ATLAS

University of Victoria

Collider Searches for Dark Matter

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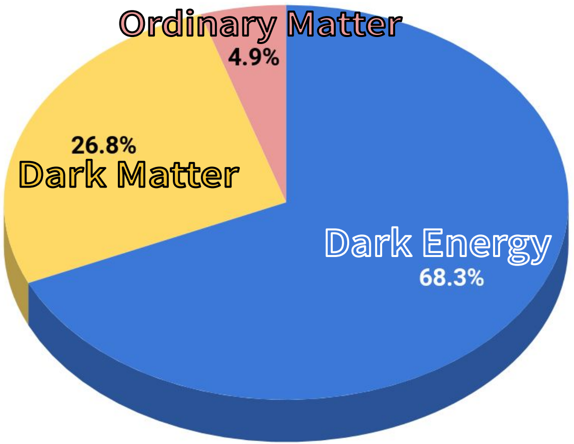
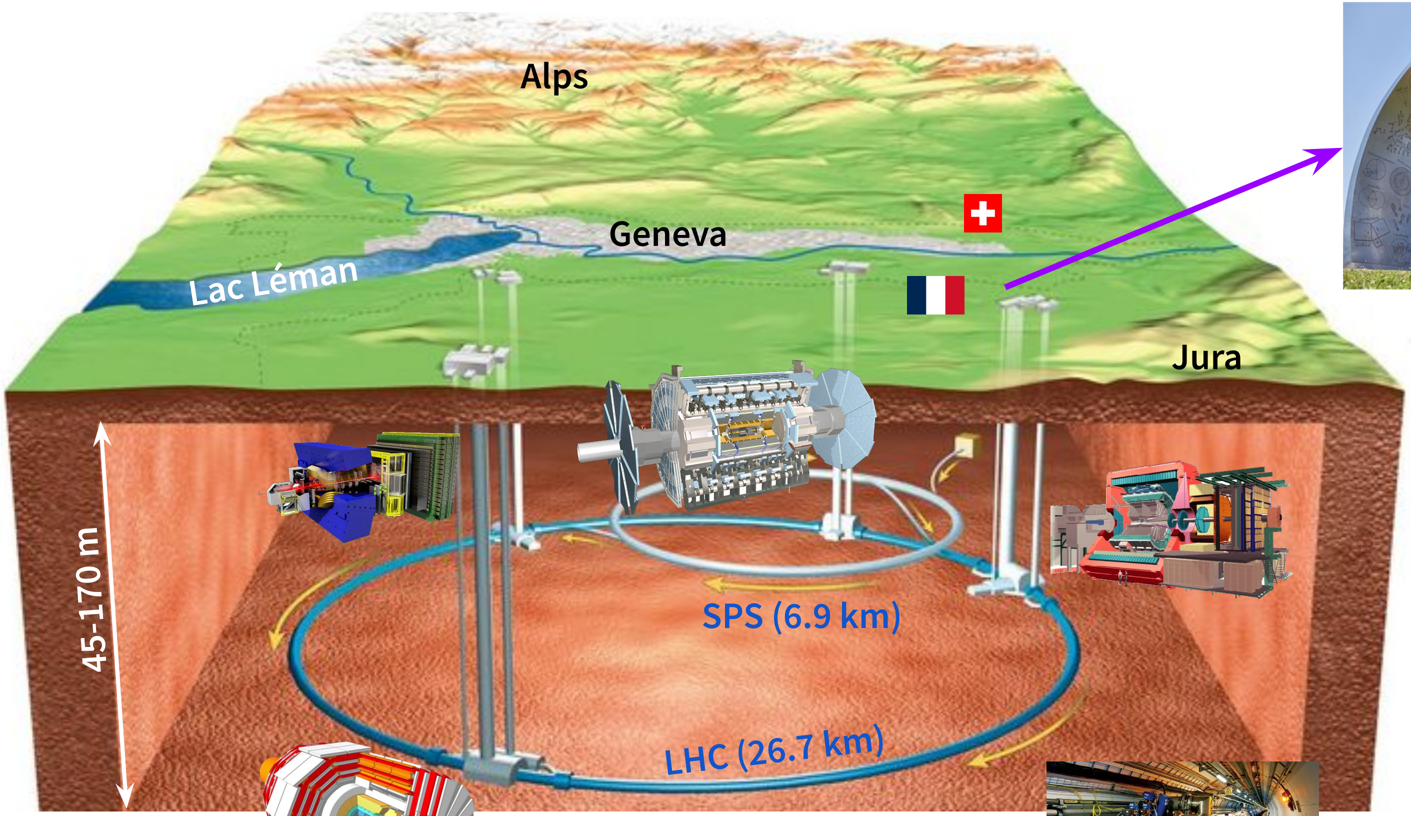
Baltic School of High-Energy Physics and Accelerator Technologies 2021

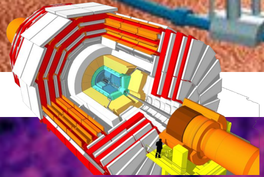
Overview

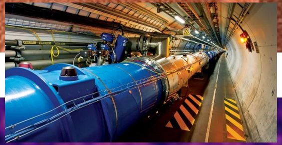
- A number of of astrophysical measurements indicate the existence of Dark Matter (DM)
- If DM can interact at all with the SM, we could produce it in colliders & measure its properties
- In this talk
  - ➥ A brief introduction to the Large Hadron Collider (LHC) & experiments
  - ➥ Description of some of this astrophysical evidence
  - ➥ Description of different methods used to search for DM
  - ➥ Examples of ATLAS searches for DM



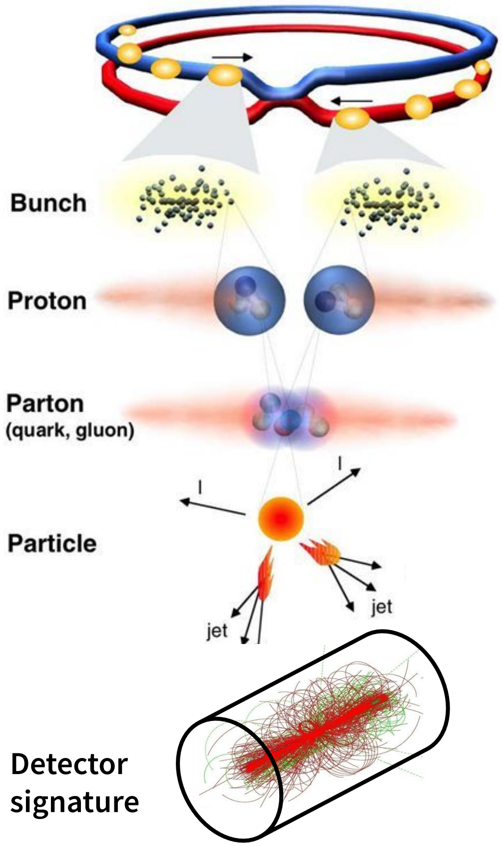
The Large Hadron Collider



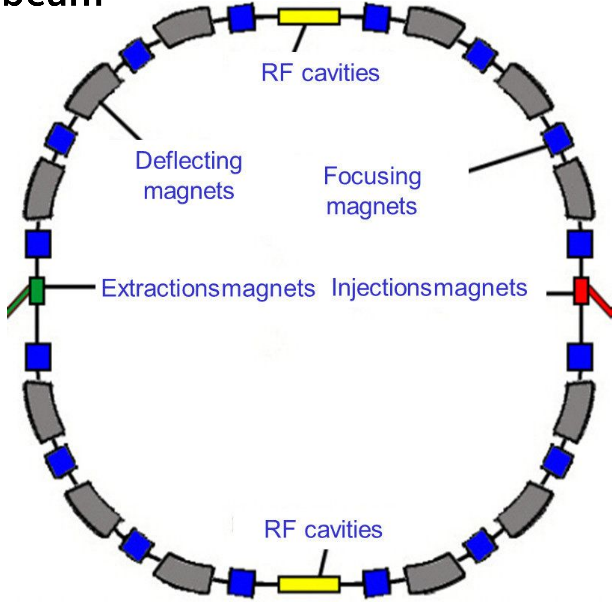




LHC Proton Beams

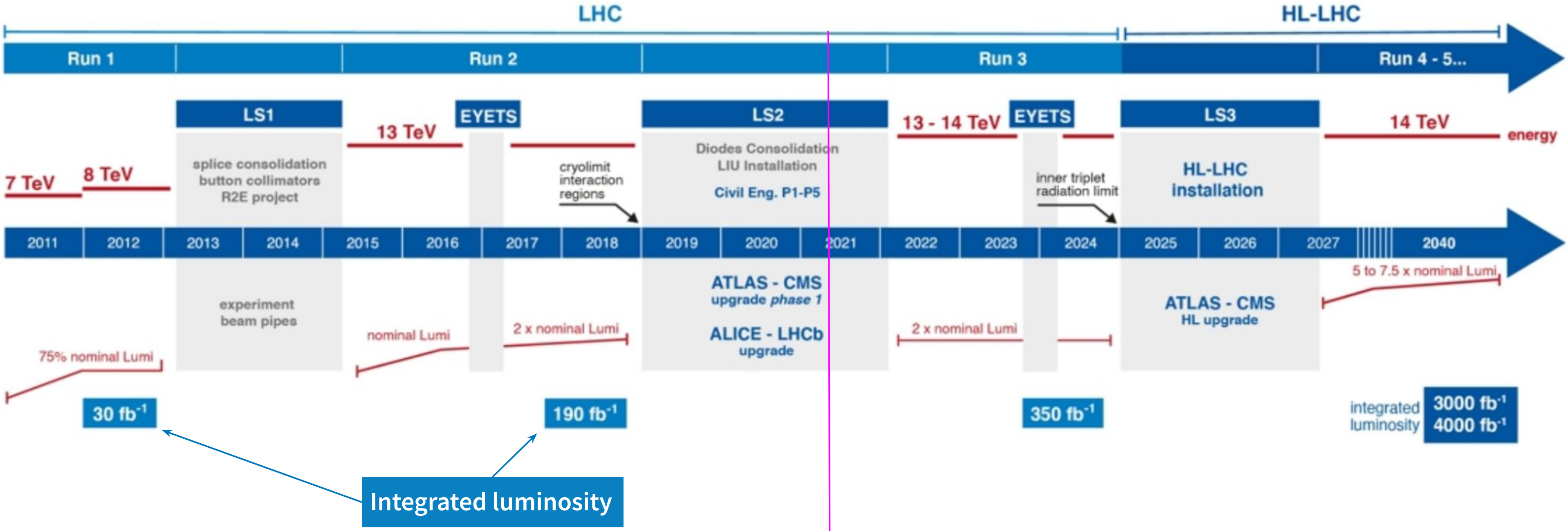


- > 50 kinds of magnets
- 1232 superconducting dipole magnets operating at -271.3°C
  - ➥ Sextupole, octupole & decapole magnets correct the beam
- 8 RadioFrequency (RF) cavities per beam



- Proton beam energy = 6.5 TeV
- 1.2 x 10^{11} protons/bunch
- ~ 2800 bunches/beam
- 25ns bunch spacing
  - ➥ 40,000,000 collisions per second

LHC Schedule

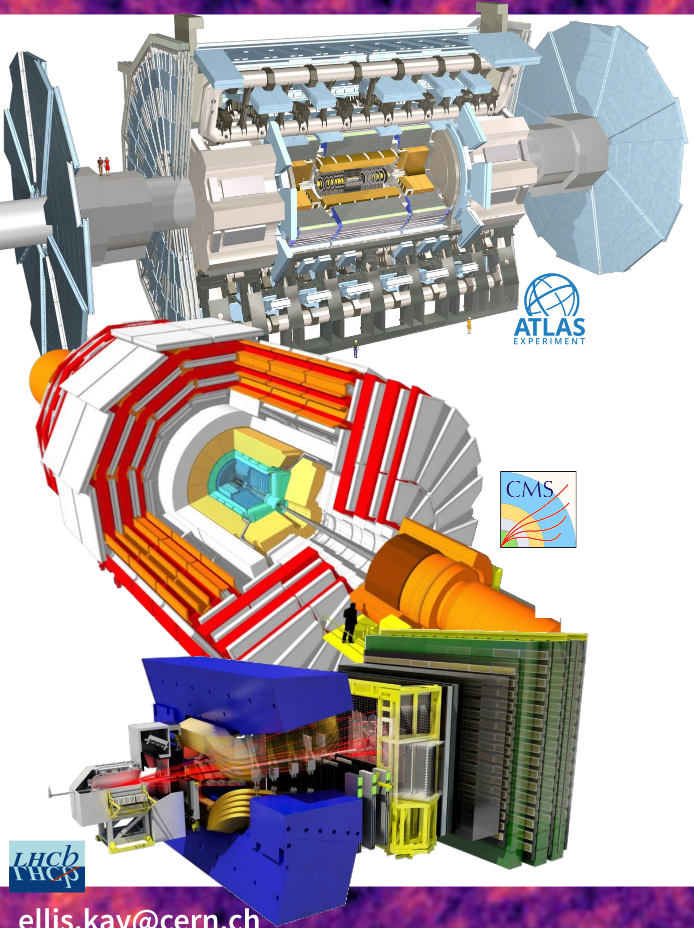


bunch intensity # bunches

Luminosity $\mathcal{L} \propto \frac{N_1 N_2 n_b}{\sigma^2}$

colliding beam size

Dark Matter Detectors at the LHC



Three of the four main LHC experiments exploit distinct technologies to conduct complementary searches for DM

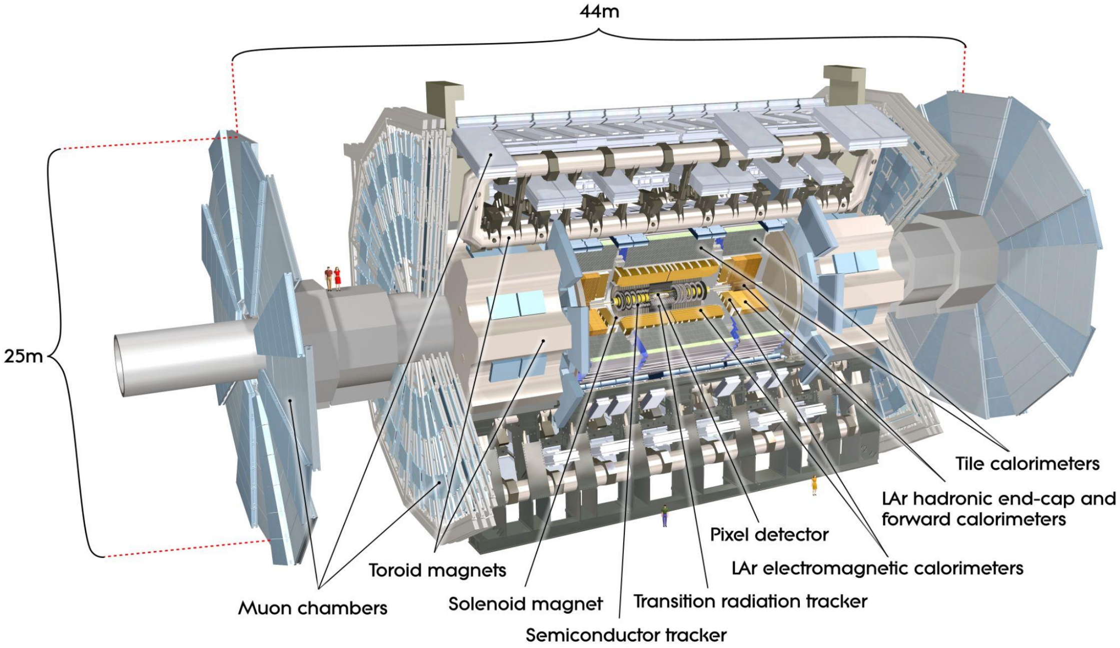
<u>ATLAS & CMS</u>

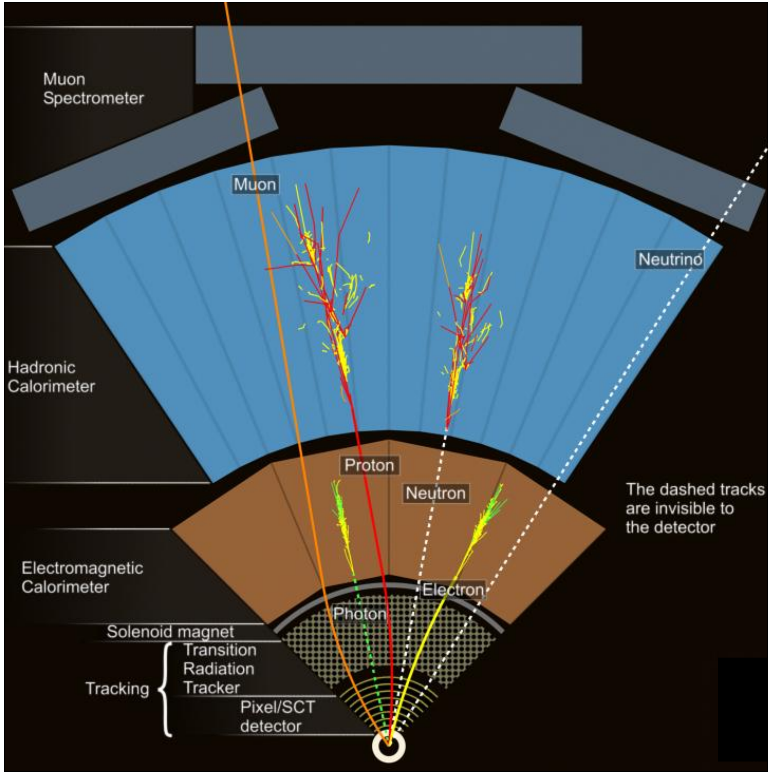
- Independently designed hermetic general-purpose detectors
  - Investigate largest range of physics possible
  - Can reconstruct missing transverse momentum (E_T^{miss}) using all measured decay products

<u>LHCb</u>

- Single arm forward spectrometer
  - Probes the forward rapidity region & triggers on particles with low p_T
  - Can explore relatively small boson masses

The ATLAS Detector



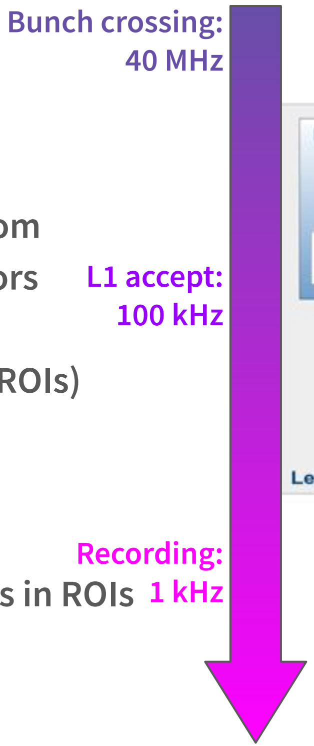


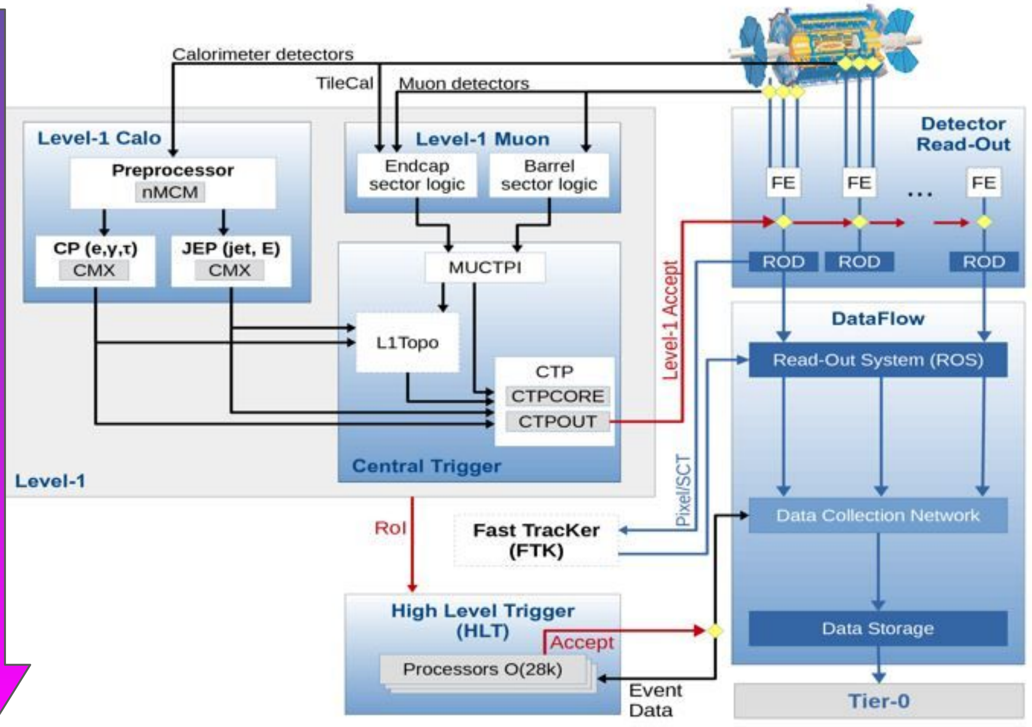
See 2007.12539

- Not all events observed by ATLAS contain interesting information…
  - ➥ Select events with trigger

