Searches for New Physics at the LHC

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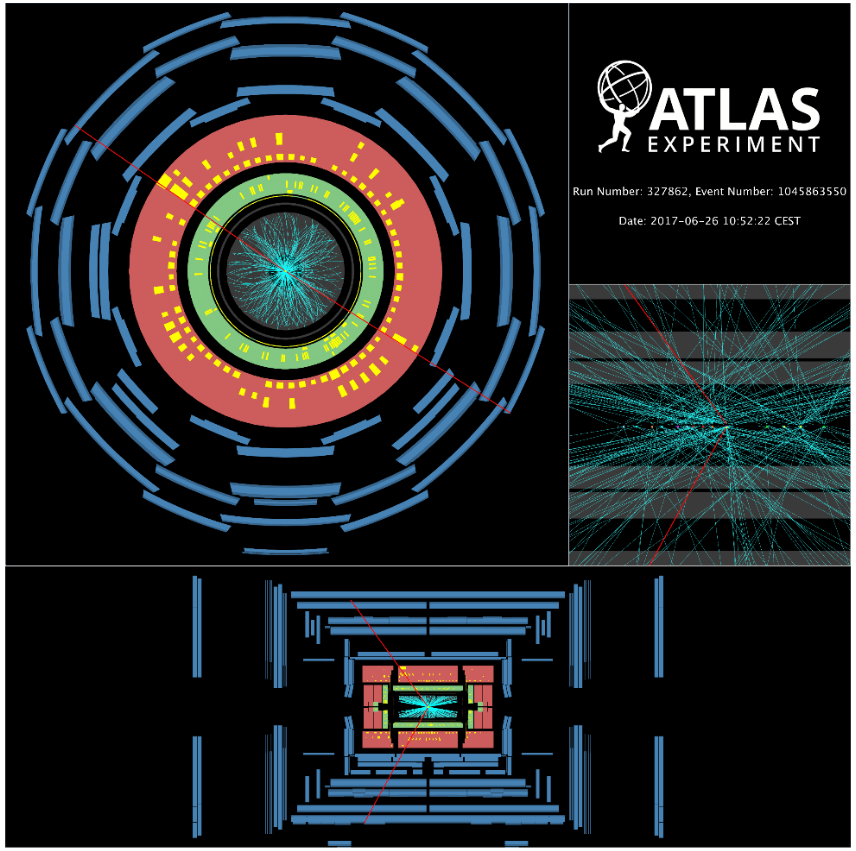
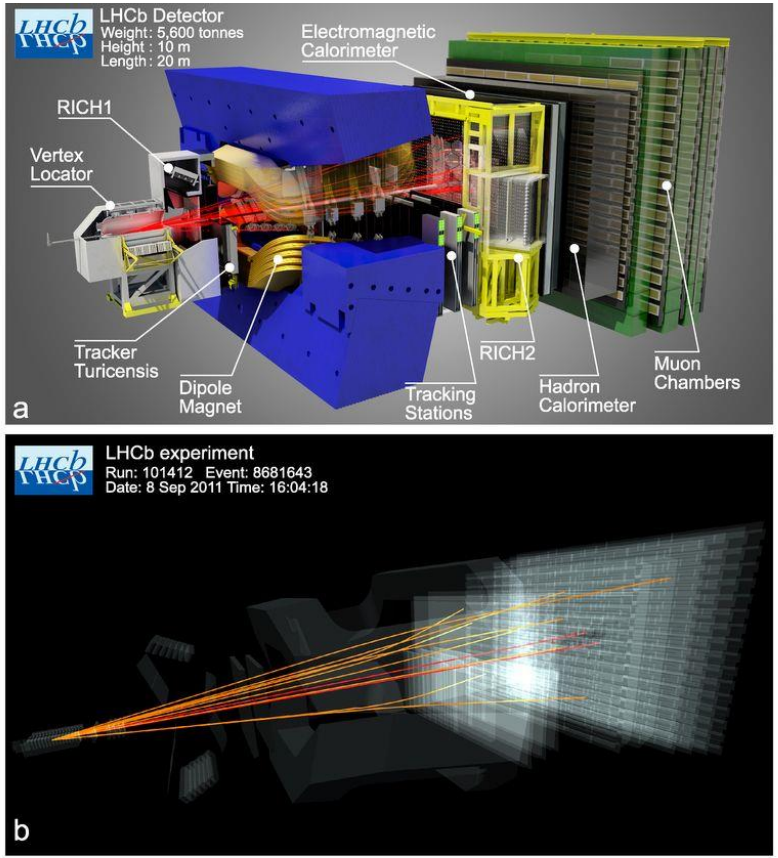
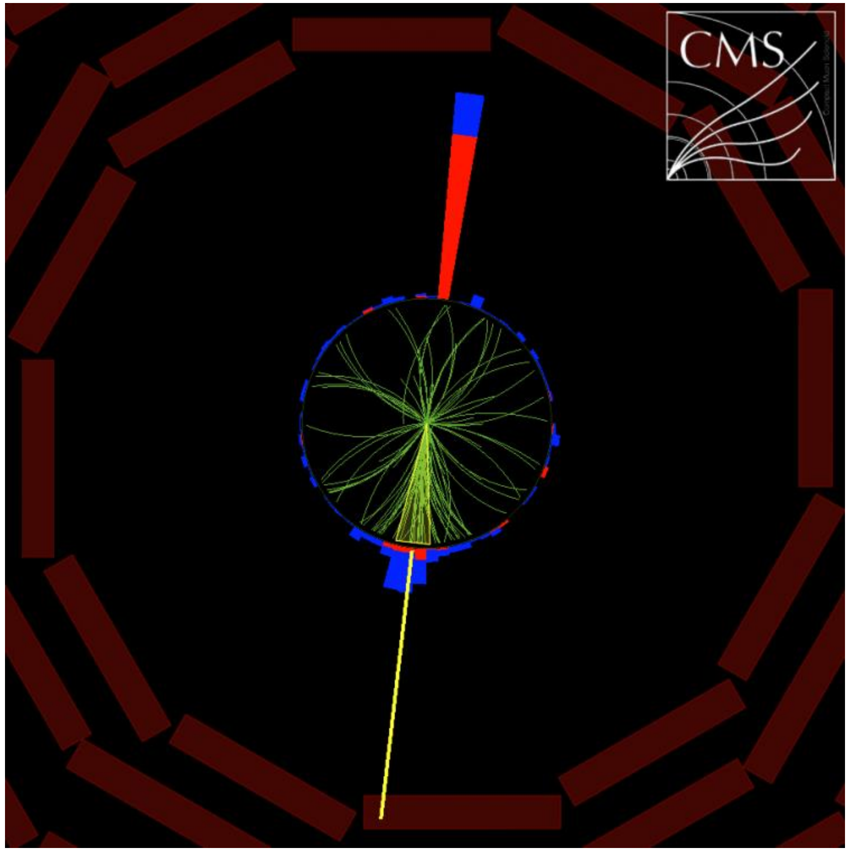
On behalf of the ATLAS, CMS and LHCb collaborations

PASCOS 2019 Manchester July 1 2019







Large Hadron Collider

Excellent performance in 2018 for √s=13 TeV proton-proton collisions

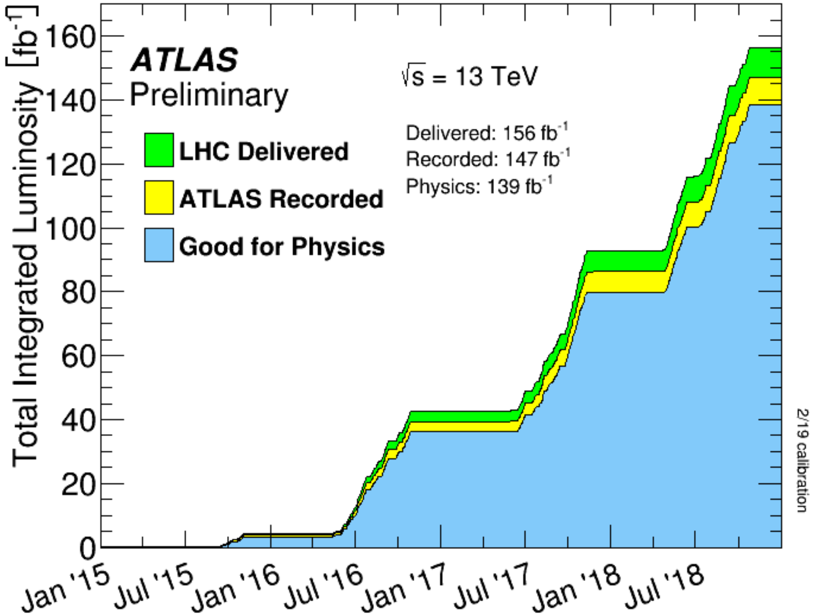
- Peak luminosity 2.1×10^{34} cm^{-2} s^{-1} is double design
- First physics results this year with 140 fb^{-1} from Run 2

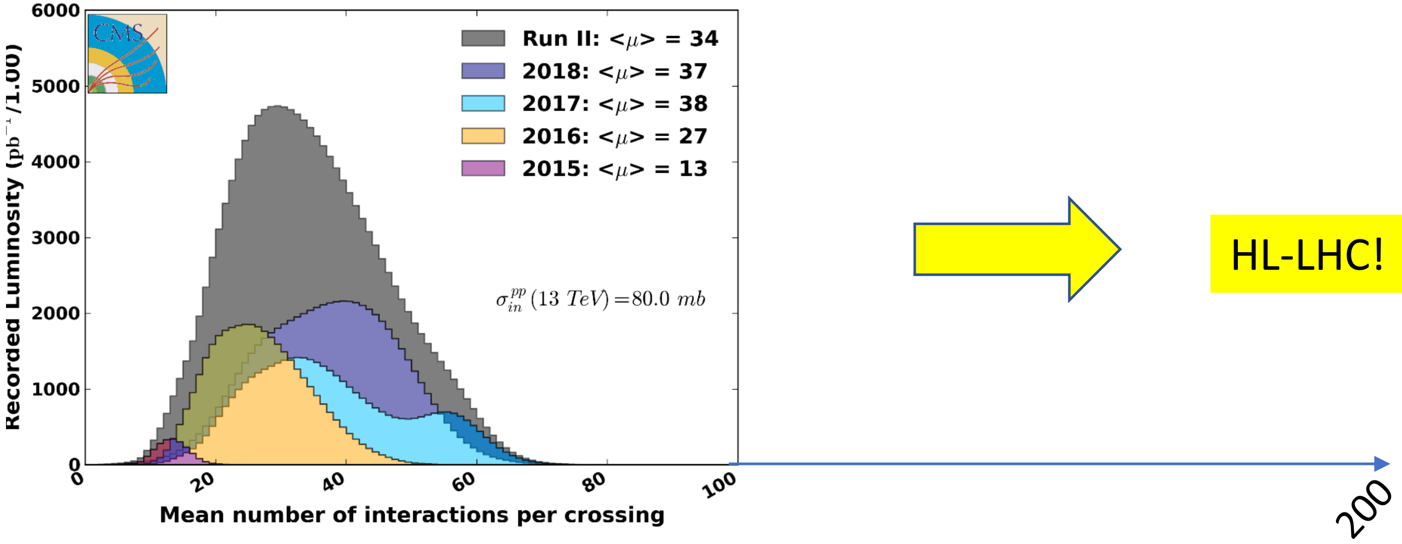
Future Run 3 from 2021-2023 at √s=14 TeV

- Goal: deliver 150 fb^{-1}

Extensive upgrades for High Luminosity LHC Run 2026-2035

- Peak luminosity 7.5×10^{34} cm^{-2} s^{-1}
- Goal: deliver over 3000 fb^{-1}

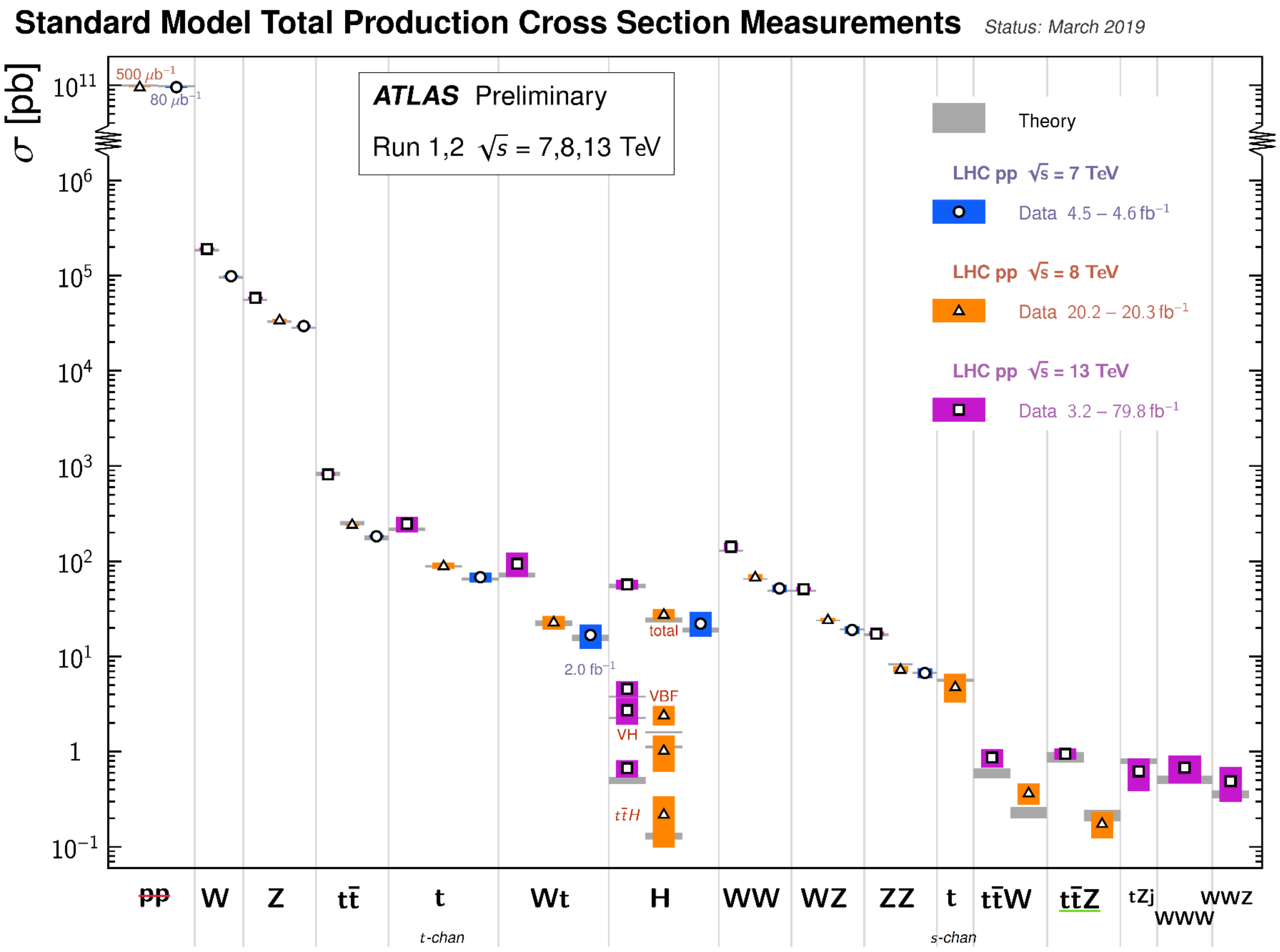




Standard Model

ATLAS ATL-PHYS-PUB-2019-010
CMS SM

- Production cross section measurements in good agreement with theoretical predictions at √s=13 TeV
- Measured diboson
  - WW
  - WZ
- Measured ttbar+boson
  - ttH
  - ttW
  - ttZ
- Measured triboson
  - WWW
  - WWZ



Overview

Introduction

Emphasis on searches with 140/fb and on searches for new signatures

Exotics Searches

- High Mass Resonances
- Low Mass Resonances

Searches for Supersymmetry

- Electroweak production
- Strong production

Unconventional Signatures*

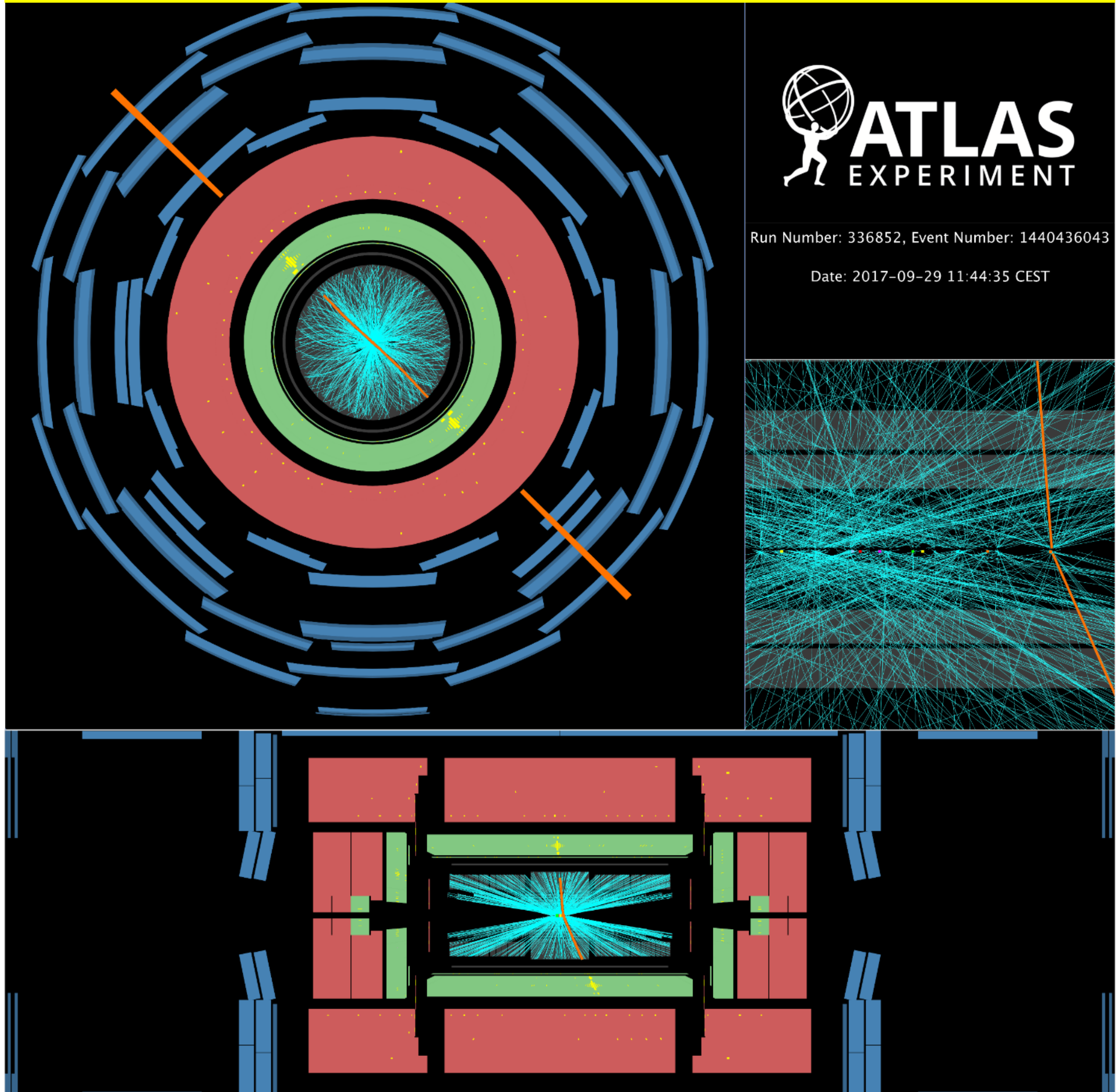
Dark Matter and Dark Energy

Summary

*Magnetic monopoles in Vasiliki Mitsou's talk on Thursday

Highest invariant mass (4.06 TeV) di-electron

- E_T of 2.01 TeV and 1.92 TeV



Dilepton

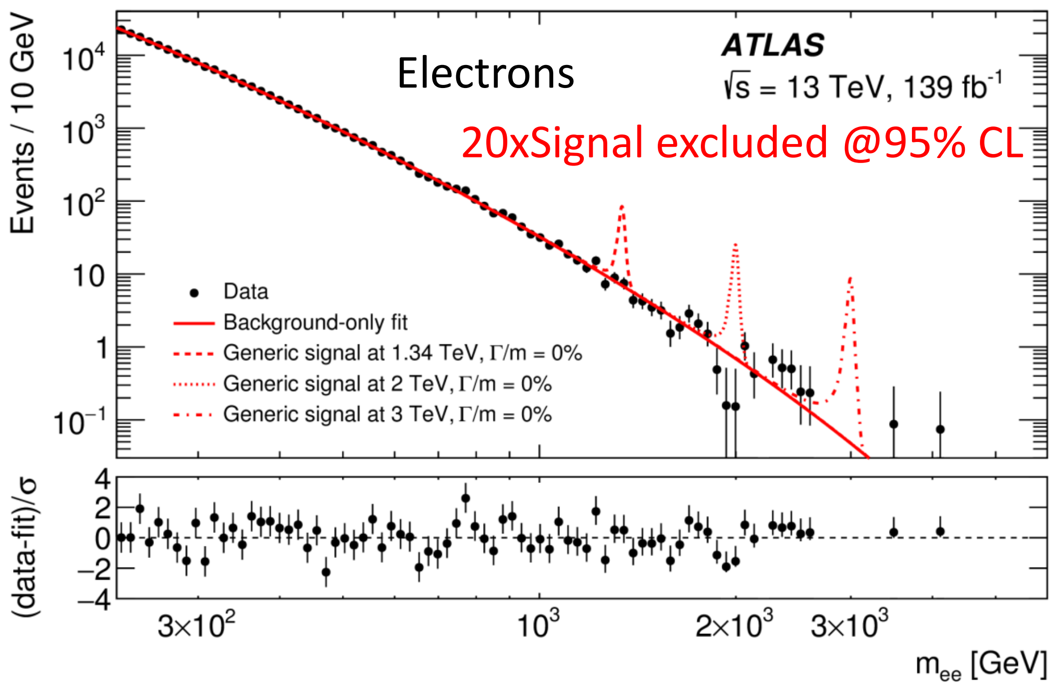
ATLAS 139/fb arXiv:1903.06248
CMS 36/fb JHEP 06 (2018) 120

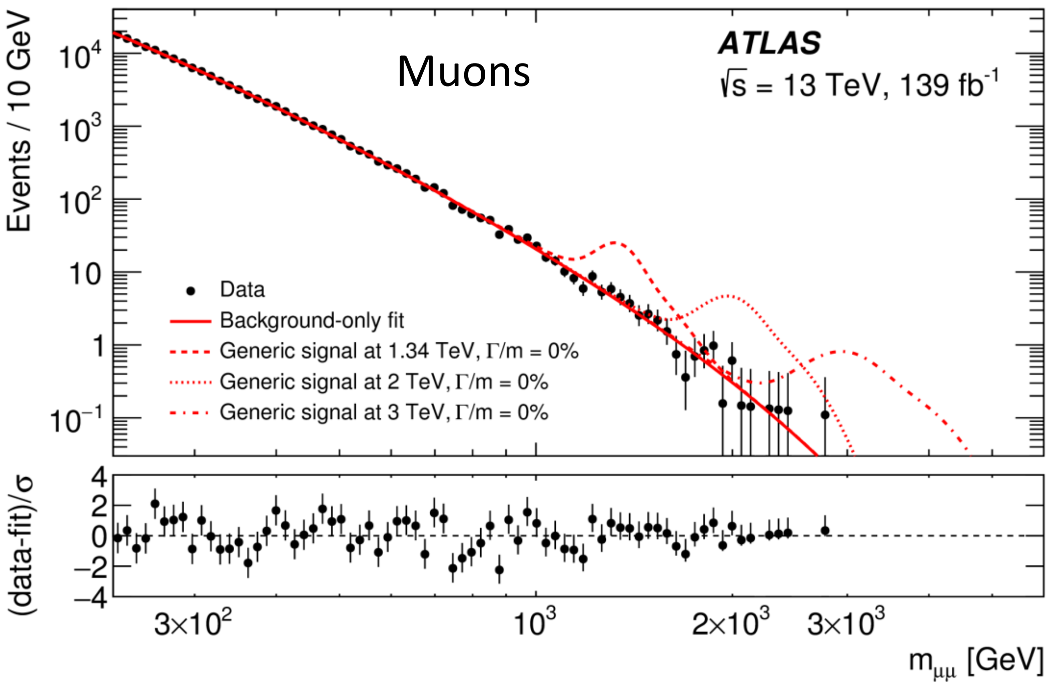
Direct production of high mass Z'

- Improved reconstruction for e and μ
- Mass resolution for electron channel < 2%, muon channel increases from 3% at 200 GeV to 15% at 3000 GeV
- Functional form fit for background

No significant excess, report limits @ 95% CL

Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1



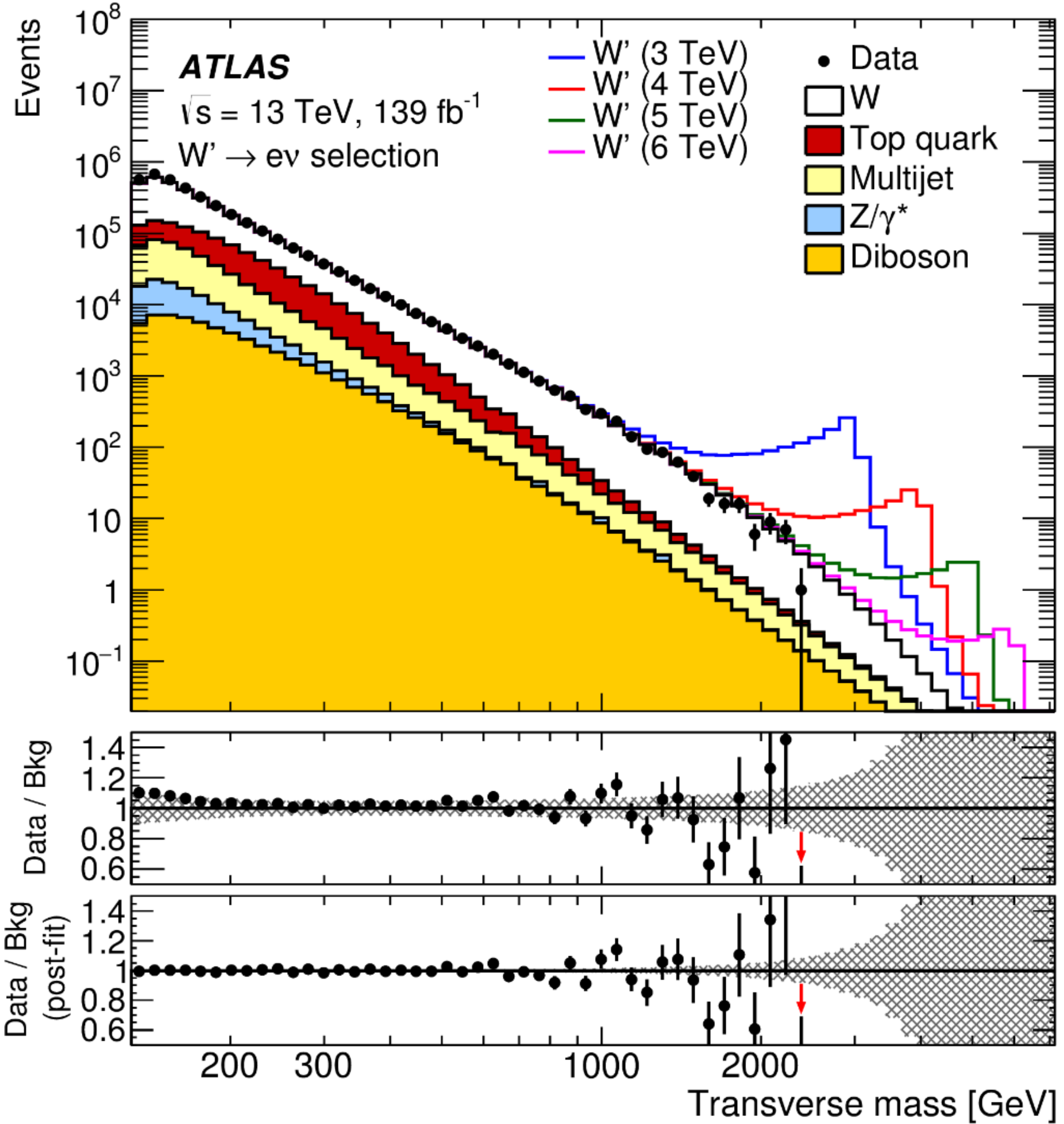


W'→lν

ATLAS 139/fb arXiv:1906.05609
CMS 36/fb JHEP 06 (2018) 128

- High mass W' decaying to lepton and neutrino (MET)
- No significant excess

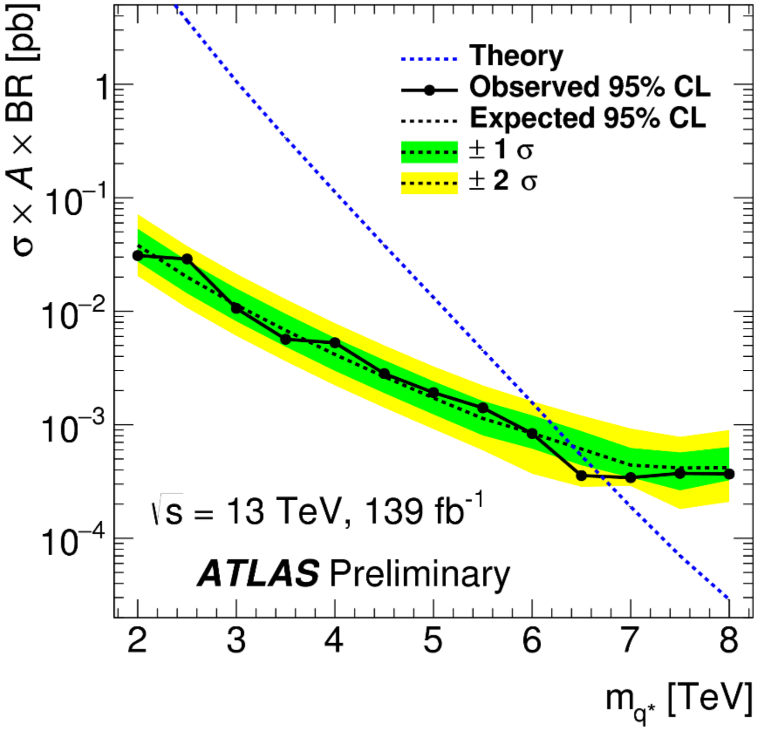
Decay	$m(W')$ lower limit [TeV] Observed	Expected
$W' \to e\nu$	6.0	5.7
$W' \to \mu\nu$	5.1	5.1
$W' \to \ell\nu$	6.0	5.8

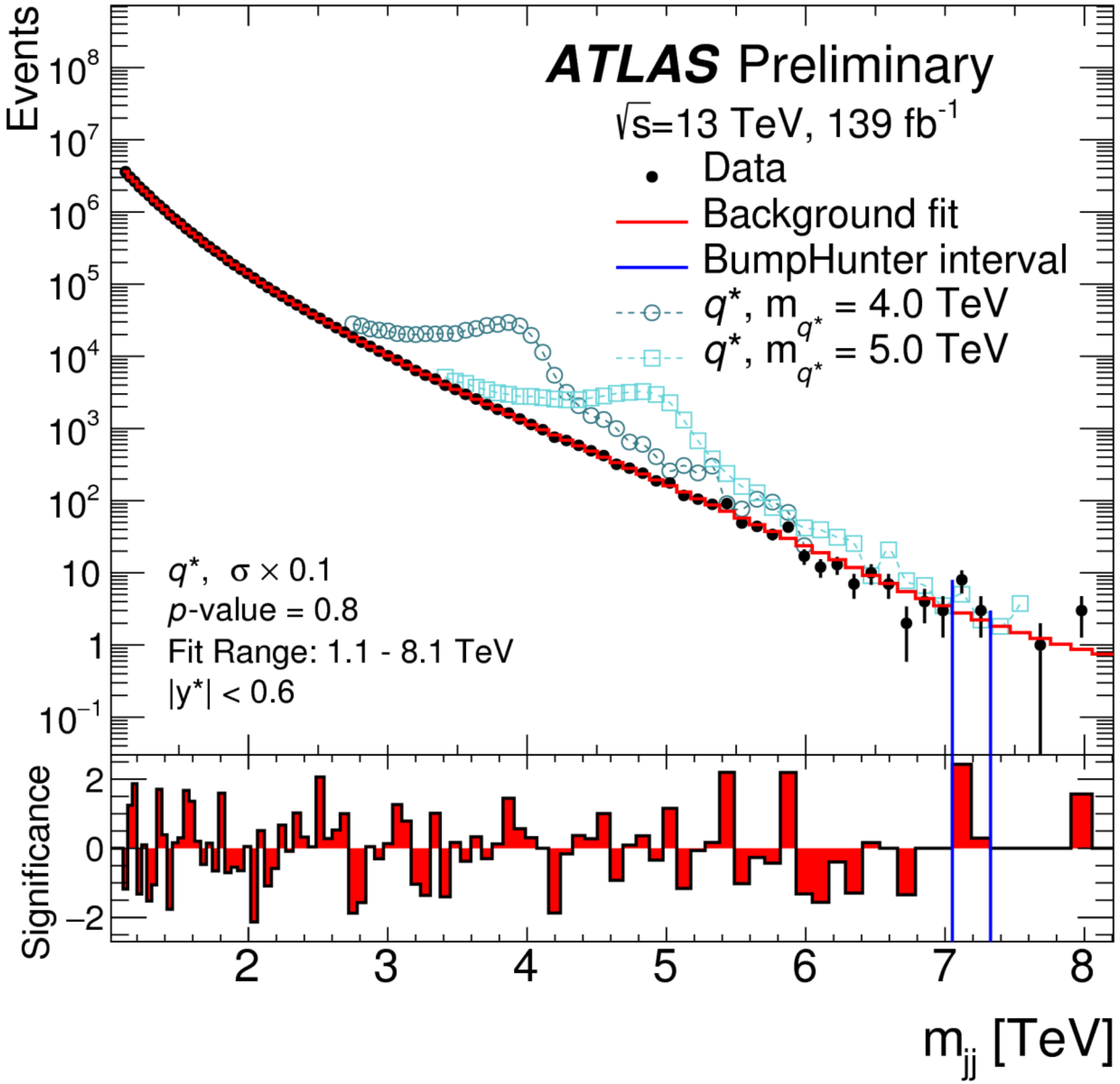


Dijet

[ATLAS 139/fb ATLAS-CONF-2019-007]
[CMS 36/fb JHEP 08 (2018) 130]

- High mass resonance decaying to jets
  - Huge background from QCD dijets
  - Lowest single jet trigger p_T>420 GeV
  - Fully efficient for dijet masses above 1.1 TeV
- Background from functional form fit
- Benchmark model: excited quark > 6.7 TeV

