Collider Searches for Dark Matter: From the WIMP to the Supersymmetric Axion

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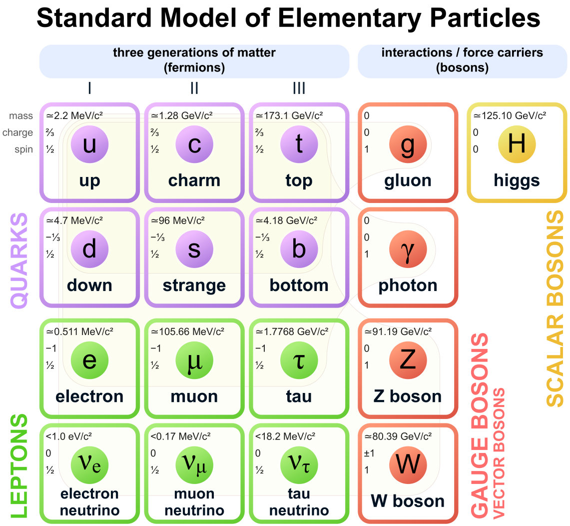
October 22, 2025

THE UNIVERSITY OF CHICAGO

ATLAS EXPERIMENT

Introduction

- This talk: two different approaches to looking for dark matter at collider experiments.
- Based on work I've done at the **ATLAS experiment** at the Large Hadron Collider.
- Rough outline:
  - General introduction to collider searches for dark matter.
  - ATLAS Higgs portal dark matter search, comparison to **WIMP** direct detection experiments.
  - Potential link between **axion** physics and collider phenomenology.
  - Brief overview of some relevant ongoing ATLAS analyses looking for **long lived particles**.
- Won't cover in this talk; other topics I'd be happy to discuss later:
  - ATLAS track trigger upgrade for High Luminosity LHC.
  - Front-end electronics for HL-LHC Inner Tracker Strip detector.
  - Muon colliders!

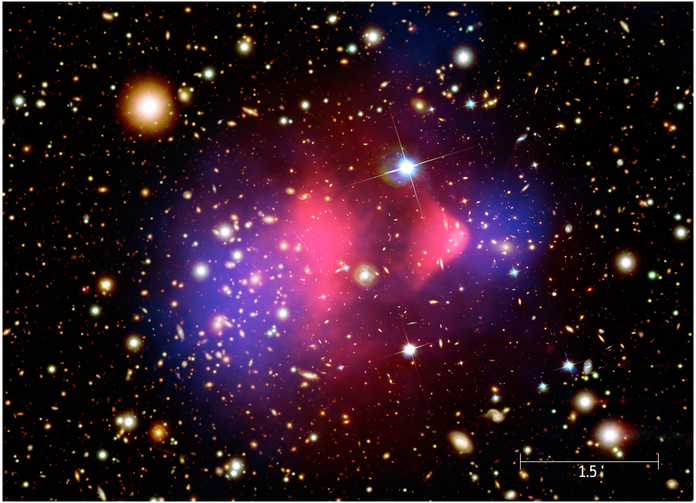


Wikimedia

- **Highly successful** theory:
  - Describes fundamental **quarks**, **leptons**, and **gauge bosons**.
  - Explains 3/4 fundamental forces.
  - Discovery of the **Higgs boson** in 2012 was last "missing piece".
- Known to be **incomplete**:
  - No quantum explanation for gravity.
  - Particle masses.
  - Hierarchy problem.
  - Nature of the Higgs boson.
  - Matter-antimatter asymmetry.
  - No explanation for **dark matter**.

Dark Matter

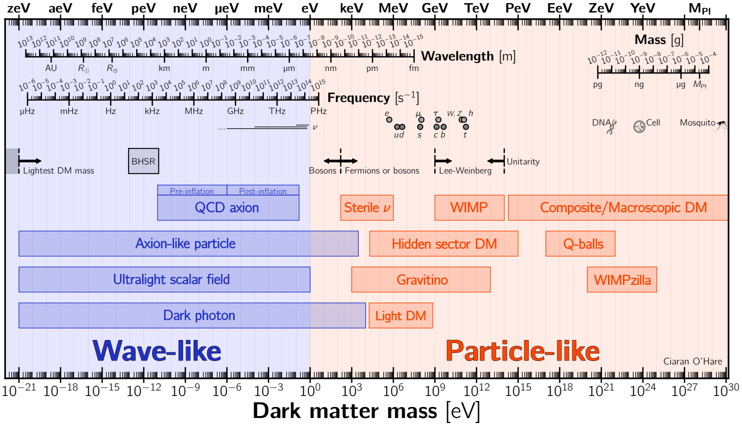
- Strong astrophysical evidence for existence of "dark matter":
    - Galactic rotation curves.
    - Gravitational lensing observations of galaxy clusters.
    - CMB measurements.
- Explanations:
    - Modified Newtonian gravity?
    - Primordial black holes?
    - New particles.
- From CMB: dark matter comprises **27%** of the universe.
- Normal "baryonic" matter (explained by SM): only **5%**.



- New image (**2025**) from James Webb Space Telescope, Chandra X-ray Observatory.

NASA

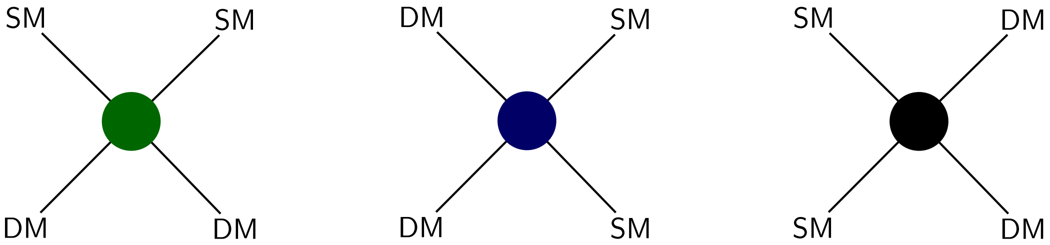
Dark Matter Models



Ciaran O'Hare

- WIMPs:
  - Weakly interacting massive particles.
  - "WIMP miracle": **electroweak-scale** mass.
  - Predicted by theories like **supersymmetry**.
- QCD axion:
  - Solves **strong CP** problem.
  - Very light; wave-like DM.
- Traditionally most popular; **many** other models.

Searches for Dark Matter



- **Direct detection**: look for evidence of DM interacting with ordinary matter.
  - WIMPs: look for weak nuclear recoil (LUX, LZ, XENON, PandaX, etc.).
  - Axions: look for axion-photon conversion in magnetic field.
- **Indirect detection**: look for particles produced from DM self-interaction.
- **Collider searches**: try to produce DM at a collider from some SM interaction.
  - Can search for **new mediator** between SM and DM.
  - Can search for **transverse momentum imbalance** ($E_{\mathrm{T}}^{\mathrm{miss}}$) from "invisible" DM.

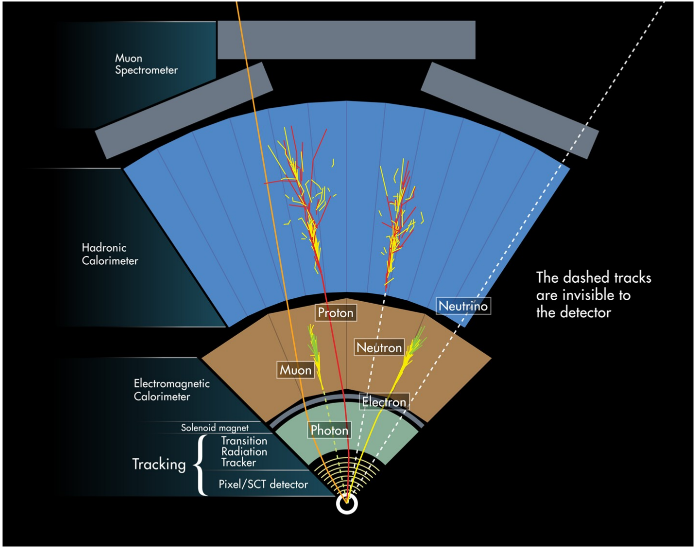
Large Hadron Collider

CERN-MI-0807031

- ATLAS experiment: **general-purpose** detector.
- LHC run 2 (2015-2018):
  - $\sqrt{s} = 13\,\text{TeV}$ protons.
  - Every $25\,\text{ns}$ (40M / second).
  - Each "collision": up to $\langle\mu\rangle = 60$ pp interactions.
  - Collected $\mathcal{L} = 139\,\text{fb}^{-1}$ ($\mathcal{L} = N/\sigma$) of data.
- Run 3 **ongoing** (2022-2026):
  - Increase to $\sqrt{s} = 13.6\,\text{TeV}$.
  - Already collected more data ($289\,\text{fb}^{-1}$) than run 2!

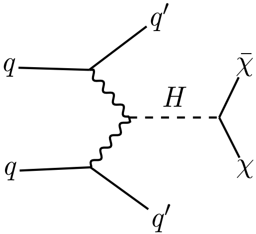
ATLAS Detector

- **Charged particles** curve in $2\,\mathrm{T}$ magnetic field, leave tracks.
- **Electrons** and **photons** deposit energy as EM showers.
- **Quarks** and **gluons** undergo hadronic showers (**jets**) due to QCD confinement.
- **Muons** escape; tracks can be measured in muon spectrometer.
- **Neutrinos** (or DM): missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$).

