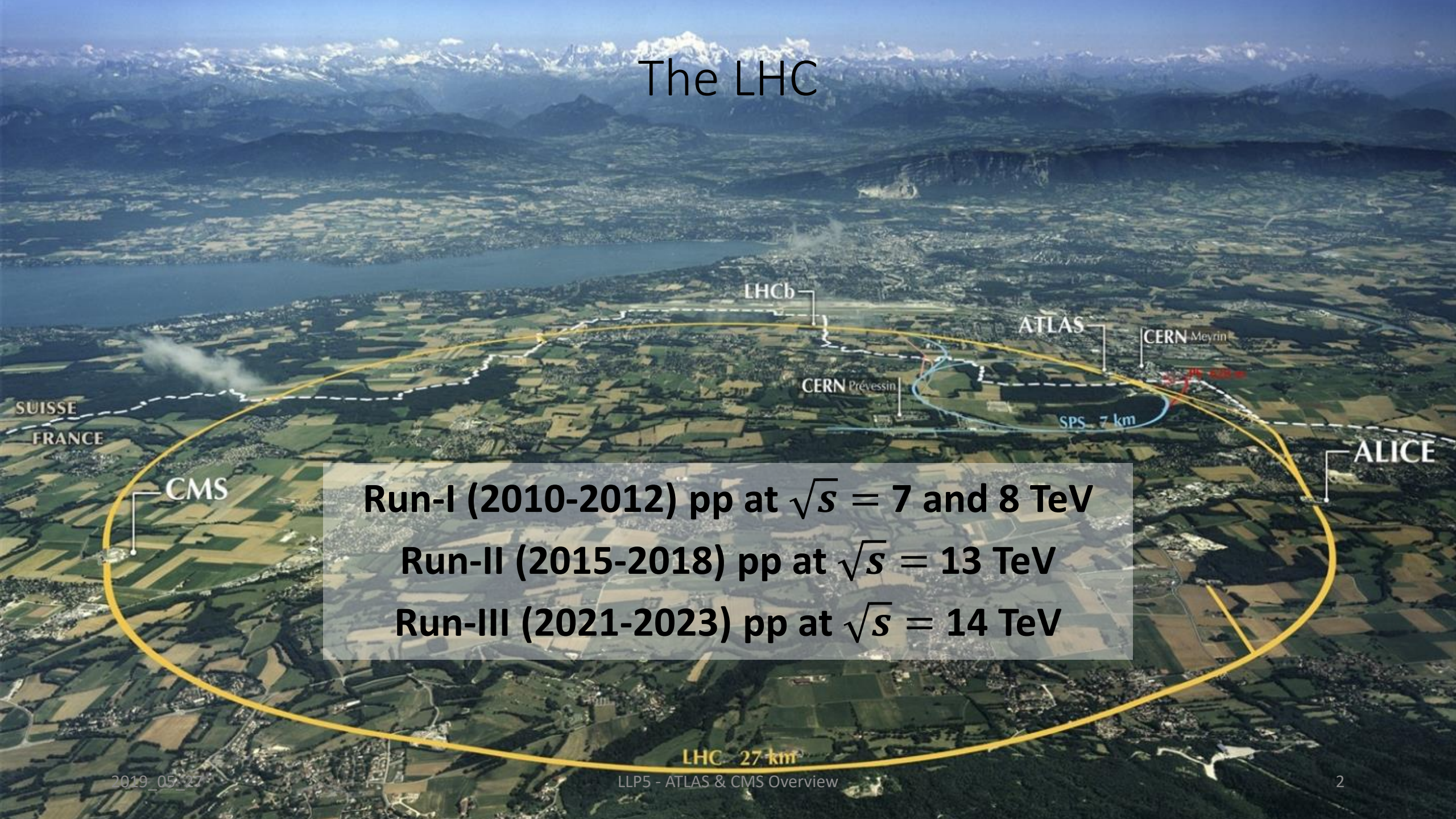
Long-Lived Particles ATLAS+CMS Experimental Overview

R Rosten (IFAE)

27th May 2019

LLP5

The LHC

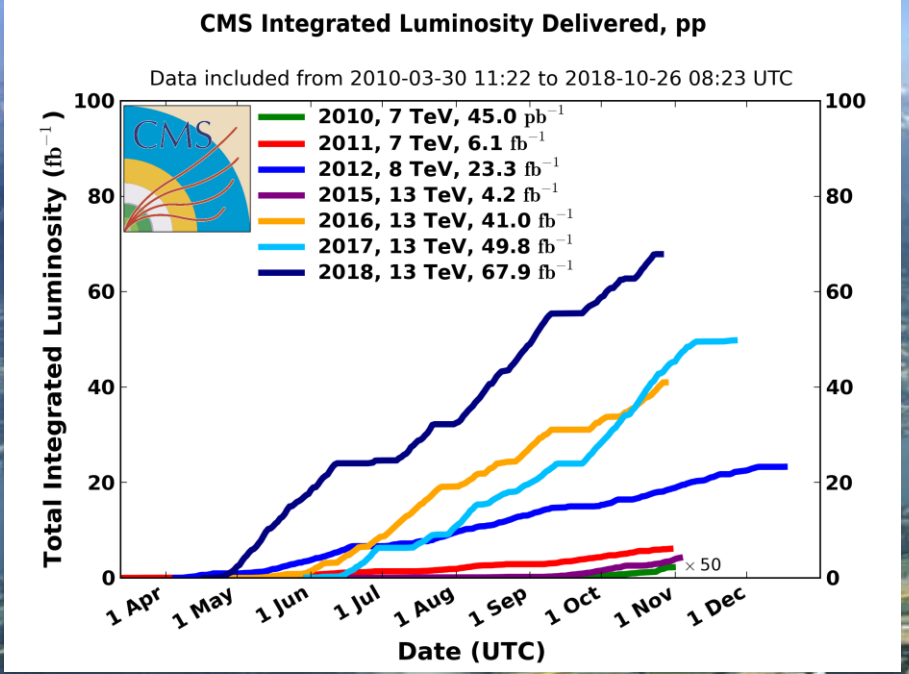


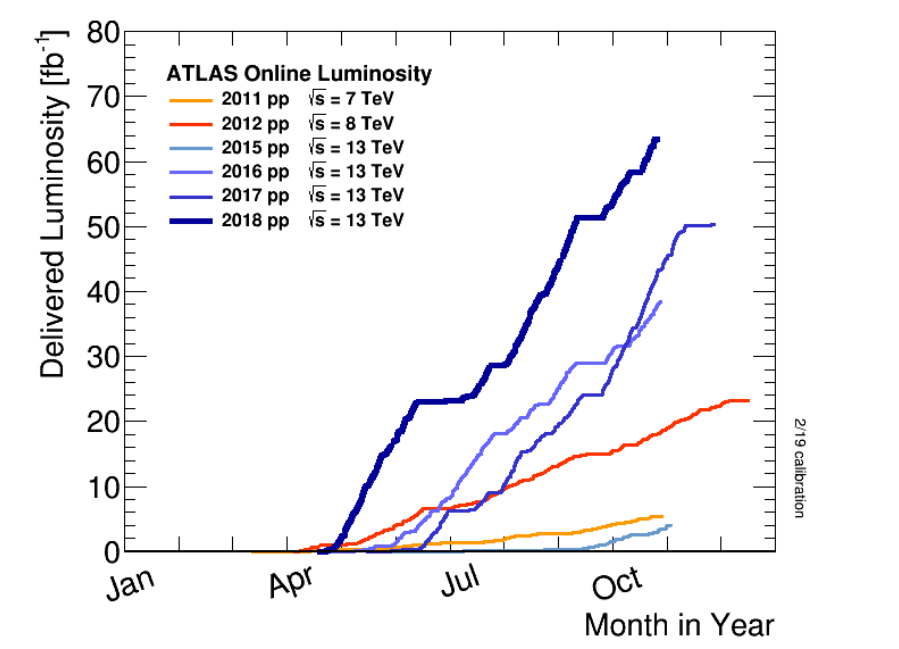
Run-I (2010-2012) pp at $\sqrt{s} = 7$ and 8 TeV

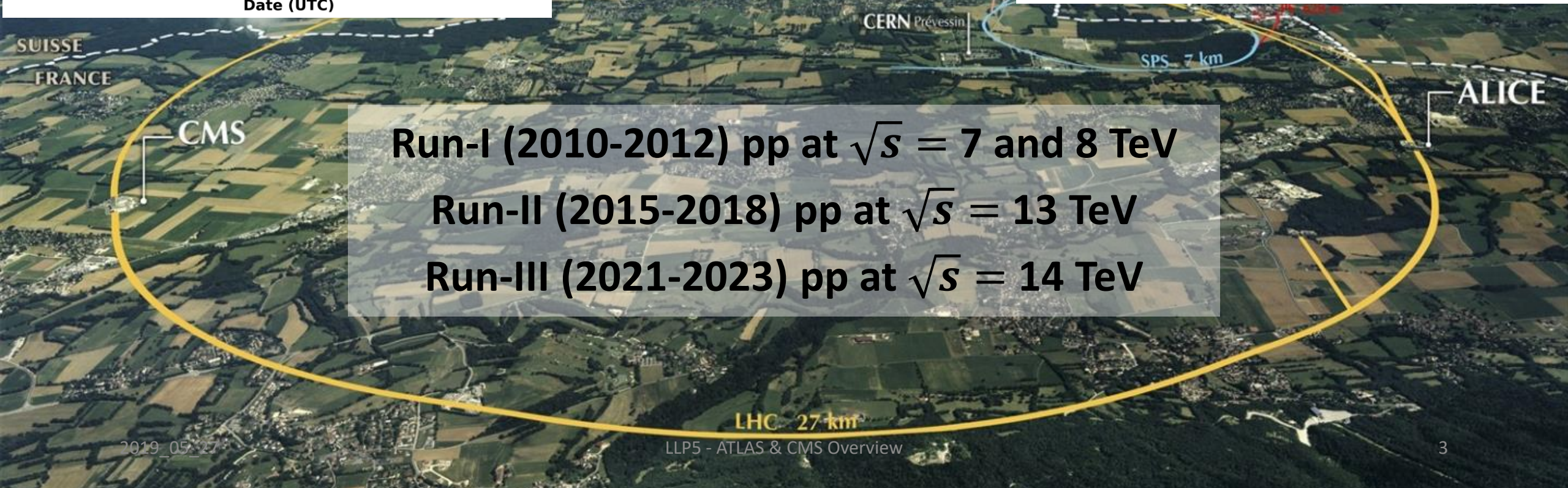
Run-II (2015-2018) pp at $\sqrt{s} = 13$ TeV

