Searches for BSM Physics with the CMS Detector

BSM@CMS@LHC

Sunil Somalwar

Rutgers University

On behalf of the CMS experiment

CIPANP'18, Palm Springs, CA.

May28-June06, 2018

Thirty searches in thirty minutes

A few (intro) slides are meant for offline consumption. I will speed through or skip them.

Factual information is from CMS. Editorial comments and attempted humor is mine

Theoretical (model) references may project erudition on my part, but no real understanding is implied.

$L\hbar c$

- The energy frontier (~3 TeV).
- The biggest & most powerful microscope (10^{-19} m)
- A telescope and a time machine that reaches all the way back to 10-100 picoseconds post big-bang.
- Built to study SU(2)xU(1) EW unification: Massive W/Z make weak interaction "weak". Higgs mechanism spontaneously breaks the gauge symmetry to make W/Z massive but photon massless.
- At the EWSB mass scale (~100GeV), the length scale is proton/1000:

$$\hbar c = 200 MeV\, fm = (100 GeV)(2 \times 10^{-18} m)$$

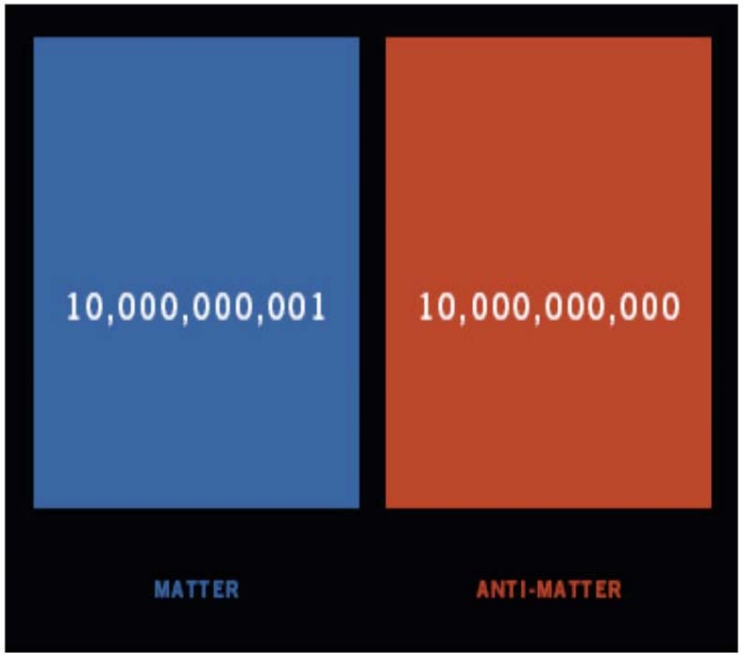
- At the contact interaction scale (do "elementary" particles have zero size?), the length scale is an order of magnitude finer

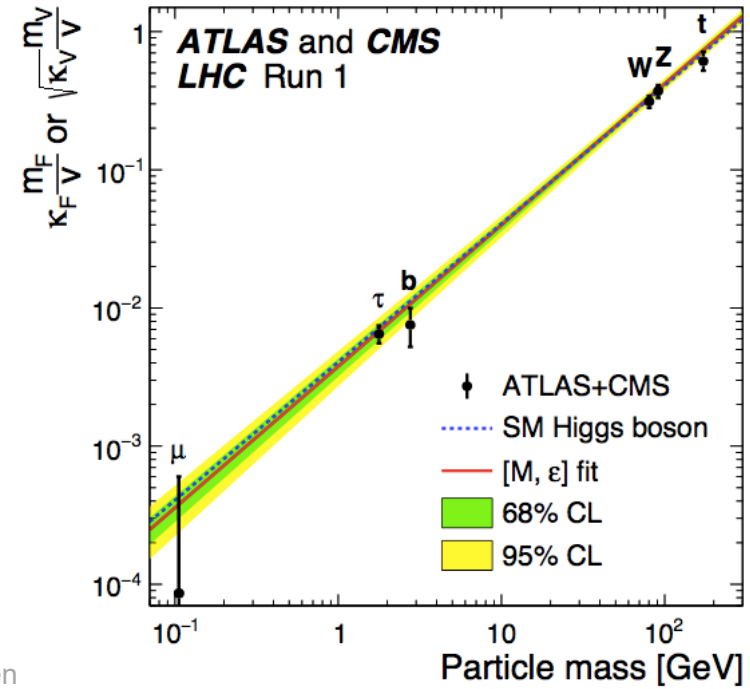
$$\hbar c = 200 MeV\, fm = (2 TeV)(10^{-19} m)$$

Fundamental questions for the LHC

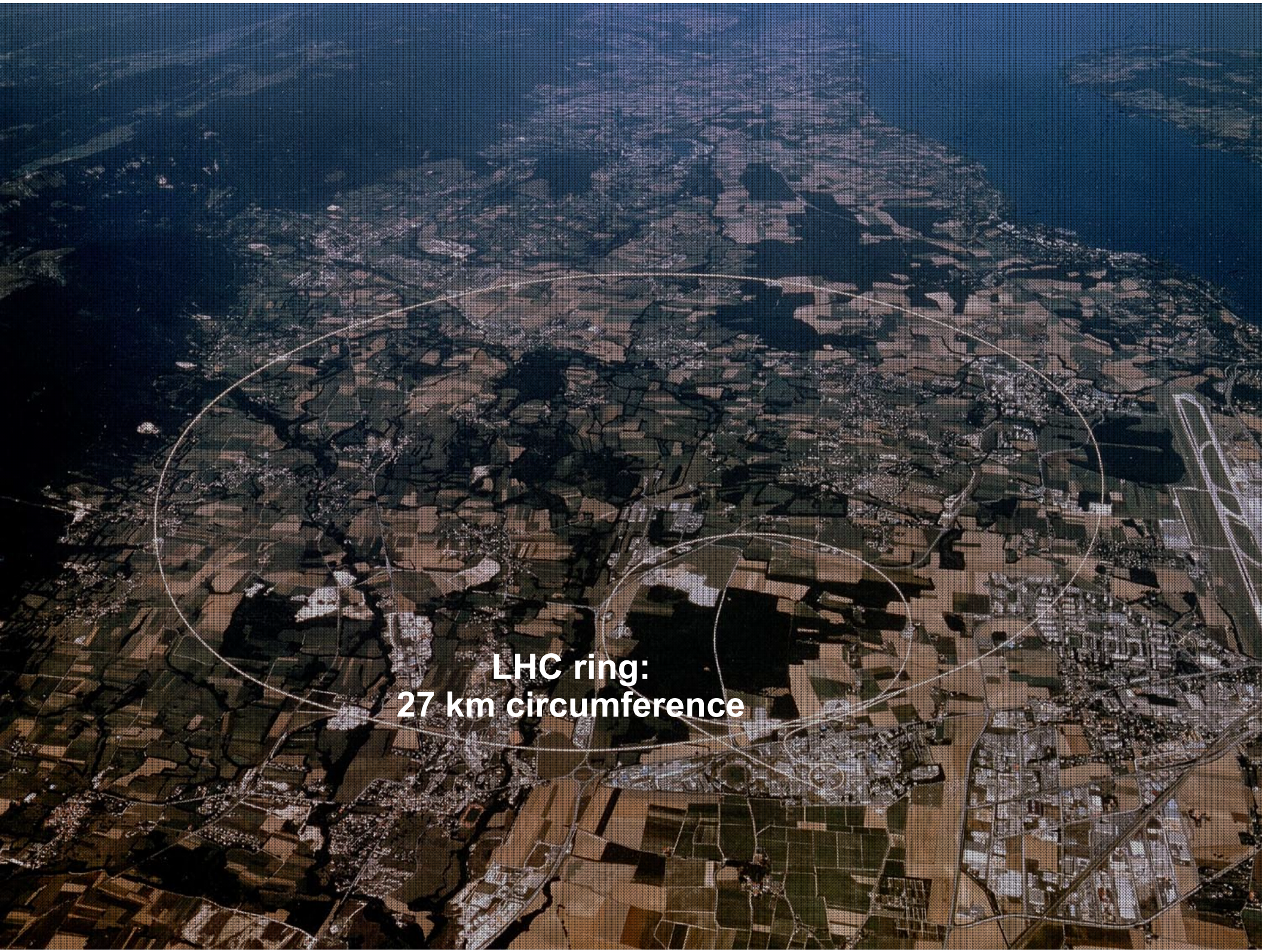
(A view from the theoretical mountain top)

- Is there a Higgs boson? (answered). Is it the Higgs boson? (Most likely.)
- Why is the electroweak scale (so) different from the Planck scale?
- What (new) physics ruled the day (!) 10-100psec after the big bang? How to explain the 10^{-11} baryon asymmetry?
- What is dark matter?
- Why three generations, flavor…





Higgs is 0^+, and has SM couplings

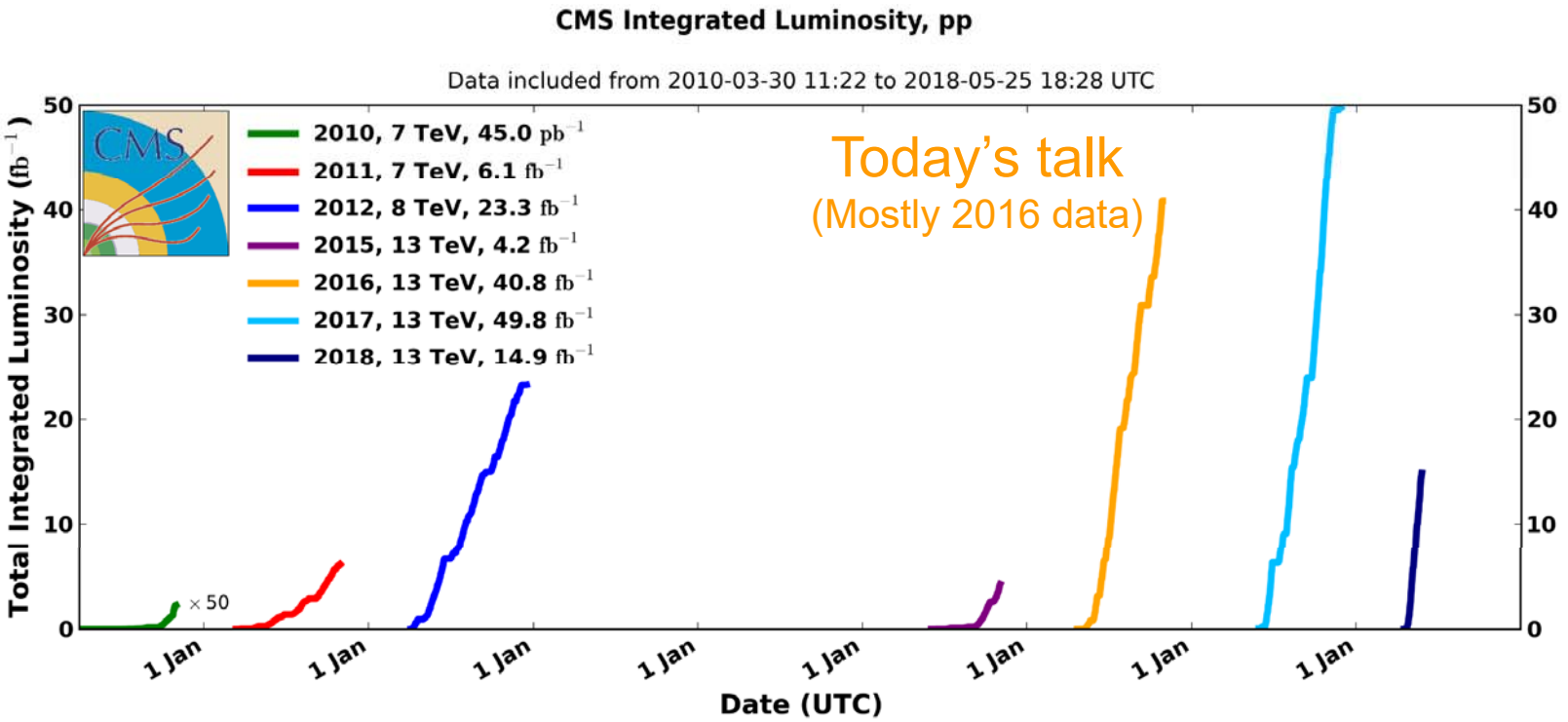

LHC ring:
27 km circumference


CMS
LHCb
ALICE
ATLAS
LHC ring:
27 km circumference

Luminosity and Cross section

- Cross section has units of area, m^2 (size of the microscopic "target" object or process)
- Small cross sections are in units of barn, e.g. picobarn = pb = 10^{-40} m^2 = $(10^{-20}$ m$)^2$
- LHC data is measured in units of *inverse* cross section, called (integrated) luminosity.
- On an average, 1 inverse pb worth of collision data contains 1 event for a process that has one pb cross section.
- [The proton size is roughly a fermi = 10^{-15}m, so it takes a lot of proton-proton collisions to pinpoint a 10^{-20}m needle in the proton haystack.]
- To maximize the rate of luminosity delivery, LHC has dense bunches of protons 25nsec (=25ft) apart from each other in counter-circulating beams. They must collide head on.

LHC Luminosity



- LHC has been running well!
- ~35/pb to ~2500x35/pb in a few years.

Particles Lingo

Tracks, photons, jets

"Leptons": electrons and muons, i.e., charged light leptons

Tau (theorist): Tau lepton, i.e., the heaviest of the charged leptons

Tau (experimentalist): Reconstructed hadronic decay of the tau lepton

Pt: Transverse momentum. Longitudinal quantities often not useful in pp collisions

Missing pt, aka ptmiss, missing ET, MET: due to neutrinos or anything not detectable.

HT/LT: scalar sums of jet or lepton pt's

ST, also effective mass: sum of HT, LT and missing pt

MT: Transverse mass (useful when there is a neutrino)

(pseudo)rapidity: relativistic version of polar angle

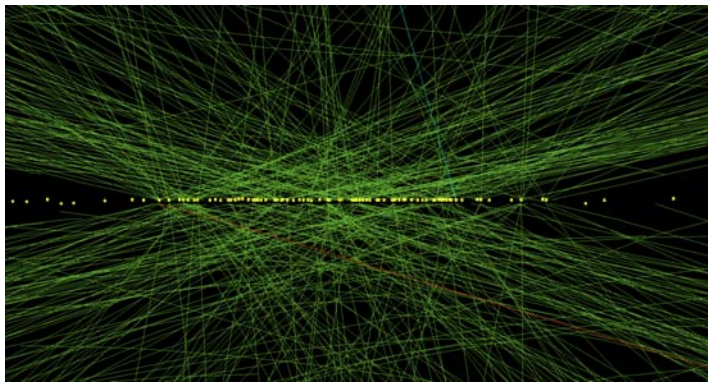
Isolated track/lepton etc: Not much else in a DR around the object

Vertex: Collision location, where most charged particles come from (78 vertices in the picture below)

Pileup: Number of vertices (due to separate pp collisions) in an event.

Prompt: From the vertex, not displaced. (b-jets are displaced)

MC: Monte Carlo = simulated events



Is there a preferred way to break the SM?

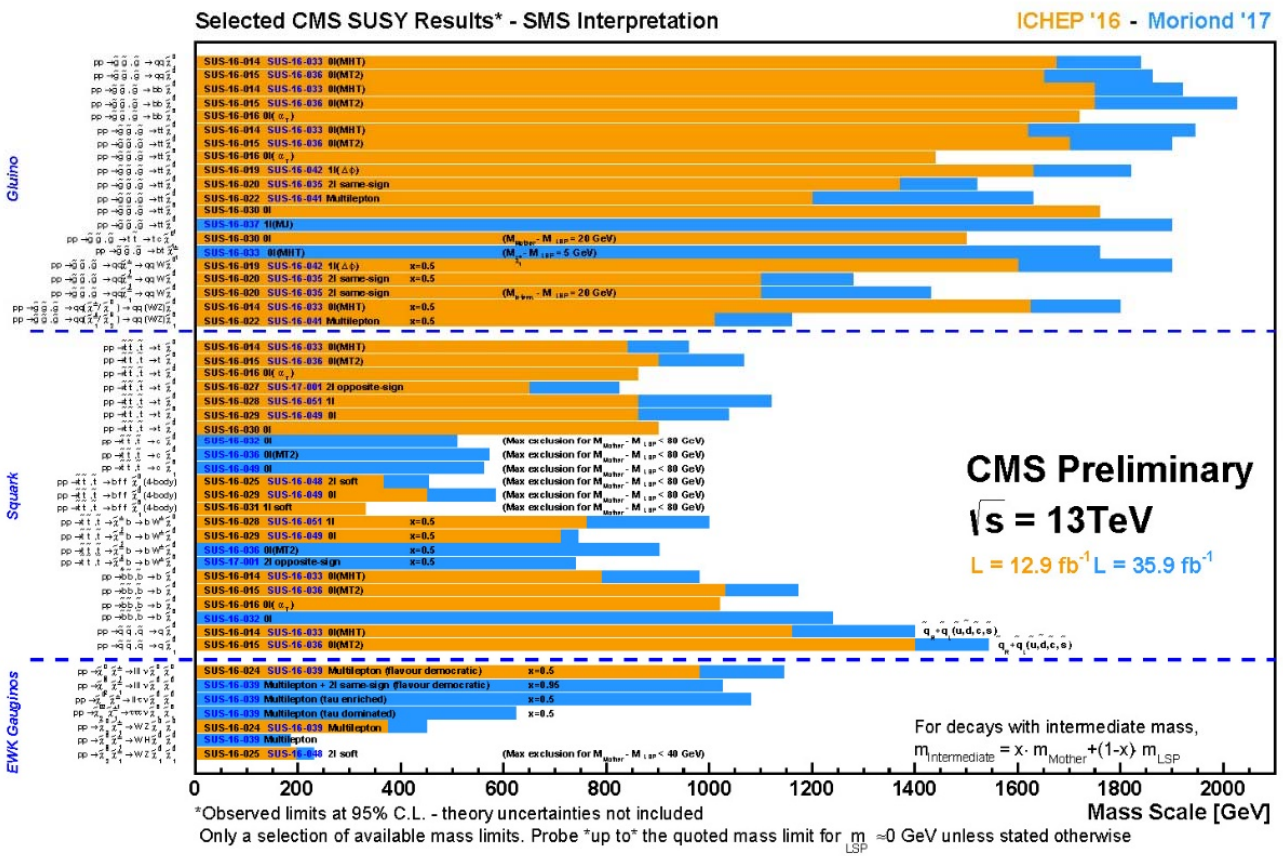
- Go for the highest possible mass reach. New particles: dijet resonance, W', Z', boosted….
- Programmatic, e.g., Supersymmetry. R-parity? Or ask questions.eg: Top quark is the heaviest particle we have. Does it decay unusually, e.g. top quark → charm quark + higgs? Maybe the new particles are long-lived.
- For the first time since the 1970's, the experimentalist playground is unsupervised by theorists. (W/Z, top, higgs were anticipated.)
- Stick to the electroweak scale (100-200GeV)? Maybe there is a higgs ghost (or two). *(Would the SM higgs have been discovered by now if it(s properties) were not anticipated?)*
- Keep hammering at the Standard Model (what else is there?) to seek Beyond Standard Model physics.

