Beyond Standard Model: Exotic Searches @LHC

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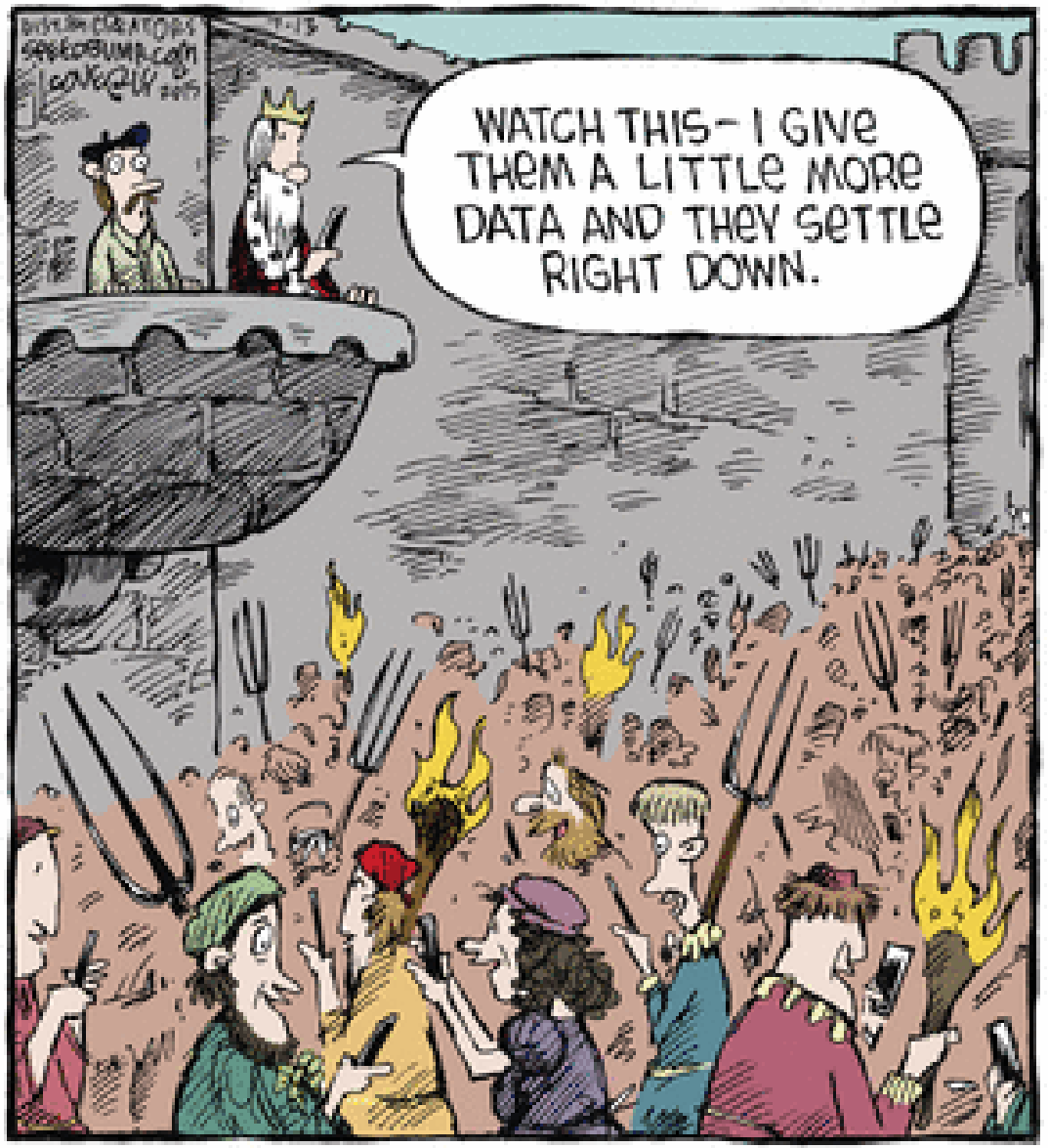
Exotic Searches Backdrop: the Machine

- LHC has been running well!

- ~35/pb to ~35/fb in a few years.
- So what have we learnt?

(Besides that new physics is not hadronic, so we can't find it by measuring how hot the beam pipe is.)



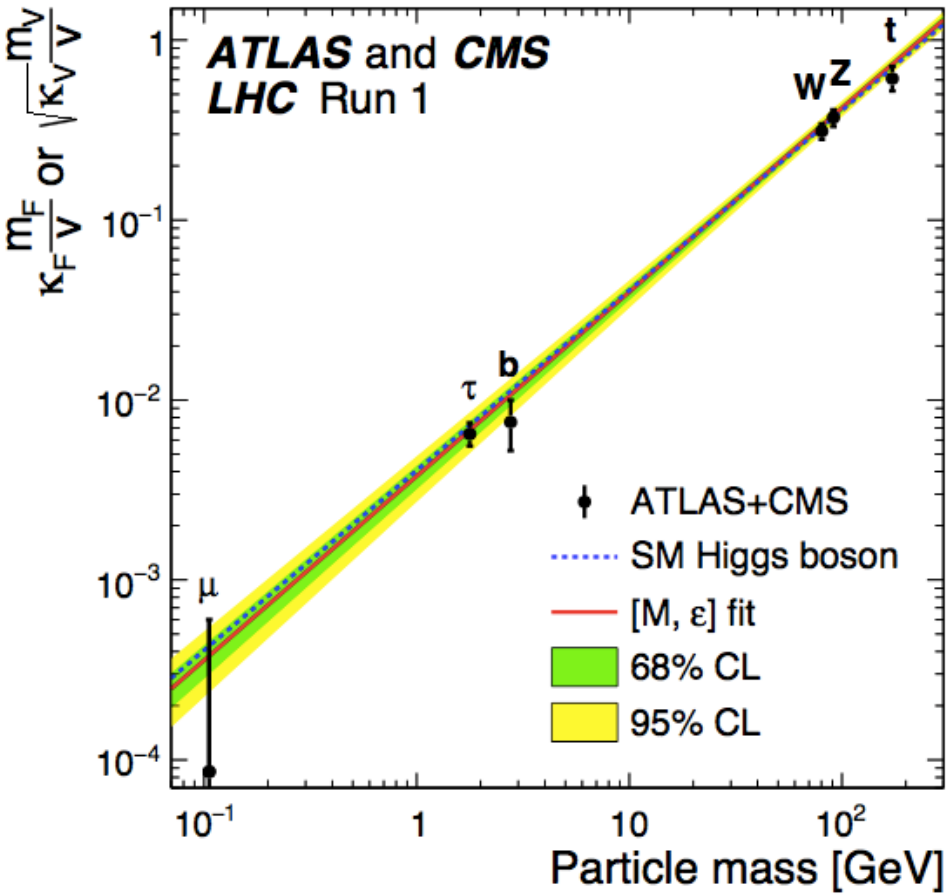
Exotic Searches Backdrop: the Higgs

- Higgs boson is a well-behaved child of the Standard Model.
  - It is 0^+
  - Has the right couplings.

- But is it the only child?

  (*a* Higgs or *the* Higgs?)

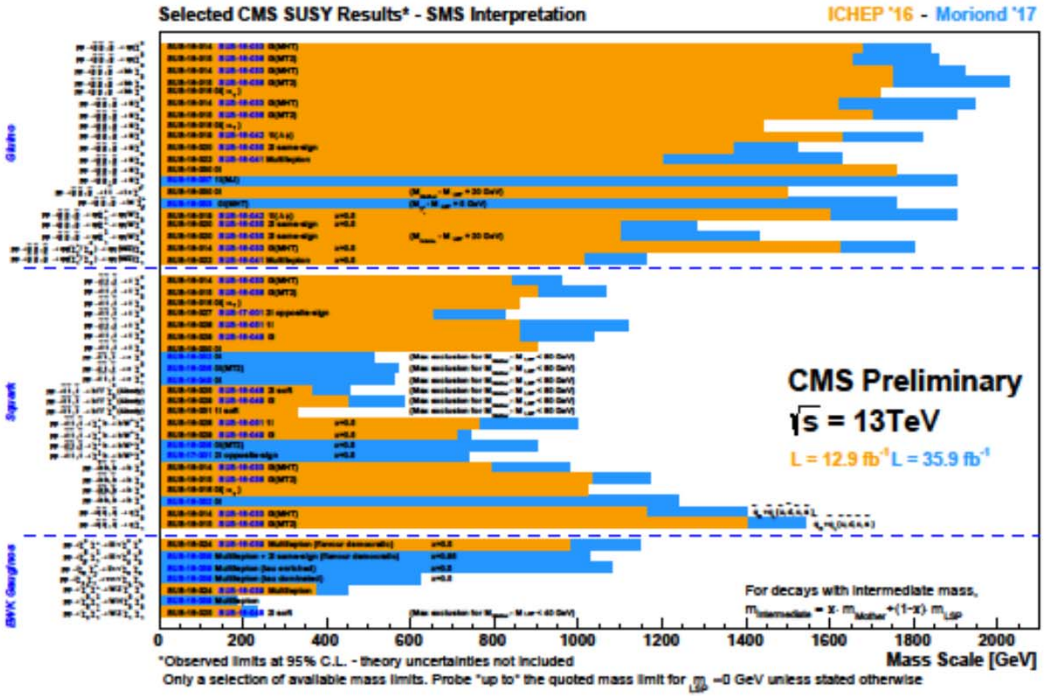
Coupling vs particle mass

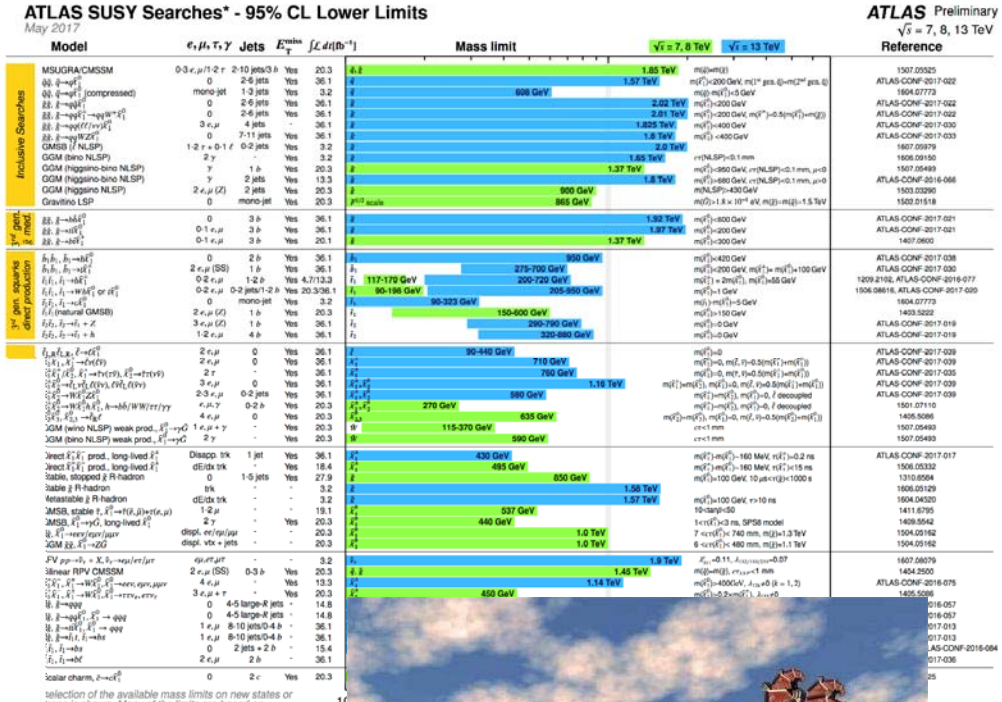


Red: best fit, Dashed: SM (theory)

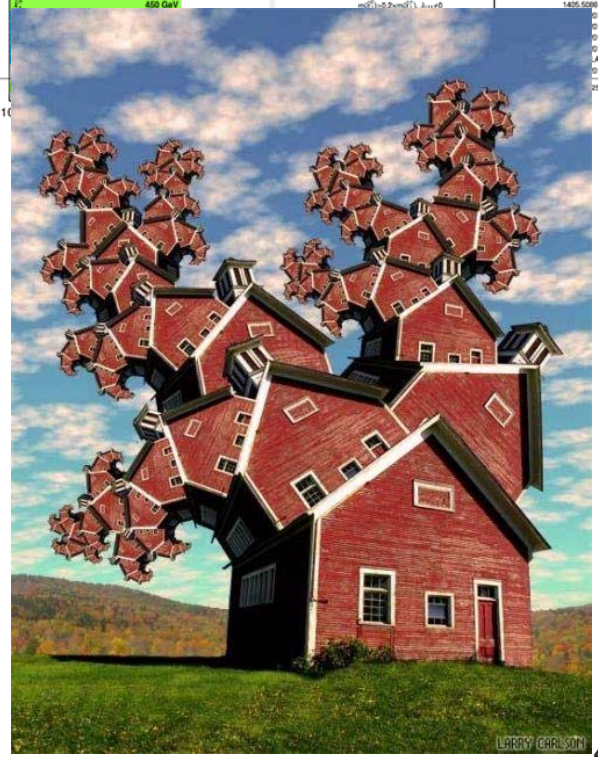
Exotic Searches Backdrop: SUSY

- "Slepton-Photon" 2019??