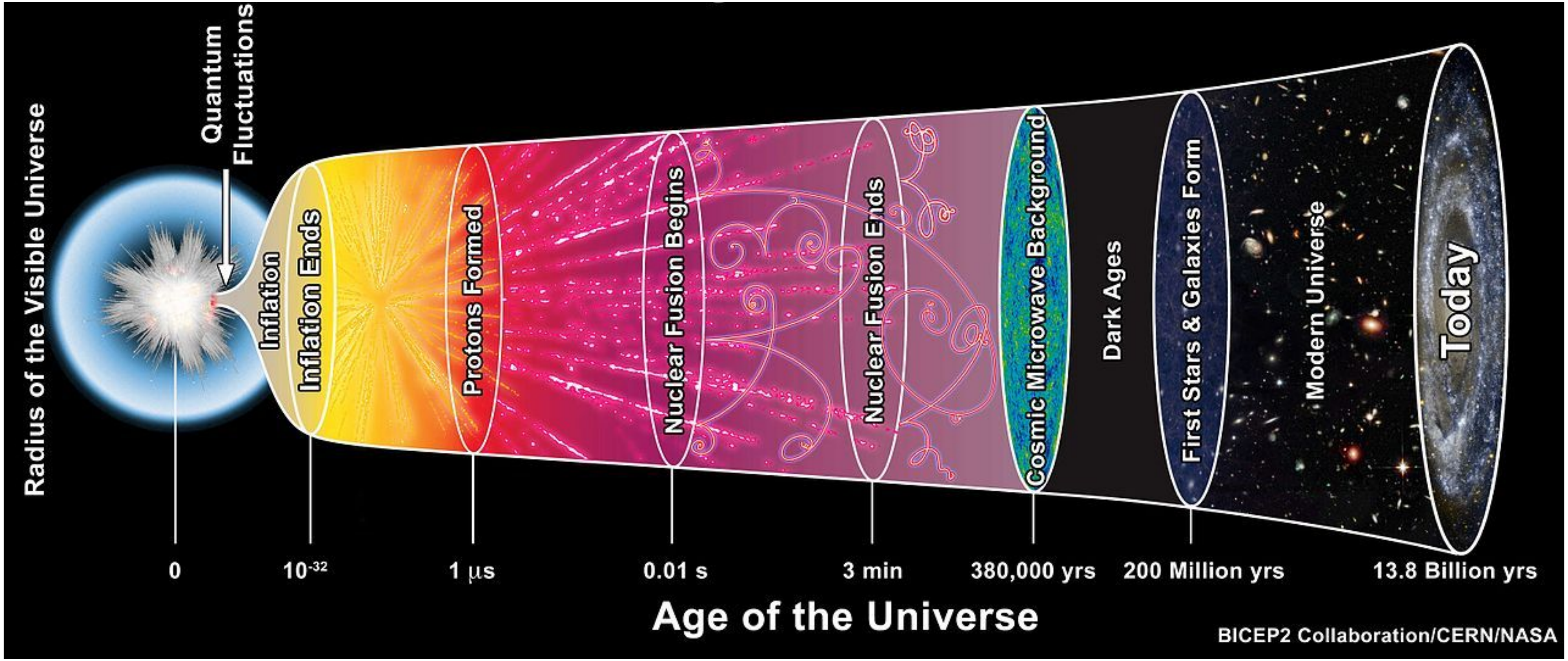
- Level-1
  - ➥ Hardware based
  - ➥ Use subset of information from calorimeters & muon detectors
  - ➥ Decision made in < 2.5 μs
  - ➥ Defines Regions Of Interest (ROIs)

- High-Level Trigger (HLT)
  - ➥ Software based
  - ➥ Detailed analysis of L1 events in ROIs

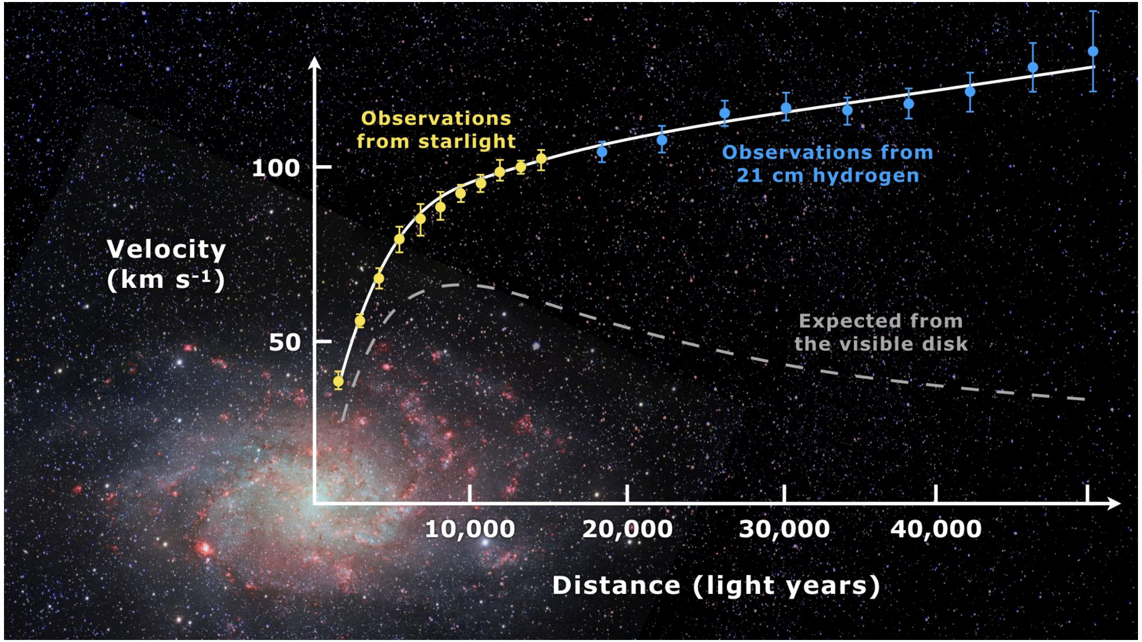




The History of the Universe



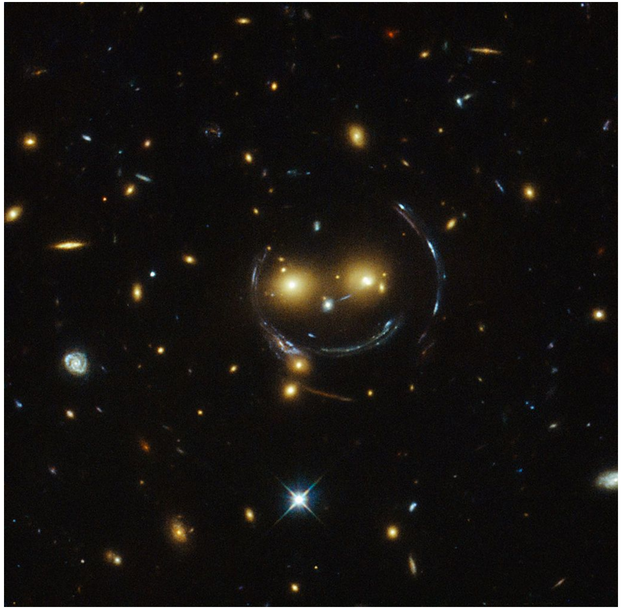
Galaxy Rotation Curves

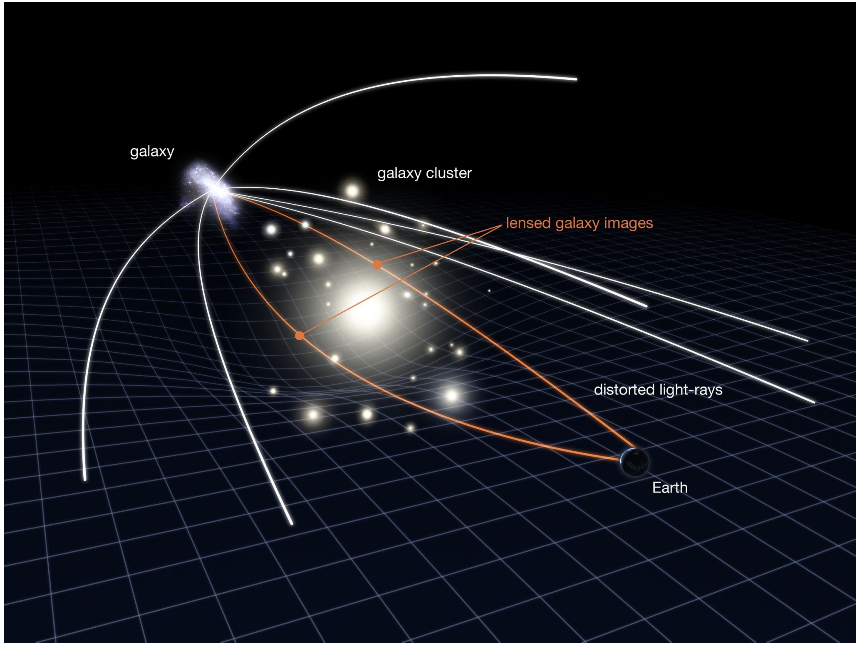


- Luminous mass density of spiral galaxy decreases with distance from the centre
- Expect rotation velocities of objects to decrease as well
- Flat rotation curves indicate the present of more non-luminous mass

Gravitational Lensing

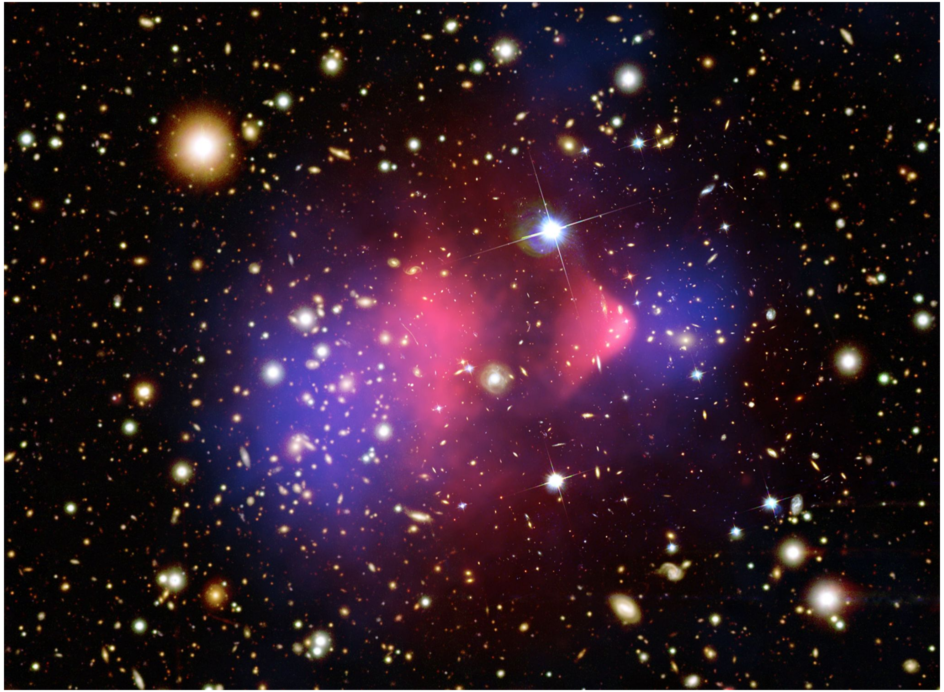
- Massive objects between a distant light source and observer distort the space around them (general relativity)
- Measure the object’s mass through extent of ‘lensing’ - look at mass/light ratio





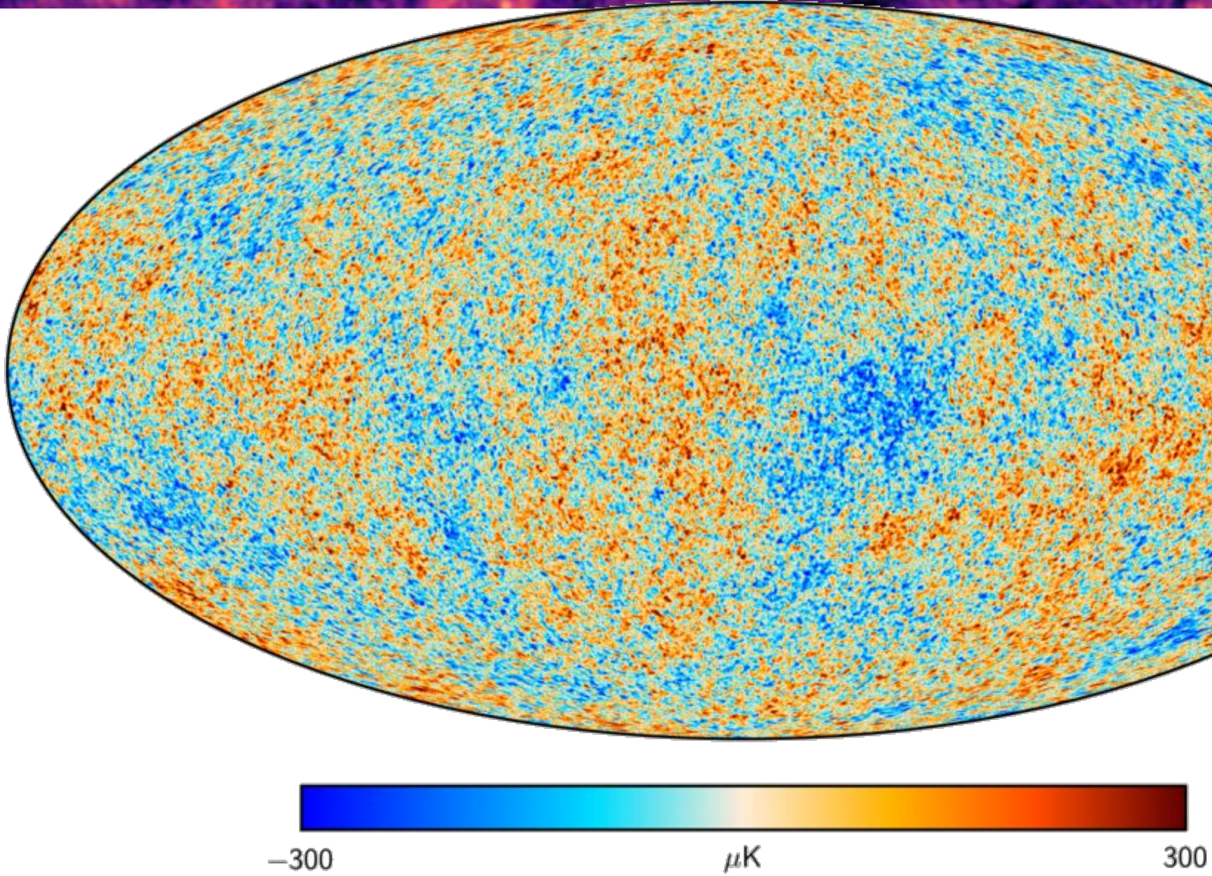
Colliding Galaxies (the Bullet Cluster)

- Two galaxy clusters colliding ~ 4 billion light years away
  - X-ray image (pink) shows where most of ordinary mass is
  - Matter distribution calculated from gravitational lensing (blue)

