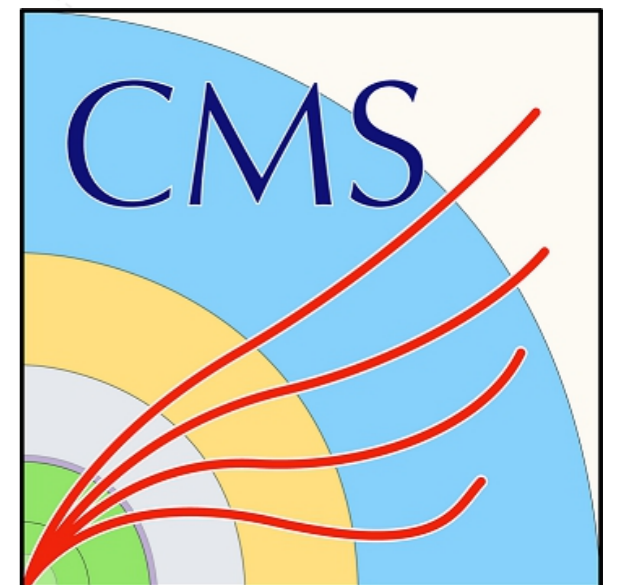


# BSM Results at the LHC

*APS DPF 2019*

Maximilian Swiatlowski,  
for the ATLAS and CMS Collaborations

Enrico Fermi Institute, University of Chicago



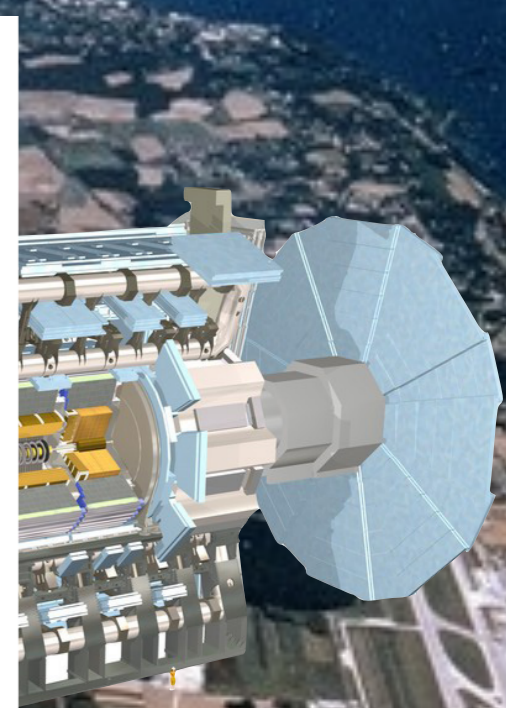
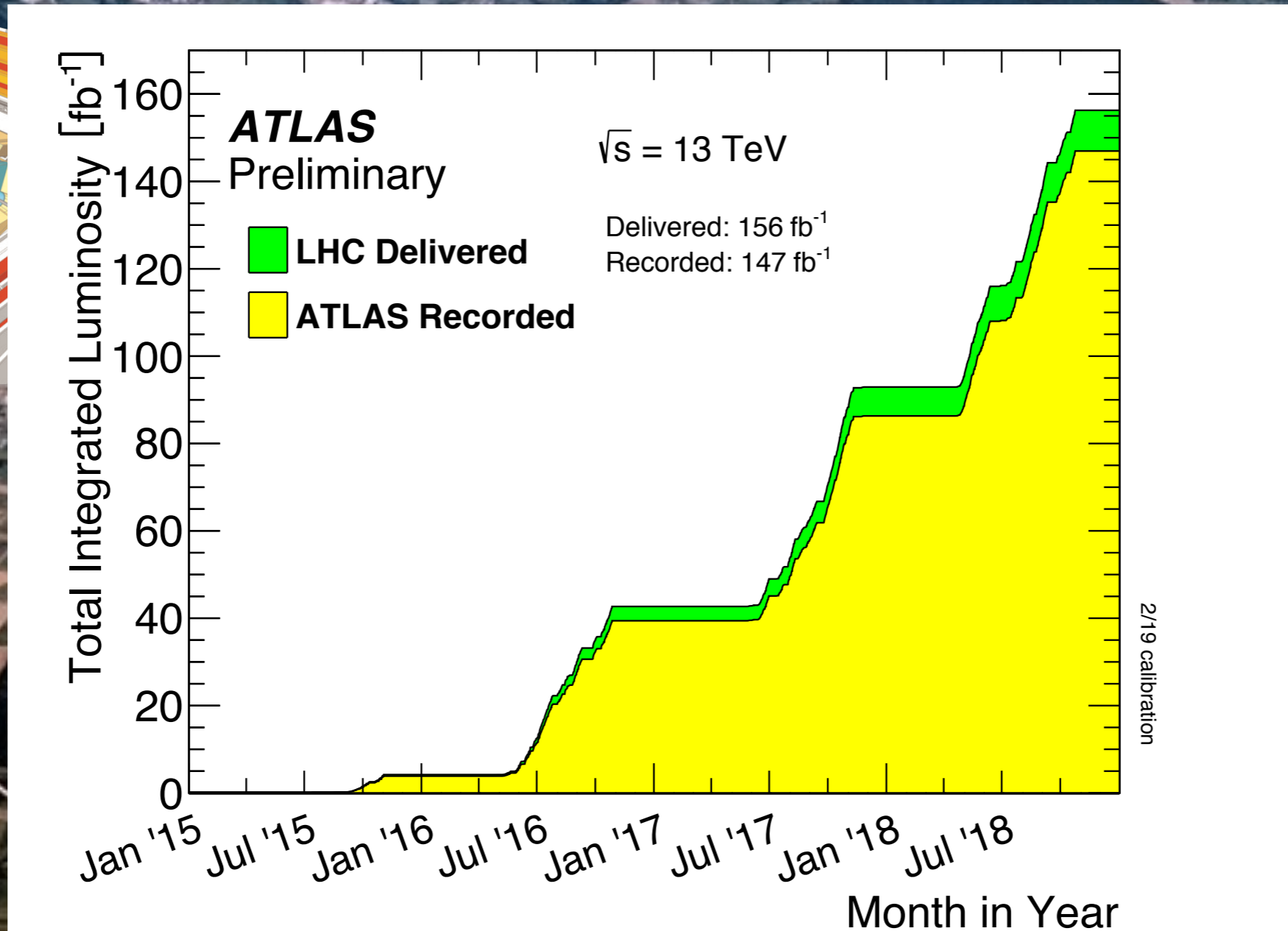
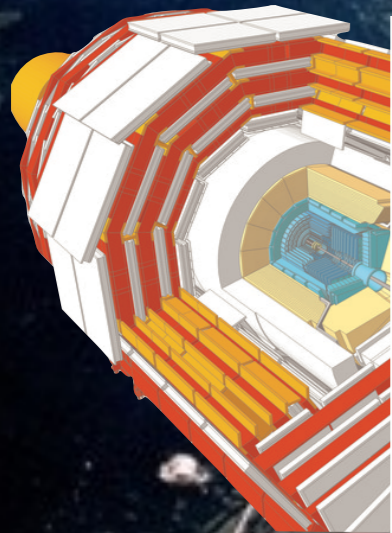
# The LHC



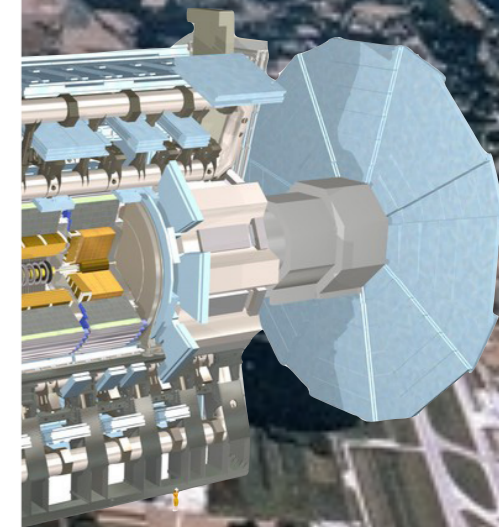
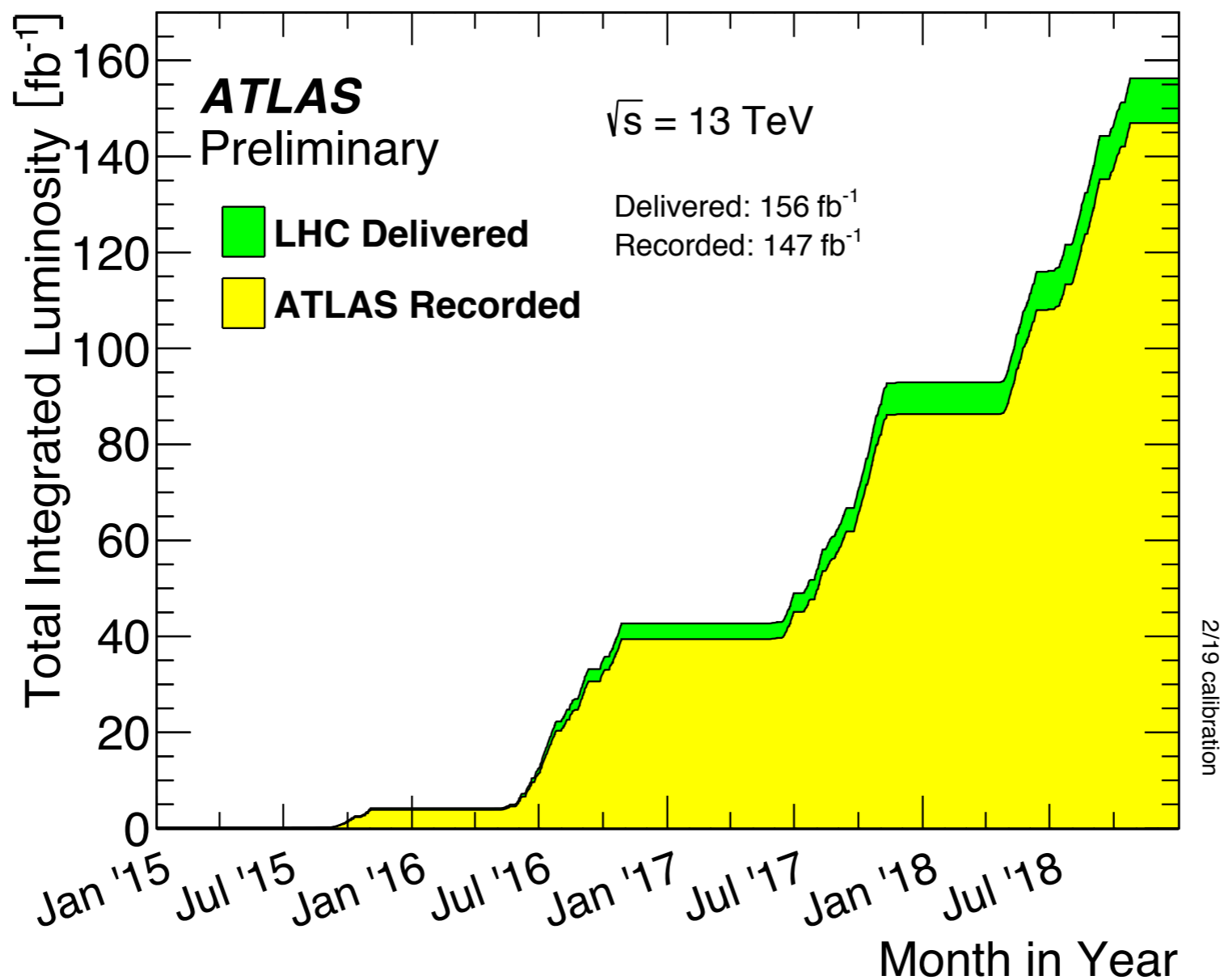
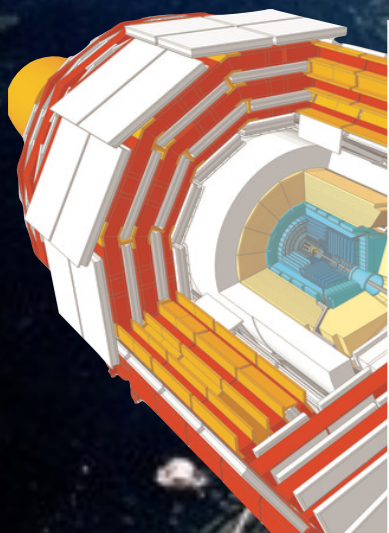
# The LHC



# The LHC



# The LHC

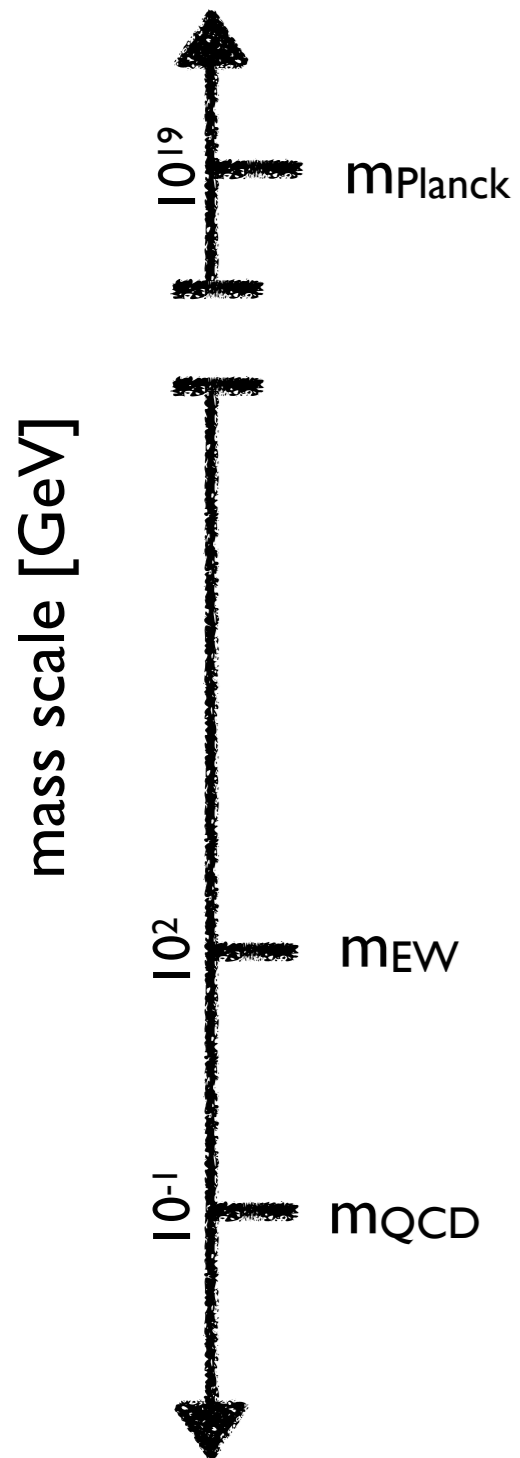


Huge recorded dataset from Run 2:  
Thank you to the LHC team and machine!

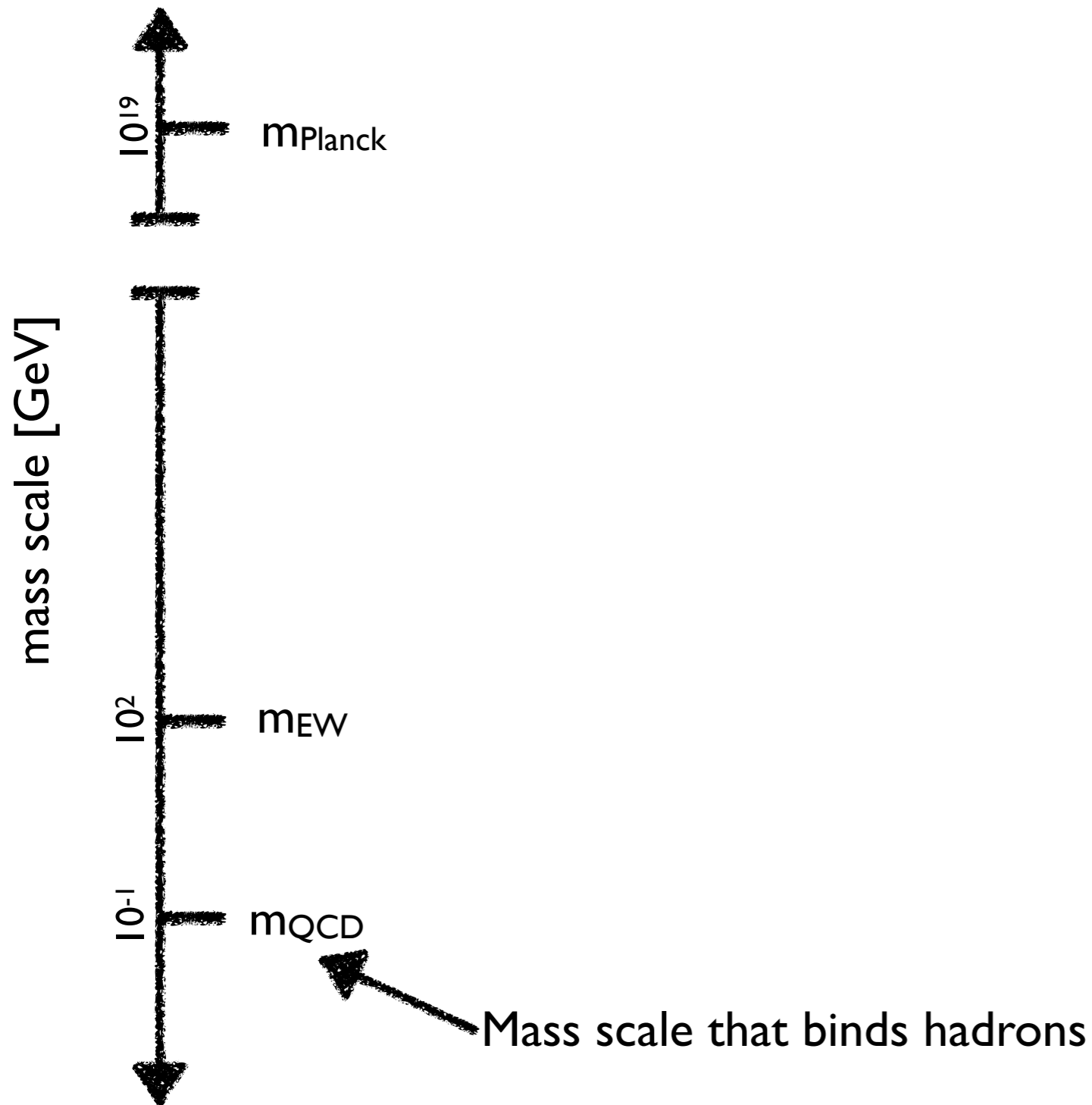
# Why BSM?



# Why BSM?

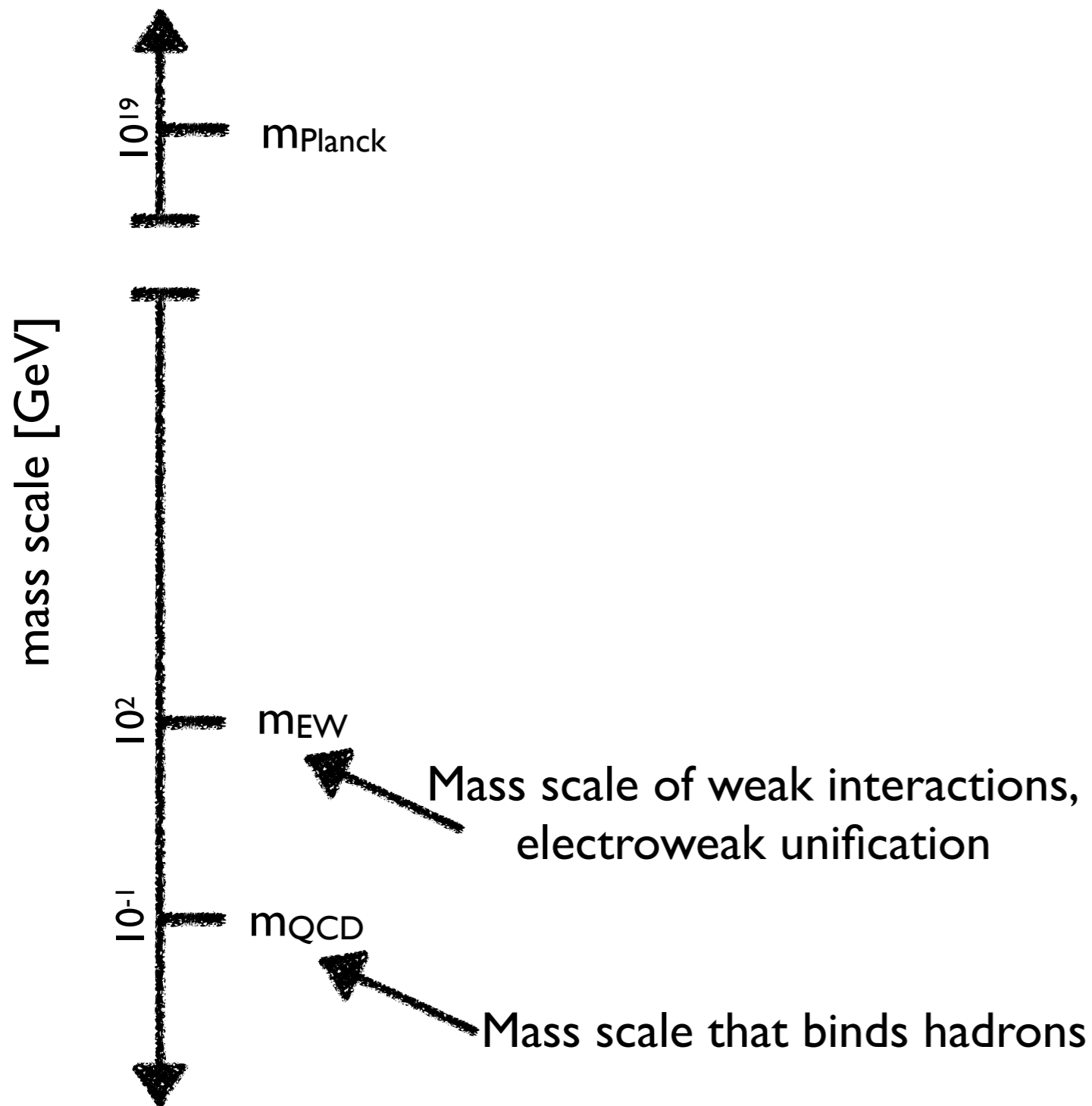


# Why BSM?

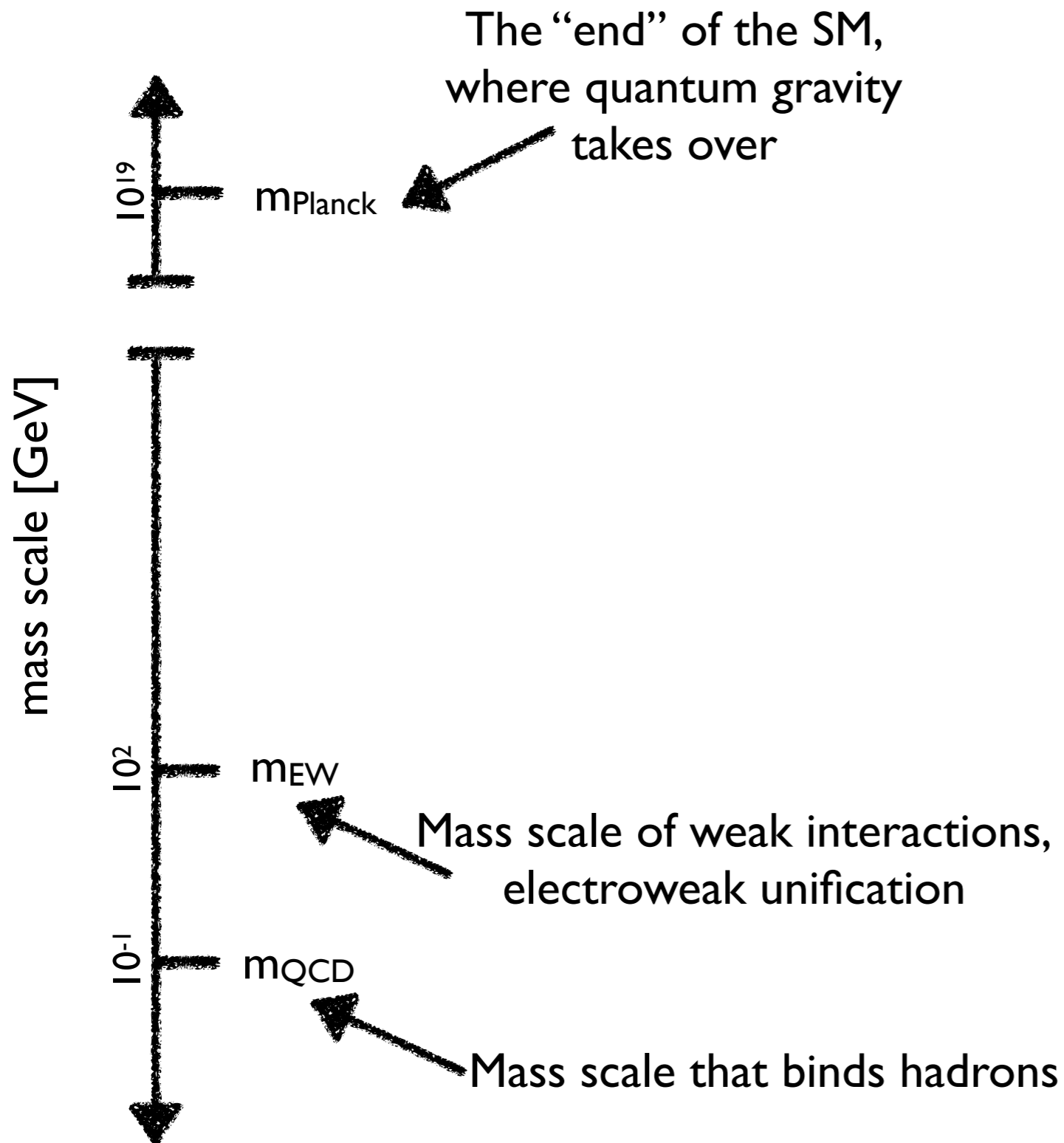




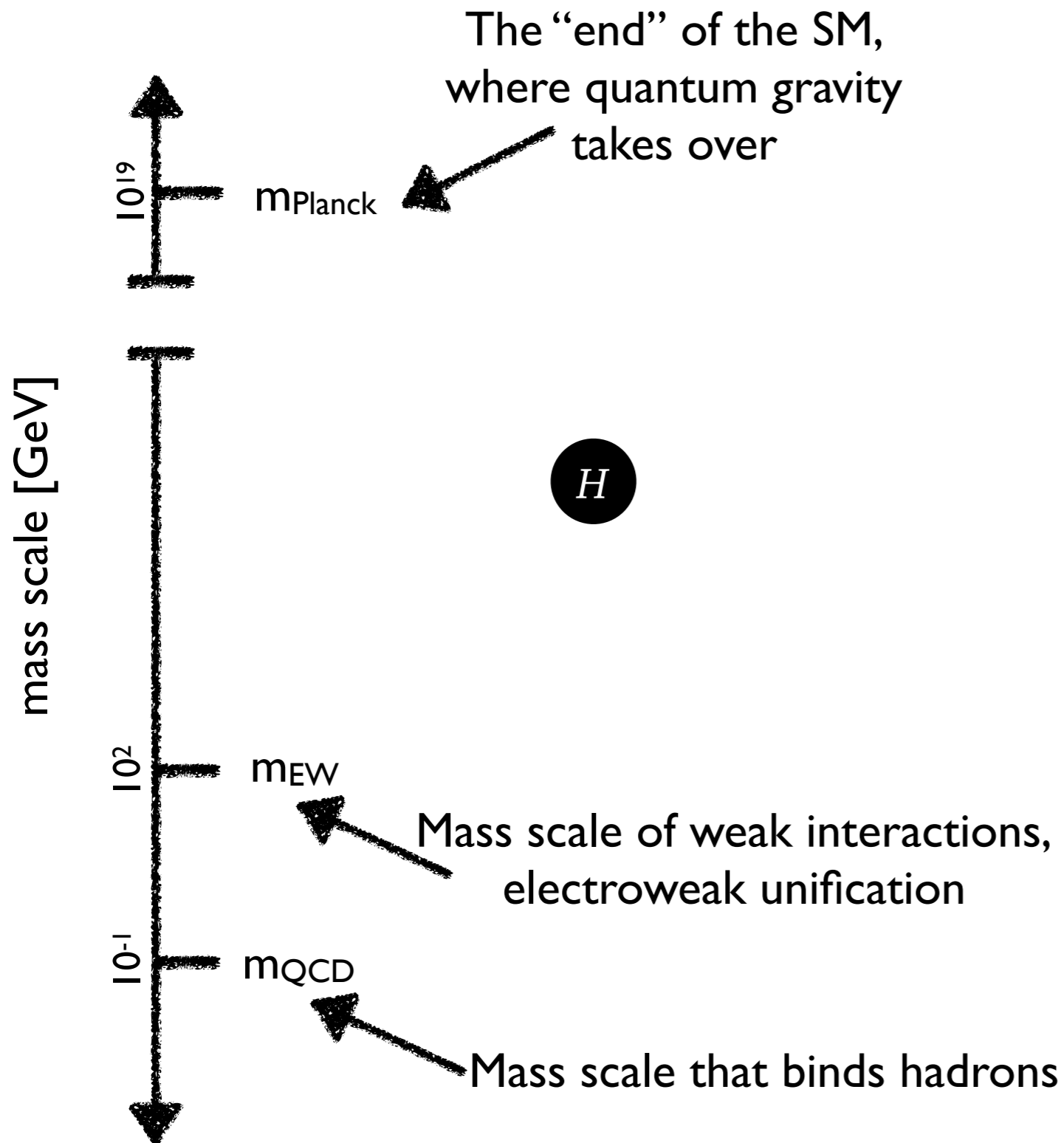
# Why BSM?



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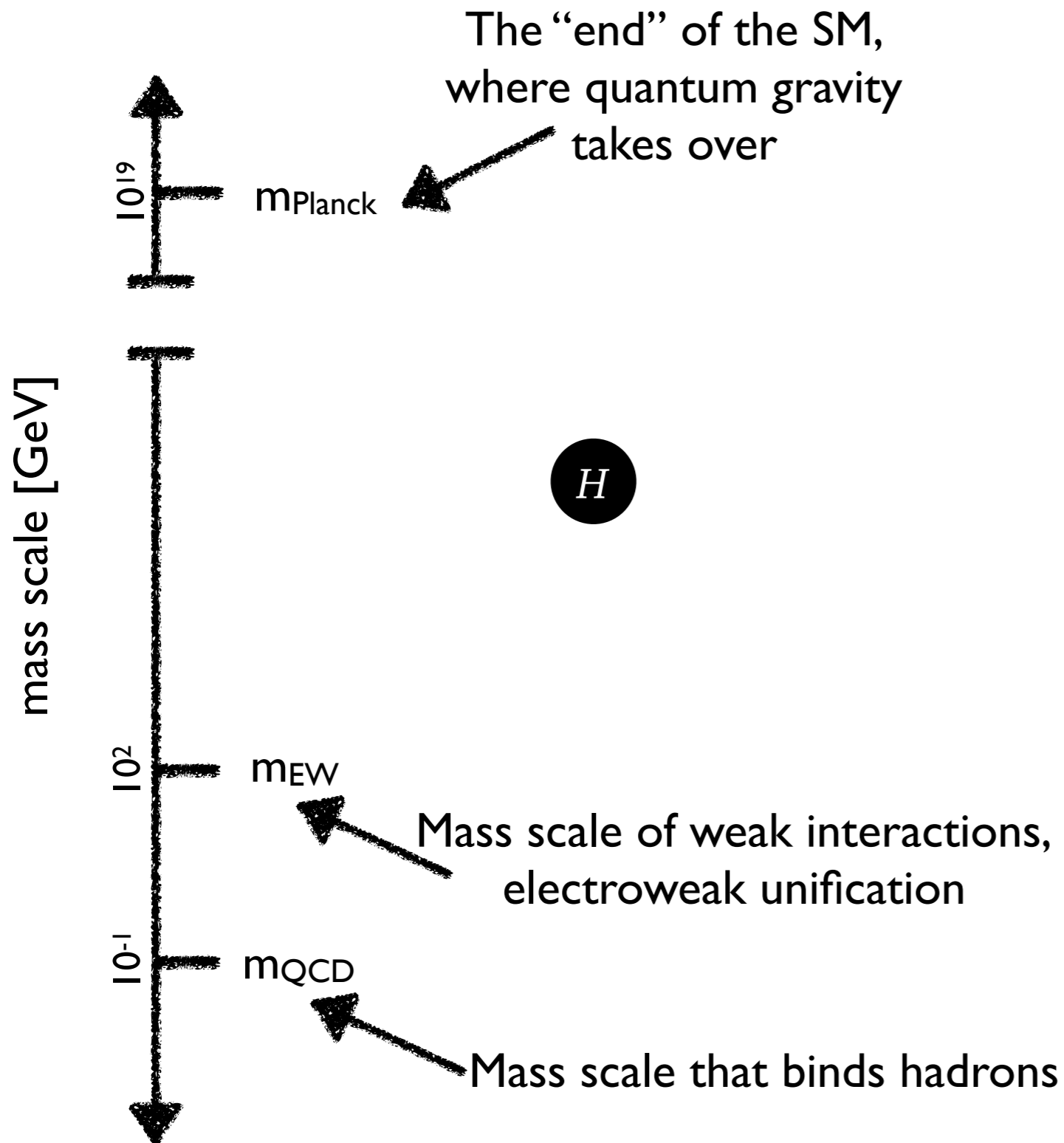


# Why BSM?



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

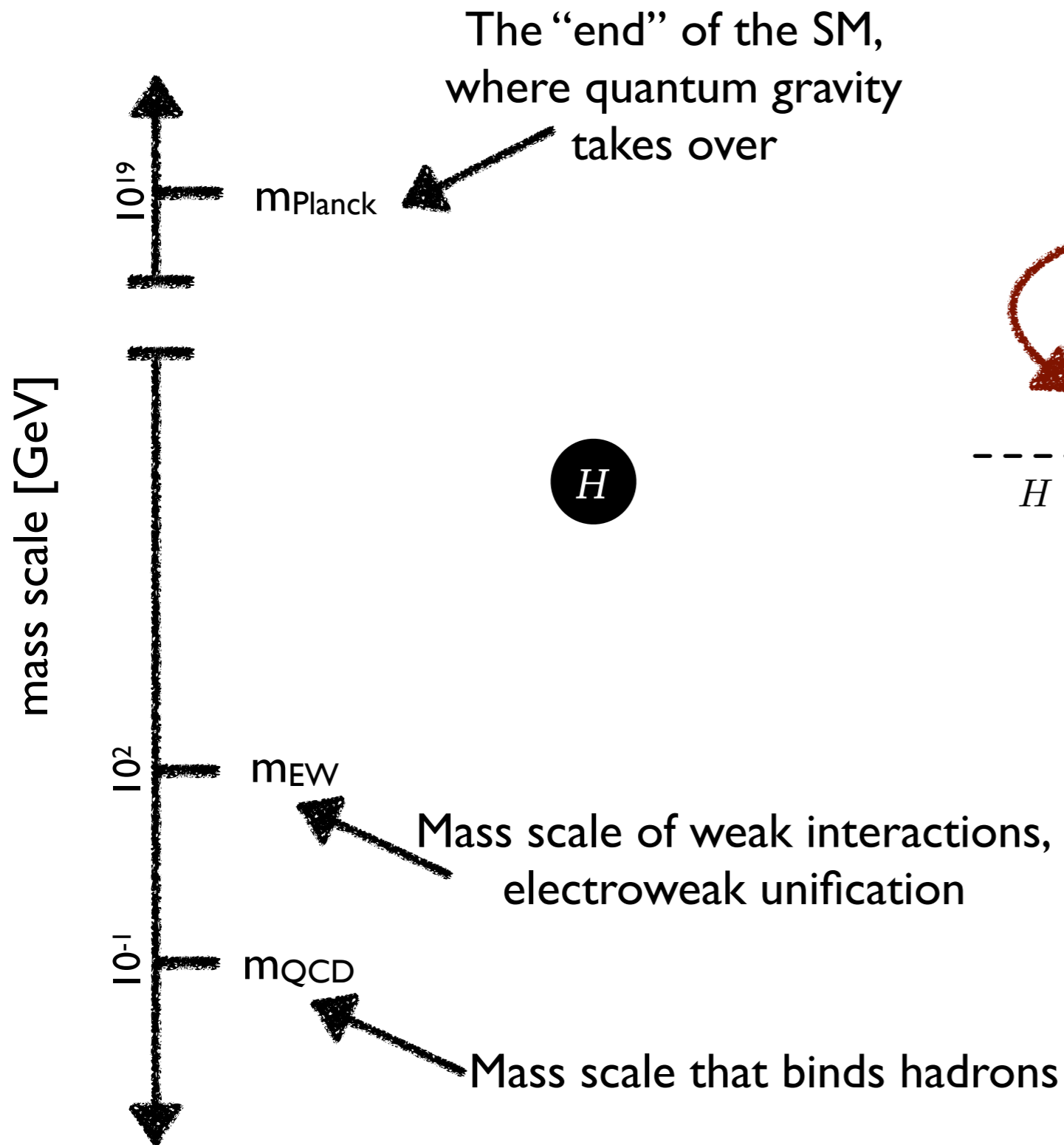
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To first order, the mass of the Higgs is a free parameter, and can be anywhere

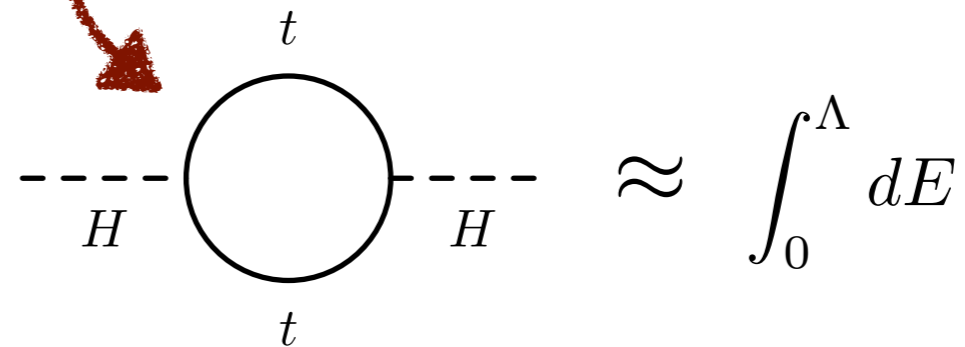
But the Higgs interacts with other particles, which affects its mass

# Why BSM?

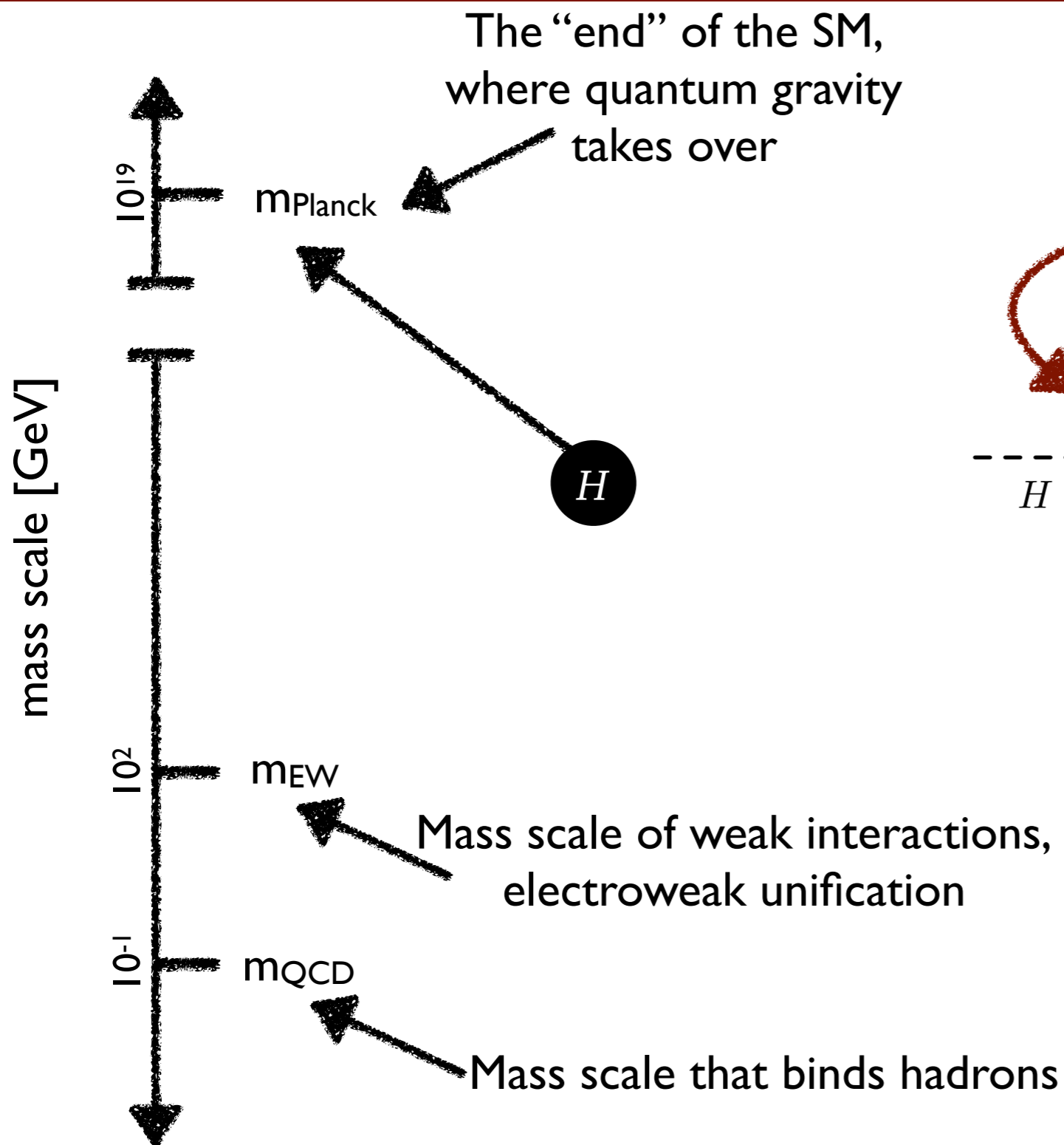


To first order, the mass of the Higgs is a free parameter, and can be anywhere

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



# Why BSM?



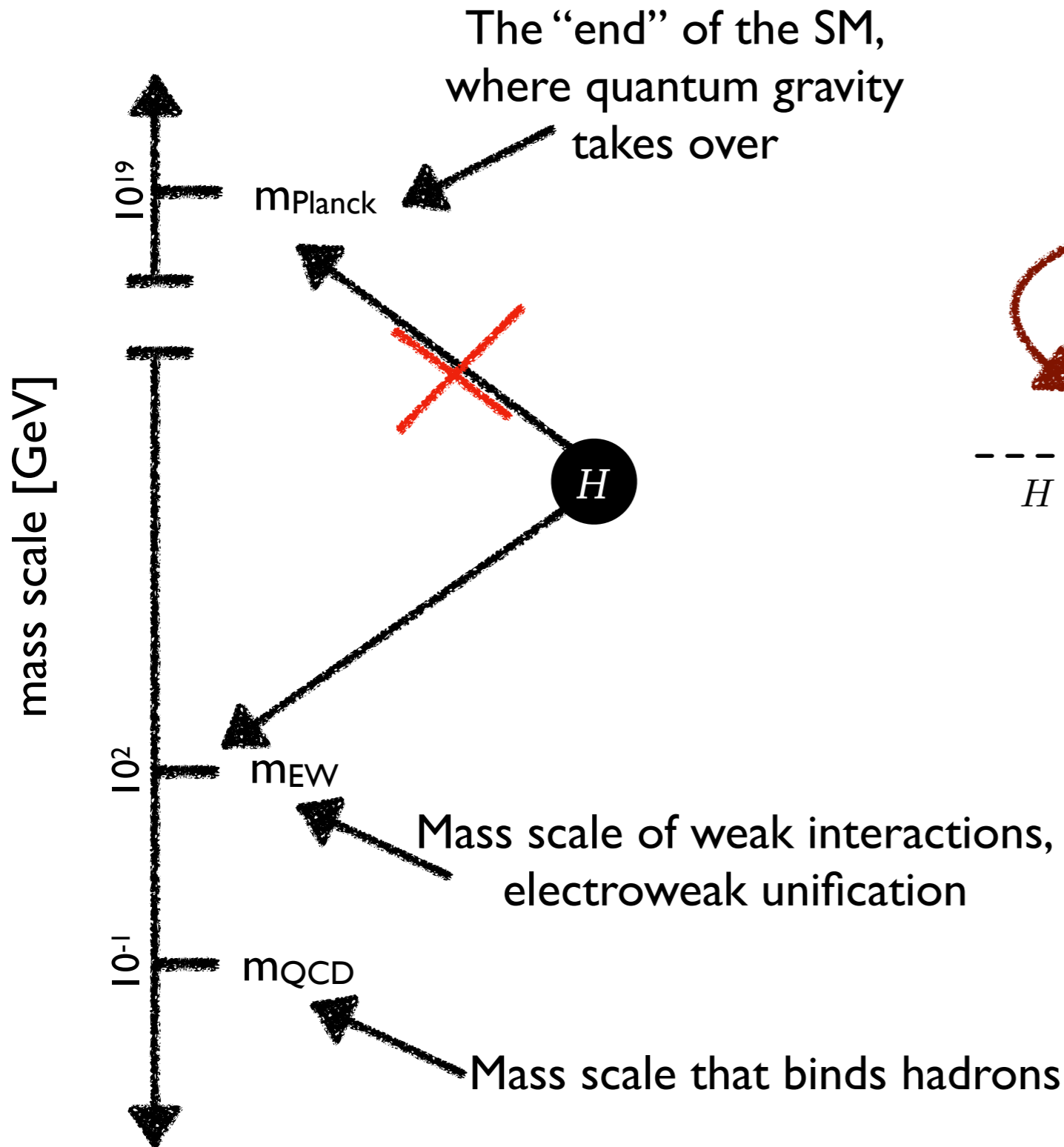
To first order, the mass of the Higgs is a free parameter, and can be anywhere

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

$$\text{---} \overset{H}{\text{---}} \text{---} \begin{array}{c} t \\ \circ \\ t \end{array} \text{---} \overset{H}{\text{---}} \text{---} \approx \int_0^\Lambda dE \approx m_{\text{Planck}}$$

In the SM, this correction should set the Higgs mass to  $\sim m_{\text{Planck}}$

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

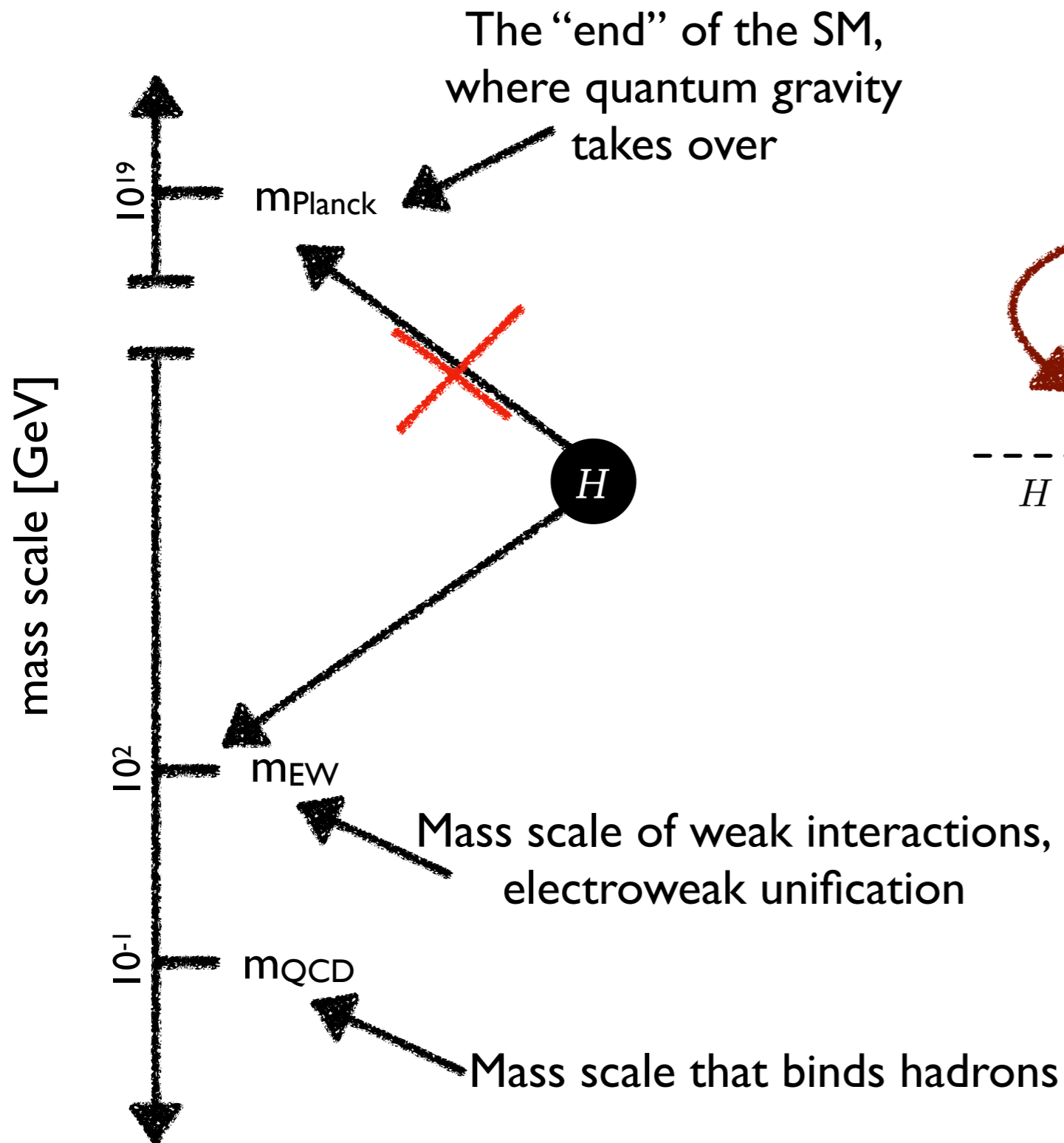
But the Higgs interacts with other particles, which affects its mass

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

In the SM, this correction should set the Higgs mass to  $\sim m_{\text{Planck}}$

But we observe it at 125 GeV!

# Why BSM?



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

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

In the SM, this correction should set the Higgs mass to  $\sim m_{\text{Planck}}$

But we observe it at 125 GeV!

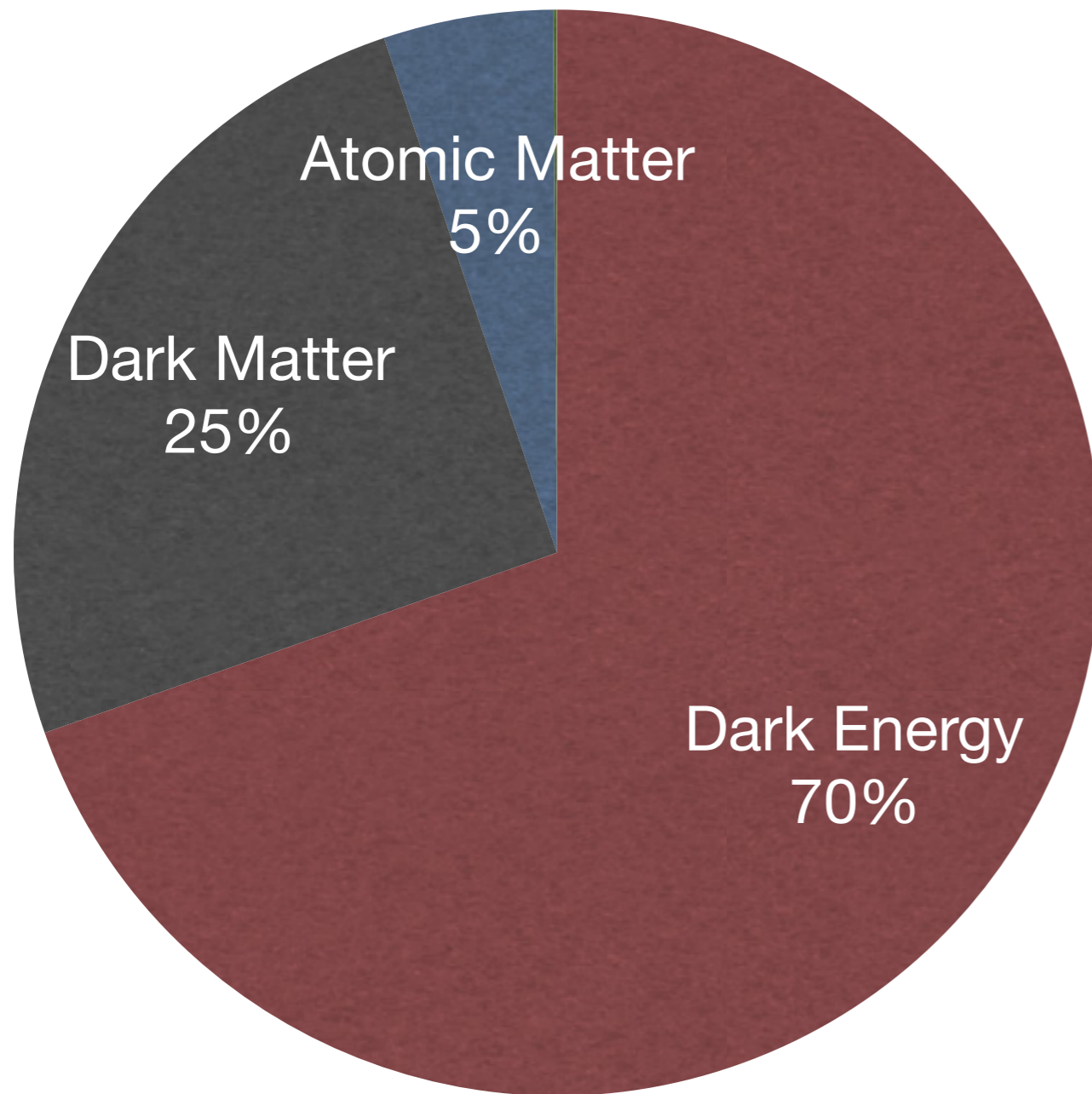
**BSM can stabilize the Higgs mass**



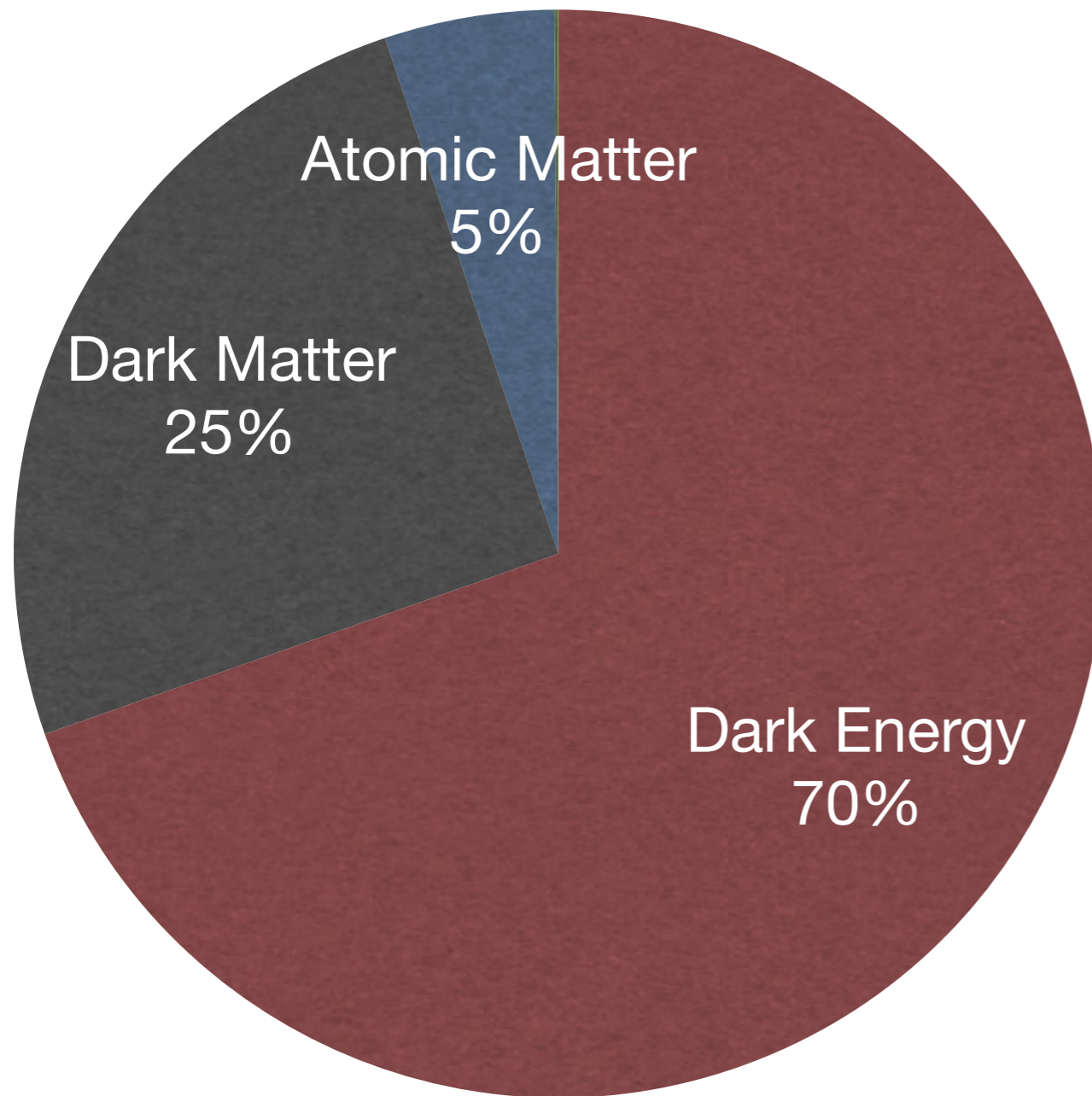
# Why BSM?



# Why BSM?

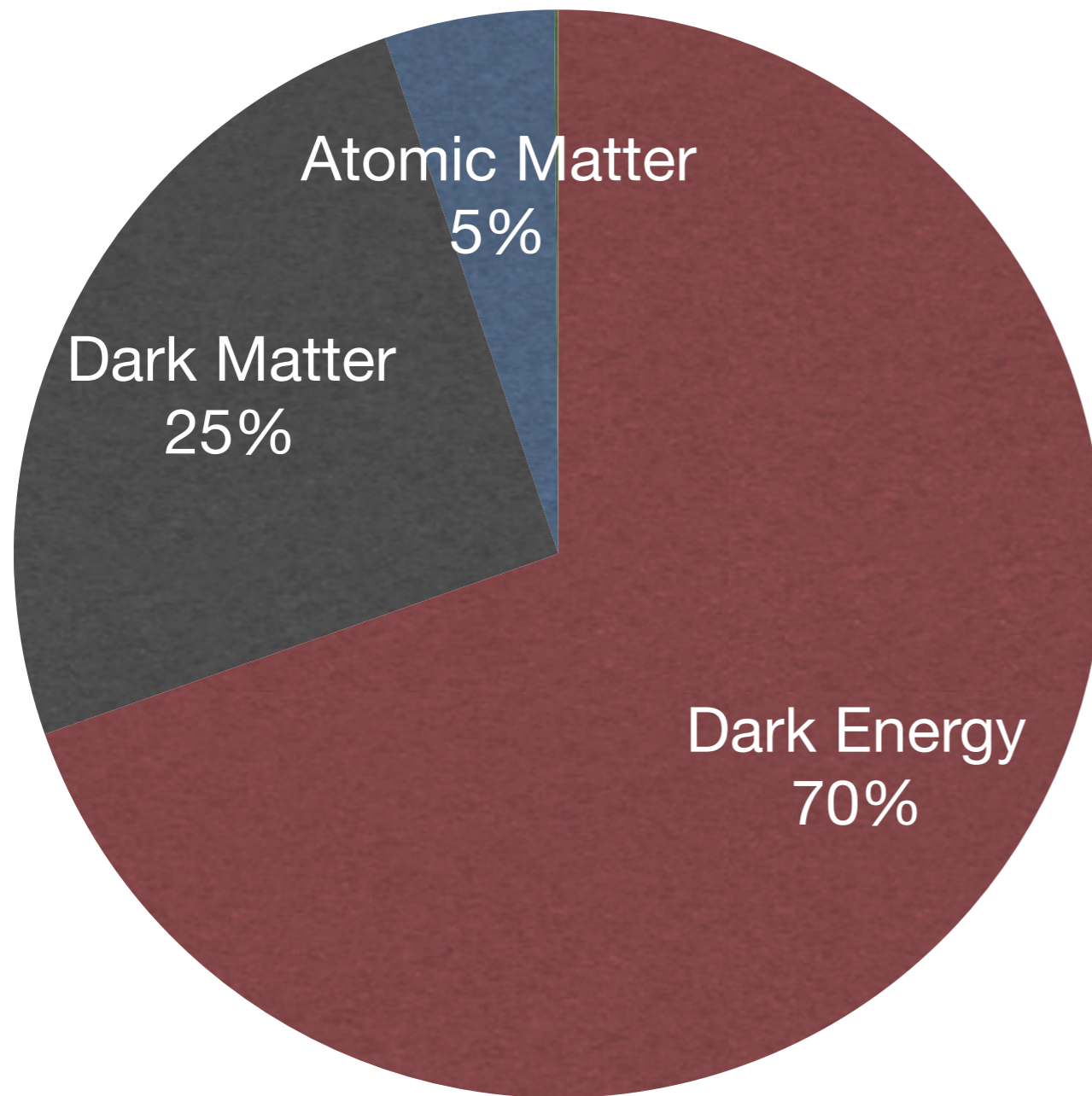


# Why BSM?



We don't understand the majority of the universe!

