Dark Matter Searches at Colliders

on behalf of the ATLAS and CMS collaborations

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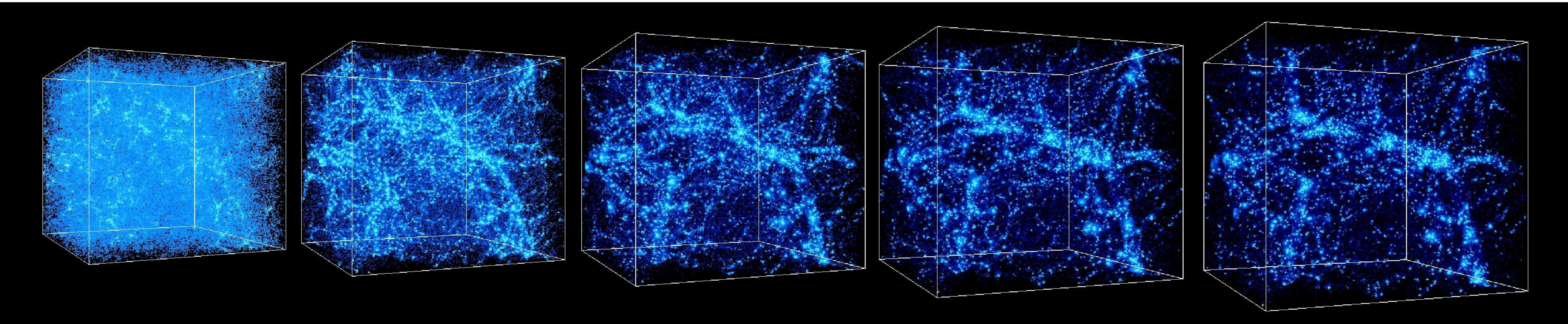
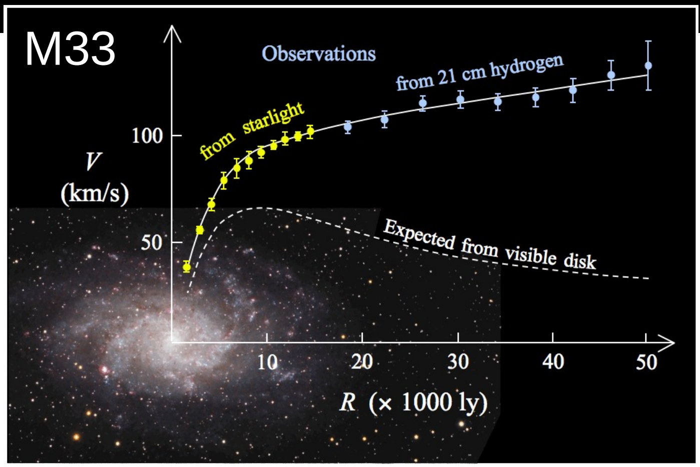
XIX International Conference on Topics in Astroparticle and Underground Physics (TAUP2025)

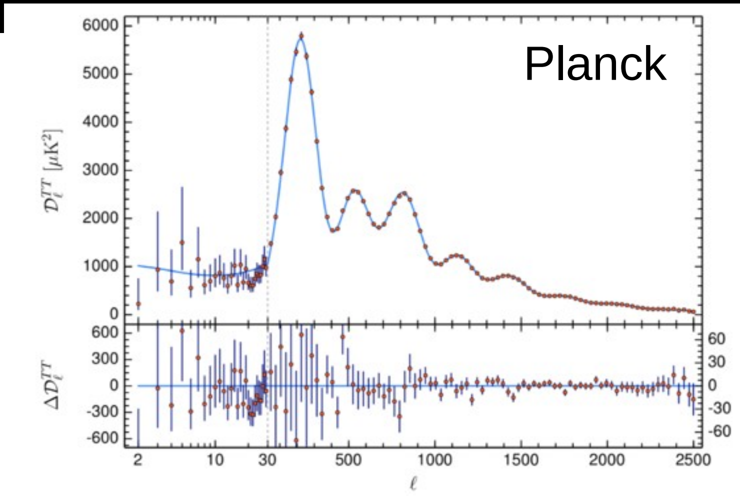
26 August 2025
Xichang, China

¿Dark matter?

Simulations on NCSA by A. Kravtsov (Uchicago) and A. Klypin (NMSU); visualization by A. Kravtsov



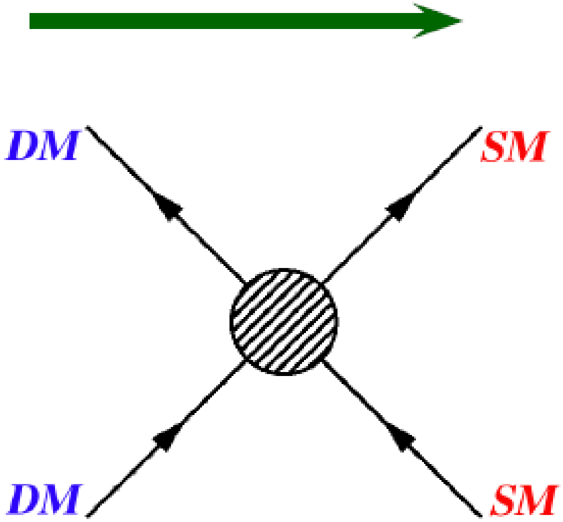


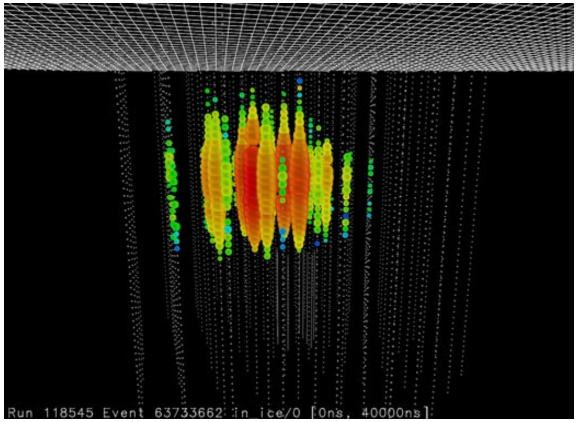


Dark Matter: ample gravitational evidence from the smallest to the largest scales

intense hunt for the discovery of the nature of dark matter

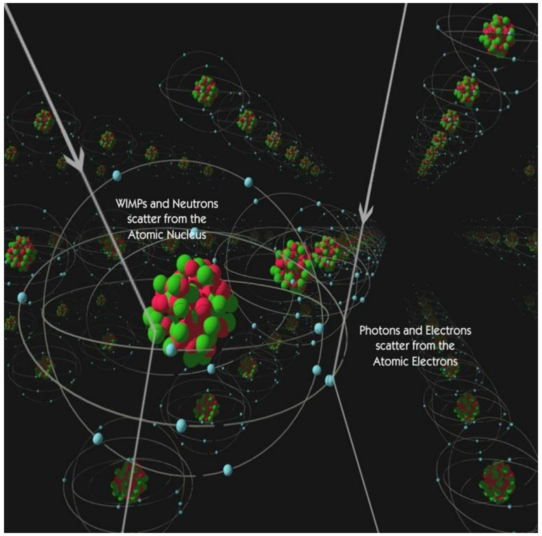
Hunting Dark Matter

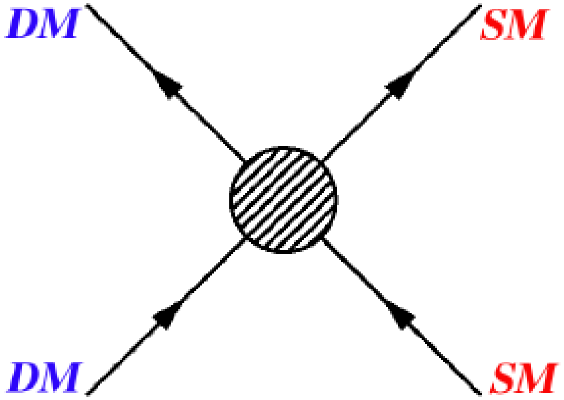




break it!

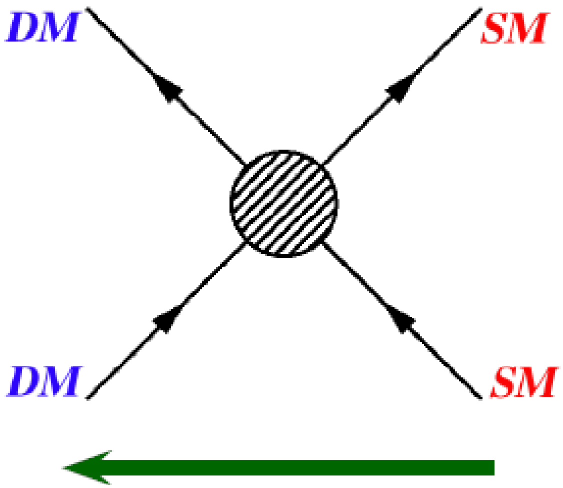
Hunting Dark Matter





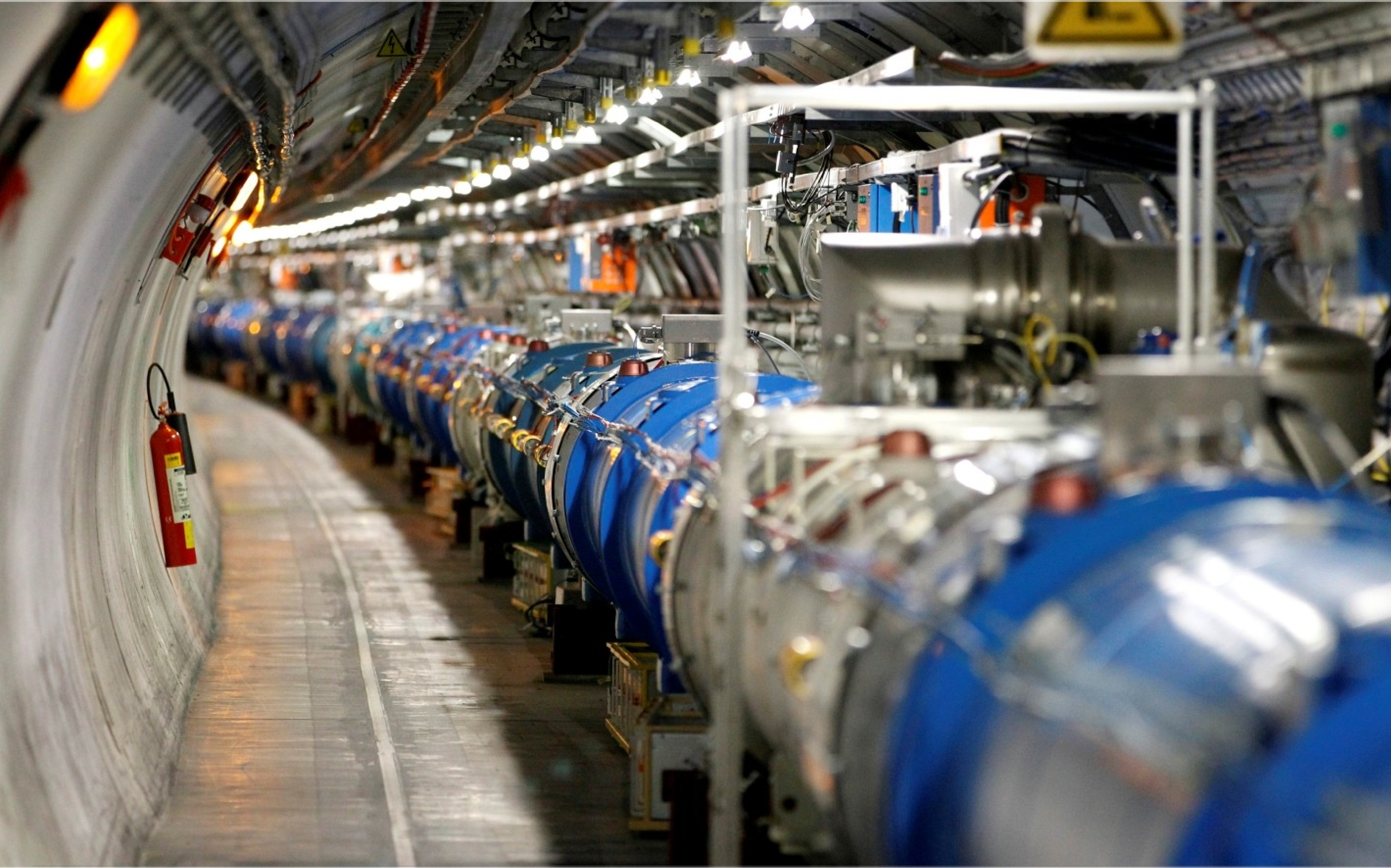
shake it!