Run-III (2021-2023) pp at $\sqrt{s} = 14$ TeV

The LHC







Run-I (2010-2012) pp at $\sqrt{s} = 7$ and 8 TeV

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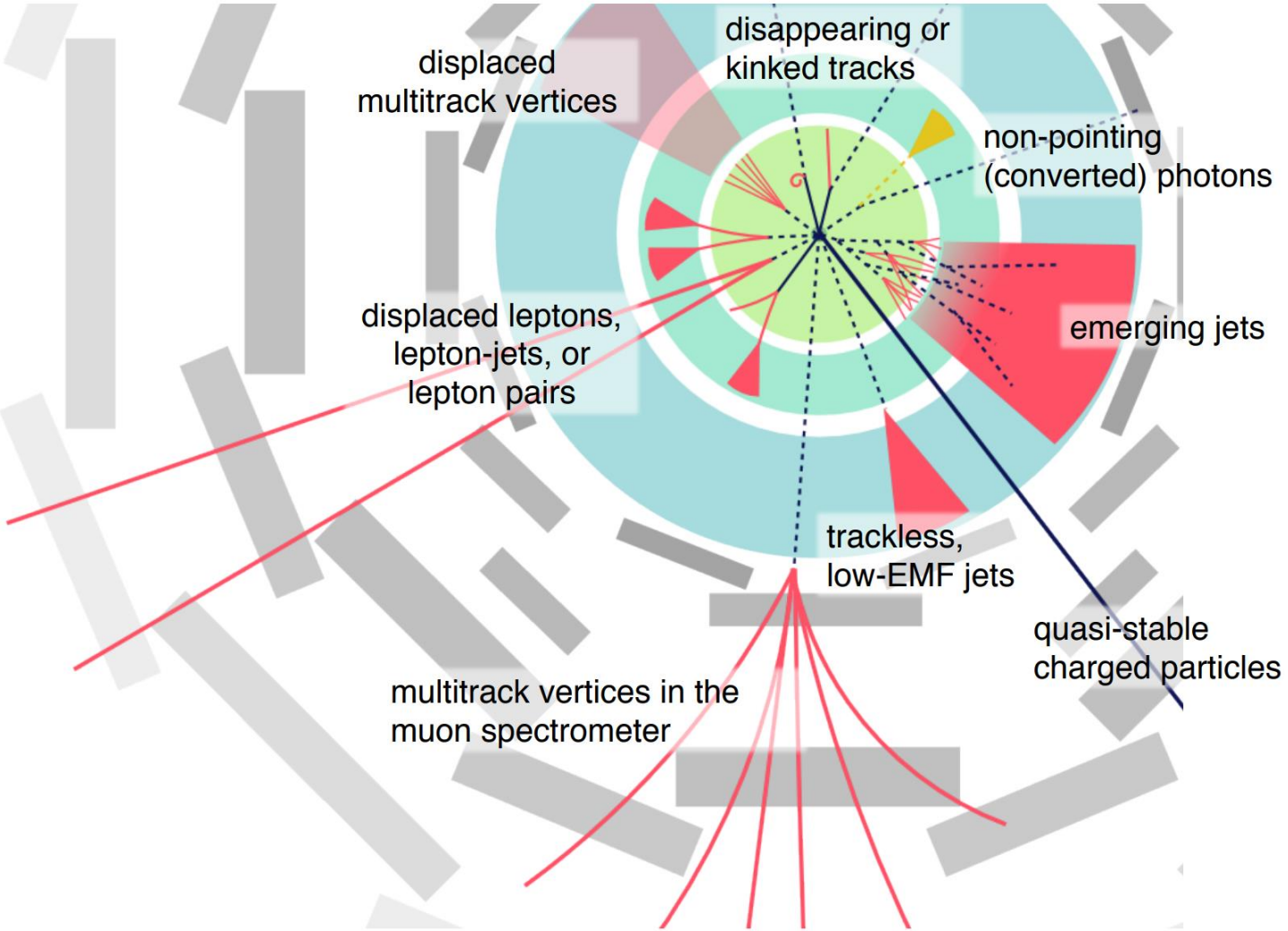
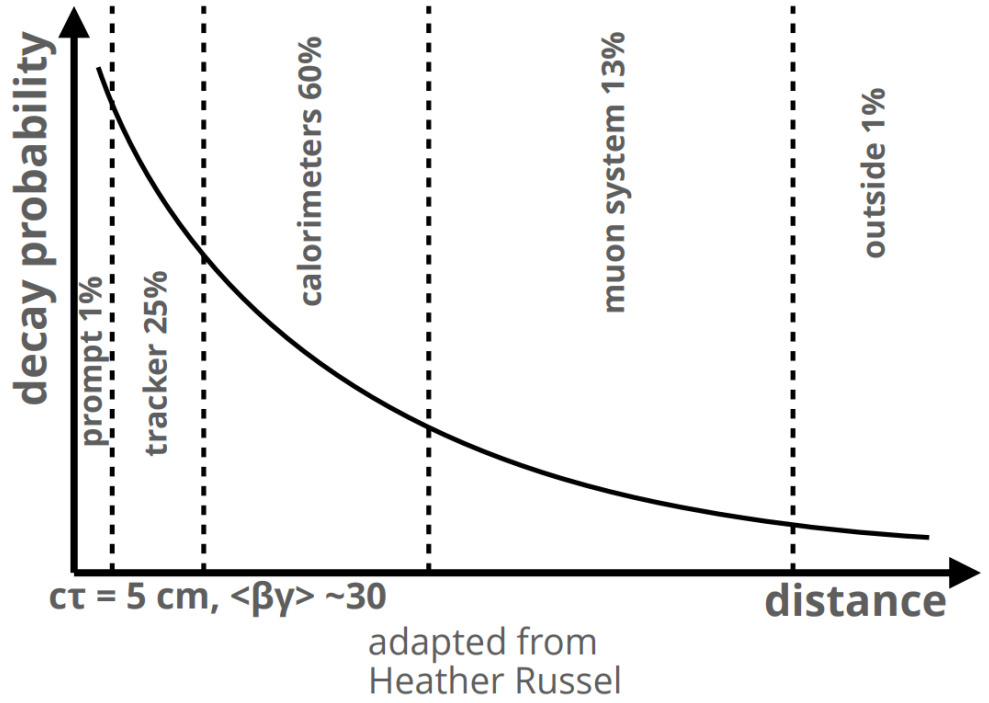
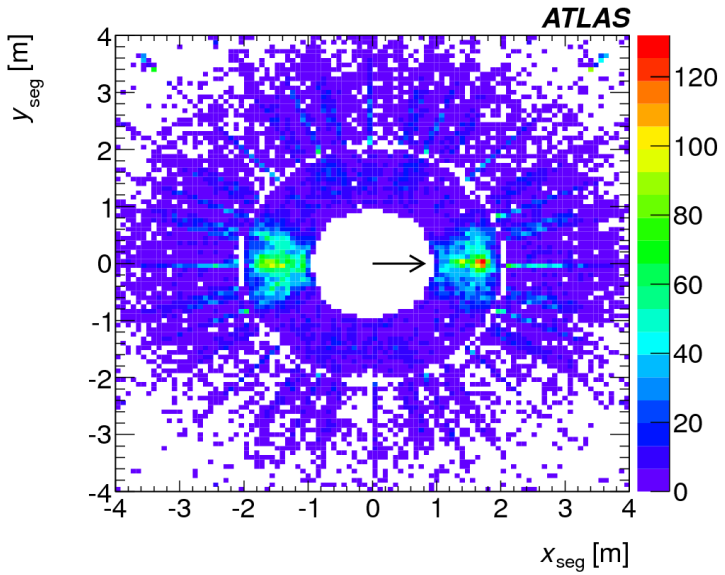
LLP Signatures – ATLAS & CMS