# 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?



# Why BSM?



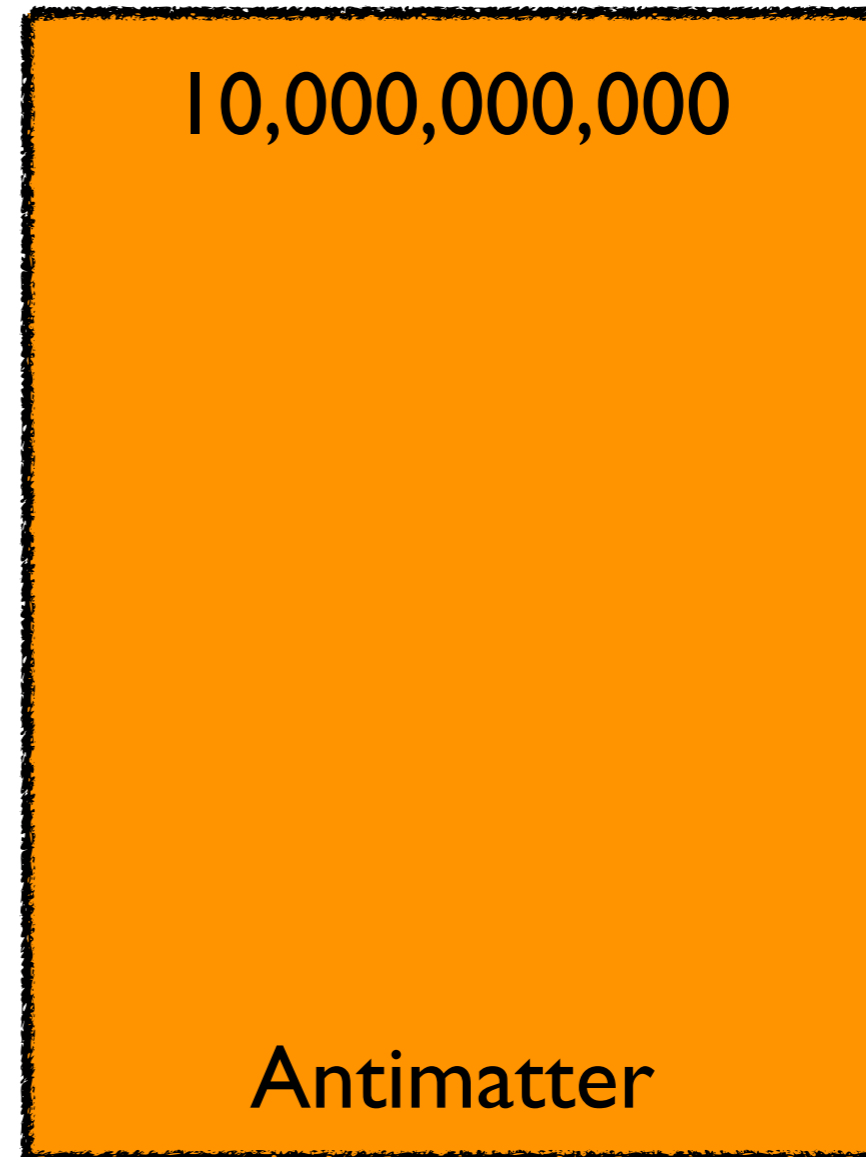
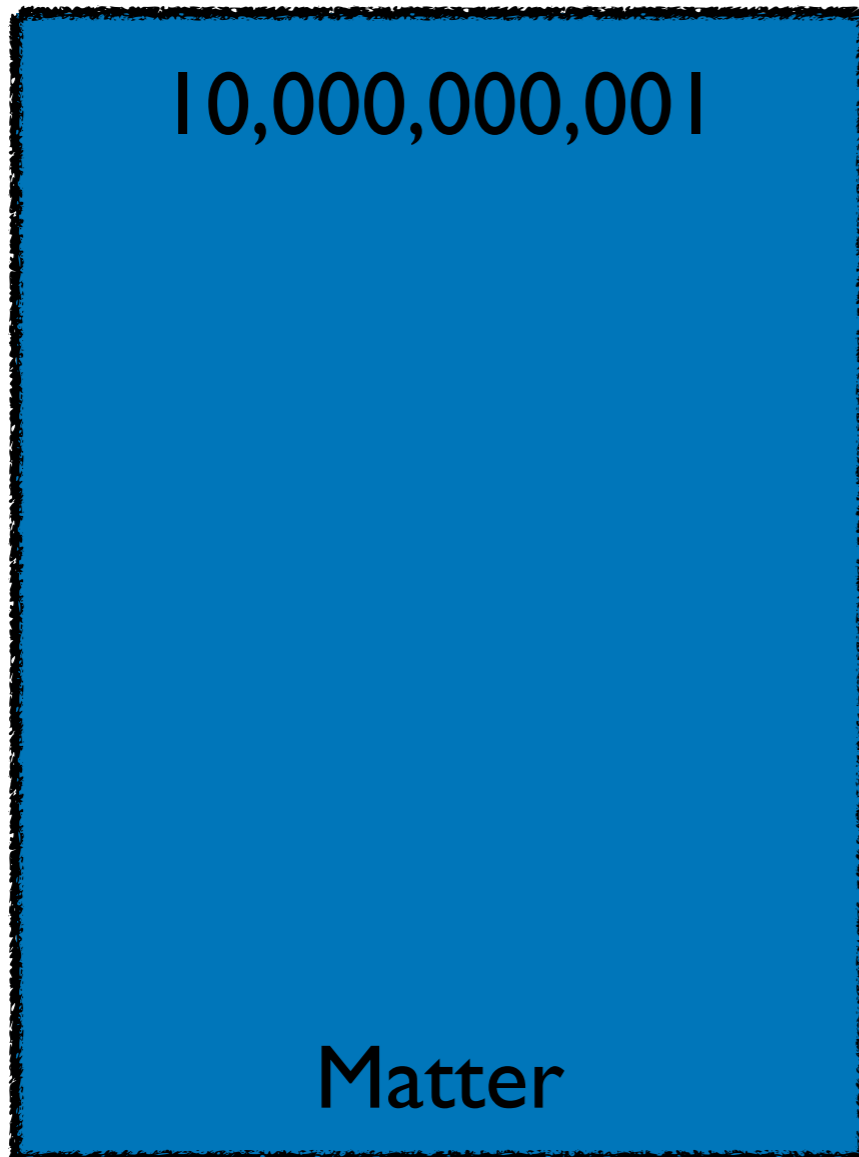
10,000,000,001

Matter

10,000,000,000

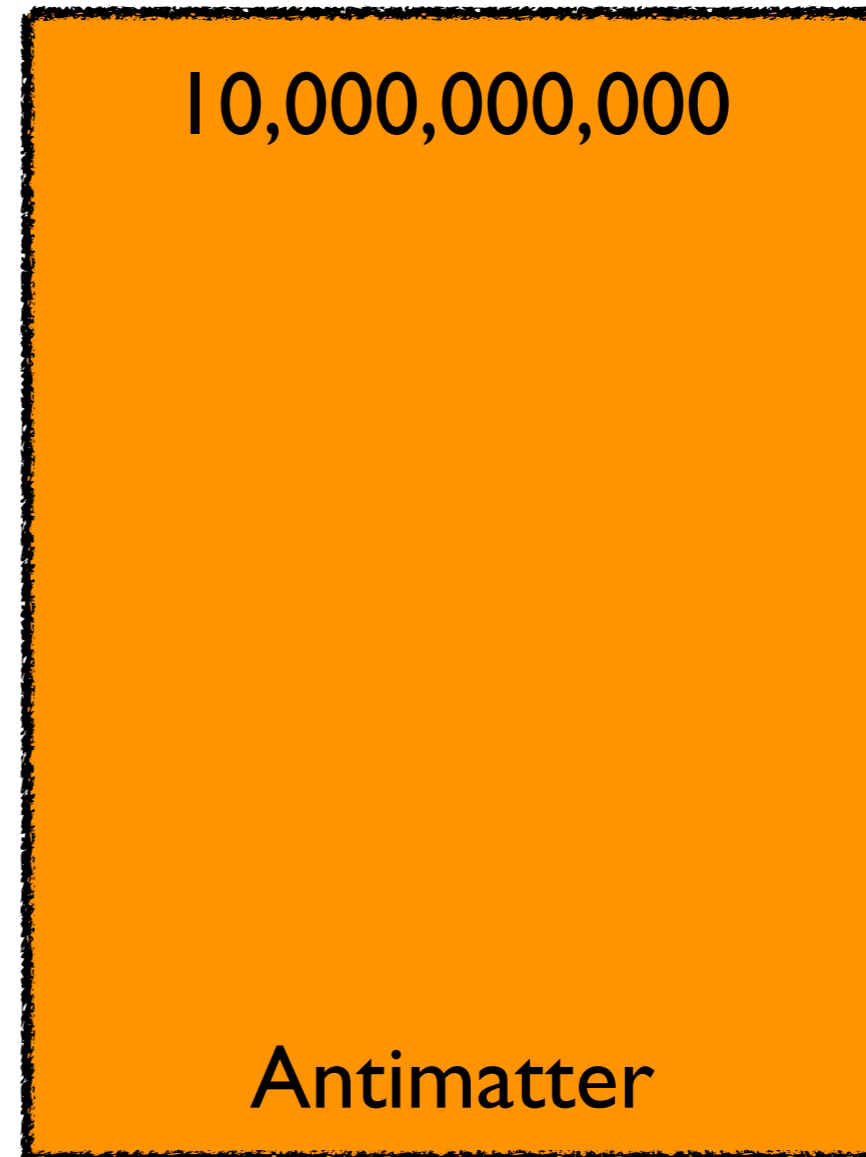
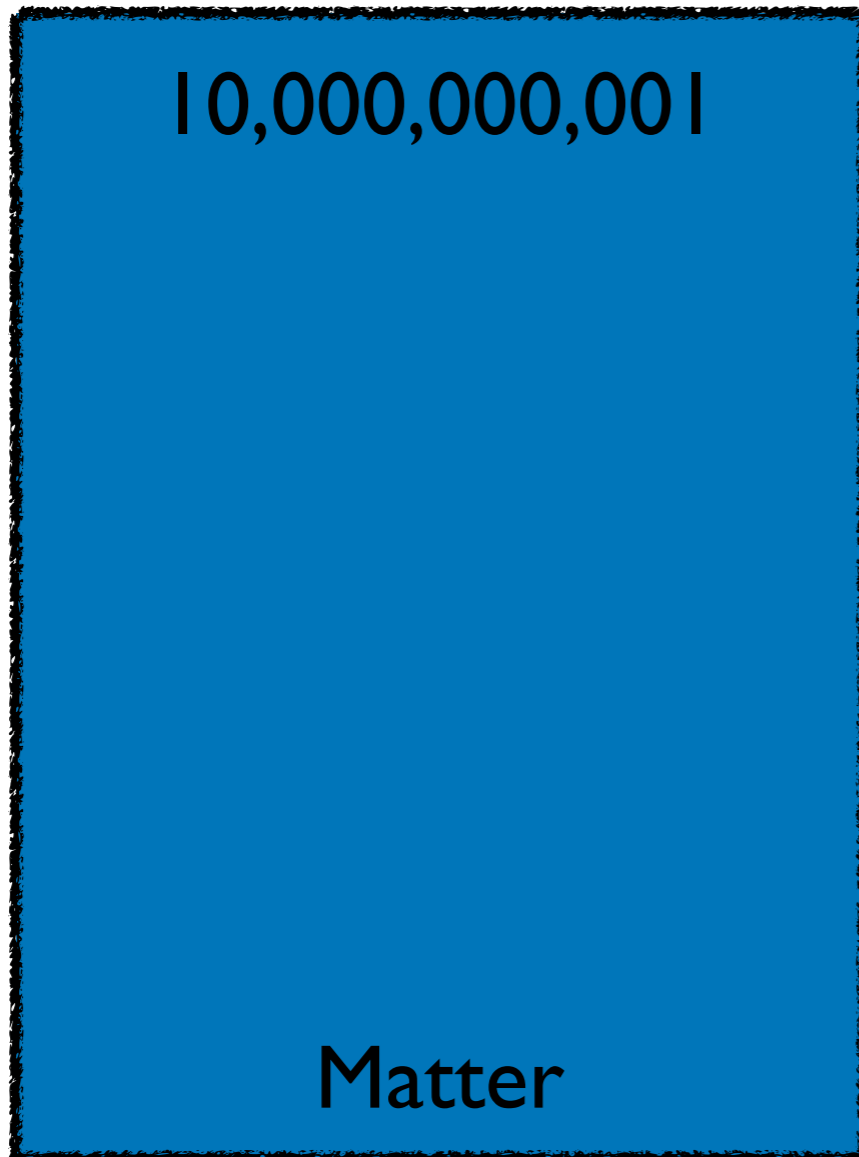
Antimatter

# Why BSM?



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

# Why BSM?

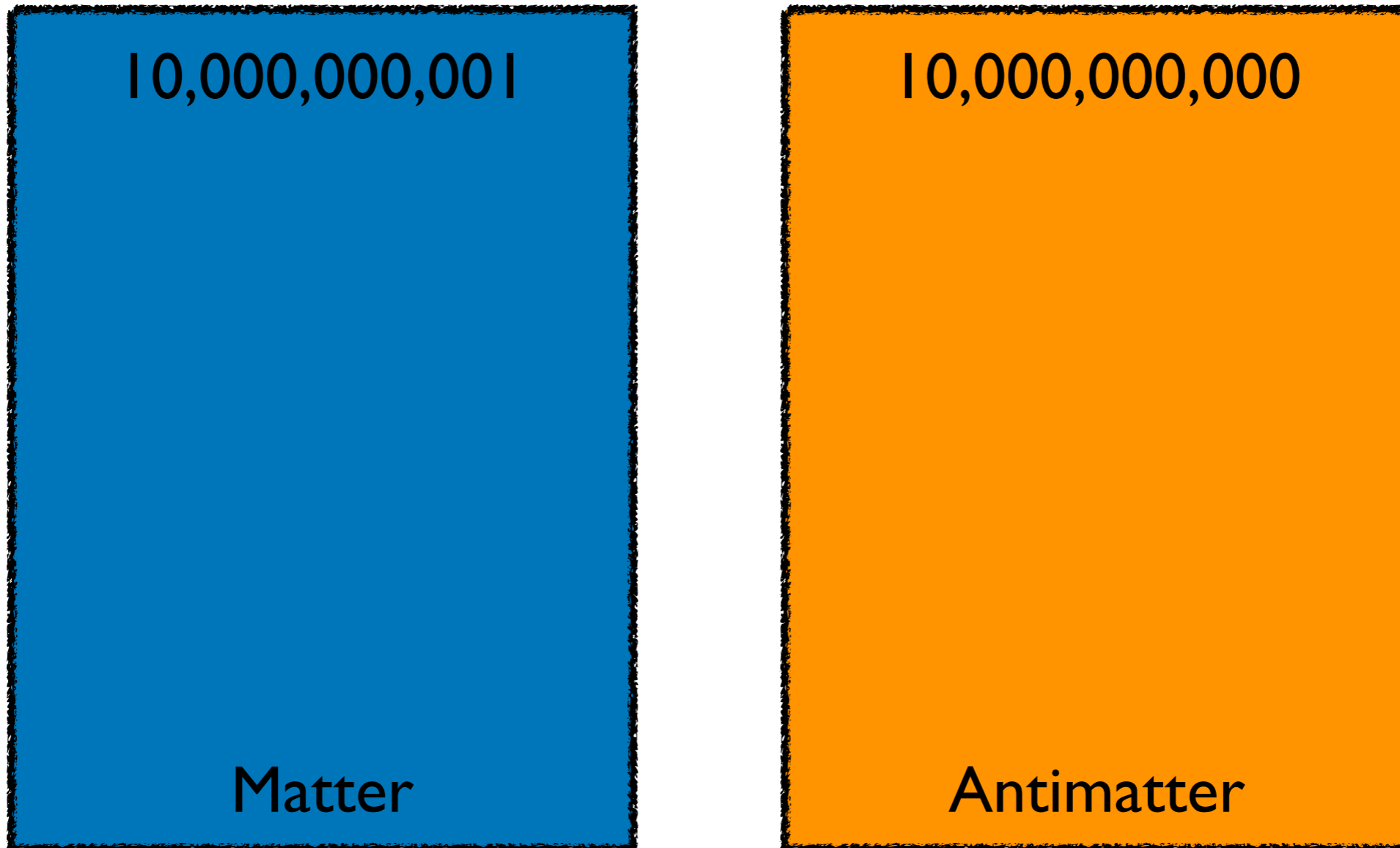


Where did the tiny matter/antimatter asymmetry that leads to a matter dominated universe arise?

CP violation in the SM is not enough



# Why BSM?



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

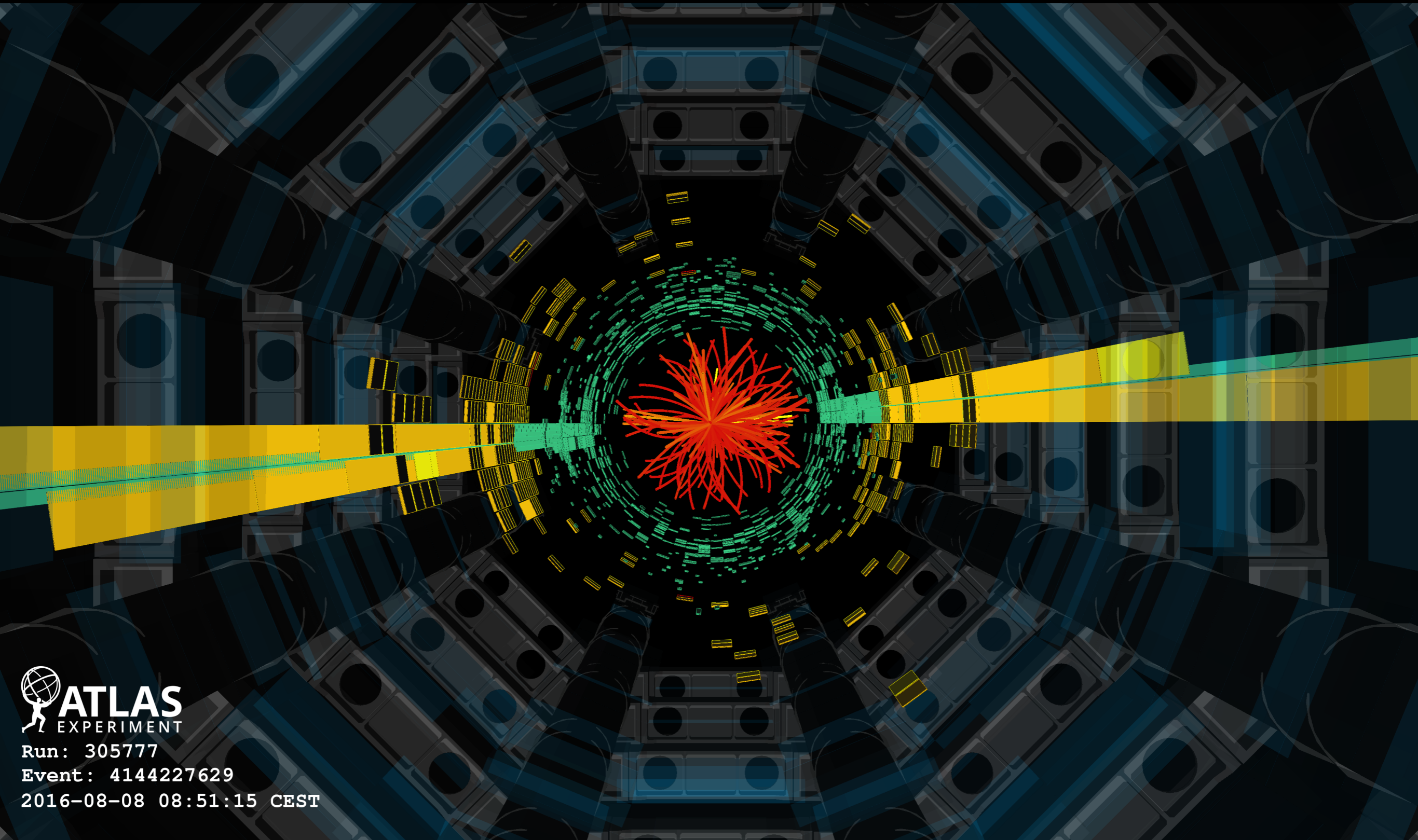
CP violation in the SM is not enough

**BSM can explain the matter dominated universe**



How do we search for BSM physics at the LHC?

# How do we search for BSM physics at the LHC?



 **ATLAS**  
EXPERIMENT

Run: 305777

Event: 4144227629

2016-08-08 08:51:15 CEST

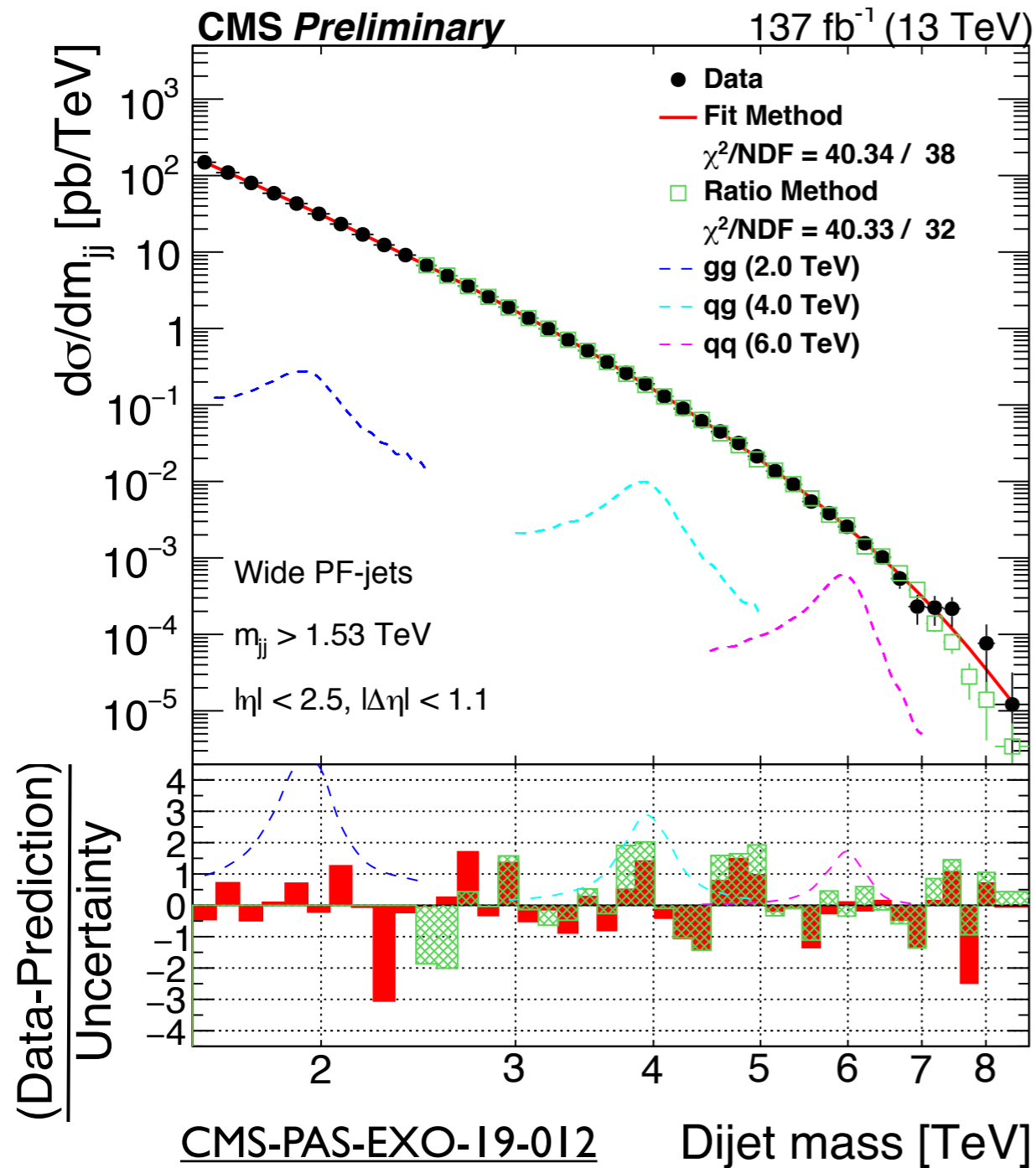
# Searching with Dijets



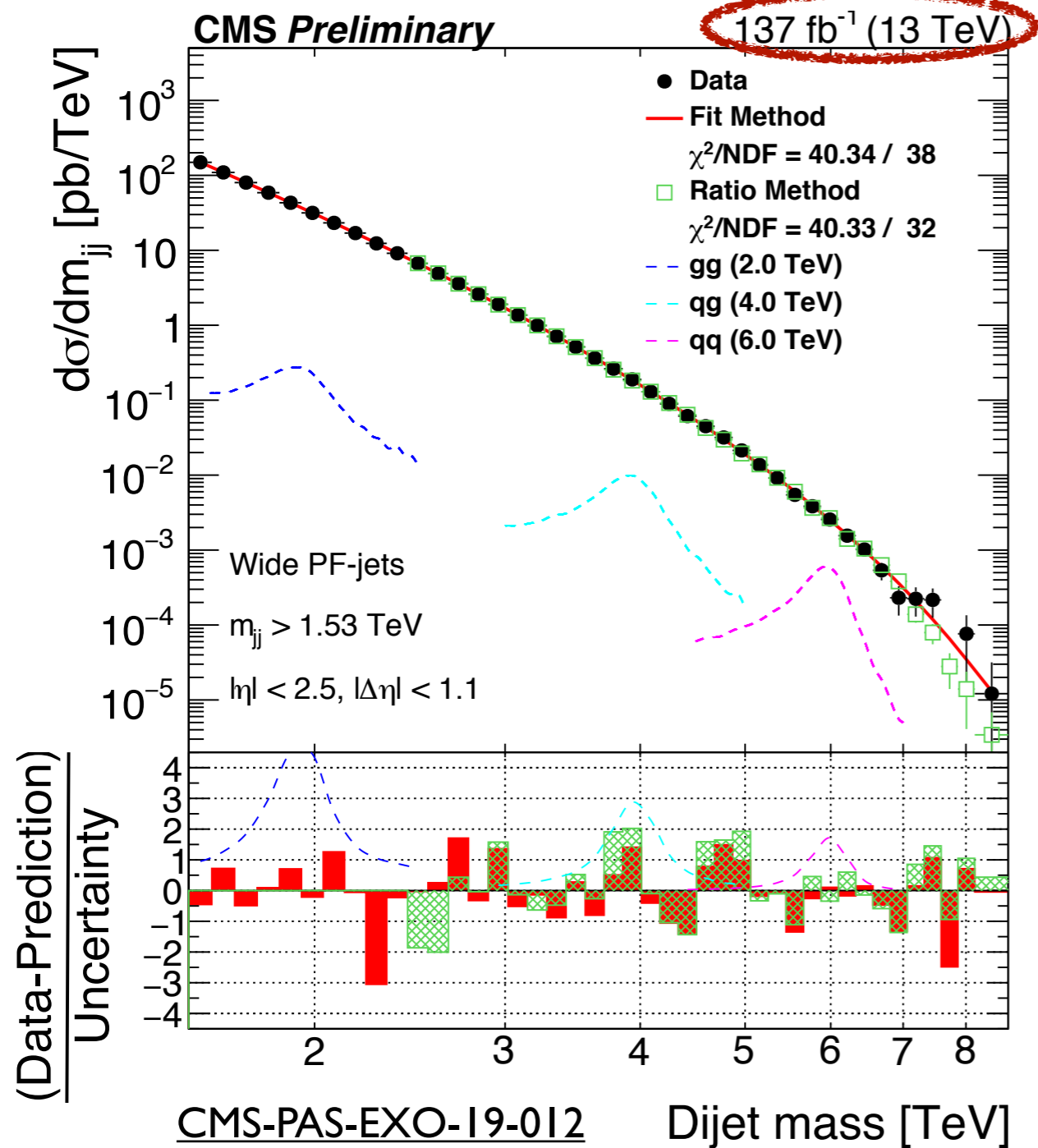
# Searching with Dijets



One of the best BSM signatures:  
pairs of jets



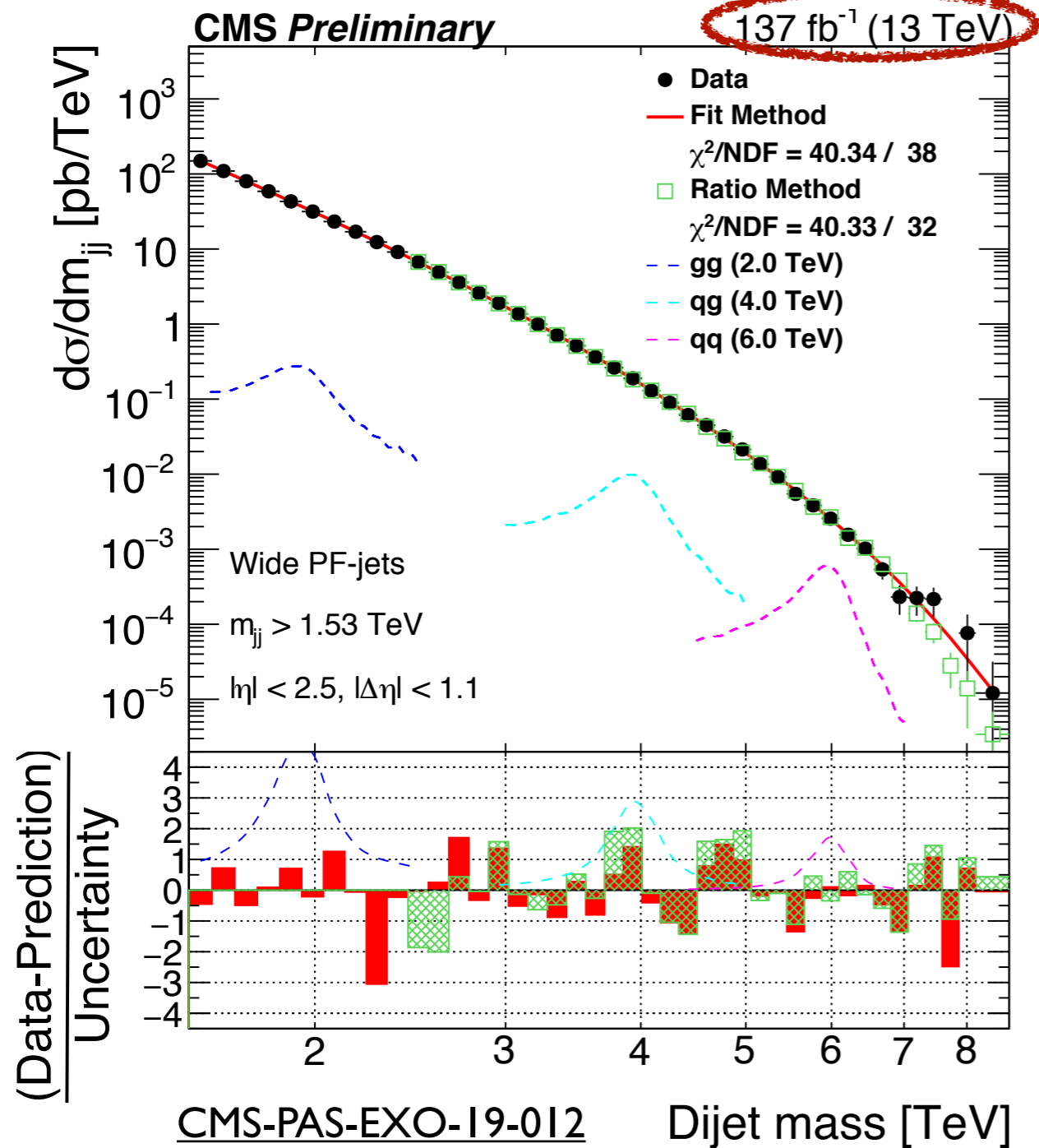
# Searching with Dijets



One of the best BSM signatures:  
pairs of jets

Huge dataset enables some of  
the best sensitivity yet!

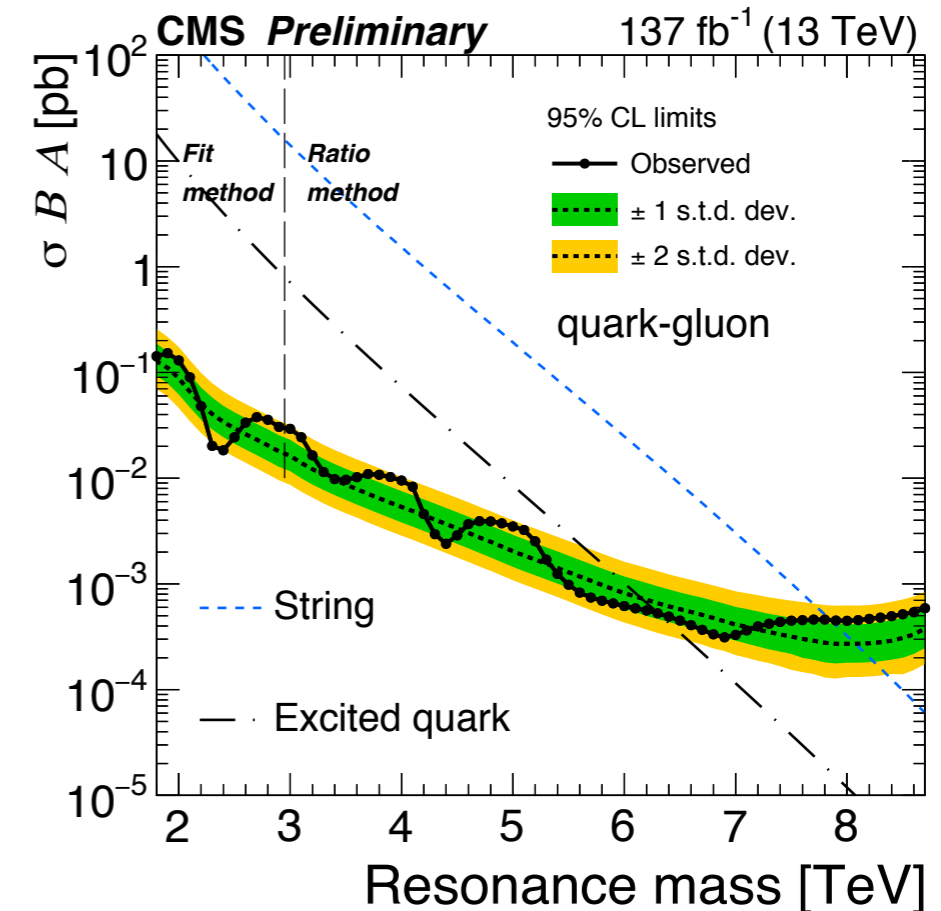
# Searching with Dijets



One of the best BSM signatures:  
 pairs of jets

Huge dataset enables some of  
 the best sensitivity yet!

But no hints of new physics...

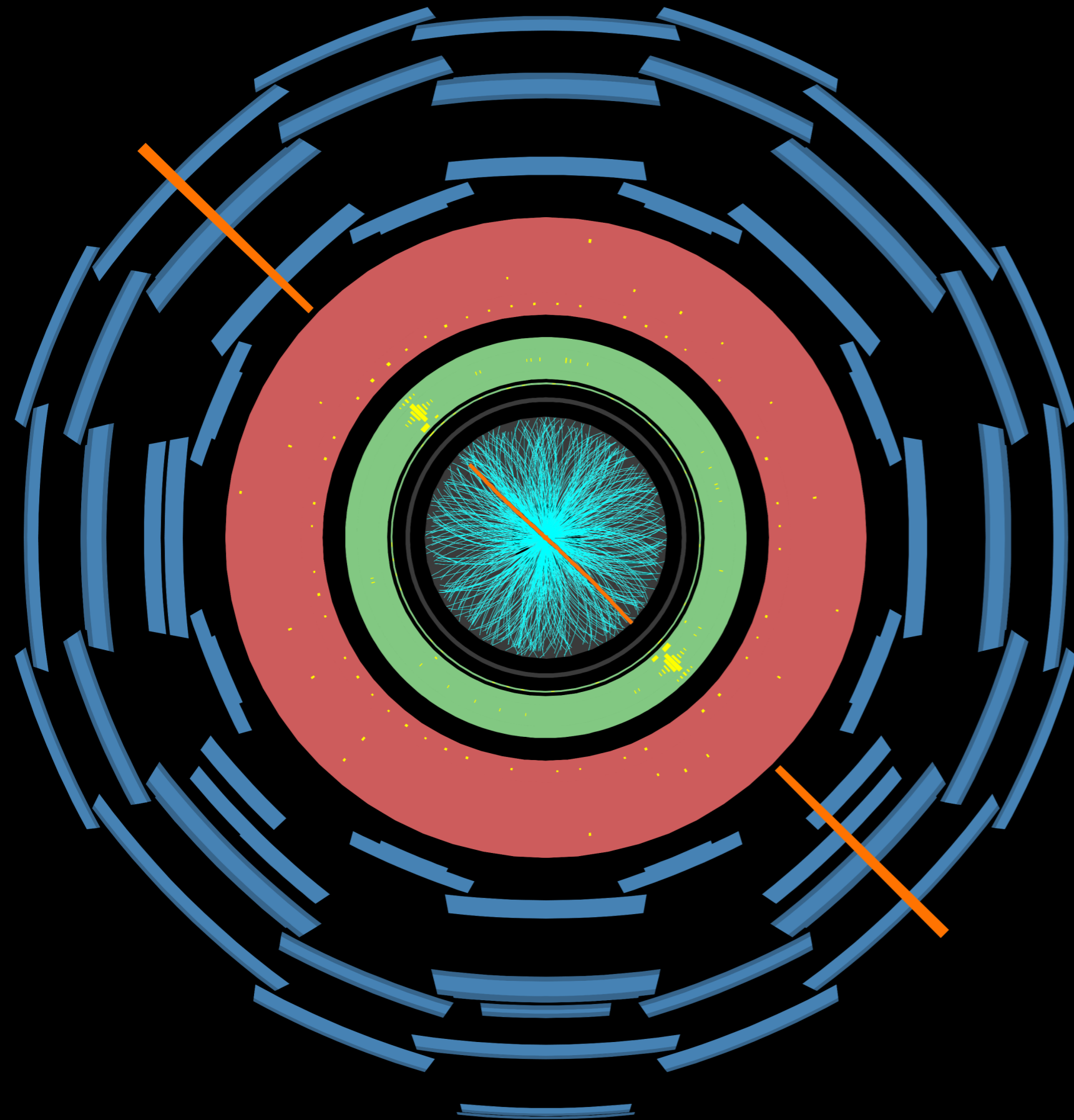






What about other particles?

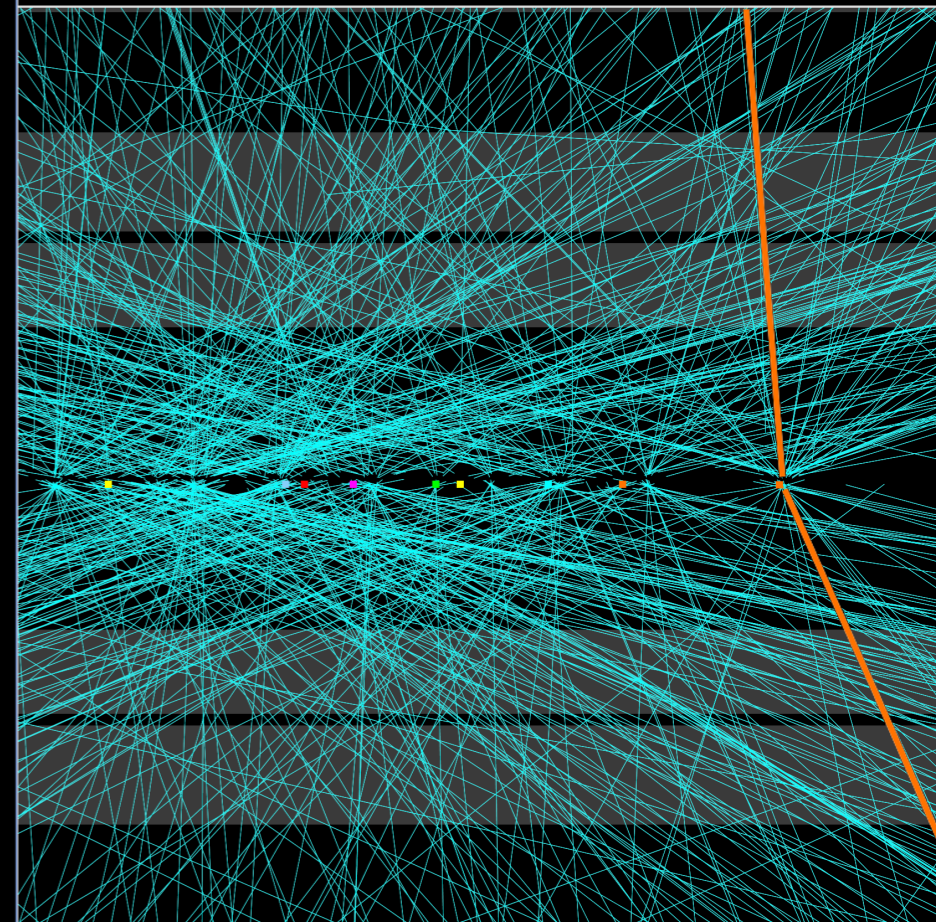
# What about other particles?



**ATLAS**  
EXPERIMENT

Run Number: 336852, Event Number: 1440436043

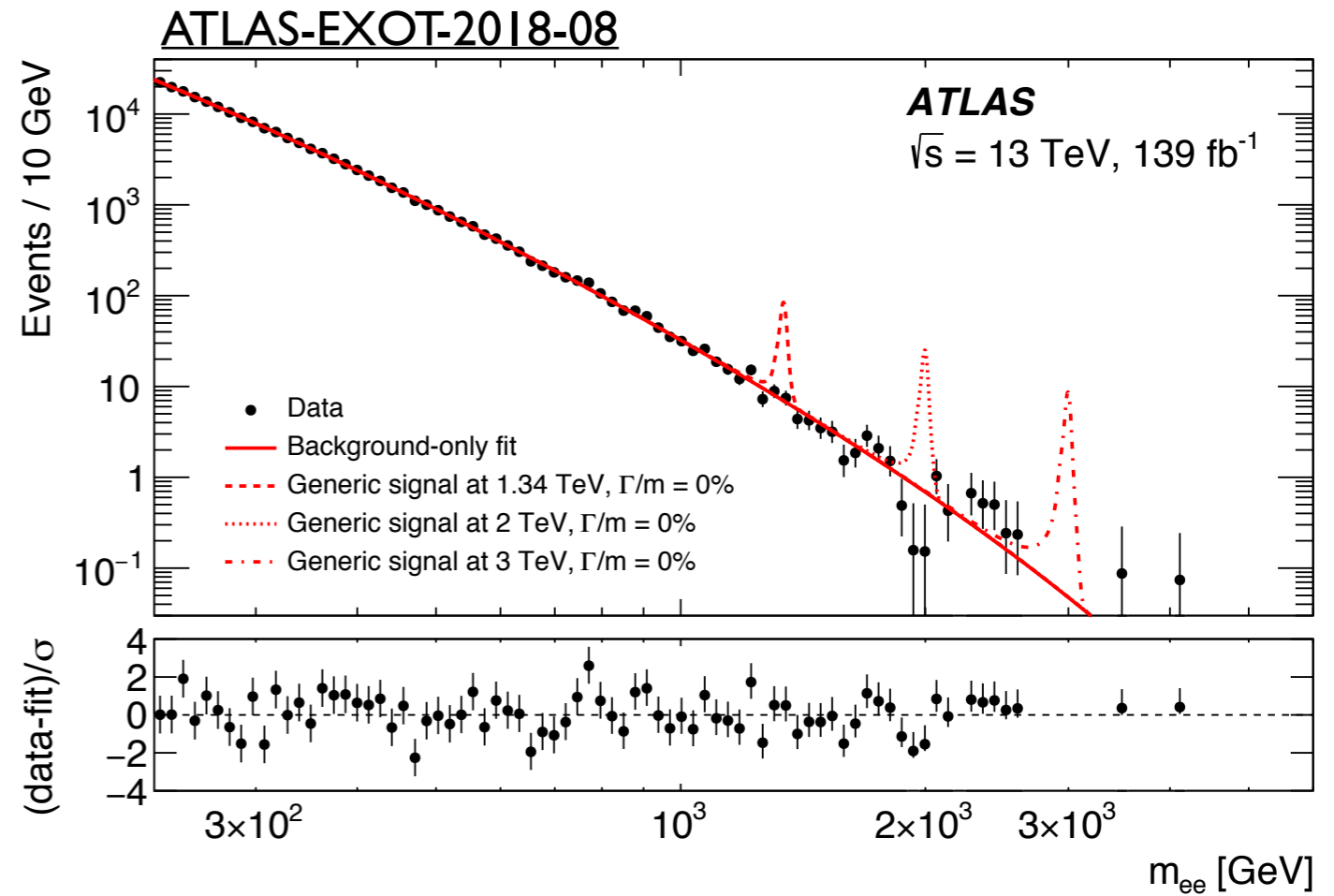
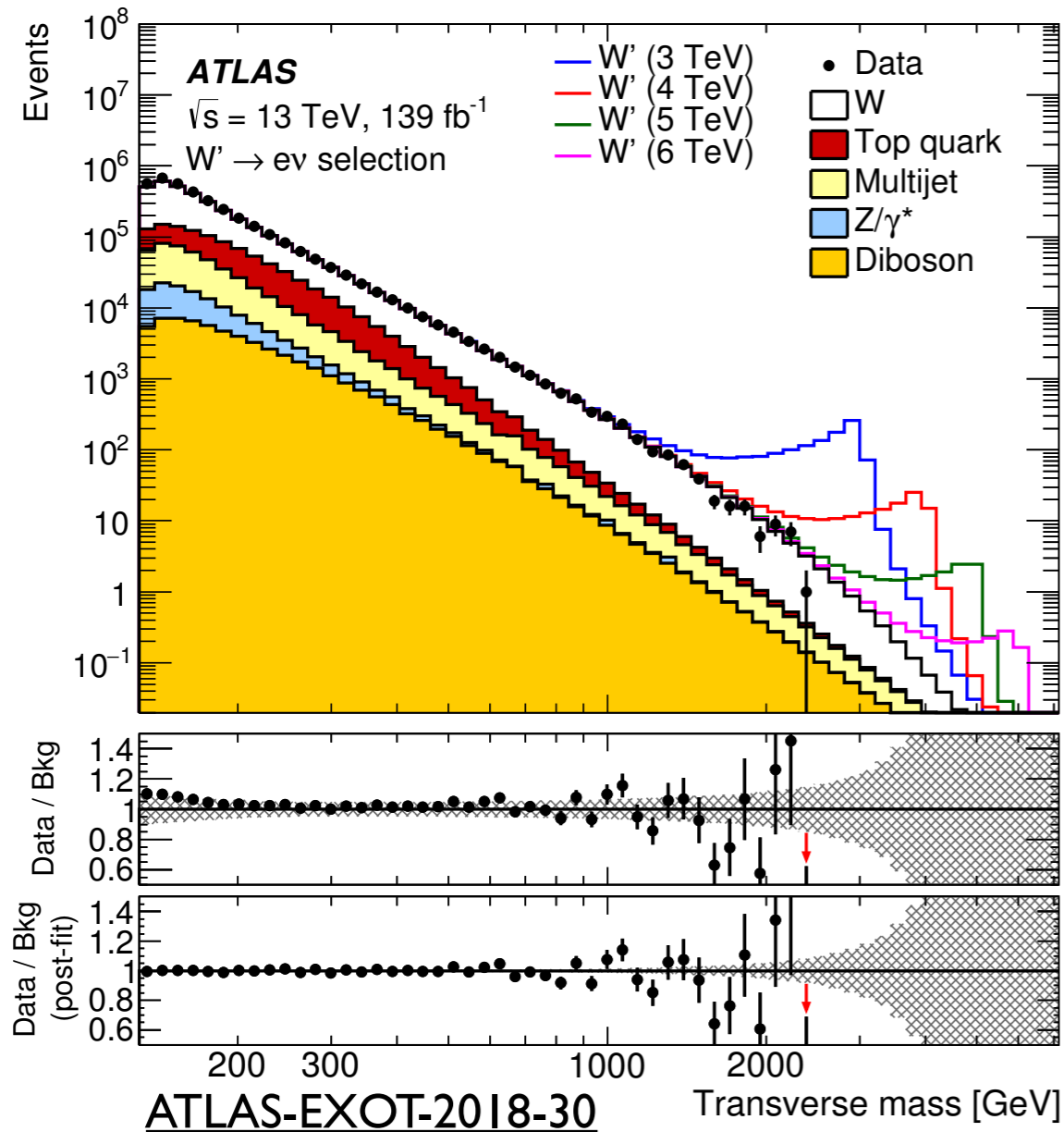
Date: 2017-09-29 11:44:35 CEST



# Searching with Leptons

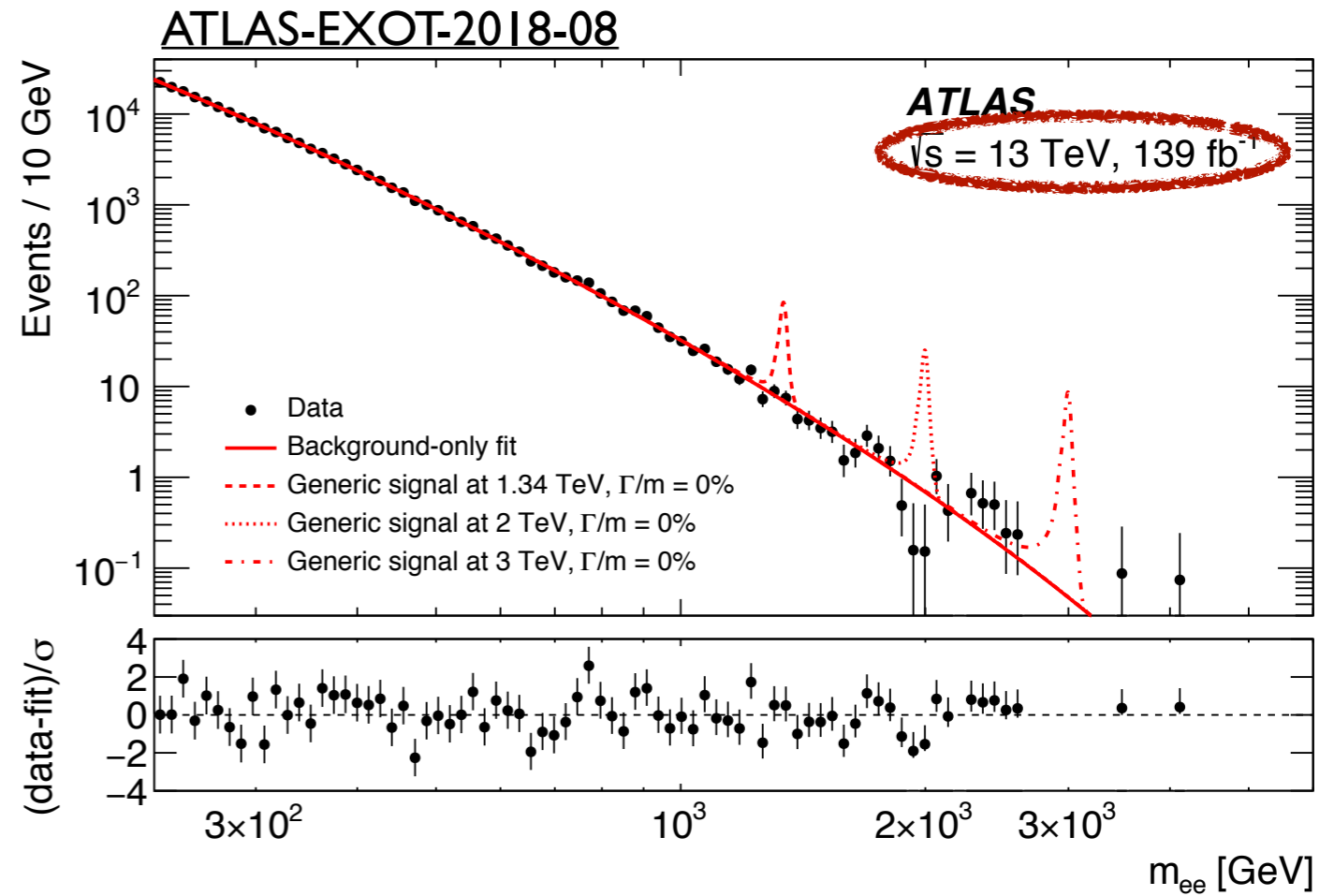
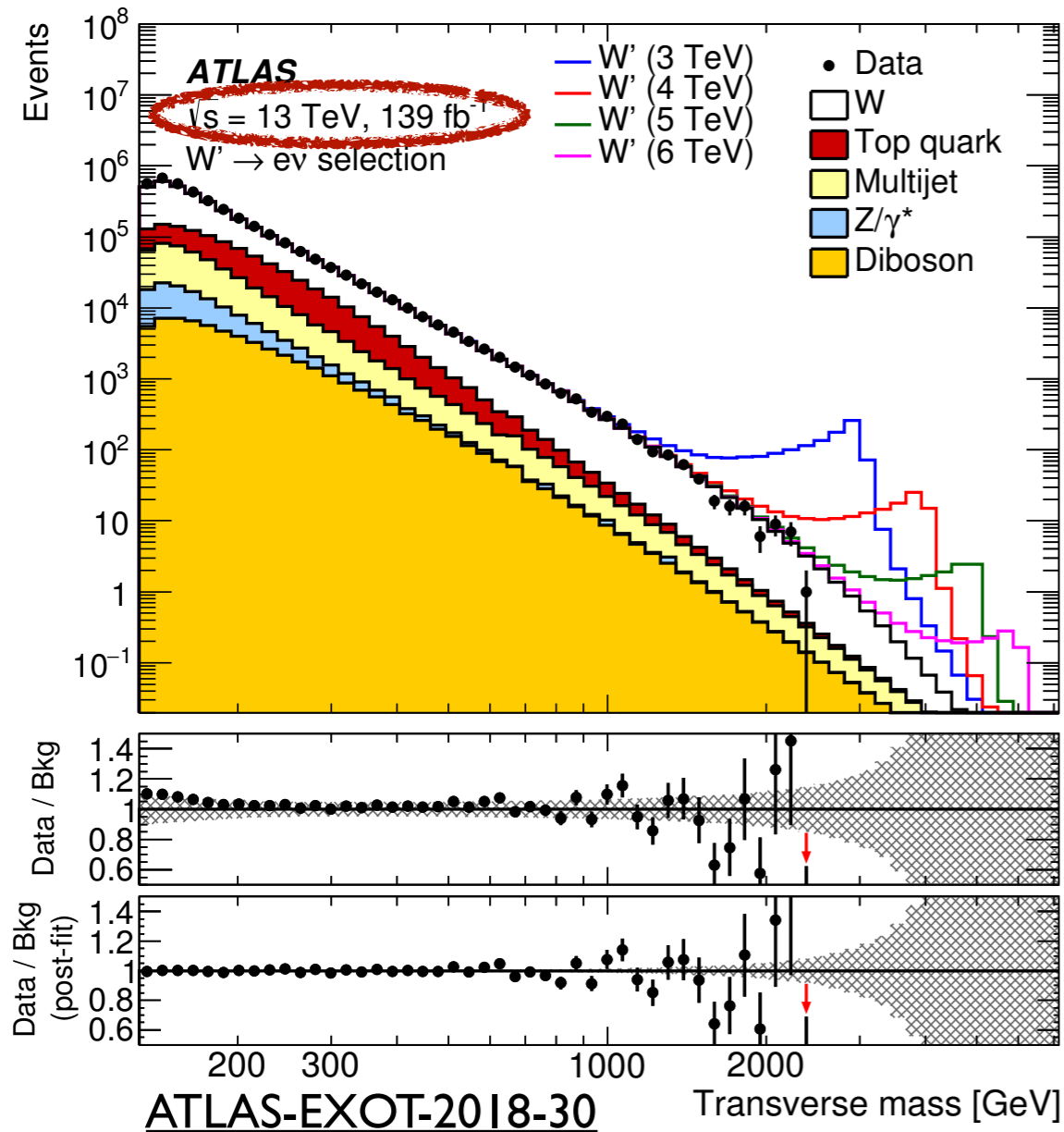


# Searching with Leptons



You can also search for BSM with lepton resonances!

# Searching with Leptons



You can also search for BSM with lepton resonances!

Not better luck here, even with the full datasets



What about  
more  
complicated  
signatures?



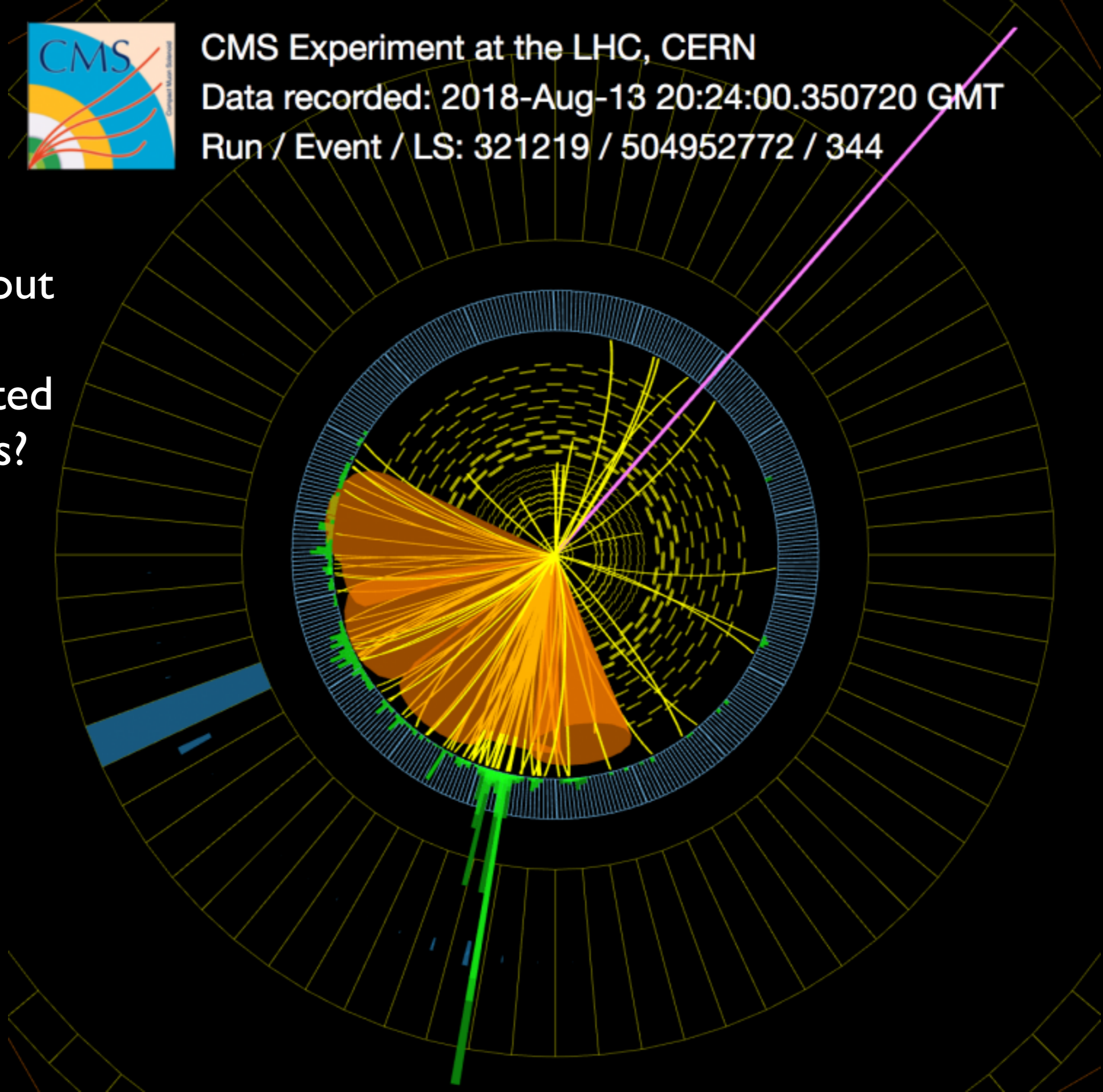


CMS Experiment at the LHC, CERN

Data recorded: 2018-Aug-13 20:24:00.350720 GMT

Run / Event / LS: 321219 / 504952772 / 344

What about  
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signatures?



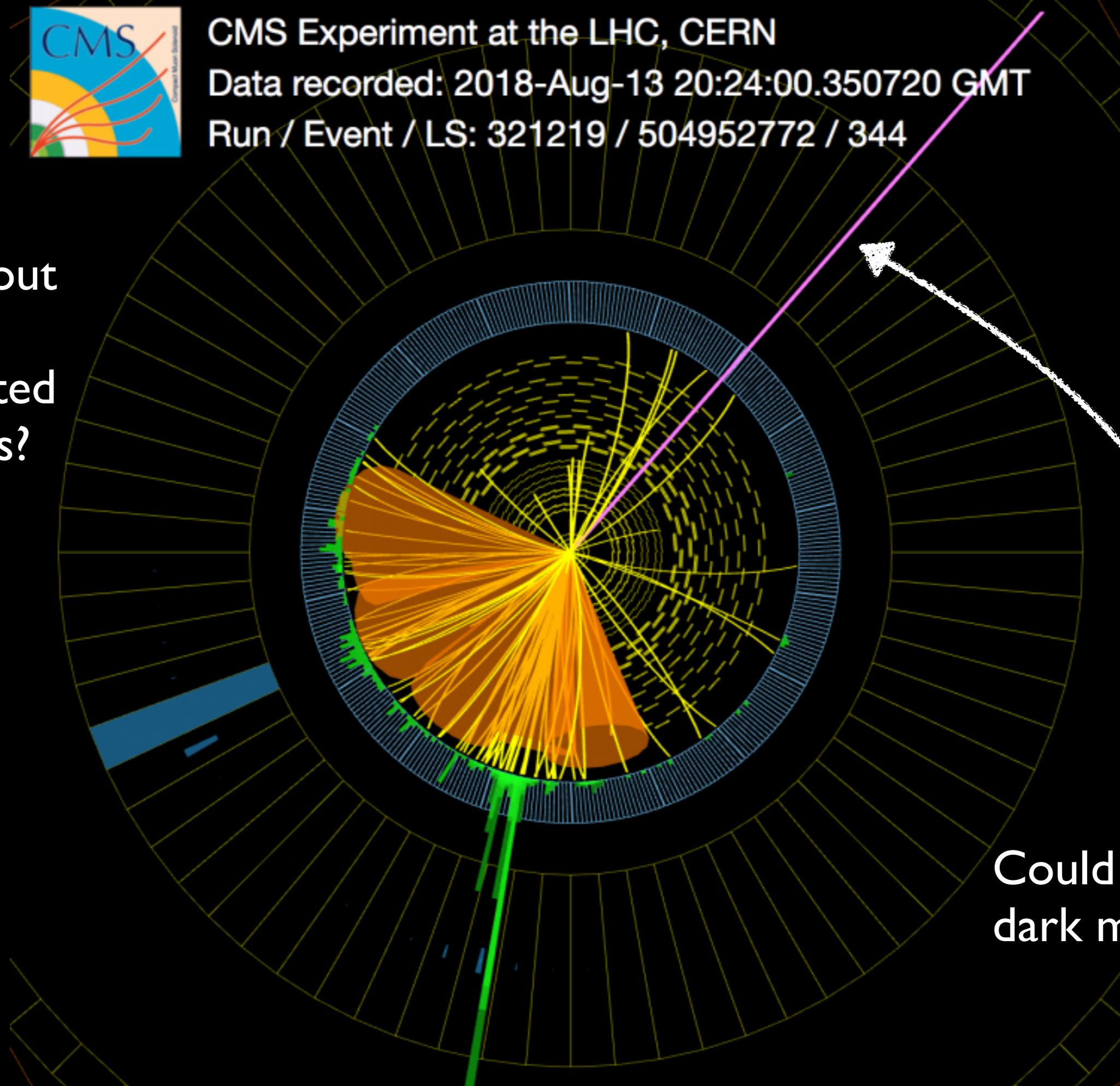


CMS Experiment at the LHC, CERN

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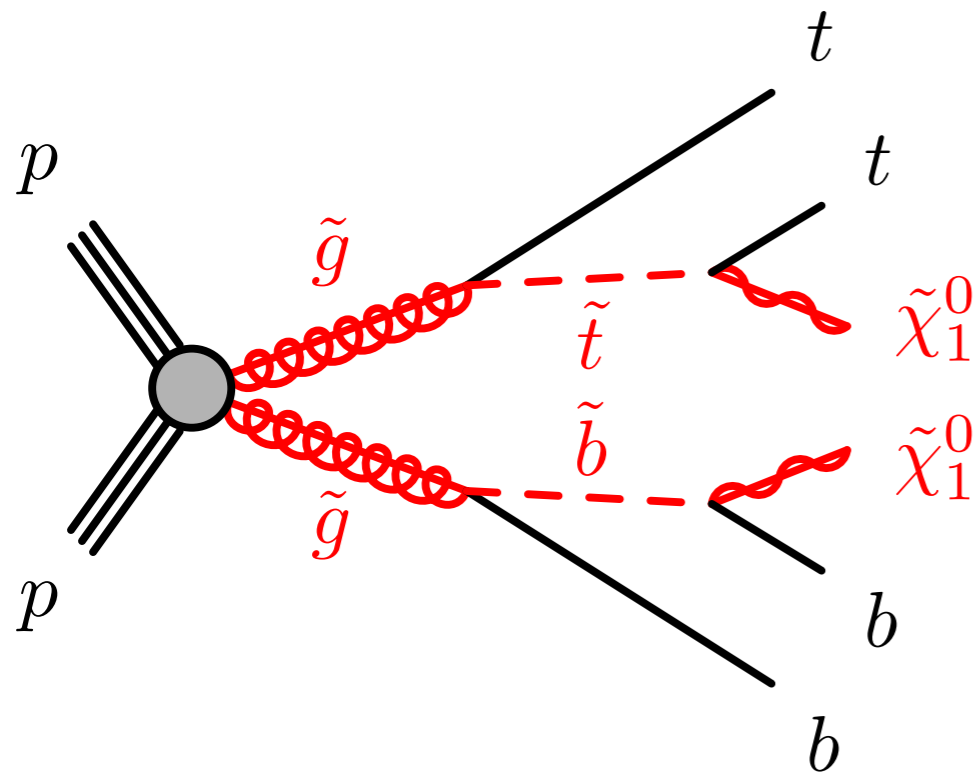


Could this be  
dark matter?

# SUSY Signatures

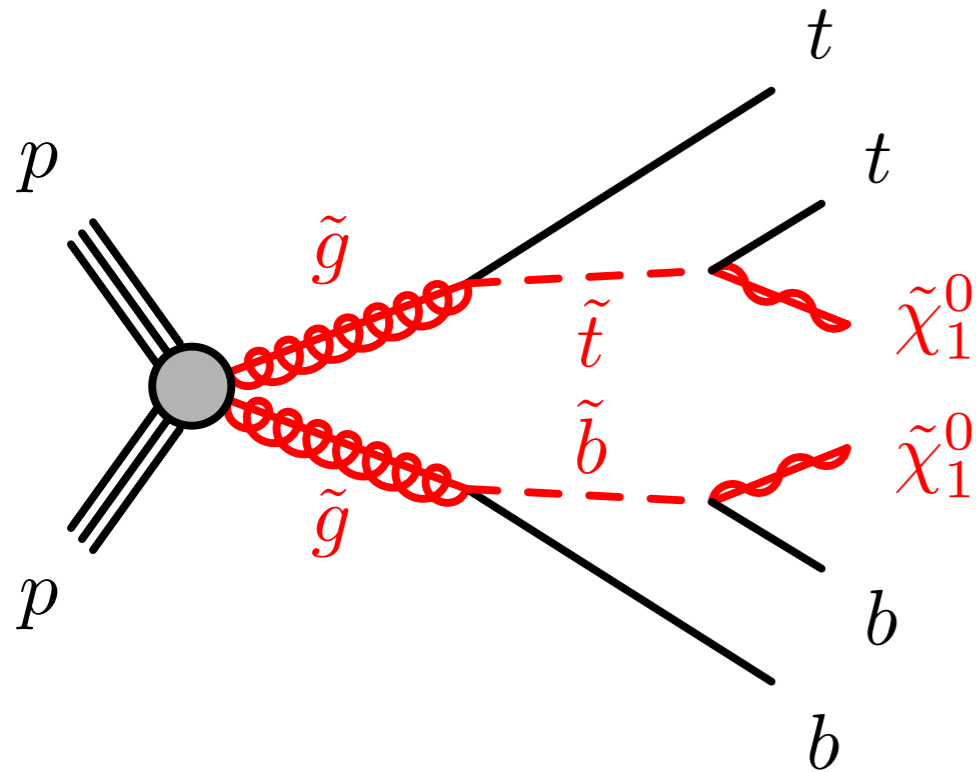


# SUSY Signatures

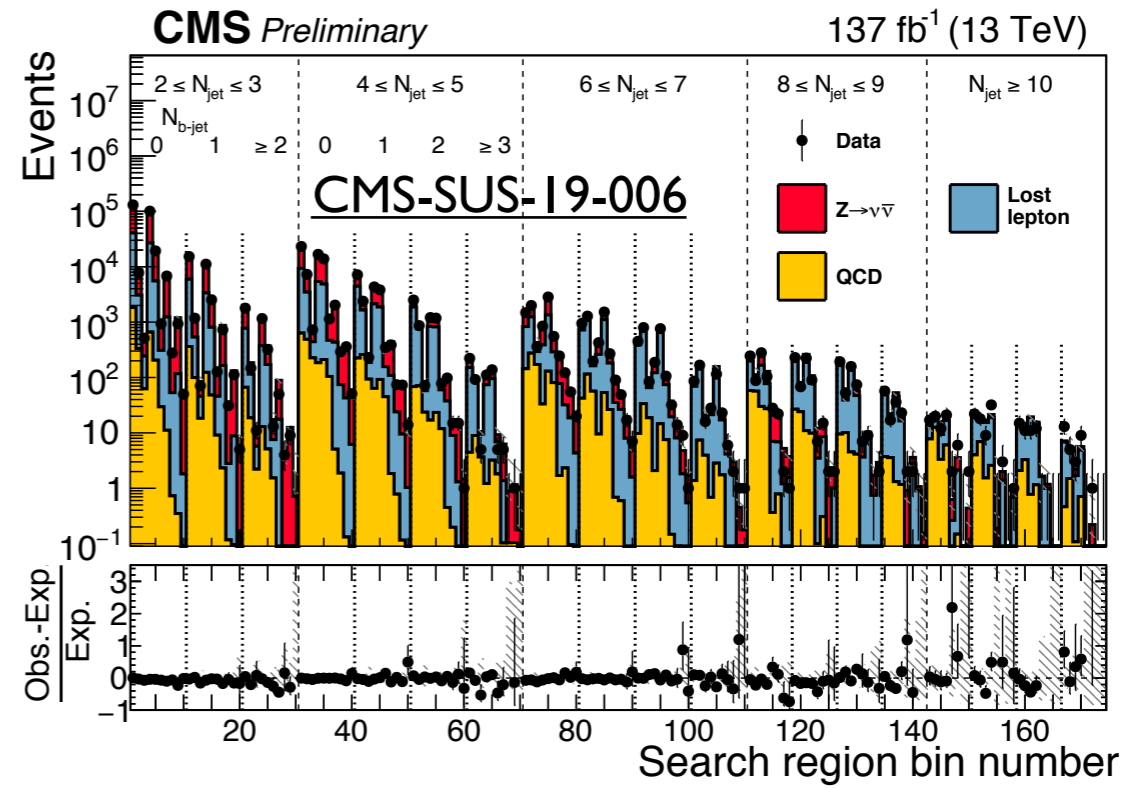


Supersymmetry predicts  
more complicated final states...

