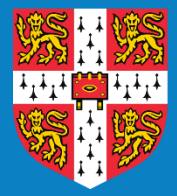

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Searches for Dark Matter and Long-Lived Particles in ATLAS and CMS

La Thuile 2022

Jon Burr on behalf of the ATLAS and CMS experiments

YSF talks at this conference:

- ATLAS HNL
- ATLAS dE/dx

Important references

[1] Collider searches for long-lived particles beyond the Standard Model

[2] Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

[3] Dark matter summary plots for s-channel and 2HDM+a models

[4] Constraints on spin-0 dark matter mediators and invisible Higgs decays using ATLAS 13 TeV pp collision data with two top quarks and missing energy in the final state

[5] Search for invisible Higgs-boson decays in events with vector-boson fusion signatures using 139 fb^{-1} of proton-proton data recorded by the ATLAS experiment

[6] Search for invisible decays of the Higgs boson produced via vector boson fusion in proton-proton collisions at $\sqrt{s}$ = 13 TeV

[7] Search for long-lived particles decaying into muon pairs in proton-proton collisions at $\sqrt{s}$ = 13 TeV collected with a dedicated high-rate data stream

[8] Search for long-lived heavy neutral leptons with displaced vertices in proton-proton collisions at $\sqrt{s}$ =13 TeV

[9] Search for long-lived charginos based on a disappearing-track signature using 136 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

[10] Search for neutral long-lived particles in pp collisions at $s\sqrt{}$=13 TeV that decay into displaced hadronic jets in the ATLAS calorimeter

[11] Search for light long-lived neutral particles that decay to collimated pairs of leptons or light hadrons in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector

[12] Search for long-lived particles decaying to a pair of muons in proton-proton collisions at $\sqrt{s}$= 13 TeV

CMS Exotica public results, CMS SUSY public results, ATLAS Exotics public results, ATLAS SUSY public results

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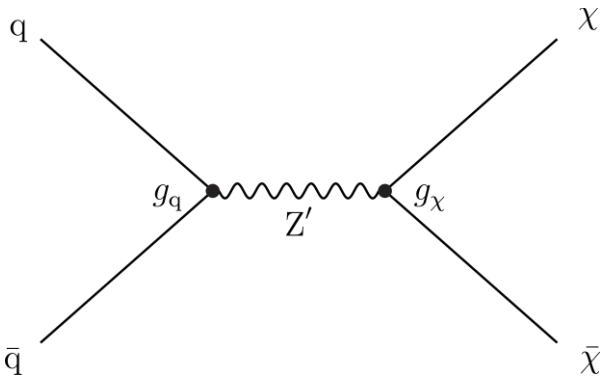
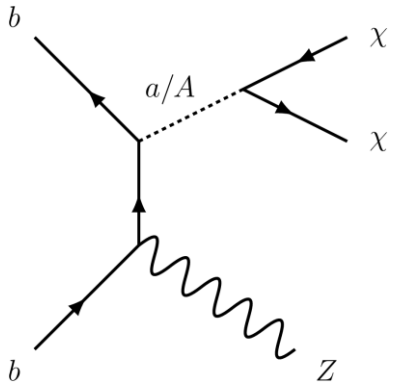
ATLAS EXPERIMENT

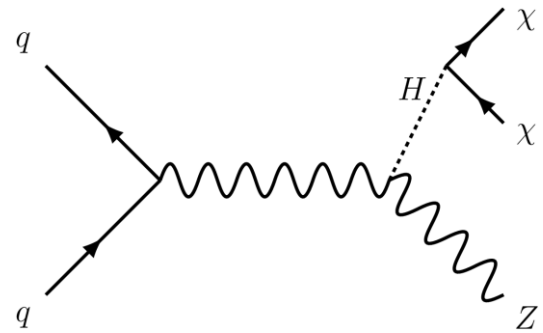
CMS

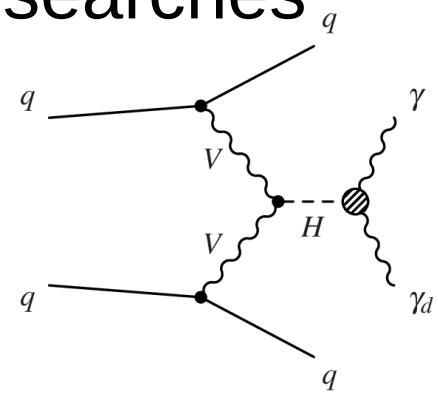
Searches for Dark Matter

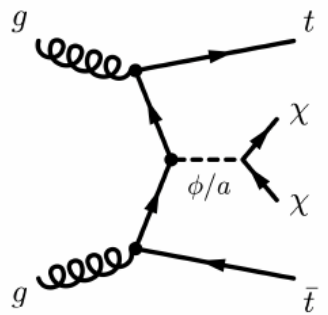
- LHC dark matter searches cover a rich variety of final states and models
- Cover a range of complete and simplified models
  - 2HDM+a, Higgs portal
- Complementarity with resonance searches











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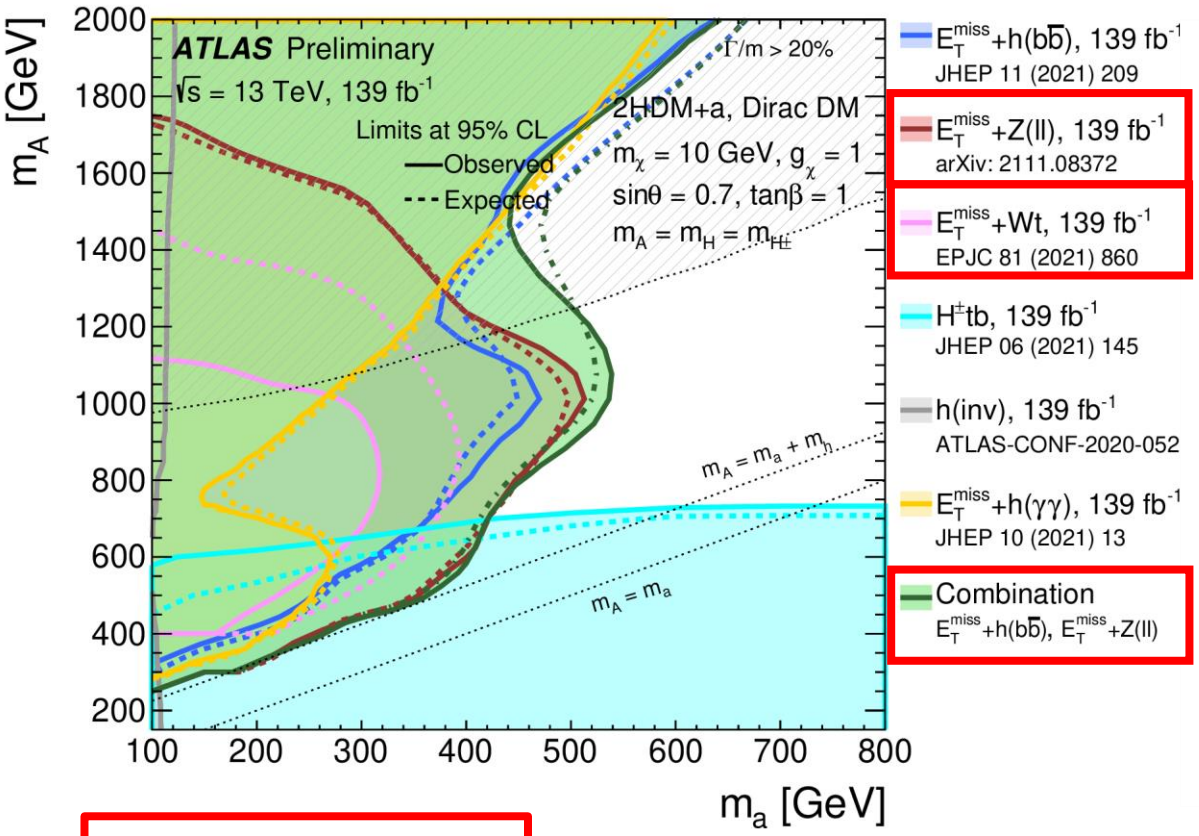
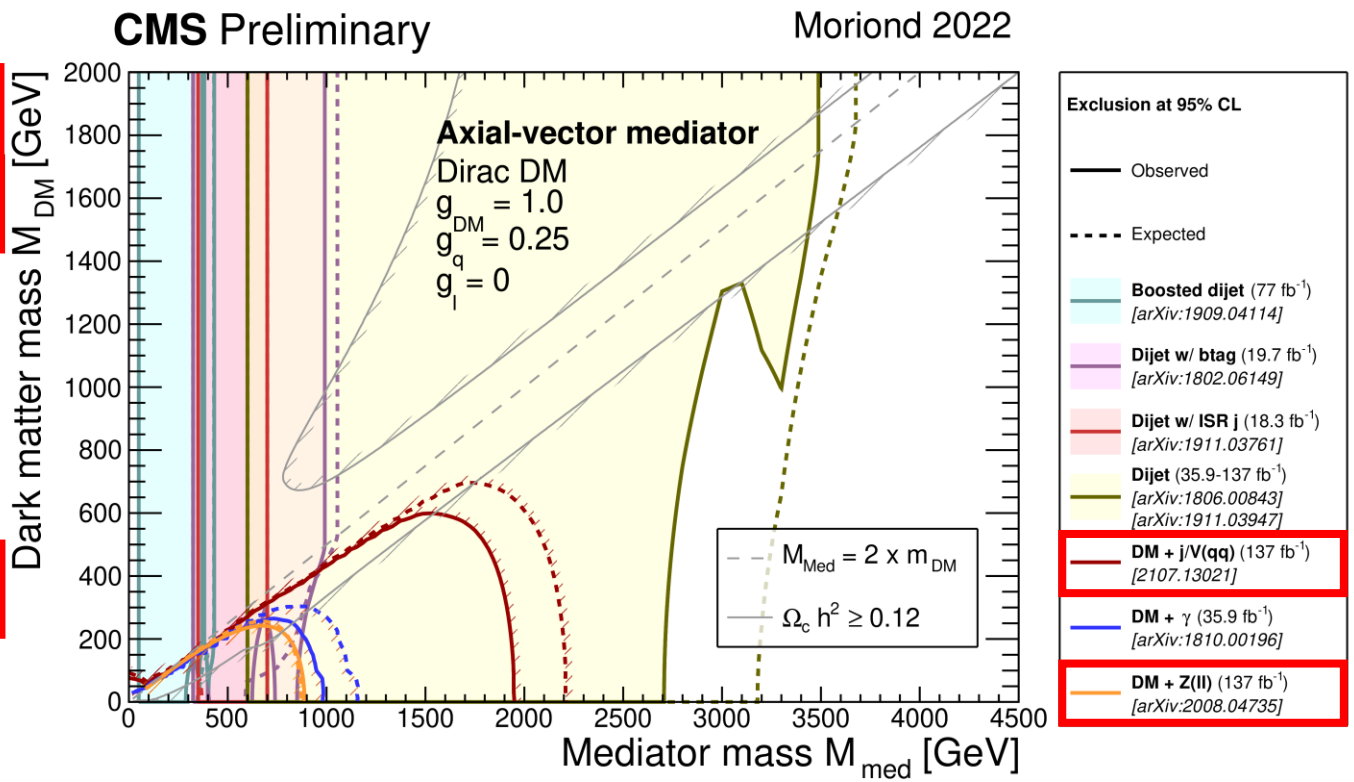
ATLAS EXPERIMENT

CMS

Searches for Dark Matter [3]





Updated in this result

Will appear here soon

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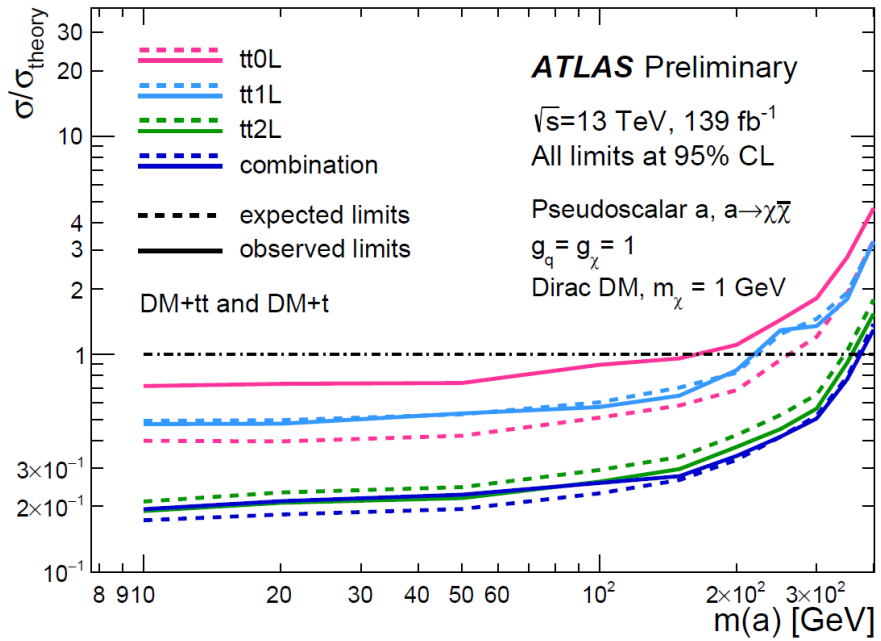
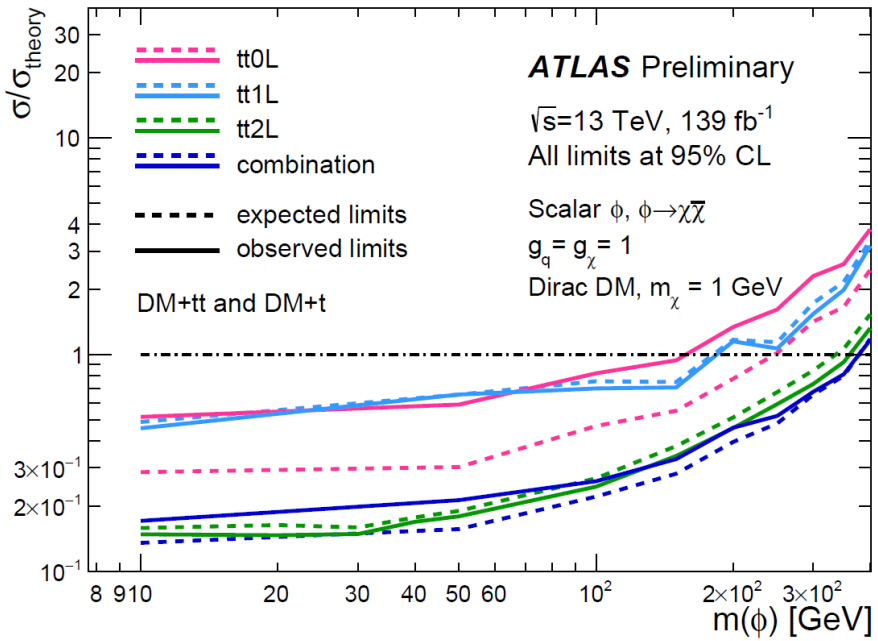
ATLAS EXPERIMENT

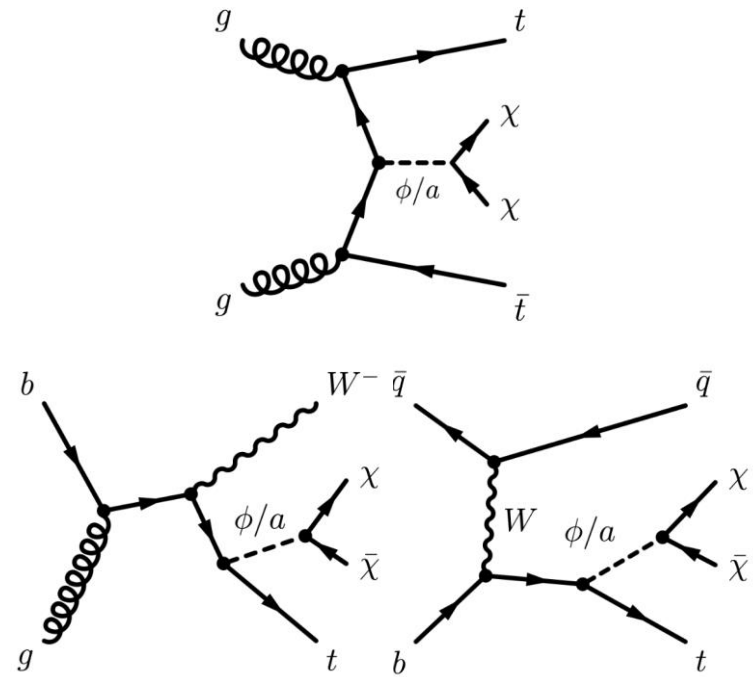
CMS

$t(\bar{t}) + E_{\mathrm{T}}^{\mathrm{miss}}$ DM Combination [4]

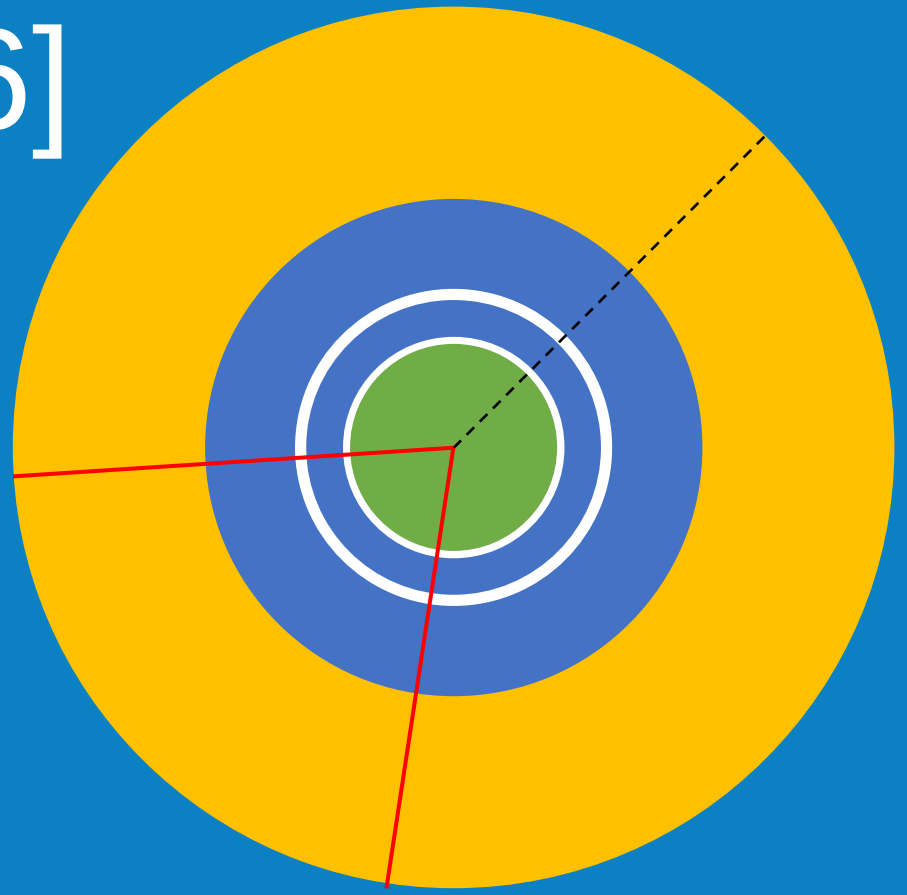
- Combine results from searches for single top and $t\bar{t}$ + $E_{\mathrm{T}}^{\mathrm{miss}}$ searches
  - 0l, 1l and 2l channels