Overview of CMS BSM parallel talks in this conference

(sans Heavy Ions)

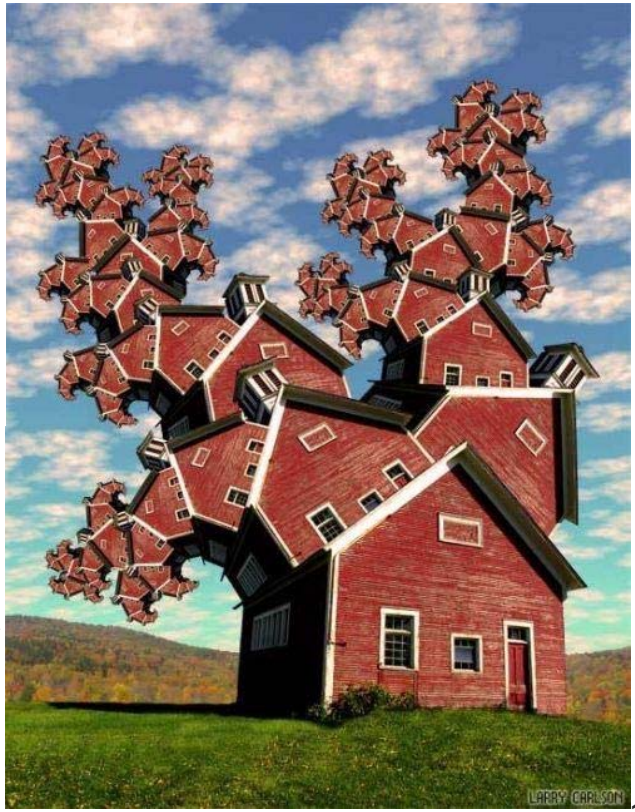
- SUSY:
  - Jim Hirschauer
- Dark Matter:
  - Siddharth Narayanan (Recoil or “Mono-X”)
  - Javier Duarte (Direct including long-lived)
- Exotic: includes B2G (Beyond 2 Generations) and non-SM Higgs
  - This talk

BSM search: supersymmetry



- squarks/gluinos
- electroweak/electrohiggs
- 3rd generation
- RPC/RPV, long-lived
- Compressed spectra
- tau's…

$$[Q^\alpha, H] = i\overline{fu}$$



House of susy signatures

One slide on "exotic" models

- ED, ADD: ADD model has 4+n dimensions but only gravity in Extra Dimensions. Exchanged virtual KK graviton modifies SM.

- Dark Matter @ collider: Brute force version of the SUSY LSP (neutralino). Produce a Z'-like mediator against a hefty recoil, decay to invisible DM pair. Also, direct production (e.g. susy neutralino), long-lived particle search.

- W'/Z'/HVT: Simplified Heavy Vector Triplet model(s) for W'/Z'.
  Model A: weakly coupled vector resonances from gauge group extension.
  Model B: strong scenarios (composite Higgs models)

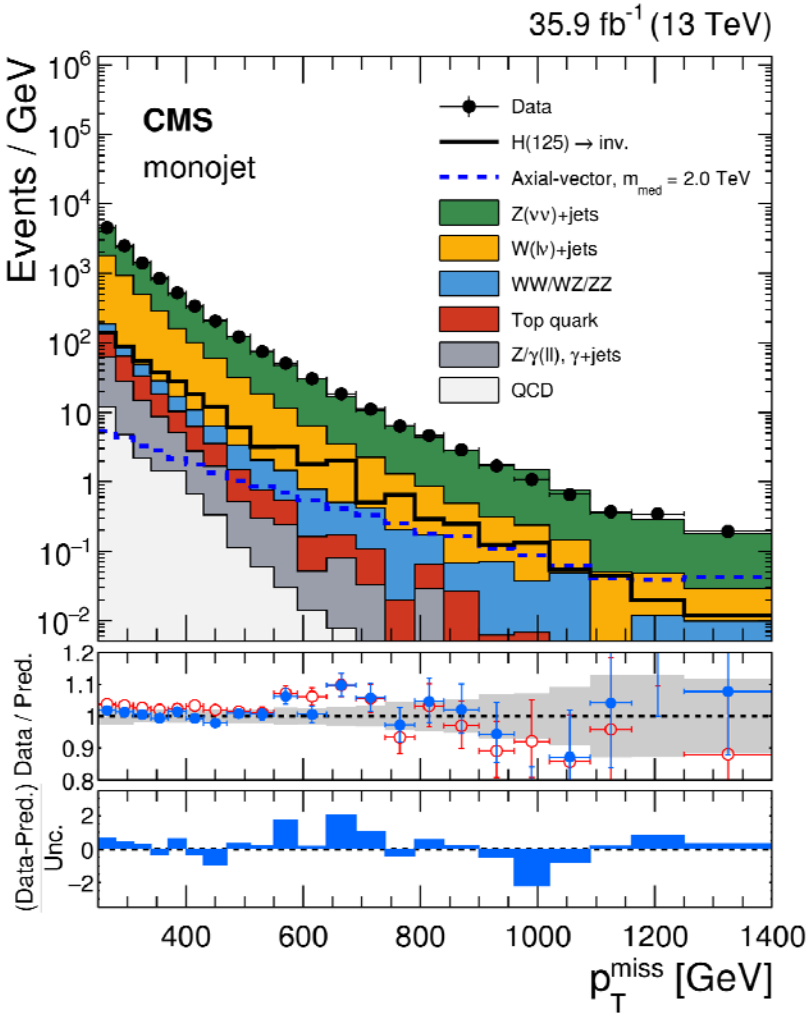
- VLQ/VLL: Vector like quarks/leptons. Workaround for particles formerly known as 4^{th} generation. BR's are free parameters, e.g. b'→tW, bZ, bH.

- Seesaw: Heavy partners who keep neutrinos light. Several models bring the mass down from Planck scale to LHC. Prolific processes which generate them in association with leptons, W/Z/H. (more later)

Unbalanced Monojet

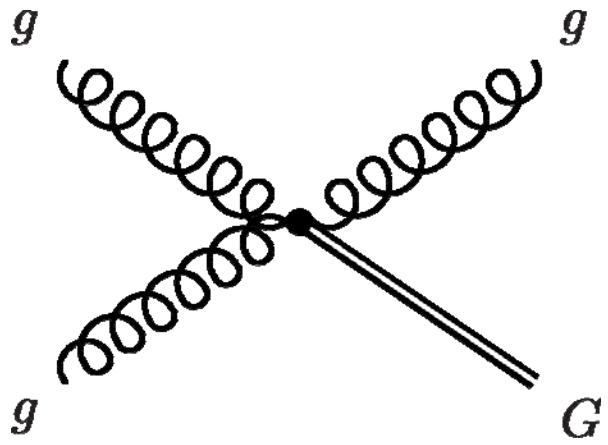
(CMS arXiv:1712.02345, EXO-16-048)

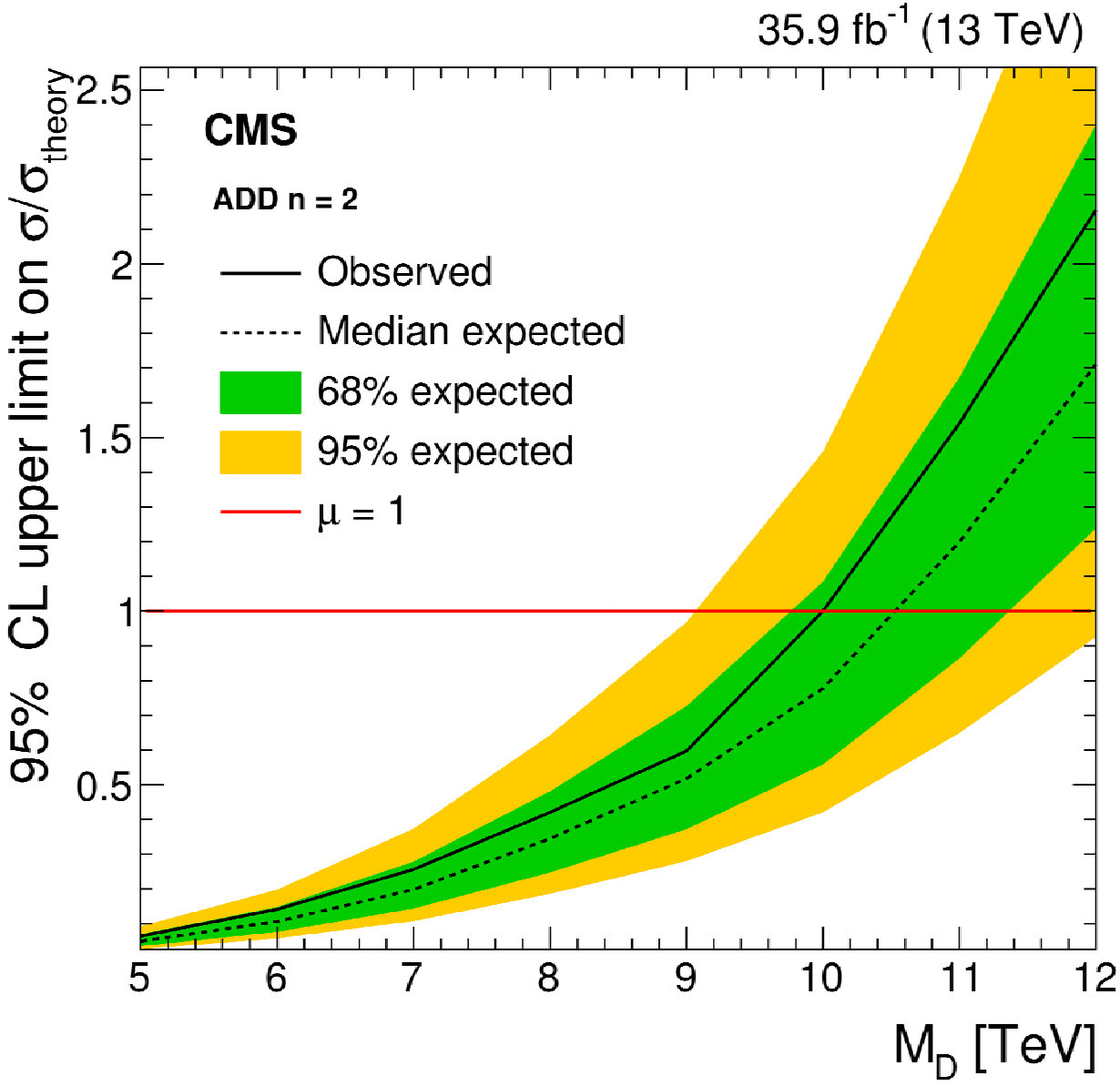
- Signature: Hefty jet & large MET, no leptons. Met, pt >250GeV
- Backgrounds: Z(invisible)+jets and W(tau-nu)+jets. Measure with Data/MC in leptonic V+jets control samples assuming hadronic recoil=MET.
- Systematics: lepton efficiency scale factors.



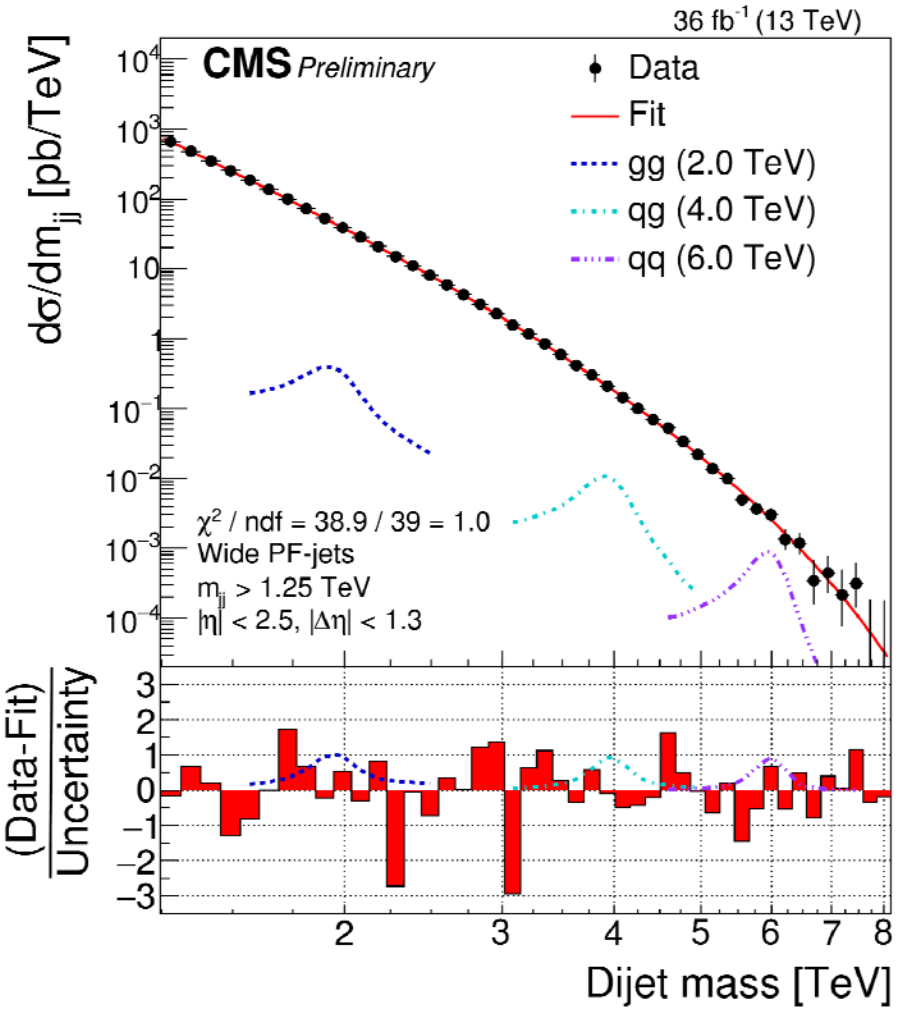
Unbalanced Monojet (contd)

- Dark Matter
- Invisible SM Higgs (gg→H,VBF,VH) 53% at 95% CL (CMS)
- ADD search for n extra dimensions at fundamental Planck scale given by M_D.
  - limits on M_D: 5-10TeV for n=6 to n=2.





Dijet resonance
(CMS EXO 16-056)



- Background: QCD Smooth shape
- Systematics: JES, Resolution, Spectrum shape

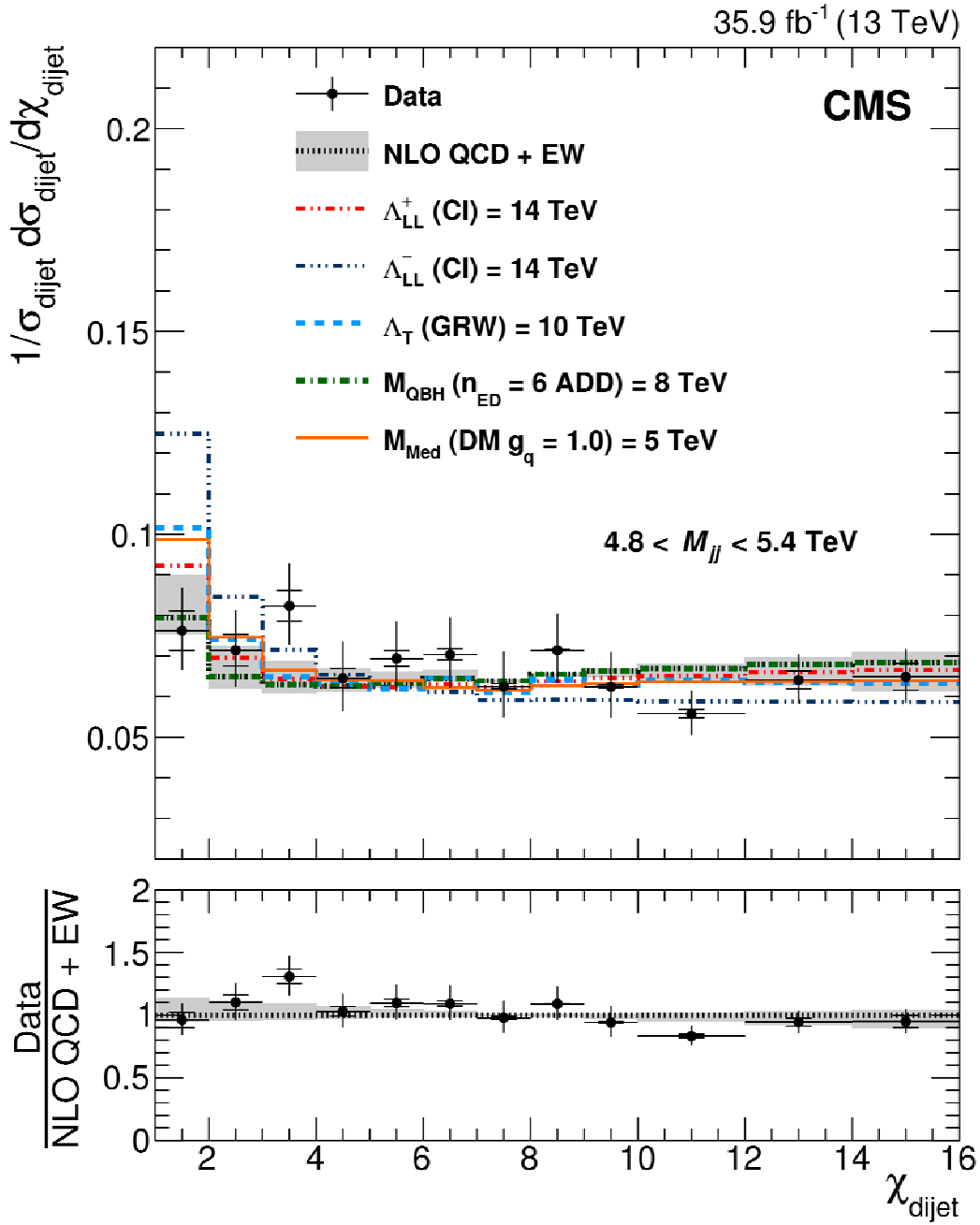
Model	Final State	Observed (expected) mass limit [TeV] 36 fb^{-1} 13 TeV	12.9 fb^{-1} 13 TeV	2.4 fb^{-1} 13 TeV	20 fb^{-1} 8 TeV
String	qg	7.7 (7.7)	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	7.2 (7.4)	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	$q\bar{q}$	6.1 (6.0)	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	6.0 (5.8)	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.4 (3.6)	3.0 (3.3)	—	—
W'	$q\bar{q}$	3.3 (3.6)	2.7 (3.1)	2.6 (2.3)	2.2 (2.2)
Z'	$q\bar{q}$	2.7 (2.9)	2.1 (2.3)	—	1.7 (1.8)
RS Graviton ($k/M_{PL} = 0.1$)	$q\bar{q}$, gg	1.7 (2.1)	1.9 (1.8)	—	1.6 (1.3)
DM Mediator ($m_{DM} = 1$ GeV)	$q\bar{q}$	2.6 (2.5)	2.0 (2.0)	—	—

Dijet rapidity spread
(CMS arXiv:1803.08030, EXO-16-046)

- Signature: $\chi = e^{(y1-y2)}$ for the two leading jets
- χ flattens Rutherford scattering (a la Dalitz plot)
- Background: QCD
- Systematics:

  Mjj<3TeV: high statistics, but ~4% Jet Energy & QCD NLO scale

  Mjj>6TeV: Low statistics ~25% stat error



Dijet rapidity spread (contd)

Physics/Models:

- Λ 10-20 TeV: fundamental particle substructure, a.k.a. quark contact interaction (back to the future with Rutherford and Bjorken-Kendall-Friedman-Taylor).

