Beyond-the-Standard-Model Searches at the LHC

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On behalf of the ATLAS and CMS Collaborations

SLAC Summer Institute
July 30 – Aug. 10, 2018

Outline

Introduction

- Why and what do we search
- Large Hadron Collider and the ATLAS/CMS experiments

Selected results from ATLAS & CMS

- New heavy resonances
- Supersymmetric particles
- Dark Matter particles

Summary and prospects

Going Beyond the Standard Model

The Standard Model is "complete"

- All the particles (including the Higgs boson) have been discovered
- All (terrestrial) experimental data agree with its predictions

At the same time, it fails to explain:

- Why 3 forces (strong, EM, weak)? Are they unified at higher energies?
- Why leptons and quarks?
- Why 3 generations?
- Why does the Universe hold more matter than anti-matter?
- What is the Dark Matter?
- Dark Energy?
- Gravity?

There must be more to it

➔ Physics beyond the Standard Model (BSM)

Going Beyond the Standard Model

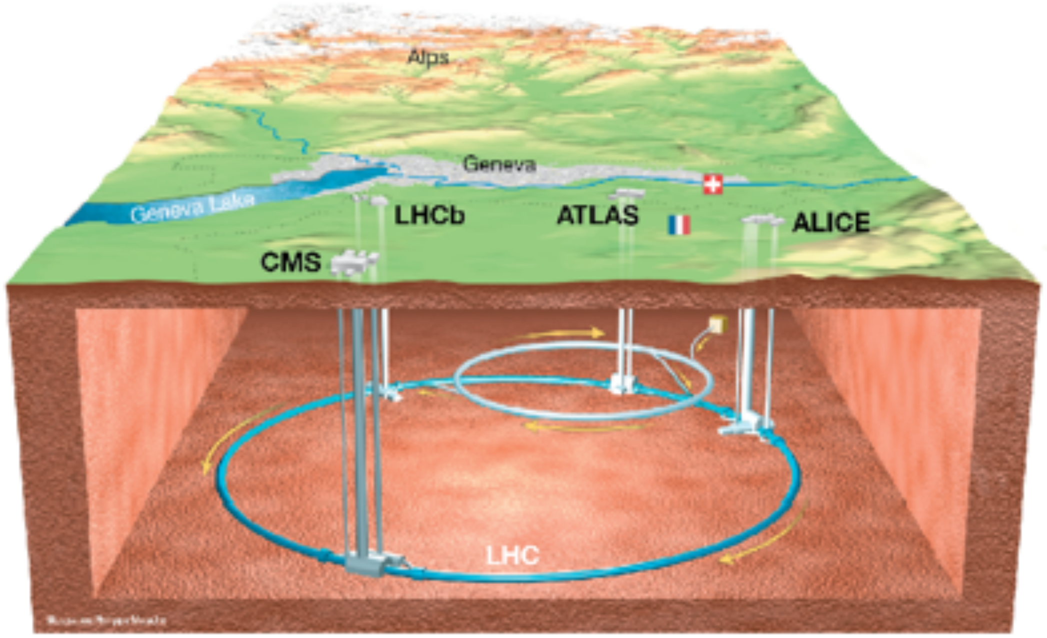
SSI2018 -- The Standard Model @ 50: Successes & Challenges										
Time/Date	30-Jul	31-Jul	1-Aug	2-Aug	3-Aug	6-Aug	7-Aug	8-Aug	9-Aug	10-Aug
9:00--10:00	Origins of the SM S. Weinberg	SM Probes in Atoms/ Molecules/ Nuclei (II) V. Cirigliano	The Development of QCD G. Sterman	QCD at the LHC (I) J. Butterworth	QCD at the LHC (II) J. Butterworth	Higgs History H. Haber	Physics of Neutrinos (I) A. de Gouvea	The Mysteries of Flavor (I) J. Zupan	What/Where is DM? T. Slatyer	Is there a no-Lose Theorem for Future Colliders? LT Wang
10:00--10:30	SSI photo	Morning Break								
10:30--11:30	Precision EWK Theory A. Freitas	EWK Precision Measurements at Colliders R. Erbacher	Precision QCD & the SM (I) F. Caola	Precision QCD & the SM (II) F. Caola	QCD on the Lattice A. Kronfeld	The Higgs in the SM S. Dawson	Physics of Neutrinos (II) A. de Gouvea	The Mysteries of Flavor (II) F. Wilson	What/Where is DM? T. Shutt	What Future Higgs Measurements Will Tell Us ? M. Peskin
11:45--12:45	SM Probes in Atoms/ Molecules/ Nuclei (I) V. Cirigliano	Low Energy Probes of the SM (I) K. Kumar	Low Energy Probes of the SM (II) B. Kiburg	Astro/Cosmo Window on the SM S. Dodelson	Astro/Cosmo Window on the SM K. Olive	Properties of the Higgs at the LHC J. Conway	Neutrinos: What Will We Learn in the Next Decade S. Soldner-Rembold	Why more baryon than antibaryons? A. Nelson	The Hierarchy & Fine-Tuning Problems A. Nelson	View Ahead Y. Kim
12:45--13:30	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch	
13:30--14:00				Klystron Gallery Tour			Klystron Gallery Tour			
14:00--14:45	Evolution of EWK Theory W. Marciano		Critical Expts (hadron colliders) P. Jenni						Project Presentations	
14:45--15:45	Evolution of Accelerators & Technology L. Evans	Q&A	Critical Expts (flavor) D. Hitlin	Q&A	CMB Constraints Z. Ahmed Ice Cube S. Robertson	Higgs Result C. Vernieri BSM Searches M. Morii	Q&A	Q&A		
15:45--16:05	Break	Break	Break	Afternoon Break						
16:05--17:30	Critical Expts (Early SLAC) M. Breidenbach	Project Kickoff	Critical Expts (neutrinos) E. Kearns	Projects Kavli Vislab Tour	Projects	MiniBooNE A.Diaz Gravitational Waves J. McIver	Projects Kavli Vislab Tour	Belle II K. Kinoshita Projects IR2 Tour	Project Presentations	
18:00	Reception	Dinner	Poster social			Dinner	Poster social	Soccer	Dinner	

➔ Physics beyond the Standard Model (BSM)

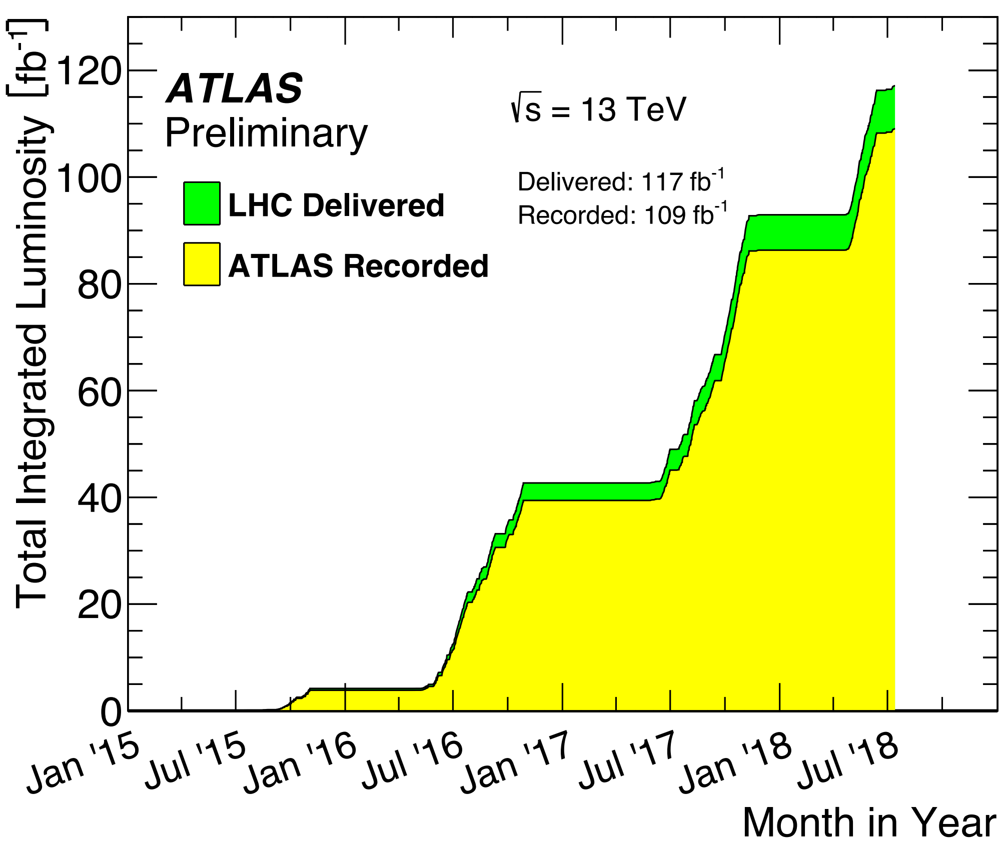
Large Hadron Collider

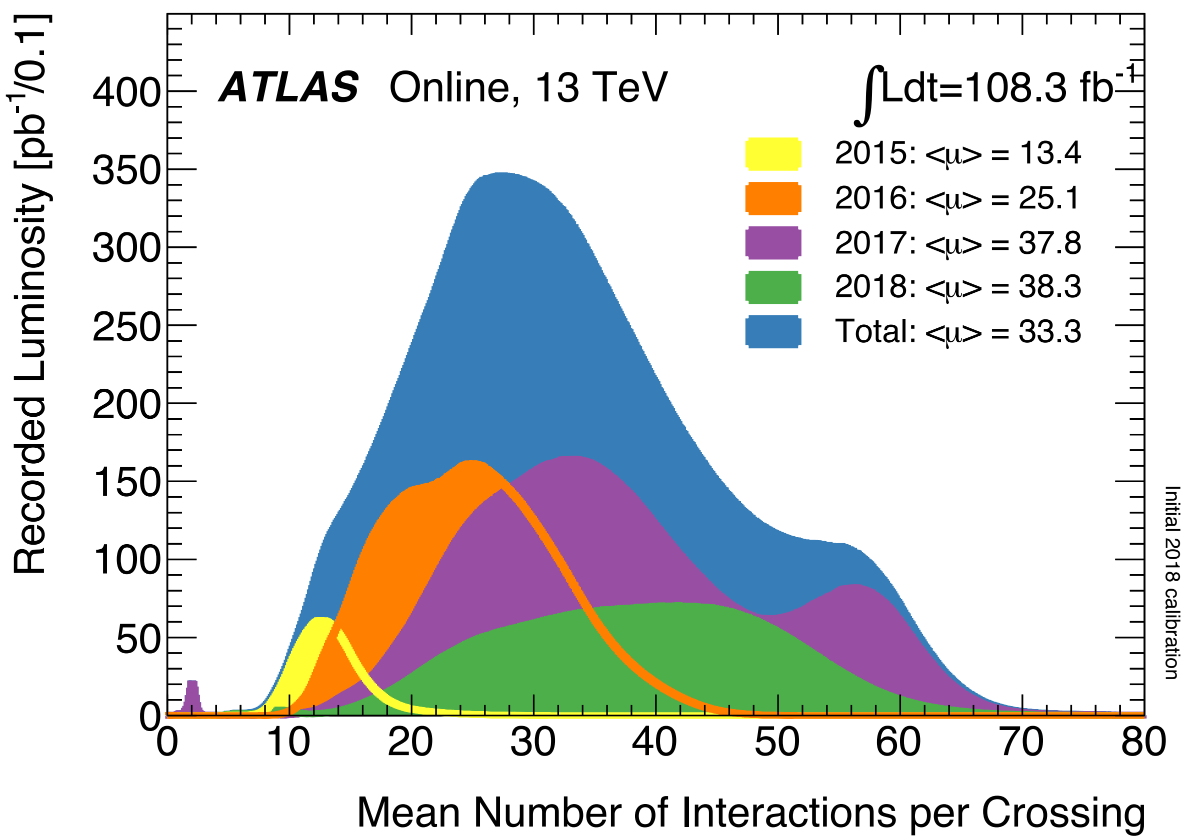
LHC collides protons with center-of-mass energies up to 14 TeV

- Counter-circulating beams of >1000 bunches of ~10^{11} protons
- Bunches cross every 25 ns producing up to 70 p-p collisions

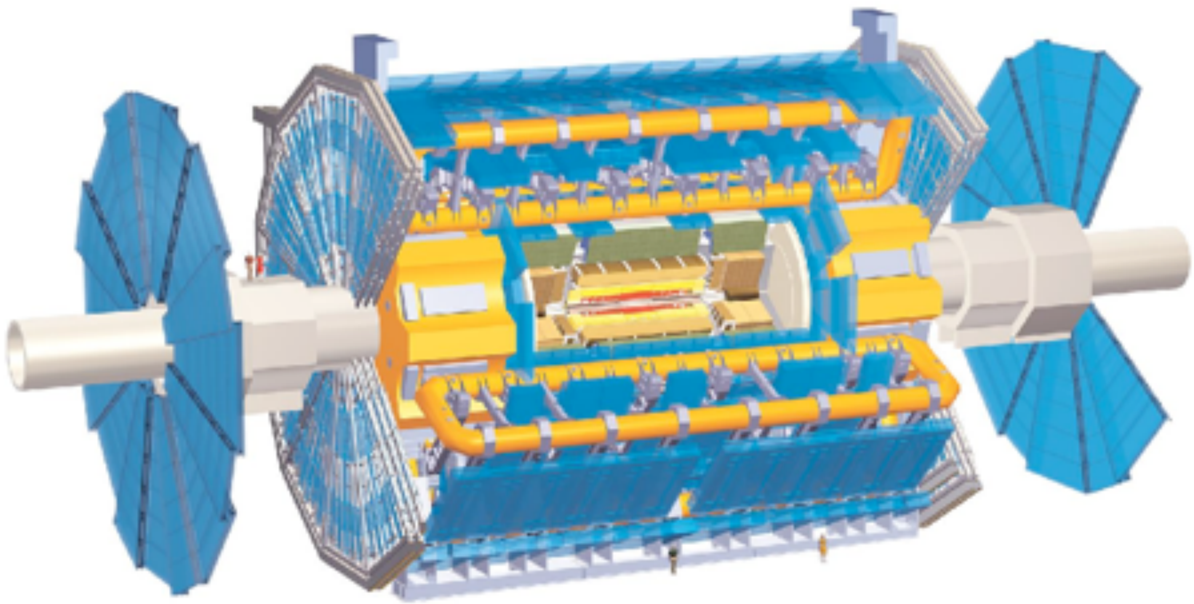


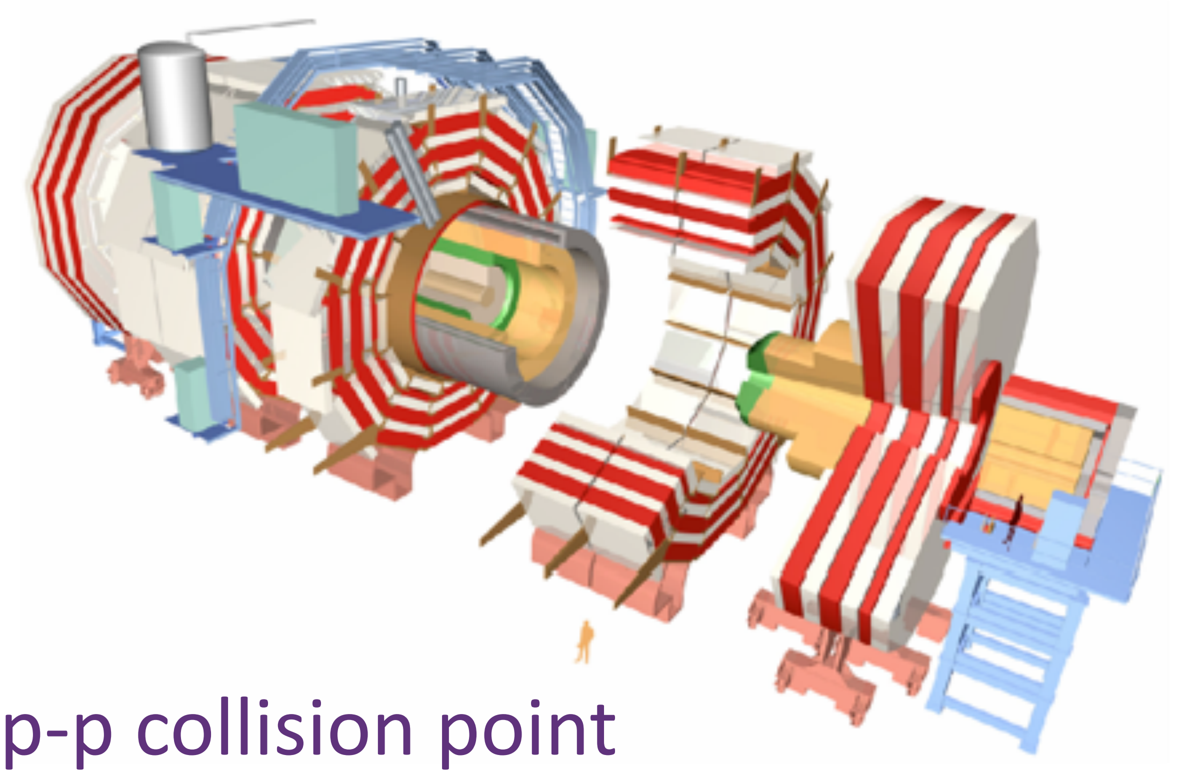
Results presented today use 13 TeV data collected in 2015–17





ATLAS and CMS detectors





Each detector is built to surround a p-p collision point

- Near-4π coverage to detect all collision products (photons, leptons, hadrons) except for neutrinos and (possibly) new invisible particles
- Energy/momentum measurement of all particles ➔ Inference of undetected particle(s) from momentum conservation in the transverse plane
  - p_T^X = transverse momentum of X (particle or group of particles)
  - MET = negative sum of p_T of all detected particles in an event
- Many BSM searches rely on MET

Looking for the Unknown

How can we look for things we don't know?

a) Signatures that stand out

- Heavy new particle ➔ Decays into many particles
  - Are all particles detected?
    - Yes ➔ Reconstruct the mass of the new particle
    - No ➔ Add up the visible energy, and deduce what's lost
- Unusual behavior, e.g., flying some distance before decaying

b) Predictions from BSM models

- Motivated by theory, e.g., supersymmetry
- Motivated by cosmology, e.g., Dark Matter

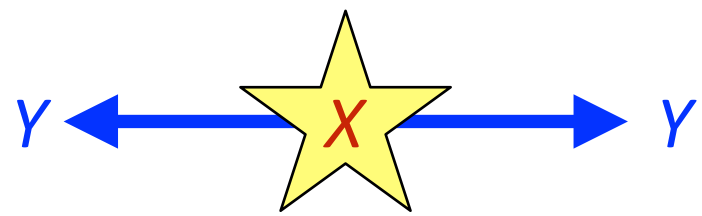
Search Sampler

I will give you a small sample of recent results from ATLAS & CMS

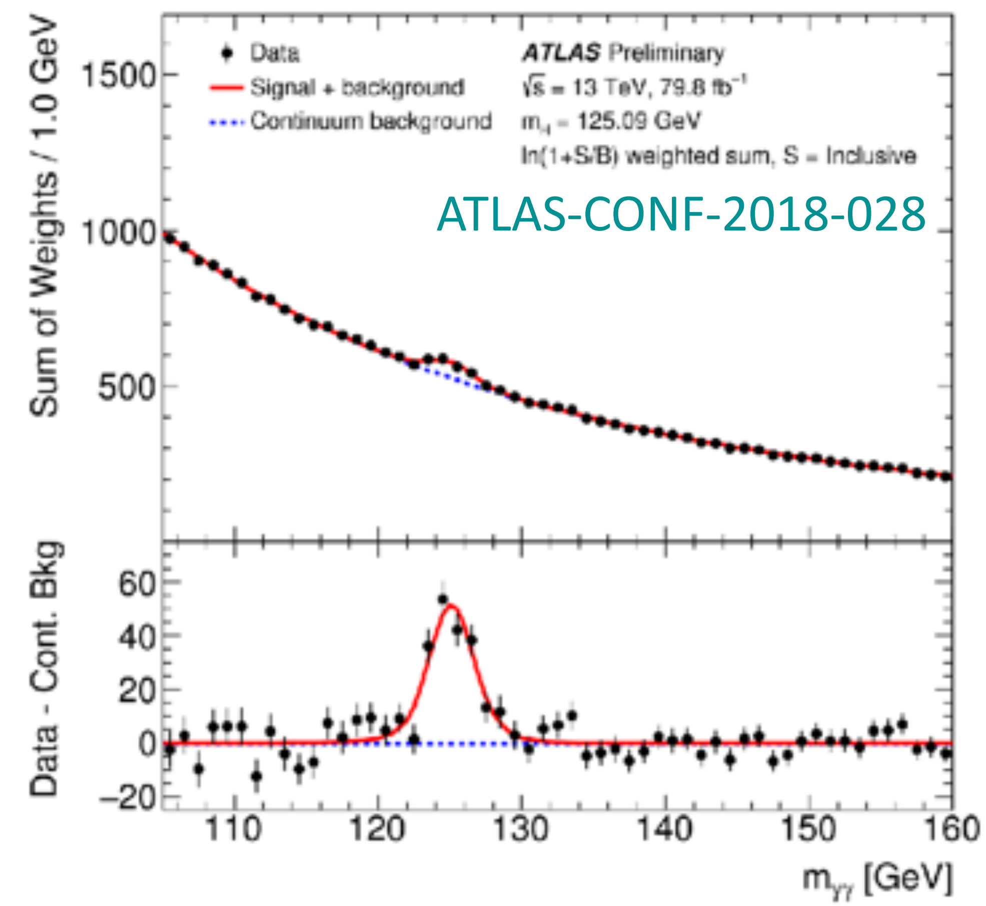
- Resonances = Heavy short-lived particle decaying into a pair of SM particles
  - $X \to$ 2 jets (= quark or gluon)
  - X $\to$ 2 weak bosons (= W or Z)
  - $X \to$ 2 Higgs bosons
- SUSY (supersymmetry) particles
  - Gluinos ($\tilde{g}$) and squarks ($\tilde{q}$)
  - Top squarks ($\tilde{t}$)
  - Charginos ($\tilde{\chi}^{\pm}$) and neutralinos ($\tilde{\chi}^{0}$)
  - Long-lived particles
- Dark Matter particle
  - MET + jet
  - MET + top quarks

