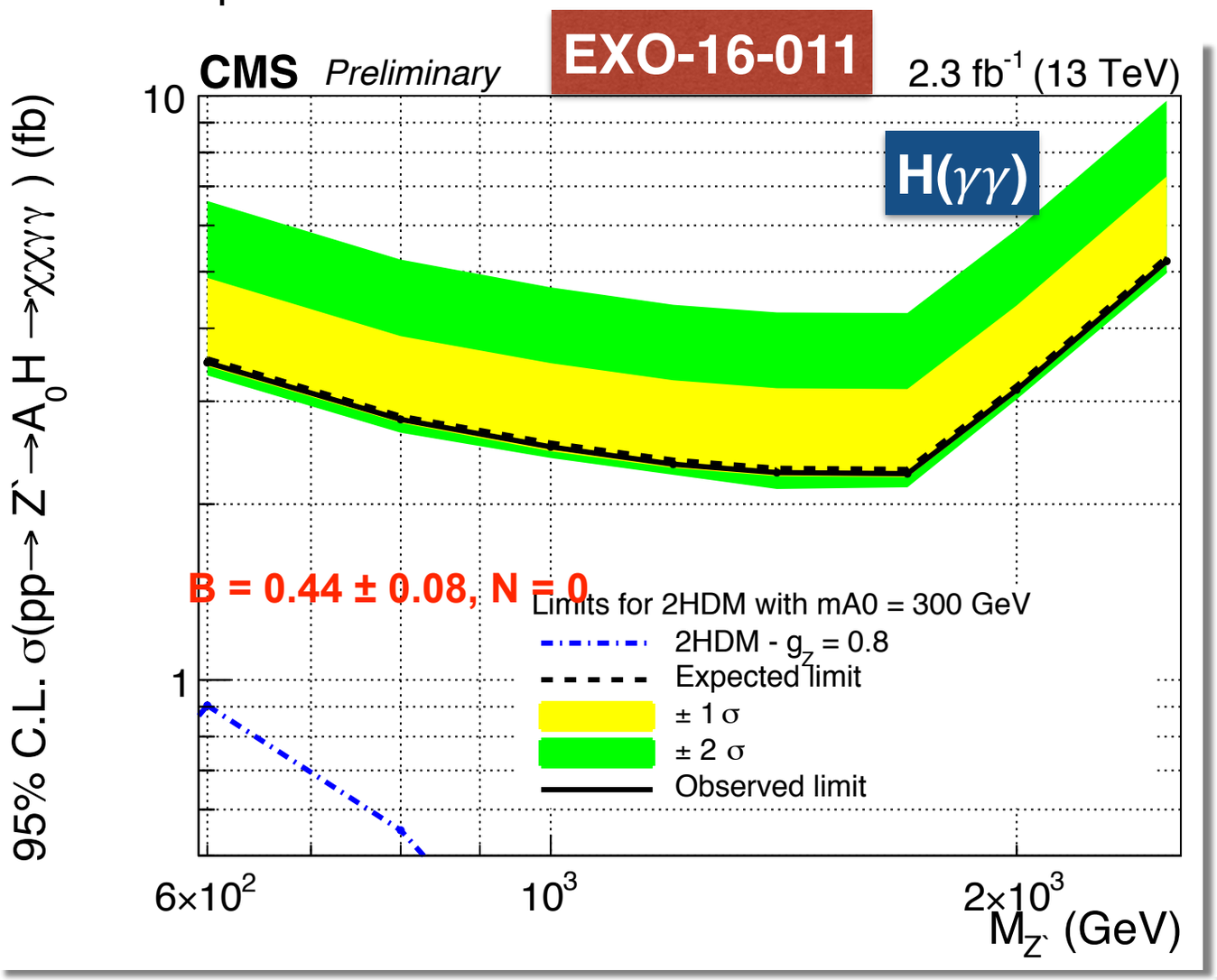


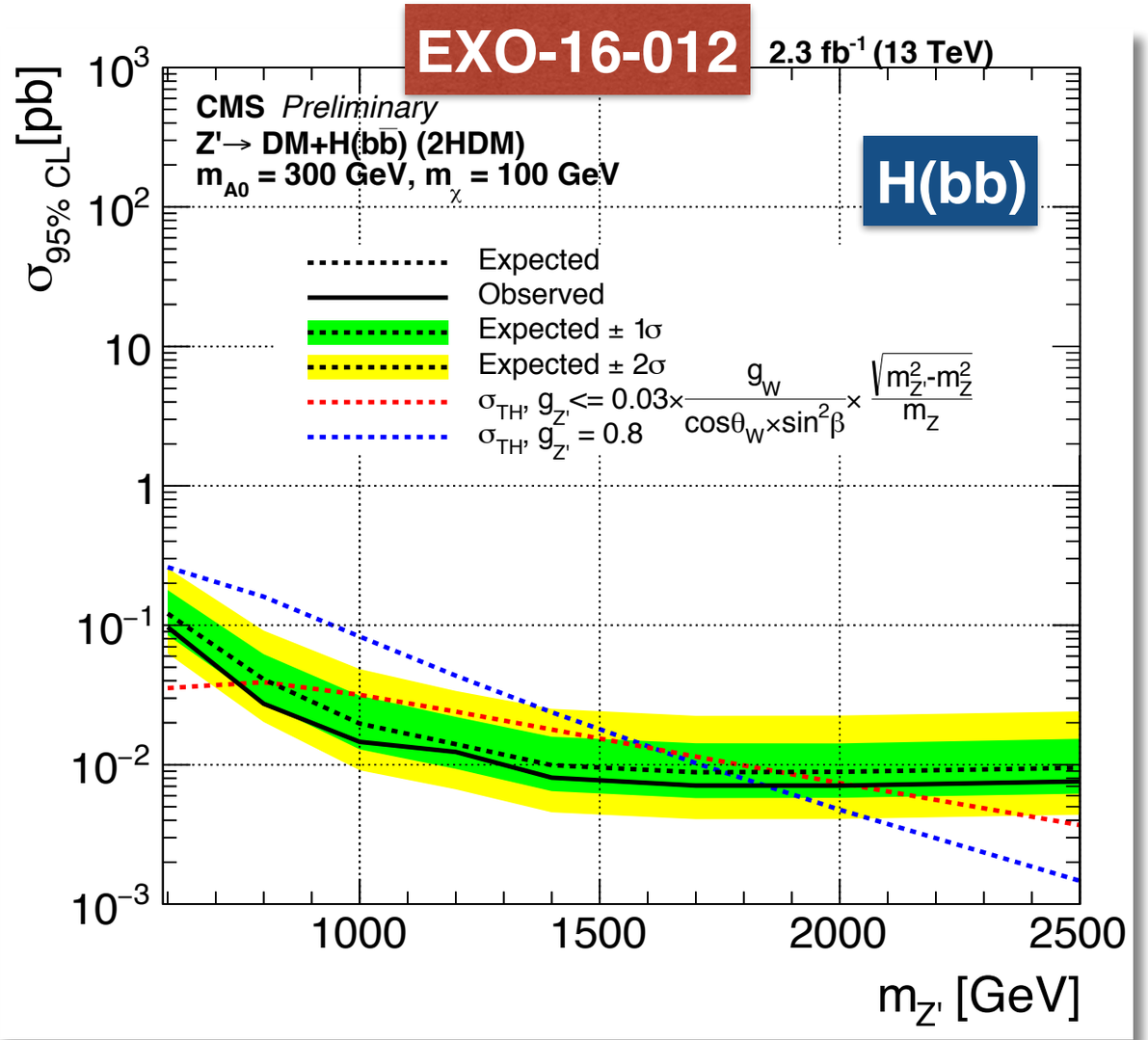


Mono-Higgs



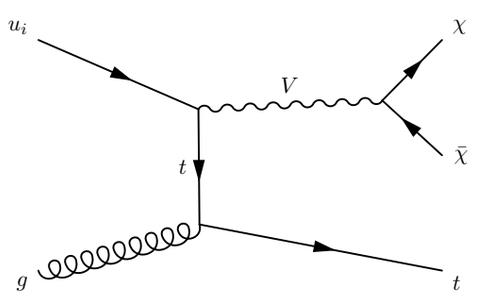
- Channel: Missing E_T + H(bb)
  - Missing E_T > 170 GeV
  - Selected boosted Higgs and resolved substructure
- Channel: Missing E_T + H($\gamma\gamma$)
  - Missing E_T > 105 GeV
  - 120 < M($\gamma\gamma$) < 130 GeV
- Interpretation in the context of 2HDM



