

# Status and opportunities in Higgs and BSM at LHC

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Assisi, 16-18 June 2019

# From SM to...

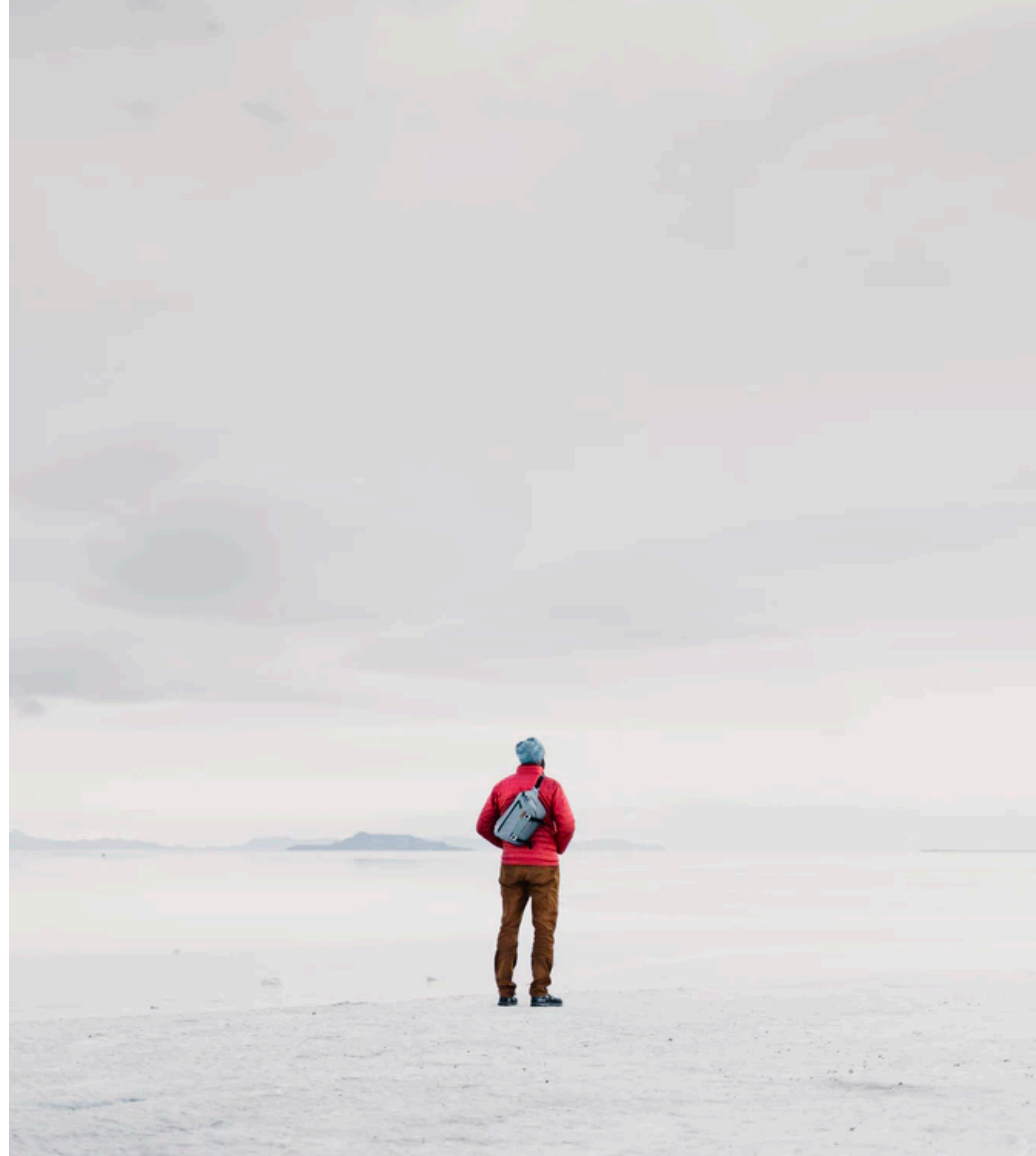
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- LHC has tested and measured the properties of SM to a very good degree of precision:

satisfying but not exhaustive

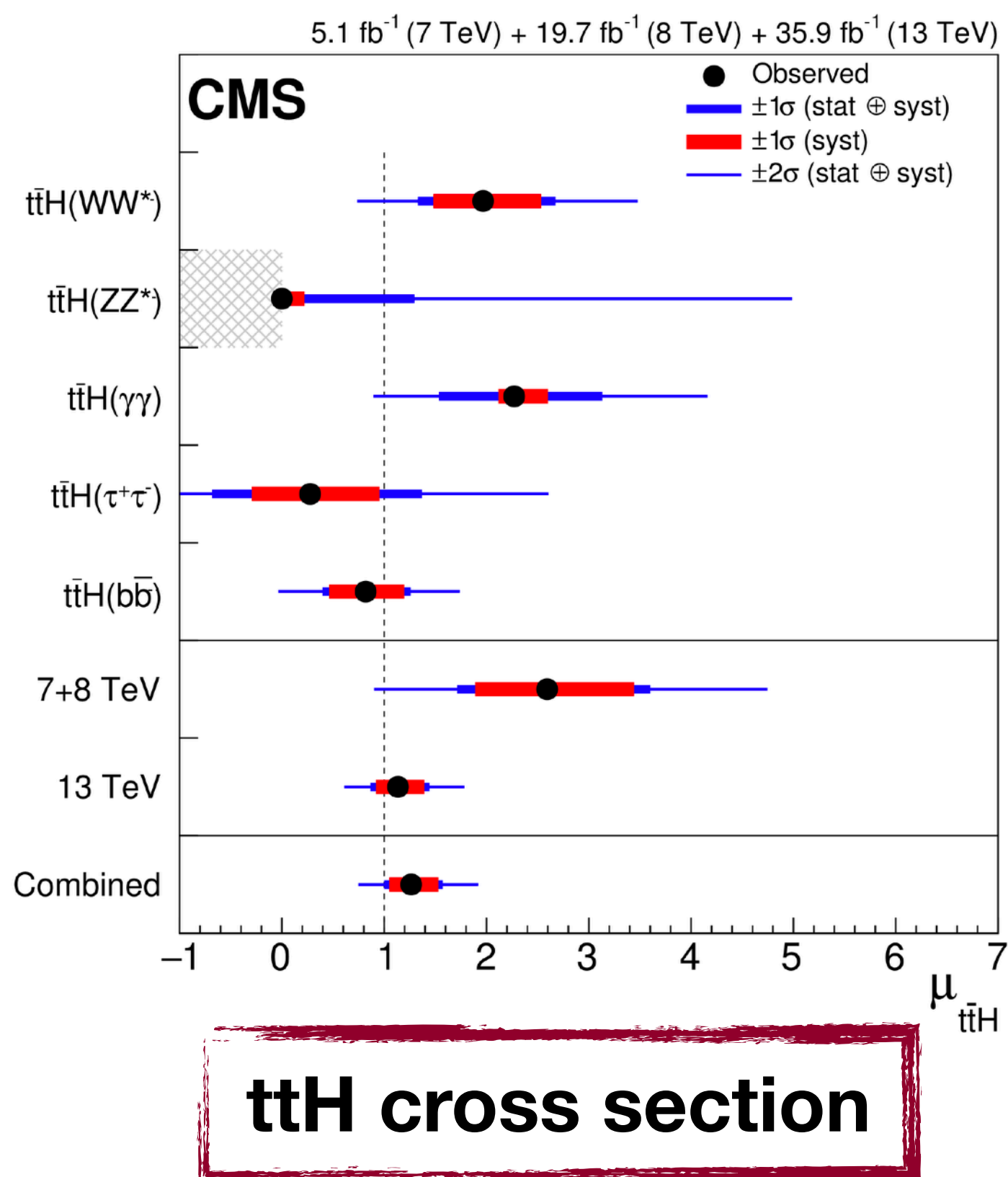
- we also like to search for what is still unknown, beyond the SM

how are we looking  
for new Physics Phenomena?

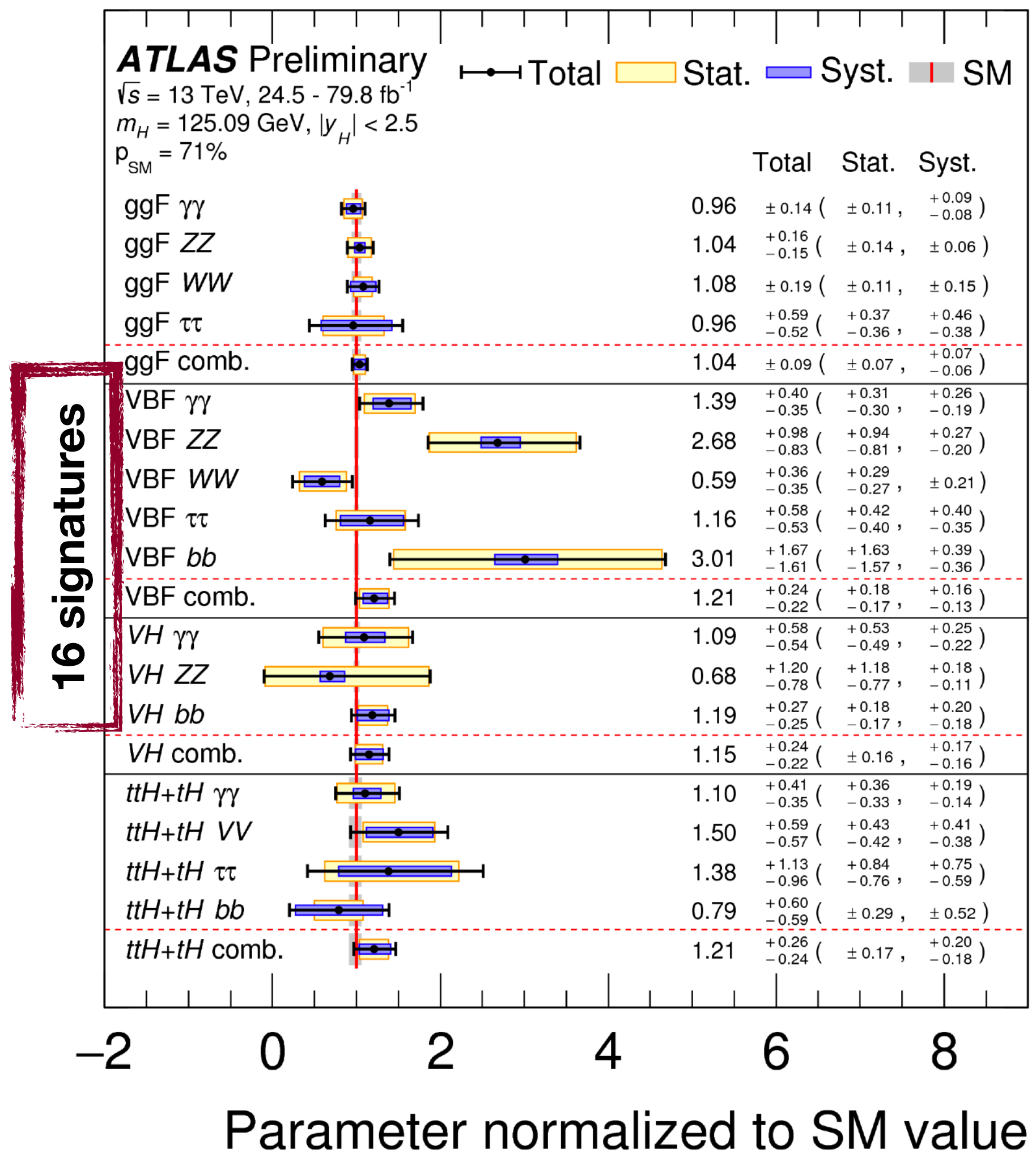
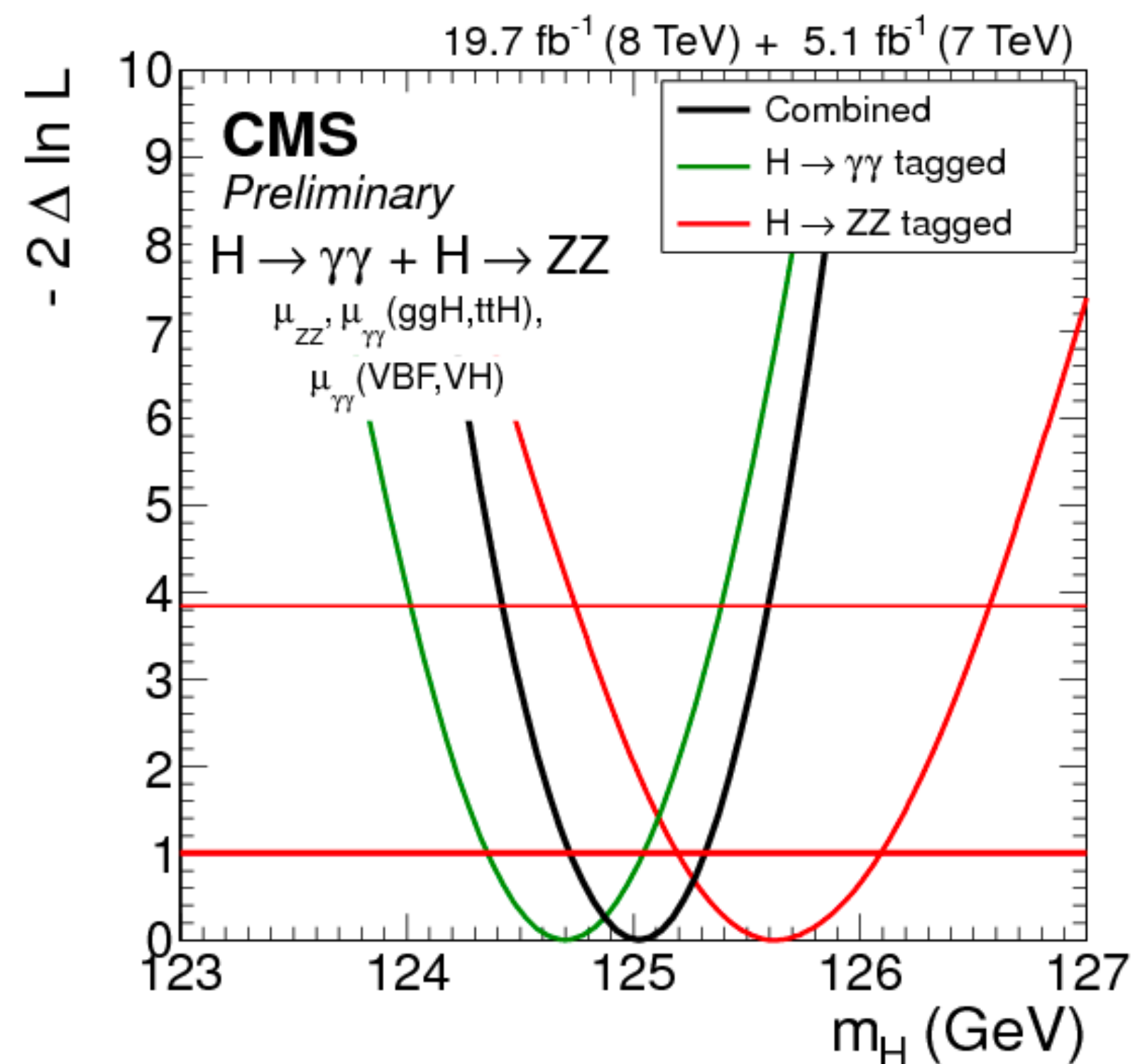


# The last great discovery: the Higgs

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

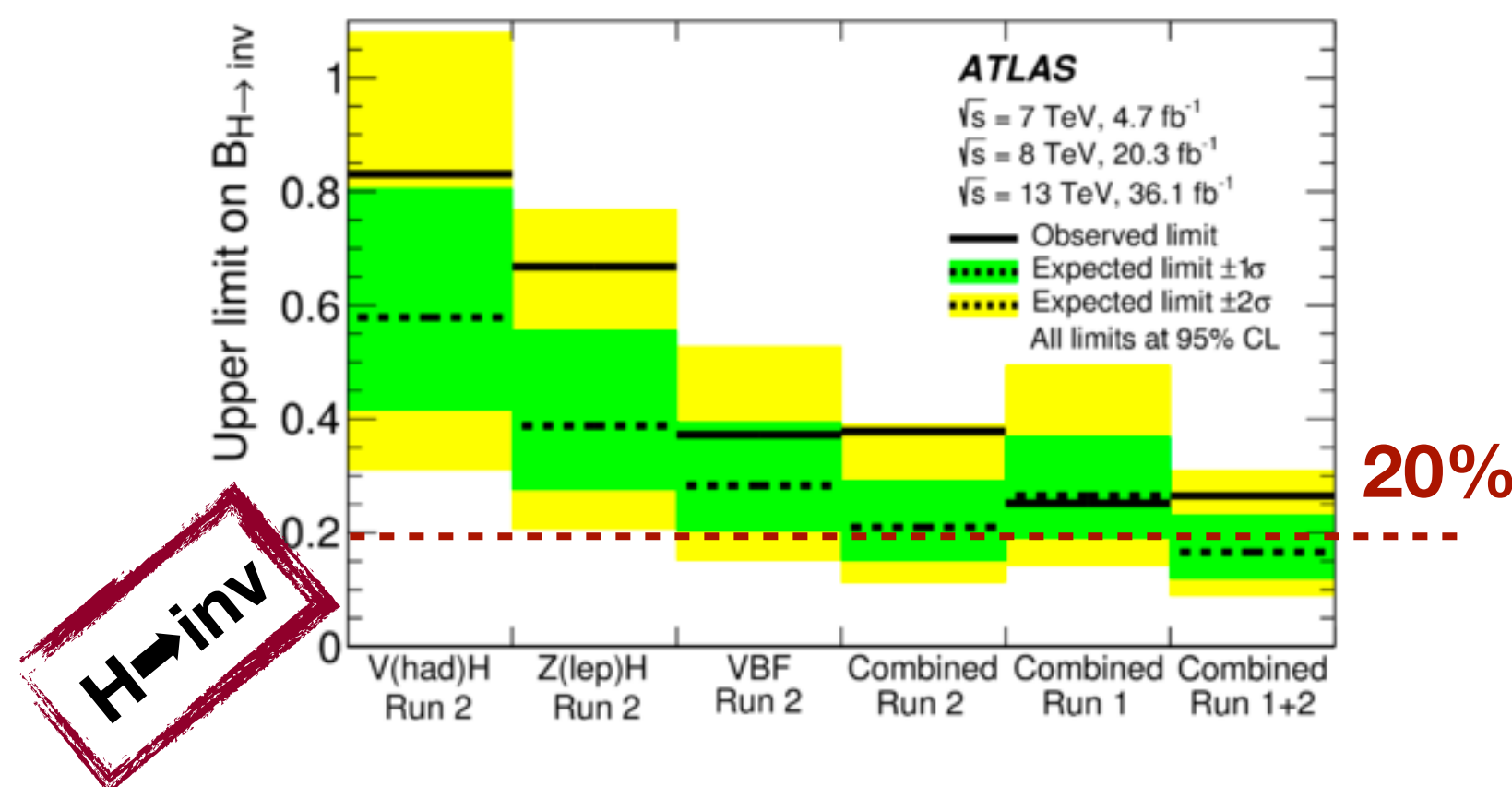
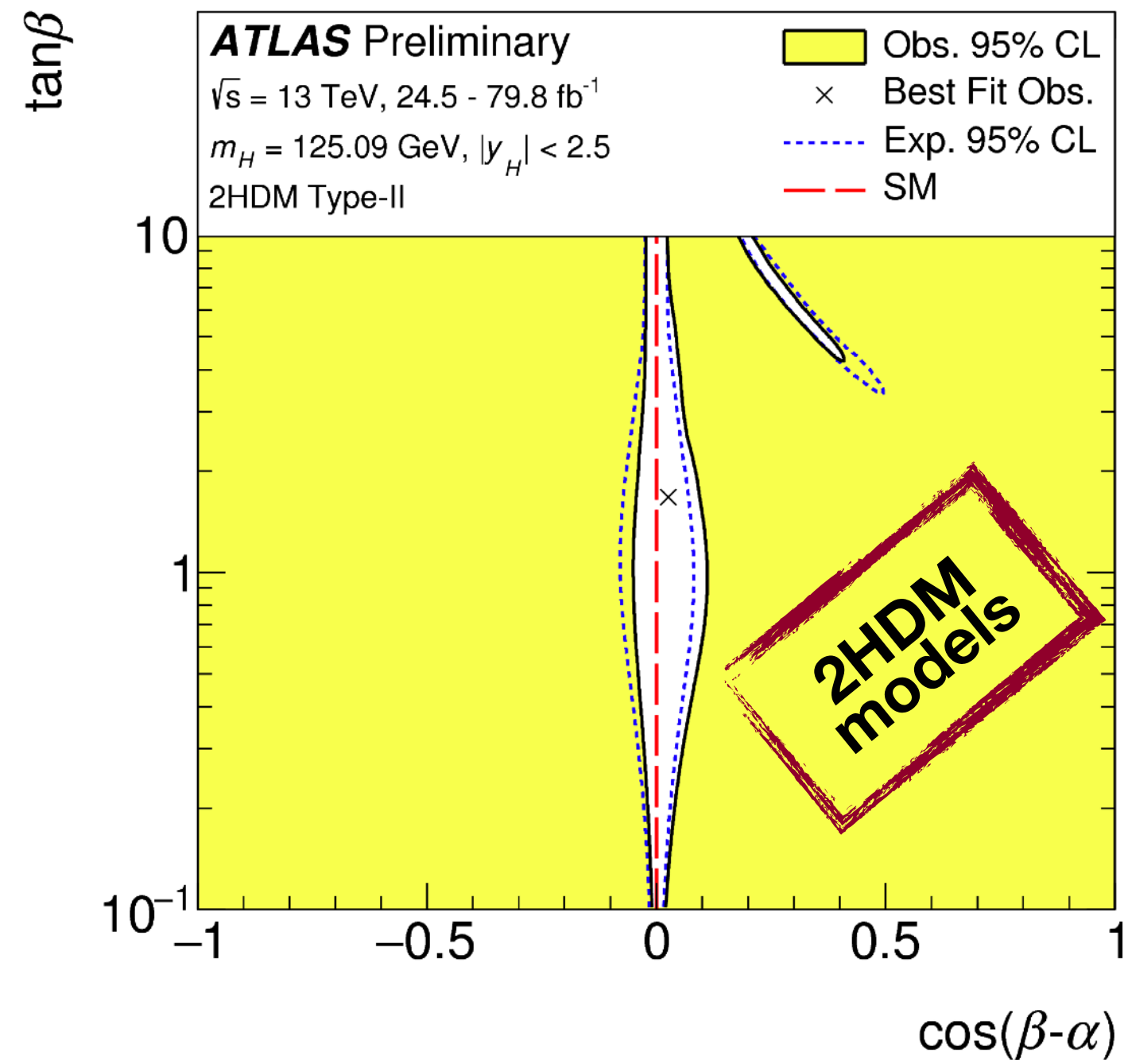
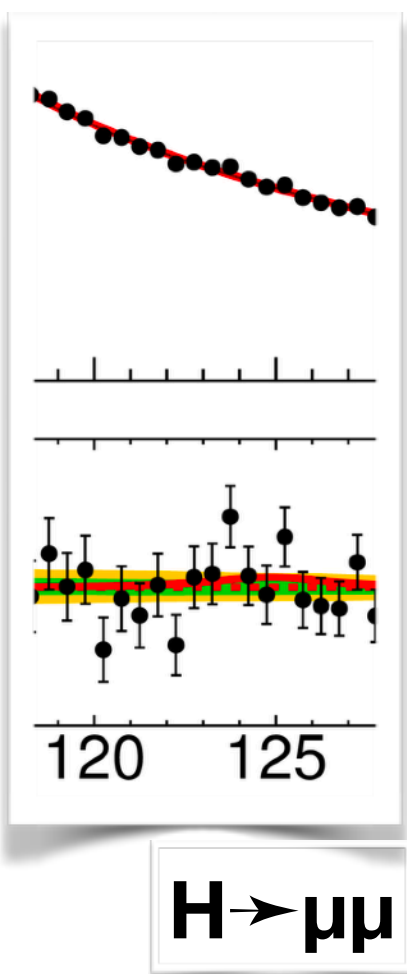
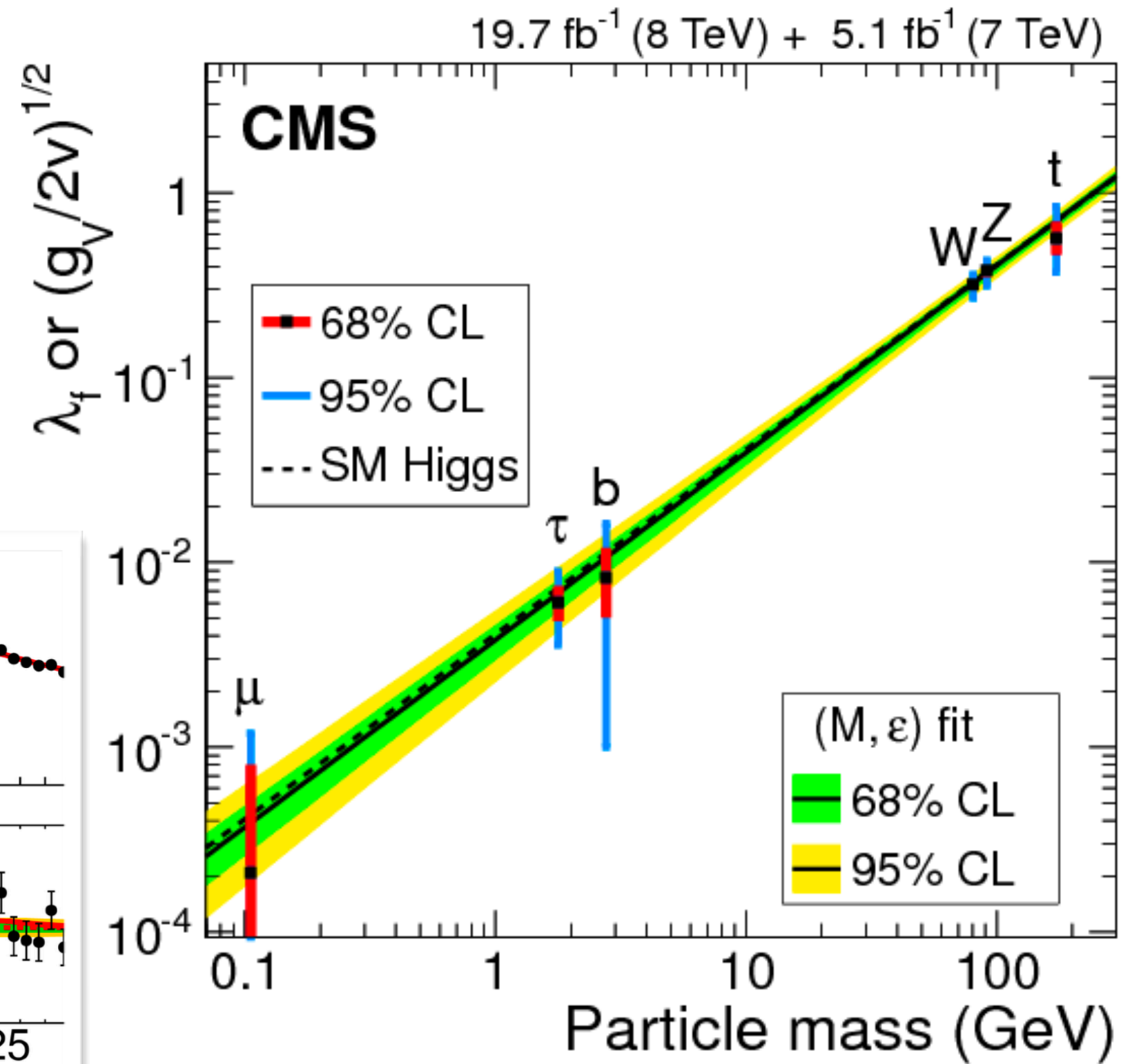


## m<sub>H</sub> combination

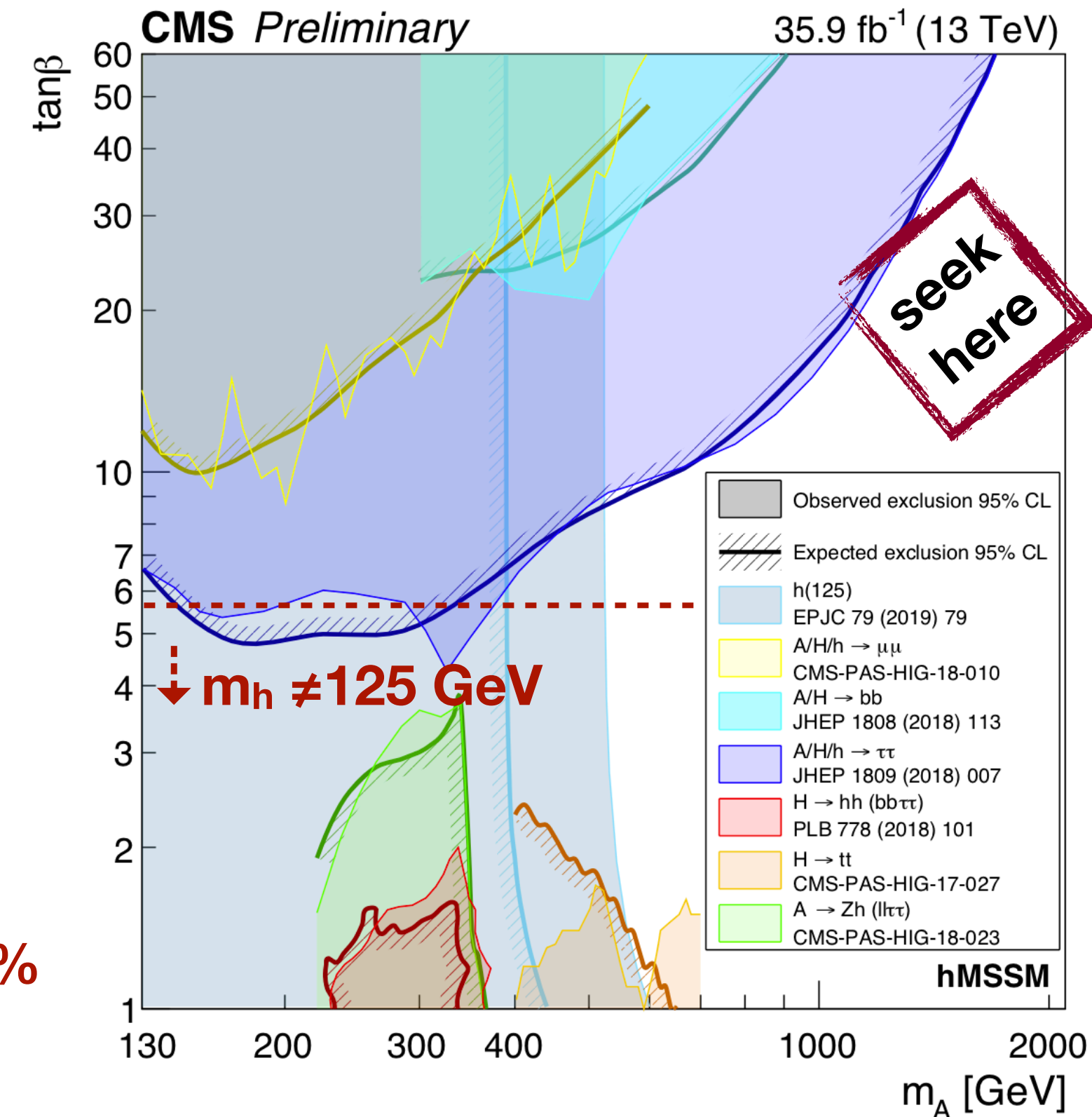


# Is it really the SM Higgs?

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

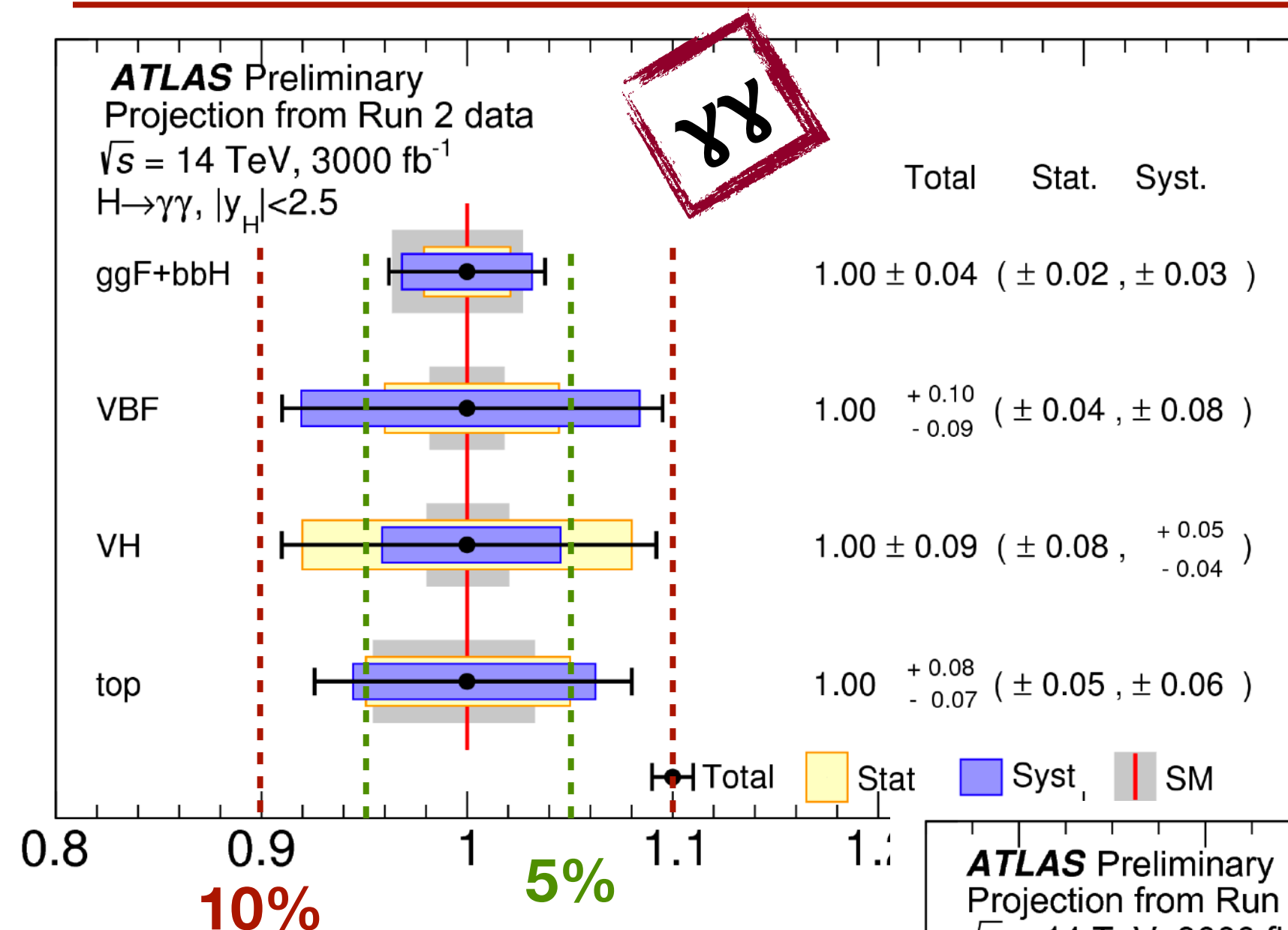


Can be the lightest of a crowded Higgs sector? (i.e. 2HDM, MSSM, etc.)

