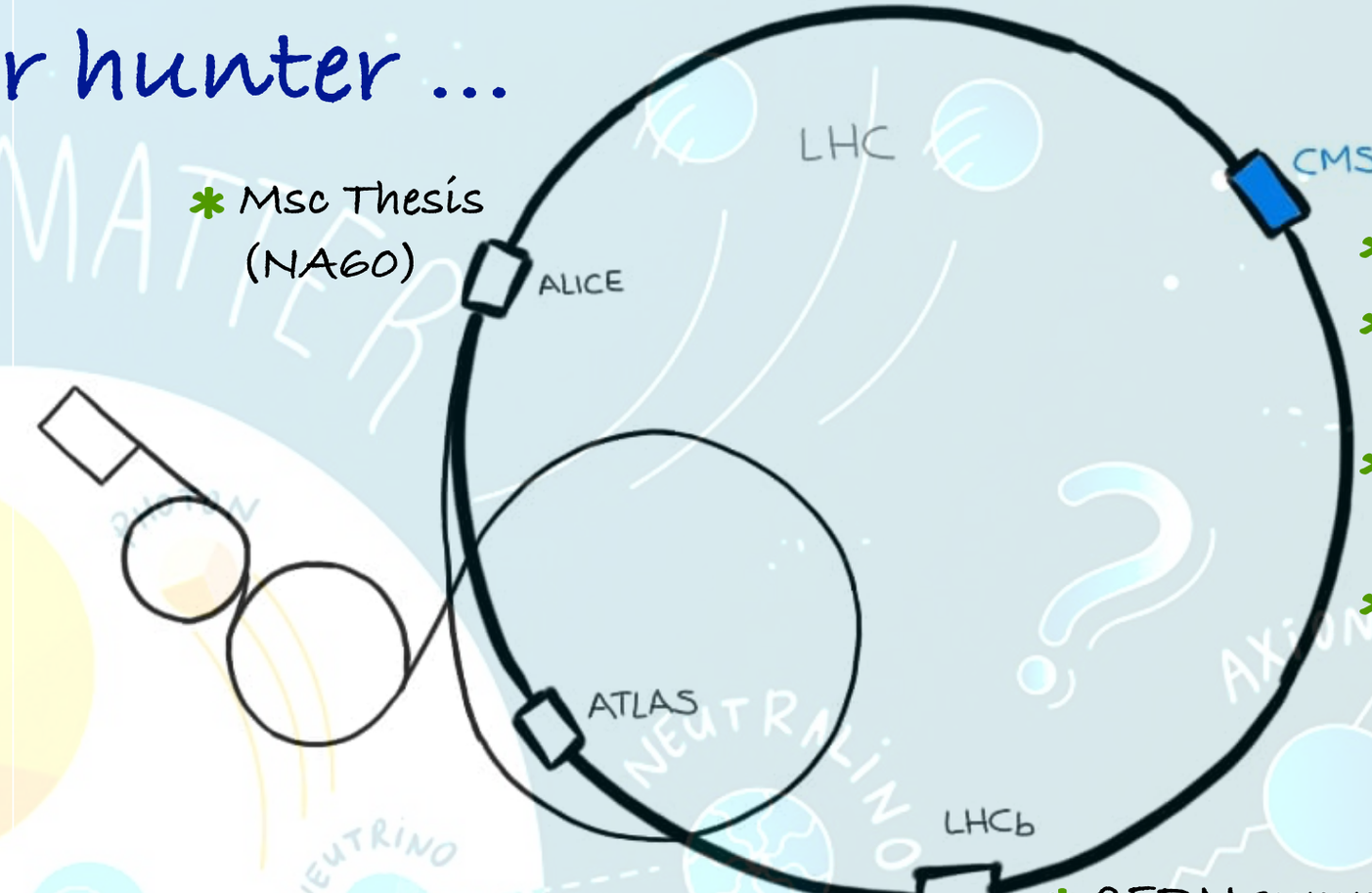
Dark Matter and BSM physics: recipe to search it at colliders

Deborah Pinna
(University of Wisconsin-Madison)

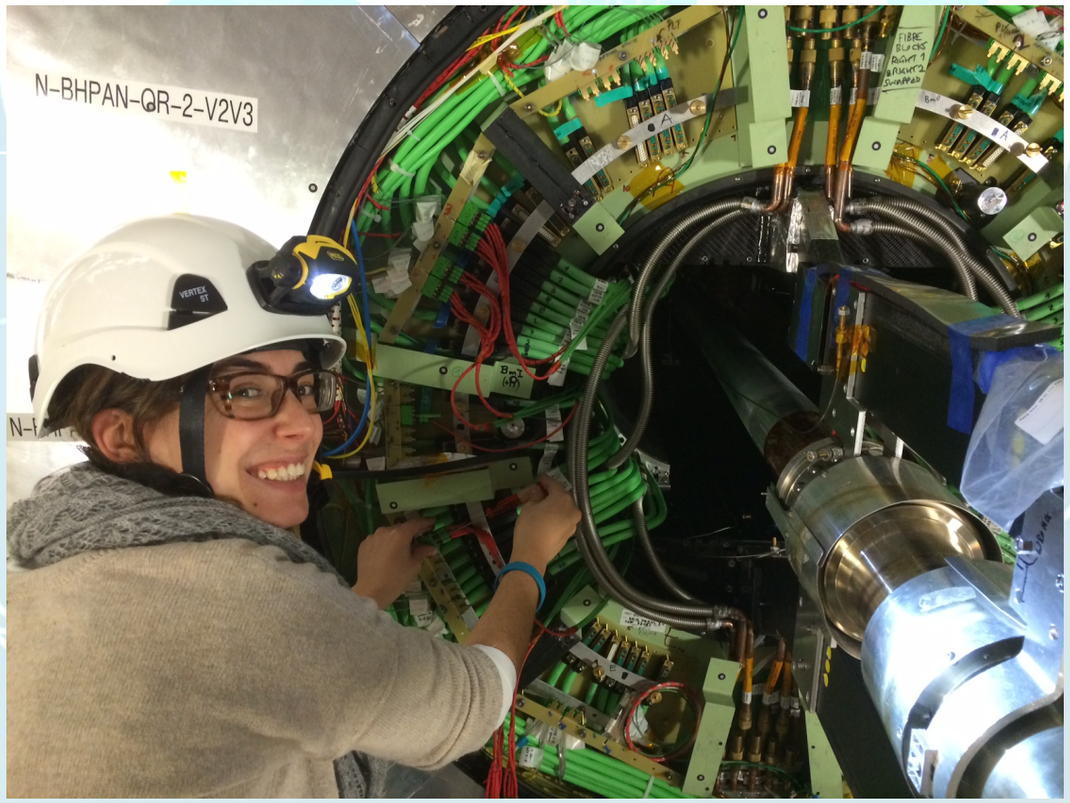
HEP Colloquia 2025

Cagliari 22 Sept 2025

Dark matter hunter ...



* Msc Thesis (NA60)
* Scientist at UW
* Post-doc at Boston University
* PhD at University of Zurich
* Erasmus at ETH Zurich
* CERN summer student 2010



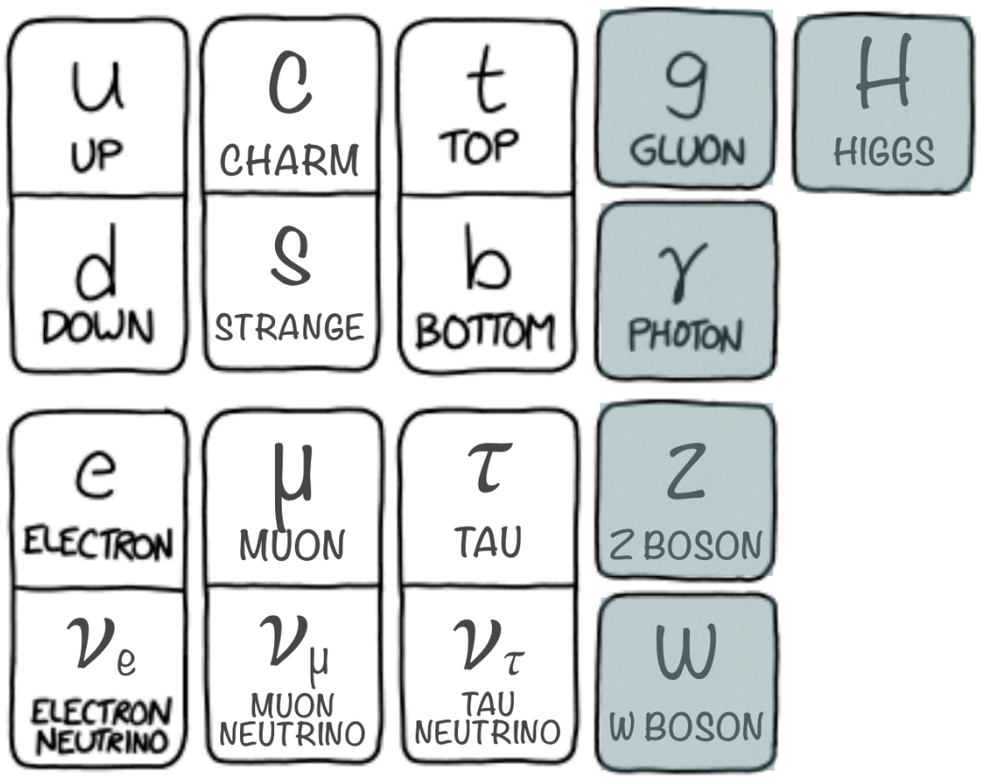
Deborah Pinna

* Scientist at University of Wisconsin-Madison
* PhD at University of Zurich
* Msc and Bsc: Universita' di Cagliari

Research

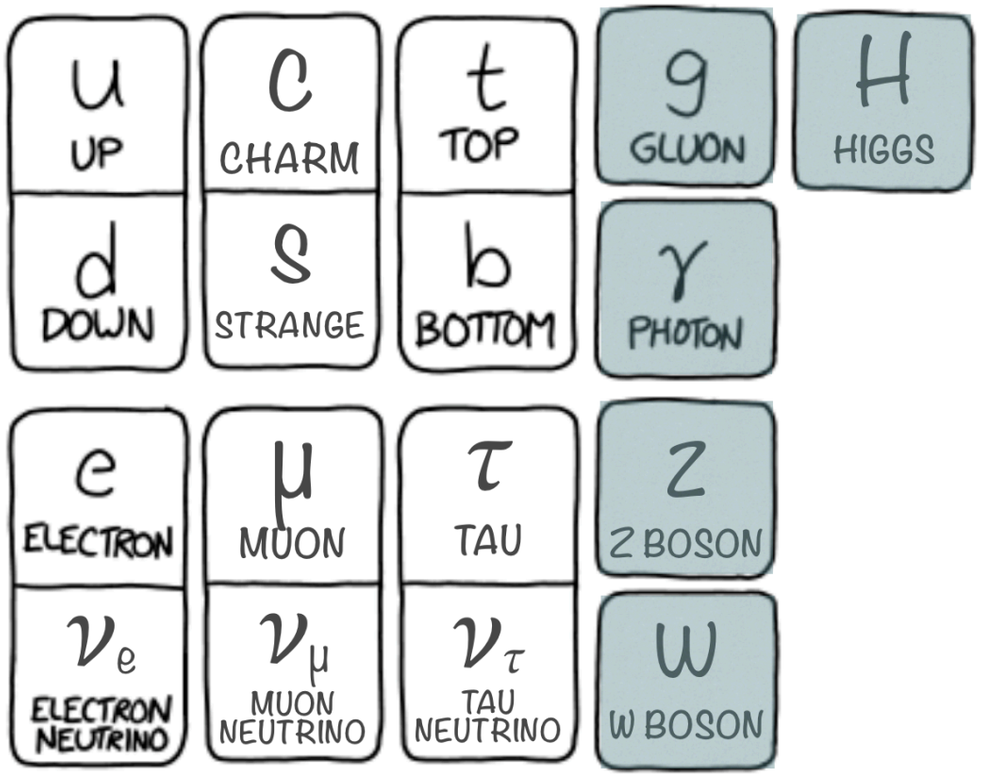
* Dark matter hunter :), new physics with top quarks and di-Higgs signatures

The Standard Model …



- Remarkable accuracy and predictive power
- LHC/CMS extended sensitivity beyond expectations
  - ~~H~~ couplings: precision already <10% for most couplings with ~5% of expected HL-LHC dataset
  - ~~HH~~: end of Run2, we reached the precision that HL-LHC studies predicted for 1000 fb^{-1}

The Standard Model … how do we modify it?



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Dark sector

Dark matter

New heavy resonances

Leptoquarks

Long lived particles

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  - direct searches for BSM particles coupling to SM sector
  - indirect searches from deviations between precision measurements and SM

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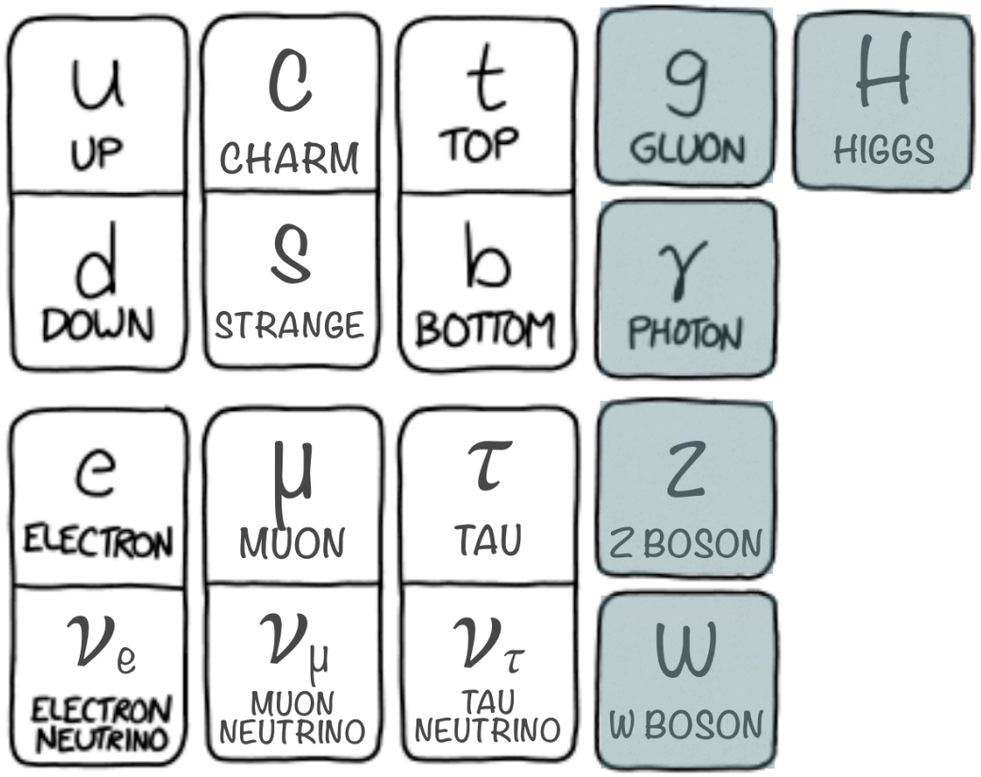

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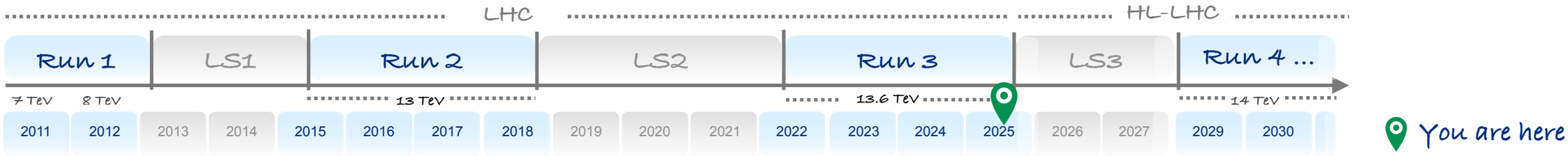
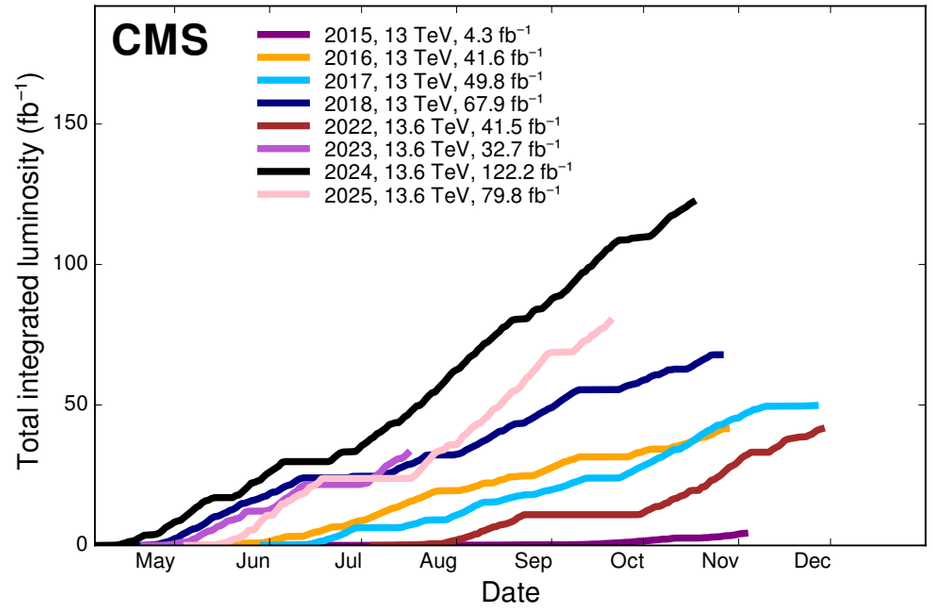
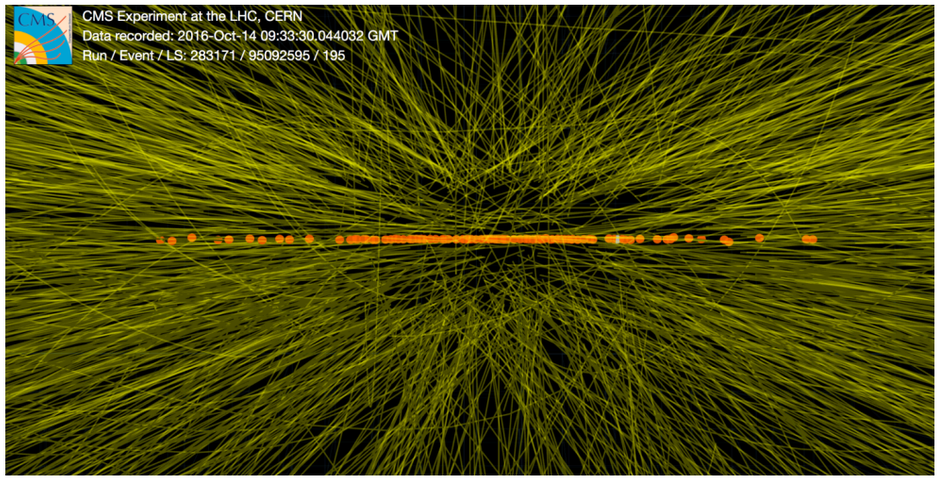
(biased) focus on dark matter and CMS

The journey towards new physics

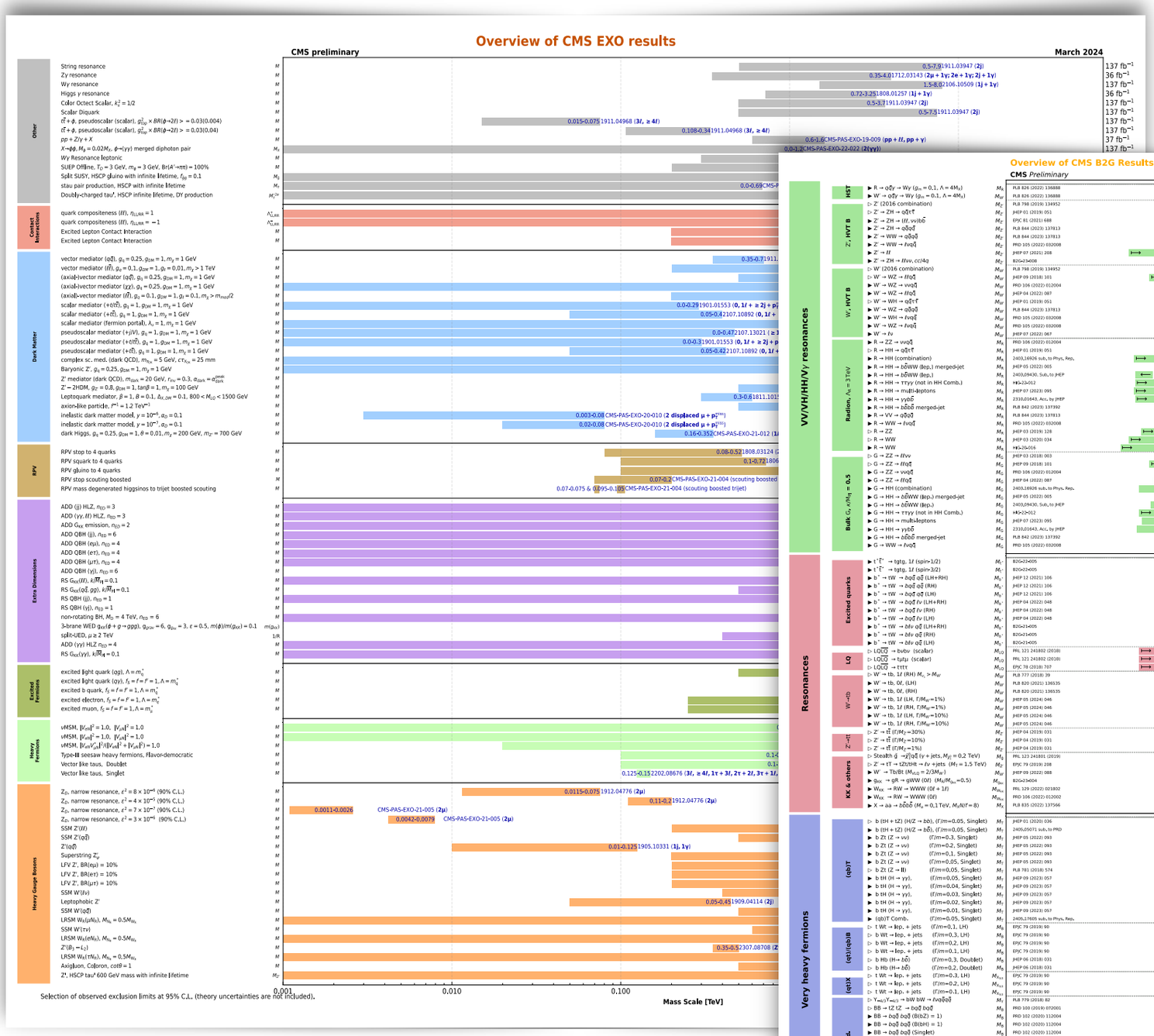


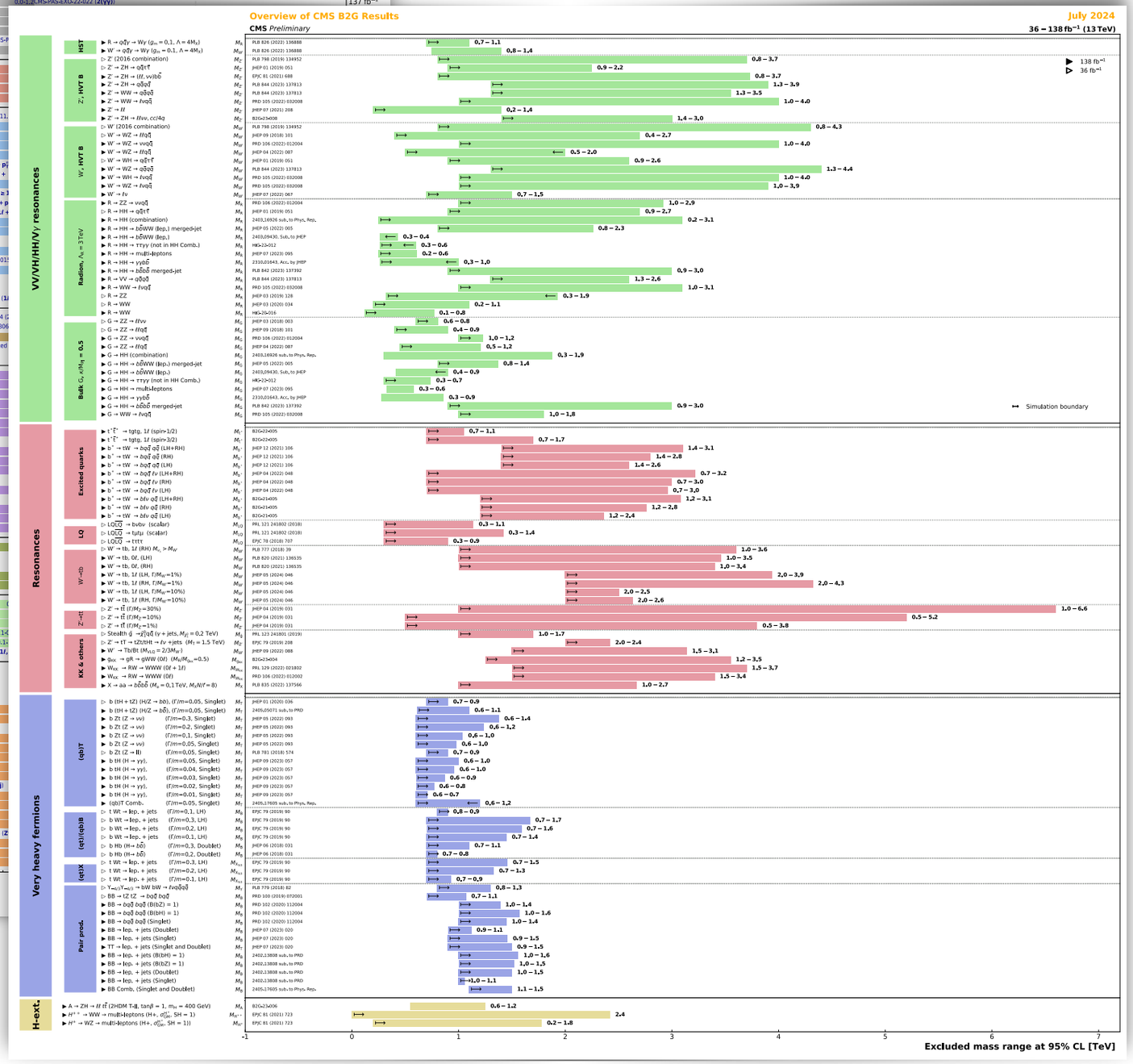
- LHC/CMS sensitivity beyond expectations
  - first phase of LHC program to be completed soon
  - already >300 fb-1 (Run 2 + Run 3)
- … but the future is already now
  - pushing the detector beyond its limits
  - recording up to 63 simultaneous collisions/event
    (2.5x CMS design, 45% of HL-LHC)
  - collecting data @7 kHz
    (70% of HL-LHC, 7x Run 2 normal operations)
- Pushing physics boundaries across multiple frontiers
  - searches, precision-, flavour-physics, …
- A key technology driver
  - multiple data-taking strategies, artificial Intelligence, …