Hunting Dark Matter

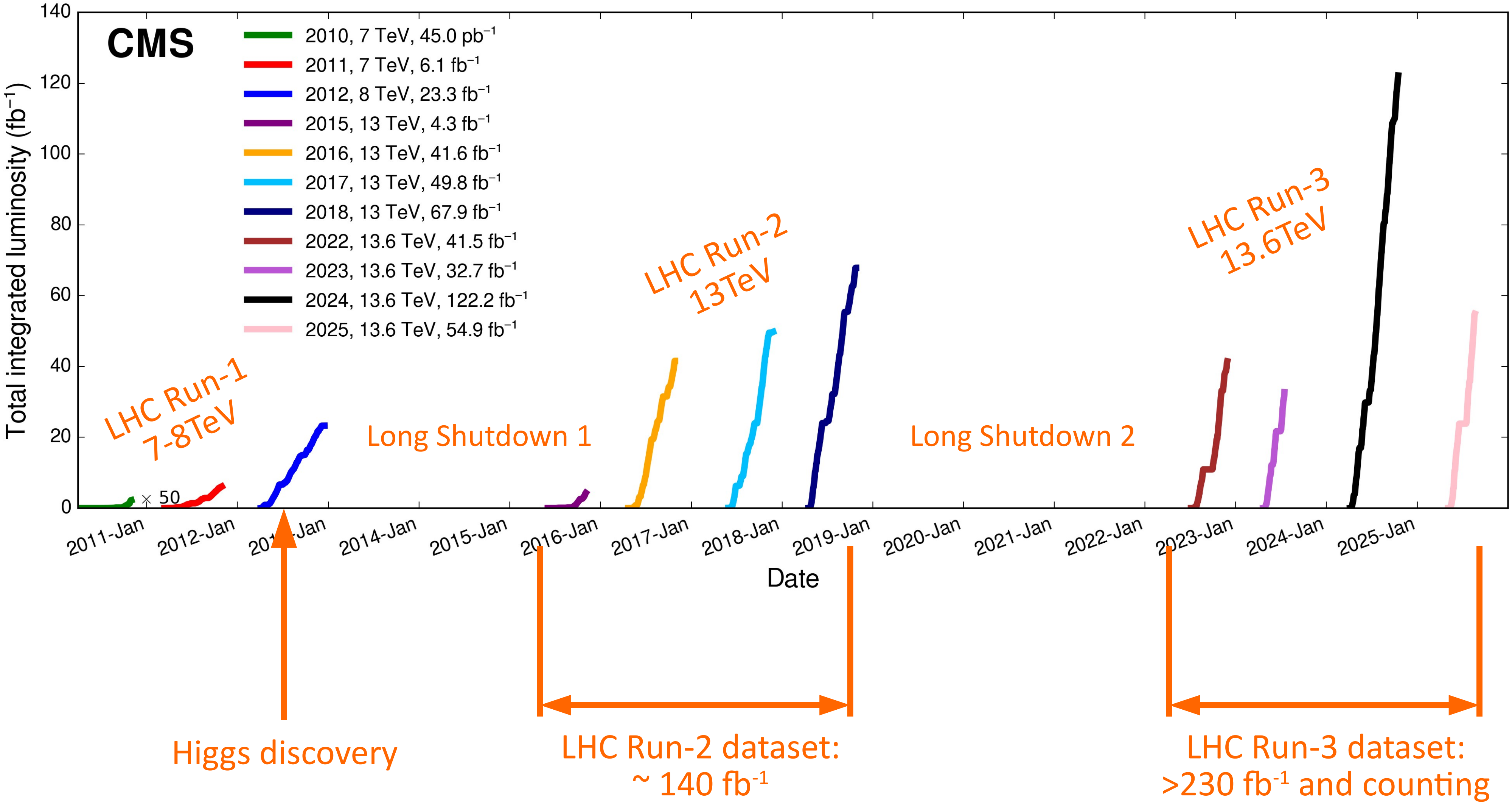


make it!

The LHC

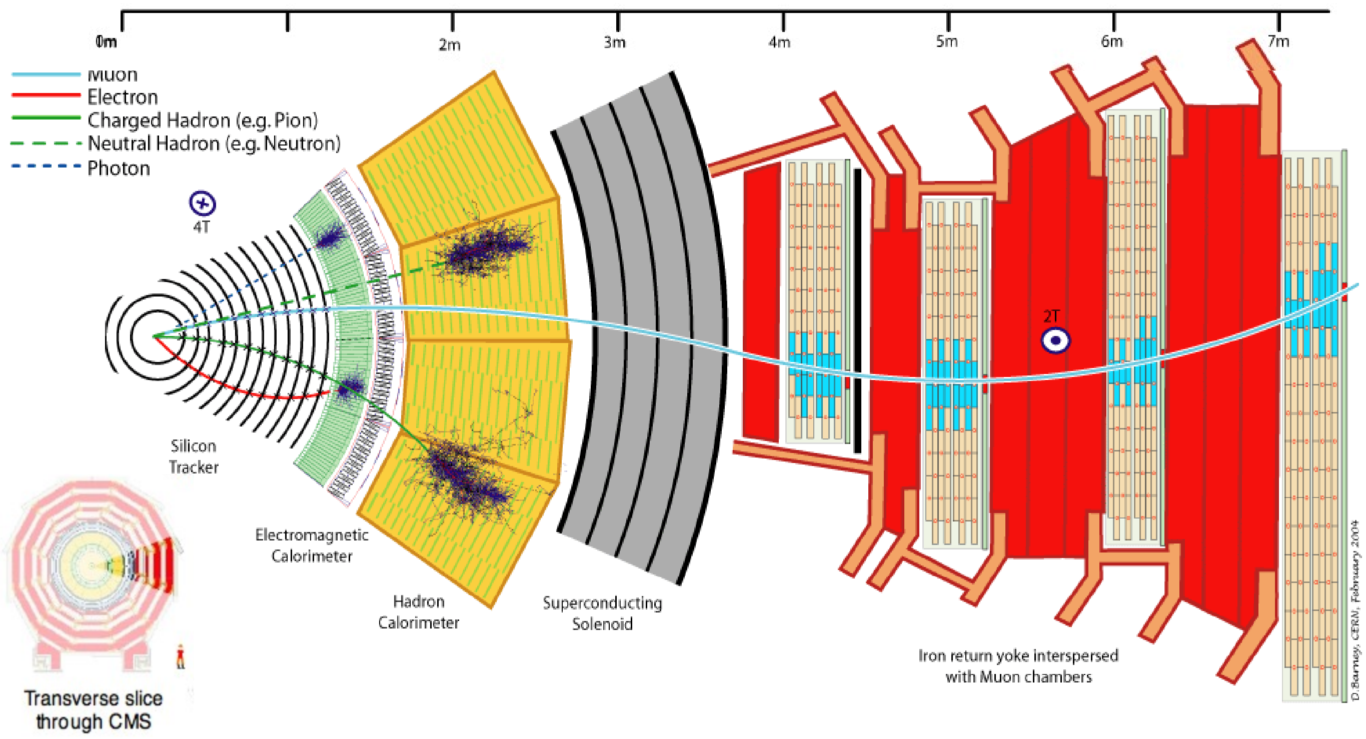


The LHC dataset



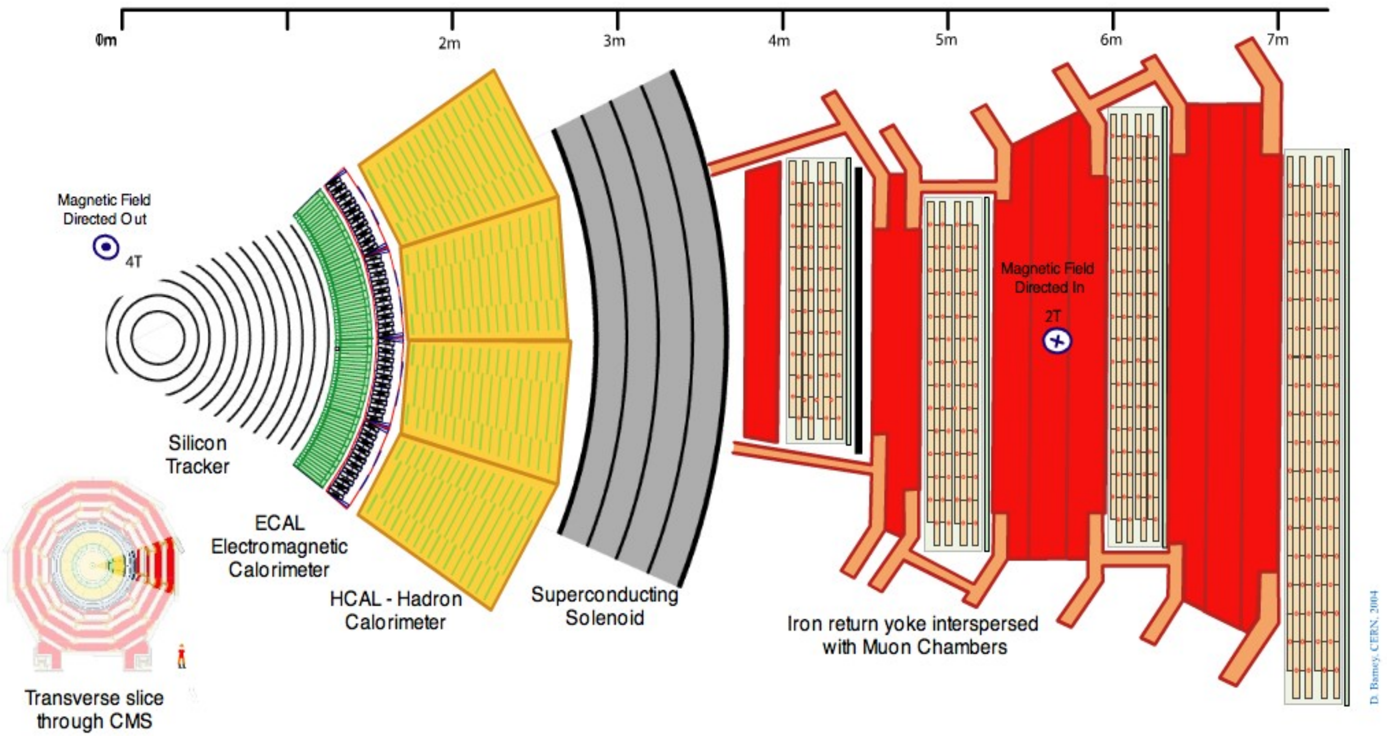
Dark Matter at the LHC

Collider experiments as DM hunters



Dark Matter at the LHC

Collider experiments as DM hunters



- original focus on WIMP-like particles: no interaction in detector
  - experimental signature: transverse momentum imbalance (MET)