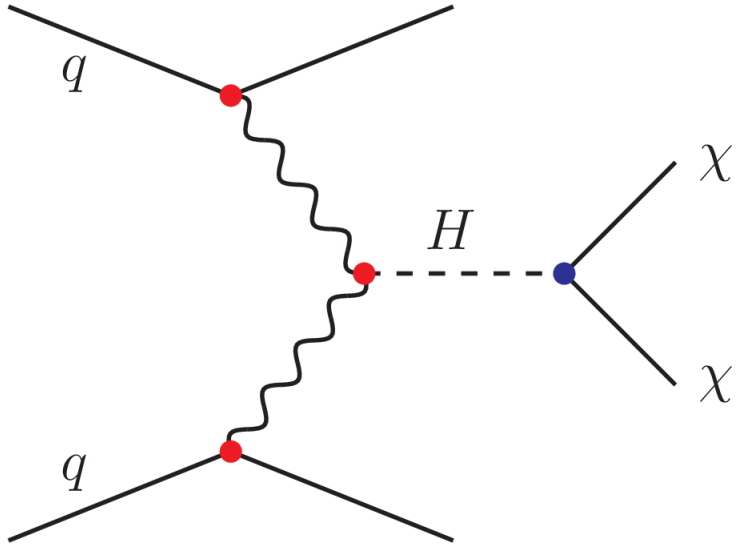




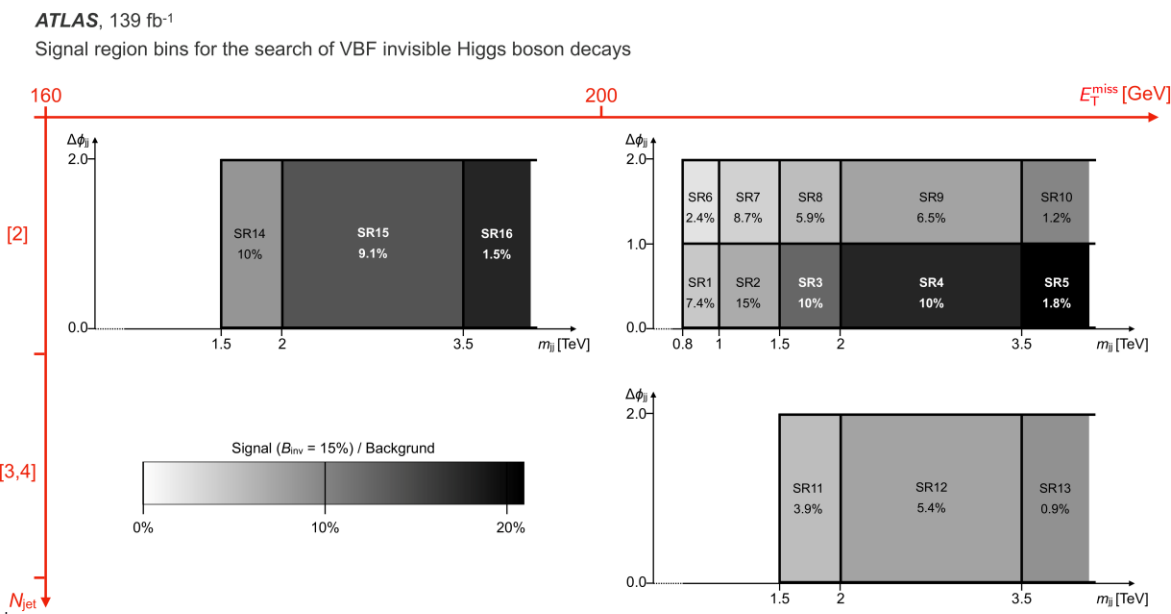
VBF Higgs to Invisible (ATLAS) [5] (CMS) [6]



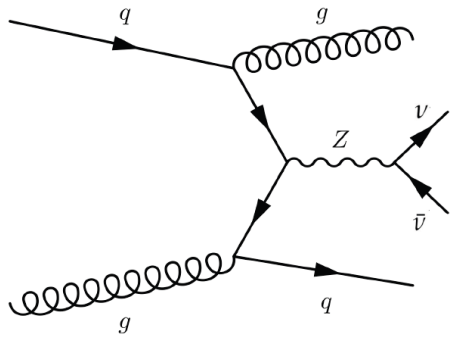
Overview



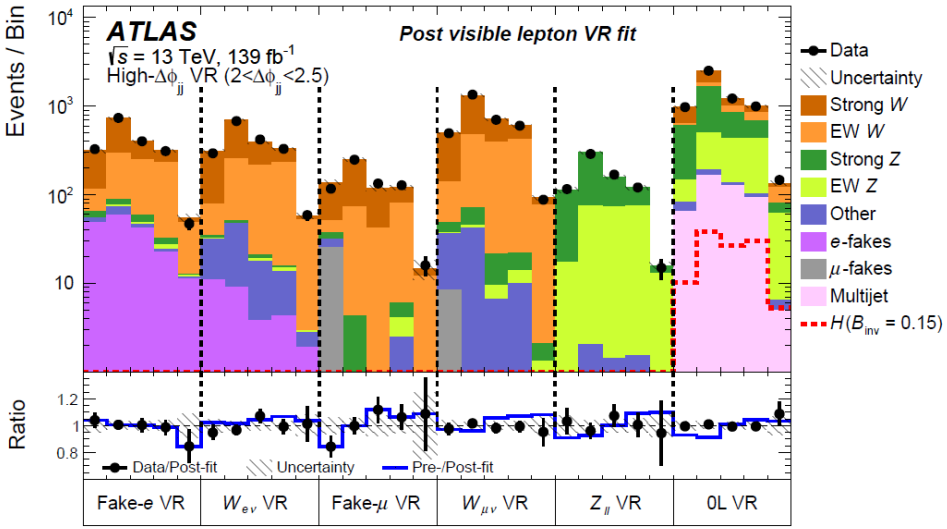
- Place limits on the $h \rightarrow \text{inv}$ branching fraction
- Search in the VBF production mode
  - Pair of forward jets with a large separation and moderate $E_{\mathrm{T}}^{\mathrm{miss}}$
- Select signal region events using $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
  - Also dedicated VBF trigger (CMS)
- Split signal regions by
  - N_{jet}
  - $E_{\mathrm{T}}^{\mathrm{miss}}$
  - $\Delta\phi_{jj}/\Delta\eta_{jj}$
  - m_{jj}



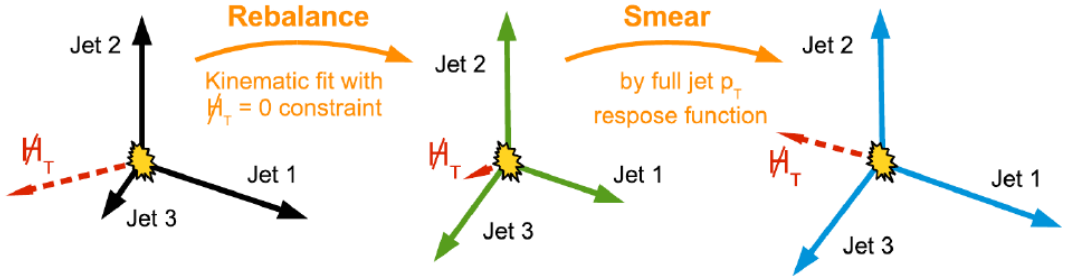
Major Backgrounds and Selections



- Major (95%) background from V+jets
  - Estimate with dedicated control regions
  - Collaboration with theorists for NLO calculations (ATLAS)
  - Extra constraint on Z+jets from W CR, γ + jets CR (CMS)
- Estimate multijet background with two methods
  - Rebalance and Smear (ATLAS)
  - control region, invert pileup/fake MET selections



M. Schröder



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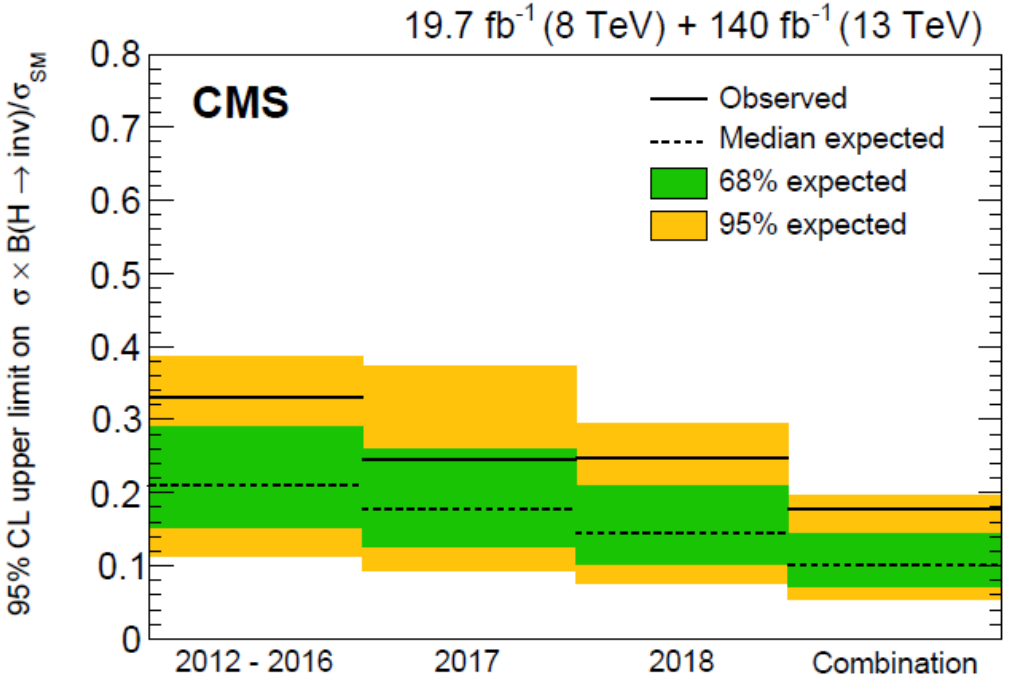
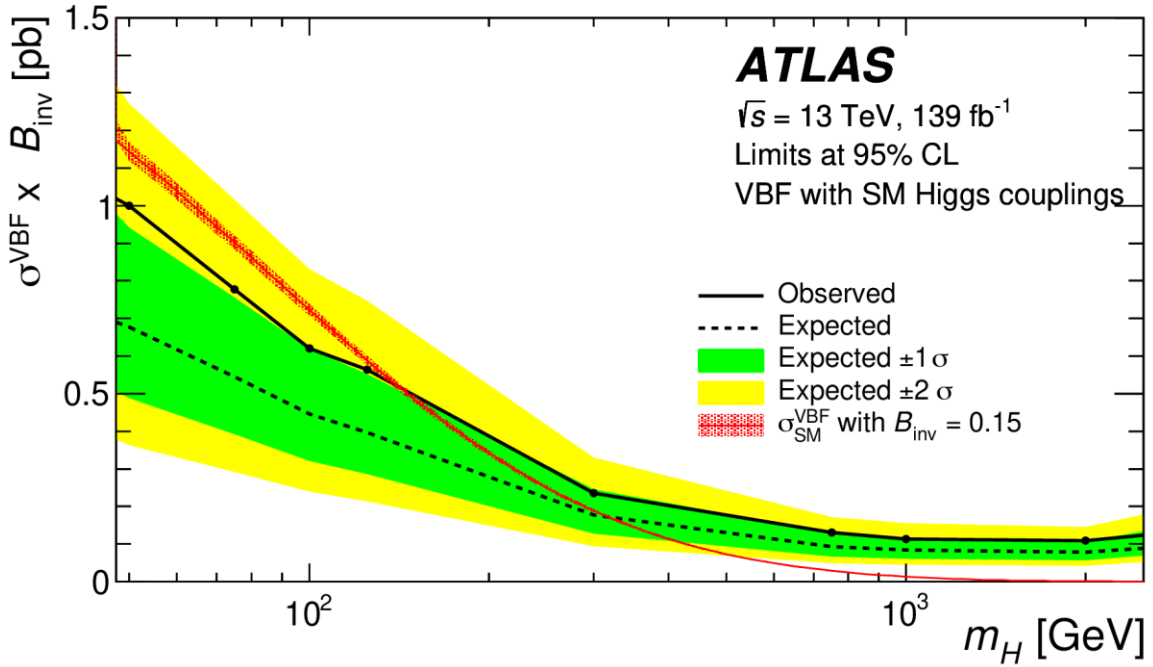
ATLAS EXPERIMENT

CMS

Results



$\mathcal{B}_{\text{inv}} < 0.18$ (95% confidence), 0.10 expected



$\mathcal{B}_{\text{inv}} < 0.145$ (95% confidence), 0.103 expected
c.f. $\mathcal{B}_{\text{inv}} < 0.11$ observed from previous combination ($\mathcal{B}_{\text{inv}} < 0.13$ from $H \rightarrow$ inv alone)
ATLAS-CONF-2020-052:

- VBF
- $t\bar{t}H$ $0\ell + 2\ell$
- Run 1 combination (VBF/VH)

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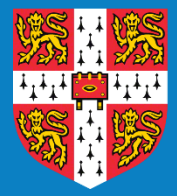
ATLAS EXPERIMENT

CMS



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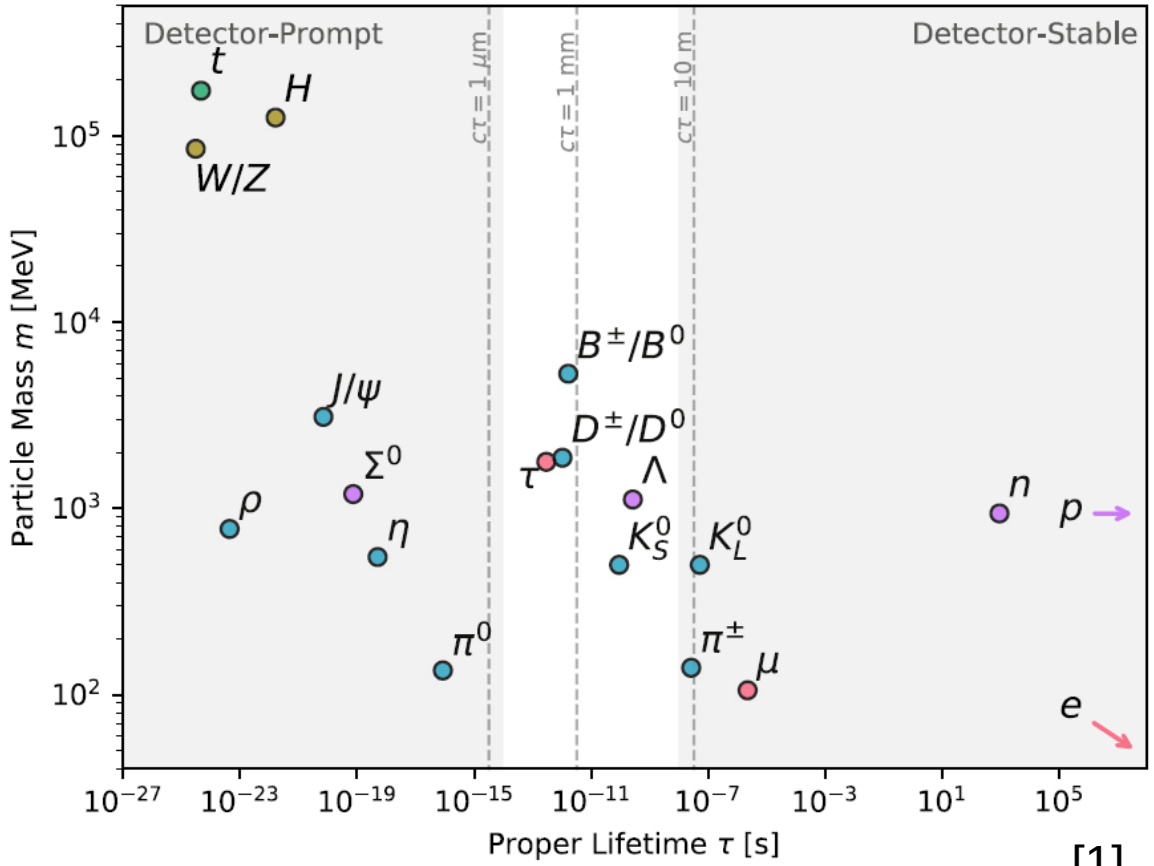
Long-Lived Particles

LLP Overview

$$\tau^{-1} = \frac{1}{2m_X}\int d\Pi_f |\mathcal{M}|^2$$

- Three main routes to yield LLPs
  - Small mass splittings
  - Small couplings
  - Very massive mediators
- Common in many BSM theories (and the SM)



[1]

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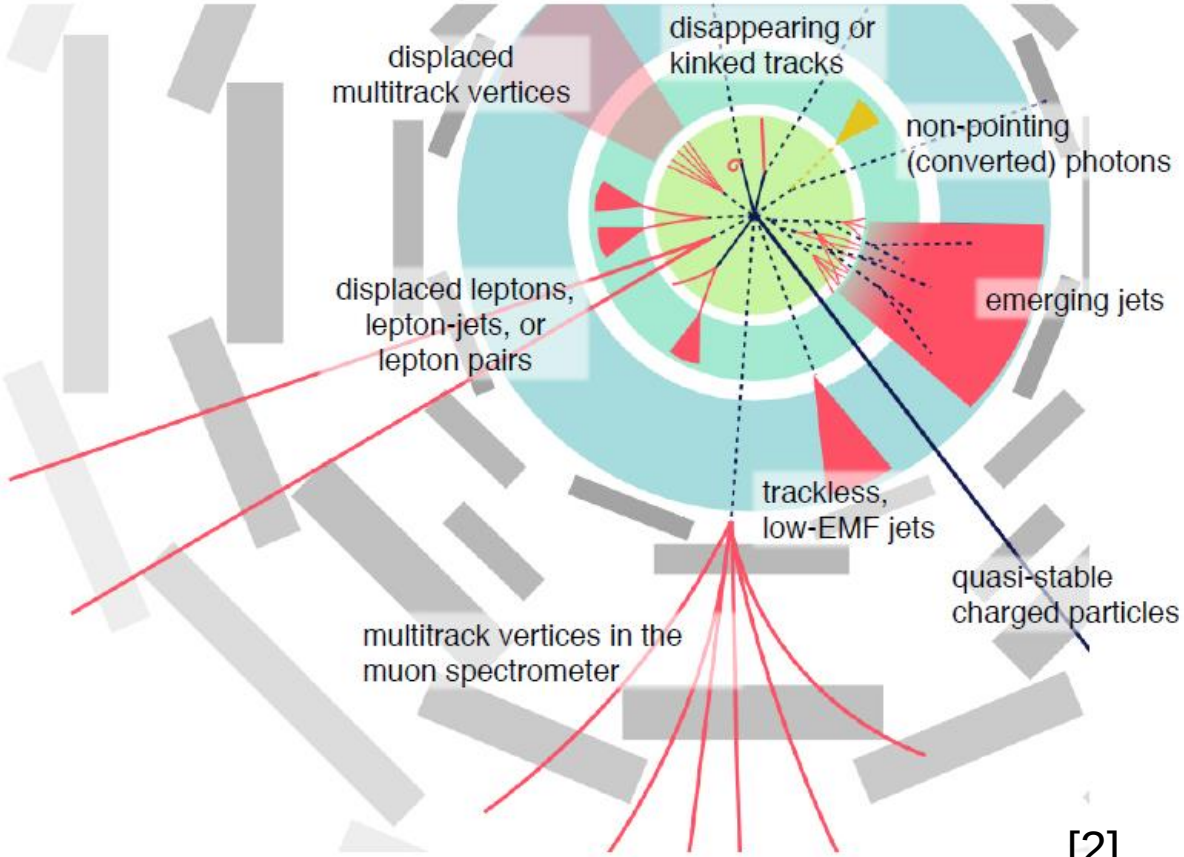
ATLAS EXPERIMENT