Also, since LHC recreates conditions ~1-10 picosecond after big bang (to address EWSB ~10-100 psec after big bang):

- Extra Dimension ADD ~10 TeV
- Quantum Black Holes 6-8TeV
- Dark matter Mediator 2.5-5 TeV

And finally,

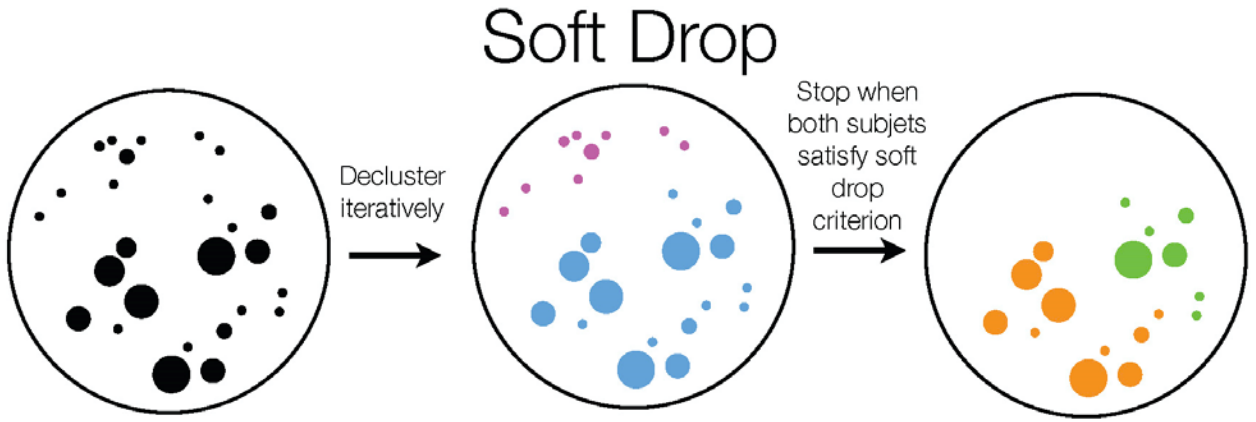
- Z' 1.5-3TeV

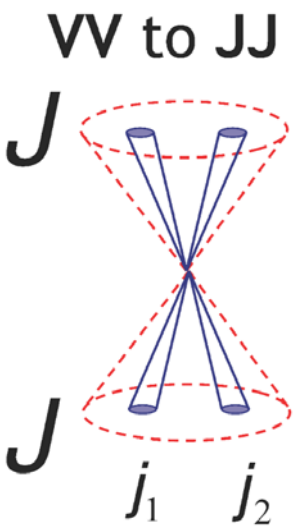
Jet substructure

Terminology: Boosted/merged fatjet/large-R, AK10 & D2. Resolved jet →substructure. Puppi, pruning, subjettiness (=3 for top, 2 for W/Z), tau2/tau1, etc

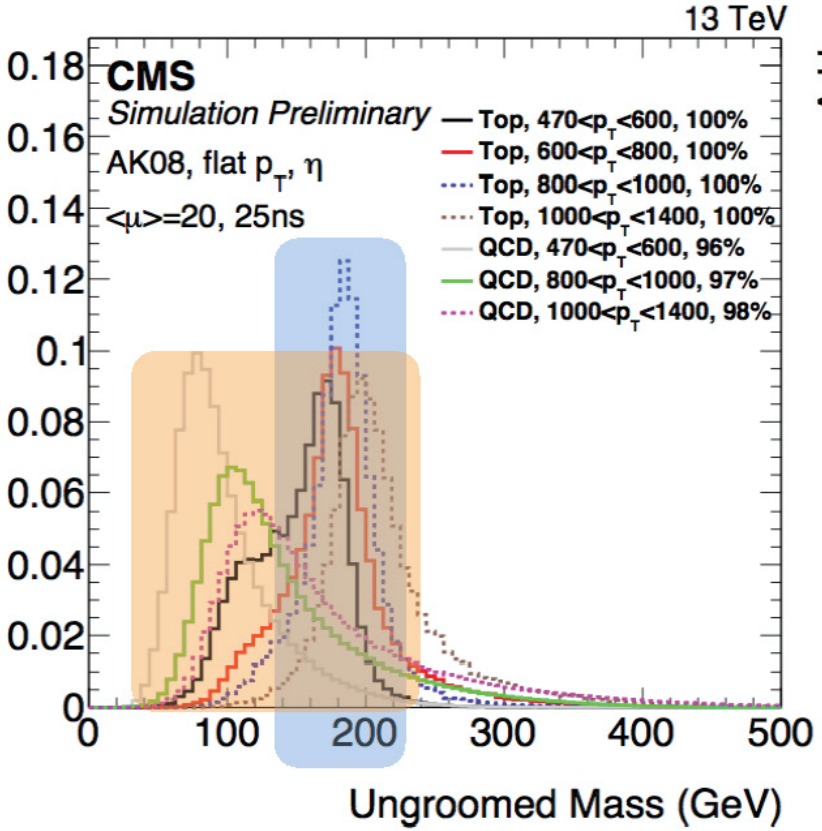
X tagger

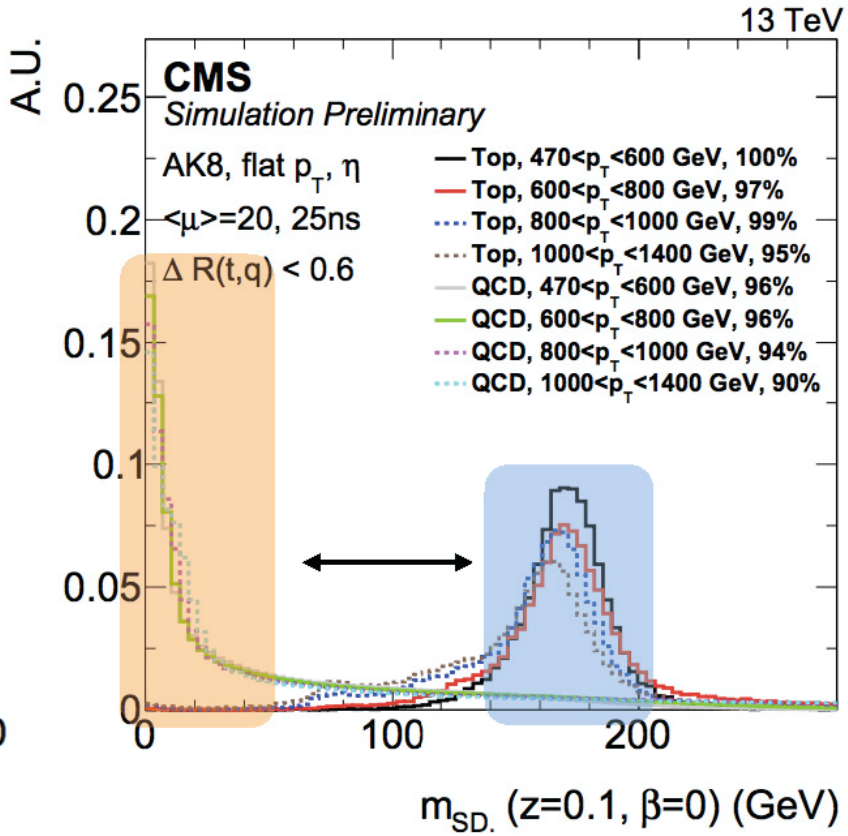
(X=W,Z,H,t)





Merged-top separation from QCD after grooming





Thx: Robin Erbacher

Editorial lament: why are substructure analyses flourishing lately?

- A statement that the hierarchy problem is getting worse?
  - Using a 13000 GeV machine for a 100 GeV problem!
  - So far, no pp → X → V/H with MX ~ 500GeV.
  - When MX ~1-2 TeV, substructure!

- Are we missing anything below ~500GeV?

- Similarly: Using an ISR jet for efficiency/triggering

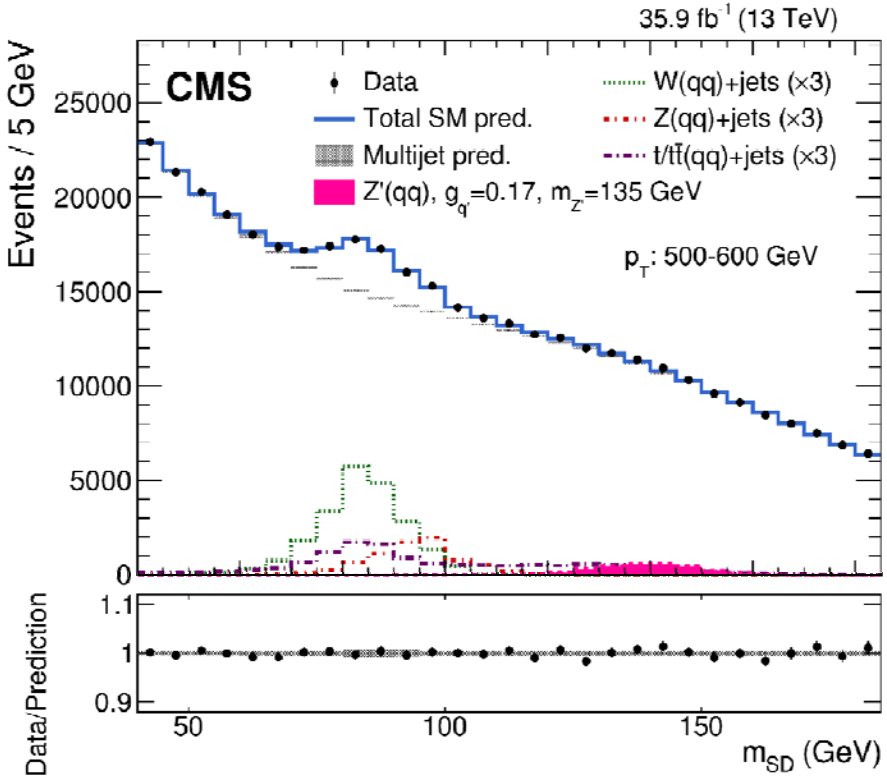
Merged (di)jet light resonance
(CMS arXiv:1710.00159, EXO-17-001)

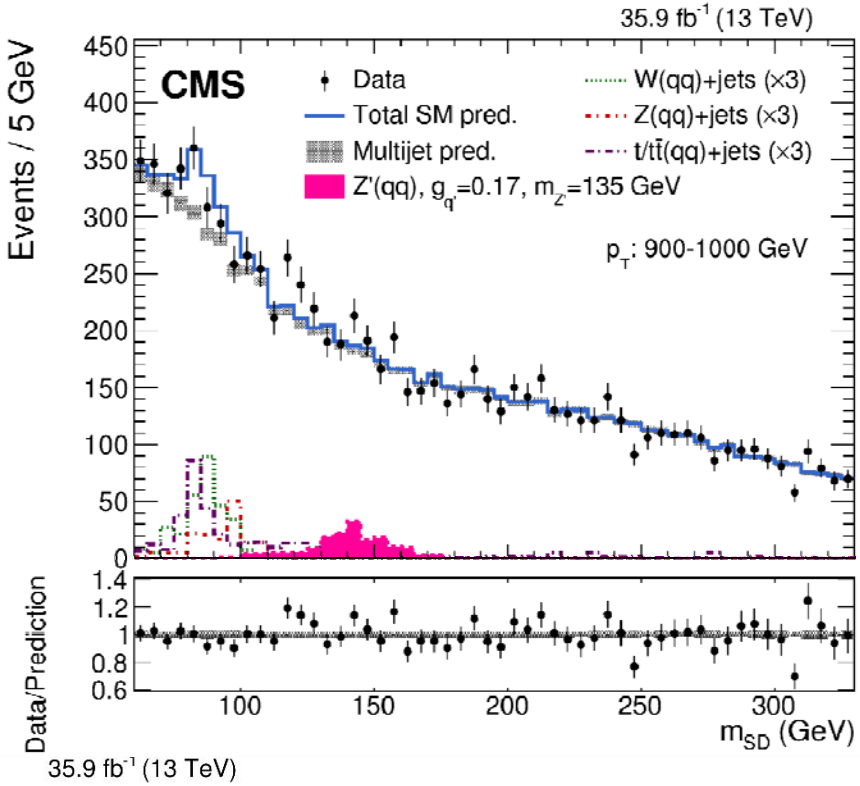
- Signature: A merged jet (with substructure) from a 50-300GeV resonance

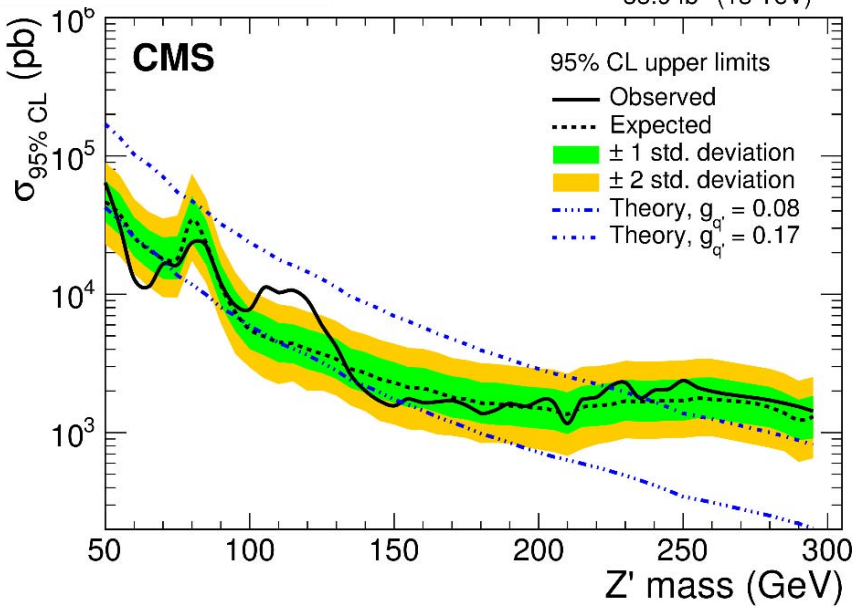
- Background: QCD jet masquerading as a merged dijet. Data-driven signal/bkgnd inversion. Also, hadronic W/Z resonant around 80/90GeV. Uncertainties from procedural fits.