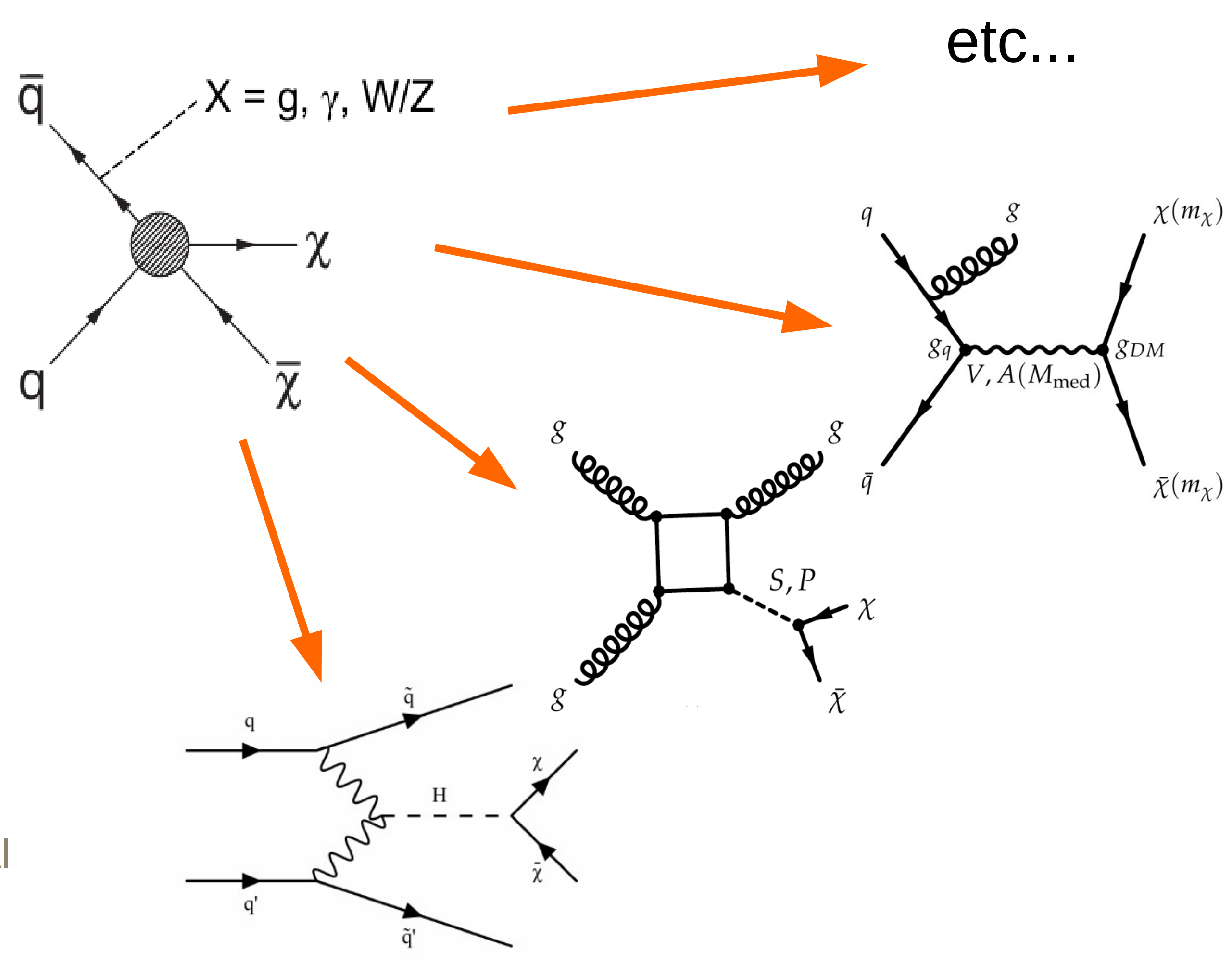
Collider experiments as DM hunters

- Dark Matter is one of the main LHC physics goals
  - it's a vast field, only some highlights
- once we find a deviation, interpretation will be challenging!
  - colliders cannot prove stability beyond the apparatus
  - colliders may not distinguish single from multiple new invisible particles
  - colliders provide poor mass resolution on the invisible (if any)
  - colliders may have no handle on nature of interaction, particle type, quantum numbers,…
- the discovery paper may not mention “Dark Matter” at all

Modelling DM production

Mediator focus

- the LHC's strength is to produce the mediator on-shell
- we must make the mediator explicit
  - an EFT "blob" is not sufficient



- model description
  - mediator type
  - production mode
  - couplings to q and DM
  - mediator and DM mass
  - consider beyond the minimal

Modelling DM production

- simplified models: SM + only few particles
  - new physics restricted to what is relevant for a certain topology
  - aim for maximal experimental coverage of that topology
  - mediator and interactions explicit
  - building blocks for recasting results in full models
  - parameter scans manageable
- 2015: LHC DM Forum
  - LHC DM searches standardized on simplified models
  - bottom-up guidelines for LHC dark-matter searches at the start of LHC Run-2
- continues in LPCC LHC DM Working Group
  - eg. common basis to present LHC results wrt other LHC and non-LHC experiments
  - most recent: arXiv:2504.10597 t-channel dark matter at the LHC

arXiv.org > hep-ex > arXiv:1507.00966 **arXiv:1507.00966 [hep-ex]** Search or Article-id

High Energy Physics - Experiment

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillelmo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristan du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, et al. (94 additional authors not shown)

(Submitted on 3 Jul 2015)

arXiv.org > hep-ex > arXiv:1603.04156 **arXiv:1603.04156 [hep-ex]** Search or Article ID (Help | Advanced search)

High Energy Physics - Experiment

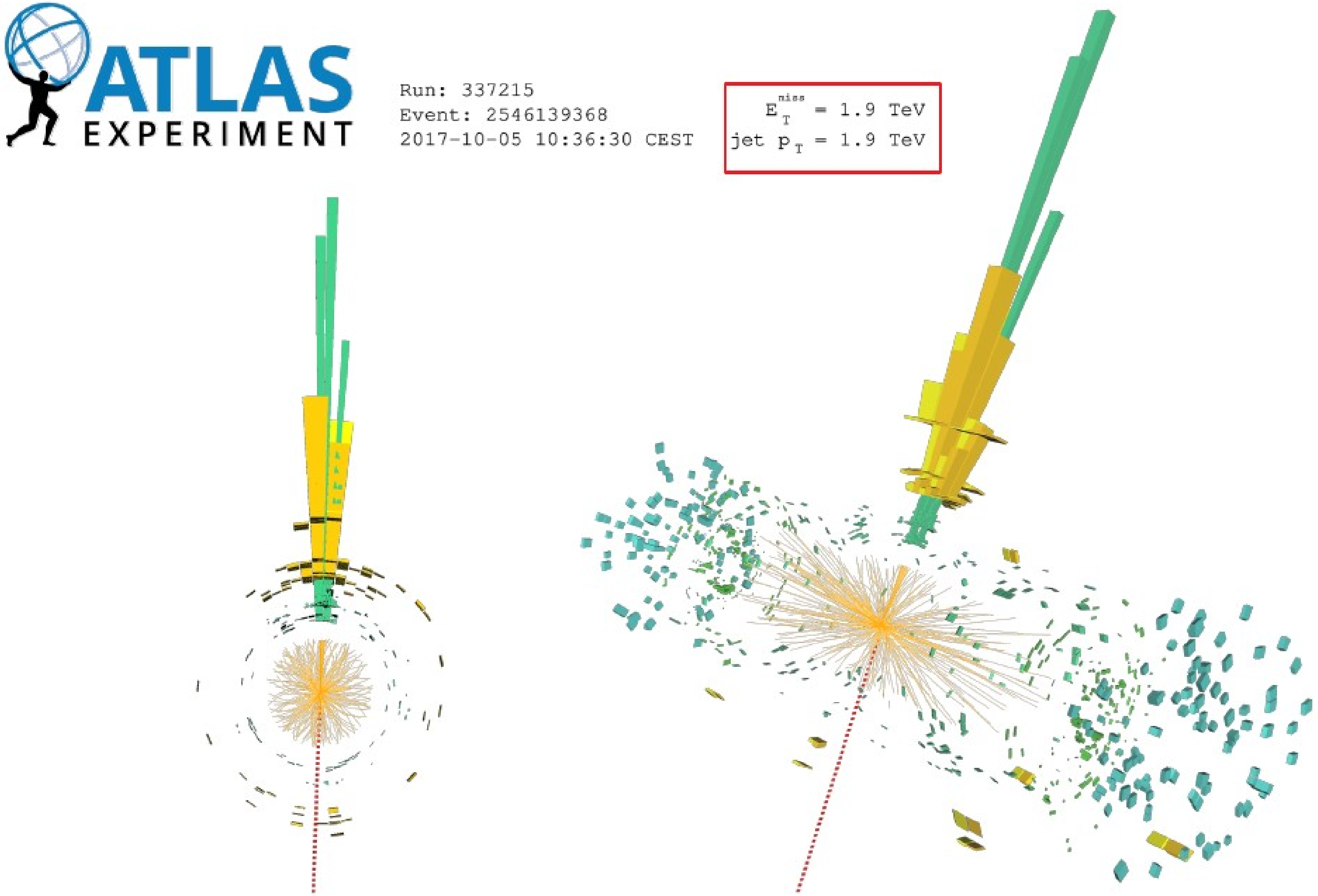
Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

Antonio Boveia, Oliver Buchmueller, Giorgio Busoni, Francesco D'Eramo, Albert De Roeck, Andrea De Simone, Caterina Doglioni, Matthew J. Dolan, Marie-Helene Genest, Kristian Hahn, Ulrich Haisch, Philip C. Harris, Jan Heisig, Valerio Ippolito, Felix Kahlhoefer, Valentin V. Khoze, Suchita Kulkarni, Greg Landsberg, Steven Lowette, Sarah Malik, Michelangelo Mangano, Christopher McCabe, Stephen Mrenna, Priscilla Pani, Tristan du Pree, Antonio Riotto, David Salek, Kai Schmidt-Hoberg, William Shepherd, Tim M.P. Tait, Lian-Tao Wang, Steven Worm, Kathryn Zurek

(Submitted on 14 Mar 2016)

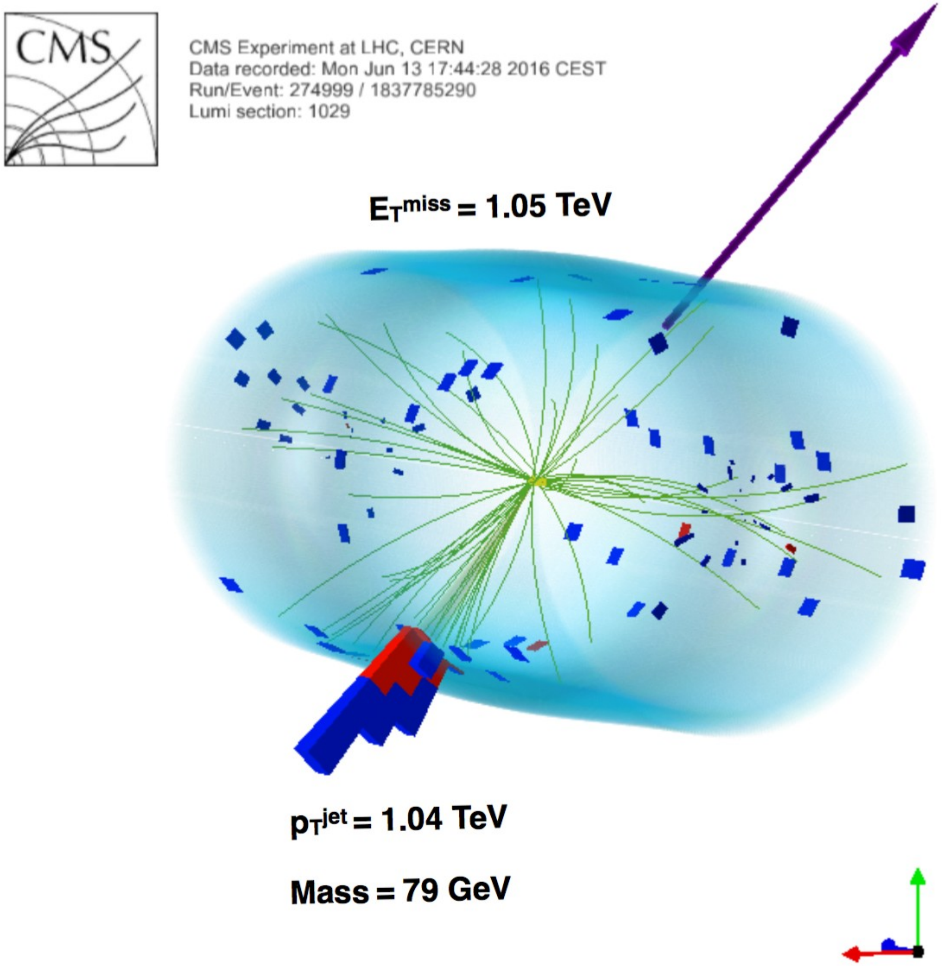
Experimental status

Spectacular spectacular!



Experimental status

Spectacular spectacular!