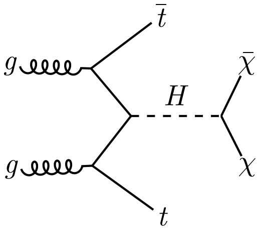


Higgs Portal Dark Matter

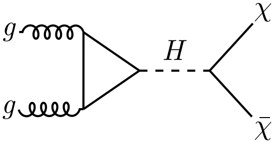
- **Higgs portal** dark matter:
  - New DM particle that couples directly to the Higgs.
  - $m_{\text{DM}} < \frac{1}{2} m_h = 62.5\,\text{GeV}$.
  - Look for evidence of Higgs production plus $E_{\text{T}}^{\text{miss}}$.
- Very unlikely in Standard Model:
  - $\mathcal{B}_{H\to\text{inv.}} \approx 1.05 \times 10^{-3}$, from $H \to ZZ^* \to 4\nu$.
- Most sensitive channel:
  - Vector boson fusion (**VBF**).
  - Stronger background rejection than gluon-gluon fusion (**ggF**).



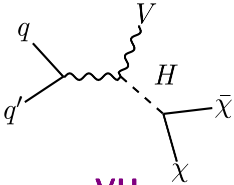
VBF (3.766 pb)



ttH

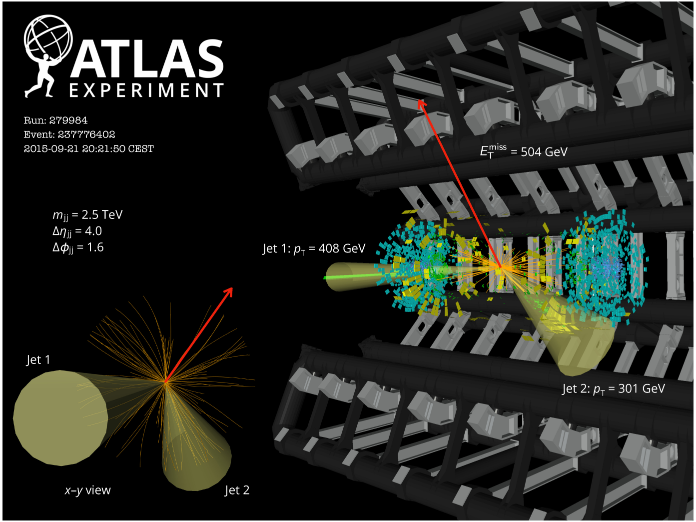


ggF (48.61 pb)



VH

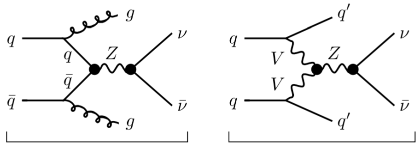
Analysis Overview



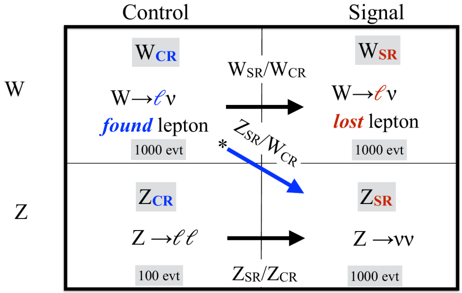
EXOT-2020-11

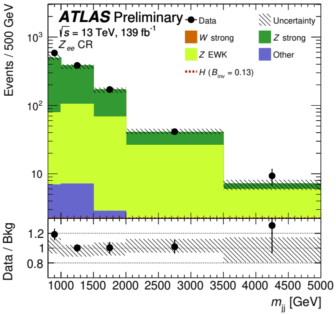
- Search for VBF jet pair:
  - Opposite sides: $\Delta\eta_{jj} > 3.8$.
  - High mass: $m_{jj} > 0.8\,\text{TeV}$.
  - Not back to back: $\Delta\phi_{jj} < 2.0$.
- Large $E_T^{miss} > 160\,\text{GeV}$ from Higgs boson decay.
- Main backgrounds:
  - $Z(\nu\nu)$+jets, $W(l\nu)$+jets; suppressed by high m_{jj} cut.
  - Multijet events w/ fake E_T^{miss}; data driven estimate.
- Set limit on $\mathcal{B}_{H\to\text{inv.}}$; **interpret** as limit on WIMP models.

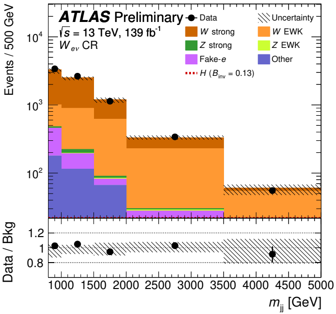
V+Jets Background Modelling



$Z + 2j$ *via strong process* $Z + 2j$ *via weak process*



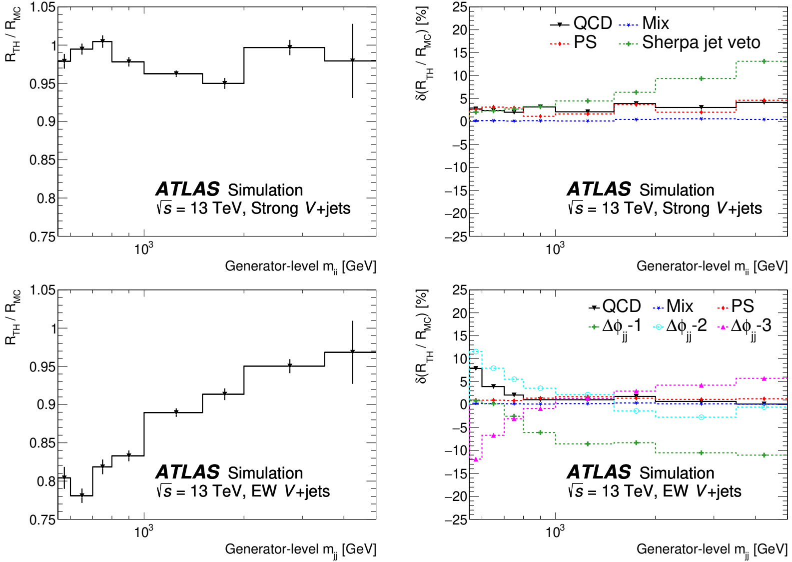




- W and Z control regions used to estimate V+Jets.
- Signal region MC ($B^{\mathrm{SR}}_{\mathrm{MC}}$) rescaled by **transfer factors**: control region data/MC ratio ($N^{\mathrm{CR}}_{\mathrm{data}}/B^{\mathrm{CR}}_{\mathrm{MC}}$).
- QCD and EWK V+Jets processes both contribute.
- Use $W \to l\nu$ to predict $Z \to \nu\nu$; higher cross section.

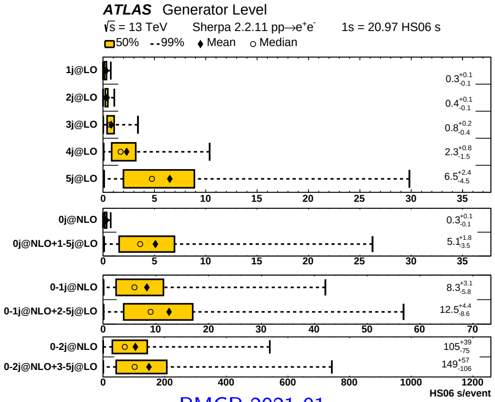
Z/W Reweighting

- Calculations from theorists (2204.07652):
  - Jonas Lindert
  - Marek Schönherr
  - Stefano Pozzorini
- Provided uncertainties:
  - QCD, QCD/EW mixing uncertainties.
  - Parton shower: vary PS model.
  - QCD reweighting: impact of jet veto.
  - EWK reweighting: diboson interference as function of $\Delta\phi_{jj}$.



V+Jets Monte Carlo Statistics

- QCD V+jets events **50 times** more likely to have low m_{jj} than high m_{jj}.
  - Limited MC stats in high-m_{jj} phase space lead to large transfer factor uncertainties.
  - Try phase space biasing to make m_{jj} slices: hard to calculate m_{jj} at **parton** level.
  - Worked with SHERPA developers to test configuration changes; needed **custom** samples.



