

DM at the LHC

R Rosten (IFAE)

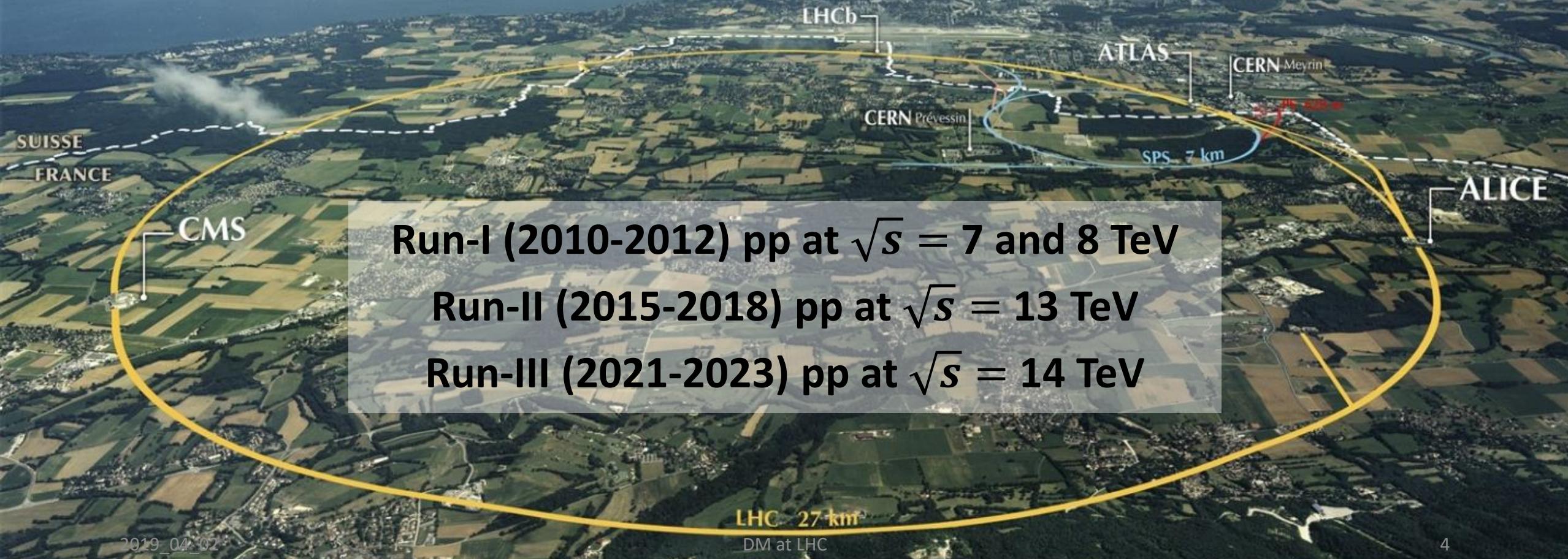


The ATLAS+CMS HL-LHC Masterlist

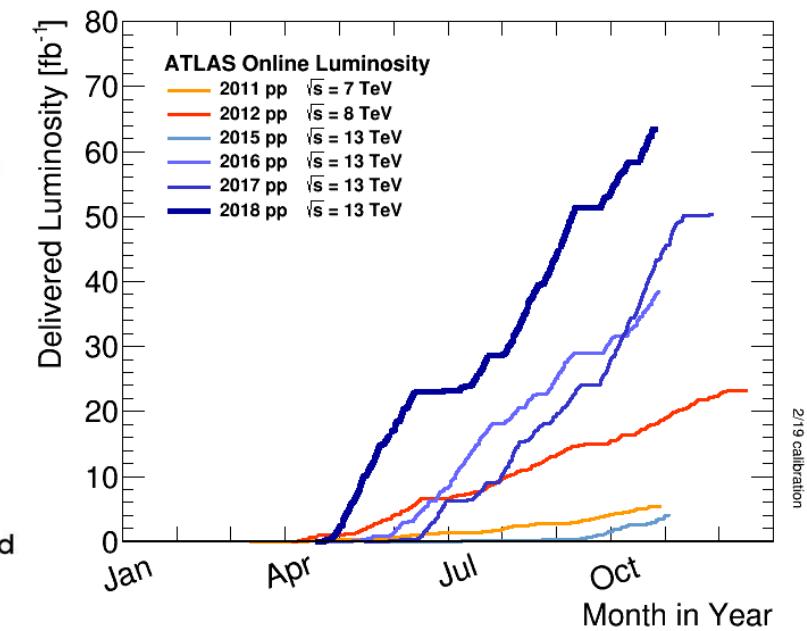
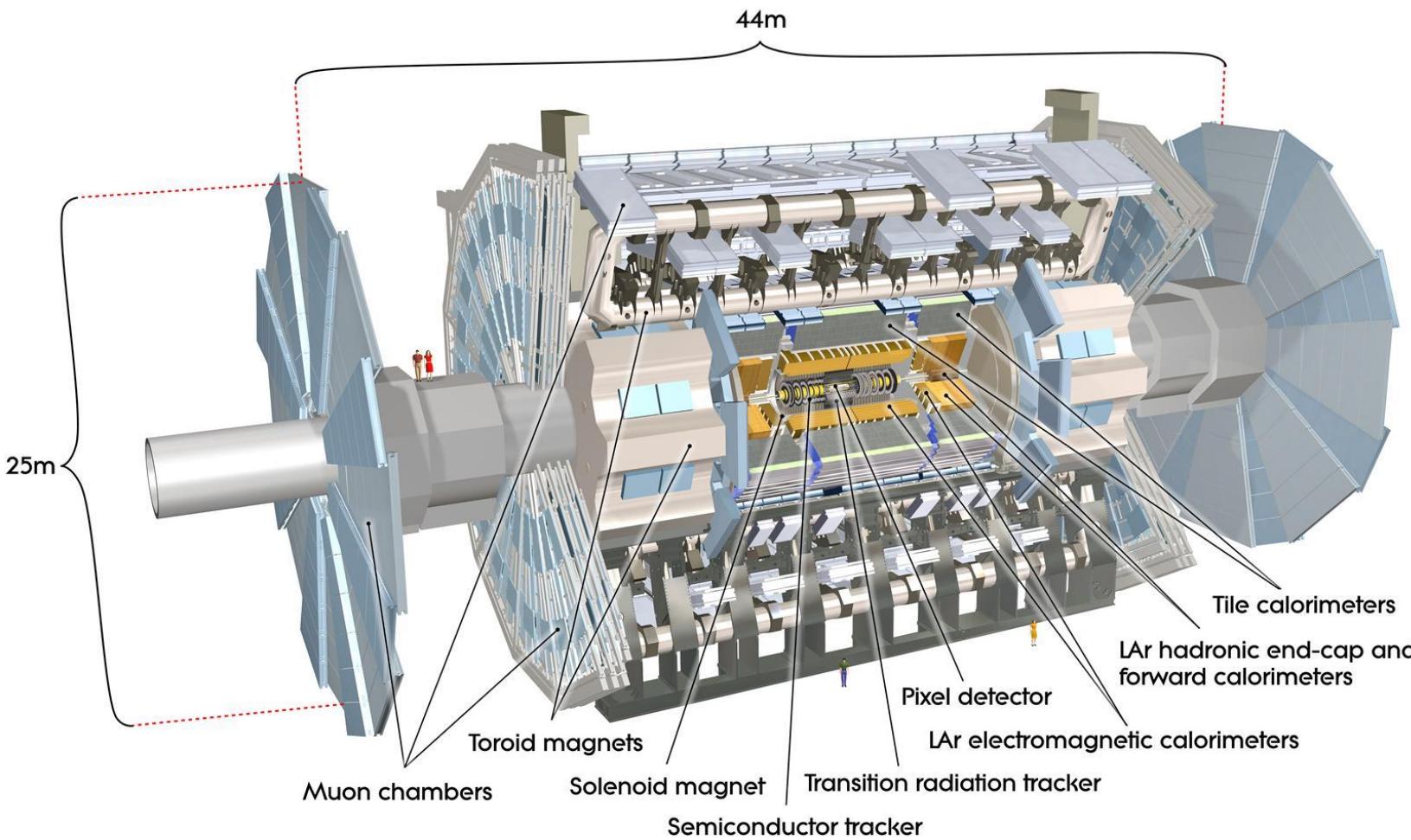
<https://arxiv.org/ftp/arxiv/papers/1902/1902.10229.pdf>

LHC and Experiments

The LHC

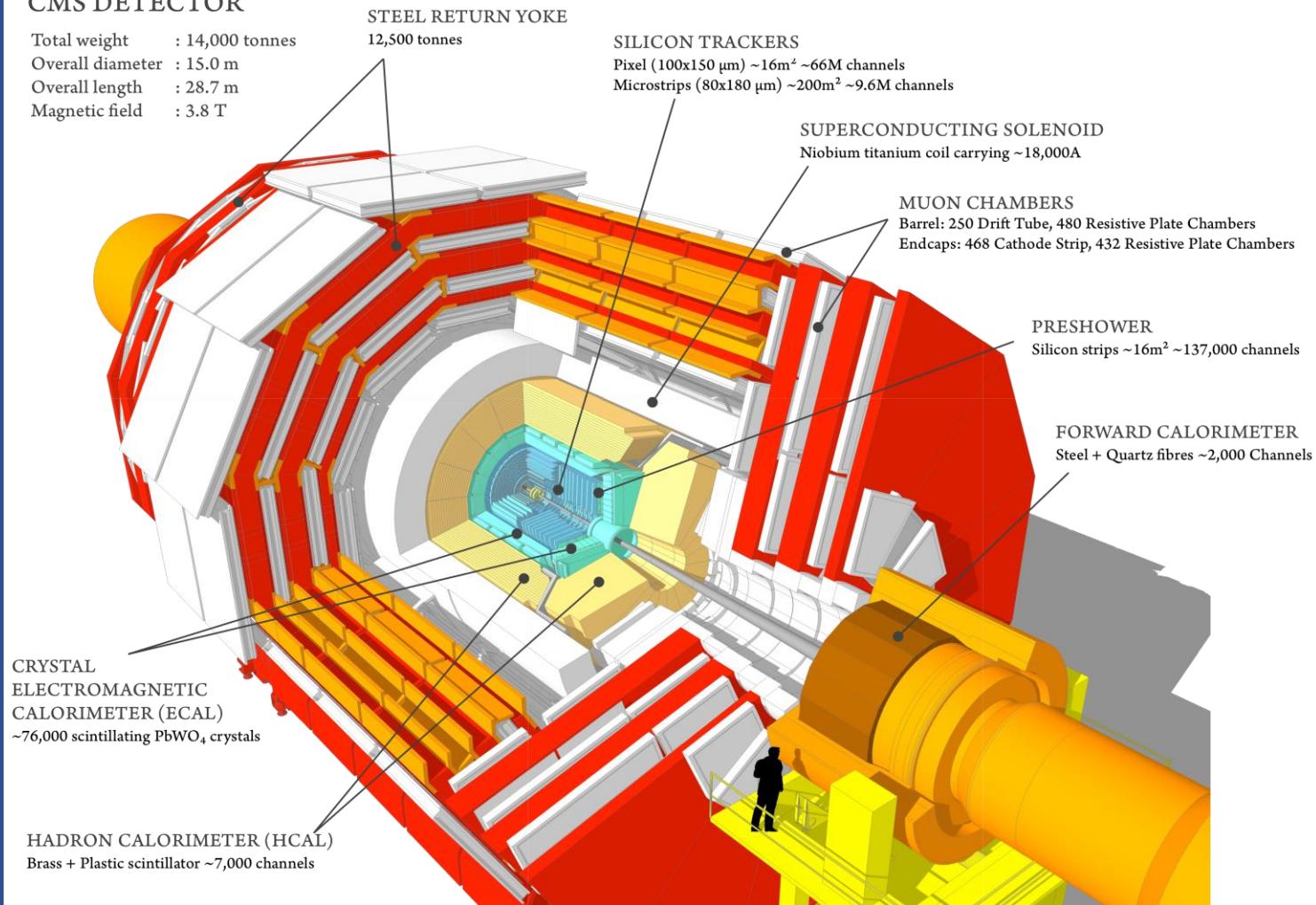


ATLAS

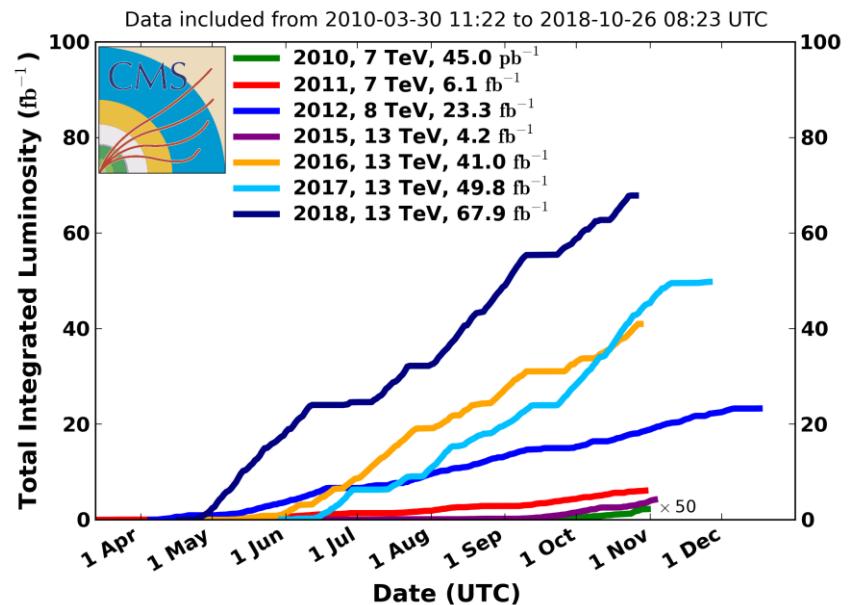


CMS

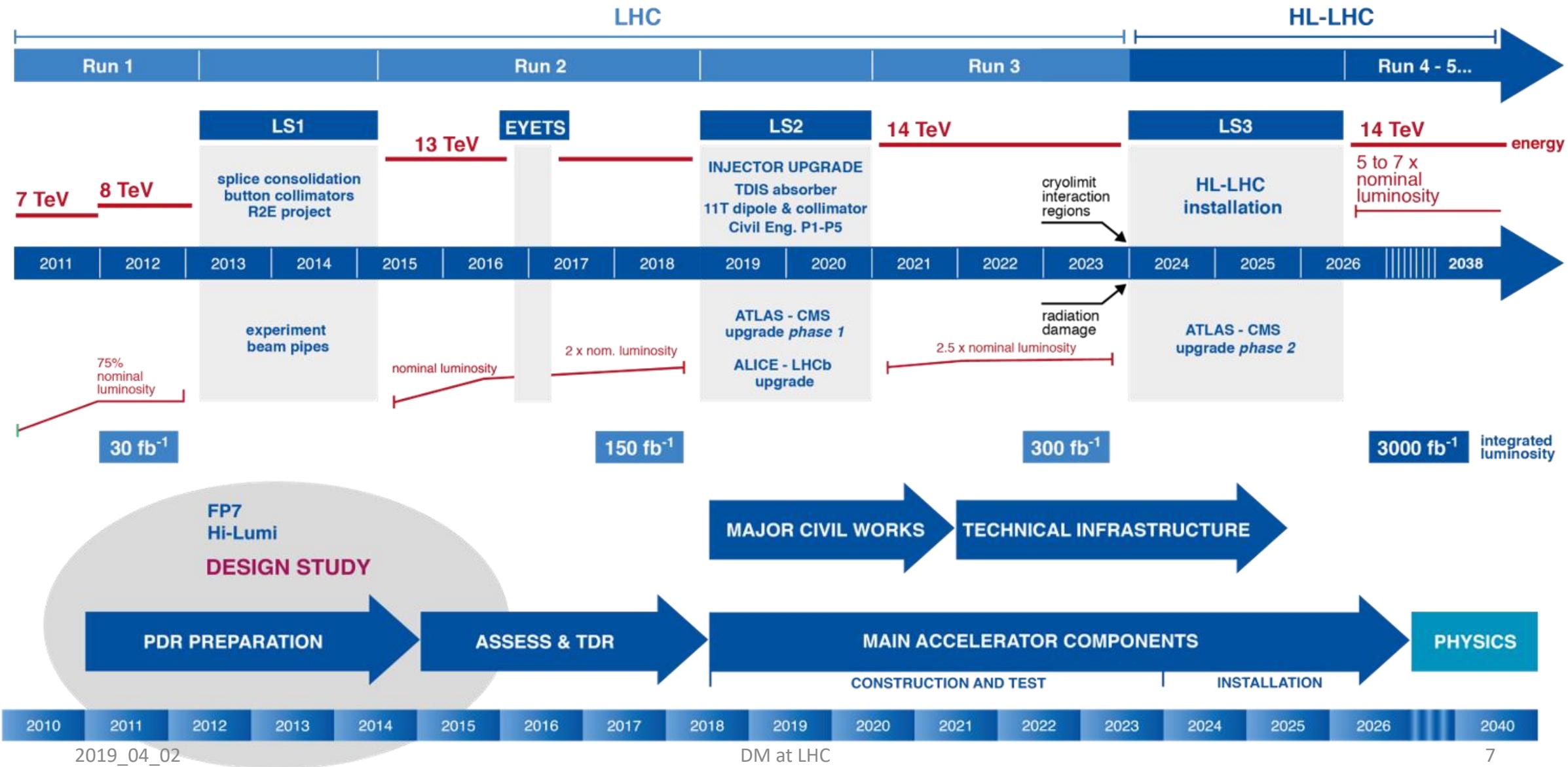
CMS DETECTOR



CMS Integrated Luminosity Delivered, pp



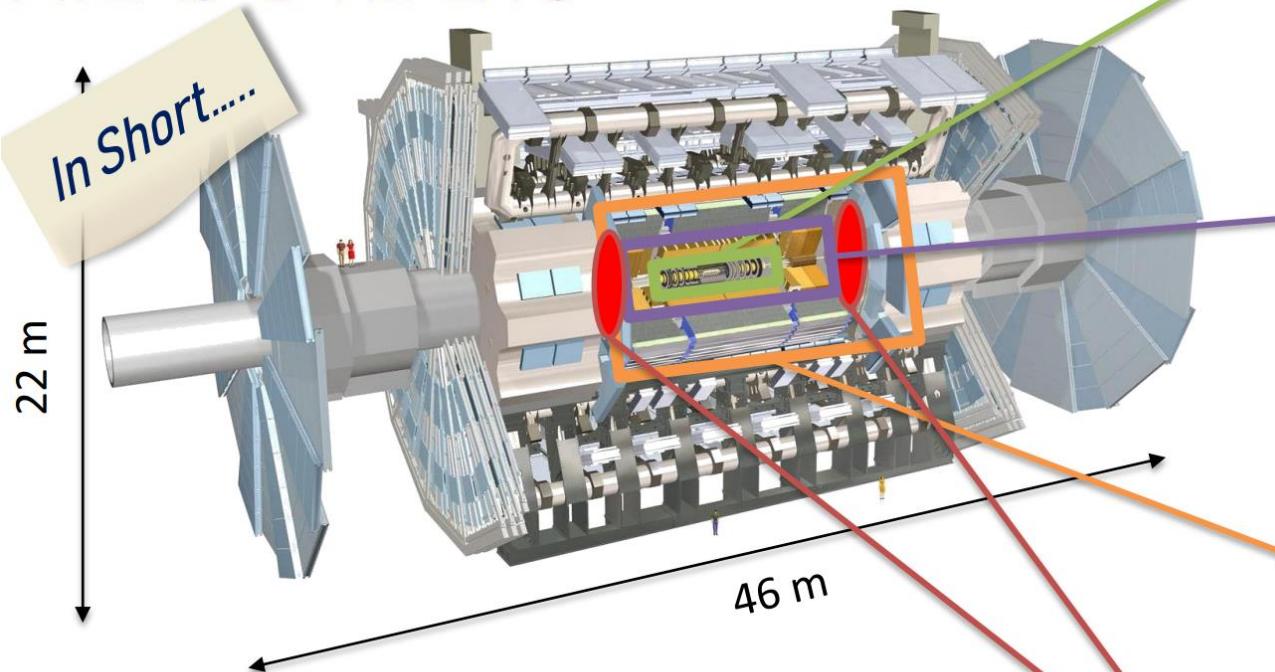
LHC / HL-LHC Plan



• 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
- ✓ $\sim 139 \text{ fb}^{-1}$ total integrated luminosity

TDAQ System

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

High Granularity Timing detector

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

- Inner Tracker (iTk)**
- ✓ 5 pixel & 4 strip barrel layers
 - ✓ Coverage up to $|\eta| < 4.0$
 - ✓ 180 m² 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

CMS @ HL-LHC

CMS Tracker

- ✓ 4 pixel & 6 strip barrel layers, fully silicon
- ✓ Coverage up to $|\eta| < 4.0$
- ✓ 100 m² 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

