BSM Results at the LHC

APS DPF 2019

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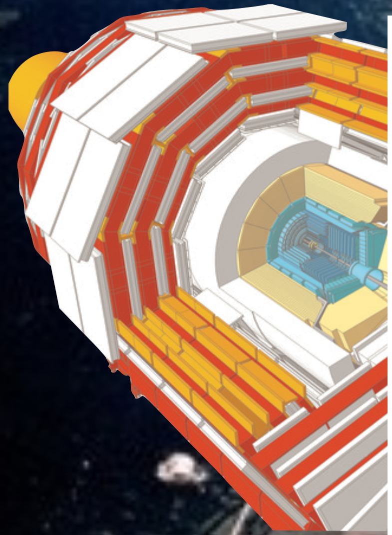
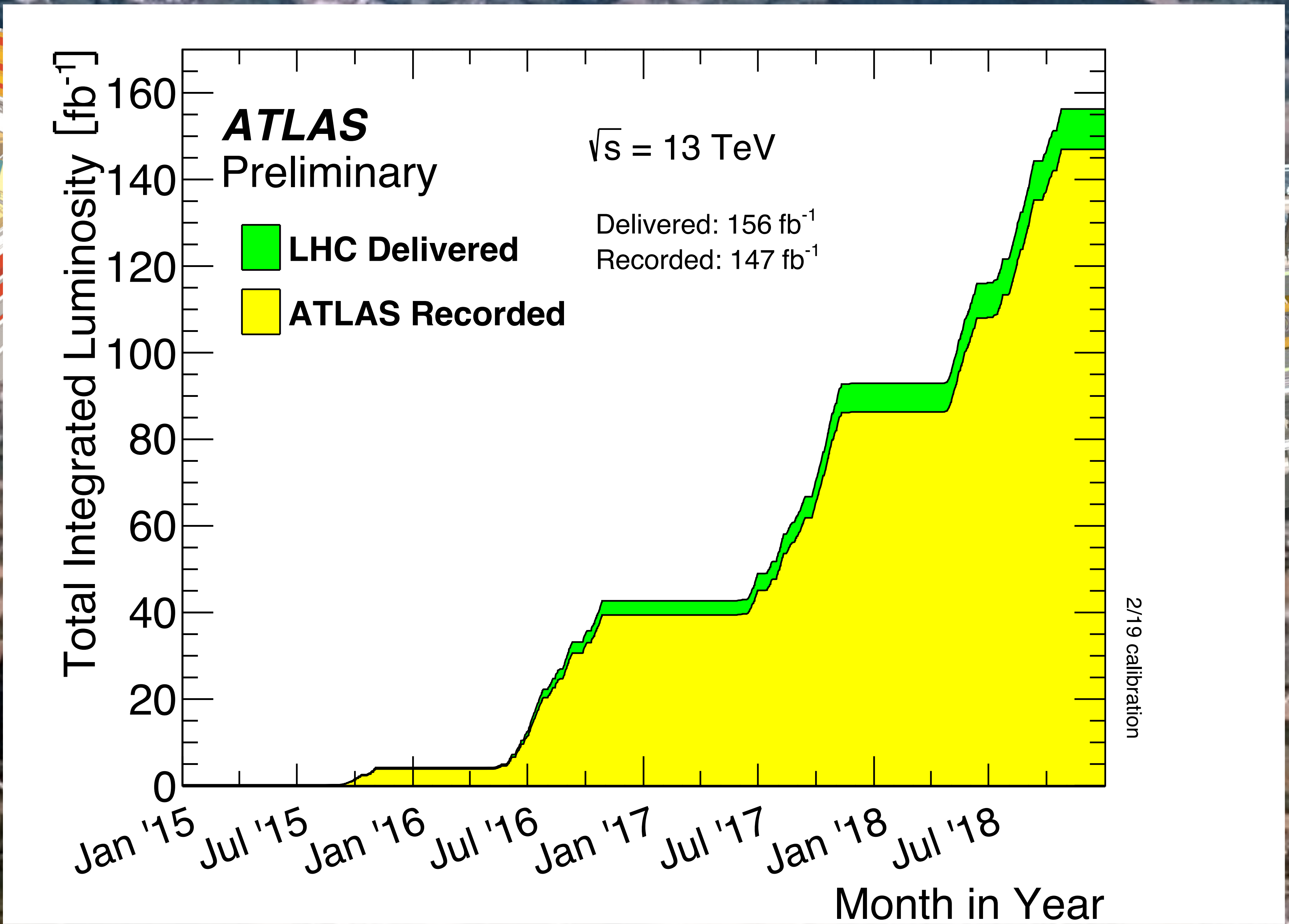
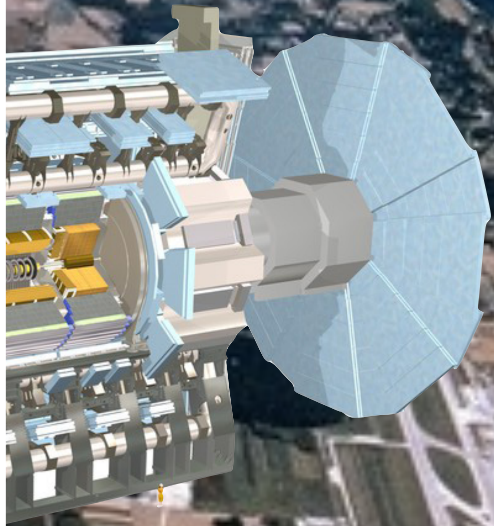
The LHC

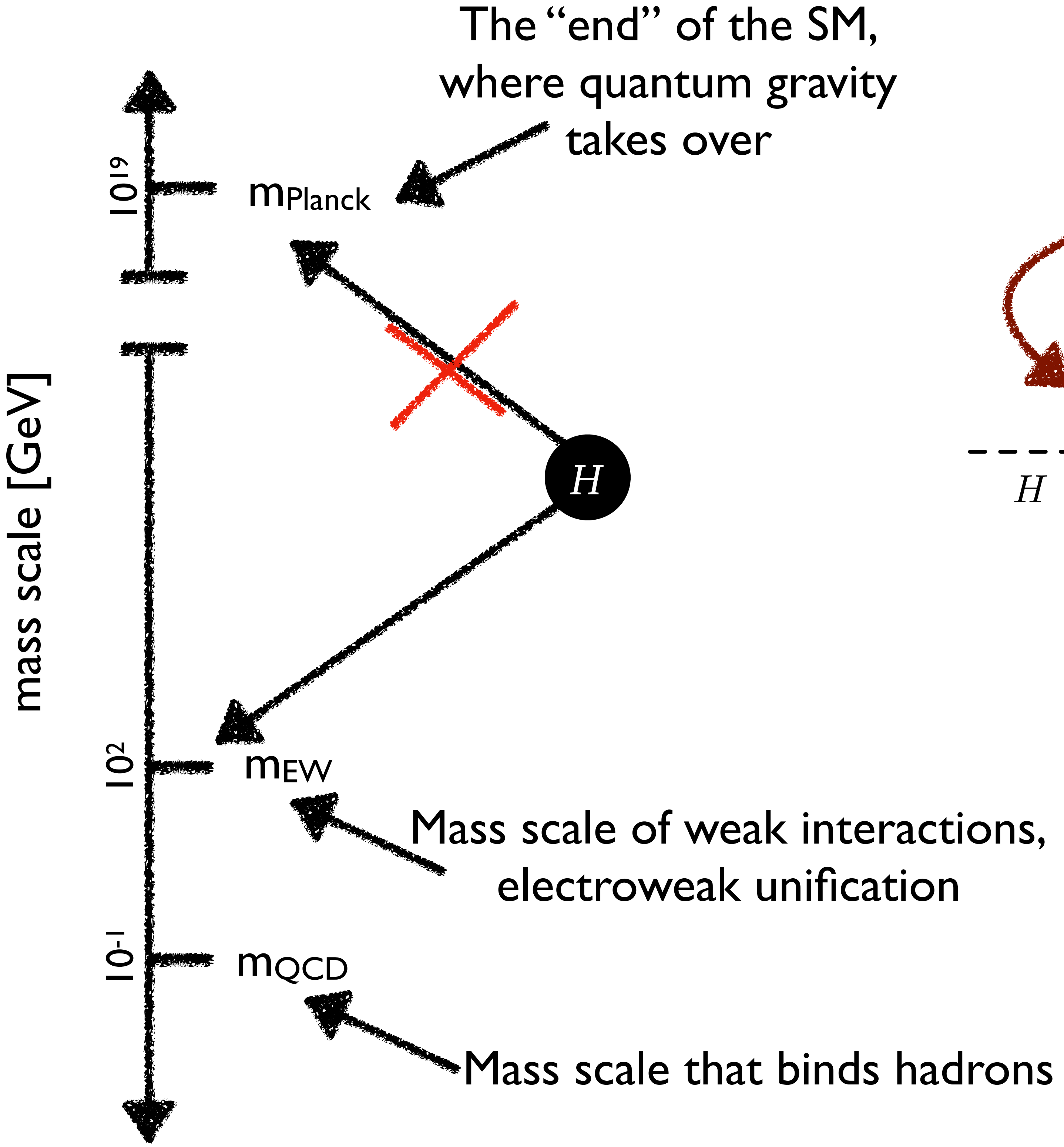






Huge recorded dataset from Run 2:
Thank you to the LHC team and machine!

Why BSM?



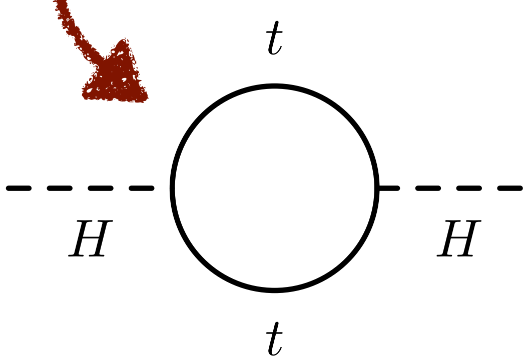
The "end" of the SM, where quantum gravity takes over

Mass scale of weak interactions, electroweak unification

Mass scale that binds hadrons

To first order, the mass of the Higgs is a free parameter, and can be anywhere

But the Higgs interacts with other particles, which affects its mass



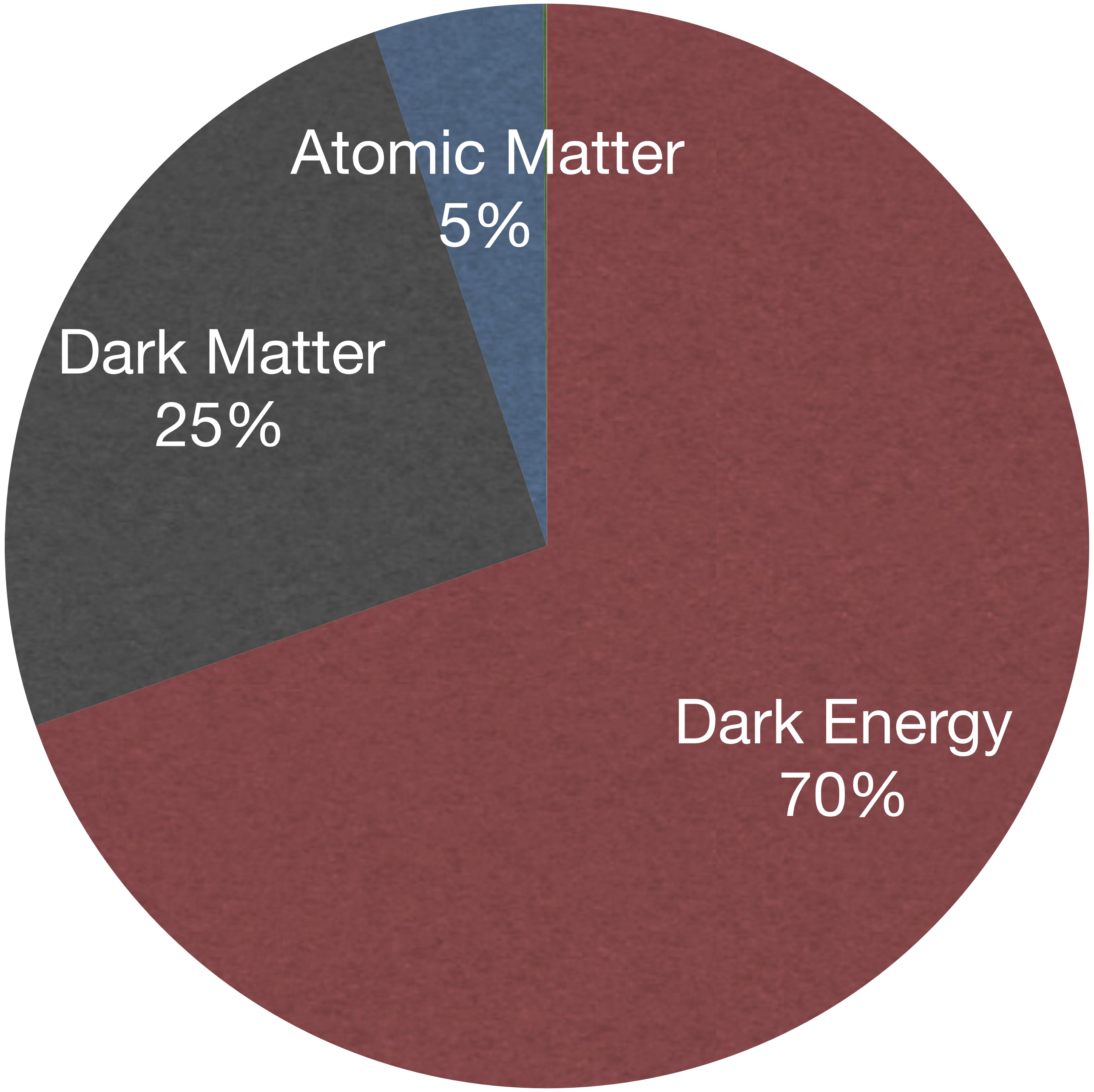
$$\approx \int_0^{\Lambda} dE \approx m_{\text{Planck}}$$

In the SM, this correction should set the Higgs mass to ~m_{Planck}

But we observe it at 125 GeV!

BSM can stabilize the Higgs mass

Why BSM?



We don't understand the majority of the universe!

BSM can provide Dark Matter candidates, which we could produce at the LHC

Why BSM?

10,000,000,001

Matter

10,000,000,000

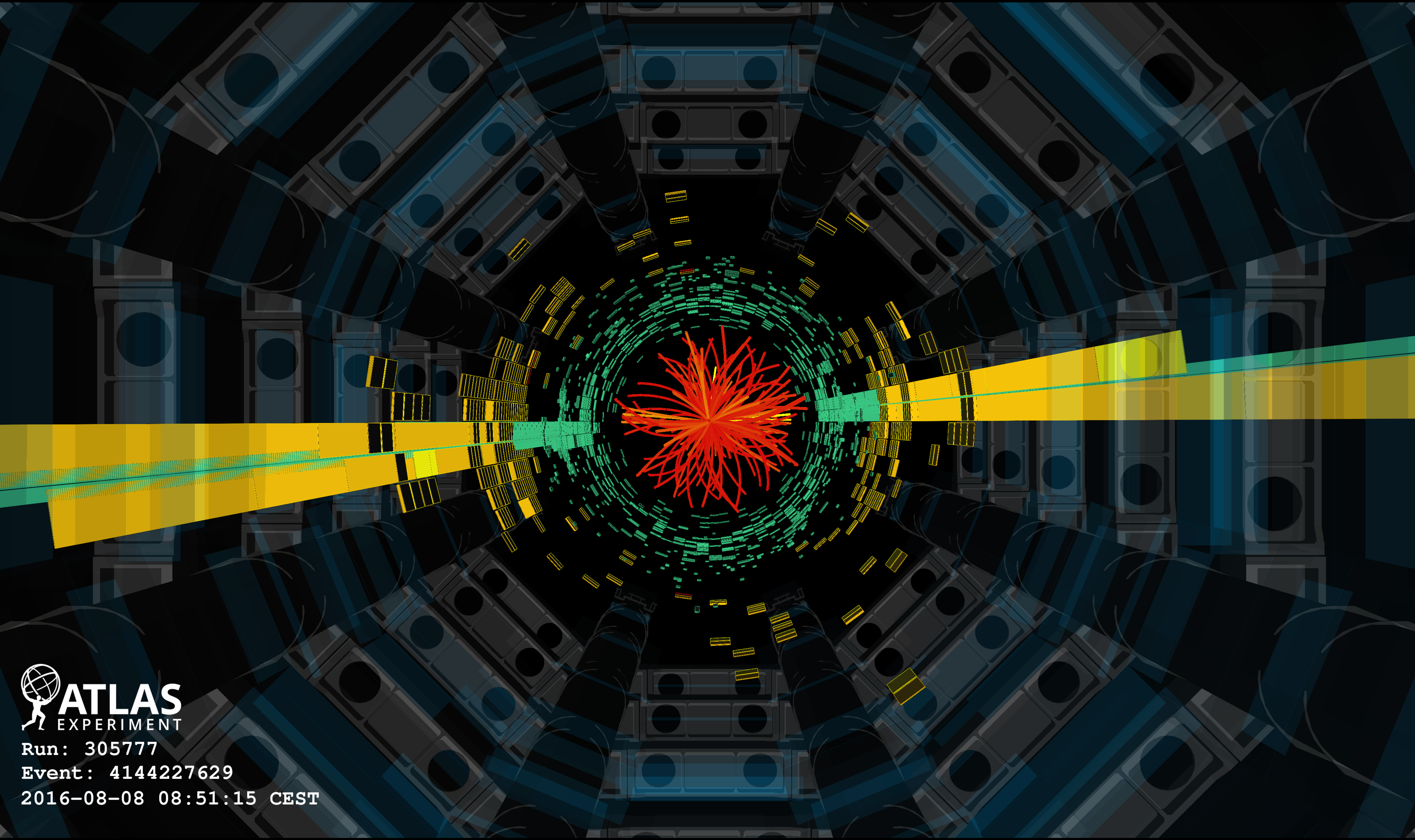
Antimatter

Where did the tiny matter/antimatter asymmetry that leads to a matter dominated universe arise?

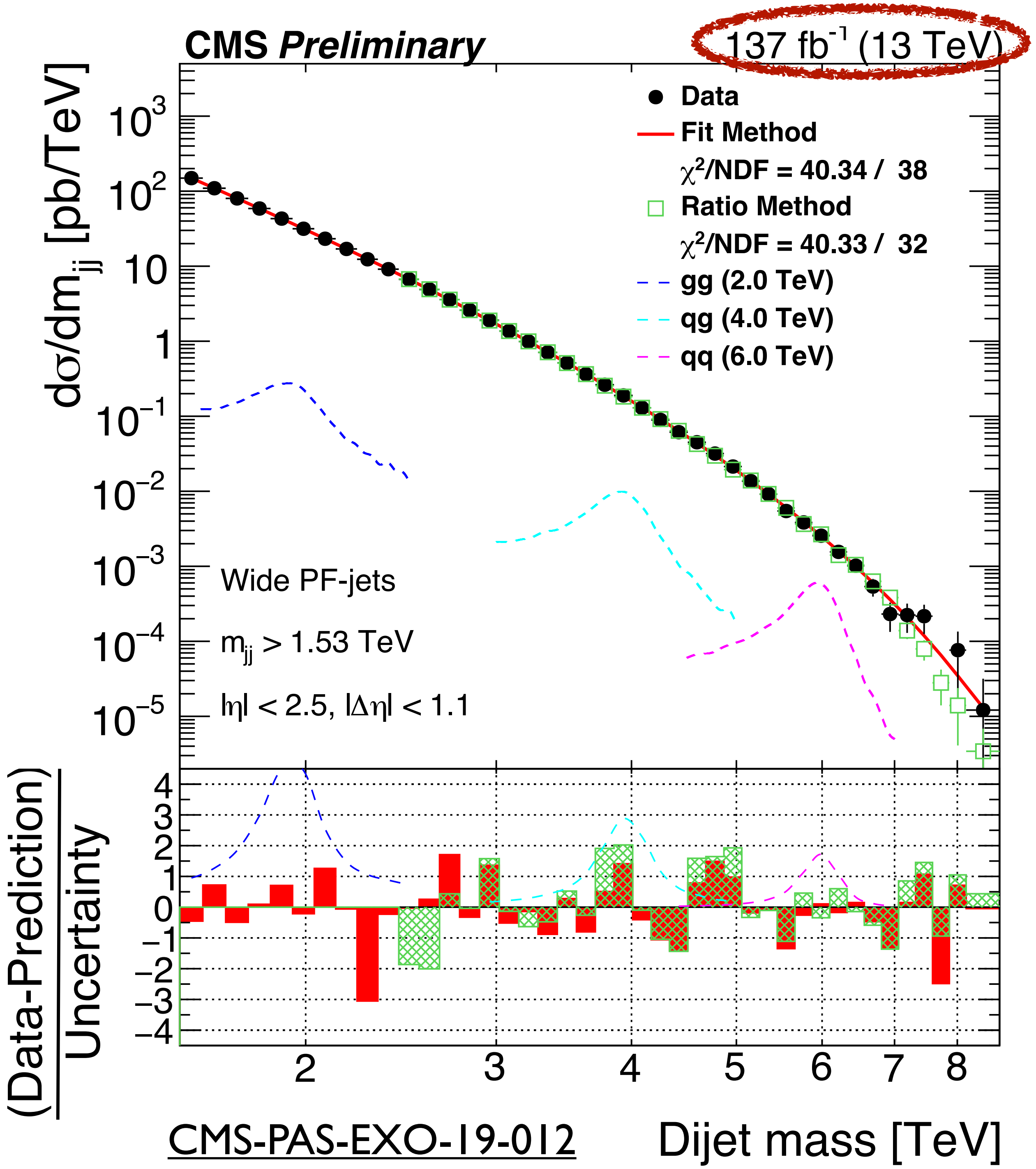
CP violation in the SM is not enough

BSM can explain the matter dominated universe

How do we search for BSM physics at the LHC?