CMS

Experimental Signatures

- Signature depends on a few factors
  - Lifetime/decay location
  - Charged vs neutral
  - Decay products



[2]

Heather Russel

Comparisons to ‘prompt’ searches

- Prompt reconstruction techniques often not suited to displaced signatures
  - Pointing to IP
  - Missing hits in trackers
  - Cleaning
- May need dedicated triggers
- Significant impact from non-collision backgrounds
- See many examples in what follows
- Prompt searches constrain LLP models (e.g. $H \rightarrow \text{inv}$)

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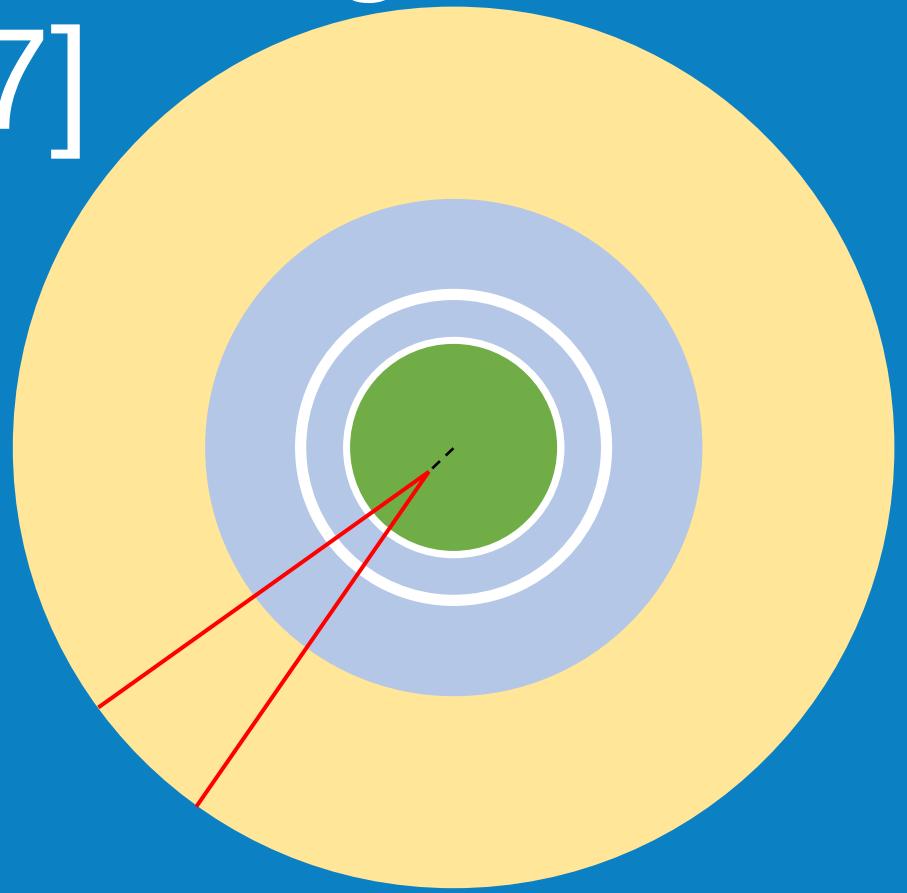
ATLAS EXPERIMENT

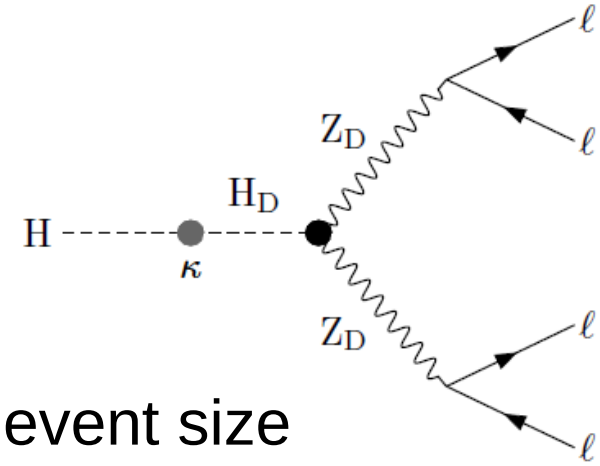
CMS

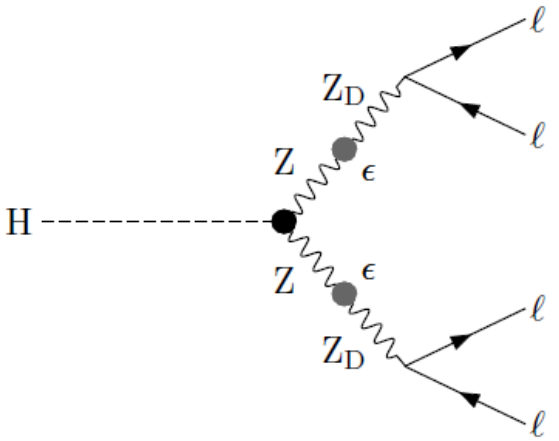
Muon pair production in high-rate data stream (CMS) [7]

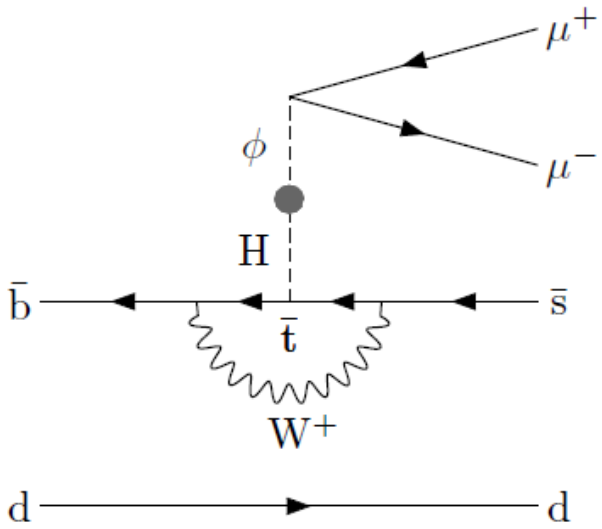


Overview

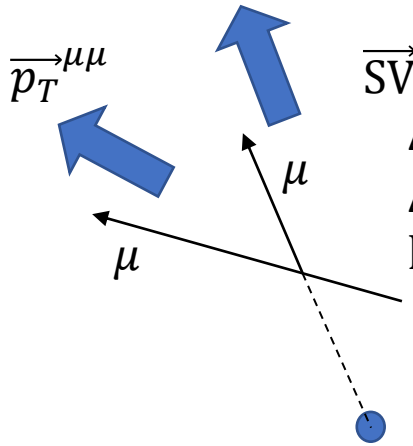
- Data scouting
  - 3kHz dimuon trigger, ~1/1000 event size
- Dimuon vertices in the ID ($l_{xy} < 11\text{cm}$)
  - $200\ \text{MeV} < \text{m}_{\mu\mu} < 50\ \text{GeV}$
- Interpret with dark photon and scalar resonance models
- Require displaced vertices
  - $|d_{xy}|/\sigma_{d_{xy}}$
  - $|d_{xy}|/(l_{xy} m_{\mu\mu}/p_T^{\mu\mu})$







Major Backgrounds

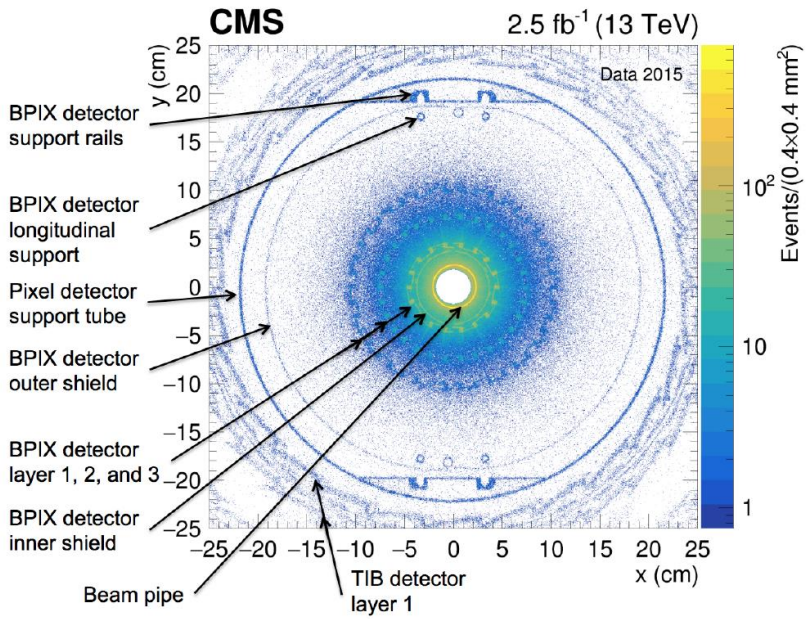


$\Delta\phi(\overrightarrow{p_T}^{\mu\mu}, \overrightarrow{\mathrm{SV}}) < 0.02\ (0.1)$

$\Delta\phi(\mu_1, \mu_2) < 2.8$

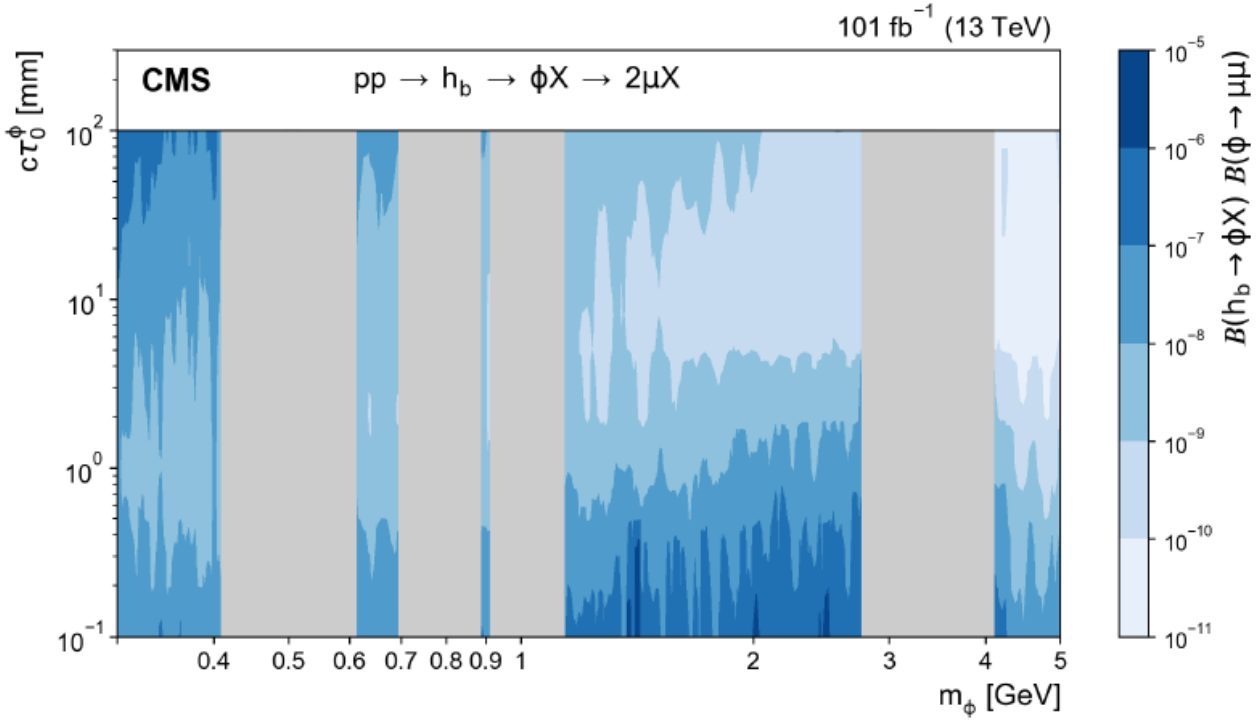
$\log_{10}(|\Delta\eta_{\mu\mu}|/|\Delta\phi_{\mu\mu}|) < 1.25$

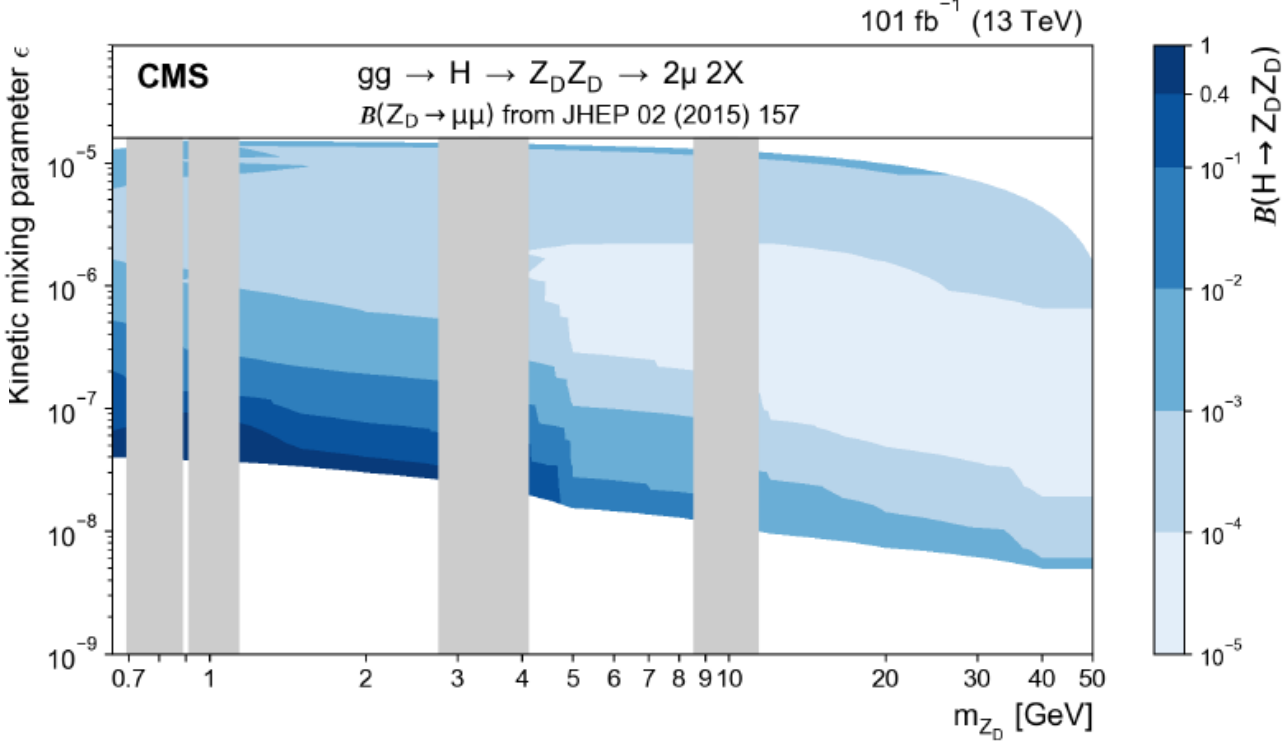
- Accidental crossings, cosmics
  - Vertex selections
- Material interactions
  - Use map to veto vertices near detector material
- Prompt muons
  - Require missing hits (where $l_{xy} > 3.5\mathrm{cm}$)
- Model backgrounds using analytic functions of $m_{\mu\mu}$
  - Mask locations of known SM resonances

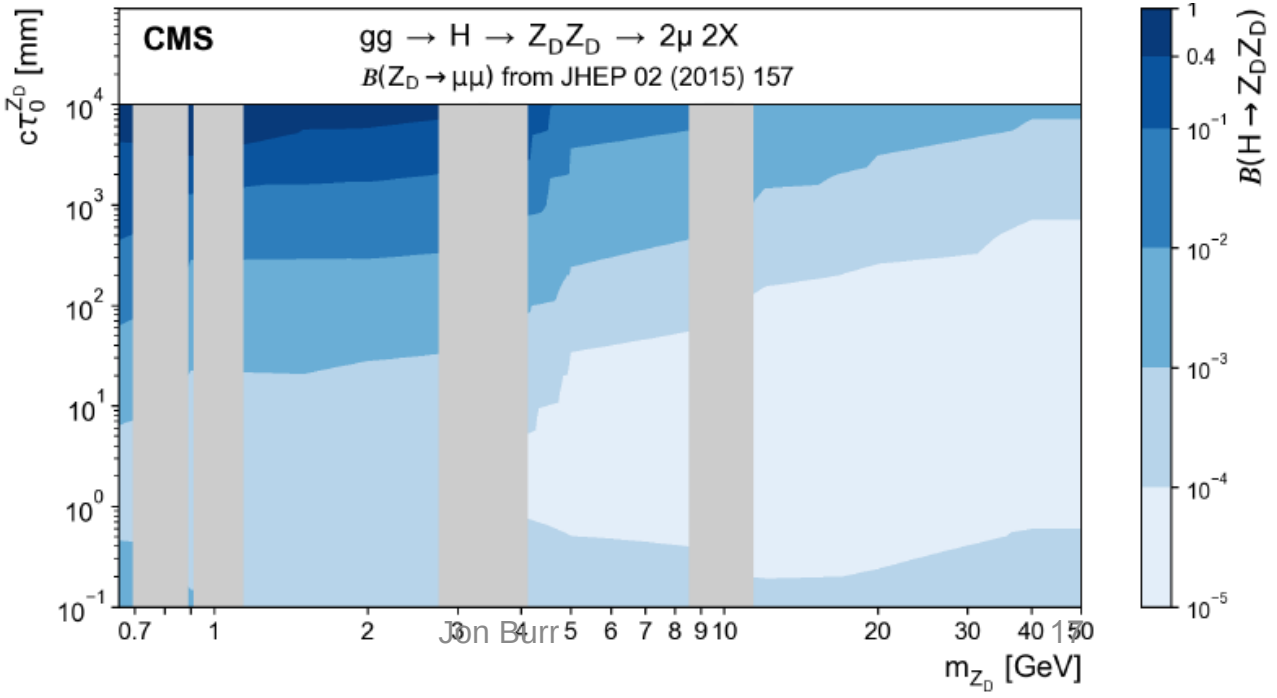


JINST 13 (2018) P10034

Results







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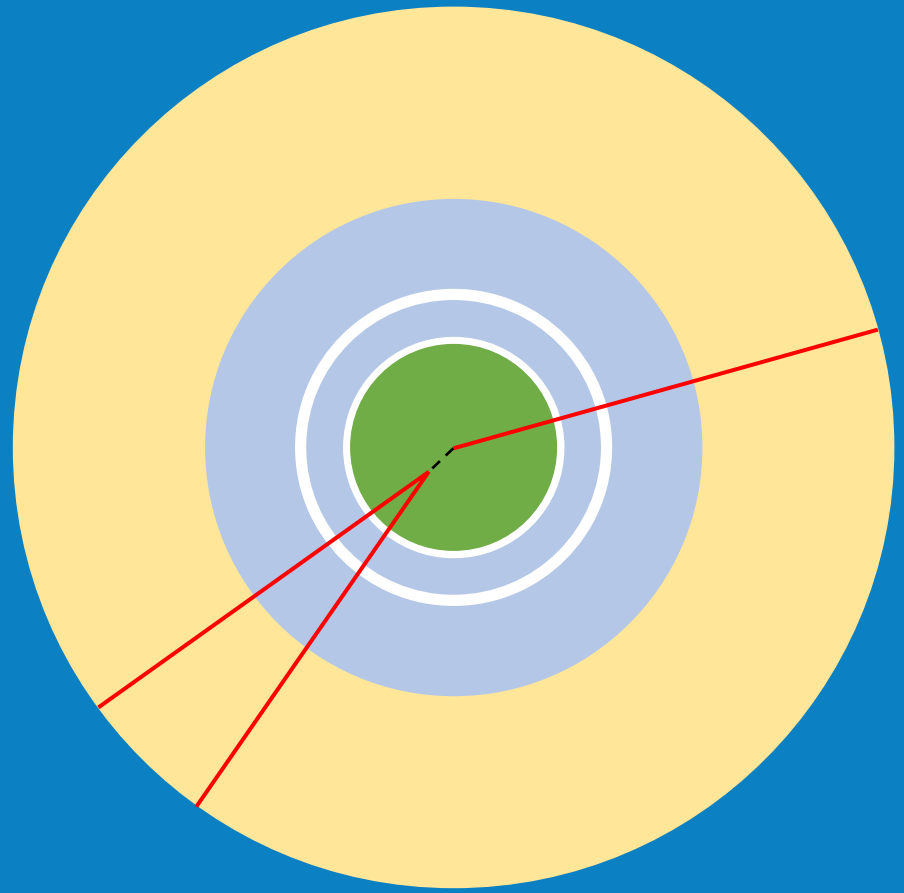
ATLAS EXPERIMENT