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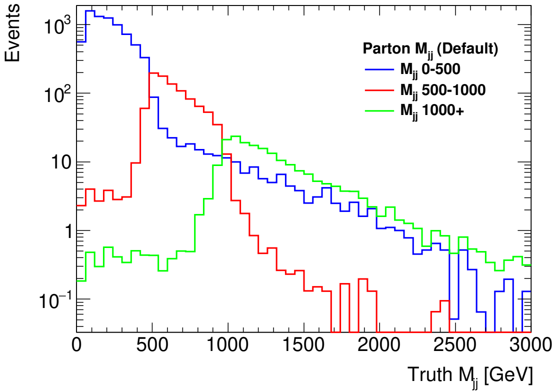
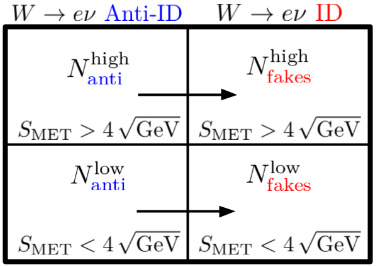


CERN-THESIS-2021-333

Fake Lepton Estimate

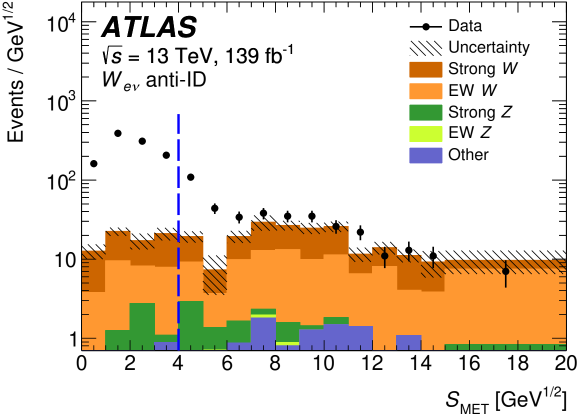
- Events with jets misidentified as lepton can contaminate W control regions.
  - Measure using fake-enriched anti-ID region: use events with low-quality leptons.
  - Estimate $N_{\text{fakes}} = \text{Data} - \text{MC}$: calculate transfer factor β from anti-ID region.
- Apply transfer factor using $E_{\text{T}}^{\text{miss}}$ significance (S_{MET}) for electrons; m_{T} for muons.

$$S_{\text{MET}} = \frac{E_{\text{T}}^{\text{miss}}}{\sqrt{p_{\text{T}}(l) + \sum_{i=0}^{N_{\text{jets}}} p_{\text{T}}(j_i)}}$$

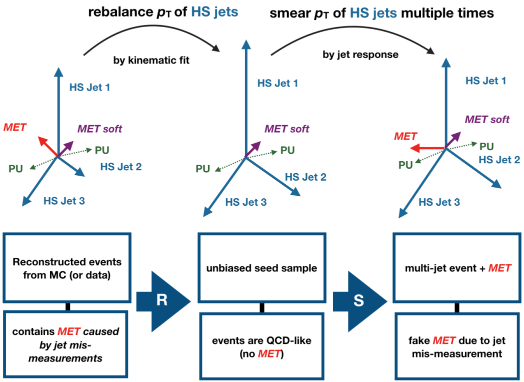


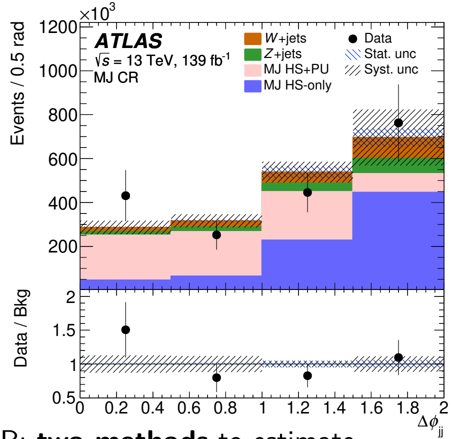
$$N_{\text{fakes}}^{\text{high}} = \beta N_{\text{fakes}}^{\text{low}}$$

$$\beta = \frac{N_{\text{anti}}^{\text{high}}}{N_{\text{anti}}^{\text{low}}}$$



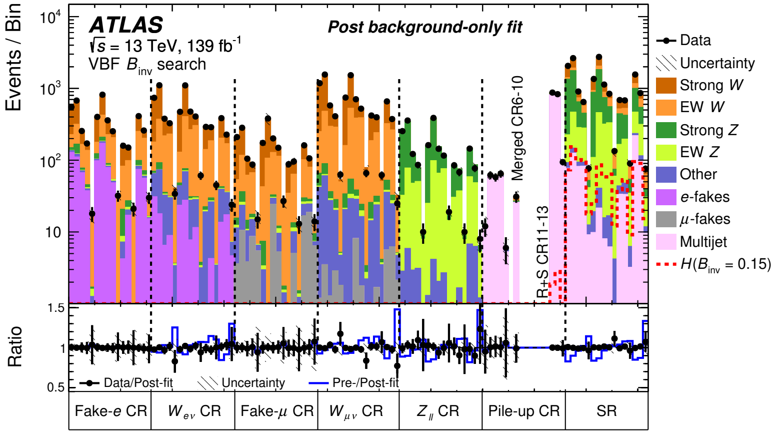
Multijet Estimate: Rebalance and Smear





- QCD events with fake E_T^{miss} can contaminate SR: **two methods** to estimate.
  - "Rebalance and smear": create fake E_T^{miss} by smearing jet p_T. **Large uncertainties**.
  - Transfer factor / ABCD method from low-E_T^{miss}, **high-pileup** region.
  - Methods agreed; preferred transfer factors due to smaller uncertainties.

Fit Results and Limit



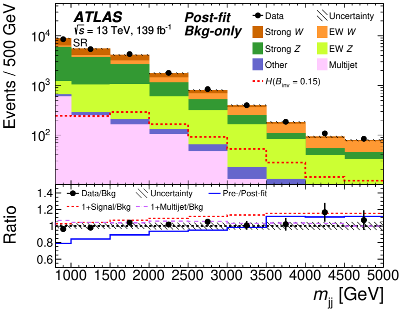
Expected	Observed	$+1\sigma$	-1σ	$+2\sigma$	-2σ
0.103	0.145	0.144	0.075	0.195	0.056

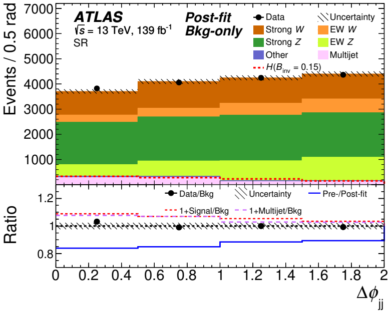
- Regions broken down into 16 independent bins.
- Perform simultaneous fit across all bins, regions.
- Single V+jets transfer factor in each bin.
- Observed (expected) 95% confidence level limit $\mathcal{B}_{\text{H}\rightarrow\text{inv.}} = 0.146(0.103)$.
- **No significant disagreement** between data/MC (1σ excess).

Uncertainties and Distributions

- Uncertainties listed both as limit impact ($\Delta\%$), contribution to total uncertainty ($\pm 1\sigma$).
- Dominant systematics: multijet and fake lepton estimate. **Not MC stats!**

Source	$\pm 1\sigma$	$\Delta\%$
Data stats.	**0.022**	8.7
V+jets stats.	**0.015**	9.4
MC stats.	0.010	3.8
Multijet	**0.014**	5.0
μ/e-fakes	**0.014**	6.5
Leptons	0.011	5.3
JER	0.011	4.2
JES	0.008	2.1
Remaining	0.010	2.8
V+jets theory	0.012	4.2
Signal theory	0.009	0.6

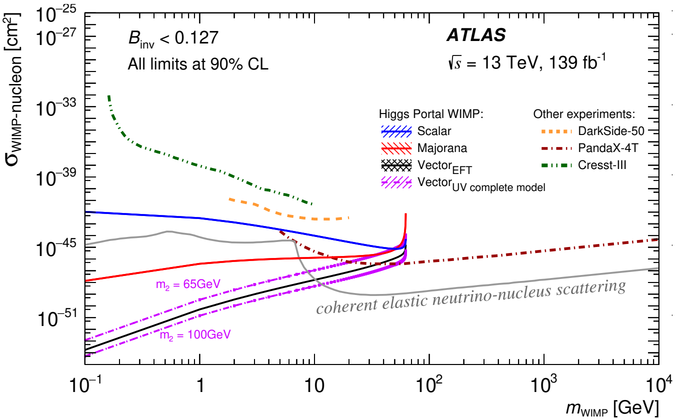




- Verify data/MC agree well post-fit without invisible Higgs signal.
- Signal strength normalized to observed limit $\mathcal{B}_{\mathrm{H}\to\mathrm{inv.}} = 0.15$.

Higgs Portal Dark Matter Interpretation

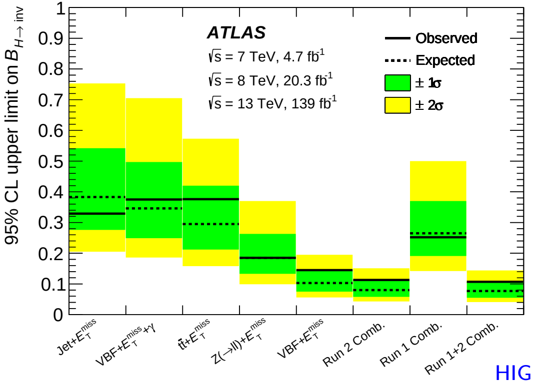
- Interpret this limit using simplified Higgs portal dark matter models:
  - New **scalar** boson
  - New Majorana **fermion**
  - New **vector** boson
  - Renormalizable **vector** model; includes "dark Higgs" with mass m_2.
- Set limit on spin-independent WIMP-nucleon cross section as function of DM mass.

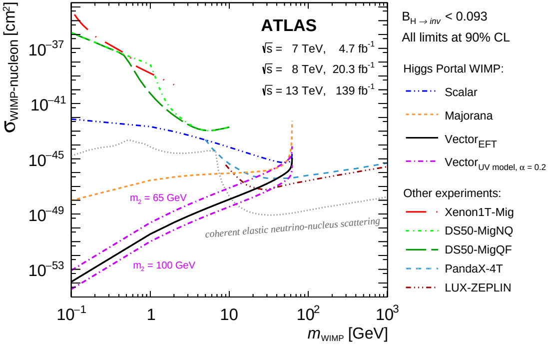


- Highly complementary to direct detection at $m_{\text{WIMP}} < 10\,\text{GeV}$.
- Already probing below the neutrino floor!