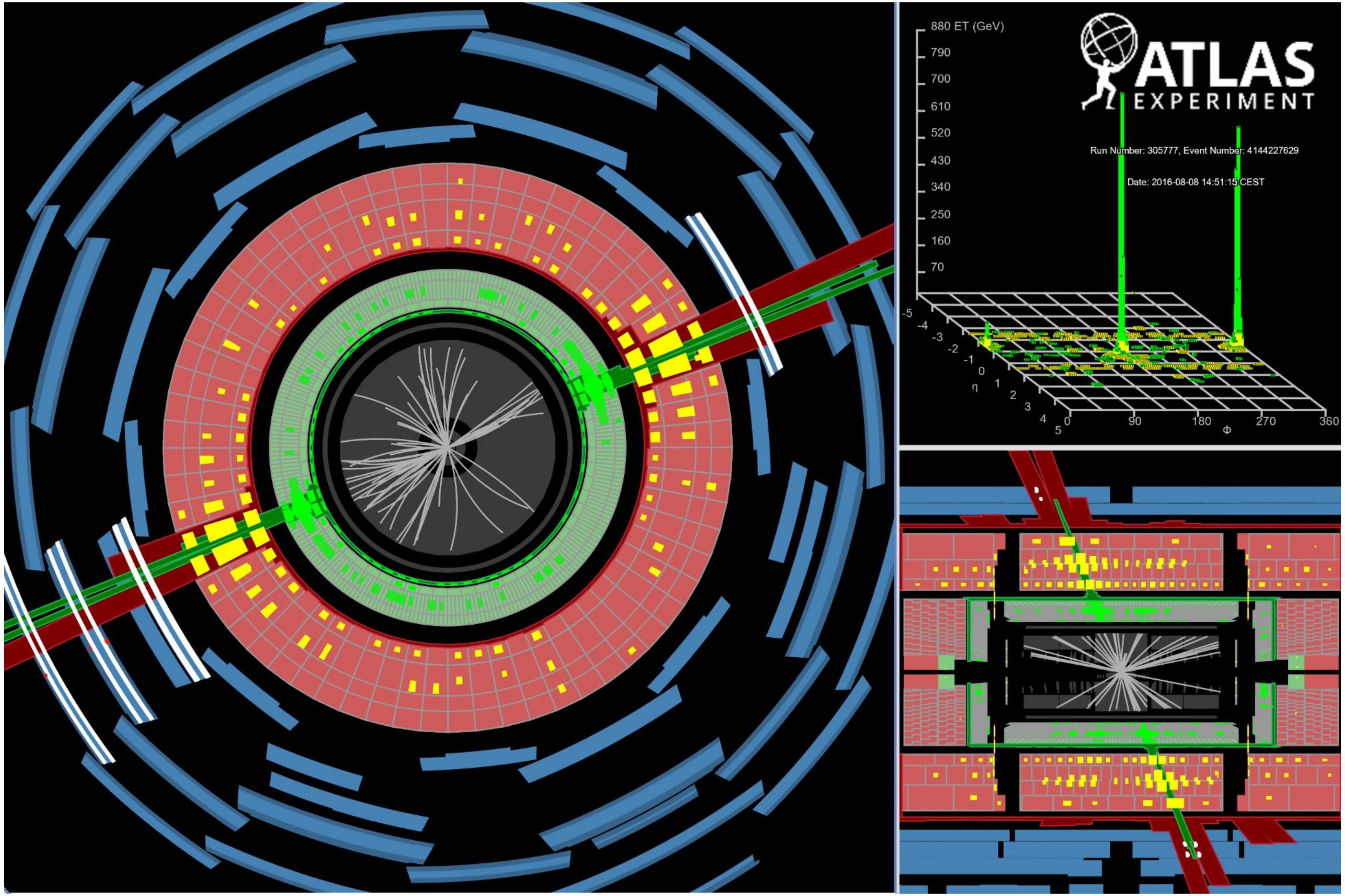




Highest invariant mass dijet event from ATLAS

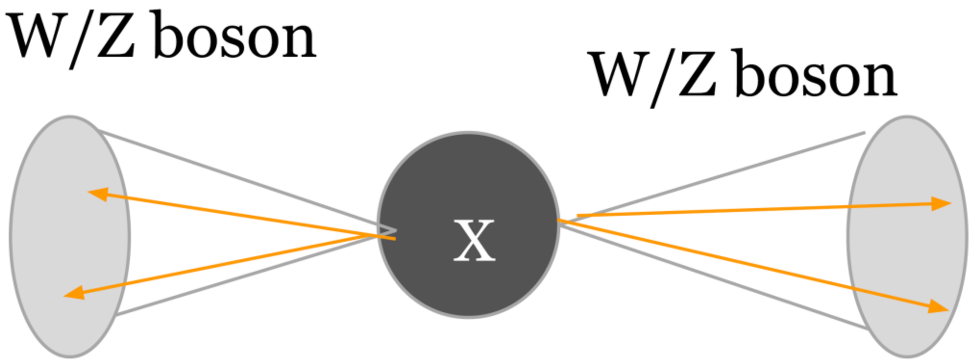
Two central jets each with high p_T of 3.74 TeV

Invariant mass is 8.02 TeV

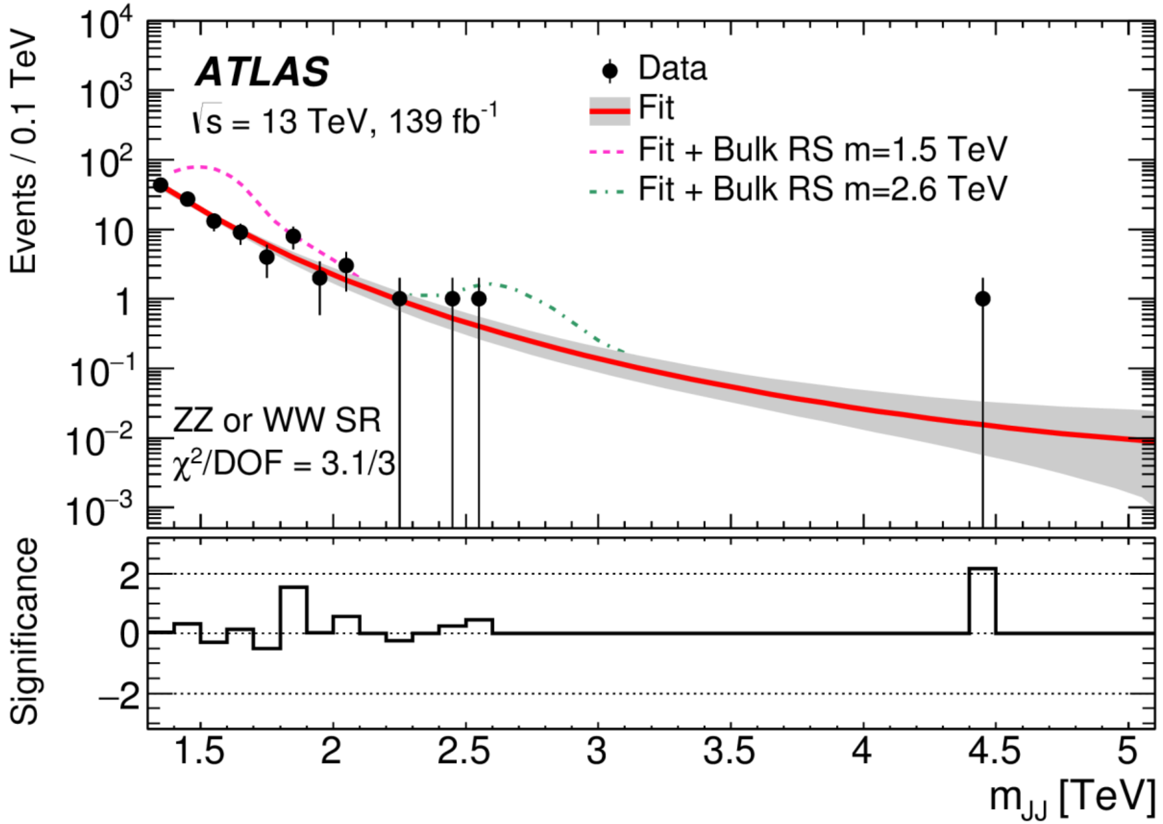


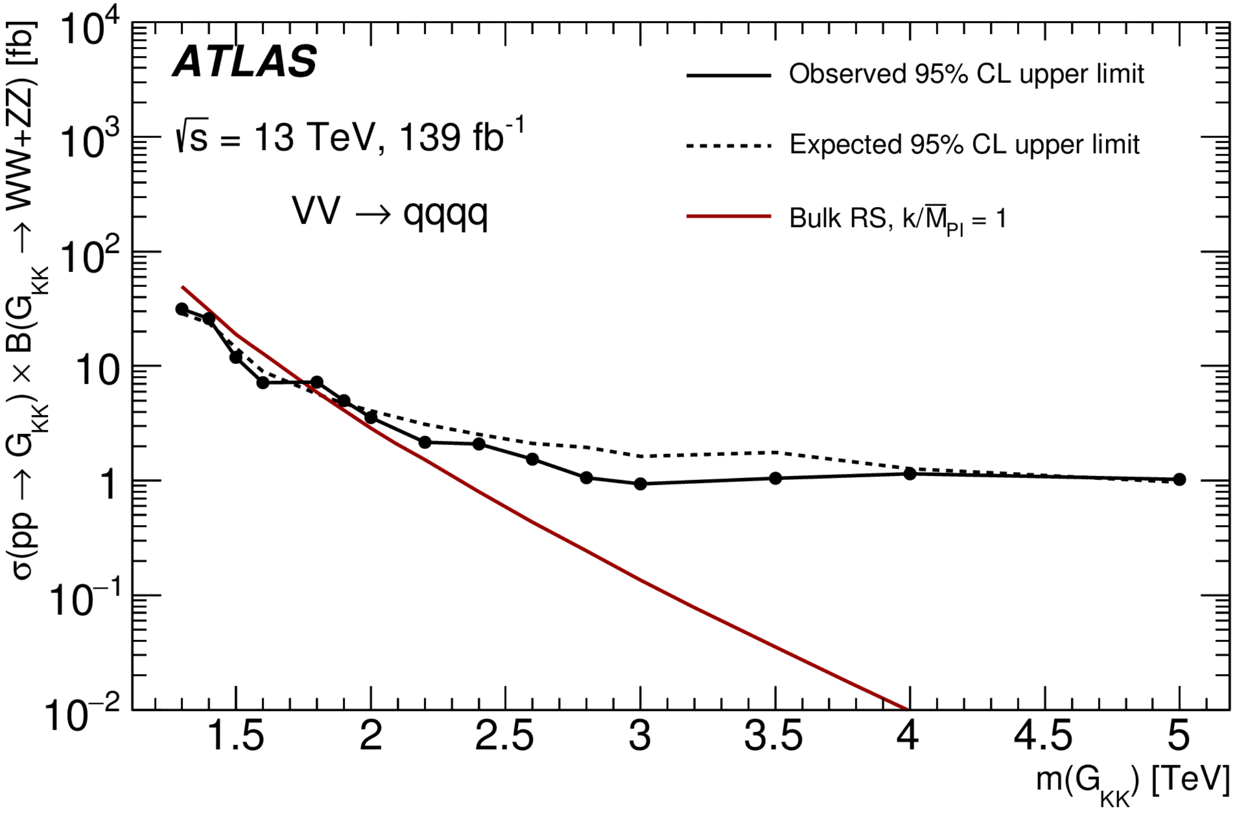
Diboson resonances

ATLAS 139/fb arXiv/1906.08589



- High mass resonance decay to WW, WZ, ZZ
  - Boson hadronic decay products highly collimated
  - Not resolvable as separate jets
  - Large jets with two-prong substructure allow to differentiate from huge QCD multi-jet background

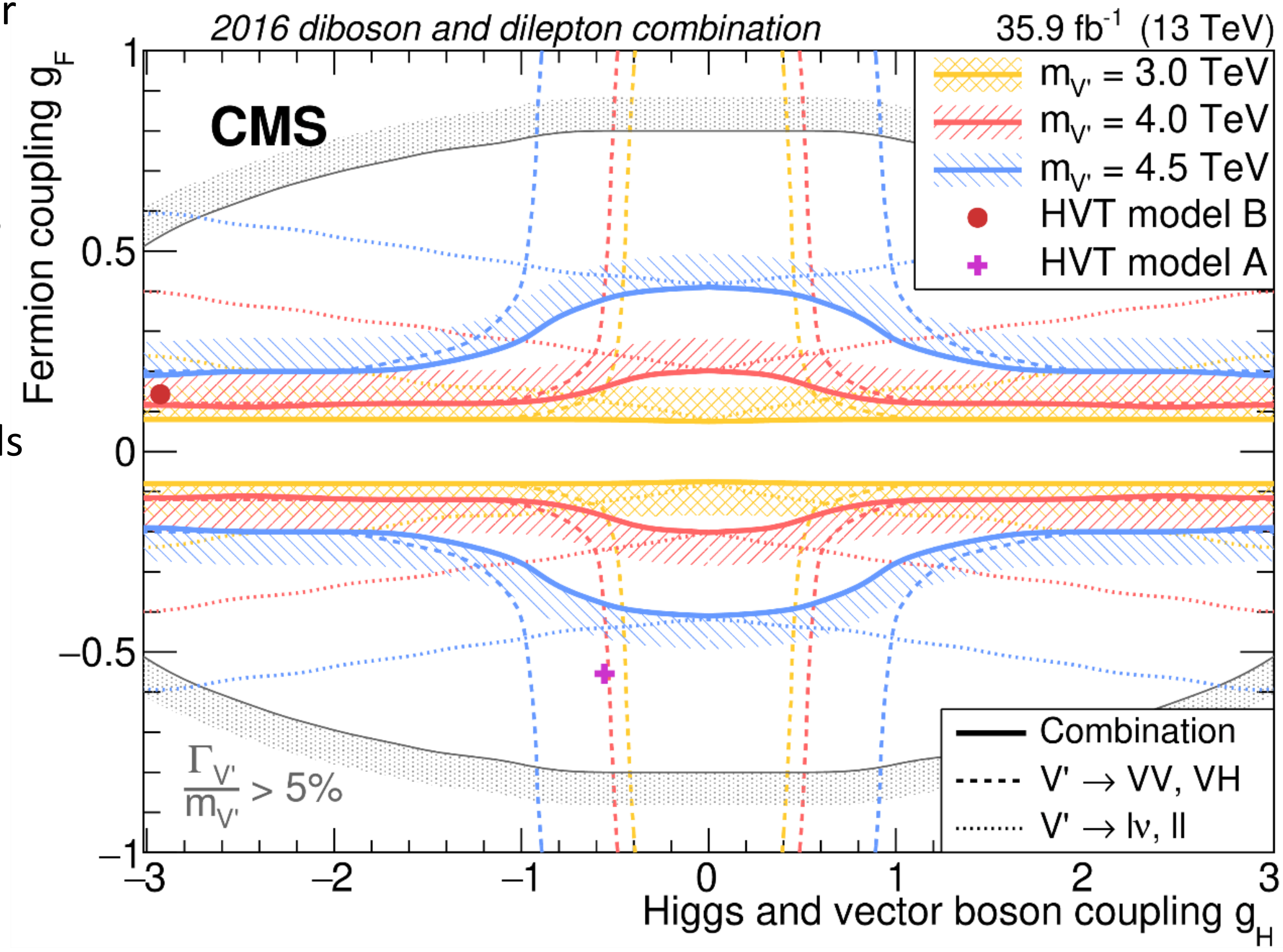




Combination

[CMS 36/fb arXiv:1906.00057]
[ATLAS 36/fb PRD 98 (2018) 052008]

- Combine diboson searches for WW, WZ, ZZ, WH, ZH with 36/fb
  - Improve limits by up to 700 GeV for HVT model B with mass-degenerate heavy vector triplet
- Combine complementary diboson and dilepton channels
  - Dibosons sensitive for large boson couplings
  - Dileptons sensitive for large fermion couplings



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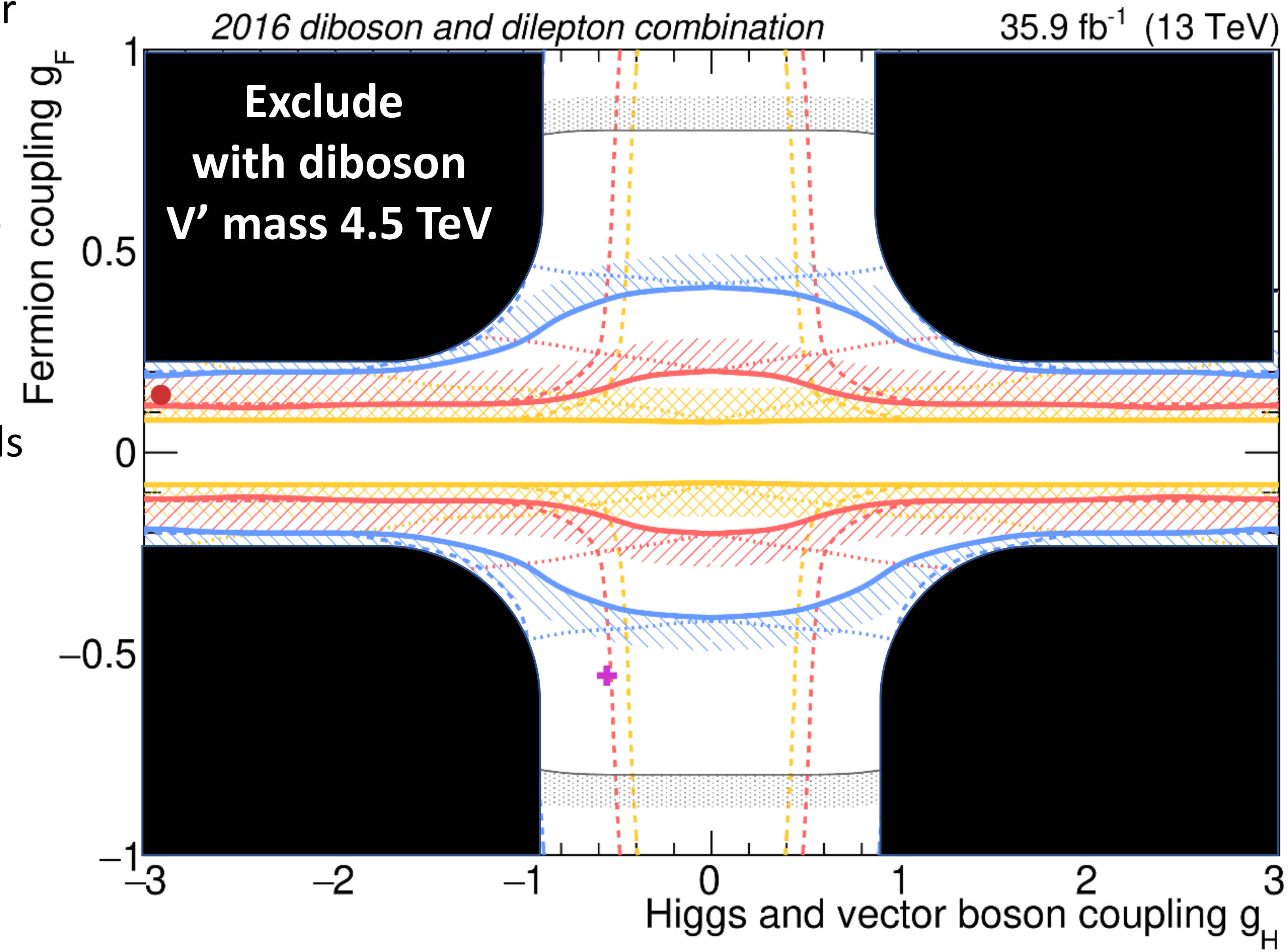

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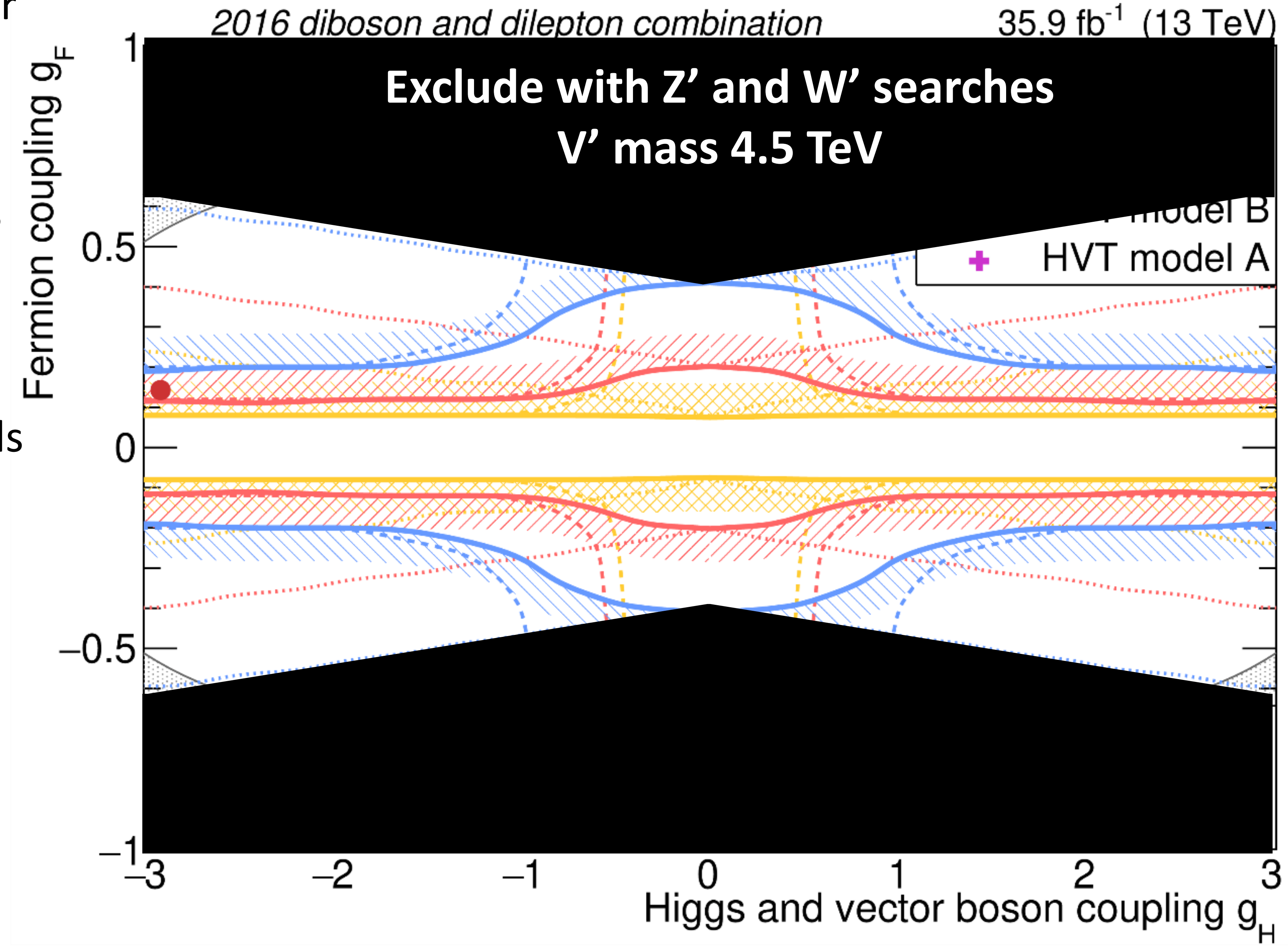
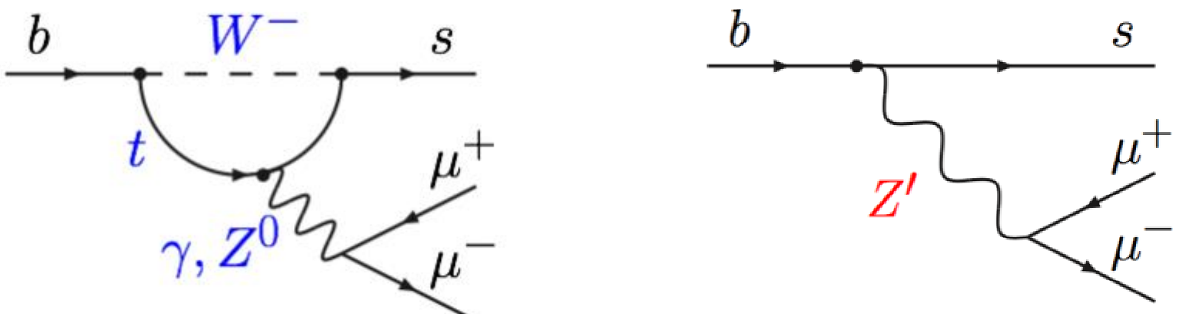
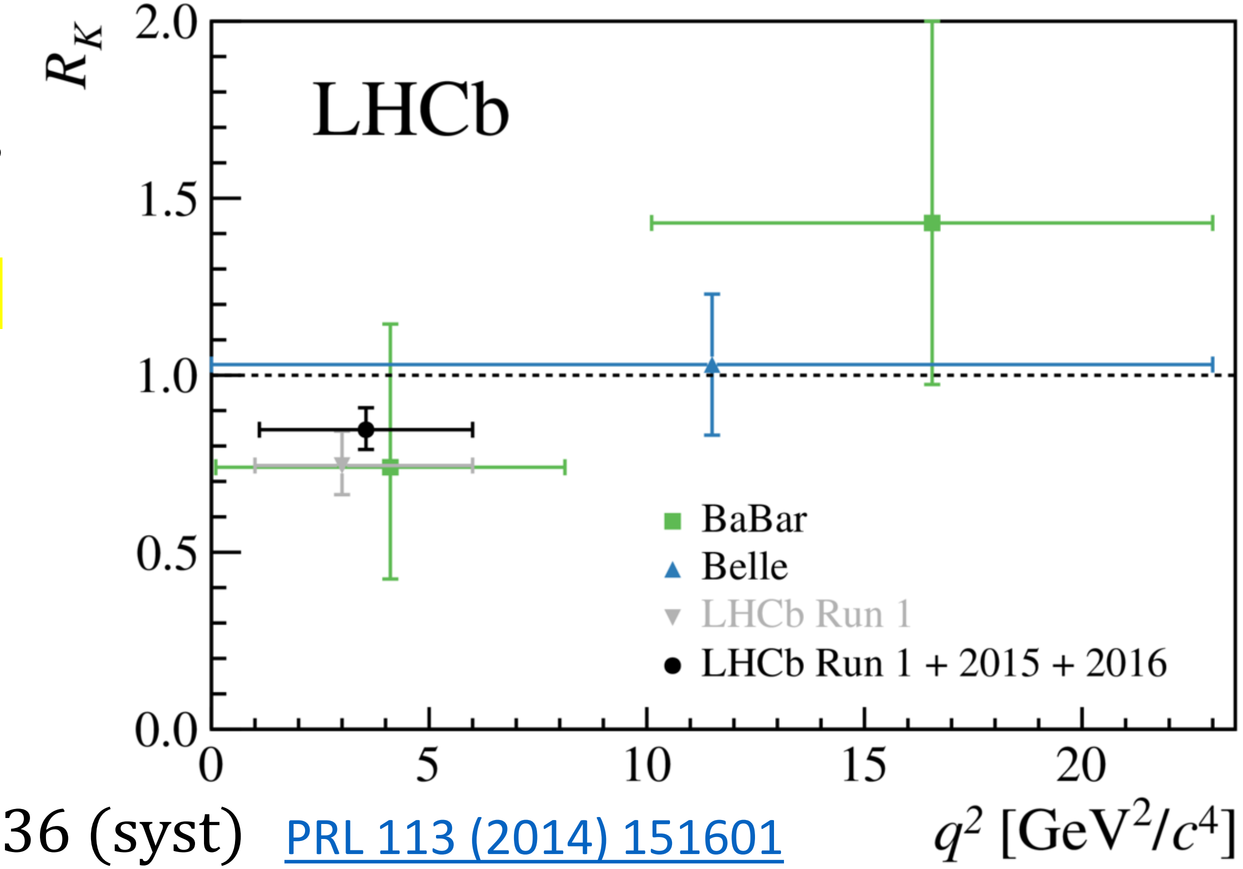


LHCb Rare Decays

- Hadron collider high statistics B physics program can investigate rare decays
- $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$
  - SM branching fractions small
  - Even small contribution from new physics can be detected
- Test lepton universality by measuring ratio of decays to muons to decays to electrons
- Ratio from 2014 was unexpectedly low
- Updated with 2x data in 2019, compatibility with SM unchanged at 2.5σ
- Lepton Flavor Universality breaking not confirmed or ruled out





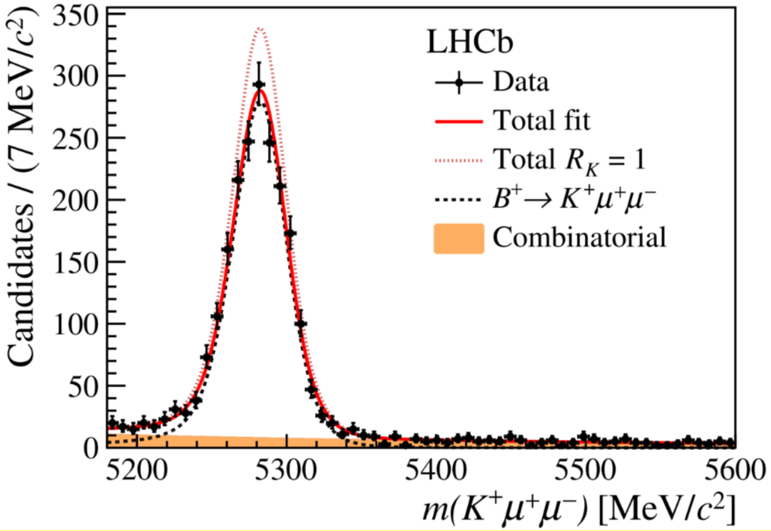
LHCb Run 1 $R_K = 0.745\,^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$ PRL 113 (2014) 151601

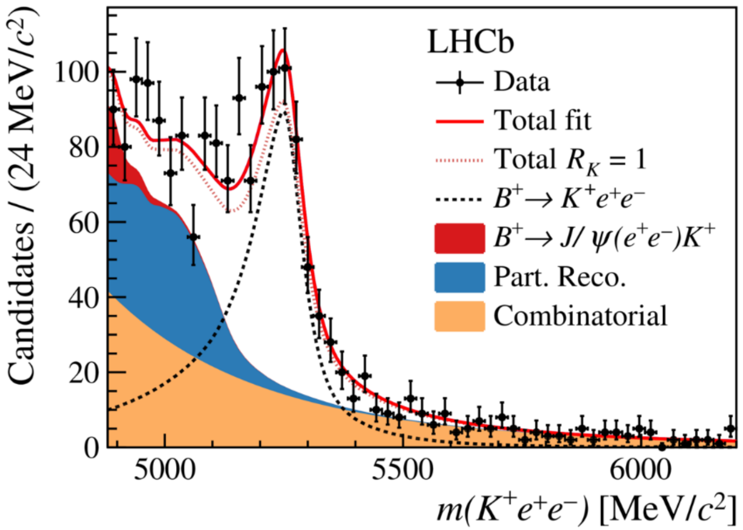
$+2015 + 2016\;\; R_K = 0.846\,^{+0.060}_{-0.054}\,(\text{stat})\,^{+0.016}_{-0.014}\,(\text{syst})$ PRL 122 (2019) 191801

CERN seminar Paula Álvarez Cartelle

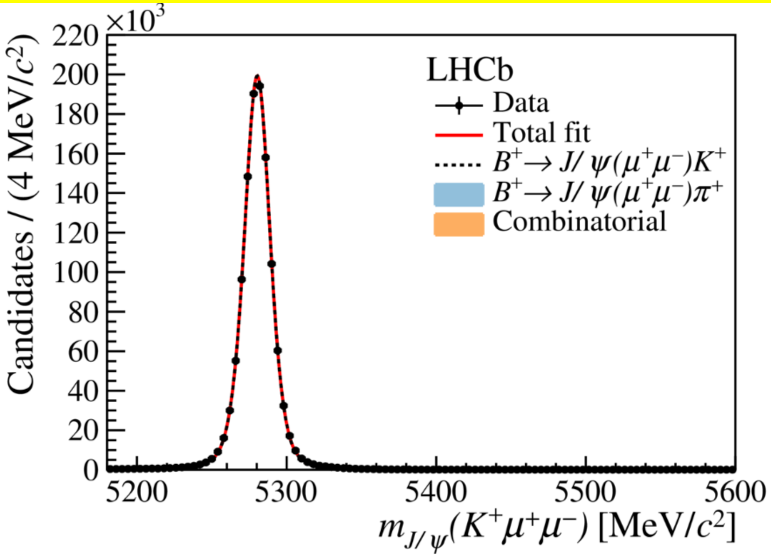
R_K double ratio cancels most systematics

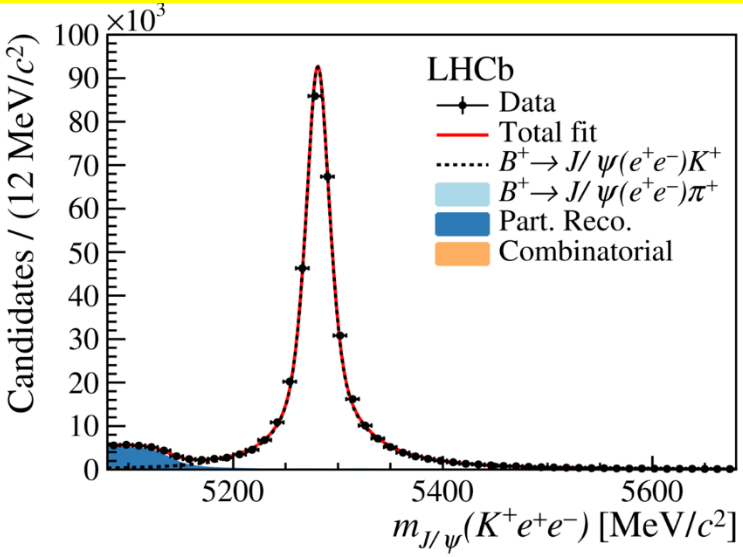
- ✓ hadronic effects
- ✓ Differences between electrons and muons from trigger, reconstruction, identification





$$R_K = \frac{N(B^+ \to K^+\mu^+\mu^-)}{N(B^+ \to K^+J/\psi(\mu^+\mu^-))} \times \frac{\varepsilon_{B^+\to K^+J/\psi(\mu^+\mu^-)}}{\varepsilon_{B^+\to K^+\mu^+\mu^-}} \Big/ \frac{N(B^+ \to K^+e^+e^-)}{N(B^+ \to K^+J/\psi(e^+e^-))} \times \frac{\varepsilon_{B^+\to K^+J/\psi(e^+e^-)}}{\varepsilon_{B^+\to K^+e^+e^-}}$$





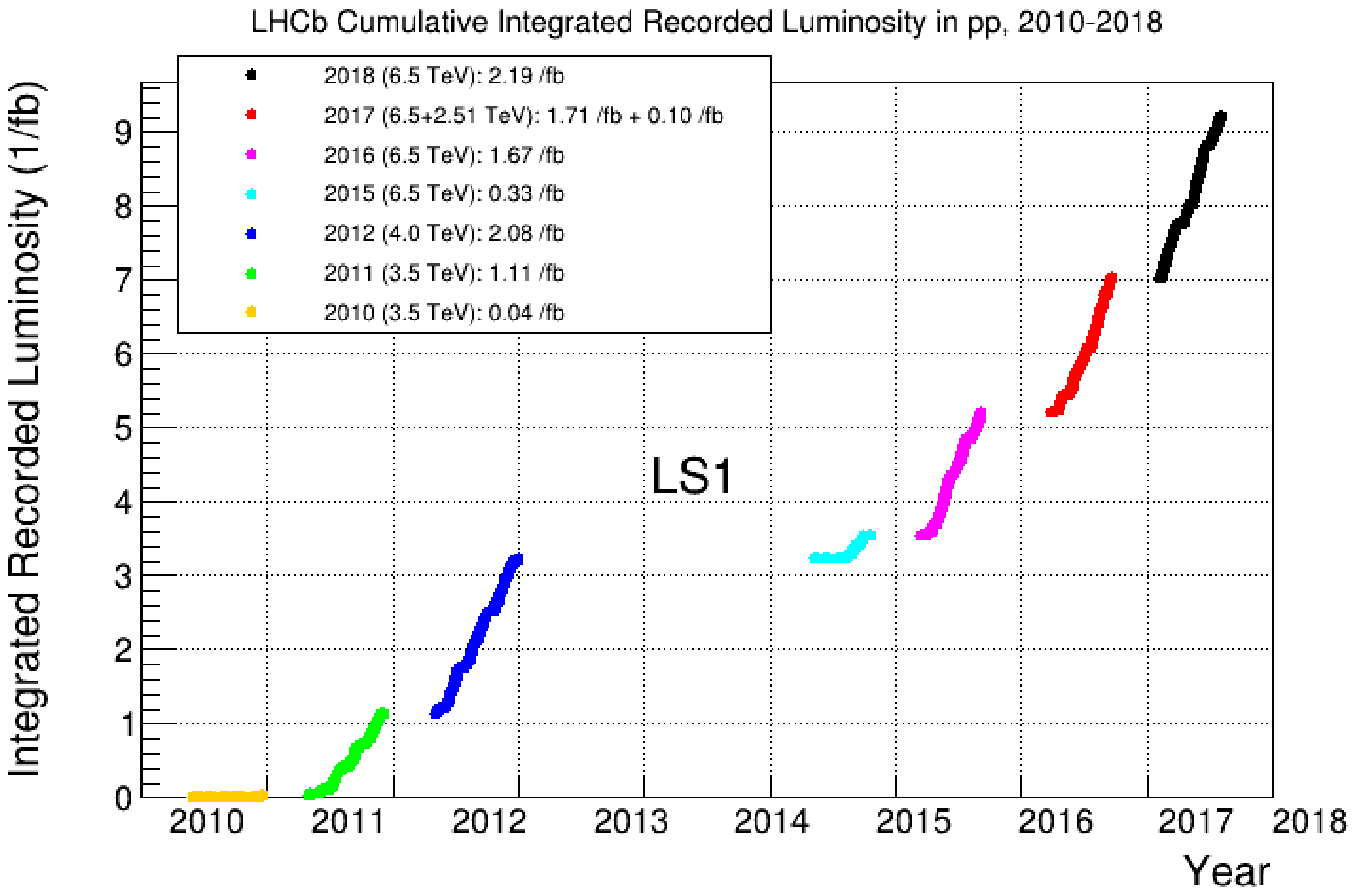
- Yields (N) from fit to invariant mass of final state particles
- Efficiencies (Ɛ) computed using simulation calibrated with control channels in data

LHCb

- Doubled statistics for B^+ with 2015-16 data added to Run 1 and improved reconstruction
- Total systematic uncertainty reduced from 4.8% to 1.7%

What's next?