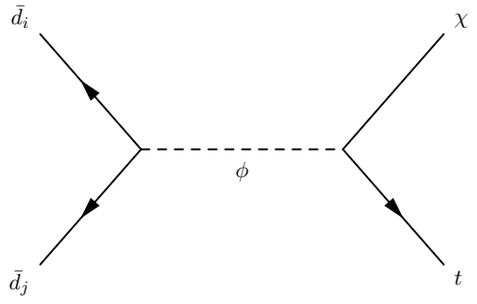


EXO-16-040

Mono-Top

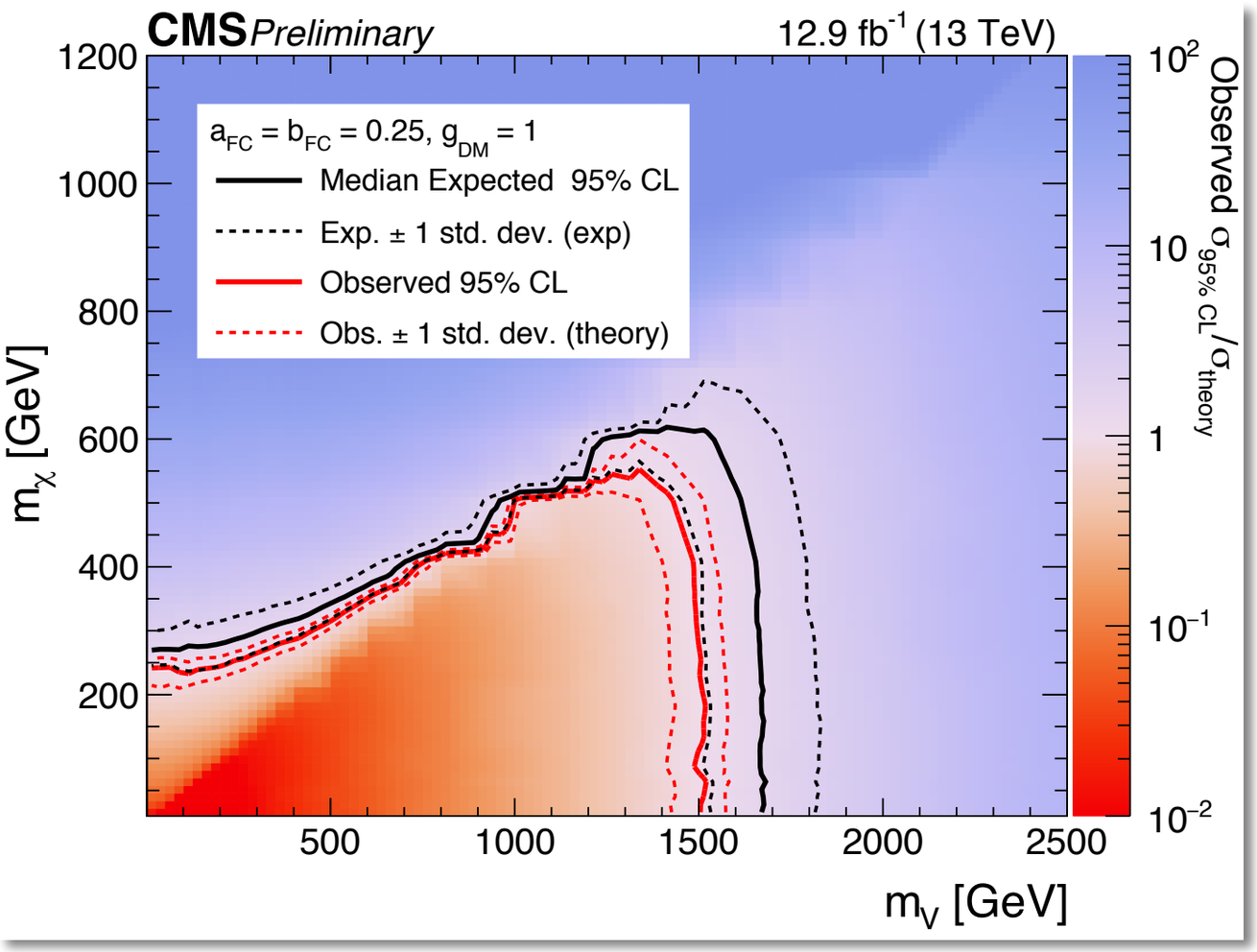


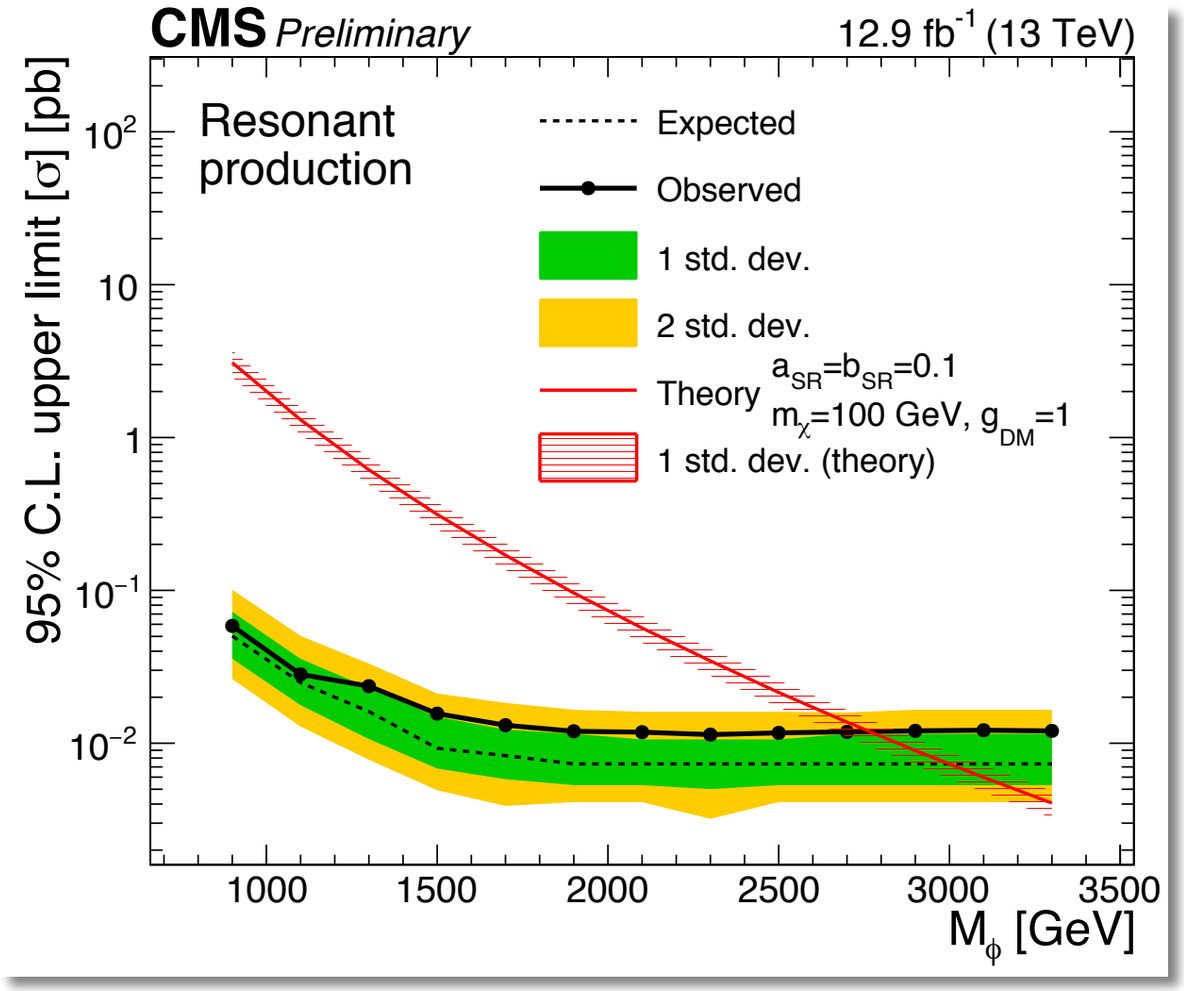
Resonant scalar



Flavor-Changing vector

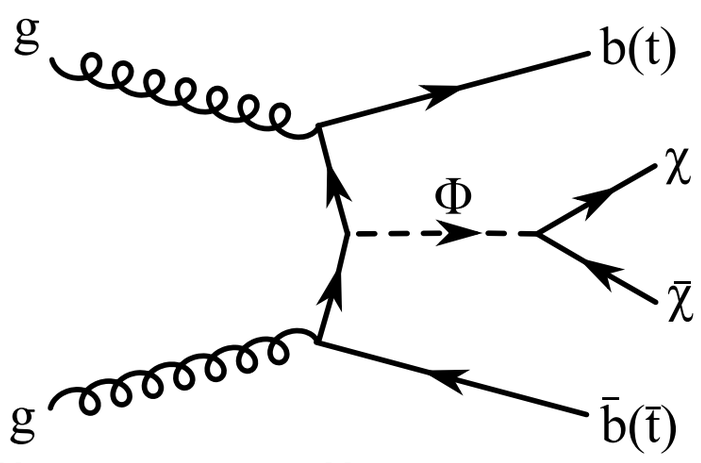
- Possible via t-channel FCNC mediator exchange or via s-channel exchange of a charged colored scalar.
- Explore boosted all-hadronic decay mode of top quark.
  - Missing E_T > 250 GeV.
  - Top tagging jets with R=1.5



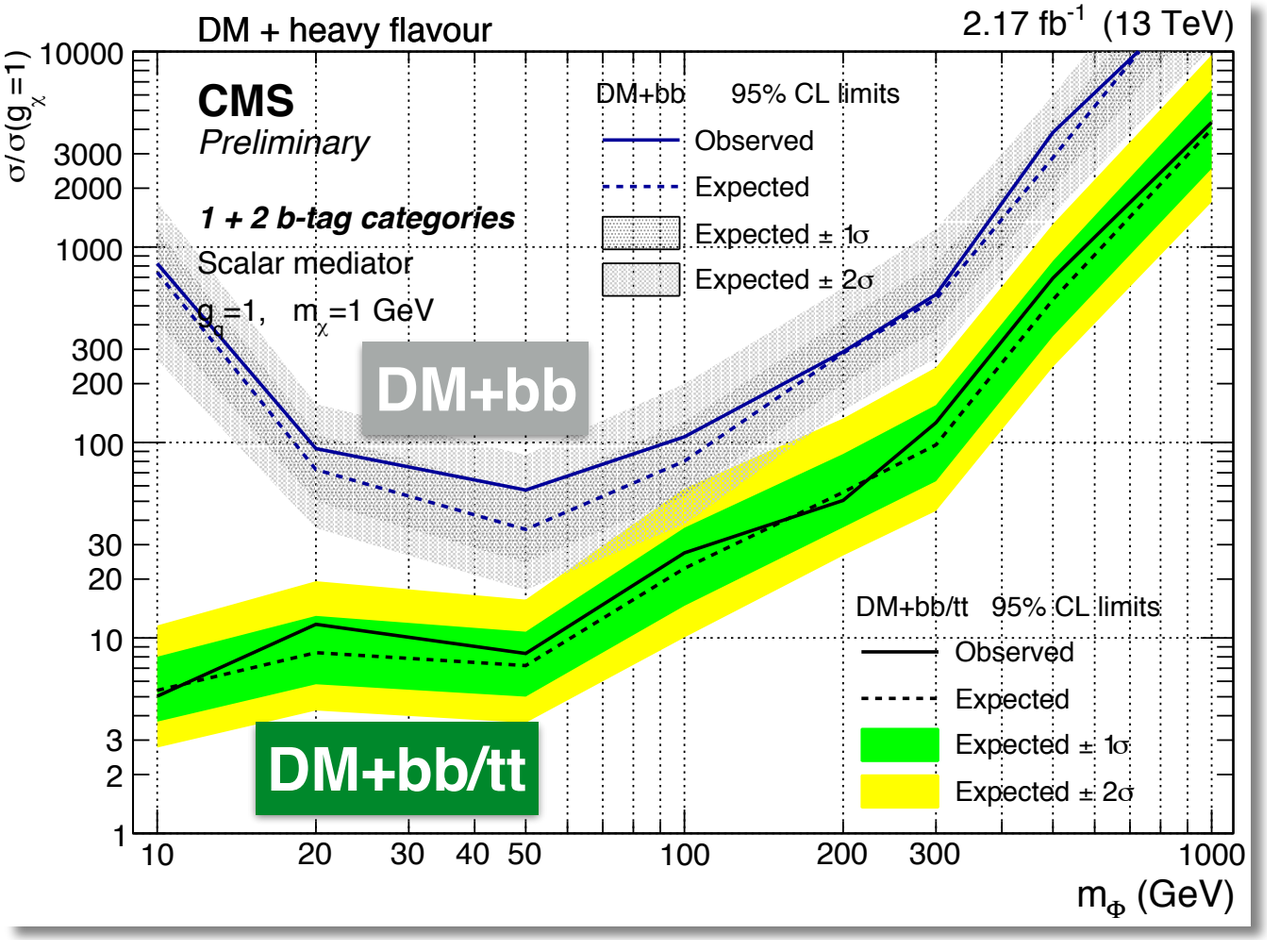


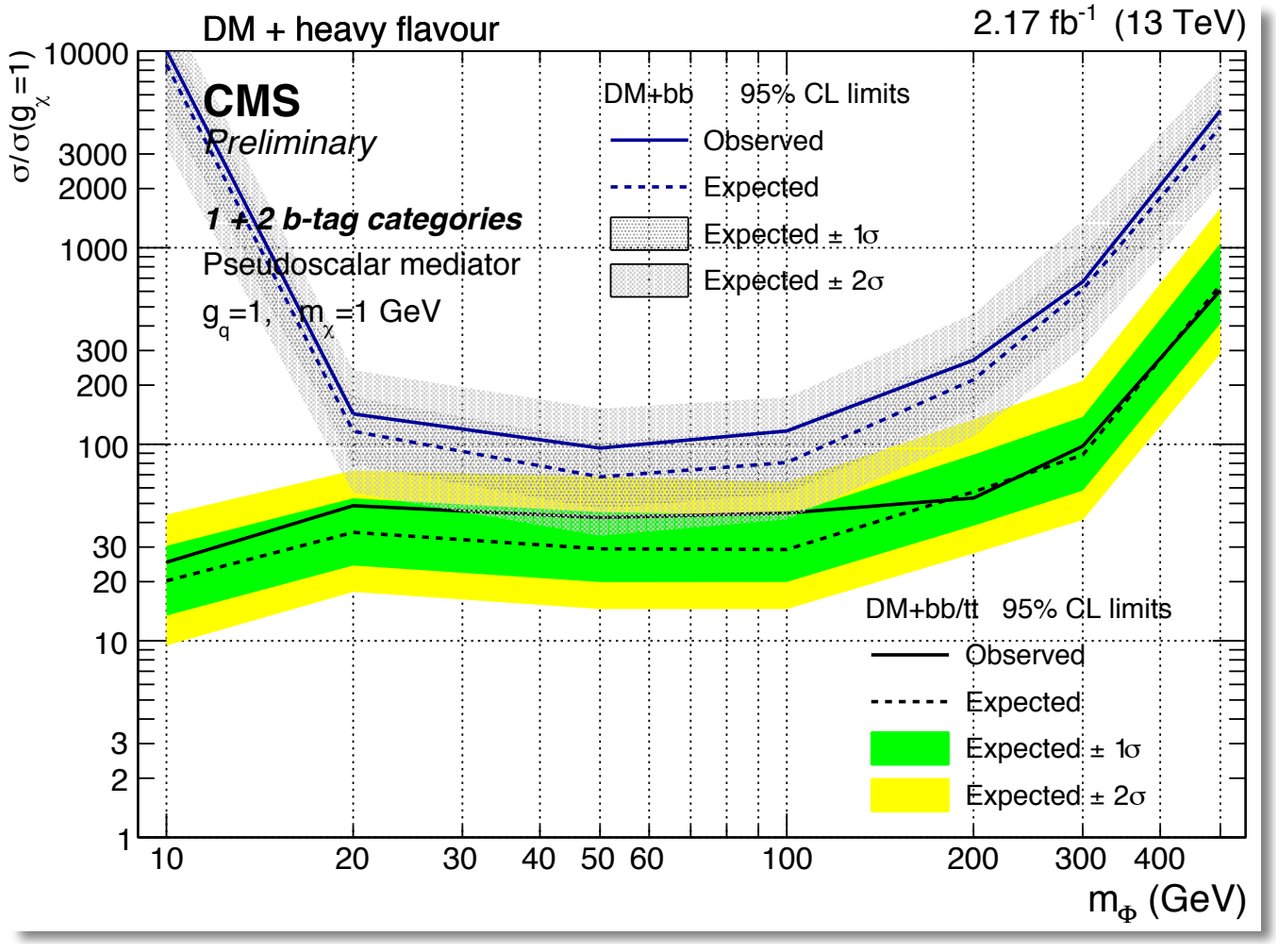
B2G-15-007

Mono-bb(tt) Production



- Probes (pseudo)scalar mediator with Higgs-like couplings.
- Combination of single and double b tag channels.
- Also sensitive to tt+DM production through b quarks from top quark decays.