- Physics/Models: Leptophobia. Z', Dark Matter

Resonant large (merged di)jet (contd)







115GeV: 2.9/2.2 sigma

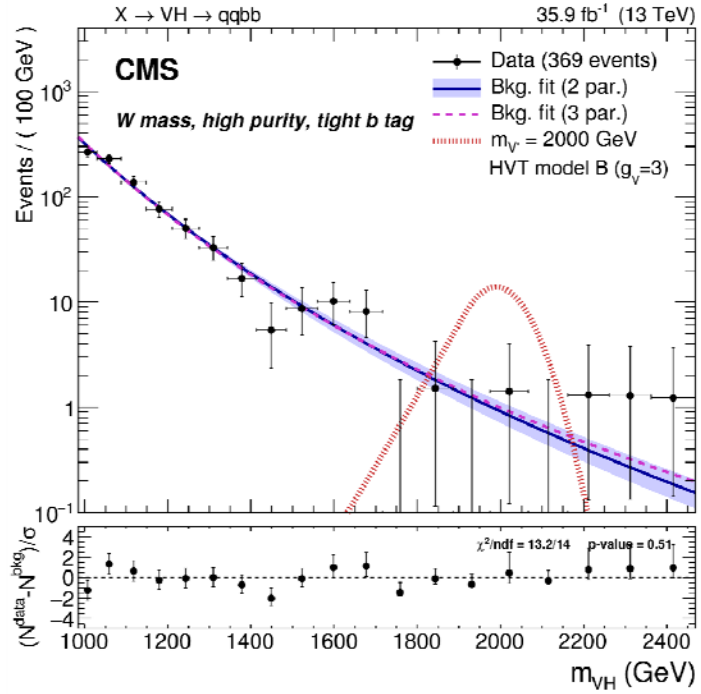
[(qq)(bb)] merged jets:VH resonance (heavy)

(CMS:1707.01303)(B2G-17-002)

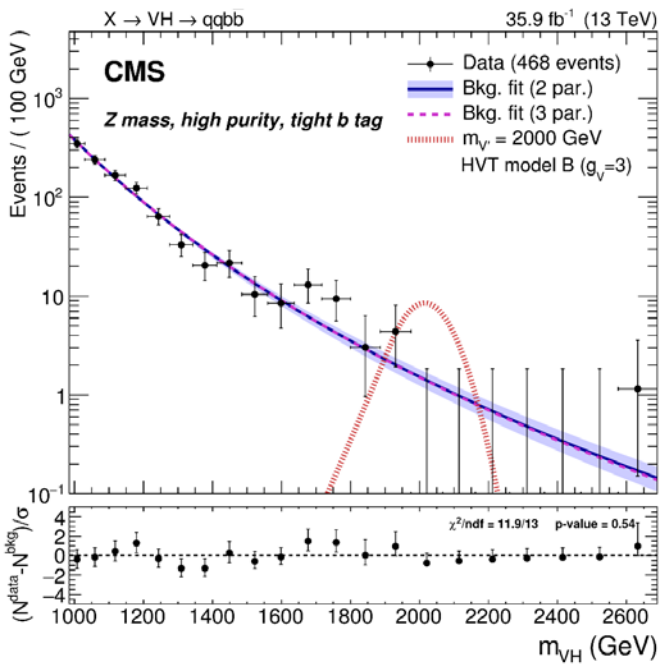
- Signature: Two large-R jets, no leptons, MET<250, (binned) b-tags
- Substructure Heavier (Higgs) jet m_J 105-135GeV. Lighter (W/Z) jet m_J 65-85 or 85-105GeV
- Scan m_{JJ} for VH resonances above 1 TeV
- Backgrounds: 95% QCD multijets,<5% tt, minor VV. Data-driven (smooth function) using sidebands and validation regions.
- Physics/Models: Composite/little higgs, ED. Heavy vector triplet (HVT)

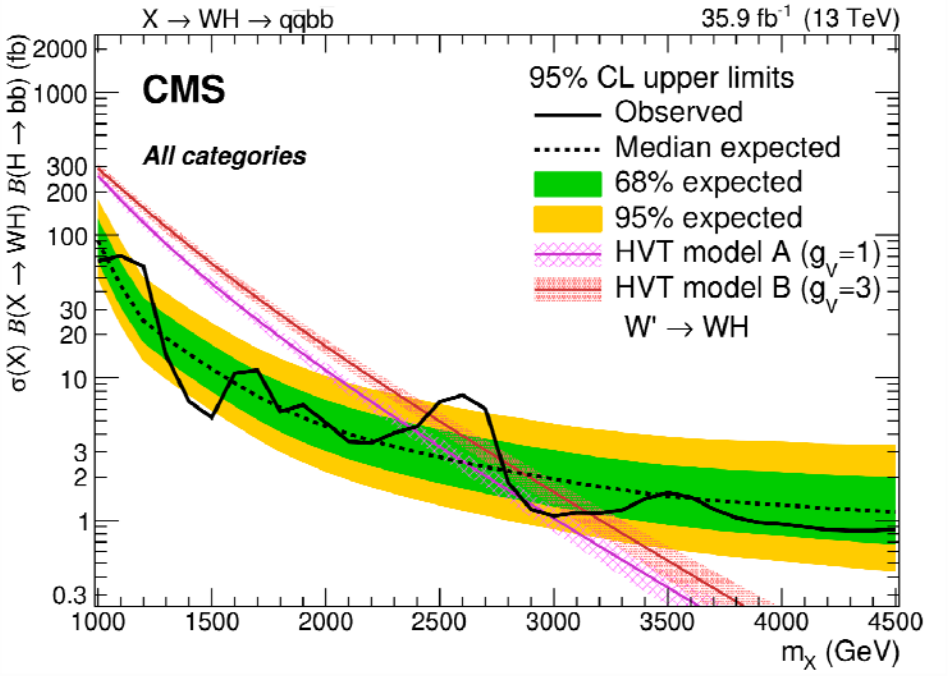
[(qq)(bb)] merged jet resonance

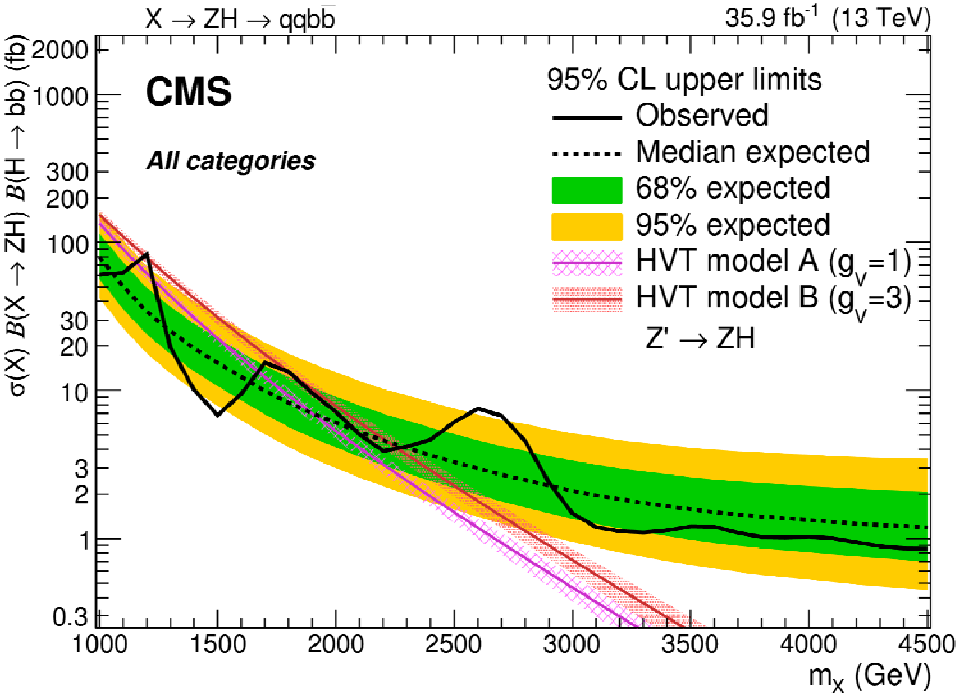
(CMS:1707.01303 B2G-17-002)



1-tag more sensitive at higher masses.

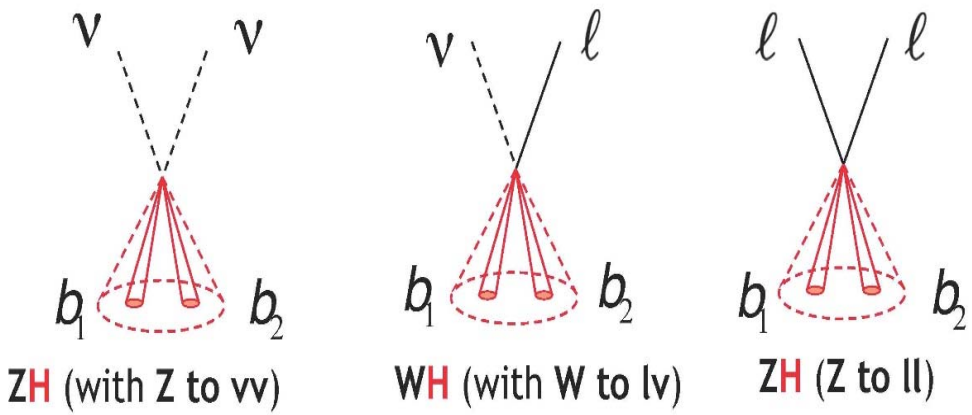


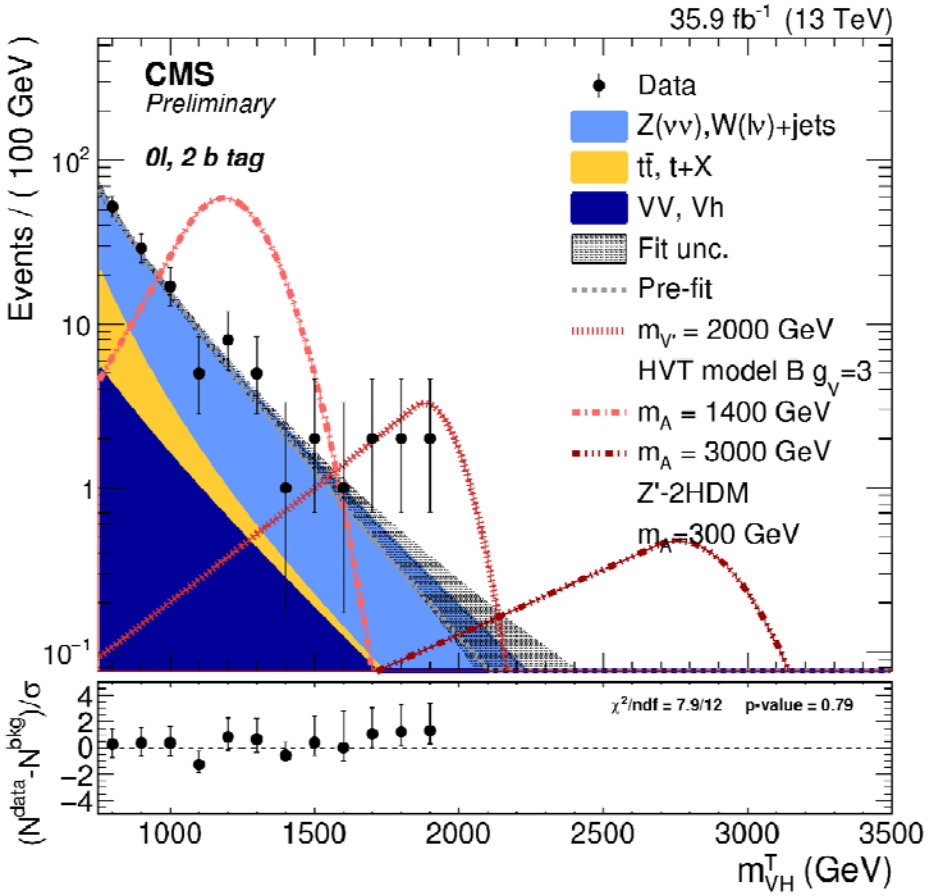




[W(lnu) or Z(ll/nunu) + H(bb)] resonance (CMS-B2G-17-004)

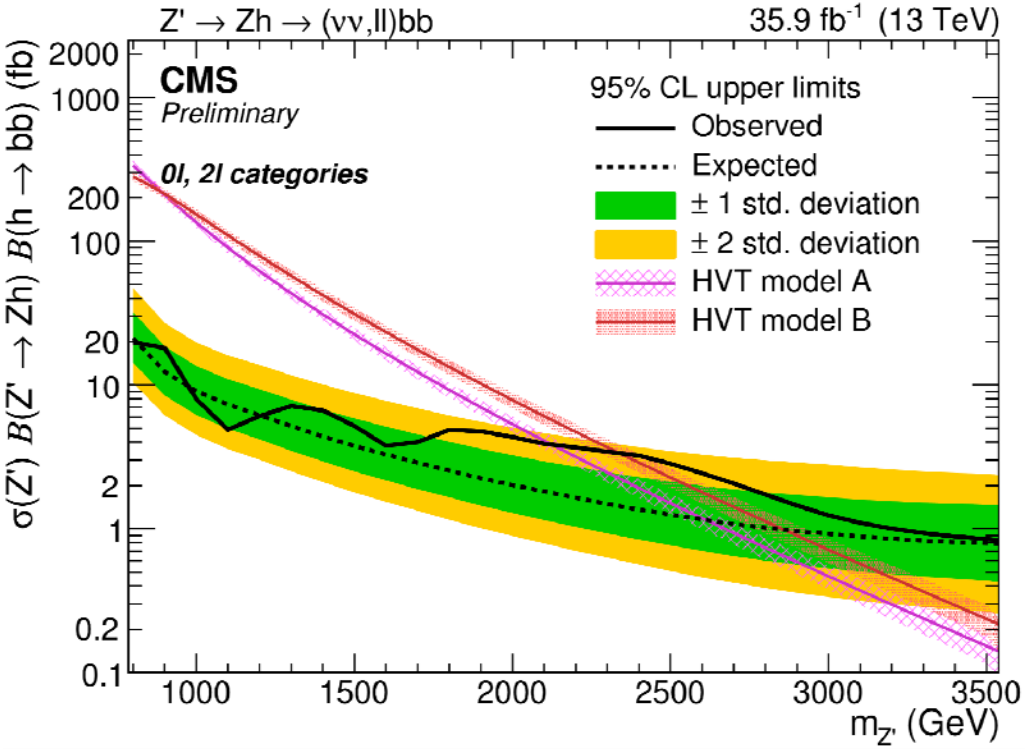
- Signature: 0lepton+met>250 OR 1lepton+met>80 OR 2leptons+Zpt>200. And subjets from AK8 jet with 1or2 b-tags and 105-135GeV mass.
- Background: Case dependent, but W/Z+jets dominant, tt (esp for WH). Prompt backgrounds from ttbar MC scaled in control region. Data-driven background model assuming smooth njet spectrum, also verified in control regions