Direct DM production

ATLAS

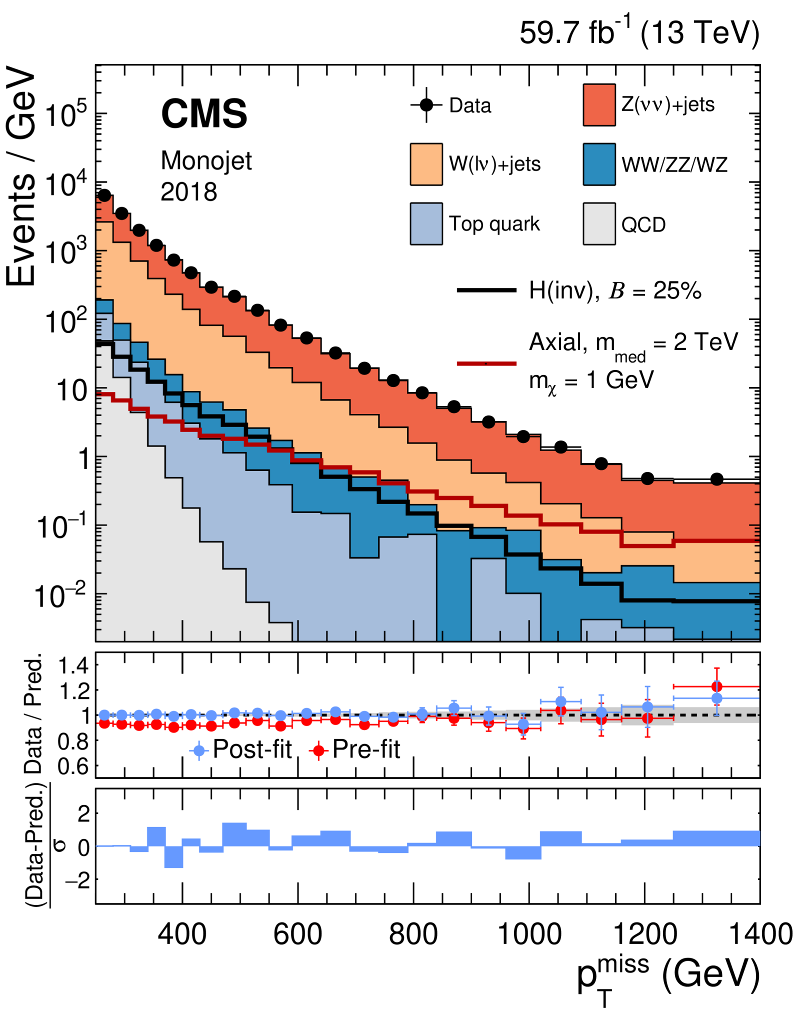
- MET+jet / V(qq)
  - 139fb^{-1} – PRD 103 (2021) 112006
  - 140fb^{-1} – JHEP 11 (2024) 126
- MET+γ
  - 139fb^{-1} – JHEP 02 (2021) 226 (incl.)
  - 139fb^{-1} – EPJC 82 (2022) 105 (VBF)
- MET+Z(ll)
  - 139fb^{-1} – PLB 829 (2022) 137066
- MET+tt/bb
  - 139fb^{-1} – JHEP 04 (2021) 165
  - 139fb^{-1} – EPJC 83 (2023) 503
- MET+t
  - 139fb^{-1} – EPJC 81 (2021) 860 (leptonic)
  - 139fb^{-1} – JHEP 05 (2024) 263 (hadronic)
  - 139fb^{-1} – EPJC 83 (2023) 603 (tW)
- MET+H/s
  - 139fb^{-1} – JHEP 11 (2021) 209 (bb)
  - 139fb^{-1} – PRL 126 (2021) 121802 (WW/ZZ hadr)
  - 139fb^{-1} – JHEP 07 (2023) 116 (WW 1lep)
  - 139fb^{-1} – JHEP 10 (2021) 13 (γγ)
- H(χχ)
  - 5fb^{-1}+20fb^{-1} +139fb^{-1} – PLB 842 (2023) 137963 (all modes)

CMS

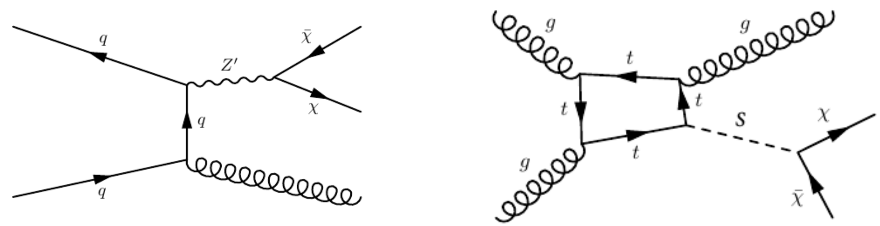
- MET+jet / V(qq)
  - 137fb^{-1} – JHEP 11 (2021) 153
- MET+γ
  - 36fb^{-1} – JHEP 02 (2019) 074
- MET+Z(ll)
  - 137fb^{-1} – EPJC 81 (2021) 13
- MET+tt/t
  - 138fb^{-1} – arXiv:2505.05300
- MET+t
  - 138fb^{-1} – arXiv:2503.20033
- MET+bb
  - 138fb^{-1} – JHEP 02 (2025) 050
  - 138fb^{-1} – CMS-PAS-SUS-23-013
- MET+H
  - 36fb^{-1} – JHEP 03 (2020) 025 (bb,γγ,ZZ)
  - 137fb^{-1} – JHEP 03 (2024) 134 (WW)
  - 138fb^{-1} – arXiv:2506.04431 (ττ)
- H(χχ)
  - 5fb^{-1}+20fb^{-1}+140fb^{-1} – EPJC 83 (2023) 933 (all modes)

Direct DM production

“Monojet” search as poster child example



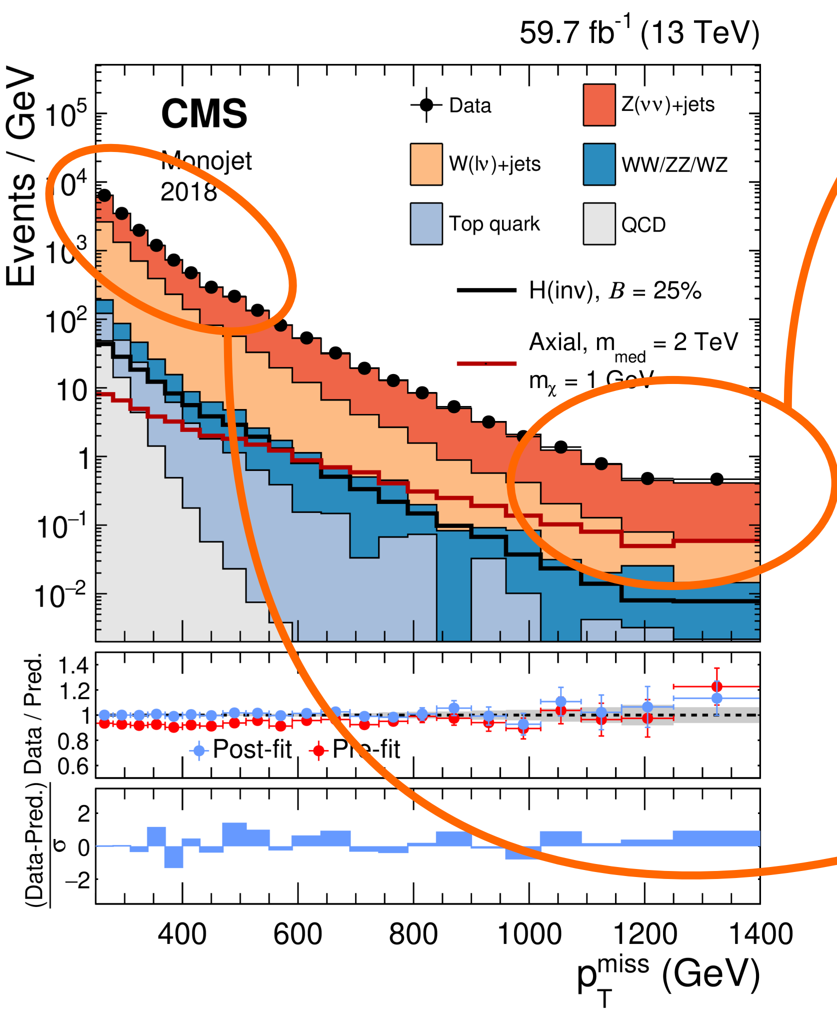
- DM recoils against a jet from QCD ISR

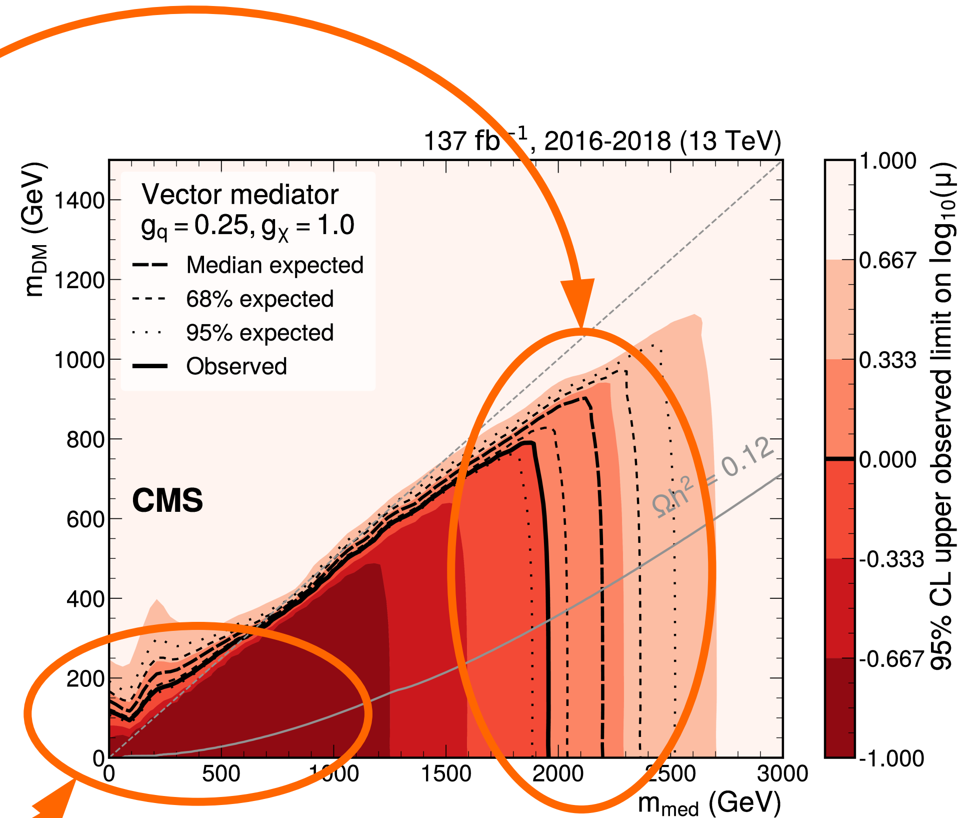


- selection highlights
  - MET as sensitive observable
    cut driven by trigger: MET > 250GeV
  - e/μ/τ and b veto → suppress top / W
  - jets-MET not aligned → suppress QCD
  - jet & MET cleaning → suppress instrumental BG
- irreducible Z→νν dominant BG
- remarkable precision achieved on BG!
  - ~% in bulk, 10% in tails
  - using constraints from Z→μμ, Z→ee, γ+jets, W→μν and W→eν control regions