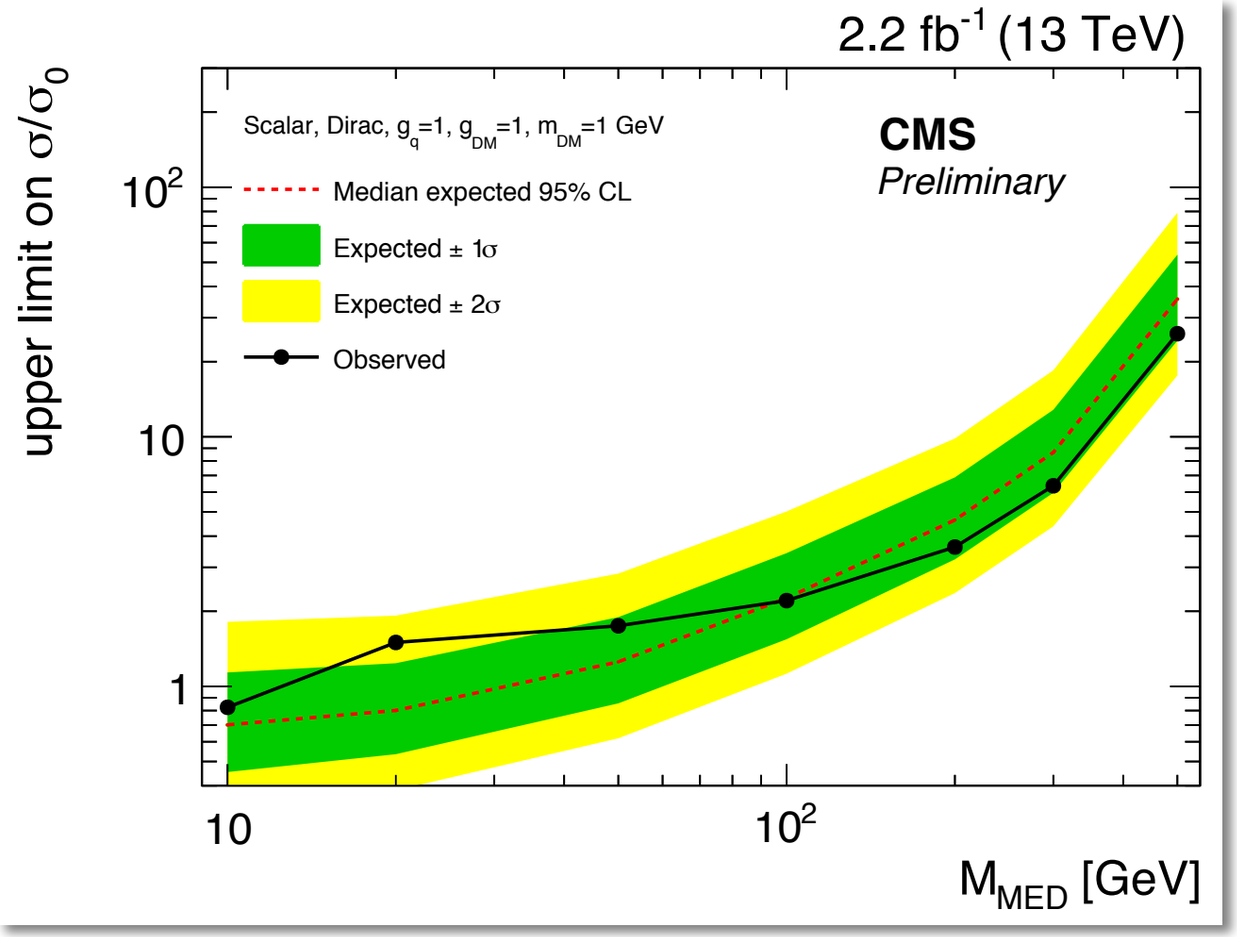


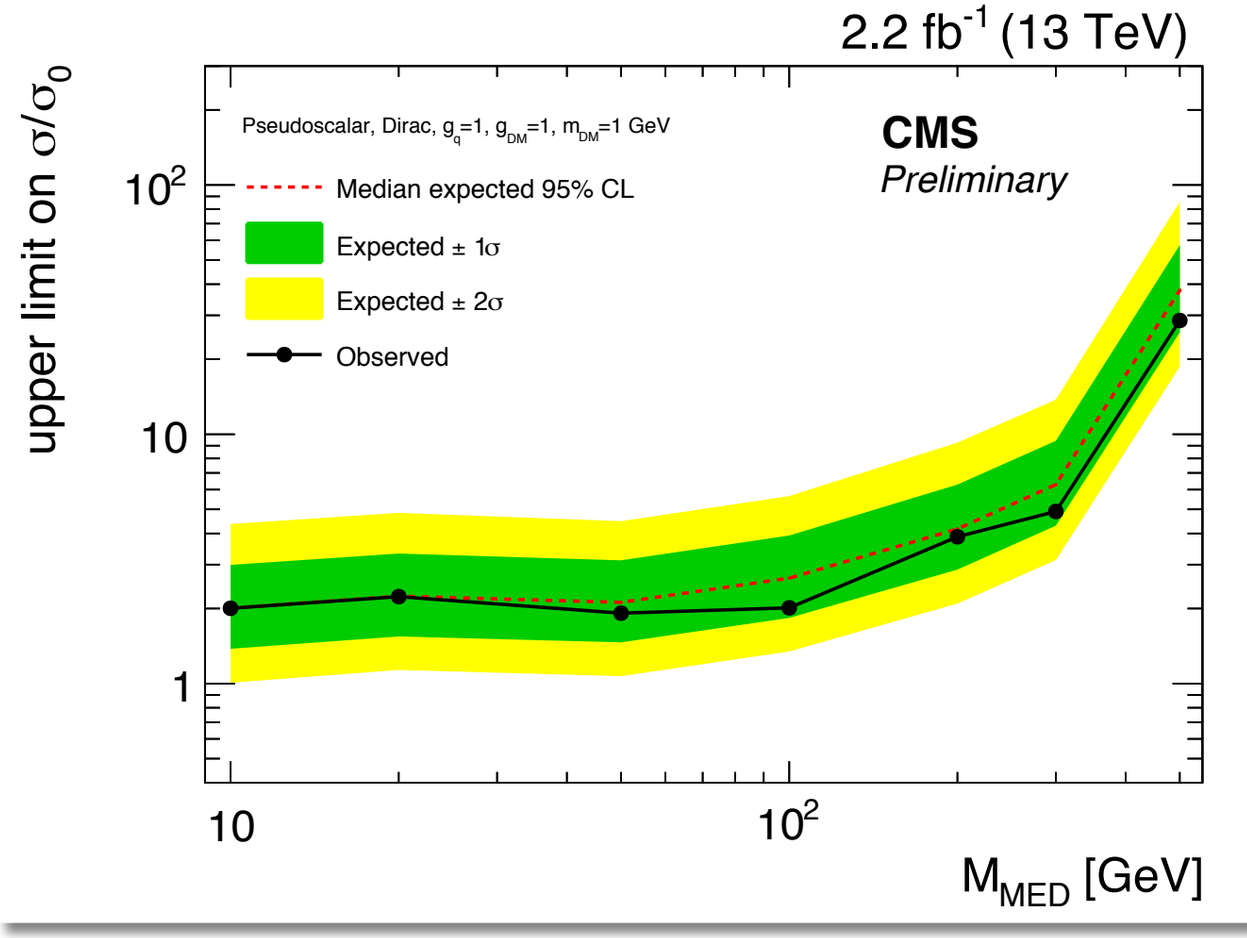


Mono-tt Production

- Search on semileptonic, boosted hadronic decays, and dilepton channels. **EXO-16-028**
  - Missing E_T > 200,160, 50 GeV for hadronic, semileptonic, dileptonic.
  - tt dominant background