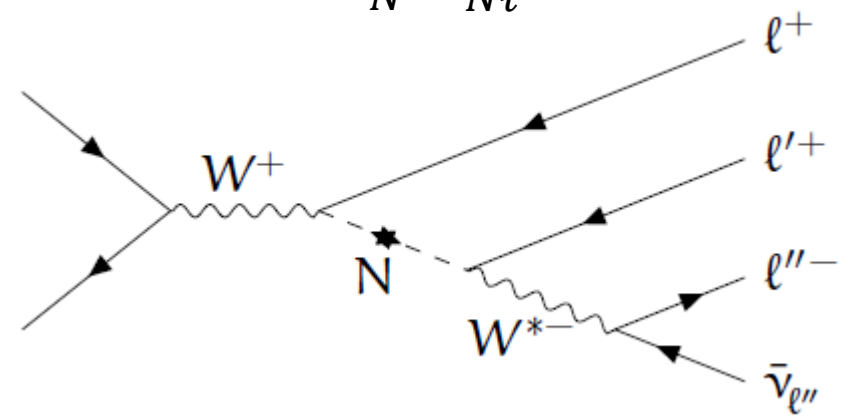
Heavy Neutral Leptons (CMS) [8]

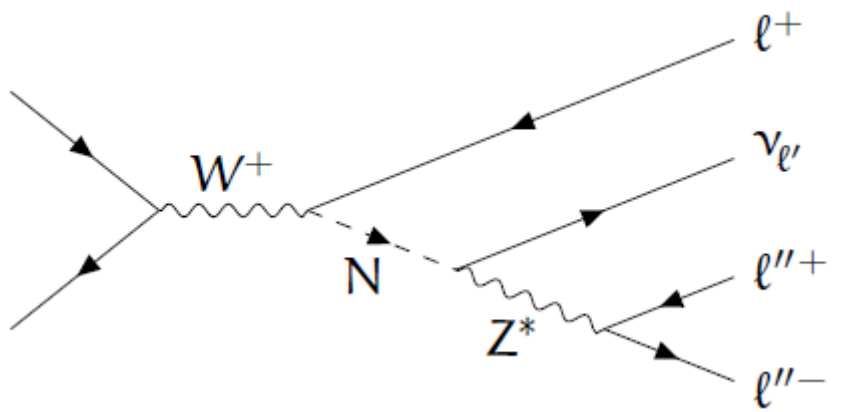


Overview

$$\tau \propto m_N^{-5} V_{N\ell}^{-2}$$

- Search for HNLs
  - Assume N couples to 1 generation => $\ell = \ell'$
- Trigger on prompt lepton from IP
- Split events into categories based on
  - Lepton flavours
  - Vertex displacement
  - $m_{\ell\ell}$
- Main backgrounds
  - π, K, B hadron decays, unidentified photon conversions
  - SM resonances
- Similar ATLAS analysis => YSF talk





$m(\ell_2\ell_3)$ (GeV)	<4				>4	
Δ_{2D} (cm)	<0.5	0.5–1.5	1.5–4	>4	<0.5	>0.5

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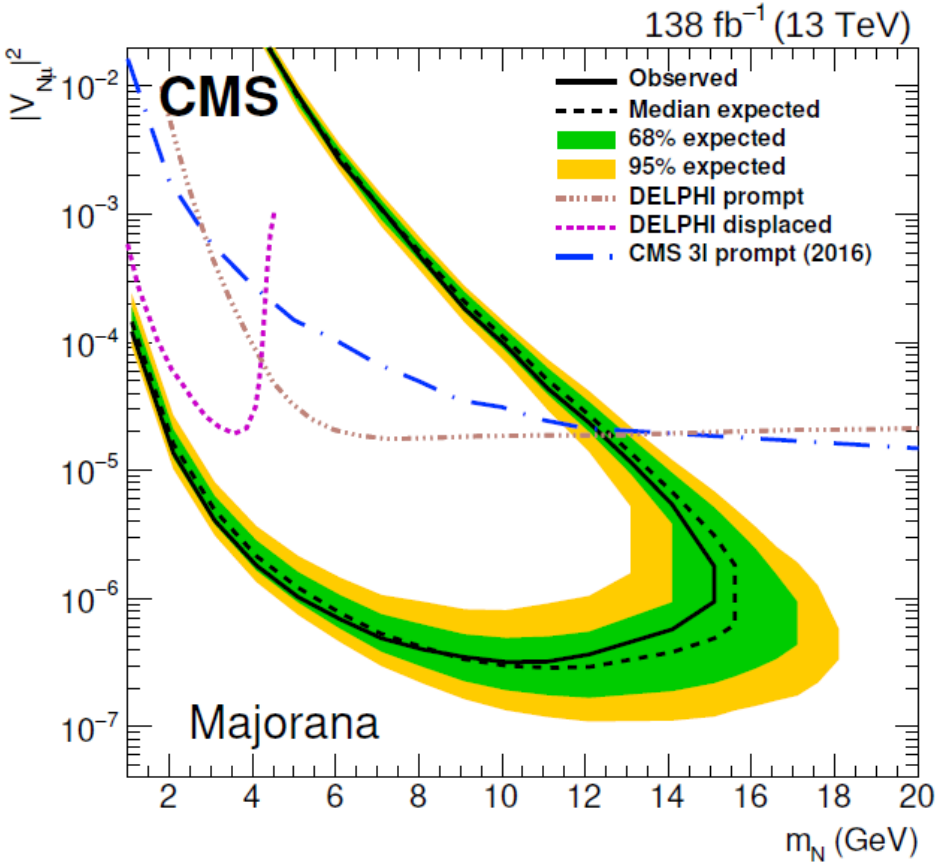
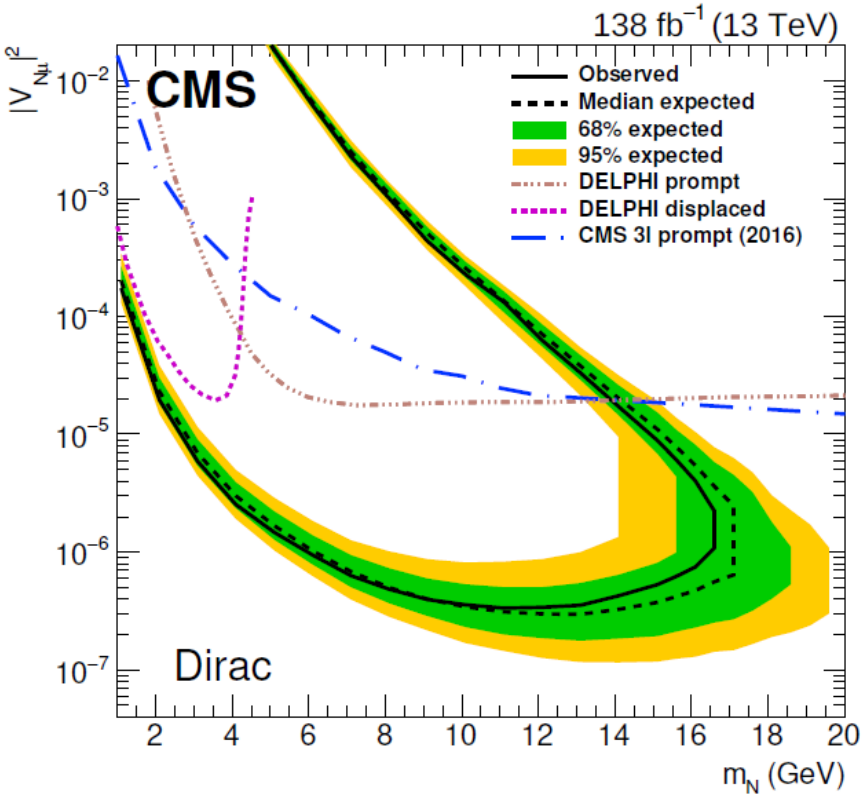
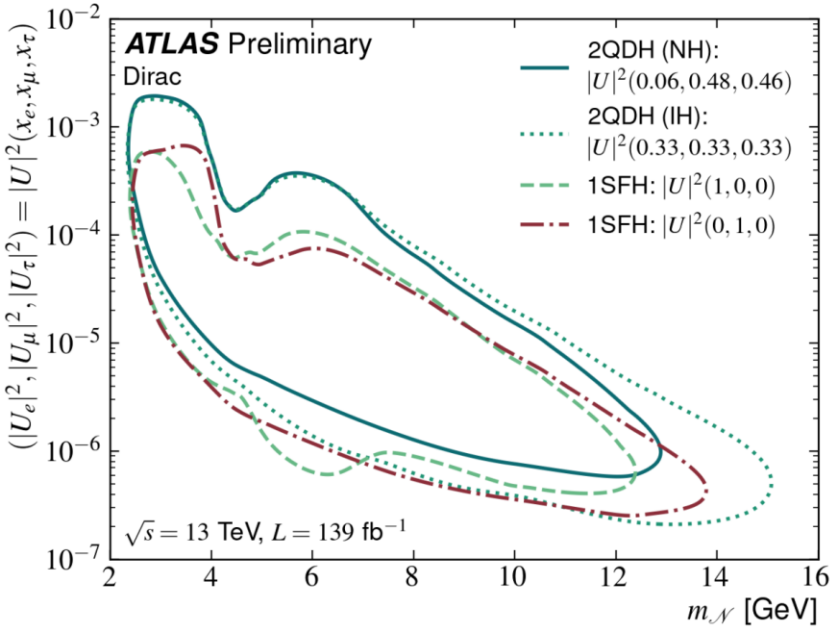
ATLAS EXPERIMENT

CMS

Results







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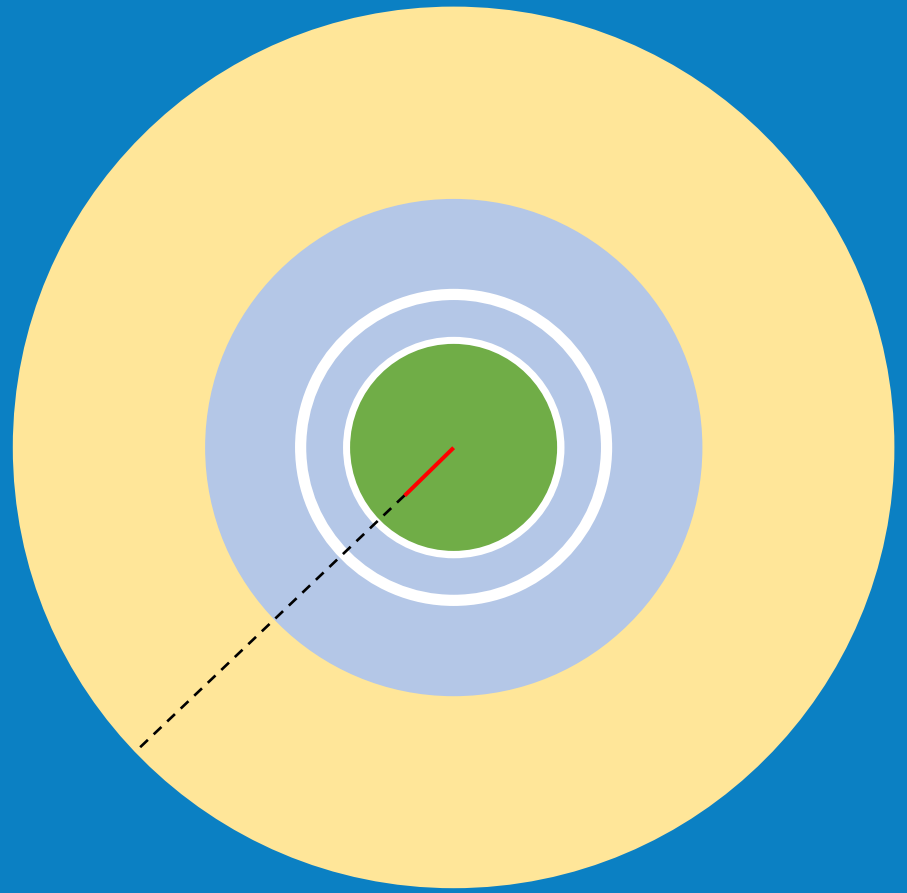
ATLAS EXPERIMENT

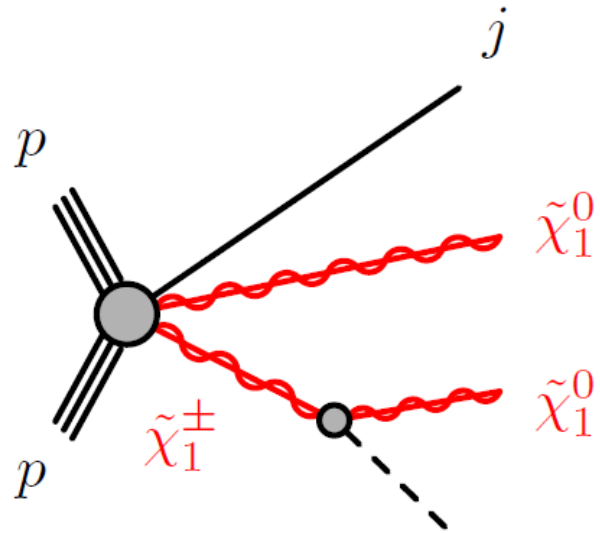
CMS

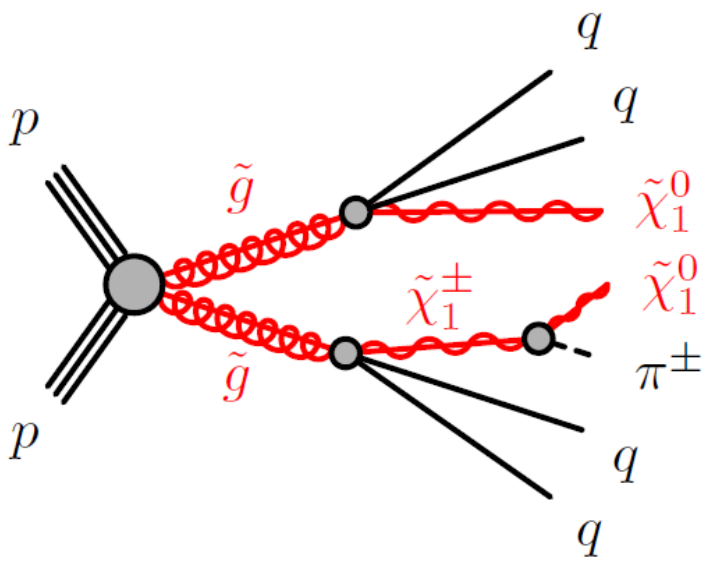
Disappearing Track (ATLAS) [9]



Overview

- Search for charged SUSY LLPs decaying in the ID
- Nearly conserved symmetry => small mass splittings (few 100 MeV)
  - $\pi^{\pm}$ falls below track reconstruction threshold
  - AMSB pure wino $c\tau \sim 58\text{mm}$
  - ‘natural’ pure Higgsino $c\tau \sim 10\text{mm}$
- Require >4 pixel hits => $l_{xy} > 122\text{mm}$
- Use $E_{\text{T}}^{\text{miss}}$ trigger to select signal events





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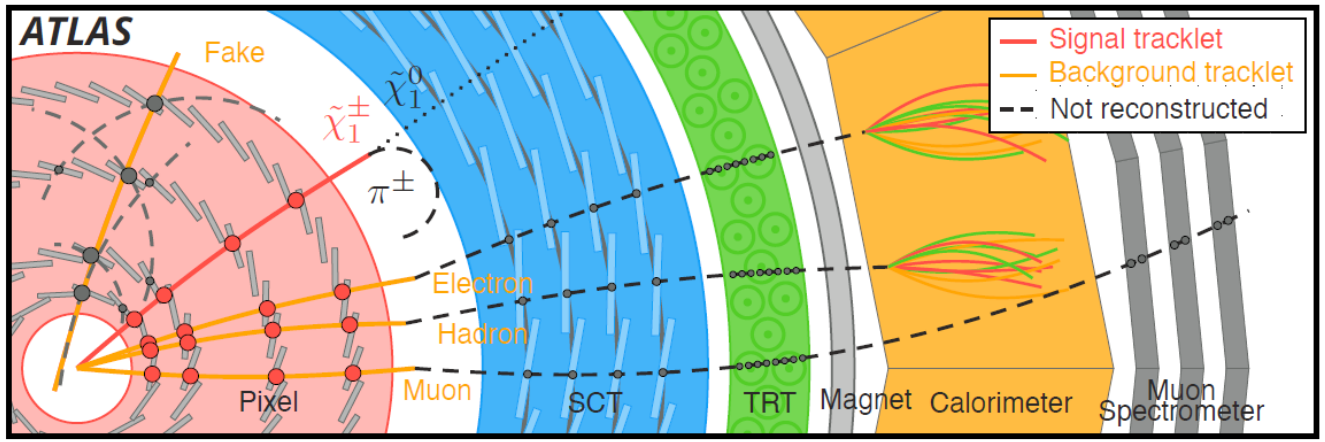
ATLAS EXPERIMENT