House of susy signatures → squarks/gluinos, electroweak…



Talk Plan

- SUSY = signature egalite, exotics =signature liberte
- SUSY searches going up the mass beanstalk tree ☹ ☹.
- Exotica fraternite must find new physics!
- Practical definition by today's agenda:

  Exotics = .NOT. (SM Higgs, BSM Higgs, SUSY)
- Recent 36/fb BSM results, *roughly organized by signature classes*, little emphasis on models.

One slide on models

(What if one of the searches finds an excess?)

- 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). Invisible DM pair decay of a Z'-like mediator against a hefty ISR recoil which acts as a proxy for detection. More in Oliver Buchmueller's talk next.
- W'/Z'/HVT: Simplified Heavy Vector Triplet model(s) for W'/Z'. Model B is Fermiphobic, Model A: gauge bosons and fermions
- 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. Single or pair-produced.
- Seesaw: Heavy partners who keep neutrinos light. Several models bring the mass down from Planck scale to LHC. Prolific processes to generate them in association with leptons, W/Z/H.

Exotics: Search Tools

- Jets/HT:
  - Number of jets (above 30 GeV, say)
  - HT = sum of Jet Pt's
  - ST = sum of all relevant transverse quantities, effective mass
  - B tagged jets
- (Variable formerly known as) missing ET
- Photons, muons, electrons, (hadronic) tau's
- Kinematics
  - Invariant masses (resonances), edges,etc
  - Fancy variables now subsumed by kinematics on Viagra (MVA:ANN, BDT..)
- Smart objects
  - Particle flow
  - Substructure
- Finite lifetimes, displaced tracking, dE/dx, etc

Classic hadronic results

→Low Signal/Background, but oodles of signal due to color production. Hard selections, boosts….

→Data-driven backgrounds determination from sidebands (Unless MET → Z(invisible))

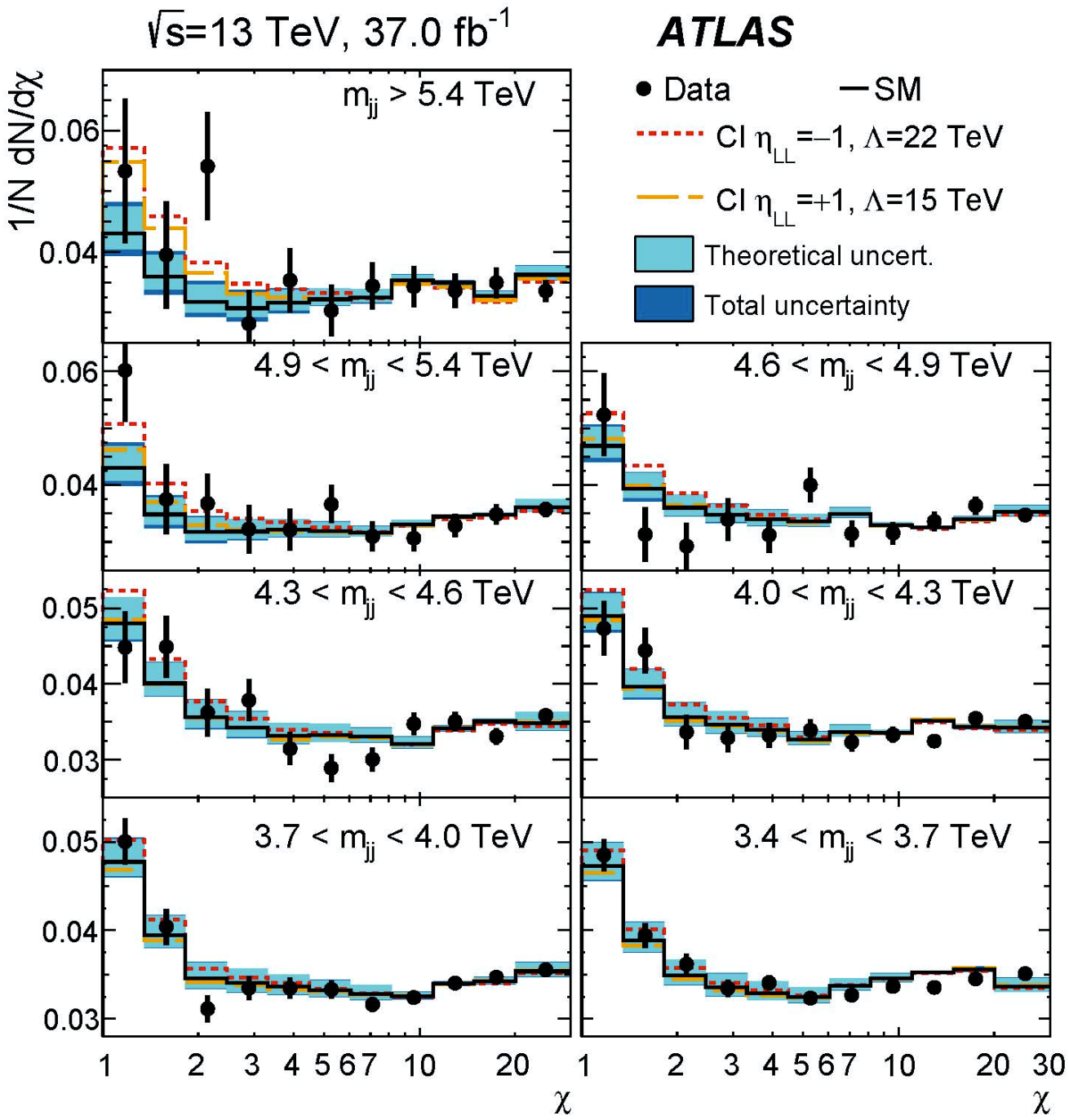
Dijet rapidity spread
(CMS EXO 16-046 ATLAS arXiv:1703.09127)

- Signature: $\chi = e^{(y1-y2)}$ for the two leading jets
- χ flattens Rutherford scattering (a la Dalitz plot)
- Background: QCD
- Systematics:
  - Select easy Mjj<3TeV:
    - high statistics, but ~4% Jet Energy & QCD NLO scale
  - Select hard: Mjj>6TeV:
    - Low statistics ~25%

Dijet rapidity spread

CMS
EXO 16-046

ATLAS
arXiv:1703.09127



Dijet rapidity spread
(CMS EXO 16-046 ATLAS arXiv:1703.09127)

Physics/Models:

- Quark contact interaction (particle substructure, back to the future with Rutherford/Bjorken-Kendall-Friedman)

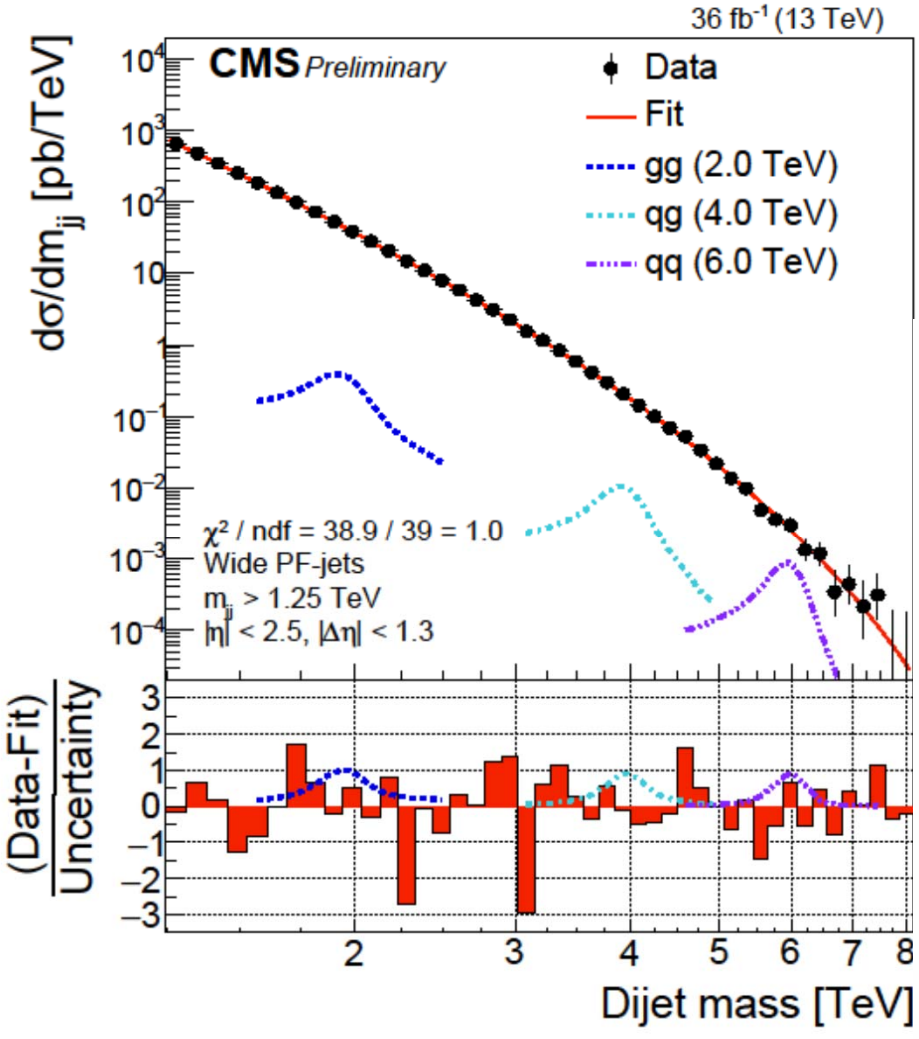
  Limits: Lambda 10-20 TeV

LHC recreates ~1-10picosecond after big bang to address EW breaking scale at 10-100 psec after big bang

- Extra Dimension ADD ~10 TeV
- Quantum Black Holes 6-8TeV
- Dark matter: Mediator mass 2.5-5 TeV
- Z' 1.5-3TeV

Dijet resonance

(CMS EXO 16-056 ATLAS arXiv:1703.09127)

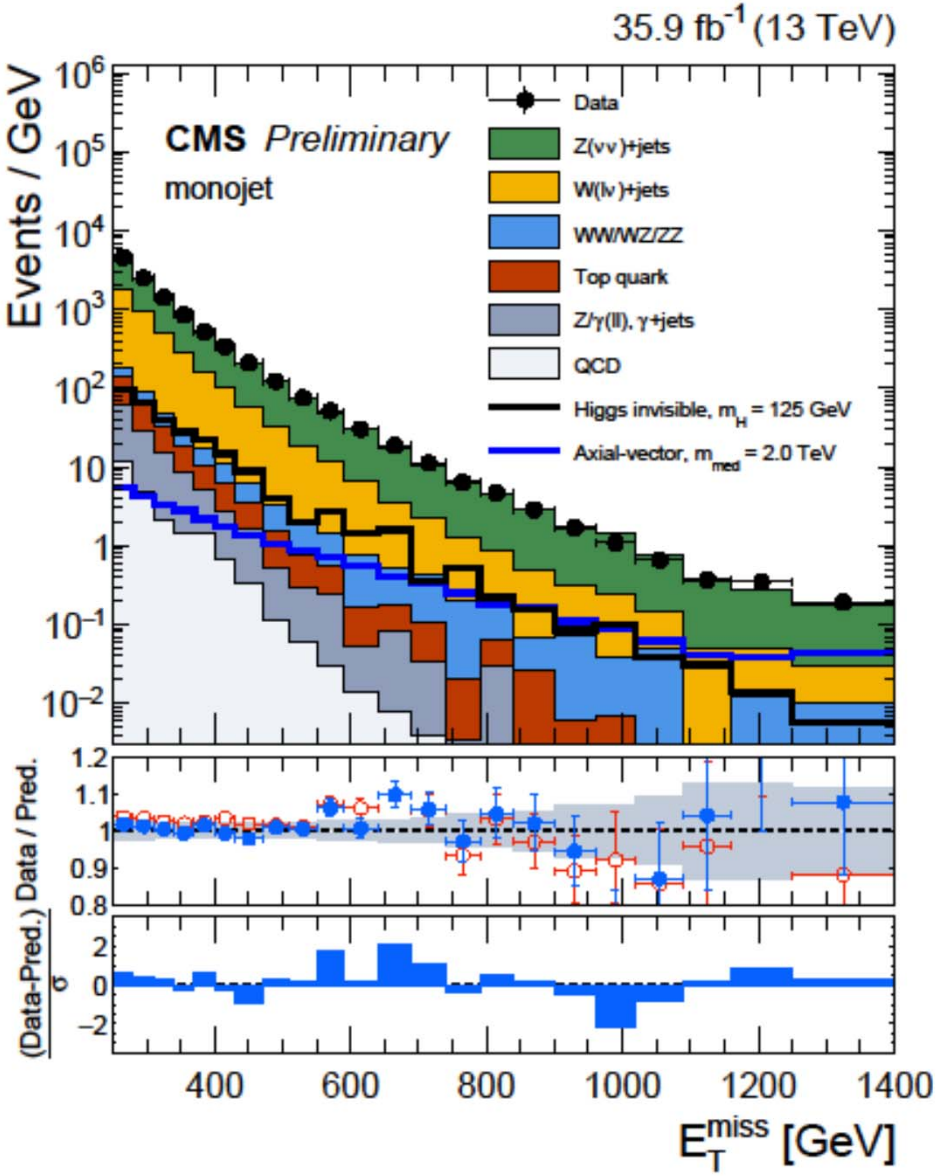


- Background: QCD Smooth shape fit
- Systematics: JES, Resolution, Spectrum shape