Direct DM production

“Monojet” search as poster child example

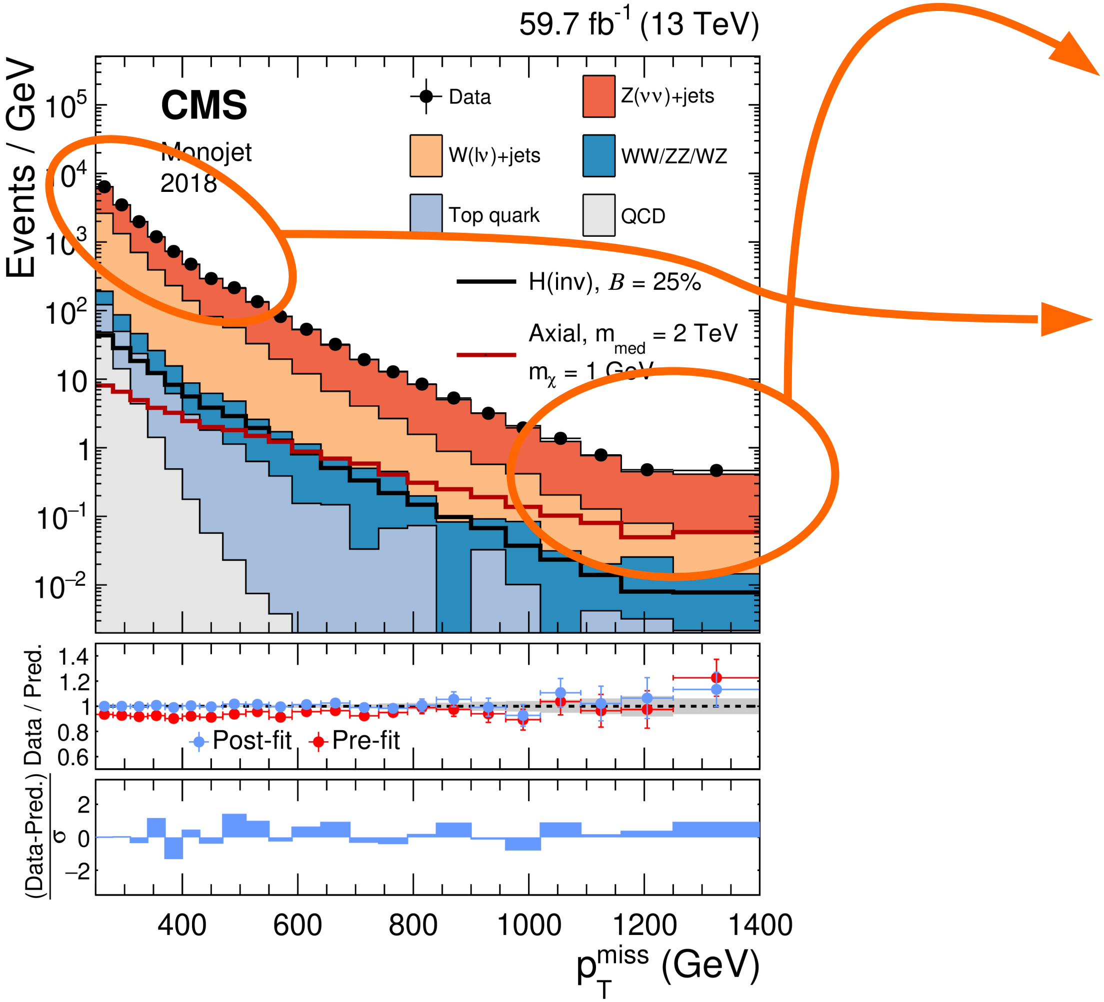




- many interpretations: DM s- and t-channel simp. models, Higgs portal, ADD ED, LQs,...

Direct DM production

"Monojet" search as poster child example

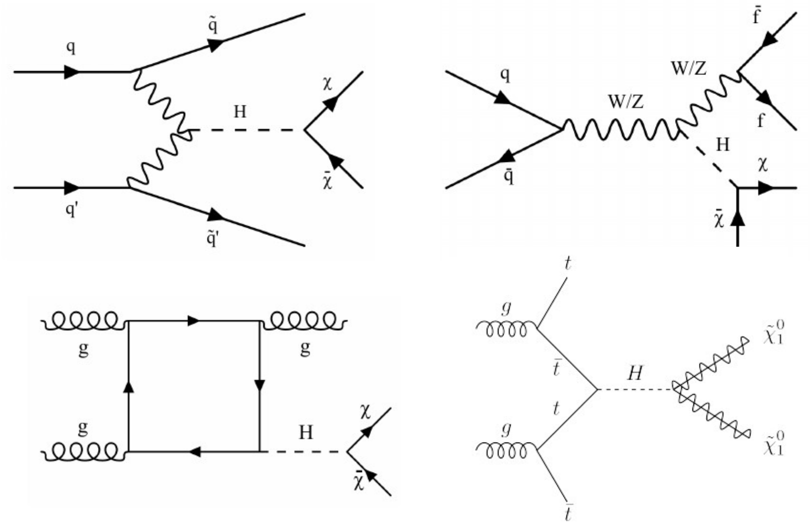


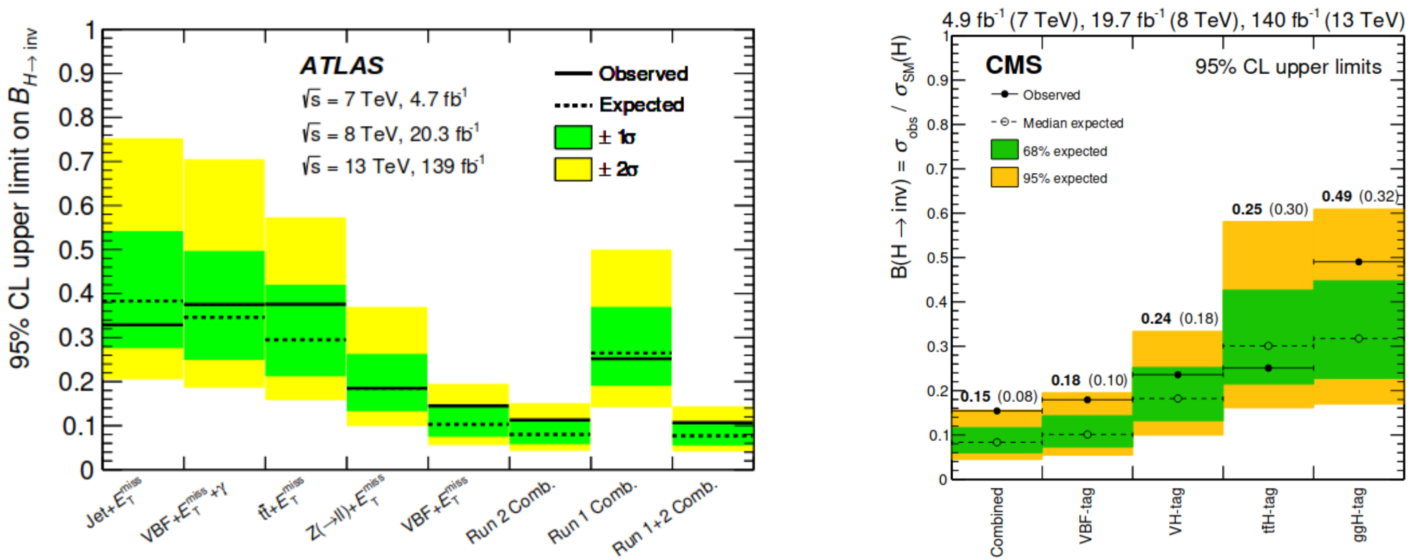
- statistically limited
  - improve slowly with luminosity
- systematically limited
  - no low-hanging fruits left
  - improve with hard work
  - challenges and opportunities at higher lumi
- theoretical uncertainties already very well controlled
  - NLO QCD+EWK
  - arXiv:1705.04664

Higgs and DM

Higgs as a portal to a dark sector

- DM search through Higgs decays
  - limited to $m_{DM} < m_H / 2$
- target various H production modes
  - VBF MET + qq most sensitive
- most sensitive results
  - ATLAS: BR(H→inv) < 0.107 (0.077 exp) @95% CL
  - CMS: BR(H→inv) < 0.15 (0.08 exp) @95% CL

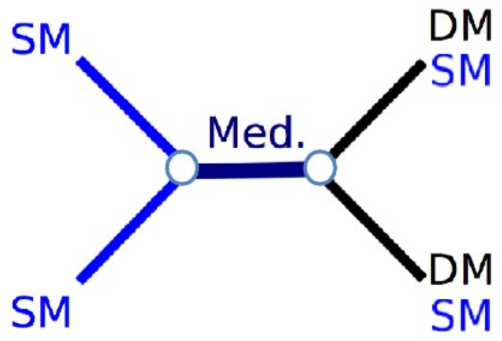




Resonance constraints on DM

Go beyond MET: link to visible

- LHC sensitivity to DM strongest when producing mediator on-shell
- new mediator may still be probed even if dark matter inaccessible (eg. kinematically) at LHC
  - quark (jet) final states guaranteed
  - muon and electron pairs possibly too
- thus we can indirectly constrain dark matter models
  - constraints on couplings
  - from searches in dijet and dilepton final states
  - model dependency!
    → always specify all parameters/assumptions



Resonance constraints on DM

ATLAS

- jet + boosted di-b-jet
  - 80 fb^{-1} – ATLAS-CONF-2018-052
- jet + boosted dijet
  - 36 fb^{-1} – PLB 788 (2019) 316
- ISR + di(-b-)jet
  - 140 fb^{-1} – PRD 110 (2024) 032002
- W(lv) + dijets
  - 139 fb^{-1} – JHEP 06 (2020) 151
- dijets (TLA)
  - 29 fb^{-1} – PRL 121 (2018) 081801
- di-b-jets
  - 36 fb^{-1} – PRD 98 (2018) 032016
- di-(b)-jets
  - 139 fb^{-1} – JHEP 03 (2020) 145
- dijet angular
  - 37 fb^{-1} – PRD 96 (2017) 052004

ATLAS mediator mass: 70 GeV, 230 GeV, 450 GeV, 570 GeV, 1.1 TeV

CMS mediator mass: 10 GeV, 50 GeV, 350 GeV, 500 GeV, 600 GeV, 1.8 TeV

mediator mass

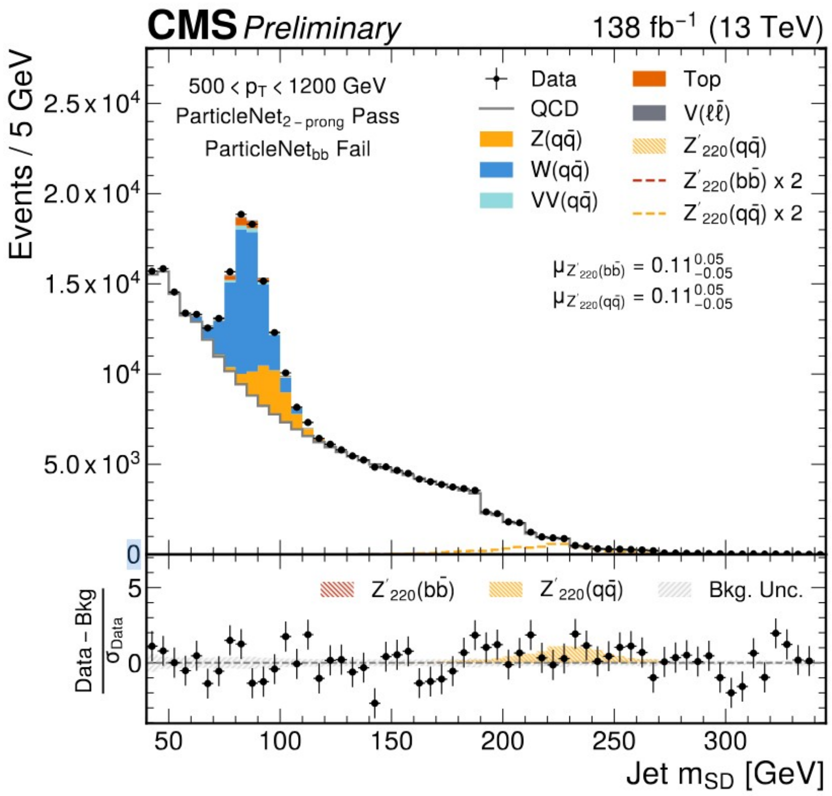
CMS

- γ + boosted dijet
  - 36 fb^{-1} – PRL 123 (2019) 23, 231803
- jet + boosted dijet
  - 138 fb^{-1} – CMS-PAS-EXO-24-007
- jet + dijet
  - 18 fb^{-1} – PLB 805 (2020) 135448
- dijets (scouting)
  - 19 fb^{-1} – PRL 117 (2016) 3, 031802
- dijets (scouting)
  - 117 fb^{-1} – CMS-PAS-EXO-23-004
- dijets
  - 138 fb^{-1} – JHEP 05 (2020) 033
- dijet angular
  - 36 fb^{-1} – EPJC 78 (2018) 789