- Update B^0 result and angular analysis
- Future result will have double statistics again with 2017-18 data
- 2021-23 Run 3 will have upgraded LHCb detector with even better performance

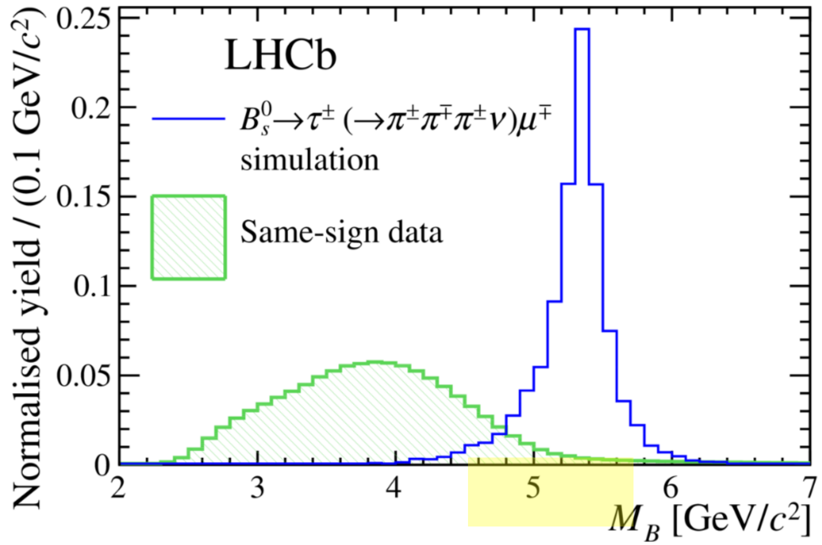


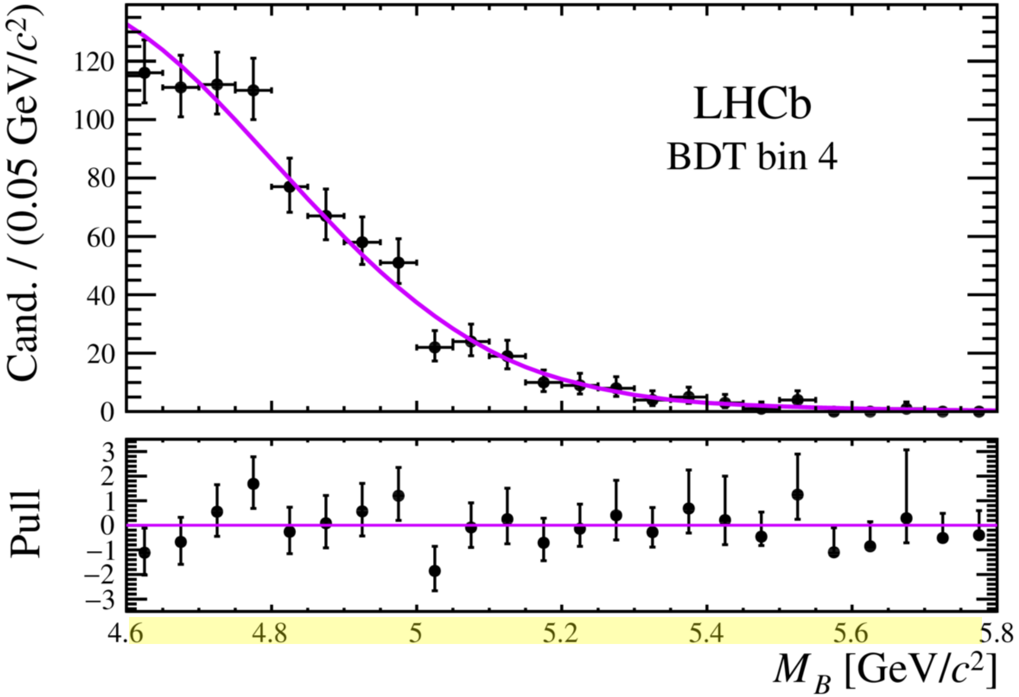
LHCb search for lepton flavor violating decays

[LHCb arXiv:1905.06614](https://arxiv.org/abs/1905.06614)

- Search for $B^0 \rightarrow \tau^- \mu^+$
  - SM branching fraction 10^{-54}
  - Indirect production of Z', leptoquarks, Pati-Salam as large as 10^{-4}
- Results with 3/fb from 2011-2012
- Reconstruct $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$ decays through two intermediate resonances $a_1(1260)^-$ and $\rho(770)^0$
- Normalize with $B^- \rightarrow D^-(K^+ \text{-} \pi^-\pi^-)\pi^+$
- First limits on B_s and improve by x2 limits on B^0

Mode	Limit	90% CL	95% CL
$B_s^0 \rightarrow \tau^\pm \mu^\mp$	Observed	3.4×10^{-5}	4.2×10^{-5}
	Expected	3.9×10^{-5}	4.7×10^{-5}
$B^0 \rightarrow \tau^\pm \mu^\mp$	Observed	1.2×10^{-5}	1.4×10^{-5}
	Expected	1.6×10^{-5}	1.9×10^{-5}

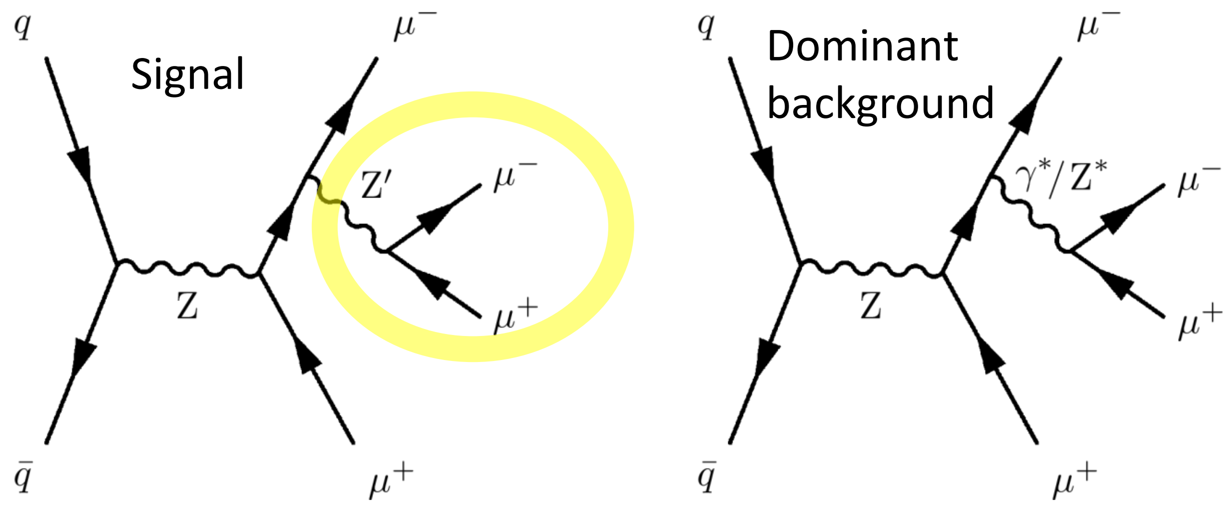


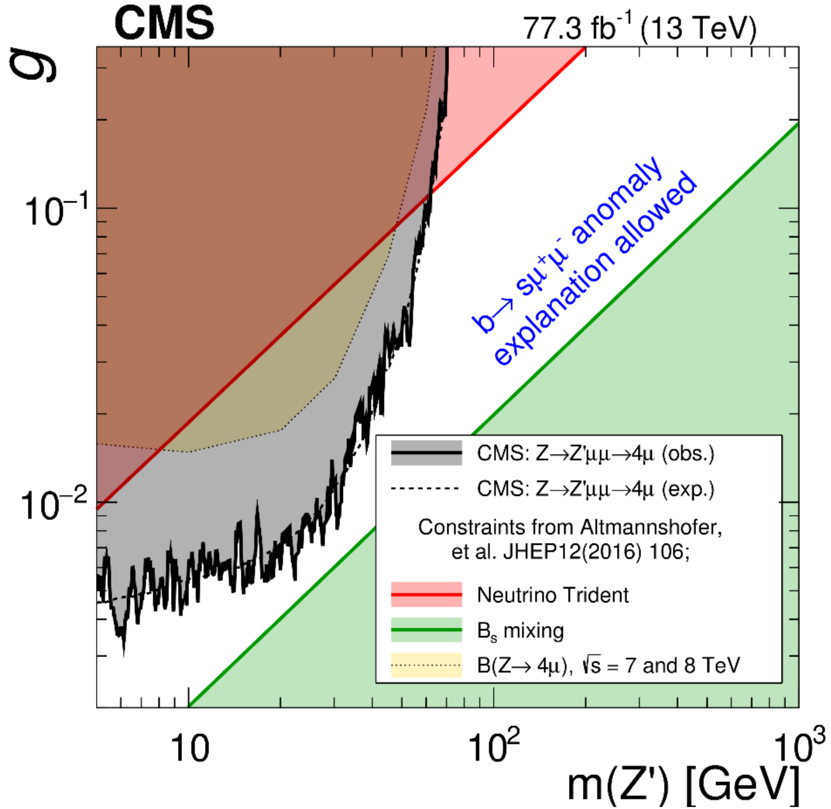


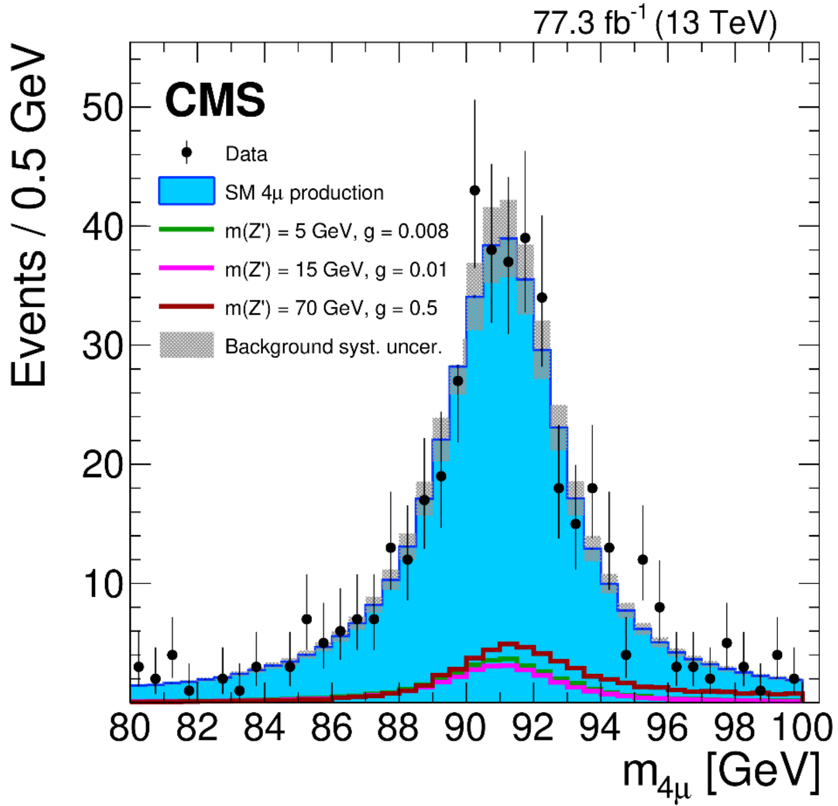
Search for 4 muons

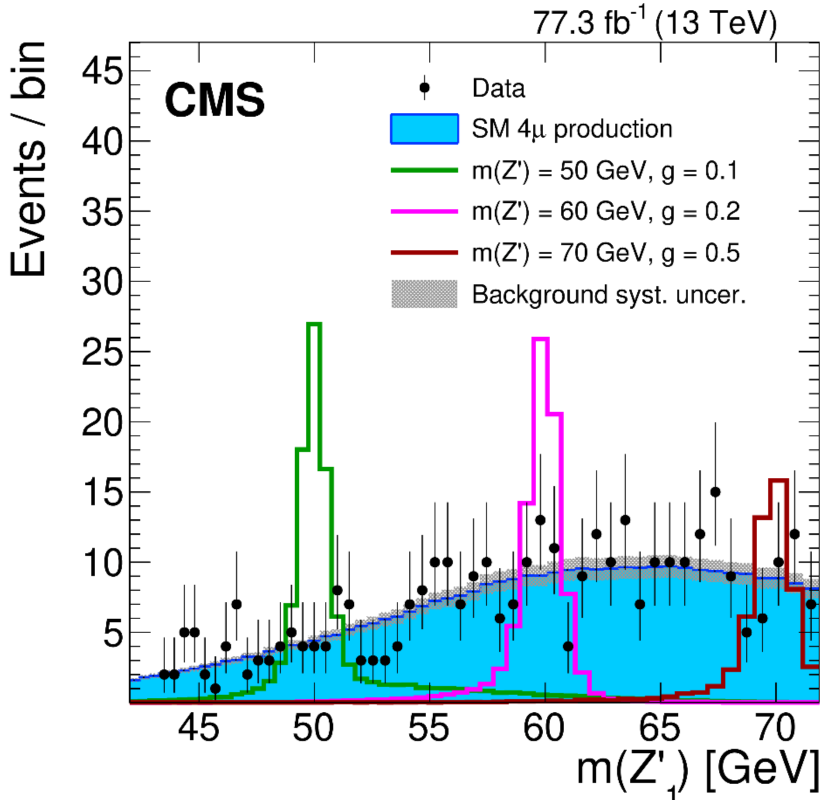
CMS 77/fb Phys. Lett. B 792 (2019) 345

- Low mass Z' from U(1) based on L_μ-L_τ
  - Z' only couples to muons and taus
- Radiate Z' from muons
  - Exploit SM $Z \rightarrow \mu^+\mu^-$ to produce muons
- Explore part of interesting parameter space





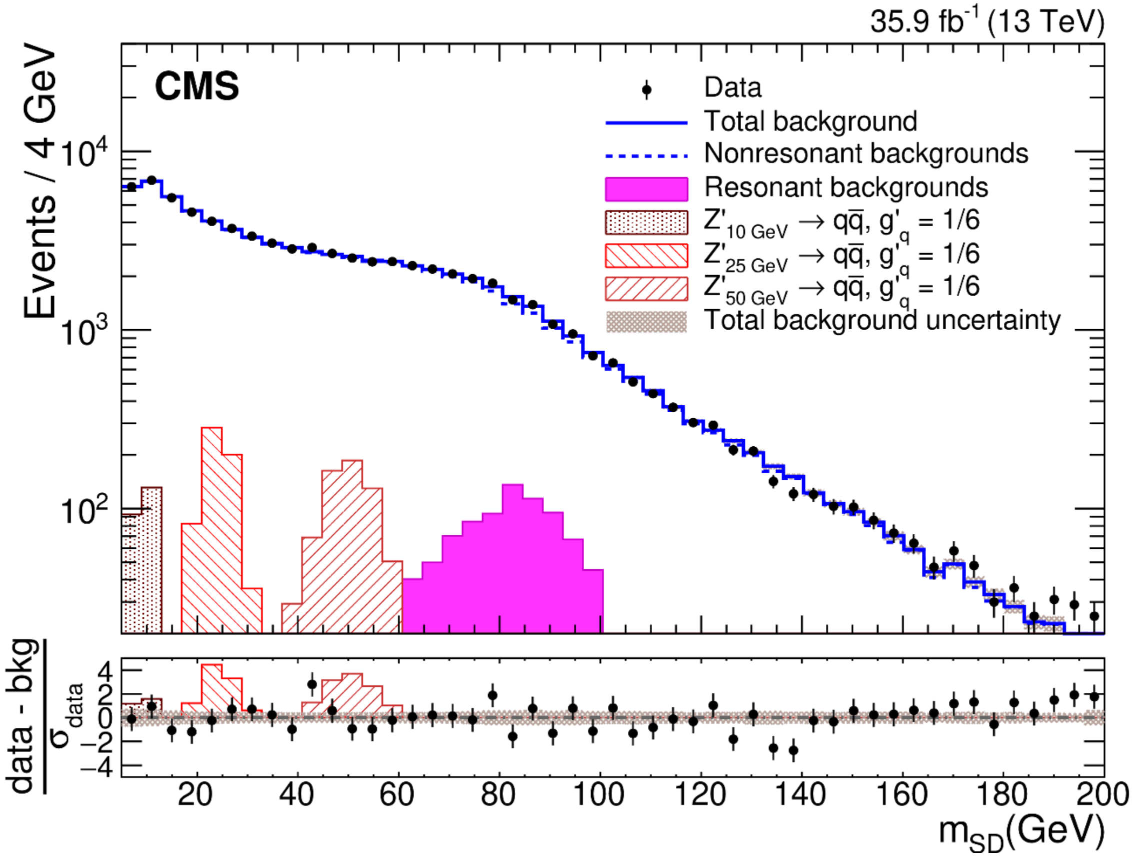


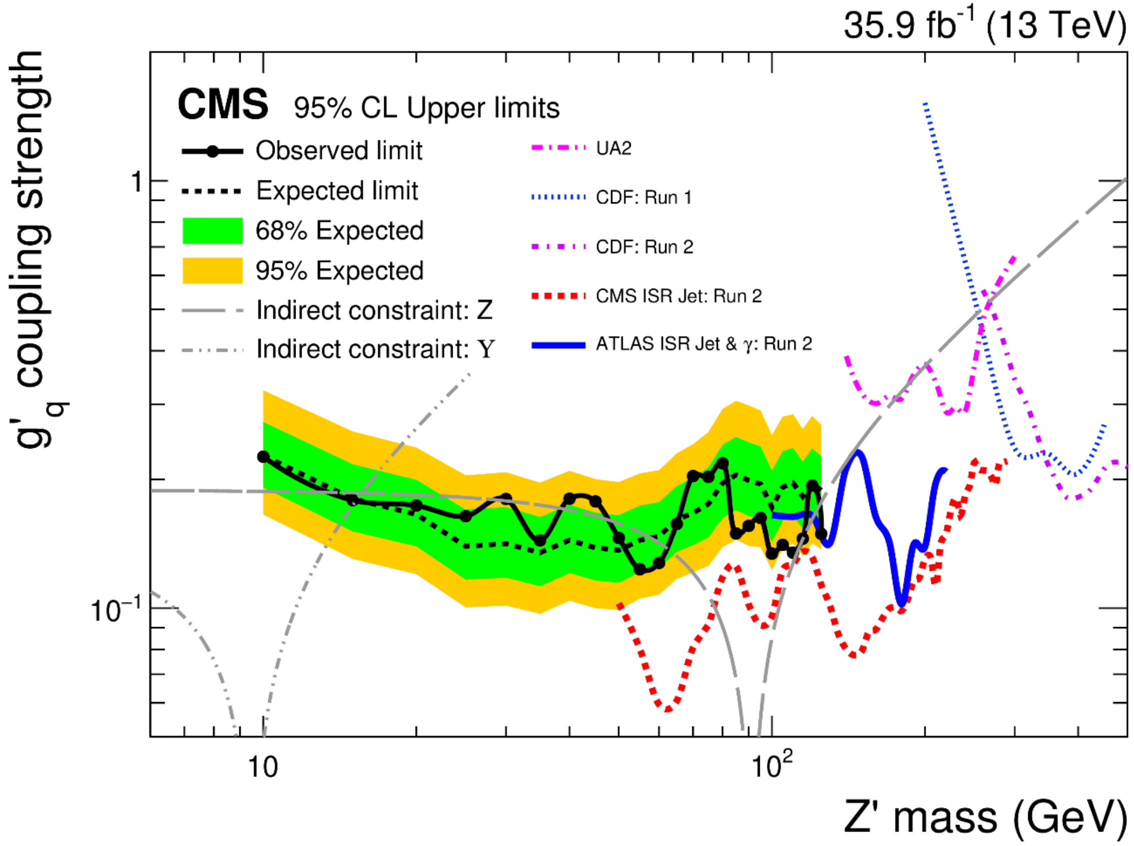


"Dijet" with ISR photon

CMS 36/fb arXiv:1905.10331 submitted to PRL
ATLAS 80/fb Phys. Lett. B 795 (2019) 56
ATLAS 80/fb ATLAS-CONF-2018-052

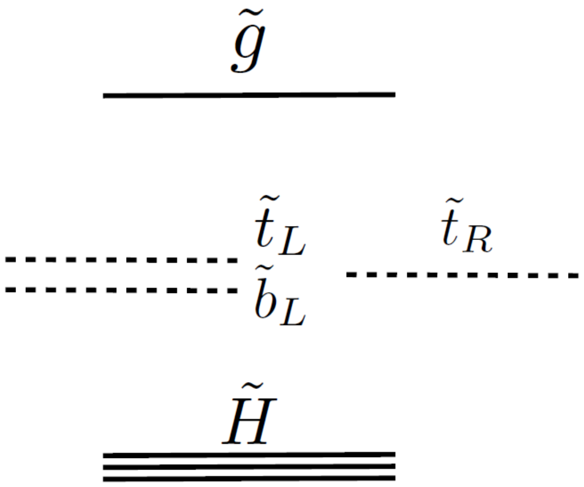
- First limits below 50 GeV at a hadron collider for low mass resonances decaying to "dijets"
- Trigger on ISR photon p_T>200 GeV, large boost of low mass resonance collimates decay products into single large radius jet with two-prong substructure
- Data-driven background estimate for non-resonant and resonant (Z+γ,W+ γ,ttbar)

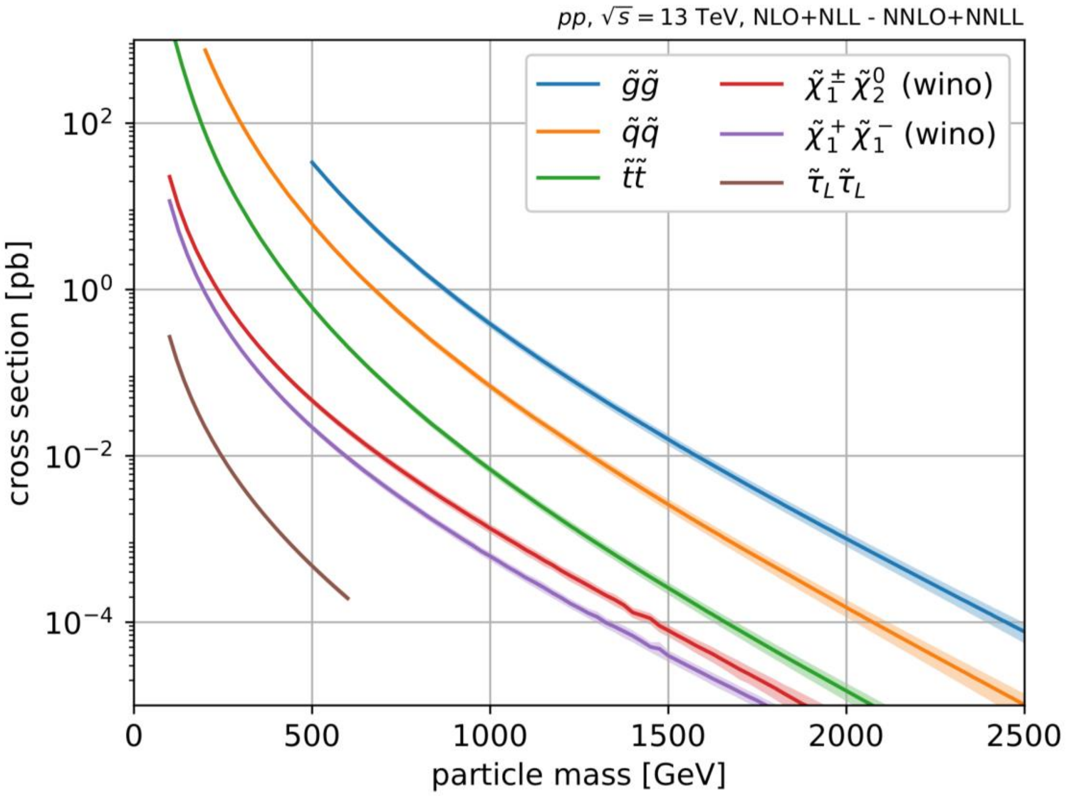




Supersymmetry

- Significant progress in challenging SUSY signatures
- Many natural models have small mass differences, for example Higgsino triplet differences of 100's MeV
  - Cascade decays give visible particles with low p_T, difficult to trigger and reconstruct
  - Compressed searches
- Non-prompt decays give unconventional signatures
  - Long-lived charged particle disappears after its decay to soft charged pion and neutral LSP
  - Searches for disappearing or short tracks
  - Long-lived neutral particle appears after its decay
  - Searches for emerging jets, displaced vertices
- **First results at a hadron collider for SUSY partner to tau lepton "stau"**



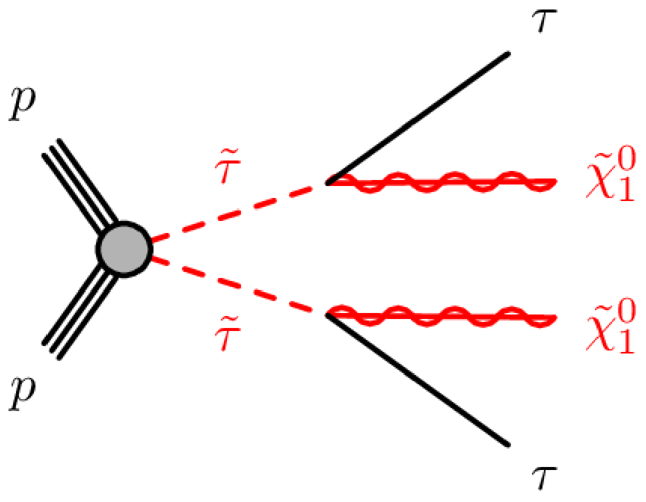


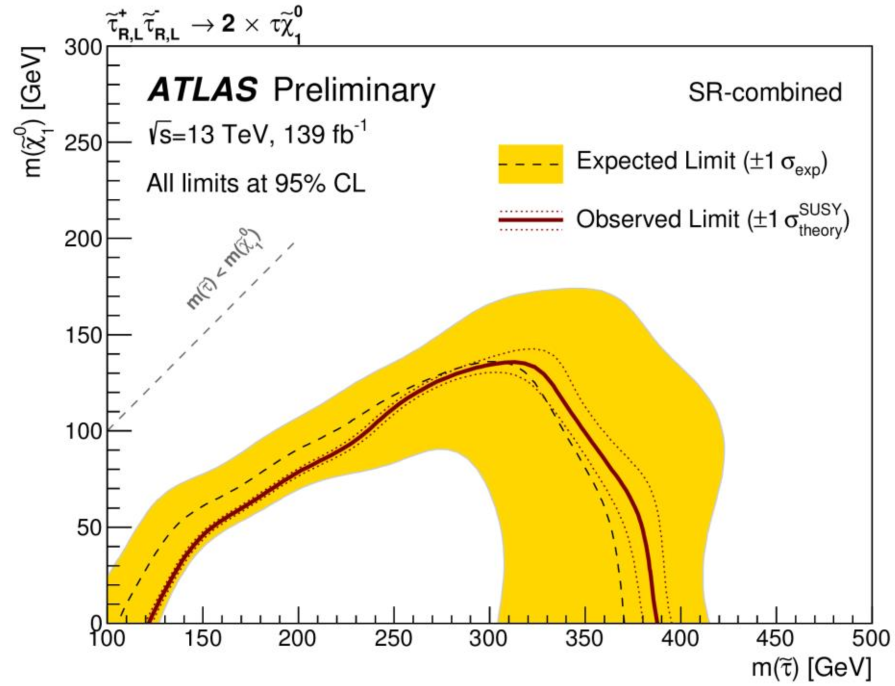
Stau

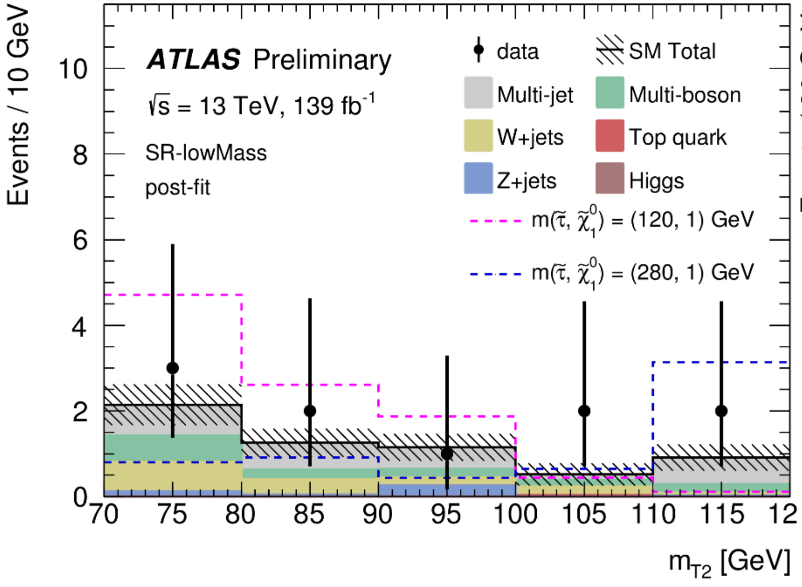
ATLAS 139/fb ATLAS-CONF-2019-018

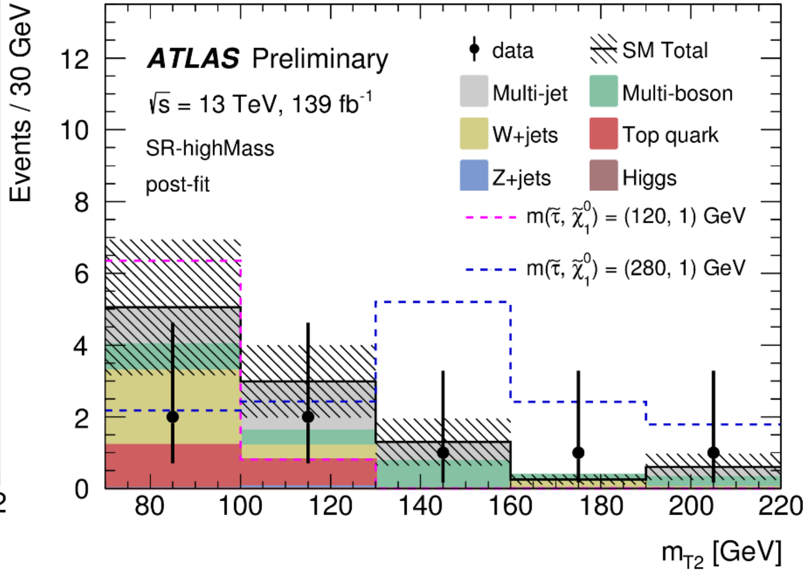
CMS 77/fb SUS-18-006

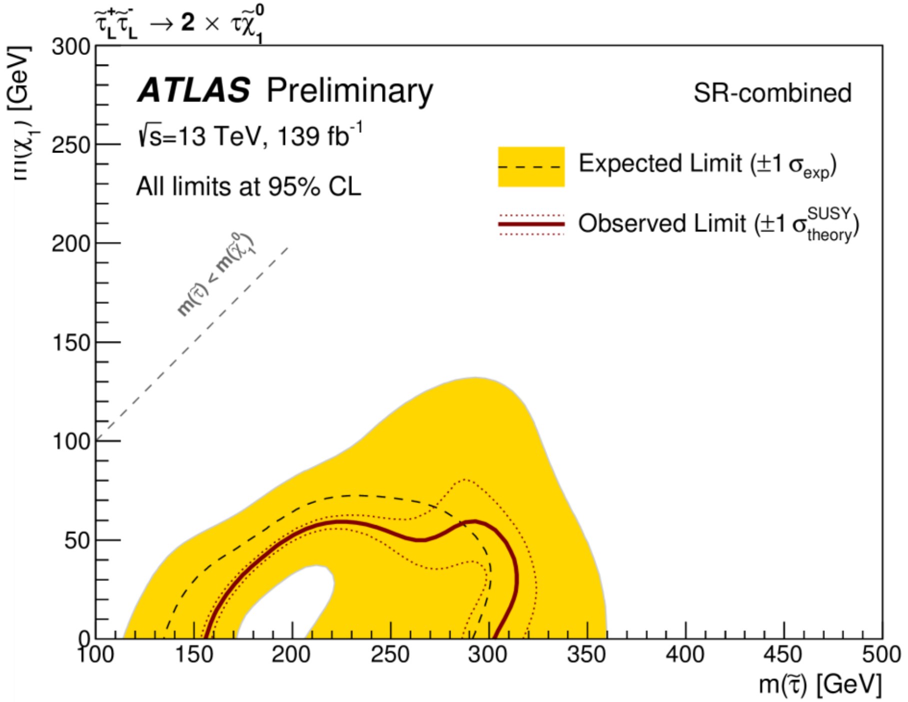
- LHC first results since LEP!!!
- Decay to di-tau and 2 LSPs
  - Large MET
  - Veto b-jets (ttbar)
  - Veto Z and H decays to taus
- Limits up to 390 GeV for mass-degenerate staus
- Limits up to 300 GeV for only “LH” staus
- No observed limits yet for “RH” staus