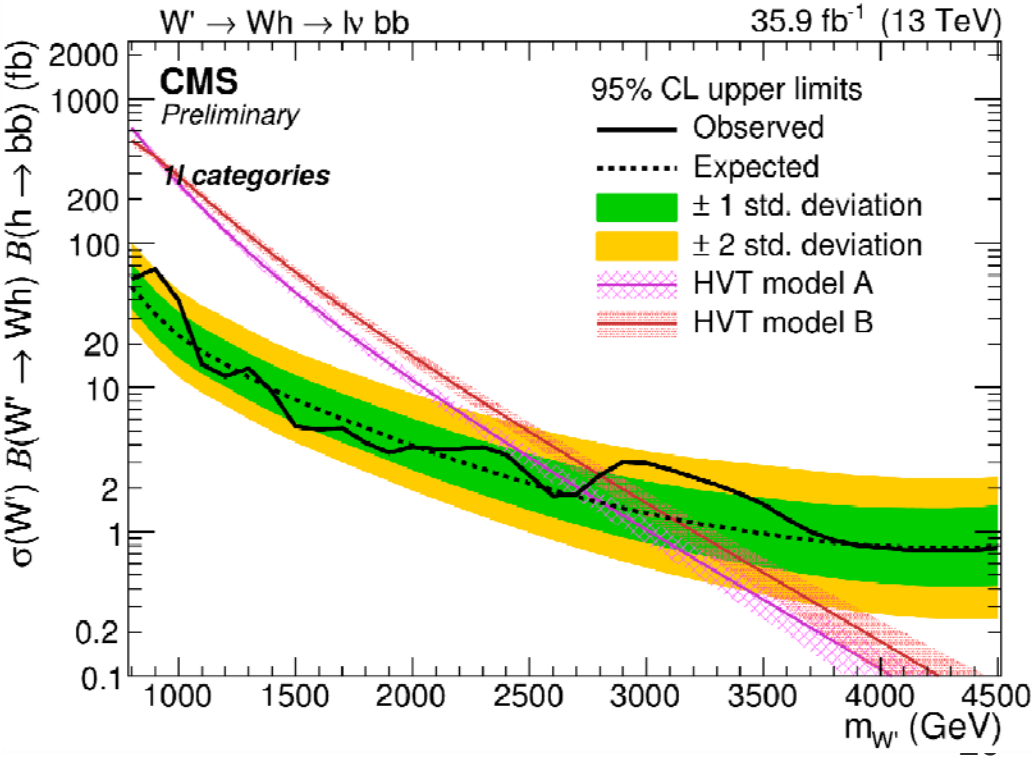




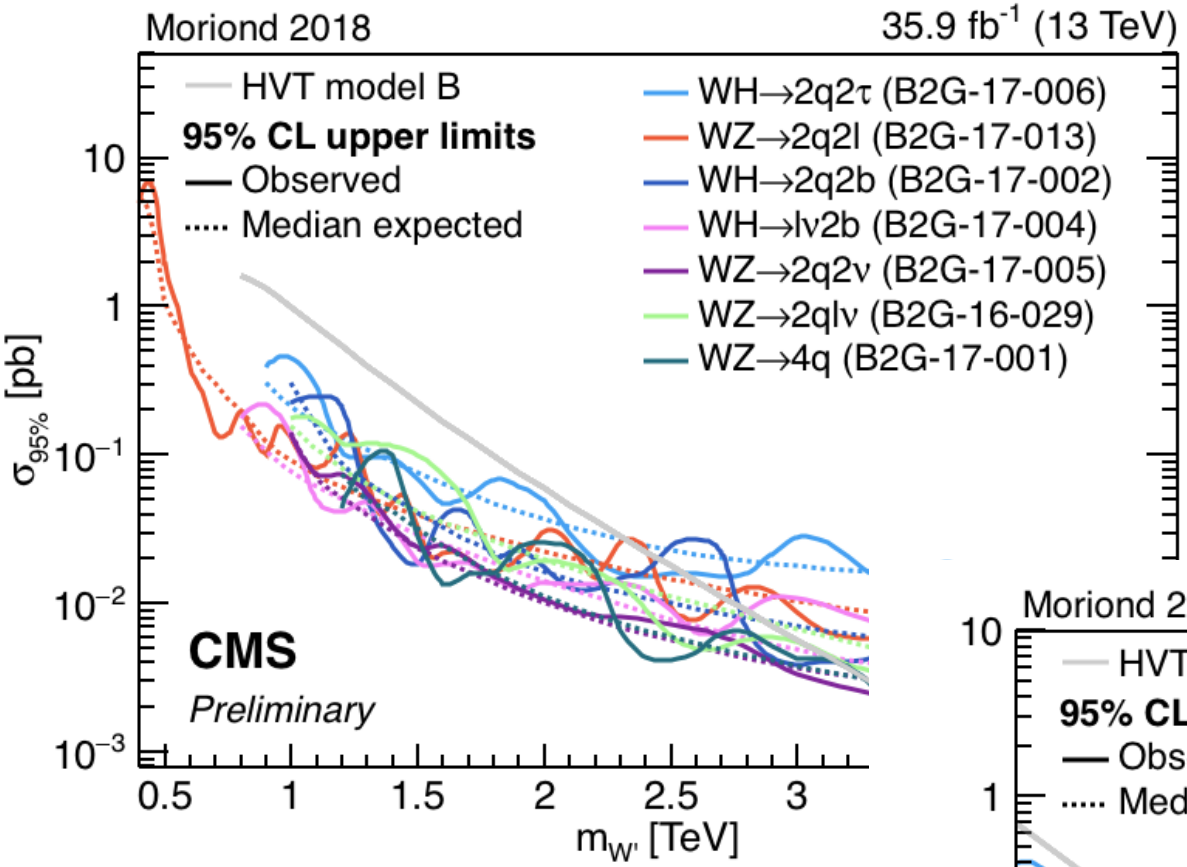
lnu,nunu,ll (W/Z) + bb(H) resonance

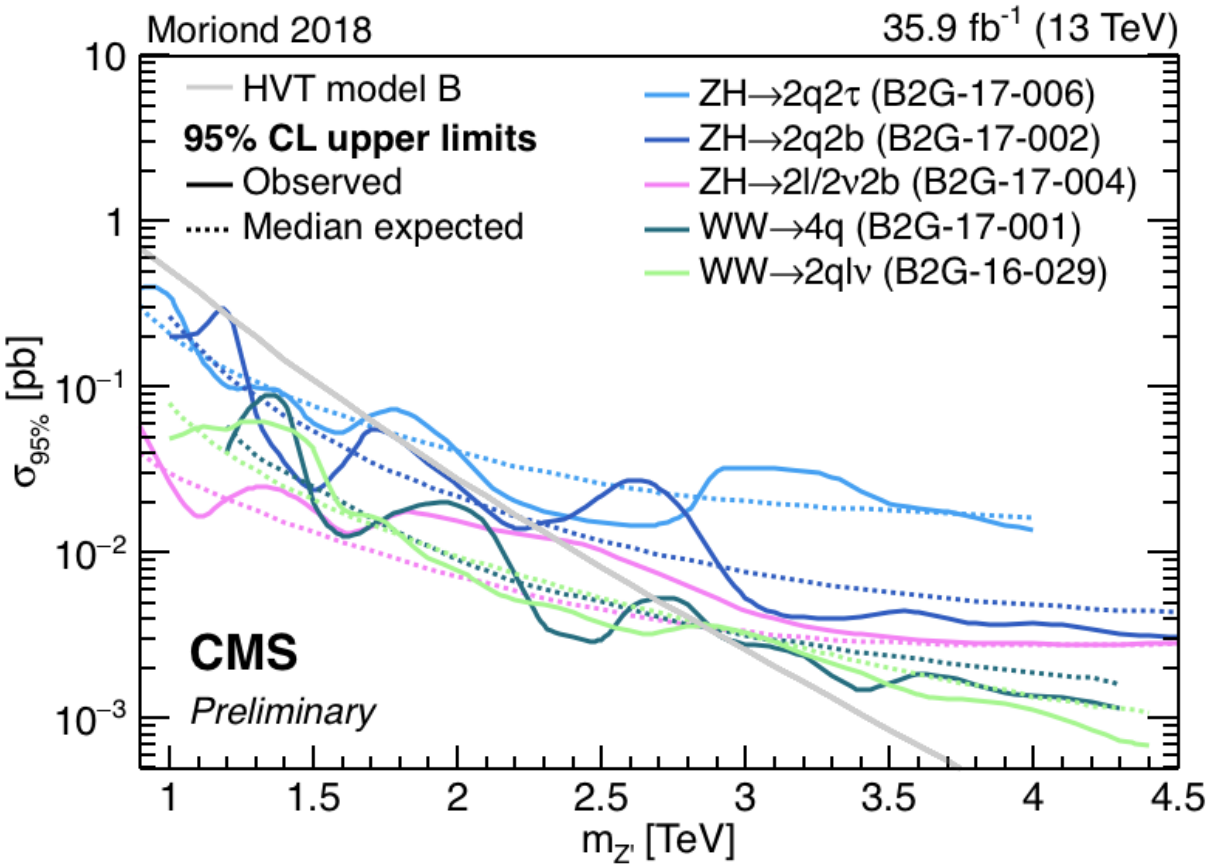
CMS-B2G-17-004



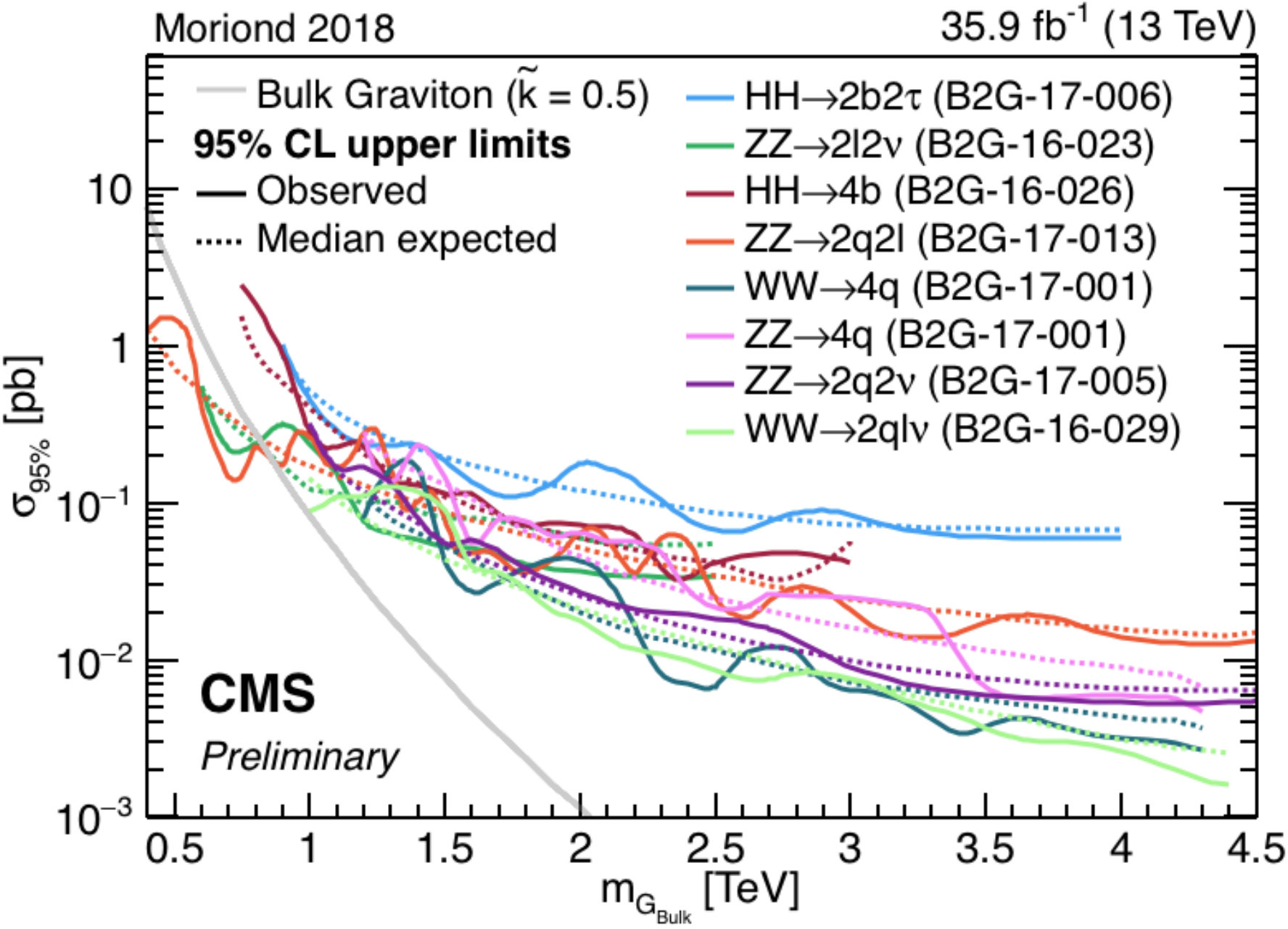


Combination plots: W' and Z'





Combination: Bulk Graviton



• Vector-Like Quarks (VLQ)

searches formerly known as the 4th generation

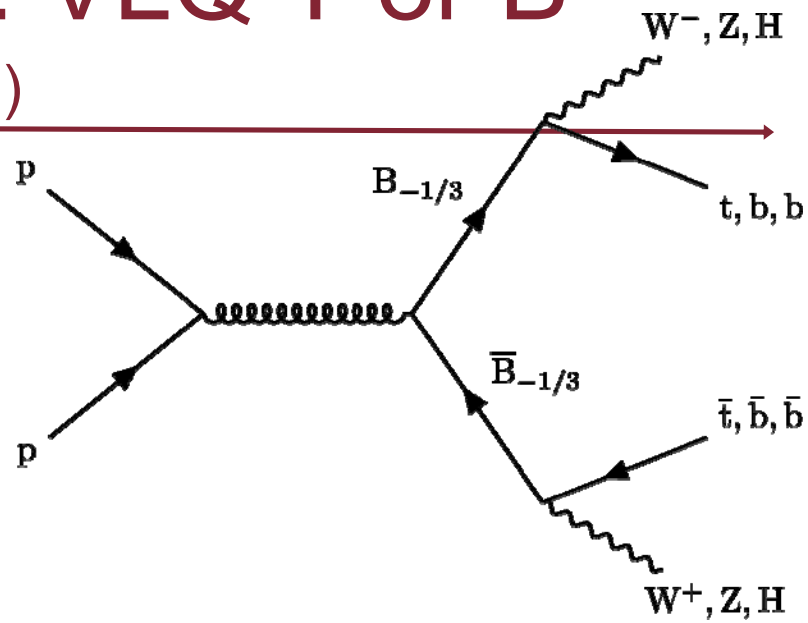
pair-produced → → singly-produced
(as mass keeps going up)

Leptons+boosted W/H: VLQ T or B

PAIR

(CMS B2G-17-011)

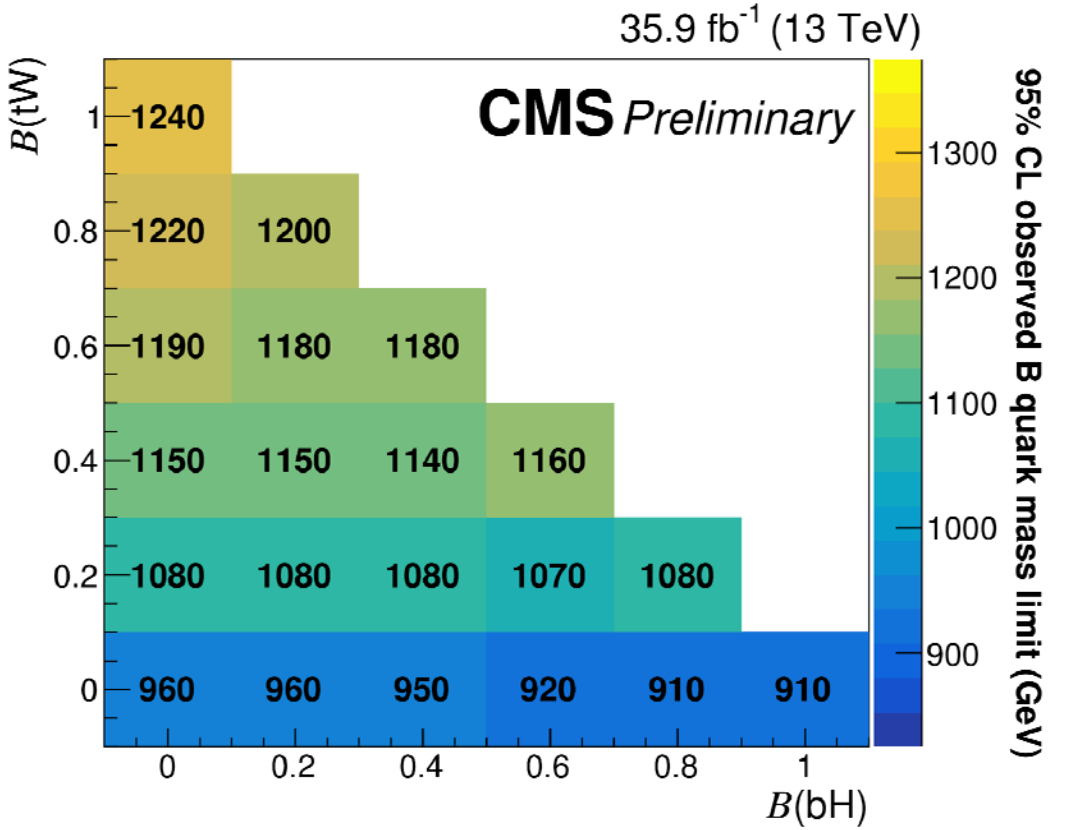
- Signature: 1 lepton, 2SS leptons, 3 or more leptons
- Substructure: boosted W or H
- Backgrounds: ttbar and W/Z/WZ
- Physics/Models: ***Pair-produced*** VLQ quarks



Sample	0 H, 0 W, 1 b	0 H, 0 W, 2 b	0 H, 0 W, ≥ 3 b
$T\bar{T}$ (1.0 TeV)	21.5 ± 1.2	12.87 ± 0.74	4.41 ± 0.29
$T\bar{T}$ (1.2 TeV)	6.48 ± 0.36	3.68 ± 0.21	1.22 ± 0.08
TOP	2030 ± 440	1070 ± 240	172 ± 39
EW	720 ± 120	94 ± 16	7.2 ± 1.4
QCD	117 ± 31	18.1 ± 9.7	5.9 ± 5.2
Total Bkg	2870 ± 470	1180 ± 240	185 ± 40
Data	2598	1054	182
Data/Bkg	0.90 ± 0.15	0.89 ± 0.18	0.98 ± 0.22

Sample	0 H, ≥ 1 W, 1 b	0 H, ≥ 1 W, 2 b	0 H, ≥ 1 W, ≥ 3 b
$T\bar{T}$ (1.0 TeV)	27.7 ± 1.4	13.91 ± 0.73	3.75 ± 0.22
$T\bar{T}$ (1.2 TeV)	8.22 ± 0.43	3.84 ± 0.20	0.92 ± 0.06
TOP	1410 ± 300	660 ± 140	95 ± 22
EW	291 ± 47	38.1 ± 7.6	2.68 ± 0.58
QCD	36 ± 13	6.6 ± 6.5	< 1
Total Bkg	1730 ± 310	700 ± 140	98 ± 22
Data	1589	594	96
Data/Bkg	0.92 ± 0.16	0.84 ± 0.17	0.98 ± 0.24

Sample	H1b, ≥ 0 W, ≥ 1 b	H2b, ≥ 0 W, ≥ 1 b
$T\bar{T}$ (1.0 TeV)	36.7 ± 2.0	7.92 ± 0.59
$T\bar{T}$ (1.2 TeV)	11.18 ± 0.60	2.39 ± 0.19
TOP	1520 ± 330	49 ± 12
EW	46.9 ± 8.1	4.2 ± 1.5
QCD	14.4 ± 6.3	< 1
Total Bkg	1570 ± 330	53 ± 12
Data	1488	44
Data/Bkg	0.95 ± 0.20	0.83 ± 0.22

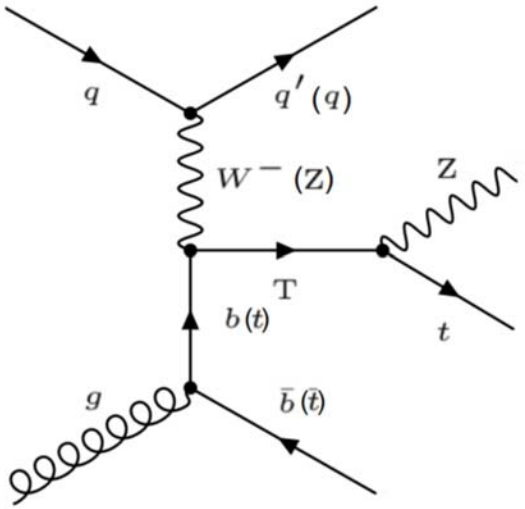


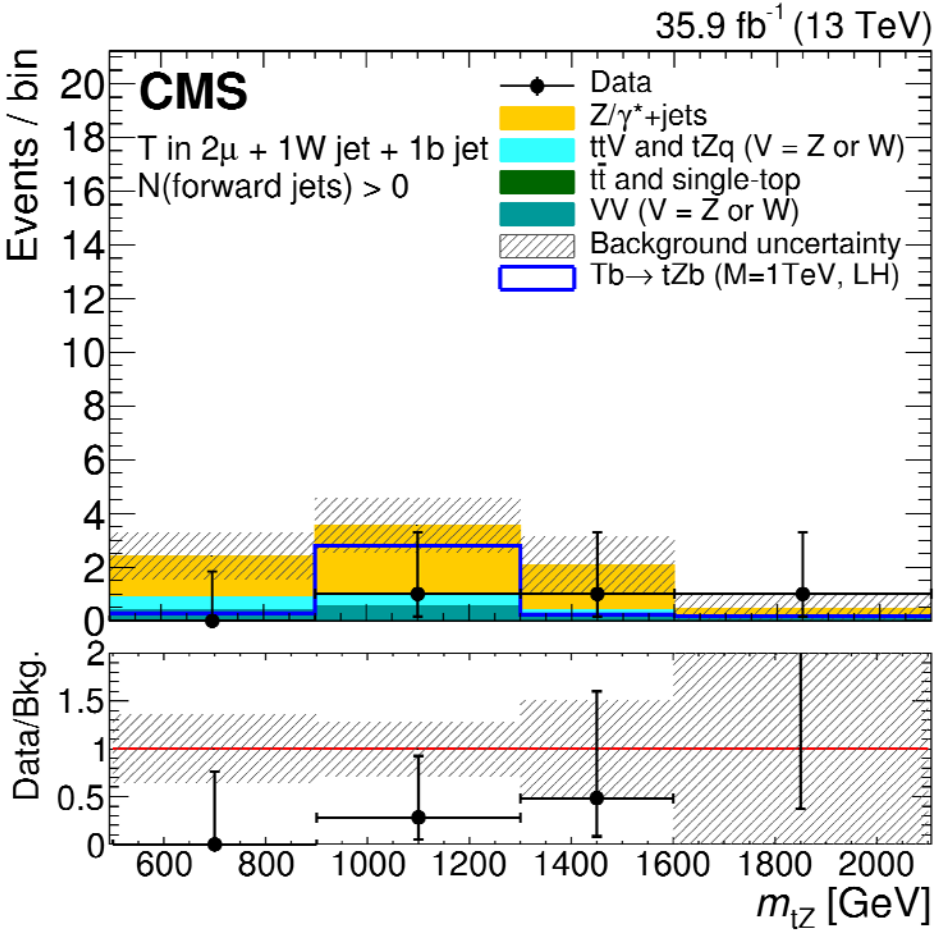
On-Z dileptons+hadronic top+forward jet: VLQ T(→tZ)