Resonances

Golden mode of new particle discovery

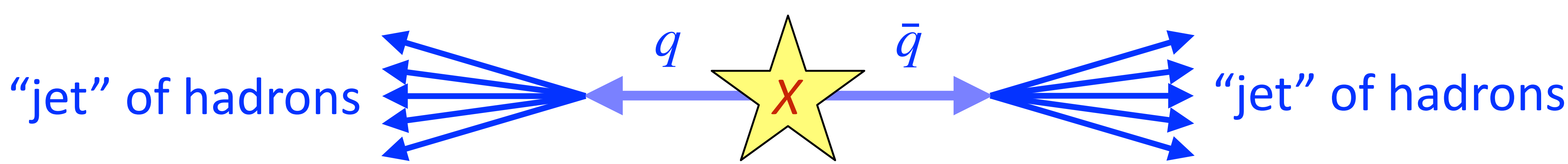


- New particle *X* decays into a pair of known particles *Y*
- A peak shows up in the *Y*-*Y* invariant mass spectrum, as it did when the Higgs was discovered at $m_{\gamma\gamma}$ = 125 GeV

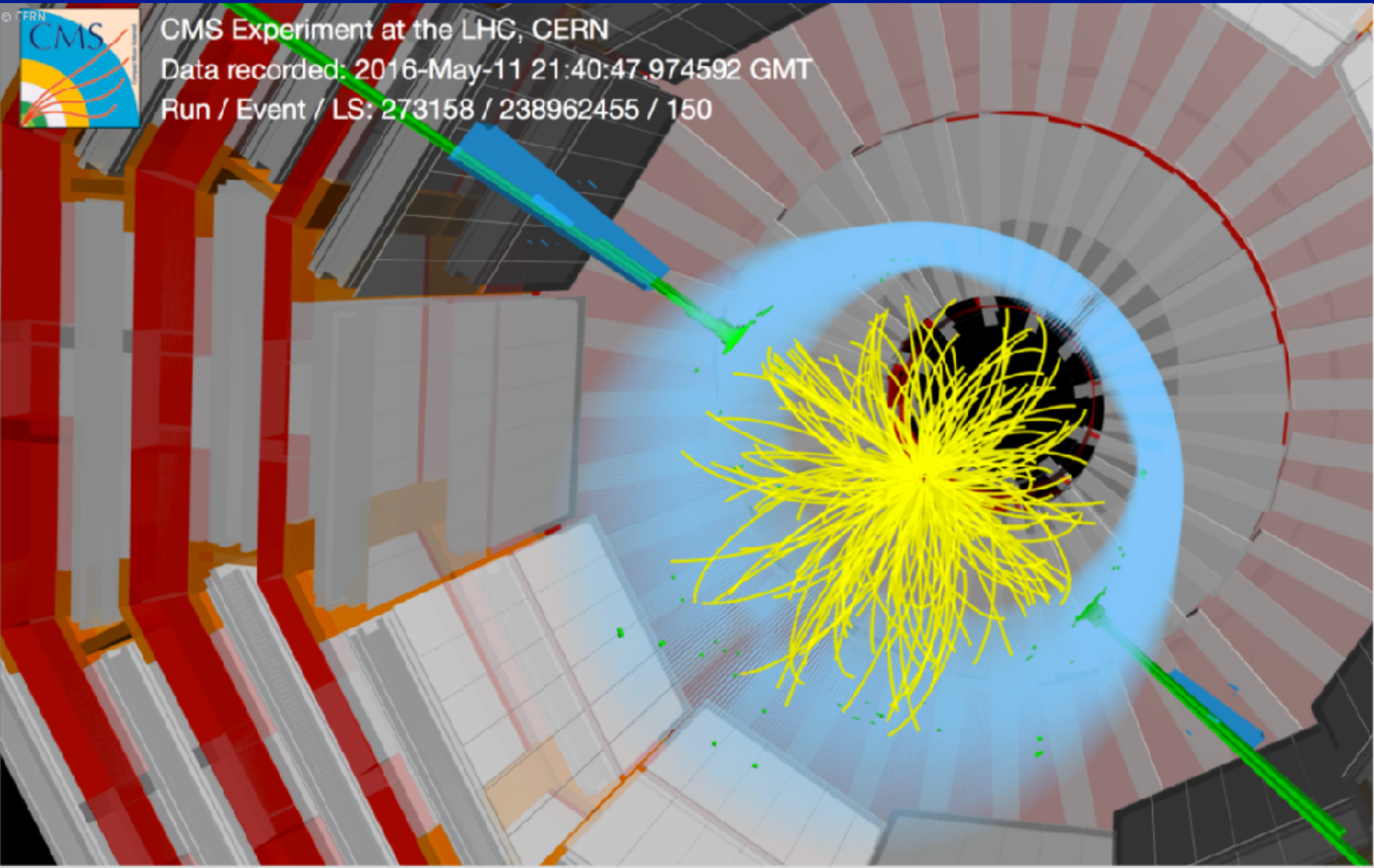


Y may be anything as long as we can measure the energy-momentum

- Let's start with *Y* = quark ➔ di-jet resonance



8 TeV Di-Jet Event in CMS

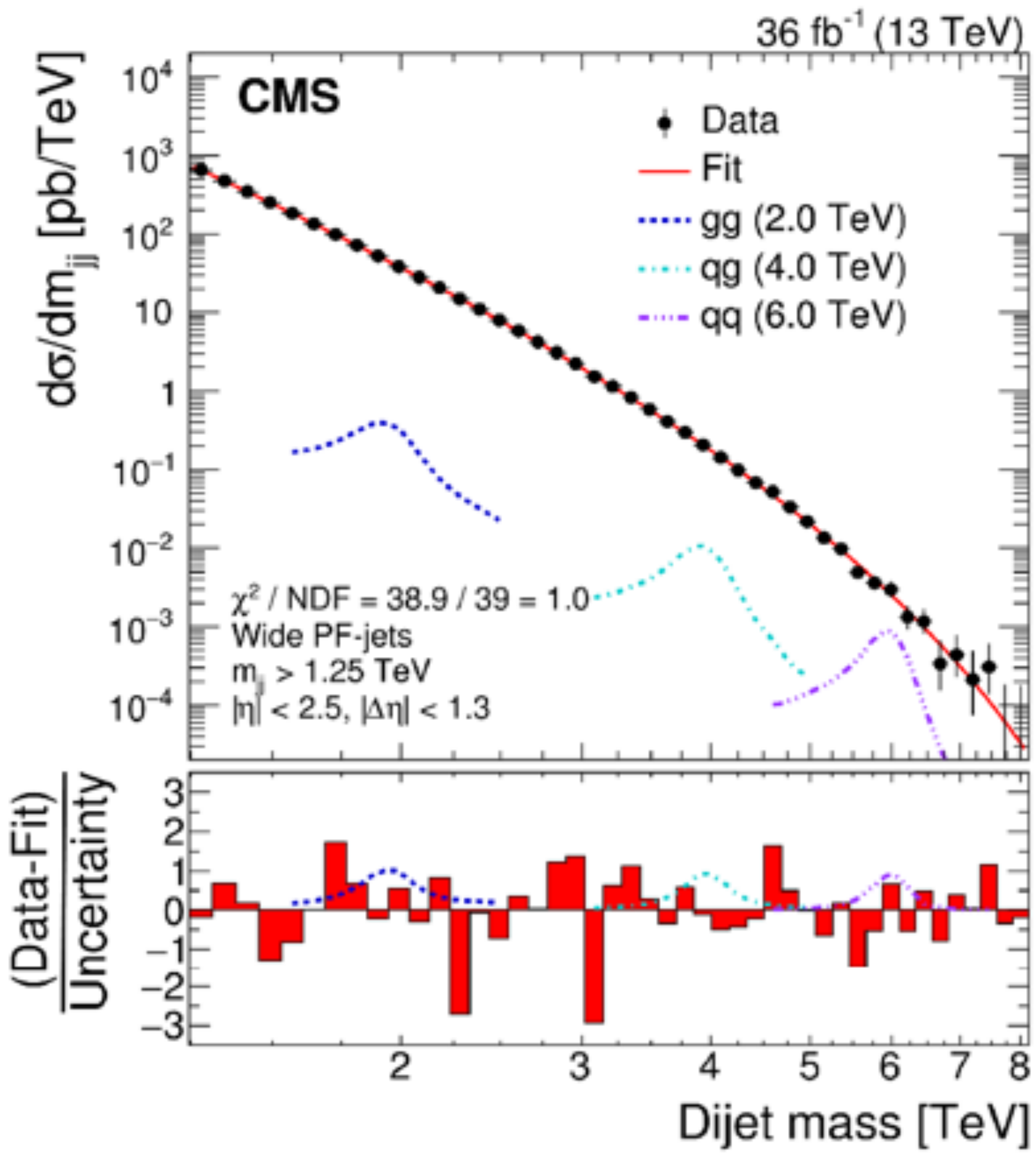


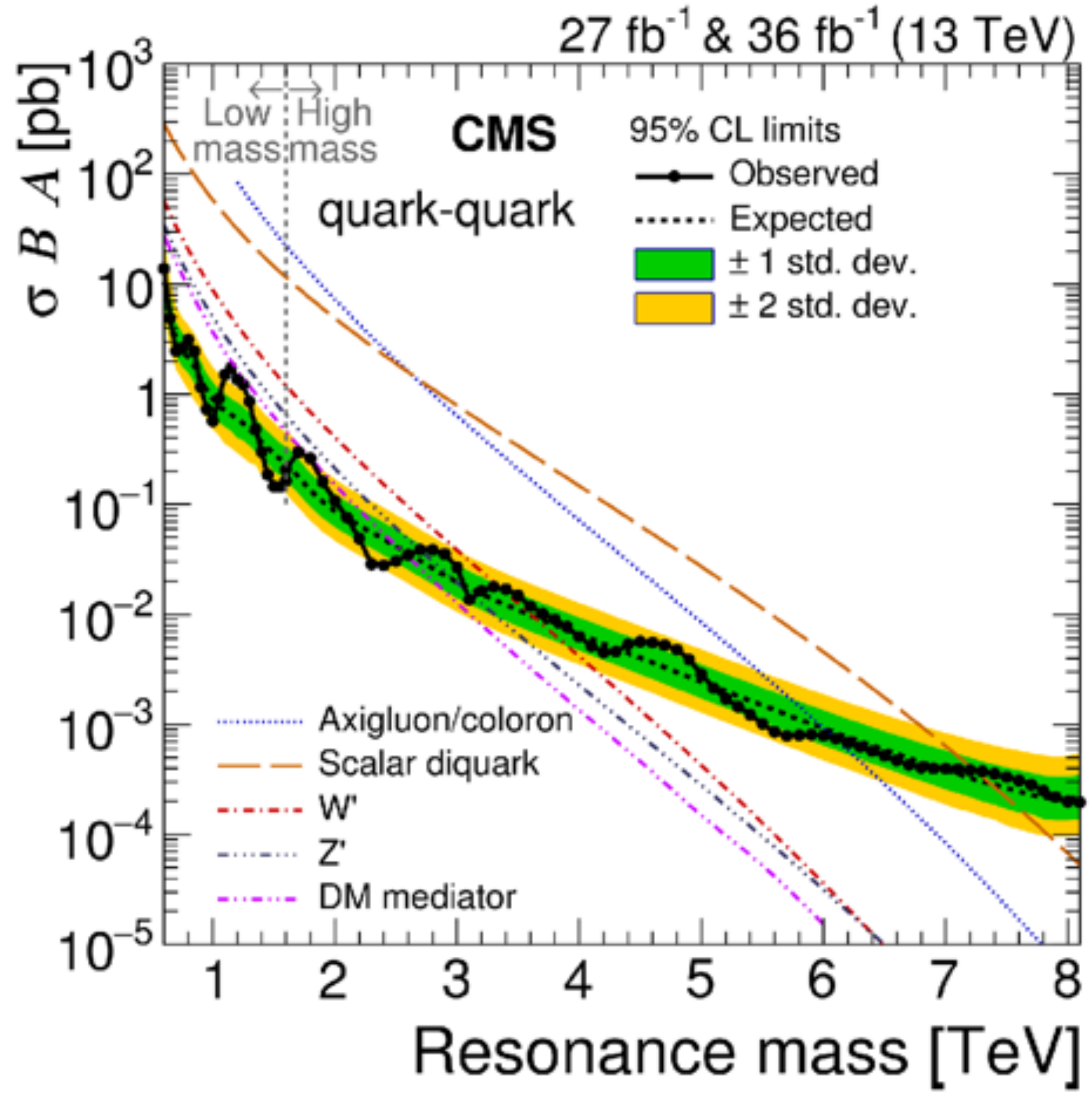
Di-Jet Resonance

CMS arXiv:1806.00843

Search for pairs of high-energy jets in 27–36 fb^{-1} of CMS data

- Signal would stick out above smoothly-falling background





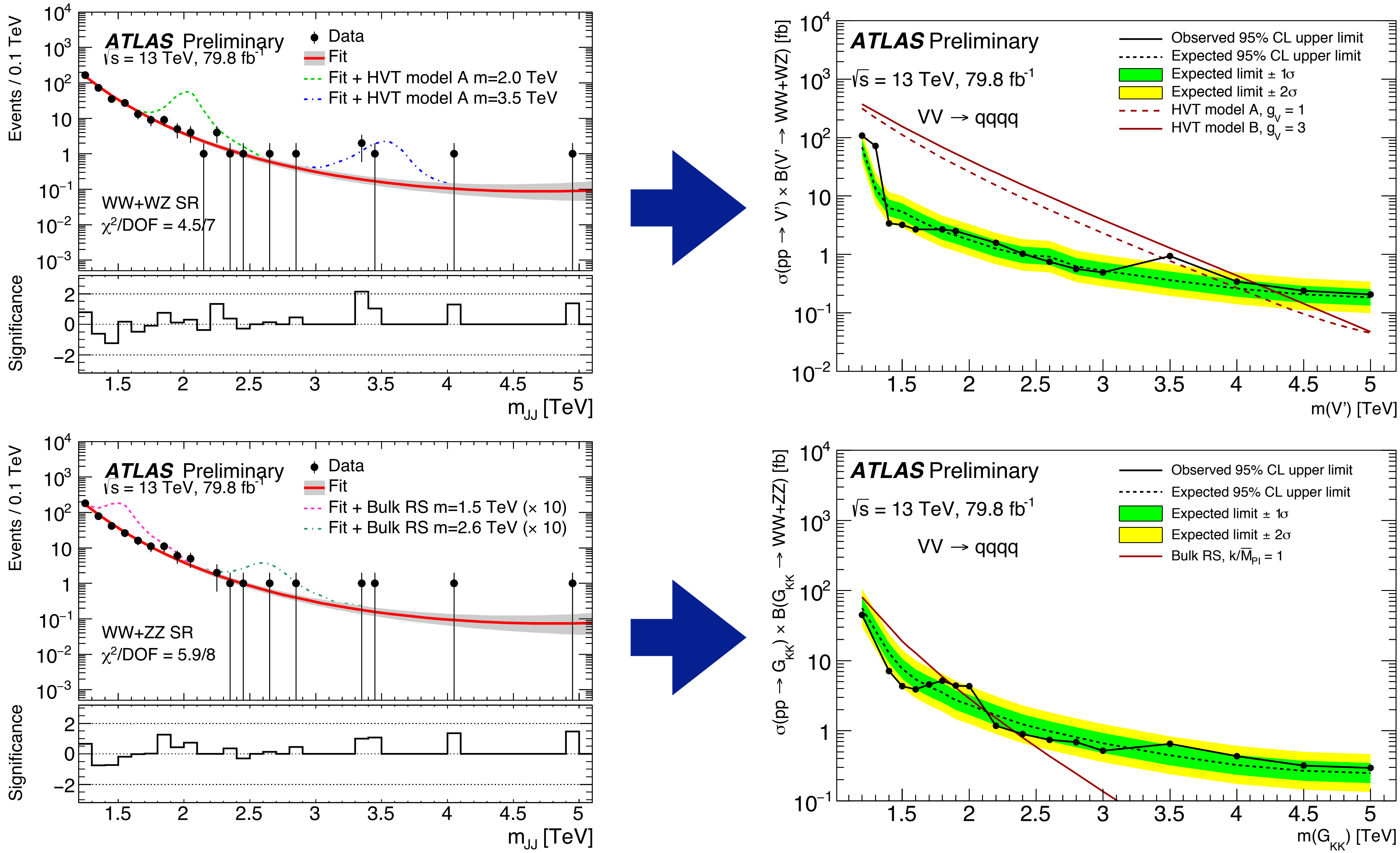
- No signal ➔ Limit on the cross-section as a function of mass

Di-Boson resonance

ATLAS-CONF-2018-016

Search for pairs of *W* or *Z* bosons in 80 fb^{-1} of ATLAS data

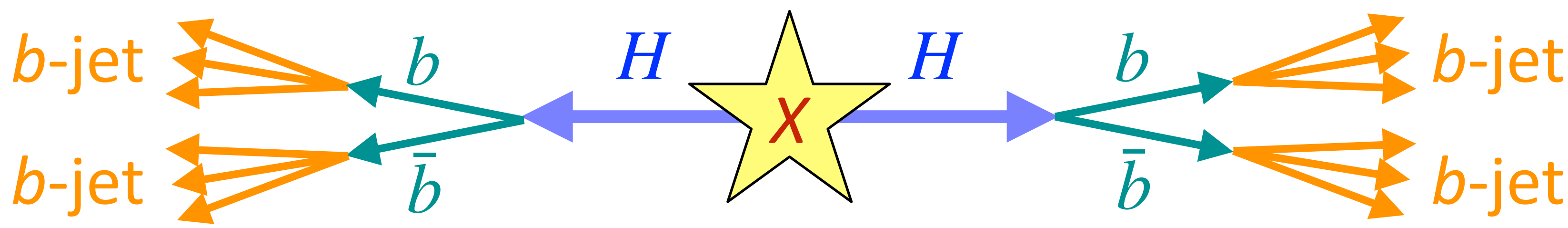
- Each W/Z boson decays into 2 quarks, reconstructed as “fat” jets



