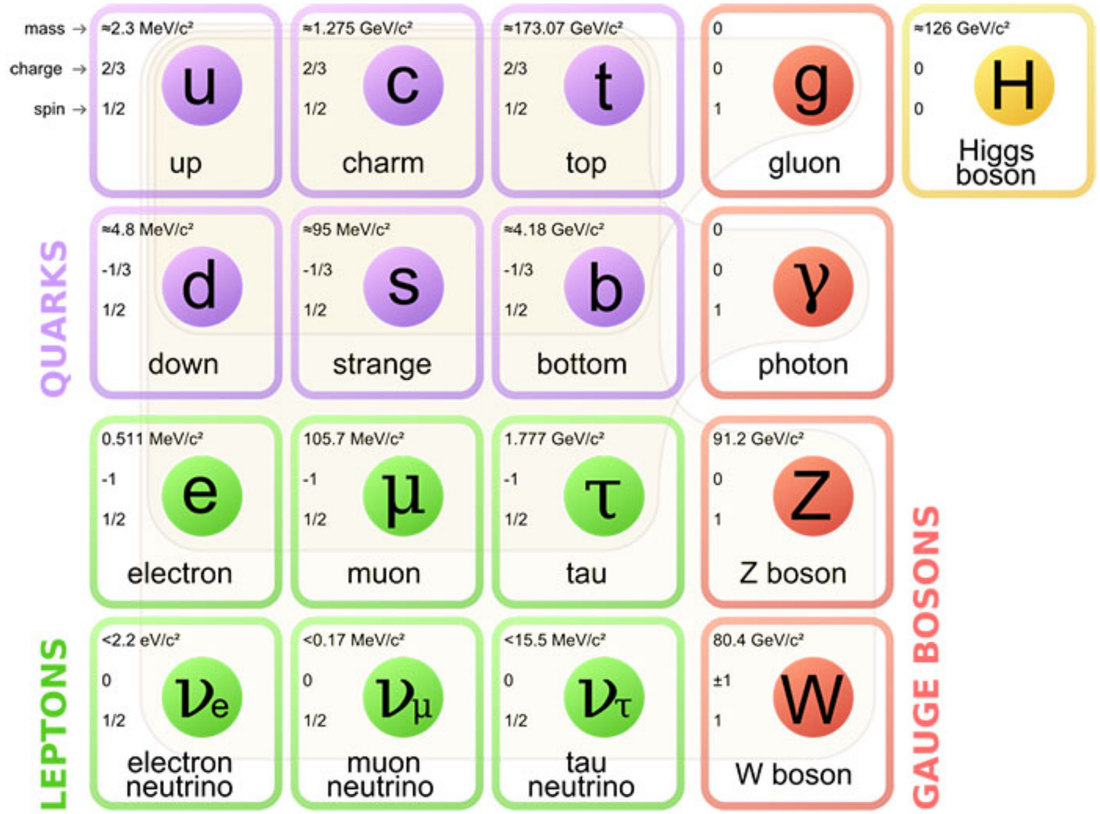
Searches for dark matter and supersymmetry with the ATLAS detector

Alvaro Lopez Solis

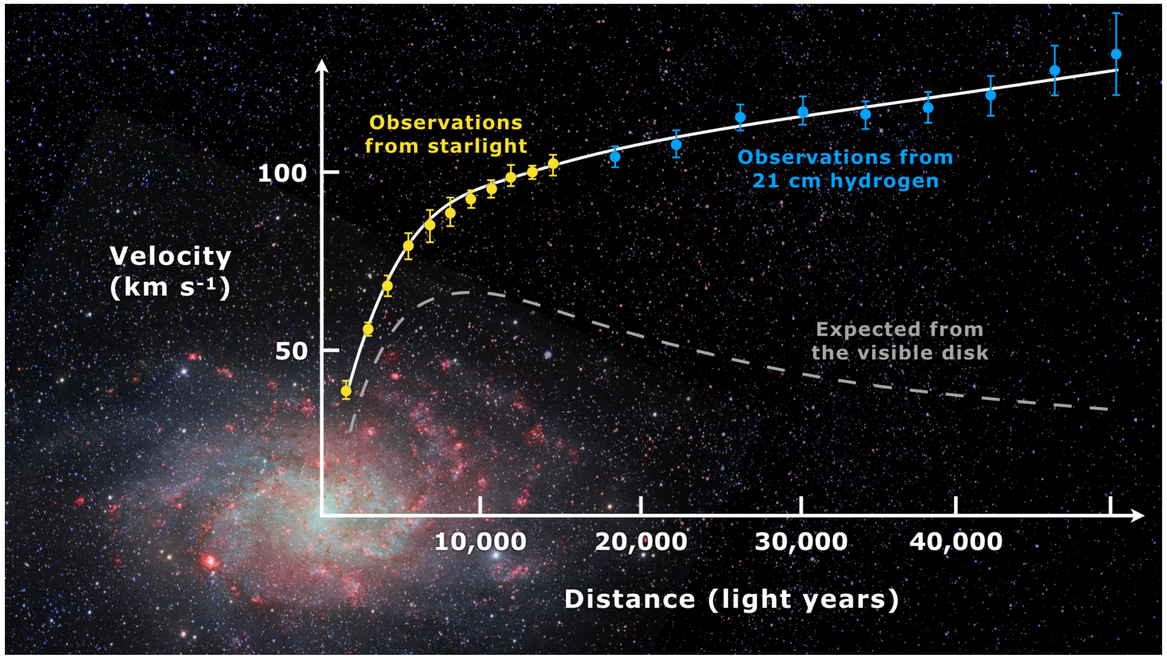
IFIC seminar
3rd June 2025

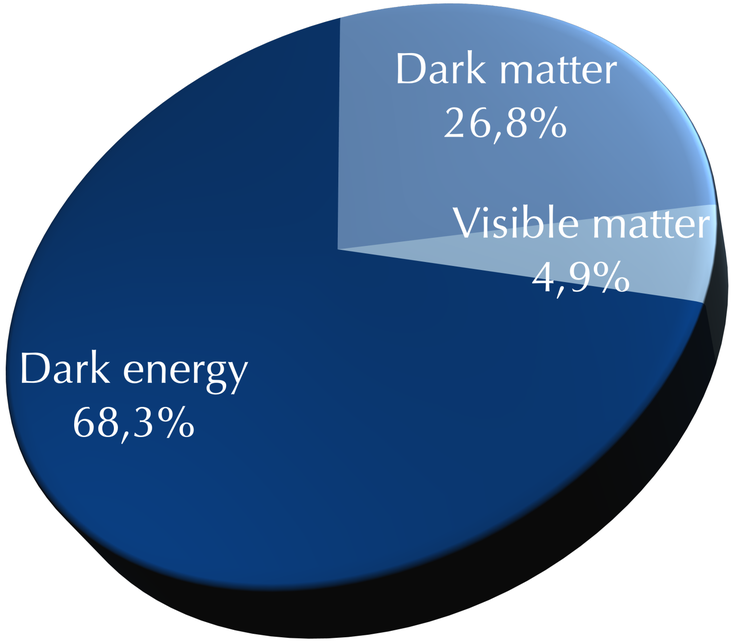
The Standard Model of Particle Physics



Best description to date of the elementary particle content of the Universe and its interactions.
However …… many questions remain open.

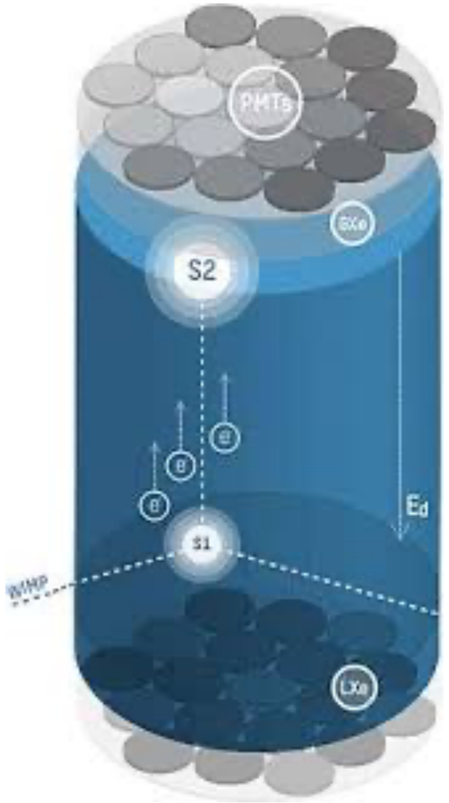
Dark matter

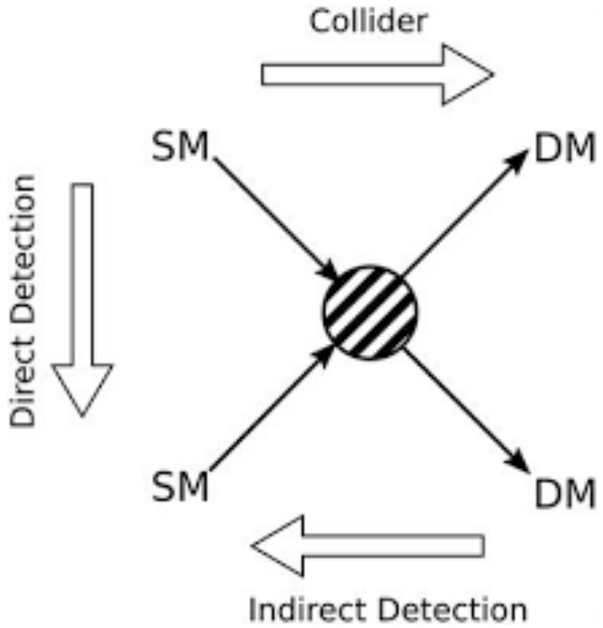


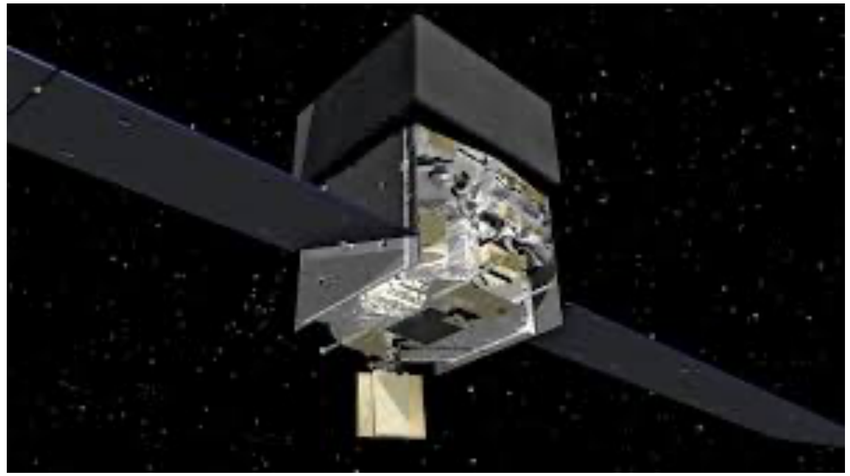


The existence of a new type of particle is supported by several measurements at cosmological and galactic scales. However, no dark matter particle still observed. Massive particles non-interacting with the electromagnetic field.

Searches for dark matter

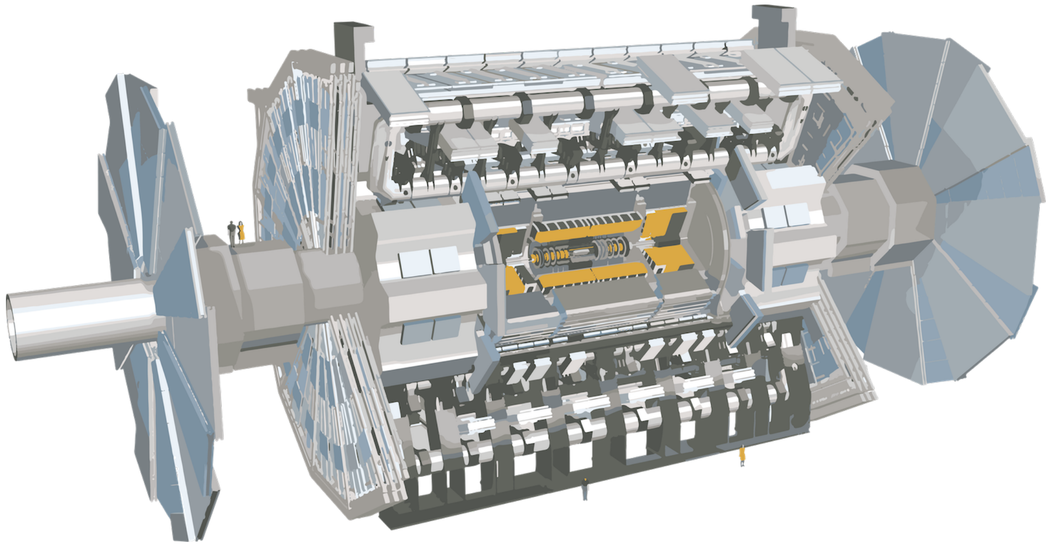


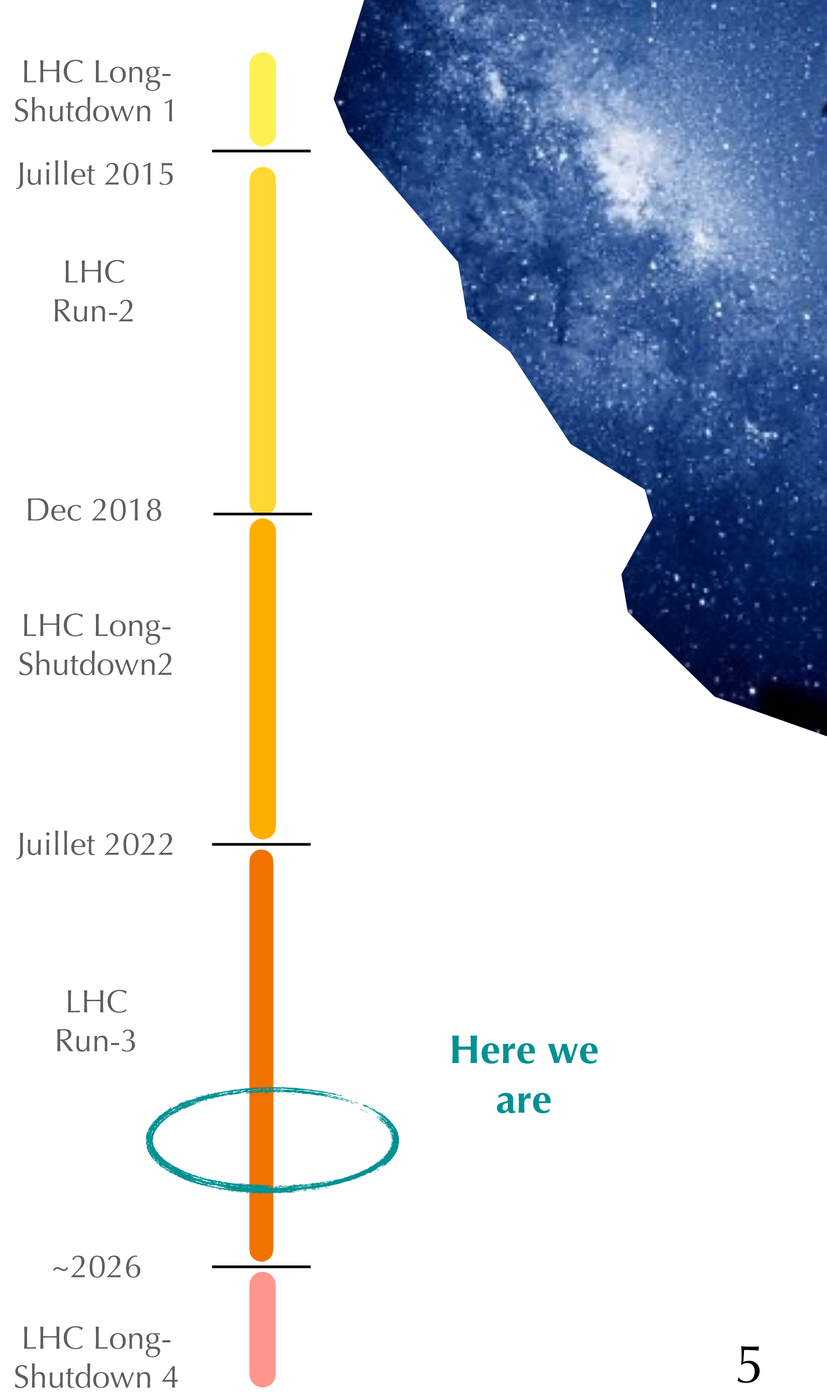




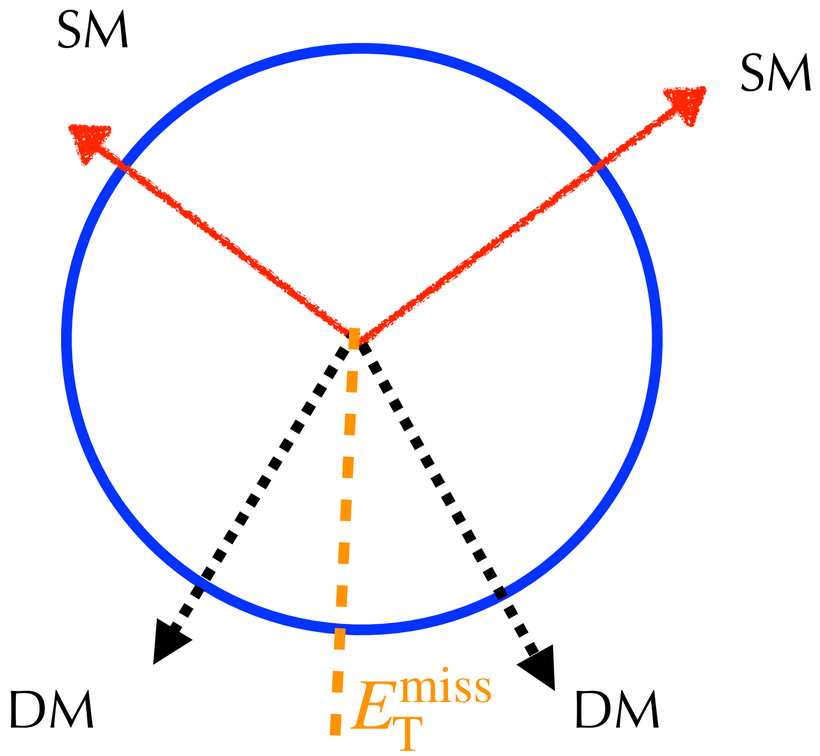
The LHC and ATLAS

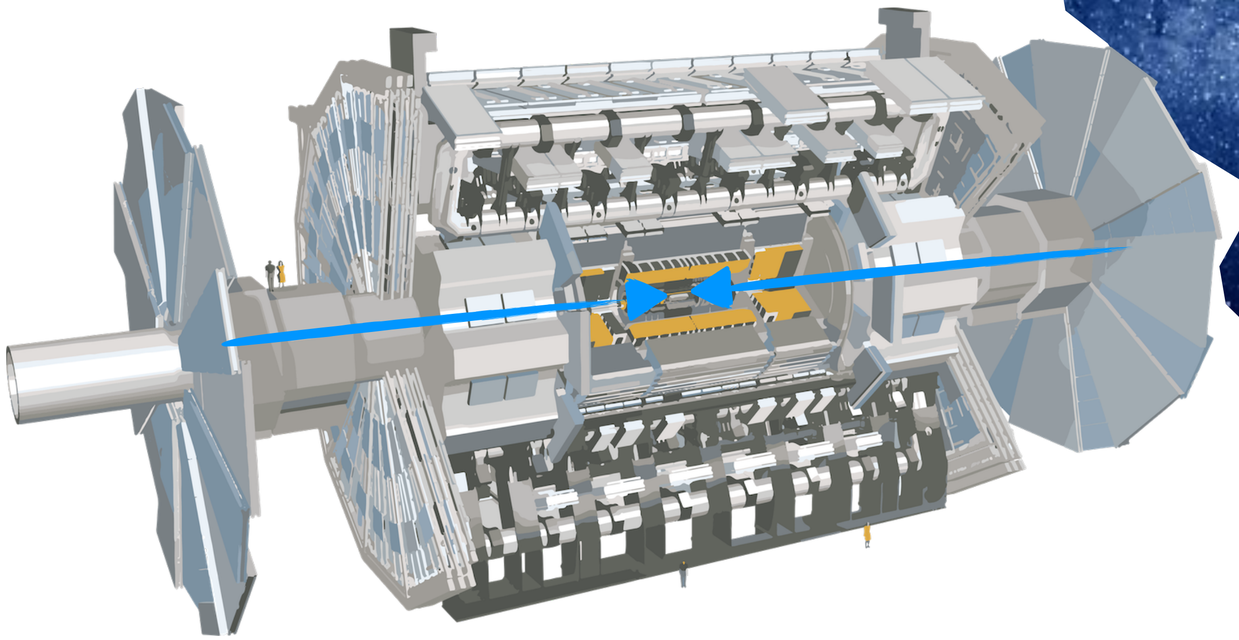
- Presenting you searches developed using ATLAS detector at LHC during Run-2 (and starting Run-3)
- Proton-proton collisions at 13 TeV of energy.





Dark matter searches at LHC

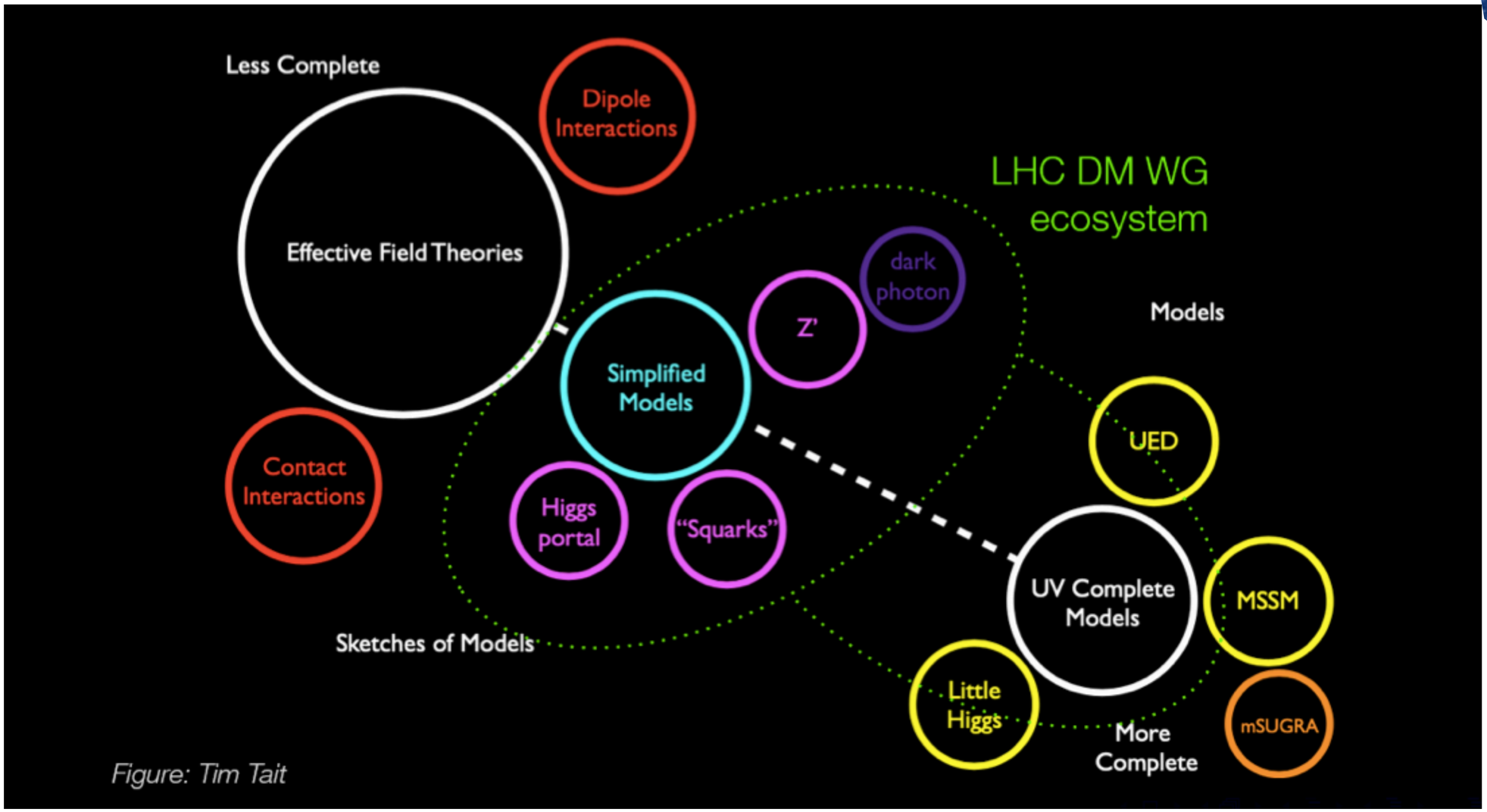




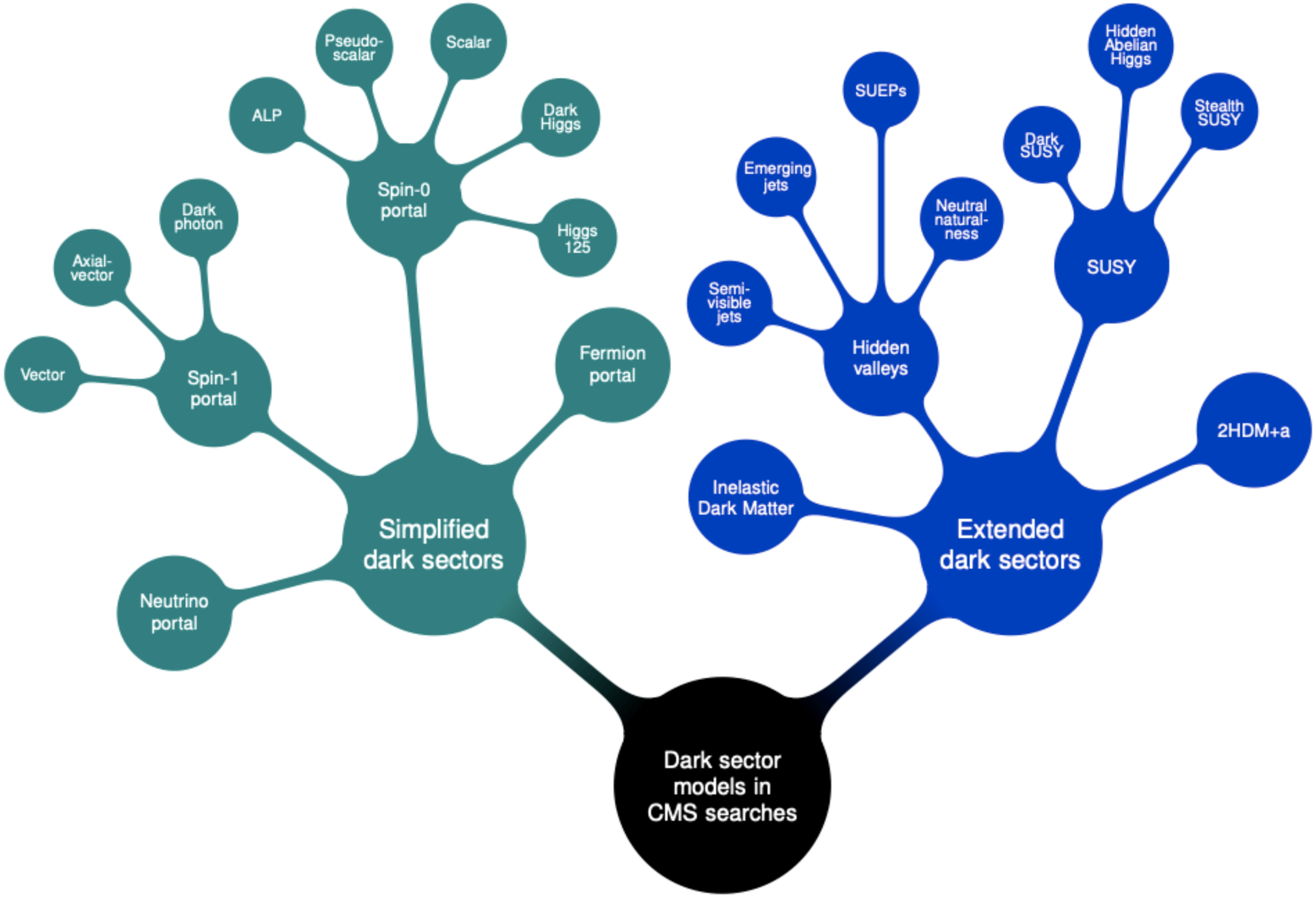
Due to its small interaction strength with the SM, DM production registered as missing transverse momentum.
Production of dark matter in colliders: SM particles together with large missing transverse momentum.