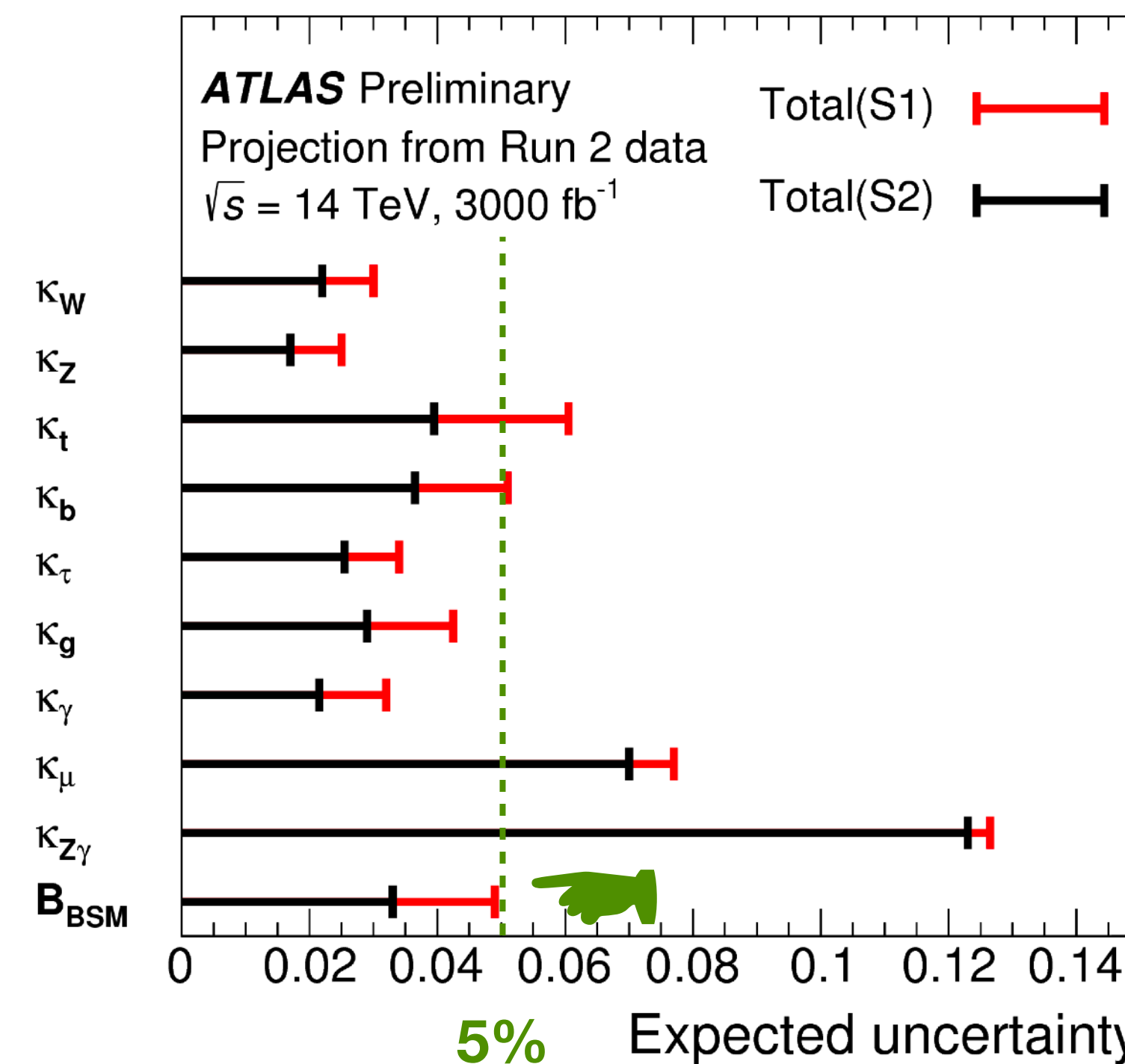


3 ab<sup>-1</sup>

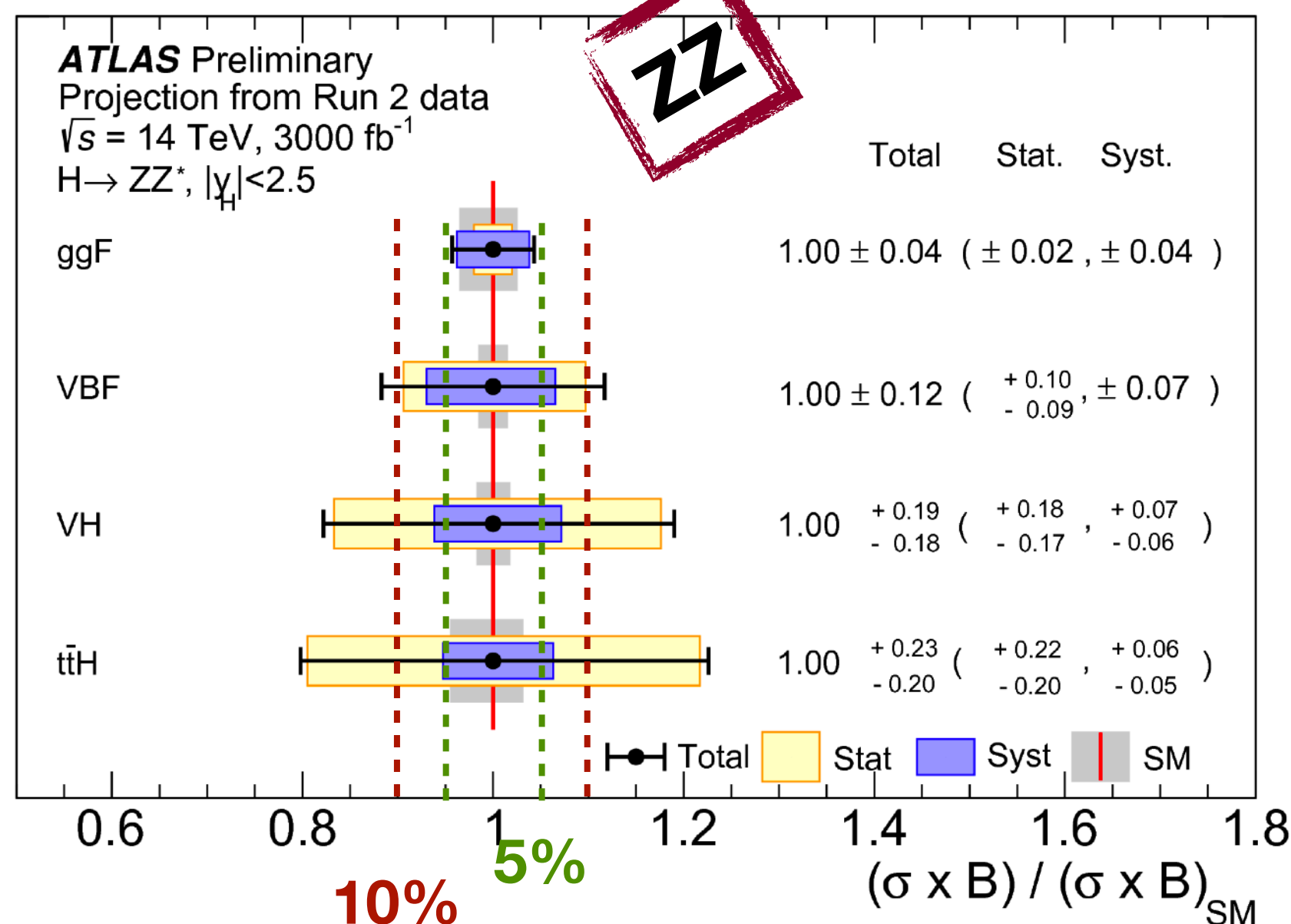
# Will the future tell us more?



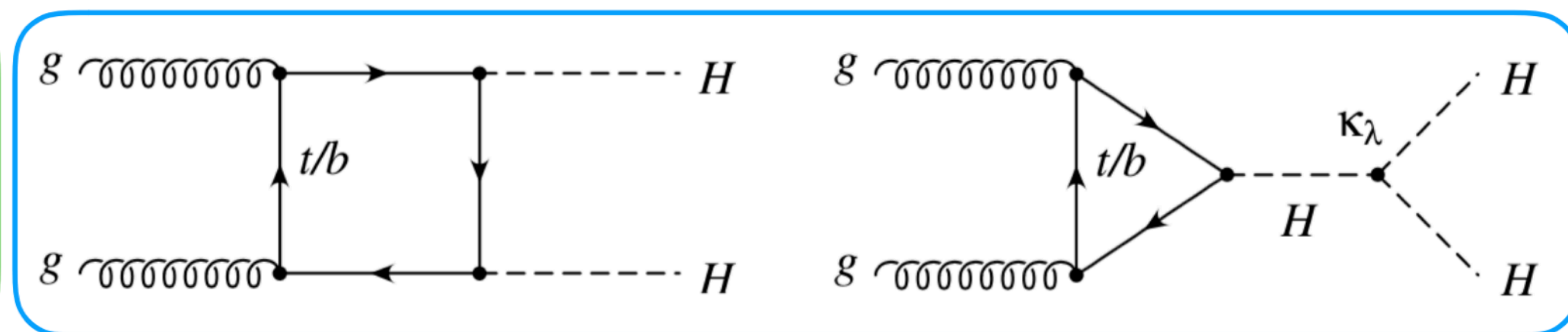
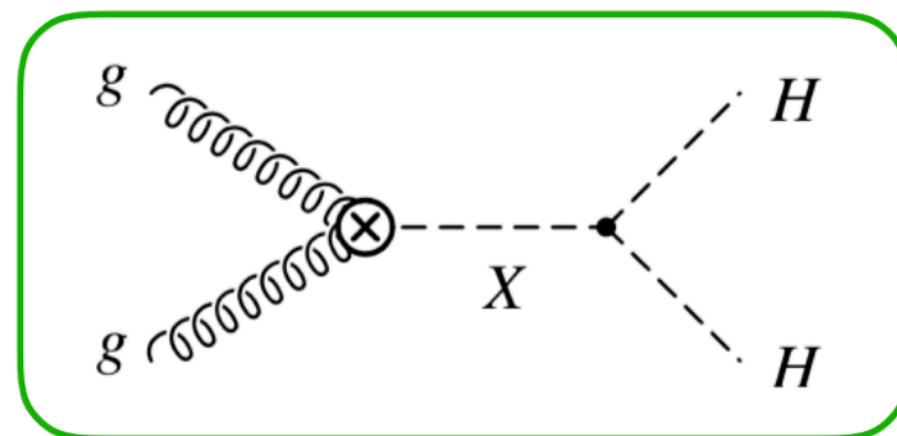
← Cross section uncertainties will be halved, though still some limited by statistics (combinations needed)



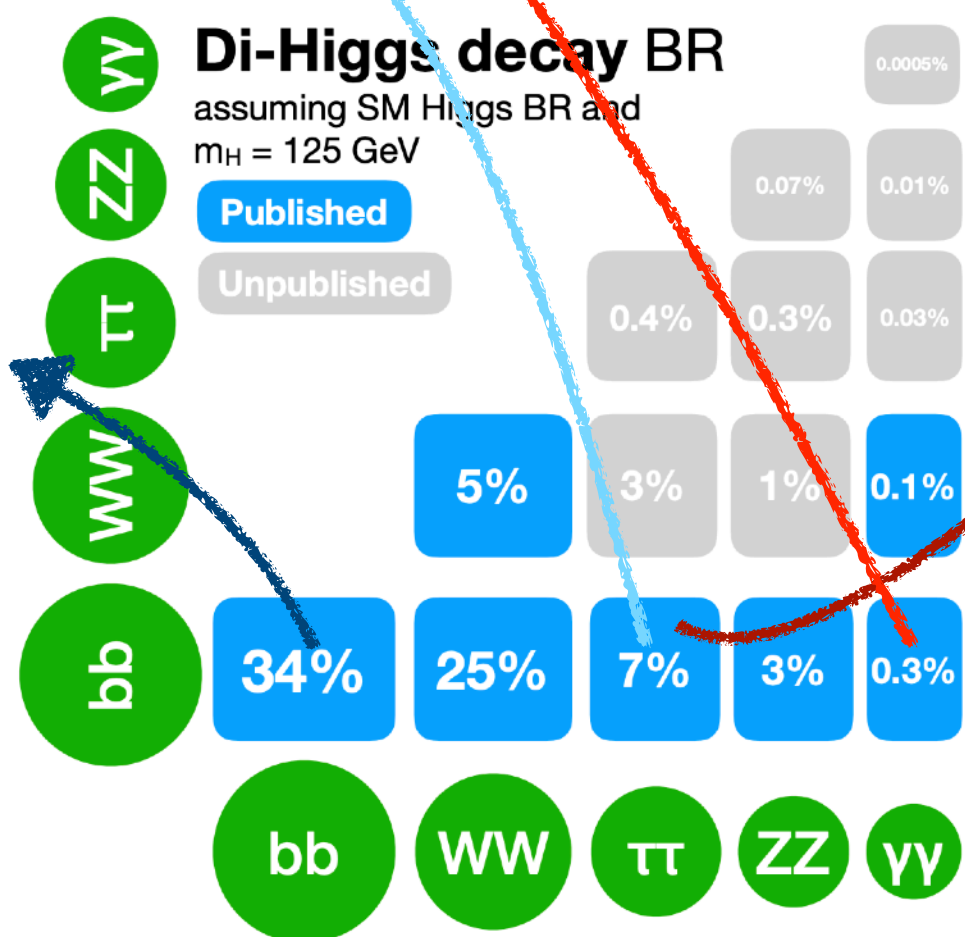
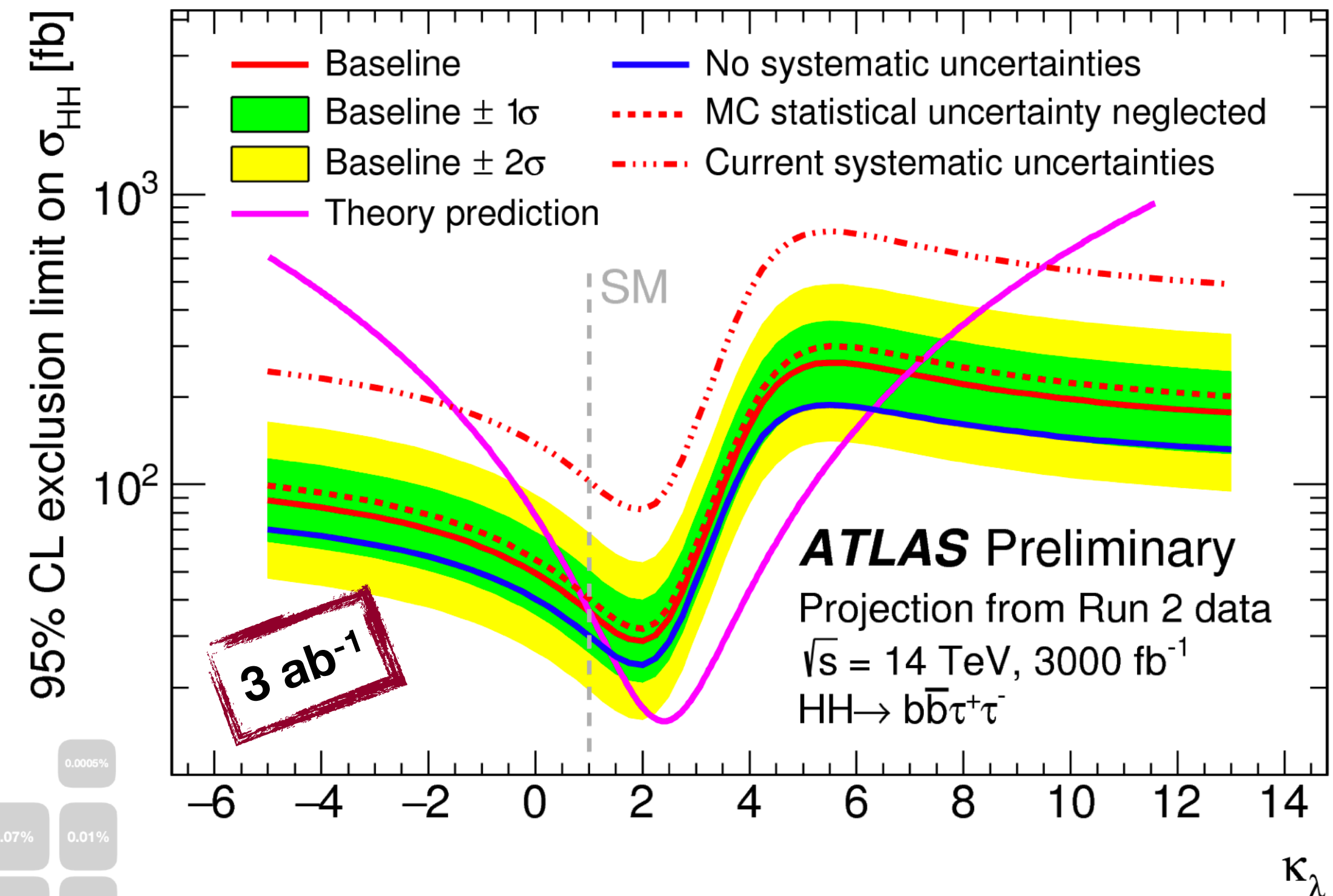
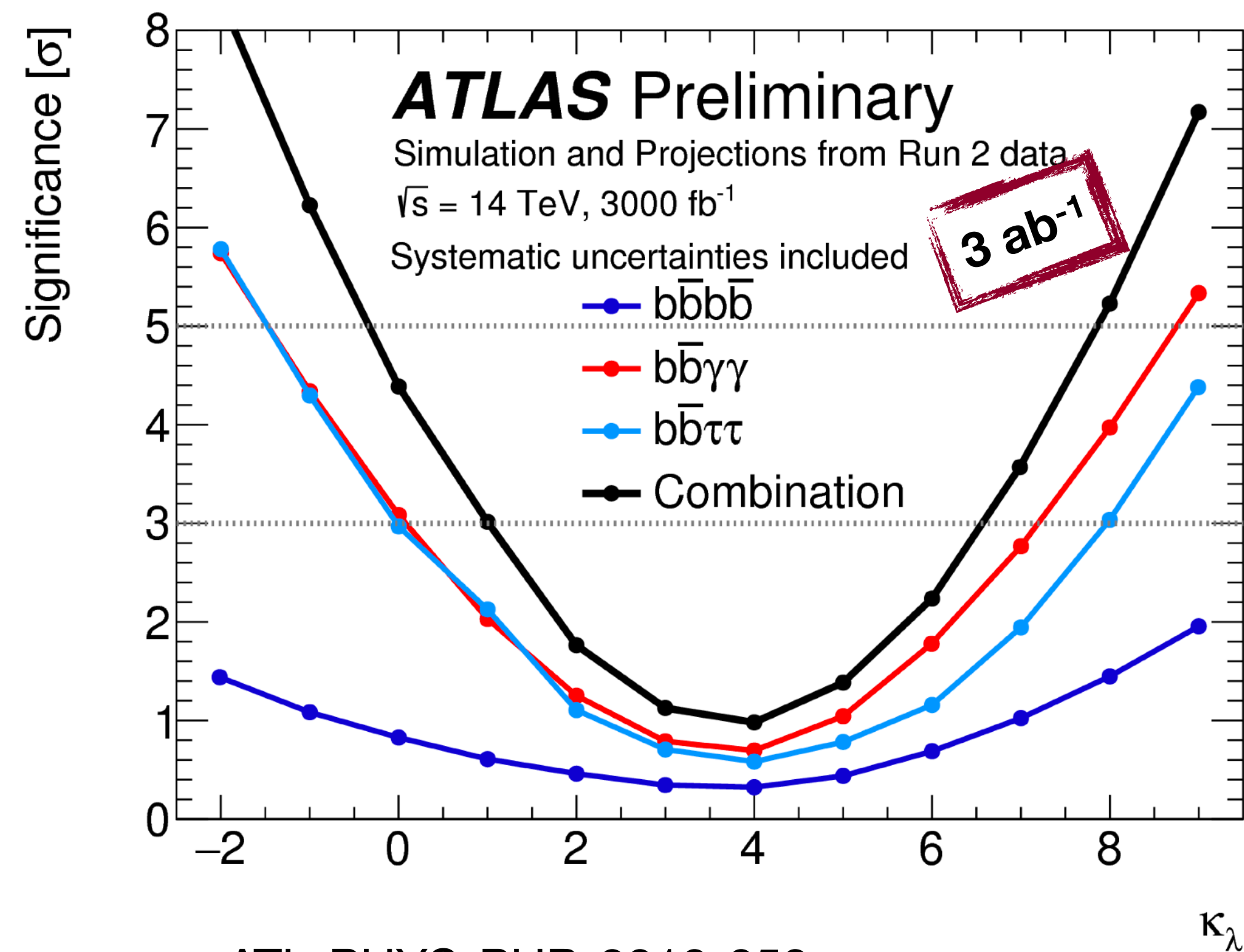
↑ Couplings will be known at the few % level



# Pair produced Higgs



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



# Always looking for more

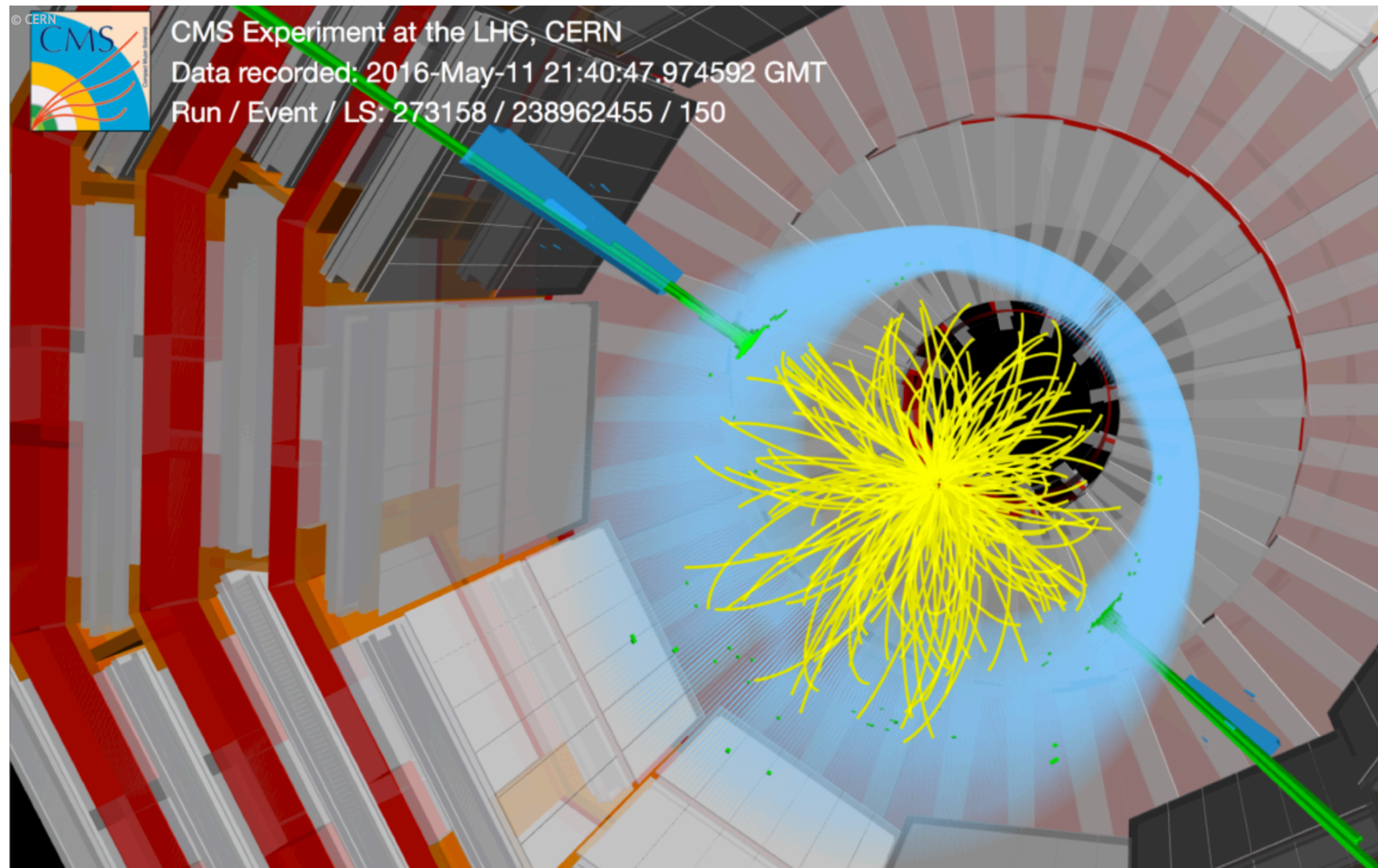
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We should seek all possible evidence for NP