Higgs to Invisible Combination

- Final full run 2 result from ATLAS: set observed (expected) limit of $0.107(0.077)$.





HIGG-2021-05

Axions and Axinos

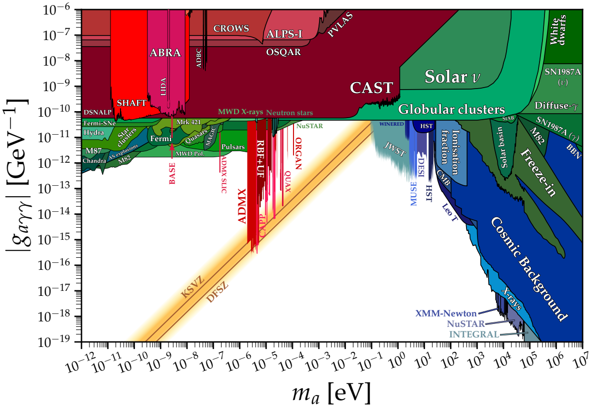
QCD Axion

- Strong CP problem: QCD **can** violate CP symmetry, but hasn't been observed.
- Peccei-Quinn: introduce new $U(1)$ symmetry for this interaction, spontaneously break it.

$$\mathcal{L}_{\text{QCD}} \supset \left(\frac{a}{f_a} + \theta\right) \frac{g^2}{32\pi^2} G\tilde{G},$$

- Axion: pseudoscalar carrying PQ charge.
- **Not** UV-complete; full theories:
  - Kim-Shifman-Vainshtein-Zakharov: new **heavy quarks** carry PQ charge.
  - Dine-Fischler-Srednicki-Zhitnitsky: **two Higgs doublets** carry PQ charge.
- Axion mass related to decay constant:

$$m_a = 5.691\,\text{meV}\left(\frac{10^9\,\text{GeV}}{f_a}\right)$$



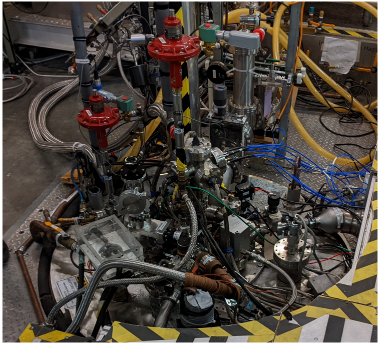
doi:10.5281/zenodo.3932430

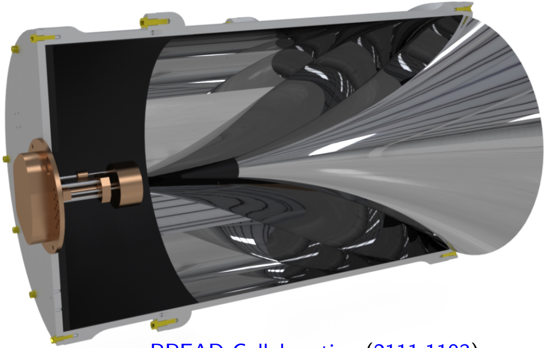
Axion Direct Detection

- Axion converts to photons in B field:
  - Coupling varies between models, but proportional to f_a.
  - $E/N = 8/3$ for DFSZ, 0 for KSZV.
- Look for photons in resonant cavity; **ADMX** most well known.
  - Others; e.g. Broadband Reflector Experiment for Axion Detection.

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi}\frac{1}{f_a}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right)$$

$$z = m_u/m_d$$

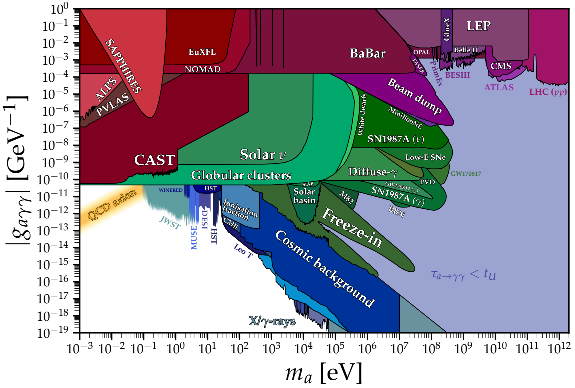




BREAD Collaboration (2111.1103)

Collider Searches?

- Heavier axions already ruled out. Colliders can search for **axion-like particles**:
  - No longer necessarily solves strong CP problem, though predicted by some models.
  - Many LHC searches now being interpreted this way, e.g. ATLAS $h \to aa \to 4\gamma$.



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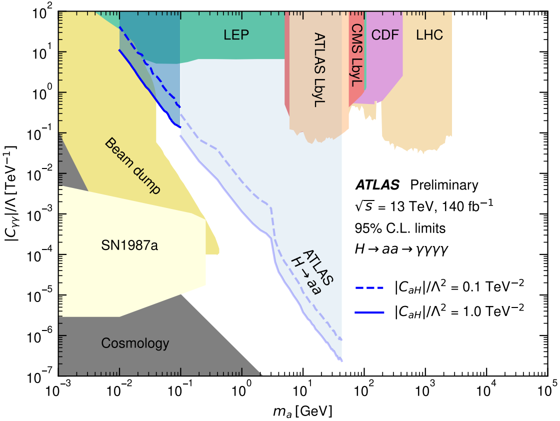

ATL-PHYS-PUB-2025-007

Axions and Supersymmetry

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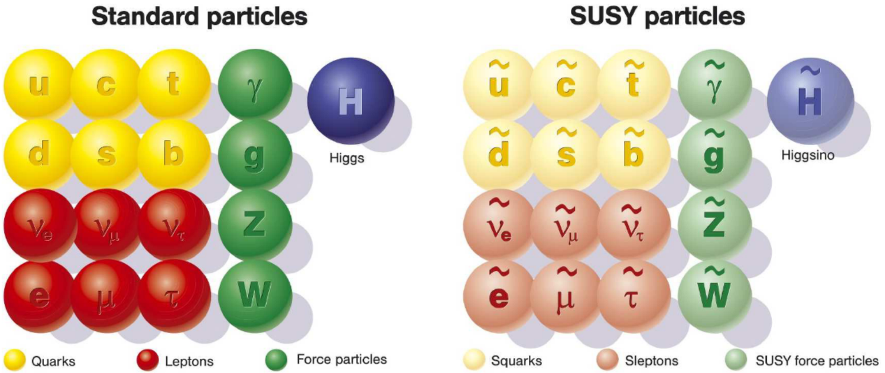
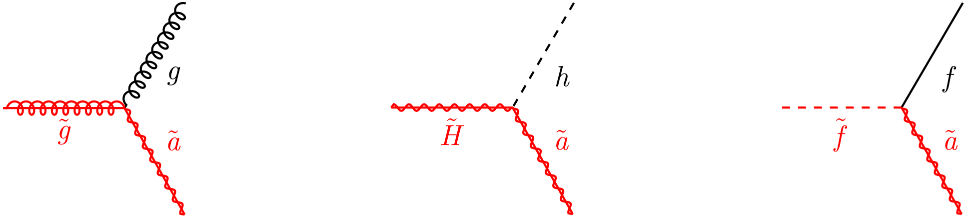


- Extend SM with new symmetry: fermions gain boson superpartners and vice versa.
  - Simplest models excluded by LHC but **no general prediction** for superpartner masses.
- If the axion exists, it should **also** have superpartners.
  - Fermionic superpartner **axino**; additional bosonic degree of freedom requires **saxion** too.
  - Saxion usually assumed to be heavy; axino could be **electroweak scale**.

Axino Phenomenology

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi}\frac{1}{f_a}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right), z = m_u/m_d$$

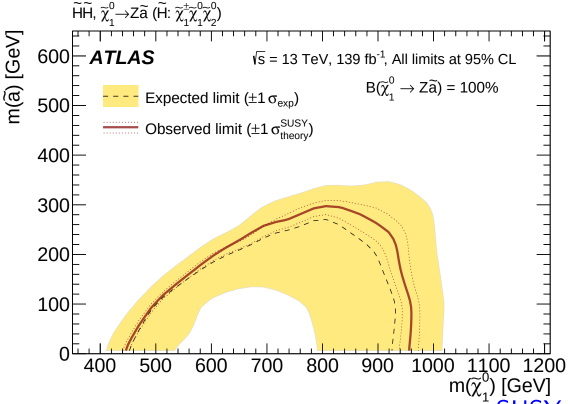
- Different axino models lead to different interactions (10.1140/epjst/e2020-000044-8):
  - **KSZV** axino only couples to gluinos, interacts with other particles through loops.
  - **DFSZ** axion can couple directly to $h\tilde{H}$, $f\tilde{f}$.

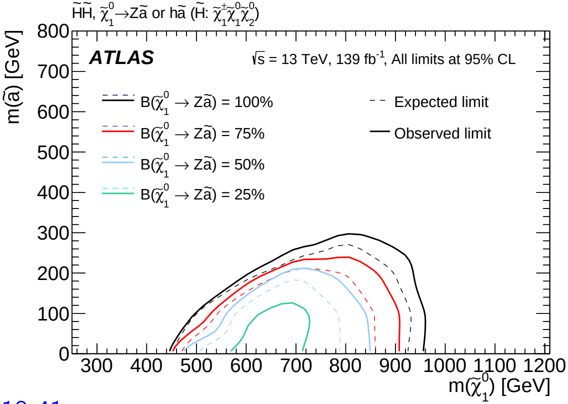


KSVZ **DFSZ** **DFSZ**

- In supersymmetric DFSZ: $g(a \to \gamma\gamma)$ becomes much smaller (1705.01134).
  - If SUSY exists: direct detection might need to probe much lower couplings.
  - If $z = \frac{m_u}{m_d} = 0.5$, $g(a \to \gamma\gamma) = 0$: photon coupling **vanishes** completely.