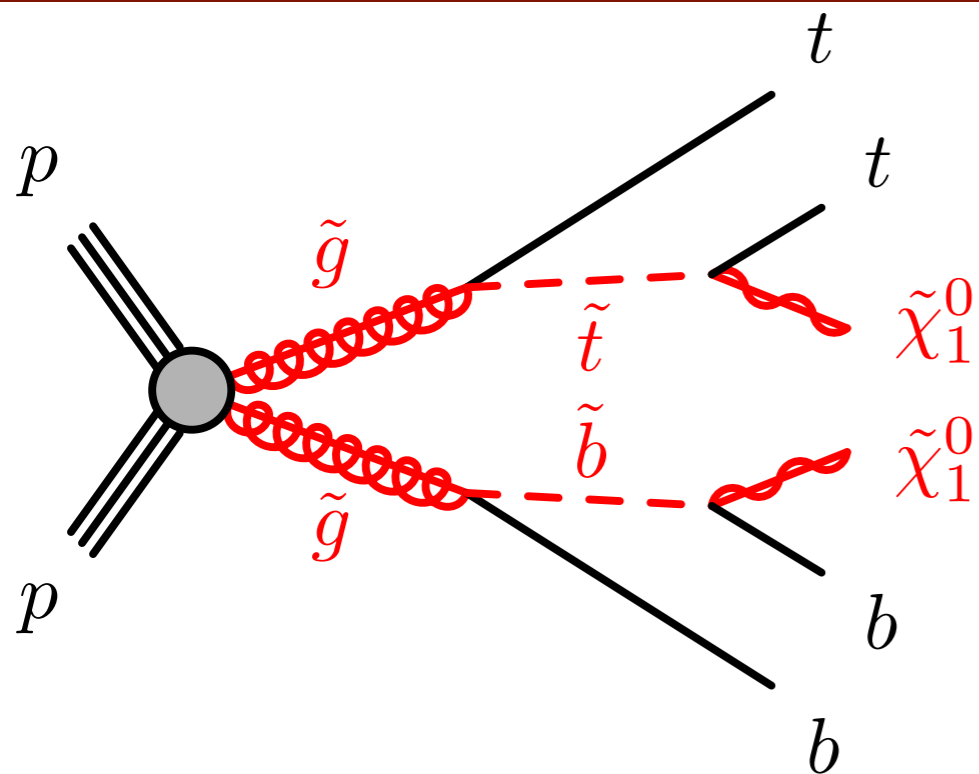
# SUSY Signatures



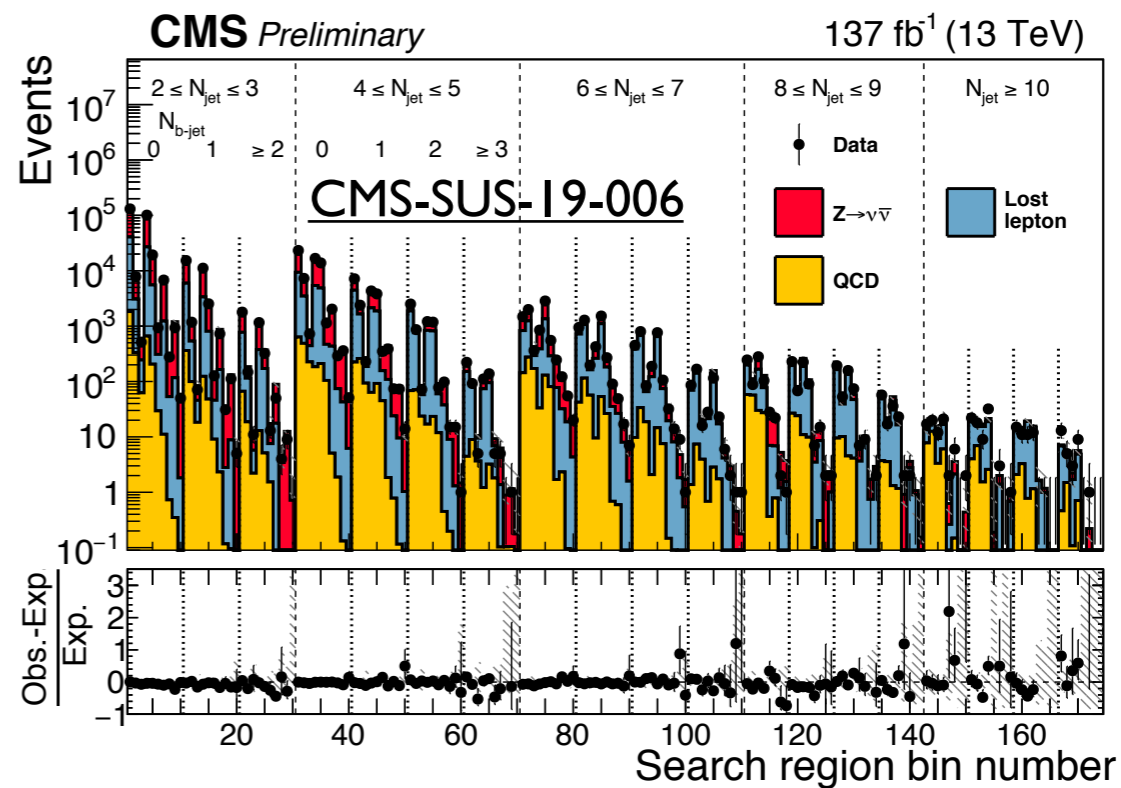
Supersymmetry predicts more complicated final states...



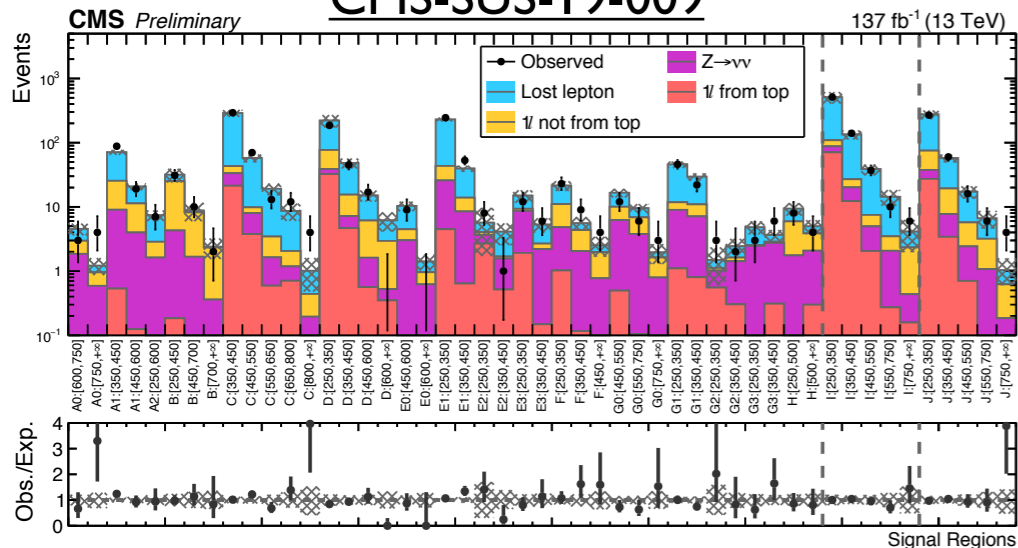
# SUSY Signatures



Supersymmetry predicts more complicated final states...



**CMS-SUS-19-009**

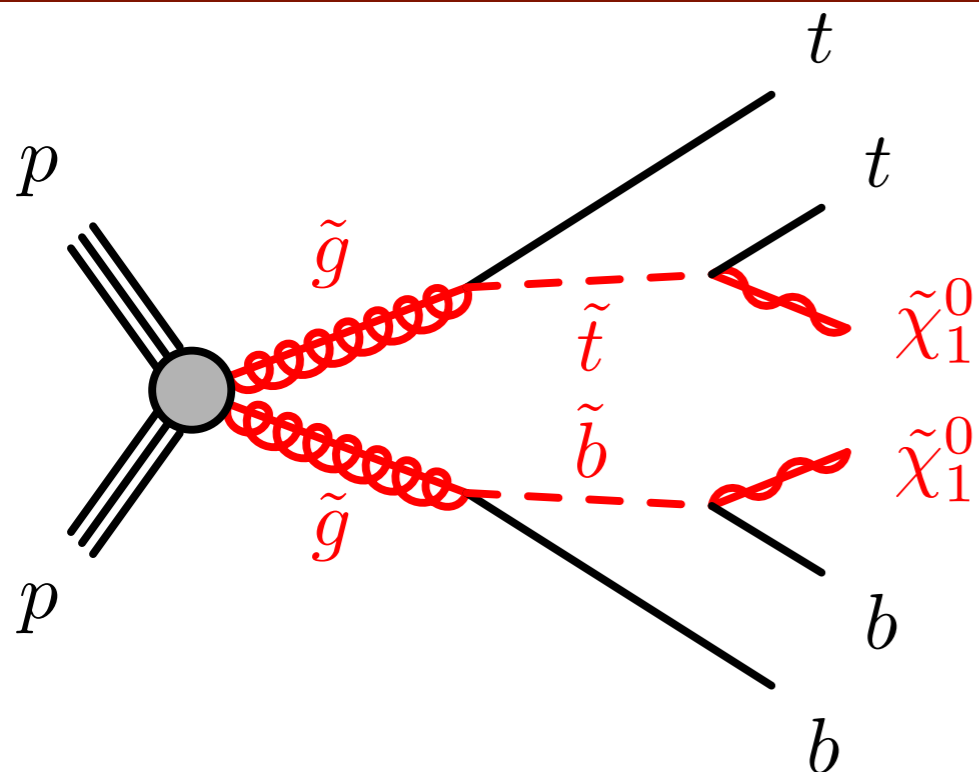


	$N_j$	$t_{\text{mod}}$	$M_{t\bar{t}}$ [GeV]
A	2-3	> 10	≤ 175
B	2-3	> 10	> 175
C	≥ 4	≤ 0	≤ 175
D	≥ 4	≤ 0	> 175
E	≥ 4	0-10	≤ 175
F	≥ 4	0-10	> 175
G	≥ 4	> 10	≤ 175
H	≥ 4	> 10	> 175

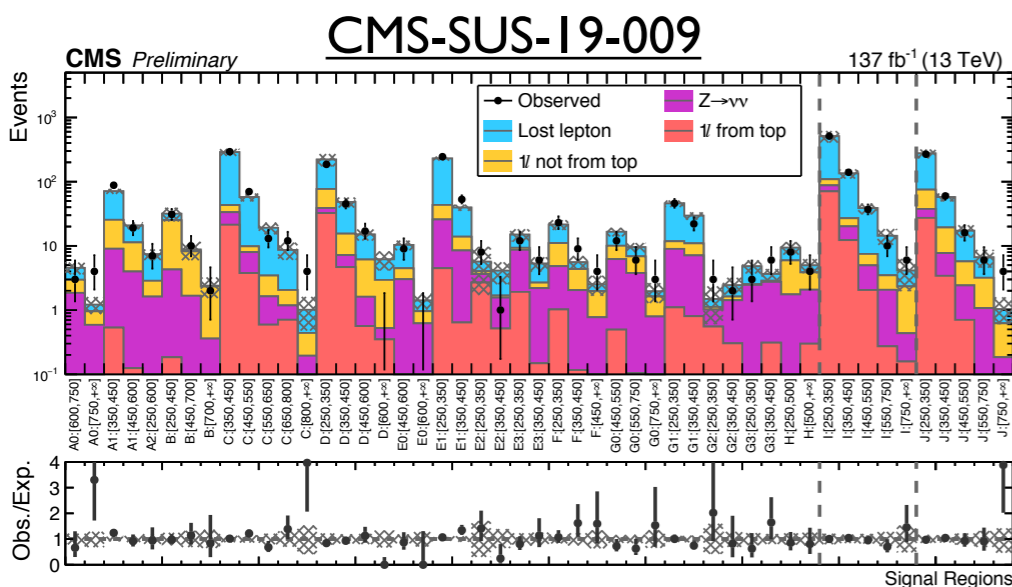
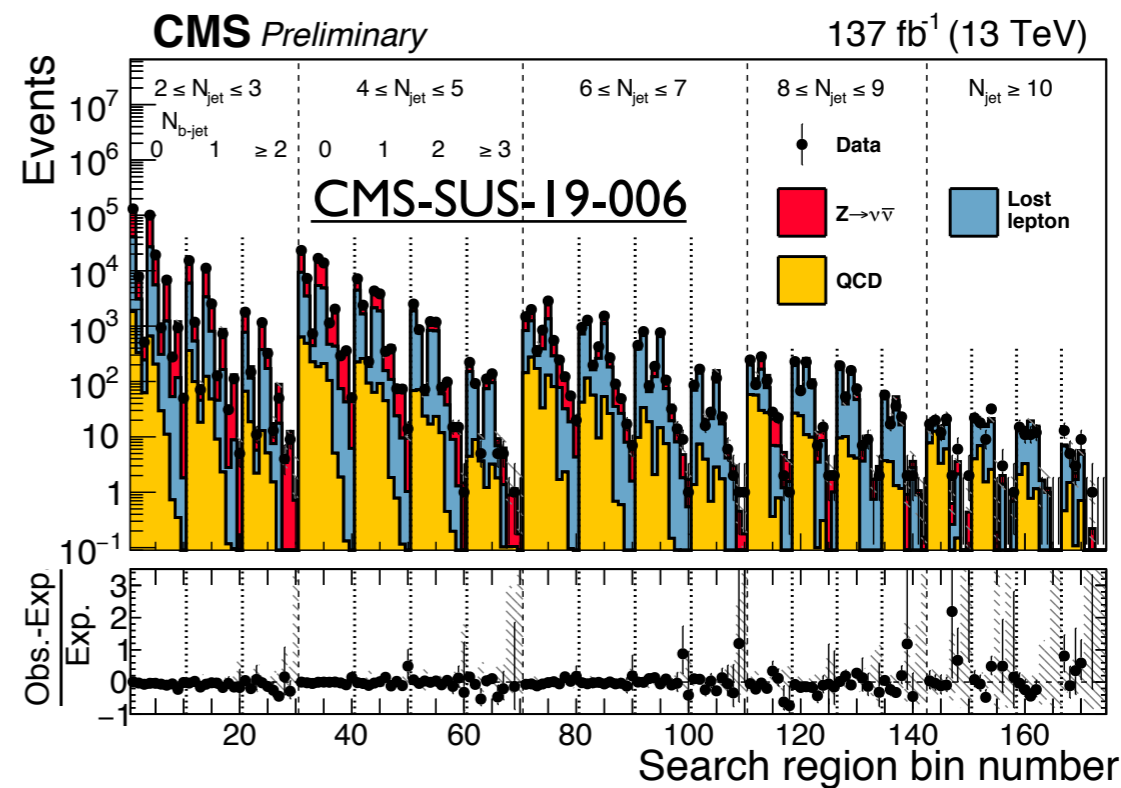
X0: Inclusive  
 X1: Untagged  
 X2: Boosted top  
 X3: Resolved top

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

# SUSY Signatures



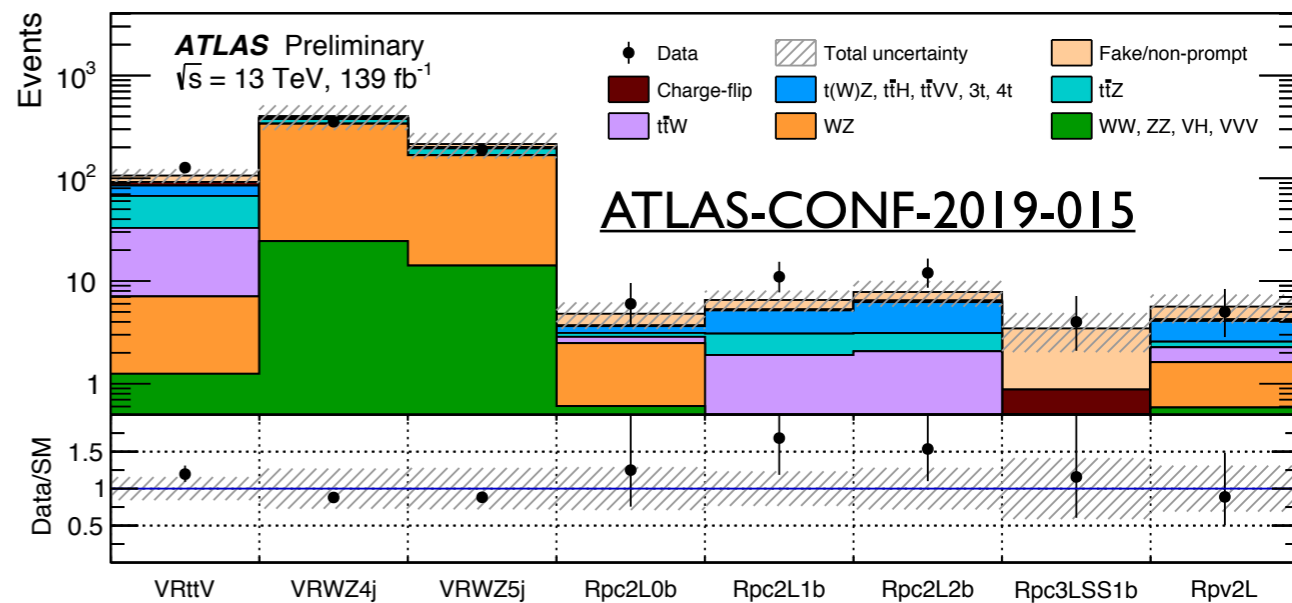
Supersymmetry predicts more complicated final states...



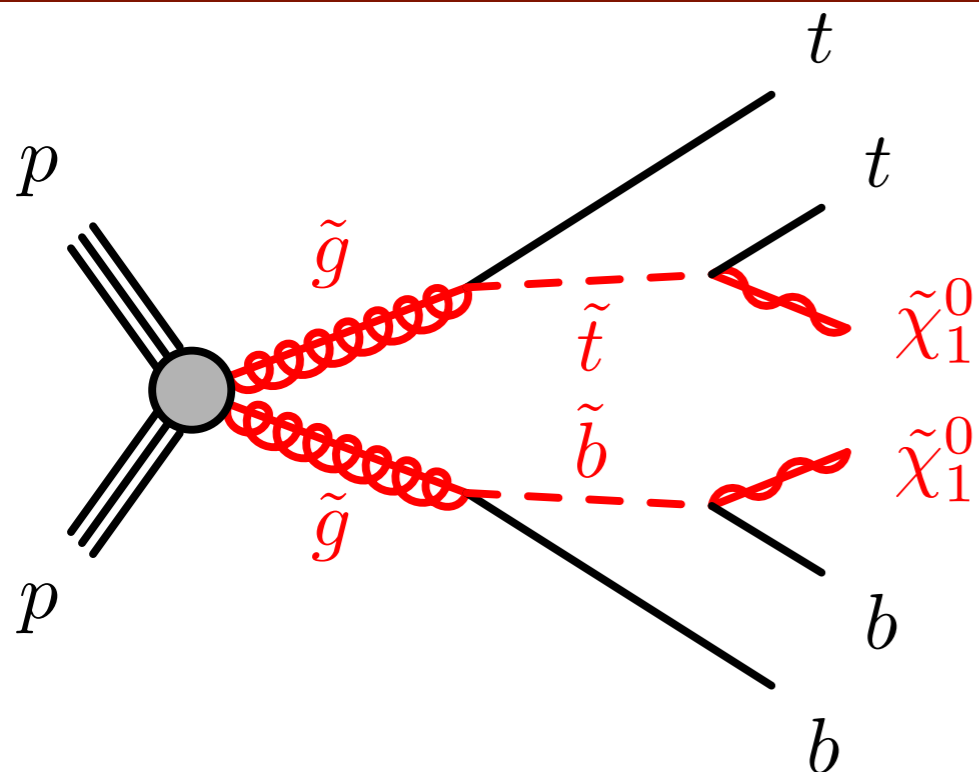
	$N_j$	$t_{\text{mod}}$	$M_{t\tilde{t}}$ [GeV]
A	2-3	> 10	≤ 175
B	2-3	> 10	> 175
C	4	≤ 0	≤ 175
D	4	≤ 0	> 175
E	4	0-10	≤ 175
F	4	0-10	> 175
G	4	> 10	≤ 175
H	4	> 10	> 175

X0: Inclusive  
X1: Untagged  
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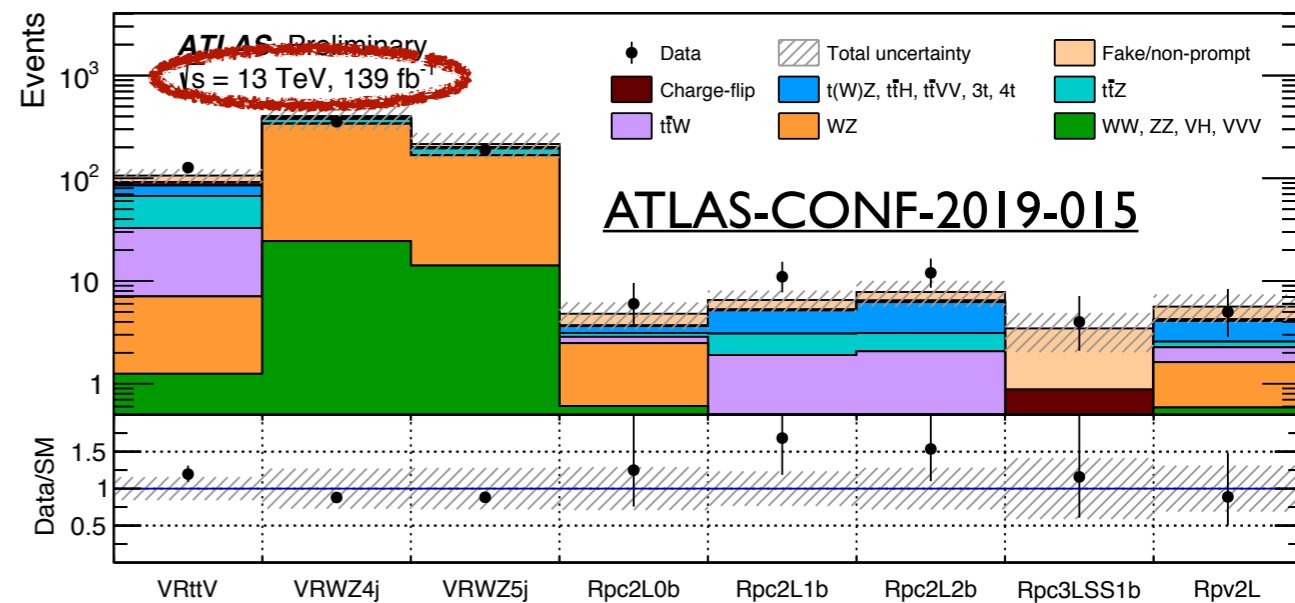
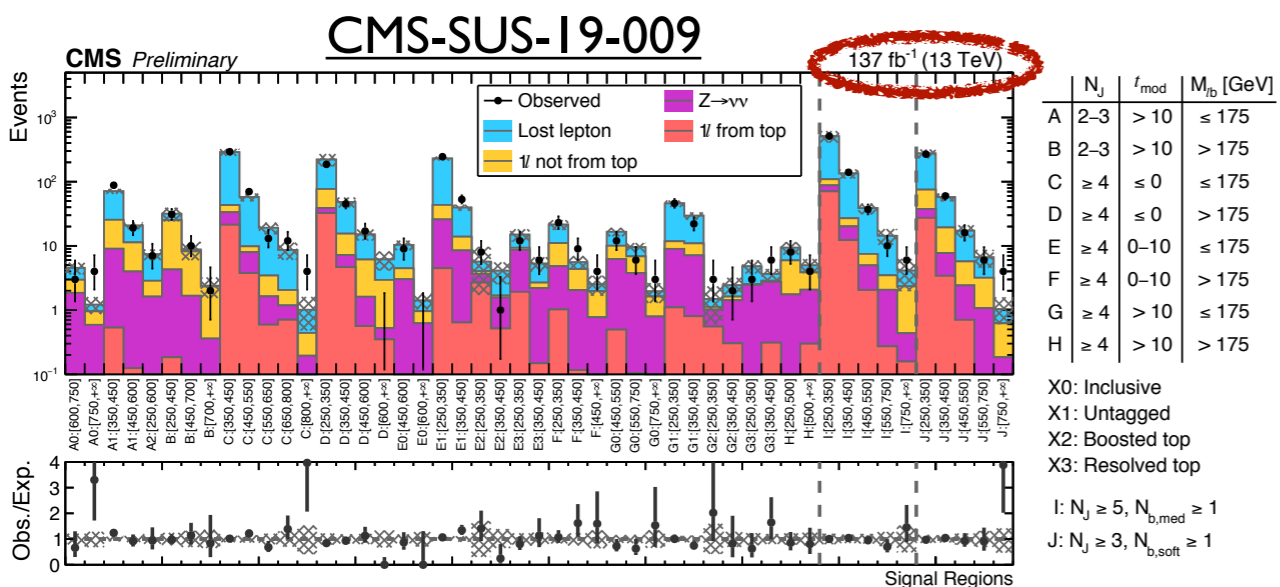
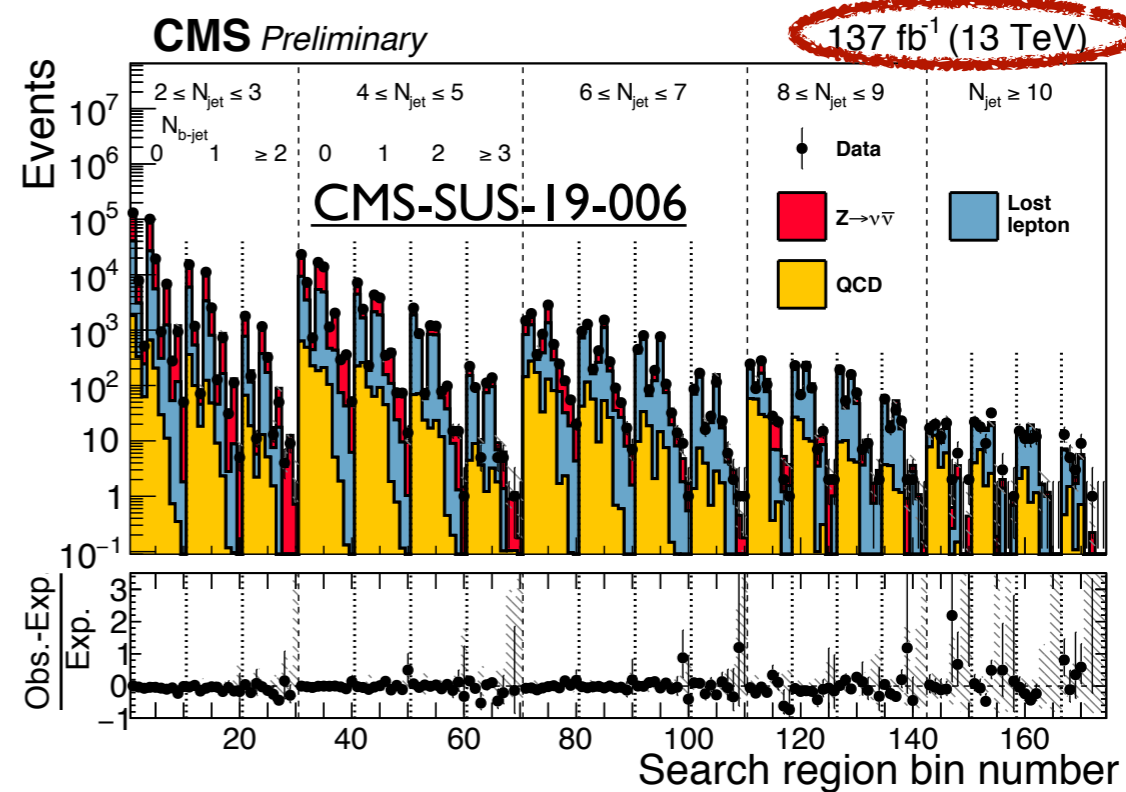
I:  $N_j \geq 5, N_{b,\text{med}} \geq 1$   
J:  $N_j \geq 3, N_{b,\text{soft}} \geq 1$



# SUSY Signatures



Supersymmetry predicts more complicated final states...



But still no hints, even with full data!



# Our Sensitivity is Better Than Ever



# Our Sensitivity is Better Than Ever



## ATLAS SUSY Searches\* - 95% CL Lower Limits

July 2019

ATLAS Preliminary

$\sqrt{s} = 13$  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 $e, \mu$ mono-jet	2-6 jets 1-3 jets $E_T^{\text{miss}}$	36.1 36.1	$\tilde{q}$ [2x, 8x Degen.] 0.9 $\tilde{q}$ [1x, 8x Degen.] 0.43, 0.71, 1.55 $m(\tilde{\chi}_1^0) < 100$ GeV $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5$ GeV	1712.02332 1711.03301
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 $e, \mu$	2-6 jets $E_T^{\text{miss}}$	36.1	$\tilde{g}$ 2.0 $\tilde{g}$ Forbidden, 0.95-1.6 $m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{\chi}_1^0) = 900$ GeV	1712.02332 1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	3 $e, \mu$ $ee, \mu\mu$	4 jets 2 jets $E_T^{\text{miss}}$	36.1 36.1	$\tilde{g}$ 1.85 $\tilde{g}$ 1.2 $m(\tilde{\chi}_1^0) < 800$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 50$ GeV	1706.03731 1805.11381
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 $e, \mu$ SS $e, \mu$	7-11 jets 6 jets $E_T^{\text{miss}}$	36.1 139	$\tilde{g}$ 1.8 $\tilde{g}$ 1.15 $m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV	1708.02794 ATLAS-CONF-2019-015
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{\chi}_1^0$	0-1 $e, \mu$ SS $e, \mu$	3 $b$ 6 jets $E_T^{\text{miss}}$	79.8 139	$\tilde{g}$ 2.25 $\tilde{g}$ 1.25 $m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV	ATLAS-CONF-2018-041 ATLAS-CONF-2019-015
	3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 / t\tilde{\chi}_1^\pm$	Multiple Multiple Multiple	Multiple Multiple Multiple $E_T^{\text{miss}}$	36.1 36.1 139	$\tilde{b}_1$ Forbidden, 0.9 $\tilde{b}_1$ Forbidden, 0.58-0.82 $\tilde{b}_1$ Forbidden, 0.74 $m(\tilde{\chi}_1^0) = 300$ GeV, $\text{BR}(b\tilde{\chi}_1^0) = 1$ $m(\tilde{\chi}_1^0) = 300$ GeV, $\text{BR}(b\tilde{\chi}_1^0) = \text{BR}(t\tilde{\chi}_1^\pm) = 0.5$ $m(\tilde{\chi}_1^0) = 200$ GeV, $m(\tilde{\chi}_1^\pm) = 300$ GeV, $\text{BR}(t\tilde{\chi}_1^\pm) = 1$
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0$		0 $e, \mu$	6 $b$ $E_T^{\text{miss}}$	139	$\tilde{b}_1$ Forbidden, 0.23-1.35 $\tilde{b}_1$ 0.23-0.48 $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	SUSY-2018-31 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 $b$ $E_T^{\text{miss}}$	36.1	$\tilde{t}_1$ 1.0 $m(\tilde{\chi}_1^0) = 1$ GeV	1506.08616, 1709.04183, 1711.11520
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$		1 $e, \mu$	3 jets/1 $b$ $E_T^{\text{miss}}$	139	$\tilde{t}_1$ 0.44-0.59 $m(\tilde{\chi}_1^0) = 400$ GeV	ATLAS-CONF-2019-017
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tau b\nu, \tilde{t}_1 \rightarrow \tau\tilde{G}$		1 $\tau + 1 e, \mu, \tau$	2 jets/1 $b$ $E_T^{\text{miss}}$	36.1	$\tilde{t}_1$ 1.16 $m(\tilde{\tau}_1) = 800$ 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 $c$ $E_T^{\text{miss}}$	36.1	$\tilde{t}_1$ 0.85 $\tilde{t}_1$ 0.46 $\tilde{t}_1$ 0.43 $m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 50$ GeV $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5$ GeV	1805.01649 1805.01649 1711.03301
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$		0 $e, \mu$	mono-jet $E_T^{\text{miss}}$	36.1	$\tilde{t}_2$ 0.32-0.88 $m(\tilde{\chi}_1^0) = 0$ GeV, $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 180$ GeV	1706.03986
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$		3 $e, \mu$	1 $b$ $E_T^{\text{miss}}$	139	$\tilde{t}_2$ 0.86 $m(\tilde{\chi}_1^0) = 360$ GeV, $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40$ GeV	ATLAS-CONF-2019-016
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 $e, \mu$ $ee, \mu\mu$	$\geq 1$ $E_T^{\text{miss}}$	36.1 139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.6 $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.205 $m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 5$ GeV	1403.5294, 1806.02293 ATLAS-CONF-2019-014
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 $e, \mu$	$E_T^{\text{miss}}$	139	$\tilde{\chi}_1^\pm$ 0.42 $m(\tilde{\chi}_1^0) = 0$	ATLAS-CONF-2019-008
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	0-1 $e, \mu$	2 $b/2 \gamma$ $E_T^{\text{miss}}$	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ Forbidden, 0.74 $m(\tilde{\chi}_1^0) = 70$ GeV	ATLAS-CONF-2019-019, ATLAS-CONF-2019-XYZ
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 $e, \mu$	$E_T^{\text{miss}}$	139	$\tilde{\chi}_1^\pm$ 1.0 $m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2019-008
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 $\tau$	$E_T^{\text{miss}}$	139	$\tilde{\tau}$ [L, R, L] 0.16-0.3, 0.12-0.39 $m(\tilde{\chi}_1^0) = 0$	ATLAS-CONF-2019-018
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 $e, \mu$ 2 $e, \mu$	0 jets $\geq 1$ $E_T^{\text{miss}}$	139 139	$\tilde{\ell}$ 0.7 $\tilde{\ell}$ 0.256 $m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 10$ GeV	ATLAS-CONF-2019-008 ATLAS-CONF-2019-014
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 $e, \mu$ 4 $e, \mu$	$\geq 3 b$ 0 jets $E_T^{\text{miss}}$	36.1 36.1	$\tilde{H}$ 0.13-0.23, 0.29-0.88 $\tilde{H}$ 0.3 $\text{BR}(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$ $\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$	1806.04030 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 $E_T^{\text{miss}}$	36.1	$\tilde{\chi}_1^\pm$ 0.46 $\tilde{\chi}_1^\pm$ 0.15 Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	Multiple	Multiple $E_T^{\text{miss}}$	36.1	$\tilde{g}$ 2.0	1902.01636, 1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq\tilde{\chi}_1^0$	Multiple	Multiple $E_T^{\text{miss}}$	36.1	$\tilde{g}$ [ $\tau(\tilde{g}) = 10$ ns, 0.2 ns ] 2.05, 2.4 $m(\tilde{\chi}_1^0) = 100$ GeV	1710.04901, 1808.04095
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	$e\mu, e\tau, \mu\tau$	$E_T^{\text{miss}}$	3.2	$\tilde{\nu}_\tau$ 1.9 $\mathcal{L}'_{311} = 0.11, \mathcal{L}'_{132/133/233} = 0.07$	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 $E_T^{\text{miss}}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [ $\lambda_{333} \neq 0, \lambda_{12k} \neq 0$ ] 0.82, 1.33 $m(\tilde{\chi}_1^0) = 100$ GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$	4-5 large-R jets	Multiple $E_T^{\text{miss}}$	36.1 36.1	$\tilde{g}$ [ $m(\tilde{\chi}_1^0) = 200$ GeV, 1100 GeV ] 1.3, 1.9 $\tilde{g}$ [ $\mathcal{L}'_{112} = 2e-4, 2e-5$ ] 1.05, 2.0 Large $\mathcal{L}'_{112}$	1804.03568 ATLAS-CONF-2018-003
	$\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple	Multiple $E_T^{\text{miss}}$	36.1	$\tilde{t}_1$ [ $\mathcal{L}'_{323} = 2e-4, 1e-2$ ] 0.55, 1.05 $m(\tilde{\chi}_1^0) = 200$ GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 $b$	Multiple $E_T^{\text{miss}}$	36.7	$\tilde{t}_1$ [ $qq, bs$ ] 0.42, 0.61 $m(\tilde{\chi}_1^0) = 200$ GeV, bino-like	1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 $e, \mu$ 1 $\mu$	2 $b$ DV $E_T^{\text{miss}}$	36.1 136	$\tilde{t}_1$ 0.4-1.45 $\tilde{t}_1$ [ $1e-10 < \mathcal{L}'_{23k} < 1e-8, 3e-10 < \mathcal{L}'_{23k} < 3e-9$ ] 1.0, 1.6 $\text{BR}(\tilde{t}_1 \rightarrow b\ell/b\mu) > 20\%$ $\text{BR}(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta_{\tilde{t}_1} = 1$	1710.05544 ATLAS-CONF-2019-006	

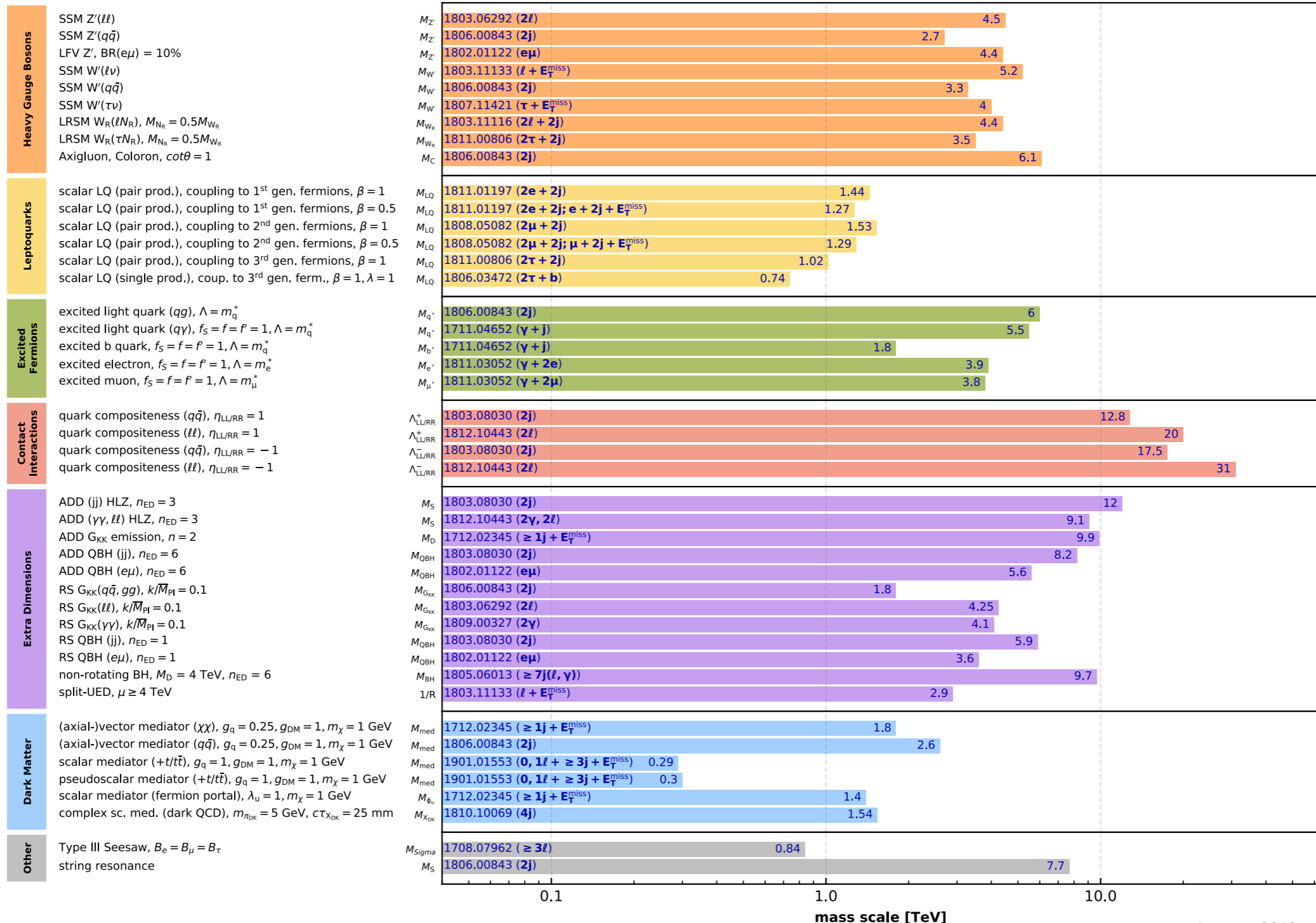
\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

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

# Our Sensitivity is Better Than Ever



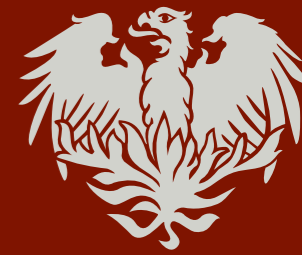
## Overview of CMS EXO results



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

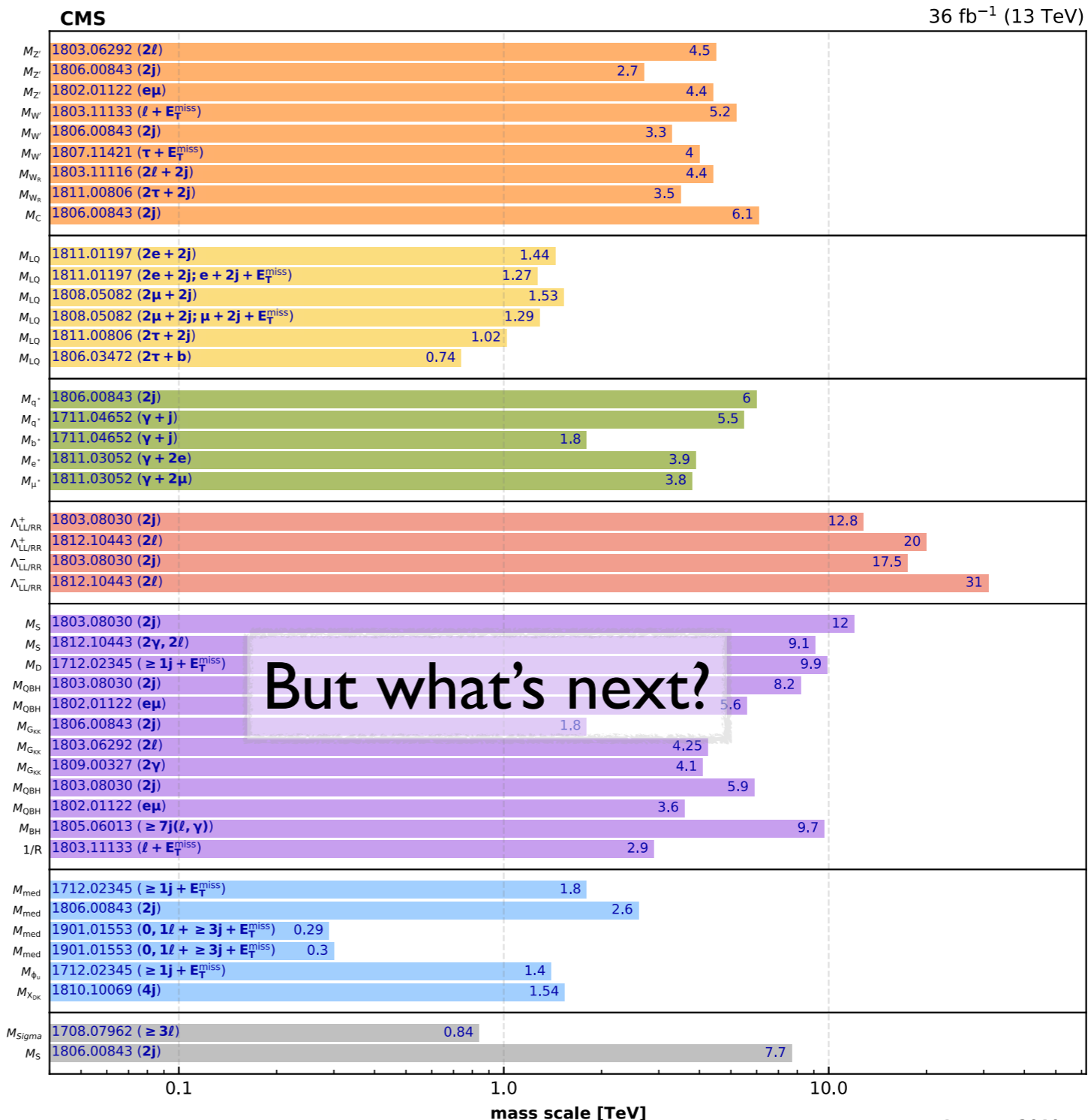
January 2019

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- Heavy Gauge Bosons**
  - SSM  $Z'(\ell\ell)$
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  - SSM  $W'(\ell\nu)$
  - SSM  $W'(q\bar{q})$
  - SSM  $W'(\tau\nu)$
  - LRSB  $W_R(\ell N_R)$ ,  $M_{N_R} = 0.5M_{W_R}$
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  - Axigluon, Coloron,  $\cot\theta = 1$
- Leptoquarks**
  - scalar LQ (pair prod.), coupling to 1<sup>st</sup> gen. fermions,  $\beta = 1$
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  - excited light quark ( $qg$ ),  $\Lambda = m_q^*$
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  - quark compositeness ( $q\bar{q}$ ),  $\eta_{LL/RR} = 1$
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- Other**
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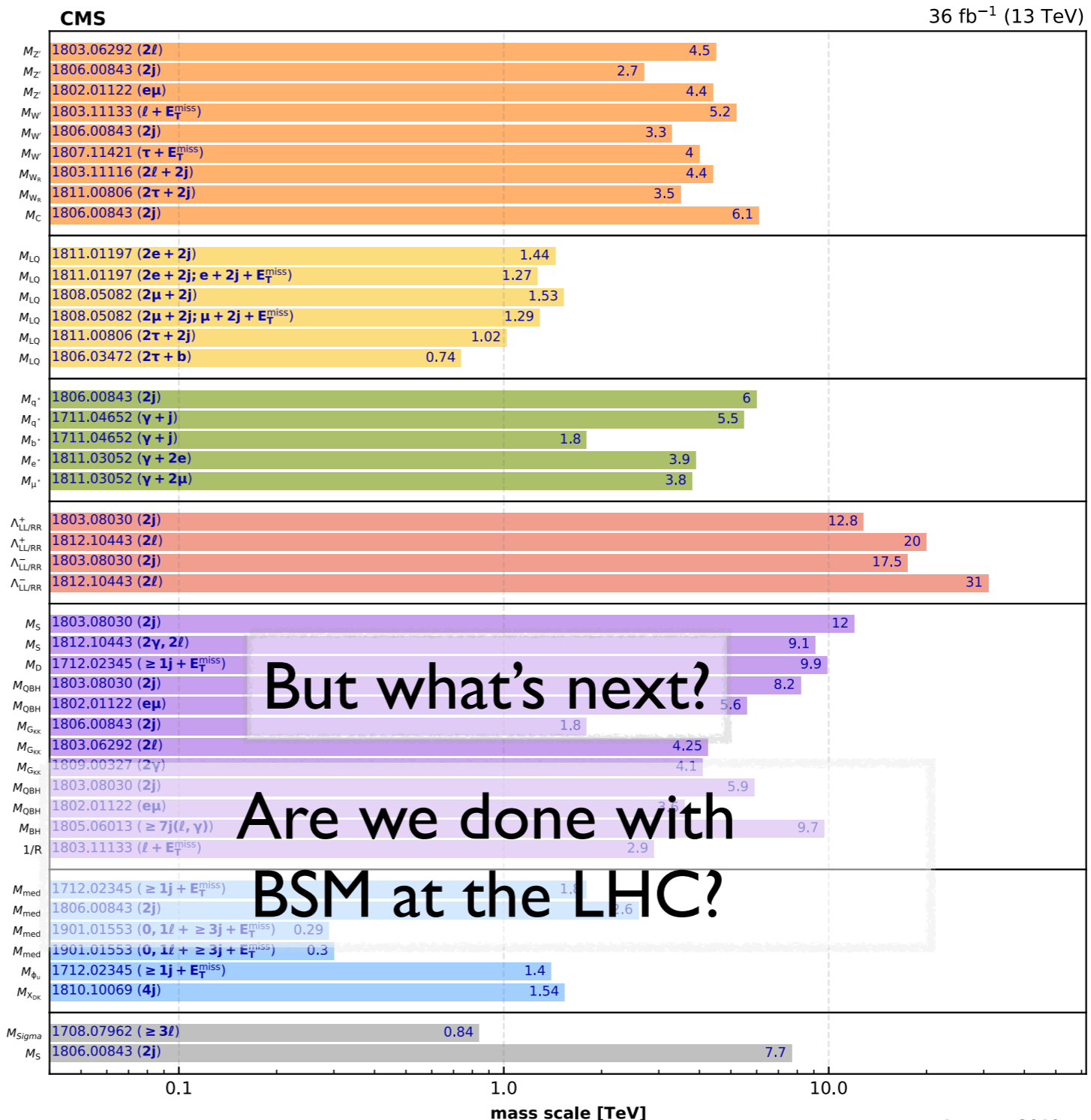
January 2019

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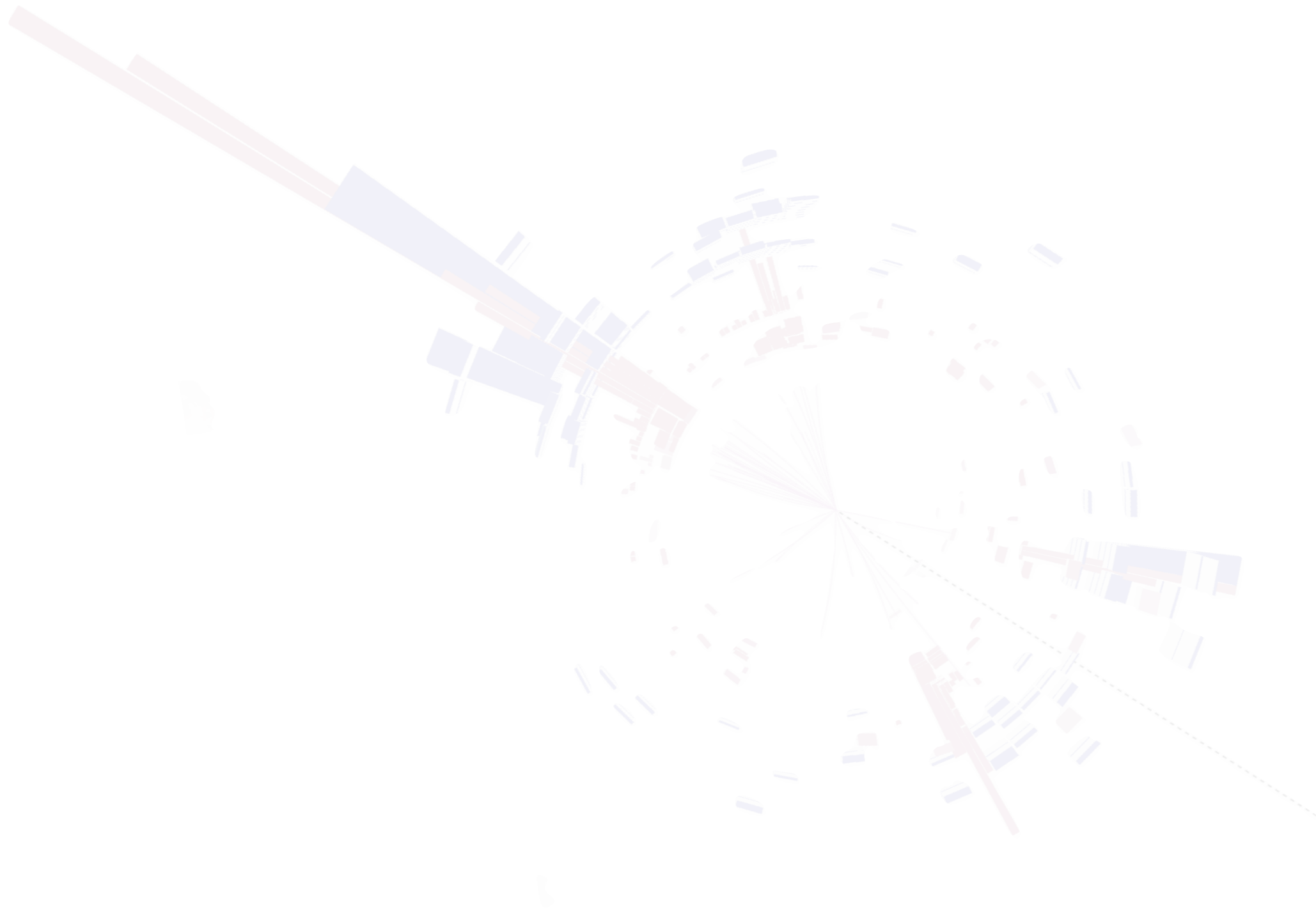
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January 2019



Low Hanging Fruit Records

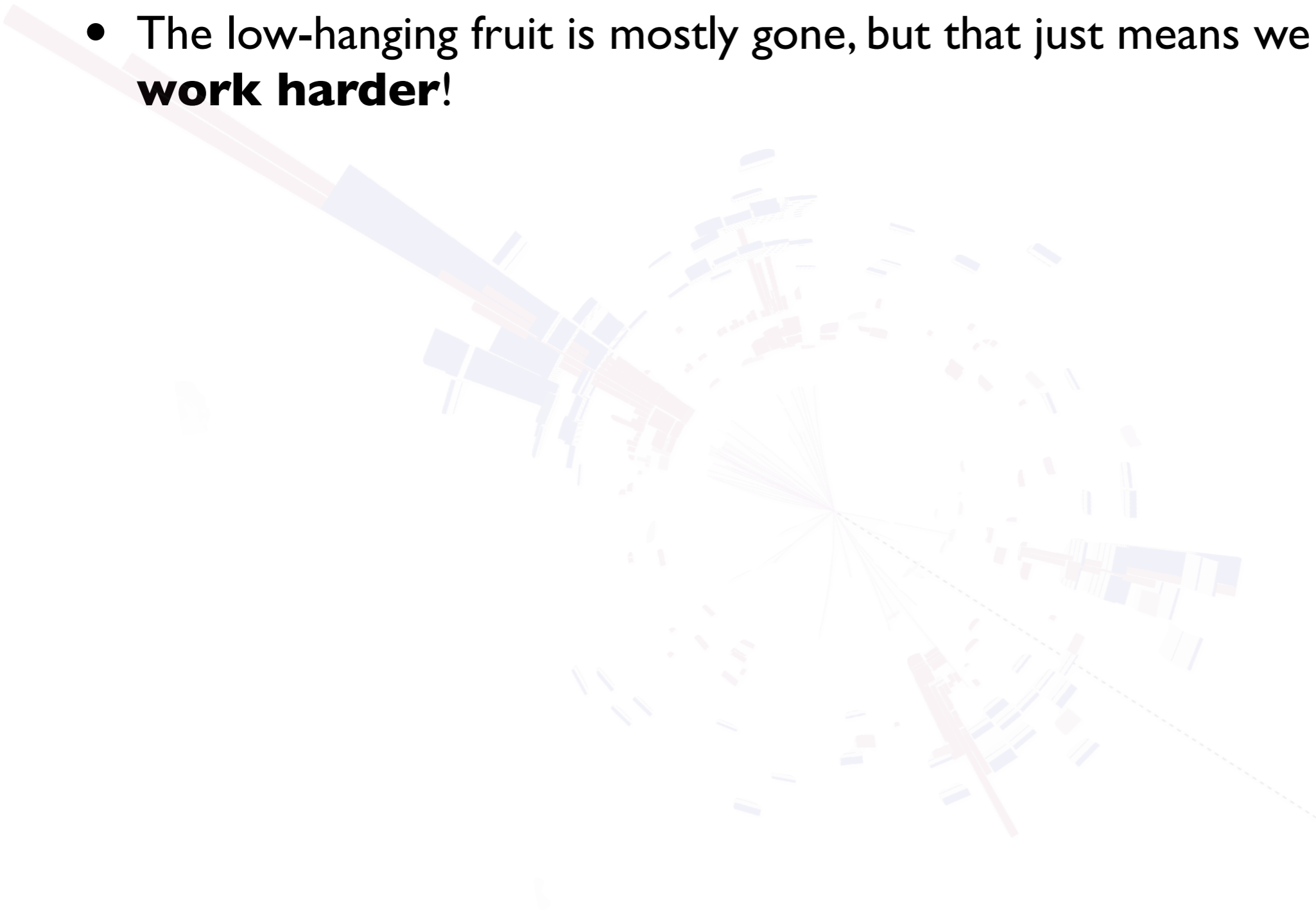
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- My apologies for omitting many interesting and exciting results!