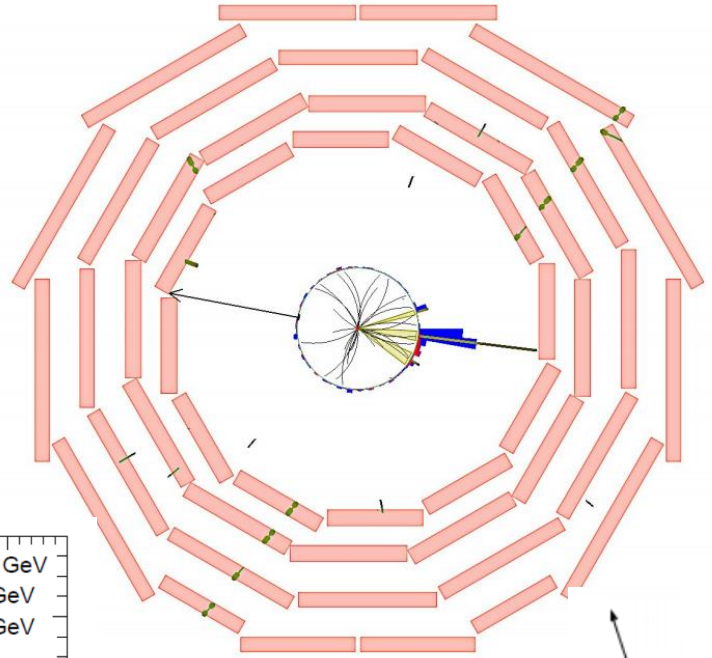


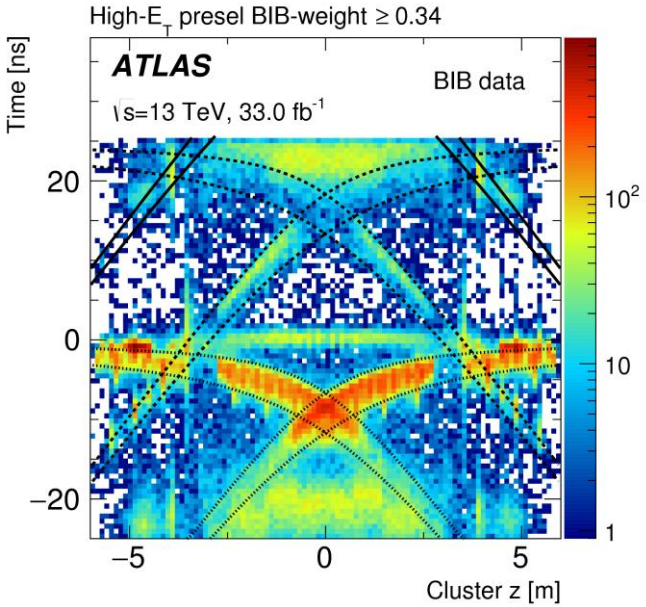


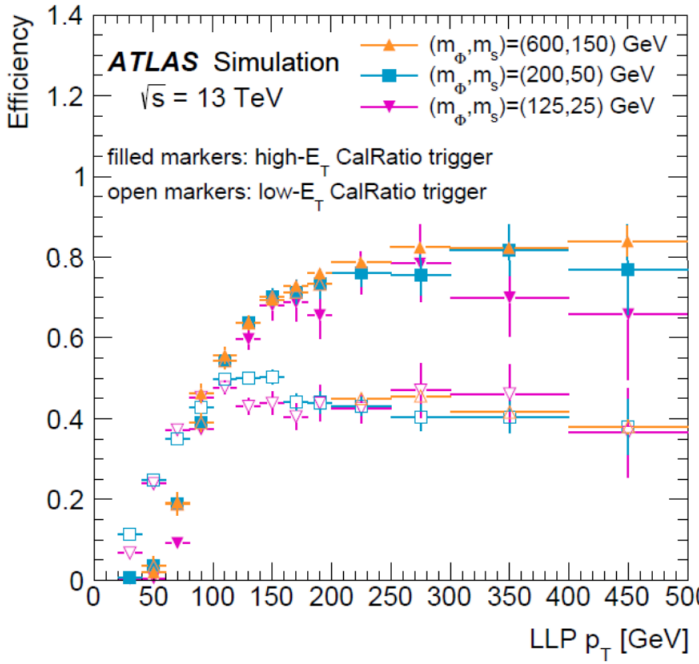
adapted from
Heather Russel

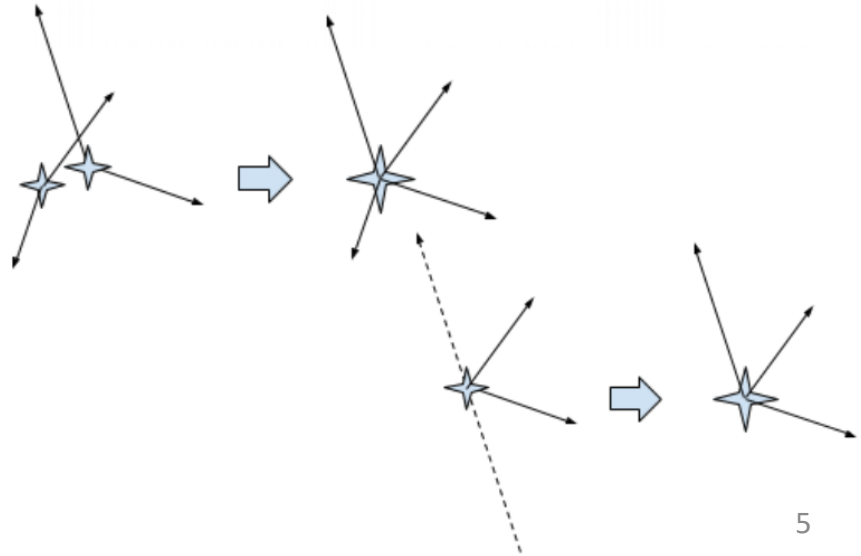
Experimental Challenges



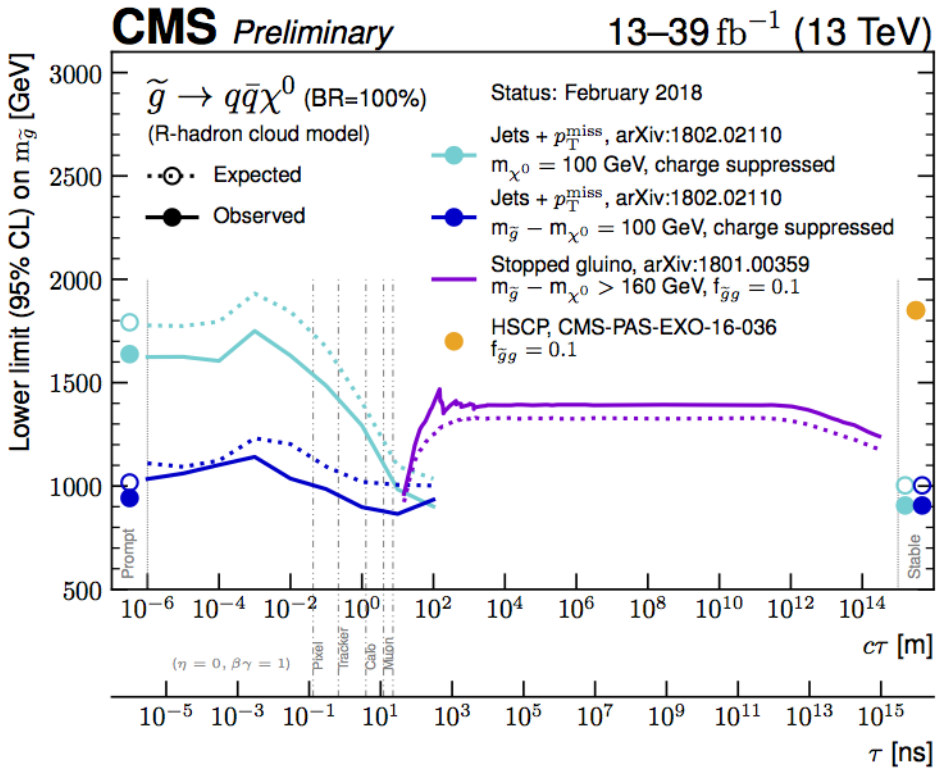




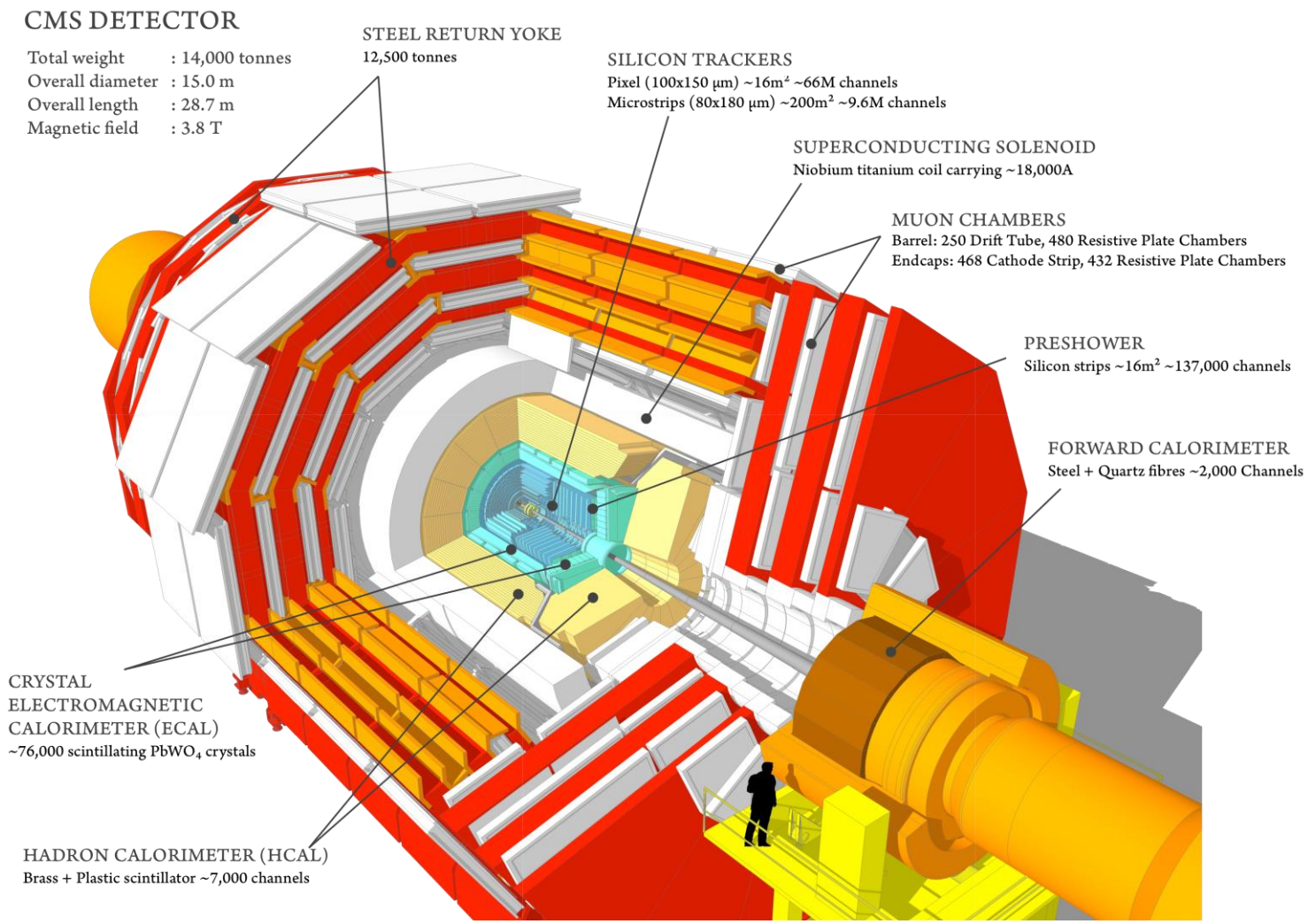




CMS

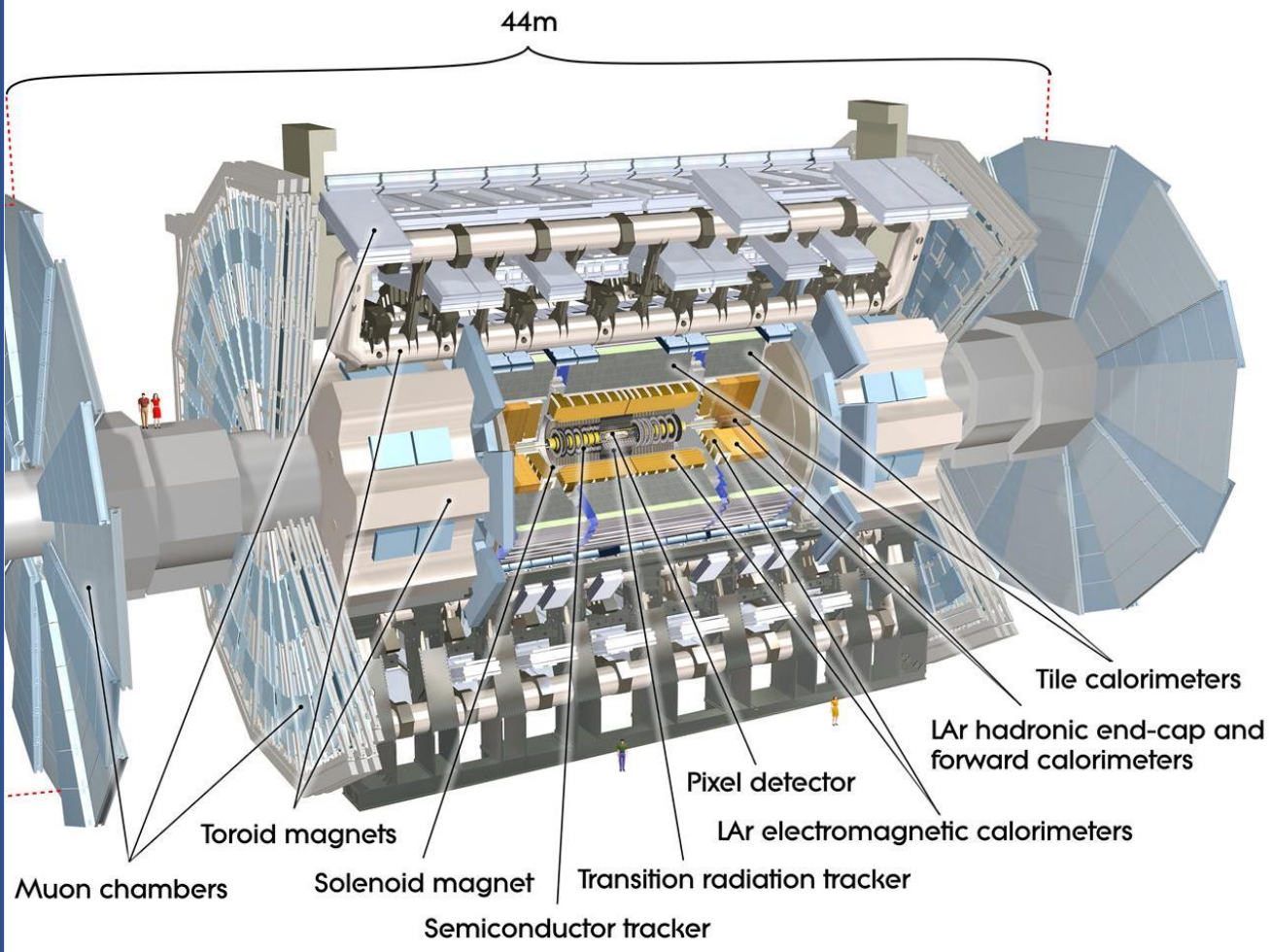


Search	arXiv
Delayed Jets	EXO-19-001
Disappearing Tracks	SUS-19-005
Displaced Jets	1811.07991

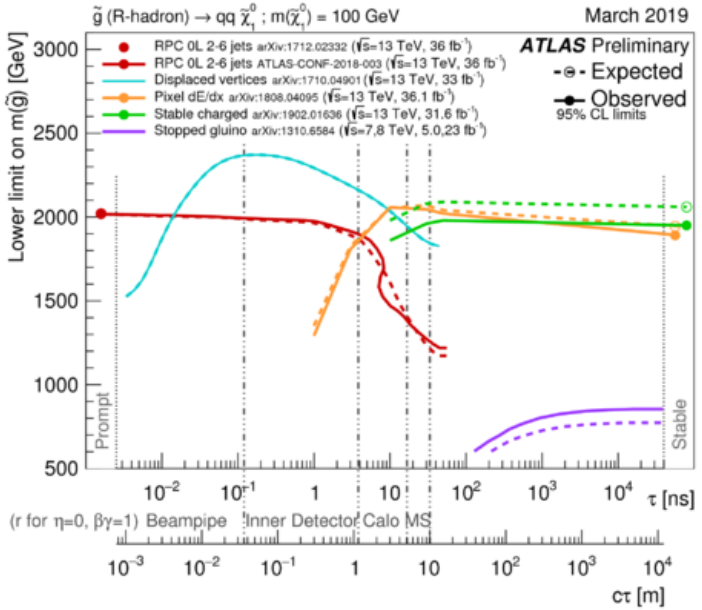


ADD lifetimes vs geometry

ATLAS



Search	arXiv
Highly ionizing particles/monopoles	1905.10130
Disp (& prompt) heavy neutral leptons	1905.09787
Displaced hadronic (CalRatio) jets	1902.03094
Heavy charged LLPs	1902.01636
Displaced vertex + displaced muon	CONF-2019-006
Multi-charged LLPs	1812.03673
Muon vertex	1811.07370
Z + Displaced hadronic (CalRatio) jet	1811.02542



A *Selection* of Results Since October 2018

Search	arXiv
Highly ionizing particles/monopoles	1905.10130
Disp (& prompt) heavy neutral leptons	1905.09787
Displaced hadronic (CalRatio) jets	**1902.03094**
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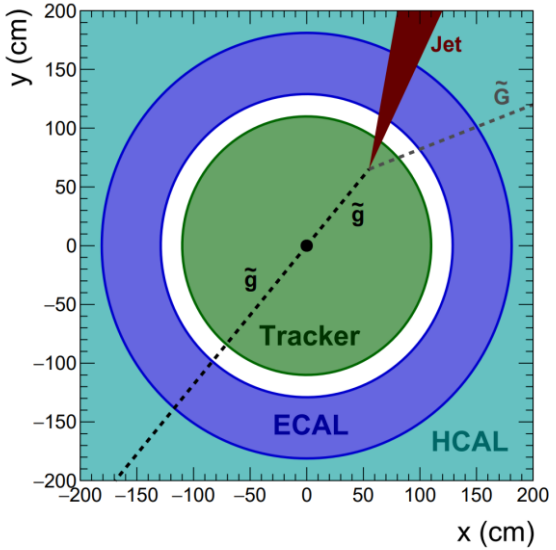
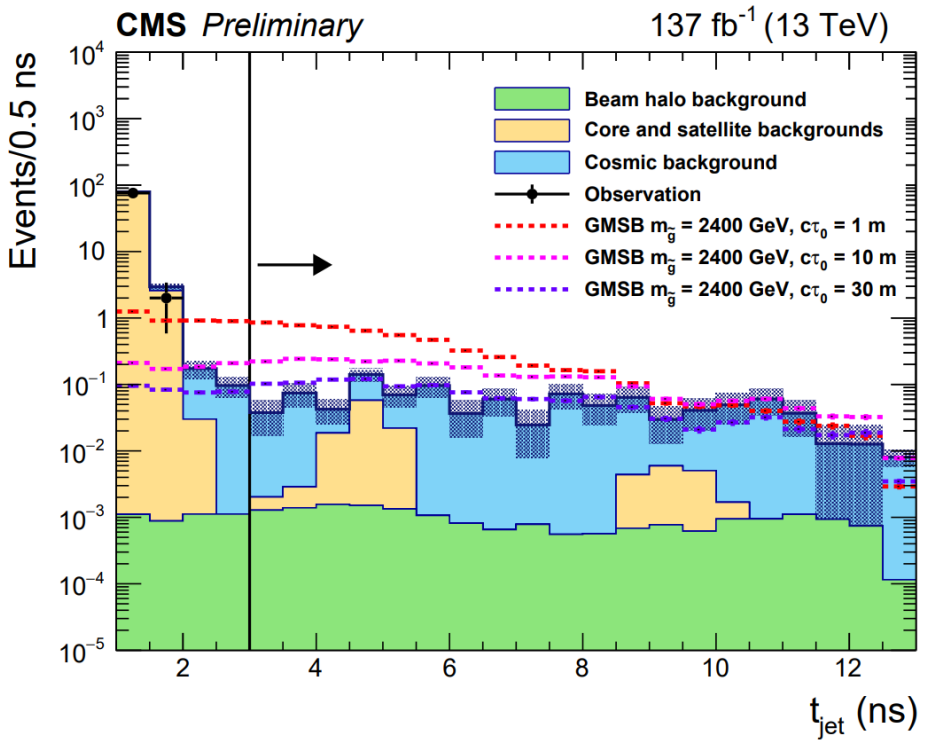
Search	arXiv
Delayed Jets	**EXO-19-001**
Disappearing Tracks	**SUS-19-005**
Displaced Jets	1811.07991

Delayed Jets

- Avoid dijet requirement from many displaced jet searches by requiring an out-of-time (but same BC) jet
- Timing from CMS ECal, first use to identify displaced jets
- Non-collision backgrounds require full detector for rejection

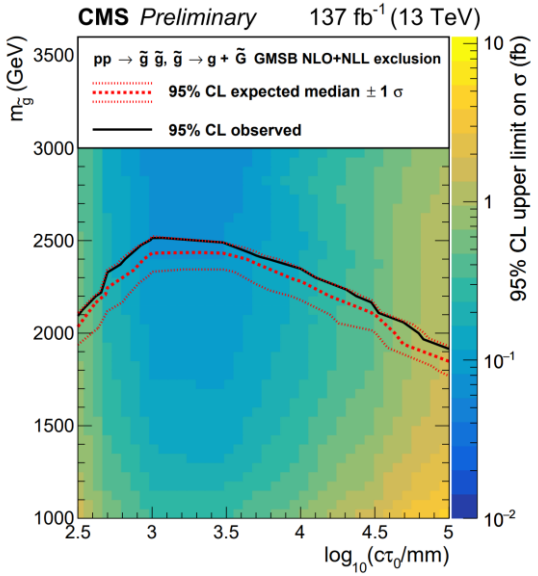
Cosmics	**Satellites**	**Beam Halo**
Drift Tubes	Tracking	Cathode Strip Chambers
Resistive Plate Chambers		HCal