Searching with Dijets

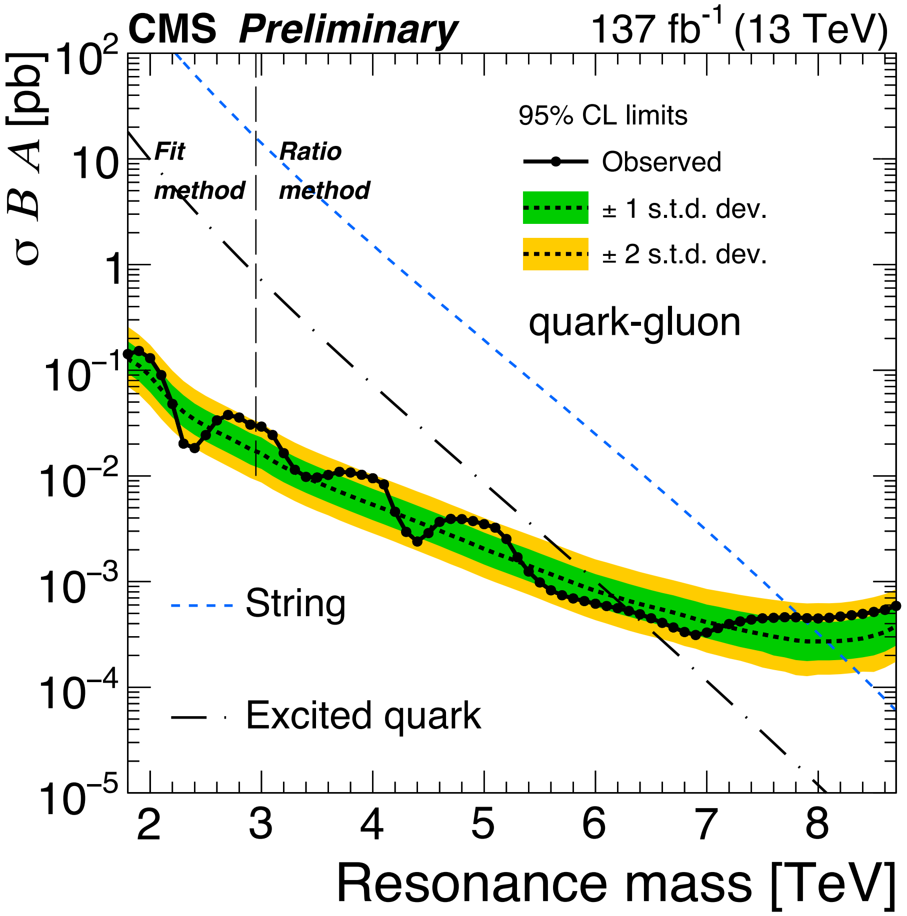


CMS-PAS-EXO-19-012

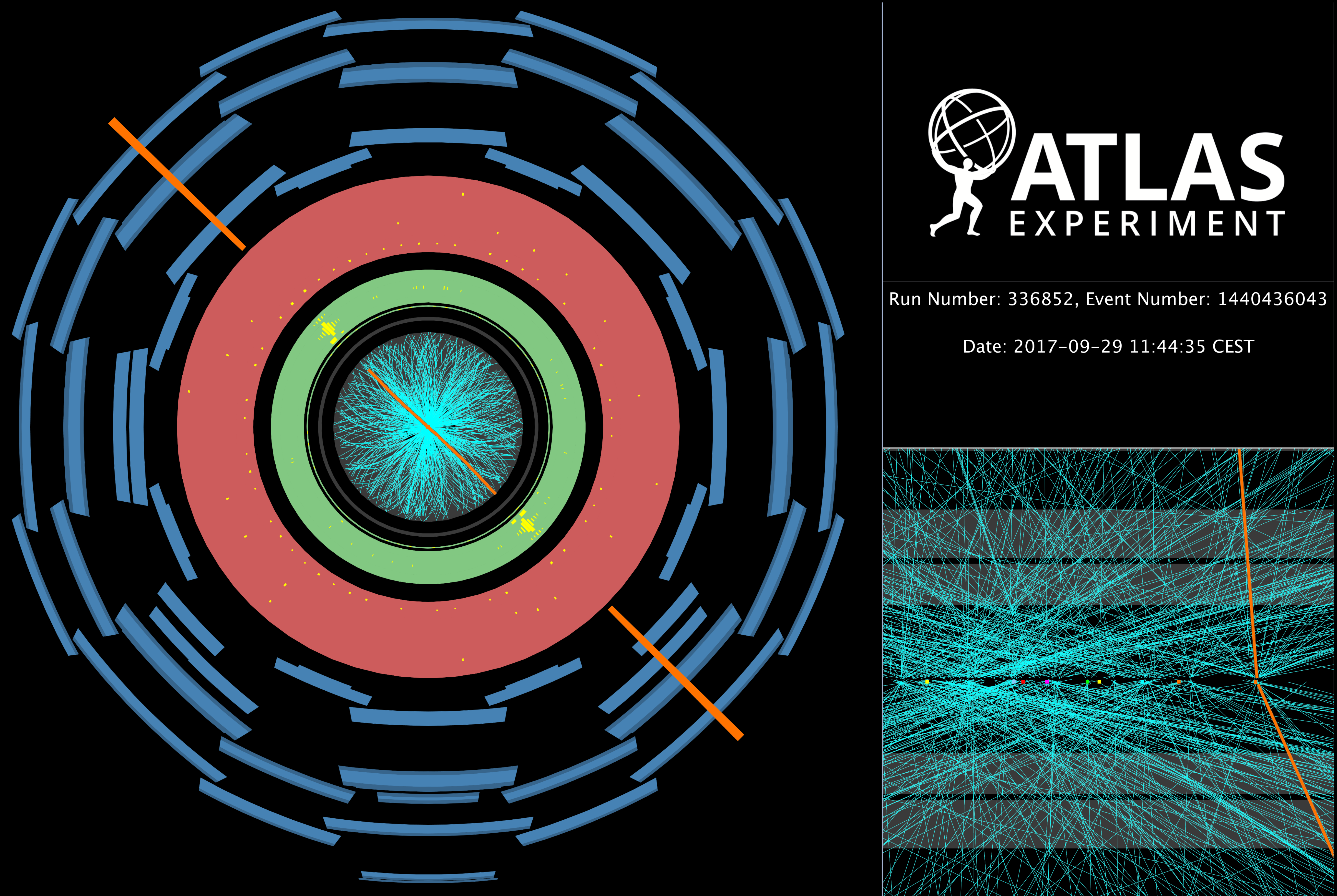
One of the best BSM signatures: pairs of jets

Huge dataset enables some of the best sensitivity yet!

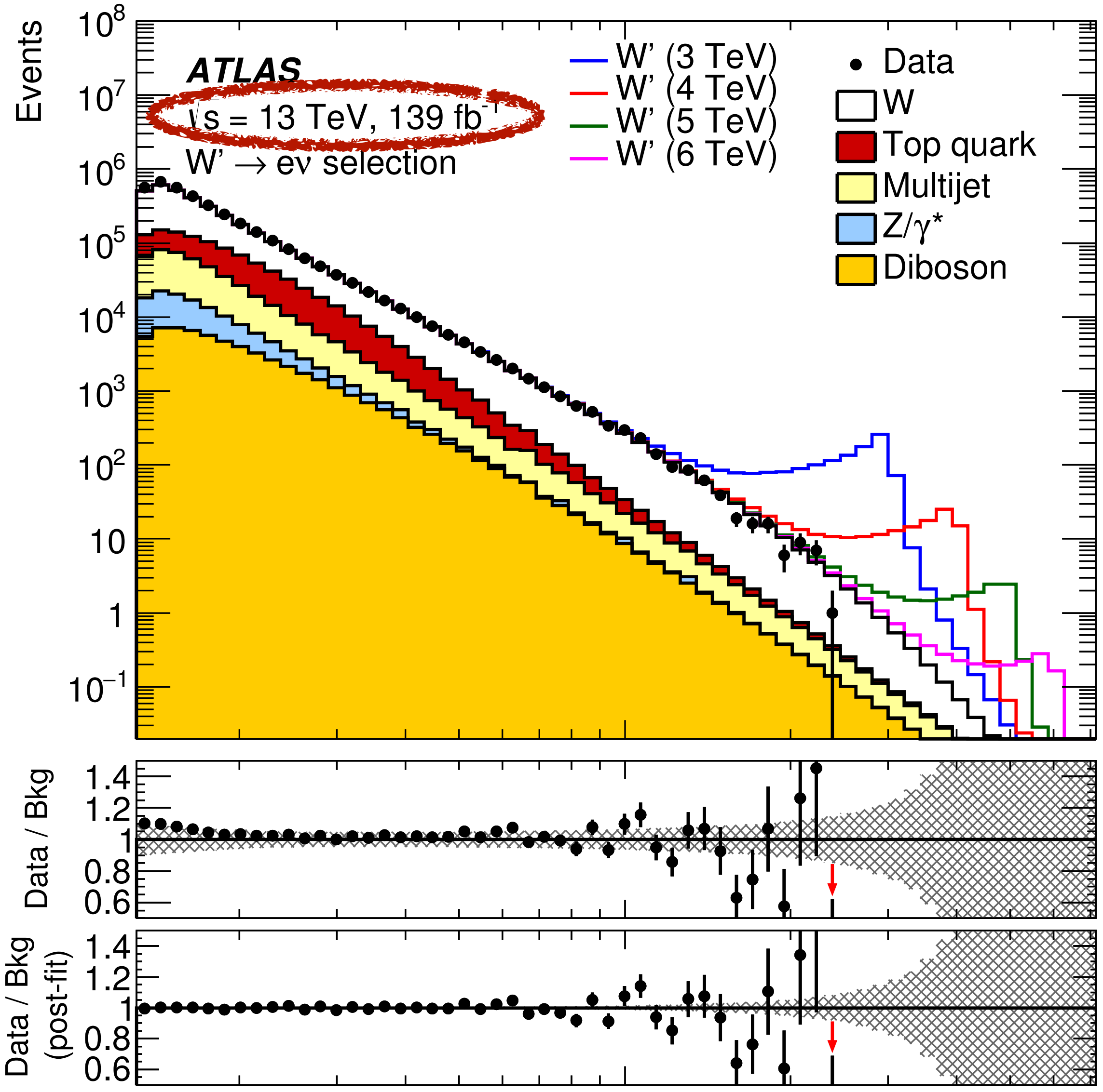
But no hints of new physics…



What about other particles?

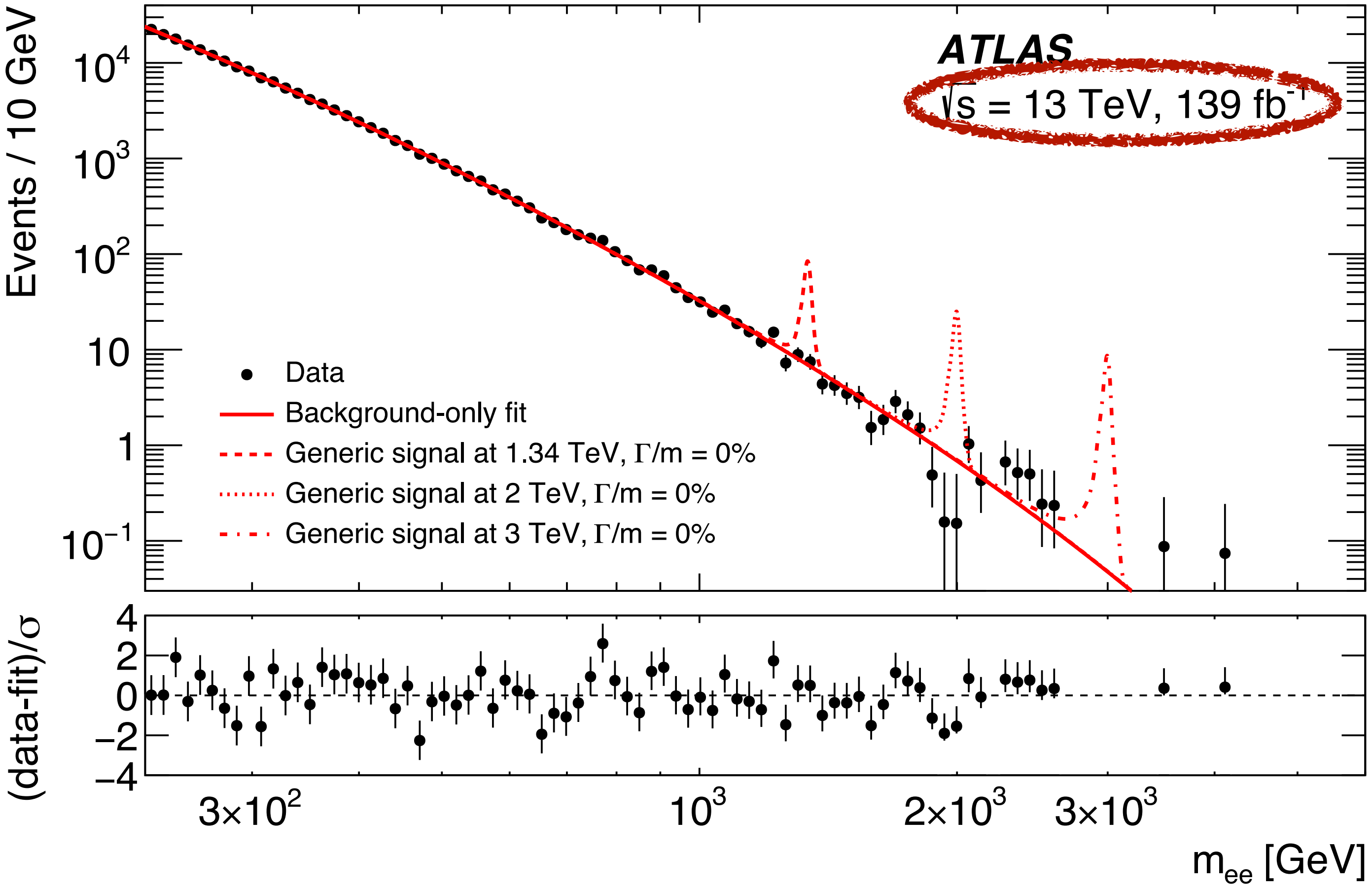


Searching with Leptons



ATLAS-EXOT-2018-30

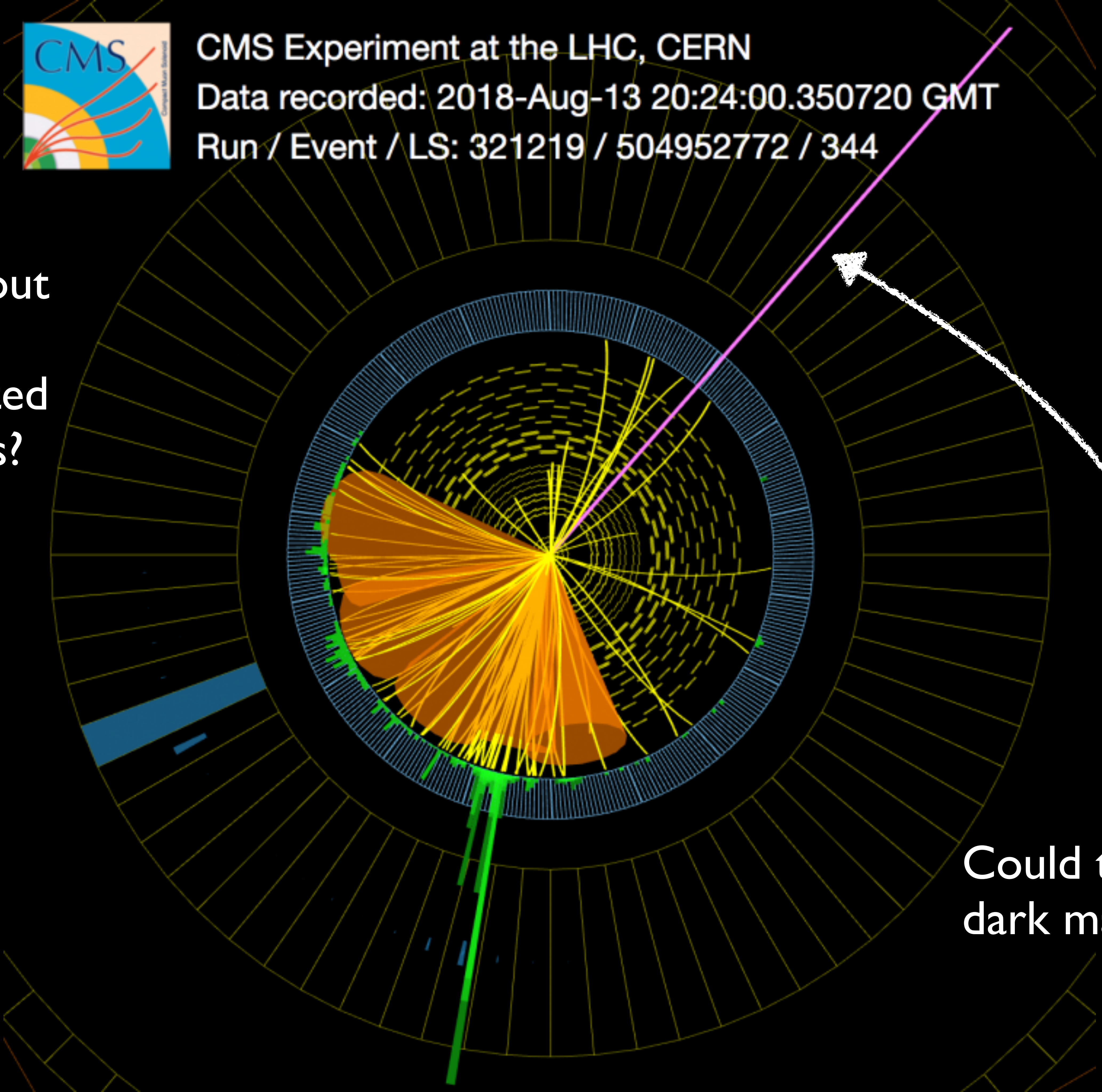
ATLAS-EXOT-2018-08



You can also search for BSM with lepton resonances!

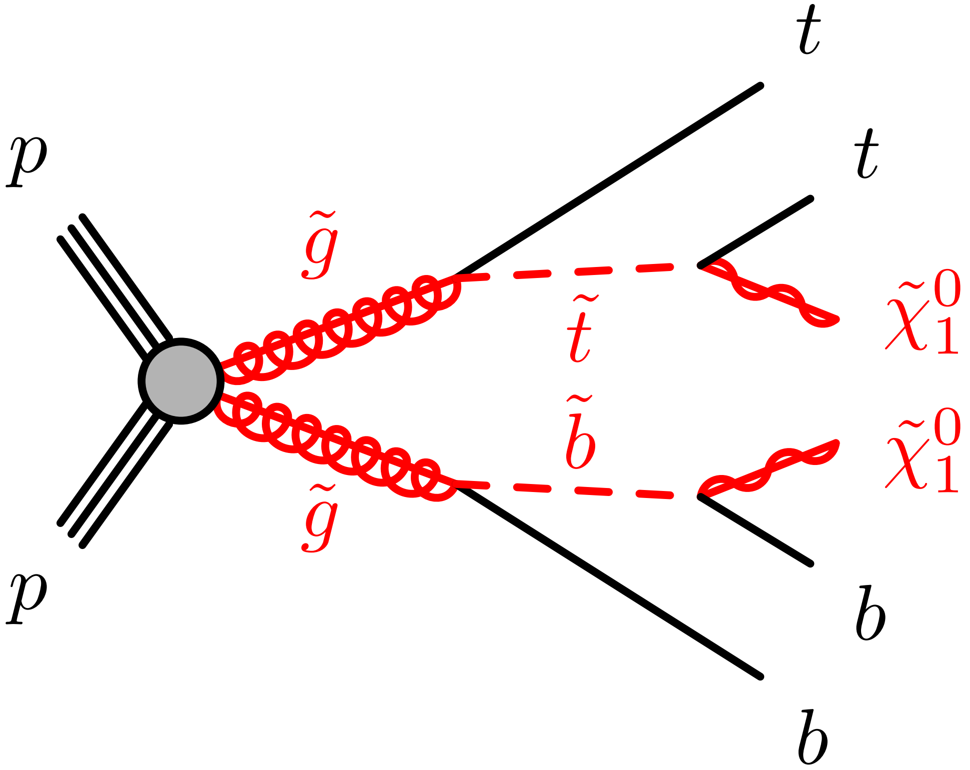
Not better luck here, even with the full datasets

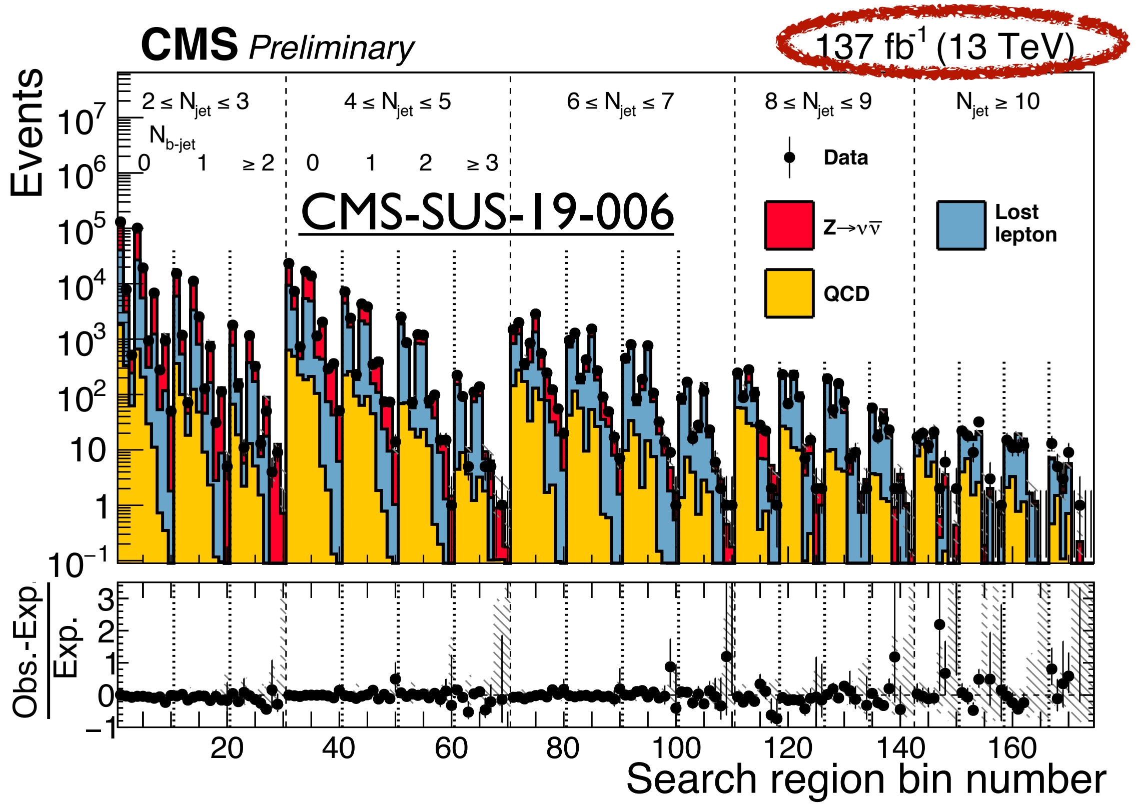
What about more complicated signatures?



Could this be dark matter?

SUSY Signatures

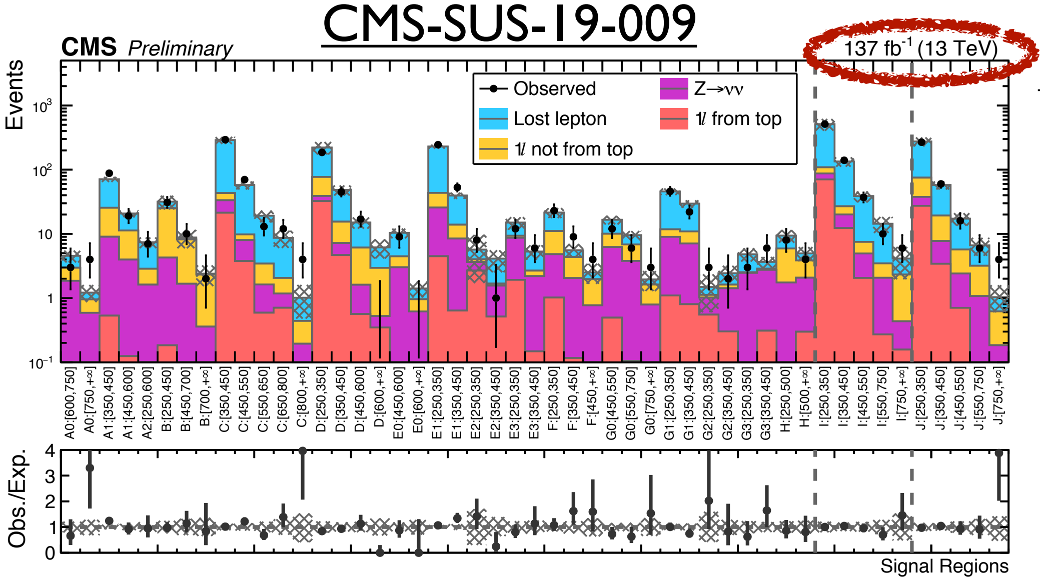




CMS-SUS-19-006

Supersymmetry predicts more complicated final states…

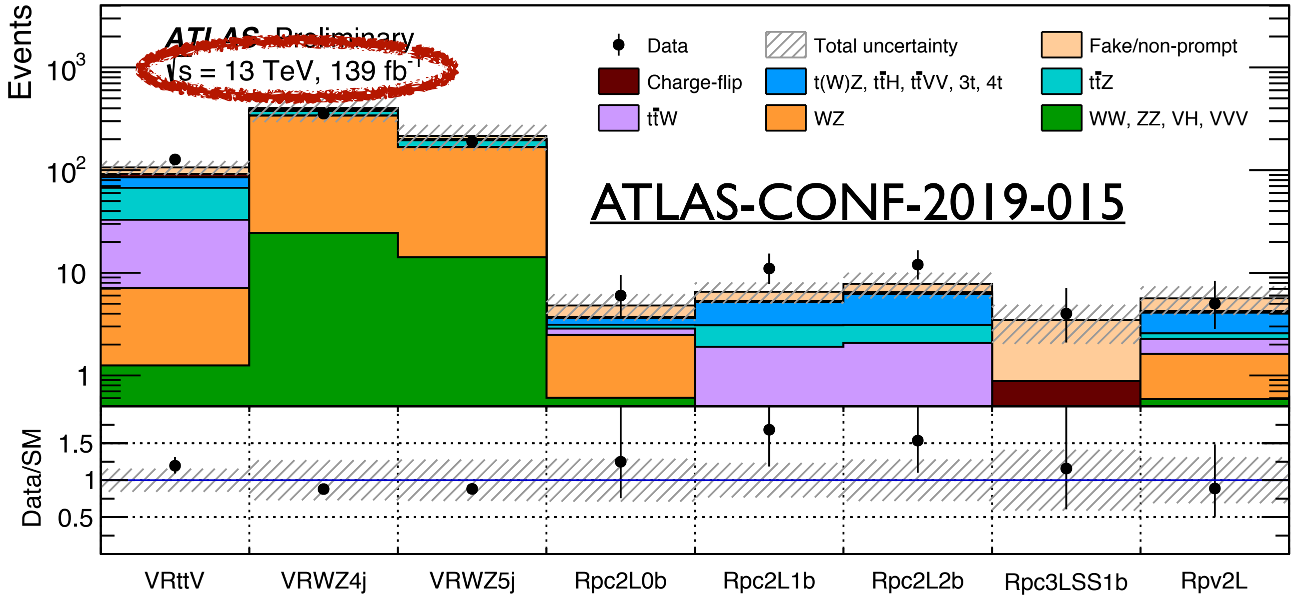
CMS-SUS-19-009



	N_J	t_{mod}	M_{lb} [GeV]
A	2–3	> 10	≤ 175
B	2–3	> 10	> 175
C	≥ 4	≤ 0	≤ 175
D	≥ 4	≤ 0	> 175
E	≥ 4	0–10	≤ 175
F	≥ 4	0–10	> 175
G	≥ 4	> 10	≤ 175
H	≥ 4	> 10	> 175