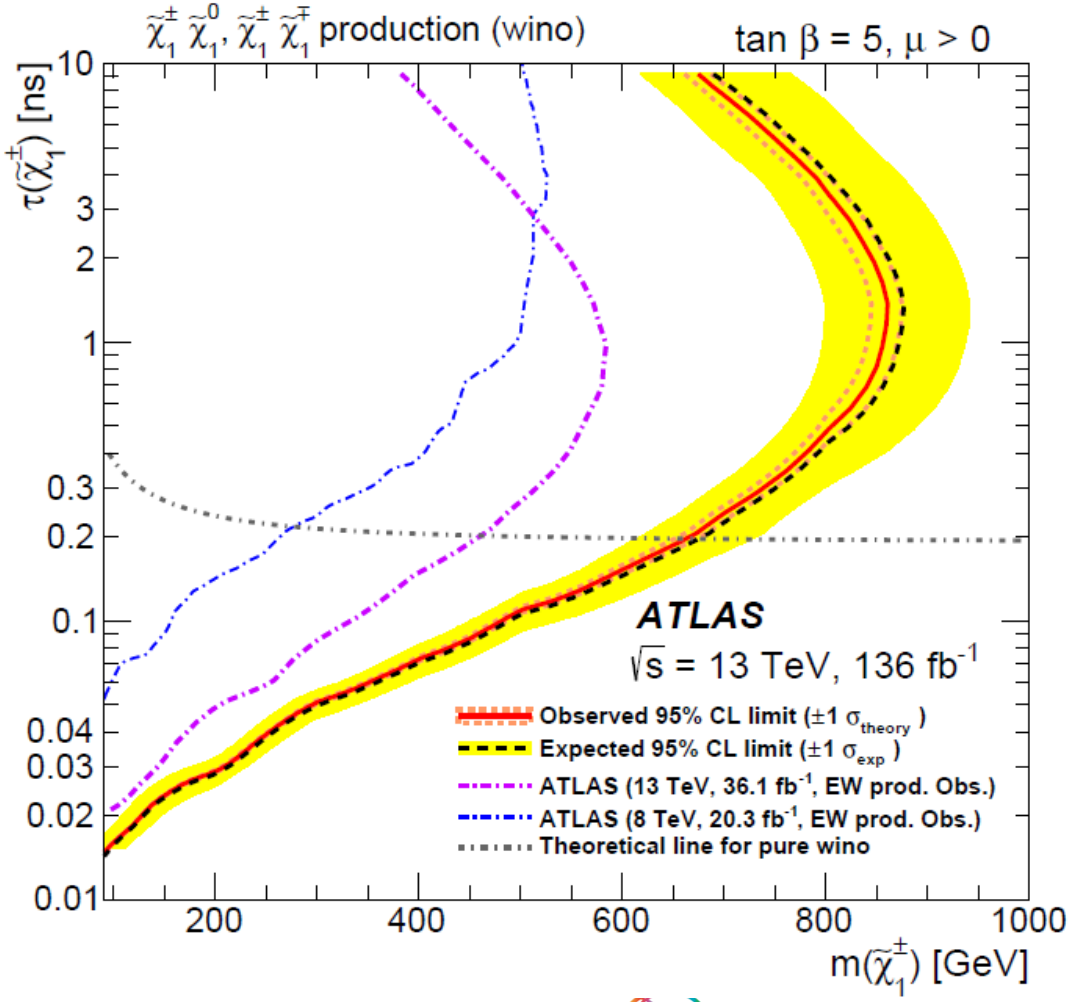
CMS

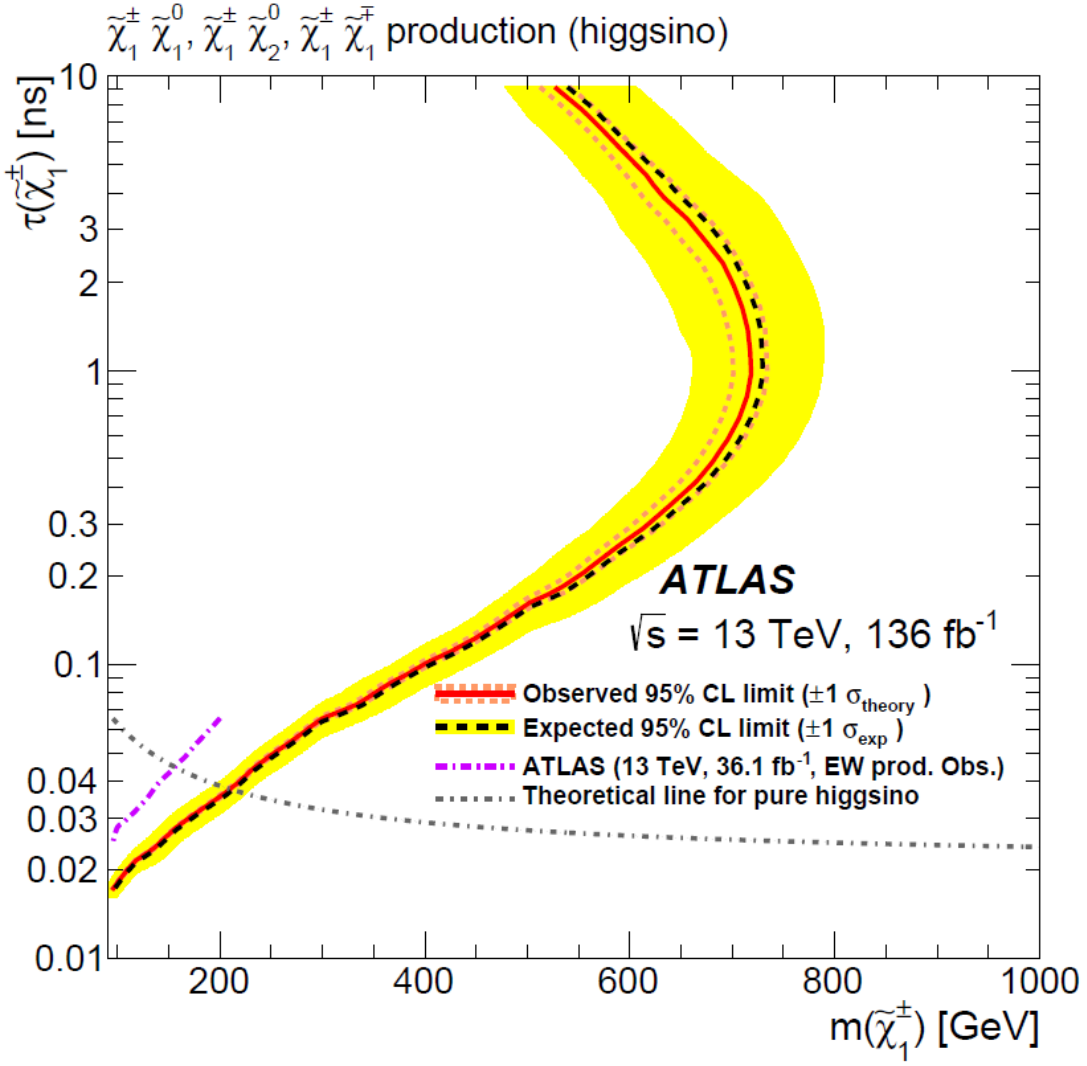
Selections and major backgrounds

- Dedicated quality selection for tracklets, require isolation
  - Isolate from other tracks, electrons, muons and calo energy
- Charged particle scattering ($t\bar{t}$, $W \to \ell\nu$)
  - Estimate with $Z \to \ell\ell$ tag and probe
- Combinatorial (fake tracklet)
  - Estimate in high $|d_0|$ region



Results





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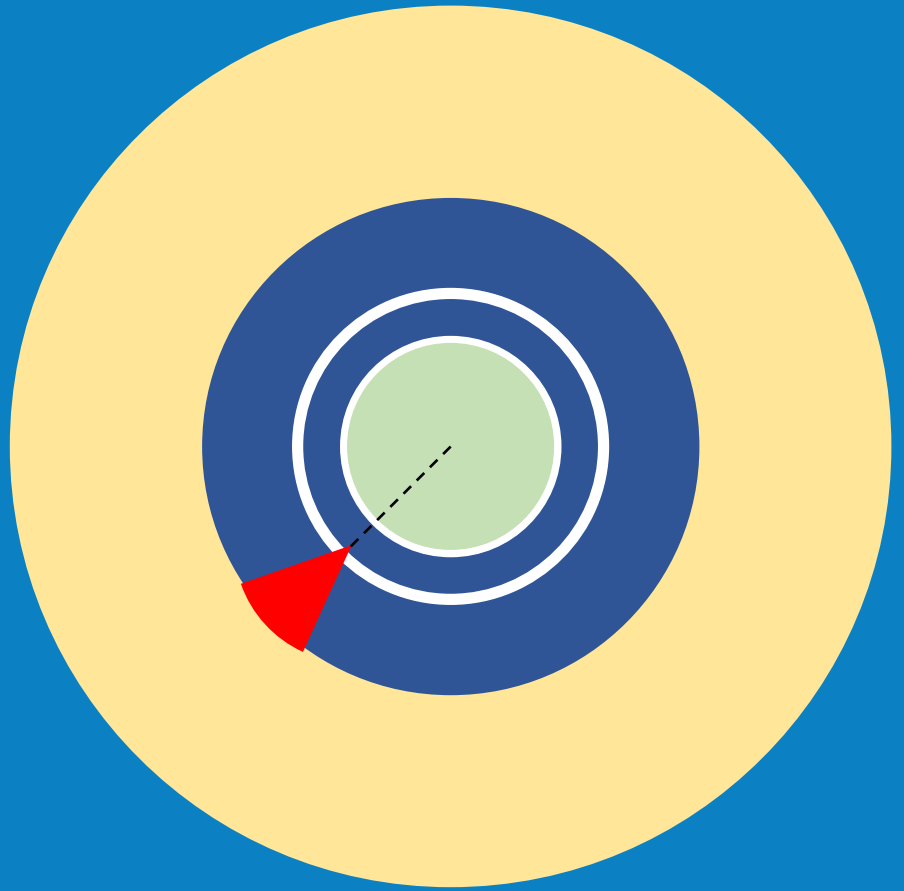
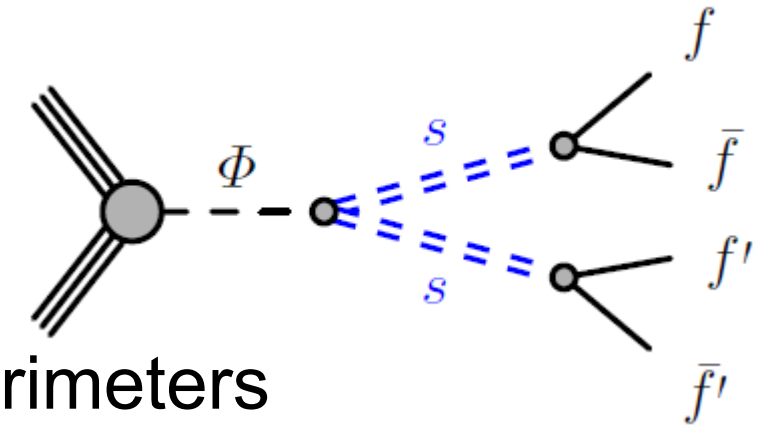
ATLAS EXPERIMENT

CMS

Calorimeter Ratio (ATLAS) [10]



Overview



- Search for LLPs decaying to jets inside the calorimeters
  - Narrow jets with few tracks and high $E_{\mathrm{H}}/E_{\mathrm{EM}}$ (CalRatio)
- Benchmark using hidden sector (HS) model
  - SM and HS connected by heavy neutral boson Φ (can be SM Higgs)
  - Long-lived neutral scalar s decays dominantly to heaviest available fermion
- Data collected with dedicated 'CalRatio' triggers
  - L1: 'Low E_T' $E_T > 30\mathrm{GeV}$, isolated from EM calorimeter deposits
  - L1 'High E_T' $E_T > 60\mathrm{GeV}, 100\mathrm{GeV}$ in 0.2×0.2 $(\Delta\eta \times \Delta\phi)$
  - HLT: Dedicated cleaning, high $E_{\mathrm{H}}/E_{\mathrm{EM}}$, low tracker activity

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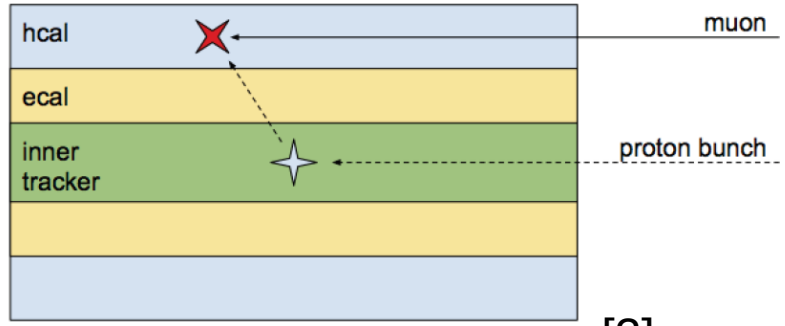
ATLAS EXPERIMENT

CMS

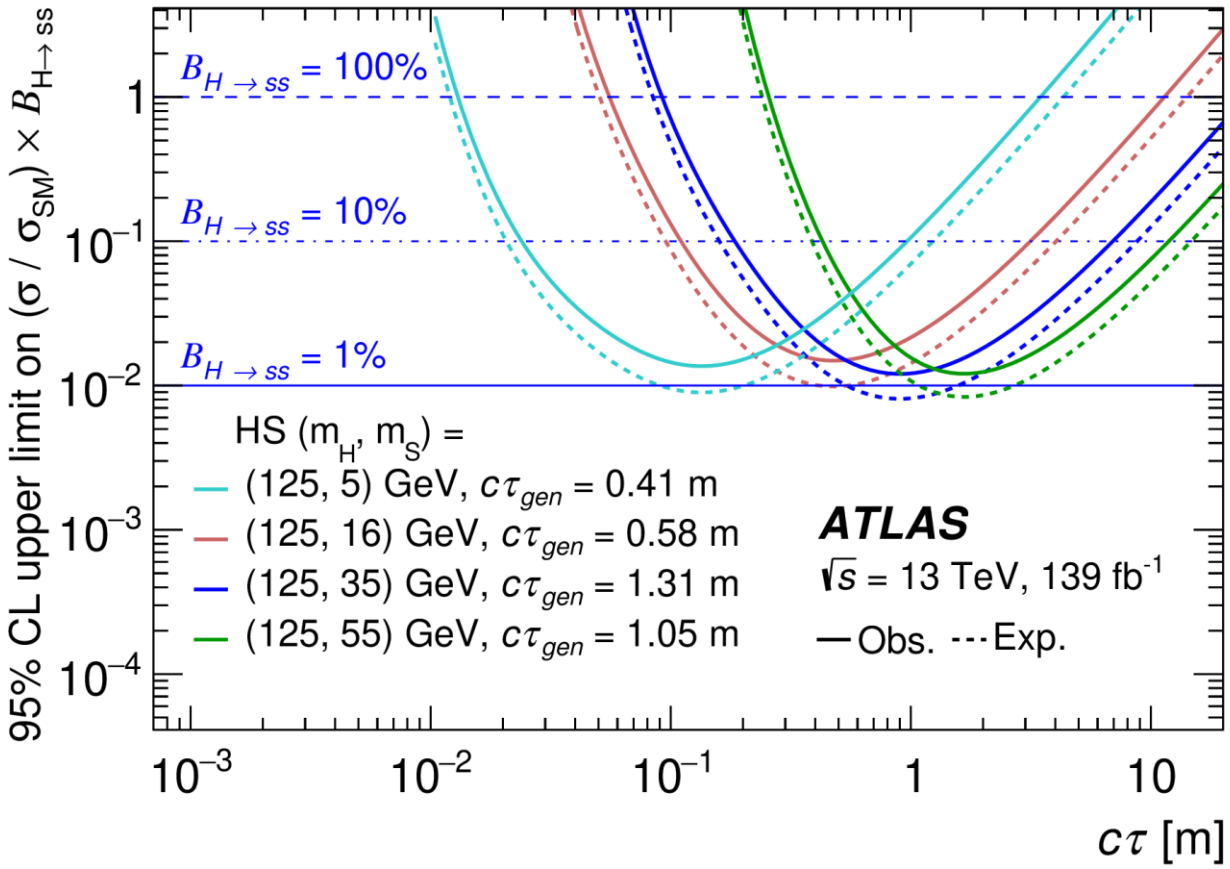
Selections and major backgrounds

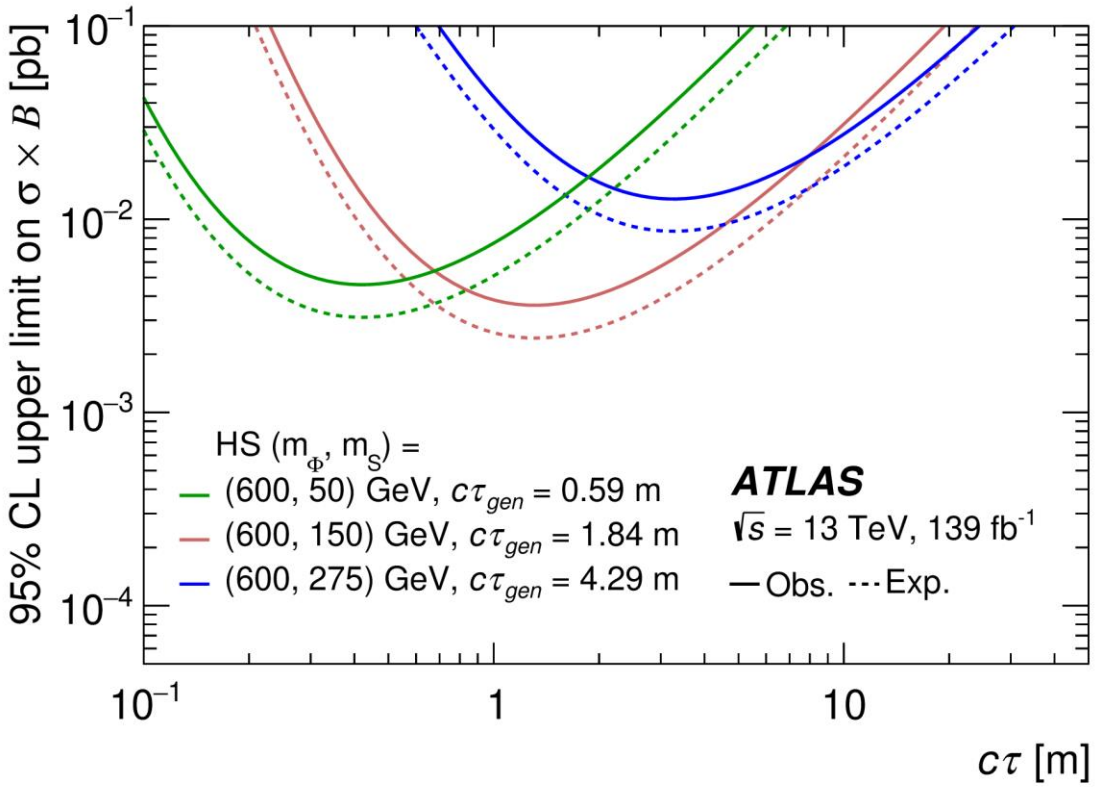


[2]

- BIB, QCD multijets
  - Train a NN to discriminate BIB, QCD and displaced signal jets
  - Input variables: timing, ID/MS track info, calorimeter topoclusters, energy per calorimeter layer
  - Use adversarial net to correct for difference between MC and data
- Event-level BDT designed to separate signal from BIB
- Two versions of NN and BDT, low E_T and high E_T

Results





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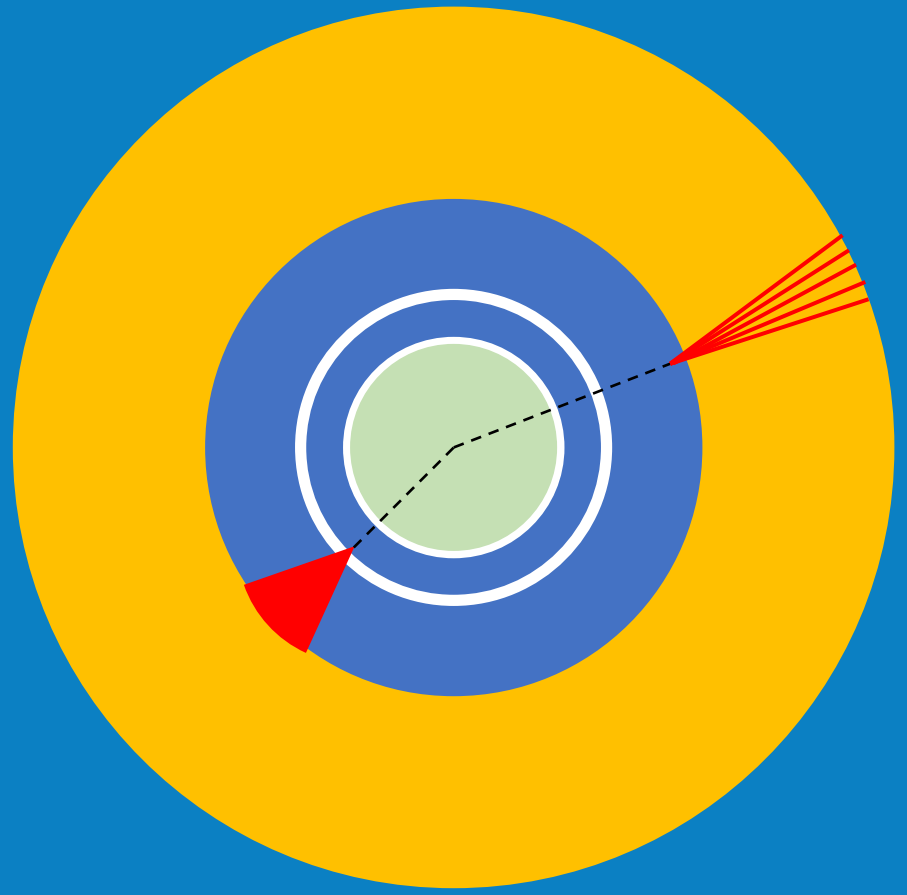
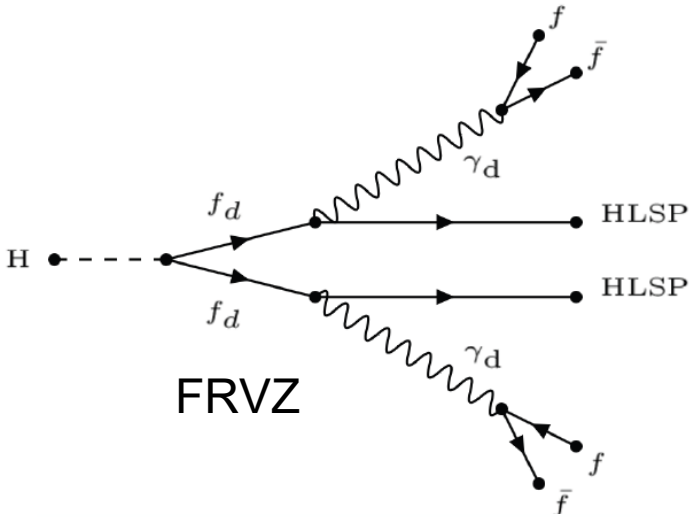
Displaced Leptons/Hadrons (ATLAS) [11]