Signature for production depending on interactions of DM with SM and also DM properties.

Dark matter properties and its interactions

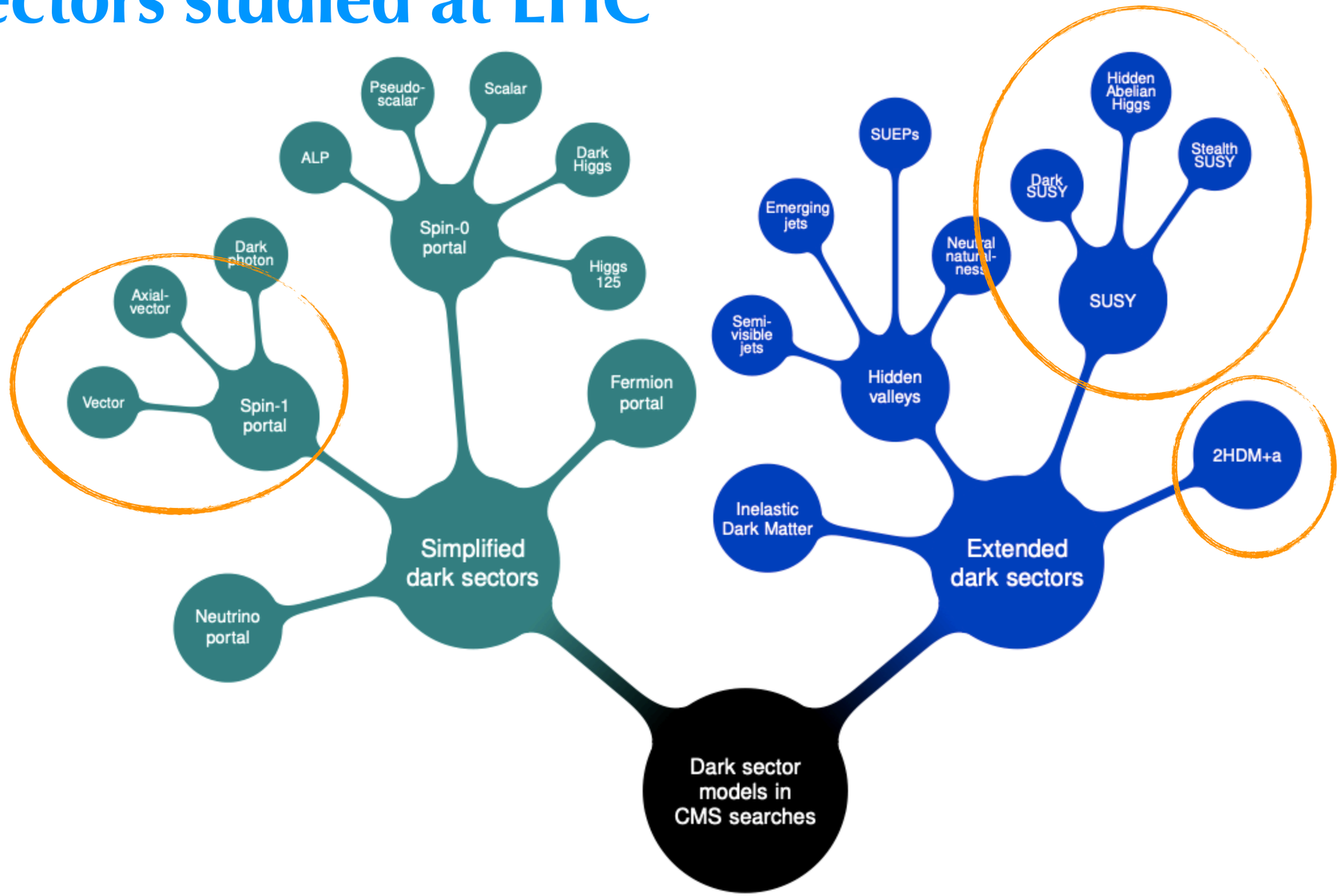


Dark sectors studied at LHC



EXO-23-005

Dark sectors studied at LHC



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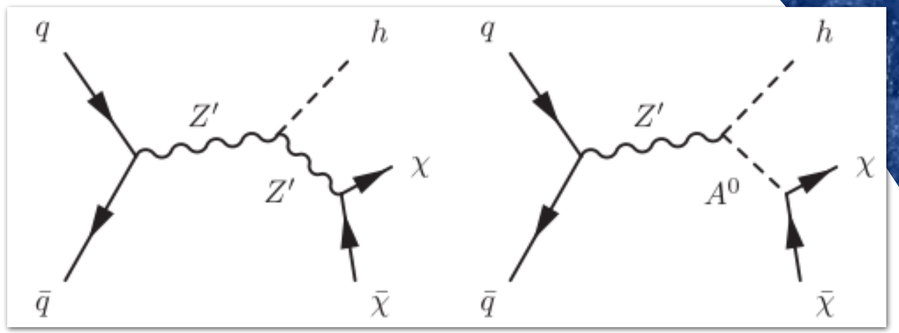
The Higgs boson and Dark matter

Assuming a new baryonic force, new spin-1 Z′ mediator
Connecting SM Higgs boson and DM.
First analysis in Run-2 looking at this final state.



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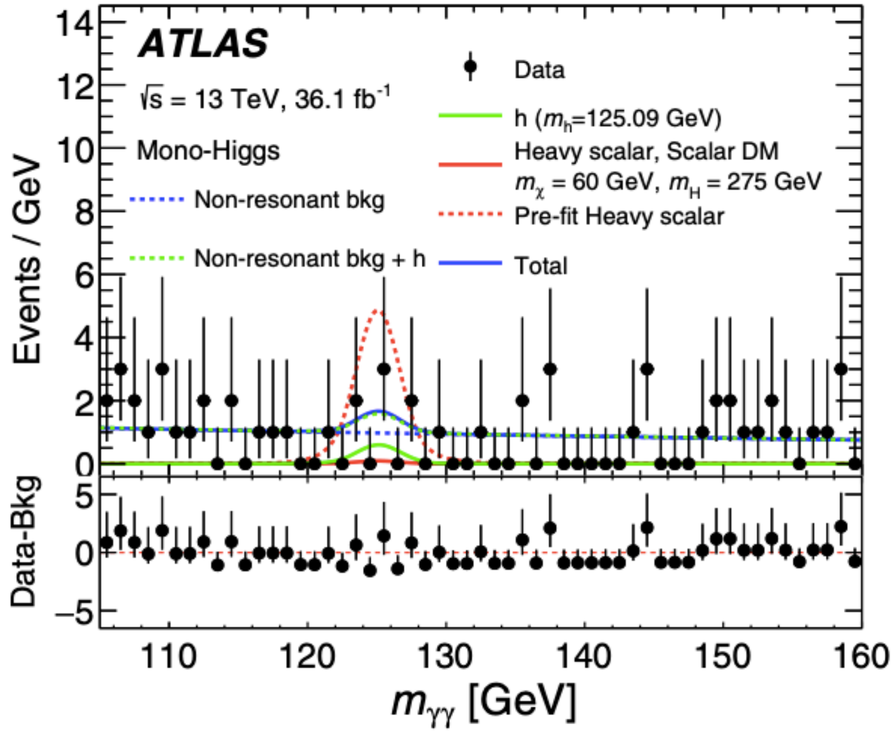
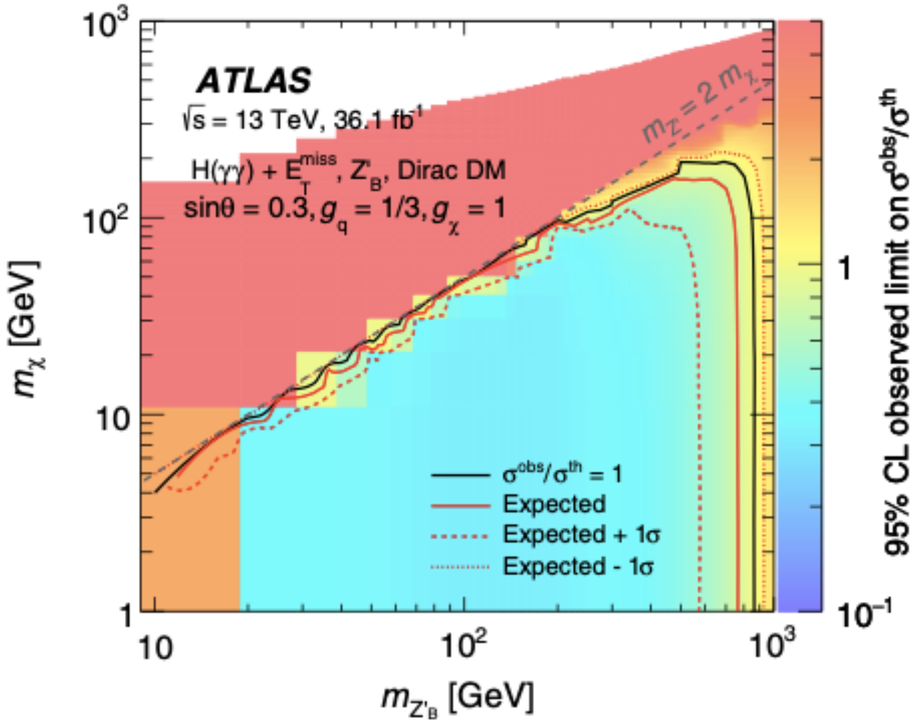




No BSM connection found and limits put up to 1 TeV for an $m_{Z'}$ connecting Higgs and DM.

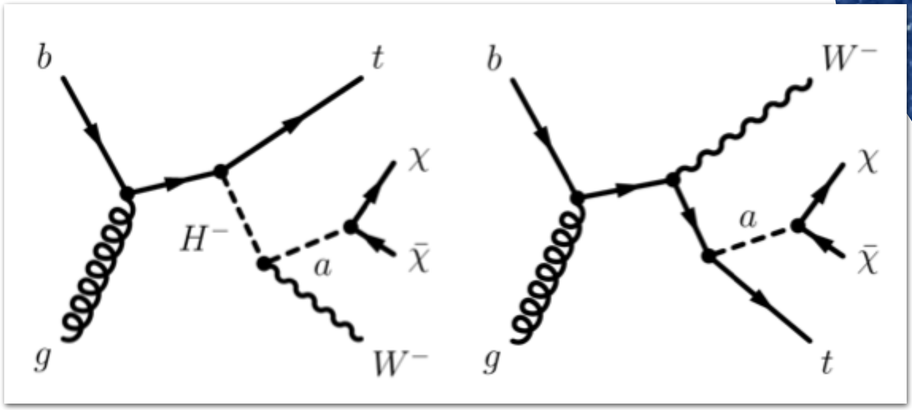
The Higgs boson and Dark matter

Extended Higgs sectors appear in several Beyond Standard Model theories —> 2HDM+a

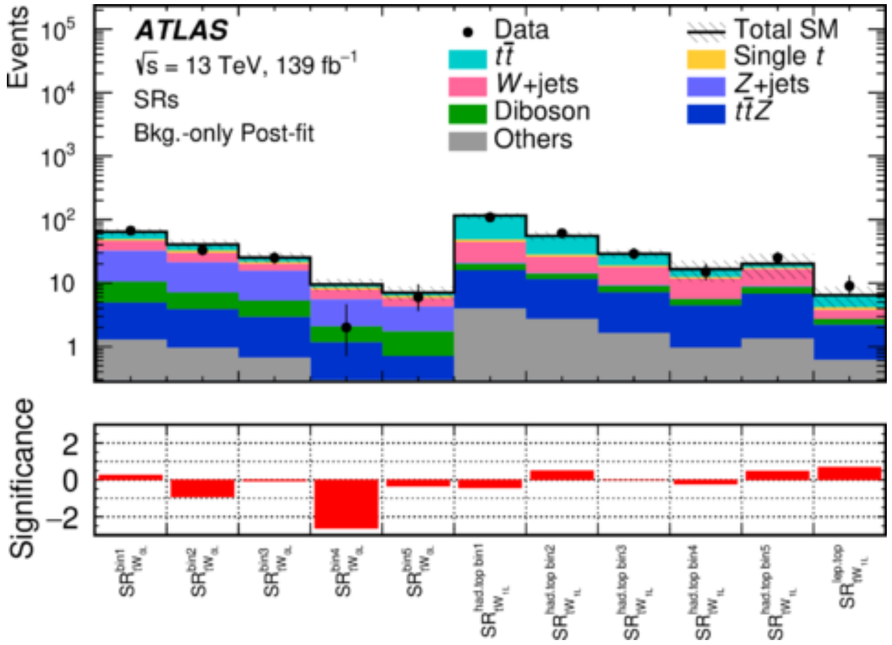
Search for dark matter production in association to a tW final state.

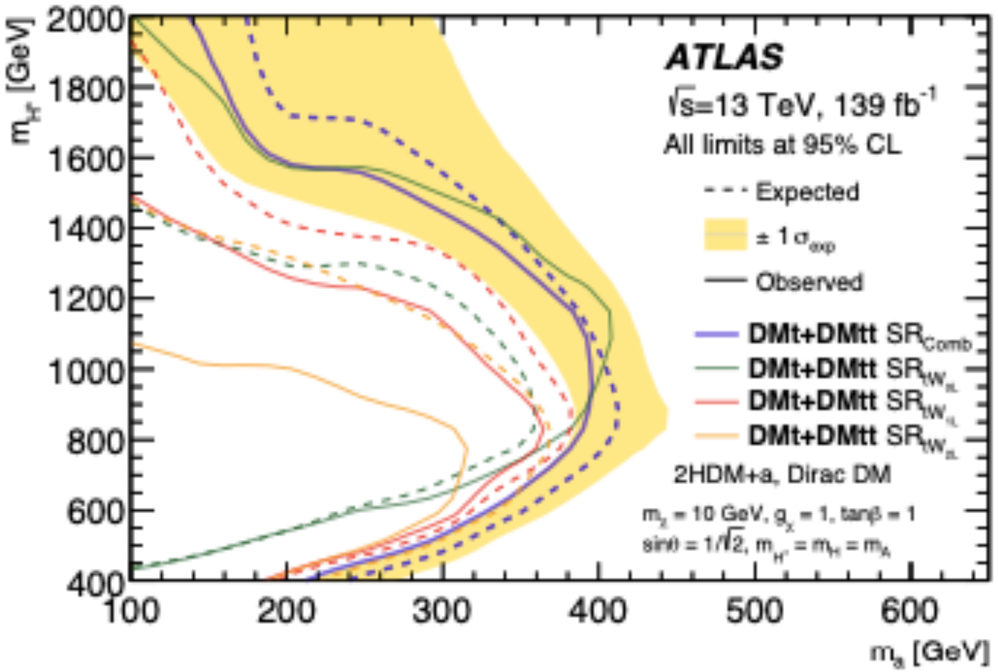
Analysis done with a team at IFIC

Phys.Dark.Univ Vol 27, 100351



EPJC, Vol 83,603, (2023)

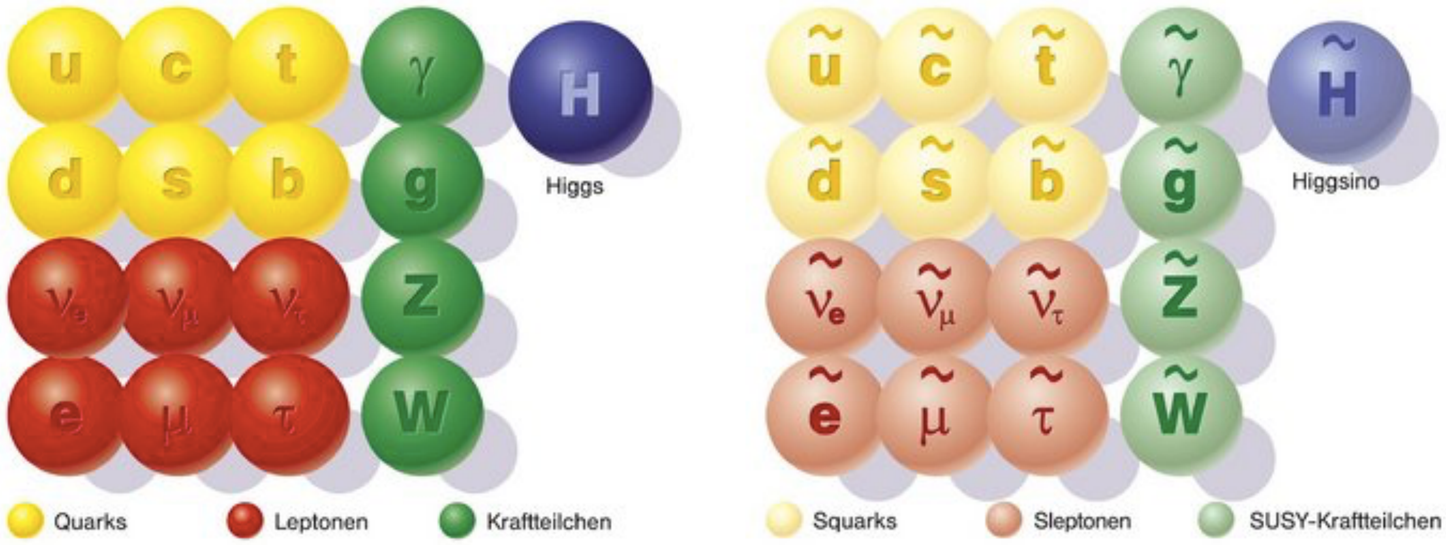




Dark matter in a complete BSM theory

One of the most attractive and complete theories beyond the Standard Model is supersymmetry.
Spin-symmetry of all the particles of the Standard Model (1/2)—> superparticles.
Key to explain the Higgs boson naturalness problem (theoretical mass in SM divergent)
3rd generation squarks have a key role in SUSY explanation of Higgs mass

A SUSY primer

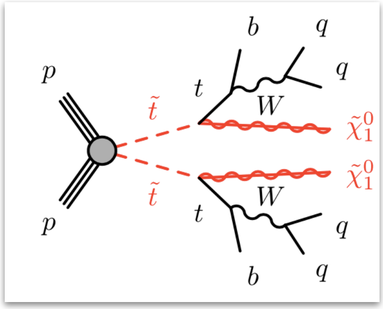


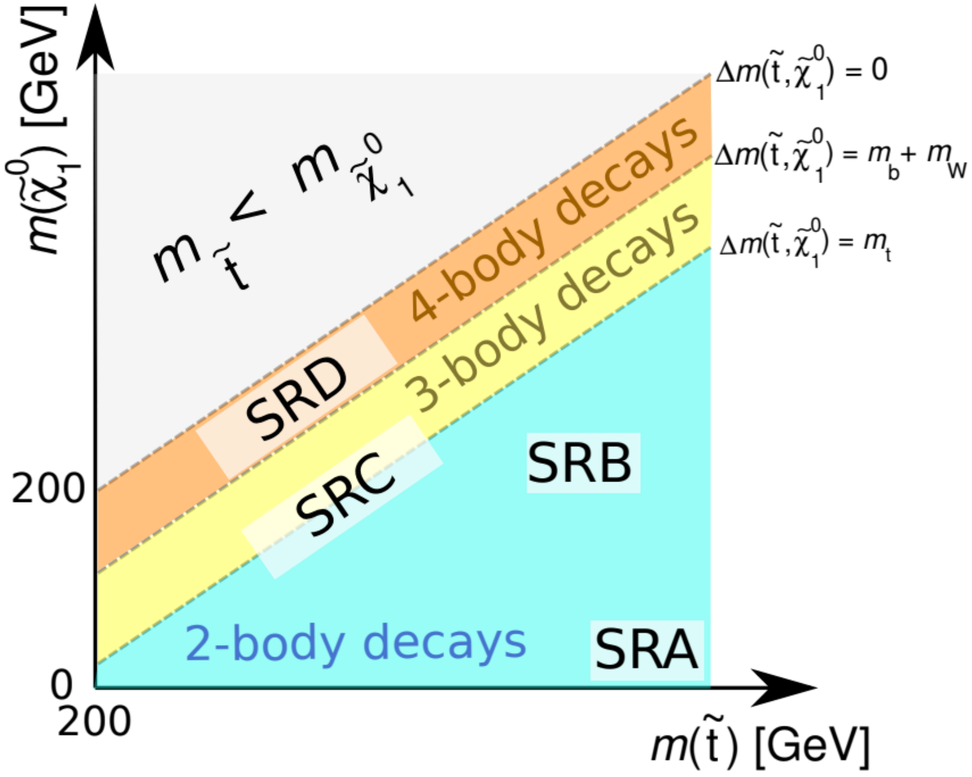
Sketch from Wikipedia

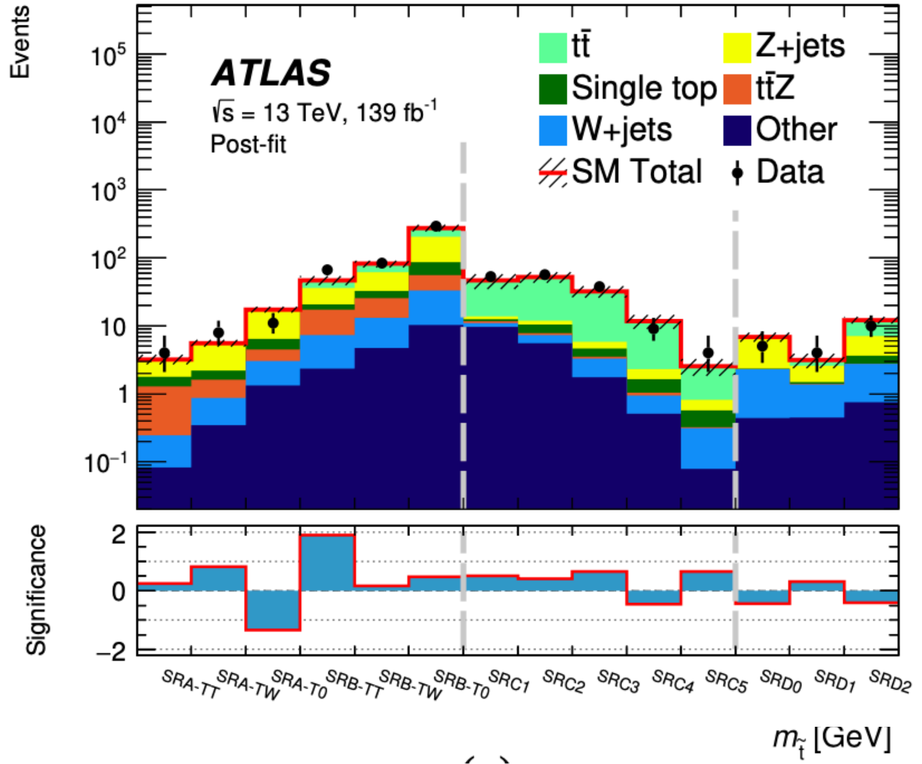
Dark matter in connection to a complete new BSM sector