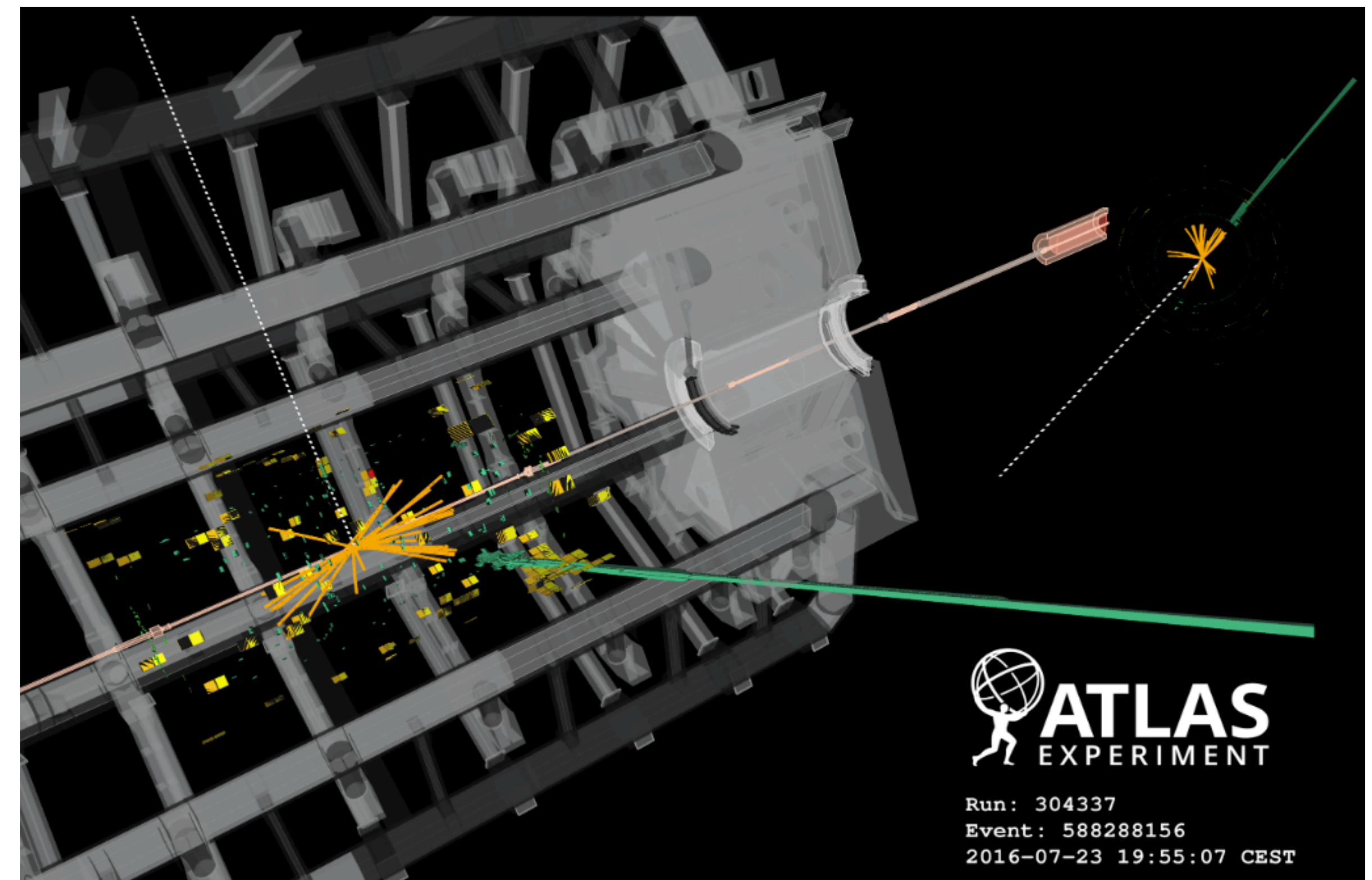


# LHC: the Ideal Machine to Search for Heavy Resonances

**8 TeV DiJet Event!**



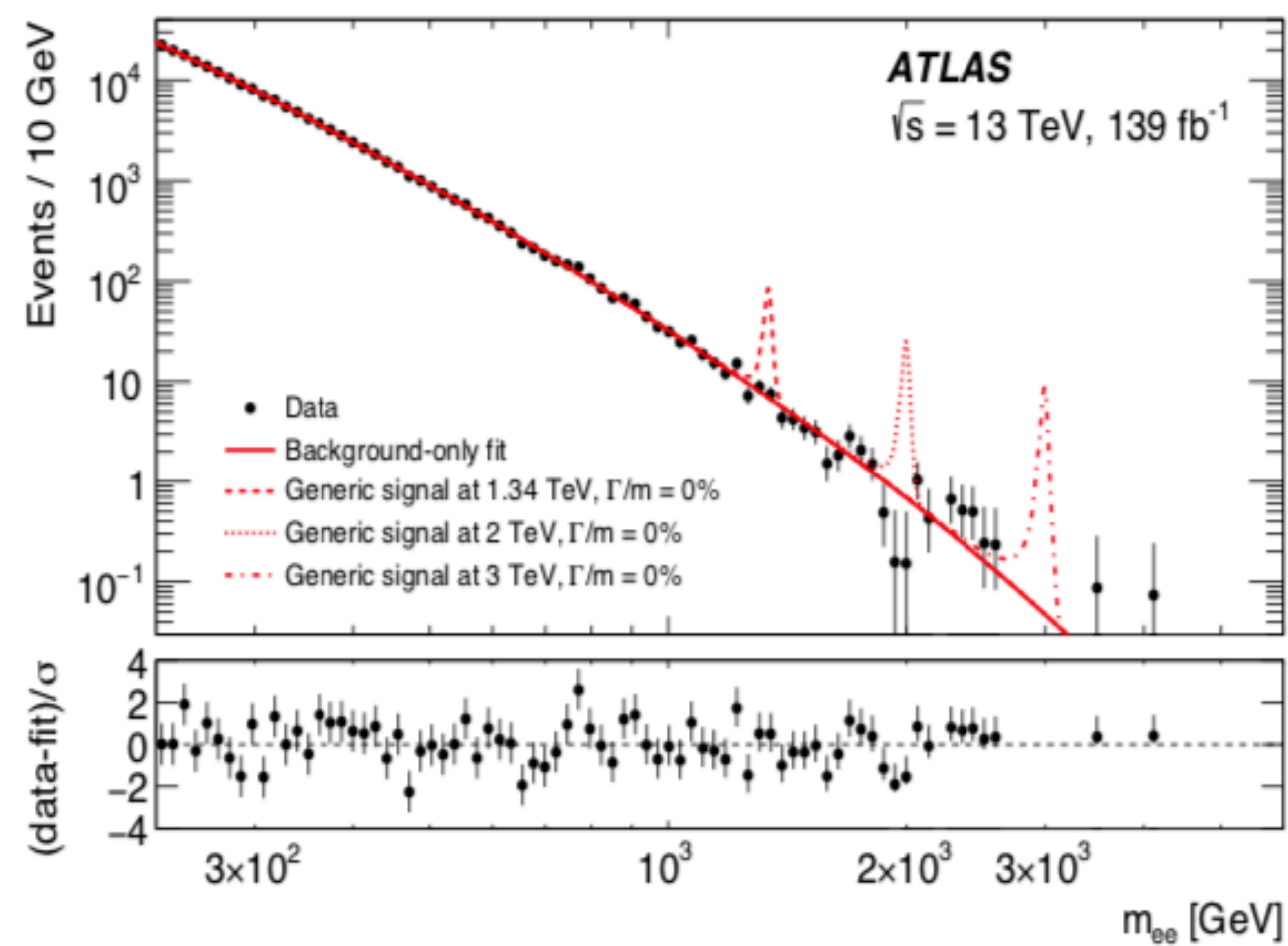
**2.2 TeV I+MET Event!**



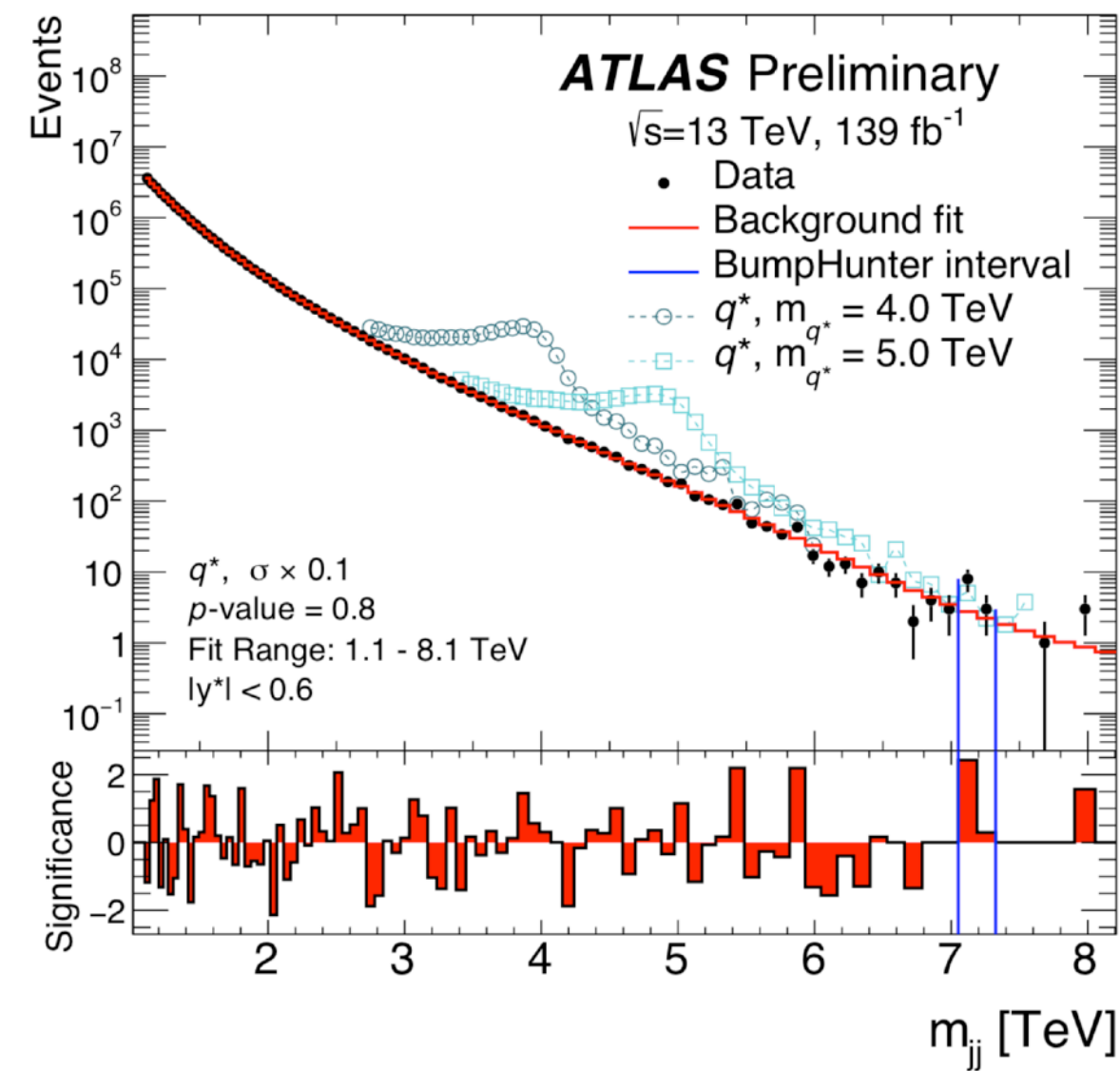


# We've Done a Lot of Bump Hunts!

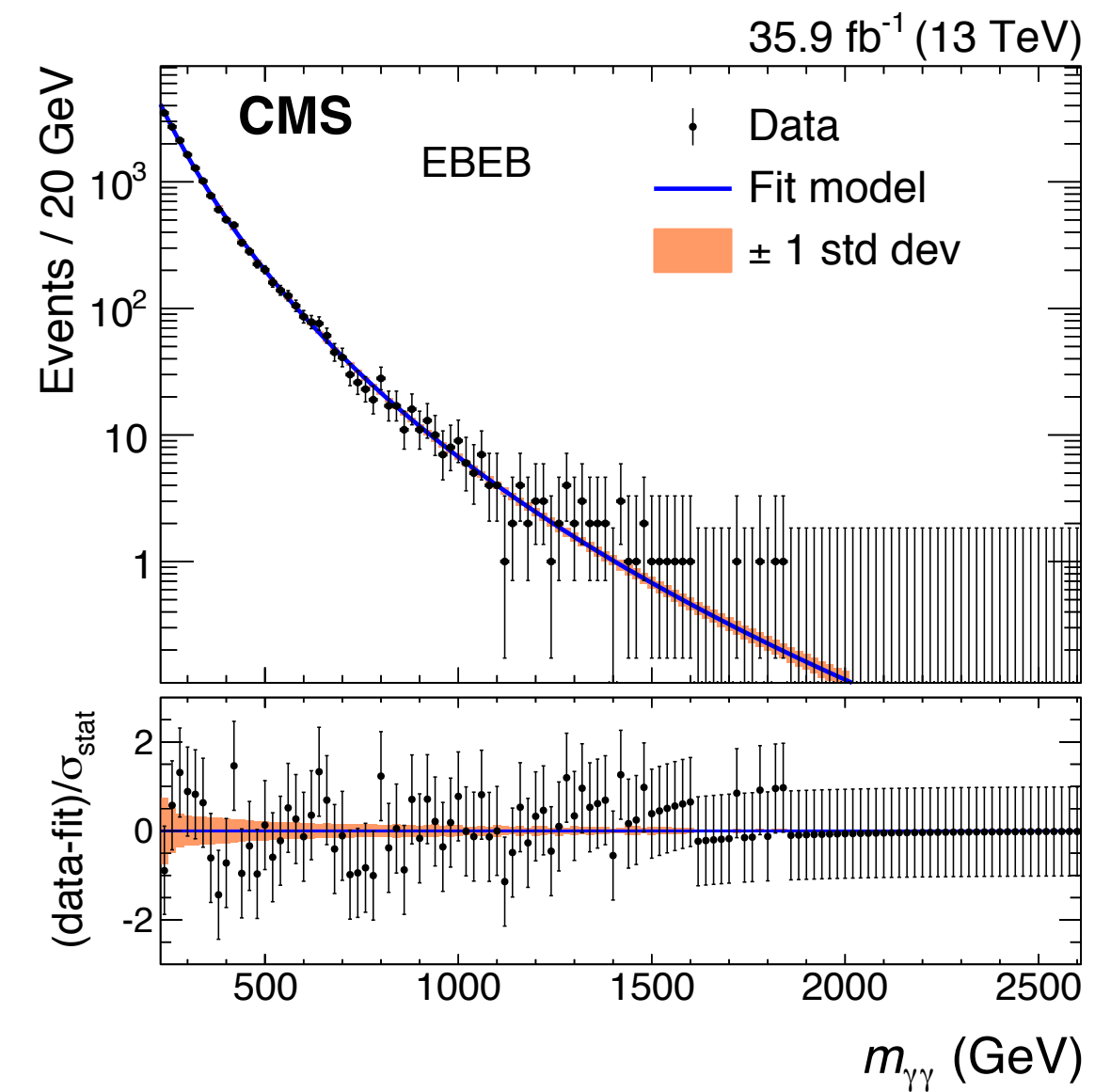
## Dileptons



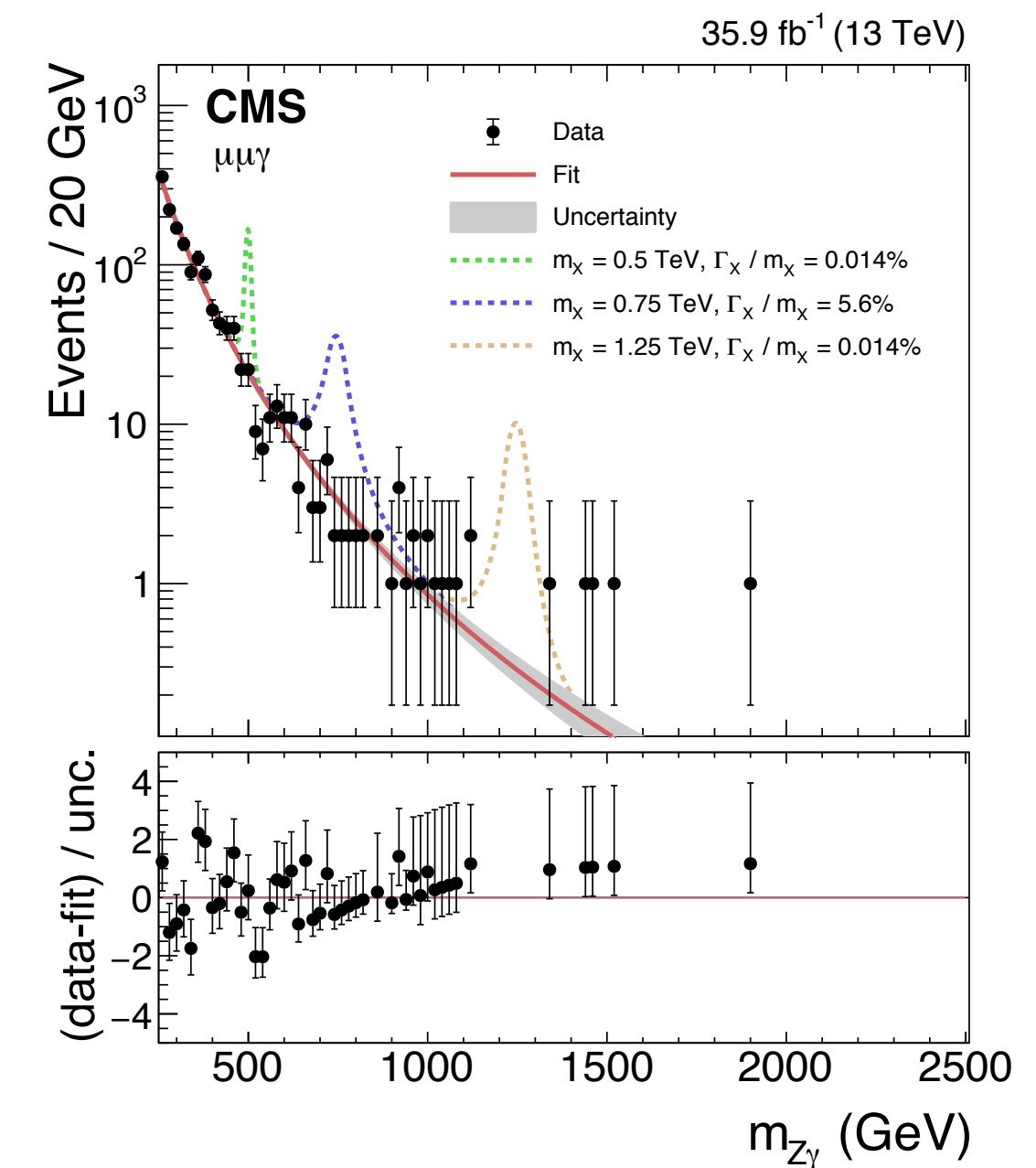
## Dijets



## Diphotons



## Z+photon

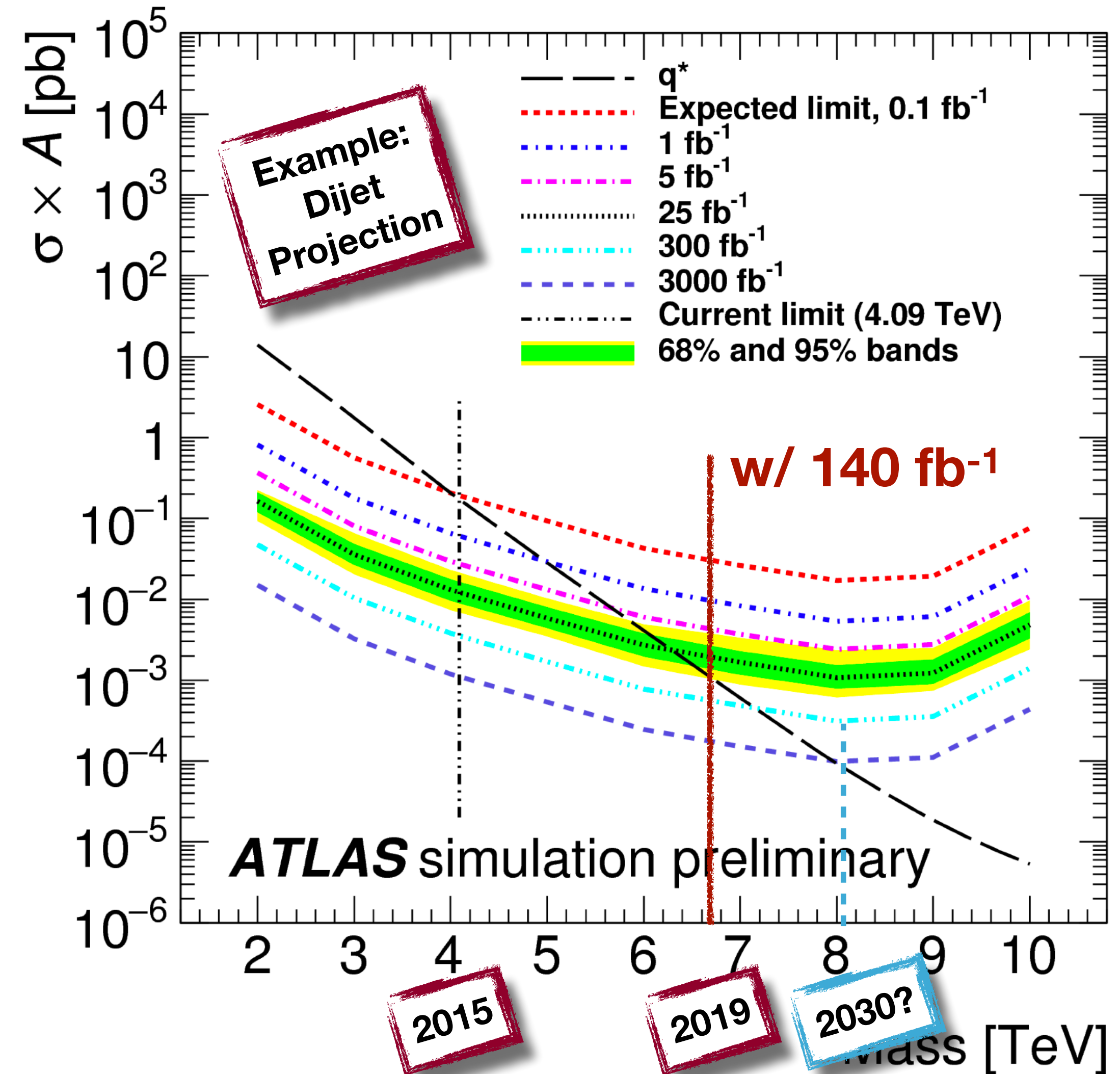


... and so on (also b's,  $\tau$ 's, top, etc)

# But Bump-Hunts Are Running Out of Steam

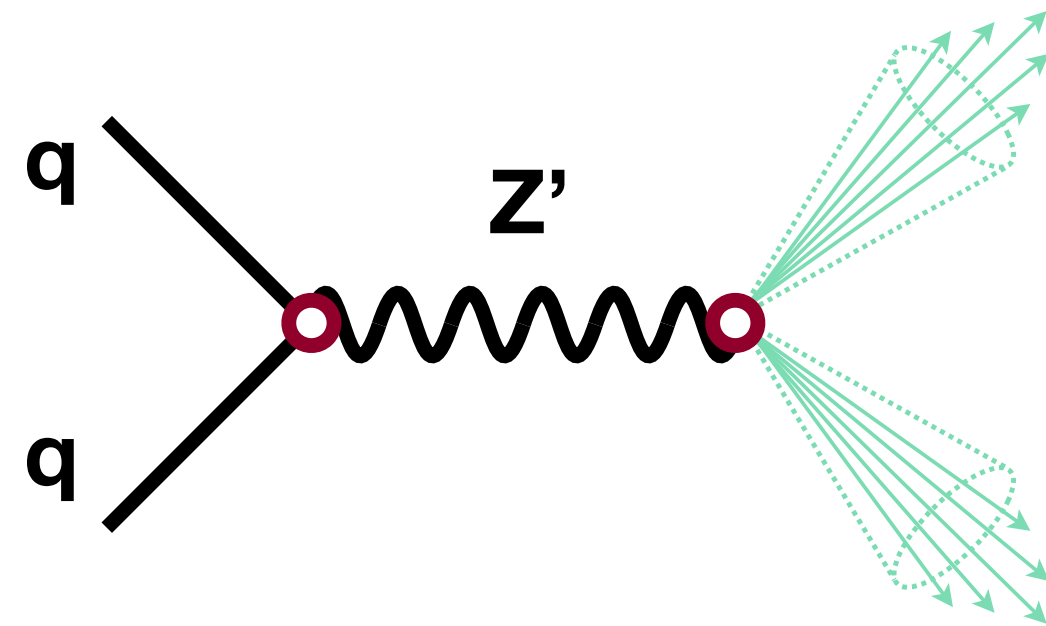
- Probing **really high** masses:  $O(10 \text{ TeV})$
- More lumi brings **marginal** improvements
- Can't just reload searches: need **new ideas**

| <i>examples</i>              | Mass Lower limit       |
|------------------------------|------------------------|
| <b>String resonance (jj)</b> | $\sim 8 \text{ TeV}$   |
| <b>Excited quark (jj)</b>    | $\sim 6.5 \text{ TeV}$ |
| <b>Z' (SSM) (ll)</b>         | $\sim 5 \text{ TeV}$   |
| <b>W' (SSM) (lv)</b>         | $\sim 6 \text{ TeV}$   |



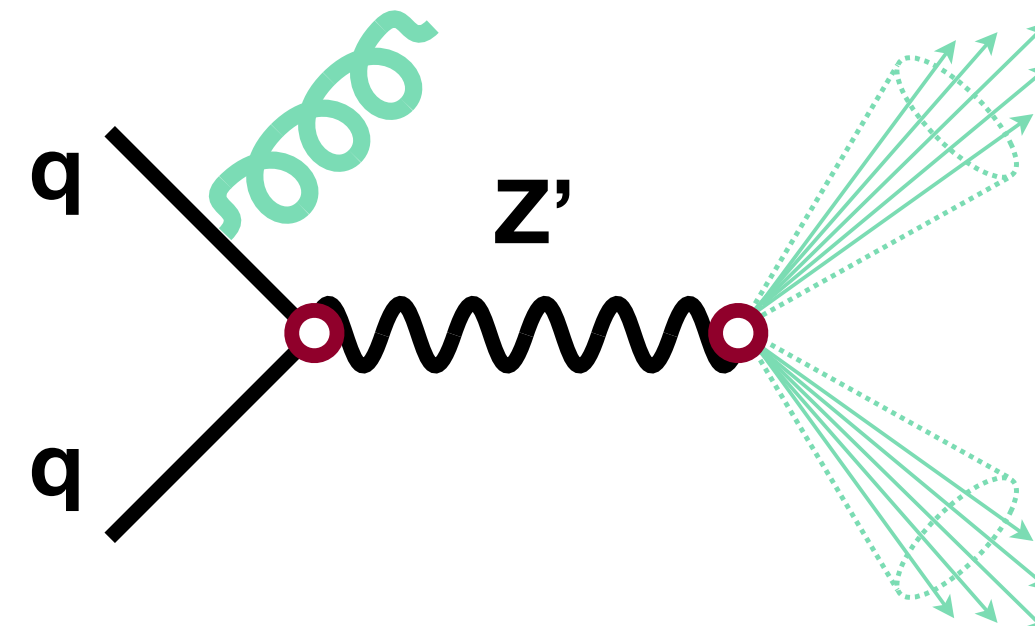
# Example: Dijets Going to Lower Mass with ISR and Substructure

**High Mass**  
( $M > 0.5-1.5$  TeV)



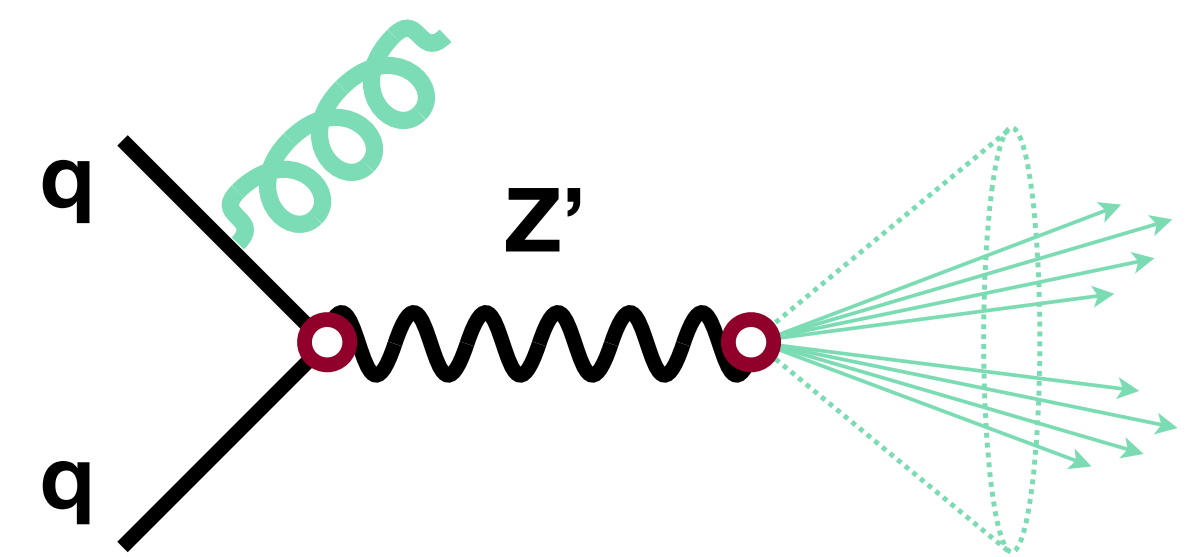
- Two high energy jets
- No problems with trigger for  $M > \sim 1.5$  TeV
- Can go down to  $\sim 0.5$  TeV with trigger-level analysis

**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)



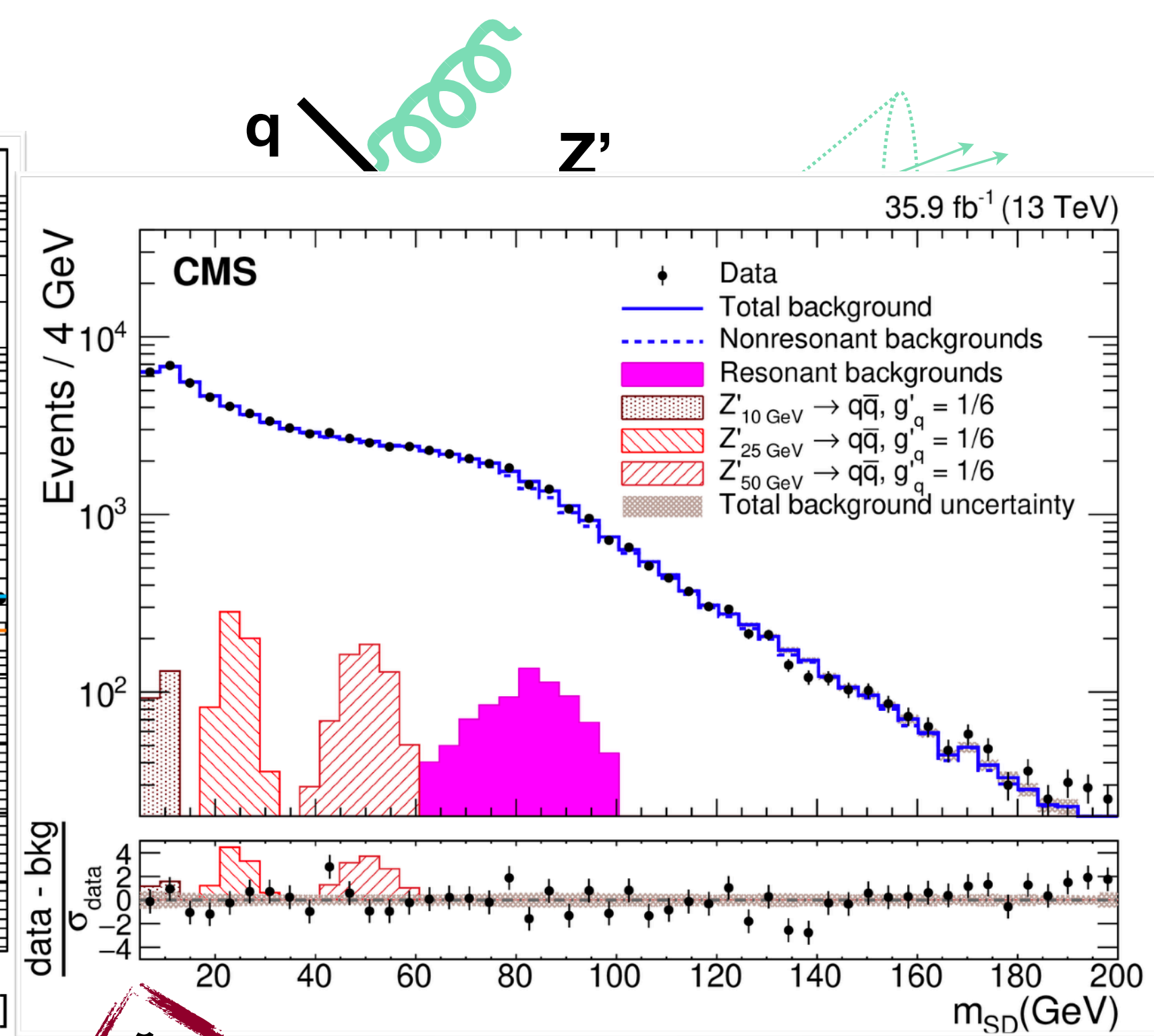
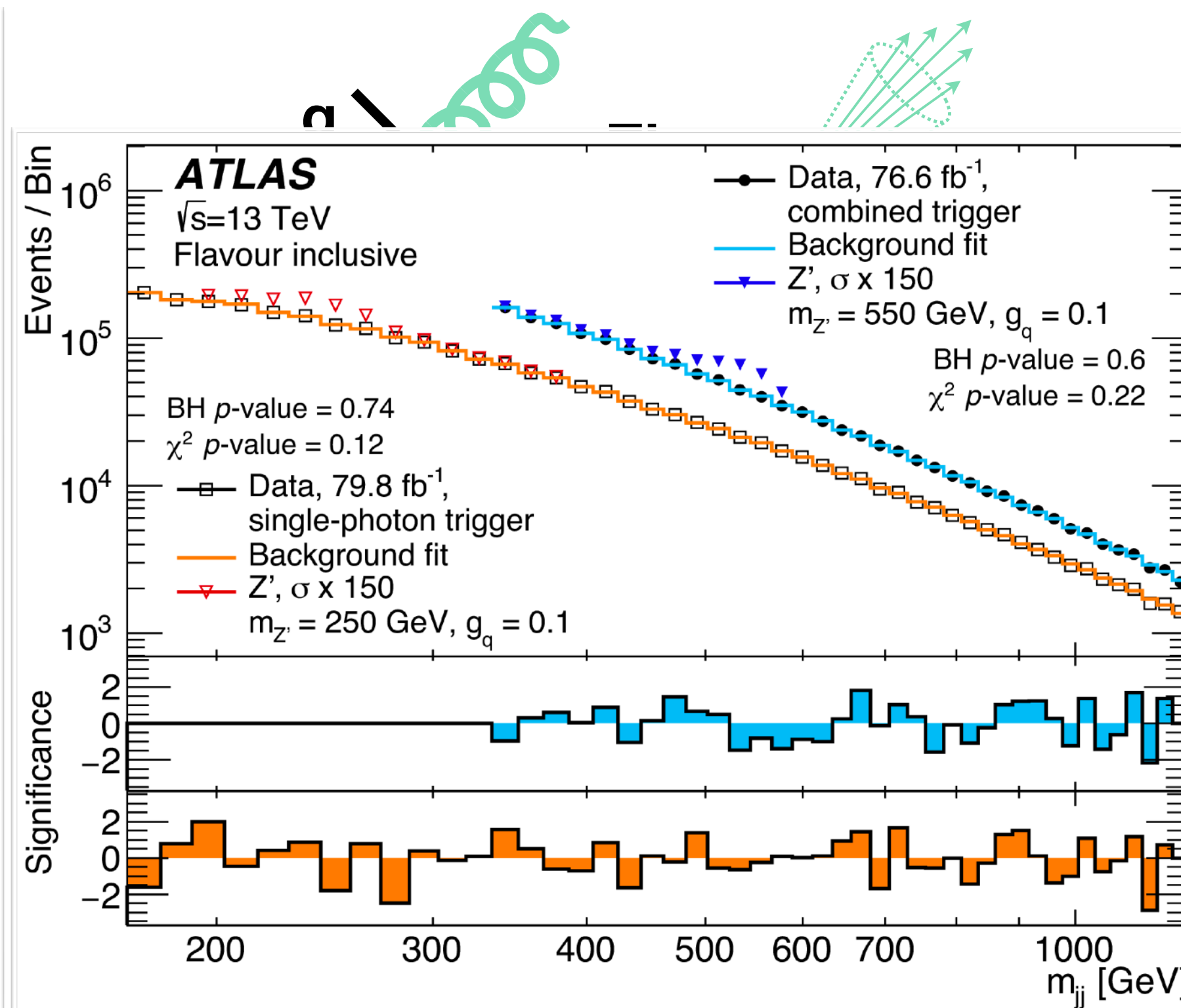
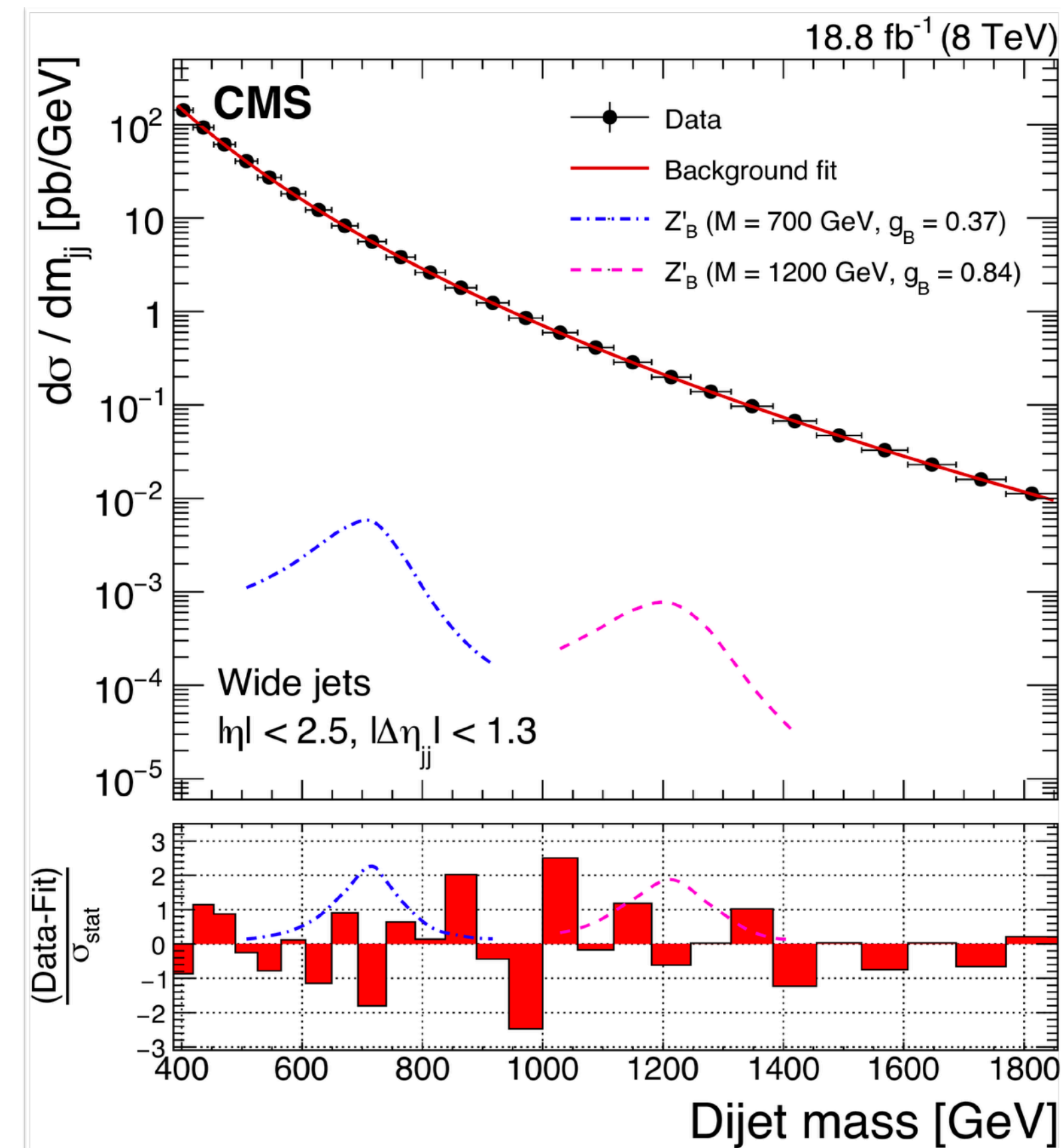
- Need hard ISR to trigger (photon or gluon)
- Light mass: large boost
- Large jet + substructure