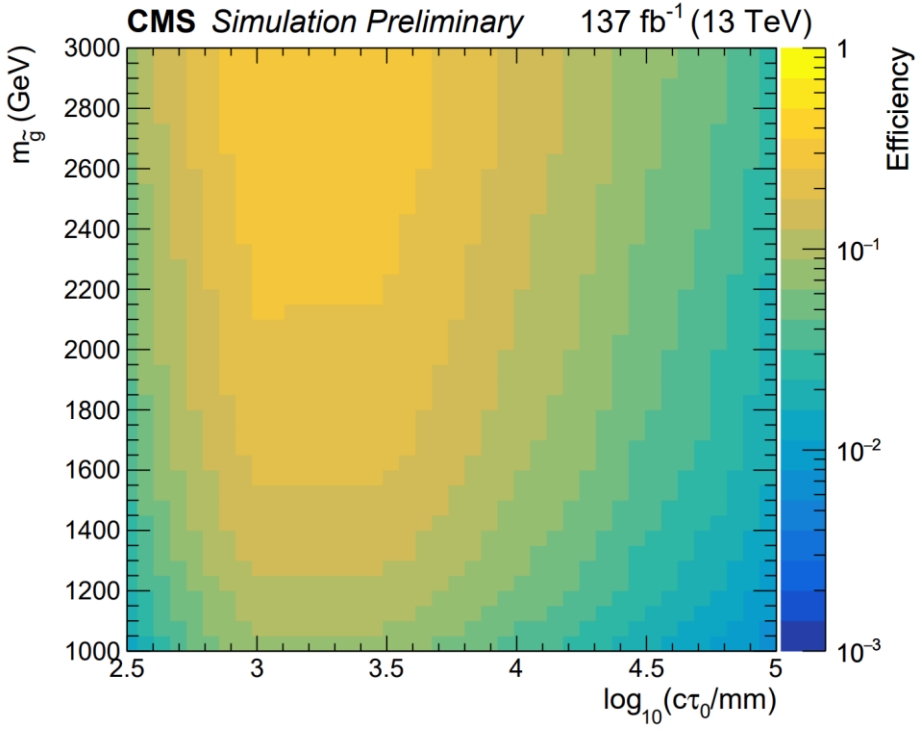


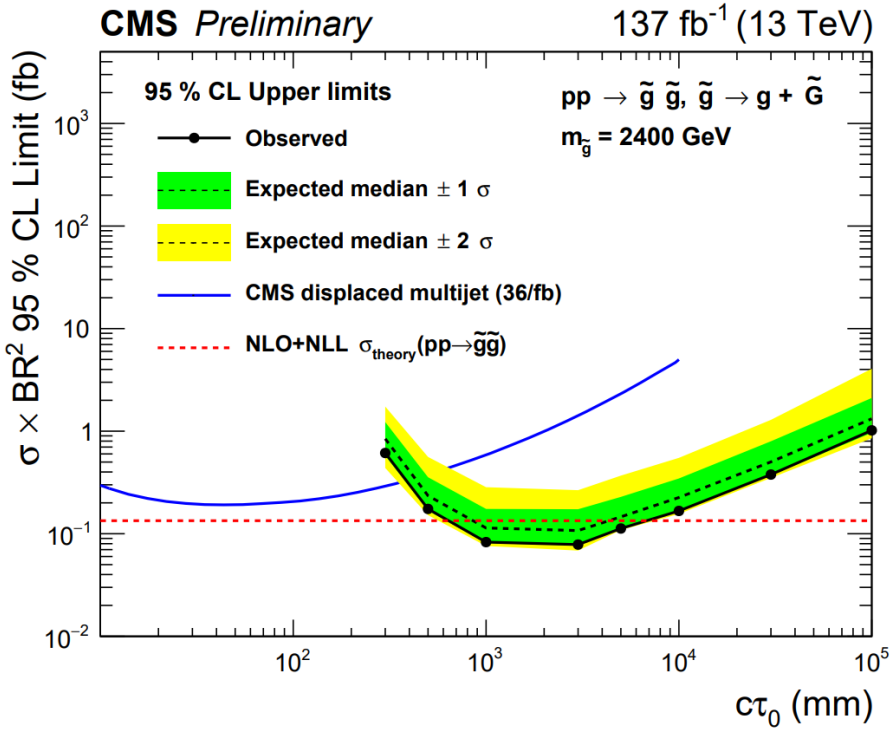


Delayed Jets

- ~0 Background analysis with high signal efficiency for late decays
- Significant improvement on higher end of $c\tau$ over tracker-based displaced jet searches



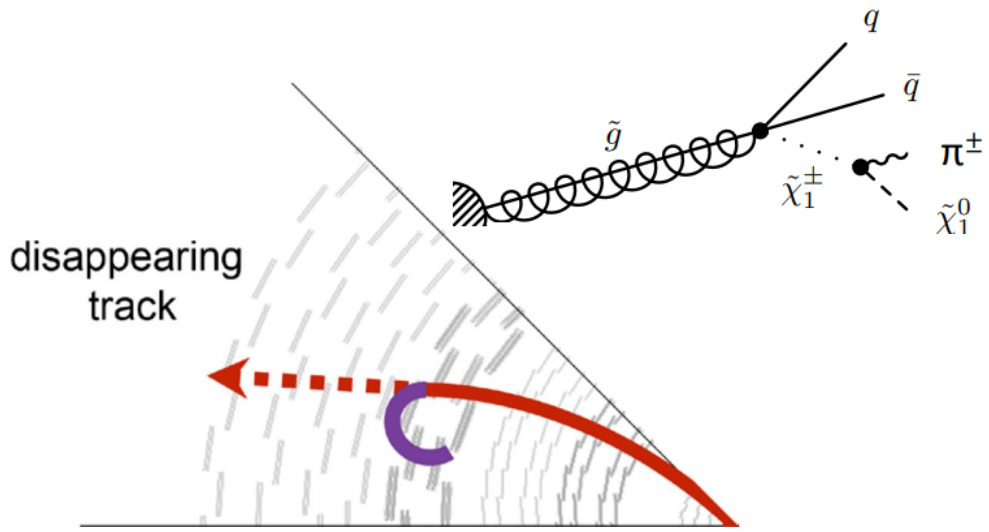


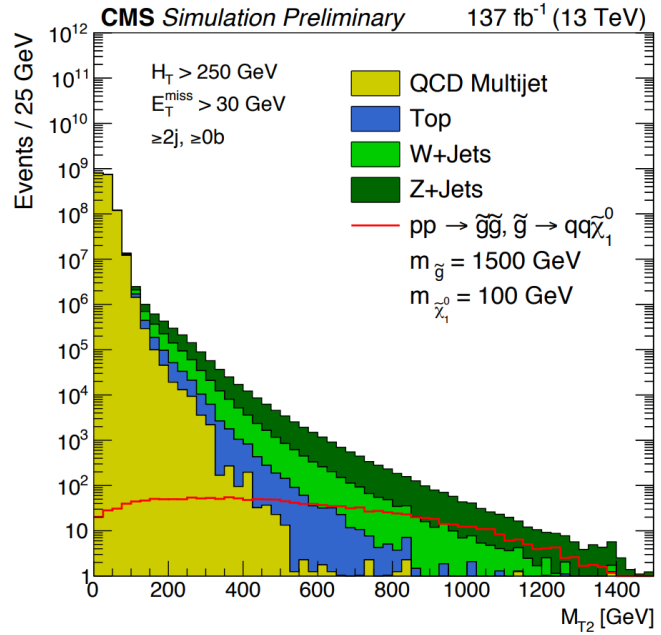


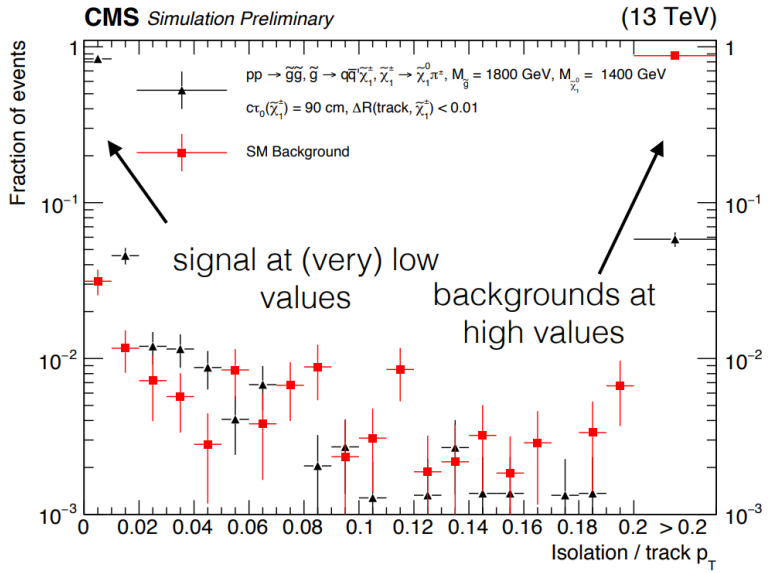
Disappearing Tracks

$$M_{T2}(m_X) = \min_{\vec{p}_T^{X(1)} + \vec{p}_T^{X(2)} = \vec{p}_T^{miss}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$

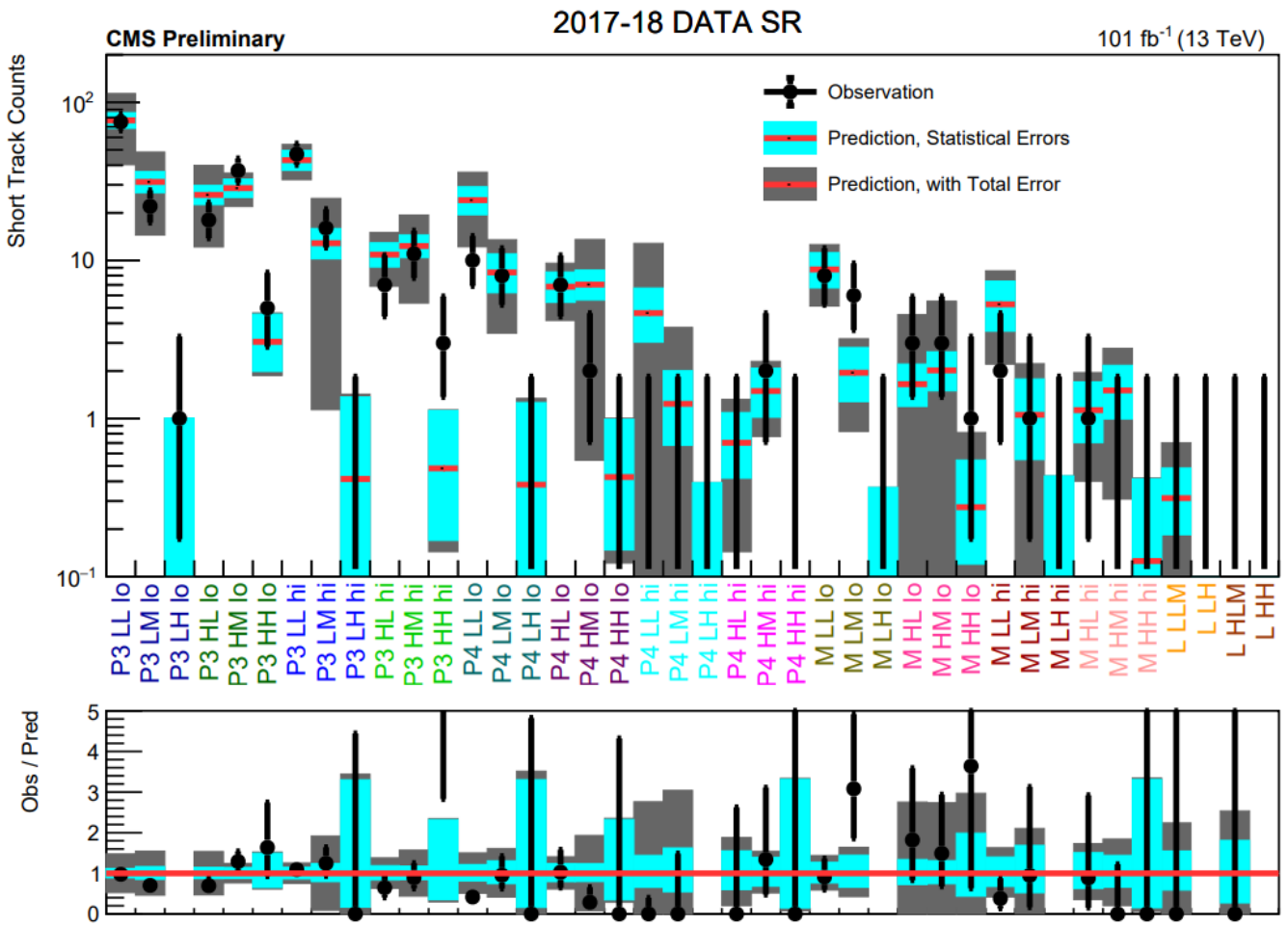
- Use non-standard tracking to identify charged particles with very light charged daughters
- Neutral daughter results in MET – trigger object
- Tackle QCD background by considering M_T for events with two invisible particles
- Suppress fake rate with strict isolation and reconstruction criteria

