Status and opportunities in Higgs and BSM at LHC

M. Bauce, F. Pandolfi

Assisi, 16-18 June 2019

From SM to…

- LHC has tested and measured the properties of SM to a very good degree of precision:

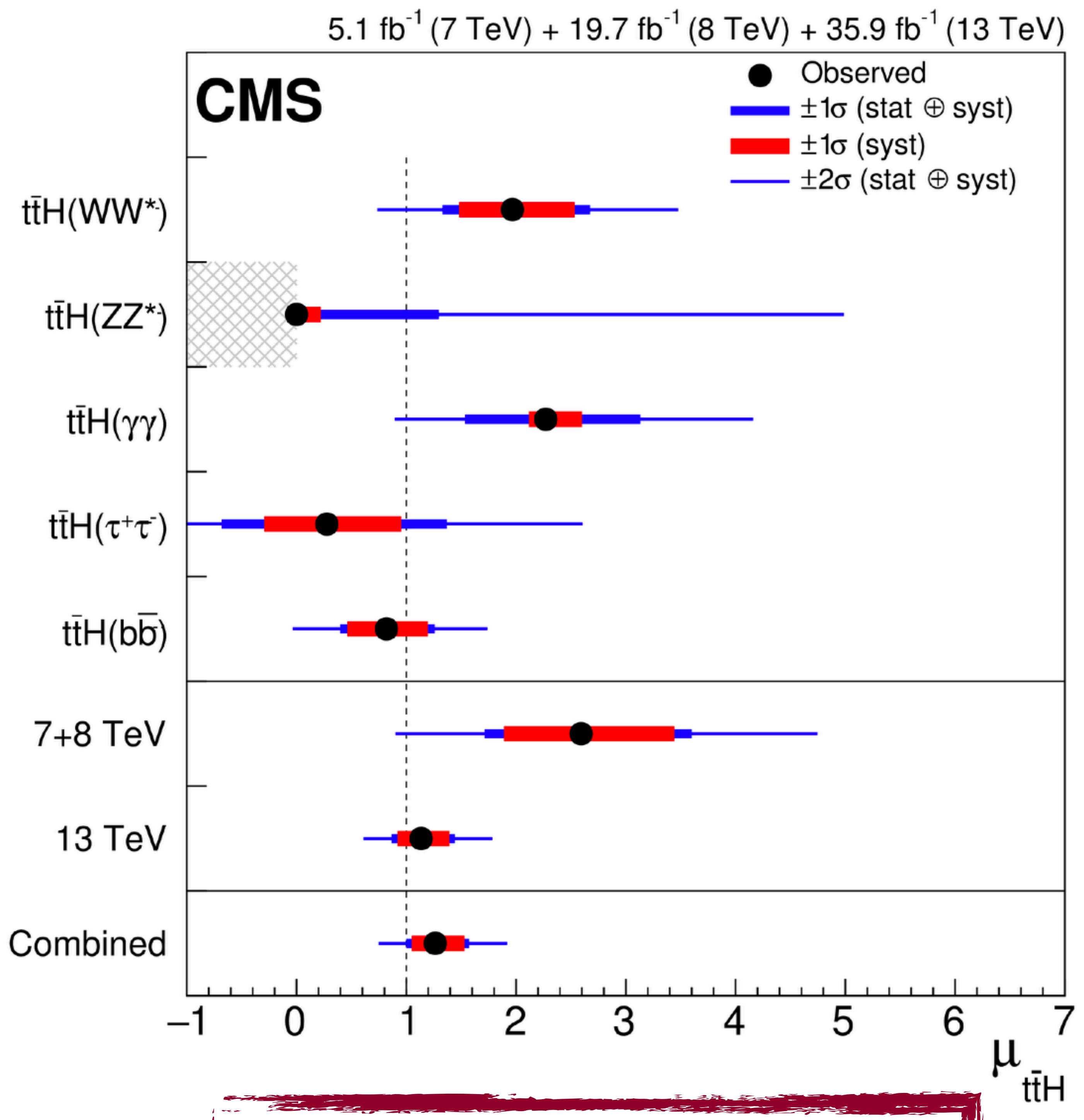
satisfying but not exhaustive

- we also like to search for what is still unknown, beyond the SM

how are we looking
for new Physics Phenomena?

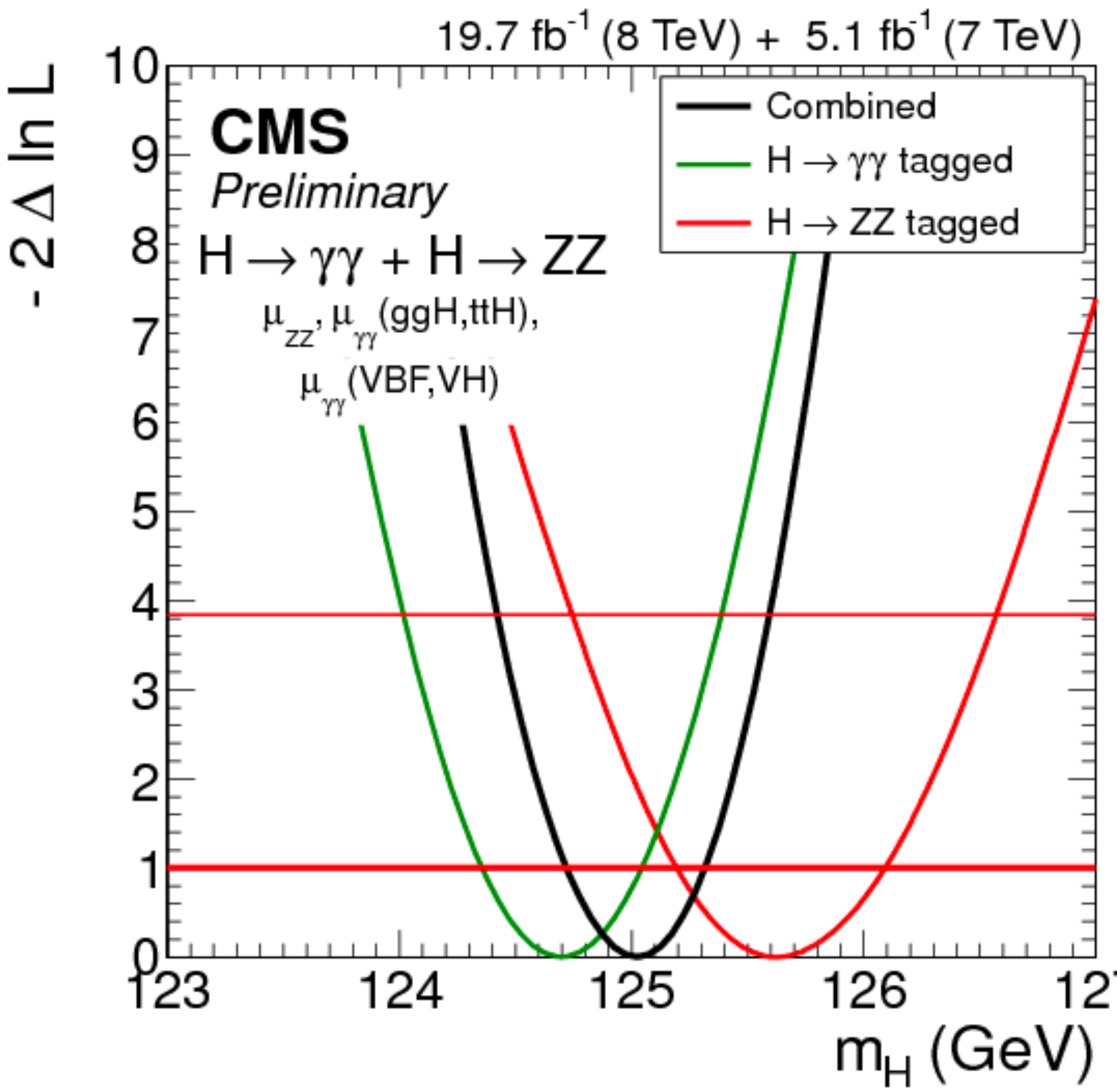
The last great discovery: the Higgs

Since ’12 the Higgs boson has been studied in full details: cross sections, mass, couplings, spin, CP

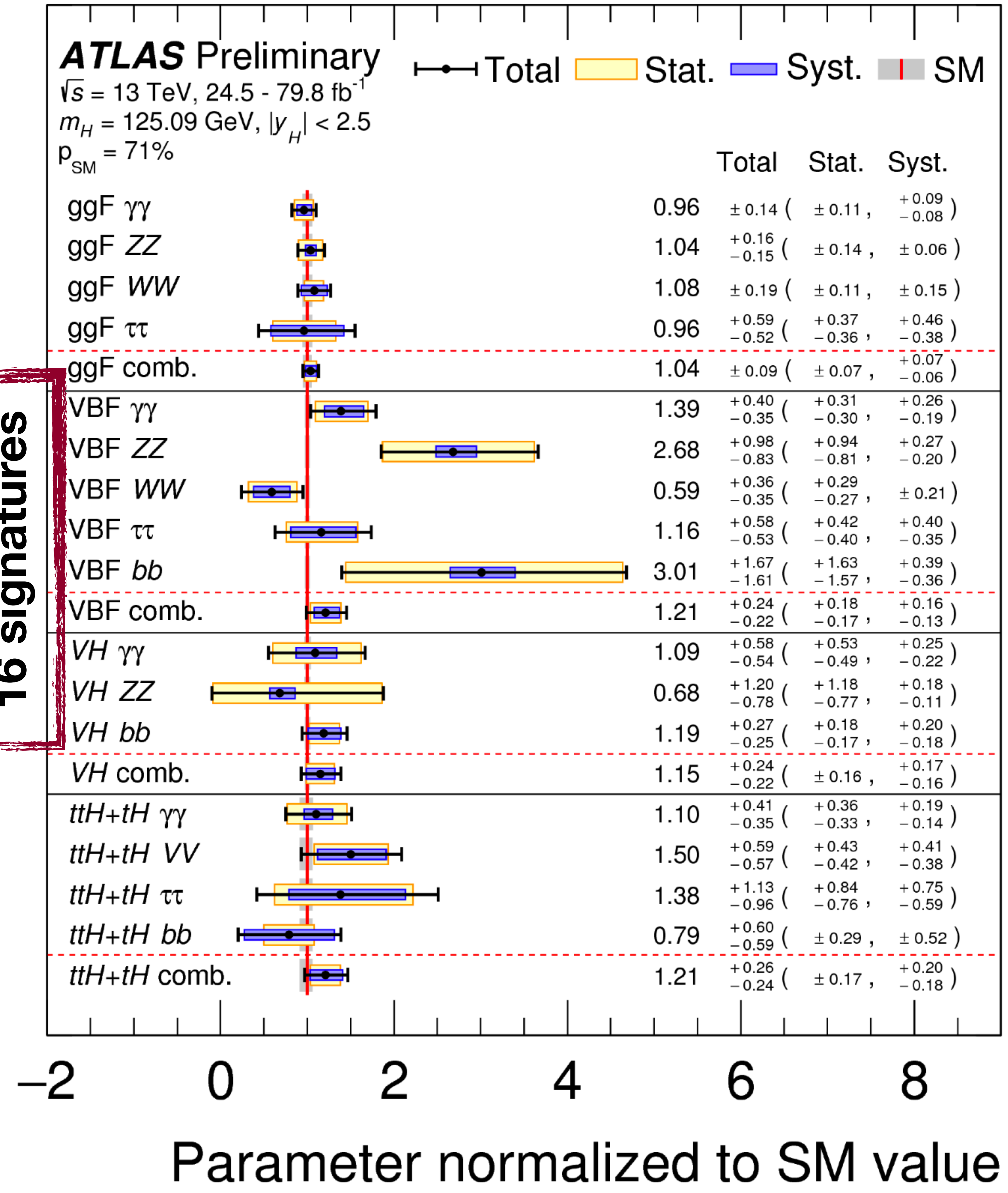


ttH cross section

m_h combination

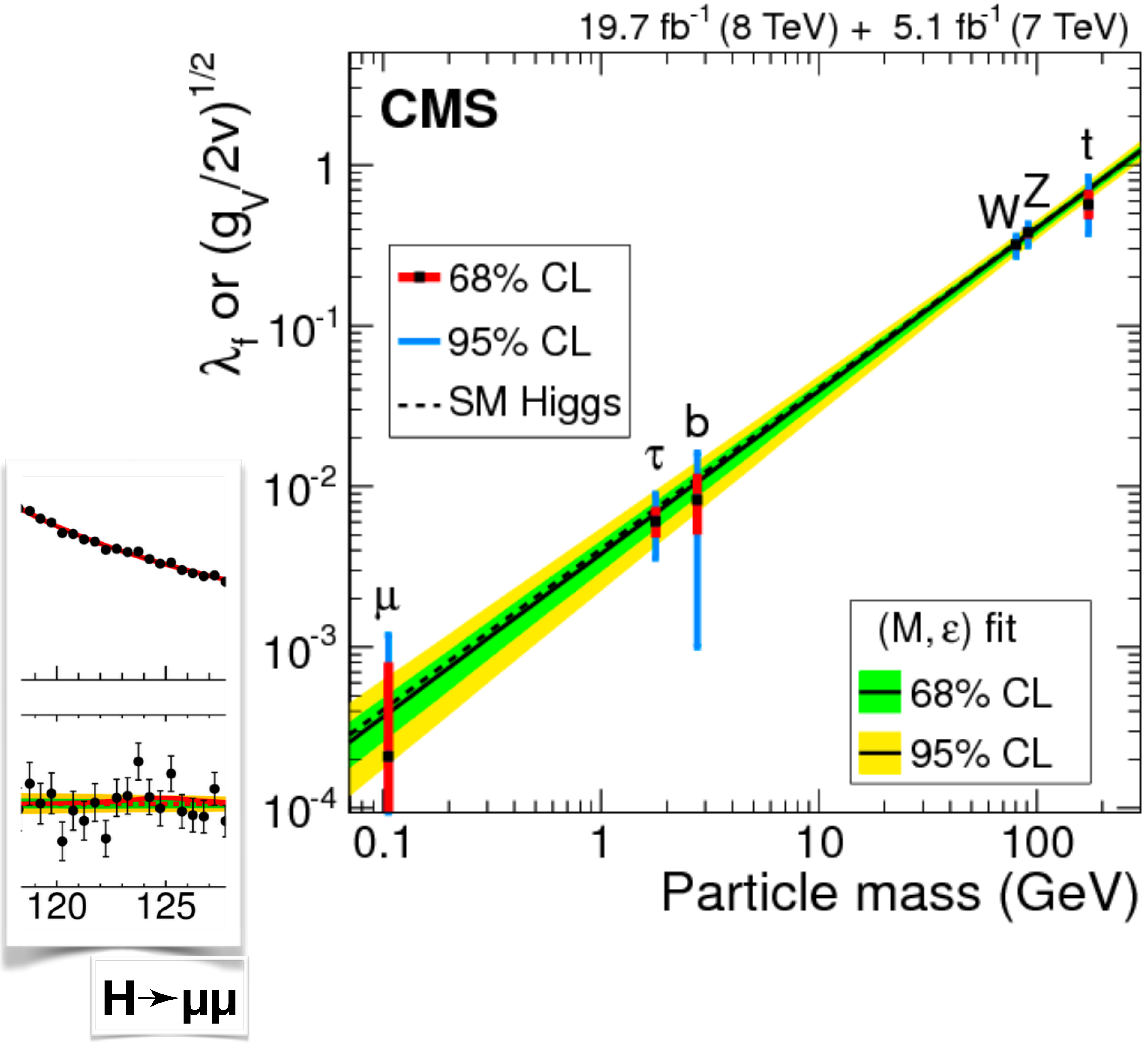


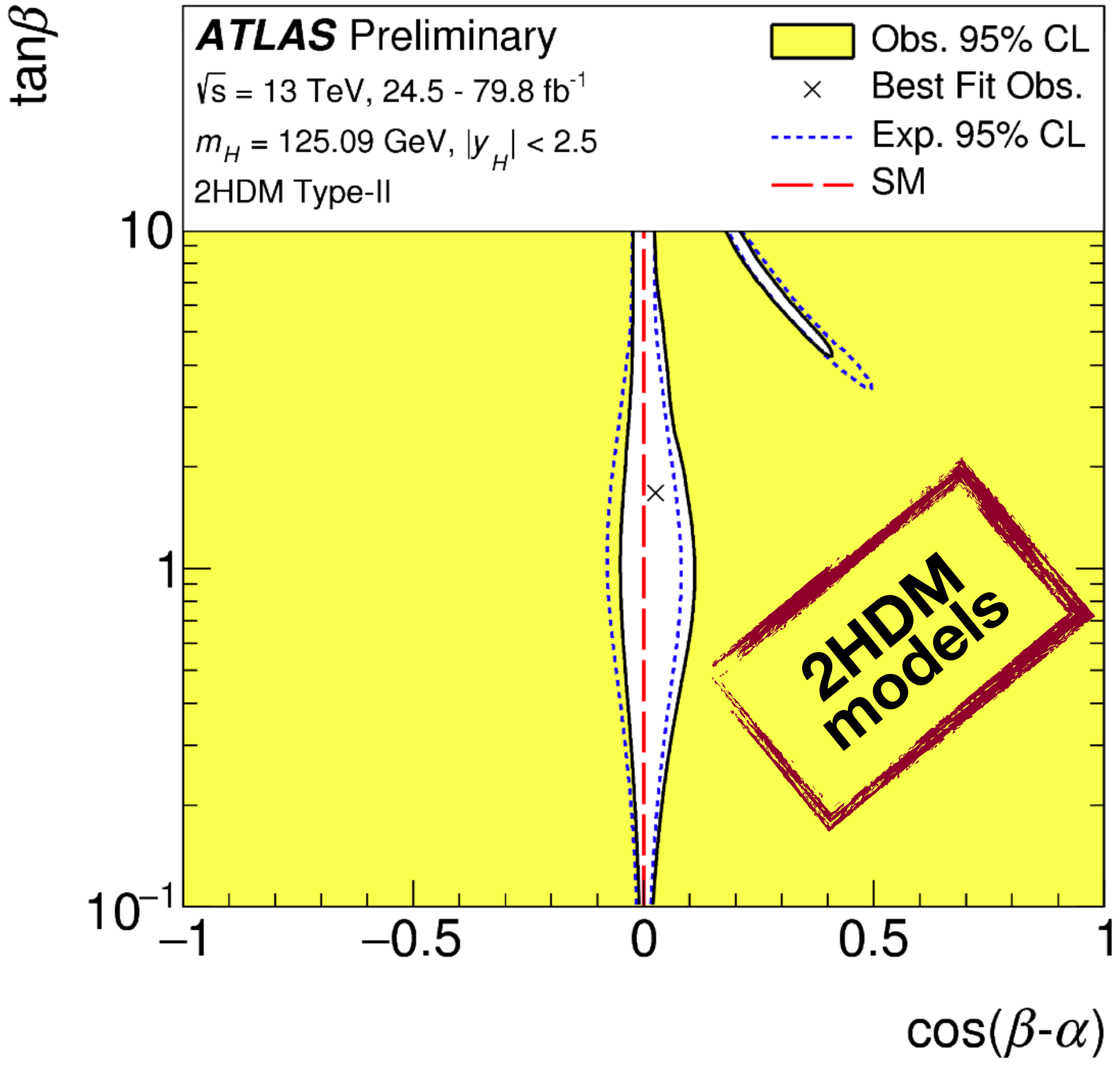
16 signatures

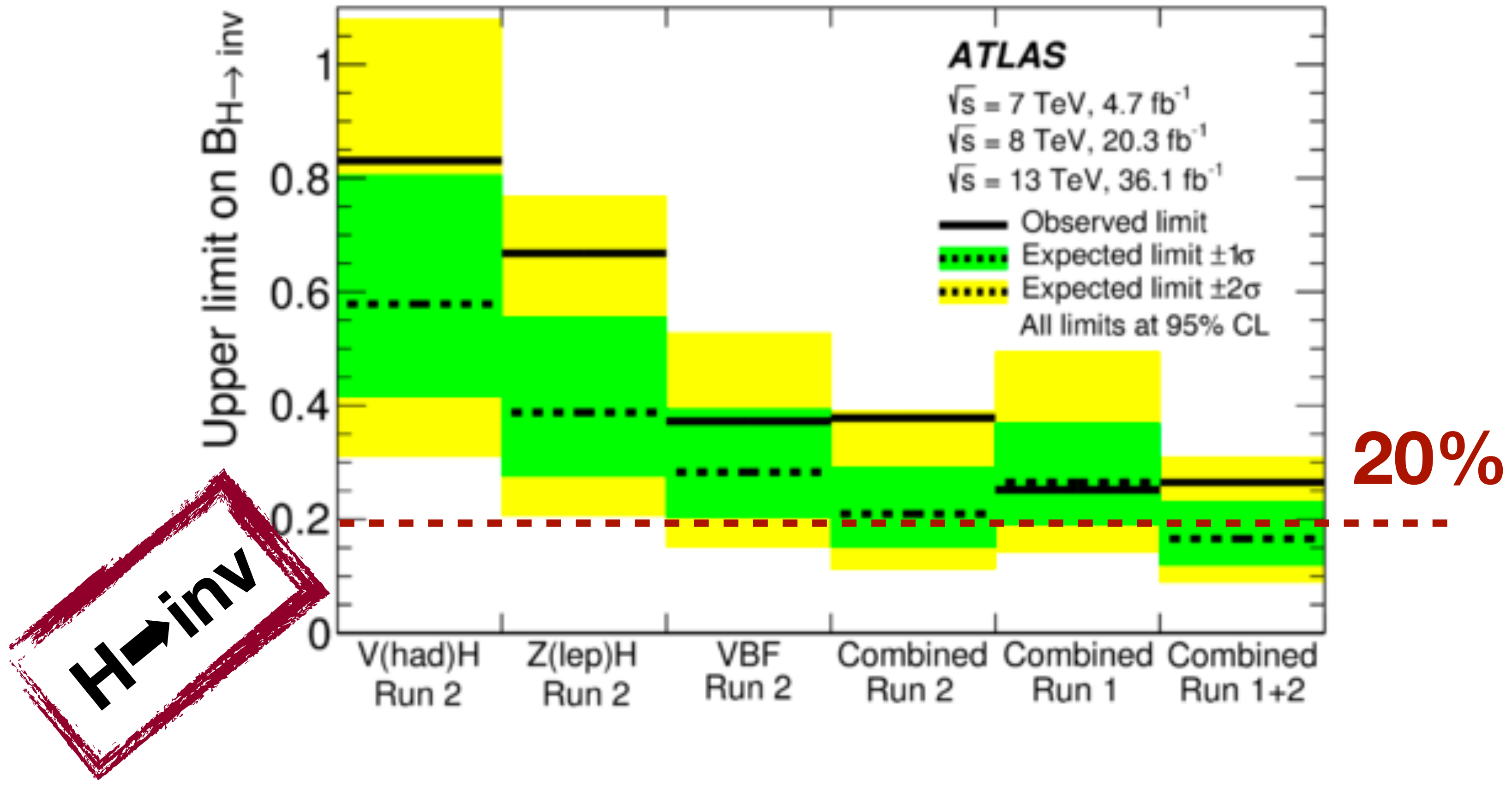


Is it really the SM Higgs?

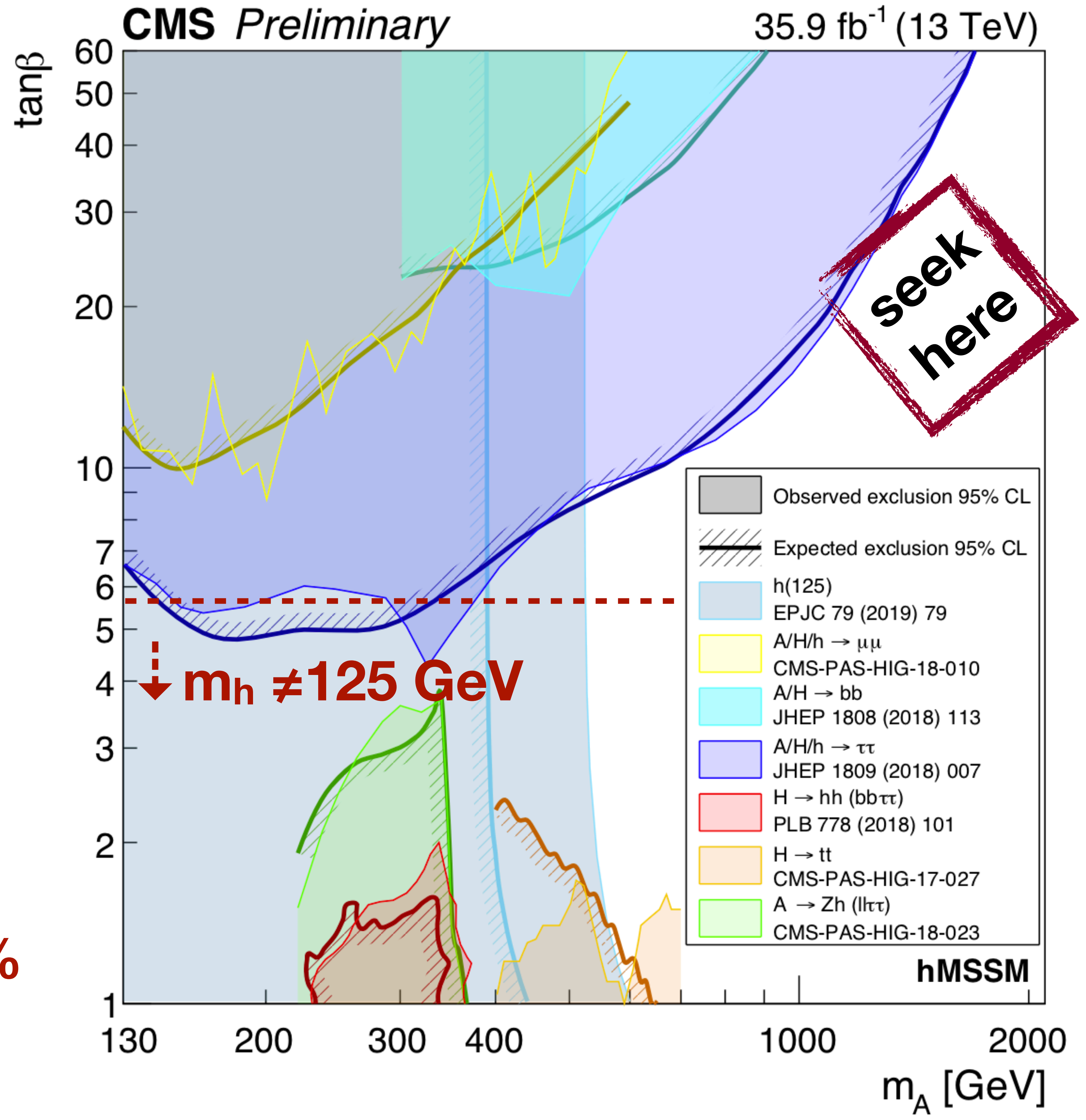
Everything looks consistent with B.E.H. predictions, *so far*





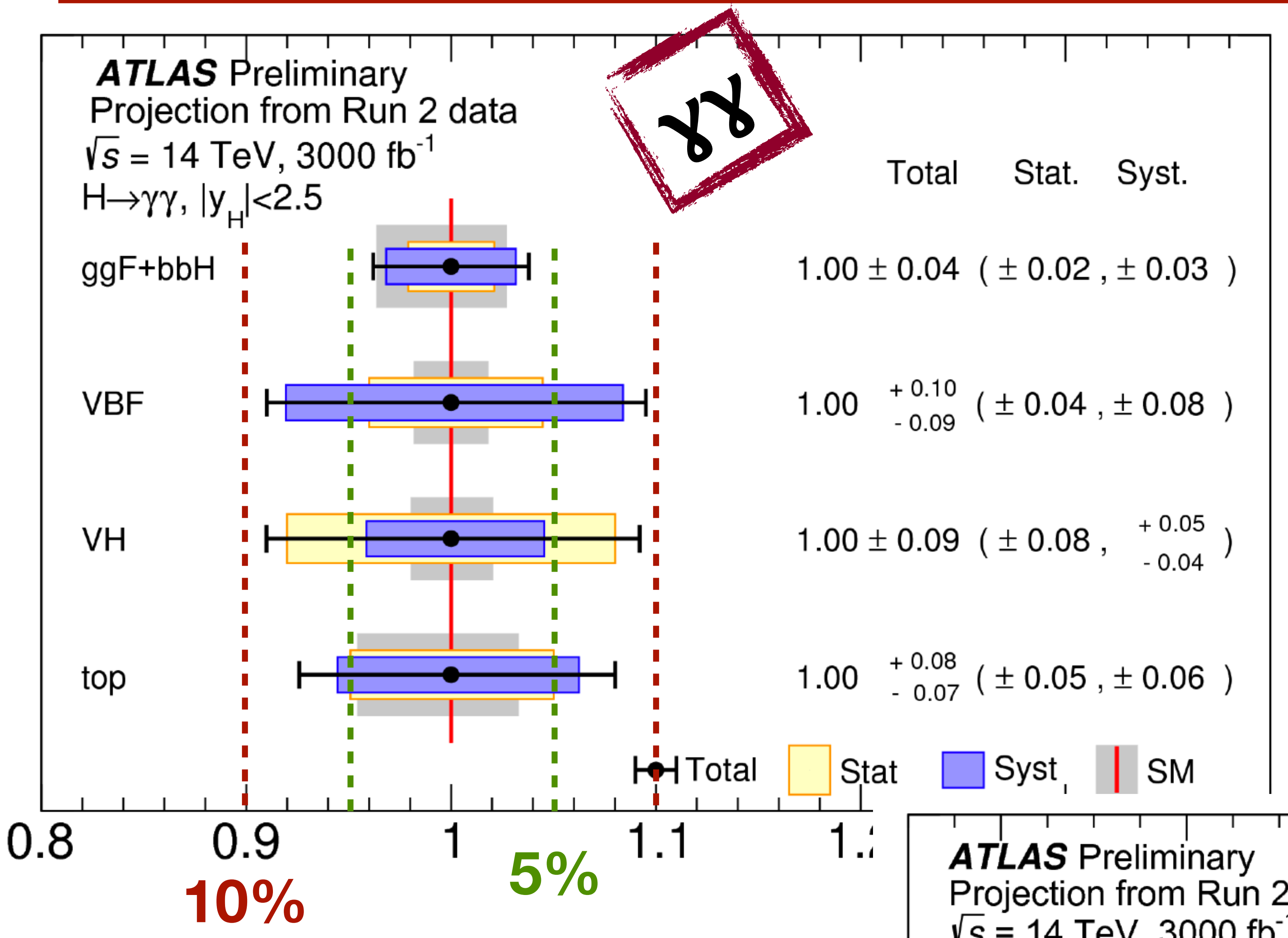


Can be the lightest of a crowded Higgs sector?
(i.e. 2HDM, MSSM, etc.)