# Example: Dijets Going to Lower Mass with ISR and Substructure

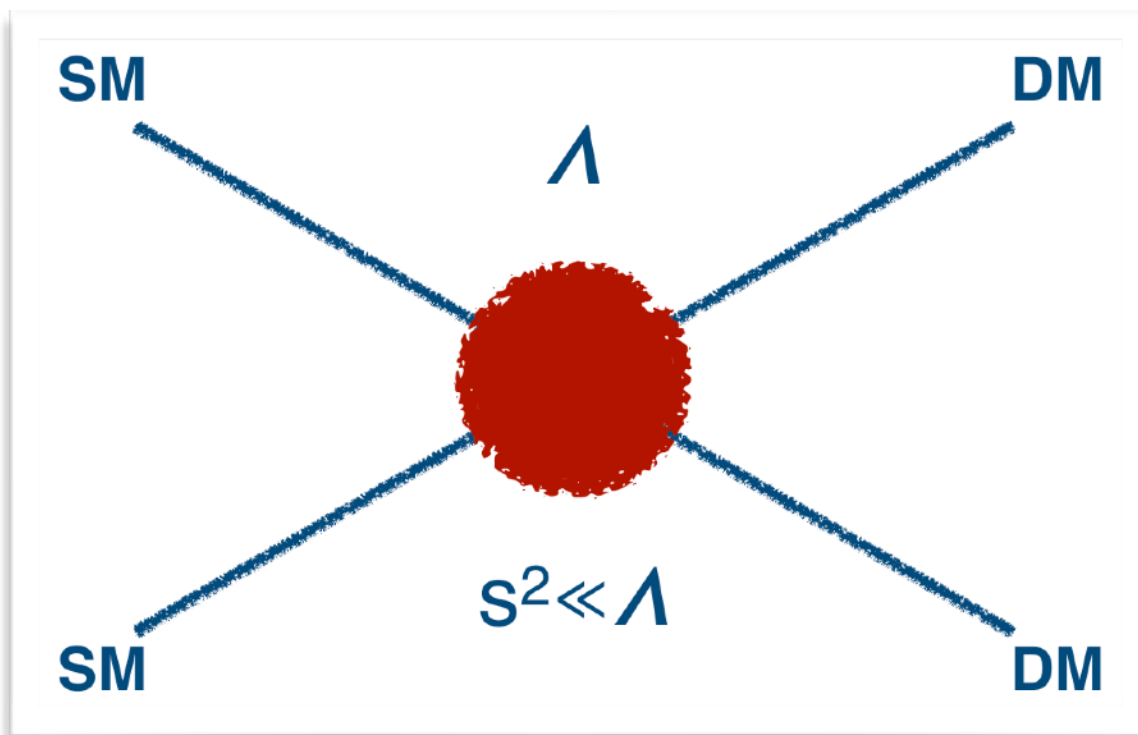
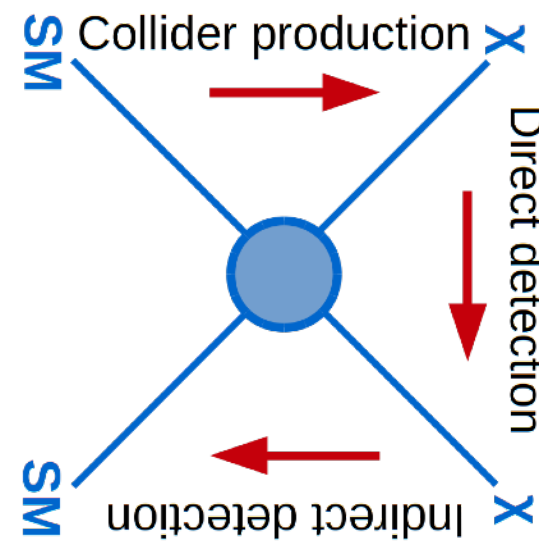
**High Mass**  
( $M > 0.5-1.5$  TeV)

**Intermediate Mass**  
( $0.2 < M < 1.0$  TeV)

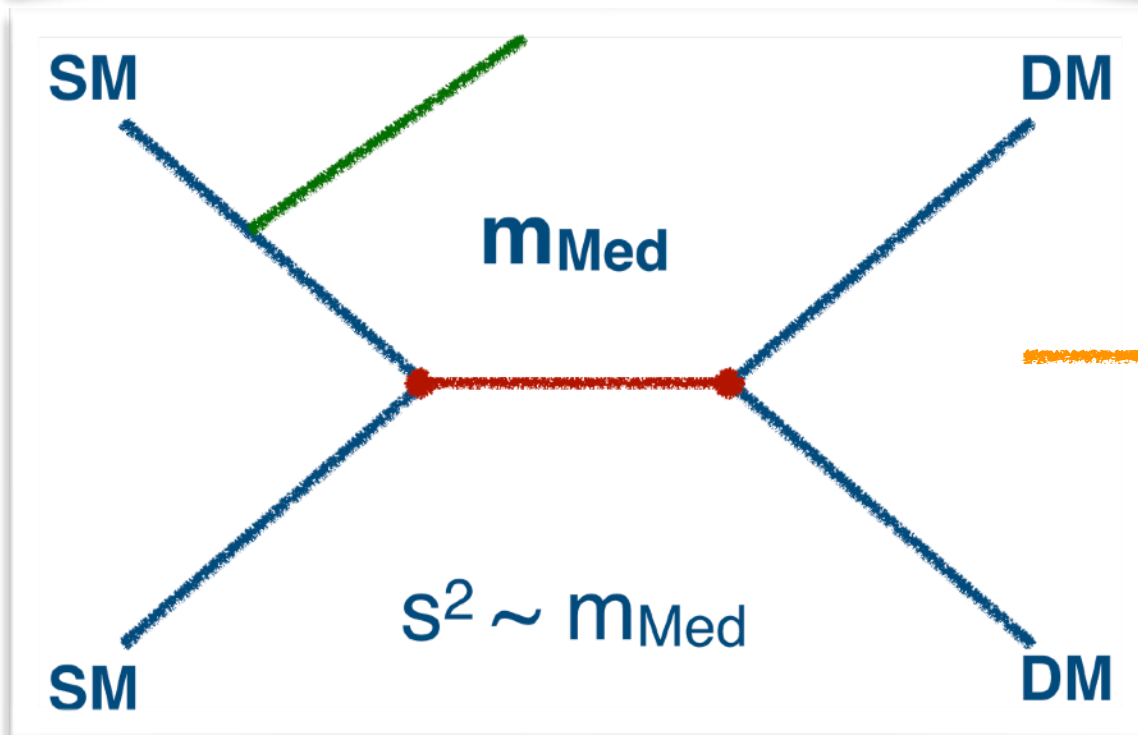
**Low Mass**  
( $M < 0.3$  TeV)



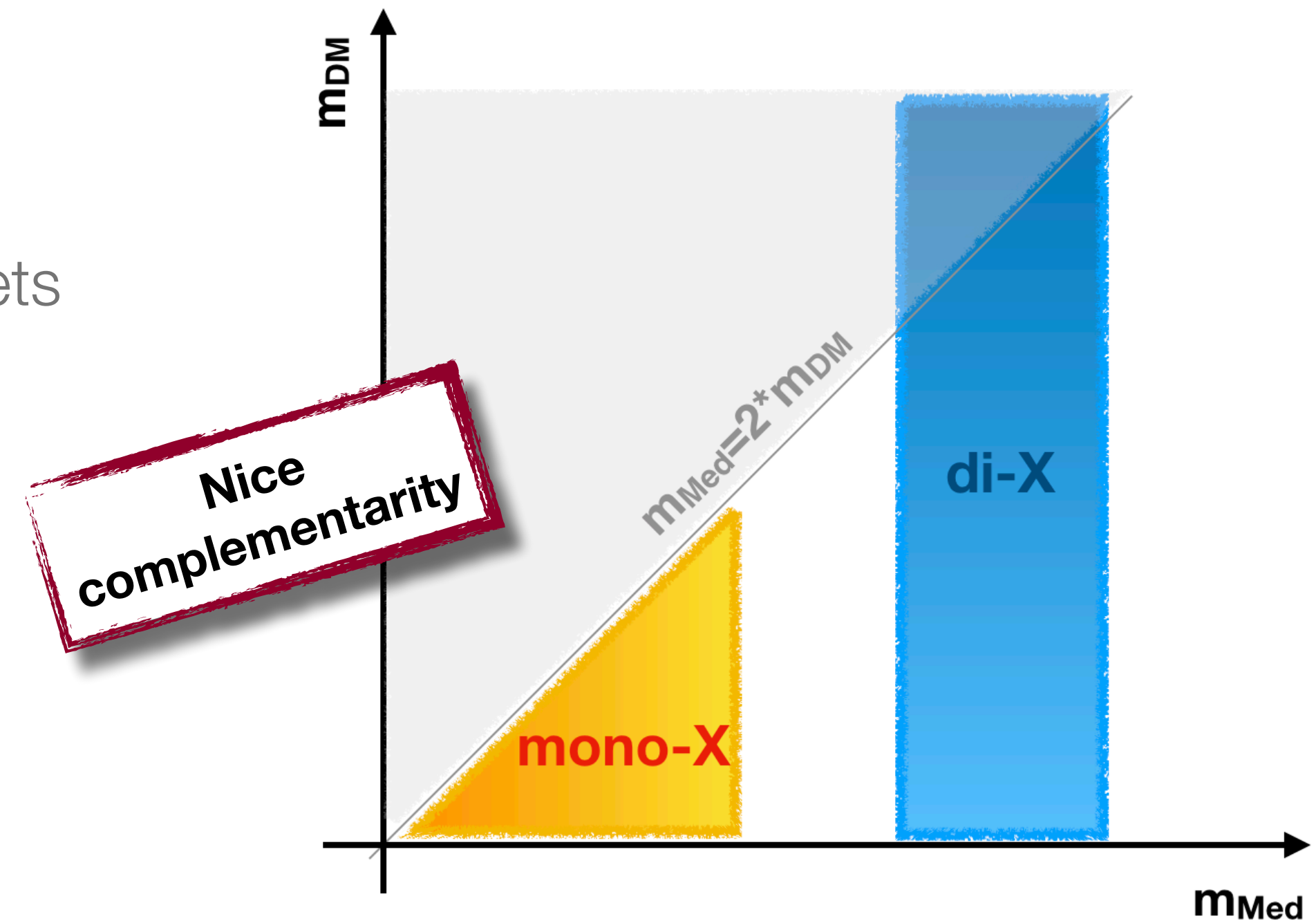
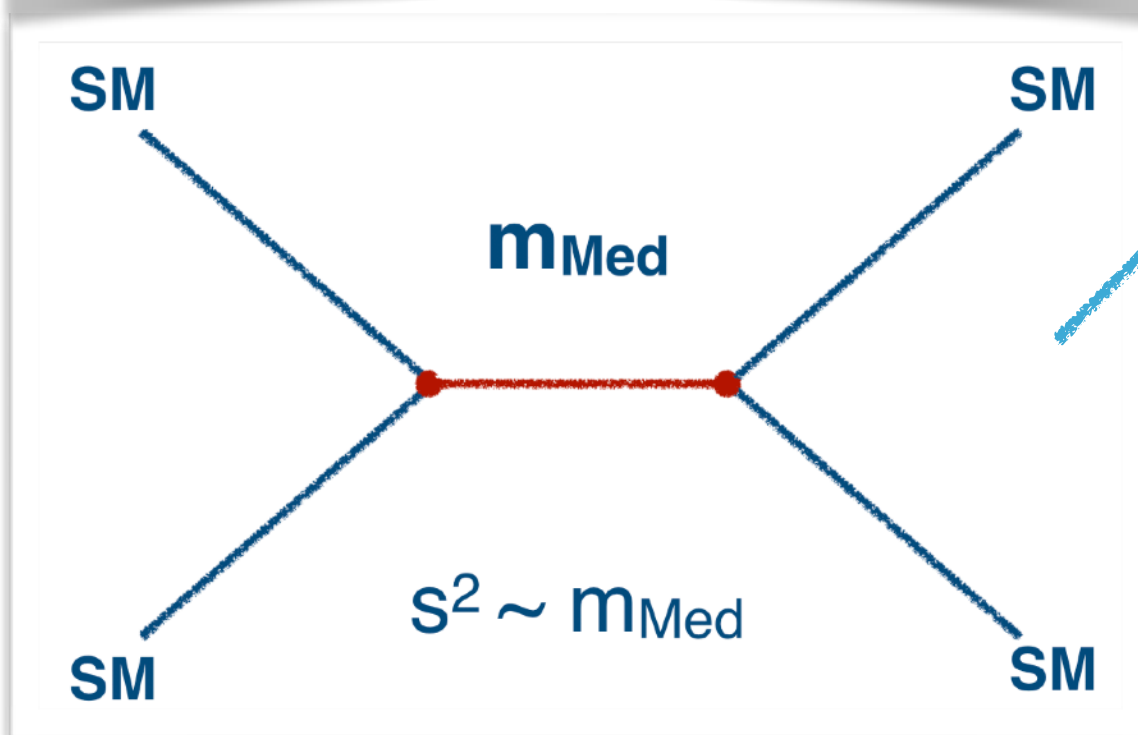
# Dark Matter, anyone?



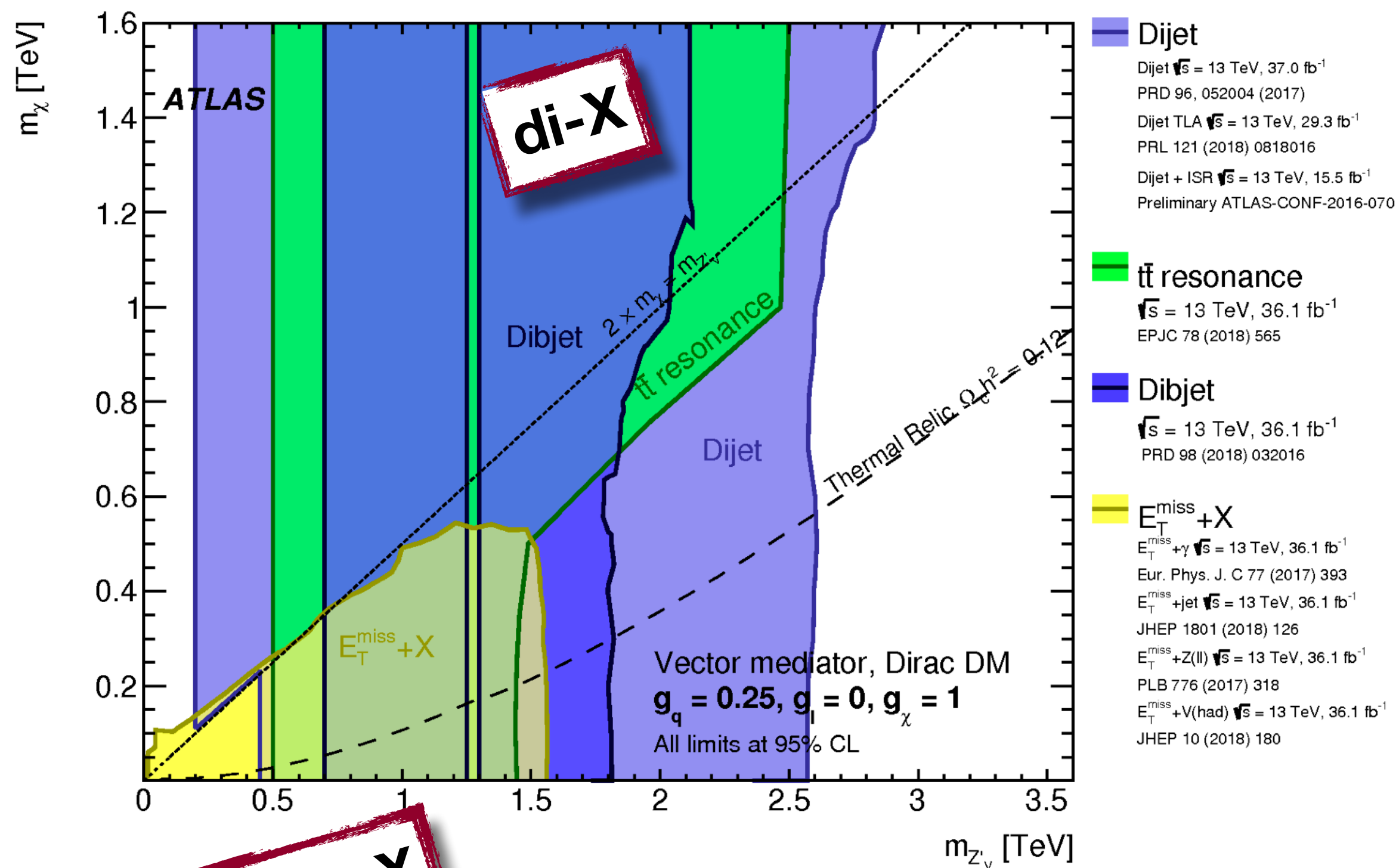
- At colliders we can only detect DM after producing that
- It means we *only* probe the SM-DM mediator:
  - simplified models are guiding us in this search
  - exploiting complementarity of different signatures:



- mono-X: X=jet,  $\gamma$ , Z, W, h
- di-X: X=leptons, jets, h.f.-jets

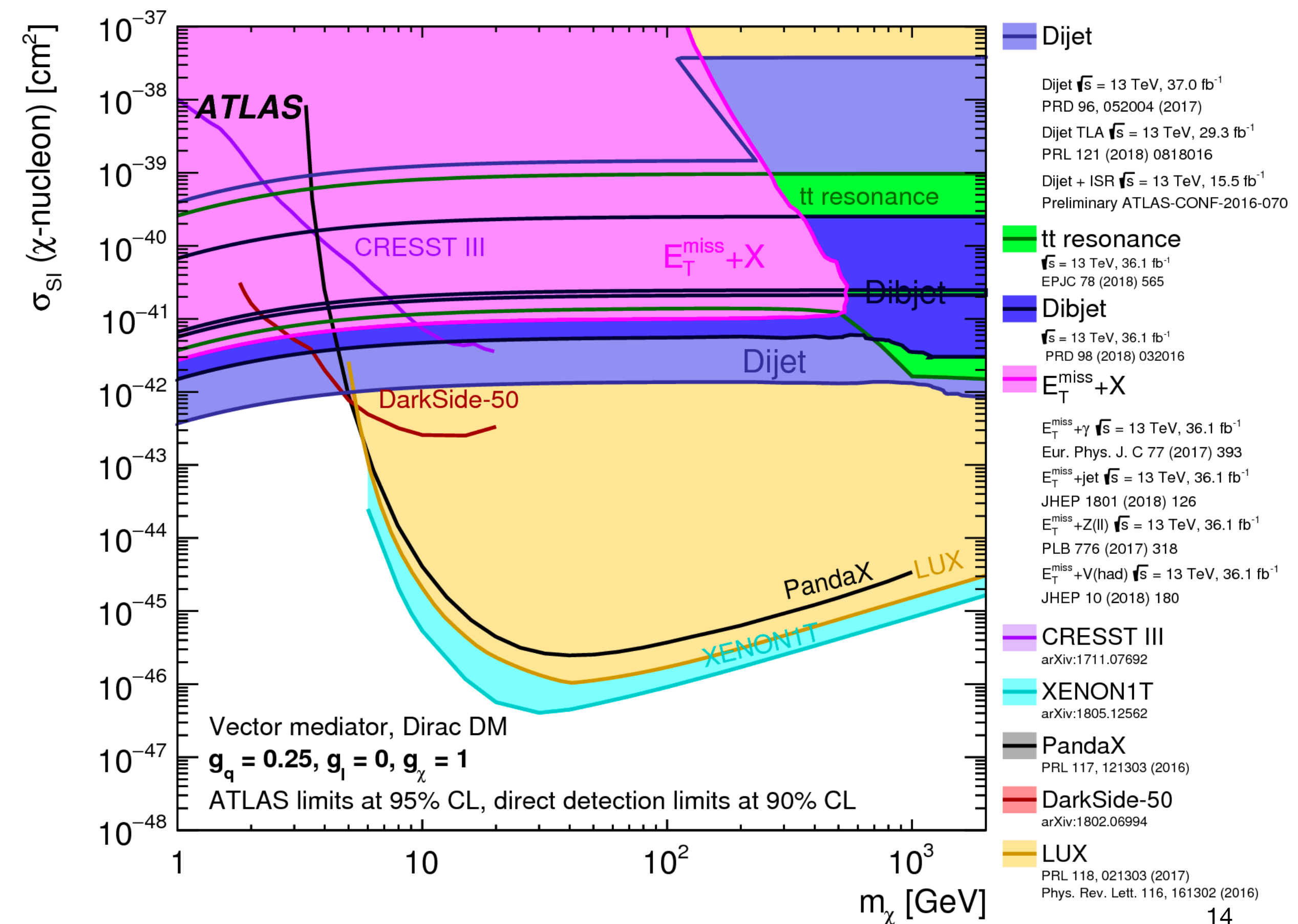


# Dark Matter Searches



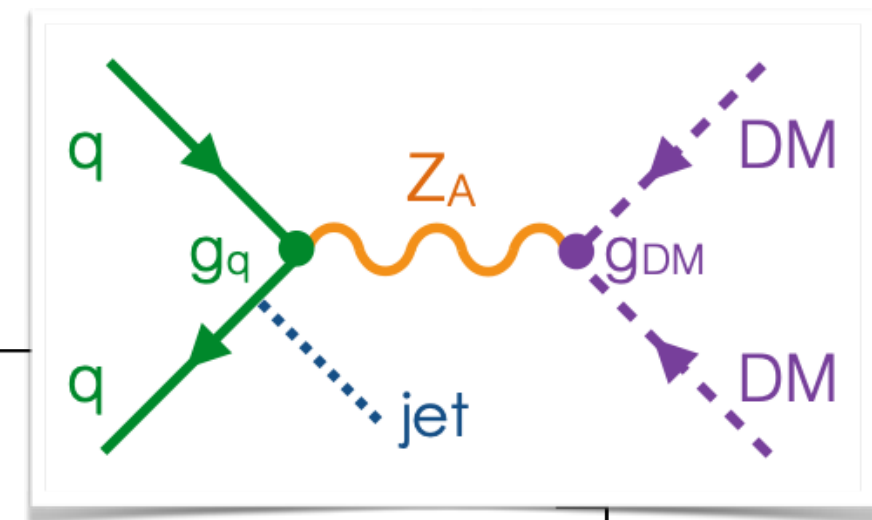
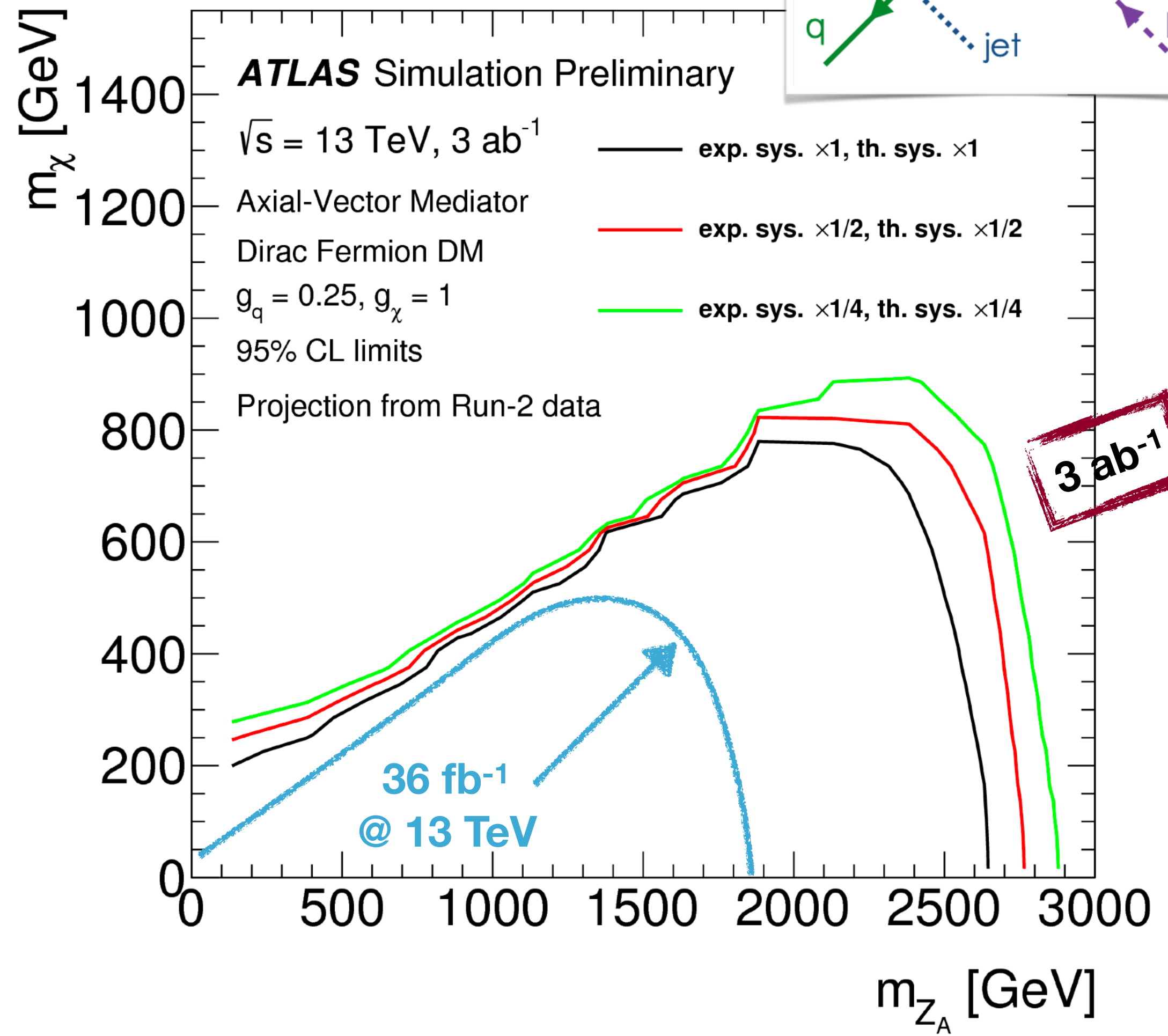
## Complementary to DD experiments

- caveats on the assumptions done in  $\sigma$  calculation



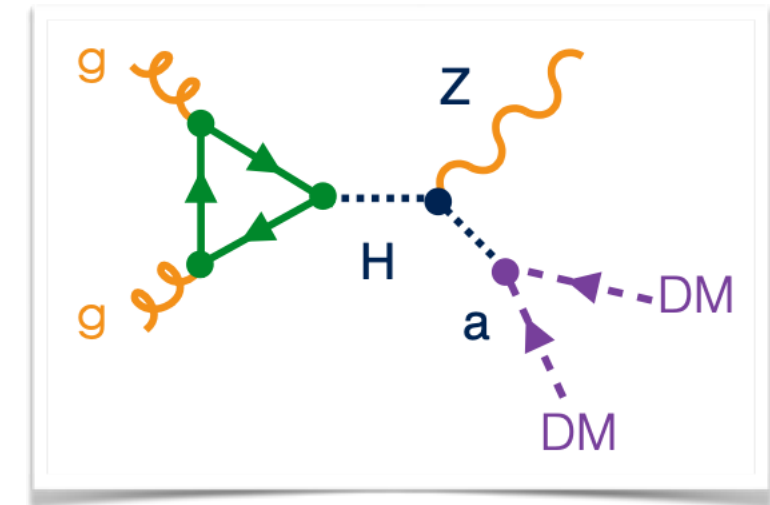
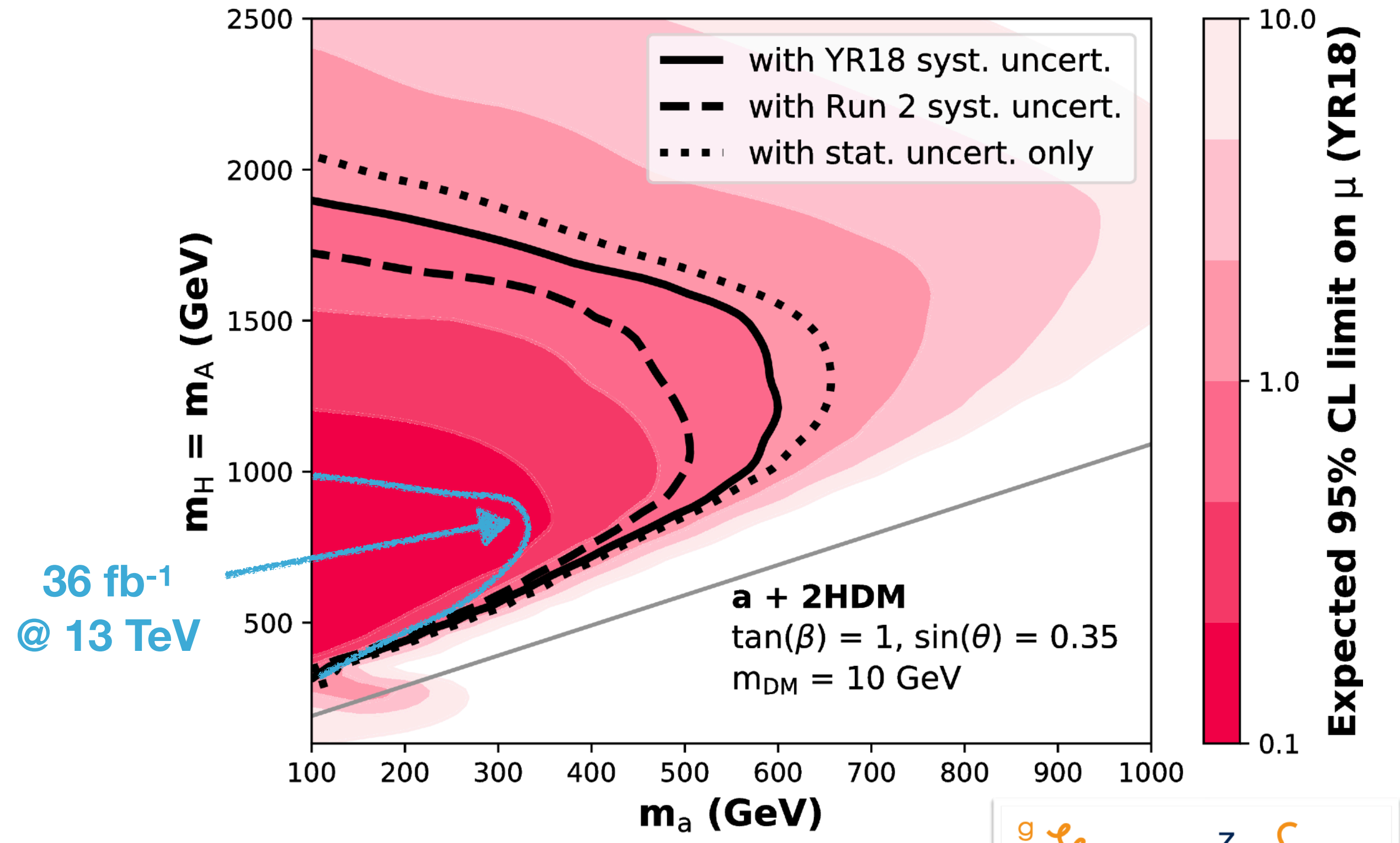
# Mono-X searches in the long run