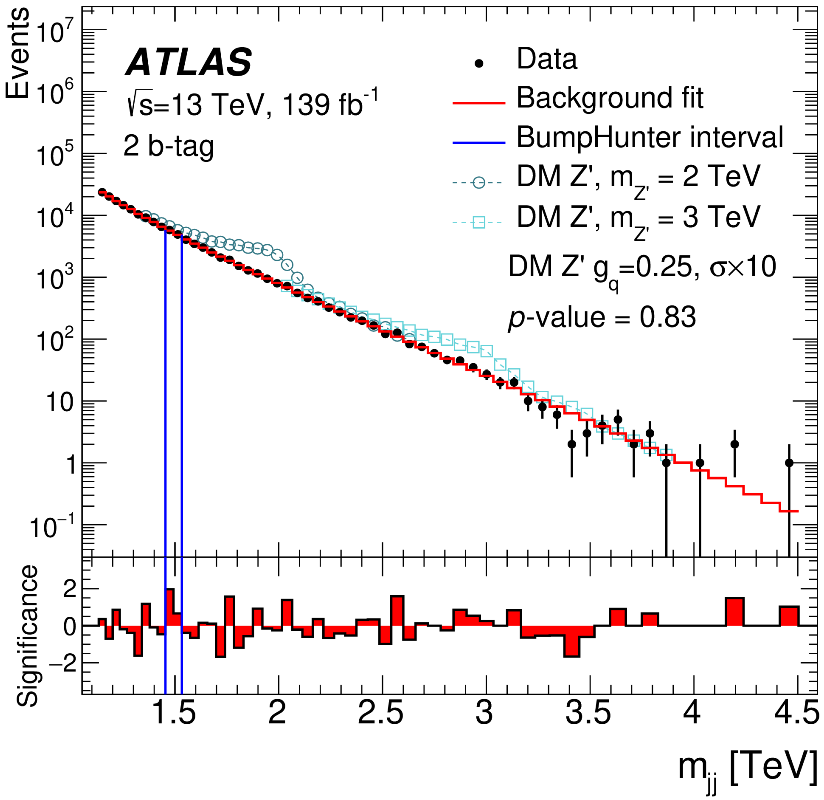
Resonance constraints on DM

Example mass spectra

jet + boosted dijet



di-b-jets

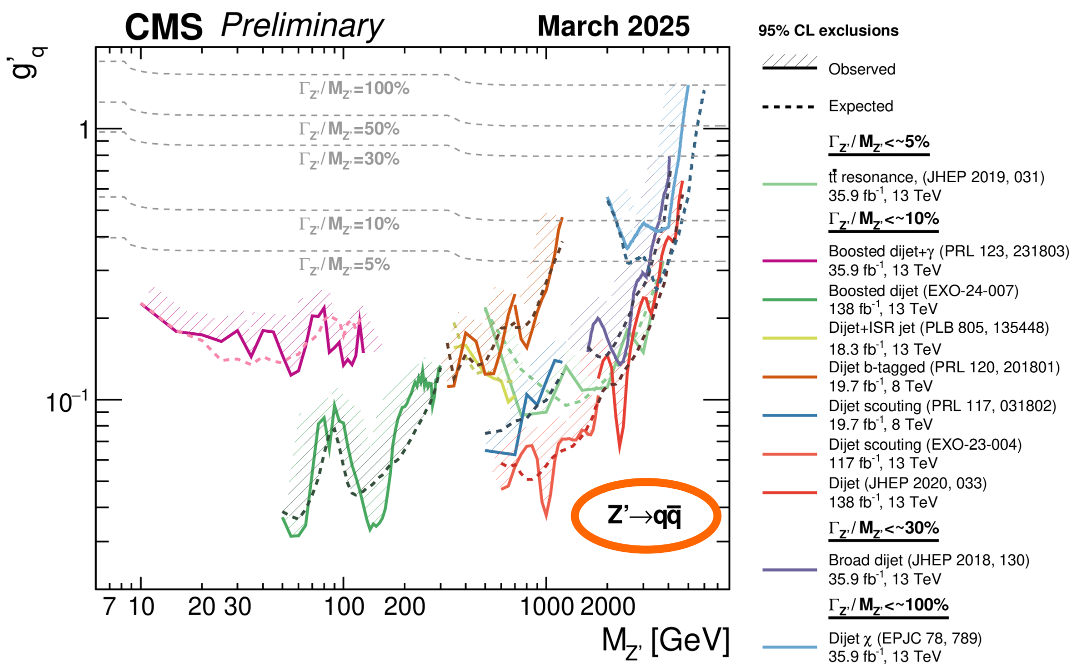


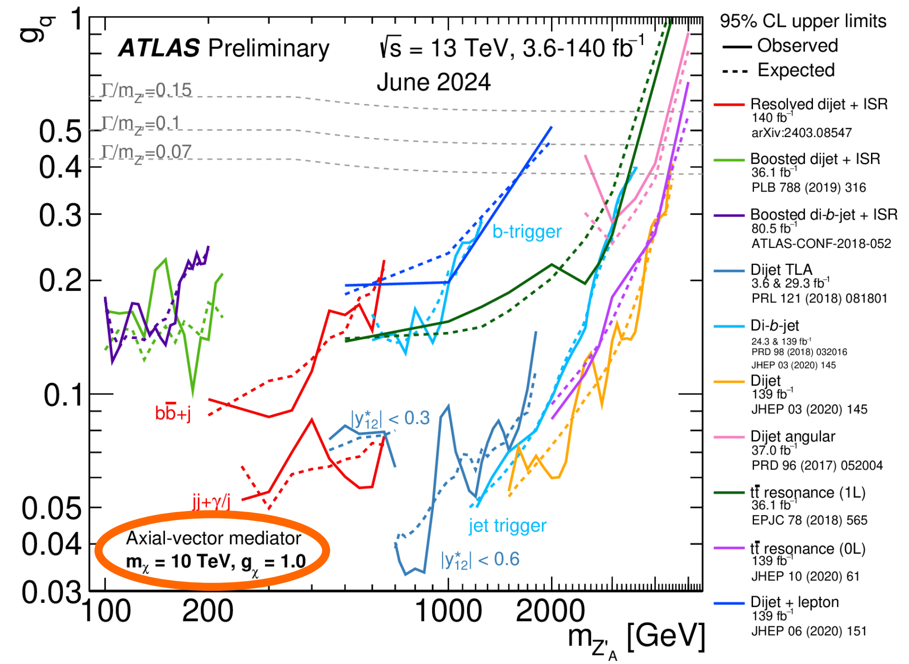
Resonance constraints on DM

Constraints on quark coupling

CMS Exotics summary plots

ATLAS Exotics summary plots



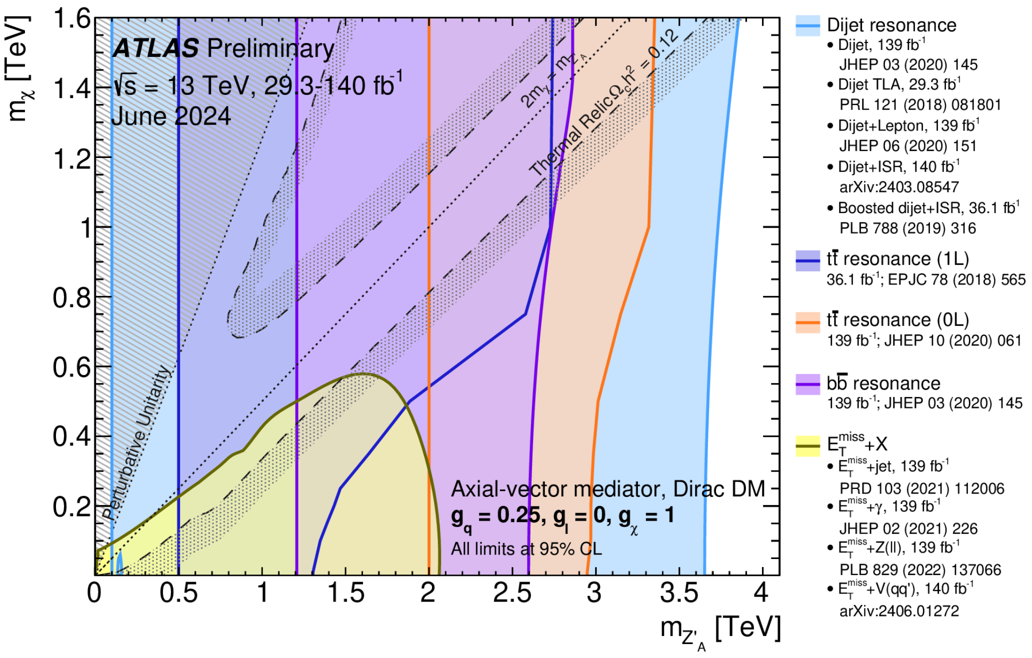


always be aware of
the model assumptions!

Interpretation results

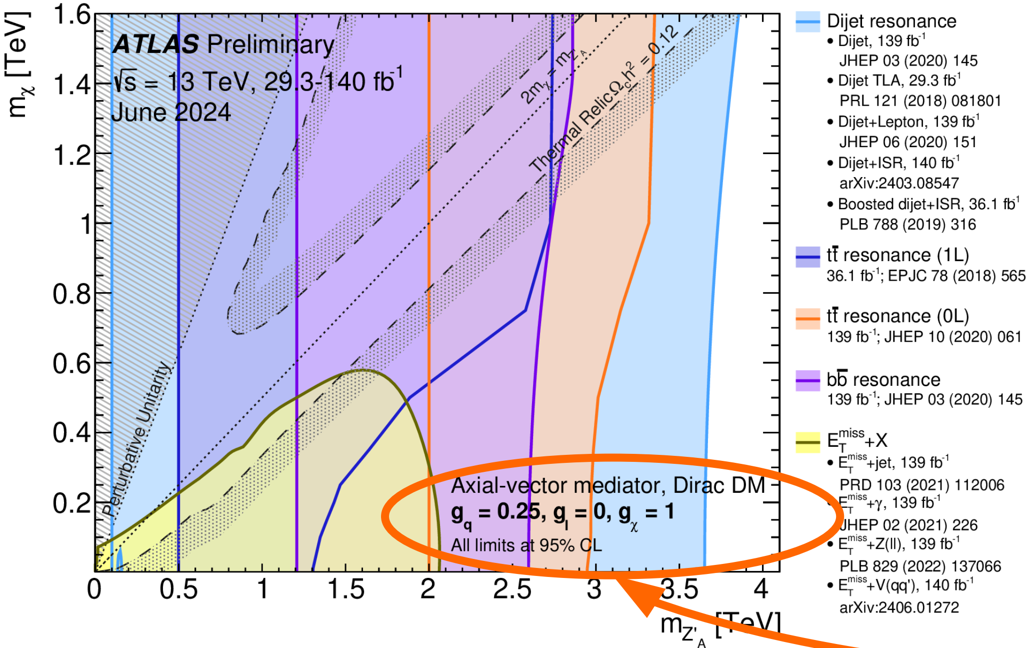
Interpretation in LHC phase space

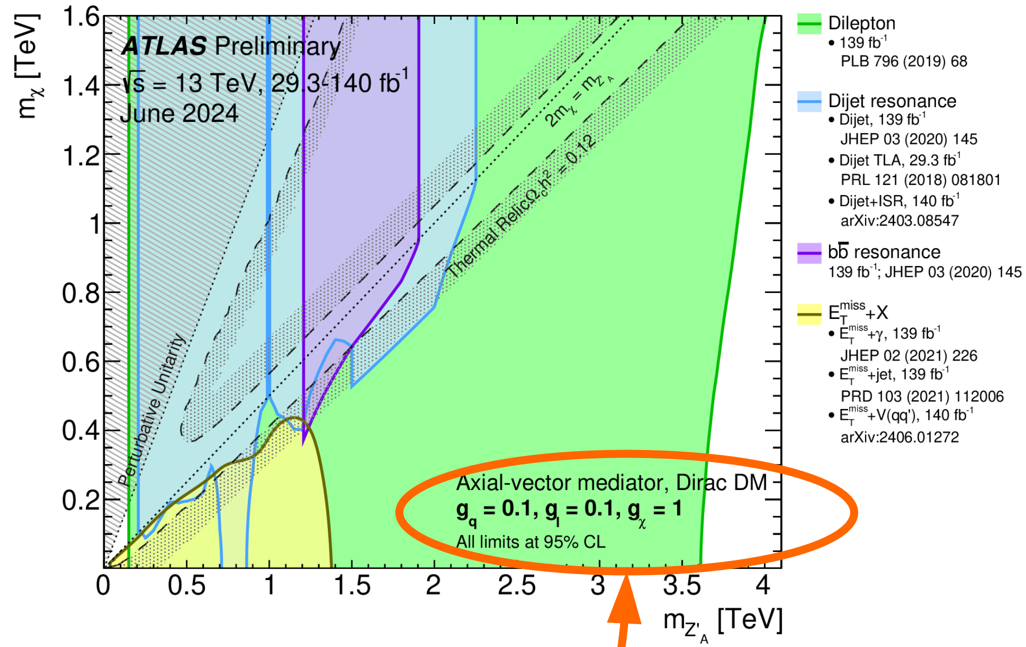
- probing (axial)vector mediators to several TeV
- (pseudo)scalar mediators harder to constrain
- complementarity of invisible and visible channels



Interpretation results

- sensitivity strongly depends on couplings to SM and DM!