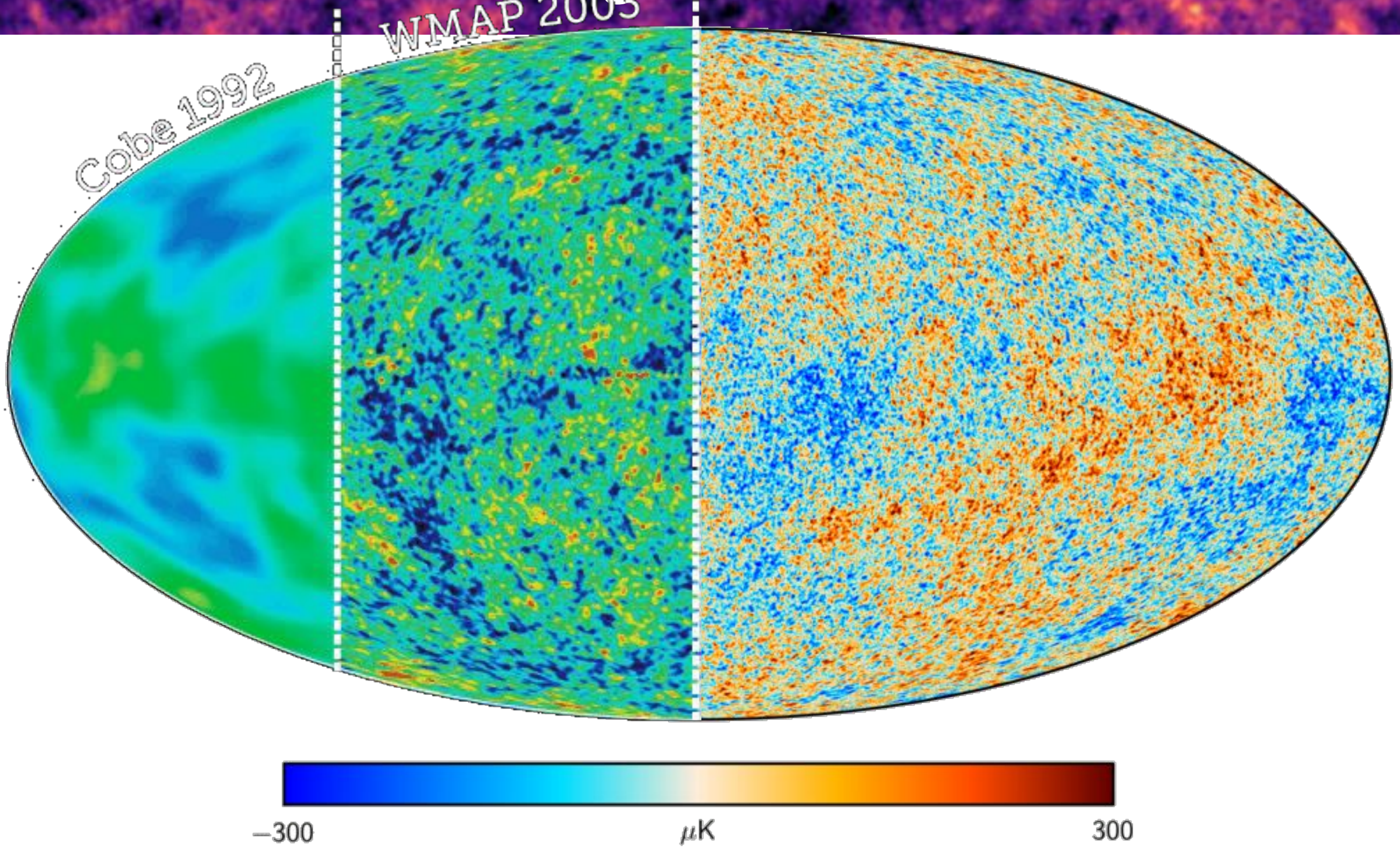


- Seems that most of the mass passed through, unhindered by the collision

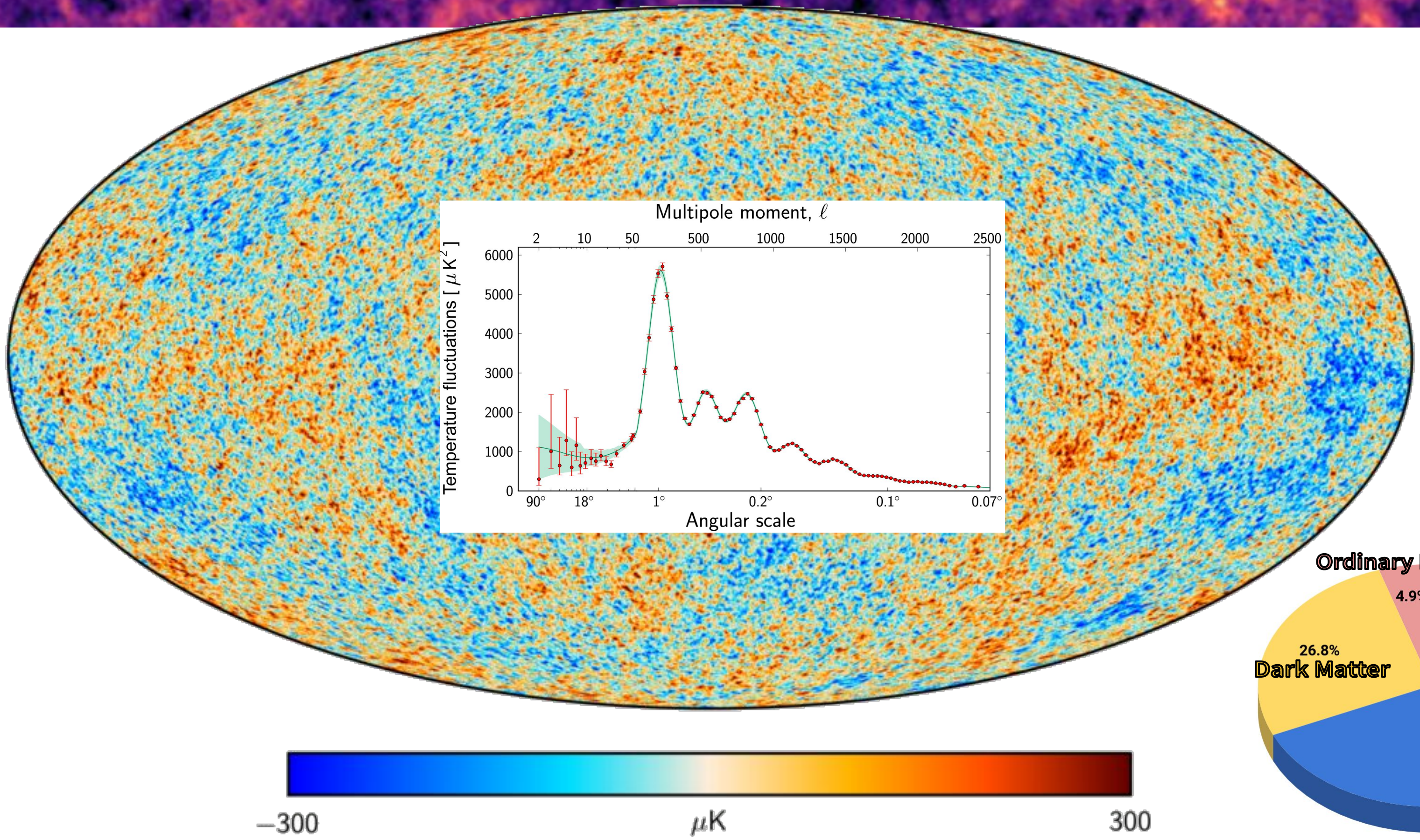
The Cosmic Microwave Background

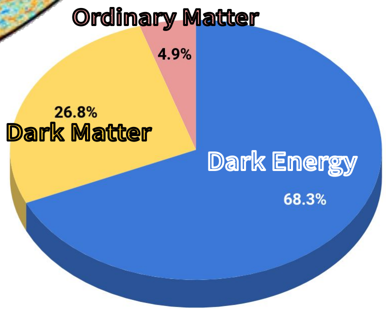


The Cosmic Microwave Background



The Cosmic Microwave Background



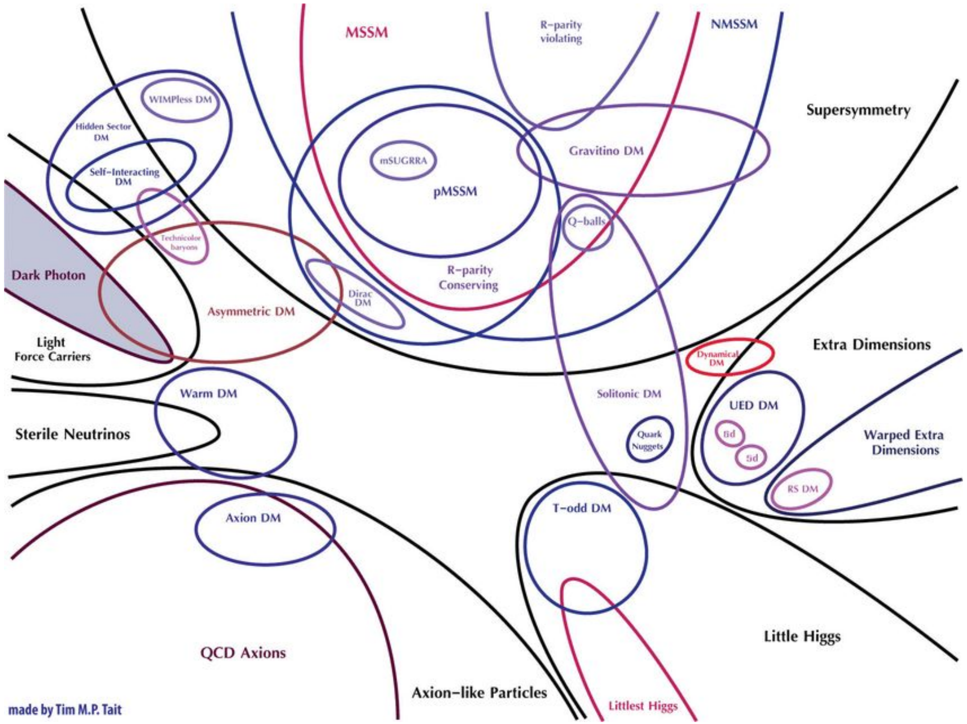


The Nature of Dark Matter

- **What could DM be made of?**
  - ➥ Only observed to have gravitational interactions
  - ➥ Has mass
  - ➥ Could be a particle

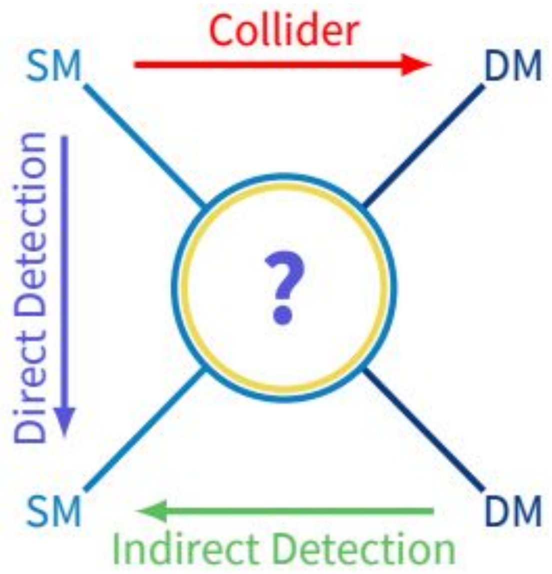
- **Non-baryonic?**
  - ➥ Weakly Interacting Massive Particle (WIMP)
  - ➥ Axion-like-particle (ALP)
  - ➥ New neutrino (e.g. Majorana)

- **Maybe not just one particle, but a whole <u>dark sector</u> consisting of many DM particles!**



Seeking to Detect Dark Matter

- Various methods exist for detecting DM, covering different ranges of DM mass, m_χ



Direct Detection (DD): see [1509.08767]

- Nuclear recoil from elastic scattering

Indirect Detection (ID): see [1604.00014]

- DM annihilation

Collider Searches:

- DM production in high energy particle interactions

- All three complementary methods continue to put mounting pressure on the WIMP hypothesis...

Dark Matter Detection: Direct

- Observe low-energy recoils of nuclei following interactions with DM
  - ➥ Scintillation photons or phonons
- Operate detectors deep underground to keep cosmic backgrounds low

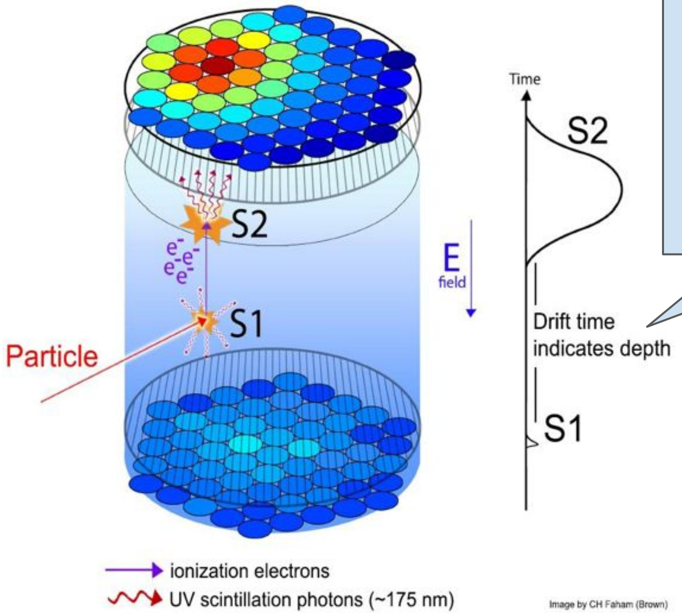
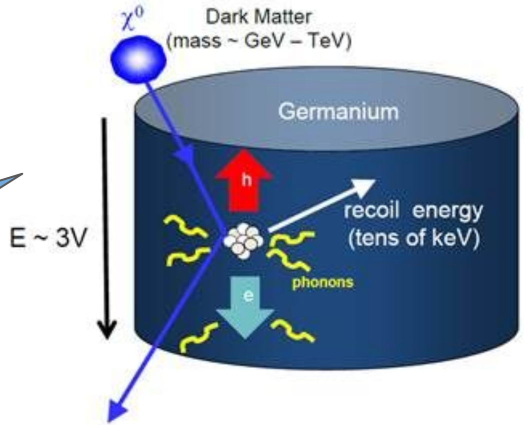


Image by CH Faham (Brown)

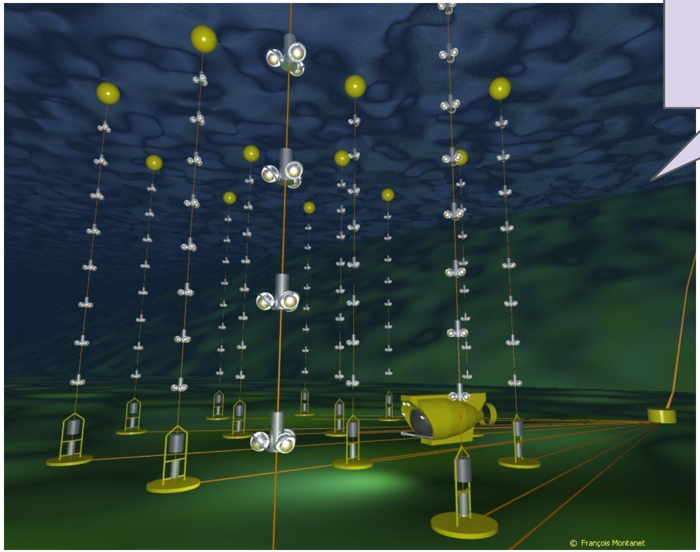
Noble liquid detectors
LUX (1211.3788)
ZEPLIN (1708.07051)
XENON (1708.07051)
…

Cryogenic detectors
CDMS
CRESST
EDELWEISS
…

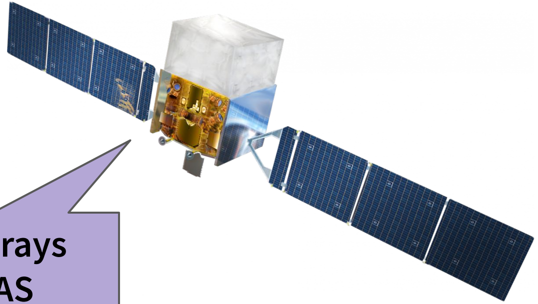


Dark Matter Detection: Indirect

- Observe products of DM annihilation or decay
  - ➥ Gamma rays, SM particles/antiparticles

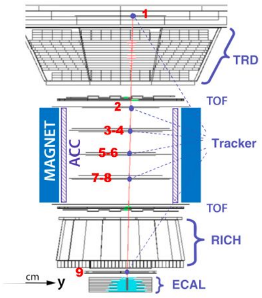


Neutrino signals
IceCube
<u>ANTARES</u>
AMANDA
…



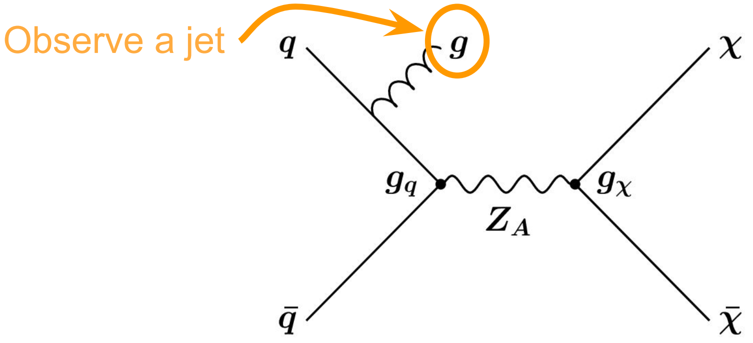
Gamma rays
VERITAS
<u>Fermi</u>
MAGIC
…

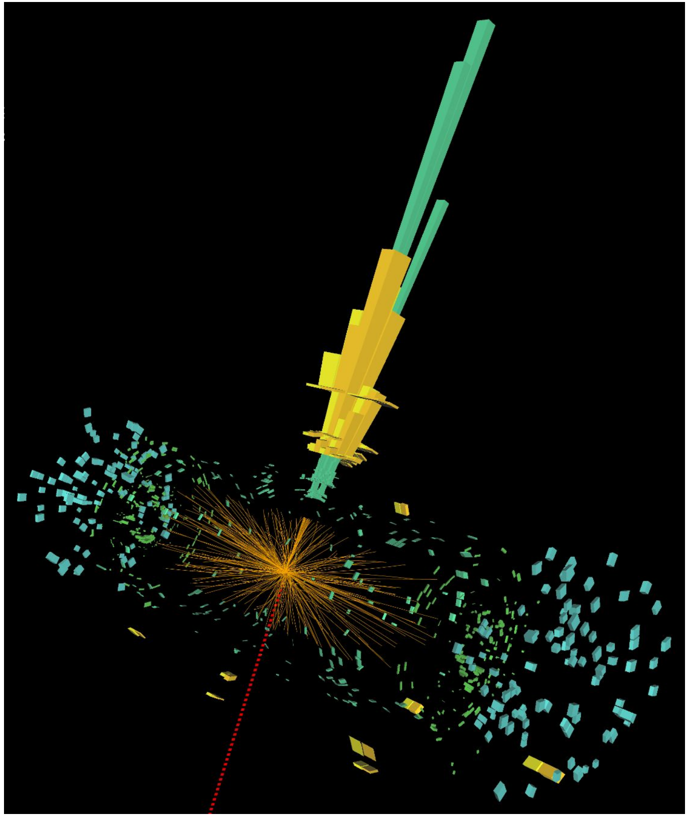
Positrons
PAMELA
<u>AMS</u>
…



Dark Matter Detection: Colliders

- Produce DM (χ), imitating big-bang conditions





- If DM only interacts through gravity… how do we detect it?
  - ➥ Momentum is conserved ∴ can infer missing momentum by measuring all detected particles

$$E_{\mathrm{T}}^{\mathrm{miss}} = \left| -\sum_{\mathrm{reconstructed}} \vec{p}_T \right| = -\sum_{\mathrm{calo}} \vec{E}_T^{\mathrm{calo}} - \sum_{\mathrm{MS}} \vec{E}_T^{\mathrm{MS}}$$

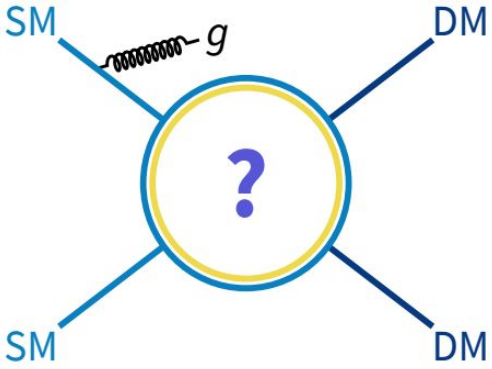
Missing transverse energy (MET/E_T^{miss})

Types of LHC DM Searches

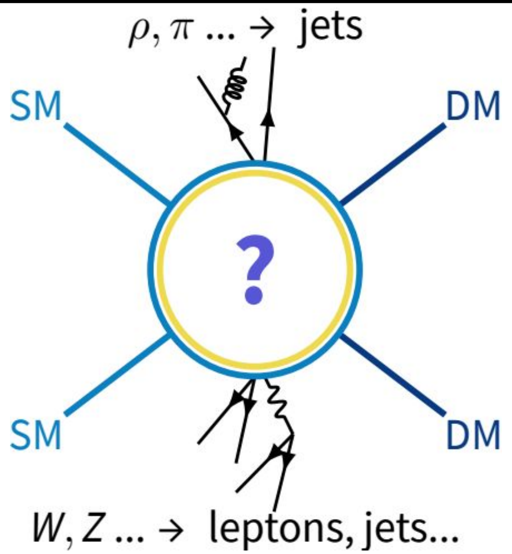
See Phys. Dark Univ. 26 (2019) 100371
& LHC DM Working Group

Dark matter is invisible to our detectors → look for associated production of visible (SM) particles

Generic Searches & Simpler Models ⟷ Specific Searches & More Complete Models



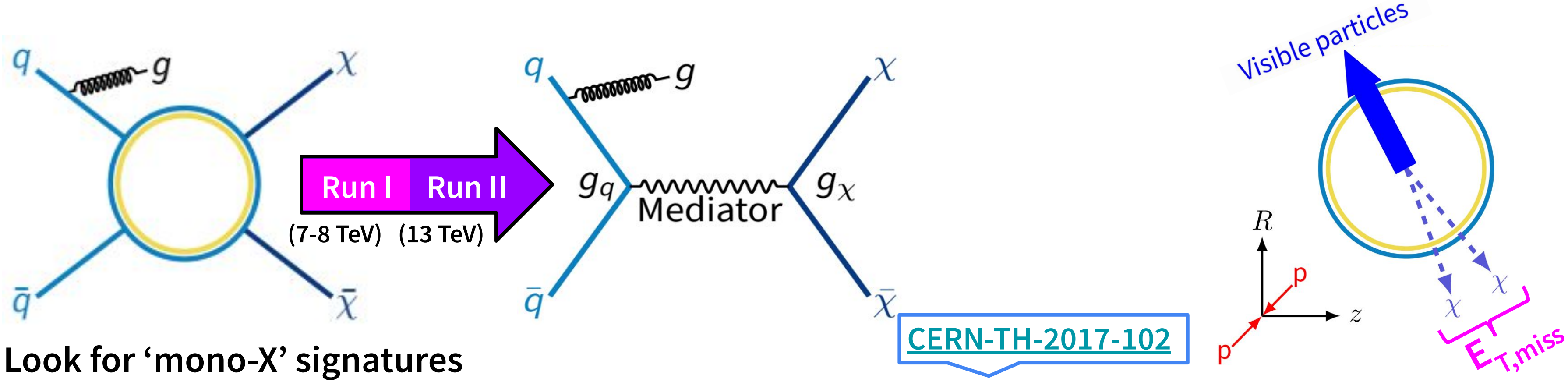
- Simple signals e.g. a single mediator
- Sizeable cross-sections
- Fewer assumptions on specific model parameters



- More reliant on model assumptions
- E.g. supersymmetry, UV complete models

Simplified Models - ‘Mono-X’

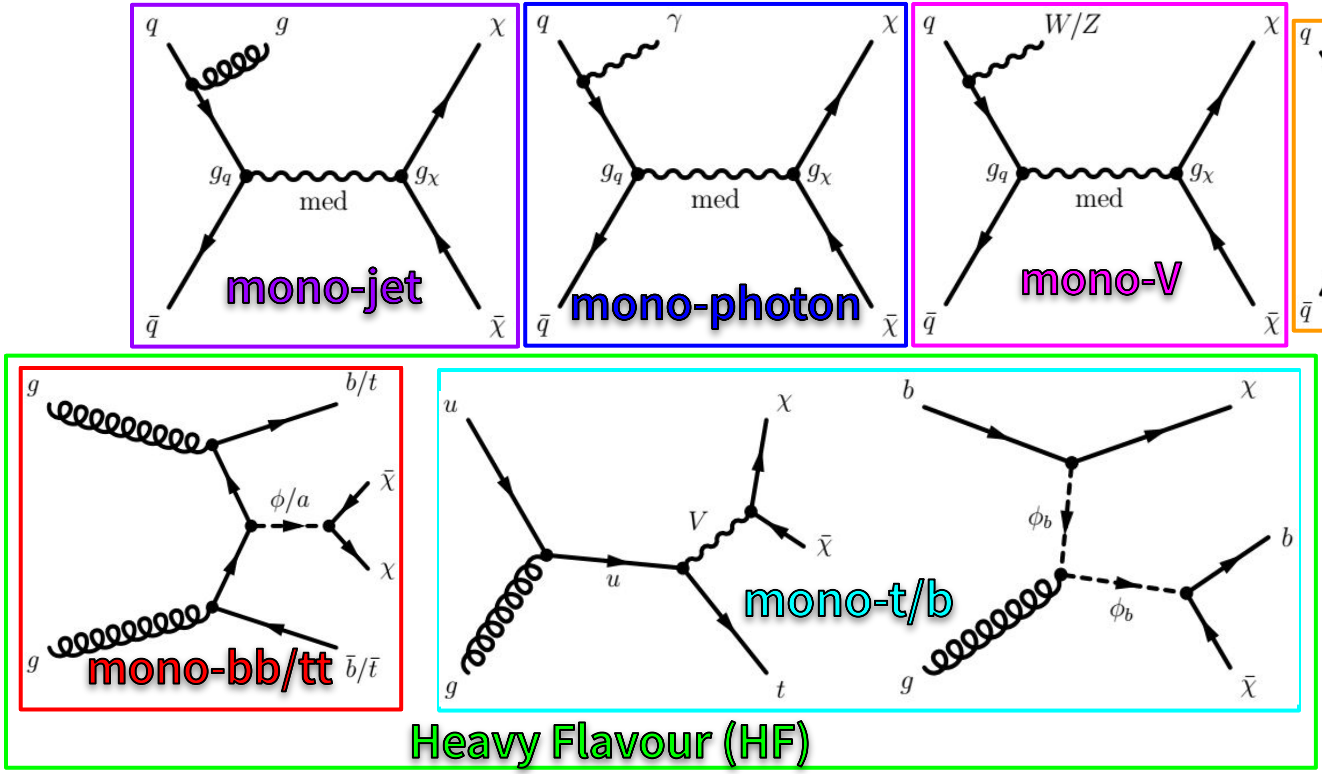
- The most general models involve contact interaction operators in Effective Field Theories (EFTs)
- These become invalid at large momentum transfer, Q^2, which is problematic for Run-II
  - ➥ Favour ‘simplified’ models with a mediator, introducing m_χ, m_{med}, g_q and g_χ



- Look for ‘mono-X’ signatures
  - ➥ Select events with ‘X’ (jet/γ/W/Z/t/H), veto other objects, precisely model backgrounds, check E_T^{miss}
  - ➥ Fix g_q, g_χ and exclude m_χ, m_{med} → CERN-LPCC-2016-001
- Also look for visible decays of the mediator to complement these searches → CERN-LPCC-2017-01
  - ➥ Re-interpret other analyses as mediator searches

Mono-X Signatures

There is a wealth of mono-X final states to be investigated at the LHC...



