BSM Results at the LHC

APS DPF 2019

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for the ATLAS and CMS Collaborations
Enrico Fermi Institute, University of Chicago

ATLAS
EXPERIMENT

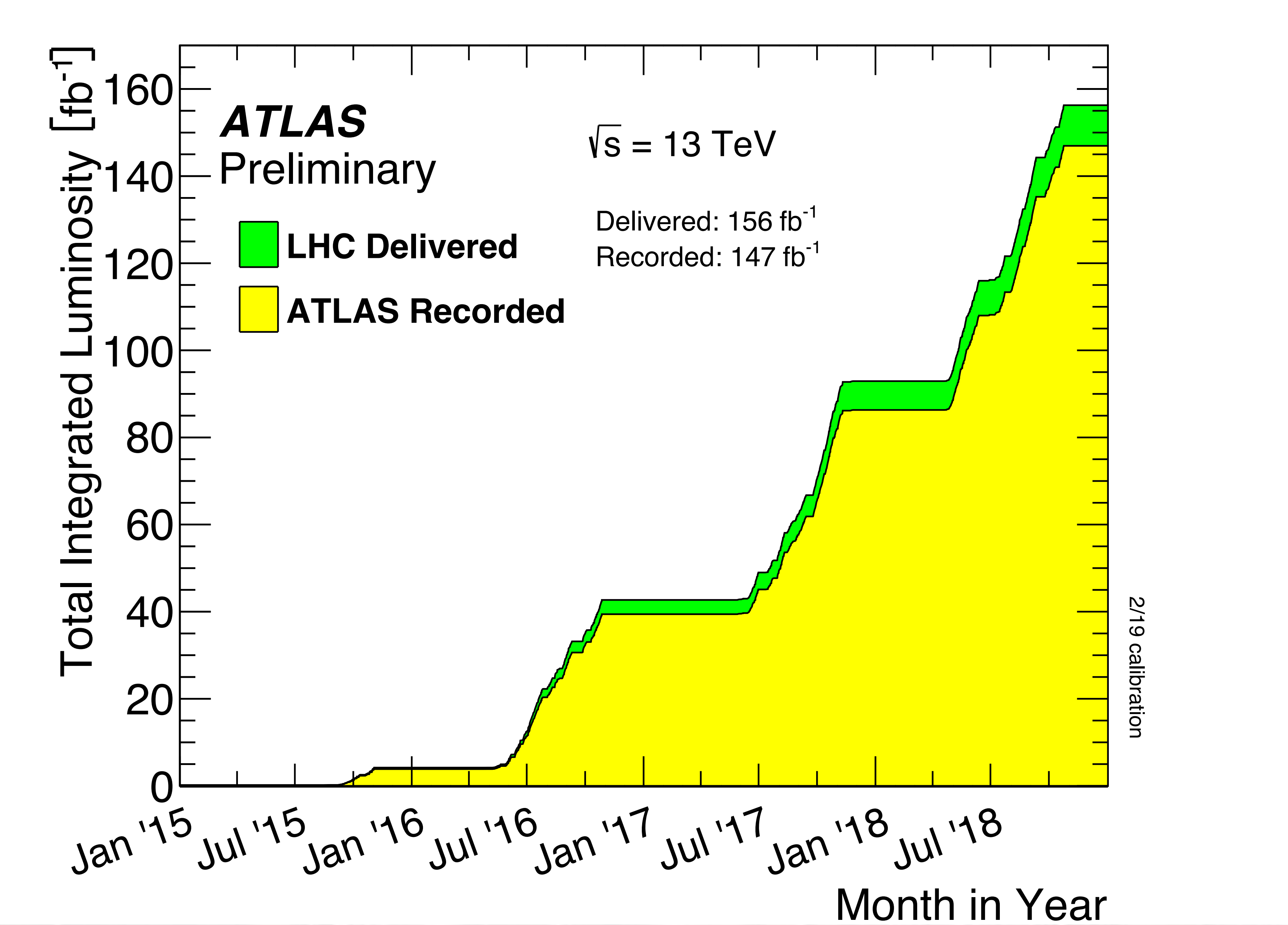
crescat scientia vita excolatur

CMS

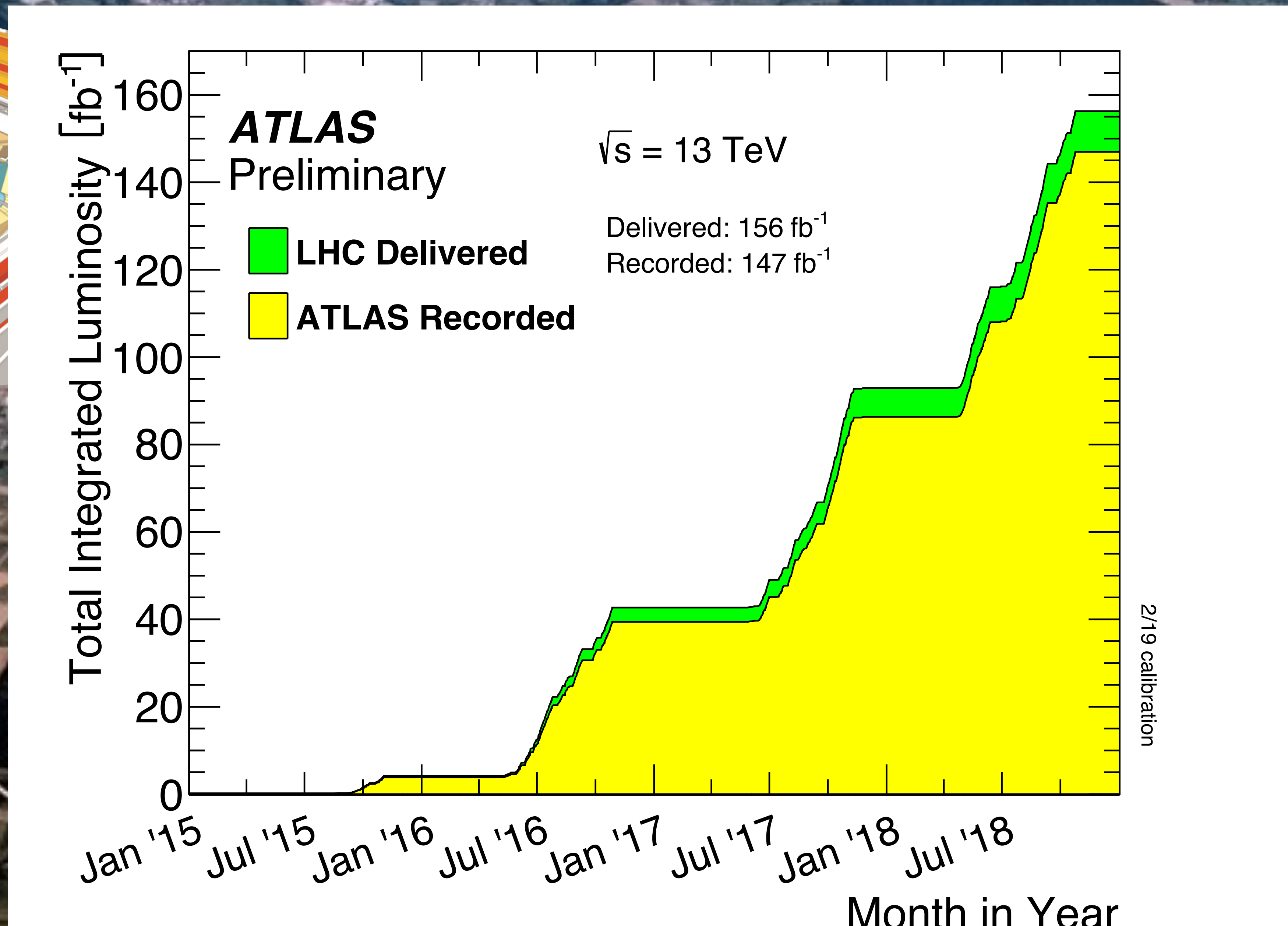
The LHC

The LHC

The LHC


ATLAS
Preliminary
√s = 13 TeV
Delivered: 156 fb⁻¹
Recorded: 147 fb⁻¹
LHC Delivered
ATLAS Recorded
Total Integrated Luminosity [fb⁻¹]
0
20
40
60
80
100
120
140
160
Jan '15
Jul '15
Jan '16
Jul '16
Jan '17
Jul '17
Jan '18
Jul '18
Month in Year
2/19 calibration

The LHC



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

Why BSM?

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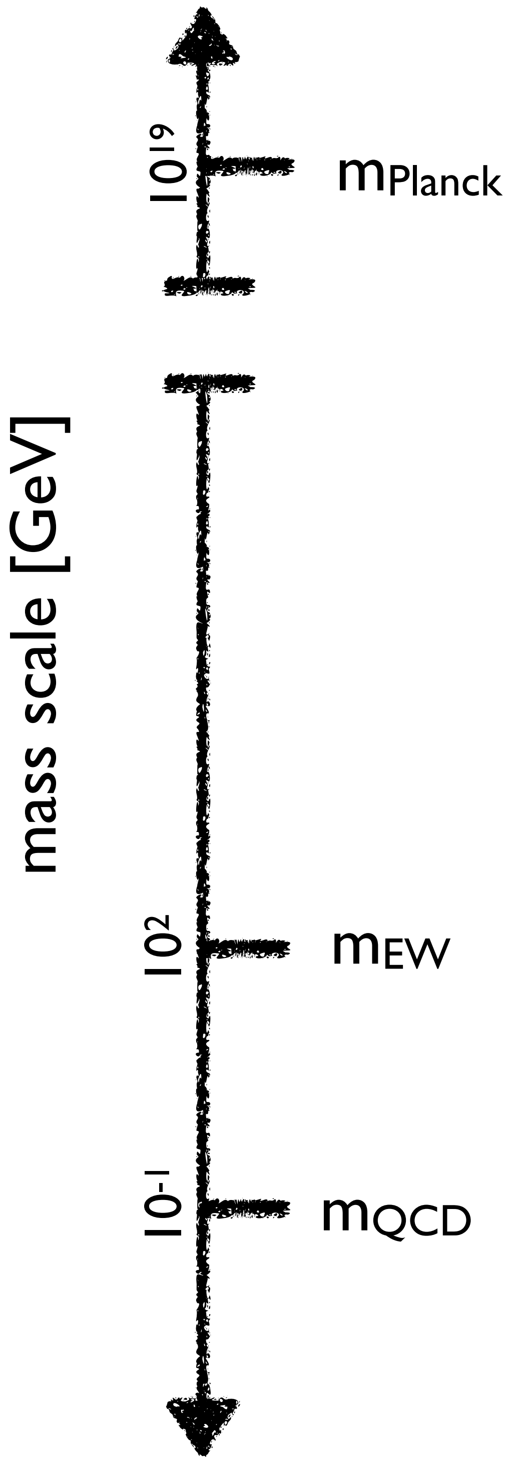

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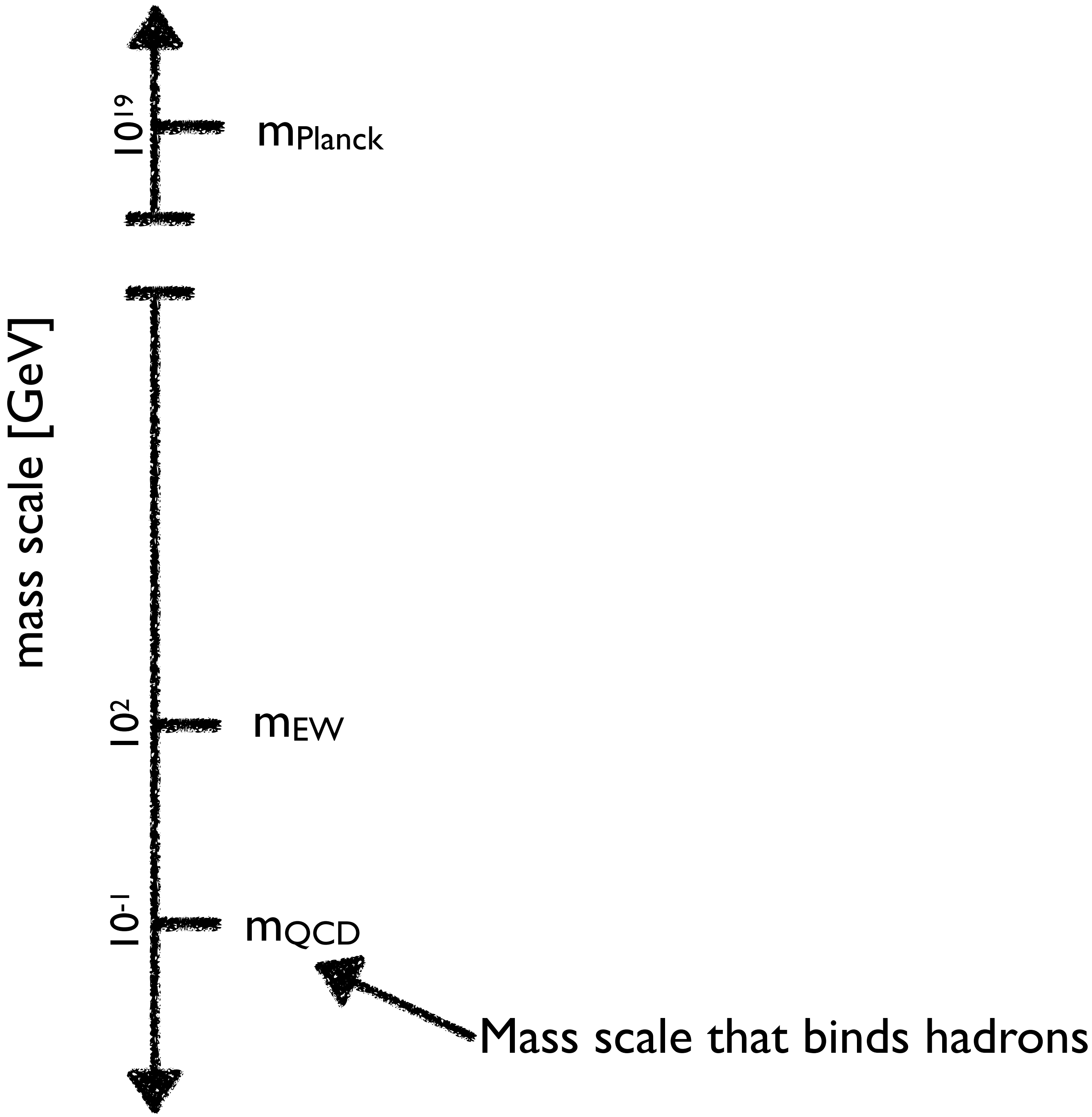
mass scale [GeV]
10^19
mPlanck
10^2
mEW
10^-1
mQCD
Mass scale that binds hadrons

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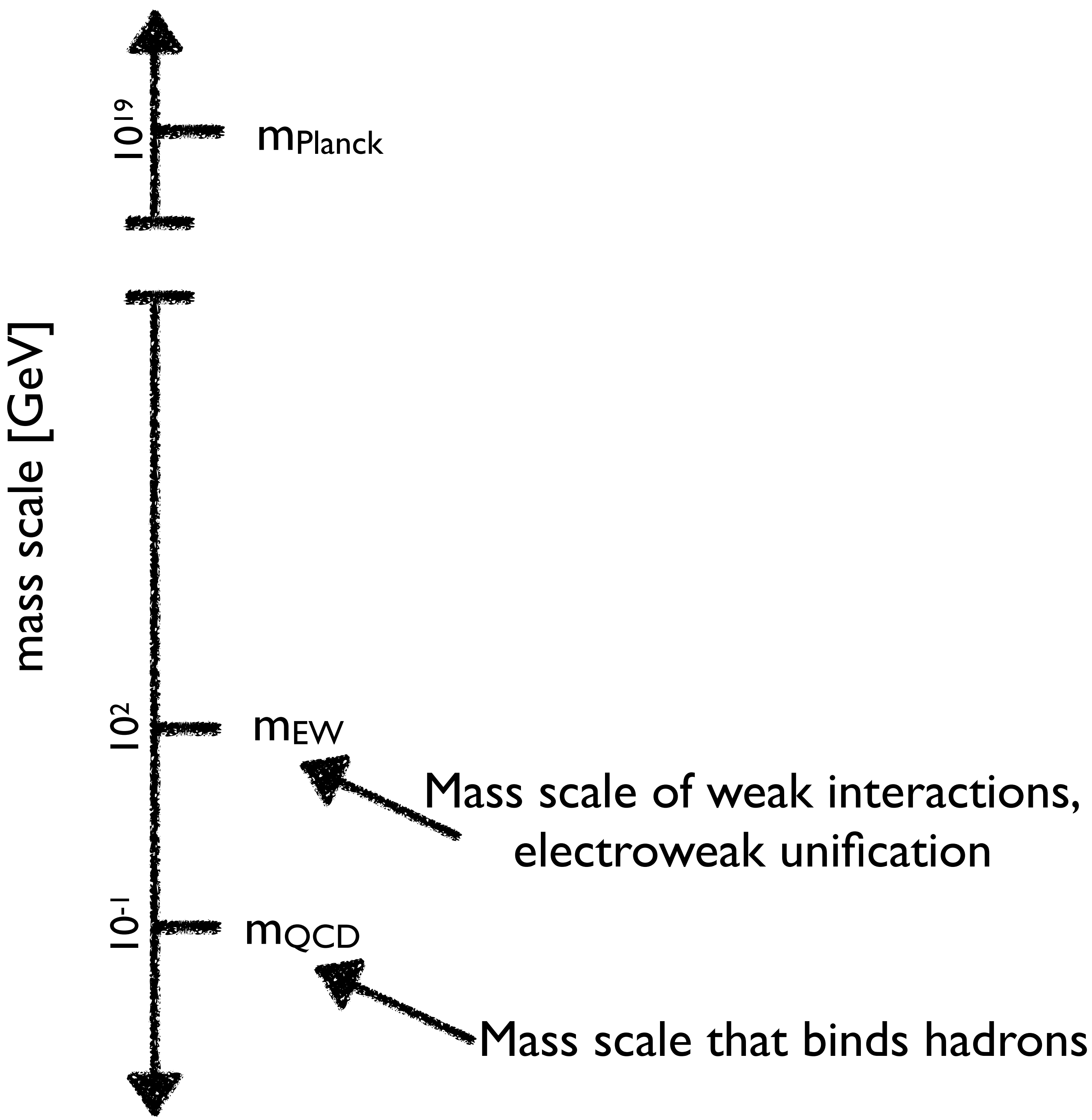
mass scale [GeV]
10^{19}
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Mass scale of weak interactions,
electroweak unification
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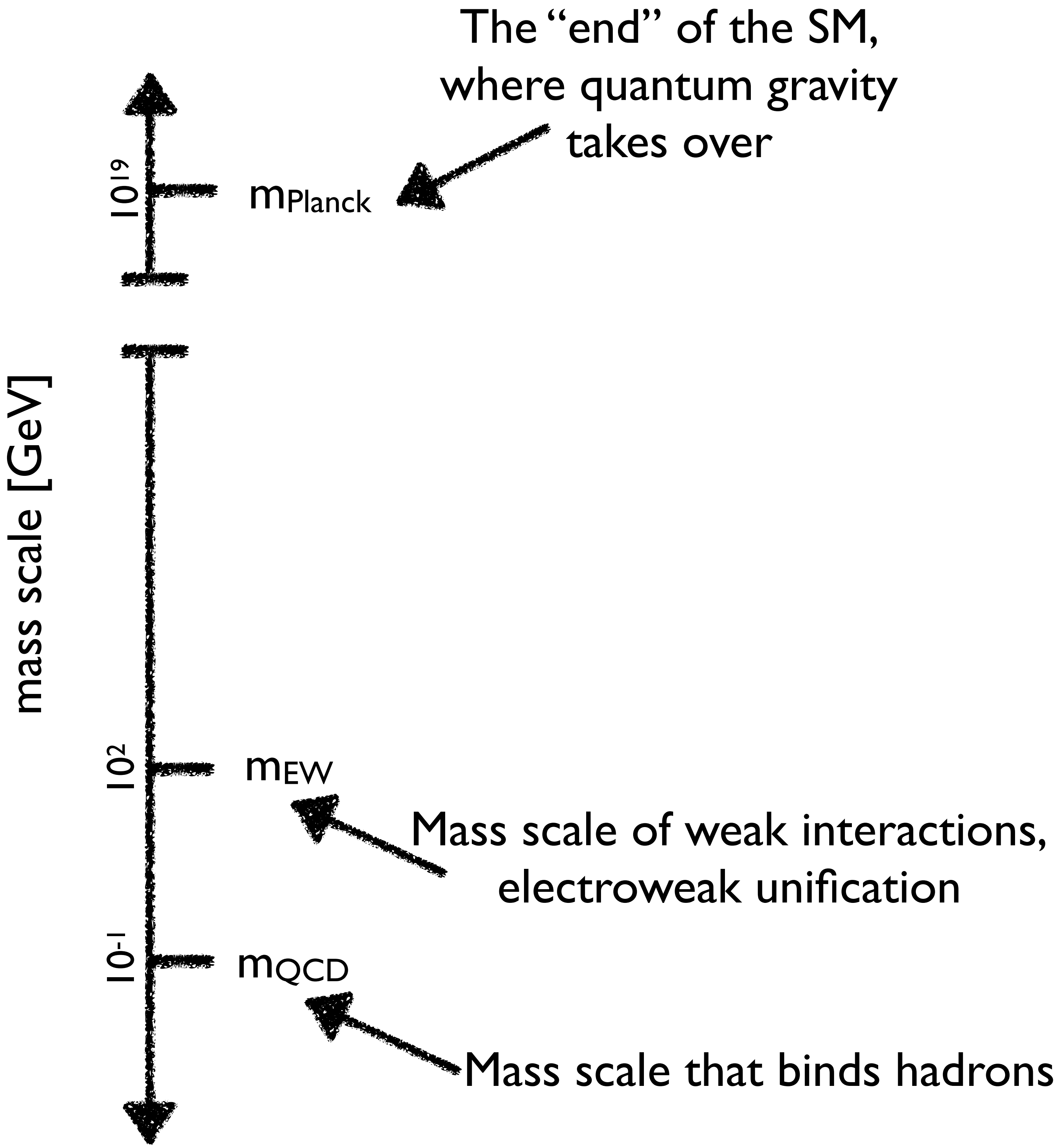
The “end” of the SM,
where quantum gravity
takes over
10^{19}
m_{Planck}
mass scale [GeV]
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m_{EW}
Mass scale of weak interactions,
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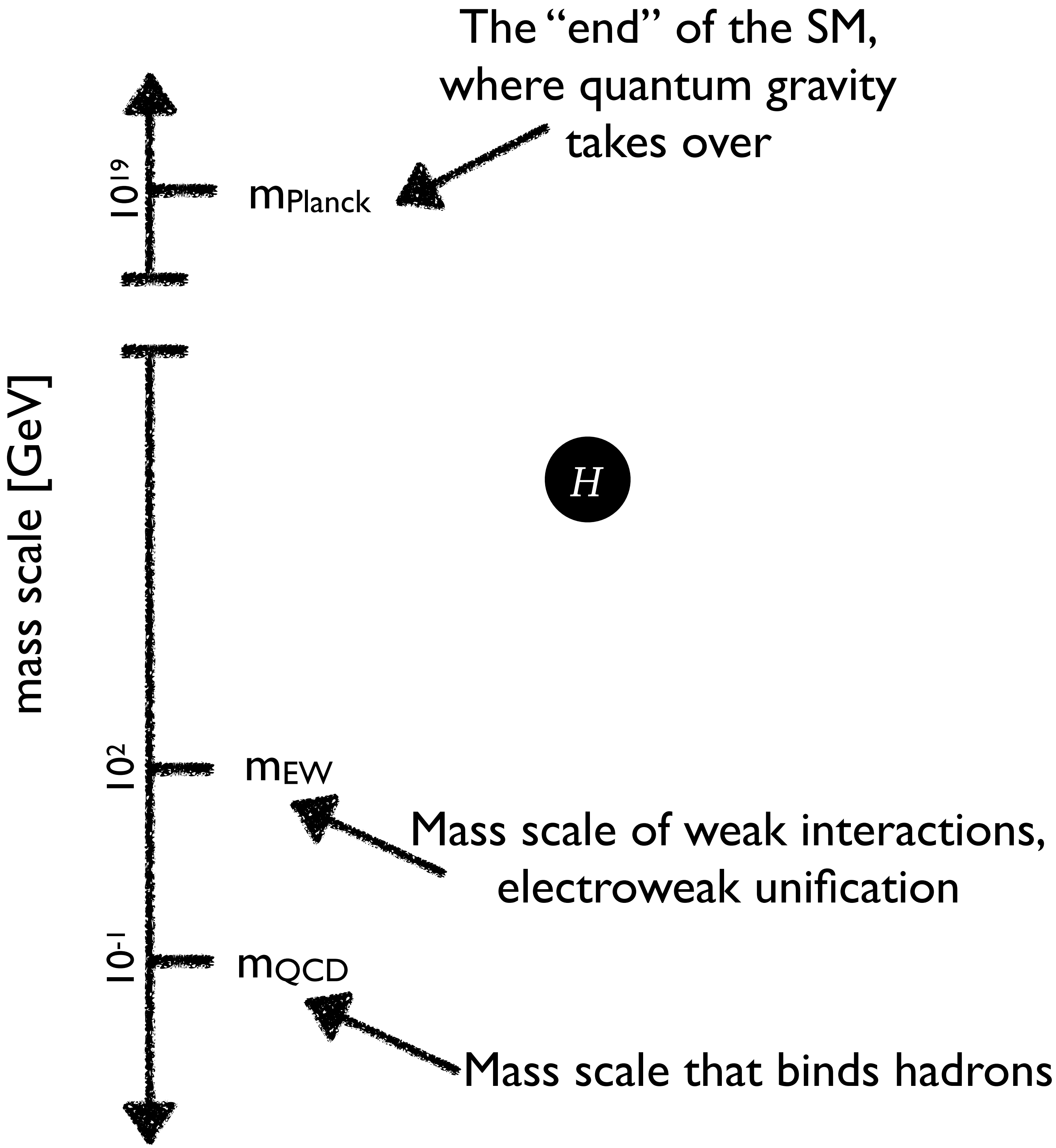
Why BSM?

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



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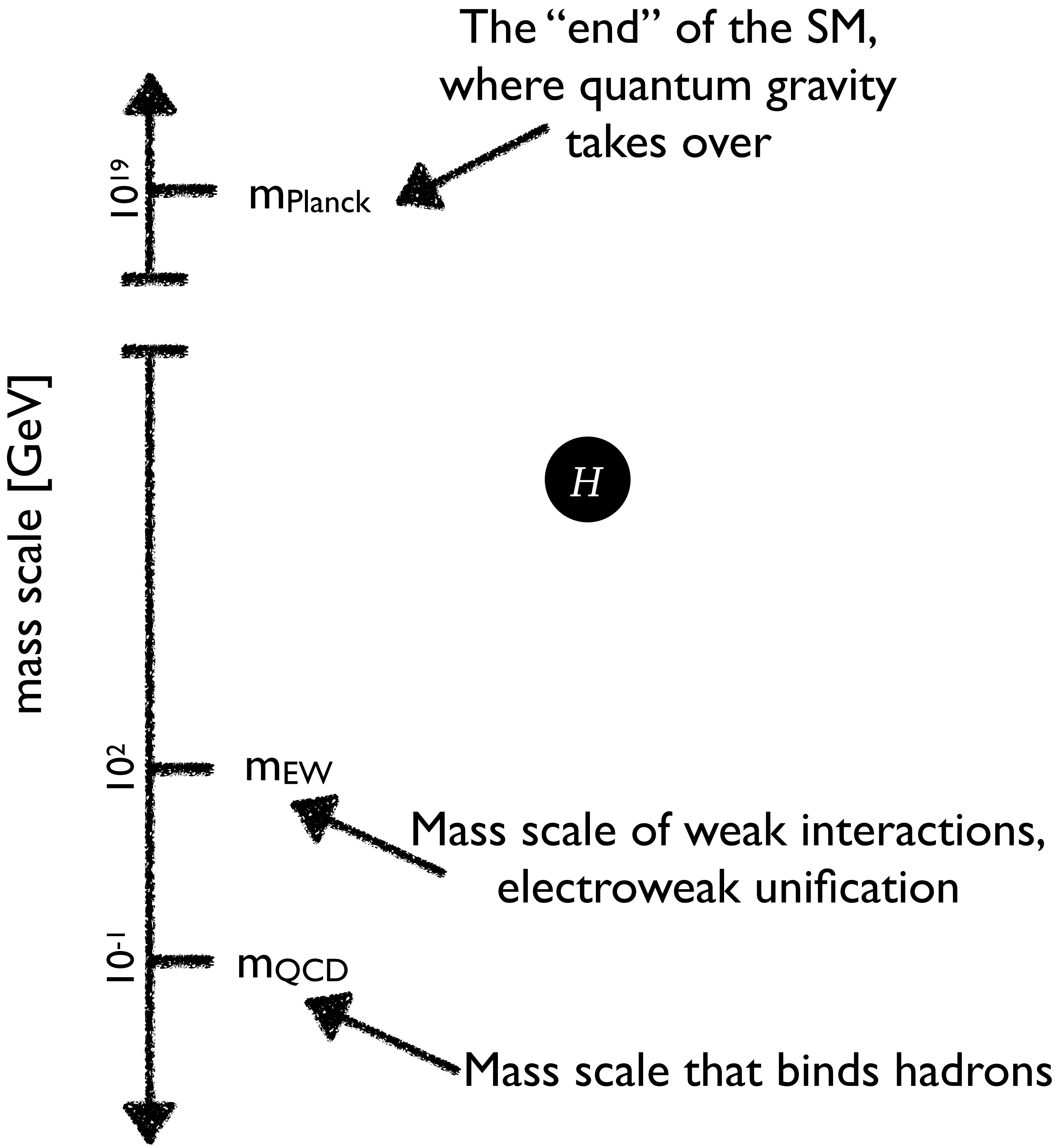

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But the Higgs interacts with other particles, which affects its mass

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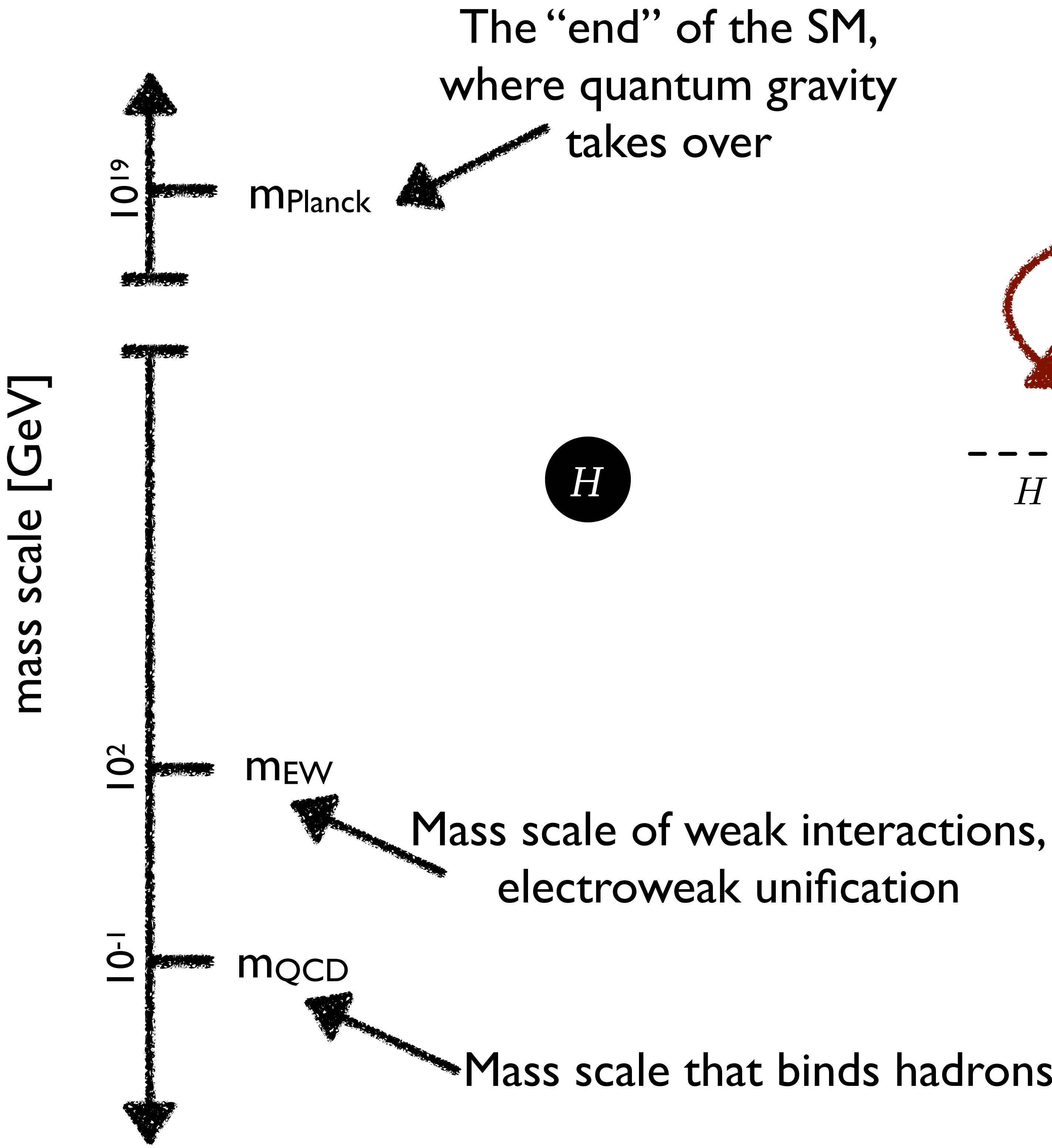

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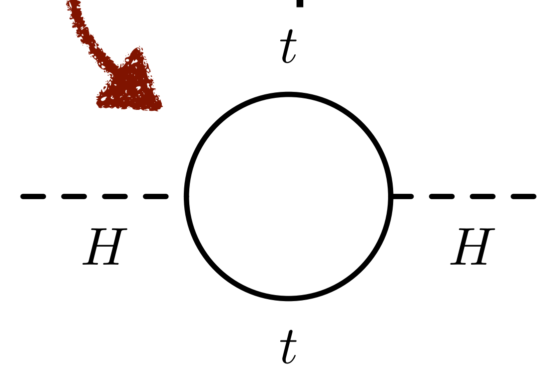

$$\approx \int_0^\Lambda dE$$

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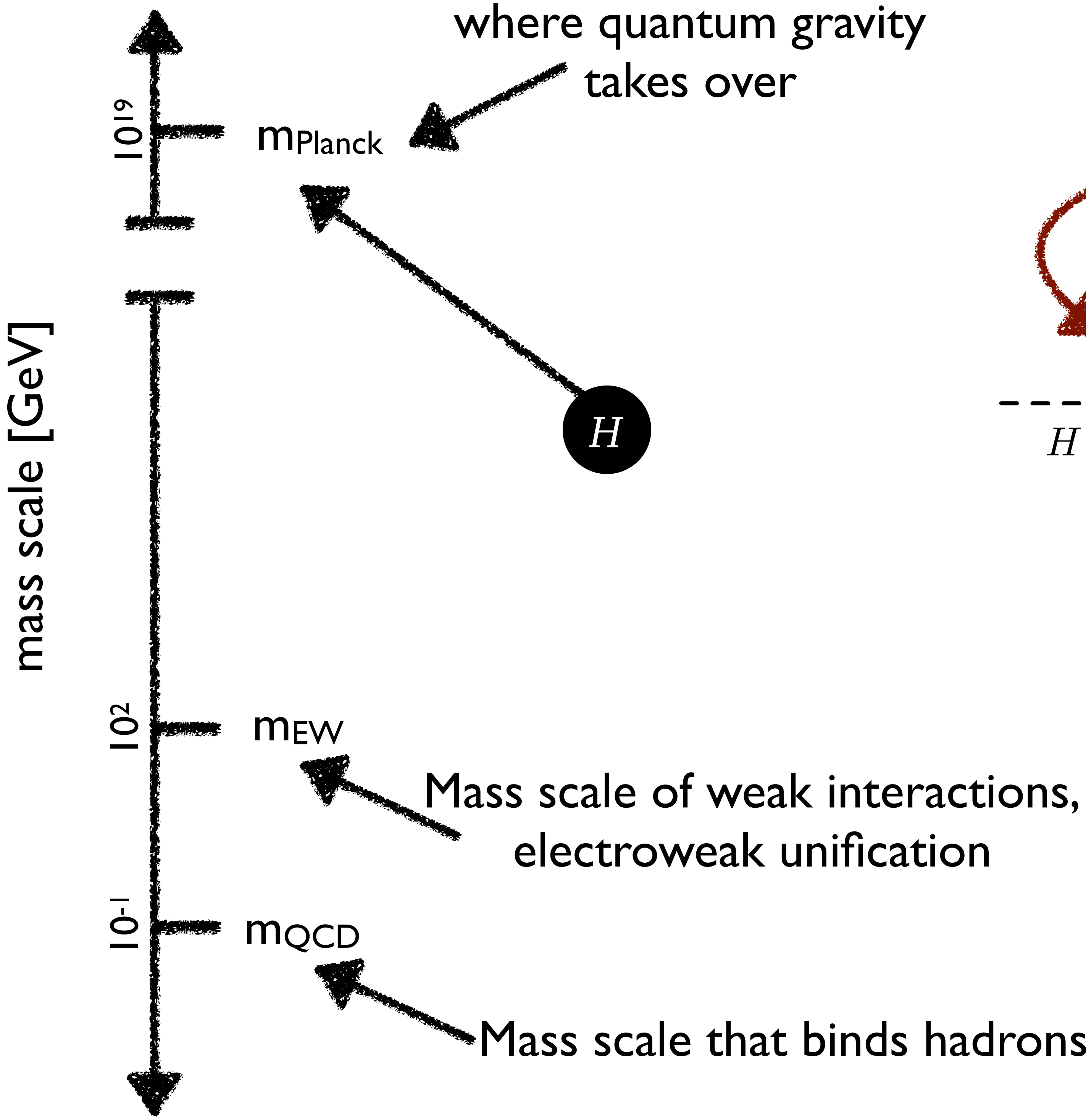

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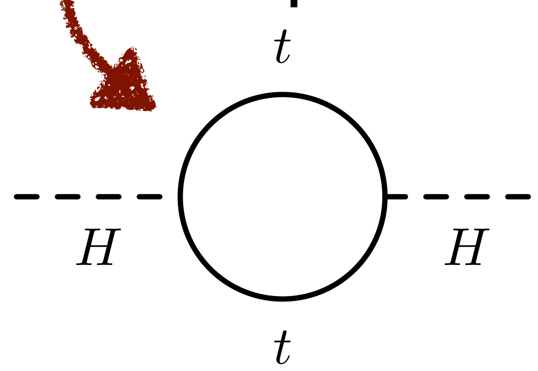

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In the SM, this correction should set the Higgs mass to ~m_{Planck}

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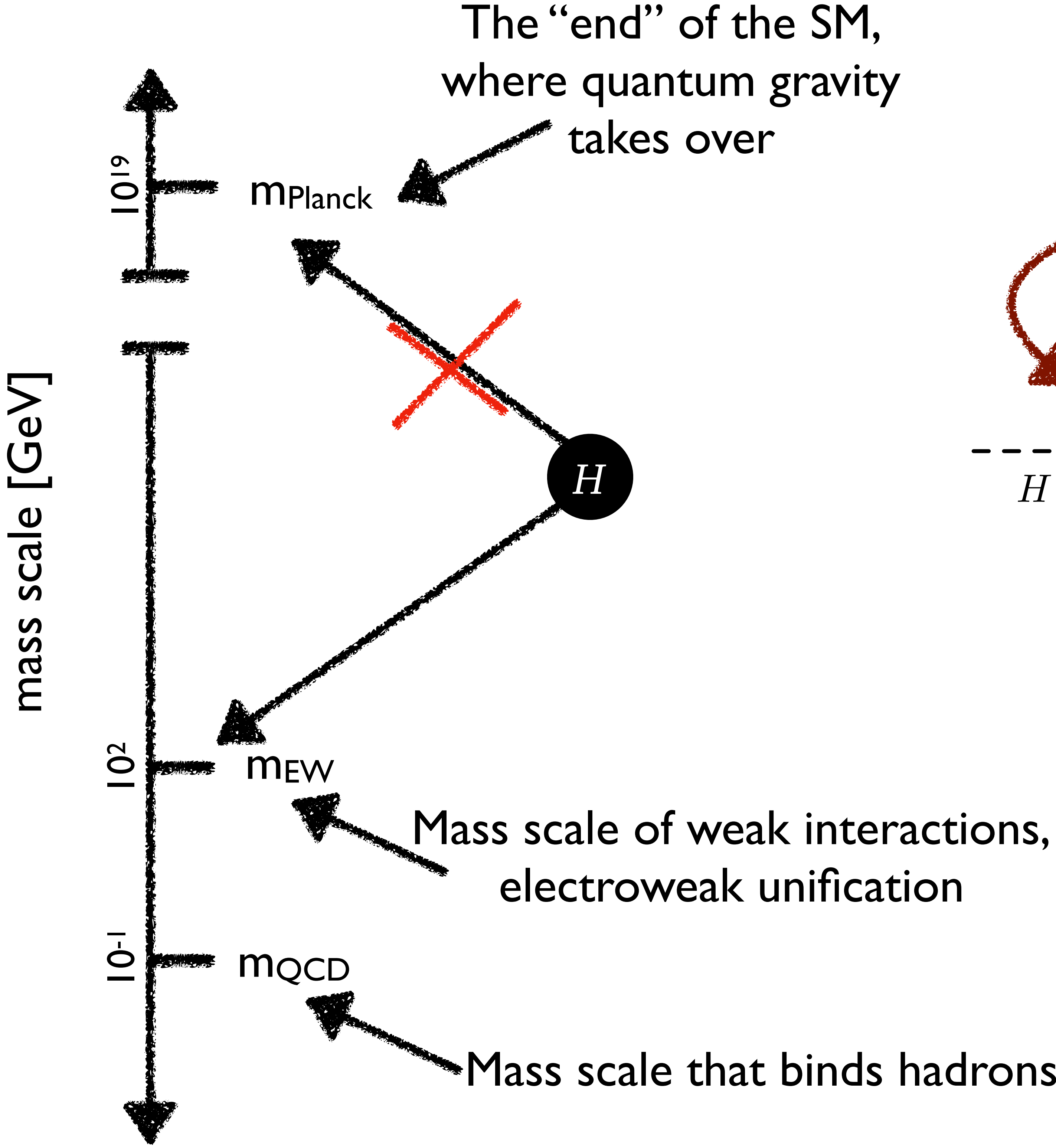

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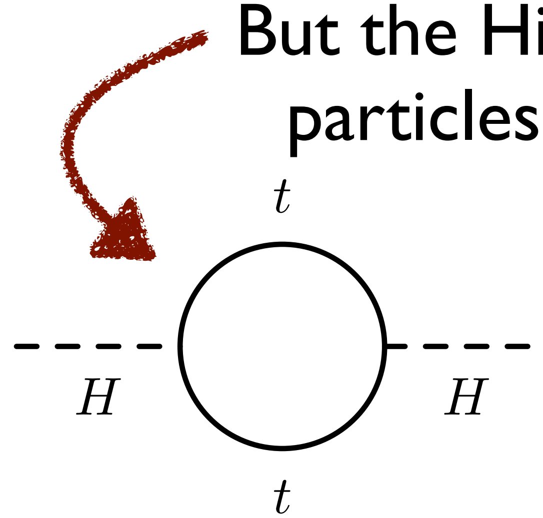

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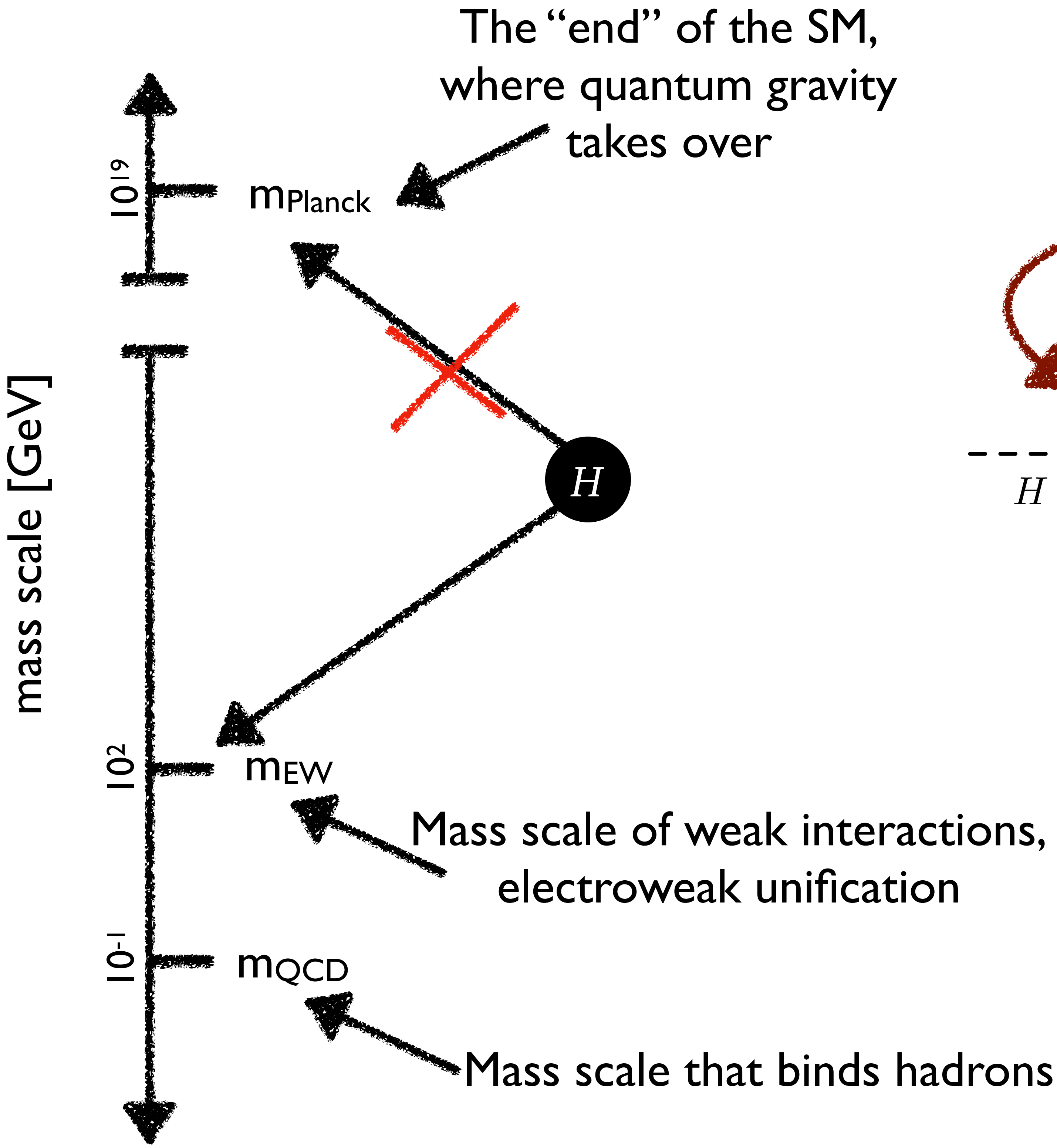
But we observe it at 125 GeV!

Why BSM?



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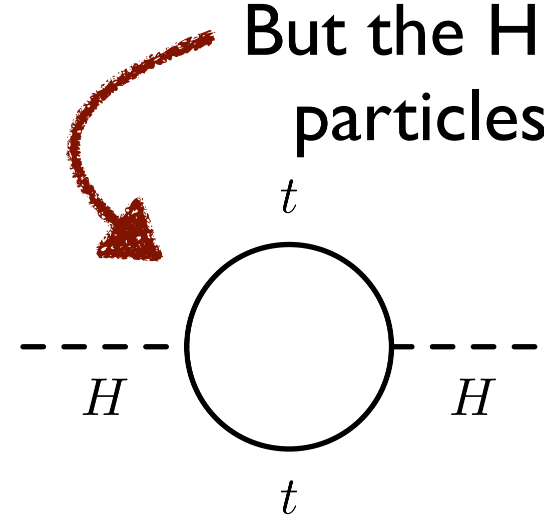

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BSM can stabilize the Higgs mass

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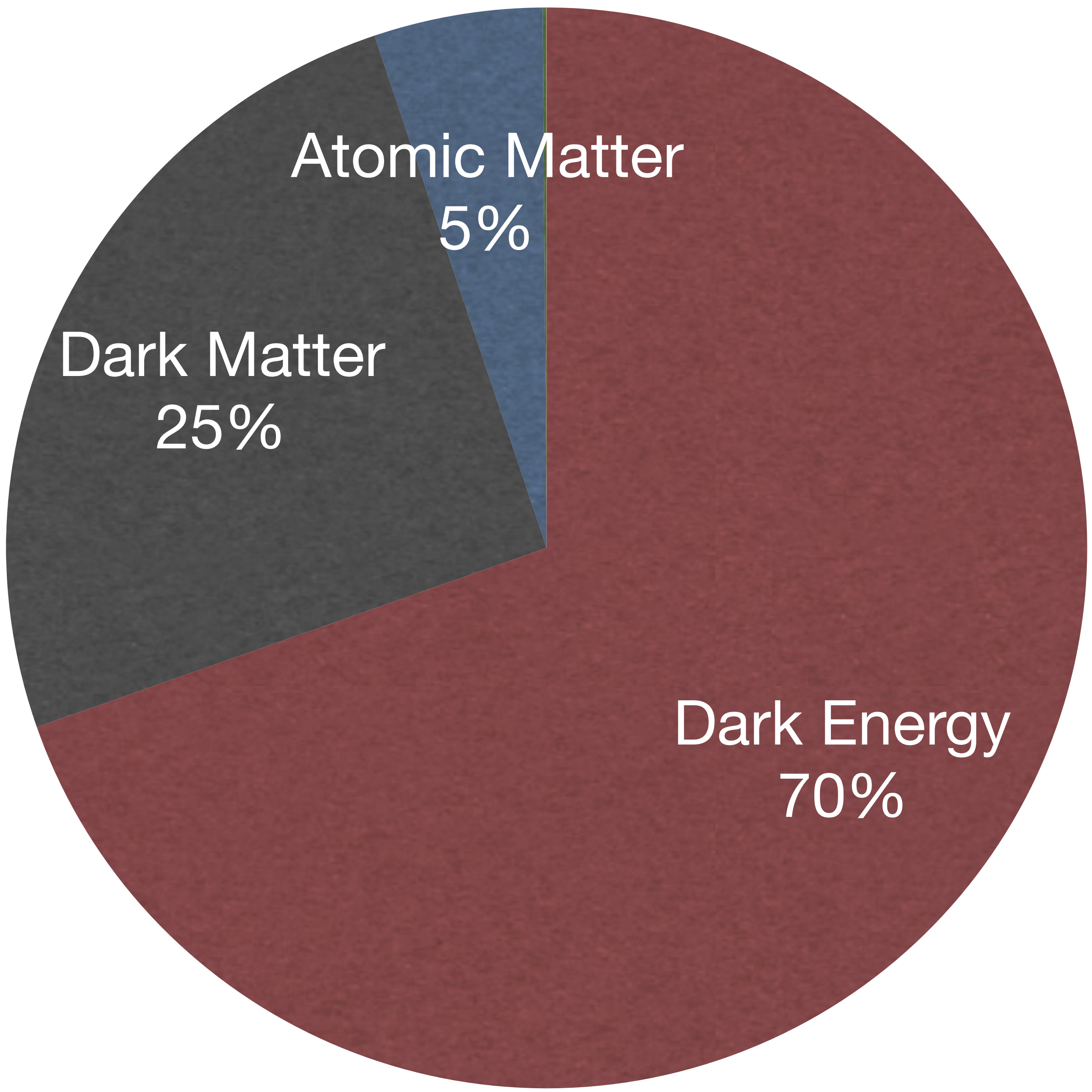

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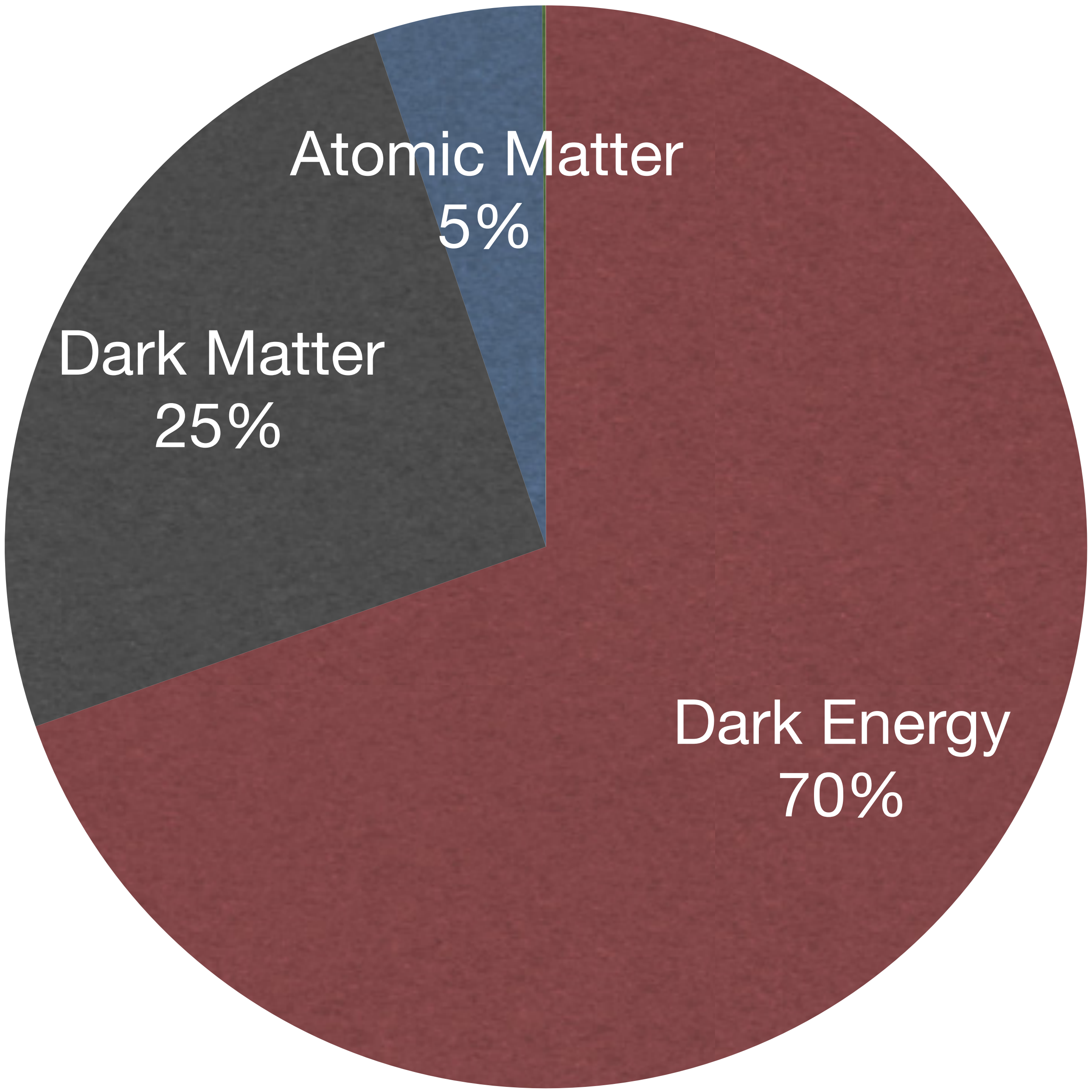

We don't understand the majority of the universe!

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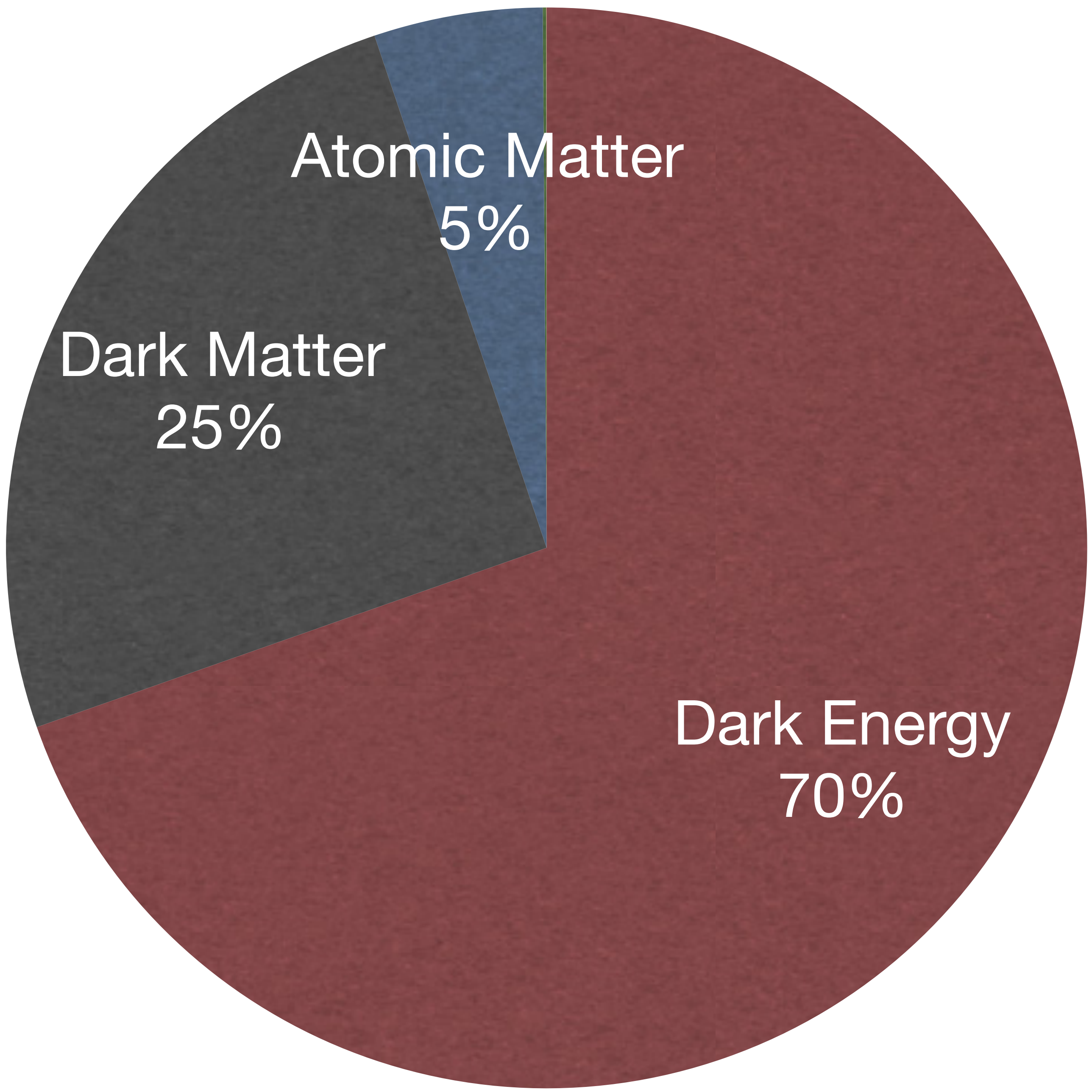

We don't understand the majority of the universe!

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

Why BSM?

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10,000,000,001

Matter

10,000,000,000

Antimatter

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?