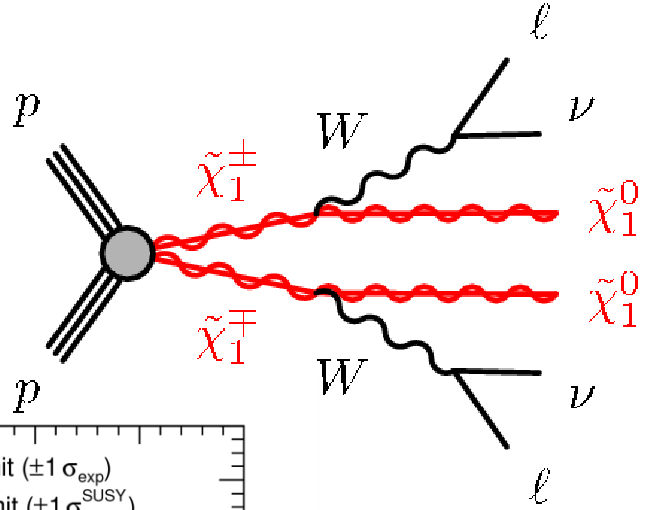


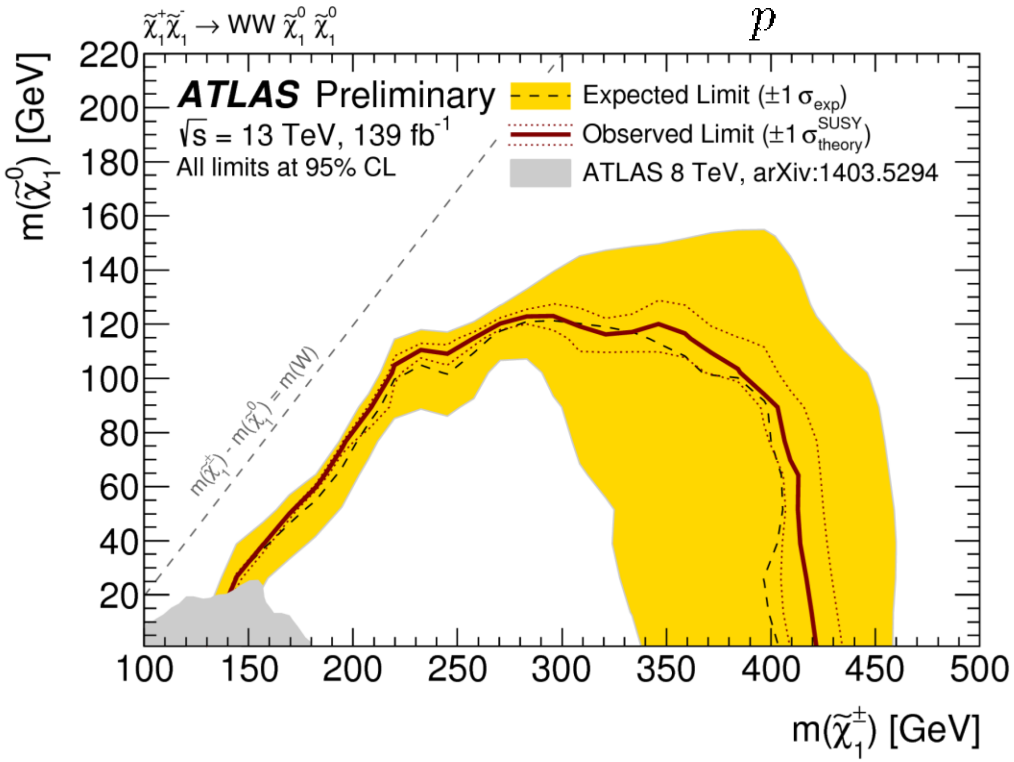
Chargino Pair Production

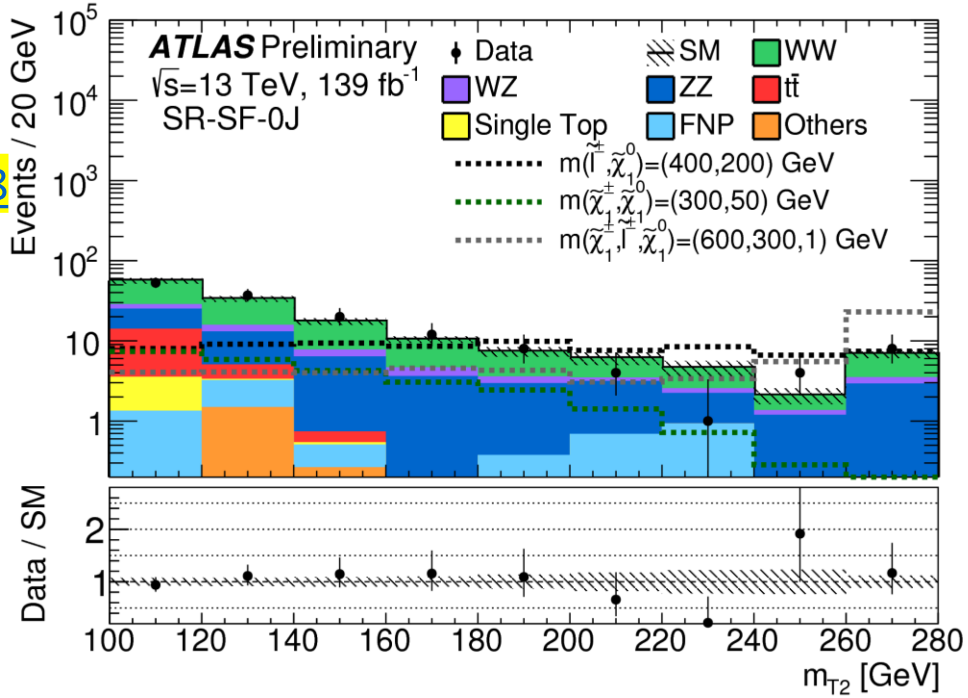
ATLAS 139/fb ATLAS-CONF-2019-008

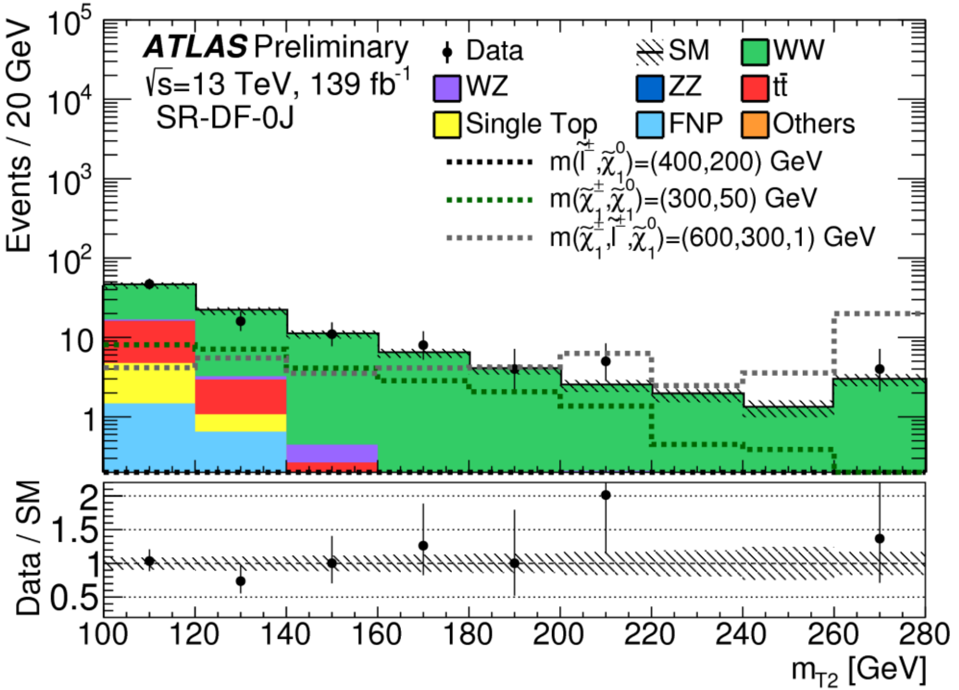
CMS 36/fb JHEP 11 (2018) 079

- Decay to WW and 2 LSPs
  - 2 leptons and MET
  - SF=Same flavor leptons
  - DF=Different flavor leptons
  - 0 Jets or 1+ Jets
- Limits set out to 400 GeV







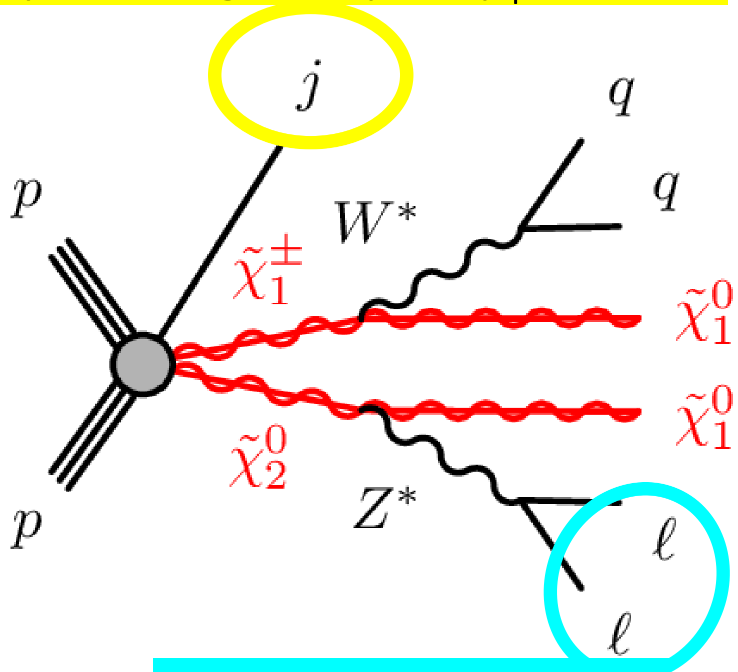


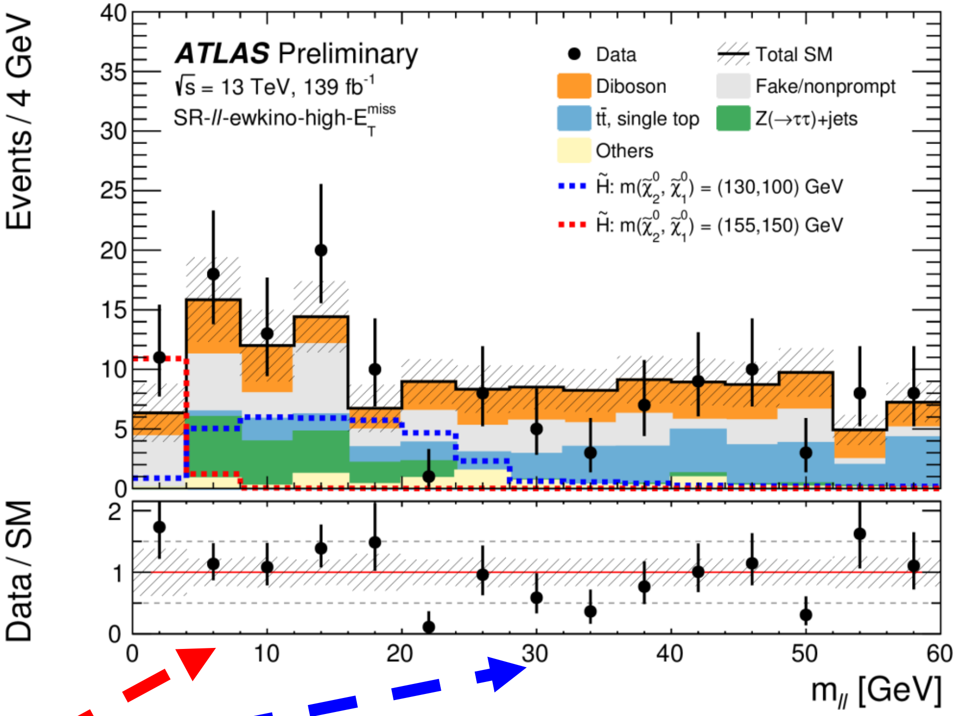
Chargino-Neutralino Production

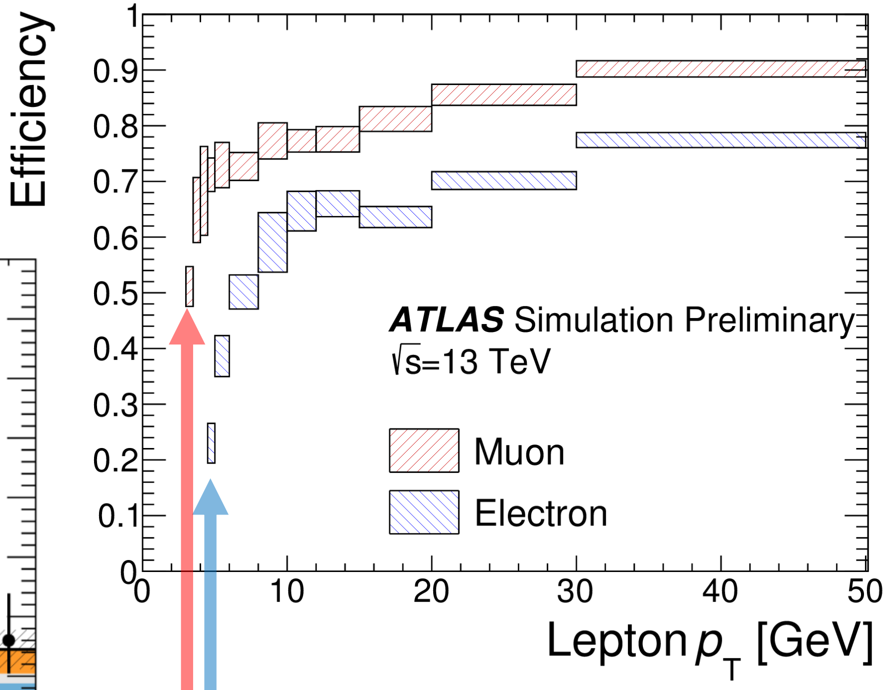
ATLAS 139/fb ATLAS-CONF-2019-014
CMS 36/fb Phys. Lett. B 782 (2018) 440
CMS 36/fb JHEP 03 (2018) 160

- Compressed region: small mass differences between $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0, \tilde{\chi}_1^0$
- W and Z bosons off-shell, giving low p_T leptons
- Improved low p_T lepton reconstruction, added low p_T tracks

High p_T ISR jet helps! Boosts C1N2 system, higher lepton p_T and MET







Electron $p_T > 4.5$ GeV
Muon $p_T > 3$ GeV
Charged particle track $p_T > 1$ GeV

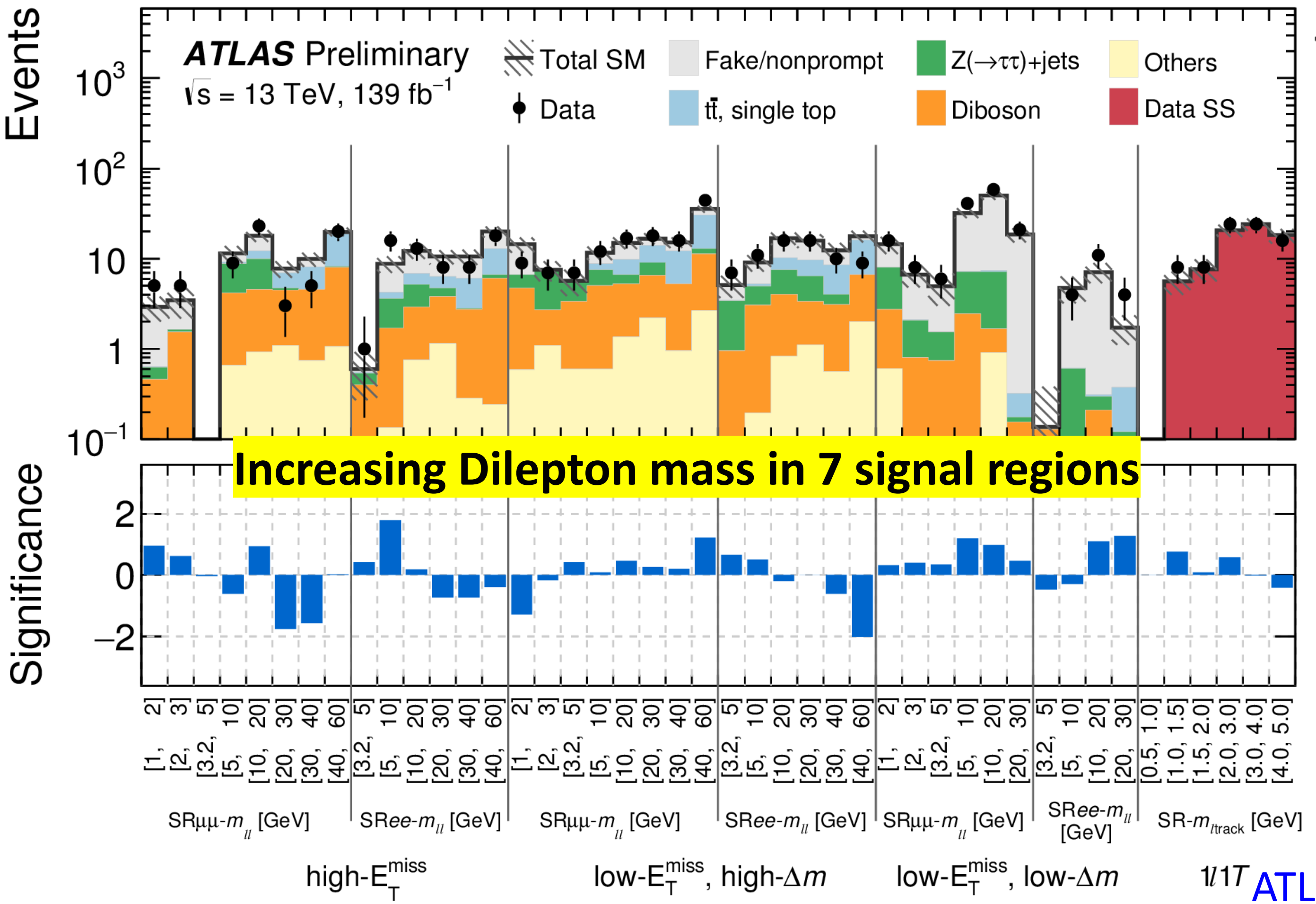
Dilepton mass endpoint at mass difference between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$

Chargino-Neutralino Production

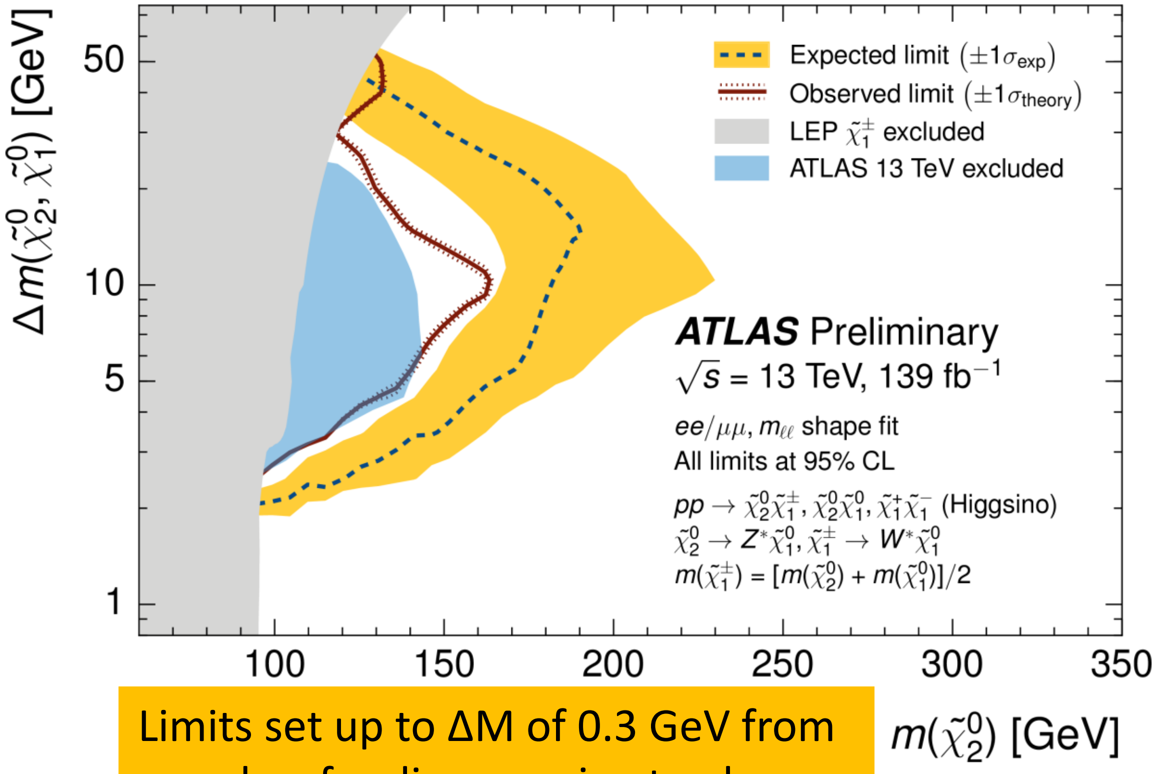
ATLAS 139/fb ATLAS-CONF-2019-014
CMS 36/fb Phys. Lett. B 782 (2018) 440
CMS 36/fb JHEP 03 (2018) 160

Limits set down to ΔM of 2.6 GeV for Higgsinos

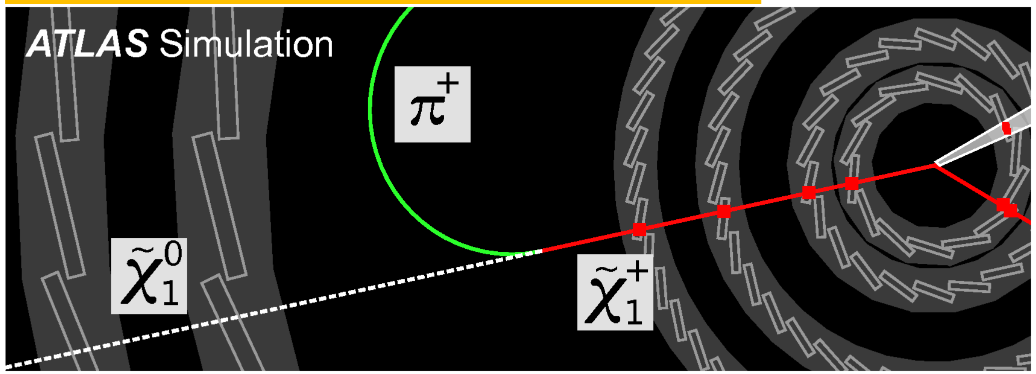
Exploring very interesting region for natural SUSY,
100 GeV Higgsinos could be hiding with ΔM[0.3,2.6] GeV



Increasing Dilepton mass in 7 signal regions



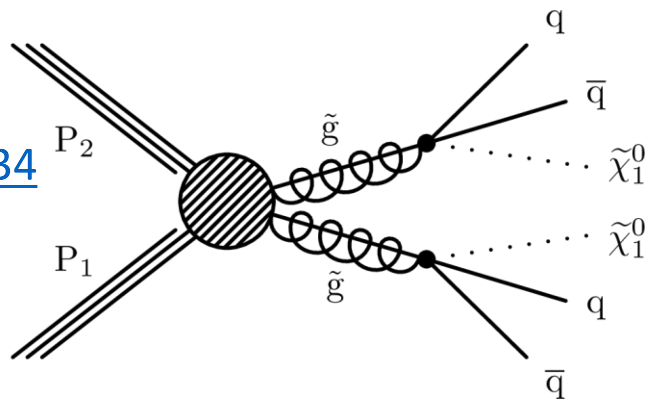
Limits set up to ΔM of 0.3 GeV from searches for disappearing tracks



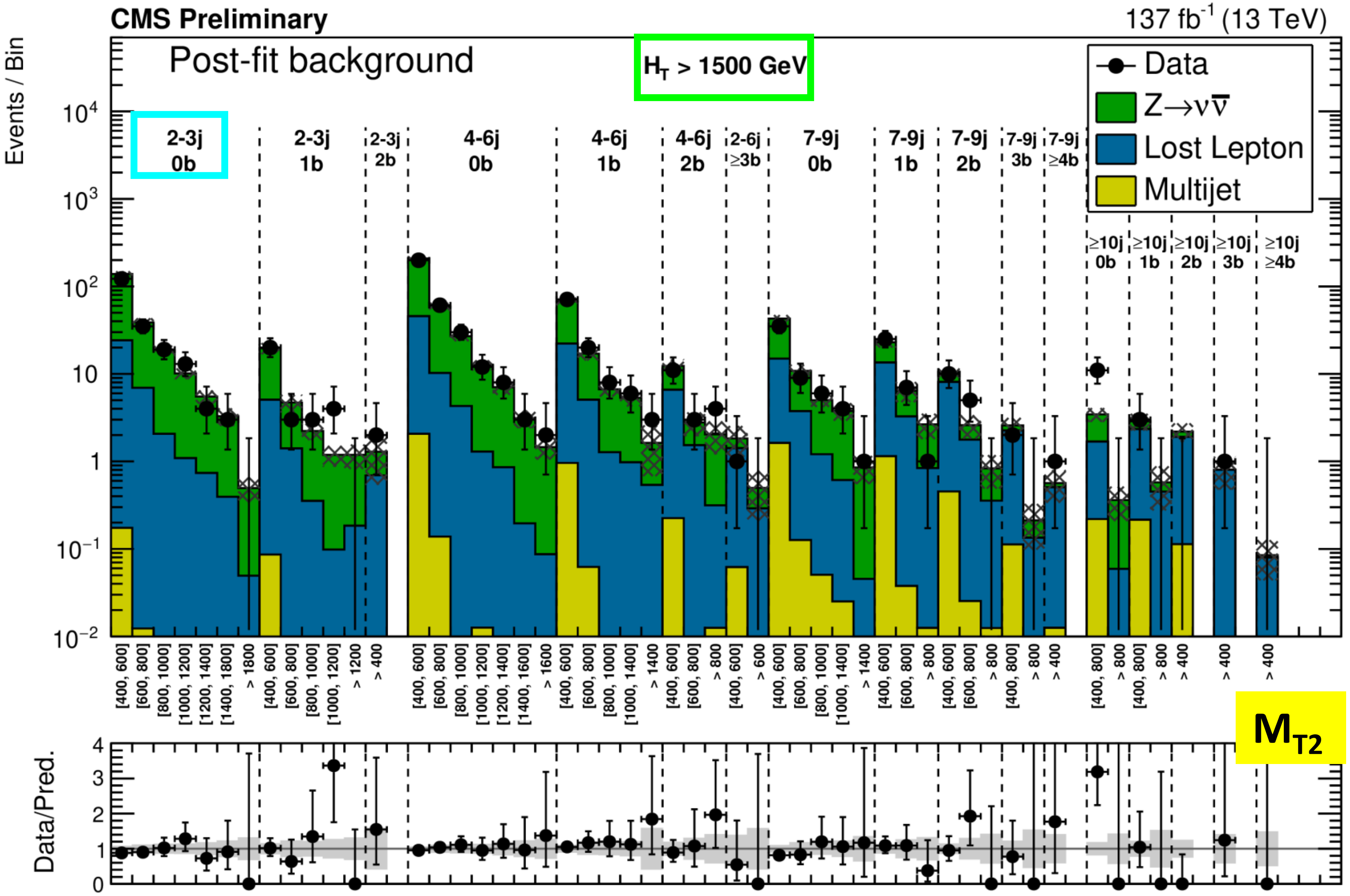
ATLAS 36/fb JHEP 06 (2018) 022 & ATLAS-PHYS-PUB-2017-019

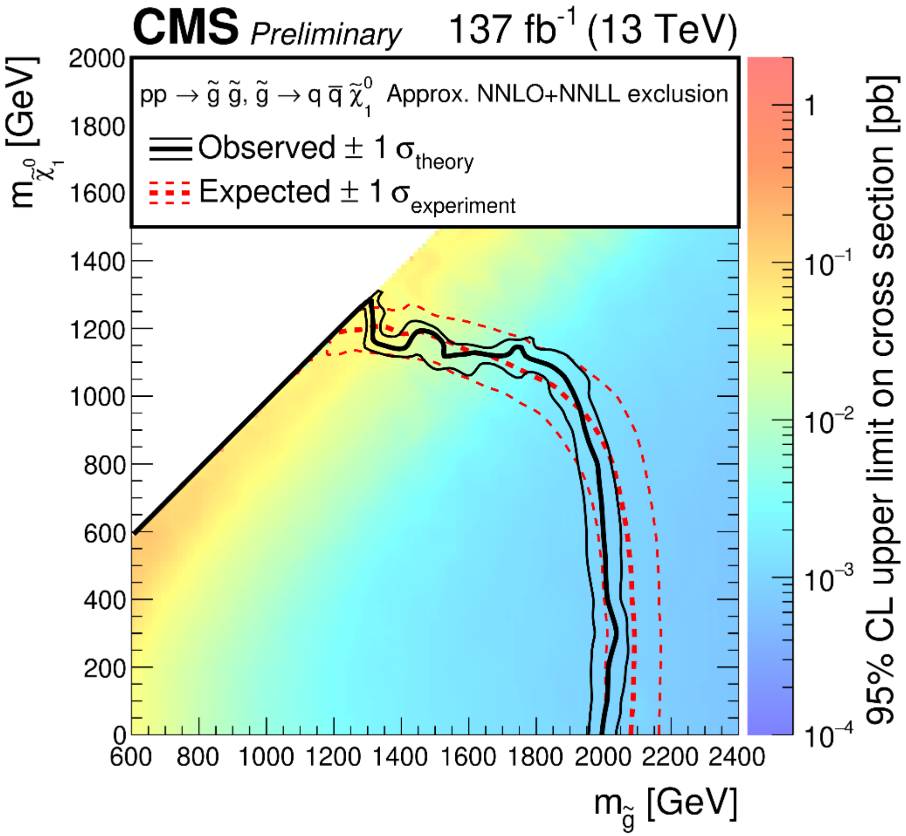
Inclusive searches: M_{T2}

CMS 137/fb SUS-19-005
ATLAS 36/fb JHEP 12 (2017) 034



- Strong pair production of gluinos or squarks
- M_{T2} search in regions of scalar sum of jet p_T (H_T) & by number of jets & b-jets
- Limits on gluino mass about 2 TeV @ 95% CL for decays to pairs of quarks + 2 LSPs



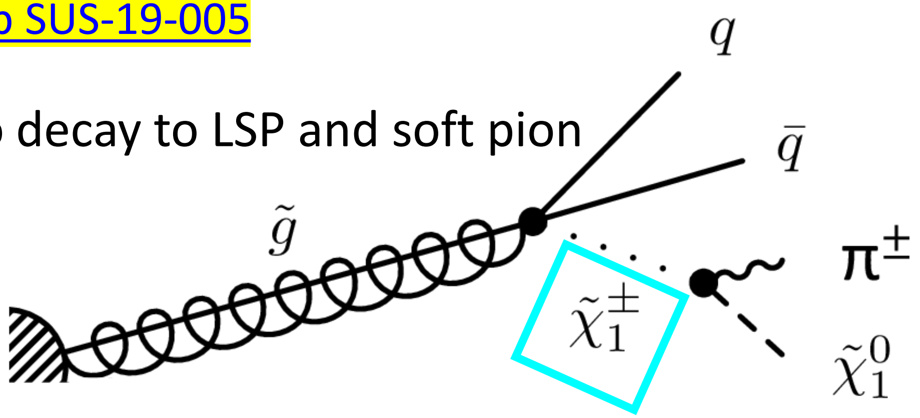


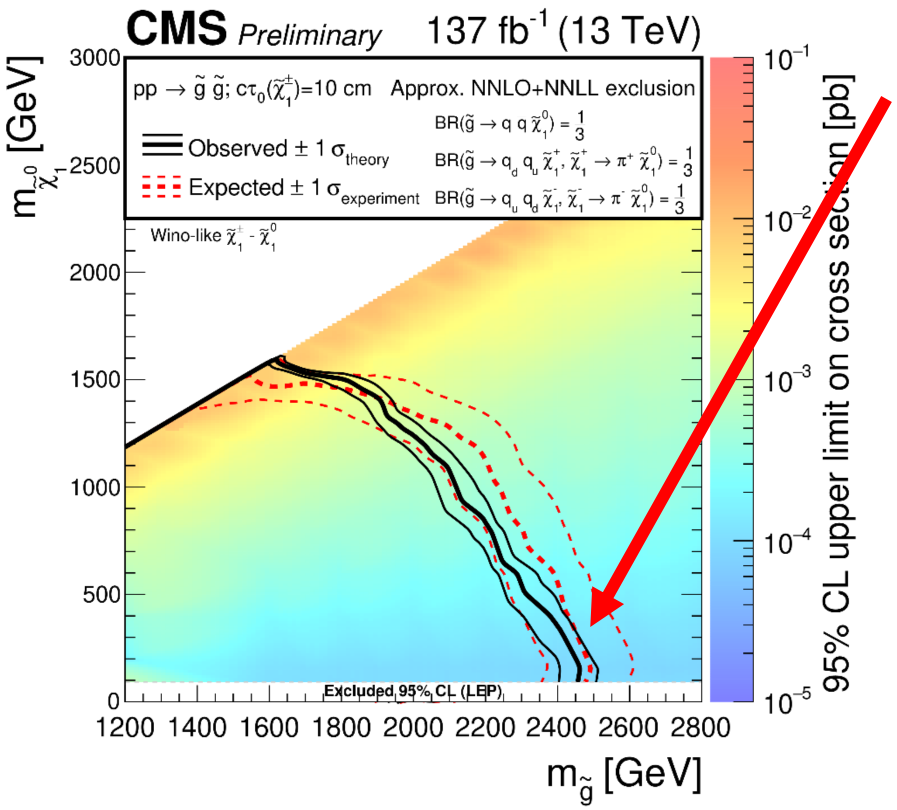
$$M_{T2} = \min_{MET(X1)+MET(X2)=MET} [\max(M_T^{(1)}, M_T^{(2)})]$$

Inclusive searches:M_{T2} with disappearing tracks

CMS 137/fb SUS-19-005

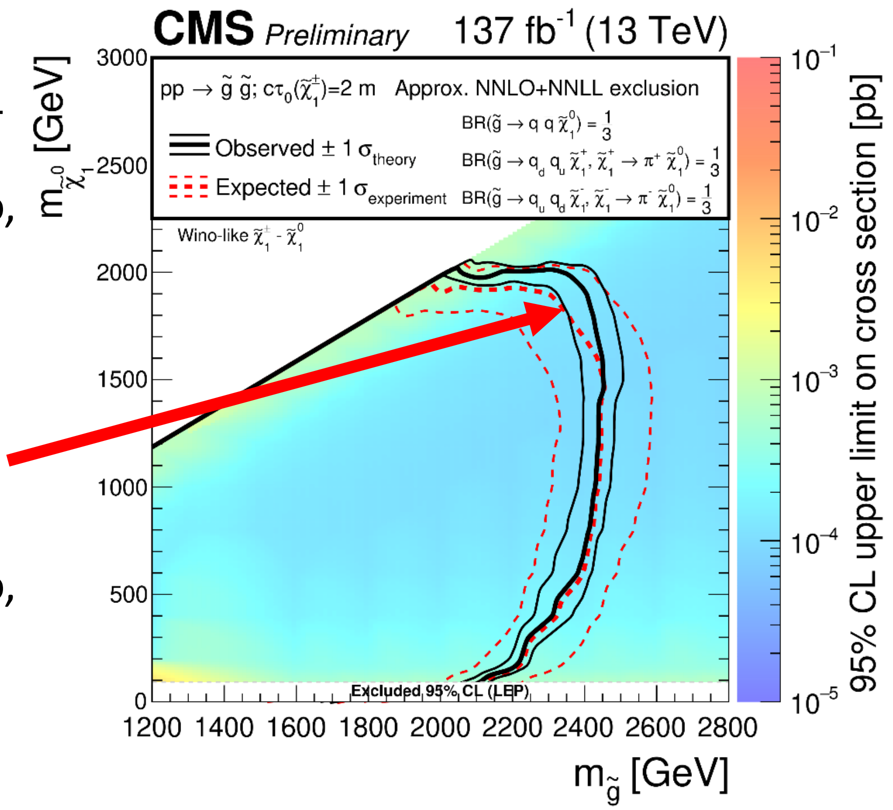
- Strong pair production of gluinos or squarks
- Compressed: chargino and LSP almost mass degenerate, chargino decay to LSP and soft pion
- Look for disappearing track from chargino
  - Several categories optimized for various track lengths
  - Up to 700 GeV improvement over inclusive search alone!