- Previous run 2 ATLAS search: interpreted with axino as lightest SUSY particle (LSP).
- Looked at $2b2q$ and $4q$ final states, set limits on Higgsino pair production ($\tilde{\chi}_1^0 \to Z\tilde{a}$).
- Didn't develop full treatment of Peccei-Quinn MSSM; treated axino as equivalent to bino.

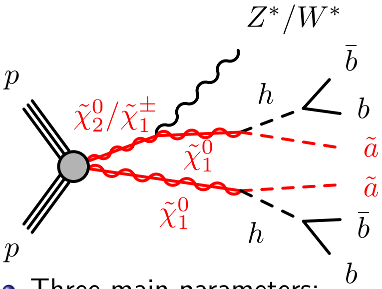




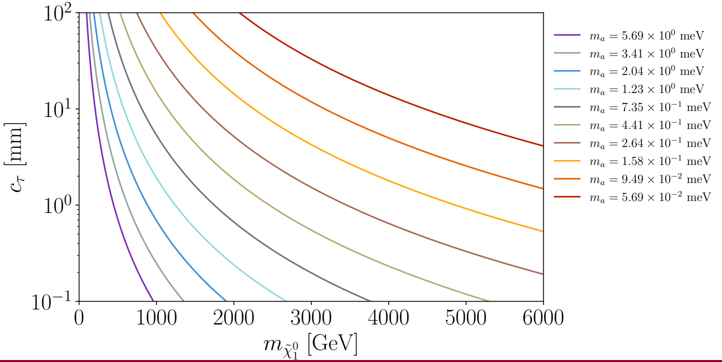
SUSY-2018-41

Peccei-Quinn DFSZ MSSM

- Collaborated with theorists (Keisuke Harigaya) to implement **complete** model:
  - Use SARAH to define Lagrangian and generate "UFO" (Universal FeynRules Output).
  - Run MadGraph5 to generate events via Monte Carlo method..
- Started with same $\tilde{\chi}_1^0 \to Z/h + \tilde{a}$ scenario: find NSLP often **long-lived**.



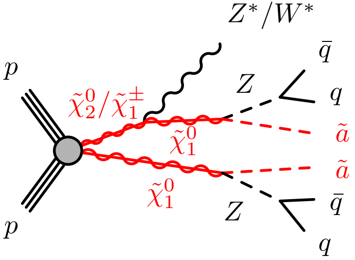
$$c\tau = 8.9\,\mathrm{mm}\left(\frac{f_a}{10^{10}\,\mathrm{GeV}}\right)^2\left(\frac{1\,\mathrm{TeV}}{\mu}\right)^3$$



- Three main parameters:
  - f_a: axion decay constant.
  - Higgsino mass $\mu = m_{\mathrm{NLSP}}$.
  - Axino mass $m_{\tilde{a}}$.

Axino/Neutralino Mixing

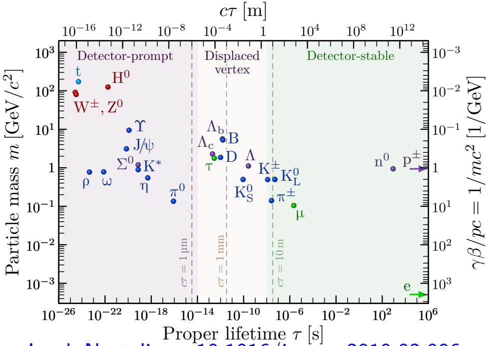
- One detail: axino only couples directly to the Higgs boson:
  - Axino **mixes** with other neutral bosonic superpartners (two Higgsinos, wino, bino).
- To implement this, need to somehow calculate **5x5 mixing matrix**:
  - Make simplifying assumptions: no coupling between wino-bino, Higgsino-axino sectors.
  - Assume $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ evenly split between $\tilde{H}_u$ and $\tilde{H}_d$, and $\tilde{\chi}_5^0$ is mostly axino.
  - Very small mass difference between $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$.
  - Assume small perturbative mixing between Higgsino and axino.
- Also assume **small mass gap** between two lightest neutralinos.



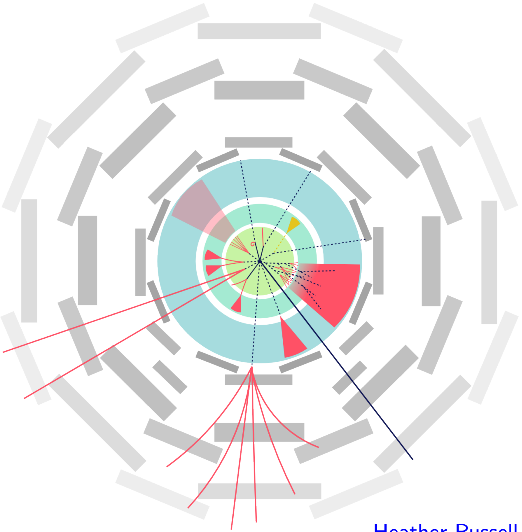
$$\begin{pmatrix} \tilde{\chi}_1 \\ \tilde{\chi}_2 \\ \tilde{\chi}_3 \\ \tilde{\chi}_4 \\ \tilde{\chi}_5 \end{pmatrix} = \begin{pmatrix} N_{11} & N_{12} & N_{13} & N_{14} & N_{15} \\ N_{21} & N_{22} & N_{23} & N_{24} & N_{25} \\ N_{31} & N_{32} & N_{33} & N_{34} & N_{35} \\ N_{41} & N_{42} & N_{43} & N_{44} & N_{45} \\ N_{51} & N_{52} & N_{53} & N_{54} & N_{55} \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W} \\ \tilde{H}_u \\ \tilde{H}_d \\ \tilde{a} \end{pmatrix}$$

Long-Lived Particles at Colliders

- LLPs travel **observable distance** before decaying inside detector:
  - Detectors not designed for this!
  - Lifetime-dependent signatures.
  - Displaced vertices: look for "large radius" tracks; find vertices.



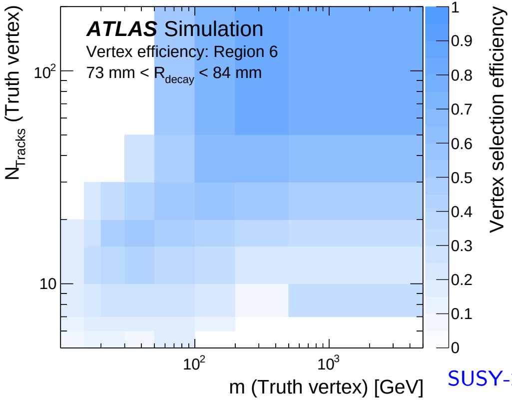
Izaak Neutelings, 10.1016/j.ppnp.2019.02.006

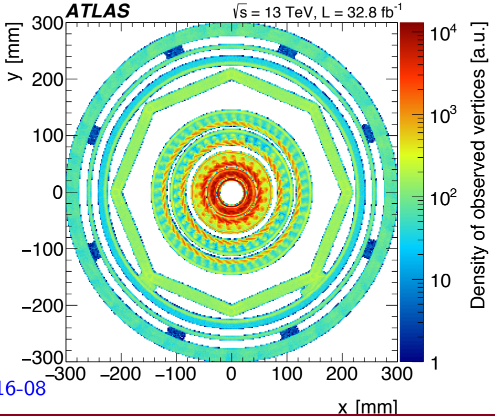


Heather Russell

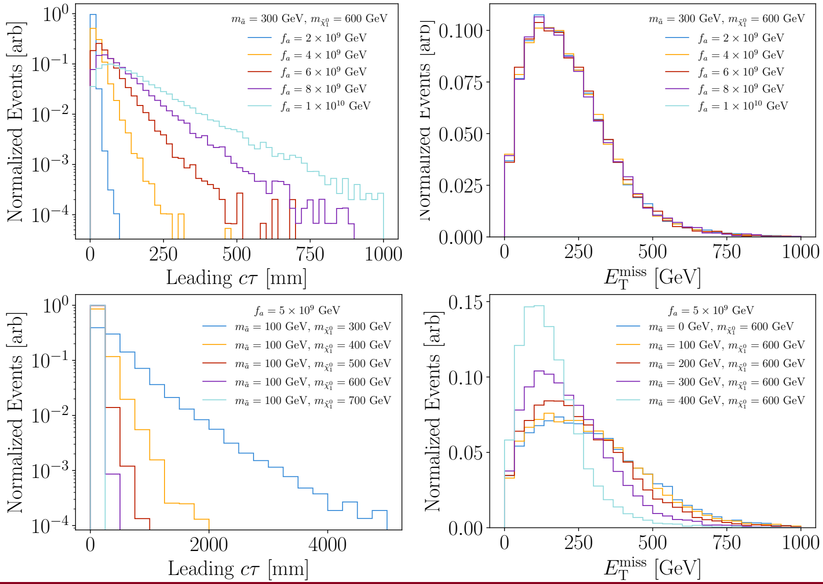
Displaced Vertices and MET

- Targeted f_a equivalent to $3 < c\tau < 300\,\mathrm{mm}$: should see DVs plus E_T^{miss} from axinos.
  - ATLAS has searched for signature; reinterpreted partial run 2 result using madanalysis.
  - Fast detector simulation; require vertex $m_{\text{DV}} > 10\,\mathrm{GeV}$, $N_{\text{tracks}} \geq 5$ and $E_T^{\text{miss}} > 150\,\mathrm{GeV}$.
  - Take vertexing efficiencies from ATLAS result; exclude regions containing detector material.