Di-Higgs Resonance

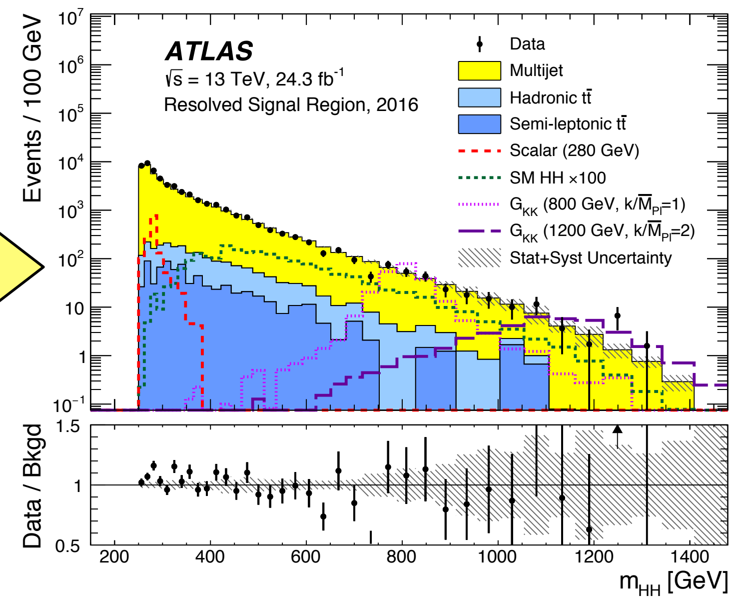
ATLAS arXiv:1804.06174

Search for pairs of Higgs bosons in 36 fb^{-1} of ATLAS data

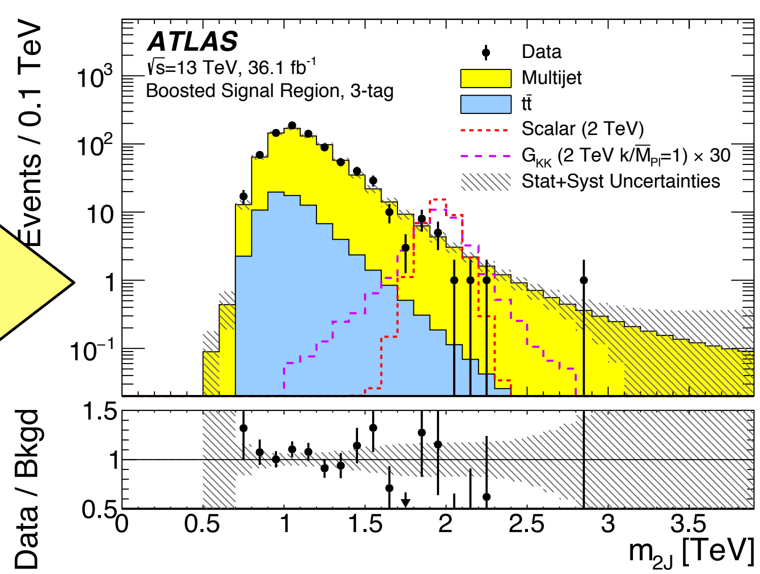


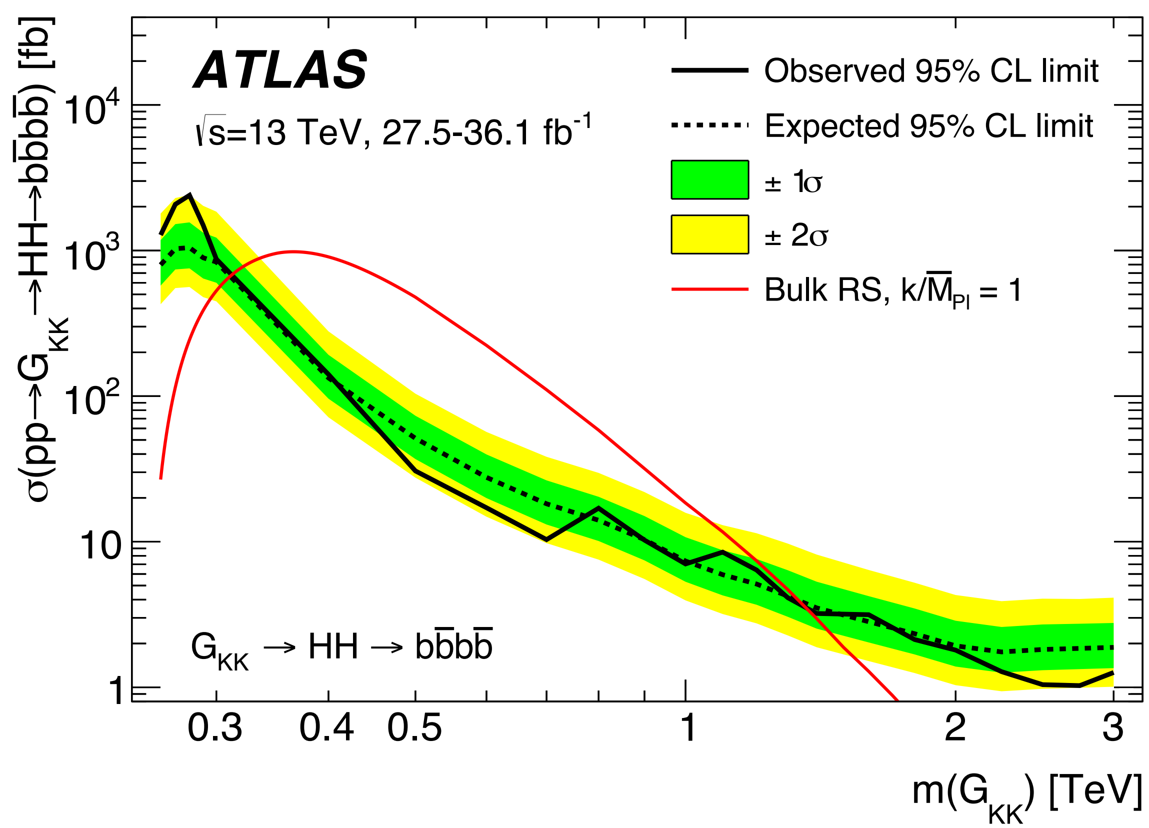
- Each Higgs boson decays into 2 *b*-quarks, “tagged” by their decay lengths

4 *b*-jets

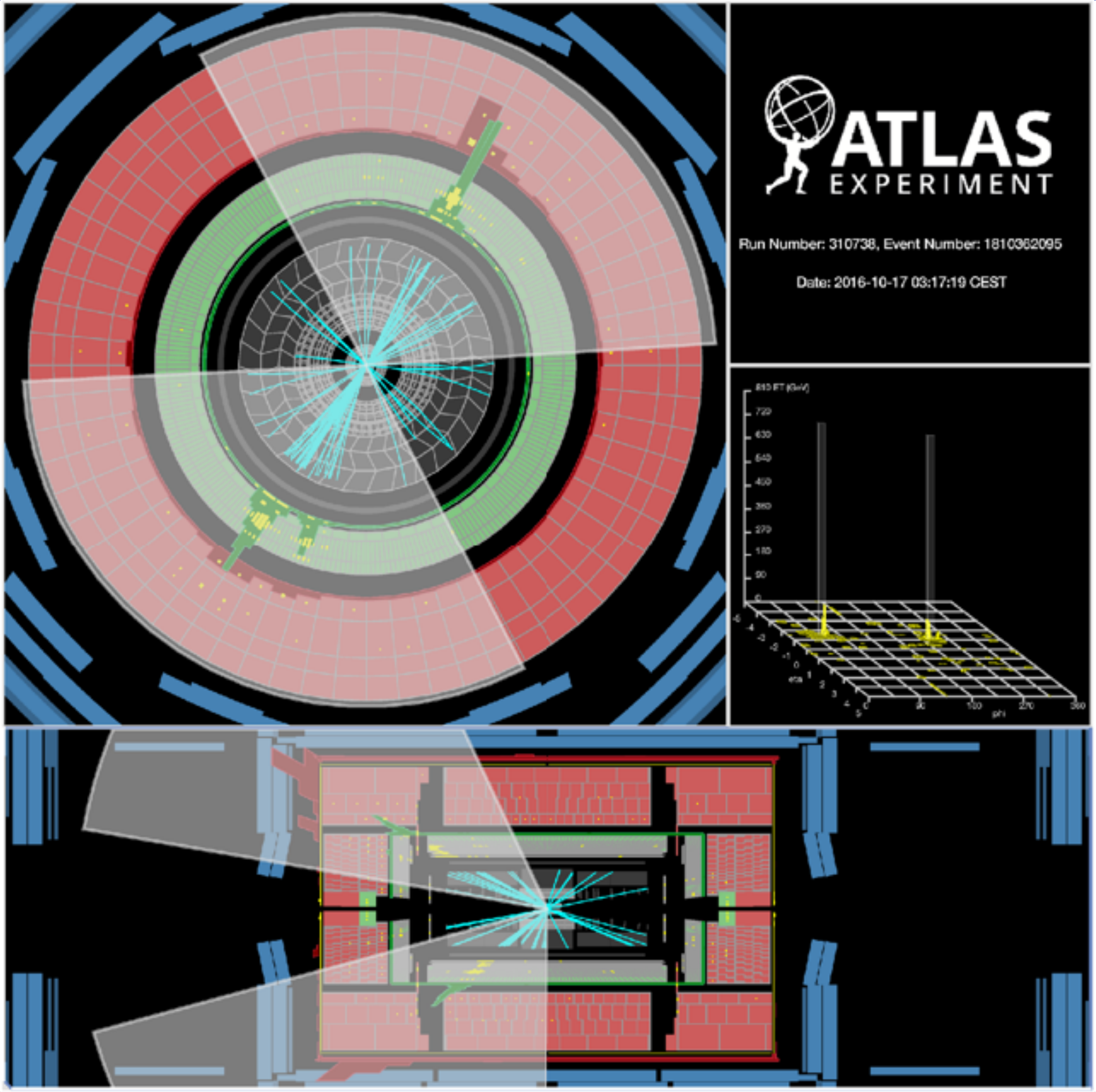


2 double *b*-jets



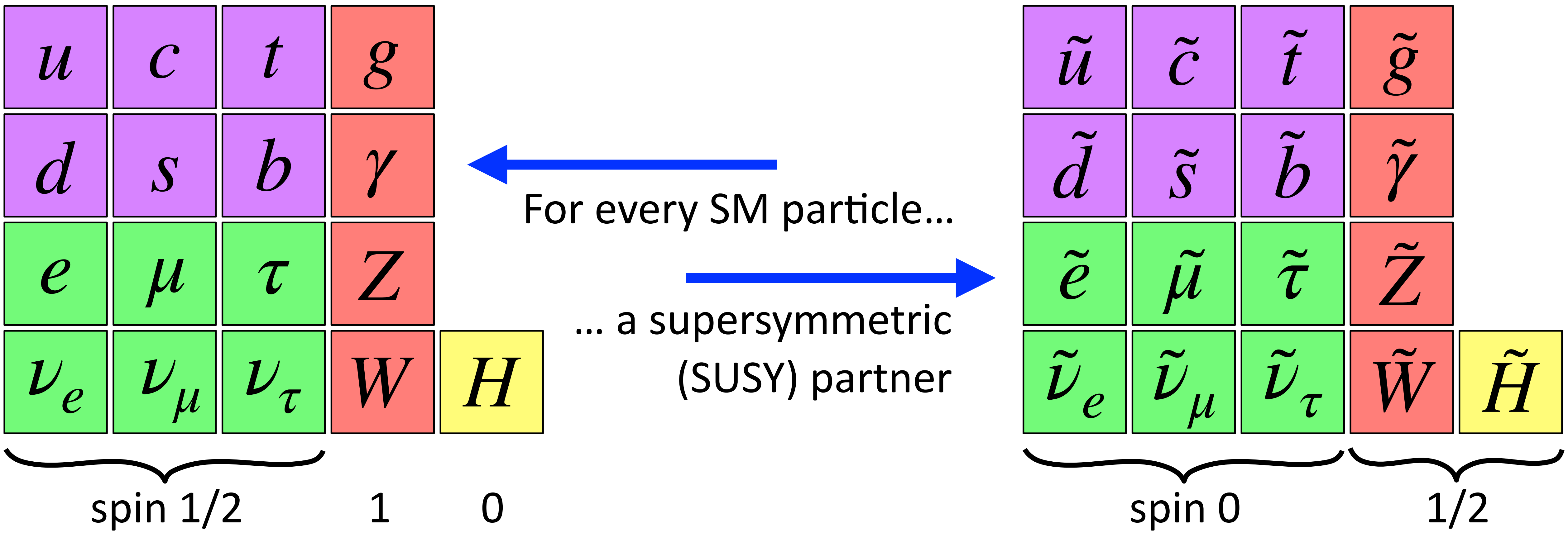


Merged-Jet Event in ATLAS



- Recorded in Oct. 2016
- Two broad jets
- Each jet contains 2 narrow jets of tracks, one of which is *b*-tagged
- Total invariant mass is 3.89 TeV

Supersymmetry



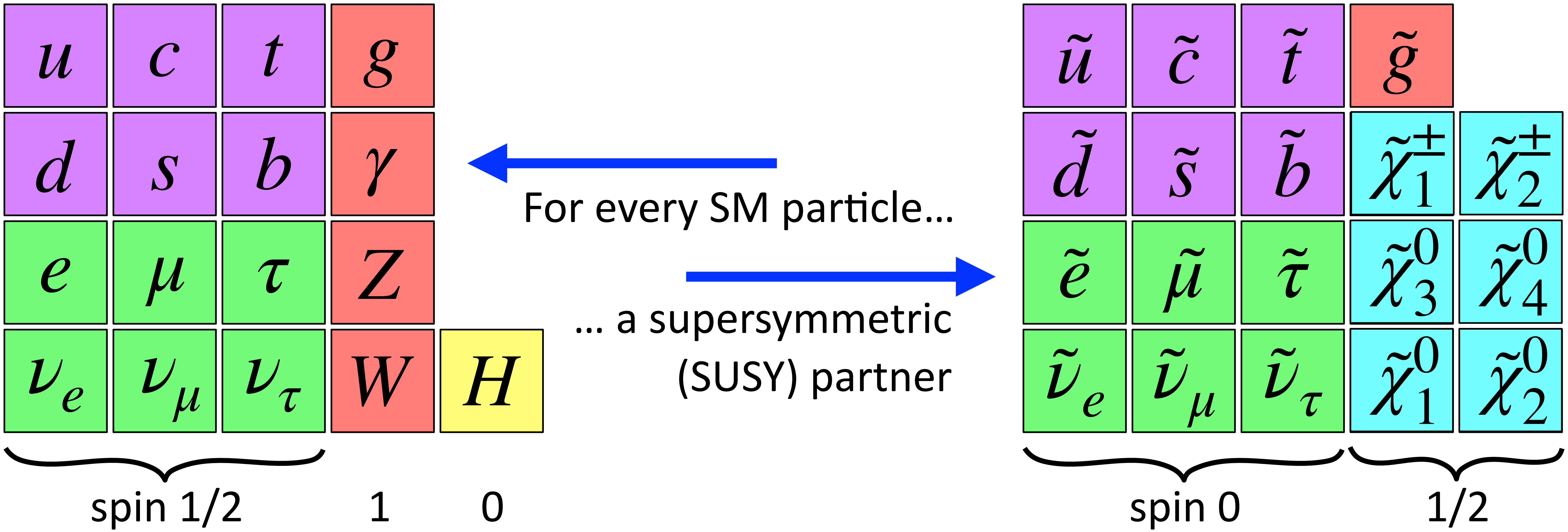
SUSY can solve many of the weaknesses of the Standard Model

- Unify the 3 forces at high energy
- Lightest SUSY Particle (LSP) may be the Dark Matter
- Solve the fine-tuning problem of the Higgs mass

Listen to Ann Nelson's lecture!

Higgs mass favors "light" gluino ($\tilde{g}$), stop ($\tilde{t}$) and higgsino ($\tilde{H}$)

Supersymmetry



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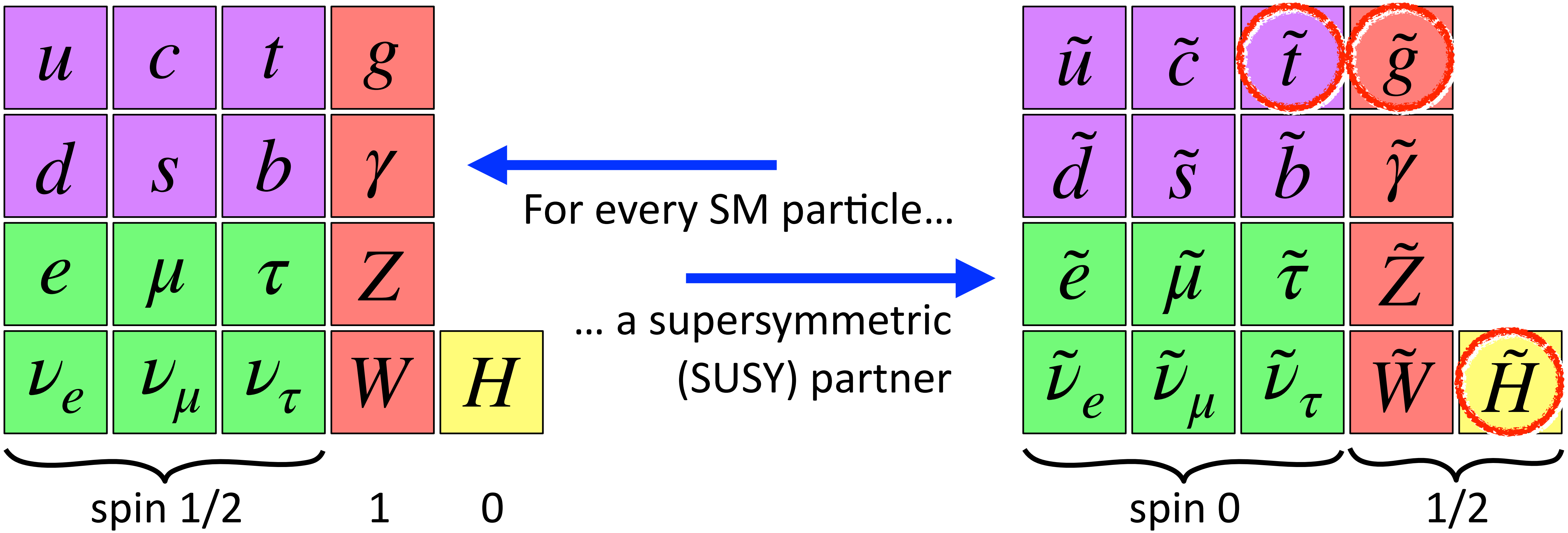

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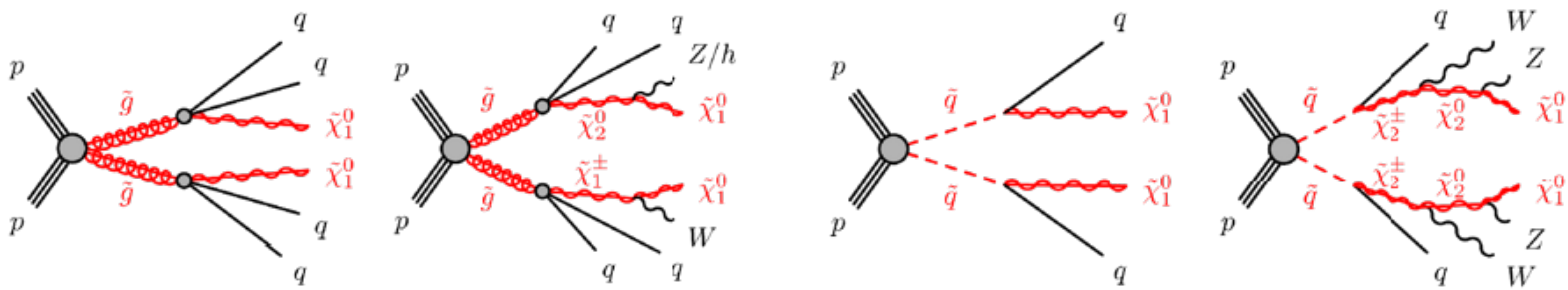
Gluinos and Squarks

Gluinos ($\tilde{g}$) and squarks ($\tilde{s}$) are pair-produced by strong interaction

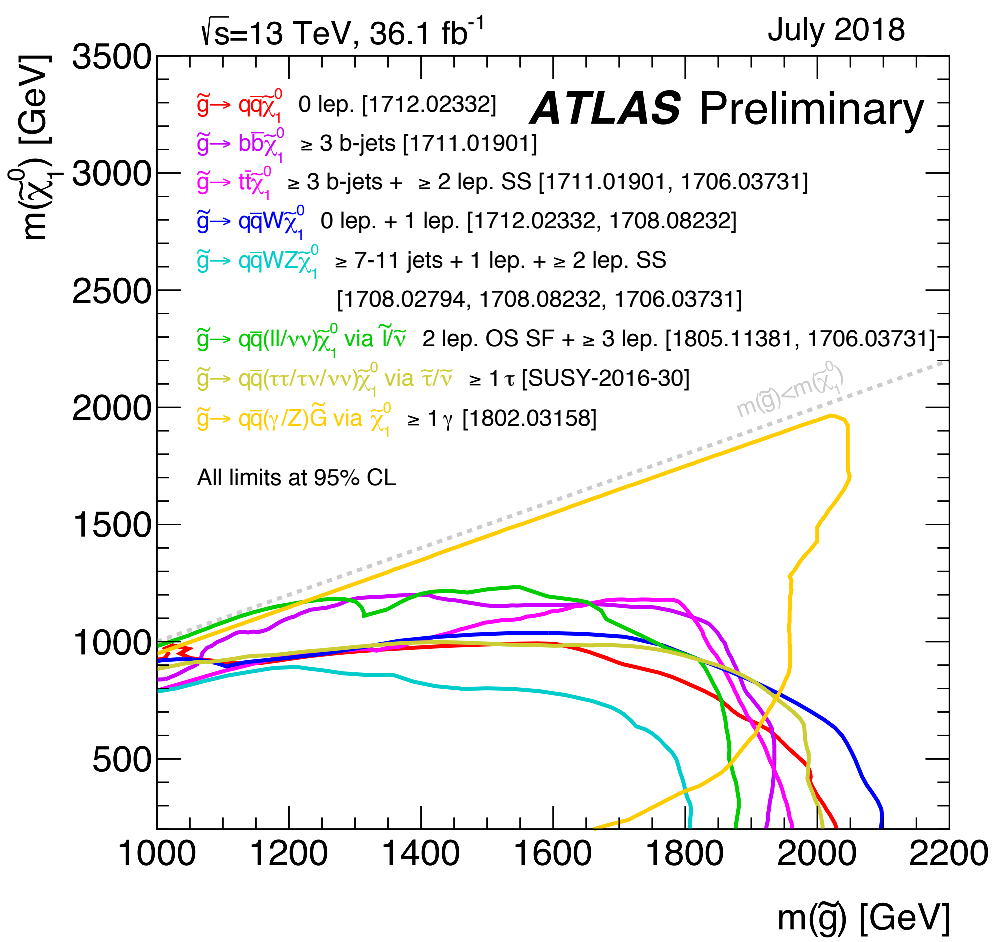
- Each gluino decays into quarks and the lightest SUSY particle (LSP = $\tilde{\chi}_1{}^0$)
- Signal events are firework of many (many!) jets and a large MET