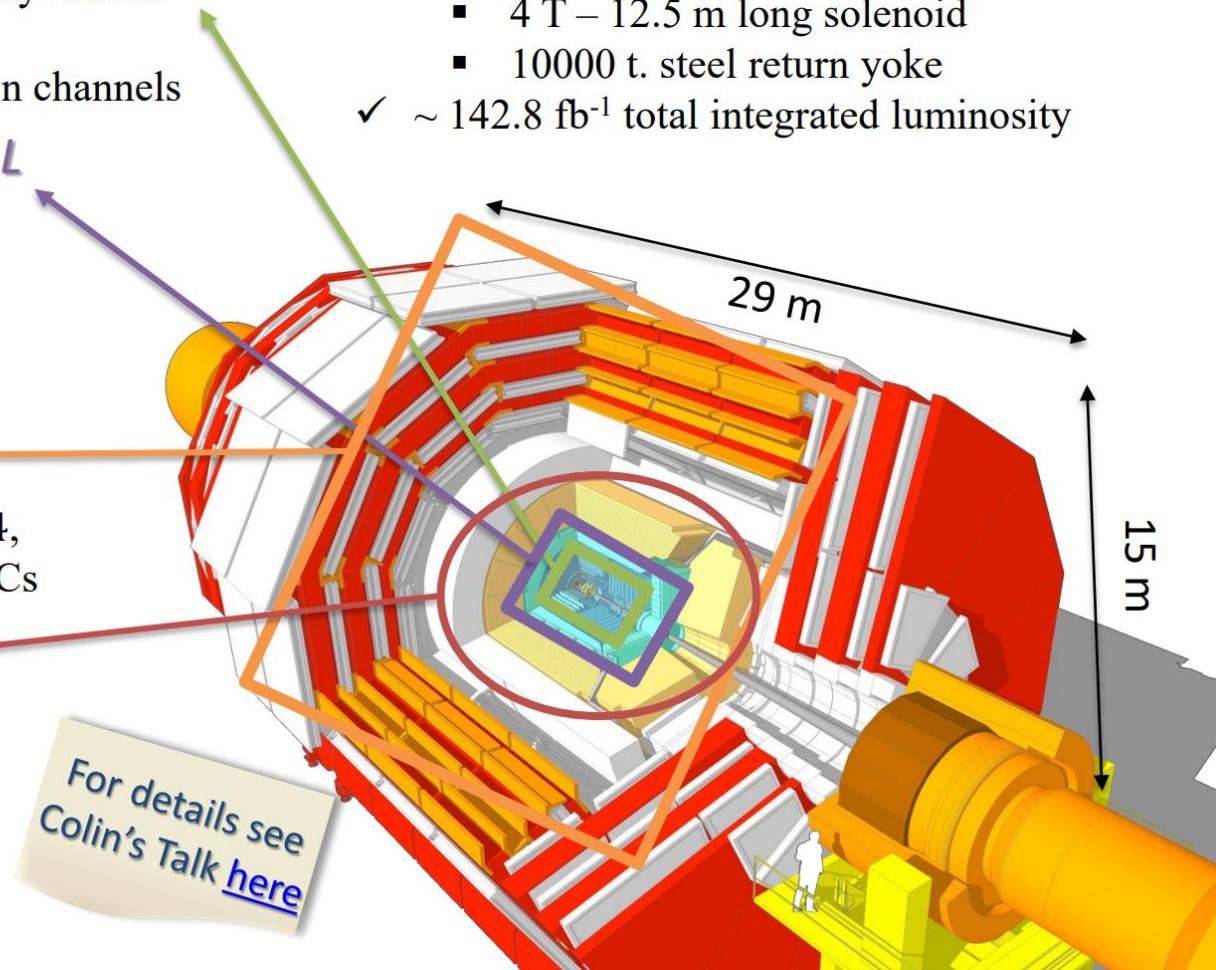
- ✓ Improve coverage in $1.5 \leq |\eta| \leq 2.4$,
- ✓ Extend to $|\eta| \leq 3.0$ using GEM/ RPCs

Timing Layer

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

Compact Muon Solenoid

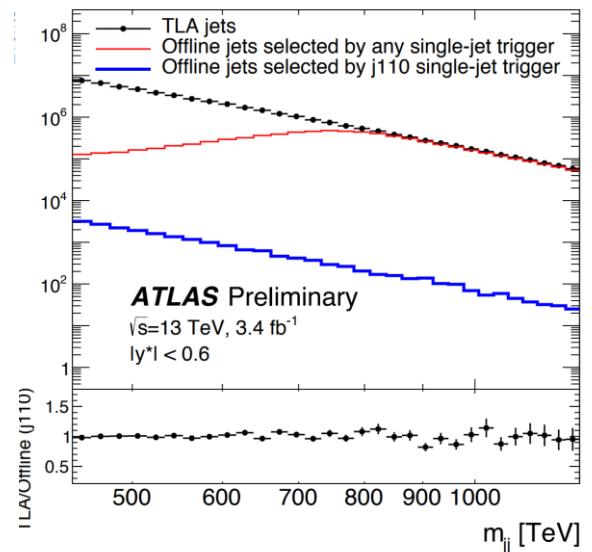
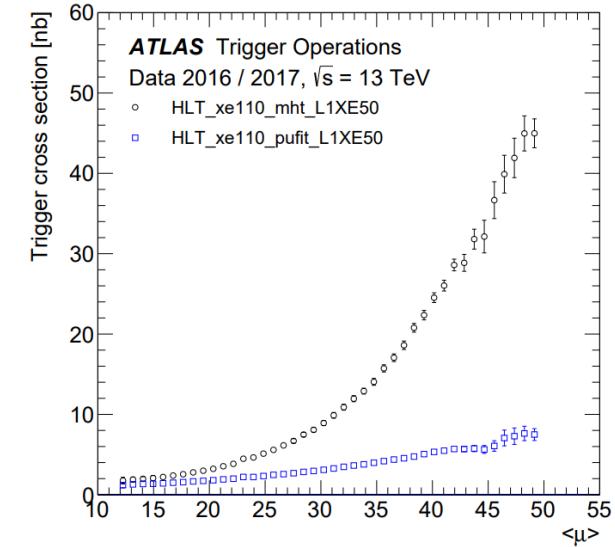
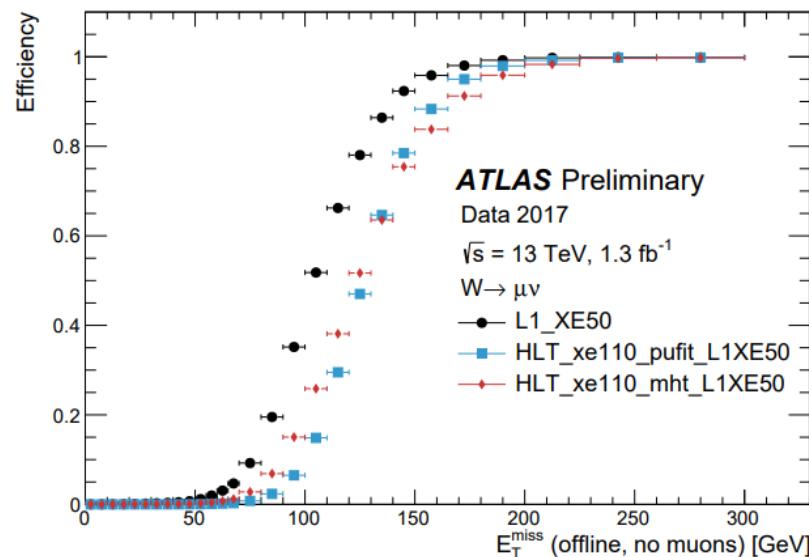
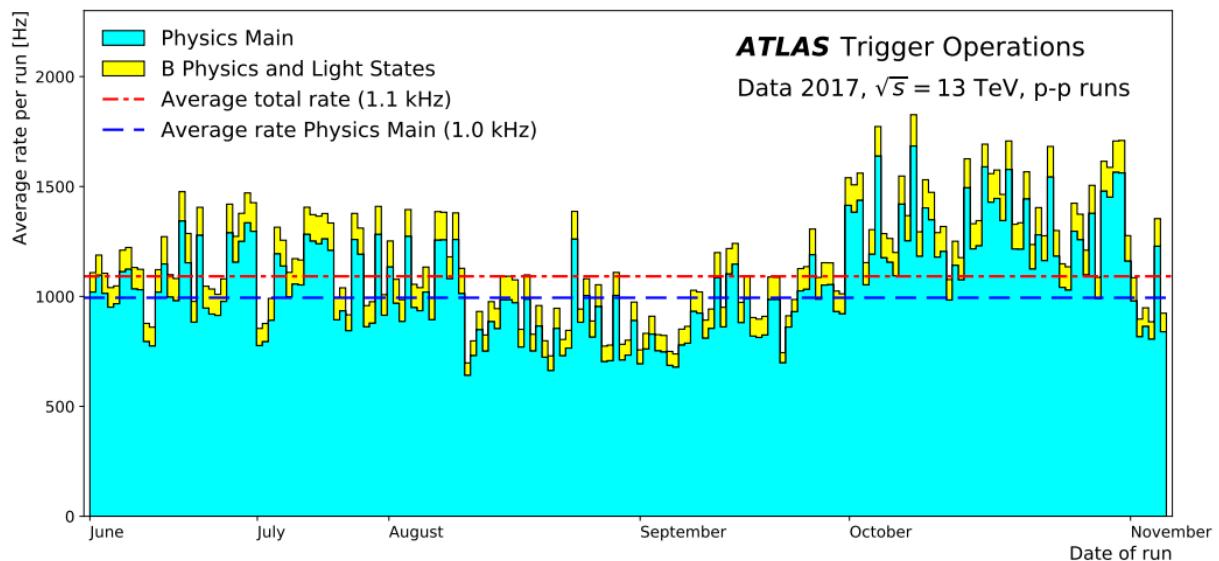
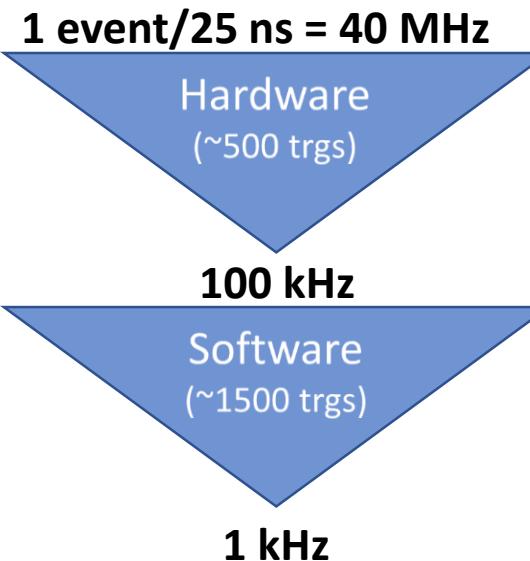
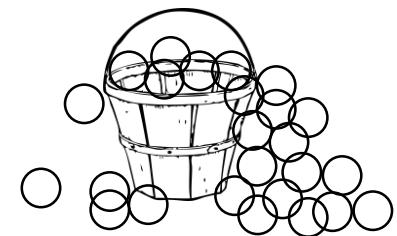
- ✓ Heaviest LHC experiment with several sub-detectors
 - 4 T – 12.5 m long solenoid
 - 10000 t. steel return yoke
- ✓ ~ 142.8 fb⁻¹ total integrated luminosity



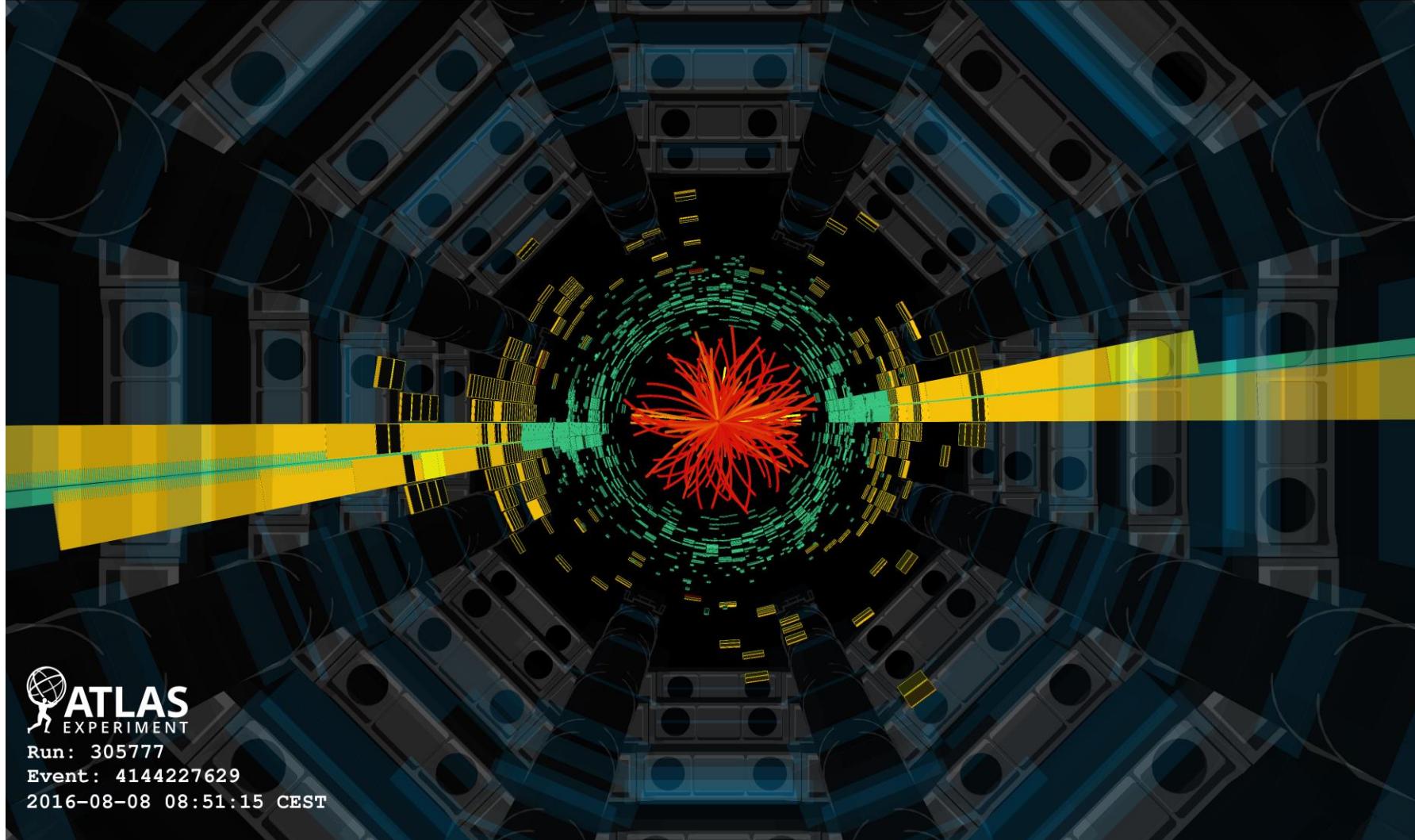
Slide stolen shamelessly from E. L. Gkougkousis (IFAE)

Building an Analysis

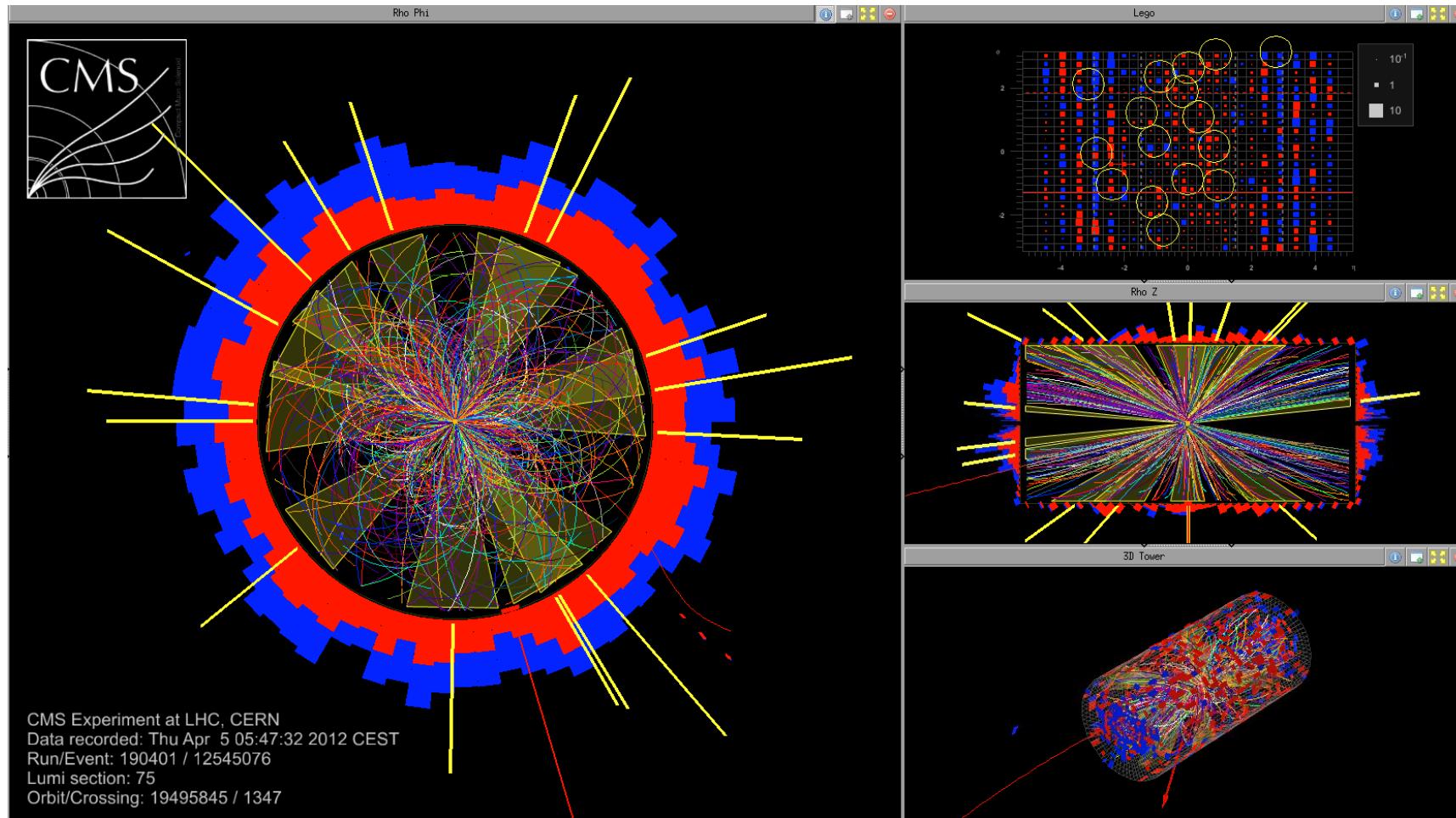
Building an Analysis – Trigger



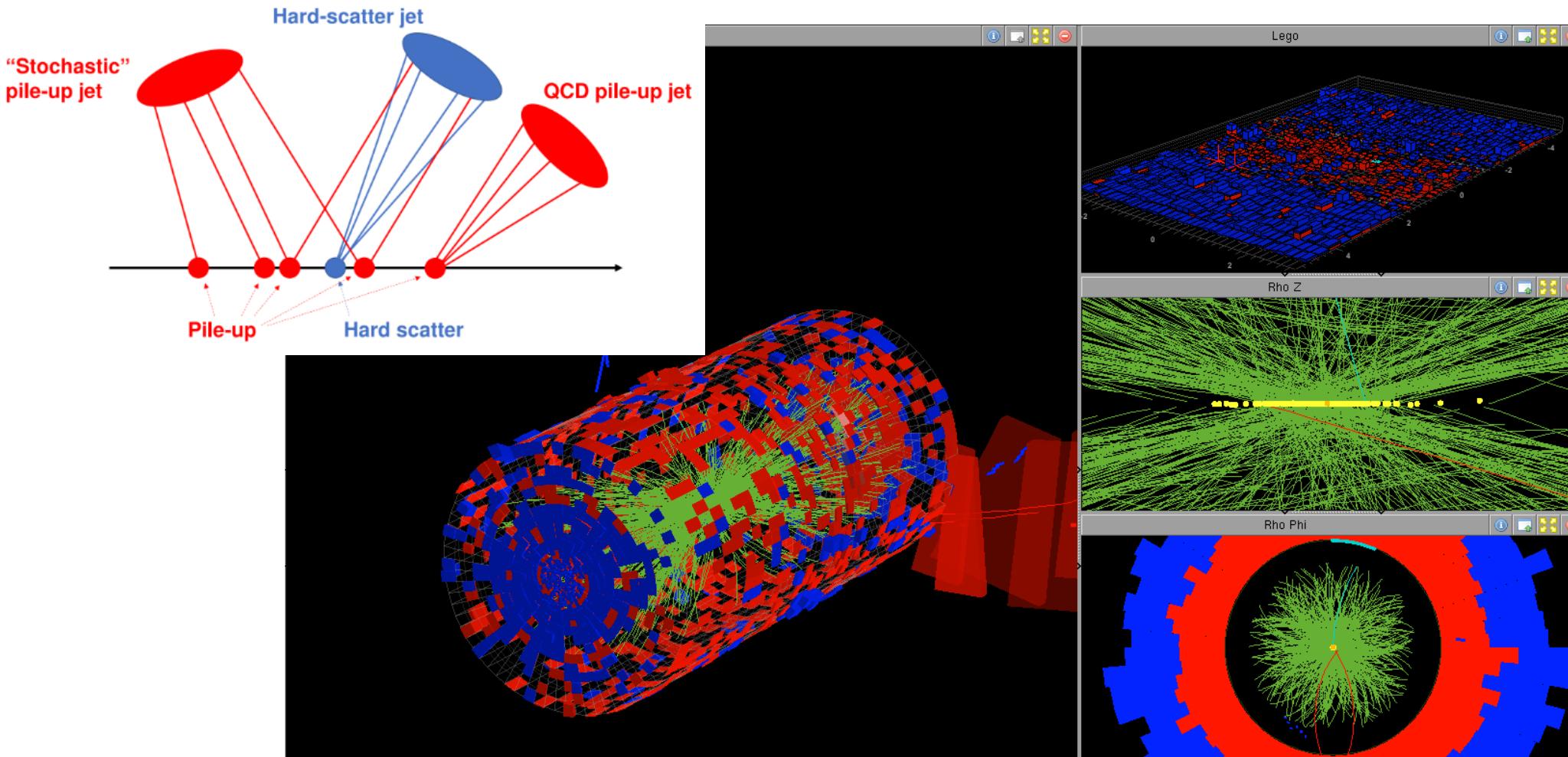
Building an Analysis – Simulation & Reconstruction