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Matter	Antimatter
10,000,000,001	10,000,000,000

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

CP violation in the SM is not enough

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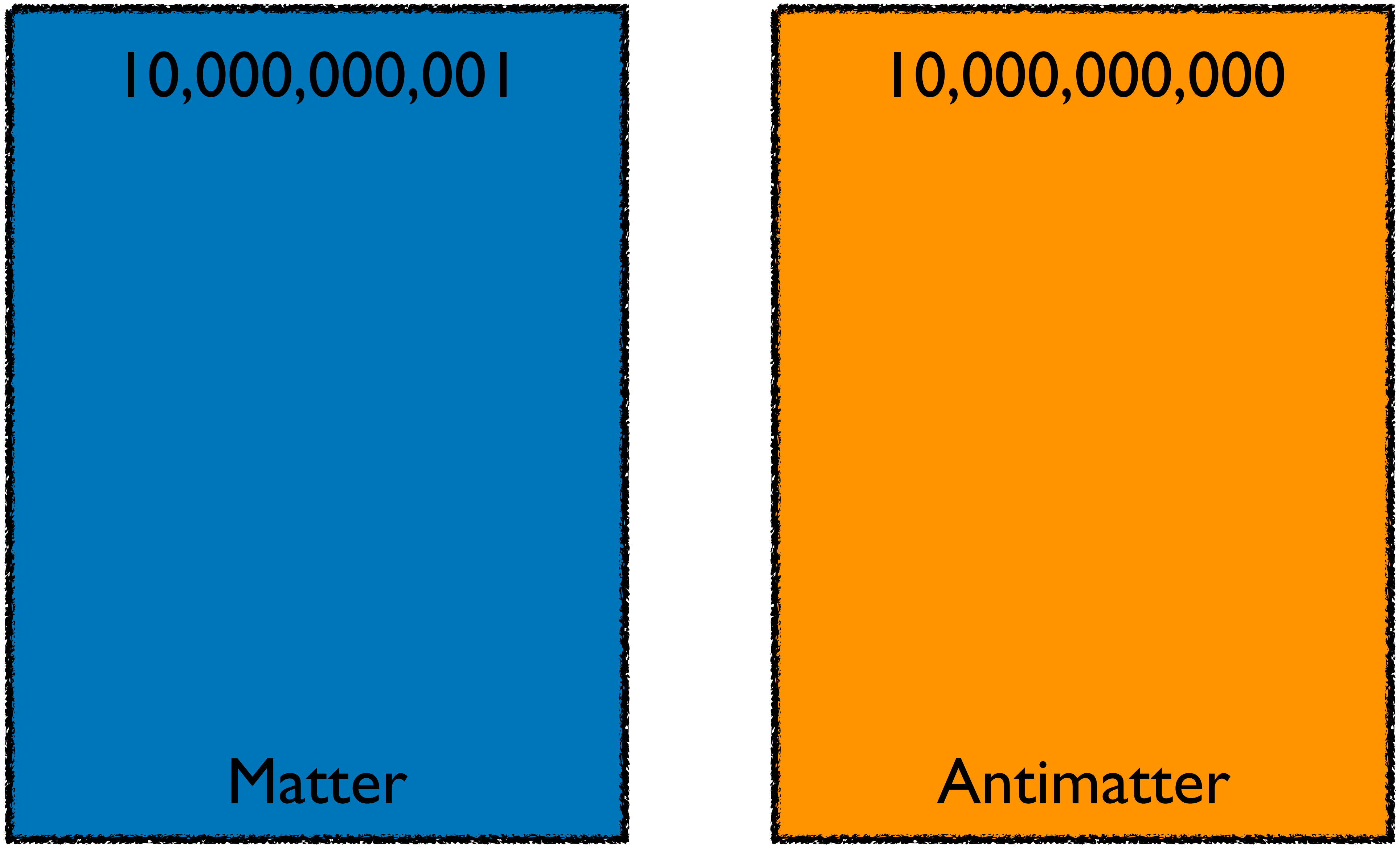

Where did the tiny matter/antimatter asymmetry that leads to a matter dominated universe arise?

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?

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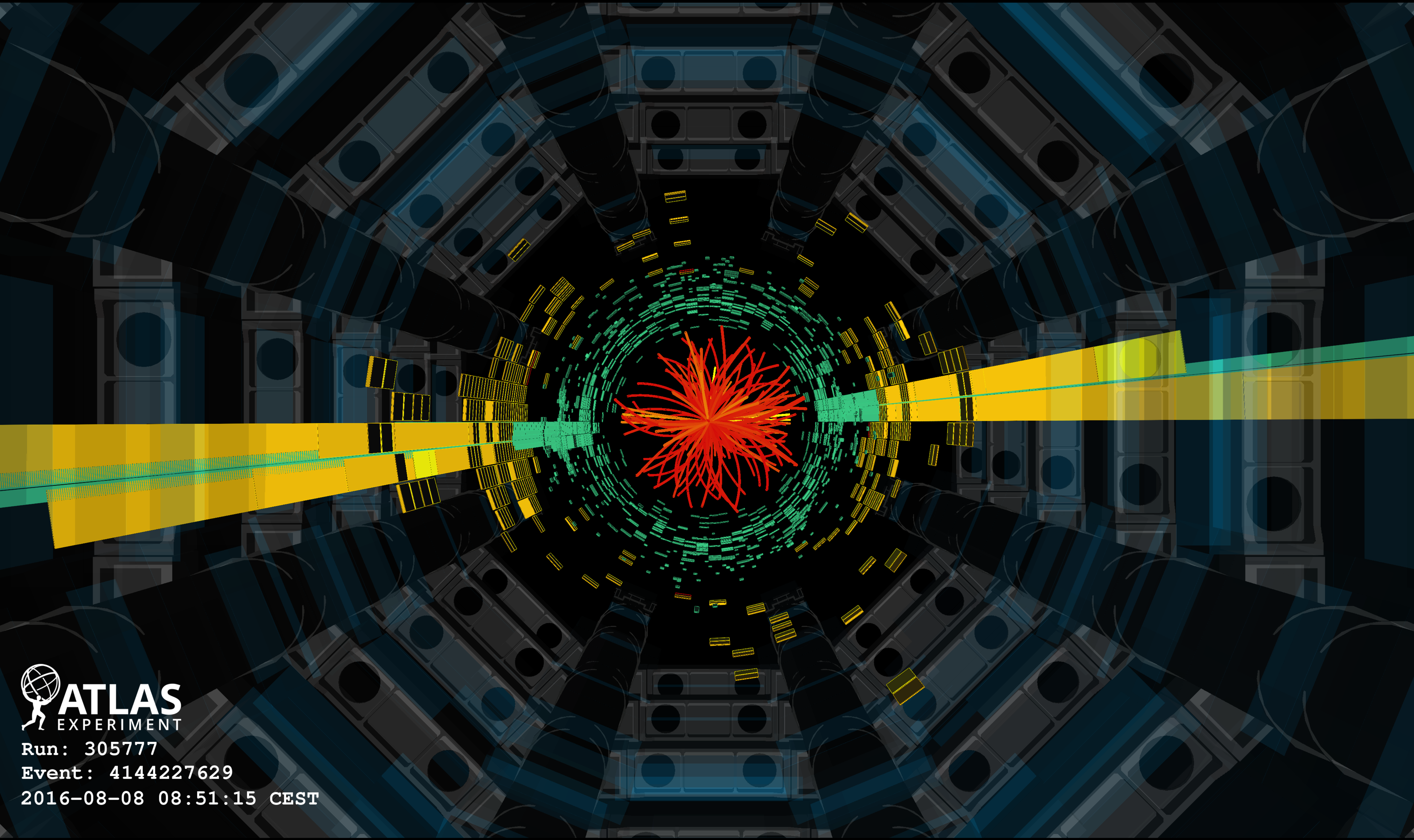

Searching with Dijets

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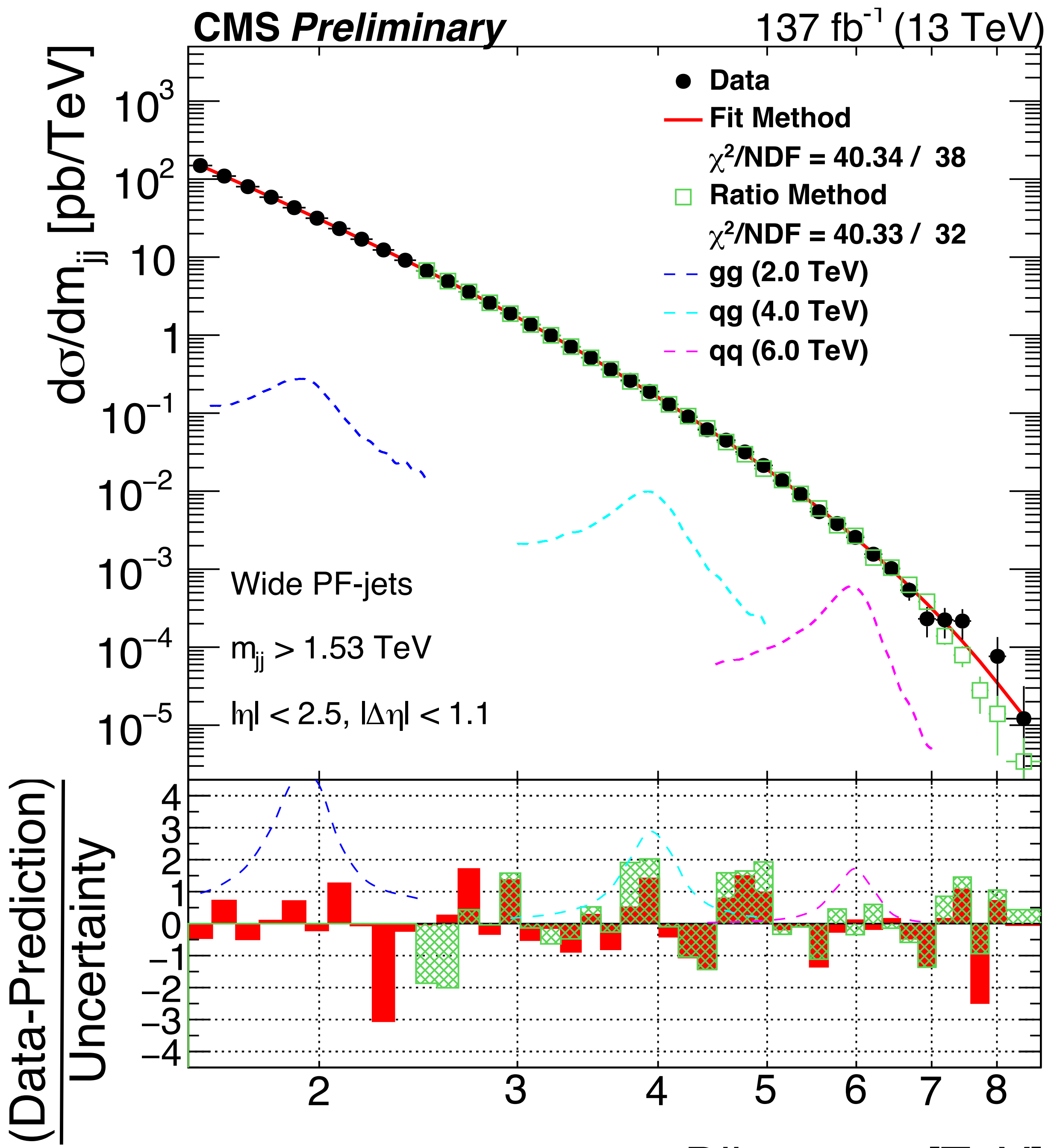
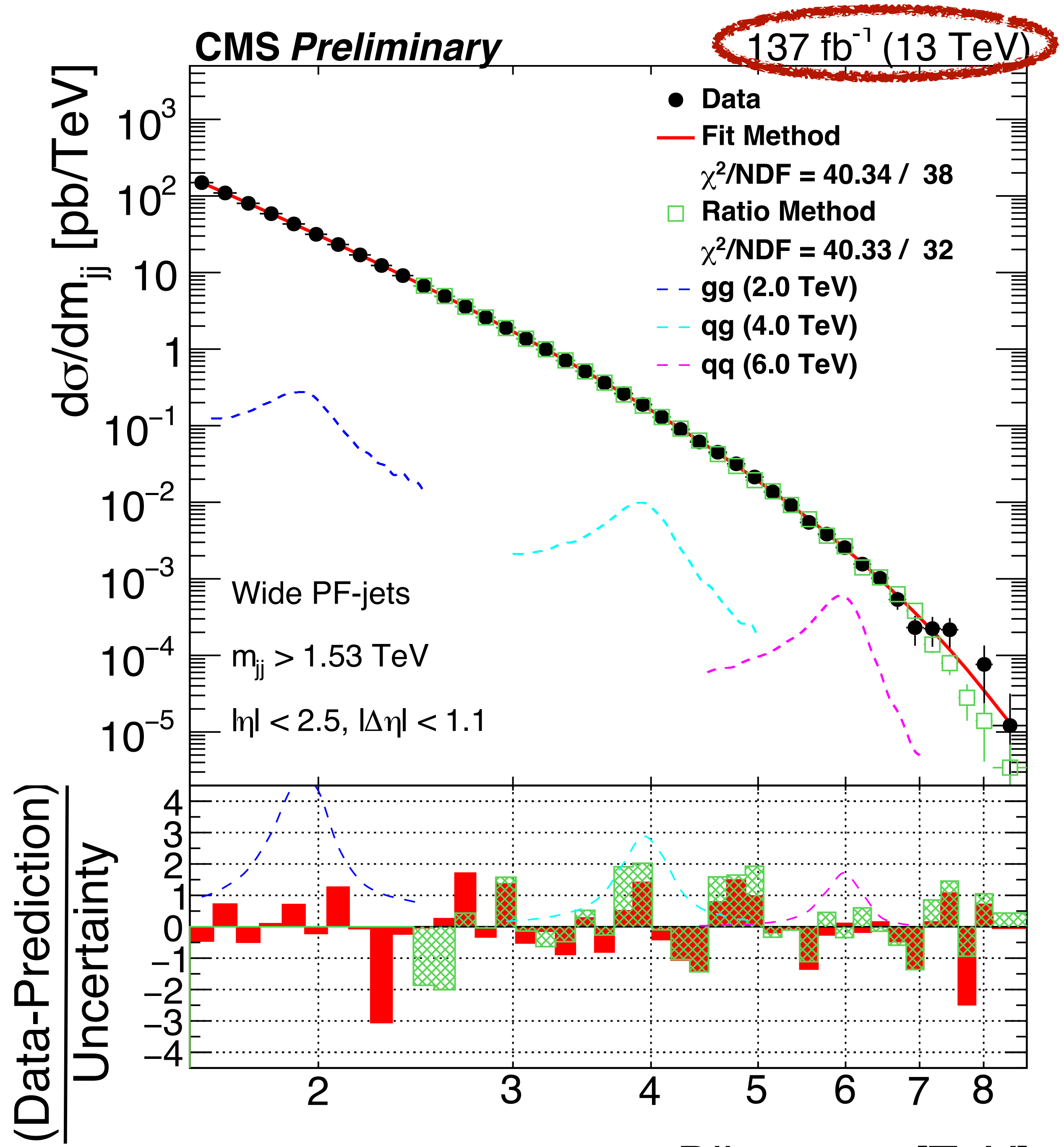


CMS-PAS-EXO-19-012

One of the best BSM signatures: pairs of jets

Searching with Dijets



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Huge dataset enables some of the best sensitivity yet!

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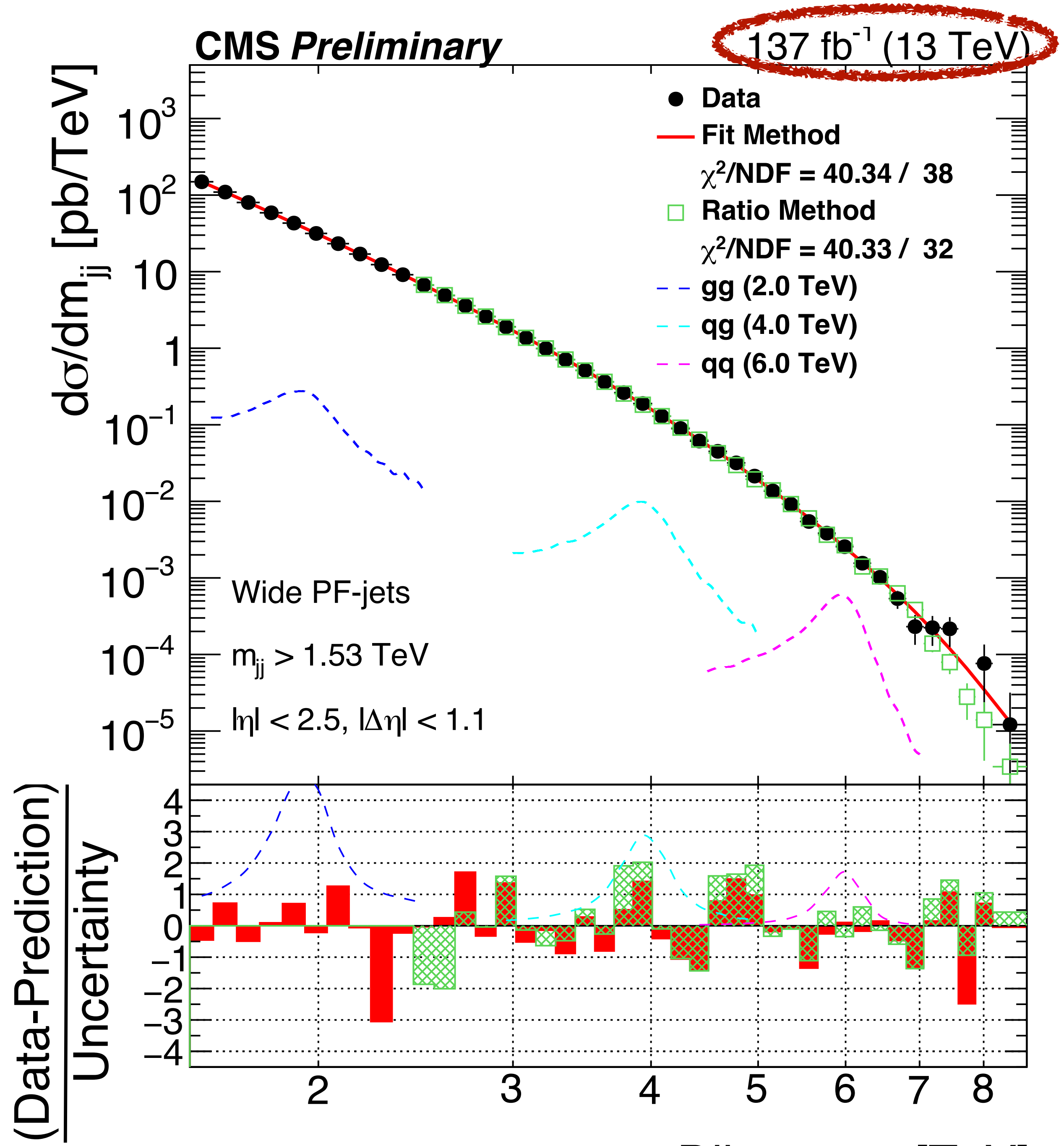
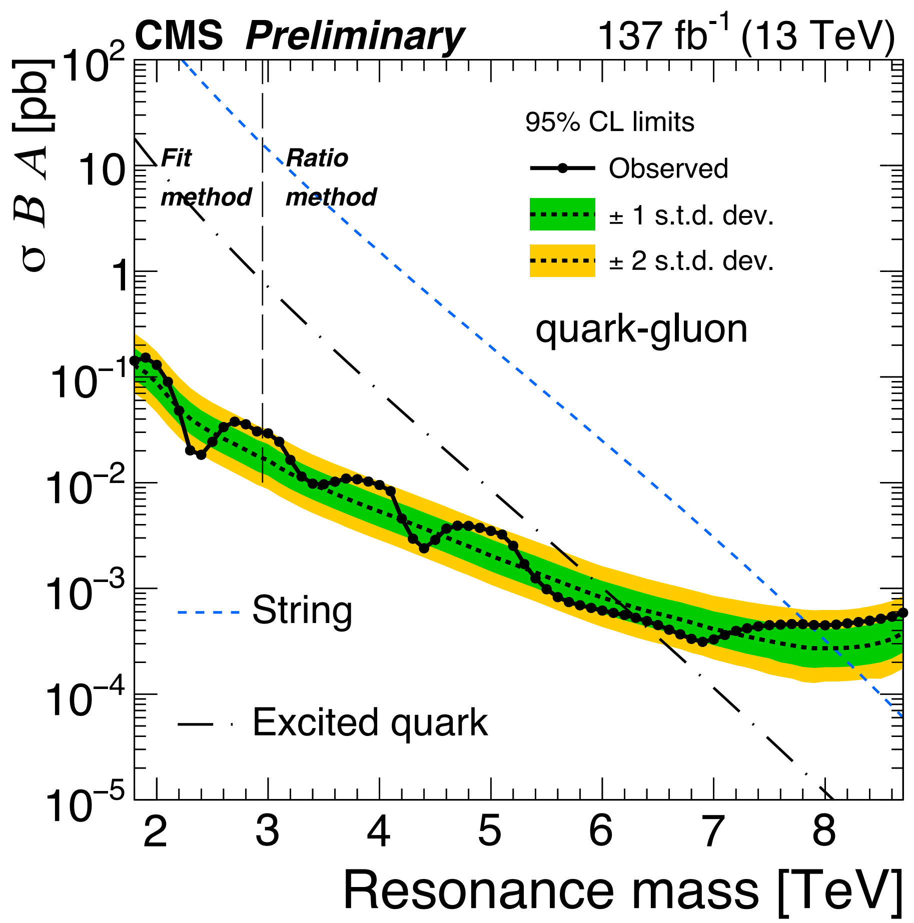


CMS-PAS-EXO-19-012

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?

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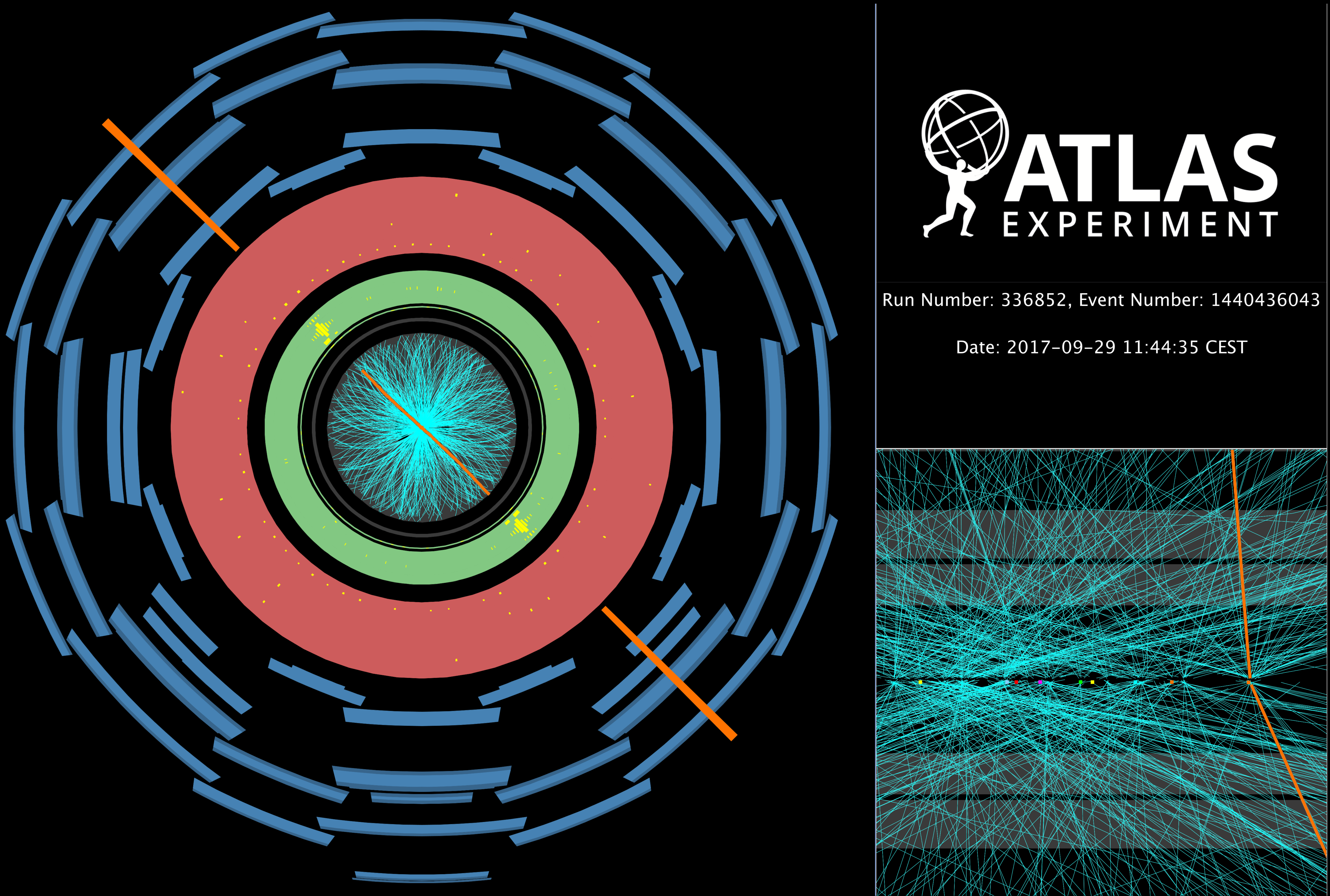

Searching with Leptons

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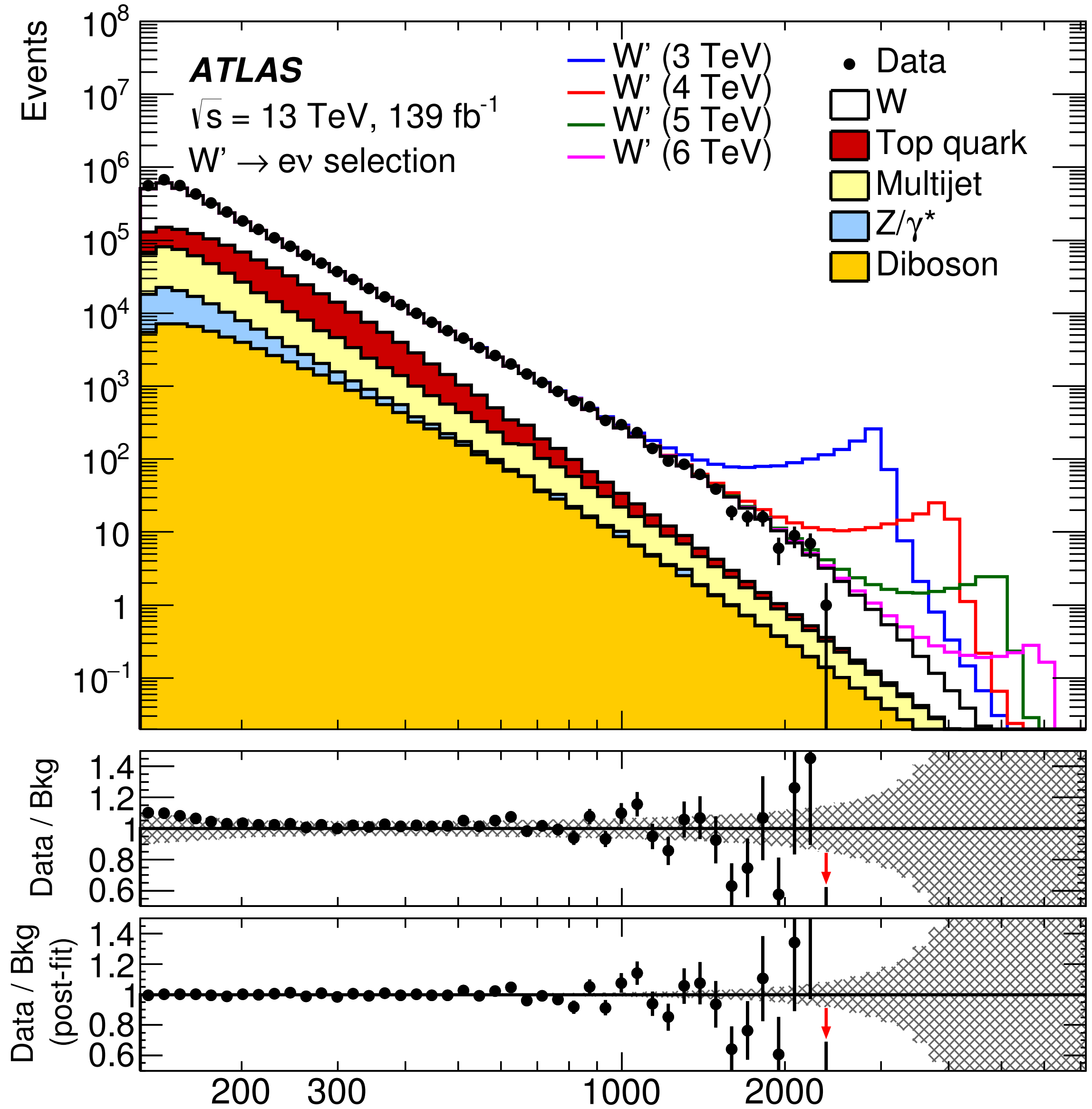
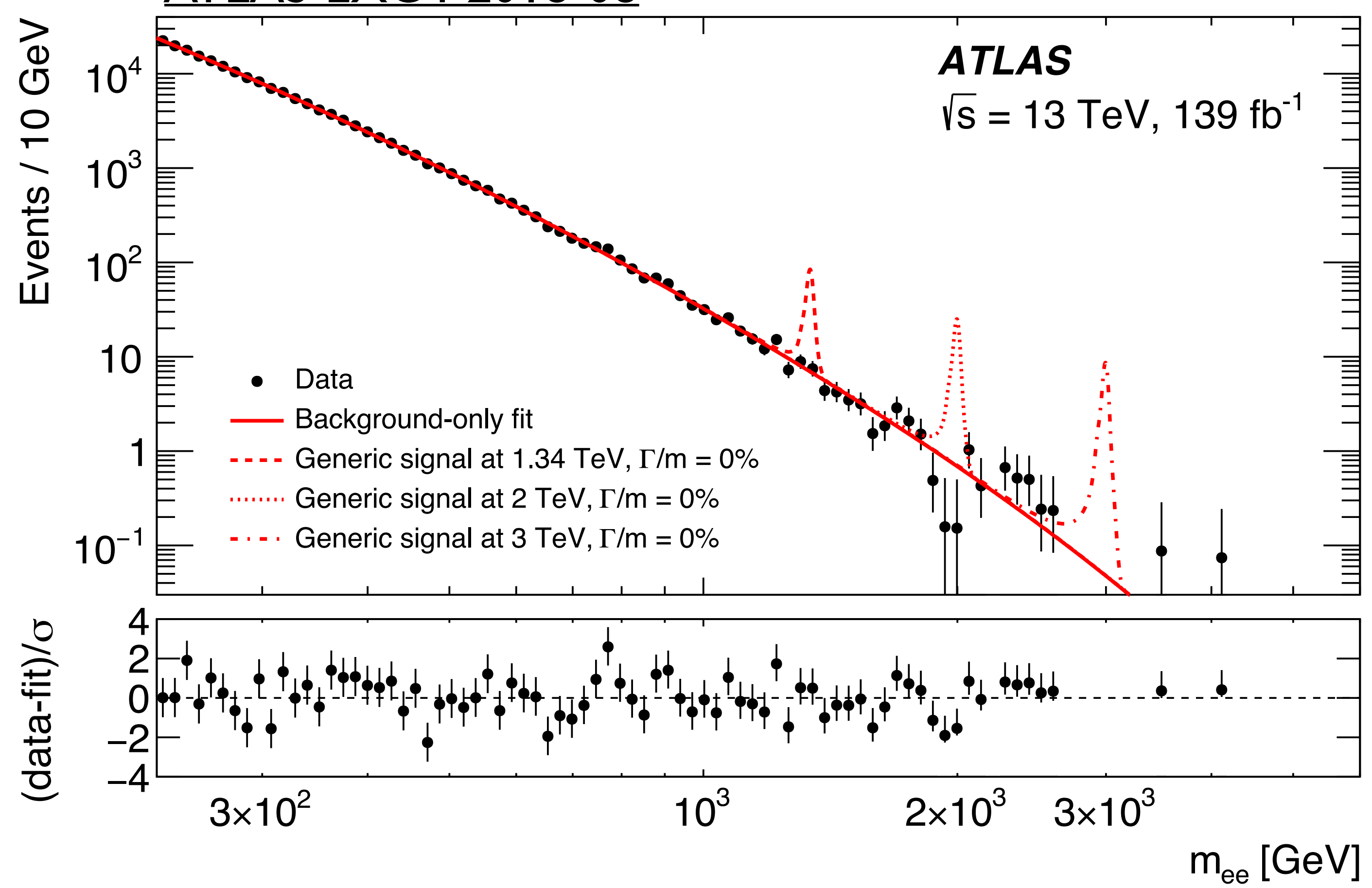


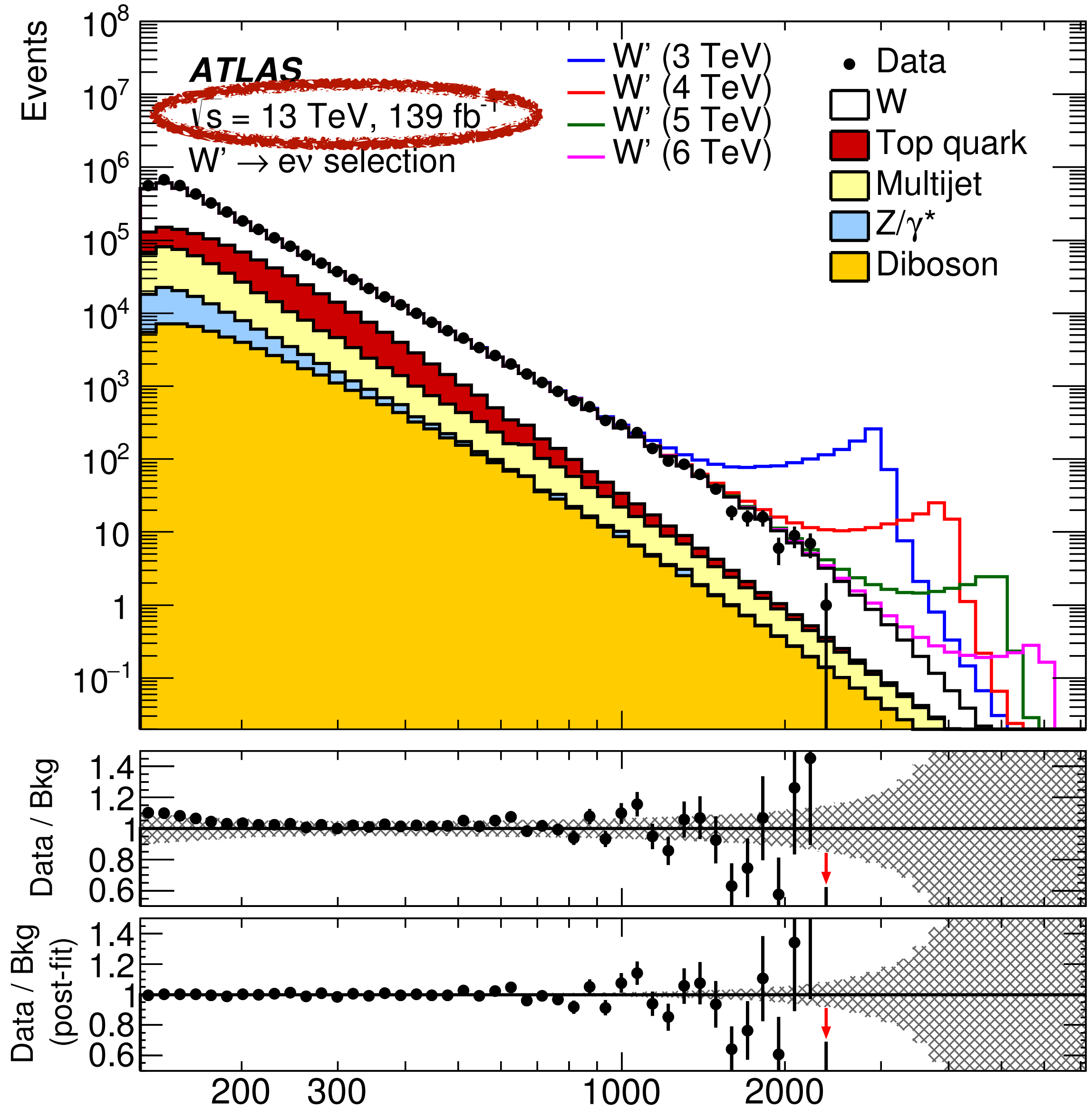
ATLAS-EXOT-2018-30

ATLAS-EXOT-2018-08



You can also search for BSM with lepton resonances!

Searching with Leptons



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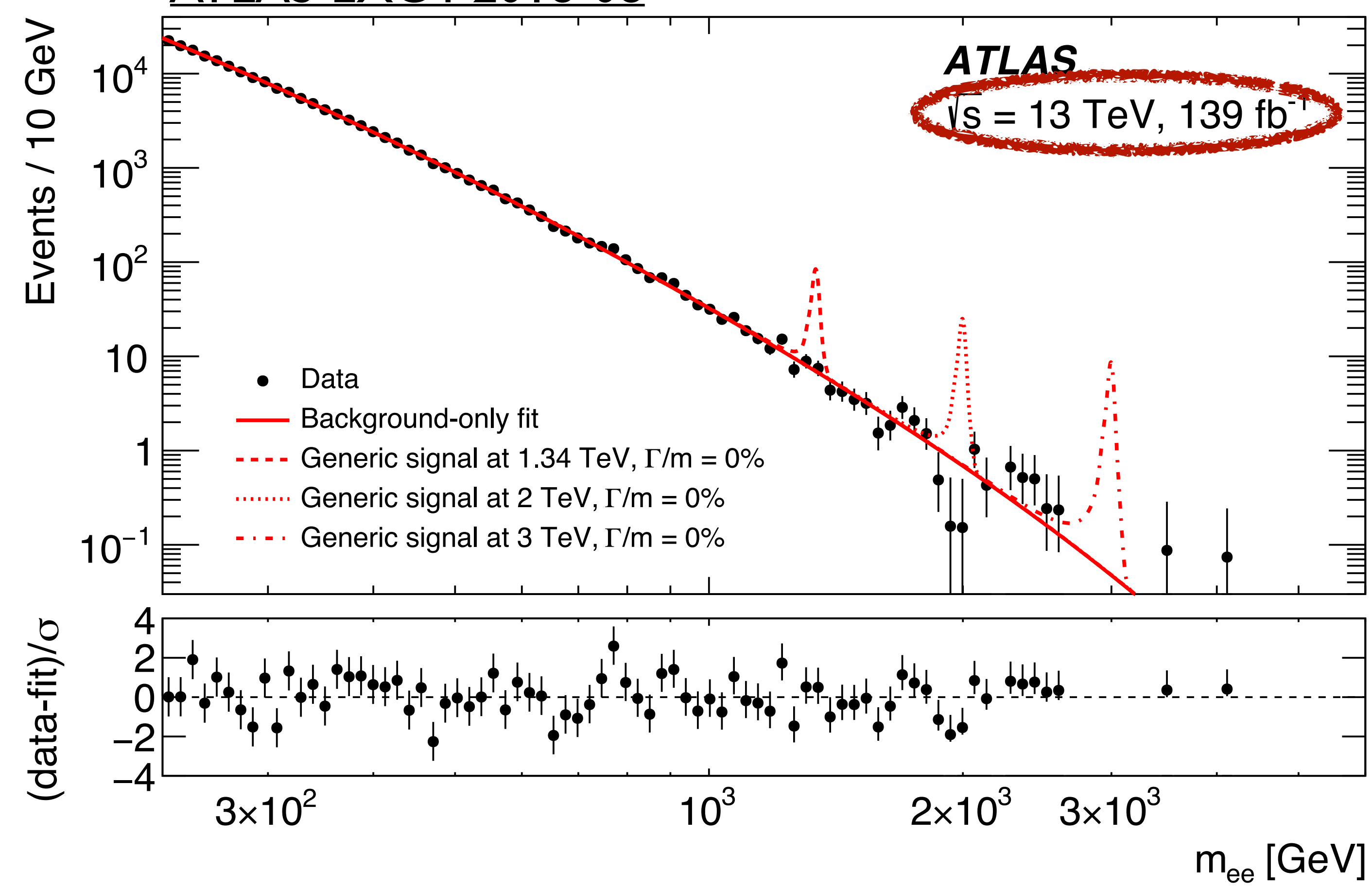

You can also search for BSM with lepton resonances!

Not better luck here, even with the full datasets

What about more complicated signatures?

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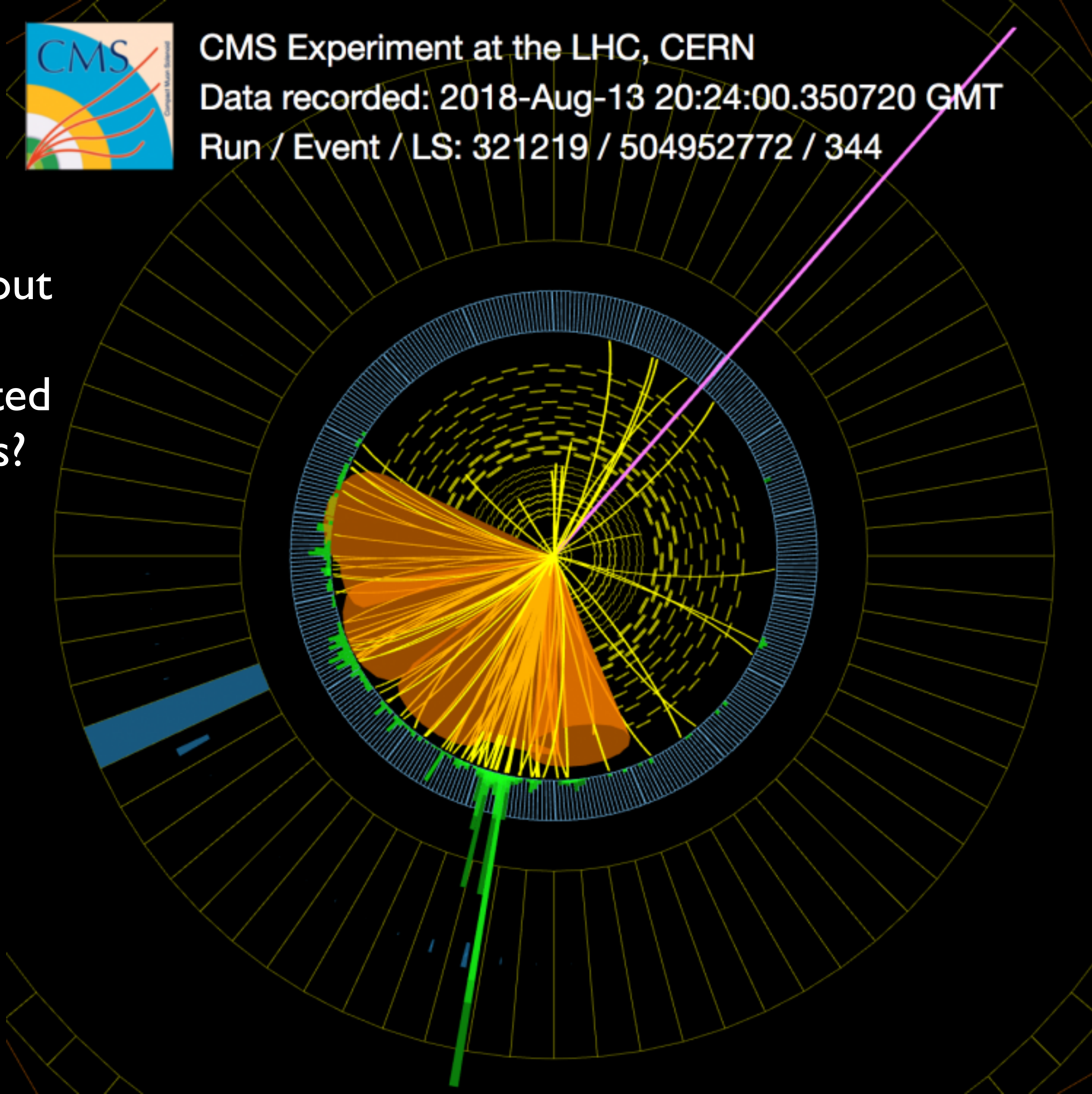

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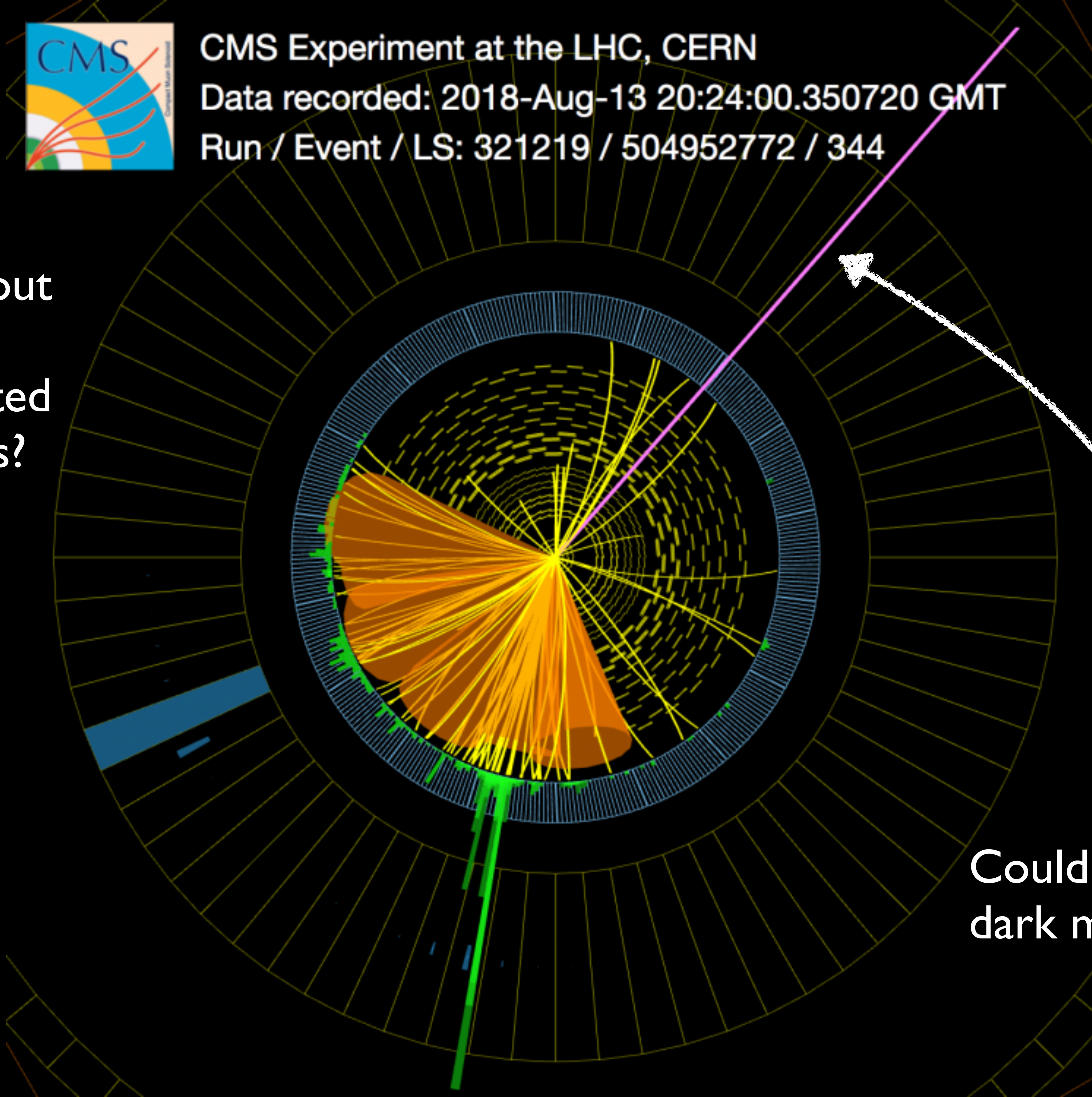

Could this be dark matter?

SUSY Signatures

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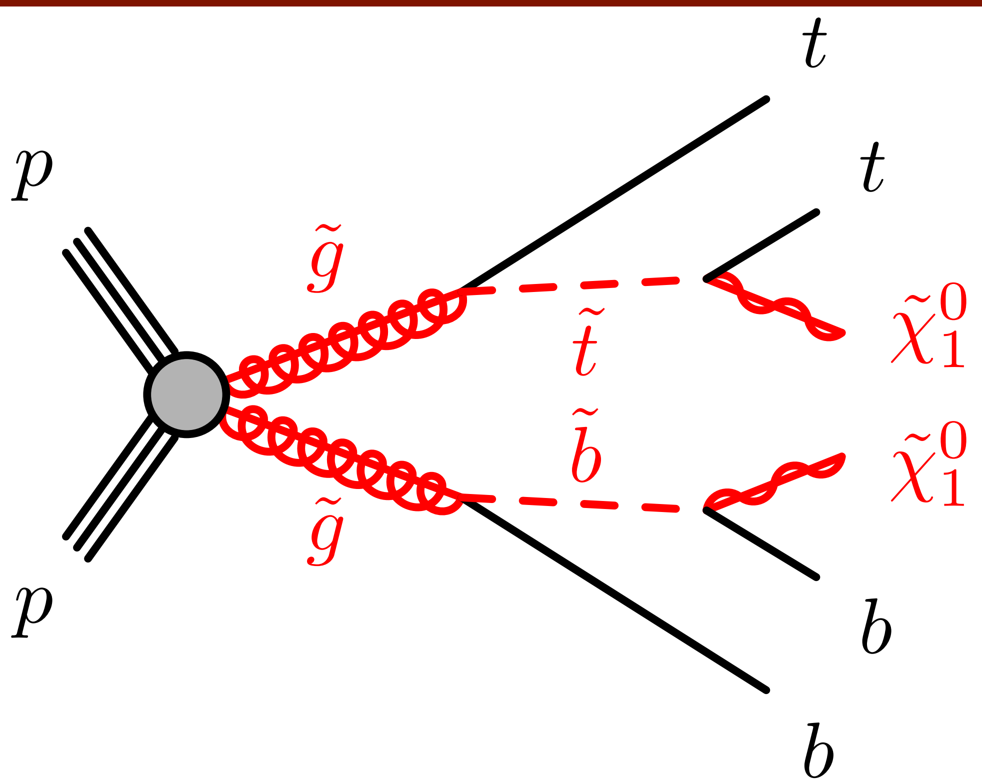
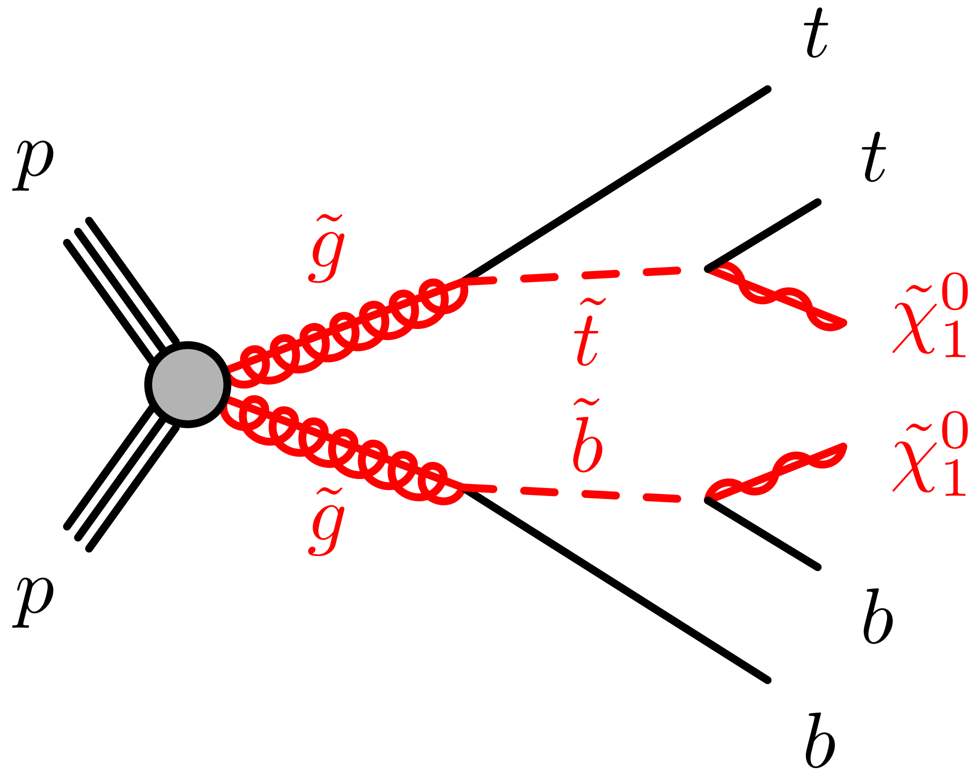


Supersymmetry predicts more complicated final states…

SUSY Signatures



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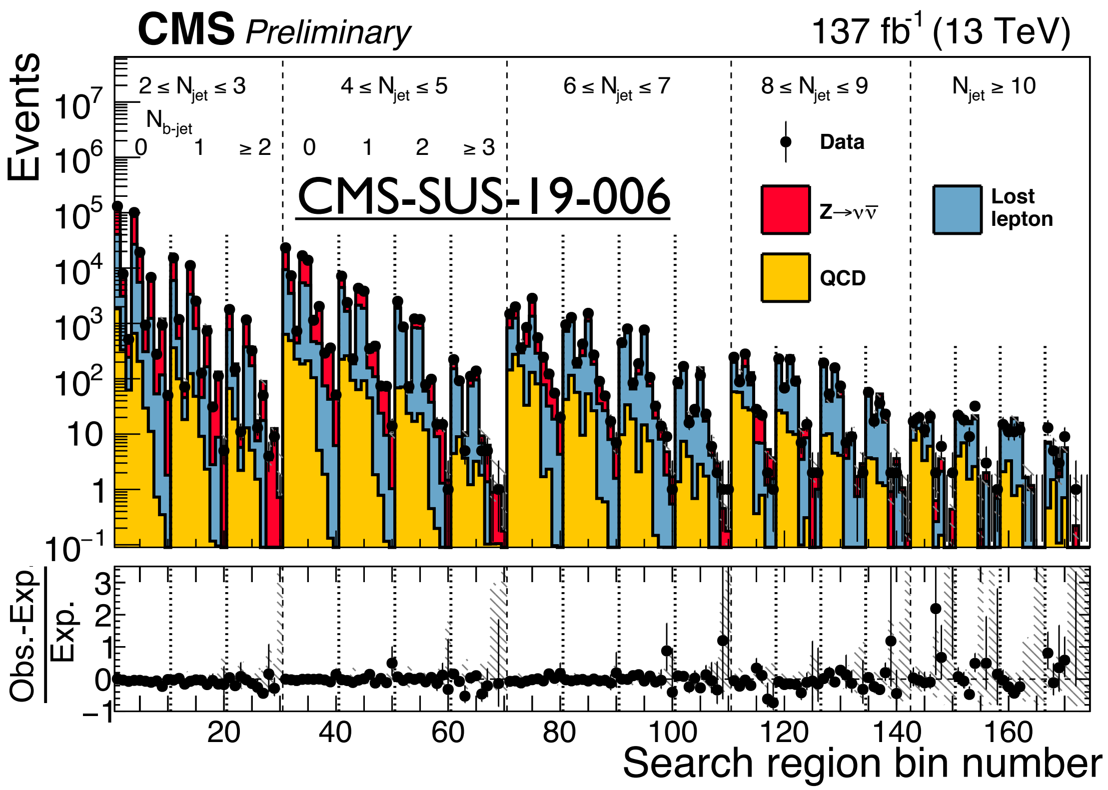

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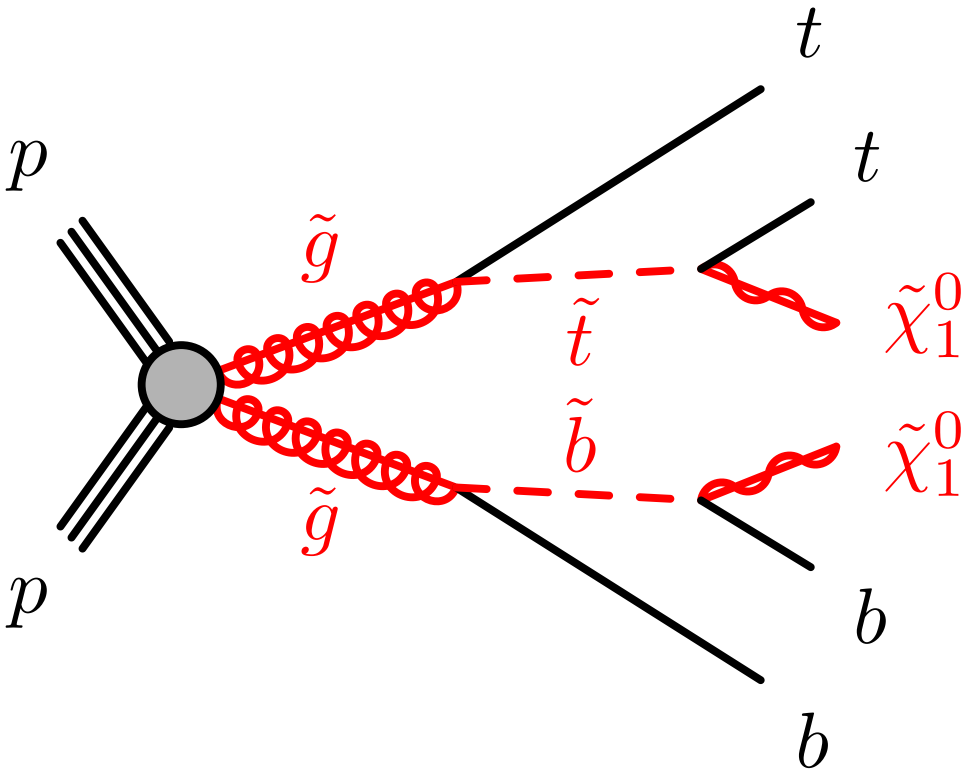

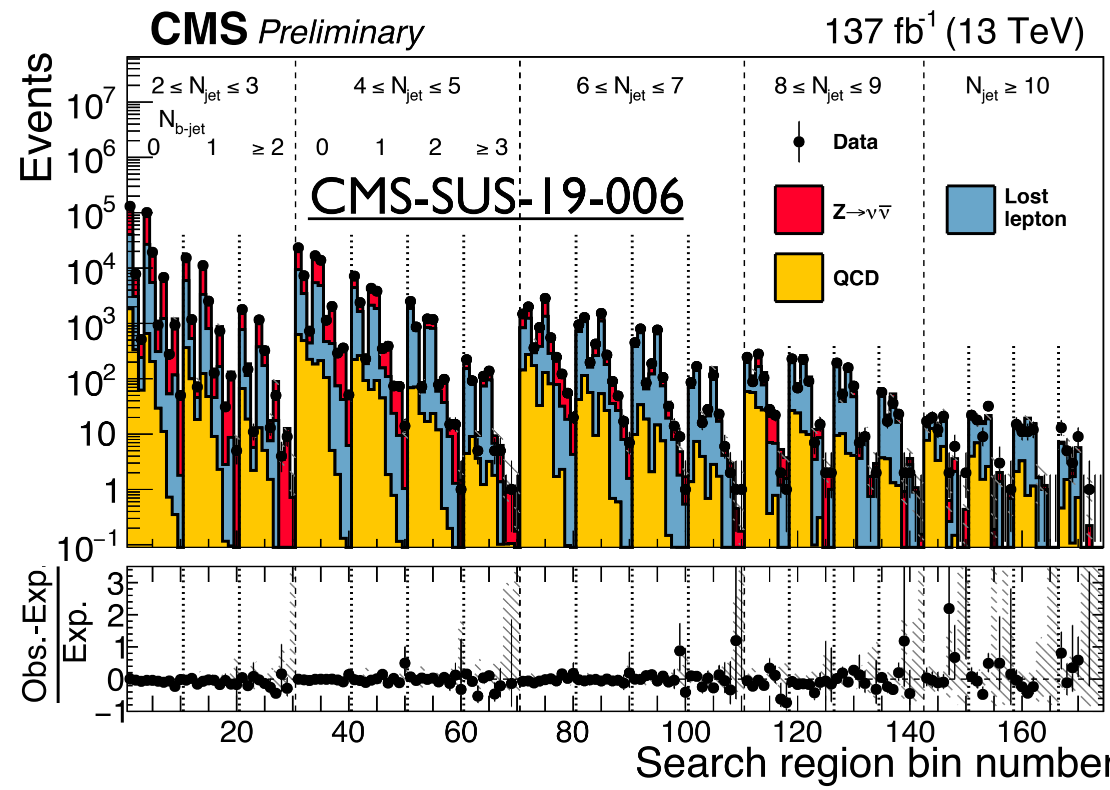

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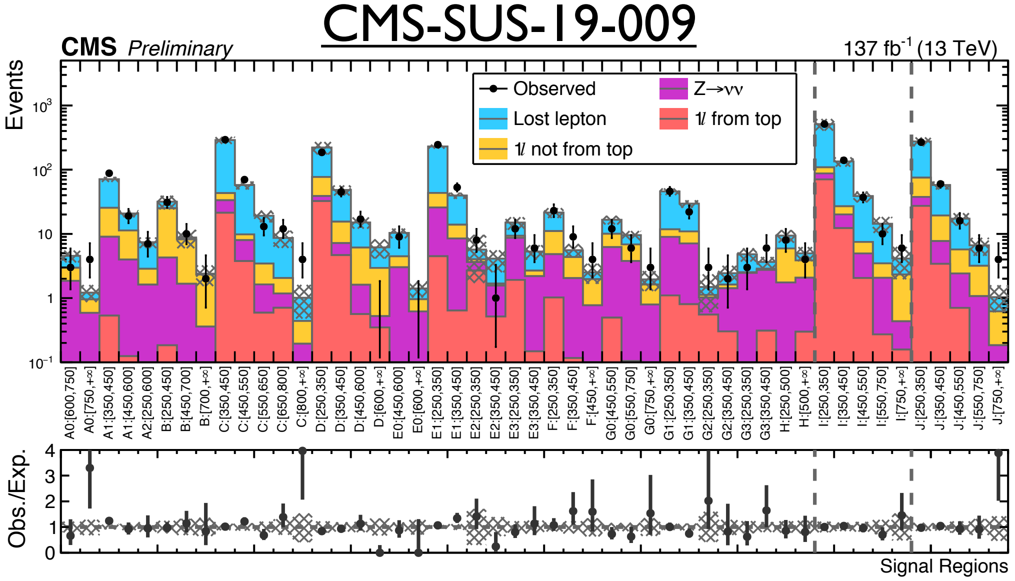
CMS-SUS-19-009