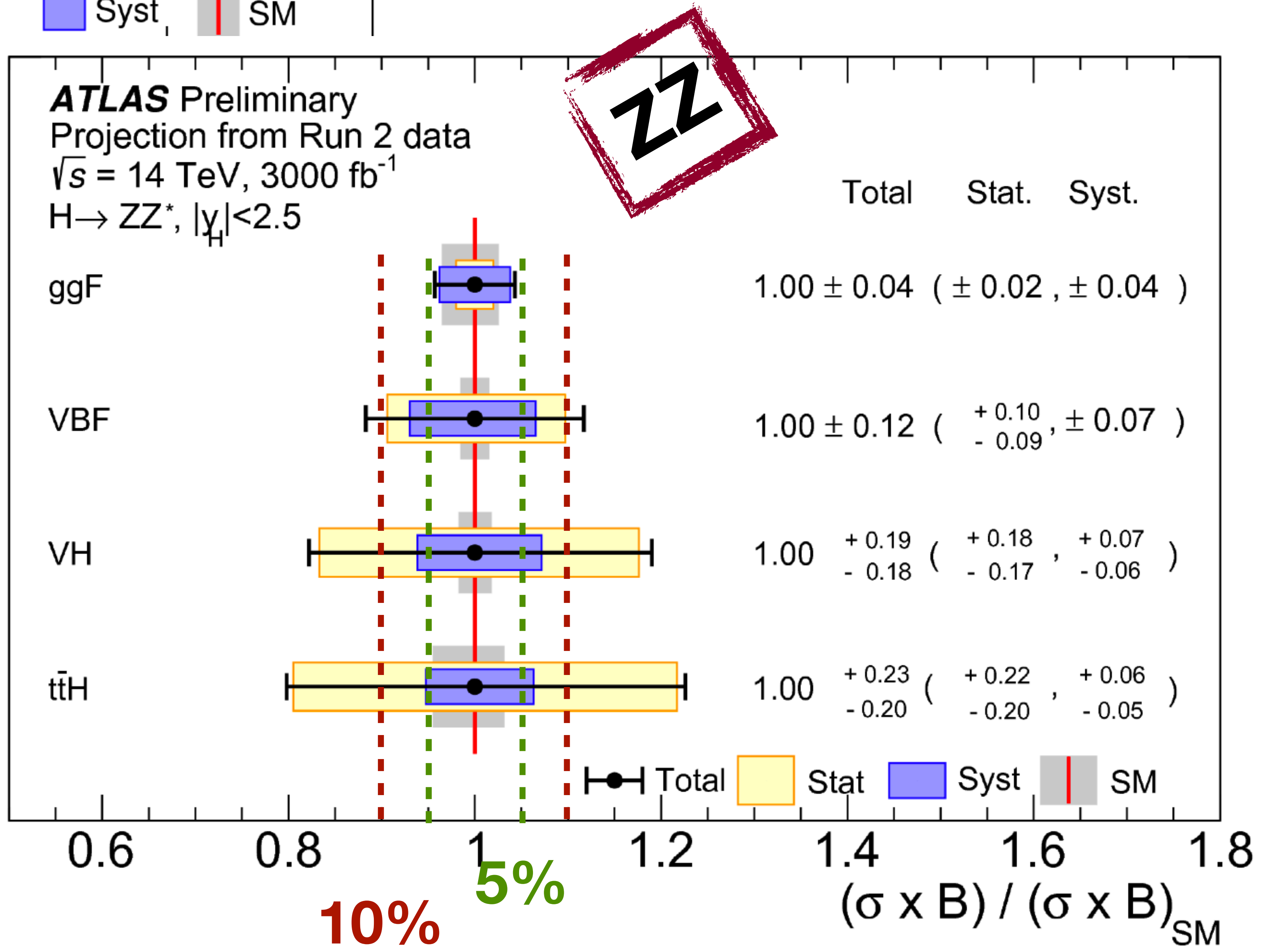


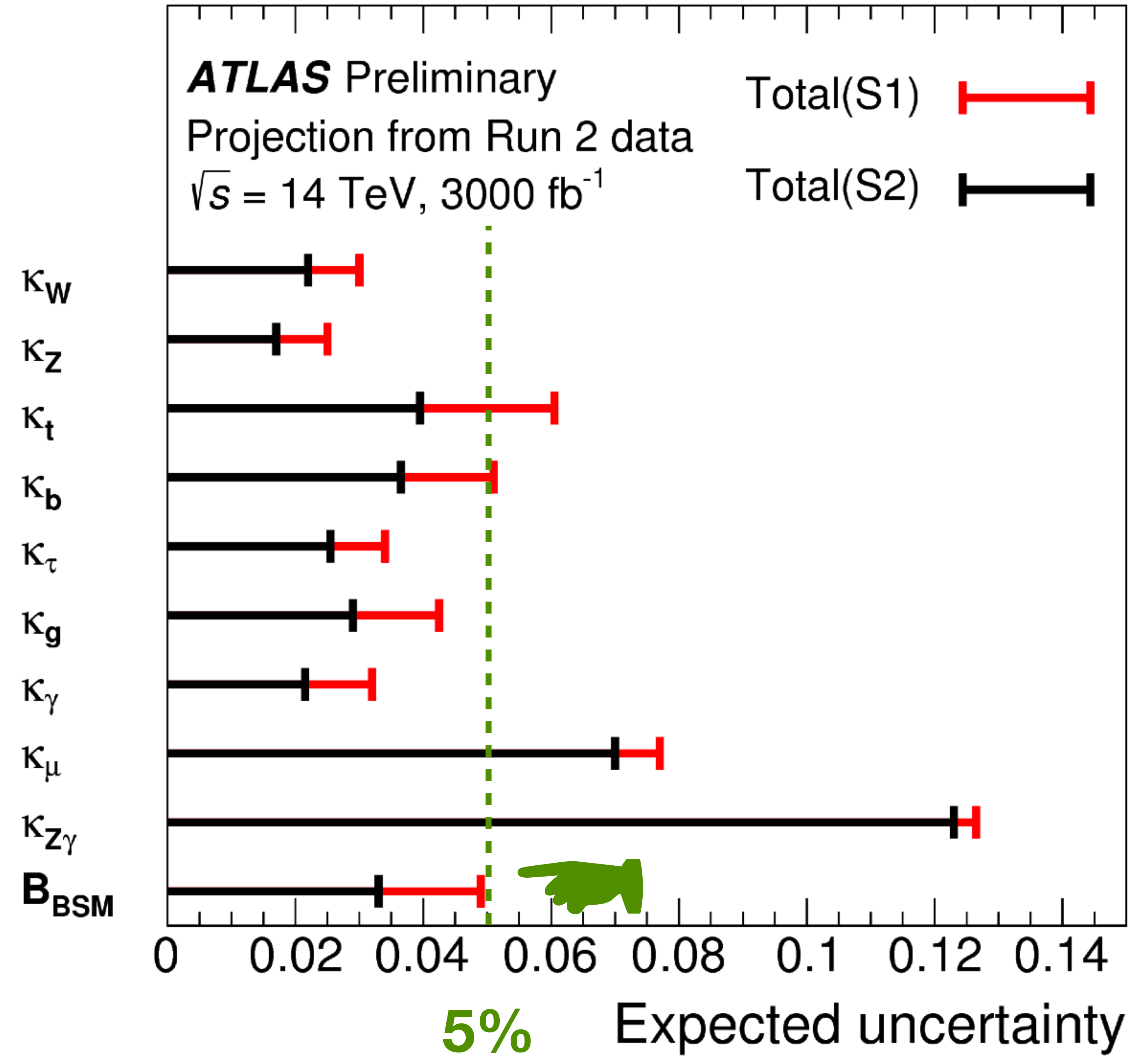
3 ab^{-1}

Will the future tell us more?



⇠ Cross section uncertainties will be halved, though still some limited by statistics (combinations needed)

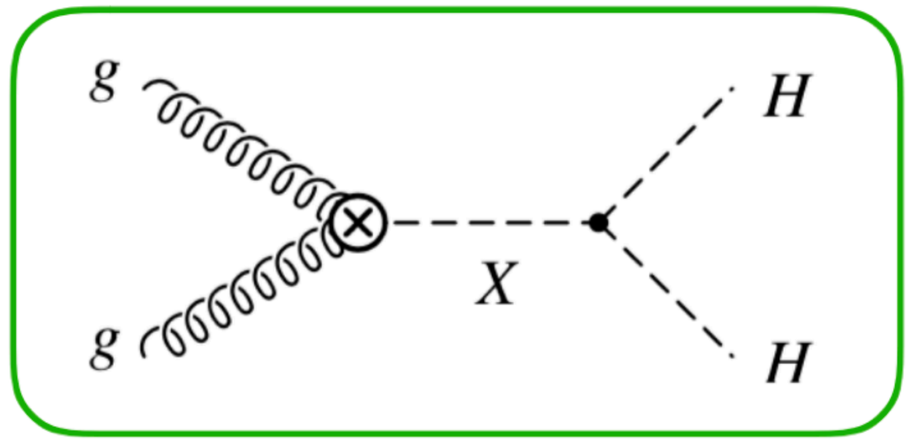


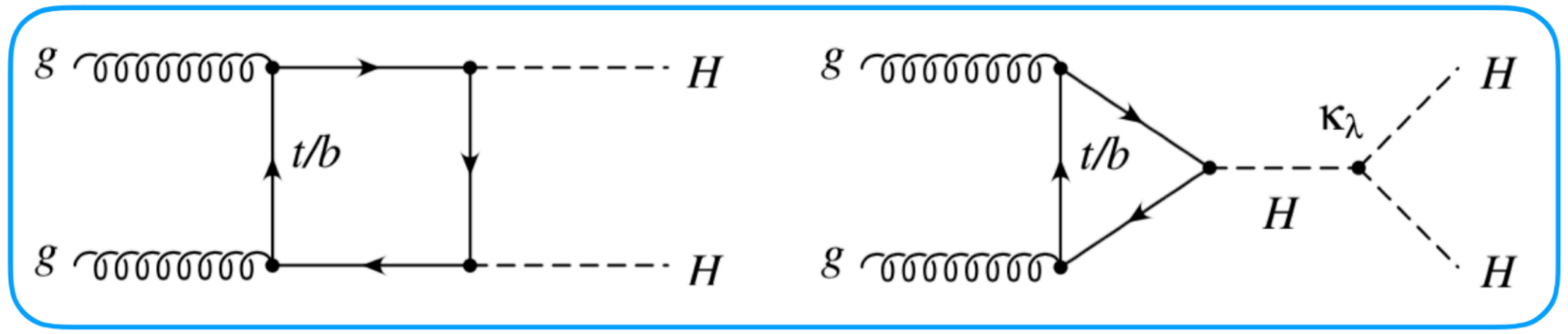


⇡ Couplings will be known at the few % level

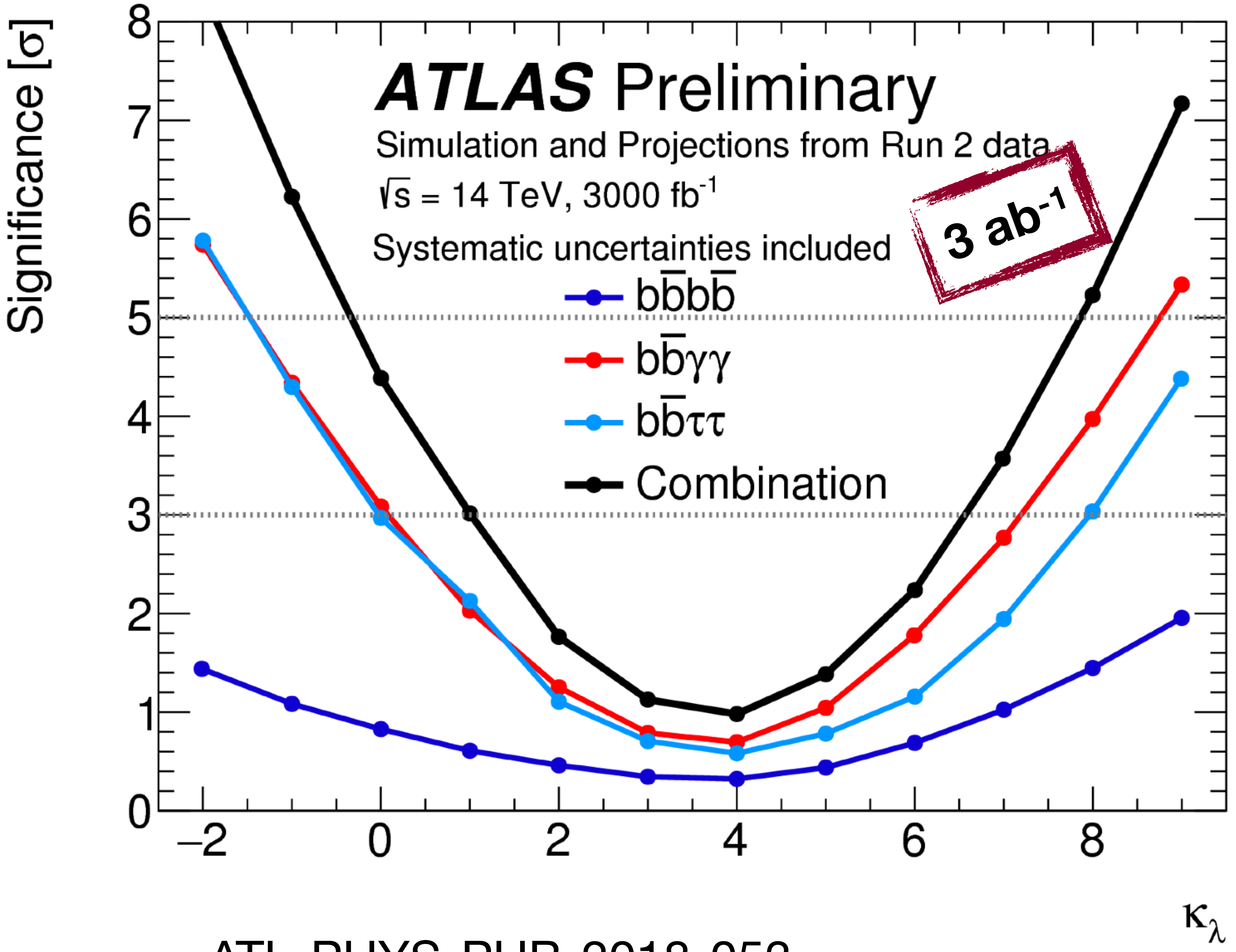
ATL-PHYS-PUB-2018-054

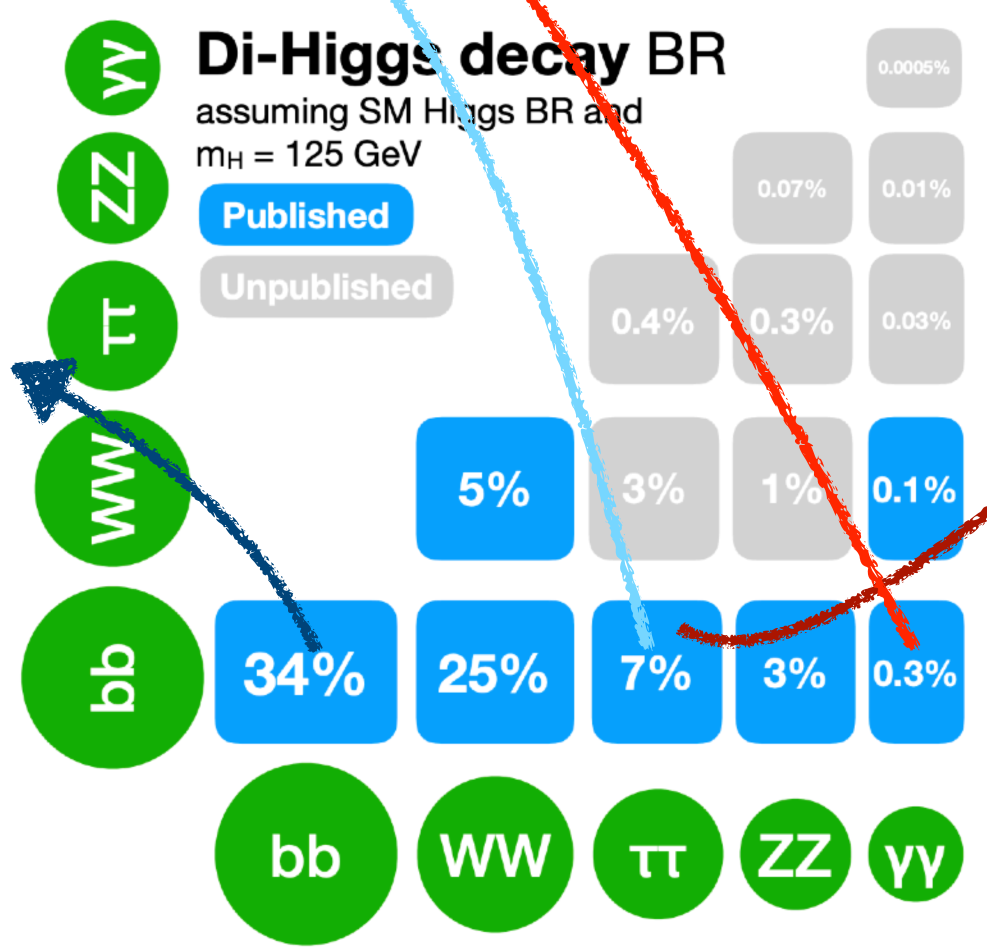
Pair produced Higgs

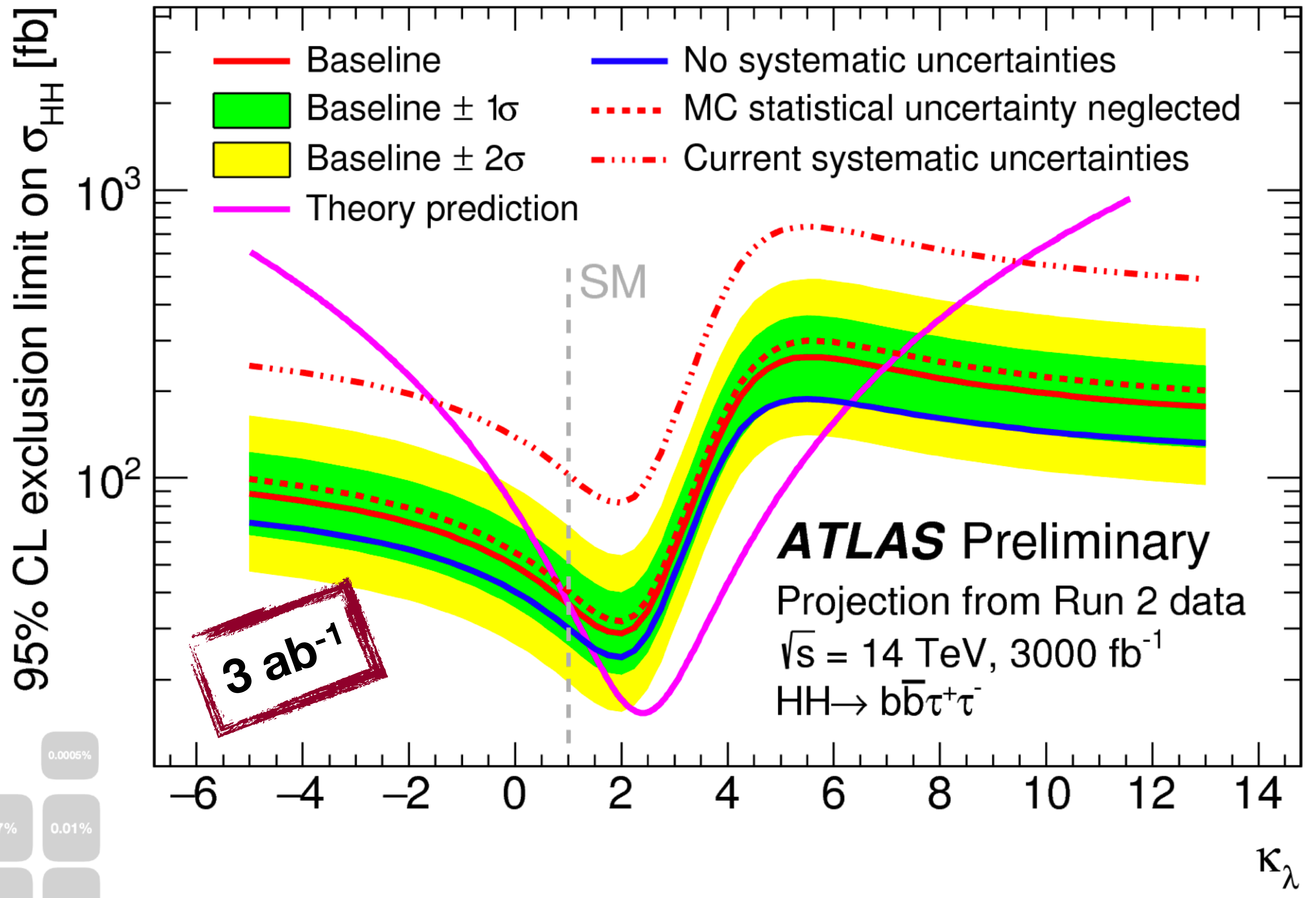




- Double Higgs production is already ongoing, but **will be sensitive to SM anomalies** with much higher statistics







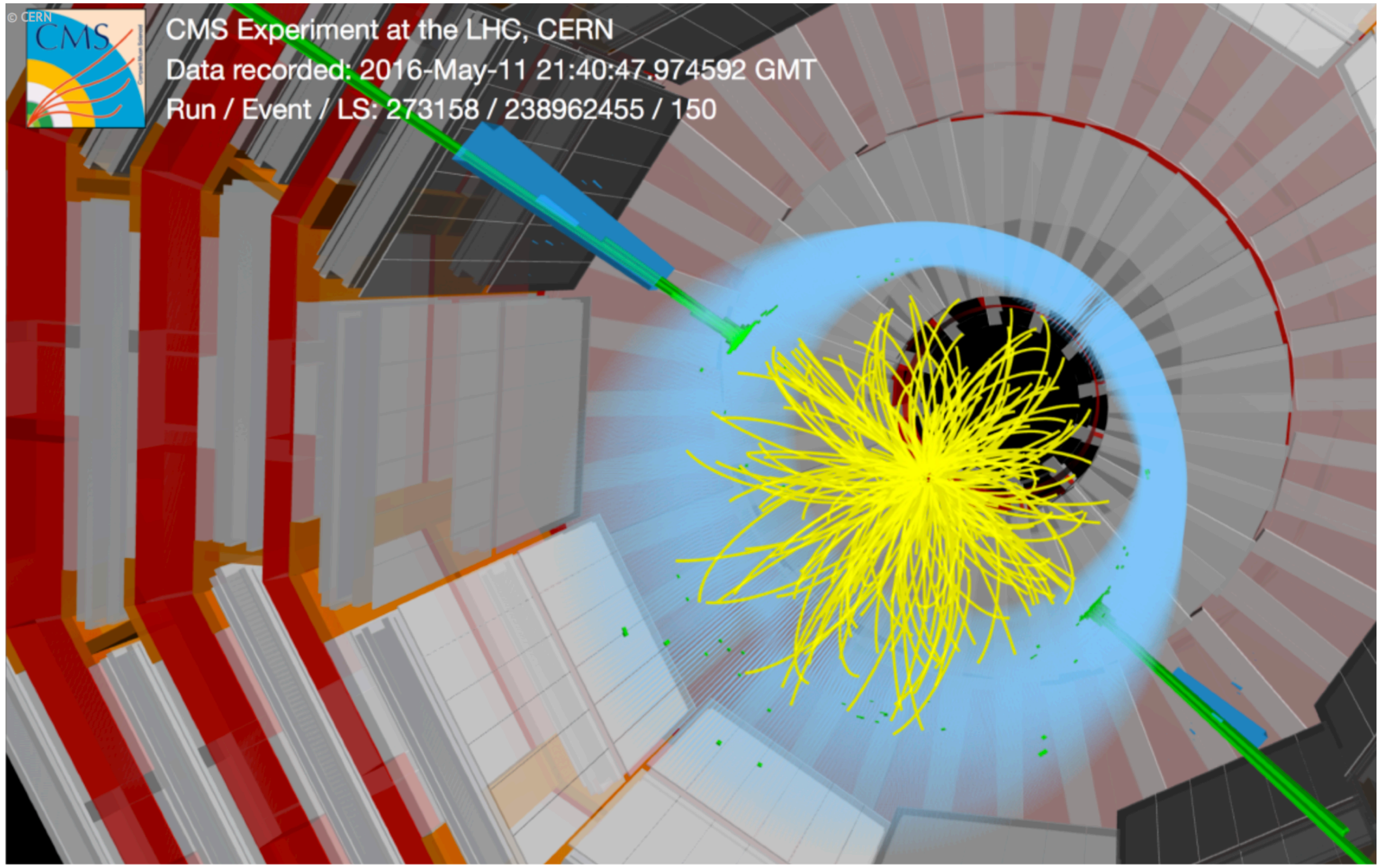
ATL-PHYS-PUB-2018-053

Always looking for more

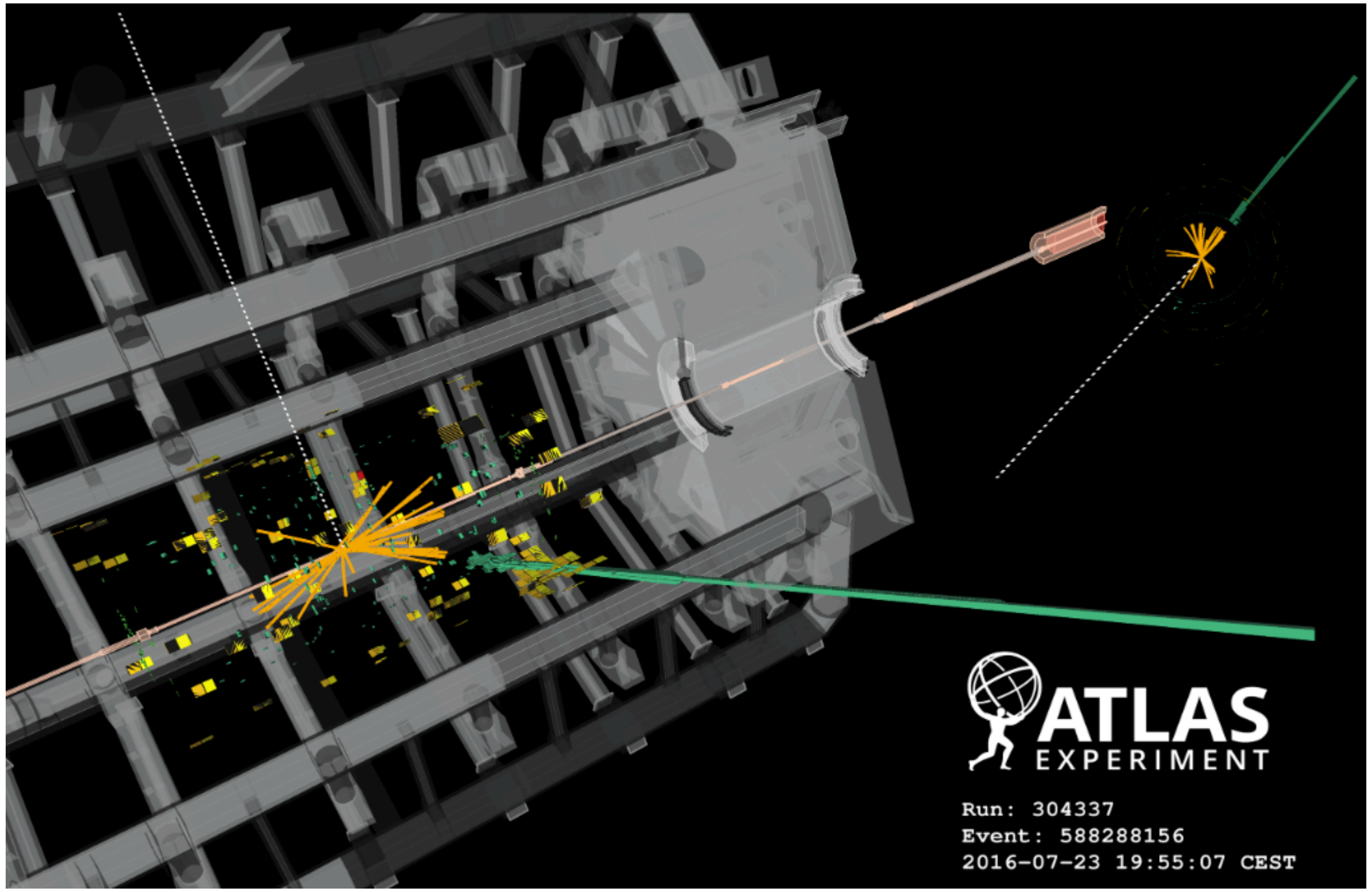
We should seek all possible evidence for NP