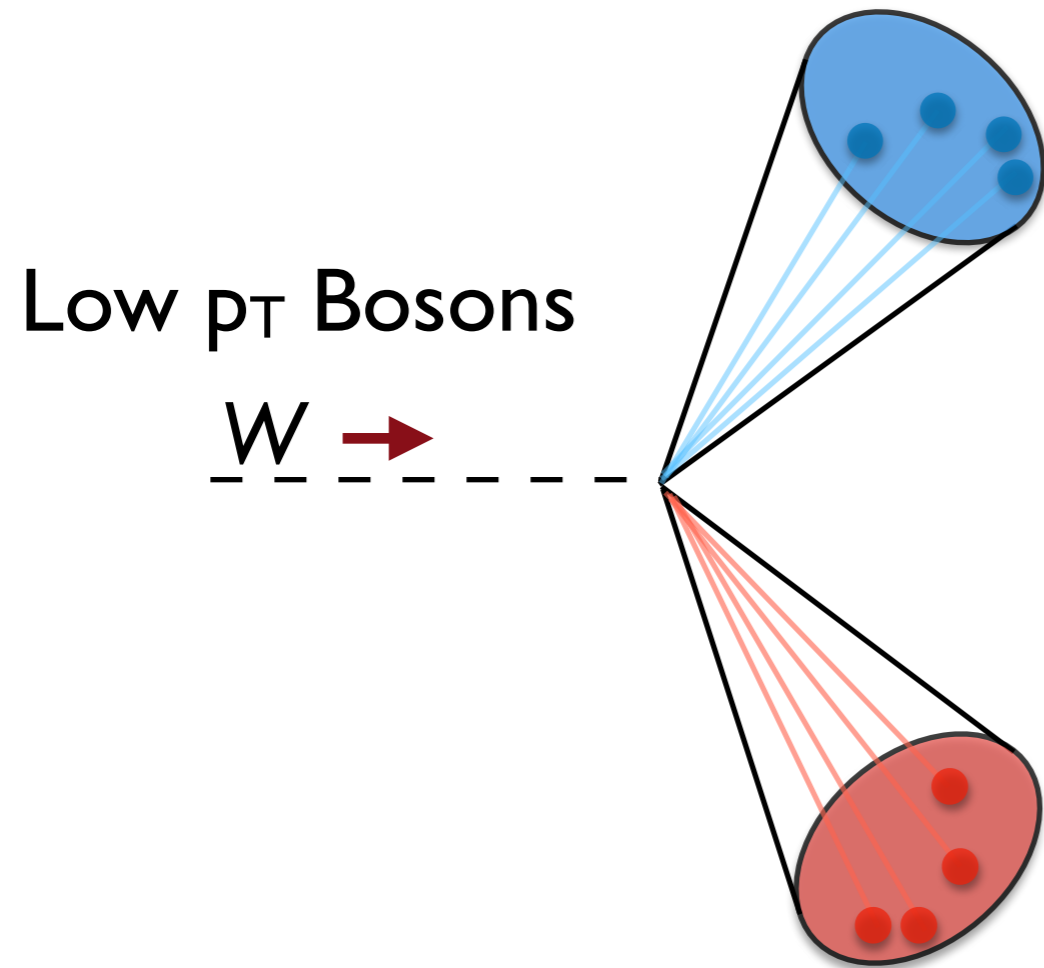
# Squeeze Every Drop

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

# The Challenge of High $p_T$

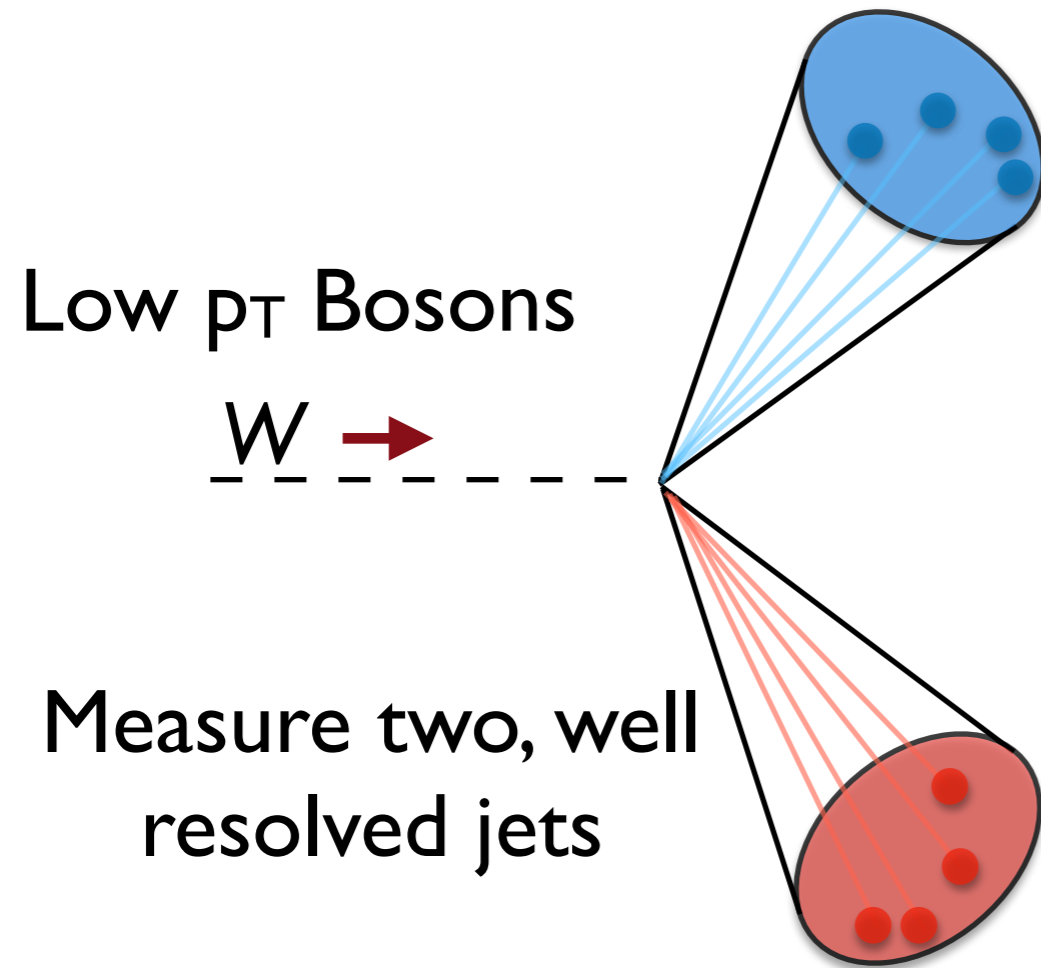


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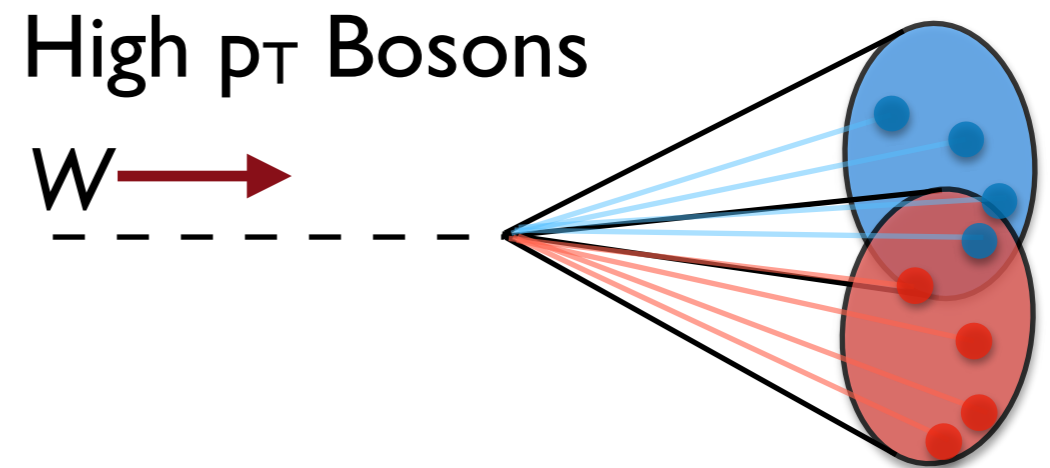
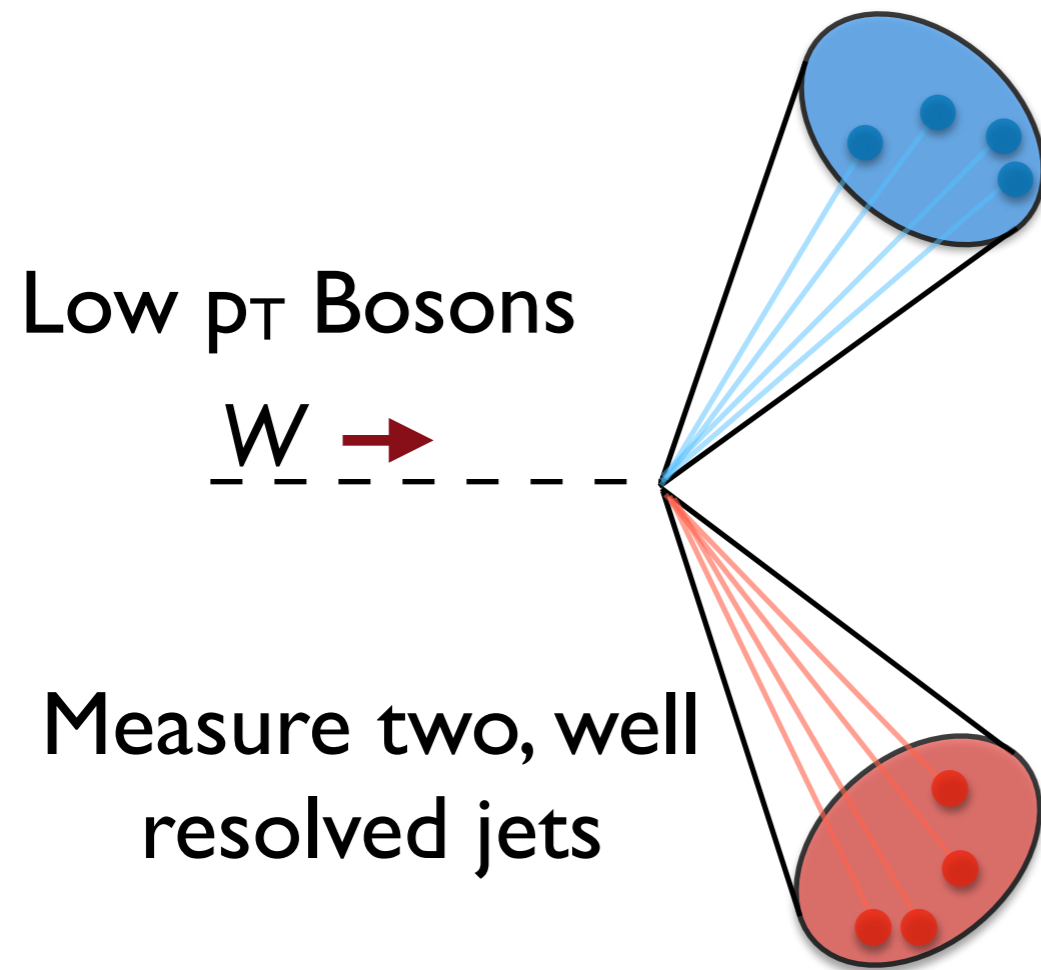




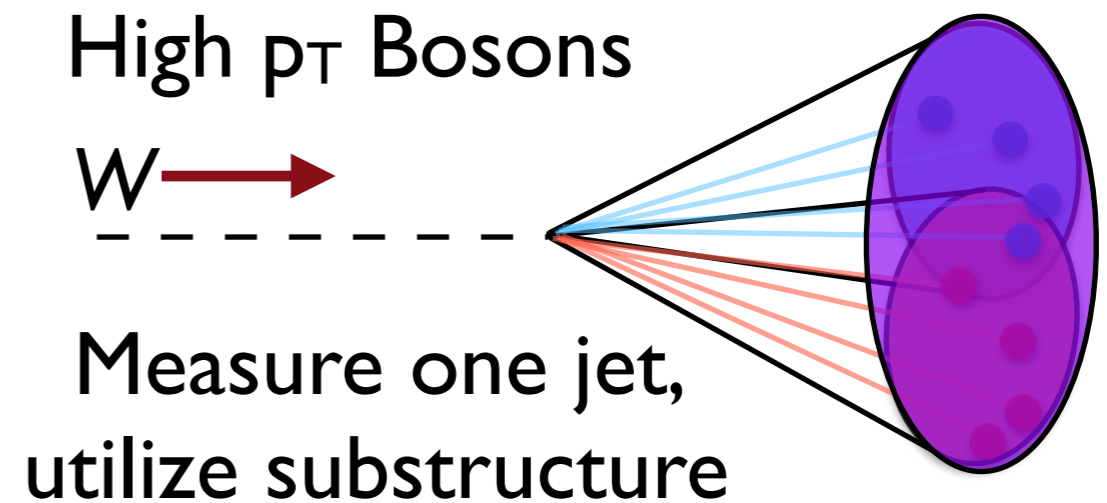
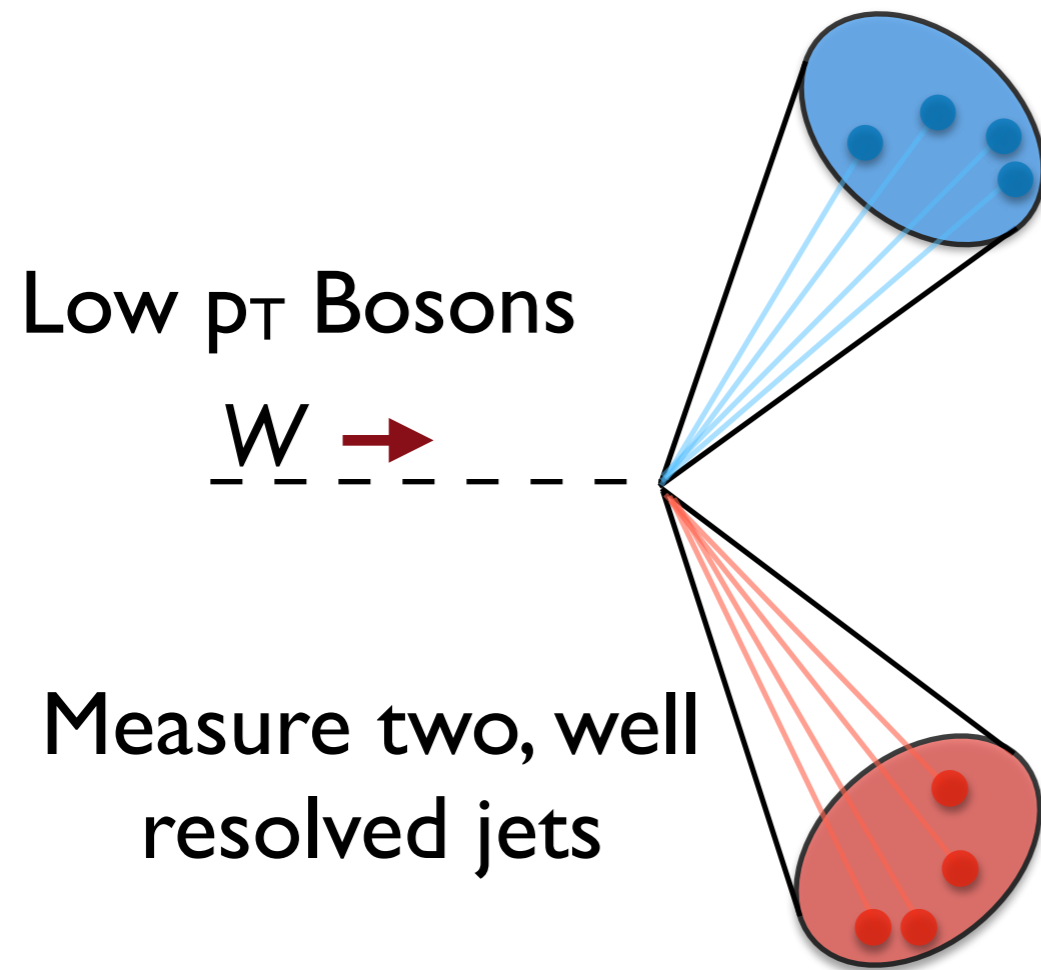
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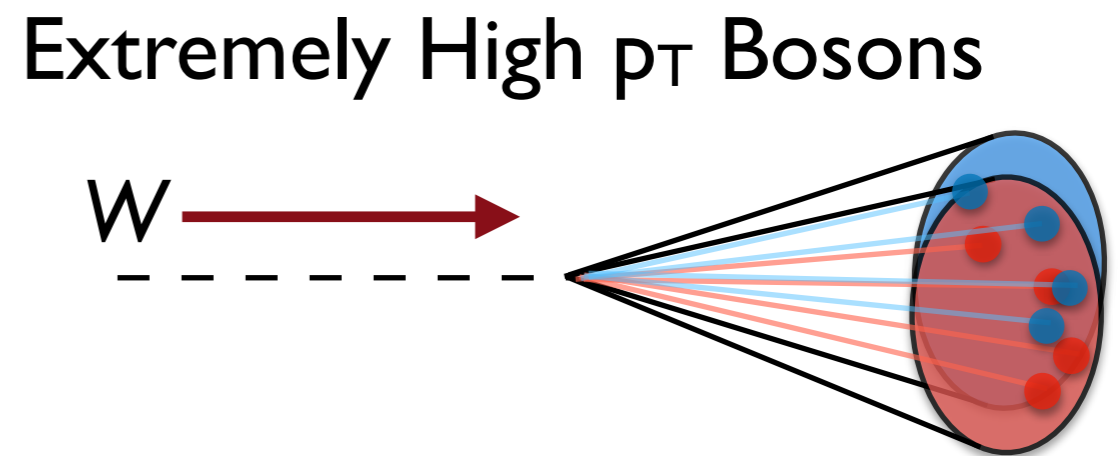
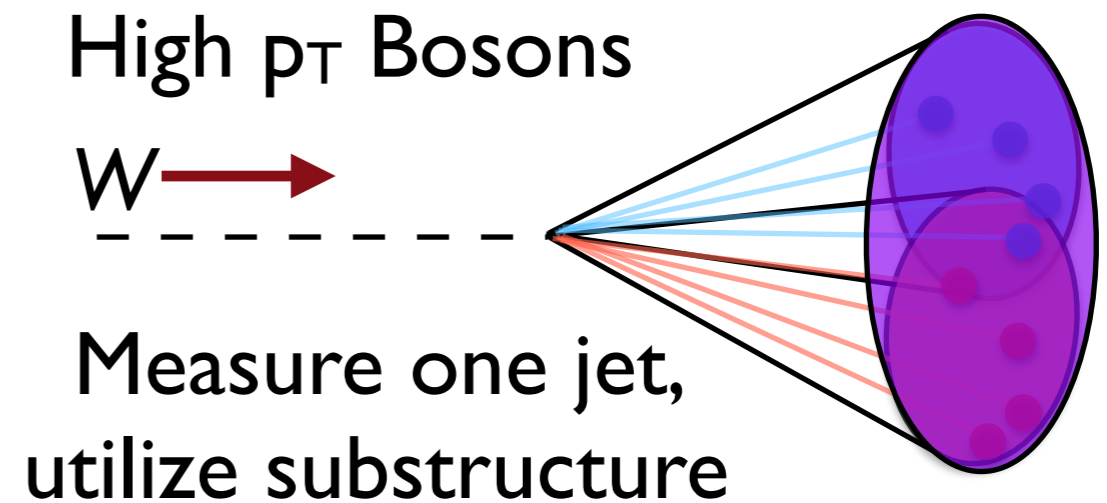
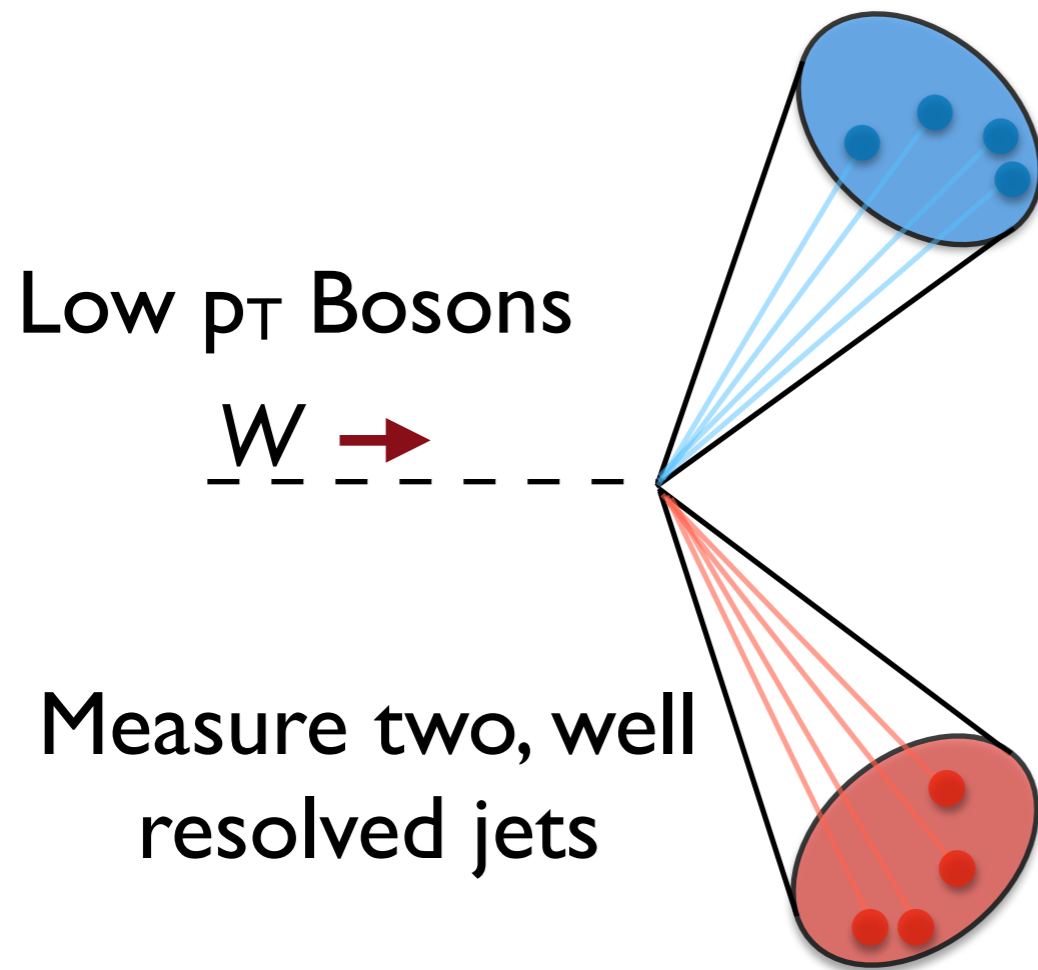
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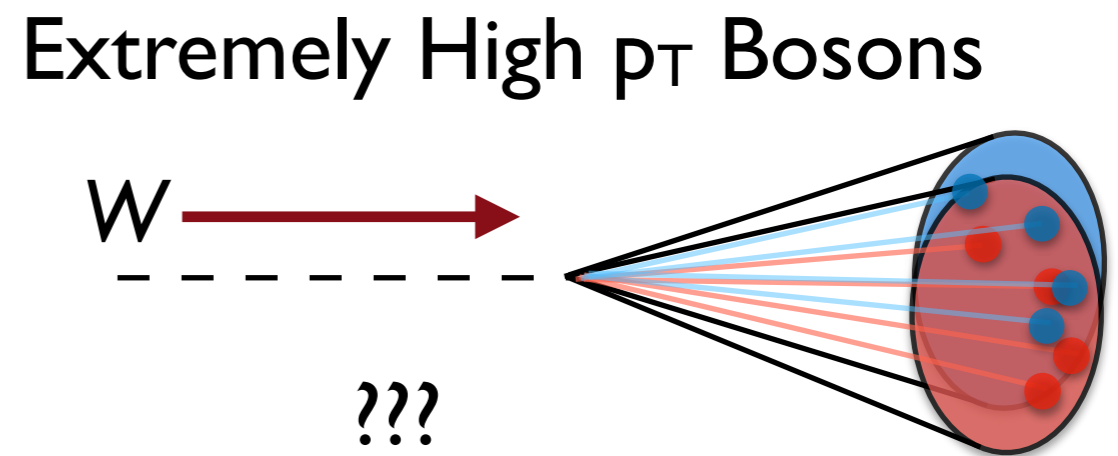
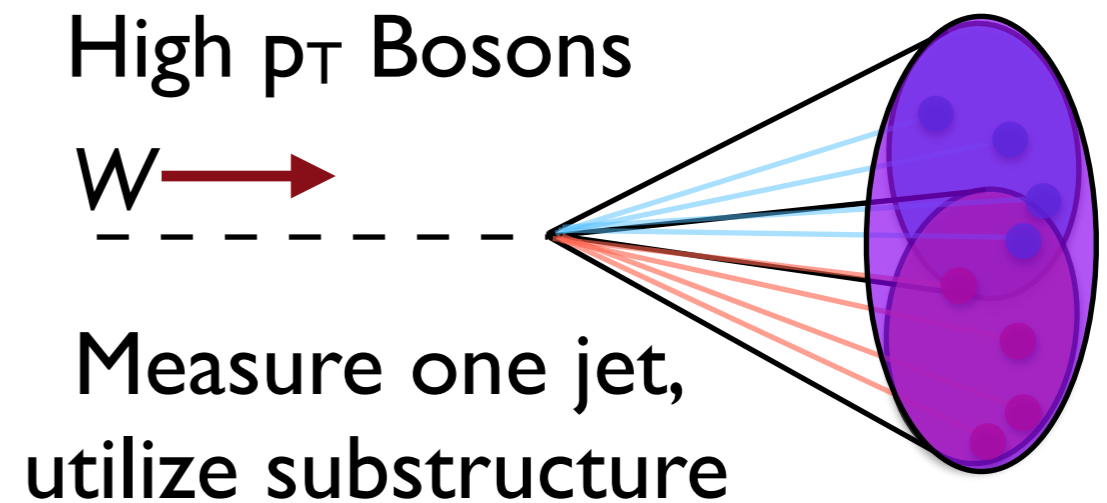
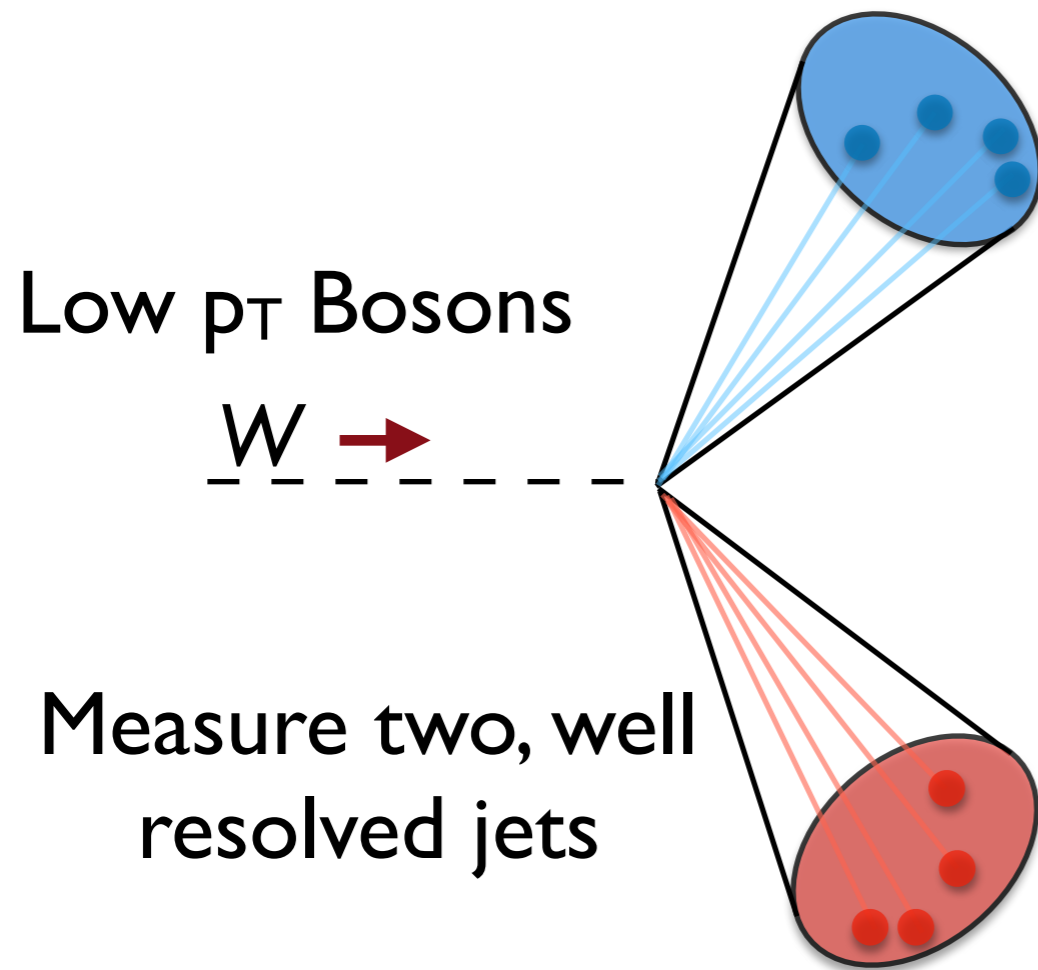
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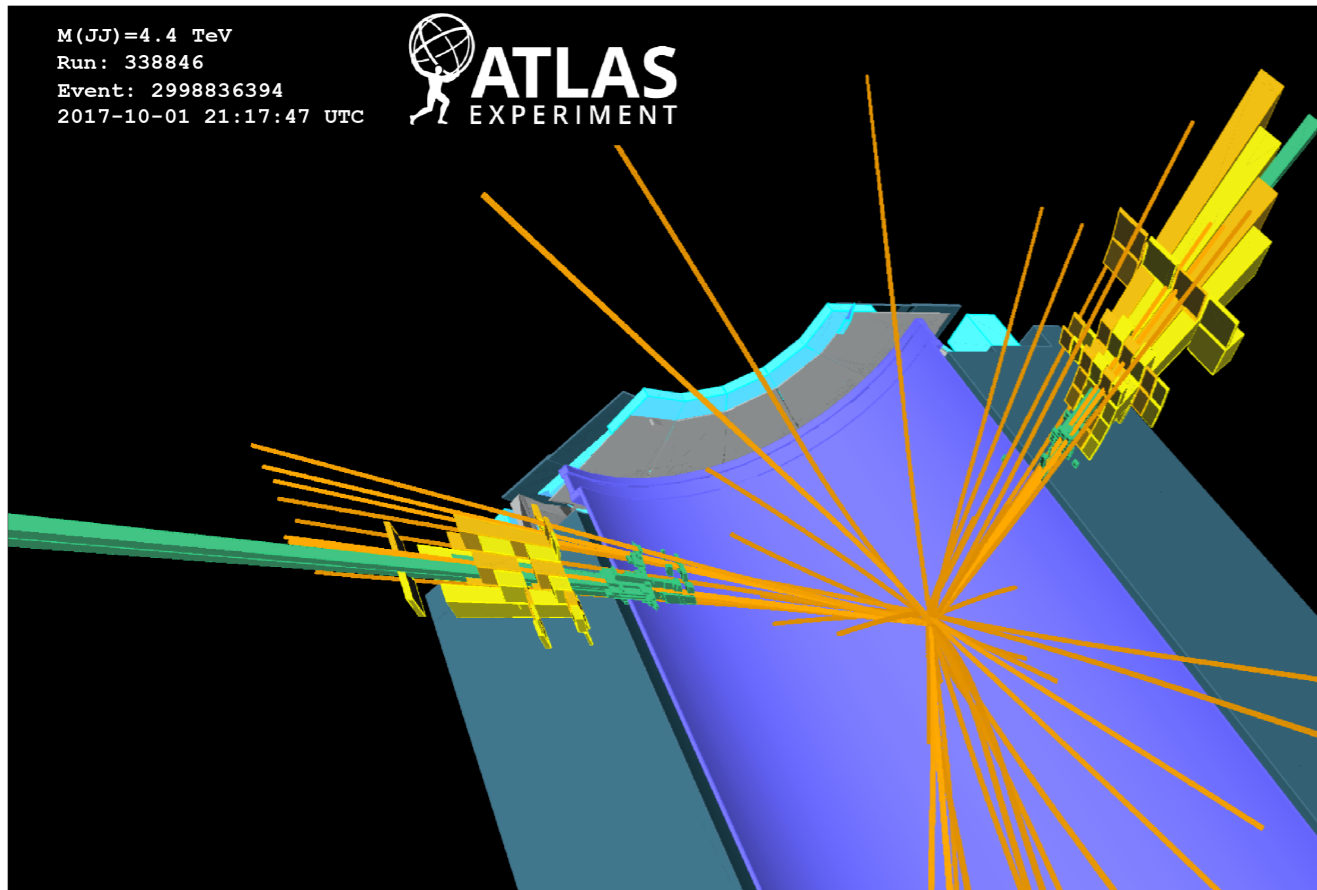
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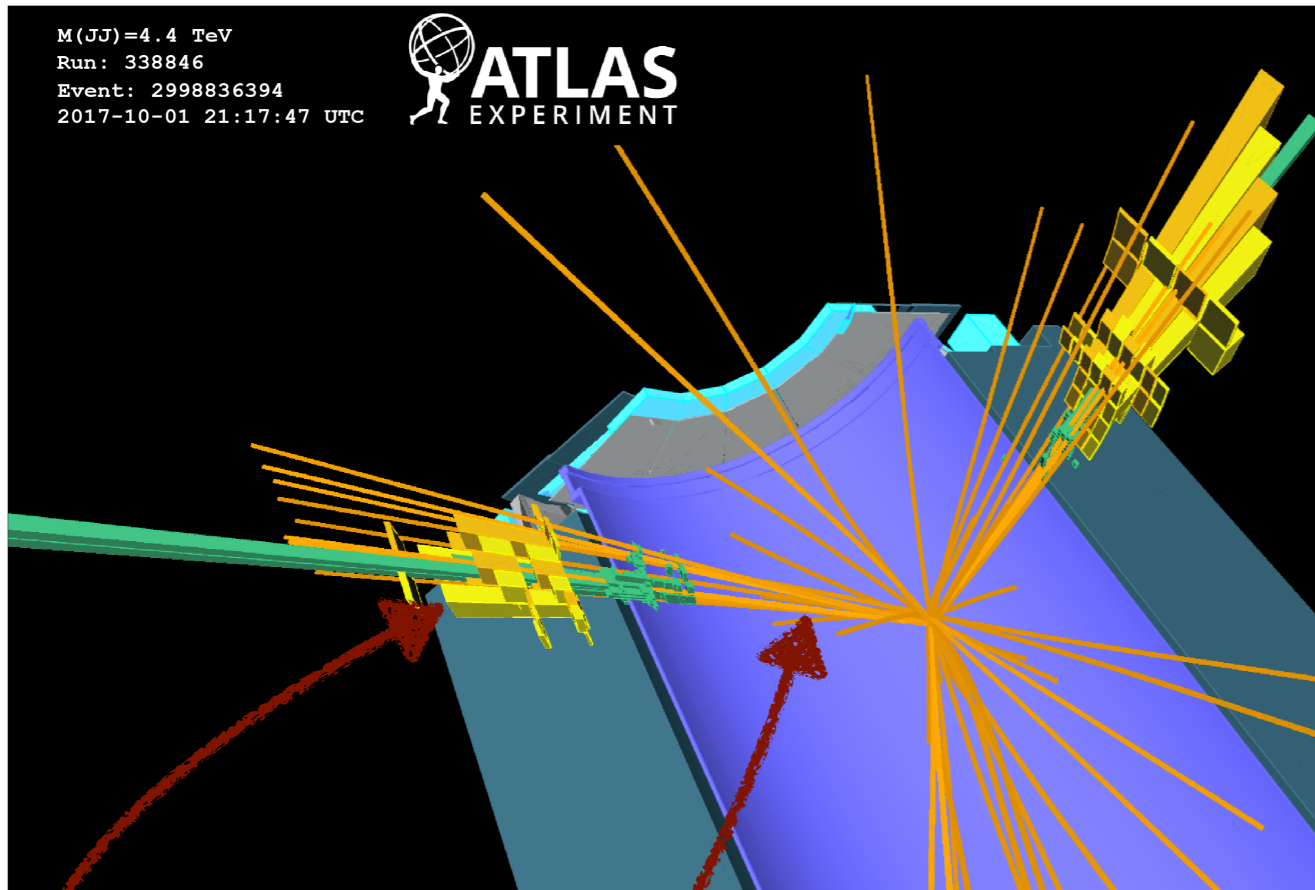
# Tagging at High $p_T$



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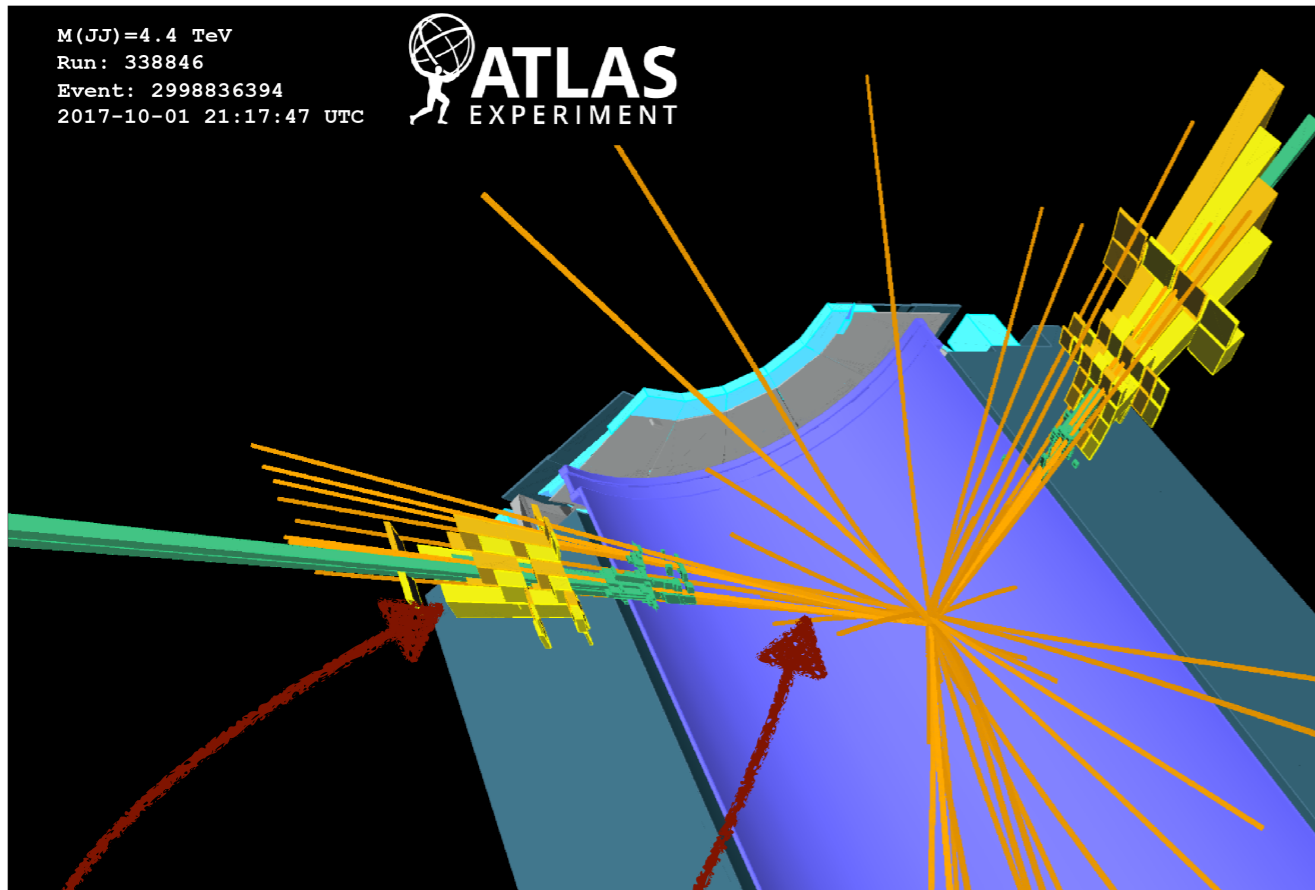
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Utilize better spatial resolution from tracker to separate energy deposits in the calorimeter!



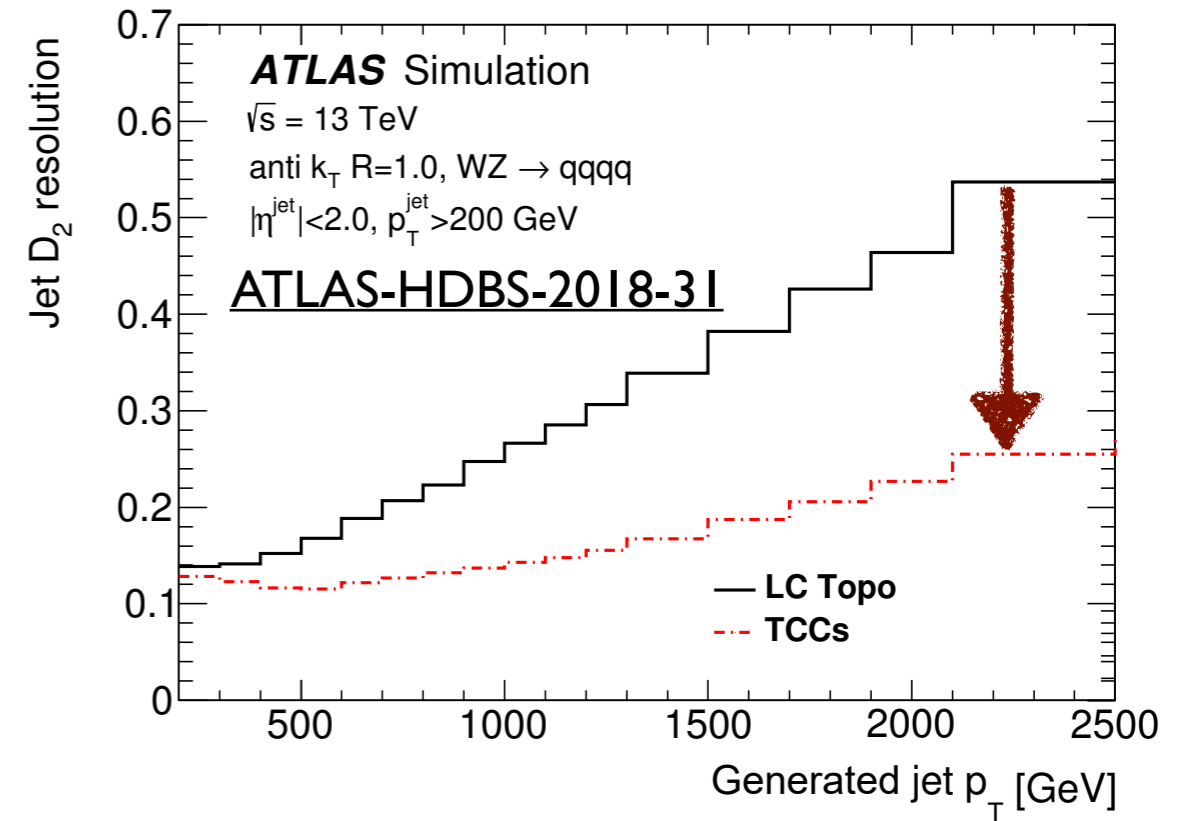
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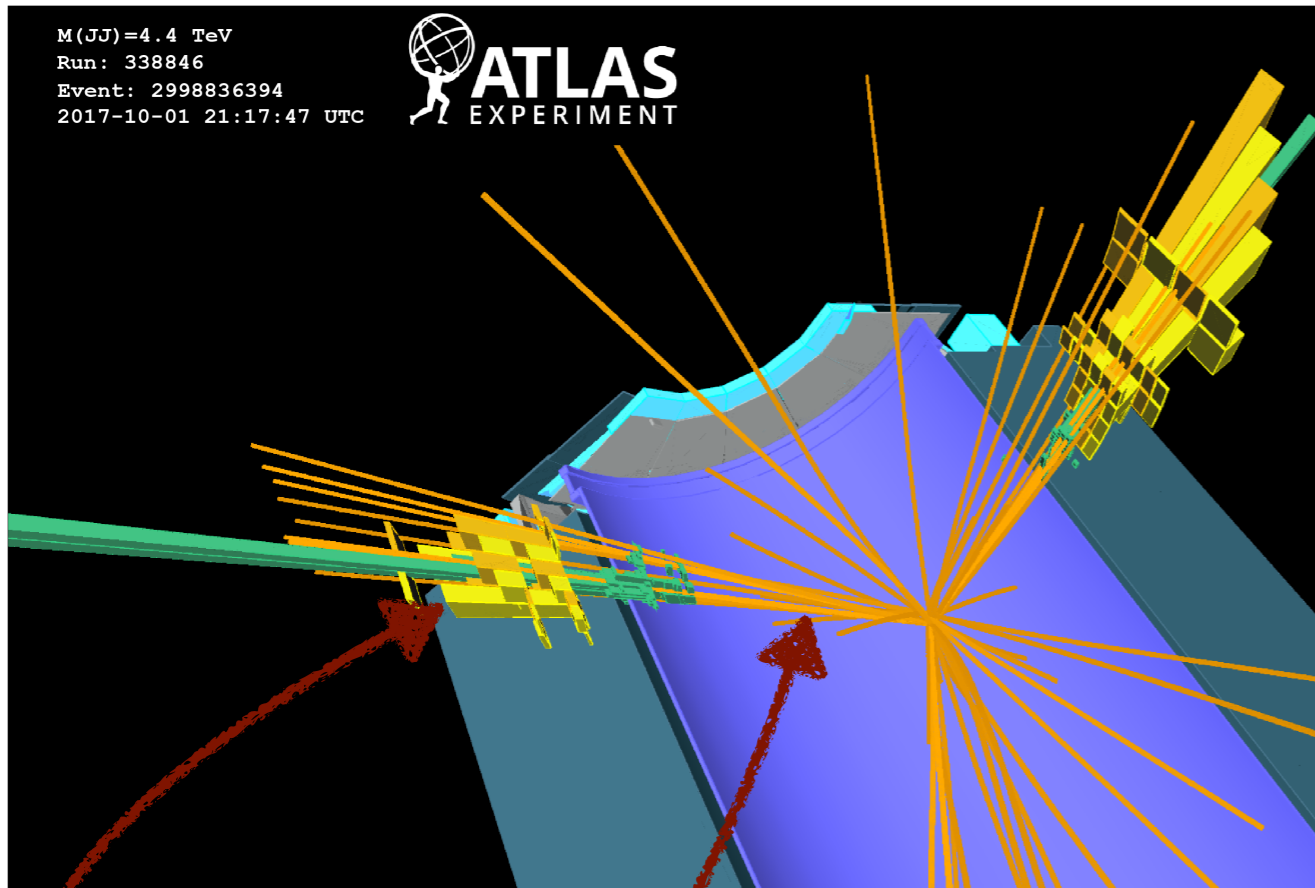
M(JJ)=4.4 TeV  
Run: 338846  
Event: 2998836394  
2017-10-01 21:17:47 UTC

**ATLAS**  
EXPERIMENT

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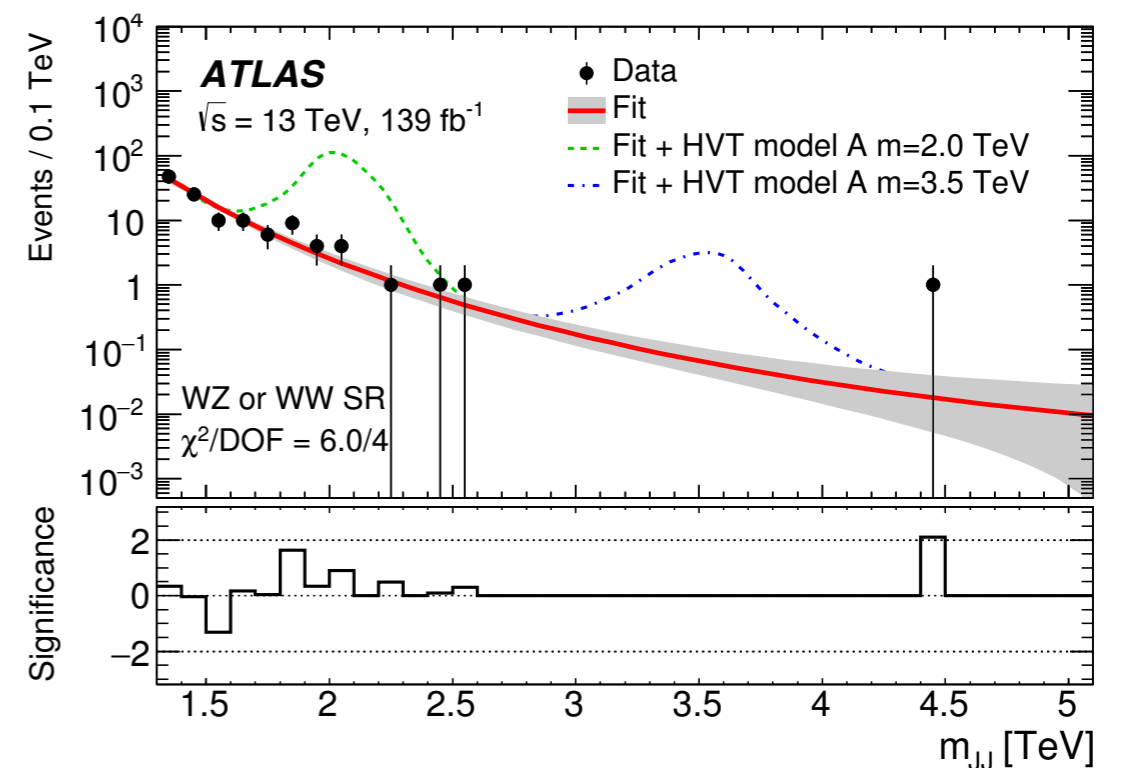
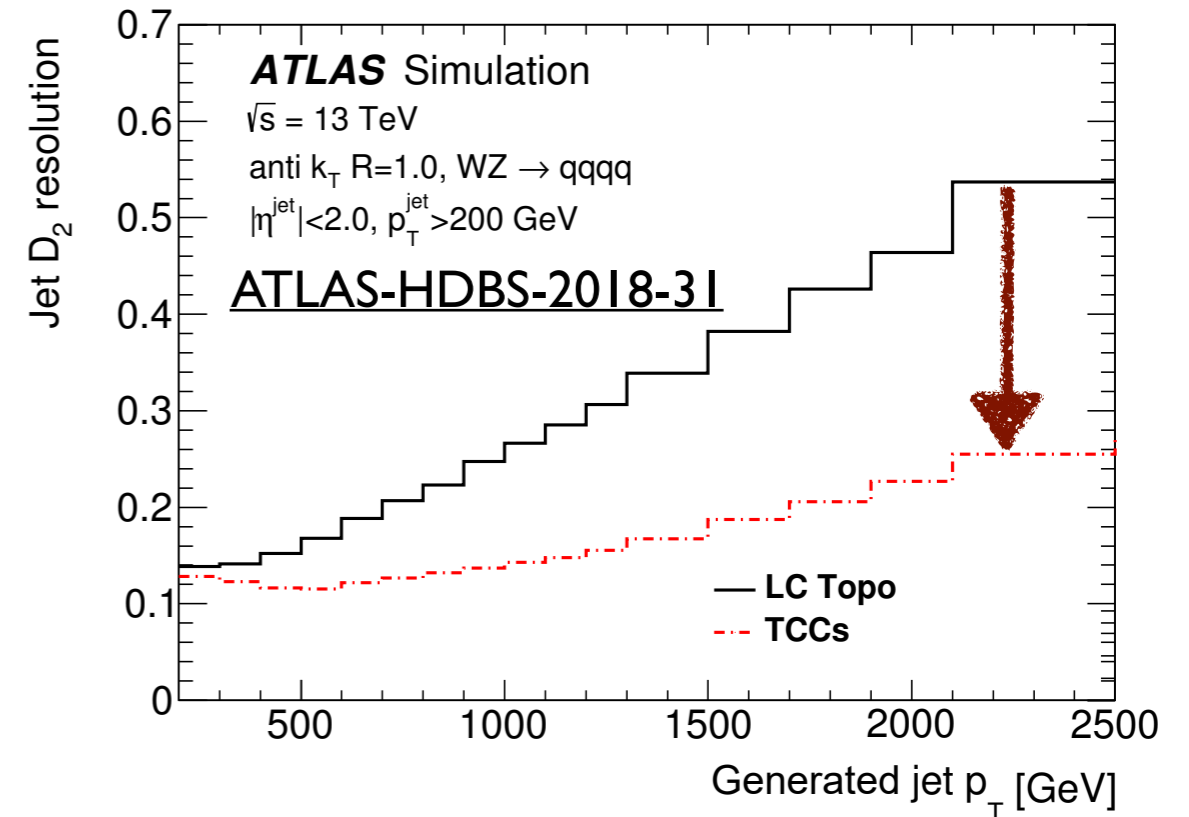


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Run: 338846  
Event: 2998836394  
2017-10-01 21:17:47 UTC

**ATLAS**  
EXPERIMENT

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

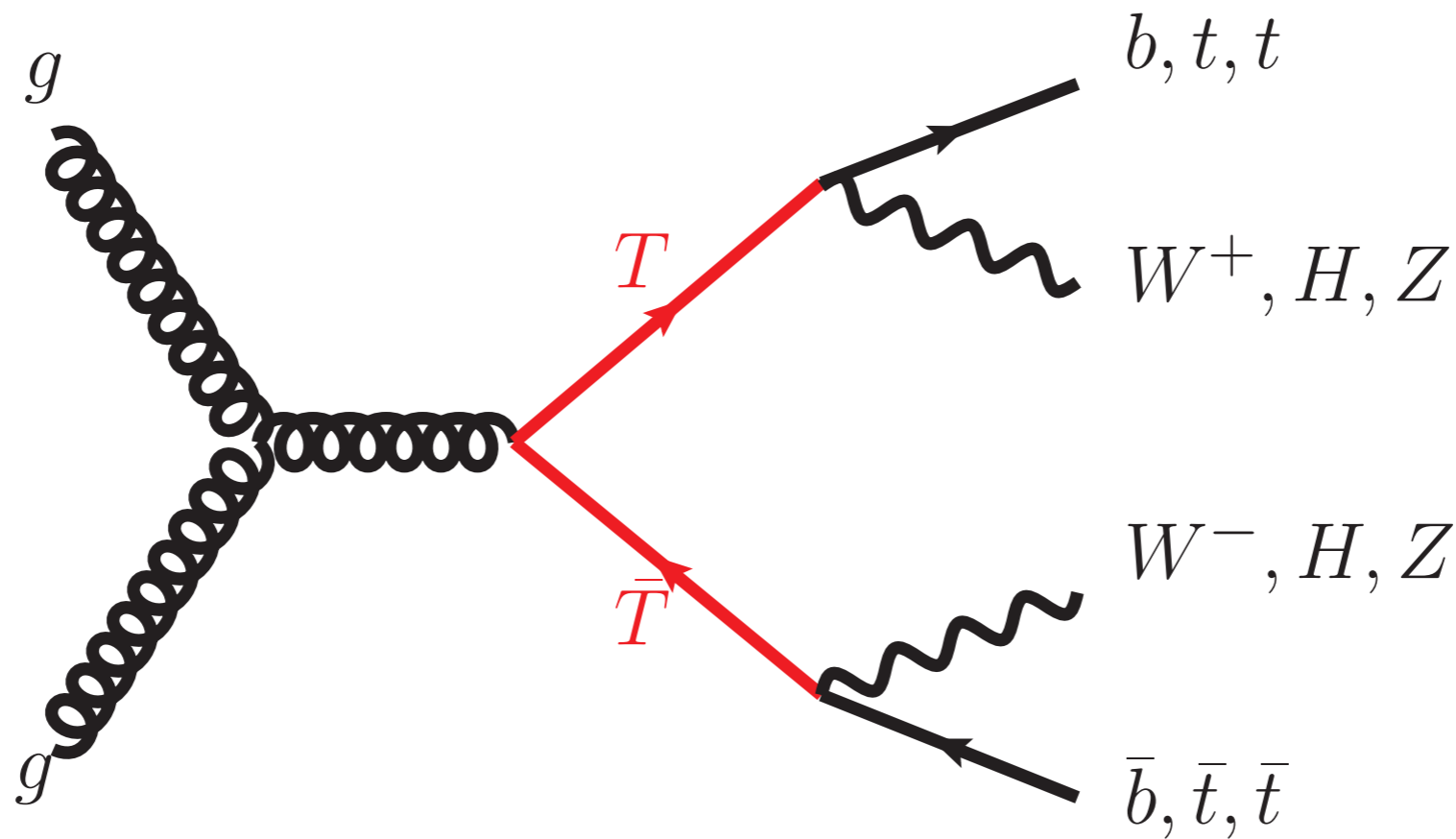
Enables strongest sensitivity yet to boosted all-hadronic final states



# The Challenge of Branching

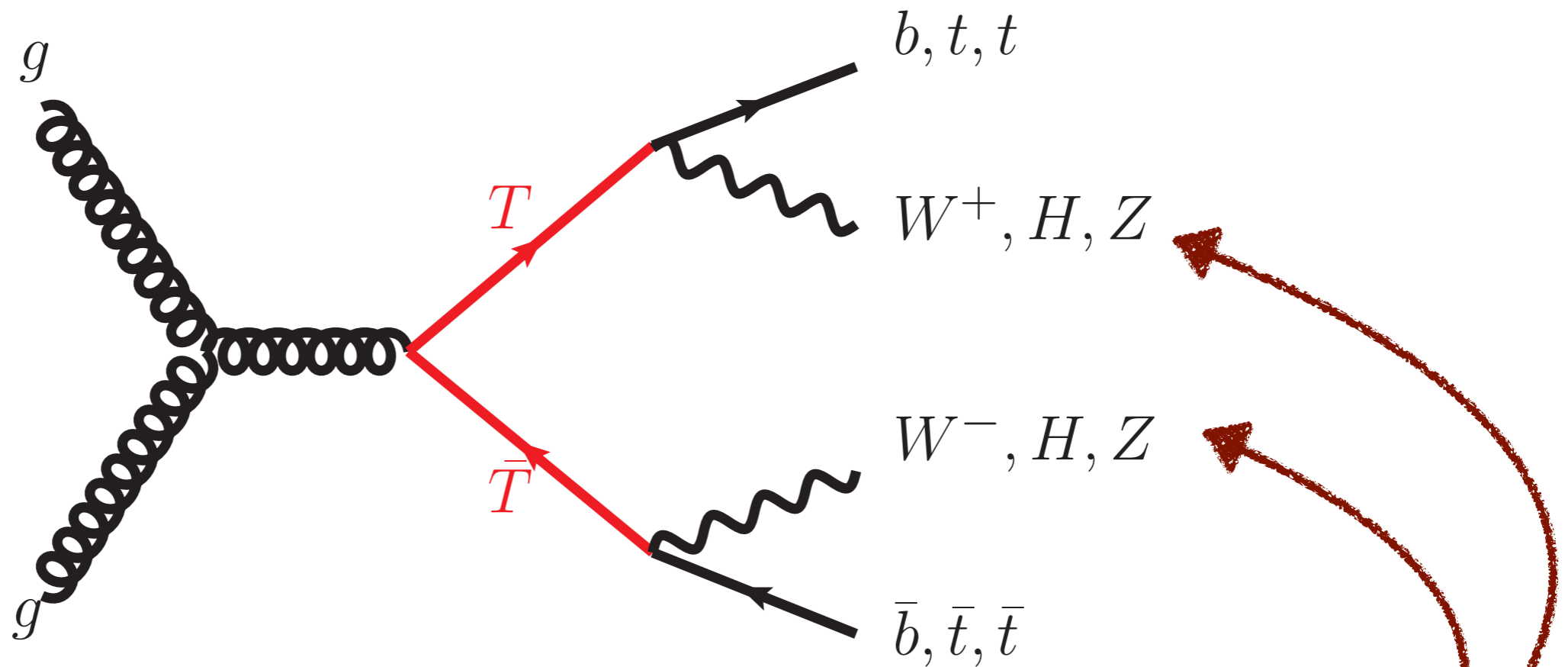


# The Challenge of Branching



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

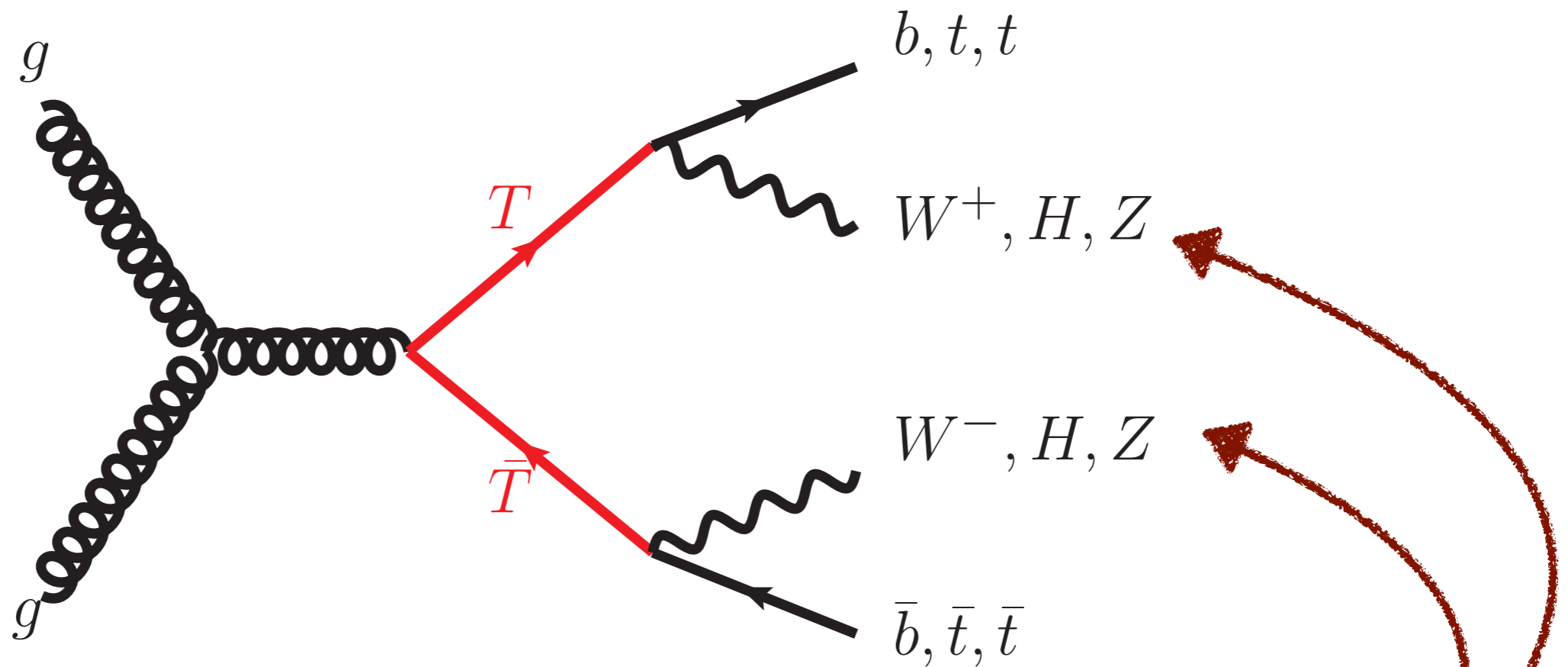
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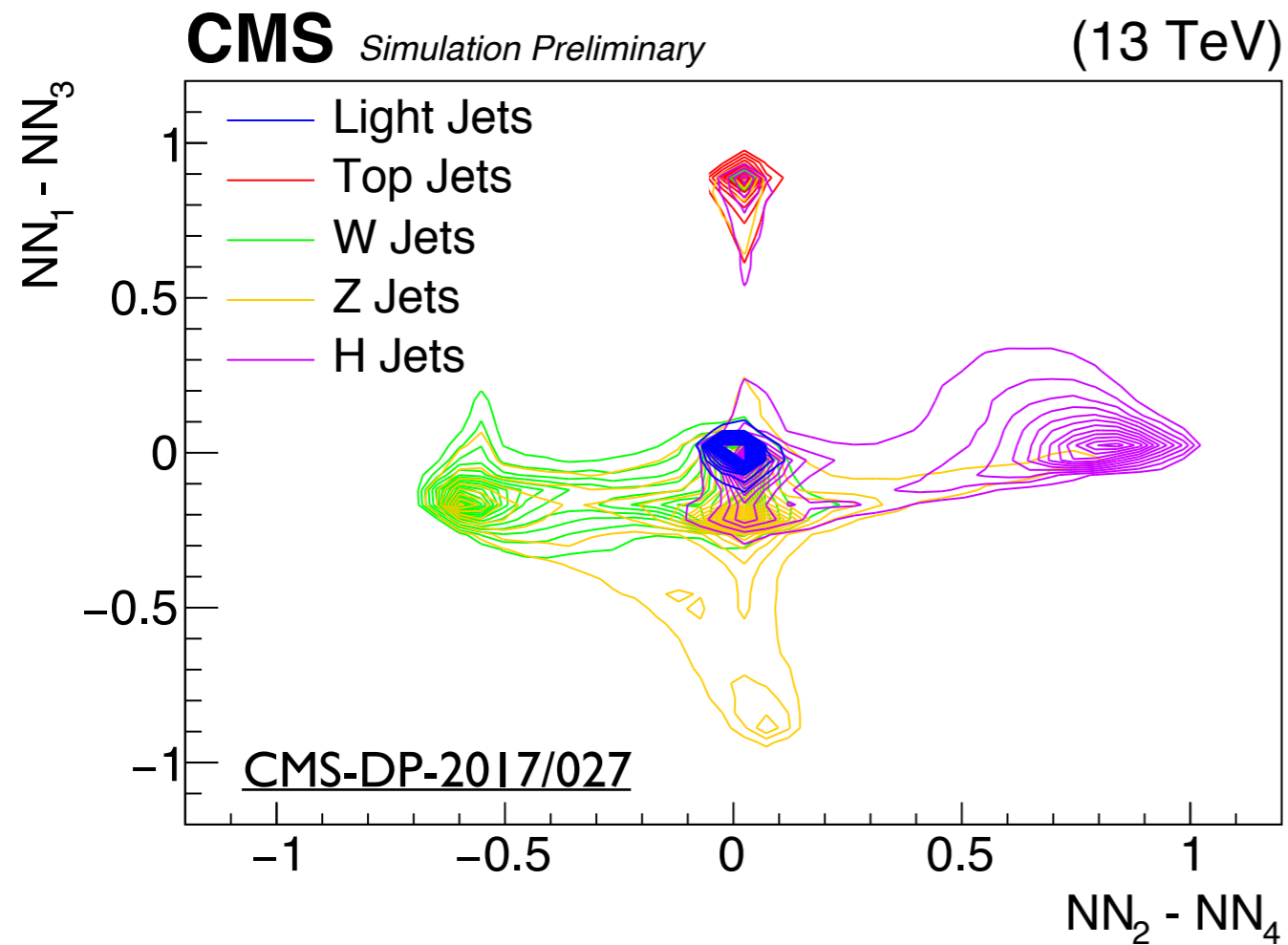
But there are a huge number of final states!

How do you search for all of these efficiently?