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)	—	—

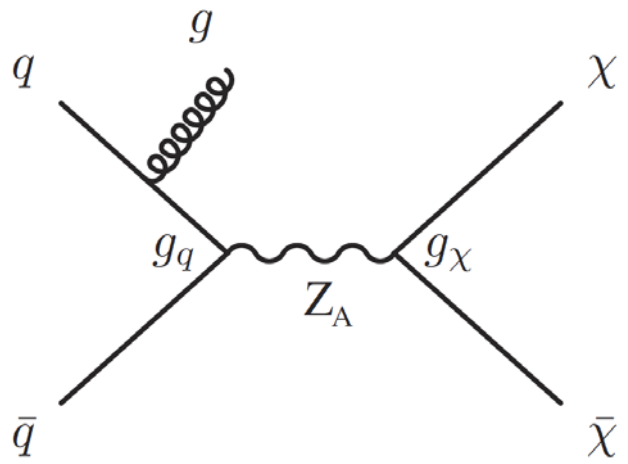
Unbalanced Monojet
(ATLAS-CONF-2017-060, CMS EXO 16-048)

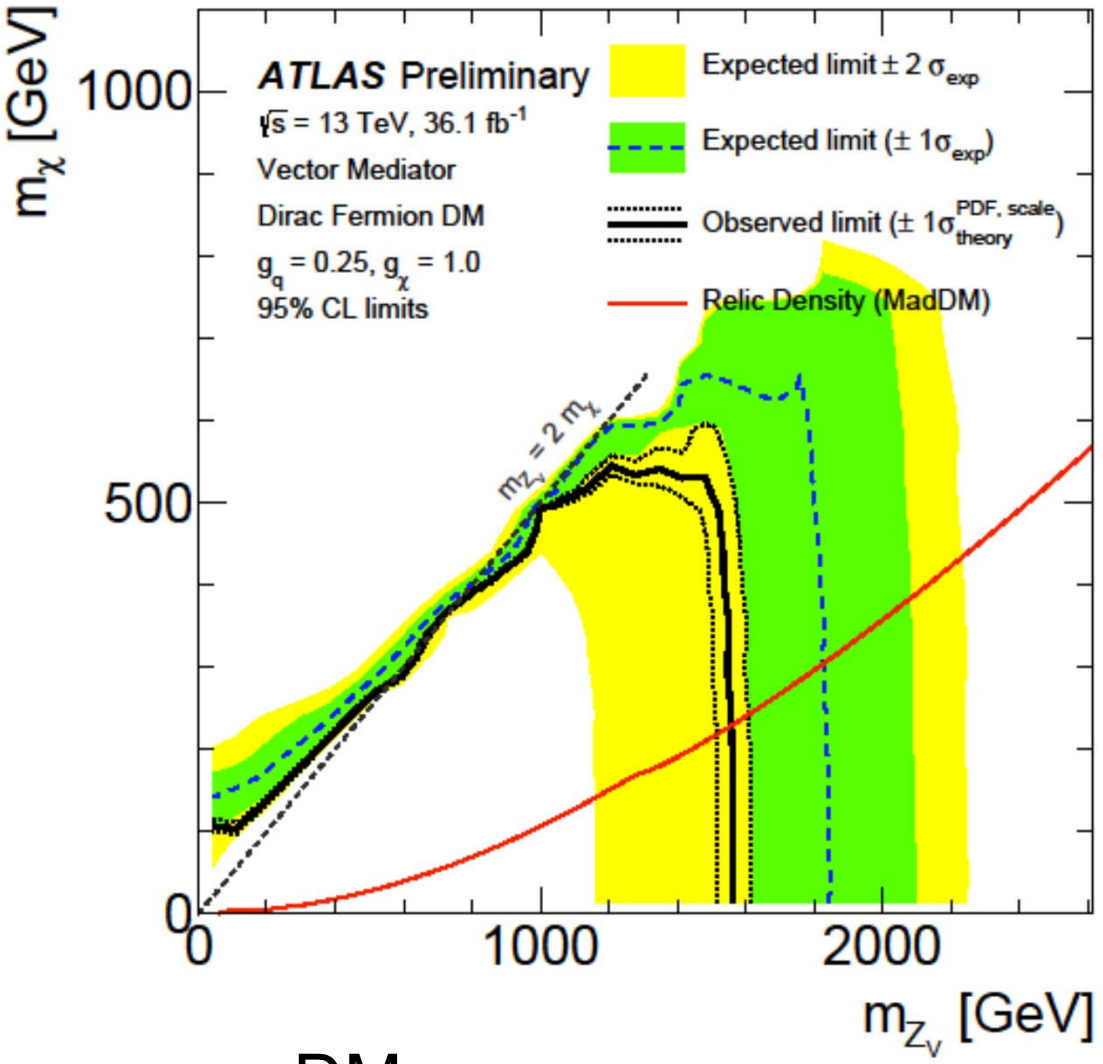
- Signature: Hefty jet & large MET, no leptons. Met, pt >250GeV
- Background: Z(invisible)+jets and W(tau-nu)+jets. Measure with Data/MC in leptonic V+jets control samples assuming hadronic recoil=MET.



Unbalanced Monojet
(ATLAS-CONF-2017-060, CMS EXO 16-048)

- Invisible SM Higgs (gg→H,VBF,VH) 53% at 95% CL (CMS)
- ADD limits on MD: 5-10TeV for n=6 to n=2.
- Dark Matter: ISR jet vs DM Mediator (decay MET) (Z'/Z_A→invisible DM)





DM mass vs Mediator mass

Jet substructure
(not to be confused with Rutherford or contact interaction)

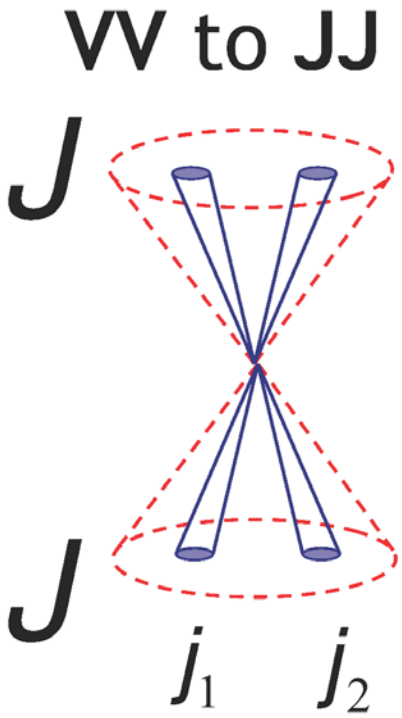
Terminology:

Boosted, Merged, Resolved, substructure

Fatjet, Large-R, AK8

Puppi, pruned, subjettiness, tau2/tau1

X tagger (X=W,Z,H,t)



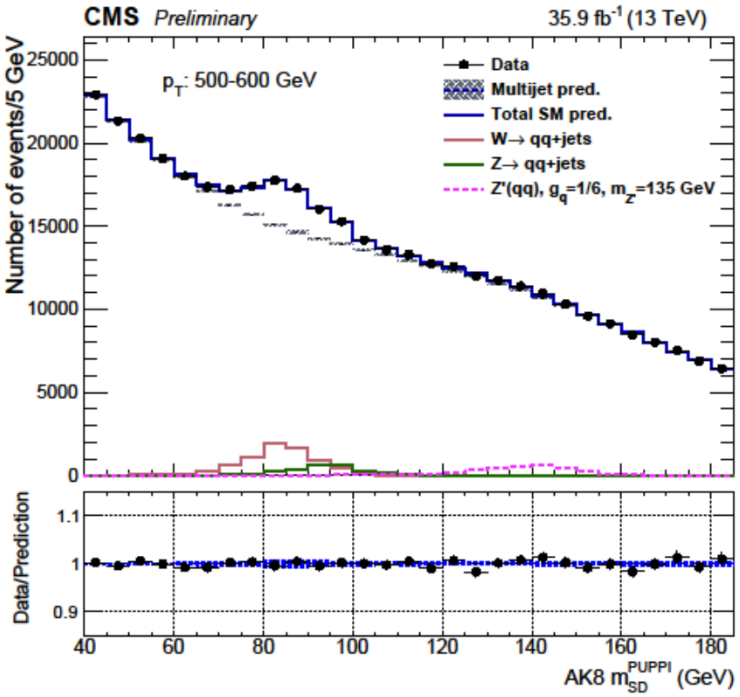
Merged (di)jet light resonance
(CMS-EXO-17-001)

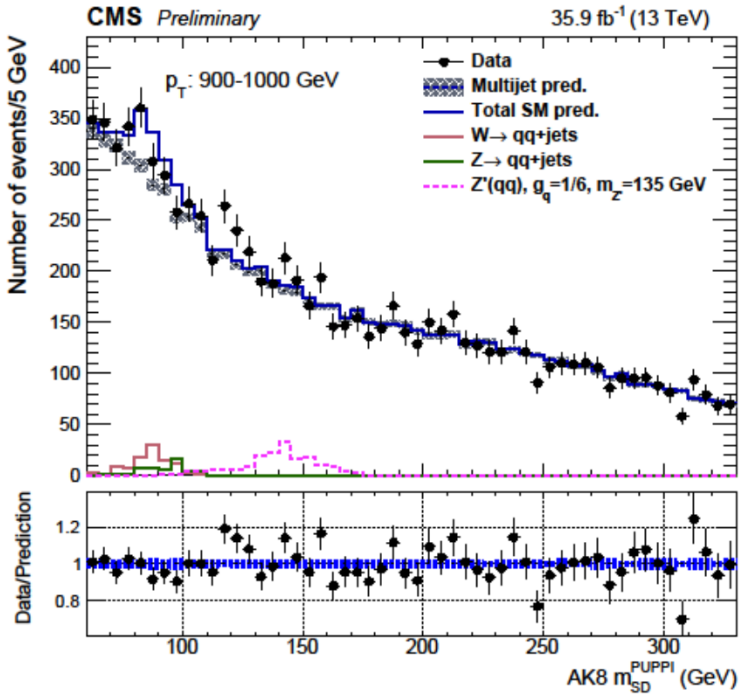
- Signature: A merged jet (+ISR jet for triggering). Substructure → 50-300GeV resonance
- Background: QCD jet masquerading as a merged dijet. Data-driven signal/bkgnd inversion of the DDT* spray. Also, W/Z hadronic resonant around 80/90GeV. Uncertainties: from procedural fits.
- Physics/Models: Leptophobia. Z', Dark Matter

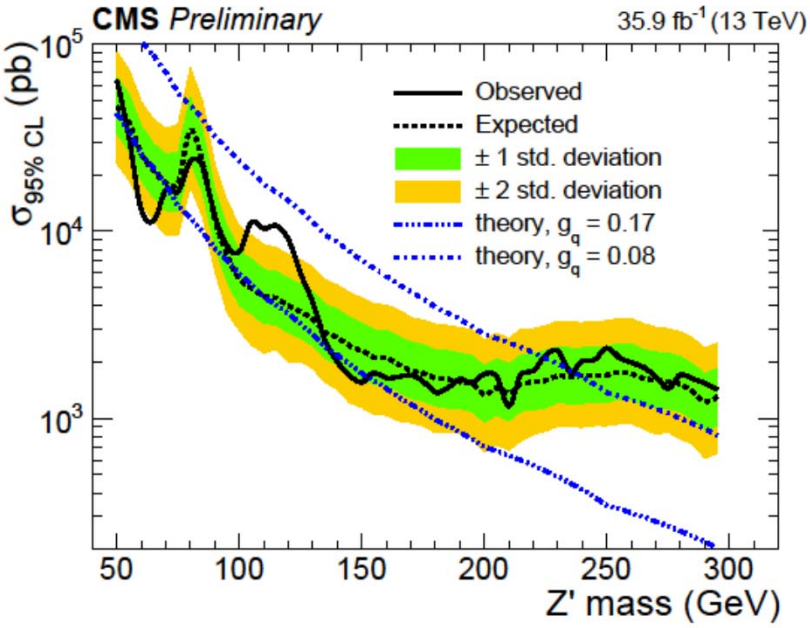
* DDT=Designing Decorrelated Taggers, from J. Dolen et al.