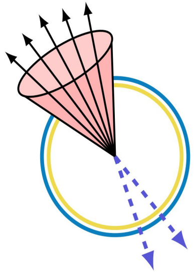
With various production mechanisms ($q\bar{q}$, gg etc.) ...

Via (axial-)vector or (pseudo-)scalar mediators...

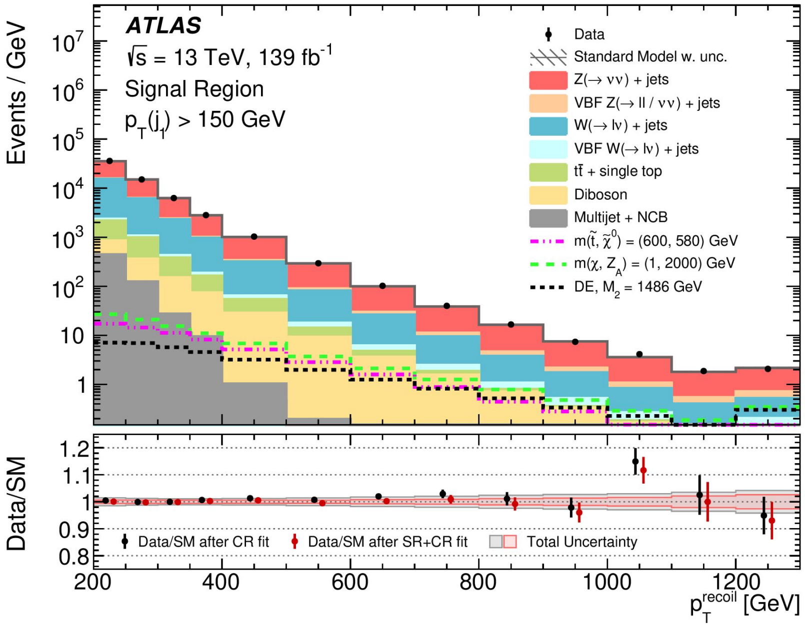
And with different couplings, depending on the benchmark

Mono-jet

Phys. Rev. D 103, 112006 (2021)



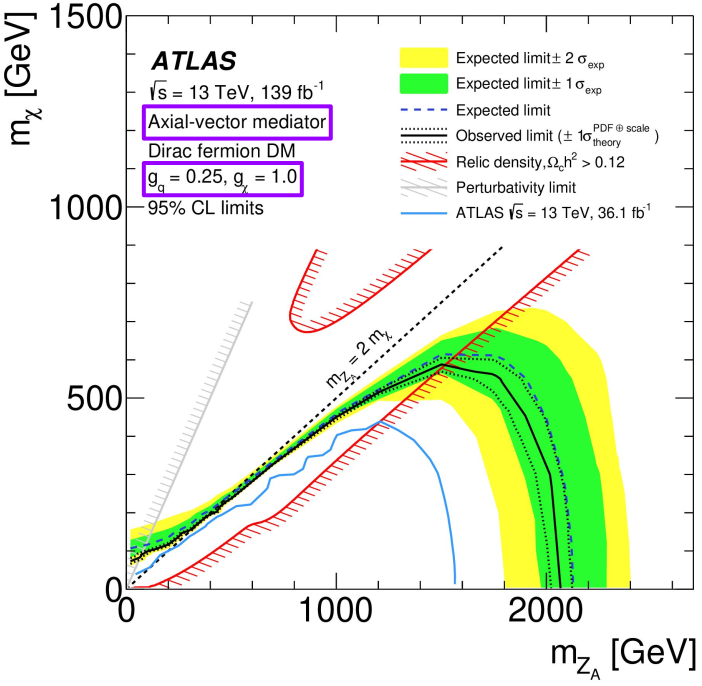
- Gluon ISR is by far the most prevalent at the LHC!

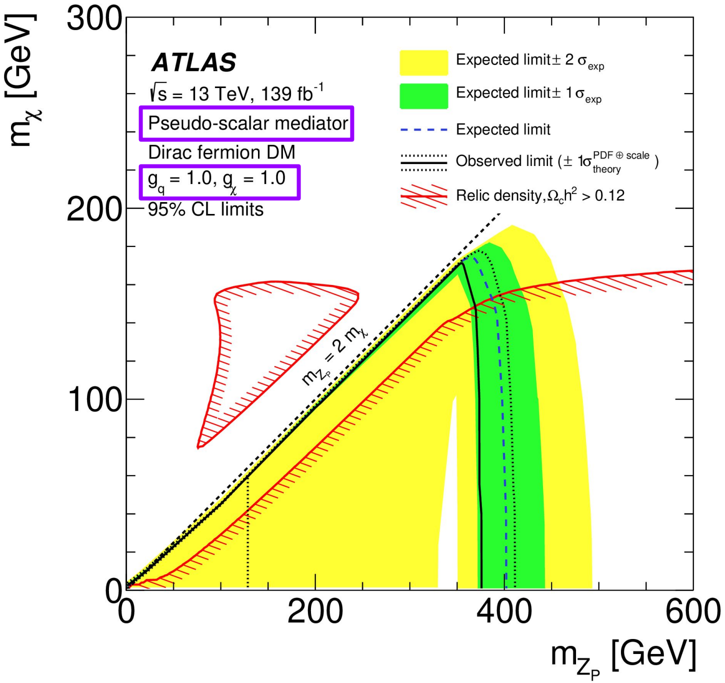


- **Signal Selections**
  - >1 jet with p_T > 150 GeV
  - E_T^{miss} > 200 GeV
  - Define signal regions (SRs) in bins of E_T^{miss}
- **Define control regions (CRs) to constrain SM BGs**
  - W→μν, W→eν, Z→μμ, Z→ee, top
- **Perform simultaneous binned bg-only likelihood fit**
  - Apply normalisation factors extracted from this fit to SM predictions

Mono-jet

- No observed excess ∴ set limits on signal cross section





Visibly Decaying Mediator Searches

PHYS. LETT. B 796 (2019) 68

JHEP 03 (2020) 145

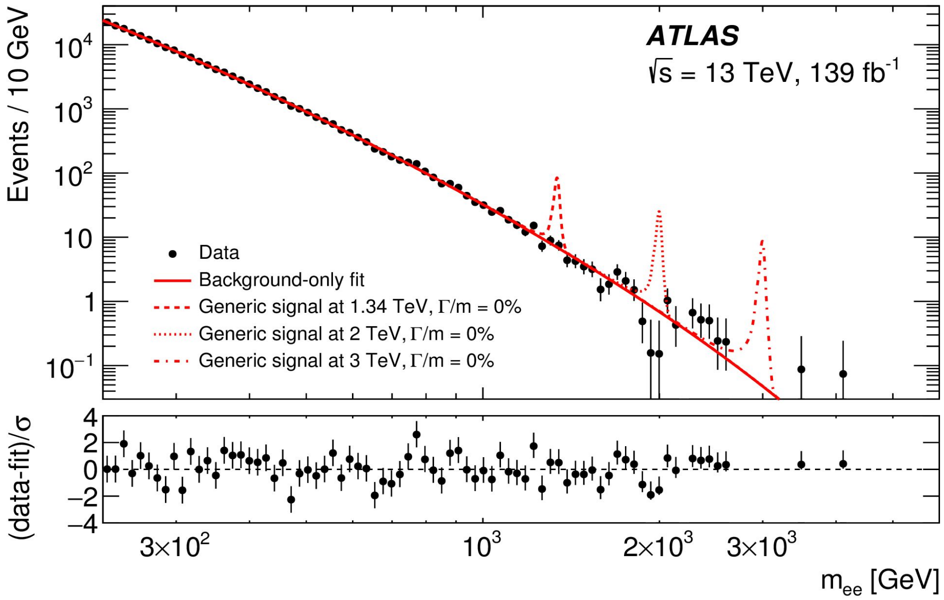
- DM cannot be produced on-shell if $2m_{DM} > m_{med}$
  - ➥ Mediator decays back to SM
  - ➥ Need to probe visible signatures to see DM interactions off-shell

- The LHC is a "mediator machine"!

- Probe high masses in search of BSM mediators.

- Look for bumps on the smoothly falling di-object distribution, which is modeled by a parameterized function.

- In absence of bump, set limits for different physics scenarios.

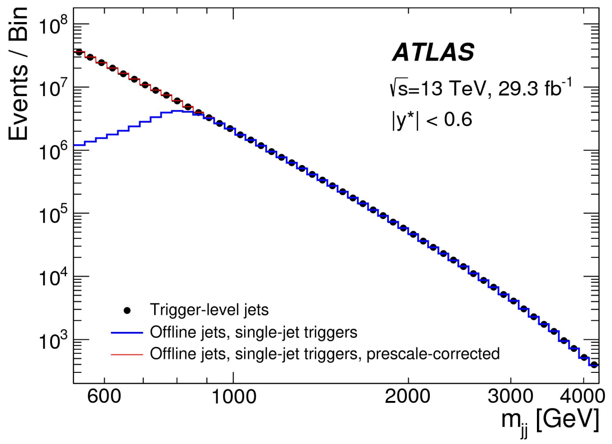


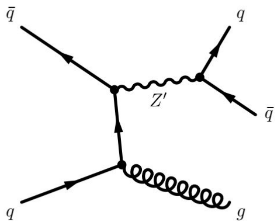
Low Mass Di-jet Searches

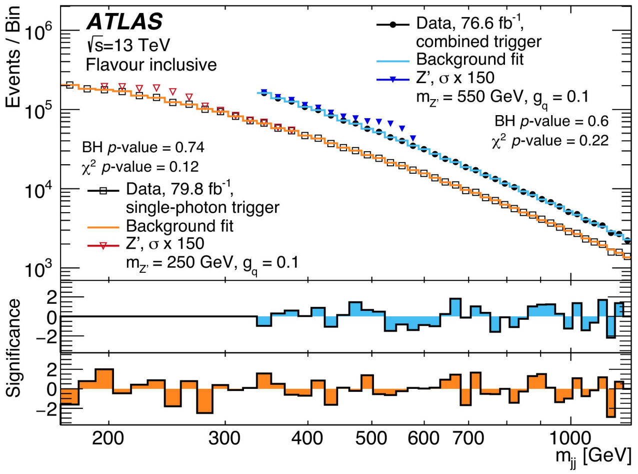
[PHYS. LETT. B 795 (2019) 56]

- Sensitivity at low (< 1 TeV) m_{jj} is limited by jet triggers
  - ➡ Data collection rates for inclusive single-jet triggers << SM multijet production rate
- "Data-scouting" / "Trigger-object Level Analysis" (TLA)
  - ➡ Use reduced data format to allow high trigger rate with low bandwidth

PHYS. REV. LETT. 121, 081801 (2018)





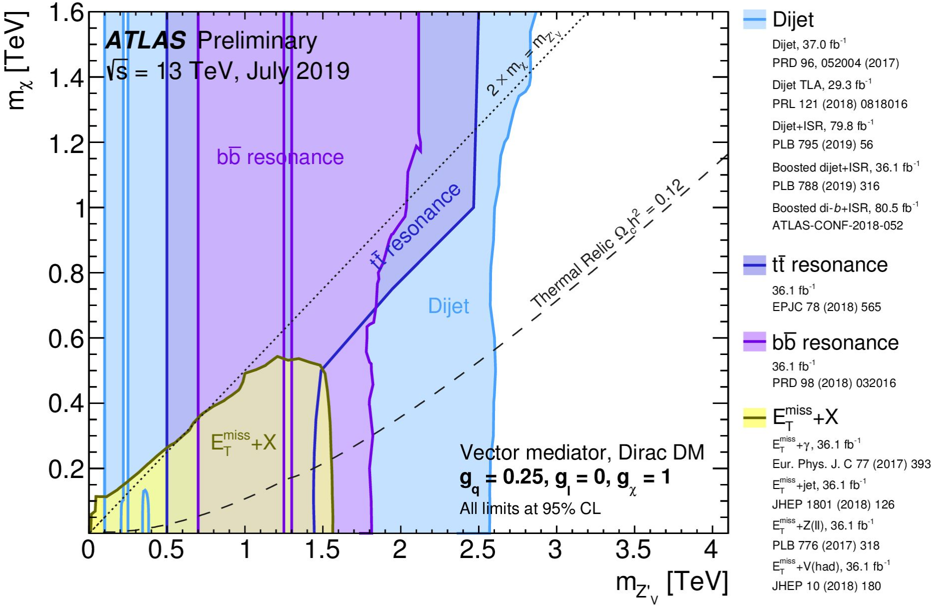


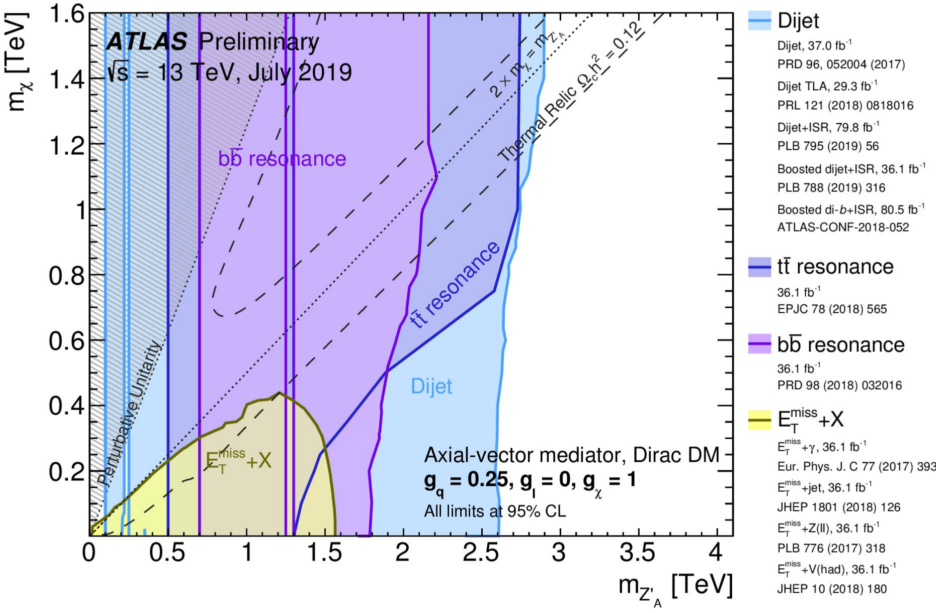
- ➡ **Introduce hard Initial-State Radiation (ISR) requirement**
  - ➡ Require ≥ 1 high p_T ISR jet in association with the *qq* resonance
  - ➡ Provides enough energy to satisfy trigger
  - ➡ Min p_T high enough that hadroisation from *qq* gives a large-R jet
  - ➡ Achieve sensitivity to even lower mediator masses
  - ➡ ATLAS: 225 - 1100 GeV

Combined Results

JHEP 05 (2019) 142

◊ Vector/Axial-vector mediator, Dirac DM, $g_\chi = 1$, $g_q = 0.25$, $g_l = 0$

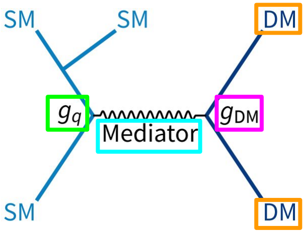




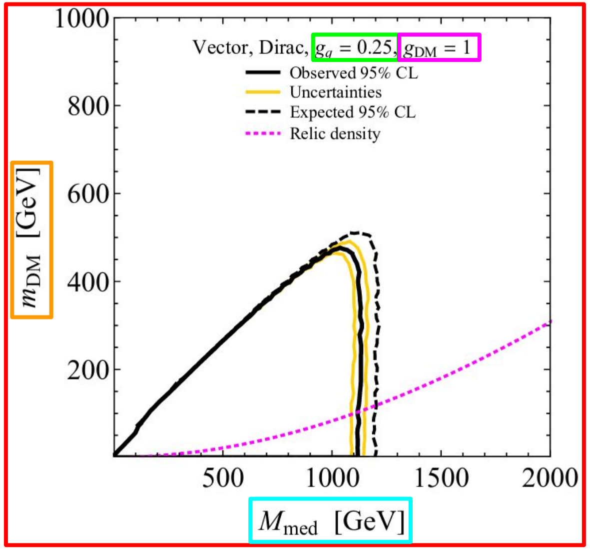
m_{med} ~ 2.5 TeV reach from mediator searches

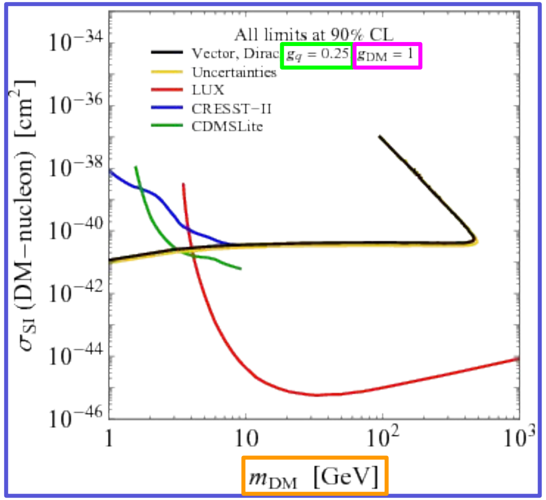
Comparing Results to DD/ID

CERN-LPCC-2016-001



- Comparisons to other experiments / channels are possible only in the context of a benchmark - need to fully specify model/parameters and be aware of any limitations
- Advised prescriptions exist for translating LHC limits (m_{DM} vs. m_{med}) to ID/DD limits.