Production cross-section is relatively large

- The sensitivity improves rapidly when the beam energy increases
- ATLAS & CMS published most 13-TeV results in 2016–17

ATLAS & CMS Limits on Gluinos

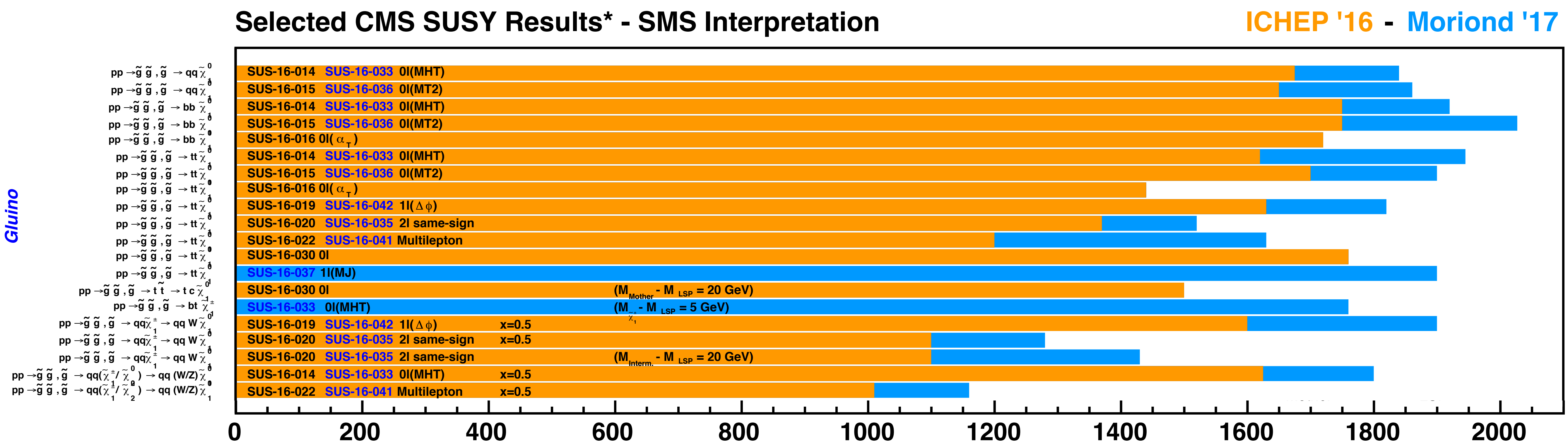


Gluino mass limits reach ≈ 2 TeV

- Caveat: Only for m(LSP) ≲ 1 TeV

Next steps:

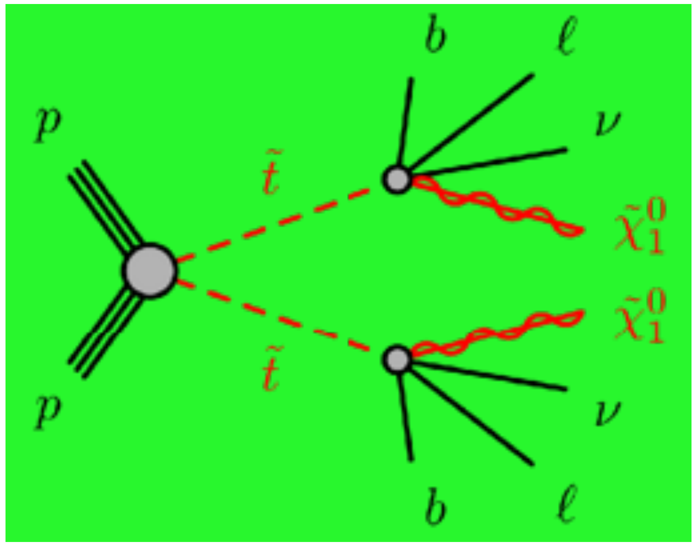
- Target heavier LSP and harder-to-find decay channels
- Update with full Run-2 data

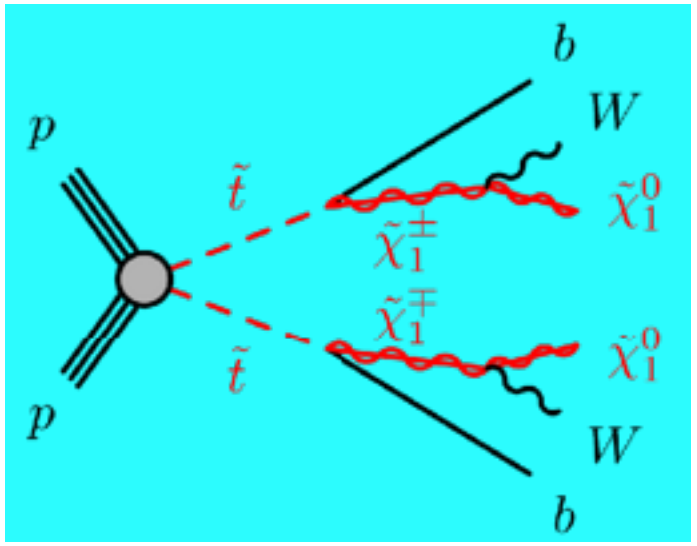


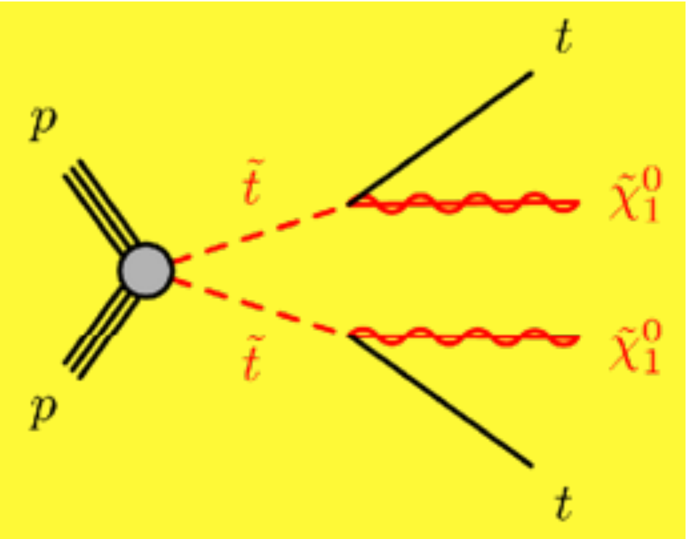
Top Squark, aka "stop"

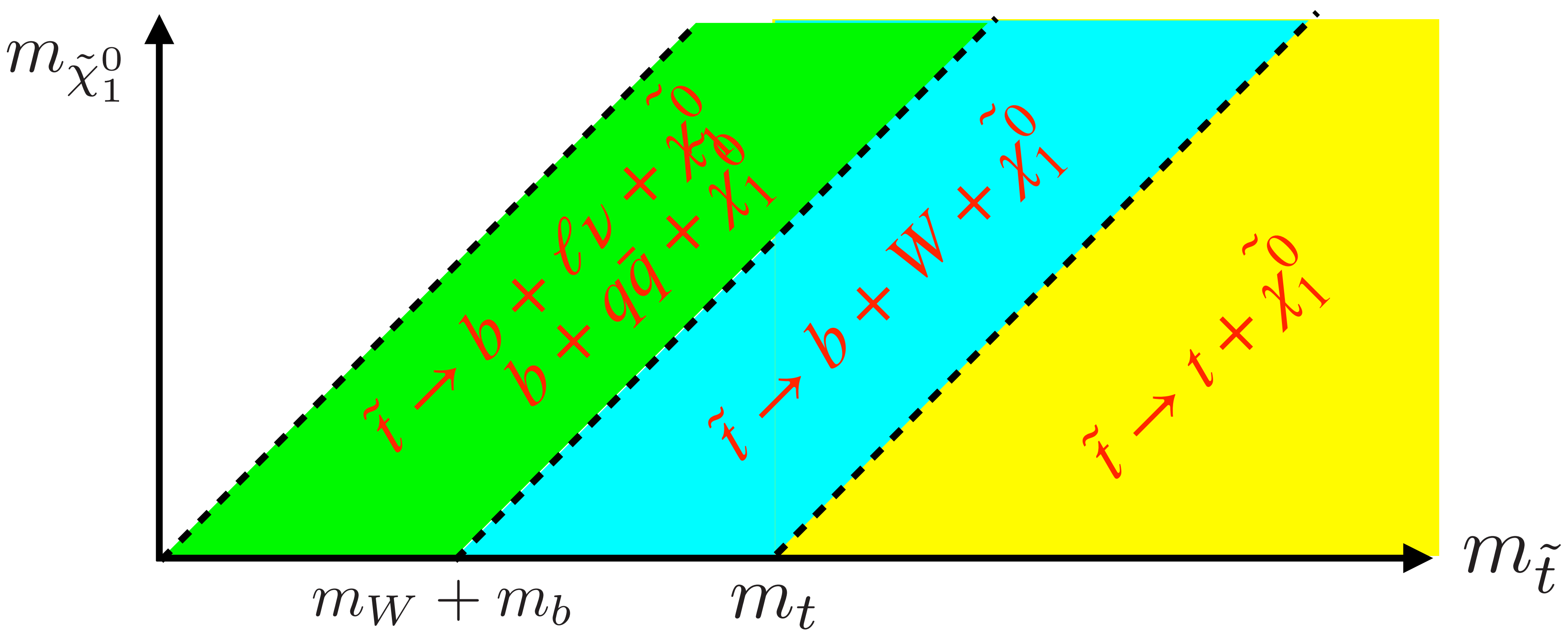
Stops are pair-produced, just like other squarks

- Their decays are more complicated, and depends on $m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$



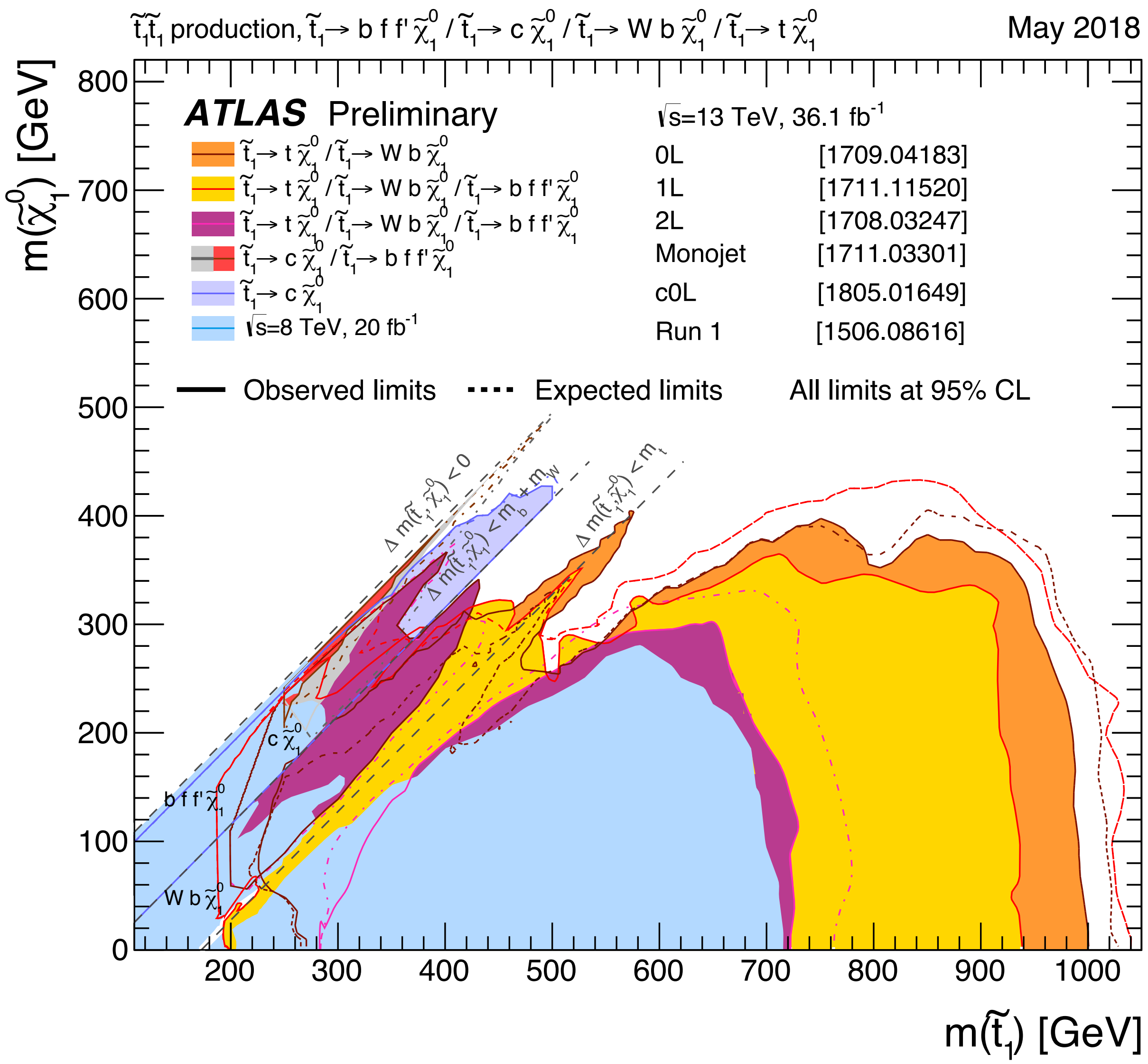


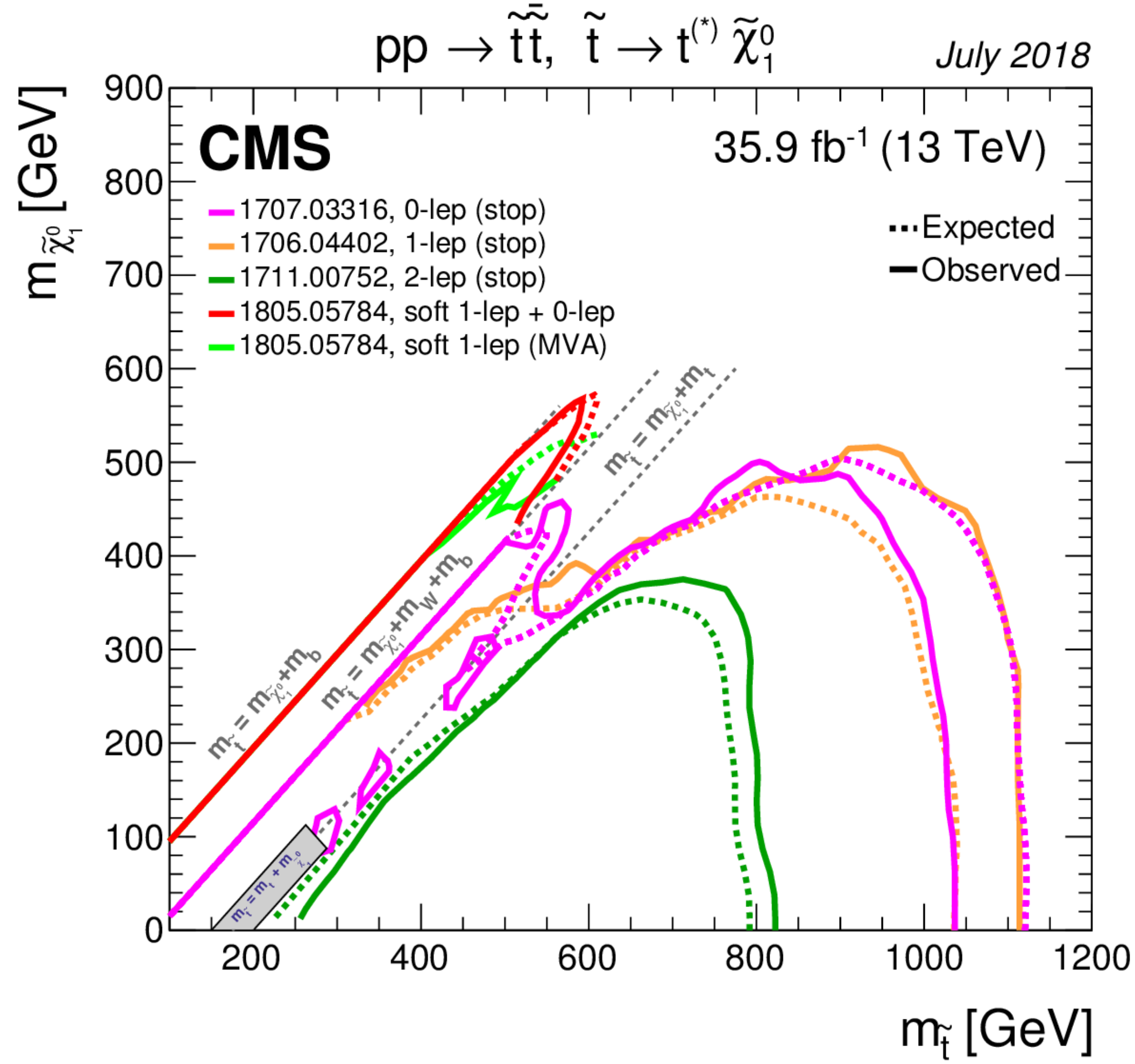




Top Squark, aka “stop”

Limits reach 1 TeV for m($\tilde{t}$) ≫ m(t) + m(LSP)





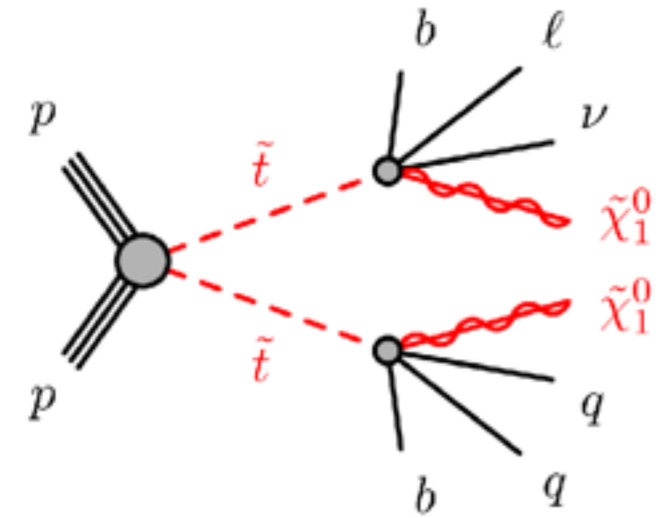
Things get messy for m($\tilde{t}$) ≲ m(t) + m(LSP)