Resonant large (merged di)jet

(CMS-EXO-17-001)



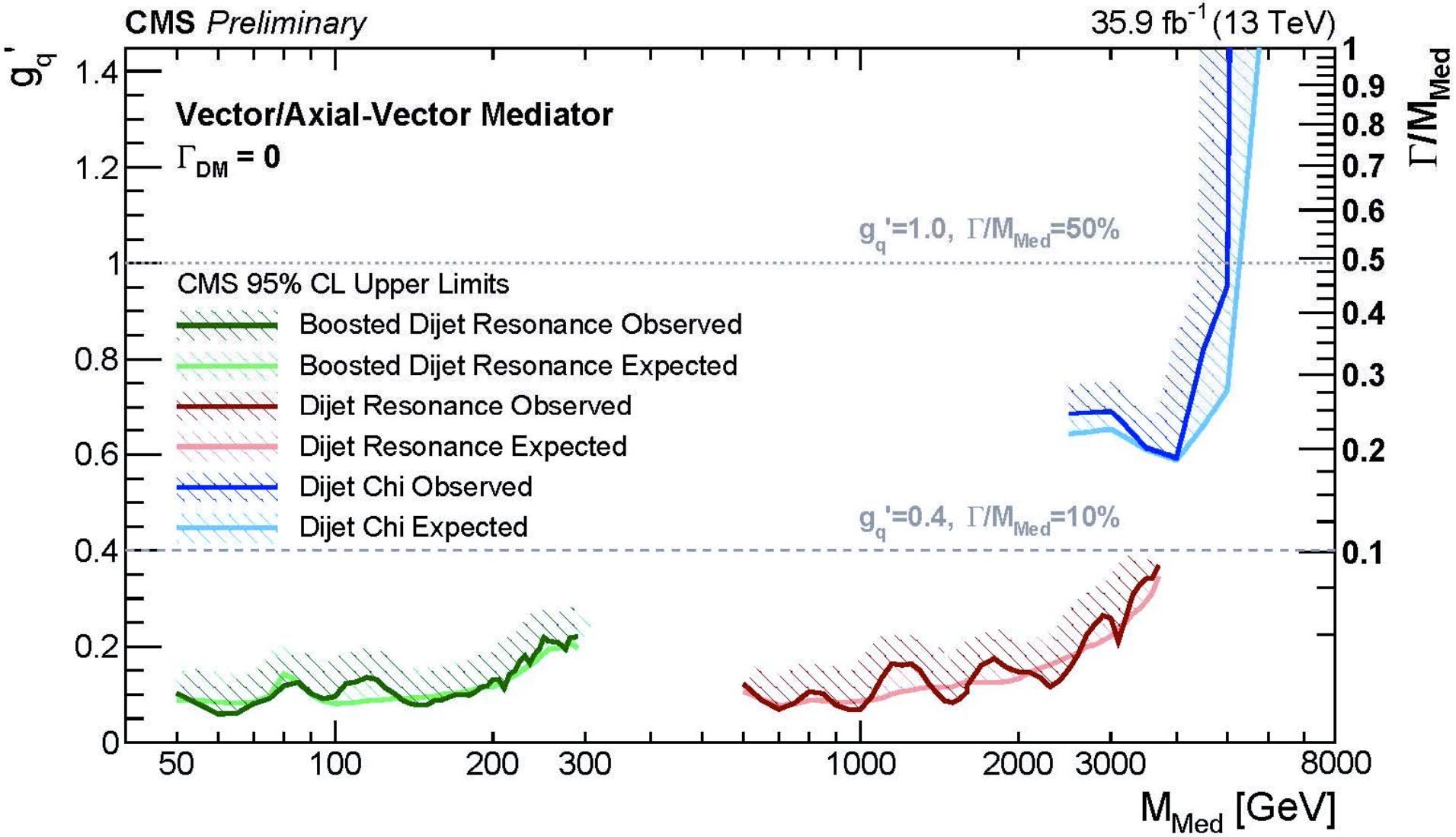




115GeV:
2.9/2.2 sigma

Combined Dijet on Dark Matter

Universal quark coupling vs Mediator mass

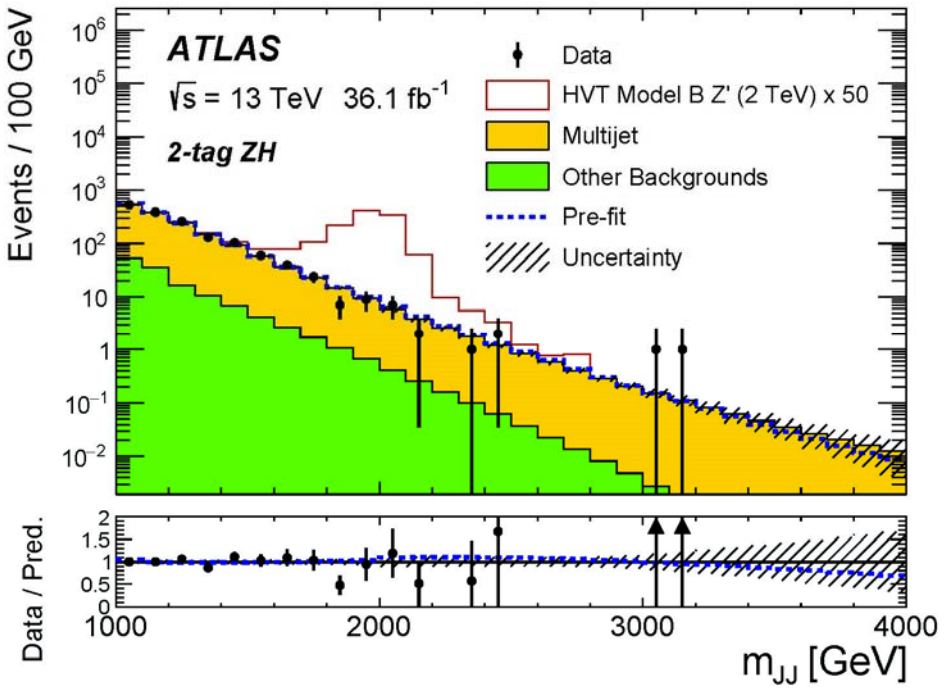


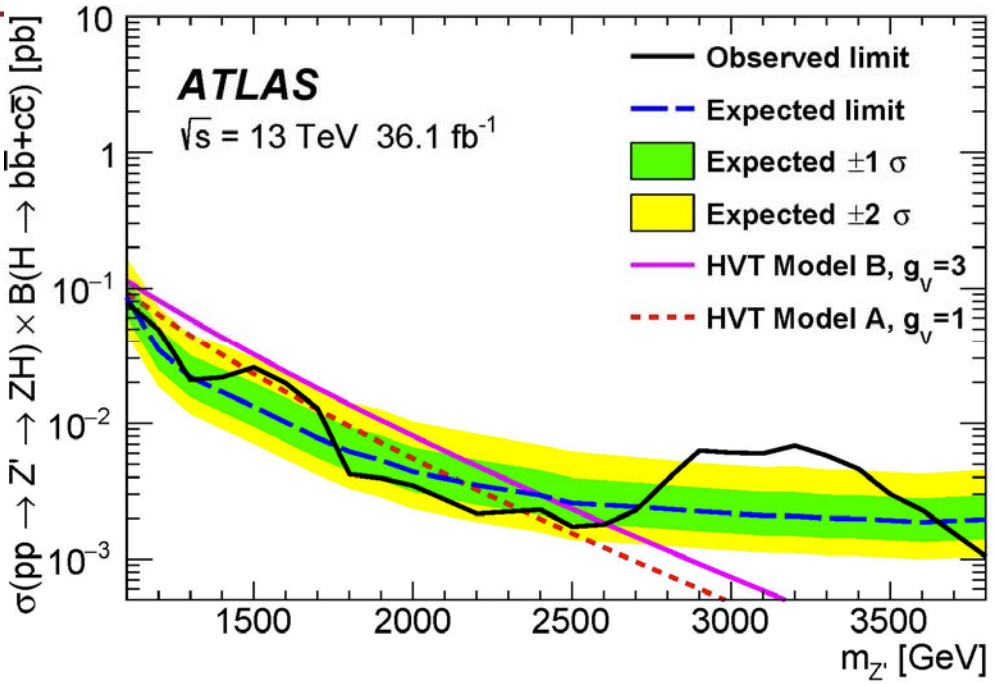
[(qq)(bb)] merged jets:VH resonance

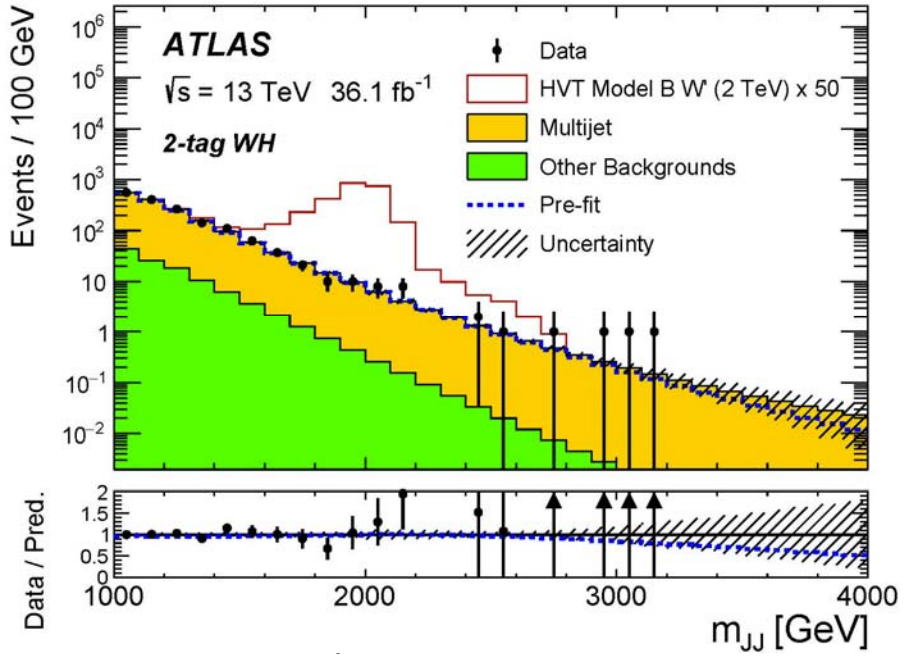
(ATLAS-arXiv:1707.06958, CMS:1707.01303)

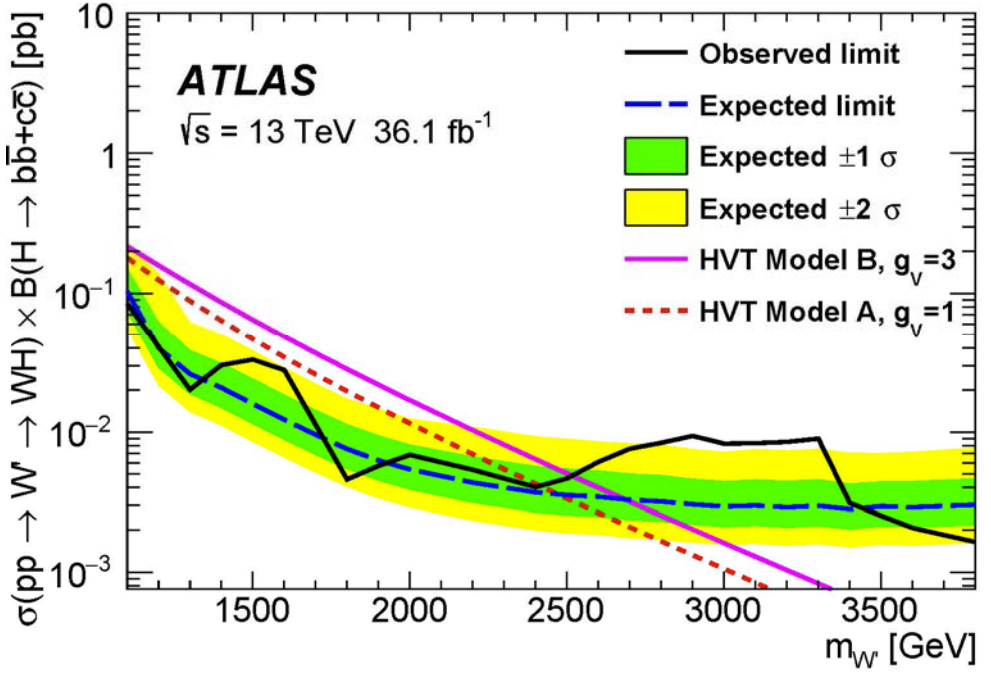
- Signature: Two large-R jets, no leptons or met.
- Substructure → The Higgs (heavier) jet must have 75-145GeV m_J & b-tag(s). The V jet must have ~65-110GeV m_J. Scan m_{JJ} above 1TeV for VH resonances.
- Backgrounds: 90% QCD multijets,10% tt. Data-driven using sidebands and validation regions.
- Physics/Models: Composite/little higgs, ED. Simplified: Heavy vector triplet (HVT)