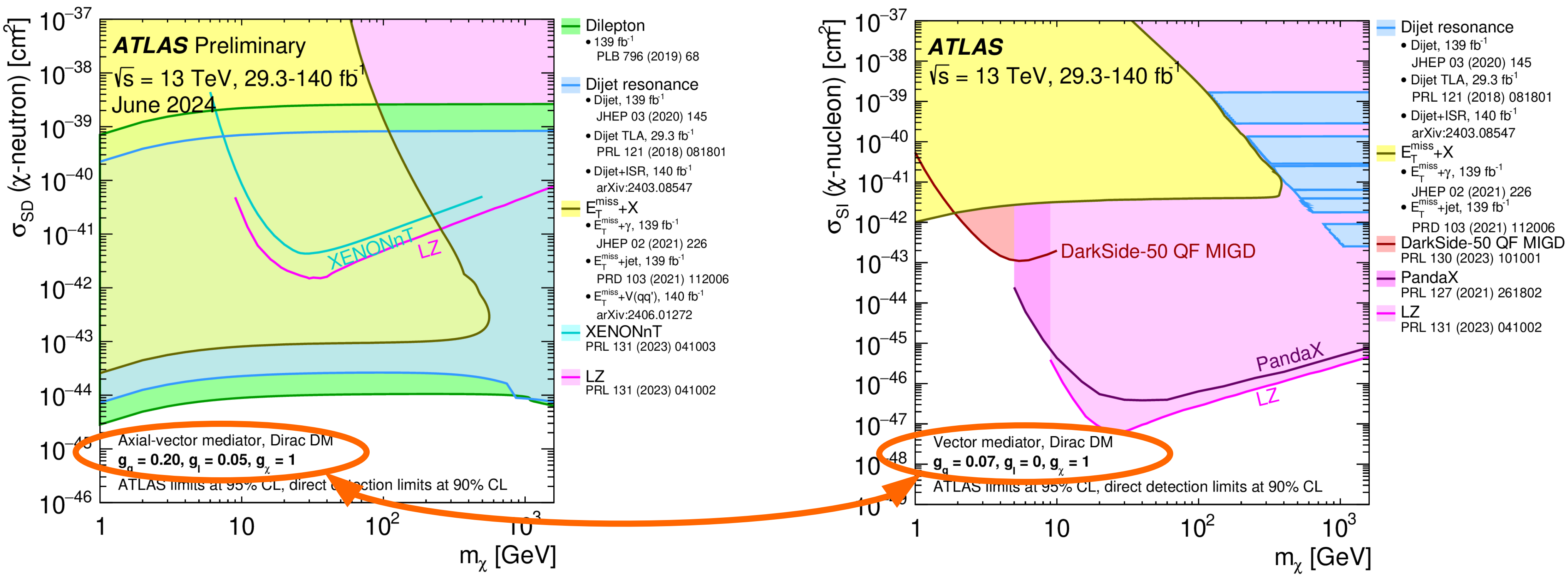




Interpretation results

Interpretation beyond LHC

- take-home message: complementarity
  - best LHC results for low-mass DM, with mediator produced on-shell
- model dependency!



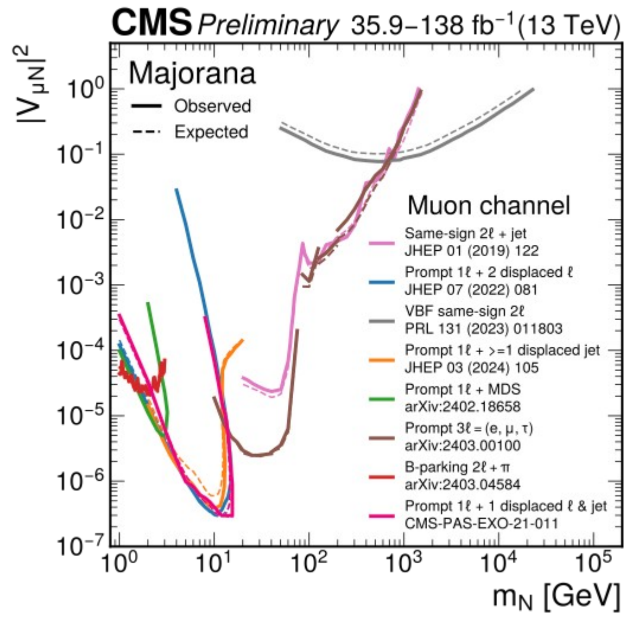
New DM frontiers

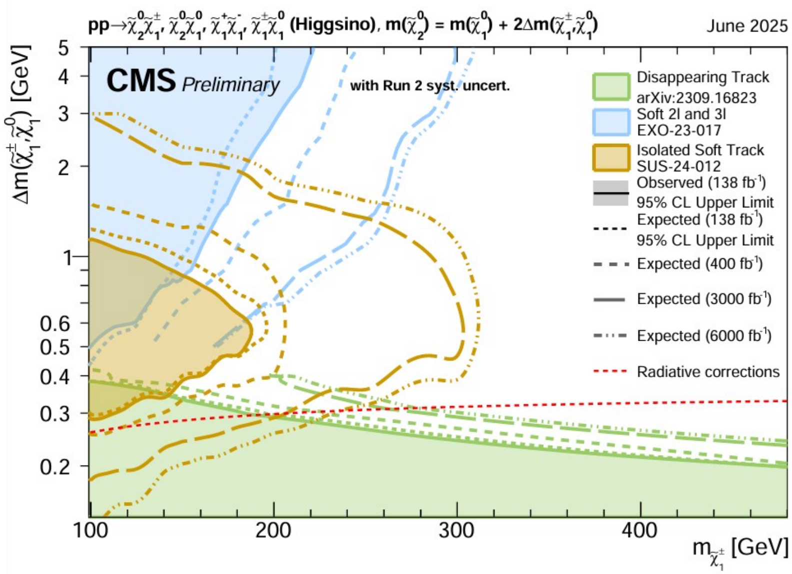
Venture beyond standard WIMPs

- WIMPs from long-lived decays
- heavy neutral leptons
- axion-like particles
- dark sector portals
- ...

Experimental frontiers

- low mass resonances
- long-lived particles
- soft signatures
- anomalous jets
- ...
- vibrant field! a lot of work on triggers, reconstruction, backgrounds, simulation,…



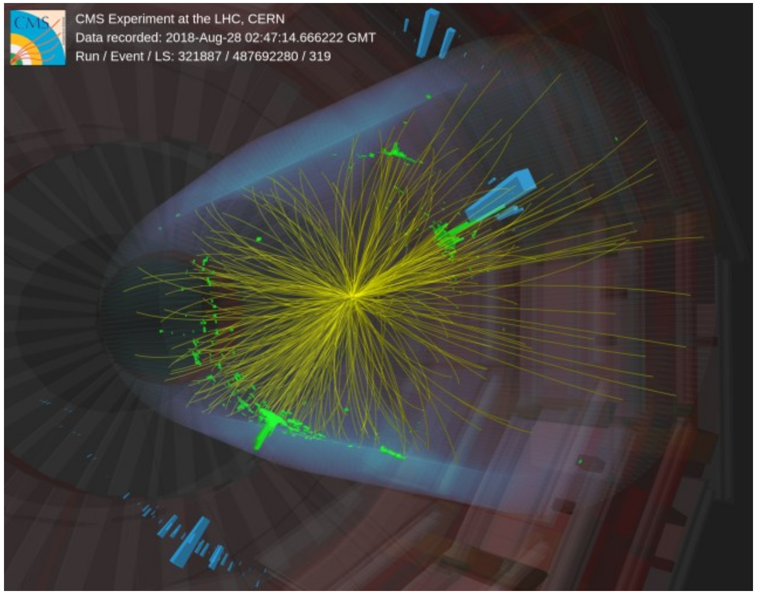


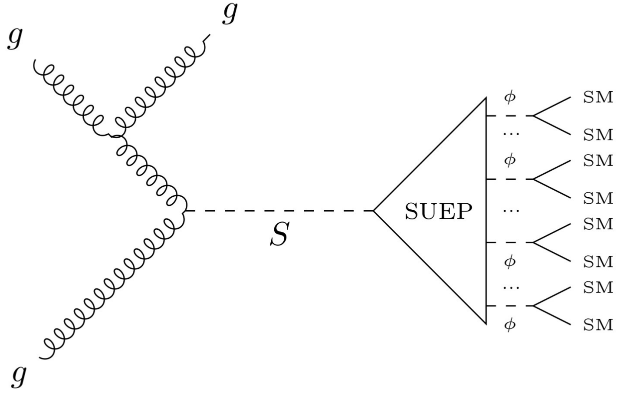
New DM frontiers

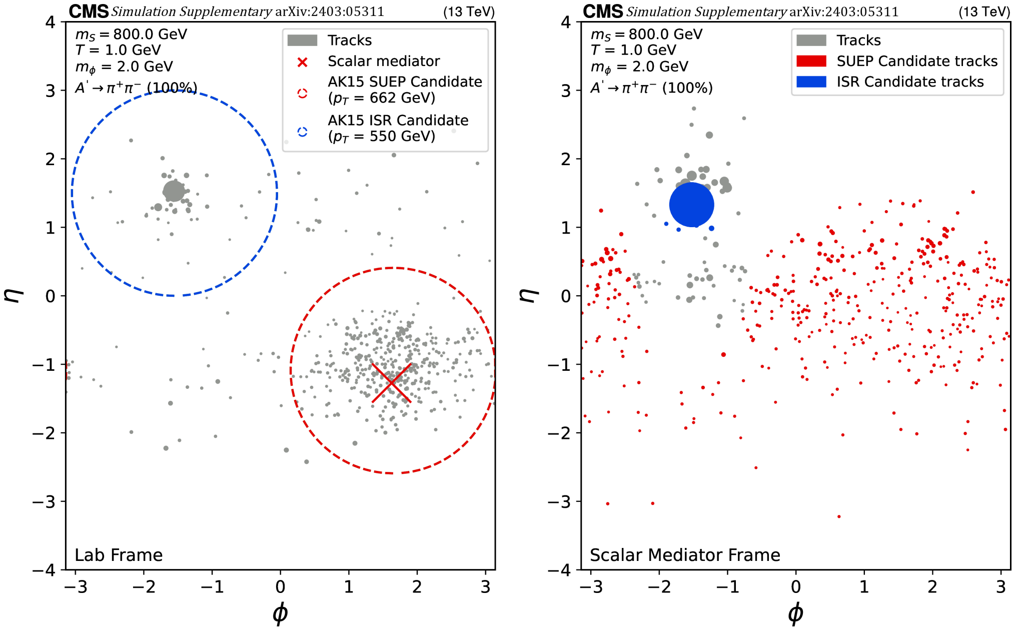
Recent example: SUEPs

- strongly coupled dark sector
  - motivated by Hidden Valley scenarios of new physics
- experimentally challenging signature:

  high-multiplicity of low-momentum particles







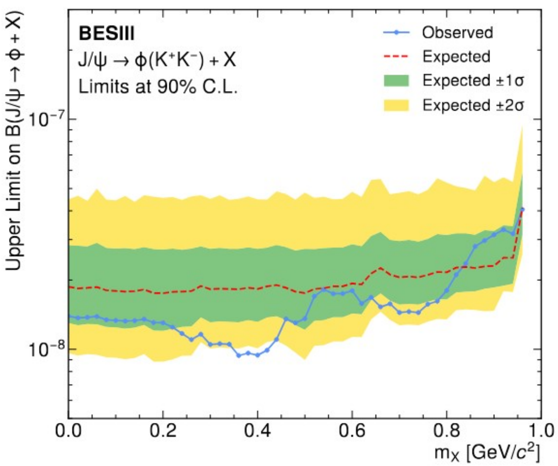
- vibrant exp+theo community
  - eg. simulation challenges
  - first searches appearing