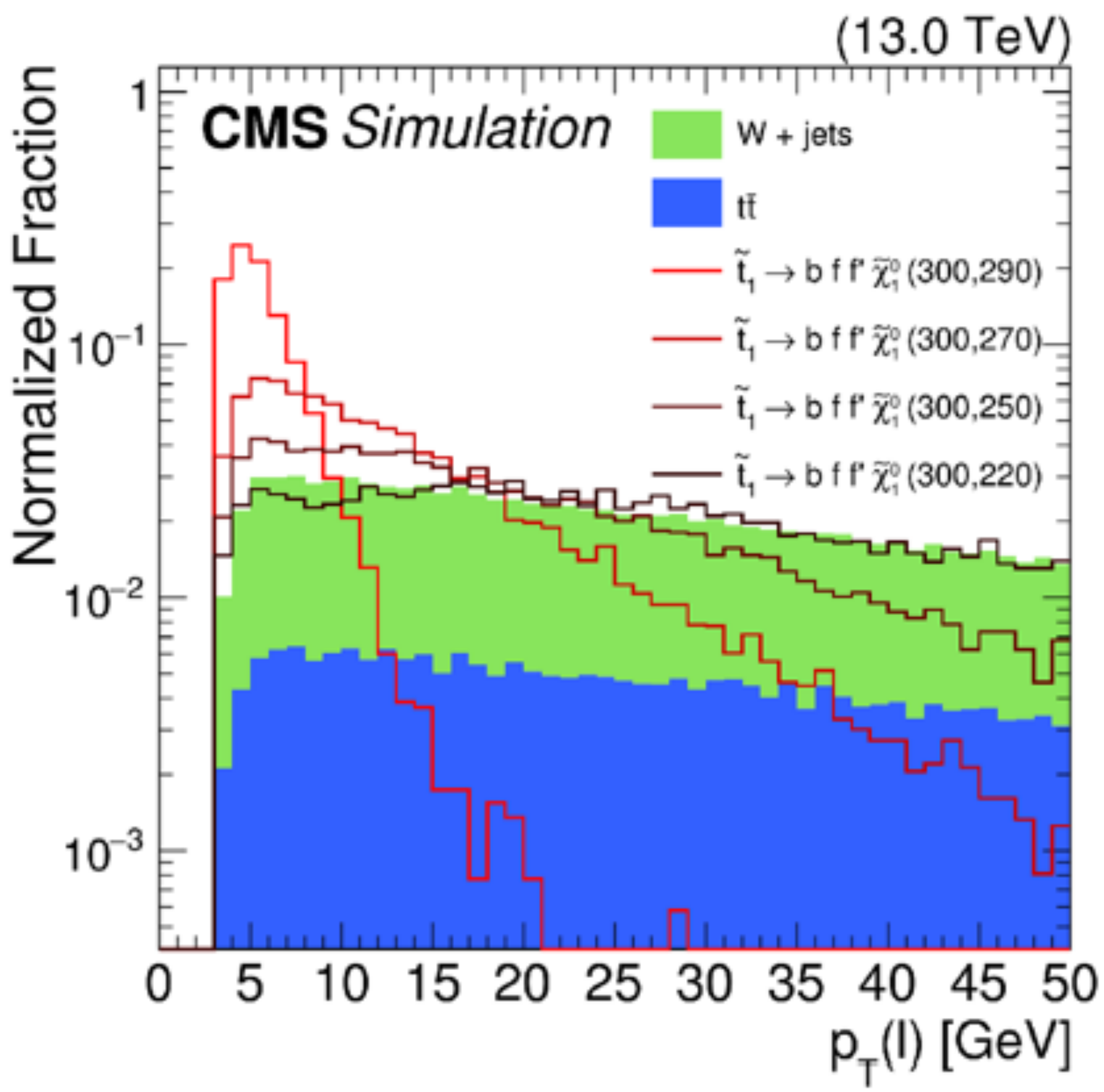
Compressed Stop

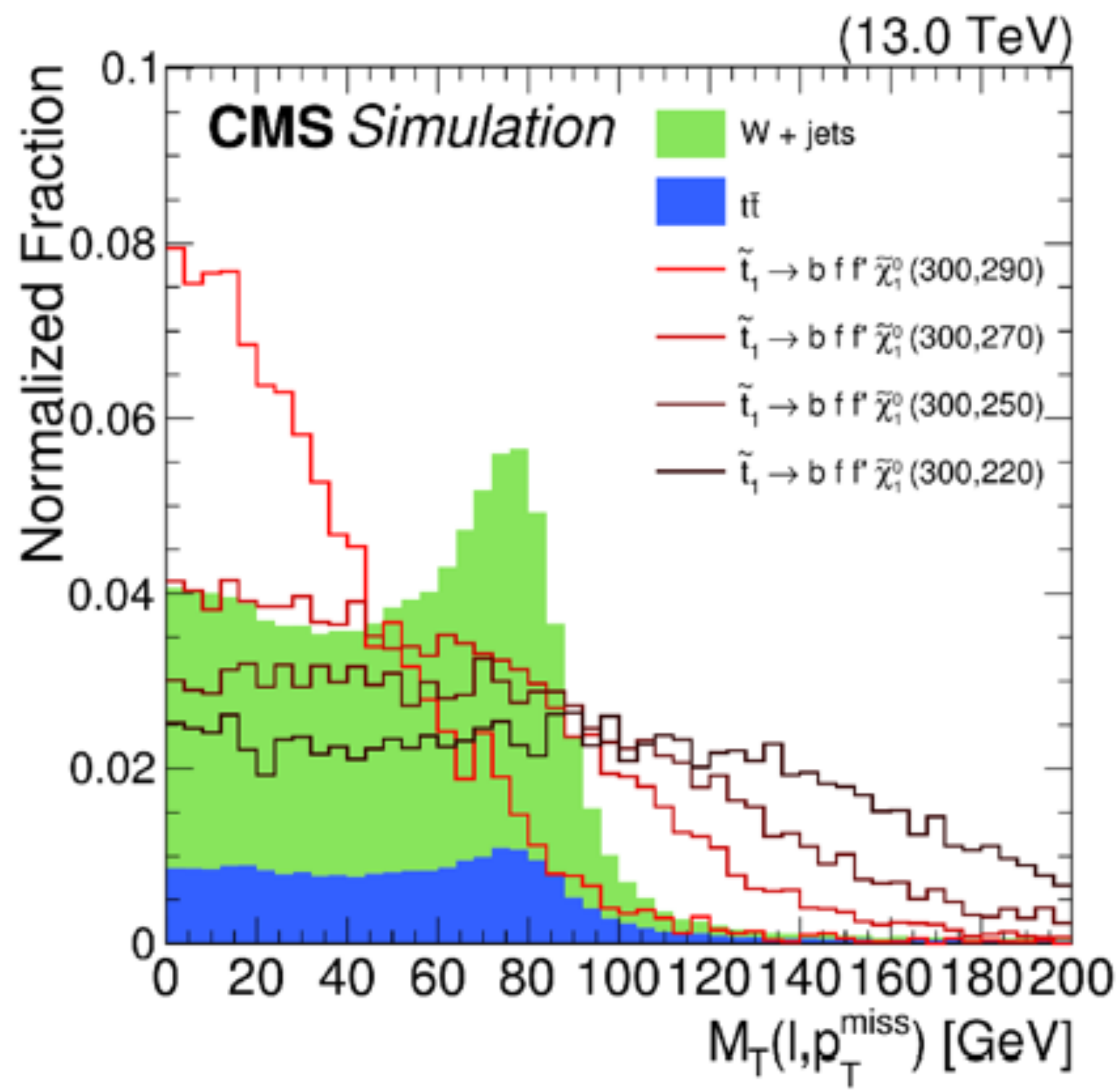
CMS arXiv:1805.05784

Search for "compressed" top squarks by CMS, 36 fb^{-1}

- Optimized to capture small m($\tilde{t}$) − m(LSP)
- Signature: 1 lepton, jets, MET (2 LSPs + ν)
- Lepton & MET have different kinematics from background





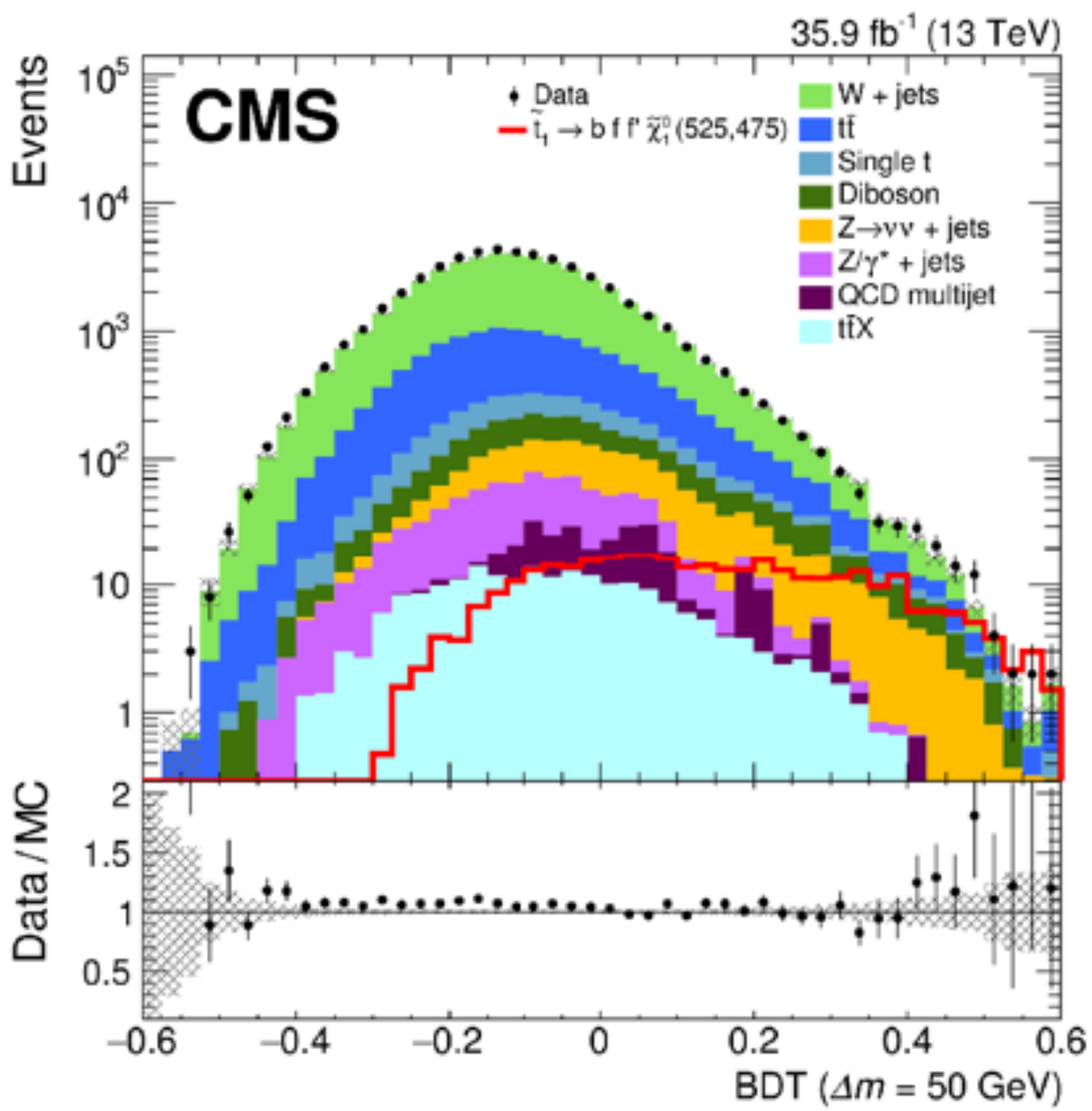


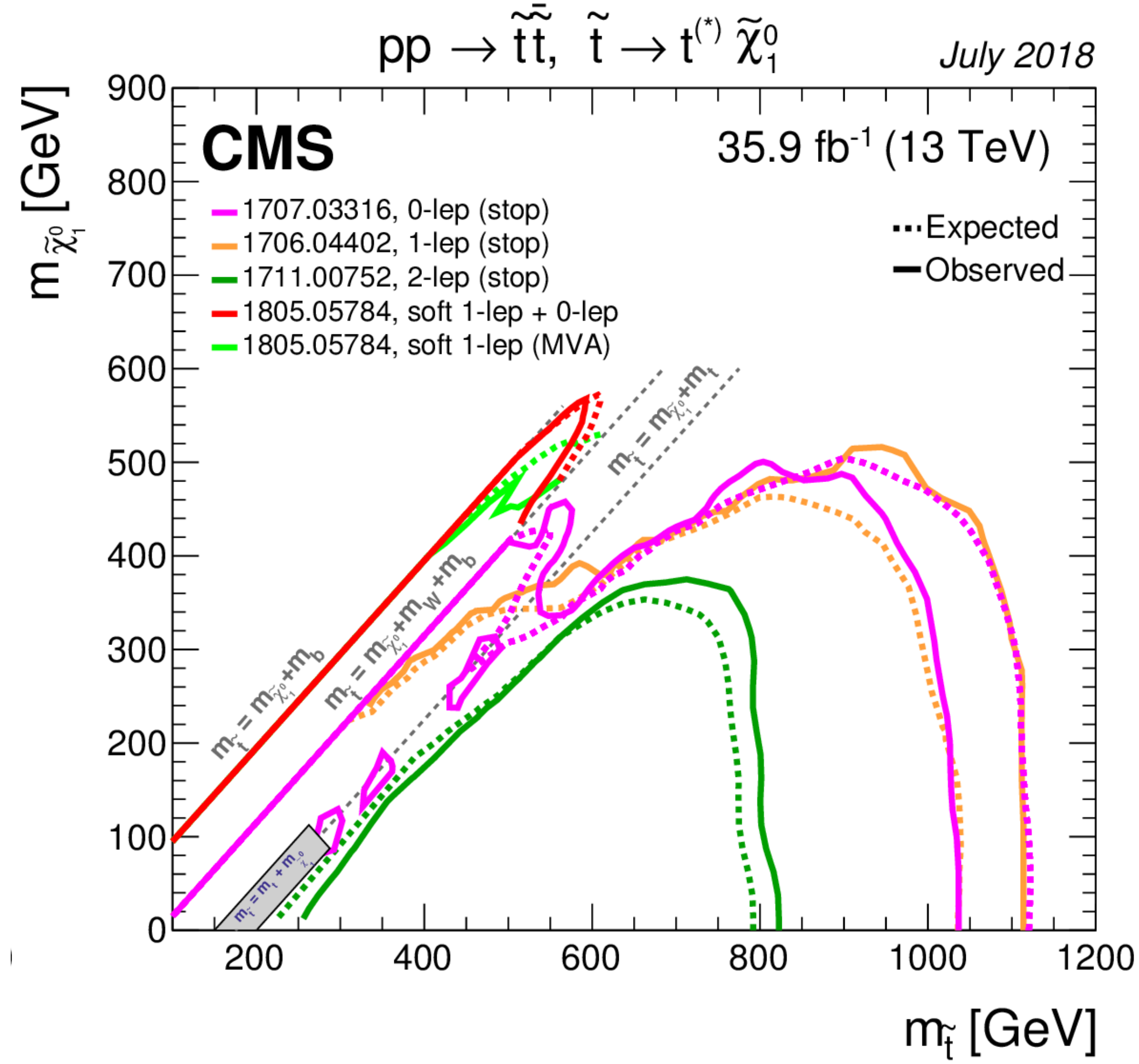
Compressed Stop

CMS arXiv:1805.05784

Search for “compressed” top squarks by CMS, 36 fb^{-1}

- Multivariate analysis maximizes signal separation
- Sensitivity down to m($\tilde{t}$) − m(LSP) = 10 GeV



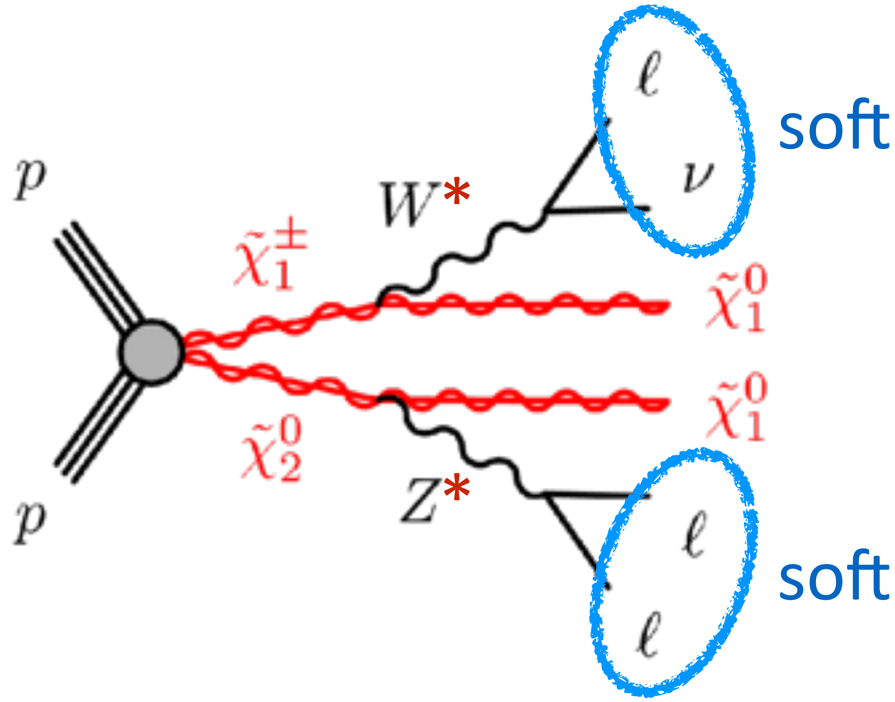


Higgsino

Light Higgsino ($\tilde{H}$) ➔ 3 lightest chargino/neutralinos $\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_2^0$

This is hard to detect:

- Electroweak production ➔ small x-section
- Signal events look like SM background
  - Small (sub-GeV) mass differences
  - Very soft leptons & jets
  - LSPs are nearly at rest ➔ small MET



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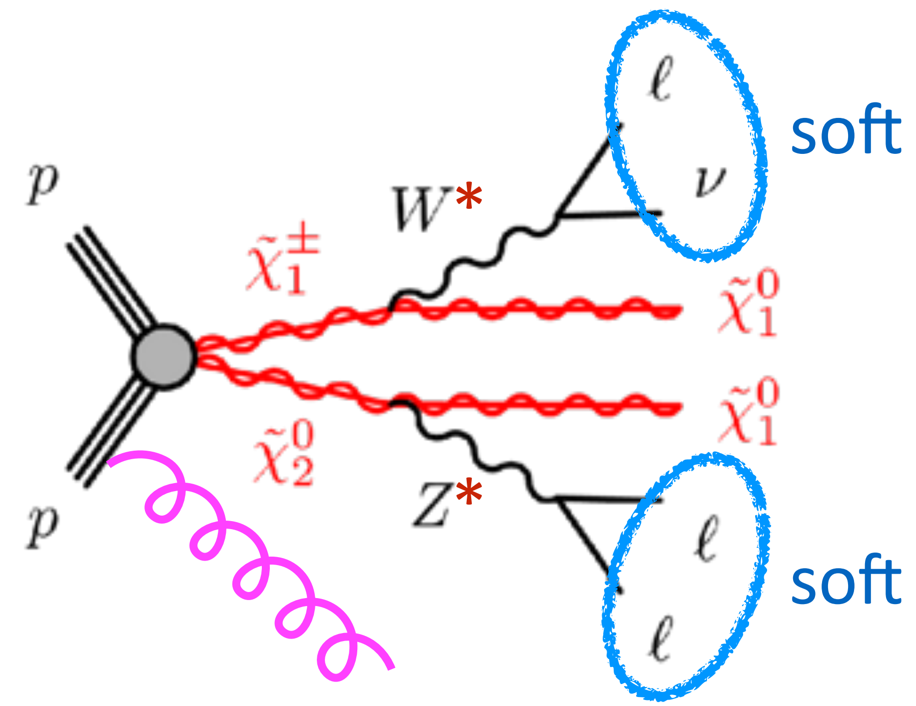


Initial State Radiation (ISR) helps

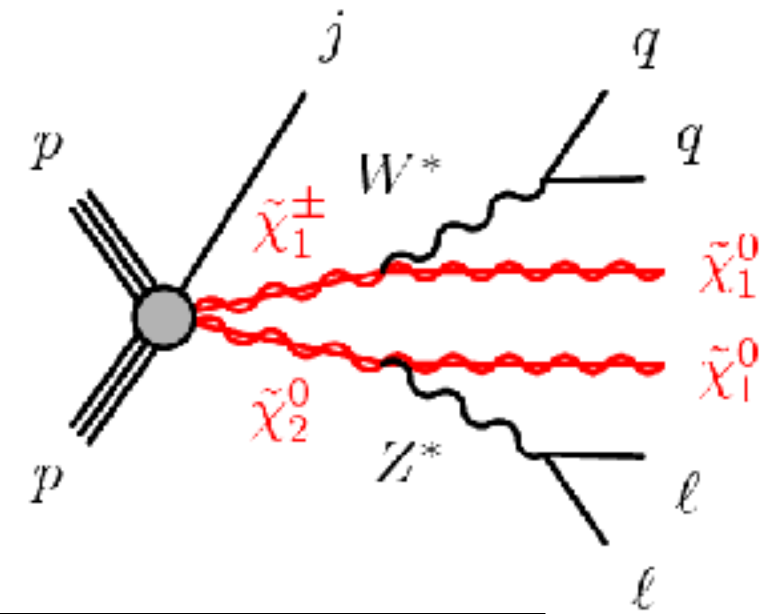
- Incoming proton emits a gluon ➔ jet
- SUSY particles recoil against the jet
- LSPs are moving fast ➔ larger MET