**mono-jet**



**CMS Projection**

**3.0 ab<sup>-1</sup> (14 TeV)**



# Weirder signatures

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Nature sometimes can be different





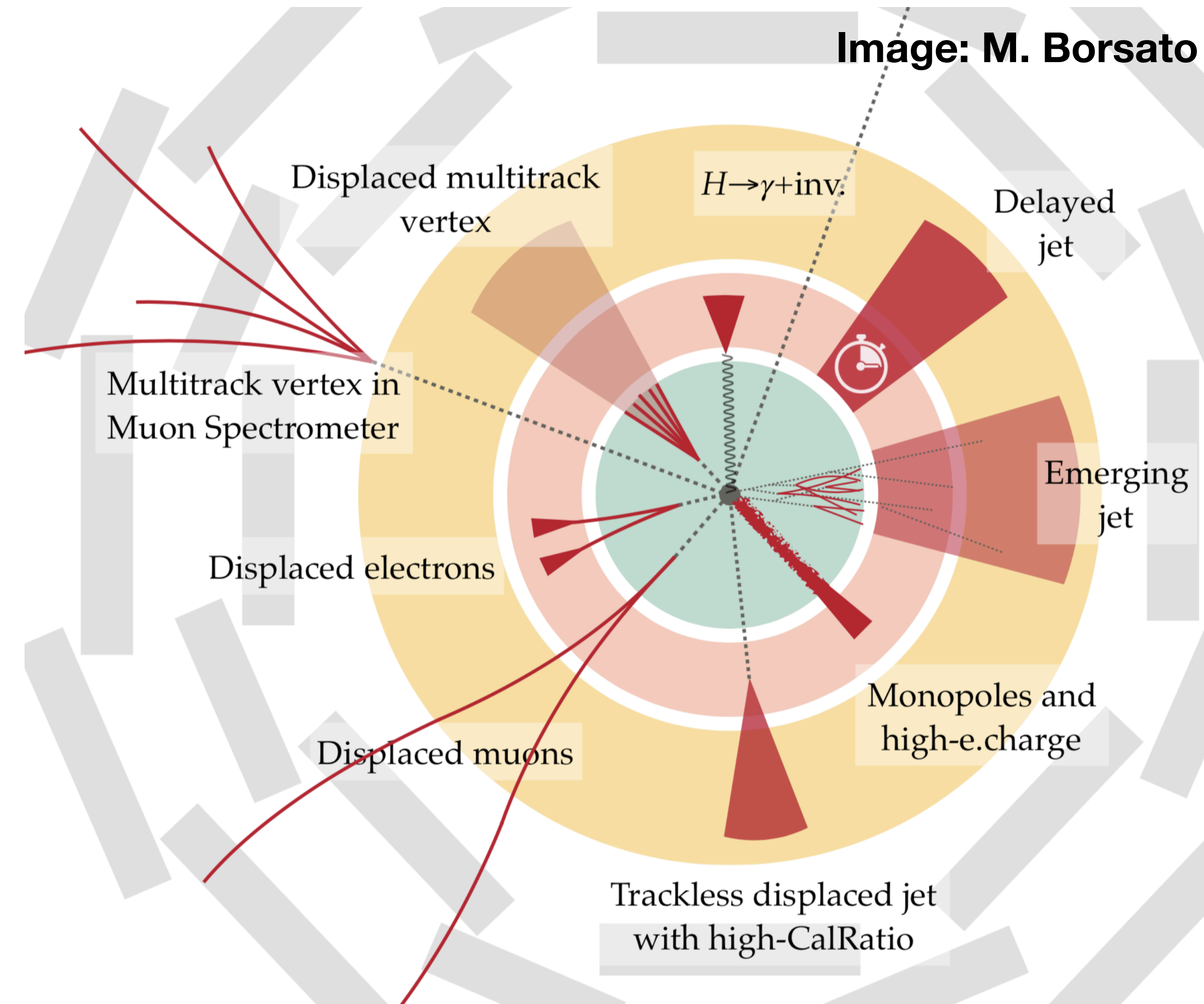
# Long-Lived Particles and Other Unconventional Signatures

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

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

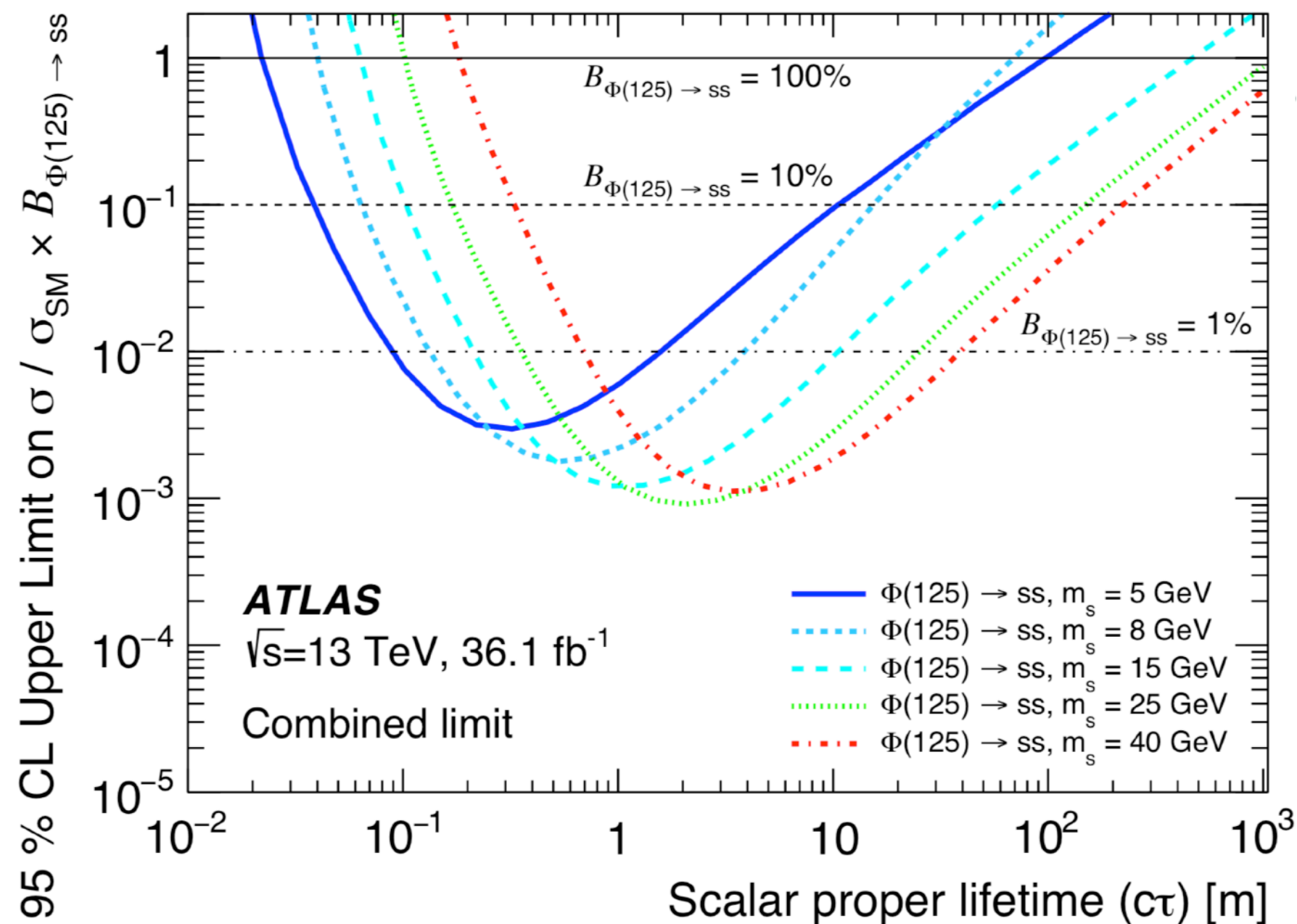
coupling suppressed      amplitude suppressed      phase space suppressed (eg compressed mass spectra)

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

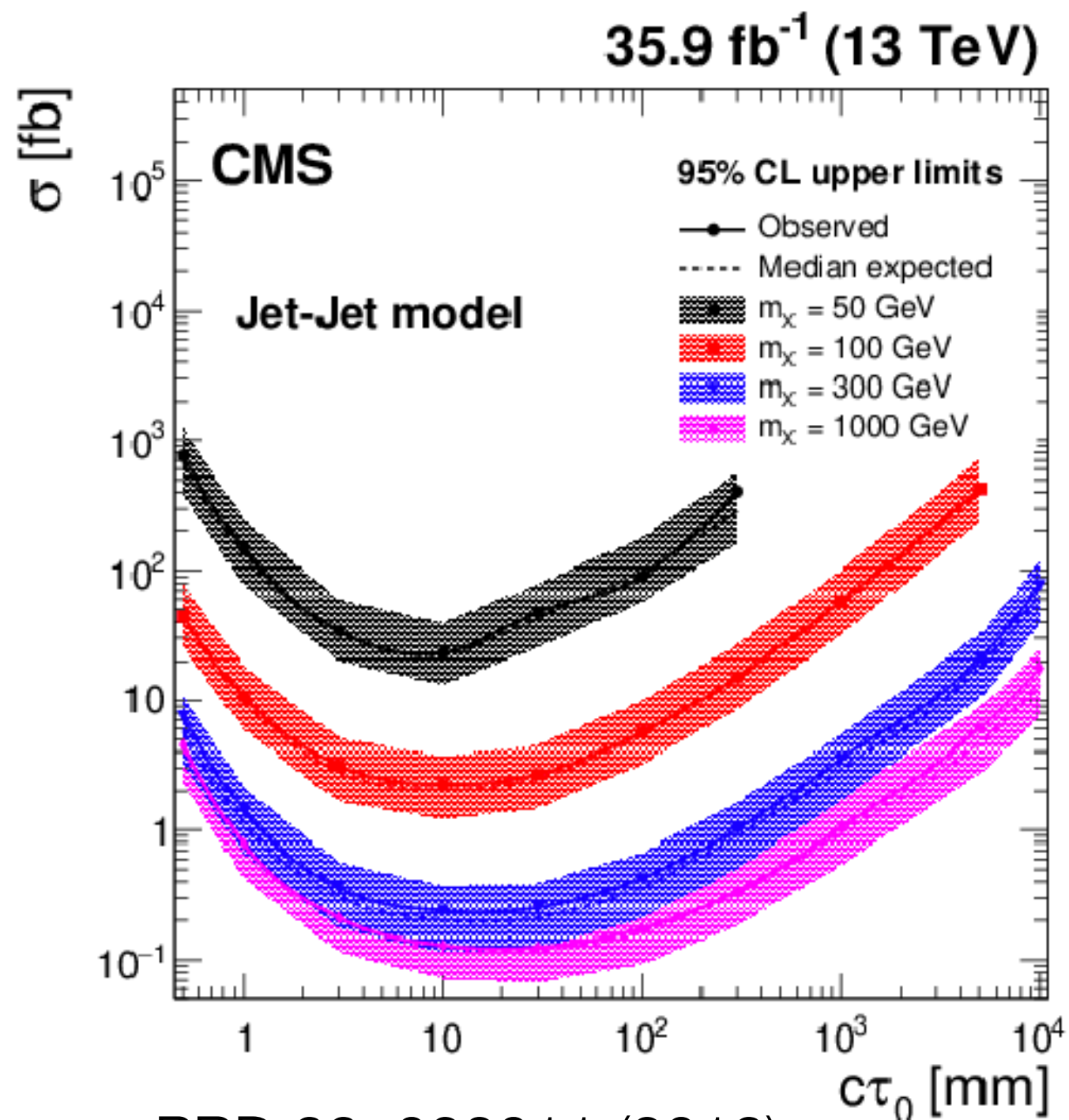


# Example: Displaced Jets

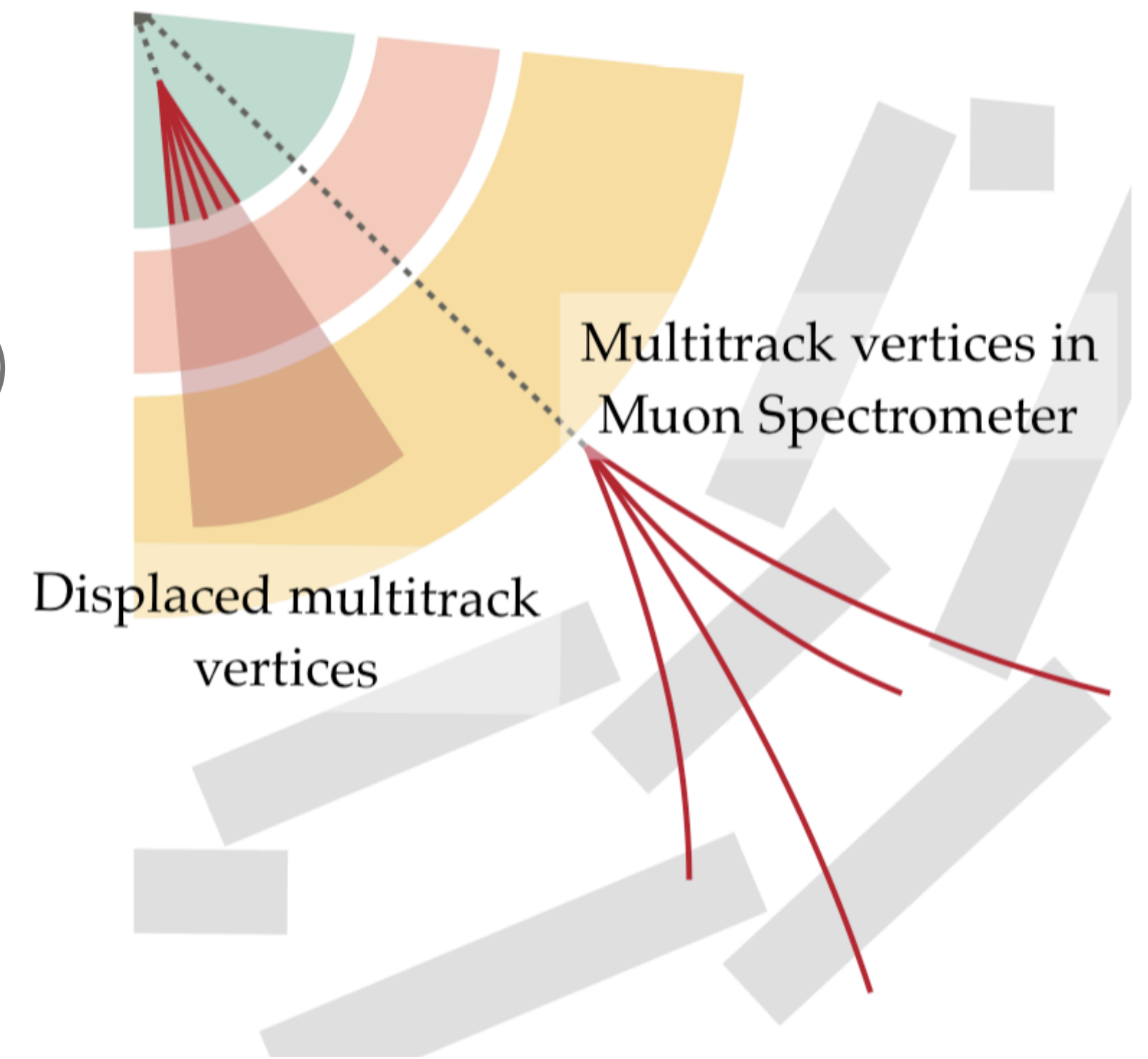
- Reconstruction of **displaced** vertices
  - in **tracker** (CMS)
  - in **muon chambers** (ATLAS)
- Interpreted in various models ( $XX \rightarrow (jj)(jj)$ , GMSB SUSY, RPV SUSY...)



PRD 99, 052005 (2019)



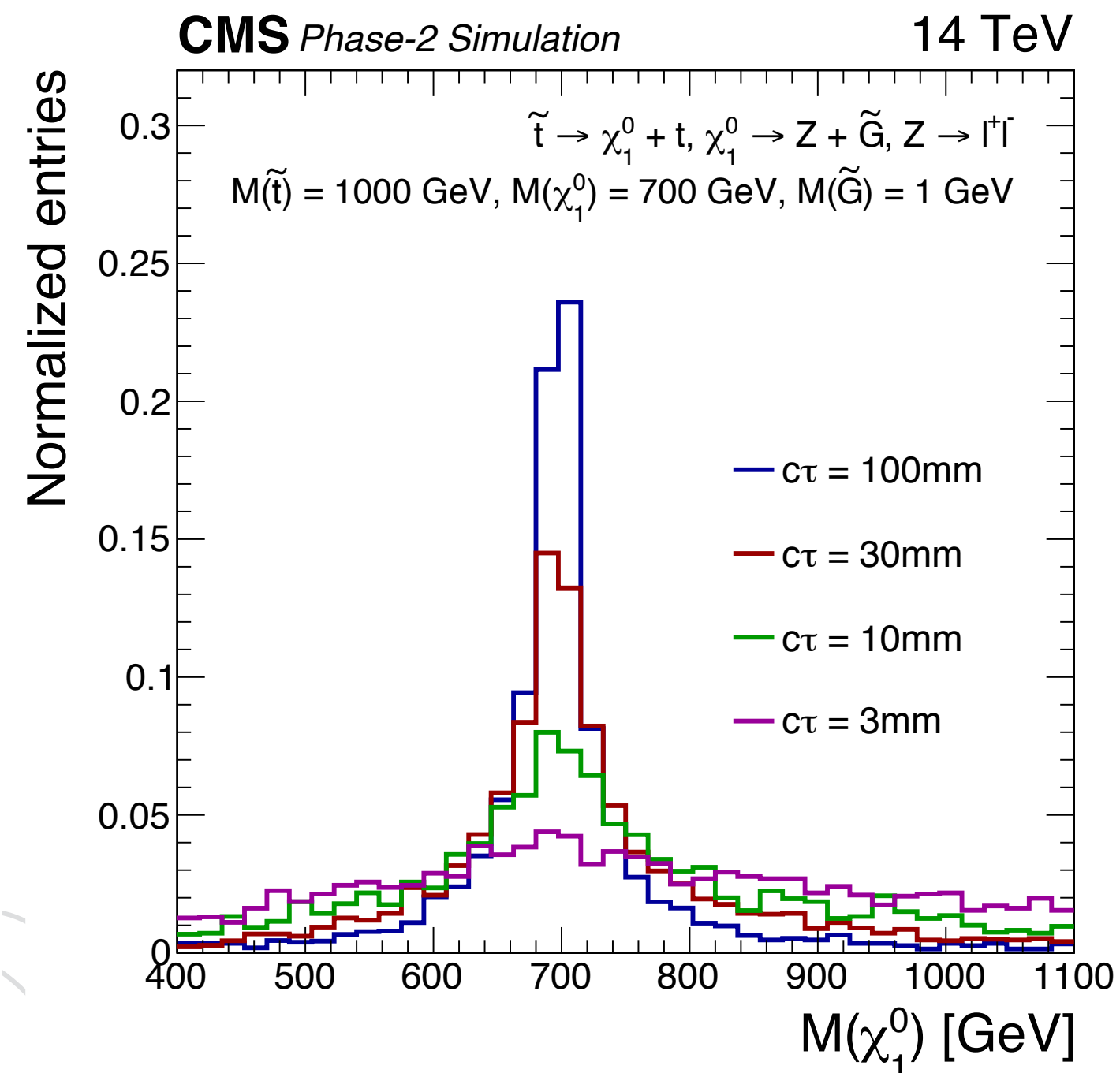
PRD 99, 032011 (2019)



# New Opportunities Thanks to Precision Timing in Phase-2

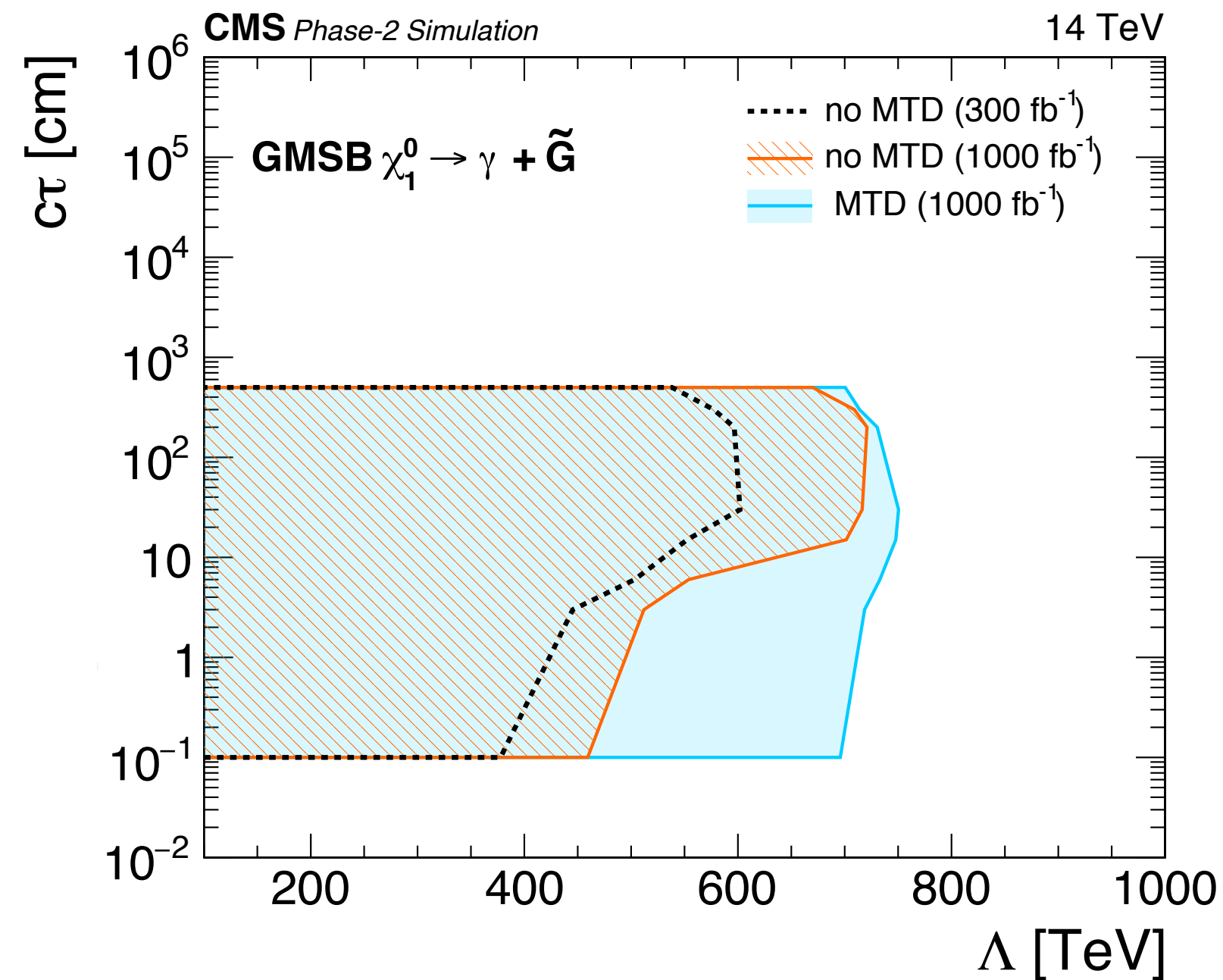
## Long-lived neutral particles

From 4D distance between PV and decay vertex  $\rightarrow \beta(\chi^0)$   
 Full mass measurement from  $V^0$



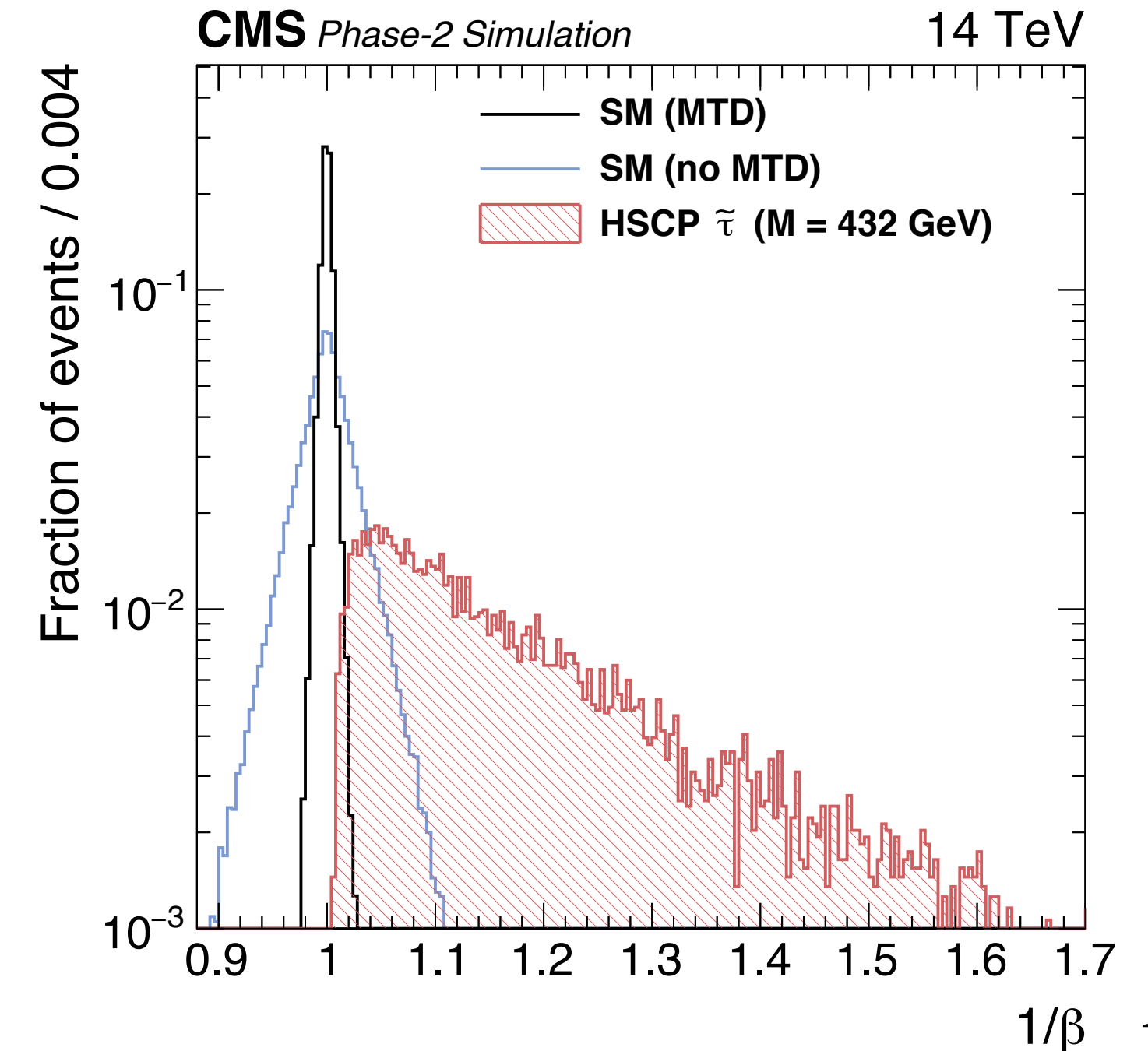
## Delayed photons

Precise timing significantly expands small- $\tau$  sensitivity



## Heavy stable charged particles

Can measure  $1/\beta$  from track only



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

ATLAS SUSY Searches\* - 95% CL Lower Limits  
March 2019

ATLAS Preliminary  
 $\sqrt{s} = 13 \text{ TeV}$

| Model   | Signature   | $\int \mathcal{L} dt [\text{fb}^{-1}]$                                       | Mass limit  | Reference   |   |  |
|---|---|--|---|---|---|--|
| Inclusive Searches  | $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$   | 0 e, $\mu$<br>mono-jet   | $E_T^{\text{miss}}$ 36.1<br>$E_T^{\text{miss}}$ 36.1                  | $\tilde{q}$ [2x, 8x Degen.]<br>$\tilde{q}$ [1x, 8x Degen.]  | $m(\tilde{\chi}_1^0) < 100 \text{ GeV}$<br>$m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$   | 1712.02332<br>1711.03301                           |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$  | 0 e, $\mu$   | 2-6 jets<br>$E_T^{\text{miss}}$ 36.1                                  | $\tilde{g}$<br>$\tilde{g}$  | $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$<br>$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 900 \text{ GeV}$   | 1712.02332<br>1712.02332                           |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$  | 3 e, $\mu$<br>ee, $\mu\mu$   | 4 jets<br>2 jets<br>$E_T^{\text{miss}}$ 36.1                          | $\tilde{g}$<br>$\tilde{g}$  | $m(\tilde{\chi}_1^0) < 800 \text{ GeV}$<br>$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 50 \text{ GeV}$  | 1706.03731<br>1805.11381                           |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$  | 0 e, $\mu$<br>3 e, $\mu$   | 7-11 jets<br>4 jets<br>$E_T^{\text{miss}}$ 36.1                       | $\tilde{g}$<br>$\tilde{g}$  | $m(\tilde{\chi}_1^0) < 400 \text{ GeV}$<br>$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200 \text{ GeV}$   | 1708.02794<br>1706.03731                           |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{\chi}_1^0$   | 0-1 e, $\mu$<br>3 e, $\mu$   | 3 b<br>4 jets<br>$E_T^{\text{miss}}$ 79.8<br>$E_T^{\text{miss}}$ 36.1 | $\tilde{g}$<br>$\tilde{g}$  | $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$<br>$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300 \text{ GeV}$   | ATLAS-CONF-2018-041<br>1706.03731                  |
| 3 <sup>rd</sup> gen. squarks direct production                    | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0/\tilde{\chi}_1^\pm$  | Multiple<br>Multiple<br>Multiple   | 36.1<br>36.1<br>36.1  | $\tilde{b}_1$<br>$\tilde{b}_1$<br>$\tilde{b}_1$   | $m(\tilde{\chi}_1^0) = 300 \text{ GeV}, \text{BR}(b\tilde{\chi}_1^0) = 1$<br>$m(\tilde{\chi}_1^0) = 300 \text{ GeV}, \text{BR}(b\tilde{\chi}_1^\pm) = \text{BR}(t\tilde{\chi}_1^\pm) = 0.5$<br>$m(\tilde{\chi}_1^0) = 200 \text{ GeV}, m(\tilde{\chi}_1^\pm) = 300 \text{ GeV}, \text{BR}(t\tilde{\chi}_1^\pm) = 1$ | 1708.09266, 1711.03301<br>1708.09266<br>1706.03731 |
|   | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b h\tilde{\chi}_1^0$   | 0 e, $\mu$   | 6 b<br>$E_T^{\text{miss}}$ 139  | $\tilde{b}_1$<br>$\tilde{b}_1$  | $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 100 \text{ GeV}$<br>$\Delta m(\tilde{\chi}_2^\pm, \tilde{\chi}_1^\pm) = 130 \text{ GeV}, m(\tilde{\chi}_1^\pm) = 0 \text{ GeV}$  | SUSY-2018-31<br>SUSY-2018-31                       |
|   | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$   | 0-2 e, $\mu$   | 0-2 jets/1-2 b<br>$E_T^{\text{miss}}$ 36.1                            | $\tilde{t}_1$   | $m(\tilde{\chi}_1^0) = 1 \text{ GeV}$   | 1506.08616, 1709.04183, 1711.11520                 |
|   | $\tilde{t}_1\tilde{t}_1$ , Well-Tempered LSP  | Multiple   | 36.1  | $\tilde{t}_1$   | $m(\tilde{\chi}_1^0) = 150 \text{ GeV}, m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}, \tilde{t}_1 \approx \tilde{t}_L$   | 1709.04183, 1711.11520                             |
|   | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1 b\nu, \tilde{t}_1 \rightarrow \tau\tilde{G}$   | 1 $\tau$ + 1 e, $\mu, \tau$  | 2 jets/1 b<br>$E_T^{\text{miss}}$ 36.1                                | $\tilde{t}_1$   | $m(\tilde{\tau}_1) = 800 \text{ GeV}$   | 1803.10178   |
|   | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0/\tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$   | 0 e, $\mu$   | 2 c<br>$E_T^{\text{miss}}$ 36.1                                       | $\tilde{t}_1$<br>$\tilde{t}_1$  | $m(\tilde{\chi}_1^0) = 0 \text{ GeV}$<br>$m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 50 \text{ GeV}$<br>$m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$  | 1805.01649<br>1805.01649<br>1711.03301             |
| $\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$ | 1-2 e, $\mu$  | 4 b<br>$E_T^{\text{miss}}$ 36.1  | $\tilde{t}_2$   | $m(\tilde{\chi}_1^0) = 0 \text{ GeV}, m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 180 \text{ GeV}$                                   | 1706.03986  |  |
| EW direct   | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ   | 2-3 e, $\mu$<br>ee, $\mu\mu$   | $E_T^{\text{miss}}$ 36.1<br>$E_T^{\text{miss}}$ 36.1                  | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$<br>$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$  | $m(\tilde{\chi}_1^0) = 0$<br>$m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 10 \text{ GeV}$   | 1403.5294, 1806.02293<br>1712.08119                |
|   | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW   | 2 e, $\mu$   | $E_T^{\text{miss}}$ 139   | $\tilde{\chi}_1^\pm$  | $m(\tilde{\chi}_1^0) = 0$   | ATLAS-CONF-2019-008                                |
|   | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh   | 0-1 e, $\mu$   | 2 b<br>$E_T^{\text{miss}}$ 36.1                                       | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$   | $m(\tilde{\chi}_1^0) = 0$   | 1812.09432   |
|   | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{t}_L/\tilde{\nu}$  | 2 e, $\mu$   | $E_T^{\text{miss}}$ 139   | $\tilde{\chi}_1^\pm$  | $m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$   | ATLAS-CONF-2019-008                                |
|   | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0, \tilde{\chi}_1^\pm \rightarrow \tilde{\tau}_1\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1\nu(\nu\tilde{\tau})$ | 2 $\tau$   | $E_T^{\text{miss}}$ 36.1  | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$<br>$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$  | $m(\tilde{\chi}_1^0) = 0, m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$<br>$m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 100 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$  | 1708.07875<br>1708.07875                           |
|   | $\tilde{t}_L\tilde{t}_L, \tilde{t}_L \rightarrow t\tilde{\chi}_1^0$   | 2 e, $\mu$<br>2 e, $\mu$   | 0 jets<br>$E_T^{\text{miss}}$ 36.1                                    | $\tilde{t}_L$<br>$\tilde{t}_L$  | $m(\tilde{\chi}_1^0) = 0$<br>$m(\tilde{t}_L) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$   | ATLAS-CONF-2019-008<br>1712.08119                  |
| $\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$ | 0 e, $\mu$<br>4 e, $\mu$  | $\geq 3$ b<br>0 jets<br>$E_T^{\text{miss}}$ 36.1<br>$E_T^{\text{miss}}$ 36.1 | $\tilde{H}$<br>$\tilde{H}$  | $\text{BR}(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$<br>$\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$            | 1806.04030<br>1804.03602  |  |
| Long-lived particles  | Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ prod., long-lived $\tilde{\chi}_1^\pm$  | Disapp. trk  | 1 jet<br>$E_T^{\text{miss}}$ 36.1                                     | $\tilde{\chi}_1^\pm$<br>$\tilde{\chi}_1^\pm$  | Pure Wino<br>Pure Higgsino  | 1712.02118<br>ATL-PHYS-PUB-2017-019                |
|   | Stable $\tilde{g}$ R-hadron   | Multiple   | 36.1  | $\tilde{g}$   |   | 1902.01636, 1808.04095                             |
|   | Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$   | Multiple   | 36.1  | $\tilde{g}$ [ $\tau(\tilde{g}) = 10 \text{ ns}, 0.2 \text{ ns}$ ]   |   | 1710.04901, 1808.04095                             |
| RPV   | LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$  | e $\mu$ , e $\tau$ , $\mu\tau$   | 3.2   | $\tilde{\nu}_\tau$  | $\lambda'_{311} = 0.11, \lambda'_{132}/\lambda'_{233} = 0.07$   | 1607.08079   |
|   | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\nu\nu$  | 4 e, $\mu$   | 0 jets<br>$E_T^{\text{miss}}$ 36.1                                    | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [ $\lambda'_{333} \neq 0, \lambda'_{124} \neq 0$ ]  | $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$   | 1804.03602   |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq$   | 4-5 large-R jets   | 36.1  | $\tilde{g}$ [ $m(\tilde{\chi}_1^0) = 200 \text{ GeV}, 1100 \text{ GeV}$ ]   | Large $\lambda'_{112}$  | 1804.03568   |
|   | Multiple  | Multiple   | 36.1  | $\tilde{g}$ [ $\lambda'_{112} = 2e-4, 2e-5$ ]   | $m(\tilde{\chi}_1^0) = 200 \text{ GeV}$ , bino-like   | ATLAS-CONF-2018-003                                |
|   | $\tilde{u}, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$  | Multiple   | 36.1  | $\tilde{g}$ [ $\lambda'_{233} = 2e-4, 1e-2$ ]   | $m(\tilde{\chi}_1^0) = 200 \text{ GeV}$ , bino-like   | ATLAS-CONF-2018-003                                |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$              | 2 jets + 2 b  | 36.7   | $\tilde{t}_1$ [ $qq, bs$ ]  |   | 1710.07171  |  |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$           | 2 e, $\mu$<br>1 $\mu$   | 2 b<br>DV<br>36.1<br>136   | $\tilde{t}_1$<br>$\tilde{t}_1$  | $\text{BR}(\tilde{t}_1 \rightarrow b\ell/\mu\mu) > 20\%$<br>$\text{BR}(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta_t = 1$ | 1710.05544<br>ATLAS-CONF-2019-006   |  |