Rich new physics program at CMS

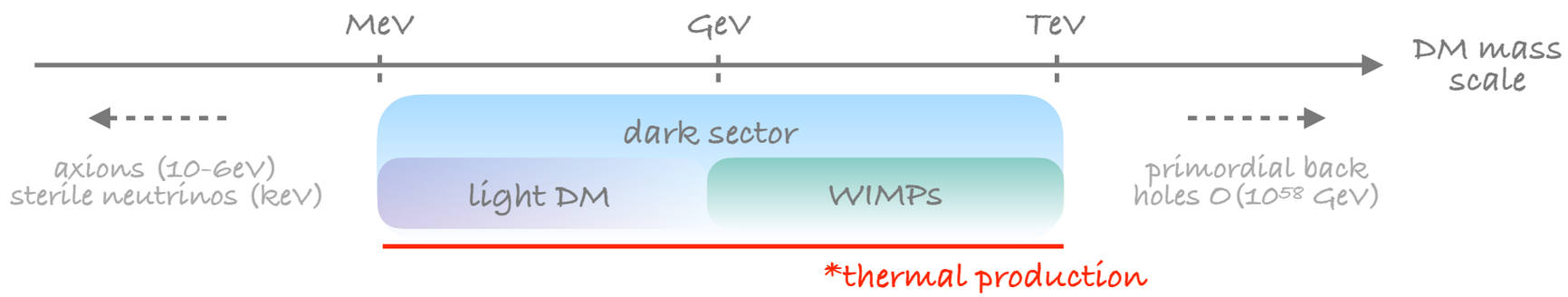




Hunt for dark matter - identikit

DM evidence

- Empirical evidence of DM from astrophysical observations at different scales
  - interacts gravitationally, long lived and neutral
  - no information about its nature (what DM could be?)
- Only measured quantitative property is DM mass abundance
  - very large set of possible masses can account for observed relic density



DM production

- DM must have some non-gravitational interactions with SM particles

MeV-GeV:

- avoid DM overproduction with new mediator below weak scale
- suff. small SM coupling for consistency with collider searches

GeV-TeV:

- WIMP models, DM has small couplings to SM particles
- most minimal scenario, one DM and one mediator

* Dark sector: DM and mediator part of a separate "dark SM" (can be fairly minimal or composite)

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assume interactions with SM

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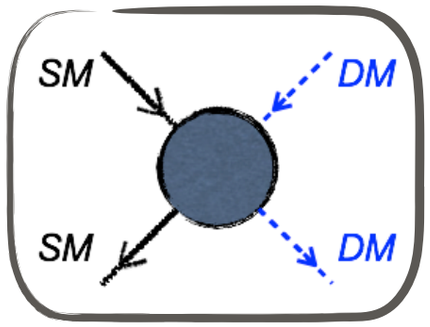

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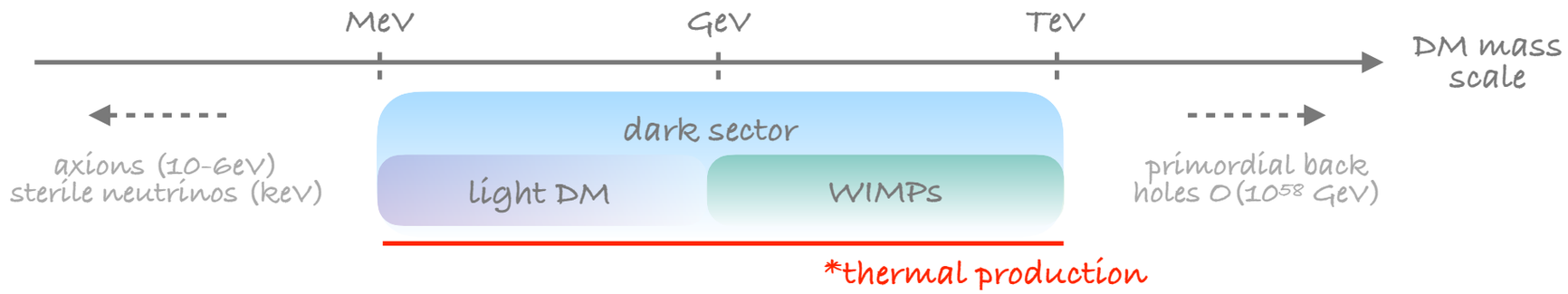

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GeV-TeV:

- extensions of the SM at the GeV-TeV scale

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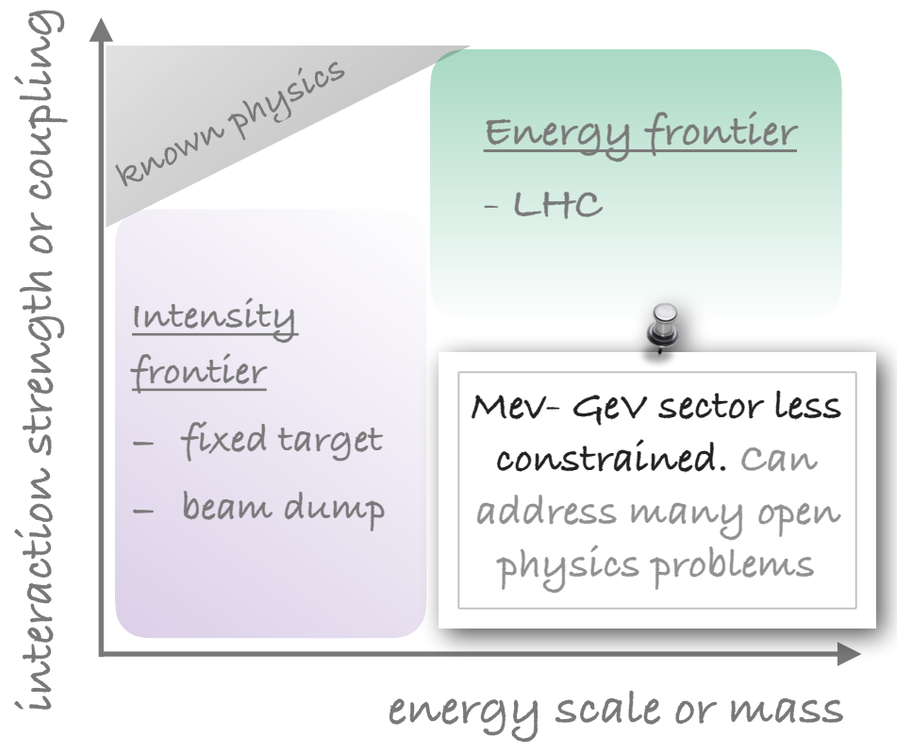
✱ Dark sector: could be heavy, light, and/or long-lived



▶ Assuming DM-SM interactions enables different searches

- *indirect detection*, products from DM annihilation
- *direct detection*, nuclear recoil from DM-nuclei scattering
- *colliders*: DM production

Complementarity between experiments essential!

eg. info about lifetime if DM discovered at colliders (~10^{-7}s), particle properties compared with cosmological constraints

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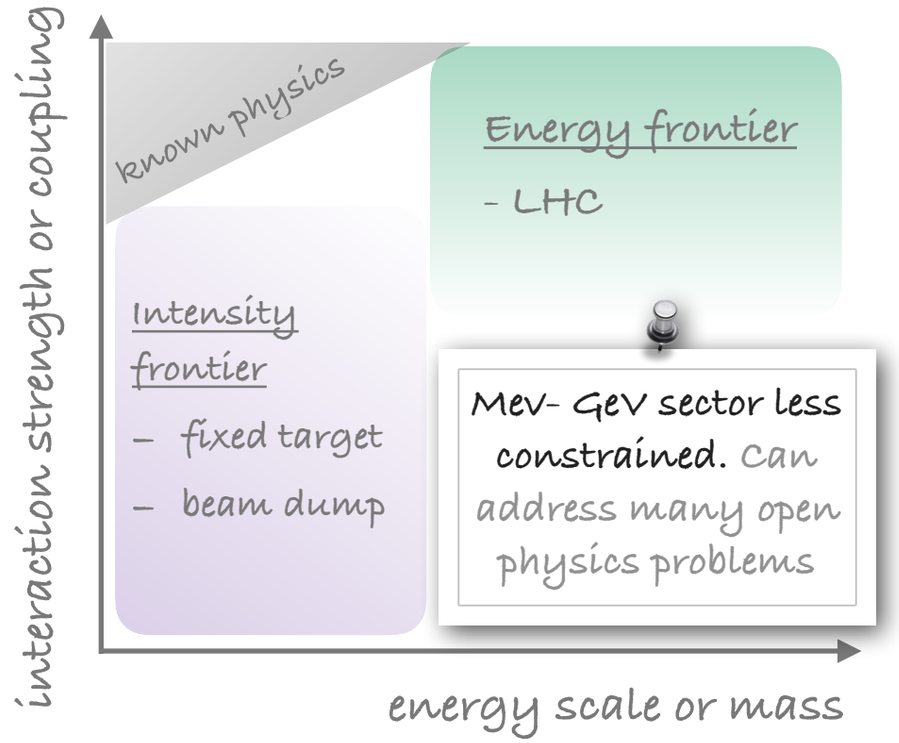

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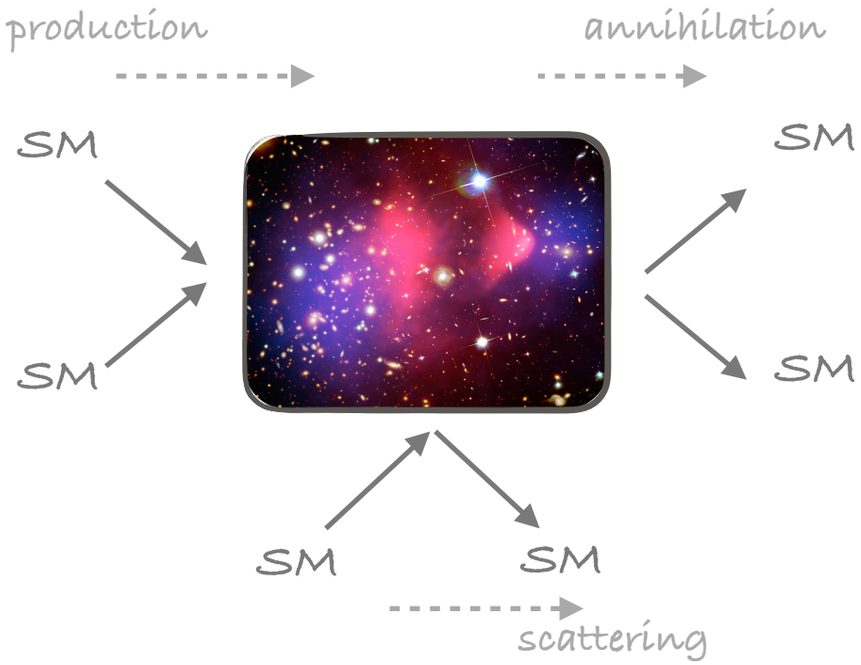

Complementarity between experiments essential!

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Hunt for dark matter - investigation tactics

- We do not have information about the DM nature, how to hunt it?
  - remain very general and make very **little assumptions**, eg."is it a 2D shape?"
  - more assumptions and tests **more specific models**, eg."is it a 2D shape, yellow color and with only 90° angles?"

Hunt for dark matter - phenomenology

Intensity frontiers: MeV-GeV

- small couplings to SM, challenging to detect but guide to relevant interactions
  - ✱ vector: dark vector boson (dark photon) mediator that mixes with SM photon
  - ✱ scalar: dark Higgs mediator, mixing with SM Higgs, which leads to couplings to fermions
  - ✱ fermion: heavy neutral lepton (HNL) mediator, that can mix with SM neutrinos
  - ✱ pseudo-scalar: axion-like particle can have couplings to SM fermions or bosons

Energy frontiers: GeV-TeV

- one new mediator, one DM particle
  - Higgs boson could be the SM-DM mediator
- limited parameters set (m_{DM}, m_{med}, g_q, g_{DM})

✳ interaction type define most sensitive signatures

Signatures

- invisible: production of DM through the decay of a portal/SM particles
- visible: dark mediator particles can decay back to SM particles (especially if sector's lightest state)
- displaced (long-lived): production of dark sector particle with significant lifetime that decays visibly to SM

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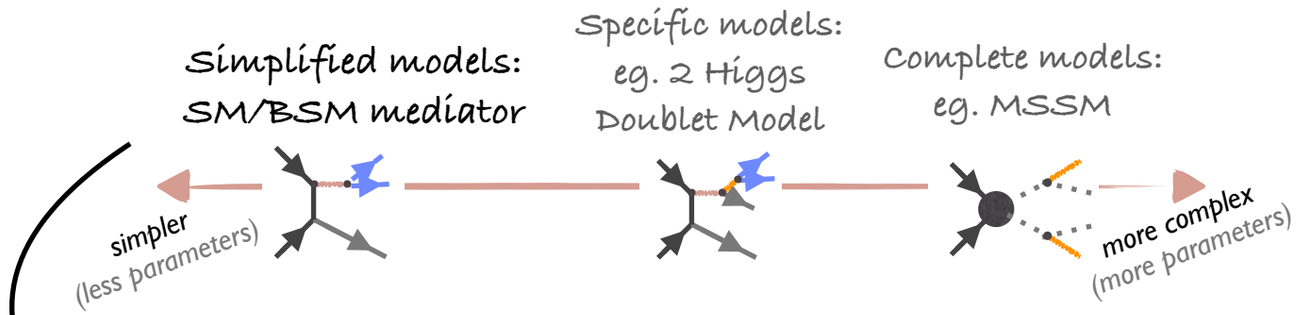

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	vector	axial-vector
spin-1	$g_q \sum_q V_\mu \bar{q}\gamma^\mu q$	$g_q \sum_q A_\mu \bar{q}\gamma^\mu\gamma^5 q$
spin-0	scalar: $g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$	pseudoscalar: $g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f}\gamma^5 f$

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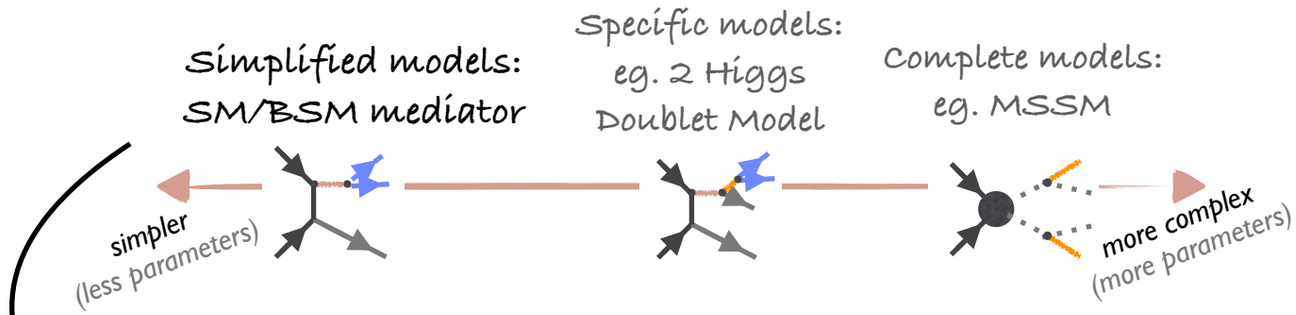

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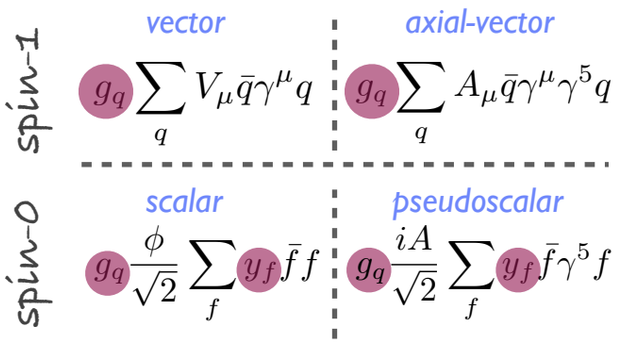

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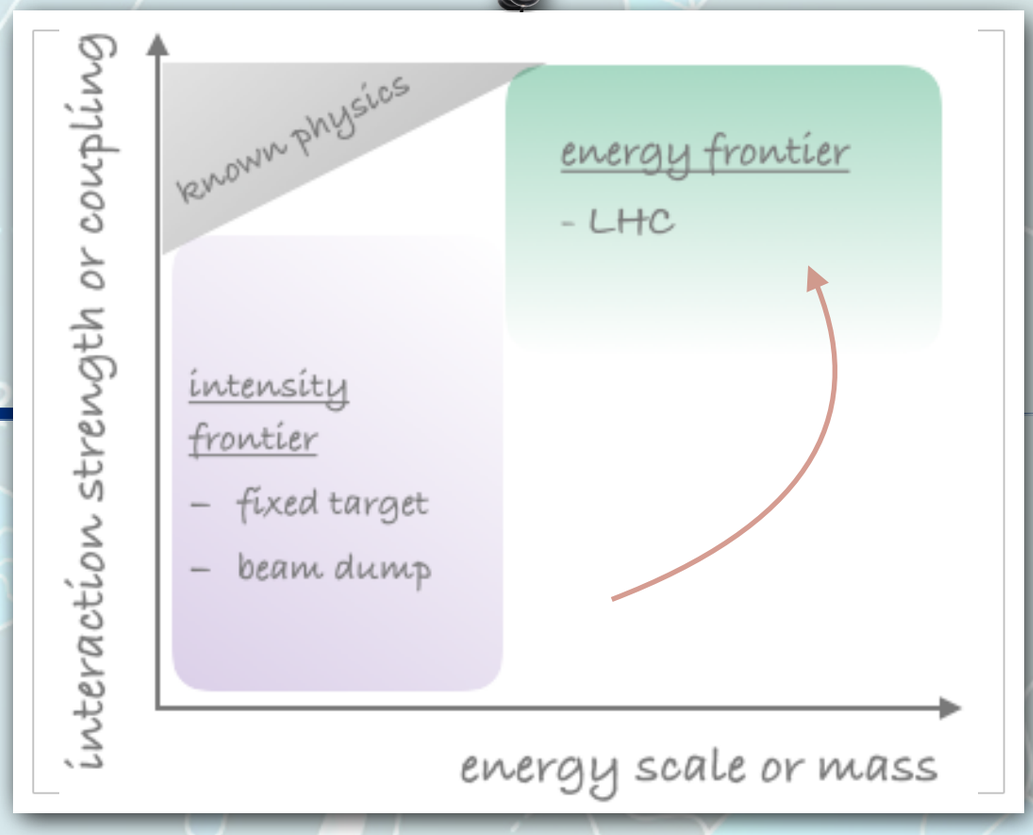
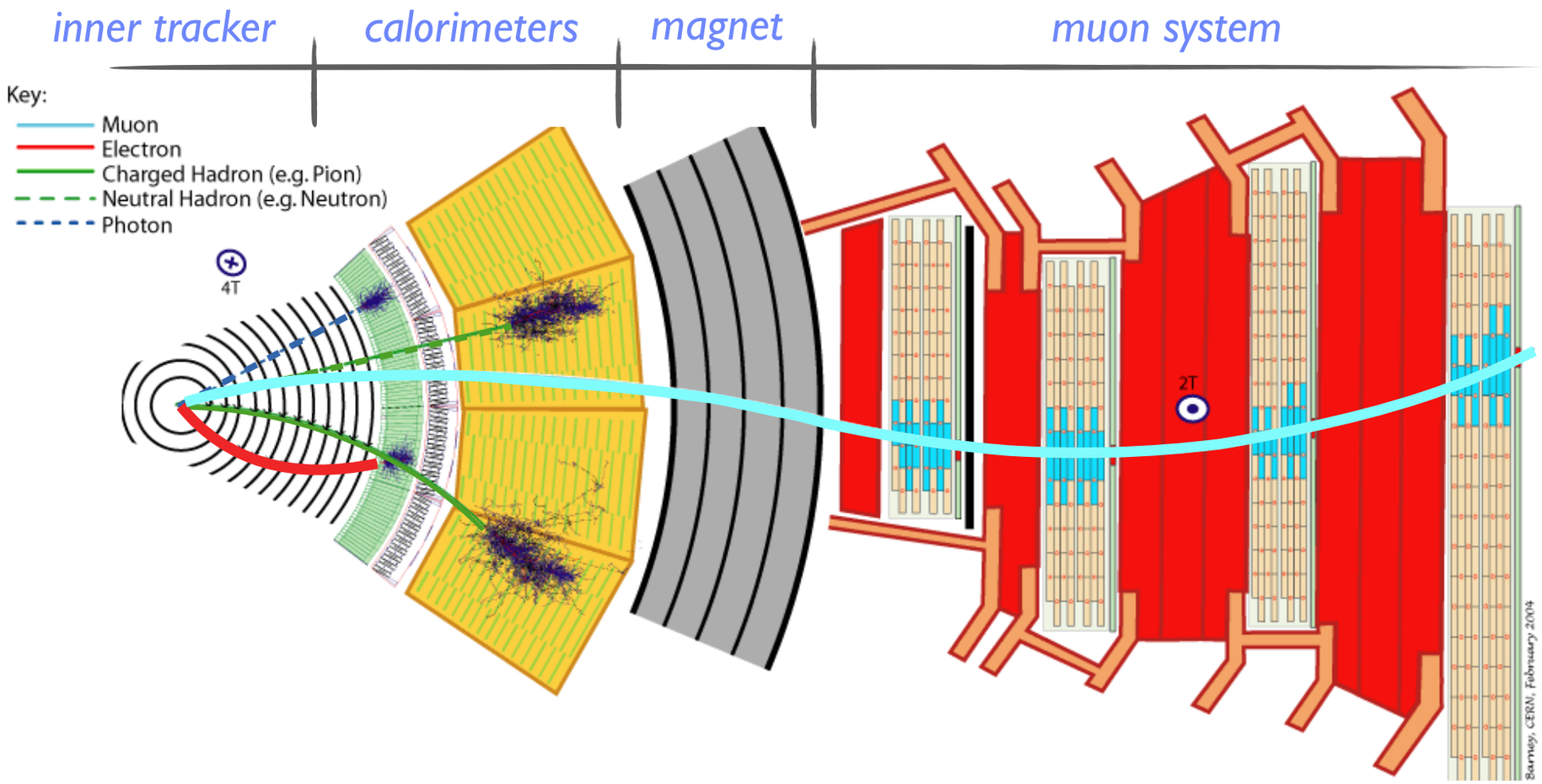


Hunt for dark matter - how to detect it?