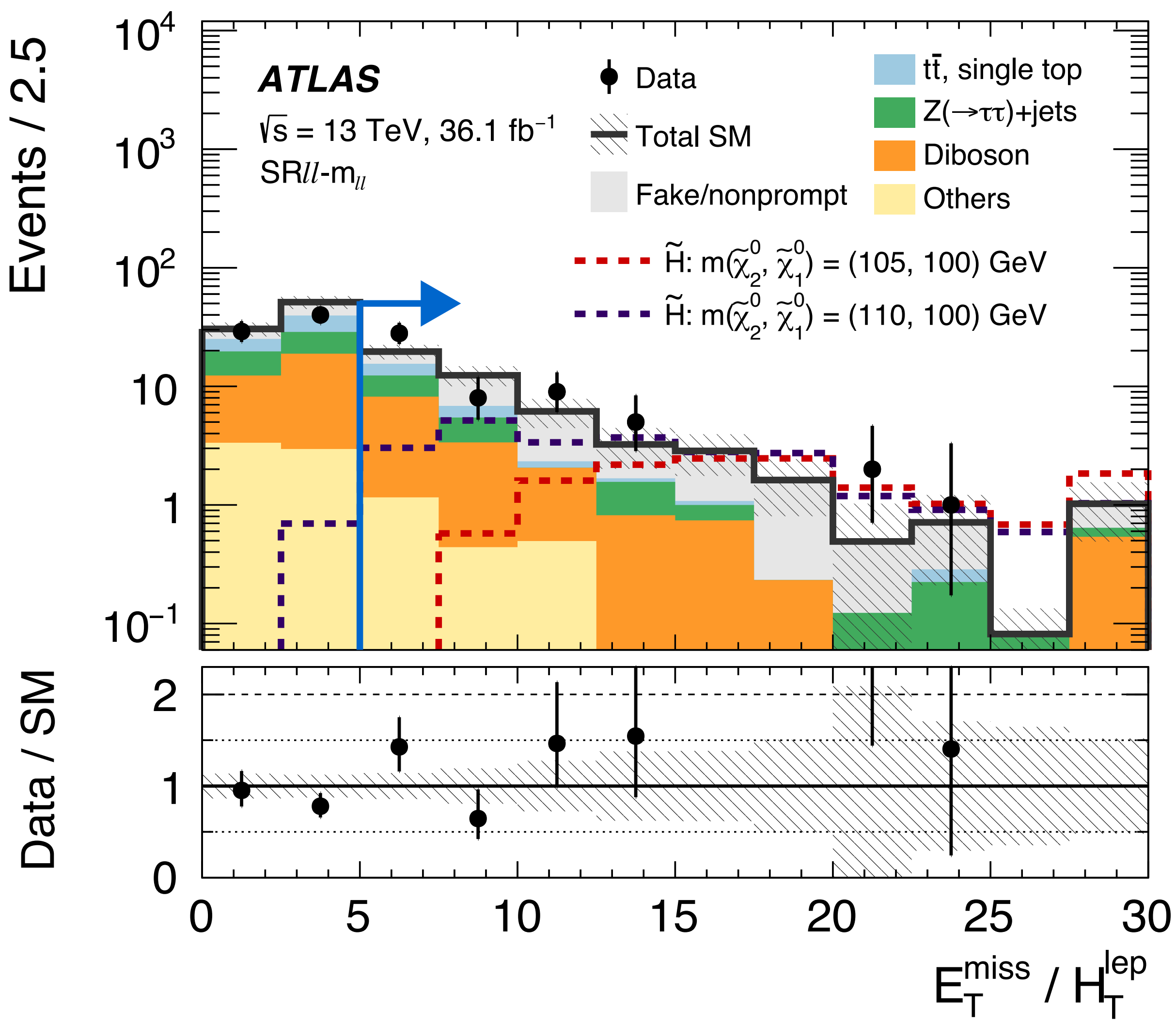
Compressed EW SUSY

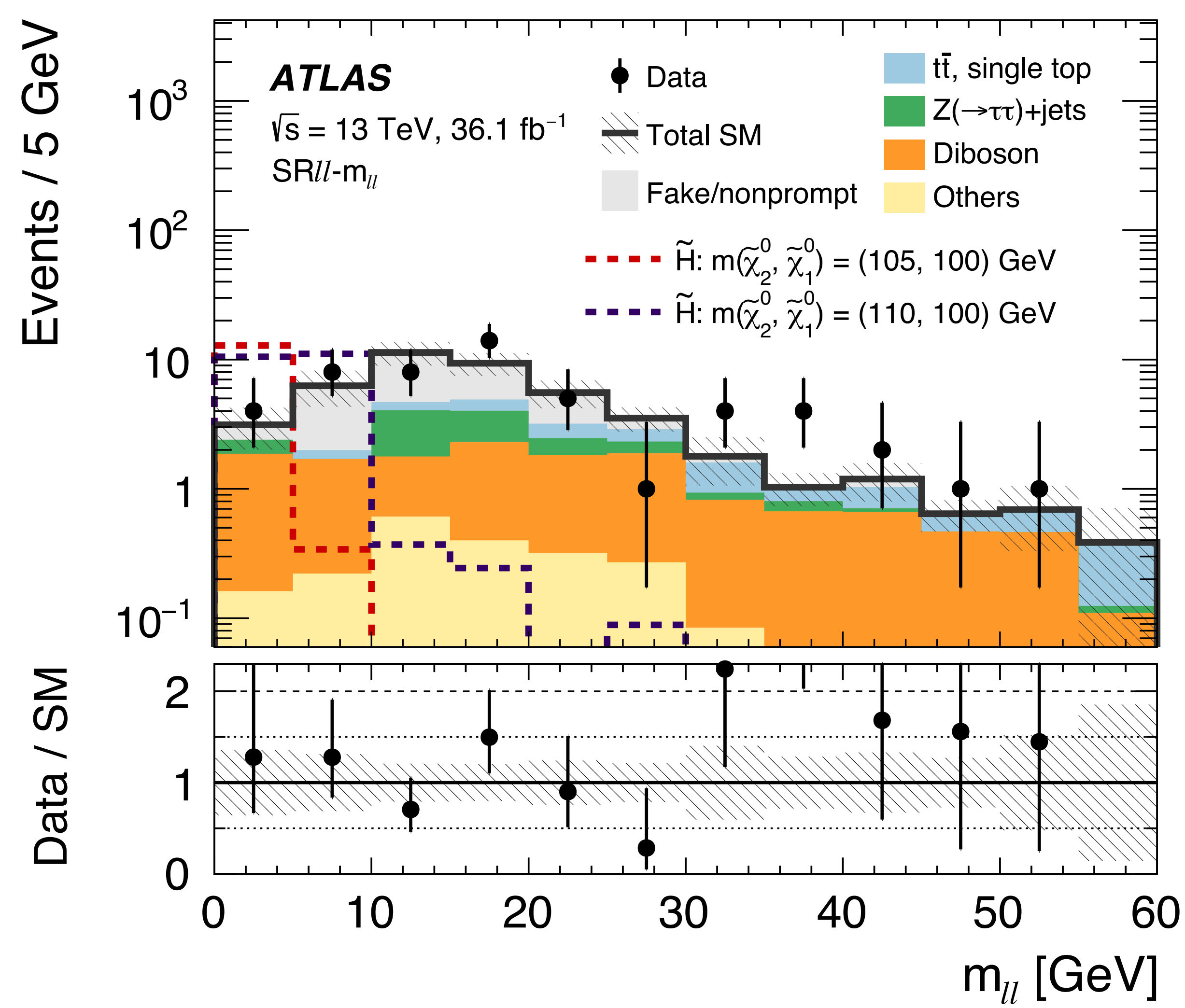
ATLAS PRD 97 (2018) 052010

Search for compressed EW SUSY by ATLAS, 36 fb^{-1}

- Signature: 2 soft leptons, jet(s) & MET
- At least 1 energetic jet (>100 GeV), pointing opposite to the leptons + MET system
- Large MET and small dilepton mass







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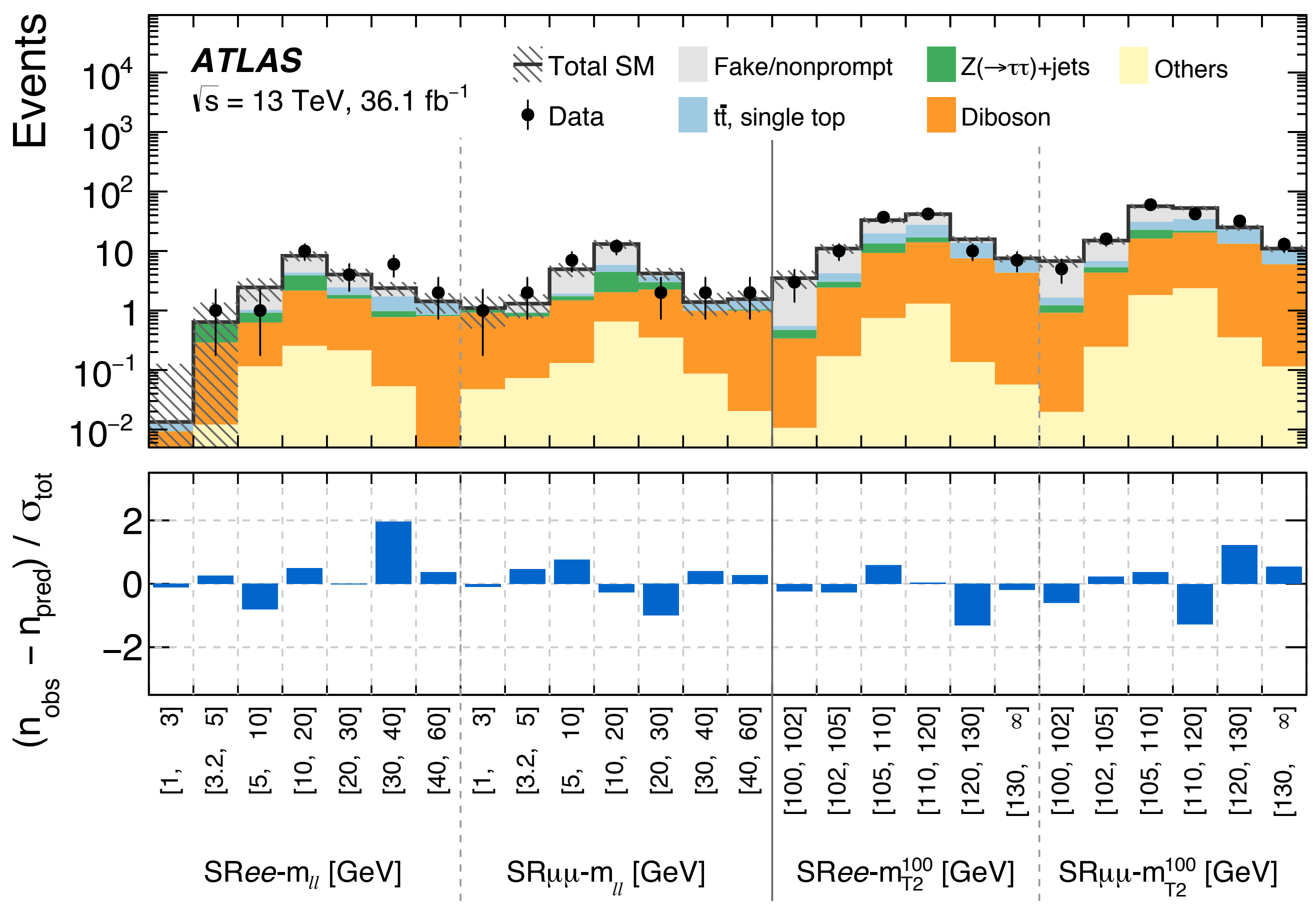
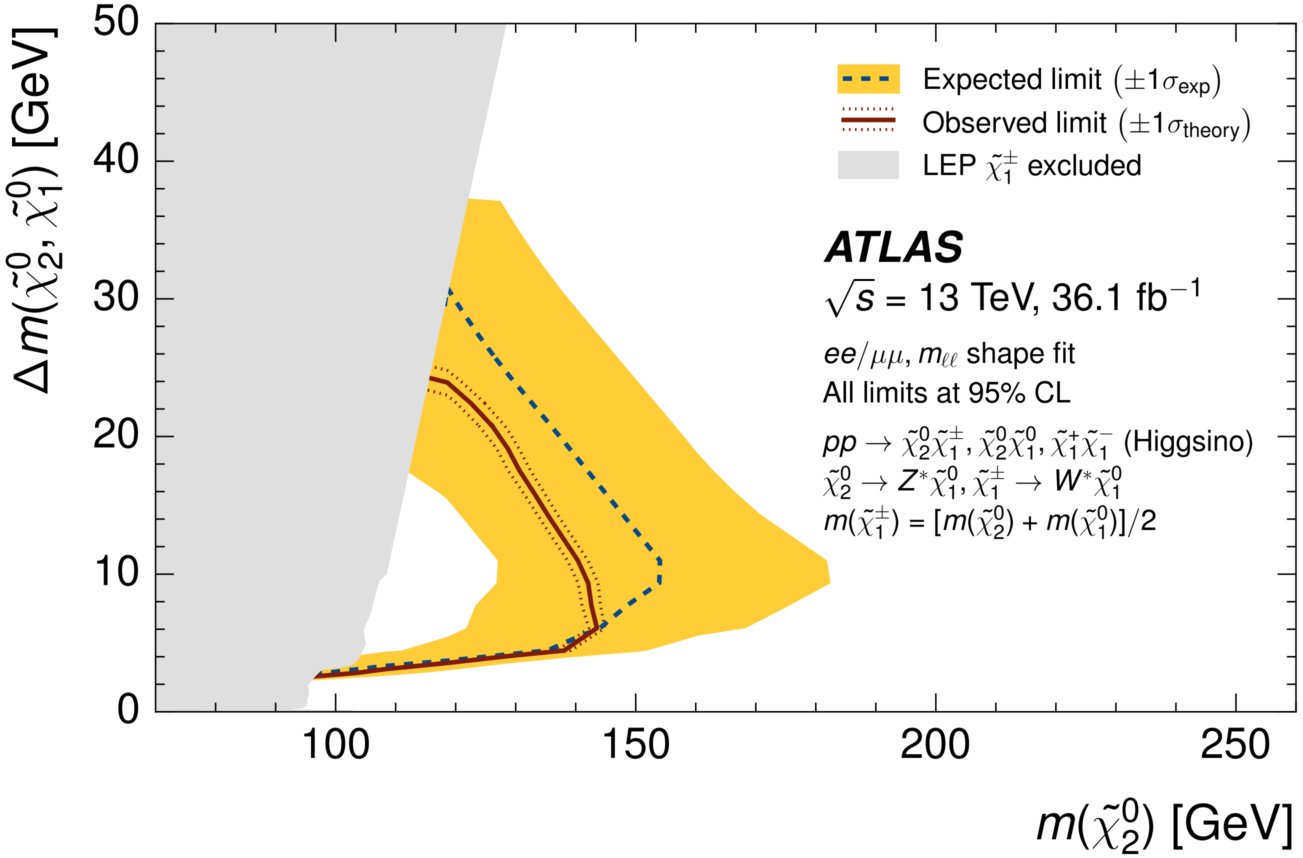