	N_J	t_{mod}	$M_{\ell b}$ [GeV]
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X0: Inclusive
X1: Untagged
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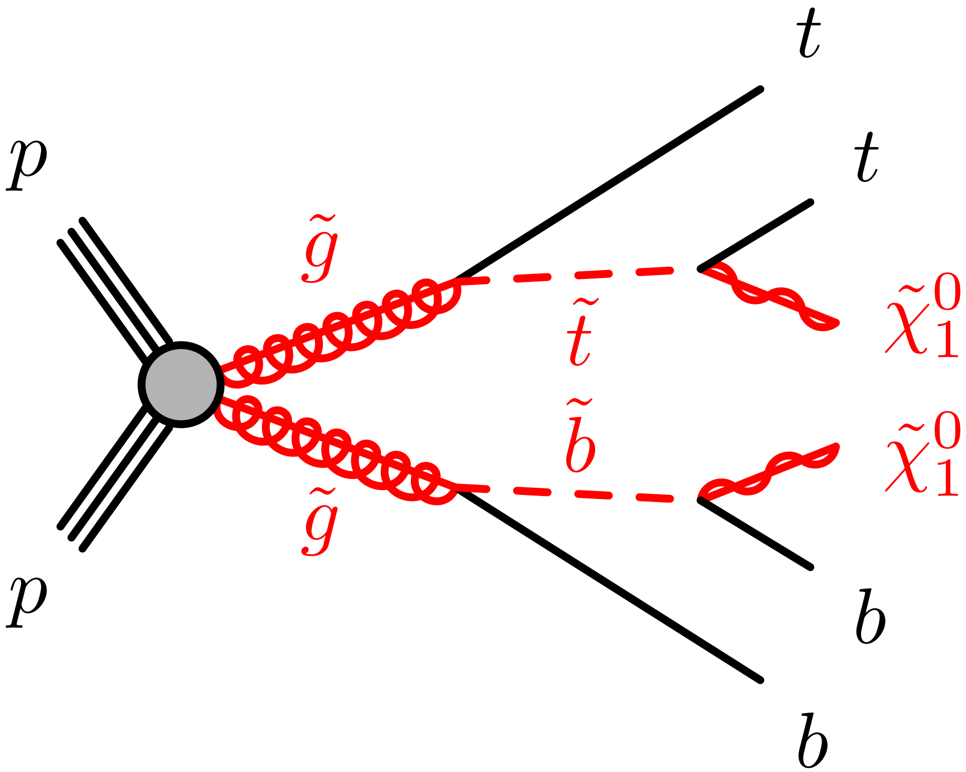
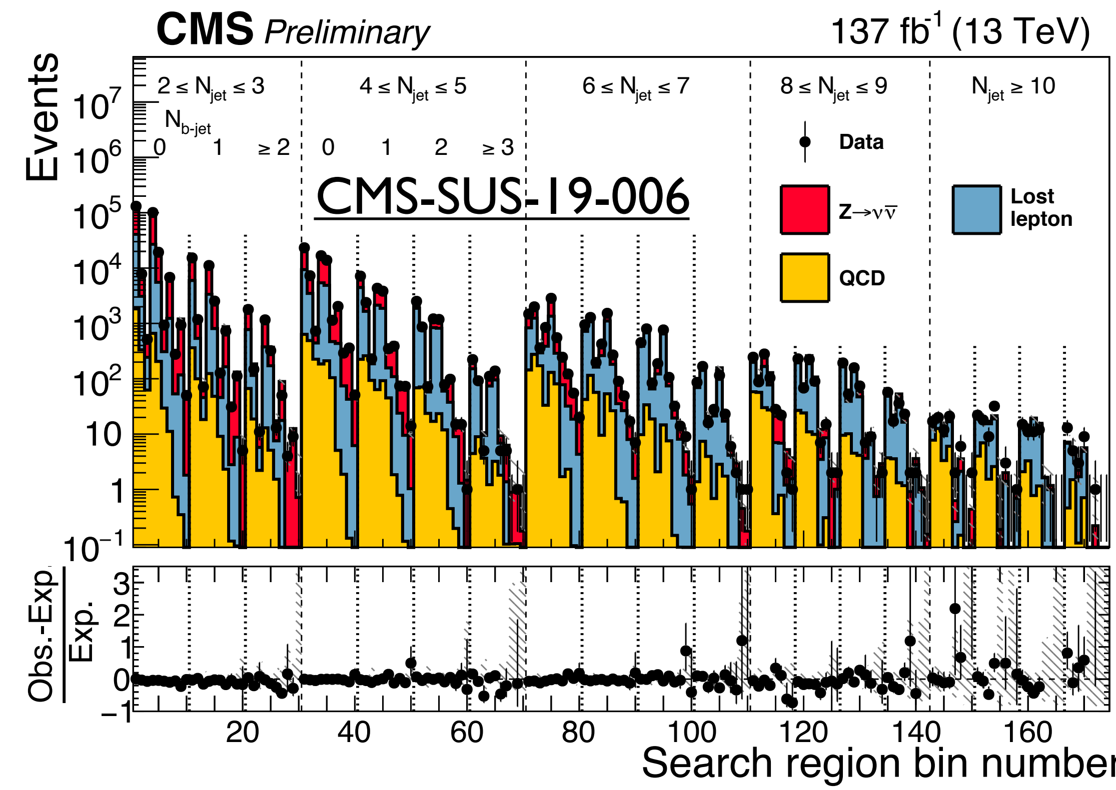
SUSY Signatures





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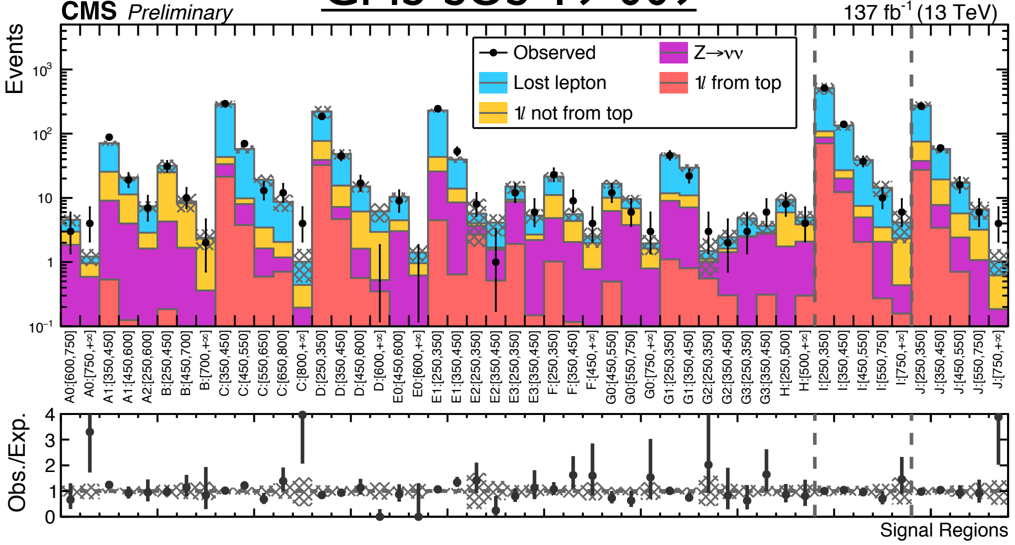

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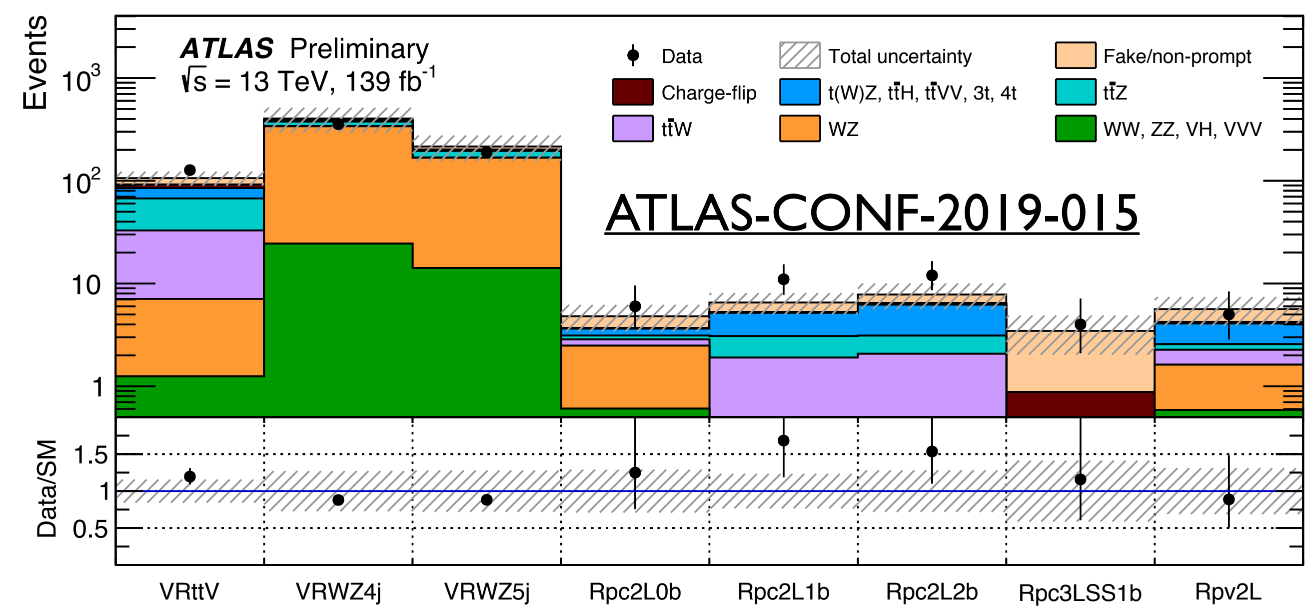

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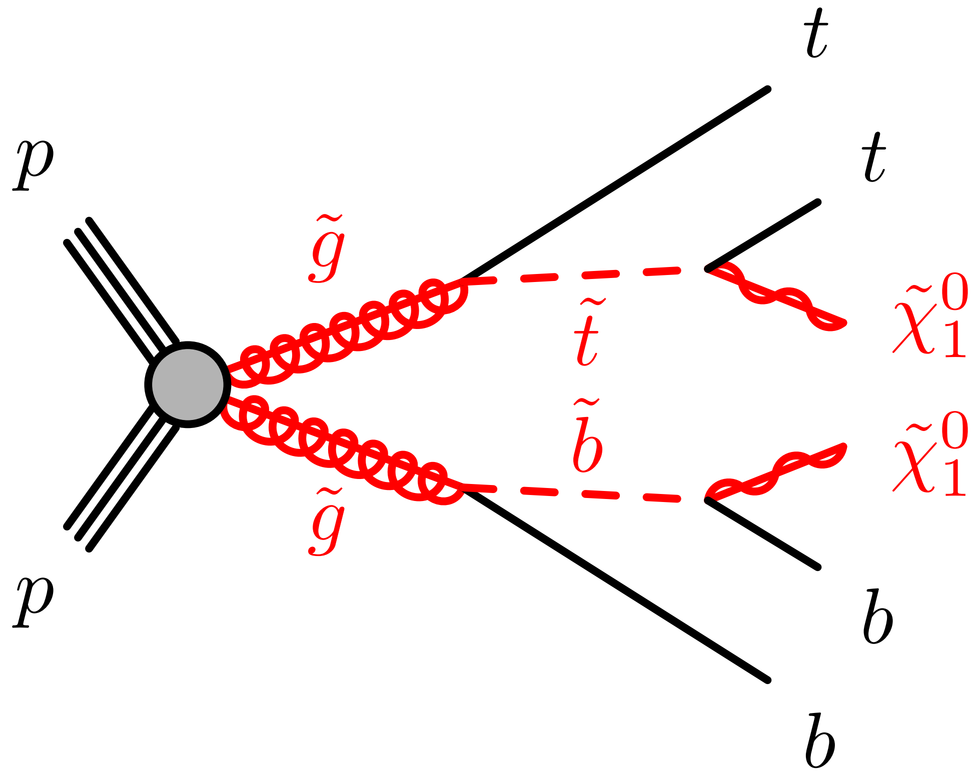

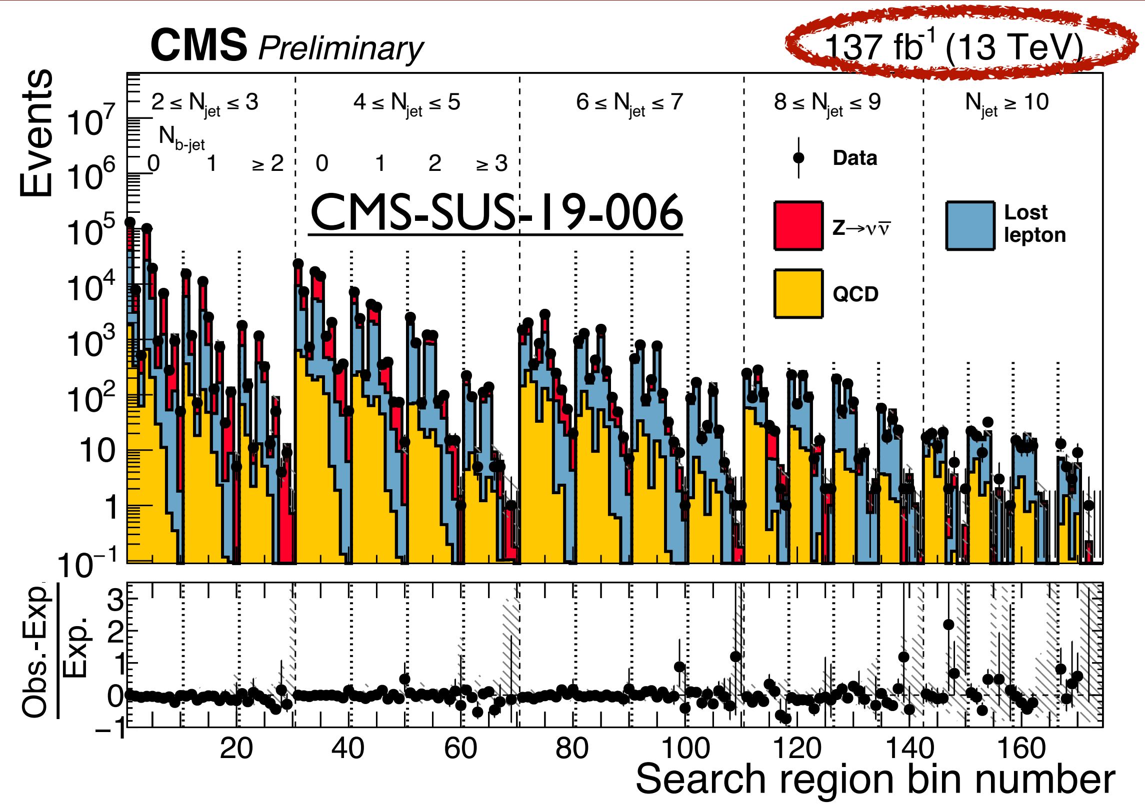

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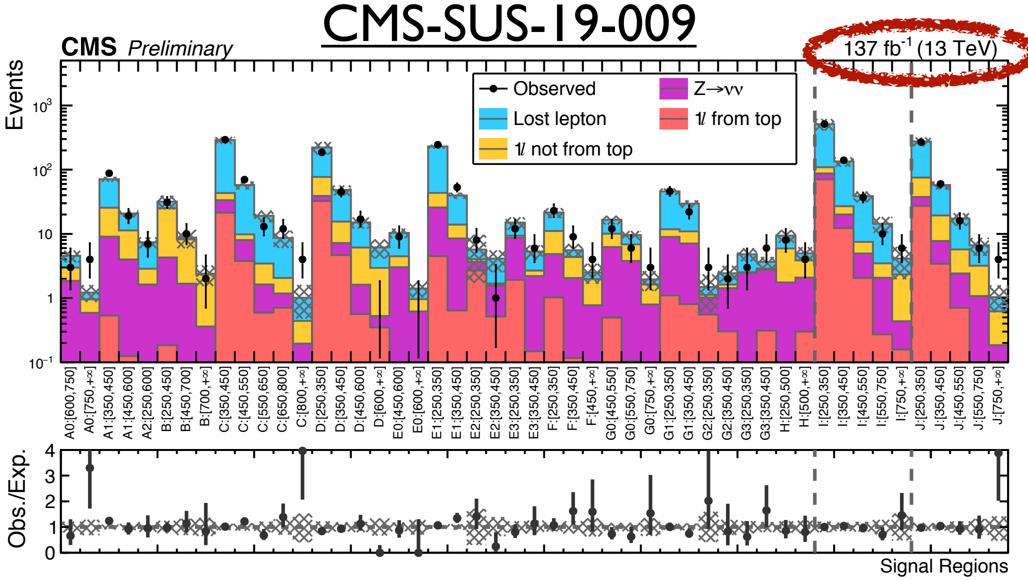

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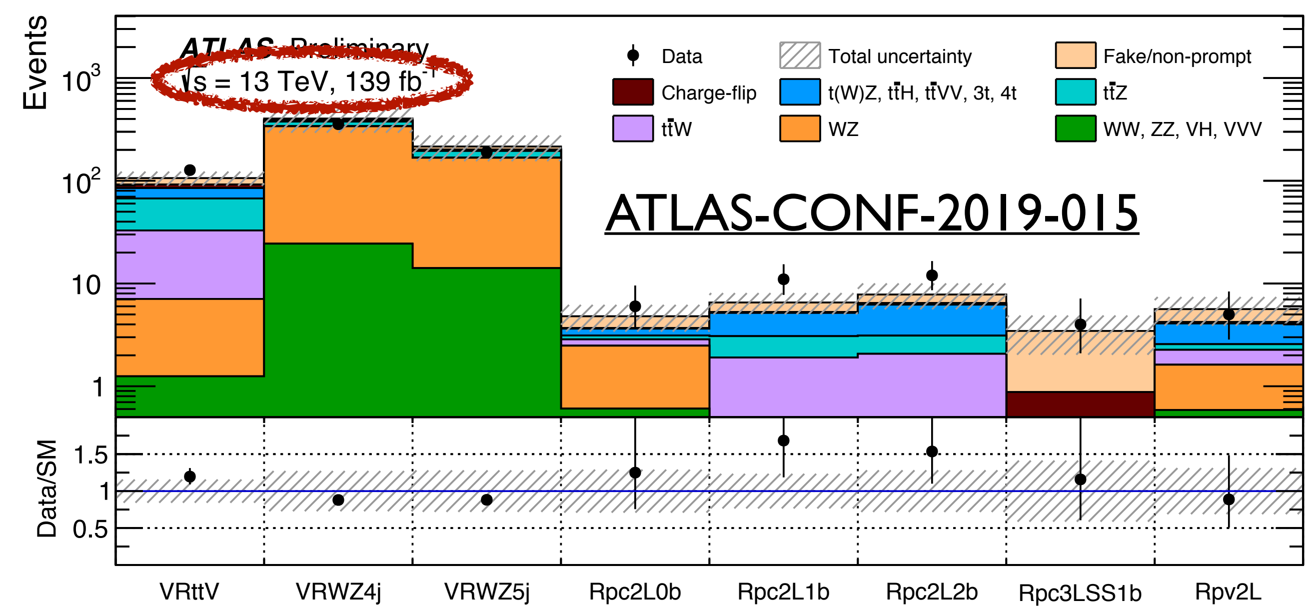

But still no hints, even with full data!

Our Sensitivity is Better Than Ever

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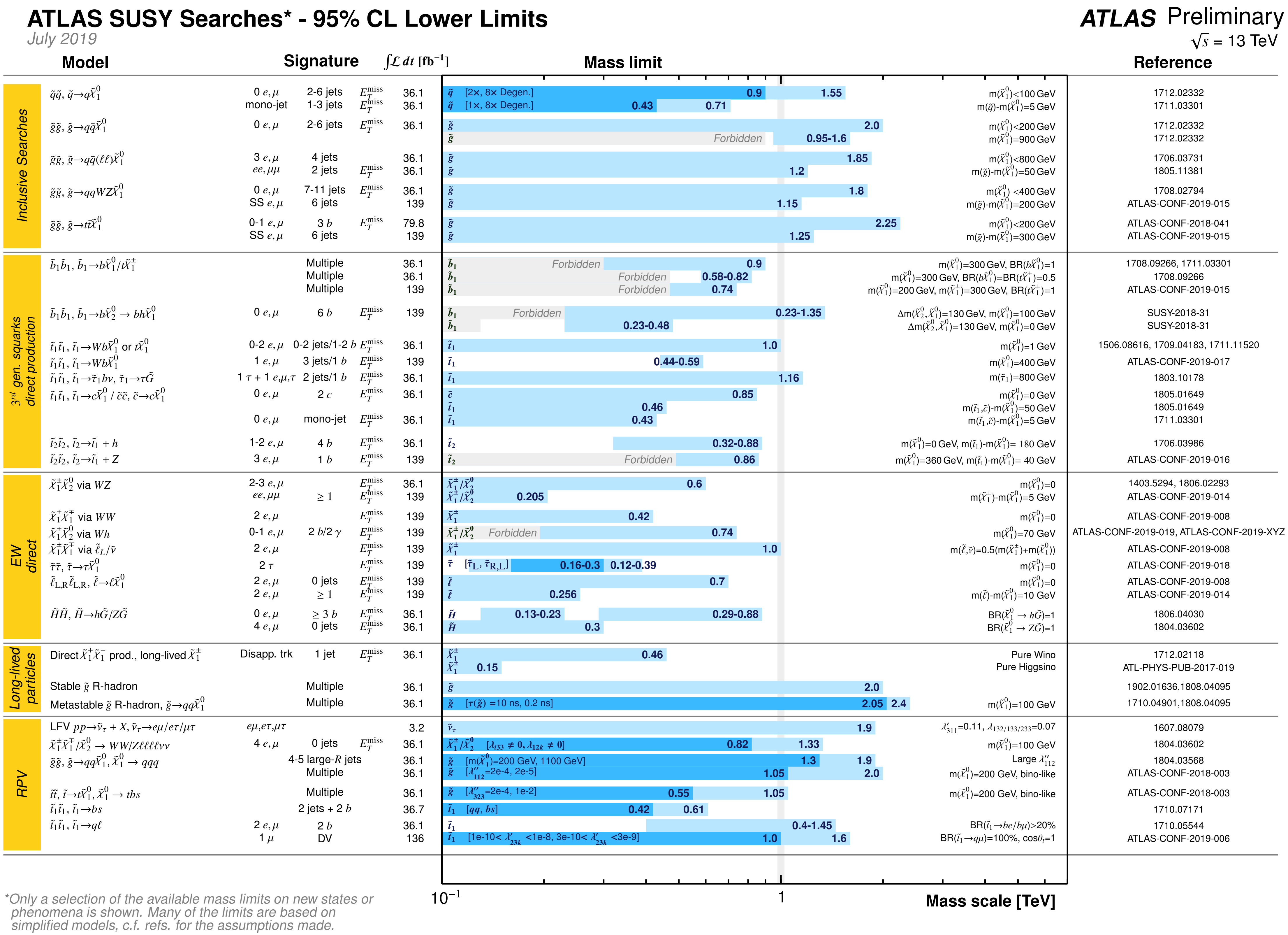

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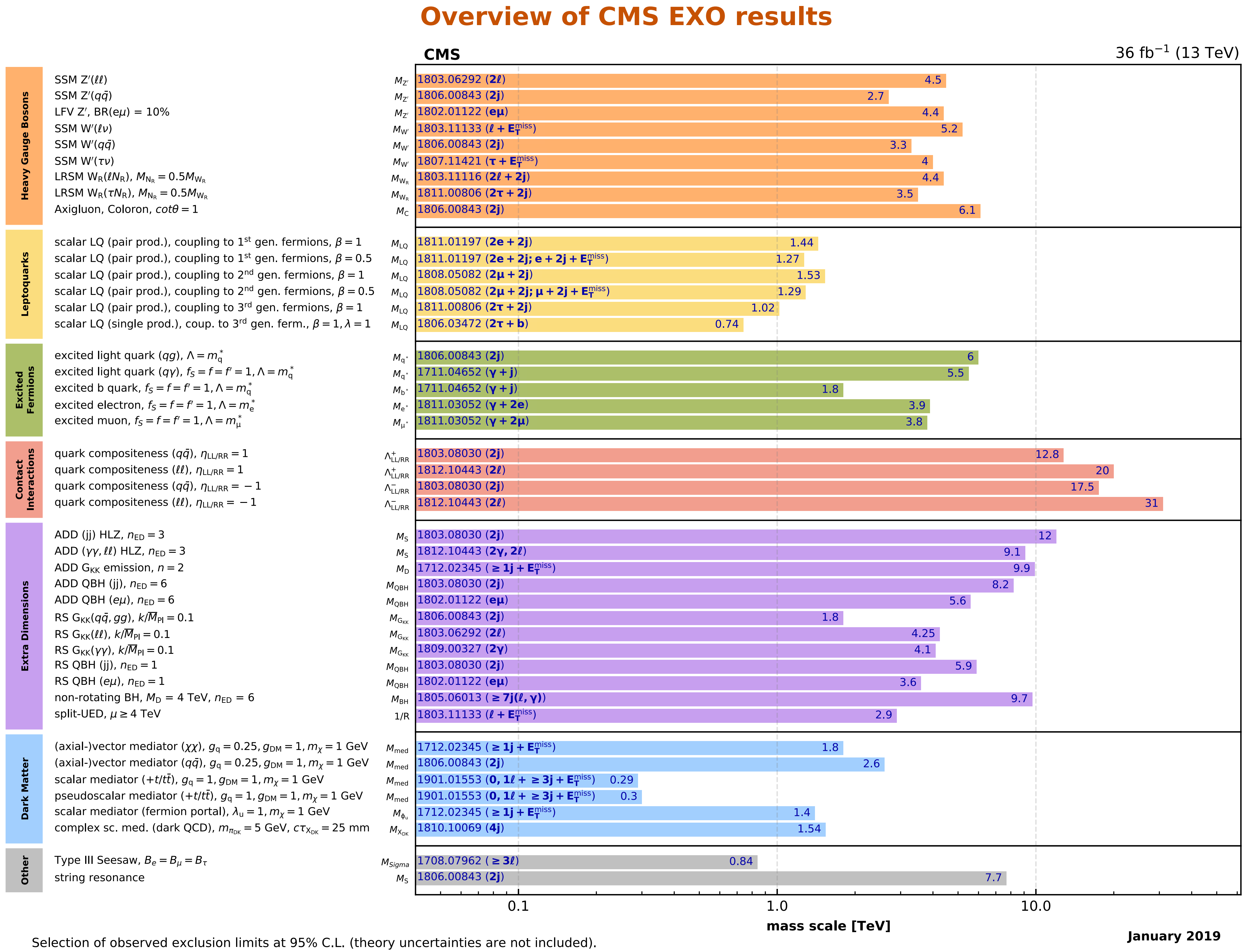

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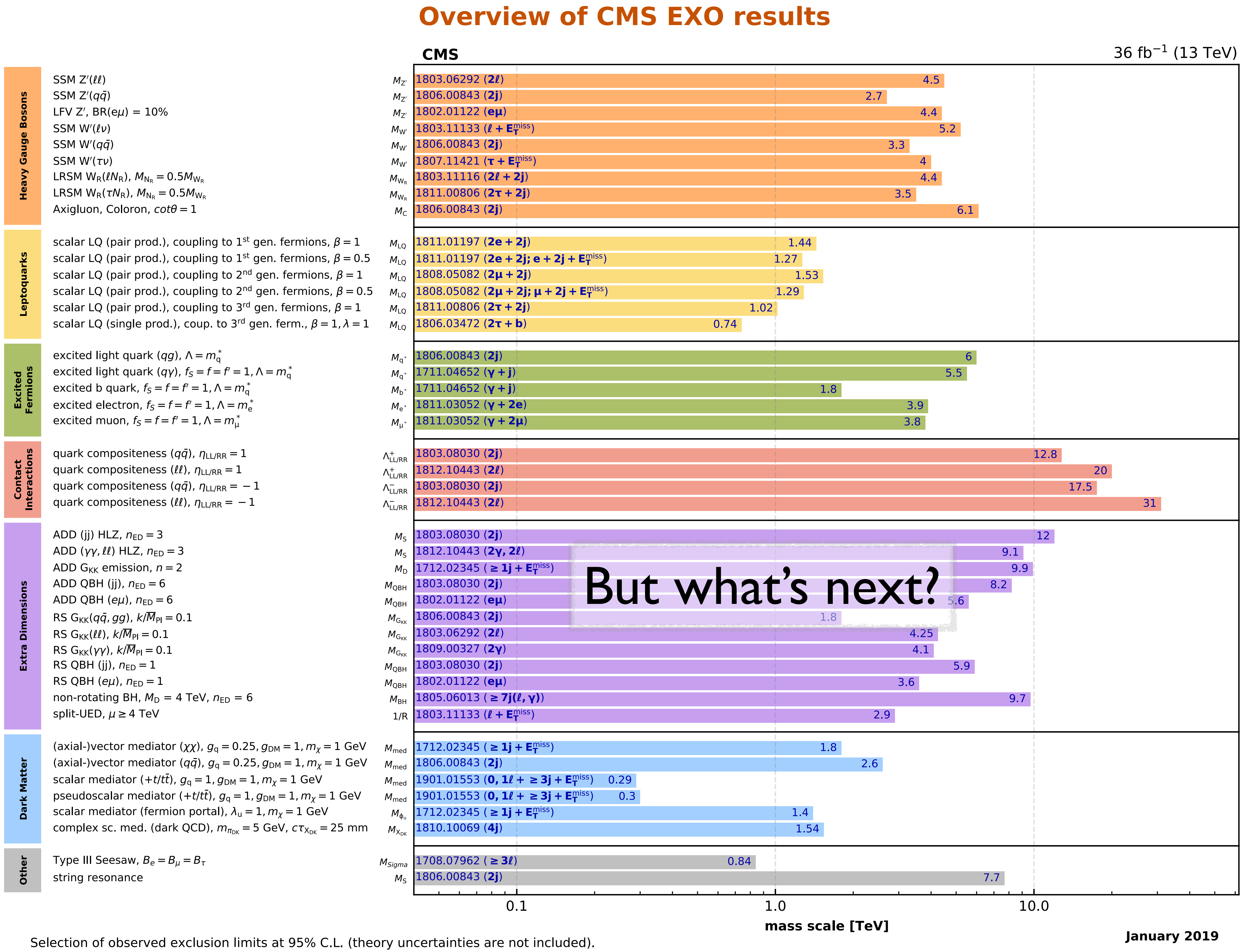

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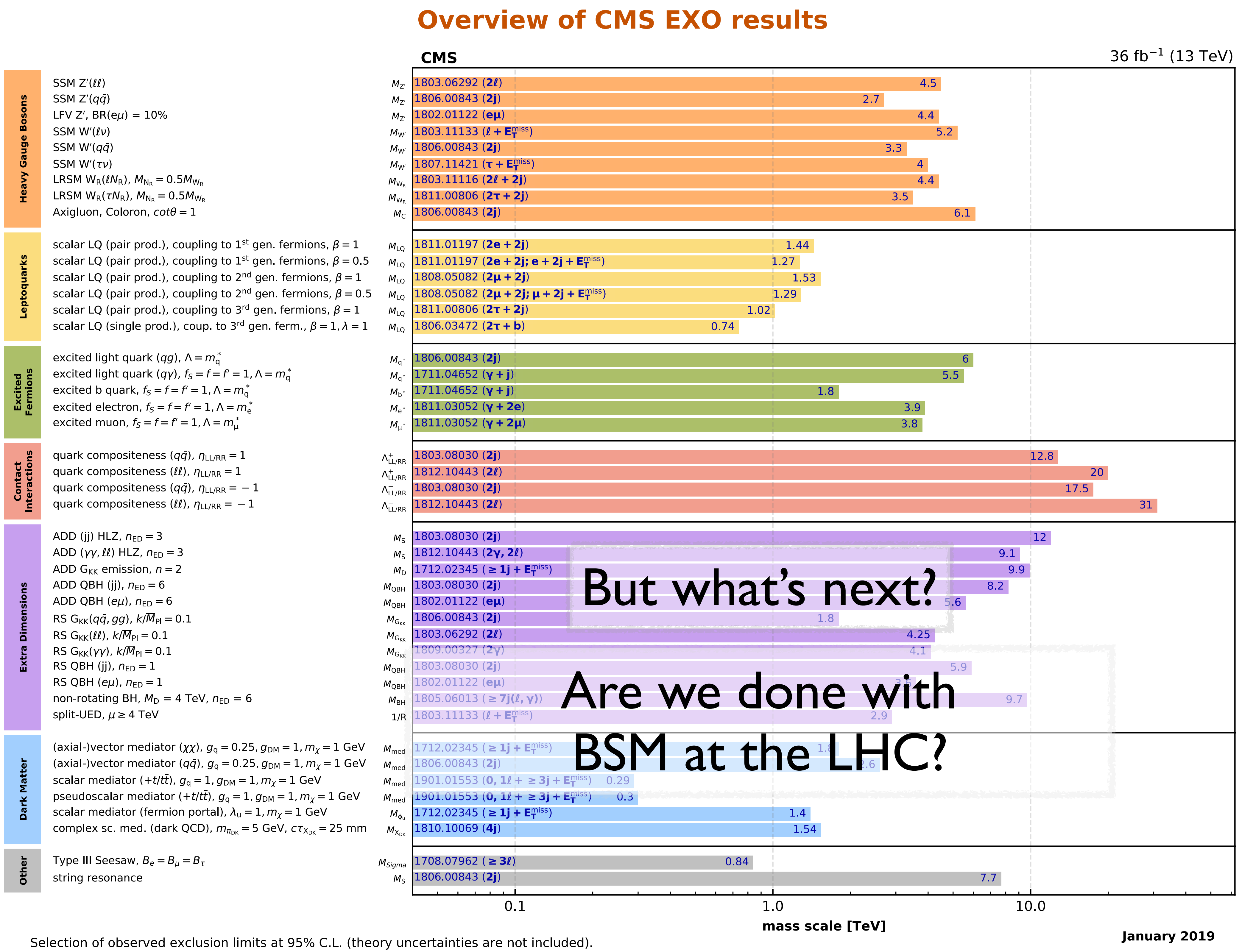

But what's next?

Are we done with BSM at the LHC?

Low Hanging Fruit Records

BSM is More Vibrant Than Ever!

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- 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

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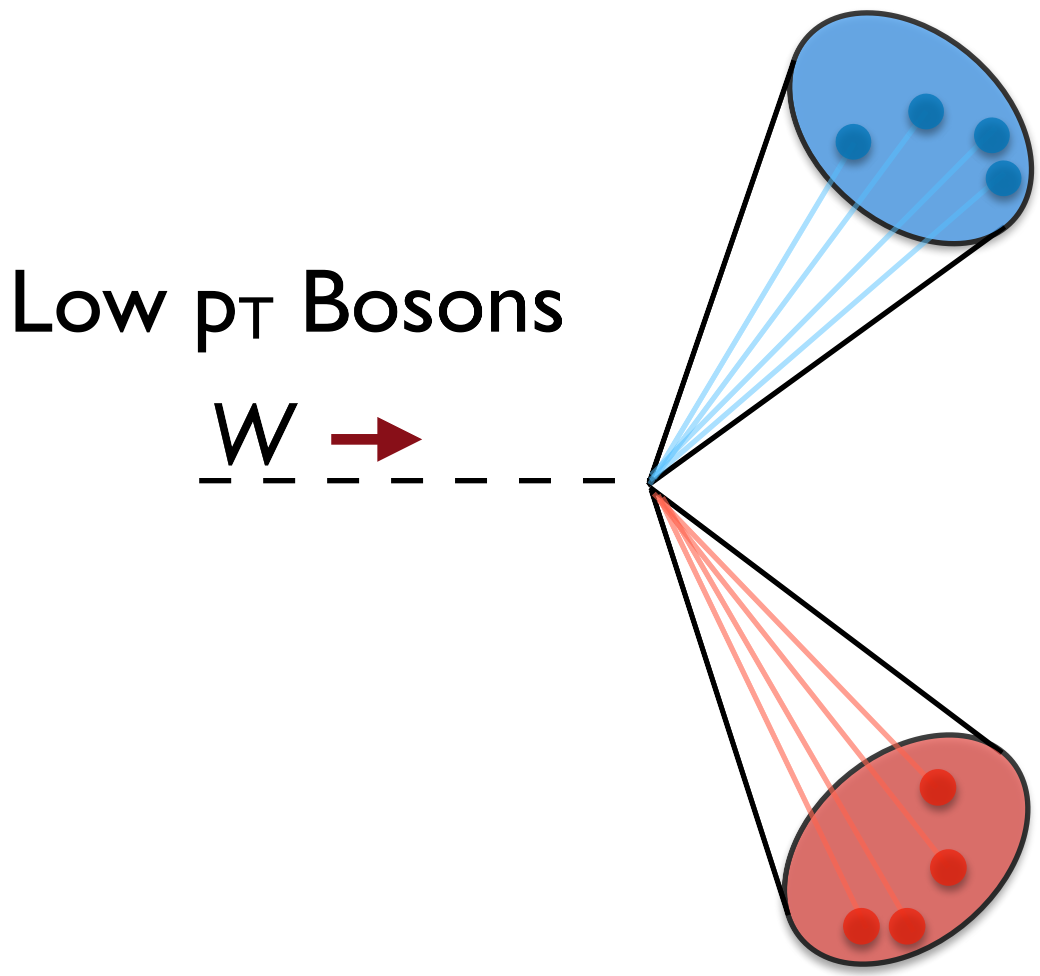
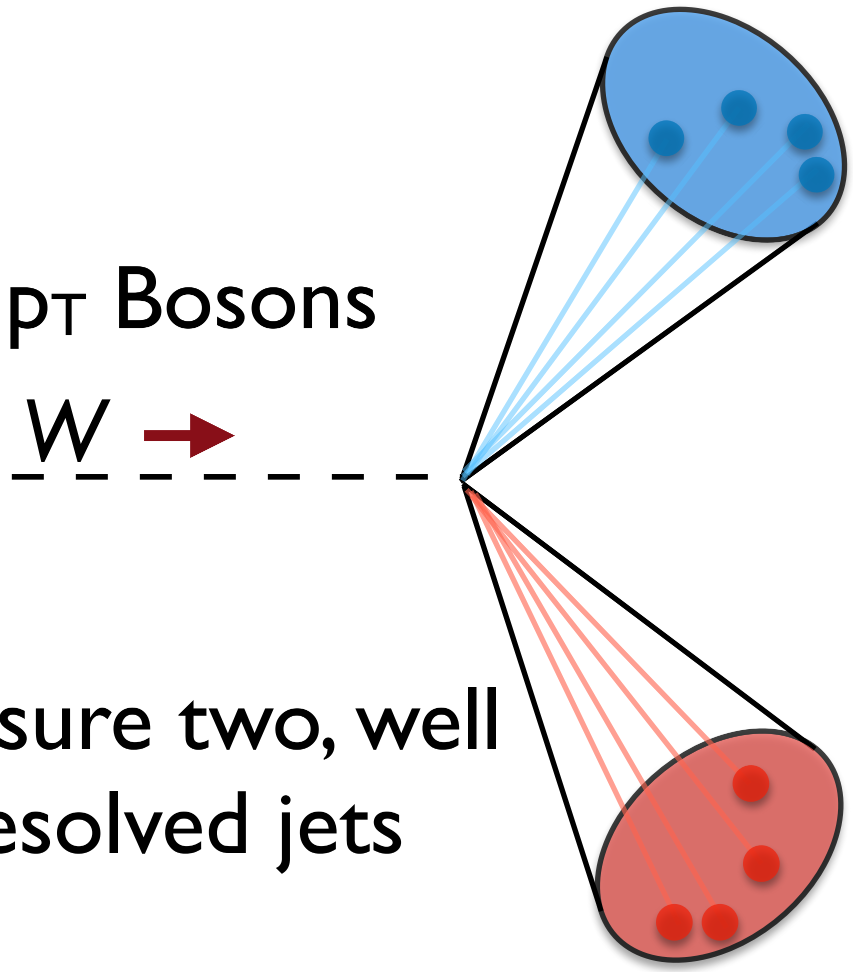


The Challenge of High p_T

Low p_T Bosons



Measure two, well resolved jets

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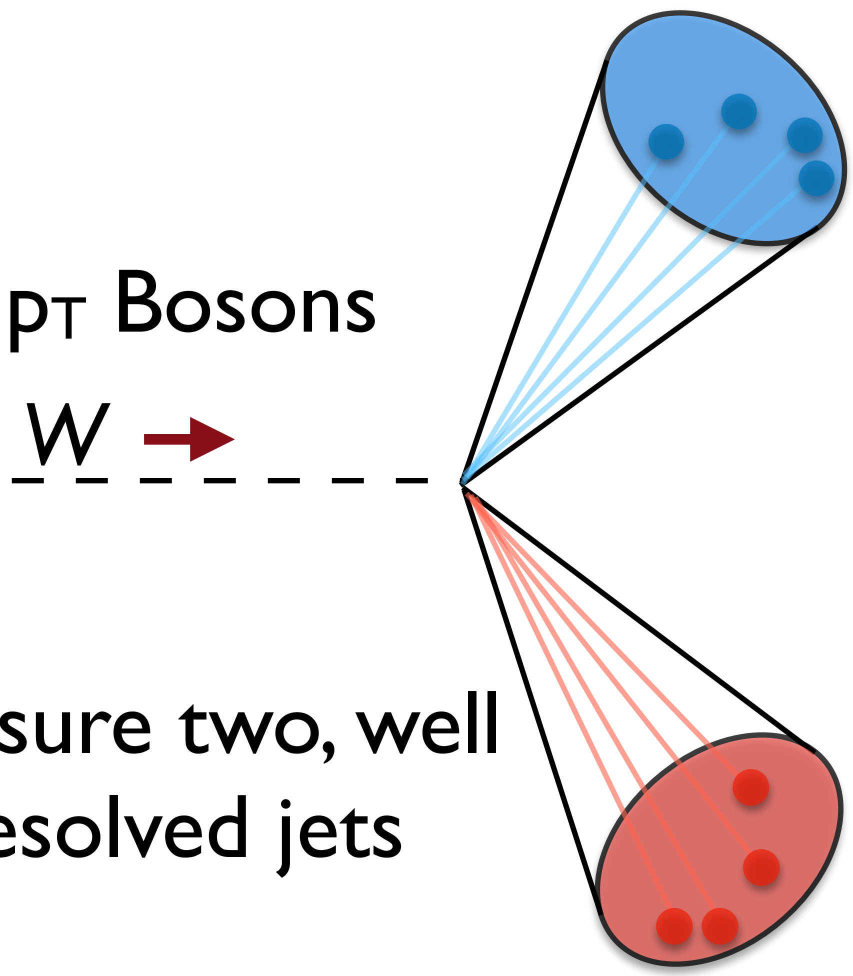

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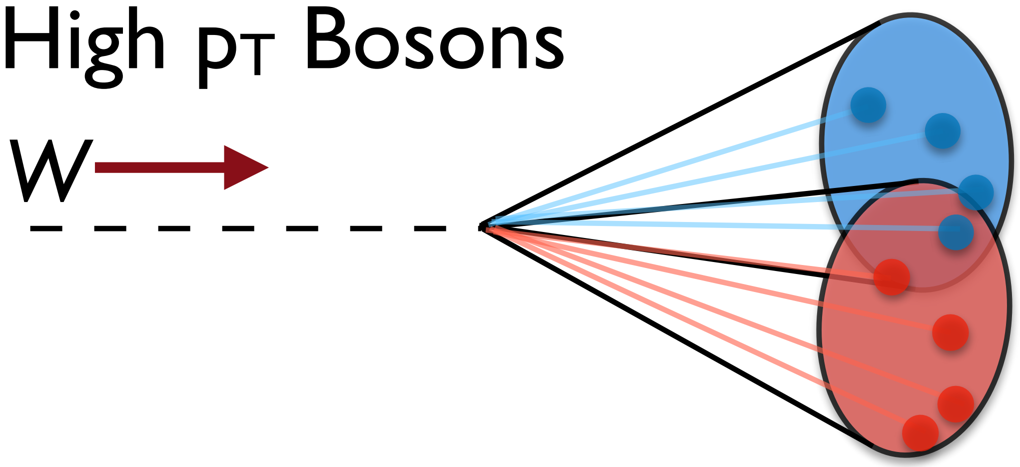

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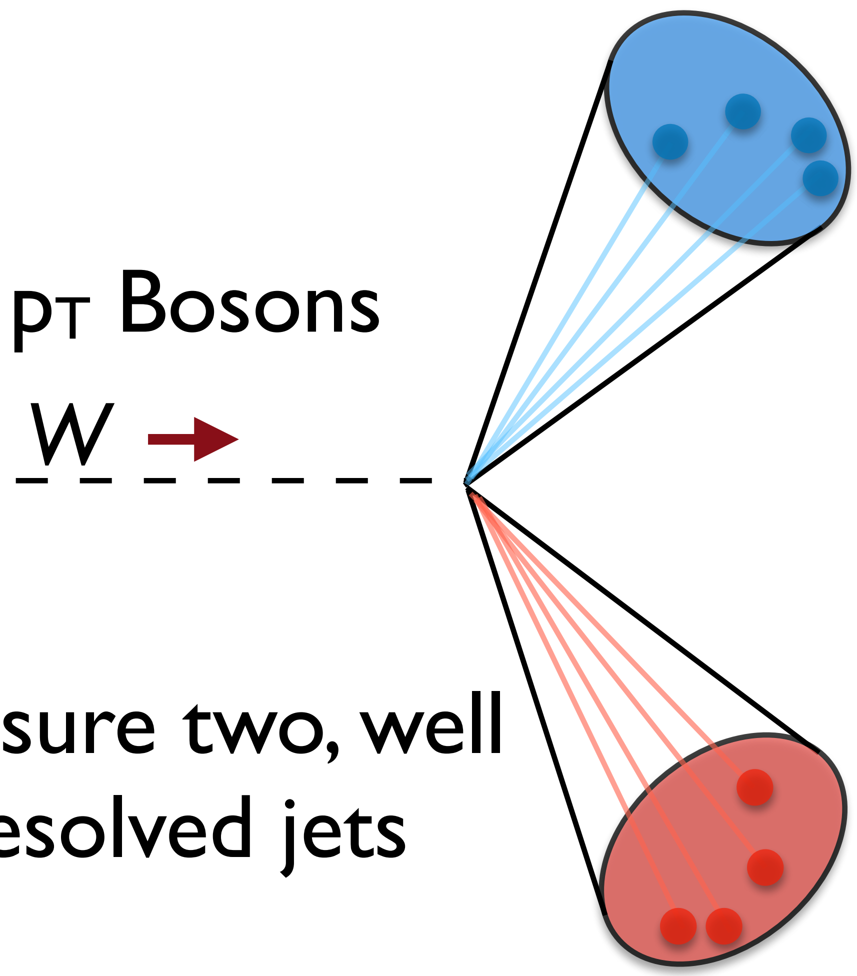

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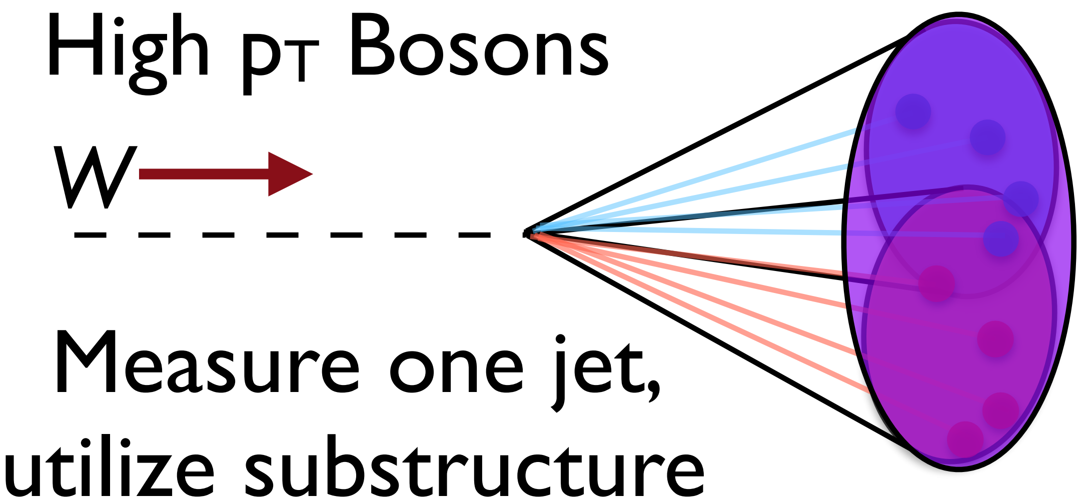
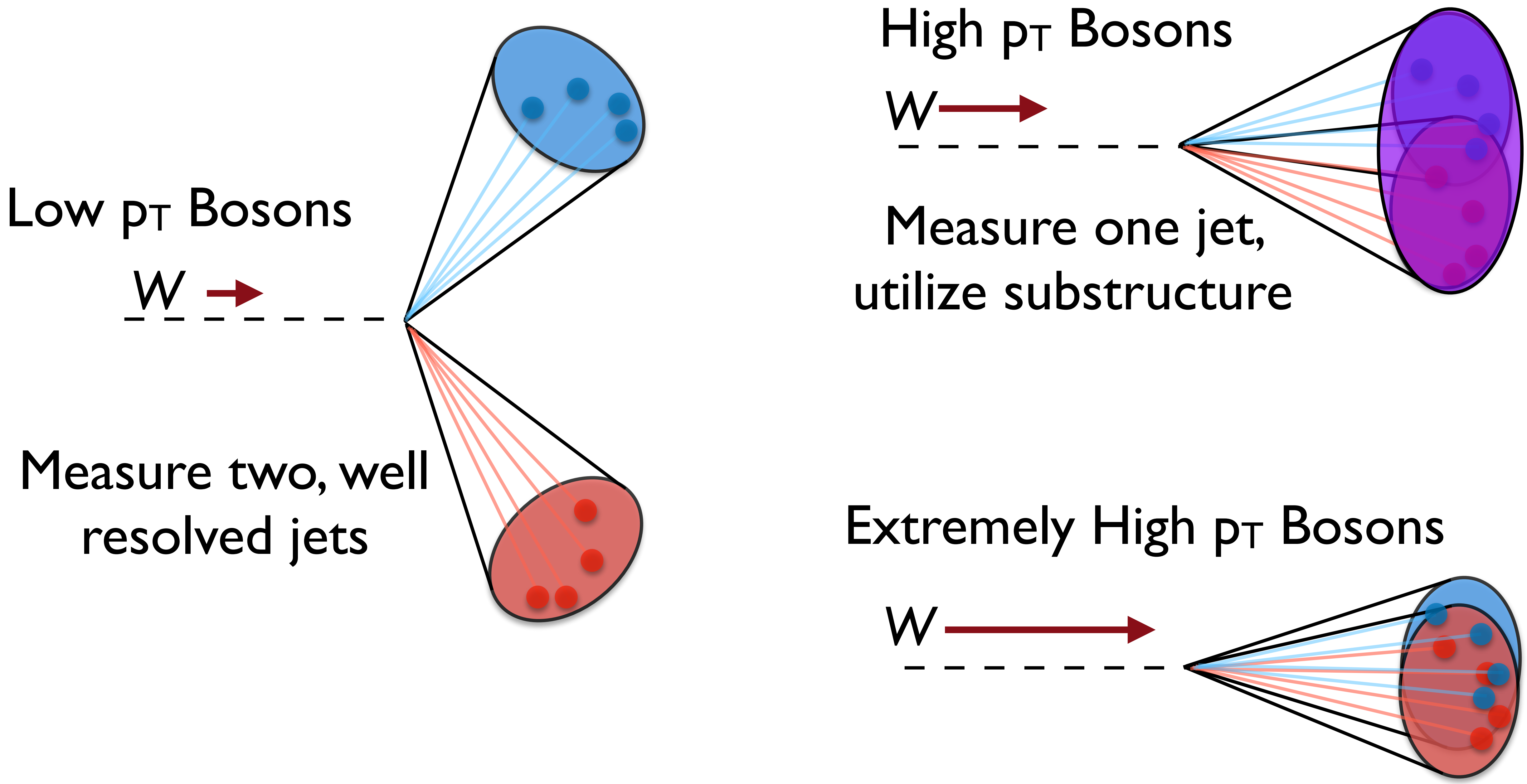


Measure one jet, utilize substructure

The Challenge of High p_T



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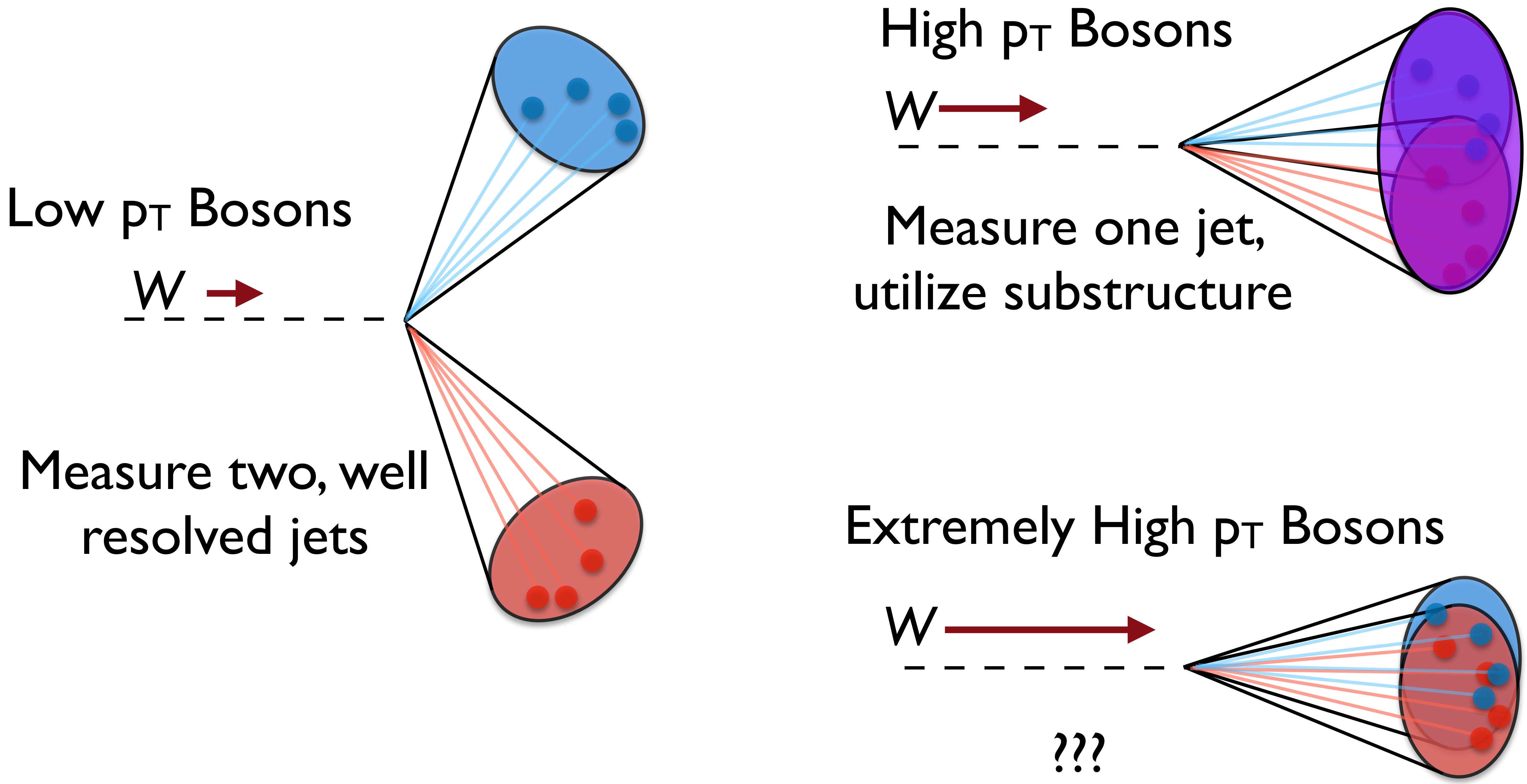

Tagging at High p_T

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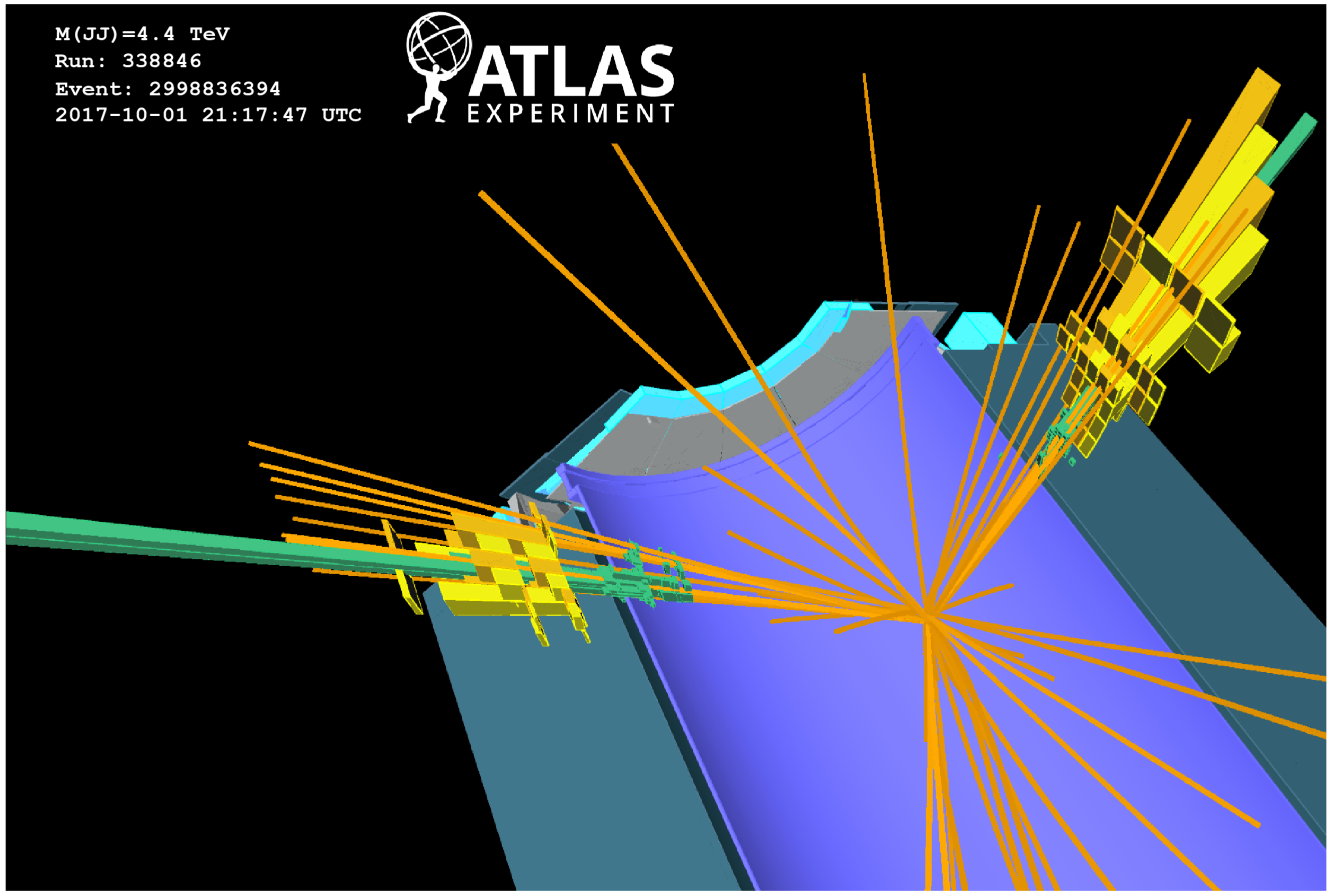

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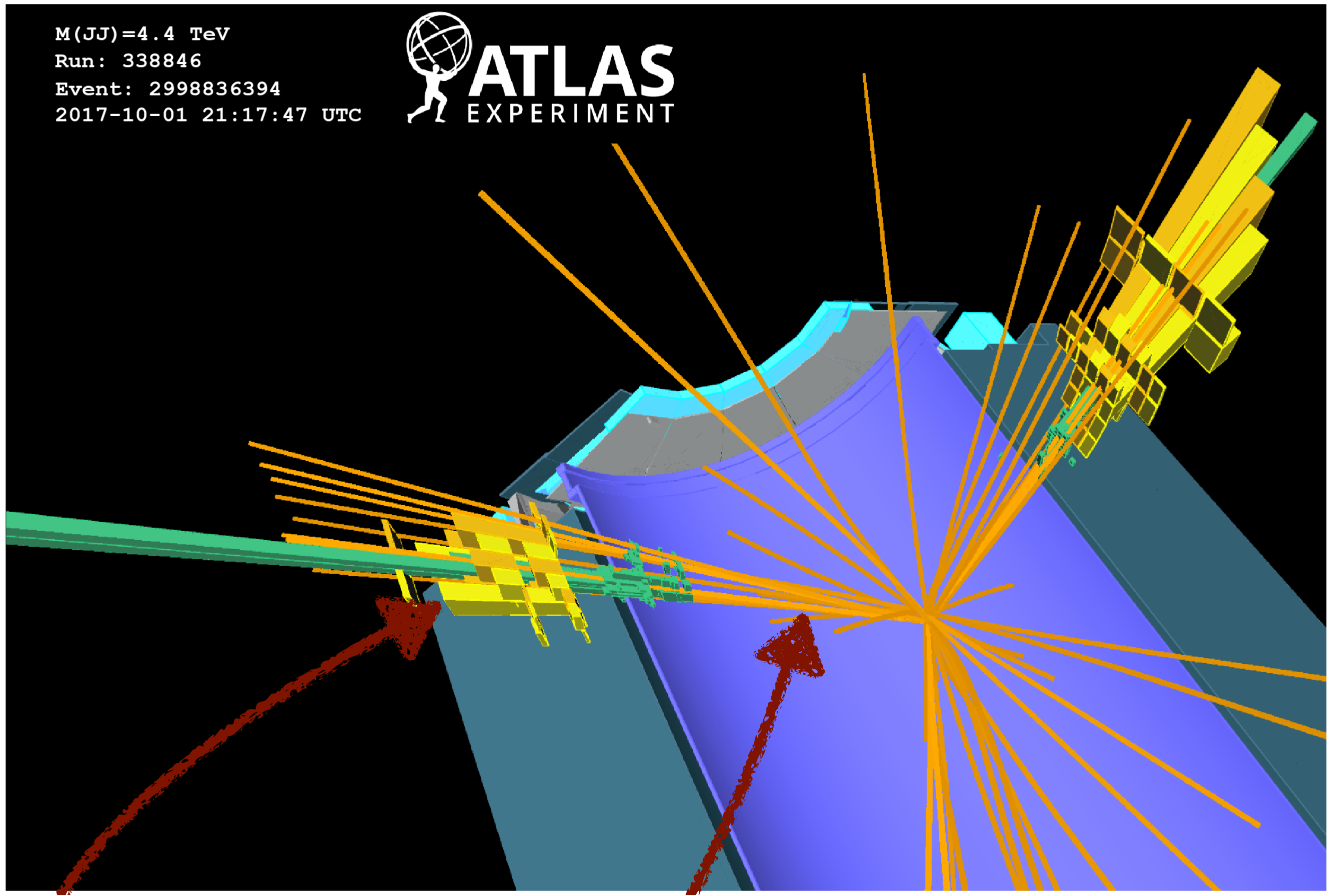

Utilize better spatial resolution from tracker to separate energy deposits in the calorimeter!