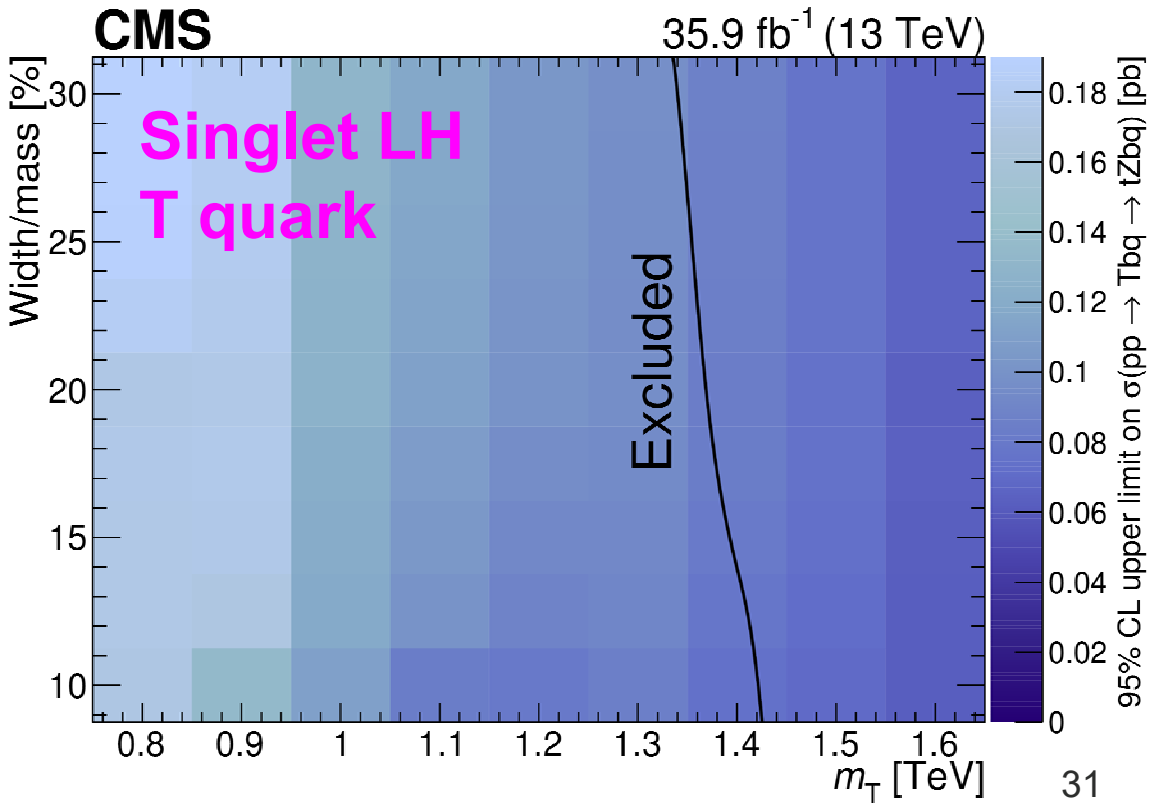
(CMS arXiv:1708.01062)(B2G-17-007)

SINGLE

- Signature: ee/μμ on Z, hadronic top, optional forward jet
- Substructure: fully/partially merged and resolved top categories
- Backgrounds: Z+jets,ttZ
- Physics/Models: ***Singly-produced*** VLQ T quarks



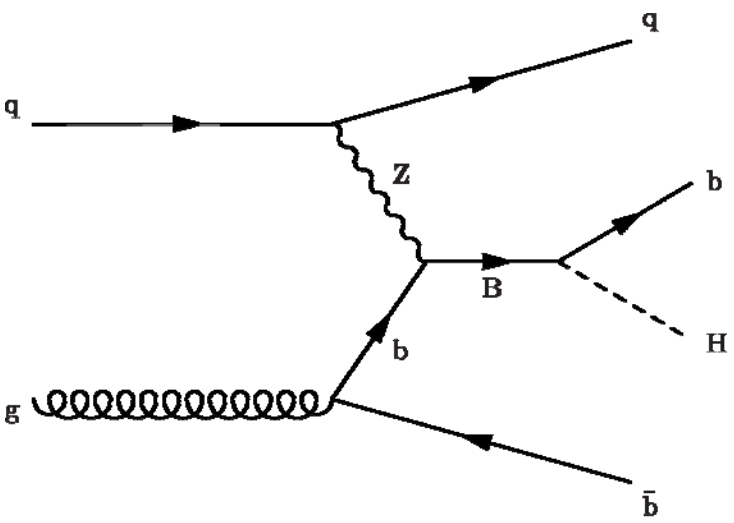


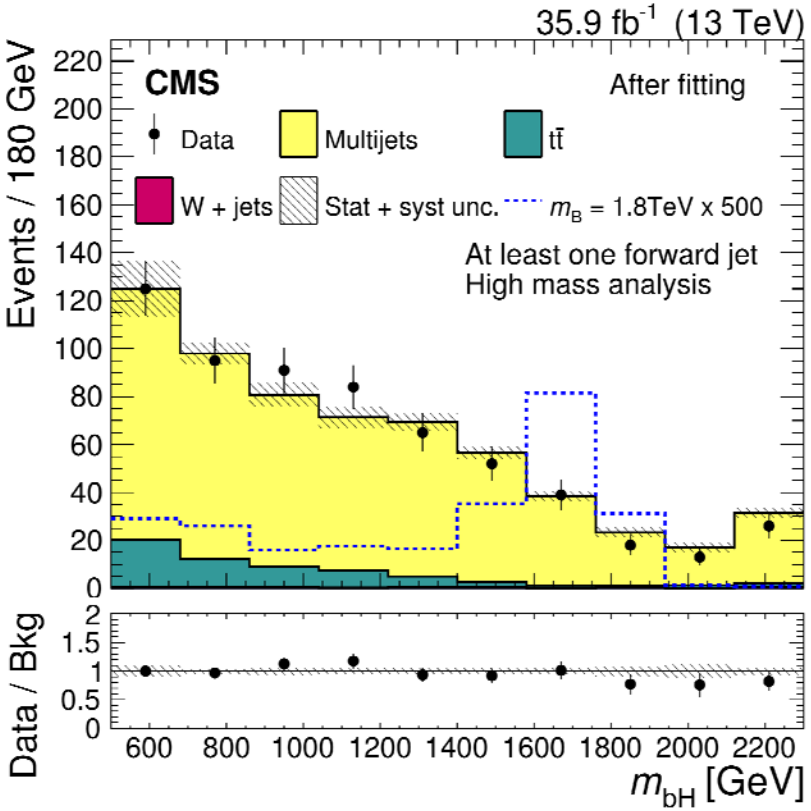


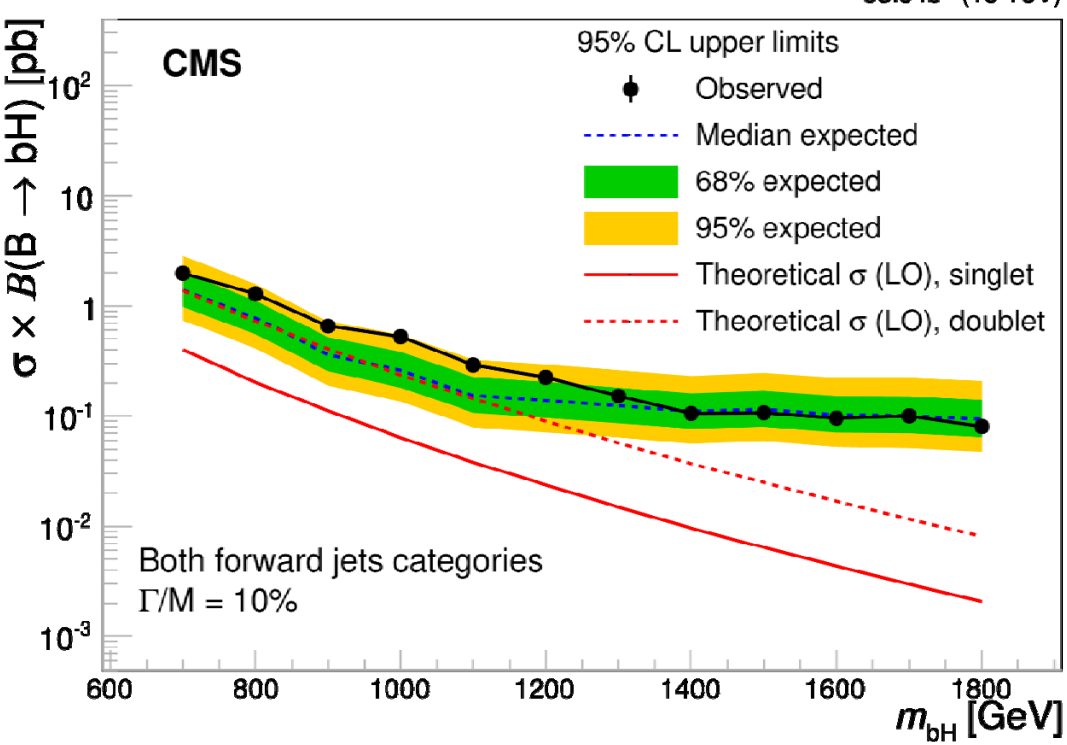
(b(bb))+forward jet: VLQ B(→bh, h→bb)
(CMS arXiv:1802.01486)(B2G-17-009)

SINGLE

- Signature: 3+ jets, 1+ bjets, “higgs” jet (105<mJ<135), ~1TeV HT, 0+ forward jet, resonant bh.
- Substructure: Large higgs jet
- Backgrounds: QCD multi(b)jet, higgs mJ vs # btags ABCD
- Physics/Models: ***Singly-produced*** VLQ B quarks







“Exotic” Higgs

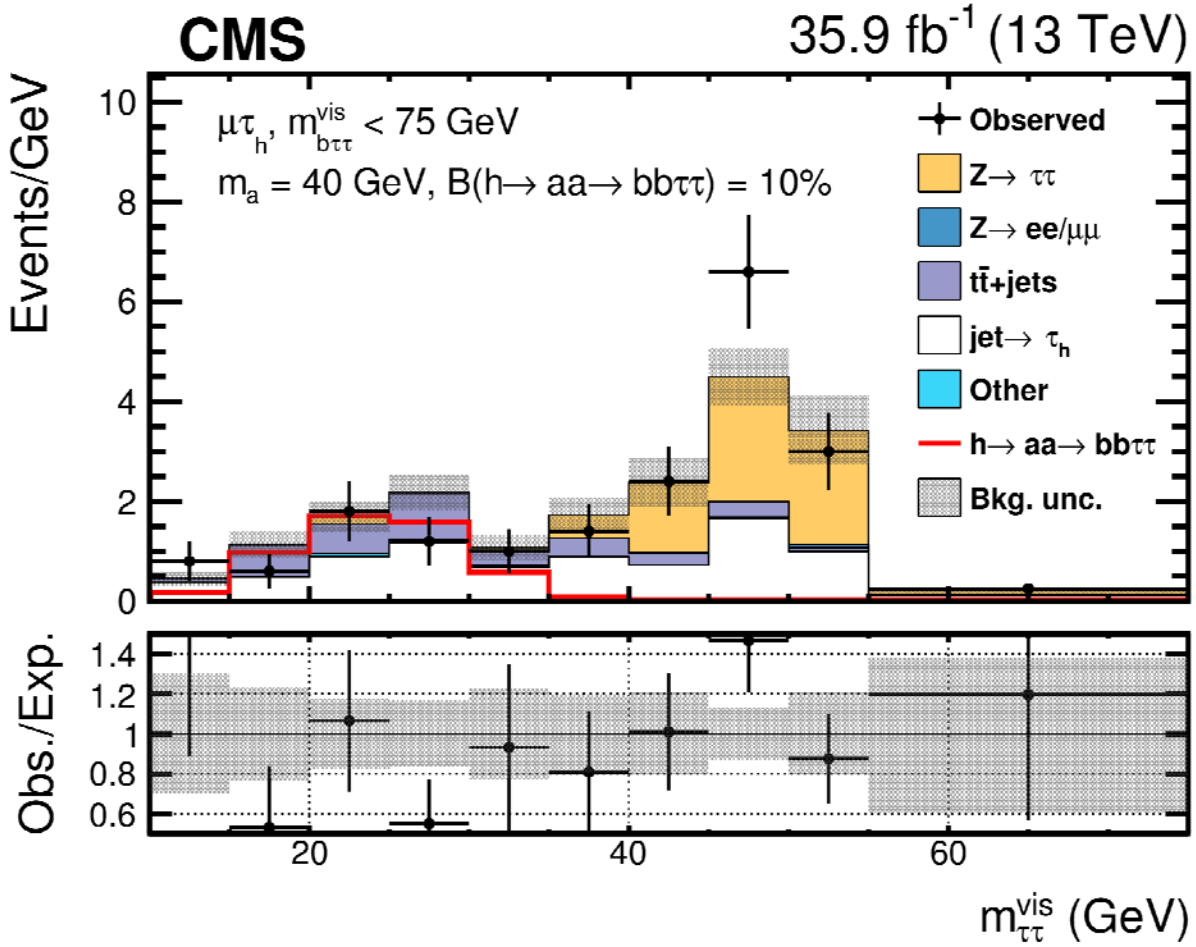
- Pseudoscalar higgs: h→ aa → (bb/μμ)(ττ)
- higgs triplet: $\Phi^{++}\Phi^{--}$,$\Phi^{++}\Phi^{-}$ →4,3 leptons

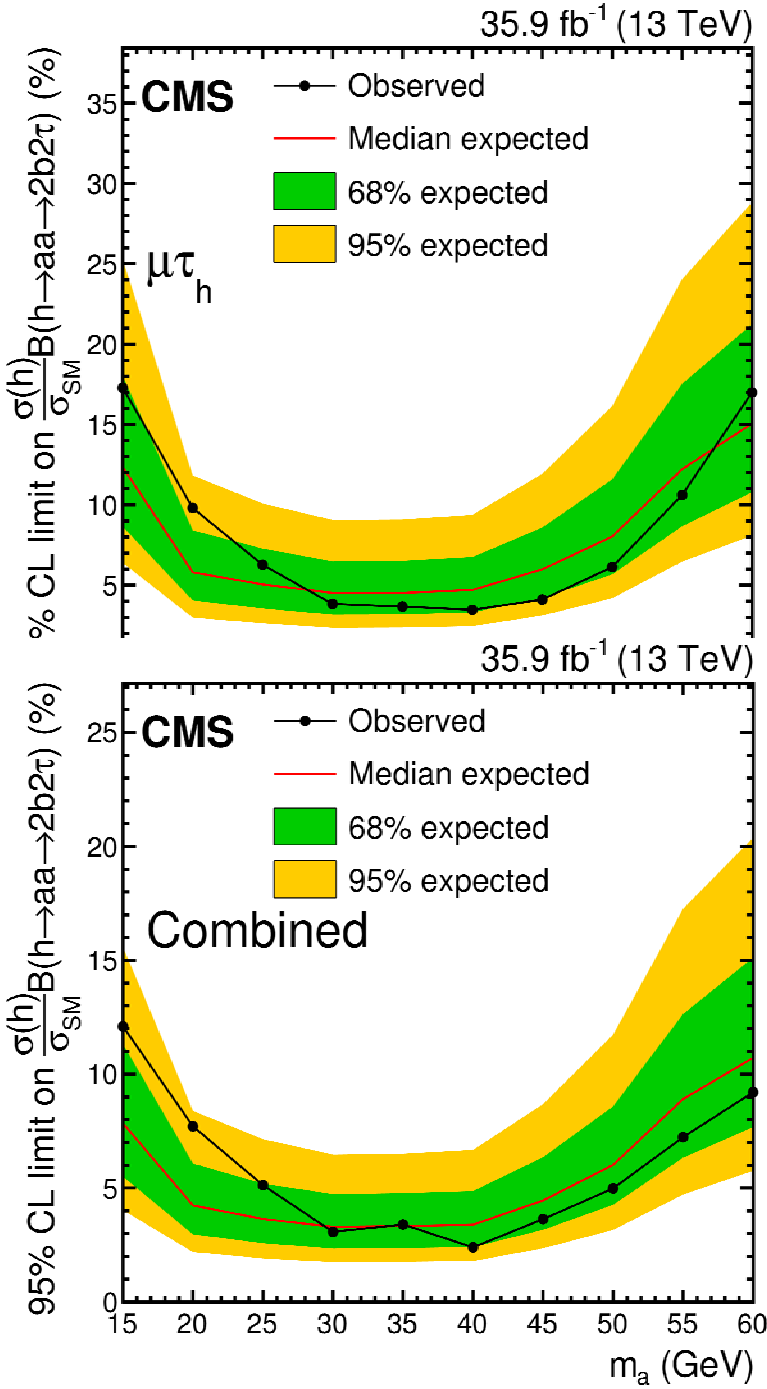
$h \rightarrow a_1 a_2 \rightarrow bb(\tau\tau) \rightarrow b(e\mu), b(e\tau_h), b(\mu\tau_h)$

(HIG-17-024)

- Signature: "resonant" $b\tau\tau$. Sub-Z mass range ➔only 1 b-jet, m_{vis} for τ (make lemonade from lemons, a_1a_2 vs aa)
- Background: Z (for $e\mu$ channel),

  for τ_h: pencil jets faking τ_h, ttbar





h→aa→(μμ)(ττ)→(μμ)(eμ/eτ$_h$/μτ$_h$/τ$_h$τ$_h$)