<u>Shorter-lived chargino with cτ=10 cm</u>
Strongest limits when large mass splitting between gluino and chargino, since large boost increases chance of chargino decay in tracking volume

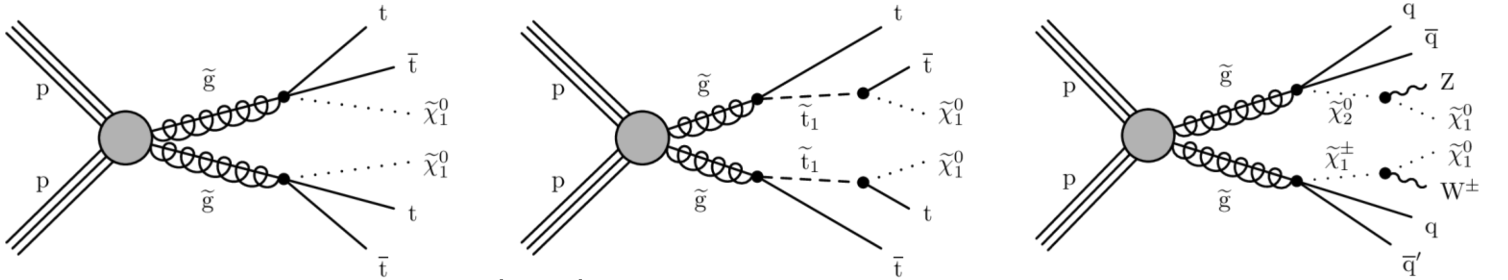
<u>Long-lived chargino with cτ=200 cm</u>
Strongest limits when small mass splitting between gluino and chargino, since small boost increases chance of chargino decay in tracking volume

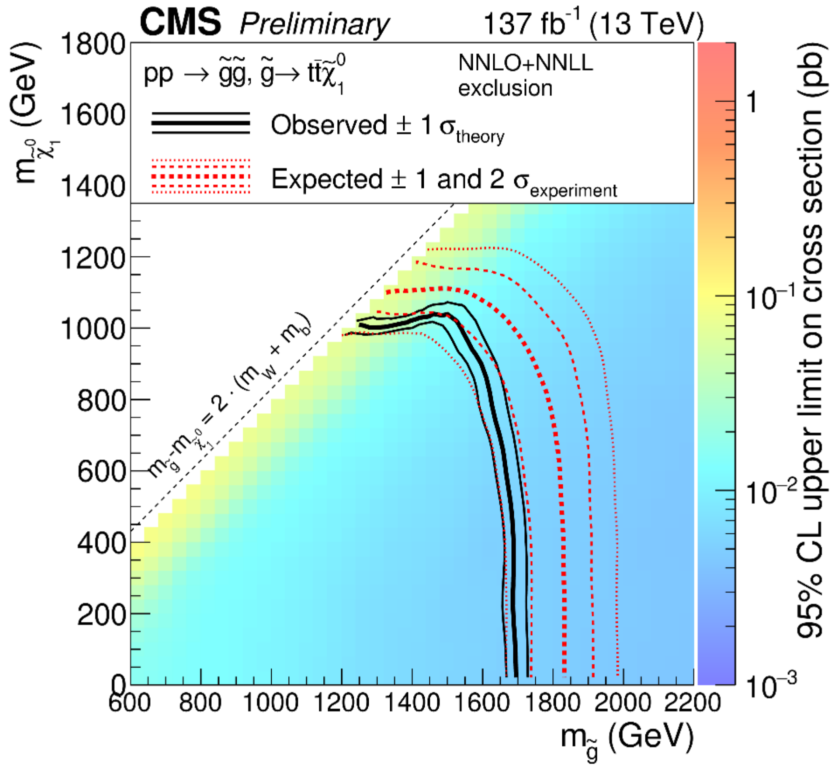


Inclusive searches with 2 or 3 leptons

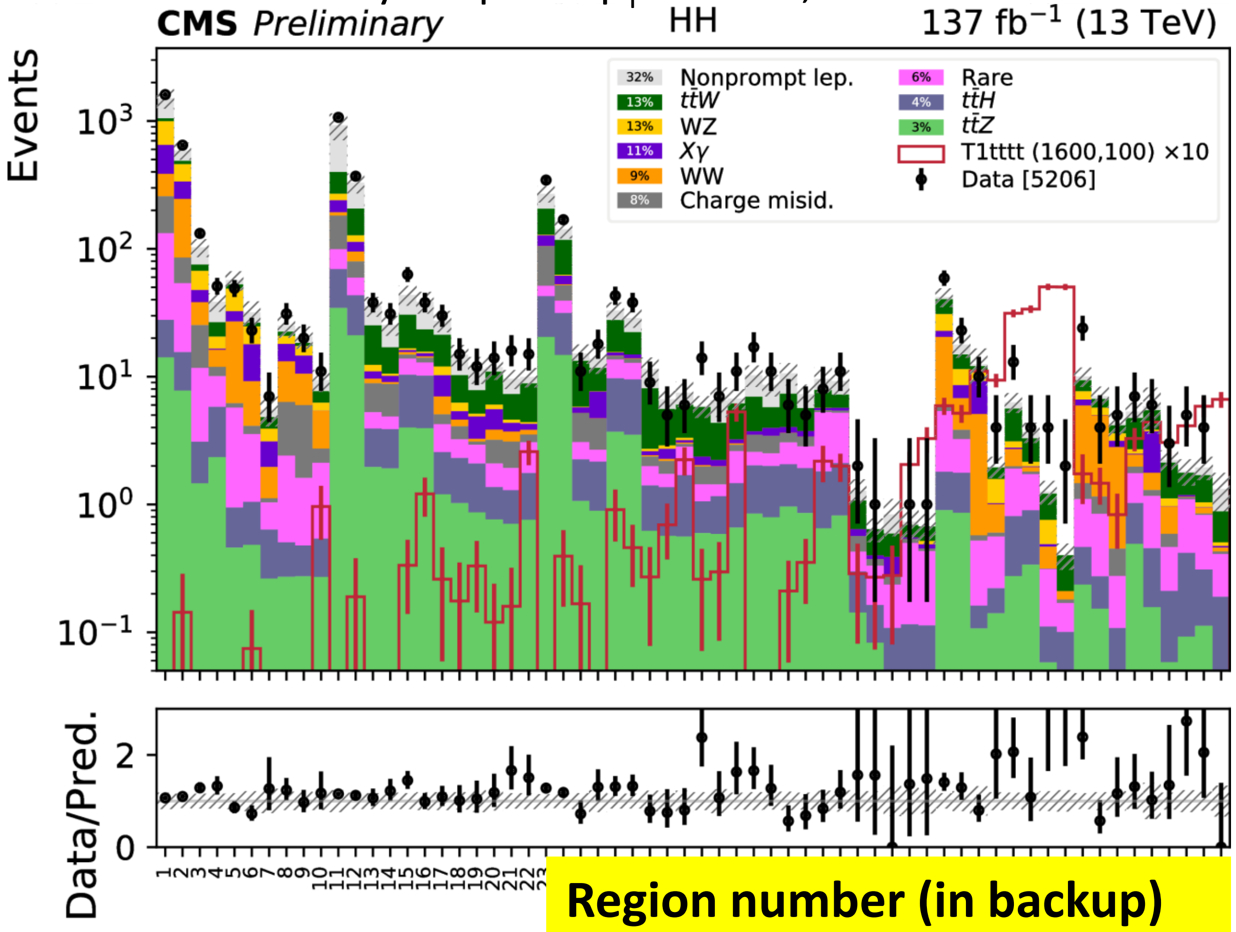
CMS 137/fb SUS-19-008
ATLAS 139/fb CONF-2019-015

- Strong pair production of gluinos or stops or sbottoms
- SM backgrounds very small for same-sign leptons and 3 leptons
- Interpret for several possible decays, including compressed and RPV





HH: exactly 2 leptons p_T>25 GeV, MET>50 GeV



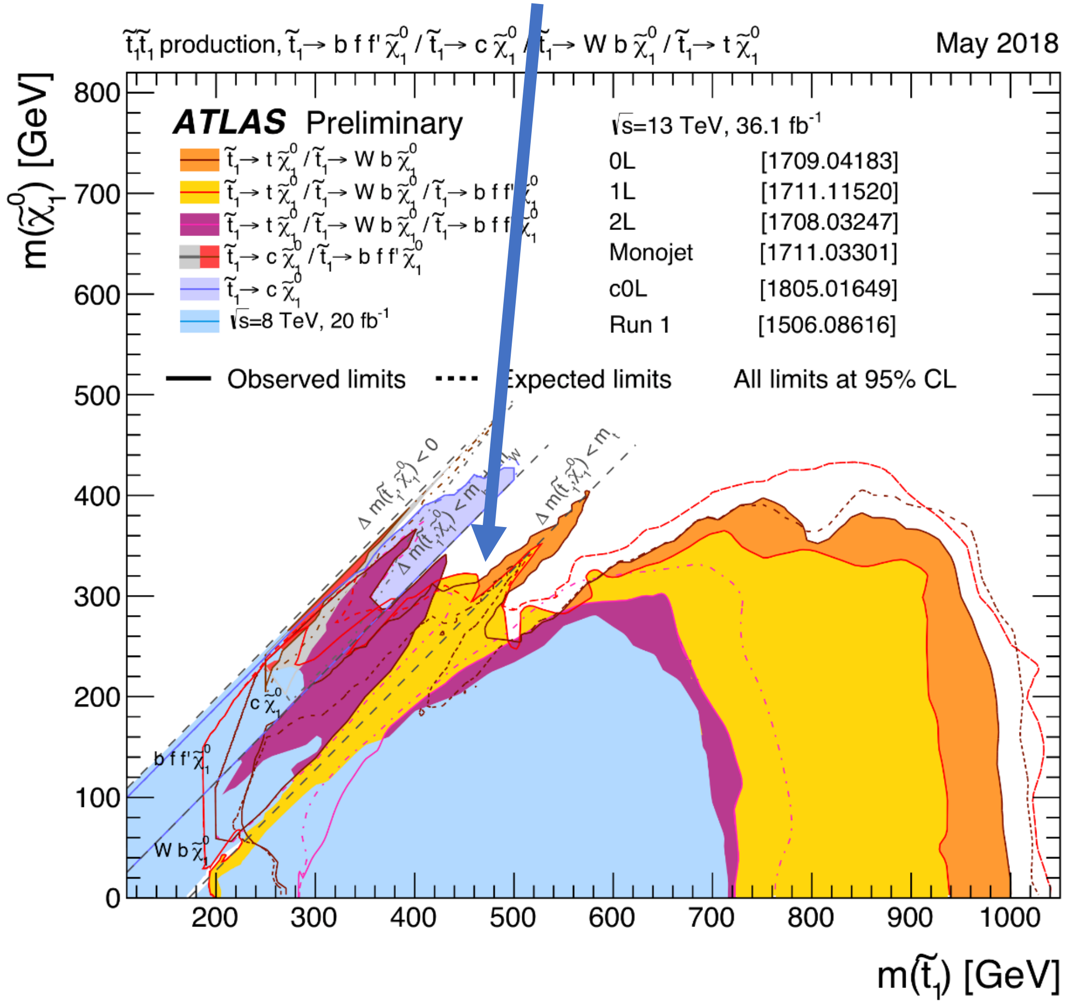
Region number (in backup)

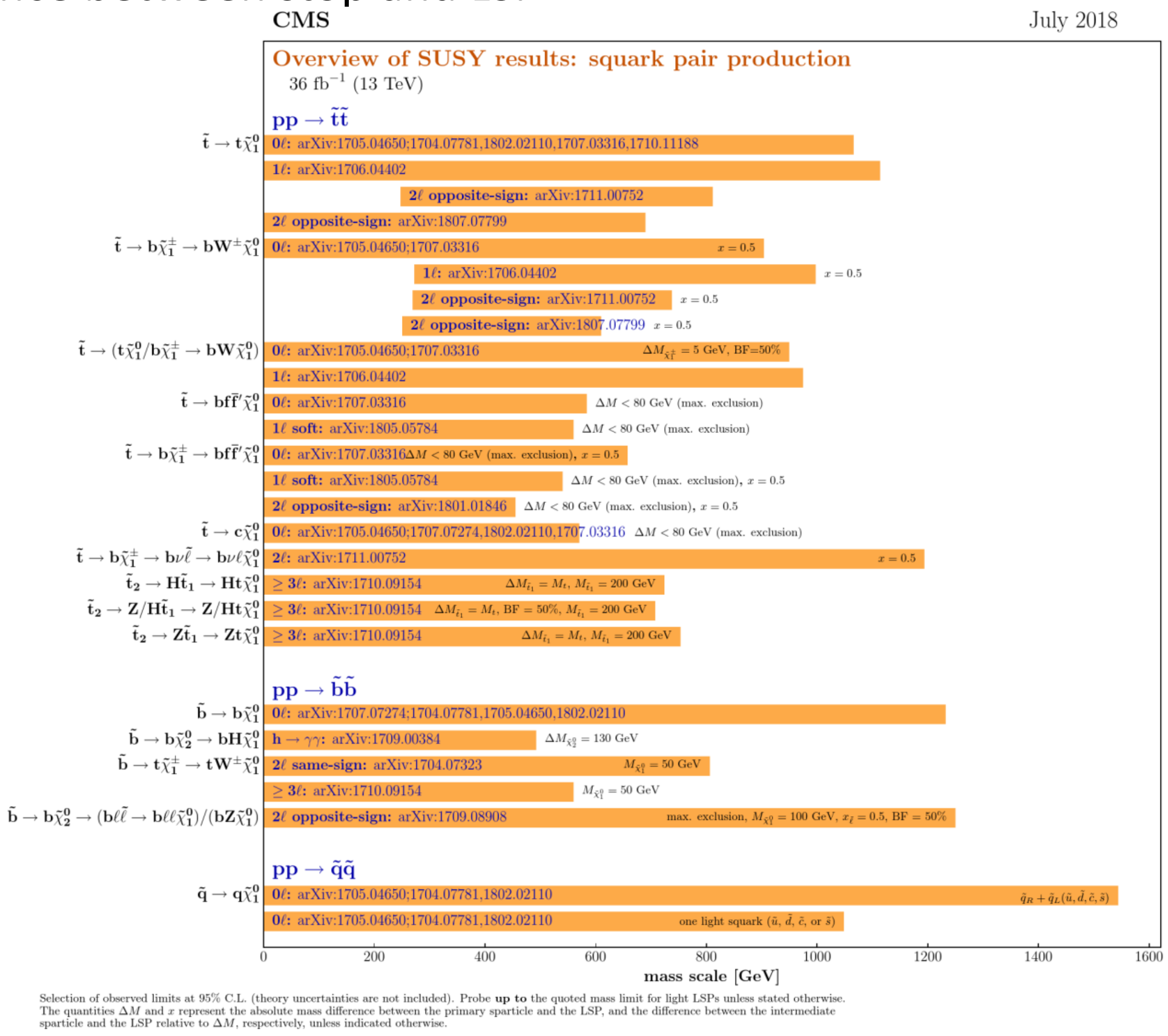
Stop Summary

[ATLAS Summary Plots SUSY](#)
[CMS Summary Plots SUSY](#)

Stop RPC

New result filling in gaps for <175 GeV mass difference between stop and LSP

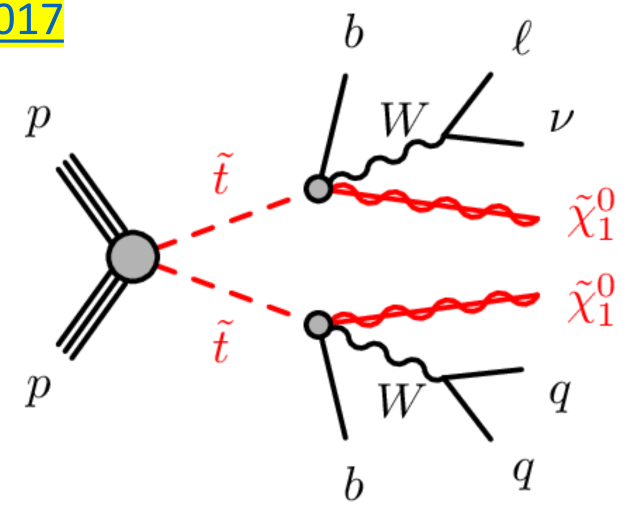


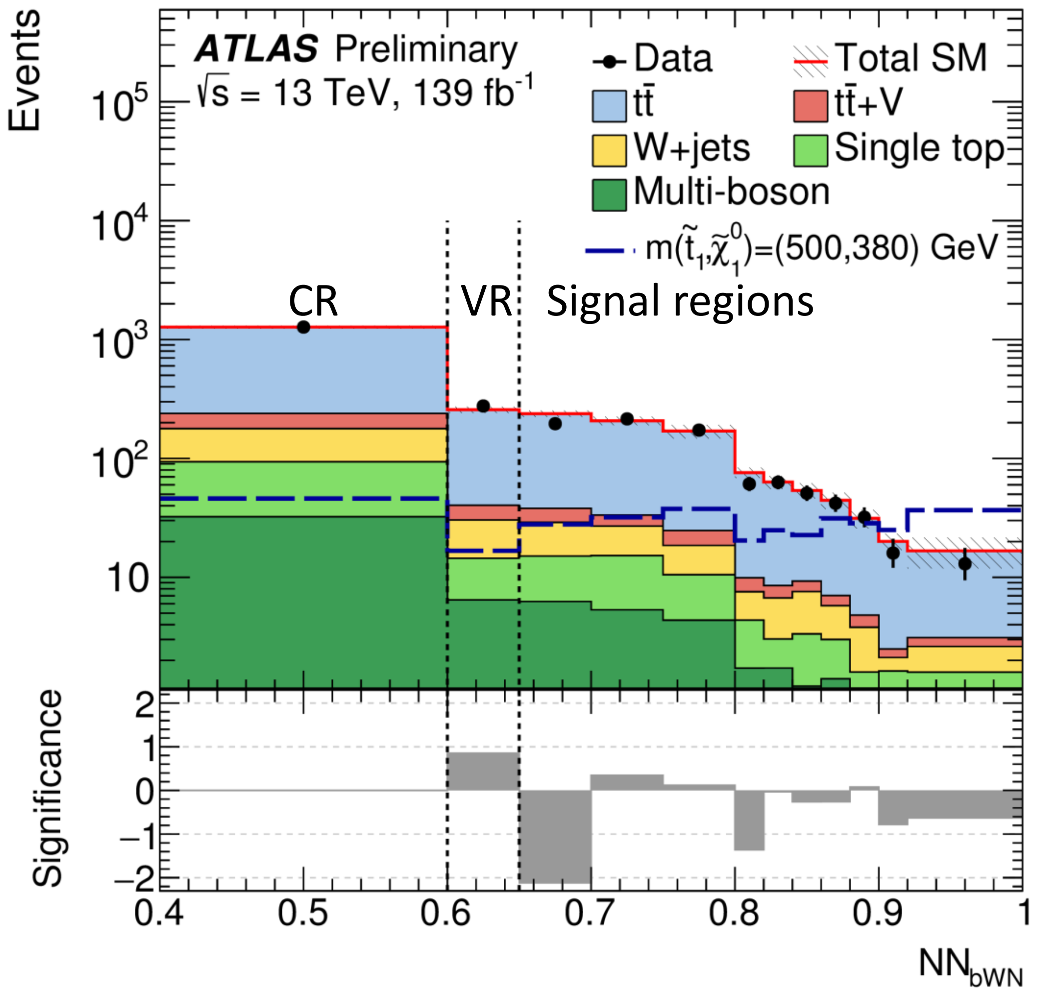


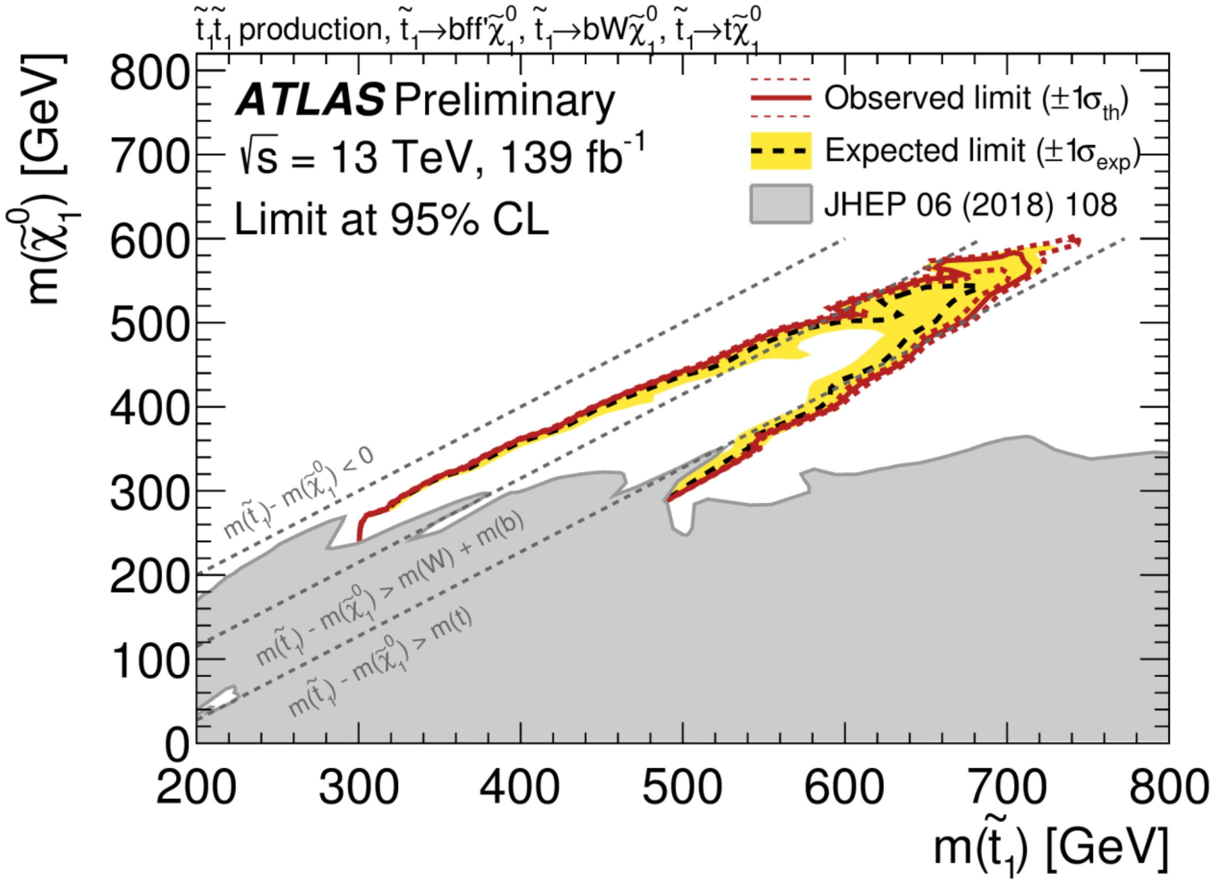
Stop 3-body decay

ATLAS 139/fb ATLAS-CONF-2019-017
CMS 36/fb JHEP 10 (2017) 019

- Challenging search with decay via off-shell top to b+W+LSP
- Machine learning with Artificial Neural Network





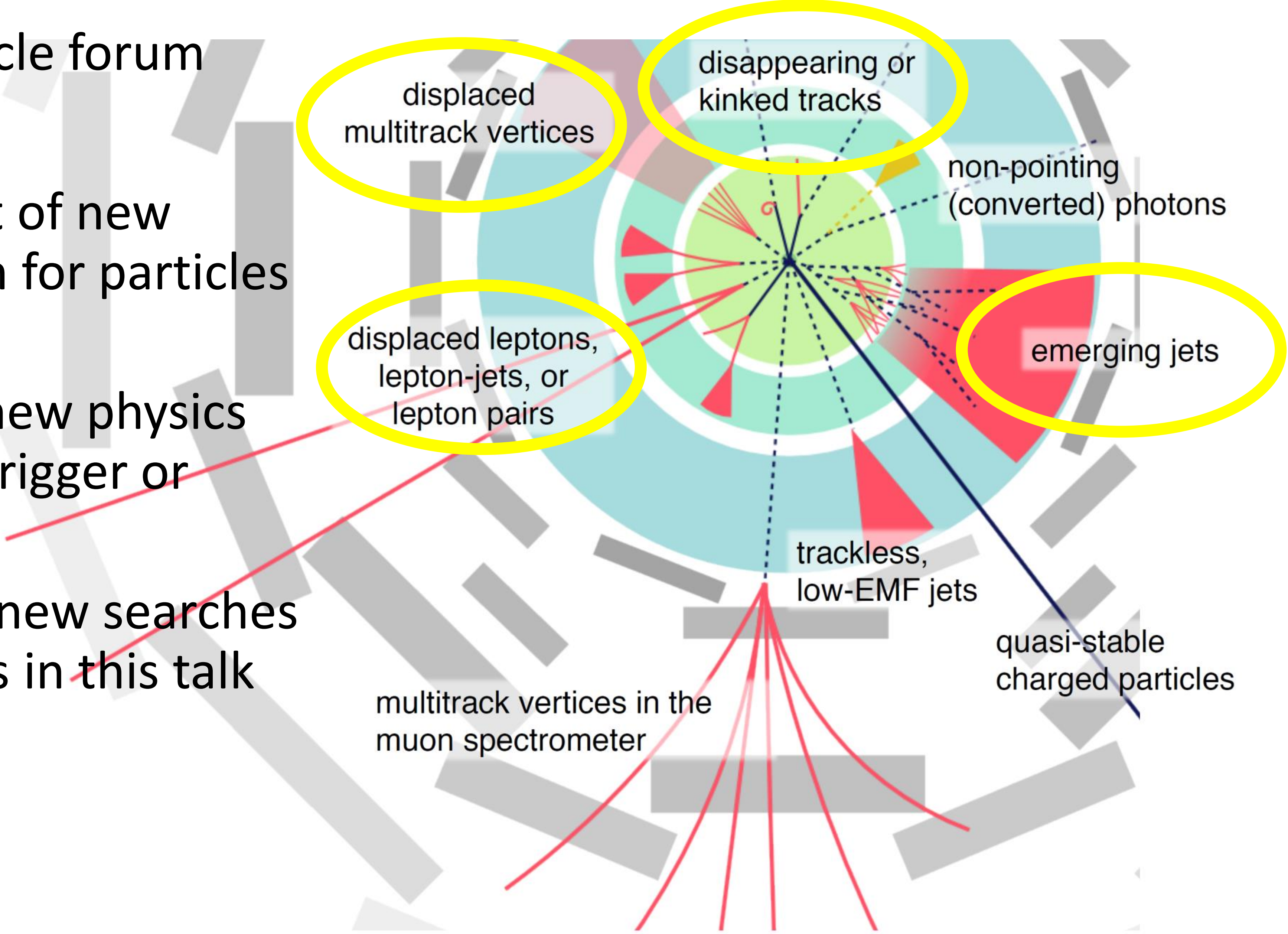


Long-lived particles & Unconventional signatures

- LHC Long-lived particle forum

arXiv:1903.04497

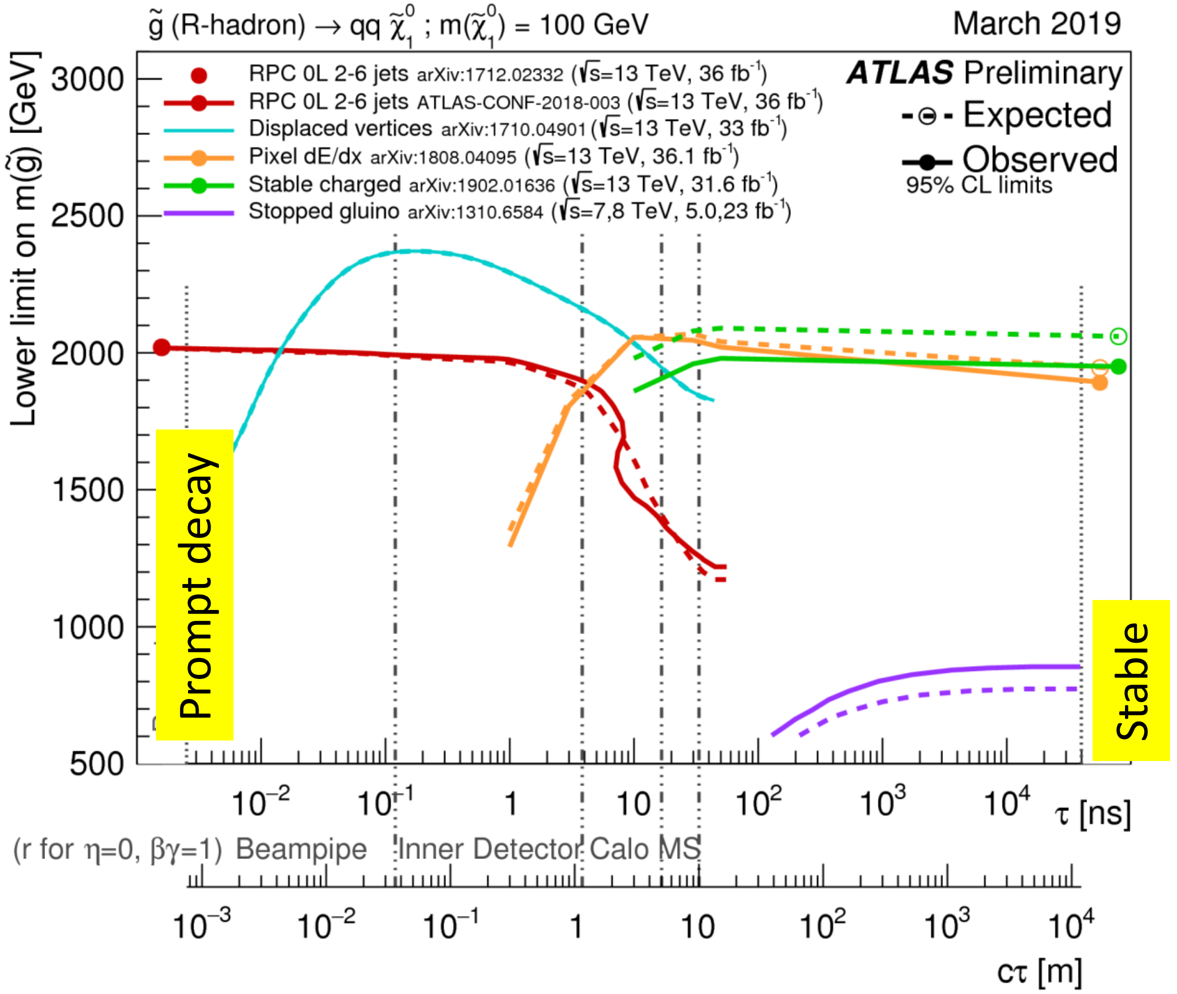
- Lots of development of new techniques to search for particles decaying in detector
- Don't want to miss new physics because of missing trigger or reconstruction…
- Highlighting several new searches with new techniques in this talk