X0: Inclusive
X1: Untagged
X2: Boosted top
X3: Resolved top

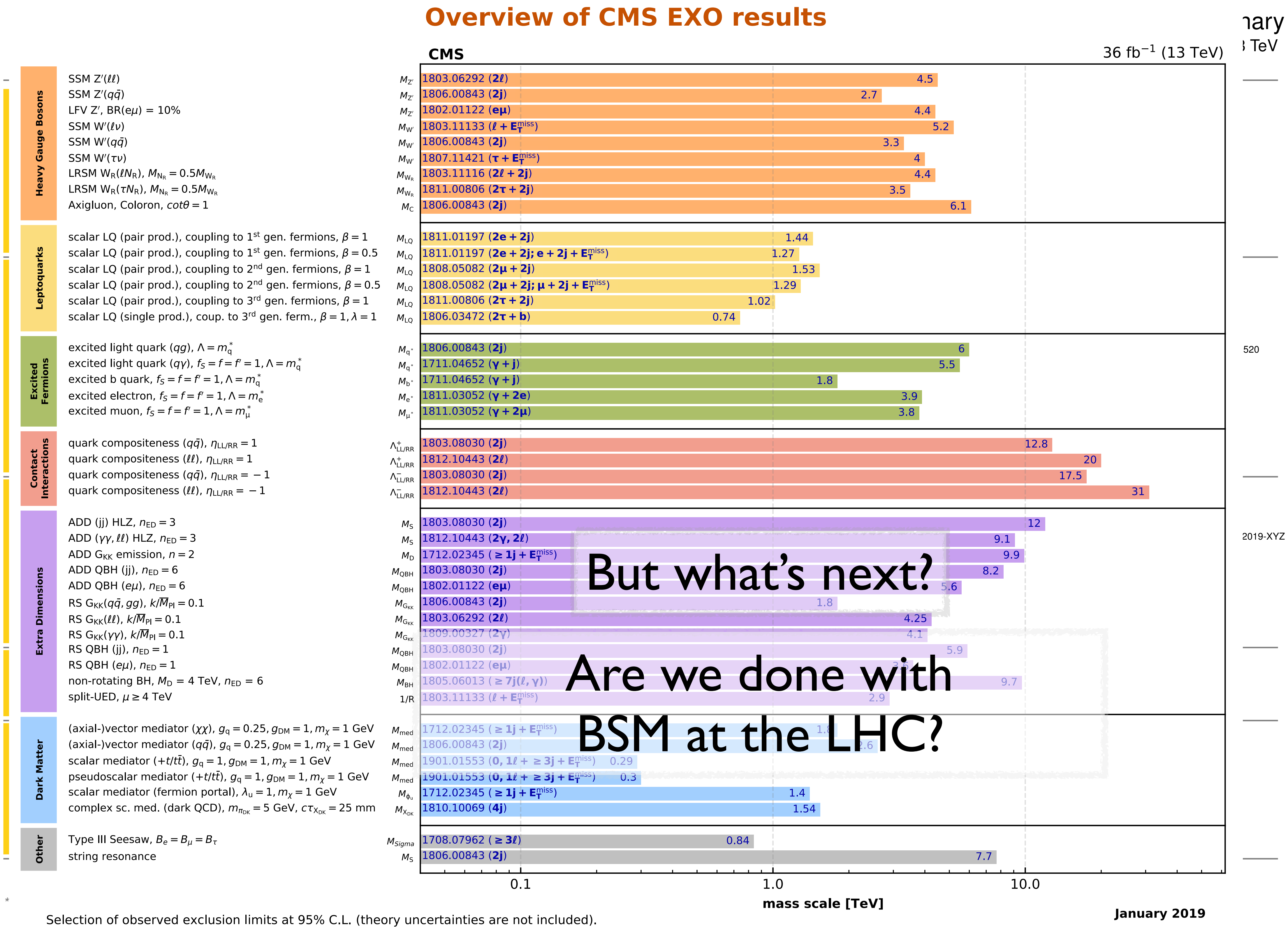
I: $N_J \geq 5$, $N_{b,med} \geq 1$
J: $N_J \geq 3$, $N_{b,soft} \geq 1$



ATLAS-CONF-2019-015

But still no hints, even with full data!

Our Sensitivity is Better Than Ever



But what's next?

Are we done with BSM at the LHC?

Low Hanging Fruit Records

BSM is More Vibrant Than Ever!

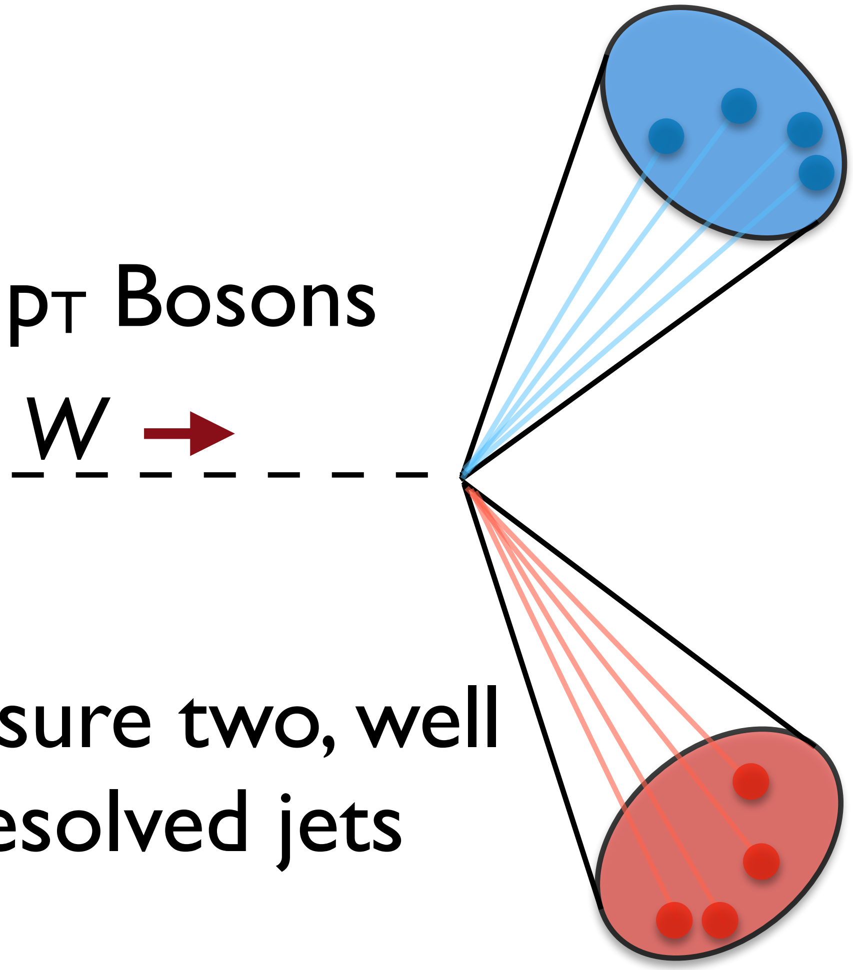
- The low-hanging fruit is mostly gone, but that just means we have to **work harder**!
- Let's take a look at the new methods which are enabling discovery today:
    - **Squeeze every last drop**: reconstruction and machine learning makes the most of our data
    - **Rarer than rare**: use huge datasets to access tiny signals
    - **Not your advisor's signals**: searching for things ATLAS and CMS weren't designed for
- My apologies for omitting many interesting and exciting results!

Squeeze Every Drop

Or: how advances in reconstruction, triggering, and machine learning are unlocking new insights into BSM

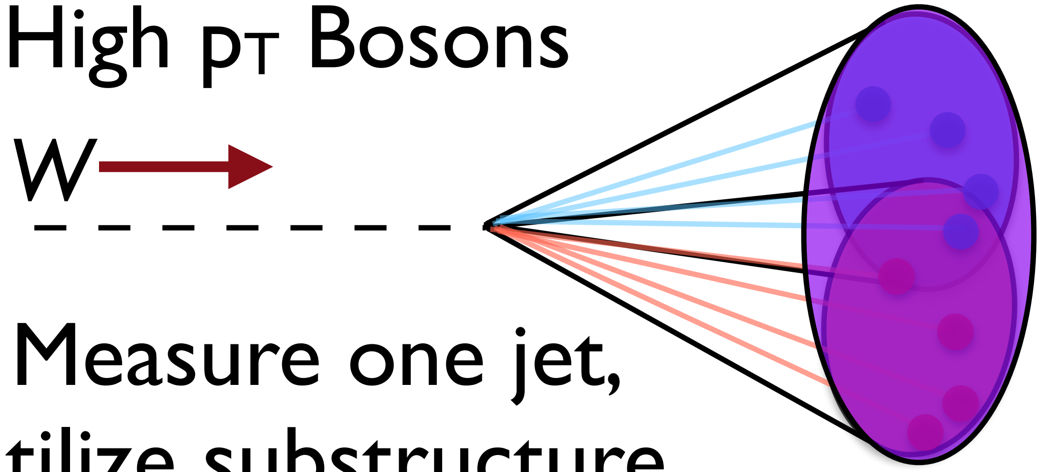
The Challenge of High p_T

Low p_T Bosons



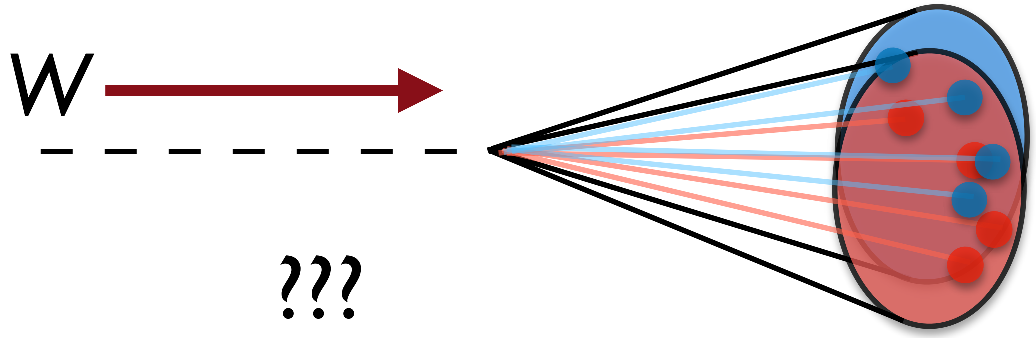
Measure two, well resolved jets

High p_T Bosons



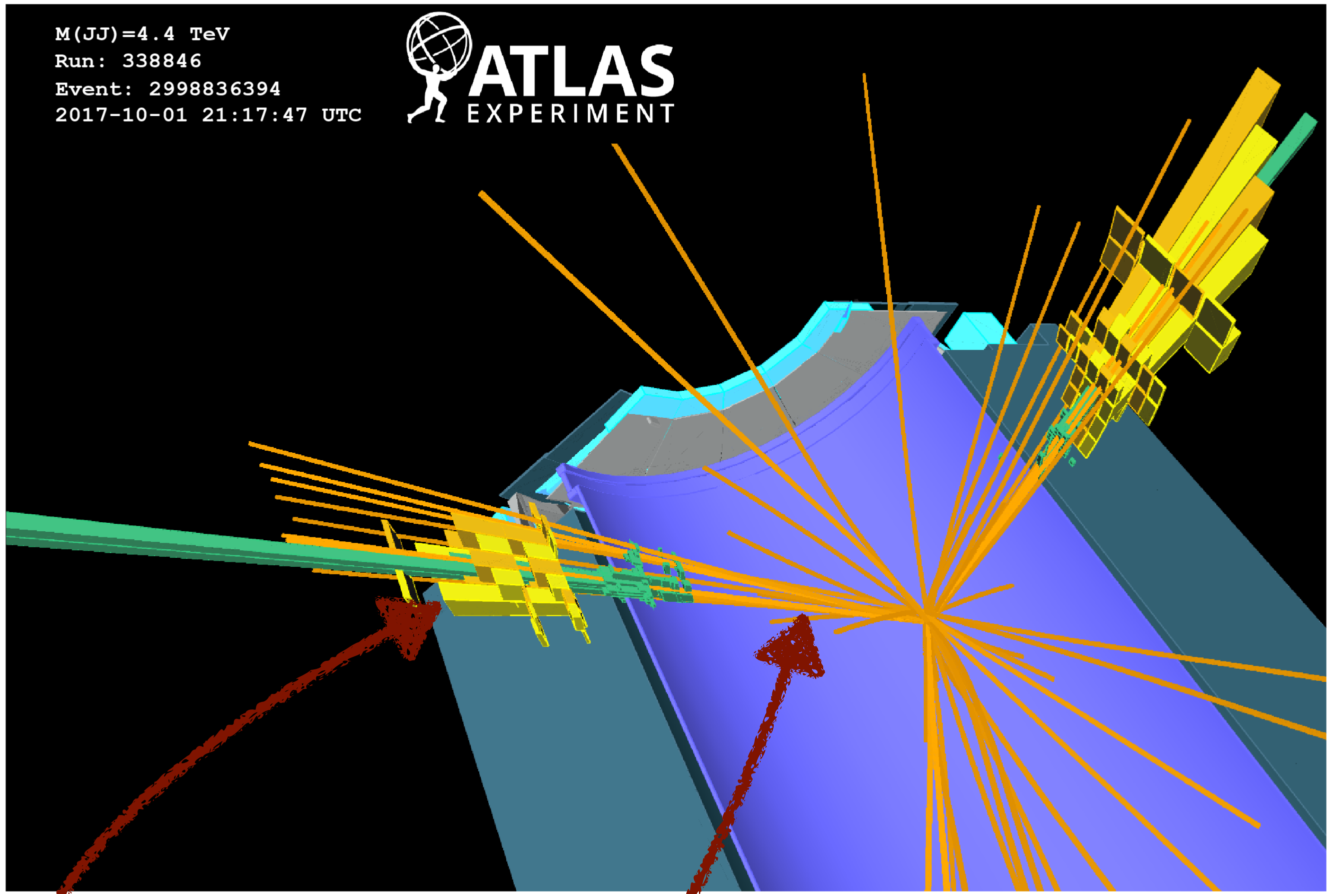
Measure one jet, utilize substructure

Extremely High p_T Bosons



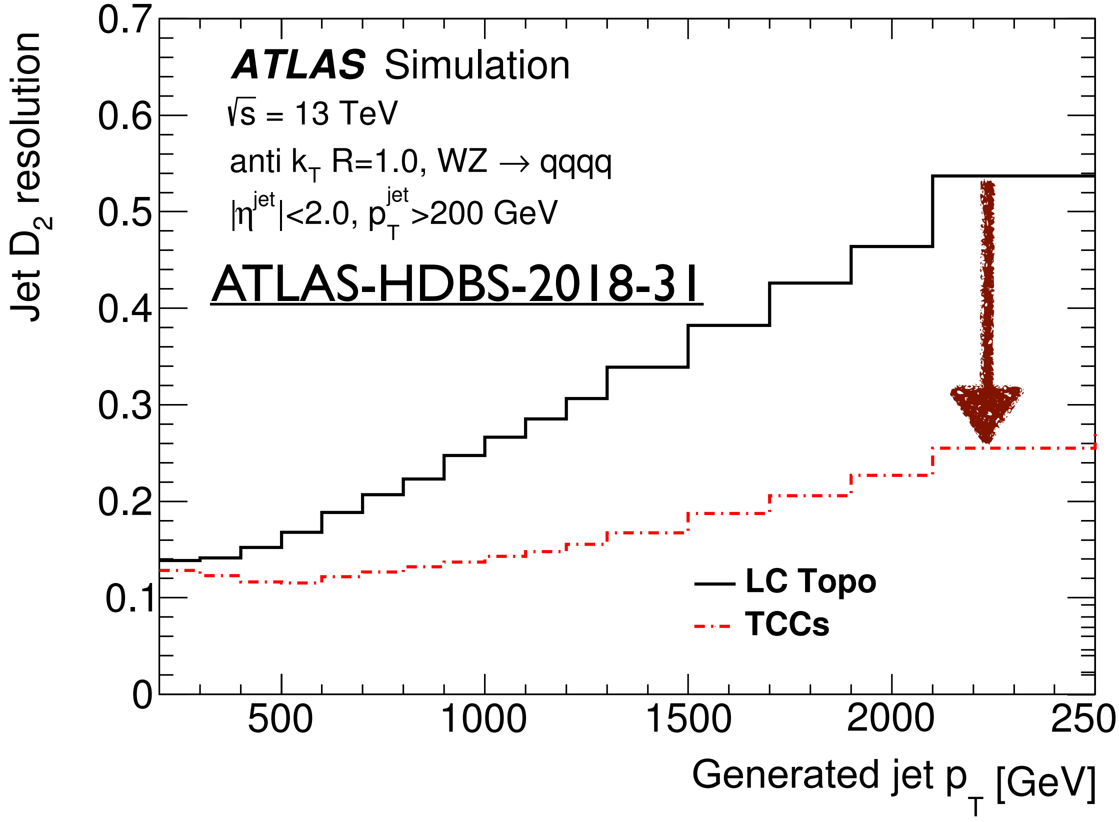
???

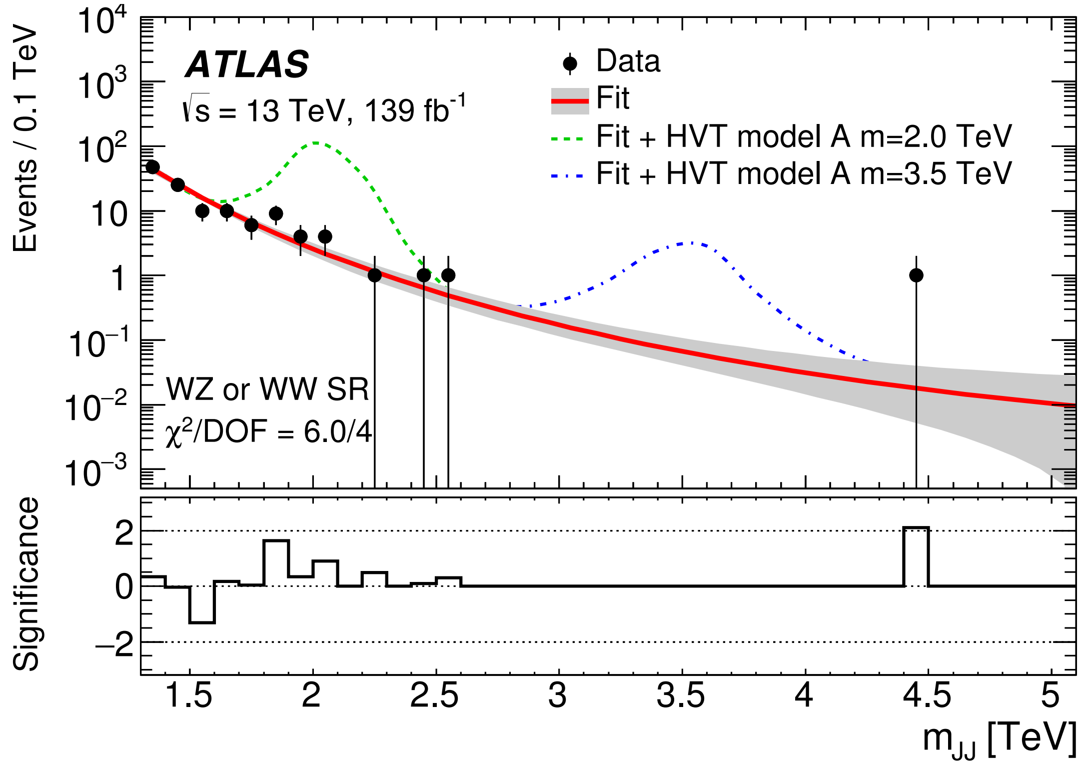
Tagging at High p_T



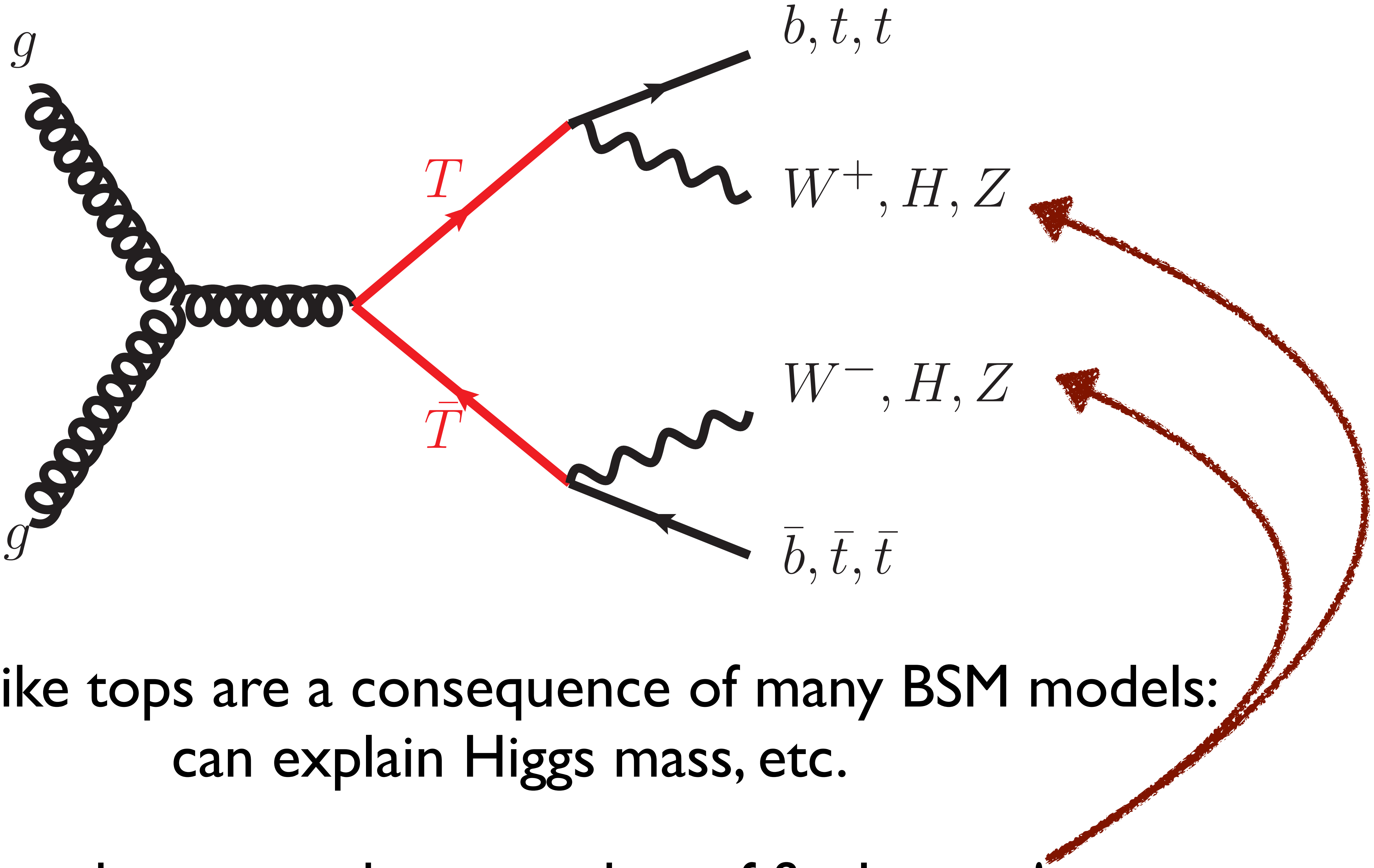
Utilize better spatial resolution from tracker to separate energy deposits in the calorimeter!