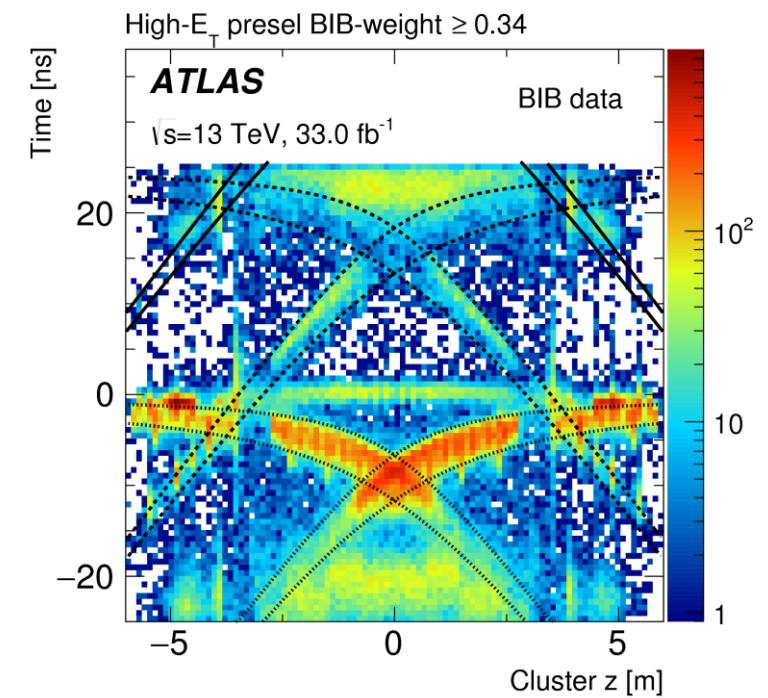
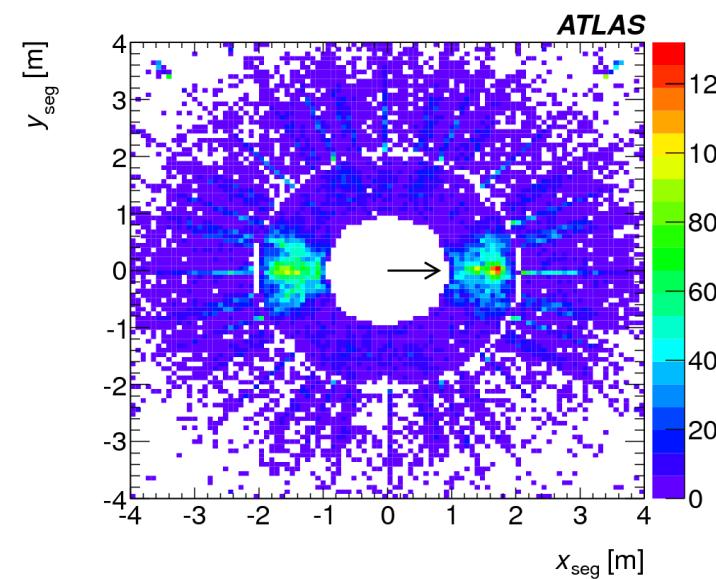
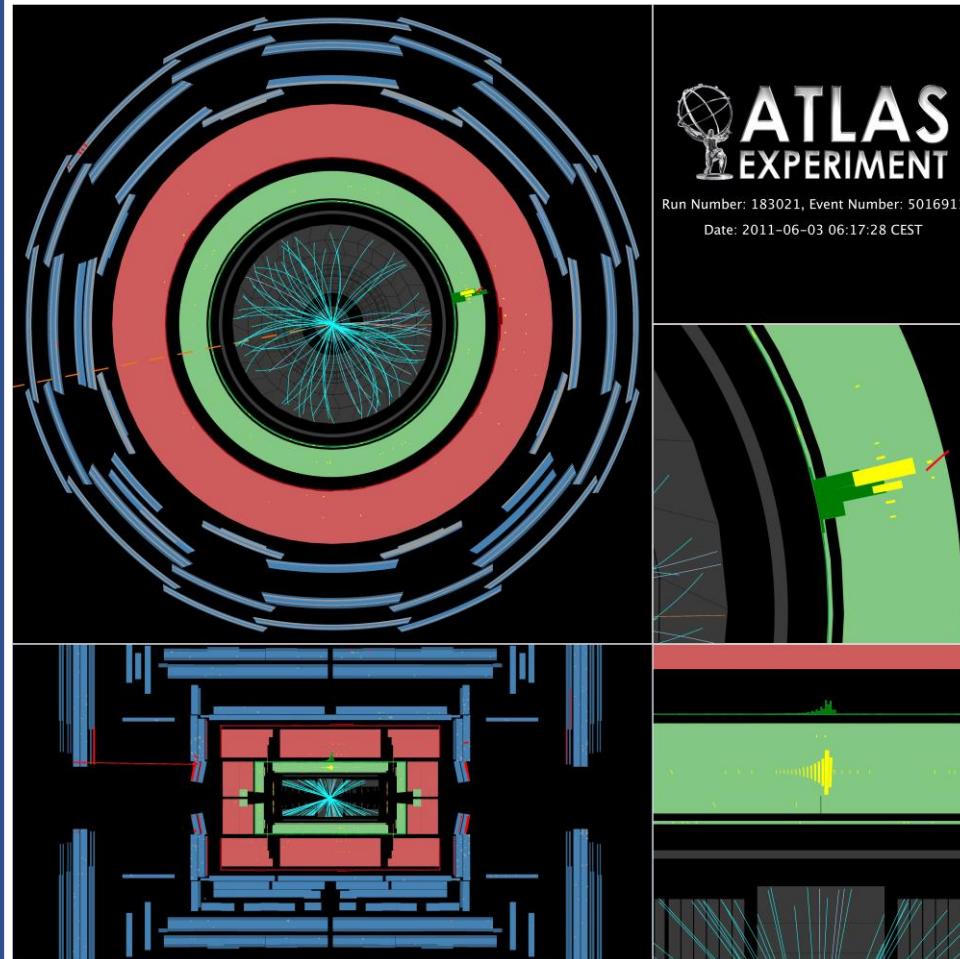
Building an Analysis – Simulation & Reconstruction



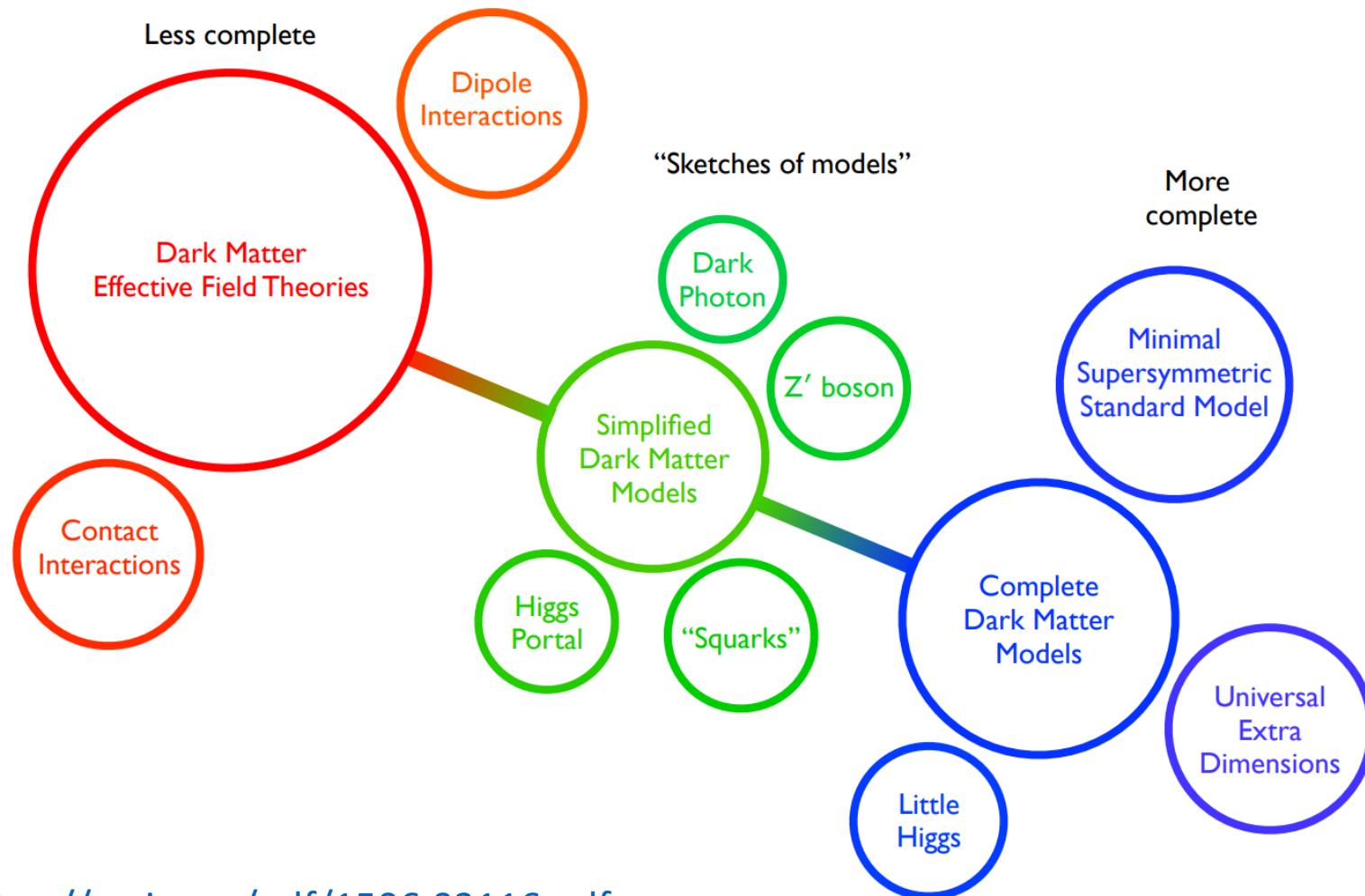
Building an Analysis – Simulation & Reconstruction



Non-Collision Backgrounds



EFT vs Simplified Models vs ... Signatures?



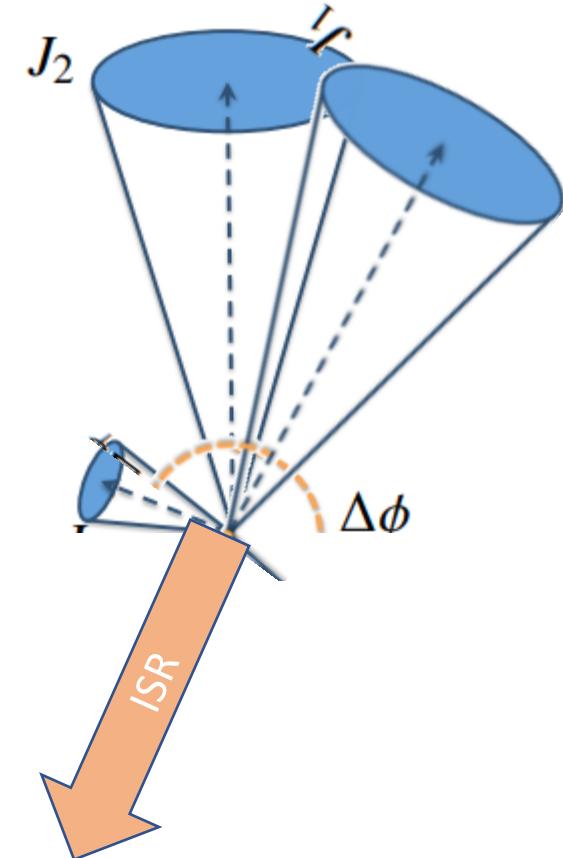
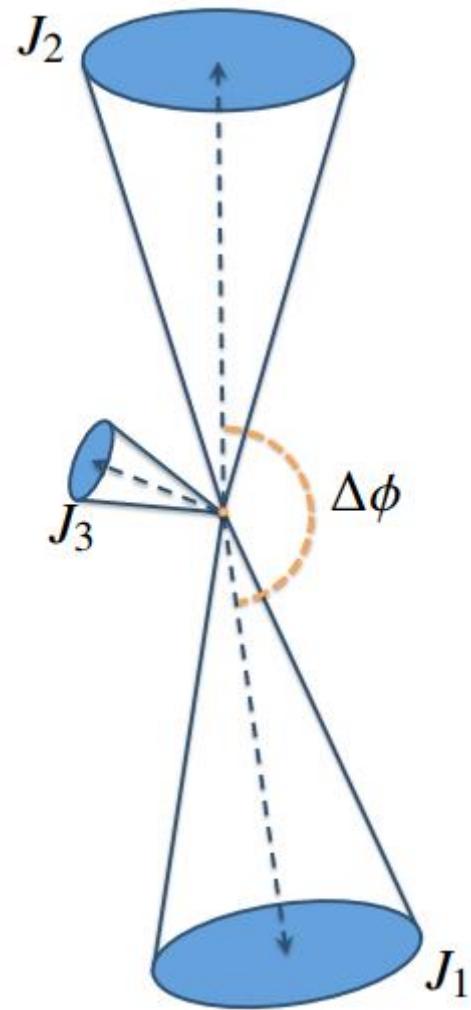
<https://arxiv.org/pdf/1506.03116.pdf>

Signature Overview

Ex: ATLAS DM overview: <https://arxiv.org/abs/1903.01400>

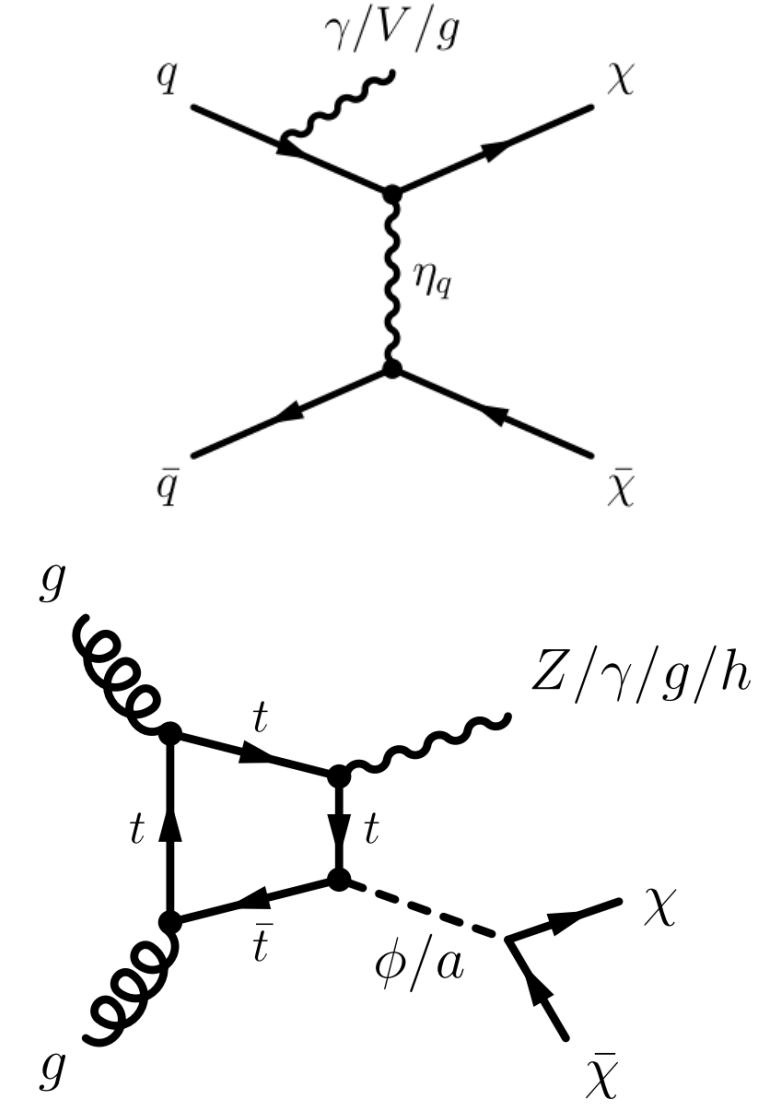
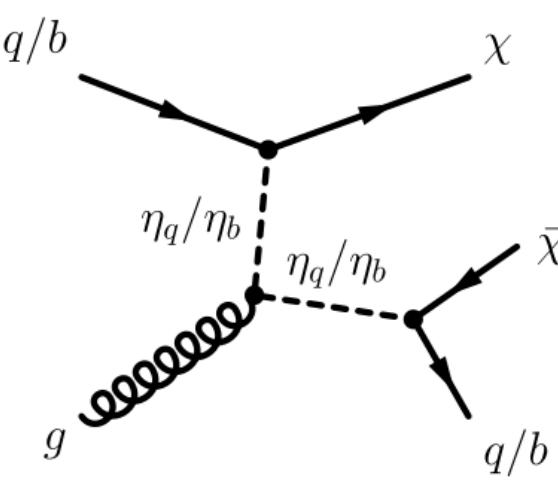
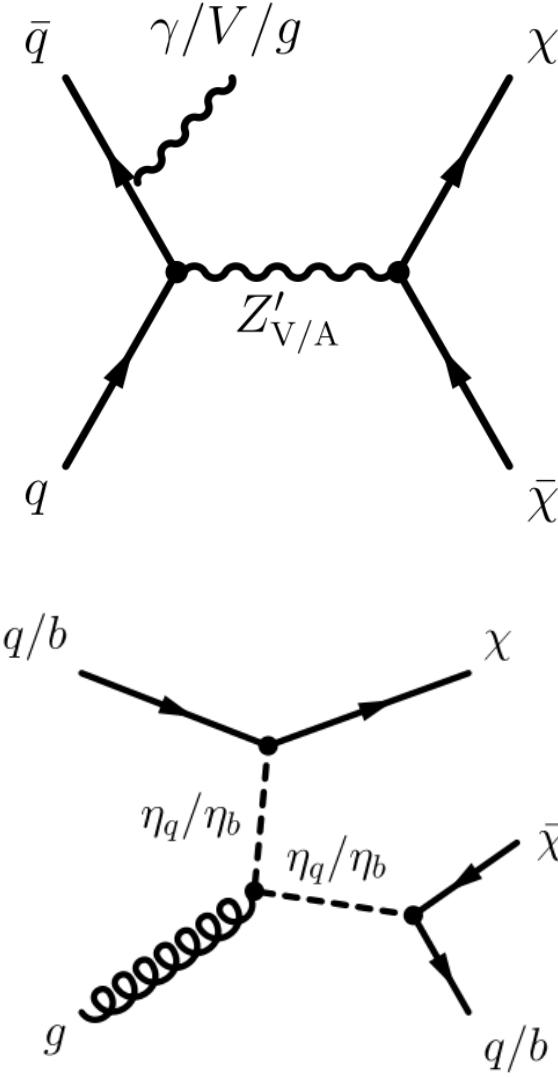
Mediator: Visible Signatures

- Dijet
- Resolved dijet + ISR
- Boosted dijet + ISR
- Trigger-Level Dijet
- Dibjet
- Dilepton
- Same-sign tt
- $t\bar{t}$ resonance



Mediator: MET Signatures

- Jet+MET
- γ +MET
- W/Z(hadronic)+MET
- Z(ll)+MET
- $h(b\bar{b})$ +MET
- $h(\gamma\gamma)$ +MET
- Heavy flavor + MET
- $h \rightarrow \text{invs}$



Long-Lived Particles

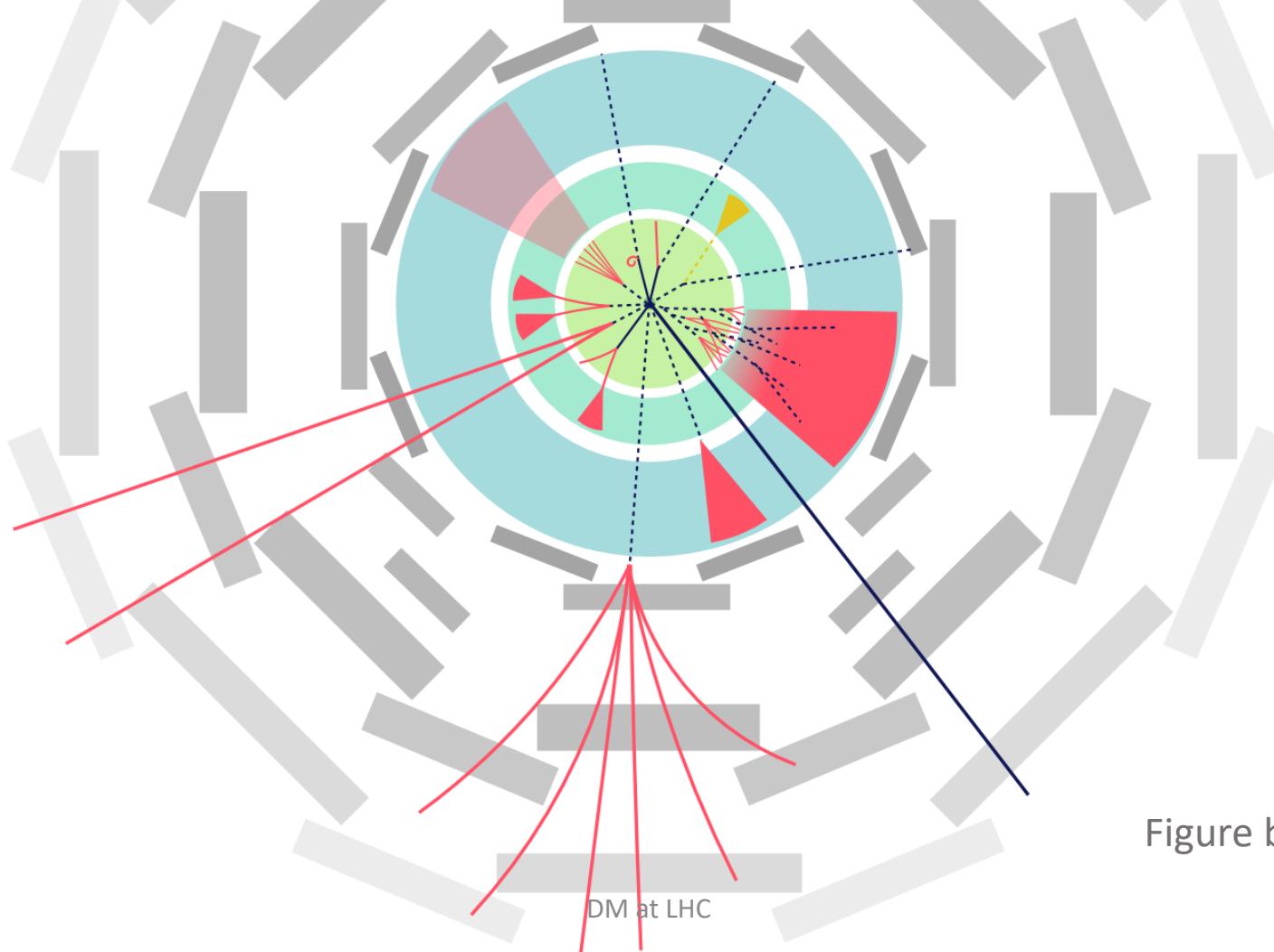
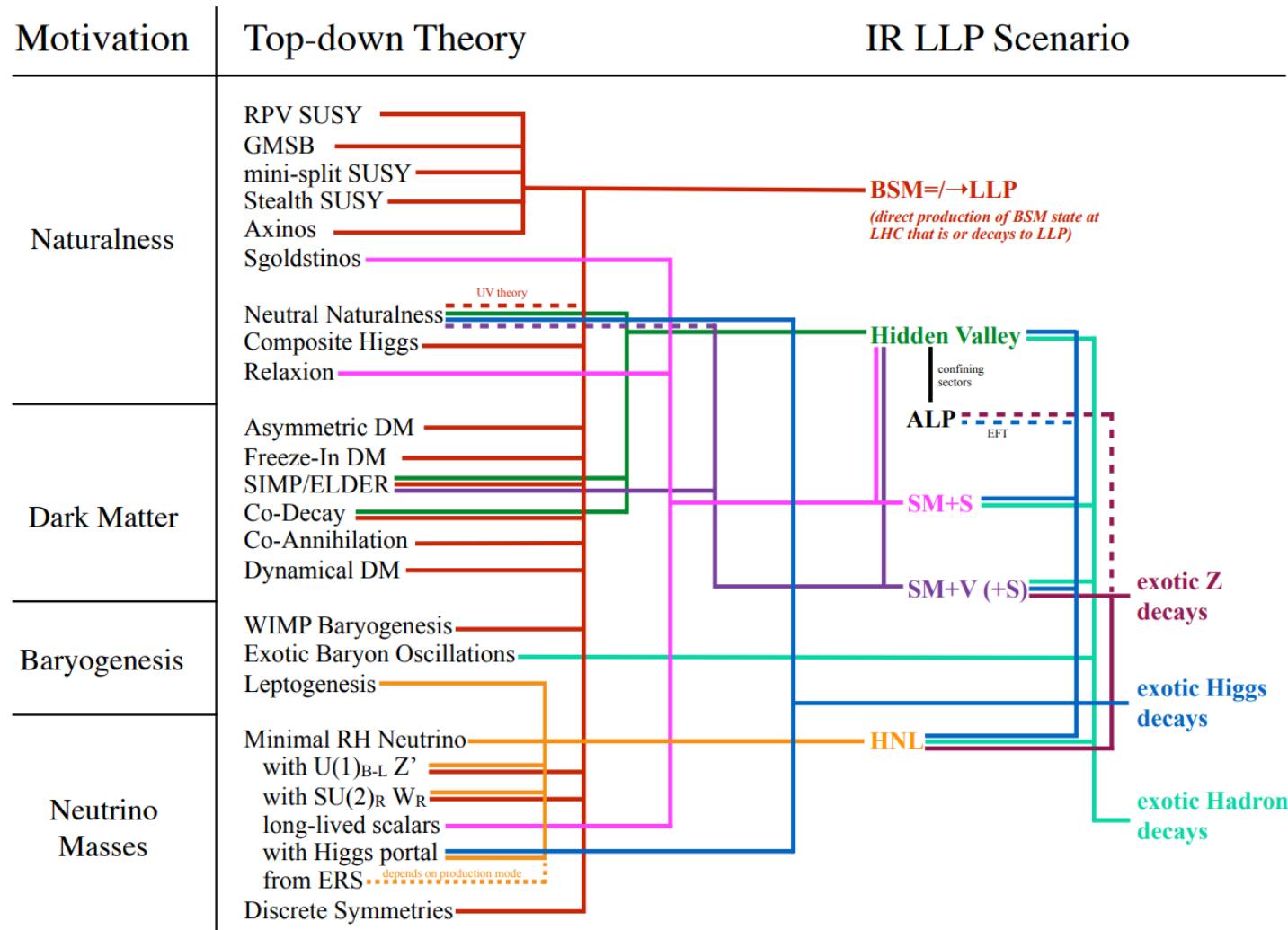