Lightest super particle to be stable in minimal SUSY models —> DM candidate

DM candidates produced as products of squark decays







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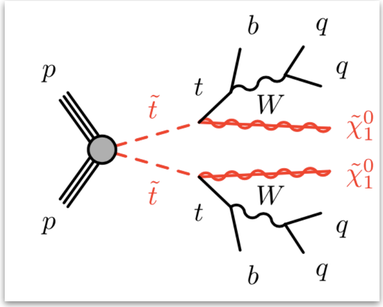
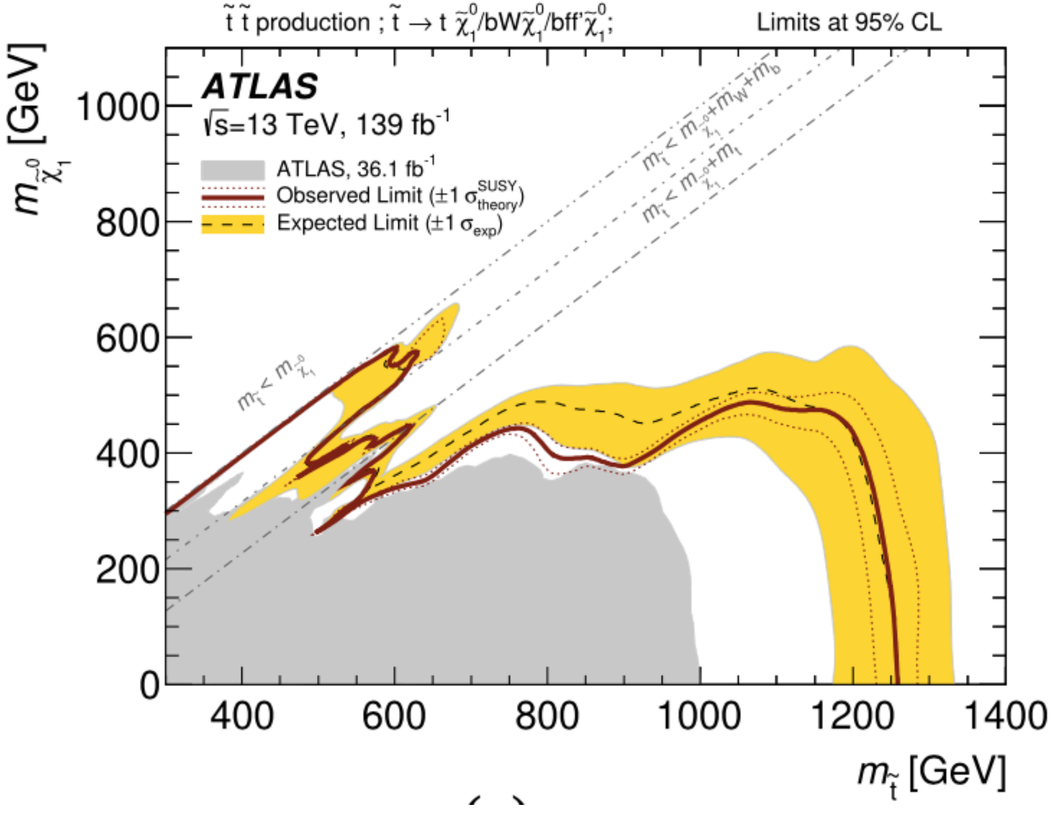


Eur. Phys. J. C 80, 737 (2020)



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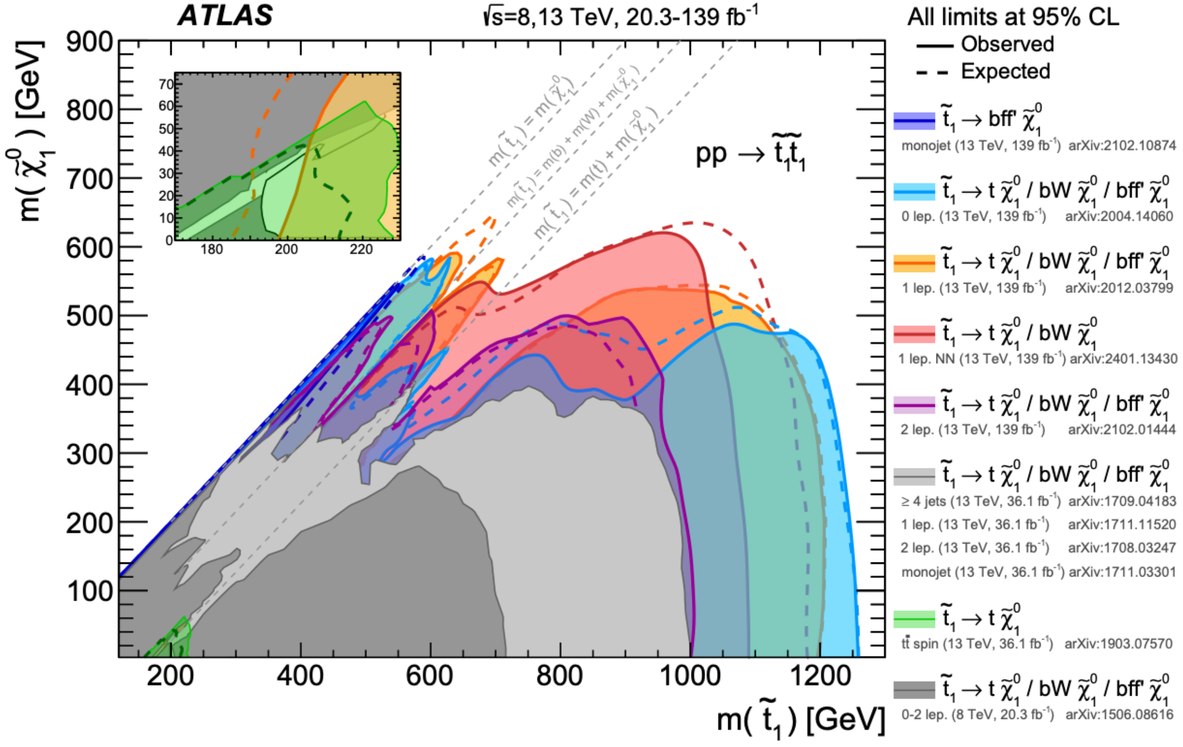

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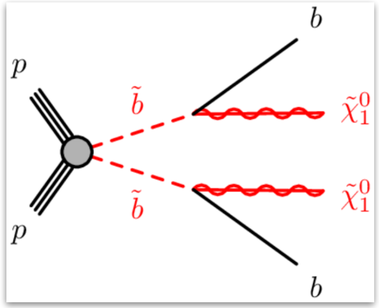

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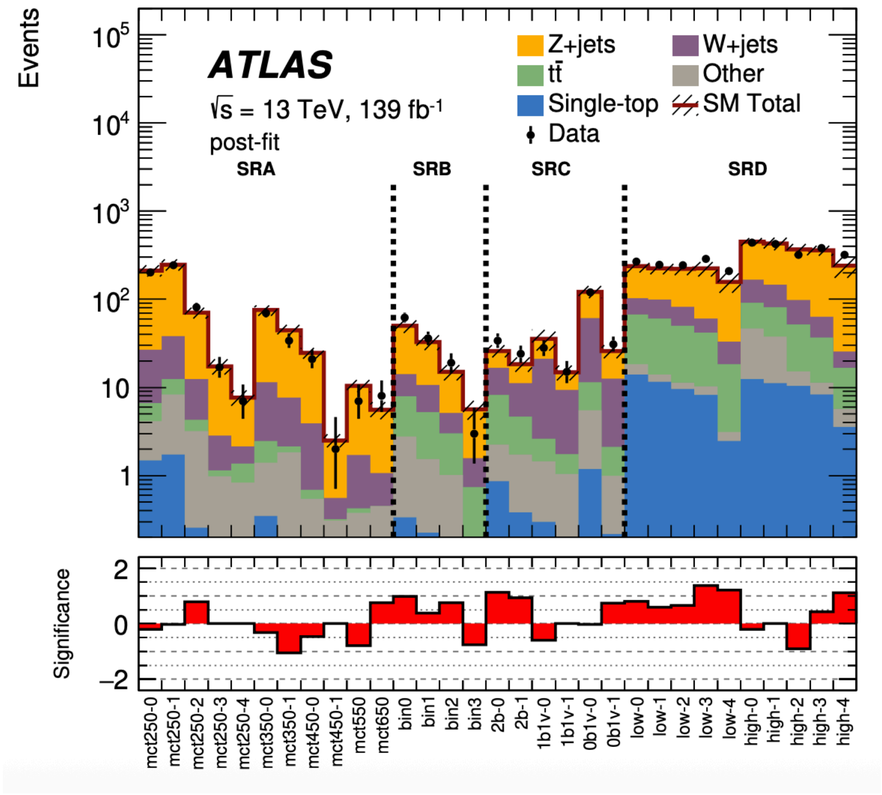
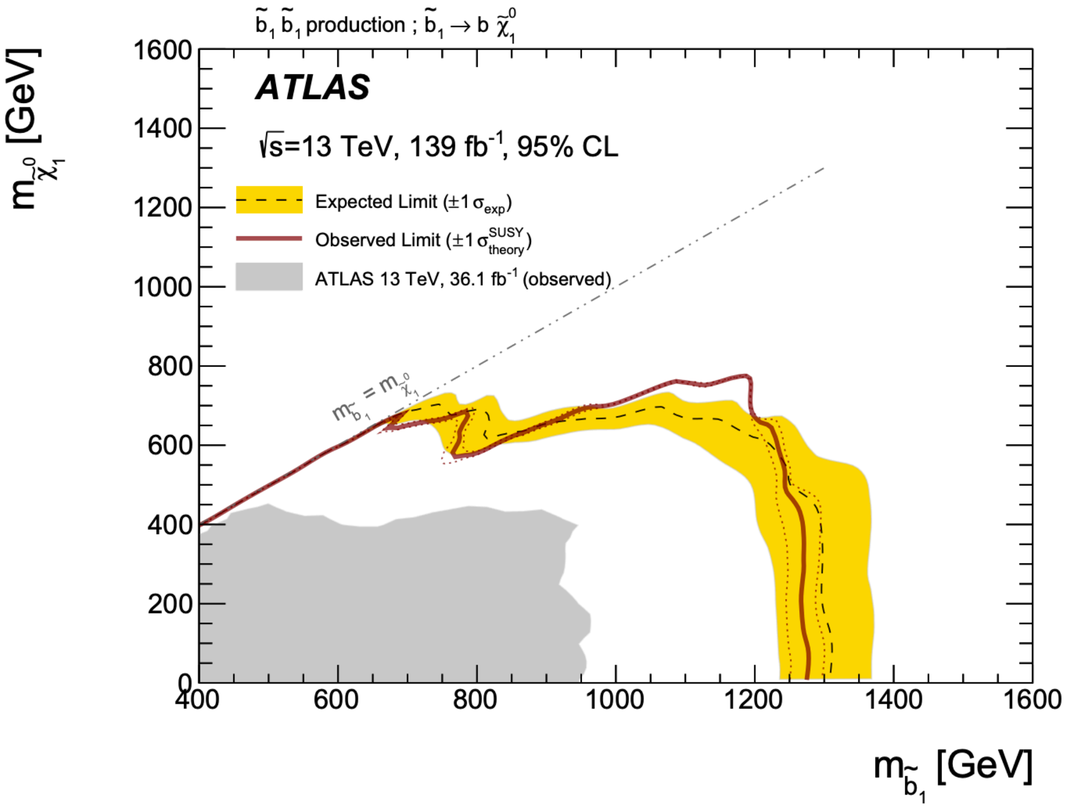


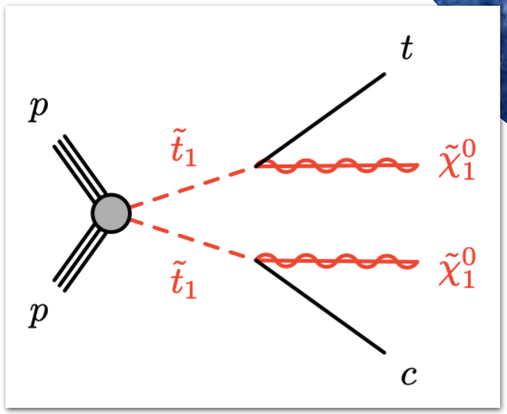


Extension to flavour violating couplings

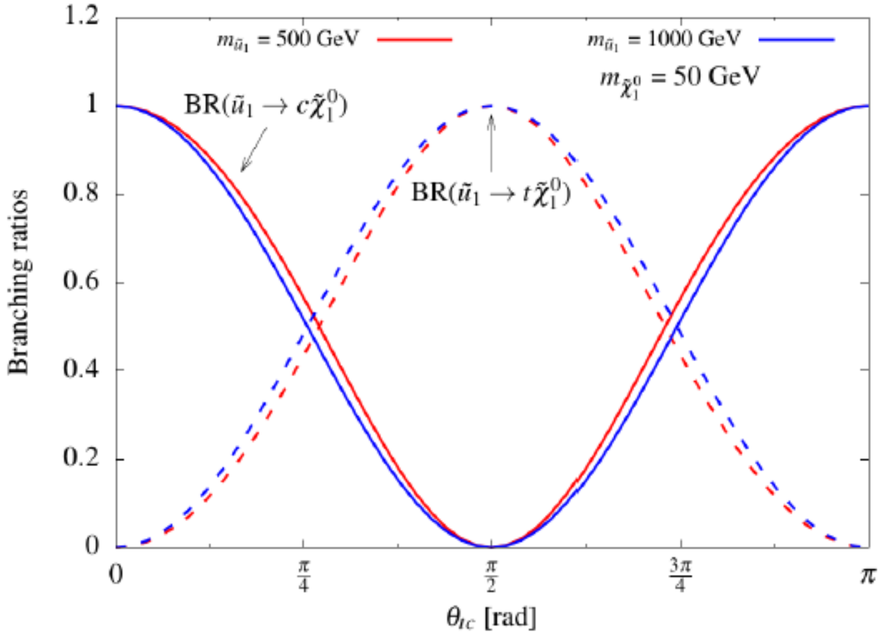
Flavour violating couplings in the SM —> Possible to have flavour violation in the BSM sectors.

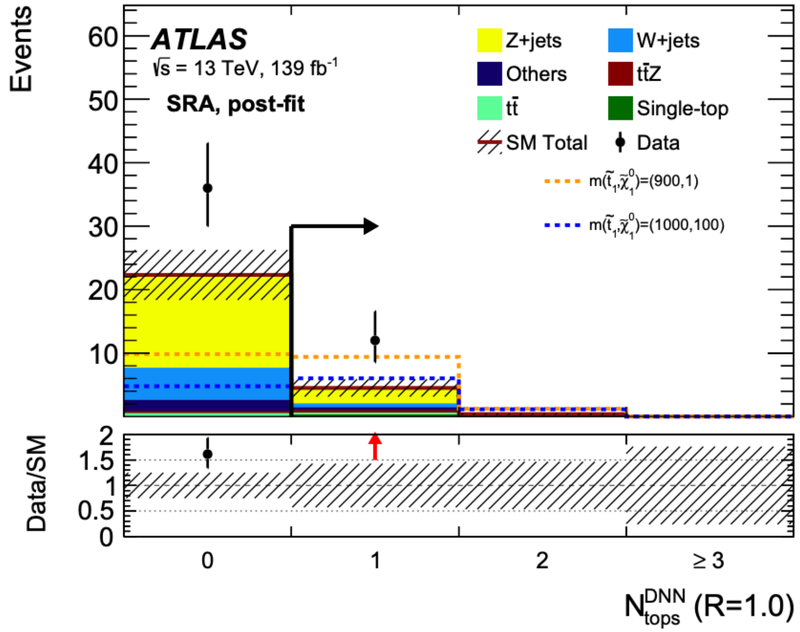
Motivated by non-minimal flavour violation SUSY simplified model (Eur. Phys. J. C78 (2018) 844)

Zero-lepton research combining top-tagging and charm tagging



$$\begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{tc} & \sin\theta_{tc} \\ -\sin\theta_{tc} & \cos\theta_{tc} \end{pmatrix} \begin{pmatrix} \tilde{c}_R \\ \tilde{t}_R \end{pmatrix}$$



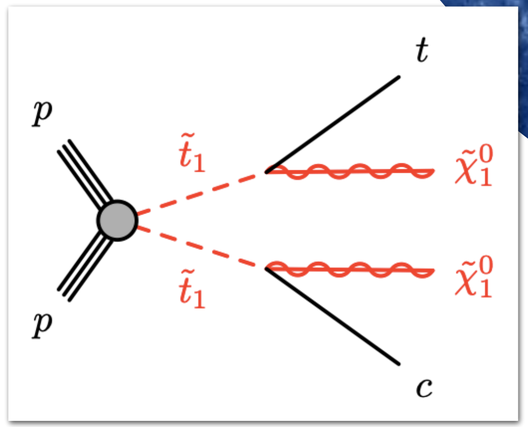


Extension to flavour violating couplings

Zero-lepton research combining top-tagging and charm tagging

- Developed a charm tagger dedicated for this search.

2σ excess in this search channel



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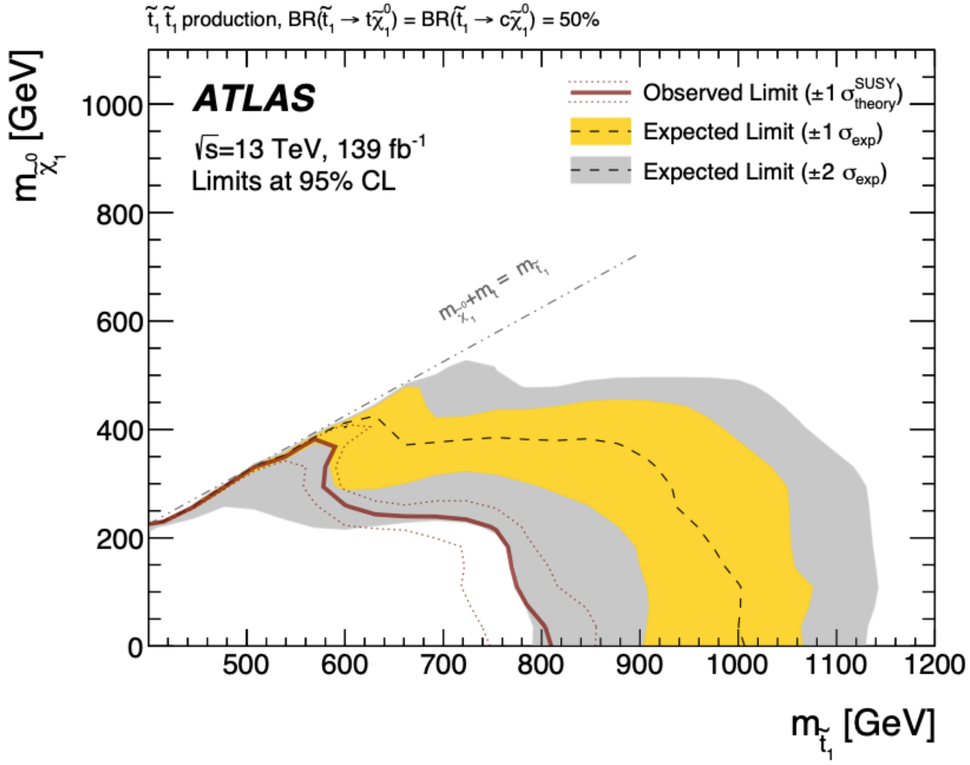
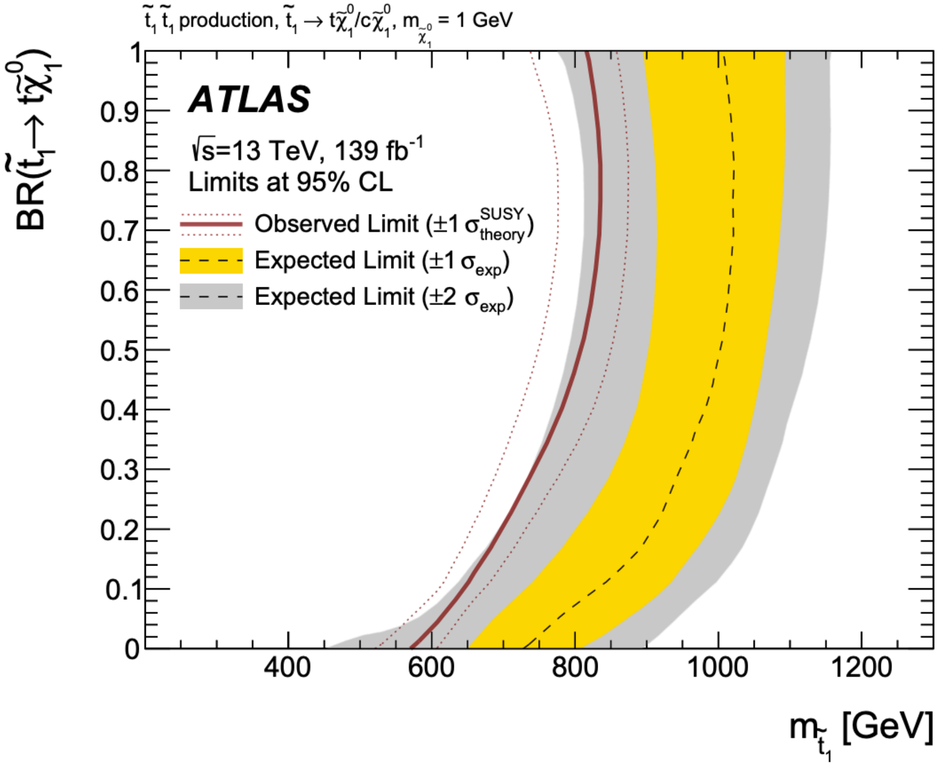
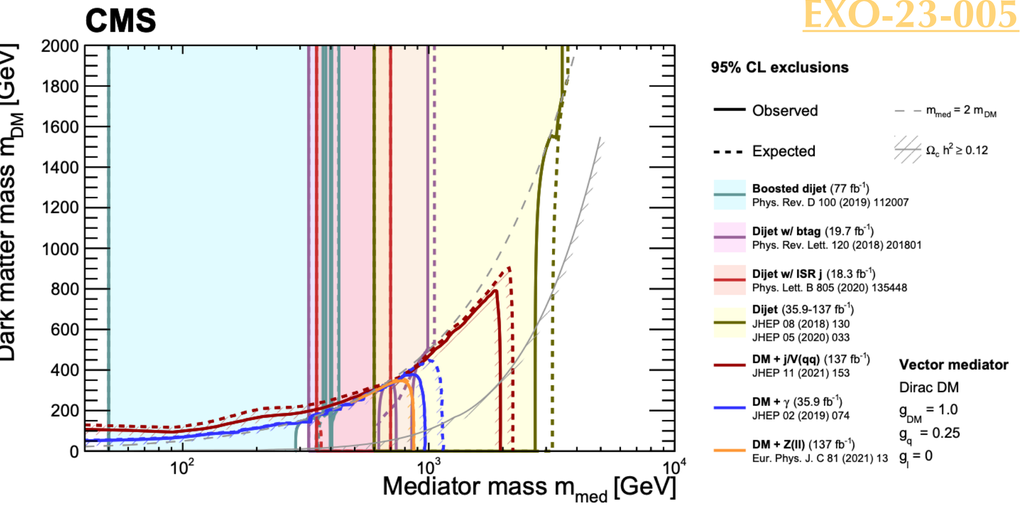
First time at LHC !