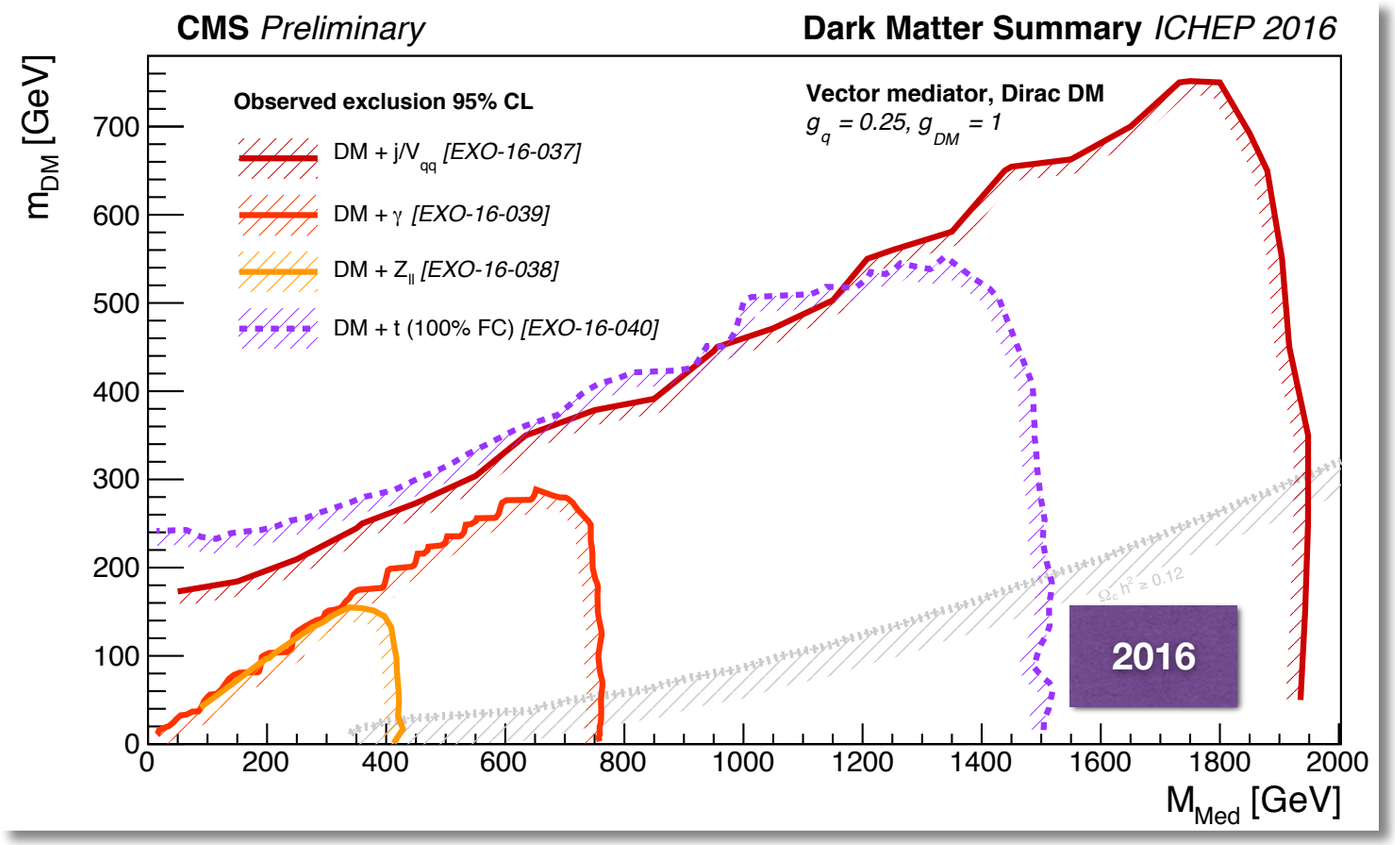
EXO-16-005

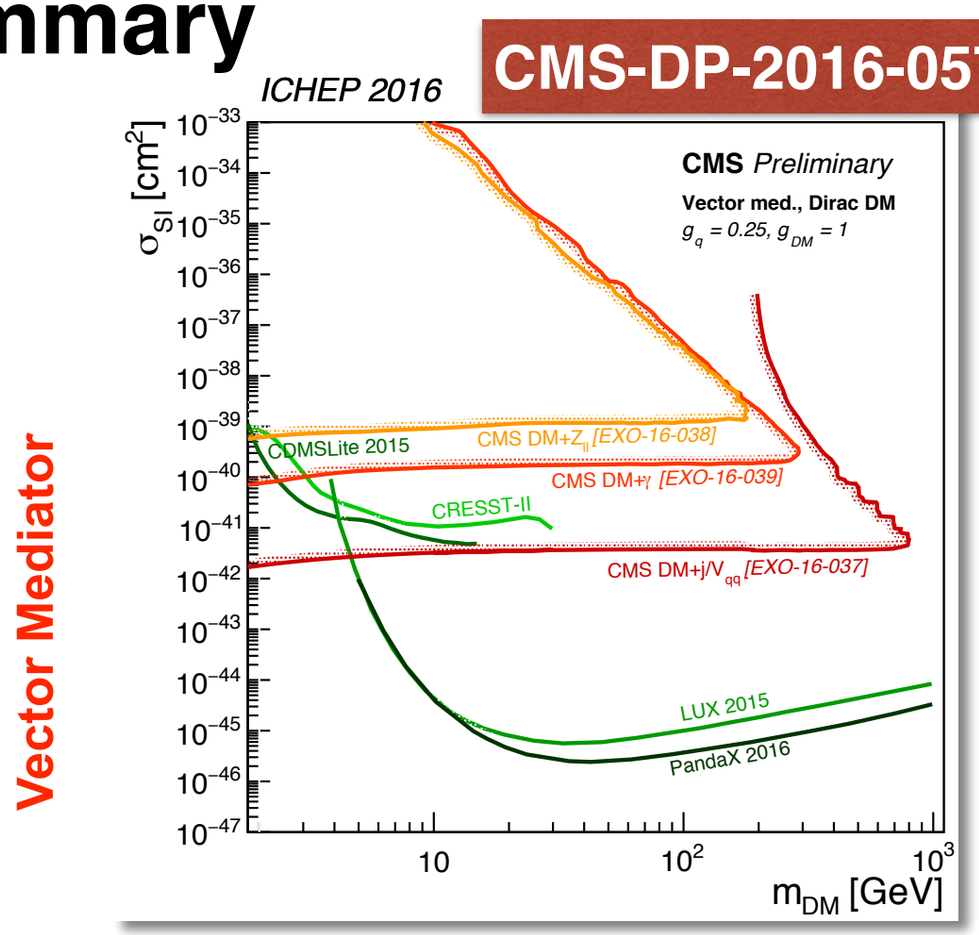




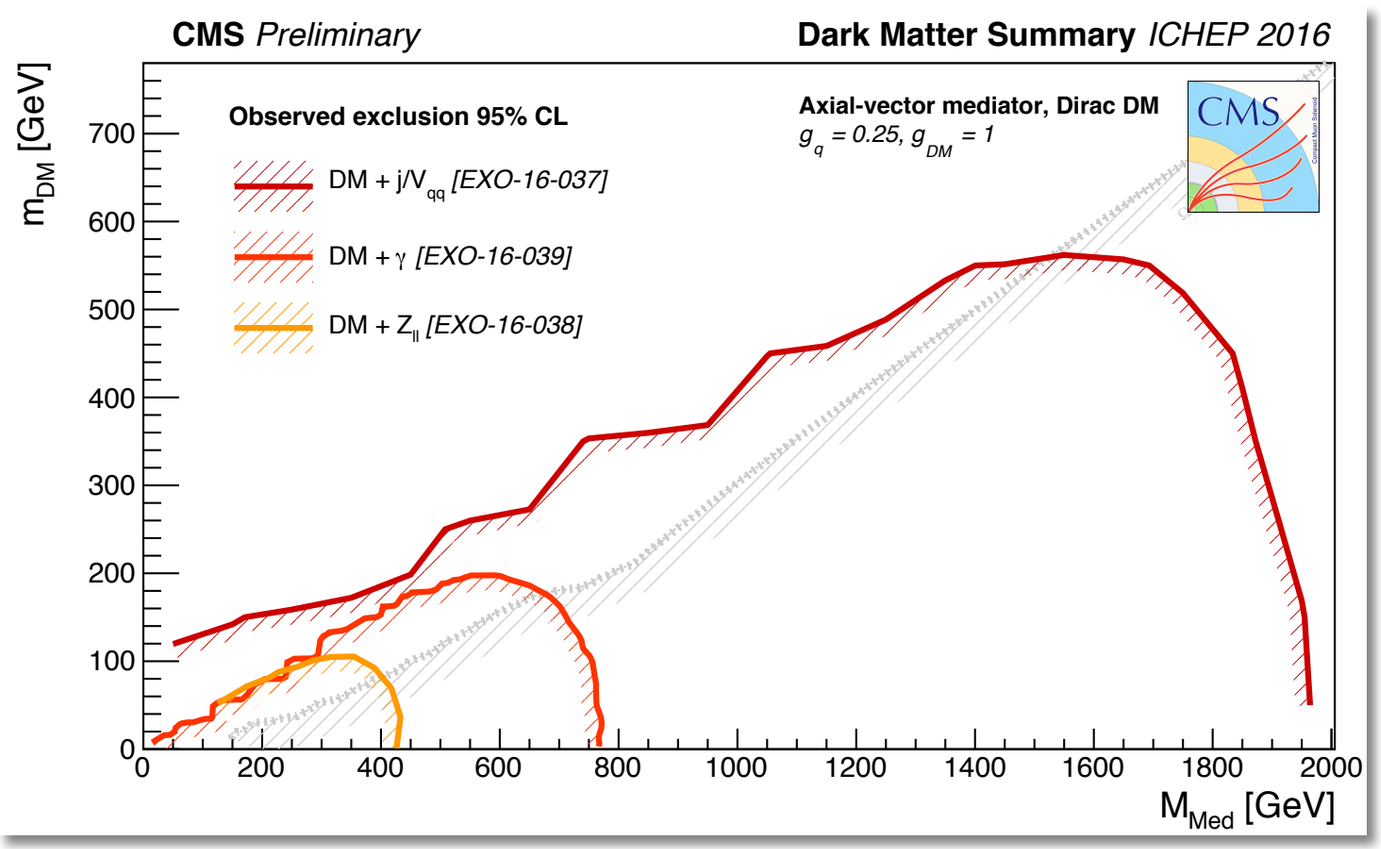
Dark Matter - Summary

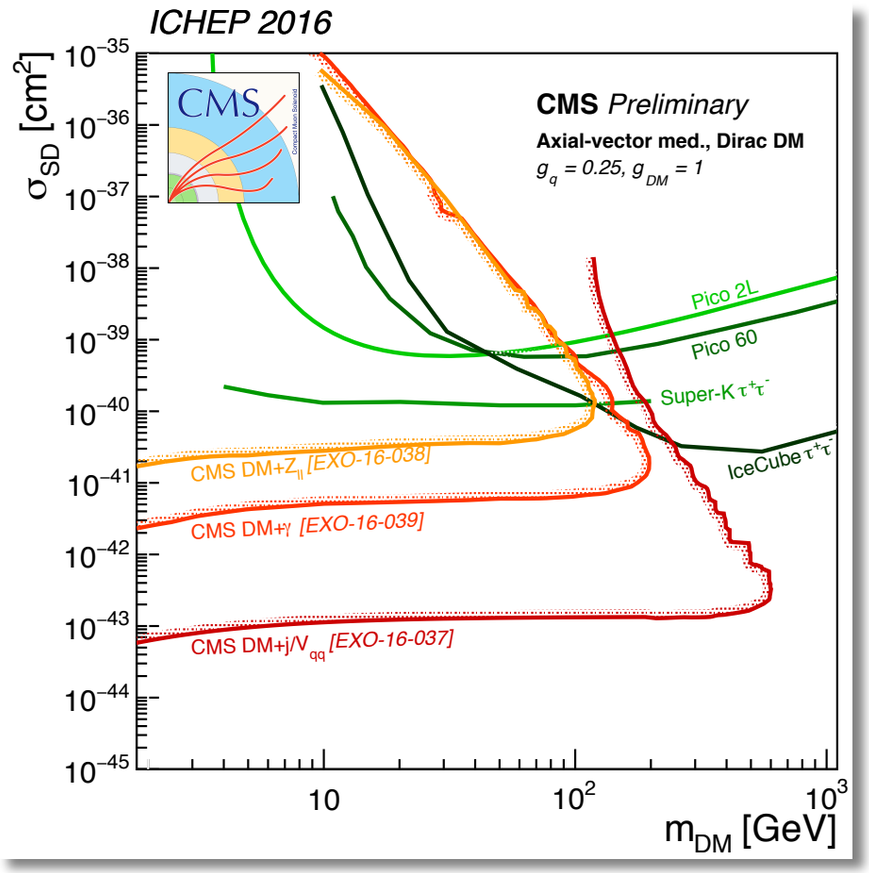
CMS-DP-2016-057





Vector Mediator



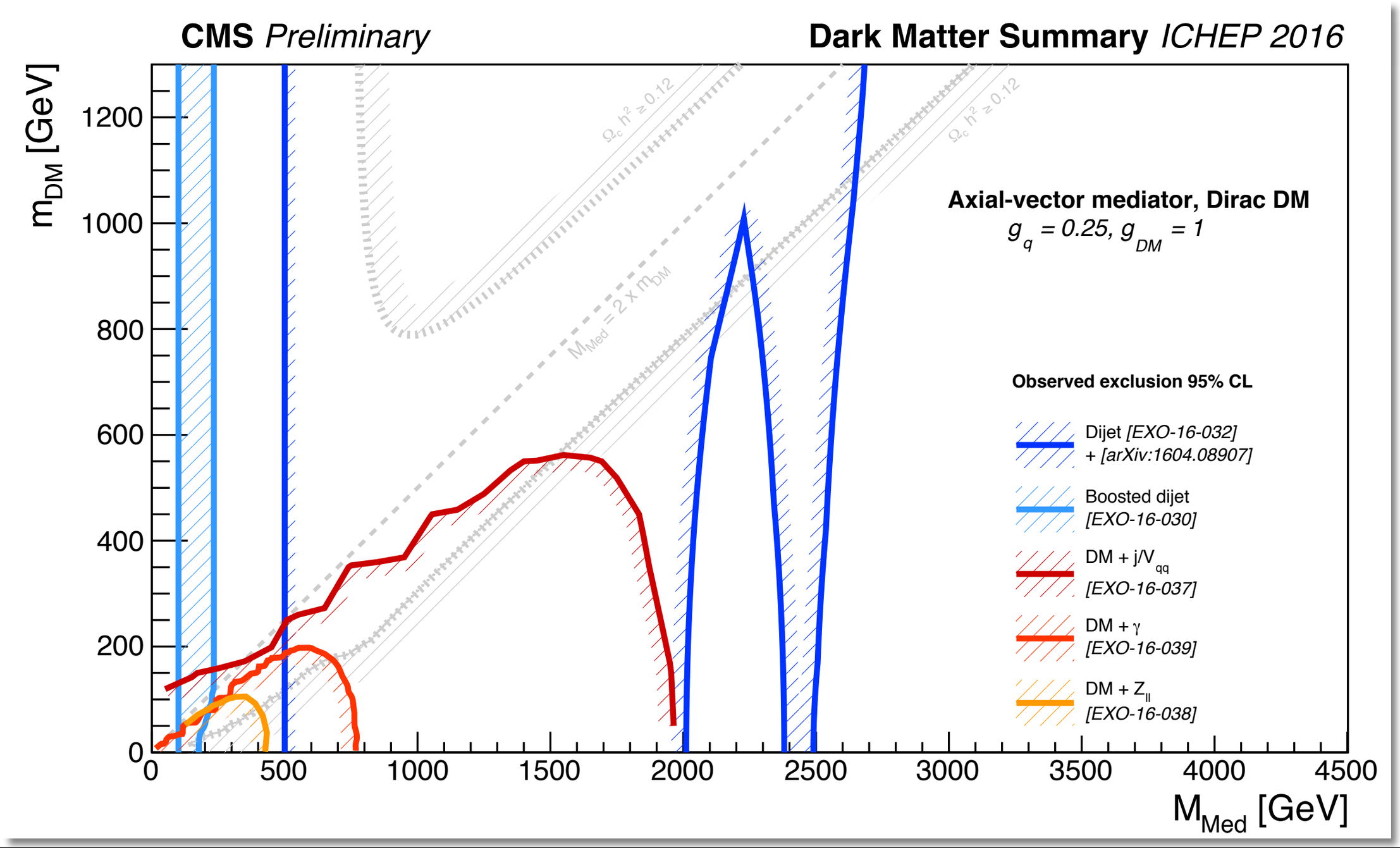


Axial-Vector Mediator

Dark Matter - Reuse Dijet Search

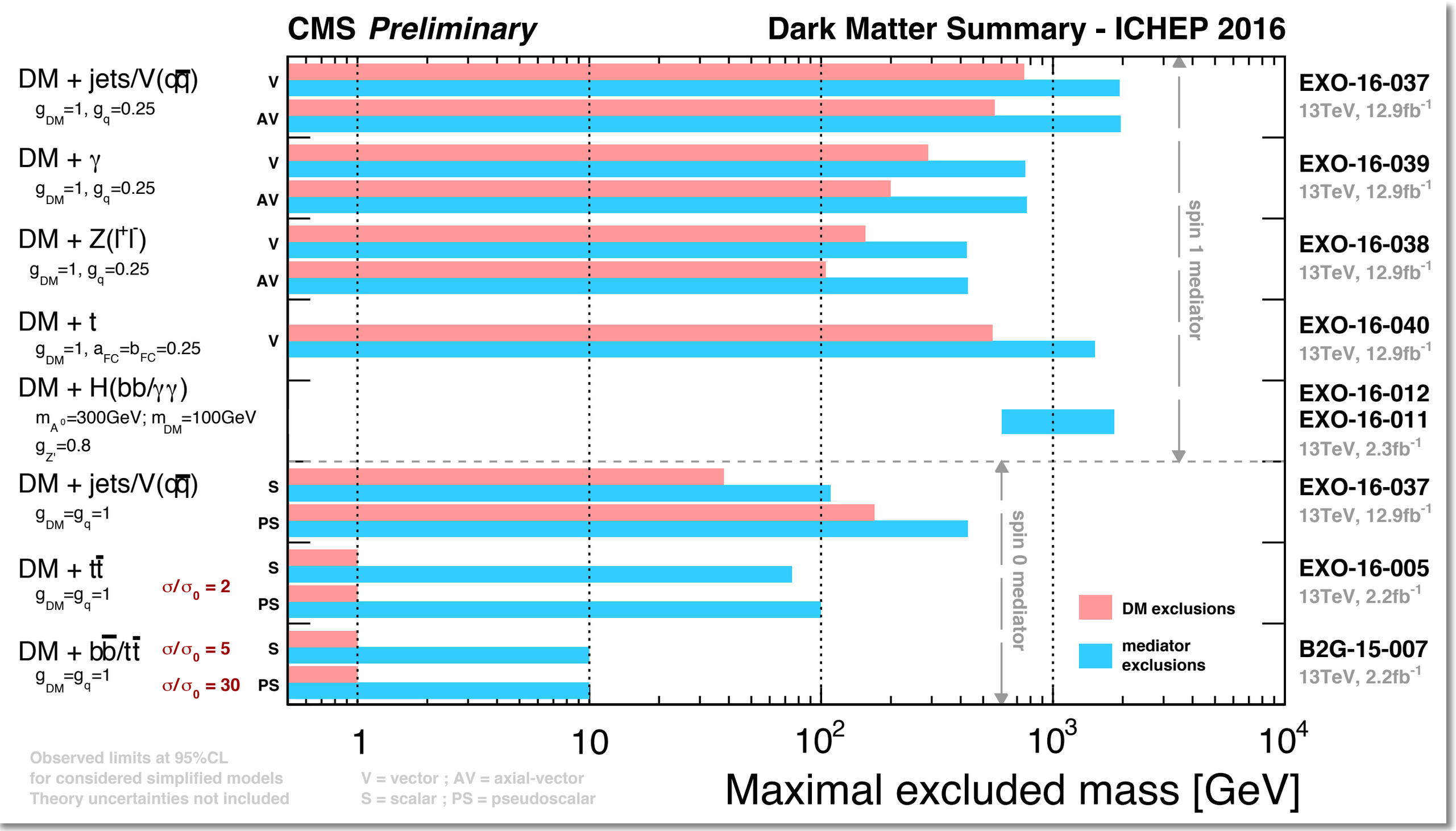