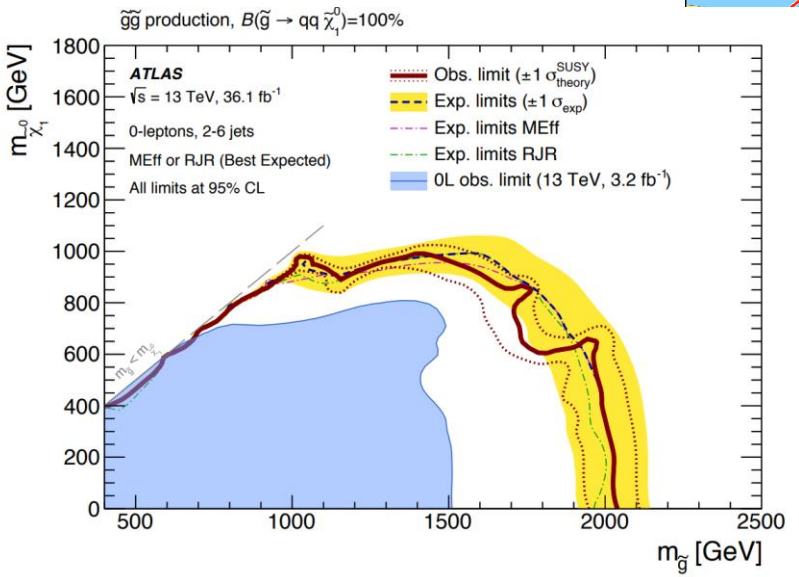


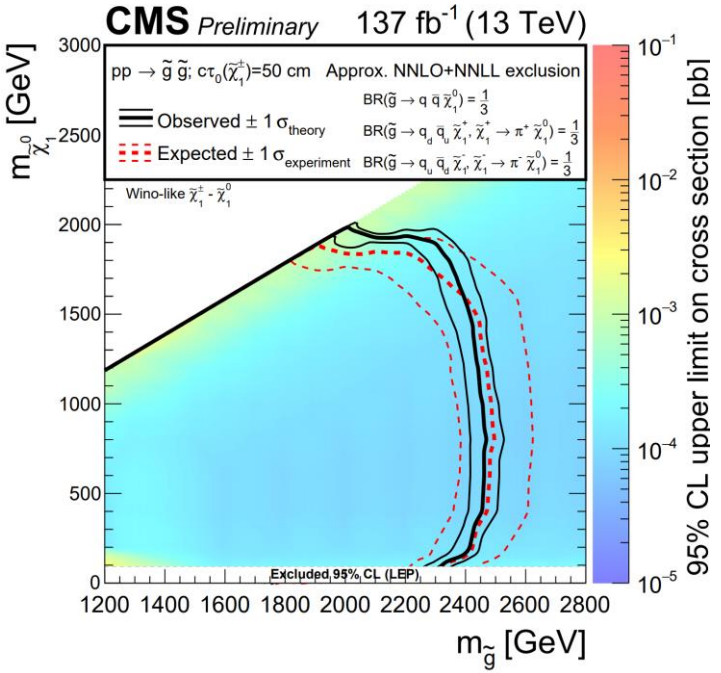




Disappearing Tracks

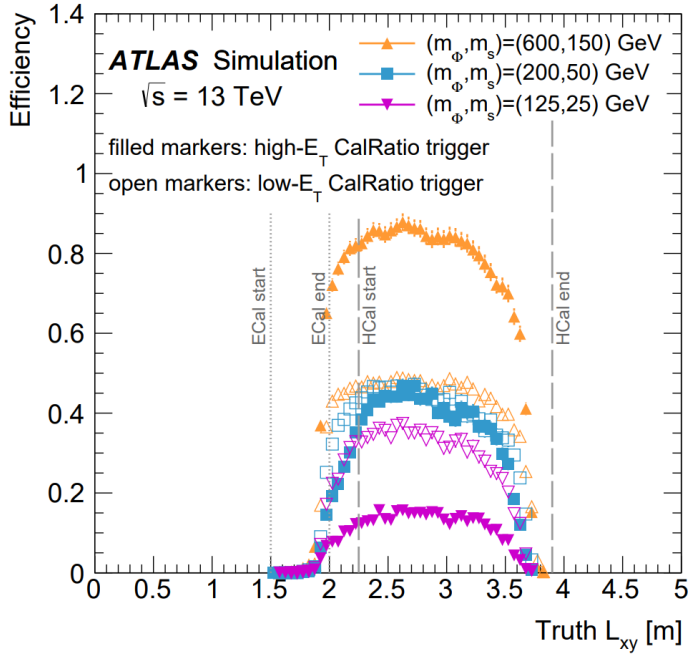


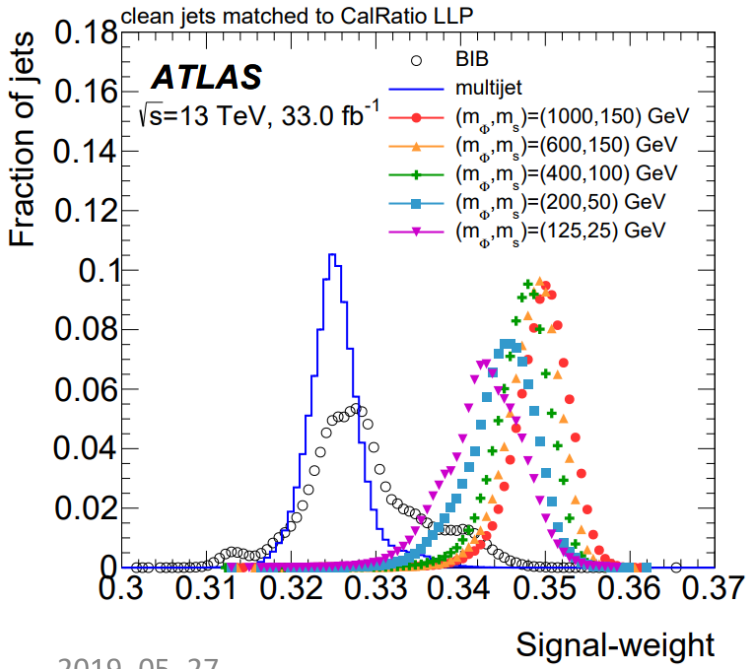


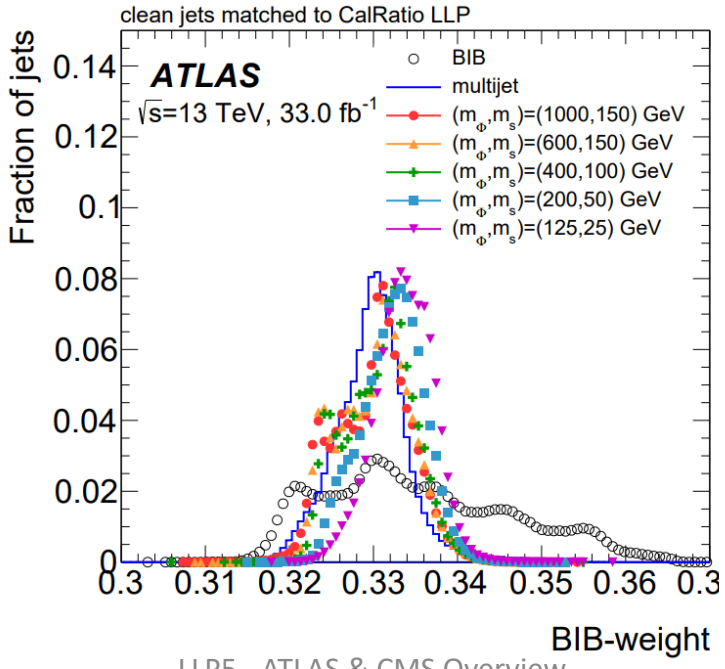


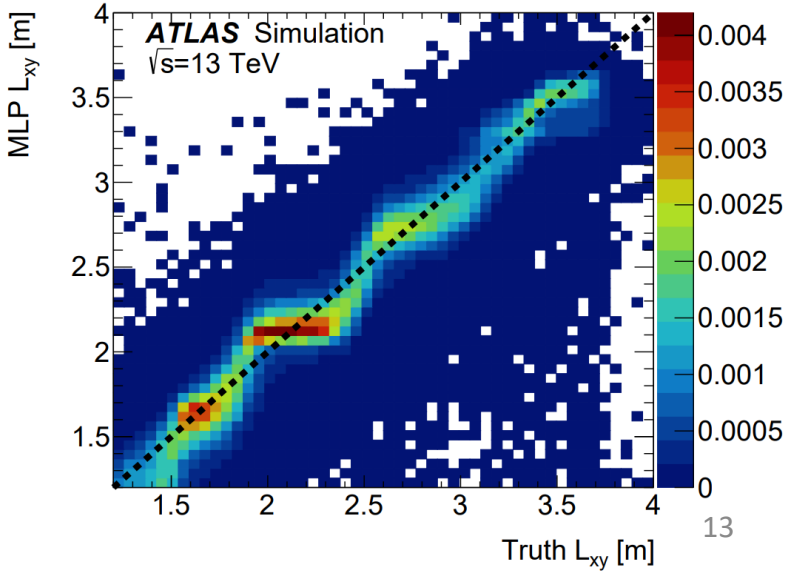
CalRatio – Displaced Hadronic Jets

- Use a dedicated trigger to identify jets with properties consistent with decays in the HCal
- Incorporate MLP to estimate decay position and BDT to discriminate between signal, QCD, and beam halo
- Remaining background estimated with modified ABCD method



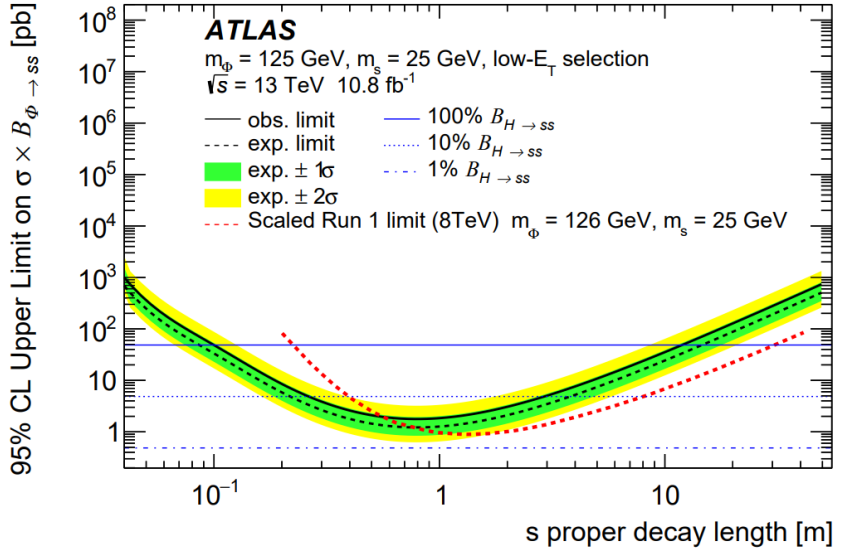


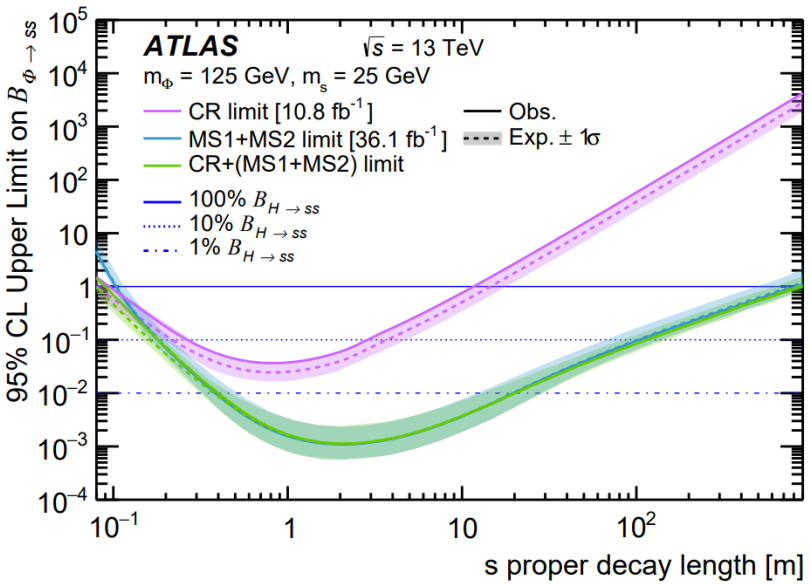


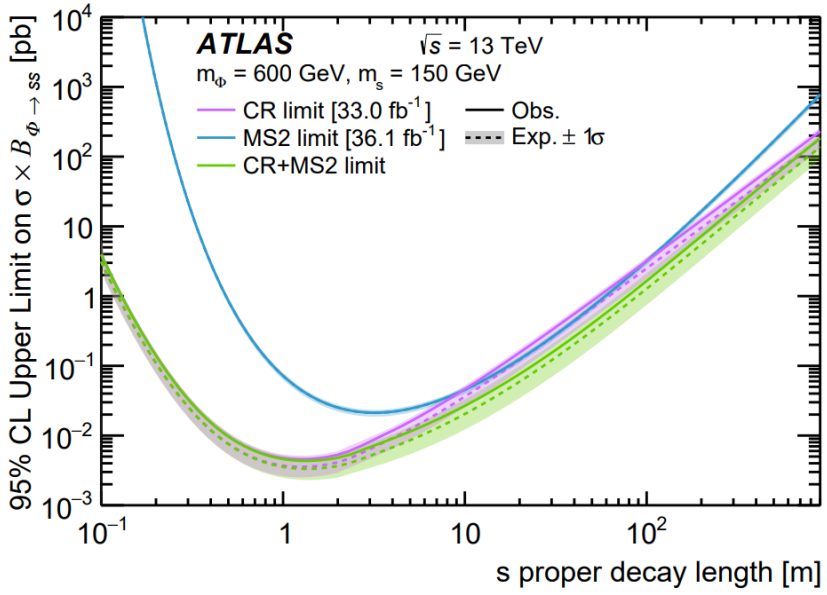


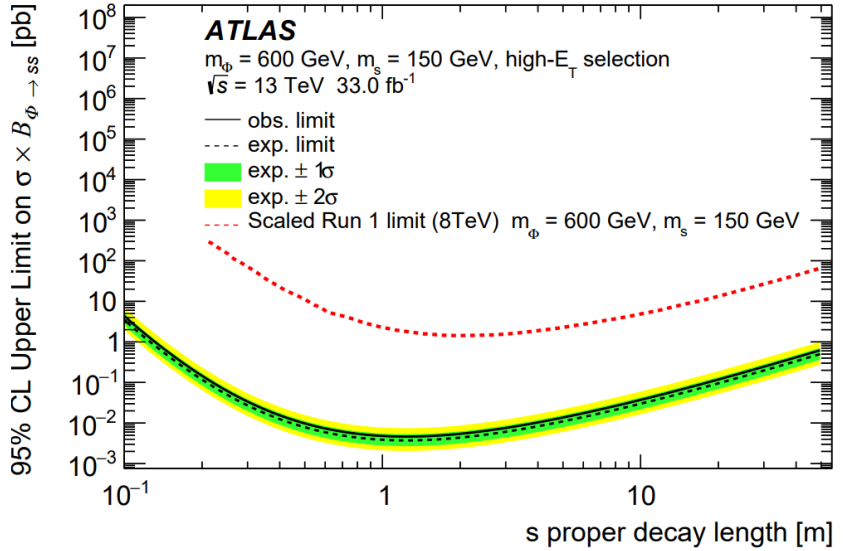
CalRatio – Displaced Hadronic Jets

- CalRatio-only limits set, along with combined limits from sister (MS-Vertex) analysis
- Analysis upgrades result in significant improvement over Run-I limits