Dark matter from ATLAS and CMS



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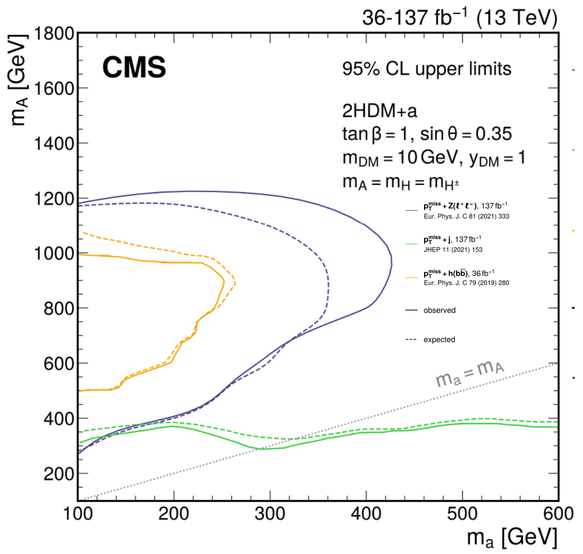

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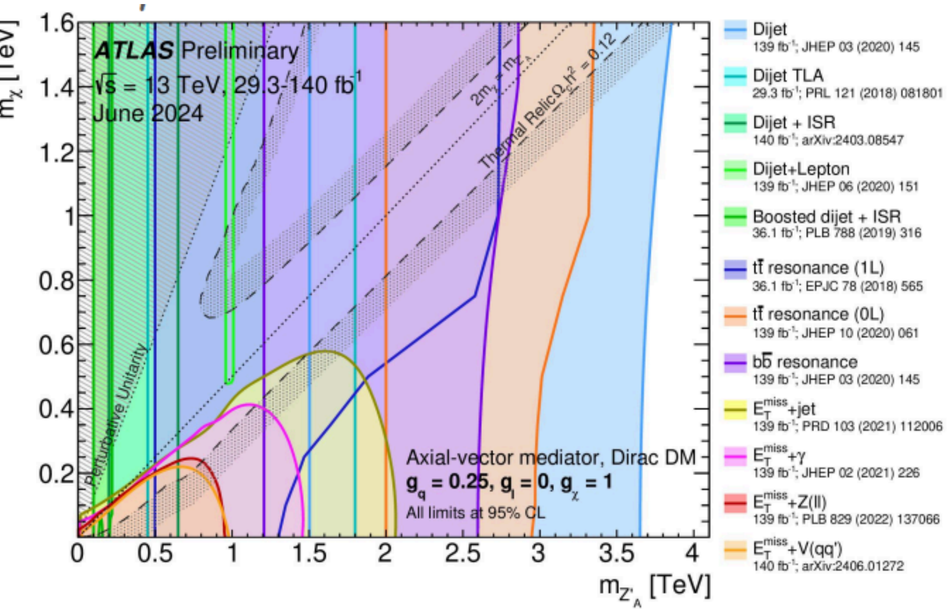
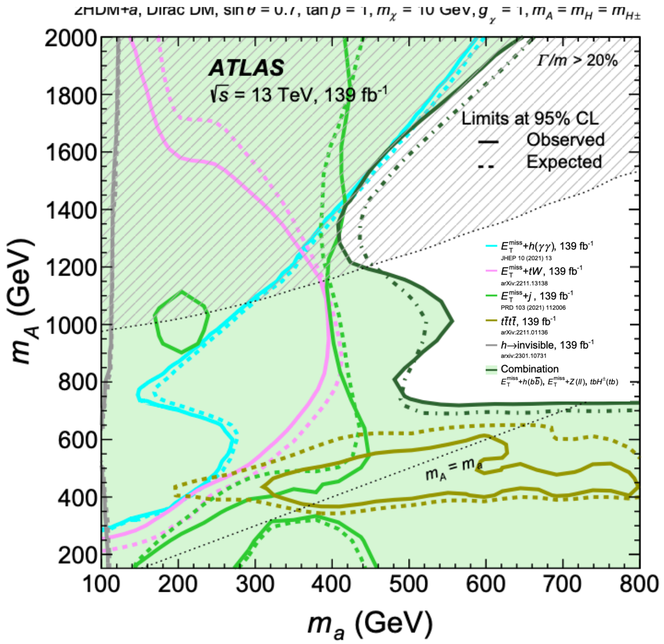
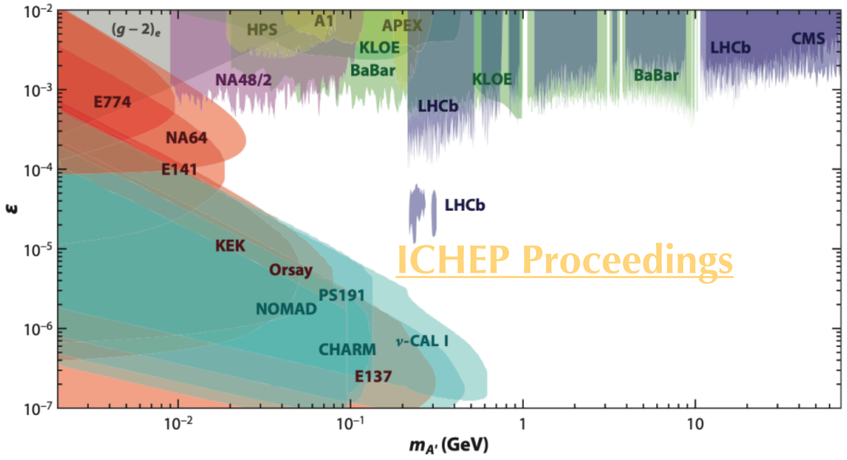






ICHEP Proceedings

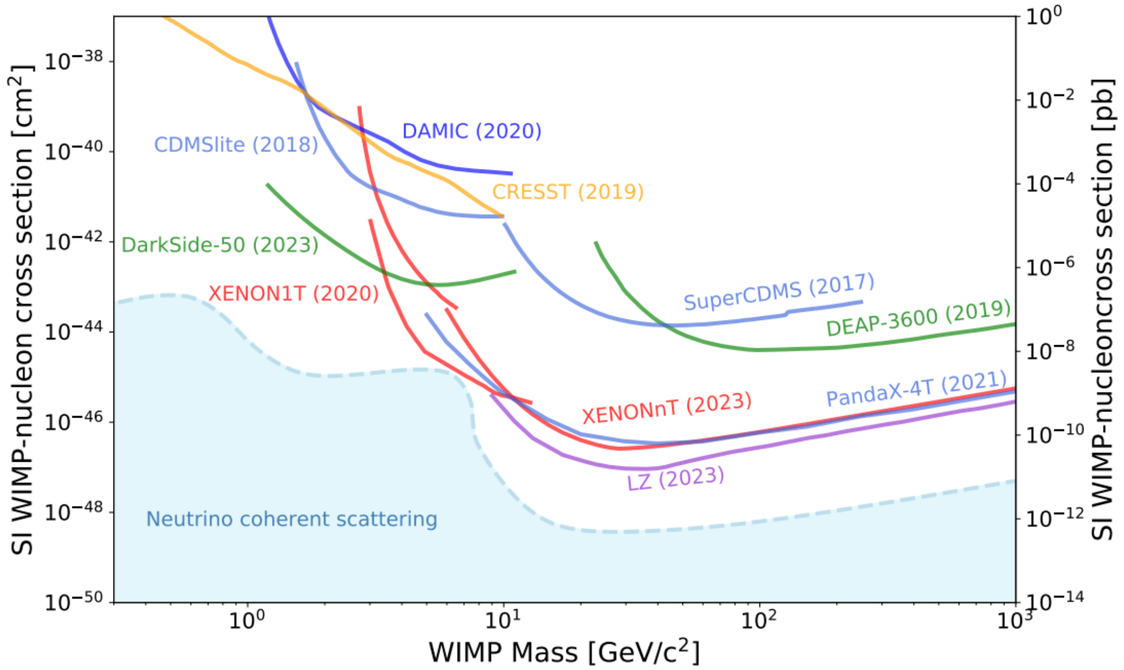
No DM found so far in the current research channels of ATLAS and CMS.

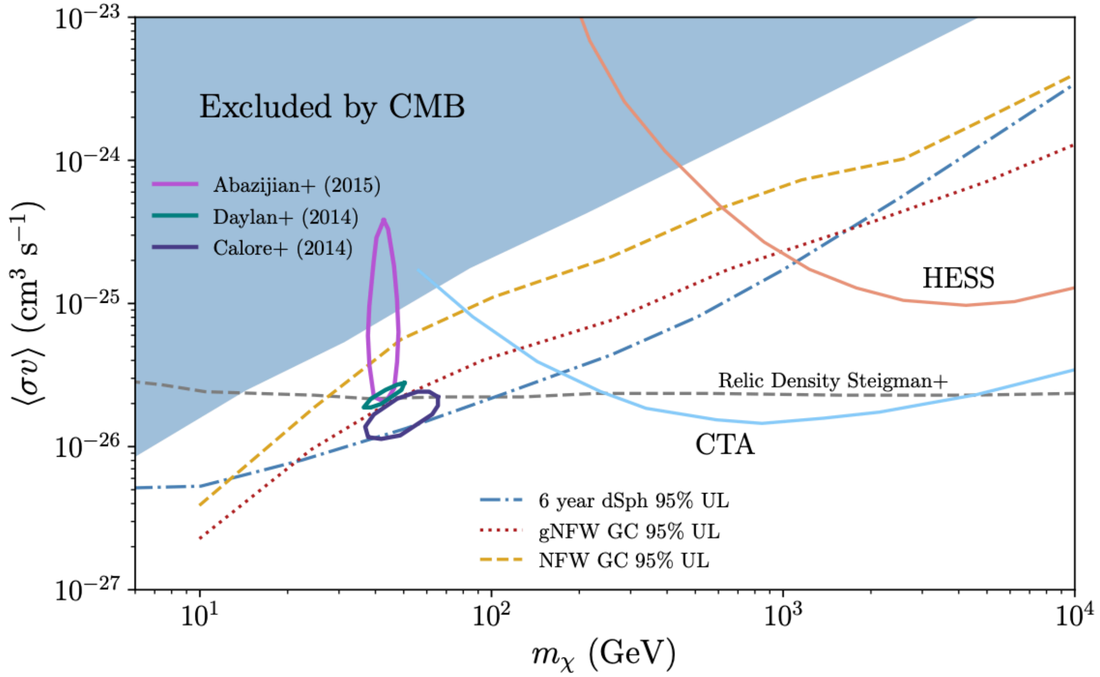
Dark matter from other experiments

Direct detection and indirect detection picture didn't also record any excess of data beyond the expected backgrounds.

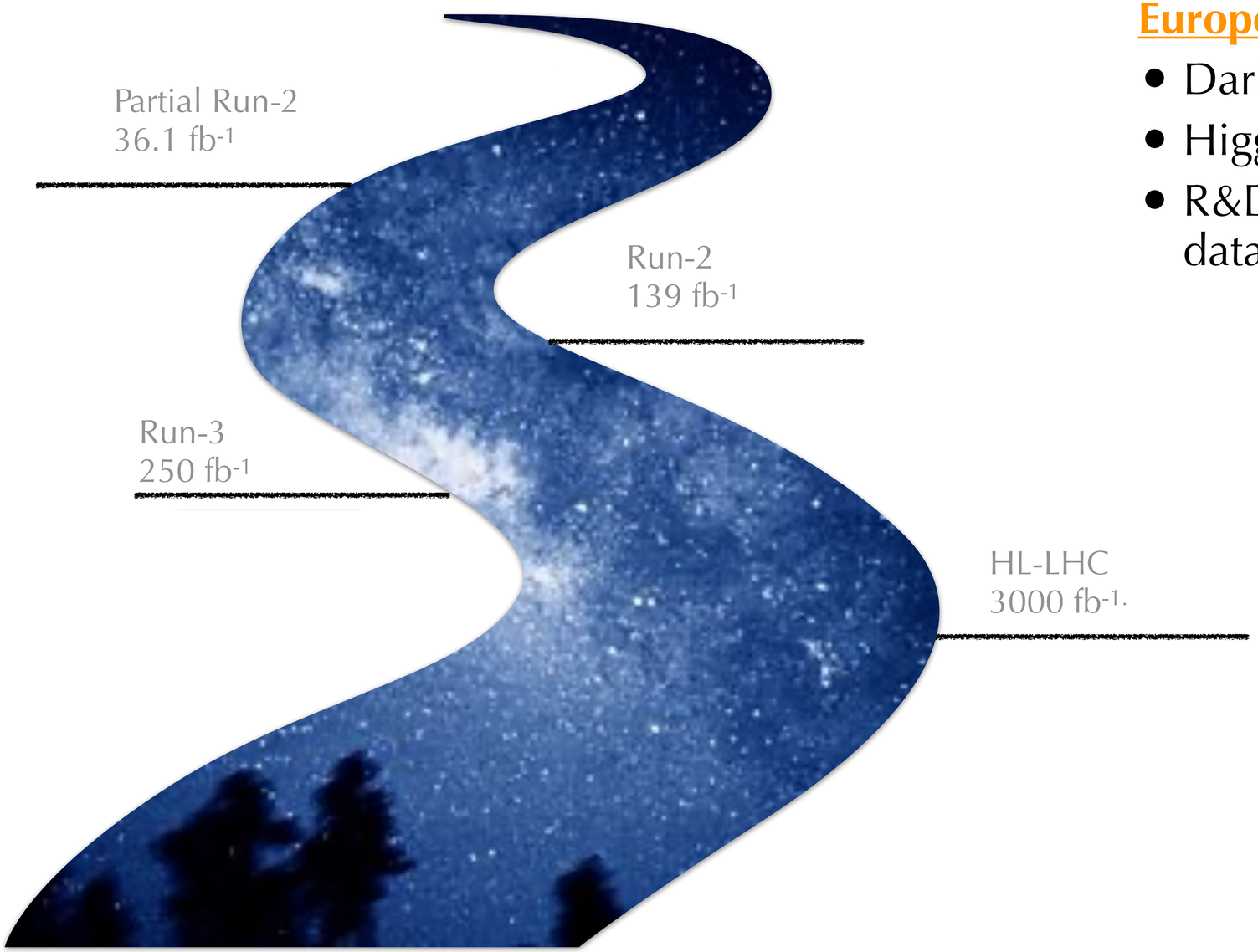
Severe constraints to several original searches.

Particle Data Group 2024





Future of DM searches: Run-3 and HL-LHC



European Strategy for Particle Physics

- Dark matter searches
- Higgs factory and Higgs measurements
- R&D of new technologies and usage of data-intensive techniques.

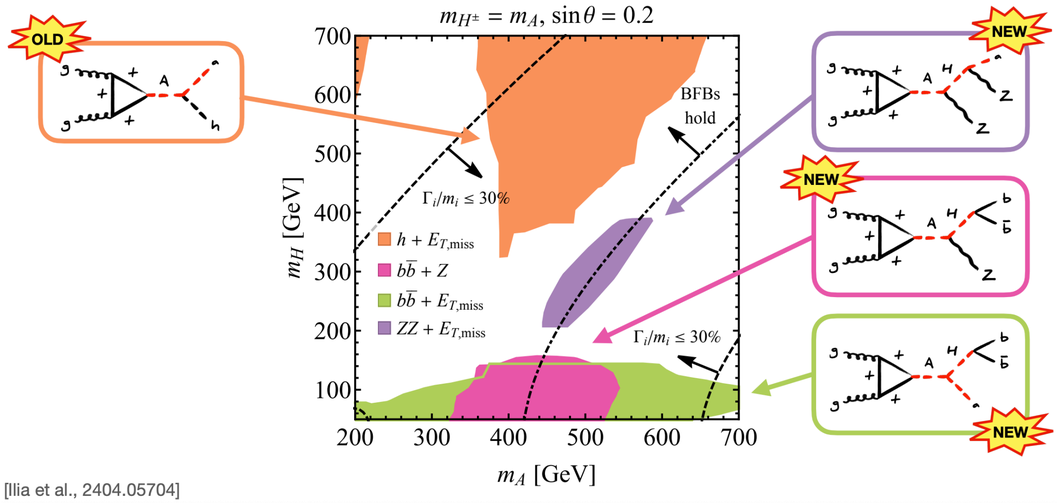
Dark matter searches at LHC during Run-3

Amplifying final states where dark matter can be motivated by theory.
Recently, interest in more complex dark sectors unconstrained with current results.

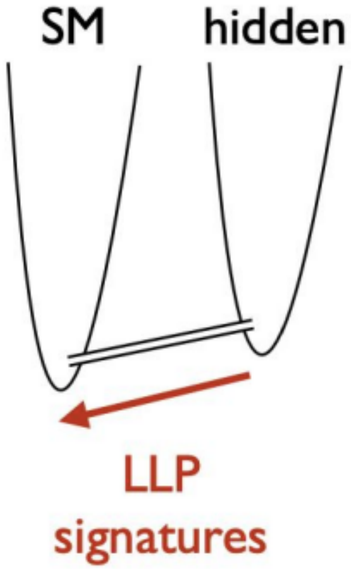
- Dark QCD: emerging jets, semi-visible jets etc
- Dark photons, dark Higgs.
- Long-lived particles
- ……

DM WG report

Old & new 2HDM+a signatures in type I



[Ilia et al., 2404.05704]



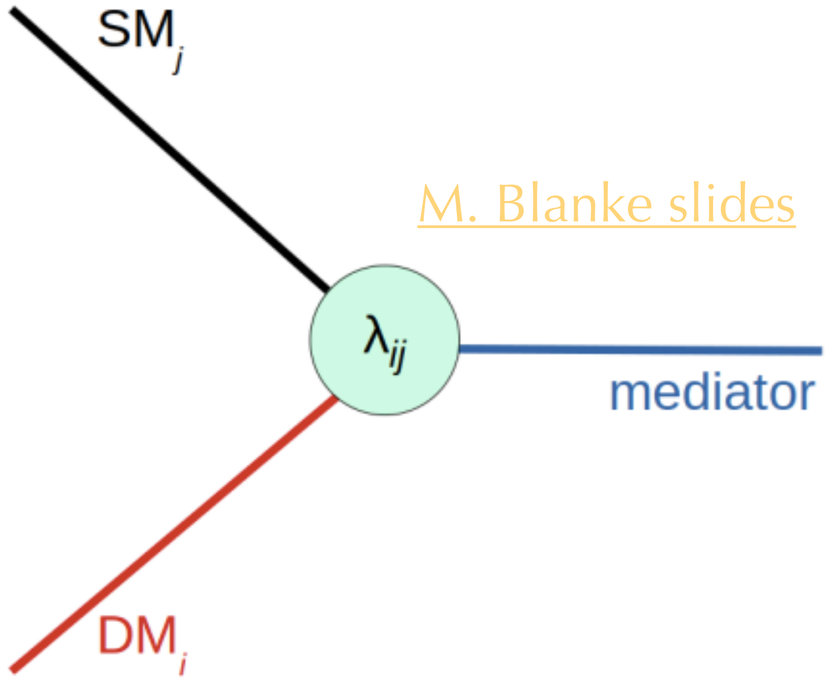
A question of flavour

JHEP 02 (2018) 105 JHEP 05 (2017) 162 JHEP 05 (2022) 086 JHEP 06 (2024) 179

Dark matter models with three generations and couplings with the SM that connect different quark and DM generations
If couplings between different generations —> flavour violation and additional source of CP violation.
Coupling mediated by a colored scalar Φ carrying the same quantum numbers as quarks.

$$\mathscr{L}_{dark} = \left(i\bar{\chi}\partial\!\!\!/\chi - M_\chi\bar{\chi}\chi\right) - \left(\lambda_{ij}\bar{q}_{L,i}\phi\chi_j + h.c\right)$$
$$+(D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi - V(\phi,H)$$

$$\lambda = U_\lambda D_\lambda \qquad \text{with}$$
$$D_\lambda = \text{diag}(D_{\lambda,11}, D_{\lambda,22}, D_{\lambda,33})\,,$$
$$U_\lambda = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23}e^{-i\delta_{23}} \\ 0 & -s_{23}e^{i\delta_{23}} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12}e^{-i\delta_{12}} & 0 \\ -s_{12}e^{i\delta_{12}} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



M. Blanke slides

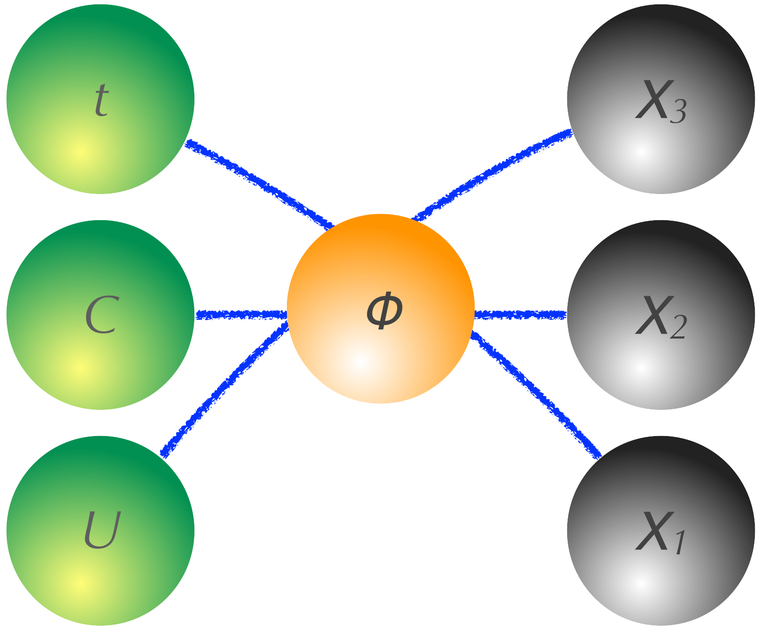
A question of flavour

JHEP 02 (2018) 105 JHEP 05 (2017) 162 JHEP 05 (2022) 086 JHEP 06 (2024) 179

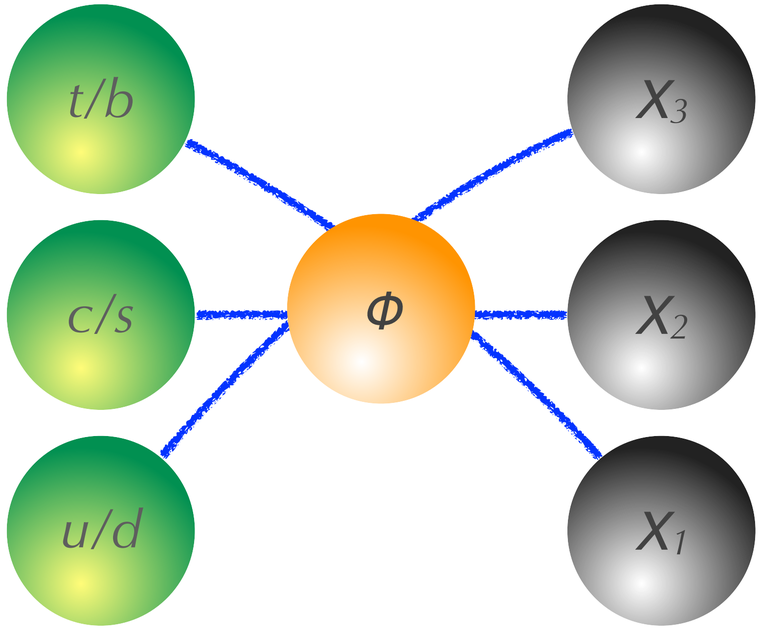
Rich phenomenology and dependent on nature of the interaction and DM particle.

- Couplings to left-handed or right-handed quarks.

Couplings to right-handed quarks



Couplings to left-handed quarks



A question of flavour

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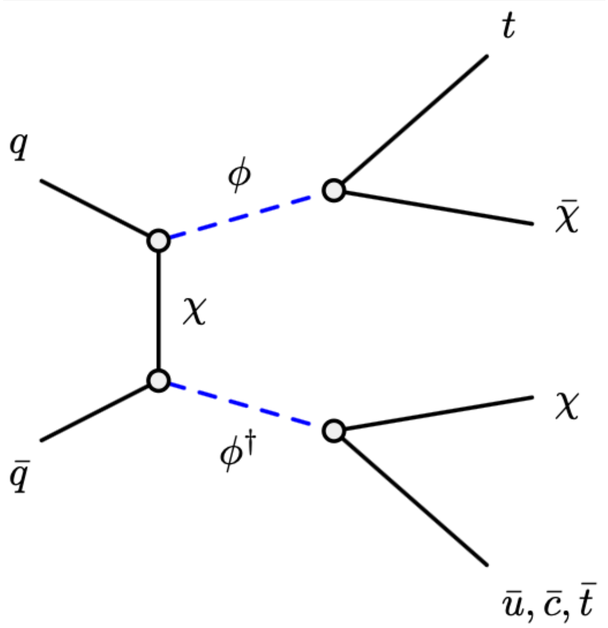
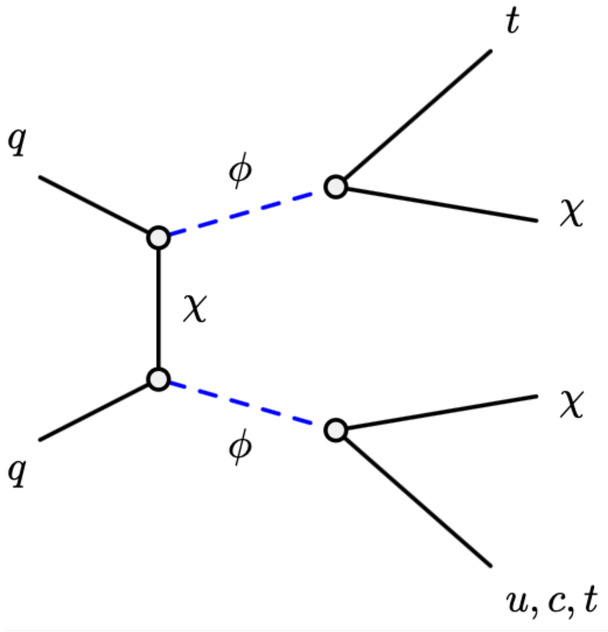
- Couplings to left-handed or right-handed quarks.
- Dirac or Majorana behavior of DM particles

Dirac type particle



Majorana type particle



A question of flavour

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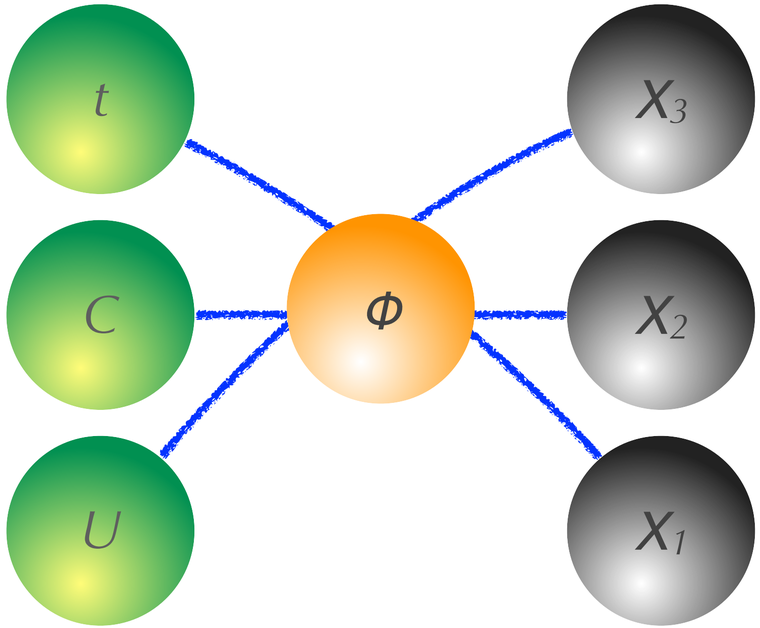
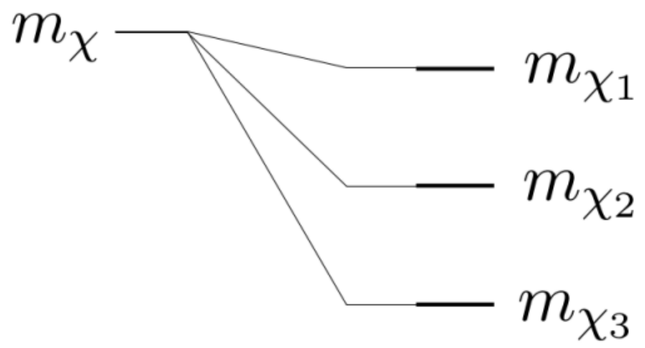
Rich phenomenology and dependent on nature of the interaction and DM particle.