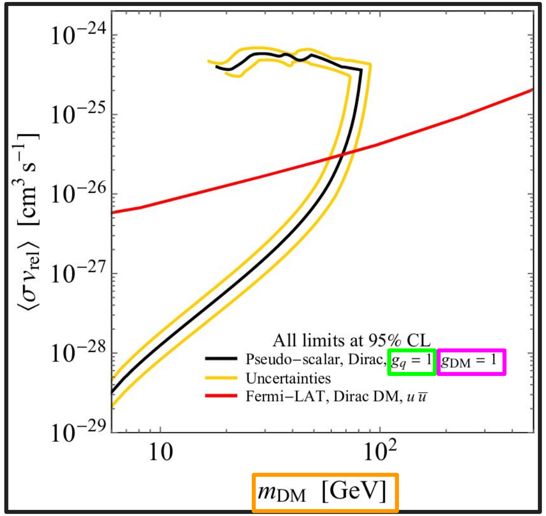


DD: spin (in)dependent DM-nucleon cross-section

σ_{SI} / σ_{SD}

ID: DM annihilation cross-section

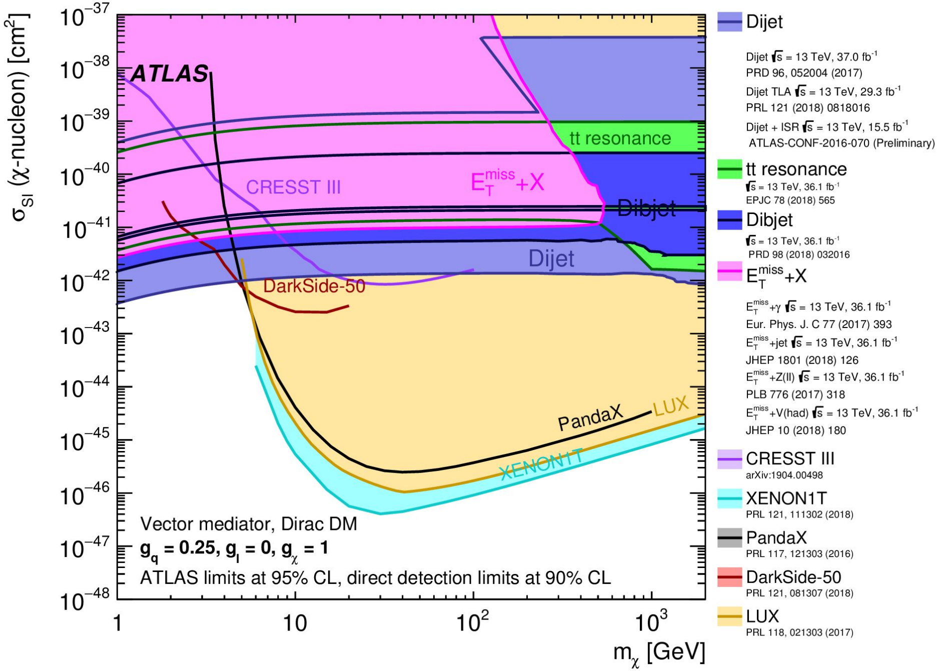
$\langle \sigma v_{rel} \rangle$

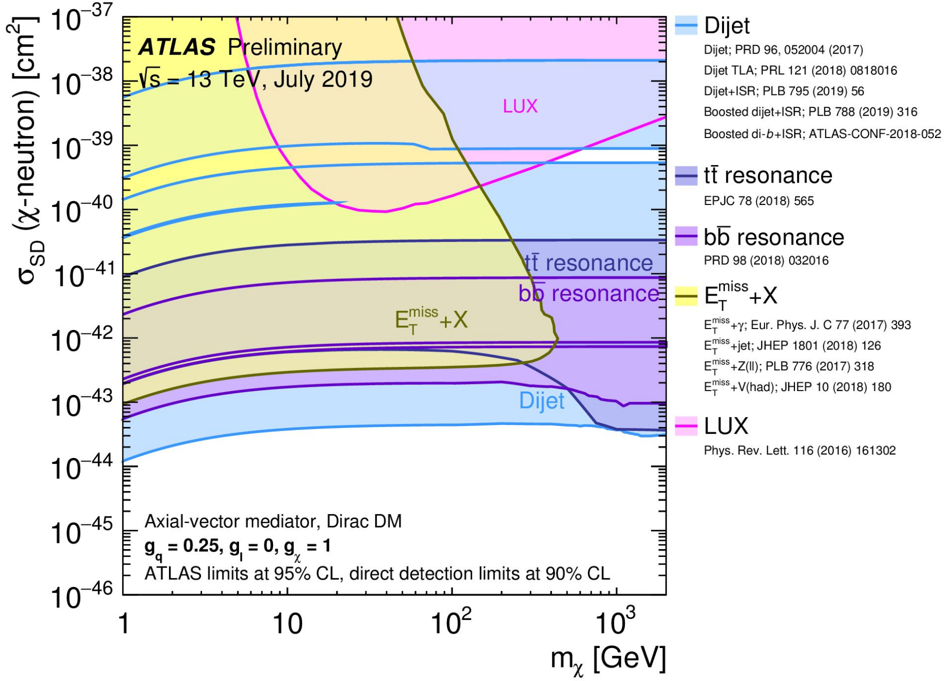


Combined Results

ATLAS: JHEP 05 (2019) 142
CMS: ICHEP 2018

- SI & SD WIMP-nucleon scattering cross-section, Dirac DM, $g_\chi = 1$, $g_q = 0.25$, $g_l = 0$
  - ➥ Strong SD limits compared to DD for these couplings in this model!





Combined Results

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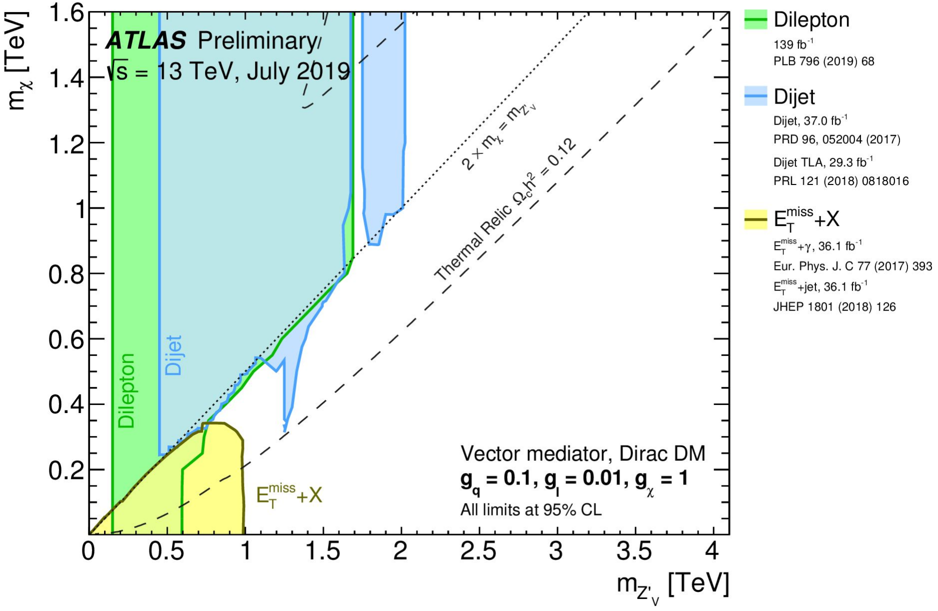
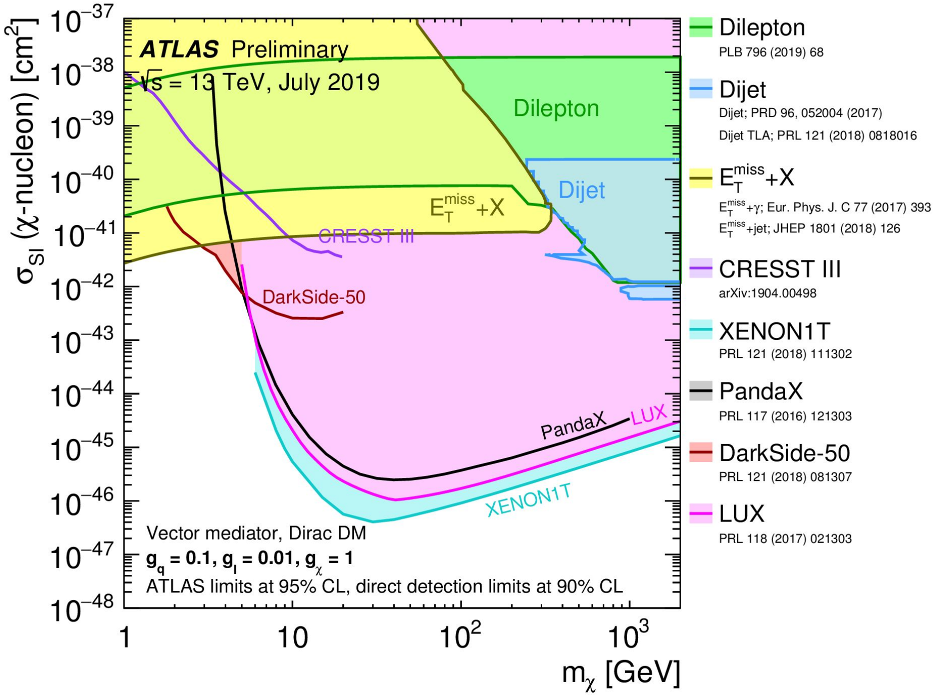
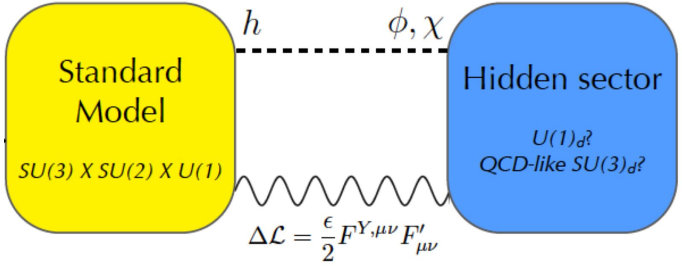
- **SI WIMP-nucleon scattering cross-section, Dirac DM, $g_\chi = 1$, $g_q = 0.1$, $g_l = 0.01$**
  - ➥ For these couplings in this model, the mono-jet search has higher sensitivity than DD at low m_χ!





'Hidden Sectors'

- What if new physics, such as DM, exists in a hidden sector, composed of particles which don't undergo SM gauge interactions?
  - ➥ Coupling to SM encoded in a mixing term in the Lagrangian
  - ➥ May communicate with the SM via mediators, which could be DM candidates OR provide 'portals' to them



1608.08632

$$\mathcal{L} \supset \begin{cases} -\dfrac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}\,, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H\,, & \text{Higgs portal} \\ y_n L H N\,, & \text{neutrino portal} \\ \frac{a}{f_a} F_{\mu\nu}\widetilde{F}^{\mu\nu}\,, & \text{axion portal.} \end{cases}$$

→ vector A' → dark Z, dark ɣ

→ scalar ϕ → dark H

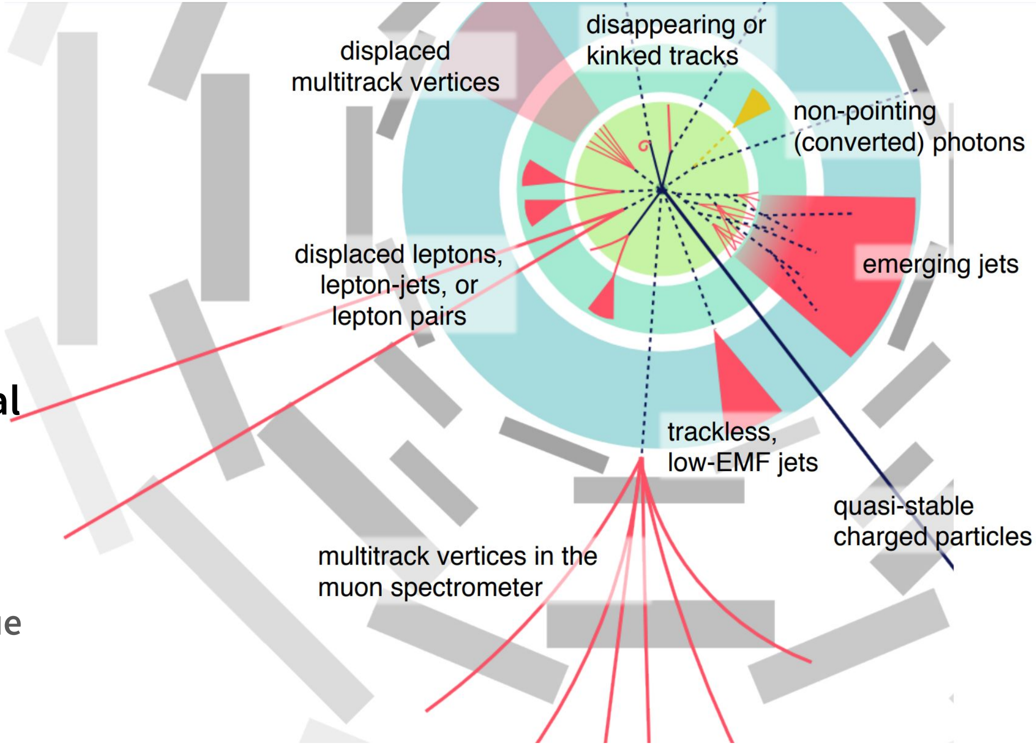
→ fermion, N → sterile neutrino

→ pseudo-scalar, ɑ → axion

- Limited ways in which the hidden sector and SM can communicate, many leading to unconventional signatures at the LHC

Unconventional Signatures

- Weak coupling to the SM leads to long-lived-particles (LLPs)
- Many possible unconventional signatures
- Detecting these can come with experimental challenges
  - Non-standard trigger requirements
  - Decays far from the primary vertex (PV), requiring special tracking
  - Unusual shower shapes in calorimeters, unique fractions of ECal/HCal energy
  - Need for timing information, which is not available in all subdetectors...

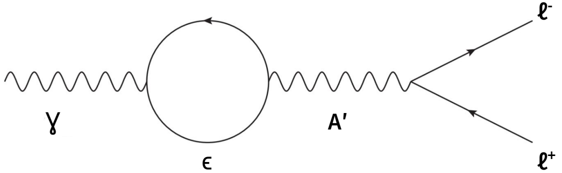


J. Phys. G: Nucl. Part. Phys. 47 090501 (2020)

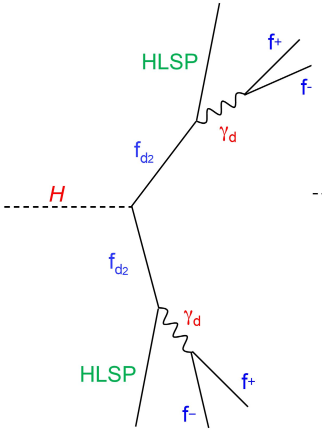
Eur. Phys. J. C 80 (2020) 450

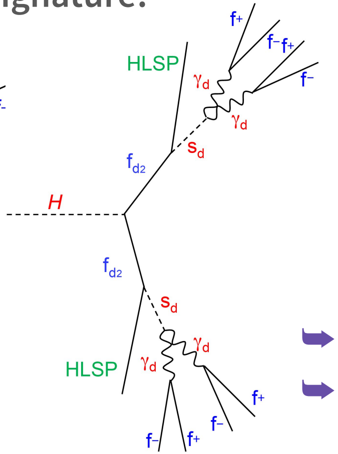
Dark Photons, A′

- U(1) extension of the SM, introducing a hidden gauge boson γ_d/A′ with kinetic mixing (ϵ) with SM
  - ➥ Benchmark FRVZ model, with Higgs boson decaying to dark fermion pair



- Low mass A′ could be produced via cascade decays of heavier states
  - ➥ Leptonic decays of A′ are prominent in the low-mass range
  - ➥ Decay to highly collimated groups of leptons, or 'lepton-jets' (LJ)
  - ➥ A distinct LHC signature!

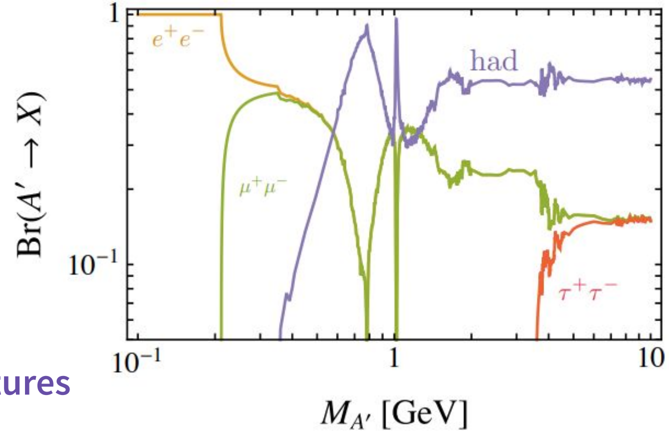




HLSP = Hidden Lightest Stable Particle
f_d = dark fermion
γ_d = dark photon
s_d = dark scalar

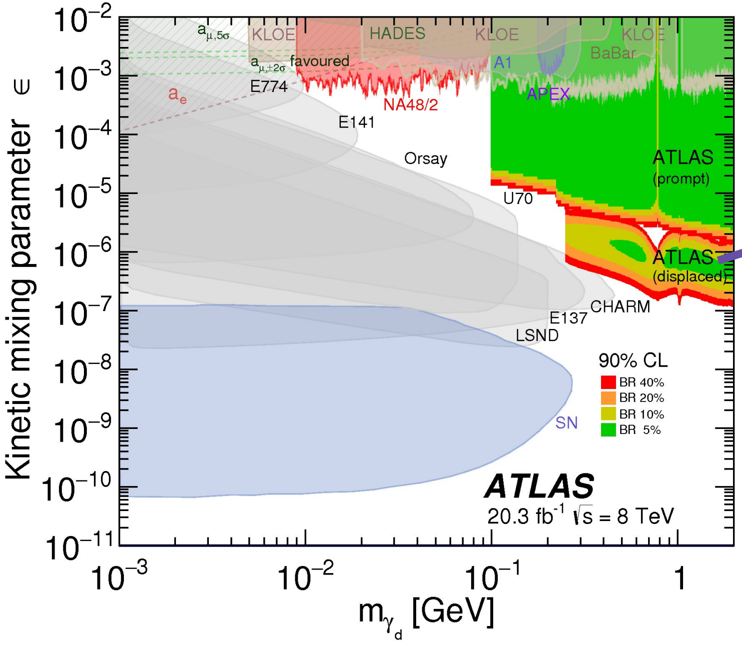
➥ Small mixing → long lifetime
➥ Prompt or displaced LJ signatures

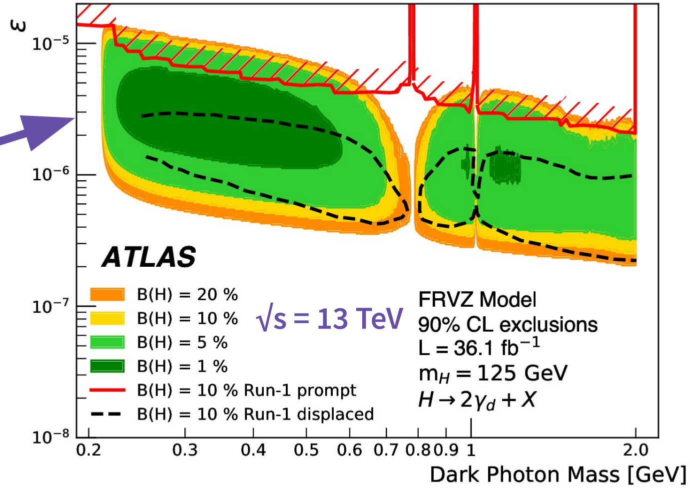
J. High Energ. Phys. (2018) 2018: 94



[Eur. Phys. J. C 80 (2020) 450]
[JHEP02(2016)062]

- Produce limits on the kinetic mixing parameter and $m_{A'}$
  - Limits shown for 10% ⩽ B(H→2γ_d+X) ⩽ 20%



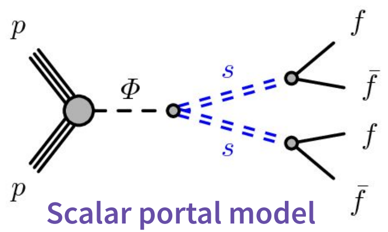


Complementary to fixed target/beam-dump experiments

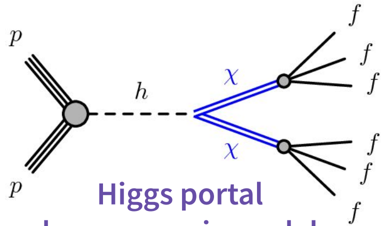
Displaced Vertices / Hadronic Jets

Phys. Rev. D 99, 052005 (2019)
Eur. Phys. J. C 79 (2019) 481
Phys. Rev. D 101, 052013 (2020)

- Long-lived particles (LLP) may decay to jets far from the interaction point (IP)
  - ➥ Standard jet reconstruction assumes ID tracks, common primary vertex…

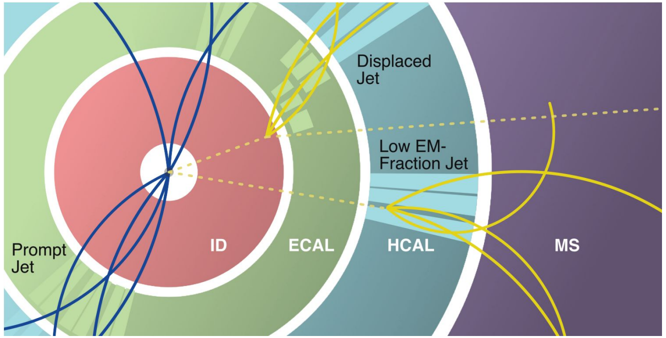


Scalar portal model



Higgs portal baryogenesis model

JPPNP 3695 (2019)



Many possible scenarios:

- Particle decays in the ID, but far from the IP / decays in the MS
  - ➥ MS-ID: ⩾ 2 jets in the ID and/or MS
  - ➥ Dedicated tracking algorithms for MS-only vertexing available (JINST 9 (2014) P02001)
- Particle decays in the middle of the calorimeters
  - ➥ CalRatio (CR): jet pair decaying in the HCal with no associated ID tracks
  - ➥ Large energy deposit in the HCal, small deposit in the ECal
  - ➥ Dedicated CalRatio triggers available (JINST 8 (2013) P07015)