~~Gluin~~ Gluinos excluded up to  $M \sim 2 \text{ TeV}$

~~Stop~~ Stop excluded up to  $M \sim 1 \text{ TeV}$

~~EW SUSY~~ EW SUSY limits somewhat lower

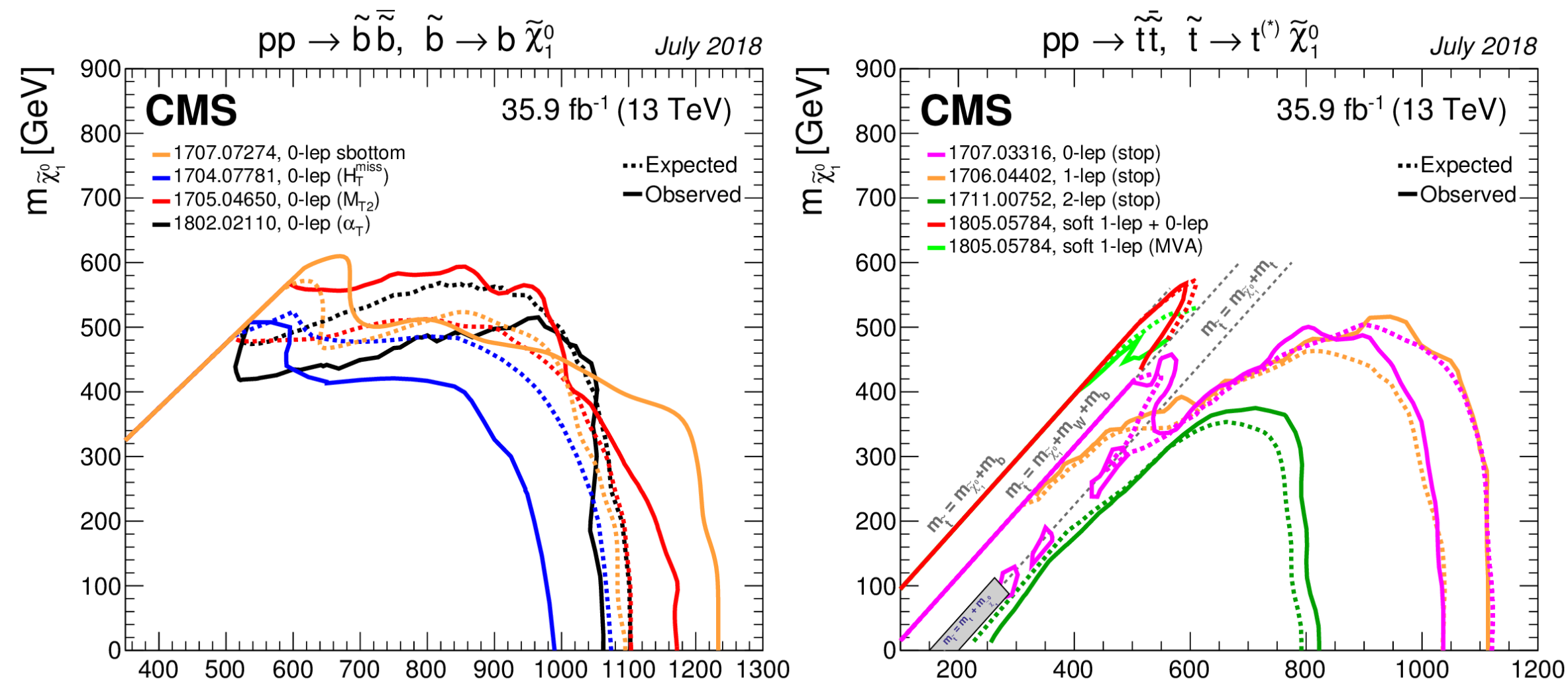
~~Also SUSY~~ Also SUSY has a Long Lived sector

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10<sup>-1</sup> 1 Mass scale [TeV]

# Some Say We're 'Just Starting' with the Interesting Regions

## Stop-sbottom Searches

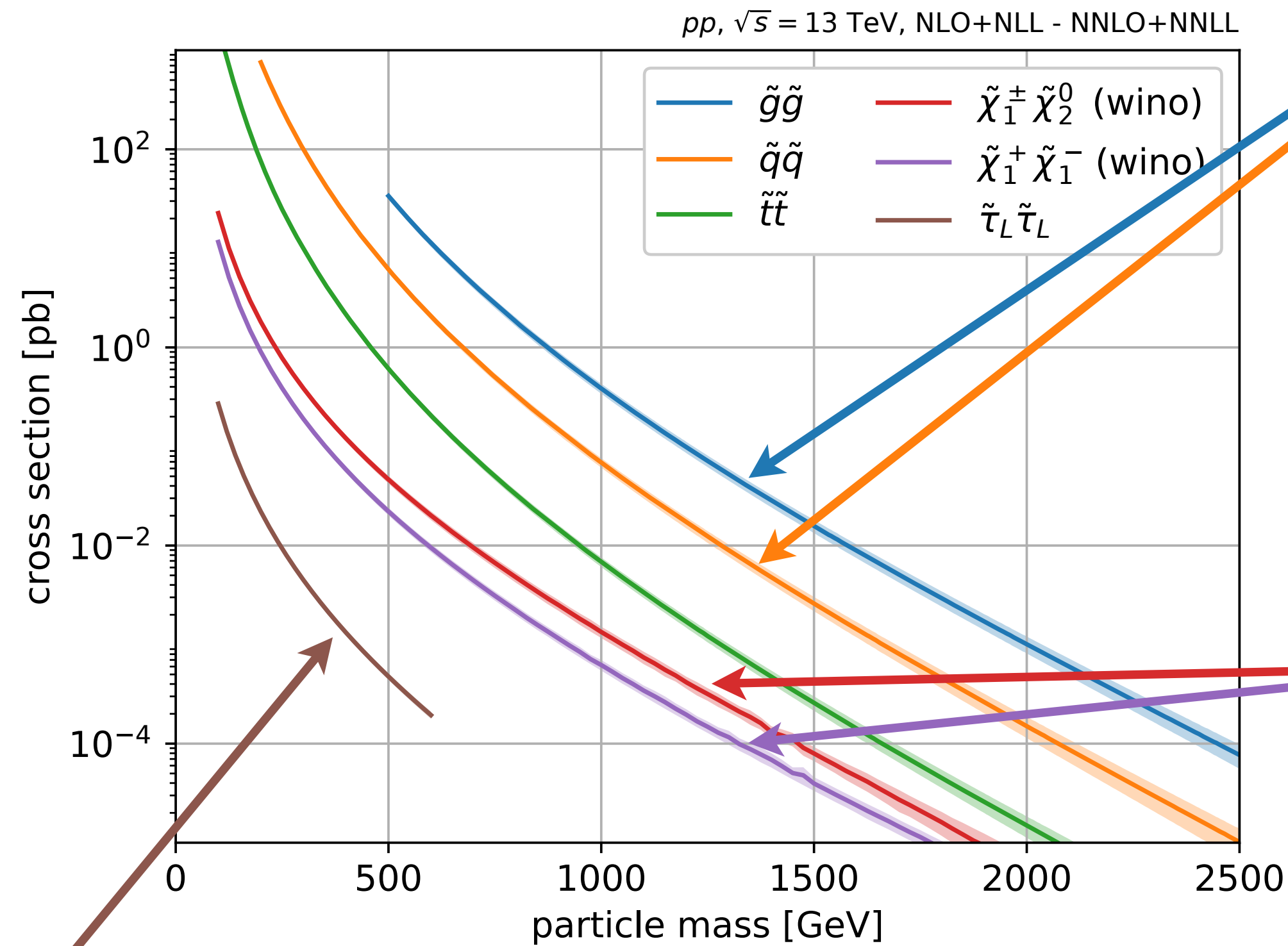


Combining all searches, in the simplest decay scenarios, it is hard to avoid the constraints of 700 GeV for bottoms and 550 GeV for stops. Islands in one search are apparently covered by other searches.

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

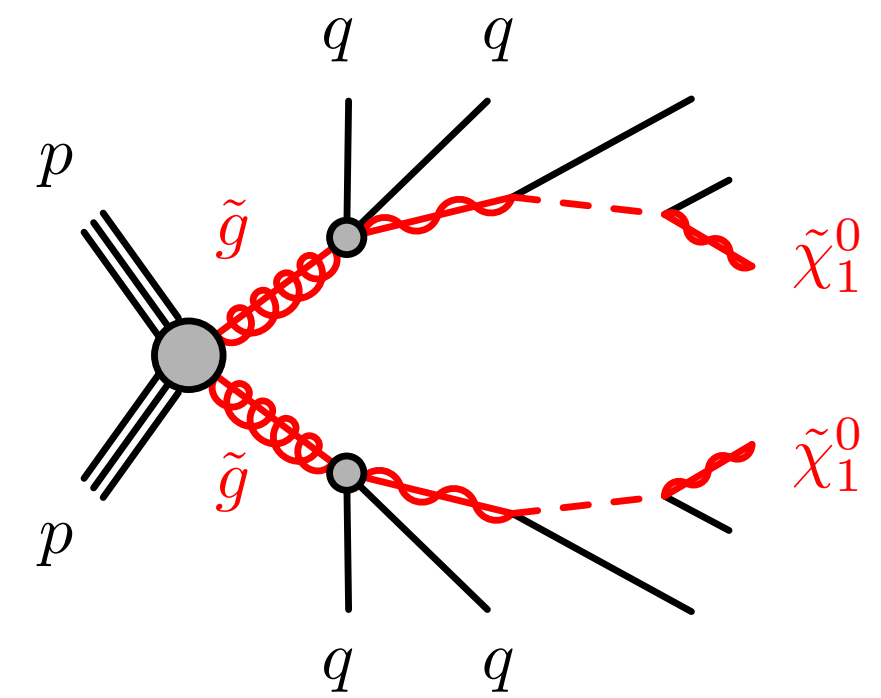
**LHCP2019  
SUSY Plenary  
Theory Talk**

# SUSY Production at 13 TeV



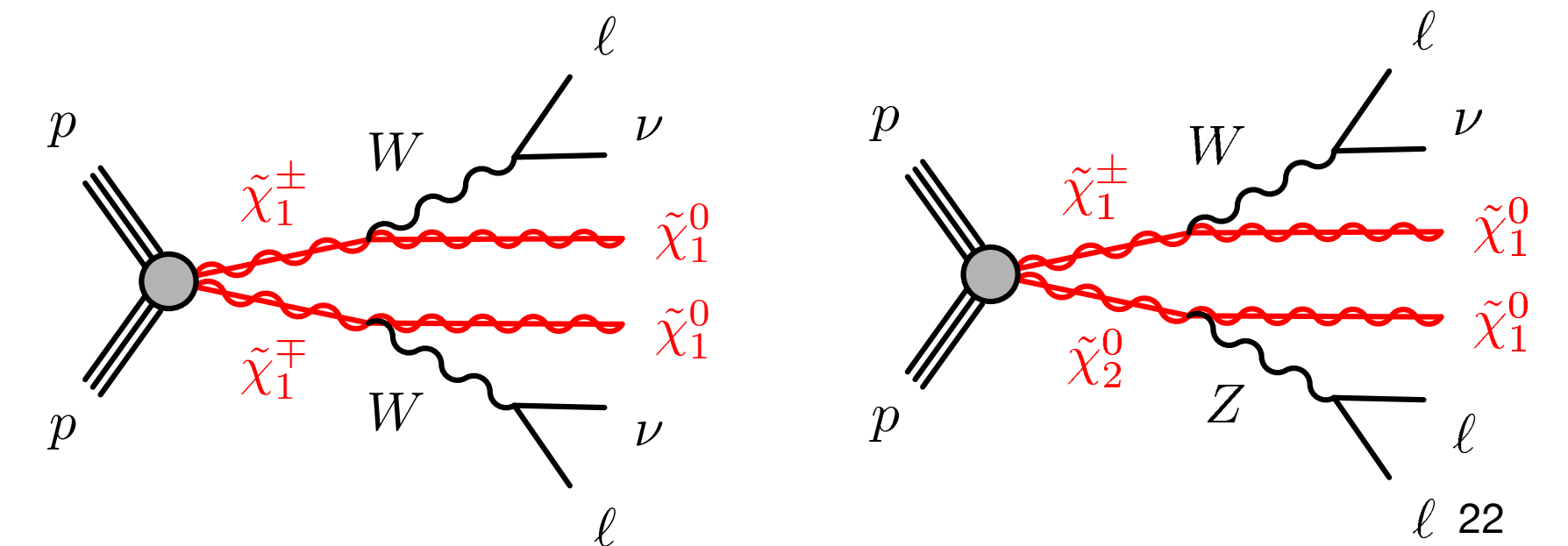
## Strong production: gluinos and squarks

Largest cross section  
Inclusive searches  
Strong limits from Run-2



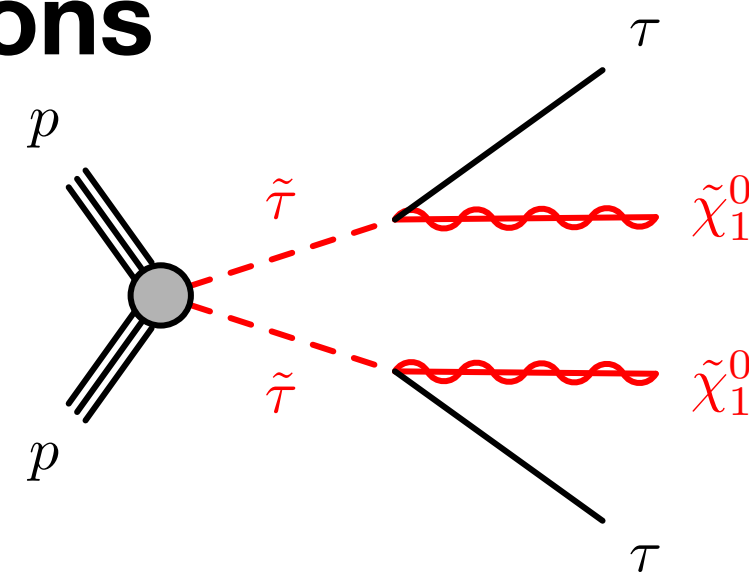
## EW production of charginos

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

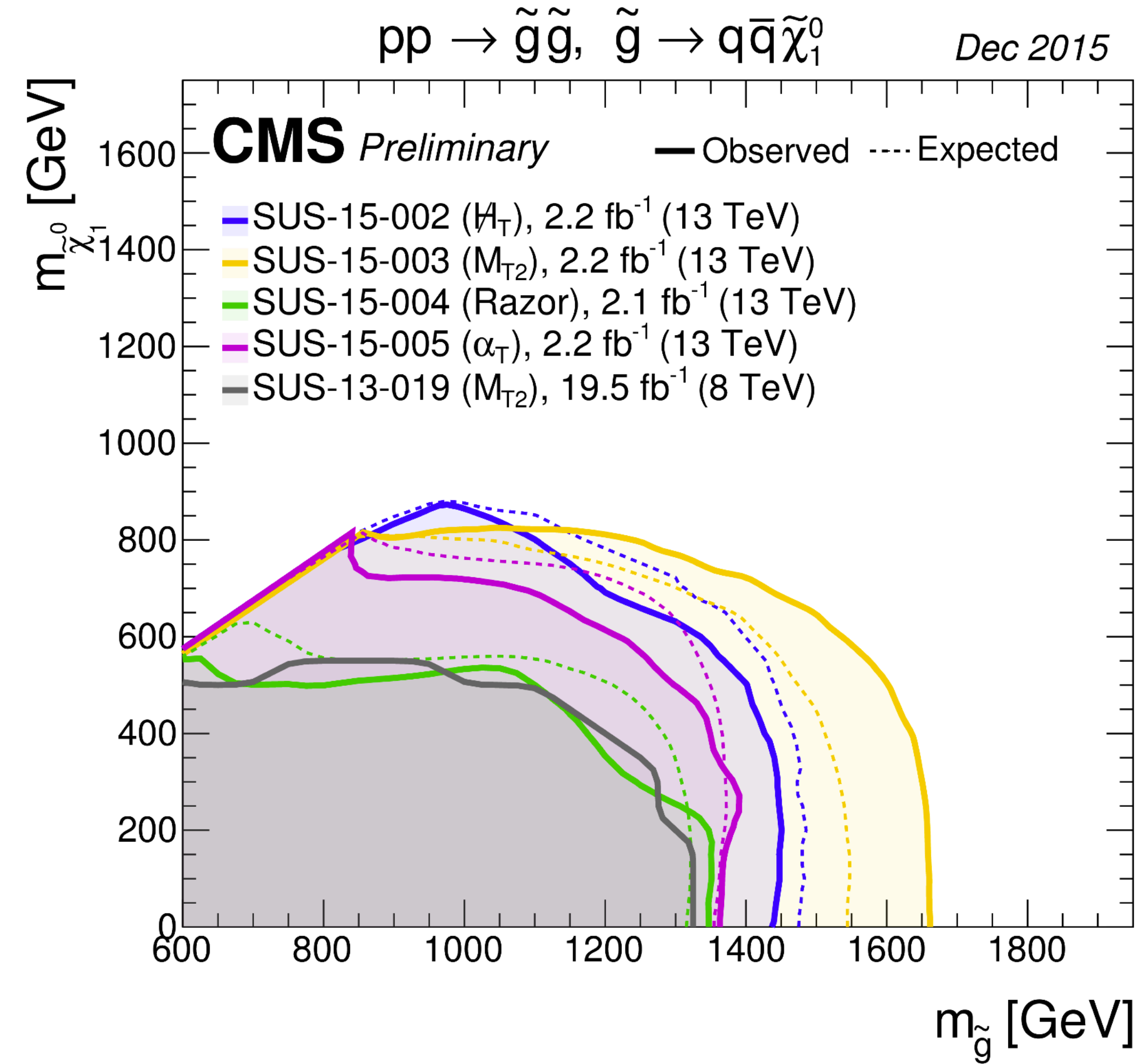


## EW direct production of sleptons

Smallest cross section  
Barely any sensitivity with Run-2



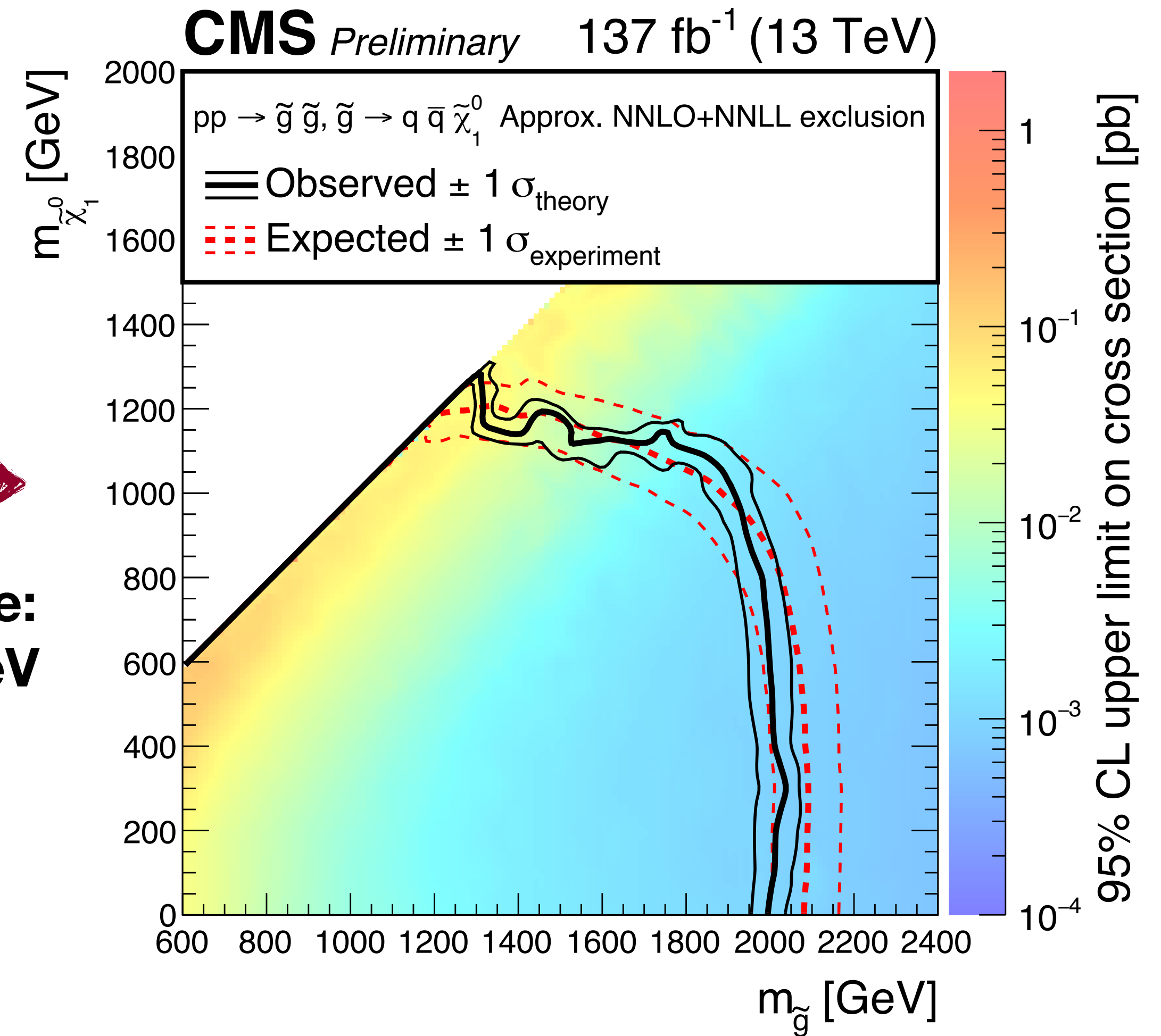
# Inclusive Searches: Small Improvements from Increase in Statistics