- Couplings to left-handed or right-handed quarks.
- Dirac or Majorana behavior of DM particles



These models are currently considering **top-flavored DM** —> Lowest mass DM particle is the particle coupling mainly to the top-quark.

$$m_{\chi,ij} = \; : m_\chi \left(1 + \eta (D_{\lambda,ii})^2 + \mathcal{O}(\lambda^4)\right) \delta_{ij} \, .$$

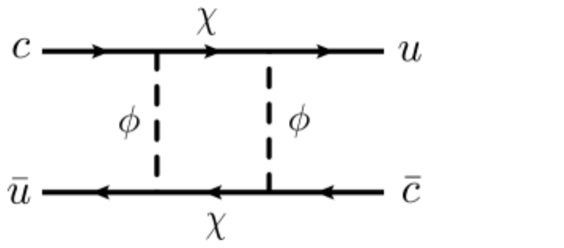


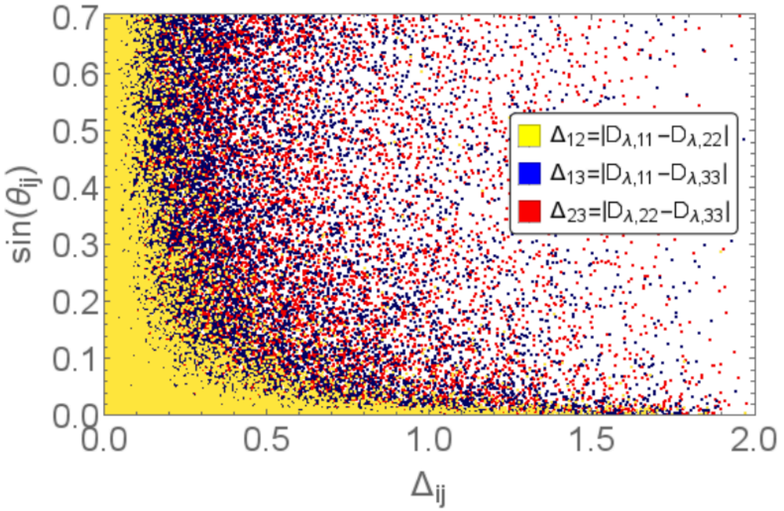
Interest of these models

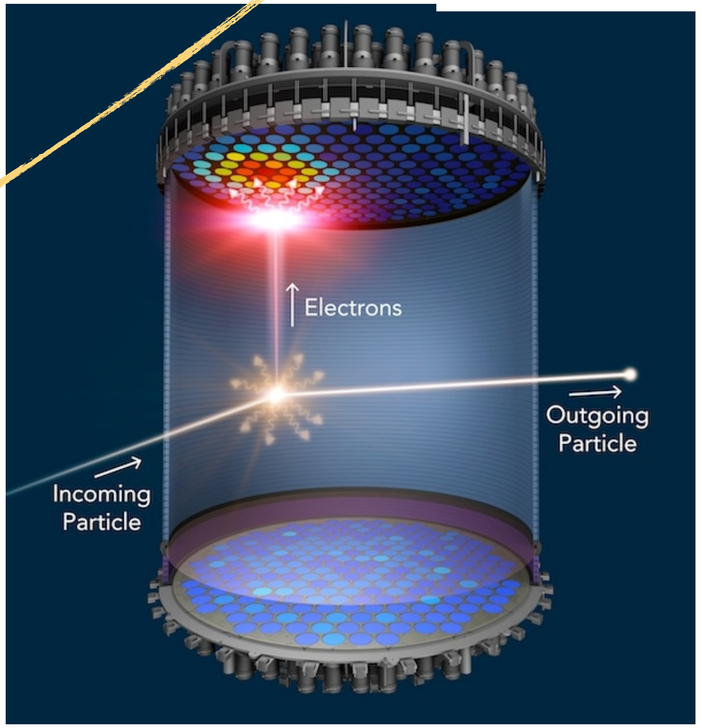
Several of constraints from DM searches can be lifted

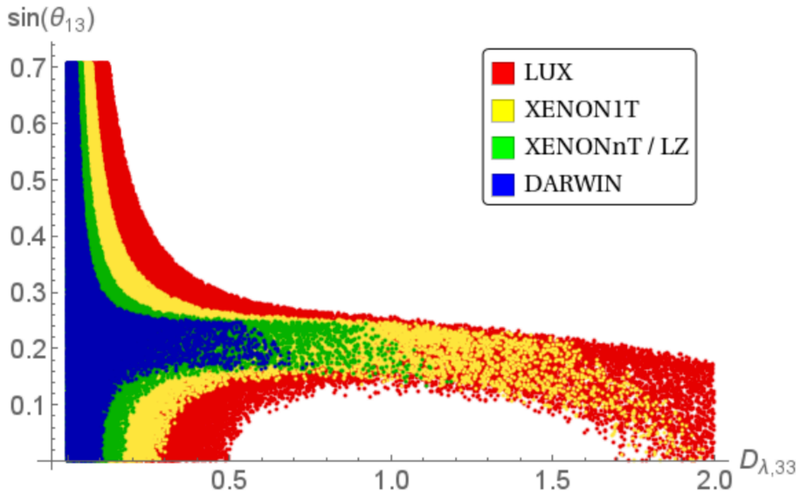
- Lack of signal in direct detection experiments: Cancellation of contributions via penguin diagrams
- Flavour physics: area of parameter space still allowed.
- Freeze-out: two scenarios allowed, either with strong couplings (canonical + prompt searches at LHC) or small couplings (conversion-driven + long-lived particles)

$$\lambda = U_\lambda D_\lambda \quad \text{with}$$
$$D_\lambda = \mathrm{diag}(D_{\lambda,11}, D_{\lambda,22}, D_{\lambda,33}),$$
$$U_\lambda = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23}e^{-i\delta_{23}} \\ 0 & -s_{23}e^{i\delta_{23}} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12}e^{-i\delta_{12}} & 0 \\ -s_{12}e^{i\delta_{12}} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$









Collider signatures and projections

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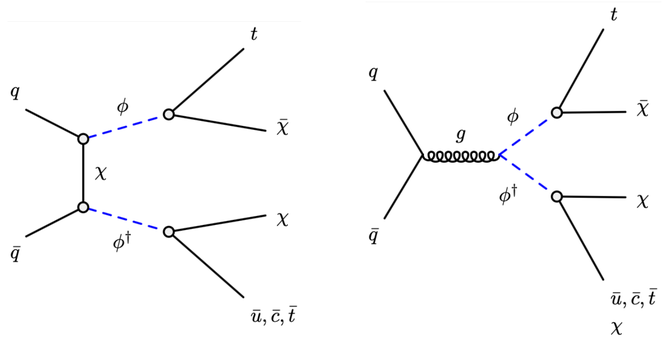
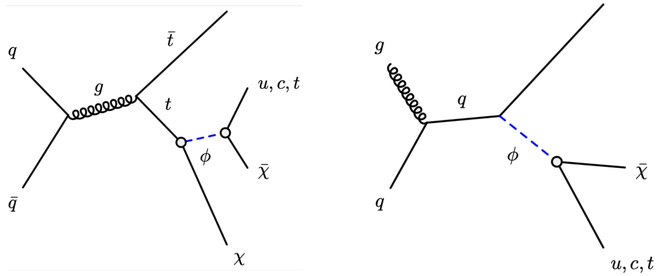
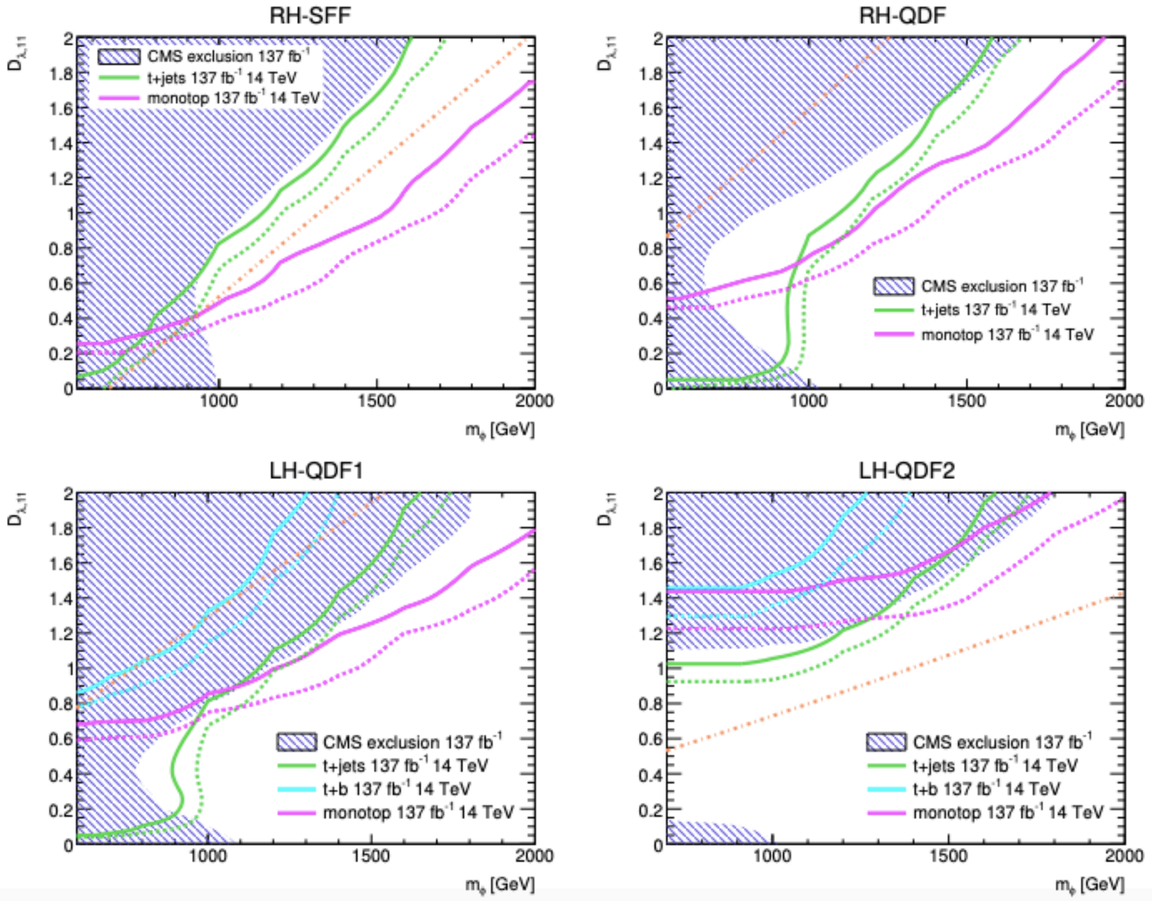
Generally, these models present qq+E_T^{miss} collider signatures. Shown that tj+E_T^{miss} and t+E_T^{miss} dedicated searches beat full Run-2 jets+E_T^{miss} and tt+E_T^{miss} results.





Benchmark	m_χ	Couplings	Mixing angles
$D_{\lambda,11} = D_{\lambda,22}$; $\theta_{12} = \theta_{23} = 0$; $\delta_{ij} = 0$			
RH-SFF	200 GeV	$D_{\lambda,33} = D_{\lambda,11} + 1.0$	$\sin\theta_{13} = 0.25$
RH-QDF	150 GeV	$D_{\lambda,33} = D_{\lambda,11} + 0.2$	$\sin\theta_{13} = 0.2$
LH-QDF1	150 GeV	$D_{\lambda,33} = D_{\lambda,11} + 0.1$	$\sin\theta_{13} = 0.1$
LH-QDF2	450 GeV	$D_{\lambda,33} = D_{\lambda,11} + 0.2$	$\sin\theta_{13} = 0.2$
Parameters to scan: m_ϕ and $D_{\lambda,11}$			

Sensitivity study on Dirac models



Other interesting signatures

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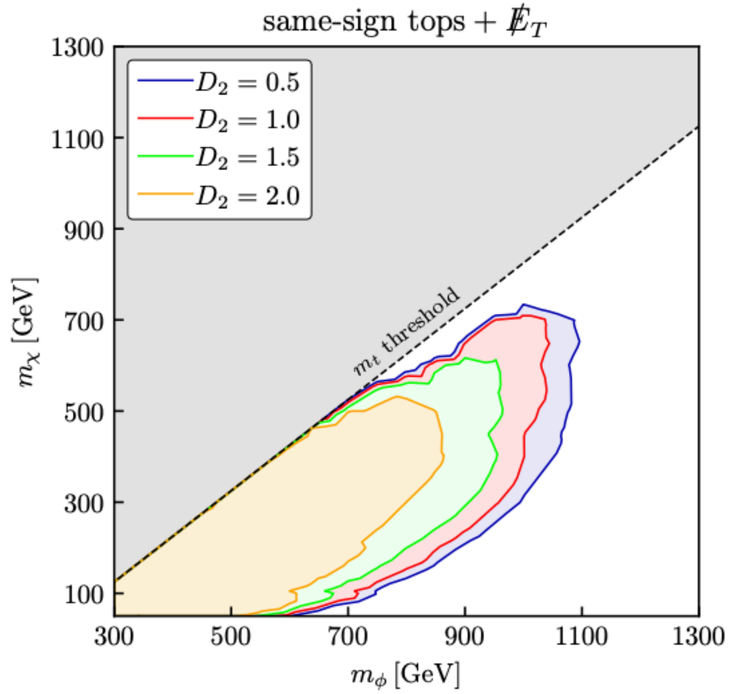
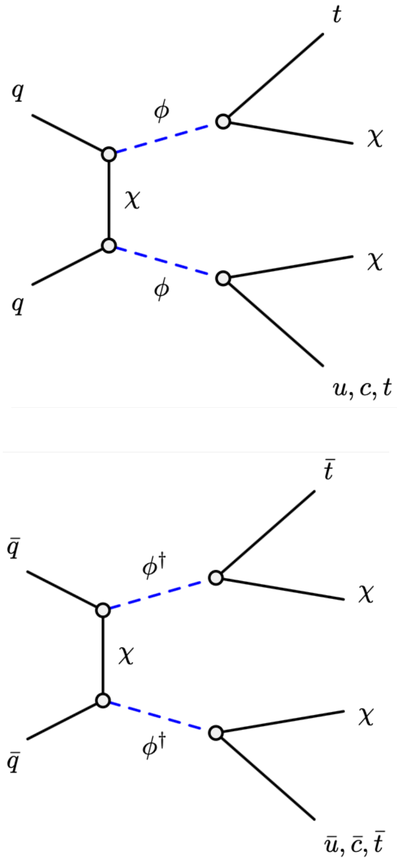
Majorana models also provide interesting observables:

- Including same-sign tt+E_T^{miss} channel.
- Charge asymmetry due to enhanced uu —> ϕϕ.

Same-sign tt+E_T^{miss} signature

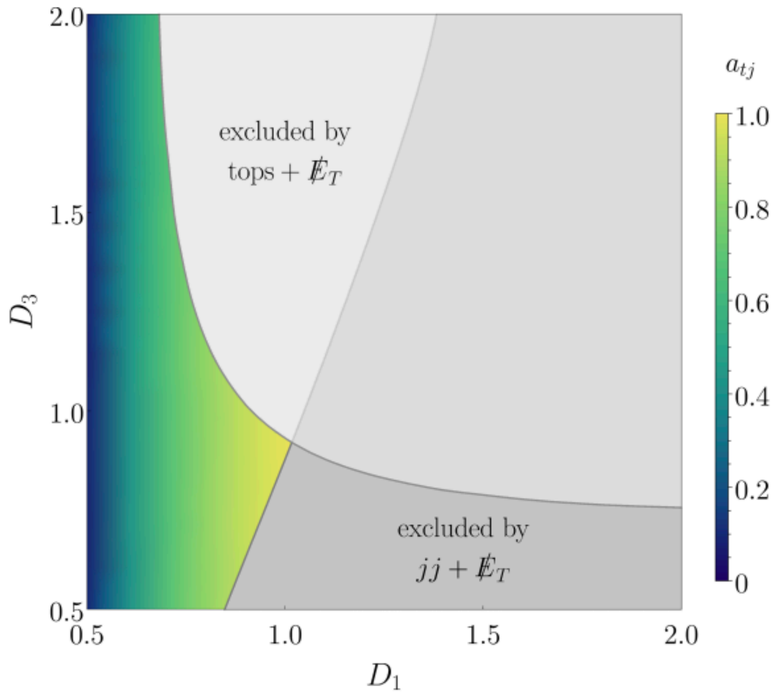


(a) $D_1 = D_3 = 2.0$



Charge asymmetry in Majorana models

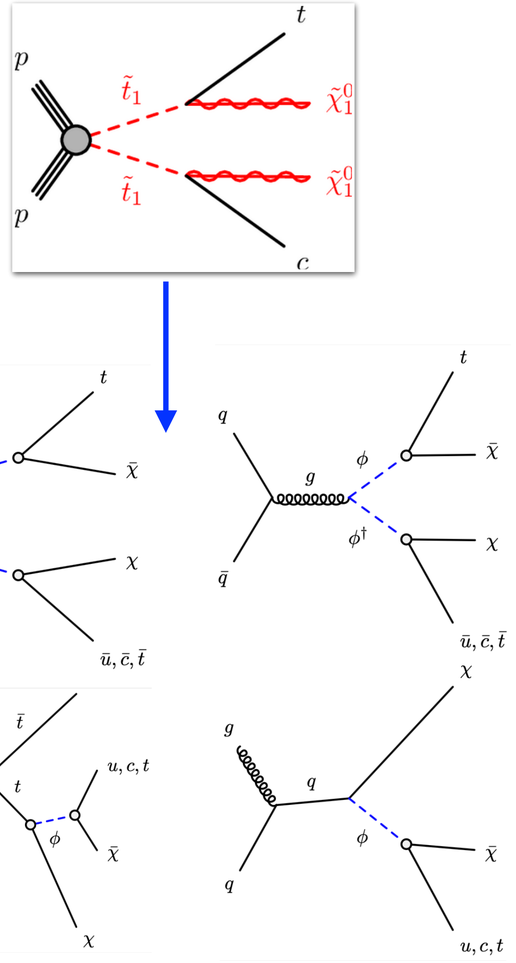
$$a_{tj} = \frac{\sigma(tj + \not{E}_T) - \sigma(\bar{t}j + \not{E}_T)}{\sigma(tj + \not{E}_T) + \sigma(\bar{t}j + \not{E}_T)}$$

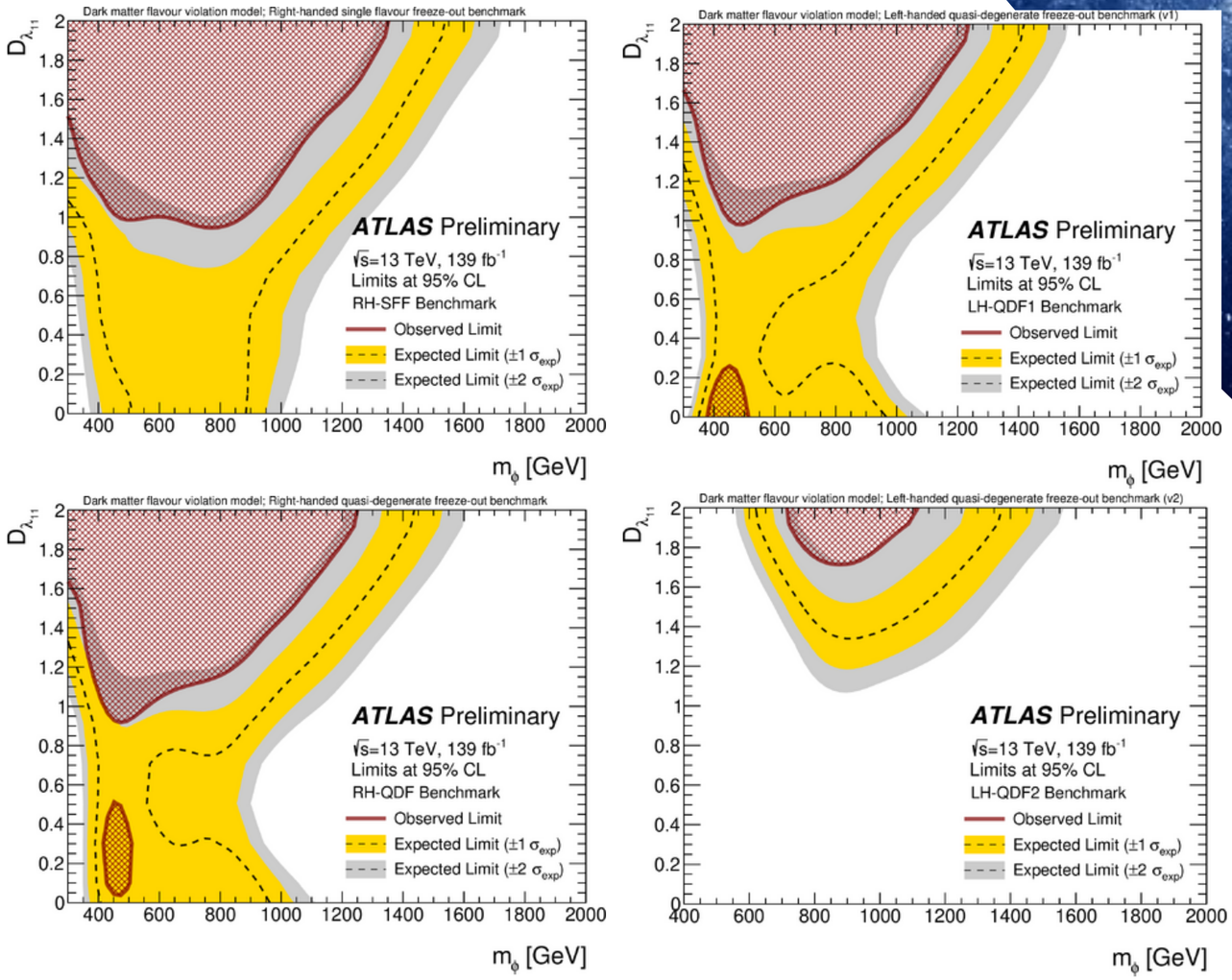


Reinterpretation of ATLAS analysis

PUB-2025-010

Sensitivity of the analysis driven by the presence of tt+E_T^{miss} and tc+E_T^{miss} signatures.



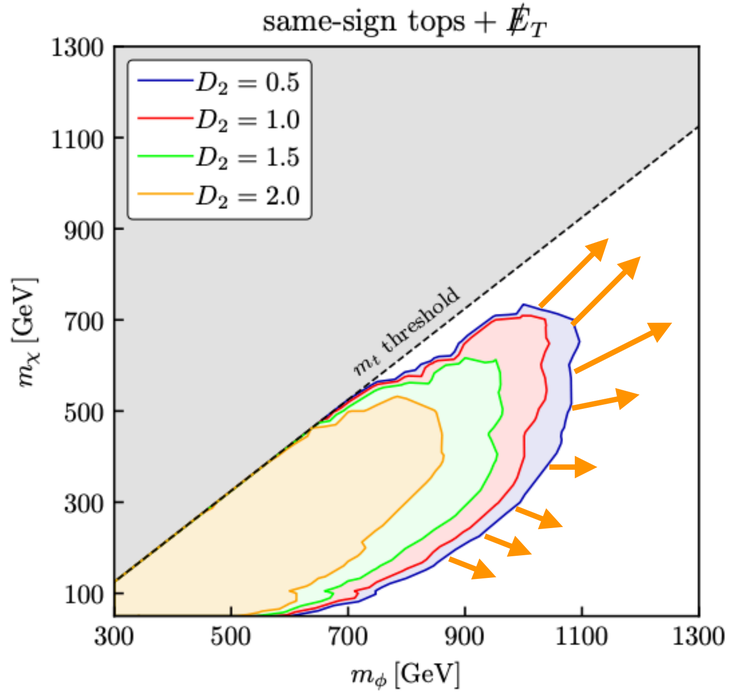


Higher sensitivity expected from including monotop and other tj+E_T^{miss} final states.
Area of the parameter space to explore larger

Searches for flavour violating dark matter models

Search for these flavour dark matter models in t+E_T^{miss} and tj+E_T^{miss} final states.