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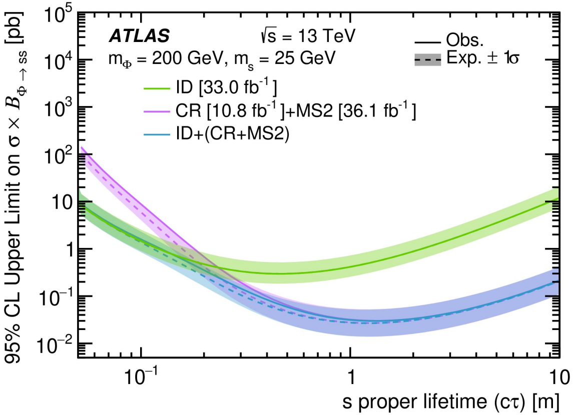
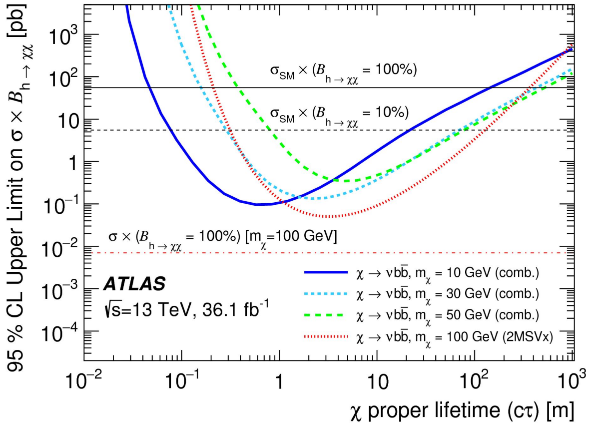
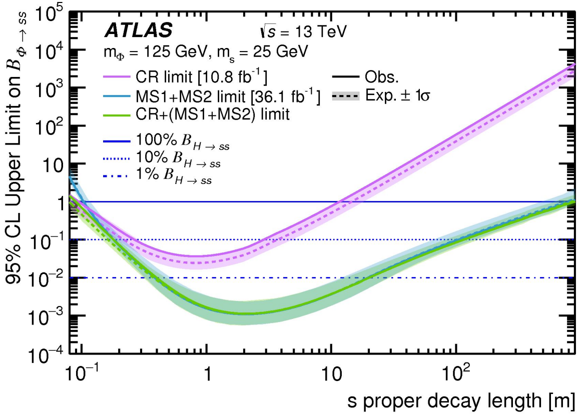
Displaced Vertices/Hadronic Jets

Phys. Rev. D 99, 052005 (2019)
Eur. Phys. J. C 79 (2019) 481
Phys. Rev. D 101, 052013 (2020)

- Search for pair-produced long-lived particles (LLP) produced by a Higgs boson / heavy scalar
  - ➥ Set limits on σ x B vs lifetime (cτ)







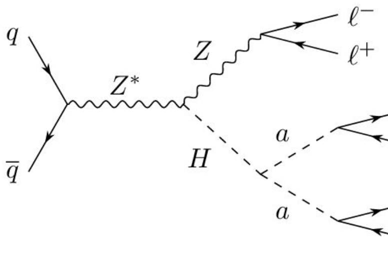
Phys. Rev. D 101, 052013 (2020)
- ➥ One LLP decays in ID, the other in MS
- ➥ Green = this search (ID)
- ➥ MS = Phys. Rev. D 99, 052005 (2019)
- ➥ CR = Eur. Phys. J. C 79 (2019) 481

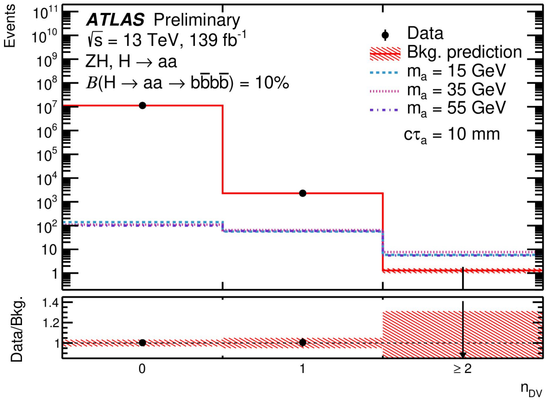
Phys. Rev. D 99, 052005 (2019)
- ➥ Two displaced vertices in the MS / one displaced vertex in the MS & some additional detector activity

Eur. Phys. J. C 79 (2019) 481
- ➥ LLPs decaying mainly in the HCal or at the outer edge of the ECal
- ➥ Use CalRatio

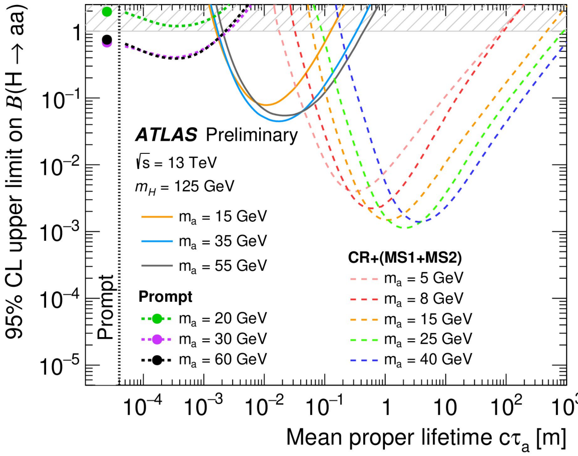
Displaced Vertices/Hadronic Jets

- Many BSM models predict exotic Higgs decays
- Can be difficult to trigger on decay products ∴ helps to look at associated production e.g. ZH mode
- Benchmark model: pseudoscalar with $15 < m_a < 55$ GeV & 10 mm $< c\tau_a <$ 1 m
- Signature: 2 leptons & 2 displaced vertices (DV) in the ID
- Dedicated Large Radius Tracking (LRT) ATL-PHYS-PUB-2017-014 & secondary vertex reconstruction optimised for LLPs ATL-PHYS-PUB-2019-013





- Zero events observed in signal region
- Limits set on BR(H→aa→bbbb)
  - ➥ Most stringent limits in this lifetime regime for $m_a < 40$ GeV



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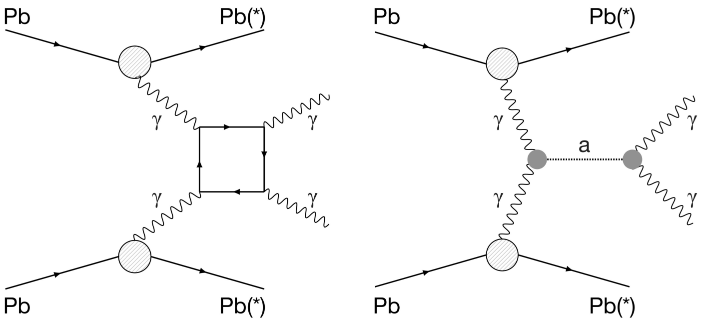
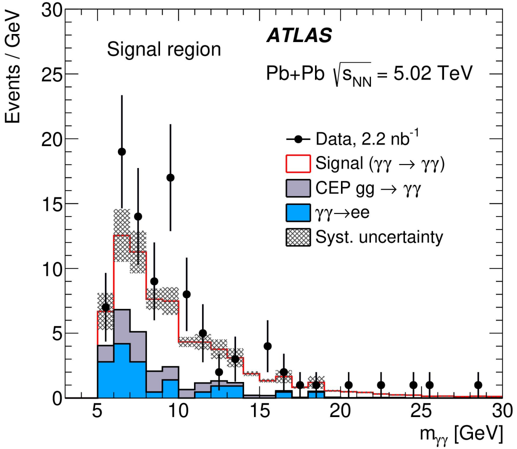
Axion-Like-Particles

- Relativistic Pb nuclei can be treated as a beam of quasi-real photons
- Photon flux associated with each nucleus scales with Z^2
  - Light-by-light scattering cross-section strongly enhanced w.r.t pp collisions
  - This scattering may arise from SM QED box diagram OR an ALP
  - Look for narrow diphoton resonances in EM calo, little ID activity

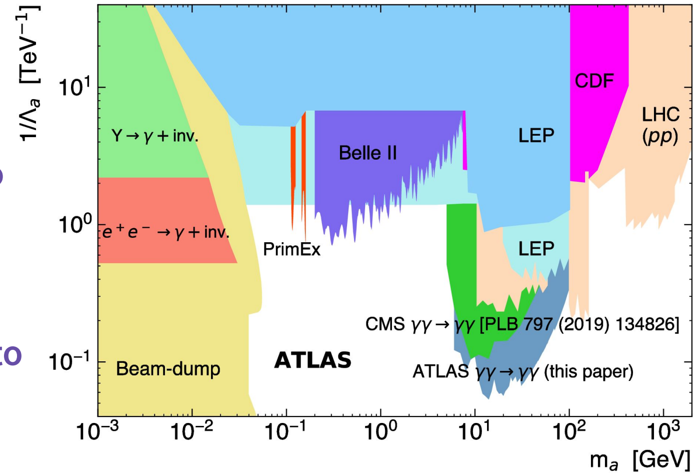




Measured mass spectrum used to set limits on ALP mass

Exclusion limits in ALP-photon coupling vs ALP mass compared to other experiments

Existing constraints from JHEP 12 (2017) 044



Conclusion

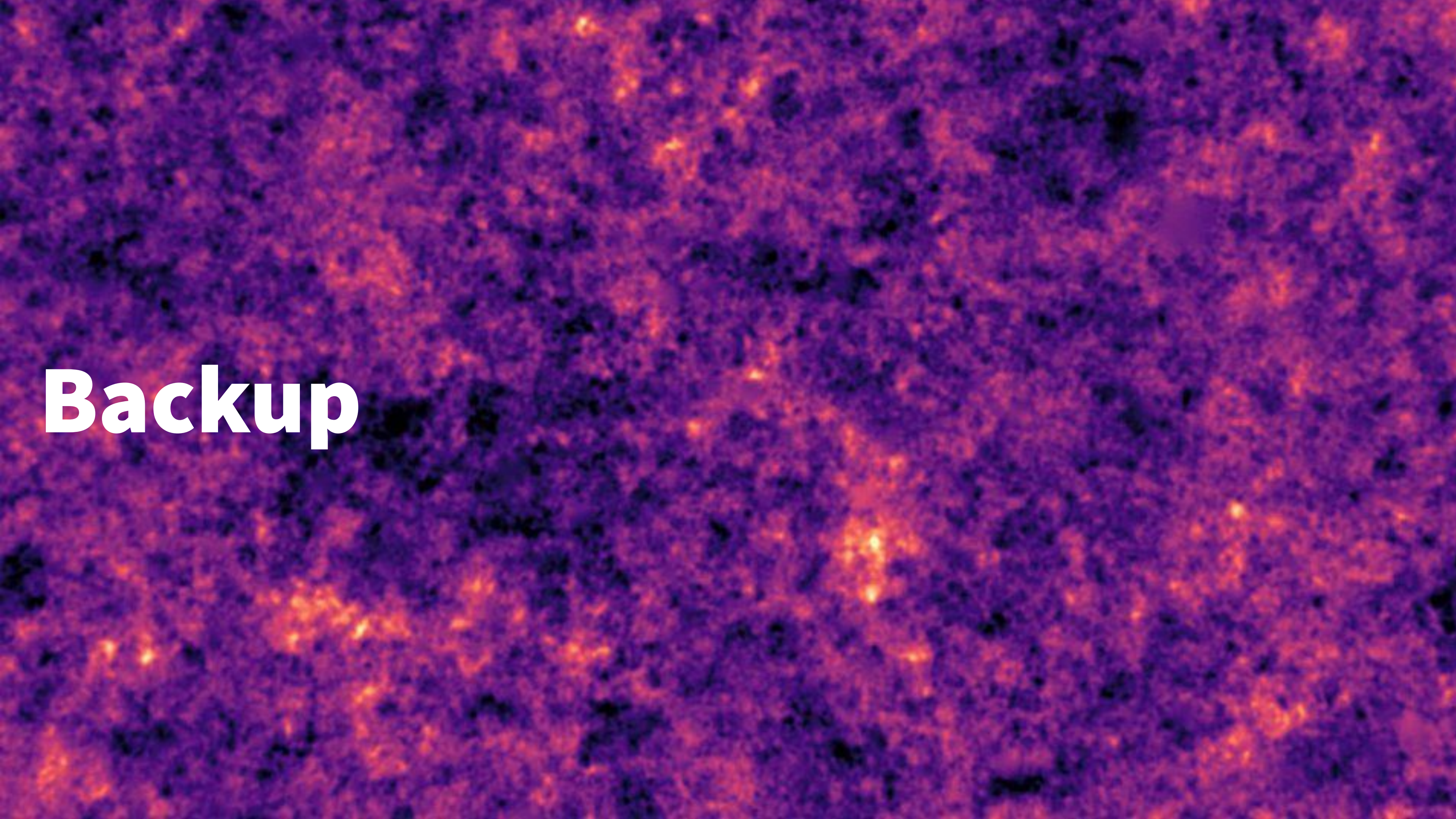
- Dark matter exists and dominates our universe, yet we do not know what is is comprised of
- There are multiple approaches currently used to detect DM, including producing it at colliders
- So far none of these experiments have found DM, but we continue to exclude parameter space in multiple theoretical frameworks
- The LHC will continue with its ever-growing DM search programme, with a new data taking period starting next year
  - ➥ Including many upgrades and increased luminosity!

Some further reading:

https://lpcc.web.cern.ch/content/lhc-dm-wg-dark-matter-searches-lhc

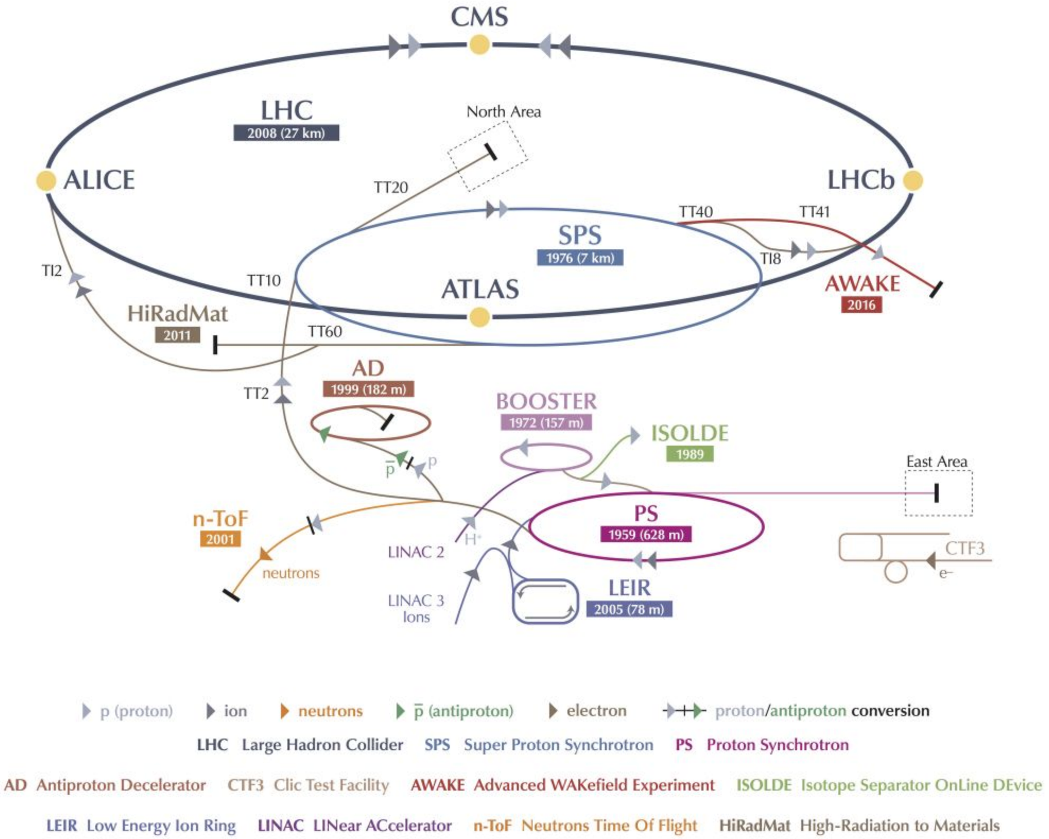
https://arxiv.org/pdf/1810.12238.pdf

https://arxiv.org/pdf/hep-ph/0404175.pdf

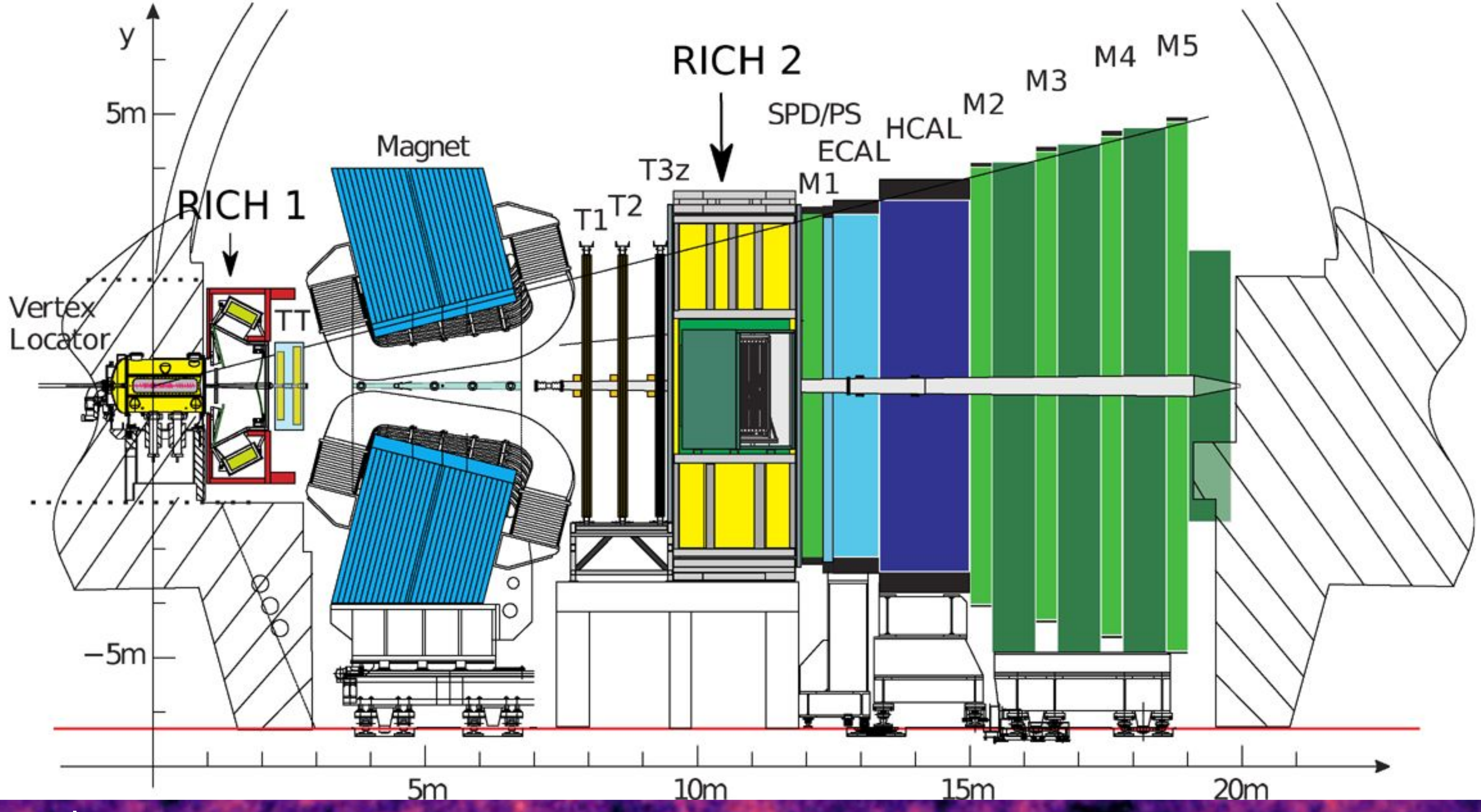


Backup

LHC Accelerator Complex

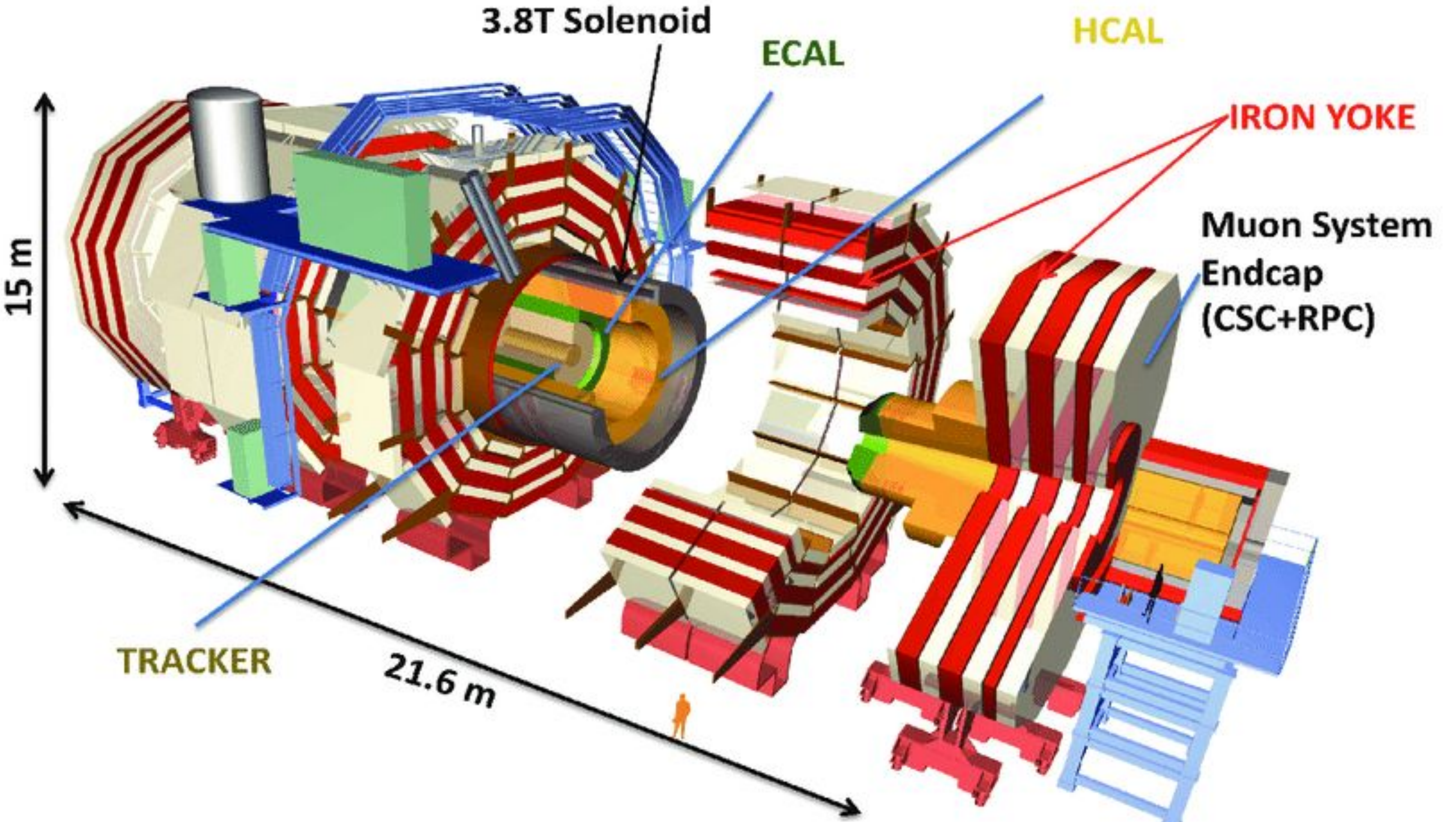


LHCb

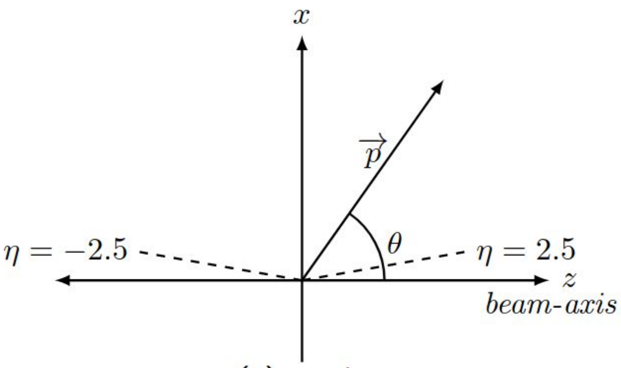


y
5m
−5m
5m
10m
15m
20m
Vertex
Locator
RICH 1
TT
Magnet
T1
T2
T3z
RICH 2
SPD/PS
ECAL
M1
HCAL
M2
M3
M4
M5

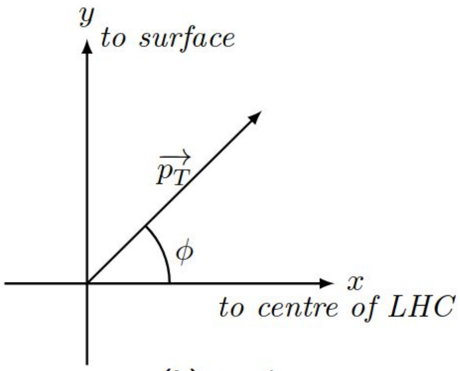
CMS


3.8T Solenoid
ECAL
HCAL
IRON YOKE
Muon System
Endcap
(CSC+RPC)
15 m
21.6 m
TRACKER

The LHC Coordinate System



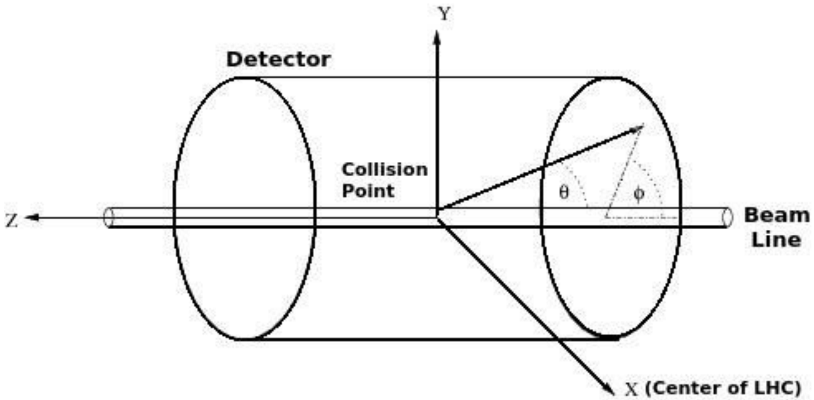
(a) xz-plane



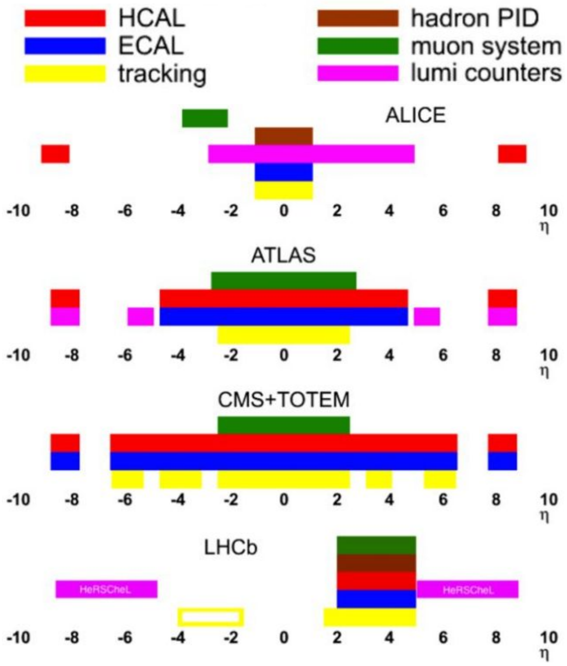
(b) xy-plane

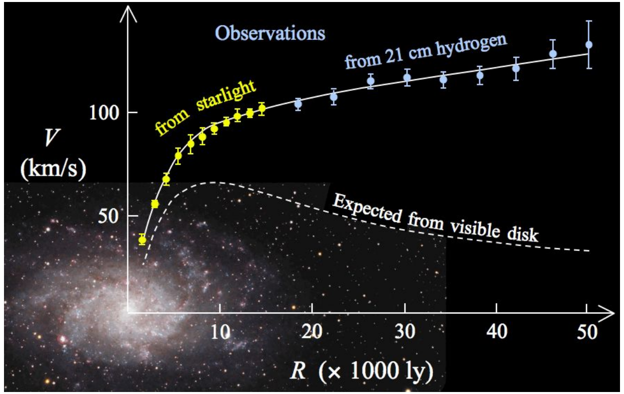
$$\eta = -\ln \tan\left(\frac{\theta}{2}\right)$$

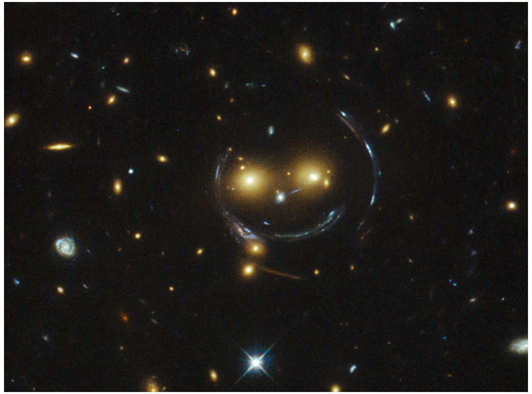
$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$



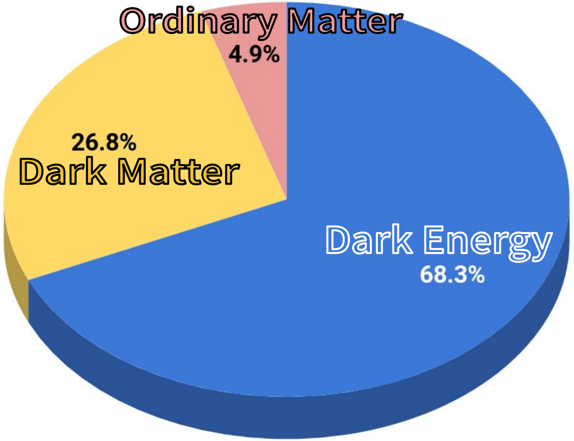
Coverage of LHC Detectors



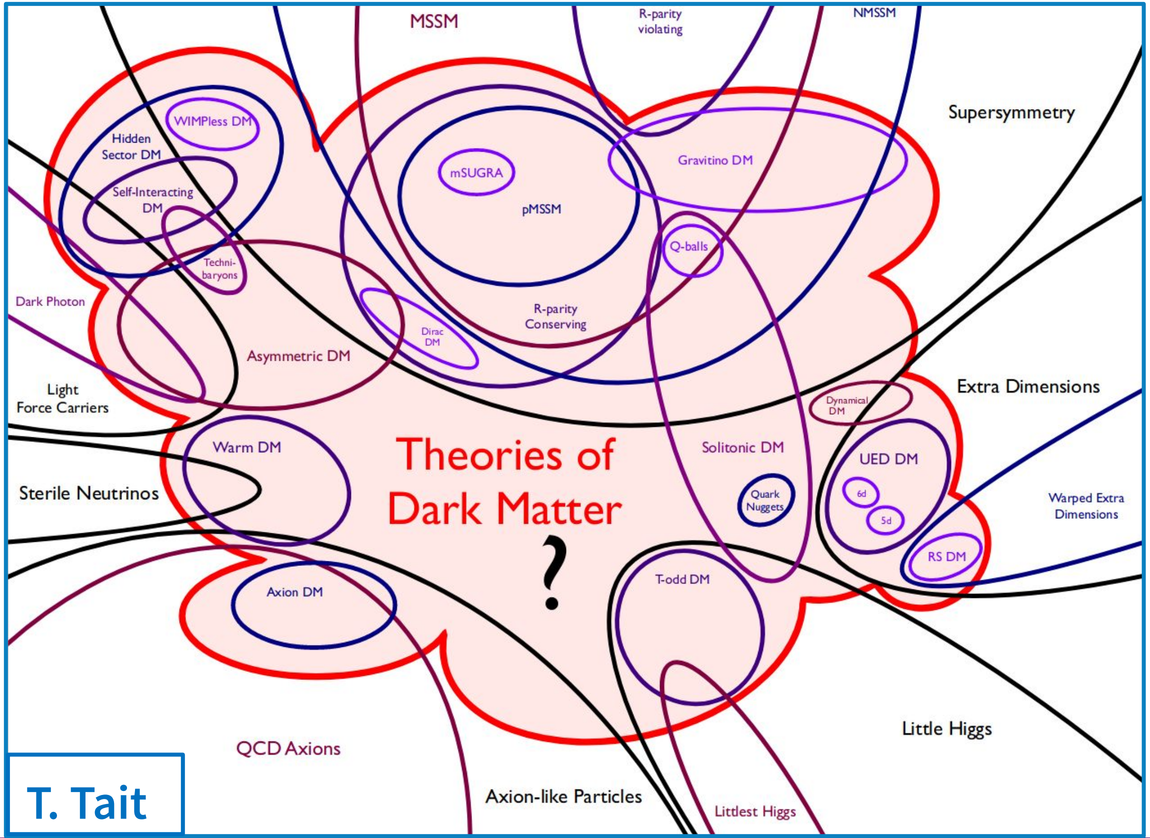




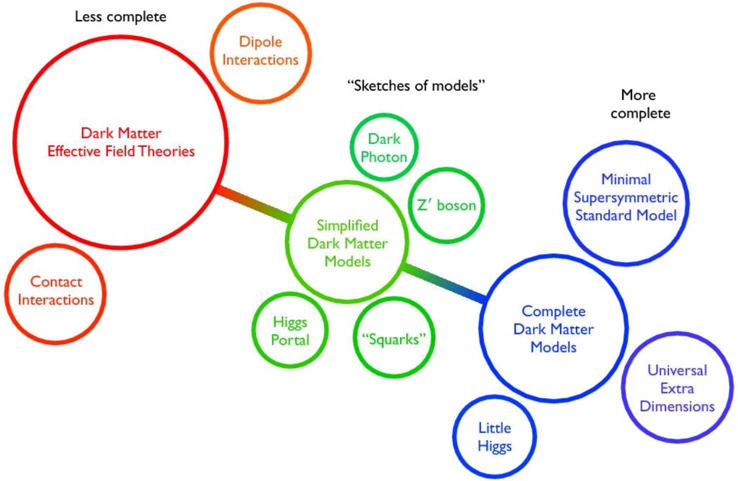
- A range of astrophysical measurements point to the existence of a non-baryonic form of matter (Phys.Rept.405:279-390,2005)
  - Galaxy rotation curves, gravitational lensing, colliding galaxy clusters…
- Weakly Interacting Massive Particles (WIMPs) are an attractive Dark Matter (DM) candidate, especially for the LHC
  - Lead to the correct relic density of non-relativistic matter
  - Non-gravitational interactions with the SM ∴ could be seen at colliders!!



Theoretical Landscape of Dark Matter



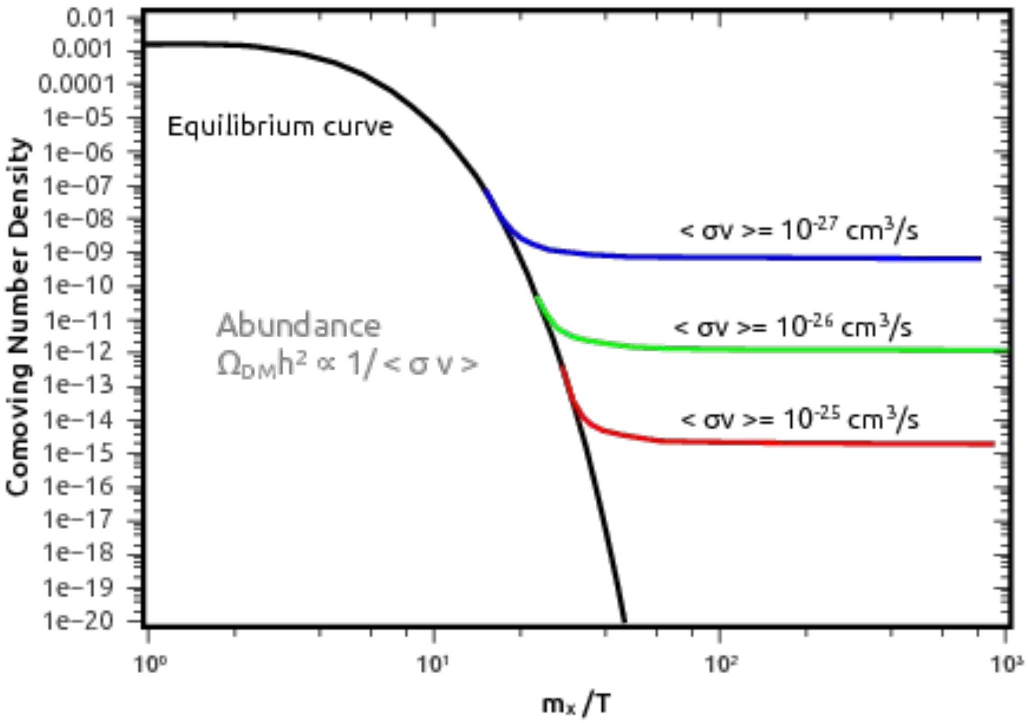
T. Tait



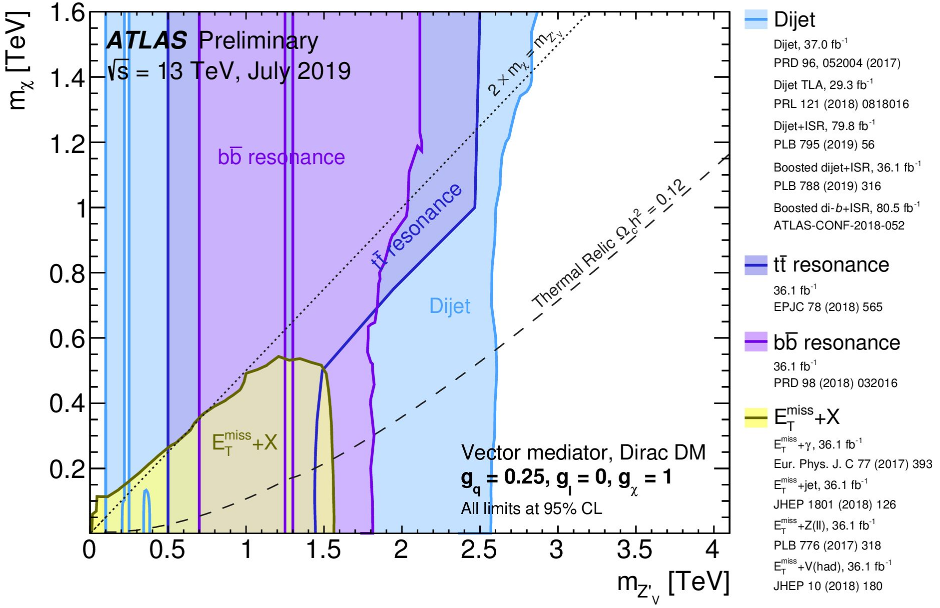
Phys. Dark Univ. 9-10 (2015) 8-23

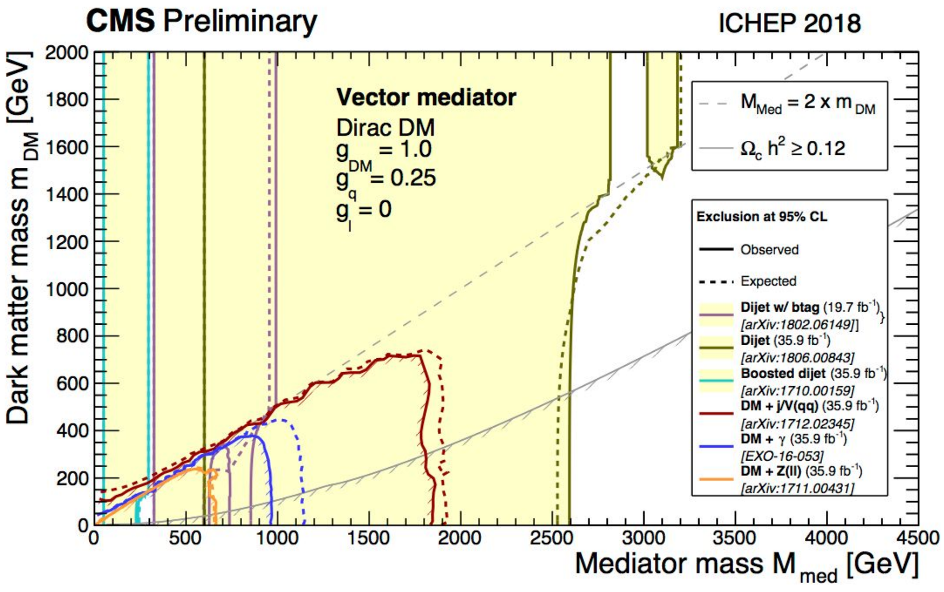
Why WIMPs?