# Multi-Node Tagging



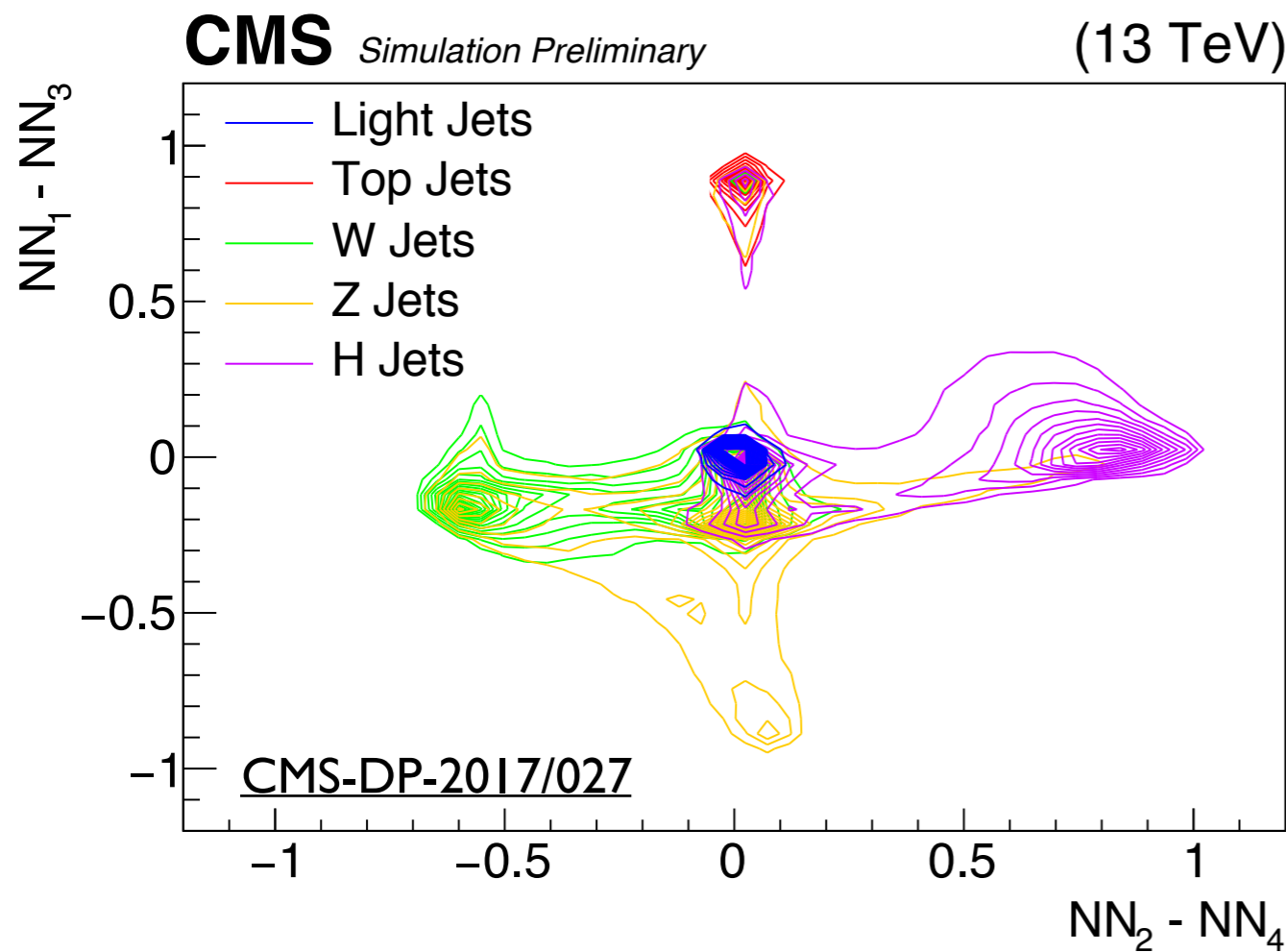
# Multi-Node Tagging



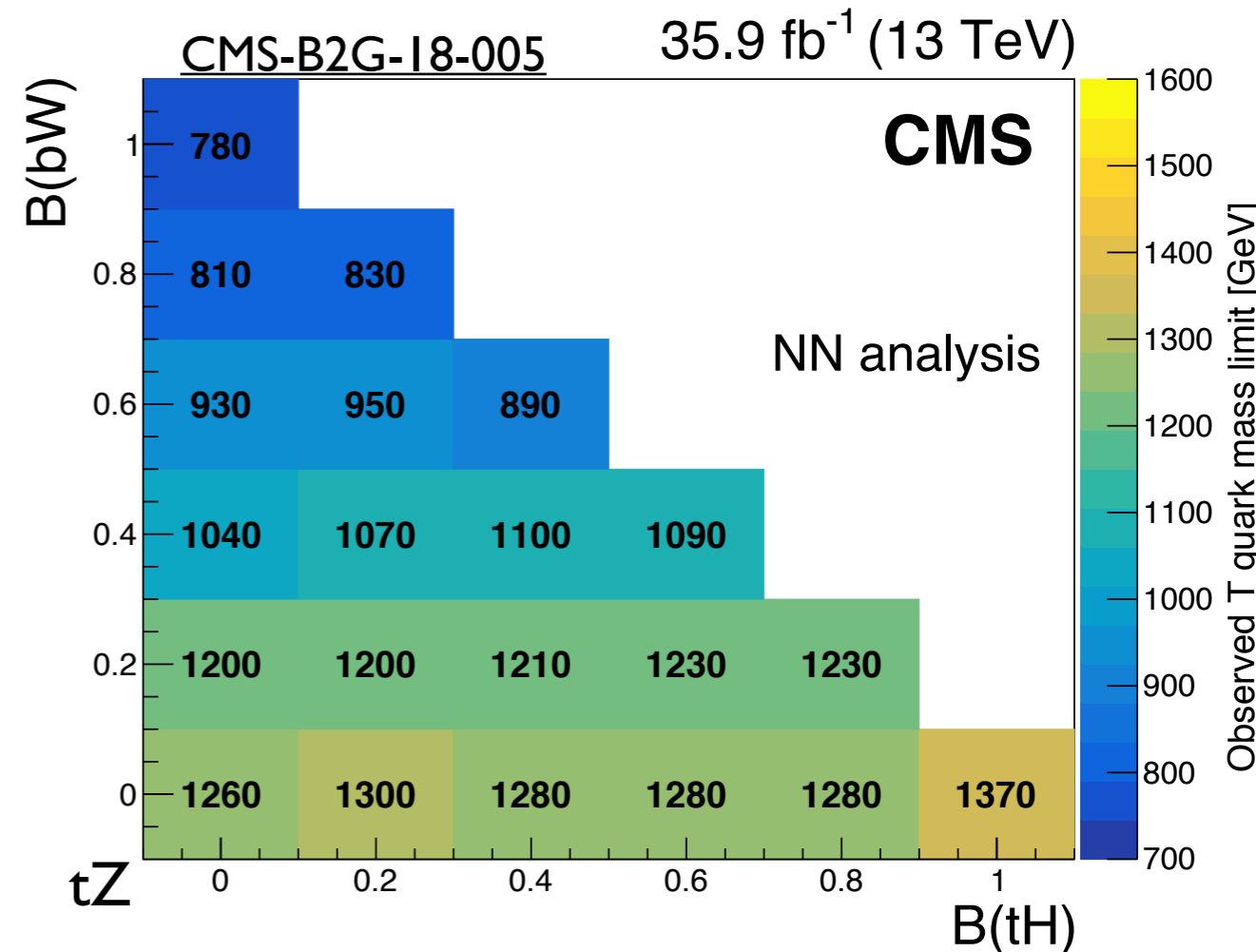
Train a neural network to distinguish all signal classes from background



# Multi-Node Tagging



Train a neural network to distinguish all signal classes from background

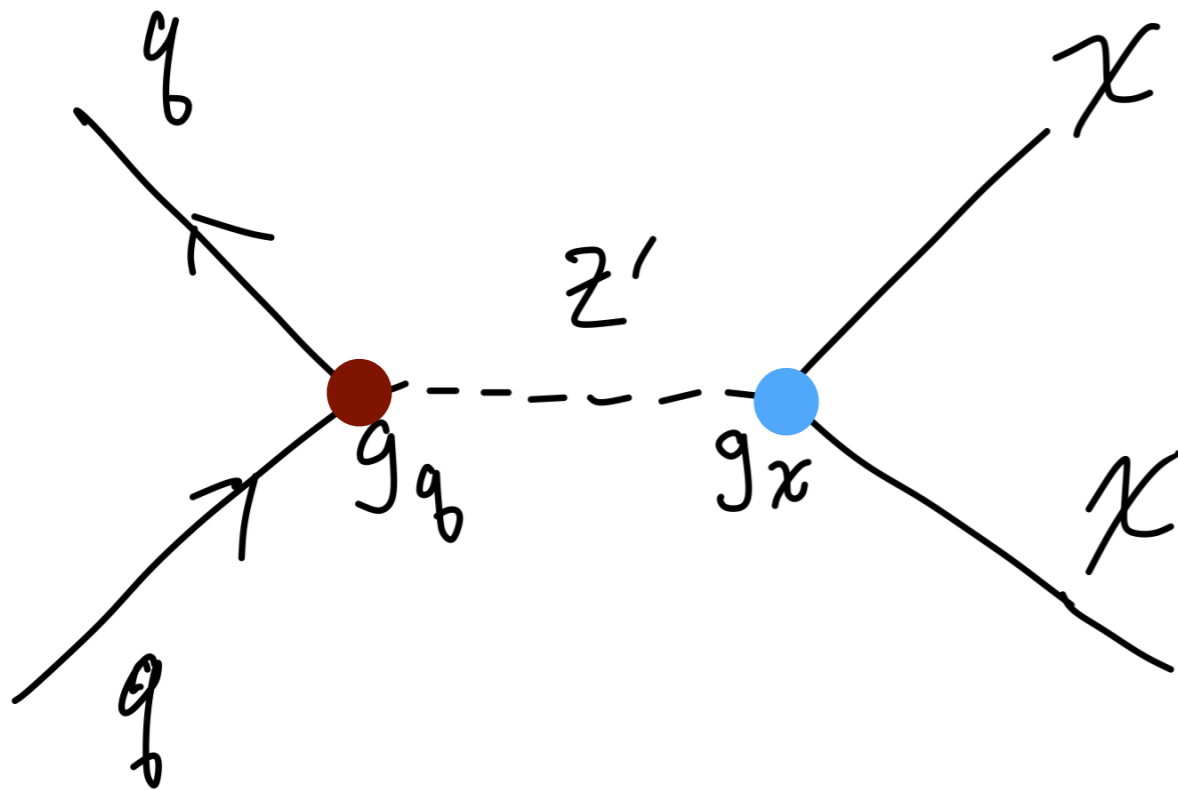


Use the NN to search for new physics in many final states at once

# The Challenges of Dijets

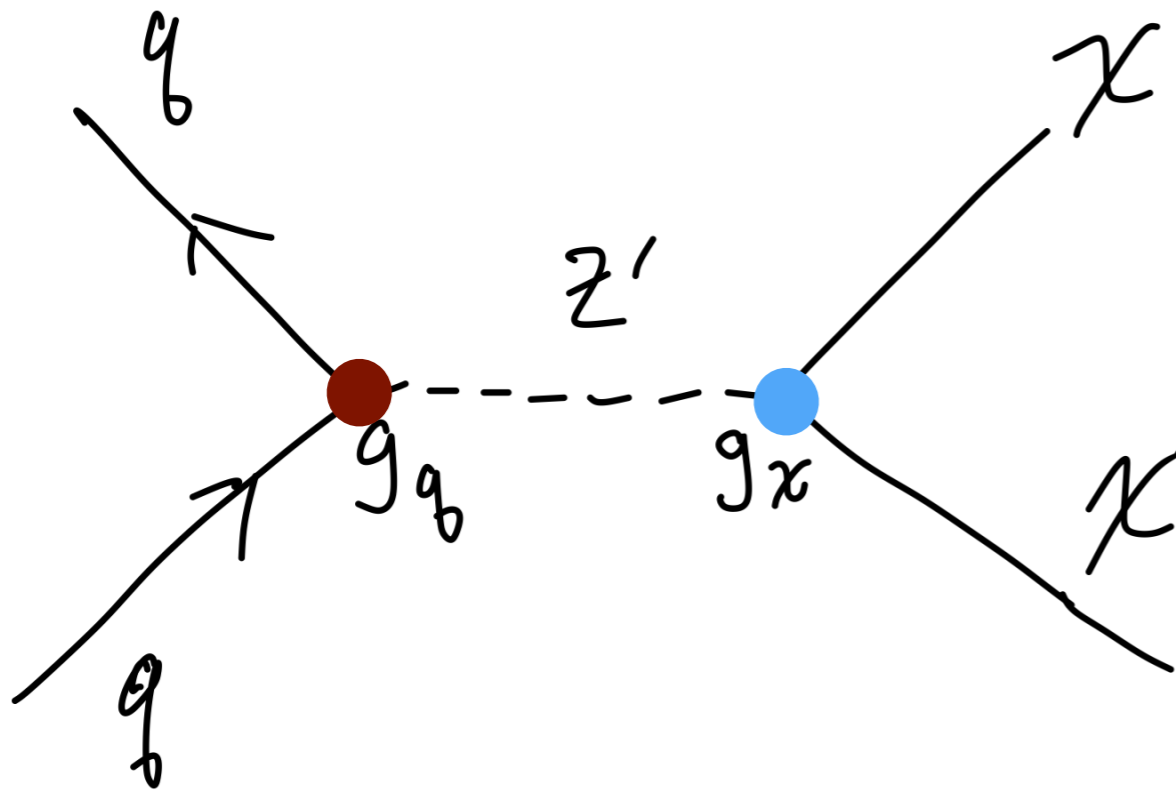


# The Challenges of Dijets

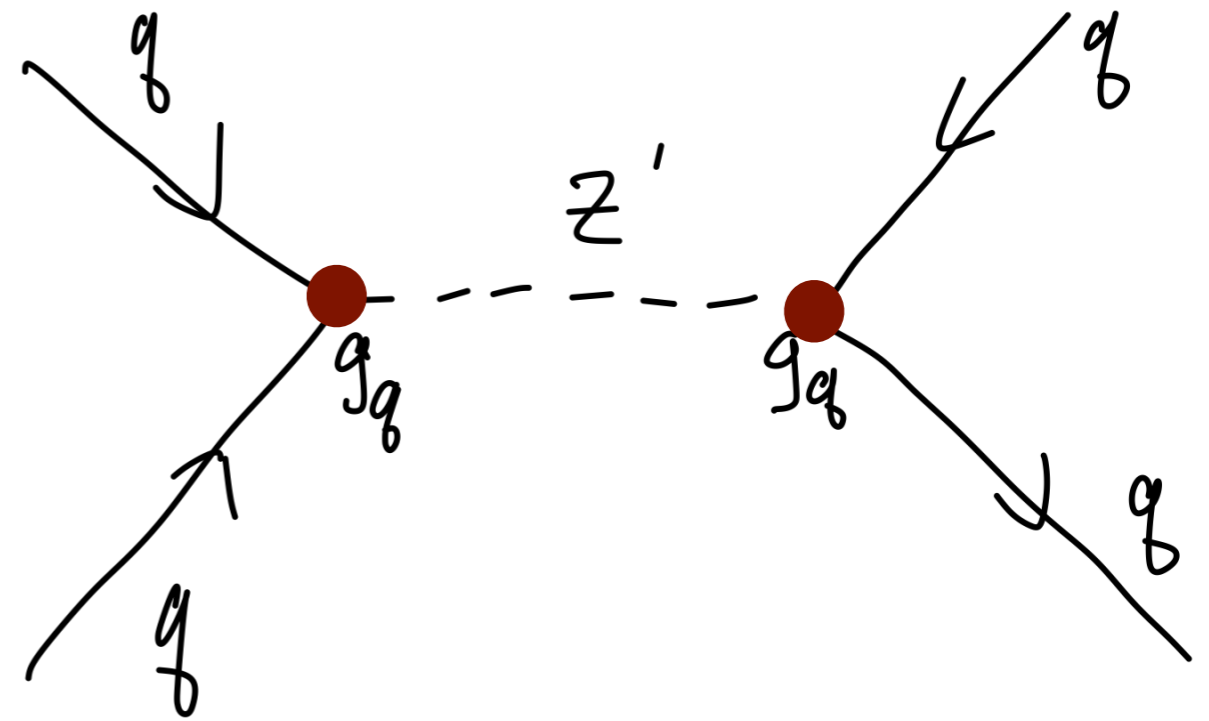


If we can produce DM  
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# The Challenges of Dijets

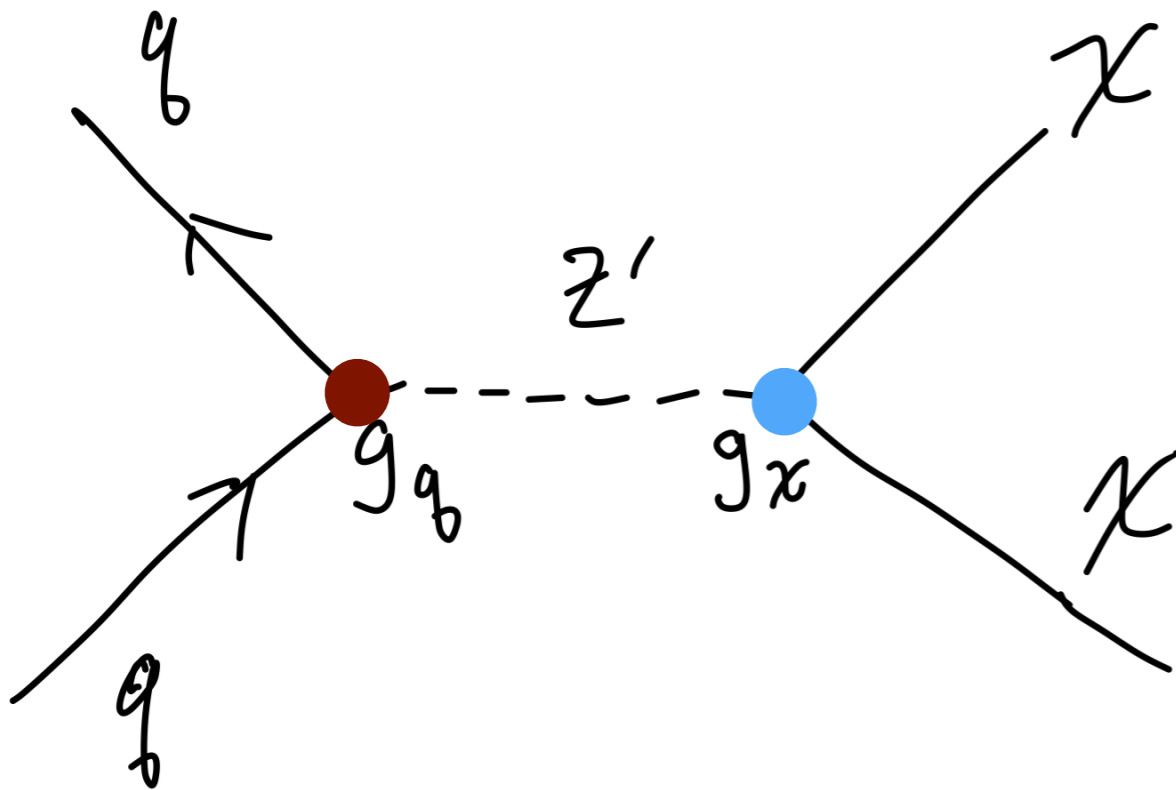


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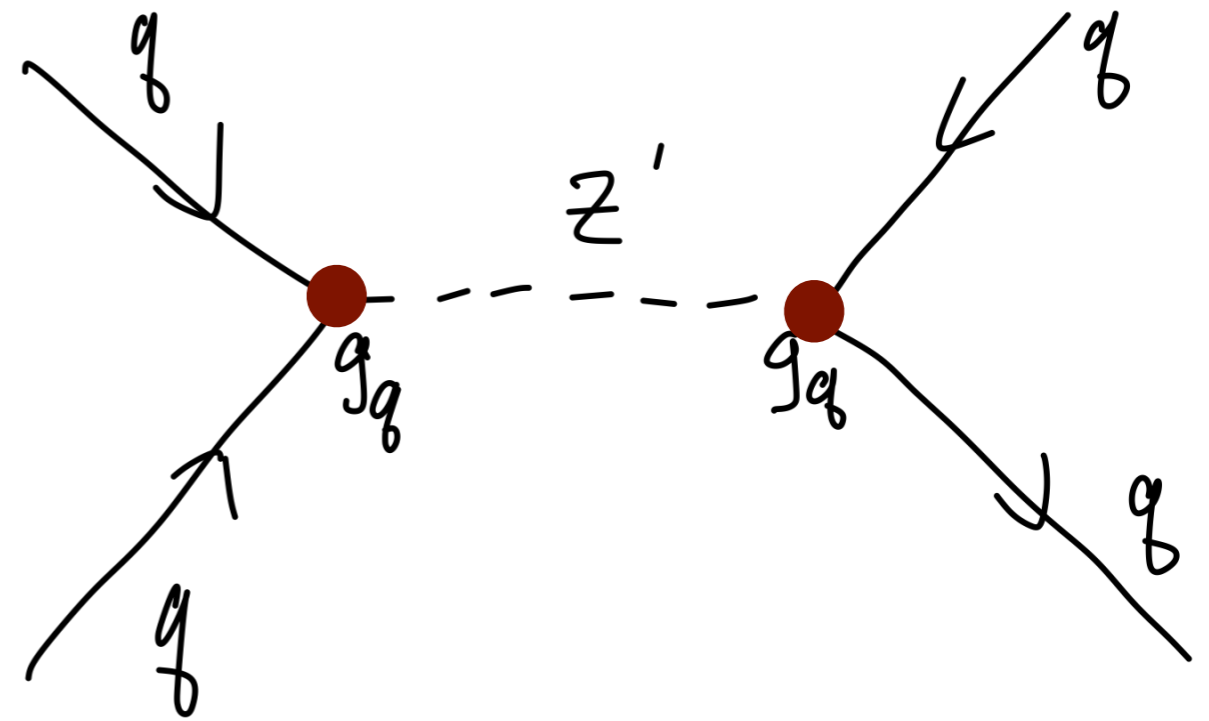


Then the mediator should decay back to jets!

# 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



# Data Scouting



Trigger limitations  
come from  
total bandwidth

# Data Scouting



Trigger limitations  
come from  
total bandwidth

Event  
Size

x

Event  
Rate

=

Total  
Bandwidth



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Size

x

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Normally, we record  
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x

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=

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$$\begin{array}{c} \text{Event} \\ \text{Size} \end{array} \times \begin{array}{c} \text{Event} \\ \text{Rate} \end{array} = \begin{array}{c} \text{Total} \\ \text{Bandwidth} \end{array}$$

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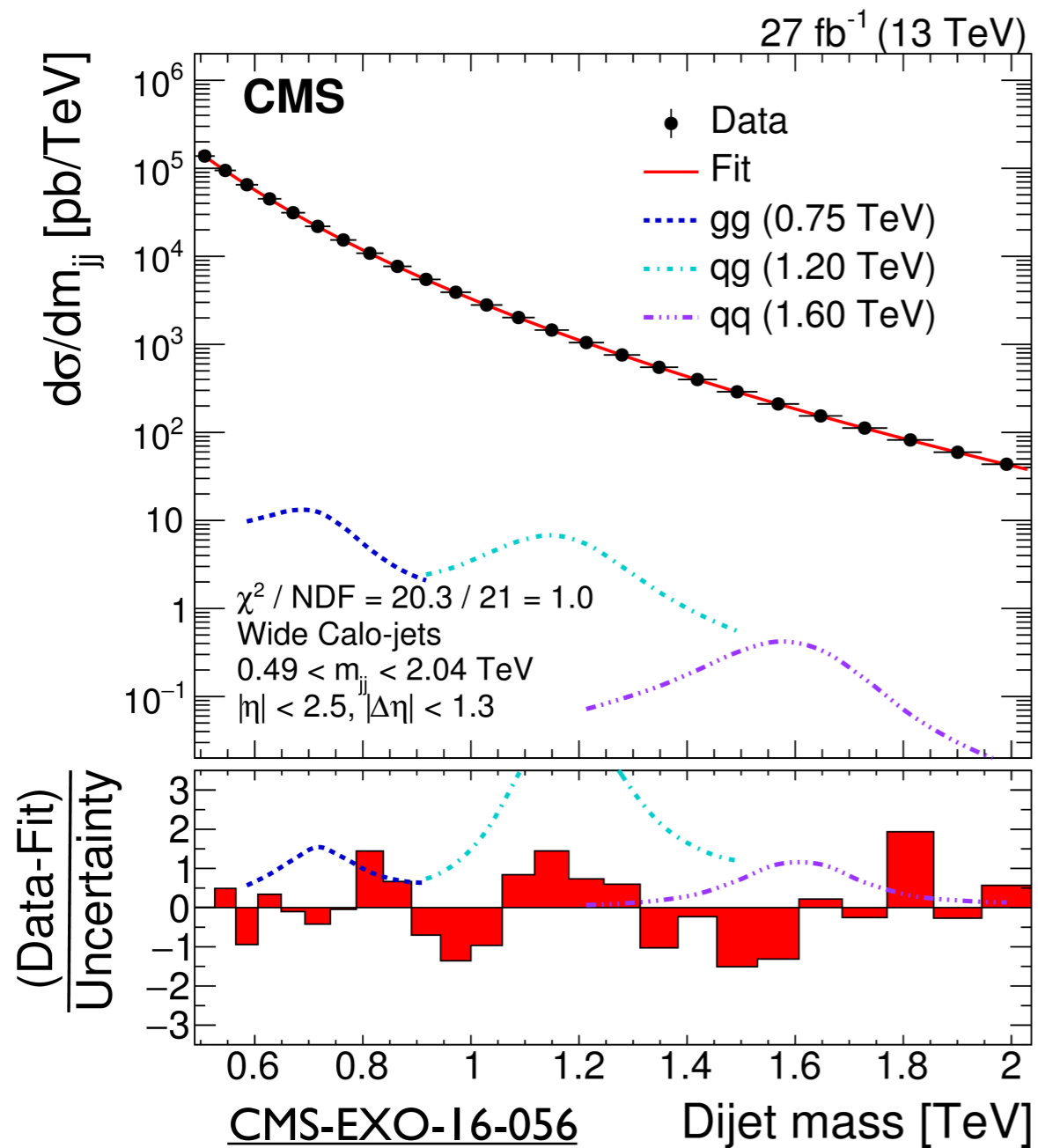
$$\text{Size} \times \text{Event Rate} = \text{Total Bandwidth}$$

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

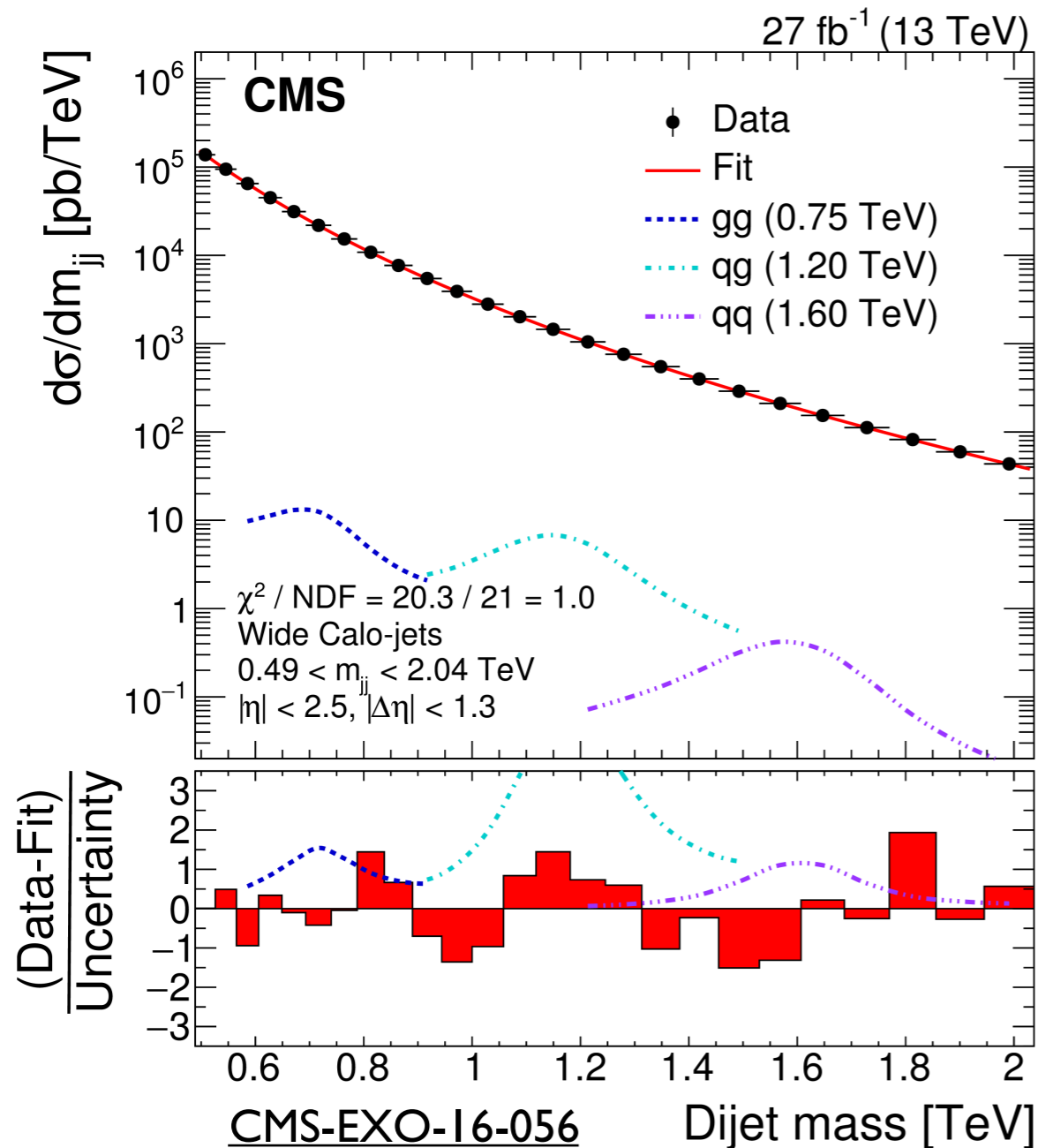
# What You Can Accomplish



# What You Can Accomplish

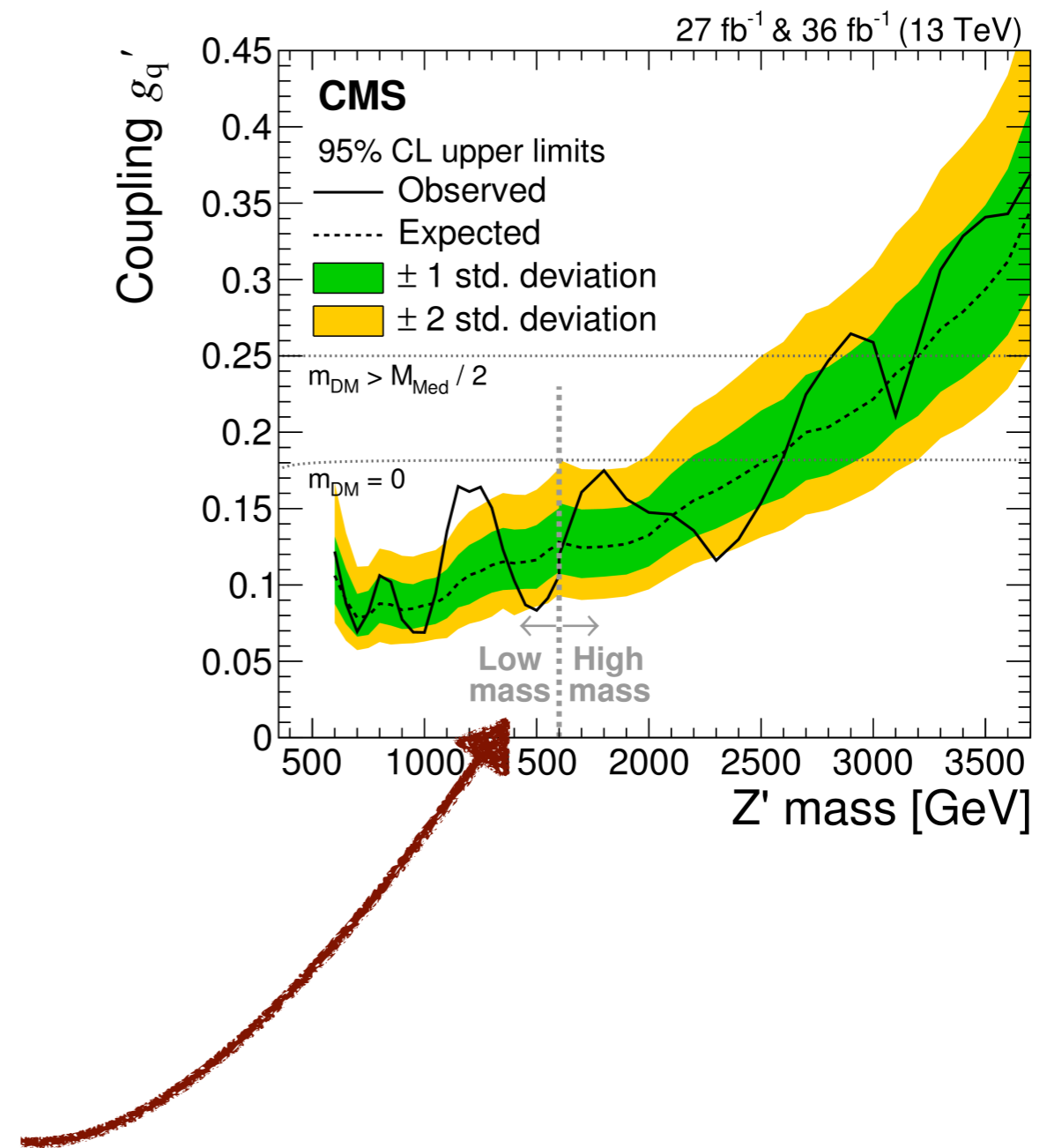
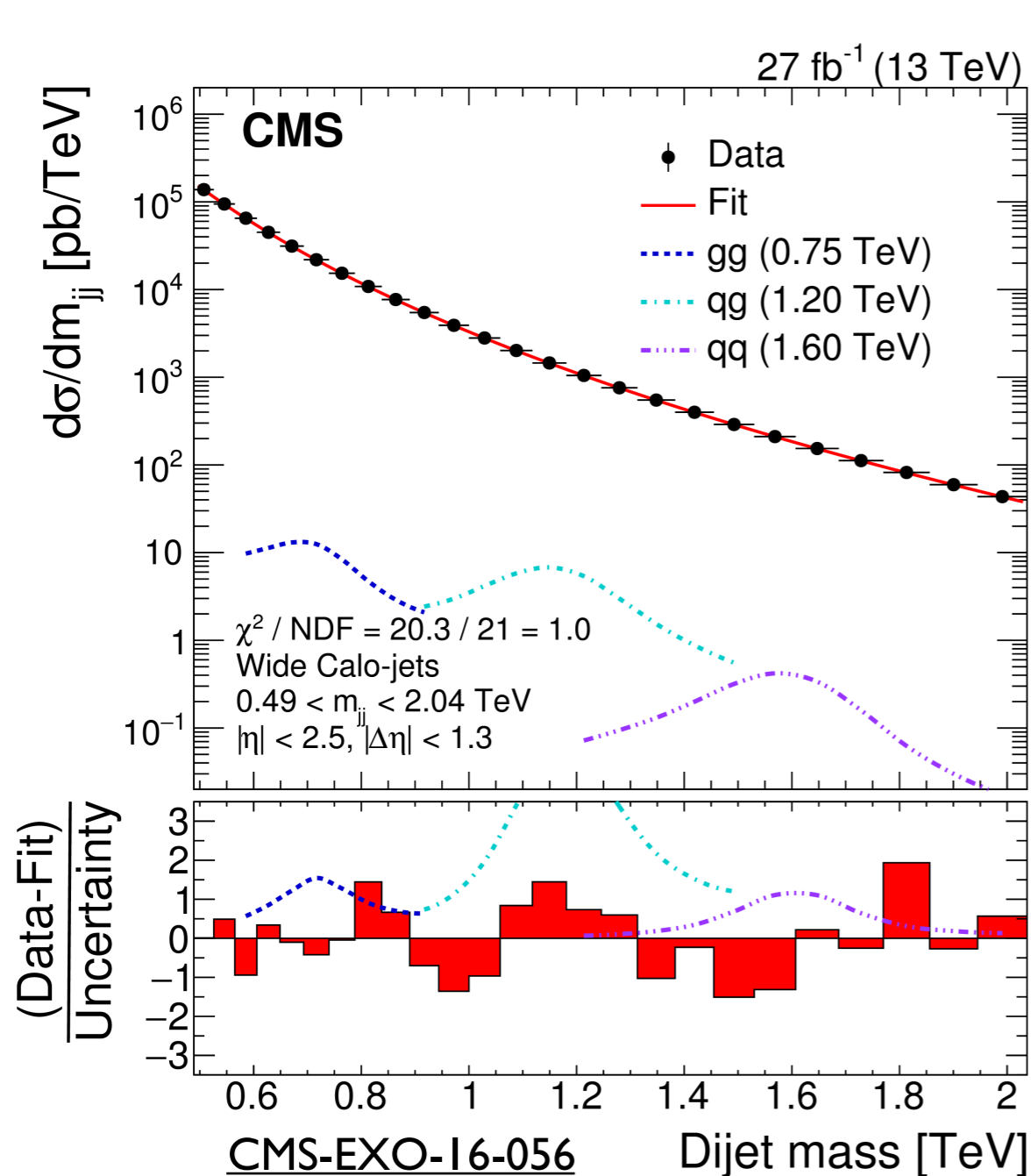


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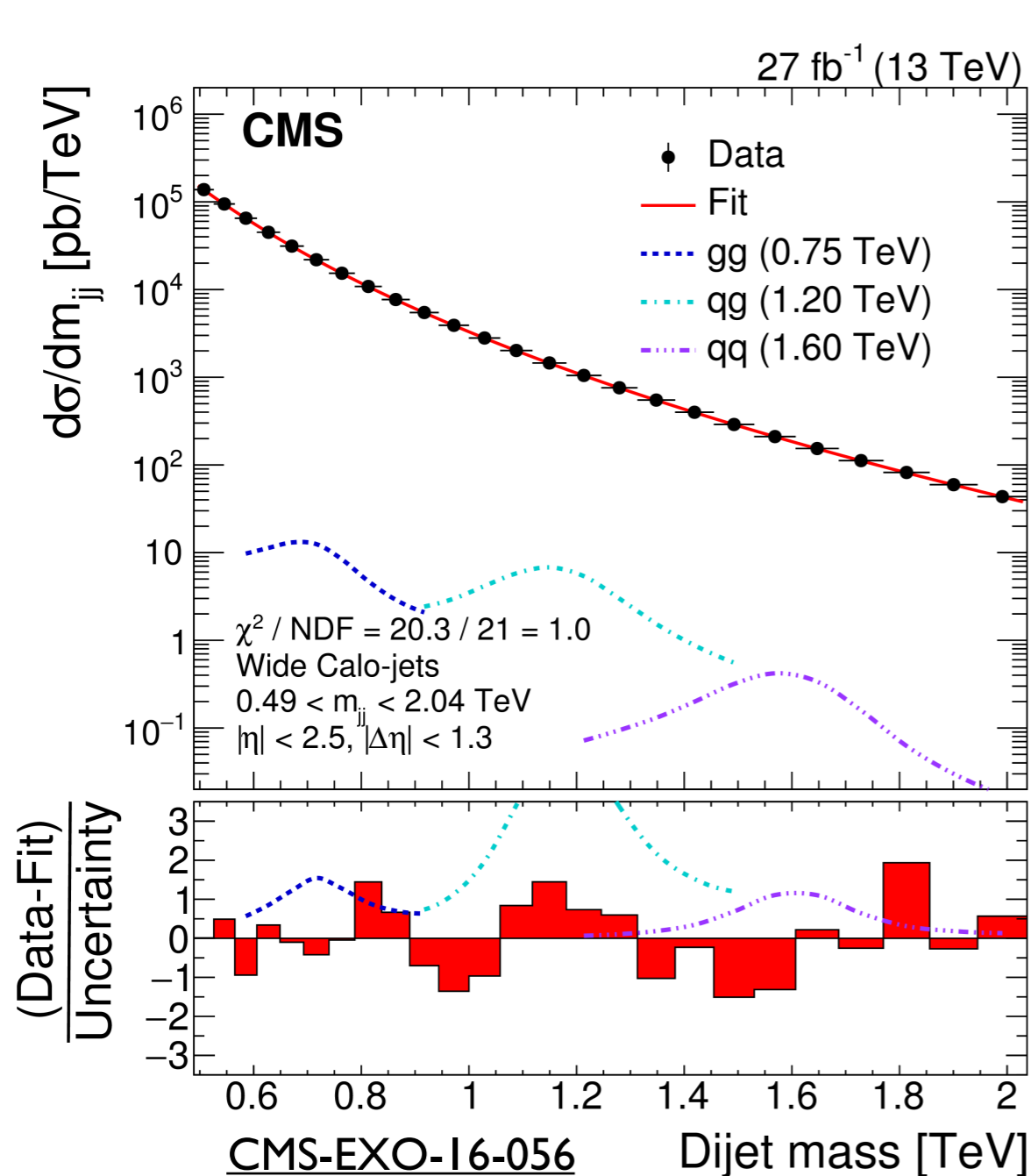
Can collect huge datasets  
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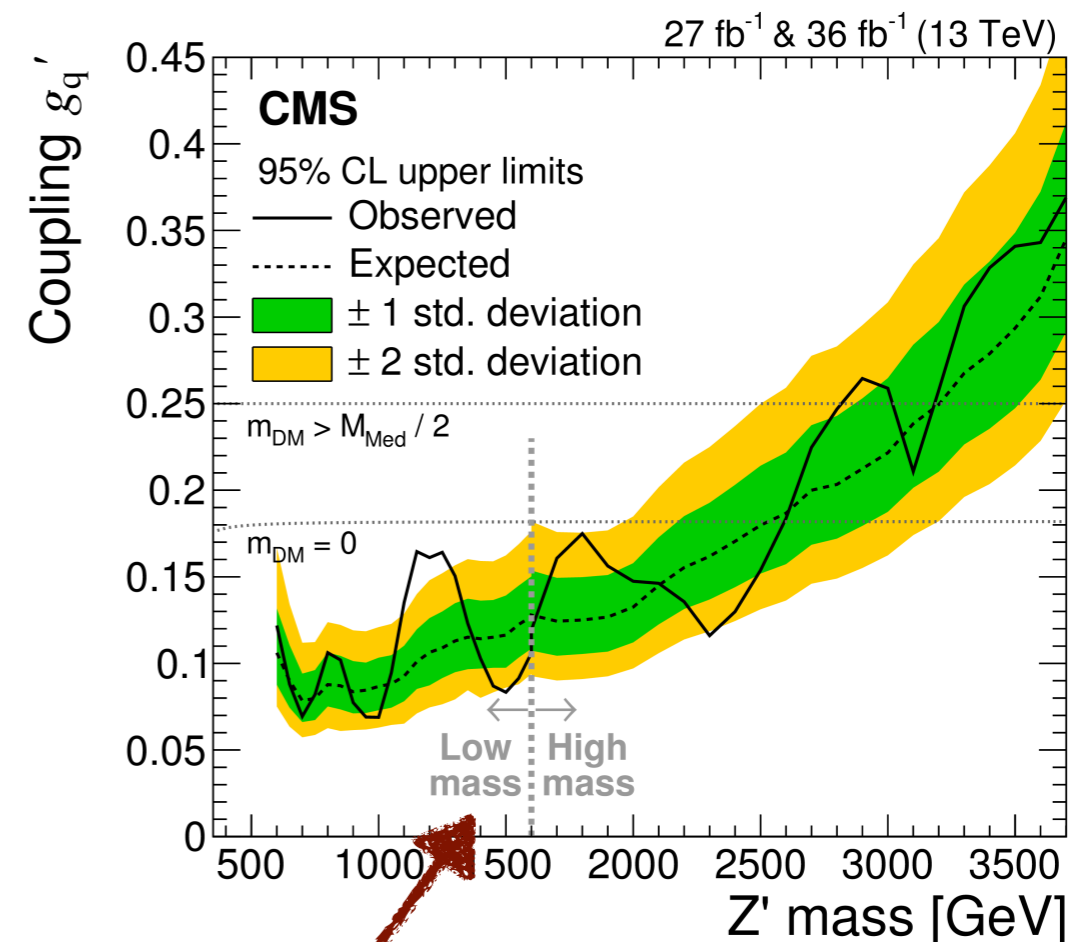


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# What You Can Accomplish



Can collect huge datasets  
at low mass using this technique!



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



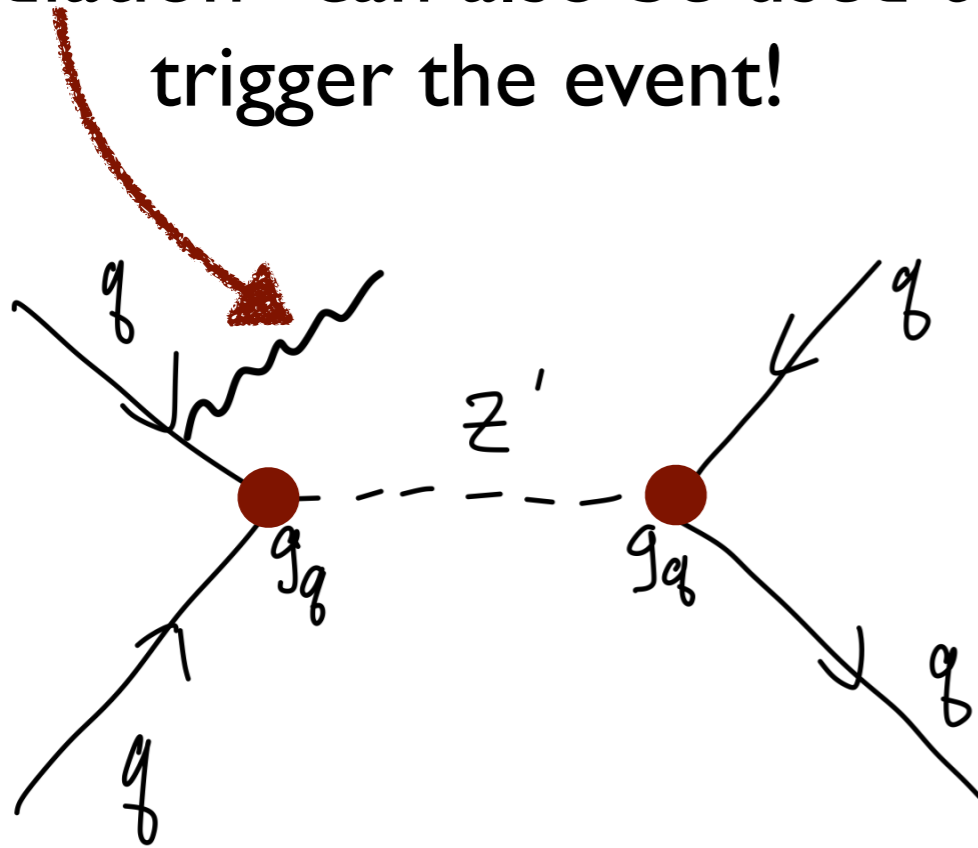
# Extra Radiation



# Extra Radiation



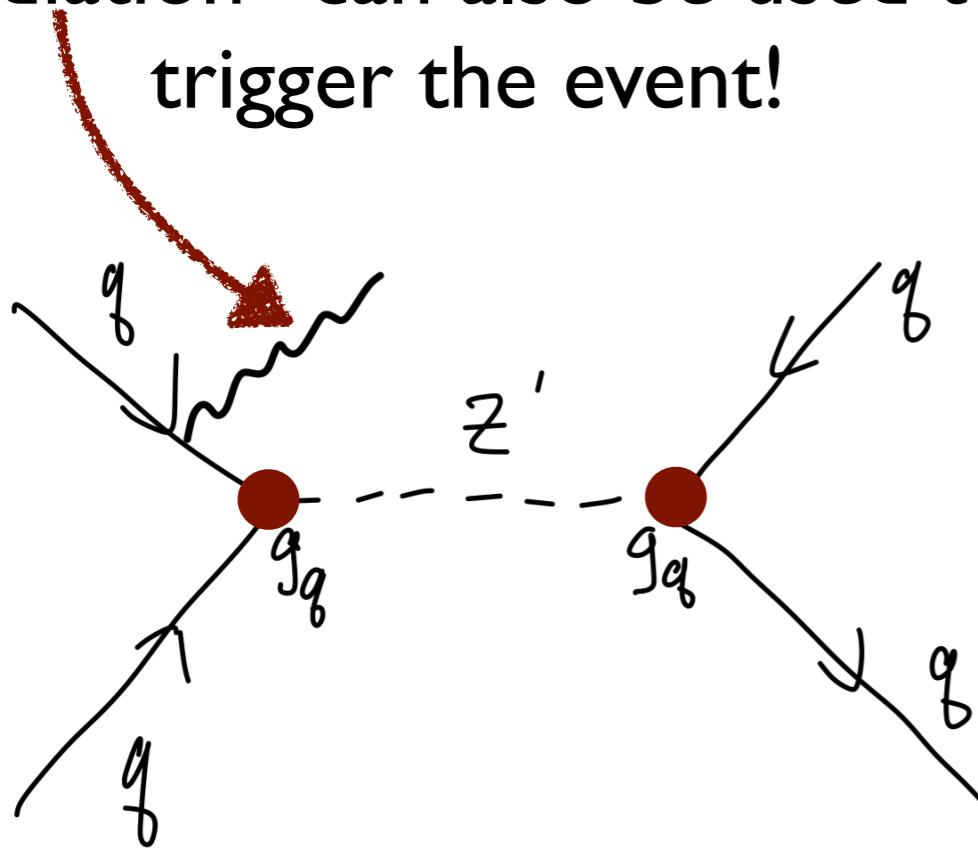
Photon or jet “initial state radiation” can also be used to trigger the event!



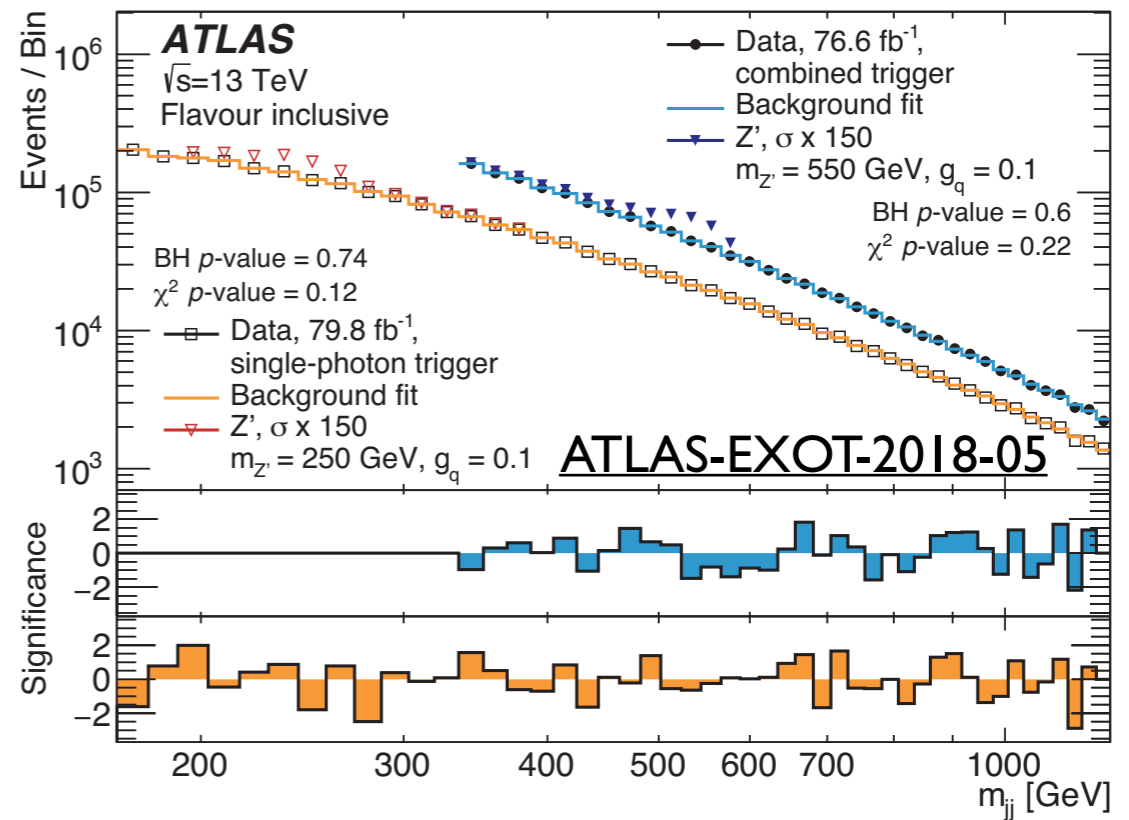
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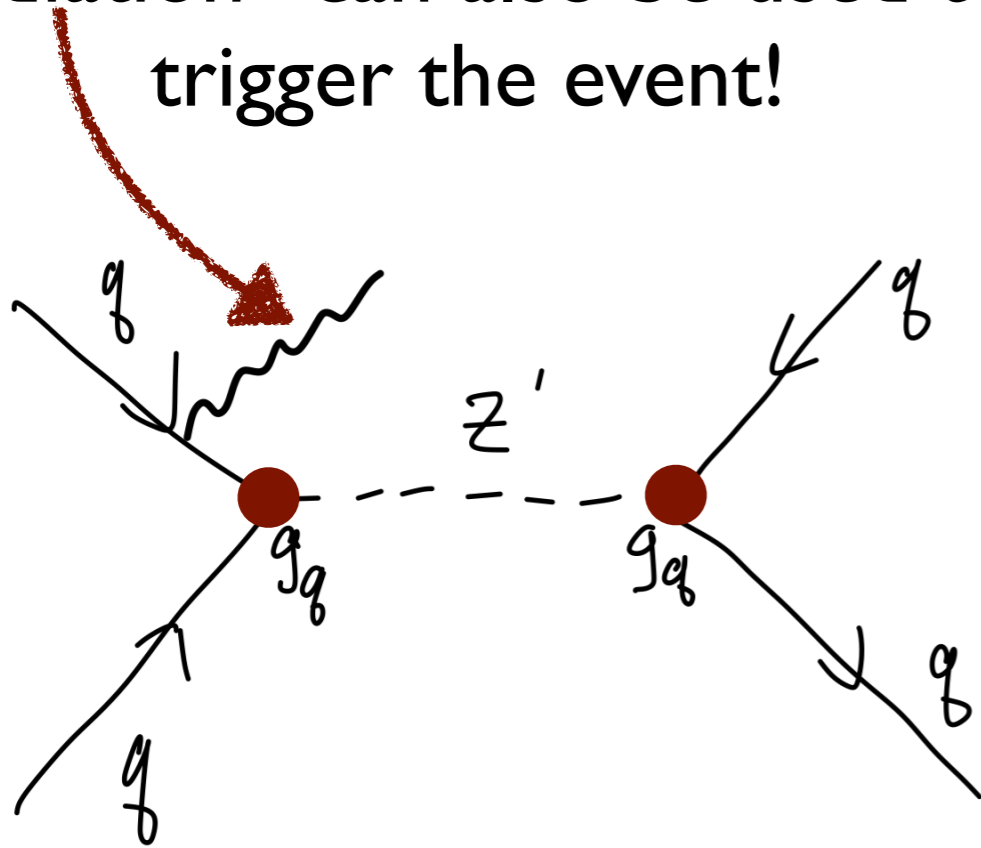
Even lower regions of mediator mass can be explored with these techniques



# Extra Radiation

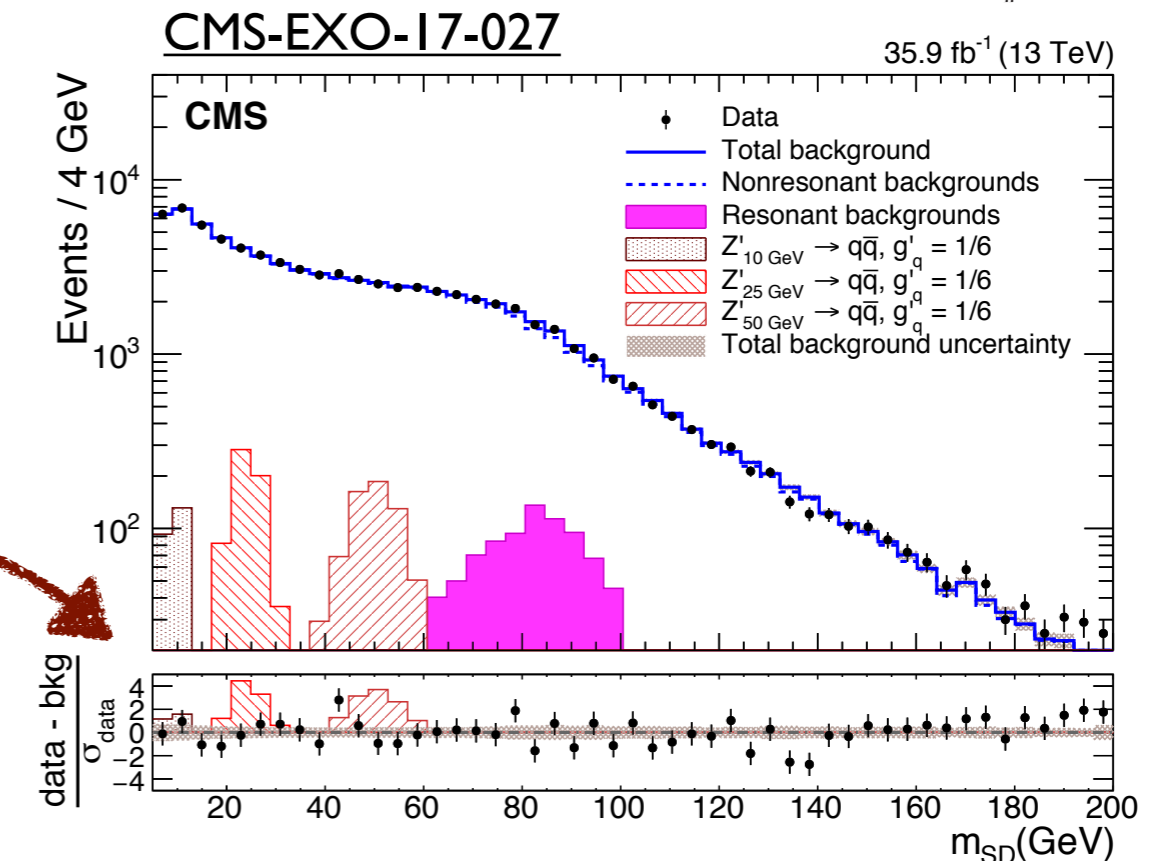
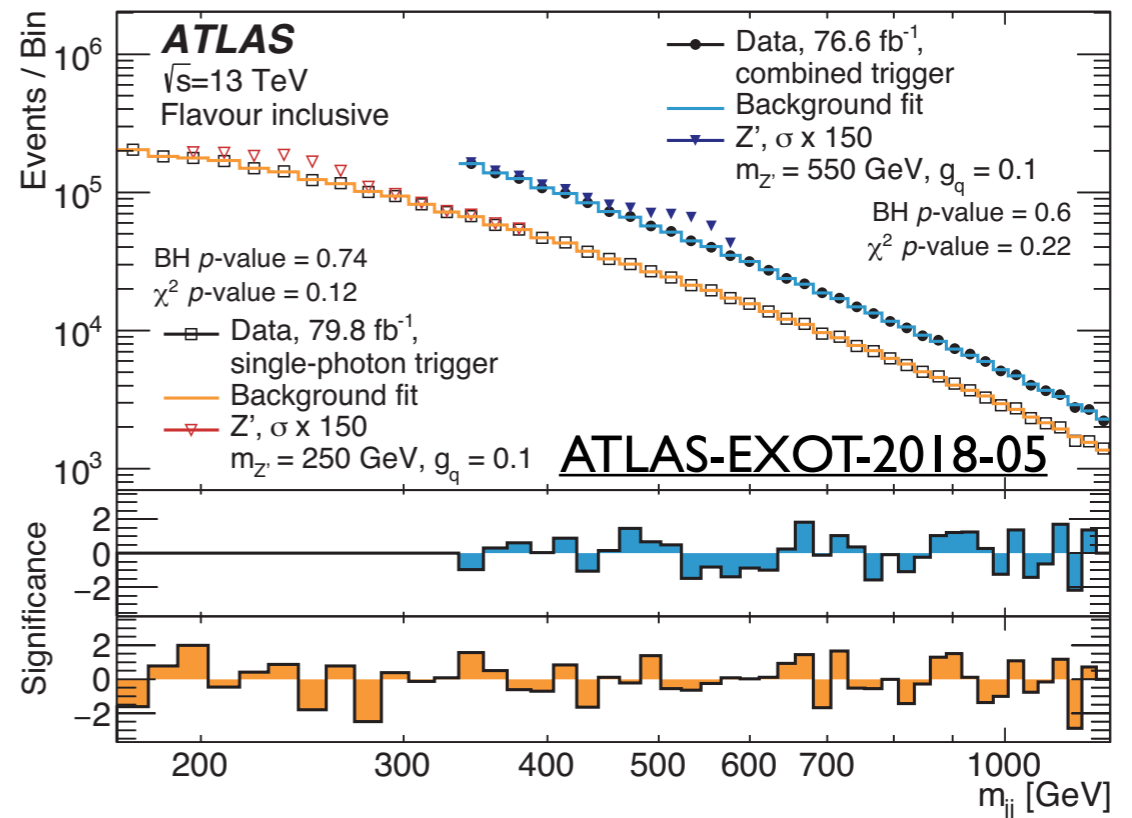


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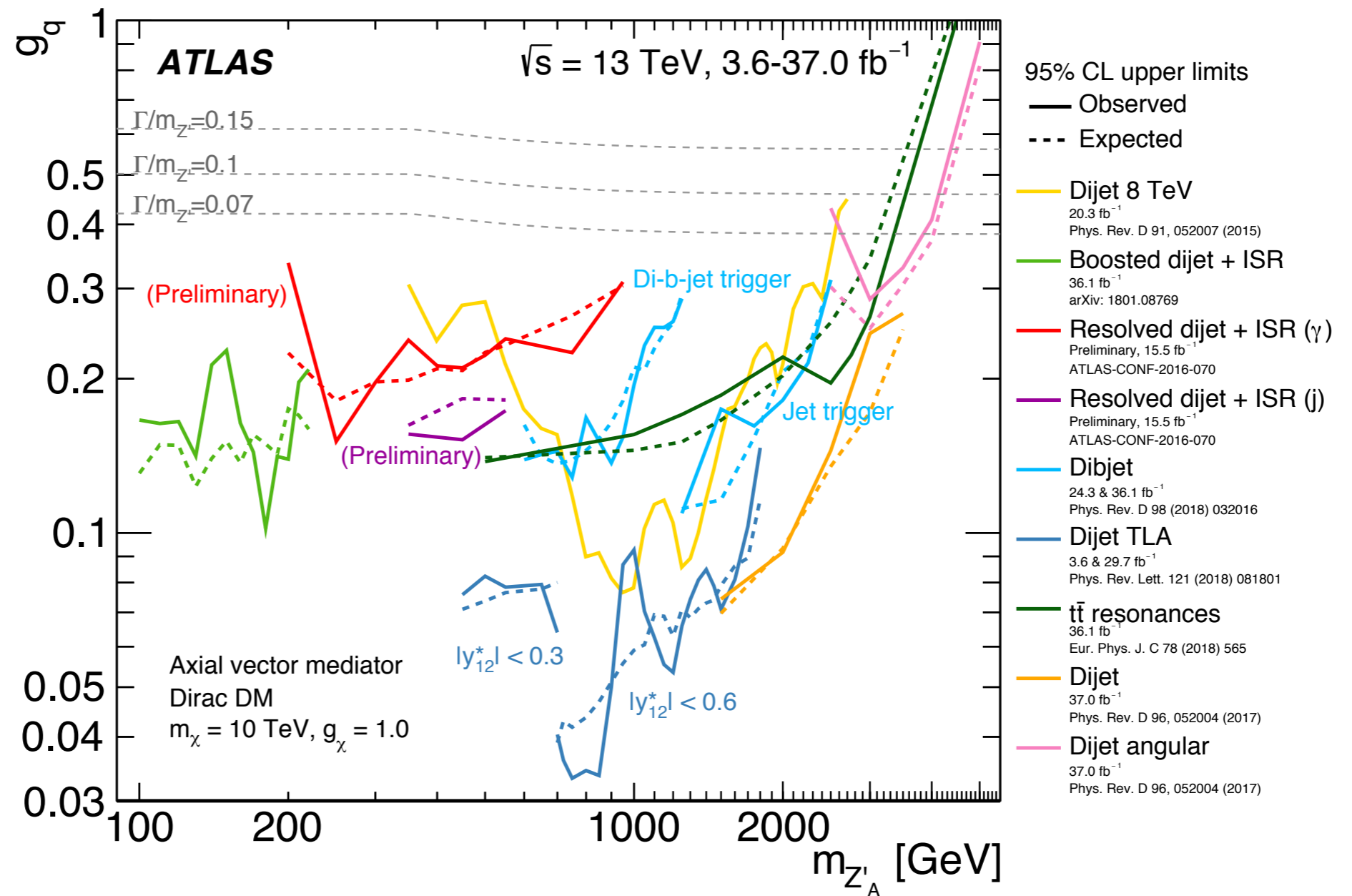
Can even search as low as 10 GeV!



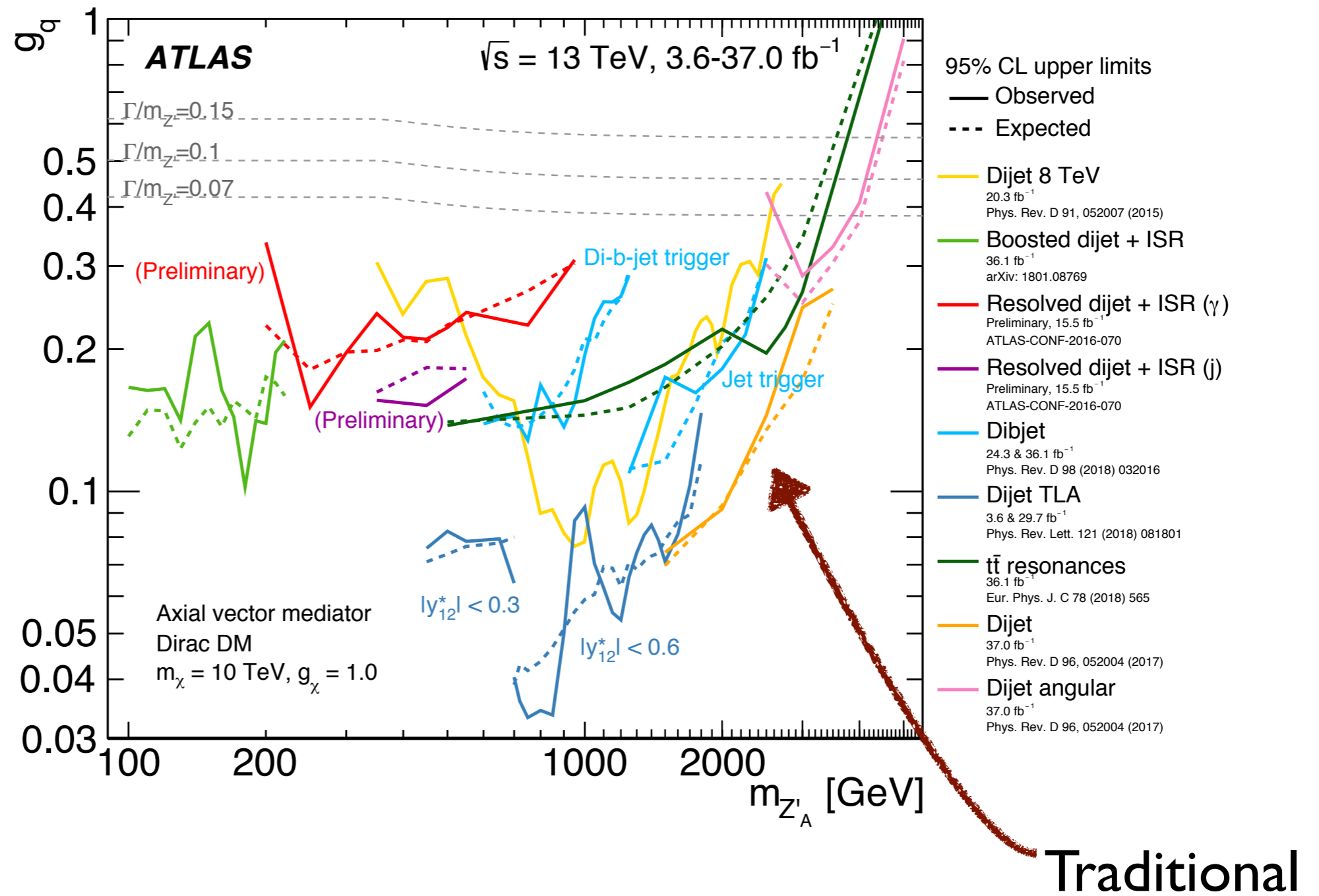
# The Big Picture for Z'



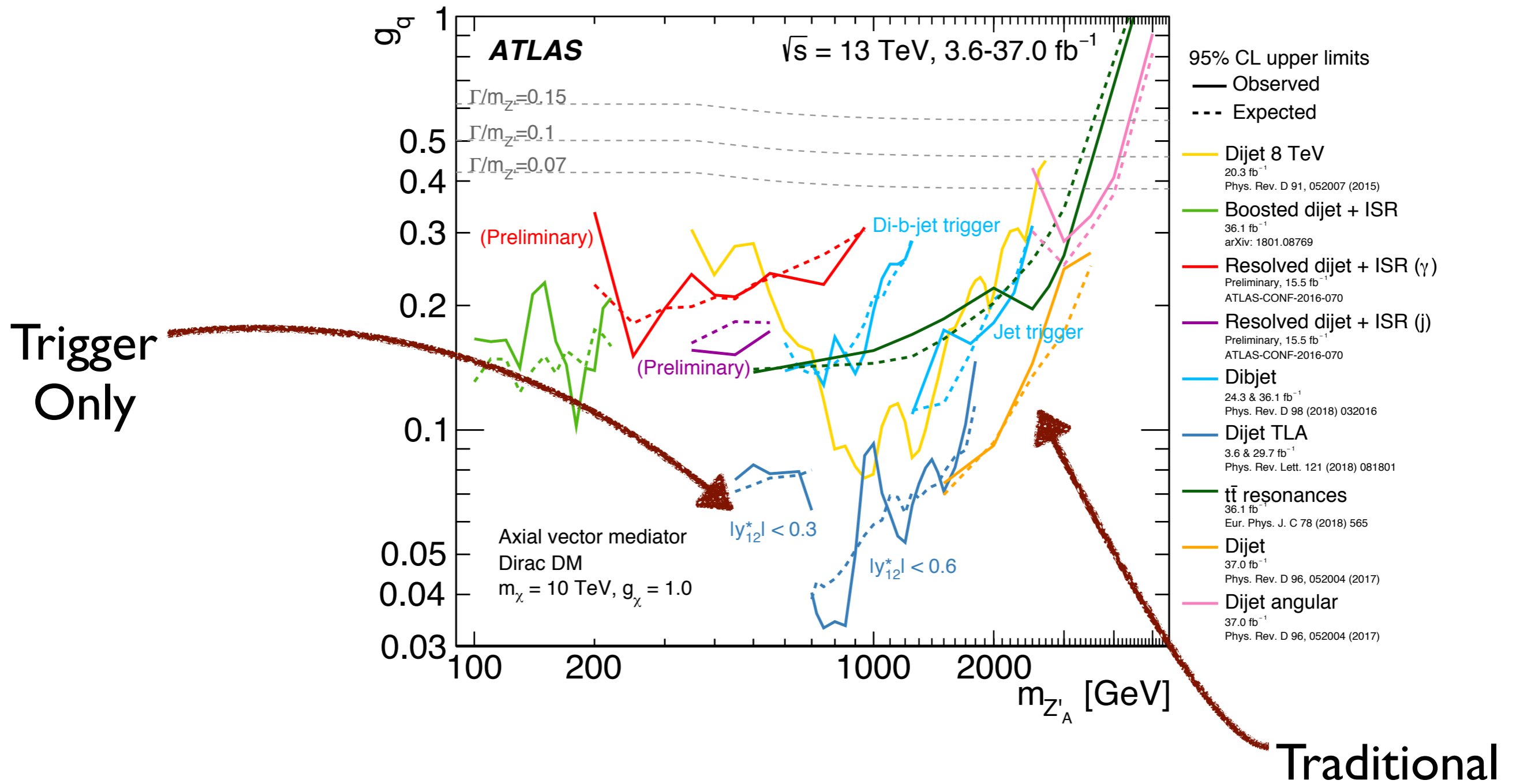
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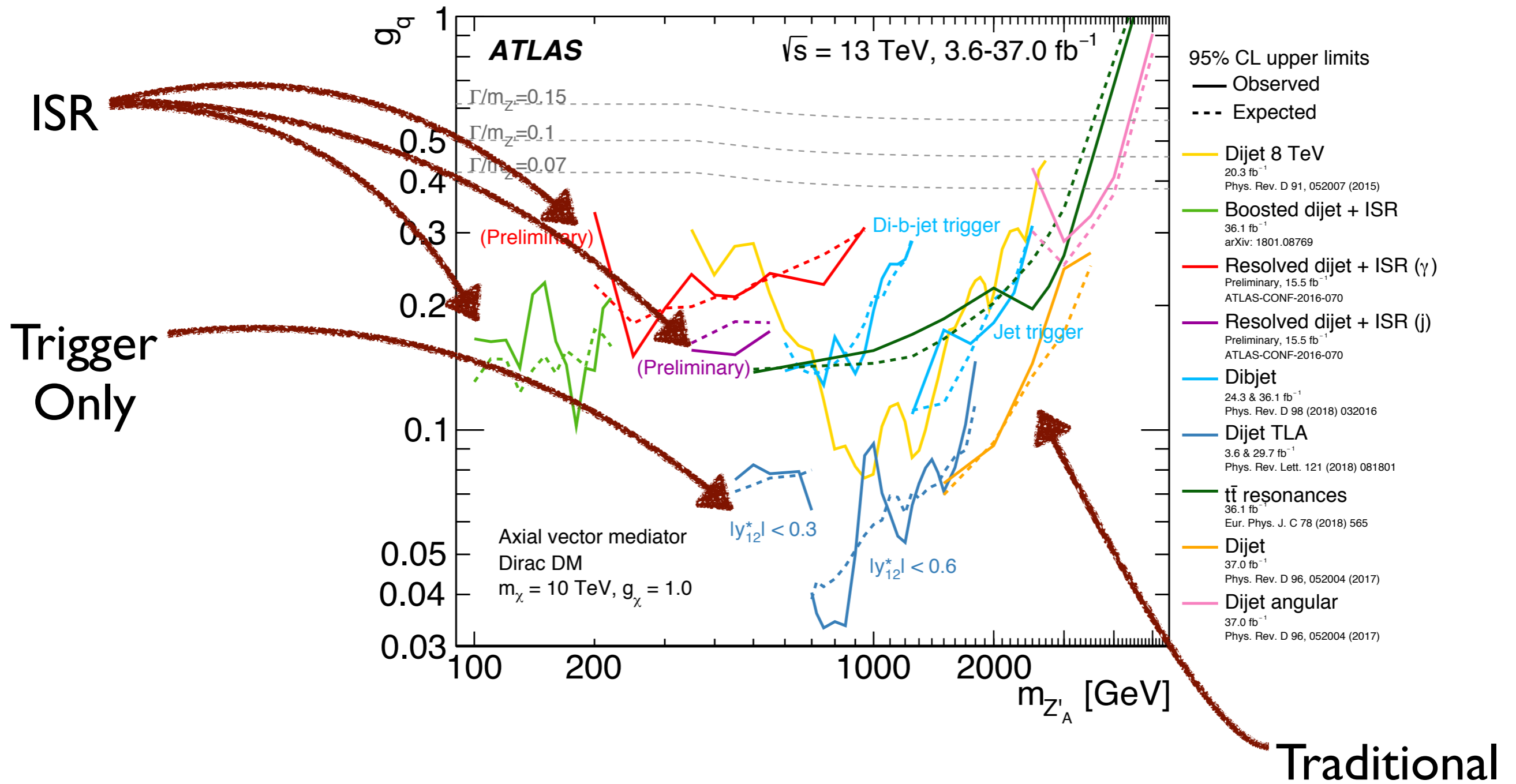


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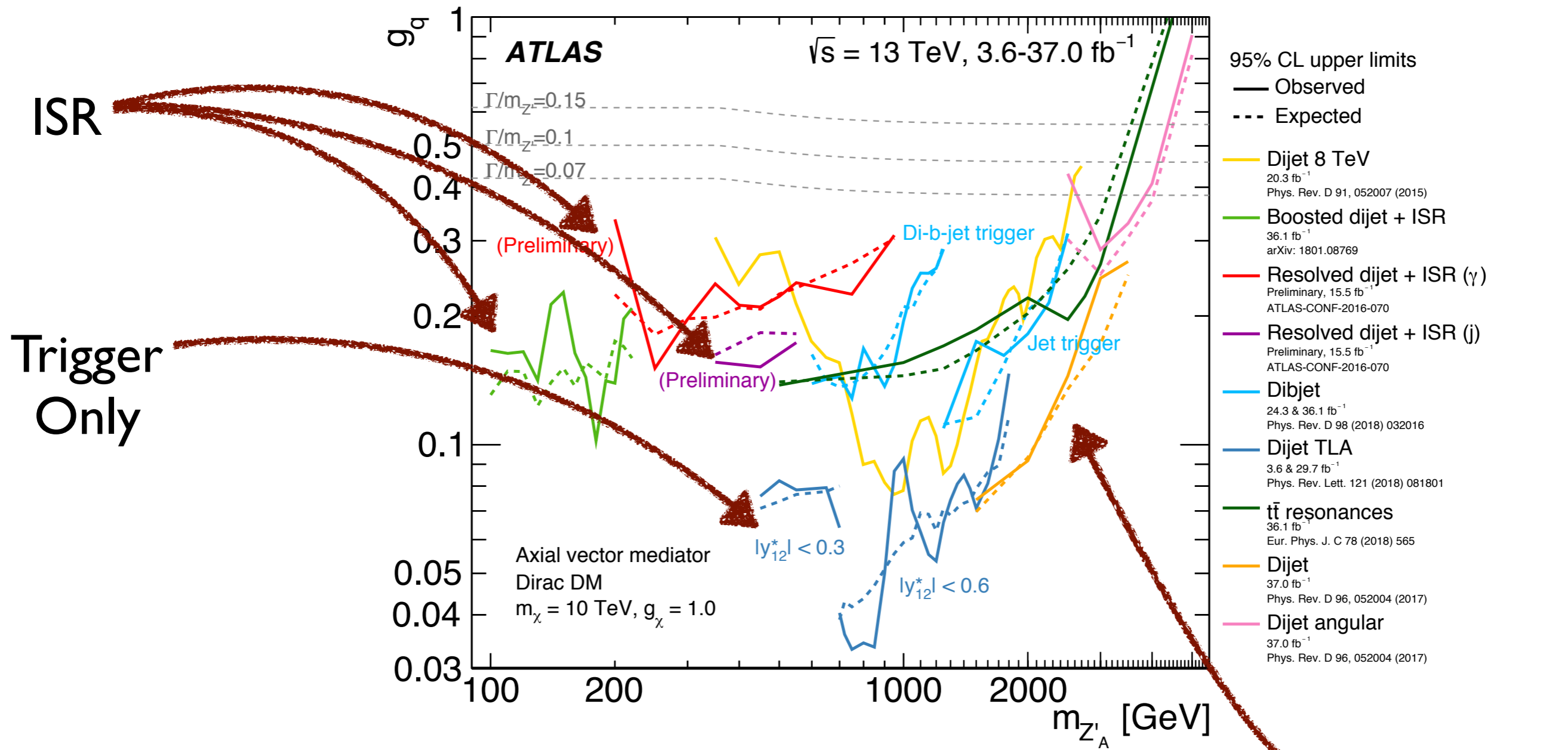




# The Big Picture for Z'



# The Big Picture for Z'



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?