    eg. PRL 133 (2024) 19, 191902
    and Phys. Rept. 1115 (2025) 448

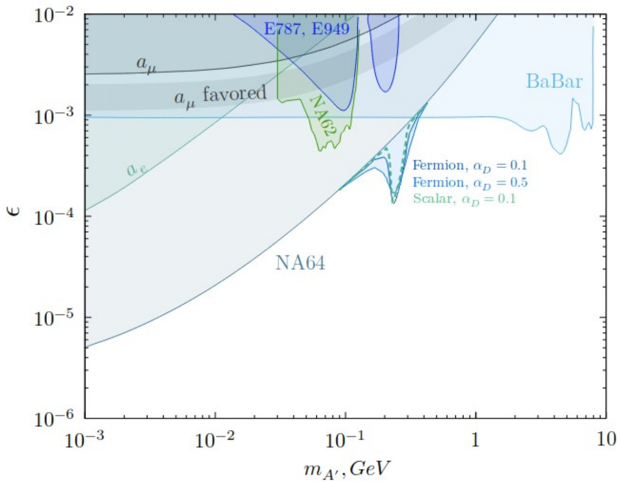
Other experiments, other accelerators

- a few of many, many examples

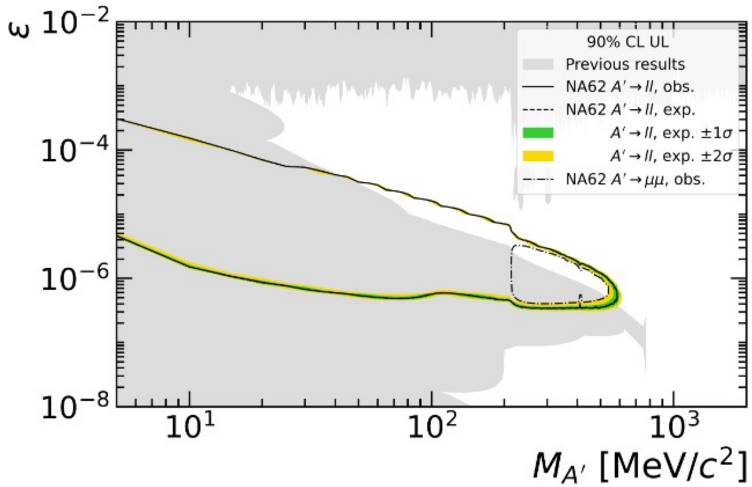
BESIII: arXiv:2506.10316



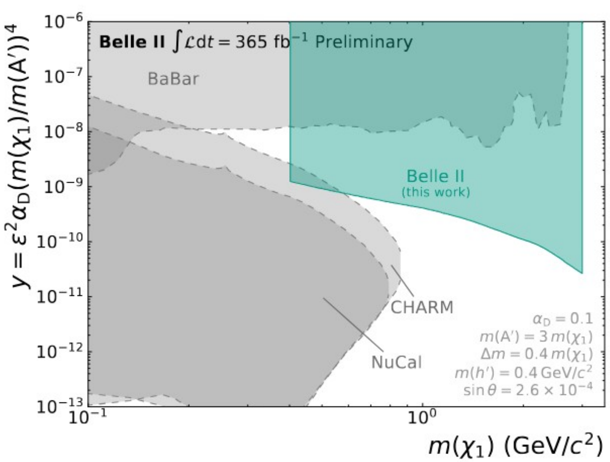
NA64: PRL 131 (2023) 16, 161801



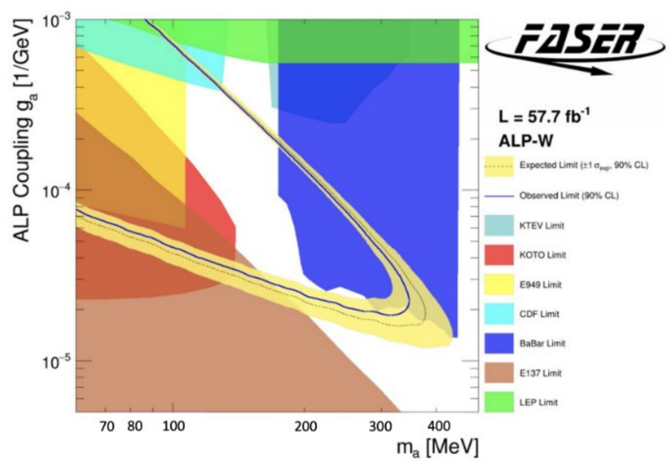
NA62: PRL 133 (2024) 11, 111802



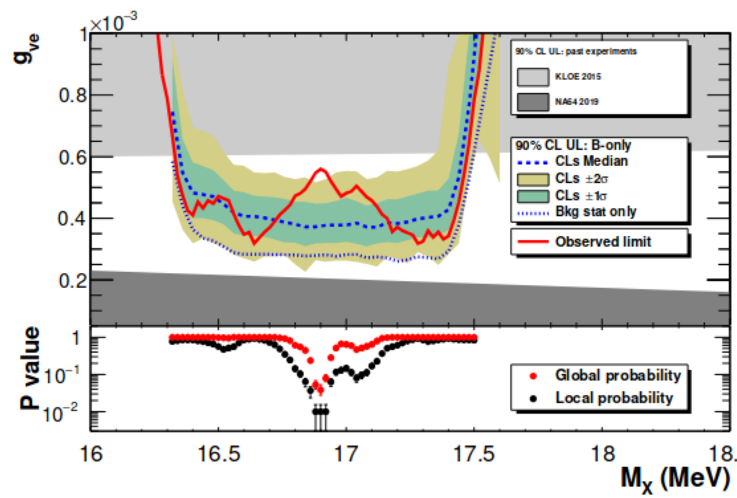
Belle-II: arXiv:2505.09705



FASER: JHEP 01 (2025) 199



PADME: arXiv:2505.24797



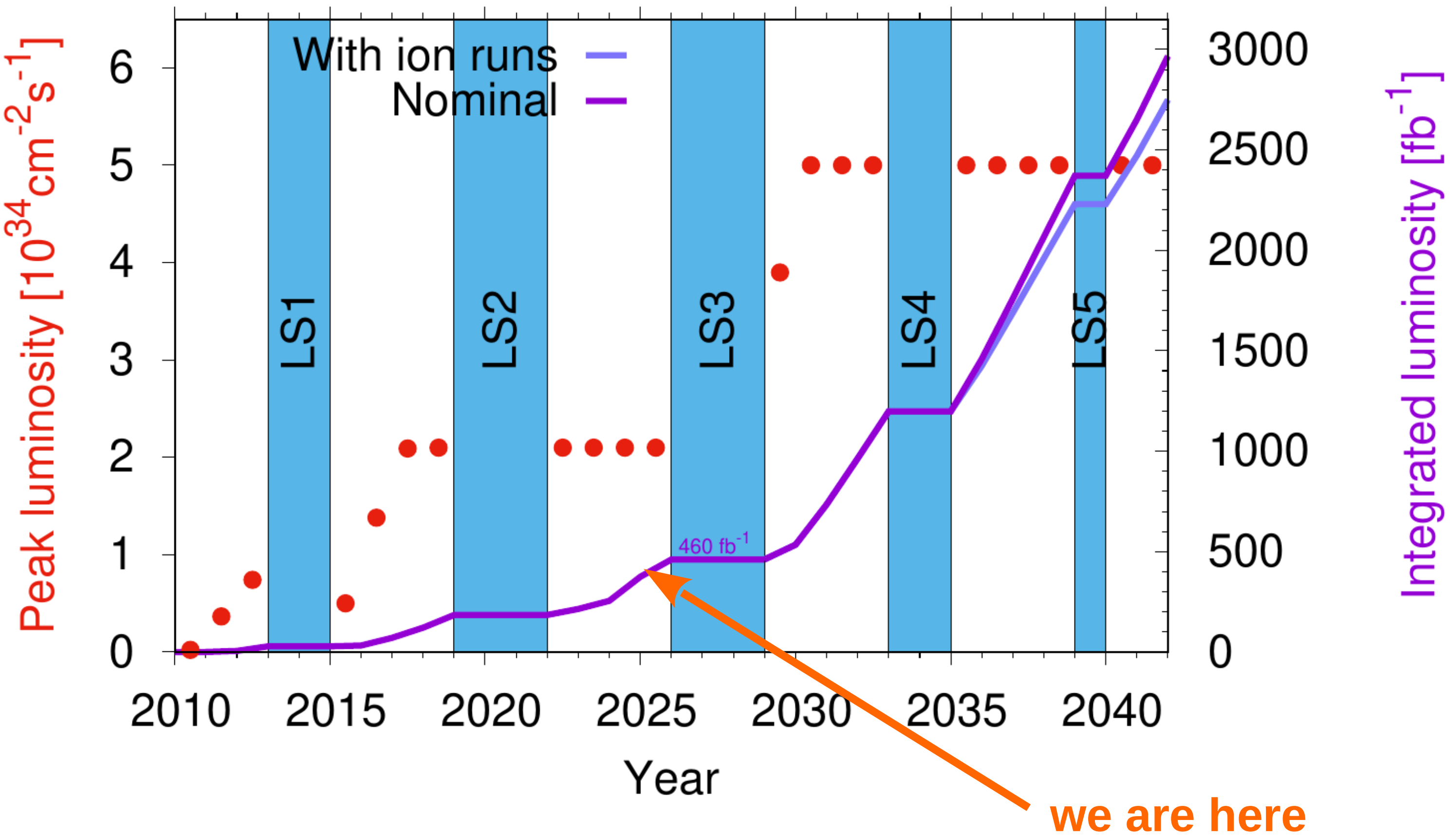
Conclusions

Dark Matter is a main physics goal at accelerators

- bread-and-butter signatures intensely searched for
  - LHC can be very competitive if mediator can be produced on-shell and/or DM is light
- connection to search for new mediator in visible decay channels
  - dijets, dileptons,… complementarity is key
- branching out to other frontiers
  - exploring other WIMP DM scenarios
  - beyond the WIMP, beyond experimental comfort zones

- LHC Run-3 in full swing, also many smaller experiments

Outlook: the HL-LHC



- HL-LHC BSM physics reach summarized in arXiv:1812.07831: Beyond the Standard Model Physics at the HL-LHC and HE-LHC
- since then: many new developments for triggering, machine learning, etc

Outlook

103 years of dark matter

FIRST ATTEMPT AT A THEORY OF THE ARRANGEMENT AND MOTION OF THE SIDEREAL SYSTEM[1]

By J. C. KAPTEYN[2]

ABSTRACT

First attempt at a general theory of the distribution of masses, forces, and velocities in the stellar system.—(1) *Distribution of stars.* Observations are fairly well represented, at least up to galactic lat. 70°, if we *assume that the equidensity surfaces are similar ellipsoids of revolution*, with axial ratio 5.1, and this enables us to compute quite readily (2) *the gravitational acceleration at various points due to such a system*, by summing up the effects of each of ten ellipsoidal shells, in terms of the acceleration due to the average star at a distance of a parsec. The *total number of stars* is taken as 47.4×10^9. (3) *Random and rotational velocities.* The nature of the equidensity surfaces is such that the stellar system cannot be in a steady state unless there is a general rotational motion around the galactic polar axis, in addition to a random motion analogous to the thermal agitation of a gas. In the neighborhood of the axis, however, there is no rotation, and the behavior is assumed to be like that of a gas at uniform temperature, but with a gravitational acceleration ($G\eta$) decreasing with the distance ρ. Therefore the density Δ is assumed to obey the barometric law: $G\eta = -\bar{u}^2(\delta\Delta/\delta\rho)/\Delta$; and taking the mean random velocity $\bar{u}$ as 10.3 km/sec., the author finds that (4) *the mean mass of the stars* decreases from 2.2 (sun = 1) for shell II to 1.4 for shell X (the outer shell), the average being close to 1.6, which is the value independently found for the average mass of both components of visual binaries. In the galactic plane the resultant acceleration—gravitational minus centrifugal—is again put equal to $-\bar{u}^2(\delta\Delta/\delta\rho)/\Delta$, $\bar{u}$ is taken to be constant and the average mass is assumed to decrease from shell to shell as in the direction of the pole. The angular velocities then come out such as to make the linear rotational velocities about constant and equal to 19.5 km/sec. beyond the third shell. If now we suppose that part of the stars are rotating one way and part the other, the relative velocity being 39 km/sec., we have a quantitative explanation of the phenomenon of star-streaming, where the relative velocity is also in the plane of the Milky Way and about 40 km/sec. It is incidentally suggested that when the theory is perfected it may be possible to determine *the amount of dark matter* from its gravitational effect. (5) The *chief defects of the theory* are: That the equidensity surfaces assumed do not agree with the actual surfaces, which tend to become spherical for the shorter distances; that the *position of the center of the system* is not the sun, as assumed, but is probably located at a point some 650 parsecs away in the direction galactic long. 77°, lat. −3°; that the average mass of the stars was assumed to be the same in all shells in deriving the formula for the variation of $G\eta$ with ρ on the basis of which the variation of average mass from shell to shell and the constancy of the rotational velocity were derived—hence either the assumption or the conclusions are wrong; and that no distinction has been made between stars of different types.

Astrophysical Journal 55 (1922) 302

Thank you!