LHC: the Ideal Machine to Search for Heavy Resonances

8 TeV DiJet Event!

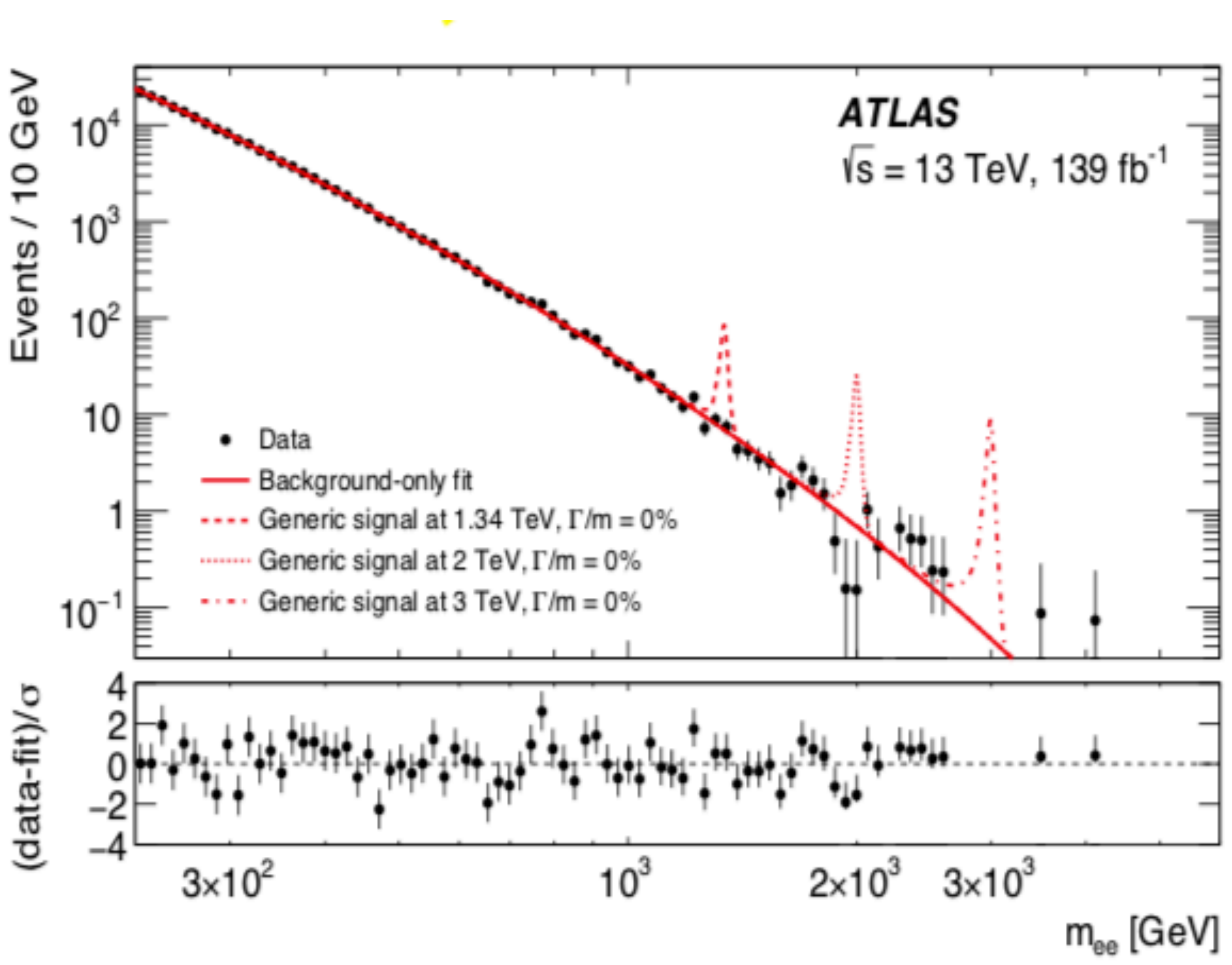


2.2 TeV l+MET Event!

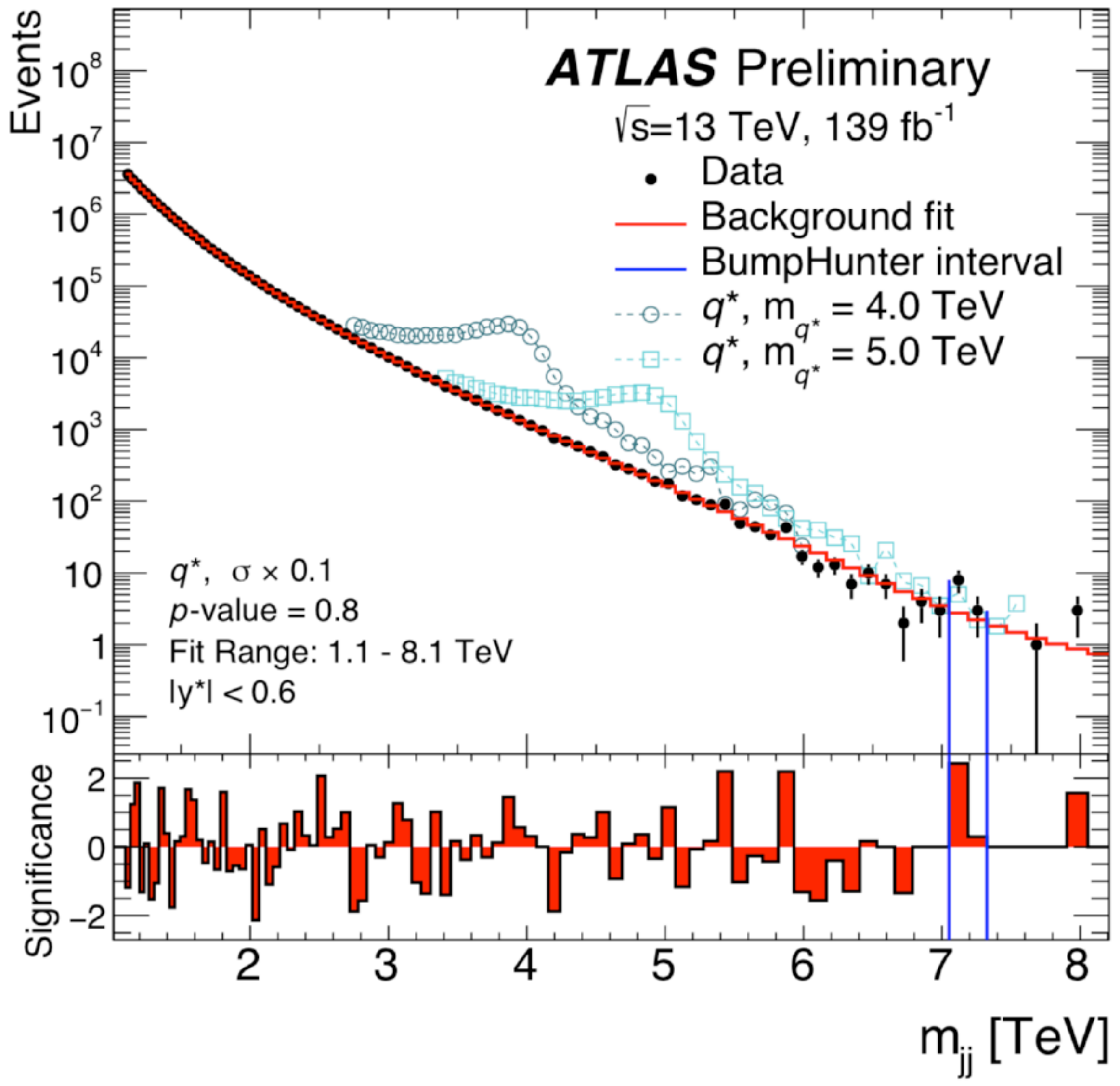


We’ve Done a Lot of Bump Hunts!

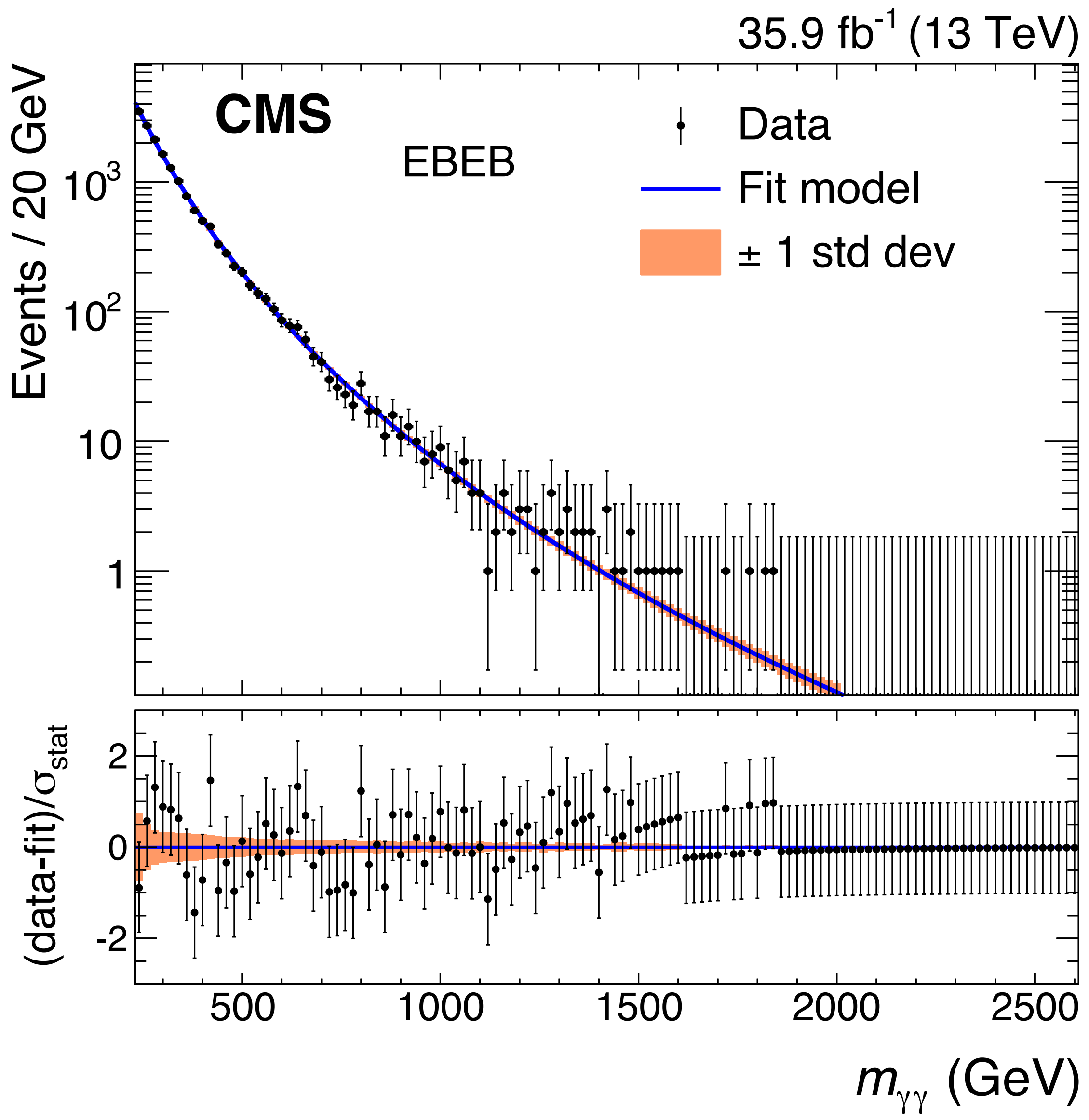
Dileptons



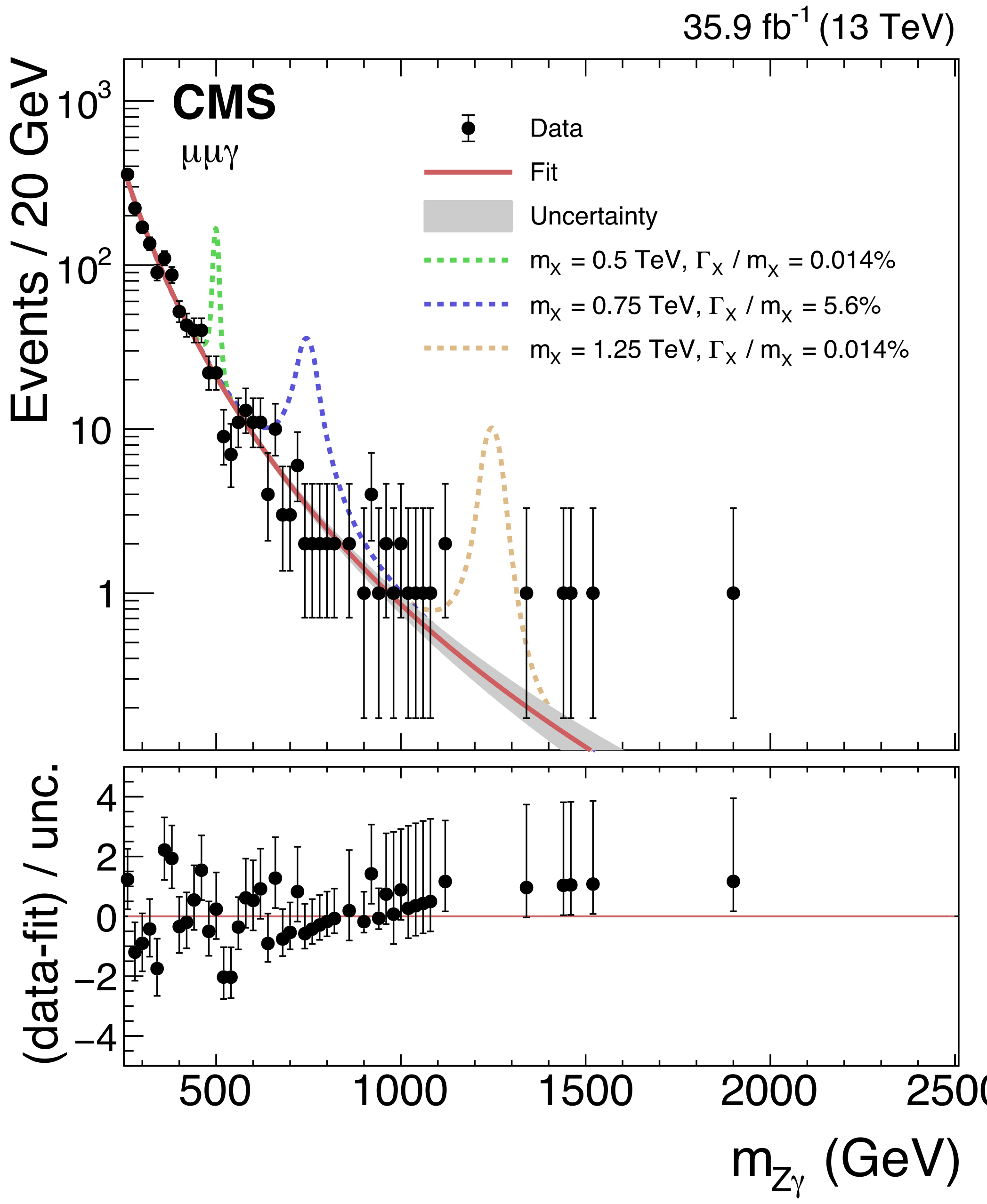
Dijets



Diphotons



Z+photon

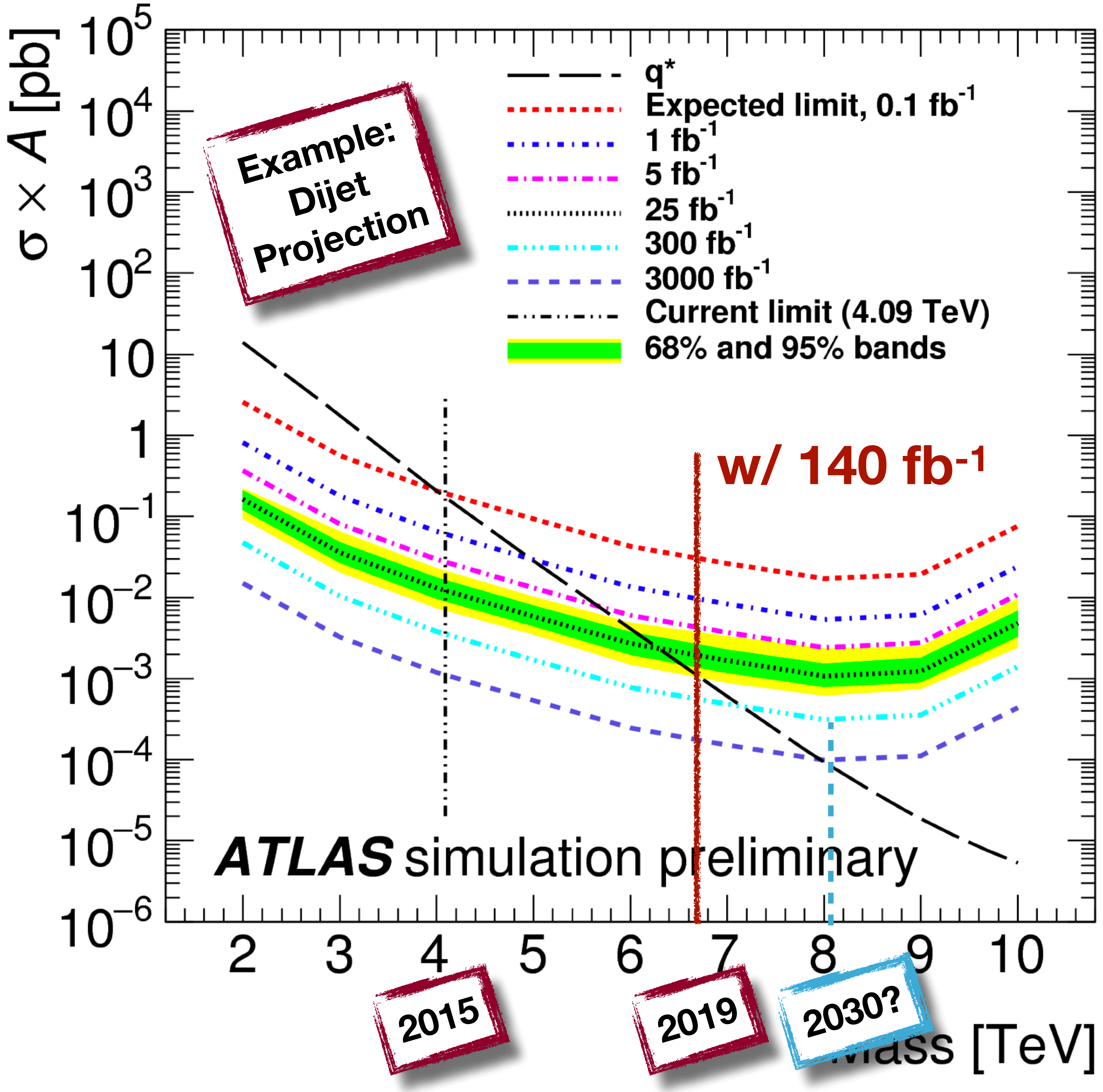


… and so on (also b’s, τ’s, top, etc)

But Bump-Hunts Are Running Out of Steam

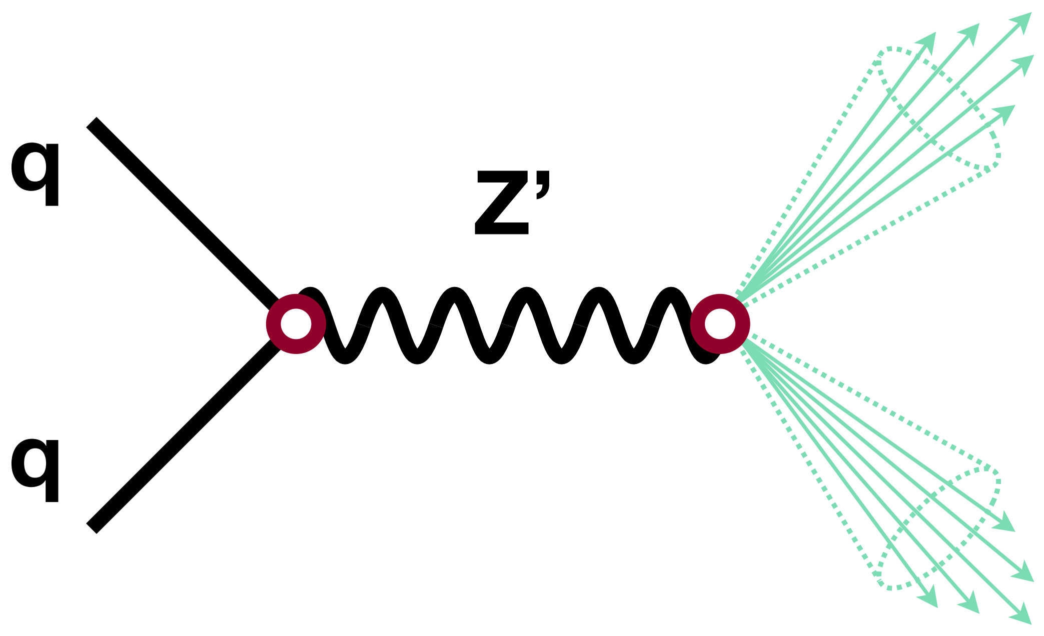
- Probing **really high** masses: O(10 TeV)
- More lumi brings **marginal** improvements
- Can't just reload searches: need **new ideas**

examples	Mass Lower limit
String resonance (jj)	~ 8 TeV
Excited quark (jj)	~ 6.5 TeV
Z' (SSM) (ll)	~ 5 TeV
W' (SSM) (lv)	~ 6 TeV



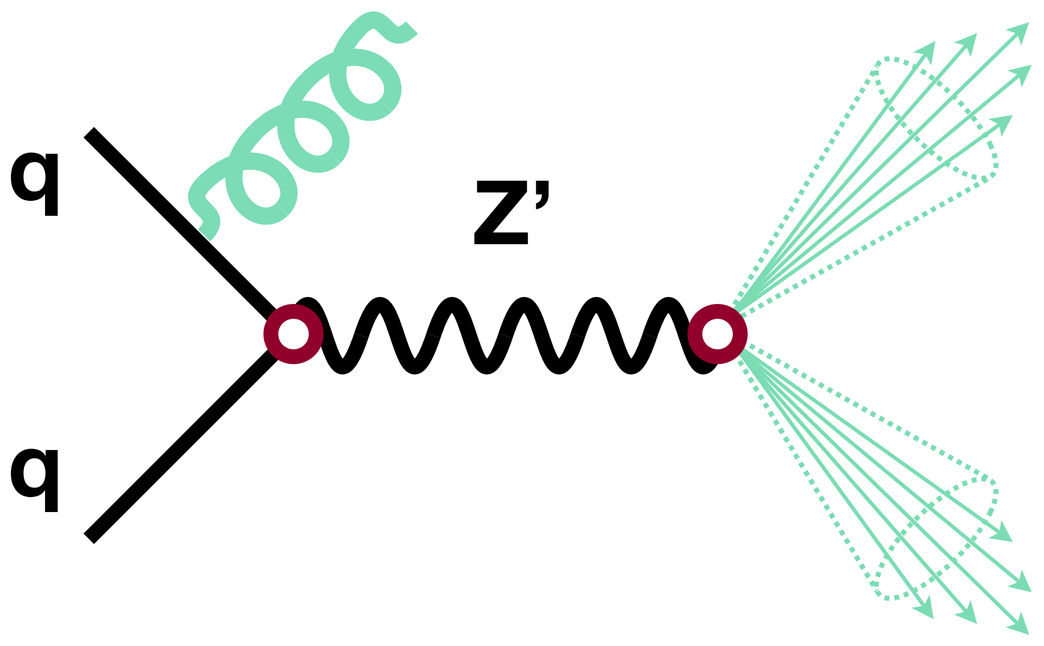
Example: Dijets Going to Lower Mass with ISR and Substructure

High Mass
(M > 0.5-1.5 TeV)



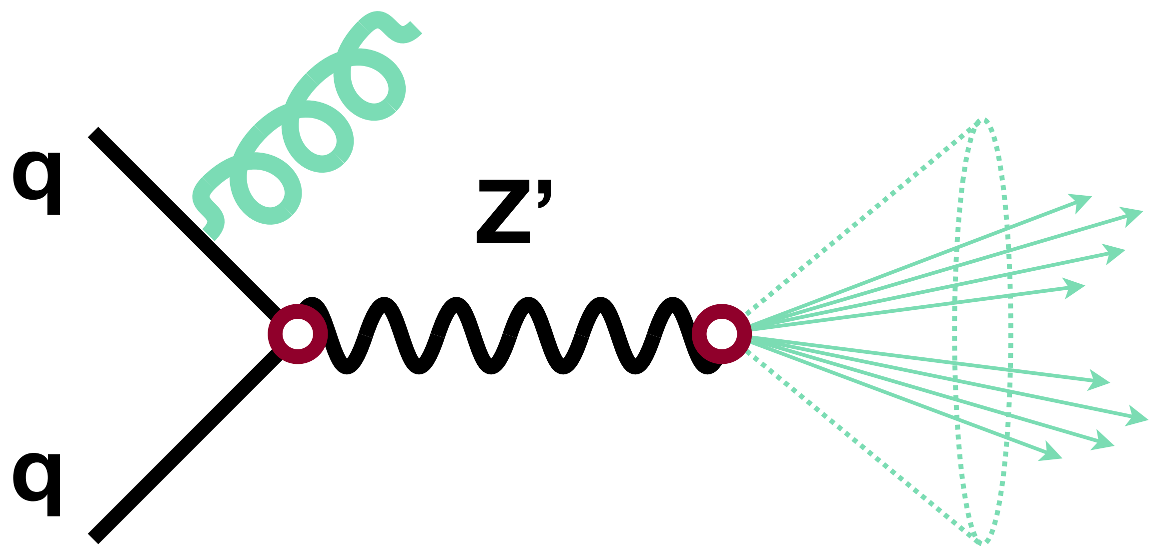
- Two high energy jets
- No problems with trigger for M >~ 1.5 TeV
- Can go down to ~ 0.5 TeV with trigger-level analysis

Intermediate Mass
(0.2 < M < 1.0 TeV)



- Need hard ISR to trigger (photon or gluon)
- Mass 'heavy enough' for two resolved jets

Low Mass
(M < 0.3 TeV)



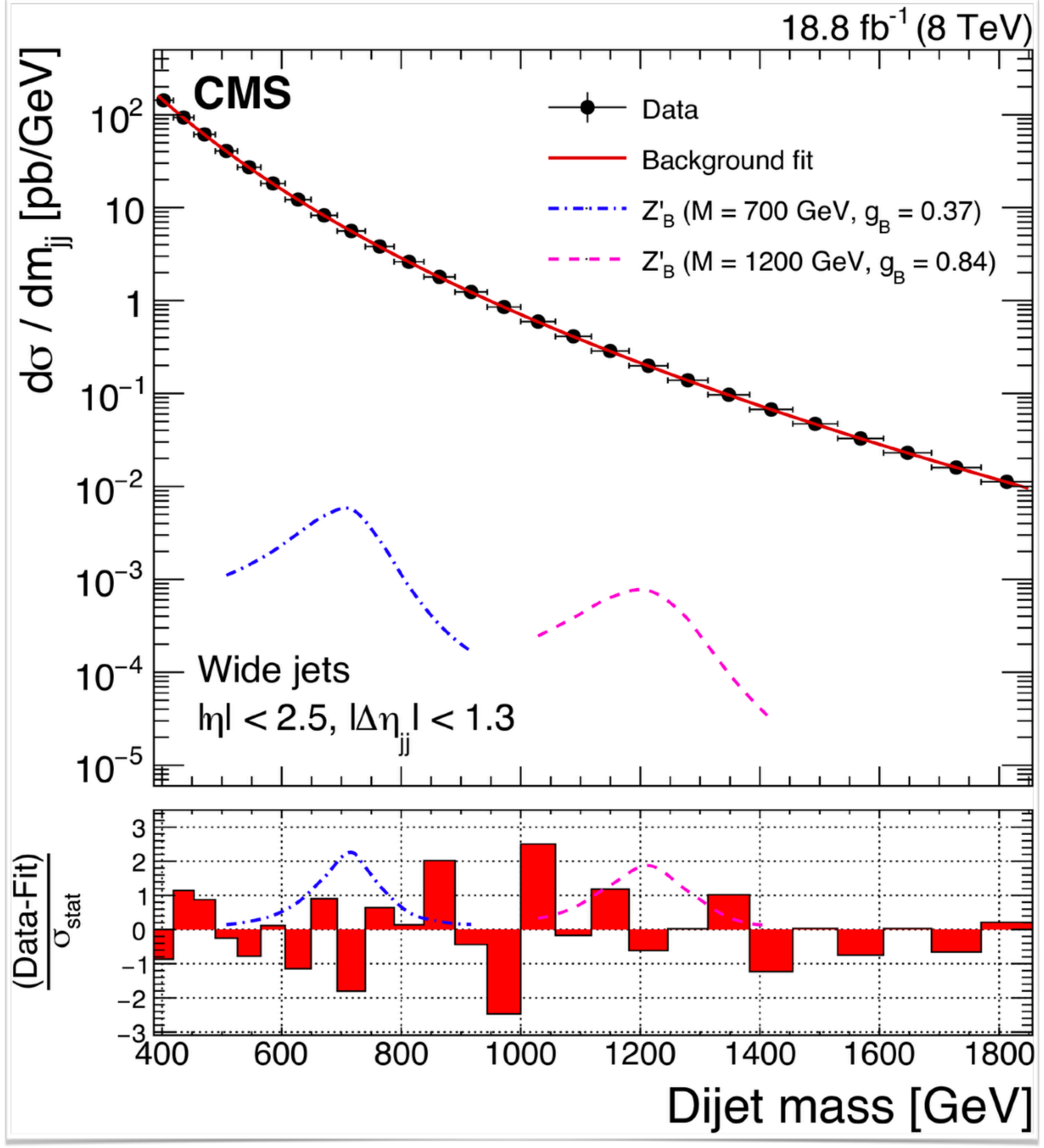
- Need hard ISR to trigger (photon or gluon)
- Light mass: large boost
- Large jet + substructure