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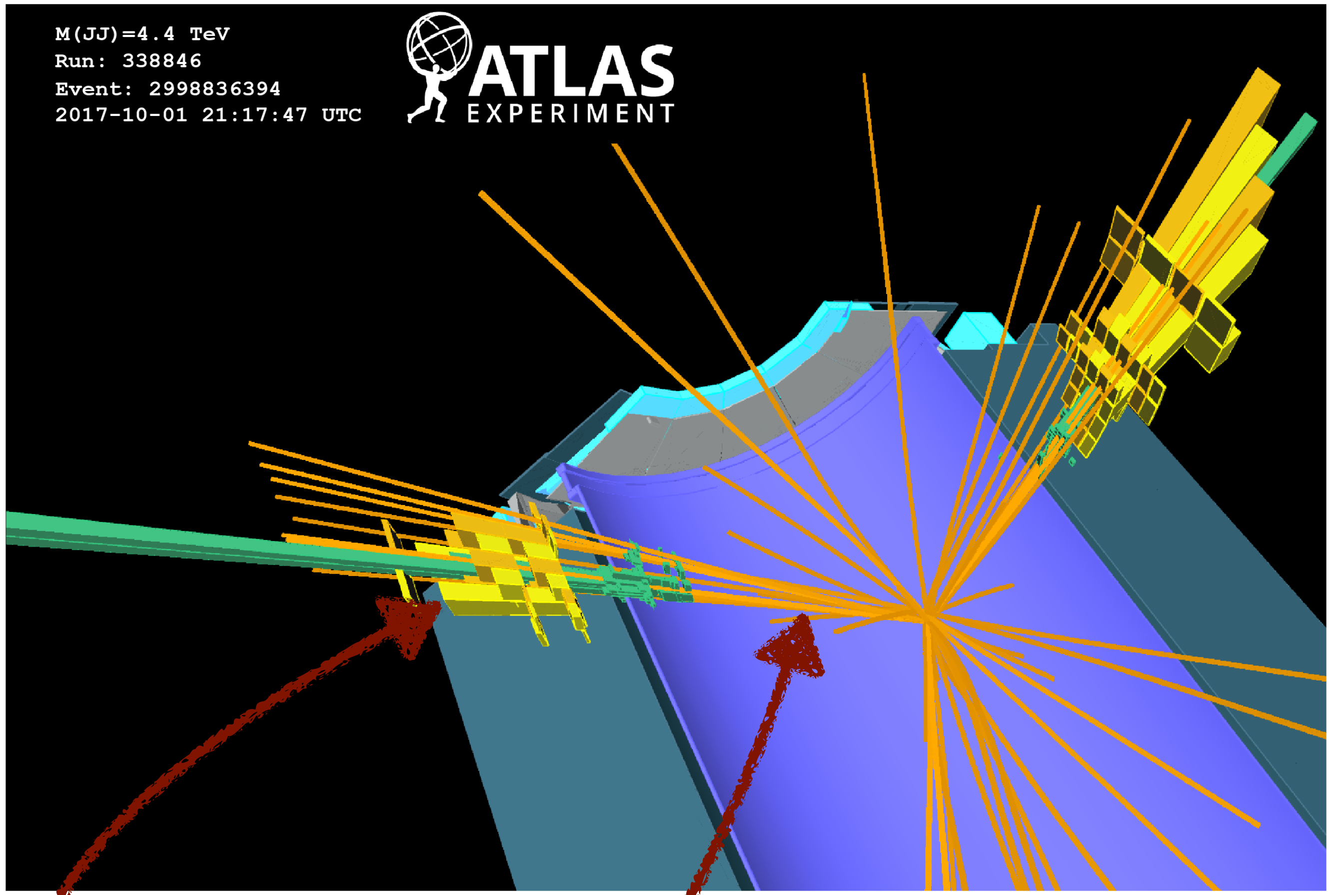

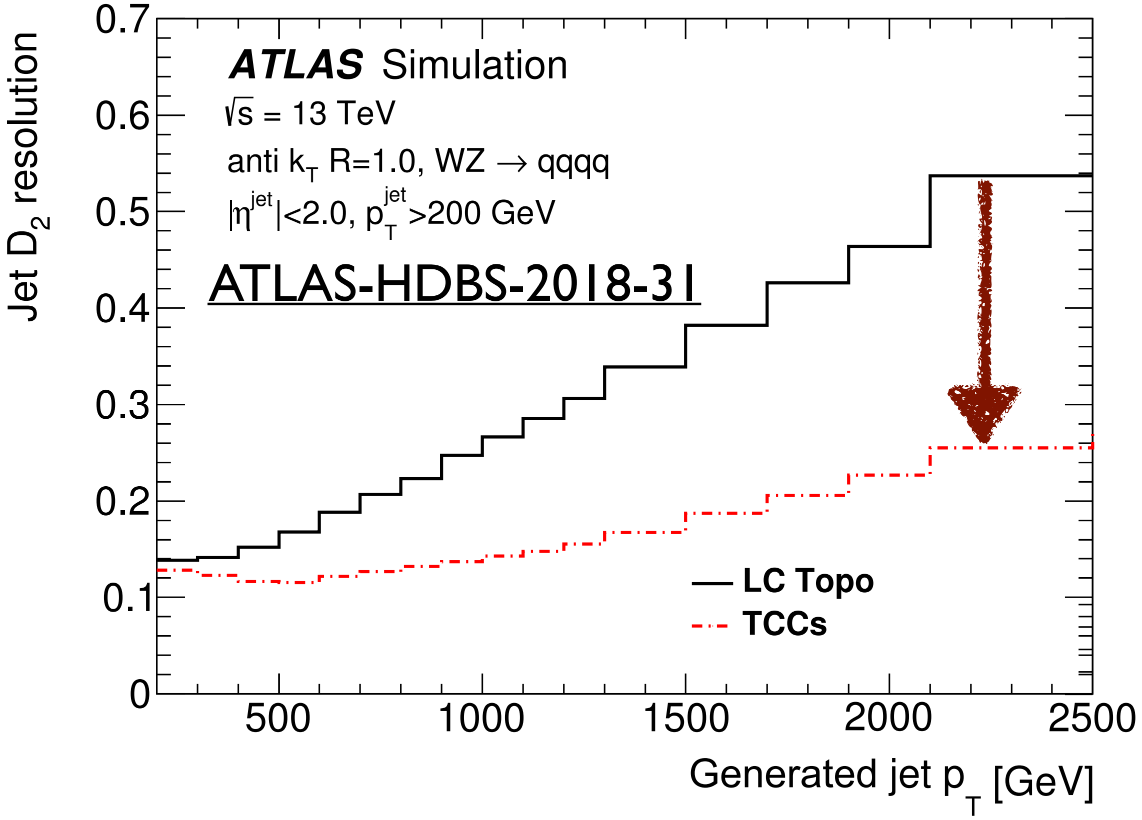

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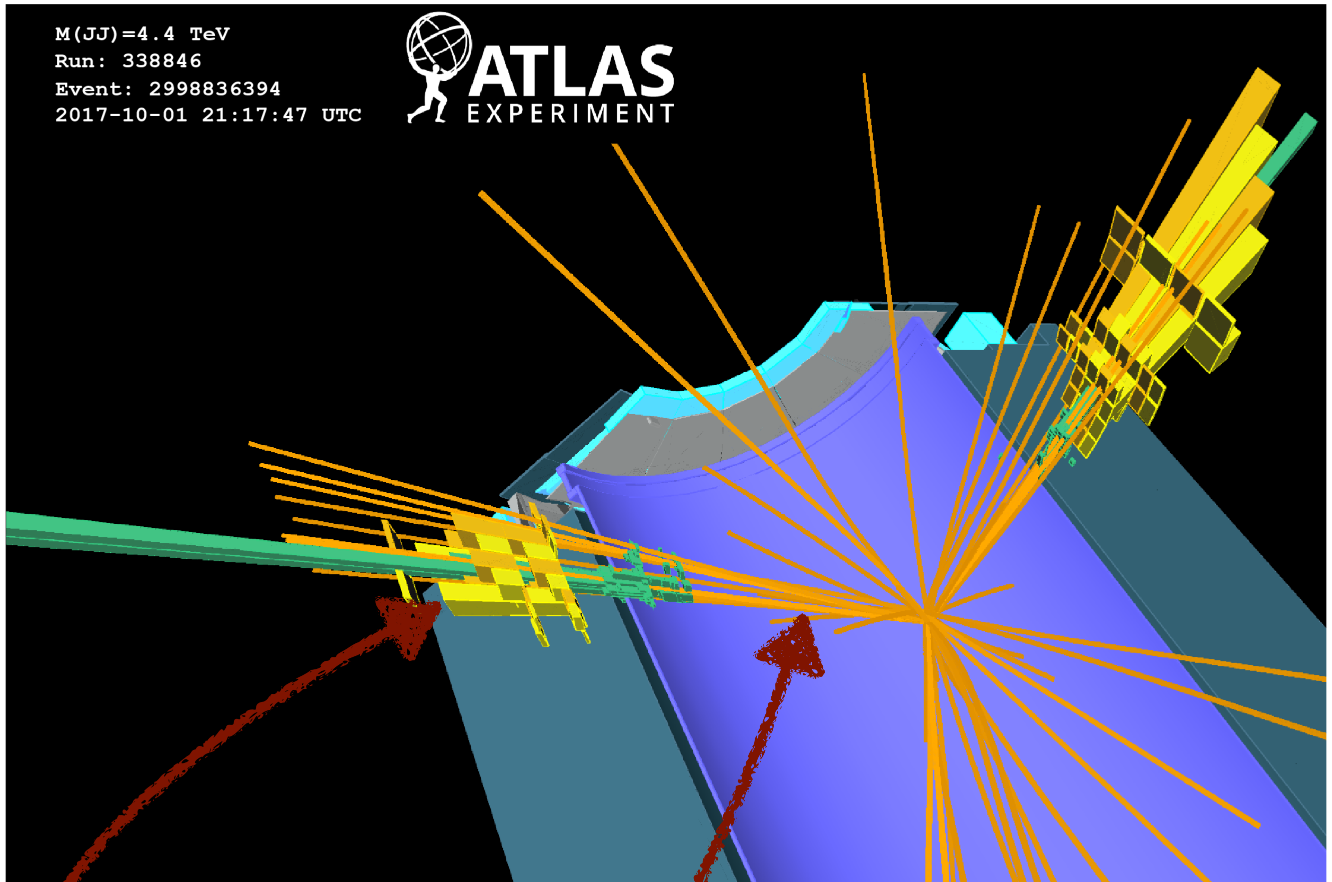

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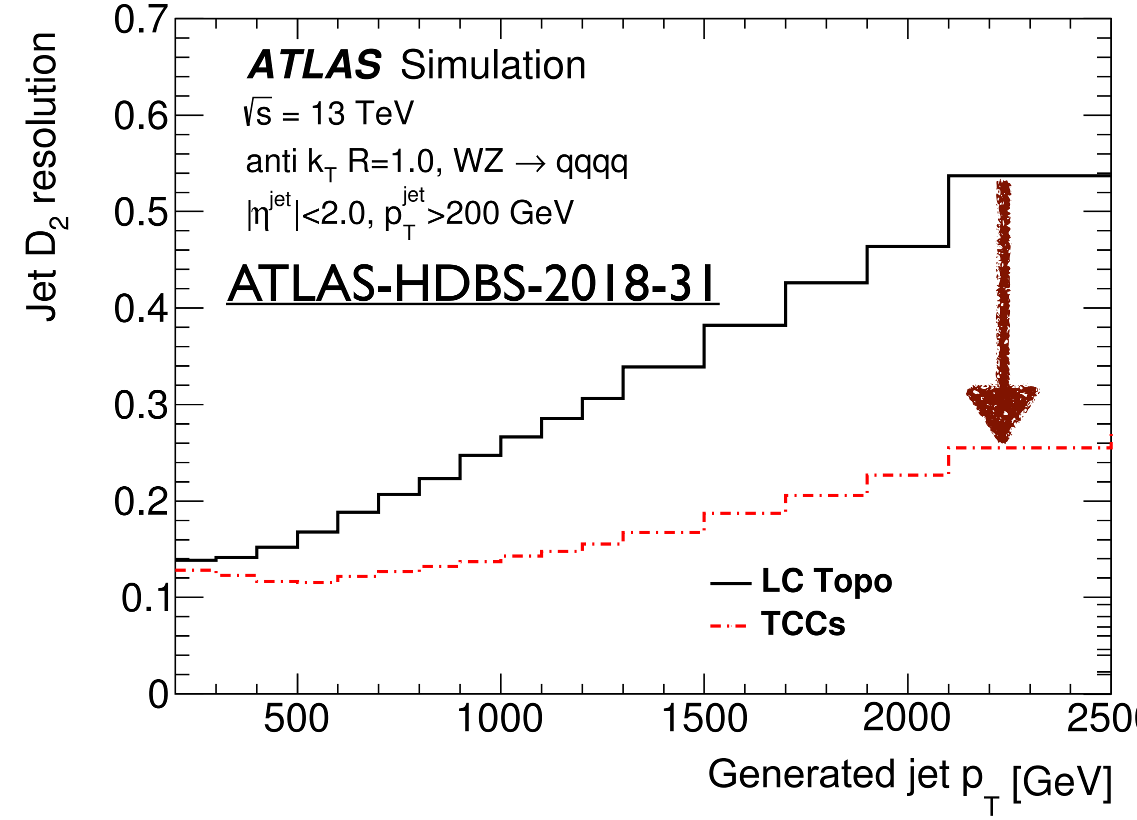
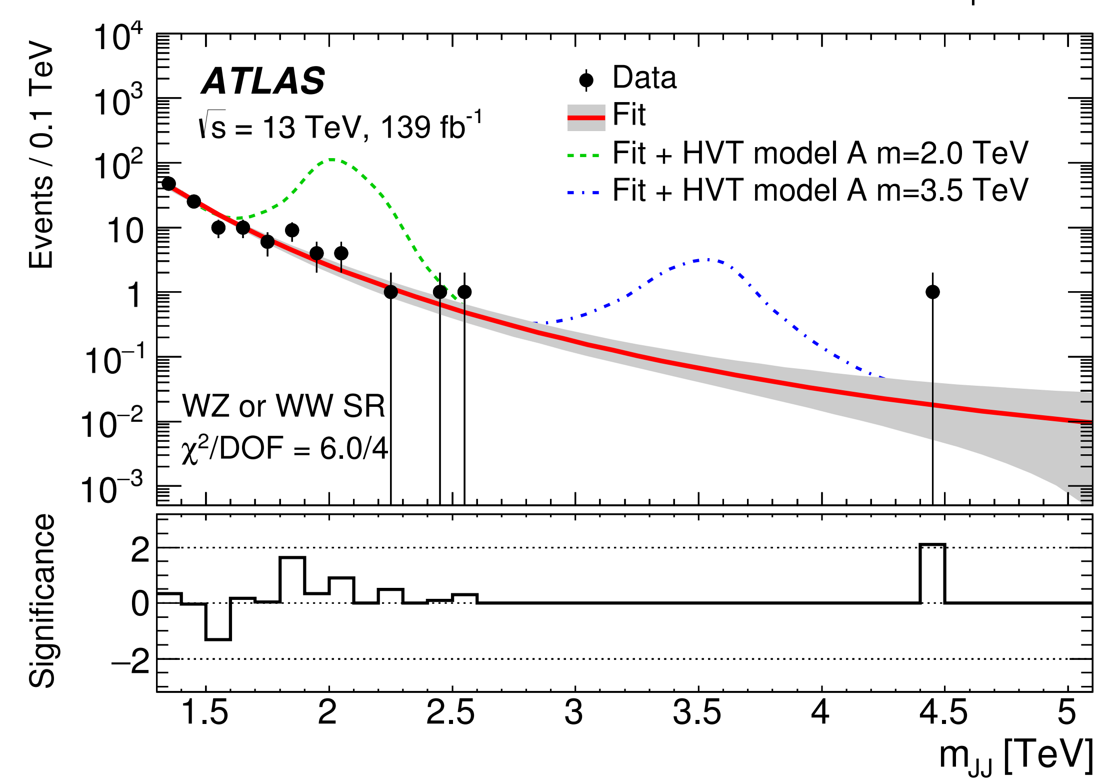
Enables strongest sensitivity yet to boosted all-hadronic final states





The Challenge of Branching

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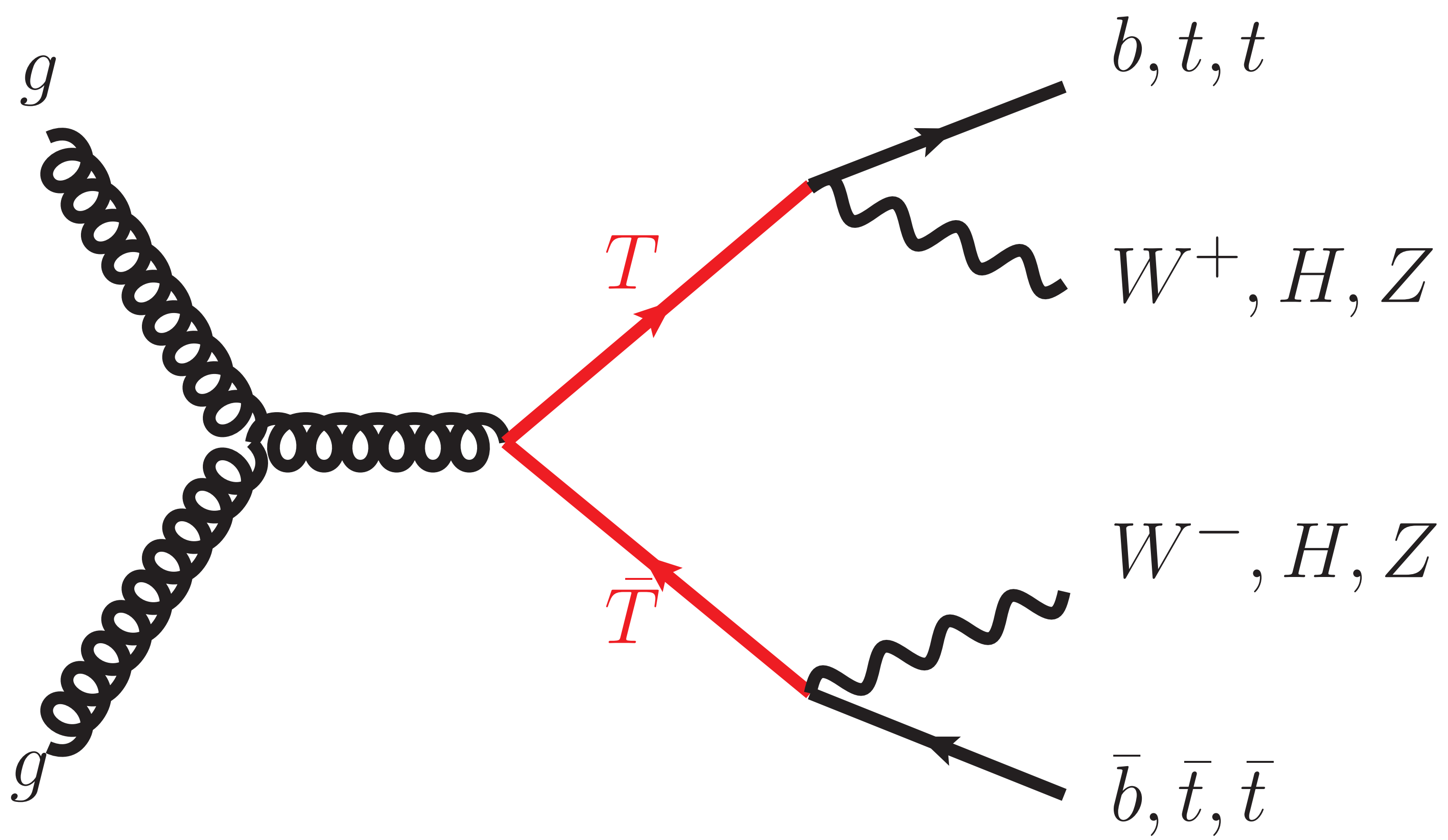

Vector-like tops are a consequence of many BSM models: can explain Higgs mass, etc.

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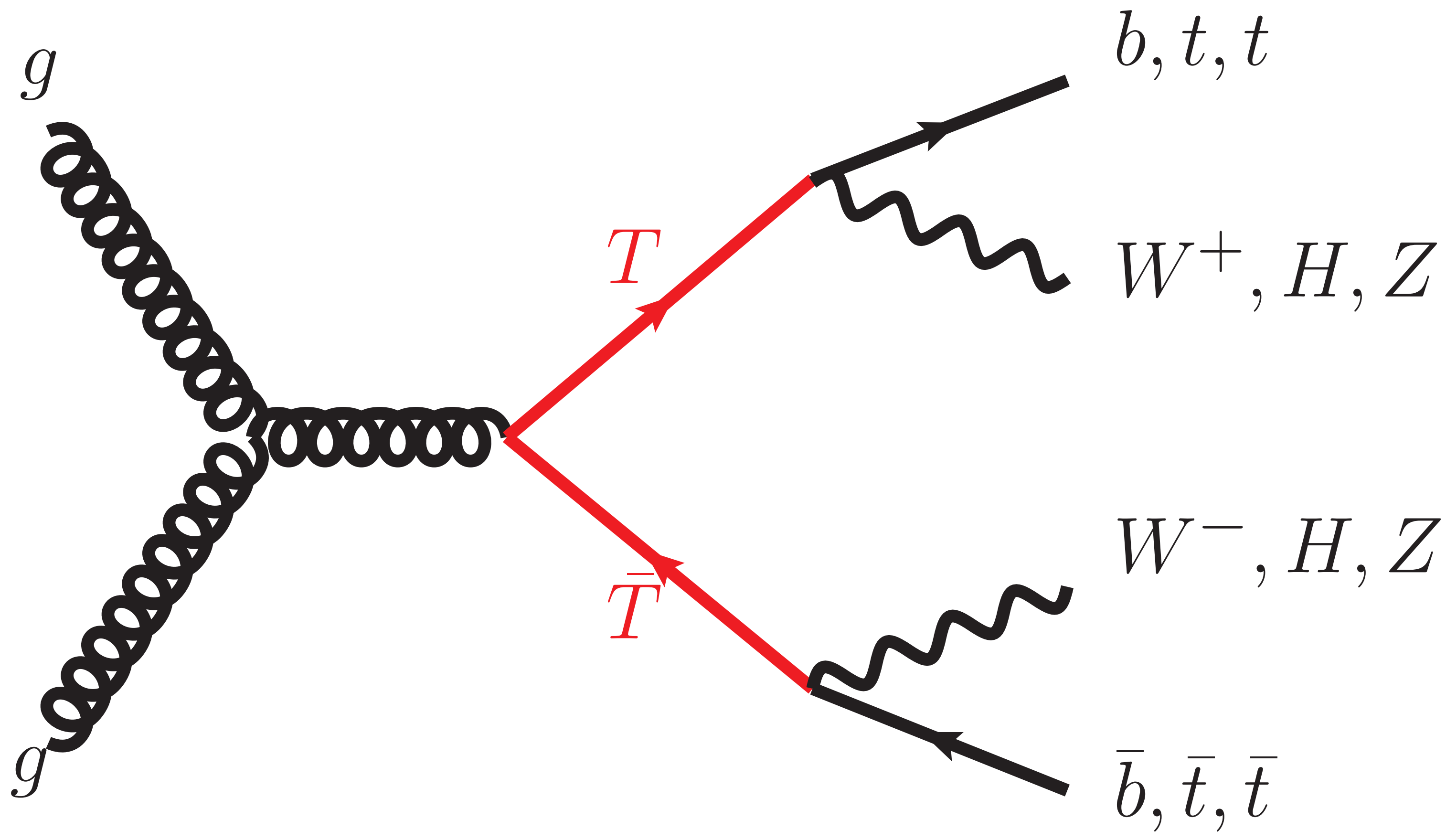

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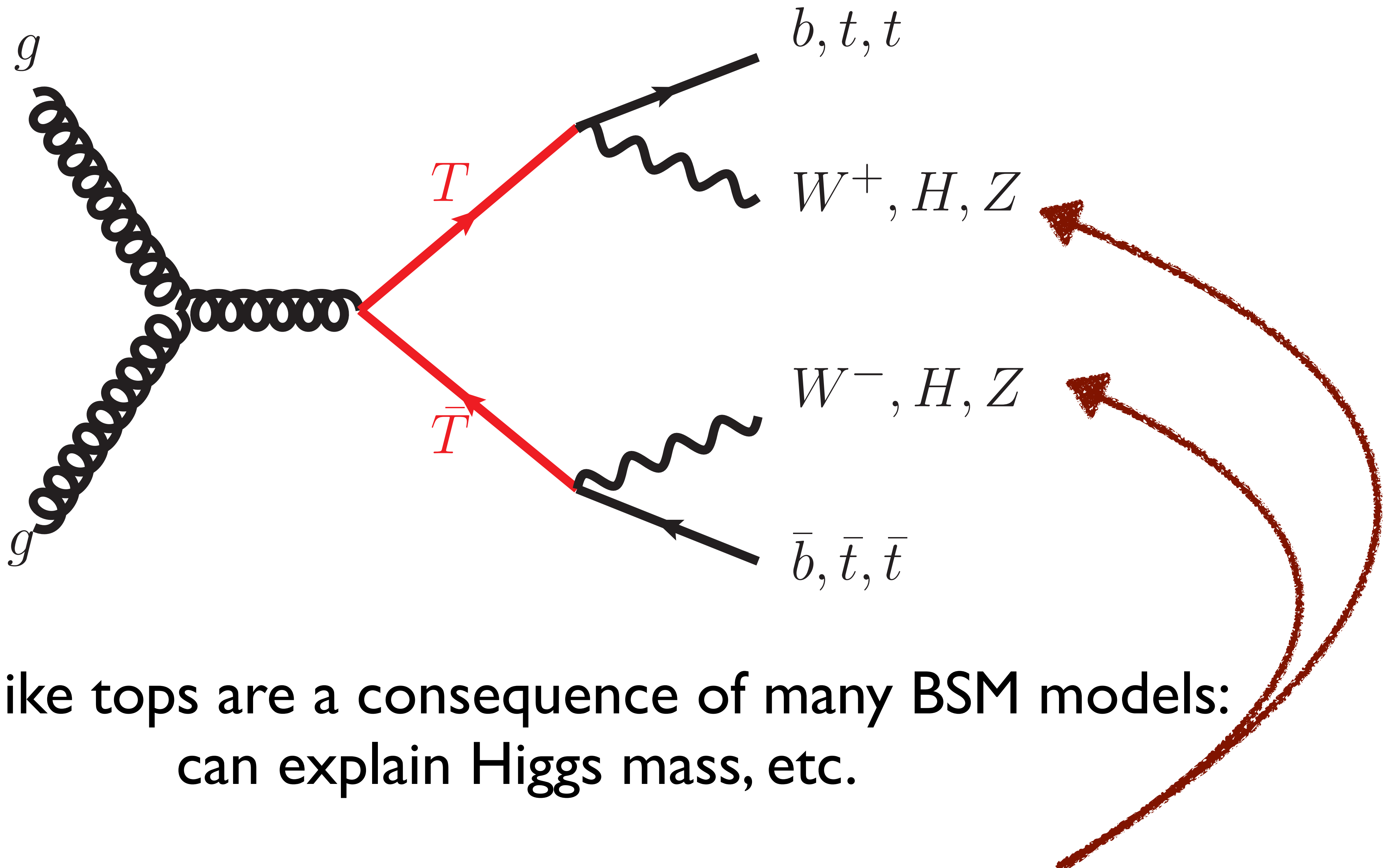


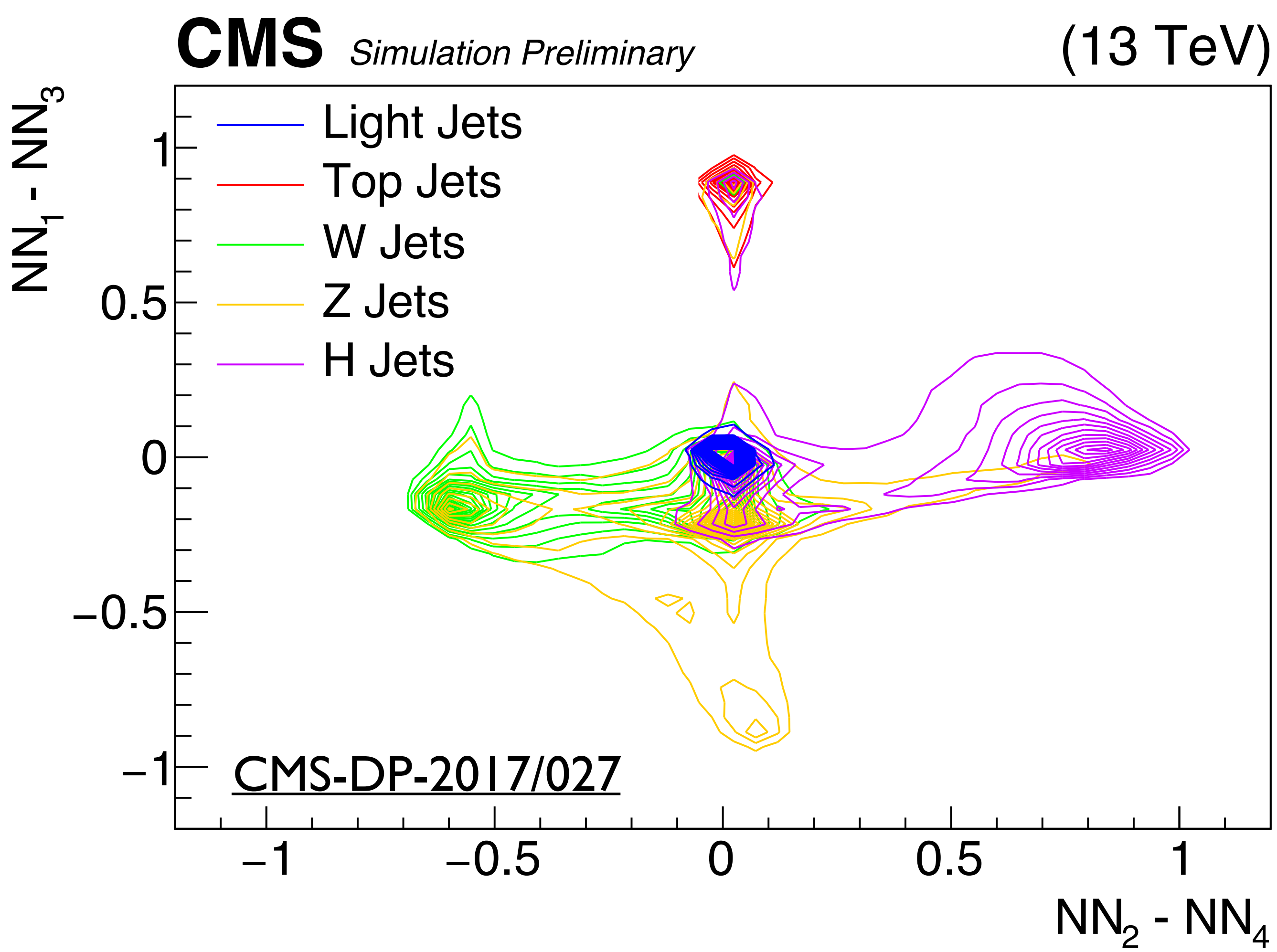
Vector-like tops are a consequence of many BSM models: can explain Higgs mass, etc.

But there are a huge number of final states!

How do you search for all of these efficiently?

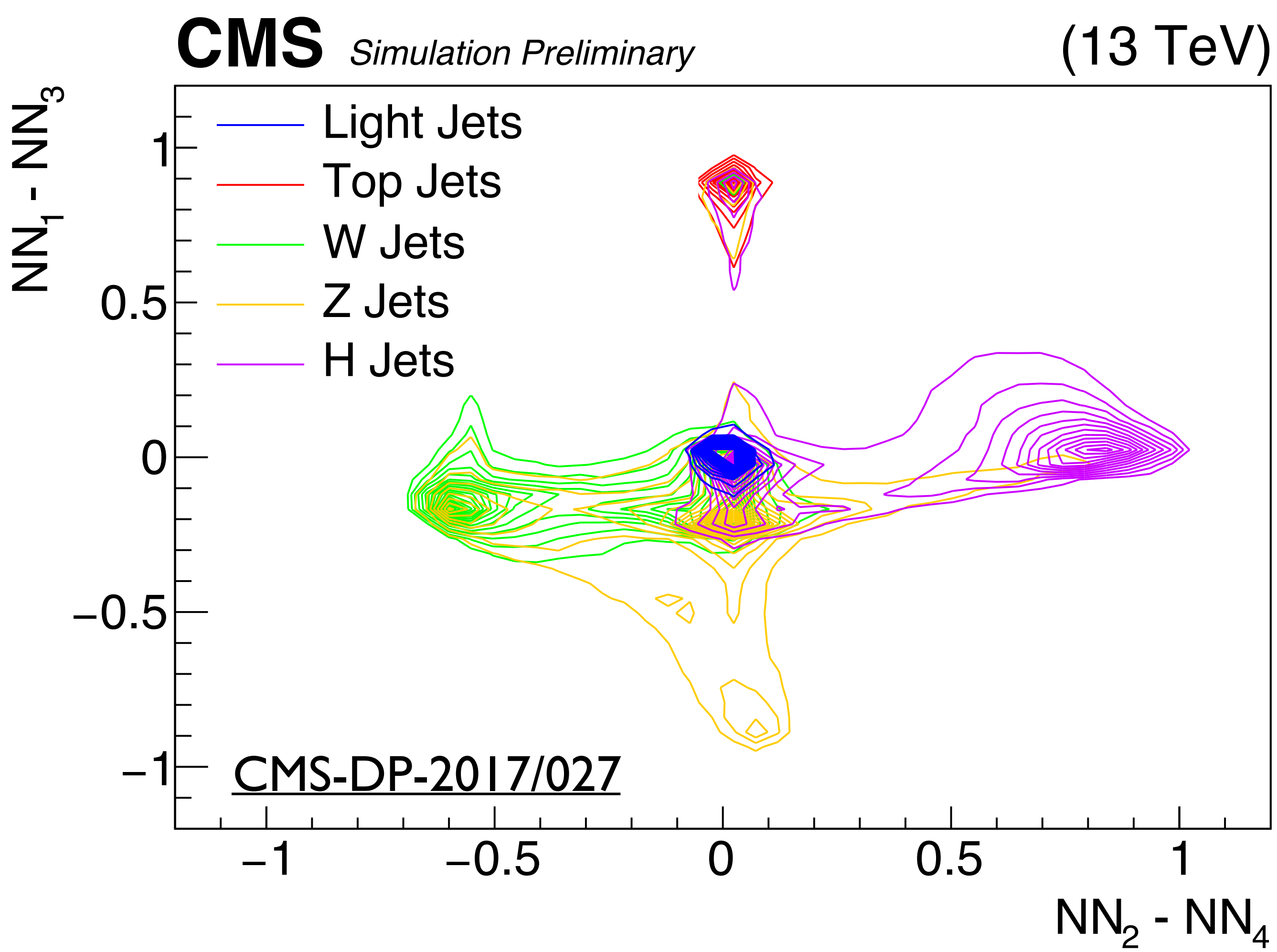
Multi-Node Tagging

Multi-Node Tagging



Train a neural network to distinguish all signal classes from background

Multi-Node Tagging



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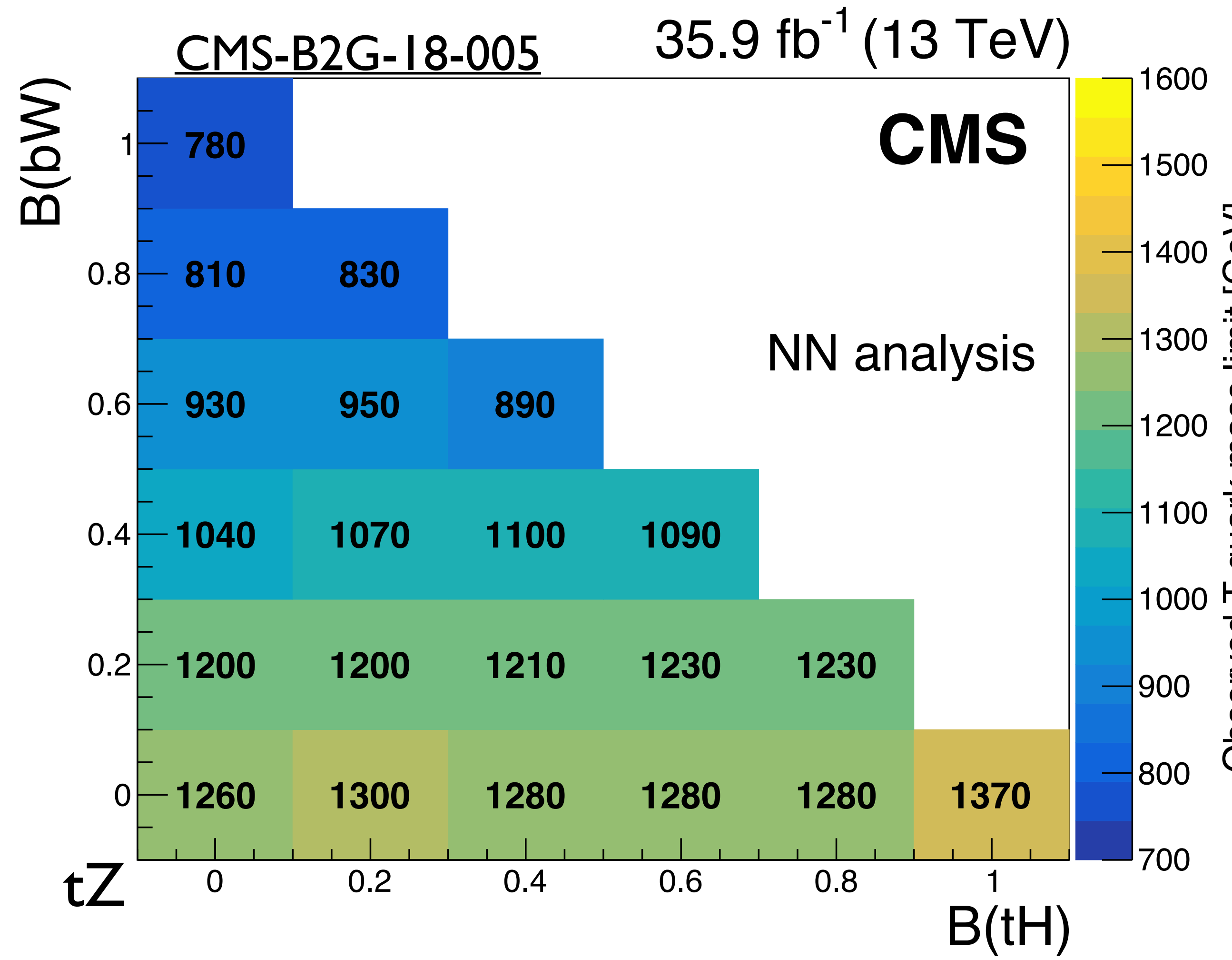

Use the NN to search for new physics in many final states at once

The Challenges of Dijets

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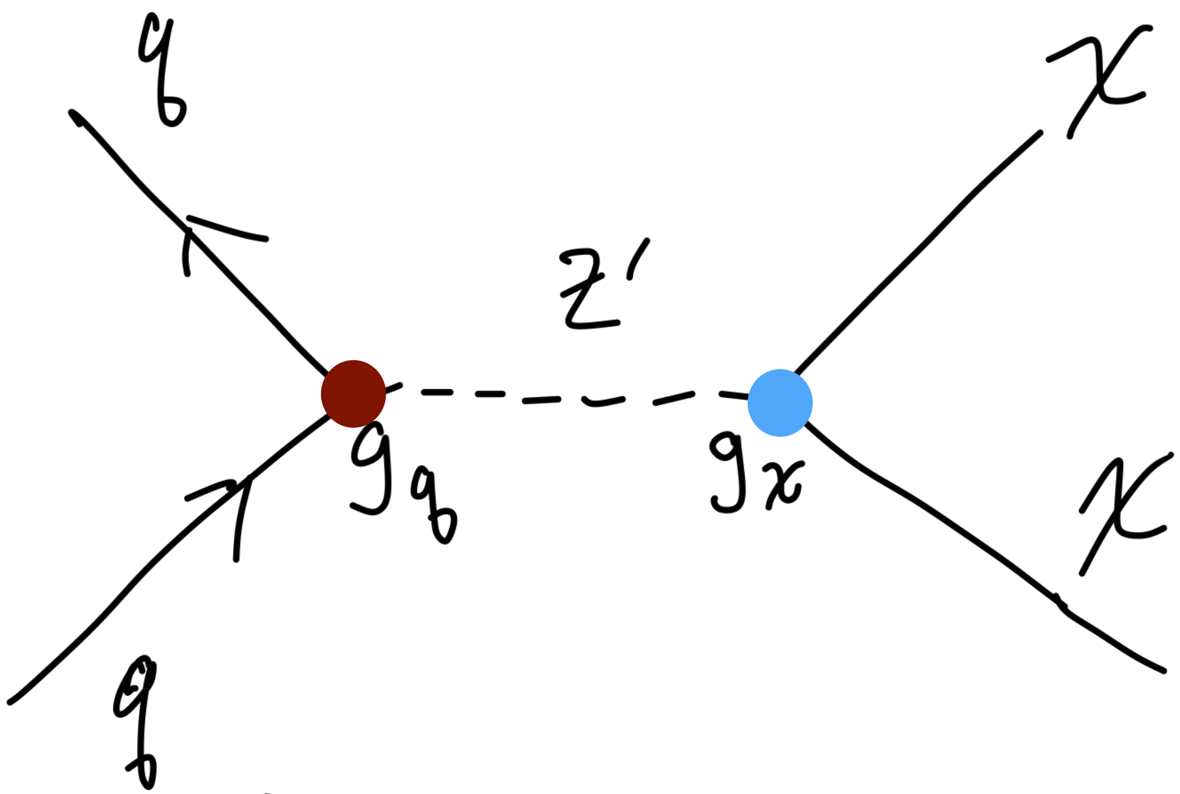

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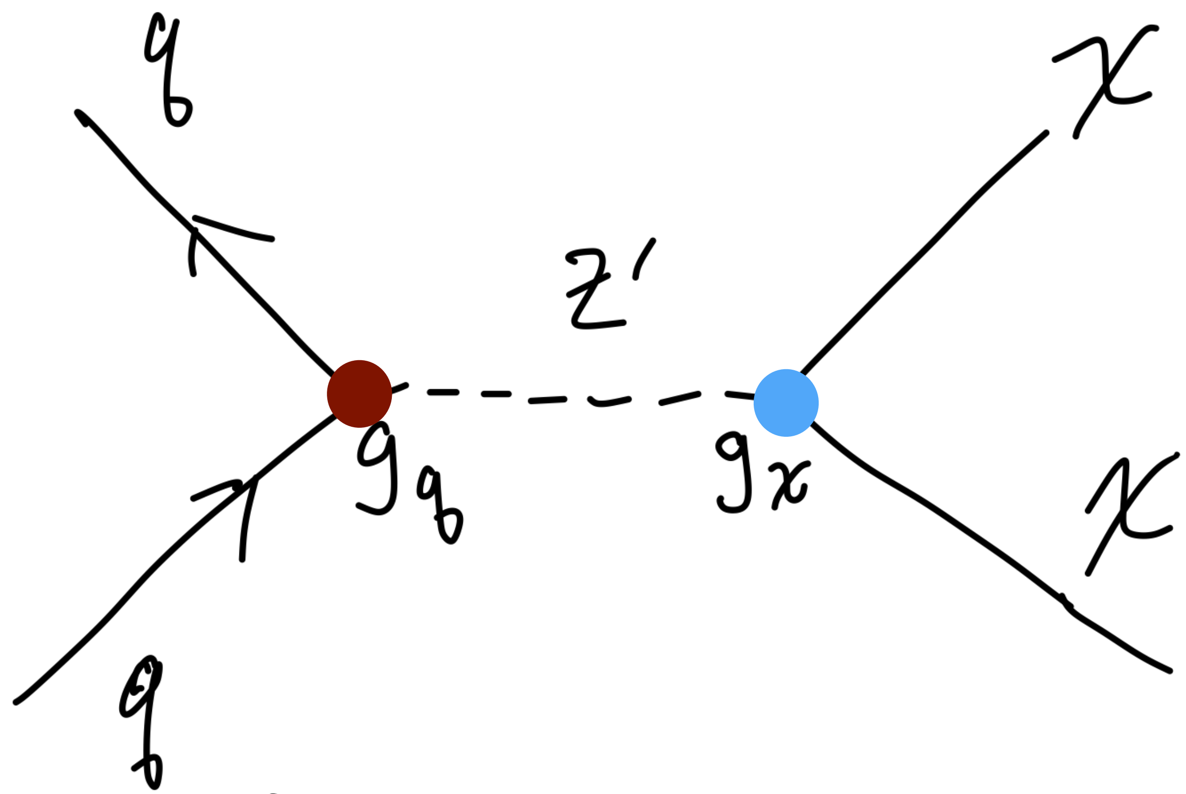
The Challenges of Dijets



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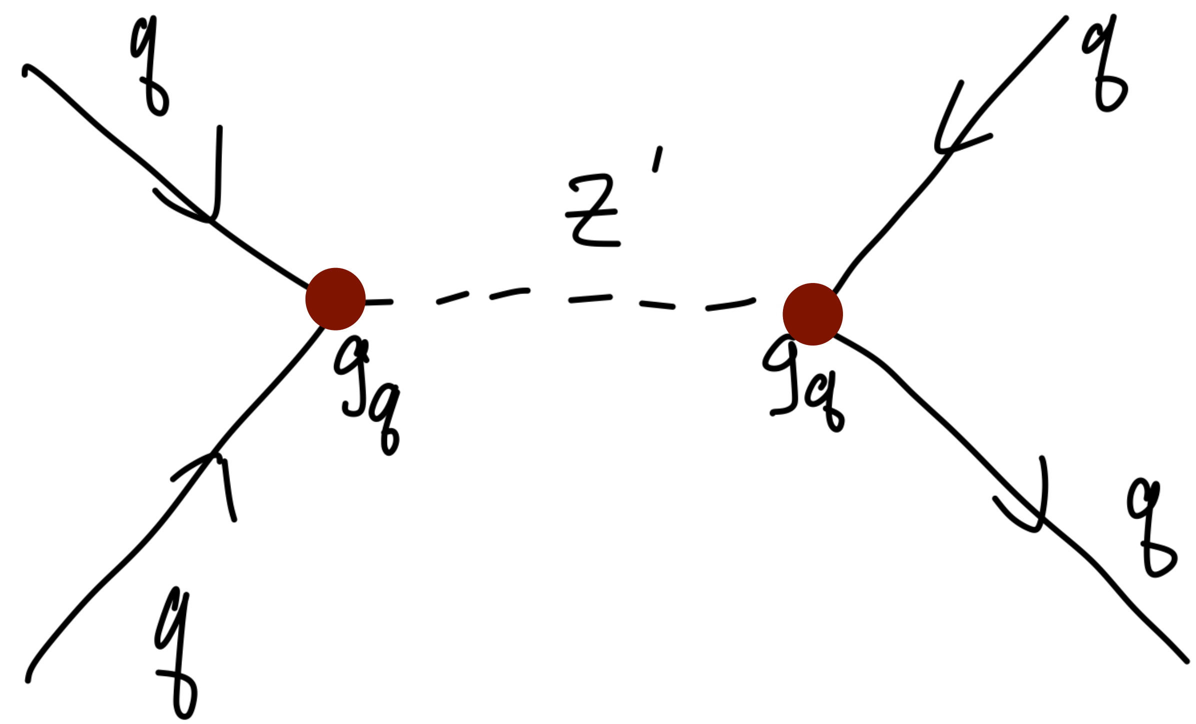

Then the mediator should decay back to jets!

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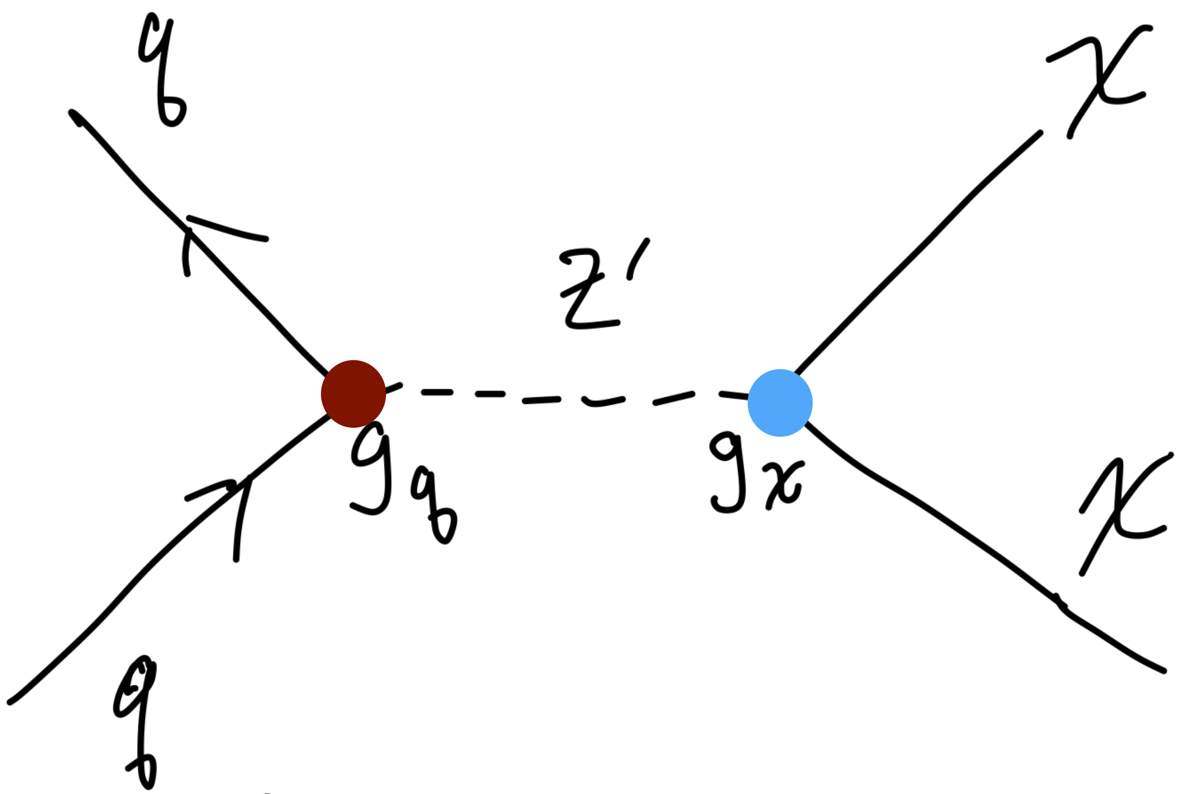

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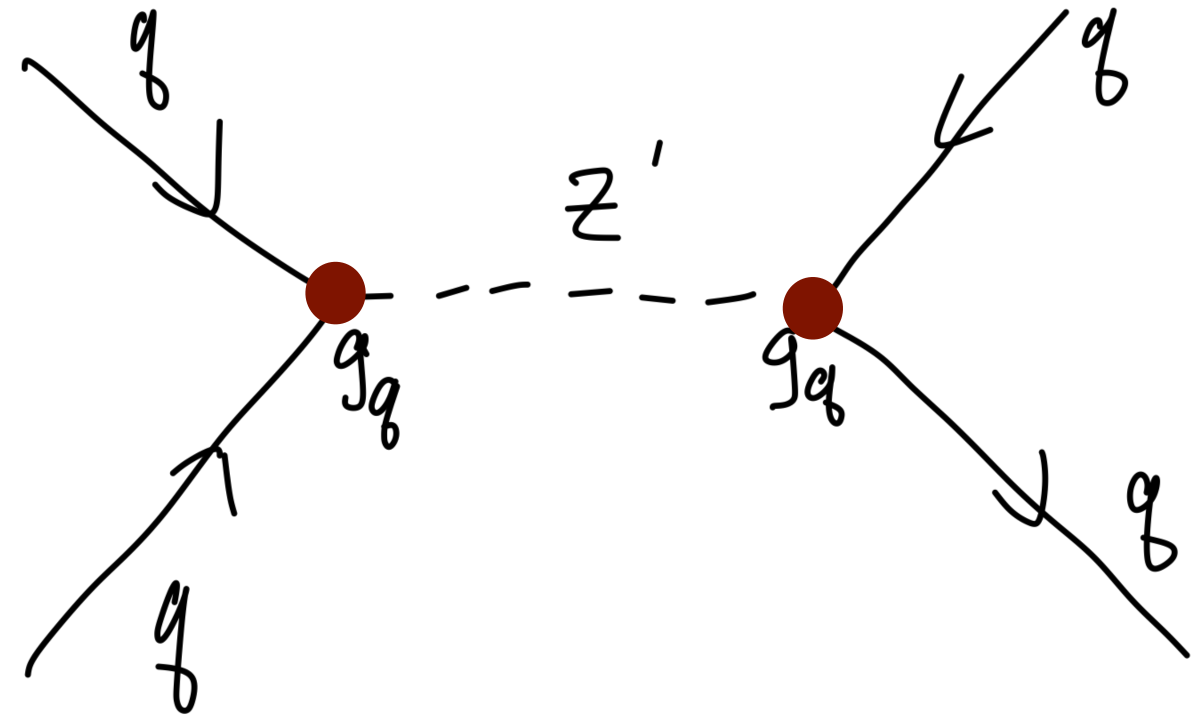

Then the mediator should decay back to jets!

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

Data Scouting

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Trigger limitations
come from
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Event Size x Event Rate = Total Bandwidth

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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

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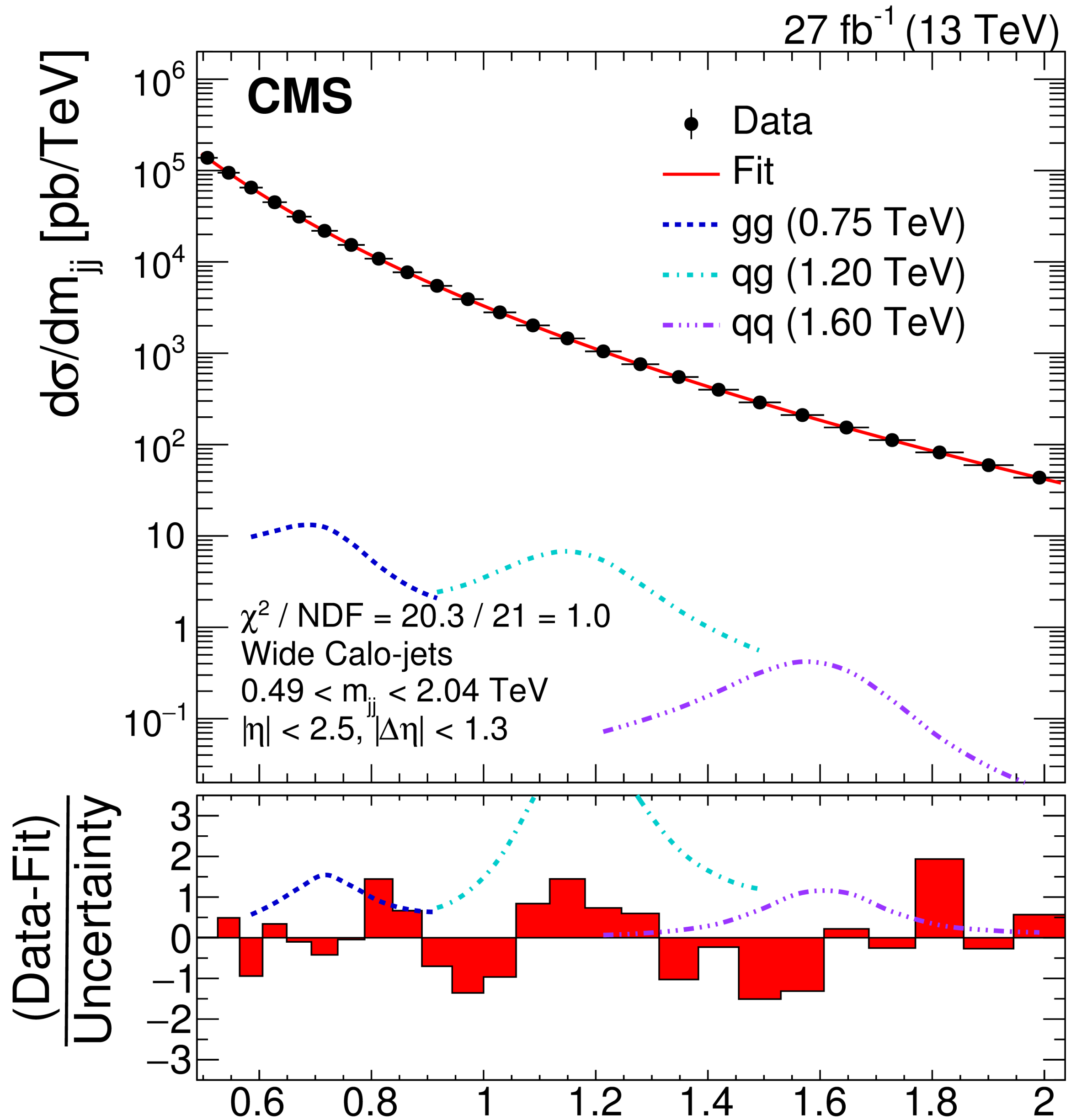

CMS-EXO-16-056

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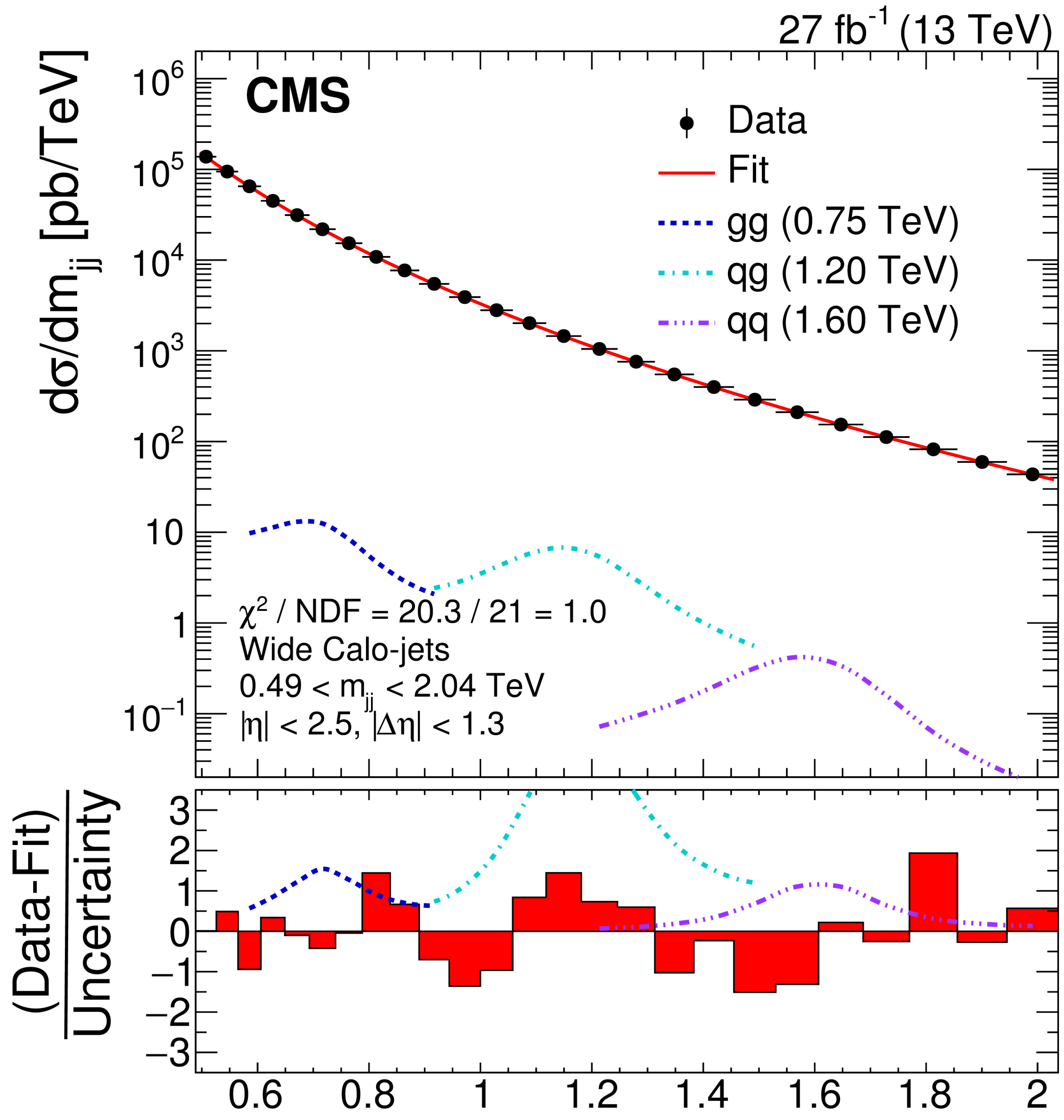

CMS-EXO-16-056

Can collect huge datasets
at low mass using this technique!