Figure by H. Russell

Neutral LLPs



1806.07396

DM at LHC

Some Analysis Examples

Reminder, Moriond 2019 results:

DM: <http://moriond.in2p3.fr/QCD/2019/TuesdayAfternoon/Pinna.pdf>

LLPs: <http://moriond.in2p3.fr/QCD/2019/TuesdayAfternoon/Pedro.pdf>

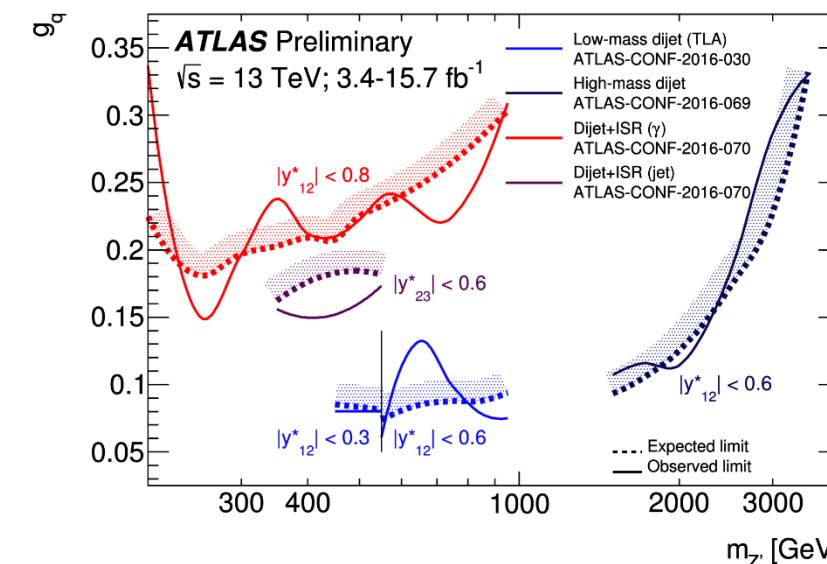
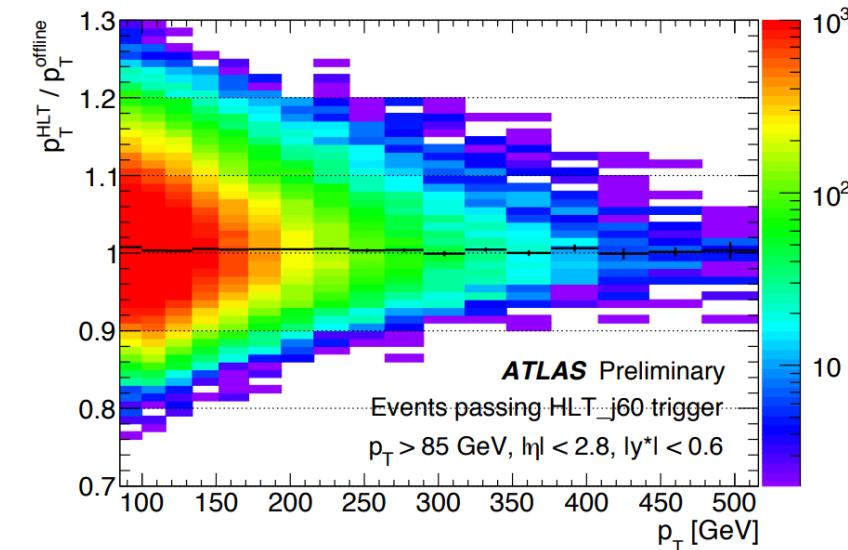
Higgs: <http://moriond.in2p3.fr/QCD/2019/SundayMorning/Brendlinger.pdf>

Higgs: <http://moriond.in2p3.fr/QCD/2019/SundayMorning/Flechl.pdf>

Trigger Level Analysis

ATLAS-CONF-2016-030

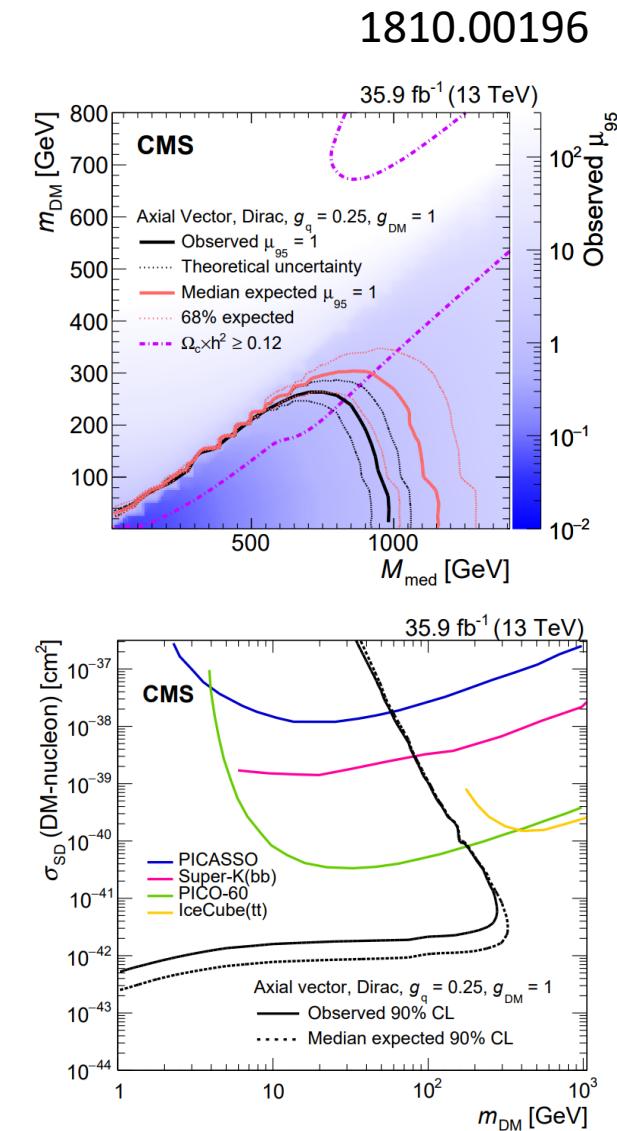
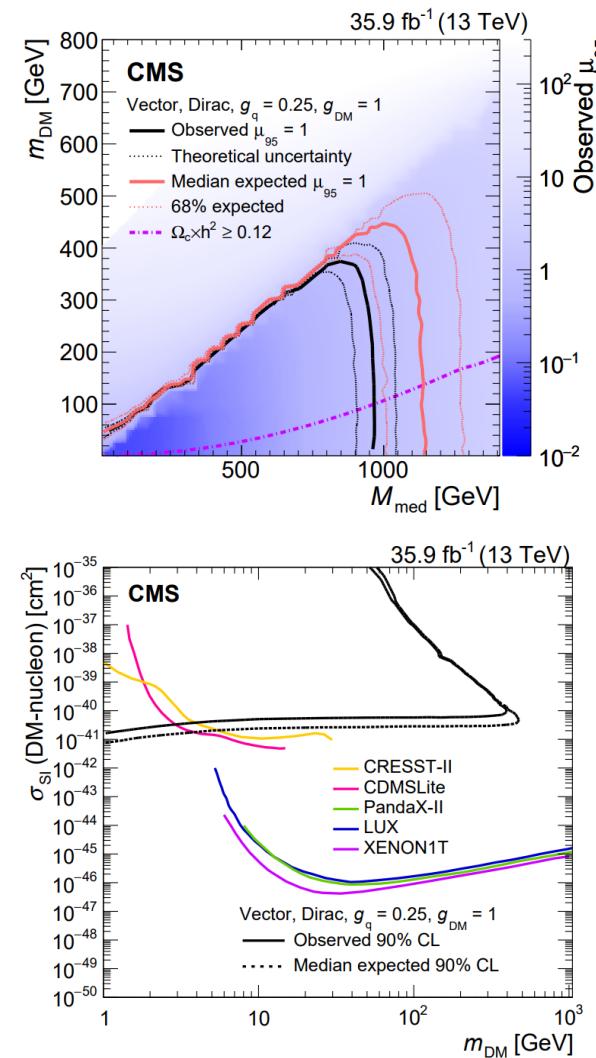
- Trigger directly on lower-energy jets and record only a portion of the event
 - Use L1 trigger to identify candidate events
 - Record jet four-momentum and some jet substructure information, but little other event information
- Required dedicated jet calibration for partially built events
- Background calculated with fit to dijet mass spectrum



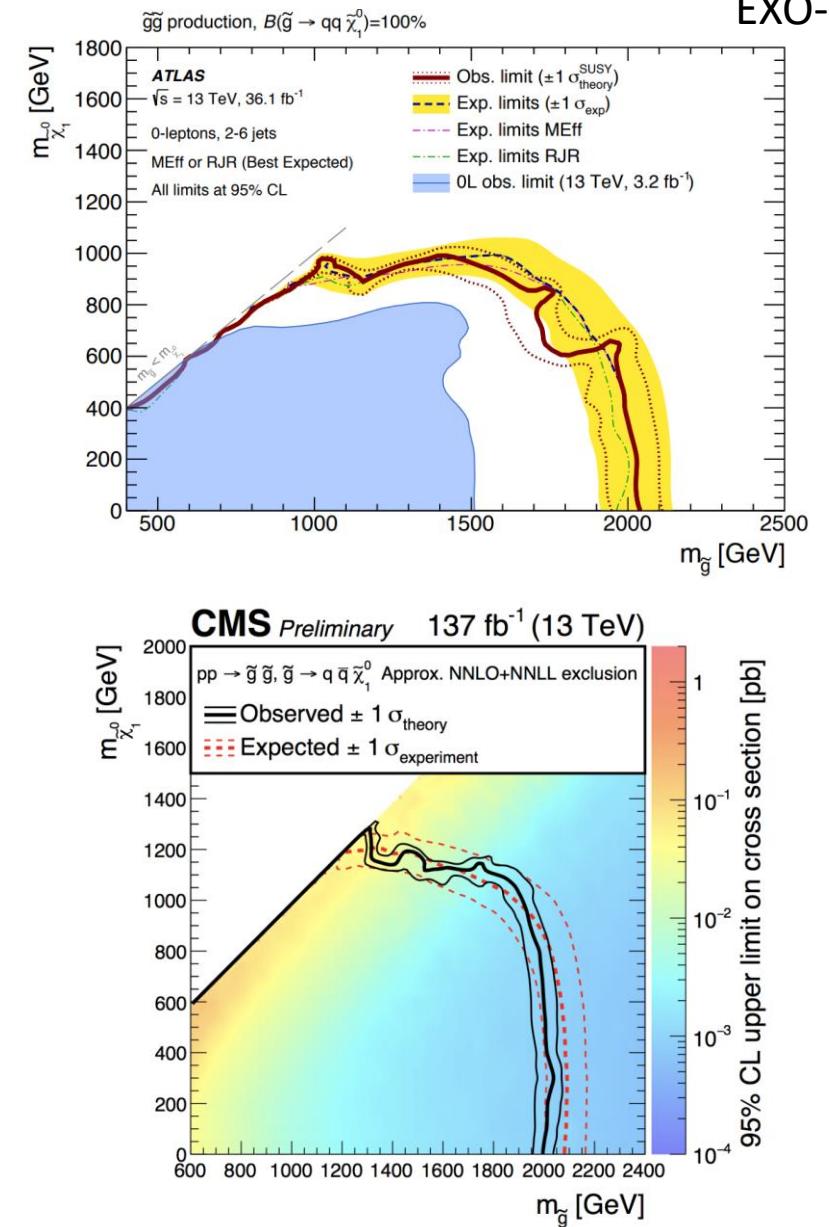
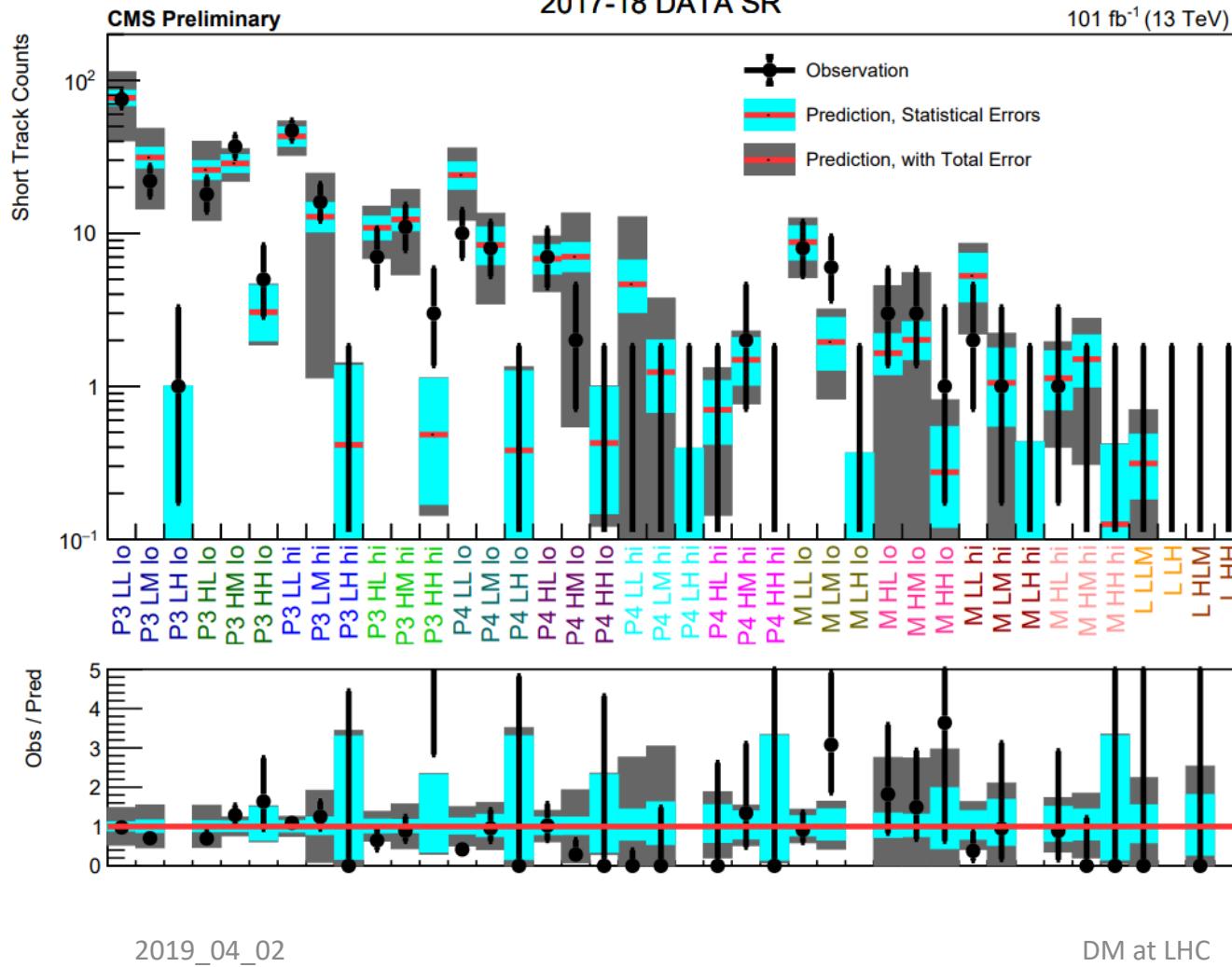
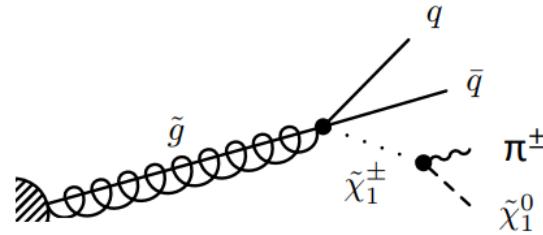
Photon + MET

- Trigger on photon, offline cut on $p_T > 175$ GeV and MET > 170 GeV
- Beam-induced and machine backgrounds require dedicated selection on shower shape/time
- SM backgrounds tackled via fits in control regions