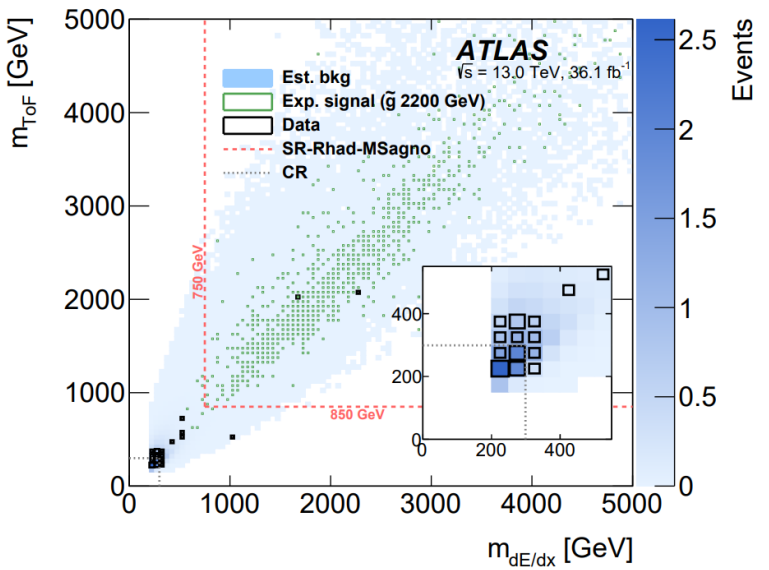


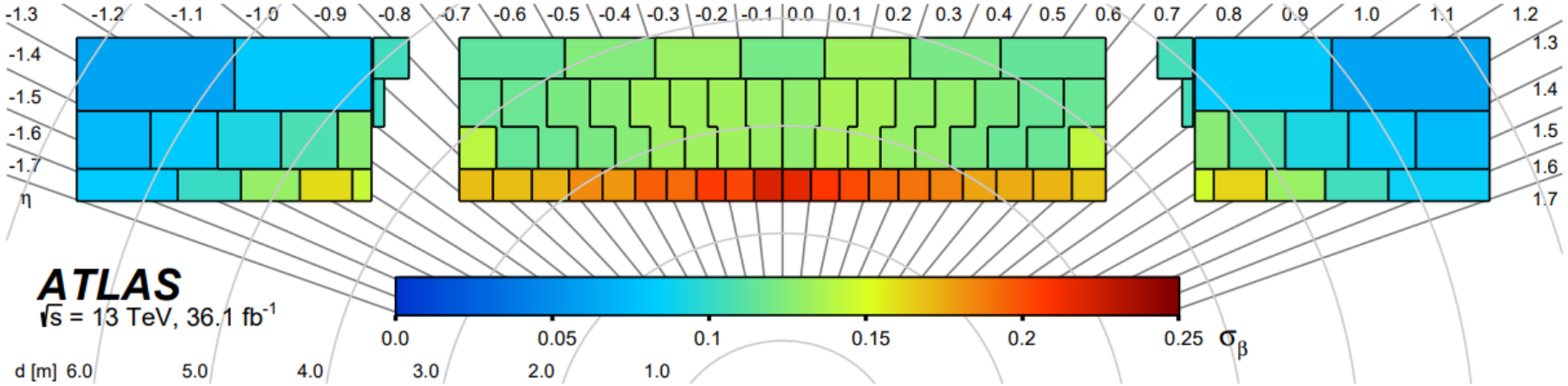




Heavy Charged LLPs

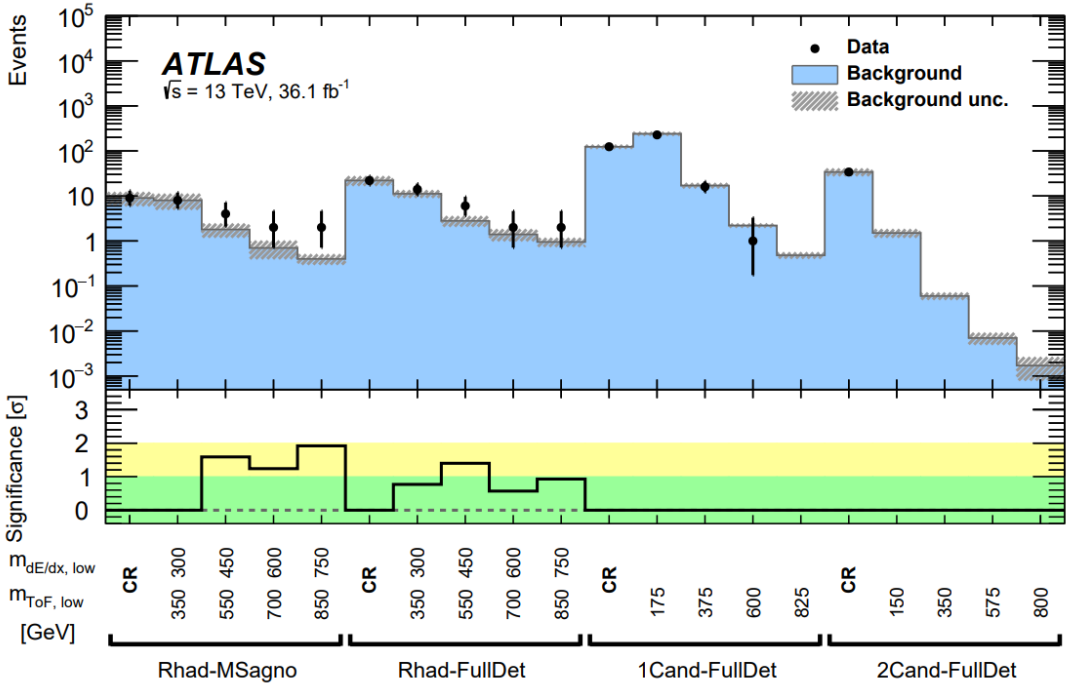
- Consider heavy charged particles moving through the full detector (but consider also MS-agnostic approach)
- Muon and MET triggers both usable
- Time of Flight (ToF) and dE/dx allow for discrimination between signal and SM particles
- Accurate ToF measurements require custom calibrations, e.g. to account for the position a particle impacts a Tile cell or run-to-run fluctuations in the timing measurement

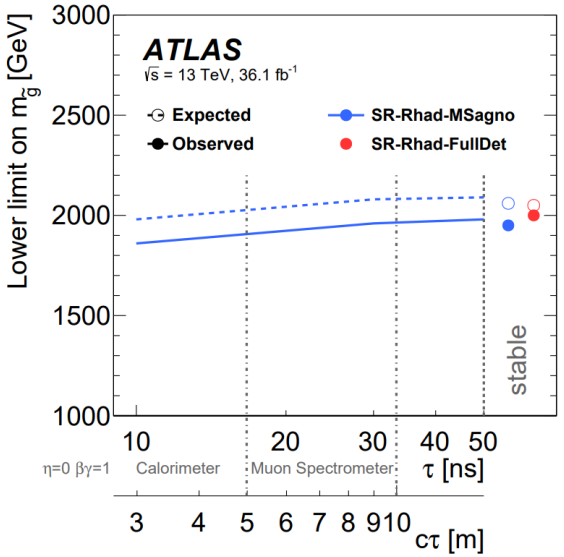


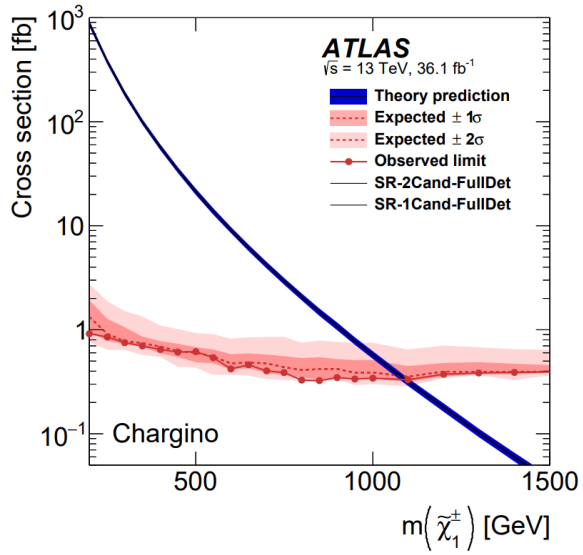


Heavy Charged LLPs

- Analysis on 2015+2016 data with no significant excess observed
- Lower limits set on particle mass for R-hadrons, staus, and charginos

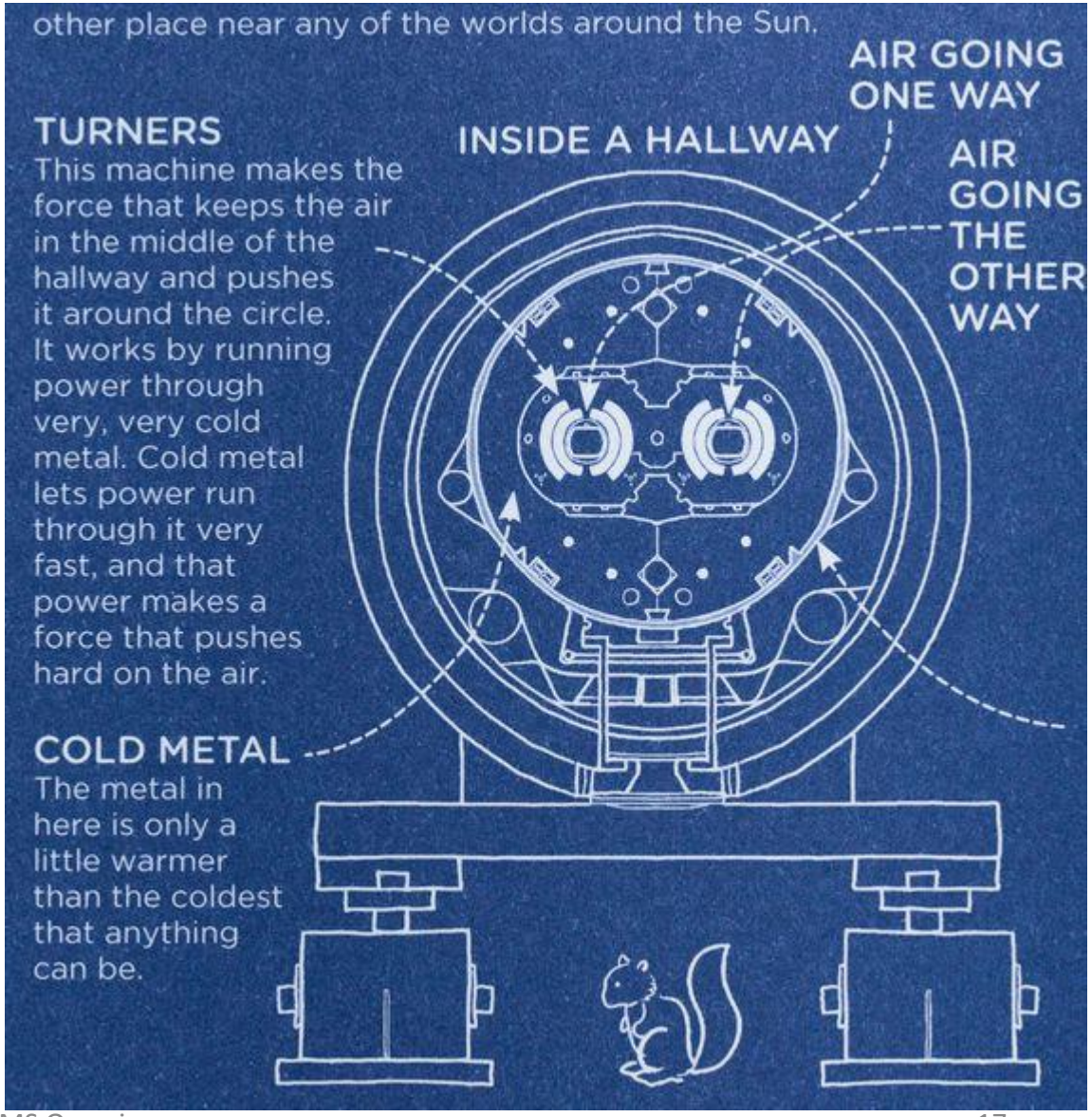






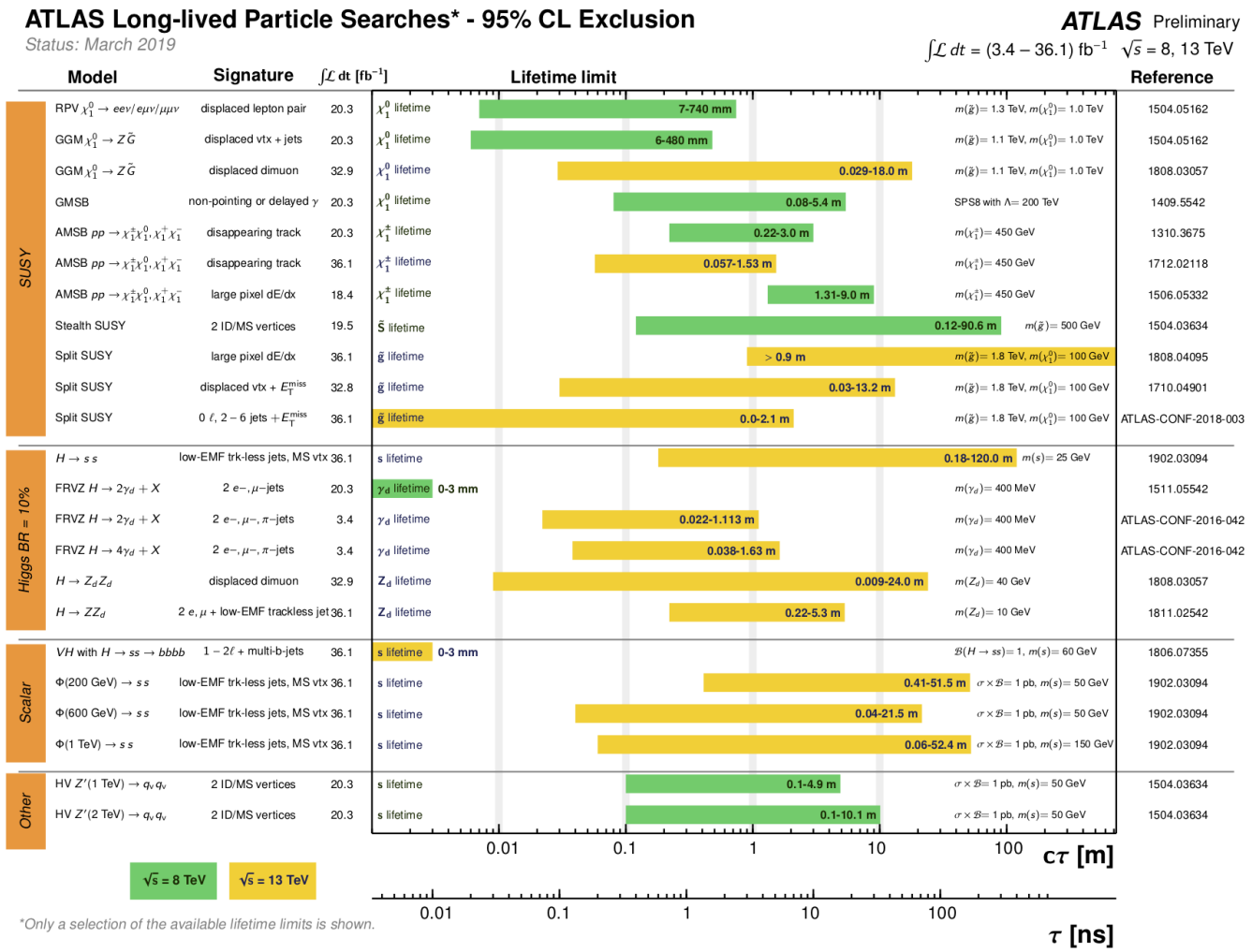
Conclusions & **Outlook**

- Run-II Analyses continue to produce new and improved results
- Strategies continue to evolve to meet challenges
- Can continue to expect Run-II publications, we're not done yet!
- Now is the time analyses are planning for future upgrades, both Run-III and HL-LHC – expect more innovations