**x100  
more data**

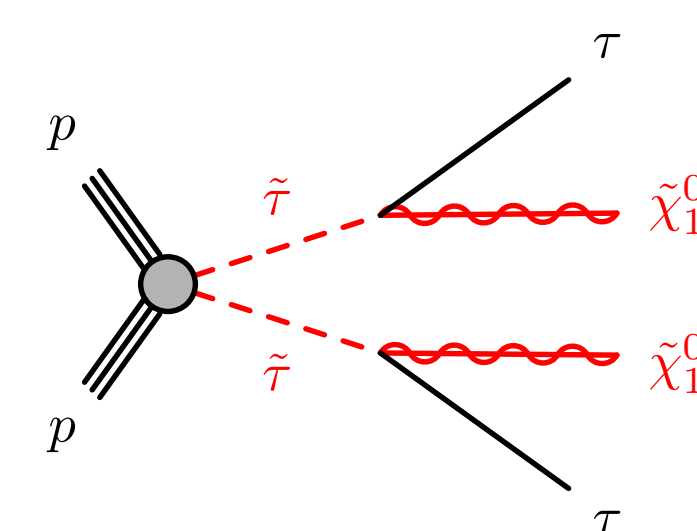
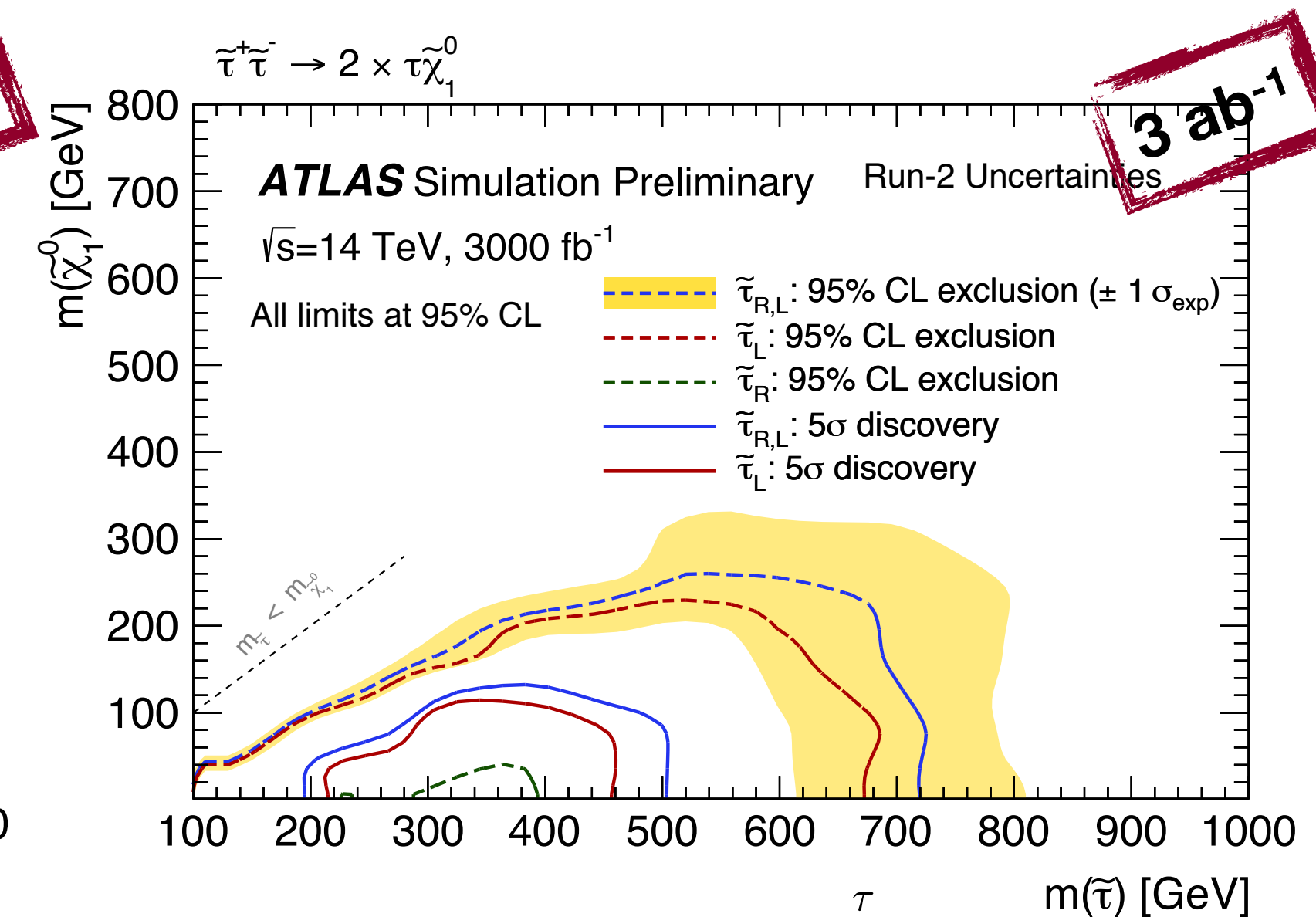
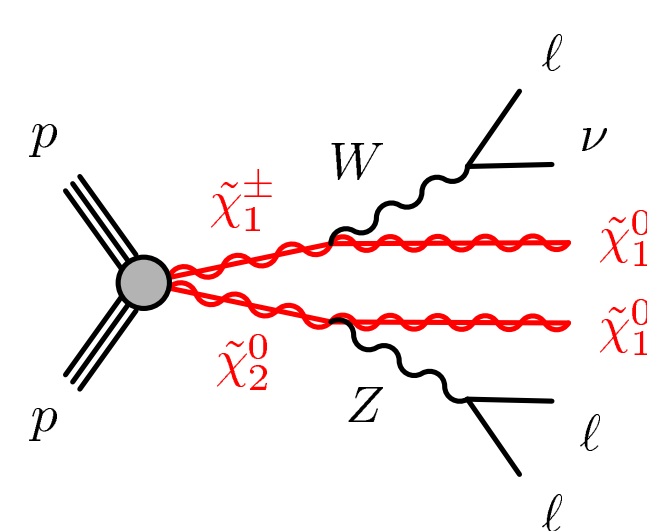
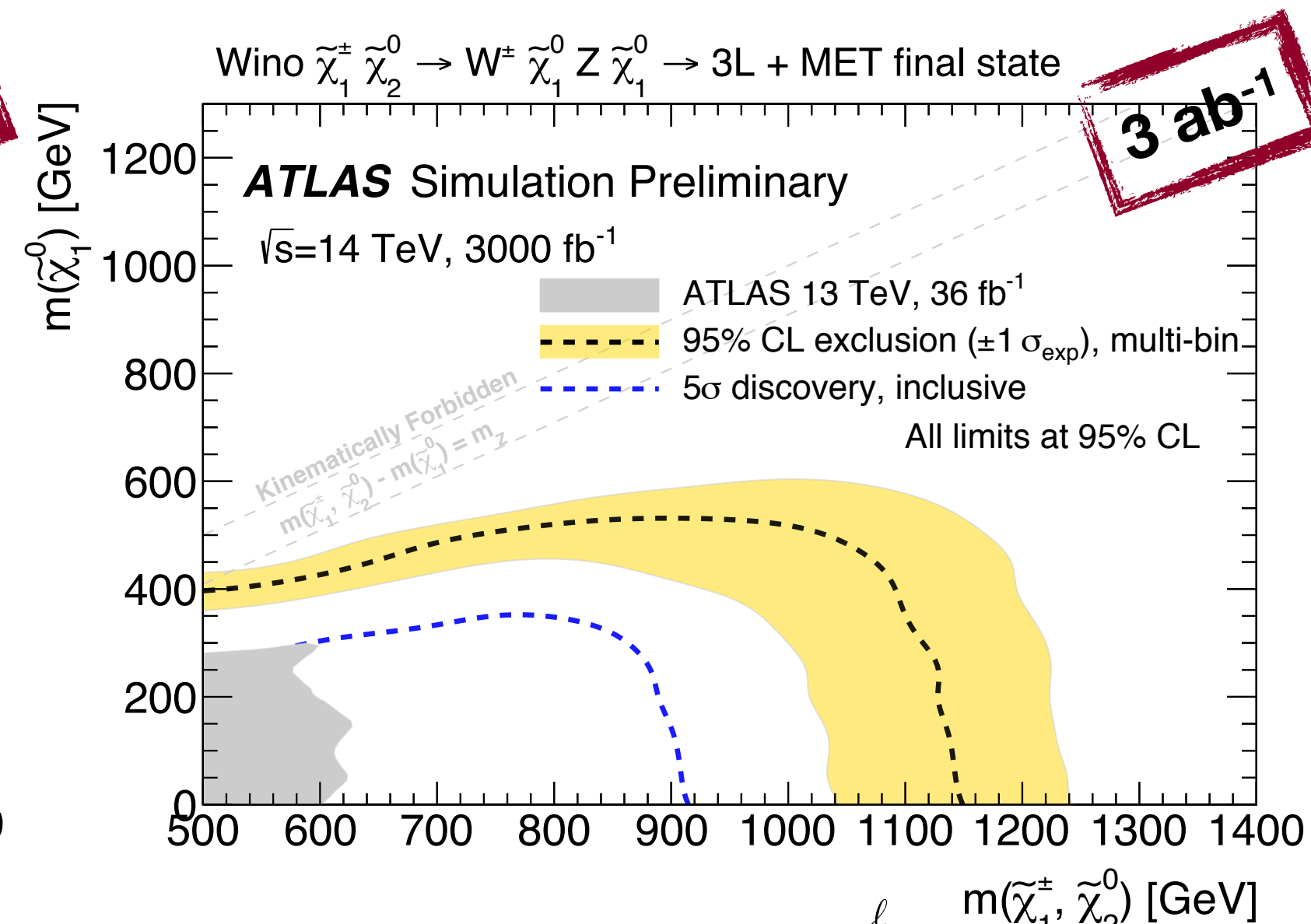
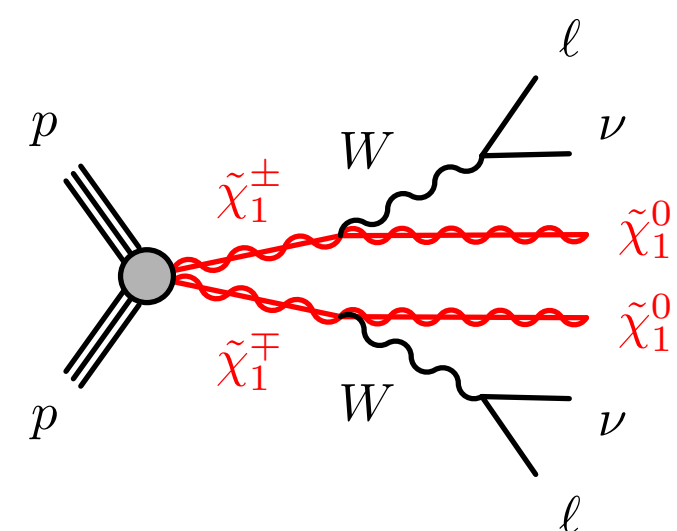
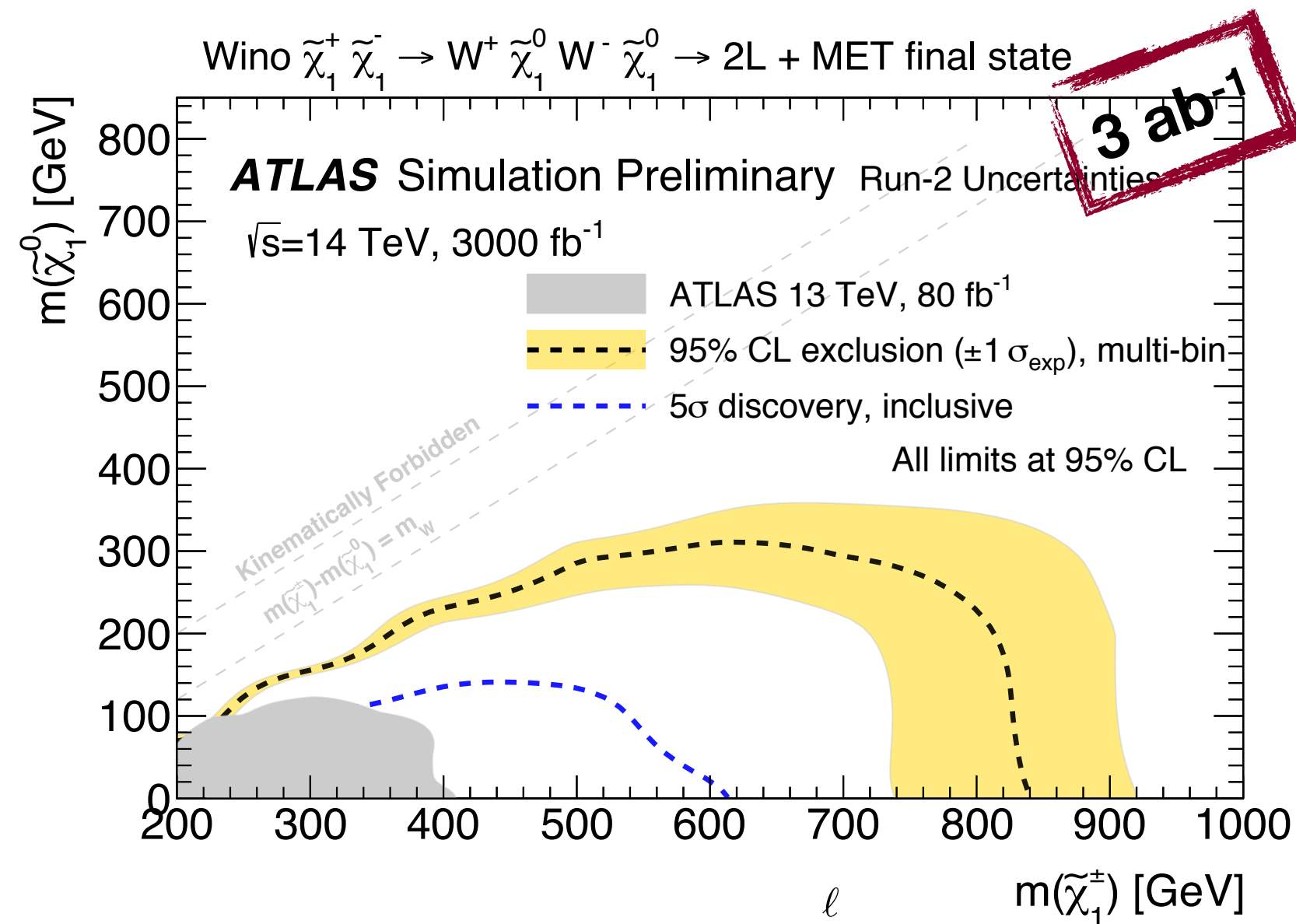
→

**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)

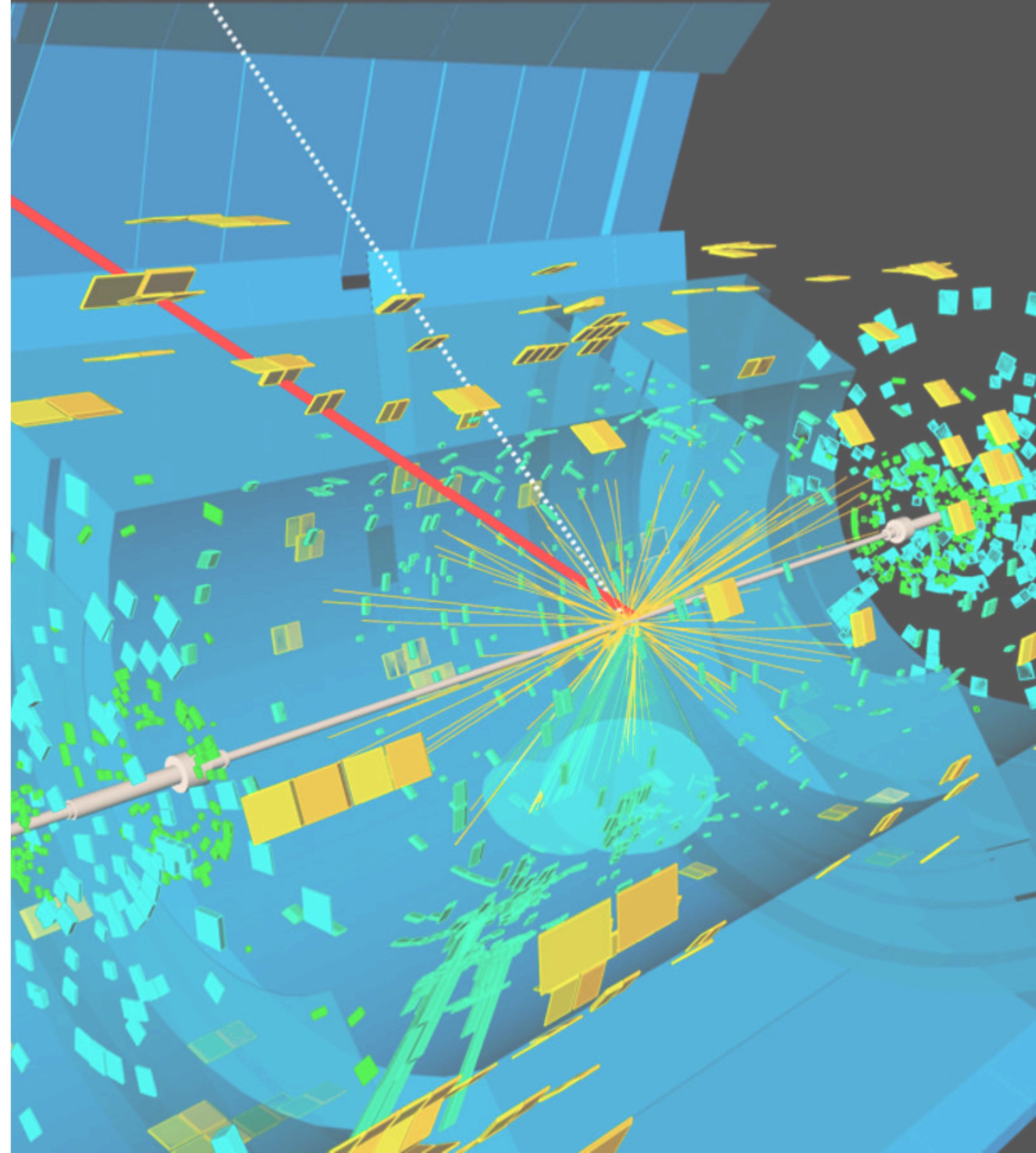




# Is this the end?

---

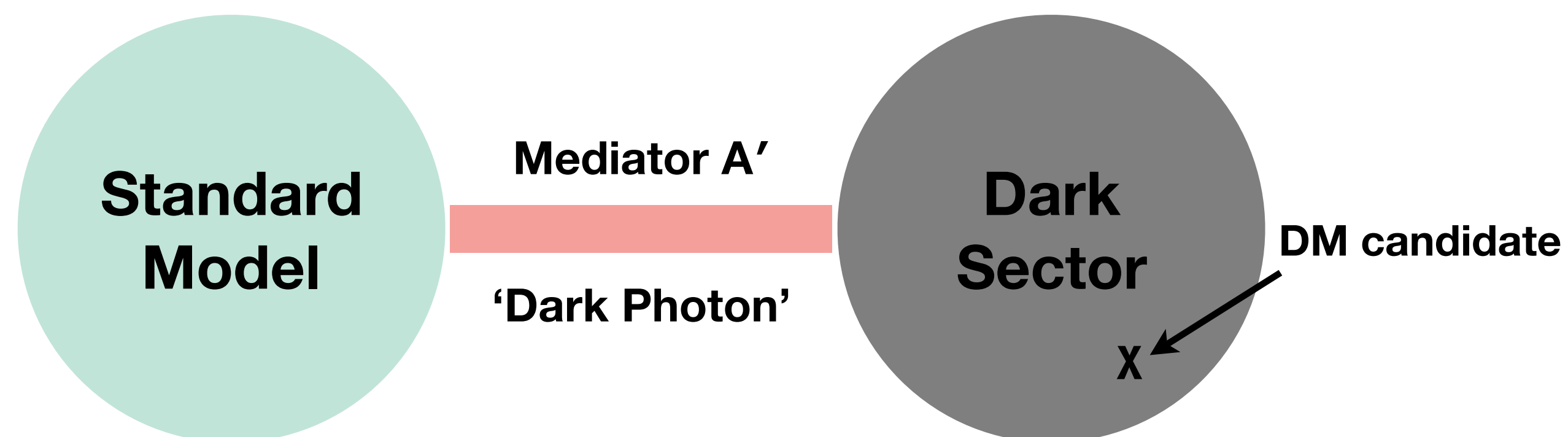
- **Yes**, it's the end of the talk:
  - though we know we missed a lot of nice searches
- **No**, it's not the end of LHC search program:
  - collecting more data will not do all the work
  - we need to be clever and explore what still we miss/forgot to look for



# BACKUP

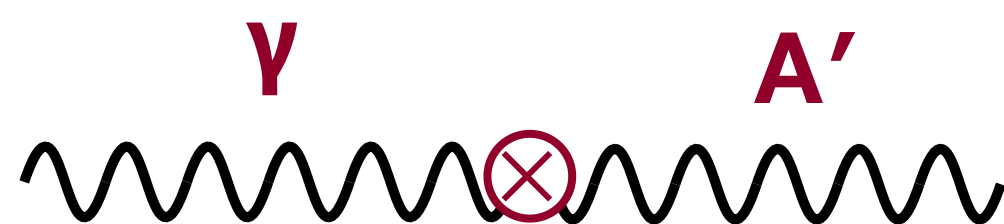
“you never know what you might need”

# Dark Photon Models with Kinetic Mixing



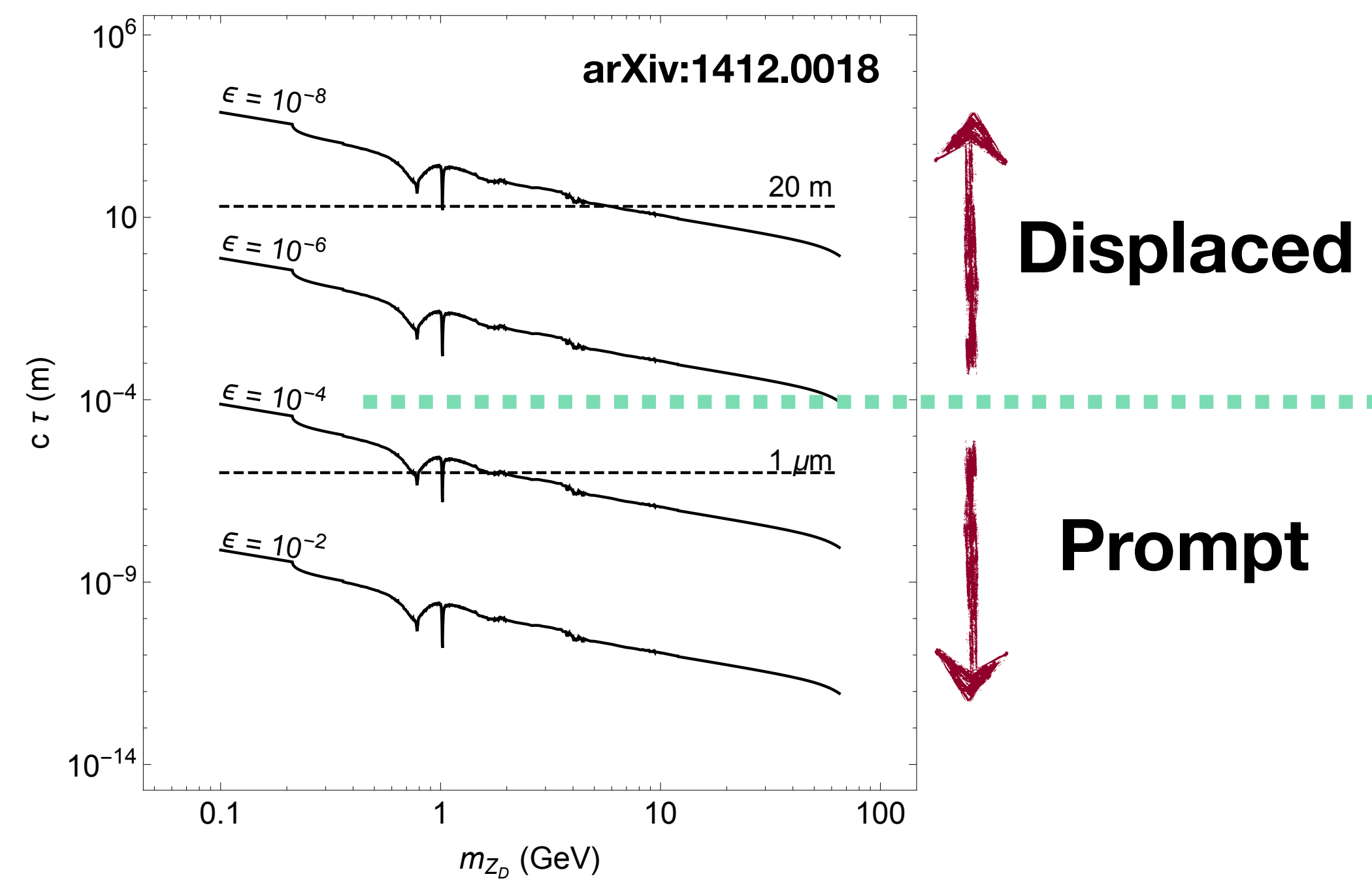
**Dark photon:** an additional U(1), connected to SM U(1) through **kinetic mixing**

$$\mathcal{L} \subset \frac{1}{2} \frac{\epsilon}{\cos \theta} (\partial^\mu A_D^\nu - \partial^\nu A_D^\mu) (\partial^\mu B^\nu - \partial^\nu B^\mu) \quad \epsilon: \text{kinetic mixing parameter}$$

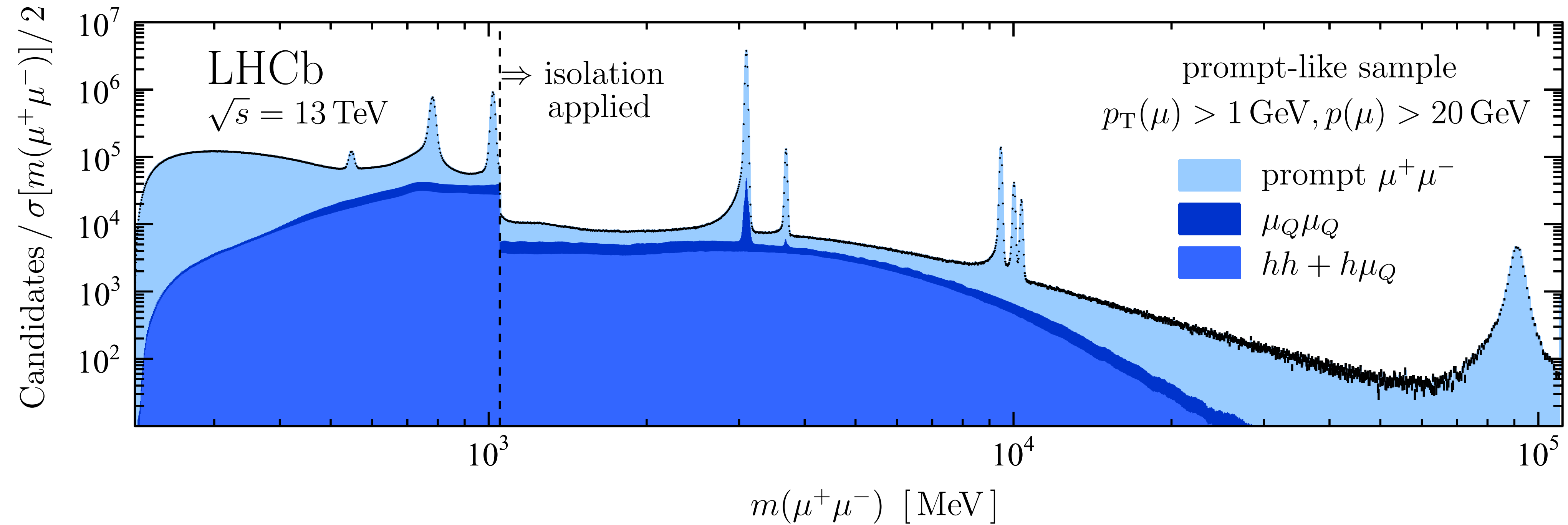


Not only way to introduce Dark Photons!  
See eg arXiv:1603.01377

## The $\epsilon$ Parameter



# LHCb Search for Dark Photons in Dimuon Channel

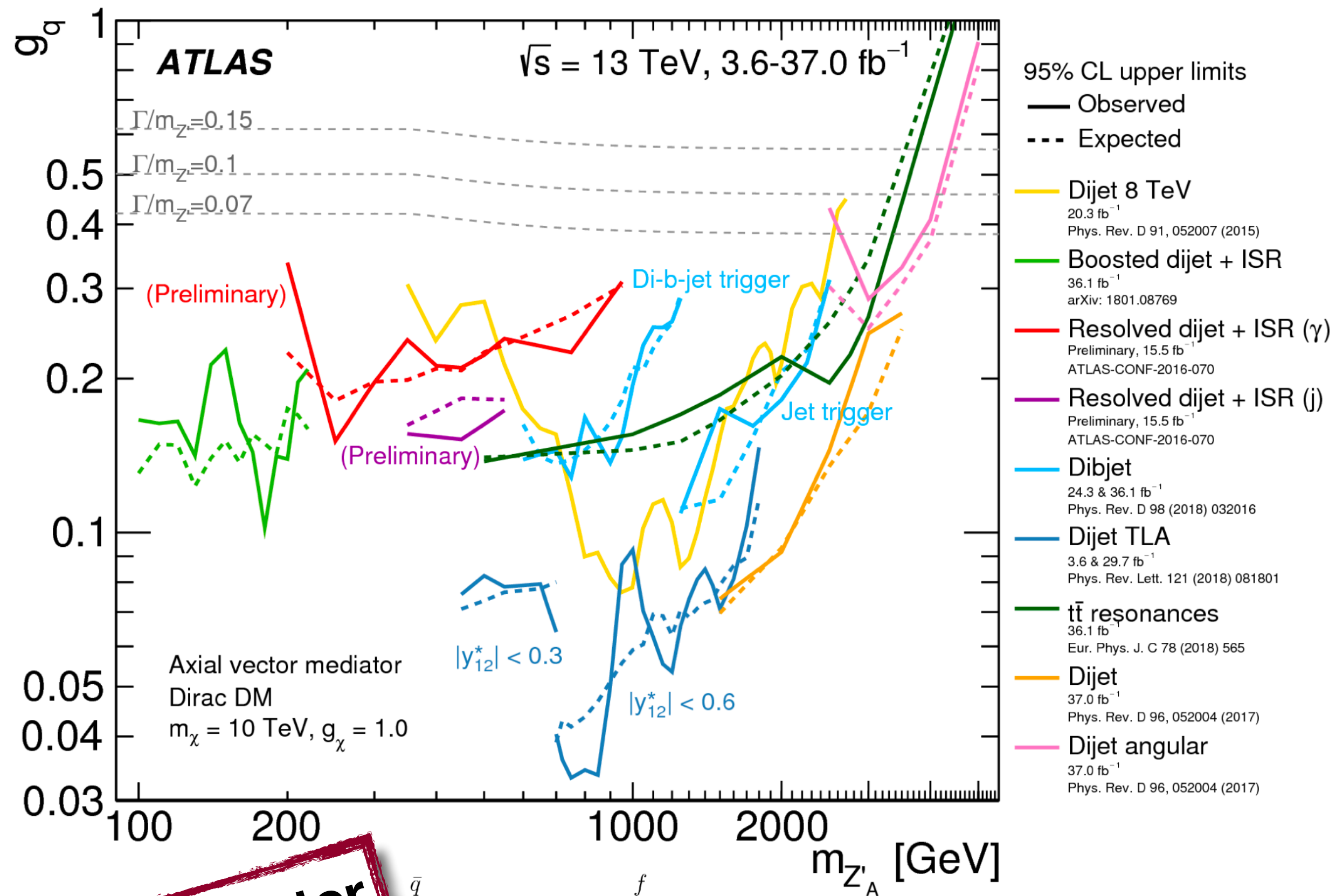


- Looking for  $A' \rightarrow \mu\mu$
- Bump hunt in dimuon spectrum from  $M \sim 2m_\mu$  to 70 GeV
- Excluding  $\varepsilon > 10^{-2}-10^{-3}$  (depending on  $M$ )