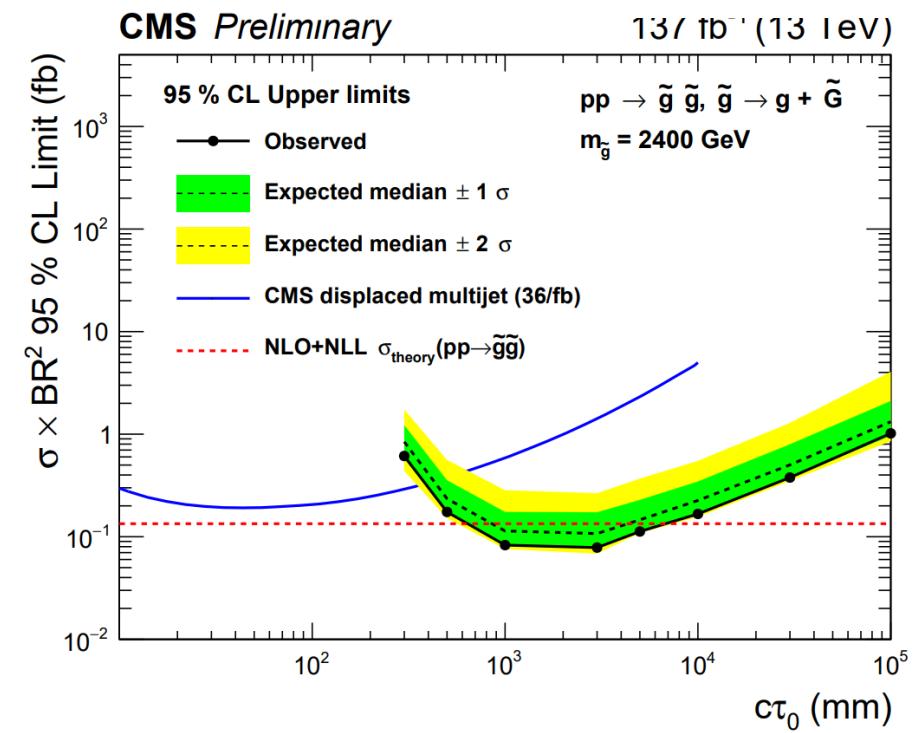
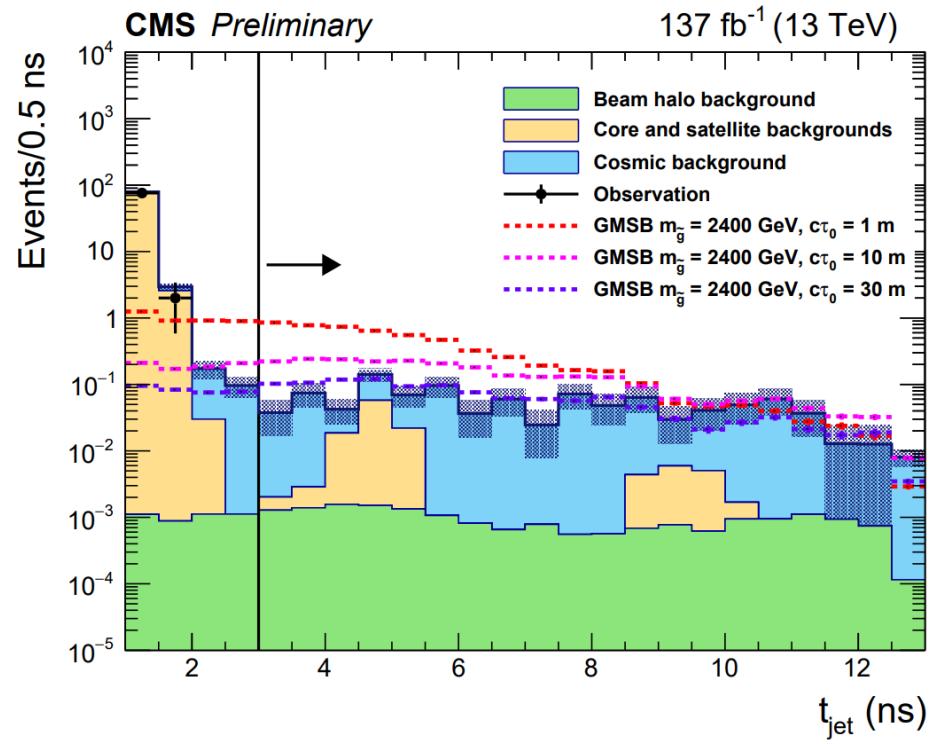
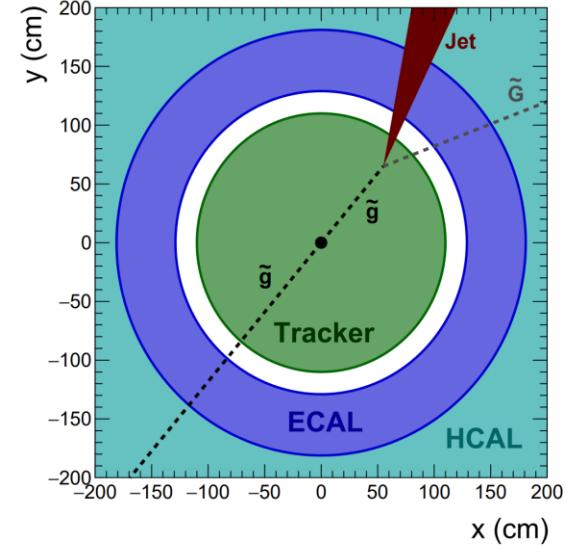
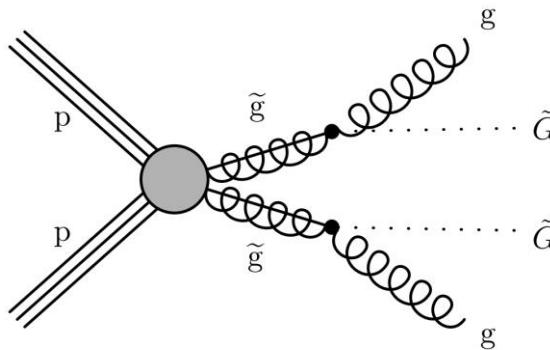
DM at LHC



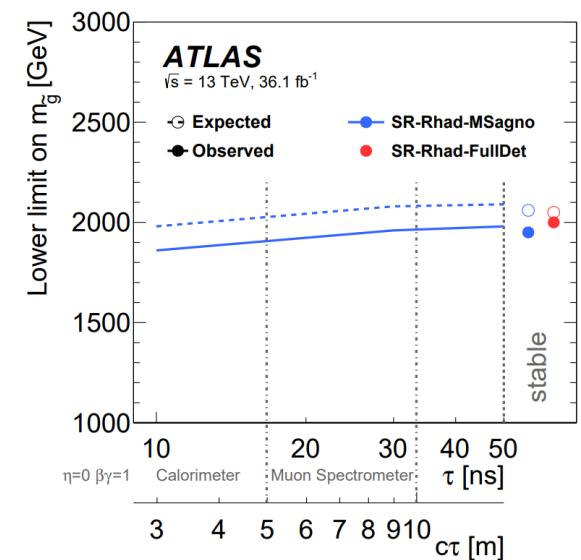
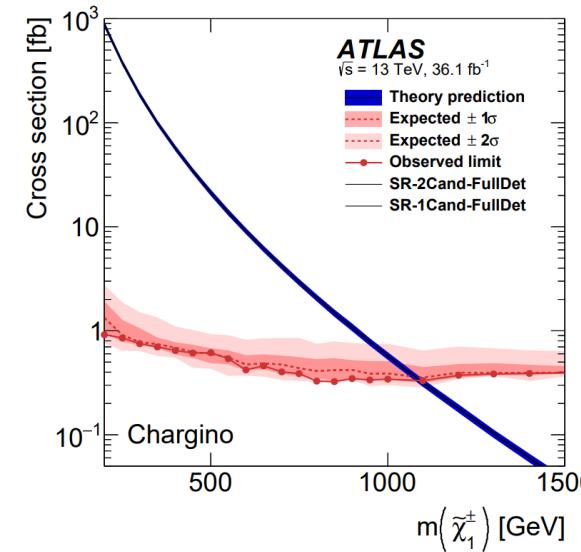
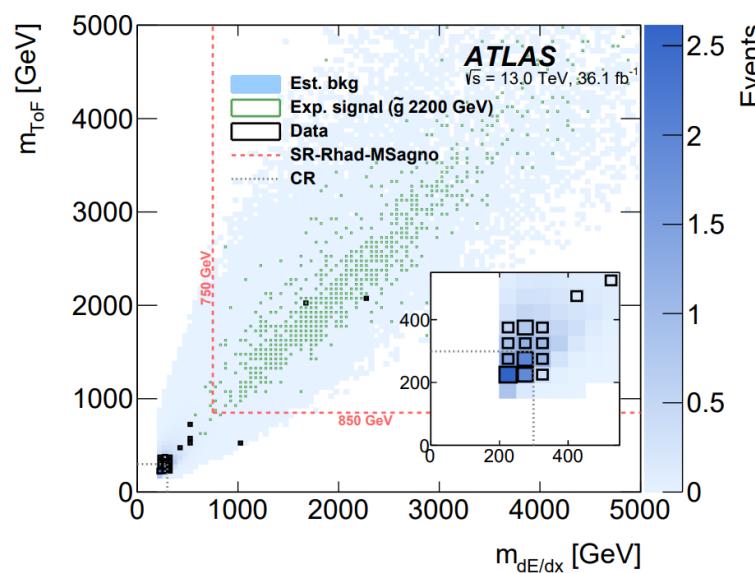
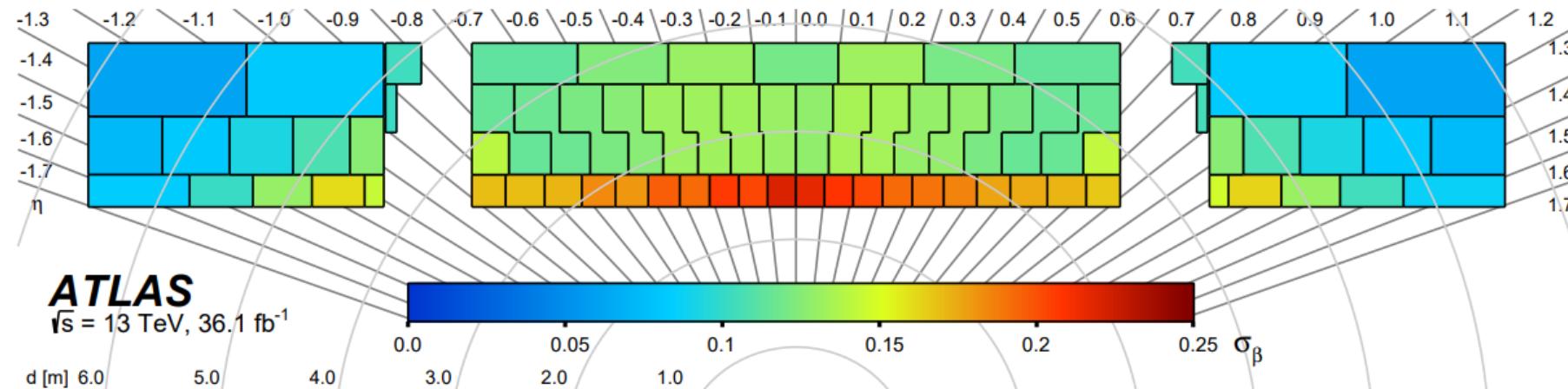
Disappearing Tracks



Delayed Jets



Heavy Charged LLPs



Some Recent HL-LHC Projections

BSM Projections

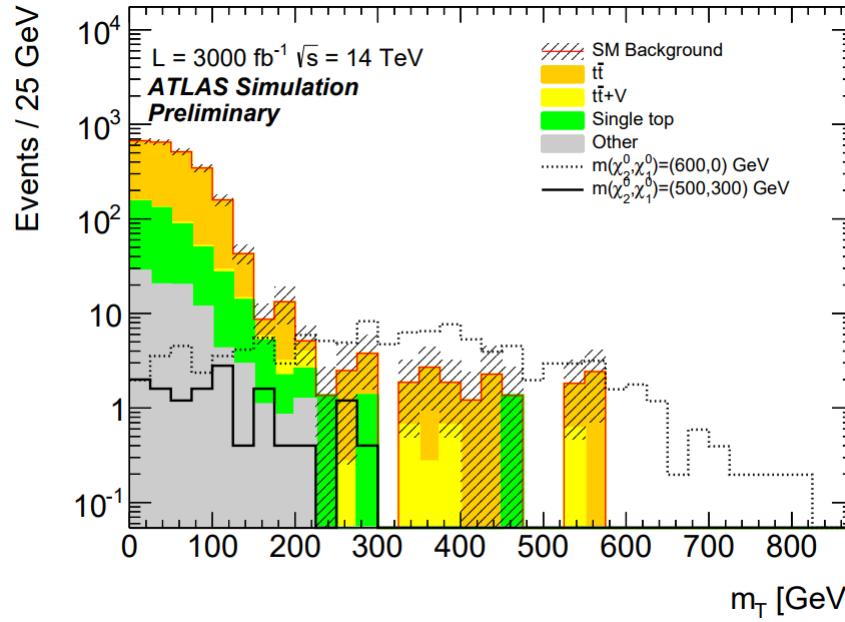
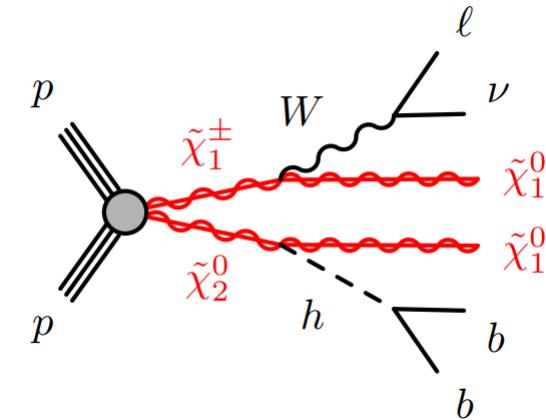
4 Beyond the Standard Model Physics	729
4.1 Estimated sensitivity for new particle searches (CMS-FTR-16-005)	730
4.2 Search for stau production (CMS-FTR-18-010)	754
4.3 Searches for staus, charginos and neutralinos (ATL-PHYS-PUB-2018-048)	771
4.4 Searches for light higgsino-like charginos and neutralinos (CMS-FTR-18-001)	800
4.5 Sensitivity to winos and higgsinos (ATL-PHYS-PUB-2018-031)	811
4.6 Top squark pair production (ATL-PHYS-PUB-2018-021)	826
4.7 Sensitivity to Two-Higgs-Doublet models with an additional pseudoscalar with four top quark signature (ATL-PHYS-PUB-2018-027)	840
4.8 Searches for new physics in hadronic final states using razor variables (CMS-FTR-18-037)	857
4.9 Extrapolation of E_T^{miss} + jet search results (ATL-PHYS-PUB-2018-043)	874
4.10 Sensitivity to long-lived particles with displaced vertices and E_T^{miss} signature (ATL-PHYS-PUB-2018-033)	889
4.11 Sensitivity to dark photons decaying to displaced muons (CMS-FTR-18-002)	902
4.12 Dark-photons decaying to displaced collimated jets of muons (ATL-PHYS-PUB-2019-002)	919
4.13 Mono-Z search for dark matter (CMS-FTR-18-007)	939
4.14 Dark Matter searches in mono-photon and VBF+ E_T^{miss} (ATL-PHYS-PUB-2018-038) . .	953
4.15 Search for invisible particles in association with single top quarks (ATL-PHYS-PUB-2018-024)	973
4.16 Dark matter produced in association with heavy quarks (ATL-PHYS-PUB-2018-036) . .	989
4.17 Excited leptons in $\ell\ell\gamma$ final states (CMS-FTR-18-029)	1010
4.18 Heavy composite Majorana neutrinos (CMS-FTR-18-006)	1019
4.19 Search for $t\bar{t}$ resonances (CMS-FTR-18-009)	1037
4.20 Search for a massive resonance decaying to a pair of Higgs bosons in the four b quark final state (CMS-FTR-18-003)	1054
4.21 Search for a massive resonance decaying to a pair of Higgs bosons in the four b quark final state (ATL-PHYS-PUB-2018-028)	1065
4.22 Search for Z' and W' bosons in fermionic final states (ATL-PHYS-PUB-2018-044) . .	1087
4.23 Pair production of scalar leptoquarks decaying into a top quark and a charged lepton (CMS-FTR-18-008)	1115
4.24 Leptoquark search in decays into τ leptons and b quarks (CMS-FTR-18-028)	1126
4.25 Heavy gauge boson W' in the decay channel with a τ lepton and a neutrino (CMS-FTR-18-030)	1138

<https://arxiv.org/abs/1902.10229>

Direct chargino and neutralino production

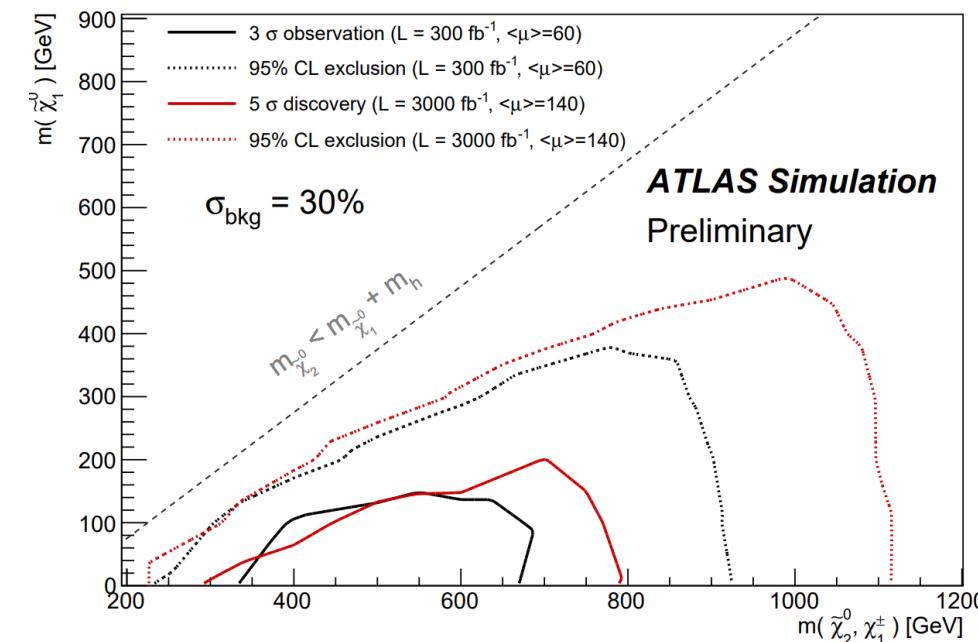
ATL-PHYS-PUB-2015-032

- Final states with $\tilde{\chi}^0$ and $\tilde{\chi}^\pm$ LSPs comprise a large fraction of R-parity conserving parameter space
- Current 95% CL exclusion limits ~ 250 GeV for massless LSP
- Selection criteria efficiency shows a dependence on pileup, degrades limits somewhat at low masses
- Major increase in exclusion possible for HL-LHC dataset



2017_12_11

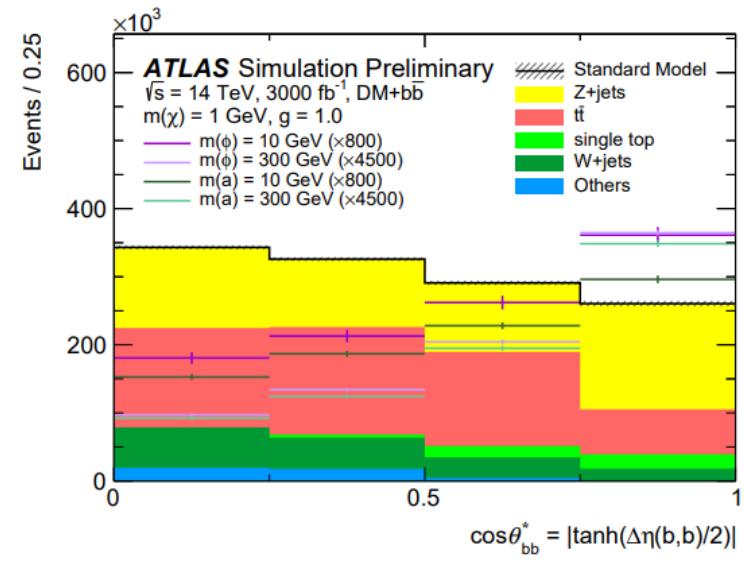
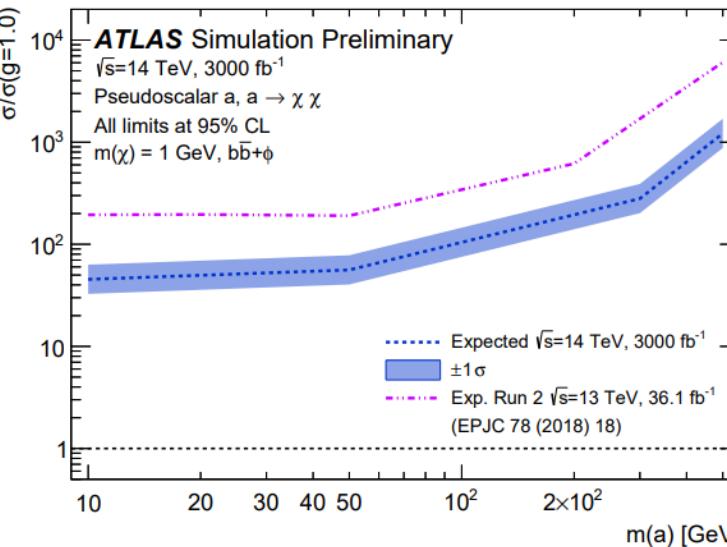
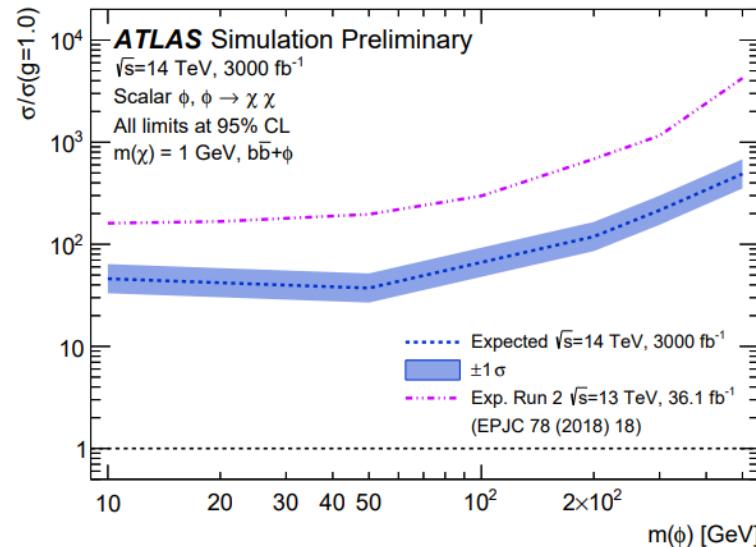
From lepton + MET



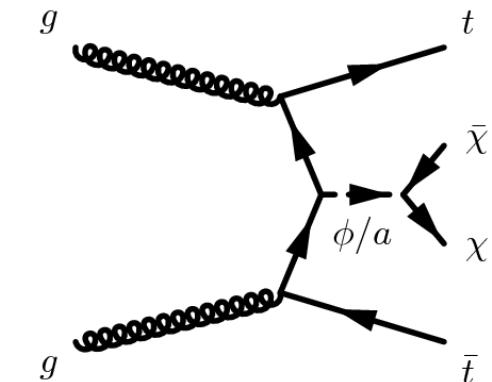
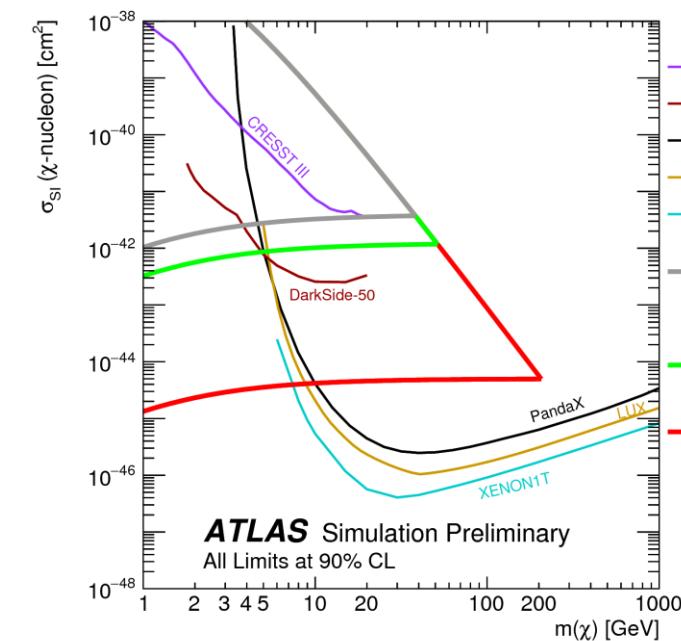
30