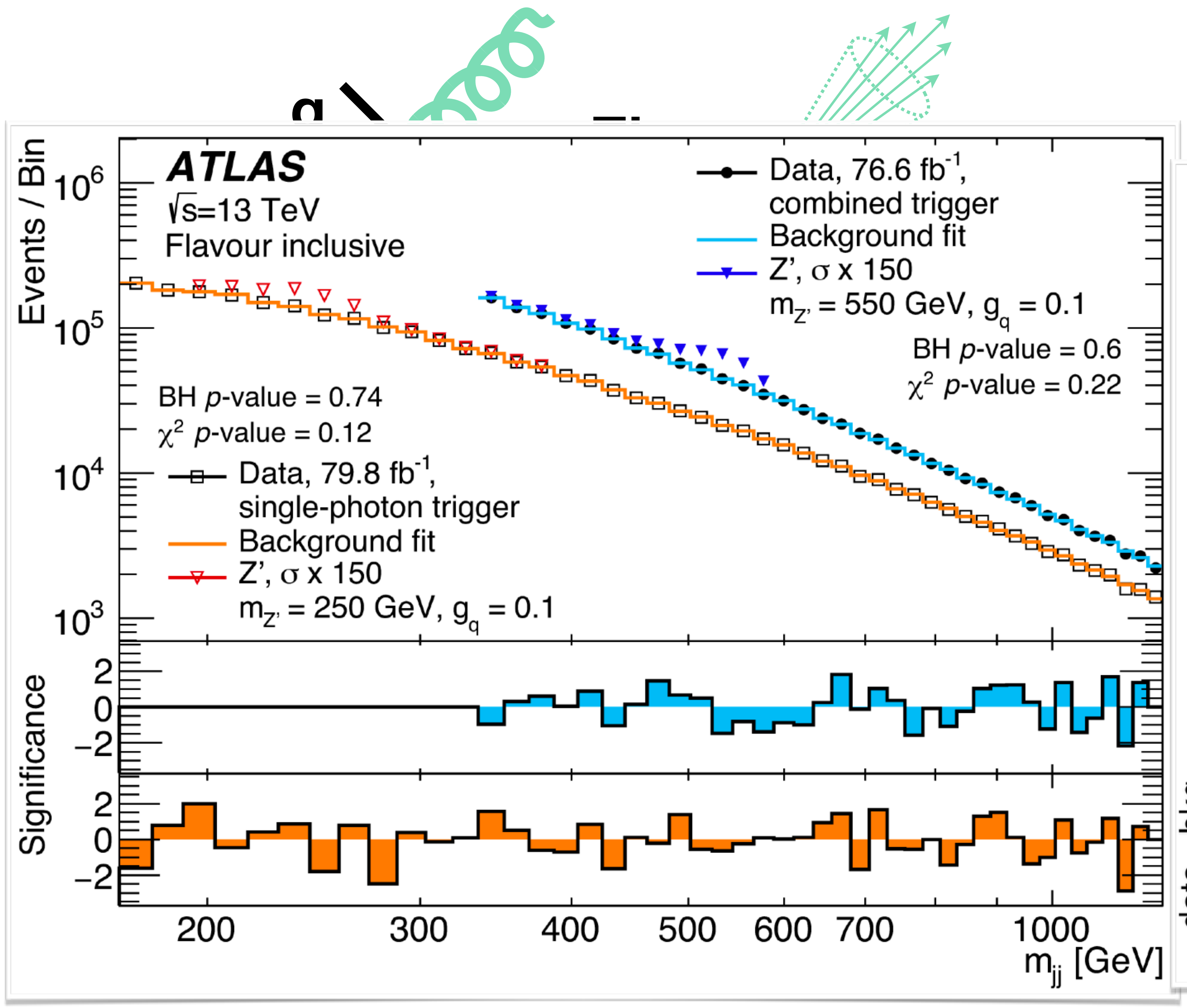
Example: Dijets Going to Lower Mass with ISR and Substructure

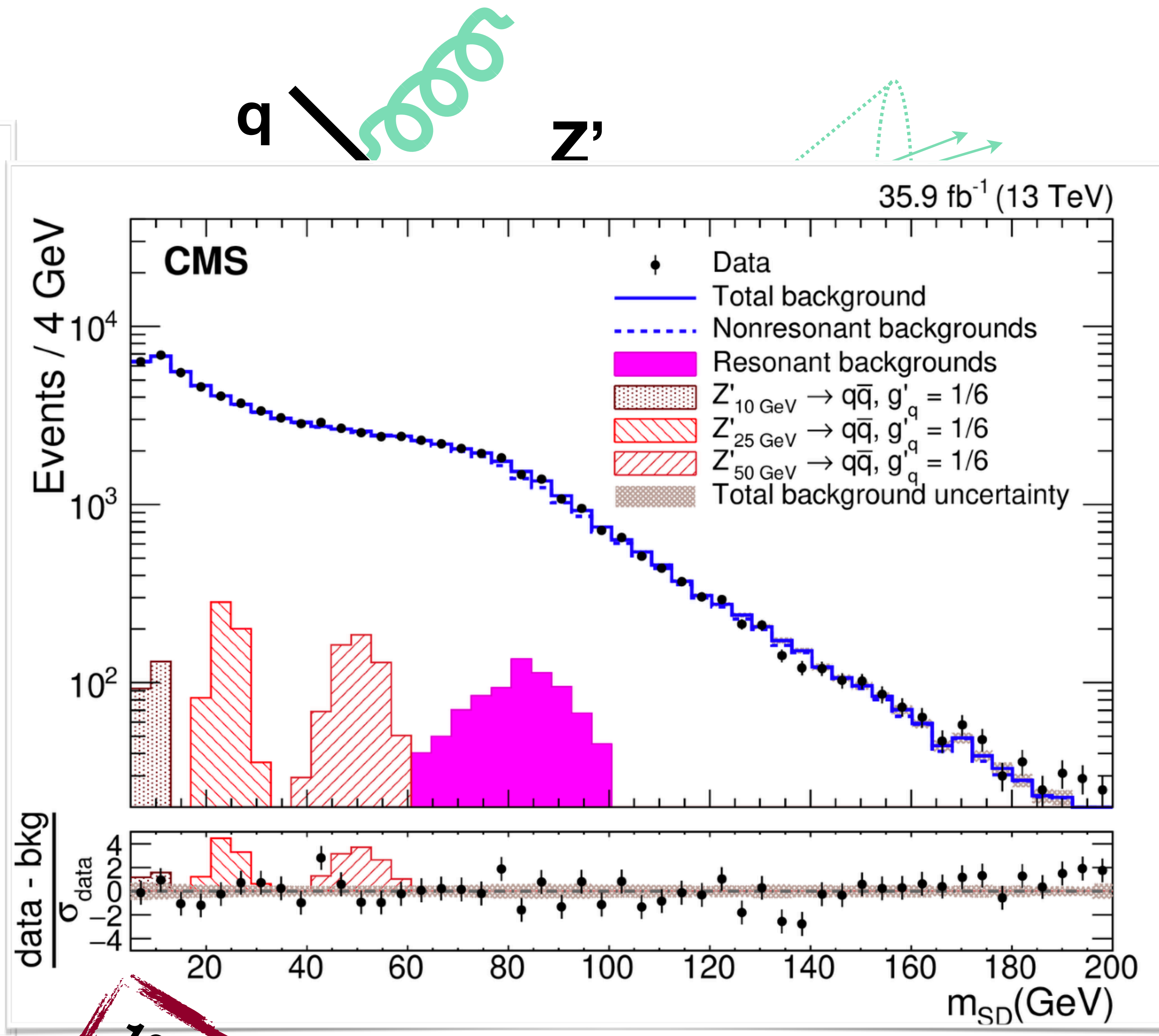
High Mass
(M > 0.5-1.5 TeV)

Intermediate Mass
(0.2 < M < 1.0 TeV)

Low Mass
(M < 0.3 TeV)

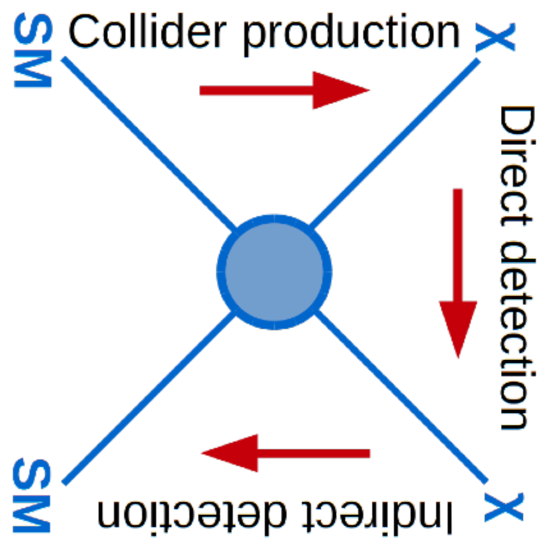


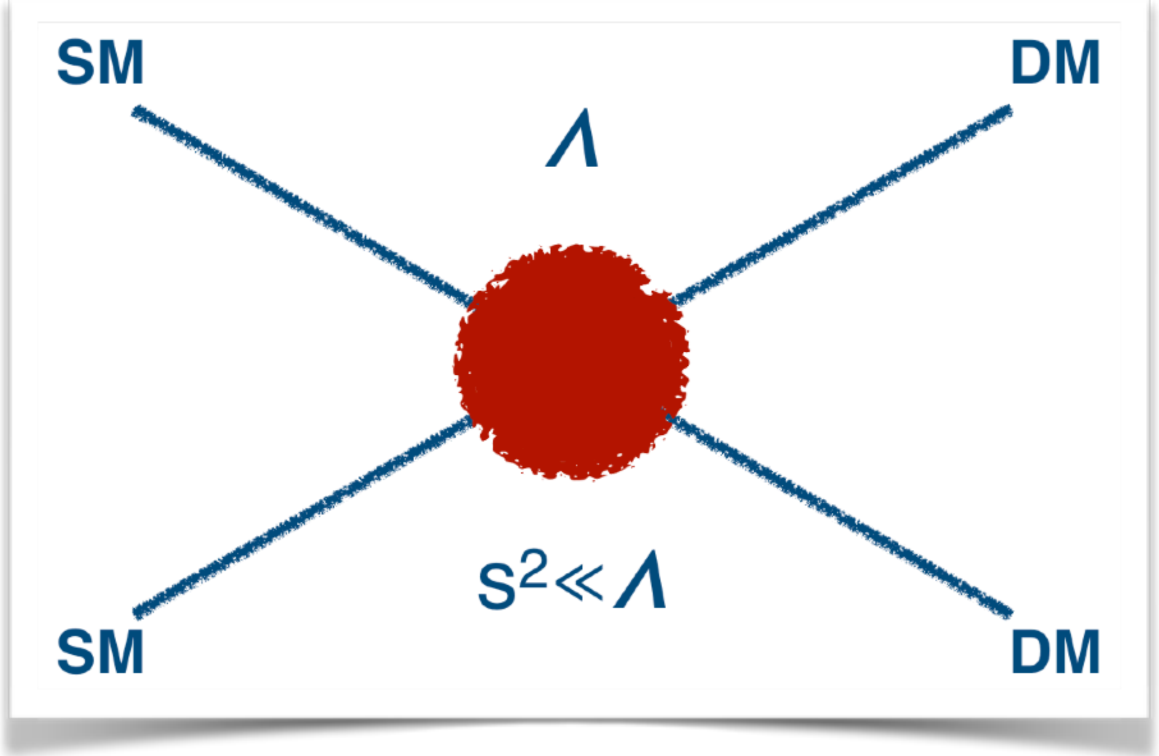


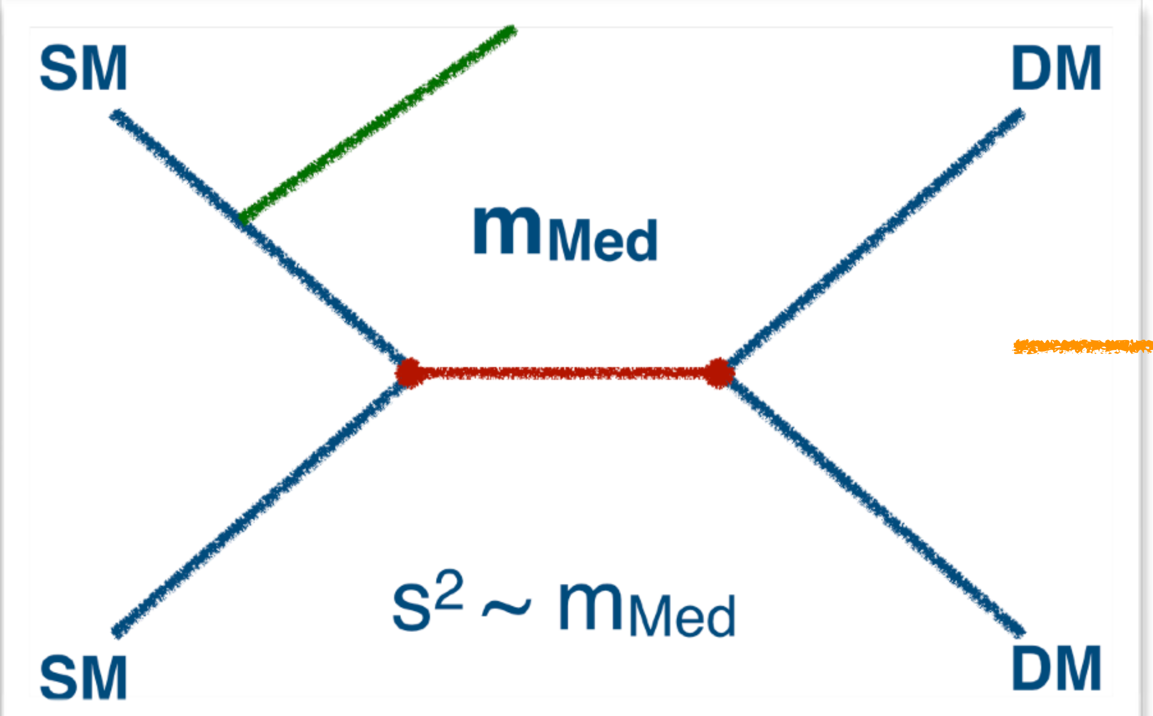


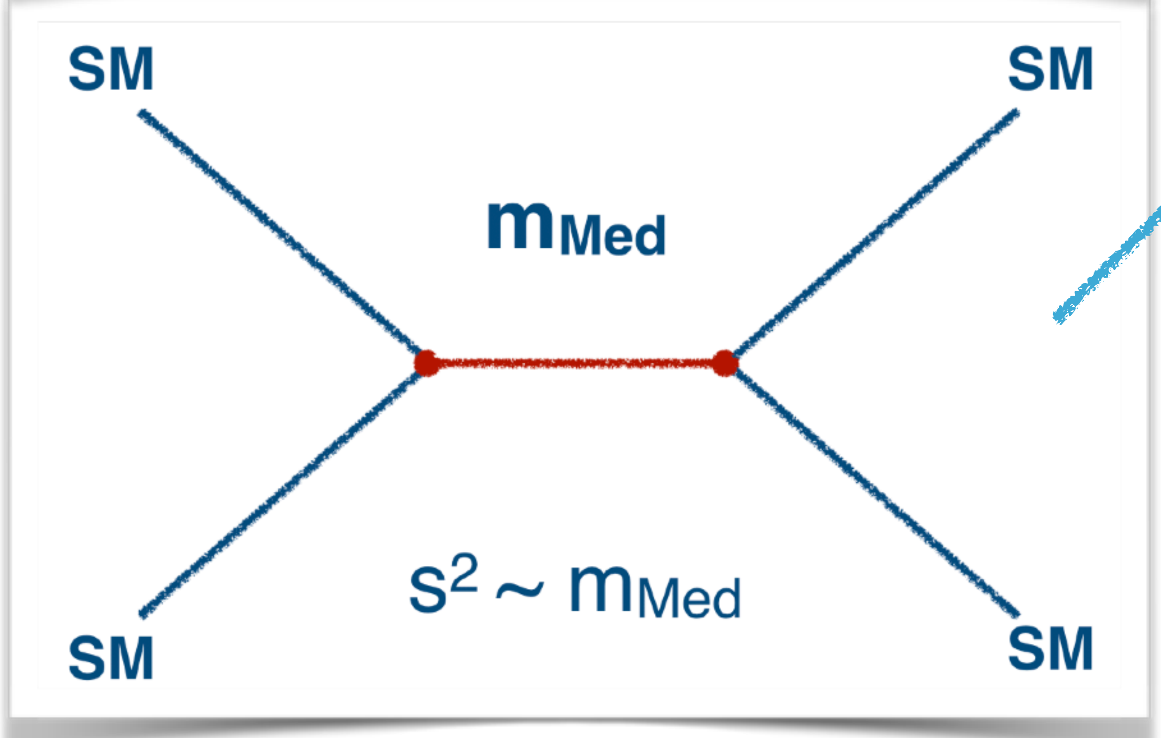
10 GeV

Dark Matter, anyone?

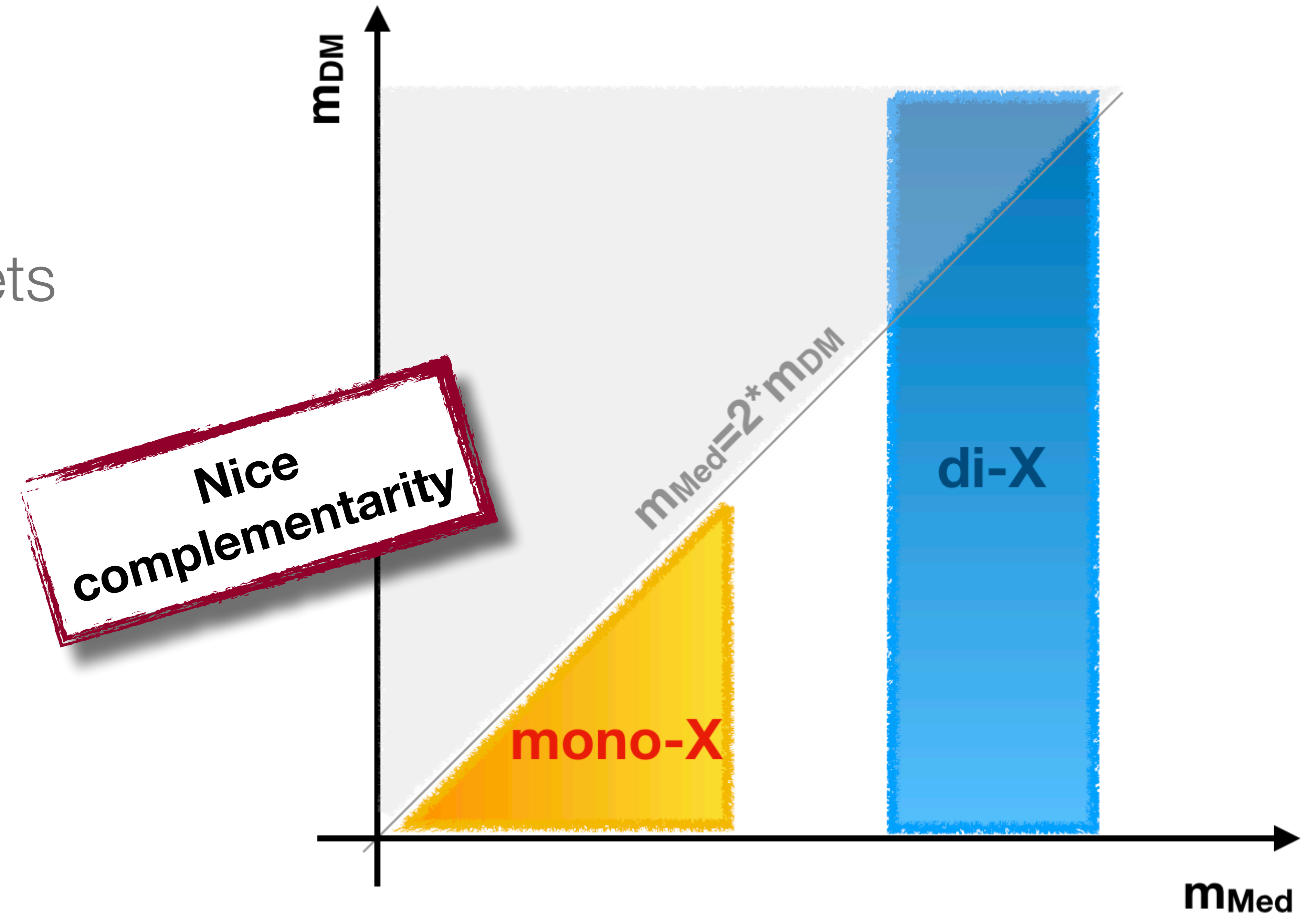




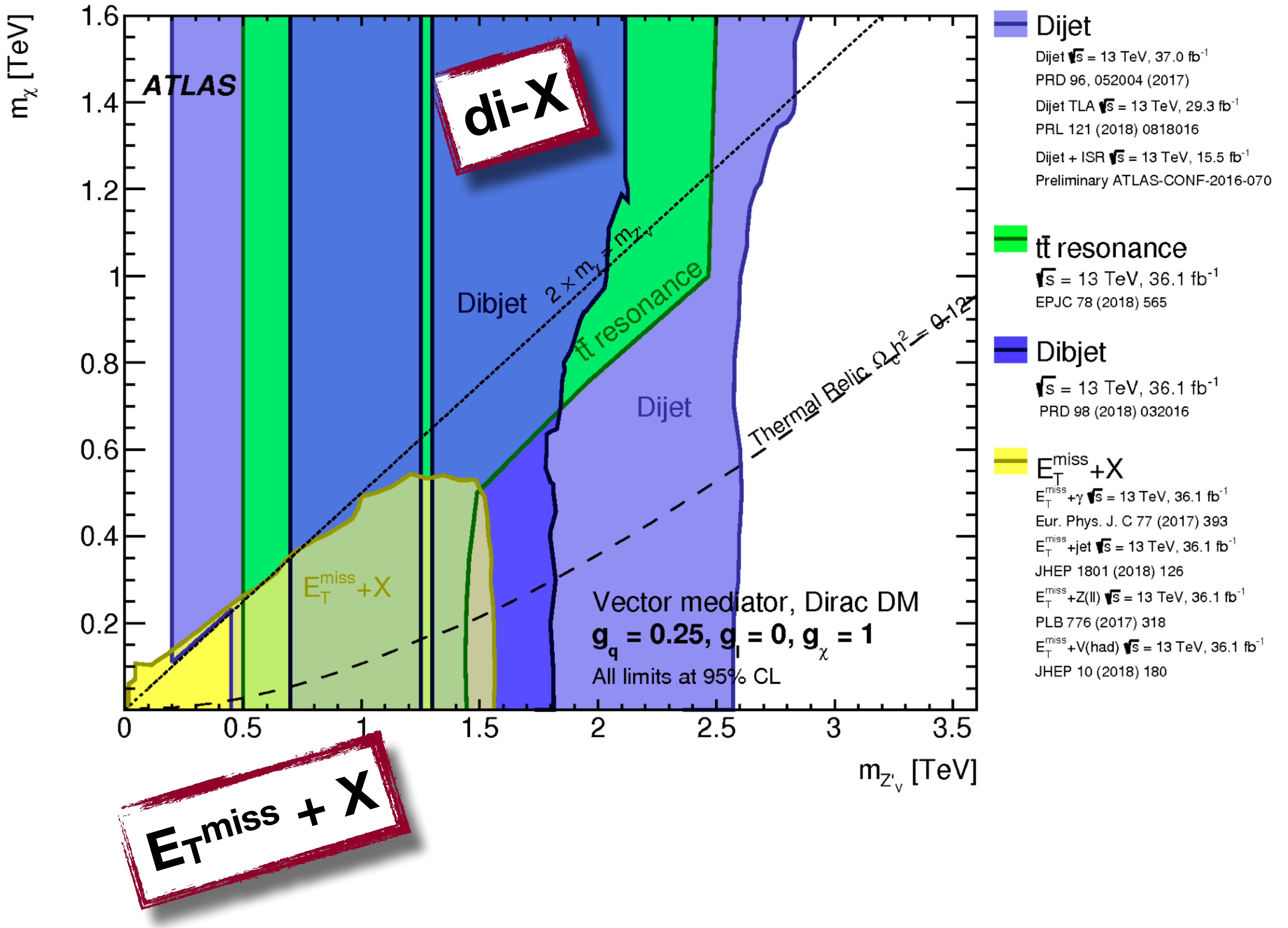




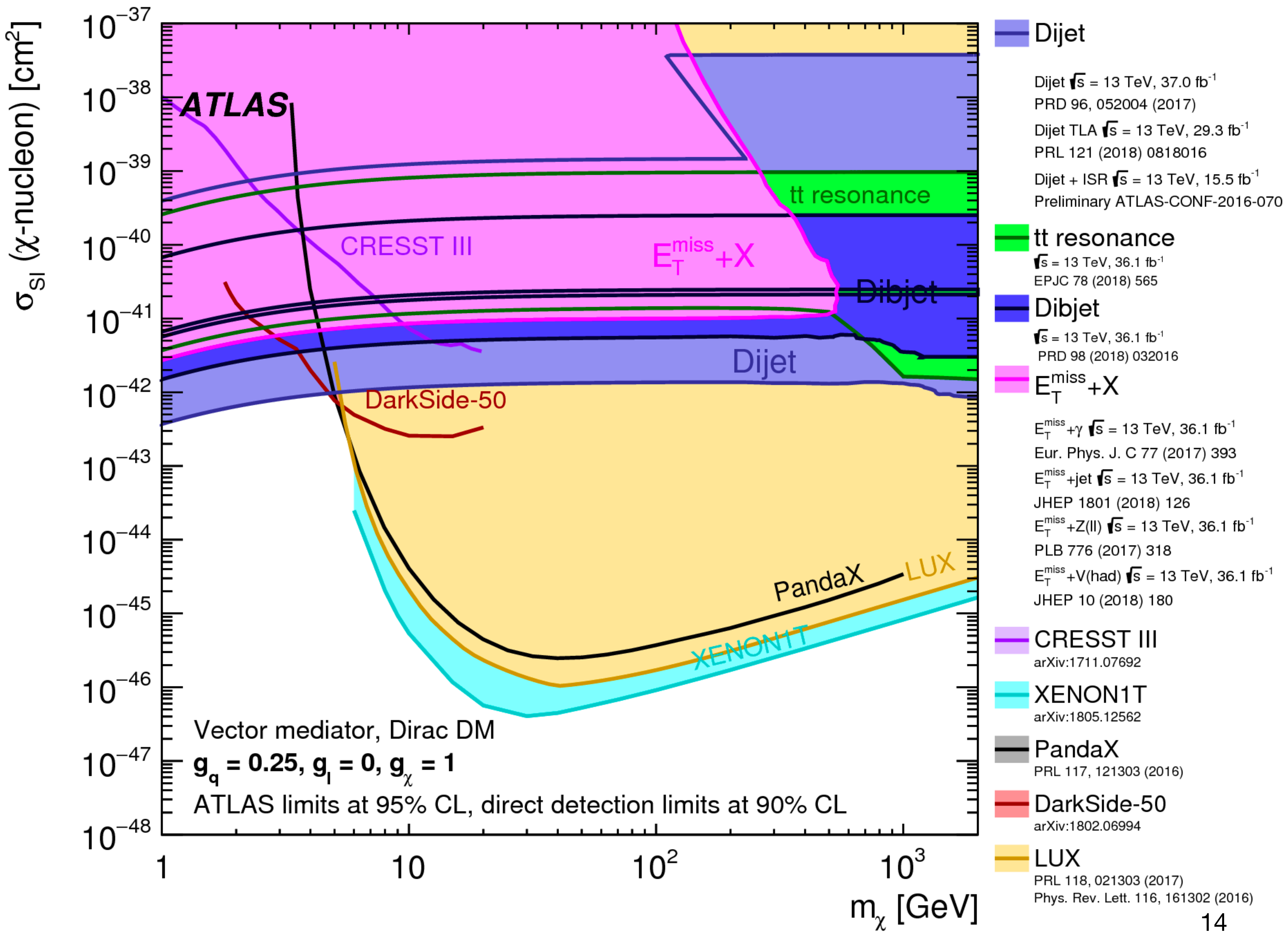
- At colliders we can only detect DM after producing that
- It means we *only* probe the SM-DM mediator:
  - simplified models are guiding us in this search
  - exploiting complementarity of different signatures:
    - mono-X: X=jet, γ, Z, W, h
    - di-X: X=leptons, jets, h.f.-jets



Dark Matter Searches



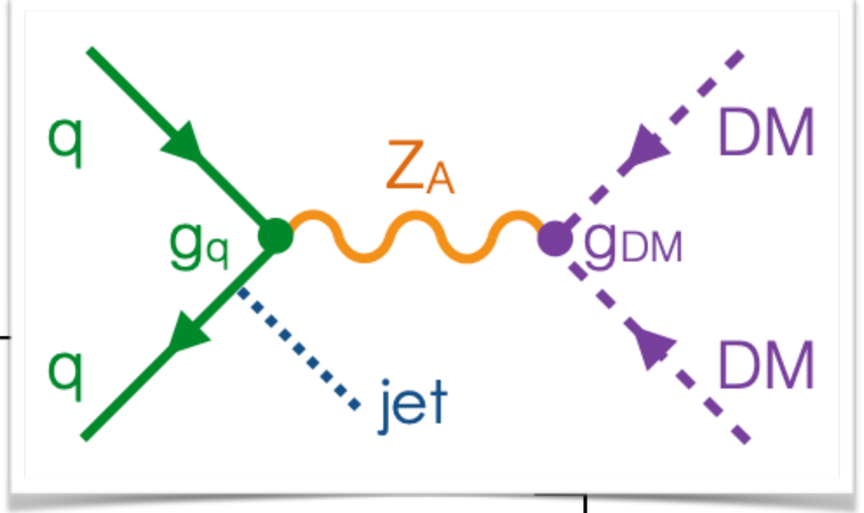
- Complementary to DD experiments
  - caveats on the assumptions done in σ calculation