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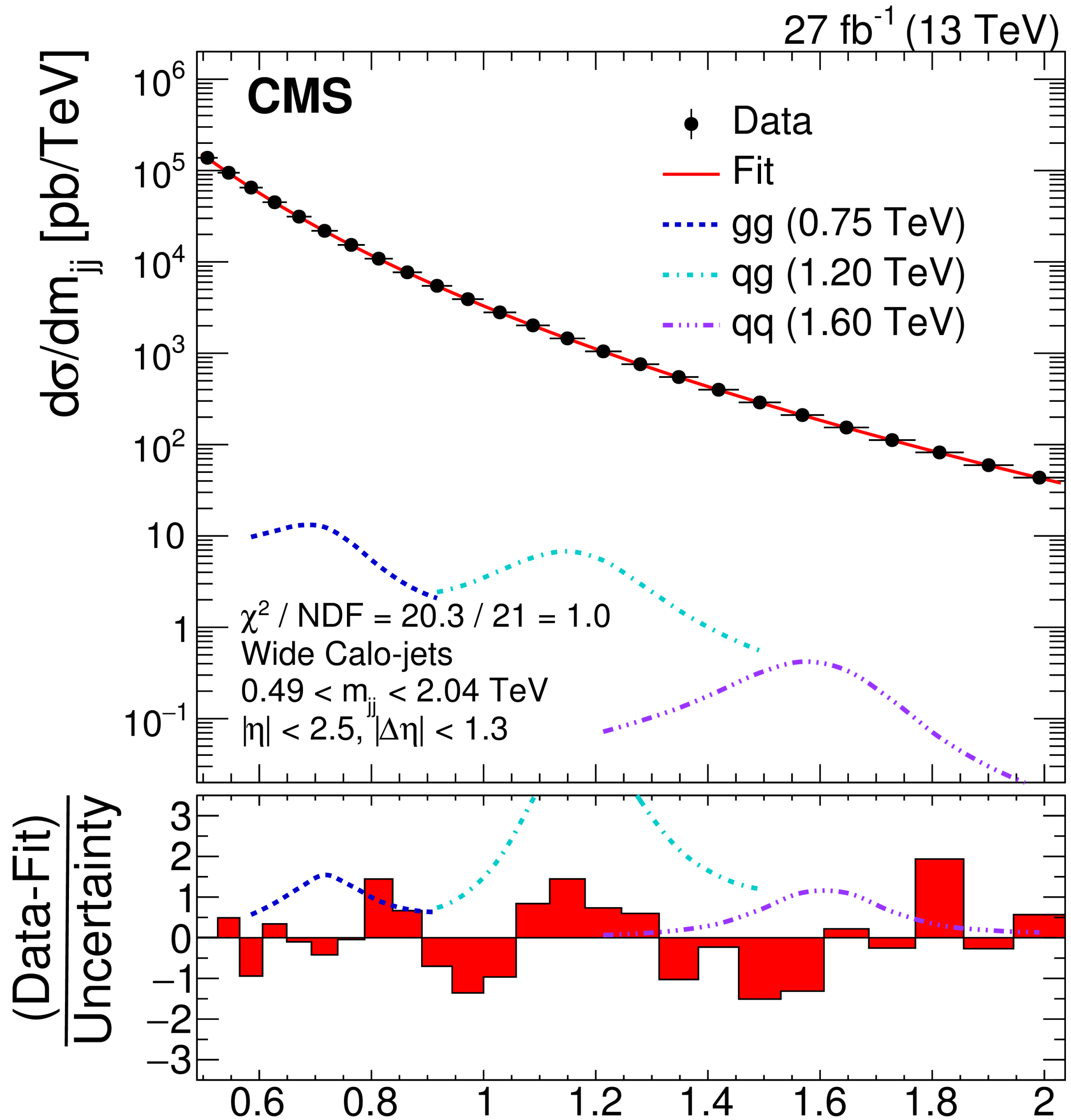

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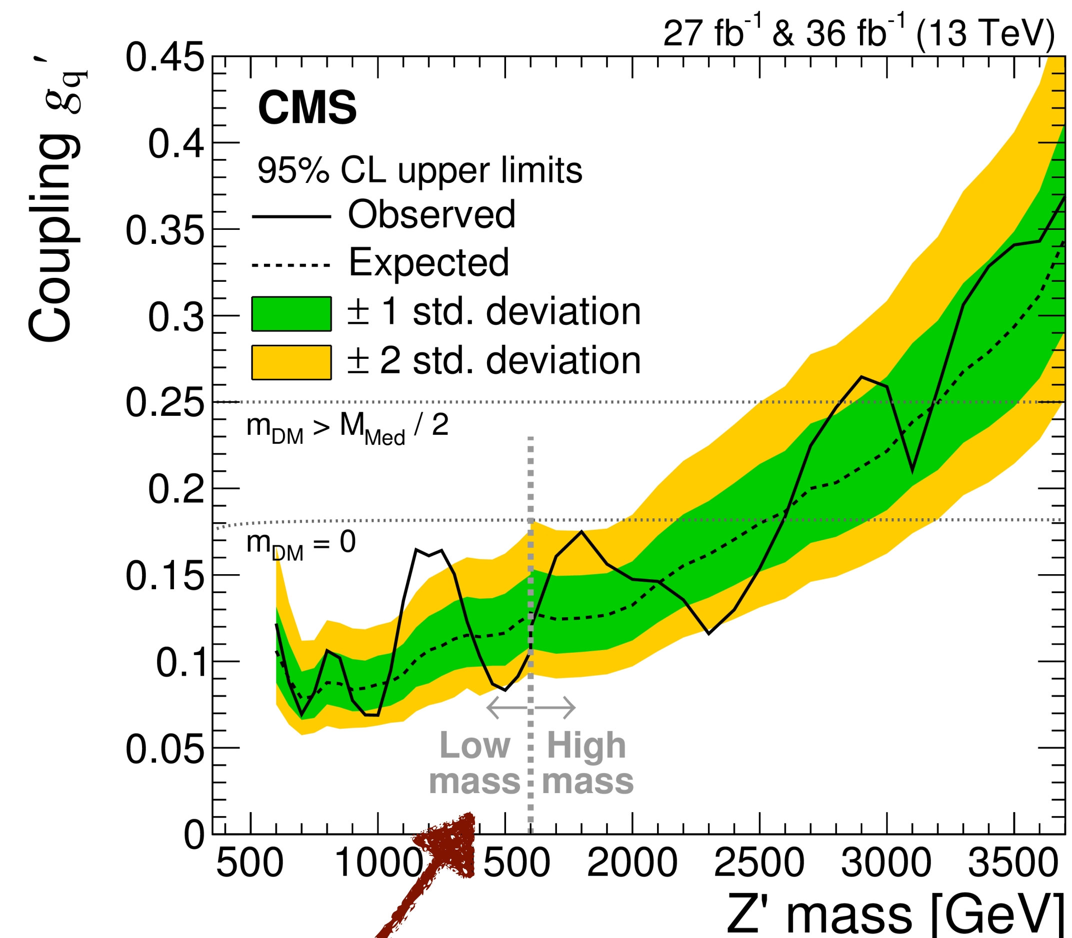

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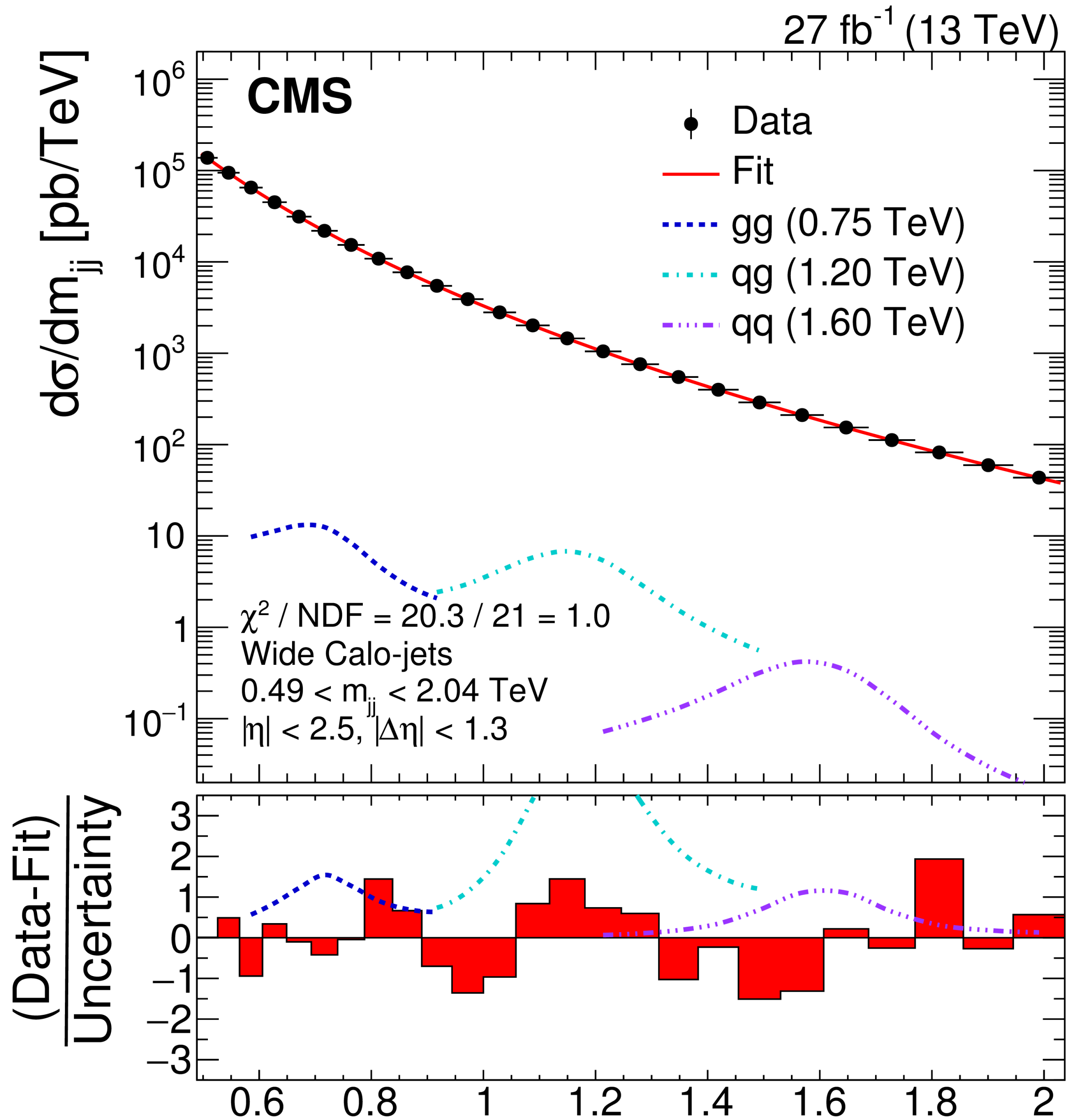

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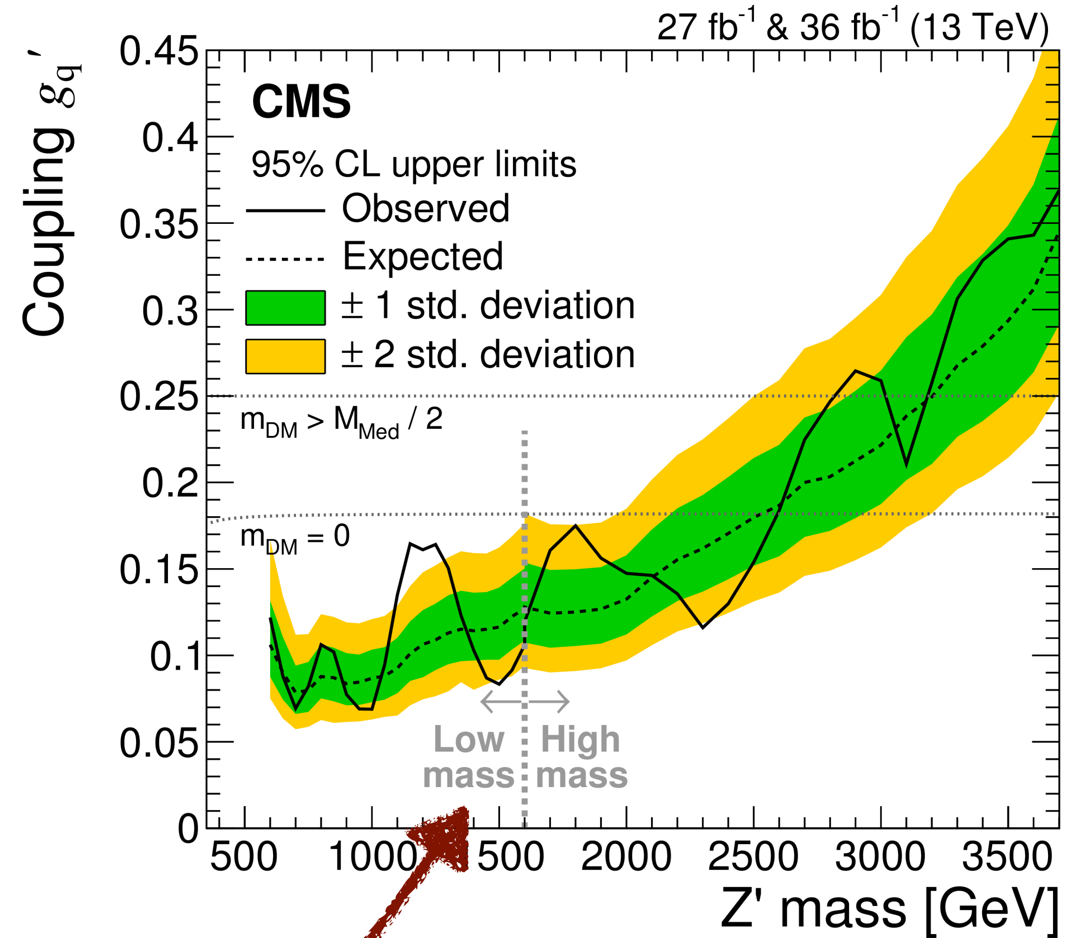


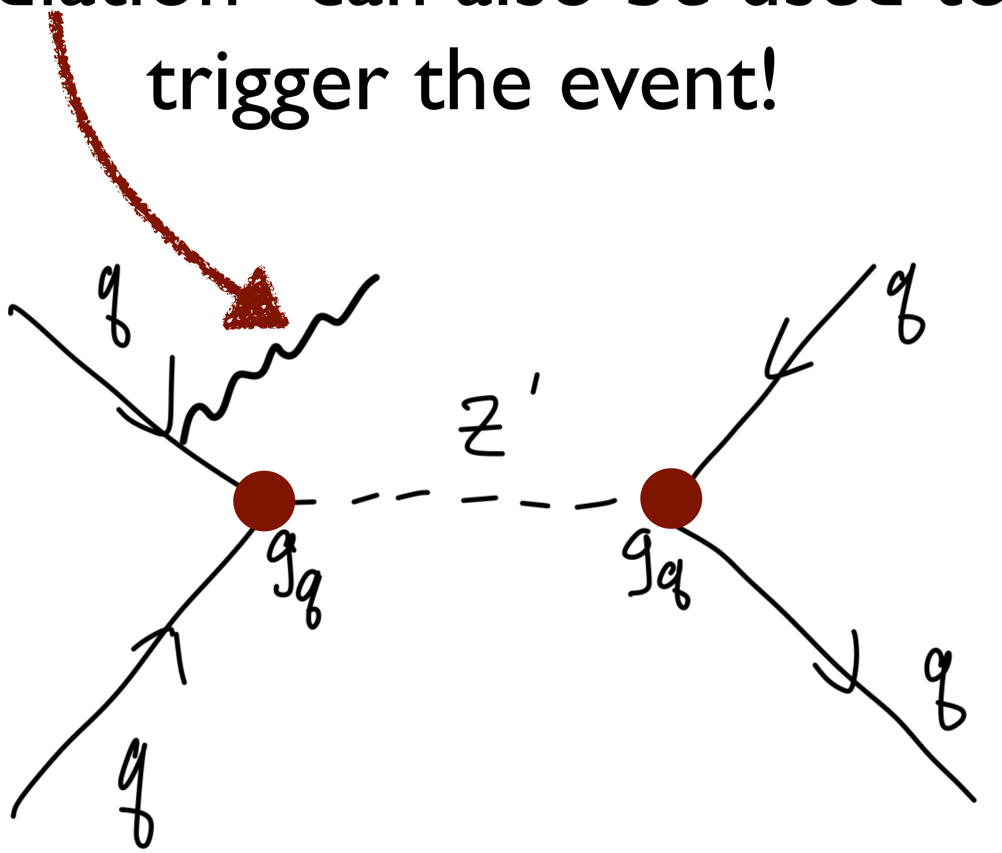
Can collect huge datasets at low mass using this technique!

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

Extra Radiation

Extra Radiation

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



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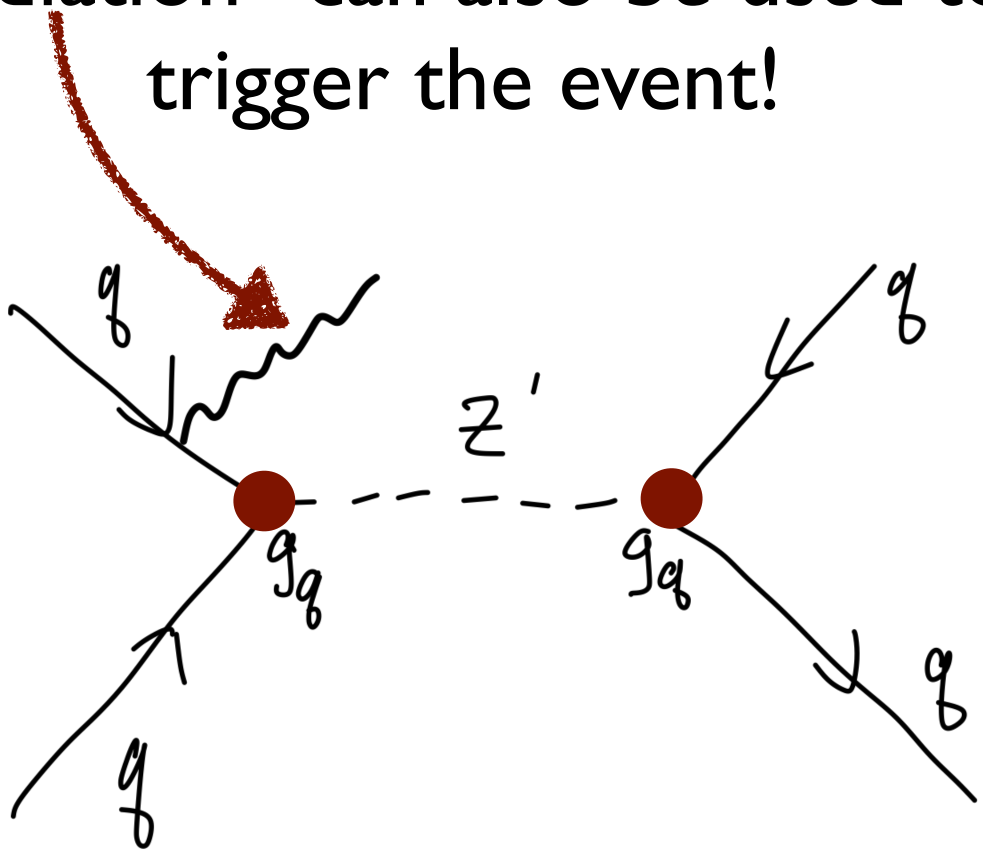

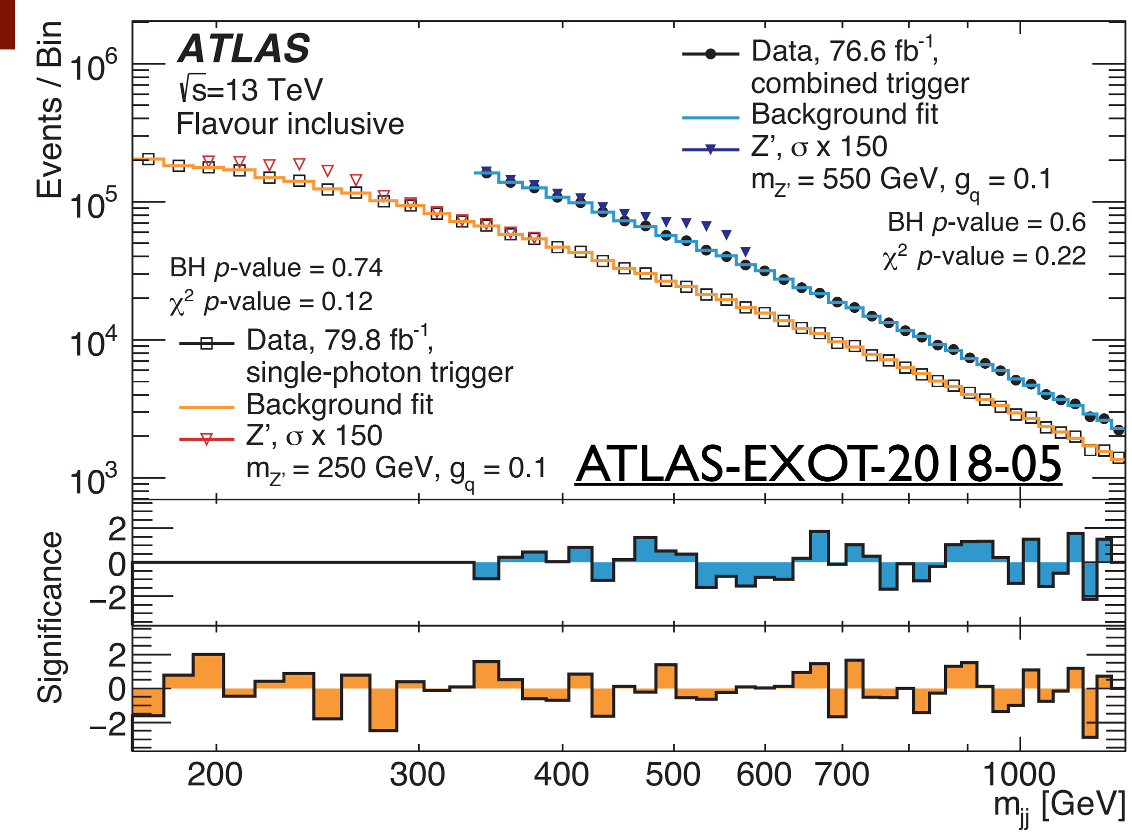

Even lower regions of mediator mass can be explored with these techniques

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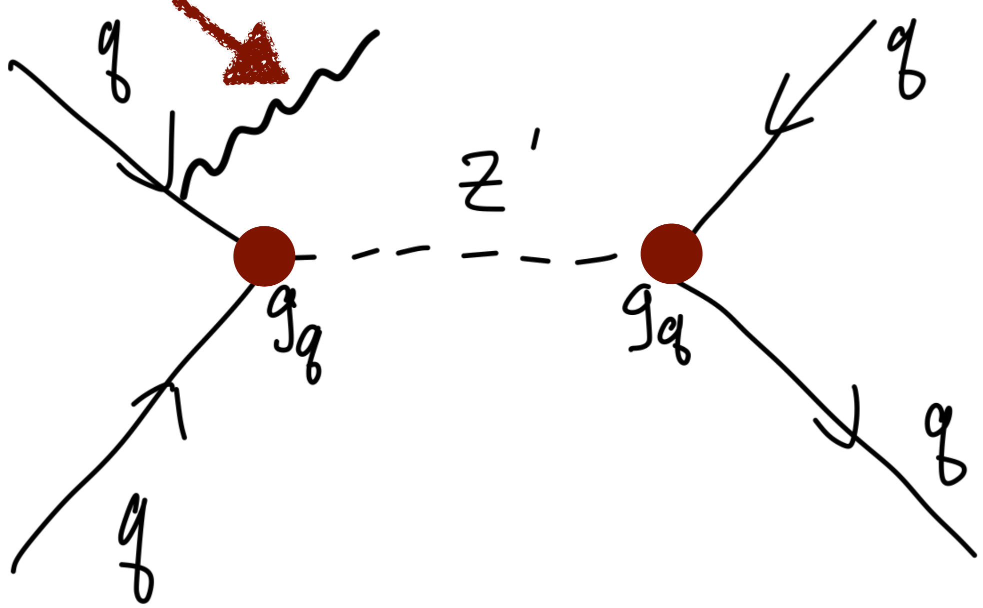

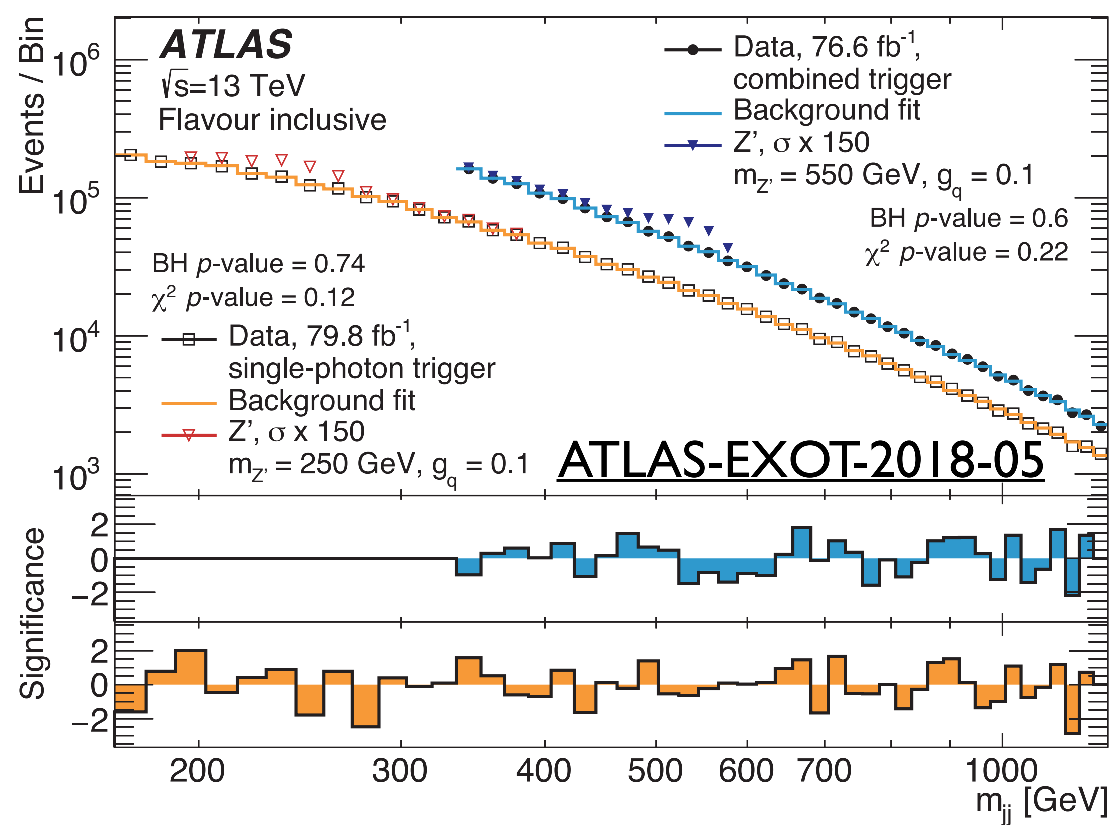

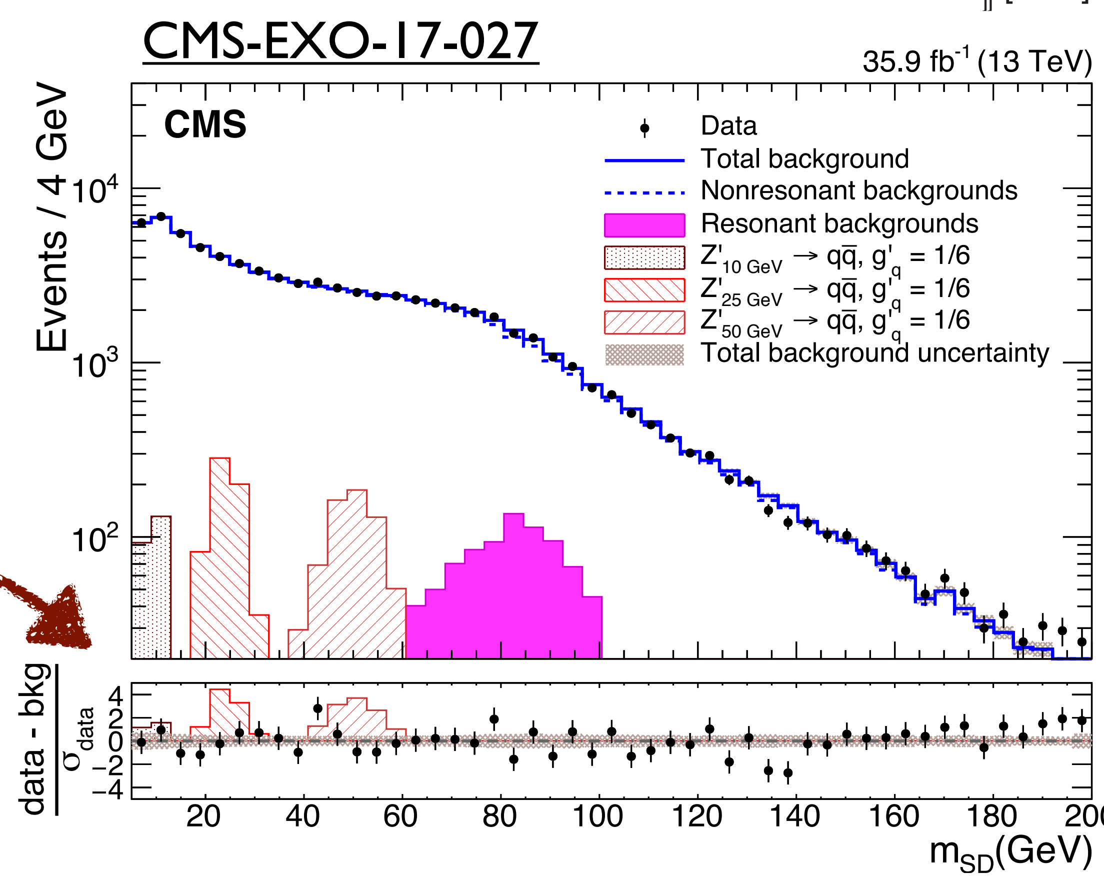

Even lower regions of mediator mass can be explored with these techniques

Can even search as low as 10 GeV!

The Big Picture for Z’

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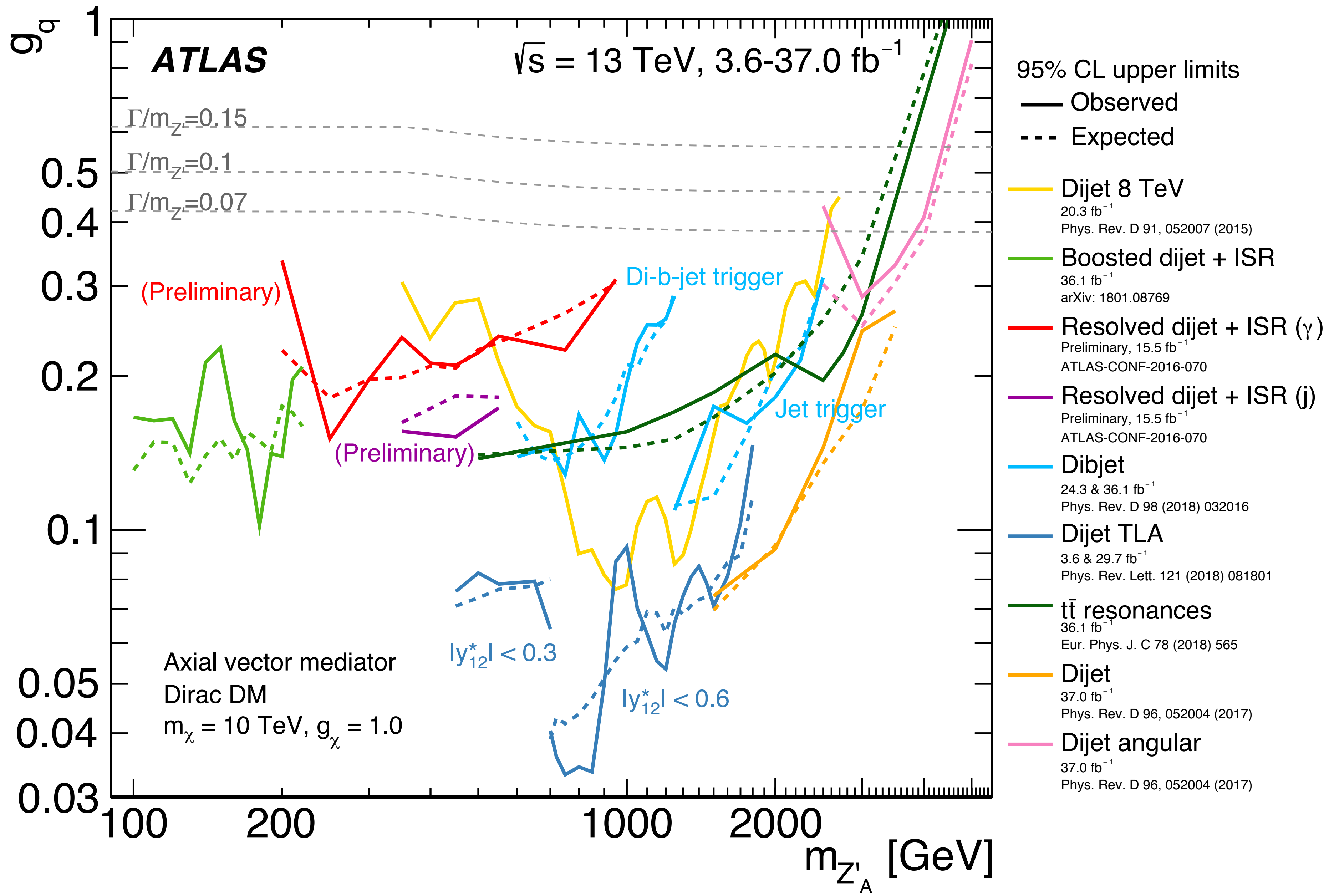

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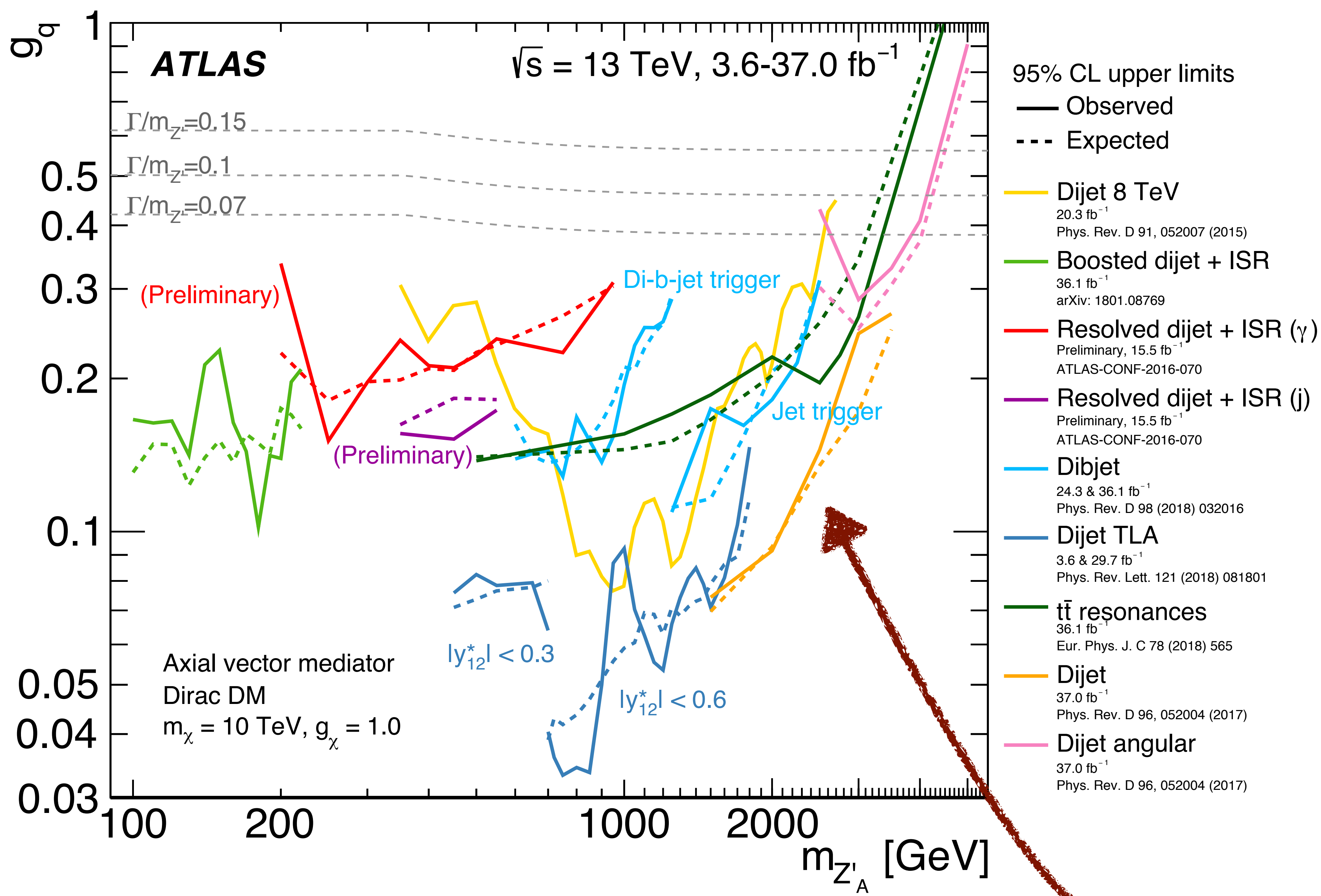
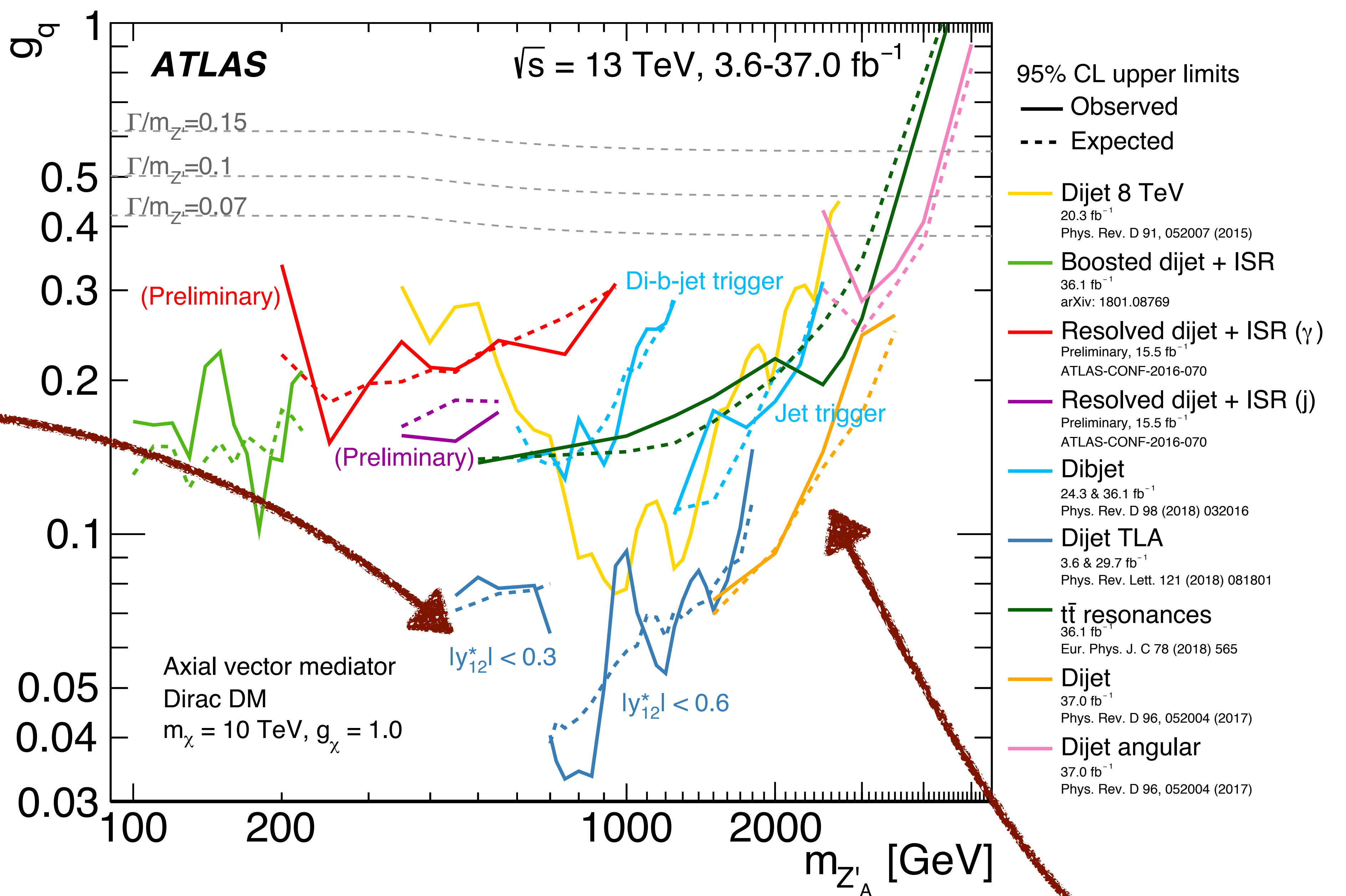


Traditional

The Big Picture for Z’

Trigger Only



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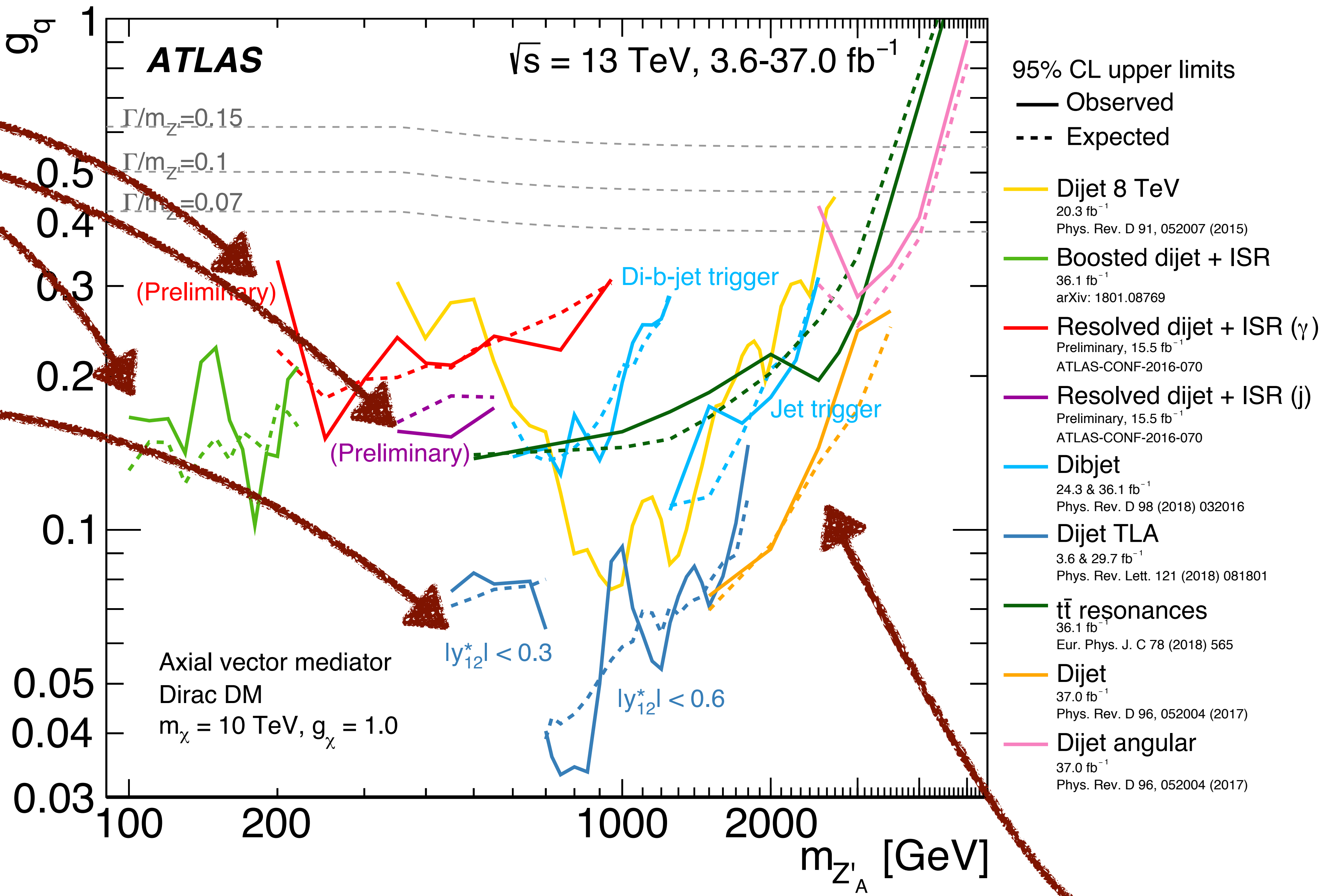
The Big Picture for Z'

ISR

Trigger Only



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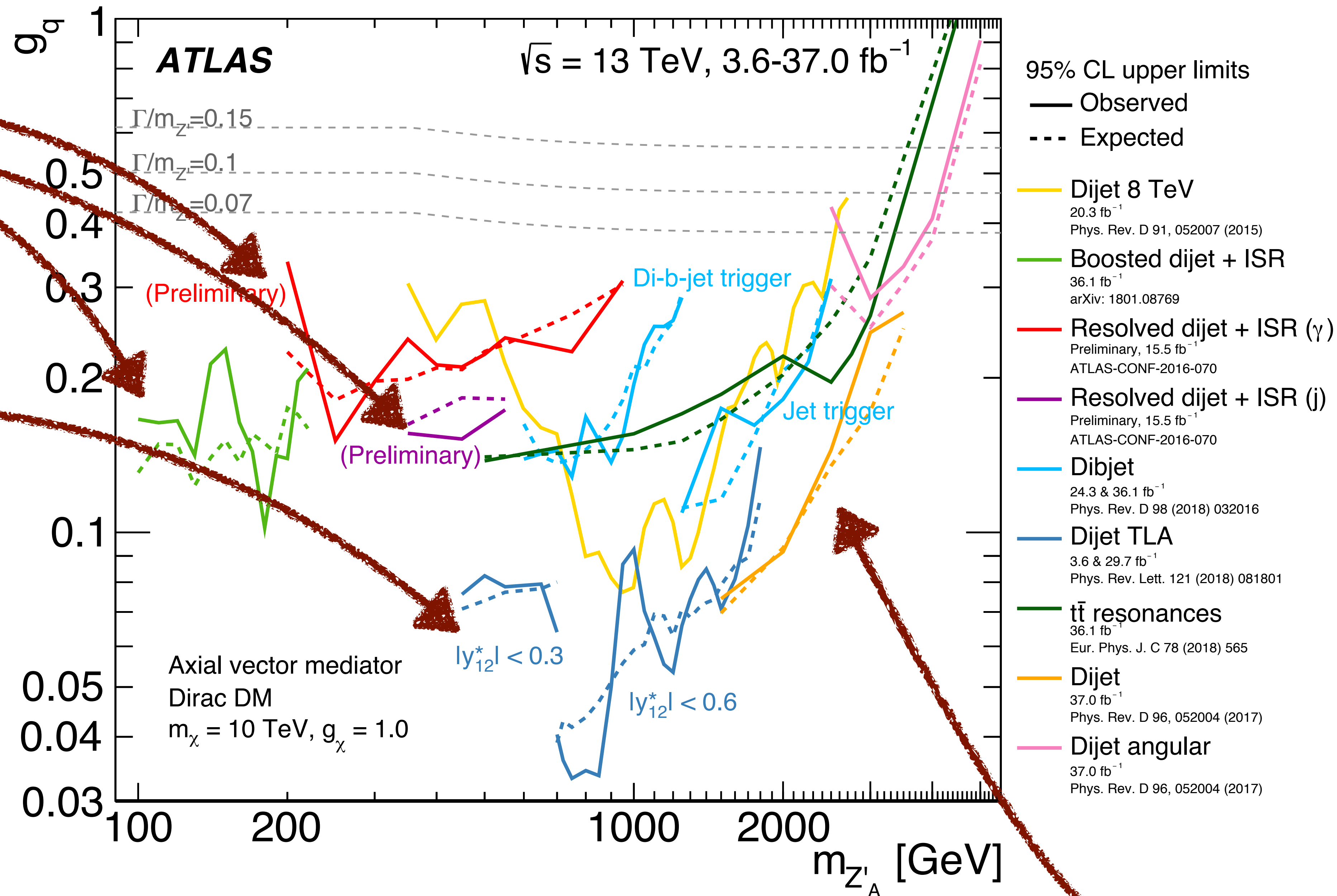

Traditional

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?

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Because many theories predict low cross-section signals!

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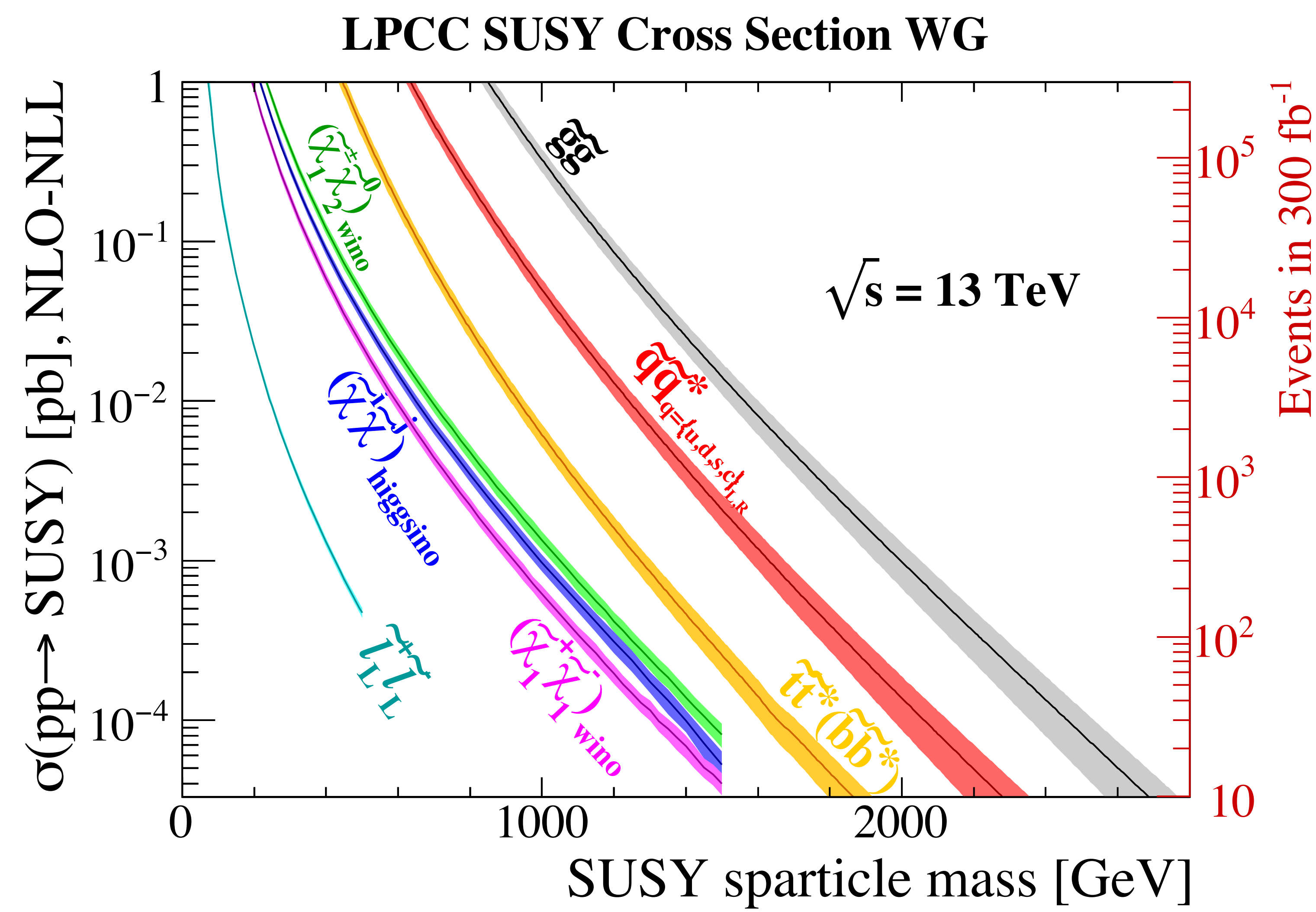

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections arXiv:1407.5066

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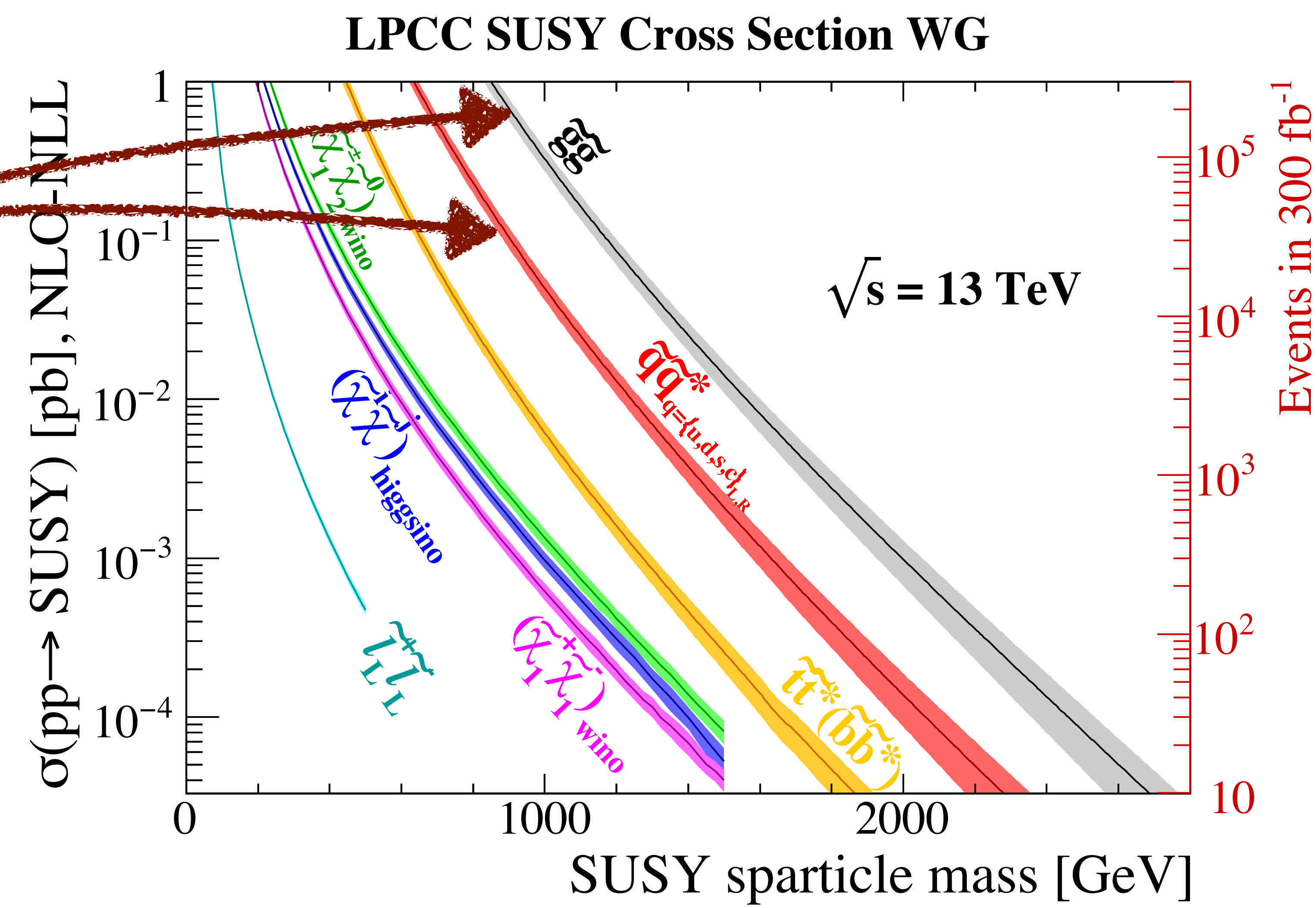

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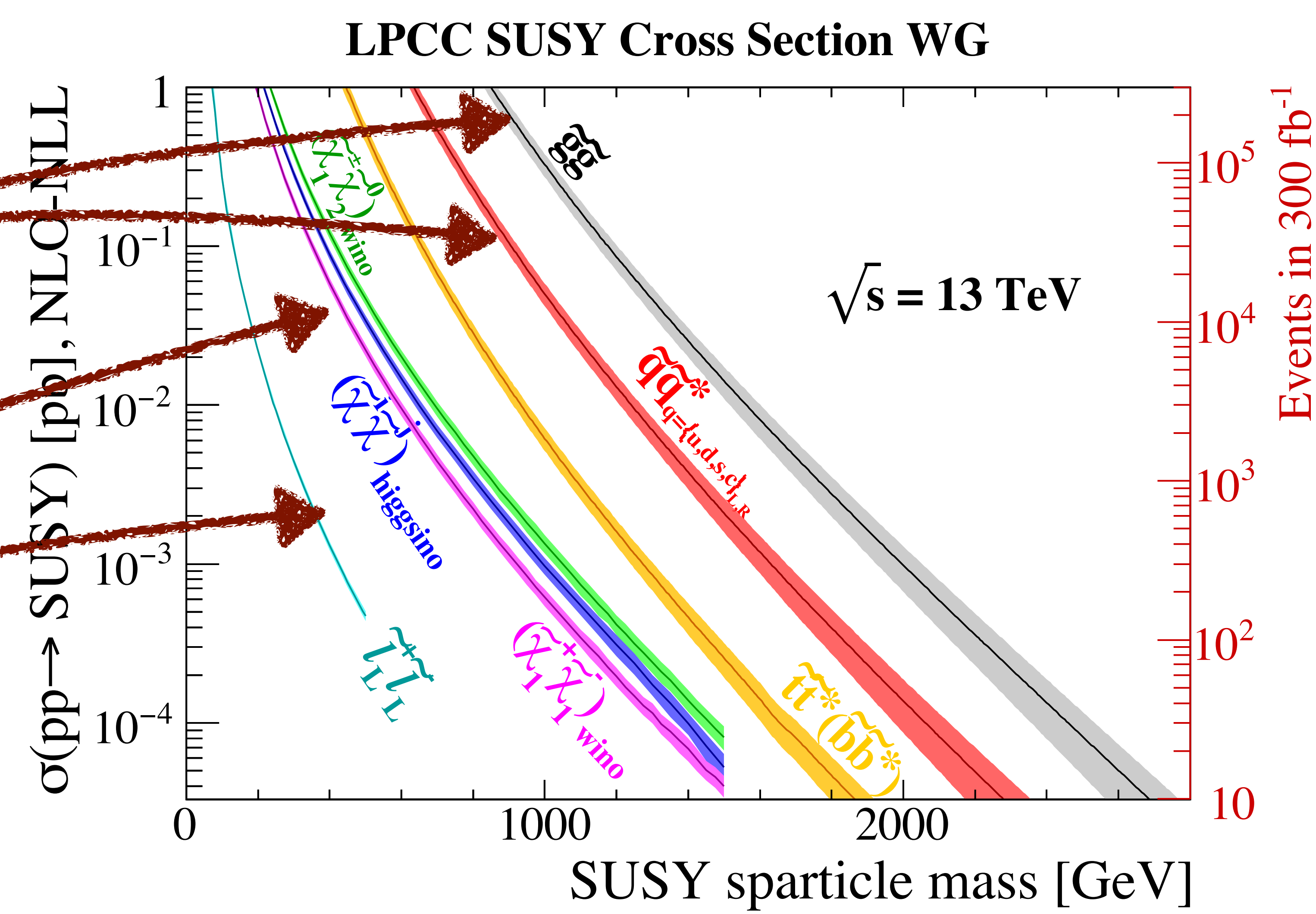
Higgsinos and sleptons might still be in sight!