# Why Search for Rare Signals?

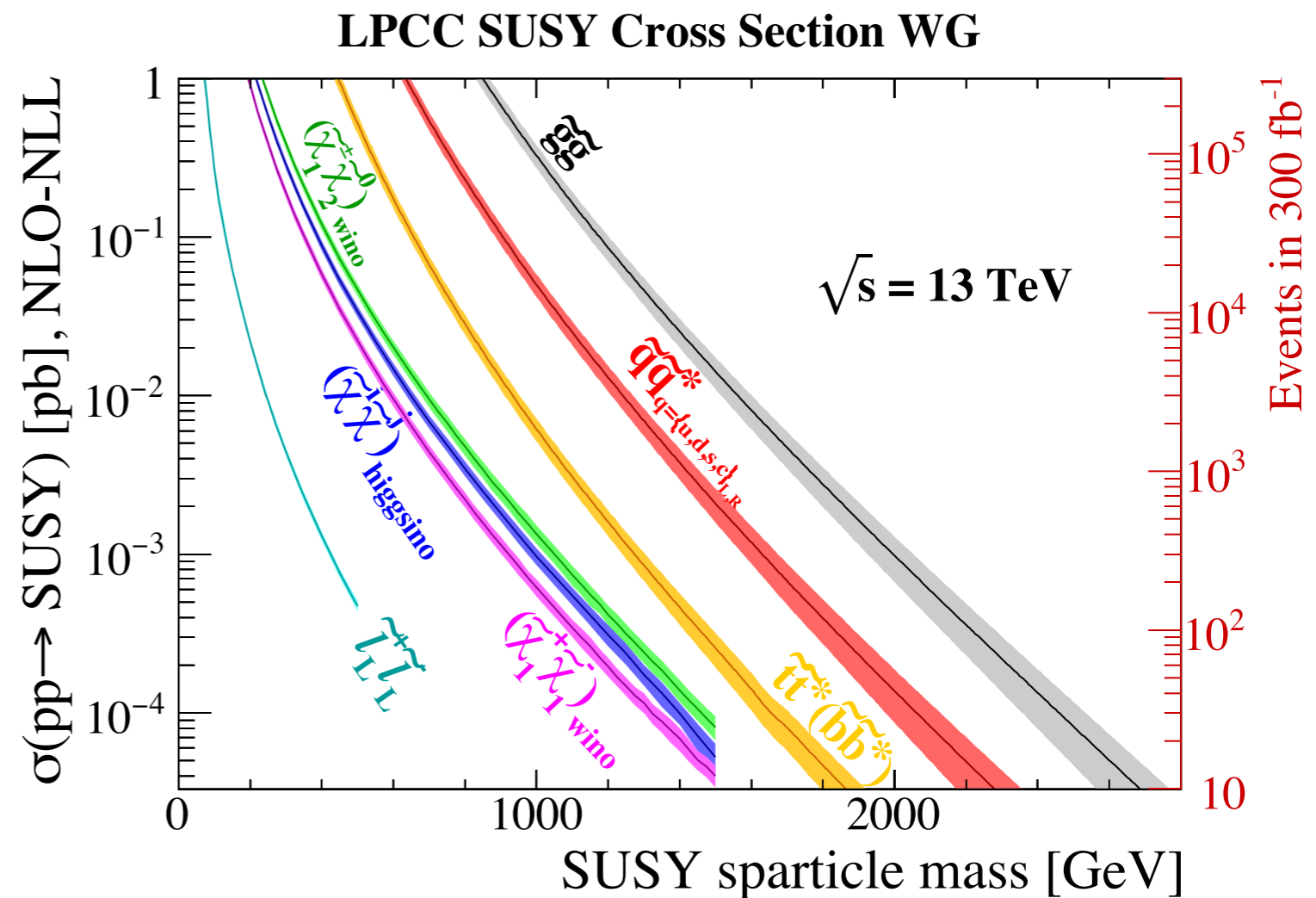


Because many theories predict low cross-section signals!

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<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections>

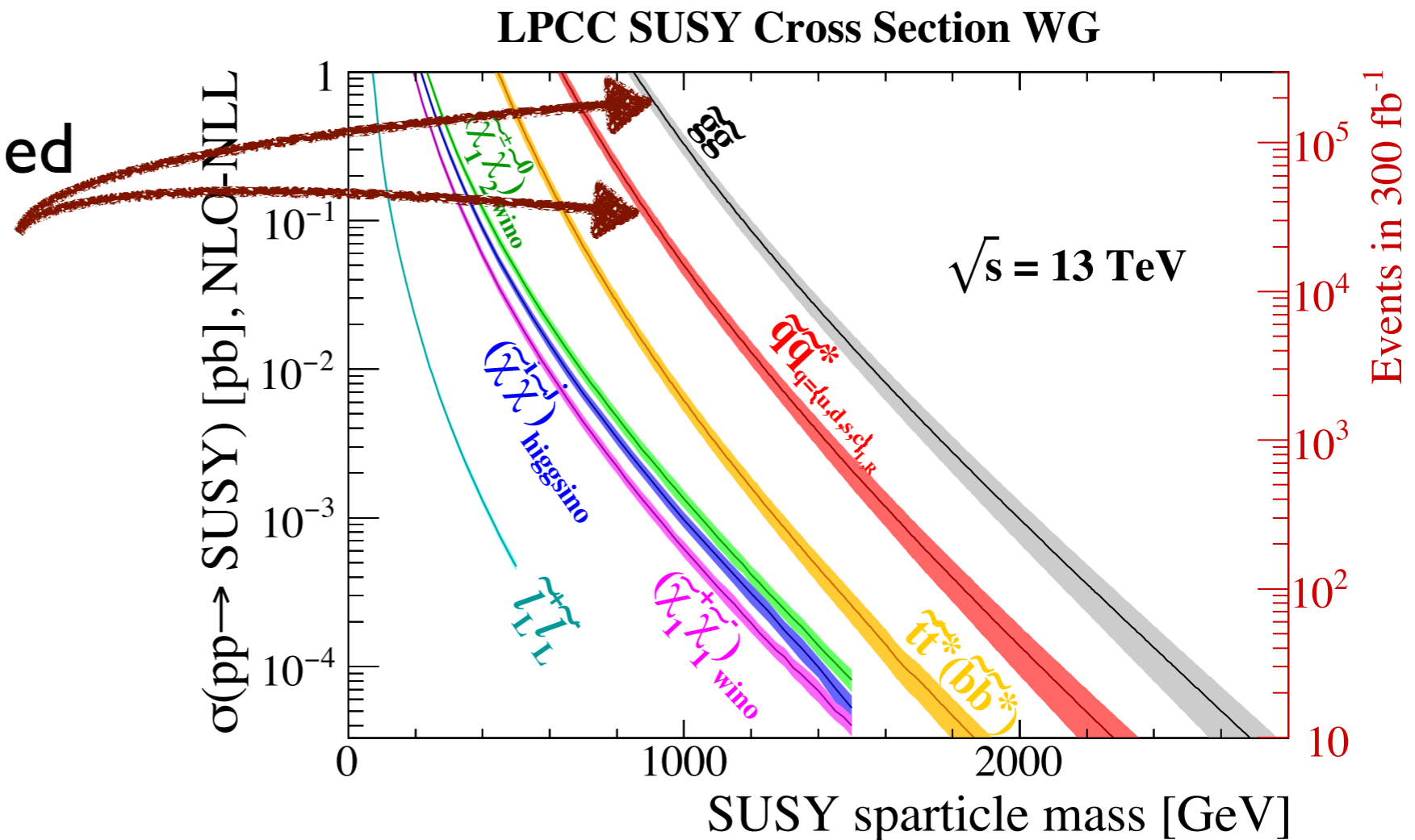
arXiv:1407.5066

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If you've already excluded  
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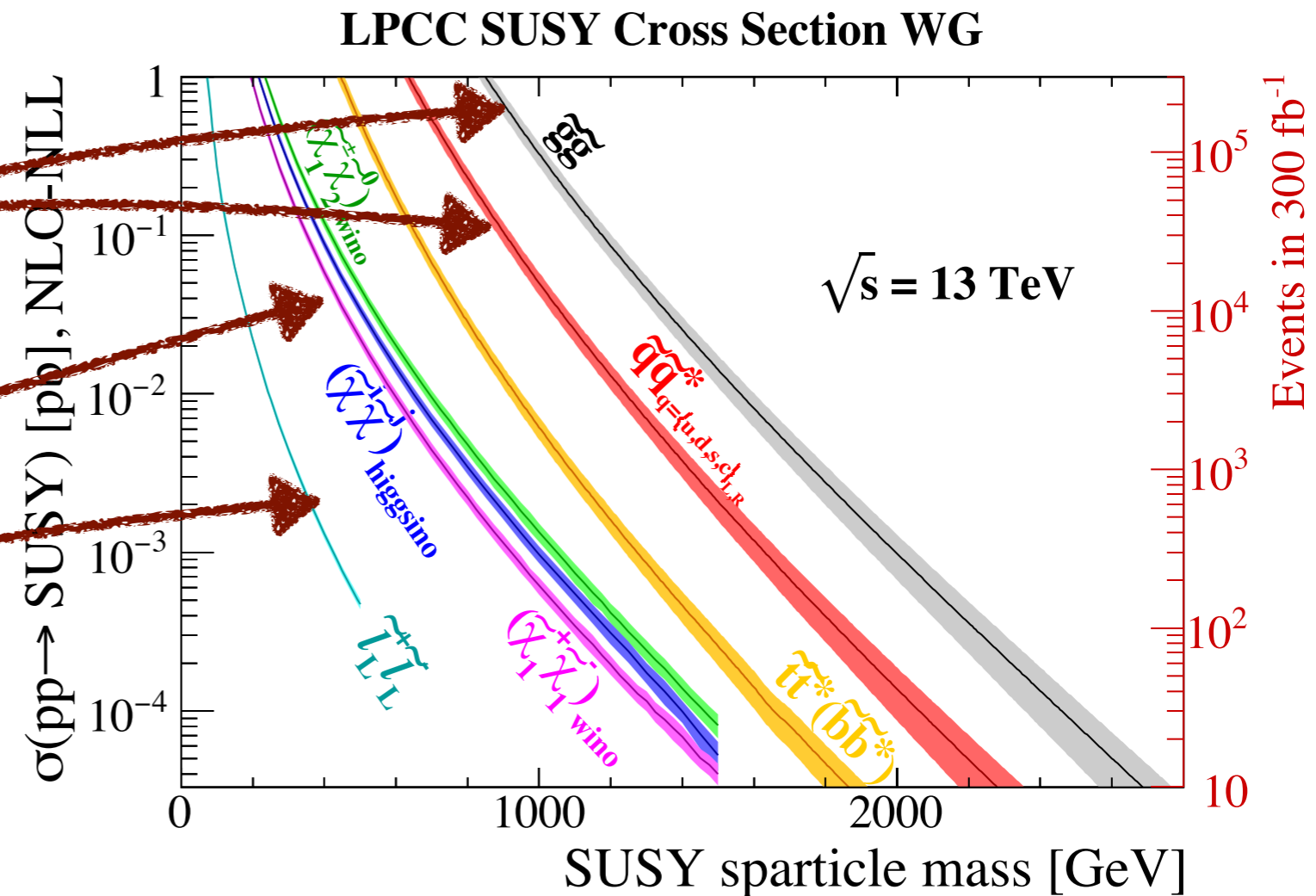
# Why Search for Rare Signals?



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If you've already excluded  
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Higgsinos and sleptons  
might still be in sight!



<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections>

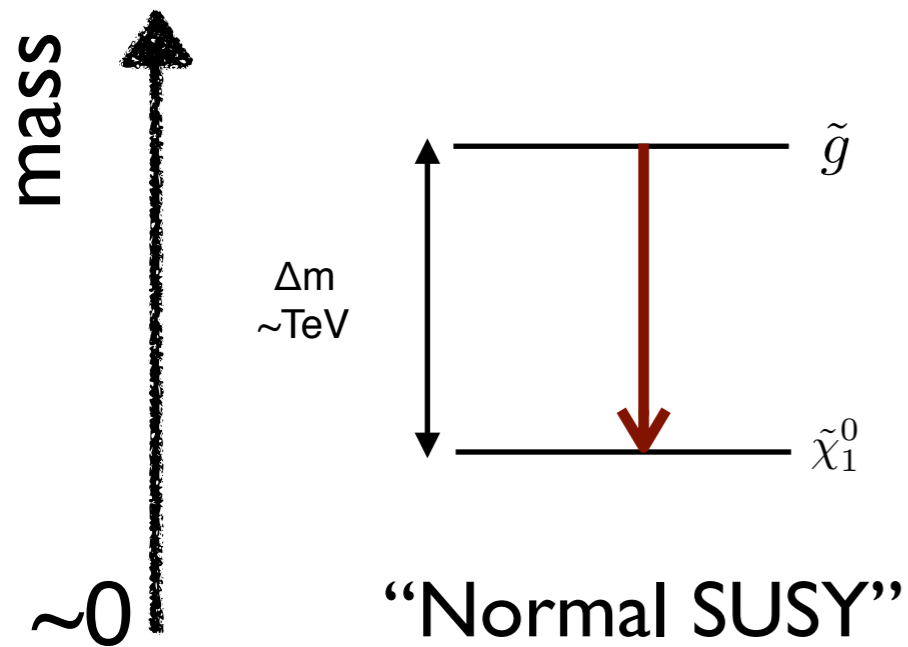
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# Higgsinos: The Challenge



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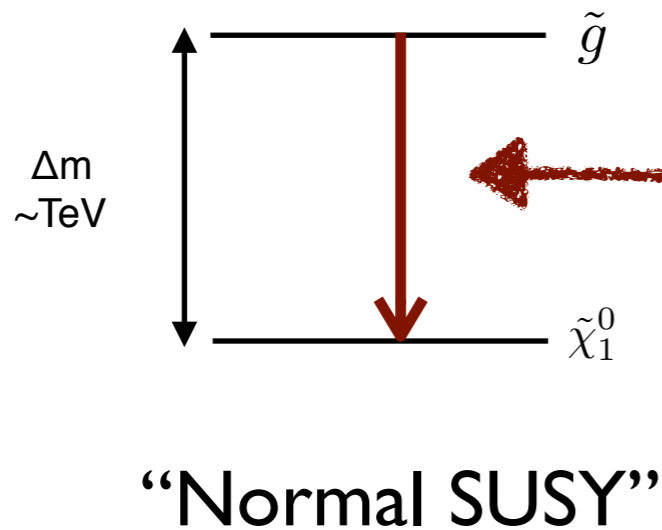


“Classic” SUSY searches exploit large mass splittings

# Higgsinos: The Challenge



mass  
↑  
~0



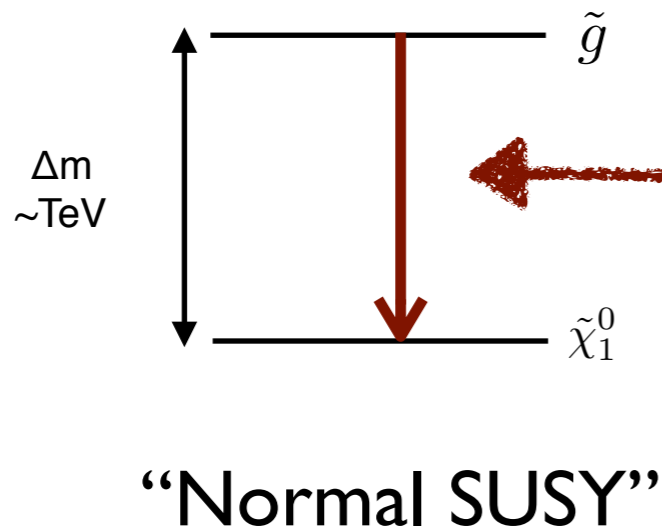
“Classic” SUSY searches exploit large mass splittings

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

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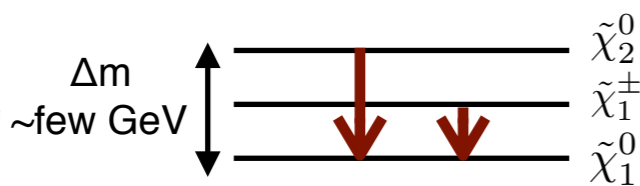
mass  
↑  
~0



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↑  
 $\mu$   
~0



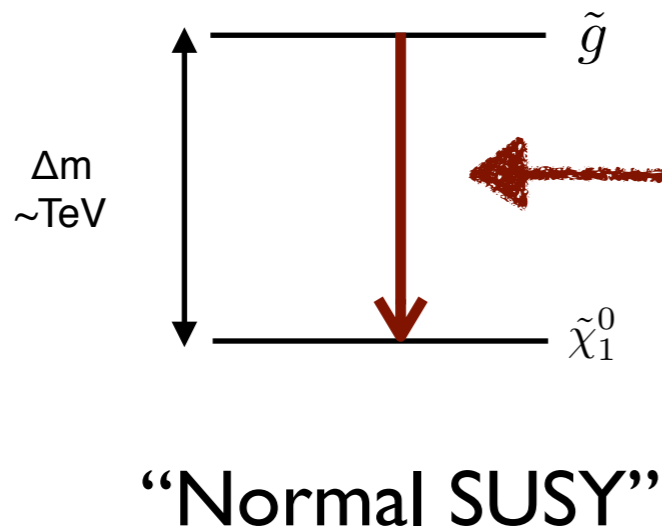
Higgsinos

Higgsinos are another story...

# Higgsinos: The Challenge



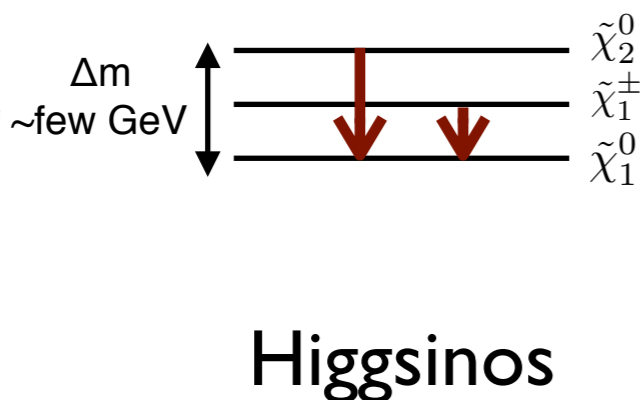
mass  
↑  
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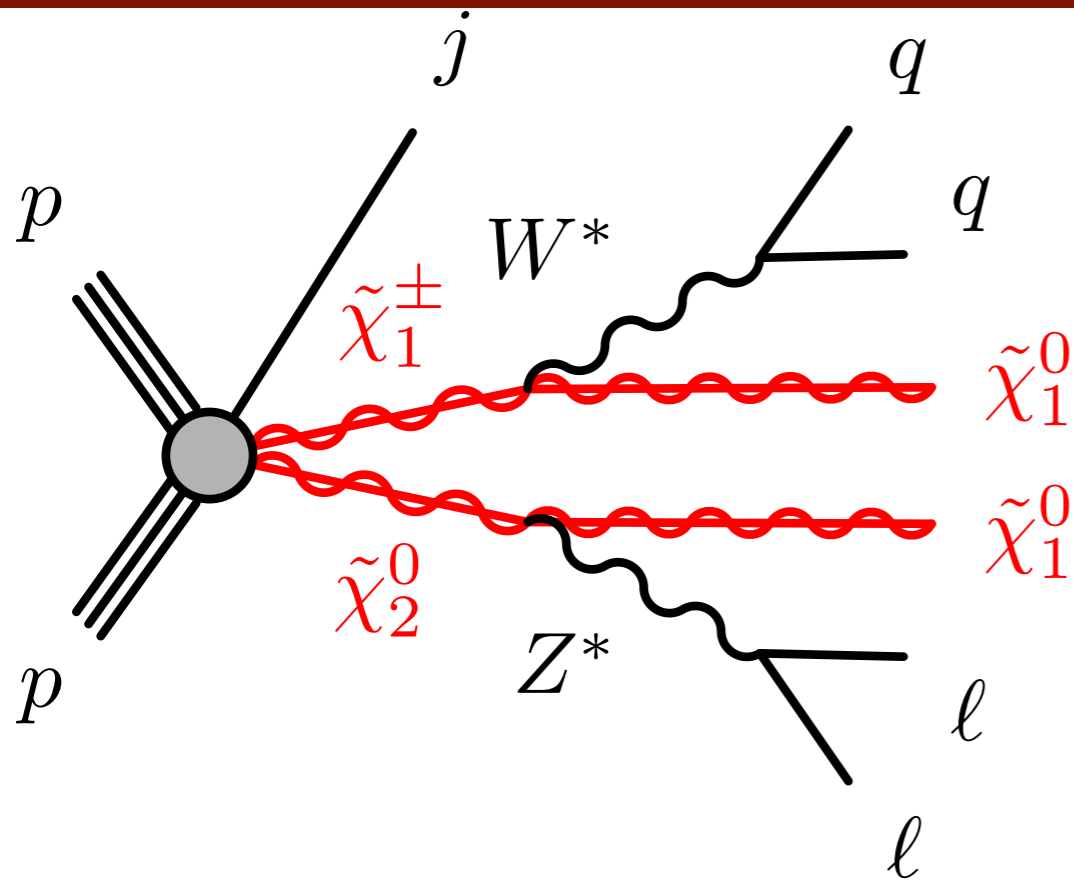
Higgsinos are another story...

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

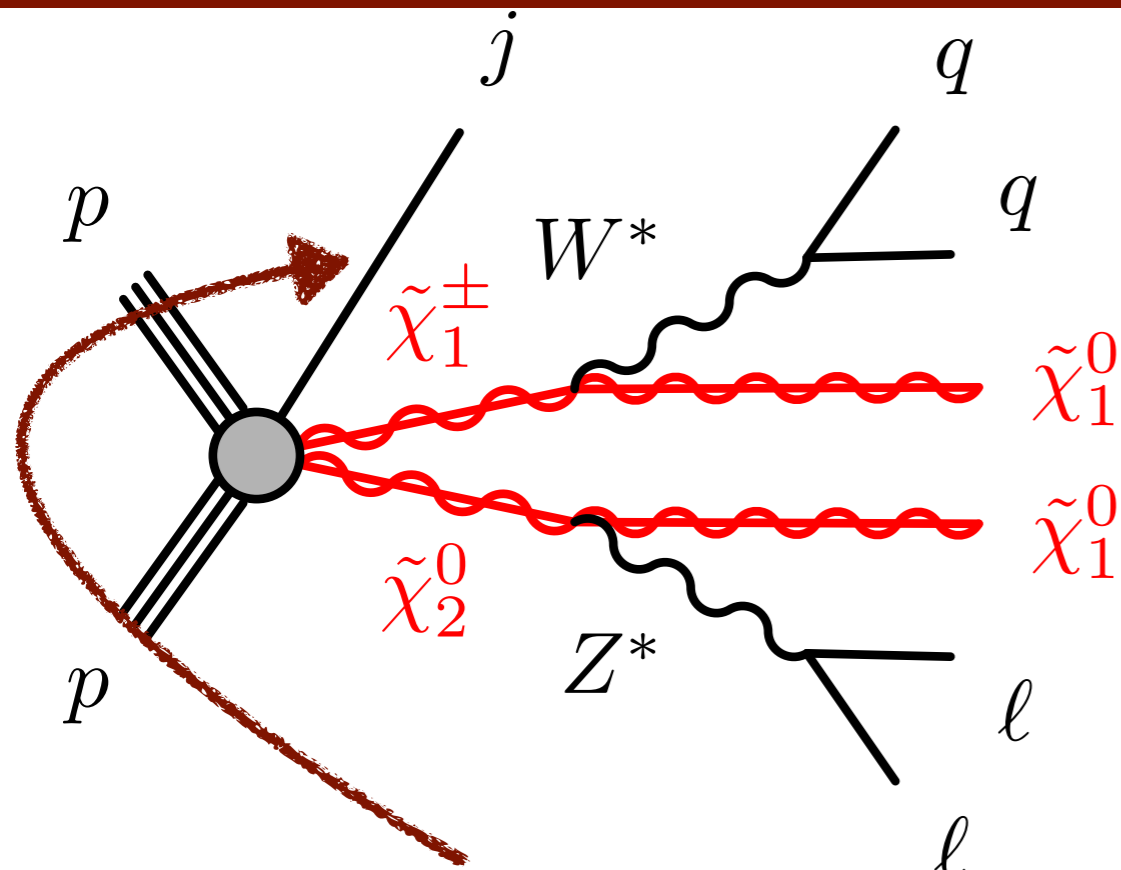
# Searching for Rare Higgsinos



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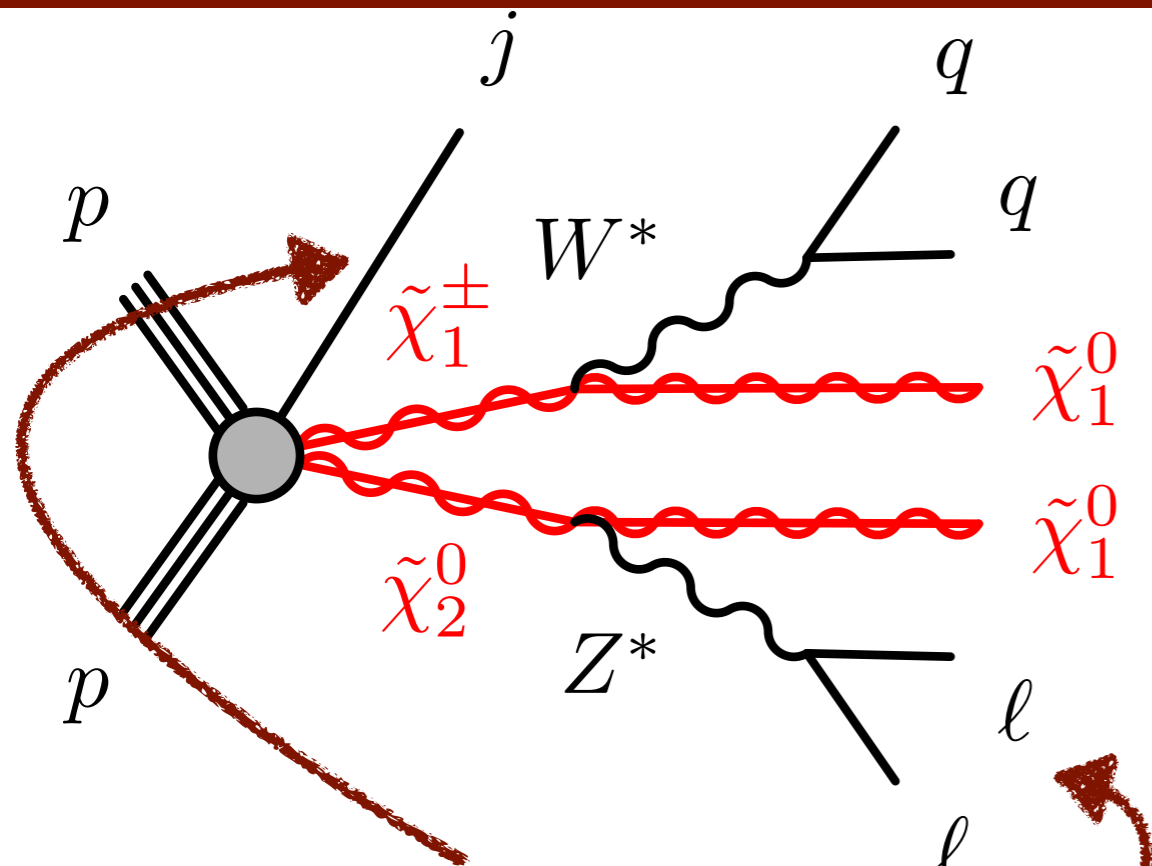
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Use an ISR jet to boost the system and trigger



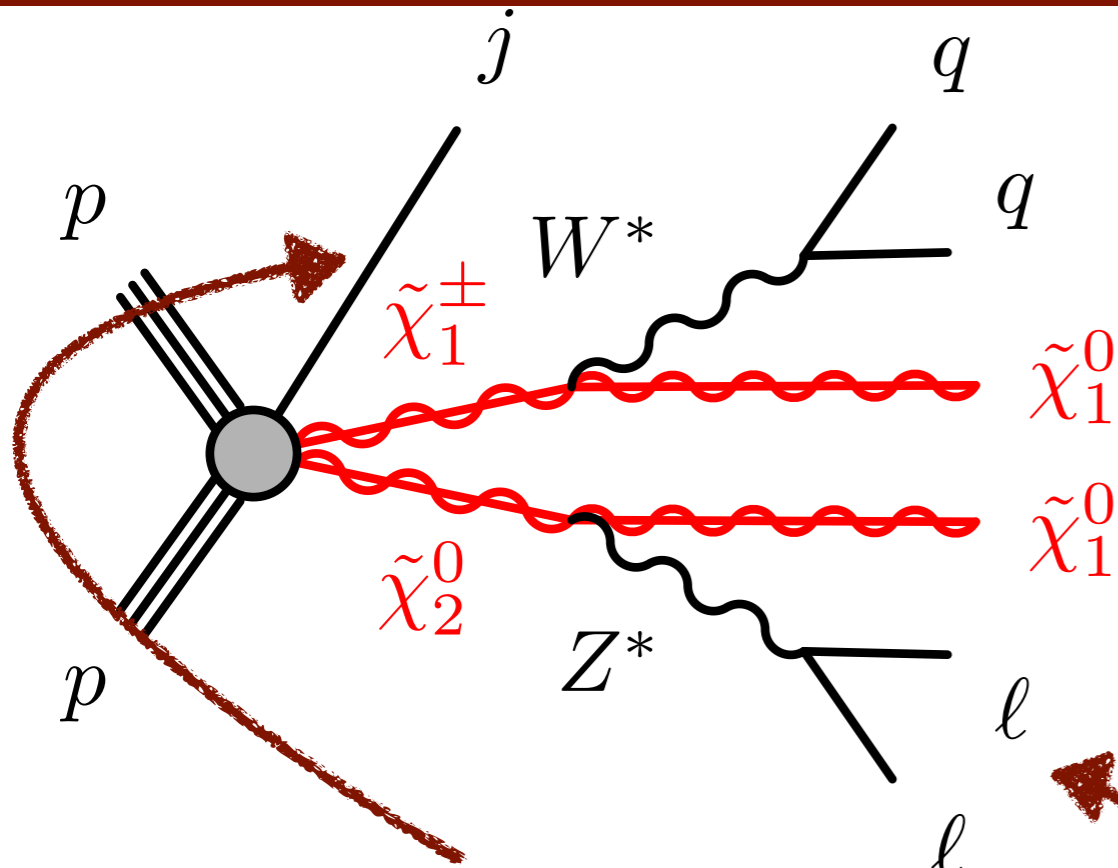
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Then, look for low-mass  $Z^*$  decays

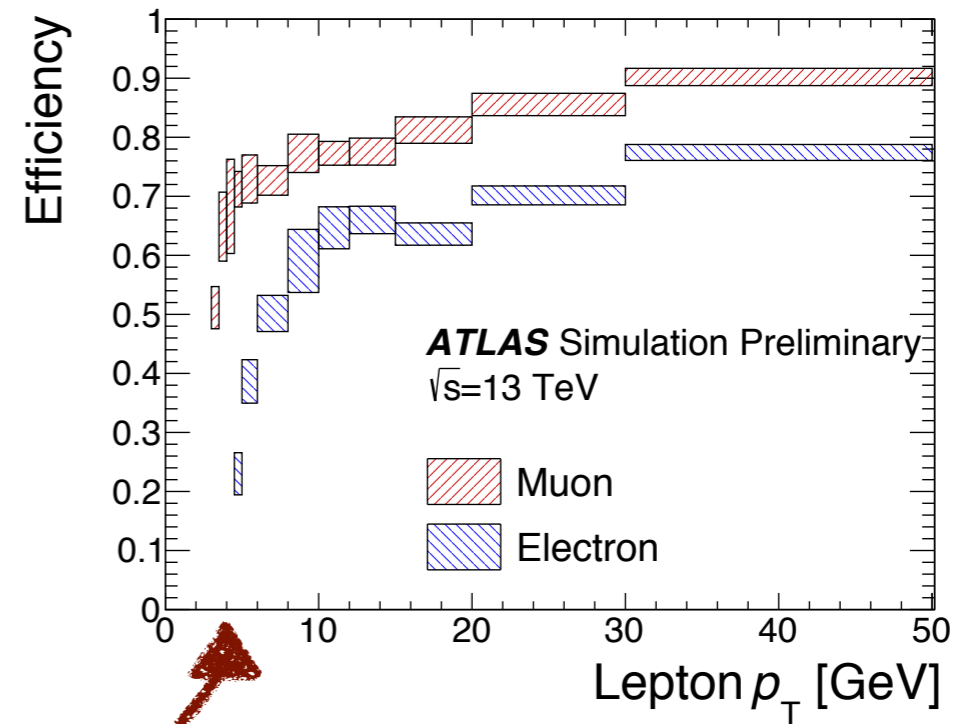
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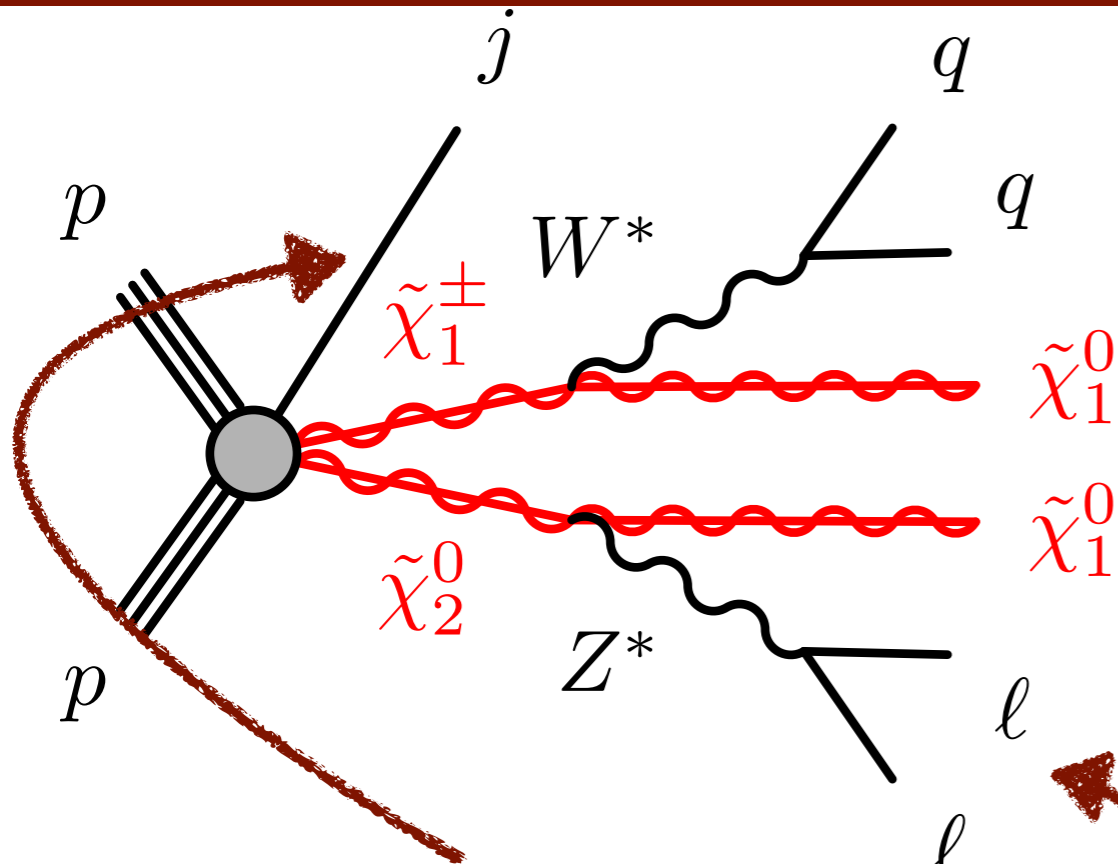
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Critical to reconstruct leptons at extremely low  $p_T$



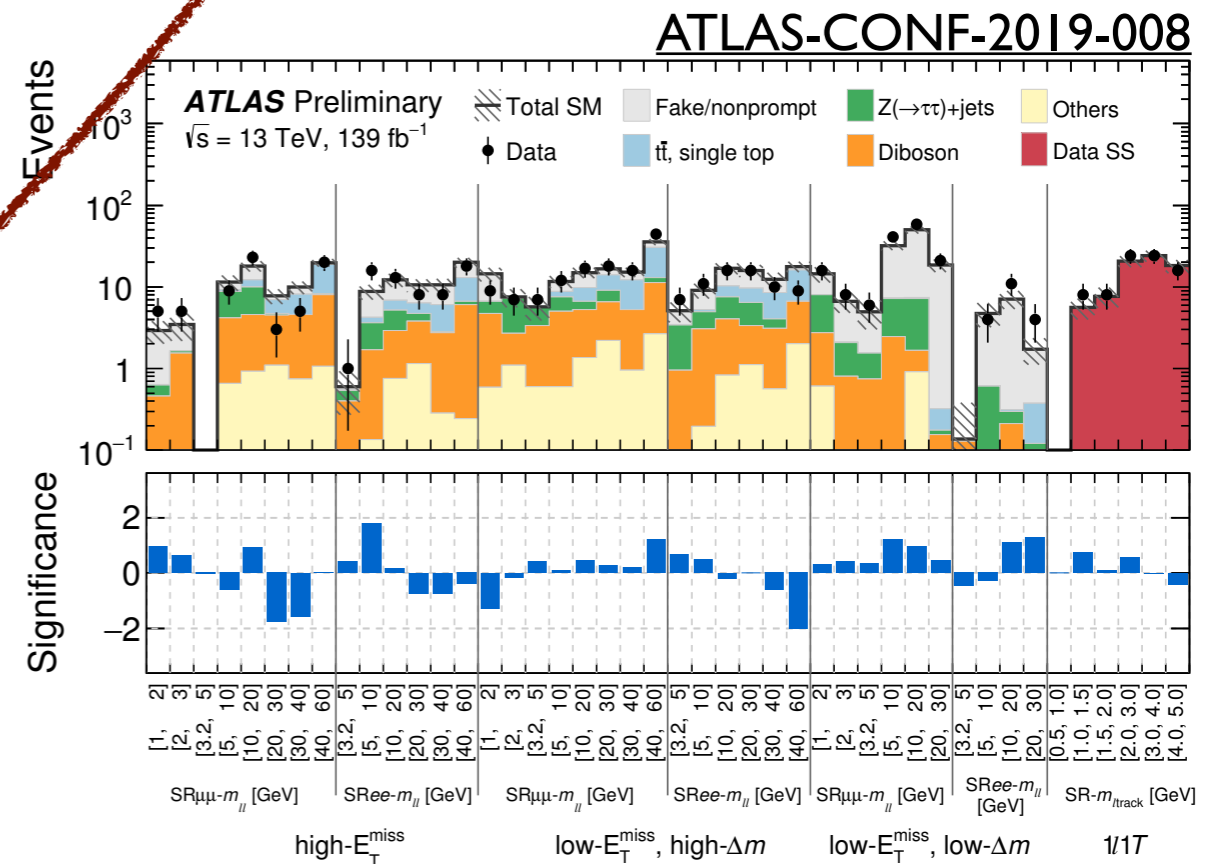
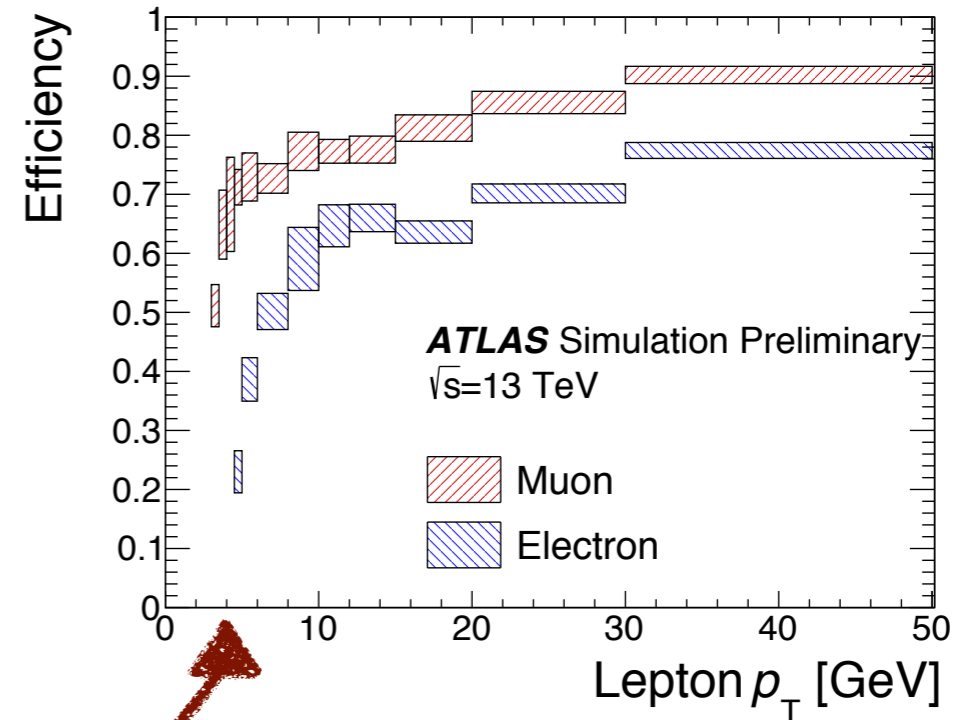
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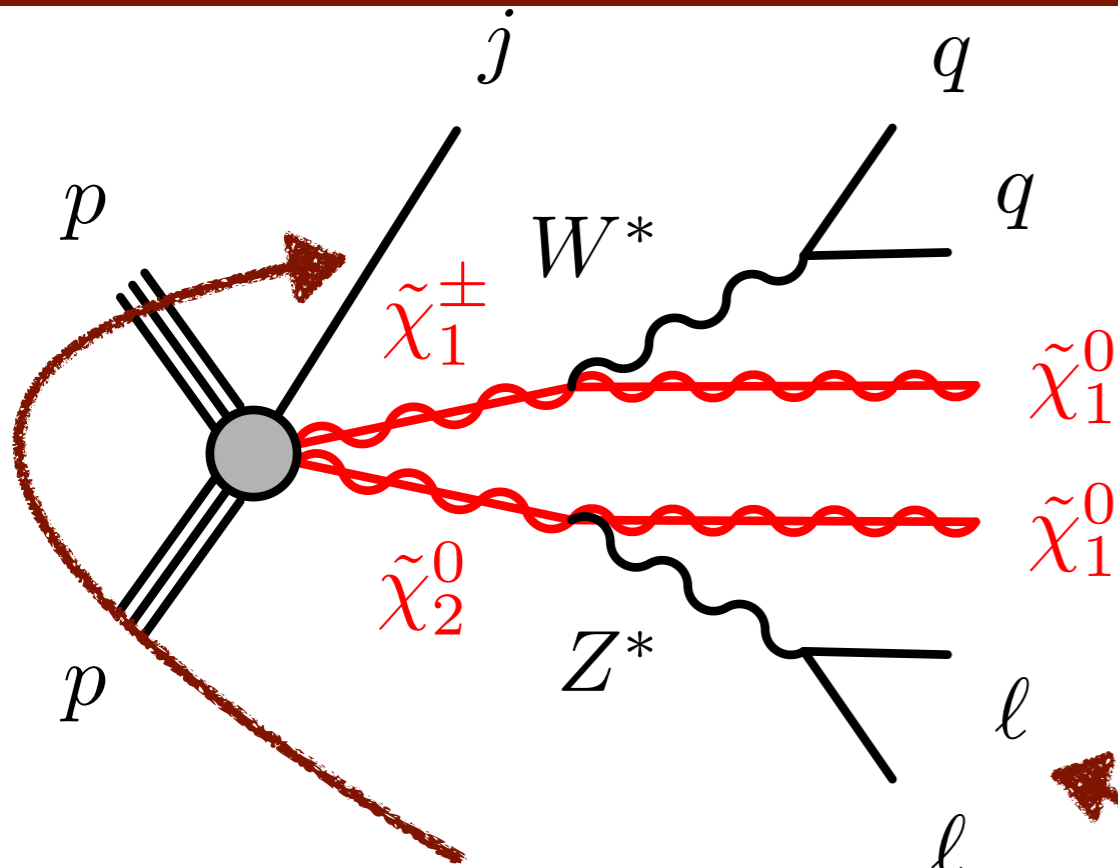
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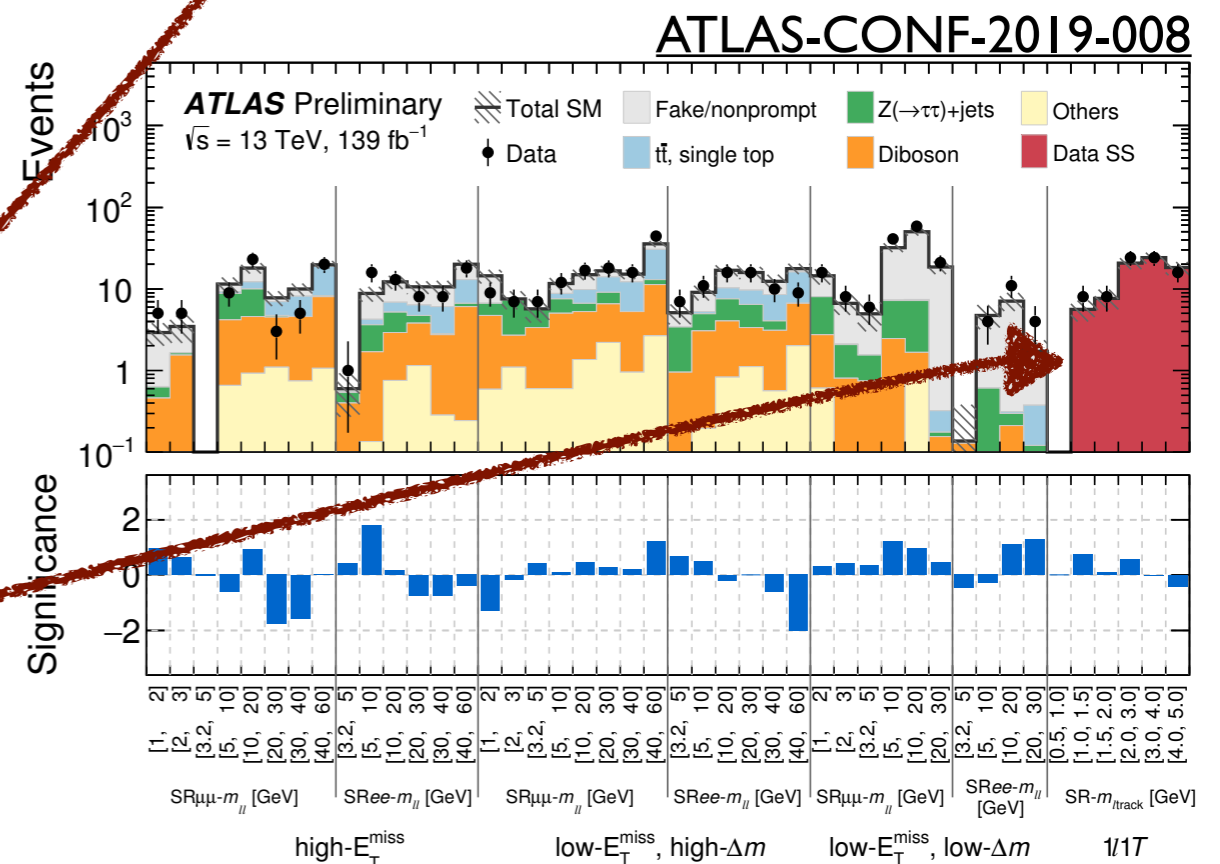
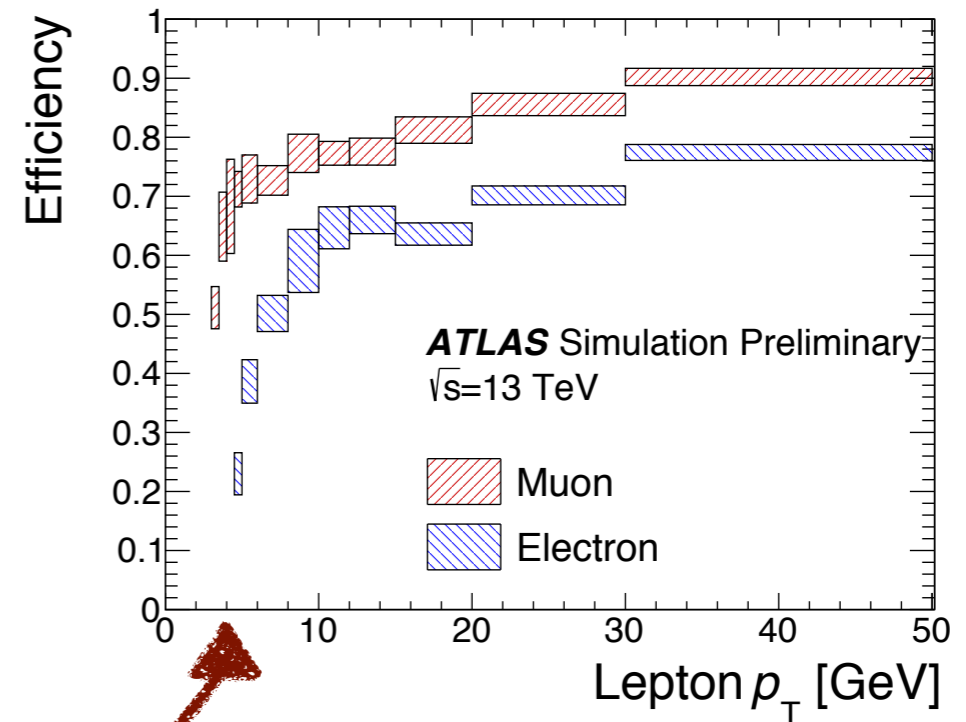


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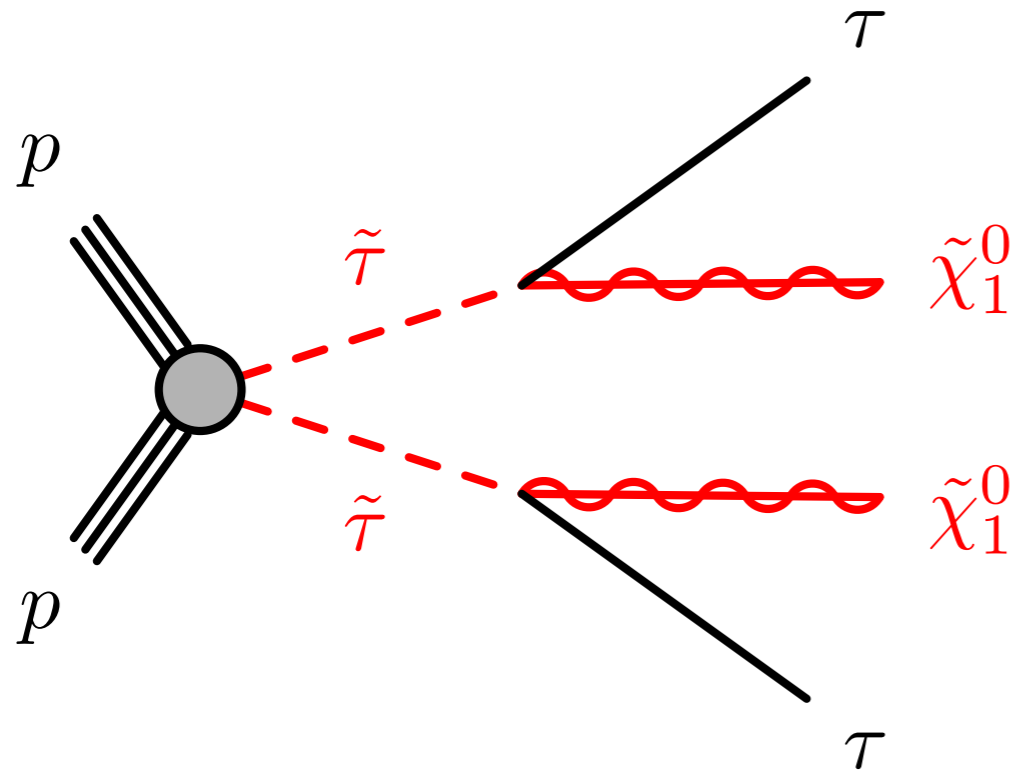
New lepton + track region extends sensitivity to even lower masses!



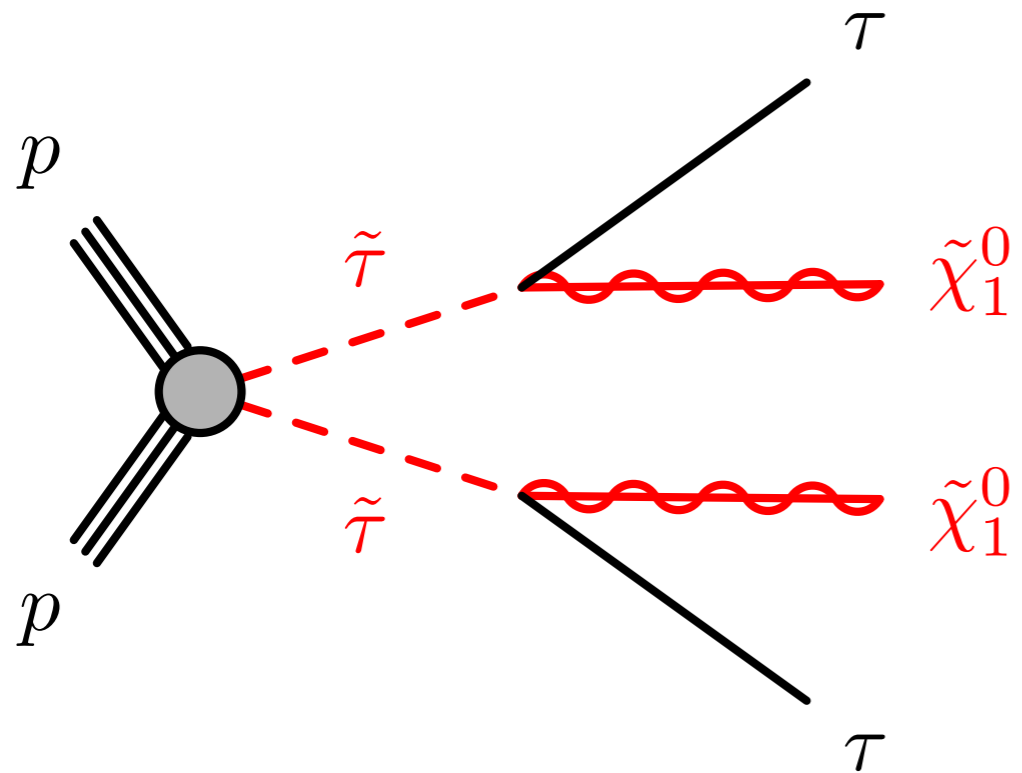
# Even Rarer: Staus



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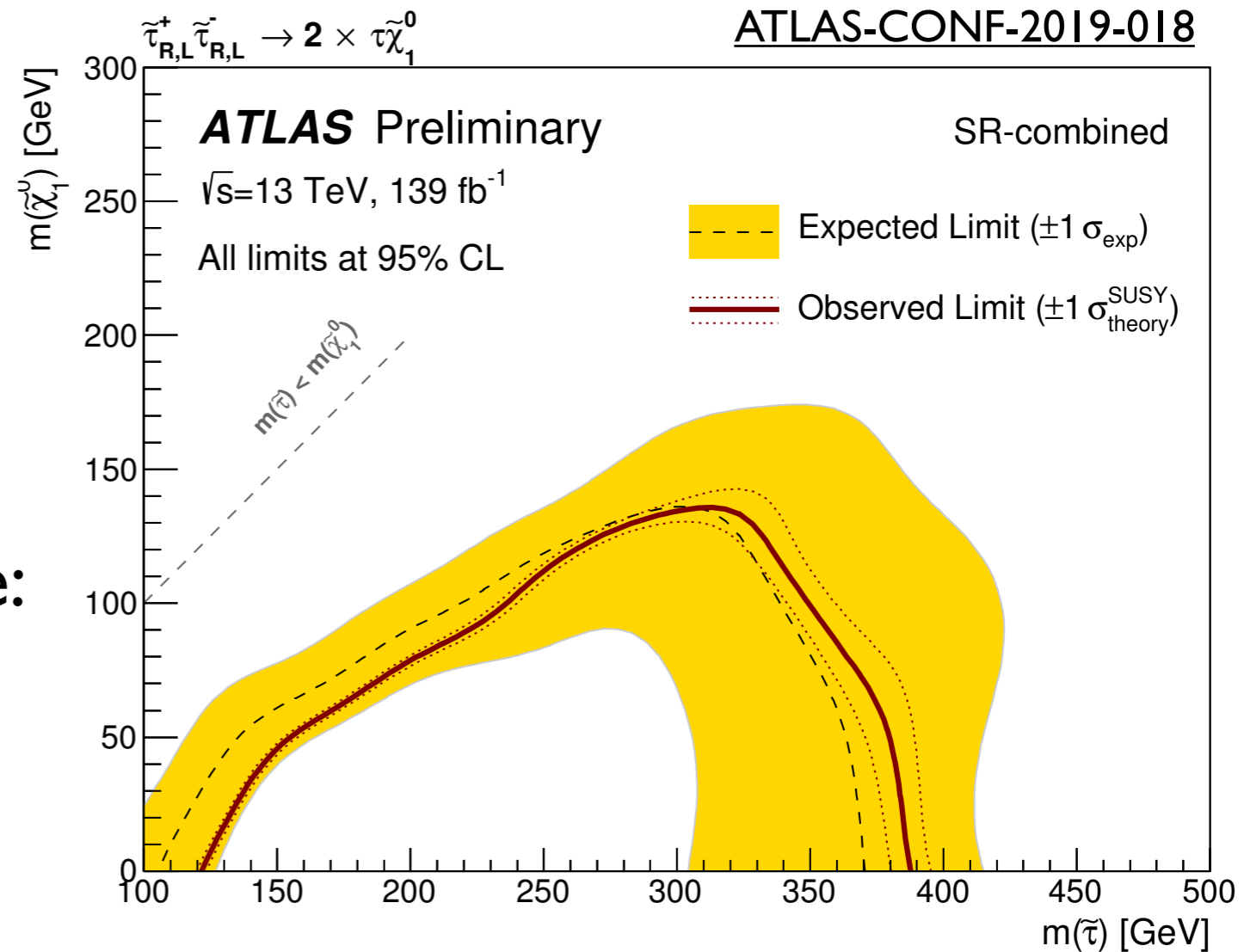
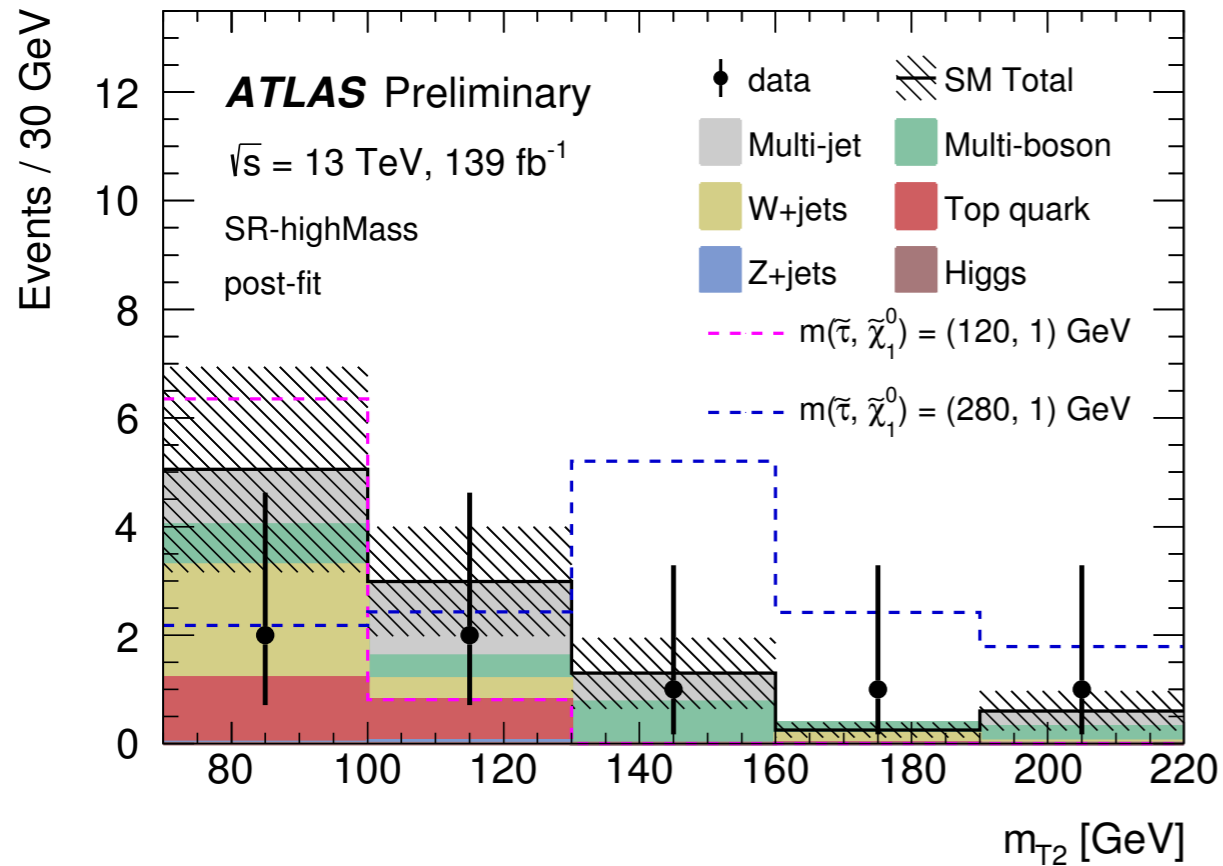


# Even Rarer: Staus



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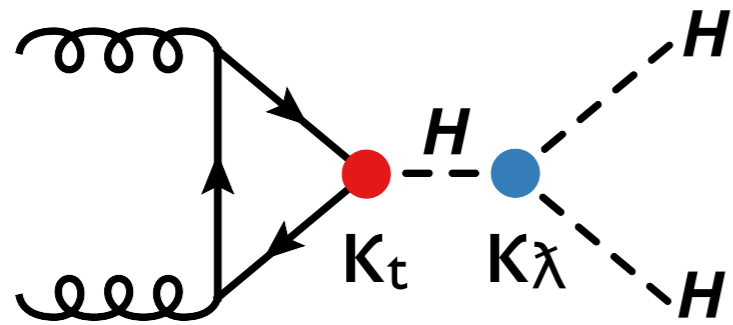
Effective triggers and the large  
 dataset enable first substantial  
 sensitivity at the LHC!