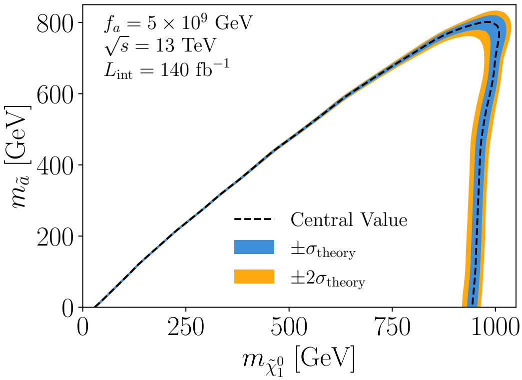
SUSY-2016-08

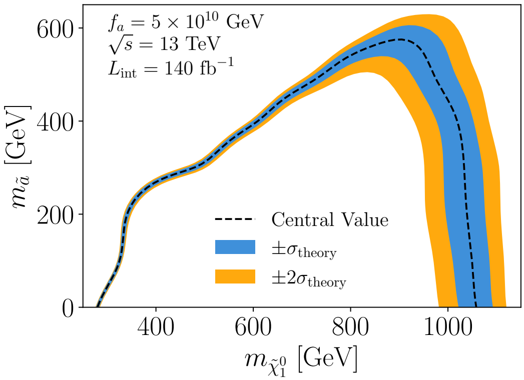


- Generated large range of samples for different $(f_a,\ m_{\tilde{a}},\ m_{\tilde{\chi}0})$ values.
- Lifetime controlled by f_a and $m_{\tilde{\chi}0}$.
- Axino mass $m_{\tilde{a}}$ only impacts $E_{\mathrm{T}}^{\mathrm{miss}}$.

Projected Exclusions

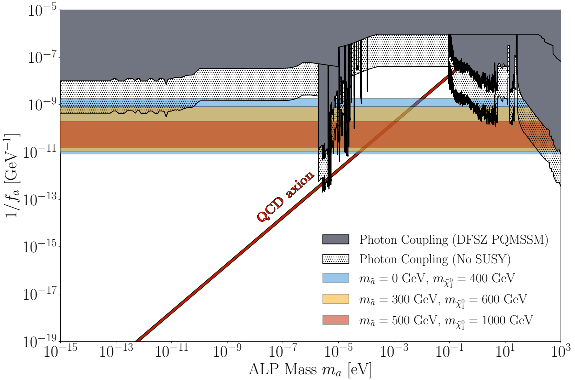
- Displaced vertex searches nearly **background-free**; made that assumption here.
- LHC is sensitive to this signature even just using run 2, depending on value of f_a.
- Assuming 100% BR($\tilde{\chi}_0 \to h\tilde{a}$); not b-tagging displaced jets, so $ZZ \to 4q$ identical.

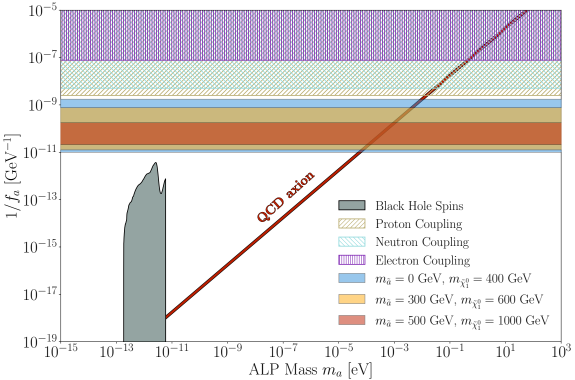




Constraining Axion Parameters

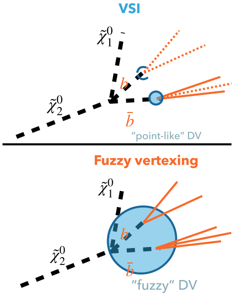
- Can now put collider limits and axion constraints on the **same plot**:
  - DV search could exclude axinos corresponding to $O(\mathrm{meV})$ QCD axions, or ALPs at any mass.
  - Can see impact of SUSY weakening direct detection constraints; comparison to other limits.

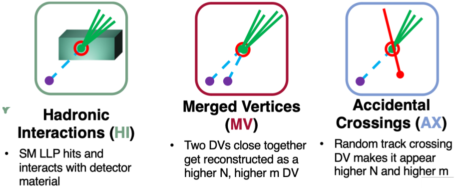




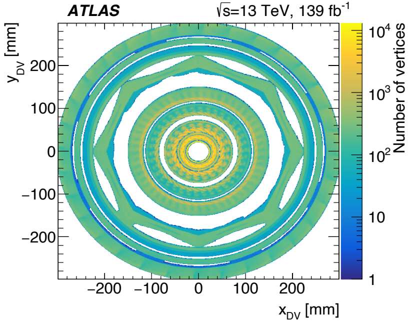
Full Run 2 DV+MET

- Worked on updated version of this search with full run 2 ATLAS dataset: not yet public...
- Some general comments:
  - Full run DV 2 searches following similar strategies: updated material map (SUSY-2018-13).
  - Thinking about alternate (non-point-like) vertexing strategies for heavy flavour.
  - "Background free": except for interactions with material, and accidental/fake vertices.
  - Hope to include axino interpretation in official result!



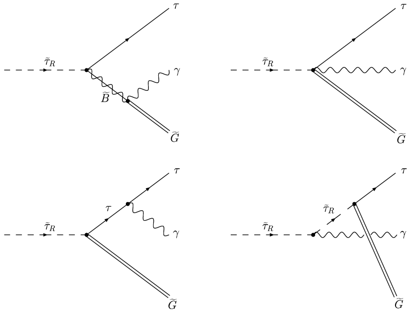


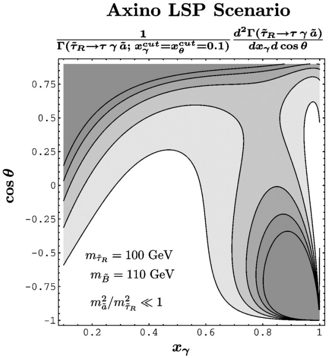
Jan Offermann

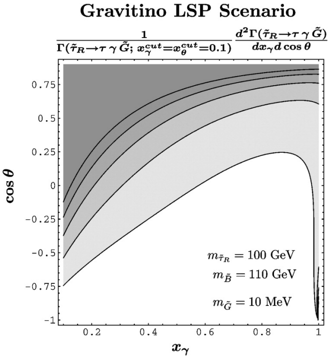


Axino vs Gravitino

- Common question: how would you tell that an axino is actually an axino?
- Another MSSM extension: gauge-mediated symmetry breaking with **gravitino** LSP.
  - Gravitino has to be **massless** to be produced in detector volume at collider.
  - Graviton and axion have different spins; so do gravitino (3/2) and axino (1/2).
- In **three-body decays**; measuring **polarization** of fermion would distinguish signatures.



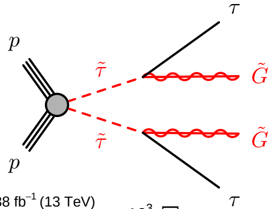


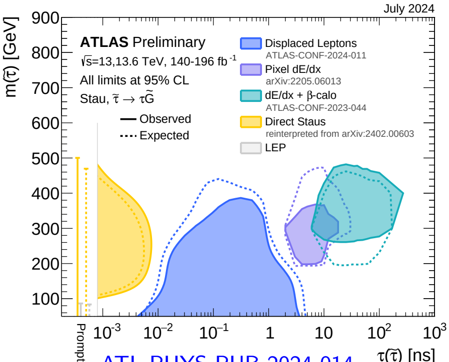


10.1016/j.physletb.2005.04.072

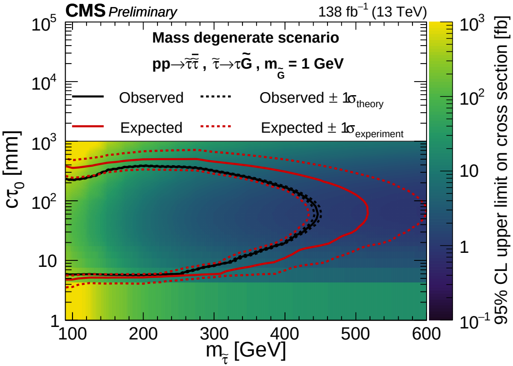
Searching for Displaced Taus

- Working on **dedicated** displaced tau search using **run 3** data:
  - Limits from generic displaced leptons searches weaker for taus.
  - Studying hadronic tau reconstruction using displaced tracks.
- CMS just released preliminary results for a very similar analysis.