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Higgsinos: The Challenge

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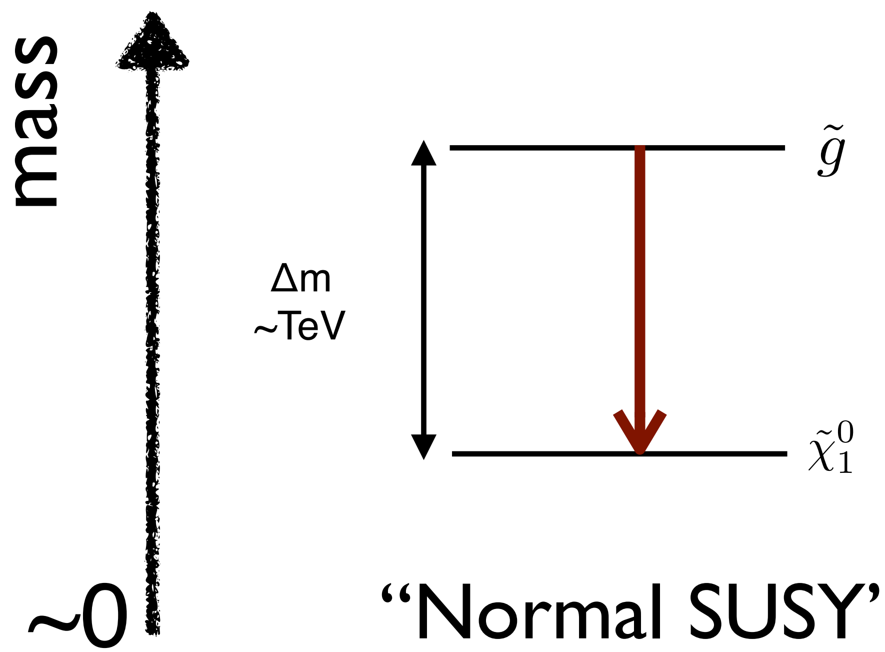
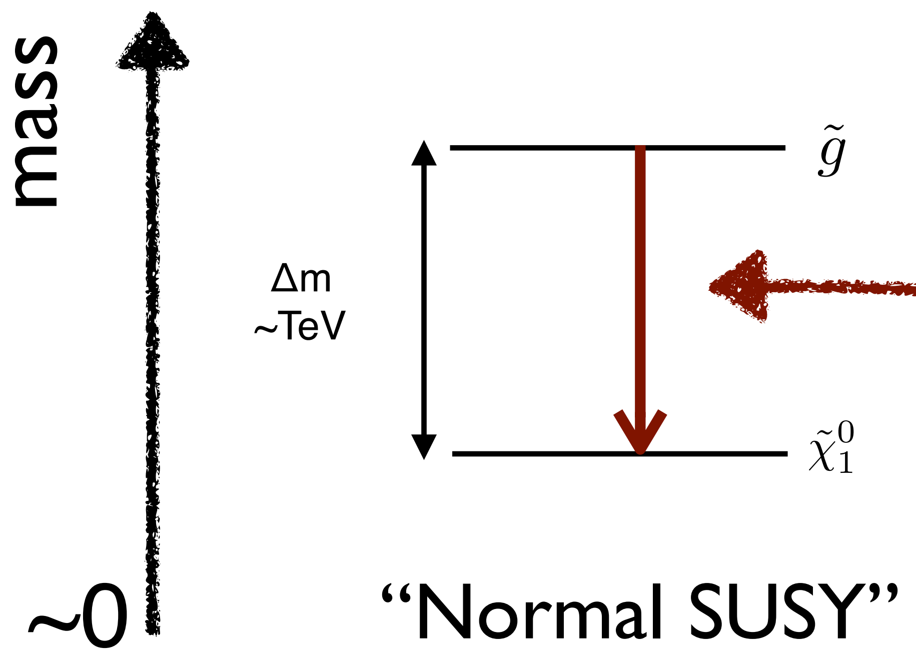


"Normal SUSY"

"Classic" SUSY searches exploit large mass splittings

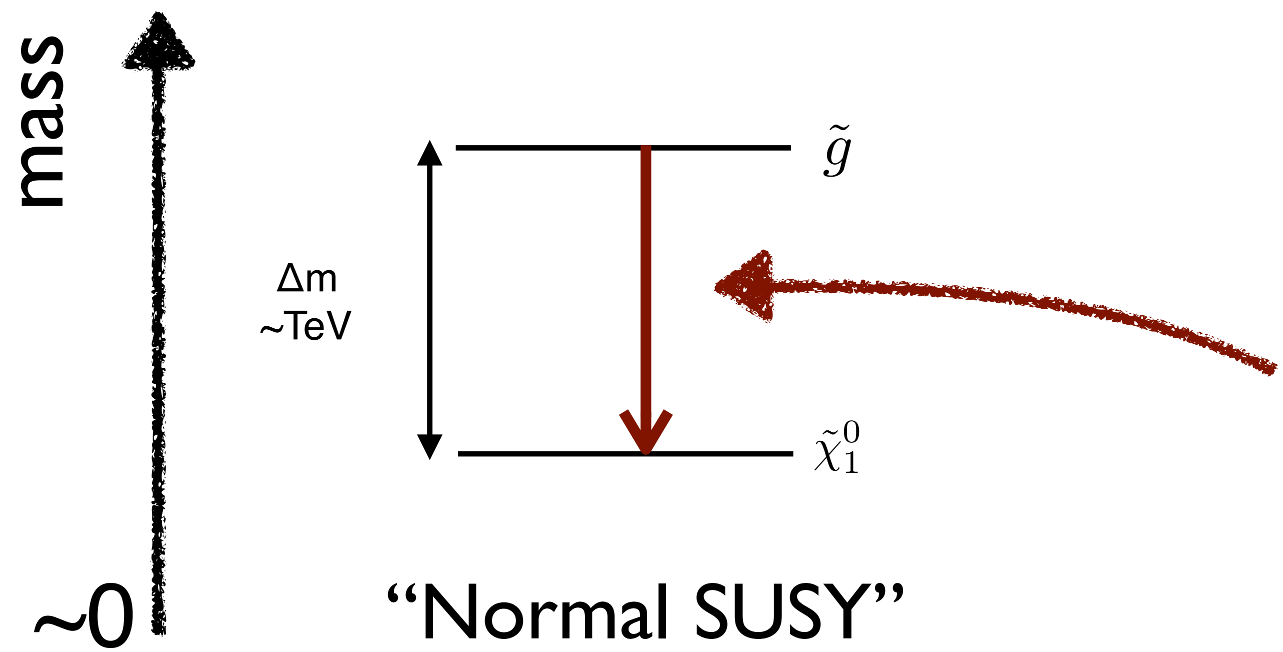
Higgsinos: The Challenge



"Classic" SUSY searches exploit large mass splittings

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

Higgsinos: The Challenge



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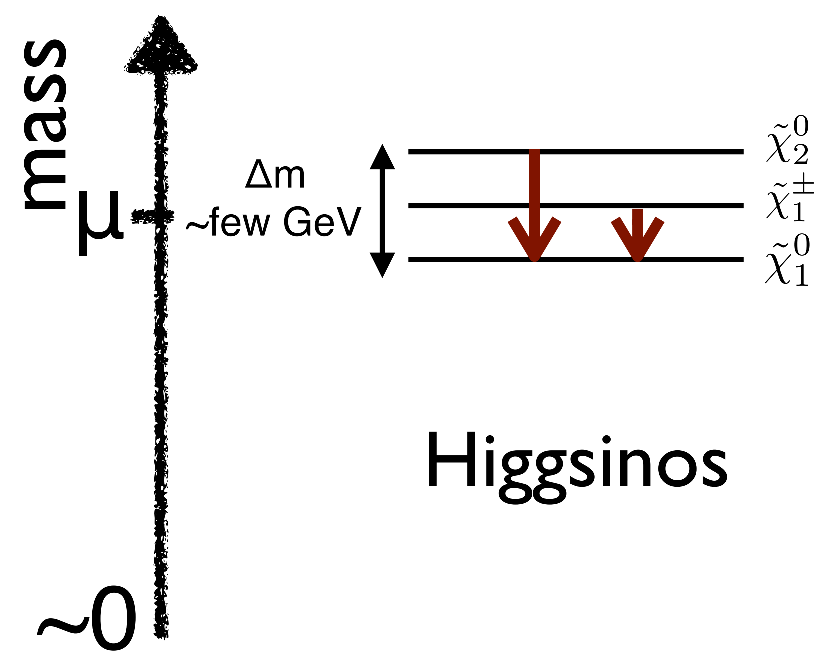

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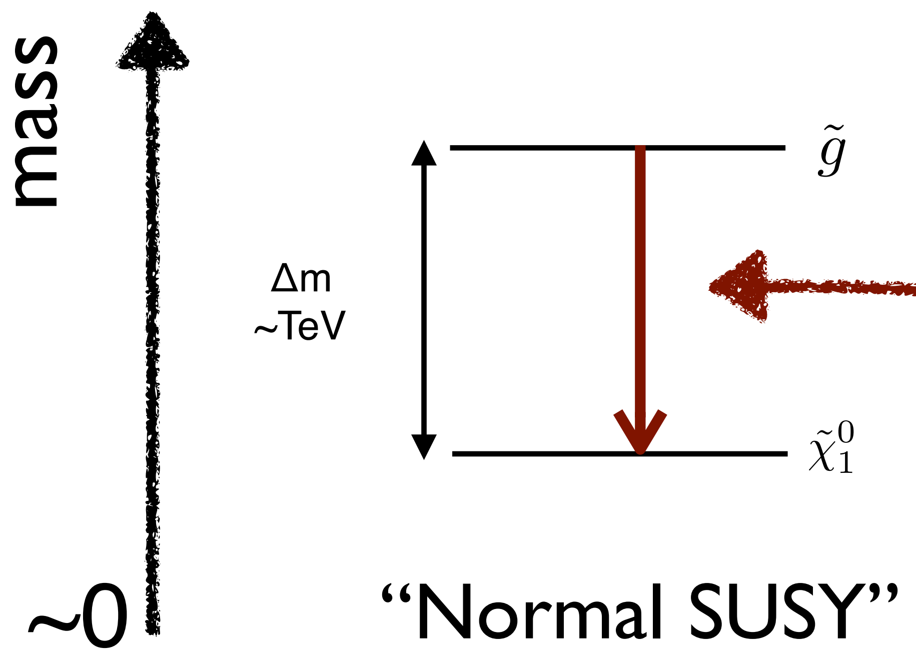

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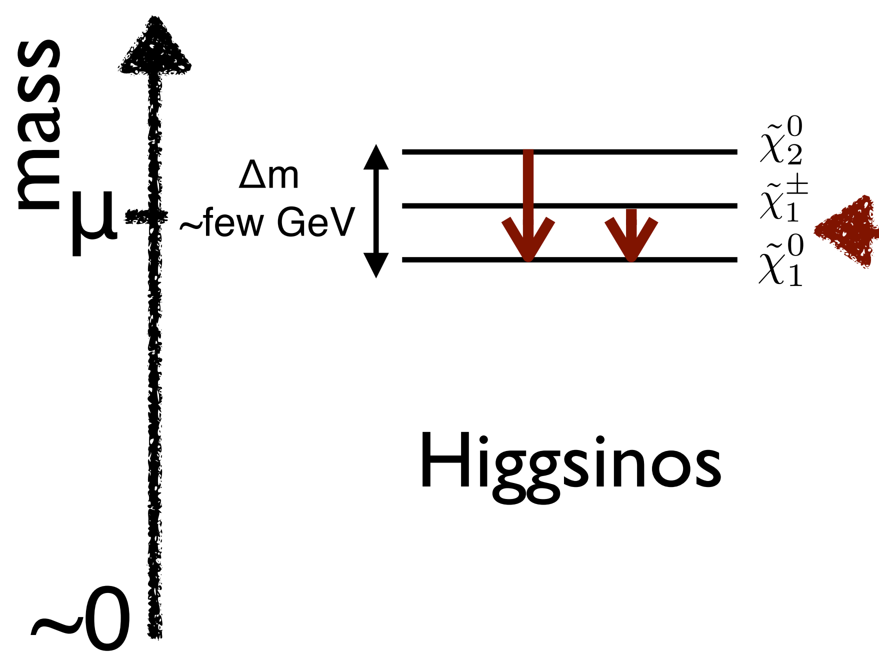

Higgsinos are another story…

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

Searching for Rare Higgsinos

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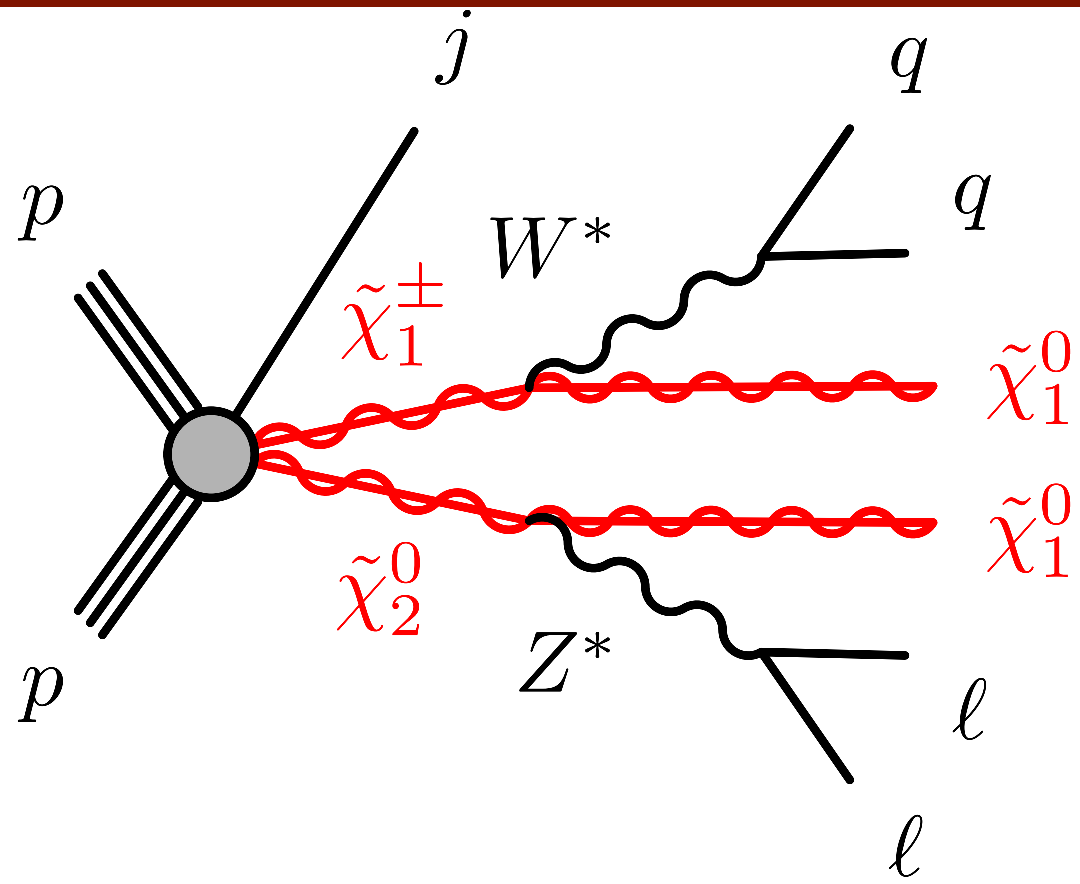

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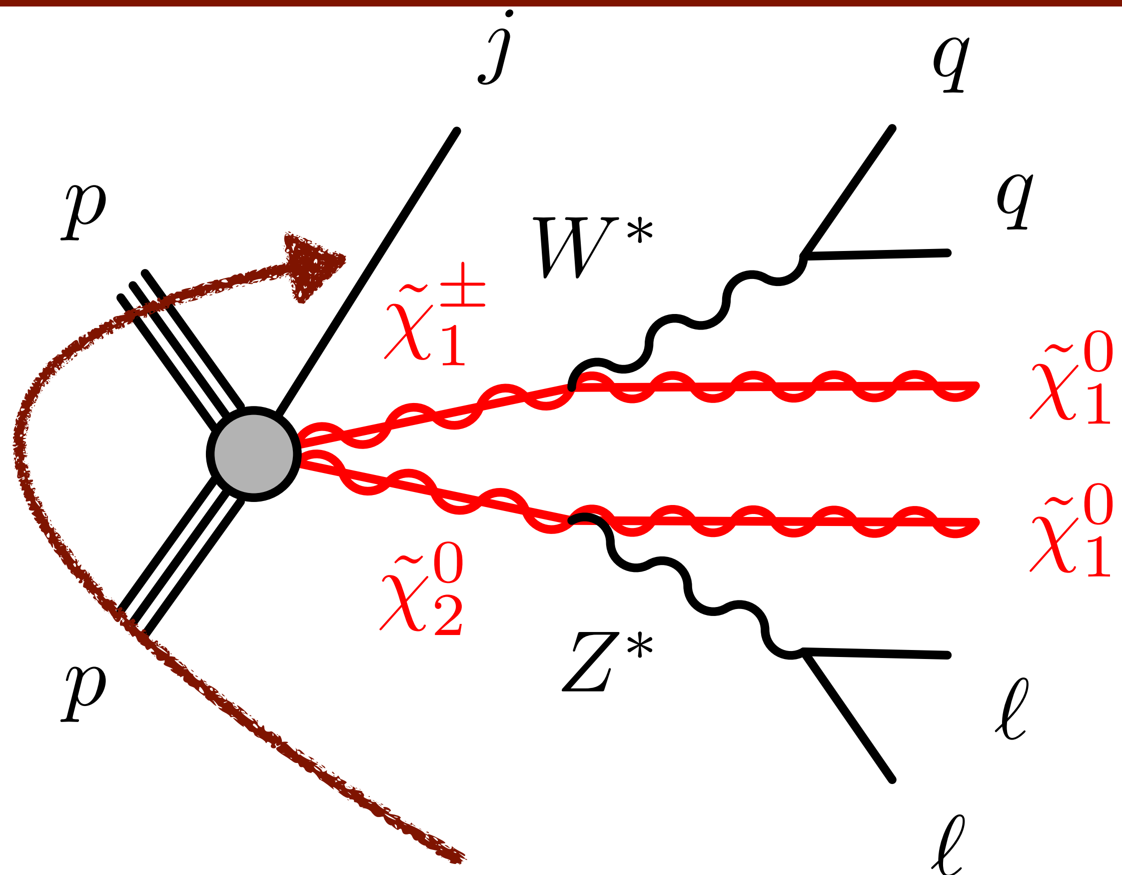
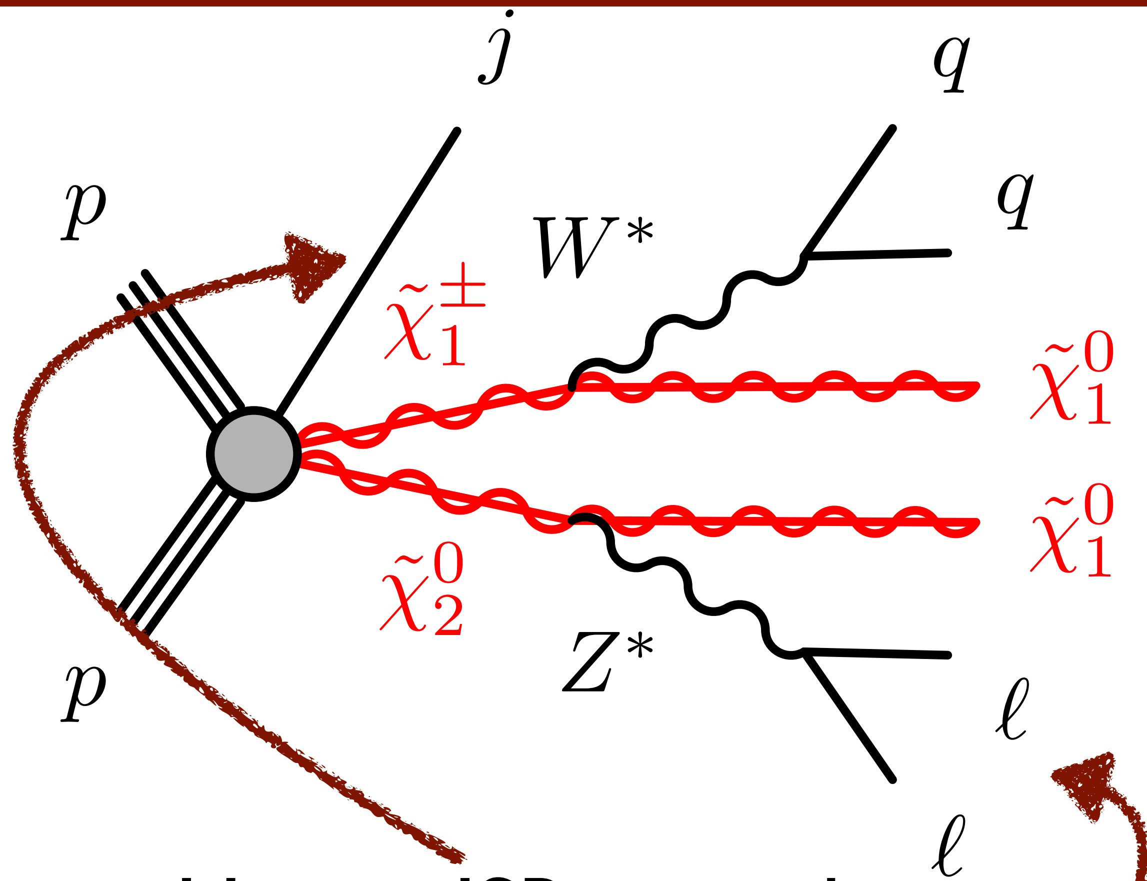


Use an ISR jet to boost the system and trigger

Searching for Rare Higgsinos



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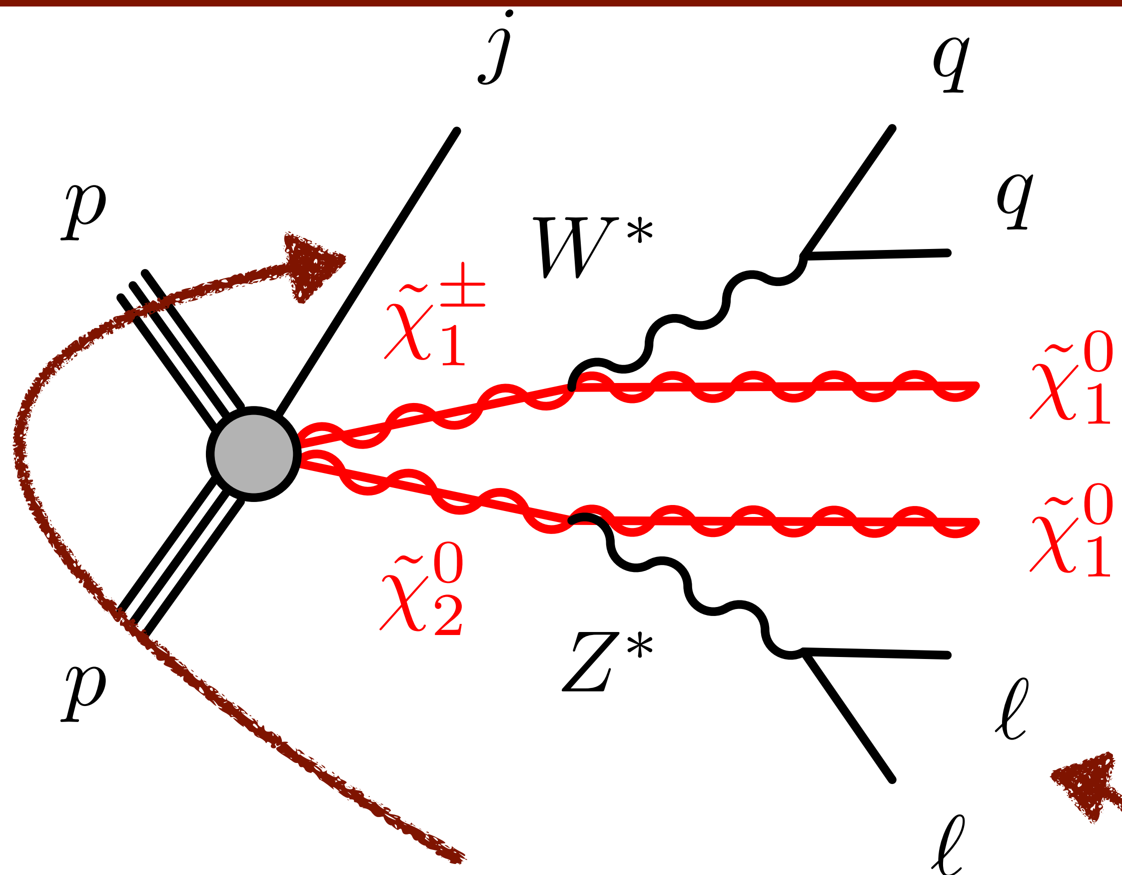

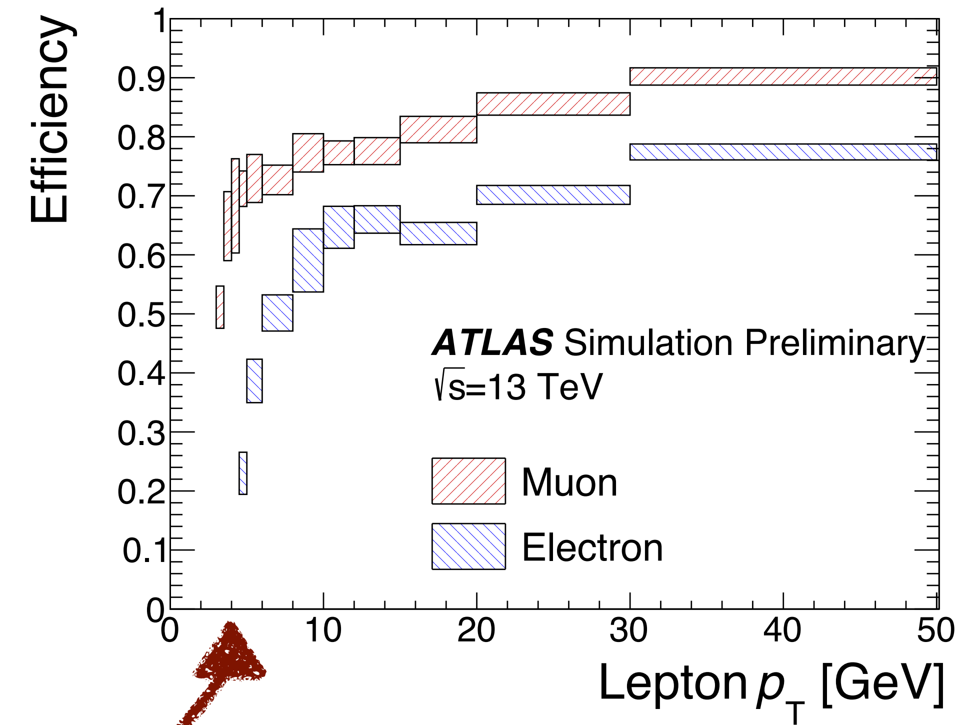

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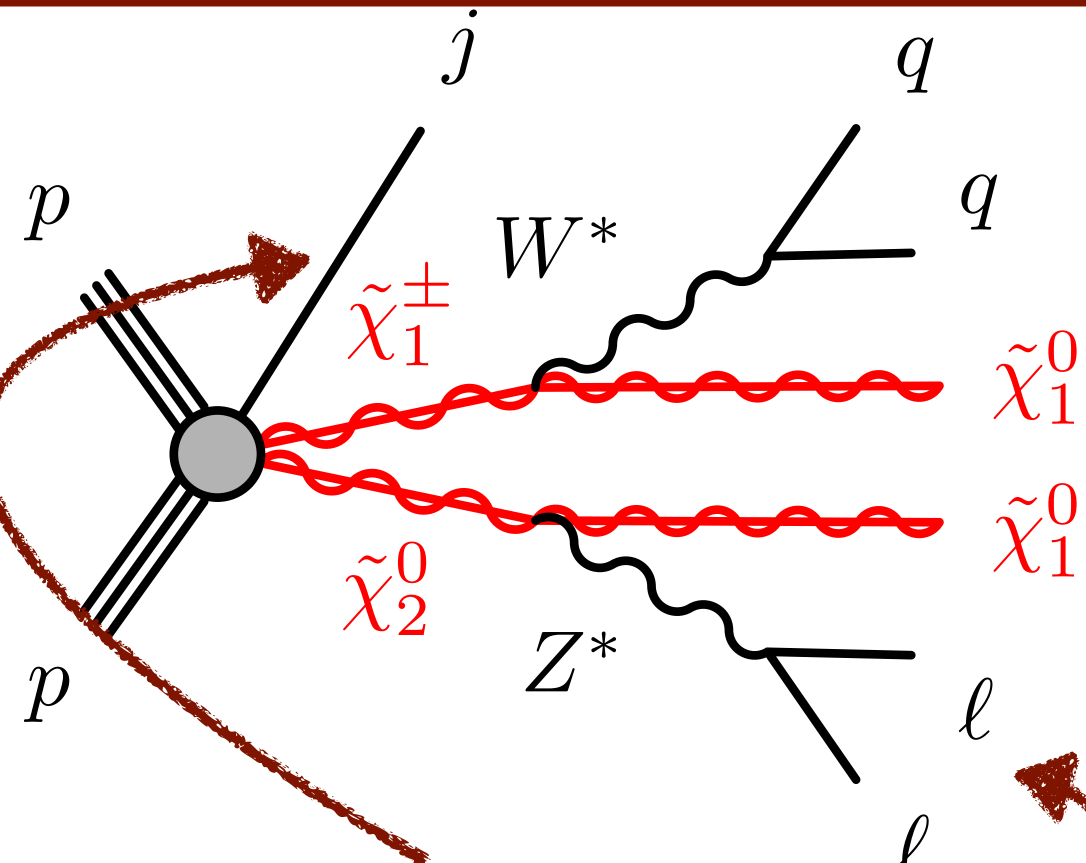

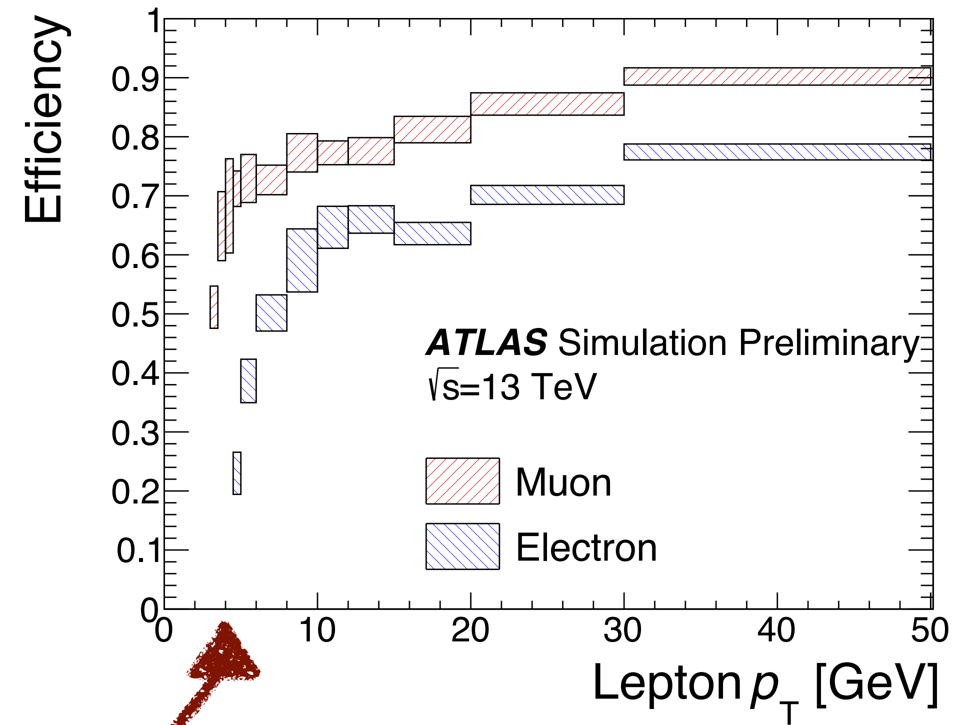

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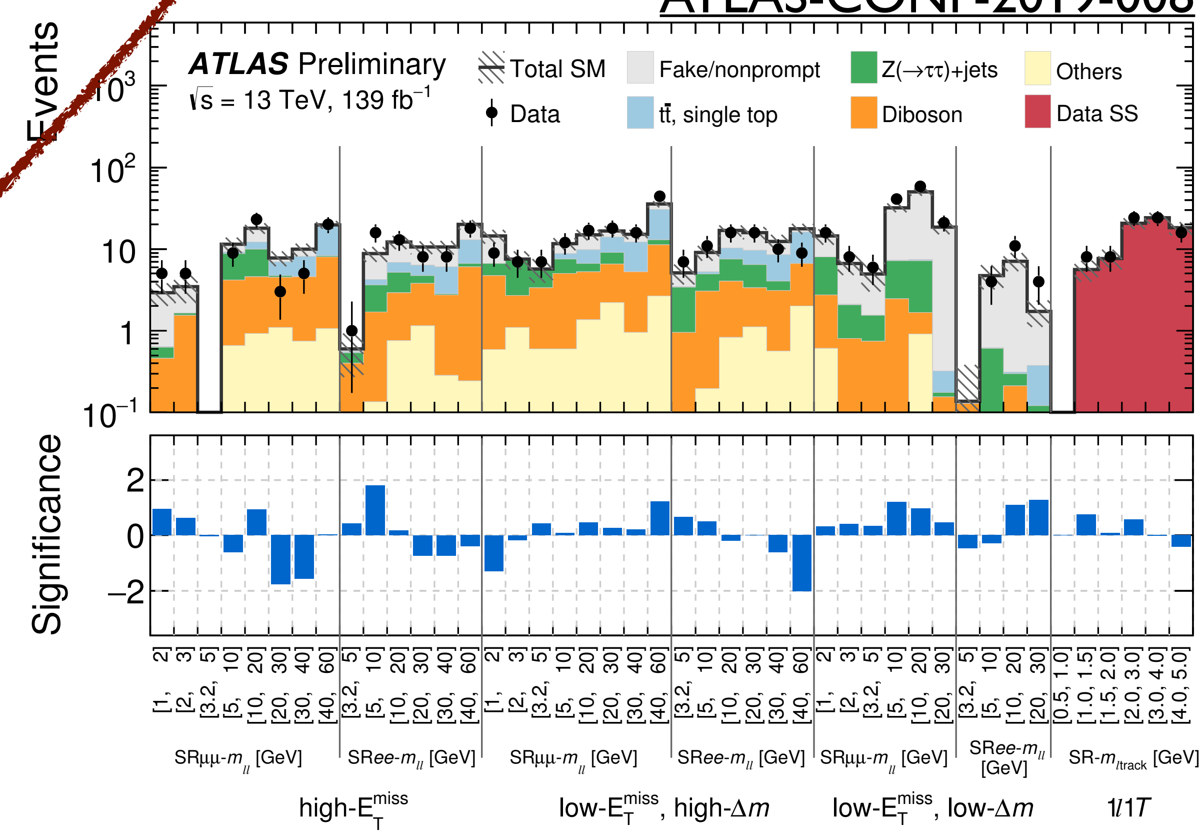

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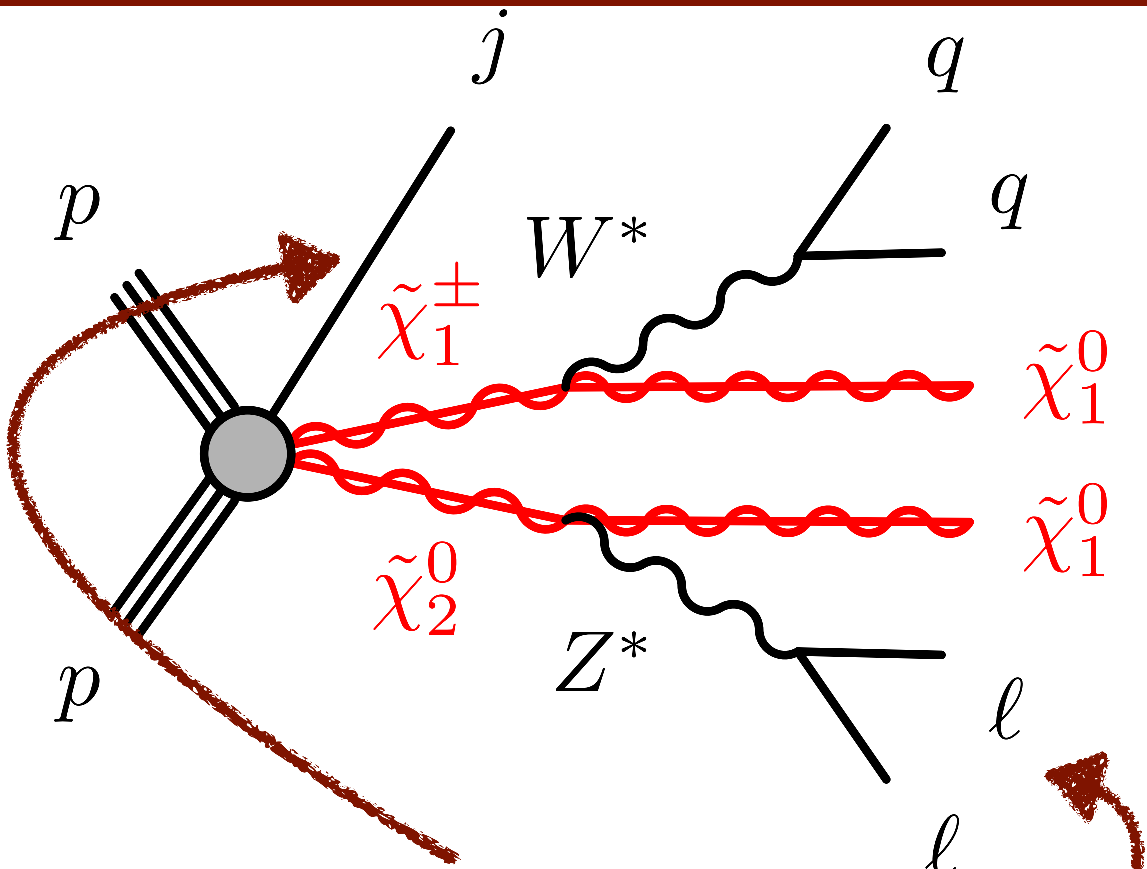

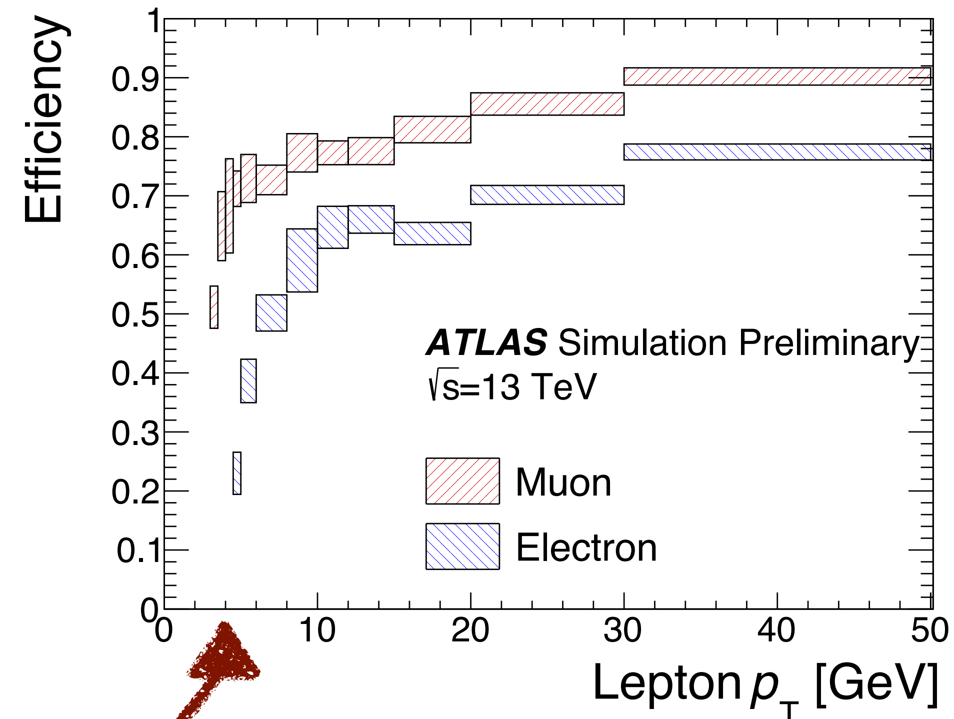

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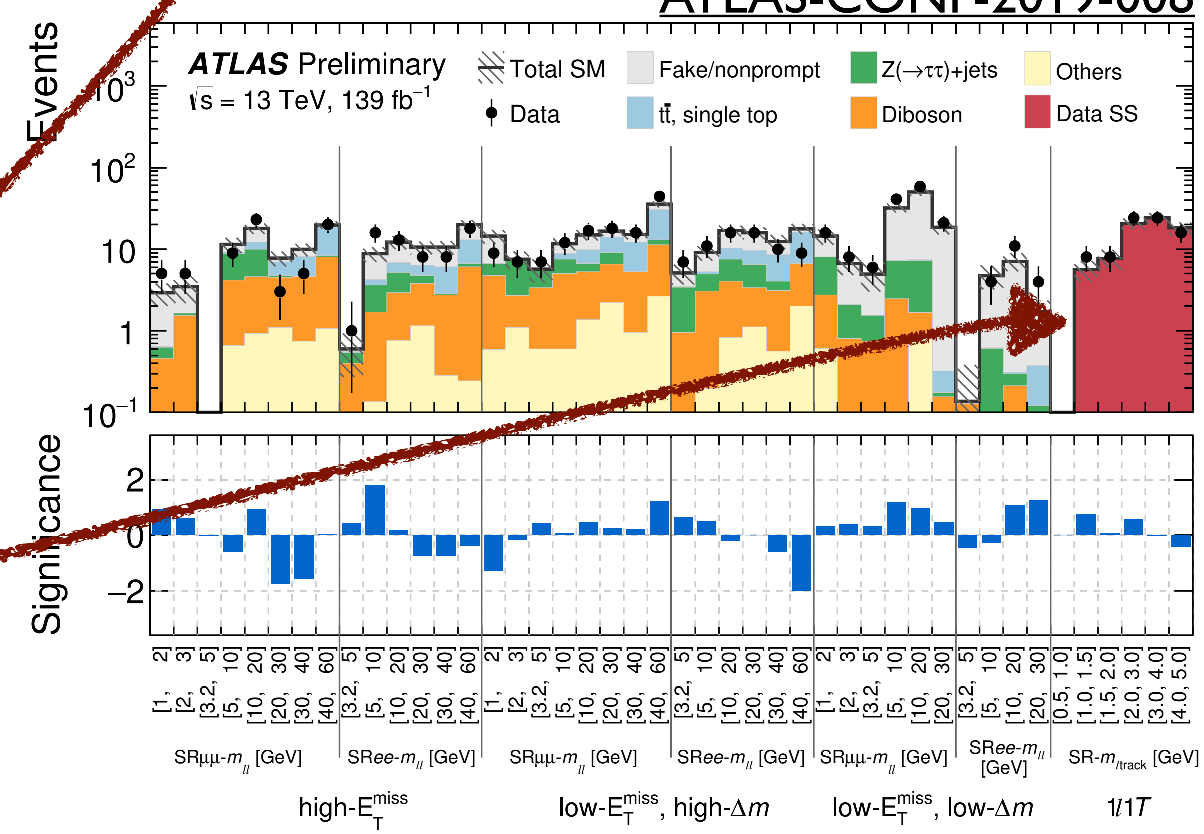


Use an ISR jet to boost the system and trigger

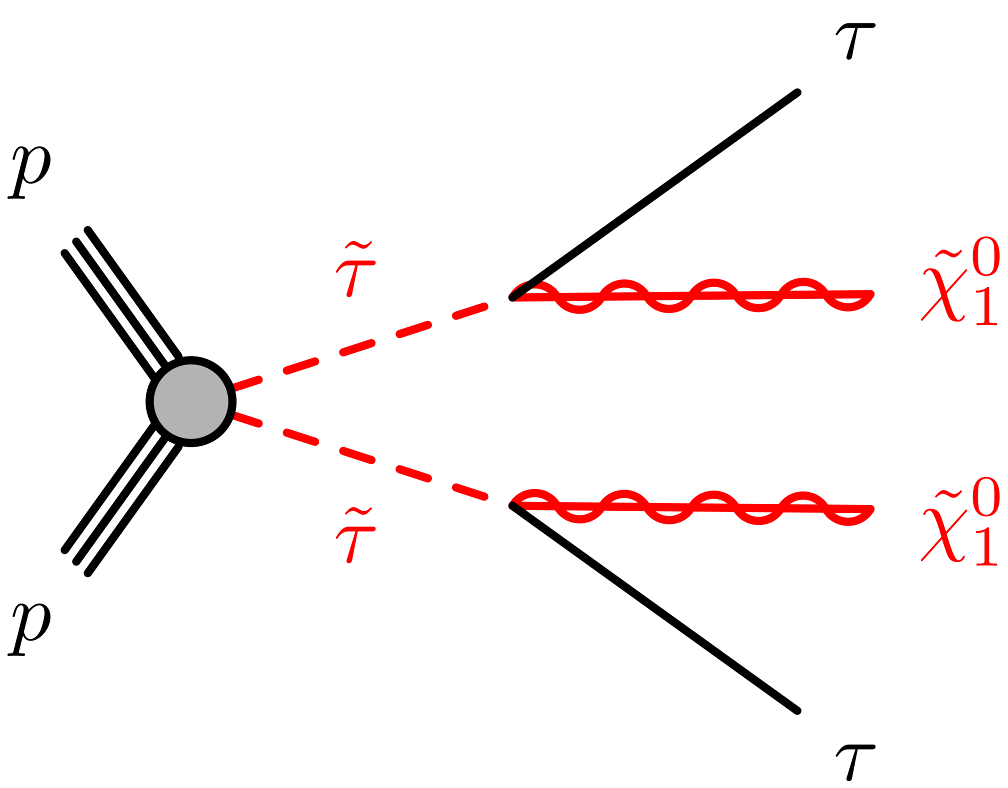
Then, look for low-mass Z* decays

Critical to reconstruct leptons at extremely low p_T

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

Even Rarer: Staus

Even Rarer: Staus



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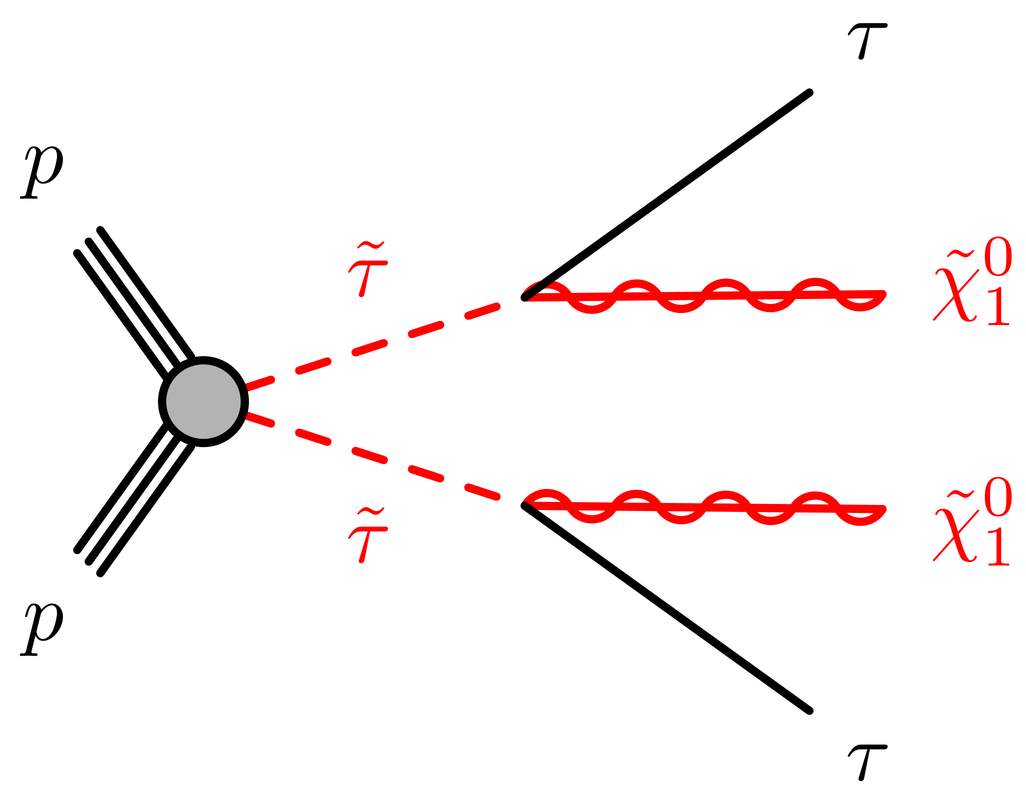
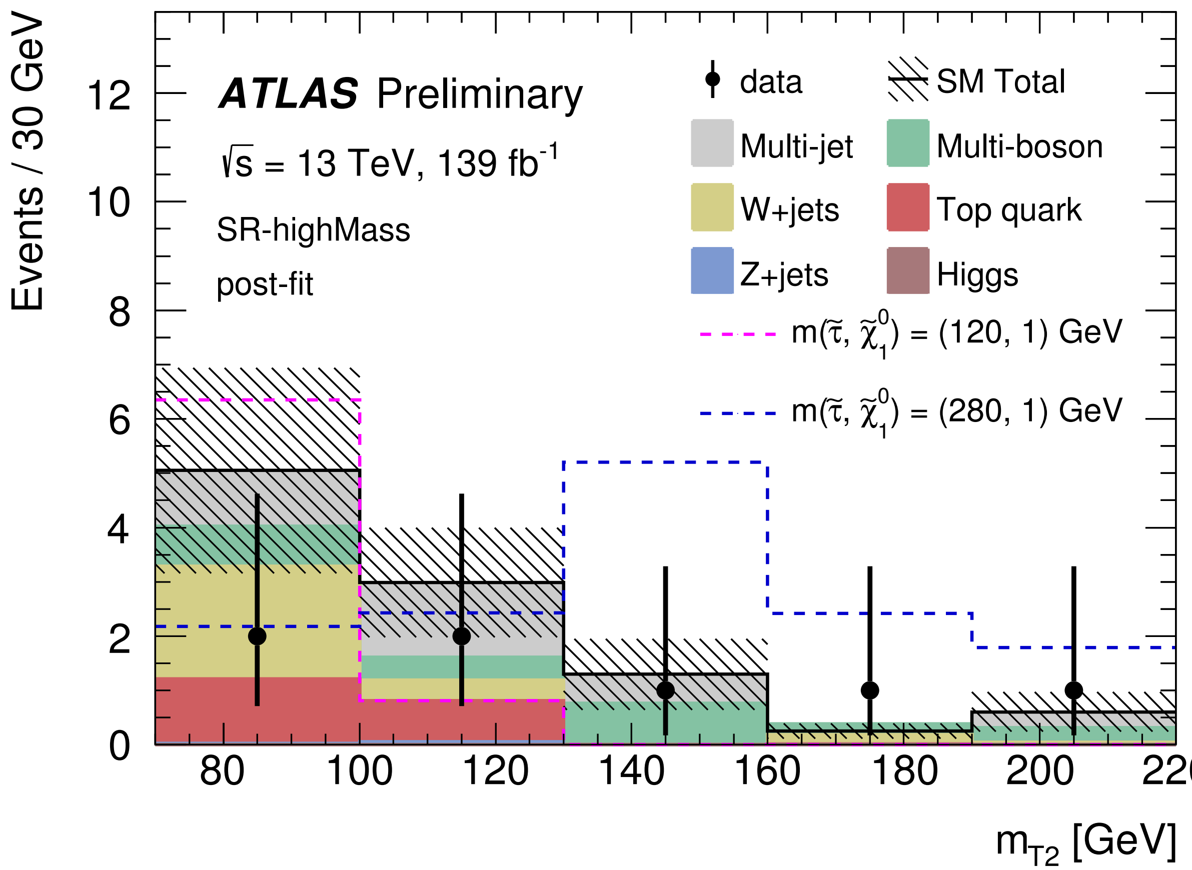


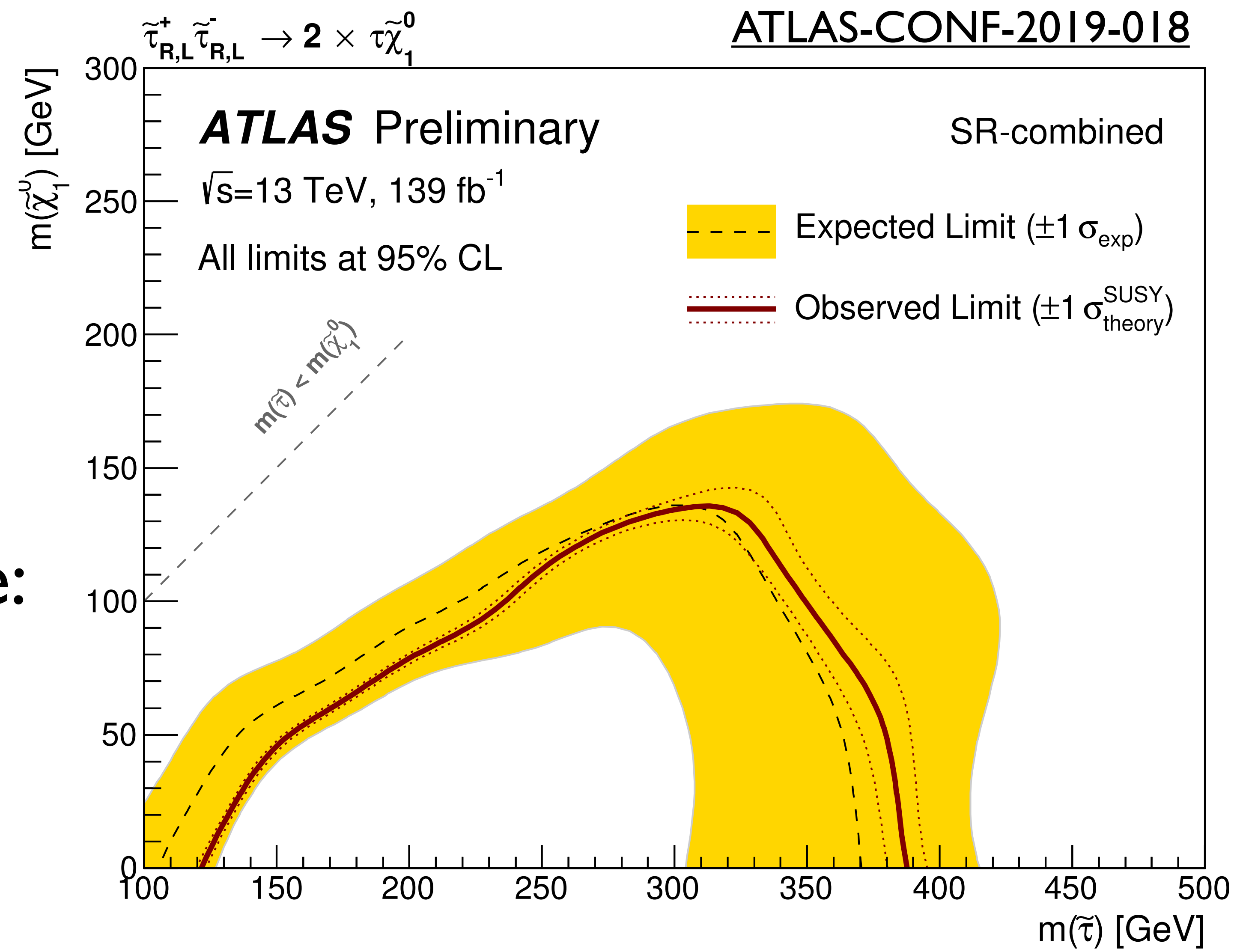
Staus are an even larger challenge: incredibly low cross-section!

Even Rarer: Staus



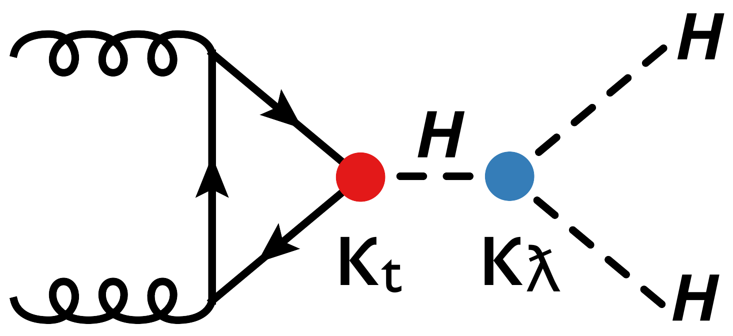
Staus are an even larger challenge: incredibly low cross-section!

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



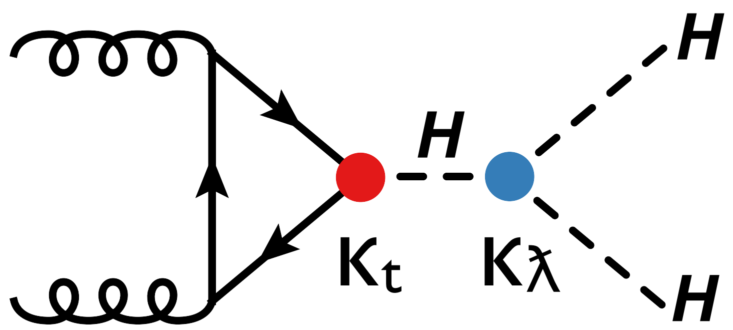
Di-Higgs at the LHC

Di-Higgs at the LHC



Di-Higgs is another exciting new target for the LHC

Di-Higgs at the LHC



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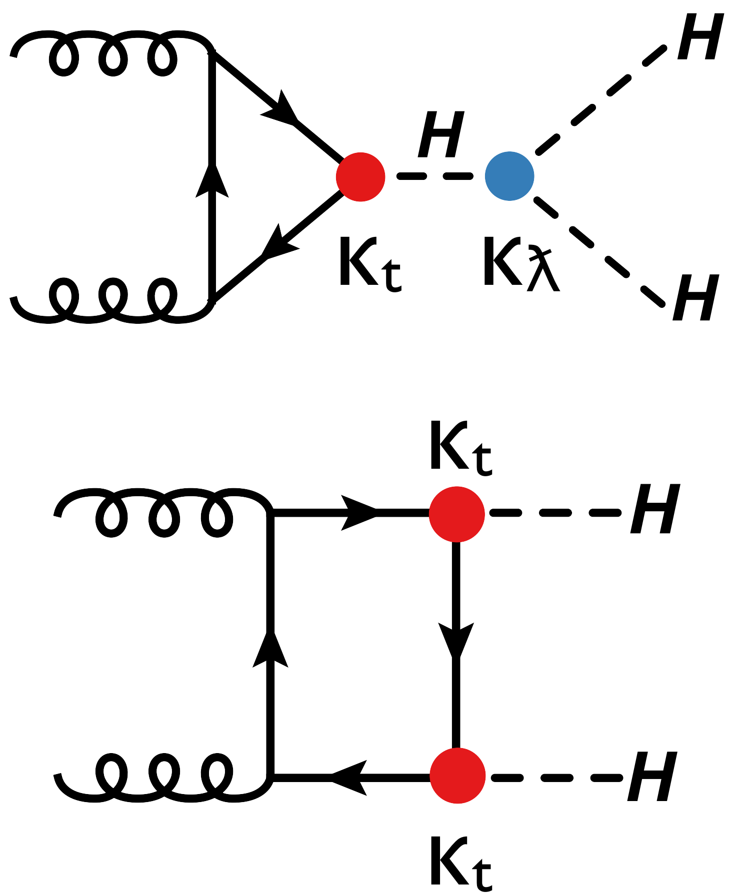
Exciting signal: can reveal the shape of the Higgs potential!