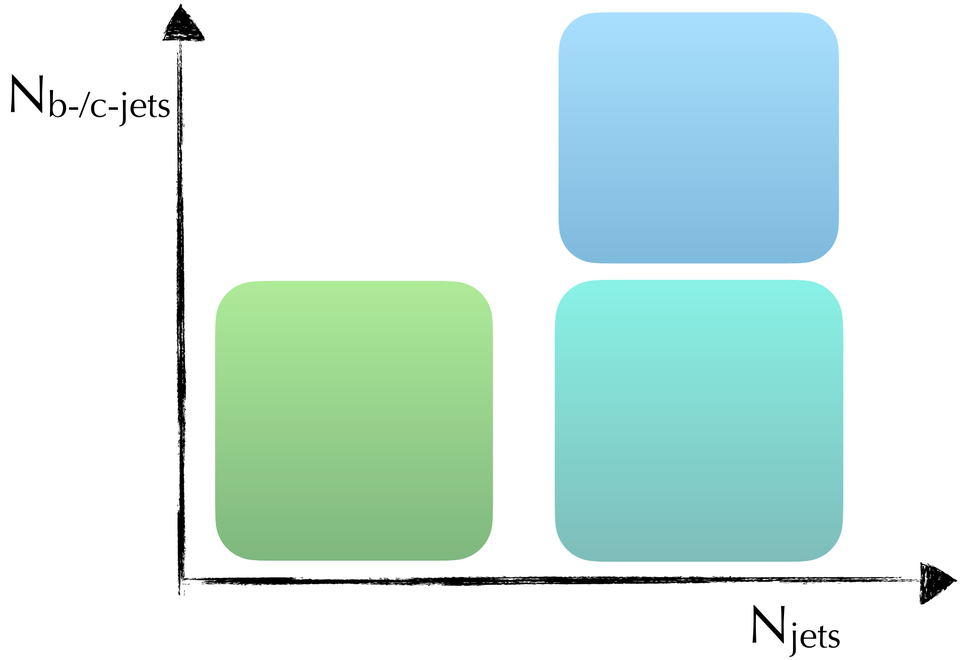
- c-tagging and b-tagging for increased sensitivity.
- Study charge asymmetry in these final states.
- Develop same-sign tt searches in <= 2L final states.



(a) $D_1 = D_3 = 2.0$

$$a_{tj} = \frac{\sigma(tj + \not{E}_T) - \sigma(\bar{t}j + \not{E}_T)}{\sigma(tj + \not{E}_T) + \sigma(\bar{t}j + \not{E}_T)}$$

tj+E_T^{miss} signatures



Beyond Dark Matter searches

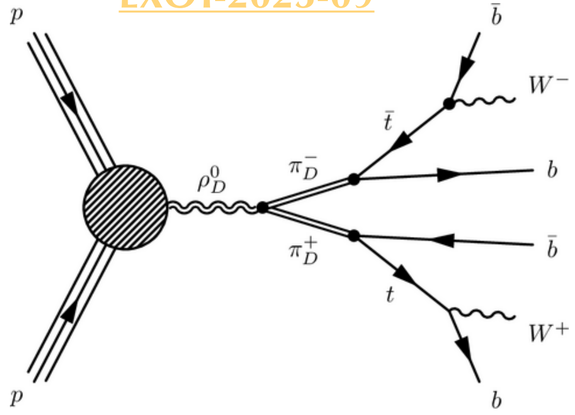
Leadership of the ATLAS HQT Exotics sub-group.

Targeting search of BSM resonances in channels with b- and top-quarks.

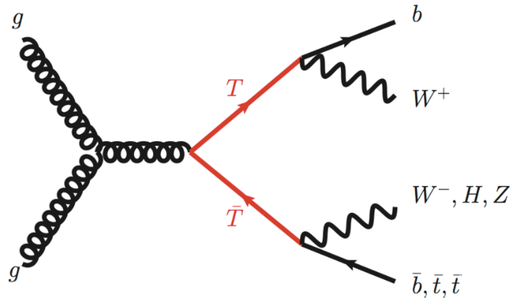
- Strongly coupled dark matter, hidden valley theories, vector-like quarks, 2HDM…

Measurements of Higgs quartic coupling in bbbbττ final state.

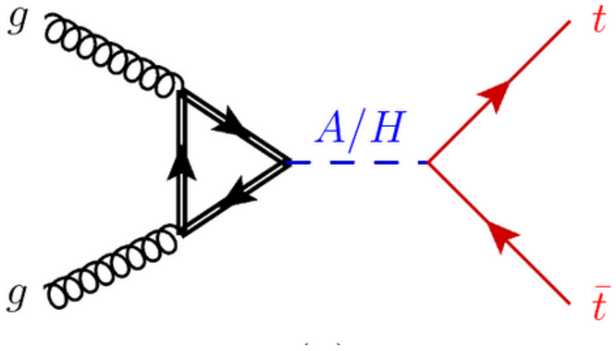
EXOT-2023-09



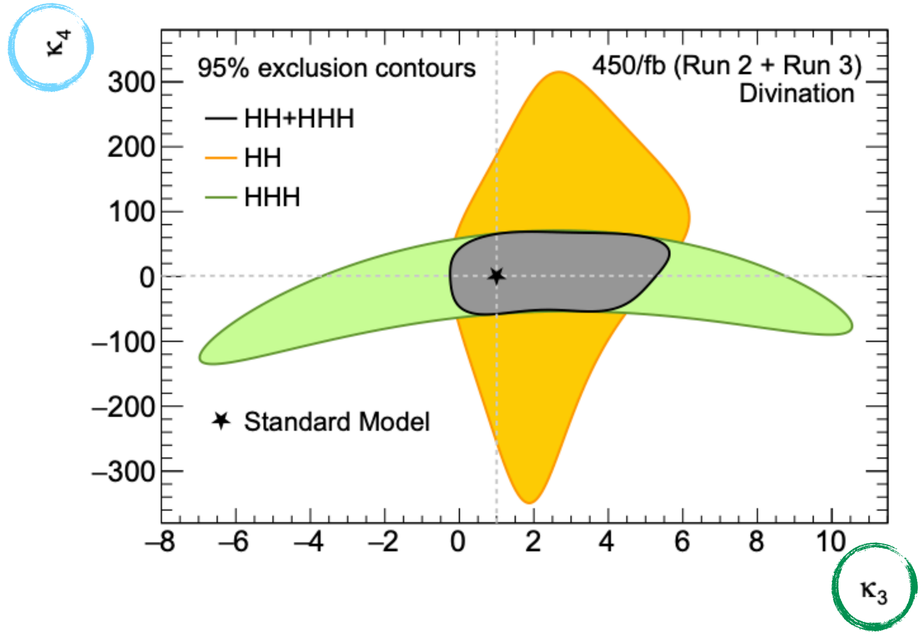
EXOT-2019-06



EXOT-2020-25



$$V(H) = \frac{1}{2}m_H^2 H^2 + \underbrace{\lambda\nu}_{\lambda_3} H^3 + \frac{1}{4}\underbrace{\lambda}_{\lambda_4} H^4$$

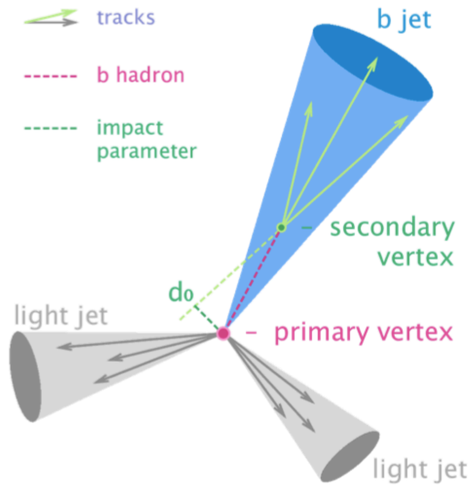


Beyond Dark Matter searches: Flavour tagging

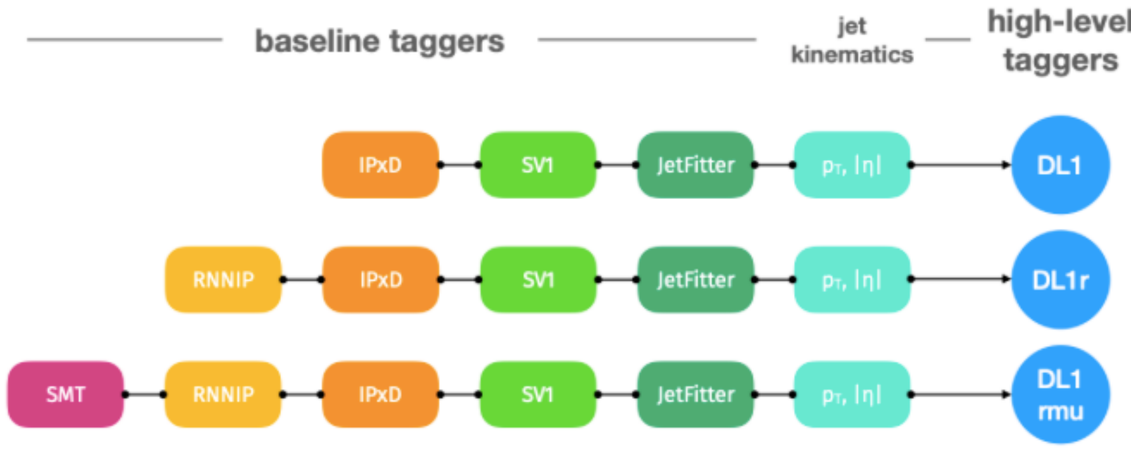
Quarks appear as jets of particles in detector

Identification of b-quarks (jets) crucial for dark matter searches.

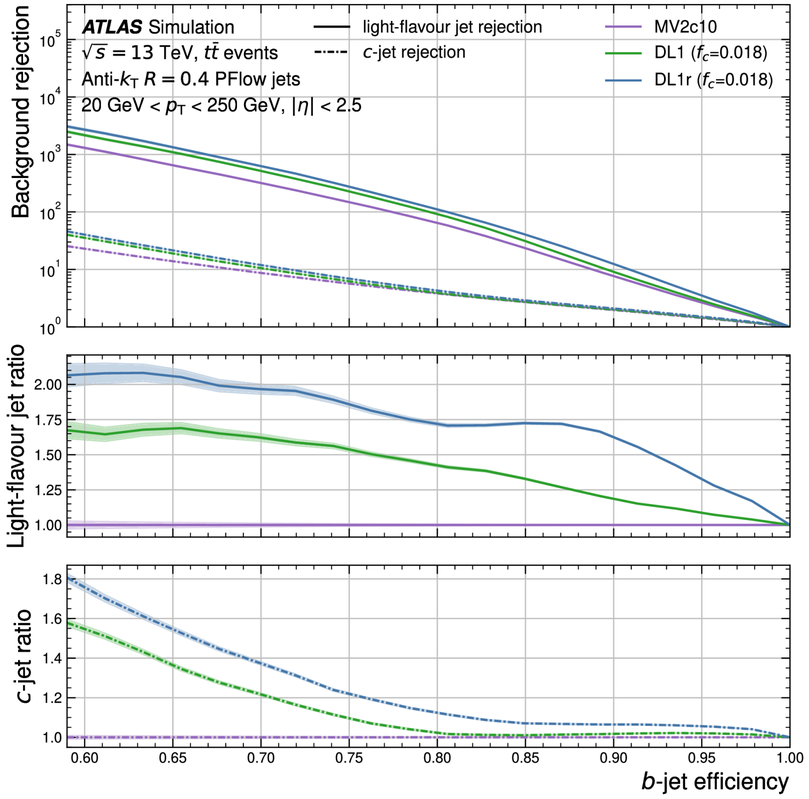
During Run-2, flavour tagging in ATLAS performed using a neural network combining information from low level taggers.



FTAG-2019-07



$$D_{\mathrm{DL1}} = \ln\left(\frac{p_b}{f_c \cdot p_c + (1 - f_c) \cdot p_{\mathrm{light}}}\right)$$



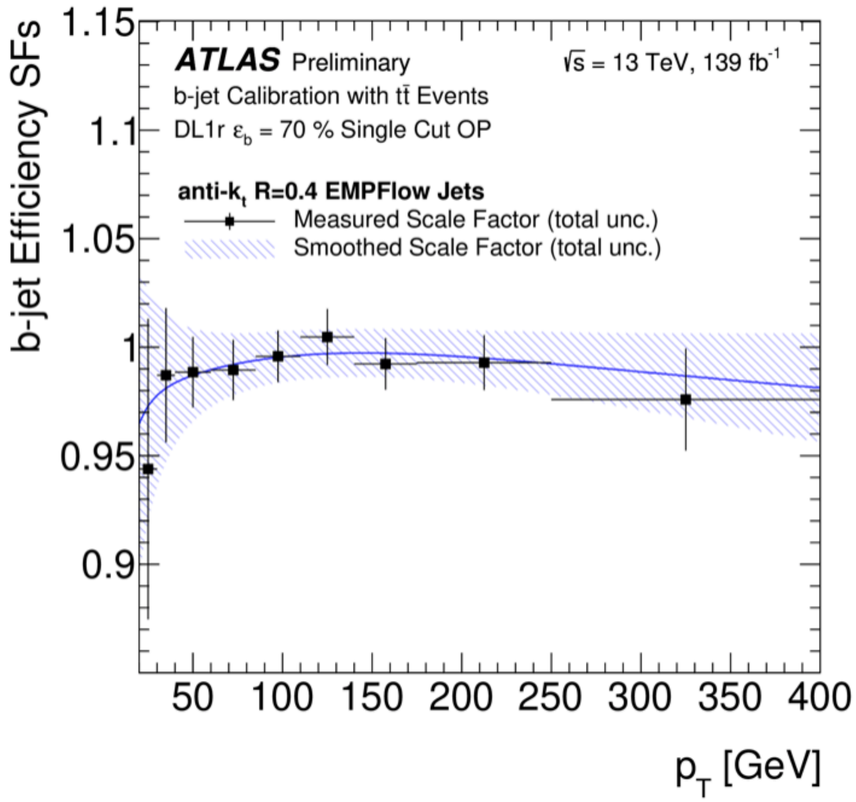
Beyond Dark Matter searches: Flavour tagging

Responsible of calibration of taggers during Run-2 and early Run-3

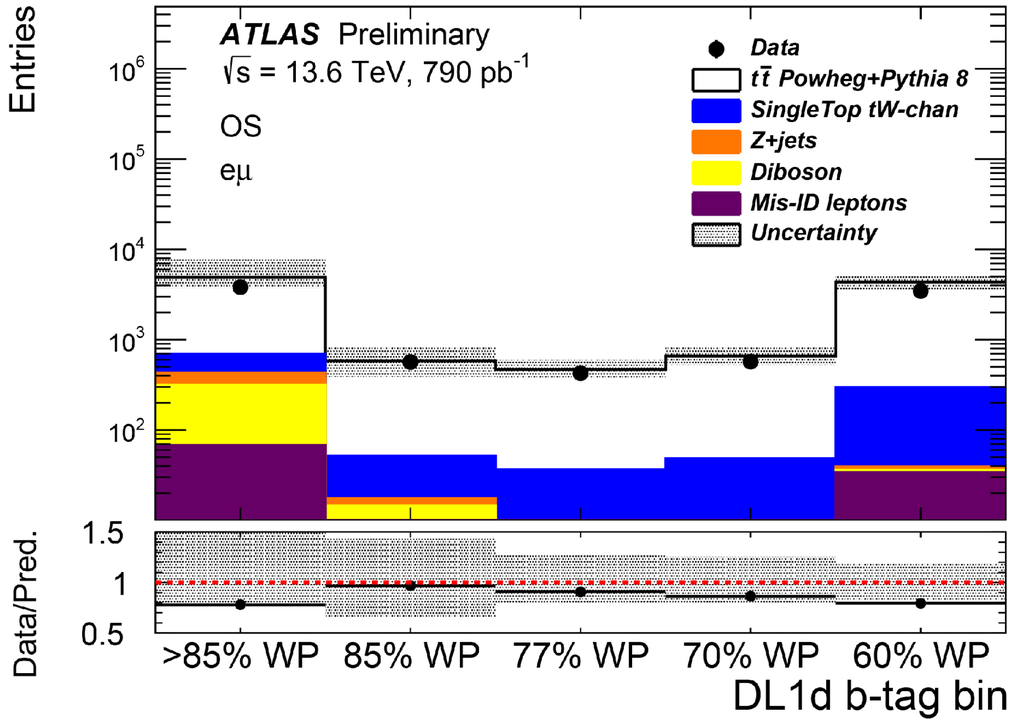
- **Responsible of the whole calibration group between 2020-2022**

Development of dedicated charm-tagger for tc+E_T^{miss} analysis.

FTAG-2021-001

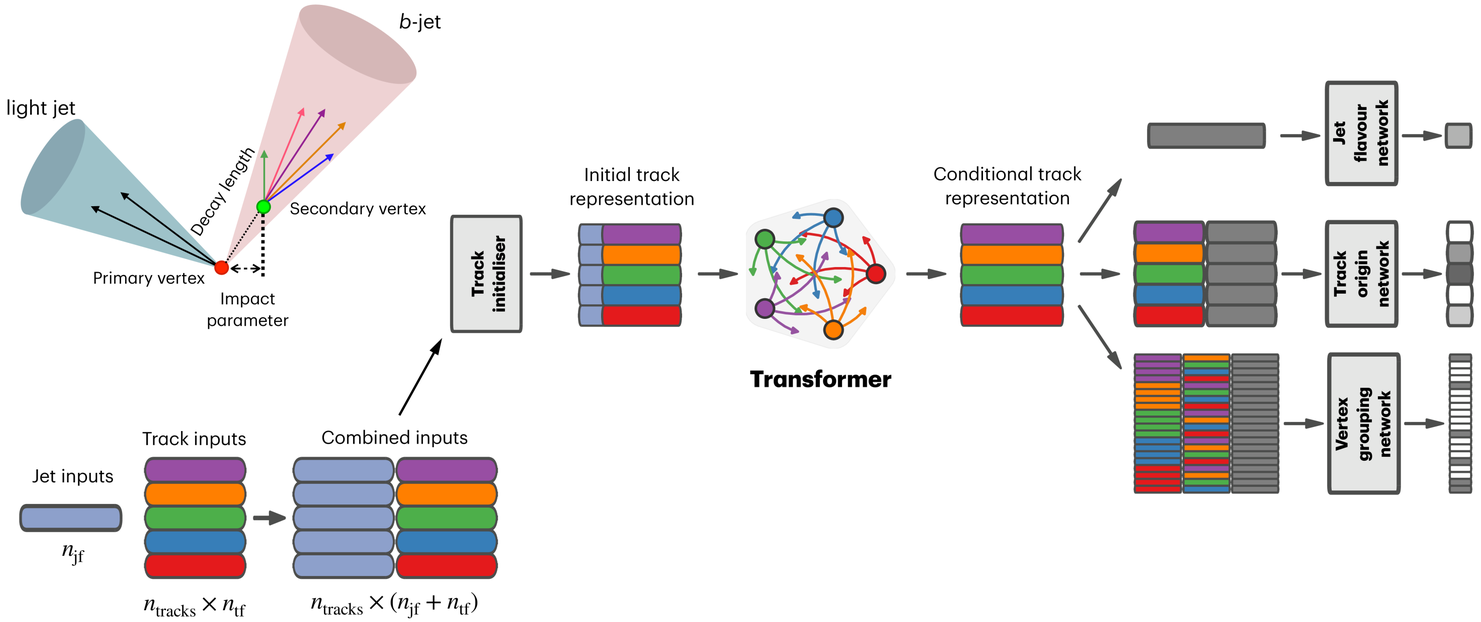


FTAG-2022-003

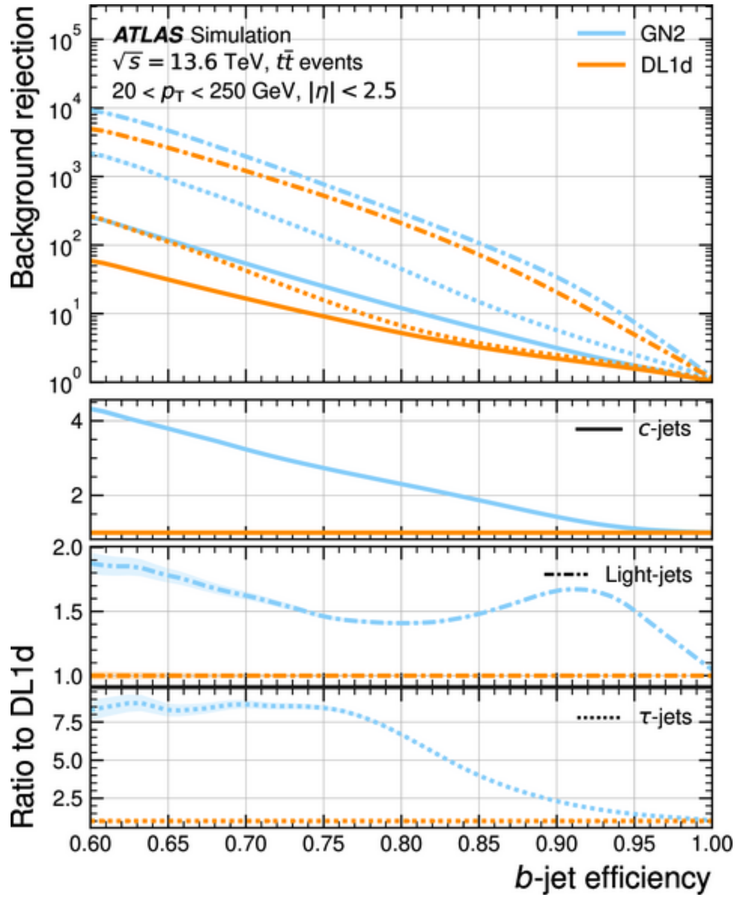


Flavour Tagging in Run-3

During Run-3, flavour tagging performed via a transformer.
Track variables as inputs, encoder and three tasks using output.



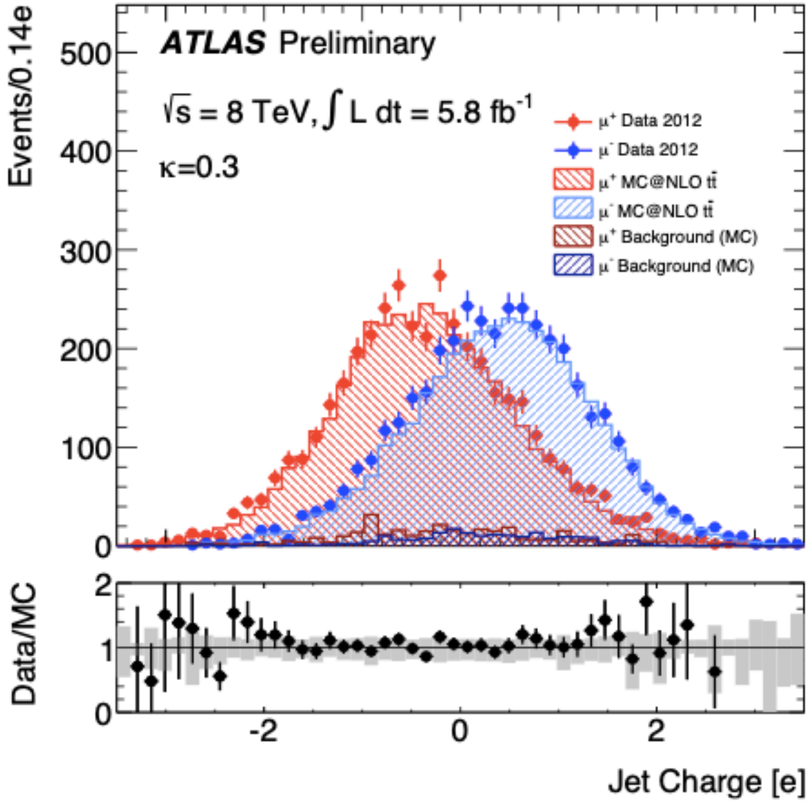
FTAG-2023-05

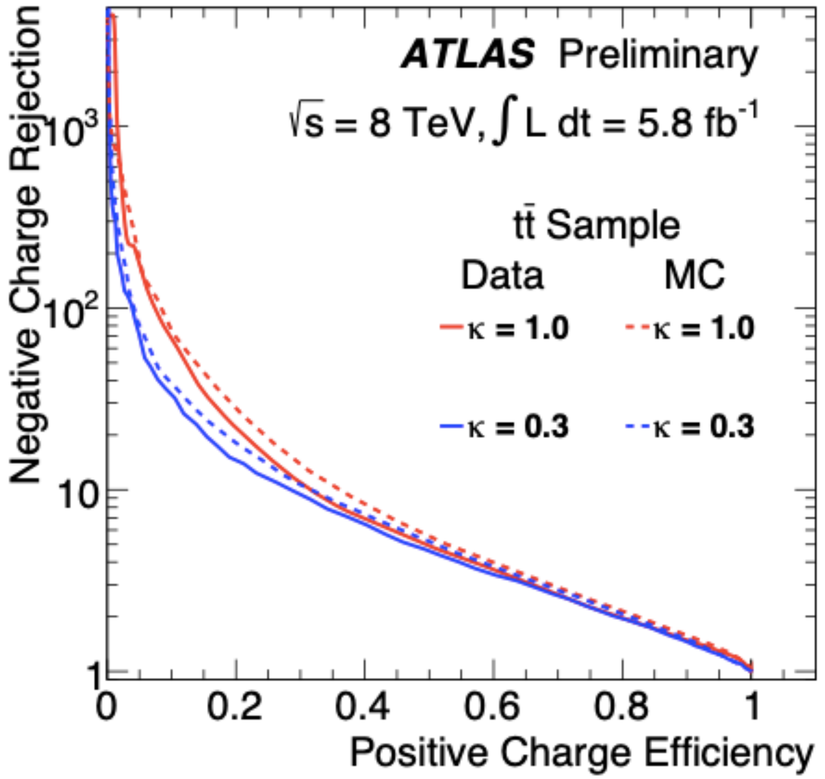


Identification of jets properties

Flavoured models with Majorana particles predict same-sign quarks in final state
Sensitivity limited due to 2L channel for top-charge —> **jet charge**
Last update since Run-I —> Large room for improvement.
Working in the flavour tagging transformer to also identify the charge of the jets.