Enables strongest sensitivity yet to boosted all-hadronic final states





The Challenge of Branching

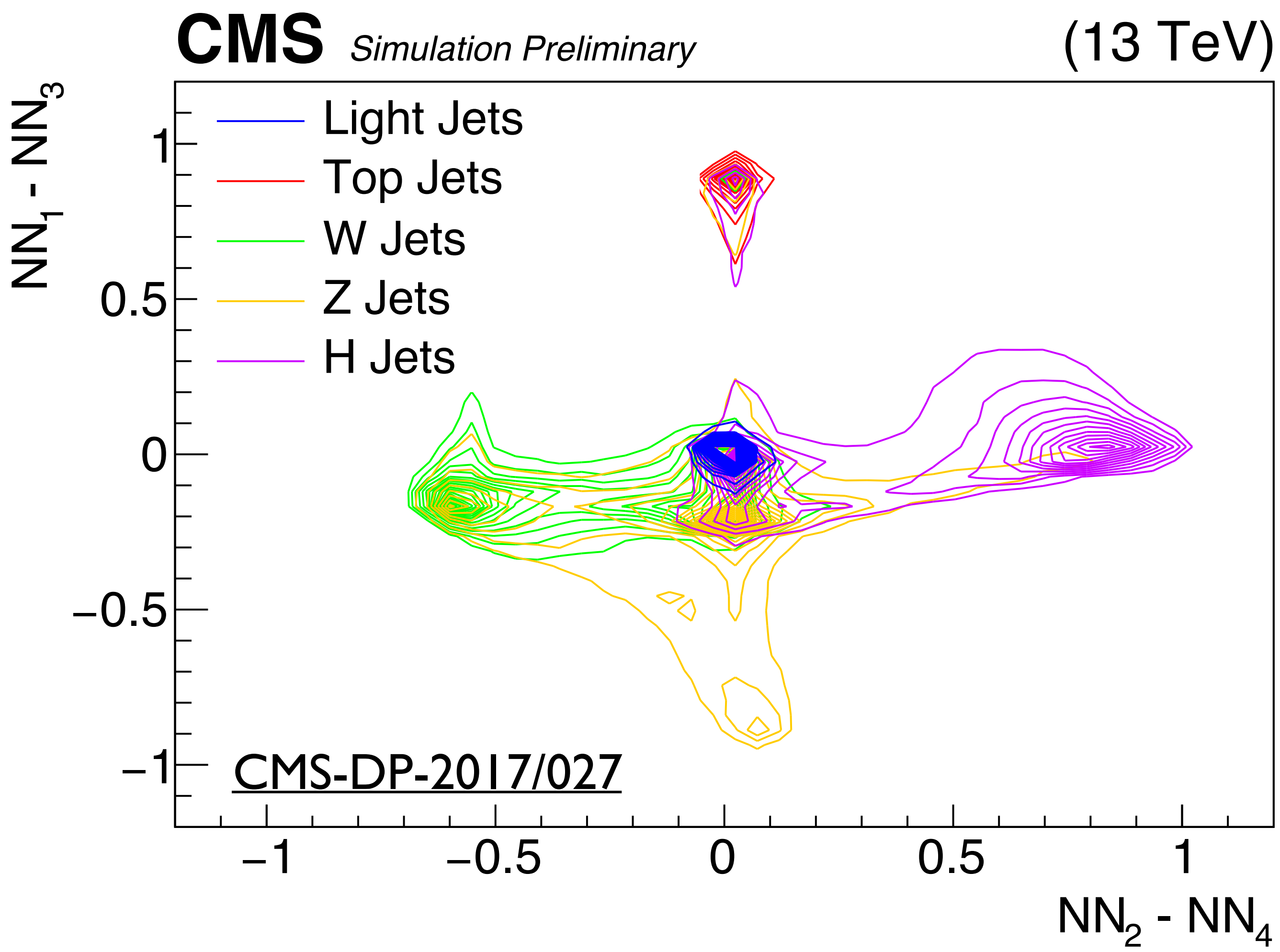


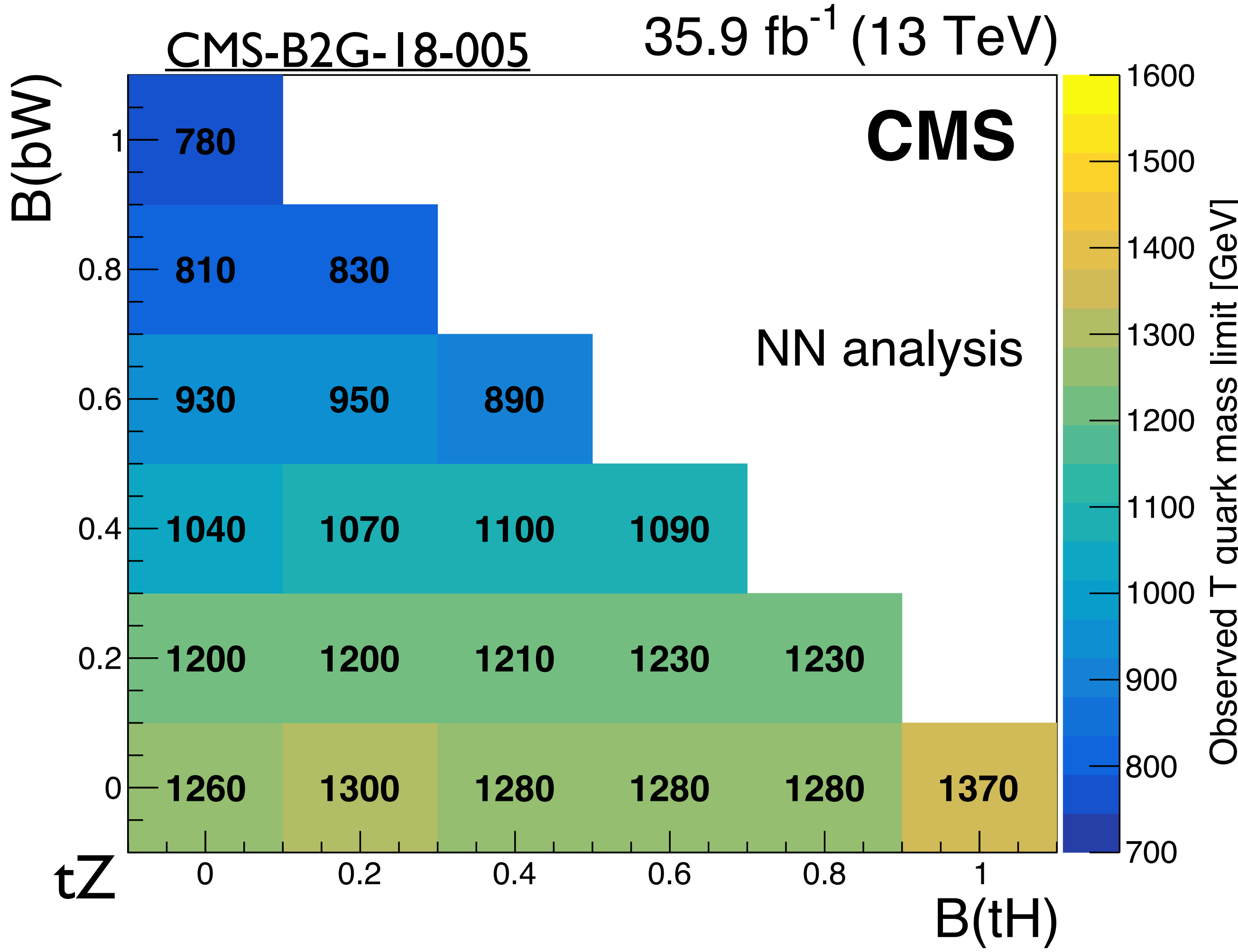
Vector-like tops are a consequence of many BSM models:
can explain Higgs mass, etc.

But there are a huge number of final states!

How do you search for all of these efficiently?

Multi-Node Tagging



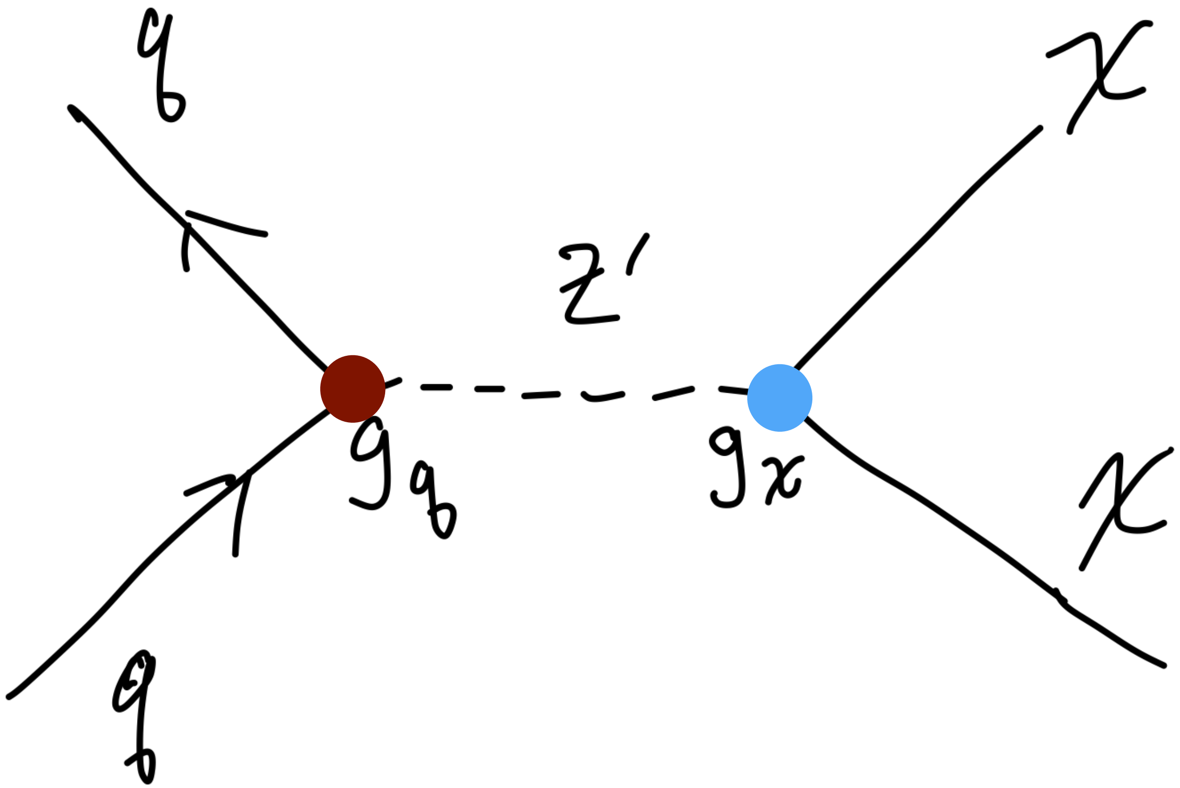


B(bW) \ B(tH)	0	0.2	0.4	0.6	0.8	1
1	780					
0.8	810	830				
0.6	930	950	890			
0.4	1040	1070	1100	1090		
0.2	1200	1200	1210	1230	1230	
0	1260	1300	1280	1280	1280	1370

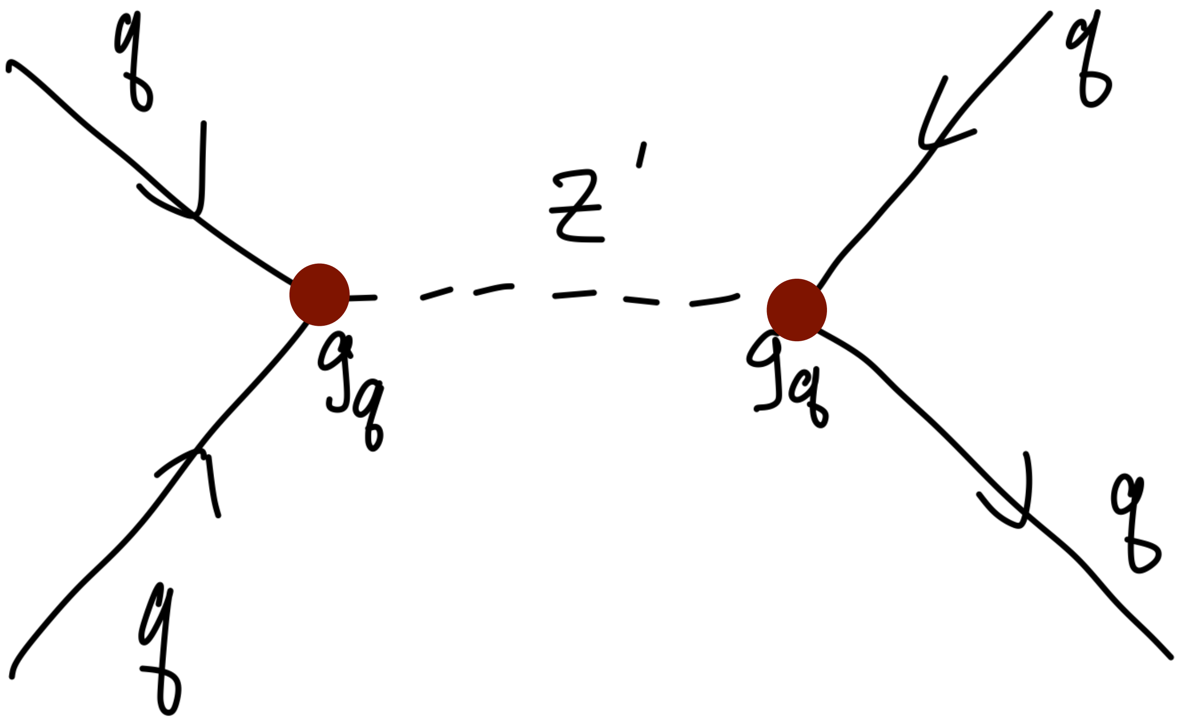
Train a neural network to distinguish all signal classes from background

Use the NN to search for new physics in many final states at once

The Challenges of Dijets



If we can produce DM
at the LHC like this…

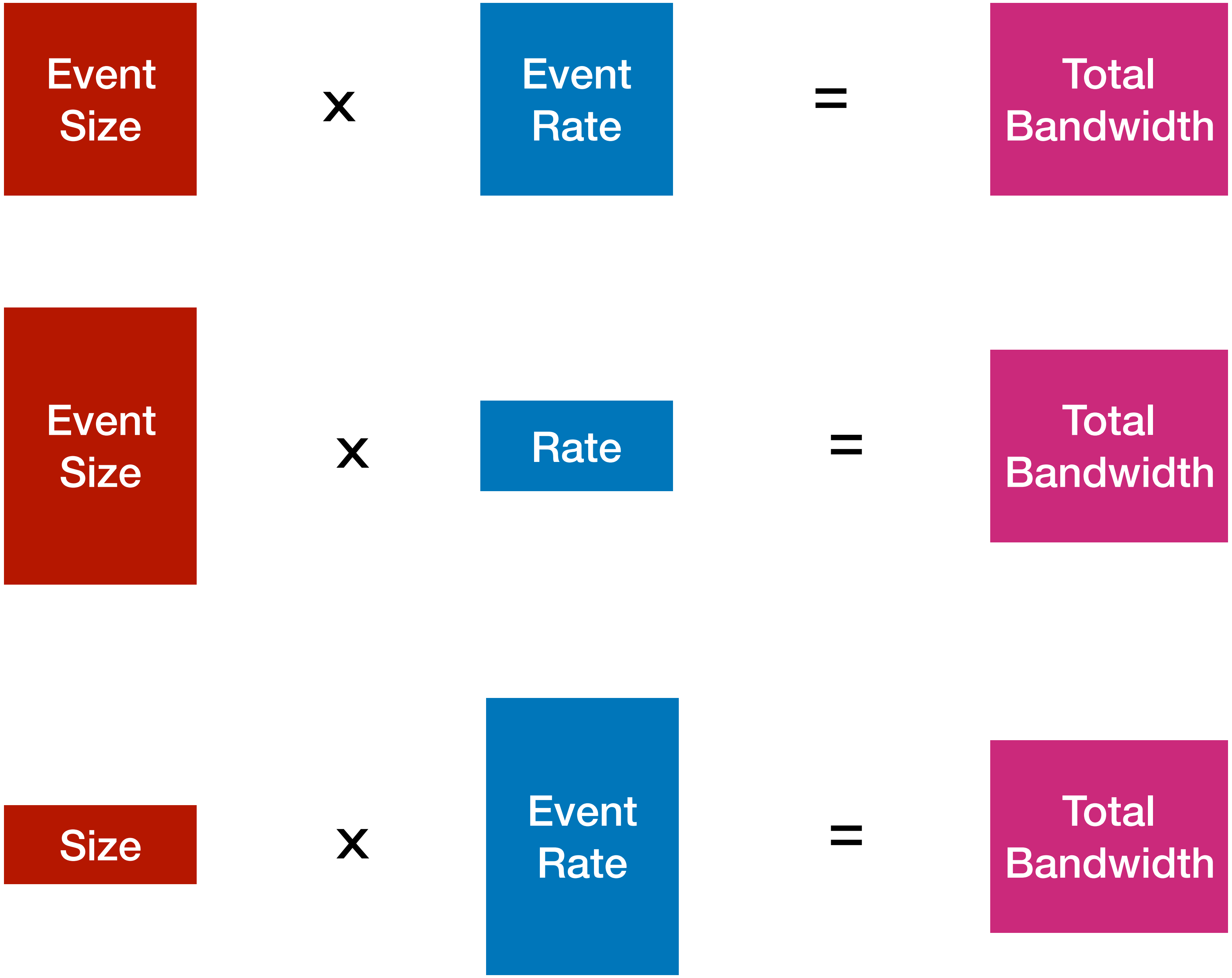


Then the mediator should decay
back to jets!

But if the Z' is low enough mass,
we won't trigger the event from the jets!

Data Scouting

Trigger limitations
come from
total bandwidth



Event Size x Event Rate = Total Bandwidth

Normally, we record
“full events,” so the
rate gets limited

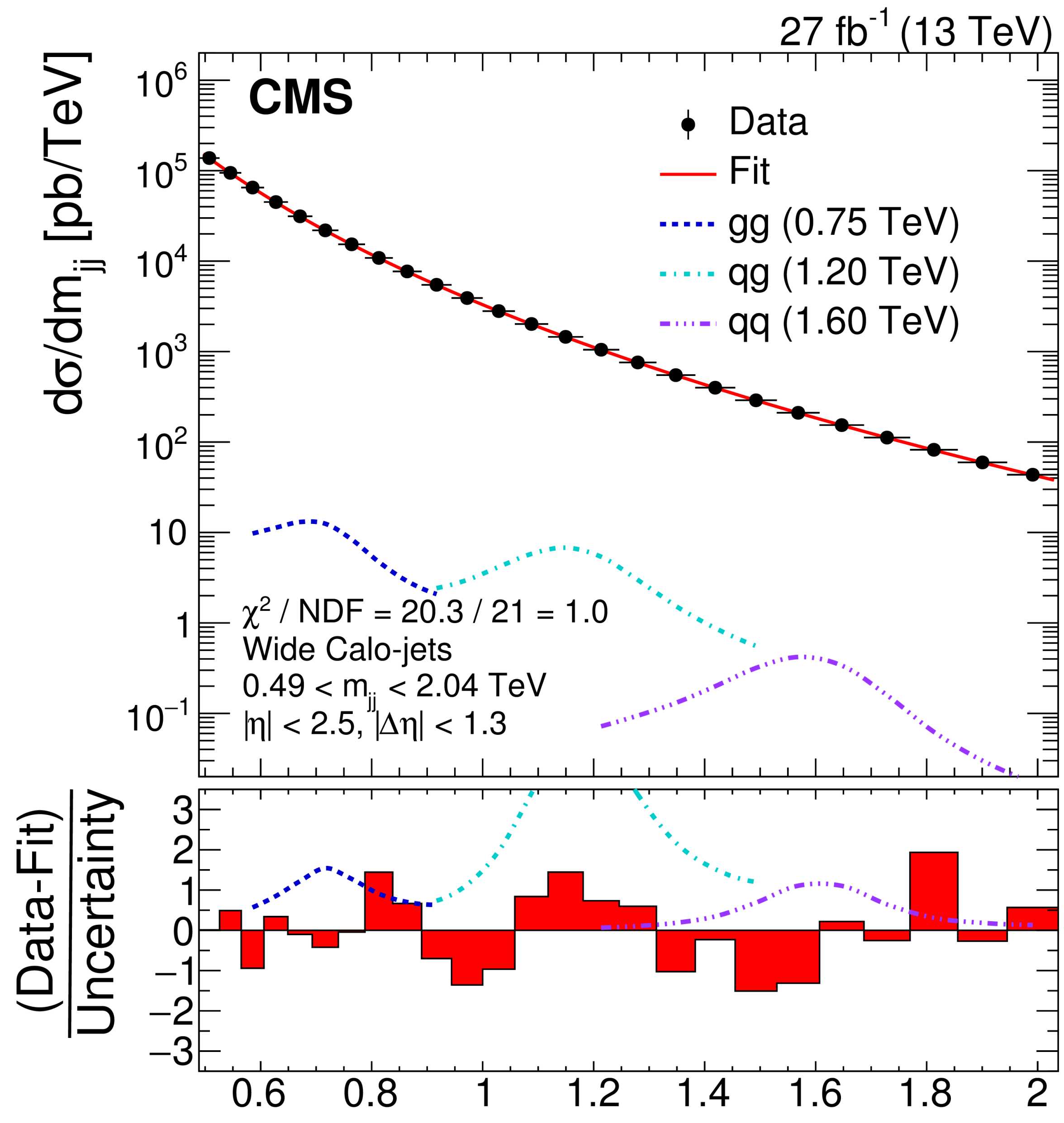
Event Size x Rate = Total Bandwidth

But we can reco
events in the trigger,
and save smaller data

Size x Event Rate = Total Bandwidth

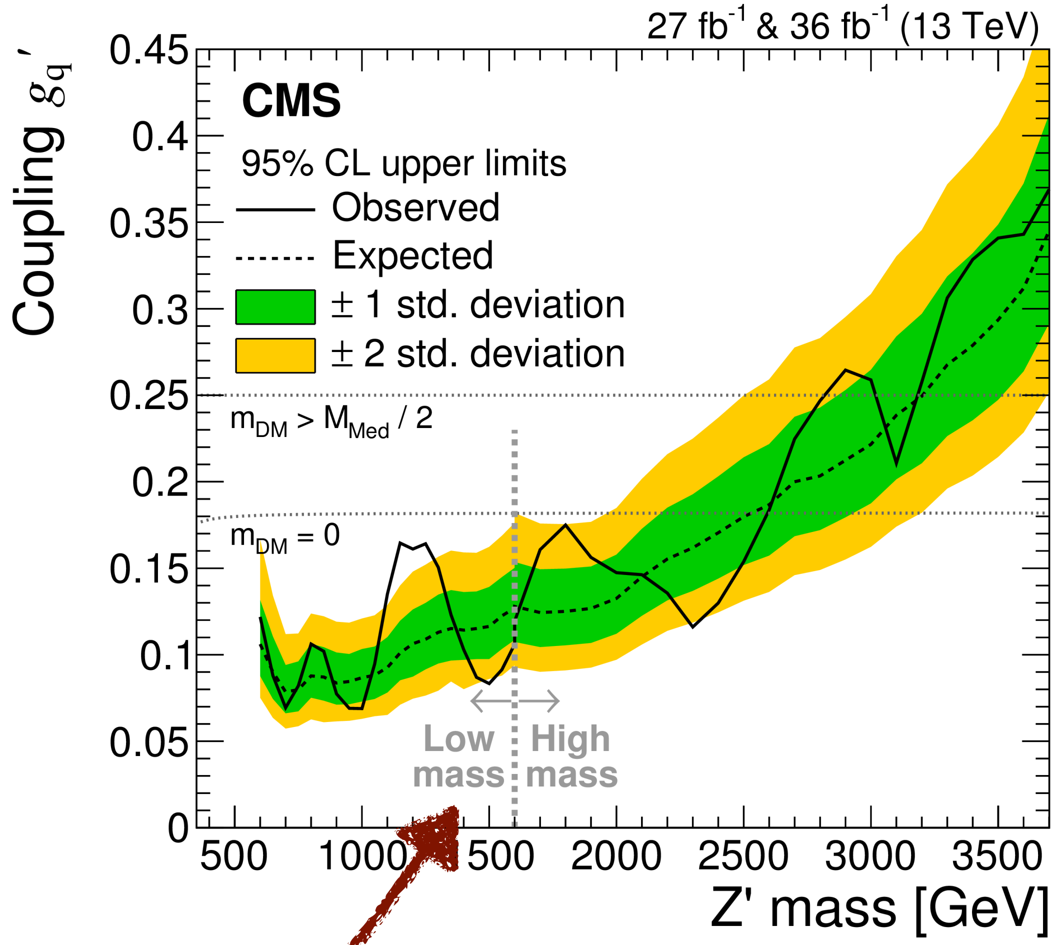
If you save smaller events, you can save more of them!

What You Can Accomplish



CMS-EXO-16-056

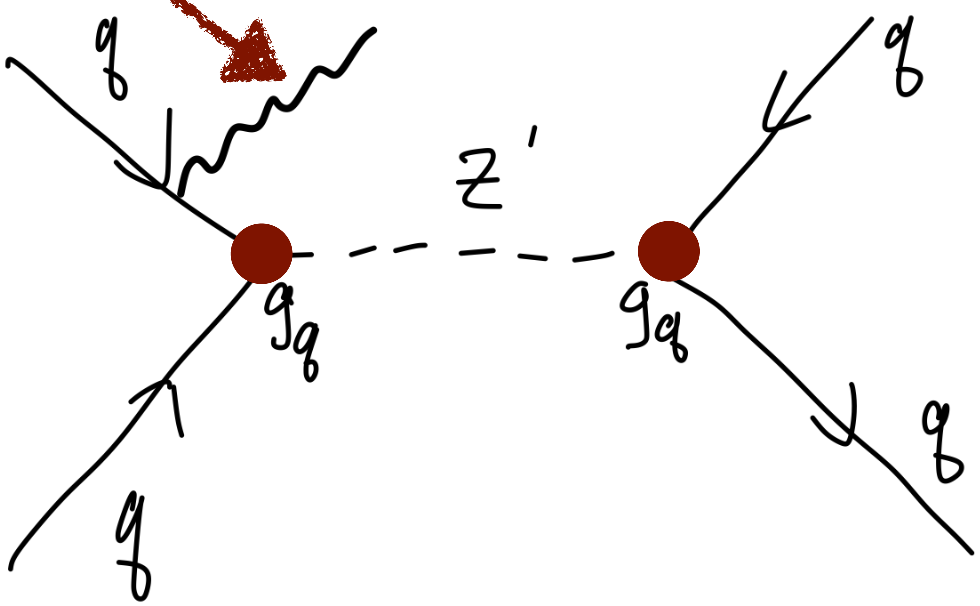
Can collect huge datasets
at low mass using this technique!