[(qq)(bb] merged jet resonance



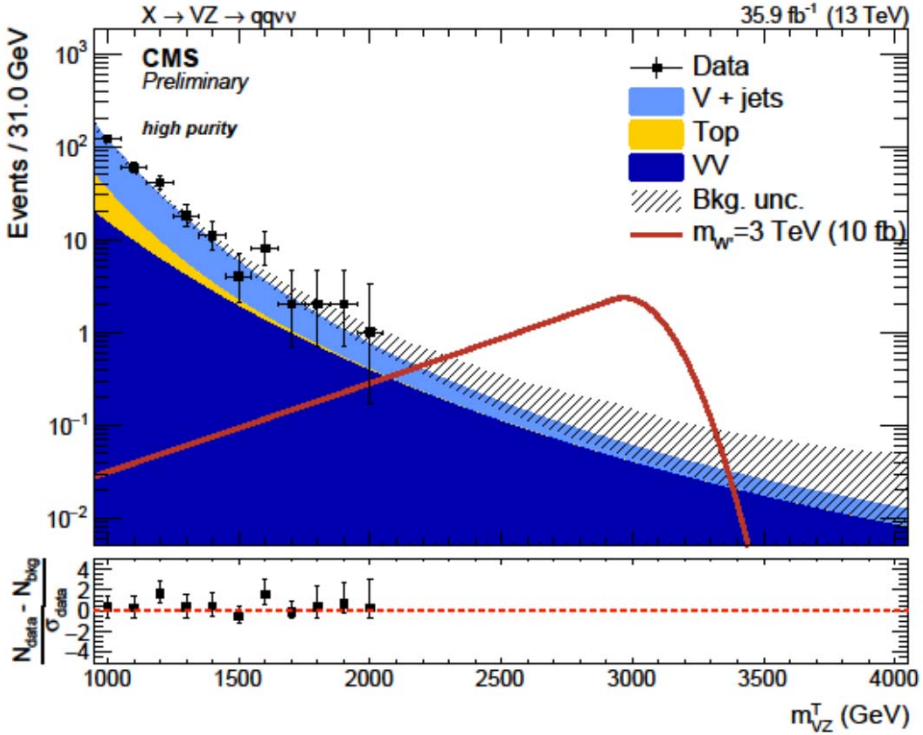


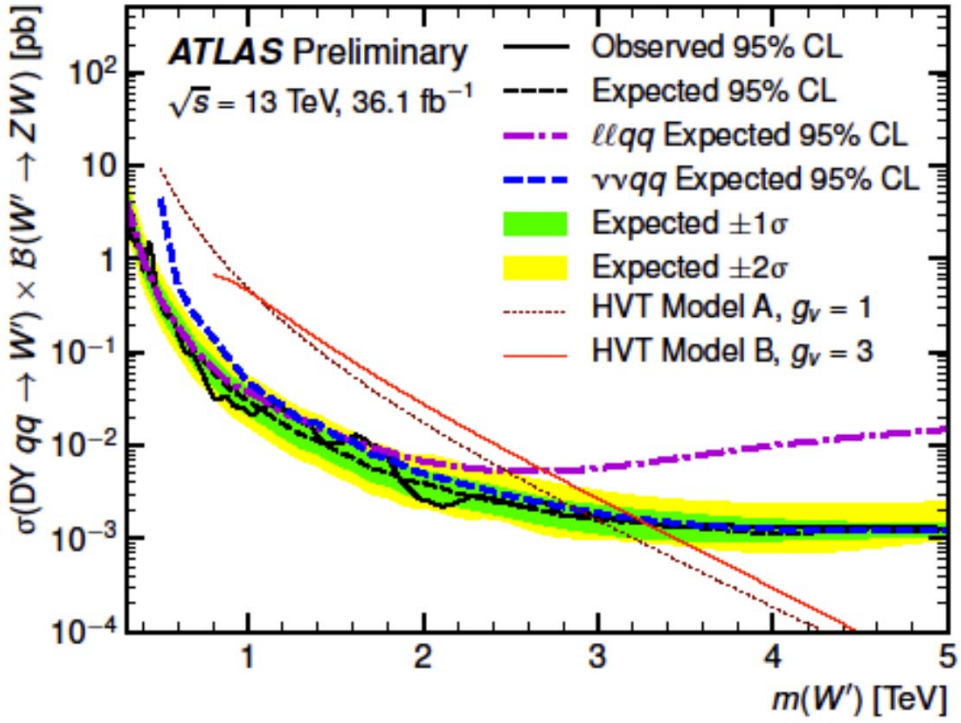




[qq merged dijet(W/Z)+νν MET(Z)] heavy resonance
(ATLAS2017-401 and CMS-B2G-17-005)

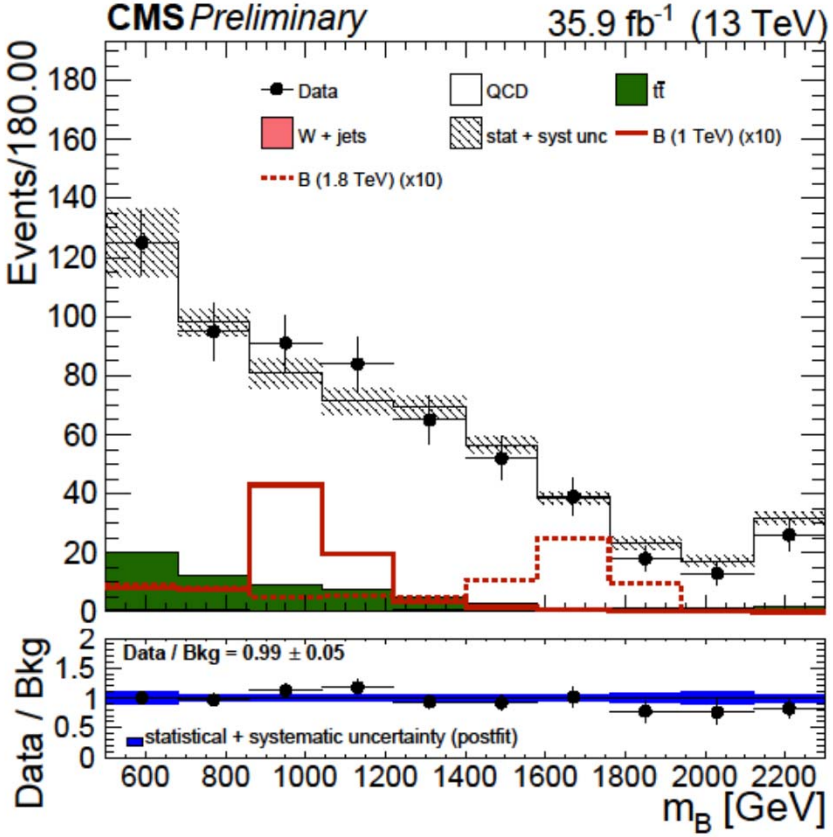
- Signature: MET+merged (substructure) dijet with m_J between ~65-~105GeV. No b,photons,leptons. Two ν assumption ➔ scan M_T
- Background: Z(inv) boosted against jet(s) which reconstruct as a merged dijet. Data-driven from mass etc sidebands.
- Physics/Models: W' (HVT), Spin 2 bulk graviton, etc

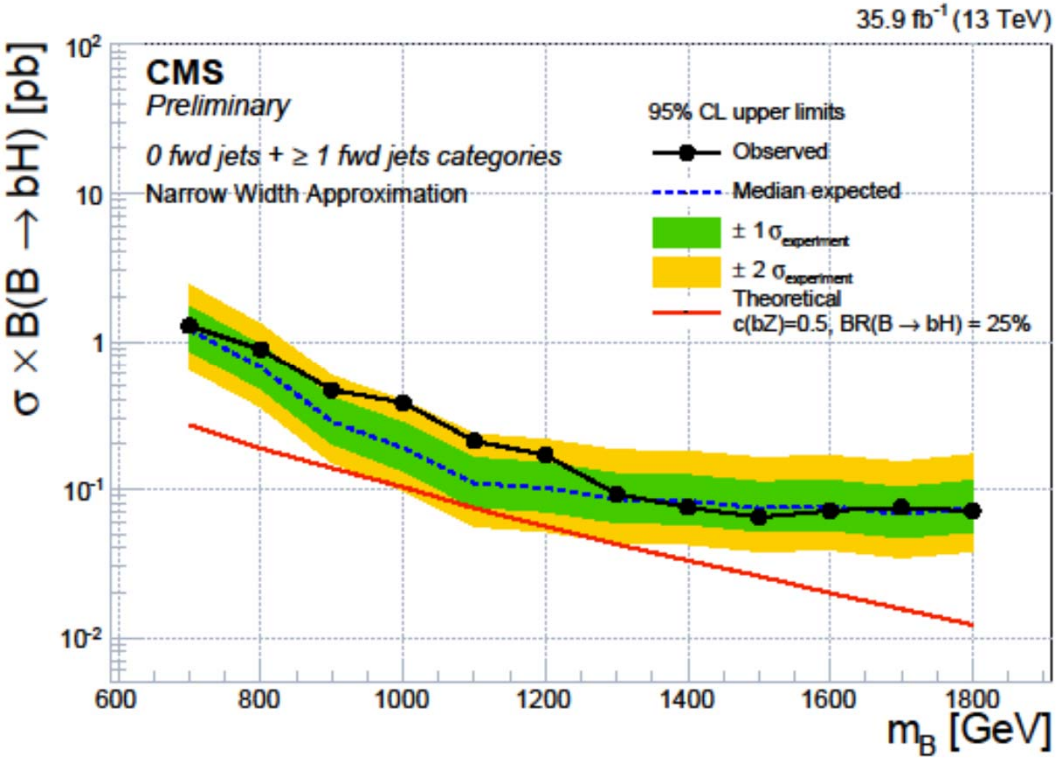




[b(bb)] jet+merged jet resonances
(CMS:B2G-17-009)

- Signature: Min 3 jets, min 1 btag, min 1 large “Higgs” jet with $105<m_J<135$, large HT (~1TeV), no leptons. Auxiliary: forward jet. Scan combined bH resonance.
- Backgrounds:QCD multi(b)jet using ABCD in Higgs mJ vs # btags.
- Physics/Models: Single VLQ B→bH (low production cross section)





A substructure non-sequitur

- Many more substructure results, eg, ATLAS-13 (2017-358) and CMS-B2G-17-001: VV resonance of merged dijets. mJ gets the V's and mJJ scans the (heavy) resonance. Physics: HVT W' and Z', bulk graviton, excited quark resonance decaying to qV.
- Why are substructure analyses flourishing over the last 2-3 years?
- 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!
- Missing anything below ~500GeV? Long-lived? (MATHUSLA???)
- More model-free inclusive searches (wide nets)?

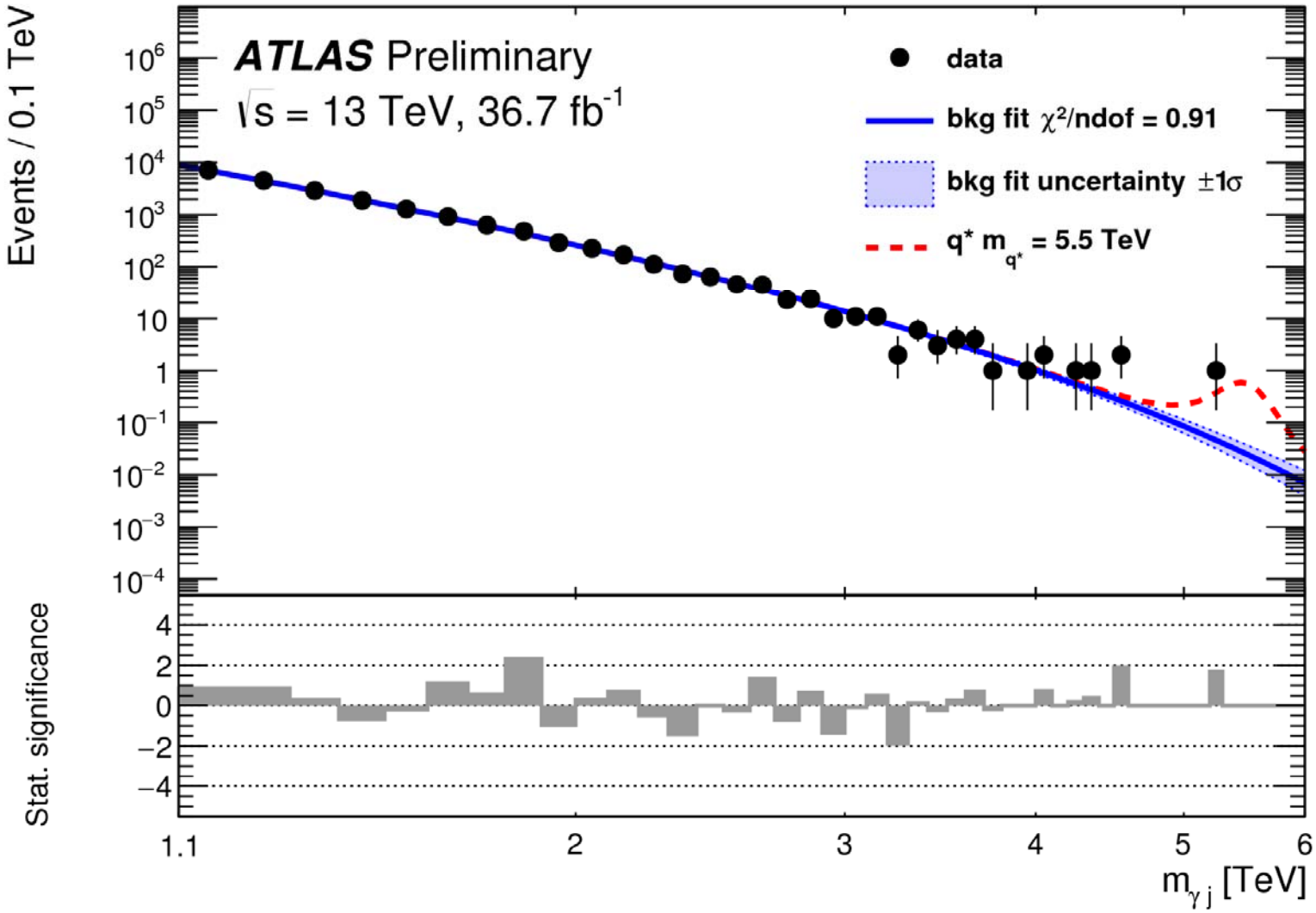
Outline: The Big Skip

- With apologies to colleagues in the data mines, a listing of intermediate S/B results with a few examples.
- Then a couple high S/B searches.
- Apologies also to difficult longer term efforts such as long-lived searches.