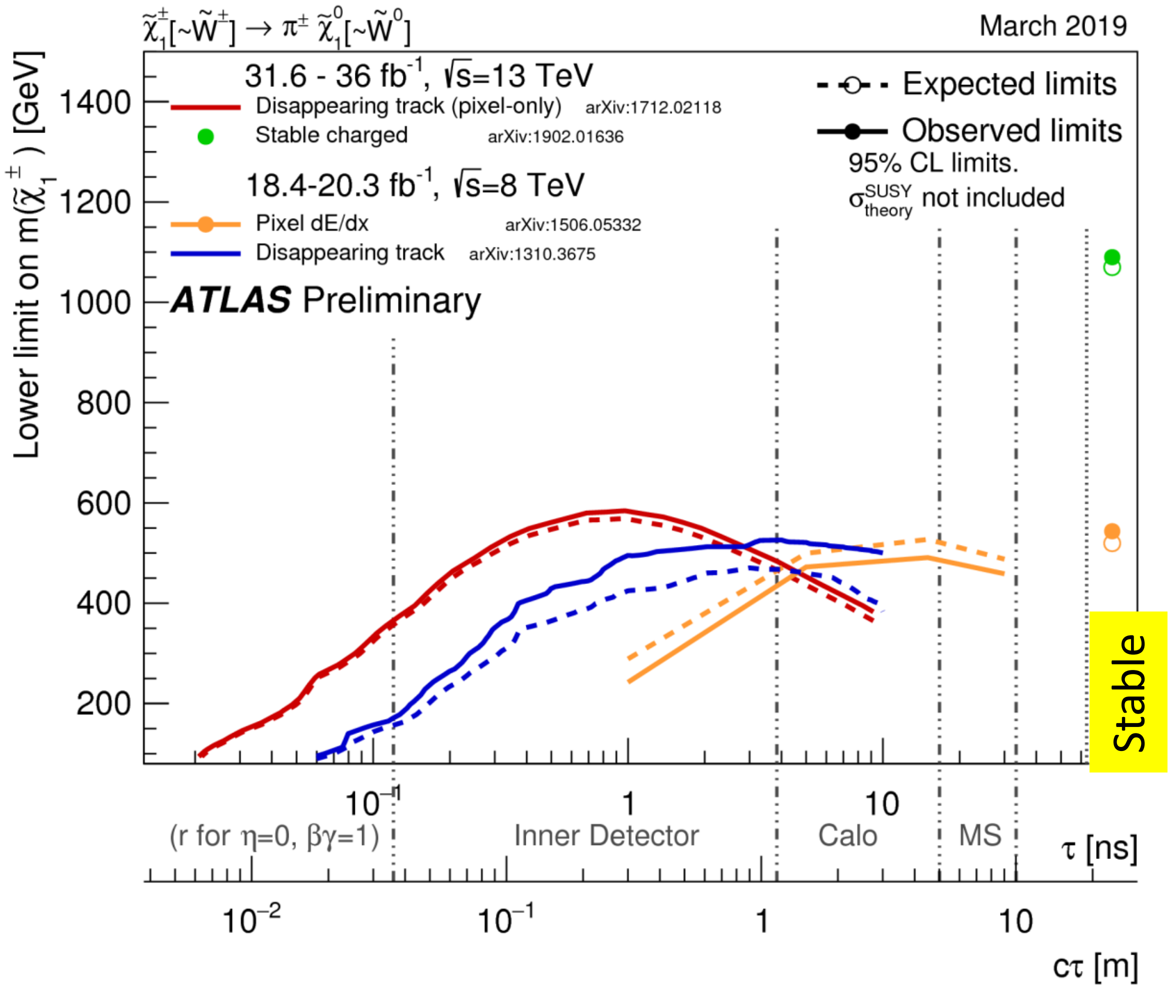


Long-lived particles: closing the gaps

[ATLAS Summary Plots SUSY]
[CMS Summary Plots SUSY]

- Gluino (R-hadron)
- Chargino (wino-type)

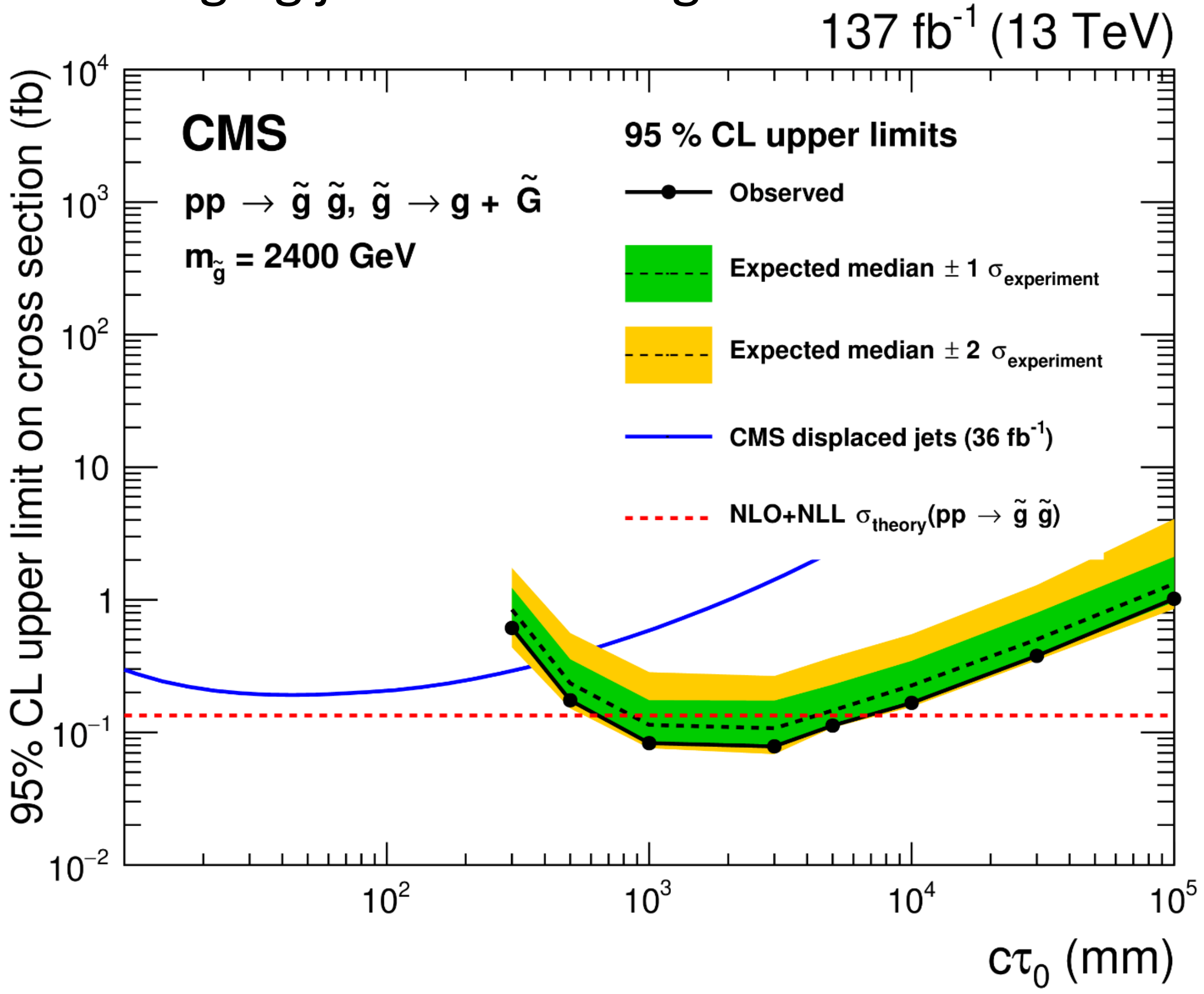


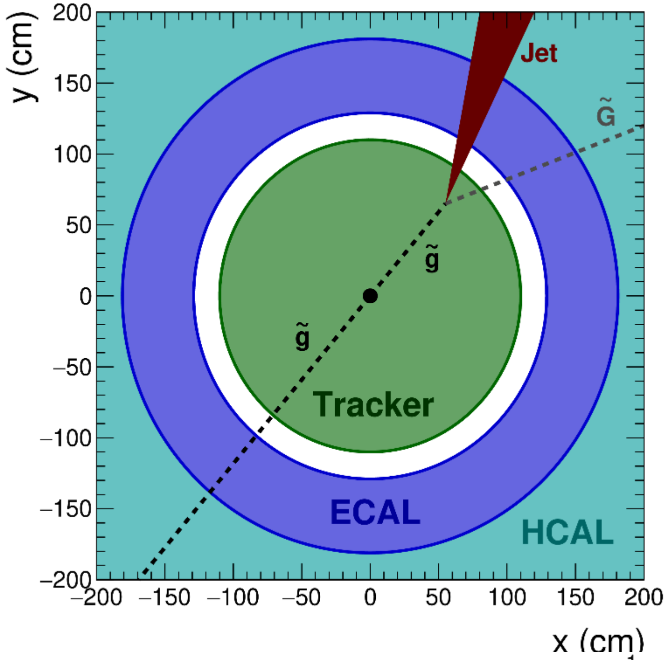


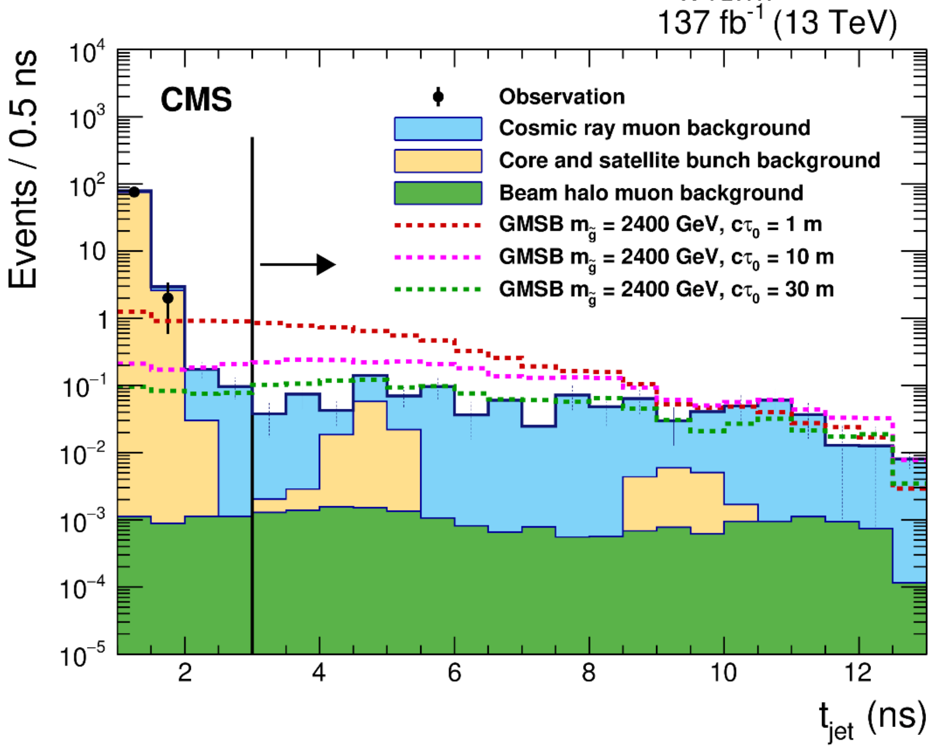
Long-lived gluino

CMS 137/fb EXO-19-001

- GMSB with gluino displaced decay to a jet & gravitino
- Emerging jets with timing in CMS EM Calorimeter







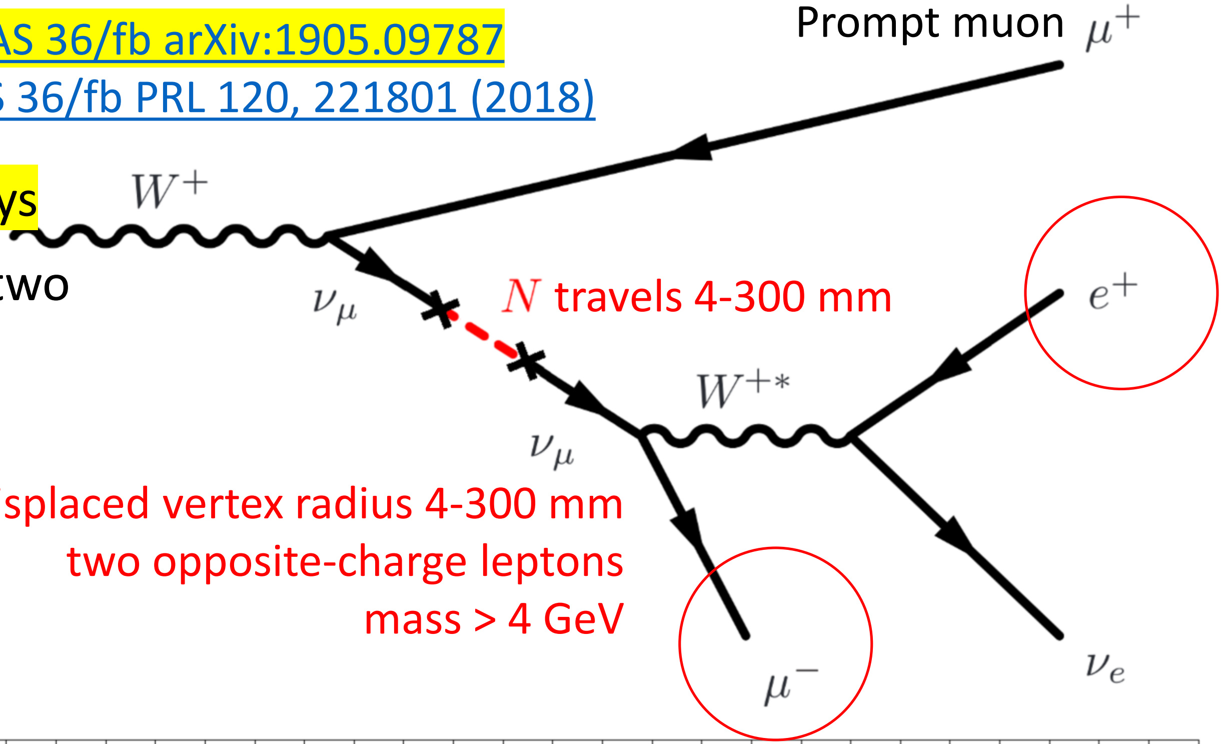
Heavy Neutral Lepton

ATLAS 36/fb arXiv:1905.09787
CMS 36/fb PRL 120, 221801 (2018)

Cover 4.5-50 GeV mass range using leptonic W boson decays

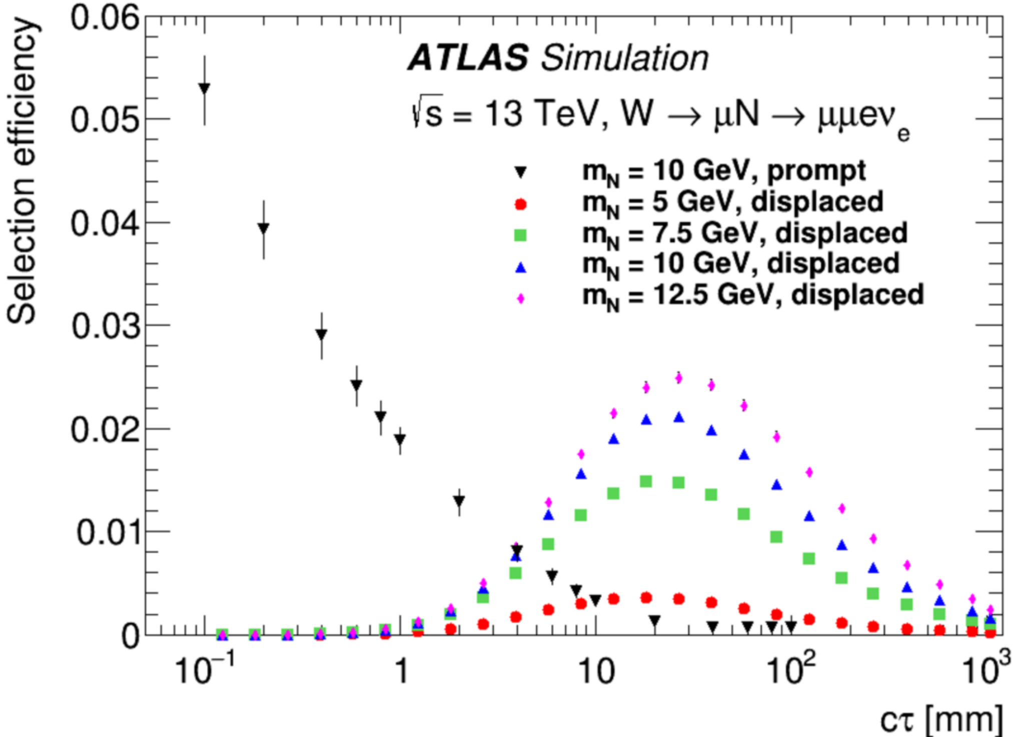
New LHC signature of prompt muon & displaced vertex of two leptons extends previous prompt searches to

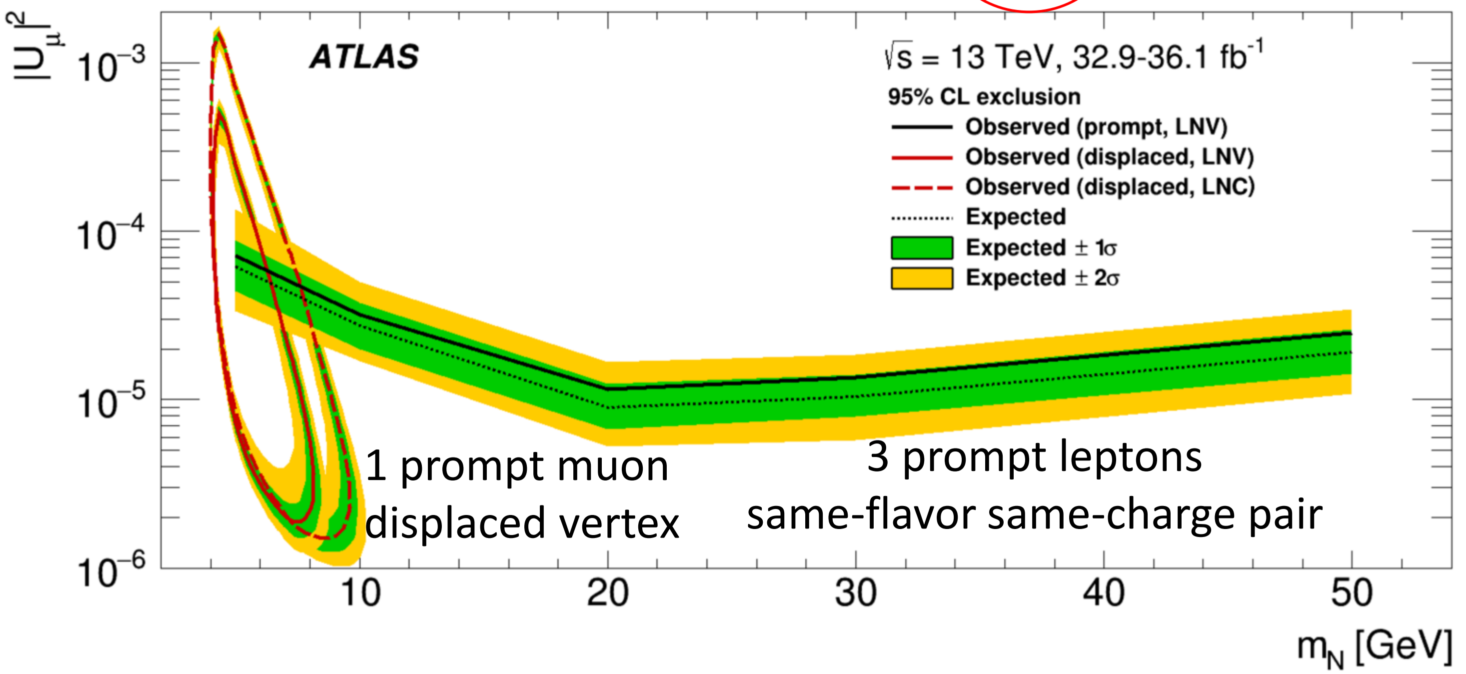
- lower masses (longer lifetimes)
- lower couplings
- lepton number conserving processes (LNC)



Displaced vertex radius 4-300 mm
two opposite-charge leptons
mass > 4 GeV

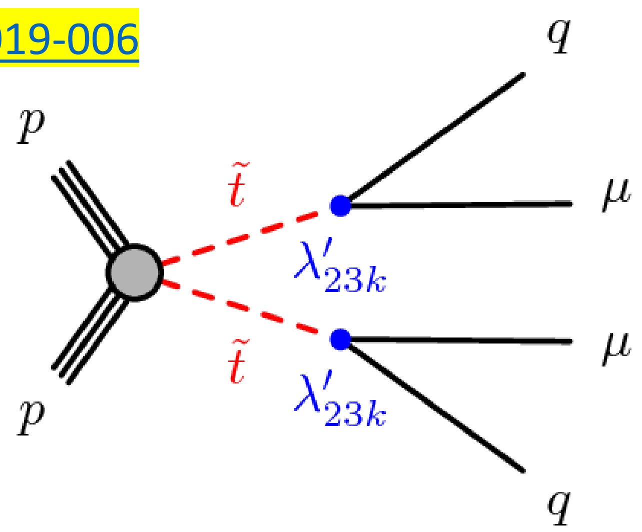
Large Radius Tracking on dimuon sample



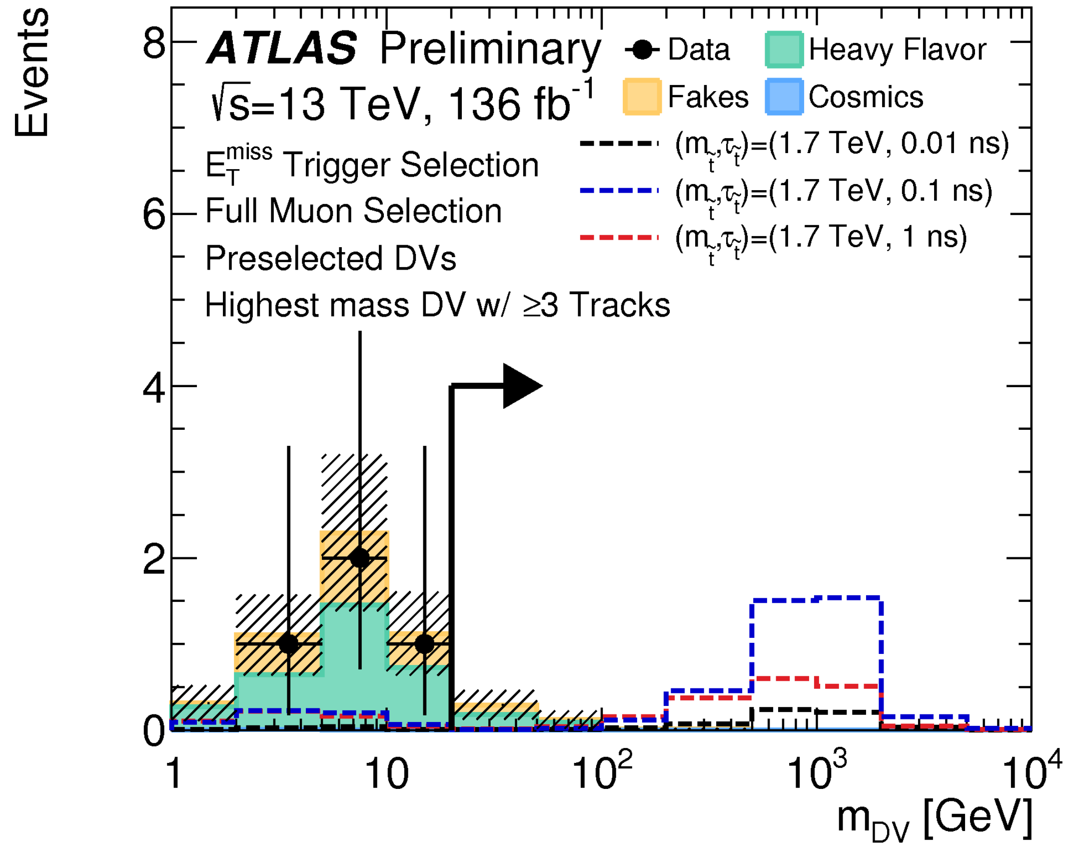


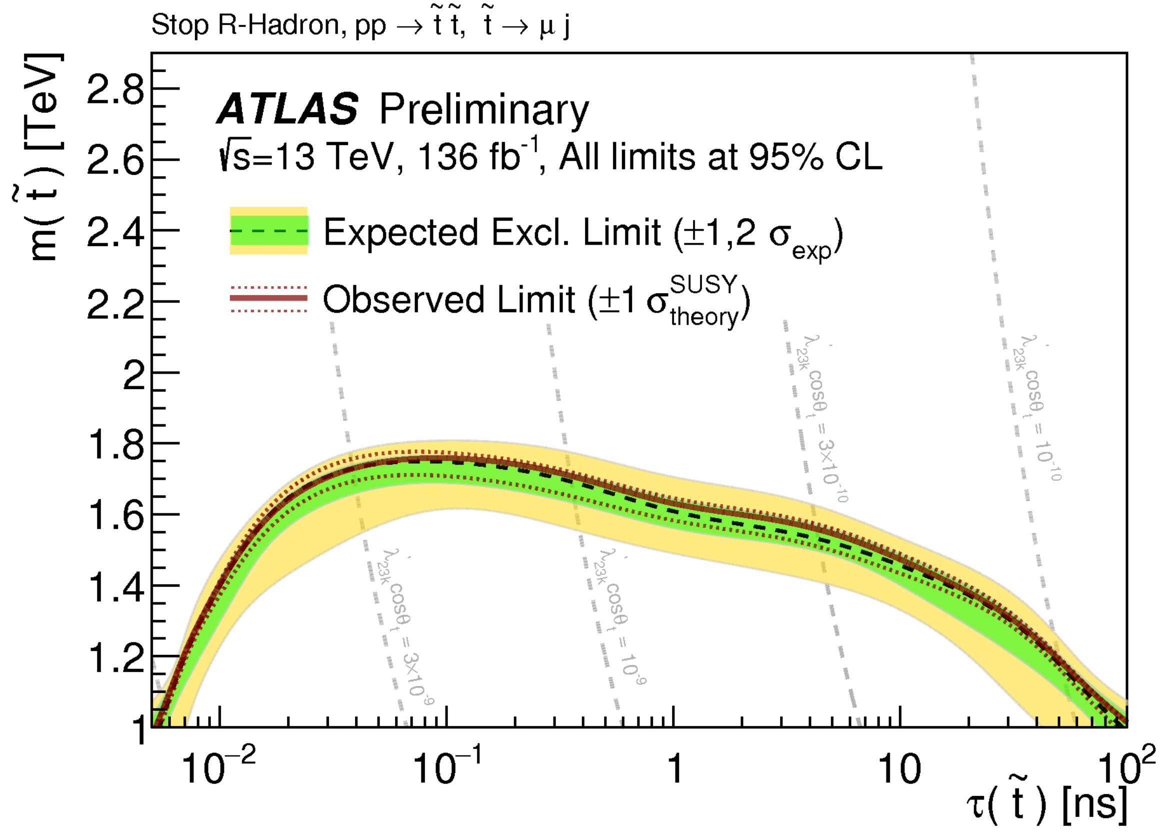
Long-lived stop

ATLAS 136/fb ATLAS-CONF-2019-006
CMS 3/fb PLB 780 (2018) 432



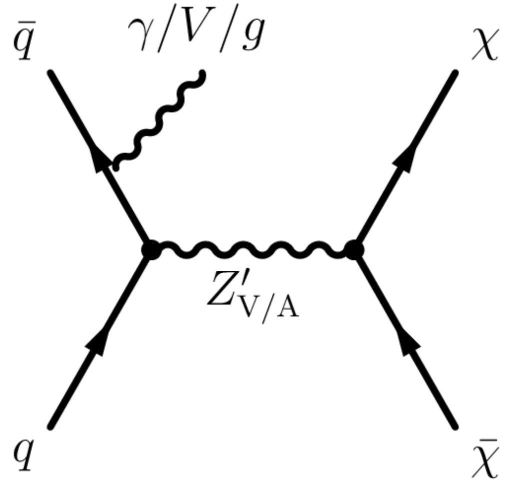
- RPV SUSY, long-lived stop decay
- Displaced vertex (≥3 tracks) and displaced muon
- Large Radius Tracking
- Exclude 1.3 TeV stop with life-time in range 0.01 – 30 ns





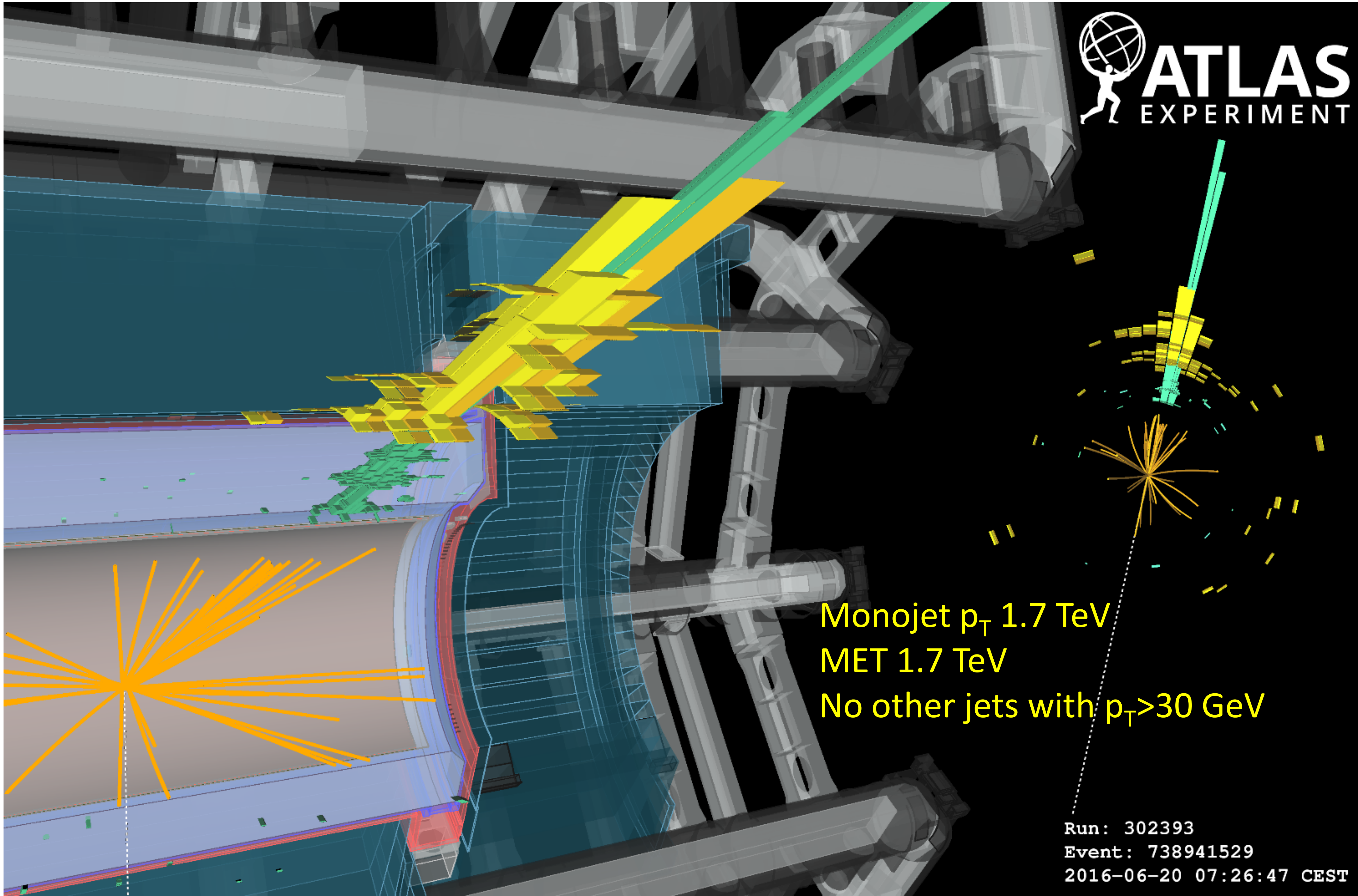
Where is dark matter?

Interpret searches for dark matter results in terms of a heavy mediator Z' model.



Classic mono-jet signature!