# Di-Higgs at the LHC

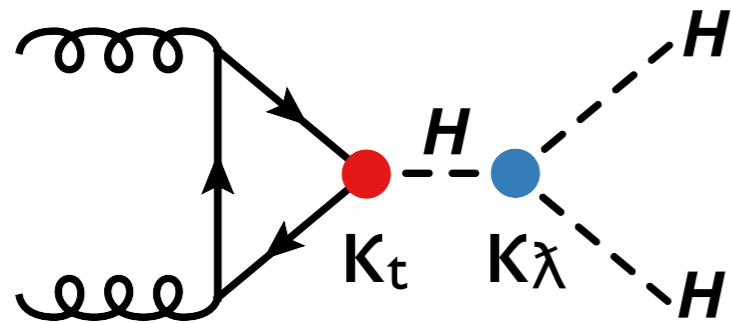


# Di-Higgs at the LHC



Di-Higgs is another exciting new target for the LHC

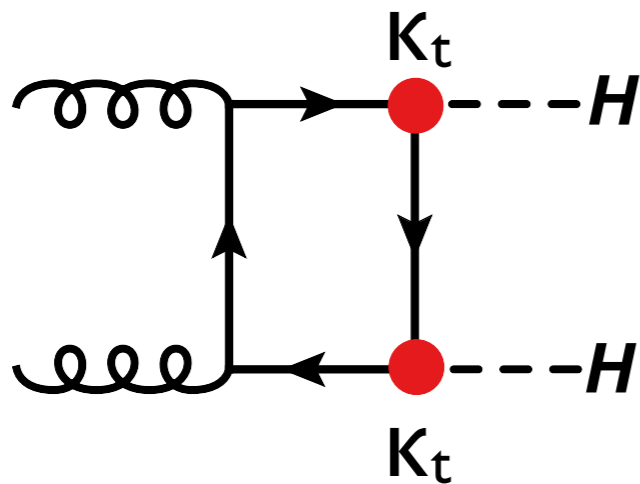
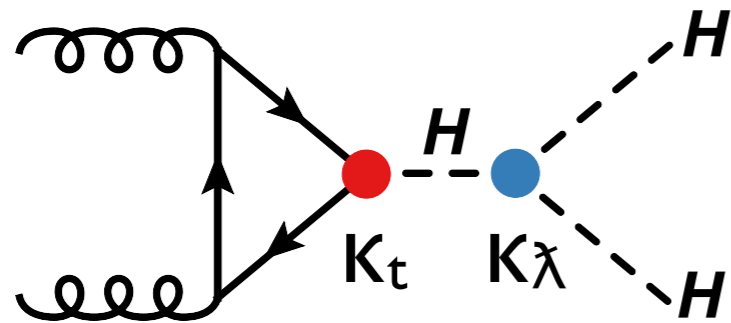
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Exciting signal: can reveal the shape of the Higgs potential!

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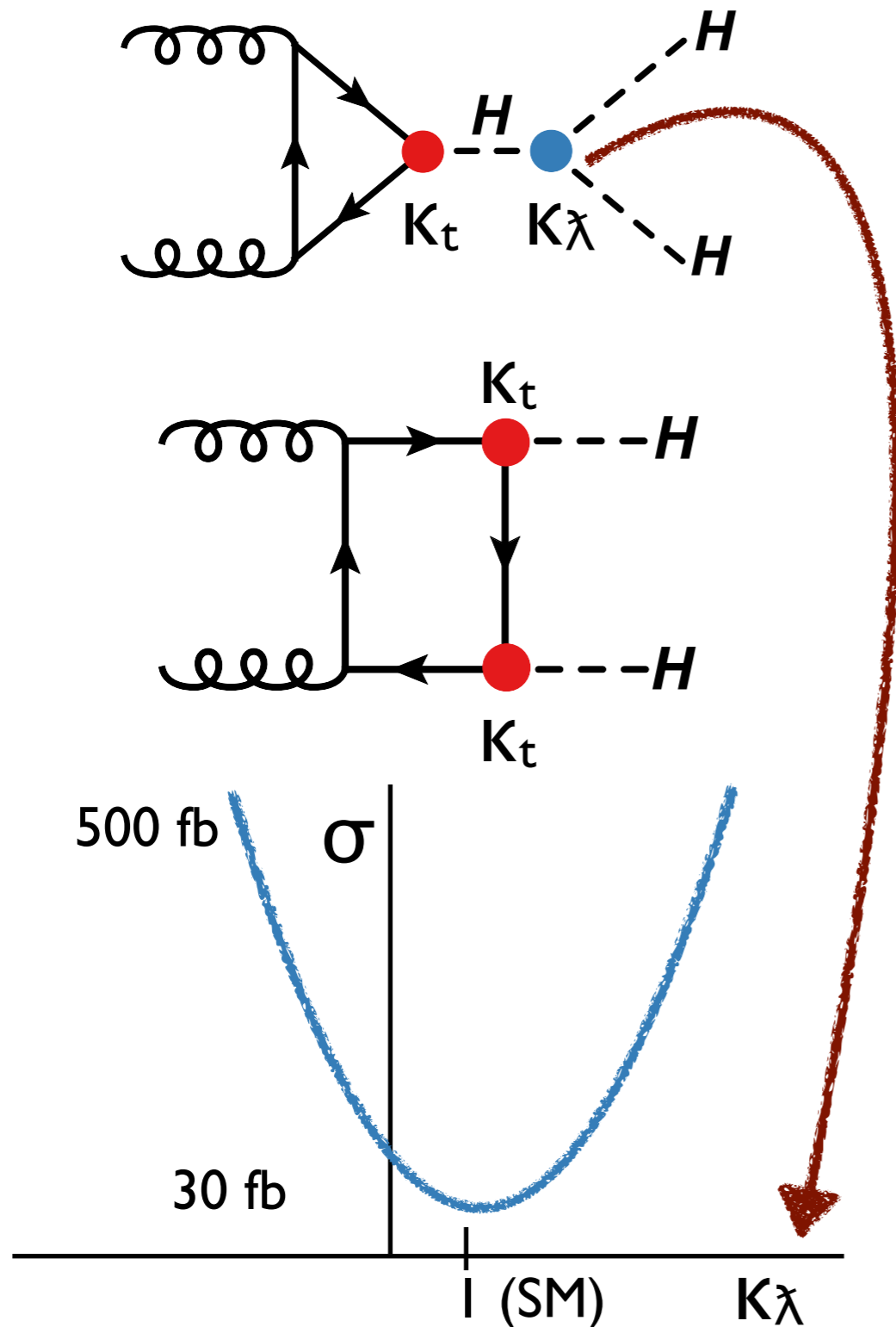


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Interference between SM diagrams leads to very low  $\sigma$ -sec

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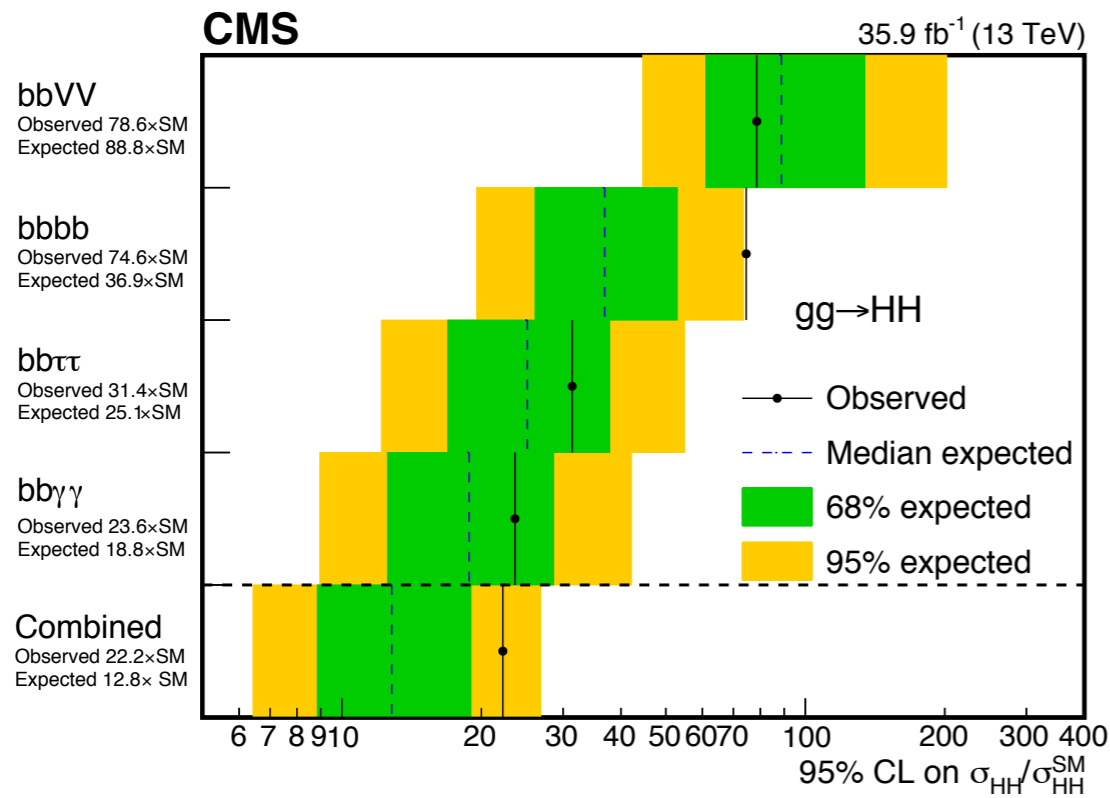
Interference between SM diagrams leads to very low x-sec

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

# Results on Di-Higgs

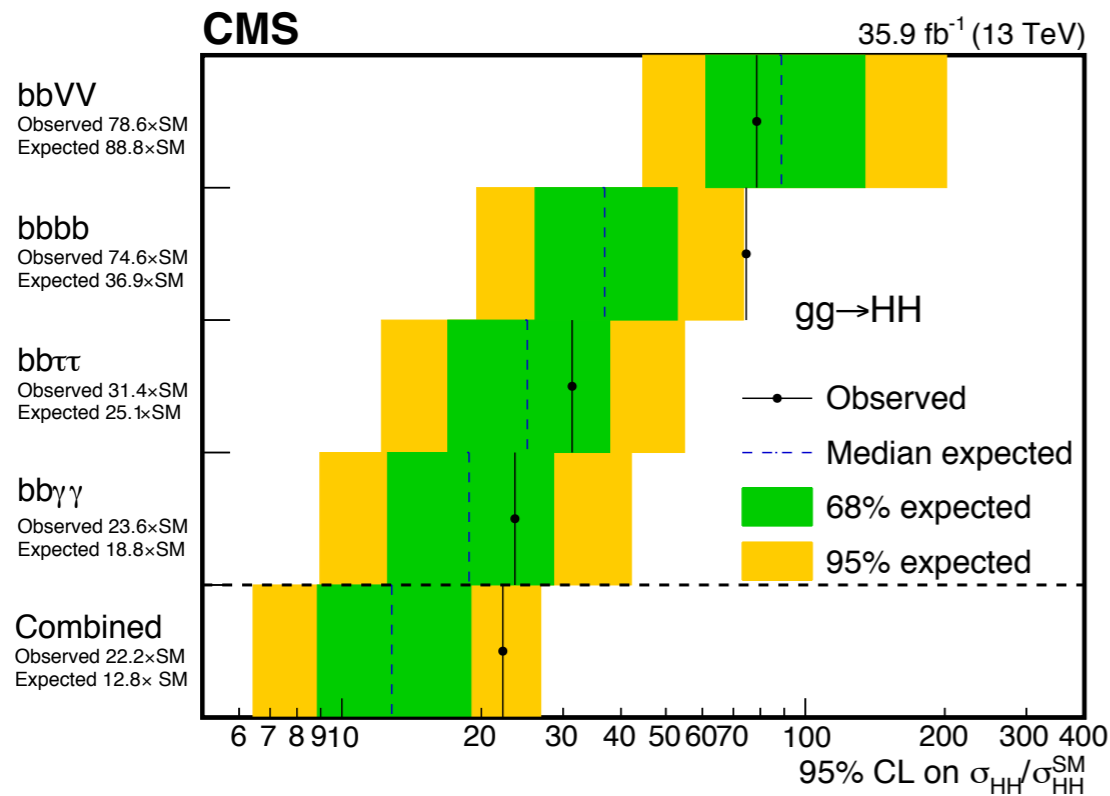


# Results on Di-Higgs



Many orthogonal channels  
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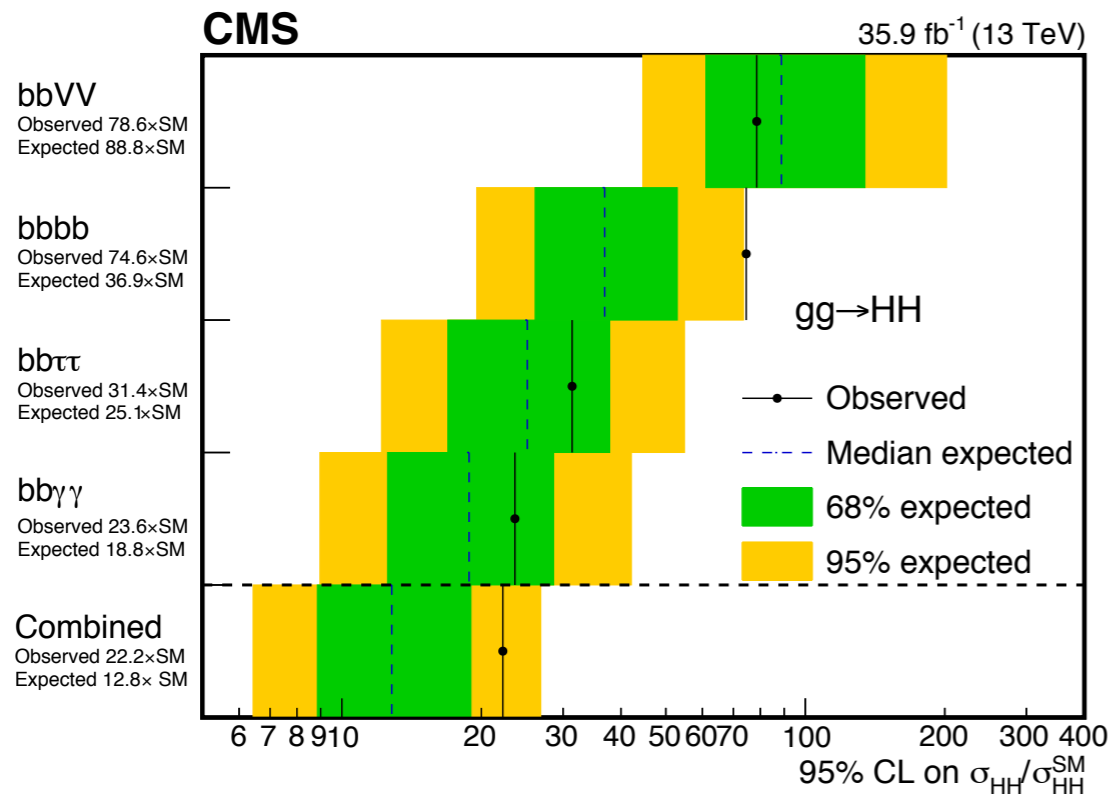


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Note the use of b-jets: rare  
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of the Higgs need to be used

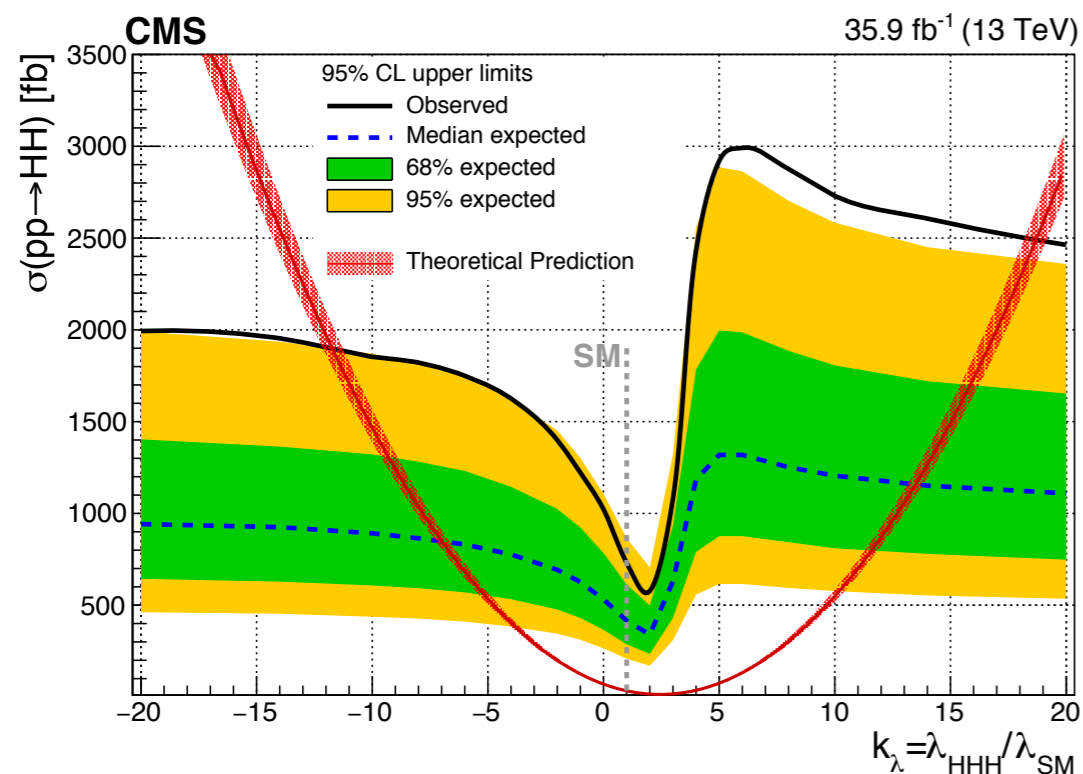


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Wide range of couplings still allowed!  
Even more data still necessary

# Hunting Rare SM Deviations



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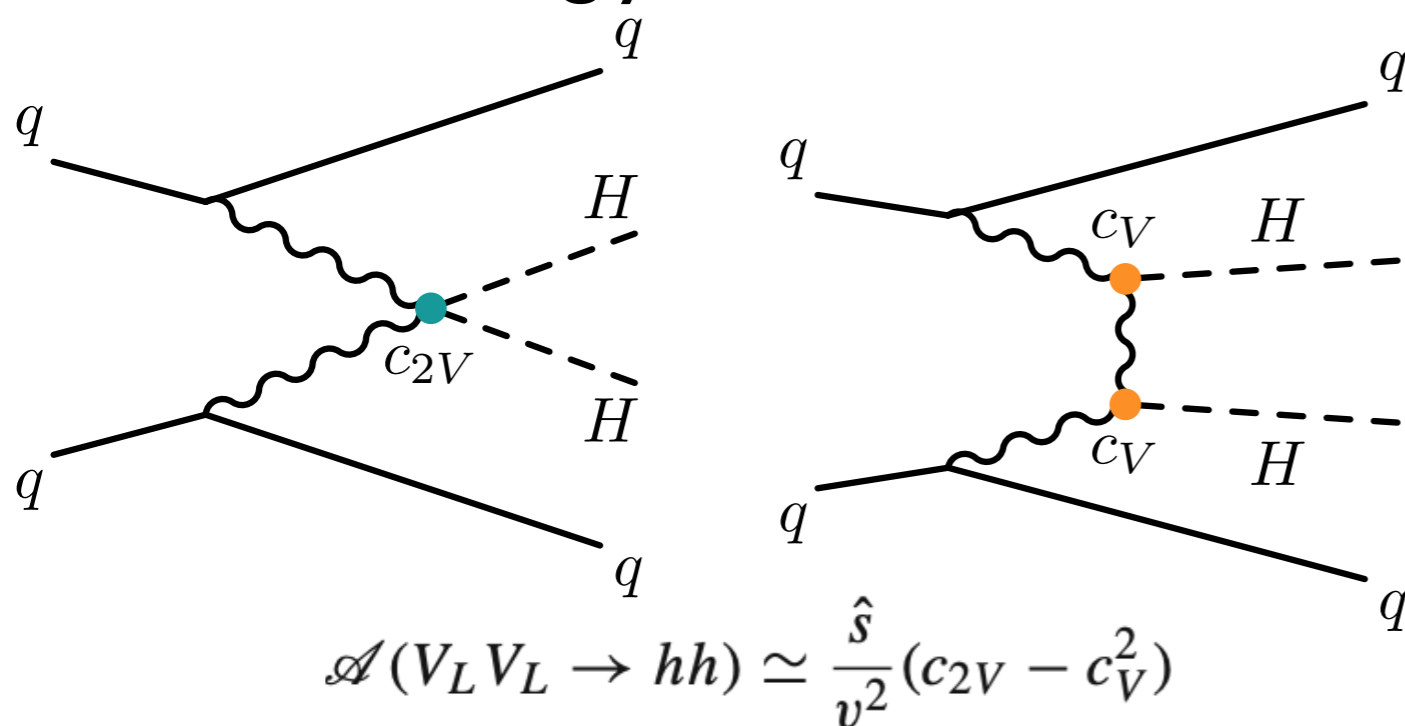


Interference in other SM diagrams lead to similar vanishingly small  $\sigma$ -sec

# Hunting Rare SM Deviations



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

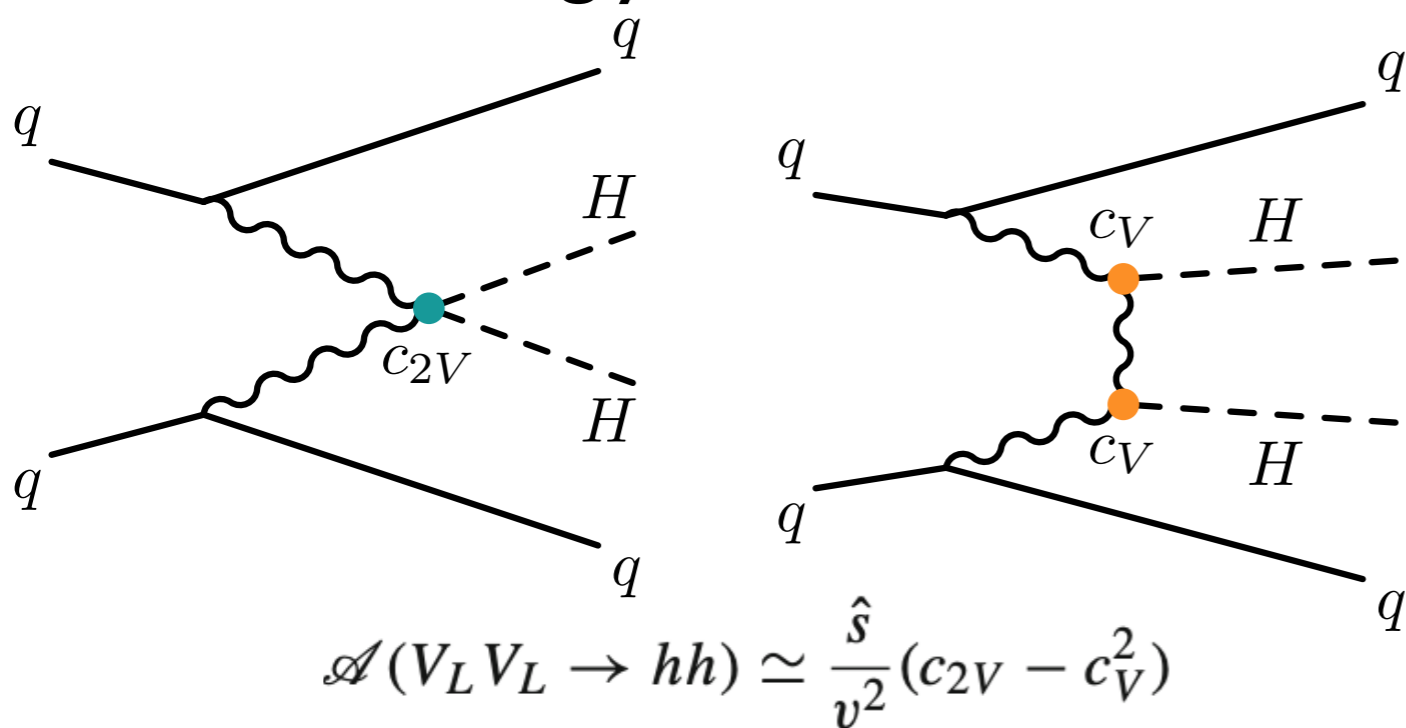


VBF di-Higgs production is one example!

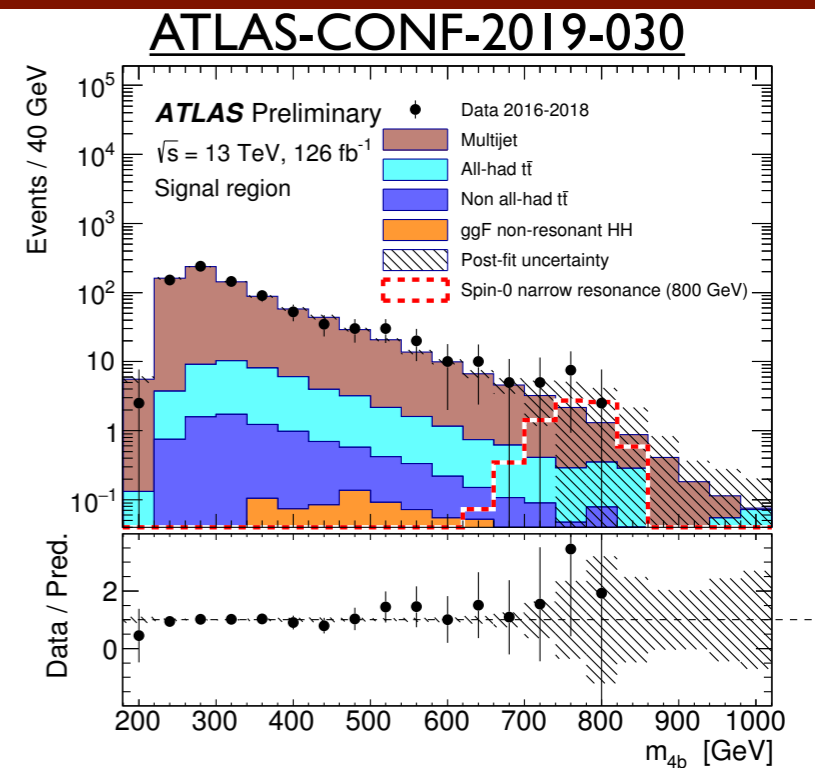
# Hunting Rare SM Deviations



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



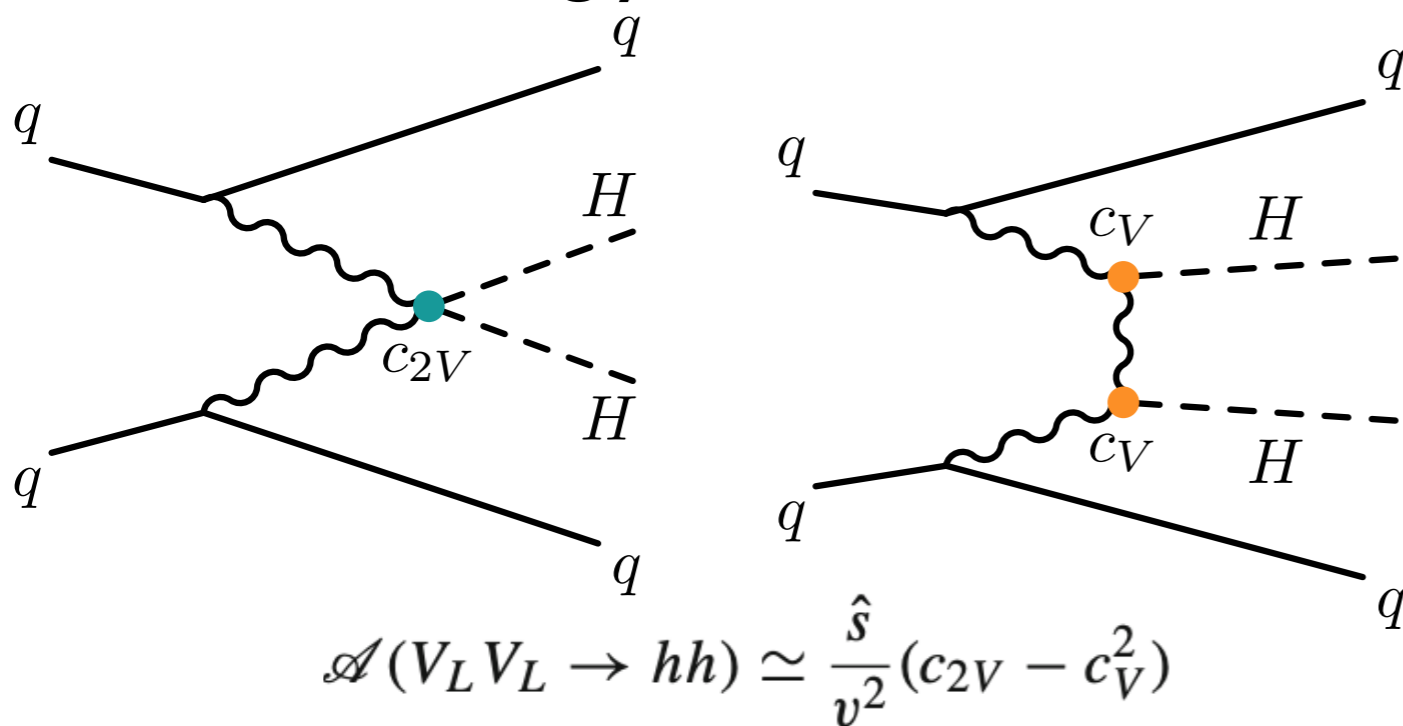
VBF di-Higgs production is one example!



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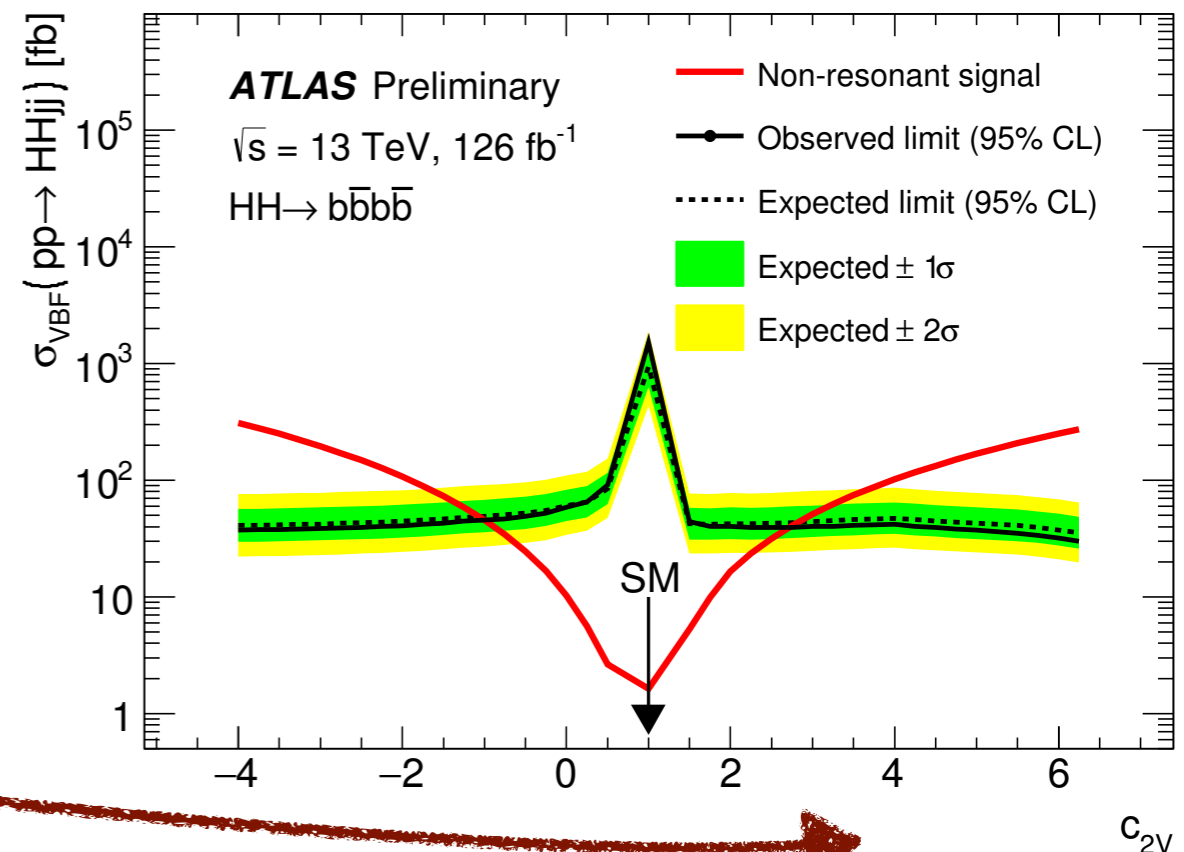
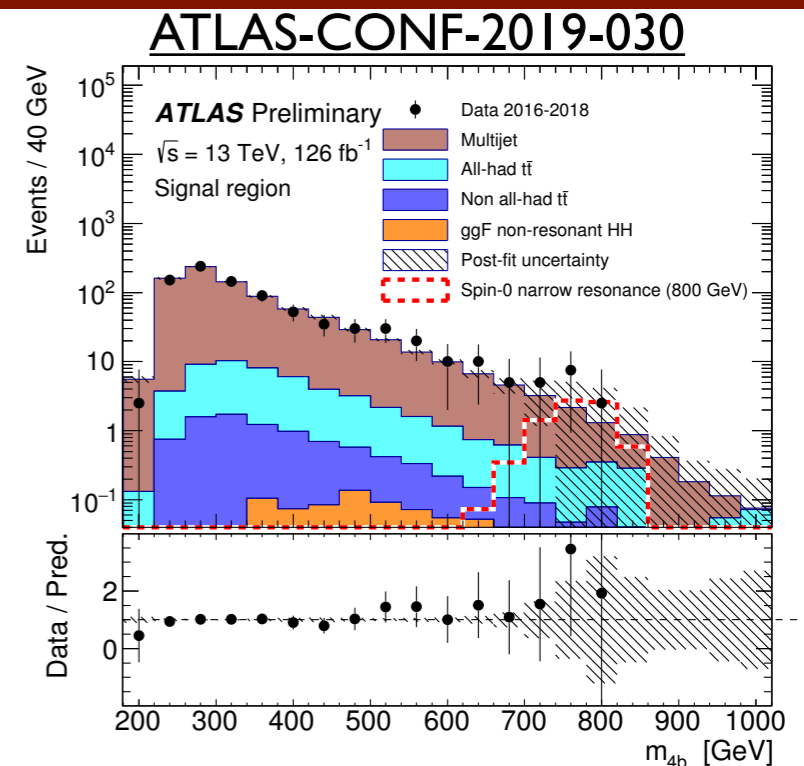


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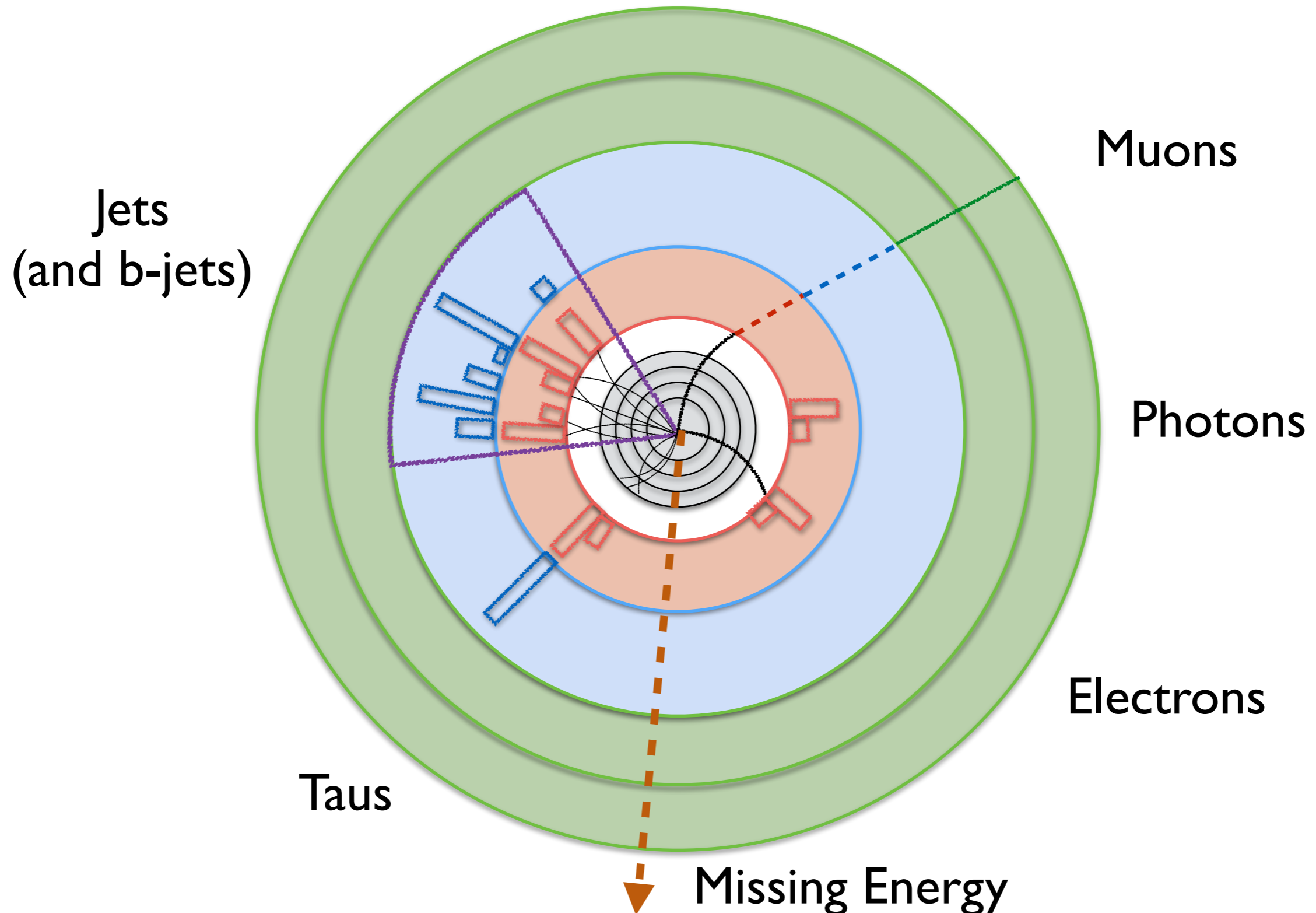
First limits on the 4-point VVHH coupling



# Not Your Advisor's Signals

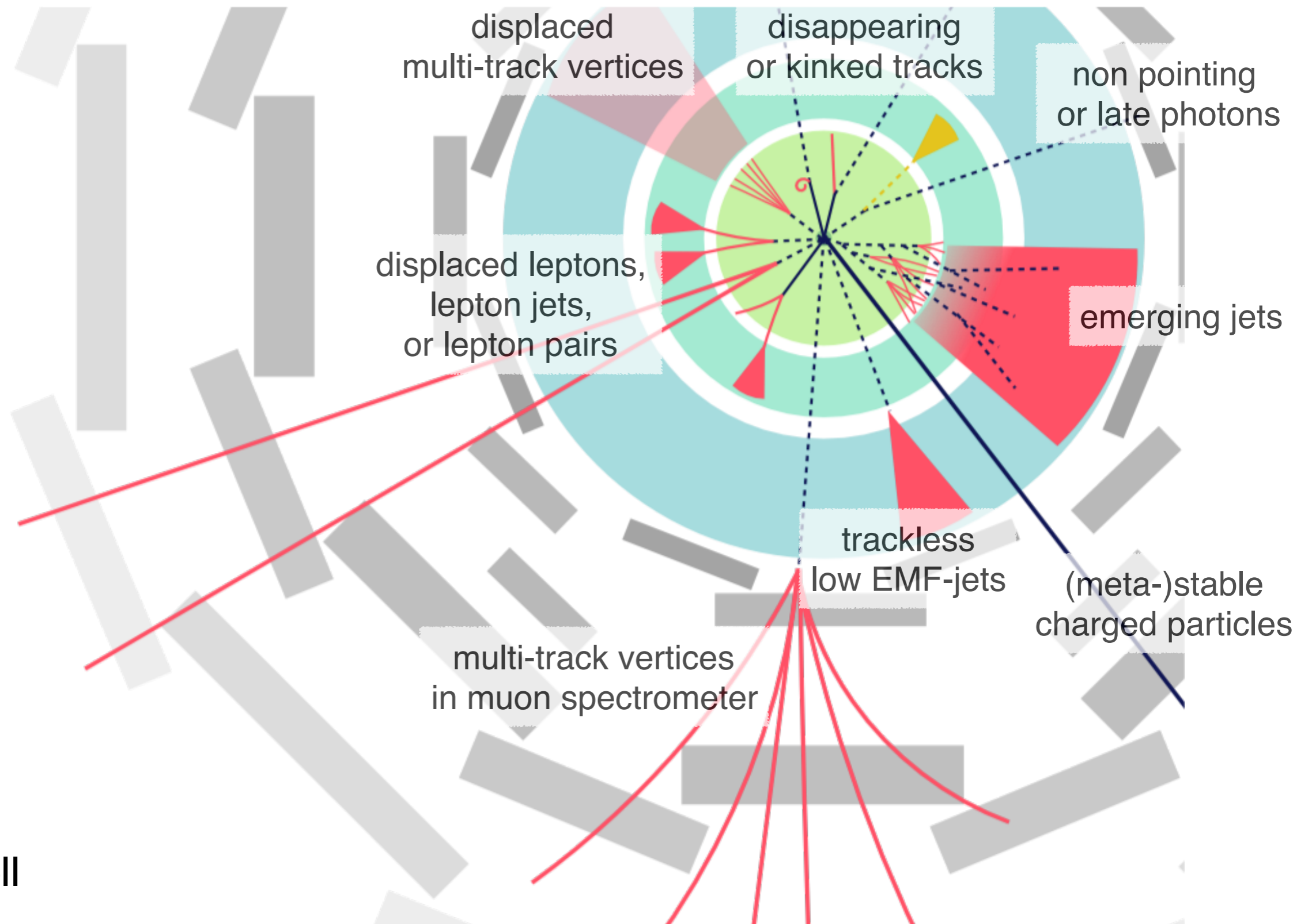
*Or: how new reconstruction strategies are expanding  
our sensitivity to signals our detectors weren't  
built to measure*

# Your Advisor's Signals





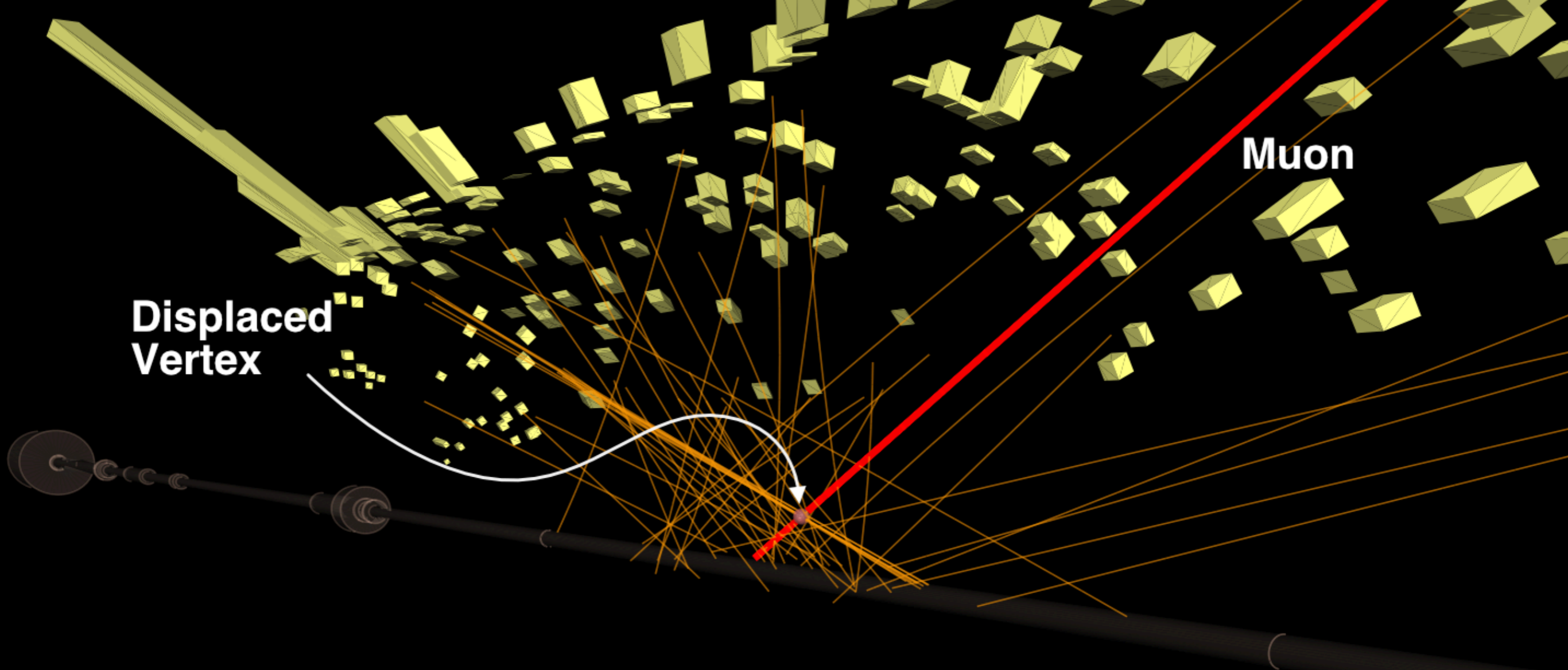
# Not Your Advisor's Signals



Heather Russell



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



Displaced  
Vertex

Muon

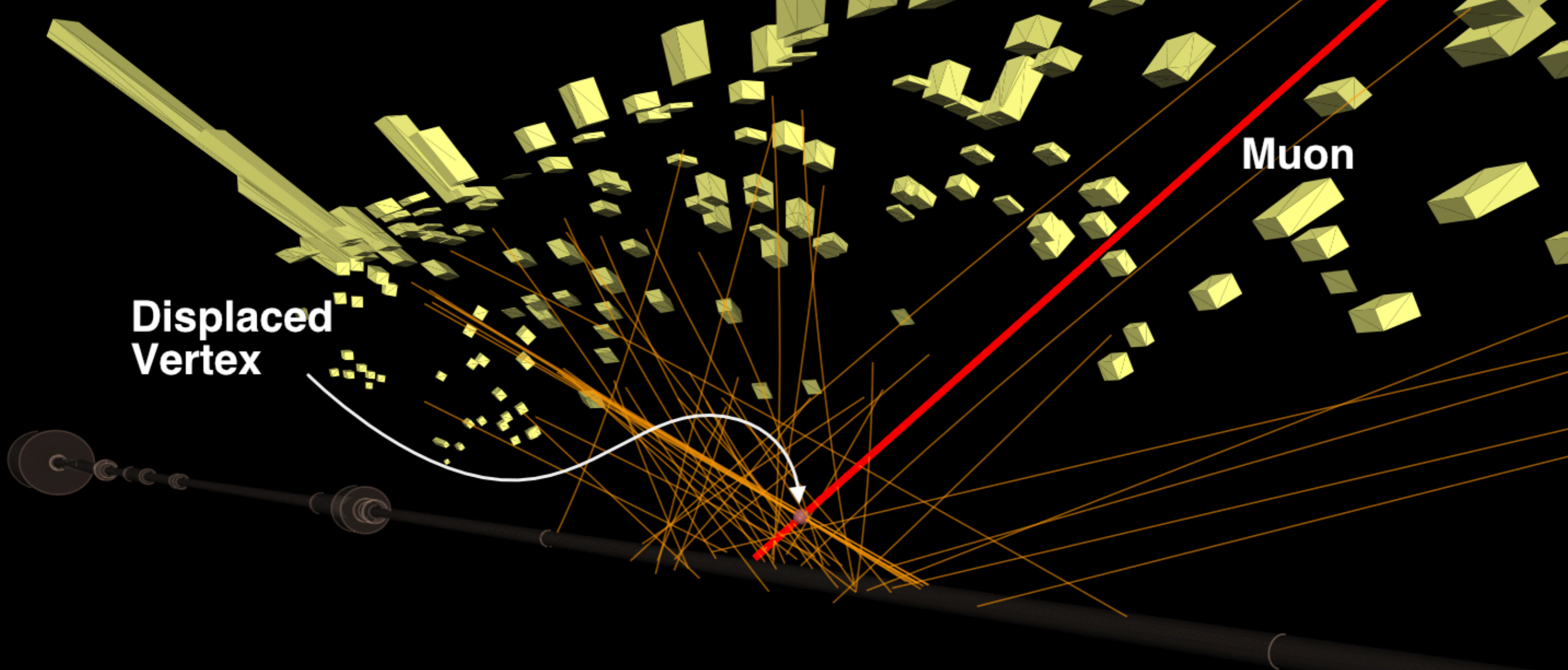
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Simulated Signal Event  
Top Squark Pair Production

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

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





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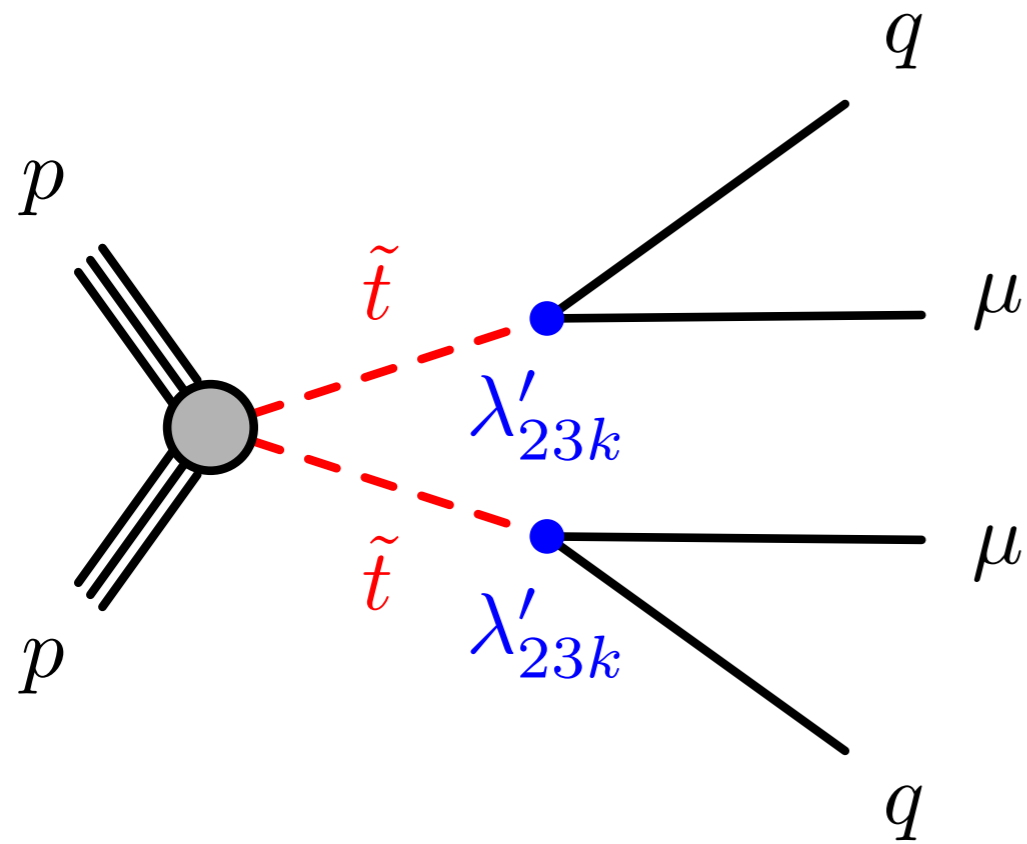
Special algorithms can reconstruct these “displaced tracks” and look for displaced vertices



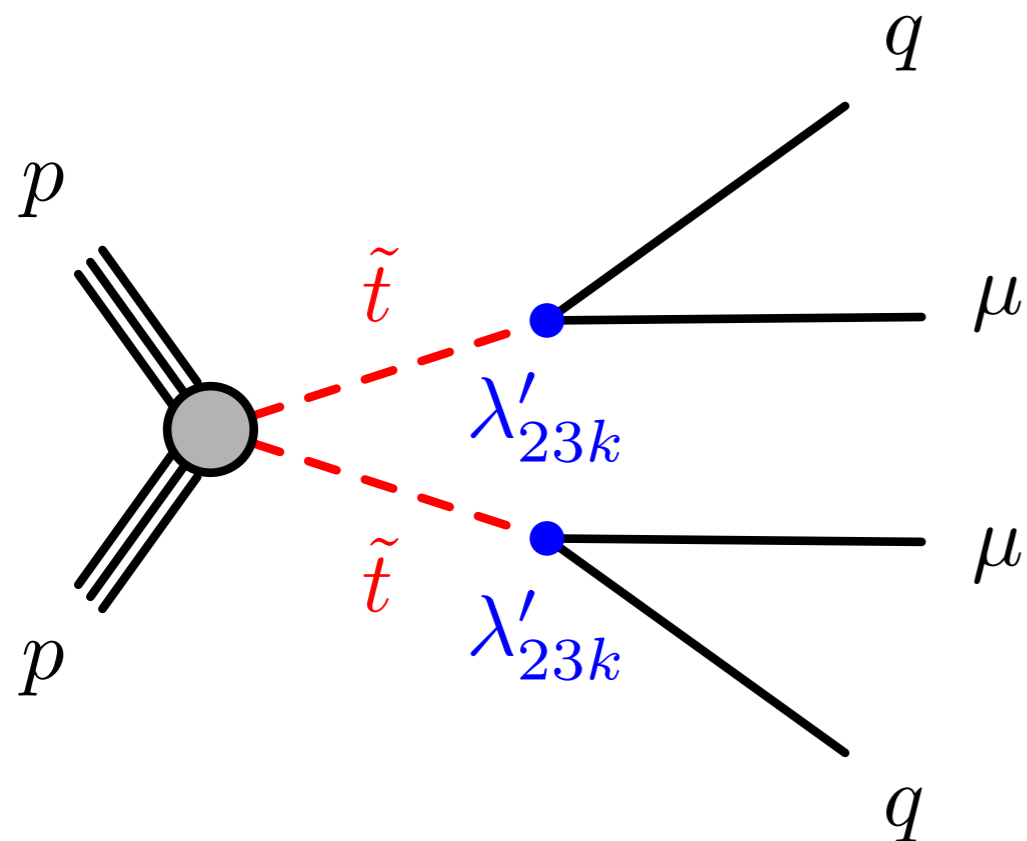
# Displaced Vertex + $\mu$



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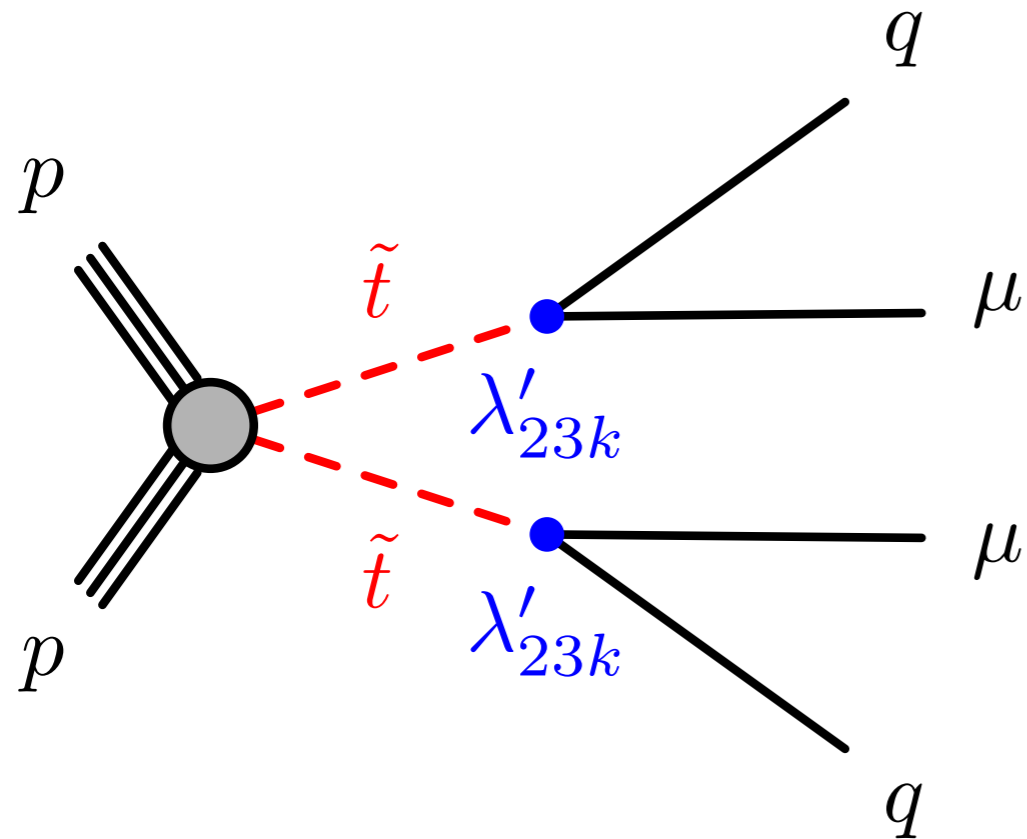
# Displaced Vertex + $\mu$



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

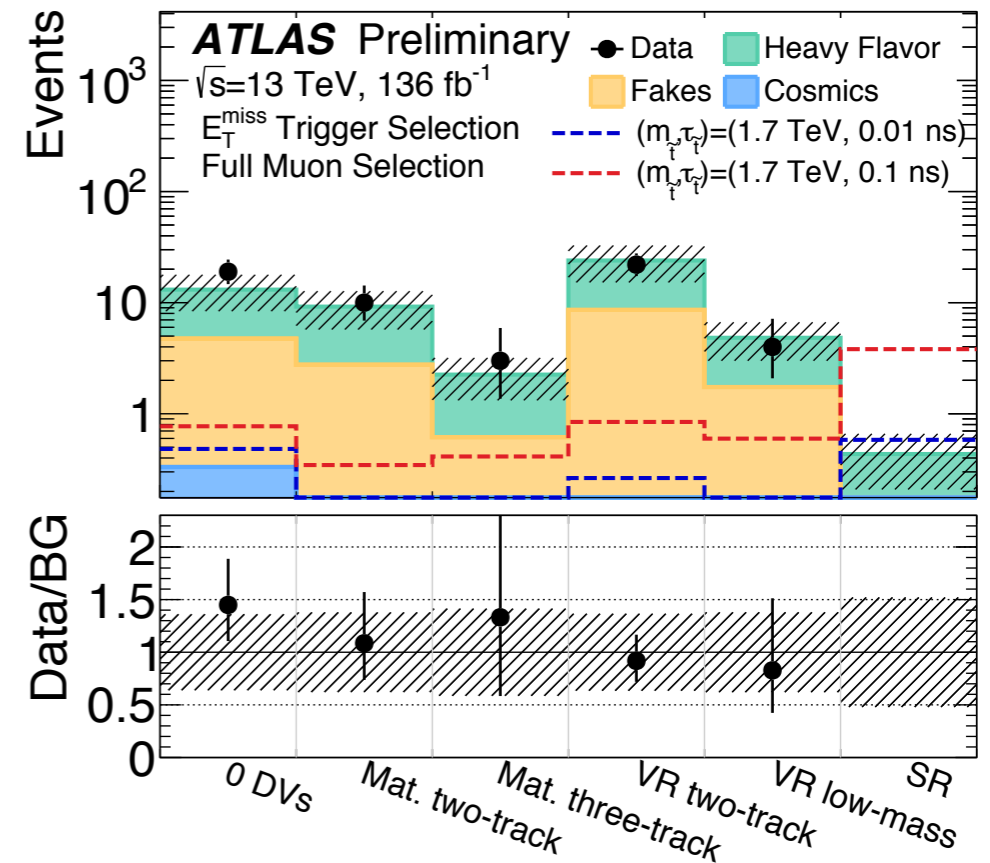


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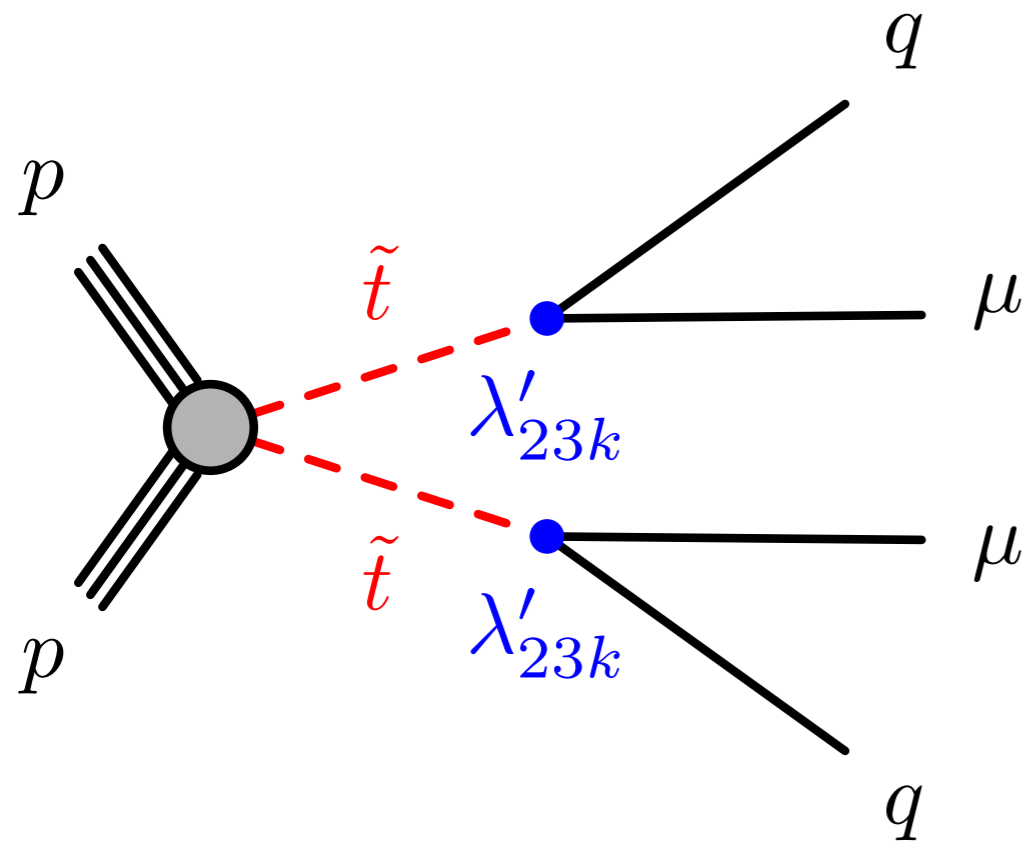


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Data-driven backgrounds estimate  
 $\sim 0$  background, with no signal observed



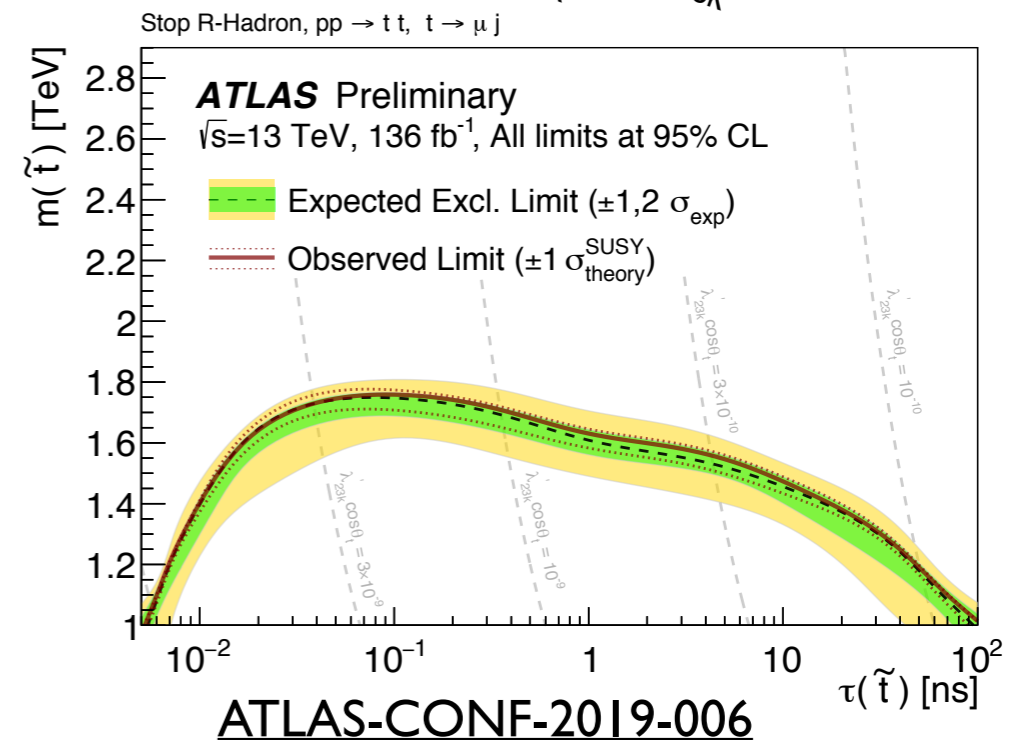
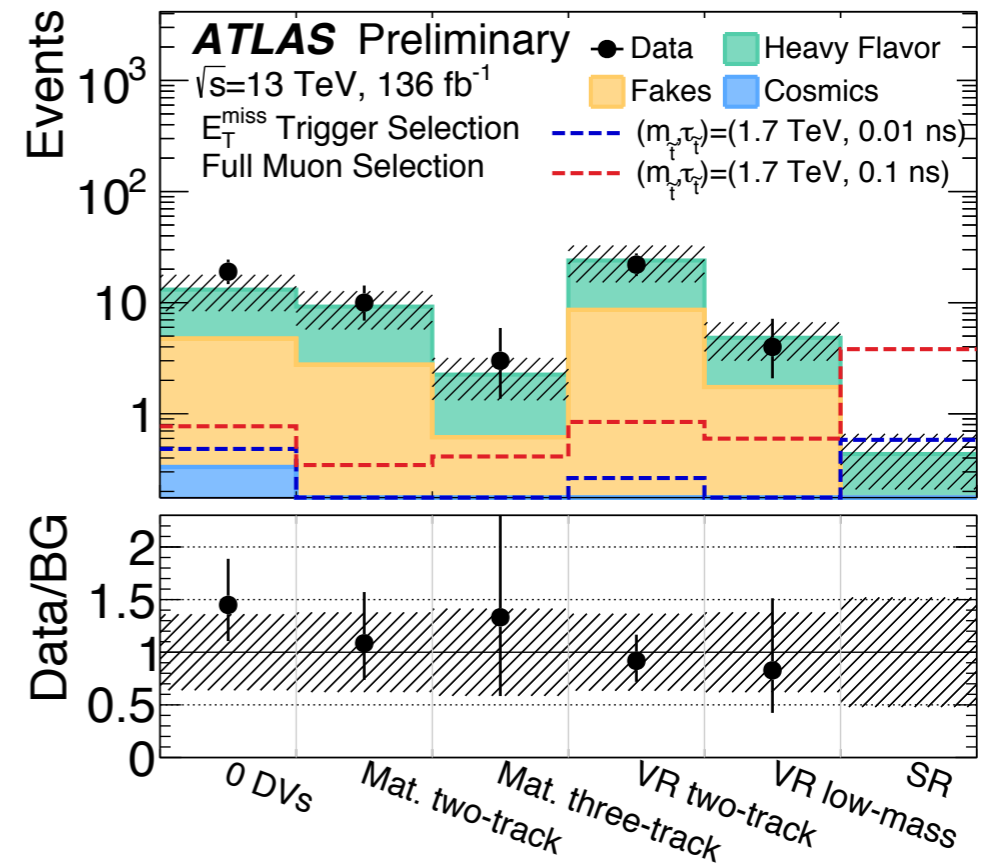
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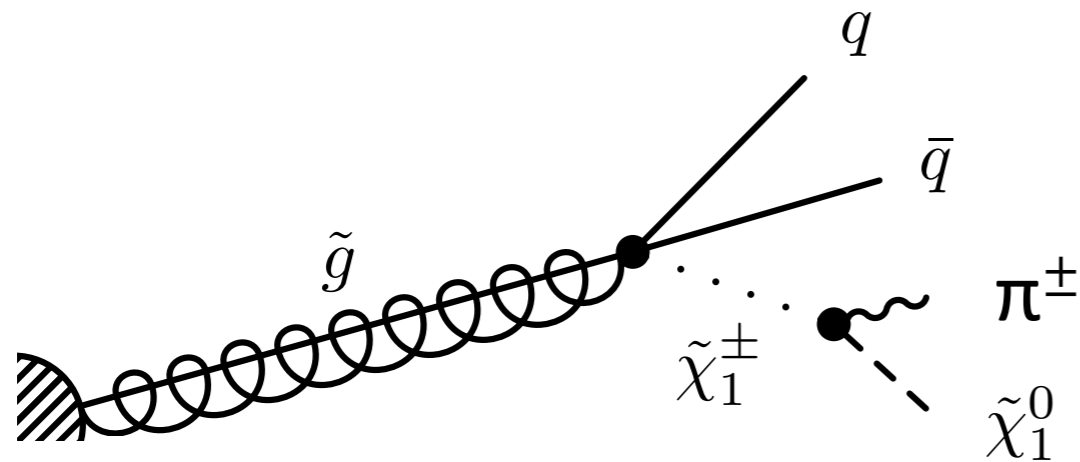
Strongest limits yet on stops!