DM + Heavy Flavor

ATL-PHYS-PUB-2018-036

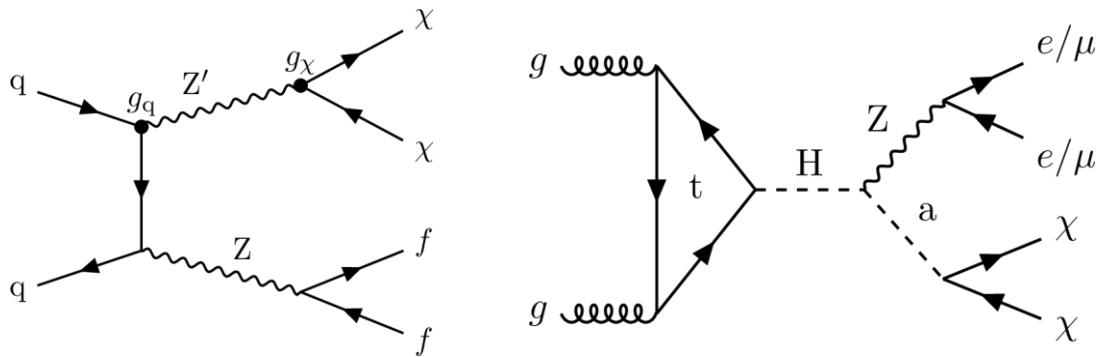


From lepton + MET

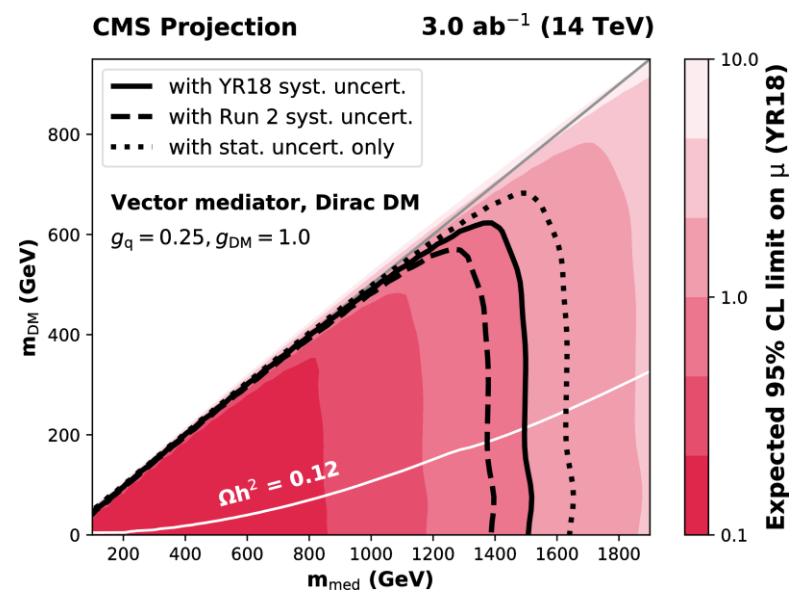


Mono-Z

FTR-18-007-pas

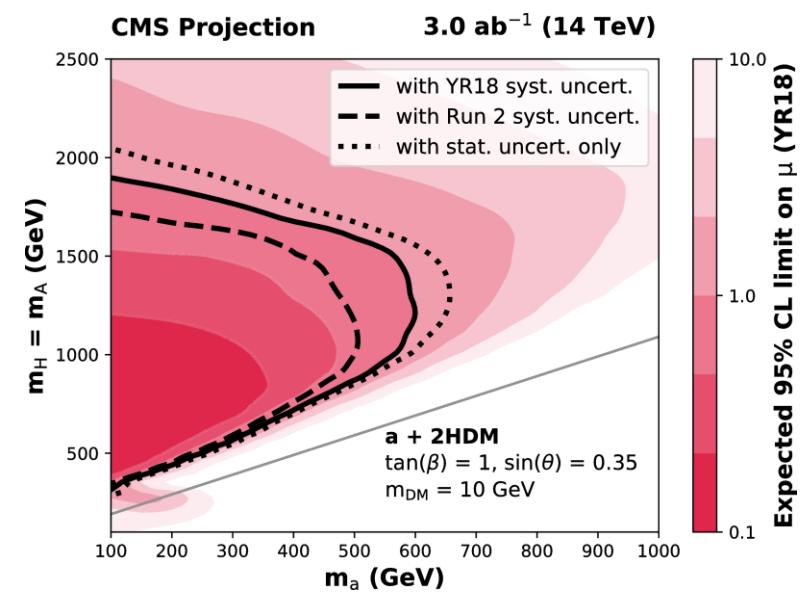


- Run 2 syst: Same size uncertainties as in Run-II, no improvements considered
- YR18 syst: Use projected improvement in control of systematic uncertainties from 2018 CERN yellow report (50% reduction)
- Stat syst: Only statistical uncertainties considered



2019_04_02

DM at LHC



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Backup

ATLAS Exotics

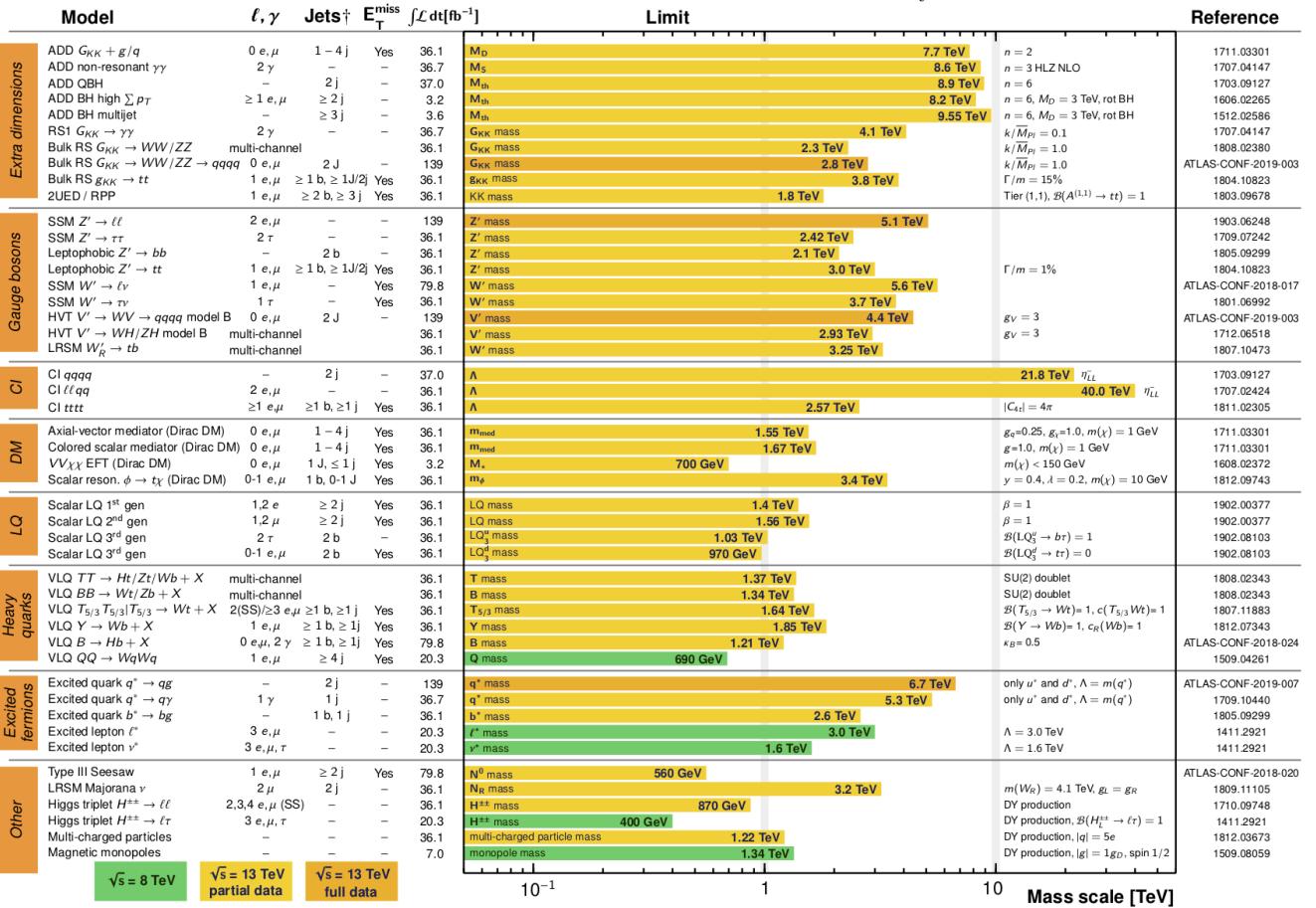
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: March 2019

ATLAS Preliminary

$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$

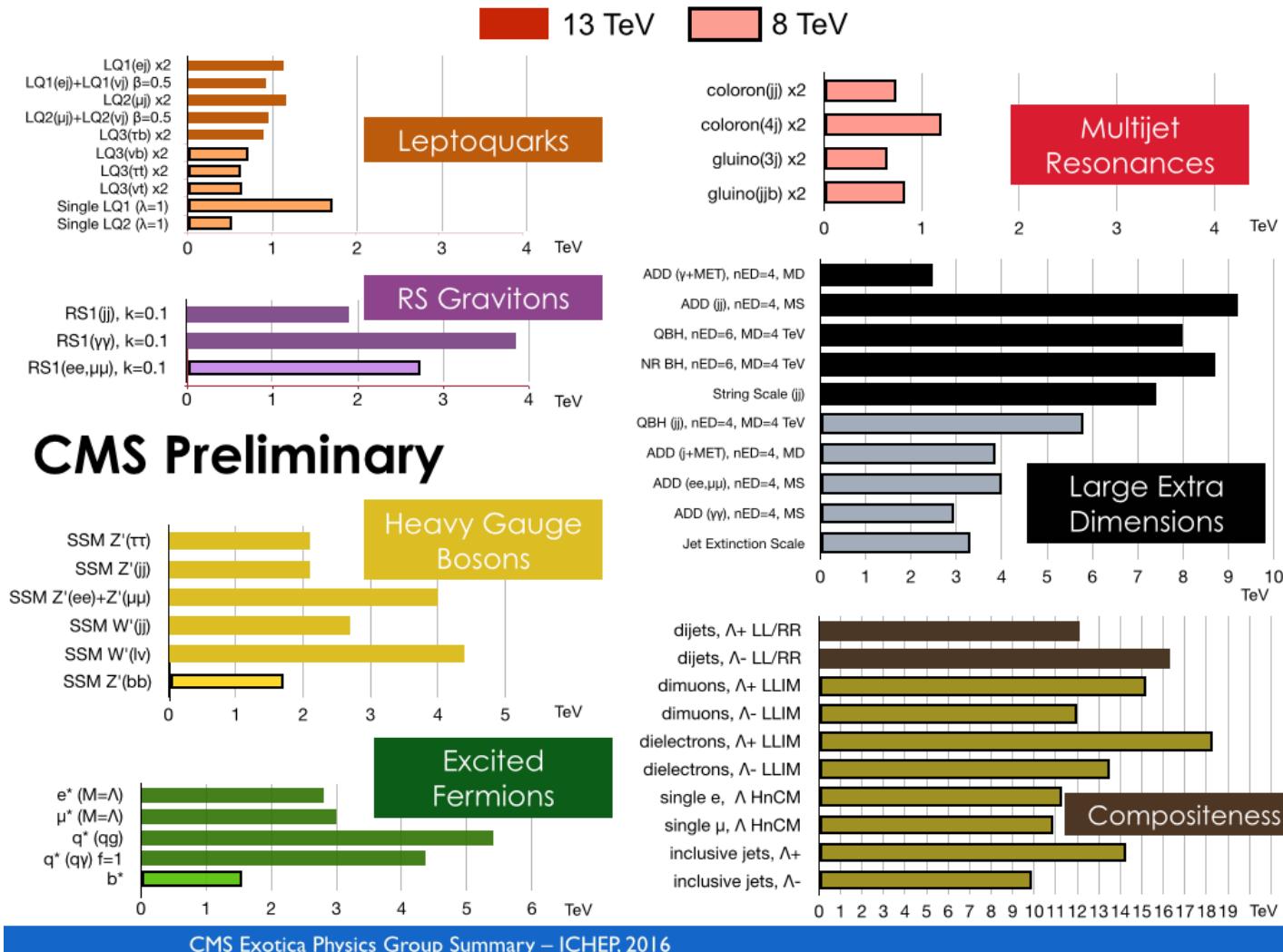
$\sqrt{s} = 8, 13 \text{ TeV}$



*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

CMS Exotics



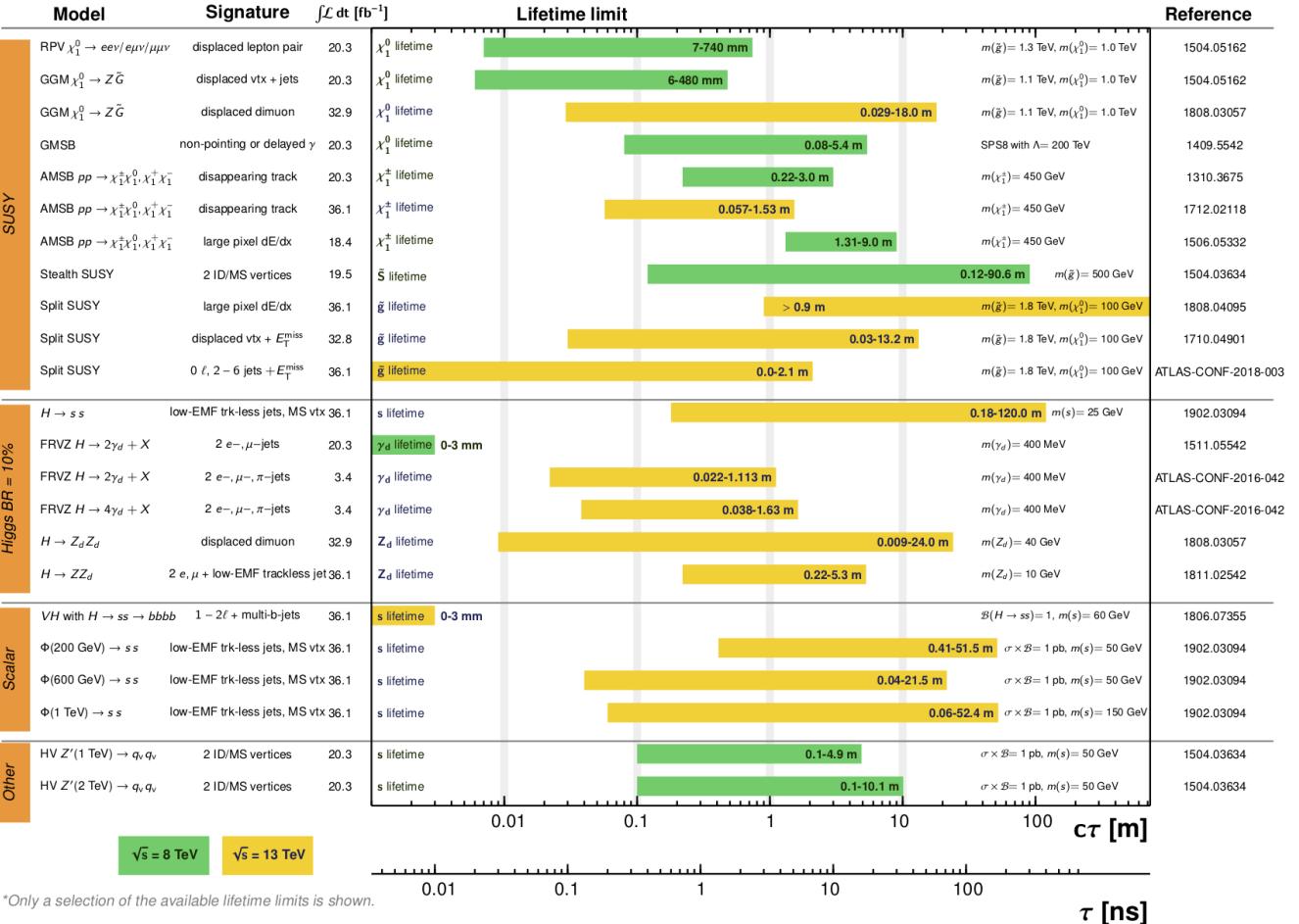
ATLAS LLPs

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

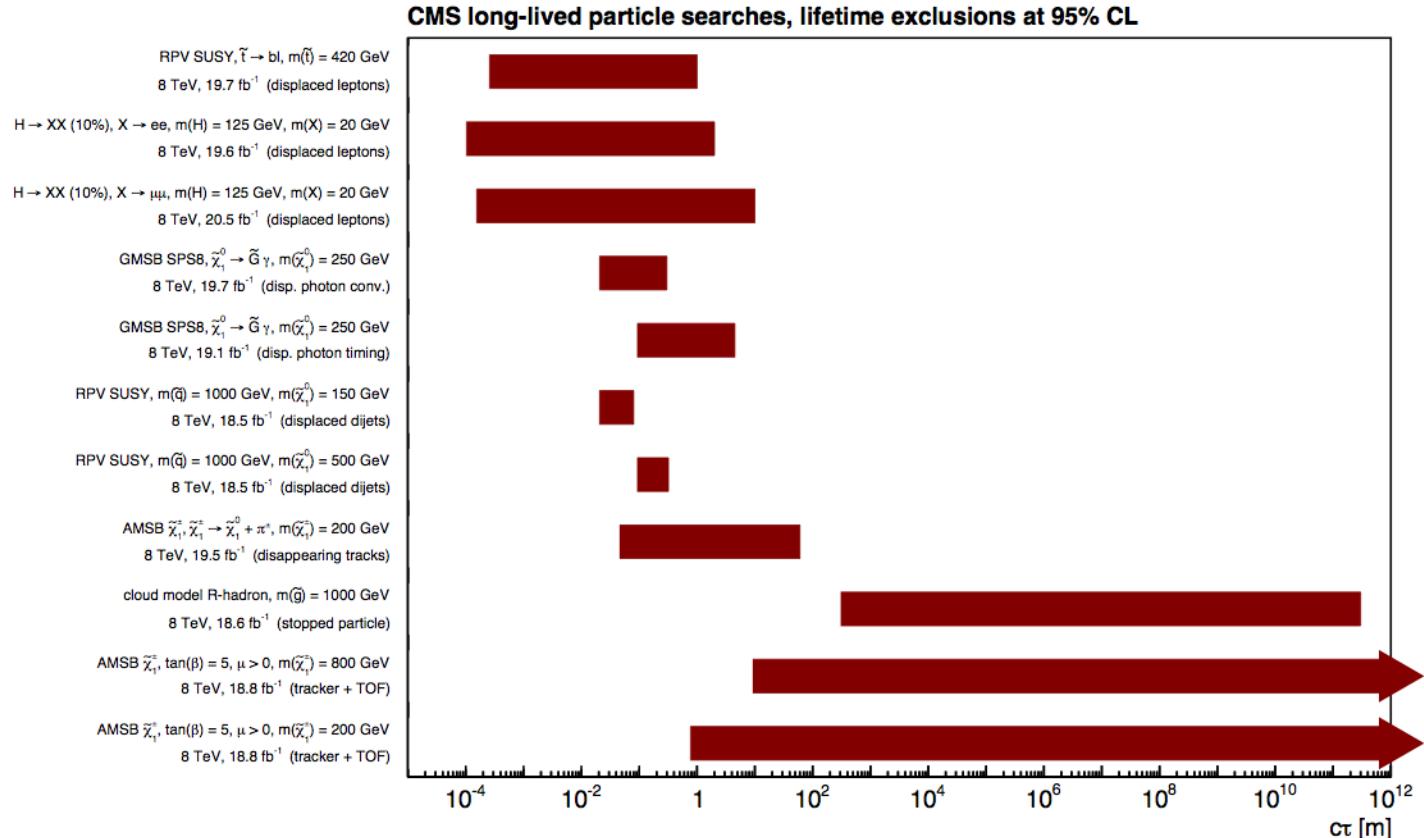
Status: March 2019

ATLAS Preliminary

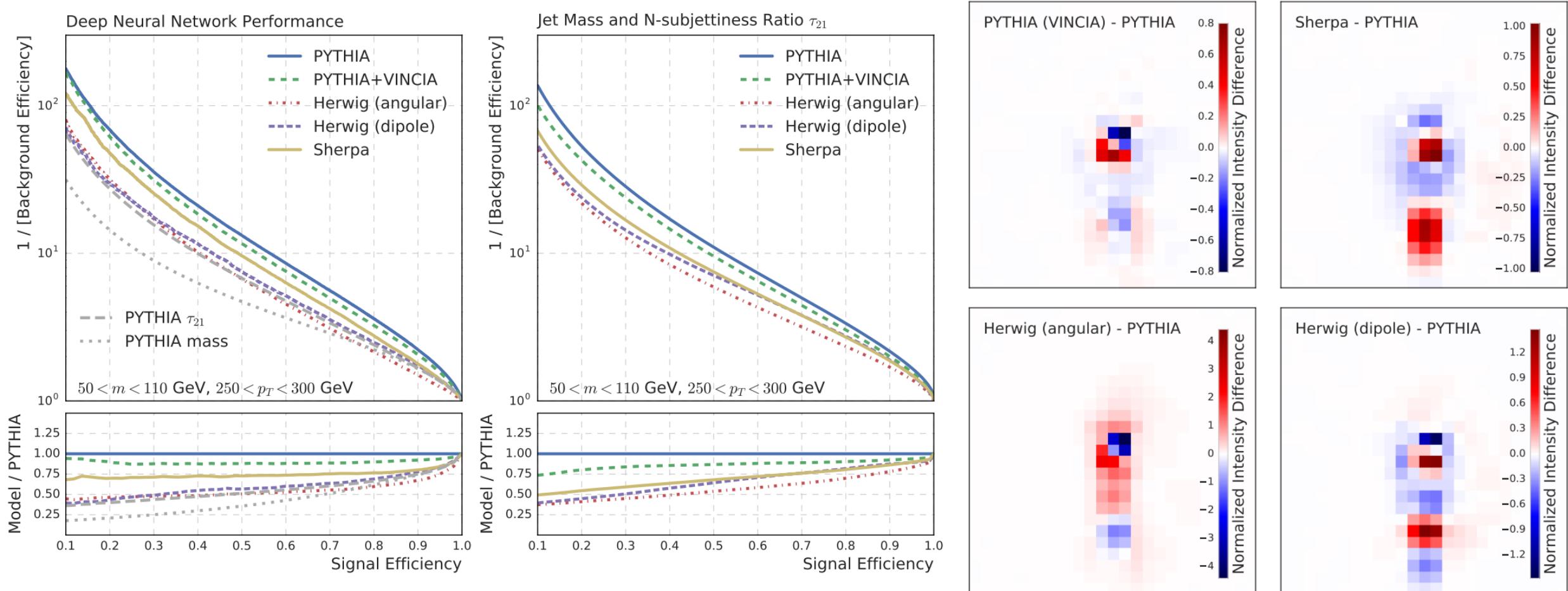
$\int \mathcal{L} dt = (3.4 - 36.1) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$