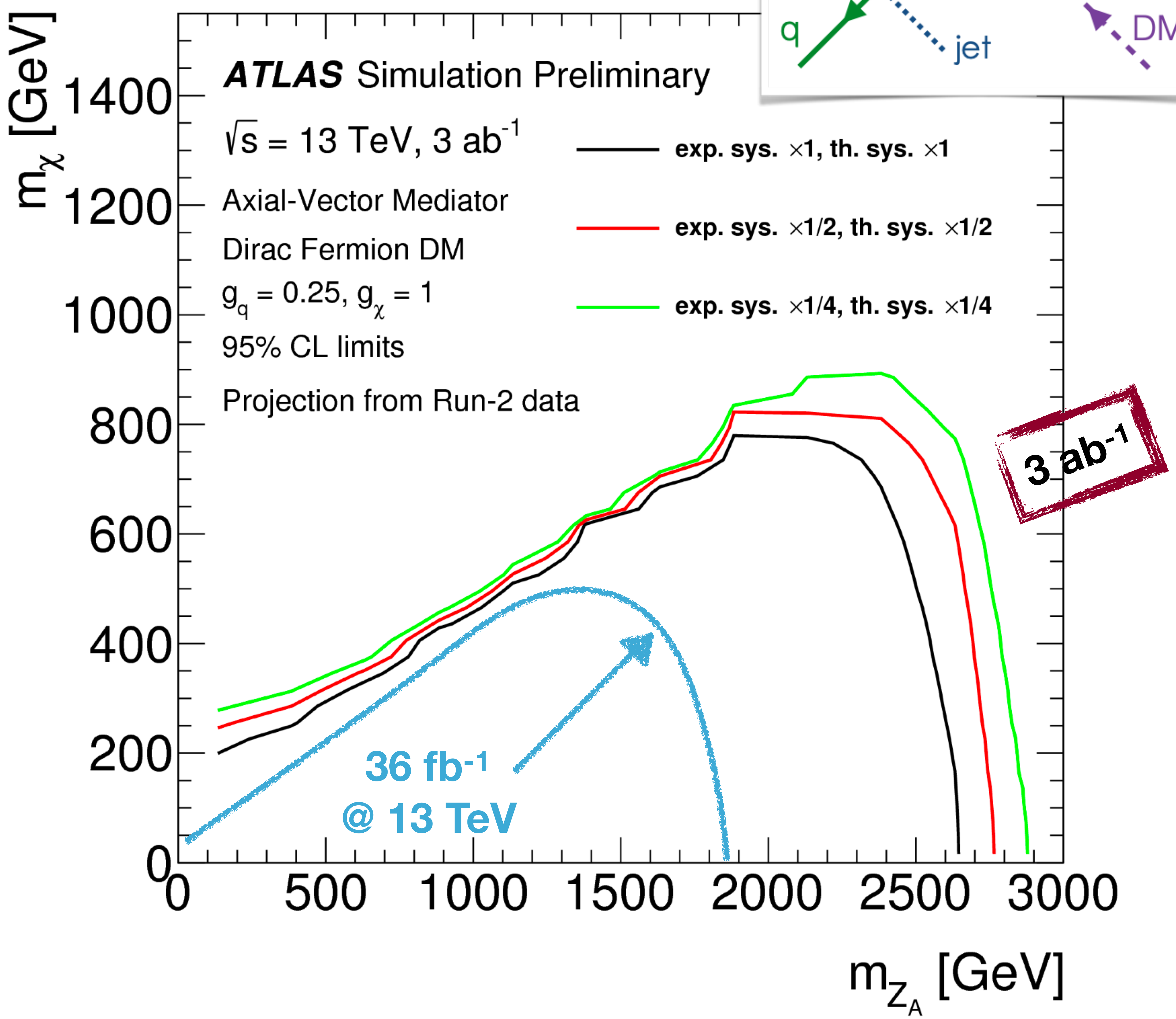


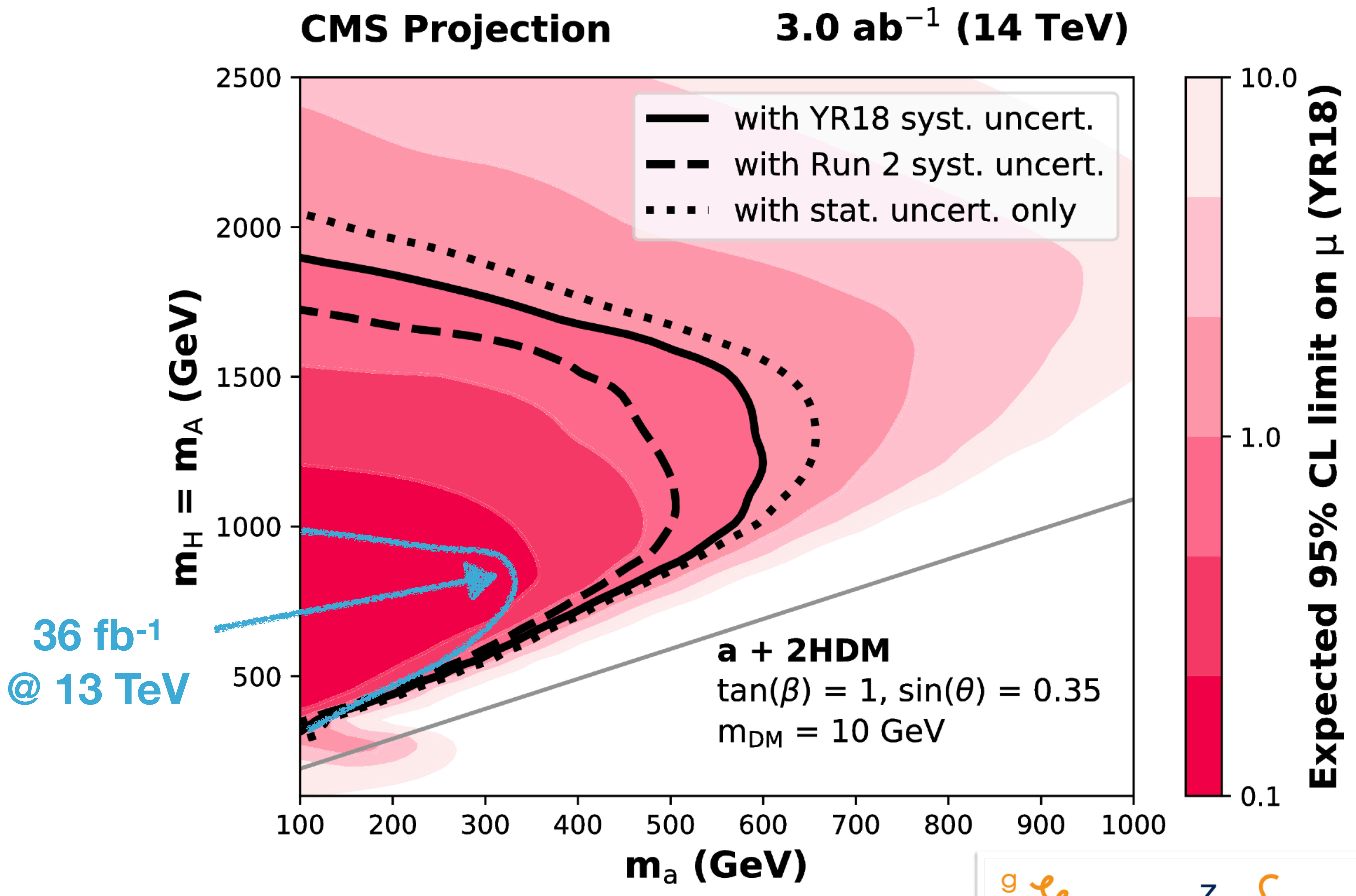
EXOT-2017-032

Mono-X searches in the long run

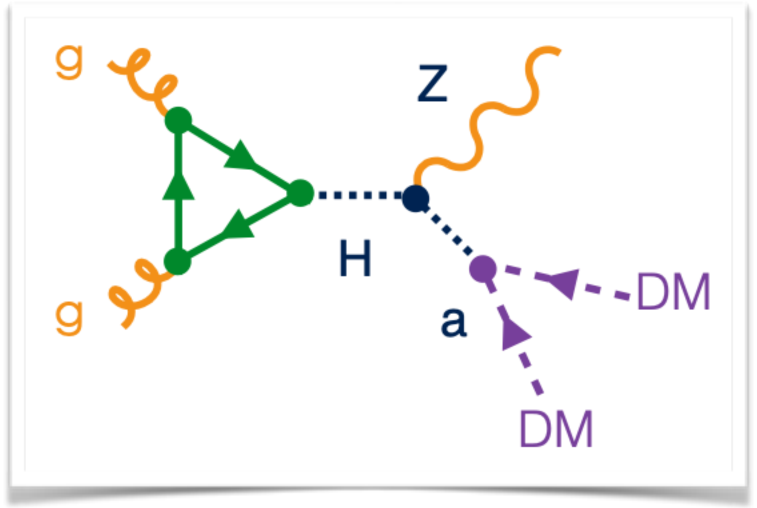
mono-jet







mono-Z(ll)



Weirder signatures

Nature sometimes can be different

Long-Lived Particles and Other Unconventional Signatures

- Many extensions of SM predict Long-lived (LL) or unconventional signatures

$$\Gamma = g^2 |A|^2 \frac{\Phi}{M}$$

phase space suppressed (eg compressed mass spectra)

coupling suppressed

amplitude suppressed

- Typically **complicated** searches
  - No reliable BG modelling in MC
  - Deep understanding of detector needed

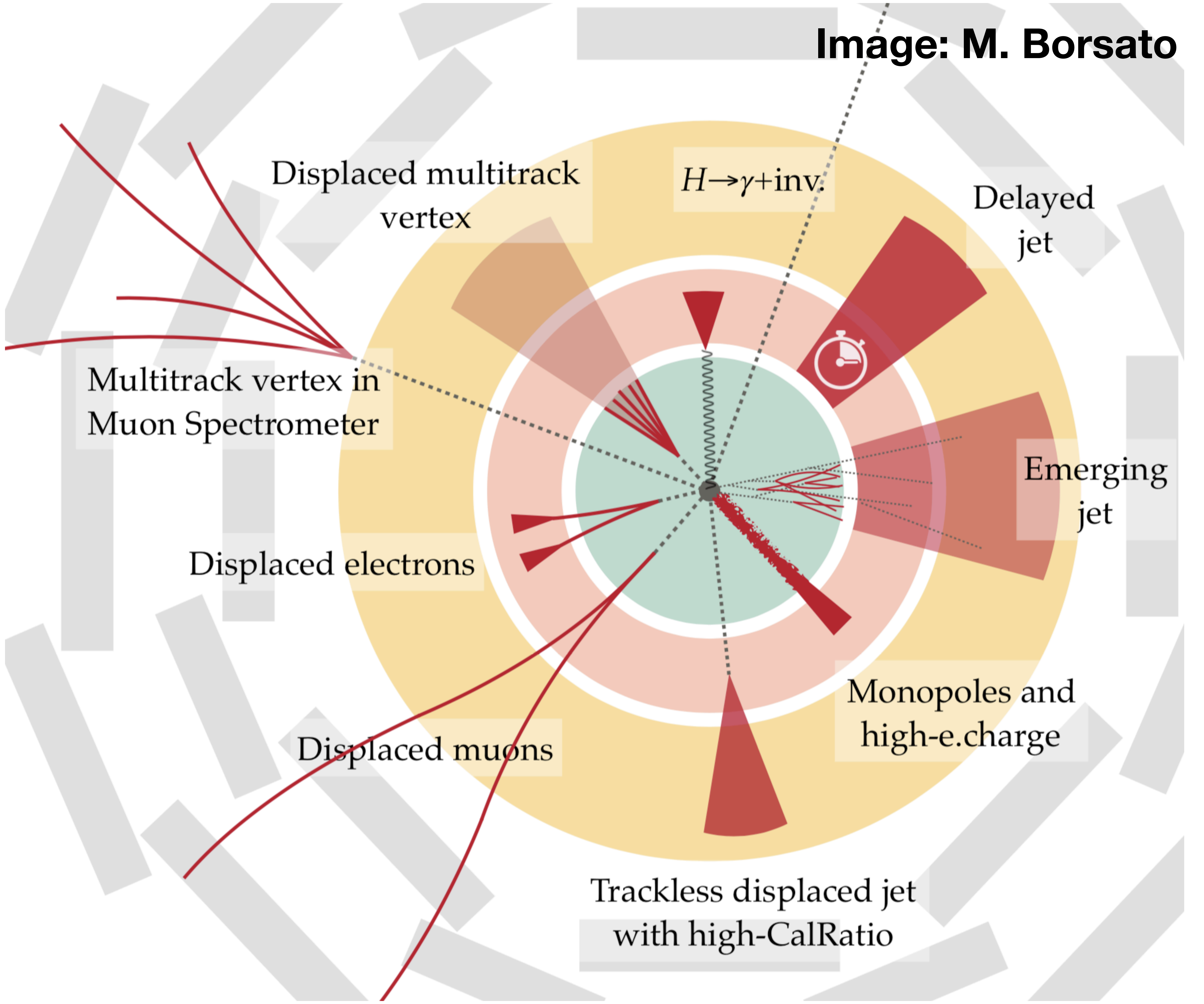
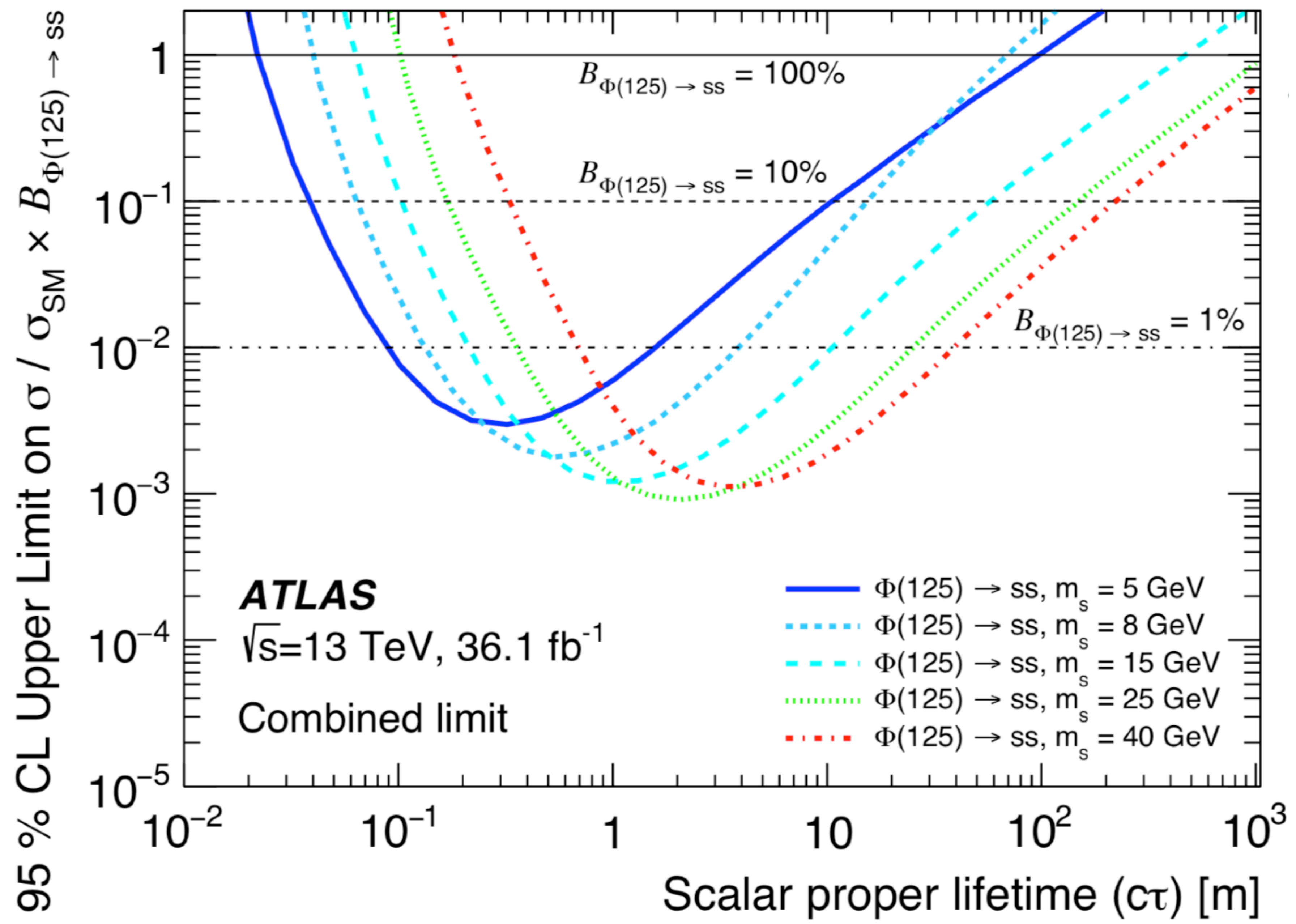


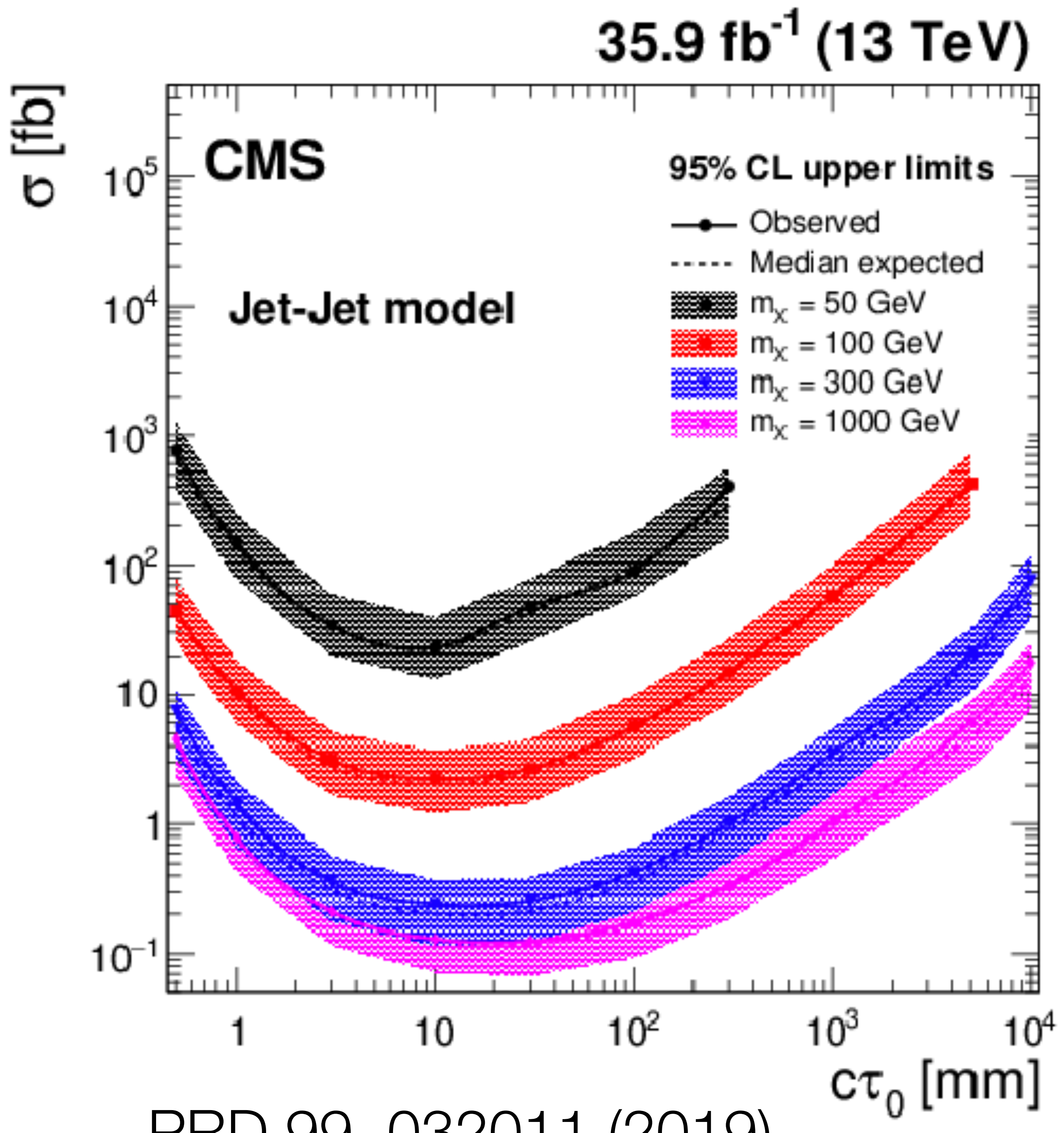
Image: M. Borsato

Example: Displaced Jets

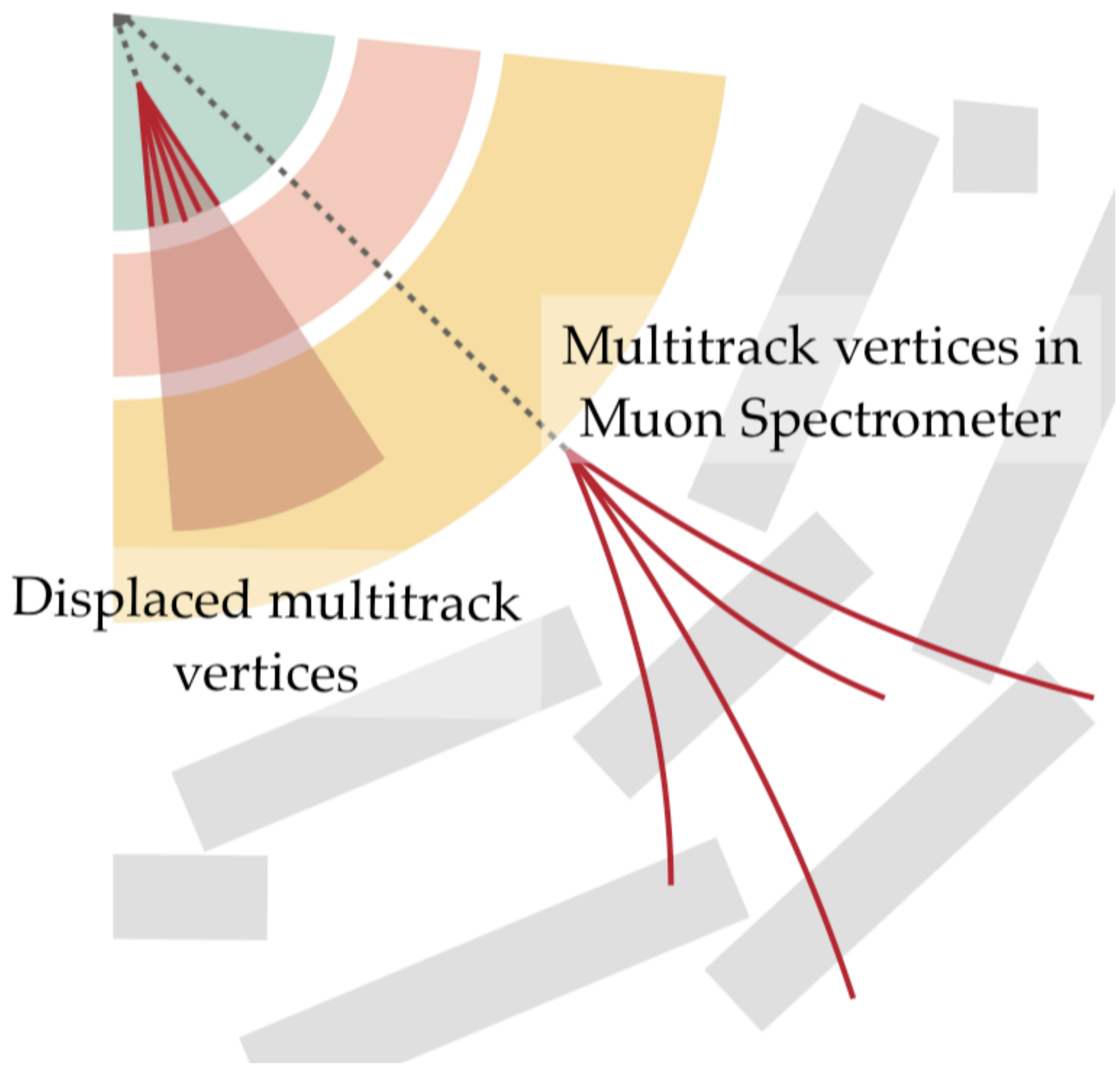
- Reconstruction of **displaced** vertices
  - in **tracker** (CMS)
  - in **muon chambers** (ATLAS)
- Interpreted in various models (XX→(jj)(jj), GMSB SUSY, RPV SUSY…)



PRD 99, 052005 (2019)

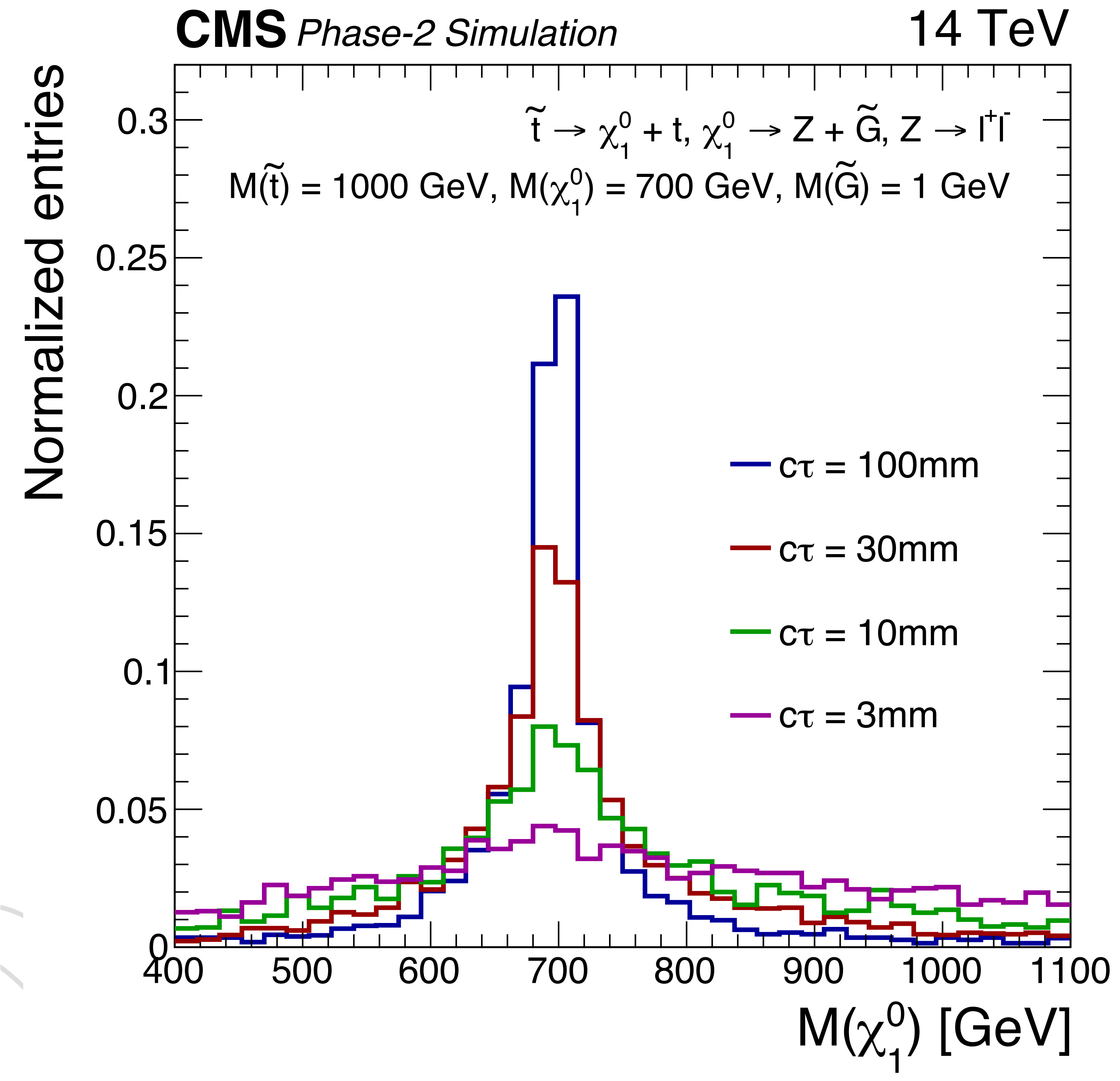


PRD 99, 032011 (2019)