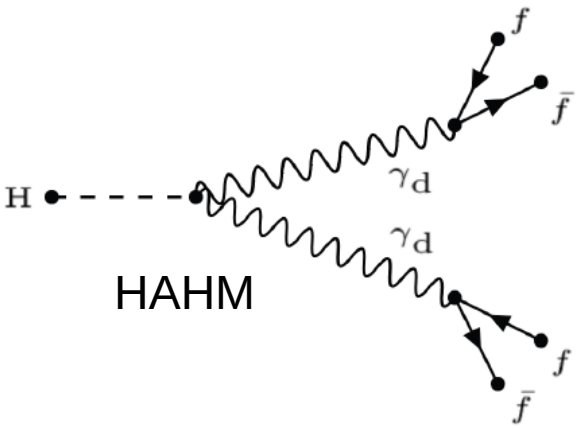


Overview

- Search for LLPs decaying to fermions in the calorimeter or MS
- Interpret using dark photon model
- Consider ‘ggF’ and ‘WH’ selections
  - ggF: use LLP triggers; CalRatio or muons without tracks in the ID
  - WH: use prompt lepton triggers
- Consider μ Dark Photon Jets (μDPJ) and caloDPJs

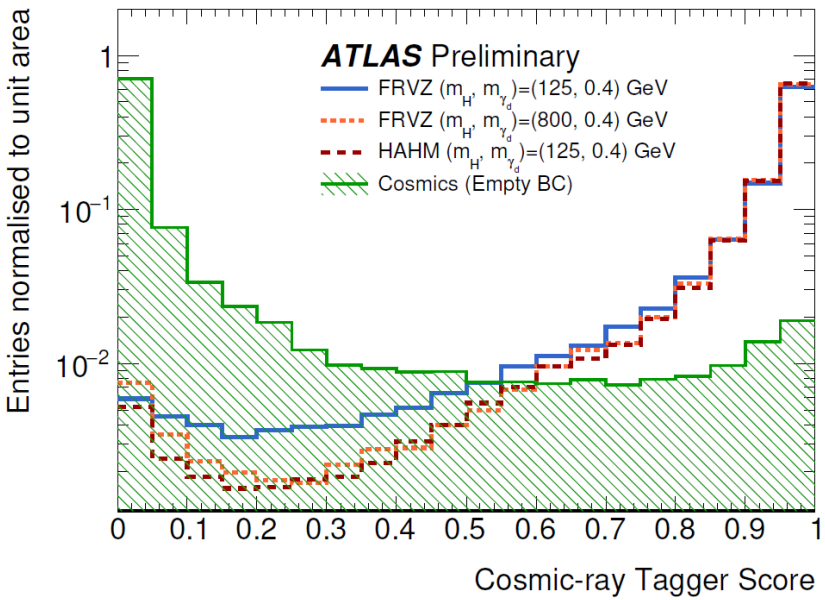


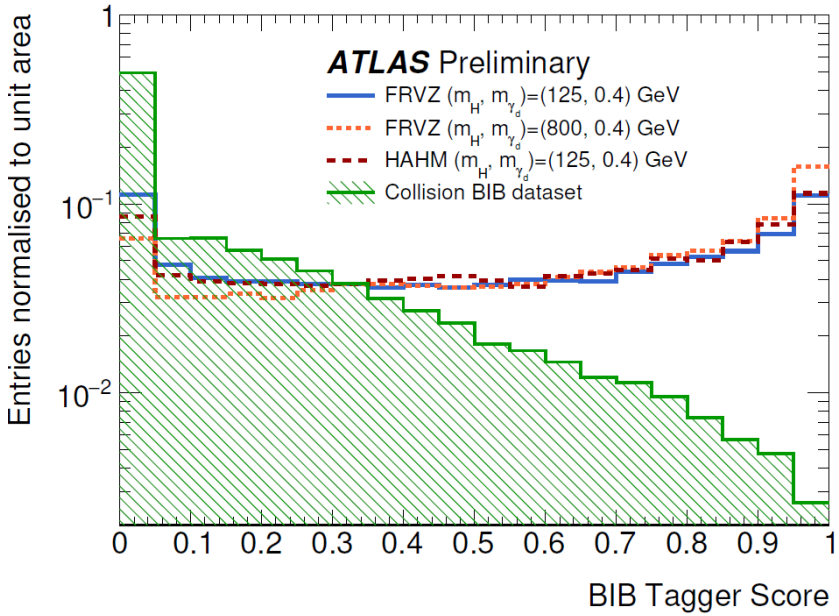
FRVZ

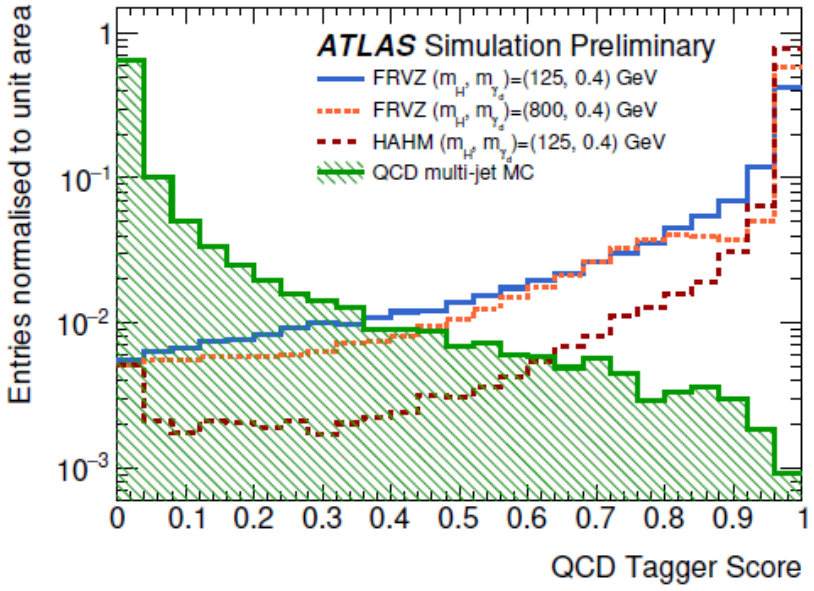


HAHM

Major backgrounds







μDPJs
Per-track DNN: timing, z_0, η, ϕ

Calo DPJs
Per jet CNN using calorimeter cells

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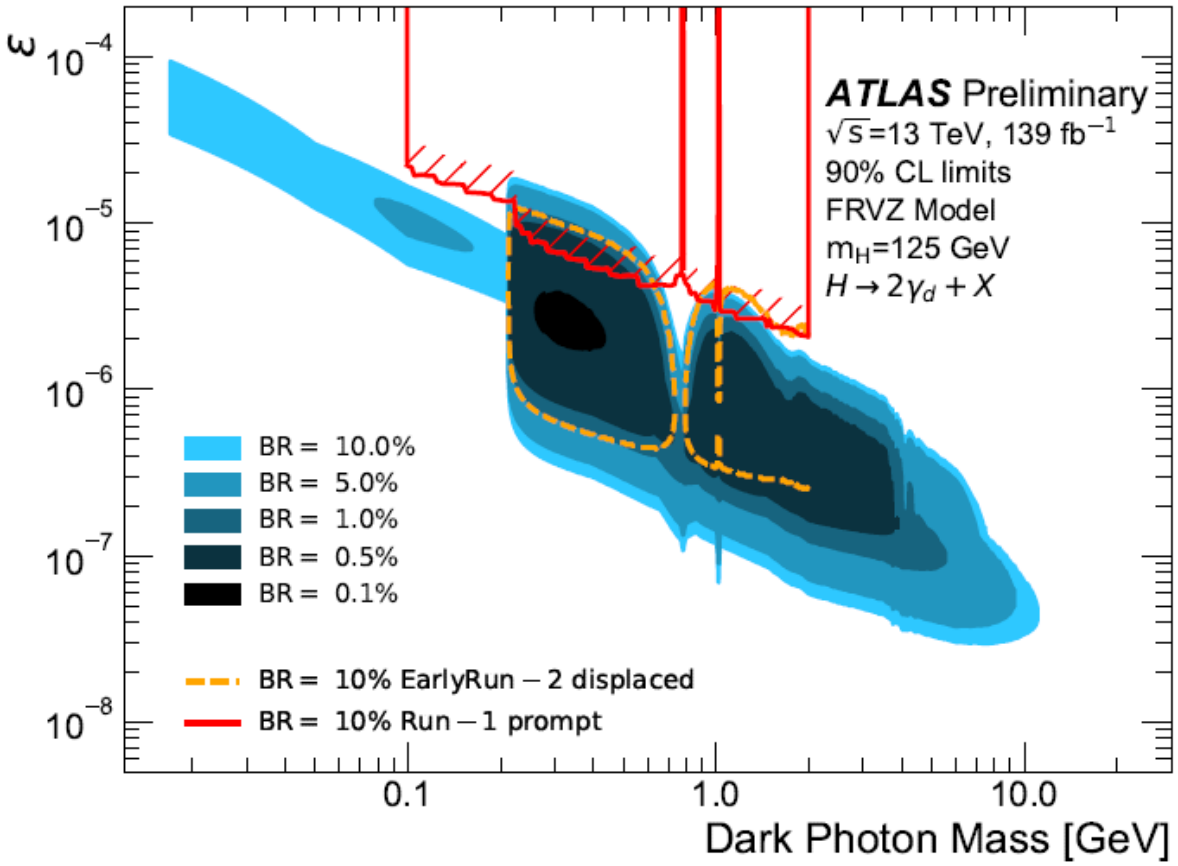
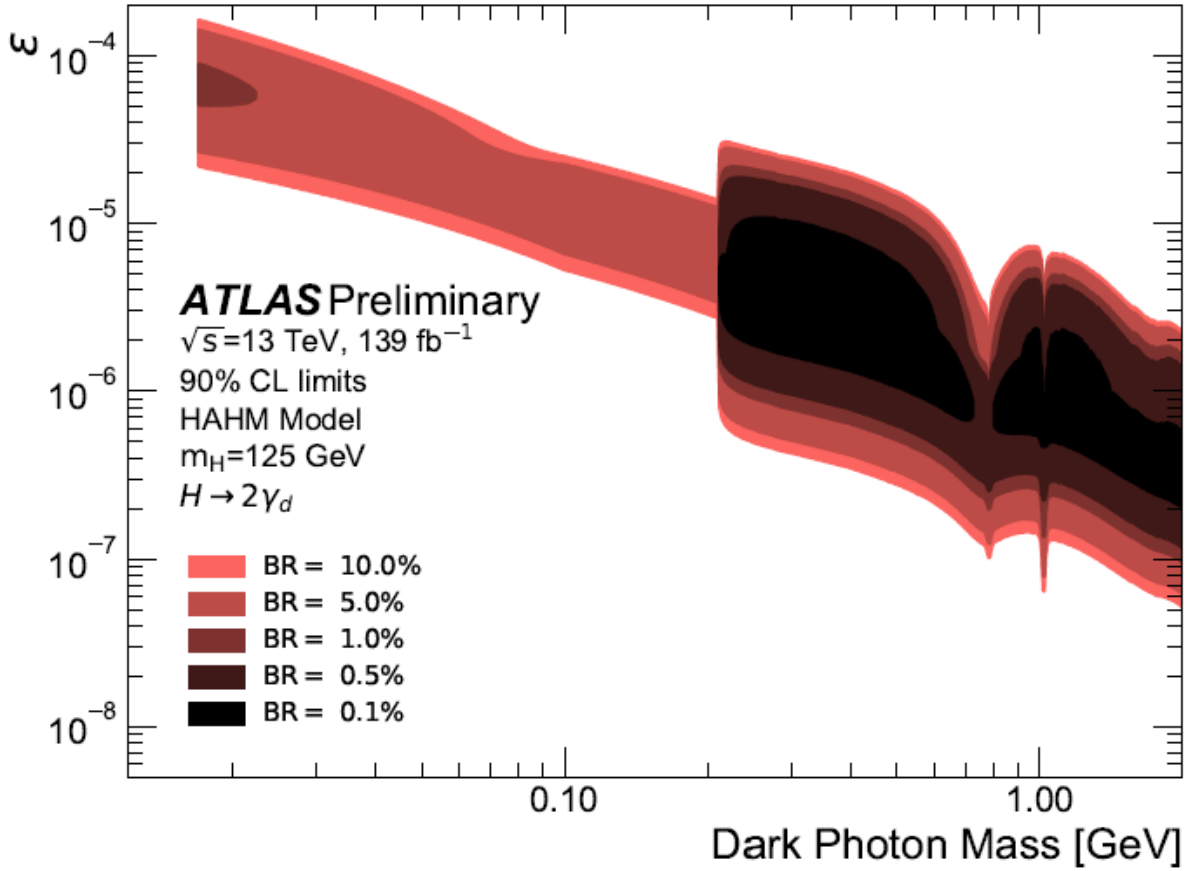
ATLAS EXPERIMENT

CMS

Results





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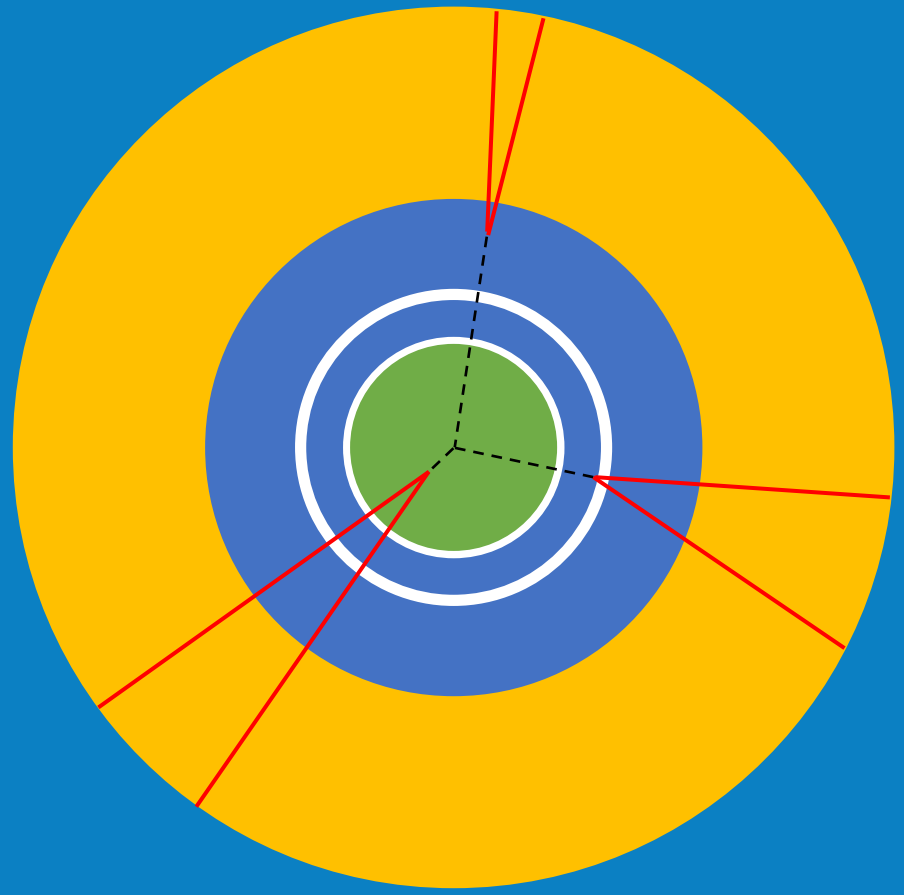
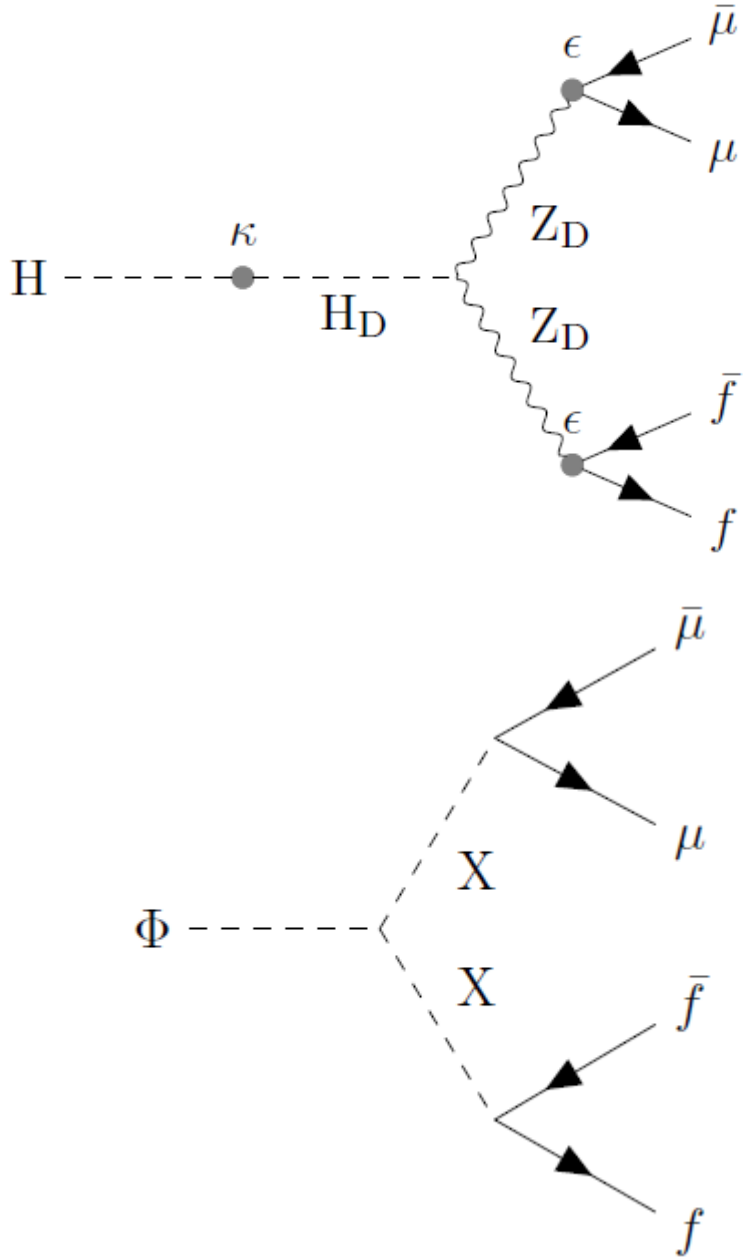
Muon Pairs (CMS) [12]