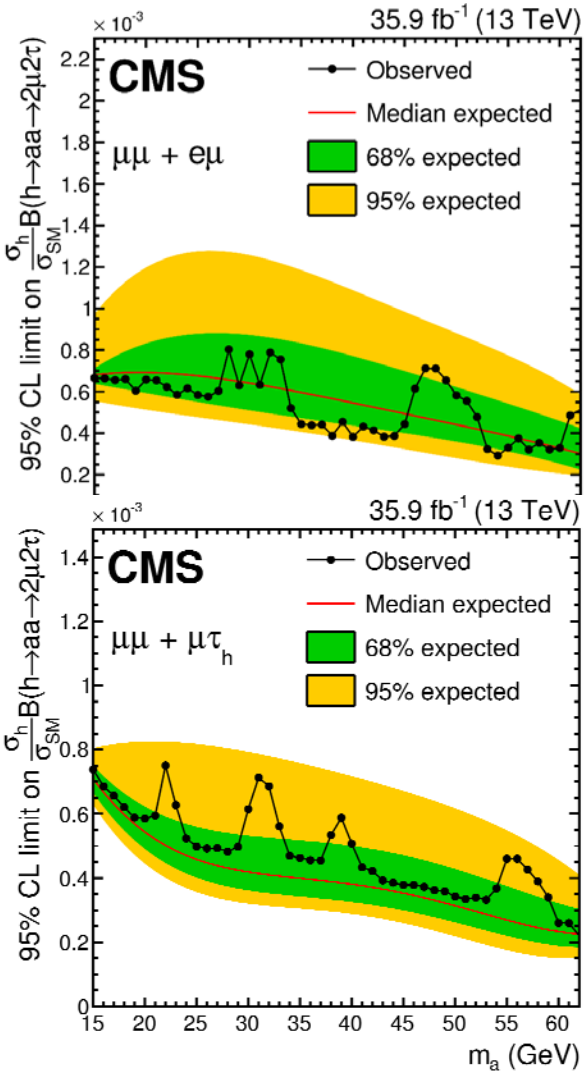
(HIG-17-029)

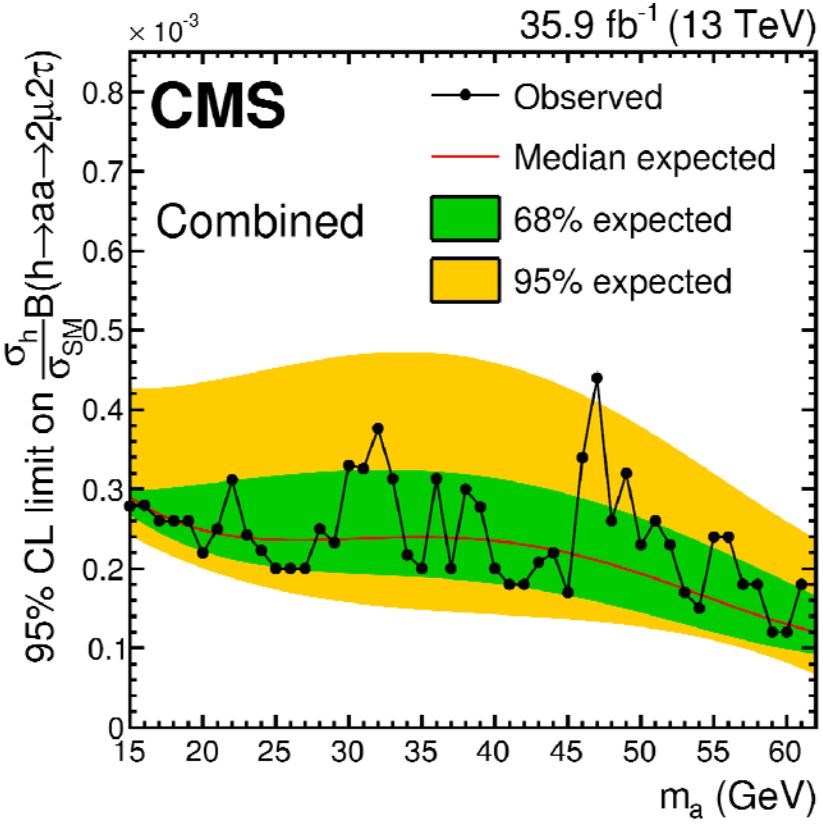
- Signature: at least 2 muons.

  (h→aa→4τ is a volunteer signal)

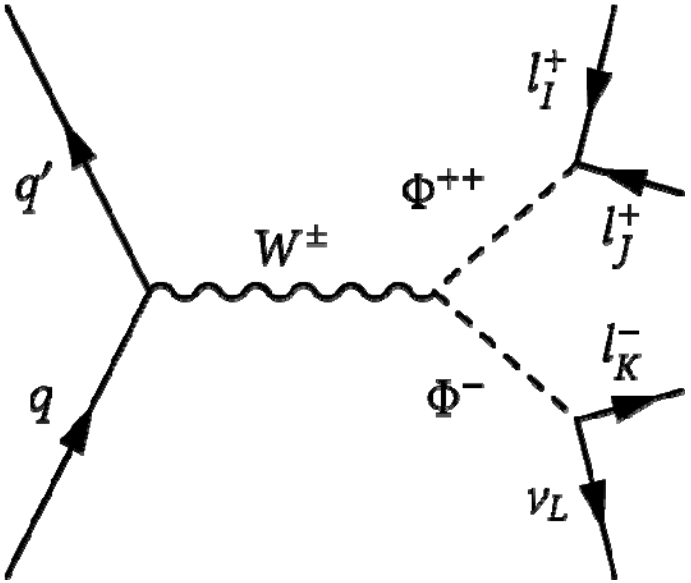
- Background: ZZ→4l, pencil jets

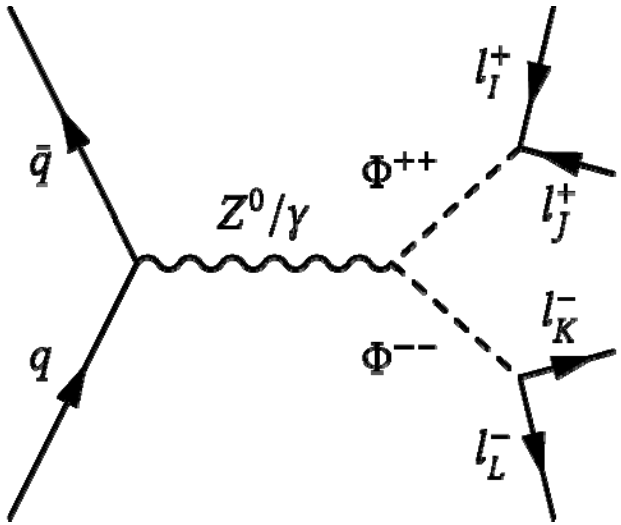
	$\mu\mu + e\mu$	$\mu\mu + e\tau_h$	$\mu\mu + \mu\tau_h$	$\mu\mu + \tau_h\tau_h$
$ZZ \to 4\ell$	1.5 ± 0.2	0.5 ± 0.1	1.2 ± 0.2	0.03 ± 0.01
Misidentified τ	13.2 ± 5.5	9.7 ± 2.5	4.0 ± 1.2	1.2 ± 0.5
$h \to aa \to 2\mu 2\tau$, $m_a = 20$ GeV	0.39	0.25	0.47	0.10
$h \to aa \to 4\tau$, $m_a = 20$ GeV	0.37	0.04	0.24	0.01
$h \to aa \to 2\mu 2\tau$, $m_a = 40$ GeV	0.57	0.28	0.68	0.14
$h \to aa \to 4\tau$, $m_a = 40$ GeV	0.68	0.09	0.48	0.02
$h \to aa \to 2\mu 2\tau$, $m_a = 60$ GeV	0.94	0.85	1.18	0.52
$h \to aa \to 4\tau$, $m_a = 60$ GeV	1.27	0.20	0.93	0.05
Observed	17	10	6	1





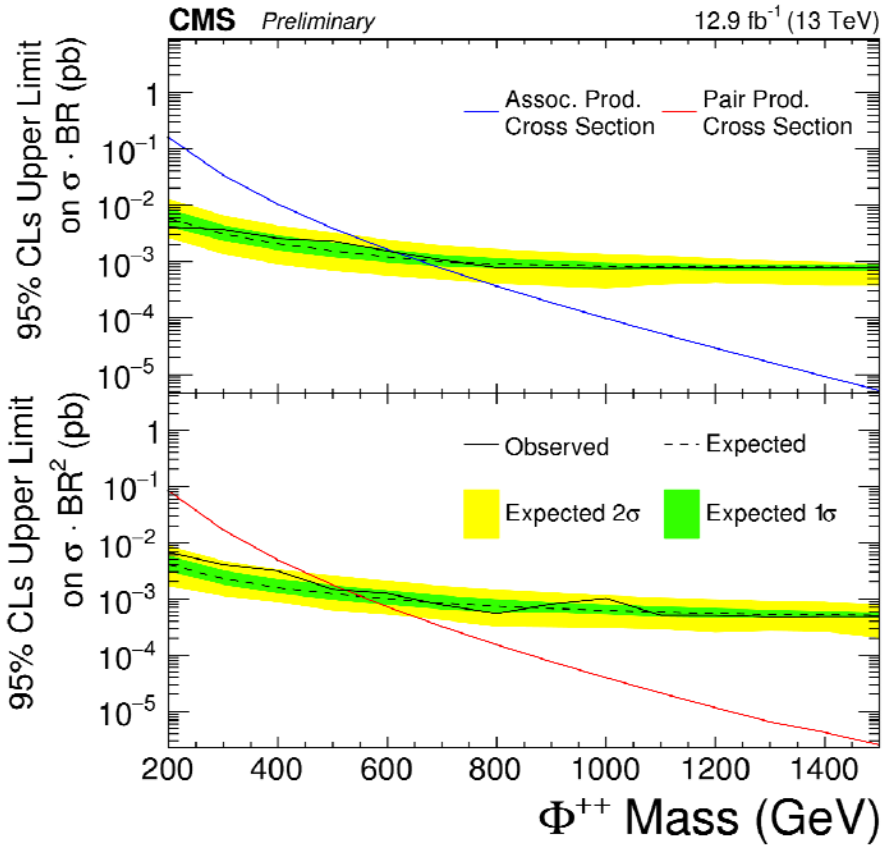
Charged Higgs: W/Z → : $\Phi^{++}\Phi^{--}$,$\Phi^{++}\Phi^{-}$ → multileptons (HIG-16-036)





- Signature: 3 or 4 leptons (*all* τ_h allowed!). Same-sign seclusion utilized.
- Background: 3l modes: Z/WZ unless τ_h is present, in which case, pencil jets dominate.

4l modes: ZZ as long as there are at least three light leptons. Otherwise….



- Neutrinos at LHC

(eh?)

Seesaw (leptonic searches)

Thx:
Halil Saka

With $M_{Majorana} >> M_{Dirac}$,

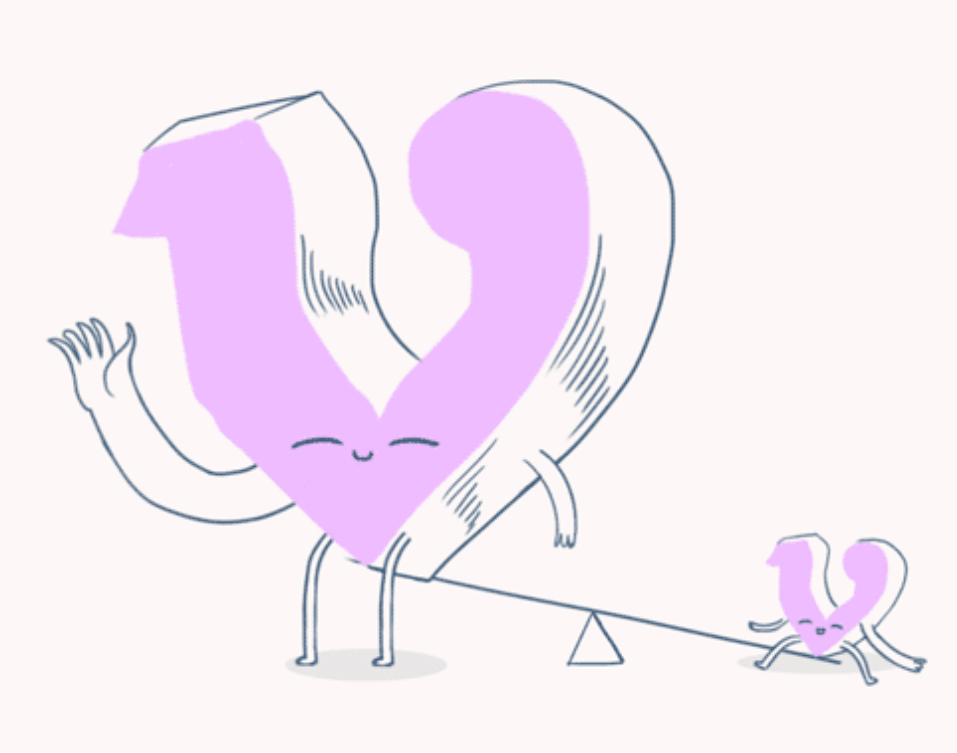
- $M_{heavy} \sim M_{Majorana}$
- $M_{light} \sim M_{Dirac} * (M_{Dirac} / M_{Majorana})$

Type-I ν_R SU(2) singlet fermion
Type-II Δ^{0+-} SU(2) triplet scalar
Type-III Σ^{0+-} SU(2) triplet fermion

Type III processes:

$\Sigma^+ \rightarrow W^+\nu$ OR Zl^+ OR Hl^+

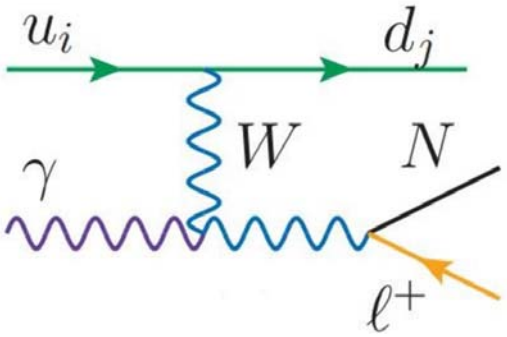
$\Sigma^0 \rightarrow Wl^+$ OR $Z\nu$ OR $H\nu$

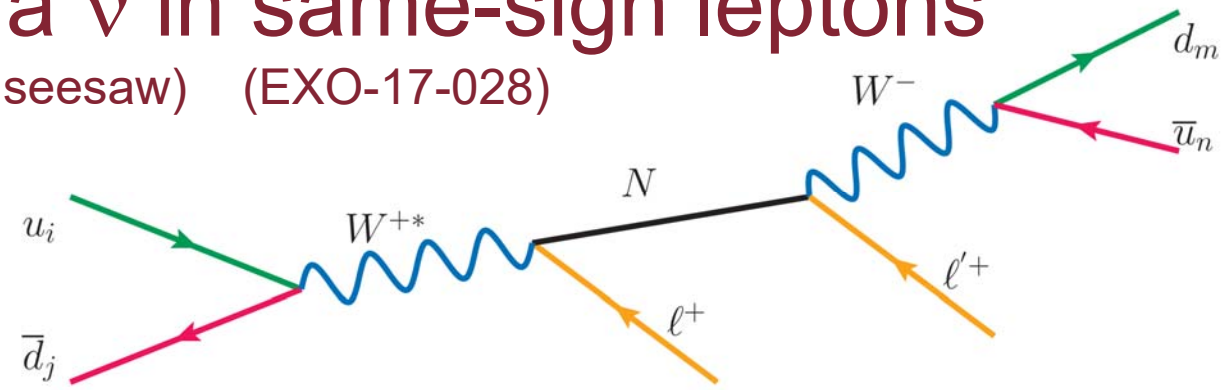


Credit: Sandbox Studio, Chicago & Ana Kova

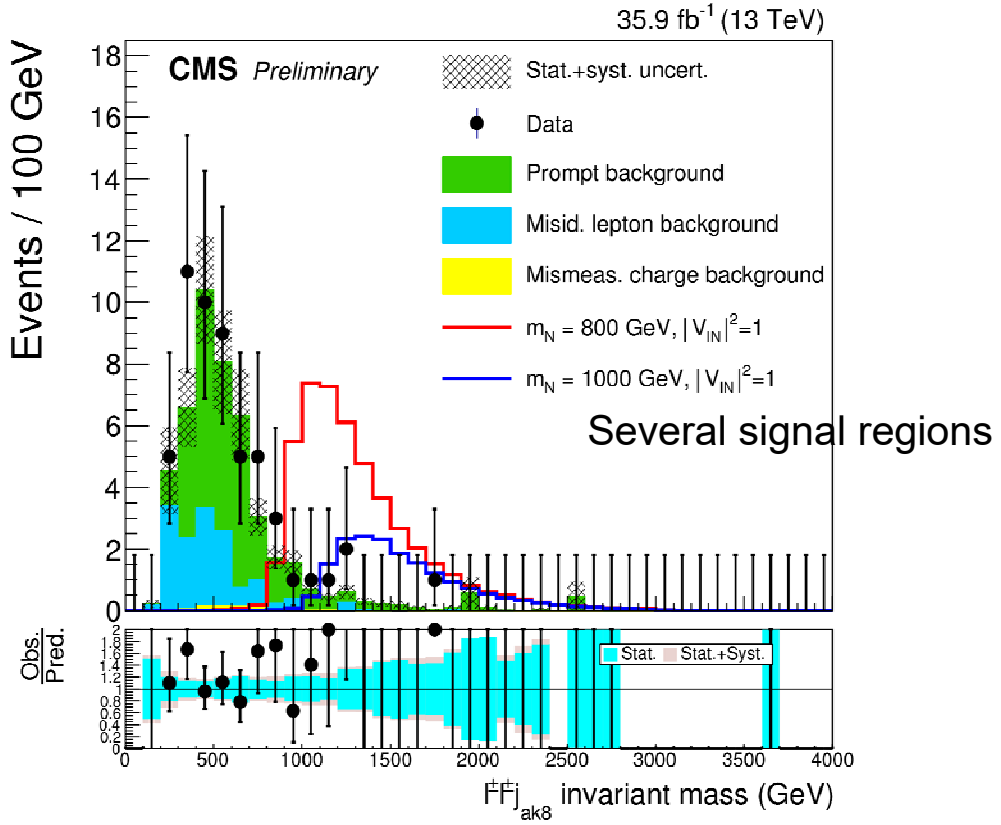
Heavy Majorana ν in same-sign leptons

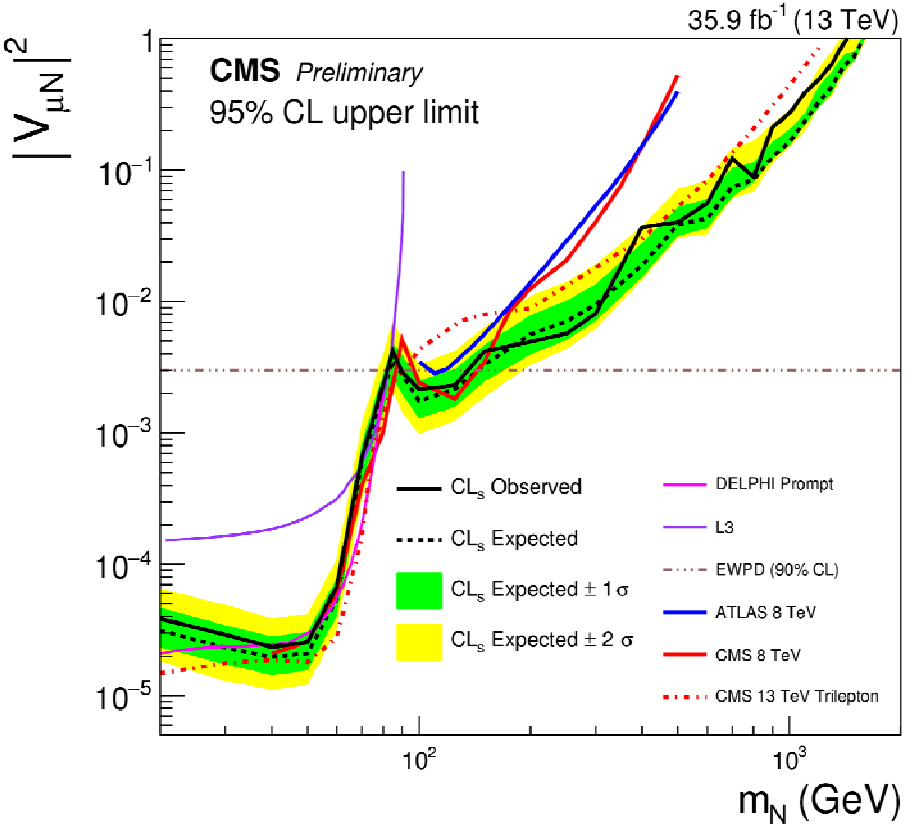
(Type-I seesaw) (EXO-17-028)