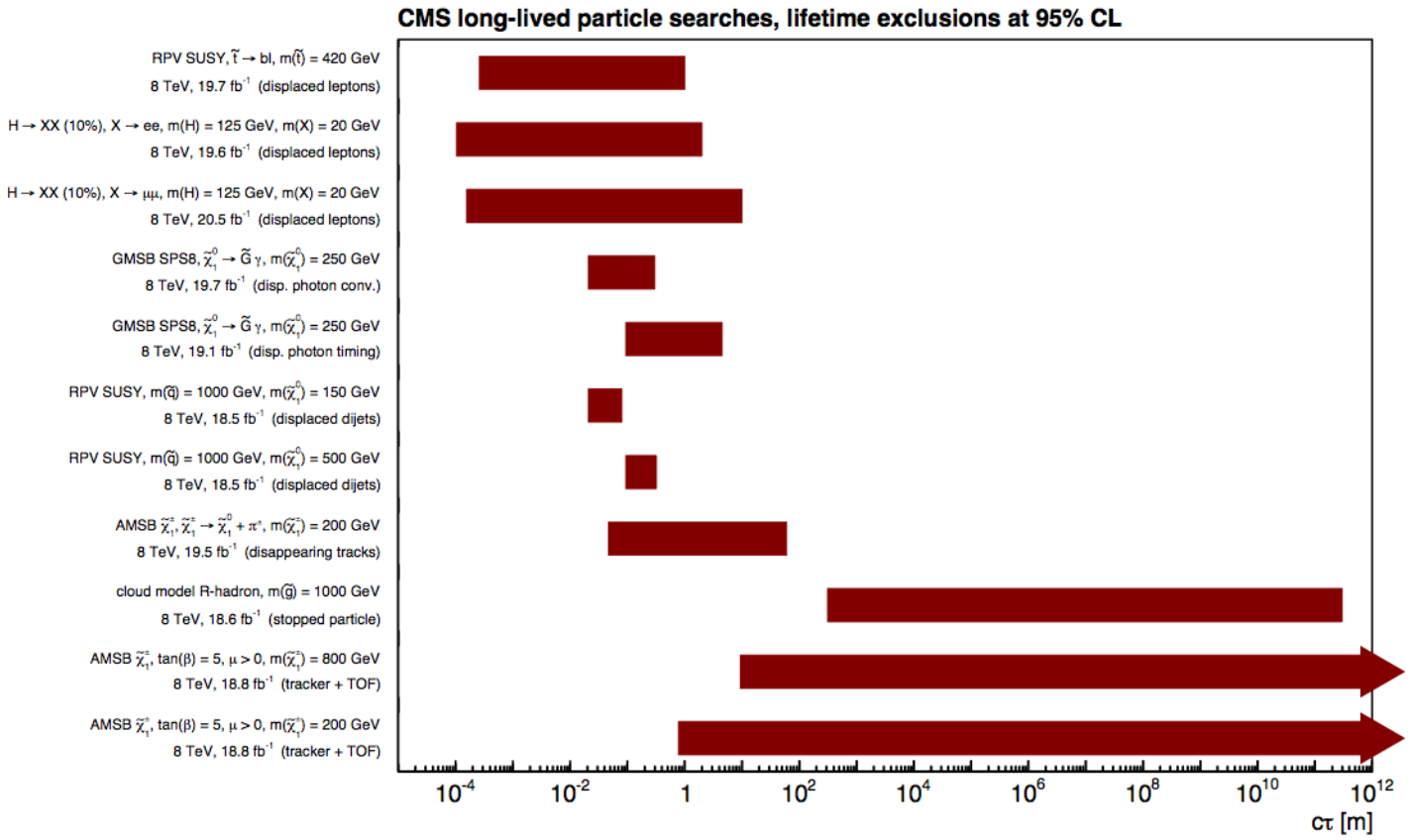


Backup

ATLAS LLPs


ATLAS Long-lived Particle Searches* - 95% CL Exclusion
Status: March 2019
ATLAS Preliminary
$\int \mathcal{L}\, dt$ = (3.4 – 36.1) fb^{-1} $\sqrt{s}$ = 8, 13 TeV
Model
Signature
$\int \mathcal{L}\, dt$ [fb^{-1}]
Lifetime limit
Reference
SUSY
RPV $\chi_1^0 \to e e\nu / e\mu\nu / \mu\mu\nu$ displaced lepton pair 20.3 χ_1^0 lifetime 7-740 mm $m(\tilde{g})$= 1.3 TeV, $m(\chi_1^0)$= 1.0 TeV 1504.05162
GGM $\chi_1^0 \to Z\tilde{G}$ displaced vtx + jets 20.3 χ_1^0 lifetime 6-480 mm $m(\tilde{g})$= 1.1 TeV, $m(\chi_1^0)$= 1.0 TeV 1504.05162
GGM $\chi_1^0 \to Z\tilde{G}$ displaced dimuon 32.9 χ_1^0 lifetime 0.029-18.0 m $m(\tilde{g})$= 1.1 TeV, $m(\chi_1^0)$= 1.0 TeV 1808.03057
GMSB non-pointing or delayed γ 20.3 χ_1^0 lifetime 0.08-5.4 m SPS8 with Λ= 200 TeV 1409.5542
AMSB $pp \to \chi_1^\pm \chi_1^0, \chi_1^+ \chi_1^-$ disappearing track 20.3 $\chi_1^\pm$ lifetime 0.22-3.0 m $m(\chi_1^\pm)$= 450 GeV 1310.3675
AMSB $pp \to \chi_1^\pm \chi_1^0, \chi_1^+ \chi_1^-$ disappearing track 36.1 $\chi_1^\pm$ lifetime 0.057-1.53 m $m(\chi_1^\pm)$= 450 GeV 1712.02118
AMSB $pp \to \chi_1^\pm \chi_1^0, \chi_1^+ \chi_1^-$ large pixel dE/dx 18.4 $\chi_1^\pm$ lifetime 1.31-9.0 m $m(\chi_1^\pm)$= 450 GeV 1506.05332
Stealth SUSY 2 ID/MS vertices 19.5 $\tilde{S}$ lifetime 0.12-90.6 m $m(\tilde{g})$= 500 GeV 1504.03634
Split SUSY large pixel dE/dx 36.1 $\tilde{g}$ lifetime > 0.9 m $m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV 1808.04095
Split SUSY displaced vtx + E_T^{miss} 32.8 $\tilde{g}$ lifetime 0.03-13.2 m $m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV 1710.04901
Split SUSY 0 ℓ, 2 – 6 jets + E_T^{miss} 36.1 $\tilde{g}$ lifetime 0.0-2.1 m $m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV ATLAS-CONF-2018-003
Higgs BR = 10%
$H \to s s$ low-EMF trk-less jets, MS vtx 36.1 s lifetime 0.18-120.0 m $m(s)$= 25 GeV 1902.03094
FRVZ $H \to 2\gamma_d + X$ 2 $e-, \mu-$jets 20.3 γ_d lifetime 0-3 mm $m(\gamma_d)$= 400 MeV 1511.05542
FRVZ $H \to 2\gamma_d + X$ 2 $e-, \mu-, \pi-$jets 3.4 γ_d lifetime 0.022-1.113 m $m(\gamma_d)$= 400 MeV ATLAS-CONF-2016-042
FRVZ $H \to 4\gamma_d + X$ 2 $e-, \mu-, \pi-$jets 3.4 γ_d lifetime 0.038-1.63 m $m(\gamma_d)$= 400 MeV ATLAS-CONF-2016-042
$H \to Z_d Z_d$ displaced dimuon 32.9 Z_d lifetime 0.009-24.0 m $m(Z_d)$= 40 GeV 1808.03057
$H \to Z Z_d$ 2 e, μ + low-EMF trackless jet 36.1 Z_d lifetime 0.22-5.3 m $m(Z_d)$= 10 GeV 1811.02542
Scalar
VH with $H \to ss \to bbbb$ $1 - 2\ell$ + multi-b-jets 36.1 s lifetime 0-3 mm $\mathcal{B}(H \to ss)$= 1, $m(s)$= 60 GeV 1806.07355
Φ(200 GeV) $\to s s$ low-EMF trk-less jets, MS vtx 36.1 s lifetime 0.41-51.5 m $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV 1902.03094
Φ(600 GeV) $\to s s$ low-EMF trk-less jets, MS vtx 36.1 s lifetime 0.04-21.5 m $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV 1902.03094
Φ(1 TeV) $\to s s$ low-EMF trk-less jets, MS vtx 36.1 s lifetime 0.06-52.4 m $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 150 GeV 1902.03094
Other
HV Z'(1 TeV) $\to q_v q_v$ 2 ID/MS vertices 20.3 s lifetime 0.1-4.9 m $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV 1504.03634
HV Z'(2 TeV) $\to q_v q_v$ 2 ID/MS vertices 20.3 s lifetime 0.1-10.1 m $\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV 1504.03634
0.01
0.1
1
10
100
$c\tau$ [m]
$\sqrt{s}$ = 8 TeV
$\sqrt{s}$ = 13 TeV
0.01
0.1
1
10
100
τ [ns]
*Only a selection of the available lifetime limits is shown.

CMS LLPs


CMS long-lived particle searches, lifetime exclusions at 95% CL
RPV SUSY, $\tilde{t} \rightarrow bl$, $m(\tilde{t})$ = 420 GeV
8 TeV, 19.7 fb^{-1} (displaced leptons)
H → XX (10%), X → ee, m(H) = 125 GeV, m(X) = 20 GeV
8 TeV, 19.6 fb^{-1} (displaced leptons)
H → XX (10%), X → μμ, m(H) = 125 GeV, m(X) = 20 GeV
8 TeV, 20.5 fb^{-1} (displaced leptons)
GMSB SPS8, $\tilde{\chi}_1^0 \rightarrow \tilde{G}\,\gamma$, $m(\tilde{\chi}_1^0)$ = 250 GeV
8 TeV, 19.7 fb^{-1} (disp. photon conv.)
GMSB SPS8, $\tilde{\chi}_1^0 \rightarrow \tilde{G}\,\gamma$, $m(\tilde{\chi}_1^0)$ = 250 GeV
8 TeV, 19.1 fb^{-1} (disp. photon timing)
RPV SUSY, $m(\tilde{q})$ = 1000 GeV, $m(\tilde{\chi}_1^0)$ = 150 GeV
8 TeV, 18.5 fb^{-1} (displaced dijets)
RPV SUSY, $m(\tilde{q})$ = 1000 GeV, $m(\tilde{\chi}_1^0)$ = 500 GeV
8 TeV, 18.5 fb^{-1} (displaced dijets)
AMSB $\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + \pi^\pm$, $m(\tilde{\chi}_1^\pm)$ = 200 GeV
8 TeV, 19.5 fb^{-1} (disappearing tracks)
cloud model R-hadron, $m(\tilde{g})$ = 1000 GeV
8 TeV, 18.6 fb^{-1} (stopped particle)
AMSB $\tilde{\chi}_1^\pm$, tan(β) = 5, μ > 0, $m(\tilde{\chi}_1^\pm)$ = 800 GeV
8 TeV, 18.8 fb^{-1} (tracker + TOF)
AMSB $\tilde{\chi}_1^\pm$, tan(β) = 5, μ > 0, $m(\tilde{\chi}_1^\pm)$ = 200 GeV
8 TeV, 18.8 fb^{-1} (tracker + TOF)
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
cτ [m]