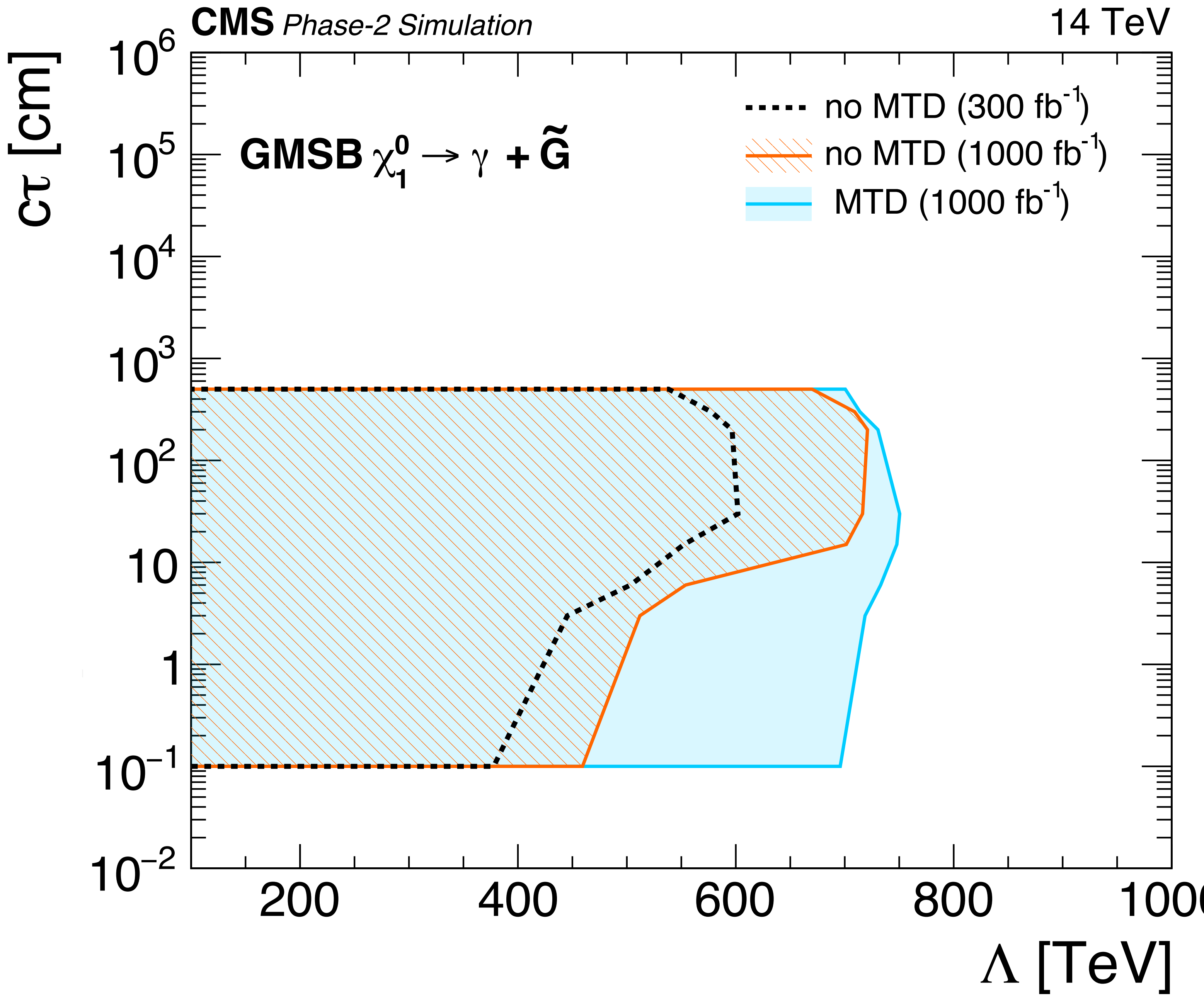


New Opportunities Thanks to Precision Timing in Phase-2

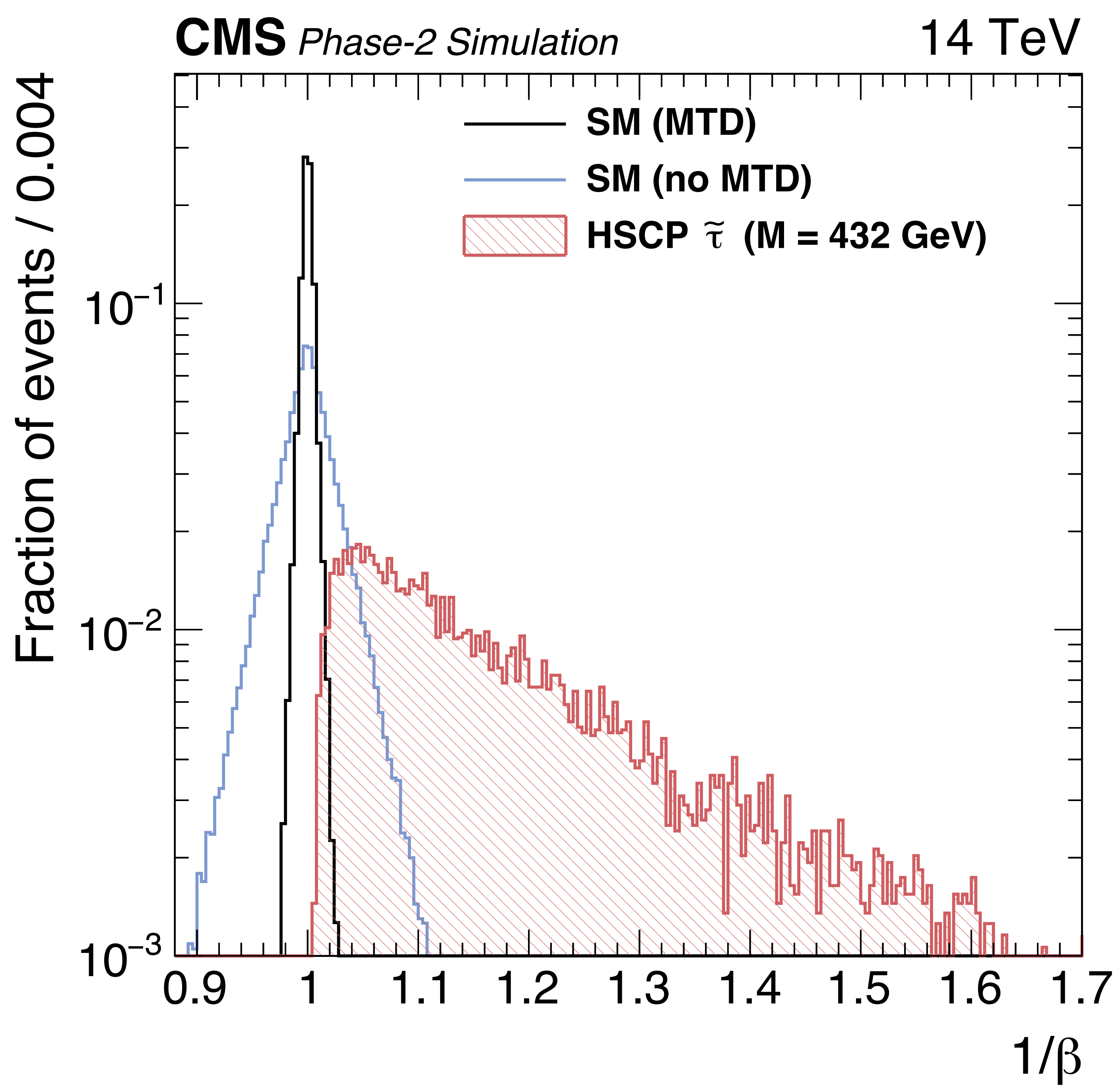
Long-lived neutral particles
From 4D distance between PV and decay vertex ➞ $\beta(\chi^0)$
Full mass measurement from V^0



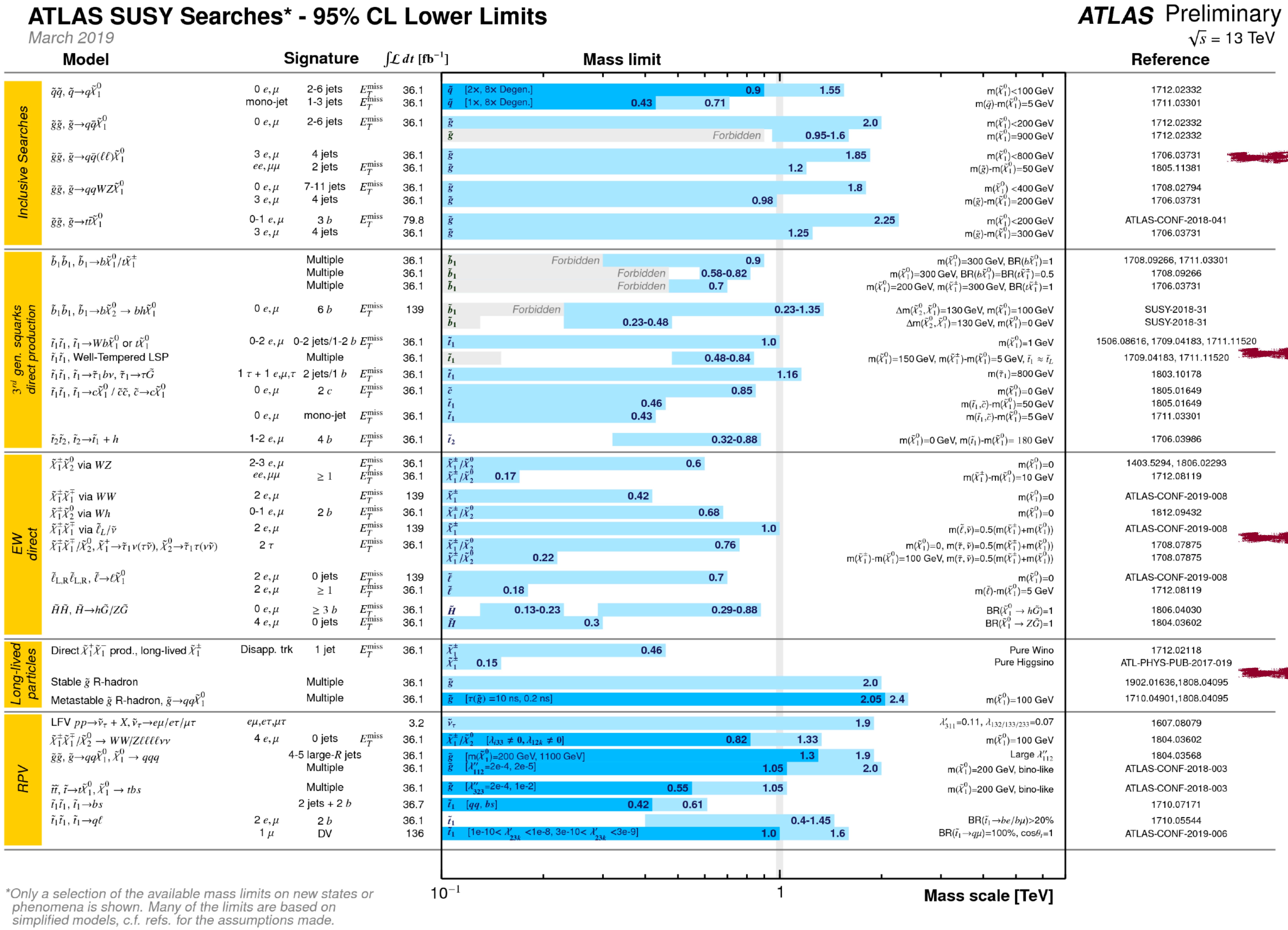
Delayed photons
Precise timing significantly expands small-τ sensitivity



Heavy stable charged particles
Can measure 1/β from track only



SUSY Has Gotten a Beating from LHC… but it's Still Alive



Gluinos excluded up to M ~ 2 TeV

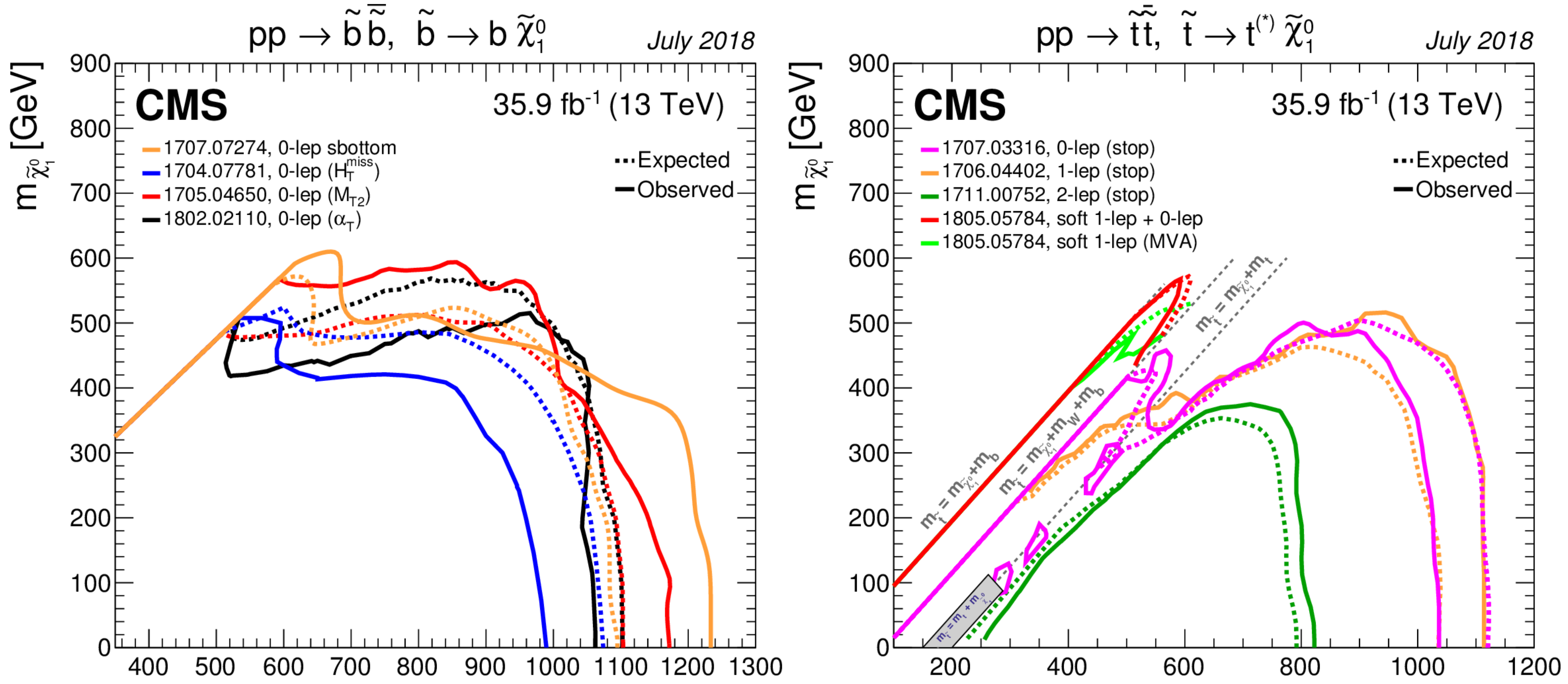
Stop excluded up to M ~ 1 TeV

EW SUSY limits somewhat lower

Also SUSY has a Long Lived sector

Some Say We’re ‘Just Starting’ with the Interesting Regions

Stop-sbottom Searches

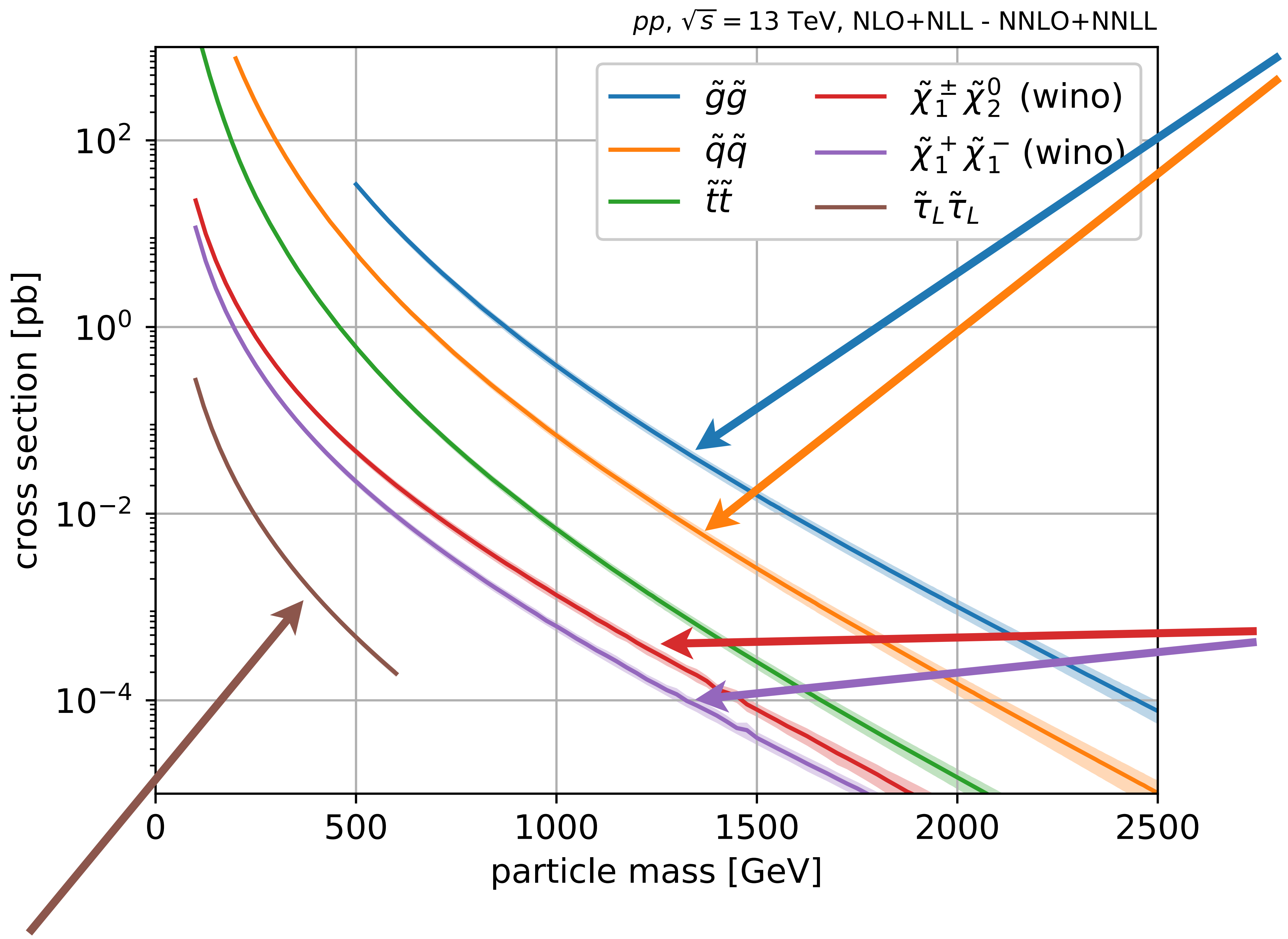


Combining all searches, in the simplest decay scenarios, it is hard to avoid the constraints of 700 GeV for bottoms and 550 GeV for stops. Islands in one search are apparently covered by other searches.

We are just starting to explore the mass region suggested by the Higgs mass determination !

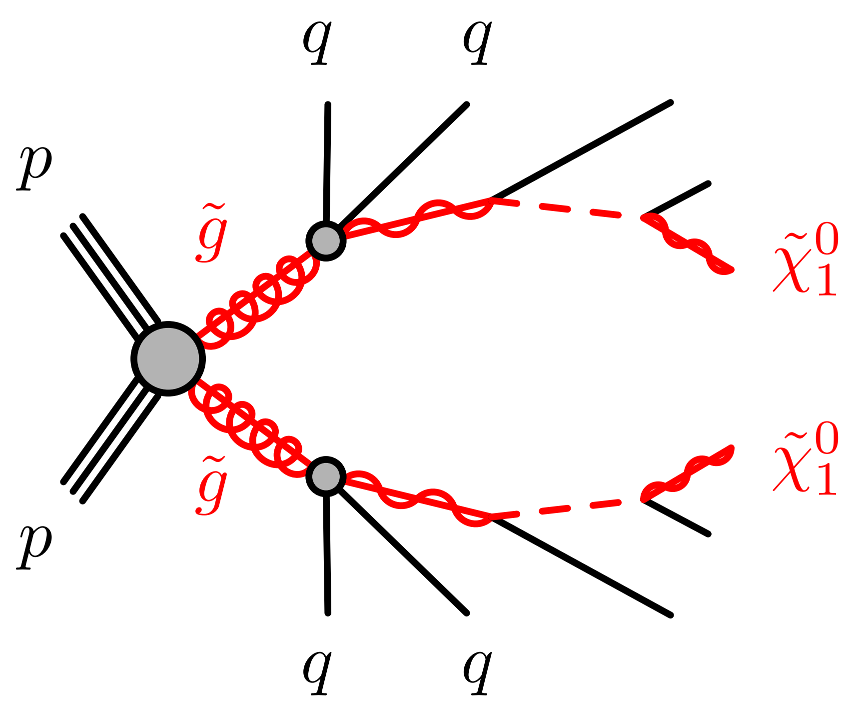
LHCP2019 SUSY Plenary Theory Talk

SUSY Production at 13 TeV



Strong production: gluinos and squarks

Largest cross section
Inclusive searches
Strong limits from Run-2

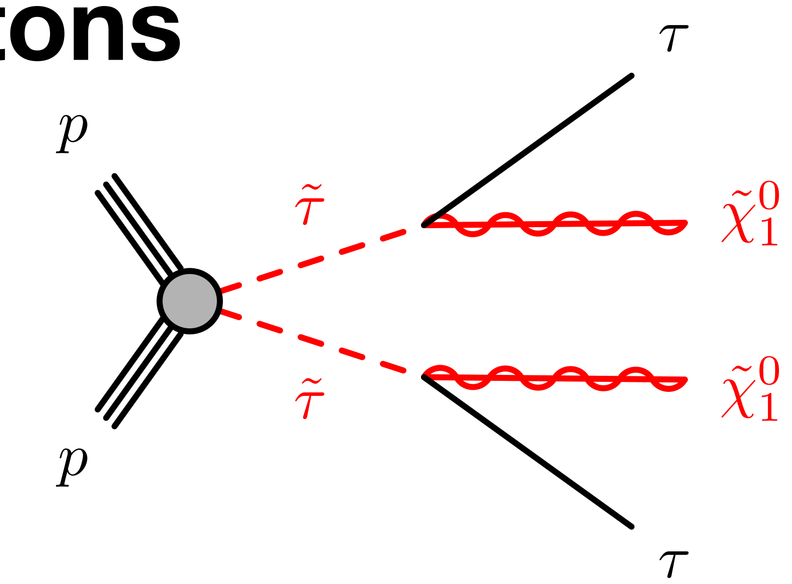


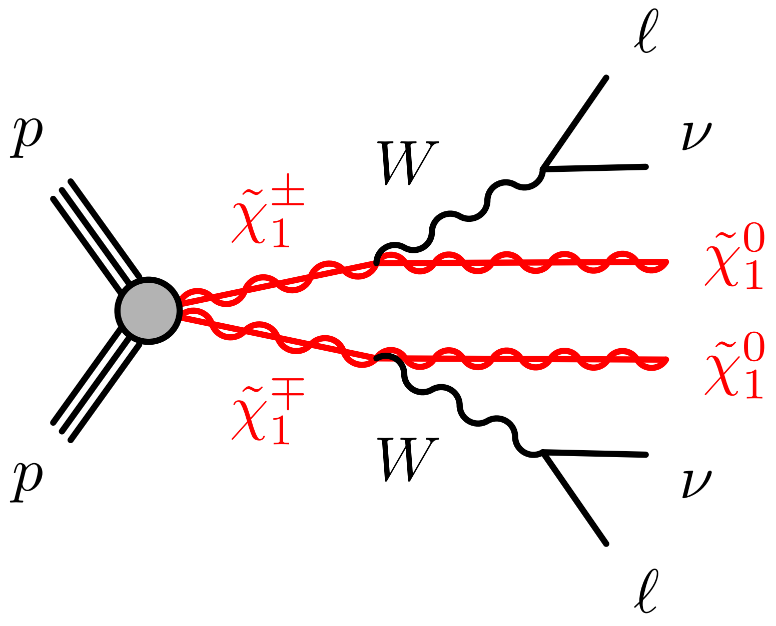
EW production of charginos

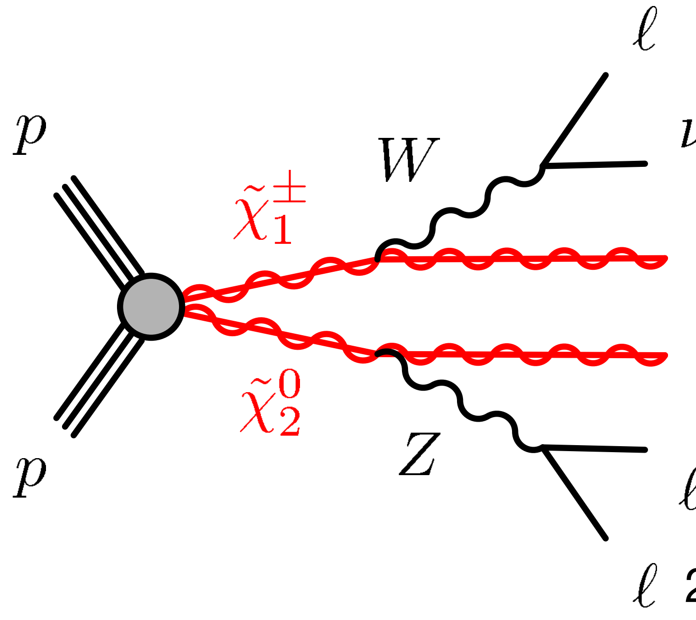
Smaller cross section
Dedicated searches (2L+ME$_T$, 3L+ME$_T$, L+H(bb)+MET, etc)
Less stringent limits from Run-2

EW direct production of sleptons

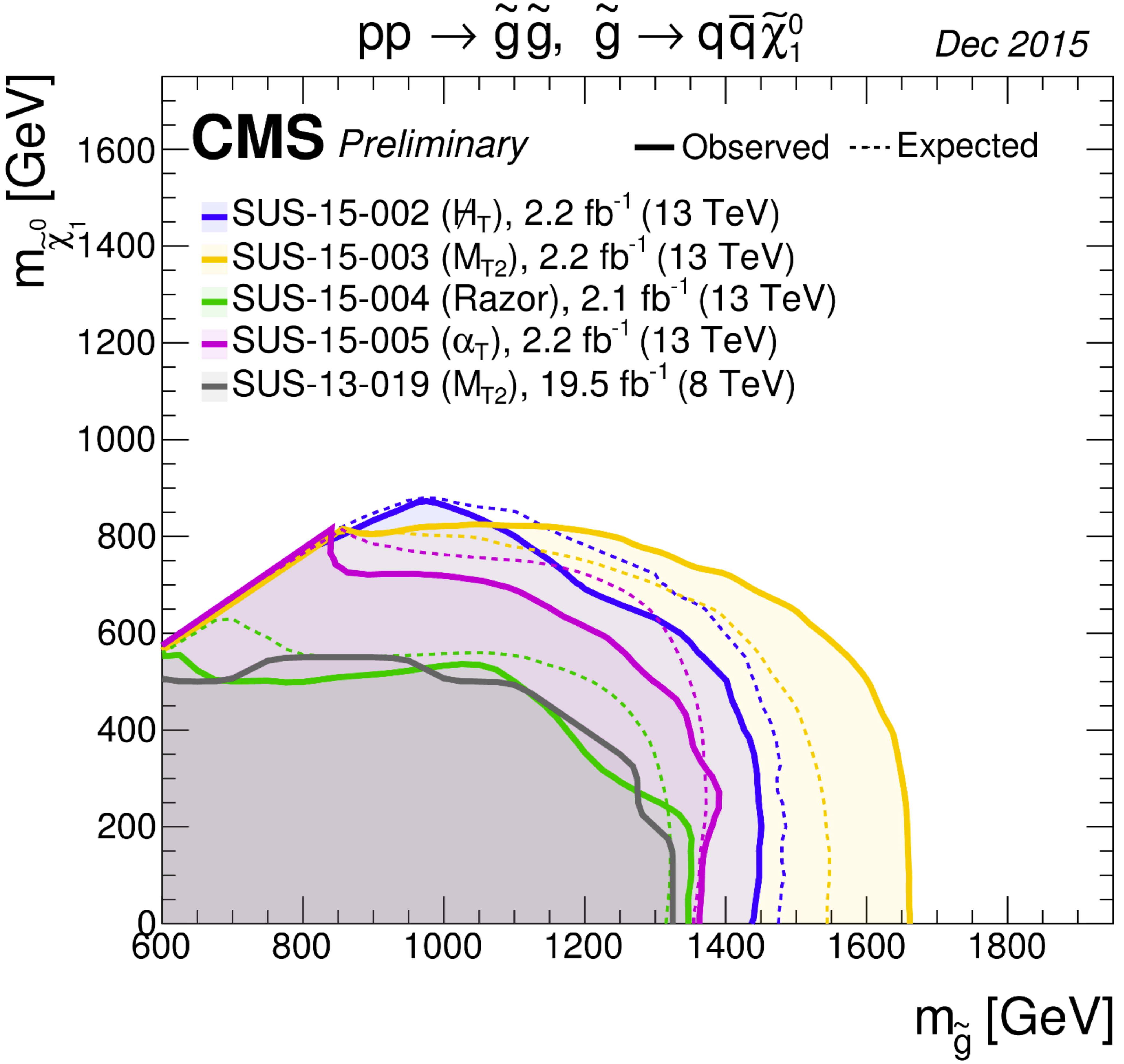
Smallest cross section
Barely any sensitivity with Run-2