- electron (muon), from inner tracker tracks and energy in calorimeter (track in muon spectrometer)
- photon, from energy deposits in electromagnetic calorimeter
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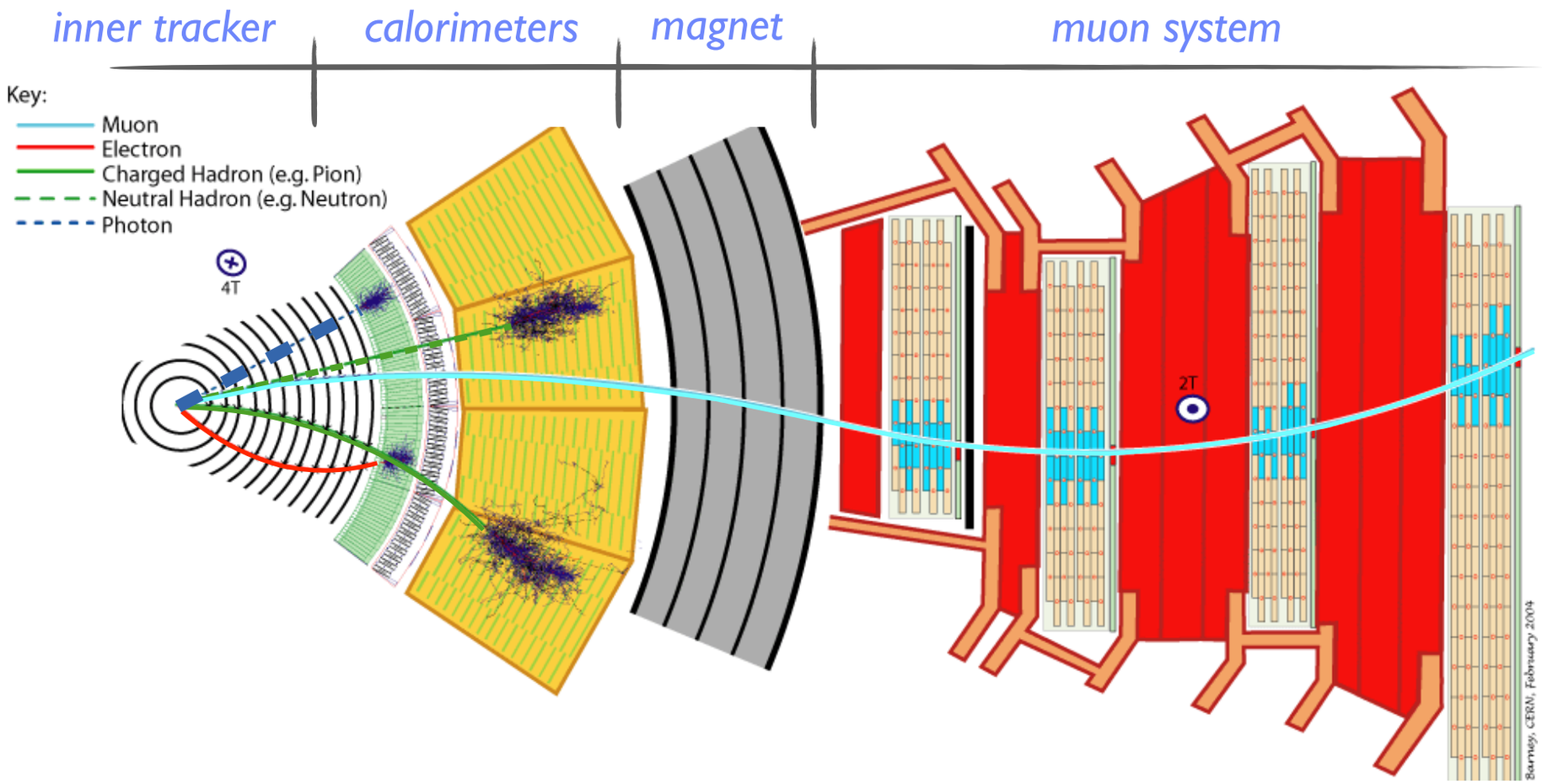

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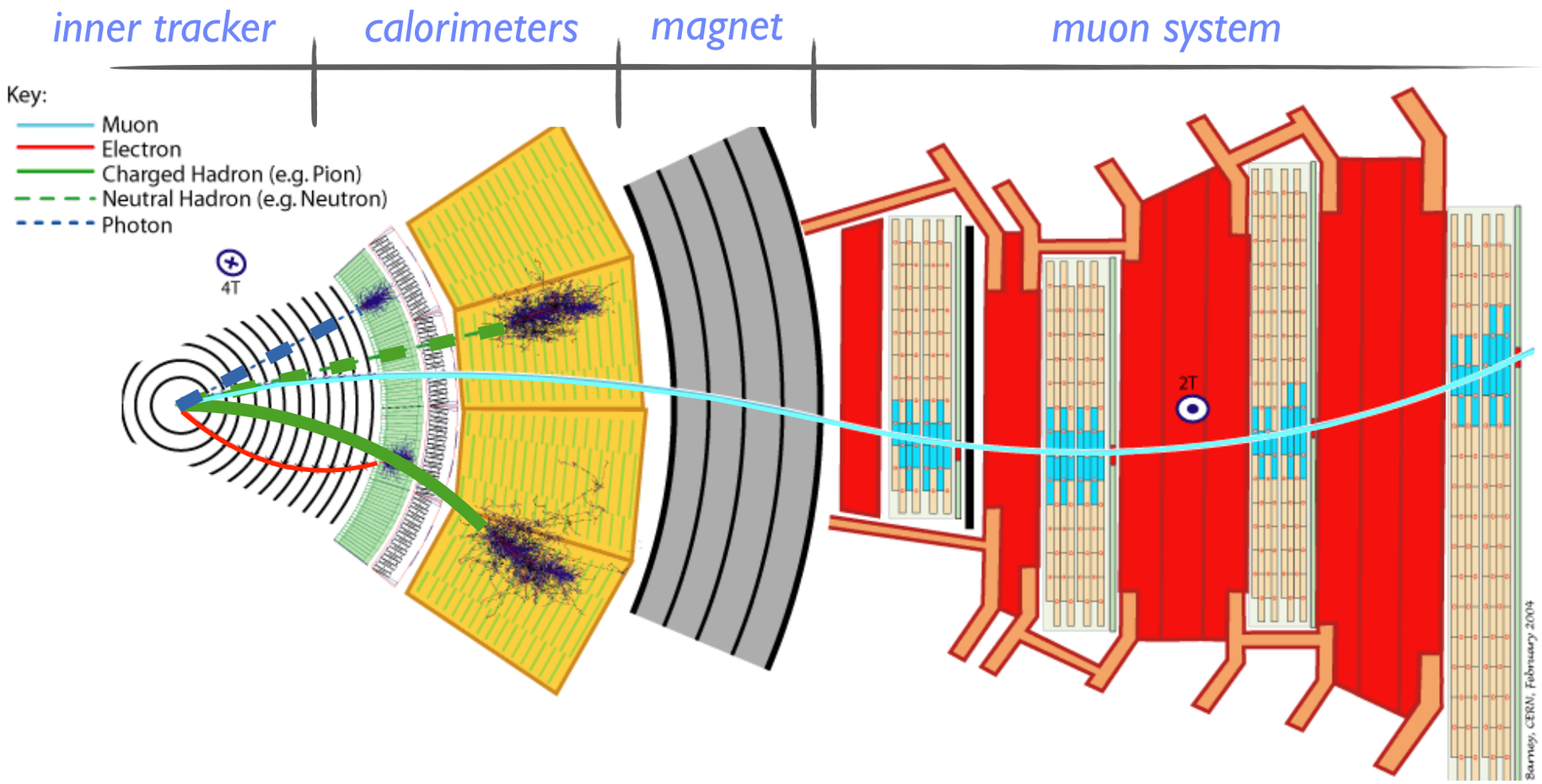

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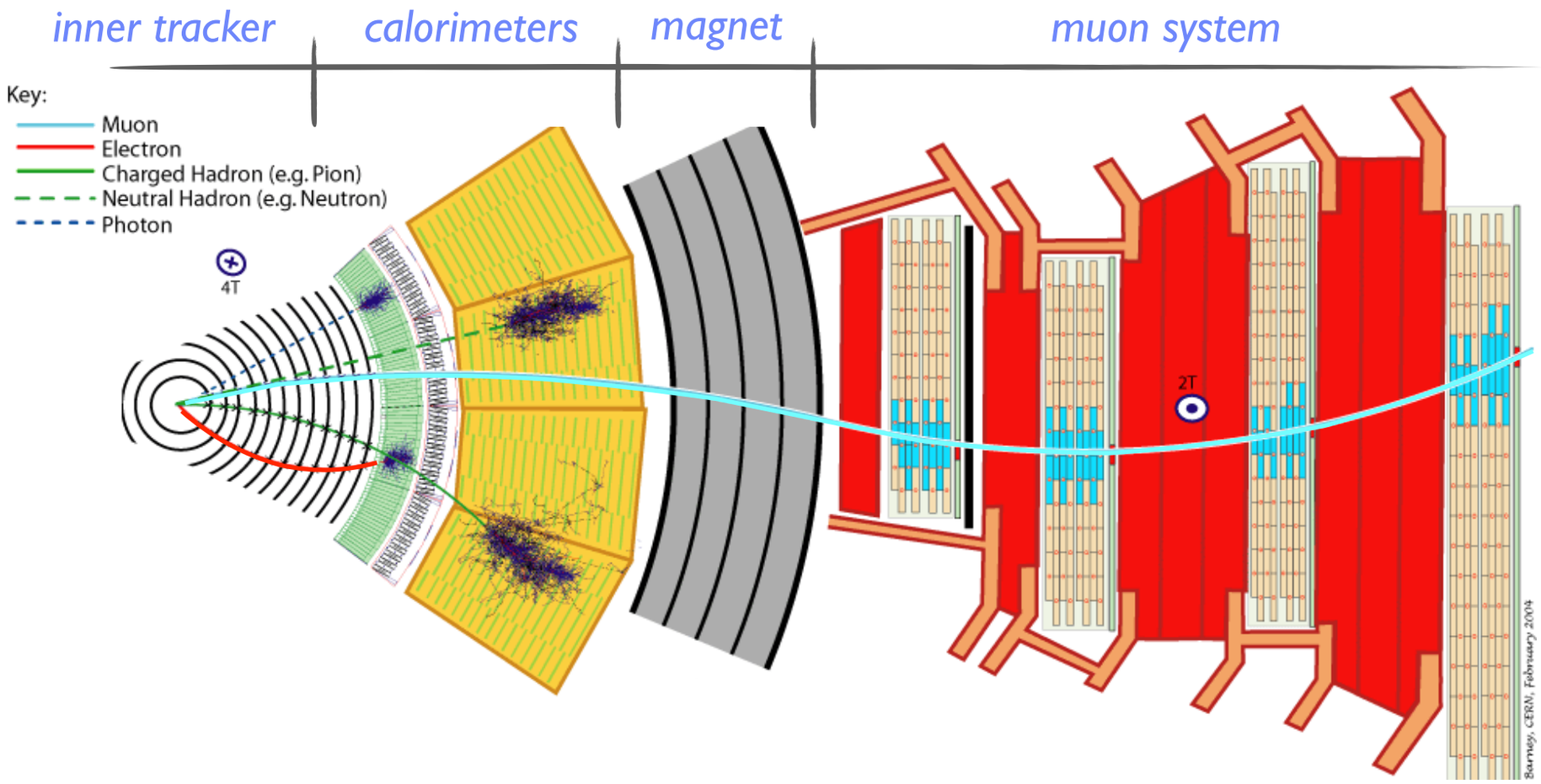

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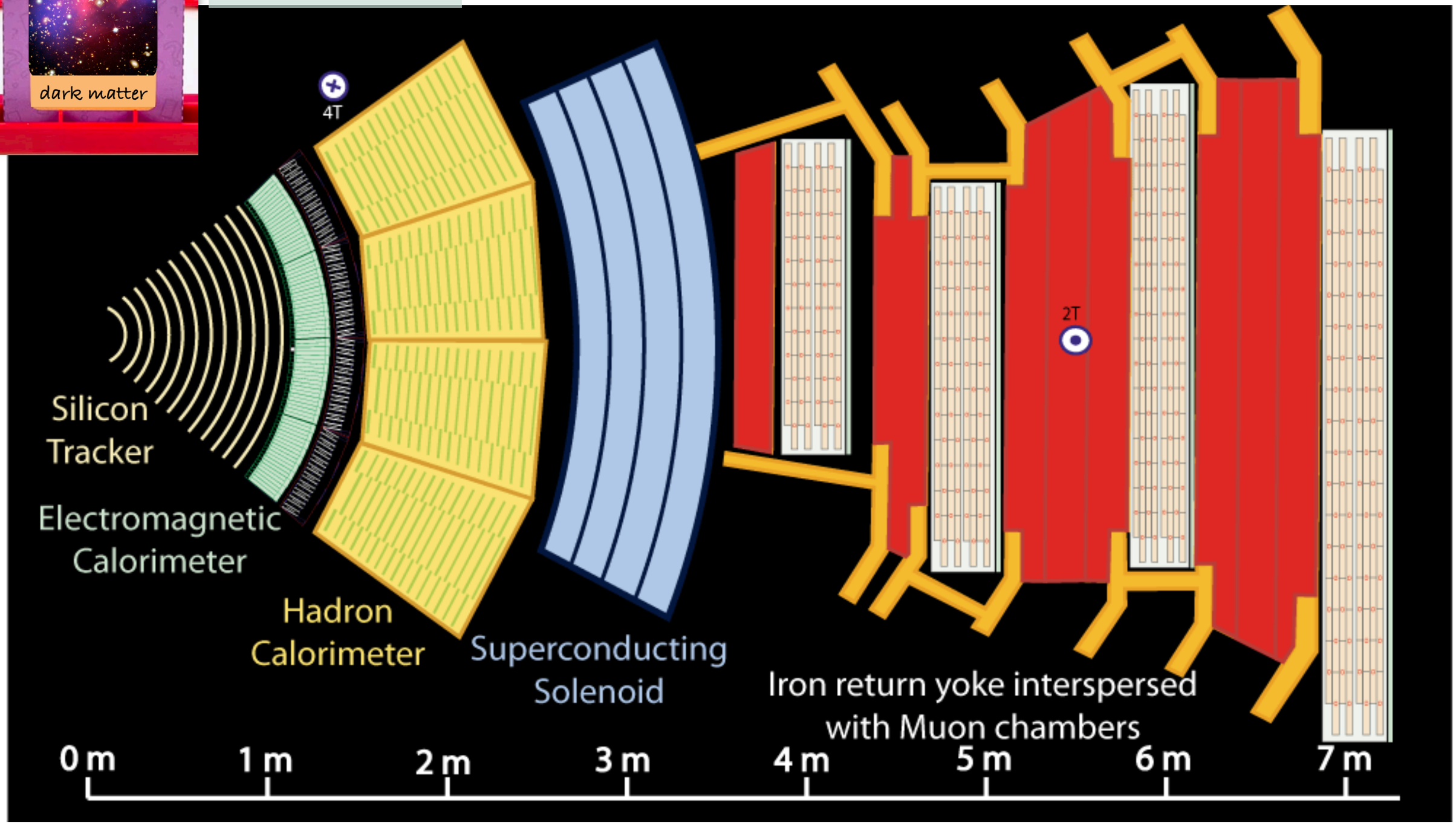
Dark matter?

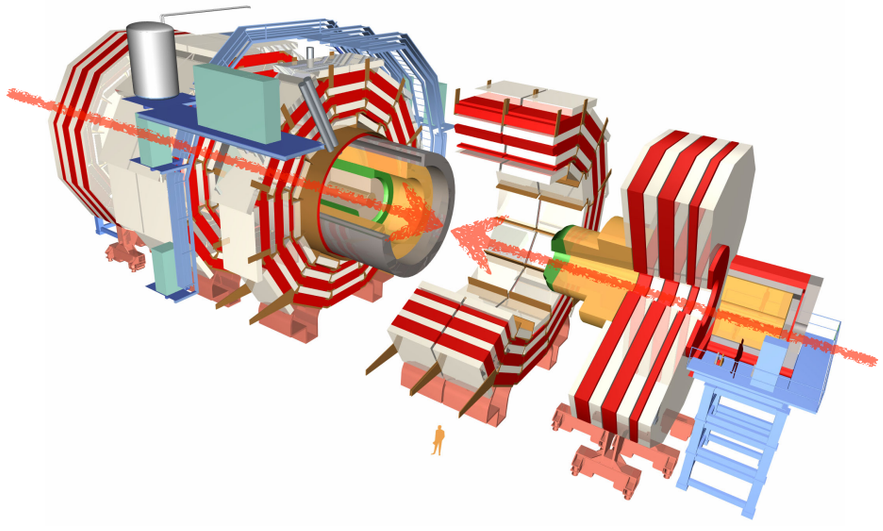
Hunt for dark matter - how to detect it?

- stable
- electrically neutral
- massive



Hunt for dark matter - signature at colliders

- DM could be produced at colliders (rare process)



no direct trace in the detector, but could create a p_T imbalance (***MET***)

conservation of momentum

- no info on longitudinal momentum of colliding partons
- but total initial parton $p_T = 0$
- need to be conserved after collision $\sum \vec{p}_T = 0$
- $\sum \vec{p}_T ! = 0$ particles escaped detector carrying $\vec{E}_T^{miss} = -\sum \vec{p}_T$
- $|\vec{E}_T^{miss}|$ = missing transverse energy (MET)

To see the invisible we need the visible ...

- need visible particle to which DM particle recoils against
- "mono-X searches": X includes jets, vector bosons, top, ...

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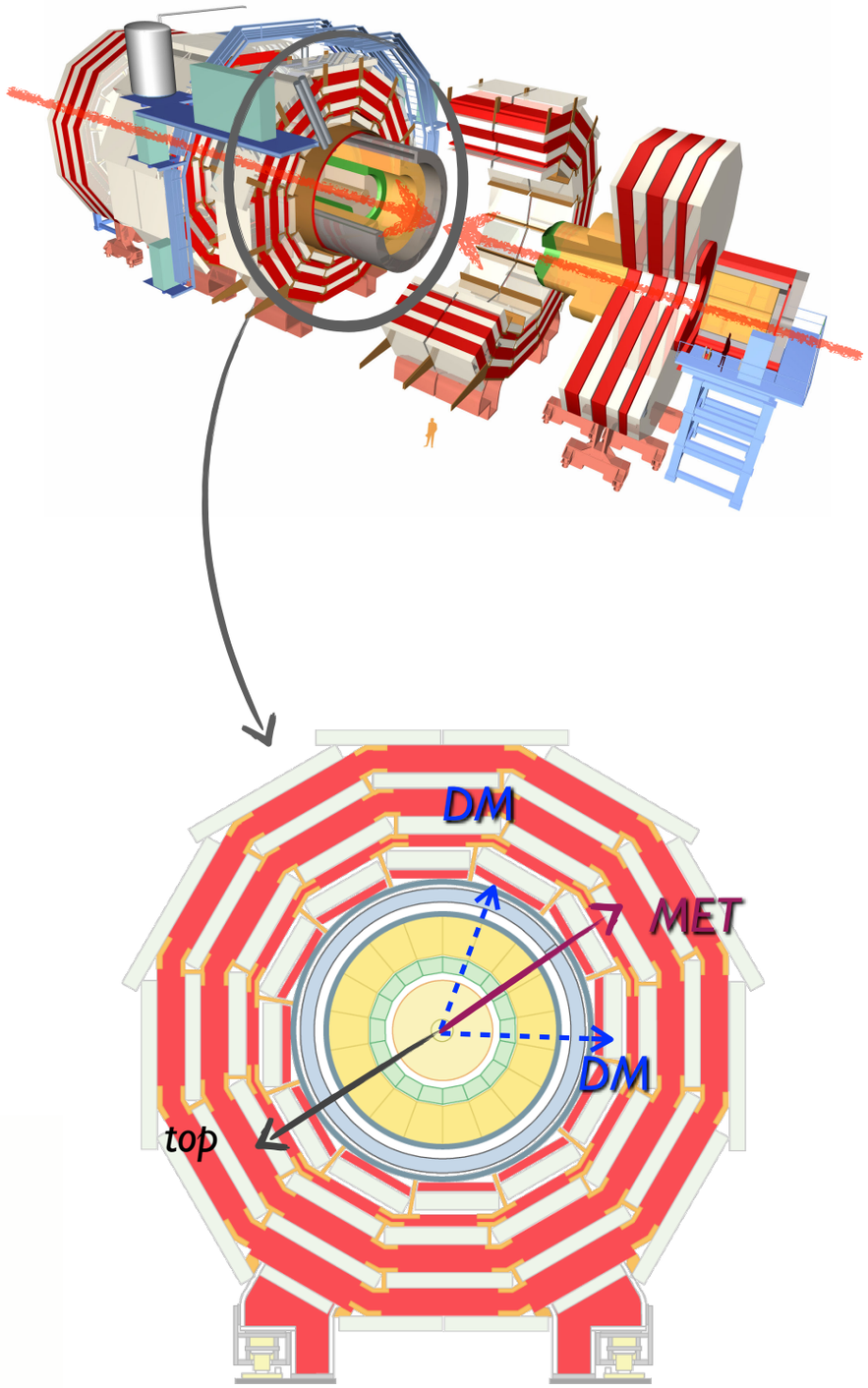

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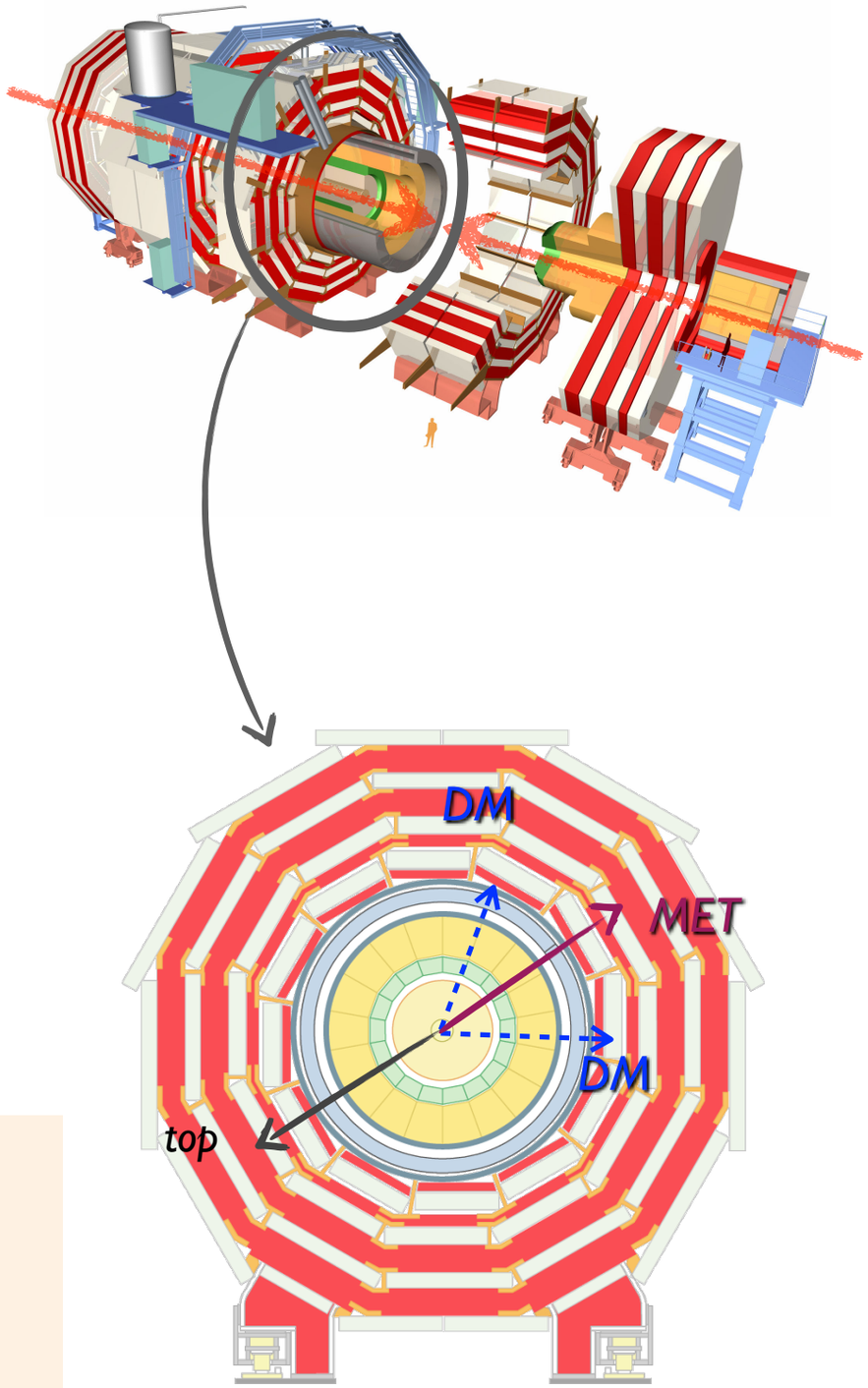