Can probe unique physics
phase space by recording
only a portion of the events!

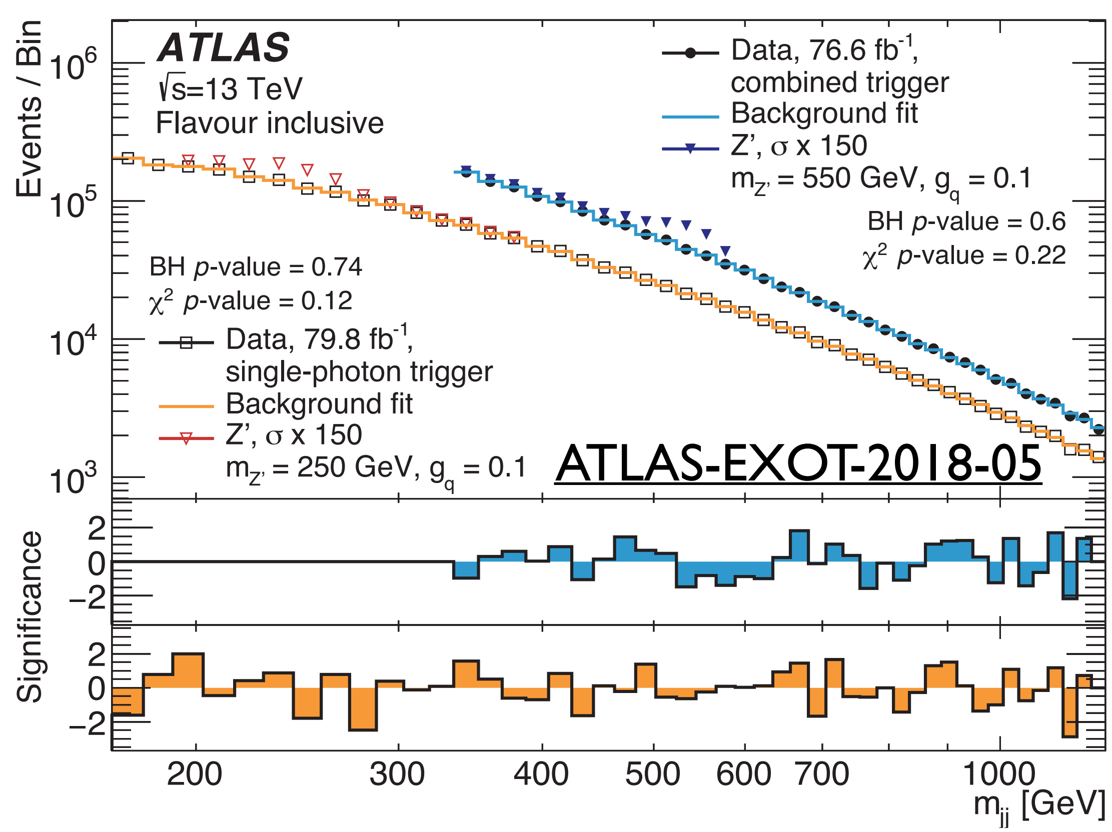
Extra Radiation

Photon or jet "initial state radiation" can also be used to trigger the event!



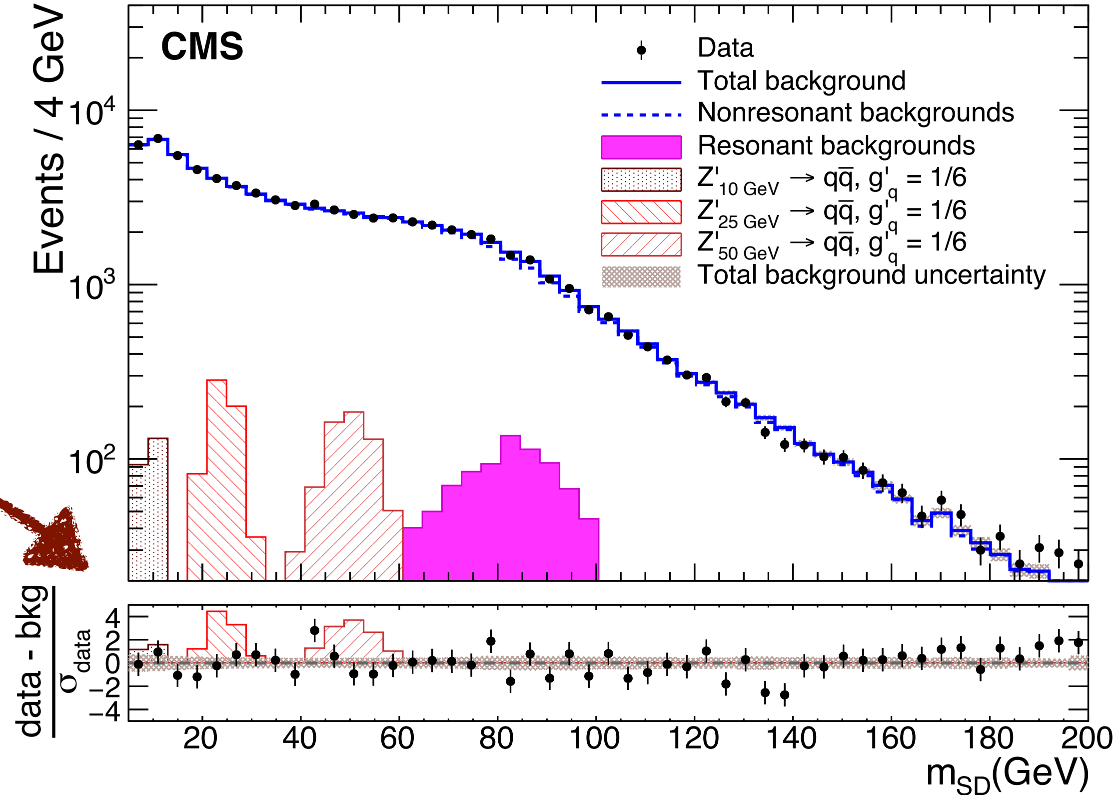
Even lower regions of mediator mass can be explored with these techniques

Can even search as low as 10 GeV!



ATLAS-EXOT-2018-05

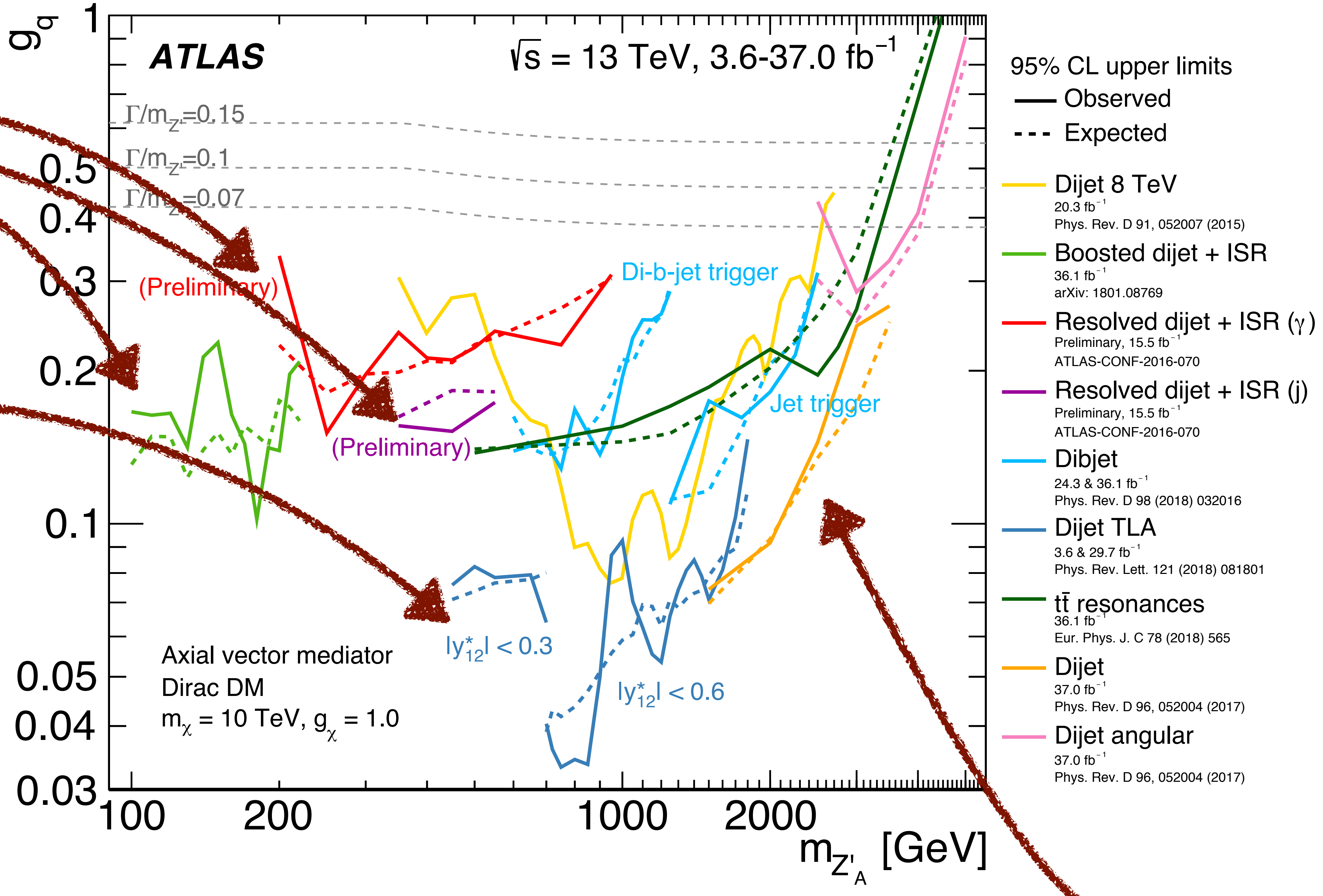
CMS-EXO-17-027



The Big Picture for Z'

ISR

Trigger Only



Traditional

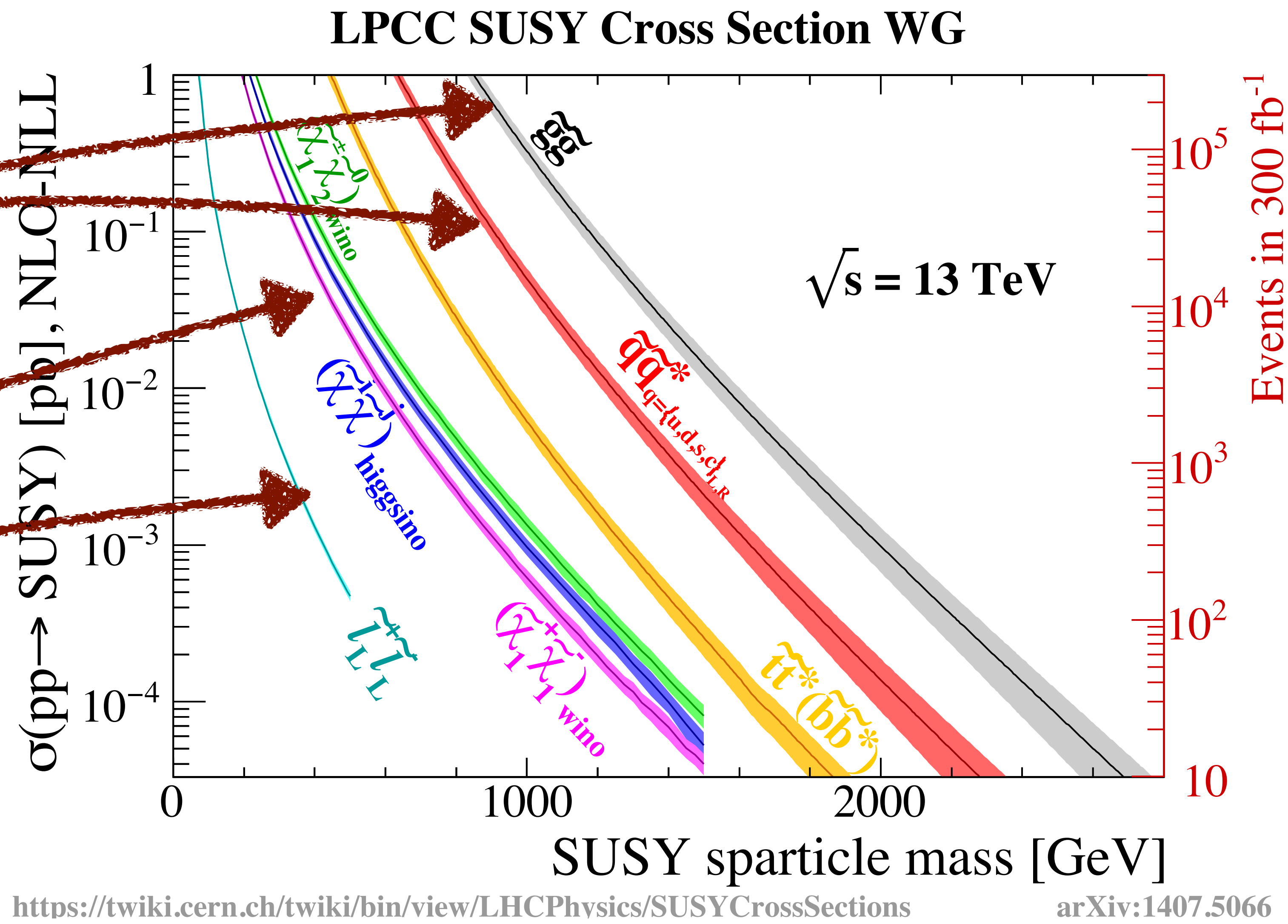
In the hunt for Z', new techniques are taking center stage!

Rarer than Rare

Or: how huge datasets and clever strategies are enabling searches for vanishingly small signals

Why Search for Rare Signals?

Because many theories predict low cross-section signals!

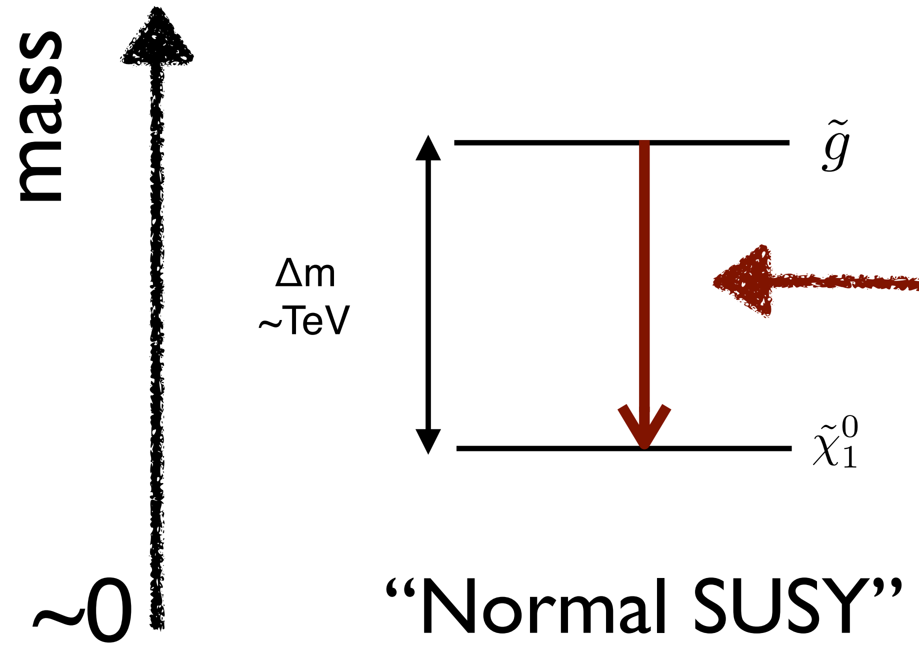


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections arXiv:1407.5066

If you've already excluded gluinos and squarks and stops…

Higgsinos and sleptons might still be in sight!

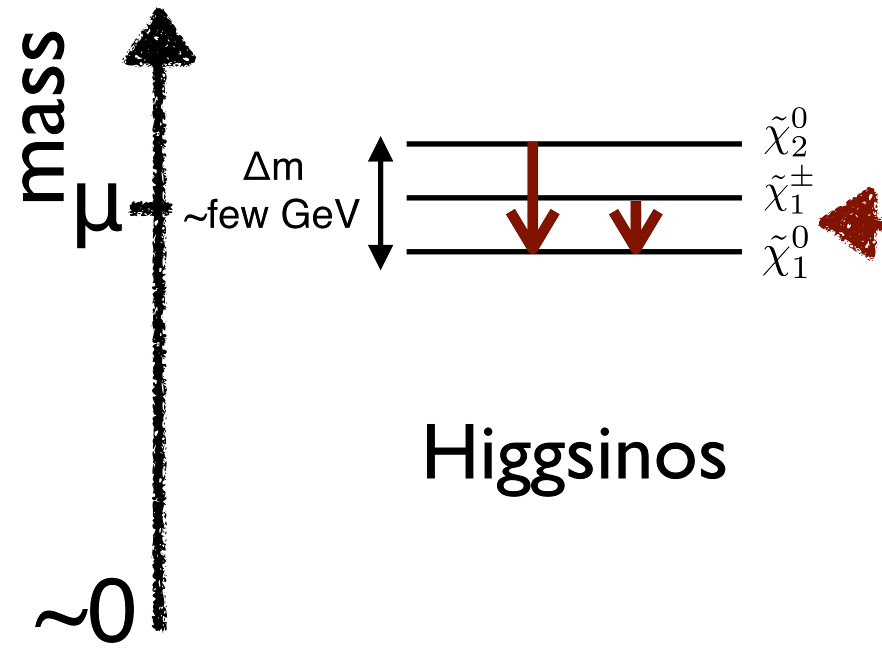
Higgsinos: The Challenge



“Normal SUSY”

“Classic” SUSY searches
exploit large mass splittings

Cascades from initial sparticles
will be high energy,
lots of missing energy

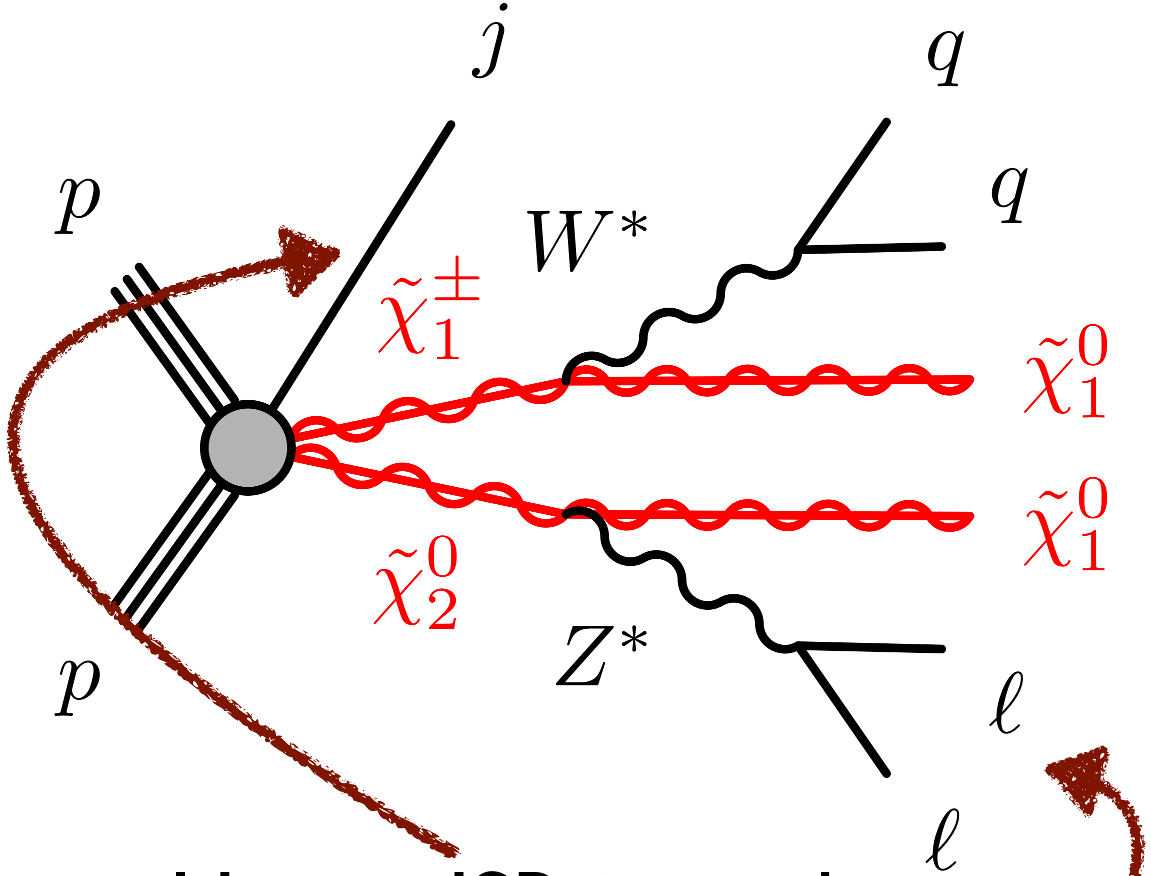


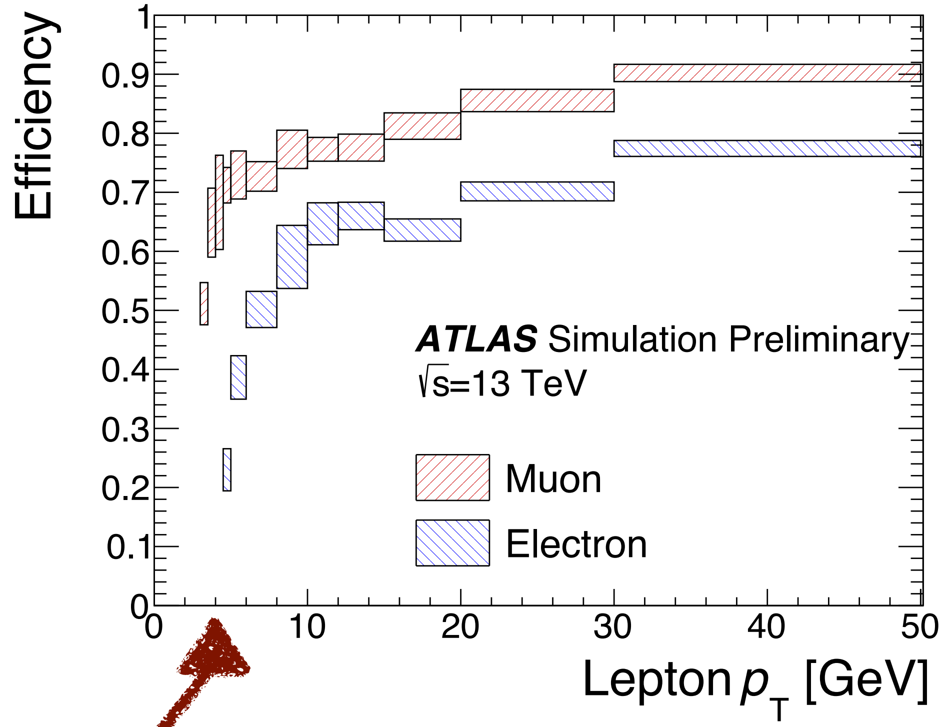
Higgsinos

Higgsinos are another story…

No large mass splitting:
very soft visible particles,
no obvious missing energy

Searching for Rare Higgsinos





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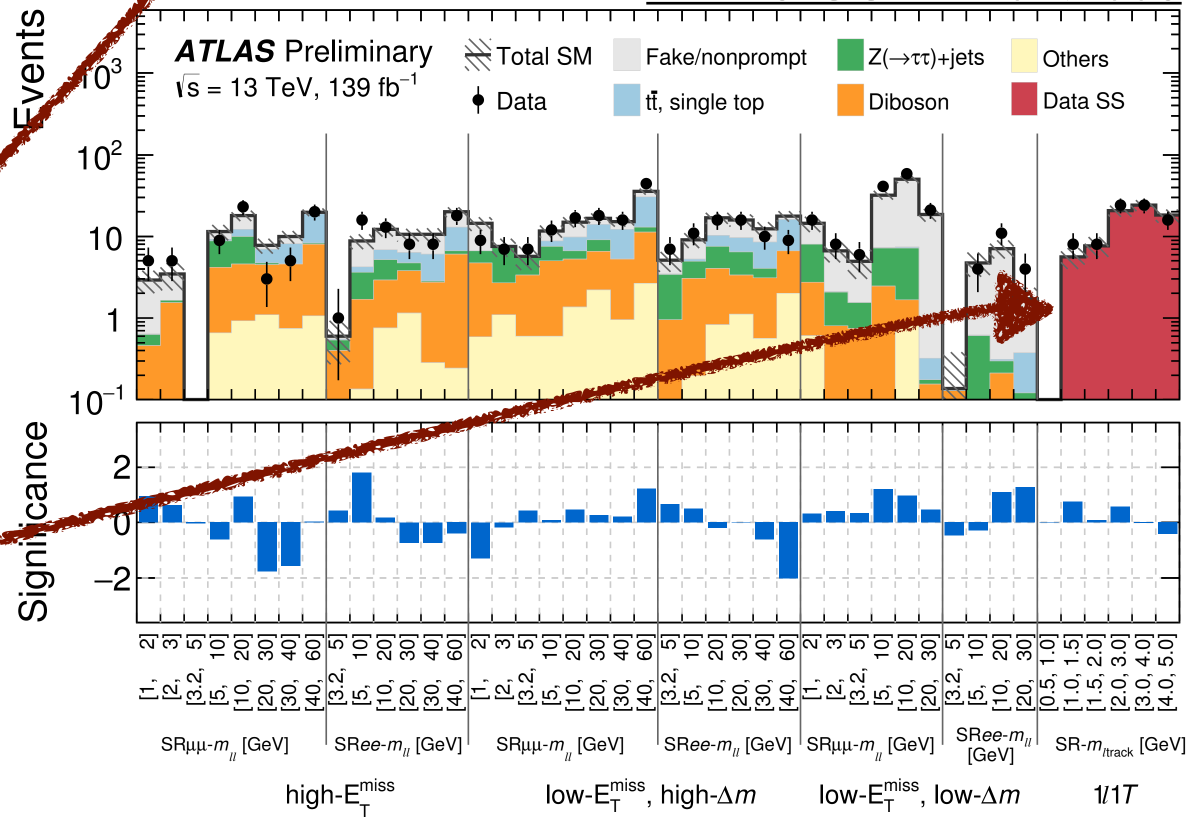