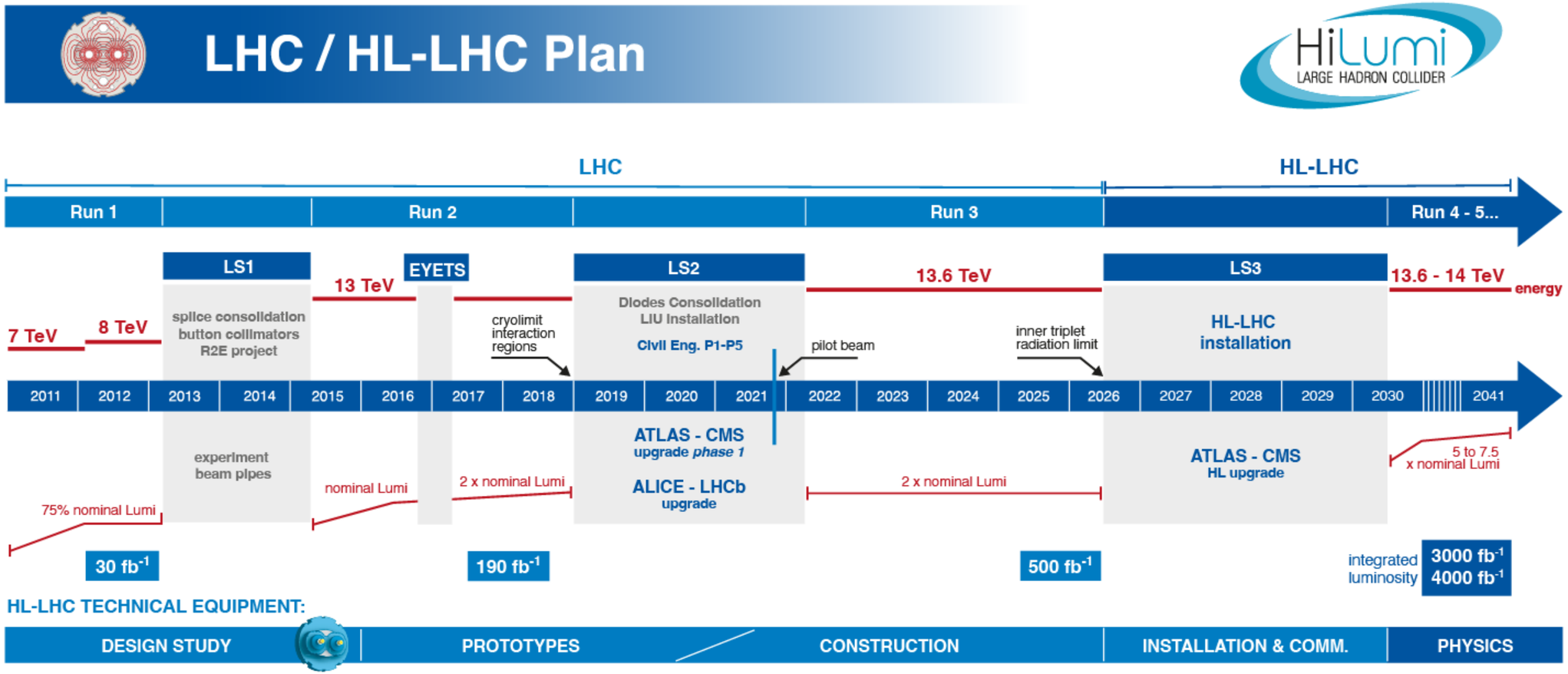
CONF-2013-086





Future of DM searches: the high-luminosity phase

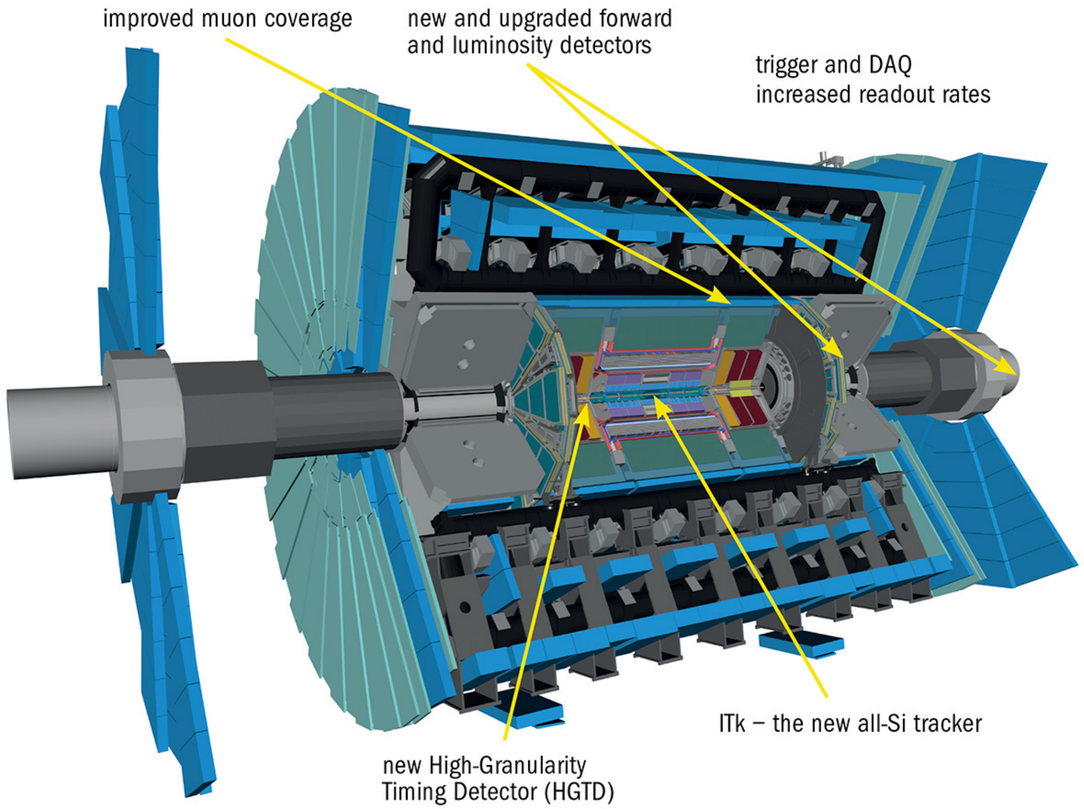
Next 20 years of searches in ATLAS dominated by the completion of the HL-LHC upgrade and analysis of recorded data during high-luminosity phase.

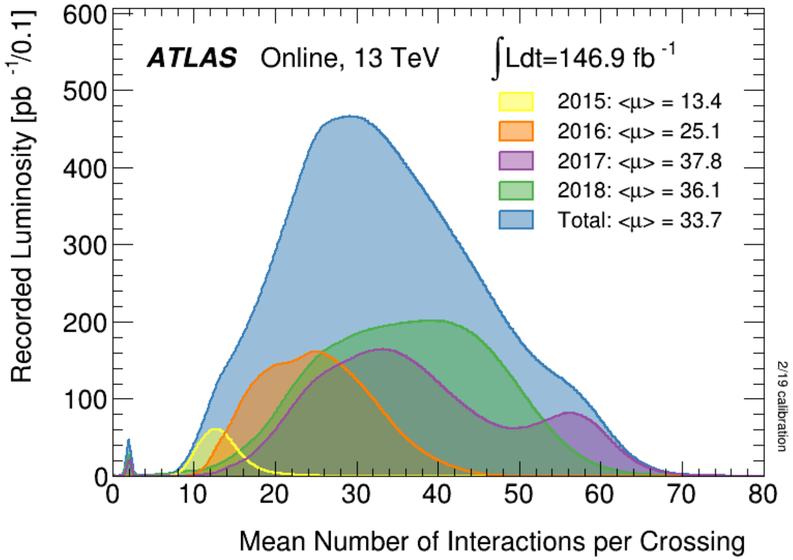


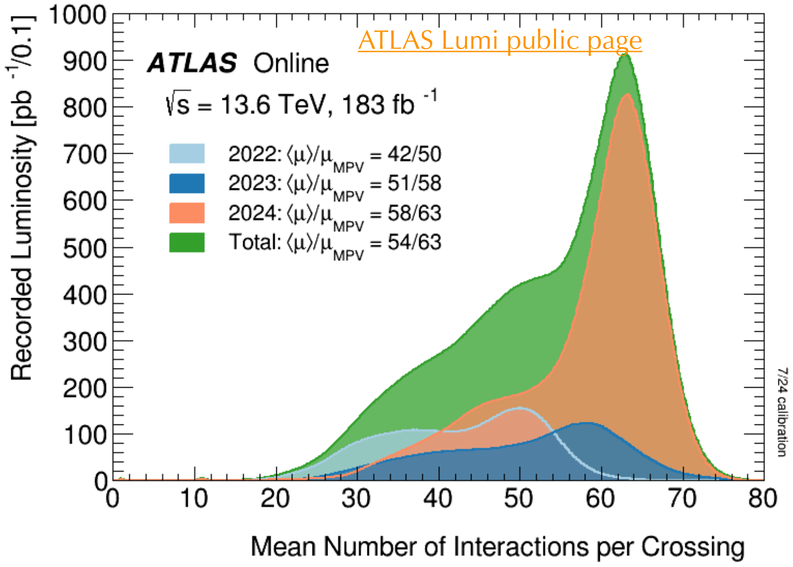
The high-luminosity phase

Expected 14 TeV and 200 interactions per bunch crossing.

- **Increased pile-up and radiation damage**
- **Necessary to upgrade the detectors**

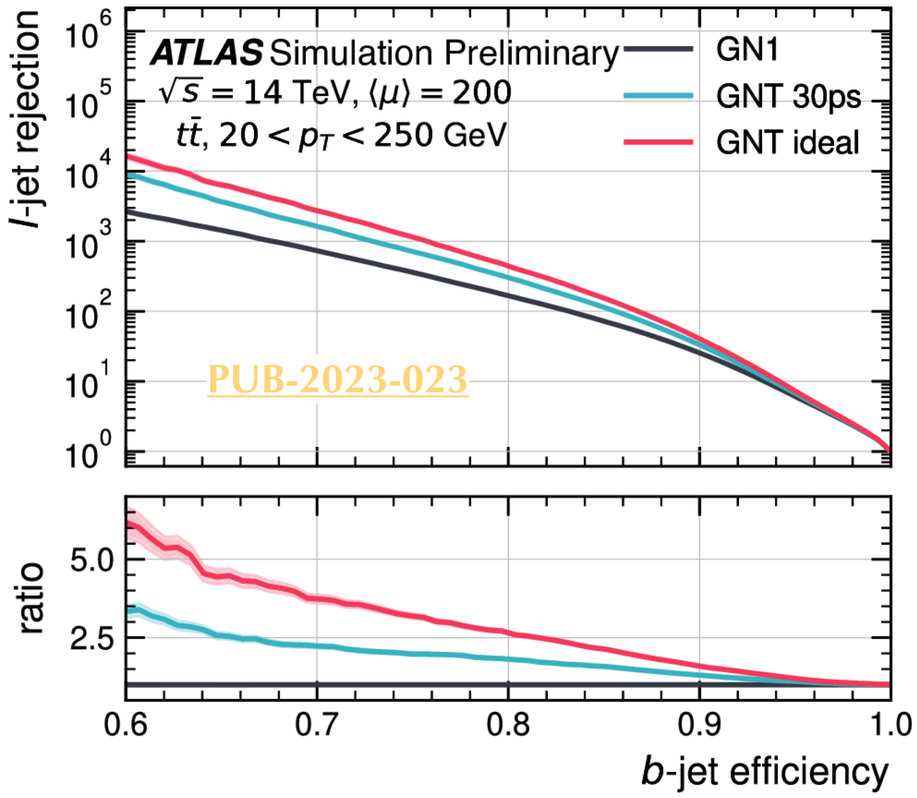


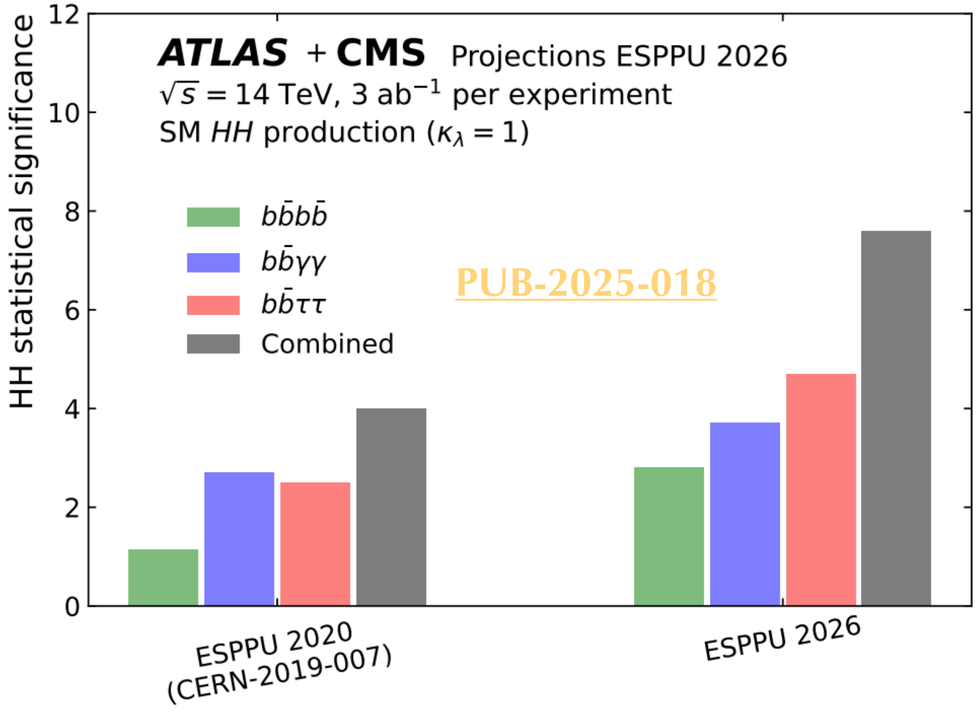




Motivation to build HL-LHC

Upgrade of the detectors key to keep performances and improve future ones.
In particular, tracker updates and inclusion of timing information allow to reject pileup more efficiently and preserve performances w.r.t previous runs.
Key for achieving physics objectives of LHC, e.g. measurement of Higgs triplet coupling, more sensitive DM searches.

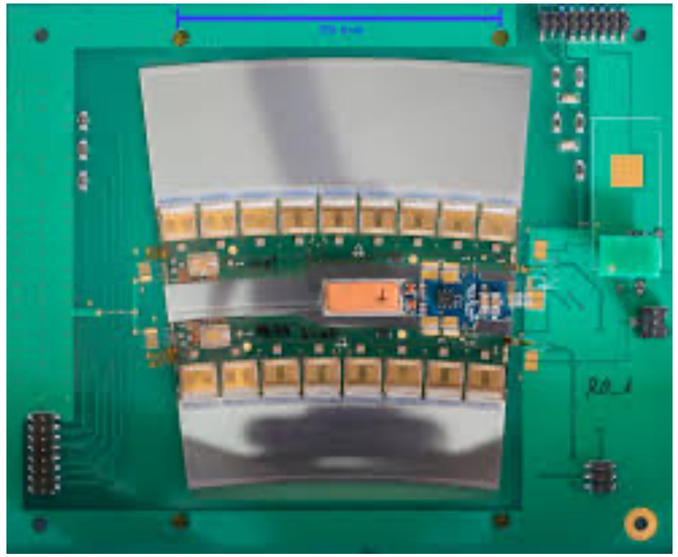


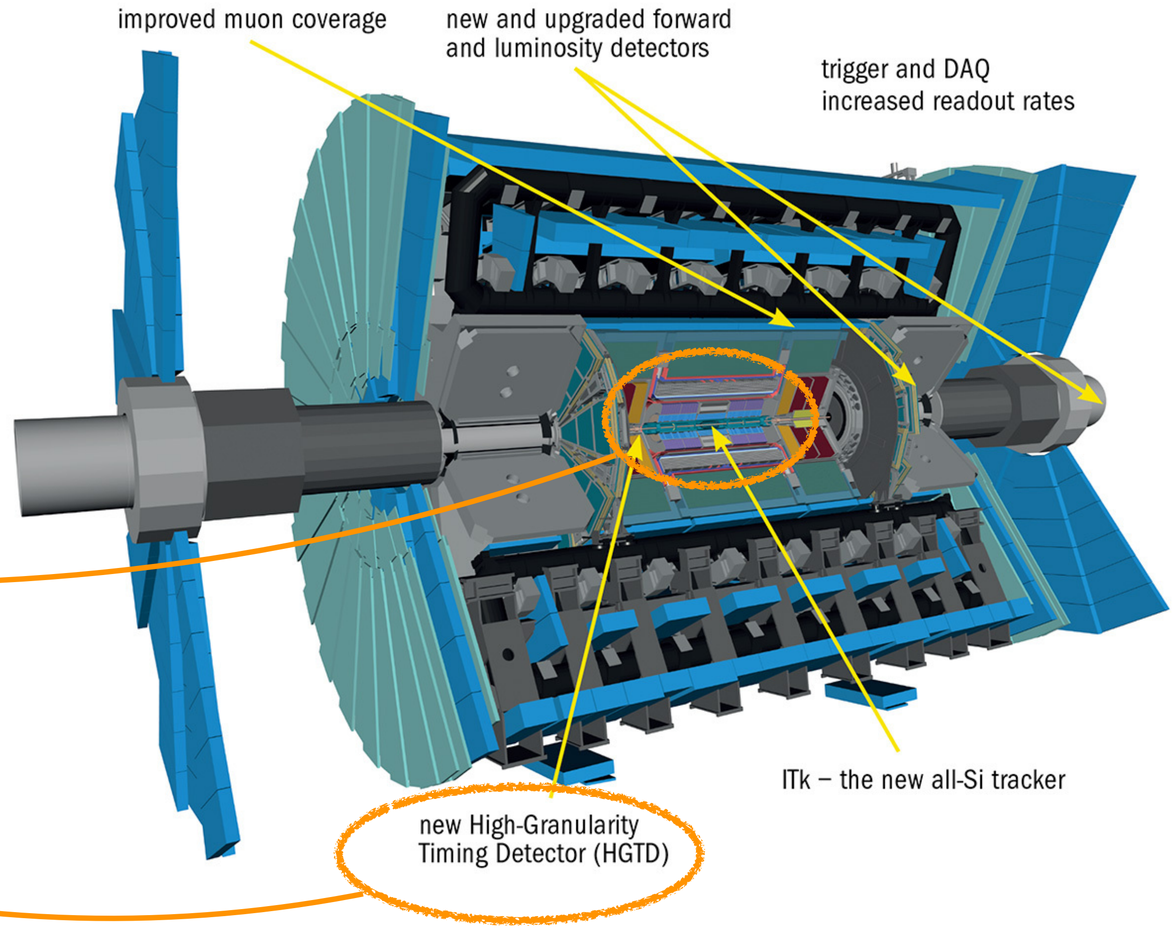


Upgrade of the ATLAS detector

Contribution to the tracker upgrade (ITk).

- Visual inspection of strip sensors
- Software of DESY interacting with the ITk database





High-Granularity Timing Detector (HGTD)

- Assembly of detector units (incoming)

Conclusion

Searches for dark matter and SUSY in Run-2 in several sectors and assuming different interactions with the SM.

- No BSM signal observed. **However, story is not over !**

Complex BSM sectors, with long-lived particles, dark QCD and additional particles at center of LHC Run-3

Interest in a set of dark matter models with flavour predicting couplings with the SM quarks.

- Constraints by direct detection, relic abundance and flavor physics still allow a significant region of the parameter space to explore.
- Motivation for searches in final states with jets and top quarks.
- Excess in these channels would not only tell us if DM exists but also if it is Dirac or Majorana.
- Flavour tagging and charge identification key to improve sensitivity.

Stay tuned for results in Run-3!

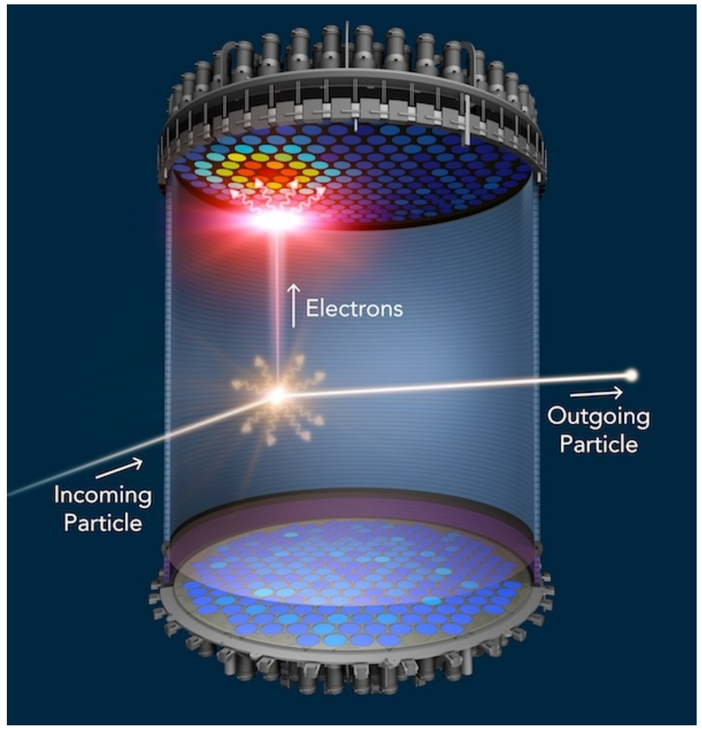
Direct detection constraints

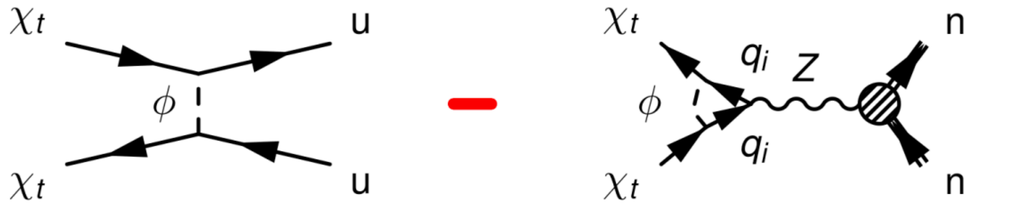
Absence of Dark Matter evidence:

- Lack of interaction of DM with 1st generation and 2nd generation quarks
- Cancellation of contributions via penguin diagrams

Cancellation of interaction cross-section mainly constraints mixing couplings and strength of interactions

- In top-flavored model, mixing of 1st and 3rd generation
- Strength of D33 coupling

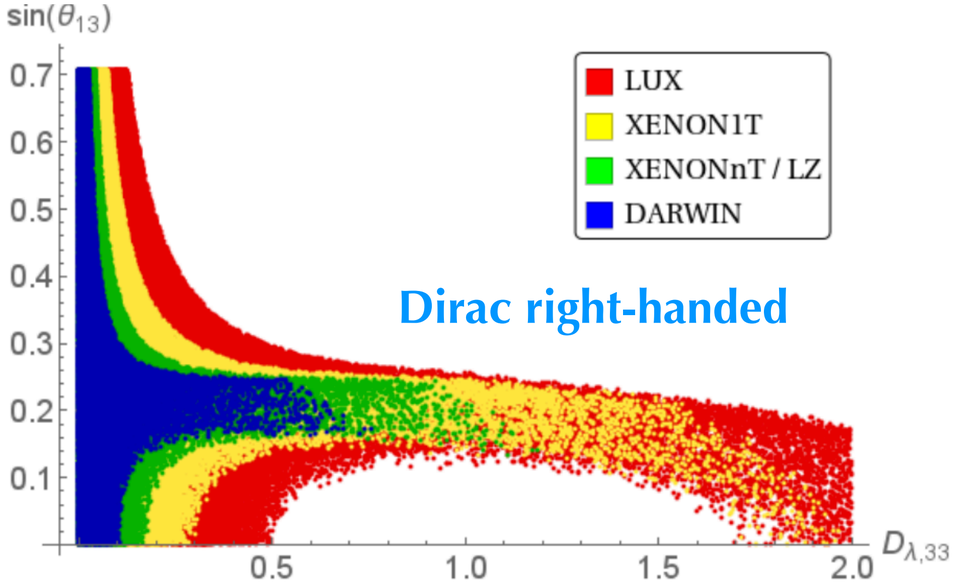




$$\lambda = U_\lambda D_\lambda \qquad \text{with}$$

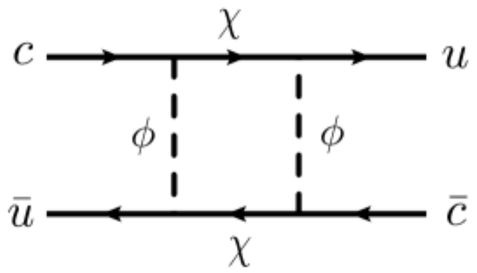
$$D_\lambda = \text{diag}(D_{\lambda,11}, D_{\lambda,22}, D_{\lambda,33})\,,$$

$$U_\lambda = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23}e^{-i\delta_{23}} \\ 0 & -s_{23}e^{i\delta_{23}} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12}e^{-i\delta_{12}} & 0 \\ -s_{12}e^{i\delta_{12}} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

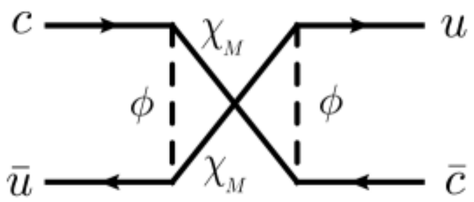


Flavour physics constraints

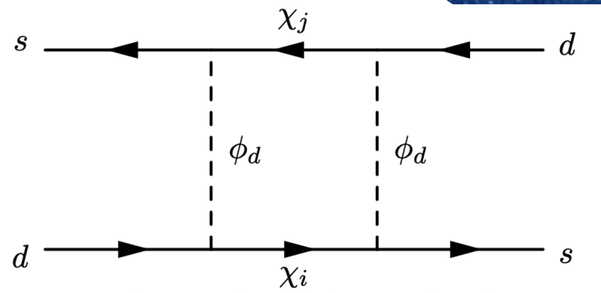
Interaction with different flavors —> flavour mixing measurements
Main constraints on the mixing angles and strength between different DM-SM quark couplings.