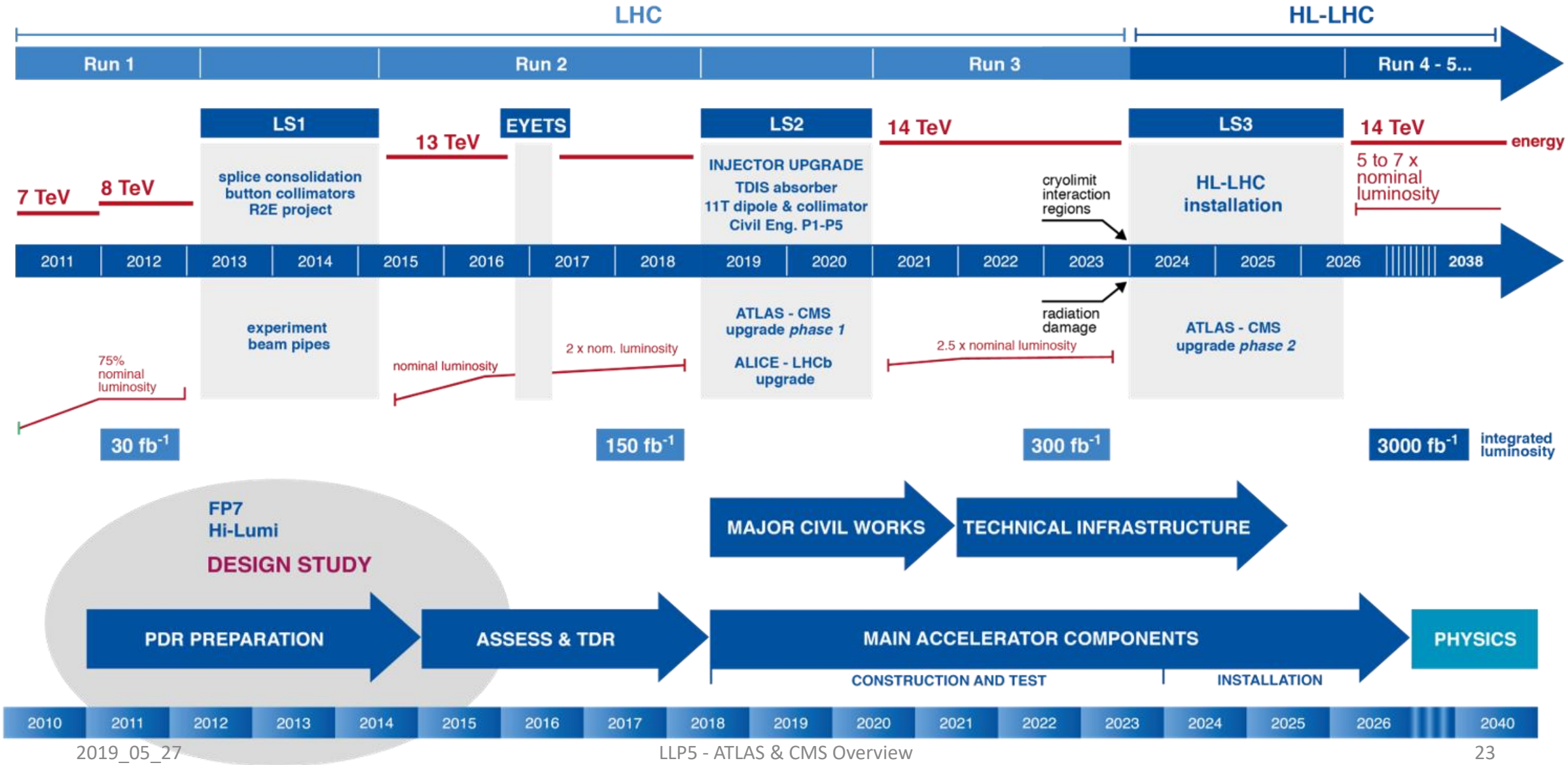
The ATLAS+CMS HL-LHC Masterlist

https://arxiv.org/ftp/arxiv/papers/1902/1902.10229.pdf

BSM Projections

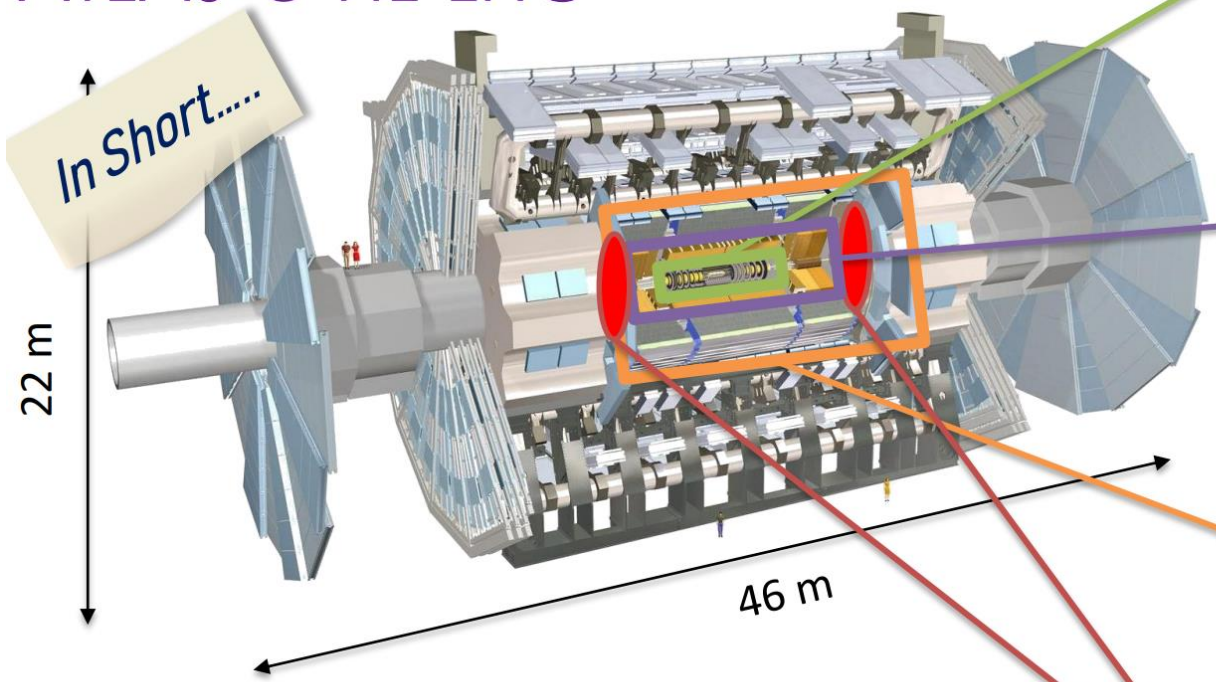
https://arxiv.org/abs/1902.10229

LHC / HL-LHC Plan



• Phase II Detector Upgrades

ATLAS @ HL-LHC



A Toroidal LHC ApparatuS

- ✓ Biggest LHC experiment with several sub-detectors
  - 2.6 T – 5.3 m long Central solenoid
  - 3.1 T – 20.1m barrel toroid
- ✓ ~ 139 fb^{-1} total integrated luminosity

Inner Tracker (iTk)

- ✓ 5 pixel & 4 strip barrel layers
- ✓ Coverage up to $|\eta| < 4.0$
- ✓ 180 m^2 of Si, 2 – 3 billion channels

LAr & Tile CAL electronics

- ✓ New 12 bit digitization boards at 40MHz
- ✓ New pre-processors with 140Tb/s for Lar and 80Tb/s for Tile

Inner Muon Spectrometer

- ✓ New on and off detector and trigger electronics
- ✓ Additional RPCs and new MDTs in barrel region

TDAQ System

- ✓ New DAQ high rate (FELIX) boards
- ✓ Distributed FPGA communication

High Granularity Timing detector

- ✓ < 30 psec/ track timing resolution
- ✓ $2.4 < \eta < 4.0$, 2 Silicon based, layers/side

Slide stolen shamelessly from E. L. Gkougkousis (IFAE)

https://indico.cern.ch/event/663474/contributions/3063611/attachments/1692743032/Gkougkousis_ICNFP18.pdf

CMS @ HL-LHC

CMS Tracker

- ✓ 4 pixel & 6 strip barrel layers, fully silicon
- ✓ Coverage up to $|\eta| < 4.0$
- ✓ 100 m^2 of pixels Si, 1.9 – 2 billion channels

Barrel and end-cap ECAL/HCAL

- ✓ New barrel readout electronics
- ✓ 12 bit 160 MHz ASIC
- ✓ Crystal Colling to 8 - 6 °C
- ✓ LYSO Crystals in endcap region

Muon system

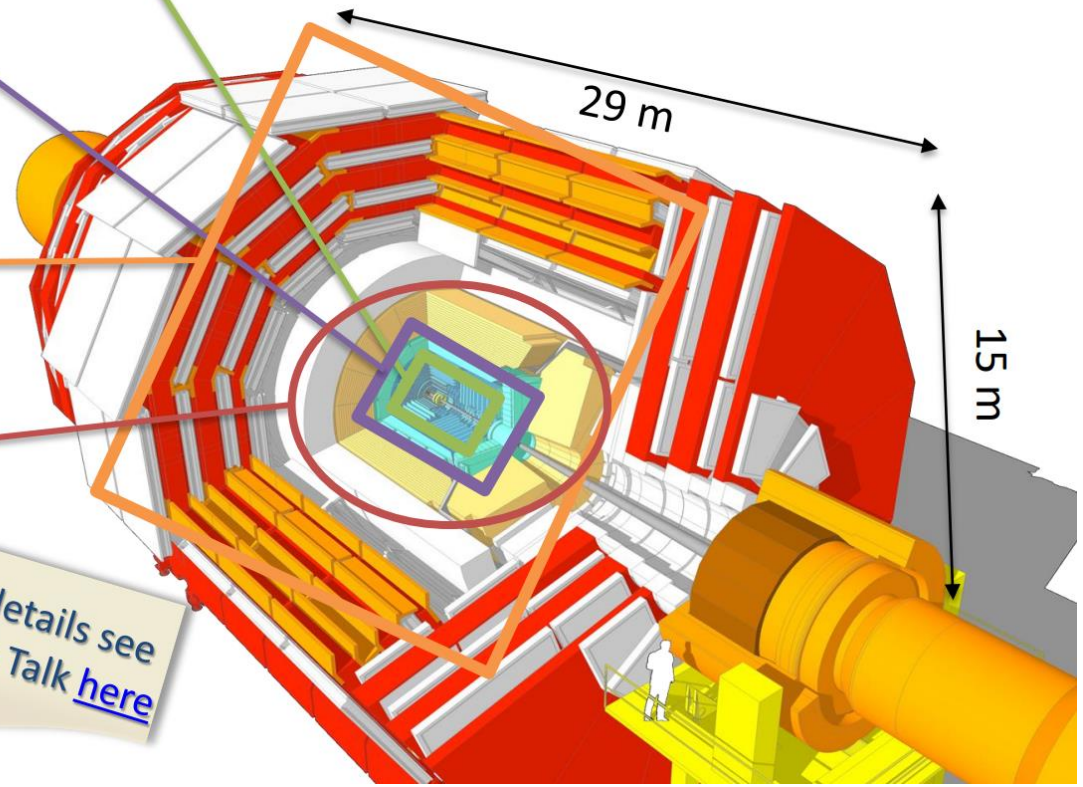
- ✓ Improve coverage in $1.5 \leq |\eta| \leq 2.4$,
- ✓ Exend to $|\eta| \leq 3.0$ using GEM/ RPCs

Timing Layer

- ✓ LYSO + SiPMs in barel region
- ✓ LGADs in forward region
- ✓ < 30 psec per track, single layer
- ✓ Full coverage

Compact Muon Solenoid

- ✓ Heaviest LHC experiment with several sub-detectors
  - 4 T – 12.5 m long solenoid
  - 10000 t. steel return yoke
- ✓ ~ 142.8 fb^{-1} total integrated luminosity



For details see Colin's Talk here

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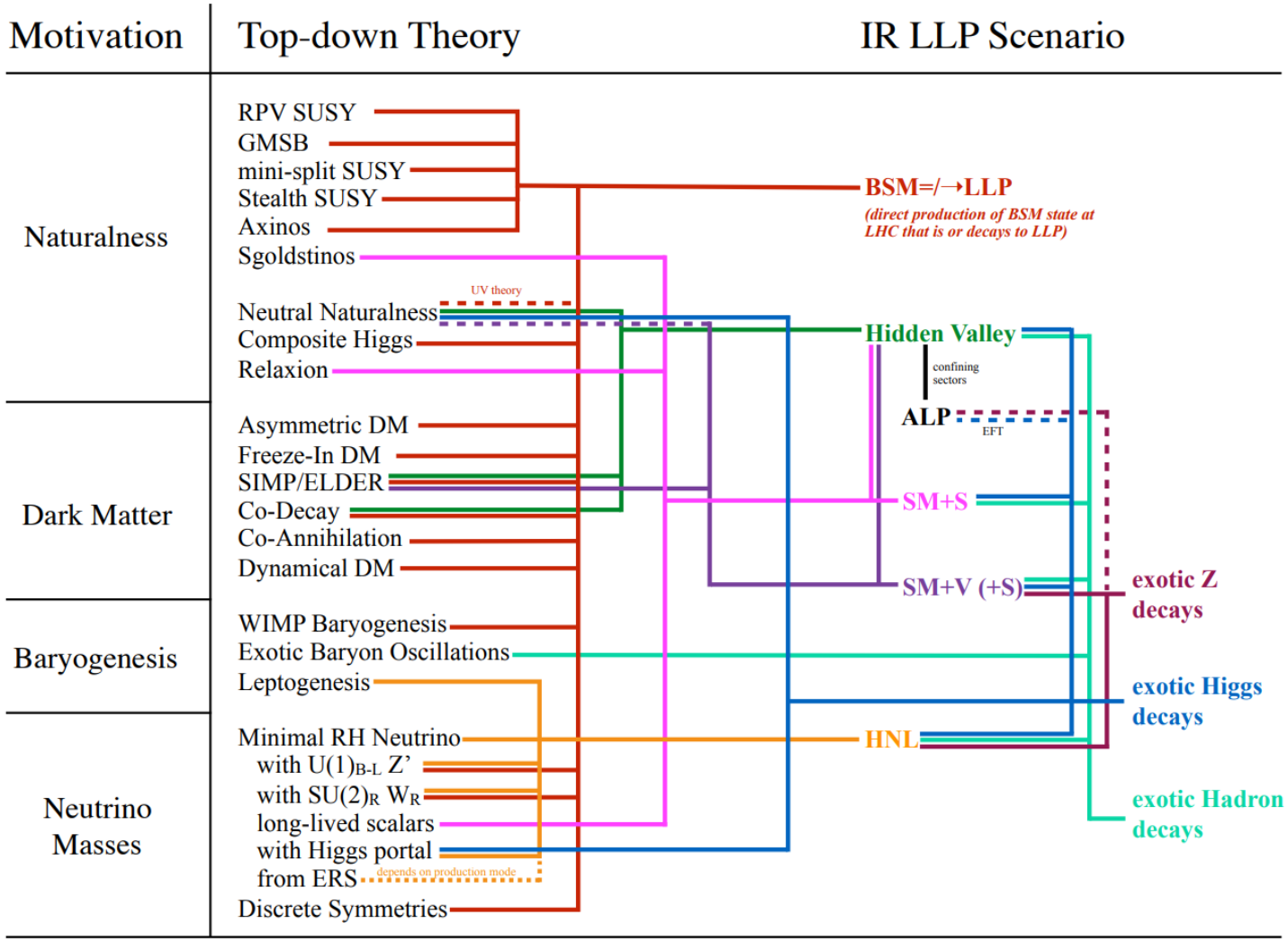
Neutral LLPs



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