CMS-DP-2016-057

- Dijets provide stringent constraints for certain couplings.
- Dijet limits on axial-vector mediator, compared with mono-DM searches



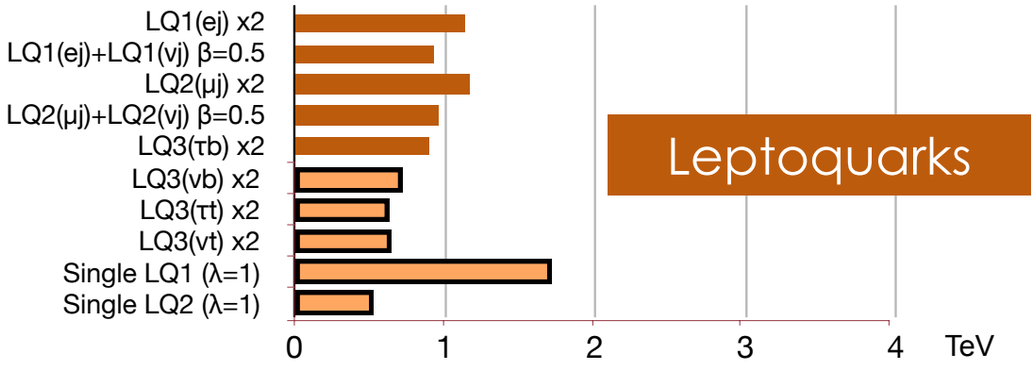
Dark Matter - Limit bar plot

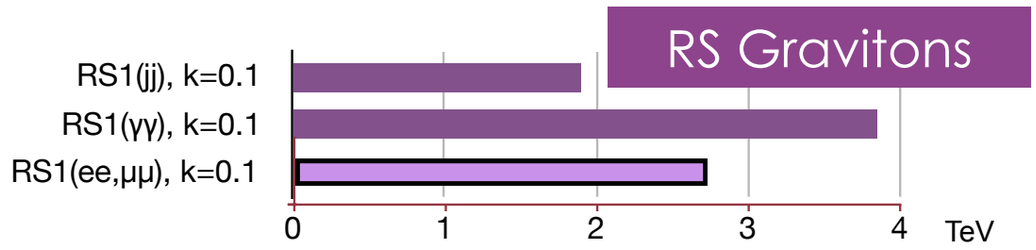
CMS-DP-2016-057

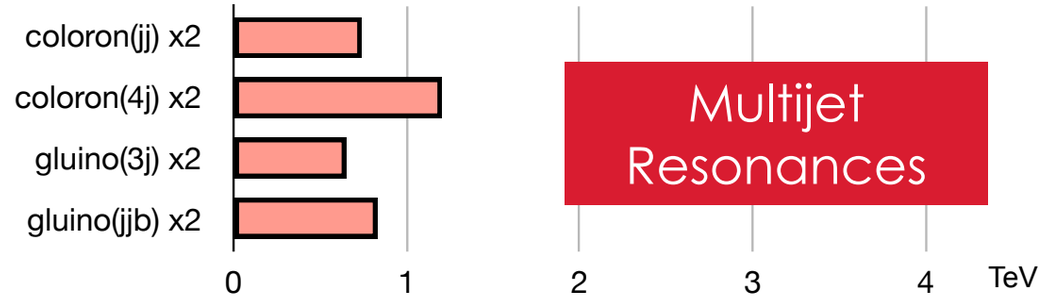


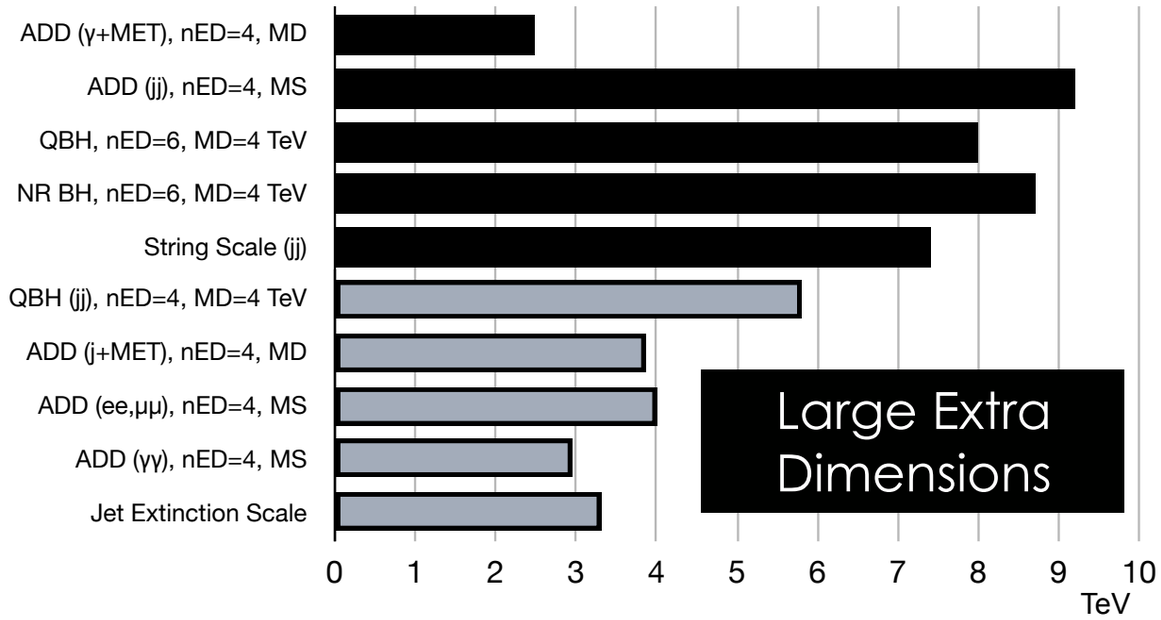
BSM - Grand Summary (1)