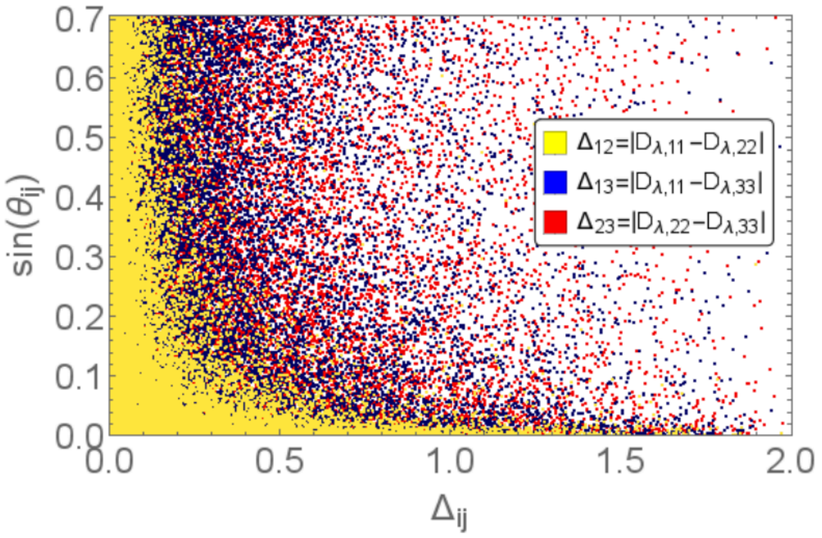
Dirac right-handed

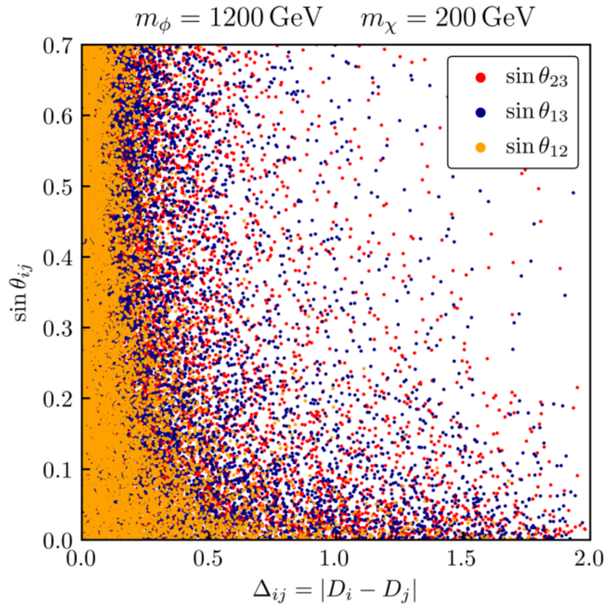


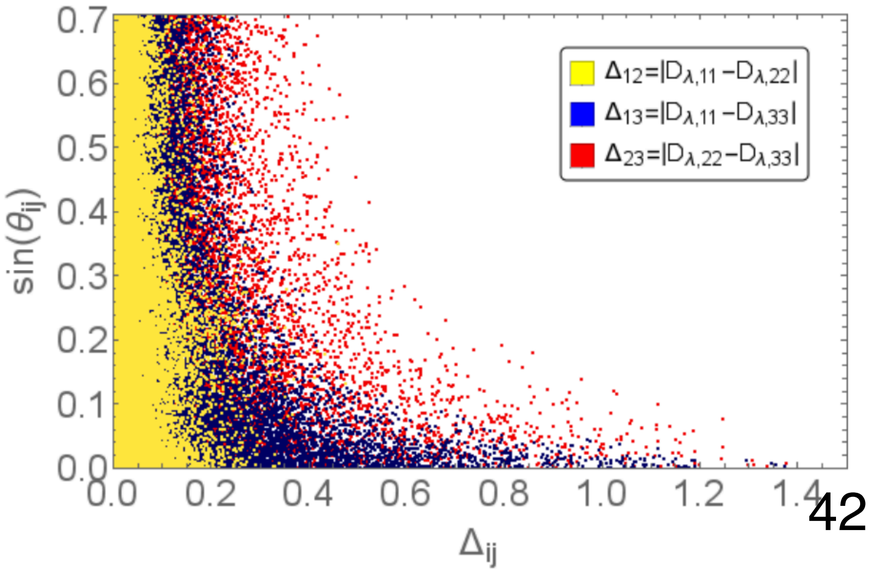
Majorana right-handed



Dirac left-handed







Freeze-out considerations

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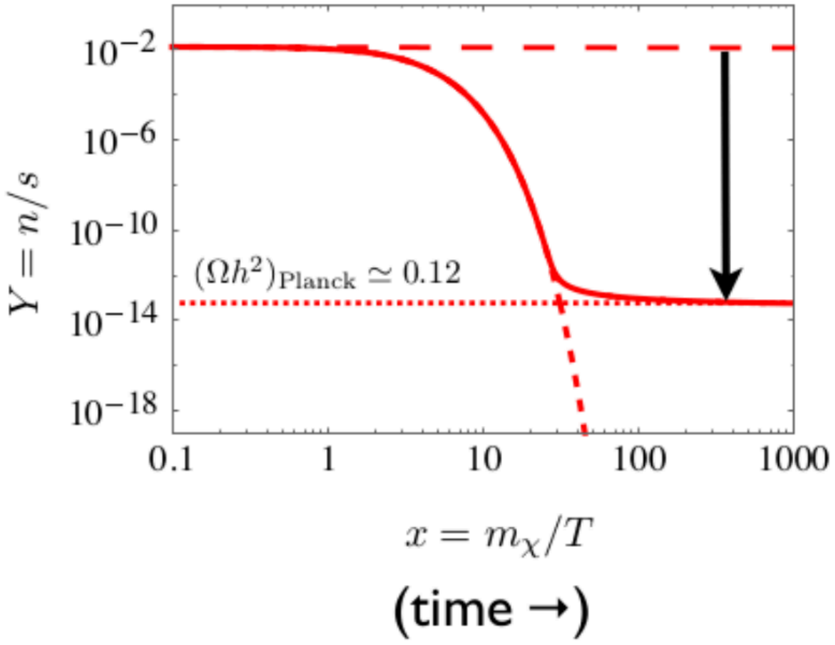
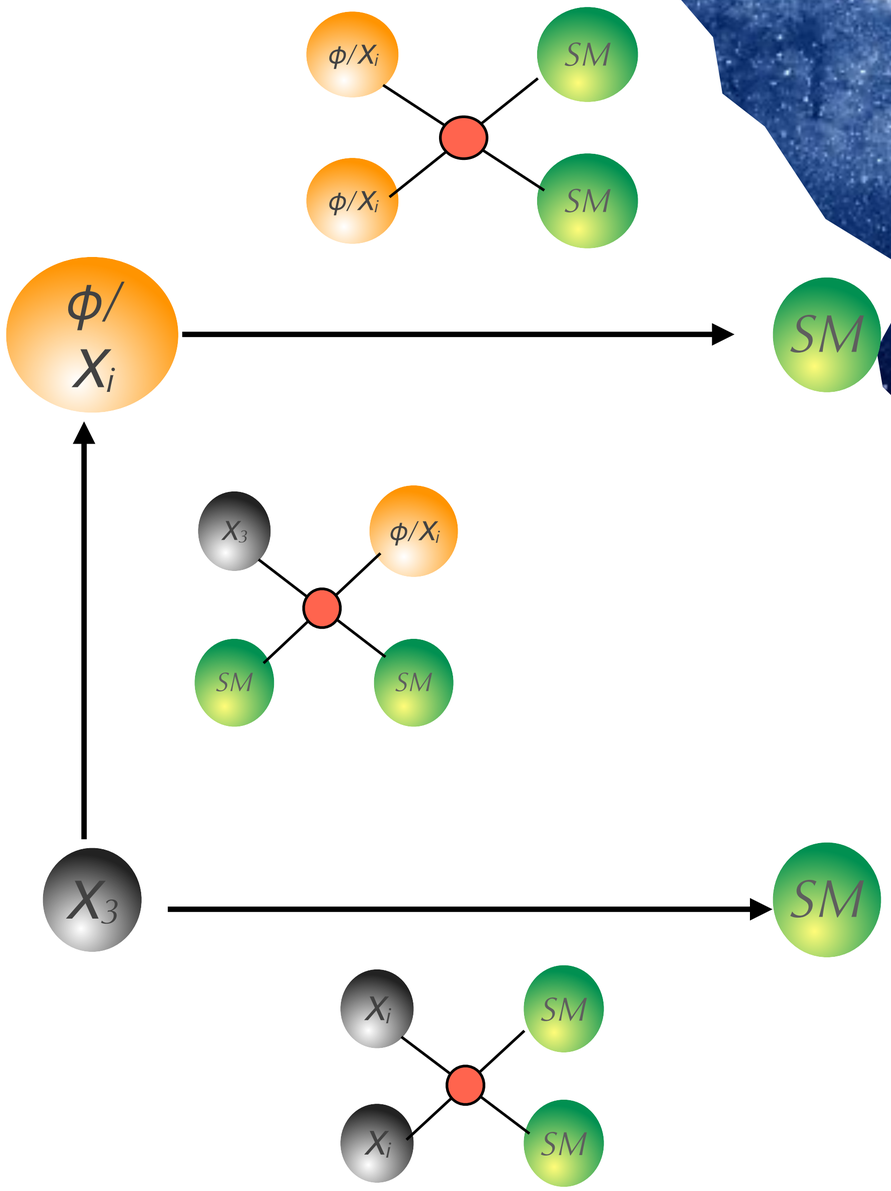
Different freeze-out scenarios can be considered for these models:





Canonical freeze-out
Large couplings between DM particles -SM quarks
Large or intermediate mass differences between DM
Prompt particles at LHC.

Freeze-out considerations

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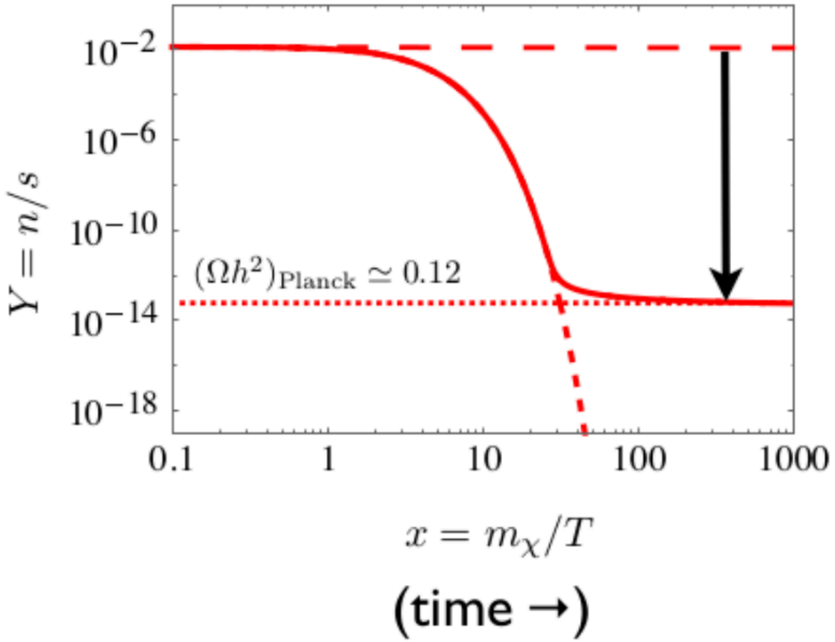
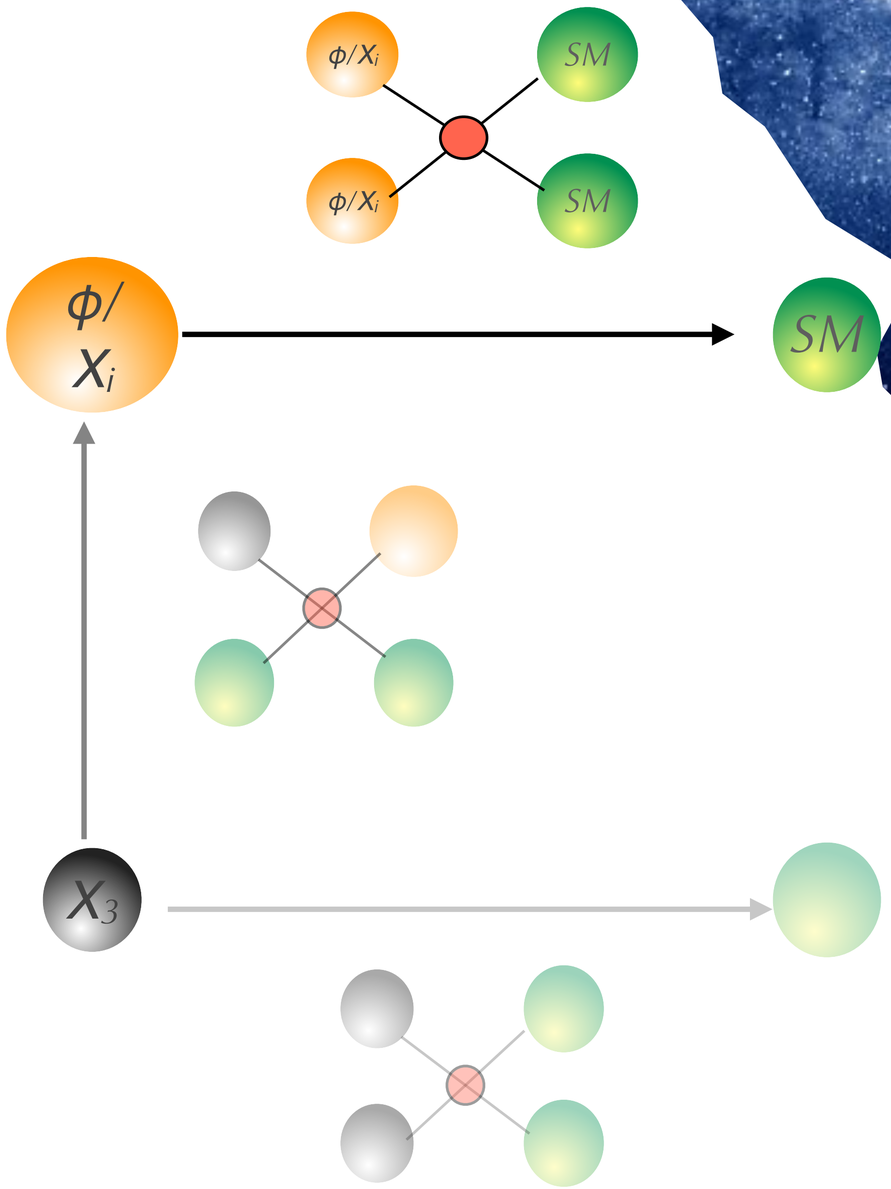
Different freeze-out scenarios can be considered for these models:





Conversion-driven freeze-out
Inefficient equilibrium between DM particles
Low coupling between DM and mediator
Long-lived particles at LHC.

Improvement of c-tagging

GNNs and transformers significantly improved of b-tagging performance in ATLAS!
But not good enough for other jet properties —> c-tagging

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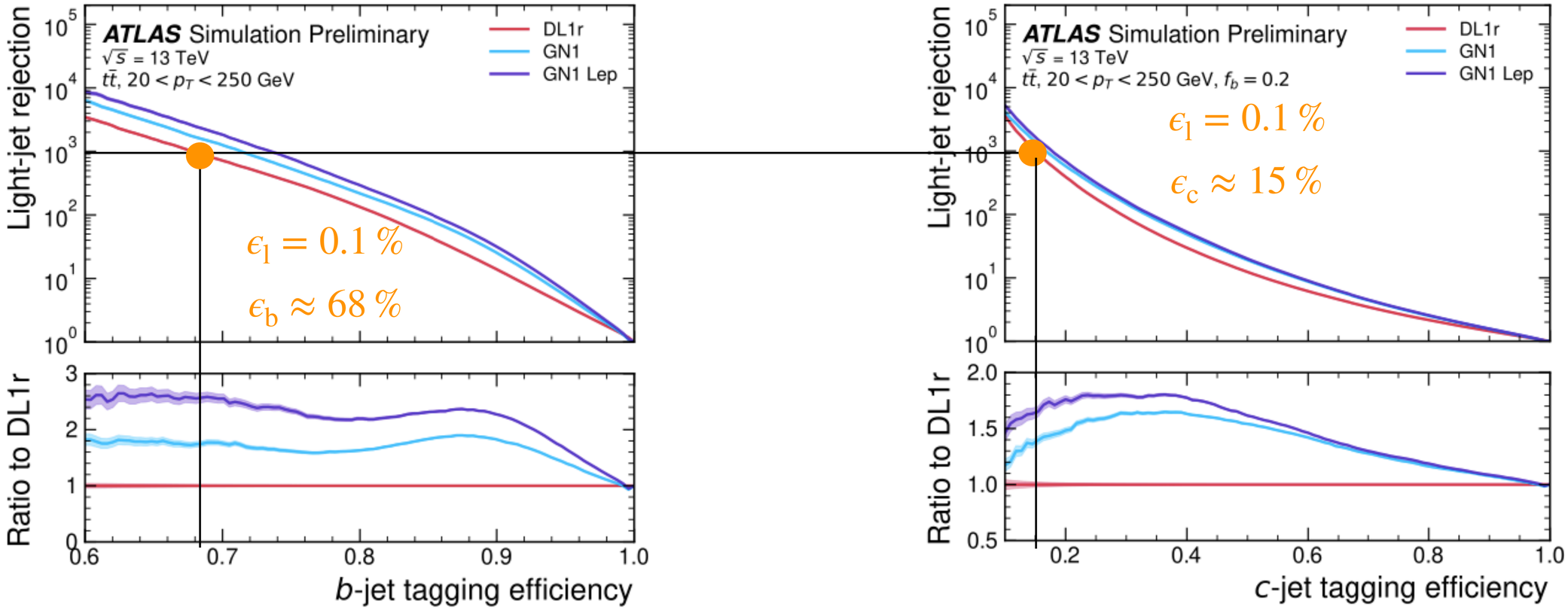
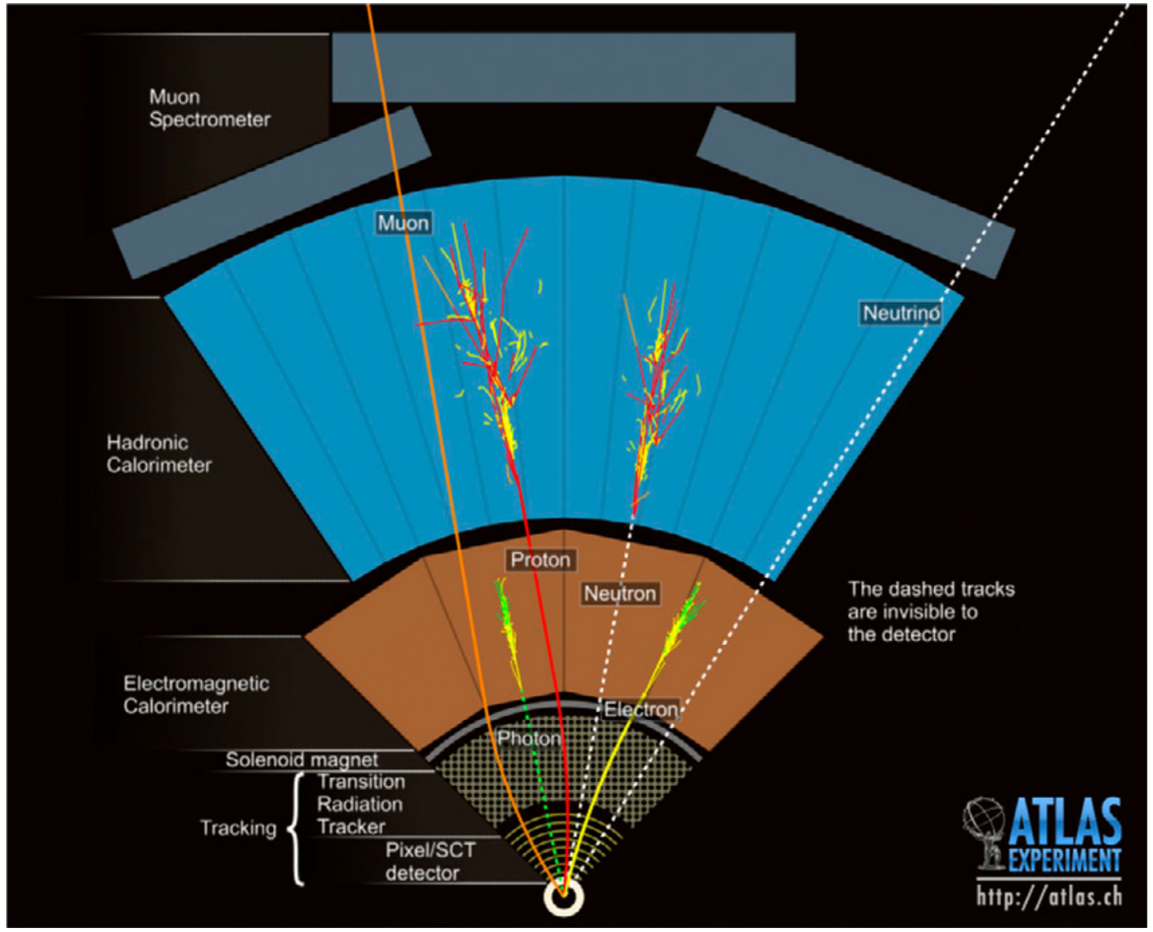
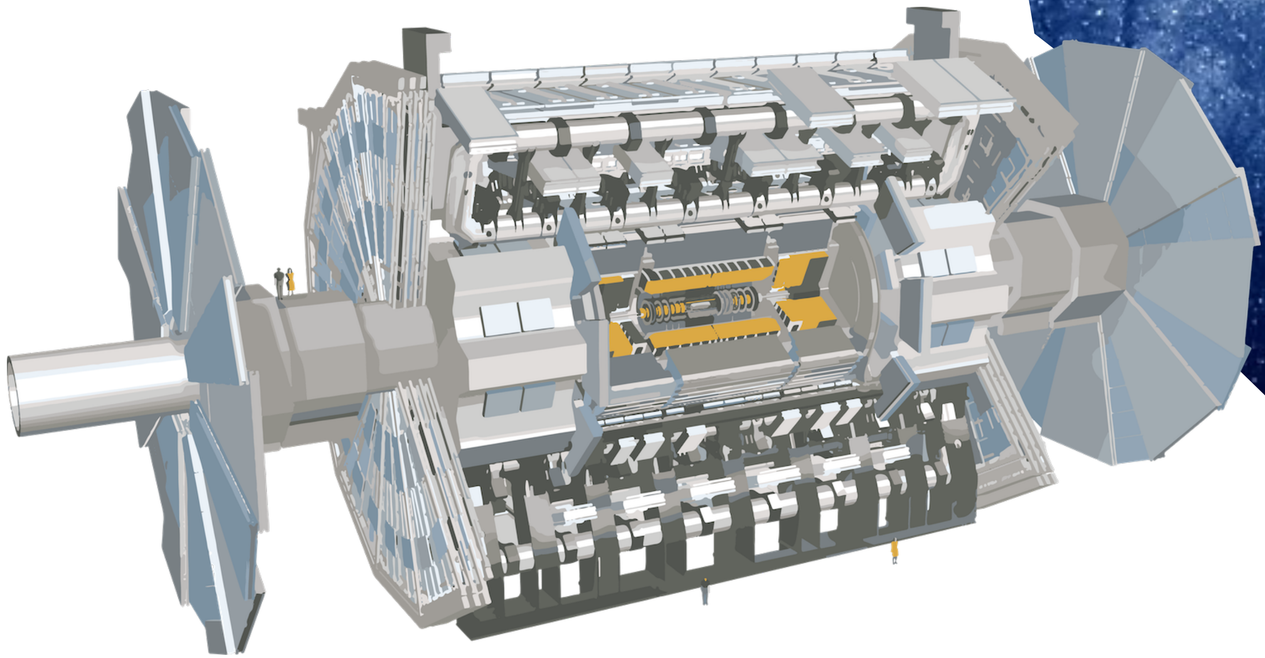


The ATLAS detector





- Subsystems to measure charged particles (inner detector), neutral and charged EM and hadronic showers (calorimeters) and muons (muon spectrometer) + additional stations (AFP, ZDC, LUCID)