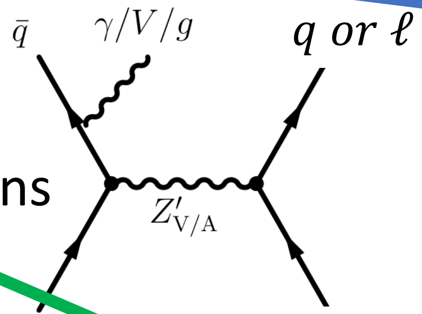
Dijet and dilepton resonances contribute if sizable Z' coupling to quarks or leptons

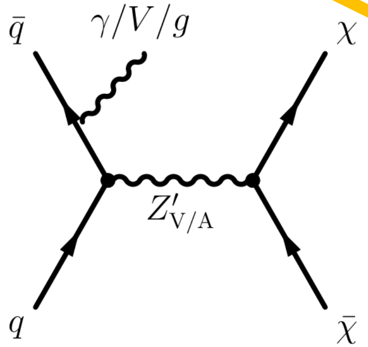


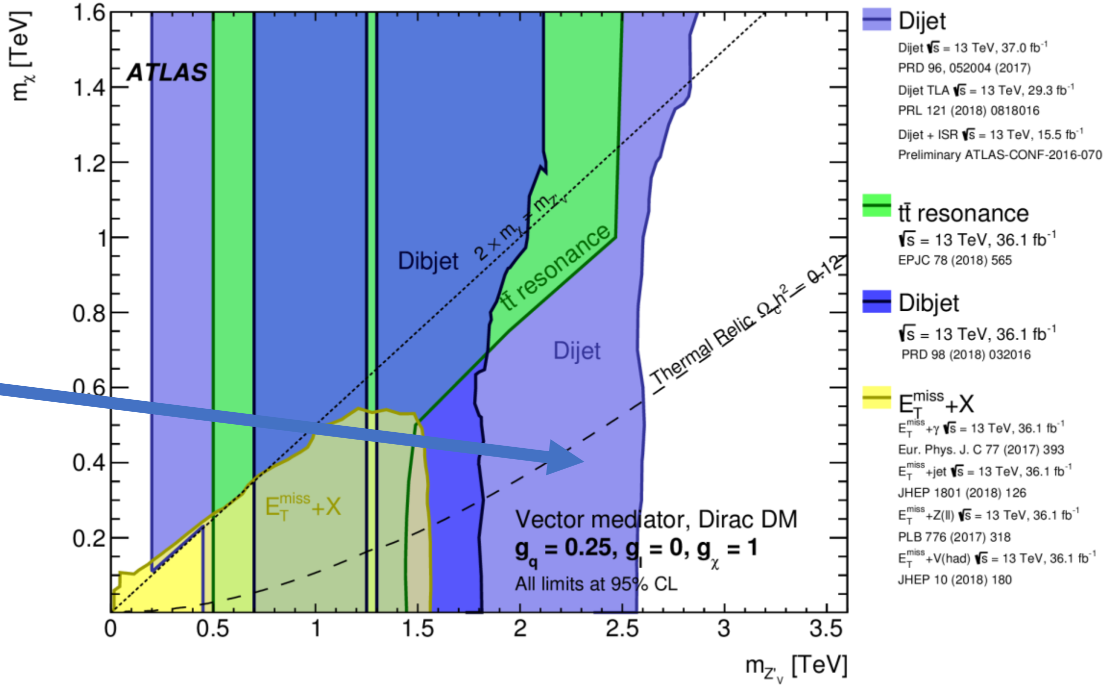
Dark Matter

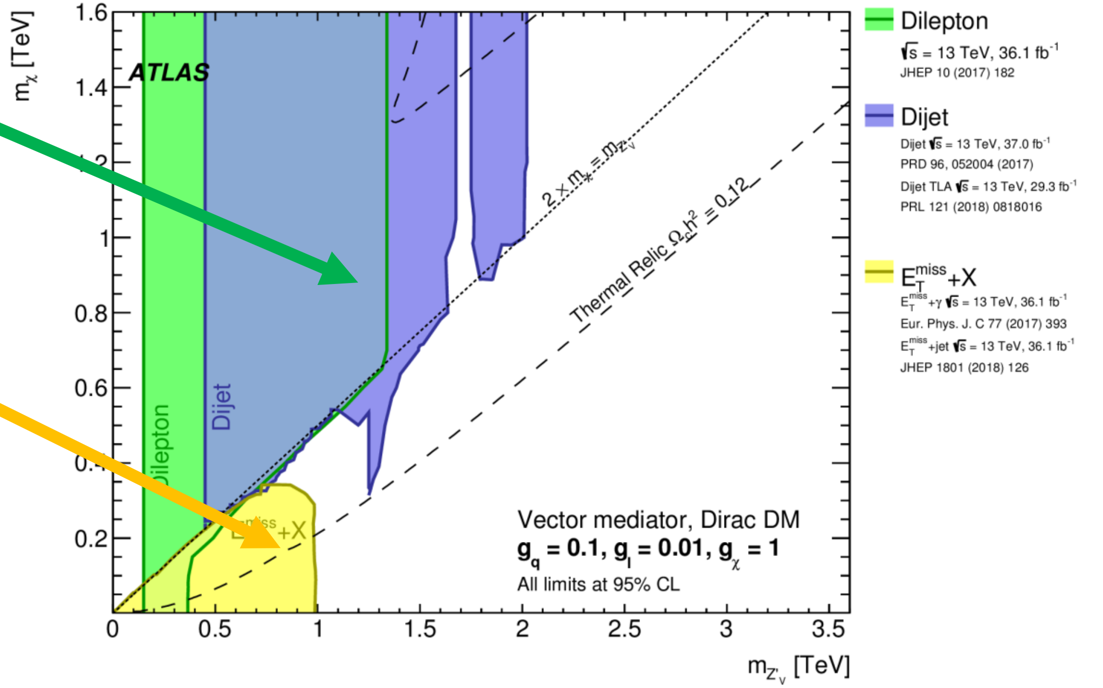
ATLAS 36/fb JHEP 05 (2019) 142
CMS Summary Plots

- Z' mediator must have coupling to quarks to be produced at LHC
- If g_q large, decay of Z' to dijets gives best sensitivity regardless of dark matter mass
- If g_l not zero, decay of Z' to dileptons also sensitive
- If g_q smaller, decay of Z' to dark matter gives best sensitivity if kinematically allowed (Z' mass double dark matter mass), rely on visible ISR and large MET from invisible dark matter
- Benchmark model:
  - Vector mediator
  - Dirac DM









Dark Matter

ATLAS 36/fb JHEP 05 (2019) 142
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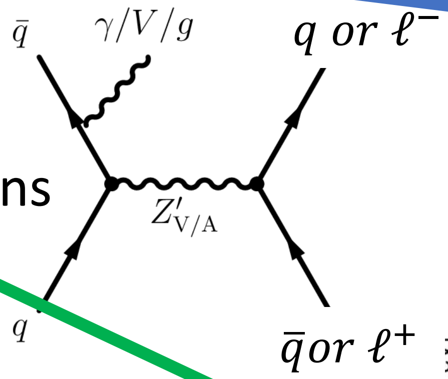
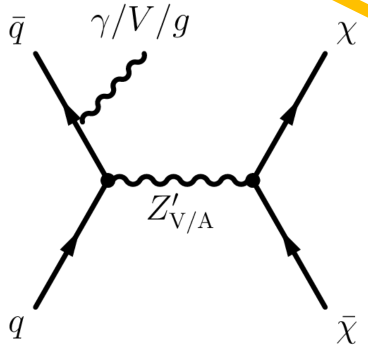
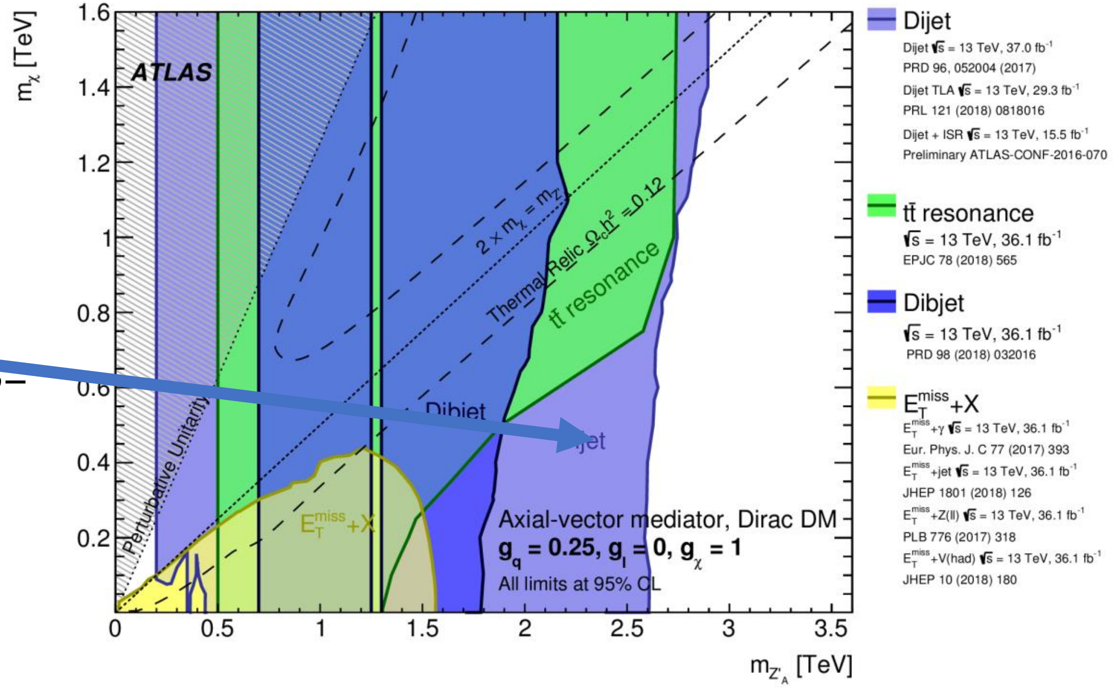
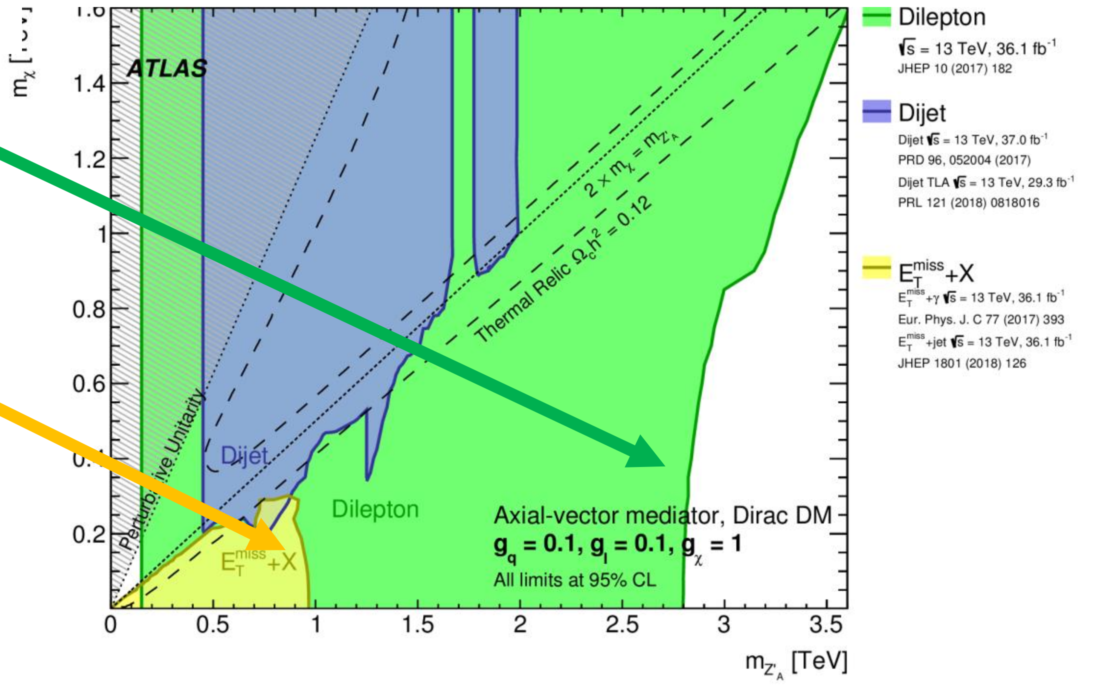
- If g_l not zero, decay of Z' to dileptons gives best sensitivity regardless of dark matter mass
- If g_q smaller, decay of Z' to dark matter still gives good sensitivity if kinematically allowed (Z' mass double dark matter mass), rely on visible ISR and large MET from invisible dark matter
- Benchmark model:
  - Axial -Vector mediator
  - Dirac DM







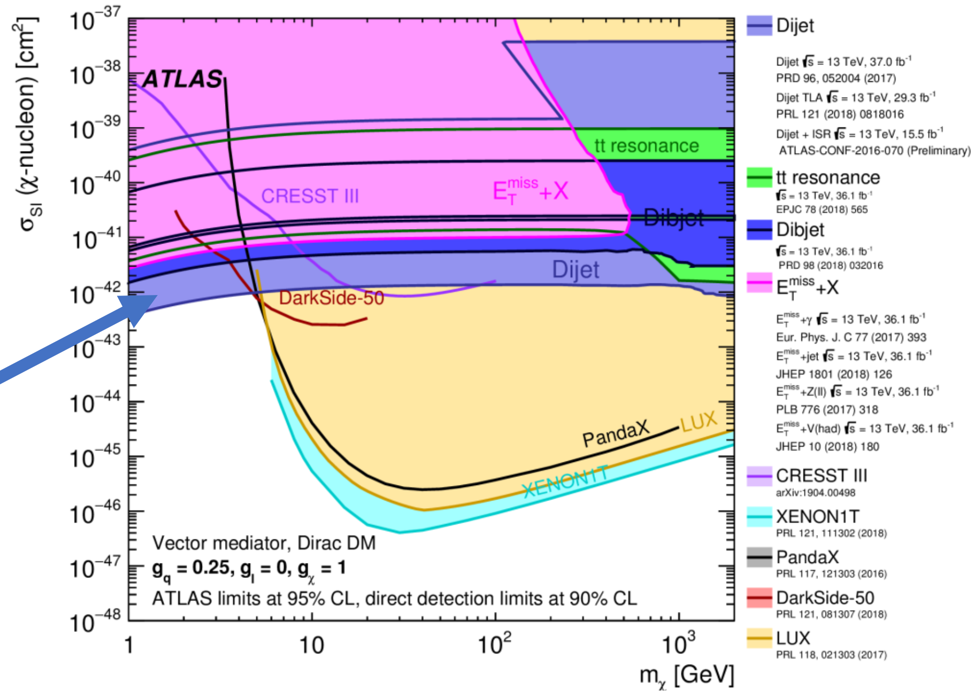


Dark Matter

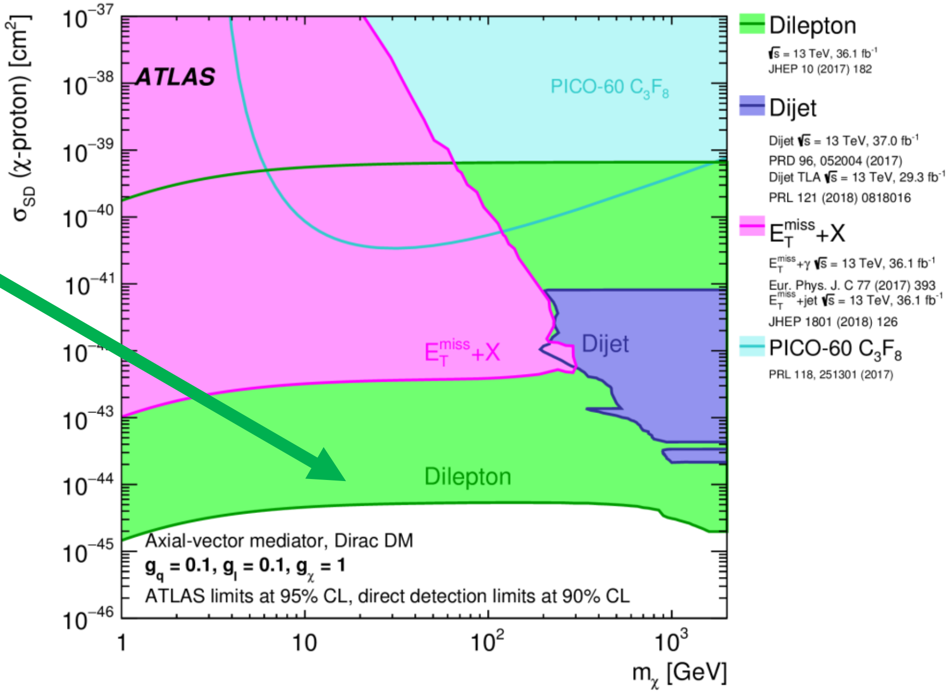
ATLAS 36/fb JHEP 05 (2019) 142

CMS Summary Plots

- Comparison of ATLAS searches at 95% CL with direct detection searches at 90% CL
- Spin-dependent WIMP-proton scattering for vector mediator leptophobic model (large g_q)



- Spin-independent WIMP-nucleon scattering for axial-vector leptophilic model



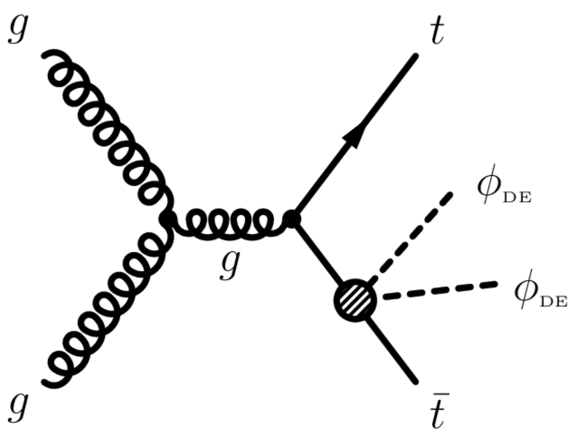
Scalar Dark Energy

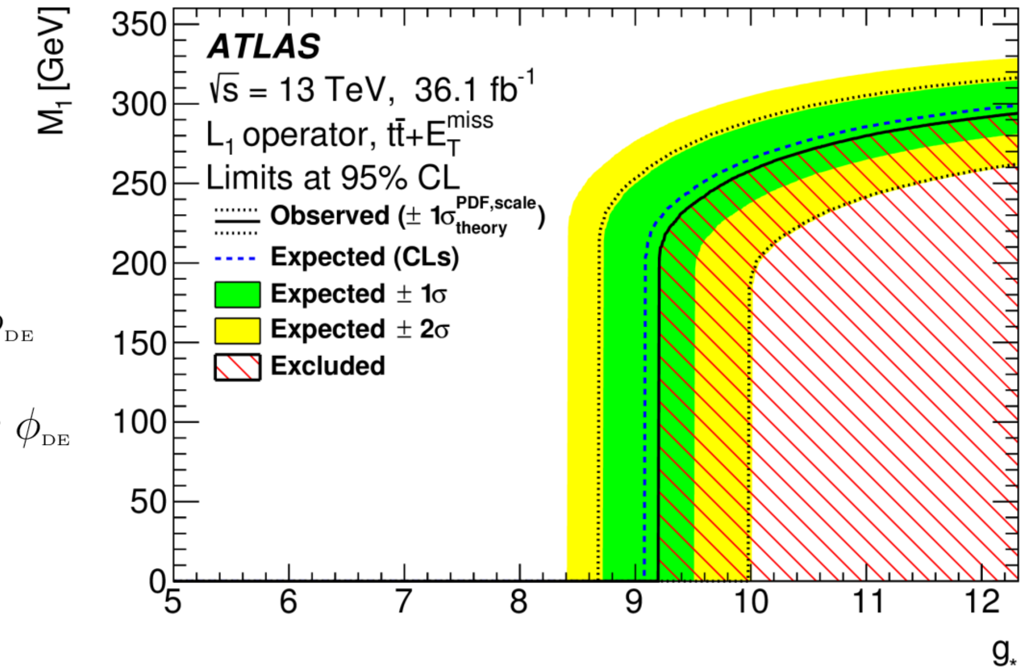
ATLAS 36/fb JHEP 05 (2019) 142

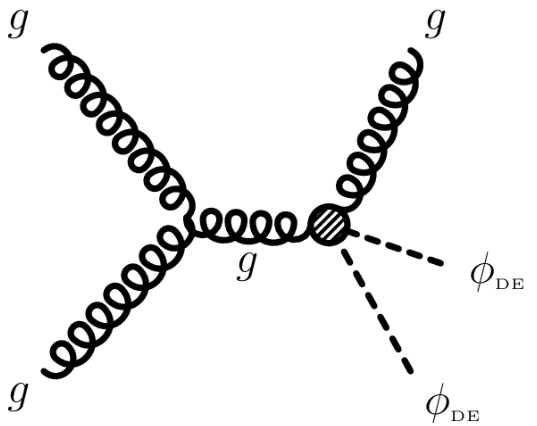
- Effective Field Theory implementation of Horndeski scalar dark energy theories
- Place first constraints on dark energy from √s=13 TeV data
- L_1 operator proportional to mass of fermions, ttbar+MET most sensitive
  - Exclude suppression scale M_1 up to 200 GeV for $g_*=\pi^2$
- L_2 operator proportional to momenta, mono-jet most sensitive
  - Exclude suppression scale M_2 up to 1200 GeV for $g_*=\pi$

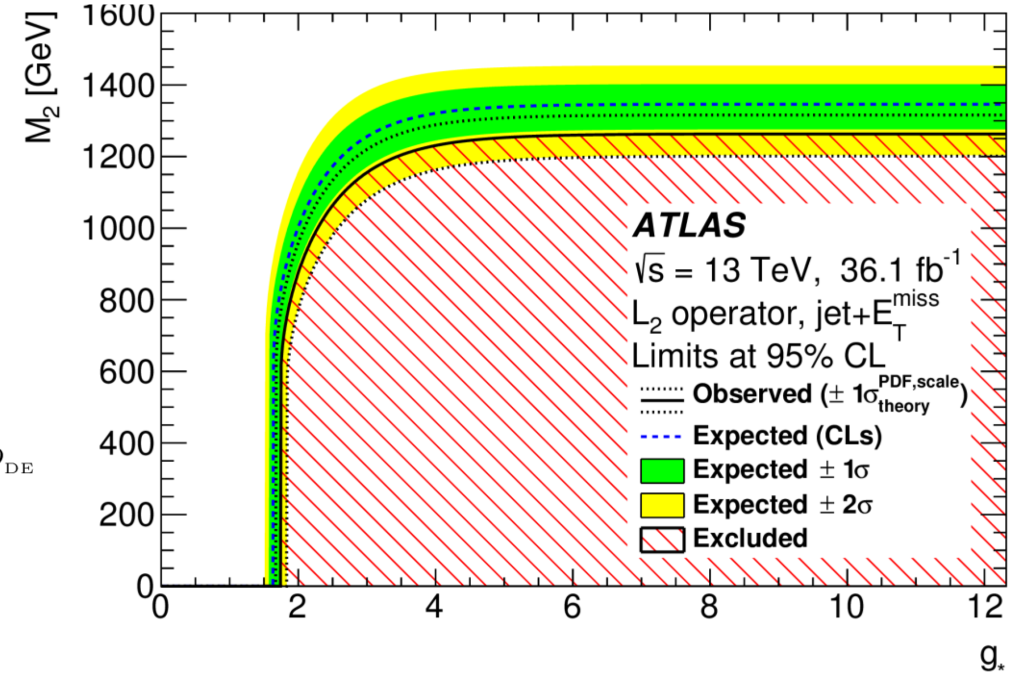
$$\mathcal{L}_1 = \frac{\partial_\mu \phi_{\rm DE} \partial^\mu \phi_{\rm DE}}{M_1^4} T^\nu_\nu$$

$$\mathcal{L}_2 = \frac{\partial_\mu \phi_{\rm DE} \partial_\nu \phi_{\rm DE}}{M_2^4} T^{\mu\nu}$$

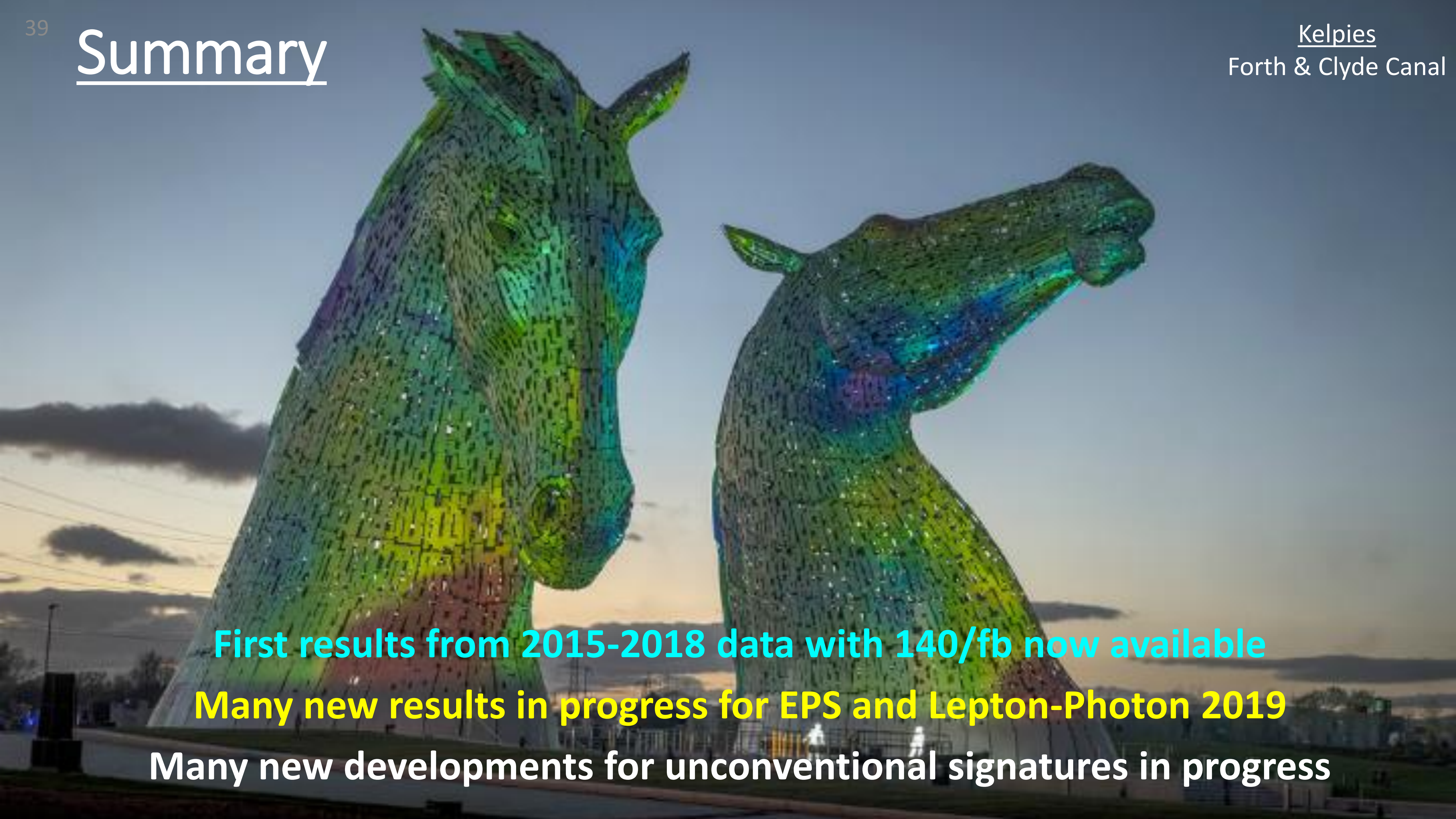








Summary



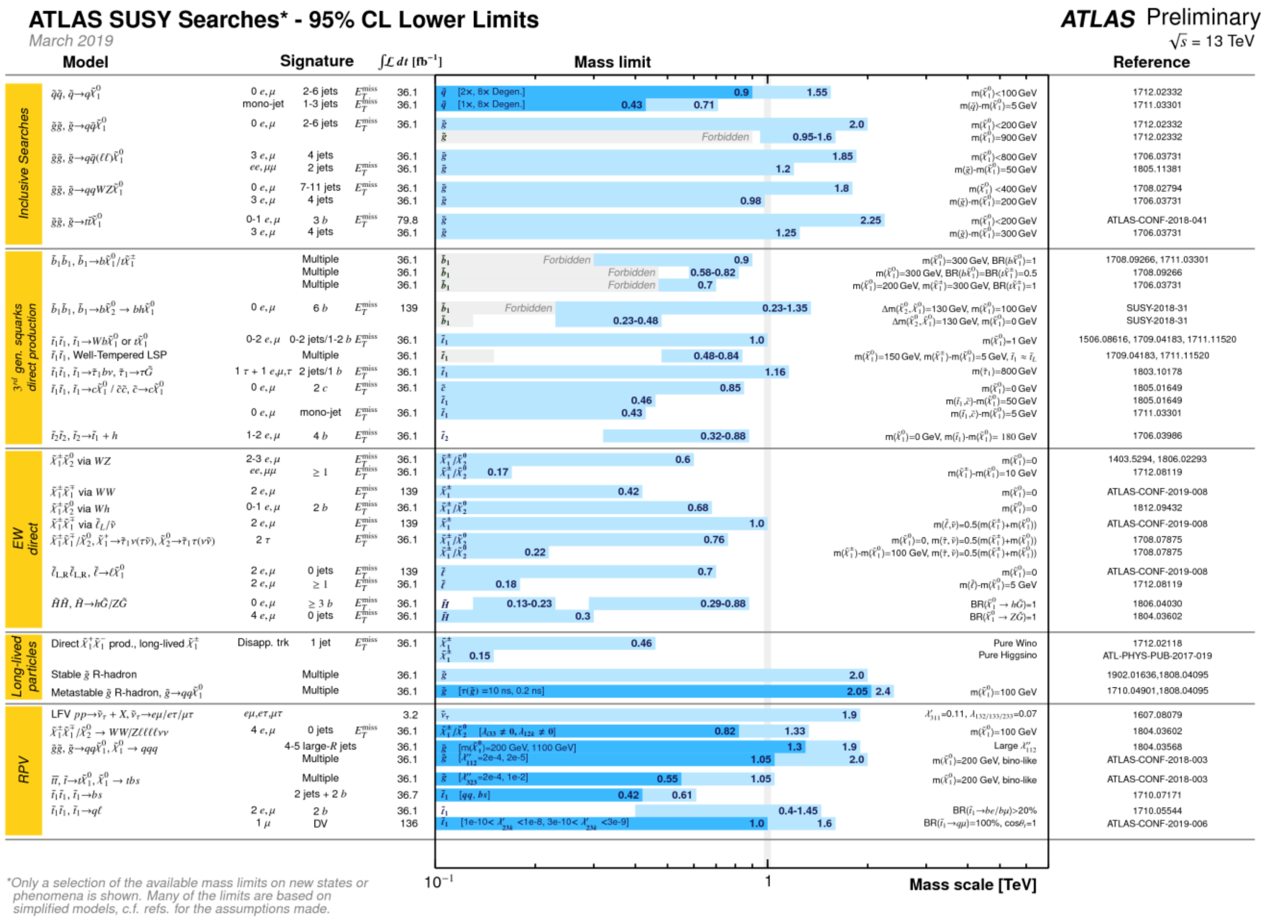
Kelpies
Forth & Clyde Canal

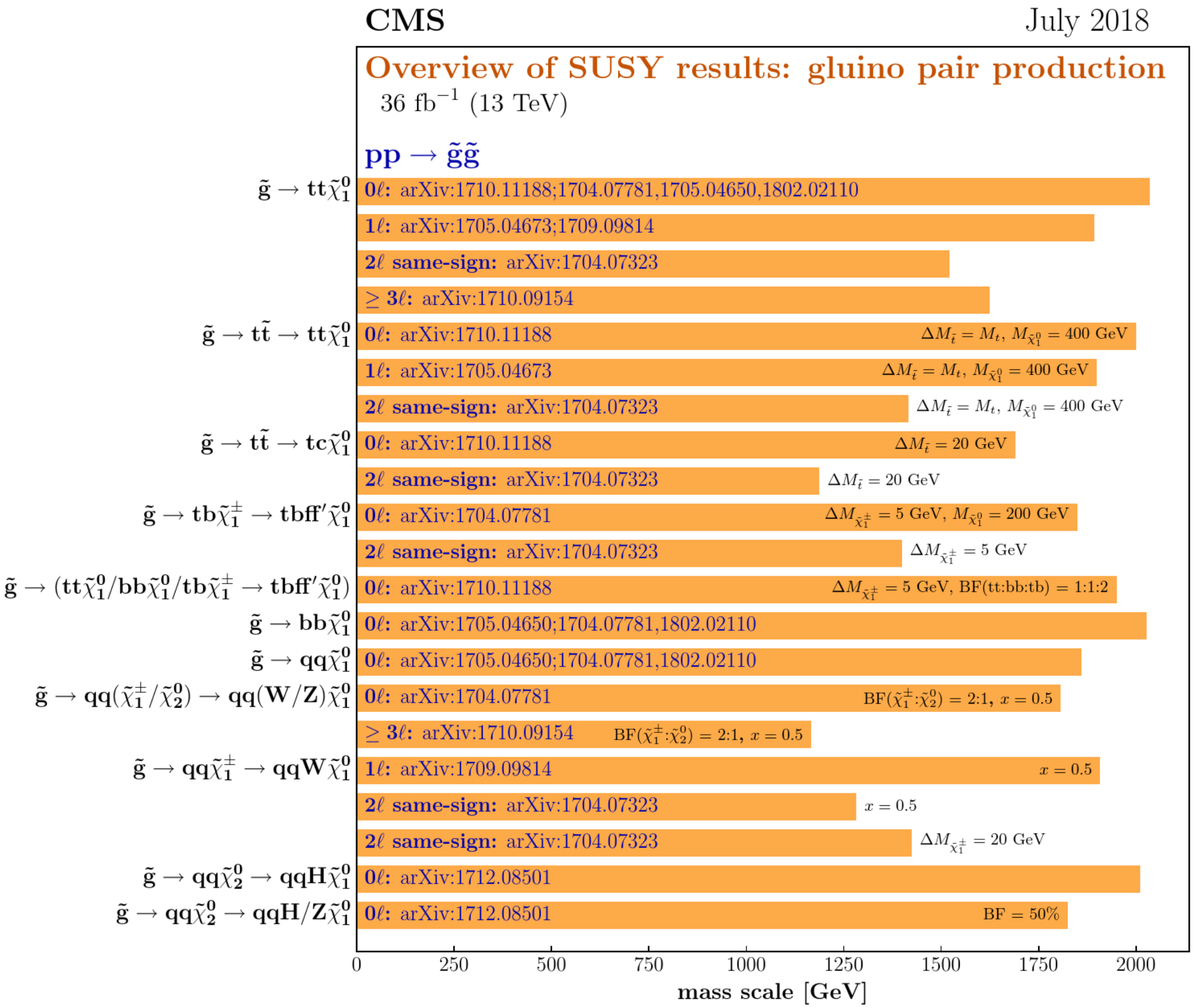
First results from 2015-2018 data with 140/fb now available