ATL-PHYS-PUB-2024-014



CMS-PAS-EXO-24-020

Conclusion

- Presented two approaches for searching for dark matter at the LHC:
  - Higgs portal dark matter (WIMPs).
  - Constrain supersymmetric **axion** models.
  - Trying to deepen connection between colliders and axion physics.
- Future colliders will also be powerful tools for searching for dark matter:
  - Short term: high luminosity LHC, up to $3000\,\mathrm{fb}^{-1}$ of data, upgraded detectors.
  - Long term: $10\,\mathrm{TeV}$ **muon collider**; exclude simplest WIMP models to 5σ.
  - Ongoing effort at Chicago to study **LLPs** at a muon collider (targeting GMSB).
- Thanks for your attention!

Bridging the divide: axion and axino phenomenology at colliders and direct-detection experiments

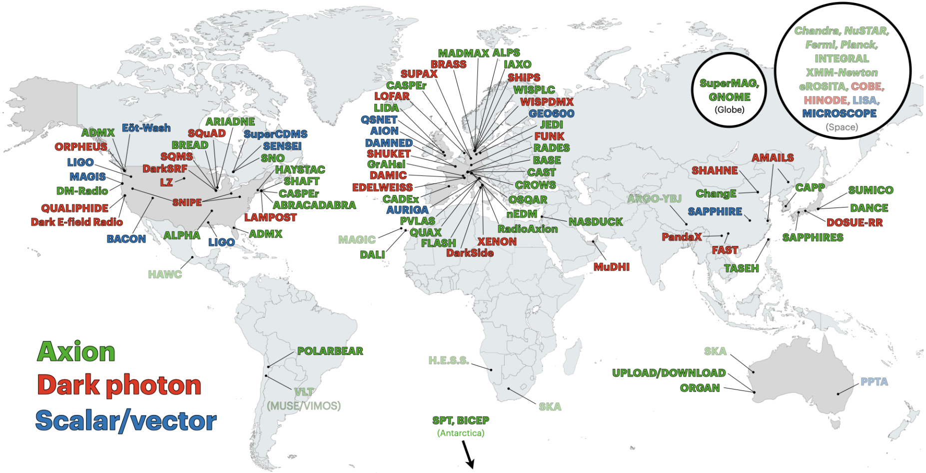
Gabe Hoshino,* Kristin Dona, Keisuke Harigaya, David W. Miller, Jan T. Offermann,† Bianca Pol,‡ Benjamin Rosser, and Cecilia Tosciri
The University of Chicago and the Enrico Fermi Institute
(Dated: October 21, 2025)

We discuss a phenomenological model extending the minimal supersymmetric standard model containing axions and their supersymmetric partner, the axino. In the case of the supersymmetric DFSZ axion model, the axino has tree level couplings to the higgs sector. Below the electroweak symmetry breaking scale, the axino additionally mixes with the other neutralino states. In the case where R-parity is conserved, collider experiments may be sensitive to decays of heavier neutralino states into lighter, mostly axino states. We present a sensitivity analysis using simple model in which two mostly higgsino NLSP states decay into a mostly axino LSP. Monte-Carlo samples were generated using MadGraph and then sensitivities were estimated using the MadAnalysis5 framework to perform cuts and a fast detector simulation. For the higgsino mass of 1 TeV, the axion decay constant below 10^{11} GeV can be probed by the Large Hadron Collider.

Paper in preparation! Hope to be on the arXiv by the end of the year; stay tuned!

Backup

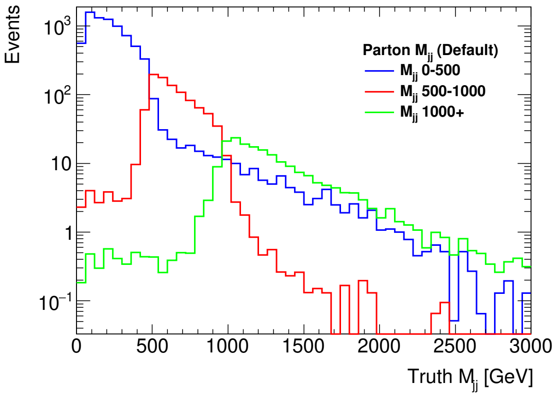
Dark Matter Experiments



doi:10.5281/zenodo.3932430

V+Jets Monte Carlo Statistics

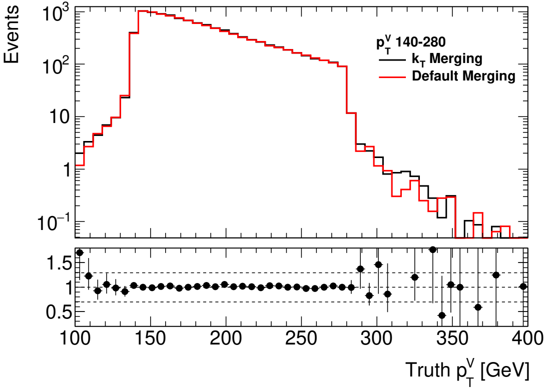
- QCD V+jets events ~ 50 times more likely to have low m_{jj} than high m_{jj}.
- Samples produced using Sherpa 2.2 at NLO: takes **two minutes** to generate **one event**.
- Limited MC stats in high-m_{jj} phase space lead to large transfer factor uncertainties.

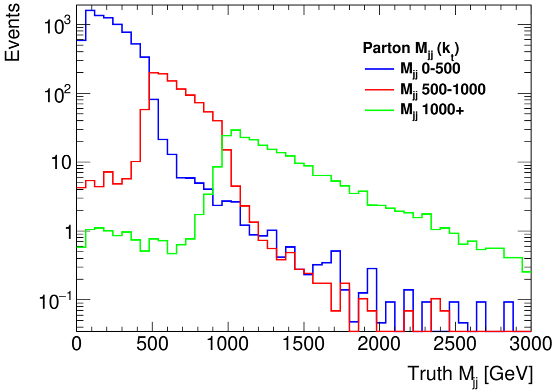


- Solution: generate **sliced** samples:
  - Split samples into m_{jj} slices.
  - Generate more events in high m_{jj} slice.
- Filter at **matrix element** level:
  - When generating events, matrix element (ME) calculated first, then matched to parton shower (PS) calculation.
  - Calculate "parton-level m_{jj}" from the ME partons before running PS.
- Unfortunately, filter **very inefficient**:
  - Contamination from low-m_{jj} slice.
  - Parton shower changes event kinematics!

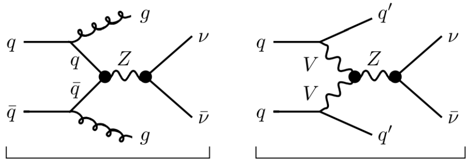
Efficient Matrix Element Filtering

- With help from Sherpa developers: change ME/PS boundary to improve filtering.
- Parton emissions below a cutoff scale classified as PS using custom k_t-like algorithm.
- Switching the criterion to just use k_t: more forward partons tagged as ME.



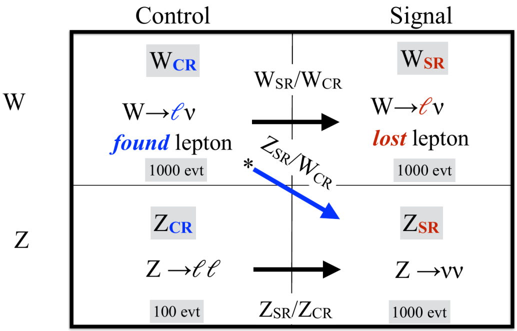


Using $W \to l\nu$ to Constrain $Z \to \nu\nu$



$Z + 2j$ *via strong process*

$Z + 2j$ *via weak process*



$$\frac{\mathrm{d}}{\mathrm{d}x}\frac{\mathrm{d}}{\mathrm{d}\vec{y}}\sigma^Z = \frac{\mathcal{R}^{Z/W}_{\text{TH}}(x)}{\mathcal{R}^{Z/W}_{\text{MC}}(x)}\frac{\mathrm{d}}{\mathrm{d}x}\frac{\mathrm{d}}{\mathrm{d}\vec{y}}\sigma^Z_{\text{MC}}$$

- $Z \to ll$ statistics much lower than $W \to l\nu$ due to lower cross section and branching ratio.
- Want to use $W \to l\nu$ to estimate $Z \to \nu\nu$,
- Worked with theorists to reweight Z/W ratio (arXiv:2204.07652):
  - Jonas Lindert, Marek Schönherr, Stefano Pozzorini became ATLAS consultants (ACEs).
  - They calculated ratio $\mathcal{R}^{Z/W}_{\text{TH}}(x)$ with full NLO corrections as 1D function of $x = m_{\text{jj}}$.
  - $\mathcal{R}^{Z/W}_{\text{MC}}(x)$ is ratio taken from ATLAS MC.
  - Allows use of **single** V+jets transfer factor.
  - Performed separately for QCD, EWK V+jets.

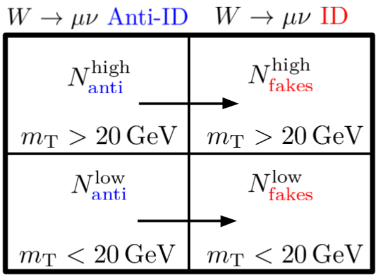
Z/W Reweighting Uncertainties

- Systematic uncertainties on Z and W still included, but now **fully correlated**.
  - Renormalization, factorisation, QSF, and CKKW scales, and PDF uncertainties.
  - Four additional sources of uncertainty on the Z/W ratio computed with help from theorists.
- **QCD** ($\delta\mathcal{R}^{Z/W}_{\text{QCD}}$) and **QCD-EW** ($\delta\mathcal{R}^{Z/W}_{\text{mix}}$) mixing uncertainties: provided by ACEs.
- **Parton shower** ($\delta\mathcal{R}^{Z/W}_{\text{PS}}$) uncertainties:
  - Provided by ACEs for strong V+jets.
  - Computed by comparing aMC@NLO and Angular ordered parton shower models for H7 EW.
- **Reweighting** uncertainties ($\delta\mathcal{R}^{Z/W}_{\text{mod}}$) on loose selection used for ratio.
  - For QCD: differences found between Z and W before and after jet veto in Sherpa MC: appears to be bug.
  - **Apply jet veto** before reweighting strong V+Jets, use **jet veto efficiency** for uncertainty.
  - For EW: diboson interference leads to $\Delta\phi_{\text{jj}}$ dependence on corrections.
  - Bin corrections in $\Delta\phi_{\text{jj}}$ (0-1, 1-2, 2+): use inclusive correction with **difference between binned and inclusive** as uncertainty.