- First LHC limit for this very soft higgsino channel

Long-Lived Particles

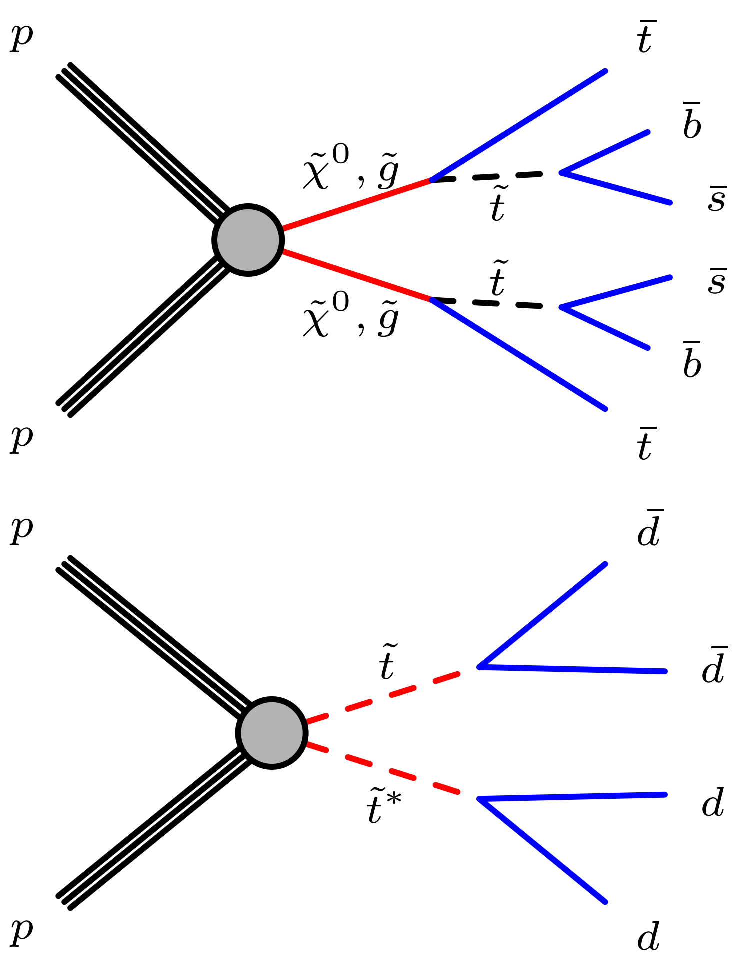
CMS-PAS-EXO-17-018

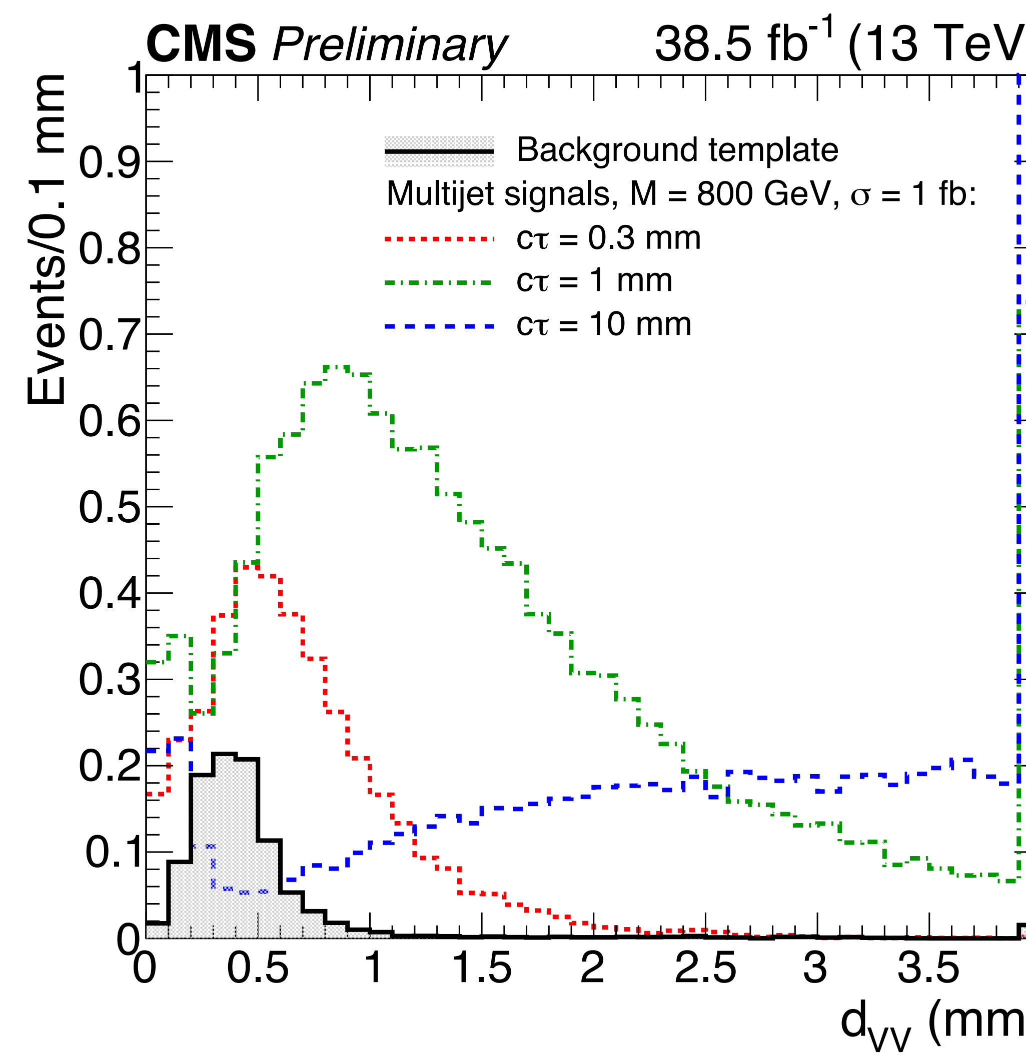
New particles may not decay immediately

- Long-lived particles (LLP) produce displaced decay vertices in the detectors

SUSY-motivated search for LLP by CMS, 38.5 fb^{-1}

- Look for events with two decay vertices separated by a few mm





Long-Lived Particles

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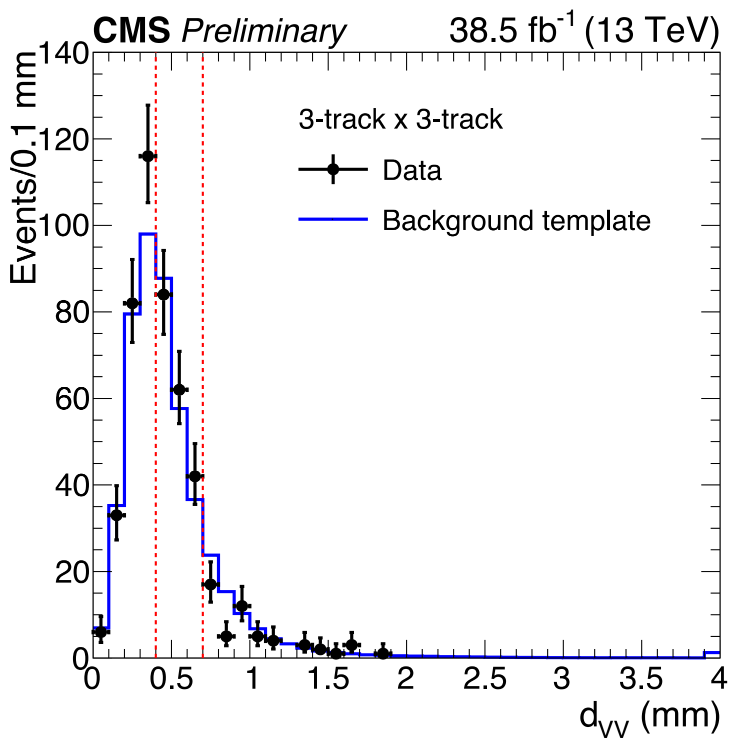
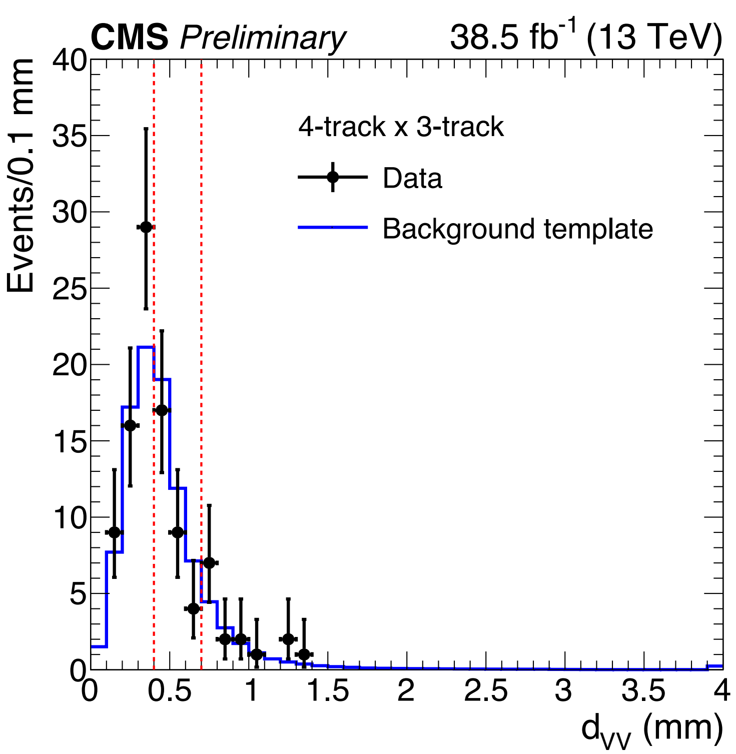
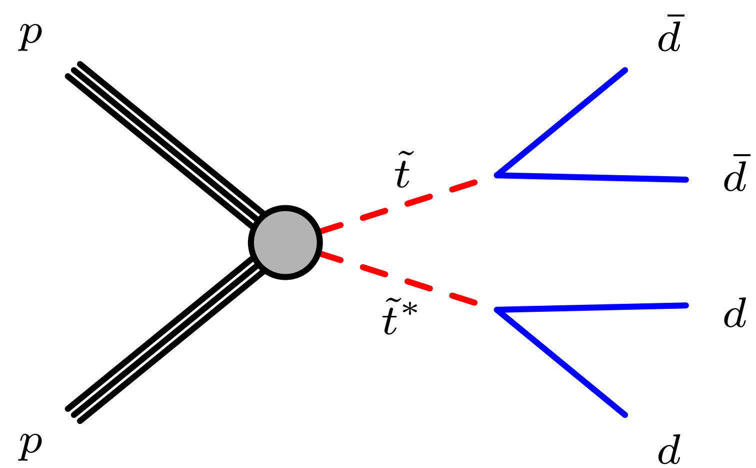
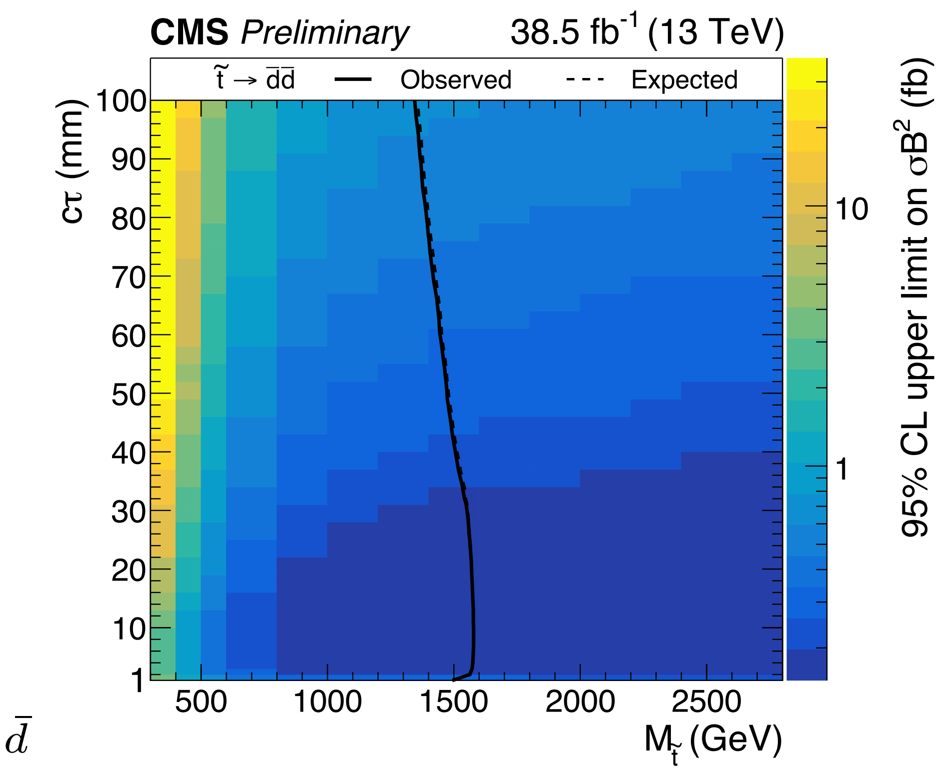
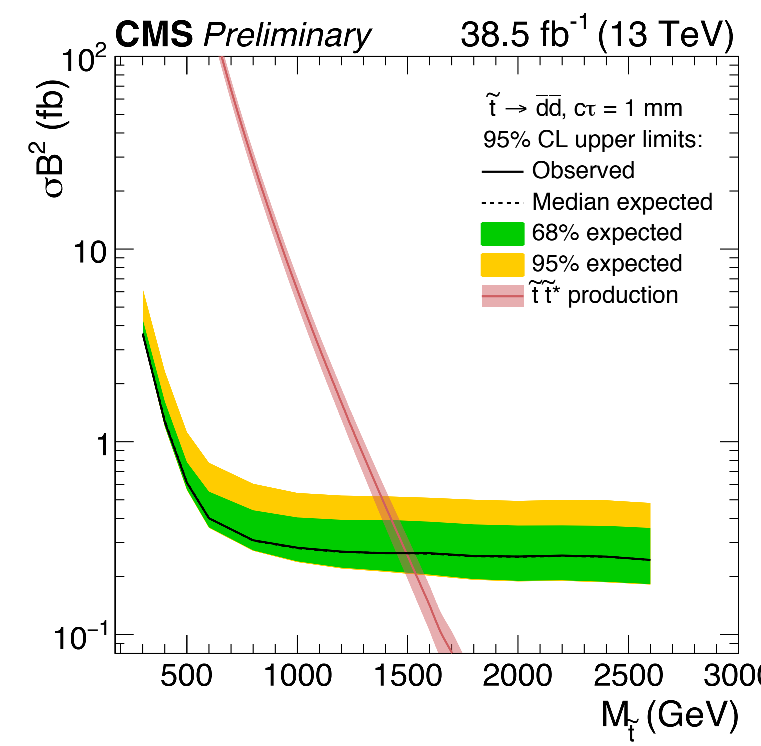




Limits are set on, e.g., R-parity violating stop decays:







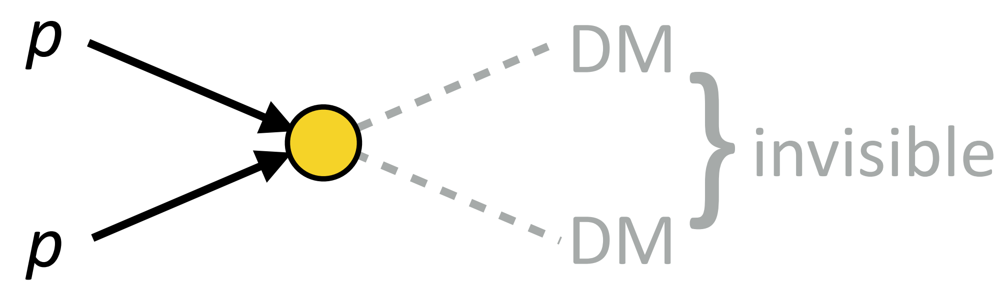
Dark Matter

Listen to Tracy Slatyer's lecture!

Dark Matter exists

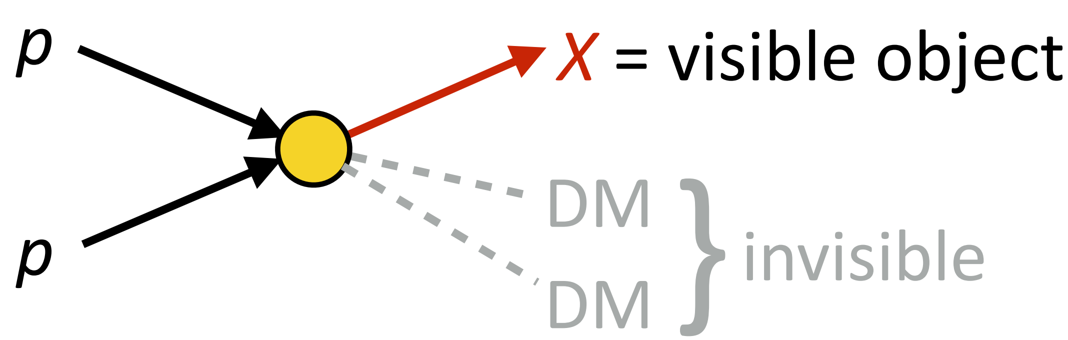
- Compelling evidences from astronomical data

DM particles may be produced at the LHC



- BUT — Experiments cannot see the final state with only DM particles
- How do we record and count such events?

We need ≥1 extra particles produced with the DM particles

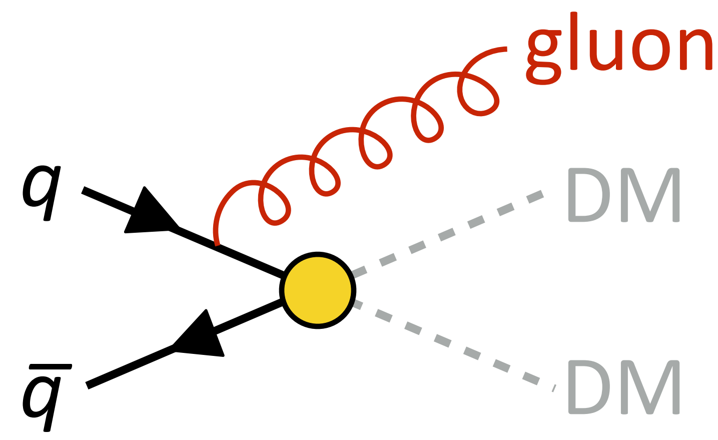


- Candidate events contain X + MET and little else
- We call it "mono-X" with X = jet, photon, Higgs, W, Z, etc.

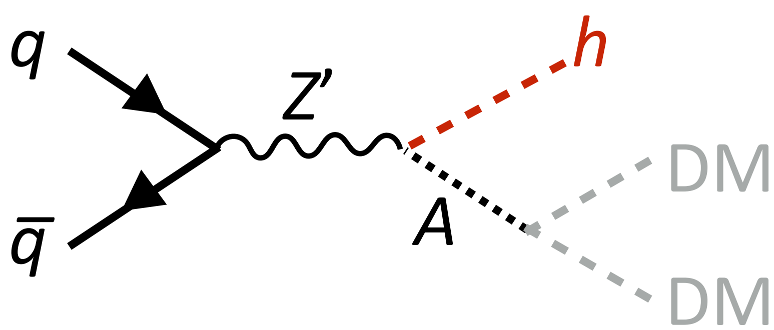
Where does "*X*" come from?

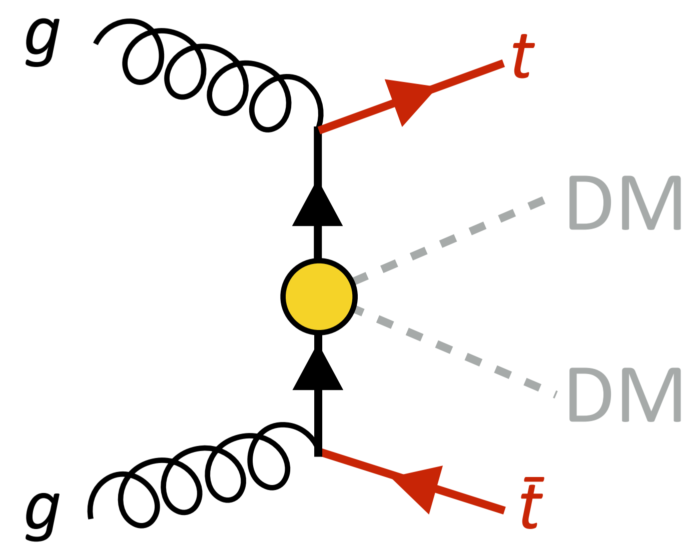
X may be radiated by the incoming quarks

- Quarks couple most strongly to gluons
- If $q\bar{q} \to \chi\bar{\chi}$ happens, $q\bar{q} \to \chi\bar{\chi} + g$ must happen
- This gives us the "mono-jet" signature



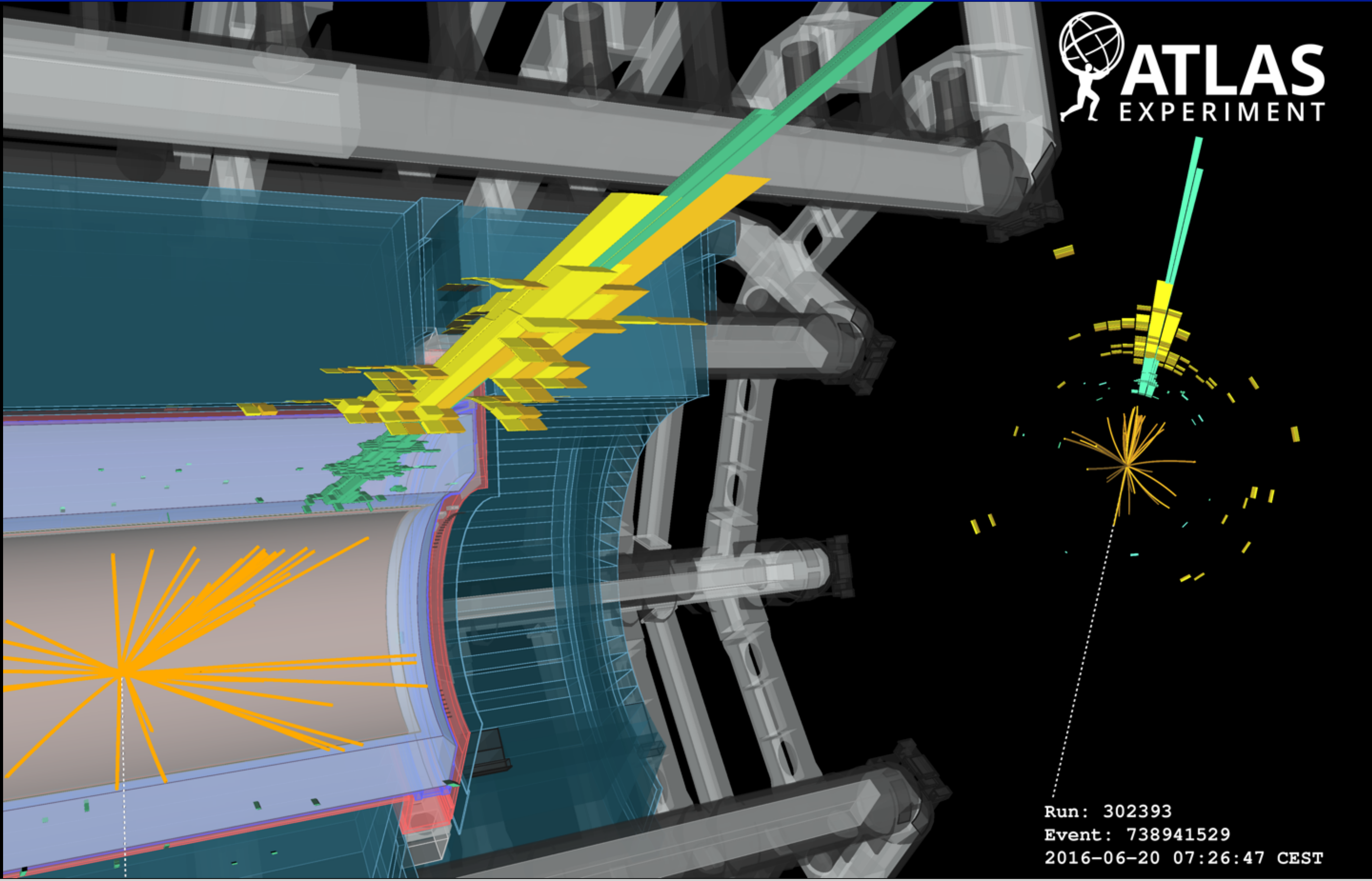
X may be more closely connected to DM production, e.g.