Overview

- Search for displaced vertices from muon pairs in the entire detector
- Interpret using dark photon and simplified scalar portal models
- Select data using MS-only dimuon triggers
- Match MS-only standalone (STA) muons to tracker+MS (TMS) muons and use TMS when available



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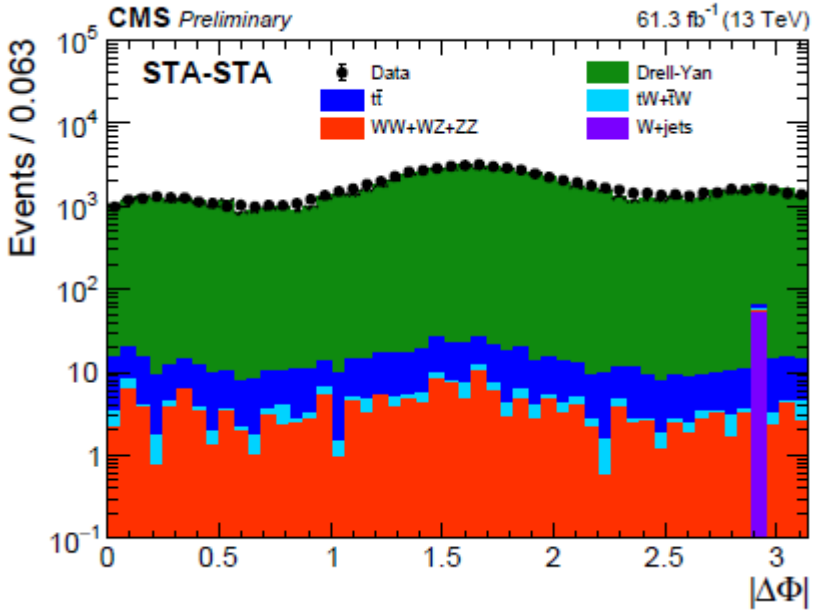
ATLAS EXPERIMENT

CMS

Major Backgrounds



- QCD punch through
  - Removed through isolation selections
- Cosmics
  - Remove back-to-back muons, remove events with multiple parallel muons (cosmic ray showers)
- SM resonances, B meson cascade decays
  - Require $m_{\mu\mu} > 10\mathrm{GeV}$
- Mismeasured prompt muons (mostly DY $\mu\mu$, $\tau\tau$)
  - $\Delta\Phi = \Delta\phi\left(\overrightarrow{p_T}^{\mu\mu}, \overrightarrow{\mathrm{SV}}\right)$
  - Use approximate $\Delta\Phi$ symmetry to predict background

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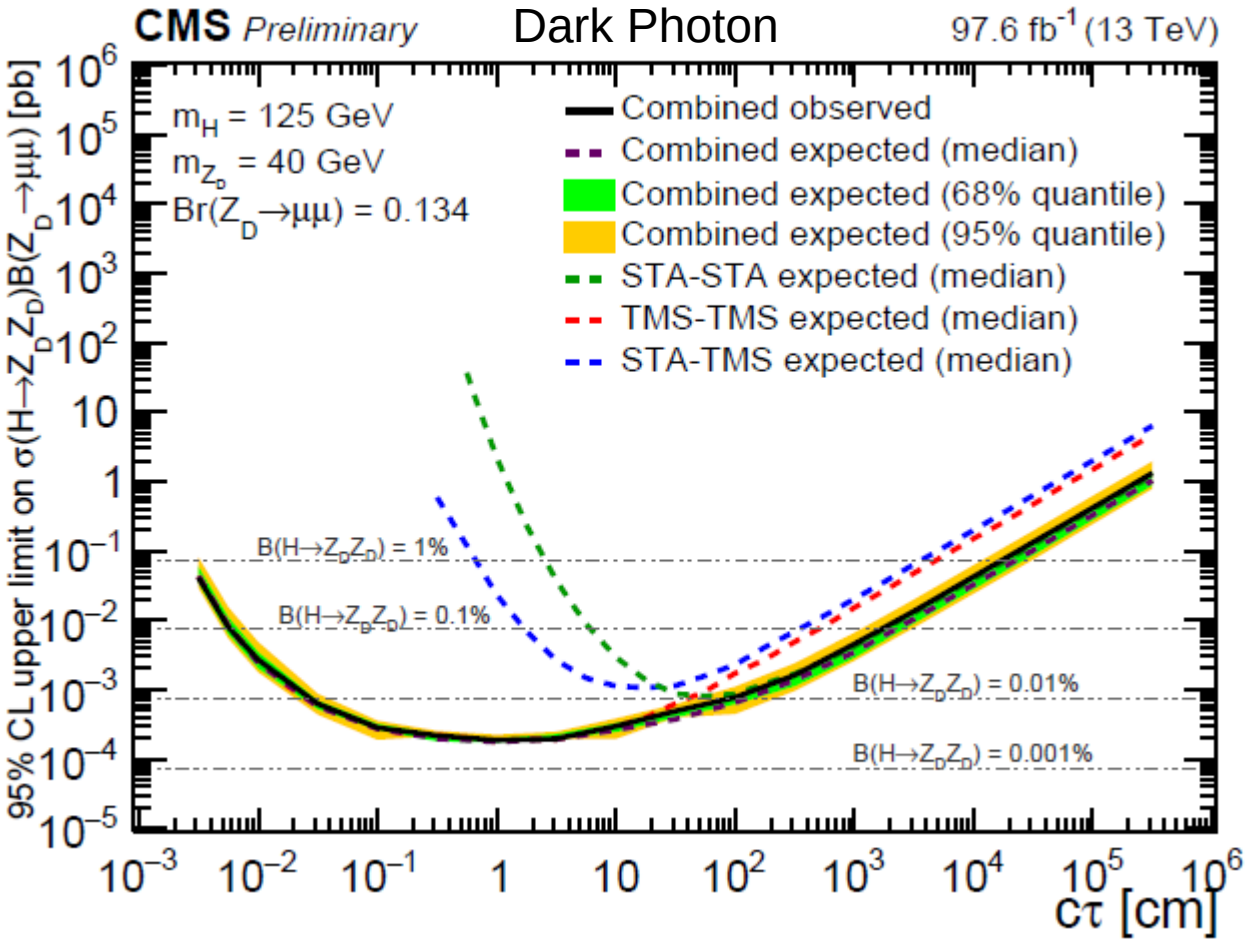
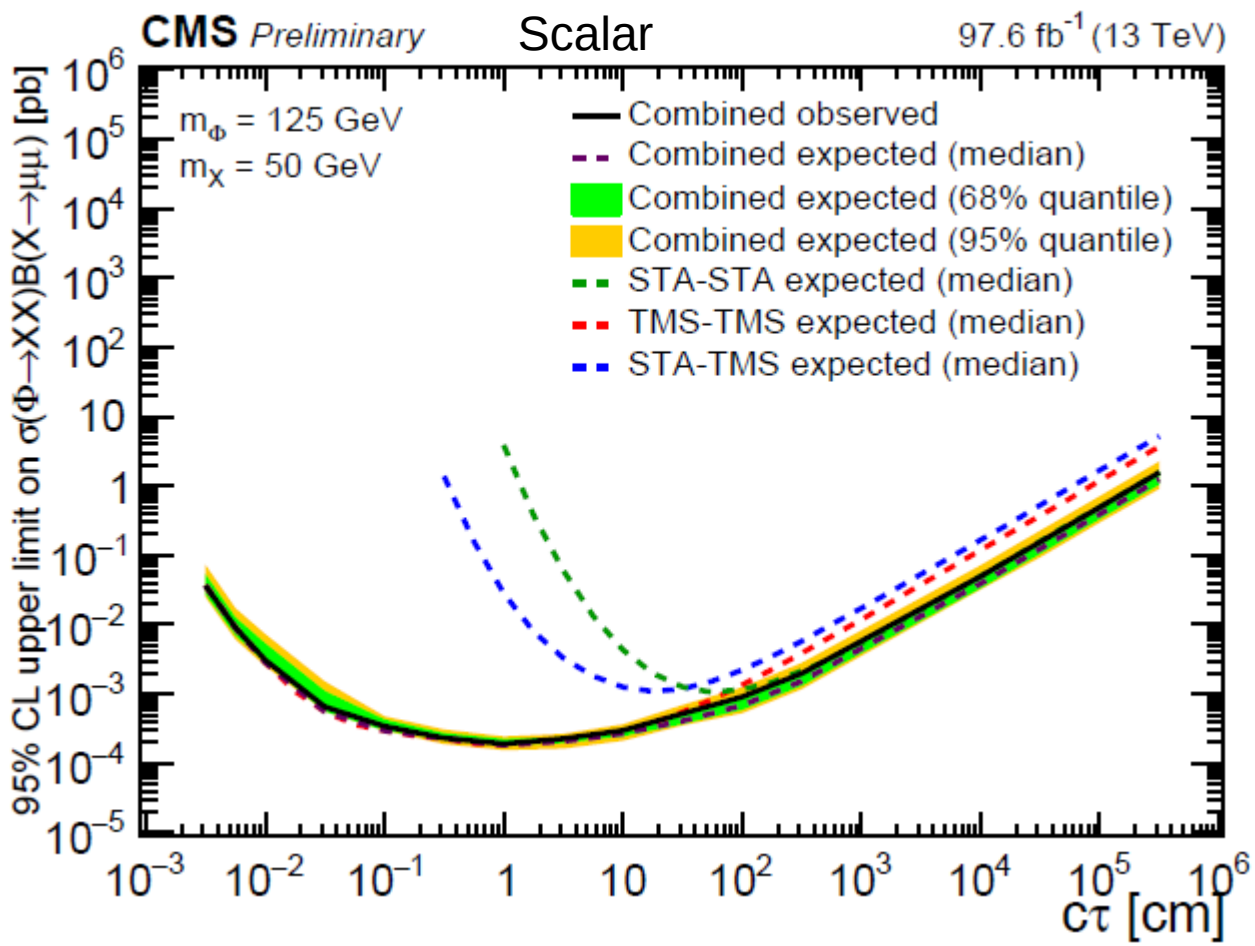
CMS

Results





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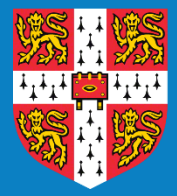
CMS



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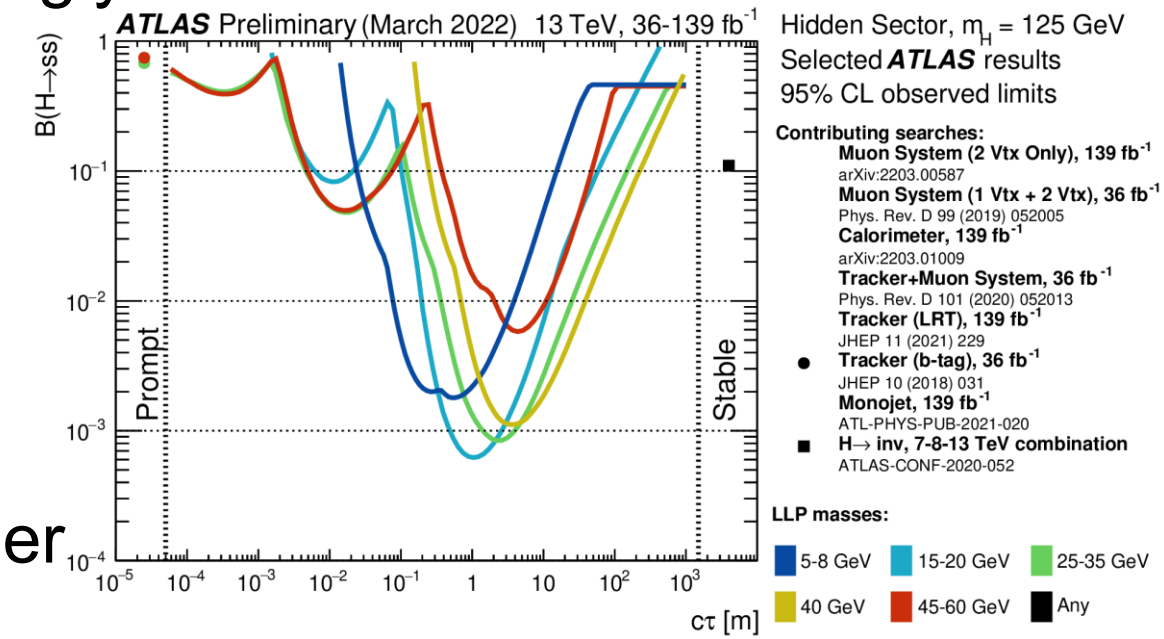
Conclusions and Outlook

Summary

- LHC DM searches continue to probe a hugely varied model space
- Many models (e.g. dark/hidden sectors) can generate both DM and LLPs
- LLP searches are becoming increasingly common
  - Many new results, with others in the pipeline
- Many interesting and challenging backgrounds, often common to multiple searches
  - LHC LLP working group white paper [2] summarizes many of these
- New dedicated Run 3 triggers will allow extending sensitivity even further



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Outlook: Beyond the main experiments

MATHUSLA

CODEX-b

AL3X

ANUBIS

FASER

SHiP
Search for Hidden Particles

milliQan

MoEDAL

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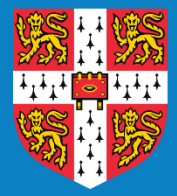
ATLAS EXPERIMENT

CMS



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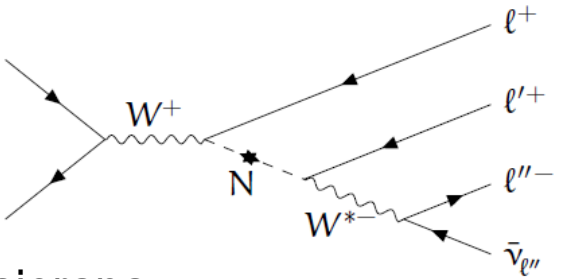
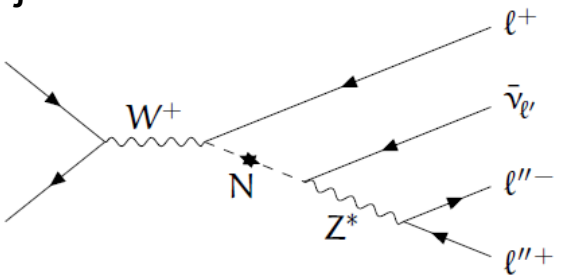
BACKUP

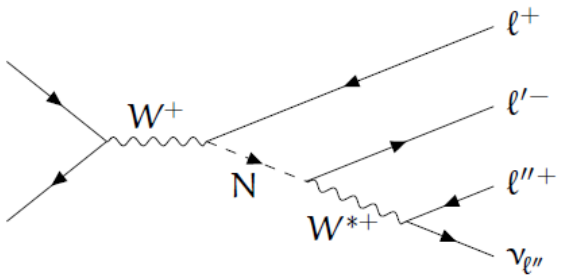
Heavy Neutral Leptons

- Interact only through mixing with SM neutrinos
  - Can help explain low neutrino masses through see-saw mechanism
- Can contribute to CP-violation
- => mass scale of 10 GeV, $10^{-11} < \left|V_{N\ell}^2\right| < 10^{-5}$
- $\tau \propto m_N^{-5} V_{N\ell}^{-2}$

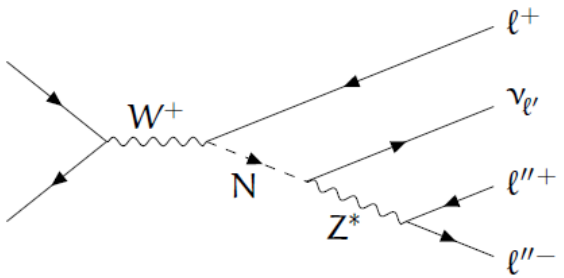


Majorana





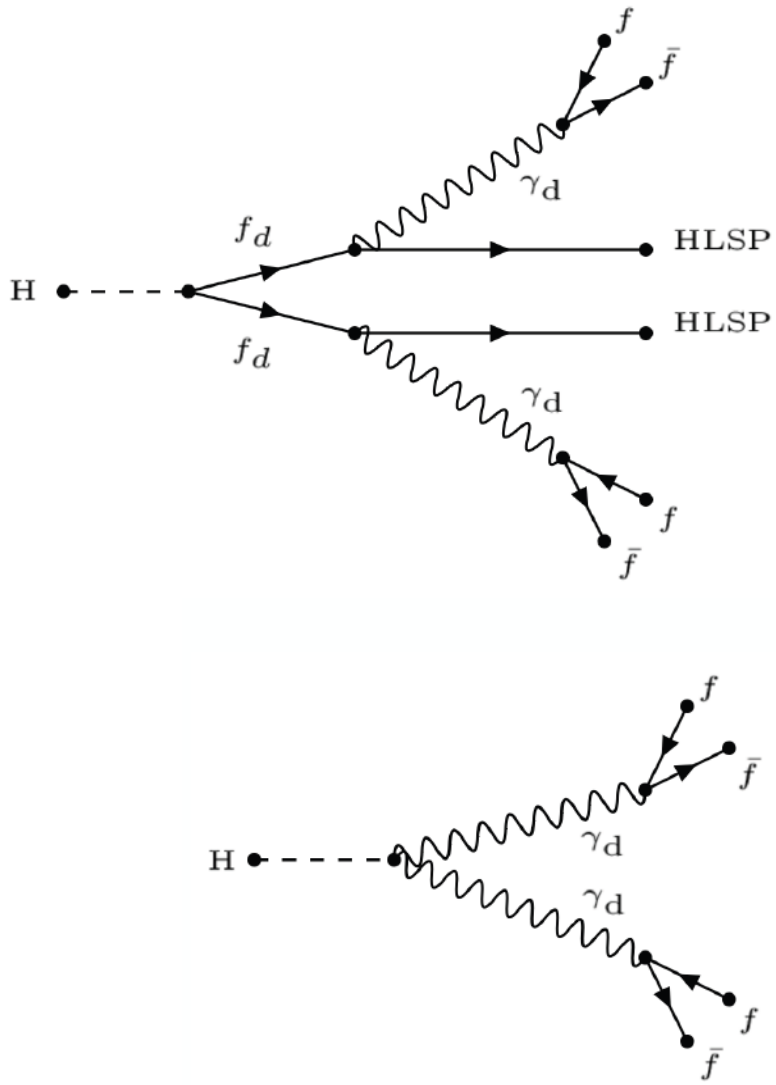
Dirac



[6]

Dark Photons

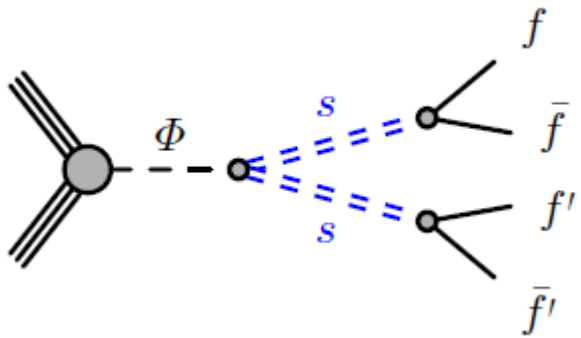
- Dark sector with Higgs portal
- Dark photon mixes with SM γ/Z
- Decays to SM leptons and light quarks
- Lifetime controlled by mixing parameter $10^{-11} < \epsilon < 10^{-2}$