Di-Higgs at the LHC



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Interference between SM diagrams leads to very low x-sec

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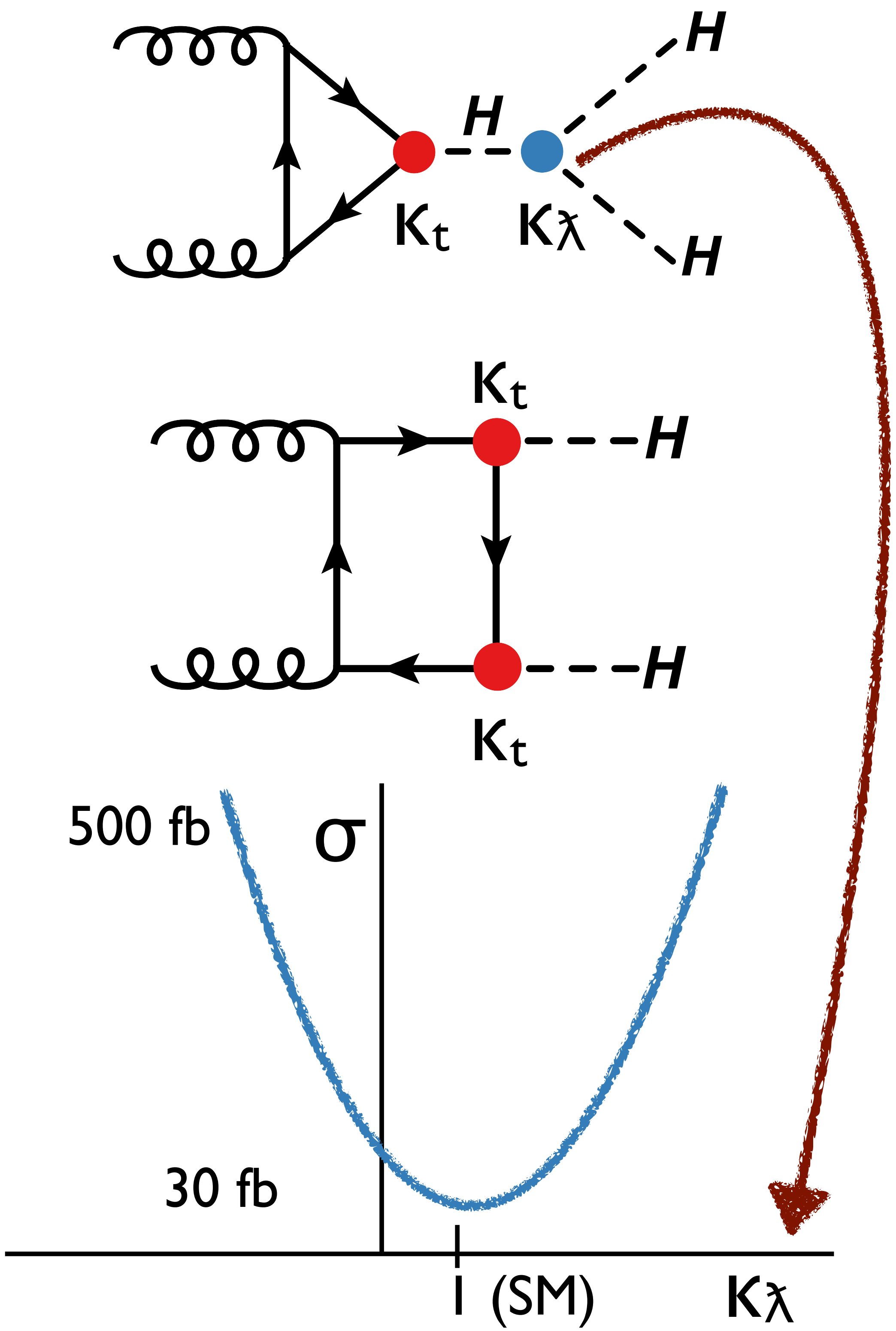

Di-Higgs is another exciting new target for the LHC

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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

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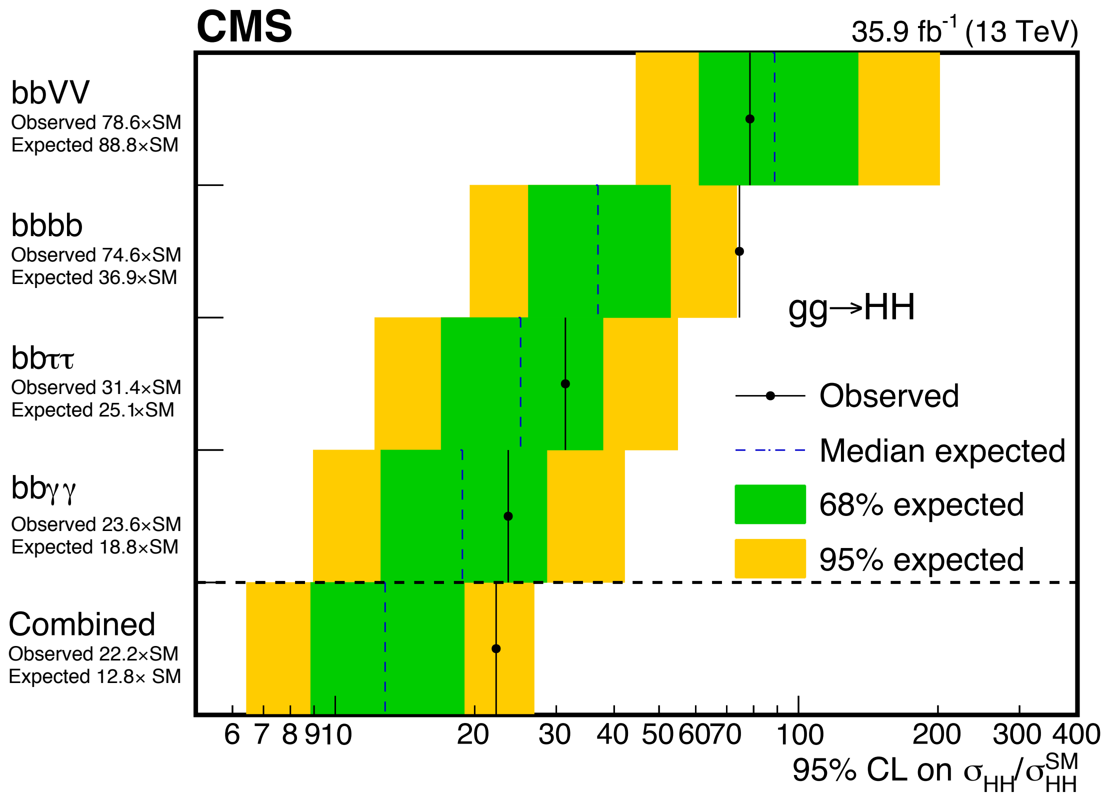
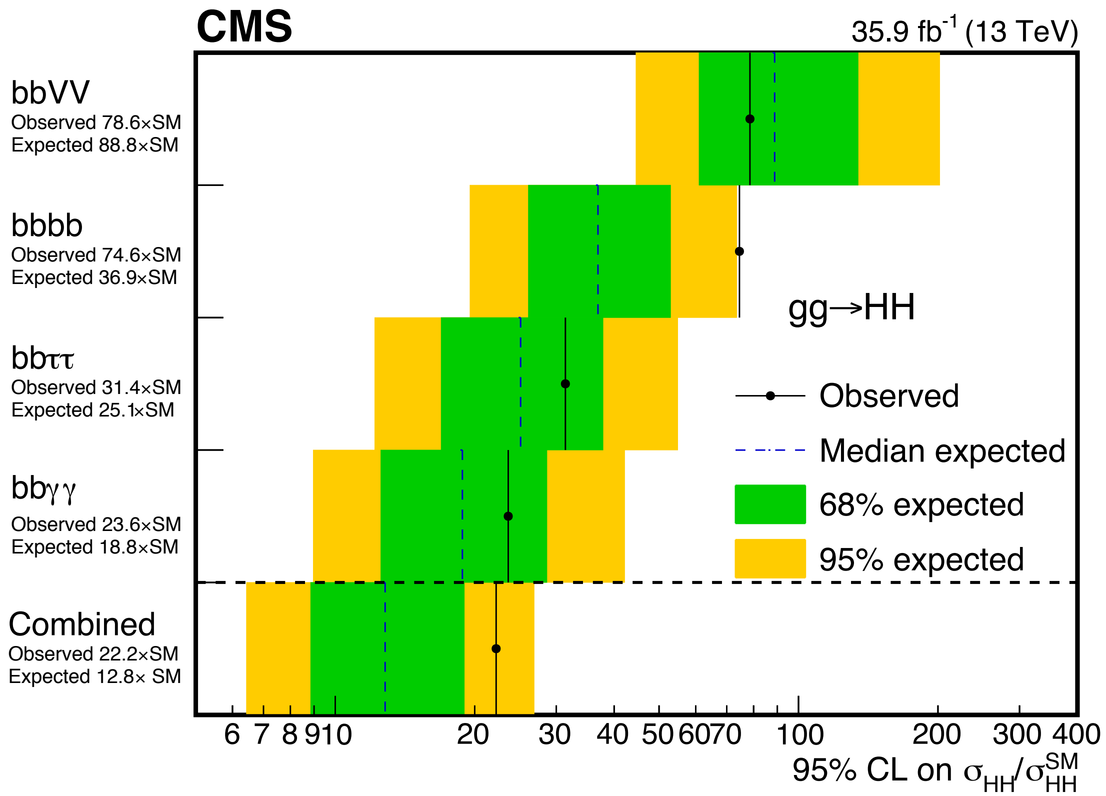


Many orthogonal channels can be combined to increase sensitivity!

Results on Di-Higgs



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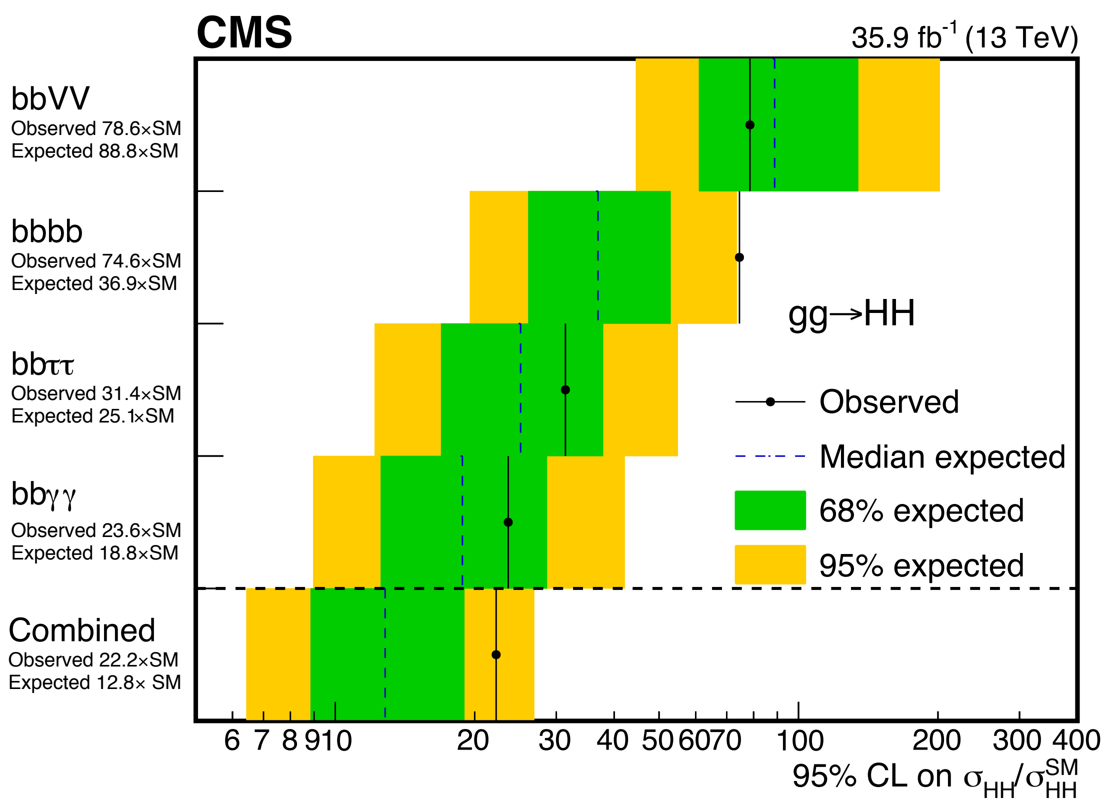

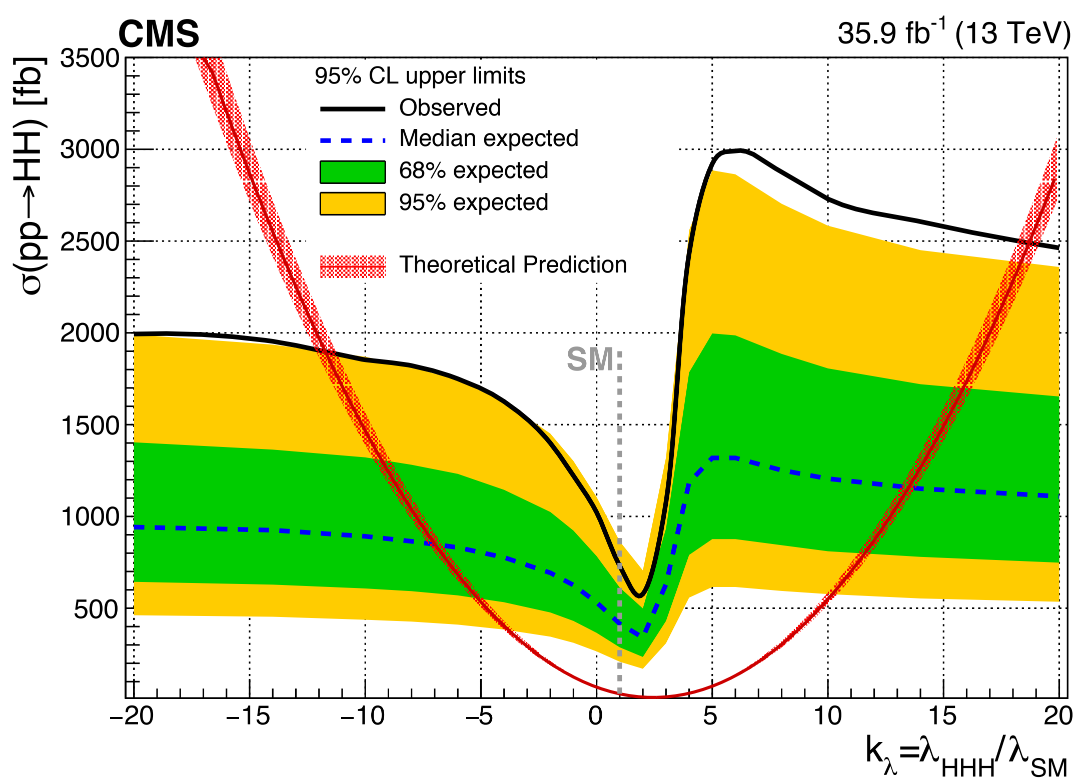

Many orthogonal channels can be combined to increase sensitivity!

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

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

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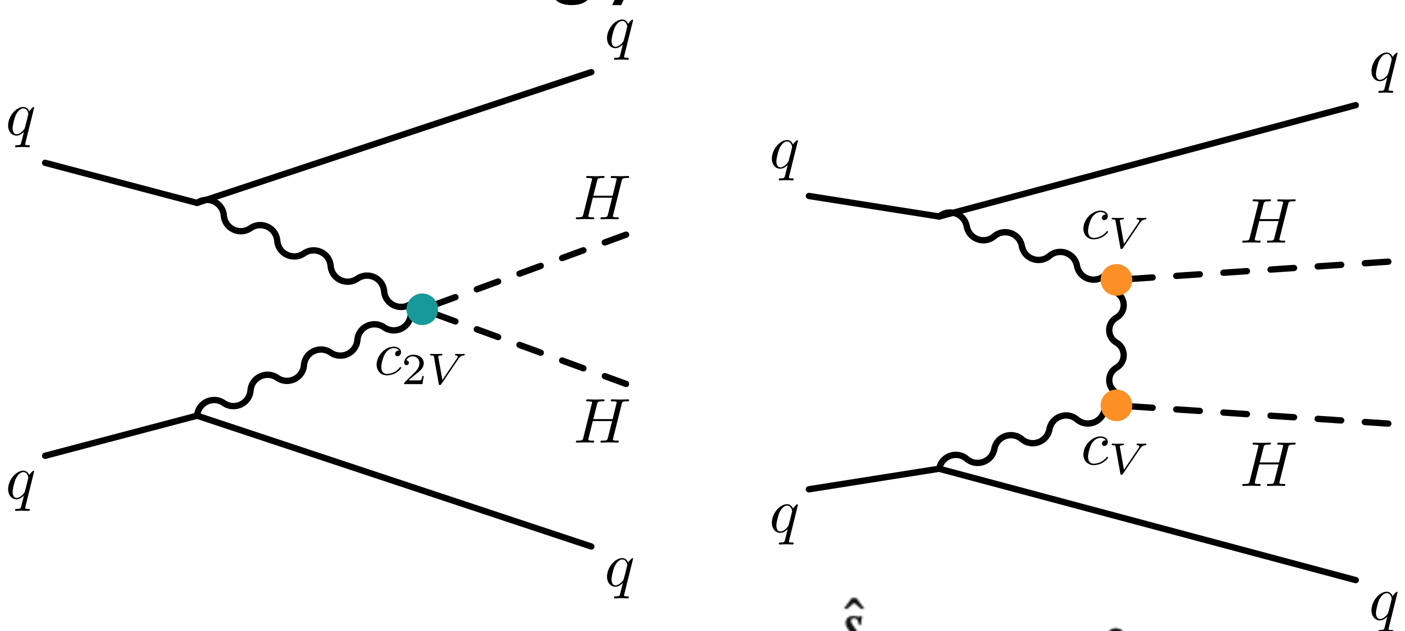
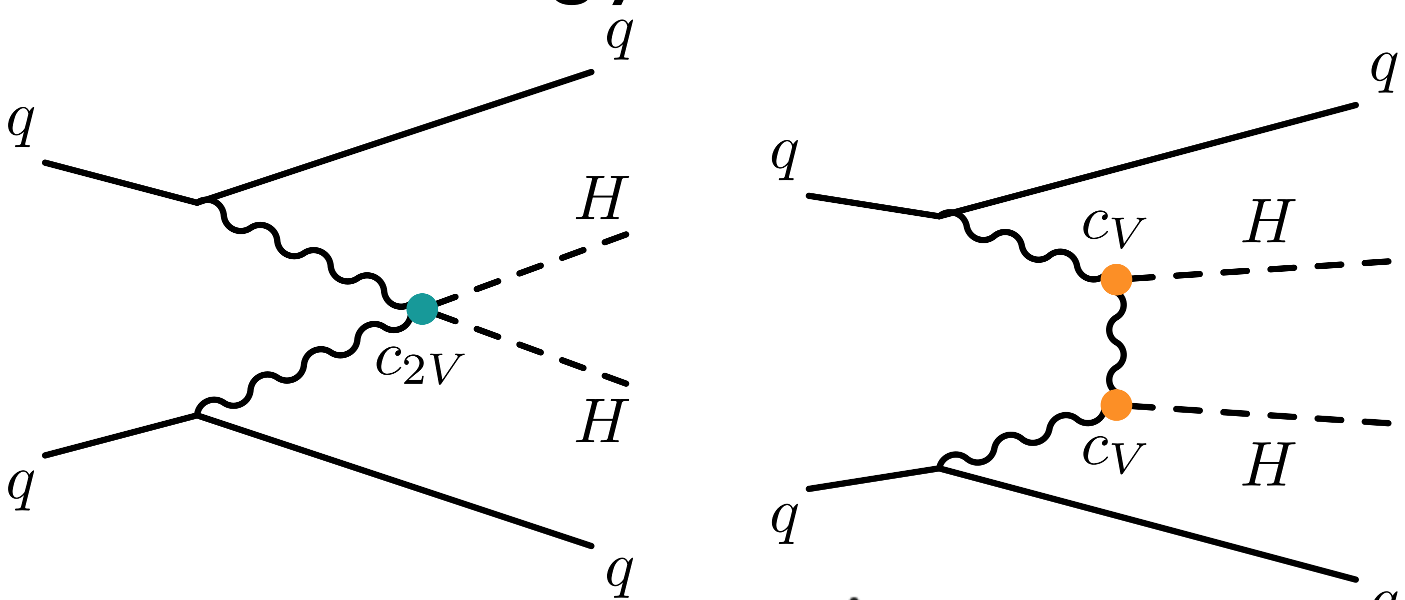


$$\mathscr{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)$$

VBF di-Higgs production is one example!

Hunting Rare SM Deviations

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



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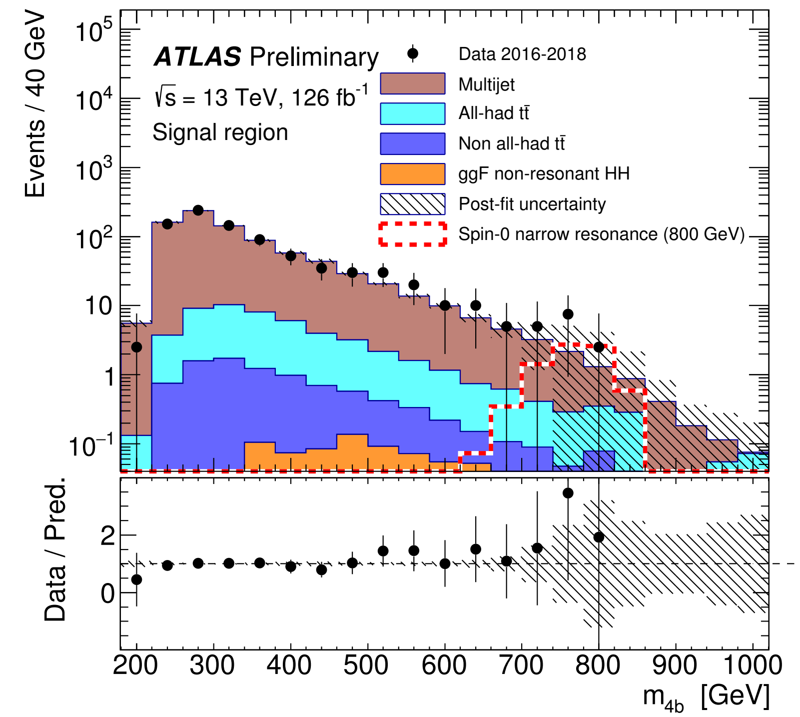
ATLAS-CONF-2019-030



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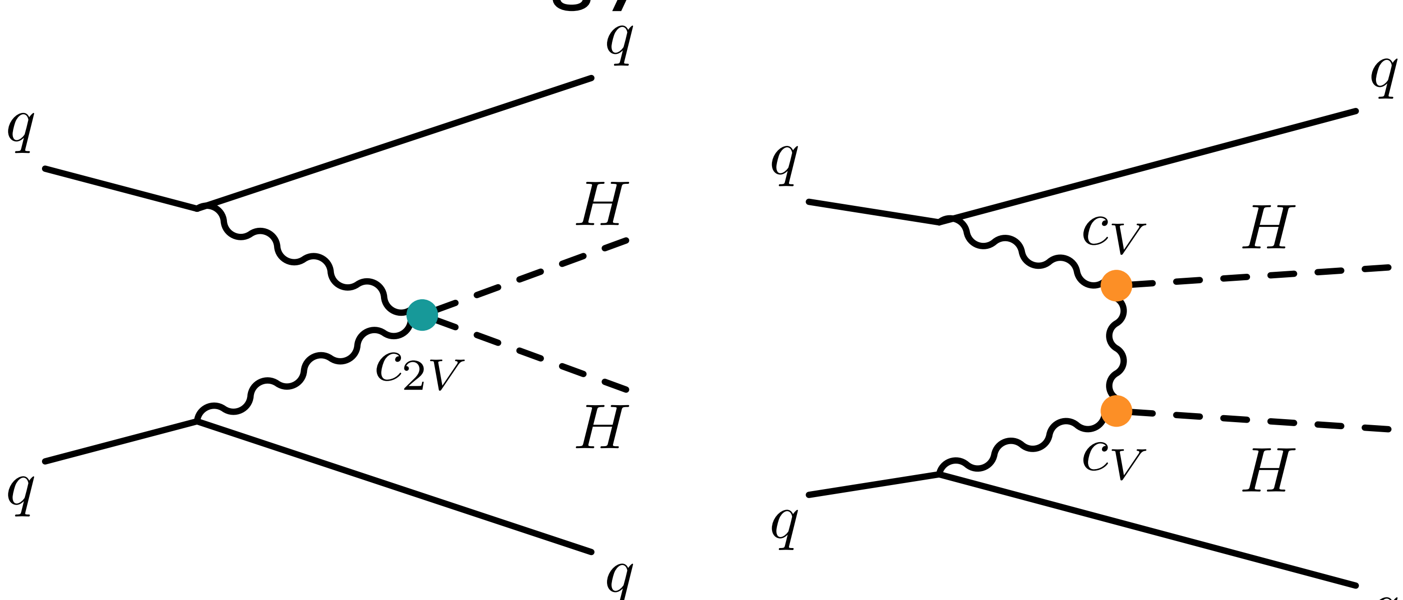

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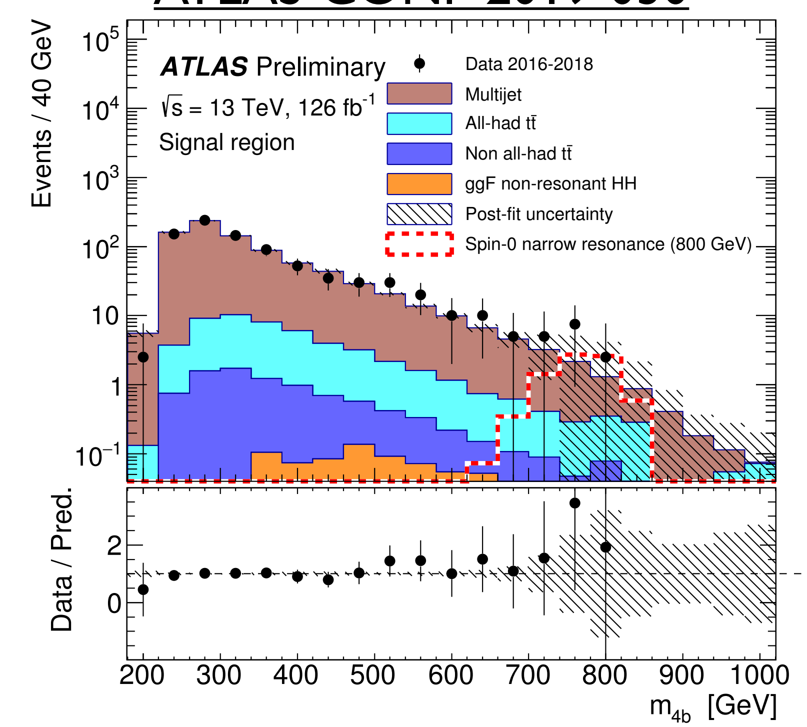
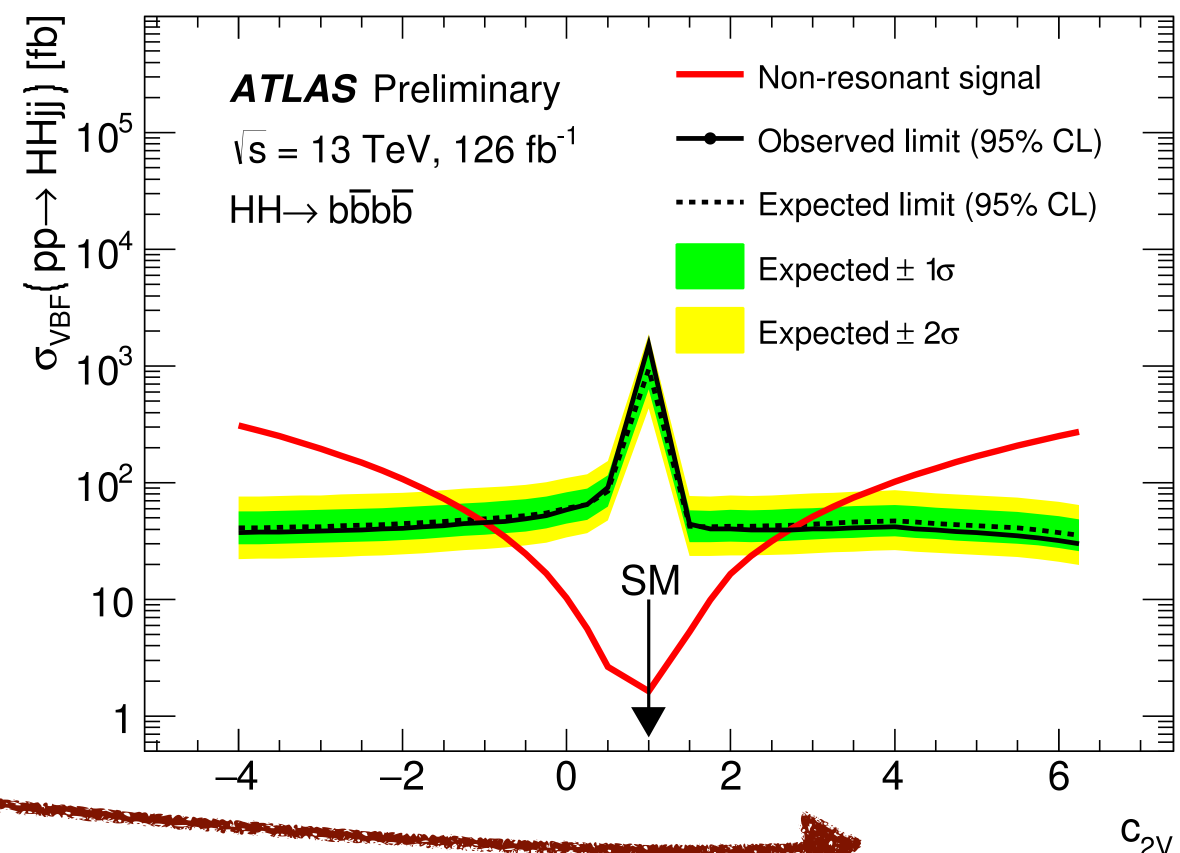
VBF di-Higgs production is one example!

First limits on the 4-point VVHH coupling

ATLAS-CONF-2019-030

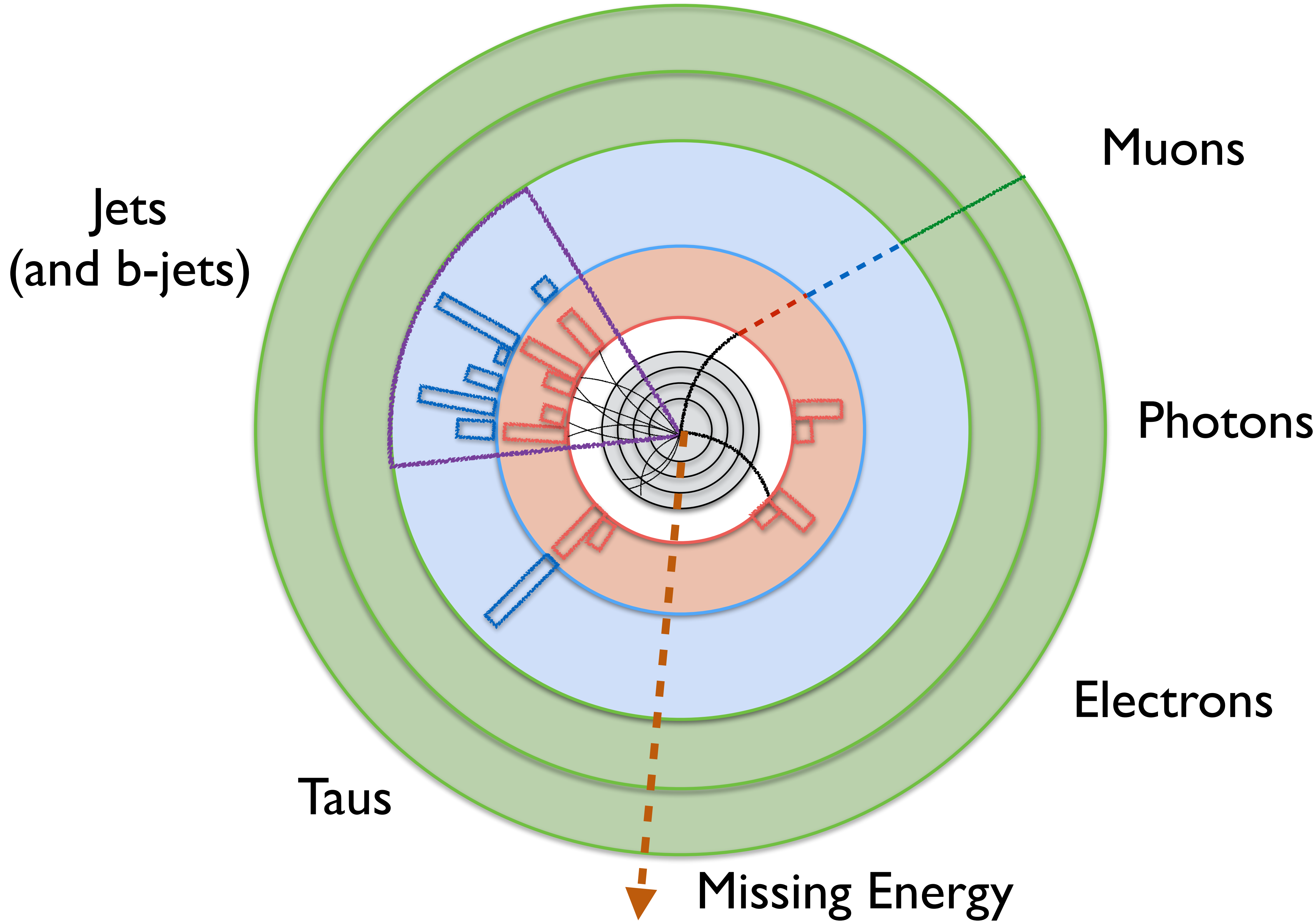




Not Your Advisor's Signals

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

Your Advisor's Signals



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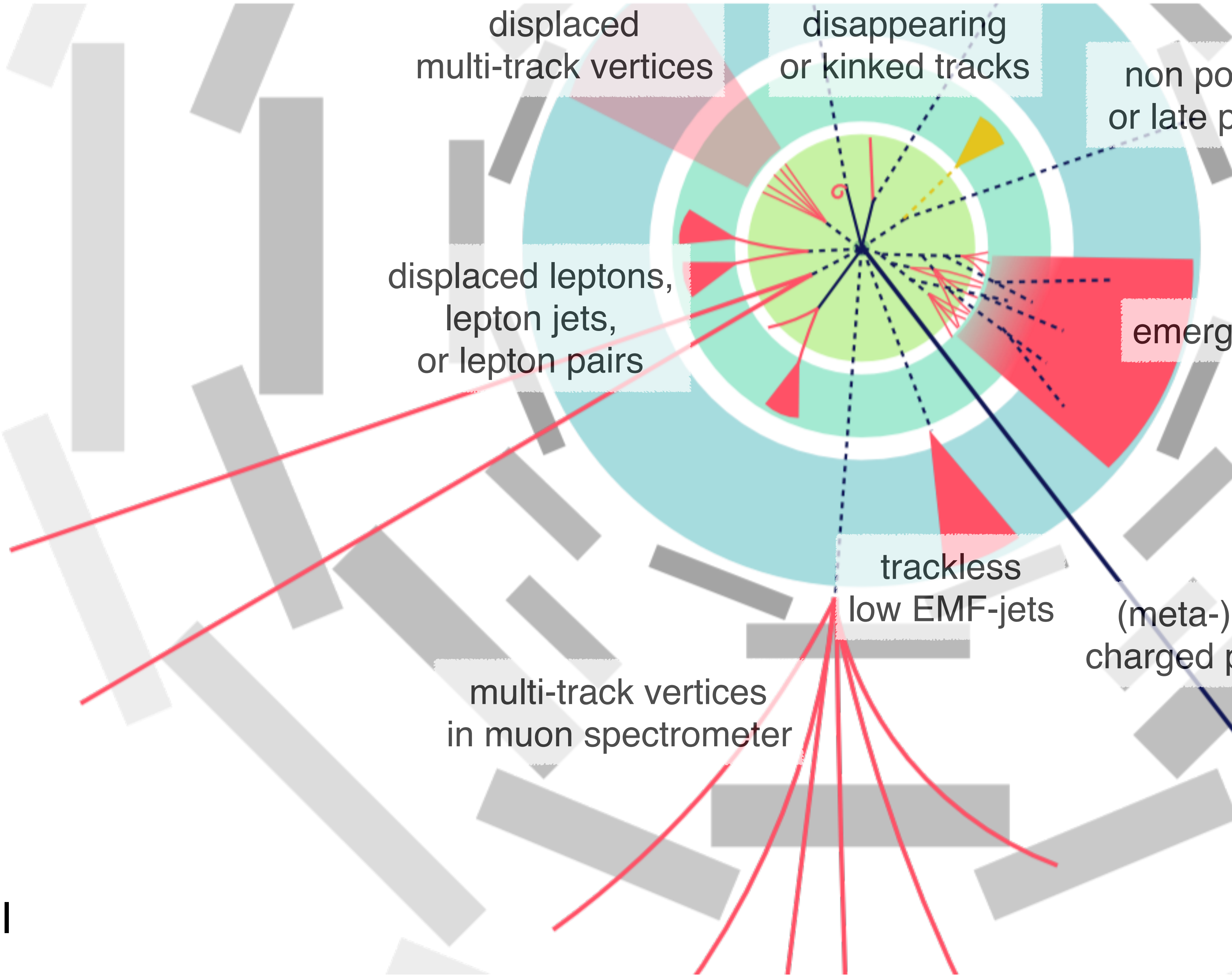
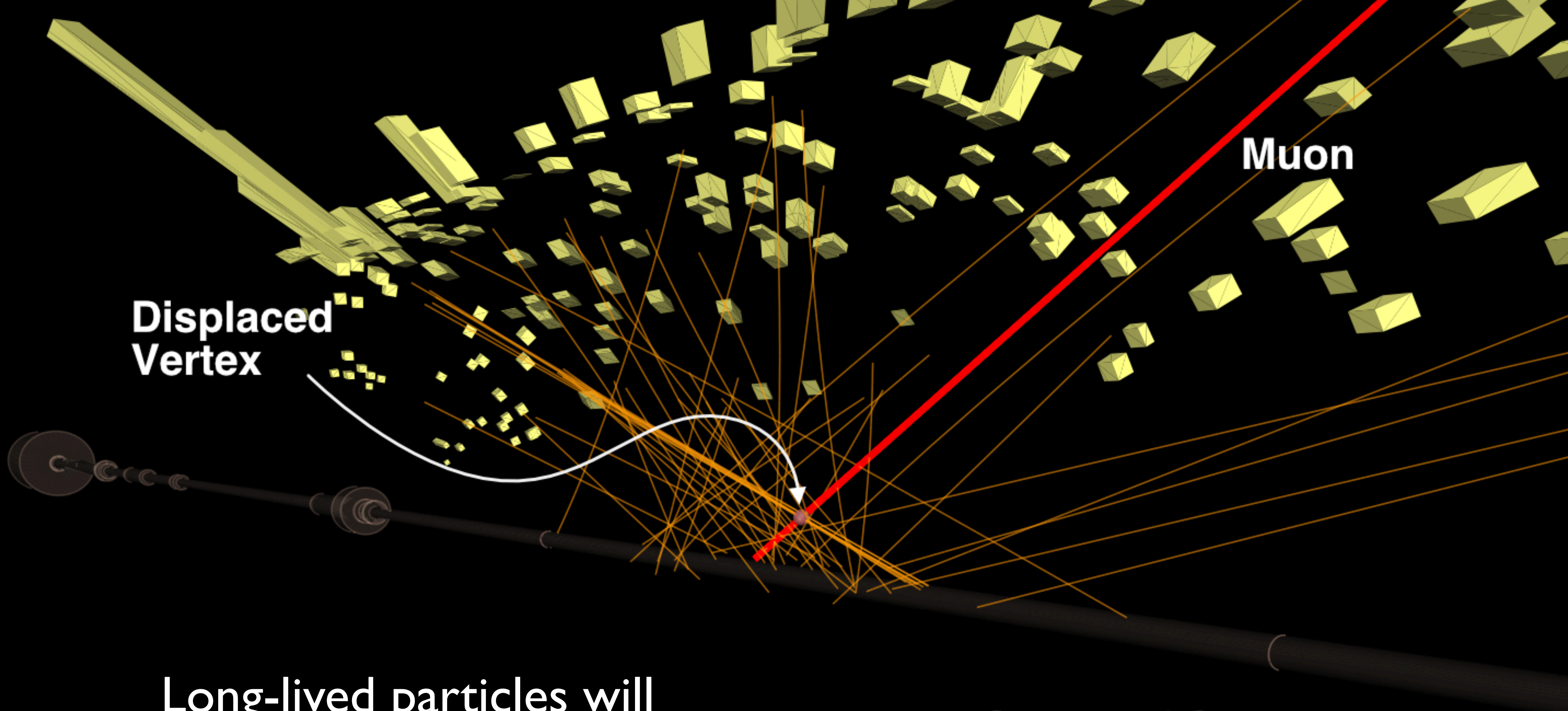


Heather Russell

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



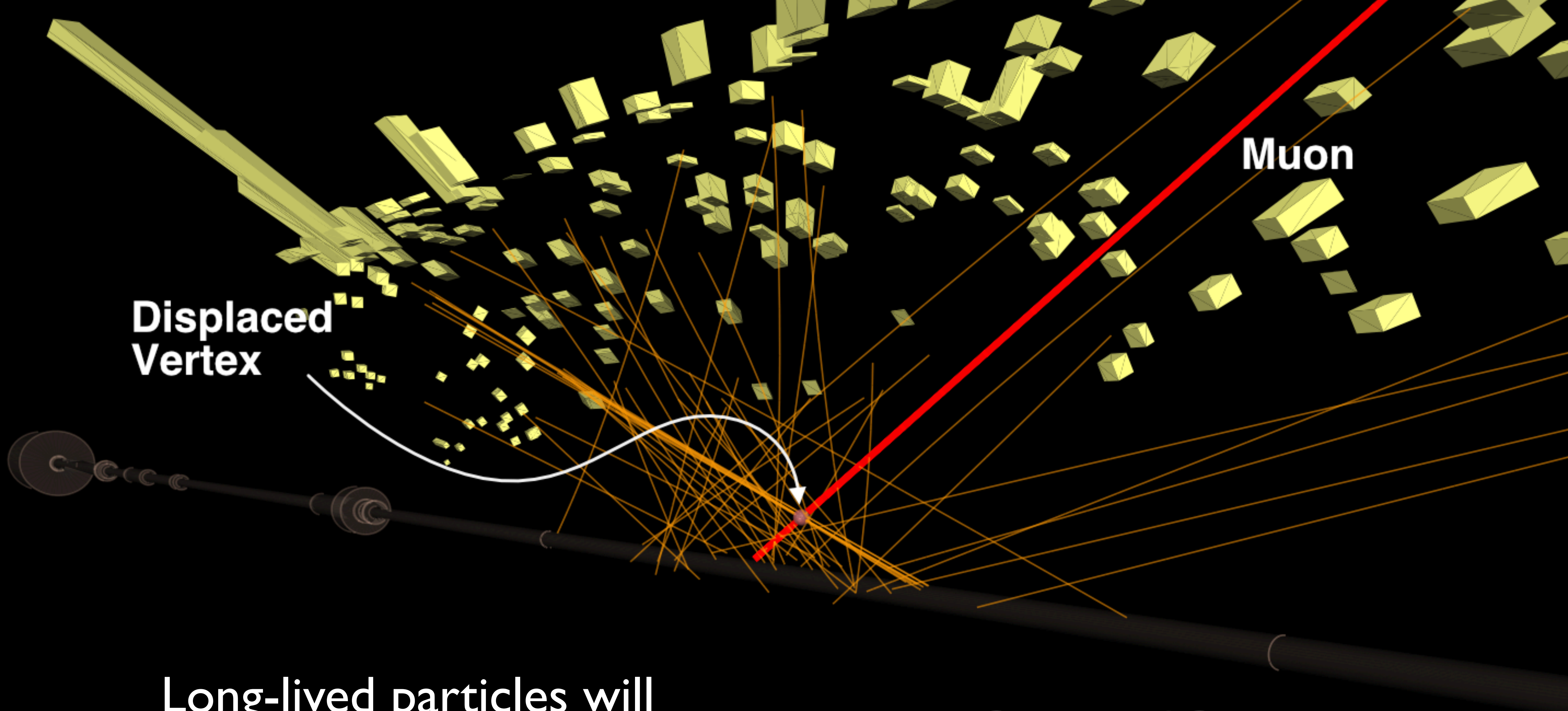
Long-lived particles will travel an appreciable distance before they decay

Simulated Signal Event
Top Squark Pair Production

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

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

ATLAS EXPERIMENT



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Special algorithms can reconstruct these "displaced tracks" and look for displaced vertices

ATLAS EXPERIMENT

Displaced Vertex + μ

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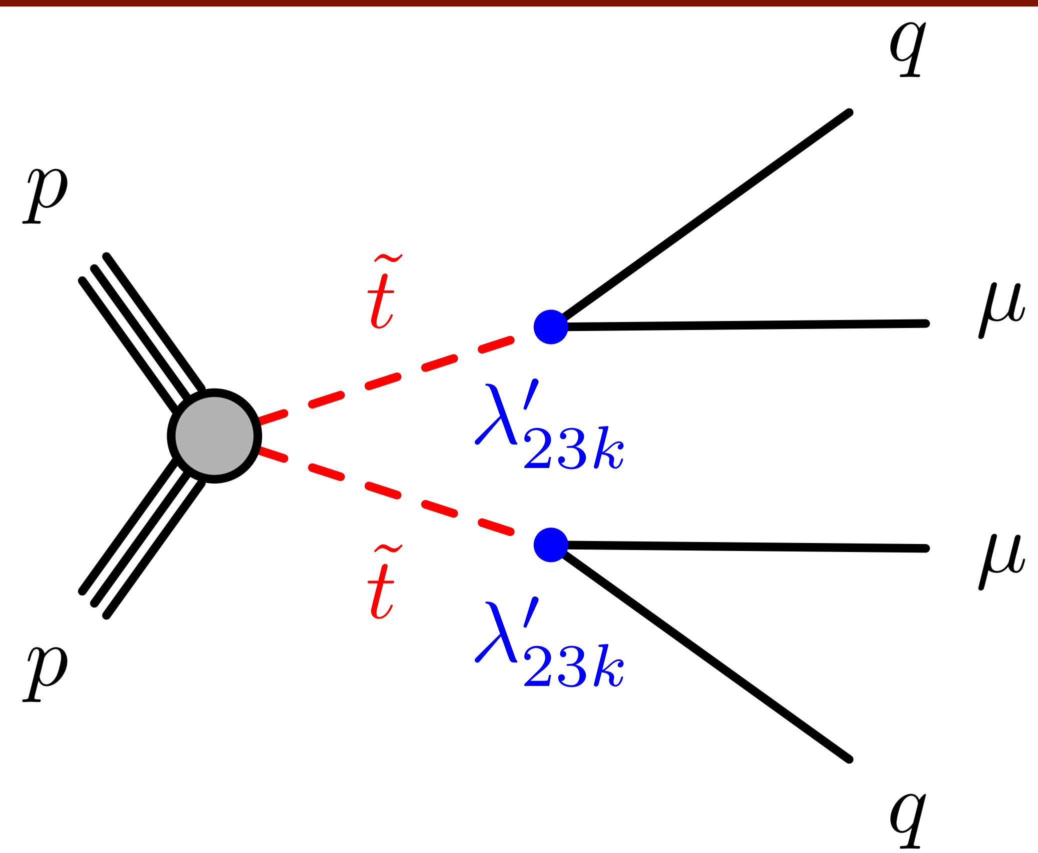

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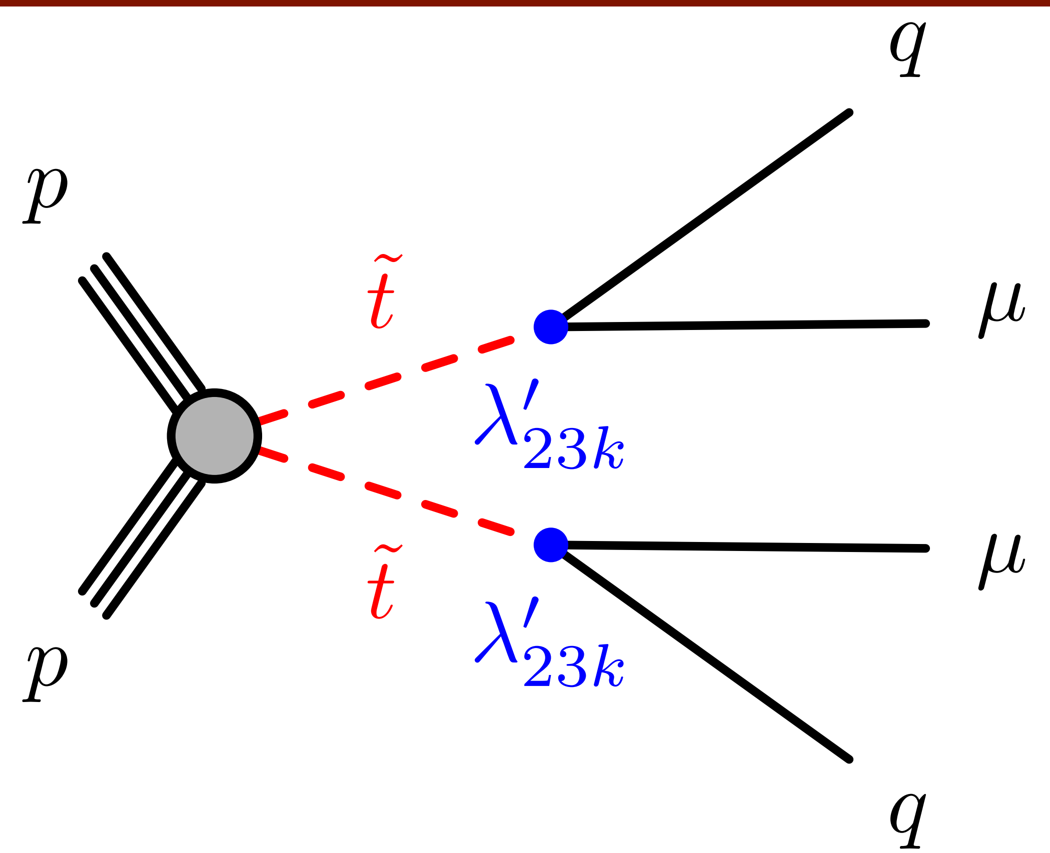
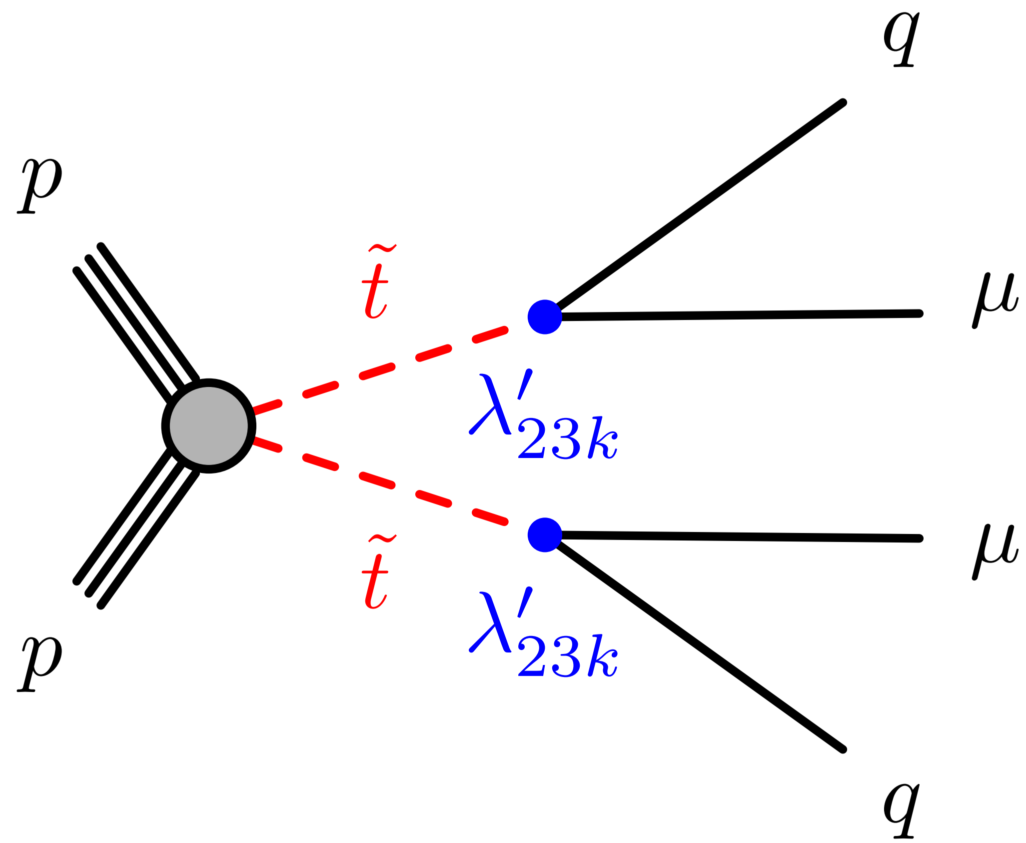
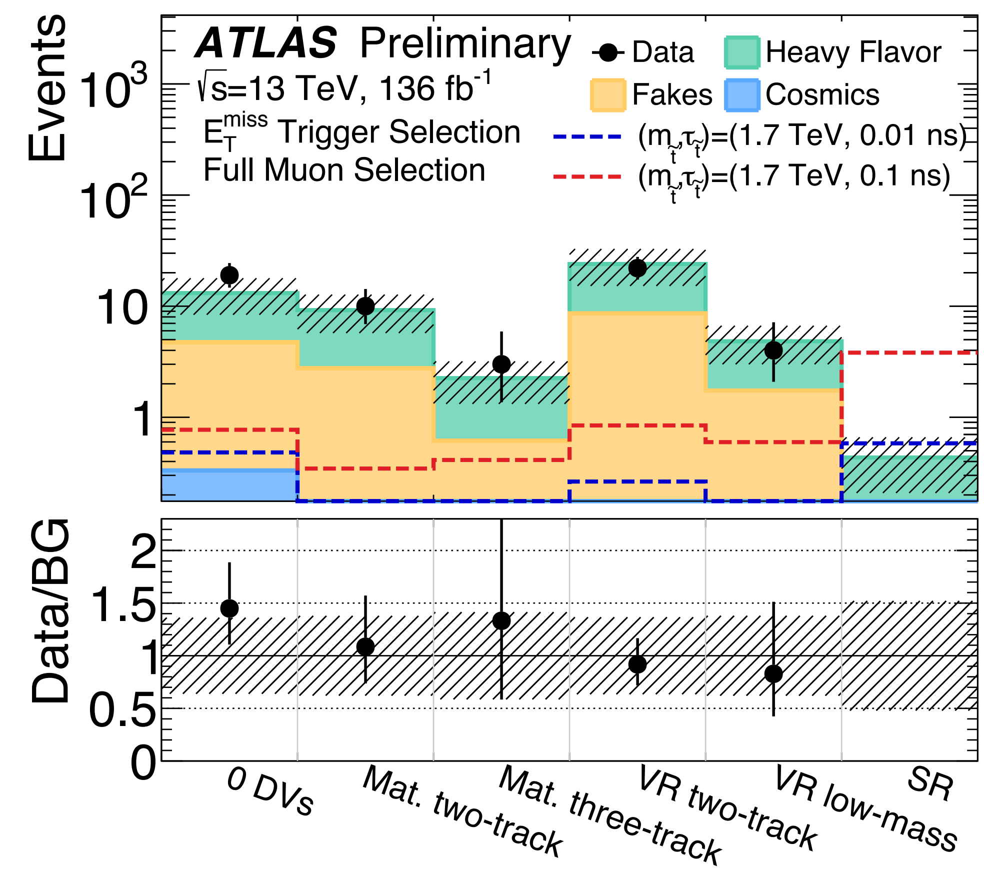


Stops can be long-lived in RPV models with small couplings

Displaced Vertex + μ





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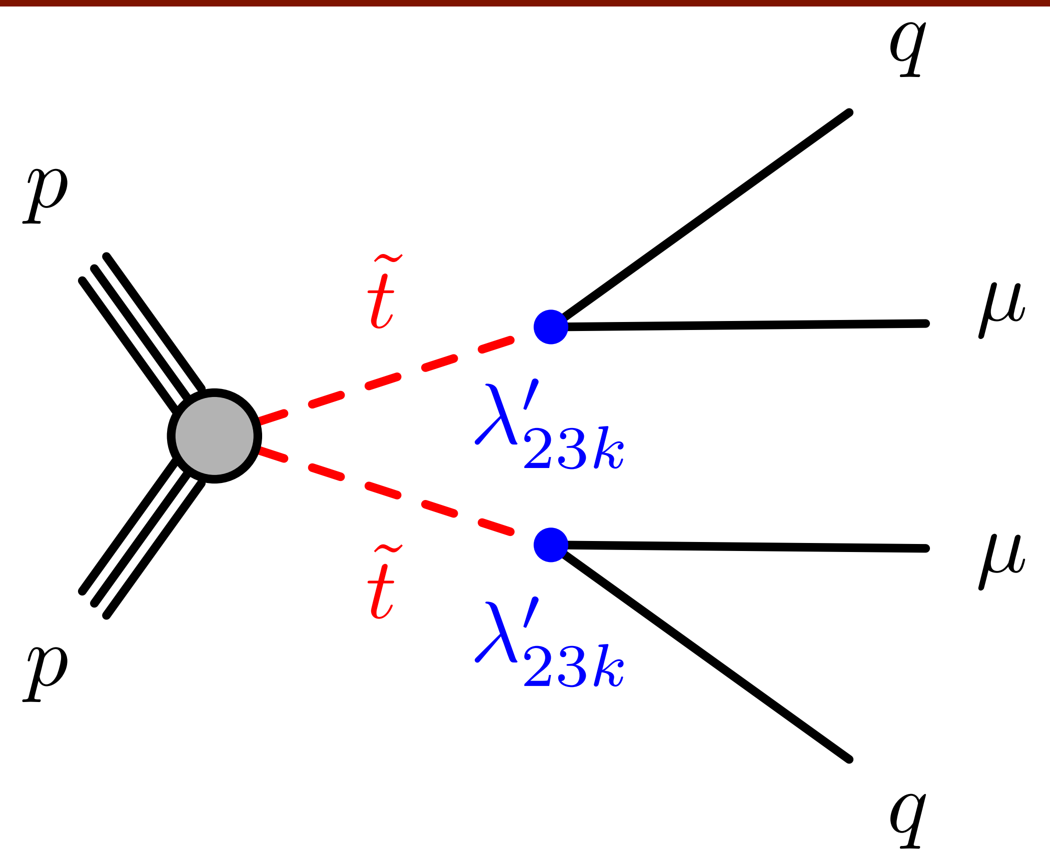
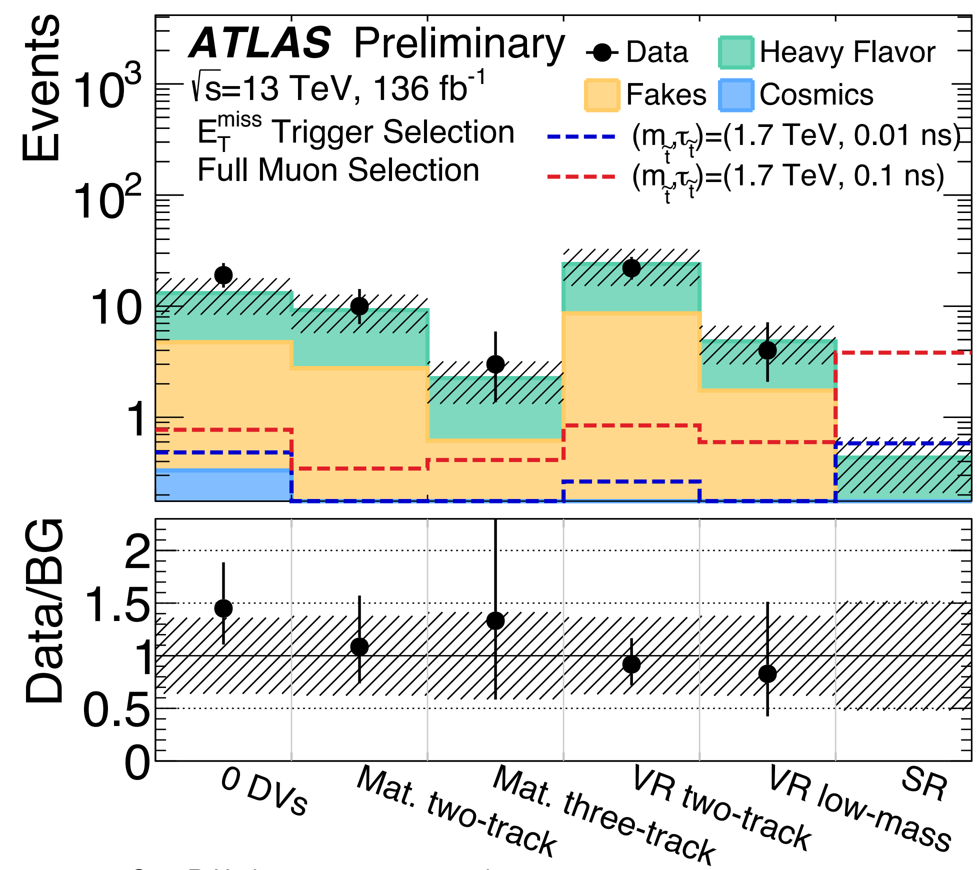
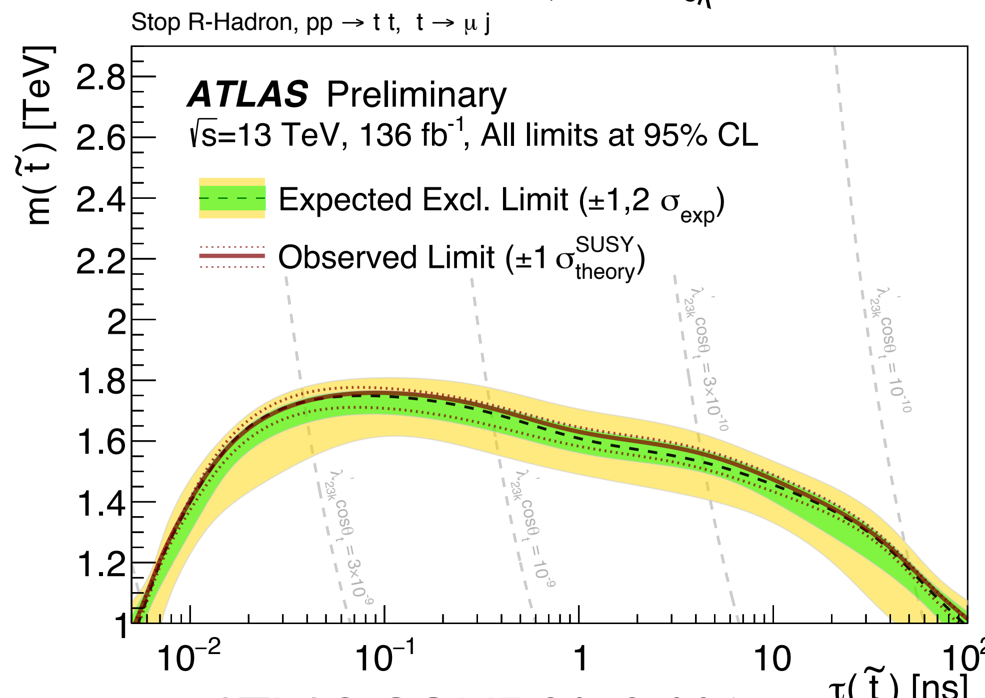
Data-driven backgrounds estimate
~0 background, with no signal observed

Displaced Vertex + μ







ATLAS-CONF-2019-006

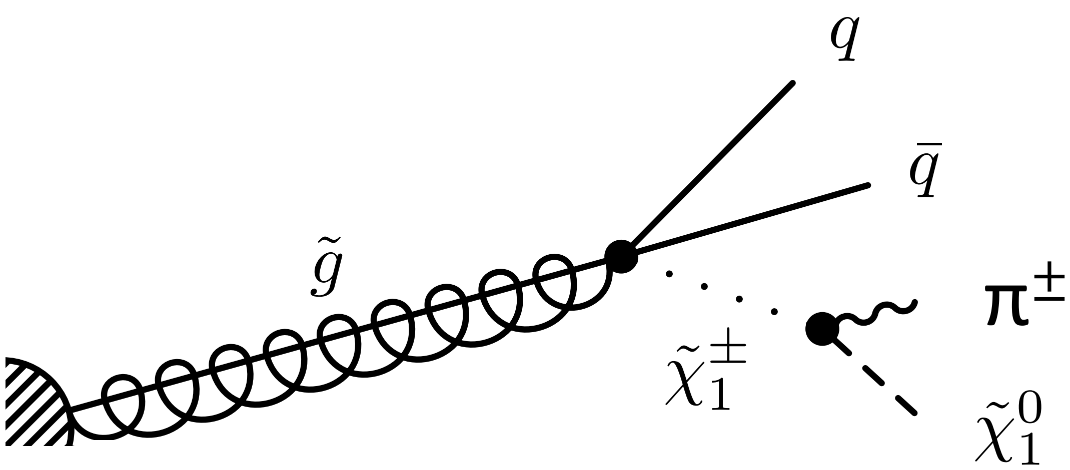
Stops can be long-lived in RPV models with small couplings

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

Strongest limits yet on stops!