- Signature: Same-sign ee/μμ + j. (Majorana →SS=OS). ~resonant signal Background: prompt, mis-id including e charge flip





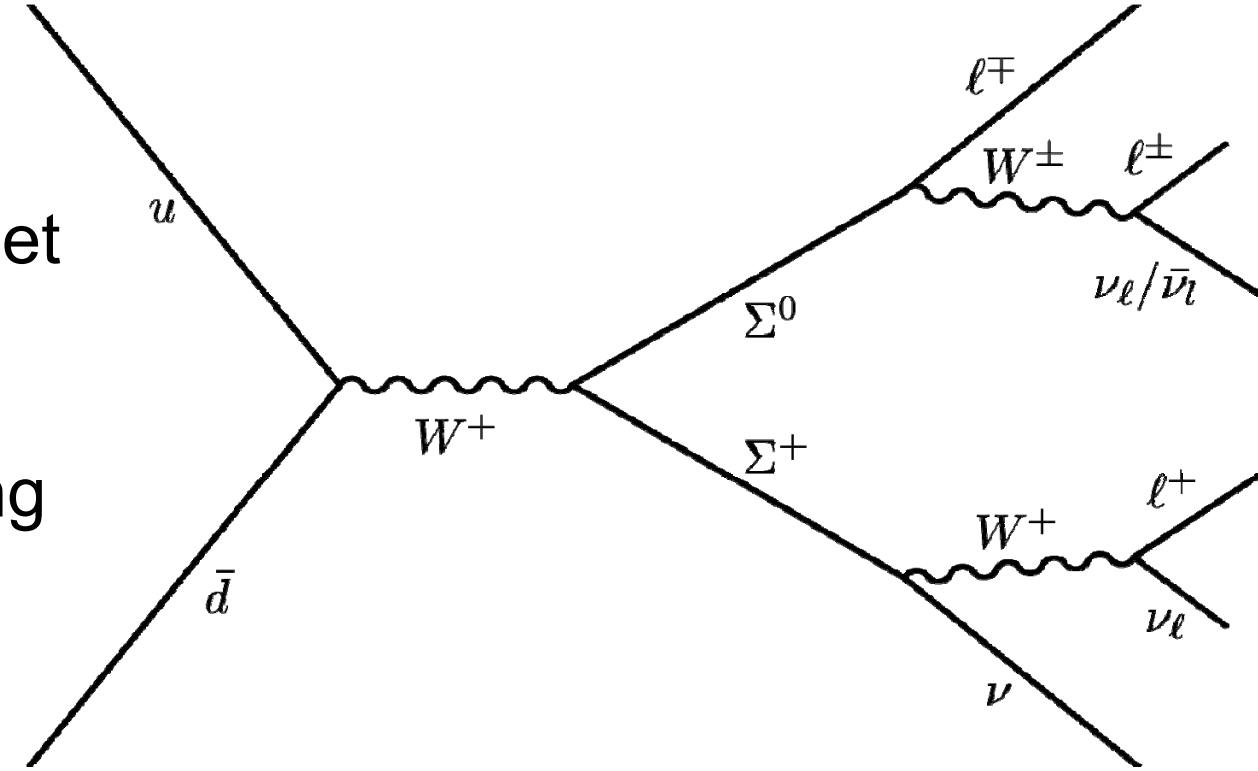
Neutrinos @LHC on a seesaw: Multileptons

CMS arXiv:1708.07962 (EXO-17-006)

Type-III seesaw

Pair produced heavy Σ triplet
→multileptons

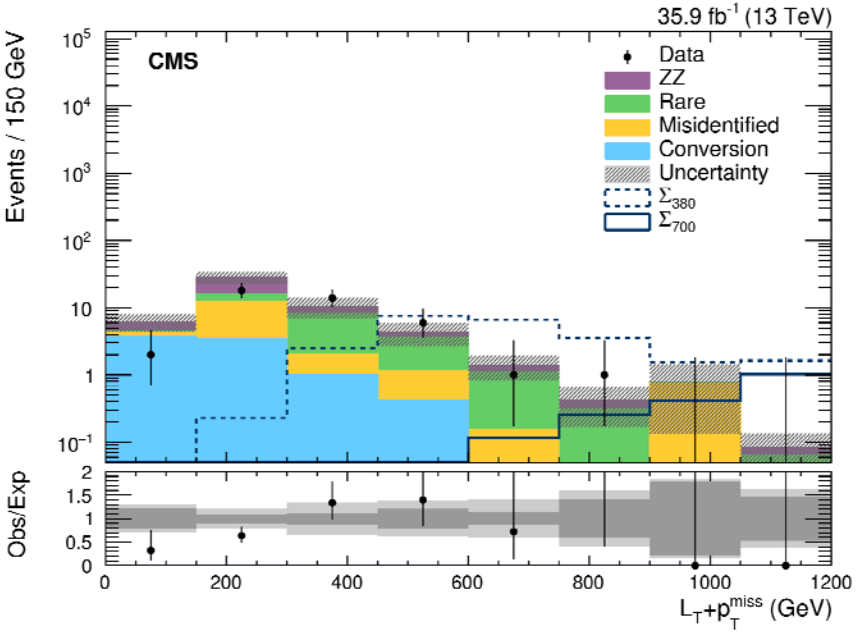
Total 27 processes including higgs in the final state



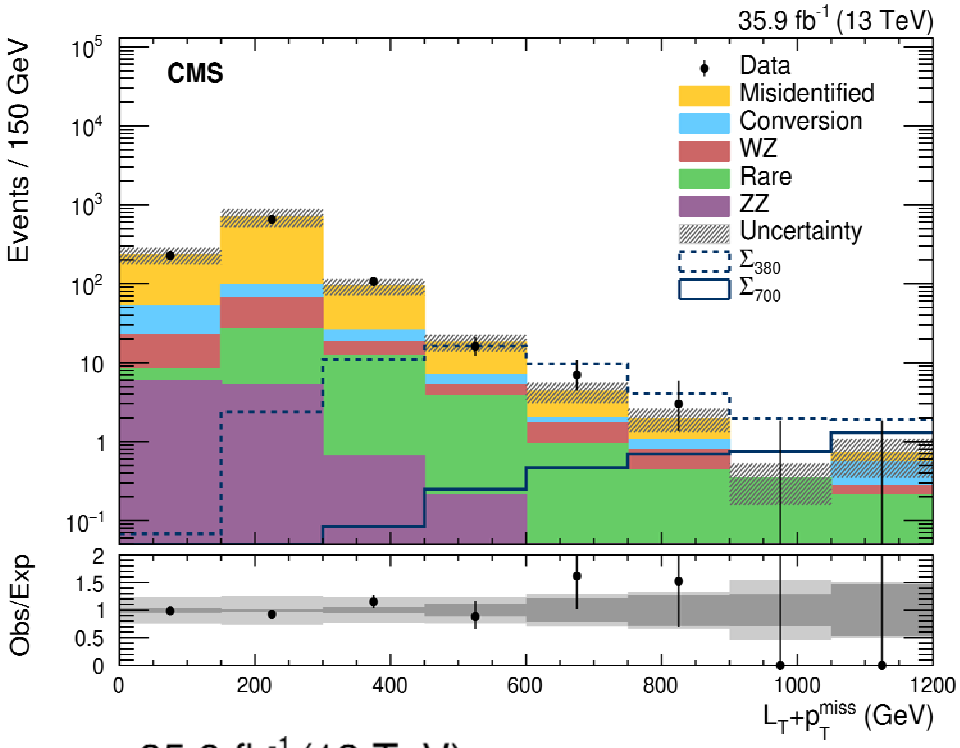
- Signature: 3 or more e's and mu's, lead pt >25GeV, bins of flavor and kinematics (on/off-Z etc). Look for excess in LT+MET bins. (LT=Lepton pt scalar sum)
- Background: Z+jets, ttbar data-driven matrix method with tight/loose rates from low-MET on-Z region. (Prompt) WZ, ZZ - normalized MC.

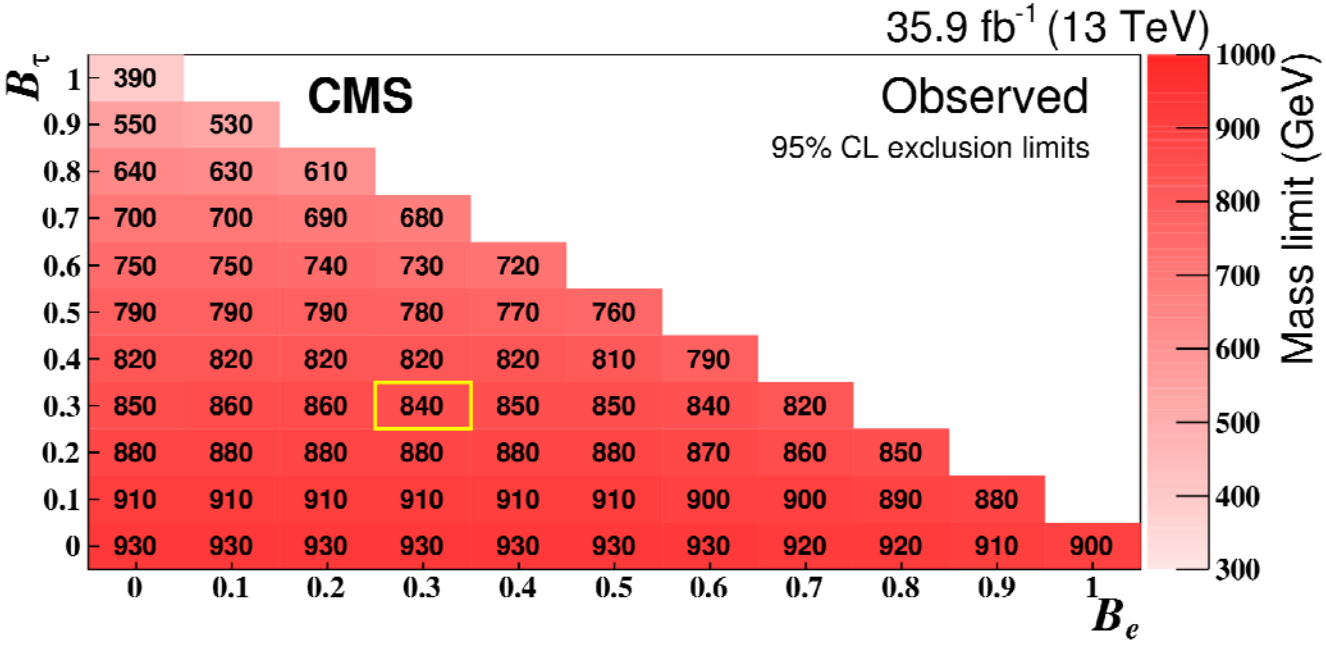
Neutrions@LHC- Multileptons Seesaw (contd)

4L, OSSF1



3L, OSSF0

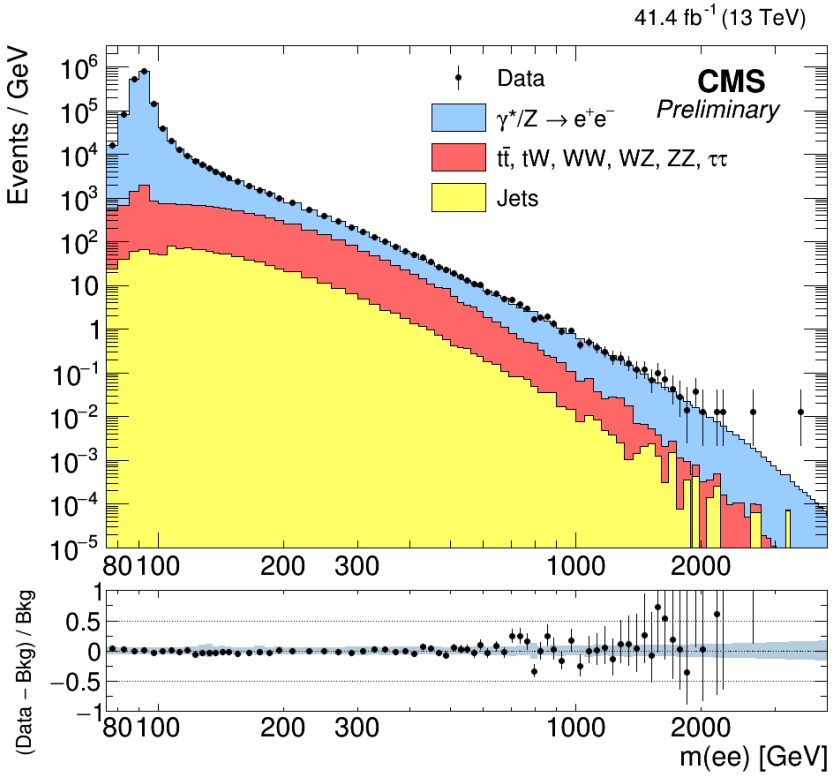




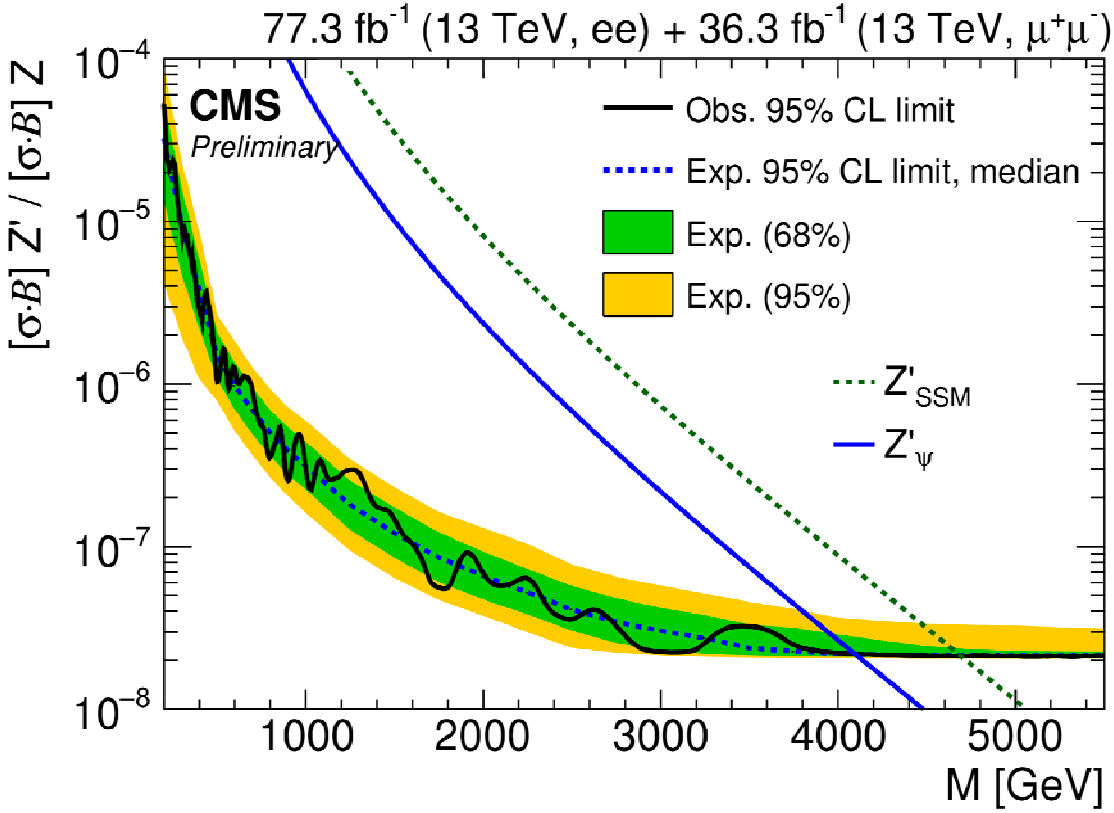
- Latest and greatest (New data)

High Mass Resonant Dielectrons (36+41 fb^{-1})

(CMS EXO-18-006)



Pt>35GeV



Z'ψ – GUT E6

So, where do we stand?

Experimental particle physicists vs. Standard Model

"I lay all this while, as the reader may believe, in great uneasiness."—*Page* 8.

LHC vs BSM Models

BSM models

LHC

Slide Credit: Stephen Martin

BSM possibilities: ways to go

New physics?

Concluding remarks

- LHC in the midst of a massive data onslaught. New ideas keep coming online as well:
  - Higgs in the final state: t', b', t→ch; in SUSY: electroweak Higgs, natural higgsino.
  - Boosted final states and substructure.
  - long lived objects.
  - generalized recoil (Dark Matter).
  - VBF..
- If Nature is kind, see you at

  "Slepton-Photon" 2019.