CMS LLPs

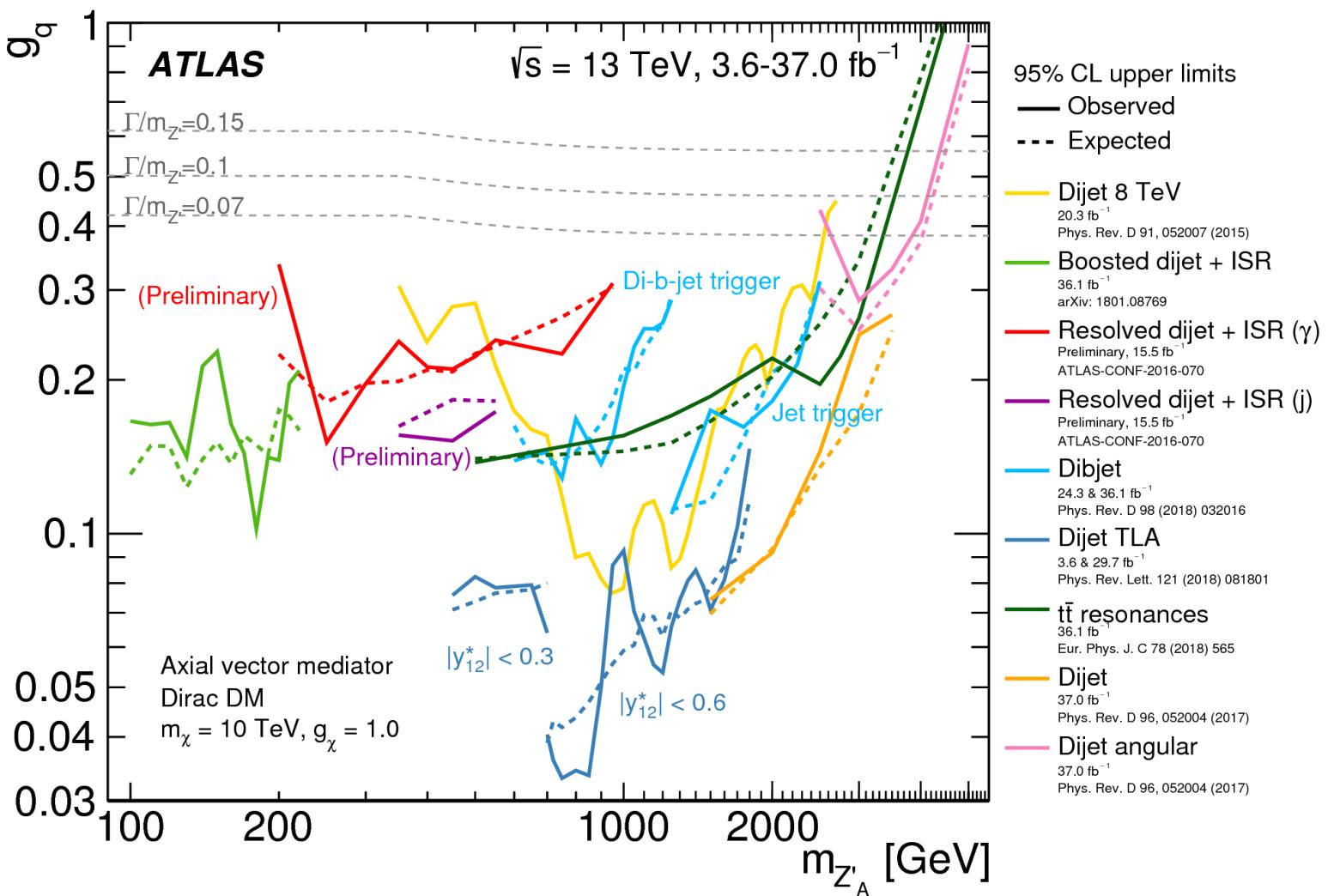


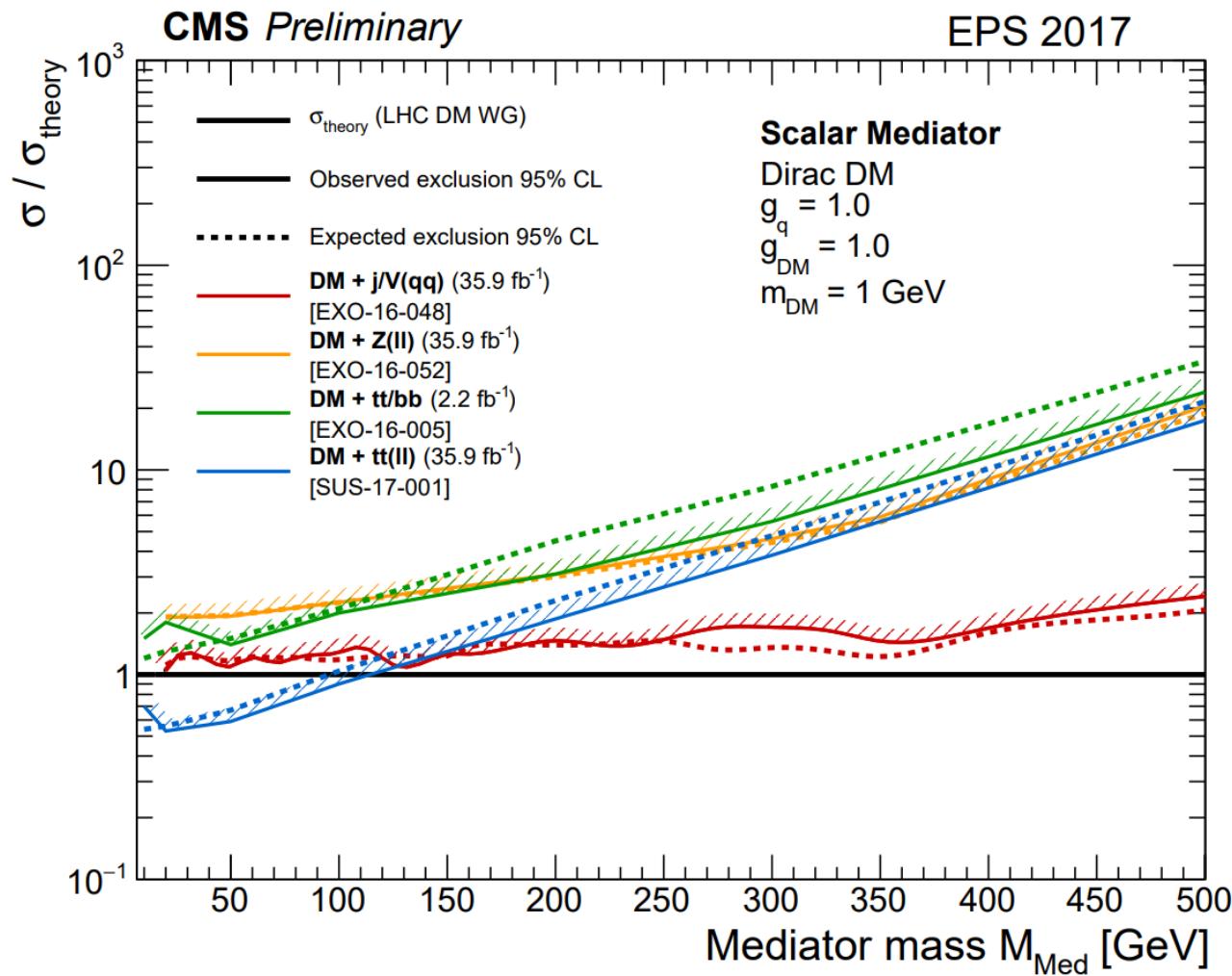
Machine Learning in Simulation

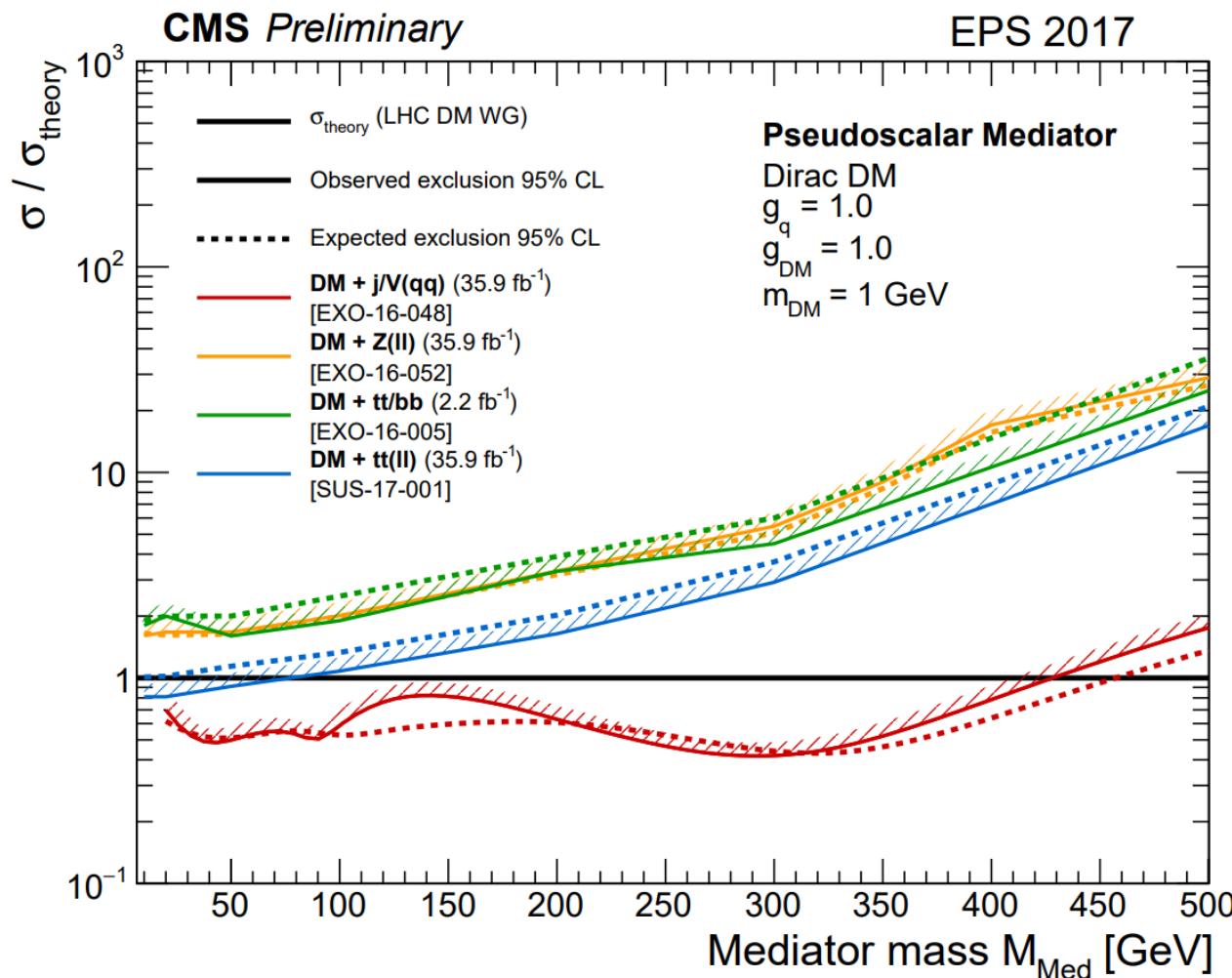


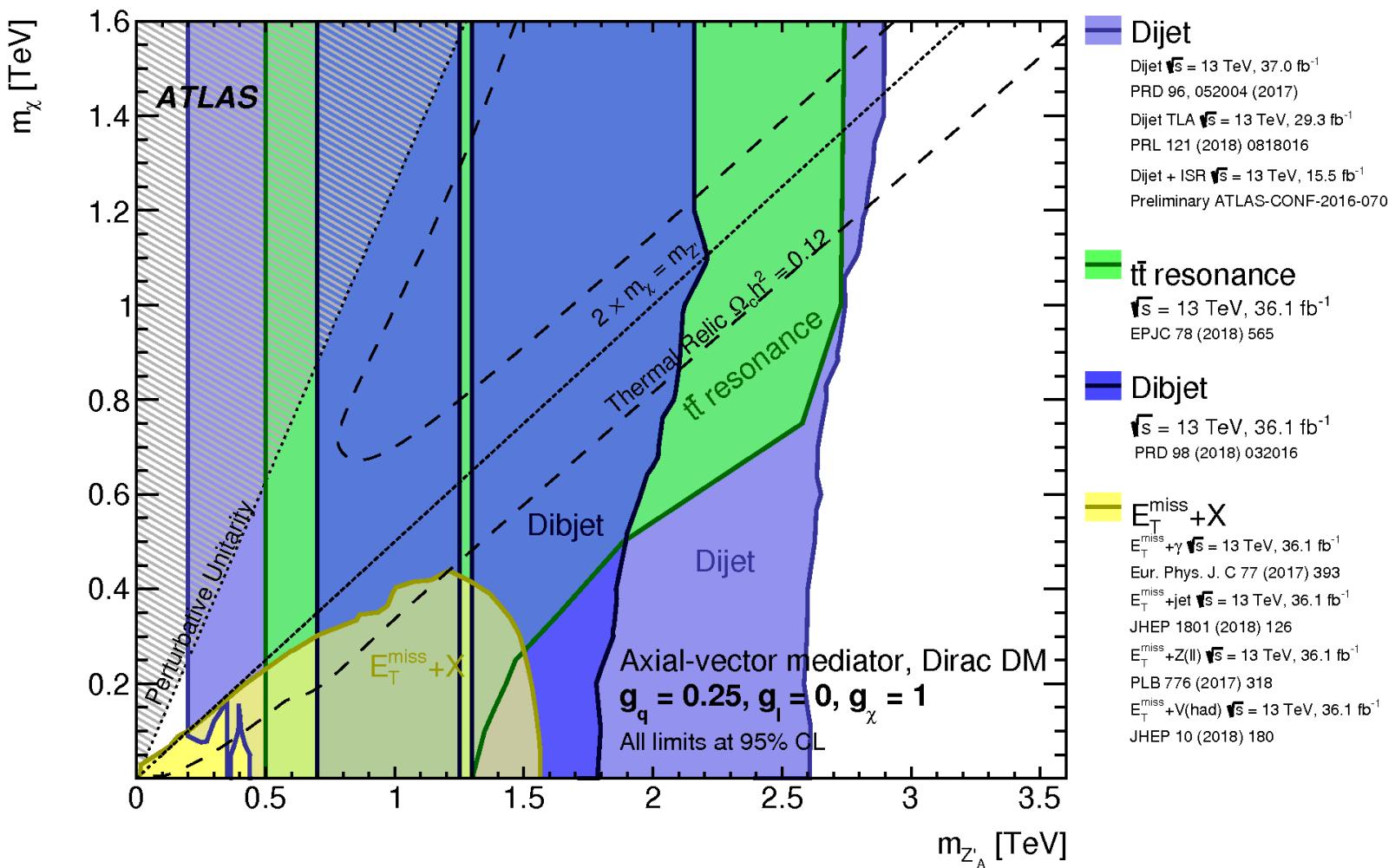
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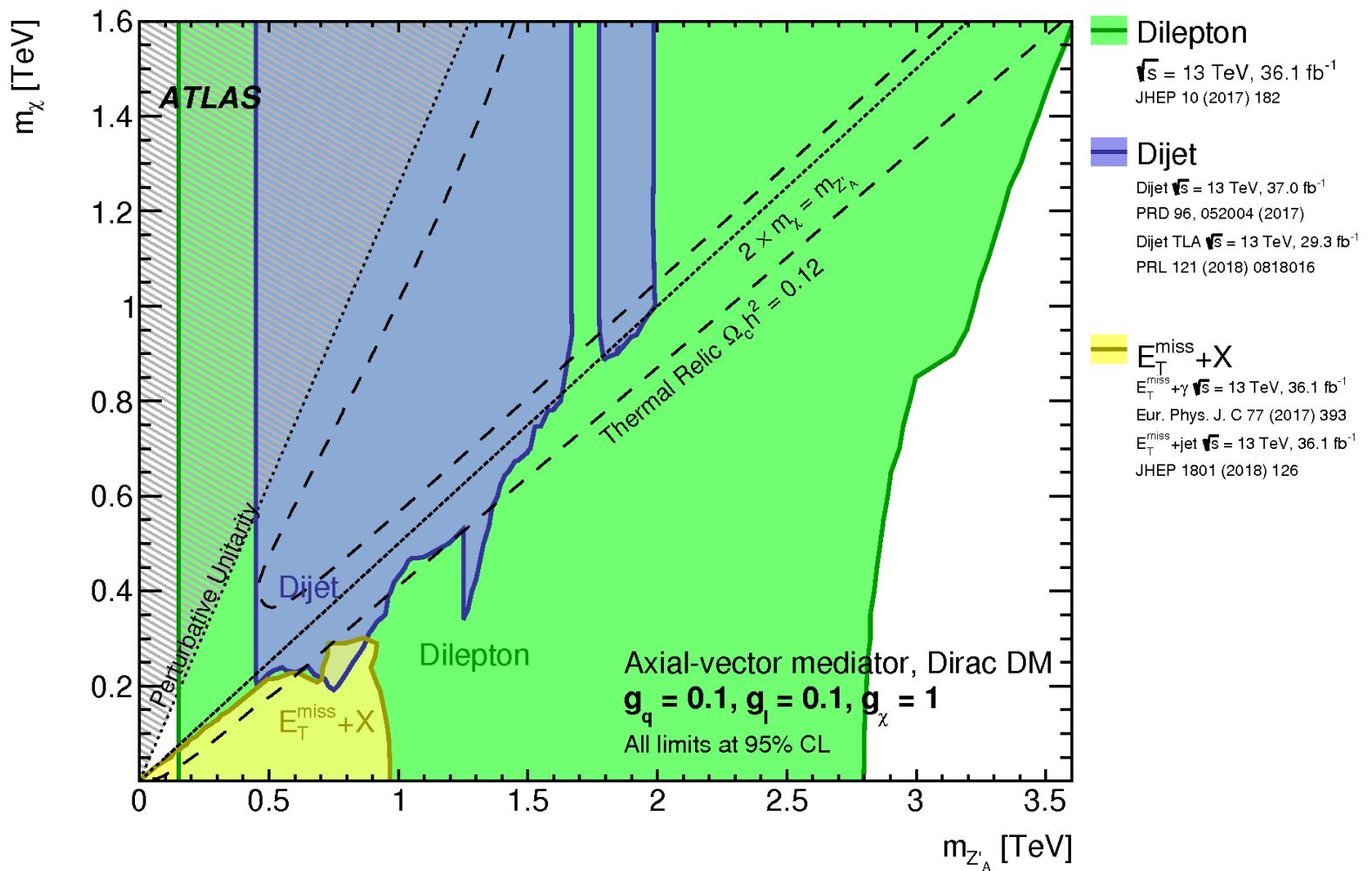
Trigger	Typical offline selection	Trigger Selection		Level-1 Peak Rate (kHz)	HLT Peak Rate (Hz)
		Level-1 (GeV)	HLT (GeV)	$L = 1.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$	
Single leptons	Single isolated μ , $p_T > 27 \text{ GeV}$	20	26 (i)	15	180
	Single isolated tight e , $p_T > 27 \text{ GeV}$	22 (i)	26 (i)	28	180
	Single μ , $p_T > 52 \text{ GeV}$	20	50	15	61
	Single e , $p_T > 61 \text{ GeV}$	22 (i)	60	28	18
	Single τ , $p_T > 170 \text{ GeV}$	100	160	1.2	47
Two leptons	Two μ , each $p_T > 15 \text{ GeV}$	2×10	2×14	1.8	26
	Two μ , $p_T > 23, 9 \text{ GeV}$	20	22, 8	15	42
	Two very loose e , each $p_T > 18 \text{ GeV}$	2×15 (i)	2×17	1.7	12
	One e & one μ , $p_T > 8, 25 \text{ GeV}$	$20 (\mu)$	7, 24	15	5
	One e & one μ , $p_T > 18, 15 \text{ GeV}$	15, 10	17, 14	2.0	4
	One e & one μ , $p_T > 27, 9 \text{ GeV}$	22 (e,i)	26, 8	28	3
	Two τ , $p_T > 40, 30 \text{ GeV}$	20 (i), 12 (i) (+jets, topo)	35, 25	5	61
	One τ & one isolated μ , $p_T > 30, 15 \text{ GeV}$	12 (i), 10 (+jets)	25, 14 (i)	2.1	10
	One τ & one isolated e , $p_T > 30, 18 \text{ GeV}$	12 (i), 15 (i) (+jets)	25, 17 (i)	4	15
Three leptons	Three loose e , $p_T > 25, 13, 13 \text{ GeV}$	$20, 2 \times 10$	$24, 2 \times 12$	1.3	< 0.1
	Three μ , each $p_T > 7 \text{ GeV}$	3×6	3×6	0.2	6
	Three μ , $p_T > 21, 2 \times 5 \text{ GeV}$	20	$20, 2 \times 4$	15	8
	Two μ & one loose e , $p_T > 2 \times 11, 13 \text{ GeV}$	$2 \times 10 (\mu)$	$2 \times 10, 12$	1.8	0.3
	Two loose e & one μ , $p_T > 2 \times 13, 11 \text{ GeV}$	$2 \times 8, 10$	$2 \times 12, 10$	1.7	0.1
One photon	One loose γ , $p_T > 145 \text{ GeV}$	22 (i)	140	28	43
Two photons	Two loose γ , $p_T > 55, 55 \text{ GeV}$	2×20	50, 50	2.6	6
	Two medium γ , $p_T > 40, 30 \text{ GeV}$	2×20	35, 25	2.6	17
	Two tight γ , $p_T > 25, 25 \text{ GeV}$	2×15 (i)	2×20 (i)	1.7	14
Single jet	Jet ($R = 0.4$), $p_T > 435 \text{ GeV}$	100	420	3.3	33
	Jet ($R = 1.0$), $p_T > 480 \text{ GeV}$	100	460	3.3	24
	Jet ($R = 1.0$), $p_T > 450 \text{ GeV}$, $m_{\text{jet}} > 50 \text{ GeV}$	100	$420, m_{\text{jet}} > 40$	3.3	29
E_T^{miss}	$E_T^{\text{miss}} > 200 \text{ GeV}$	50	110	5	110
Multi-jets	Four jets, each $p_T > 125 \text{ GeV}$	3×50	4×115	0.5	16
	Five jets, each $p_T > 95 \text{ GeV}$	4×15	5×85	5	10
	Six jets, each $p_T > 80 \text{ GeV}$	4×15	6×70	5	4
	Six jets, each $p_T > 60 \text{ GeV}$, $ \eta < 2.0$	4×15	$6 \times 55, \eta < 2.4$	5	15
b -jets	One b ($\epsilon = 40\%$), $p_T > 235 \text{ GeV}$	100	225	3.3	15
	Two b ($\epsilon = 60\%$), $p_T > 185, 70 \text{ GeV}$	100	175, 60	3.3	12
	One b ($\epsilon = 40\%$) & three jets, each $p_T > 85 \text{ GeV}$	4×15	4×75	5	15
	Two b ($\epsilon = 70\%$) & one jet, $p_T > 65, 65, 160 \text{ GeV}$	$2 \times 30, 85$	$2 \times 55, 150$	1.2	15
	Two b ($\epsilon = 60\%$) & two jets, each $p_T > 65 \text{ GeV}$	$4 \times 15, \eta < 2.5$	4×55	3.2	13
B-Physics	Two μ , $p_T > 11, 6 \text{ GeV}$	11, 6	11, 6 (di- μ)	2.5	47
	Two μ , $p_T > 6, 6 \text{ GeV}$, $2.5 < m(\mu, \mu) < 4.0 \text{ GeV}$	$2 \times 6 (J/\psi, \text{topo})$	$2 \times 6 (J/\psi)$	1.6	48
	Two μ , $p_T > 6, 6 \text{ GeV}$, $4.7 < m(\mu, \mu) < 5.9 \text{ GeV}$	$2 \times 6 (B, \text{topo})$	$2 \times 6 (B)$	1.6	5
	Two μ , $p_T > 6, 6 \text{ GeV}$, $7 < m(\mu, \mu) < 12 \text{ GeV}$	$2 \times 6 (\Upsilon, \text{topo})$	$2 \times 6 (\Upsilon)$	1.4	10
Total Rate			85	1550	