13 TeV 8 TeV

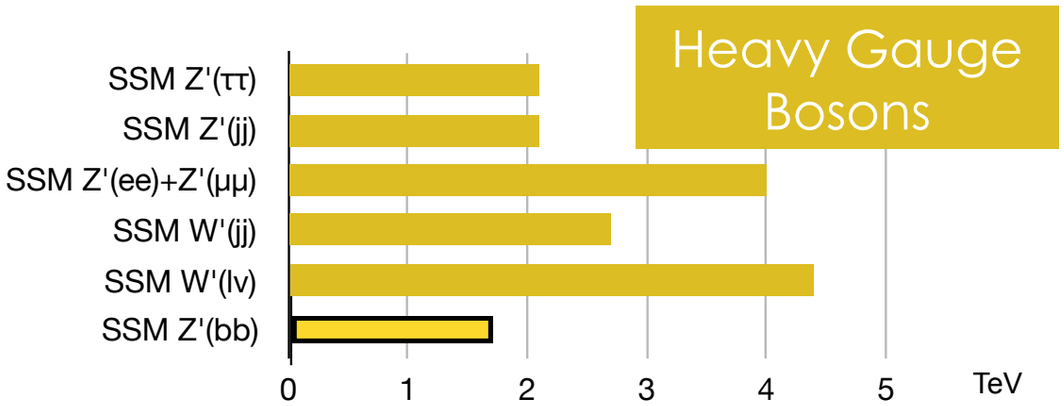


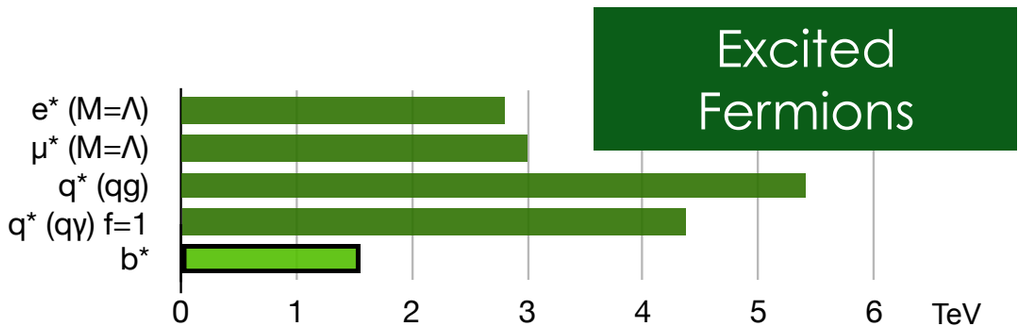


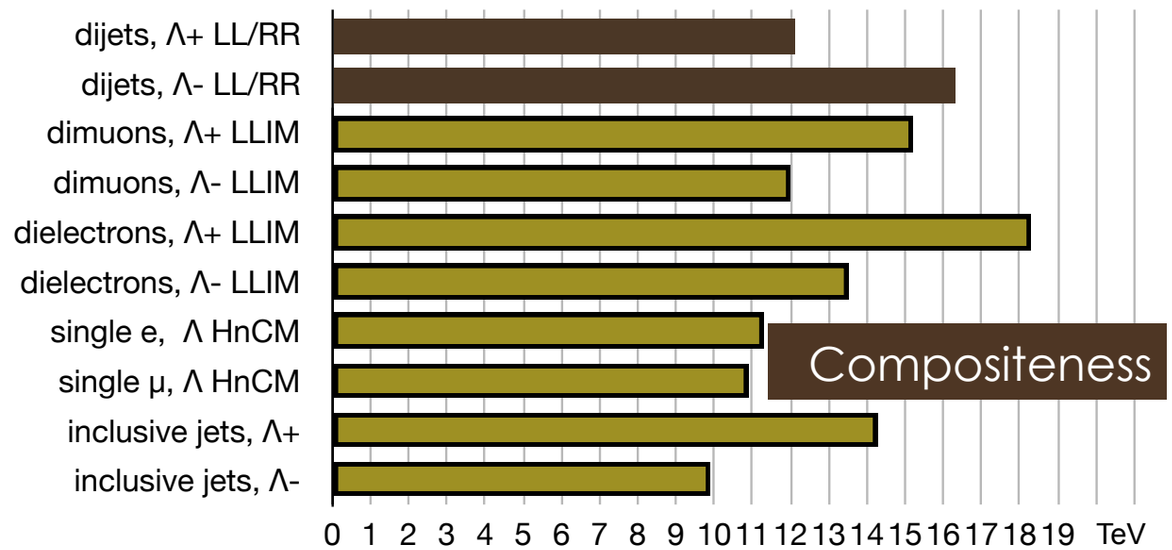




CMS Preliminary



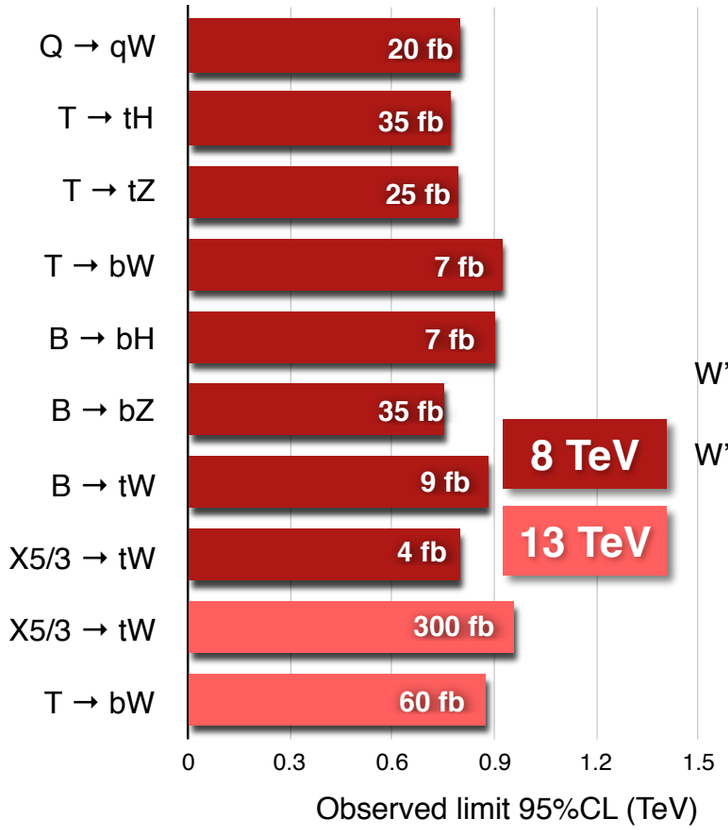




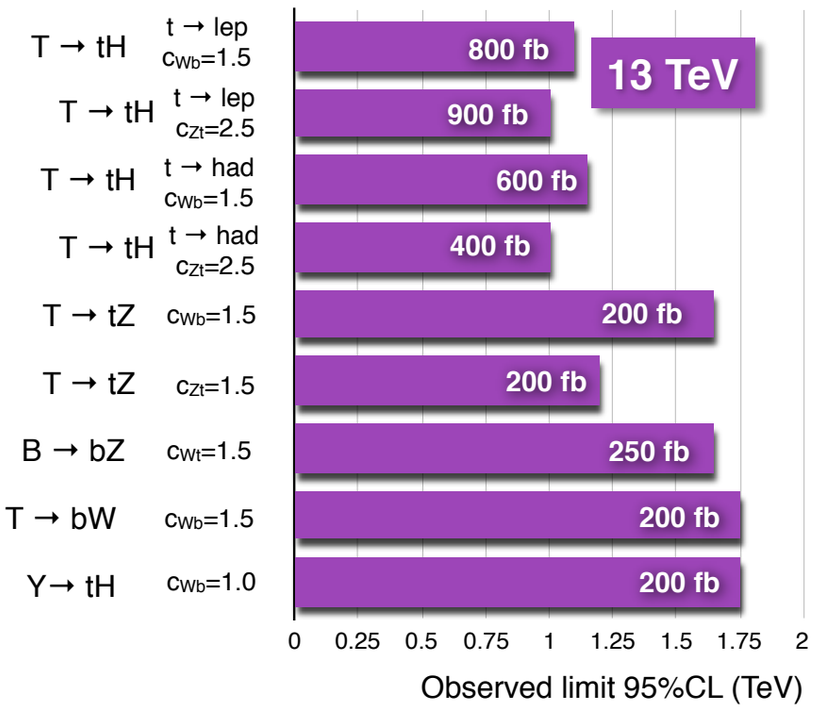
CMS Exotica Physics Group Summary – ICHEP, 2016

BSM - Grand Summary (2)

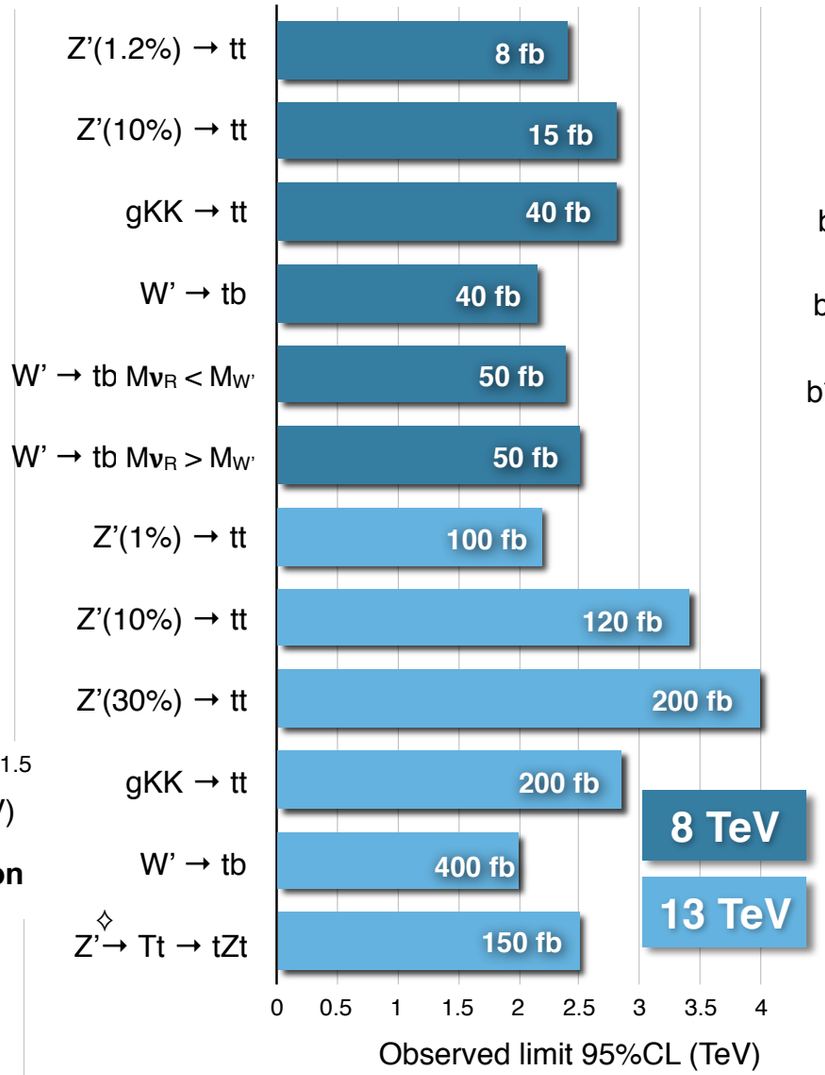
Vector-like quark pair production



Vector-like quark single production

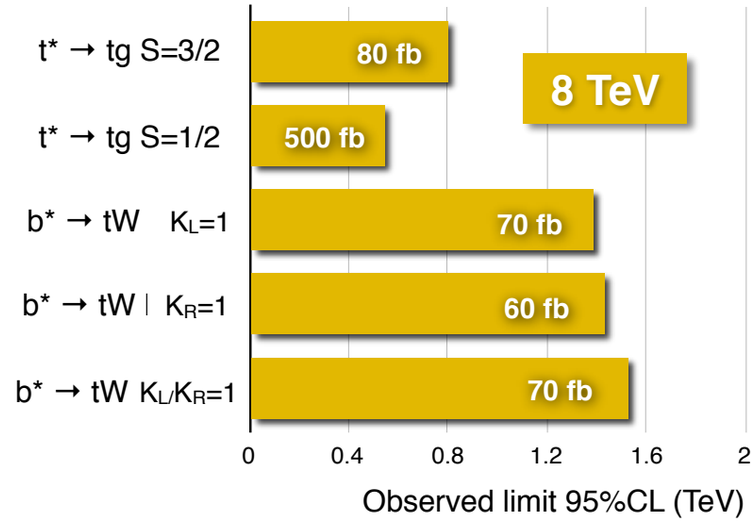


Resonances to heavy quarks

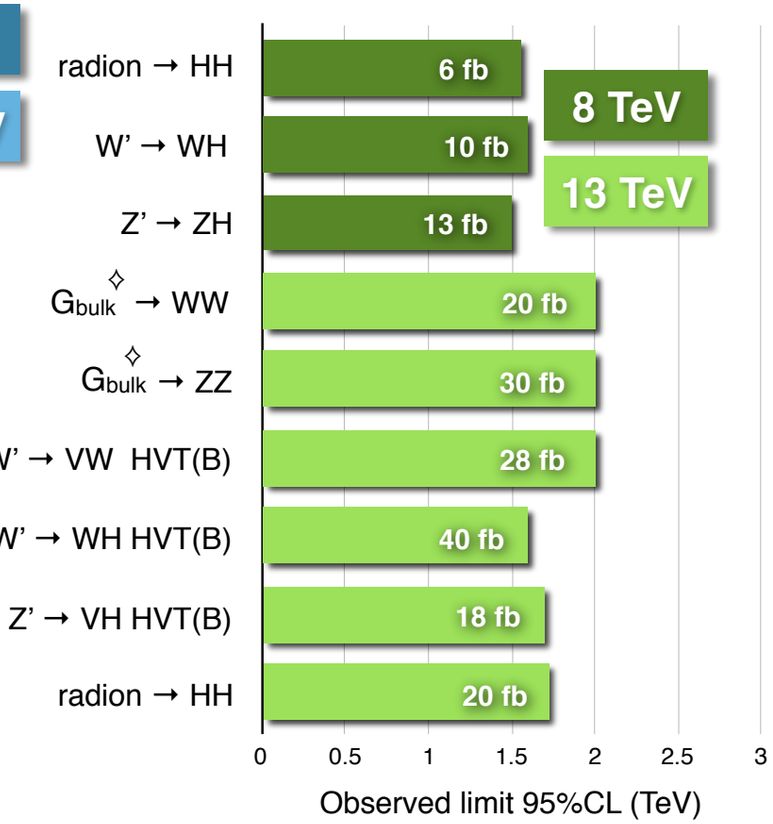


B2G
new physics searches with heavy SM particles

Excited quarks



Resonances to dibosons



✧model-independent

still waiting for
the coming
of New Physics

Museum Hotel Santo Domingo, Antigua

a long journey still ahead of us

Conclusions

- A large number of searches for new physics are on going and covering “all” possible phase space available at the LHC.
- Some of the excess from Run-1 are vanishing with early Run-2 data.
- Analyses are being optimized and reloading the full Run-2 data set. Stay tune for updates.
- What is next?
  - Atlas and CMS detectors are being upgraded during the technical stop 2016-2017.
    - CMS upgrade of pixel, calorimeter, trigger detectors.
    - These improvements will help extent the search for new physics

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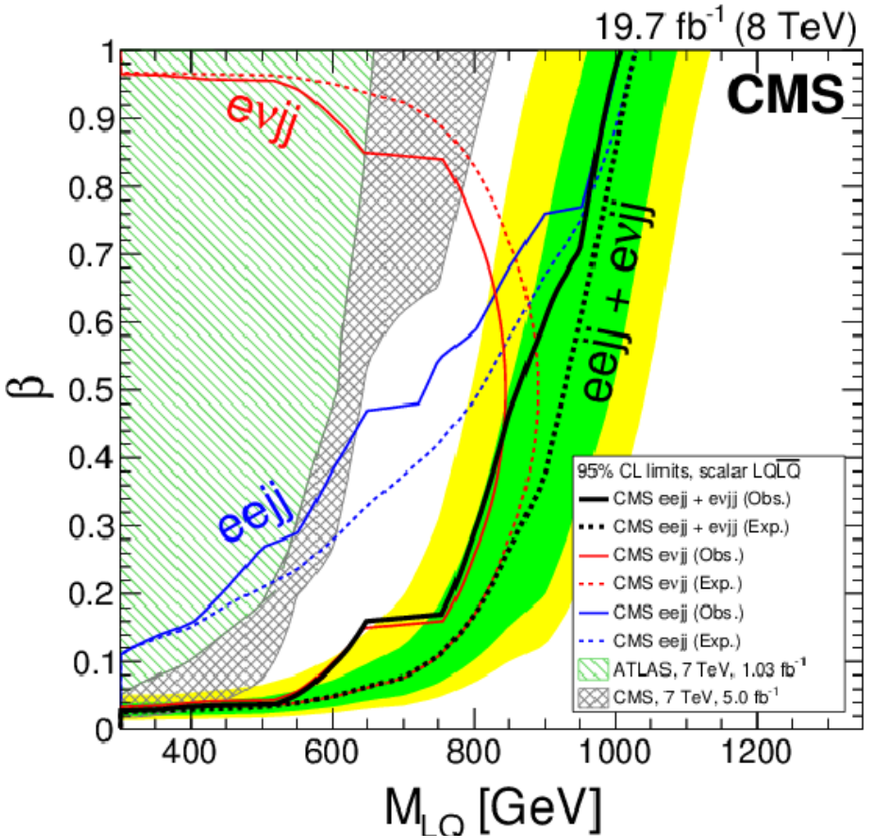
Gracias