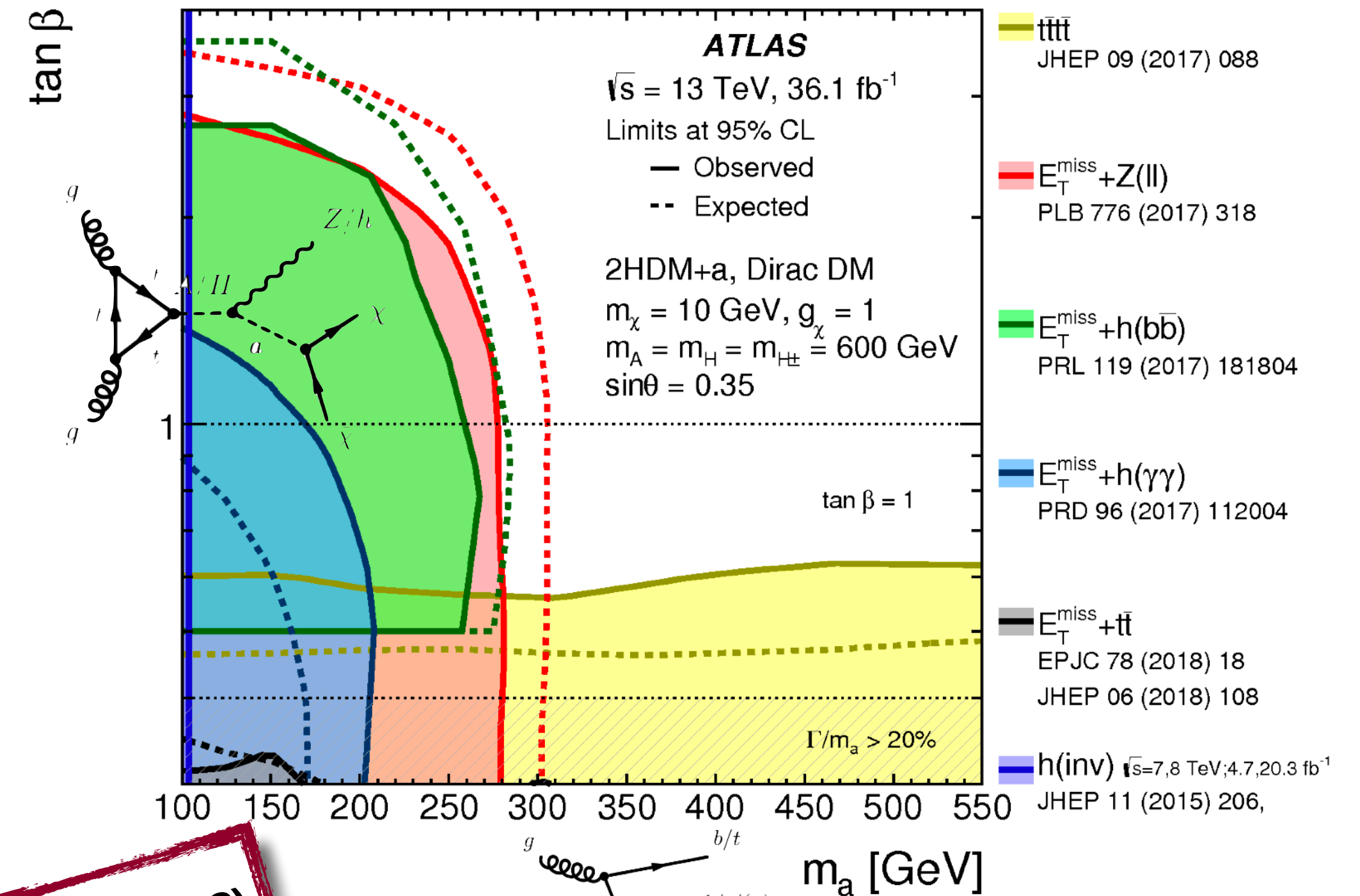
**CMS Search  
coming soon!**

# Look for any kind of DM, in any place

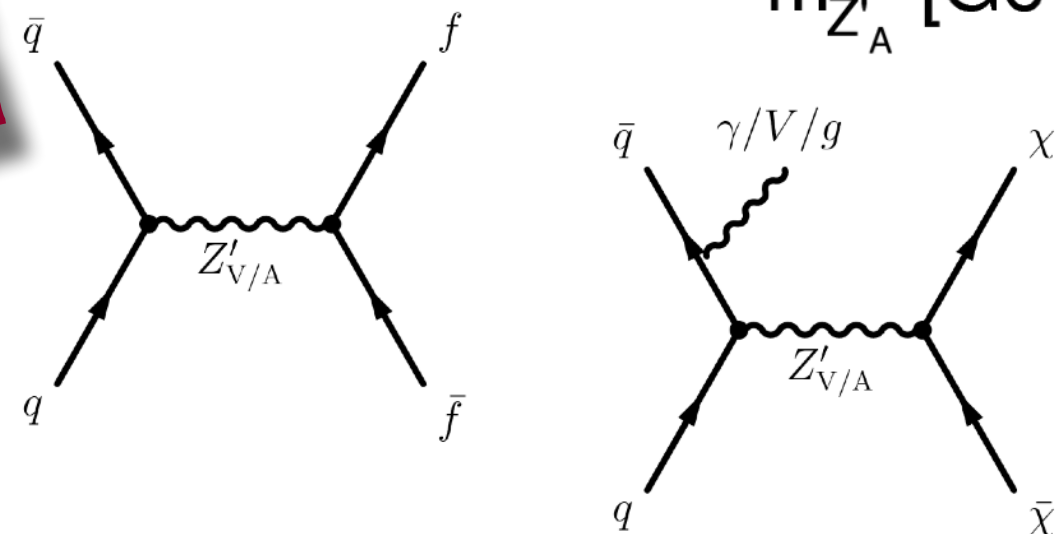
just a very small representative sample



Spanned a large range of simplified model with different mediator assumptions

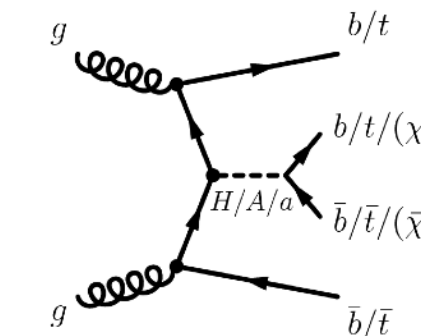


**A-V mediator**



EXOT-2017-032

**2HDM+a(PS)**



# New physics searches overview (ATLAS)

## ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$   $\sqrt{s} = 8, 13 \text{ TeV}$

| Model   | $\ell, \gamma$   | Jets†                 | $E_T^{\text{miss}}$    | $\int \mathcal{L} dt [\text{fb}^{-1}]$ | Limit                                       | Reference                        |
|---|--|-----------------------|------------------------|--|---|----------------------------------|
| <b>Extra dimensions</b>                         | ADD $G_{KK} + g/q$   | $0 e, \mu$            | $1-4 j$                | Yes                                    | 36.1  | $M_0$ <b>7.7 TeV</b>             |
|   | ADD non-resonant $\gamma\gamma$                              | $2 \gamma$            | -                      | -                                      | 36.7  | $M_s$ <b>8.6 TeV</b>             |
|   | ADD QBH  | -                     | $2 j$                  | -                                      | 37.0  | $M_{\text{th}}$ <b>8.9 TeV</b>   |
|   | ADD BH high $\sum p_T$                                       | $\geq 1 e, \mu$       | $\geq 2 j$             | -                                      | 3.2   | $M_{\text{th}}$ <b>8.2 TeV</b>   |
|   | ADD BH multijet  | -                     | $\geq 3 j$             | -                                      | 3.6   | $M_{\text{th}}$ <b>9.55 TeV</b>  |
|   | RS1 $G_{KK} \rightarrow \gamma\gamma$                        | $2 \gamma$            | -                      | -                                      | 36.7  | $G_{KK}$ mass <b>4.1 TeV</b>     |
|   | Bulk RS $G_{KK} \rightarrow WW/ZZ$                           | multi-channel         | -                      | -                                      | 36.1  | $G_{KK}$ mass <b>2.3 TeV</b>     |
|   | Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\bar{q}\bar{q}$ | $0 e, \mu$            | $2 J$                  | -                                      | 139   | $G_{KK}$ mass <b>1.6 TeV</b>     |
|   | Bulk RS $G_{KK} \rightarrow tt$                              | $1 e, \mu$            | $\geq 1 b, \geq 1J/2j$ | Yes                                    | 36.1  | $G_{KK}$ mass <b>3.8 TeV</b>     |
| 2UED/RPP  | $1 e, \mu$   | $\geq 2 b, \geq 3 j$  | Yes                    | 36.1                                   | $KK$ mass <b>1.8 TeV</b>                    |                                  |
| <b>Gauge bosons</b>                             | SSM $Z' \rightarrow \ell\ell$                                | $2 e, \mu$            | -                      | -                                      | 139   | $Z'$ mass <b>5.1 TeV</b>         |
|   | SSM $Z' \rightarrow \tau\tau$                                | $2 \tau$              | -                      | -                                      | 36.1  | $Z'$ mass <b>2.42 TeV</b>        |
|   | Leptophobic $Z' \rightarrow b\bar{b}$                        | -                     | $2 b$                  | -                                      | 36.1  | $Z'$ mass <b>2.1 TeV</b>         |
|   | Leptophobic $Z' \rightarrow t\bar{t}$                        | $1 e, \mu$            | $\geq 1 b, \geq 1J/2j$ | Yes                                    | 36.1  | $Z'$ mass <b>3.0 TeV</b>         |
|   | SSM $W' \rightarrow \ell\nu$                                 | $1 e, \mu$            | -                      | Yes                                    | 139   | $W'$ mass <b>6.0 TeV</b>         |
|   | SSM $W' \rightarrow \tau\nu$                                 | $1 \tau$              | -                      | Yes                                    | 36.1  | $W'$ mass <b>3.7 TeV</b>         |
|   | HVT $V' \rightarrow WZ \rightarrow qq\bar{q}\bar{q}$ model B | $0 e, \mu$            | $2 J$                  | -                                      | 139   | $V'$ mass <b>3.6 TeV</b>         |
|   | HVT $V' \rightarrow WH/ZH$ model B                           | multi-channel         | -                      | -                                      | 36.1  | $V'$ mass <b>2.93 TeV</b>        |
|   | LRSM $W_R \rightarrow t\bar{b}$                              | multi-channel         | -                      | -                                      | 36.1  | $W_R$ mass <b>3.25 TeV</b>       |
|   | LRSM $W_R \rightarrow \mu N_R$                               | $2 \mu$               | $1 J$                  | -                                      | 80  | $W_R$ mass <b>5.0 TeV</b>        |
|   | CI $q\bar{q}q\bar{q}$  | -                     | $2 j$                  | -                                      | 37.0  | $\Lambda$ <b>21.8 TeV</b>        |
|   | CI $\ell\ell q\bar{q}$                                       | $2 e, \mu$            | -                      | -                                      | 36.1  | $\Lambda$ <b>40.0 TeV</b>        |
| CI $t\bar{t}t\bar{t}$                           | $\geq 1 e, \mu$  | $\geq 1 b, \geq 1 j$  | Yes                    | 36.1                                   | $\Lambda$ <b>2.57 TeV</b>                   |                                  |
| <b>DM</b>                                       | Axial-vector mediator (Dirac DM)                             | $0 e, \mu$            | $1-4 j$                | Yes                                    | 36.1  | $m_{\text{med}}$ <b>1.55 TeV</b> |
|   | Colored scalar mediator (Dirac DM)                           | $0 e, \mu$            | $1-4 j$                | Yes                                    | 36.1  | $m_{\text{med}}$ <b>1.67 TeV</b> |
|   | VV $\chi$ EFT (Dirac DM)                                     | $0 e, \mu$            | $1 J, \leq 1 j$        | Yes                                    | 3.2   | $M_s$ <b>700 GeV</b>             |
|   | Scalar reson. $\phi \rightarrow t\bar{t}$ (Dirac DM)         | $0-1 e, \mu$          | $1 b, 0-1 J$           | Yes                                    | 36.1  | $m_\phi$ <b>3.4 TeV</b>          |
| <b>LQ</b>                                       | Scalar LQ 1 <sup>st</sup> gen                                | $1, 2 e$              | $\geq 2 j$             | Yes                                    | 36.1  | LO mass <b>1.4 TeV</b>           |
|   | Scalar LQ 2 <sup>nd</sup> gen                                | $1, 2 \mu$            | $\geq 2 j$             | Yes                                    | 36.1  | LO mass <b>1.56 TeV</b>          |
|   | Scalar LQ 3 <sup>rd</sup> gen                                | $2 \tau$              | $2 b$                  | -                                      | 36.1  | LQ mass <b>1.03 TeV</b>          |
|   | Scalar LQ 3 <sup>rd</sup> gen                                | $0-1 e, \mu$          | $2 b$                  | Yes                                    | 36.1  | LQ mass <b>970 GeV</b>           |
| <b>Heavy quarks</b>                             | VLQ $TT \rightarrow Ht/Zt/Wb + X$                            | multi-channel         | -                      | -                                      | 36.1  | T mass <b>1.37 TeV</b>           |
|   | VLQ $BB \rightarrow Wt/Zb + X$                               | multi-channel         | -                      | -                                      | 36.1  | B mass <b>1.34 TeV</b>           |
|   | VLQ $T_{5/3} T_{5/3} \rightarrow Wt + X$                     | $2(SS)/\geq 3 e, \mu$ | $\geq 1 b, \geq 1 j$   | Yes                                    | 36.1  | $T_{5/3}$ mass <b>1.64 TeV</b>   |
|   | VLQ $Y \rightarrow Wb + X$                                   | $1 e, \mu$            | $\geq 1 b, \geq 1 j$   | Yes                                    | 36.1  | Y mass <b>1.85 TeV</b>           |
|   | VLQ $B \rightarrow Hb + X$                                   | $0 e, \mu, 2 \gamma$  | $\geq 1 b, \geq 1 j$   | Yes                                    | 79.8  | B mass <b>1.21 TeV</b>           |
| VLQ $QQ \rightarrow WqWq$                       | $1 e, \mu$   | $\geq 4 j$            | Yes                    | 20.3                                   | Q mass <b>690 GeV</b>                       |                                  |
| <b>Excited fermions</b>                         | Excited quark $q^* \rightarrow qg$                           | -                     | $2 j$                  | -                                      | 139   | $q^*$ mass <b>6.7 TeV</b>        |
|   | Excited quark $q^* \rightarrow q\gamma$                      | $1 \gamma$            | $1 j$                  | -                                      | 36.7  | $q^*$ mass <b>5.3 TeV</b>        |
|   | Excited quark $b^* \rightarrow bg$                           | -                     | $1 b, 1 j$             | -                                      | 36.1  | $b^*$ mass <b>2.6 TeV</b>        |
|   | Excited lepton $\ell^*$                                      | $3 e, \mu$            | -                      | -                                      | 20.3  | $\ell^*$ mass <b>3.0 TeV</b>     |
|   | Excited lepton $\nu^*$                                       | $3 e, \mu, \tau$      | -                      | -                                      | 20.3  | $\nu^*$ mass <b>1.6 TeV</b>      |
|   | Type III Seesaw  | $1 e, \mu$            | $\geq 2 j$             | Yes                                    | 79.8  | $N^0$ mass <b>560 GeV</b>        |
| LRSM Majorana $\nu$                             | $2 \mu$  | $2 j$                 | -                      | 36.1                                   | $N_R$ mass <b>3.2 TeV</b>                   |                                  |
| Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$ | $2, 3, 4 e, \mu$ (SS)  | -                     | -                      | 36.1                                   | $H^{\pm\pm}$ mass <b>870 GeV</b>            |                                  |
| Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$ | $3 e, \mu, \tau$   | -                     | -                      | 20.3                                   | $H^{\pm\pm}$ mass <b>400 GeV</b>            |                                  |
| Multi-charged particles                         | -  | -                     | -                      | 36.1                                   | multi-charged particle mass <b>1.22 TeV</b> |                                  |
| Magnetic monopoles                              | -  | -                     | -                      | 34.4                                   | monopole mass <b>2.37 TeV</b>               |                                  |

$\sqrt{s} = 8 \text{ TeV}$   $\sqrt{s} = 13 \text{ TeV}$  partial data  $\sqrt{s} = 13 \text{ TeV}$  full data

\*Only a selection of the available mass limits on new states or phenomena is shown.

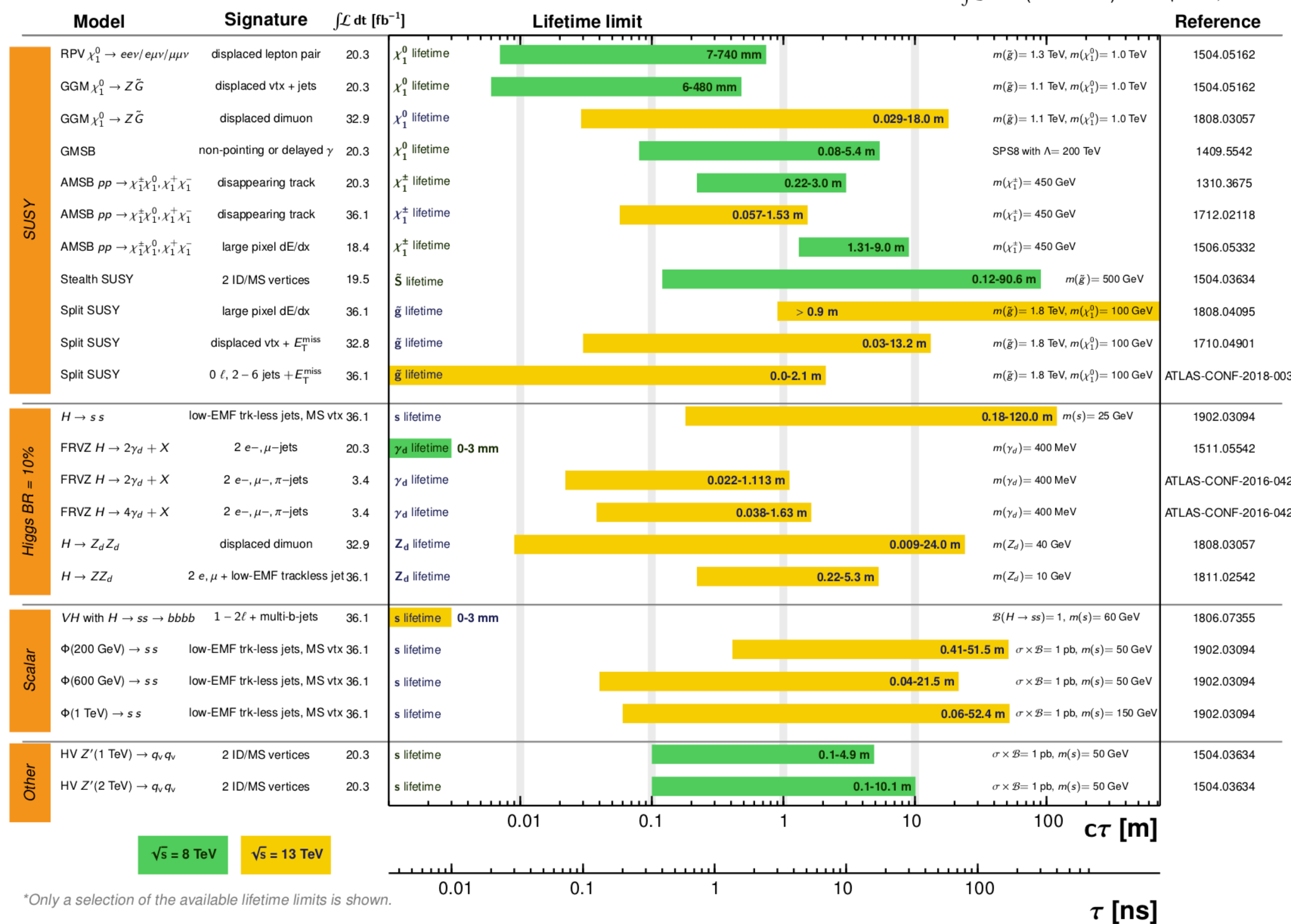
†Small-radius (large-radius) jets are denoted by the letter  $j$  ( $J$ ).

## ATLAS Long-lived Particle Searches\* - 95% CL Exclusion

Status: March 2019

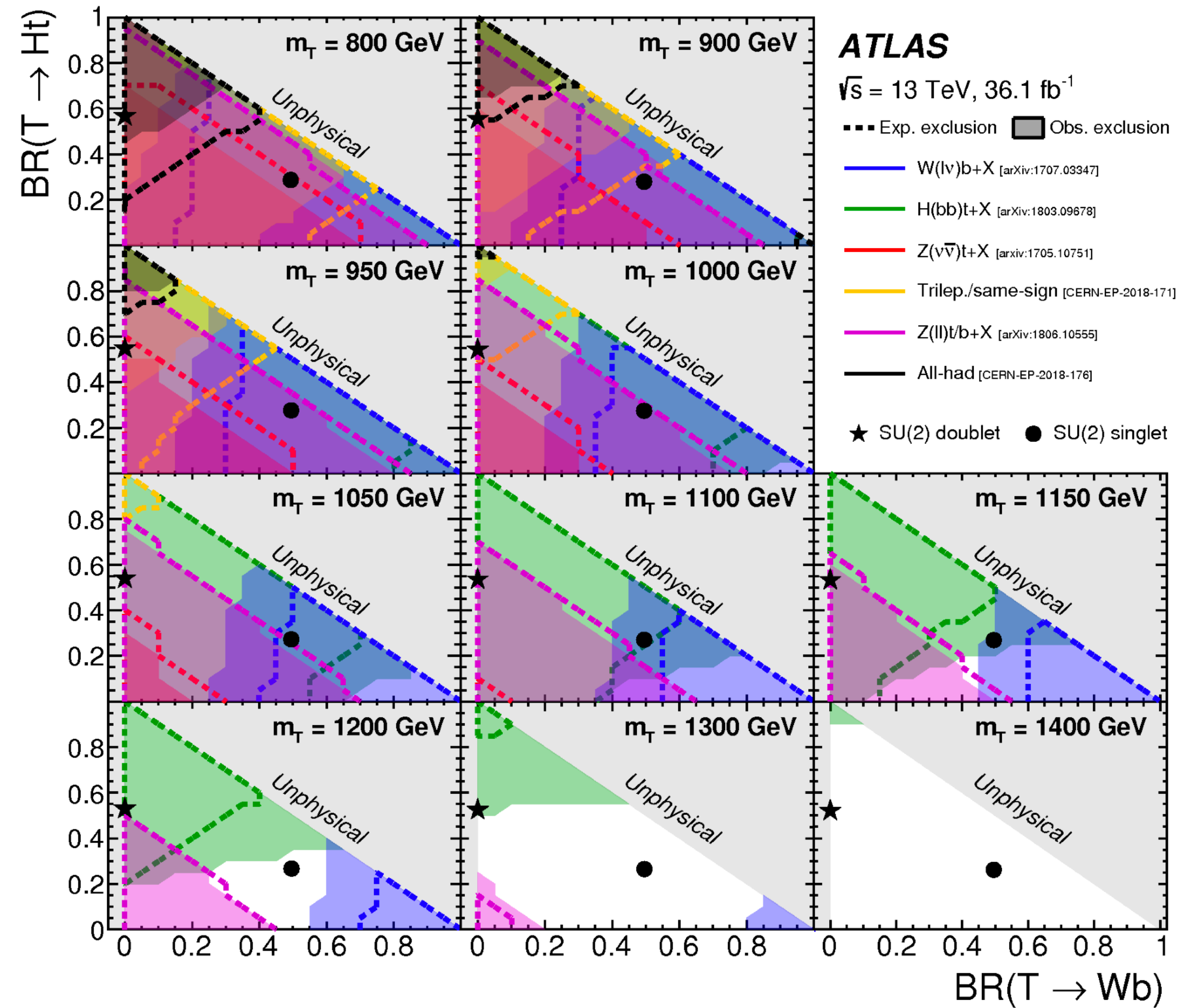
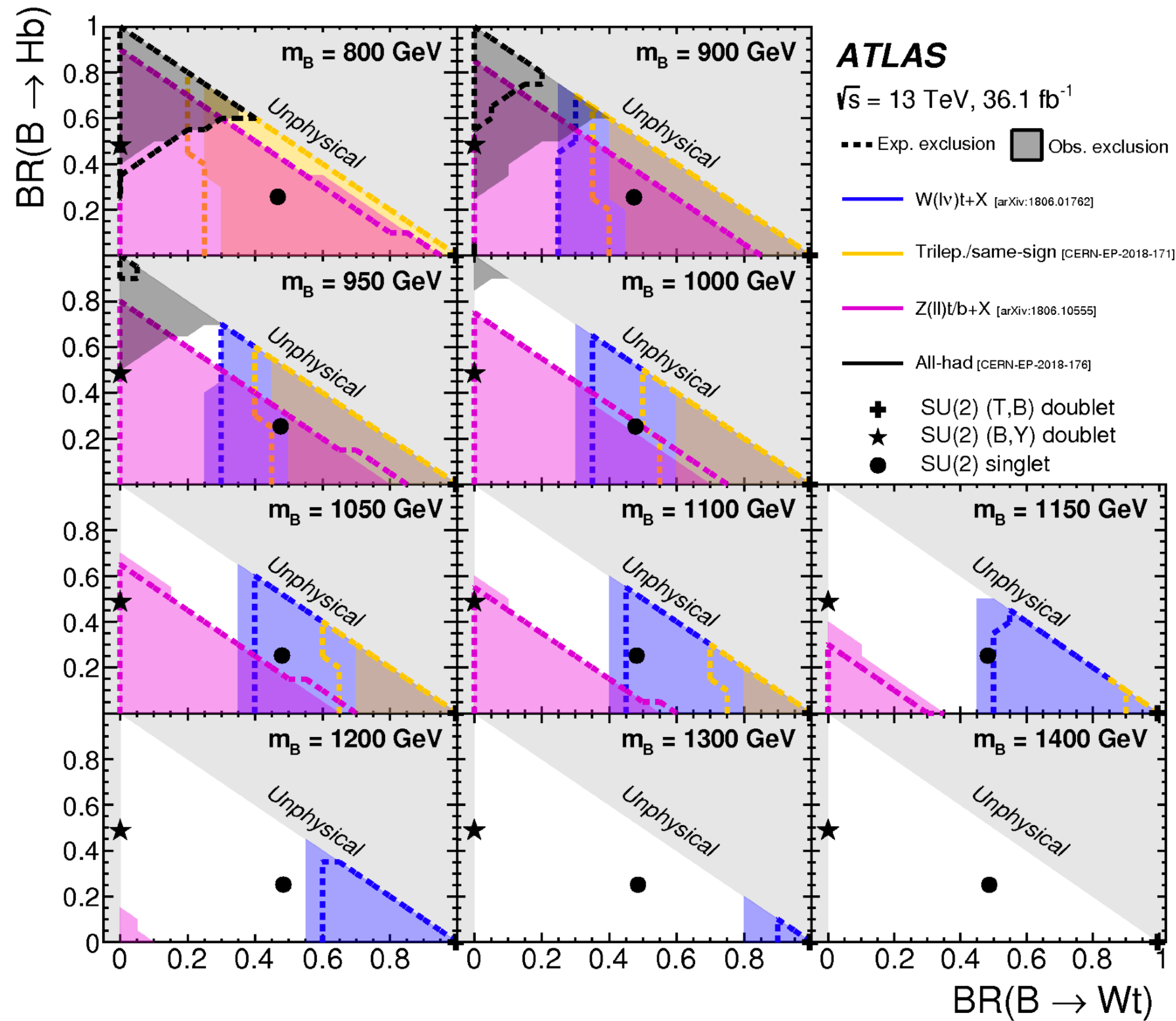
ATLAS Preliminary

$\int \mathcal{L} dt = (3.4 - 36.1) \text{ fb}^{-1}$   $\sqrt{s} = 8, 13 \text{ TeV}$



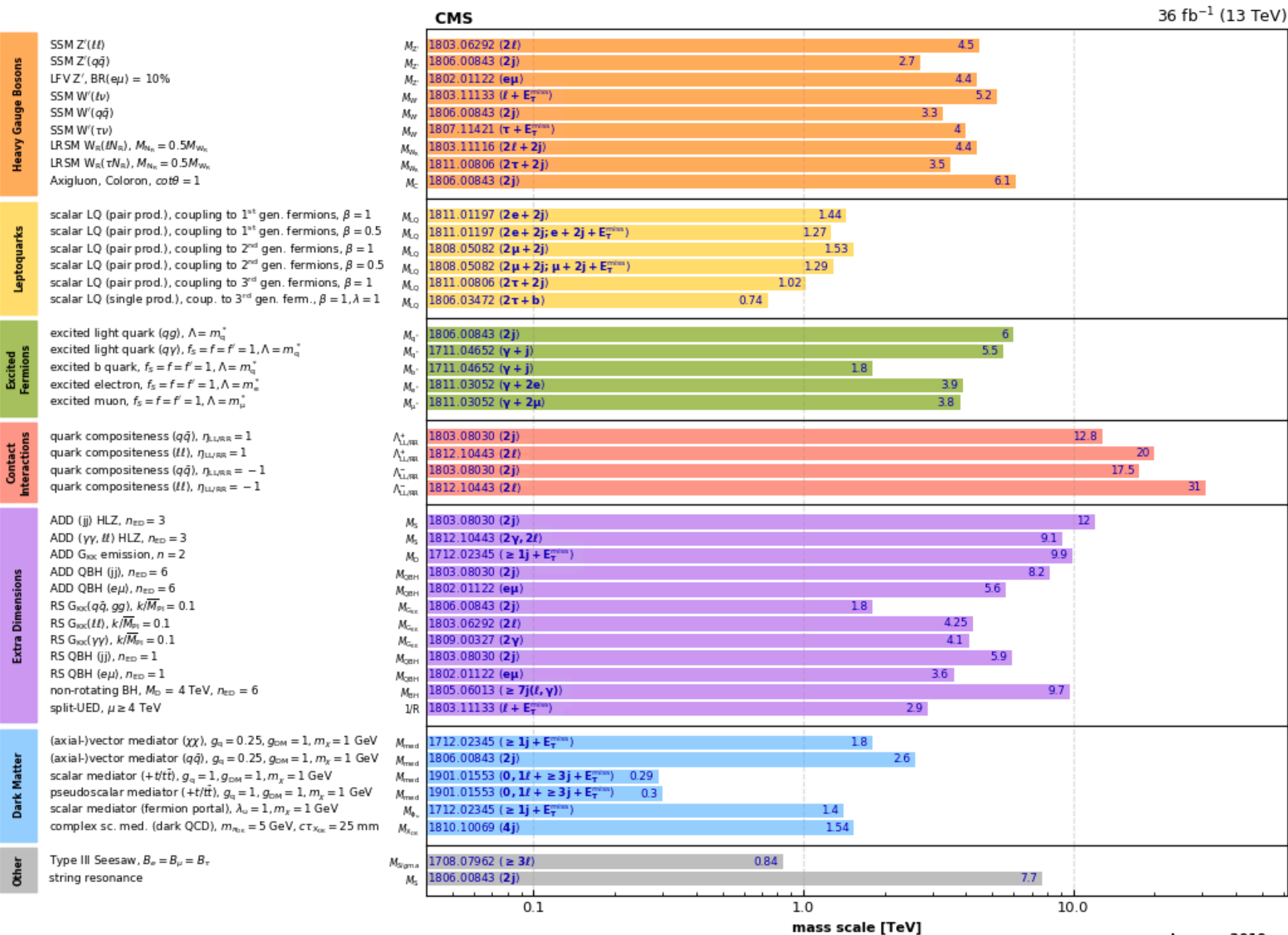
\*Only a selection of the available lifetime limits is shown.

# New physics searches overview (ATLAS)



# New physics searches overview (CMS)

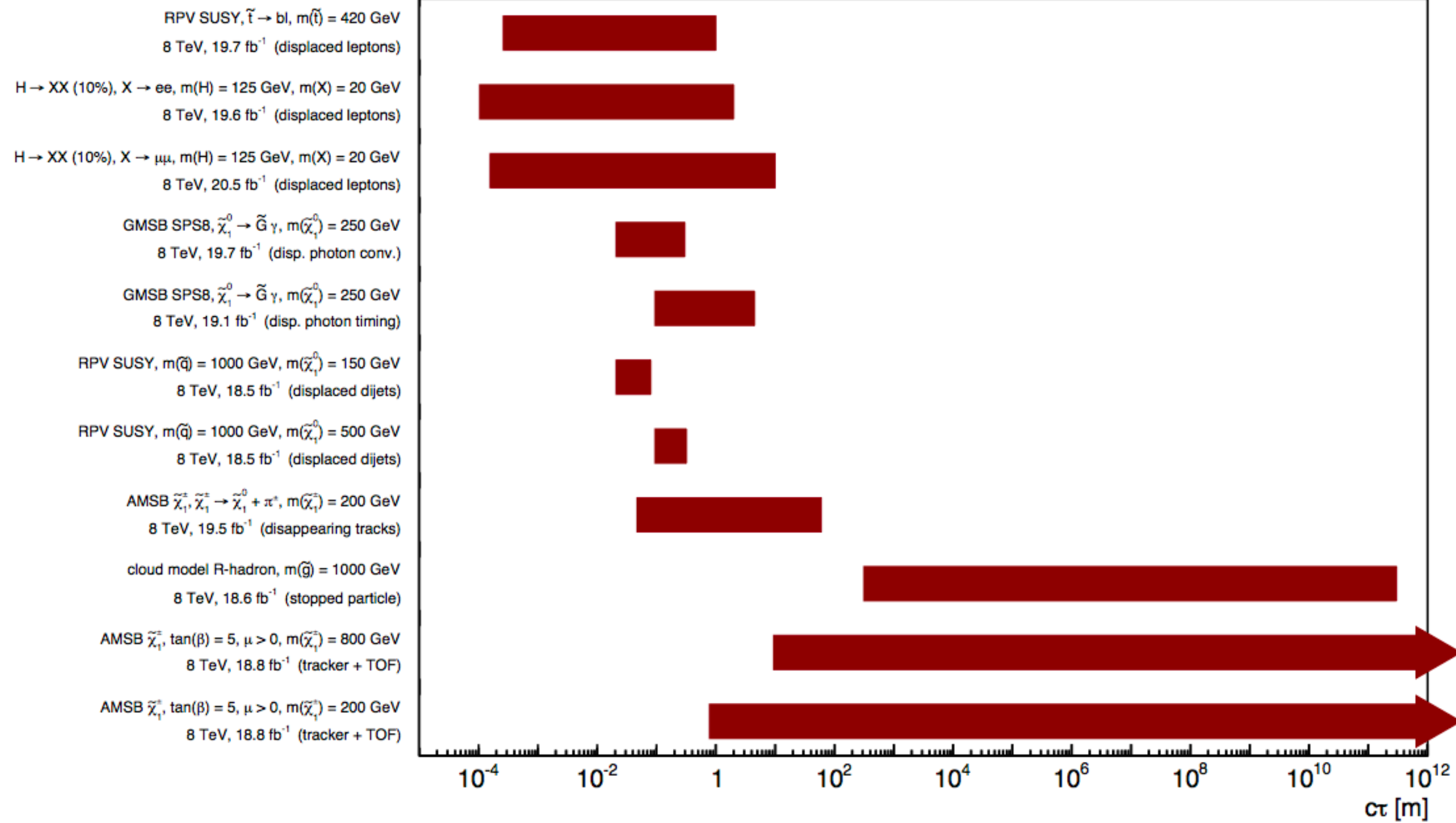
## Overview of CMS EXO results



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

January 2019

## CMS long-lived particle searches, lifetime exclusions at 95% CL

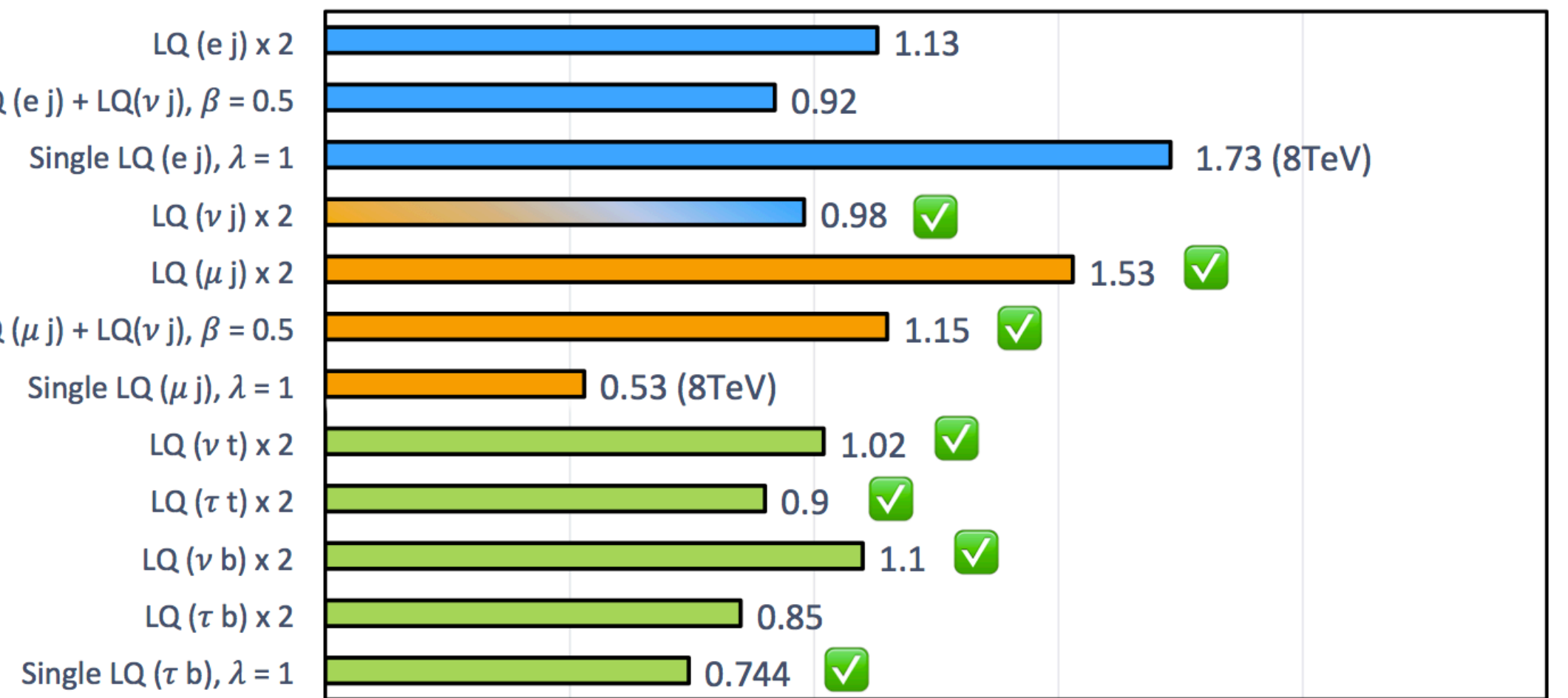




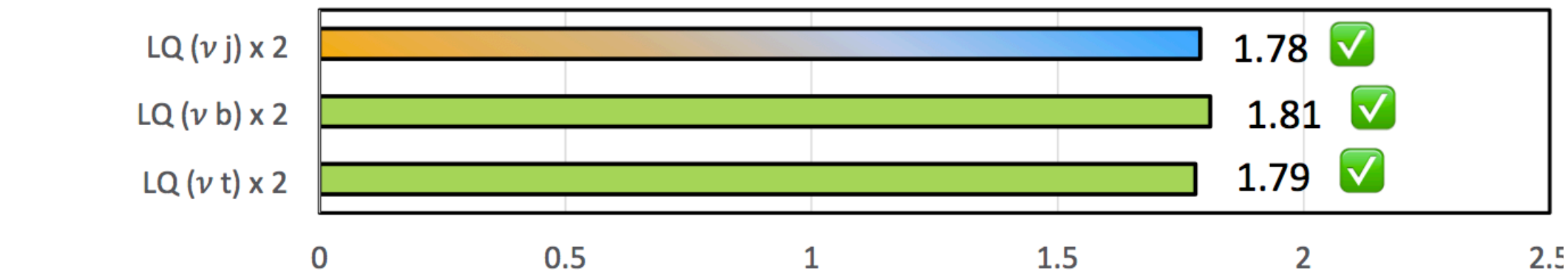
# New physics searches overview (CMS)

May 2018 LQ → 1st gen. 2nd. gen. 3rd gen. ✓ Full 2016 dataset

Scalar LQ



Vector LQ  
(LQ model used: 1801.07641)



LeptoQuark mass (TeV)