- Cross-section depends on the exact model and the couplings
- May be large even if $q\bar{q} \to \chi\bar{\chi}$ is small

1.7 TeV Mono-Jet Event in ATLAS

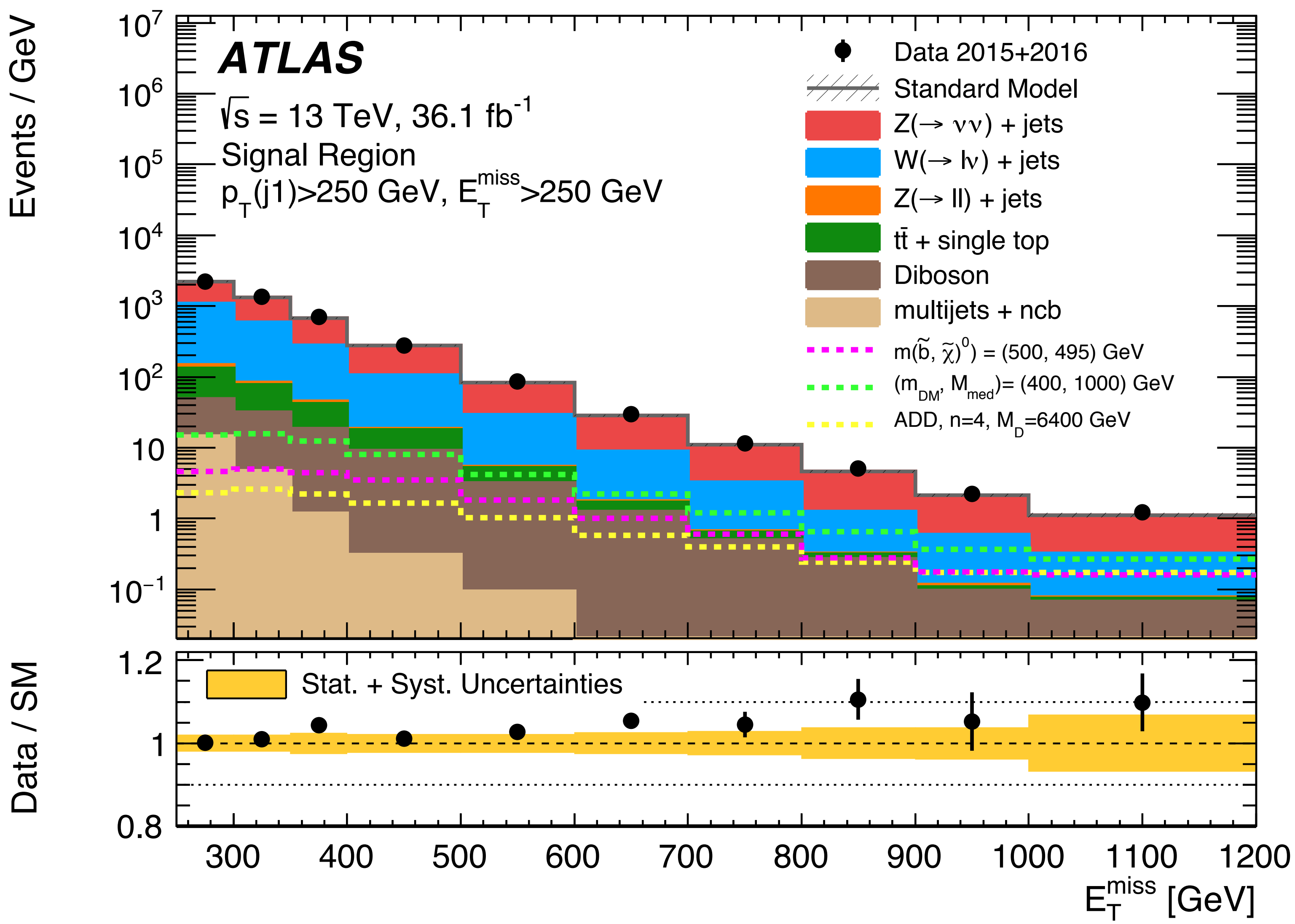


Mono-Jet

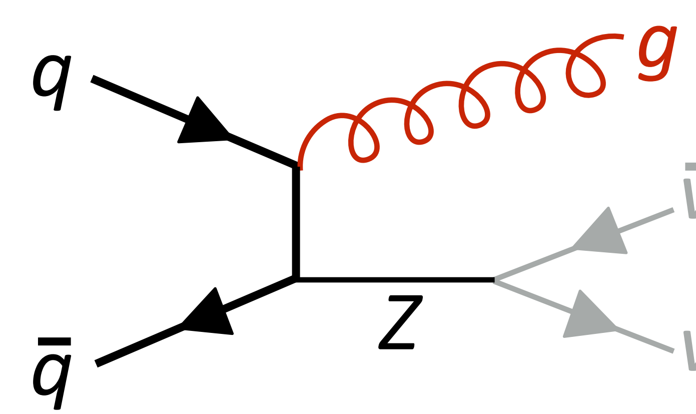
ATLAS JHEP 01 (2018) 126

Search for DM + jet(s) by ATLAS, 36 fb^{-1}

- Select events with ≥1 energetic jet (>250 GeV) and large MET (>250 GeV)



- Dominant background is $Z\,(\rightarrow \nu\bar{\nu})$ + jet



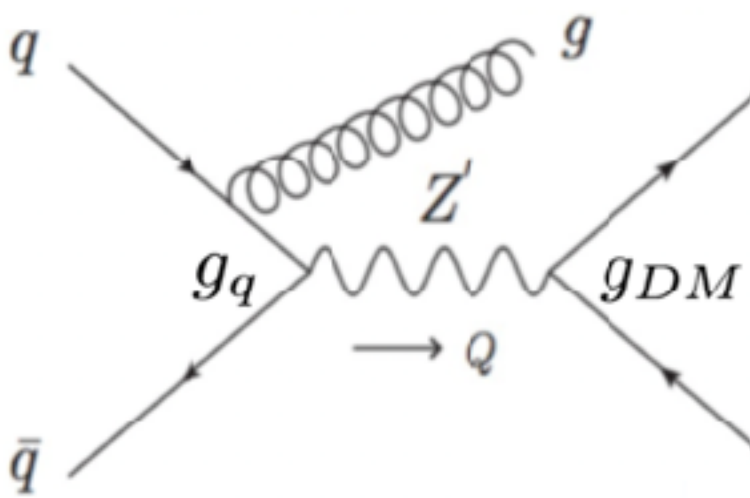
- Irreducible → Estimate from $Z\,(\rightarrow \ell\ell)$ and $W\,(\rightarrow \ell\nu)$ + jet in data, and subtract

Mono-Jet

ATLAS JHEP 01 (2018) 126

Search for DM + jet(s) by ATLAS, 36 fb^{-1}

- Result is interpreted with a simplified model:



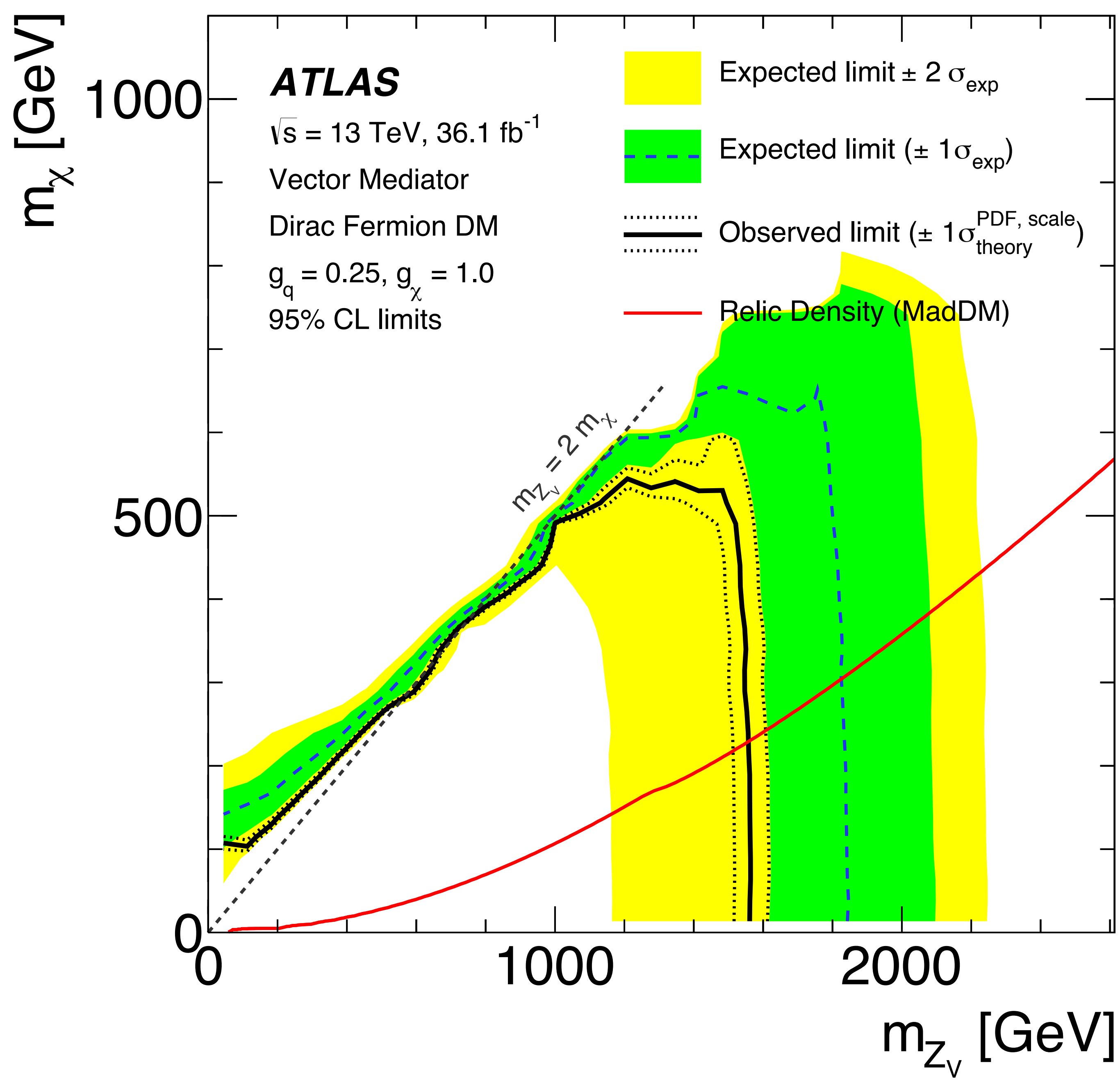
$$\sigma = K' \frac{g_q^2 g_{DM}^2}{M^4 \Gamma_{med}}$$

g_q = *coupling to SM*

g_{DM} = *coupling to DM*

M = *mediator mass*

Γ_{med} = *mediator width*

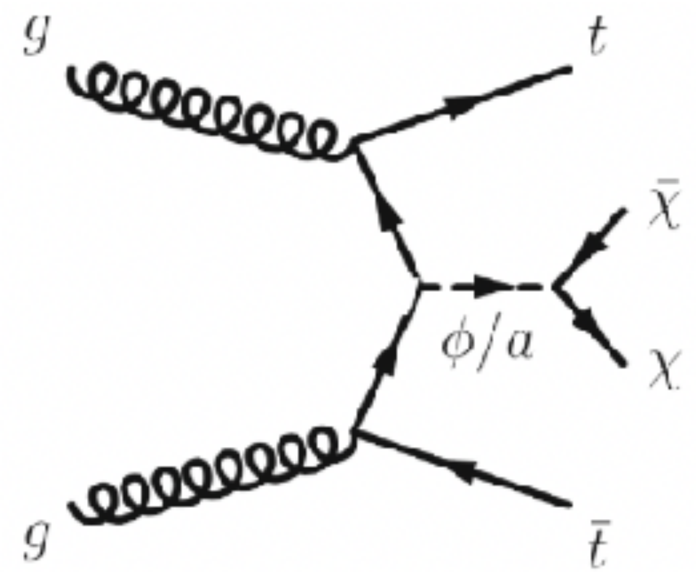


MET + $t\bar{t}$

CMS-EXO-16-049

Suppose the DM particles couple only to a spin-0 mediator

- Like the Higgs, the coupling favors heavy fermions, i.e., top quarks
- Final state = $t\bar{t} + \chi\bar{\chi}$(= MET)



Search for MET + $t\bar{t}$ events by CMS, 36 fb^{-1}

- Event selection depends on how the top quarks decay:

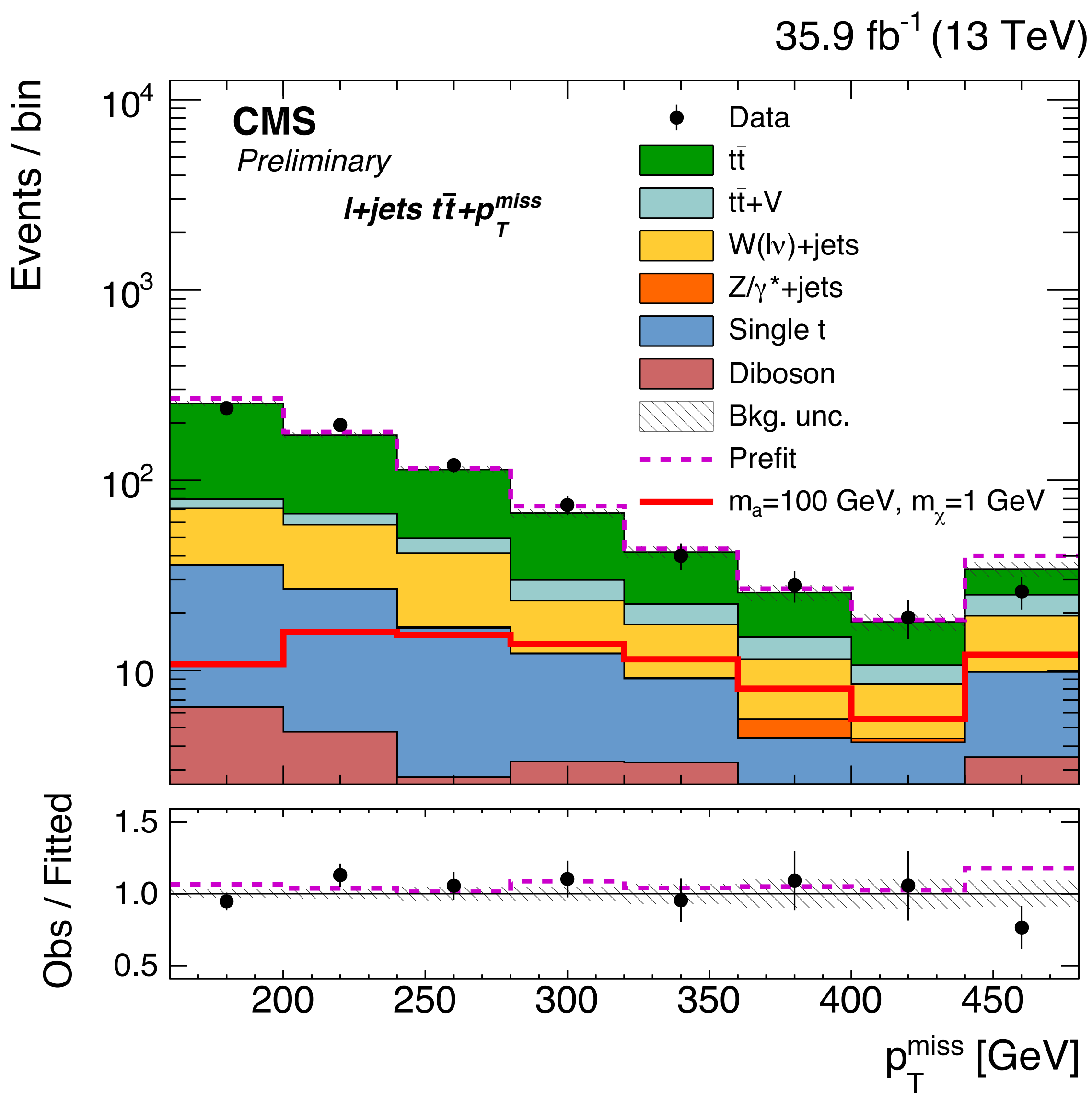
Leptons	Jets (b-tagged)	MET
0	≥4 (≥1)	>200 GeV
1	≥3 (≥1)	>160 GeV
2	≥2 (≥1)	>50 GeV

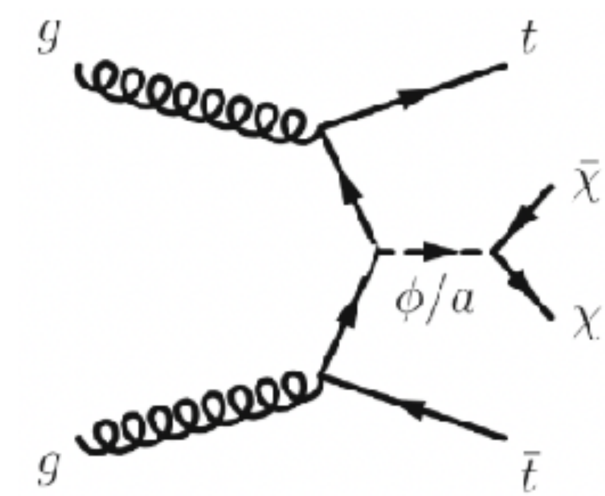
- Expect signal at high MET

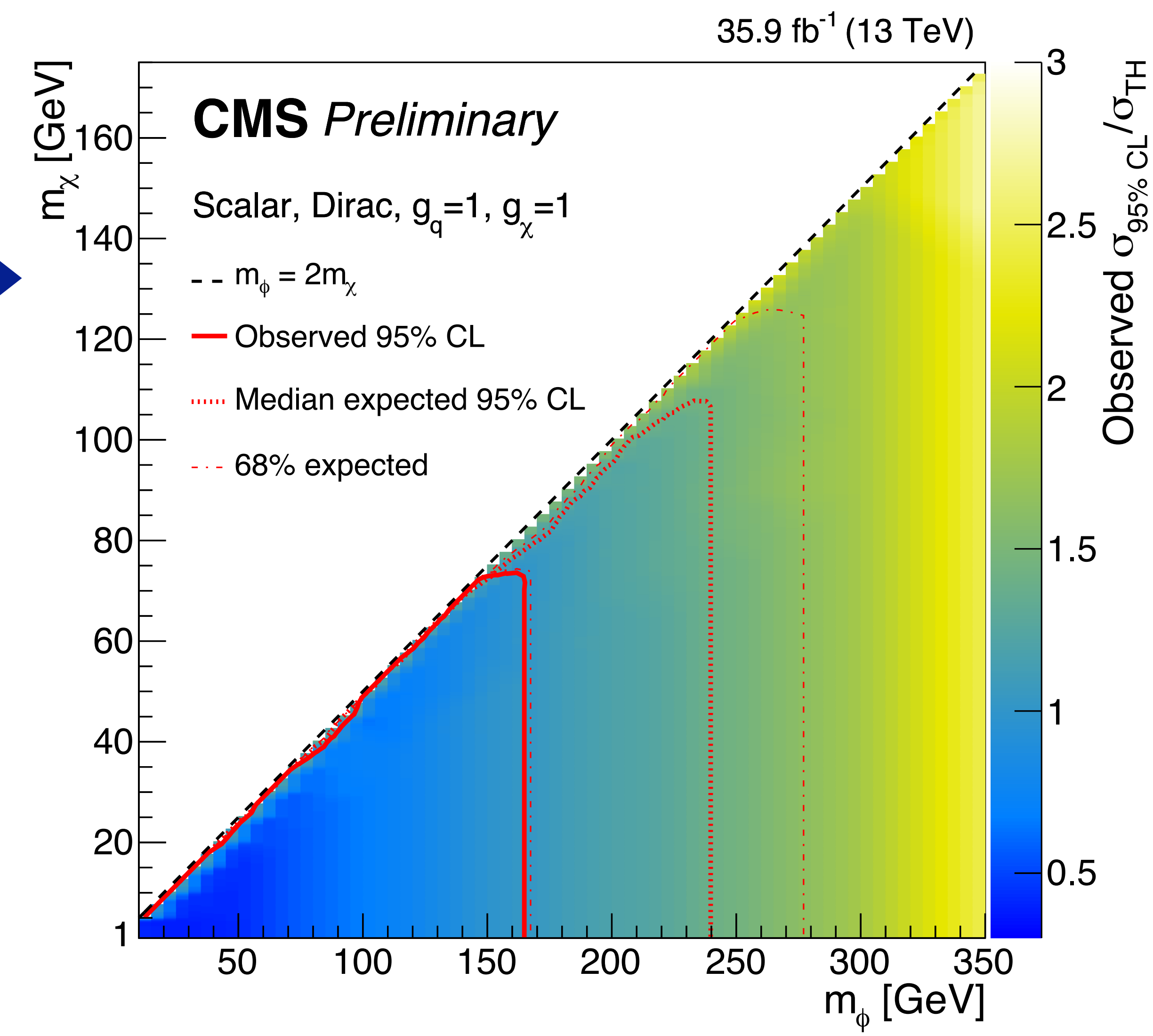
MET + $t\,\bar{t}$

CMS-EXO-16-049

Search for MET + $t\,\bar{t}$ events by CMS, 36 fb^{-1}





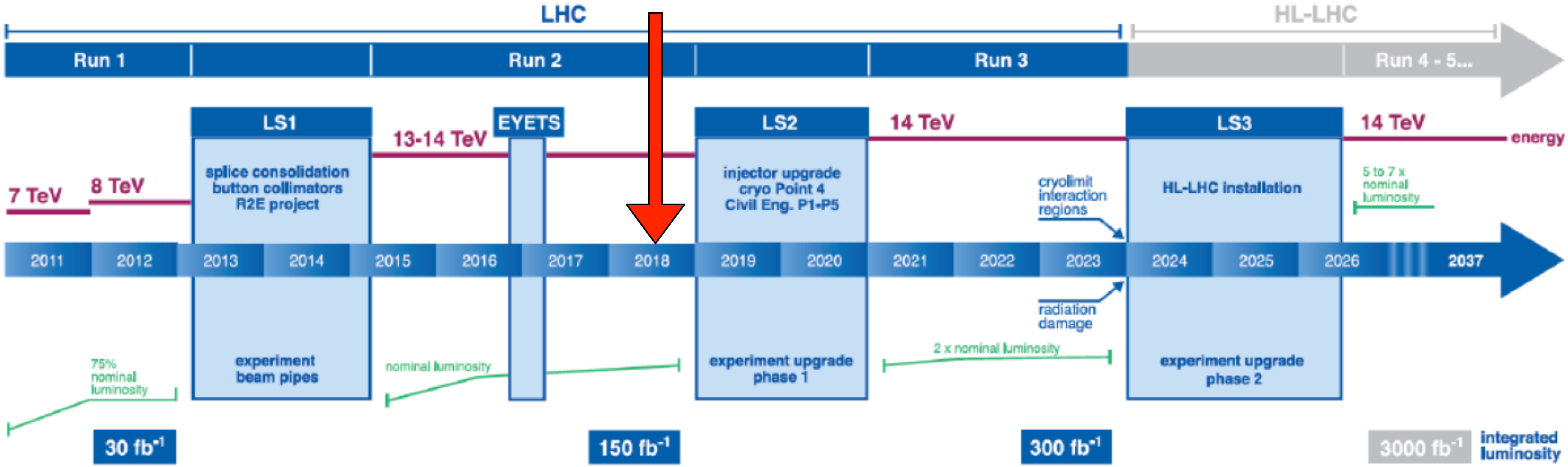


Summary and Prospects

ATLAS & CMS take advantage of massive data at 13 TeV to search for New Physics beyond the Standard Model

- Resonances, SUSY particles, Dark Matter, leptoquarks, vector-like quarks, …
- Also: don't forget flavor physics at LHCb & ATLAS & CMS

No discovery yet — Pushing limits higher and deeper



More data are coming: Run 3 (2021–23) and HL-LHC (2026–)

Prospects

What will Run 3 (300 fb^{-1}) and HL-LHC (3000 fb^{-1}) bring?

ATL-PHYS-PUB-2014-010