Many new results in progress for EPS and Lepton-Photon 2019

Many new developments for unconventional signatures in progress

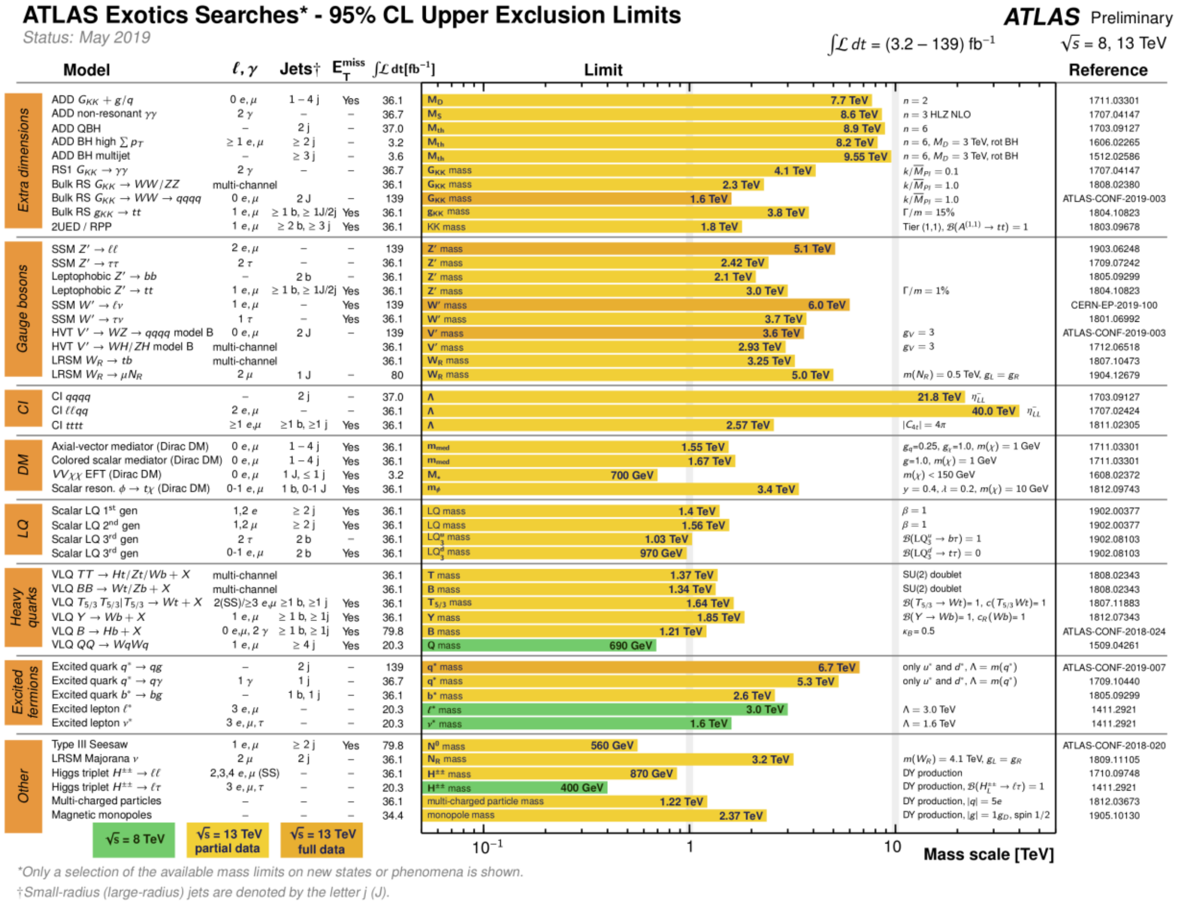
ATLAS & CMS SUSY summary plots

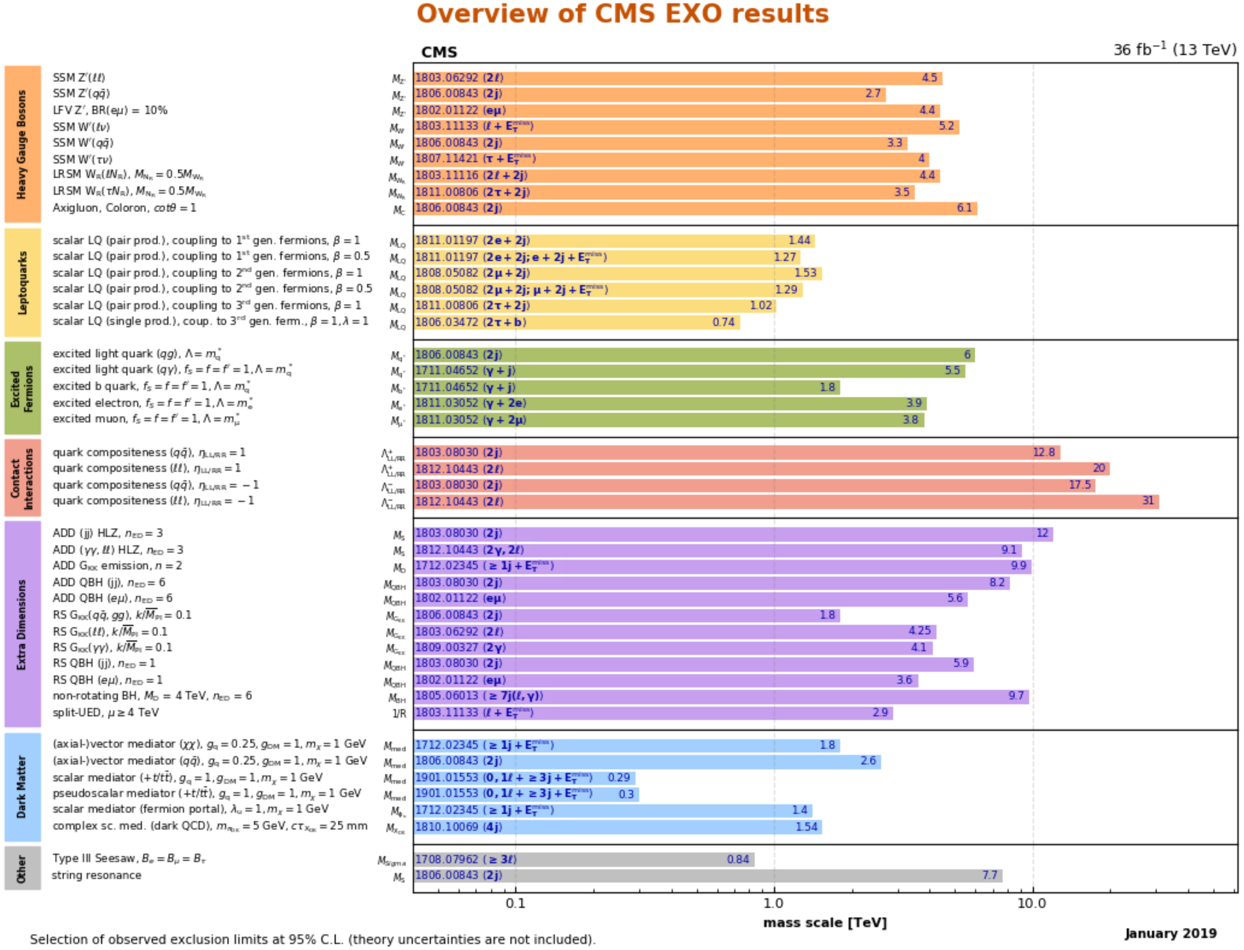




Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

ATLAS & CMS Exotics summary plots

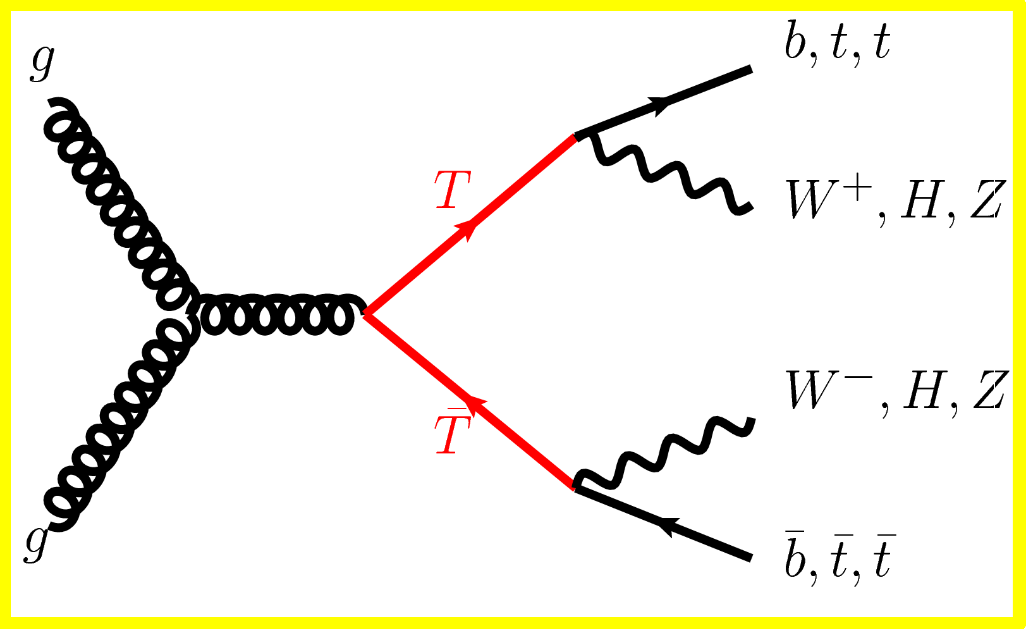


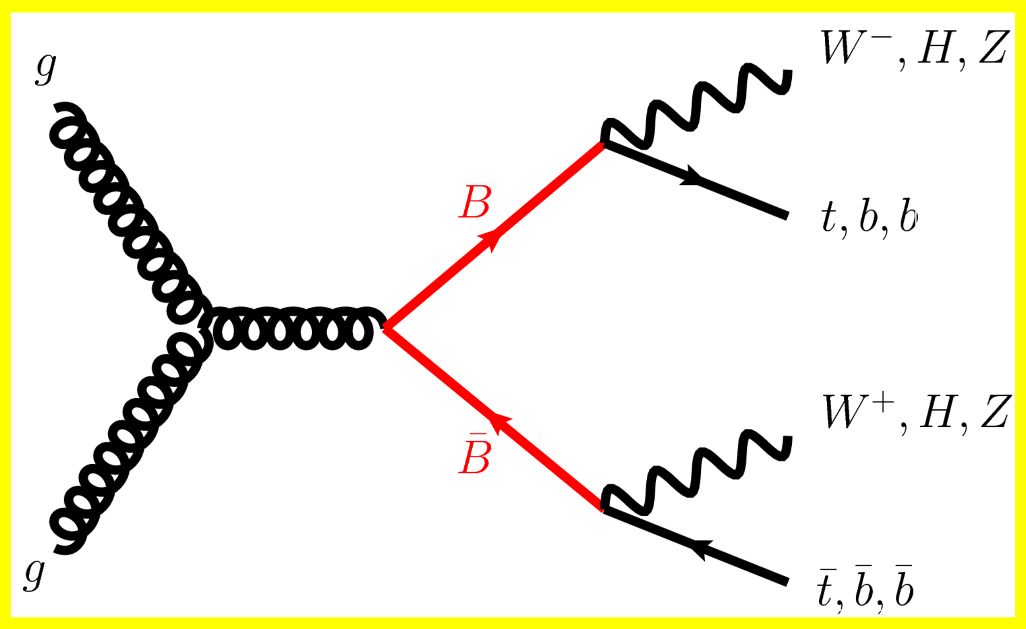


Backup topics

- Vector-like leptons
- Vector-like quarks
- Leptoquarks
- Type III Seesaw

Vector-like means identical left-handed and right-handed interactions in SU(2)xU(1). Can't obtain mass from Higgs Yukawa coupling, so not bounded by constraints from Higgs production.
Can cancel quadratic divergences to Higgs boson mass.
Little Higgs and Composite Higgs models



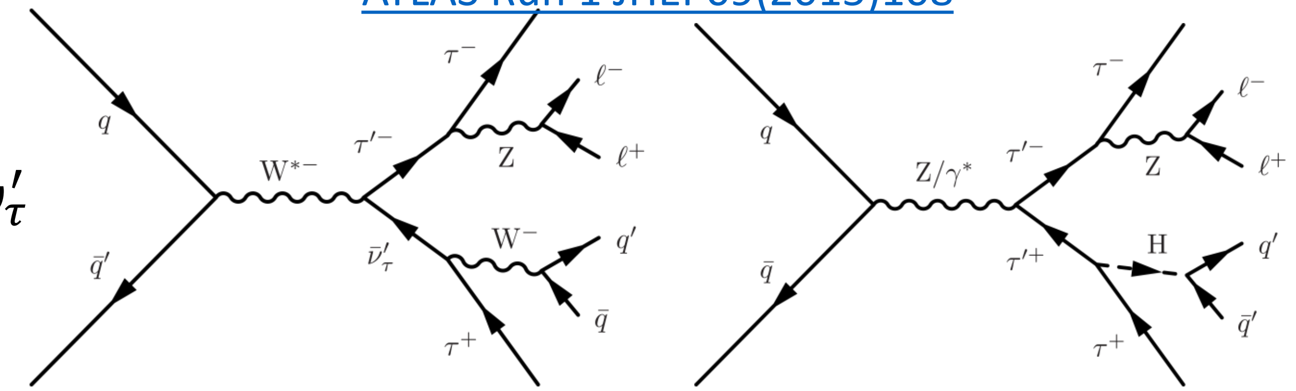


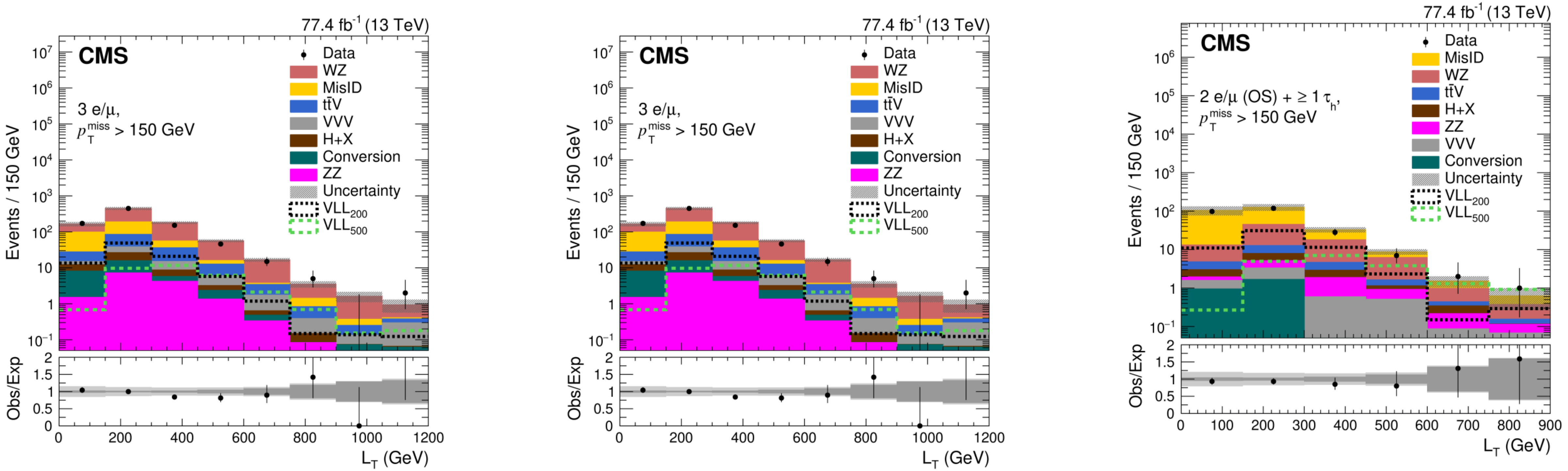
Vector-like Leptons

CMS 77/fb arXiv:1905.10853

ATLAS Run 1 JHEP09(2015)108

- SU(2) doublet of non-chiral tau leptons
- Pair production of $\tau'\tau'$ and $\tau'\upsilon'_\tau$ and $\upsilon'_\tau\, \upsilon'_\tau$
- τ' decay to Zτ or Hτ
- υ'_τ decay to Wτ
- Signal regions with 4 leptons, 3 leptons, 2 leptons & 1 tau lepton (L_T is scalar p_T sum of leptons)
- Exclude mass degenerate 3rd gen VLL in range 120-790 @ 95% CL

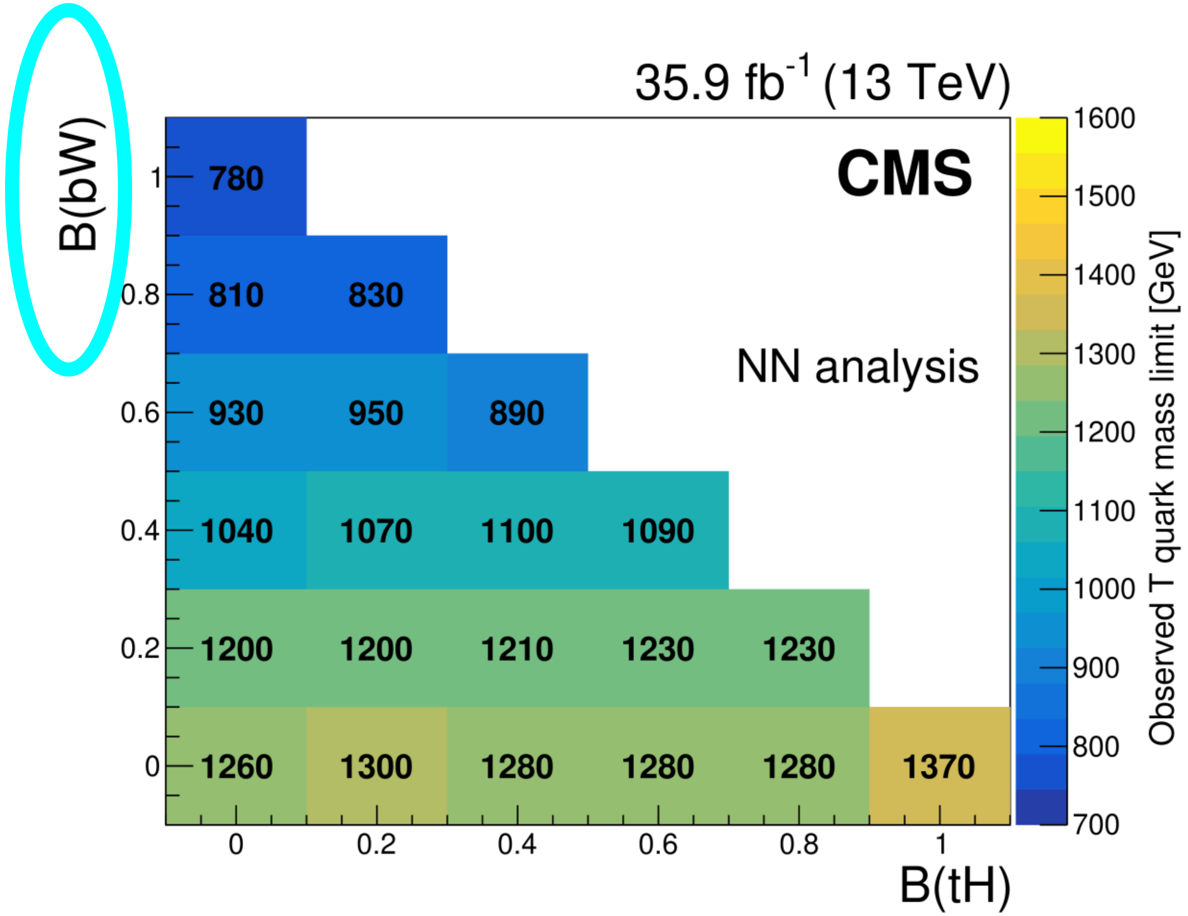




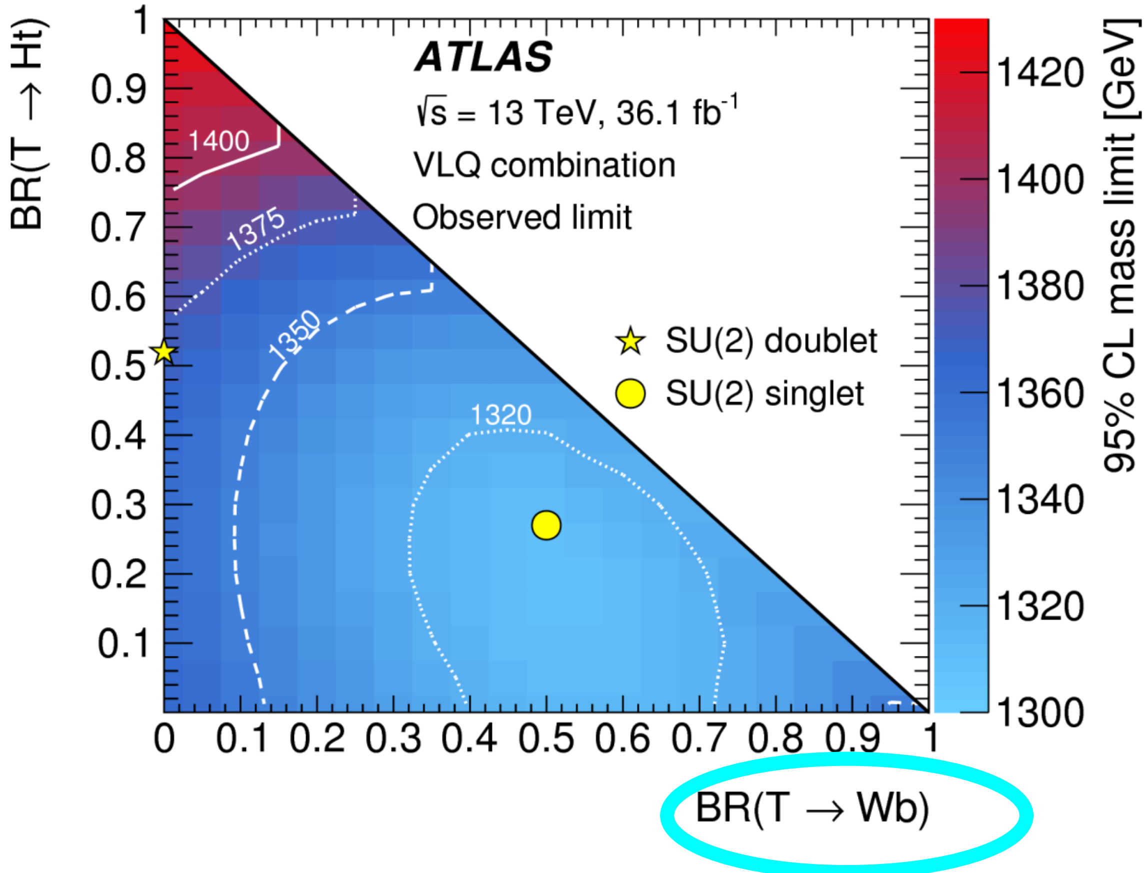
Vector-like Quarks

[ATLAS 36/fb PRL 121 (2018) 211801](#)
[CMS 36/fb B2G-18-005](#)

- CMS inclusive search for all decays using boosted event shape classifier for six types of jets (from top, H, Z, W, b, and quark/gluon)



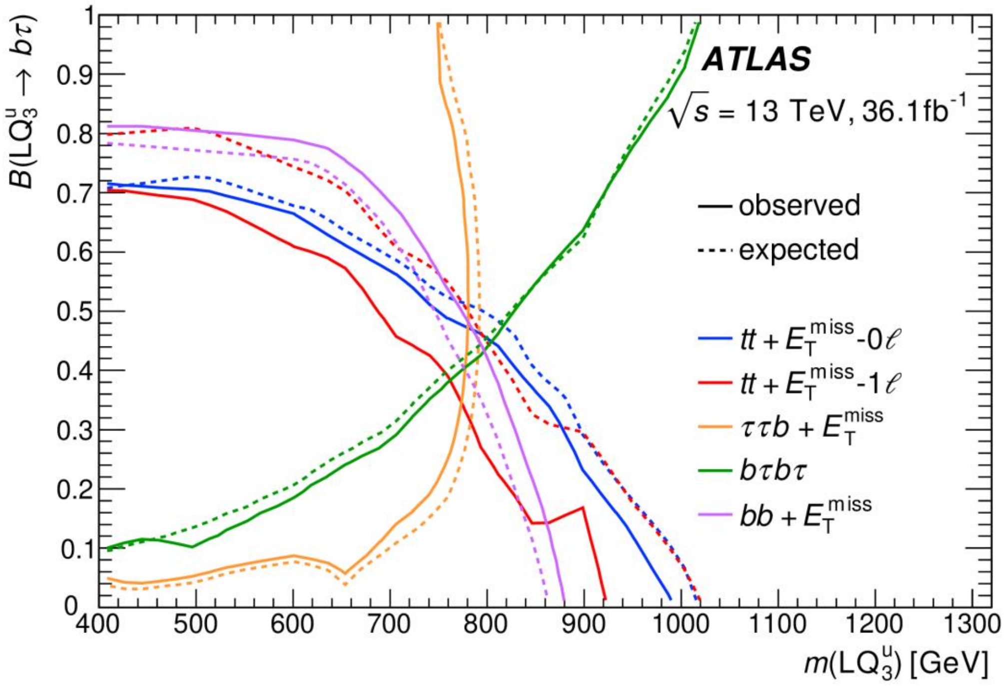
- ATLAS combination of searches
- Exclude T < 1.31 TeV and B < 1.03 TeV for any branching ratio

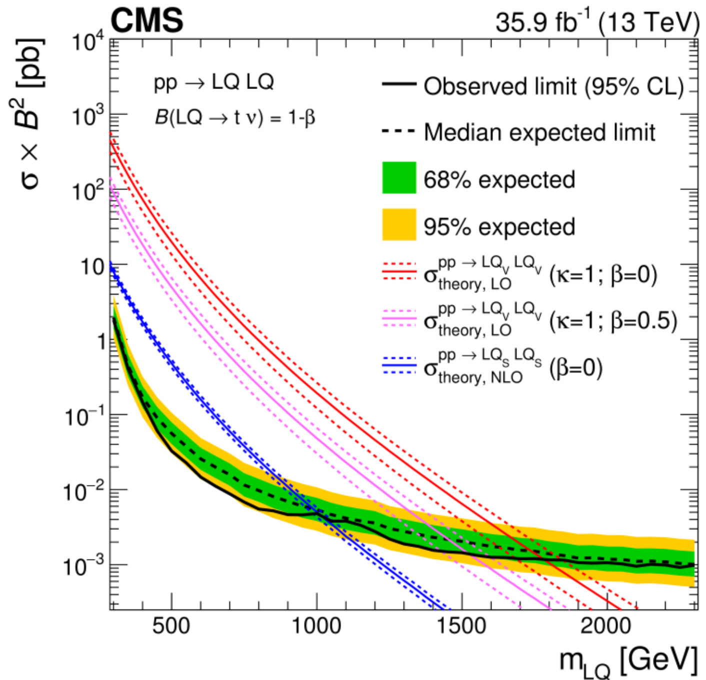


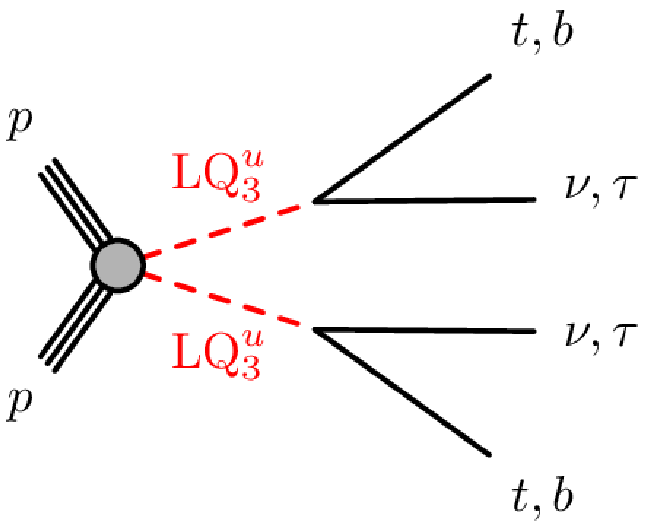
Leptoquarks

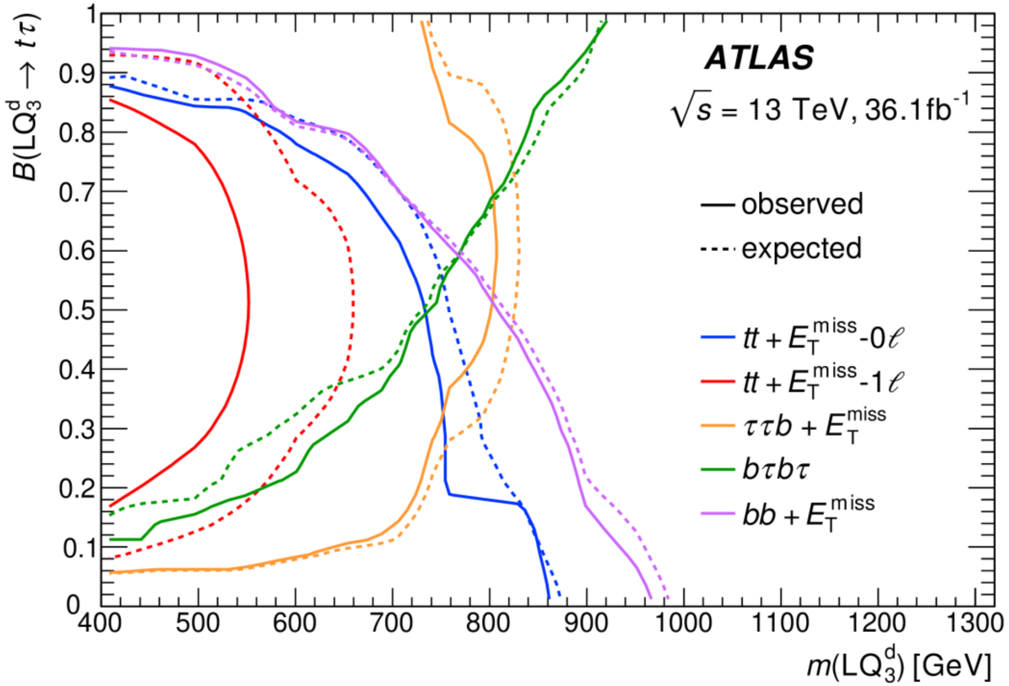
ATLAS 36/fb arXiv:1902.08103
CMS 36/fb PRD 98 (2018) 032005
CMS 36/fb JHEP 03 (2019) 170

- Candidates to explain B meson anomalies, 3rd generation especially interesting here
- Limits from dedicated searches and reinterpretations of SUSY searches
- Scalar LQ masses below 800 GeV excluded for any branching fraction
- Vector LQ masses also excluded





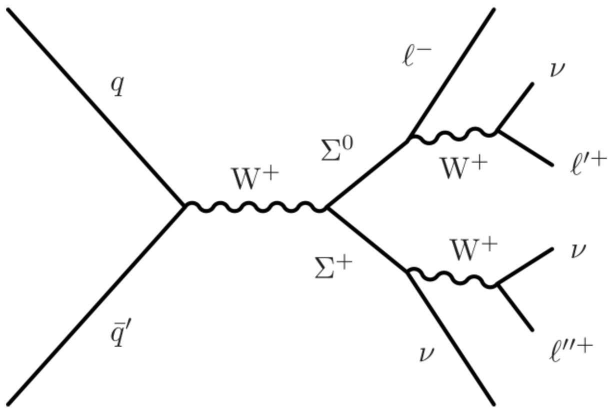


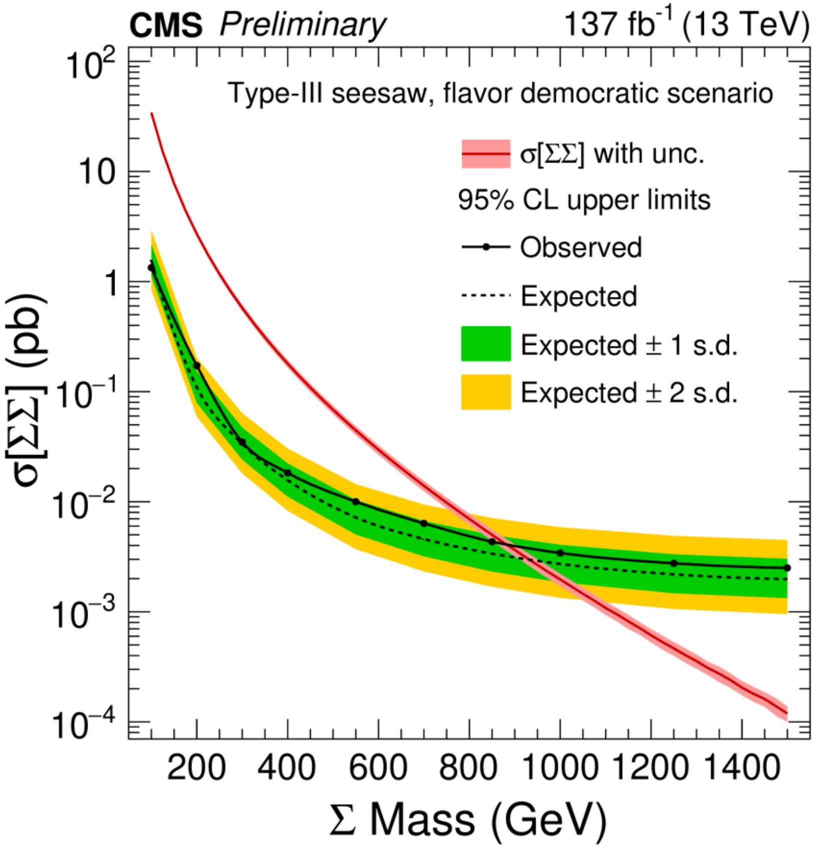


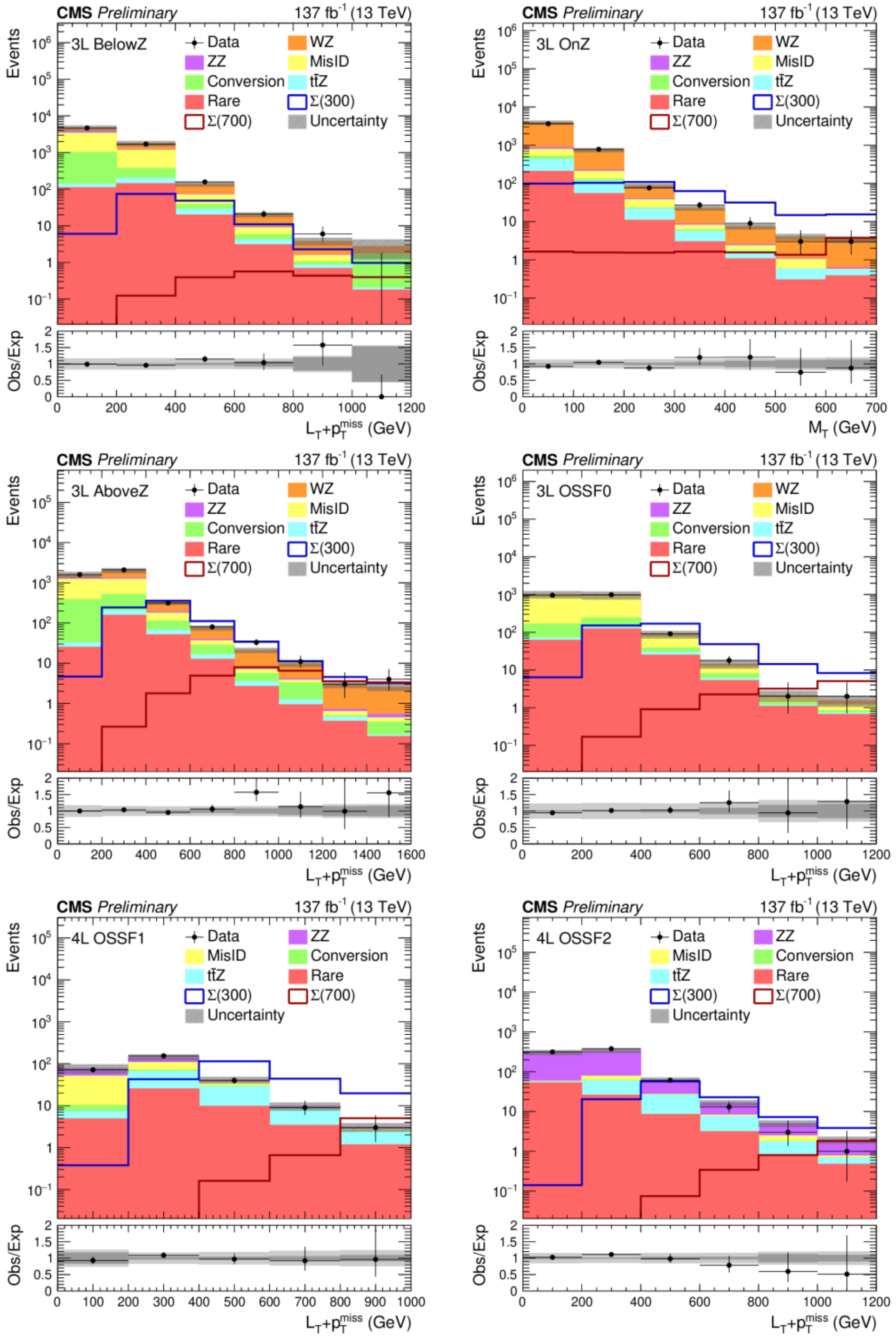
Type III Seesaw

[CMS 137/fb EXO-19-002]

- 3 or more leptons: scalar p_T sum of leptons & MET
- Seesaw model mass degenerate SU(2) triplet of Dirac charged leptons and Majorana neutral lepton
- Exclude heavy fermions with masses below 800 GeV for lepton flavor democratic scenario







Scalar (pseudoscalar) boson

CMS 137/fb EXO-19-002

- 3 or more leptons: dilepton resonance
- First search for this signature
- Exclusions in 15-75 GeV and 108-340 GeV for branching ratios to dielectrons and dimuons above 0.003 (0.03) and 0.004 (0.04) for scalar(pseudoscalar)