Mid-range S/B (partial list)

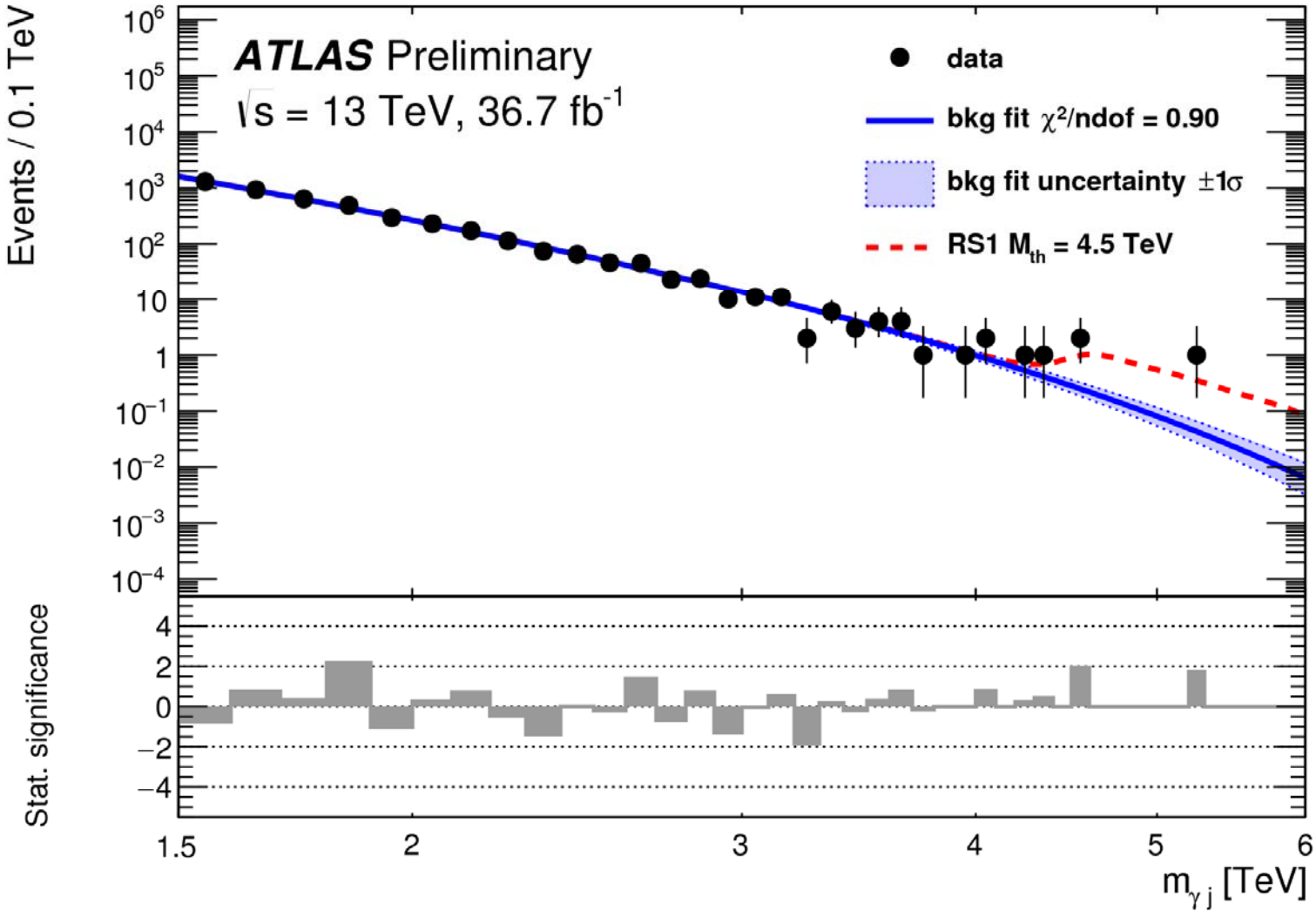
- Single photon/lepton etc:
  - Gamma-jet (CMS-exo-17-002, ATL-exot-16-26)
  - Lepton+jet excited top pair (CMS-b2g-16-025)
  - Lepton+jets VLQ top pair (CMS-b2g-17-003)
  - Lepton+jet+met VLQ top pair (ATL arXiv:1705.1075)
  - Lepton+jets VLQ Wb (ATL arXiv:1707.03347)
  - Lnuqq WW WZ resonance (ATL-conf-17-051)
  - Lepton+met heavy boson resonance (ATL arXiv:1706.04786)
- dielepton etc
  - LL(Z)+met DM,Hinv, LED (CMS-exo-16-052)
  - LL+met VV resonace (CMS-b2g-16-023)
  - Diphotons (ATL arXiv:1707.04147v2)
  - LL high mass (ATL arXiv:1707.02424)
  - LLqq VV resonances (ATL-exot-16-29)(also has nunuqq, as shown above)

Gamma-jet plots from ATL-exot-16-26



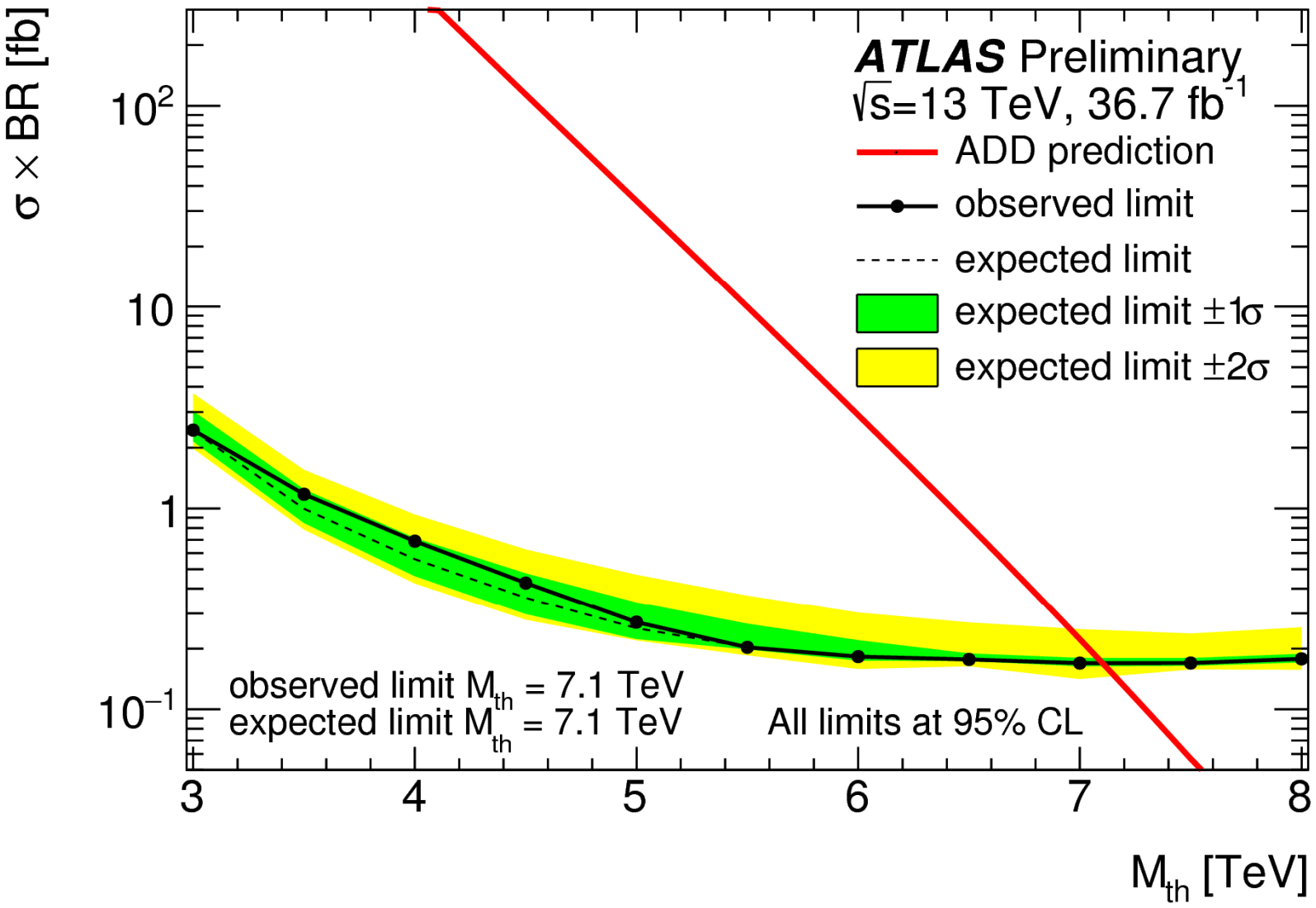
Excited quarks (quark compositeness): 5.3TeV

Gamma-jet plots from ATL-exot-16-26



RS Graviton: 4.4TeV

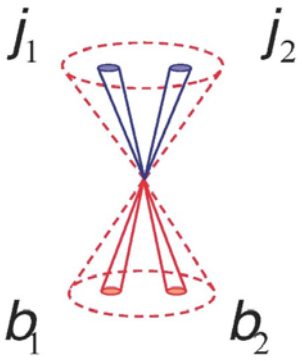
Gamma-jet plots from ATL-exot-16-26



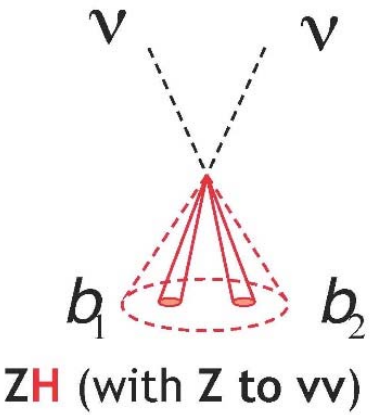
lnu,nunu,ll (W/Z) + bb(H) resonance

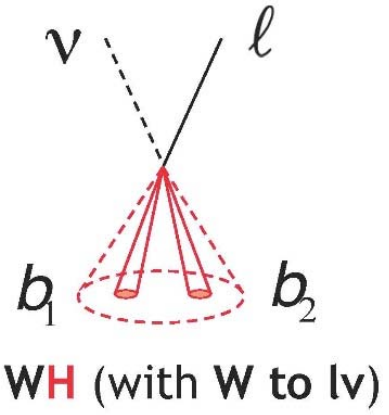
(ATL-CONF-2017-055) (A compendium!)

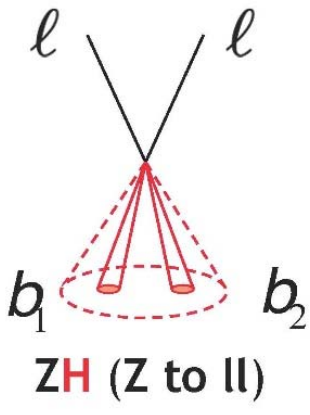
- Signature: (0,1,2) leptons + 2jets (can be merged), b-tag(s). Varying MET for W and Z→nunu. Scan combined M(Vh), but M_T(Vh) for Z→nunu 0 lepton channel. 3+ b-tag channels for bbA search.
- Background: Case dependent W,Z, tt prompts from MC. Data-driven multijet with 1 fake lepton for 1-lepton 1-btag resolved channel.