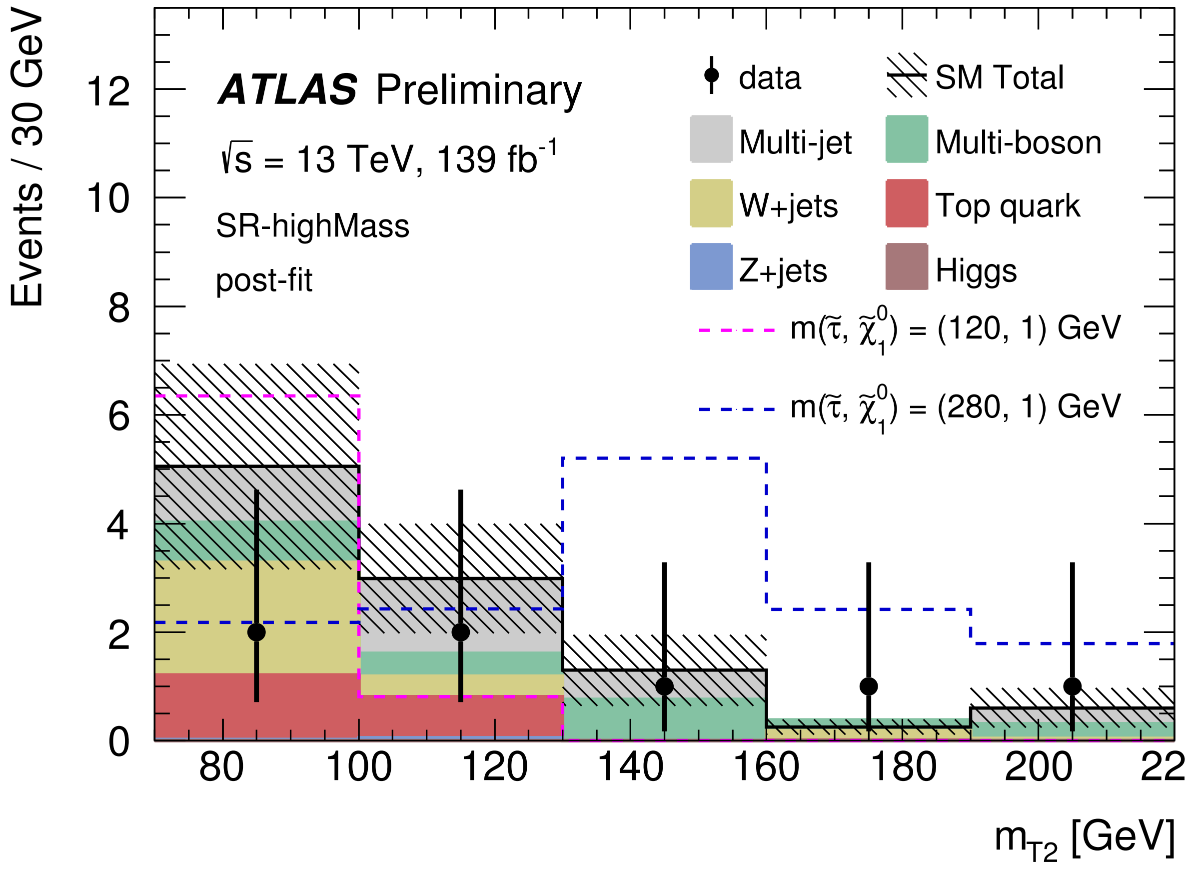
Use an ISR jet to boost the system and trigger

Then, look for low-mass Z* decays

Critical to reconstruct leptons at extremely low pT

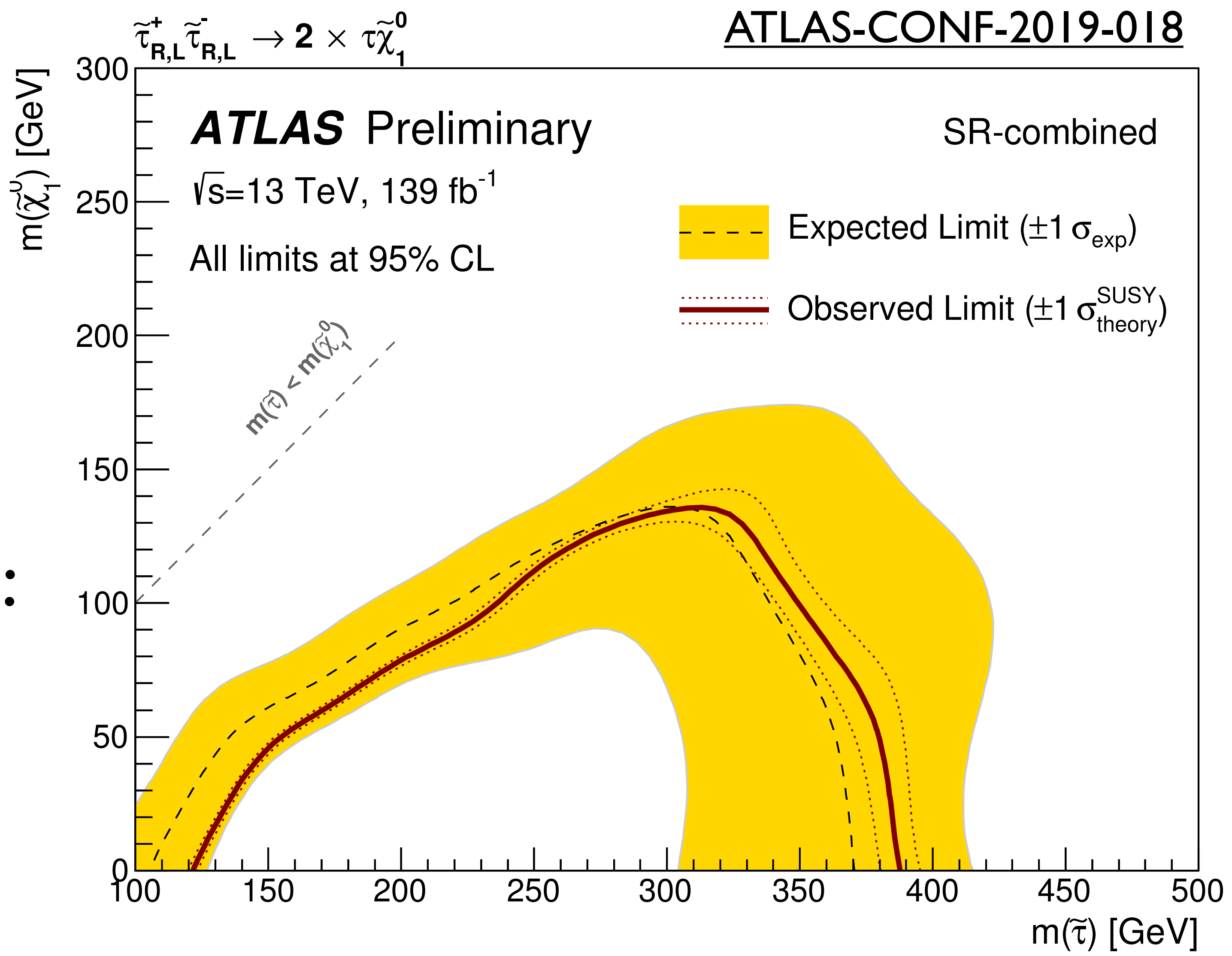
New lepton + track region extends sensitivity to even lower masses!

Even Rarer: Staus

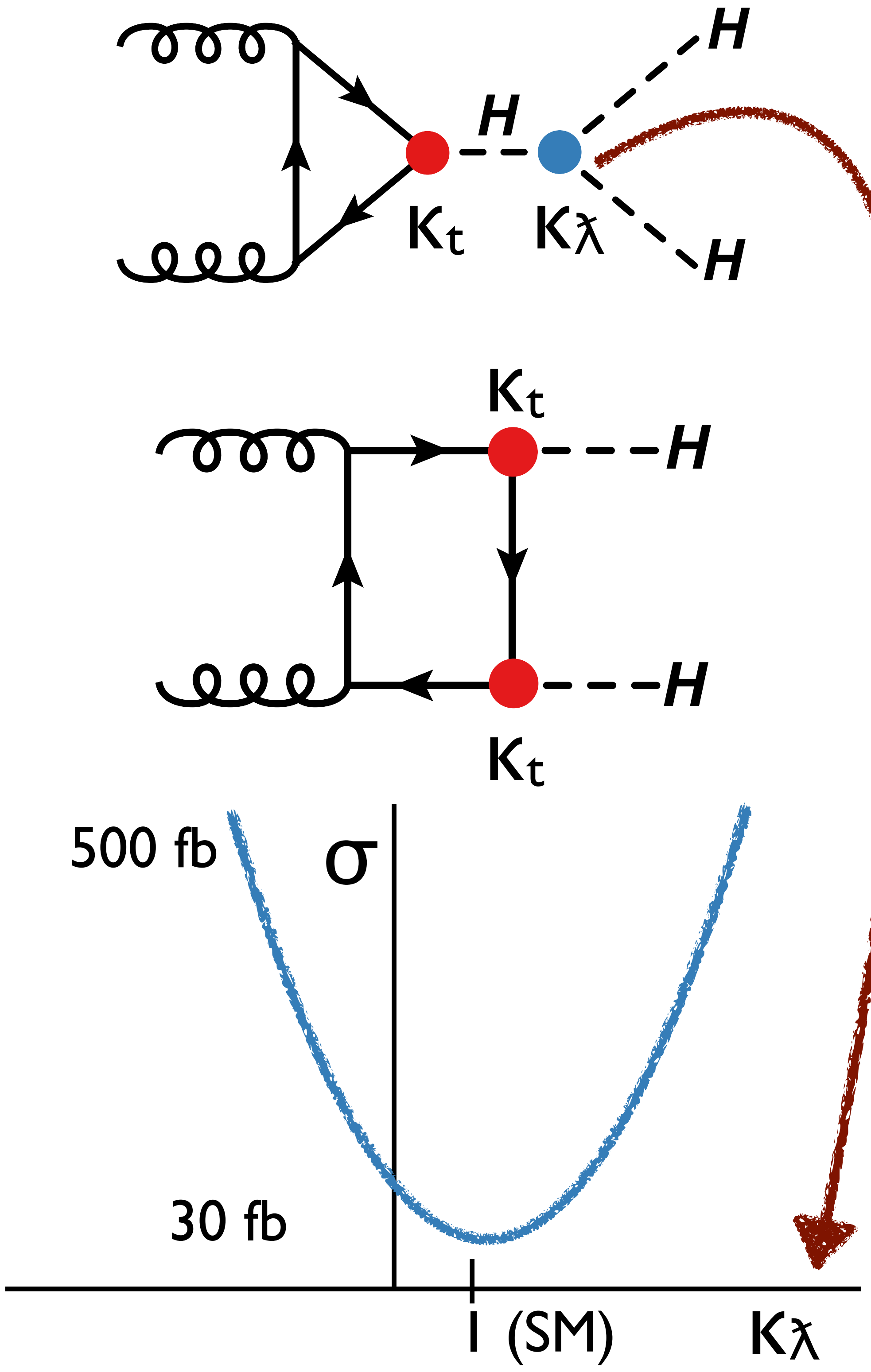


Staus are an even larger challenge: incredibly low cross-section!

Effective triggers and the large dataset enable first substantial sensitivity at the LHC!



Di-Higgs at the LHC



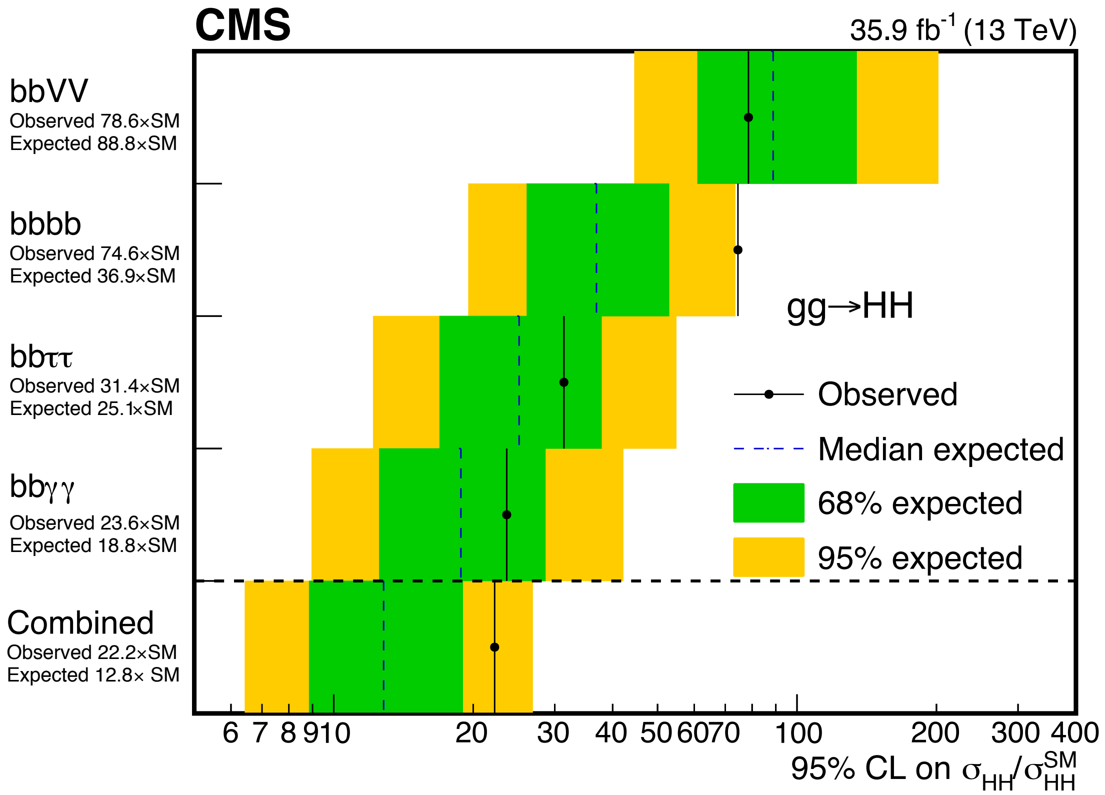
Di-Higgs is another exciting new target for the LHC

Exciting signal: can reveal the shape of the Higgs potential!

Interference between SM diagrams leads to very low x-sec

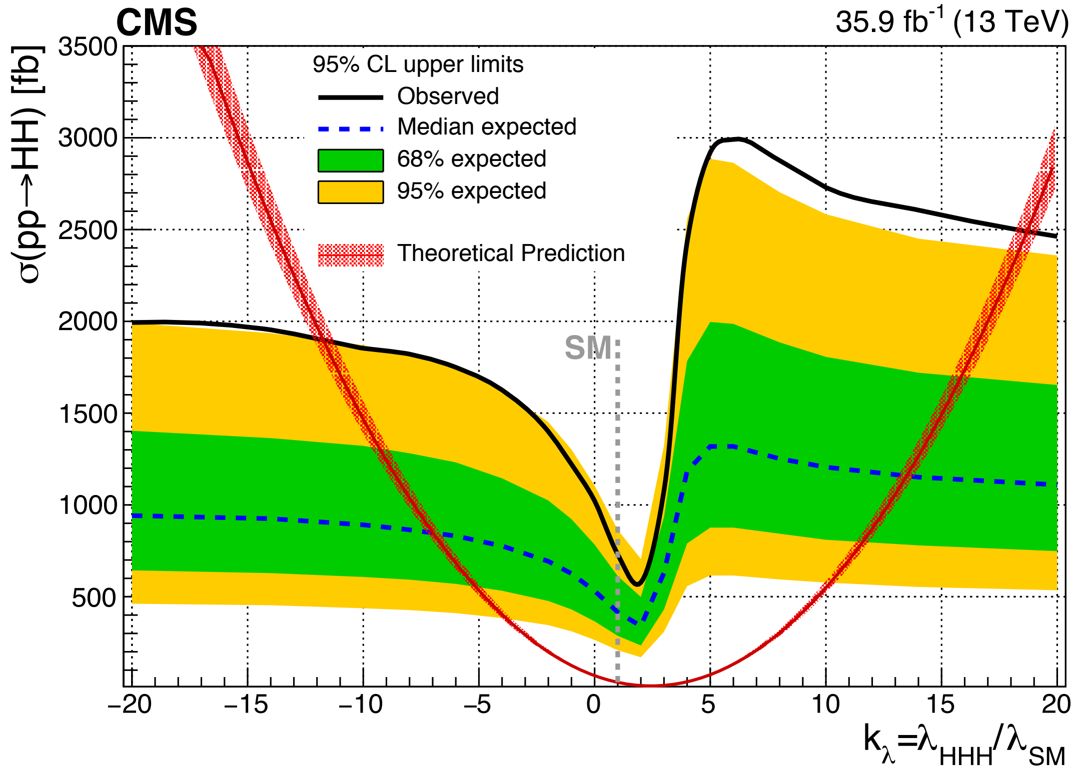
But small deviations from the SM can lead to huge x-sec increases!

Results on Di-Higgs



Many orthogonal channels can be combined to increase sensitivity!

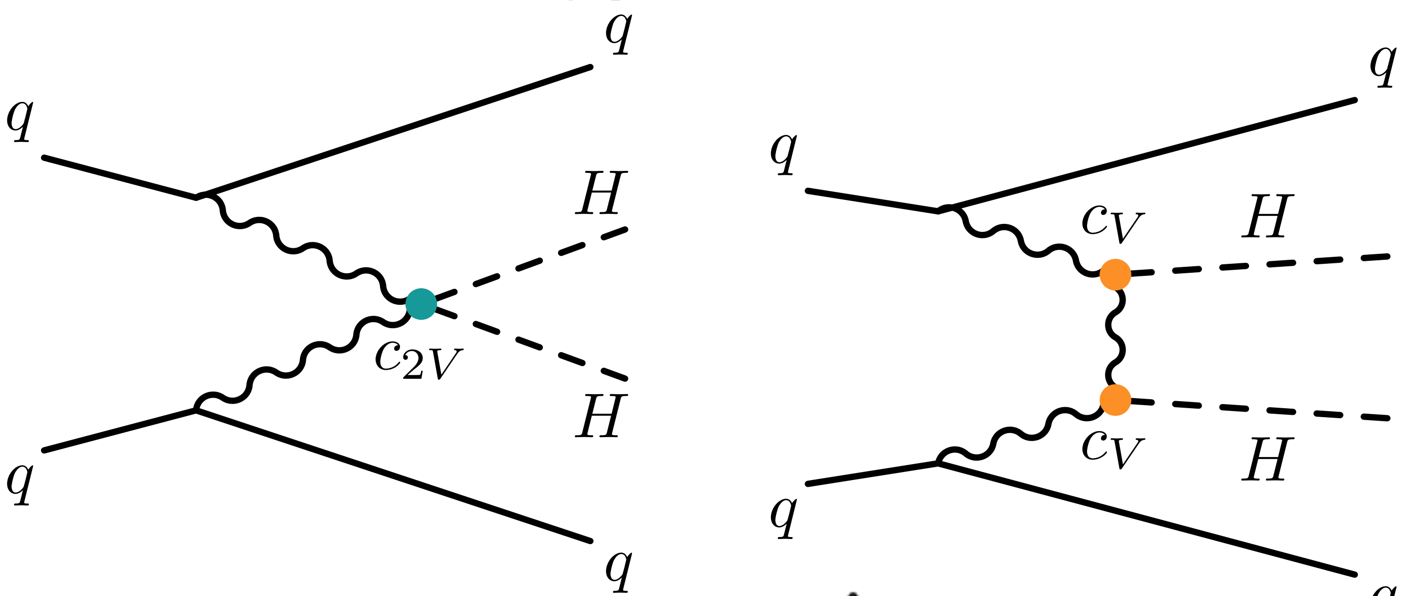
Note the use of b-jets: rare signals mean that high-BR decays of the Higgs need to be used



Wide range of couplings still allowed!
Even more data still necessary

Hunting Rare SM Deviations

Interference in other SM diagrams lead to similar vanishingly small x-sec

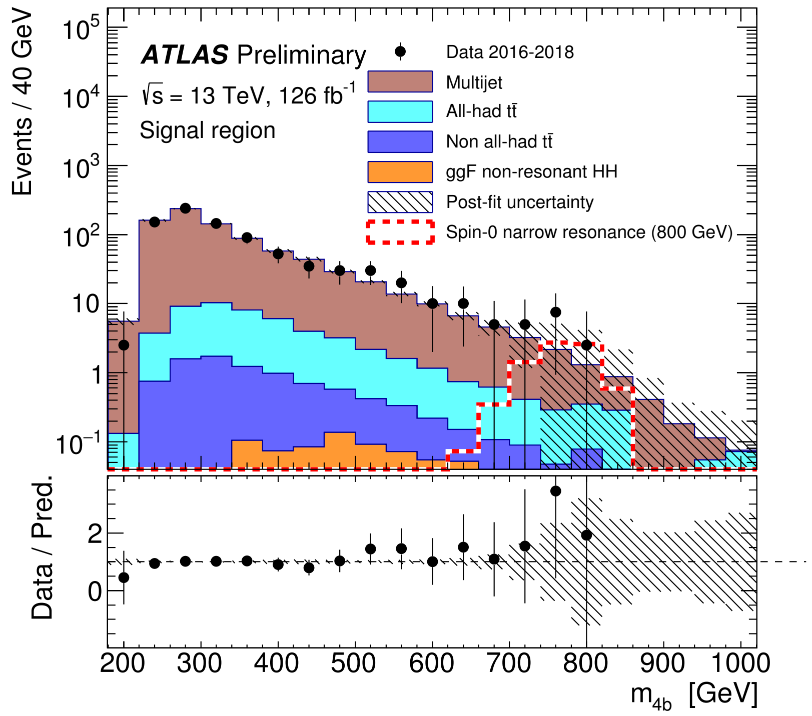


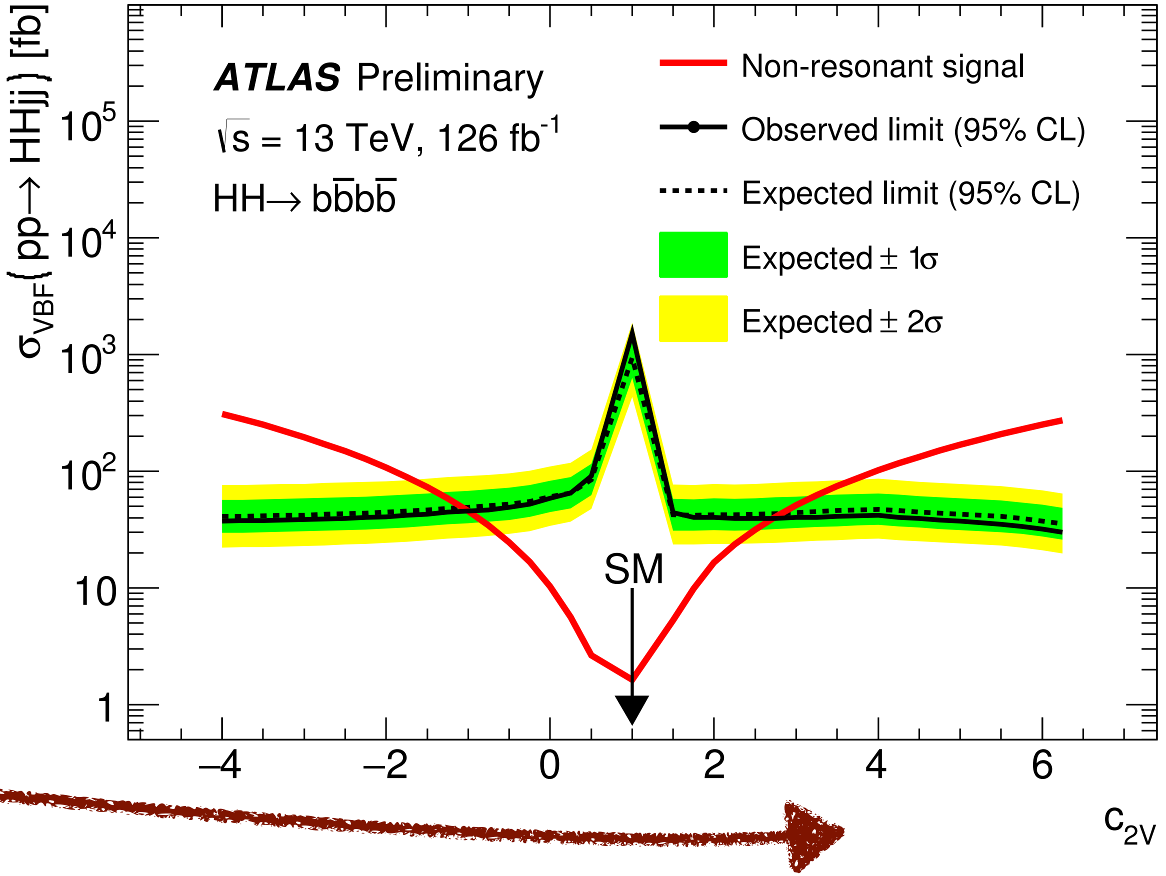
$$\mathcal{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)$$

VBF di-Higgs production is one example!