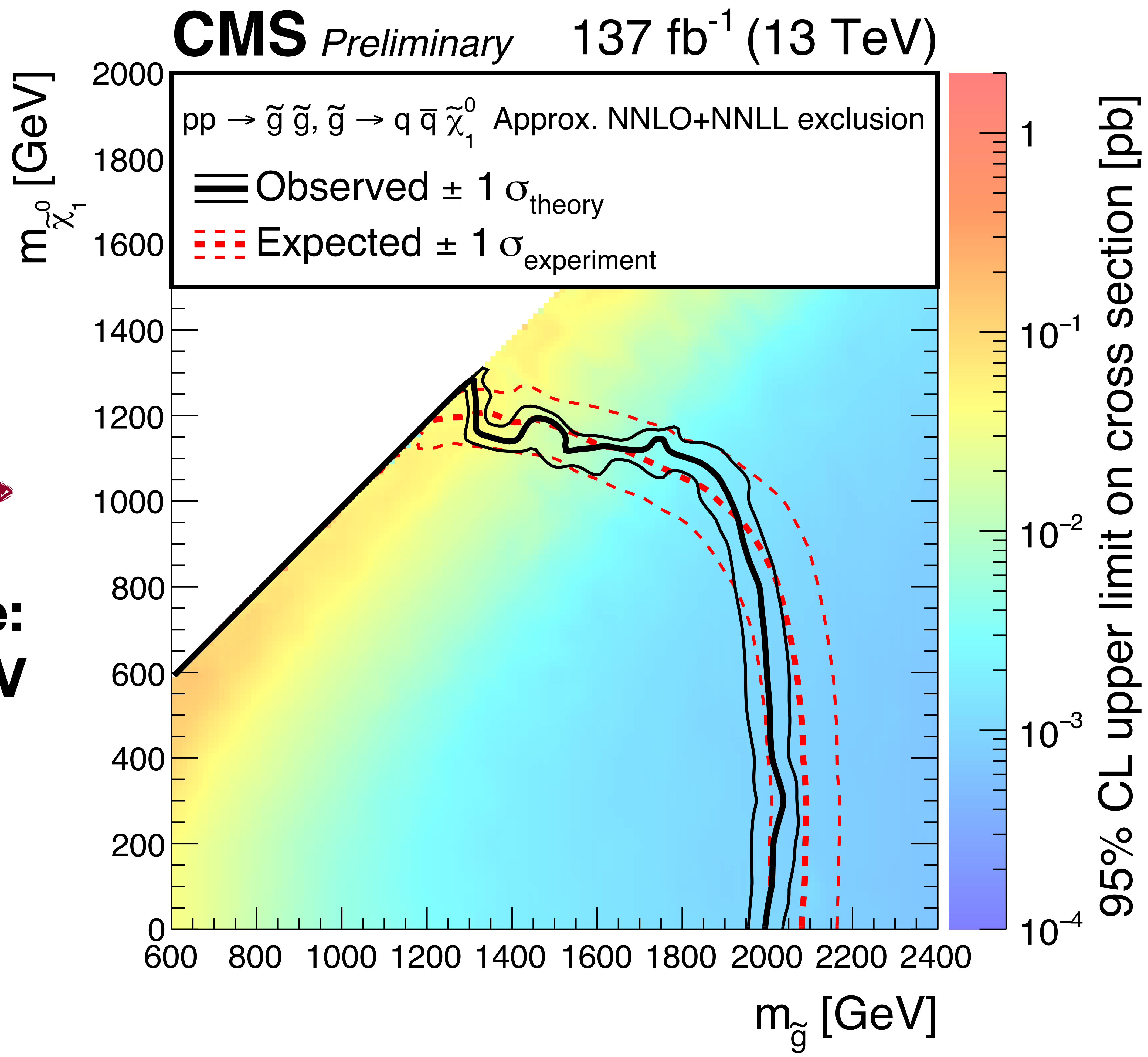


Inclusive Searches: Small Improvements from Increase in Statistics



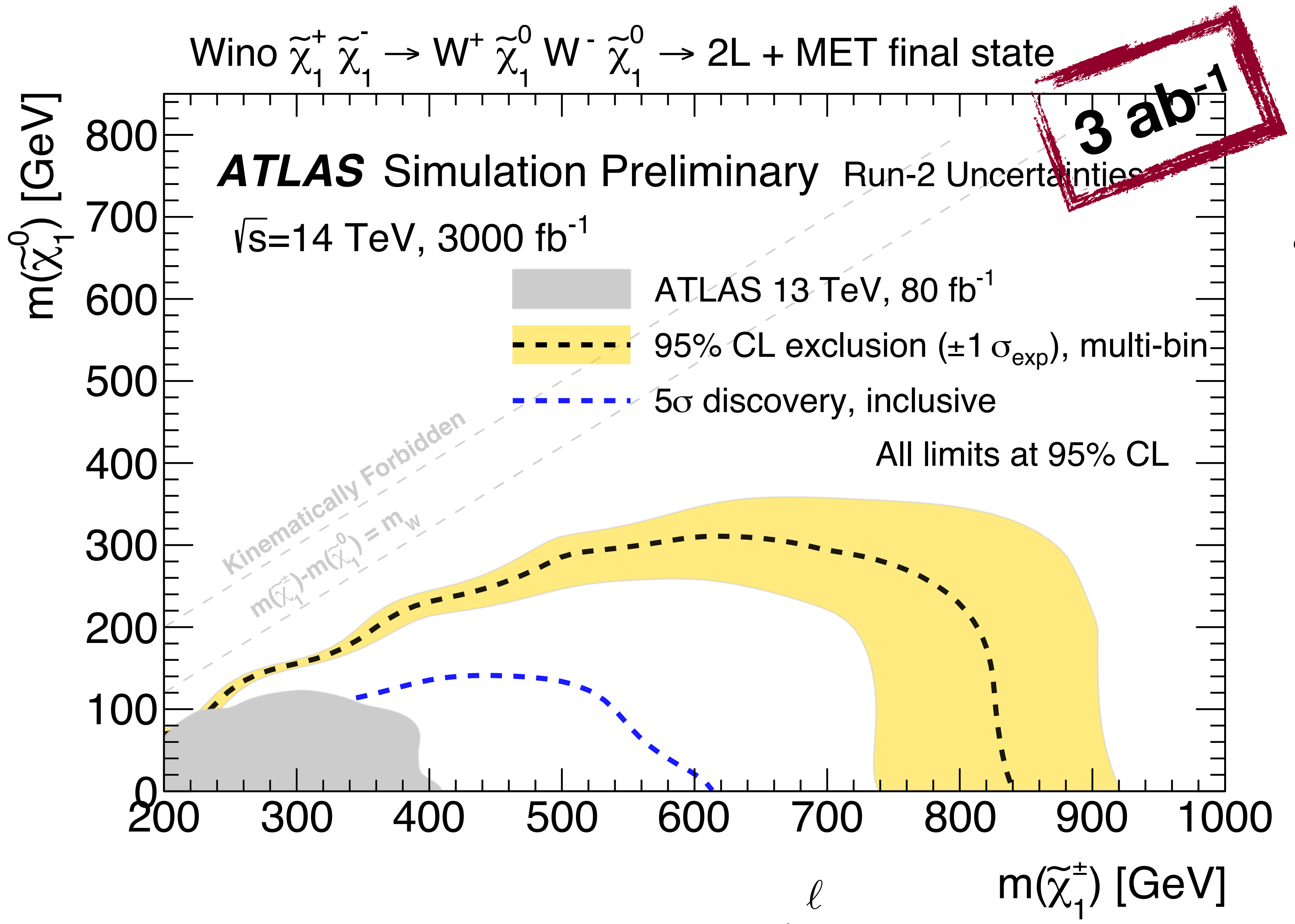
x100 more data

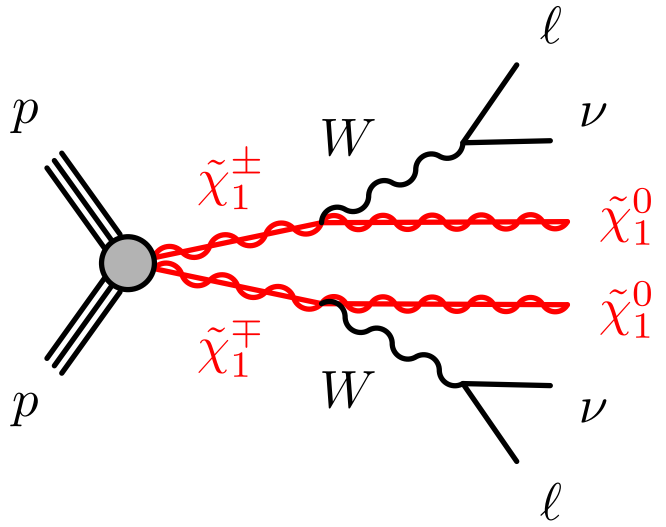
Limit increase: only ~ 500 GeV

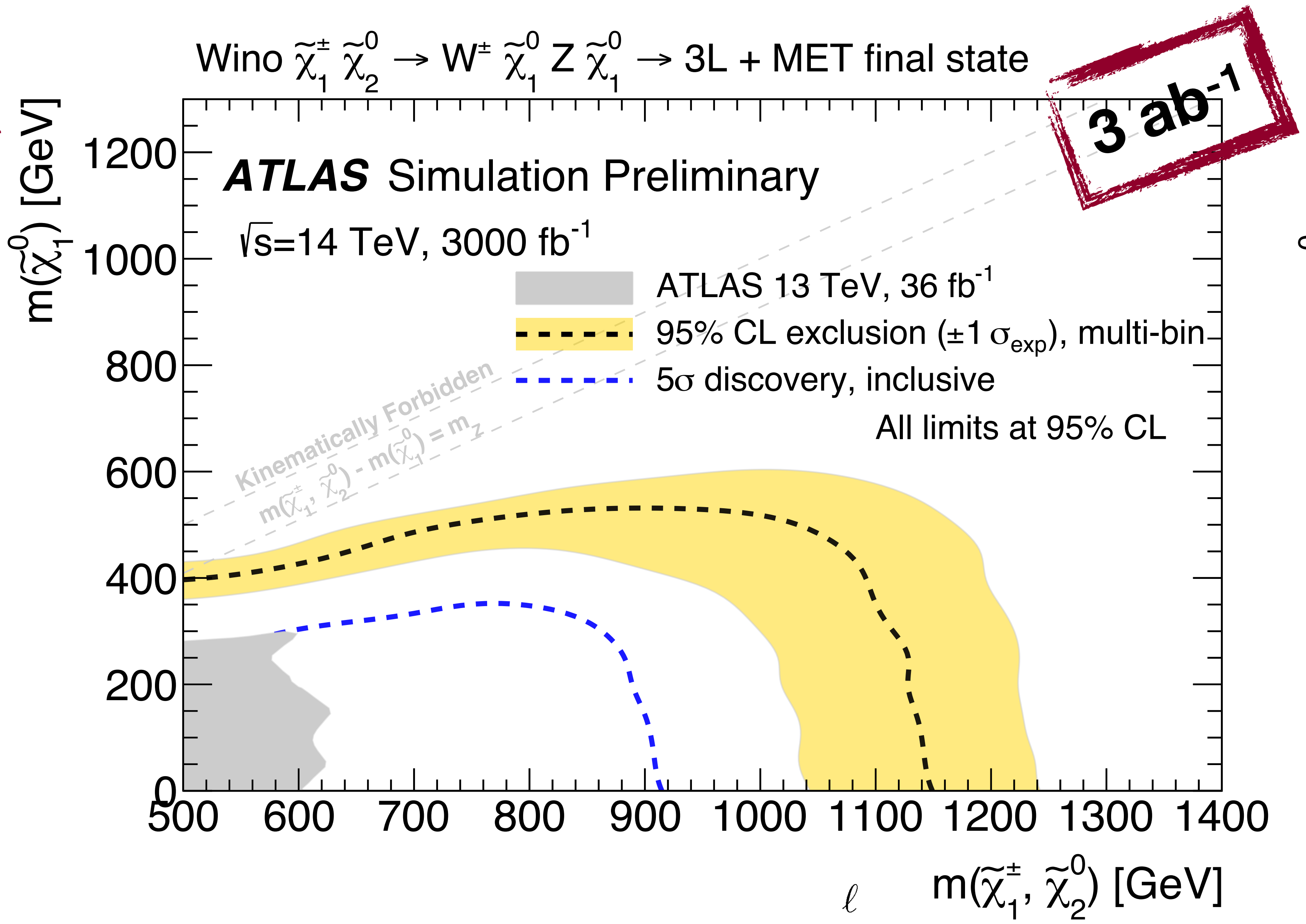


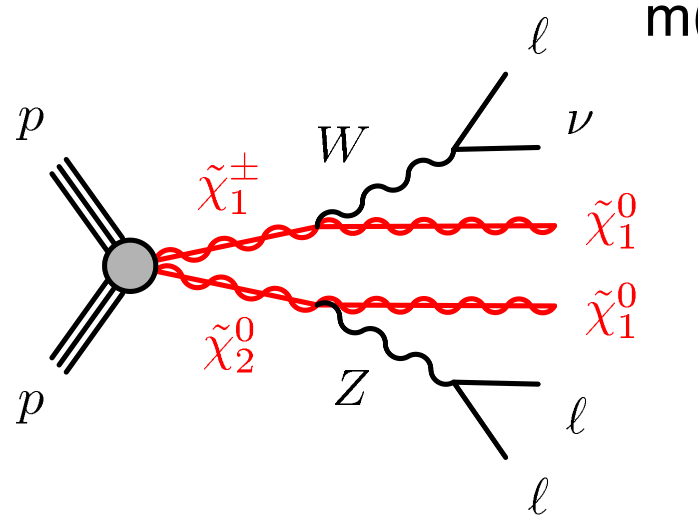
HL-LHC: First Real Sensitivity to Electroweak SUSY

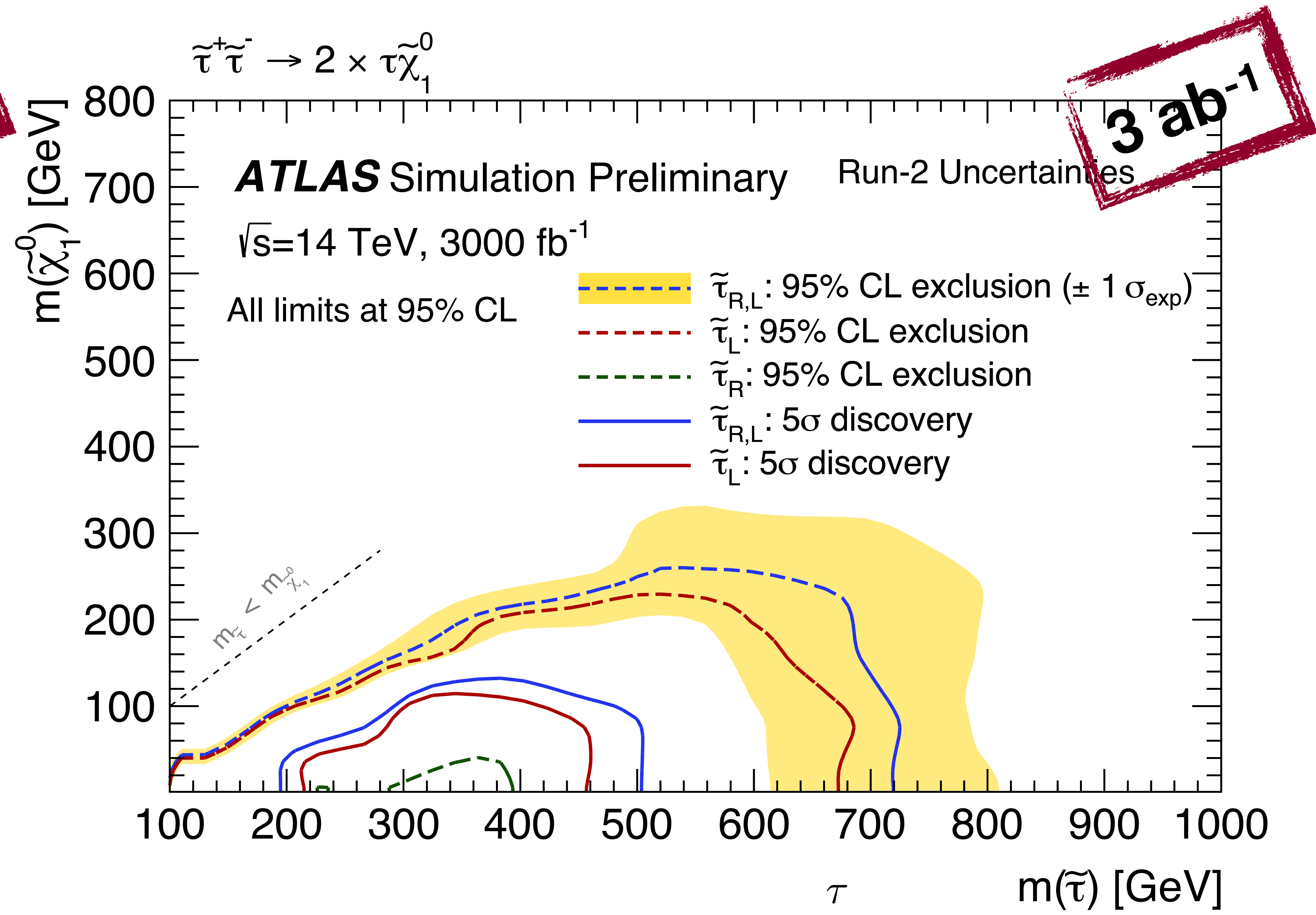
- Most current limits are very weak: reach can be ~doubled with HL-LHC
- Discovery potential for some mass regions (currently ~none)

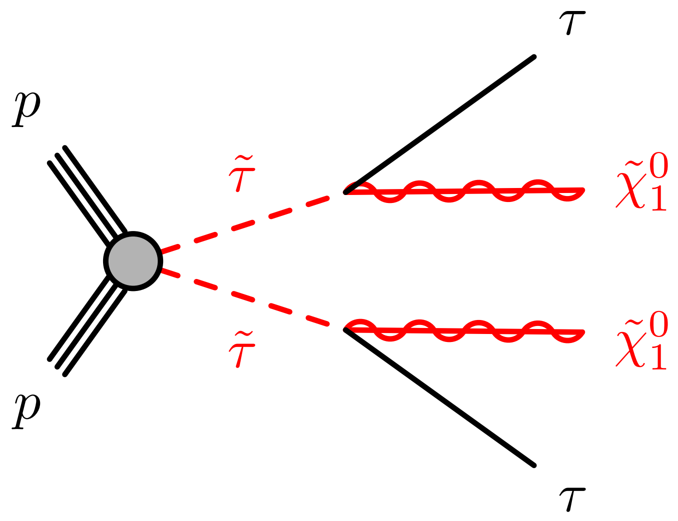








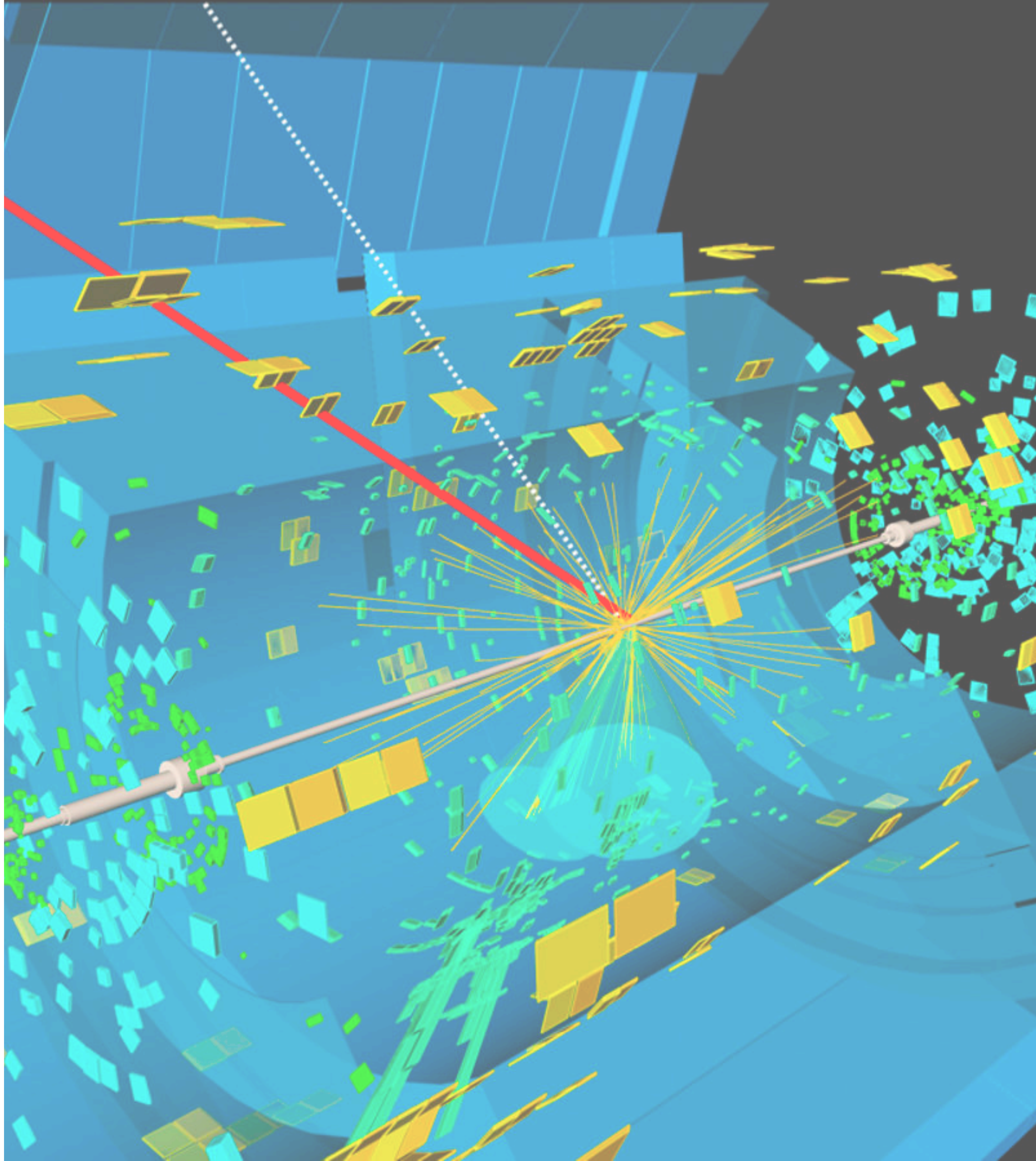




Is this the end?

- **Yes**, it's the end of the talk:
    - though we know we missed a lot of nice searches

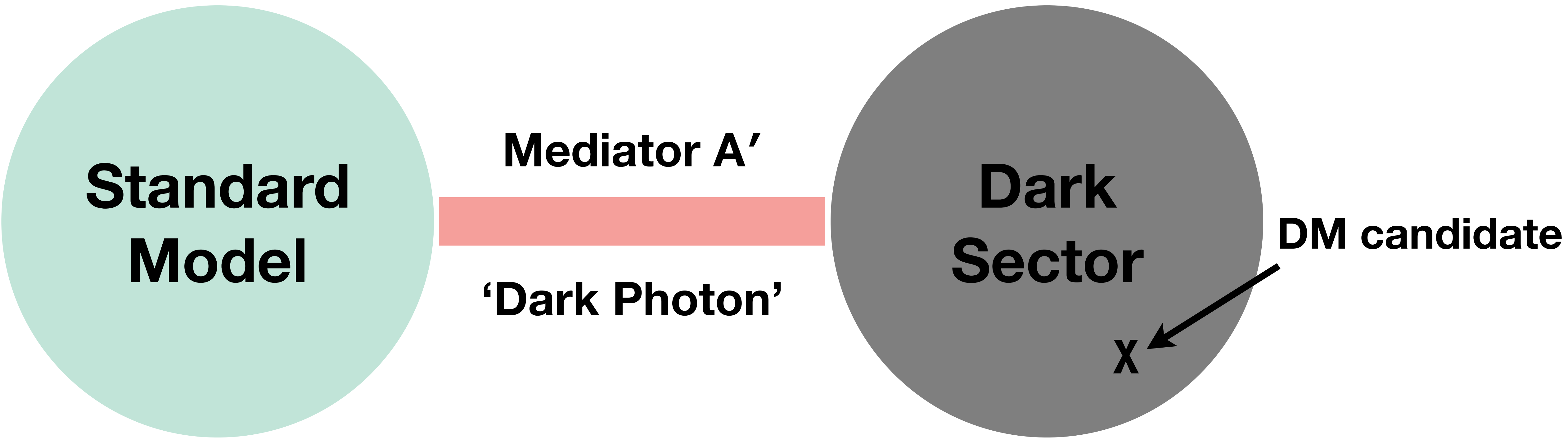
- **No**, it's not the end of LHC search program:
    - collecting more data will not do all the work
    - we need to be clever and explore what still we miss/forgot to look for



BACKUP

"you never know what you might need"

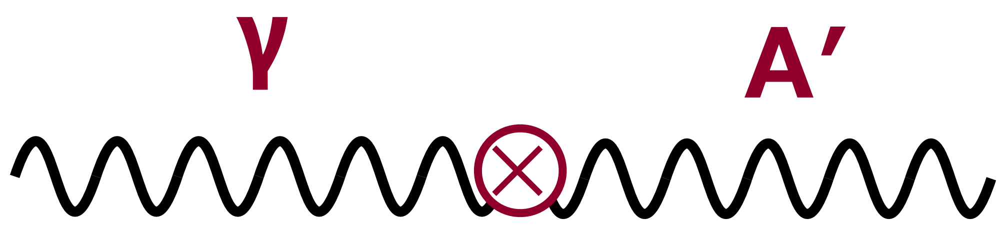
Dark Photon Models with Kinetic Mixing



Dark photon: an additional U(1), connected to SM U(1) through **kinetic mixing**

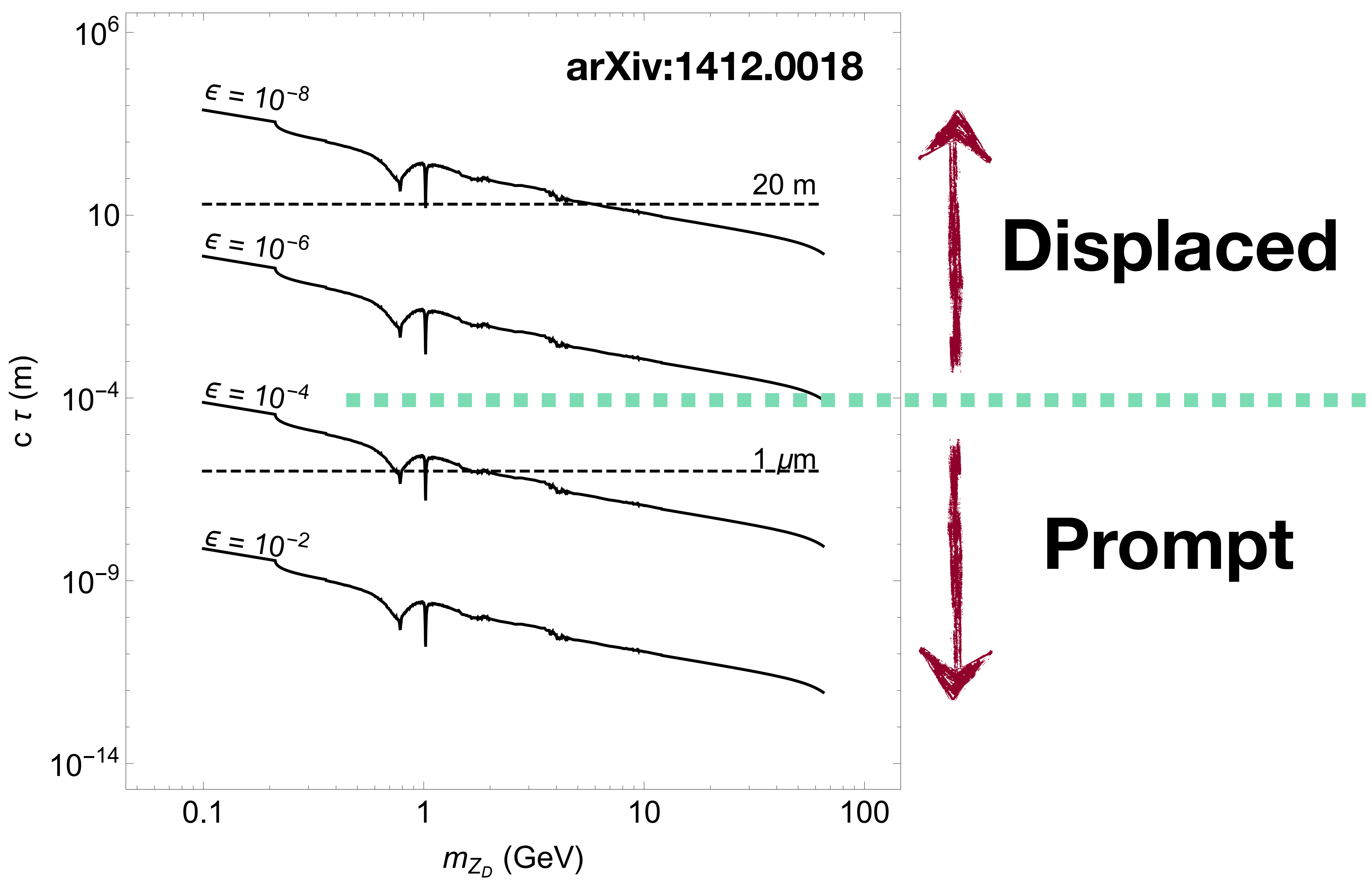
$$\mathscr{L} \subset \frac{1}{2}\frac{\epsilon}{\cos\theta}(\partial^\mu A_D^\nu - \partial^\nu A_D^\mu)(\partial^\mu B^\nu - \partial^\nu B^\mu)$$

ε: kinetic mixing parameter

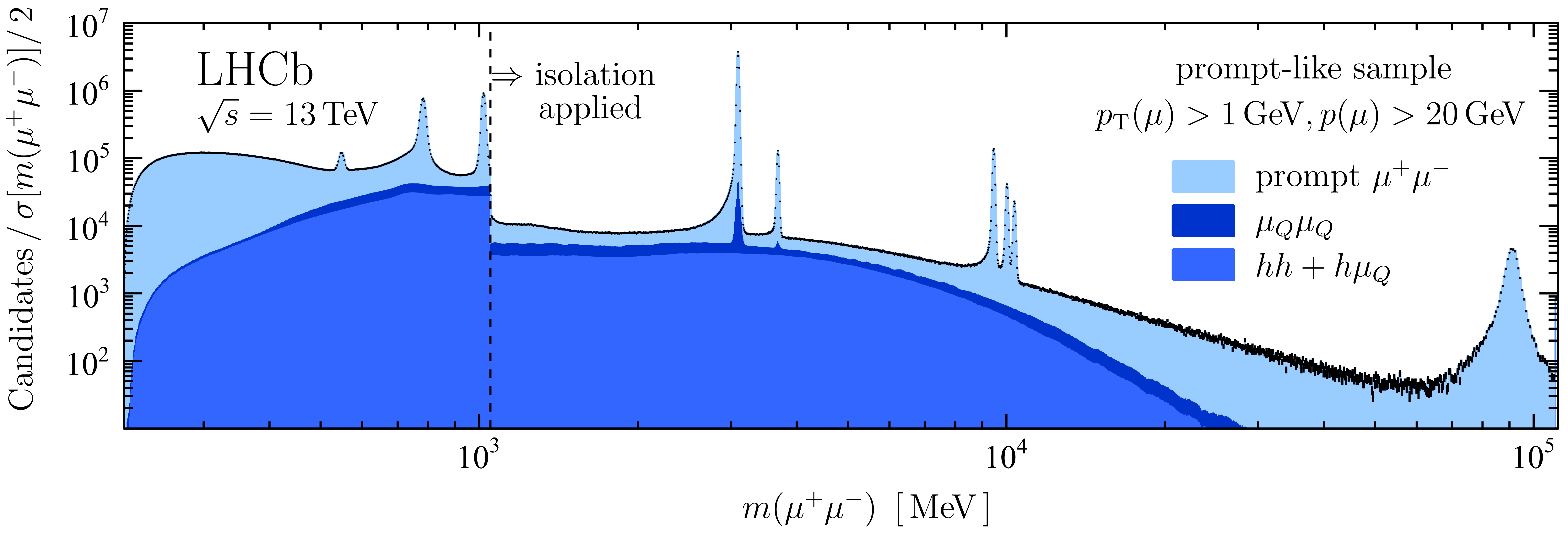


Not only way to introduce Dark Photons! See eg arXiv:1603.01377

The ε Parameter



LHCb Search for Dark Photons in Dimuon Channel

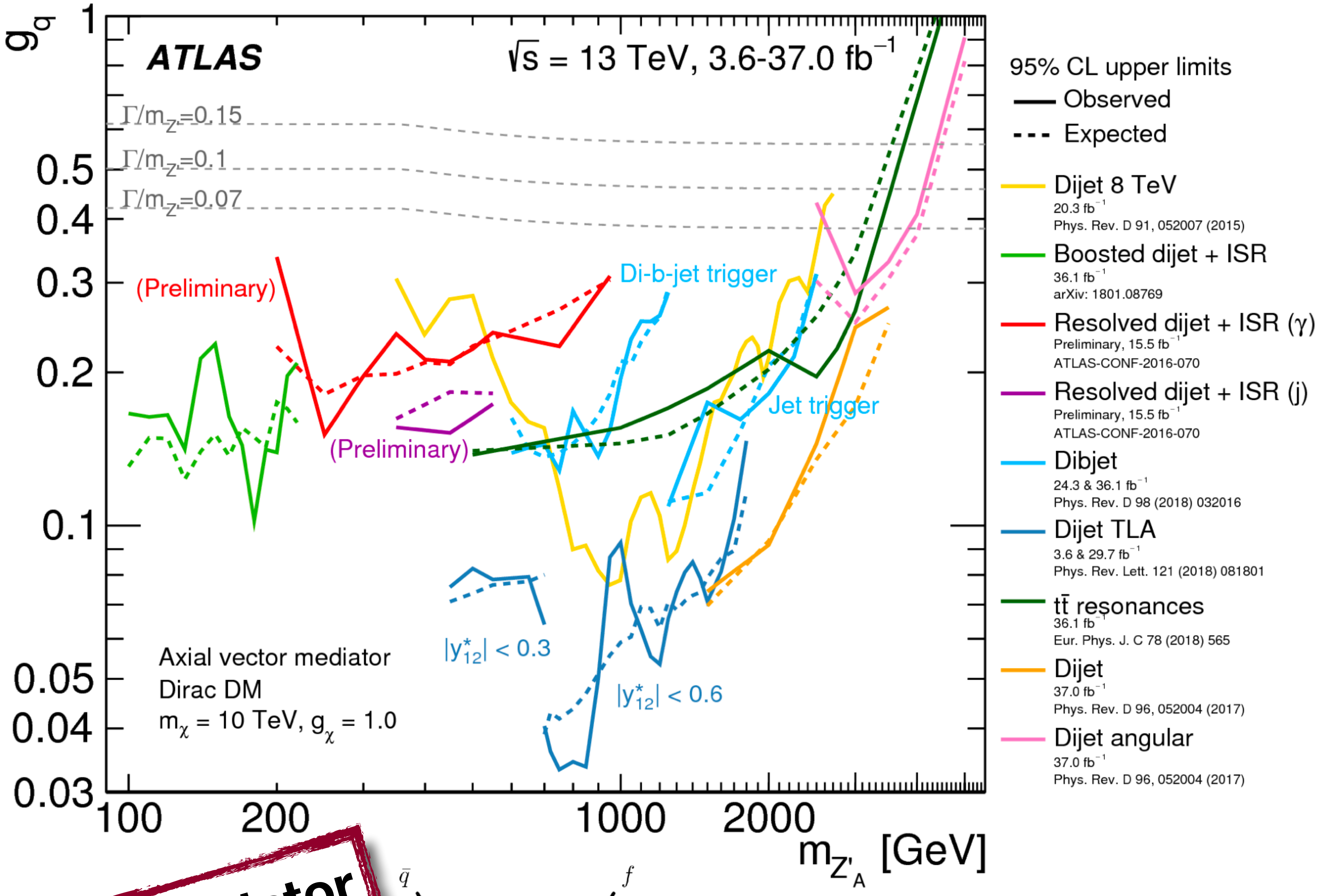


- Looking for $A' \rightarrow \mu\mu$
  - Bump hunt in dimuon spectrum from M ~ $2m_\mu$ to 70 GeV
- Excluding $\varepsilon > 10^{-2}$-10^{-3} (depending on M)

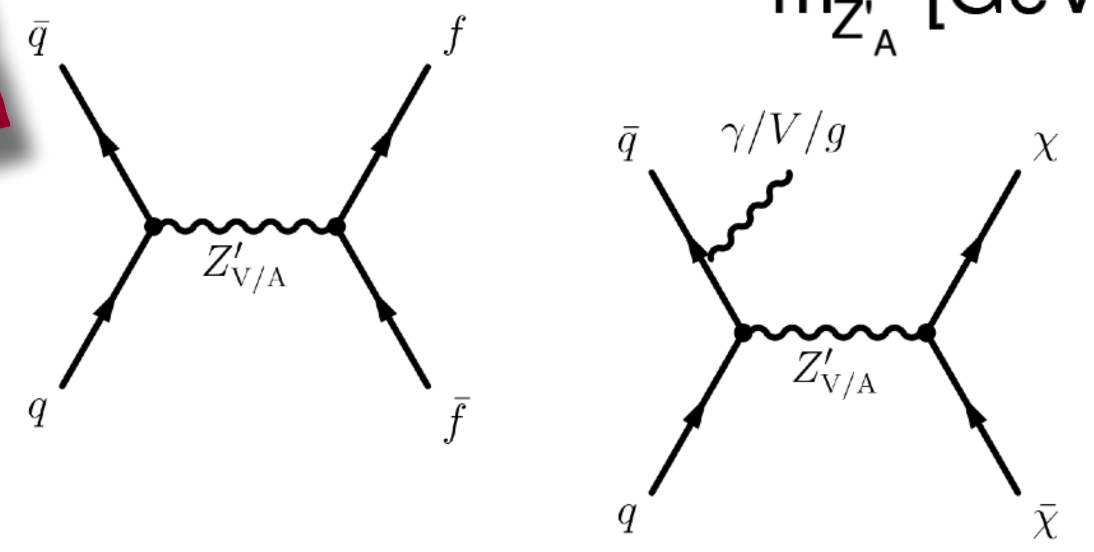
CMS Search coming soon!