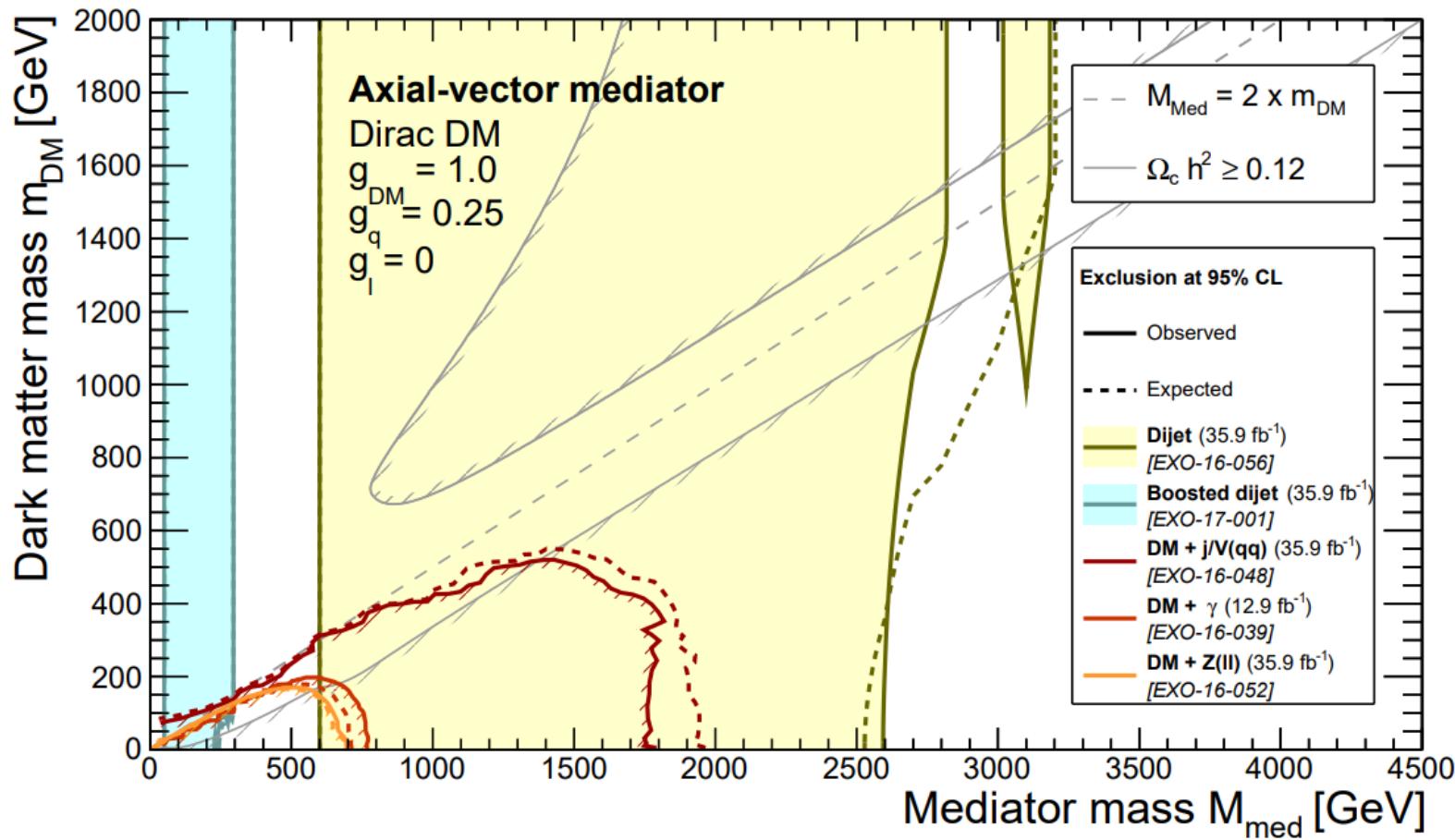






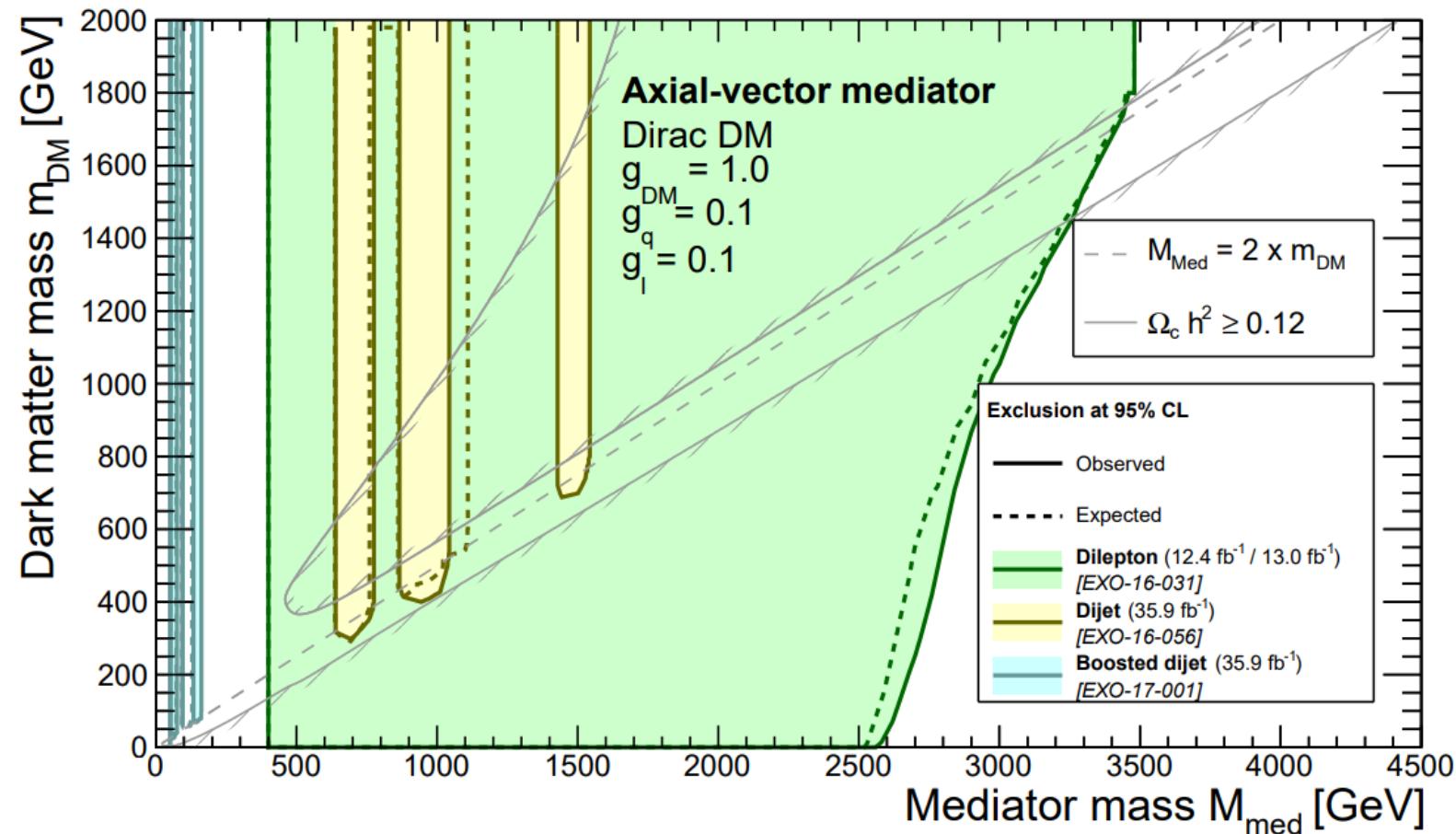
CMS Preliminary

LHCP 2017



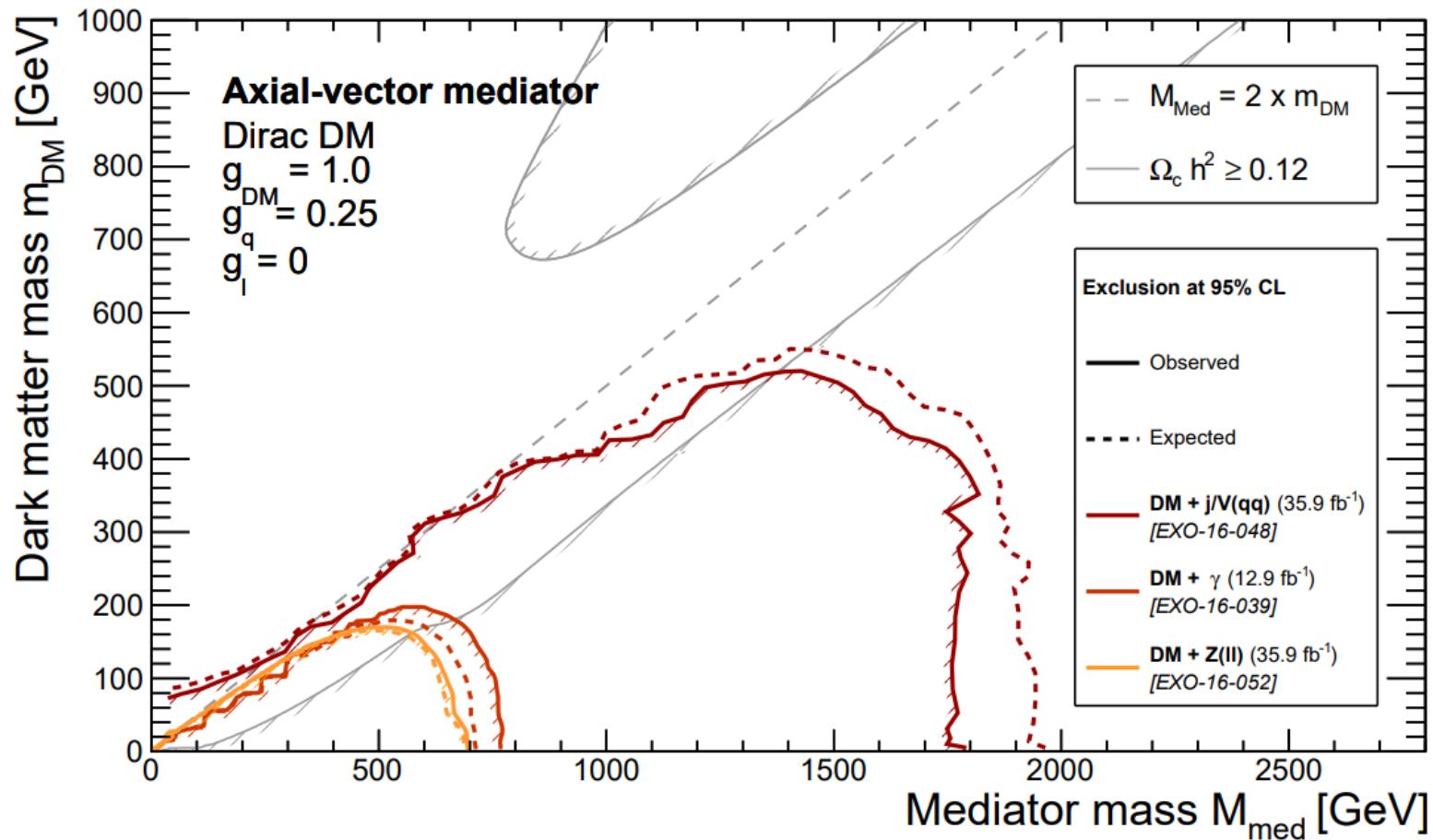
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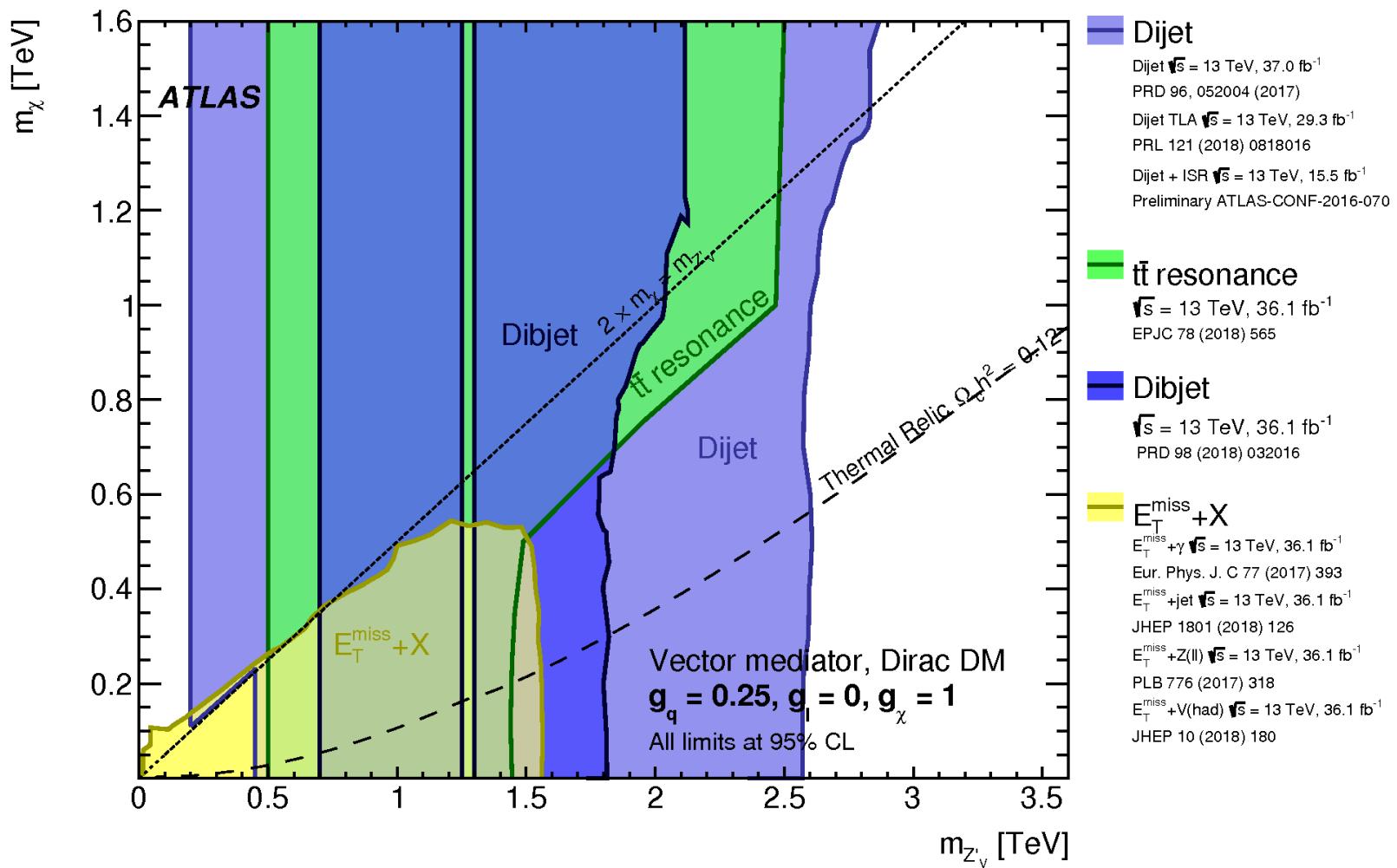
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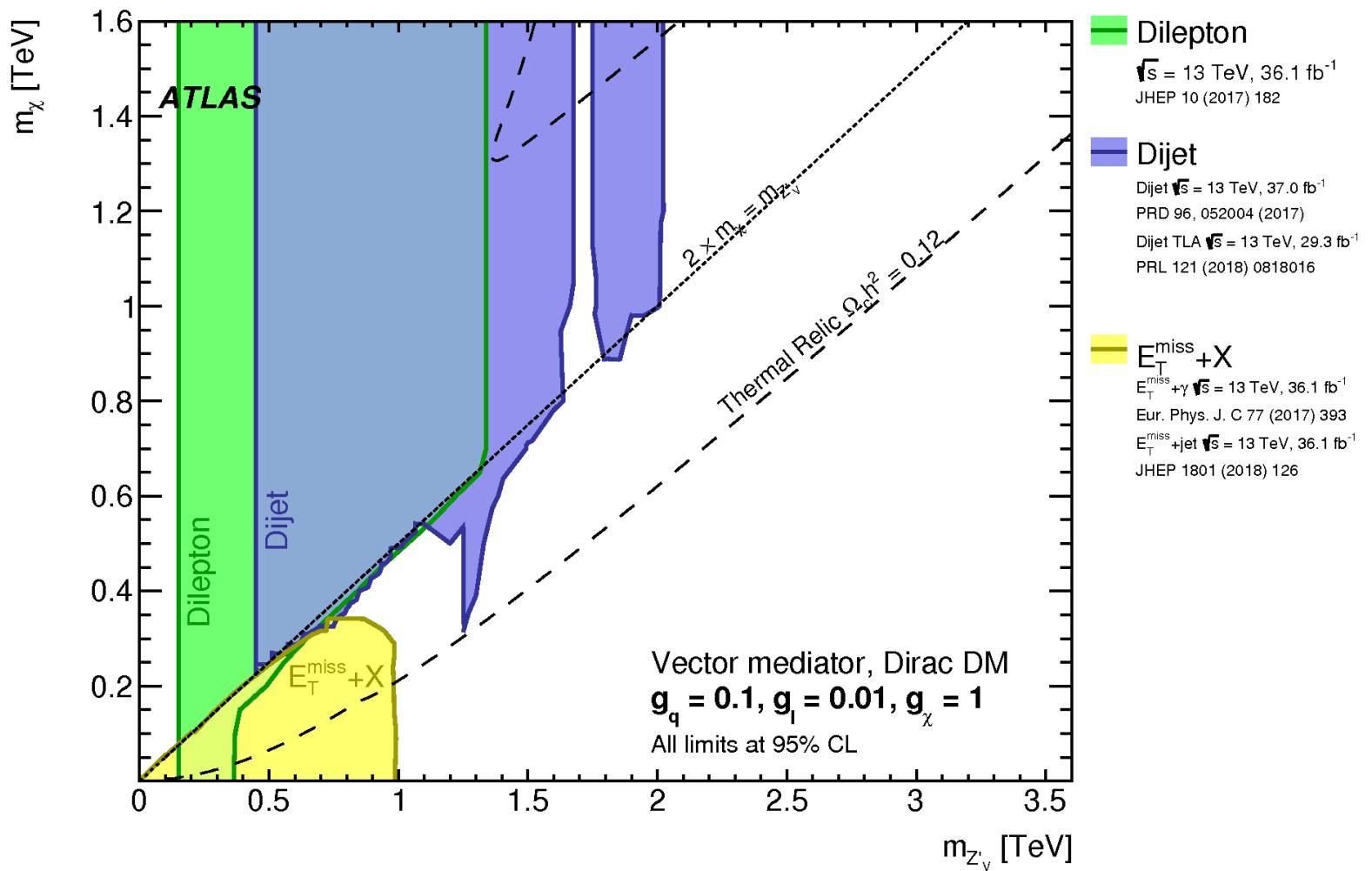


CMS Preliminary

LHCP 2017







CMS Preliminary

LHCP 2017