All hadronic





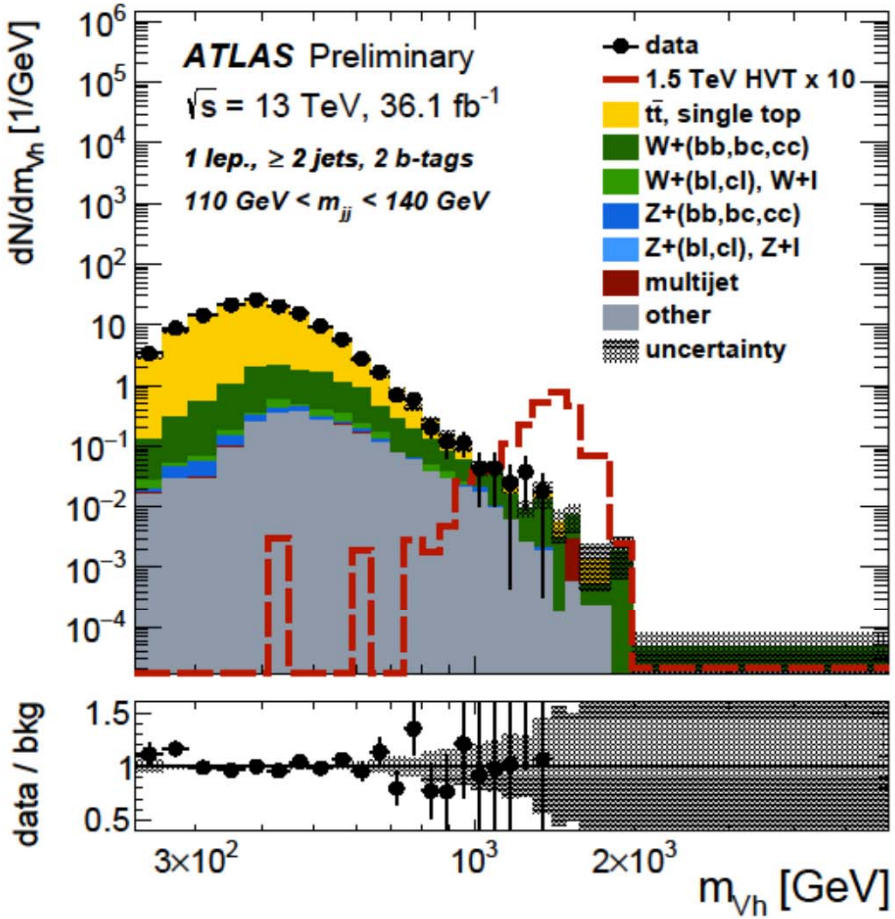


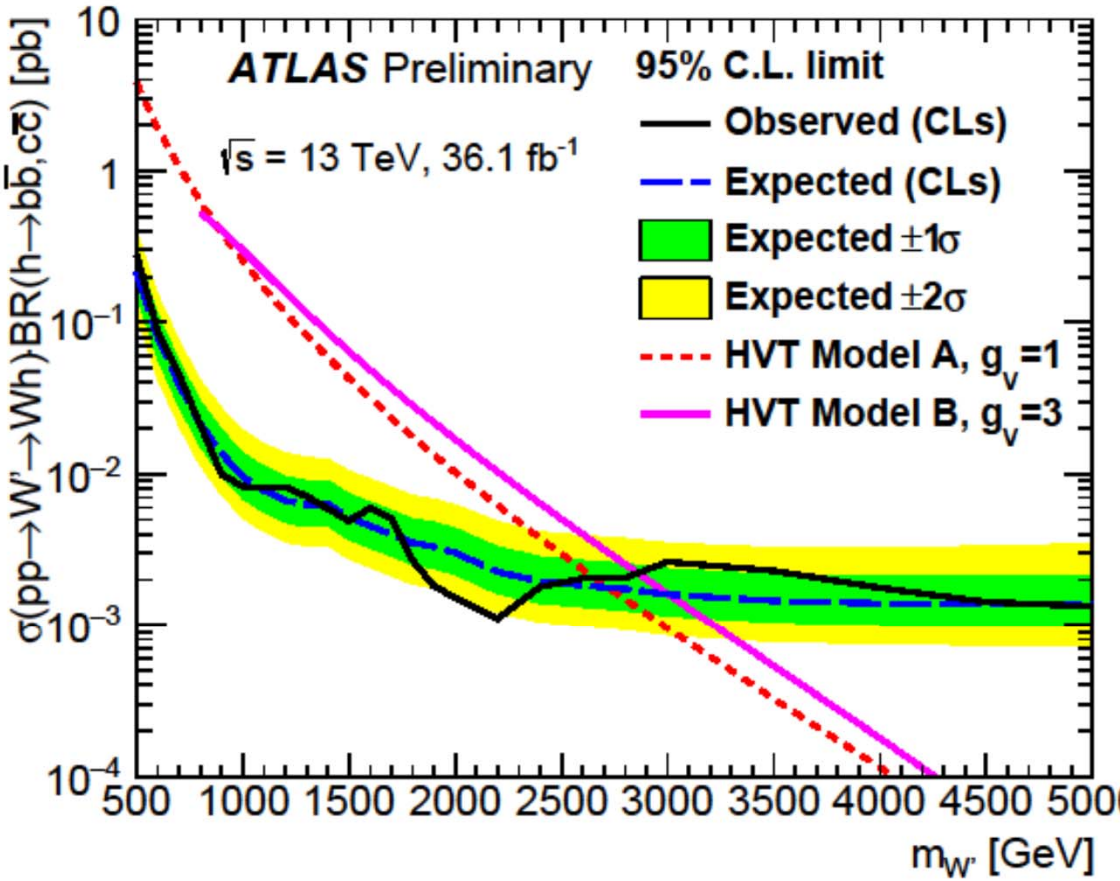
With lepton/met

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

(ATL-CONF-2017-055) (17 channel compendium!)

- Physics/Models: W'/Z' (HVT) in 2.6 to 2.9TeV range,
  also bbA (2HDM)



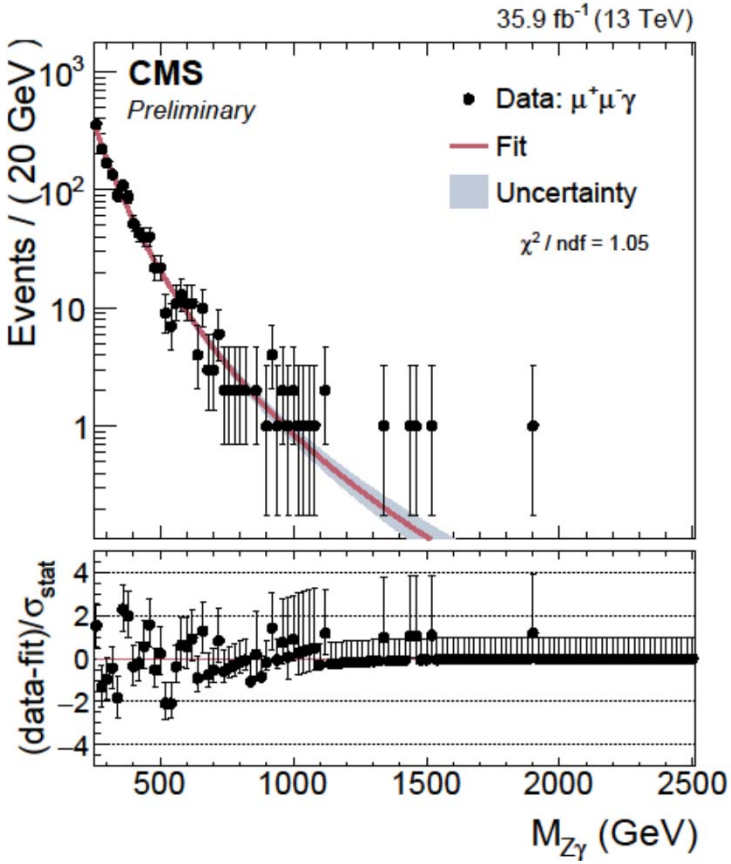


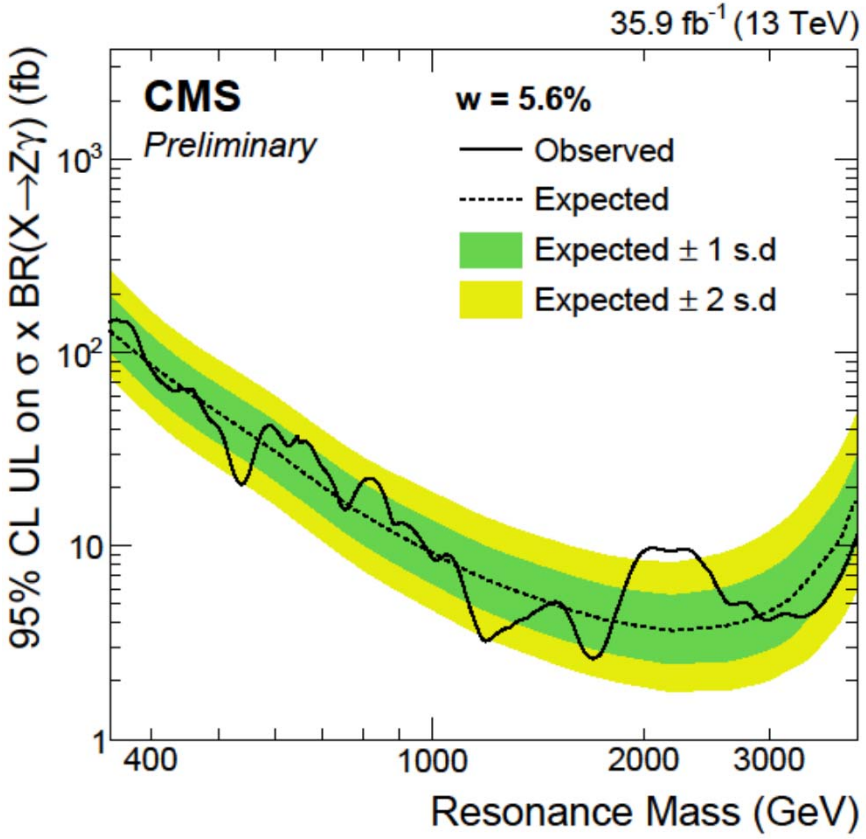
Next:
High S/B multi-X (3 or more objects)

High mass [(ee/mm/jj on Z) + Gamma] Resonance

CMS-EXO-17-005

- Signature: photon with pt>40-65GeV, m(ee) or m(mu+mu-) between 50-130GeV, or a merged dijet (pt>200GeV) with mJ 75-105GeV. Photon must be significant (pt > 25% of combined mass), Z→bb preserved with b-tagged channels. Combined range 300GeV to 4TeV
- Background: Smoothly falling m(Zgamma) shape fits
- Physics/Models: Generic resonance in subchannels & combinations

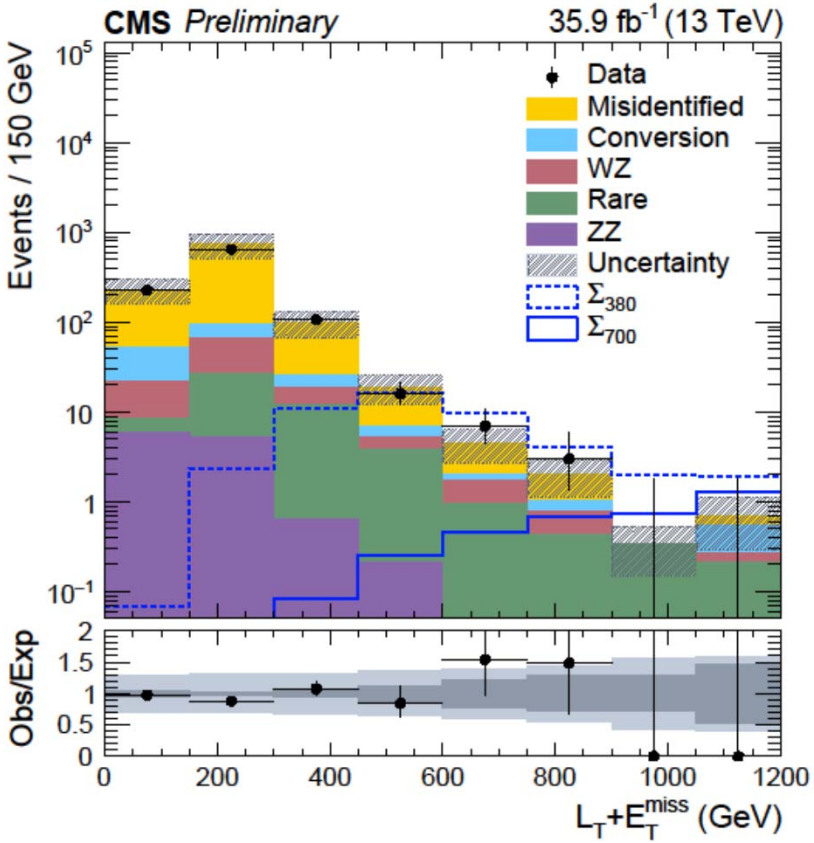


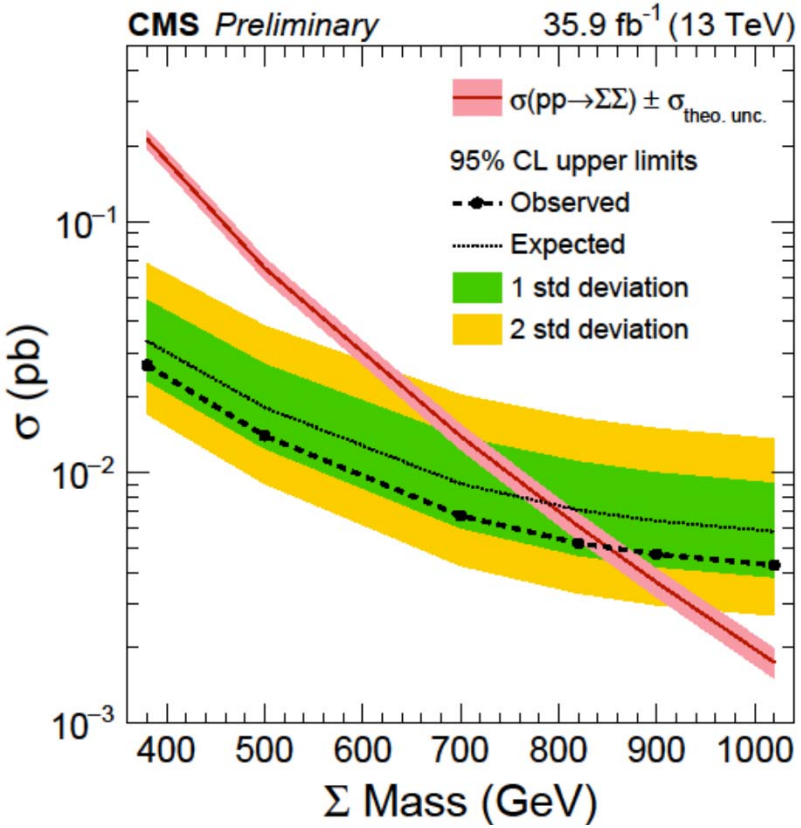


Multileptons (e's and mu's)

CMS-EXO-17-006

- 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.
- Physics/Models: Type-III seesaw (27 processes including higgs)