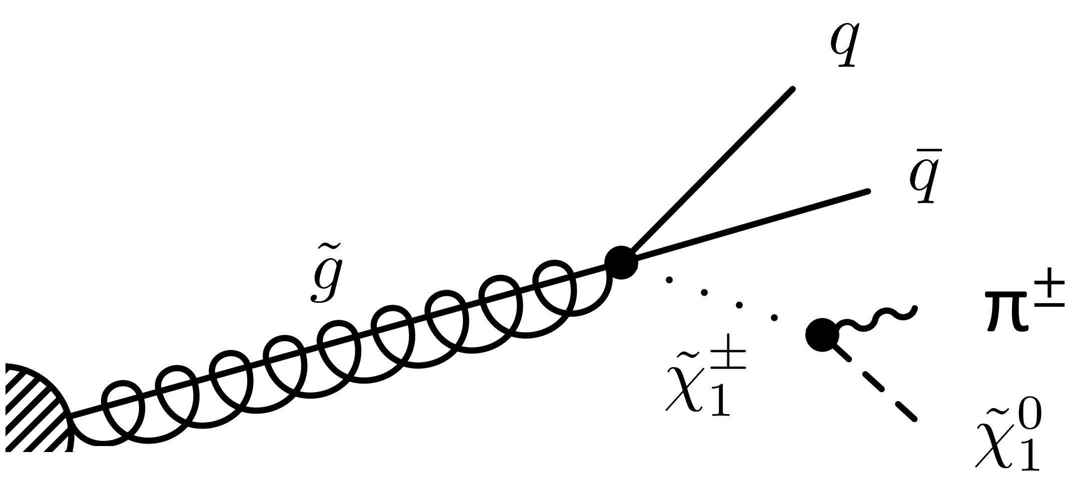
Disappearing Tracks

Disappearing Tracks



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

Disappearing Tracks



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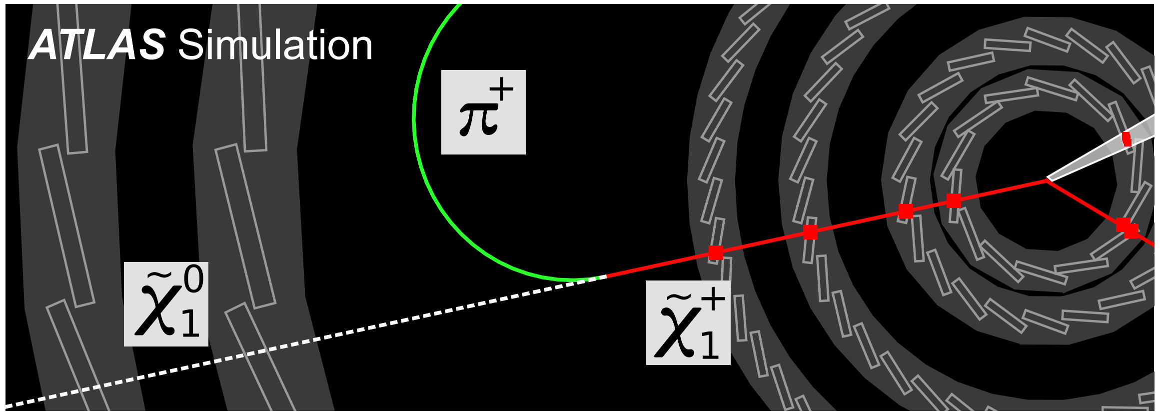
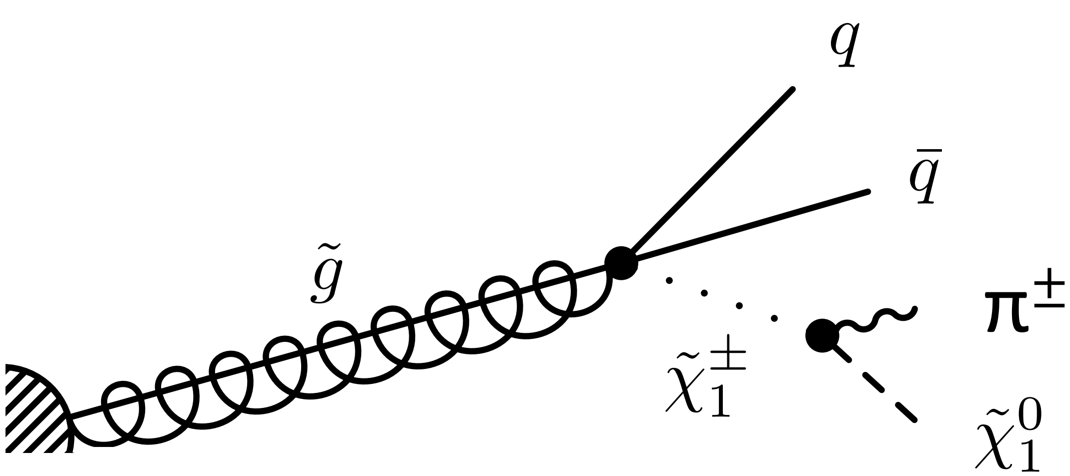


Can interact with the first few layers of the tracker, and then "disappear"

Disappearing Tracks



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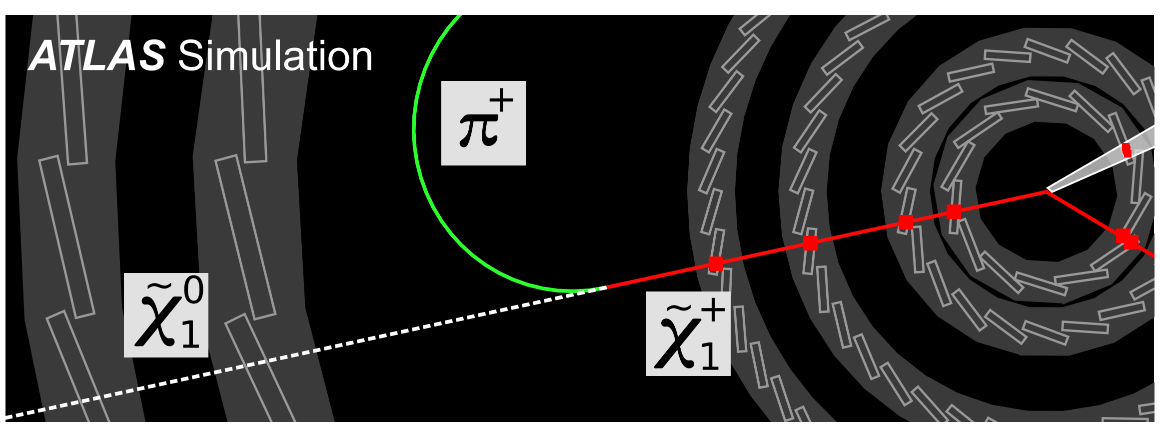

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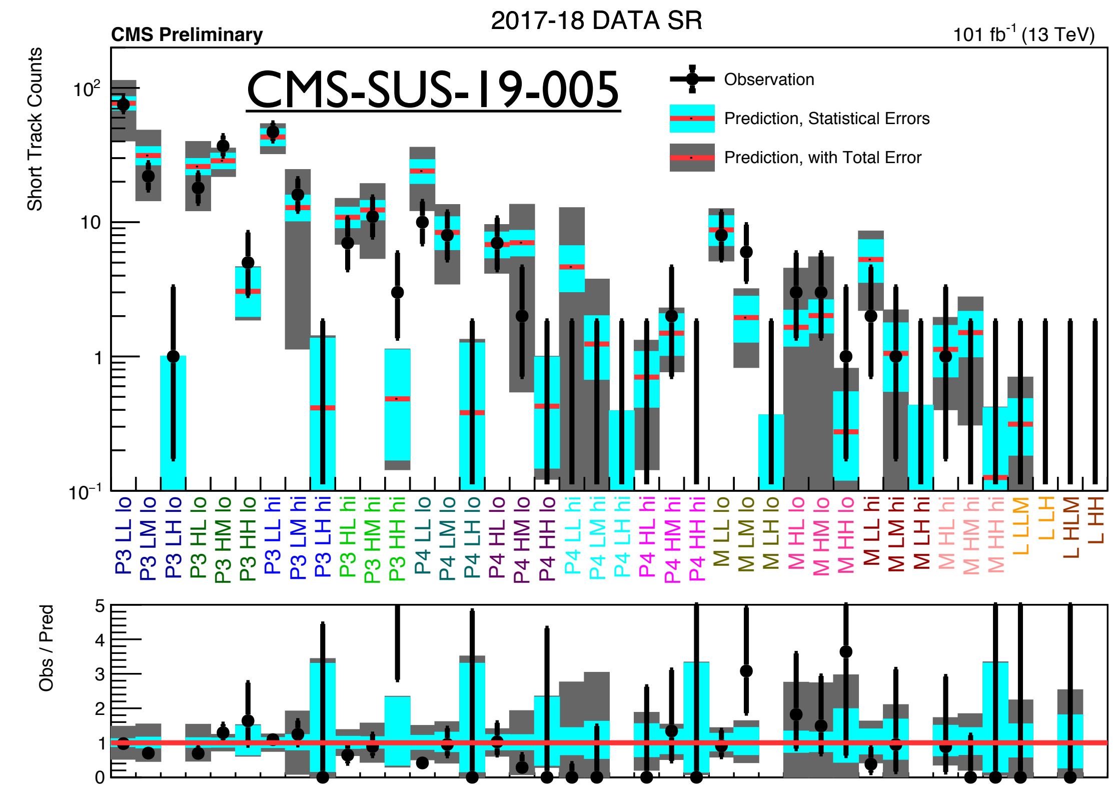

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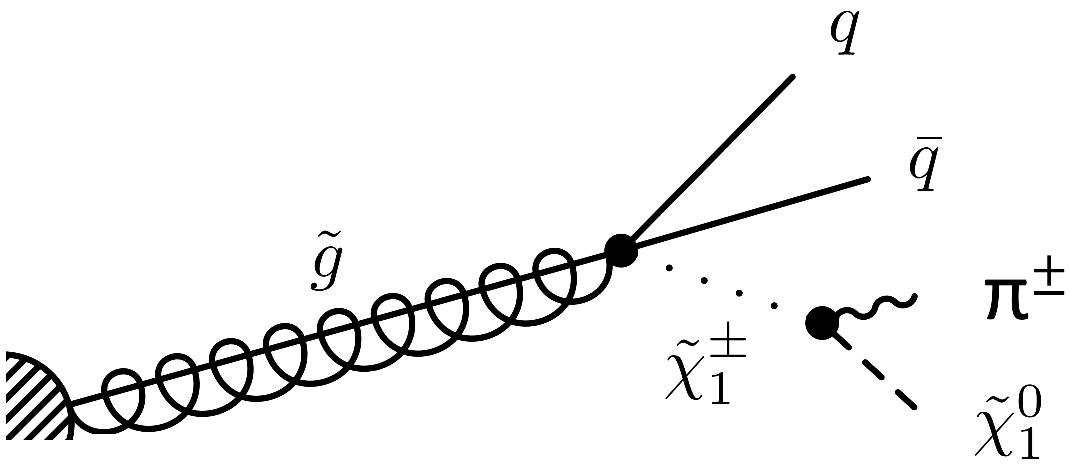

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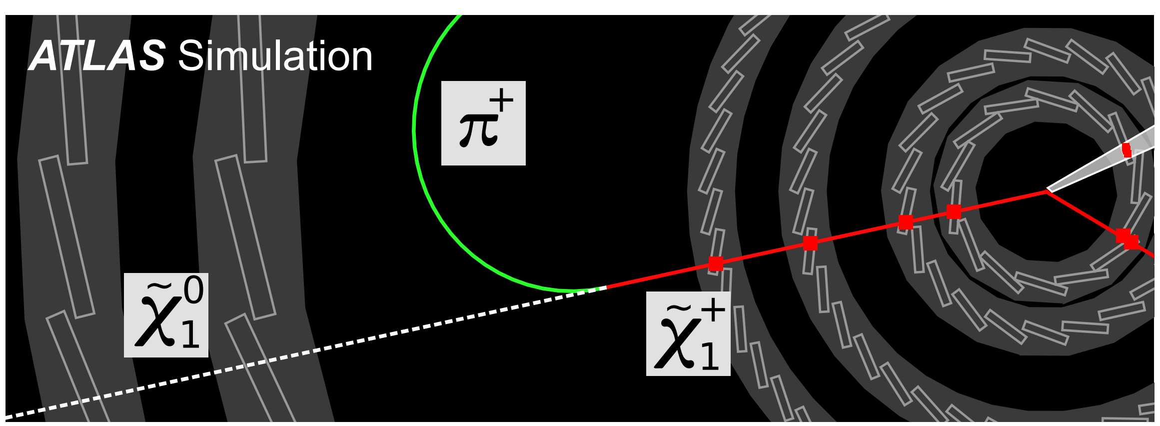

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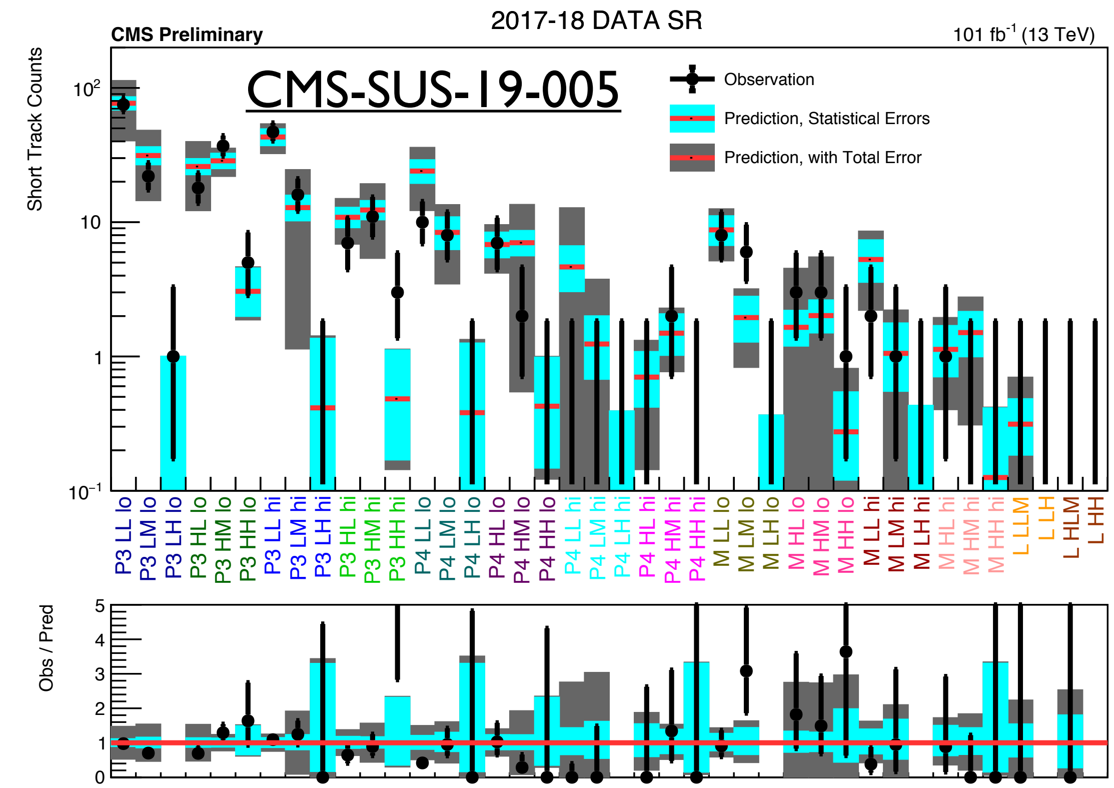

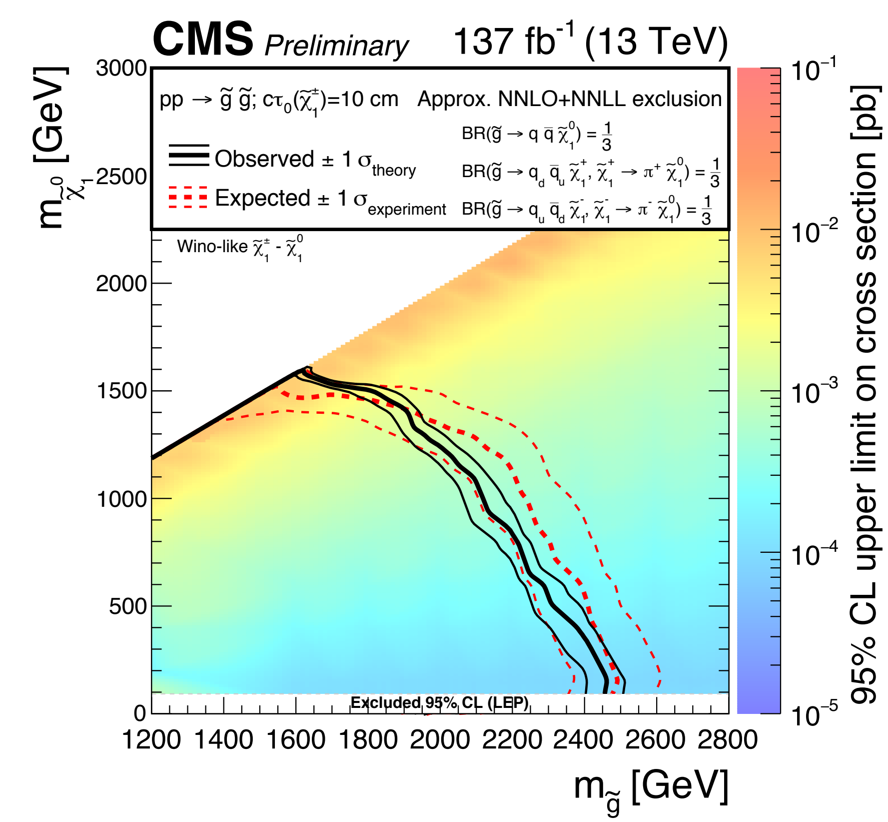

Can also extend reconstruction using additional information: **timing**

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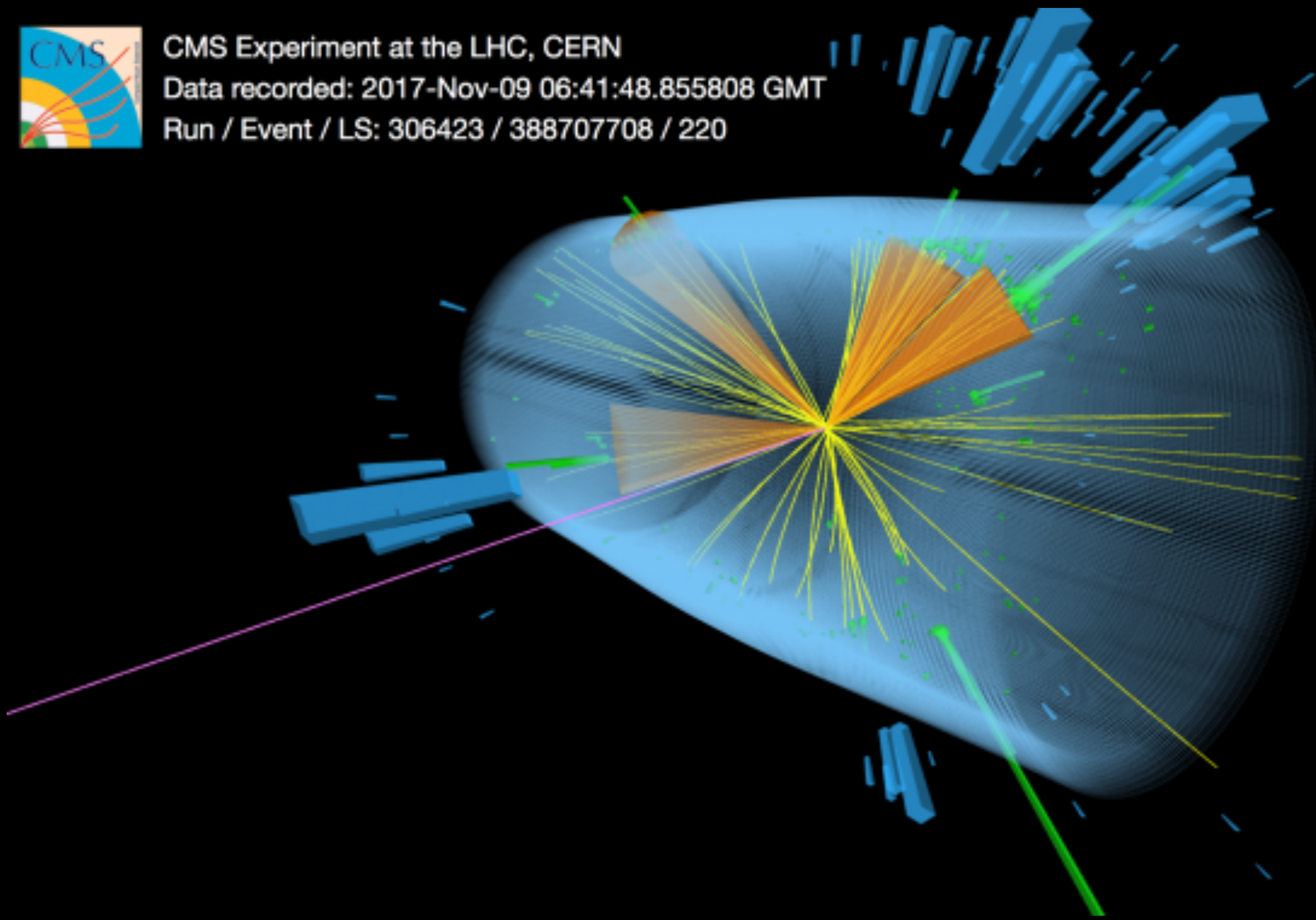

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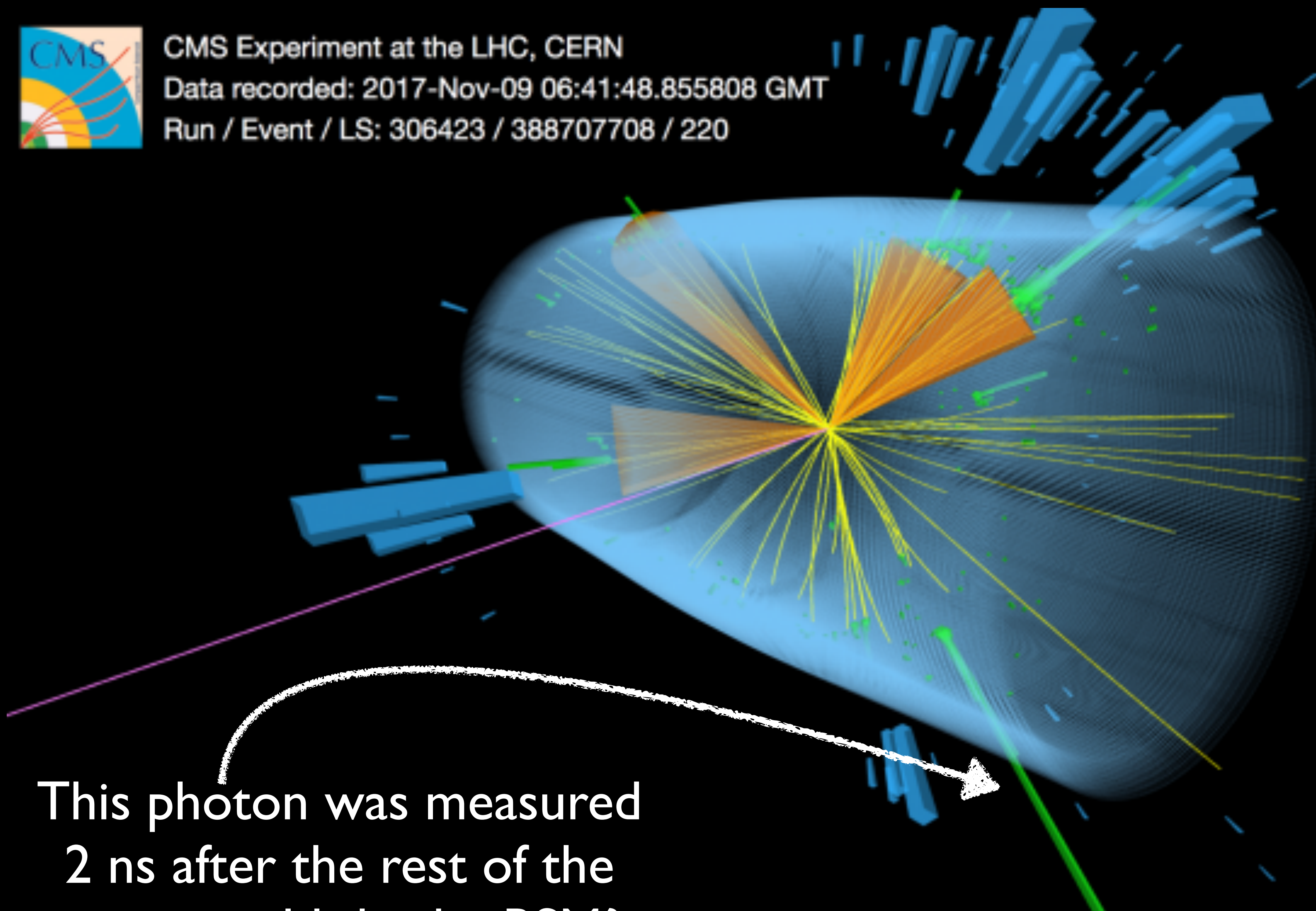
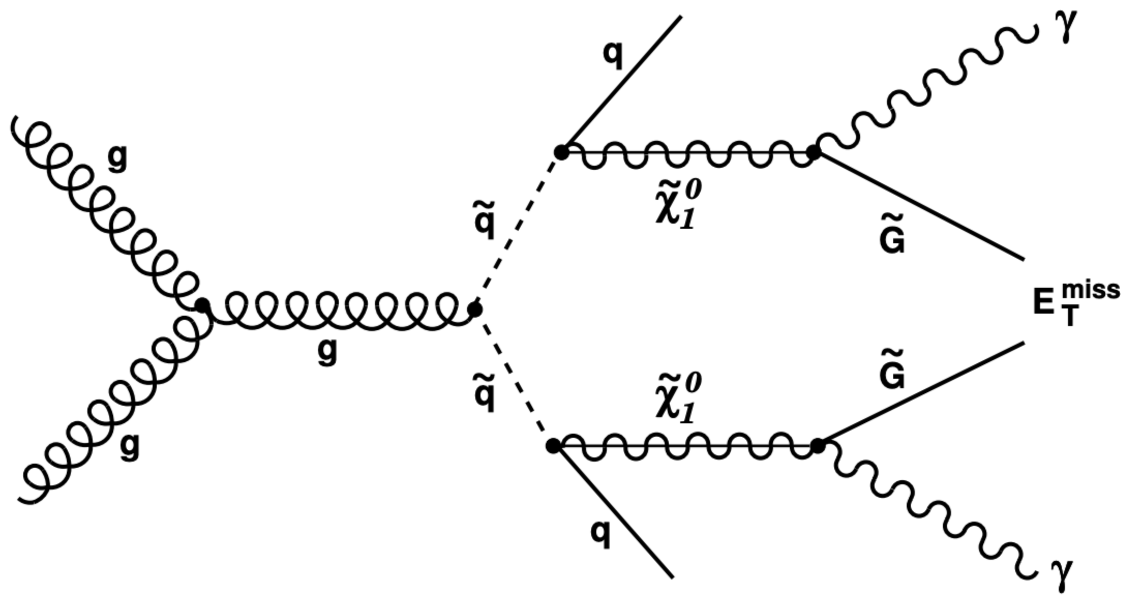


This photon was measured 2 ns after the rest of the event: could this be BSM?

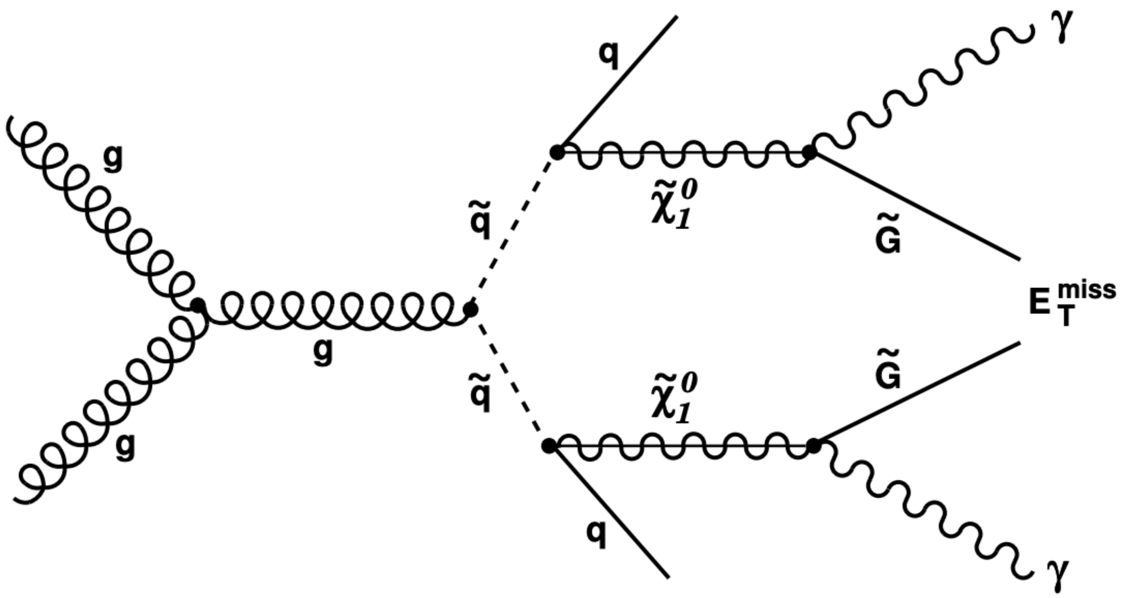
Delayed Photons

Delayed Photons



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

Delayed Photons



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

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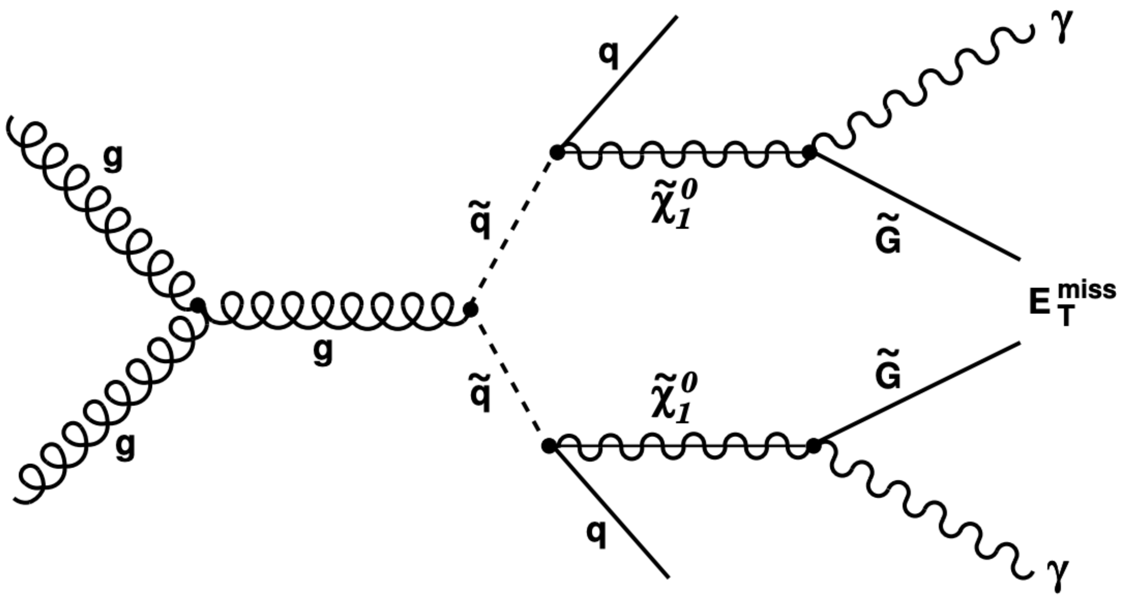

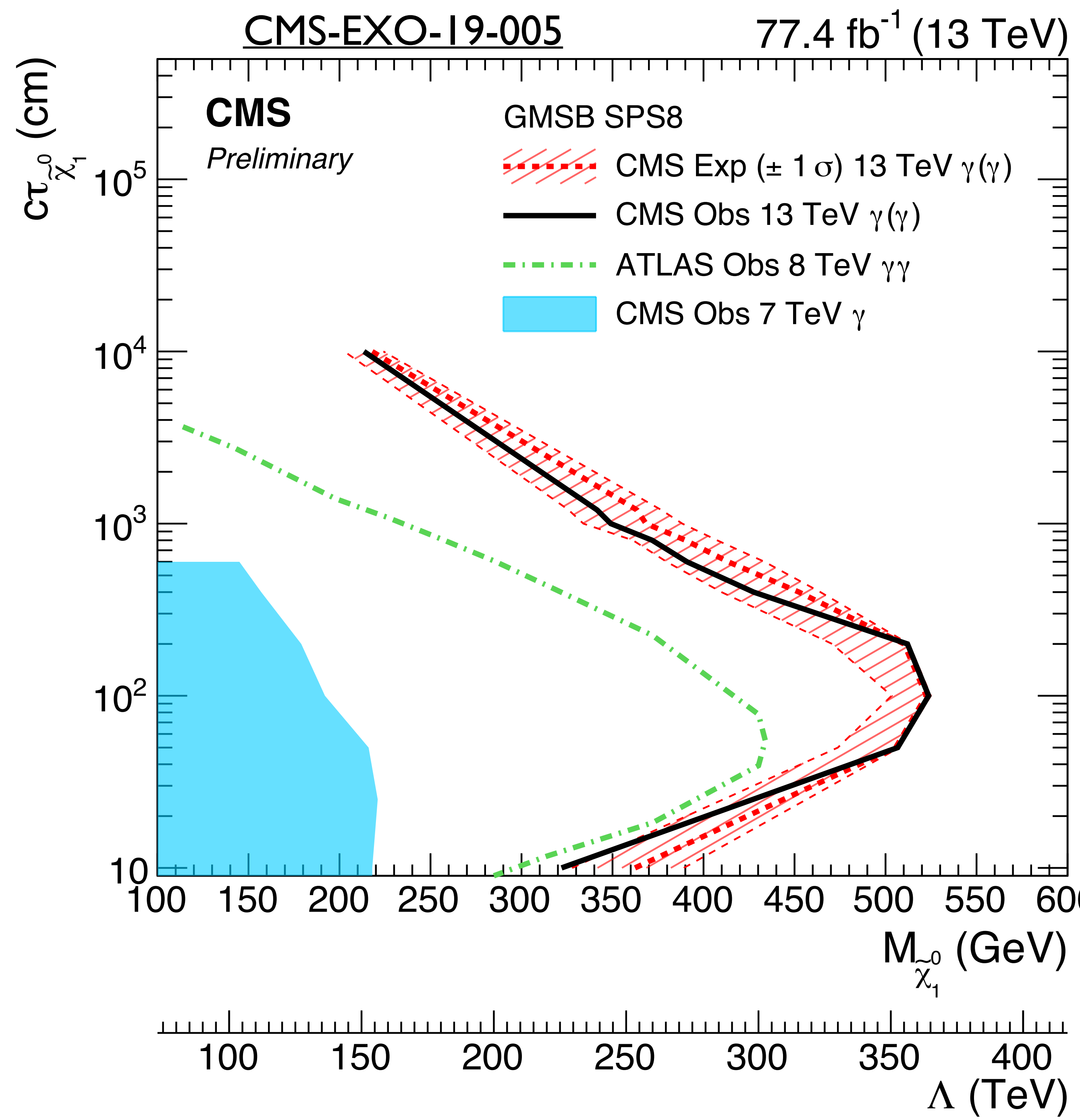

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Conclusions

Keep Looking!

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

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Low Hanging Fruit Records

Keep Looking!

BSM is extremely well motivated at the LHC!

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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

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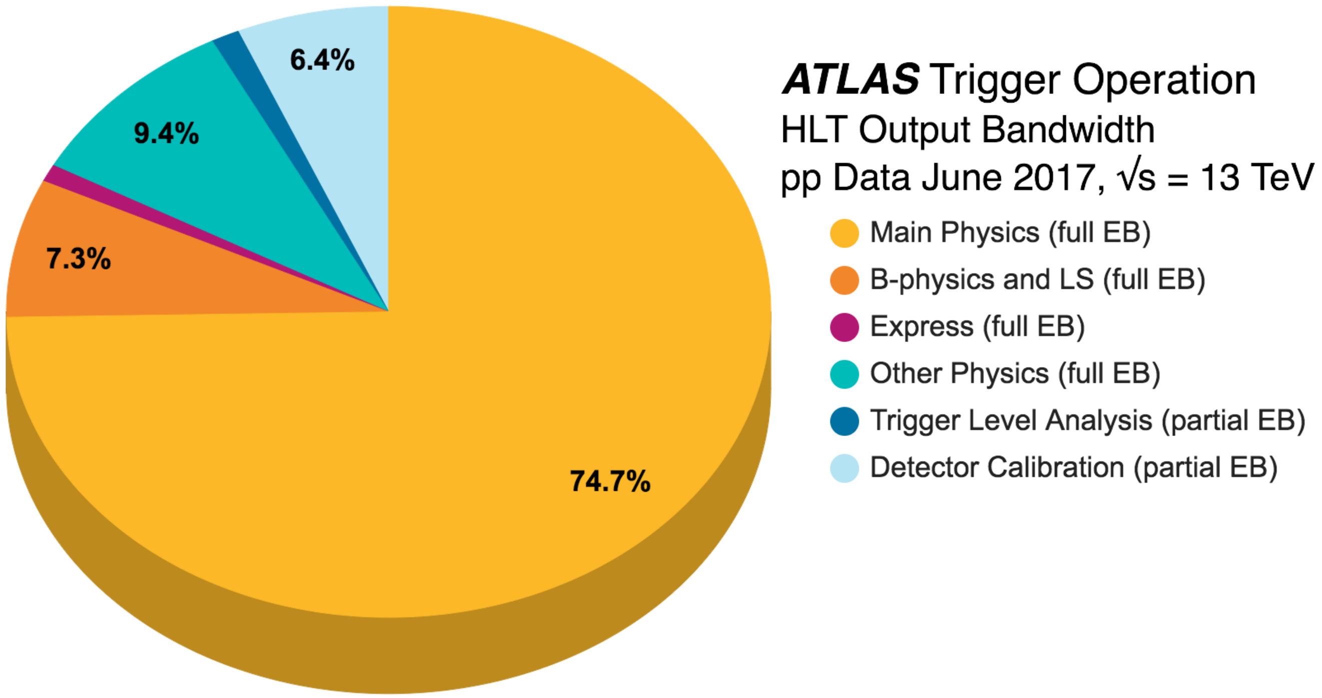

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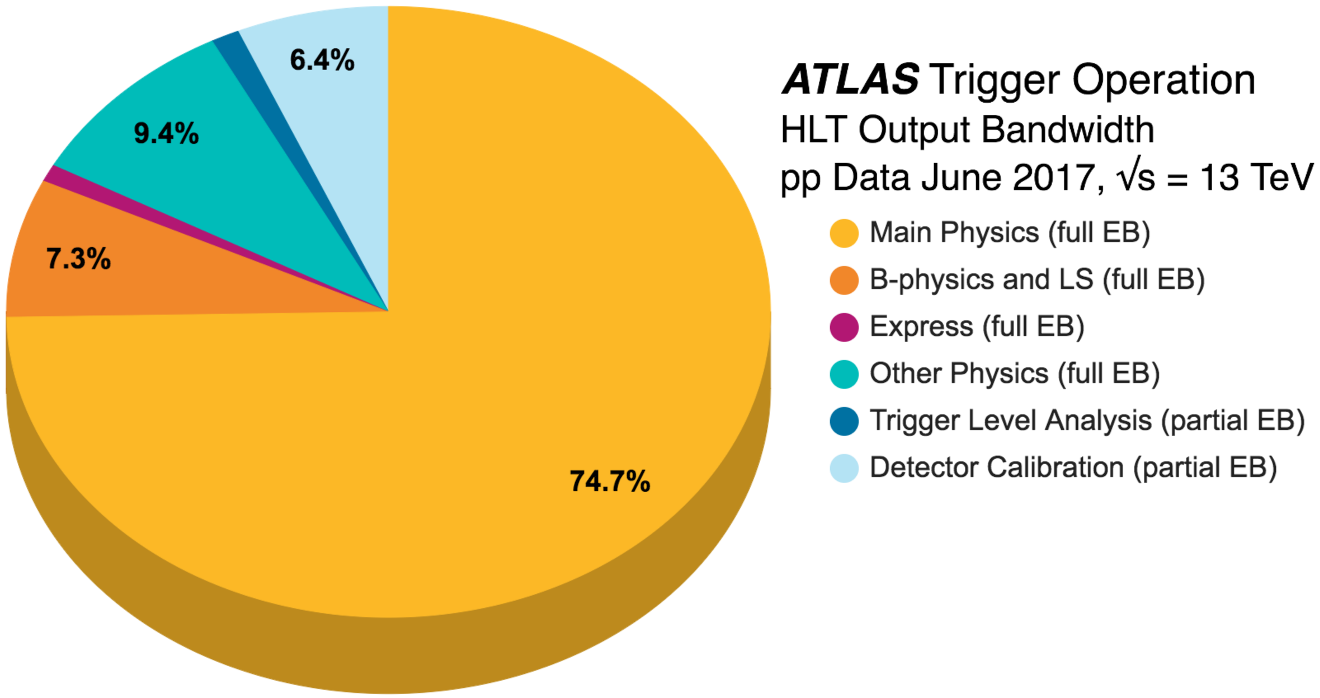

Most of the time, record the "full event" when triggered

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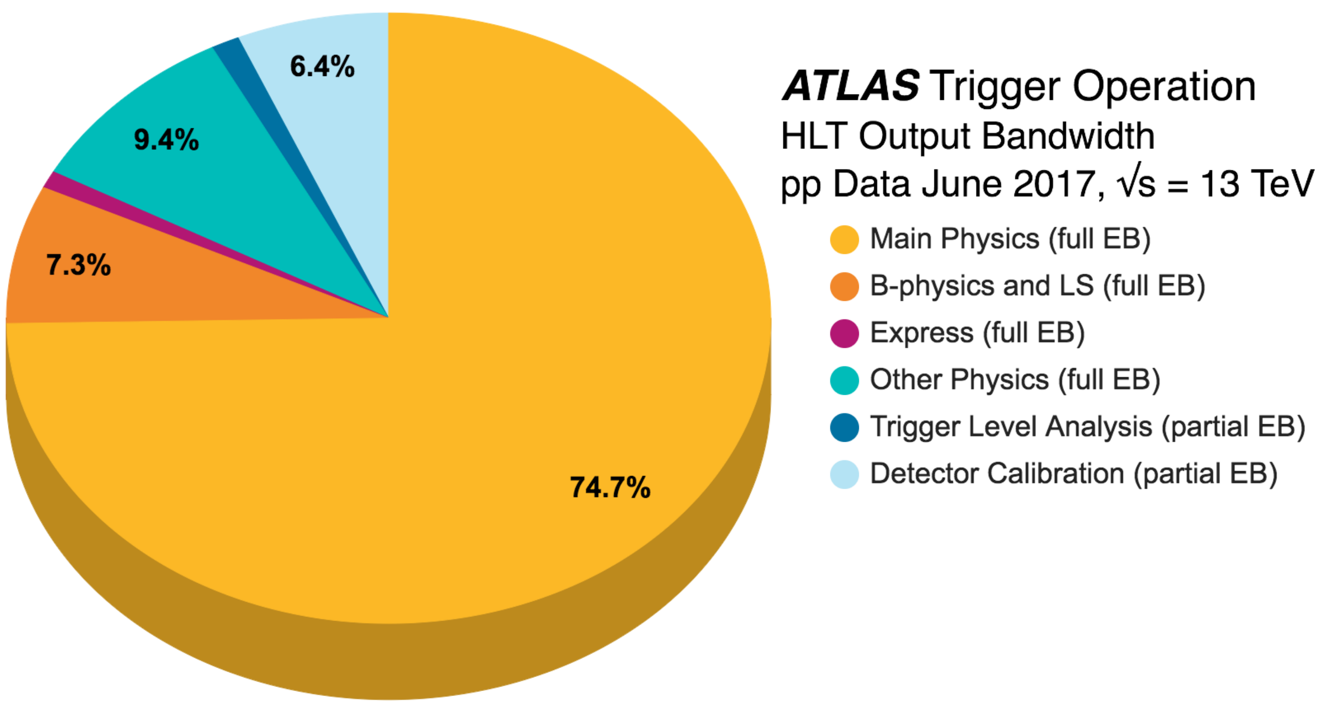

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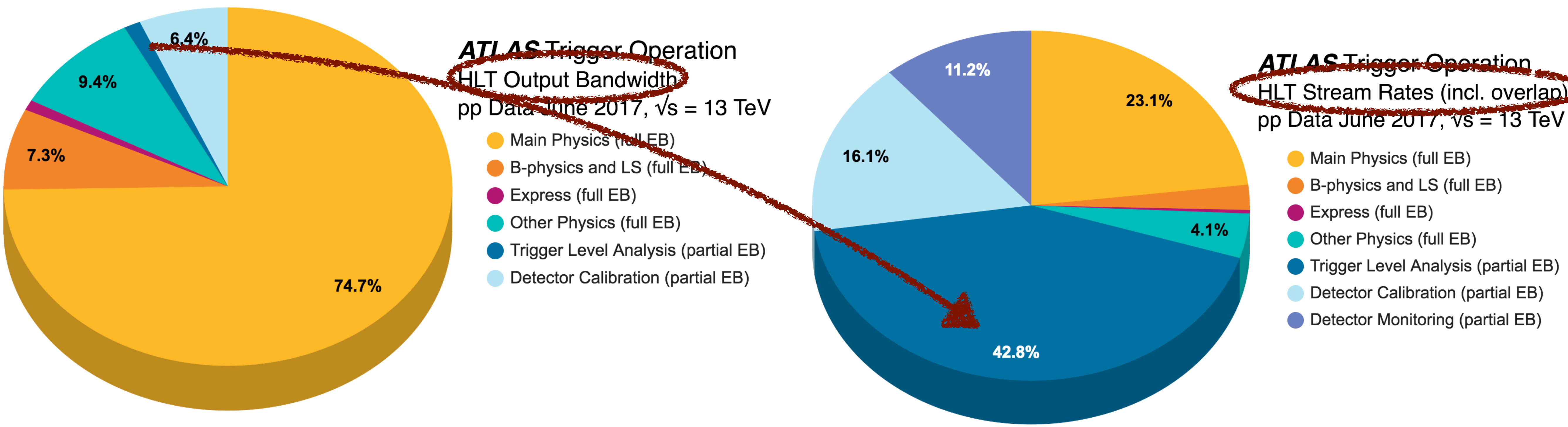

Most of the time, record the "full event" when triggered

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

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Rare signals are an excellent target for machine learning!

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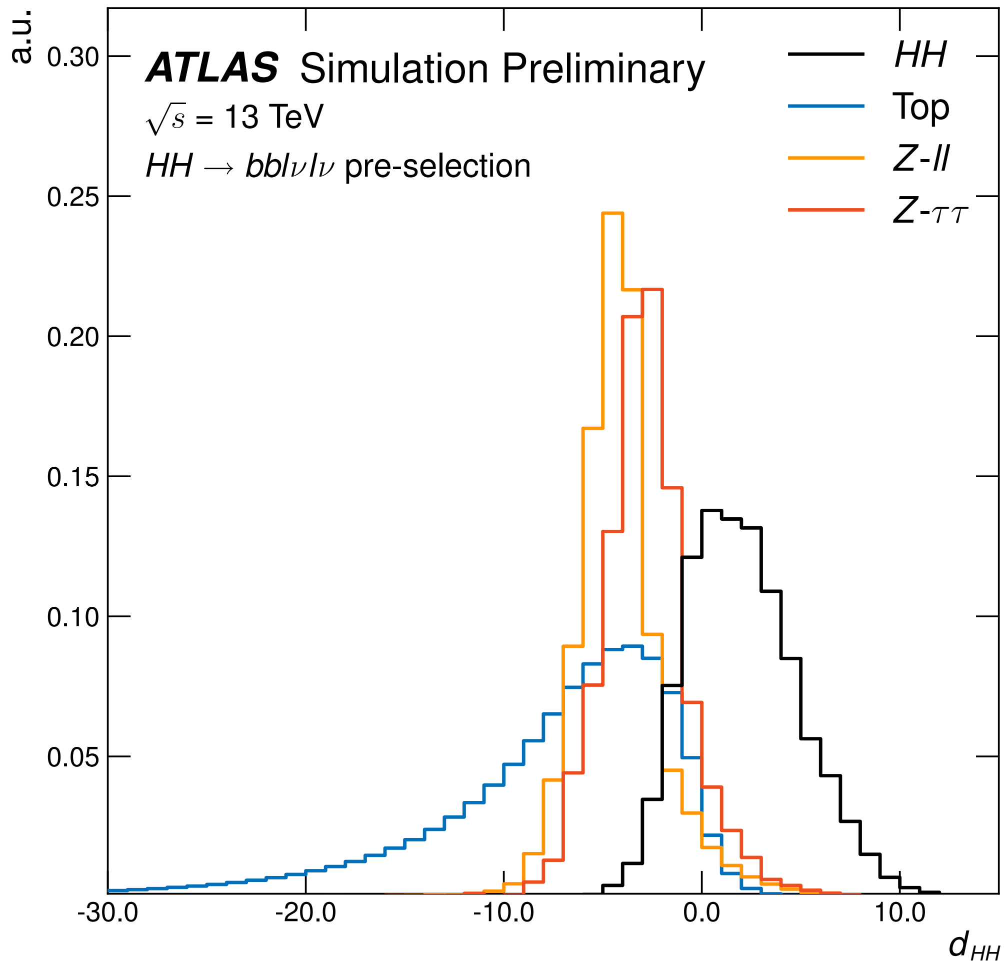

ATLAS uses a DNN to search for di-Higgs in bbll final state

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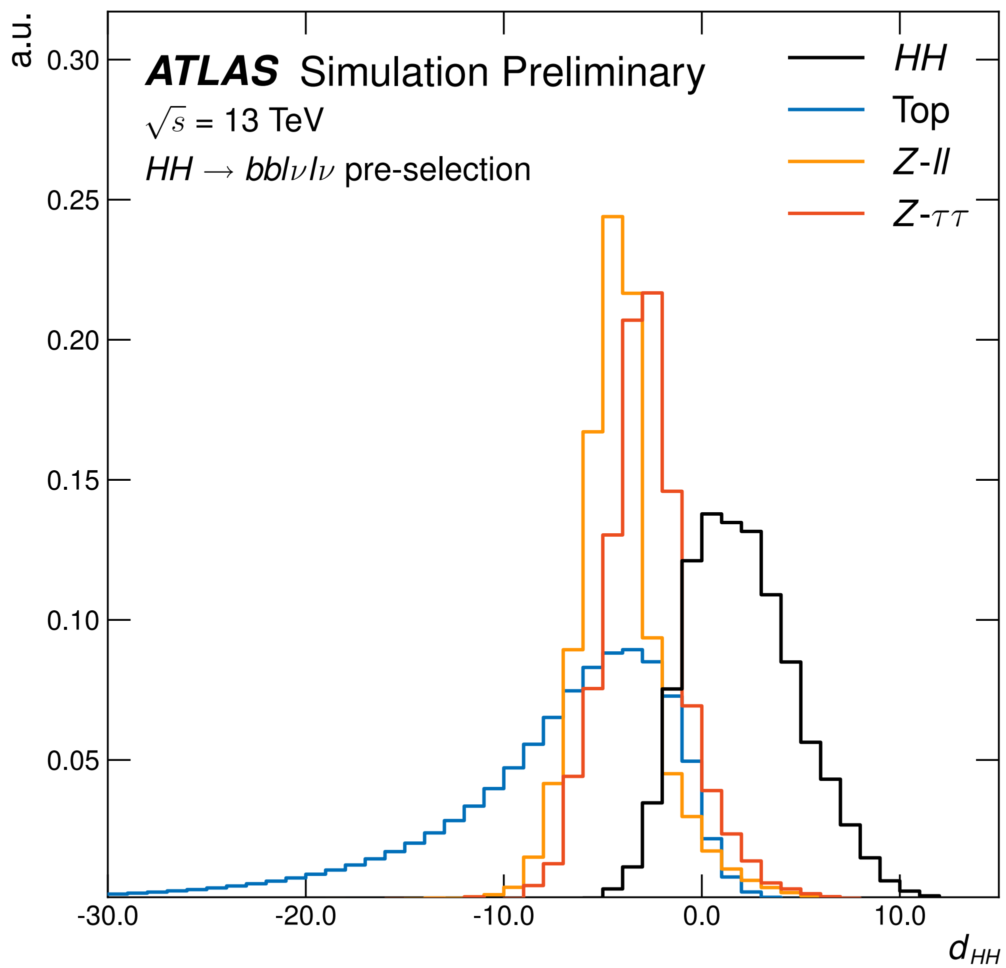

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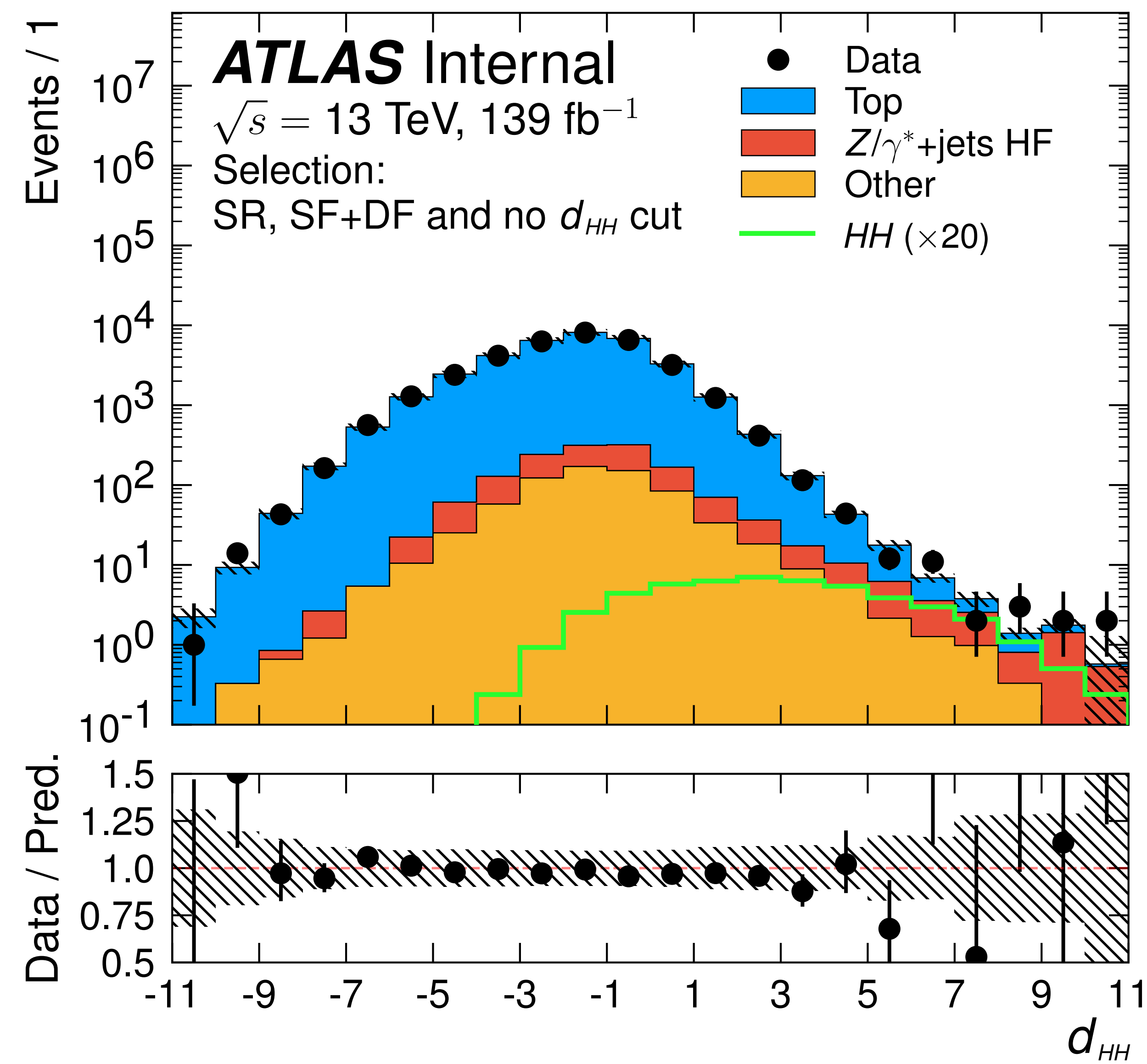

Machine learning can make this rarer channel competitive in the hunt for di-Higgs!

CMS Jet Timing

ATLAS WH results