# Disappearing Tracks

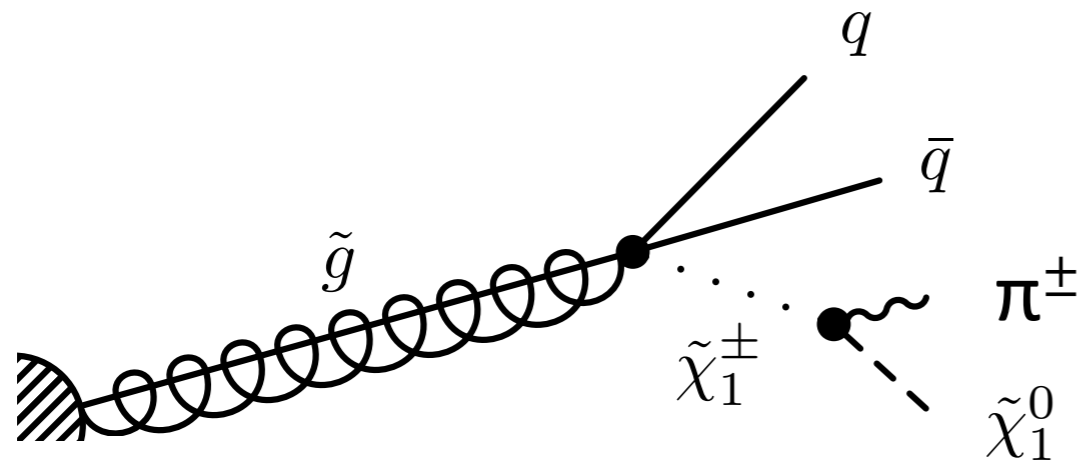


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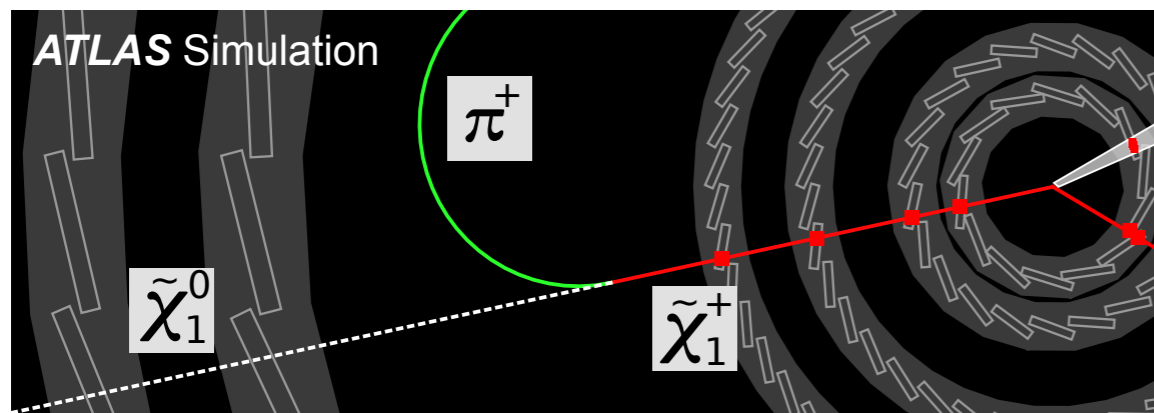


With extremely small mass splittings between SUSY particles, charginos can become long-lived!

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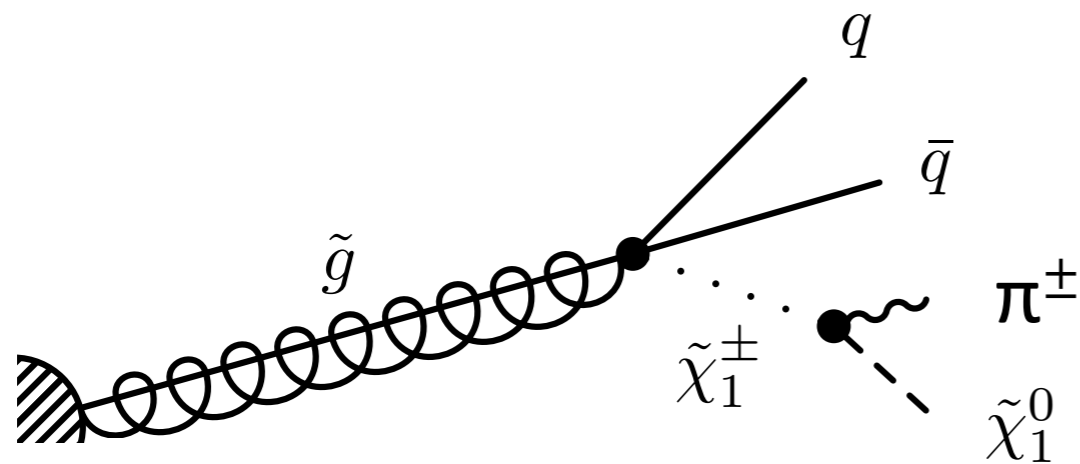


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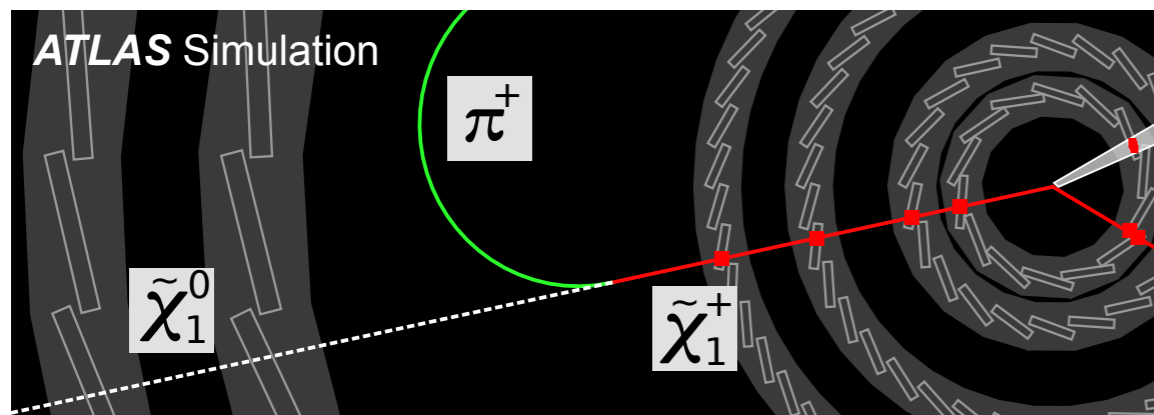


Can interact with the first few layers of the tracker, and then “disappear”

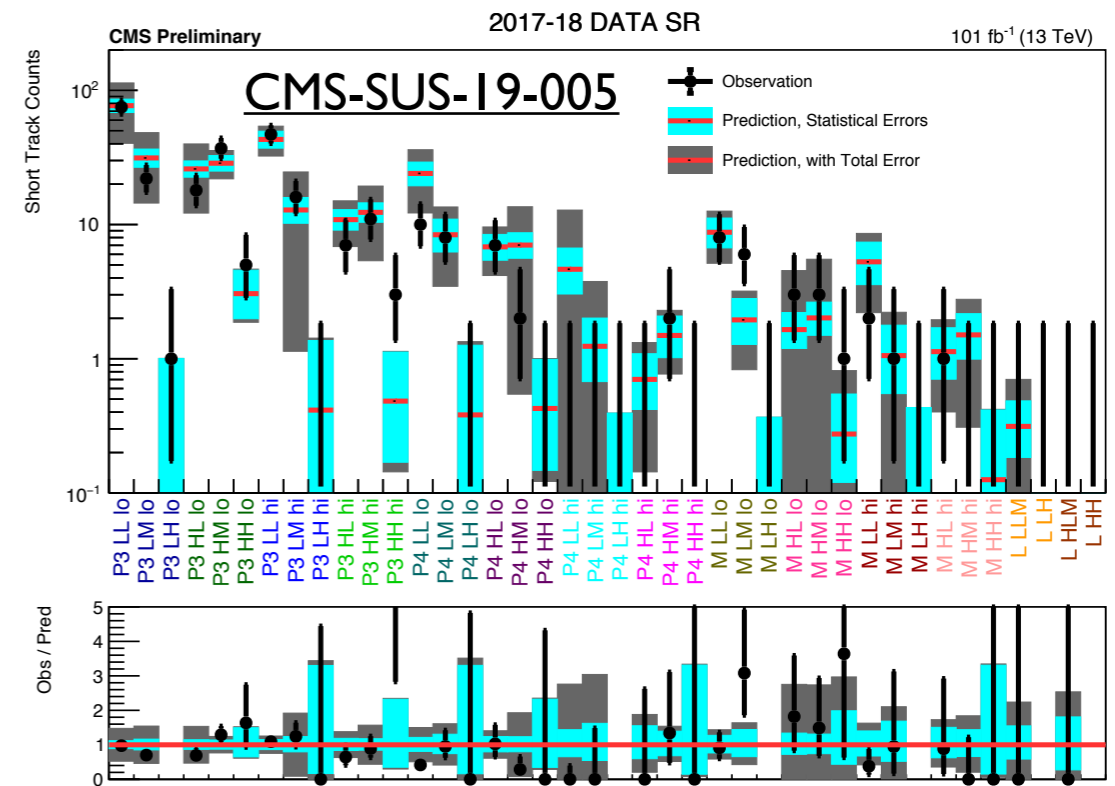
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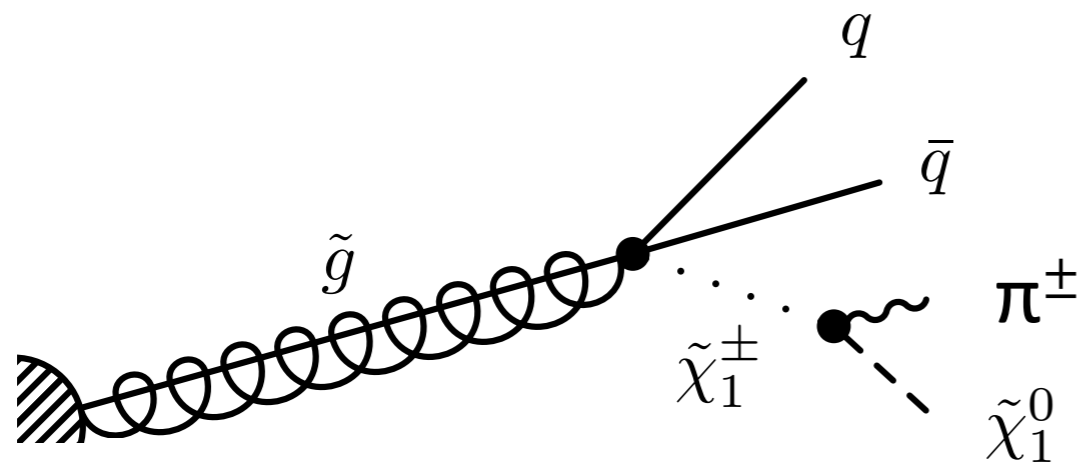
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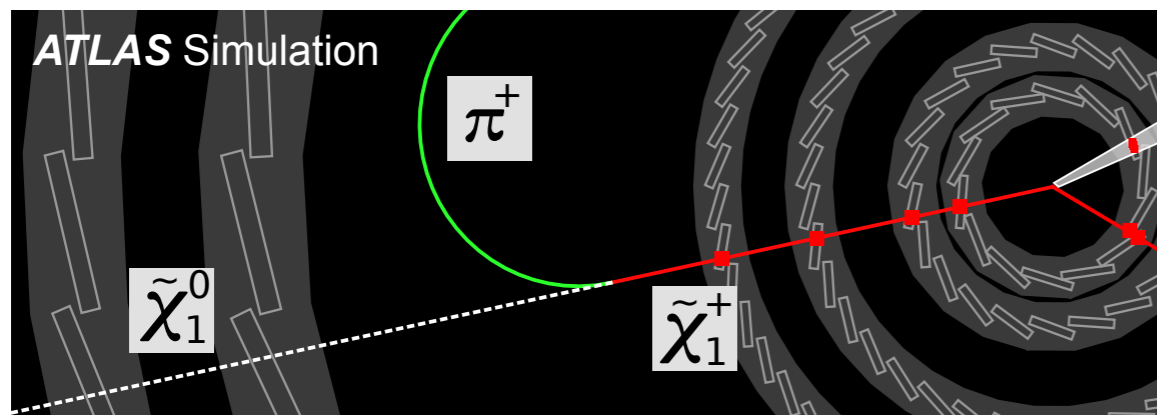
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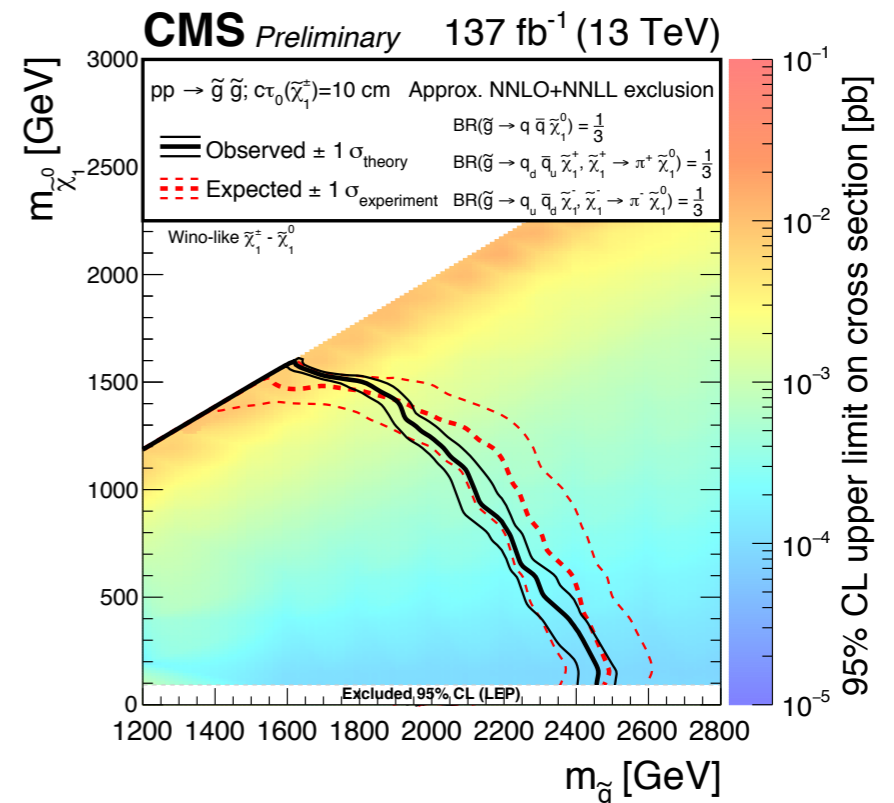
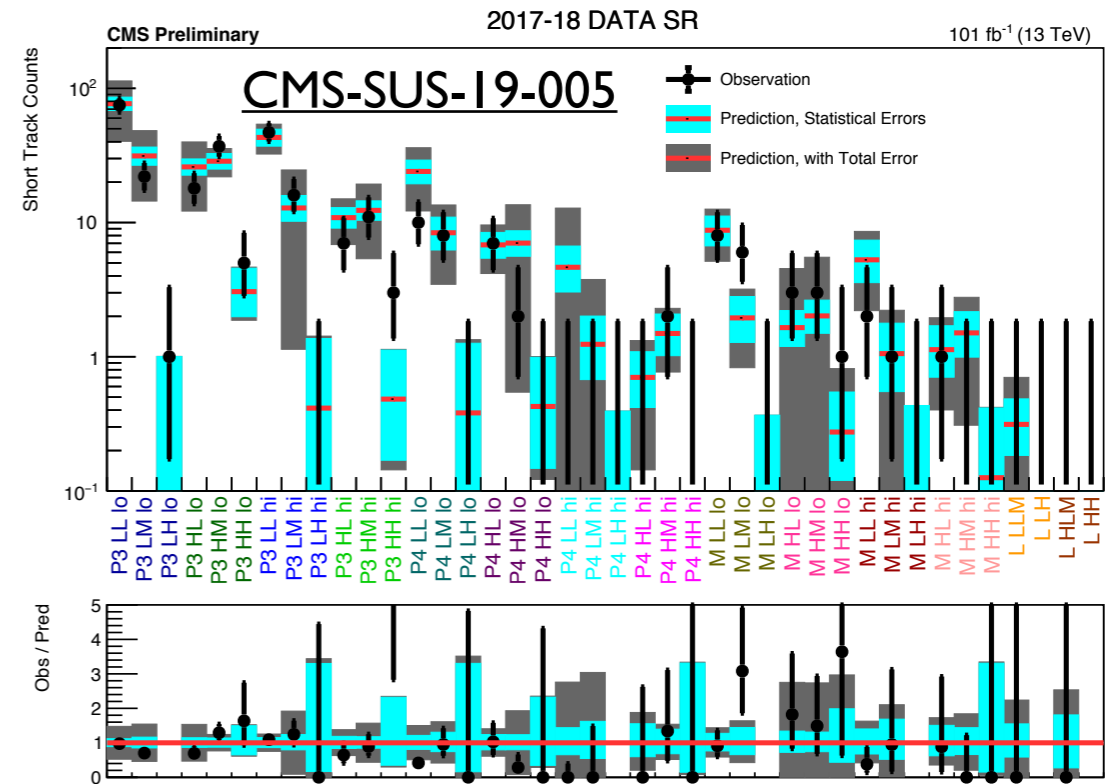
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Can also extend reconstruction using additional information: **timing**

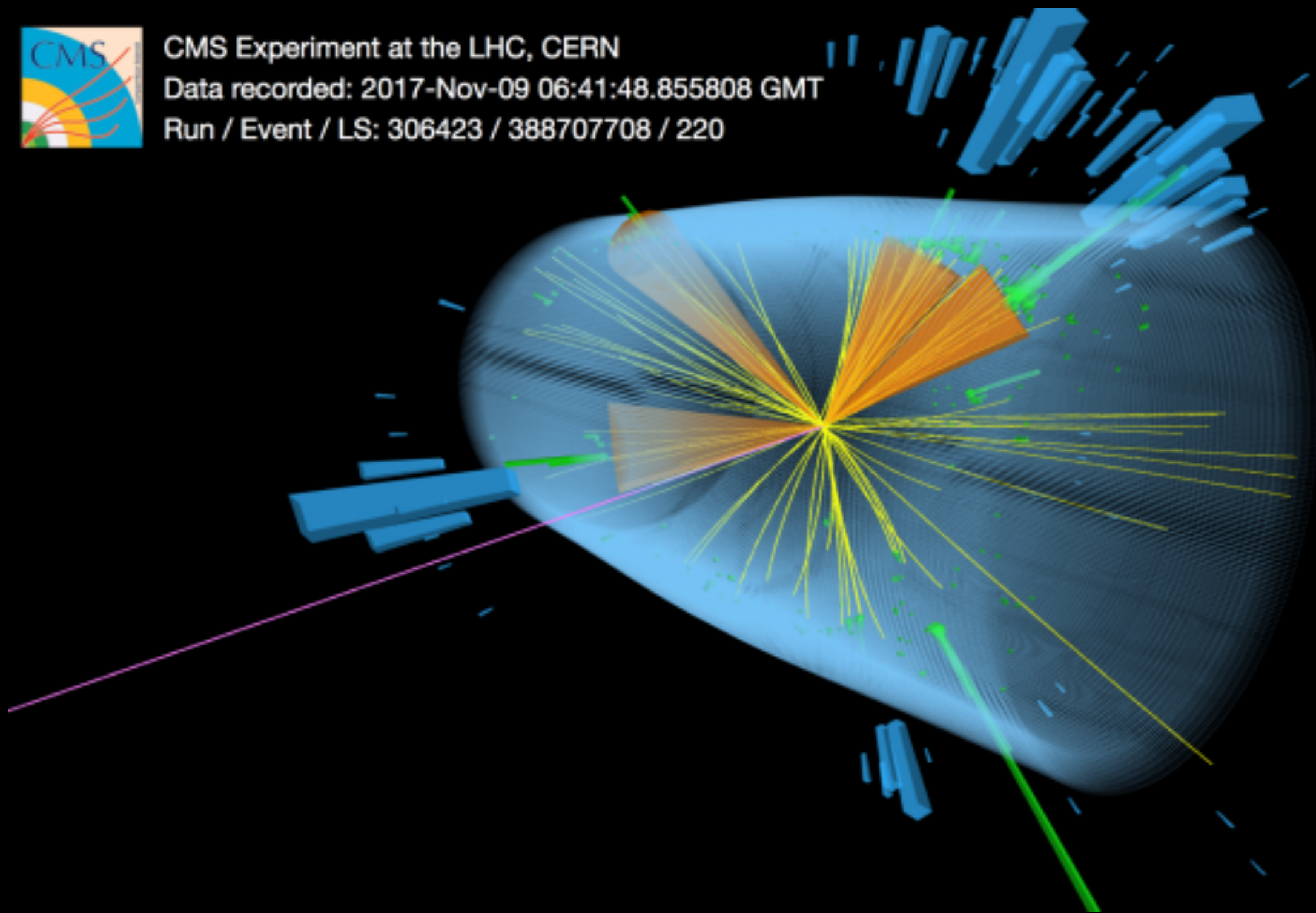
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CMS Experiment at the LHC, CERN

Data recorded: 2017-Nov-09 06:41:48.855808 GMT

Run / Event / LS: 306423 / 388707708 / 220



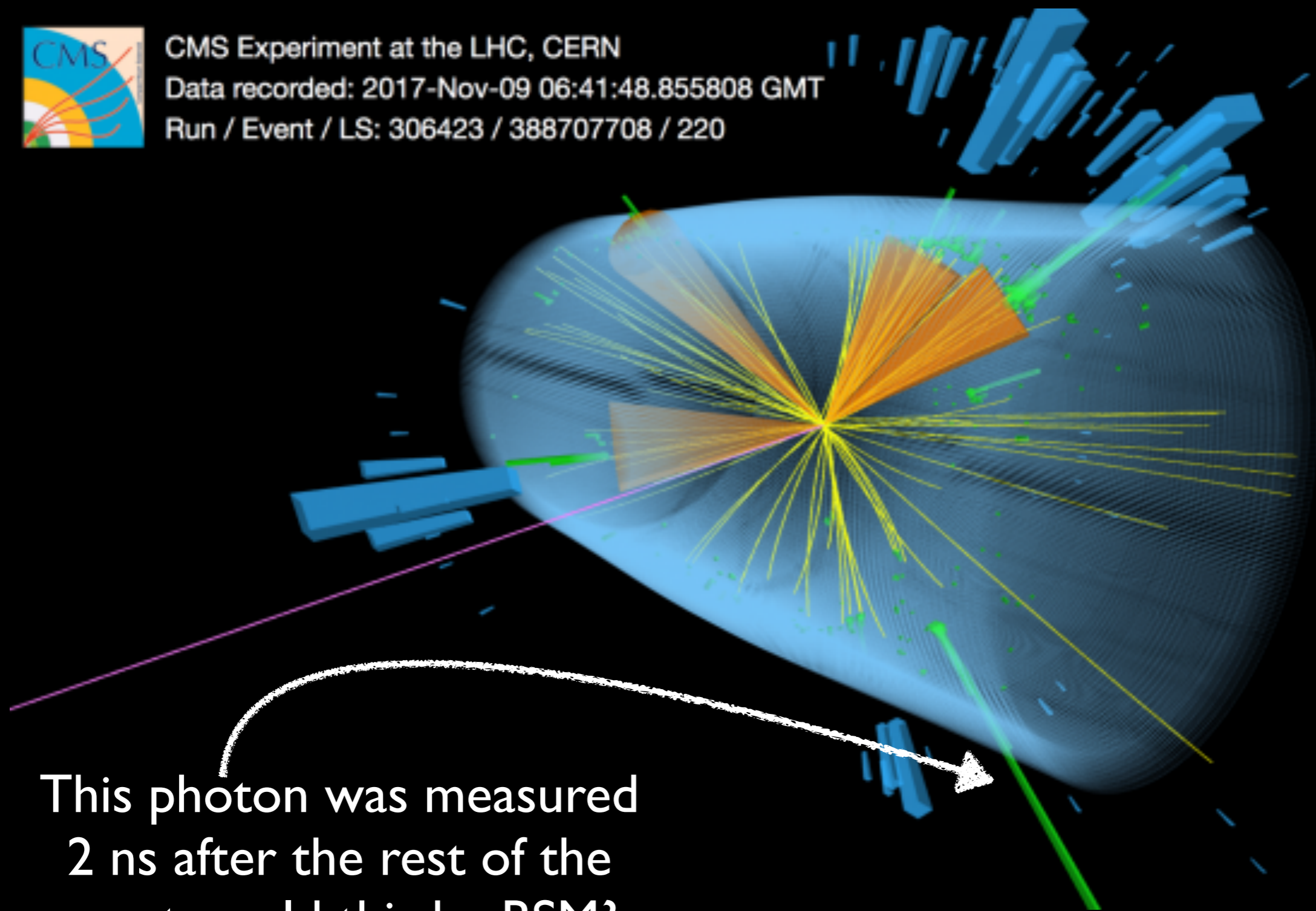
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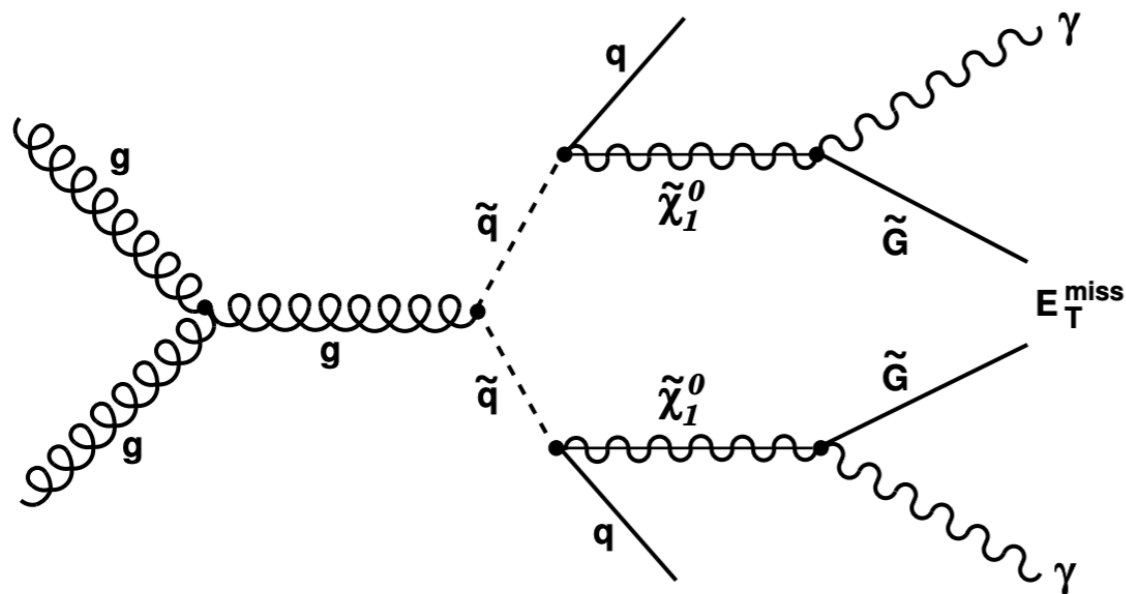


This photon was measured  
2 ns after the rest of the  
event: could this be BSM?

# Delayed Photons

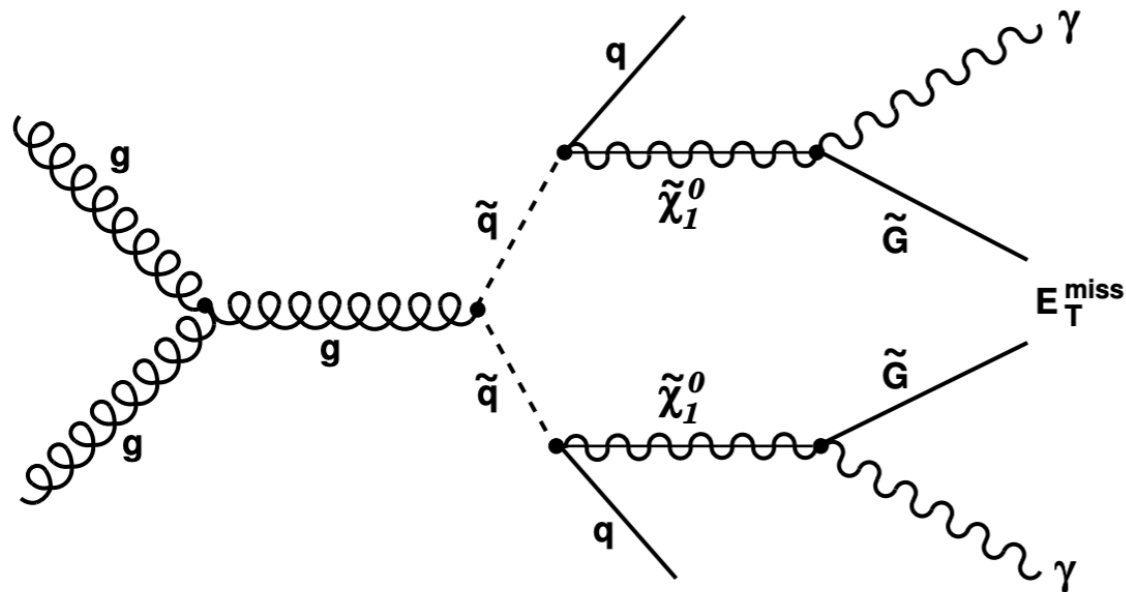


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Many models (GMSB SUSY, etc.) have long-lived particles decaying to photons

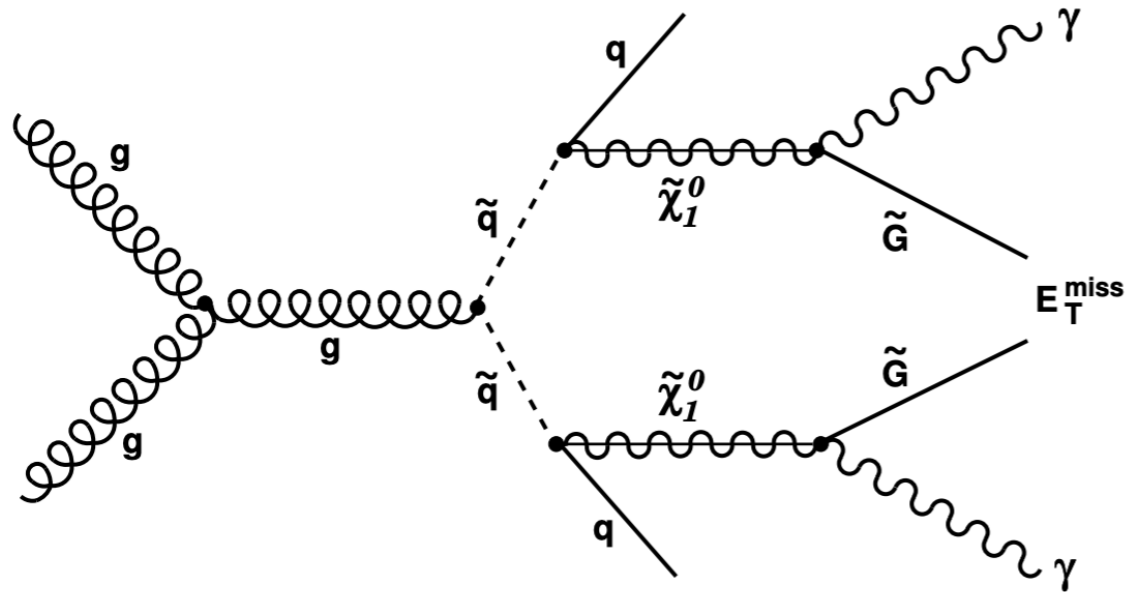
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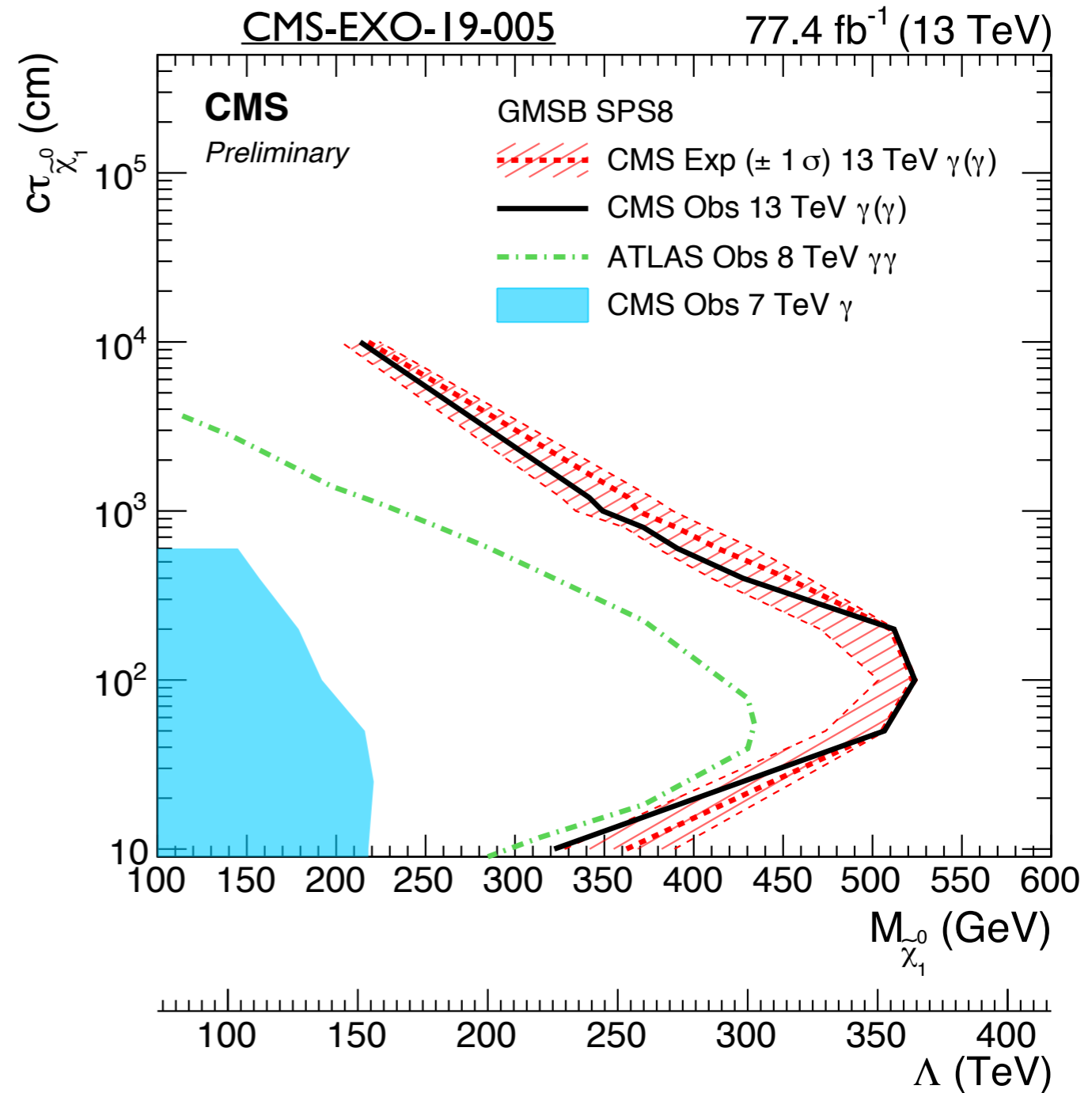
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# Conclusions



# Keep Looking!



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Naturalness, dark matter, and  
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Low Hanging Fruit Records

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

**Thank you!**

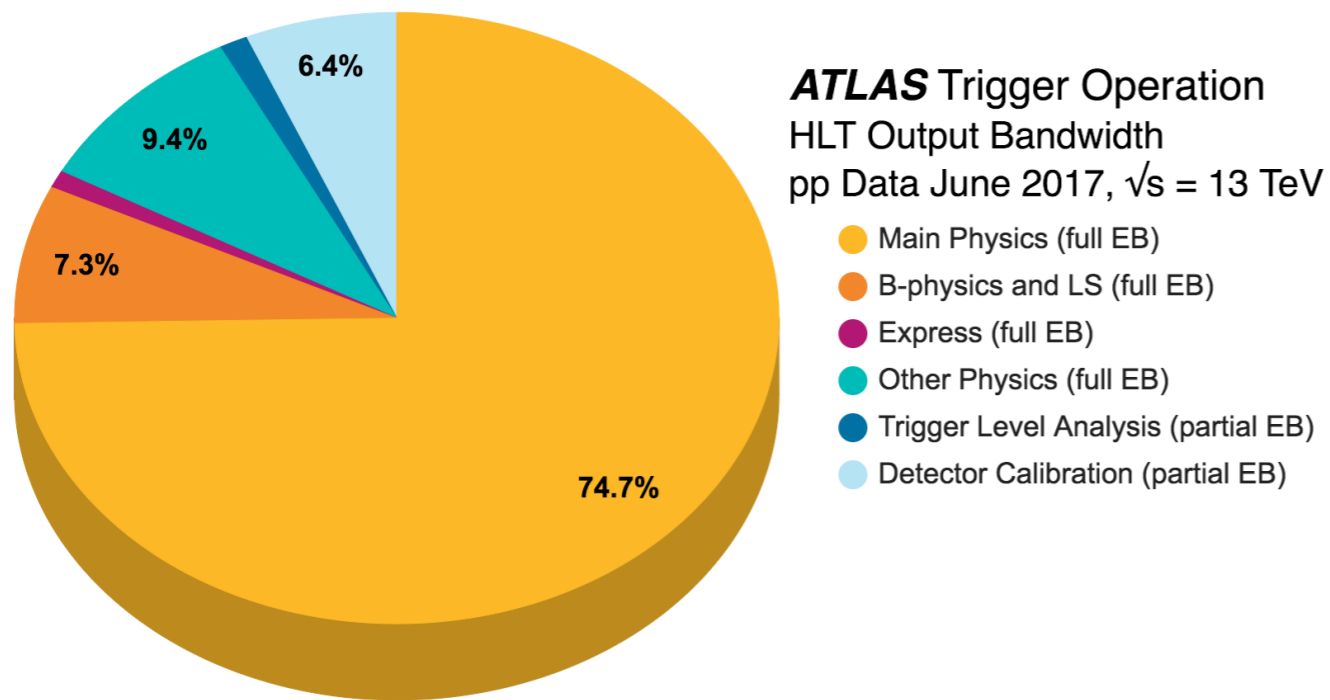
# Backup

# Data Scouting

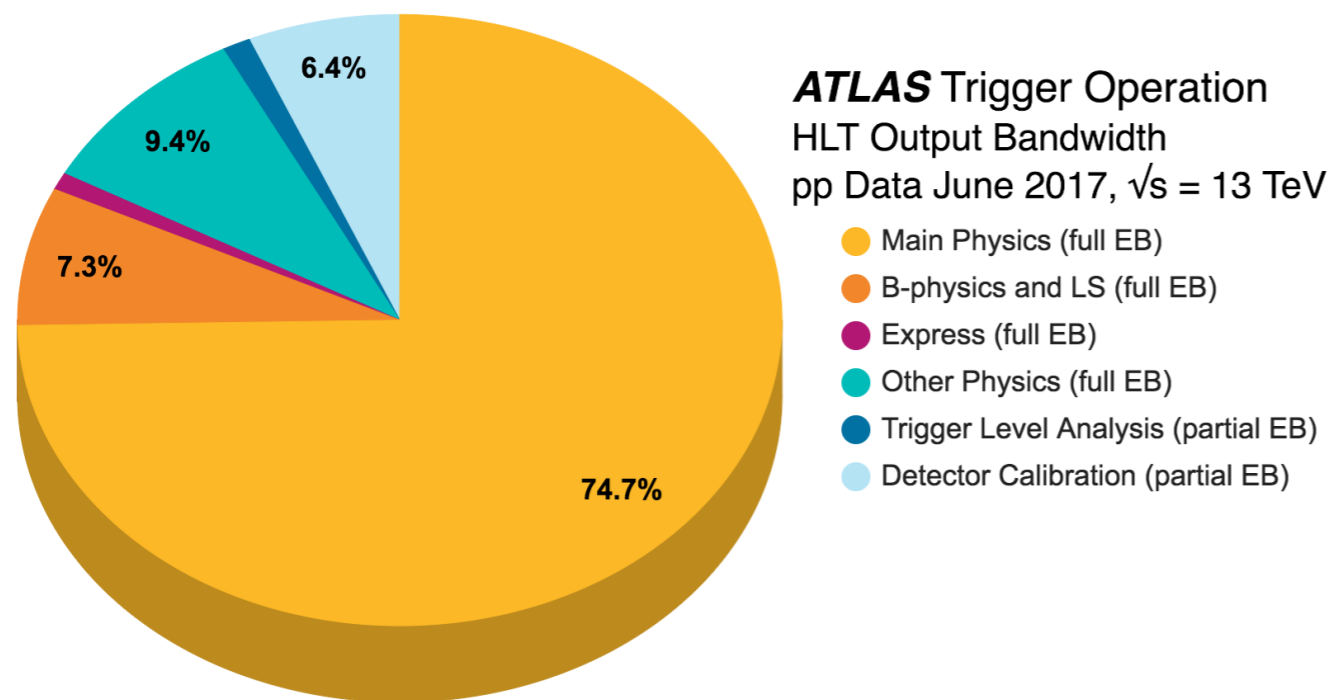




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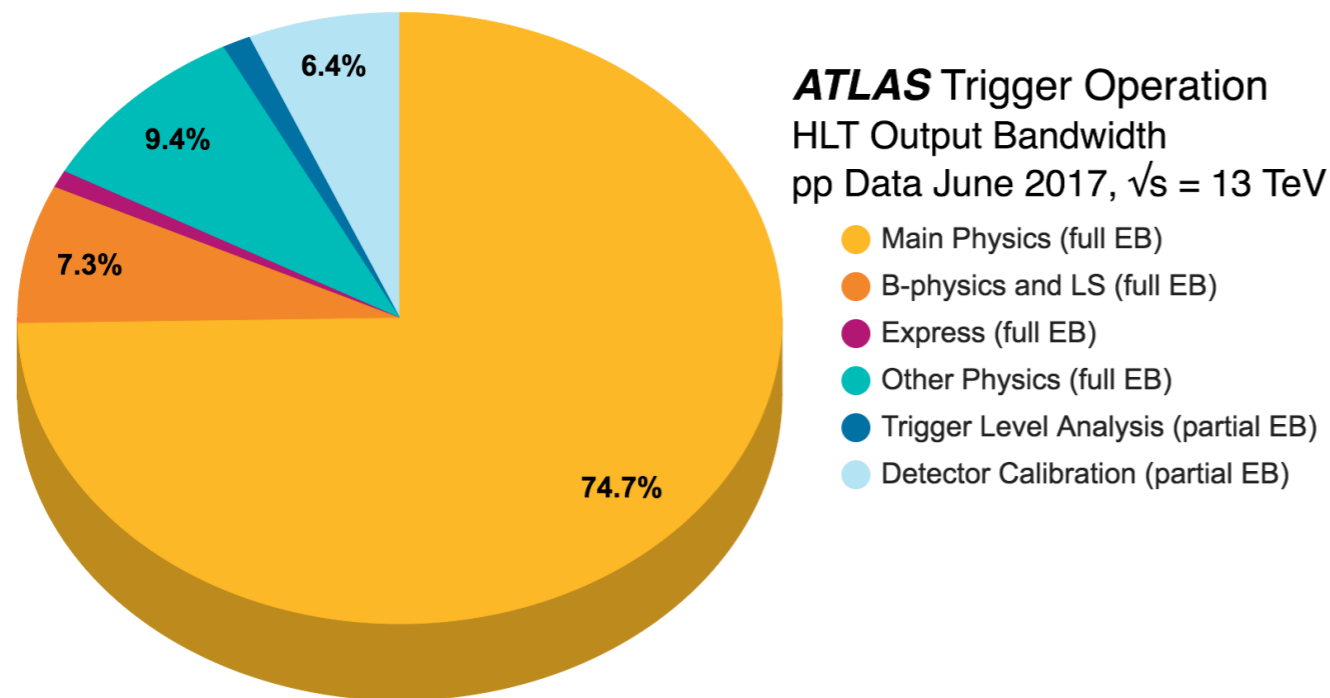


# Data Scouting



Most of the time, record the “full event” when triggered

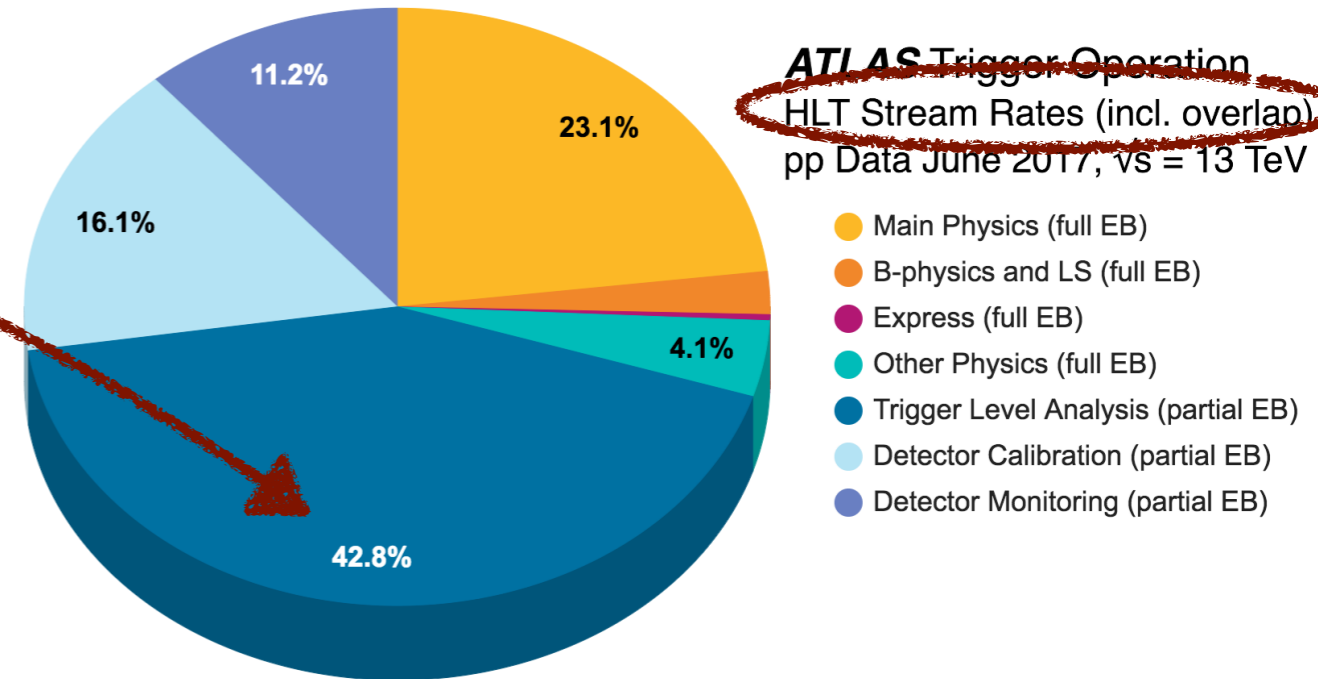
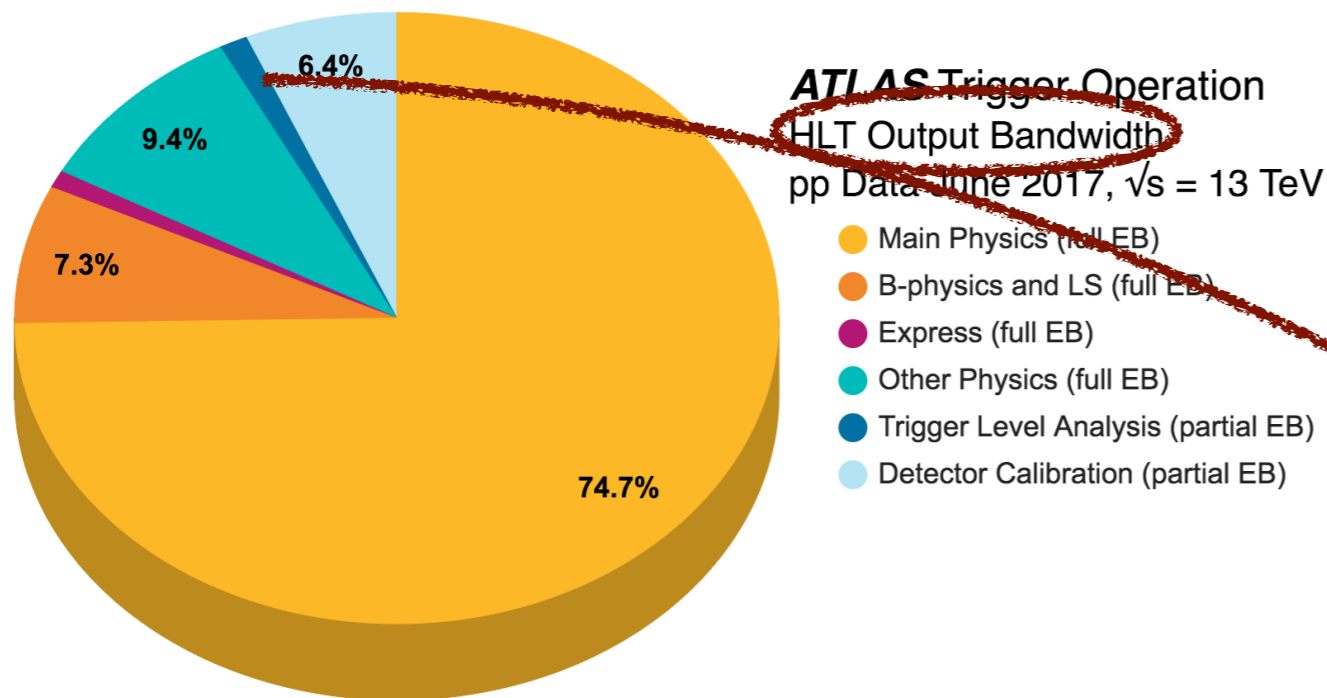
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If you make the event small, then  
you can record a lot more data!

# Machine Learning for di-Higgs



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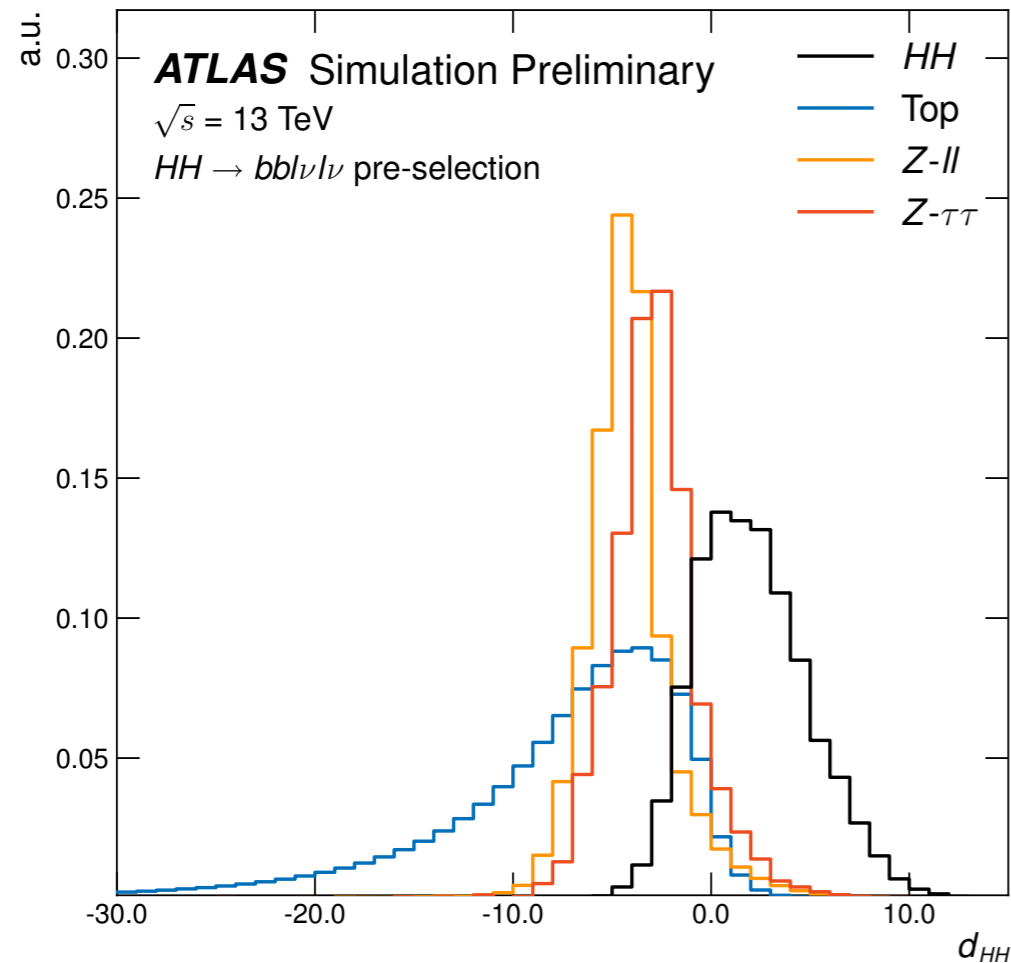


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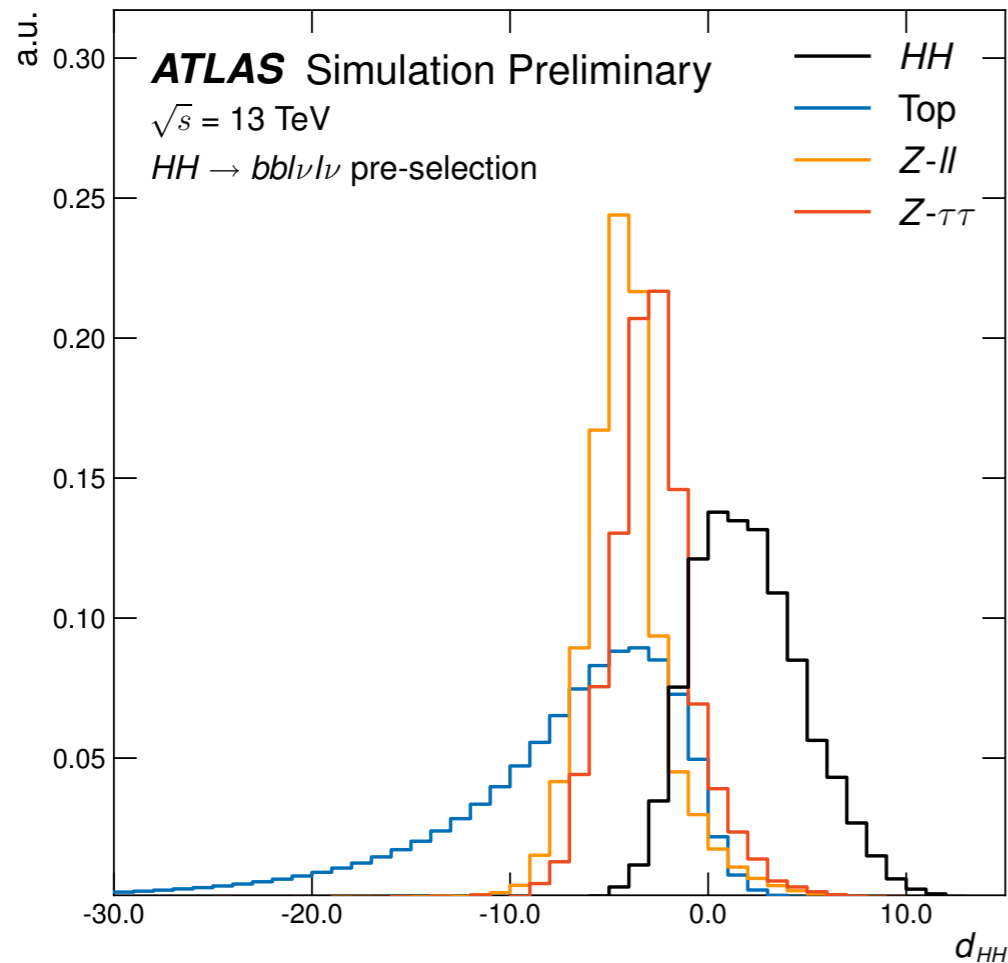


ATLAS uses a DNN to search for di-Higgs in  $bbl$  final state

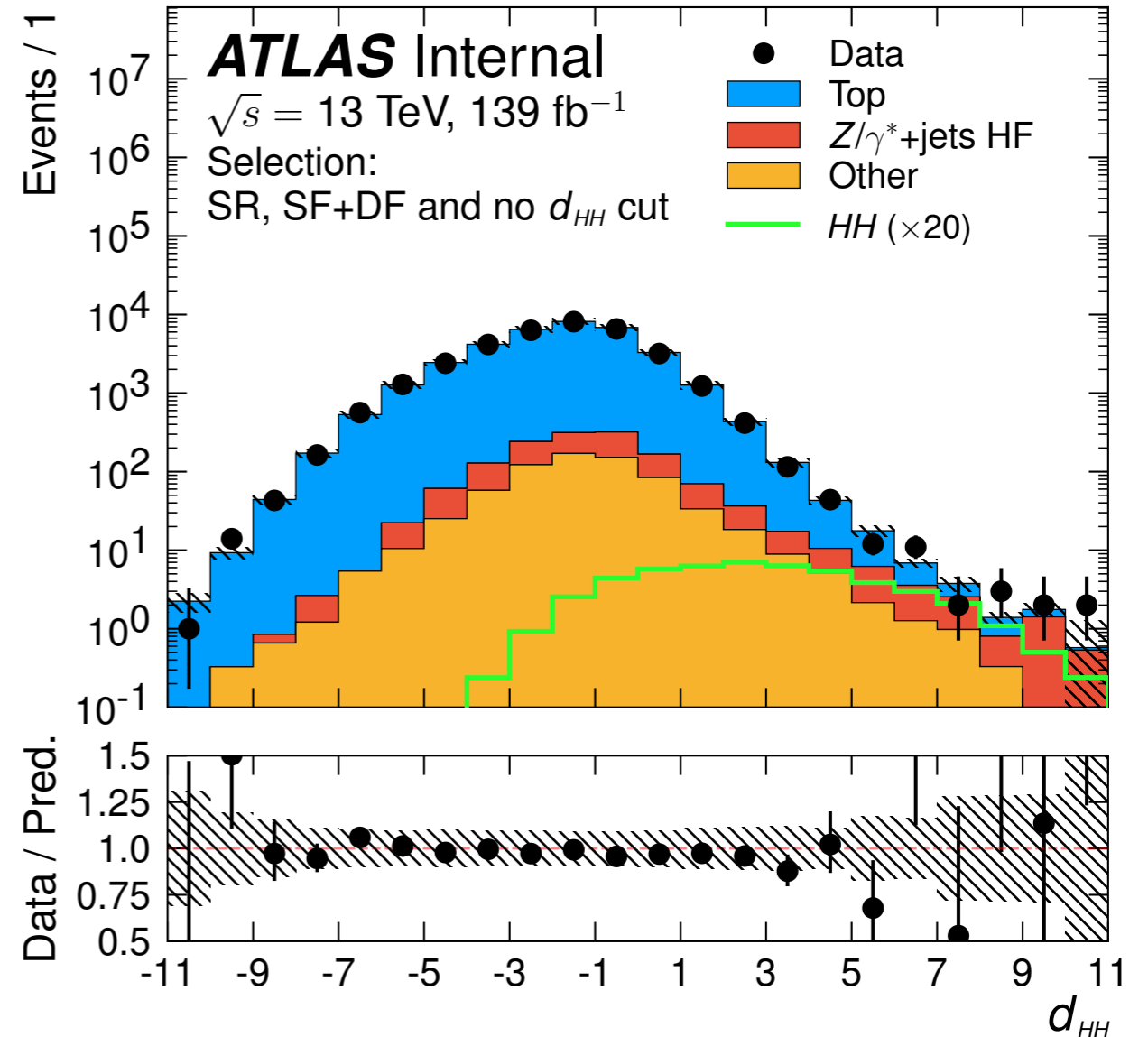
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Machine learning can make this rarer channel competitive in the hunt for di-Higgs!



# CMS Jet Timing



# ATLAS WH results