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1- Selection: DM appears as events excess in MET tail wrt SM

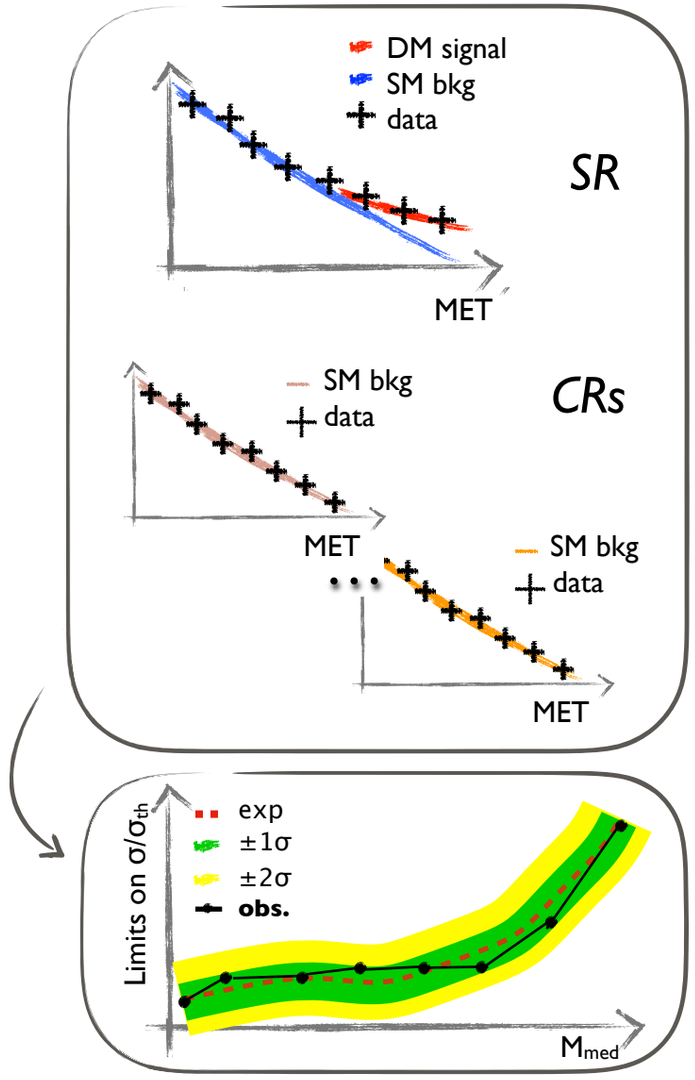
- no striking signature, eg. mass peak, m_T kinematic endpoint
- look for excess in region enriched in signal (signal region - SR)

2- Bkg: precise evaluation of SM processes in SR essential

- achieved through use of multiple control regions (CRs)

3- Results: compare SM predictions with data

- Excess of events in data, did we find DM?
- No excess, interpret result in terms of theory model parameters



Experimental challenges for invisible signatures

- accurate *E* calibration/resolution of visible objects (*"fake" MET from mis-measured jets*)
- precise particle reconstruction and identification
- mitigate effects from additional *pp* collisions (pile-up)
- MET thresholds affected by trigger (very high collision rates)

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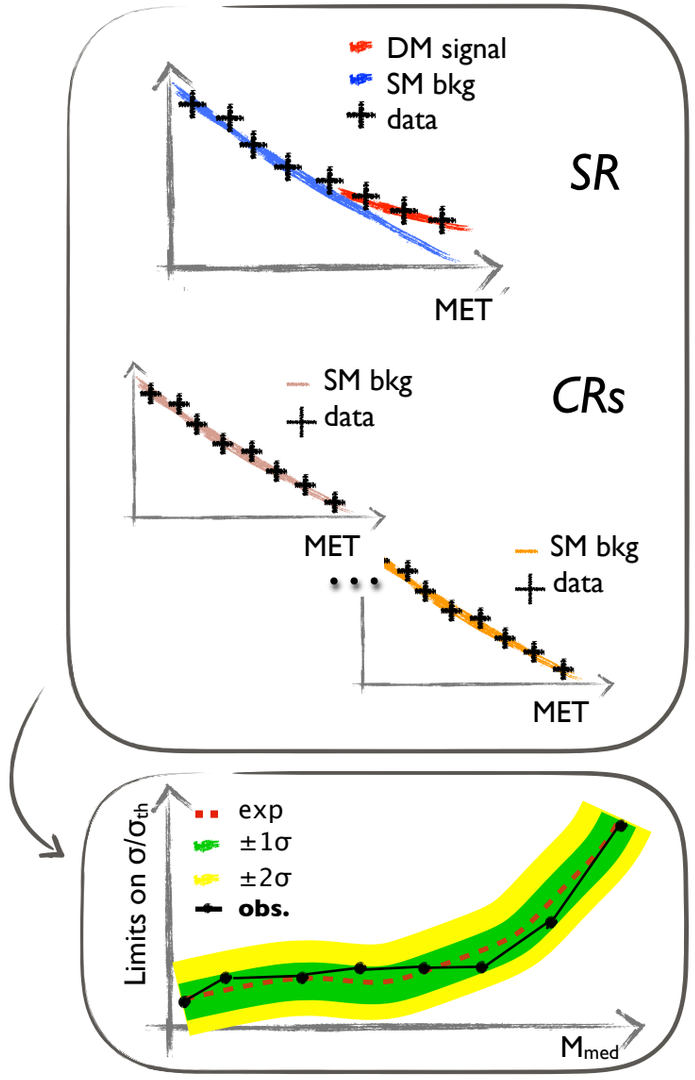

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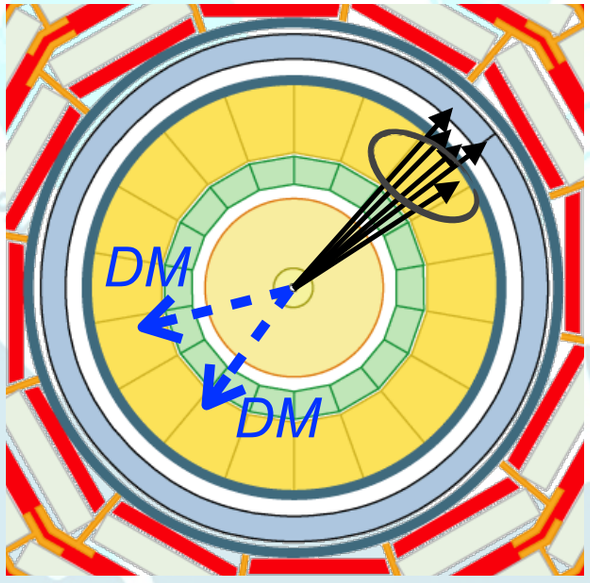
- MET thresholds affected by trigger (very high collision rates)

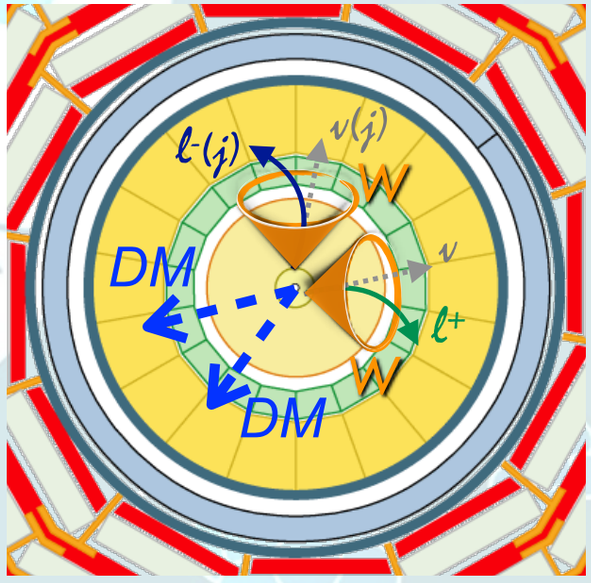
Invisible signatures

mono-jet/V(=W,Z)

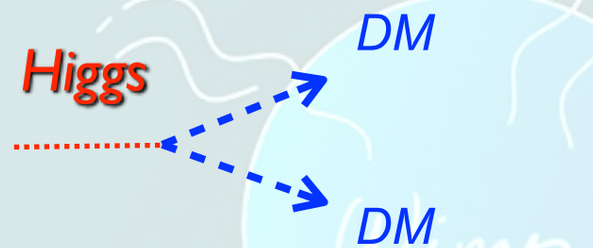


* *CMS: EXO-20-004*

mono-WW



* *CMS: EXO-21-012*



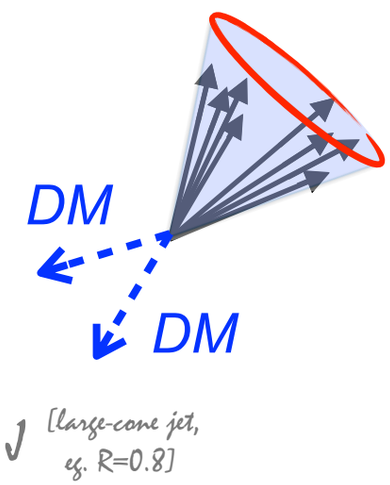
* *ATLAS: PLB842(2023)*
* *CMS: HIG-21-007*

* *selected recent results*

CMS: EXO-20-004

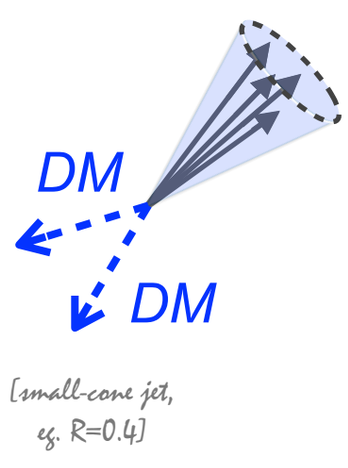
Hunt for dark matter - DM+jet/V search

- 1 - Selection: events categorized based on jet nature



mono-V

- MET > 250 GeV
- ≥ 1 jets, $p_T(j_1) > 250$ GeV
- *ML technique* to identify V hadronic decays
- *jet mass* consistent with V



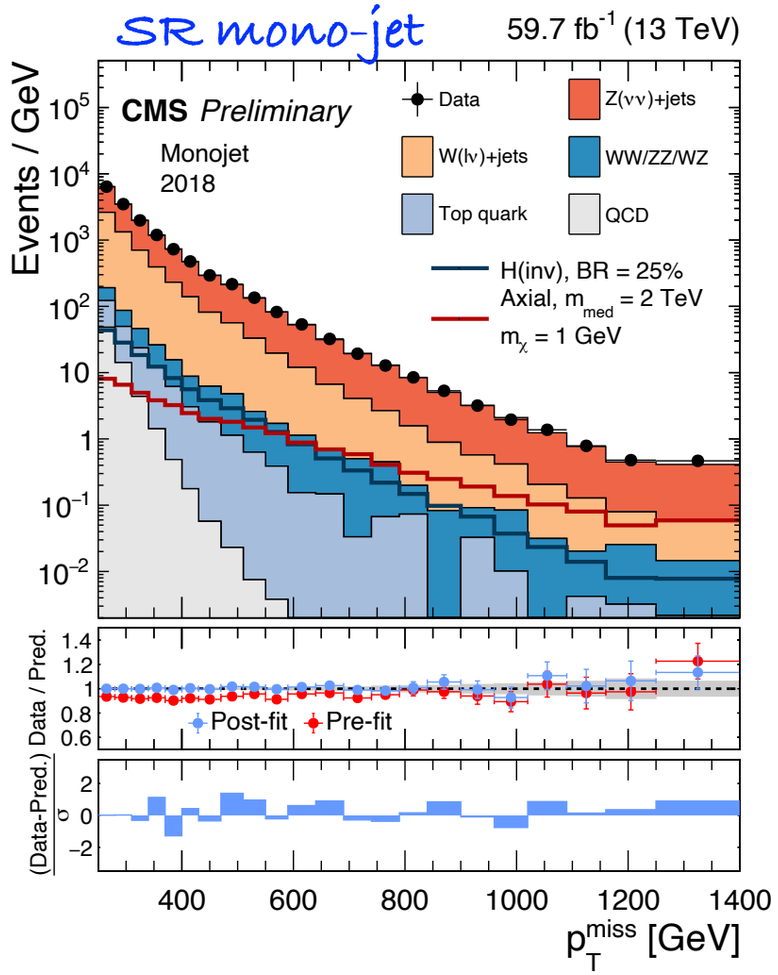
mono-jet

- not selected as mono-V
- ≥ 1 jets, $p_T(j) > 100$ GeV
- b-tagged jets veto

- 2- Bkg:
  - **Z(vv)+jets and W(lv)+jets** from CRs

- 3- Results: *combined fit of SRs, CRs*
  - systematic unc. included as nuisance parameters

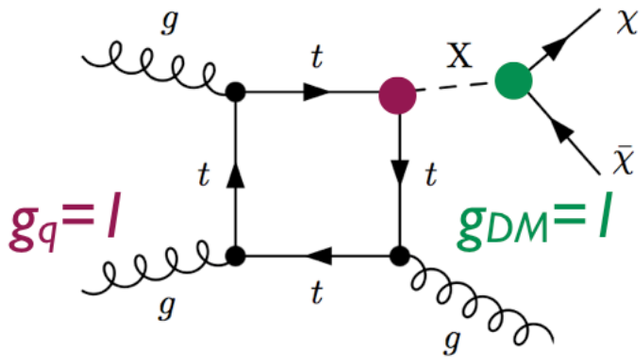
- prefit: as from simulation
- post-fit: after allowing simulation to vary within unc and the scaling factors from CRs

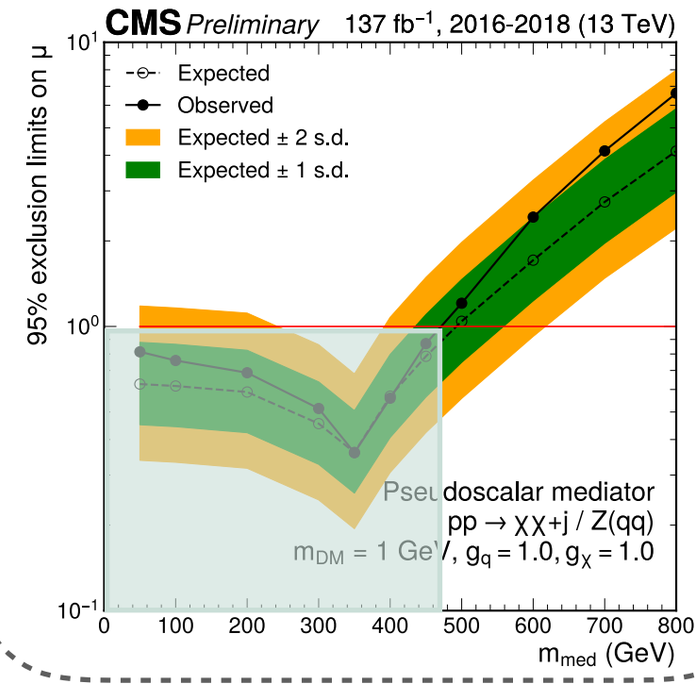


Hunt for dark matter - DM+jet/V search

- 3- Results: interpretation in terms of DM model, upper limits at 95% CL on cross section

Simplified pseudo model





Simplified axial-vector model

- $\mu = \sigma/\sigma_{th}$, $\mu = 1$ exclude the theory value, $\mu < 1$ exclude below theory value, $\mu > 1$ does not exclude theory value
- parameter: cannot scan all parameters at once. Fixed ones only affect xsec but not kinematic (selection)

- here $\mu = \sigma/\sigma_{th}$, in on z axis (notice here $\log_{10}(\mu)$)
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Hunt for dark matter - DM+jet/V search

- 3- Results: interpretation in terms of DM model, upper limits at 95% CL on cross section

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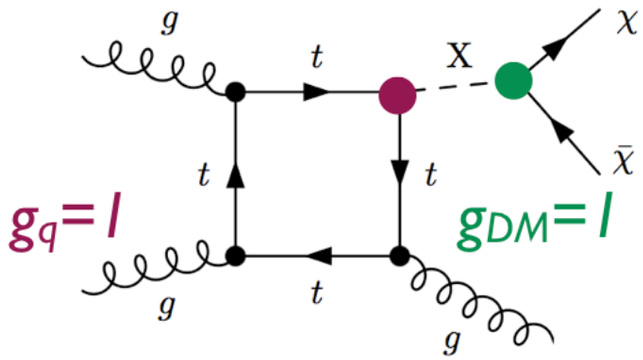

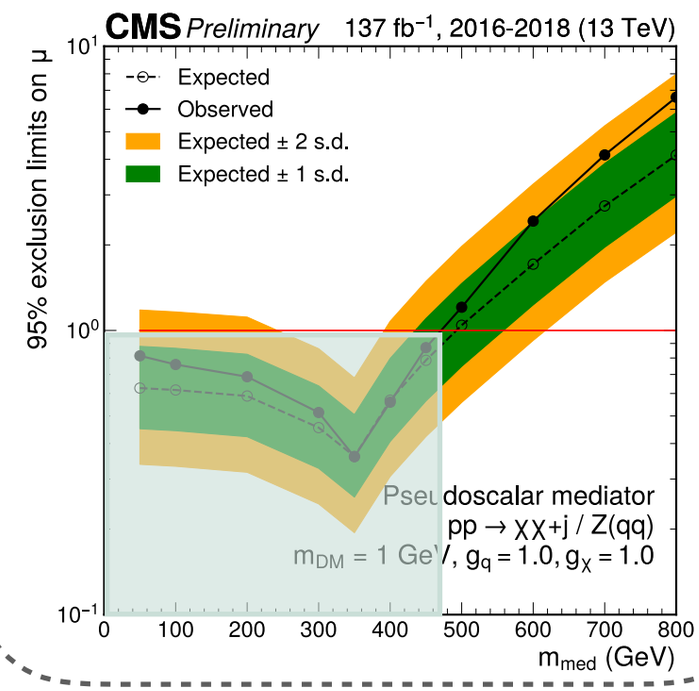

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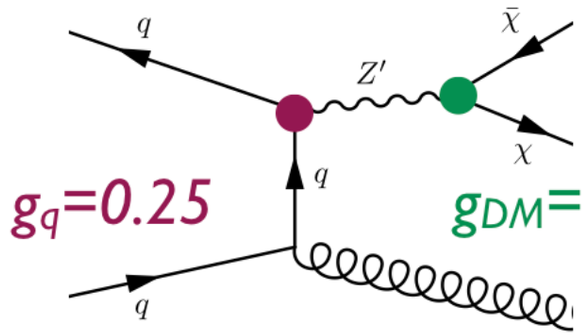

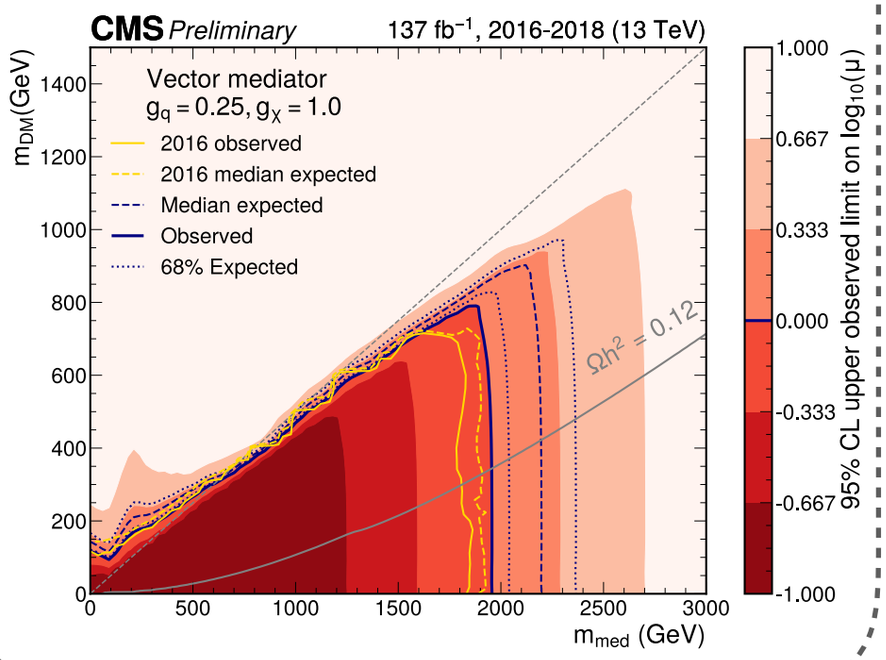

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Hunt for dark matter - DM+jet/V search

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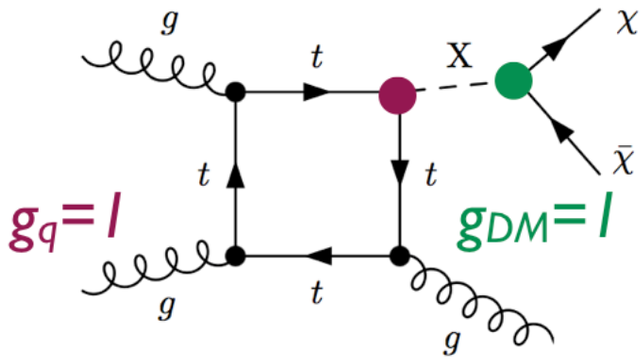

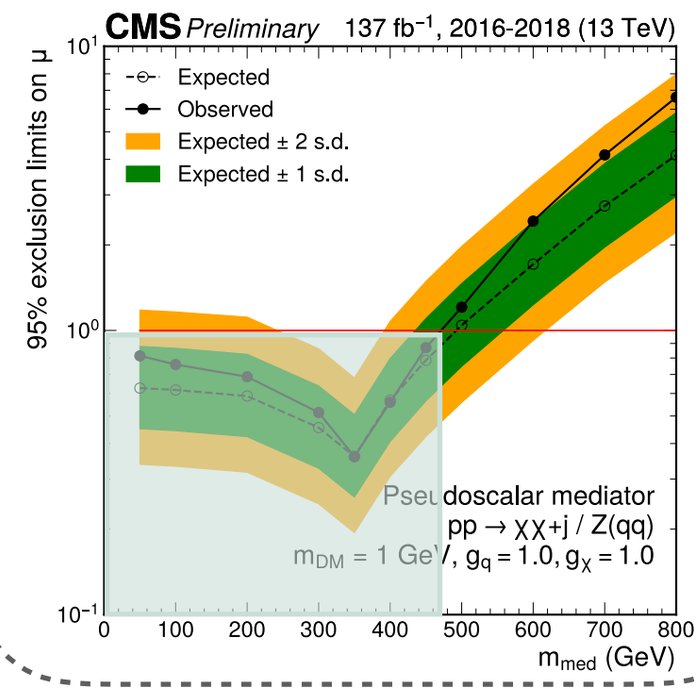

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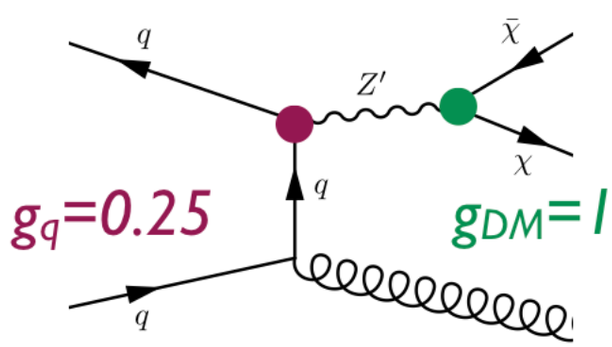