Look for any kind of DM, in any place

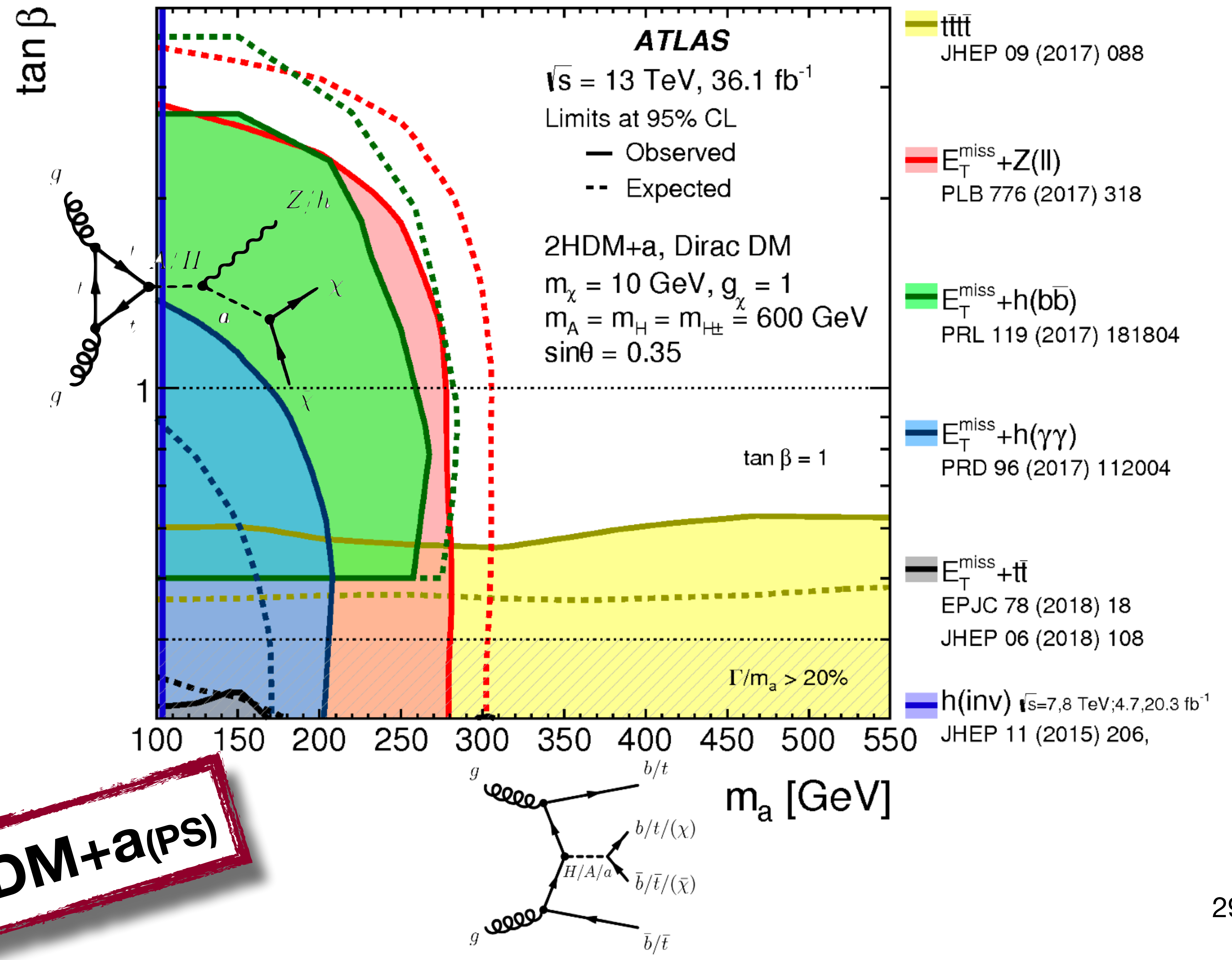
just a very small representative sample



A-V mediator



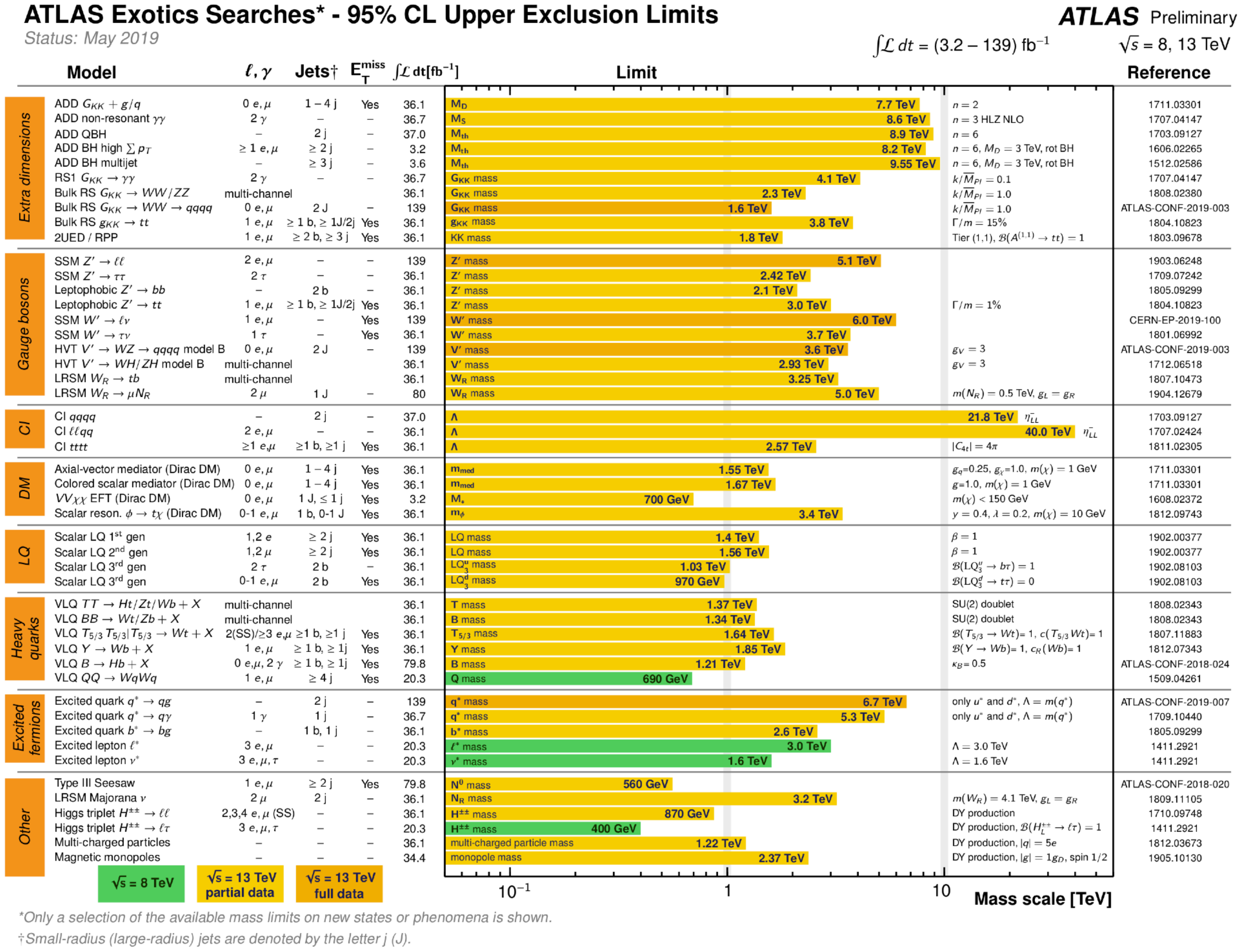
Spanned a large range of simplified model with different mediator assumptions

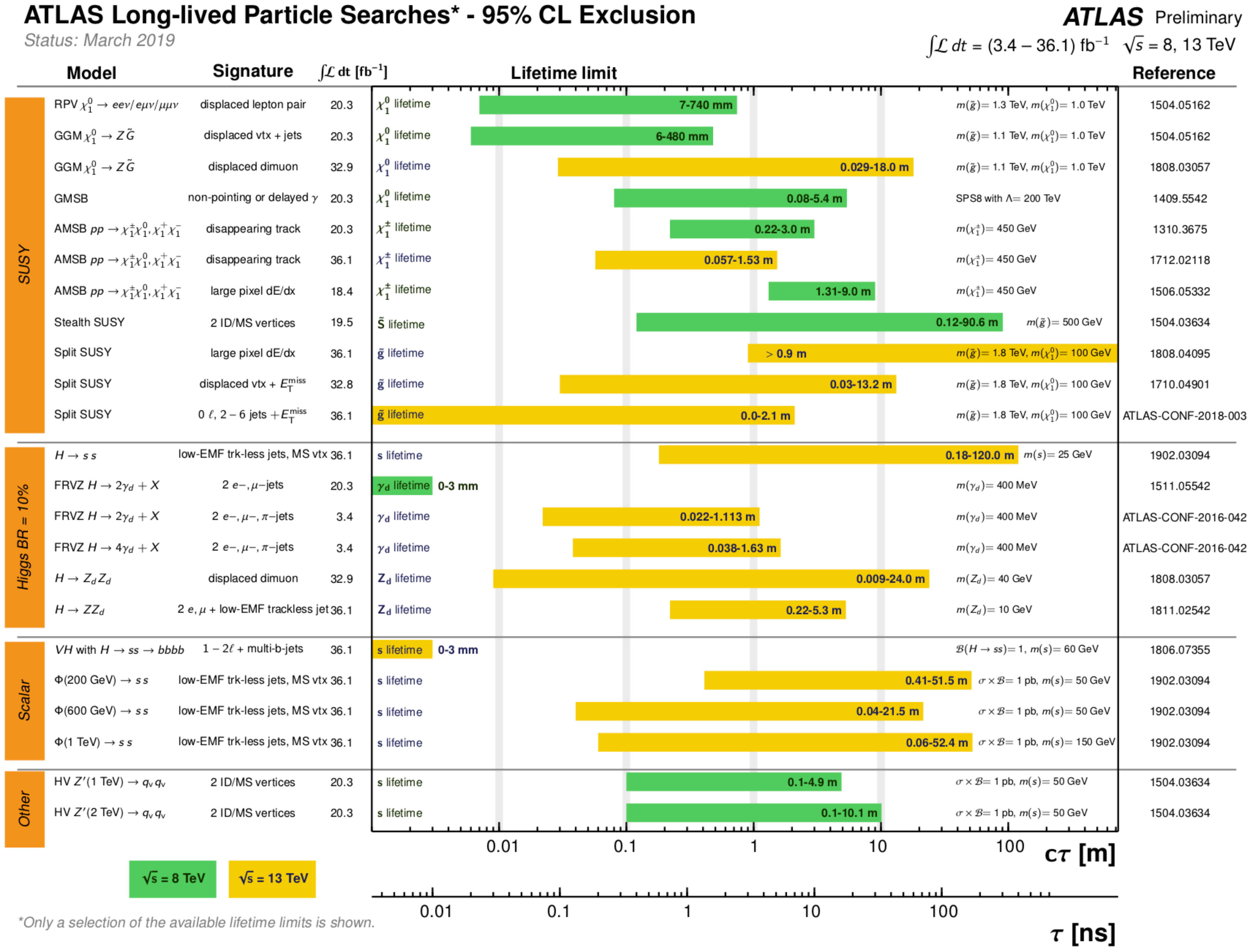


2HDM+a(PS)

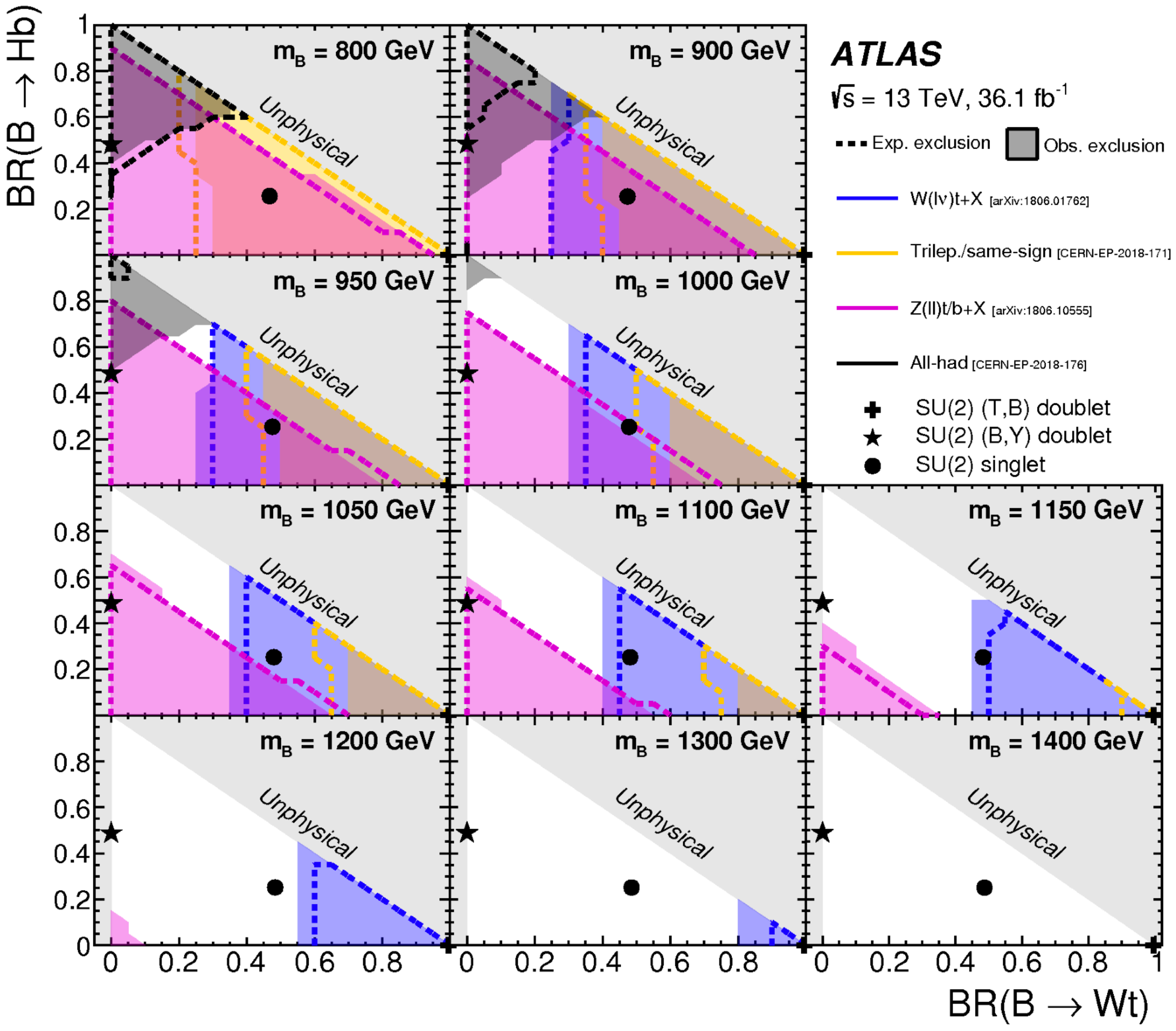
EXOT-2017-032

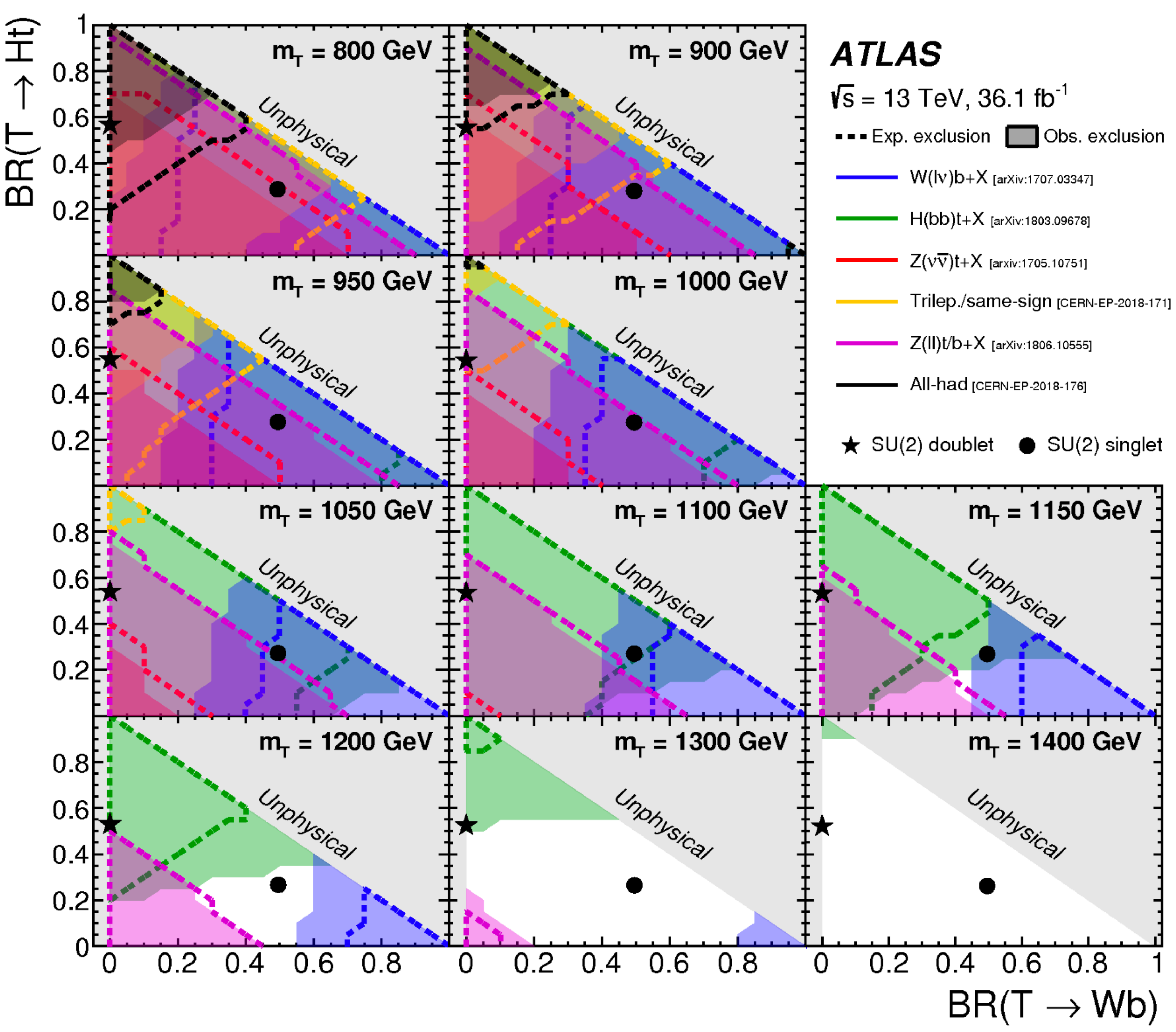
New physics searches overview (ATLAS)



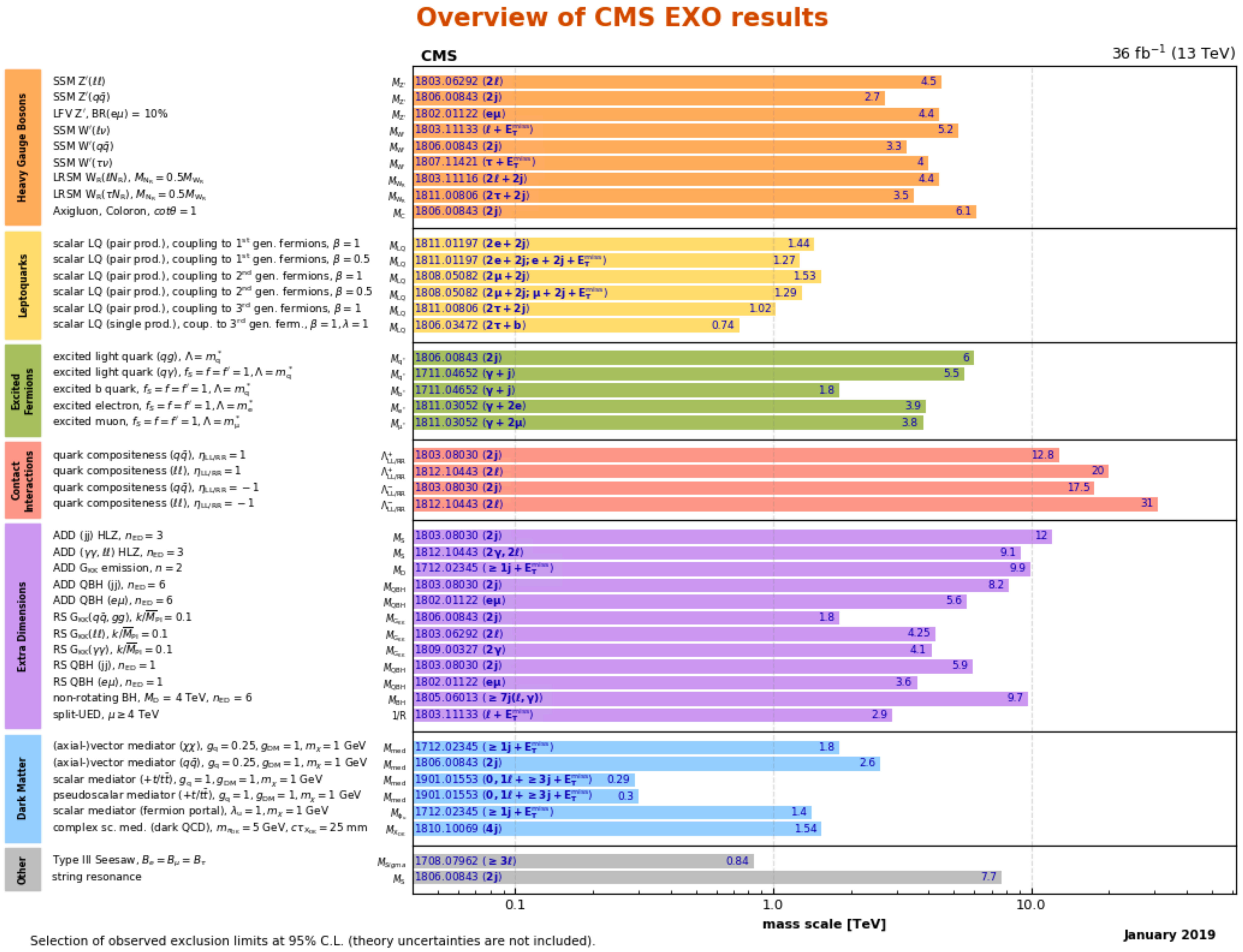


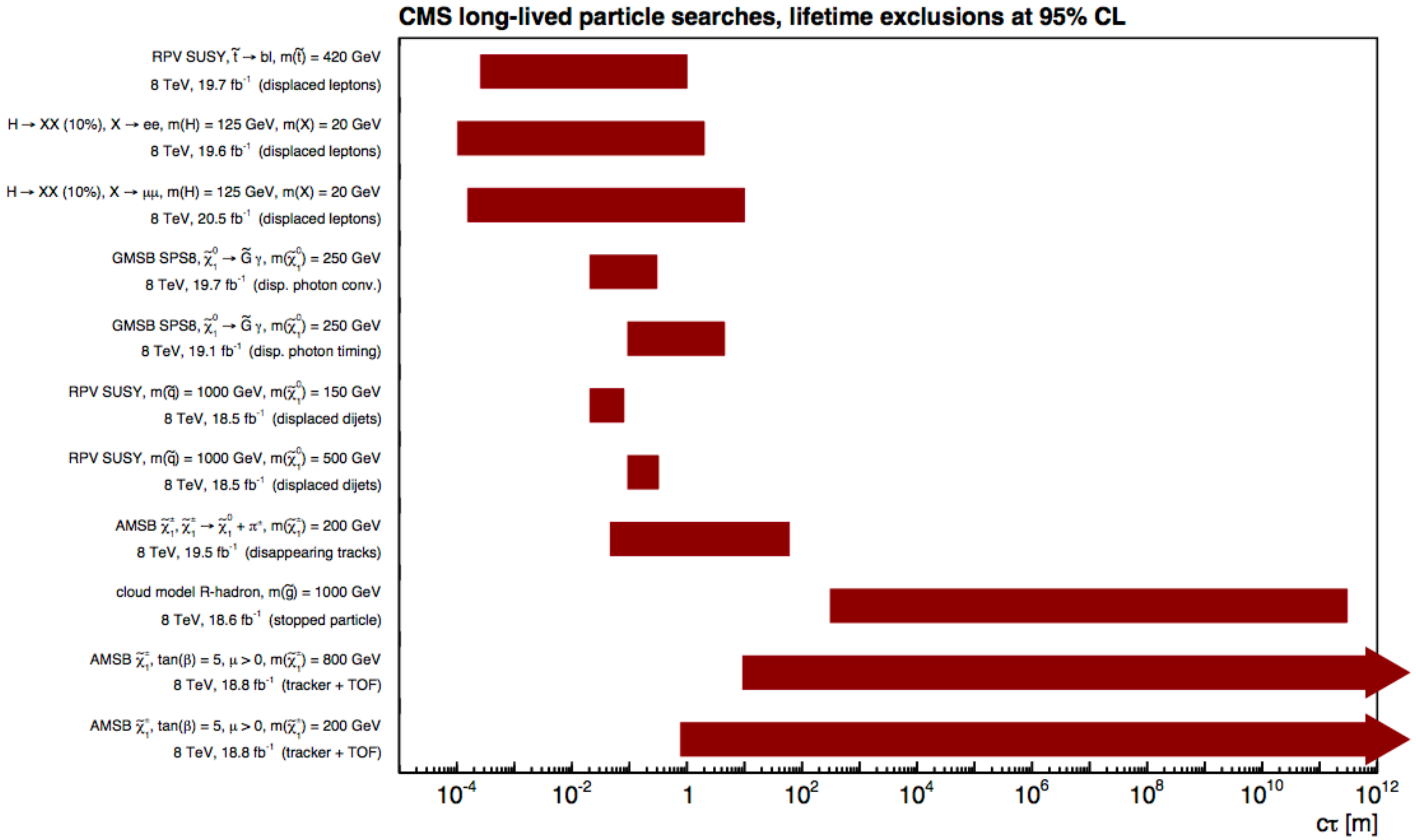
New physics searches overview (ATLAS)





New physics searches overview (CMS)





New physics searches overview (CMS)