[3]

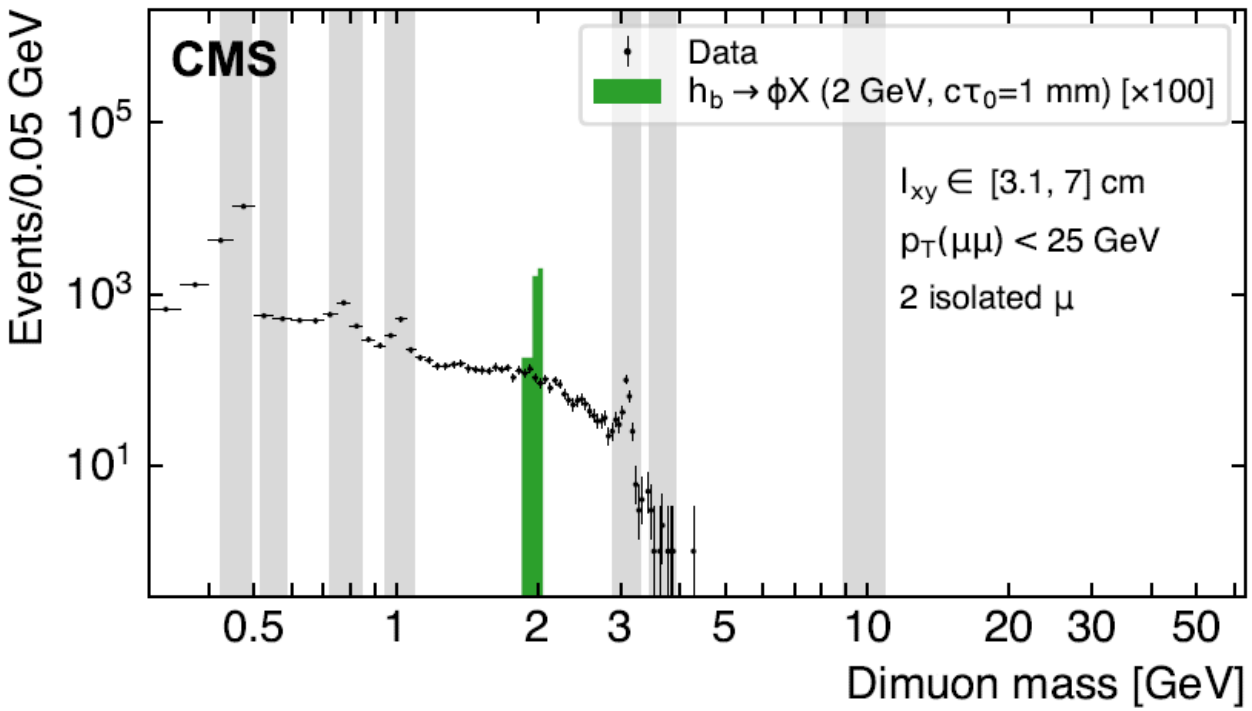
Light Neutral Boson

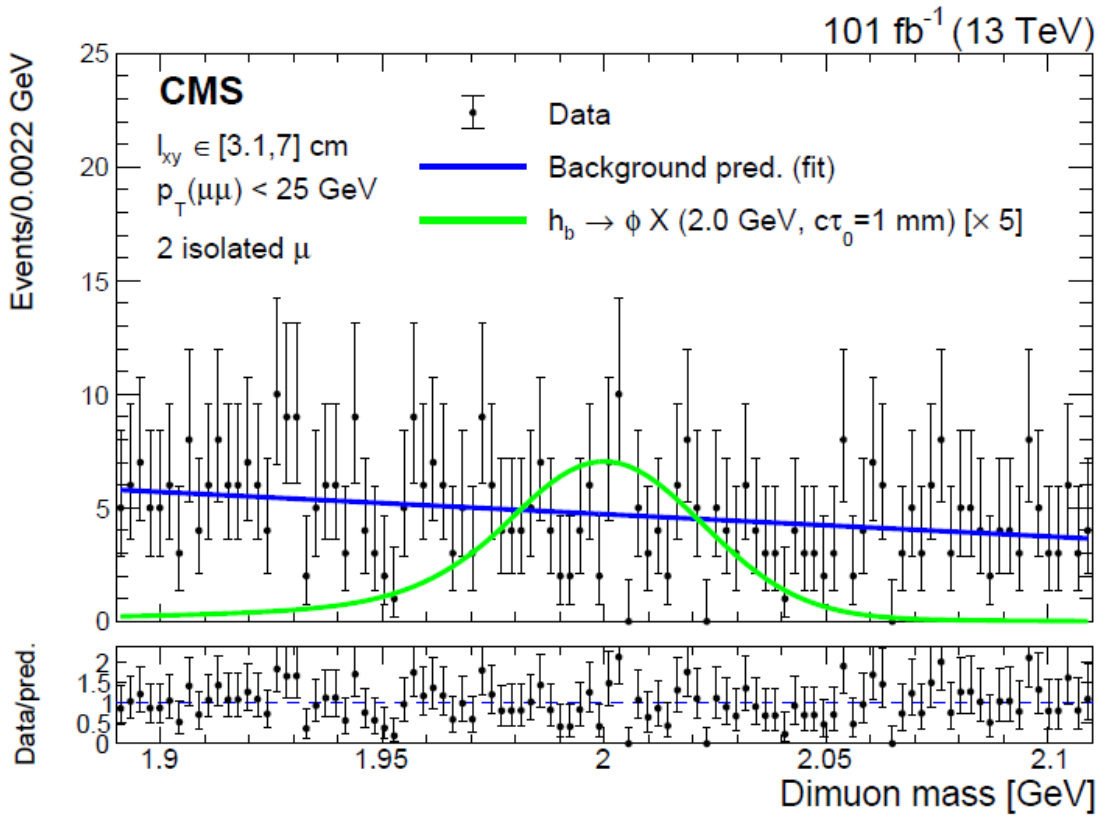
- Hidden sector connected to SM through heavy neutral boson Φ
  - $\Phi$is allowed to be the SM Higgs
- $\Phi \rightarrow ss$ where s is a neutral LLP
- s decays to fermions with the largest BR to the heaviest available species



[8]

CMS Data Stream Muon $m_{\mu\mu}$





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ATLAS EXPERIMENT

CMS

CMS HNL Selections

Selection criteria	
$\Delta R(\ell_2, \ell_3)$	< 1
$\lvert\Delta\phi(\ell_1, \ell_{2/3})\rvert$	> 1
$m(\ell_1\ell_2\ell_3)$	$\in [50,80]$ GeV
number of b jets	$= 0$
$p_{\mathrm{T}}(\ell_2\ell_3)$	> 15 GeV
$\cos\theta(\mathrm{SV}, \ell_2\ell_3)$	> 0.99
p_{SV}	> 0.001
$S(\Delta_{2\mathrm{D}})$	> 20
$m(\ell\ell)$	$\notin$ vetoed ranges

Resonance	Vetoed range (GeV)
ω	0.78 ± 0.08
ϕ	1.02 ± 0.08
J/ψ	3.10 ± 0.08
$\psi(2\mathrm{S})$	3.69 ± 0.08
$\Upsilon(1\mathrm{S})$	9.46 ± 0.08
$\Upsilon(2\mathrm{S})$	10.02 ± 0.08
$\Upsilon(3\mathrm{S})$	10.36 ± 0.08
Z	91.2 ± 10.0

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ATLAS Disappearing Track Selections

Signal region	Electroweak production	Strong production
Number of electrons and muons	0	
Number of pixel tracklets	≥ 1	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 200	> 250
Number of jets ($p_{\mathrm{T}} > 20$ GeV)	≥ 1	≥ 3
Leading jet p_{T} [GeV]	> 100	> 100
Second and third jet p_{T} [GeV]	–	> 20
$\Delta\phi_{\mathrm{min}}^{\mathrm{jet}-E_{\mathrm{T}}^{\mathrm{miss}}}$ (up to 4$^{\mathrm{th}}$ jet with $p_{\mathrm{T}} > 50$ GeV)	> 1.0	> 0.4

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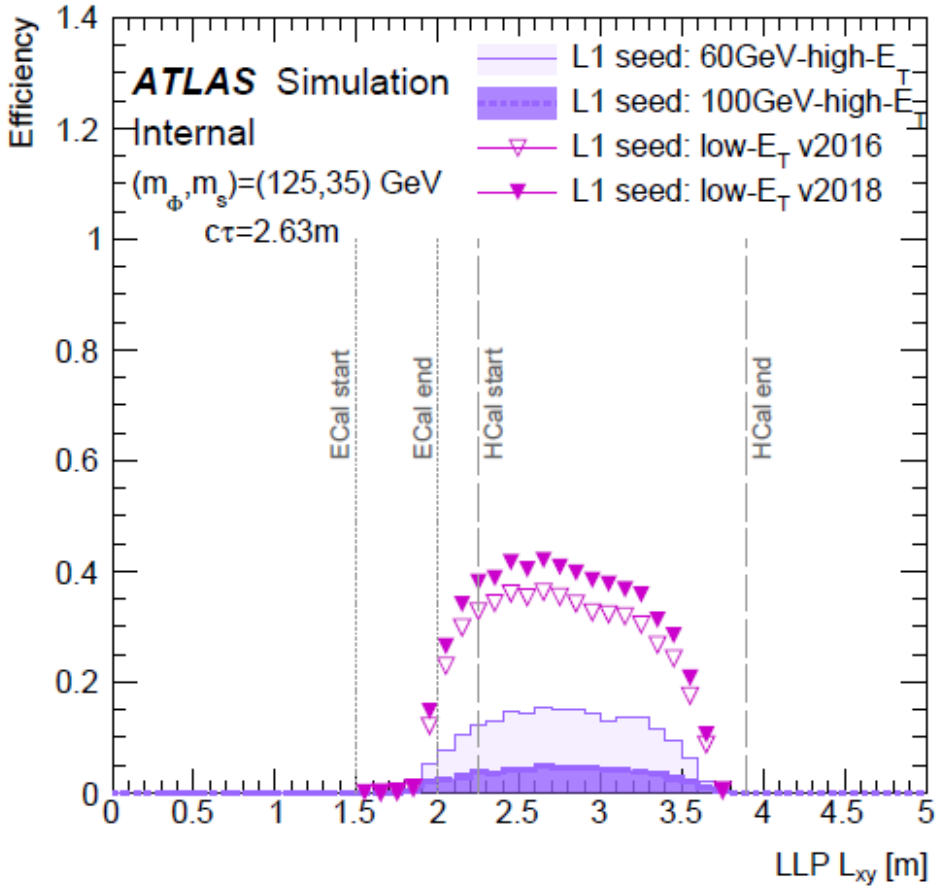
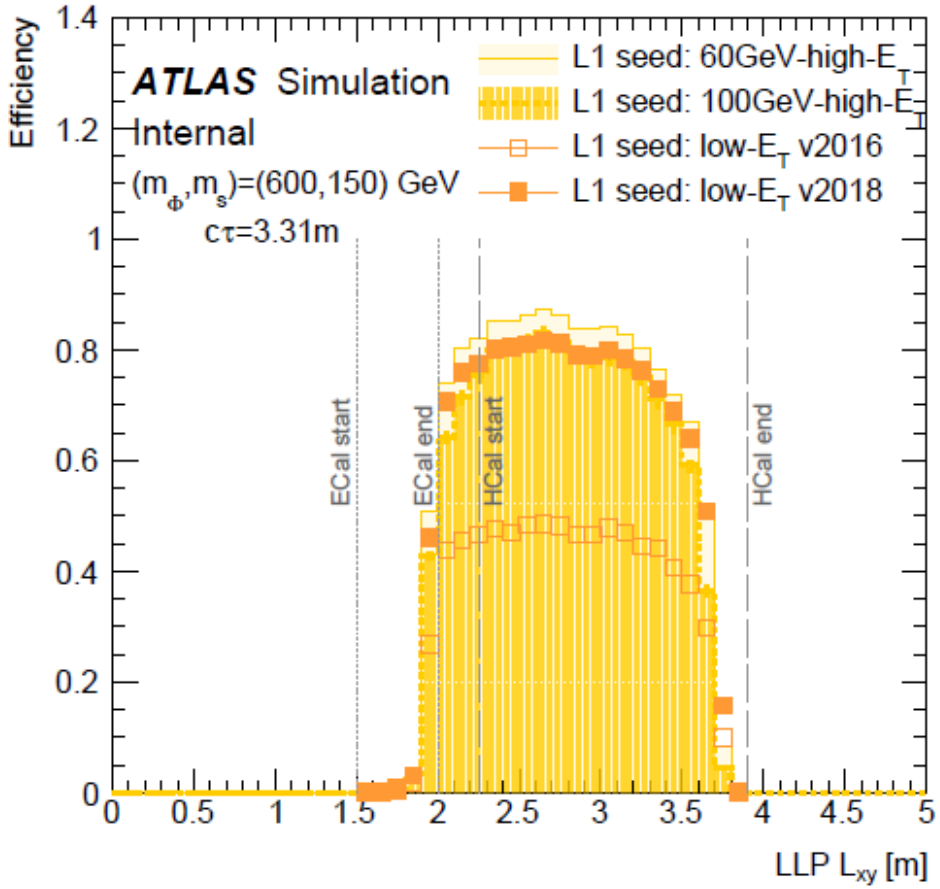
ATLAS CalRatio Triggers





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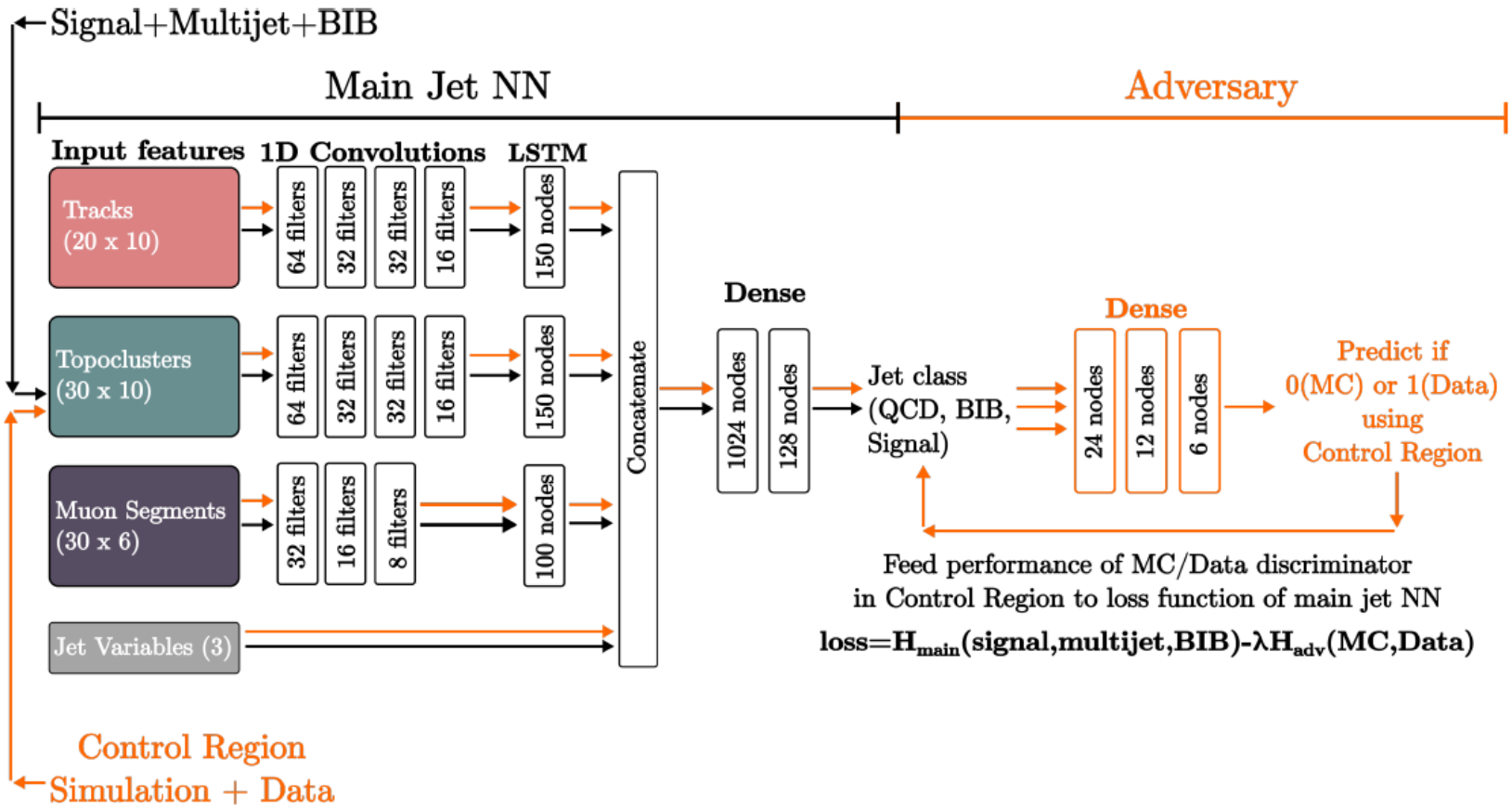
ATLAS CalRatio NN architecture



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ATLAS CalRatio Selections

Low-E_T selection	High-E_T selection
$H_T^{miss}/H_T < 0.6$	$H_T^{miss}/H_T < 0.6$
$(\sum_{jet^{sig_{1l}}, jet^{sig_{2l}}} \log_{10}(E_H/E_{EM})) > 2$	$(\sum_{jet^{sig_{1h}}, jet^{sig_{2h}}} \log_{10}(E_H/E_{EM})) > 1$
$p_T(jet^{sig_{1l}}) > 80$ GeV	$p_T(jet^{sig_{1h}}) > 70$ GeV
$p_T(jet^{sig_{2l}}) > 80$ GeV	$p_T(jet^{sig_{2h}}) > 80$ GeV
low-E_T NN product > 0.7	high-E_T NN product > 0.5

ATLAS Displace Lepton/Hadron selections

Requirement / Region	$SR^{ggF}_{2\mu}$	SR^{ggF}_{2c}	$SR^{ggF}_{c+\mu}$
Number of μDPJs	2	0	1
Number of caloDPJs	0	2	1
Tri-muon MS-only trigger	yes	-	-
Muon narrow-scan trigger	yes	-	yes
CalRatio trigger	-	yes	-
$\lvert\Delta t_{\text{caloDPJs}}\rvert$ [ns]	-	< 2.5	-
caloDPJ JVT	-	< 0.4	-
$\Delta\phi_{\text{DPJ}}$	$> \pi/5$	$> \pi/5$	$> \pi/5$
BIB tagger score	-	> 0.2	> 0.2
$\max(\sum p_{\text{T}})$ [GeV]	< 4.5	< 4.5	< 4.5
$\prod$ QCD tagger	-	> 0.95	> 0.9

Requirement / Region	SR^{WH}_{c}	SR^{WH}_{2c}	$SR^{WH}_{c+\mu}$
Number of μDPJs	0	0	1
Number of caloDPJs	1	2	1
Single lepton trigger (μ,e)	yes	yes	yes
m_{T} [GeV]	> 120	-	-
$\lvert t_{\text{caloDPJ}}\rvert$ [ns]	< 4	< 4	< 4
leading (far) caloDPJ width	< 0.08	< 0.10 (0.15)	< 0.1
caloDPJ p_{T} [GeV]	> 30	-	-
JVT	< 0.6	< 0.6	< 0.6
$\min(\Delta\phi)$	$< 3\pi/5$	$< 3\pi/10$	$< 7\pi/20$
min(QCD tagger)	> 0.99	> 0.91	> 0.9

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ATLAS EXPERIMENT

CMS