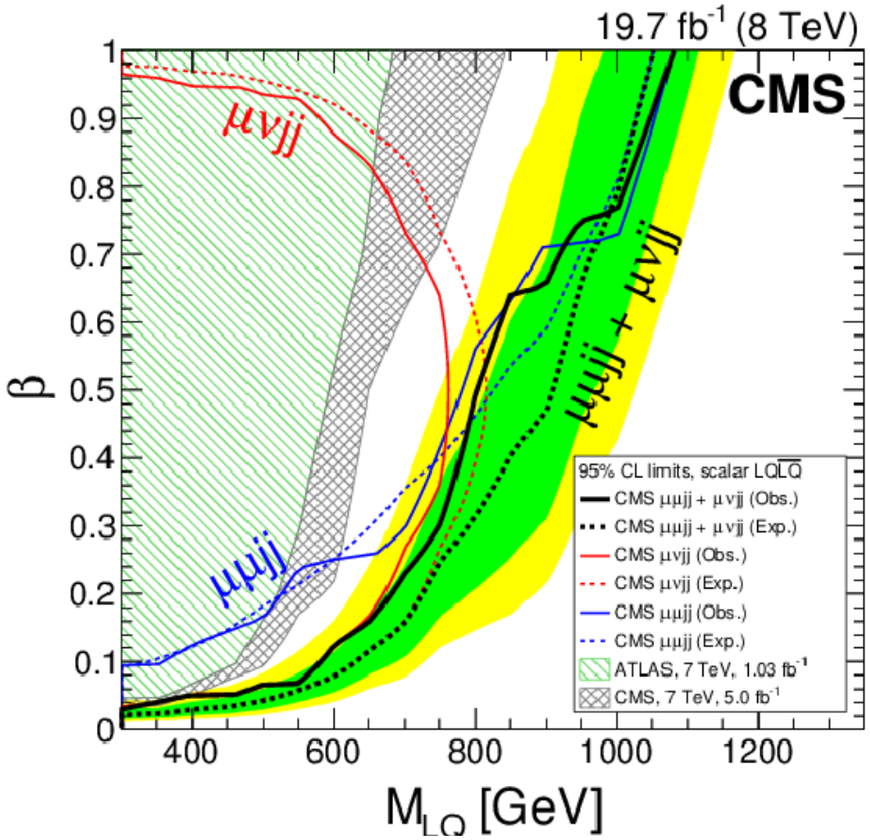
Backup Slides

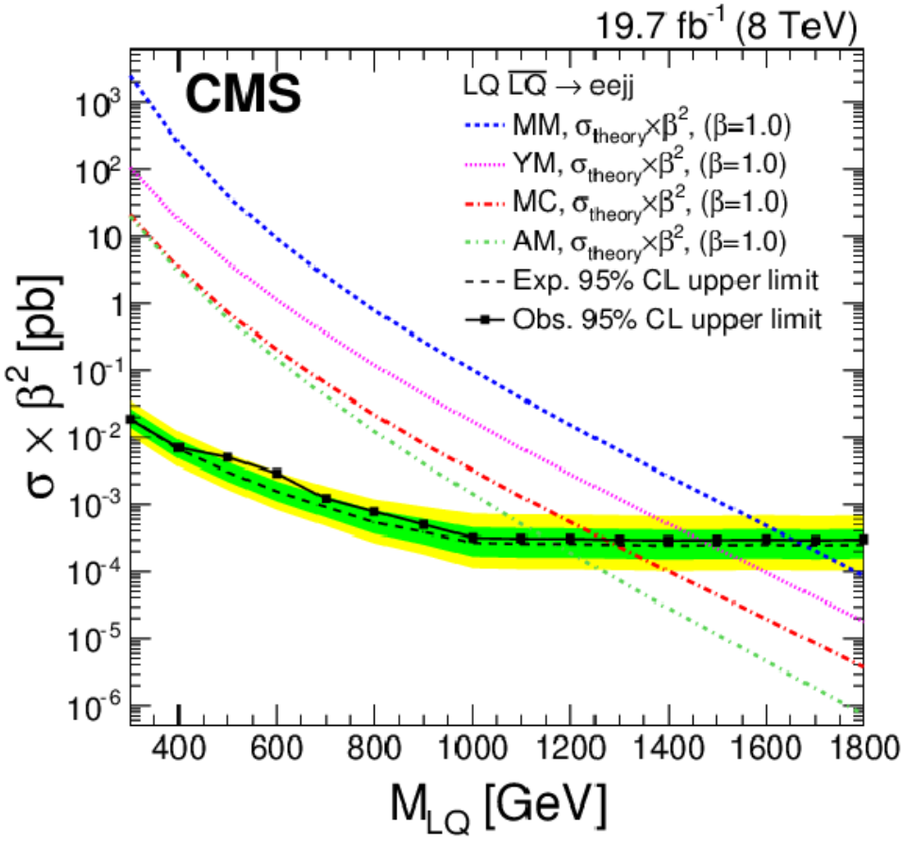
Presented CMS analyses

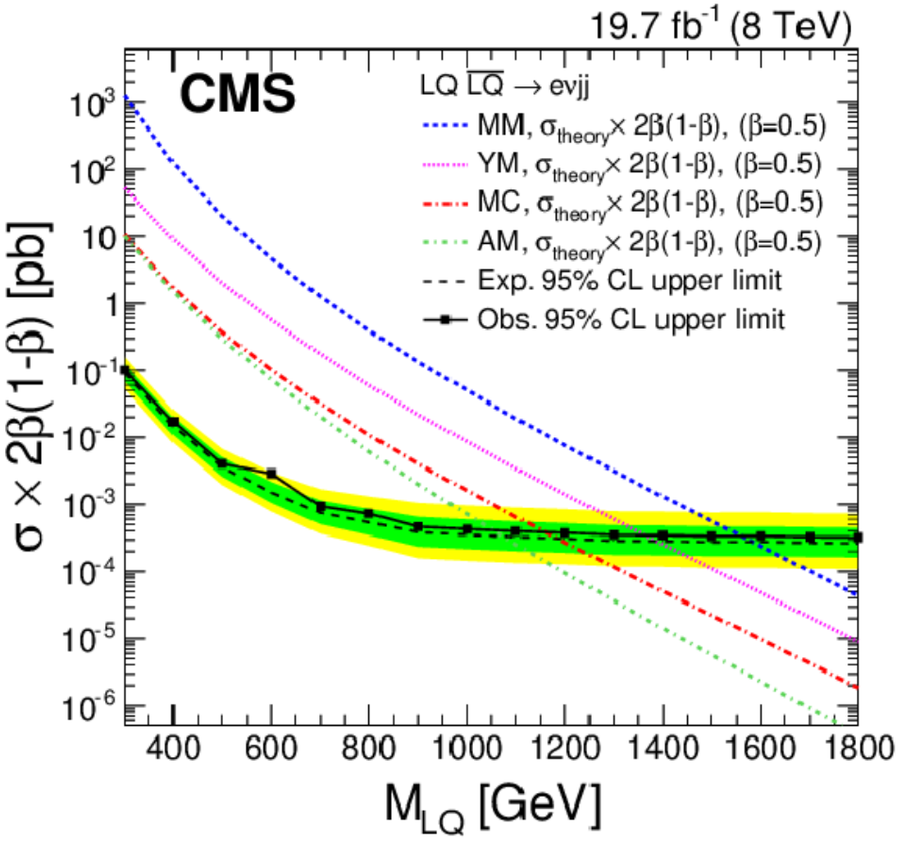
- EXO-12-041
- EXO-12-024
- EXO-16-027
- EXO-16-029
- EXO-16-031
- B2G-15-002
- B2G-15-003
- B2G-16-017
- B2G-16-009
- EXO-16-008
- EXO-16-006