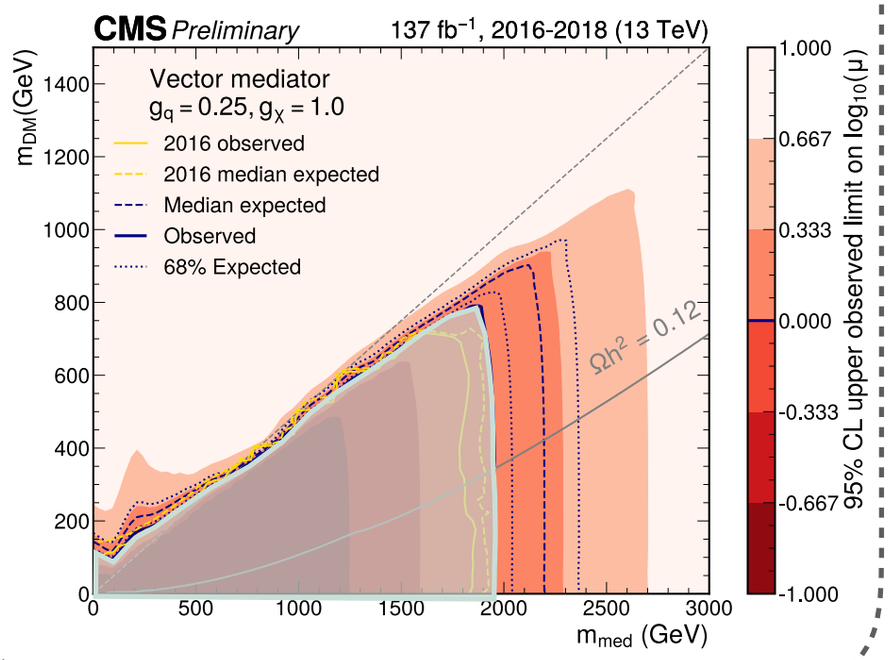

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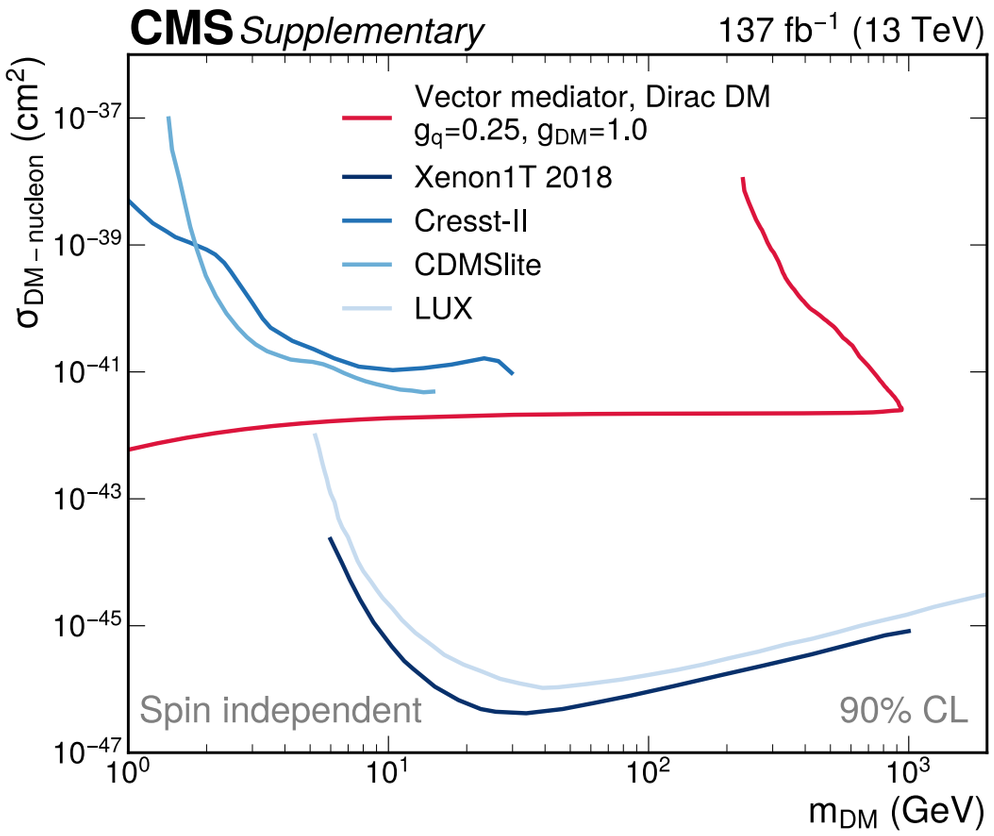
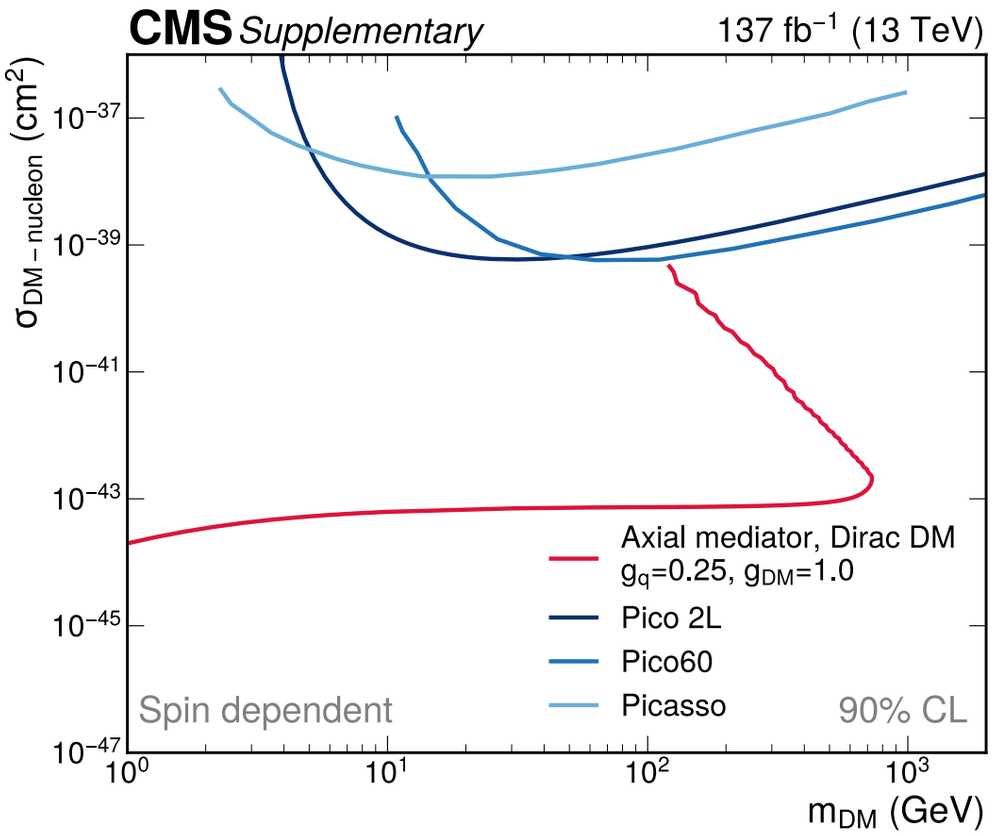
CMS: EXO-20-004

Hunt for dark matter - interplay with direct detection

- 3- Results: 90% CL lower limits on interaction xsec between DM and nuclei





Comparison *recommendations [arXiv:1603.04156]*

- DM non-relativistic: dominant DM-nuclei interactions spin-independent and spin-dependent scattering
  - vector/scalar mediator lead to a SI interaction
  - axial-vector/pseudo-scalar lead to SD interaction
- very model dependent
  - DD bounds may be valid for multiple models, LHC limits hold exclusively for considered models

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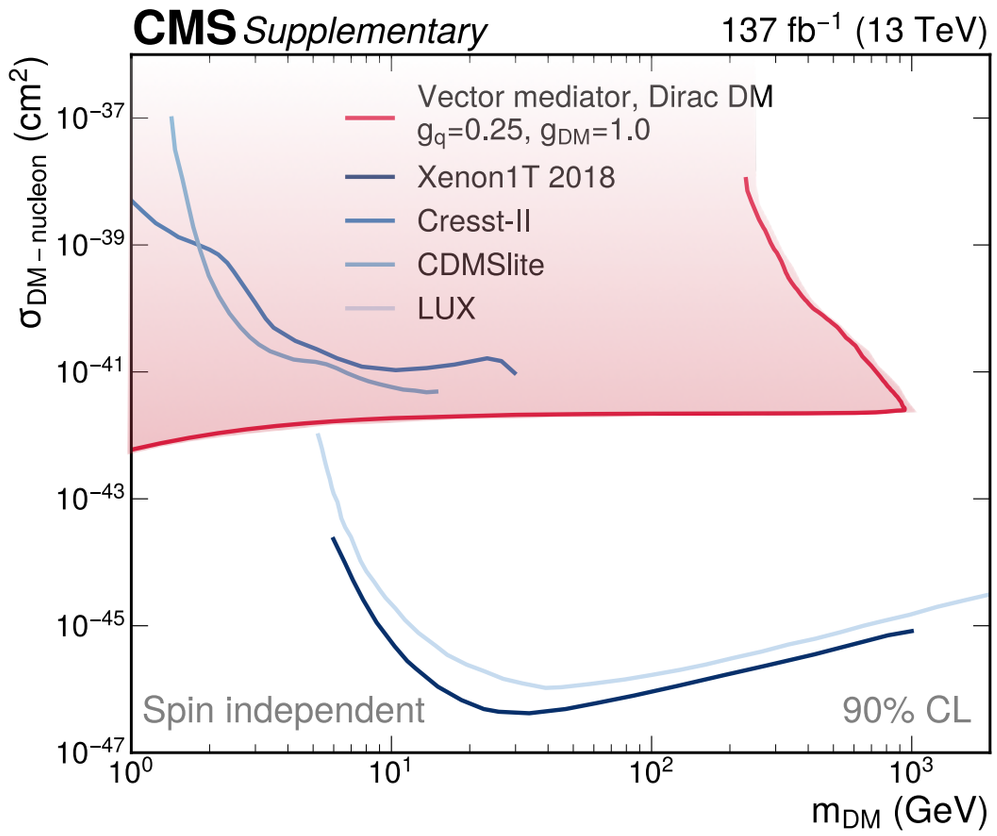

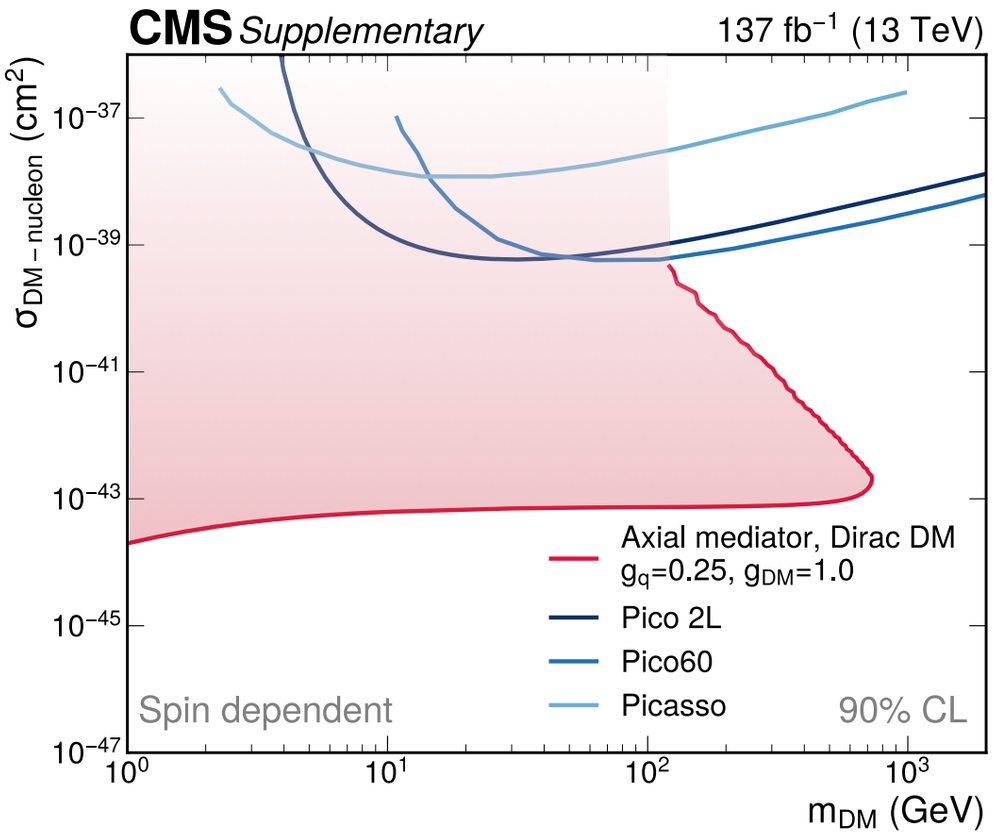

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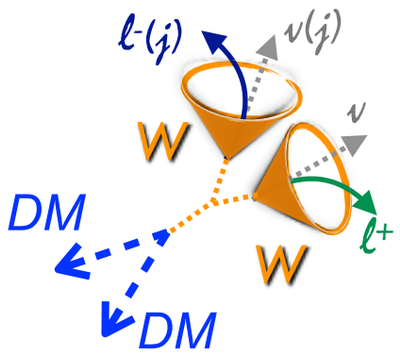
CMS: EXO-21-012

Hunt for dark matter - DM+WW search

1- Selection: #lep categorization

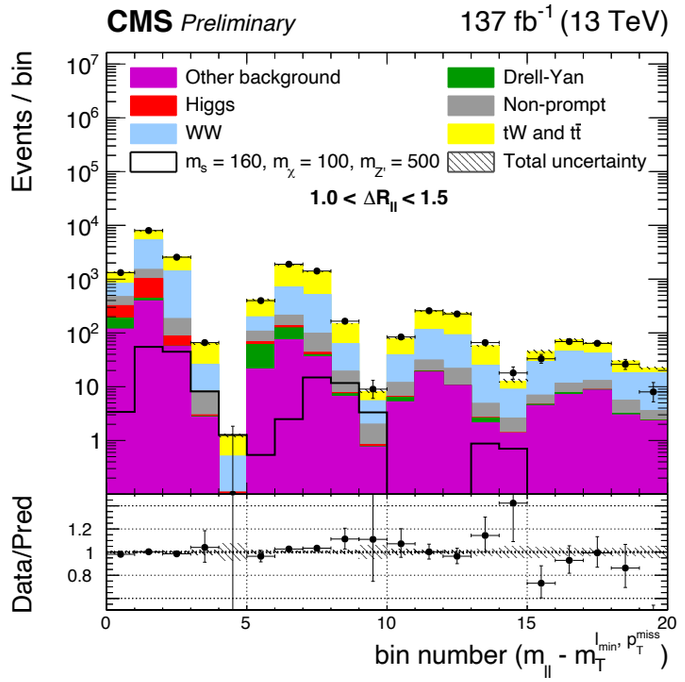


1ℓ
- 1 lep, ≥ 2 jets (m_{jj} ~ W mass)
- 0 b-tagged jets, MET > 60 GeV
- MVA to recover sensitivity

2ℓ
- 1 opposite-charge $\ell\ell$ pair
- 0 b-tagged jets, MET > 20 GeV
- events categ. on dark-H boost

2- Bkg:

- ***tt, tW, W/ Z+jets, WW*** *main bkg, from CRs*



3- Results: upper limits at 95% CL on cross section

Dark-Higgs model: dark Higgs (s) can be lighter than DM, observed relic can be attained

Hunt for dark matter - DM+WW search

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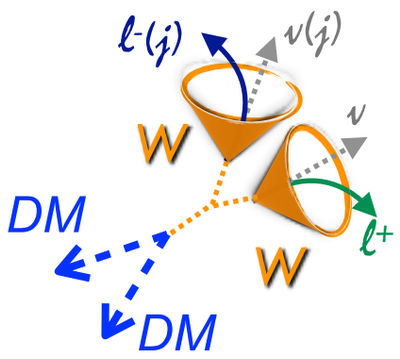

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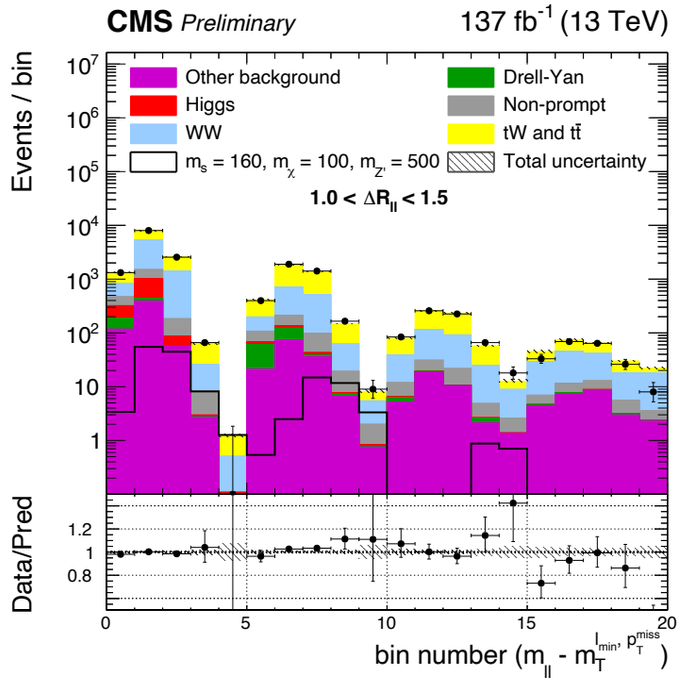

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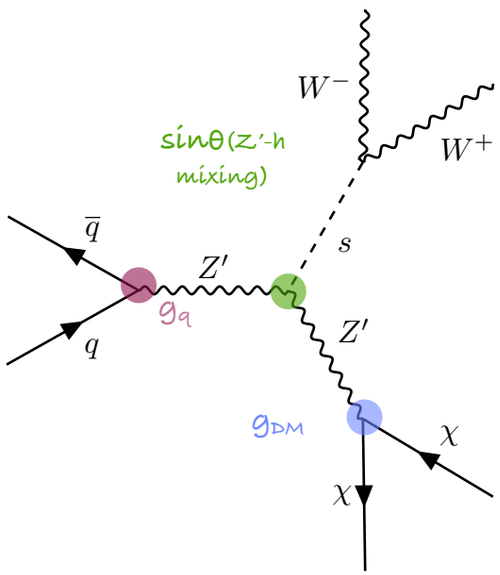
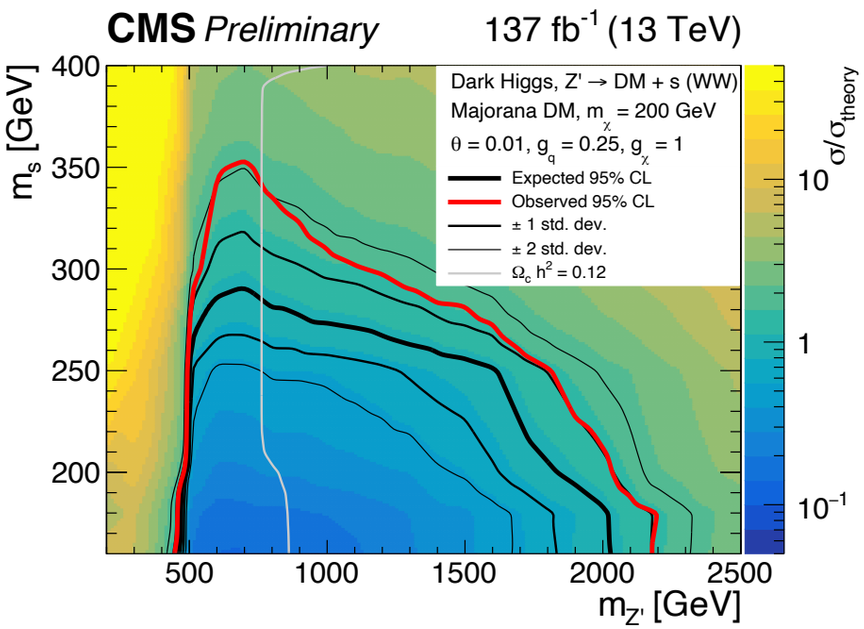
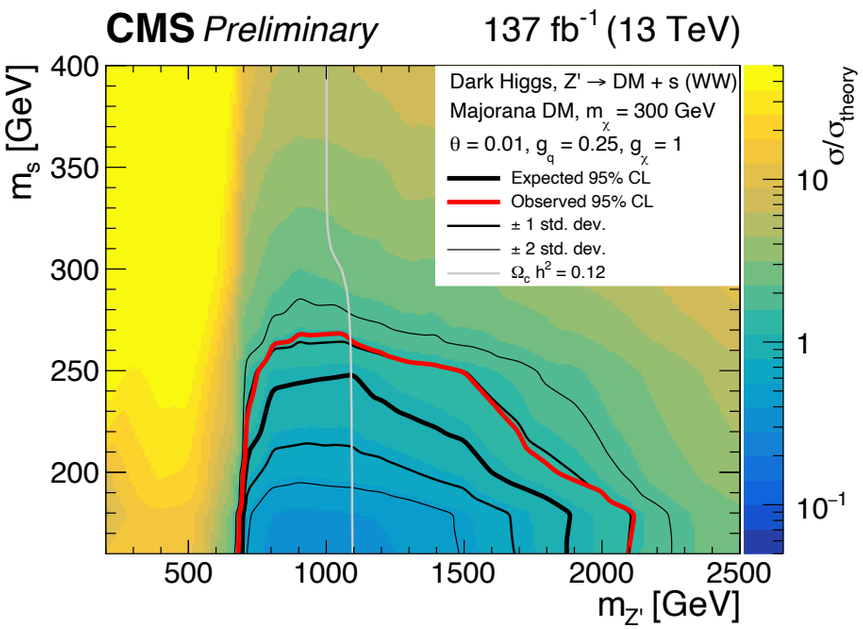




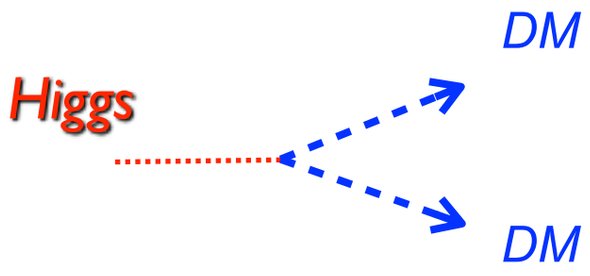


Hunt for dark matter - Higgs can be a portal?

ATLAS: PLB842(2023)
CMS: HIG-21-007

- DM-SM interactions mediated by Higgs boson: DM coupling enhance H invisible BR (SM ~0.1%)

- Higgs production as in SM
  - gluon fusion (MET+j)
  - associated VH (MET+V), ttH (MET+tt)
  - vector-boson fusion (MET+2jets)



- 3- Results: translated in spin-independent DM-nucleon elastic scattering xsec limit ($m_{DM} < m_H/2$)

LHC searches complementary to direct detection (under model assumptions)

BR(H→inv) <0.15(0.08) obs(exp.)

BR(H→inv) <0.11(0.08) obs(exp.)