- For typical weak-scale self-annihilation cross sections, $\sigma \sim G_F^2 T^2$ (with $T \sim m_\chi /20$), and EW mass scales, $m_\chi \sim 200$ GeV, the thermal relic density matches the observed cosmological density.
- Independent theoretical reasons (e.g. the hierarchy problem) lead us to expect new physics at this scale.
    - “WIMP miracle”



Vector mediator, Dirac DM, $g_\chi = 1$, $g_q = 0.25$, $g_l = 0$



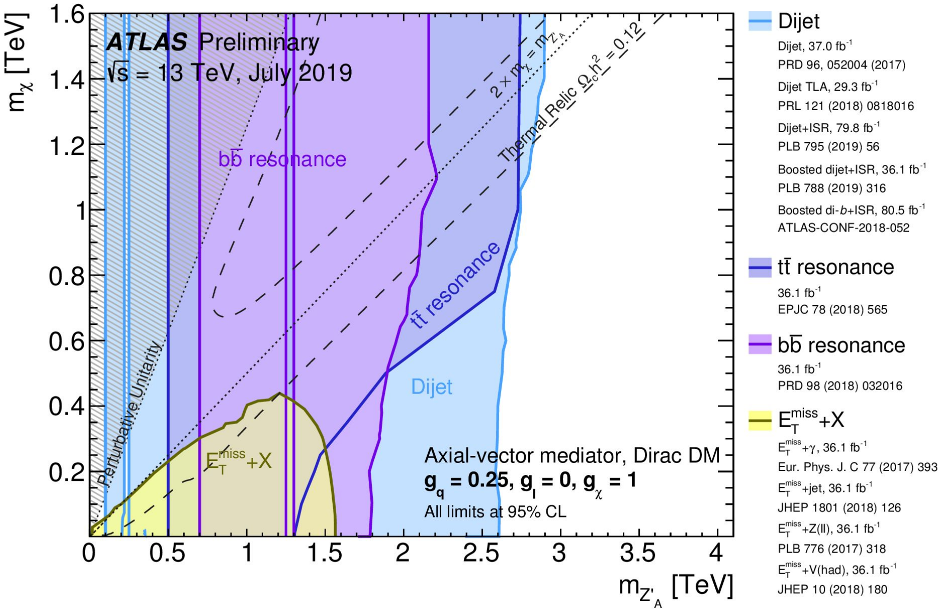


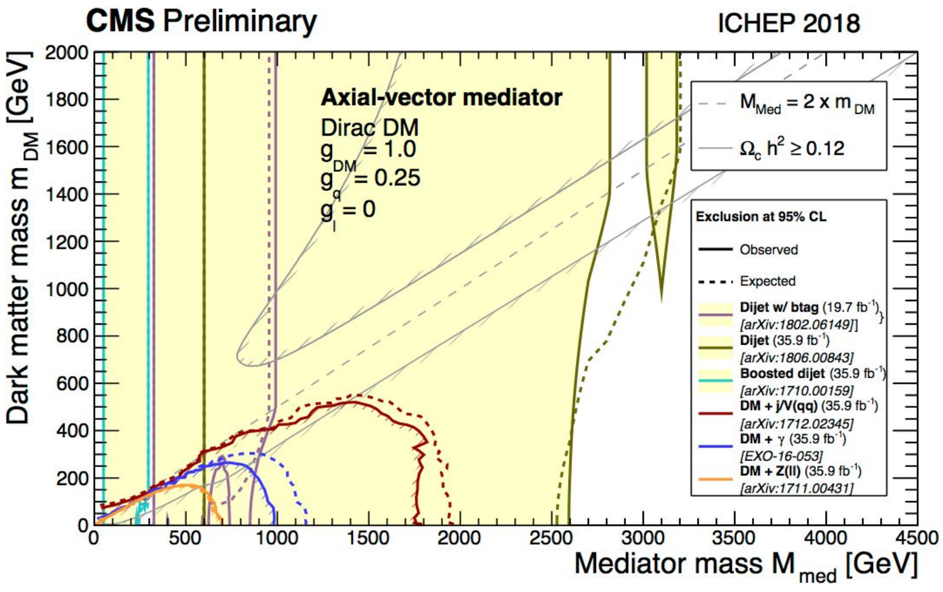
m_{med} ~ 2.5 TeV reach from mediator searches

Combined Results

ATLAS: JHEP 05 (2019) 142
CMS: ICHEP 2018

Axial-vector mediator, Dirac DM, $g_X = 1$, $g_q = 0.25$, $g_l = 0$

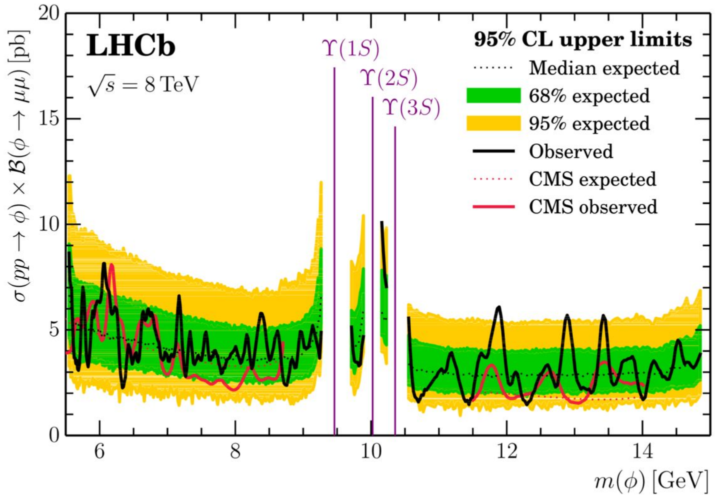




LHCb Dark Boson Searches

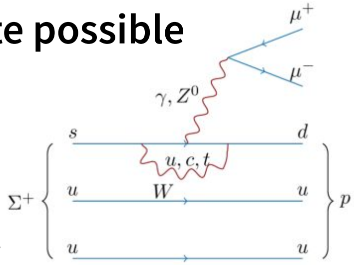
$pp \to \phi \to \mu^+\mu^-$ In *gg* fusion JHEP 09 (2018) 147

- Narrow resonance search in Υ mass region
- Analysis designed is model-independent
  - Independent of production mech, spin
- First limits set in previously unexplored $8.7 < m(\phi) < 11.5$ GeV

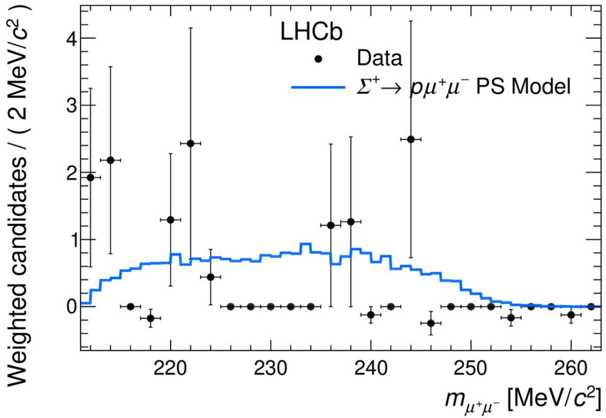


In $\Sigma^+ \to p\mu^+\mu^-$ PRL 120, 221803 (2018)

- Narrow range of $\mu\mu$ masses from 3 candidates observed at HyperCP indicate possible intermediate particle X^0

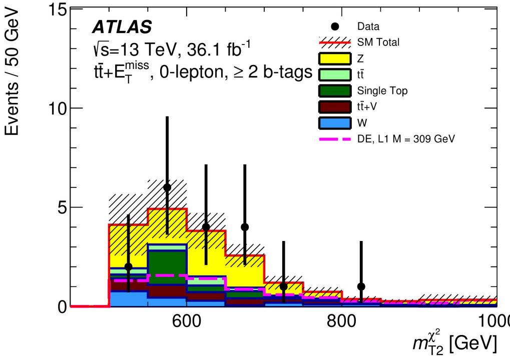


- LHCb observes the Σ^+ decay
- BUT no significant $m_{\mu\mu}$ *peak!*

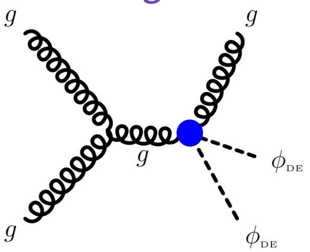


Dark Energy

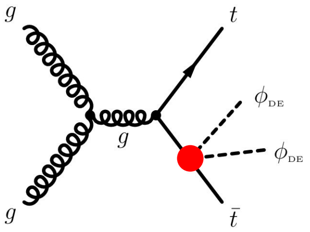
JHEP 05 (2019) 142



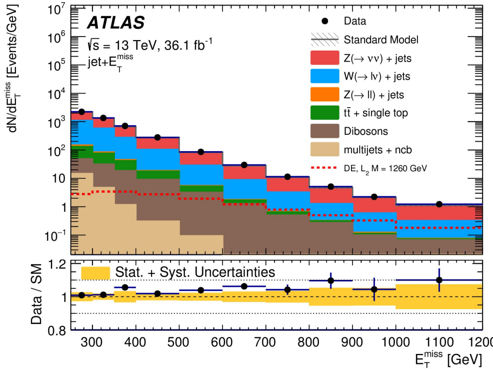
- Horndeski model in EFT
  - Introduce DM scalar, creating MET signature in colliders

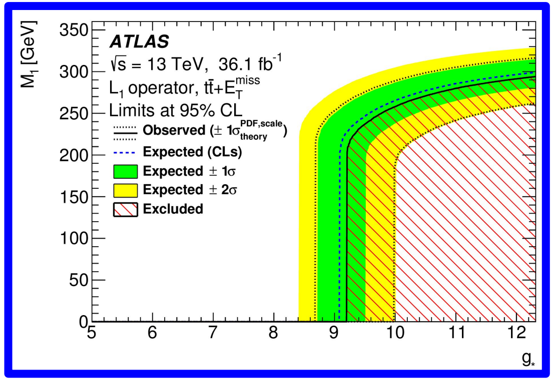


Disformal coupling $\mathcal{L}_1$

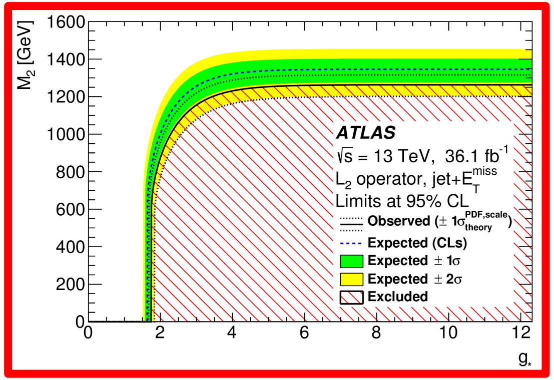


Conformal coupling $\mathcal{L}_2$





- Limits set on suppression scale (M) for least suppressed operators:
  - $\mathcal{L}_1$: coupling proportional to fermion mass, tt̄+MET
  - $\mathcal{L}_2$: coupling scales with momentum transfer, jet+MET
- g_* = effective coupling, UV completion



Dark Energy

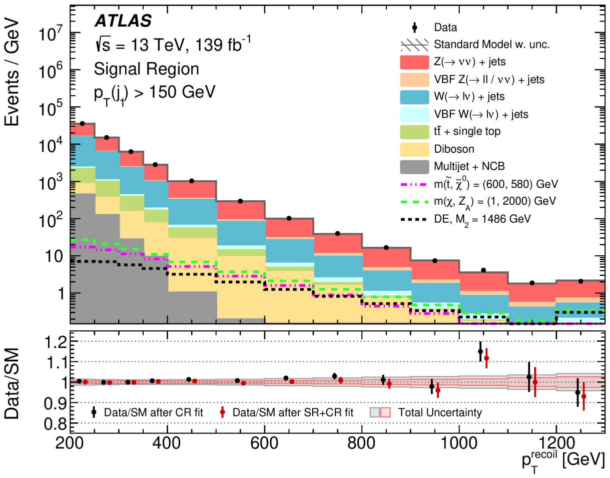
- New mono-jet results with full run-2 data
- Set 95% CL limits on suppression scale
  - Horndeski DE with $m_\phi = 0.1$ GeV, $c_{i\neq 2} = 0$, $c_2 = 1$
  - Suppression scales $M_2 \lesssim 1.5$ TeV excluded

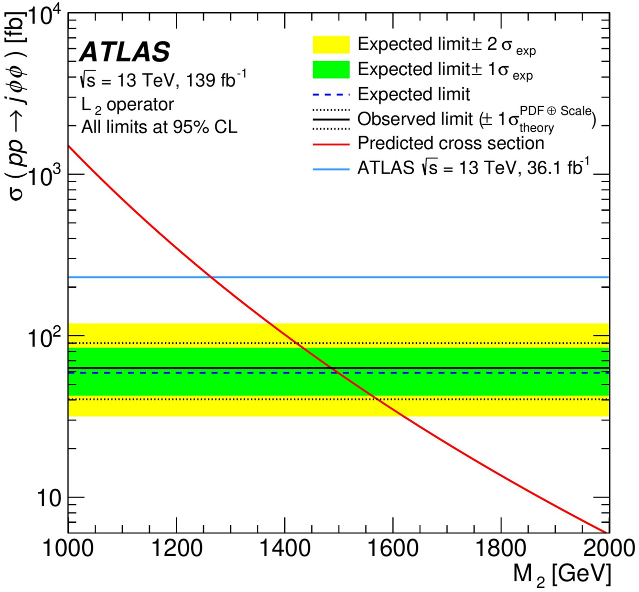
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{i=1}^{9} c_i \mathcal{L}_i = \mathcal{L}_{\mathrm{SM}} + \sum_{i=1}^{9} \frac{c_i}{M_i^{d-4}} O_i^{(d)},$$

d = operator dimension, c_i = Wilson coefficients, M = energy scale

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

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

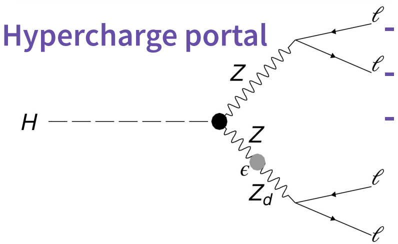




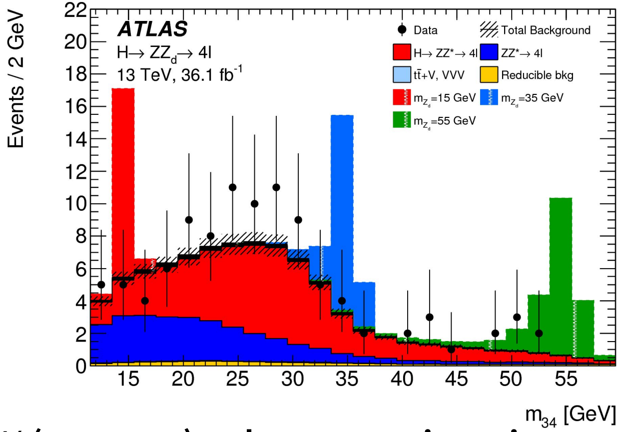
Exotic Higgs Decays

Higgs decays to 4 leptons via PROMPTLY decaying bosons

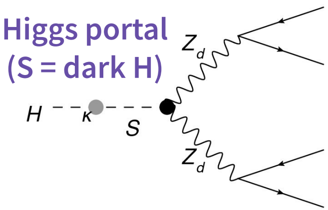
Hypercharge portal



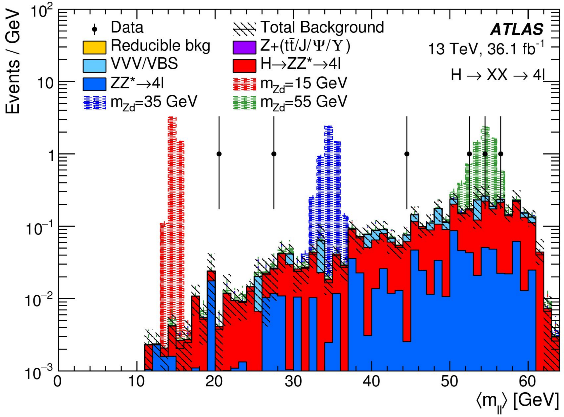
- $H \to ZX \to 4e/4\mu/2e2\mu$
- SR: $m_{4\ell} \in [115, 130]$ GeV
- Constraints on kinetic mixing (ε) and mass-mixing (δ) parameter



Higgs portal (S = dark H)



- High mass: $H \to XX \to 4e/4\mu/2e2\mu$
  $15 < m_{ZD} < 62.5$ GeV
- Low mass: $H \to 4\mu$
  $1 < m_{ZD} < 15$ GeV
- Veto at quarkonia mass resonances
- Constraints on Higgs mixing parameter (κ)

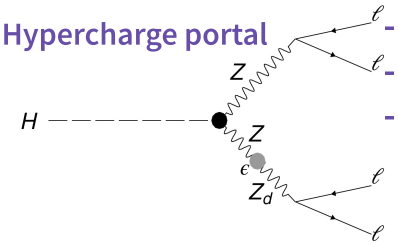


$\langle m_{\ell\ell} \rangle = ½(m_{12}+m_{34})$, where m_{xy} = invariant masses of dileptons in a quadruplet and $|m_{12} - m_Z| < |m_{34} - m_Z|$

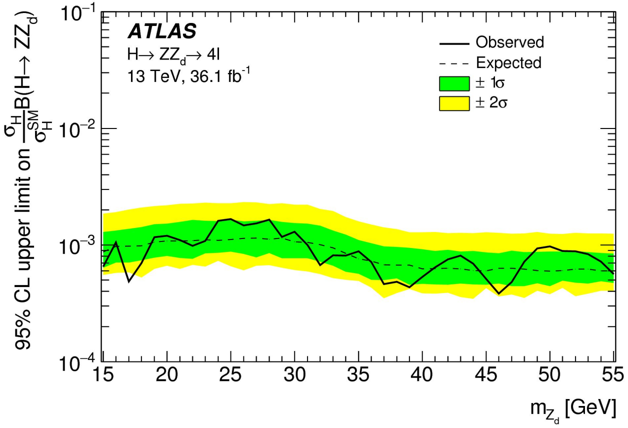
Exotic Higgs Decays

Higgs decays to 4 leptons via PROMPTLY decaying bosons

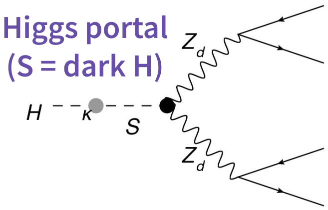
Hypercharge portal



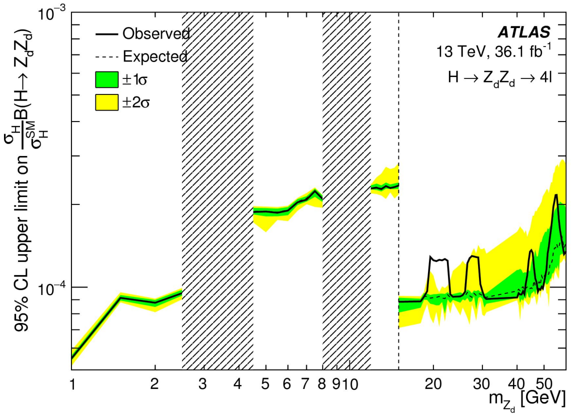
- $H \rightarrow ZX \rightarrow 4e/4\mu/2e2\mu$
- SR: $m_{4\ell} \in [115, 130]$ GeV
- Constraints on kinetic mixing (ε) and mass-mixing (δ) parameter



Higgs portal (S = dark H)



- High mass: $H \rightarrow XX \rightarrow 4e/4\mu/2e2\mu$
  $15 < m_{ZD} < 62.5$ GeV
- Low mass: $H \rightarrow 4\mu$
  $1 < m_{ZD} < 15$ GeV
- Veto at quarkonia mass resonances
- Constraints on Higgs mixing parameter (κ)



$\langle m_{\ell\ell} \rangle = \frac{1}{2}(m_{12}+m_{34})$, where m_{xy} = invariant masses of dileptons in a quadruplet and $|m_{12} - m_Z| < |m_{34} - m_Z|$

Heavy Neutral Leptons

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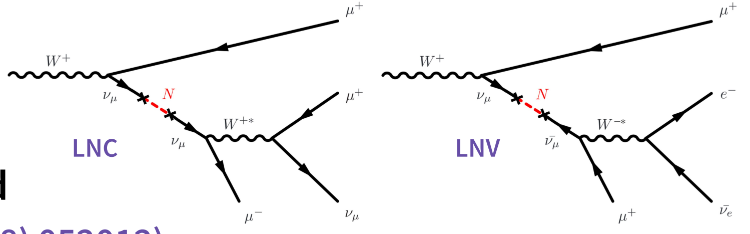
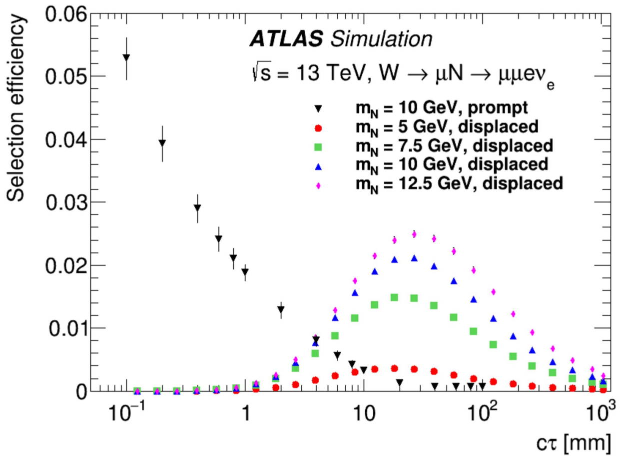
- Postulate new right-handed neutrinos with Majorana masses below the EW scale
  - ➡ Explain neutrino masses, matter-antimatter asymmetry, DM…
  - ➡ Decays may be lepton number violating (LNV) or conserving (LNC), depending on nature of neutrinos
- Both prompt & displaced leptonic decay signatures studied
  - ➡ Displaced vertex reconstruction algorithm (Phys. Rev. D 97 (2018) 052012)





➡ Set limits on mass and coupling strength for prompt & displaced

➡ Displaced limit contour oblique ellipse approximately corresponds to HNL proper decay lengths in the range 1-30 mm