Leptoquark 1st and 2nd Generation Limits 8TeV

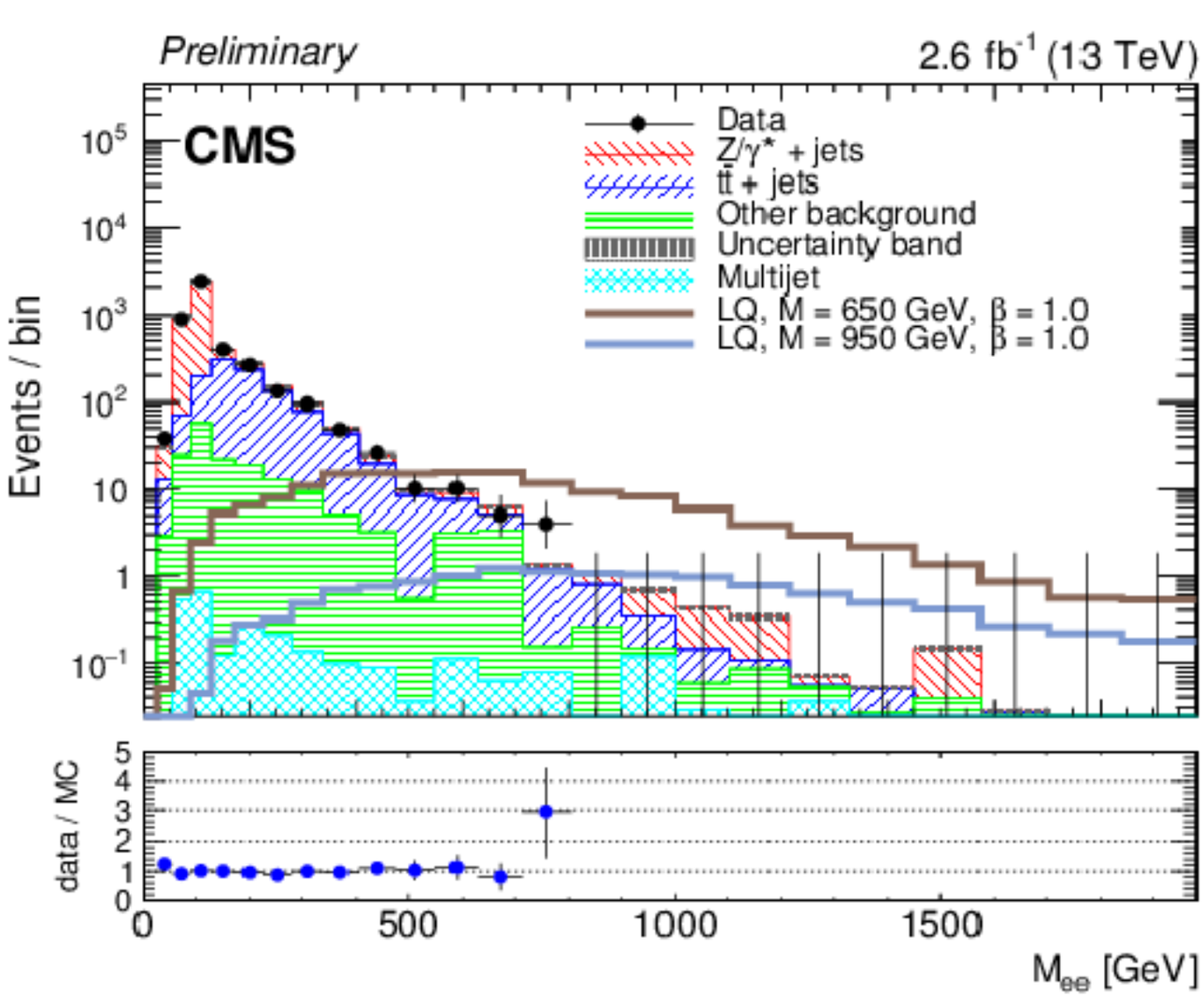


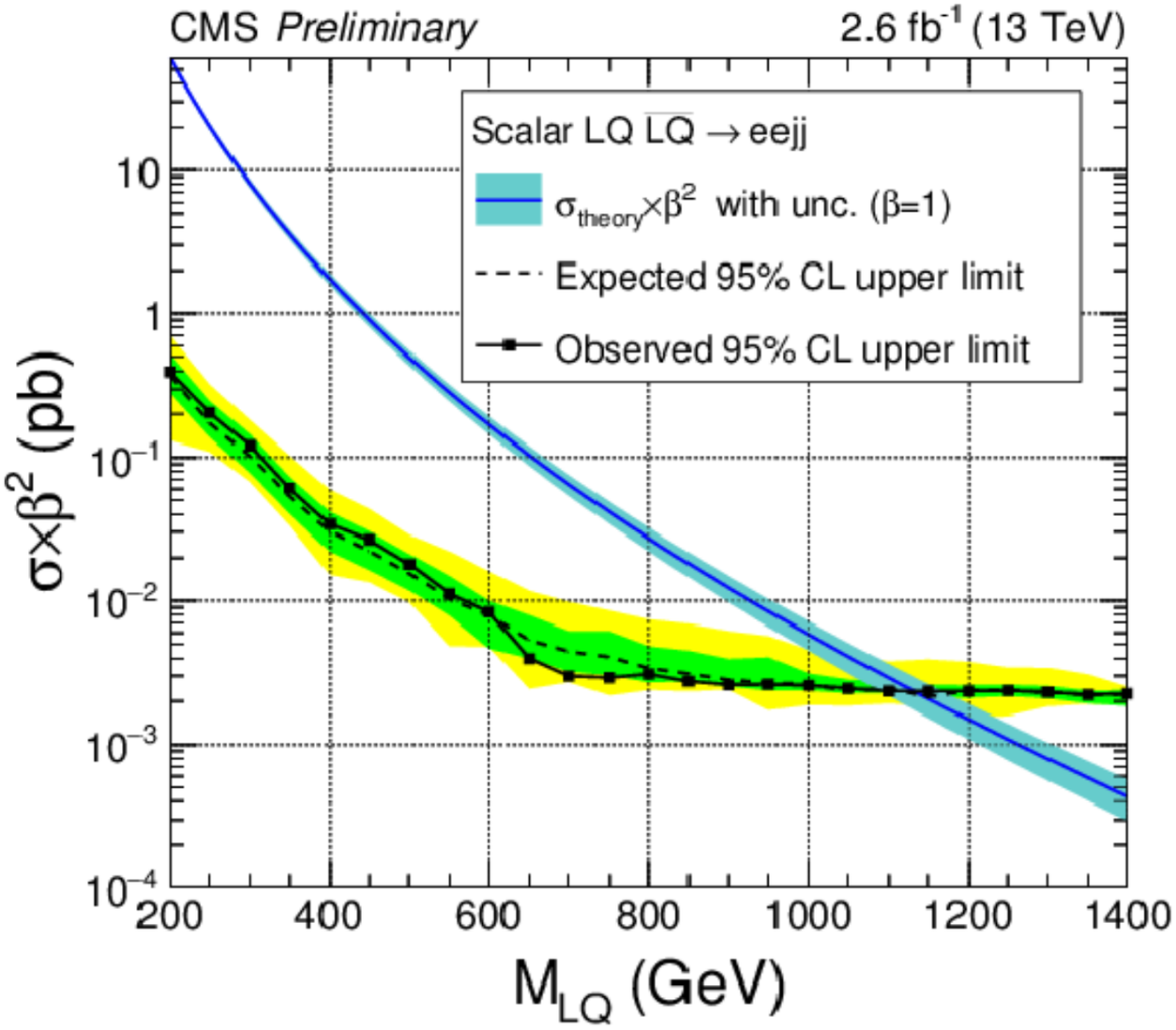




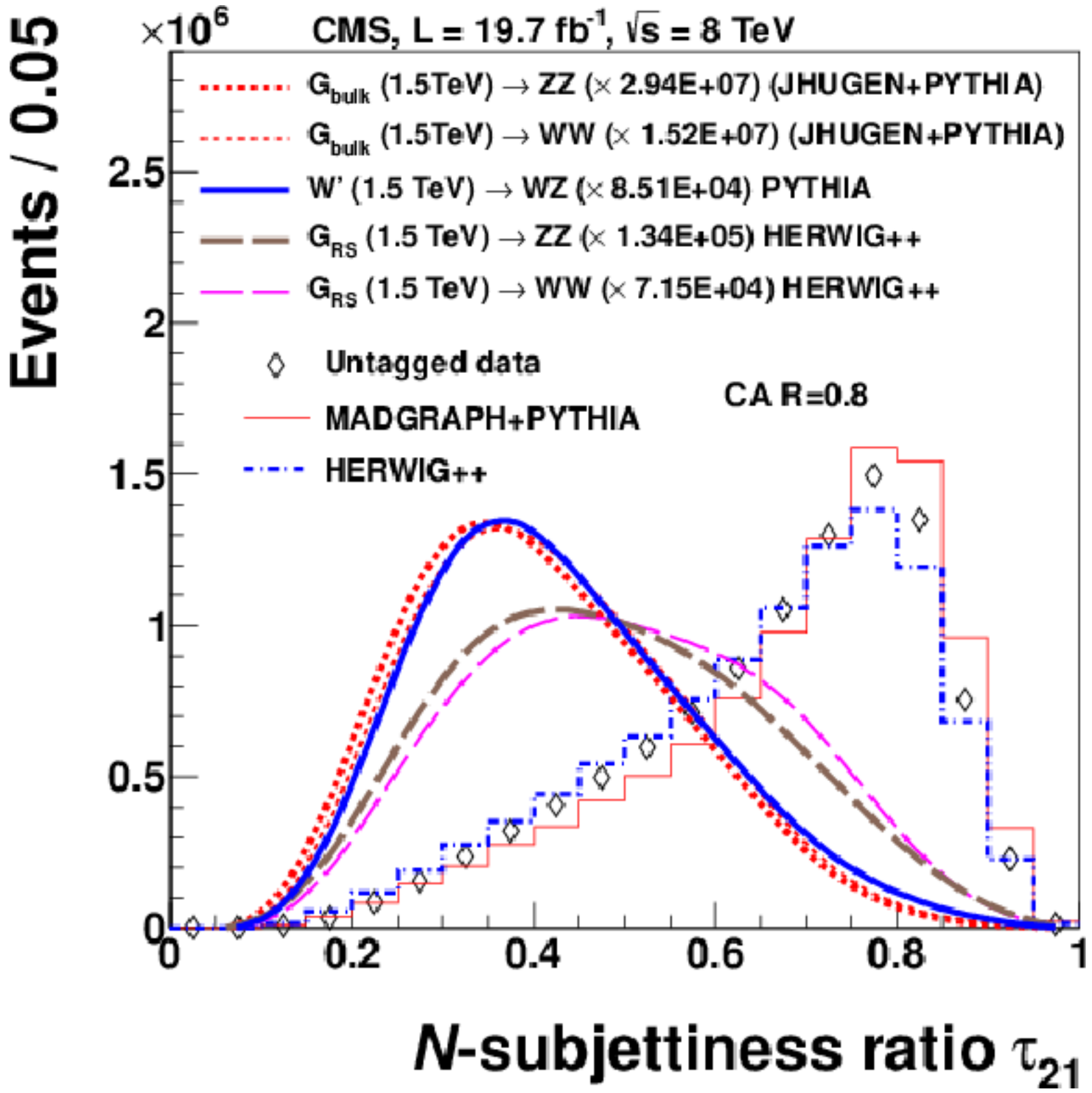


Leptoquark 1st (ee) at 13TeV with 2.6 fb^{-1}

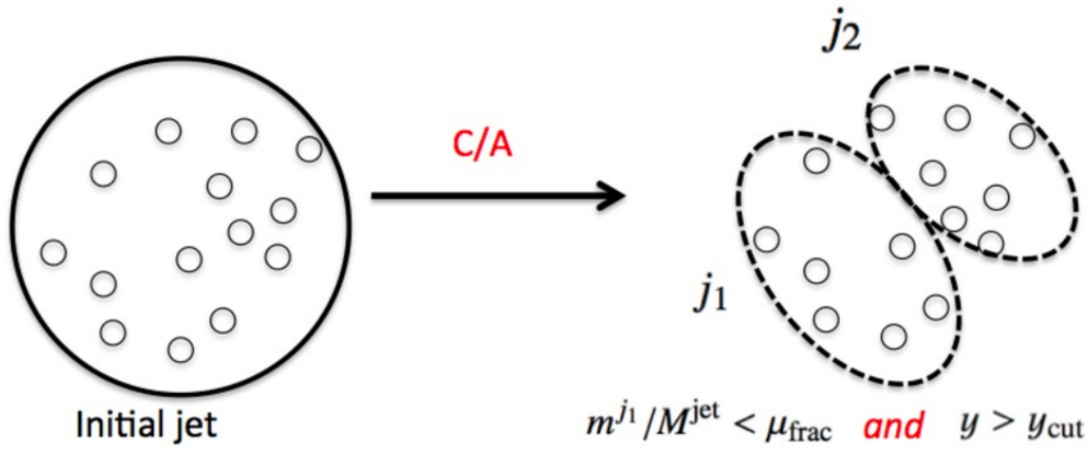




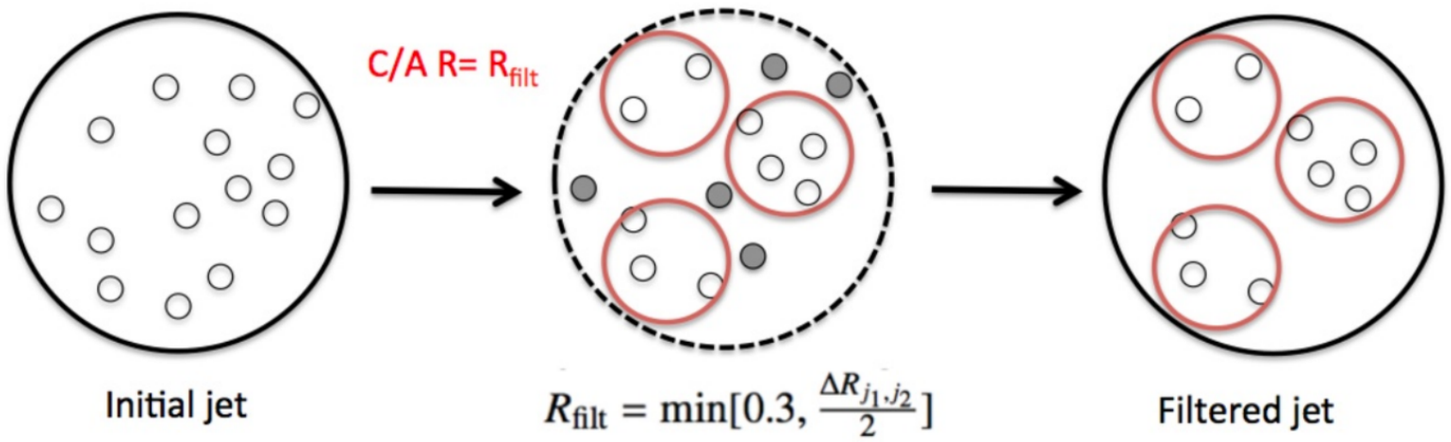
Boosted VV


CMS, L = 19.7 fb^{-1}, $\sqrt{s}$ = 8 TeV
×10^6
Events / 0.05
G$_{bulk}$ (1.5TeV) → ZZ (× 2.94E+07) (JHUGEN+PYTHIA)
G$_{bulk}$ (1.5TeV) → WW (× 1.52E+07) (JHUGEN+PYTHIA)
W' (1.5 TeV) → WZ (× 8.51E+04) PYTHIA
G$_{RS}$ (1.5 TeV) → ZZ (× 1.34E+05) HERWIG++
G$_{RS}$ (1.5 TeV) → WW (× 7.15E+04) HERWIG++
Untagged data
MADGRAPH+PYTHIA
HERWIG++
CA R=0.8
2.5
2
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
N-subjettiness ratio τ_{21}

Jet substructure Techniques



(a) The mass-drop and symmetric splitting criteria.



(b) Filtering.

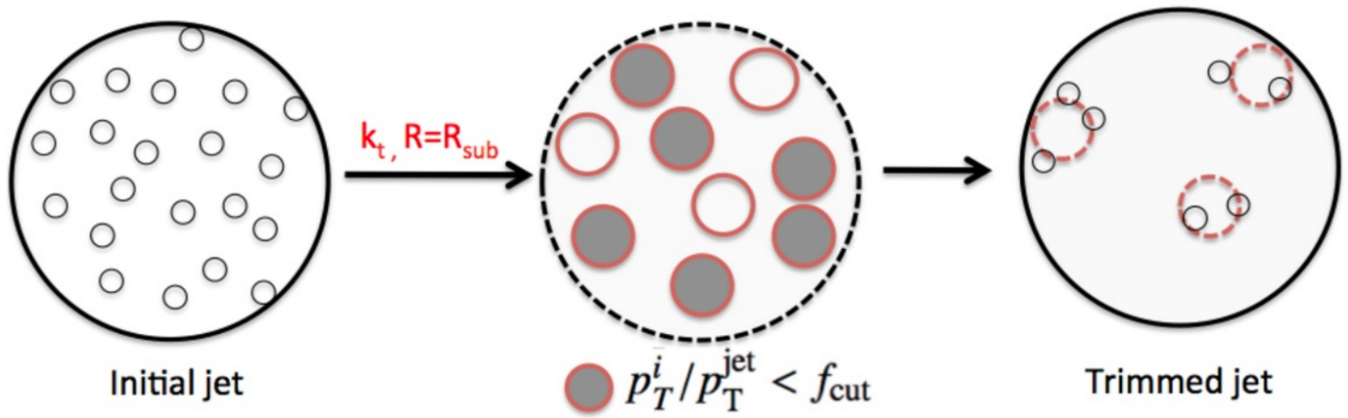


Figure 4. Diagram depicting the jet trimming procedure.