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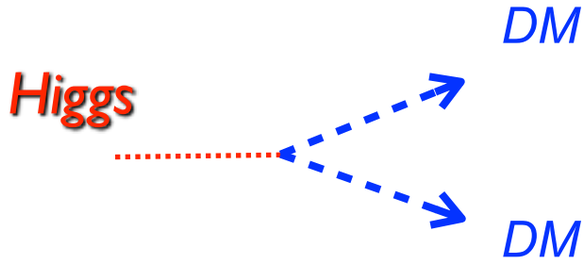

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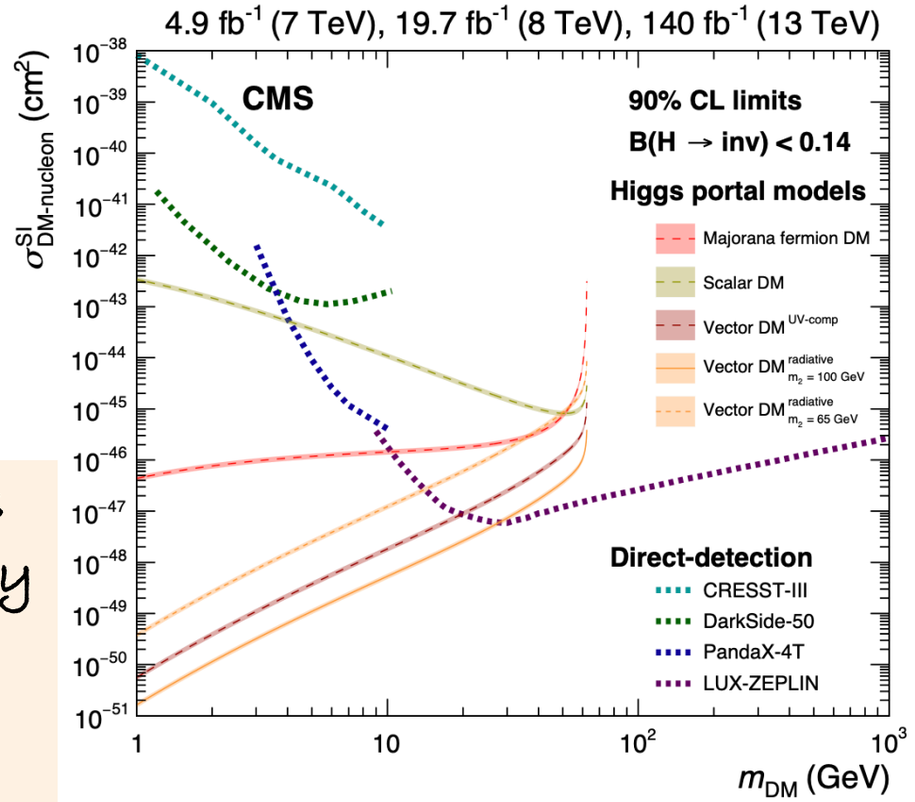

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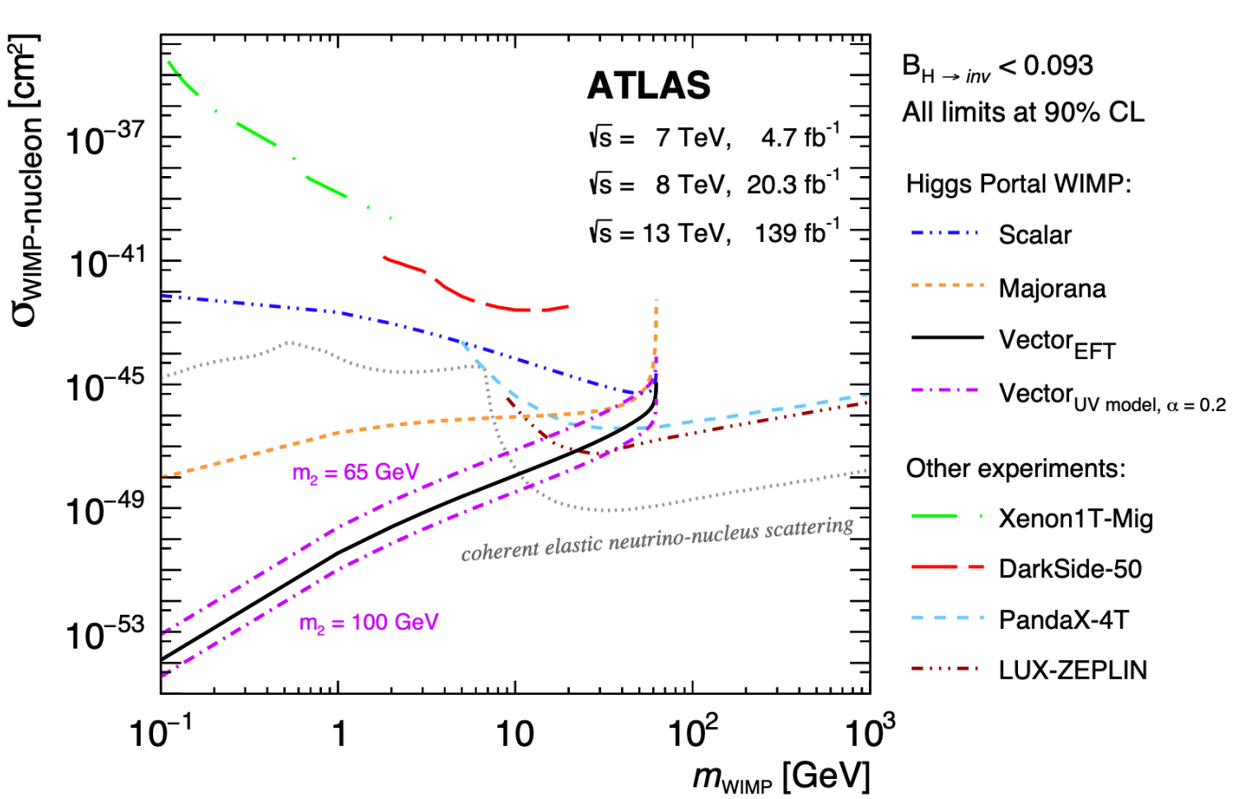


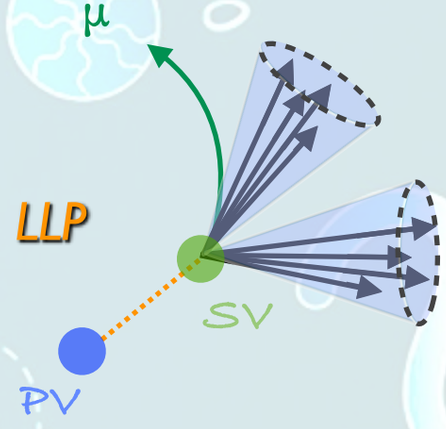
BR(H→inv) <0.11(0.08) obs(exp.)

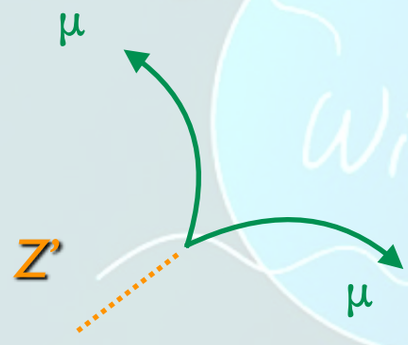
LHC searches complementary to direct detection (under model assumptions)

Visible signatures

- massive long-lived particles:
  - ✱ LHCb: EPJC373(2022)

- di-muon resonances:
  - ✱ CMS: EXO-21-005

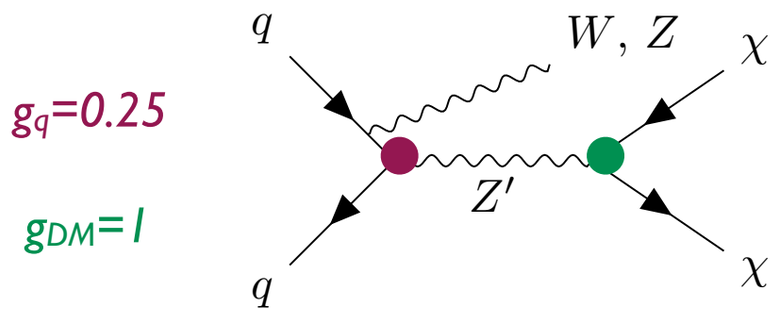




✱ *selected recent results*

Hunt for dark matter - hints from indirect searches

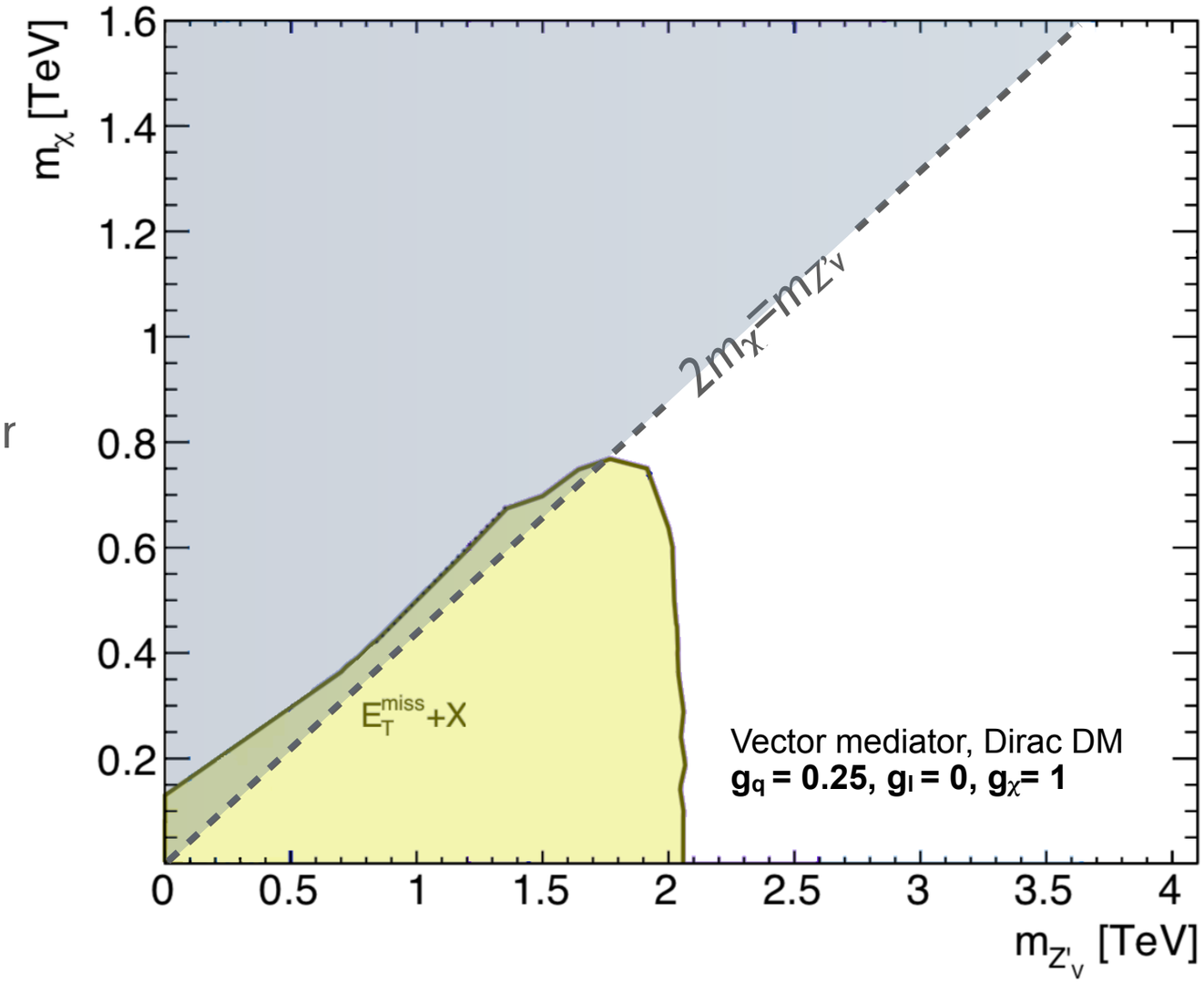
Simplified vector model



- low sensitivity to off-shell region due to strong reduction of production cross-sectior

- Can we recover the sensitivity?

* ATLAS:ATL-PHYS-PUB-2021-006

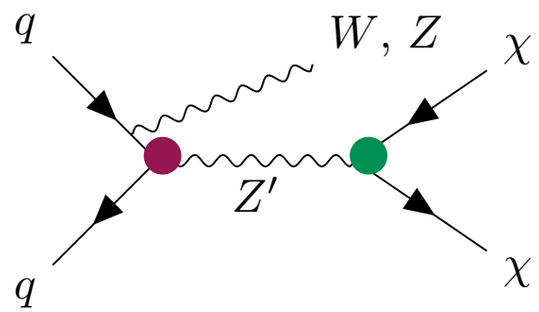


Hunt for dark matter - hints from indirect searches

Simplified vector model

g_q=0.25

g_{DM}=1



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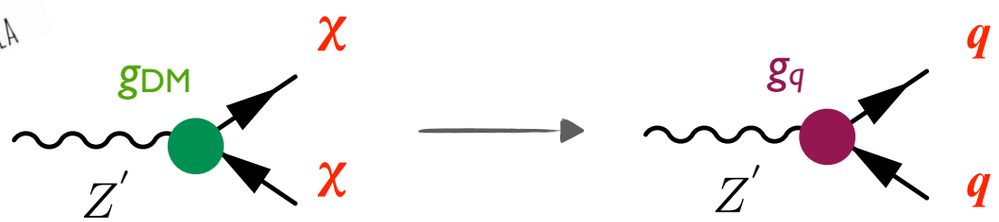
visible decays



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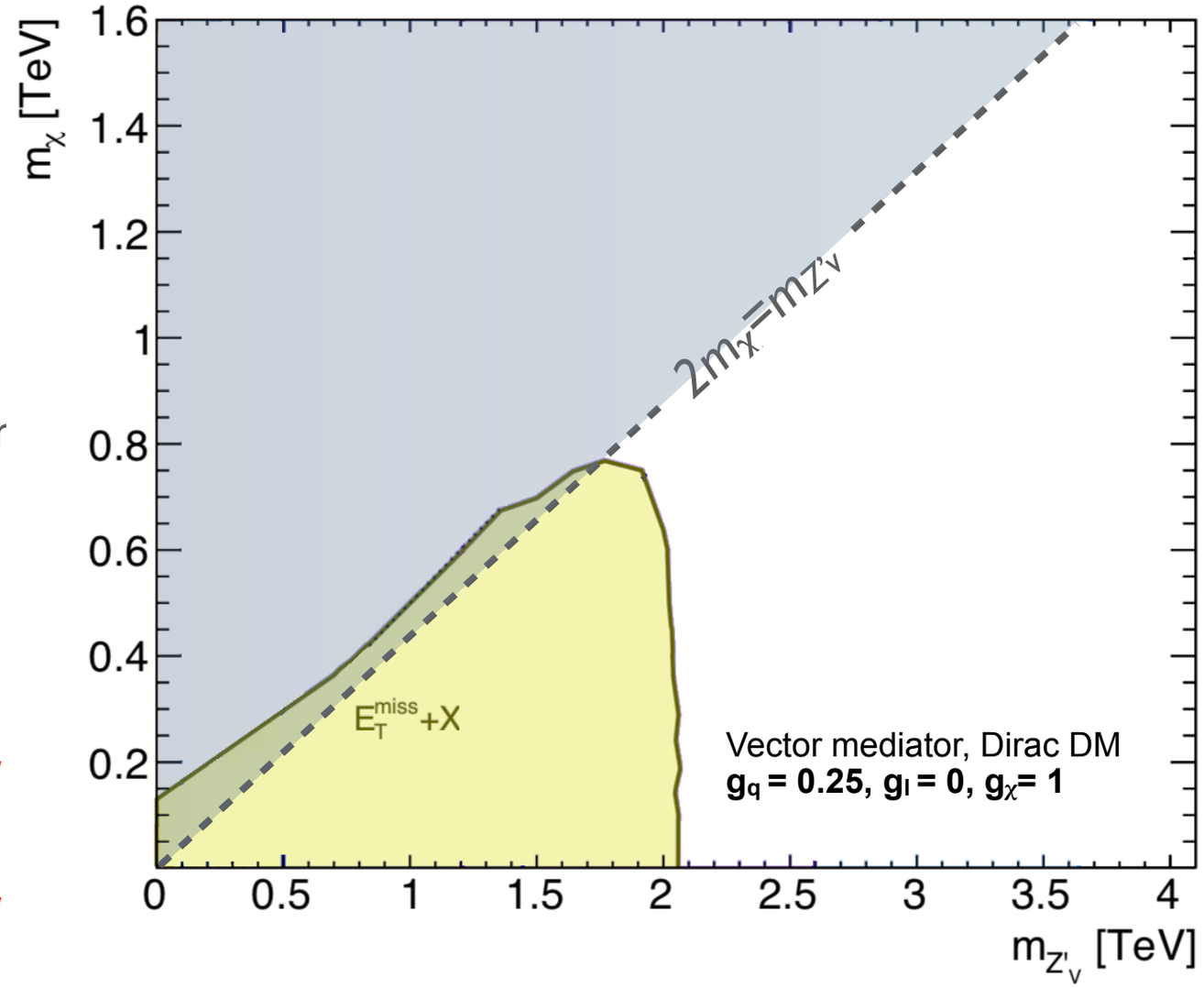

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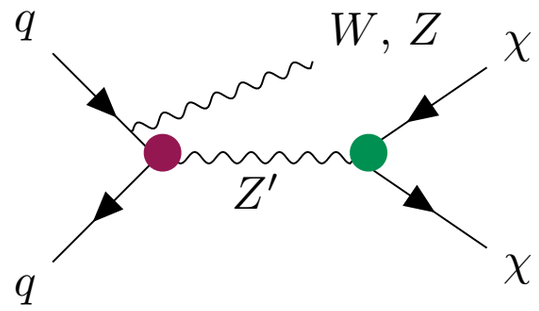

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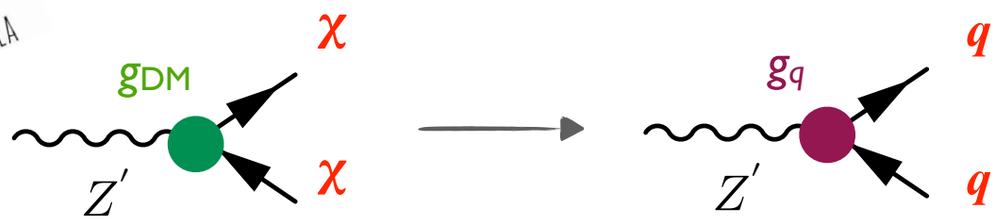
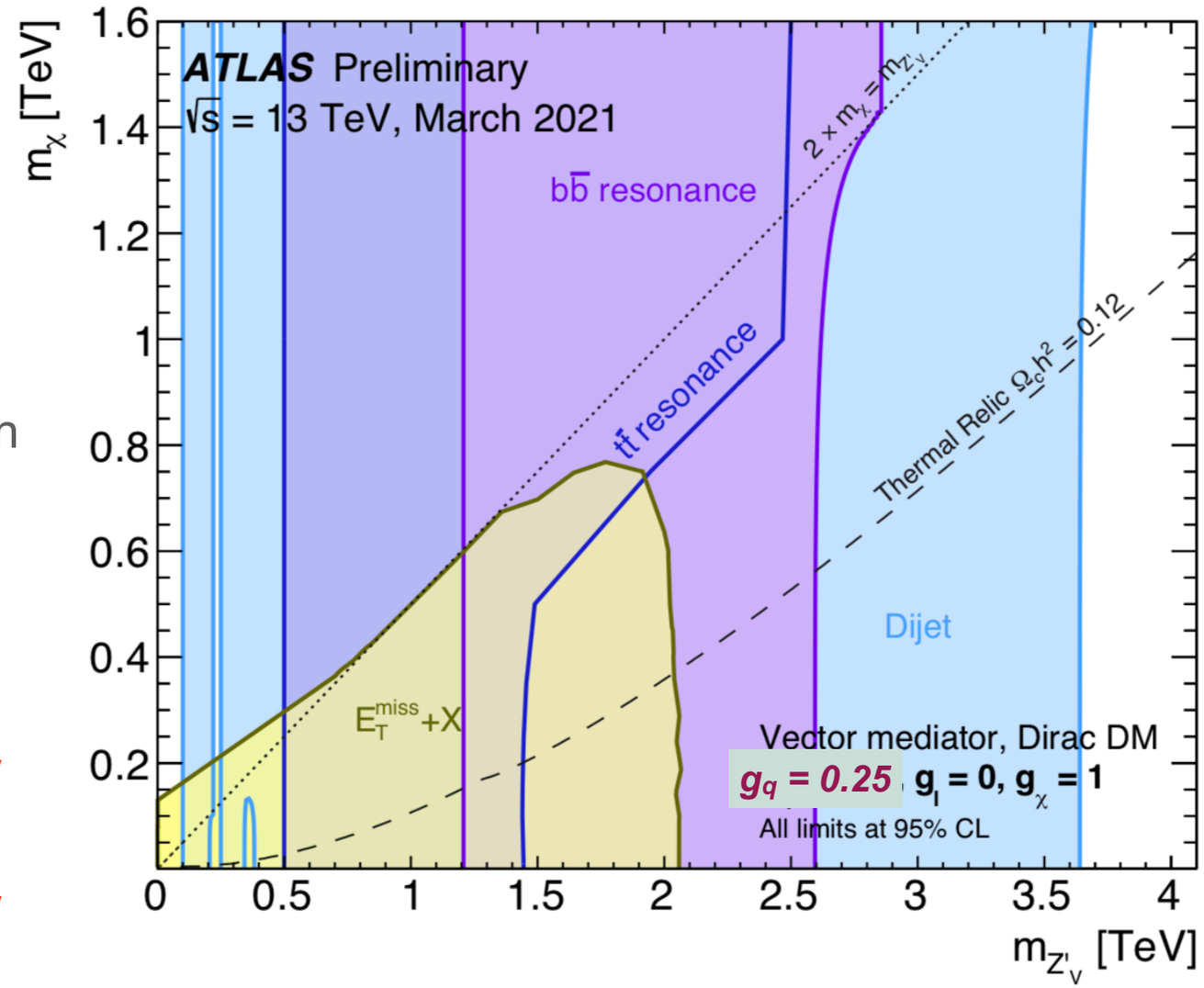


* mediator

g_q=
- narrow resonance
- wide resonance

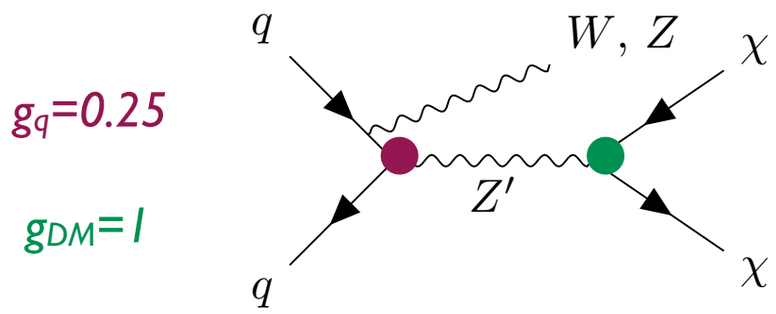
Did we exclude already everything?

* ATLAS:ATL-PHYS-PUB-2021-006



Hunt for dark matter - hints from indirect searches

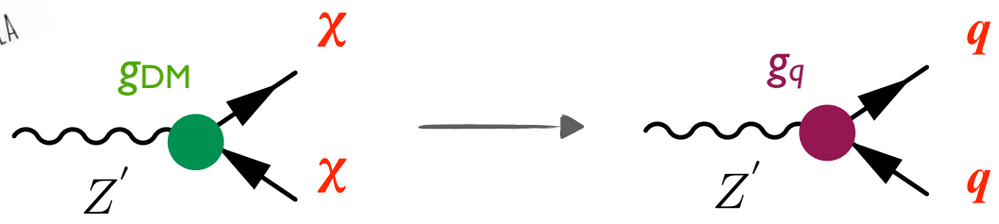
Simplified vector model



- low sensitivity to off-shell region due to strong reduction of production cross-sectior

- Can we recover the sensitivity?

visible decays

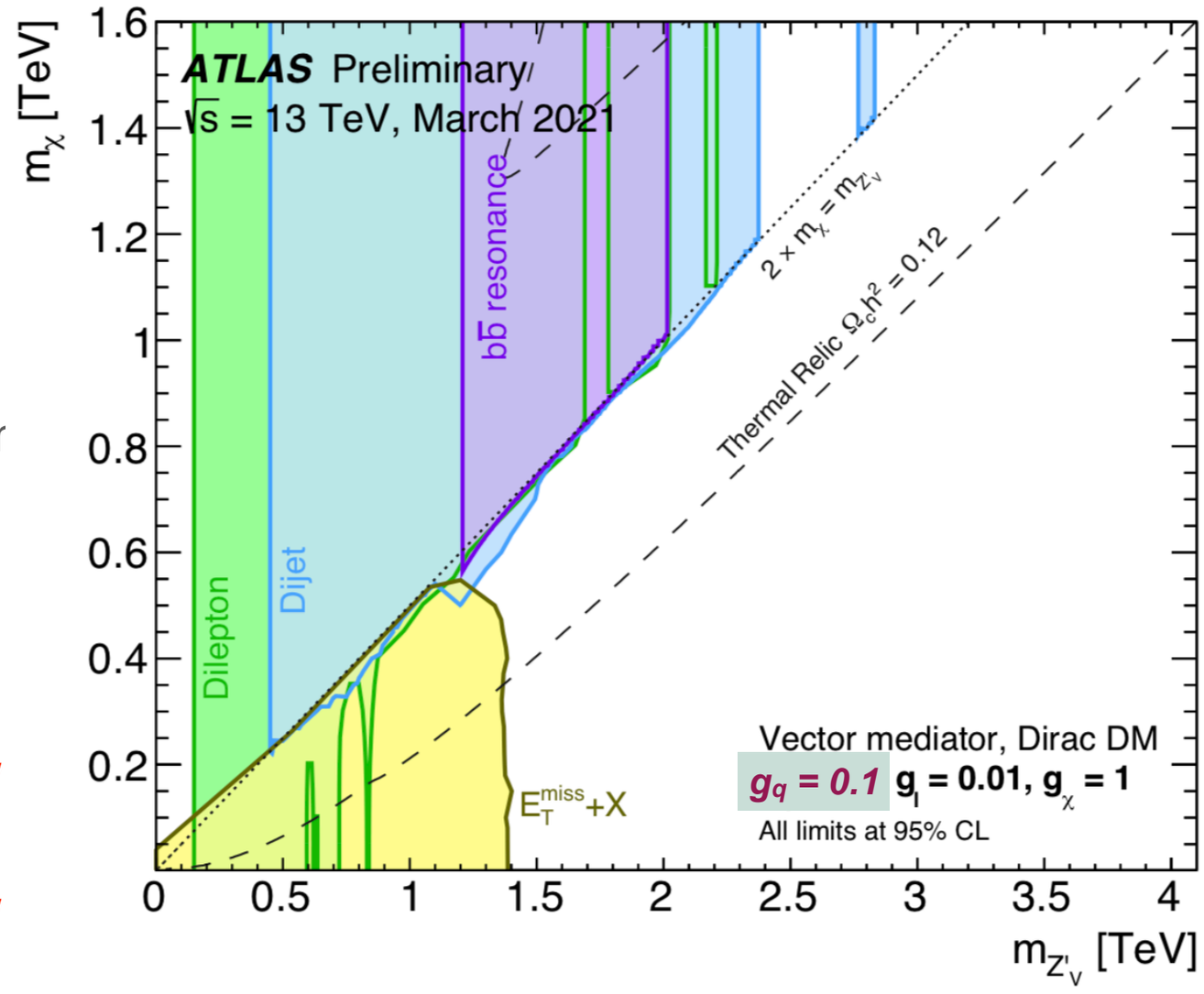


g_q=

- ✱ mediator
  - narrow resonance
  - wide resonance
- ✱ interplay changes

Did we exclude already everything? NO!