First limits on the 4-point VVHH coupling

ATLAS-CONF-2019-030

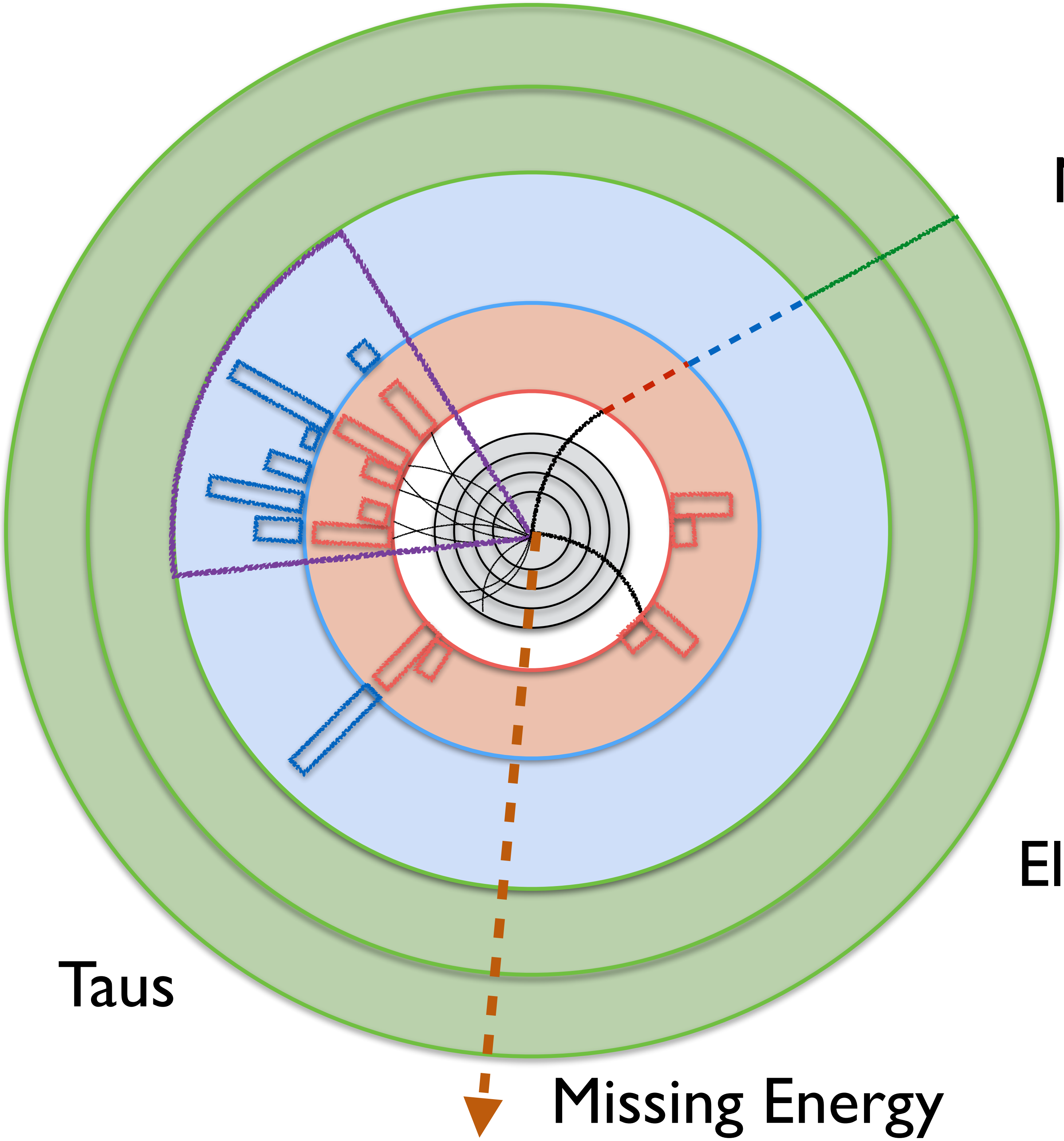




Not Your Advisor's Signals

Or: how new reconstruction strategies are expanding our sensitivity to signals our detectors weren't built to measure

Your Advisor's Signals



Jets
(and b-jets)

Muons

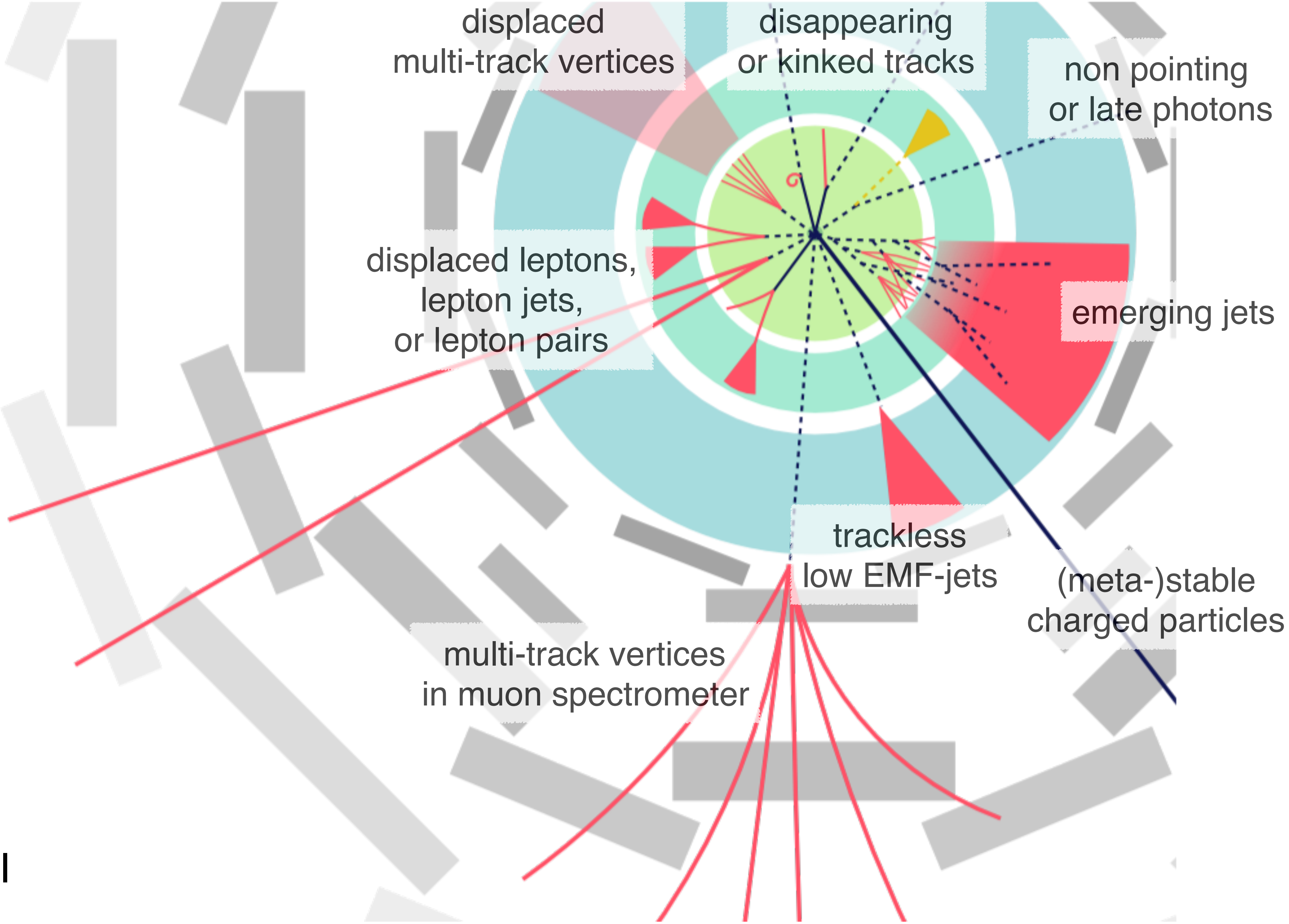
Photons

Electrons

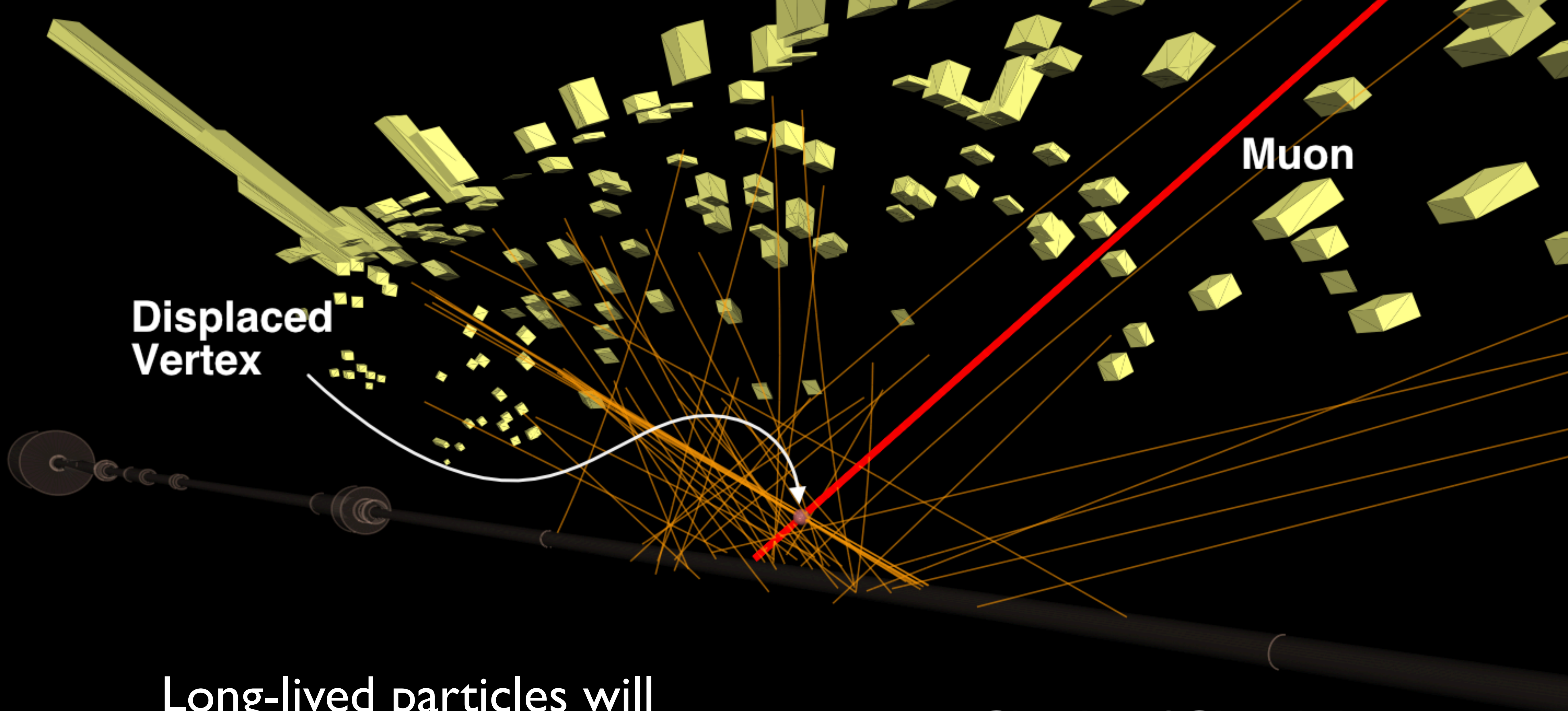
Taus

Missing Energy

Not Your Advisor's Signals



Heather Russell



Simulated Signal Event
Top Squark Pair Production

$m(\tilde{t}) = 1.5\ \text{TeV},\ \tau(\tilde{t}) = 1\ \text{ns}$

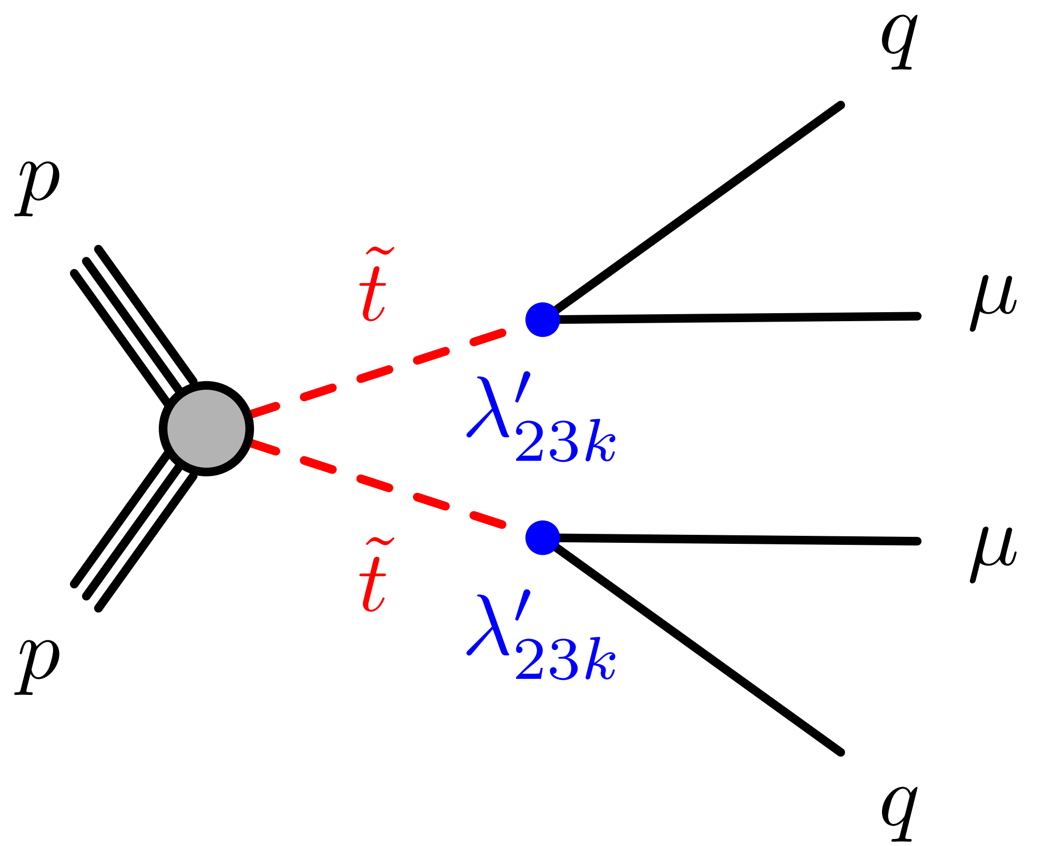
$\tilde{t} \rightarrow \mu j$

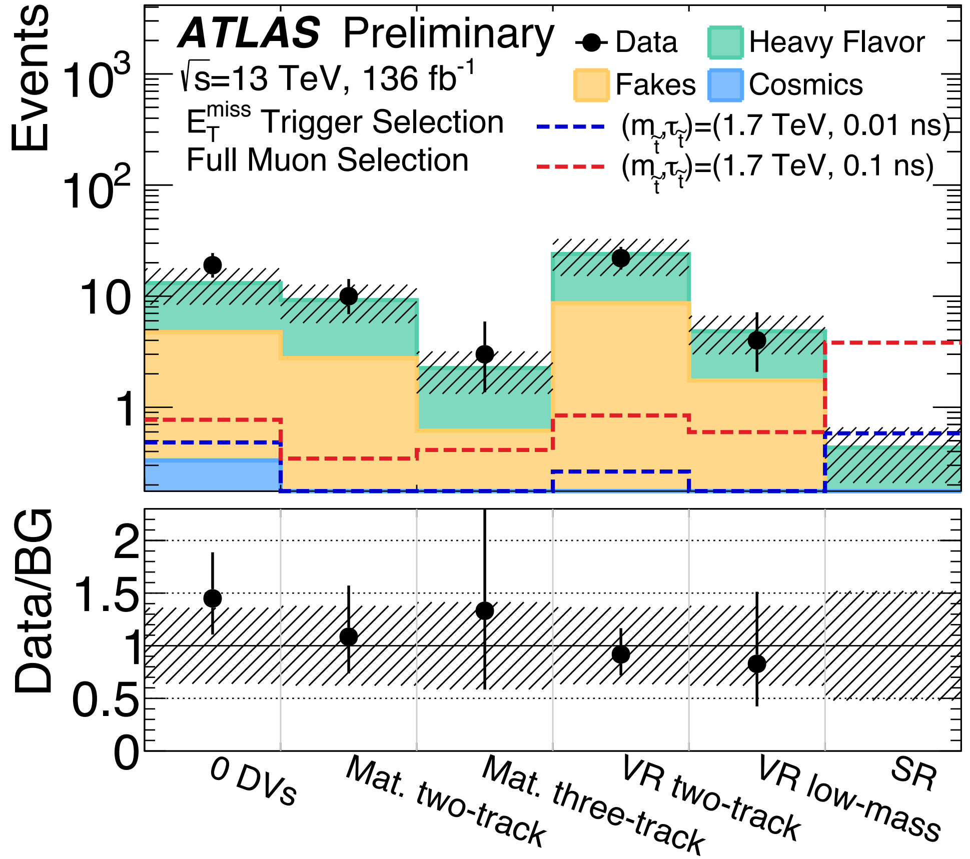
Long-lived particles will travel an appreciable distance before they decay

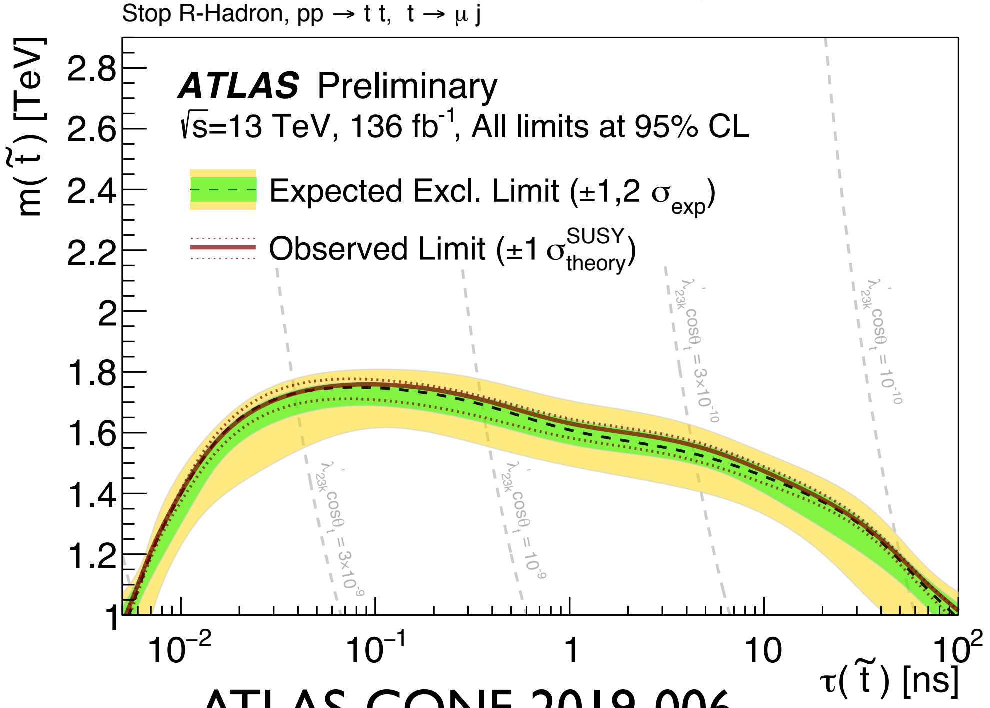
Special algorithms can reconstruct these “displaced tracks” and look for displaced vertices

ATLAS
EXPERIMENT

Displaced Vertex + μ







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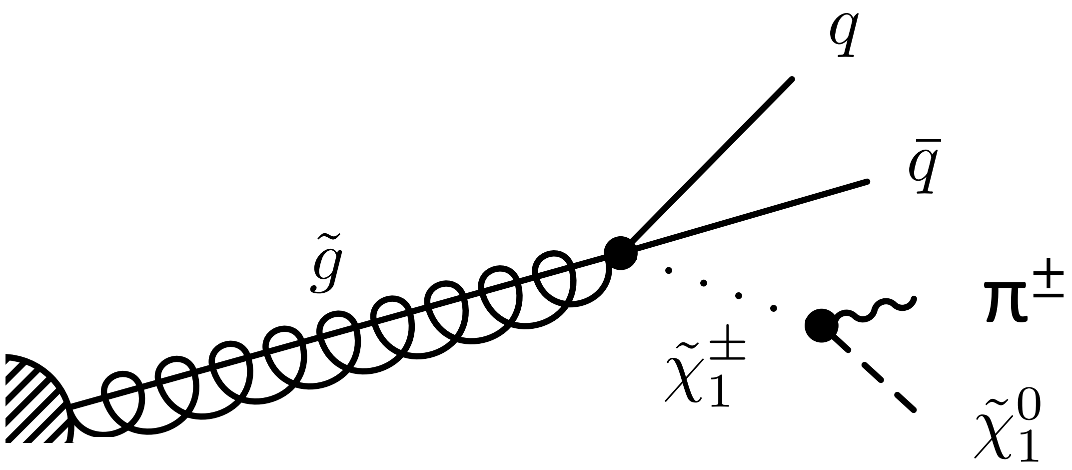
Stops can be long-lived in RPV models with small couplings

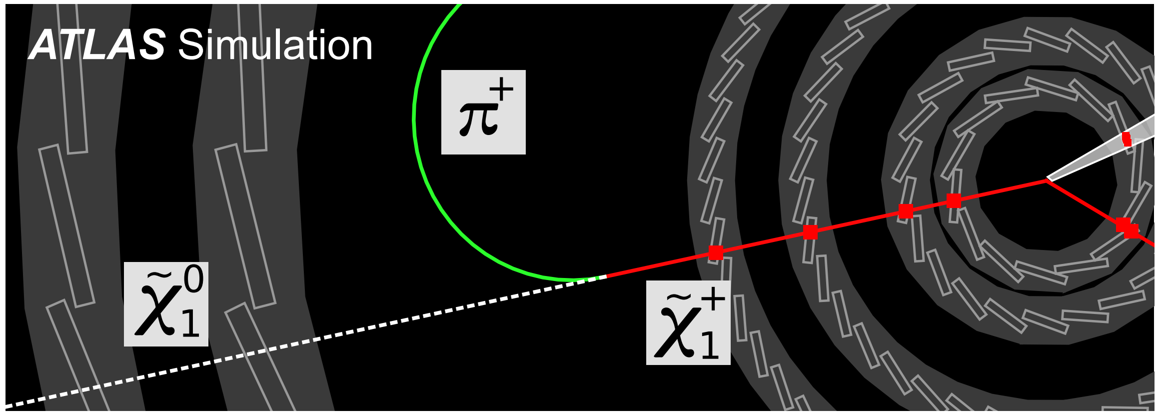
Data-driven backgrounds estimate ~0 background, with no signal observed

Strongest limits yet on stops!