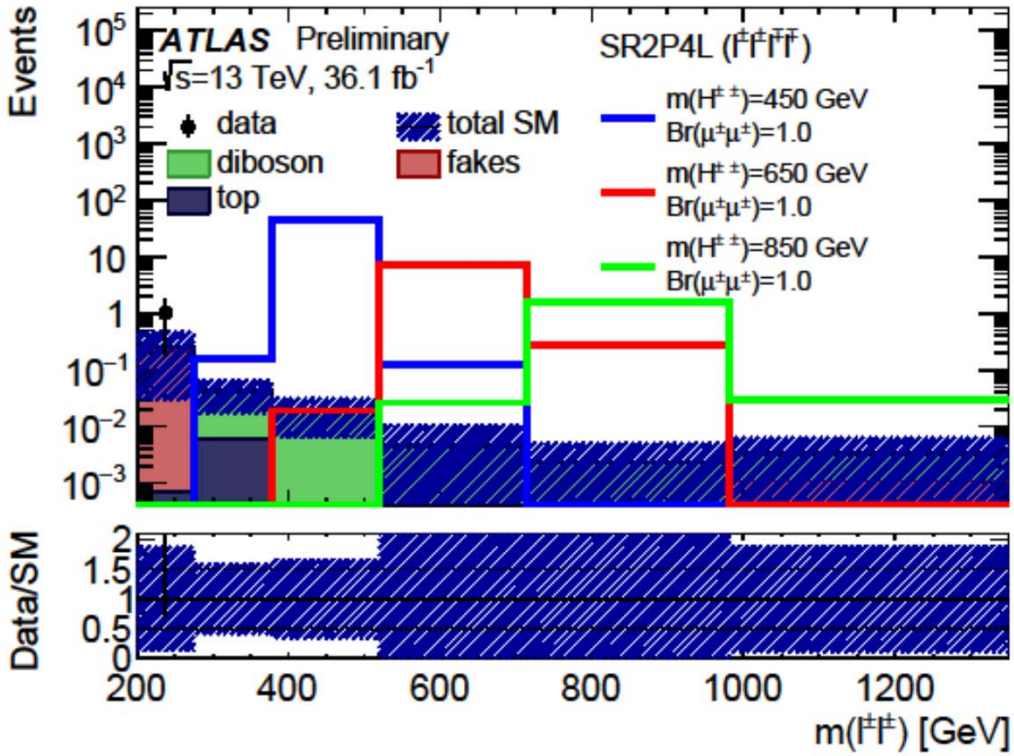


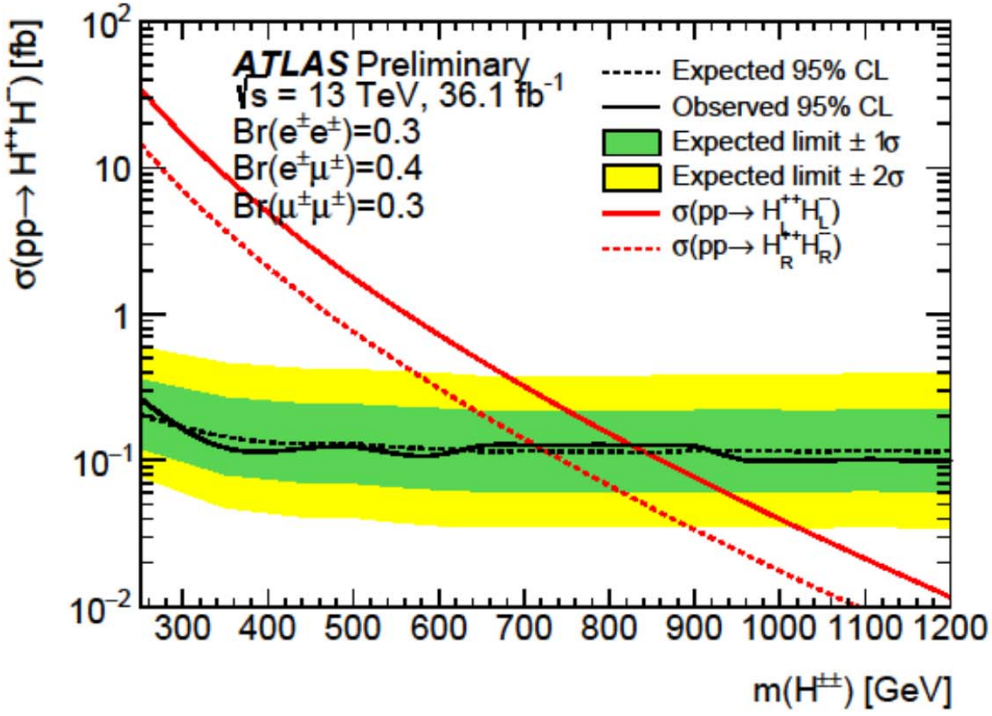


Multileptons e's and mu's(incl SS Dileptons)

ATLAS-CONF-2017-053

- Signature: Same sign dileptons or 3 or 4 e's and mu's, b-veto, m(SS)>200GeV, LT>300GeV,etc, bins of flavor and kinematics.
- Background: e charge misid, Z+jets with tight-loose, ttbar substantially eliminated with a b-veto, prompts from MC
- Physics/Models: Doubly charged Higgs associated production





LHC vs BSM Models

BSM models

LHC

Slide Credit: Stephen Martin

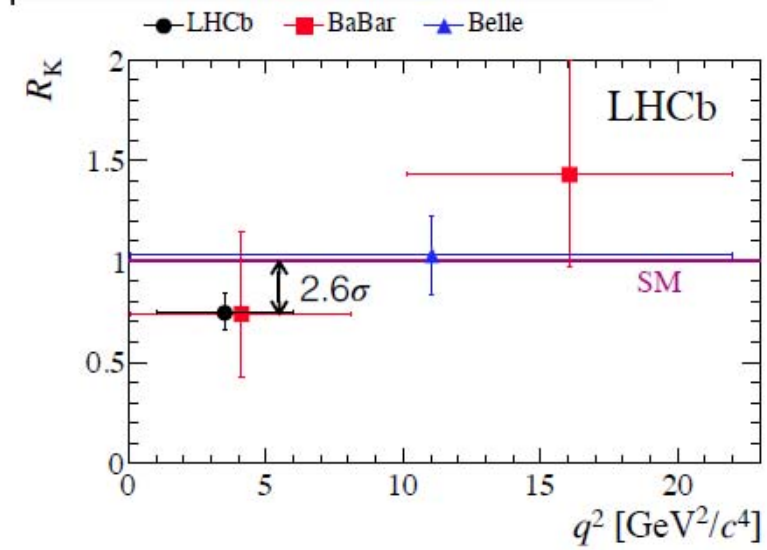
BSM possibilities: ways to go

New physics?

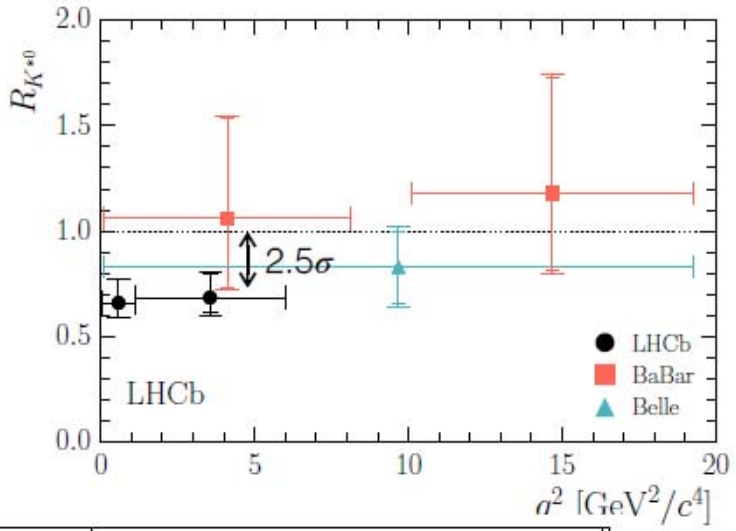
LHCb

(maybe the answer will come from the left field)

R(K)=μμK/eeK



R(K*)=μμK*/eeK*



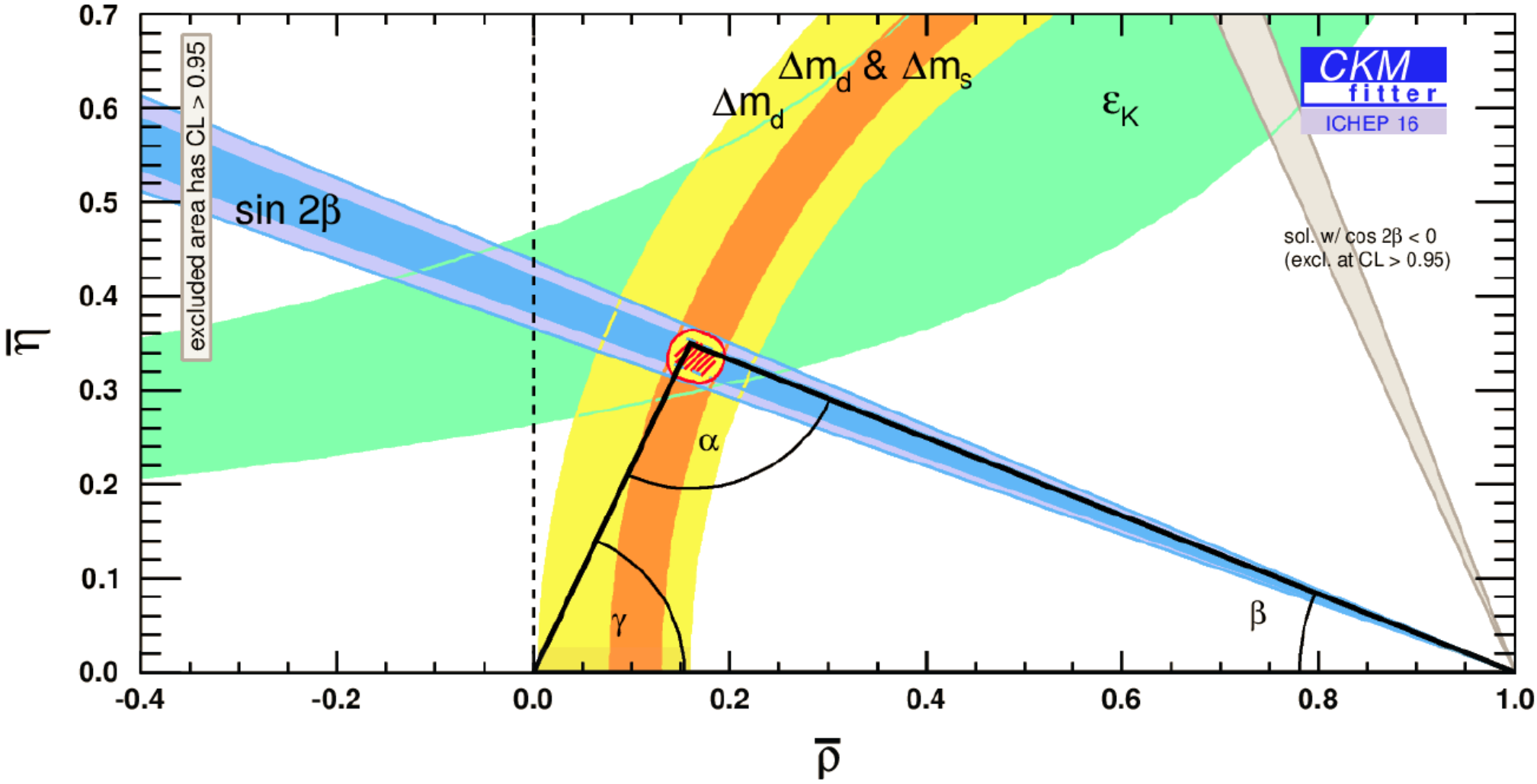
	SM	Exp.
$R_K^{[1-6]}$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074} \pm 0.036$
$R_{K^*}^{[1.1-6]}$	1.00 ± 0.01	$0.685^{+0.113}_{-0.069} \pm 0.047$
$R_{K^*}^{[0.045,1.1]}$	0.91 ± 0.03	$0.660^{+0.110}_{-0.070} \pm 0.024$

How to verify?

From: Paris Sphicas, EPS'17

Sunil Somalwar, Lepton Photon 2017

LHCb



$$\gamma = (76.8\,^{+5.1}_{-5.7})^\circ$$

From: Paris Sphicas, EPS'17

Concluding remarks

- New ideas keep coming online. Since Higgs discovery, Higgs in the final state: t', b', t→ch, in SUSY: electroweak Higgs, natural higgsino….. Boosted final states and jet substructure, long lived objects, generalized recoil (Dark Matter), VBF…
- Discovery lessons from New Jersey-CP Violation and CMB. Cronin/Fitch and Penzias/Wilson didn't expect "new physics". Anomalous production of….

→ Inclusive signature classes instead of microfine sculpting specifically for a model.

→ Overstated systematic error = Waste of taxpayers' money. (Henry Frisch, ~30 years ago.)

High density words on Dark Matter

(From an old poster, as an appetizer for the next talk)

WIMP chi is Dirac Fermion (conclusions for Majorana Fermions also possible). SM – chi mediator is very heavy, chi is only new particle in LHC reach. Effective field theory approach: Contact Interaction. Limits in terms of the WIMP mass and the suppression scale M*. Interaction via different operators (eg vector interaction operator D5). Comparable to thermal relic density from WMAP. Effective field theory allows comparison of LHC to indirect detection experiments. Interaction operator dependent bounds on WIMP-nucleon cross section for spin-dependent or spin-independent cases, e.g. spin-dependent axial-vector operator D8 and tensor operator D9.

Thanks to:

LP'17 organizers !!

LHC staff.

CMS/ATLAS members and leadership