✱ ATLAS:ATL-PHYS-PUB-2021-006



Dilepton
139 fb^{-1}
PLB 796 (2019) 68

bb̄ resonance
139 fb^{-1}
JHEP 03 (2020) 145

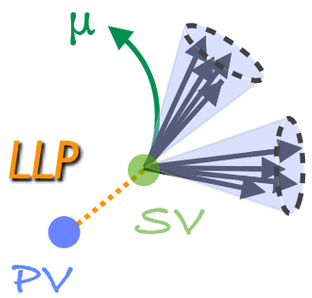
Dijet
Dijet, 139 fb^{-1}
JHEP 03 (2020) 145
Dijet TLA, 29.3 fb^{-1}
PRL 121 (2018) 081801

E_T^{miss}+X
E_T^{miss}+γ, 139 fb^{-1}
arXiv:2011.05259
E_T^{miss}+jet, 139 fb^{-1}
arXiv:2102.10874

LHCb: EPJC373(2022)

Hunt for dark matter - LLPs → μ+jets search

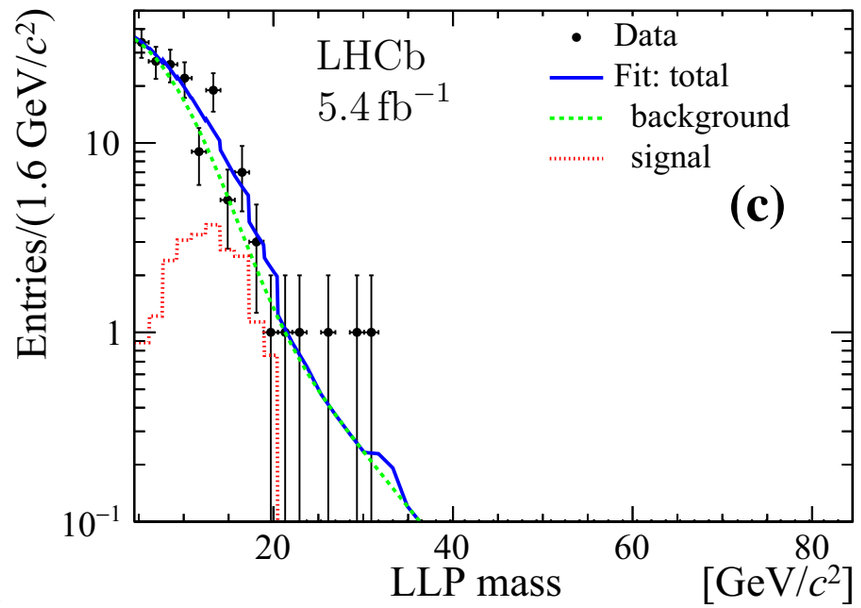
▶ 1- Selection:



- 1 displaced vertex from any PV containing 1μ
- ≥1 LLP candidates : ≥3 tracks (1μ) with inv mass above B resonances
- MVA techniques to recover sensitivity

▶ 2- Bkg:

- *bb processes and material interactions*



▶ 3- Results: combined fit to LLP reconstructed mass in SRs and C

Upper limits at 95% CL on cross section

Massive long-lived particles (LLP)

- (a) Higgs-like particle h^0 produced by ggF, decays into two LLPs
- (b) direct LLP production from quark interactions

heavier particles → lower lifetime/boost

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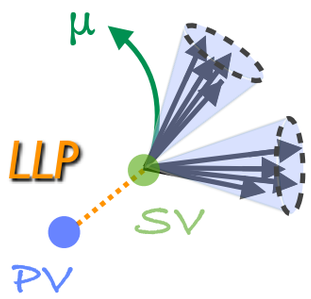

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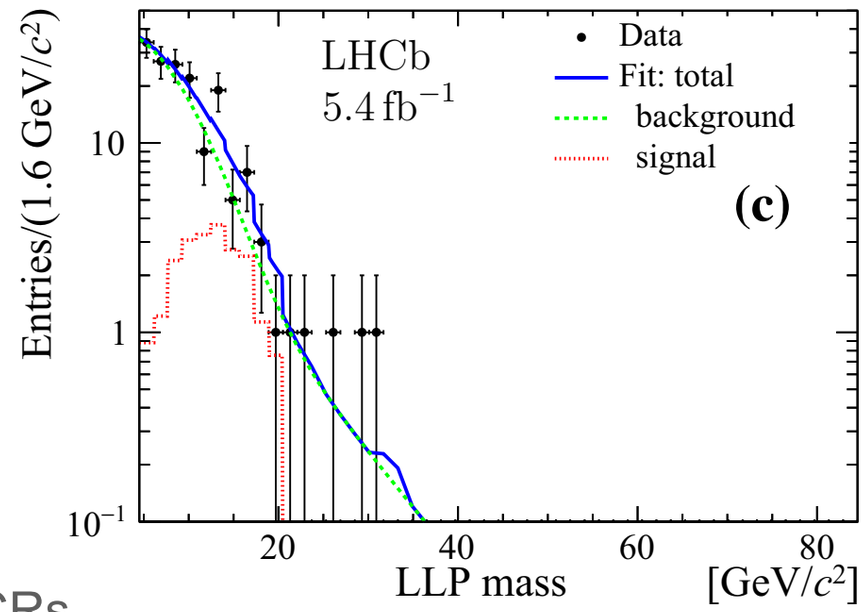

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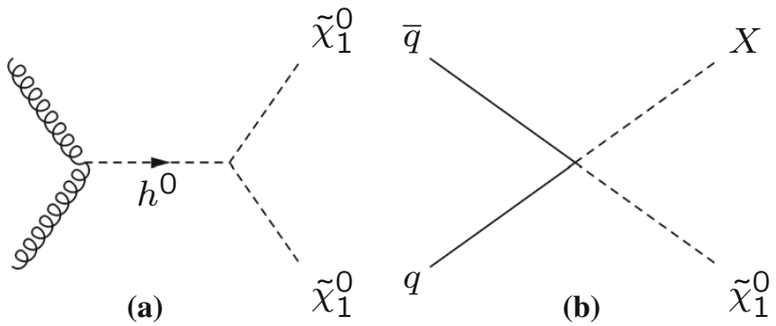

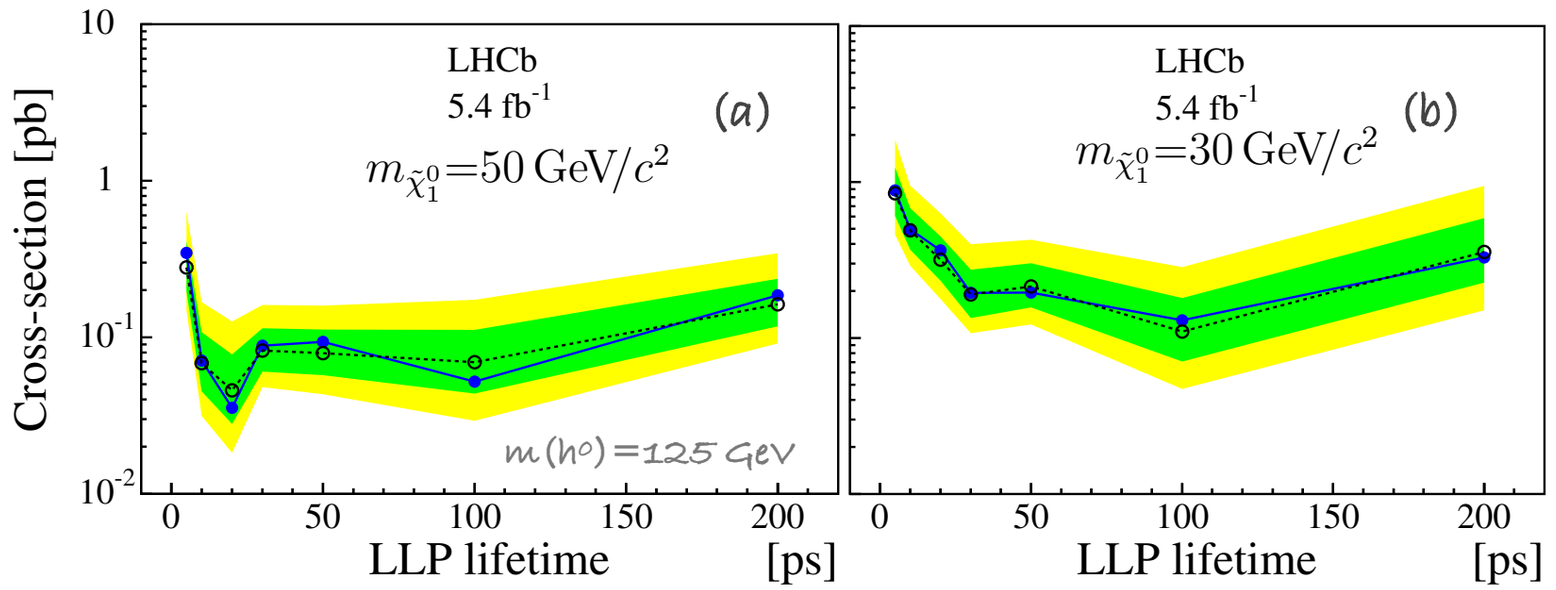

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CMS: EXO-21-005

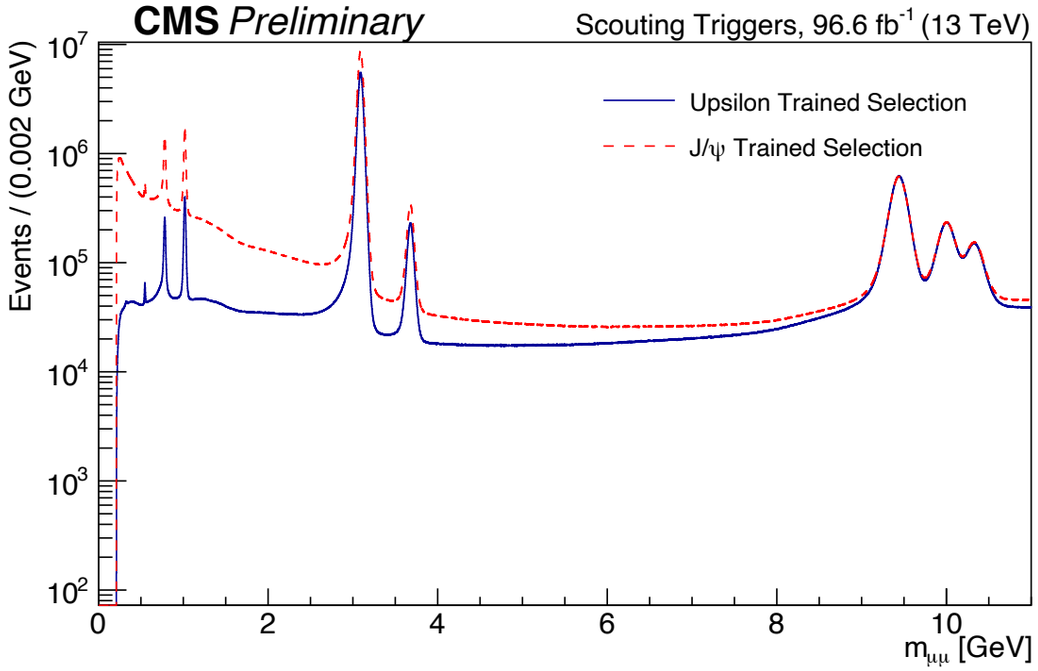
Hunt for dark matter - di-muon low-mass resonances

1 - Selection: resonance as peak wrt SM invariant mass

- 1 opp.-sign μ pair, categories on $p_T(\mu\mu)$
  - dedicated $\mu\mu$ trigger: low p_T thresholds, high rate, retain only 4-momentum, isolation, track information
  - muon identification based on MVA techniques

2 - Bkg:

- known resonances, D meson decays to kaons (from CR)



3- Results: fit to $\mu\mu$ invariant mass, upper limits at 90% CL on mixing coefficient ε

Dark photon: dark/SM sectors interaction through dark photon Z_D, with kinetic mixing ε

Higher sensitivity at low masses

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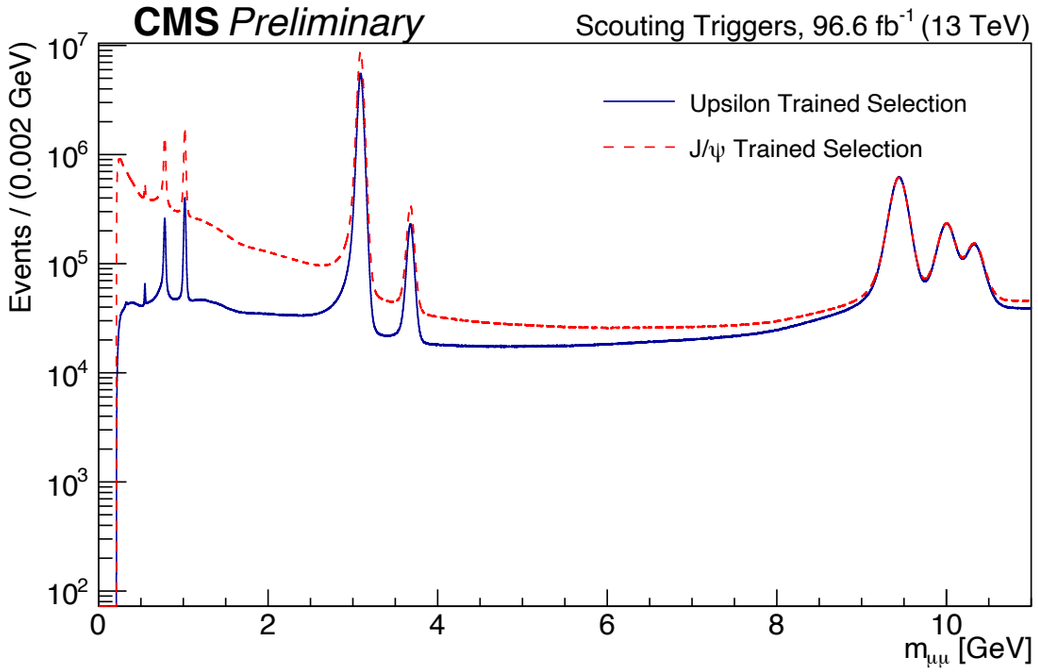

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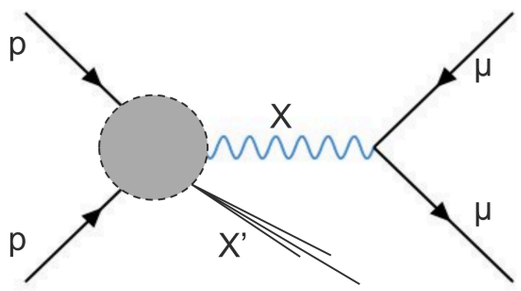

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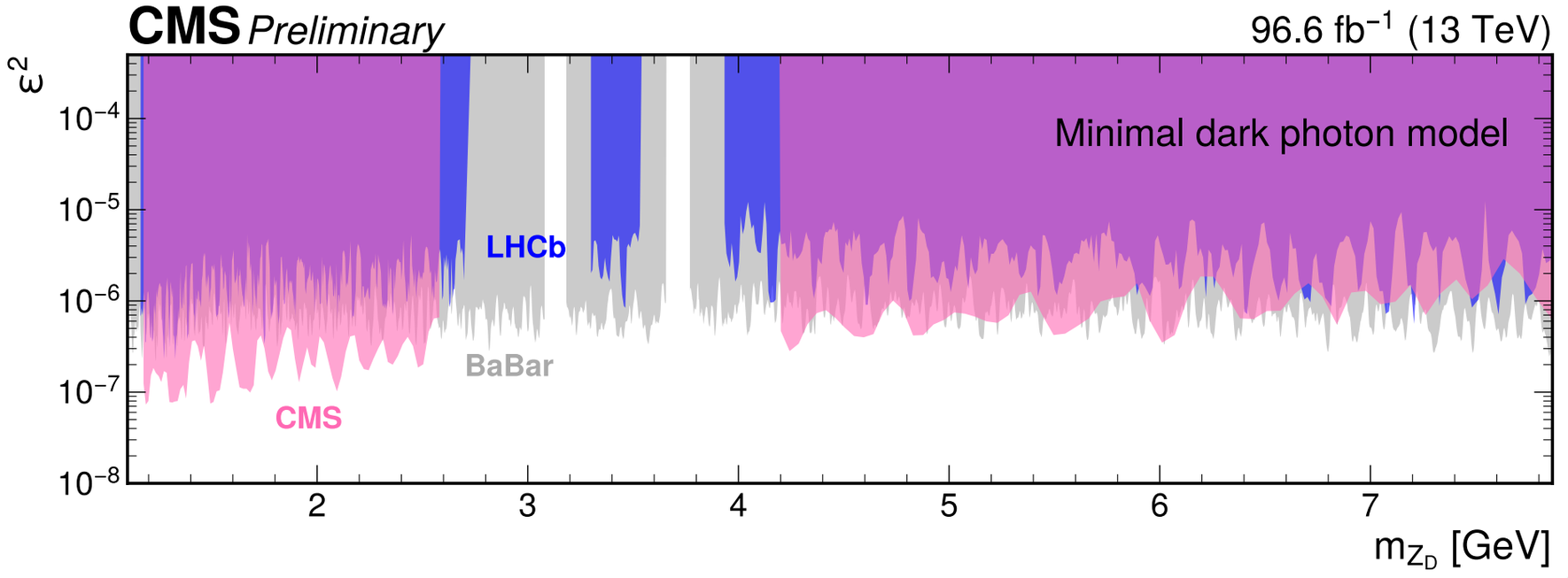
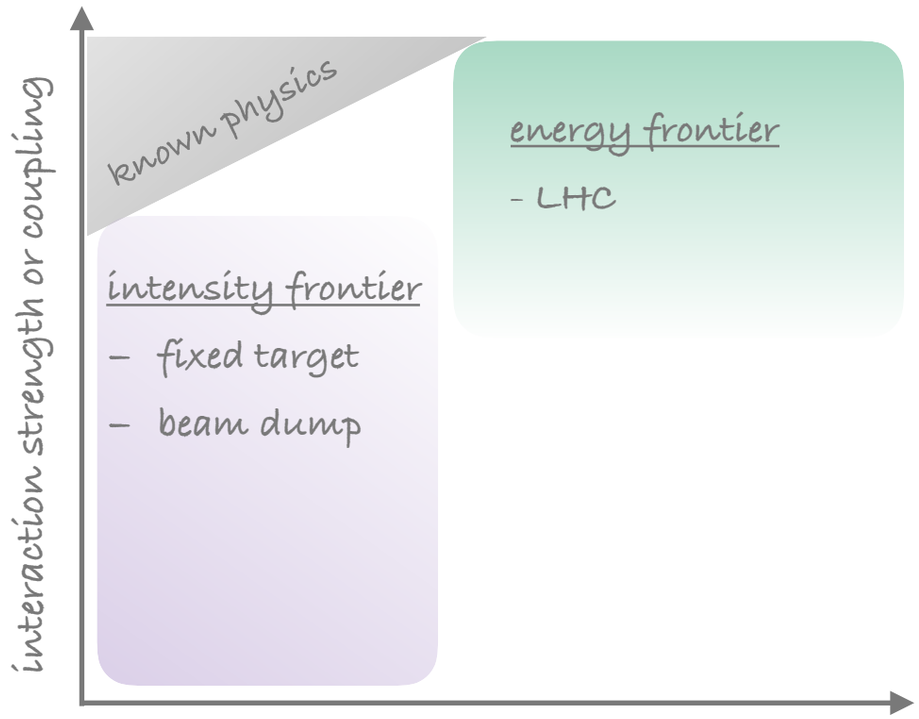


… connecting the ~~dots~~ results

Hunt for dark matter - complementarity

- **Luminosity:** determines size of coupling that can be probed
- **Energy:** determines probed mass range
- **Invisible/visible:** directly probe DM or mediator



Complementarity essential!