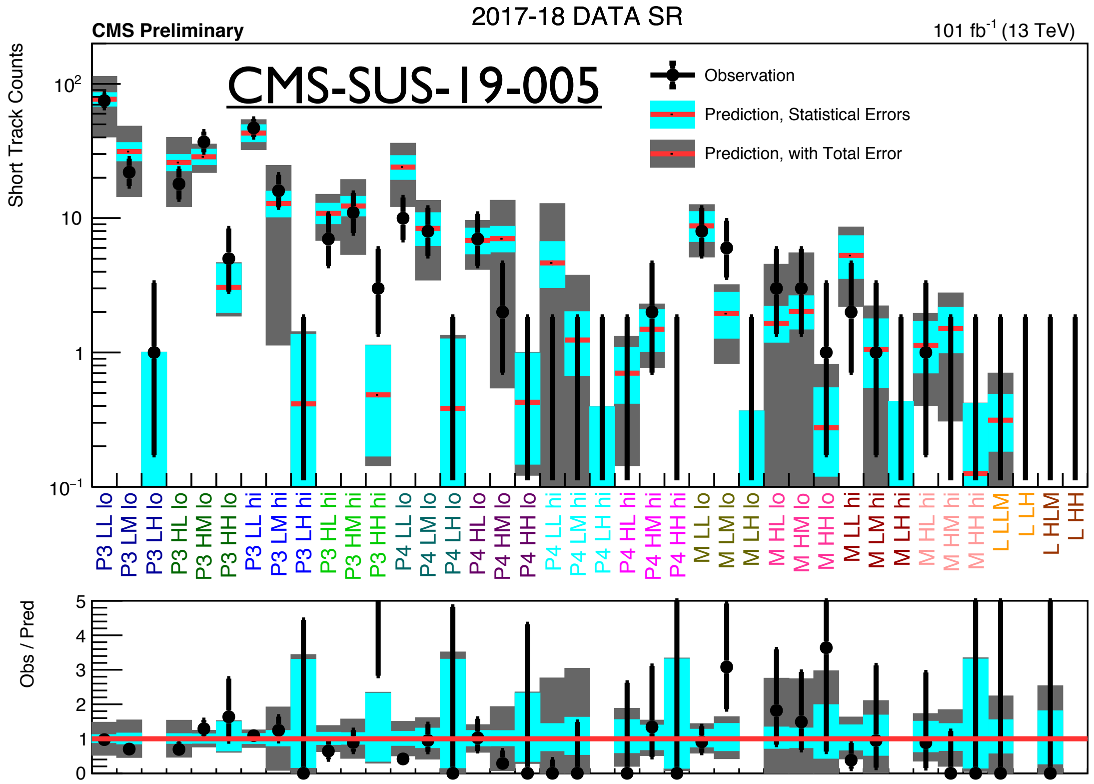
Disappearing Tracks

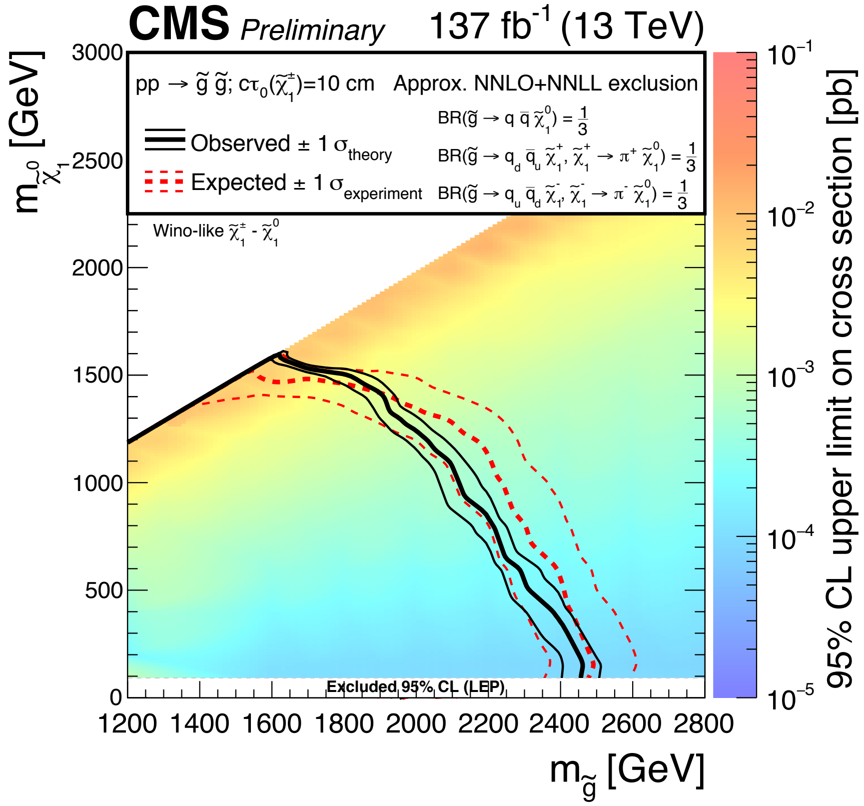


With extremely small mass splittings between SUSY particles, charginos can become long-lived!

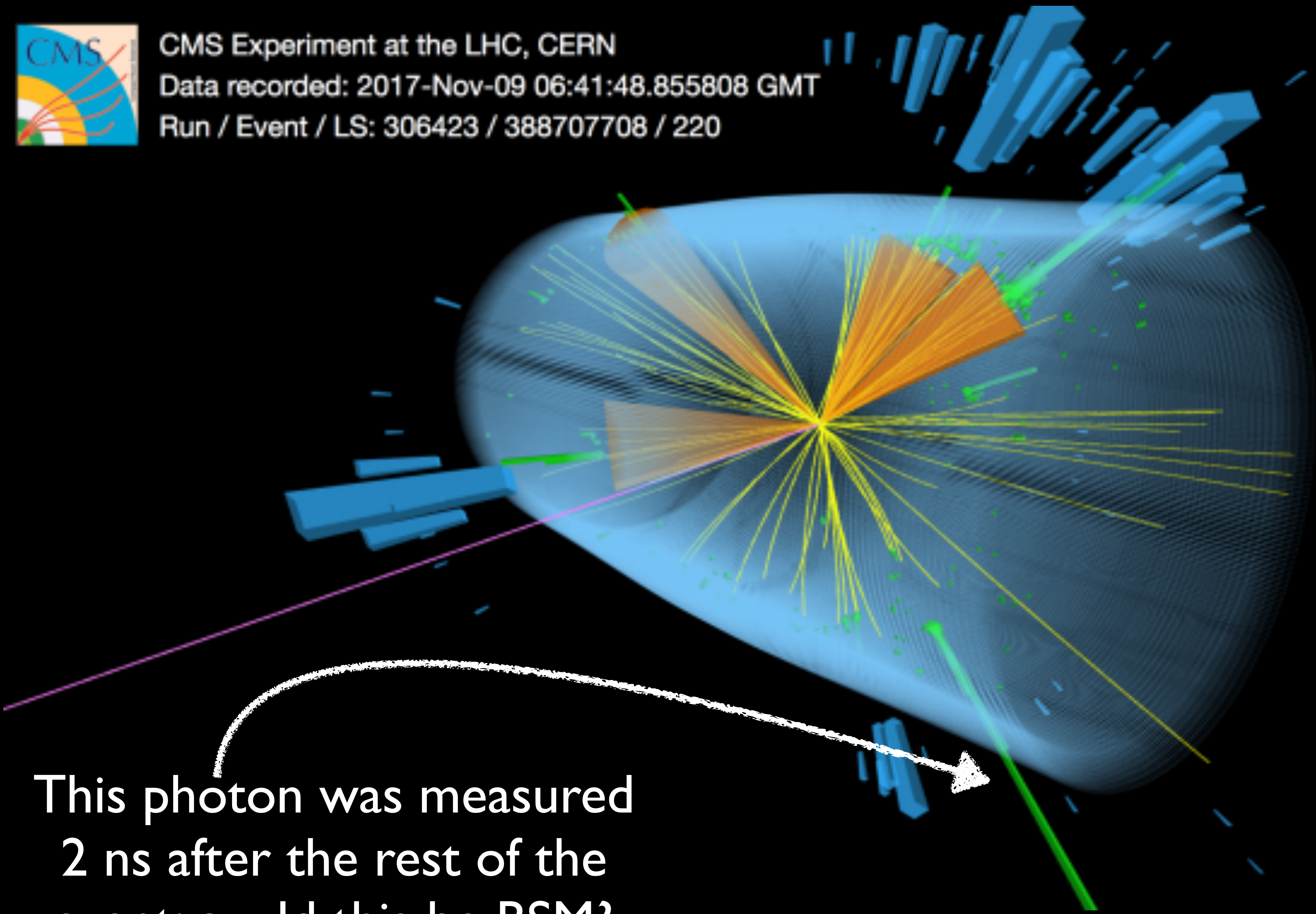


Can interact with the first few layers of the tracker, and then "disappear"



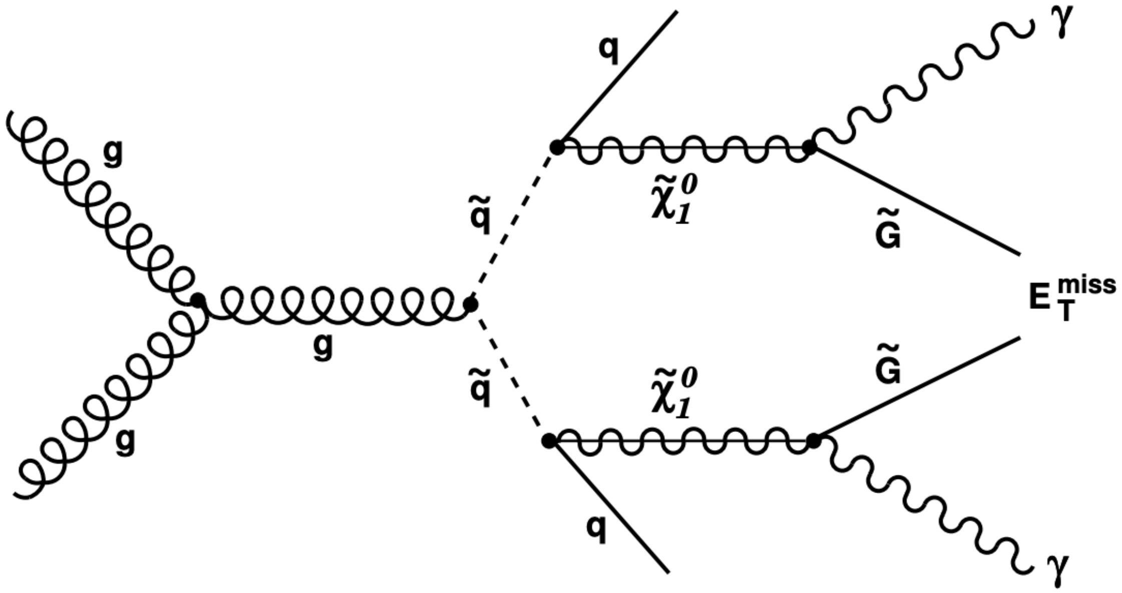


Can also extend reconstruction using additional information: **timing**



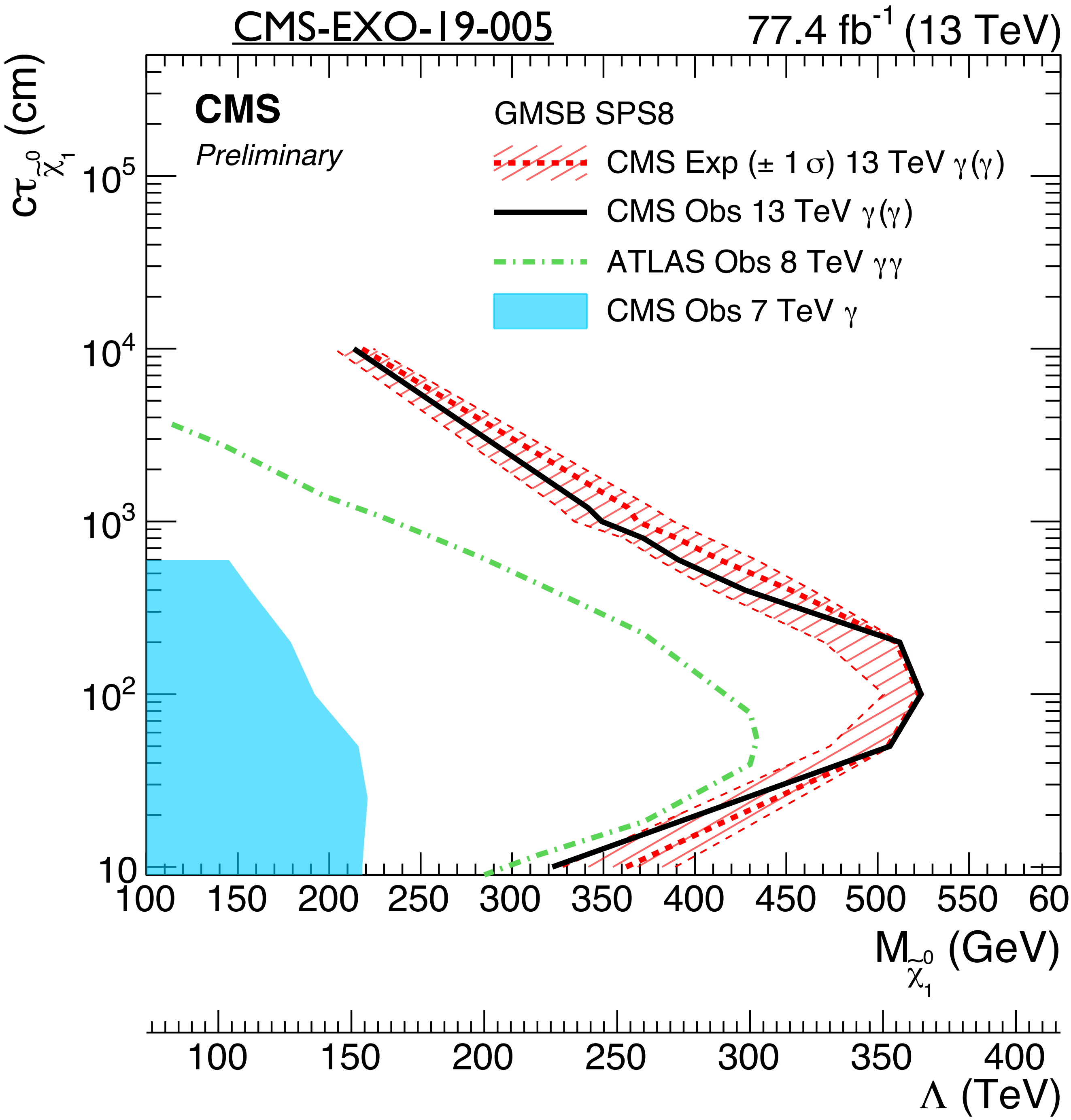
This photon was measured 2 ns after the rest of the event: could this be BSM?

Delayed Photons



Many models (GMSB SUSY, etc.) have long-lived particles decaying to photons

These appear "late" compared to other energy in the event: use crystal timing in CMS to search



Conclusions

Keep Looking!

BSM is extremely well motivated at the LHC!

Naturalness, dark matter, and baryogenesis all need answers, and the LHC could find them

Searches are moving into a new era: the low-hanging fruit has been picked, and the challenge is increasing

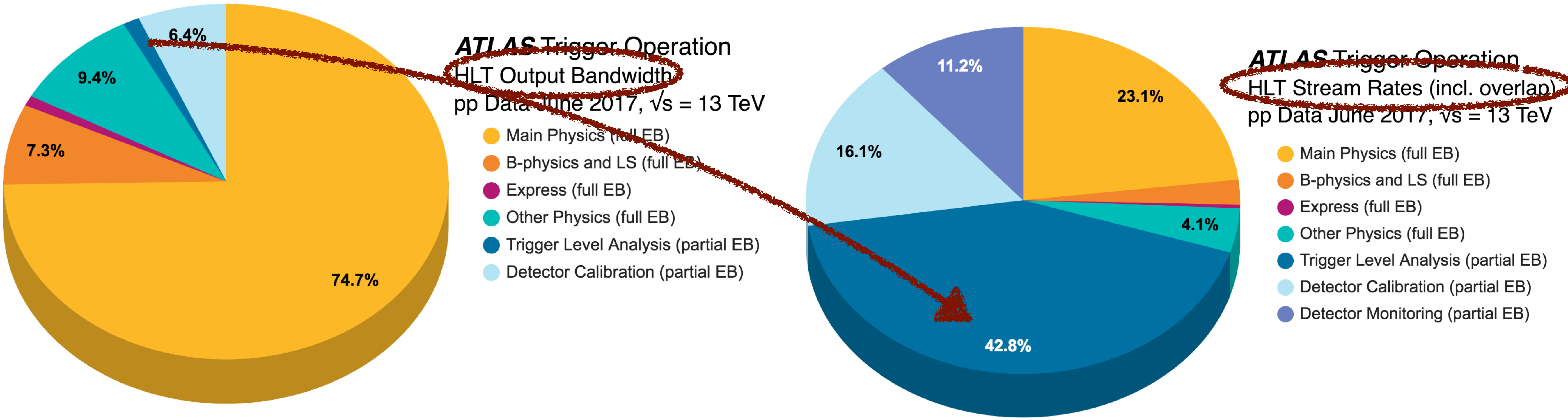
Low Hanging Fruit Records

But new tools, large datasets, and creative reconstruction mean we can rise to the challenge!

Thank you!

Backup

Data Scouting



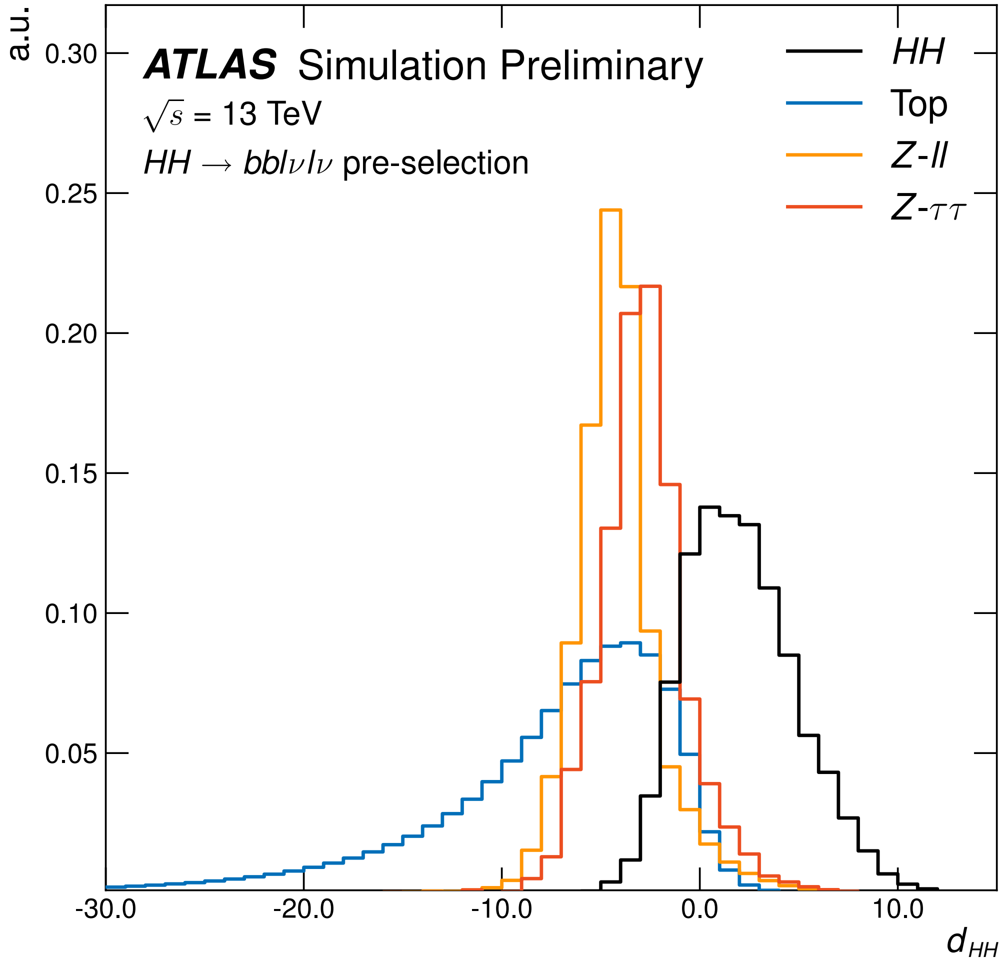
Most of the time, record the "full event" when triggered

But for some analyses, we don't need the full event:
just the jets can be enough to do physics!

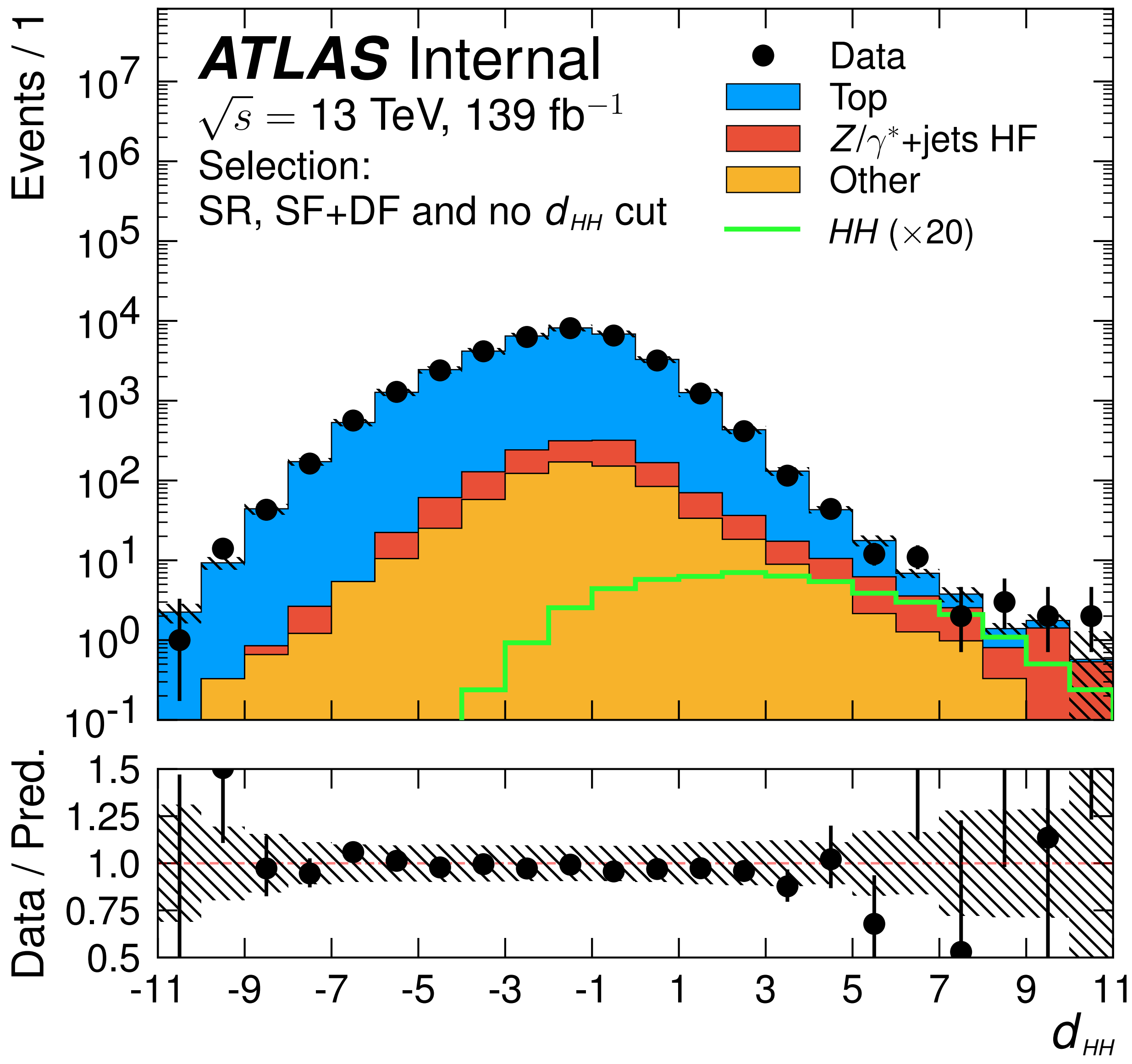
If you make the event small, then
you can record a lot more data!

Machine Learning for di-Higgs

Rare signals are an excellent target for machine learning!



ATLAS uses a DNN to search for di-Higgs in bbll final state



Machine learning can make this rarer channel competitive in the hunt for di-Higgs!

CMS Jet Timing

ATLAS WH results