- results often presented in terms of different mediator masses, notation and model assumptions

Concerted effort to align models and representation to exploit complementary of energy- and intensity-frontiers to discover DM/dark-sector

… also with direct-detection

- *accelerator-based* directly characterize DM particle properties, explore relativistic DM production
- *direct detection* explores a combination of DM properties with their cosmological abundance, probe non-relativistic scattering

Different type of interactions can be suppressed or enhanced based on velocity → complementarity

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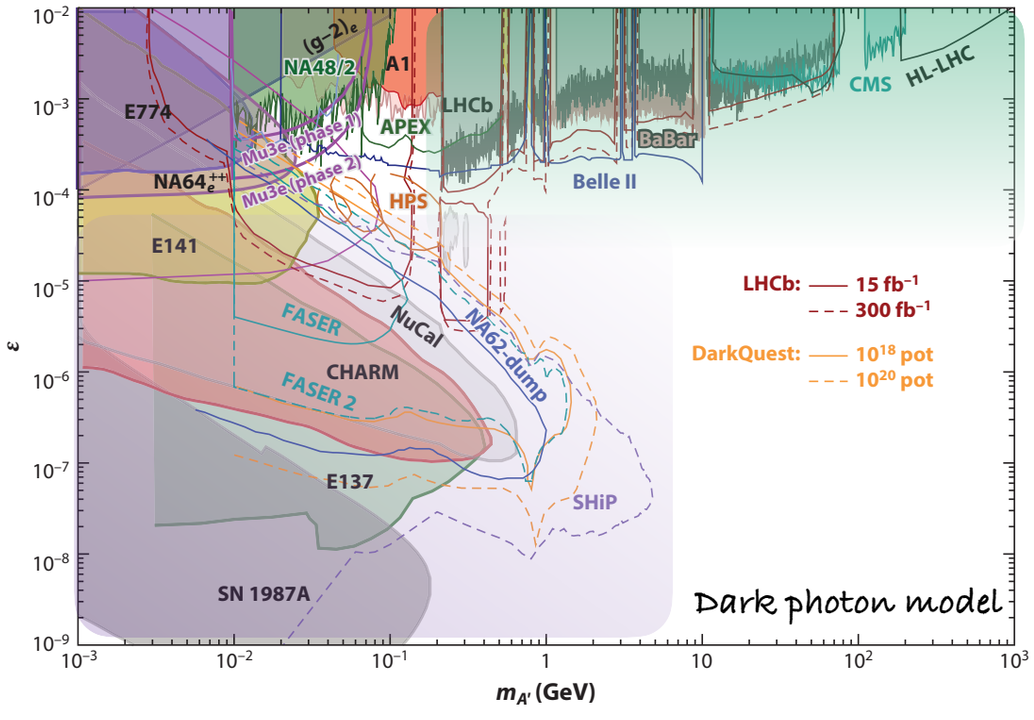

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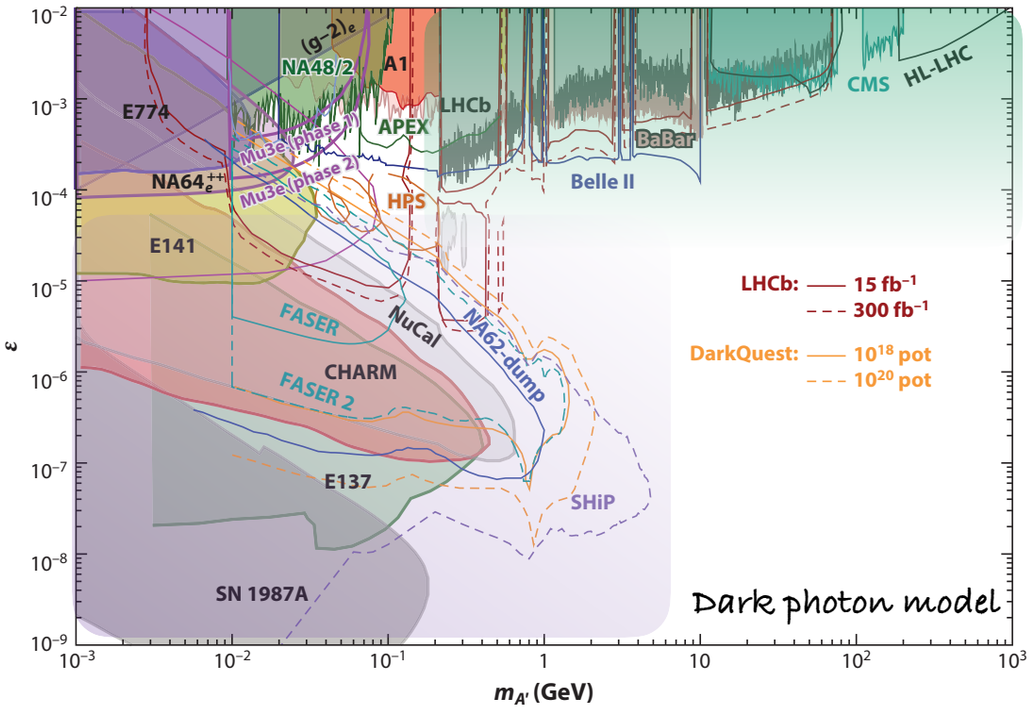

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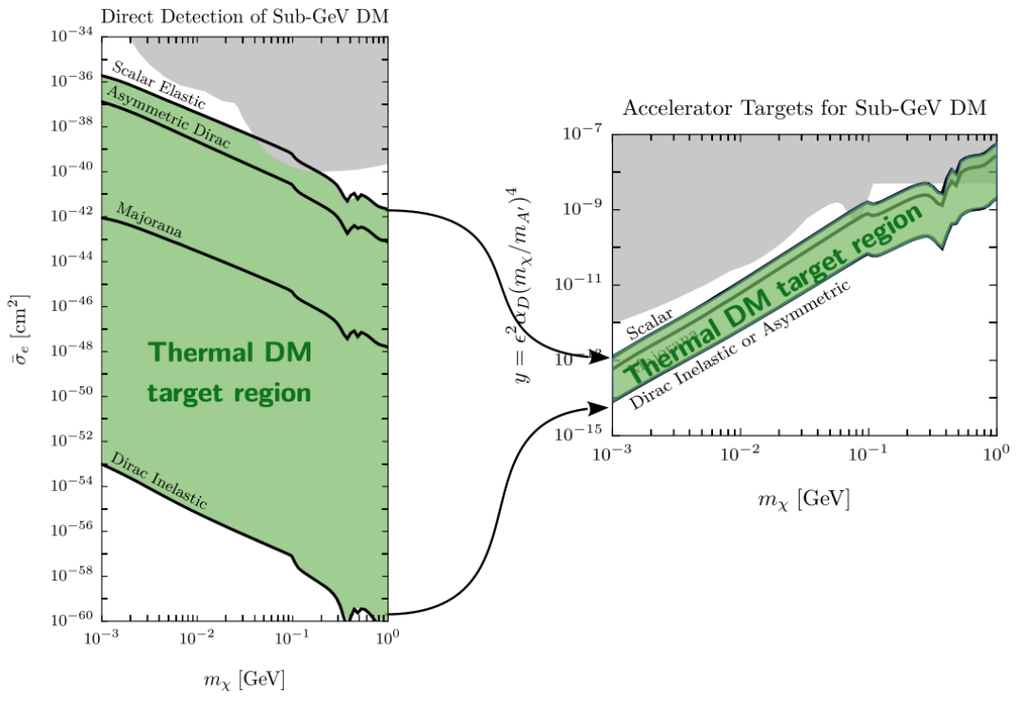

Hunt for dark matter - in a nutshell

DM nature
(large region of parameter space of DM models excluded)

assume interaction with SM

DM/dark-sector production

different interactions/signature

benchmark models to interpret the results

- Rich DM physics program at high-energy and high-intensity experiments
  - essential complementarity among experiments and with non-collider searches
  - inputs from various signatures (mono-X, resonances, H→inv, visible, …)
- Many new results/experiments expected in the near future!

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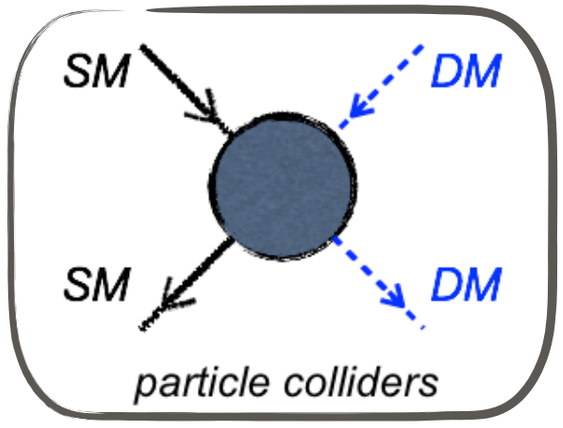

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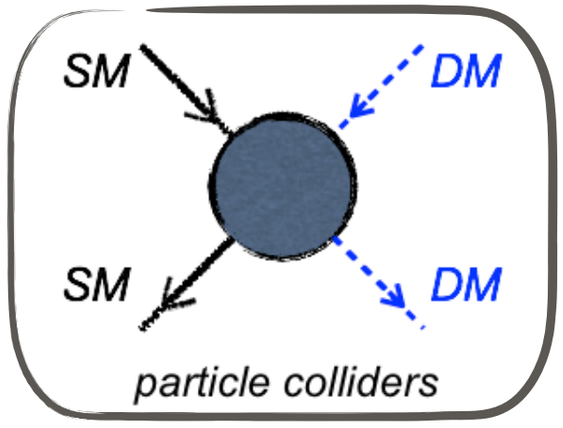

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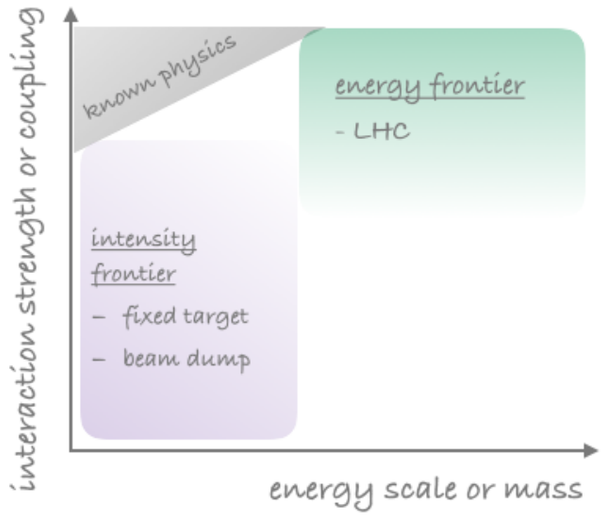

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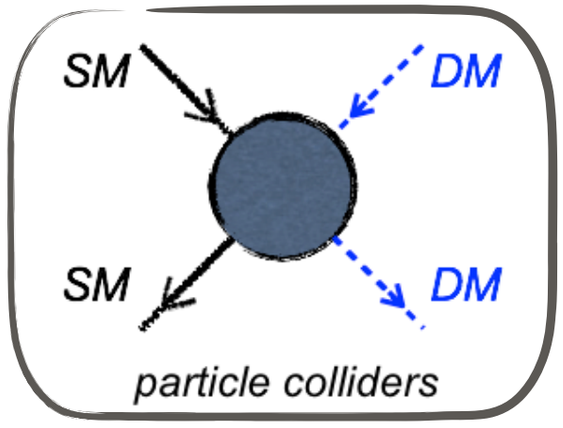

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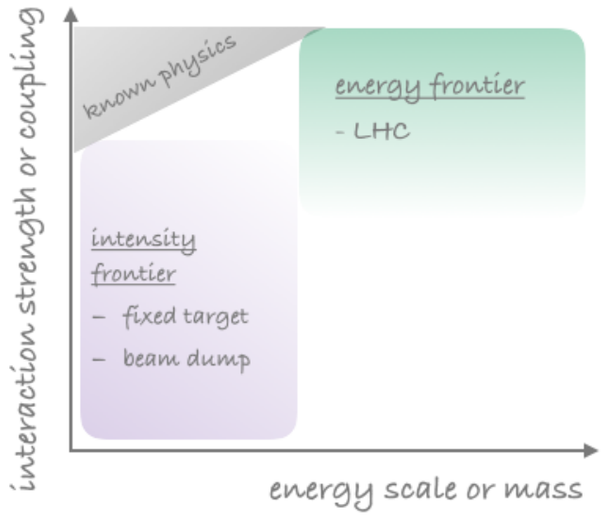

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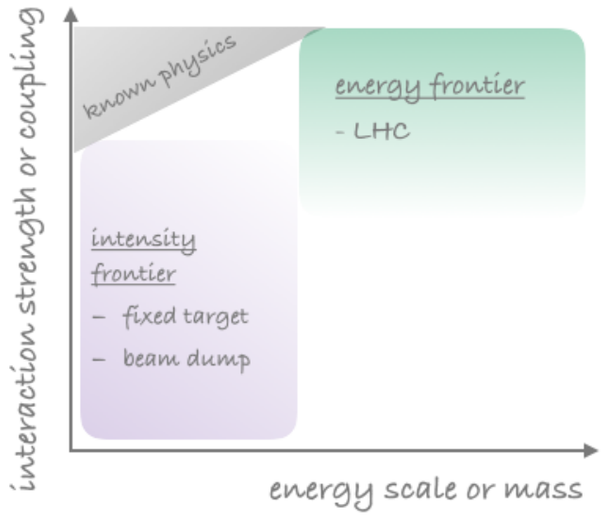

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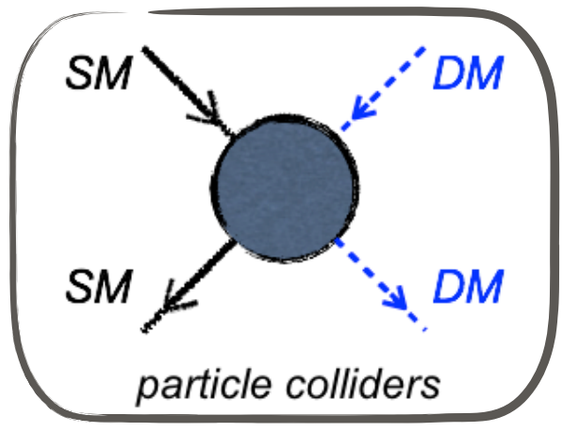

benchmark models to interpret the results

- Rich DM physics program at LHC
  - essential complementarity among experiments and with non-collider searches
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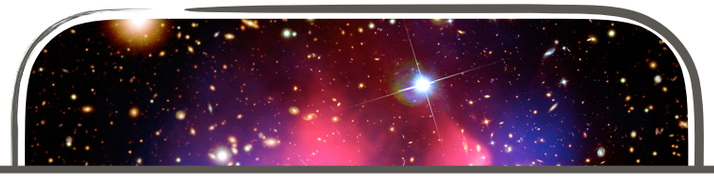
Hunt for dark matter - in a nutshell

re



assume interaction

An eye towards the (near) future

New physics working group (LHC BSM WG)

guidelines and recommendations for the benchmark models, interpretation, and characterisation of BSM searches at the LHC

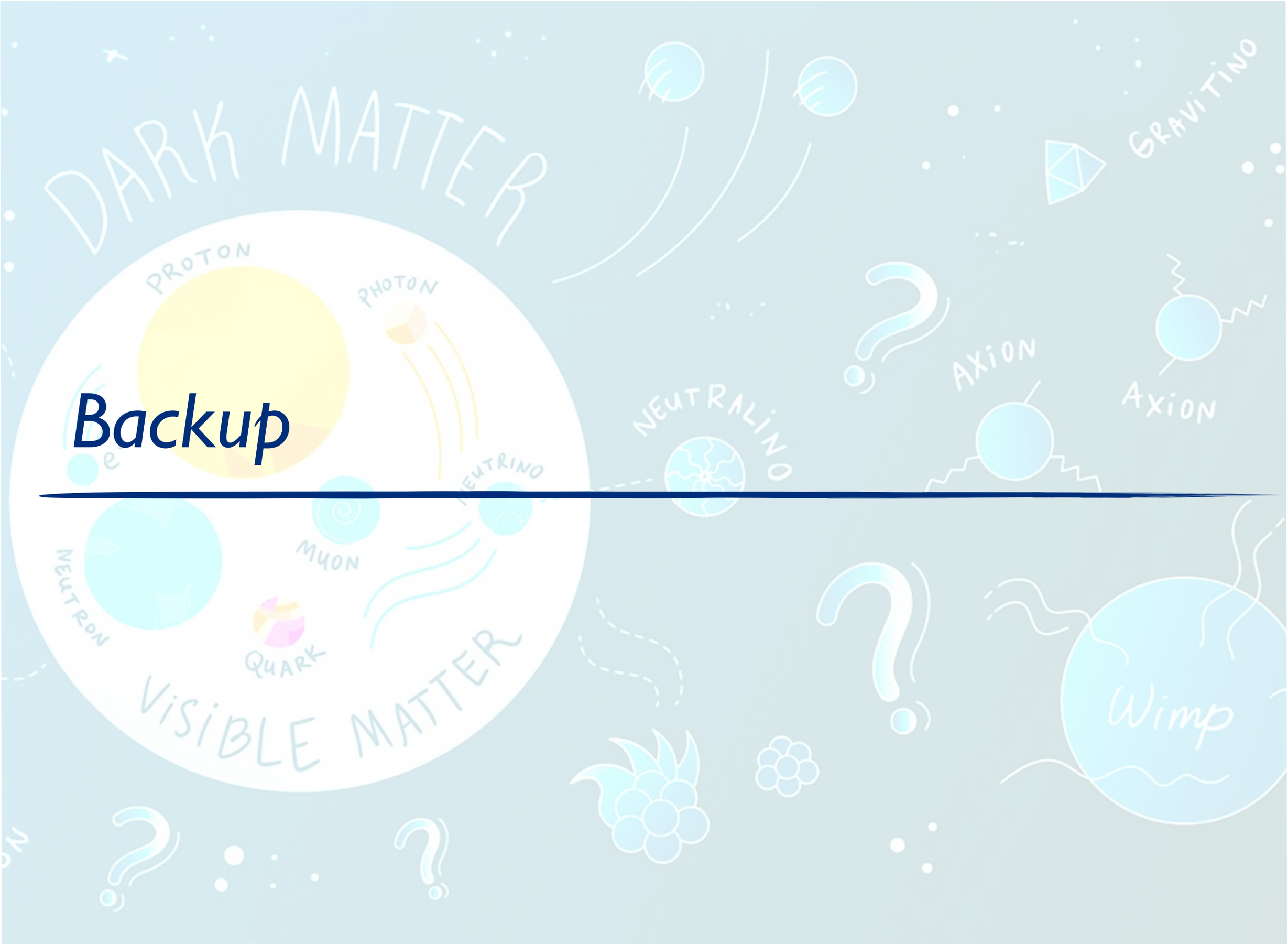
first general meeting in 10-13 November 2025 (indico)

- inputs from various signatures (mono-X, resonances, H→inv, visible, …)

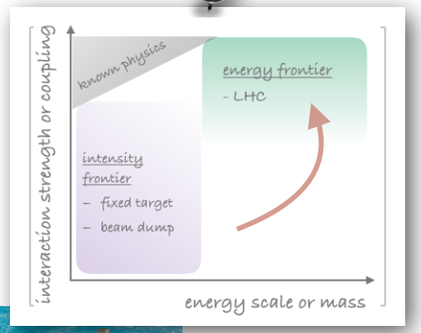
Many new results/experiments expected in the near future!

Thank you!

Backup

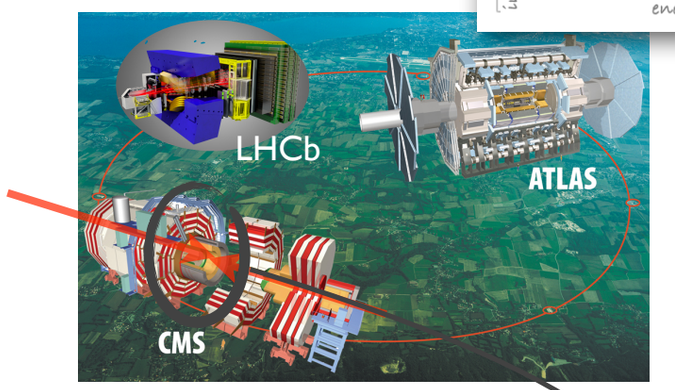

DARK MATTER
PROTON
PHOTON
NEUTRALINO
AXION
AXION
GRAVITINO
MUON
NEUTRON
QUARK
VISIBLE MATTER
Wimp

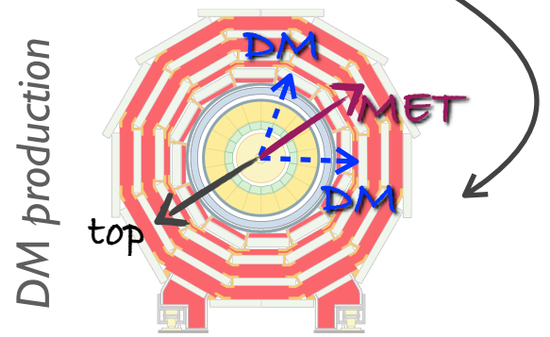
Collider experiments: ATLAS, CMS, LHCb



ATLAS and CMS multipurpose detectors at LHC

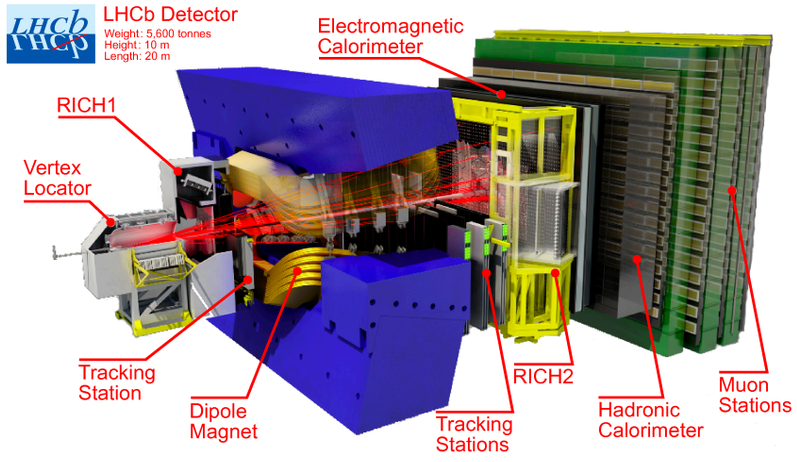
- goals: precision test of SM, search for new physics
- particle identification, energy and momenta measurements
- trigger system: select events interesting for physics analysis
- pp collisions
  - Run2: 13 TeV, ~140 fb^{-1} | Run3: 13.6 TeV, already collected ~70fb^{-1}
  - more than 8.5 million Higgs boson produced!
- DM could be produced at colliders (rare process):
  - invisible signature: no direct trace in the detector, but …
    - can be inferred from p_T imbalance (***MET***)
    - need visible particle to which DM particle recoils against "mono-X"





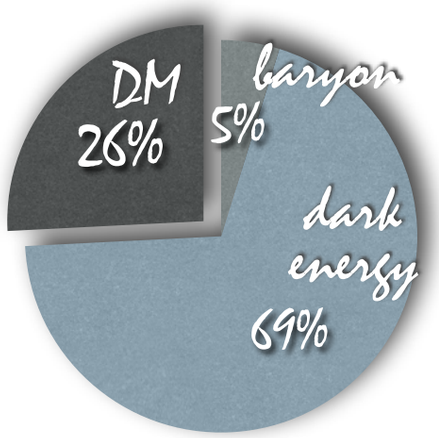
LHCb at LHC

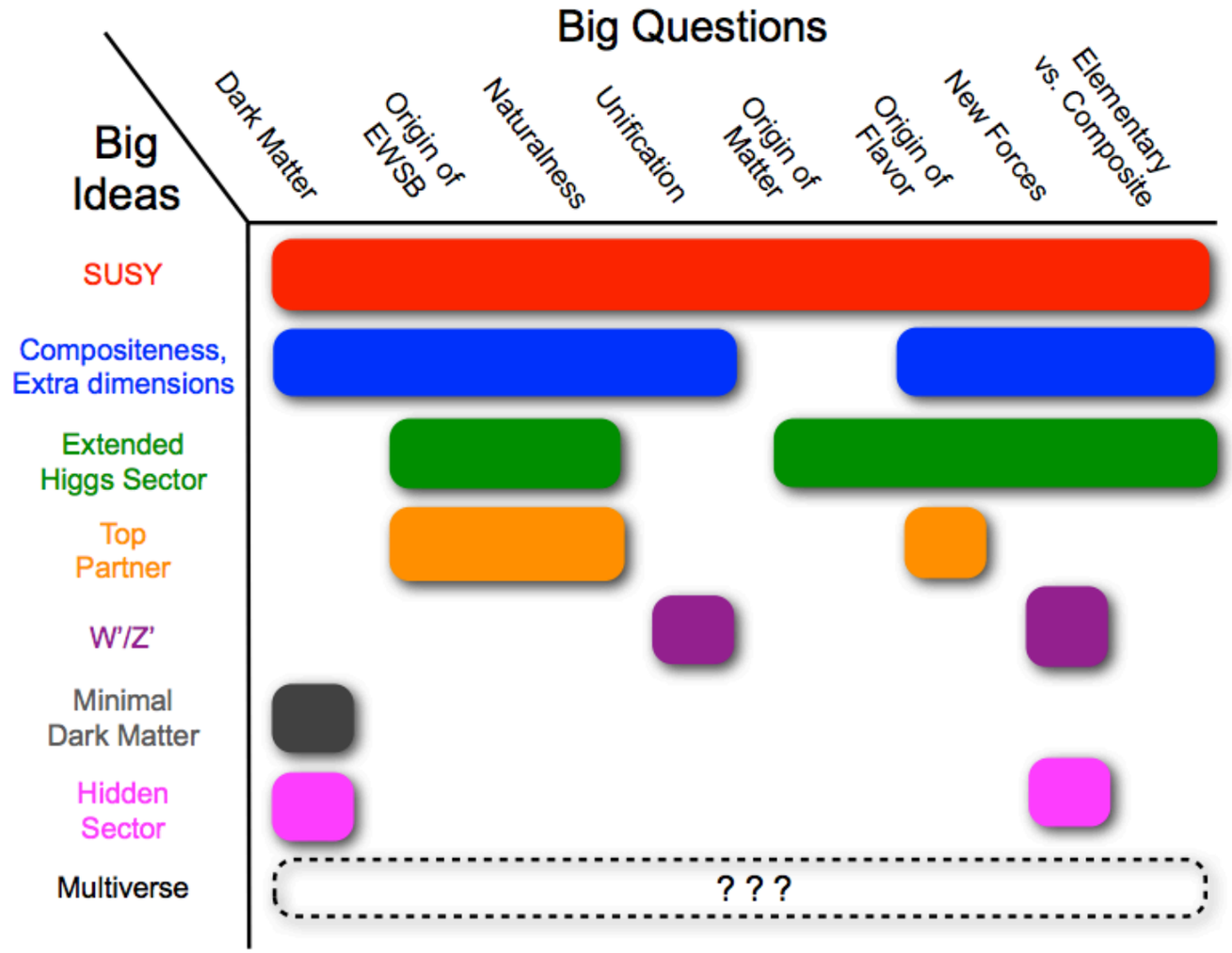
- single-arm spectrometer originally devoted to heavy flavour physics, now a general purpose experiment
- triggers with low p_T thresholds, probes rapidity region only partially accessible to other LHC experiments
- excellent vertex, mass and lifetime resolution, particle identification
- can operate in collider and fixed target mode
- pp collisions: ~1/20 ATLAS/CMS, reduced luminosity by offset beam collisions



Rich new physics program at ATLAS and CMS

- *Despite the accuracy of the SM and its predictive power many open outstanding questions, eg.:*
  - matter-antimatter asymmetry
  - hierarchy problem
  - describes only ~5% of the universe, explanations for DM are not provided
  - gravitational force cannot be included in the current theoretical framework





[arXiv:1311.0299]