Fake Muon Estimate

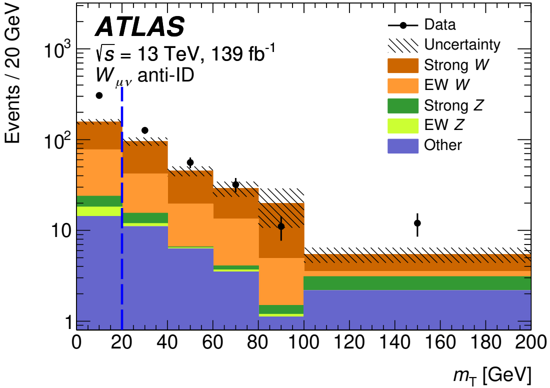
- Jets can also be misidentified as a muon and contaminate $W \to \mu\nu$ CR.
- Use same basic procedure: calculate fake muon transfer factors from anti-ID region.
- S_{MET} not as effective; used different variable, m_{T}. Fake muon background much smaller.

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}(l) E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi_{\mathrm{l,miss}})}$$



$$N_{\mathrm{fakes}}^{\mathrm{high}} = \beta N_{\mathrm{fakes}}^{\mathrm{low}}$$

$$\beta = \frac{N_{\mathrm{anti}}^{\mathrm{high}}}{N_{\mathrm{anti}}^{\mathrm{low}}}$$

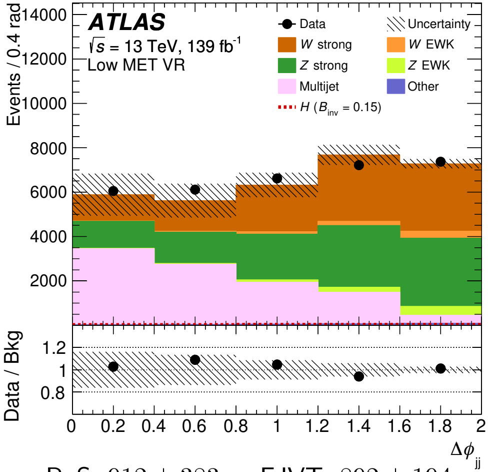


Multijet Estimate: FJVT Control Region

- Forward jet vertex tagging:
  - Identify likelihood of forward jet originating from pileup vertex V.
  - Jets must pass FJVT $< 0.2(0.5)$ if $E_{\mathrm{T}}^{\mathrm{miss}} > 160(200)\,\mathrm{GeV}$ to not be pileup.

$$\mathsf{FJVT} = \max_{i \in V} \frac{p_{\mathrm{T}}^{\mathrm{miss},i} \cdot p_{\mathrm{T}}^{\mathrm{jet}}}{|p_{\mathrm{T}}^{\mathrm{jet}}|^2}$$

- **Invert** FJVT requirement to create multijet CR; take data - MC difference as estimate.
- Normalize with transfer factors using multijet-enriched $E_{\mathrm{T}}^{\mathrm{miss}} < 160\,\mathrm{GeV}$.
- **Agrees well** with rebalance and smear estimate, with **smaller** uncertainties.



RnS: 912 ± 383 vs FJVT: 892 ± 194

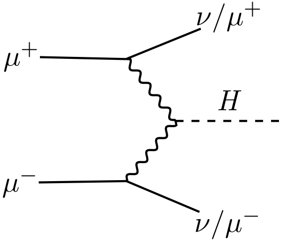
Axino/Neutralino Mixing Implementation

$$\begin{pmatrix} \tilde{\chi}_1 \\ \tilde{\chi}_2 \\ \tilde{\chi}_3 \\ \tilde{\chi}_4 \\ \tilde{\chi}_5 \end{pmatrix} = \begin{pmatrix} 0 & 0 & \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & \frac{v Y_{\text{axion}}(\sin(\beta)-\cos(\beta))}{2(\mu - m_{\tilde{a}})} \\ 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{v Y_{\text{axion}}(\sin(\beta)+\cos(\beta))}{2(\mu + m_{\tilde{a}})} \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & \frac{v Y_{\text{axion}}(\mu\cos(\beta)-m_{\tilde{a}}\sin(\beta))}{\sqrt{2}(m_{\tilde{a}}^2-\mu^2)} & \frac{v Y_{\text{axion}}(\mu\sin(\beta)-m_{\tilde{a}}\cos(\beta))}{\sqrt{2}(m_{\tilde{a}}^2-\mu^2)} & 1 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W} \\ \tilde{H}_u \\ \tilde{H}_d \\ \tilde{a} \end{pmatrix}$$

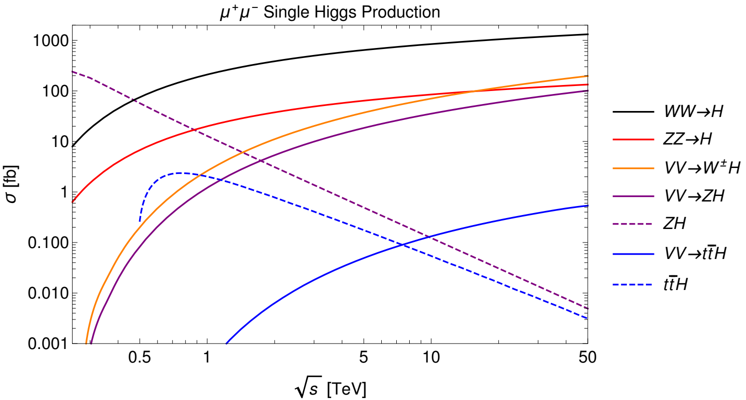
- Theorists provided formulas for the Higgsino-axino mixing in terms of a few parameters:
  - Axino mass $m_{\tilde{a}}$ and Higgsino mass $\mu = m_{\tilde{\chi}_1}$; we take $m_{\tilde{\chi}_2} = m_{\tilde{\chi}_1} + \Delta m$, for $\Delta m \leq 10\,\text{GeV}$.
  - Higgs VEV v and mixing angle $\tan(\beta)$; small impact once $\tan(\beta) > 5$.
  - Axion Yukawa term $Y_{\text{axion}} = \sqrt{2}\frac{\mu N_{\text{color}}}{f_a N_{\text{dw}}}$, where domain wall number $N_{\text{dw}} = 3N_{\text{color}}$.
- Originally tried implementing this in the model itself:
  - After various issues, confusion with inconsistent indices, etc. abandoned this approach.
  - Decided to calculate for each grid point as part of param card / joboptions.

The Case for 10 TeV

- LHC had "no-lose theorem": either find light Higgs with $m < 1\,\mathrm{TeV}$ **or** BSM physics.
- **No such guarantee** for future colliders at present!



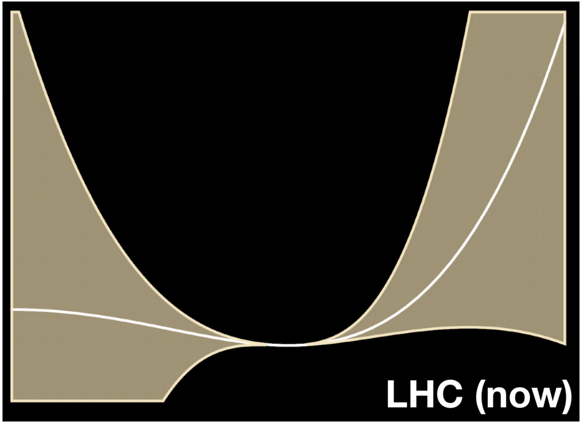
- So why 10 TeV?
  - Muon collider becomes **electroweak** collider.
  - VBF/VBS becomes dominant over s-channel.
  - "Electroweak PDF"

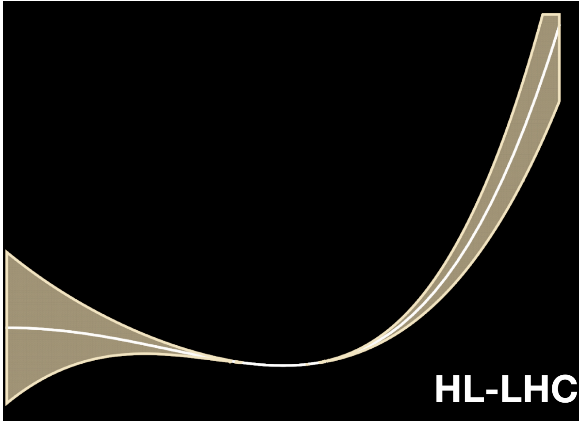


M. Forslund, P. Meade (10.1007/JHEP08(2022)185)

Higgs Potential

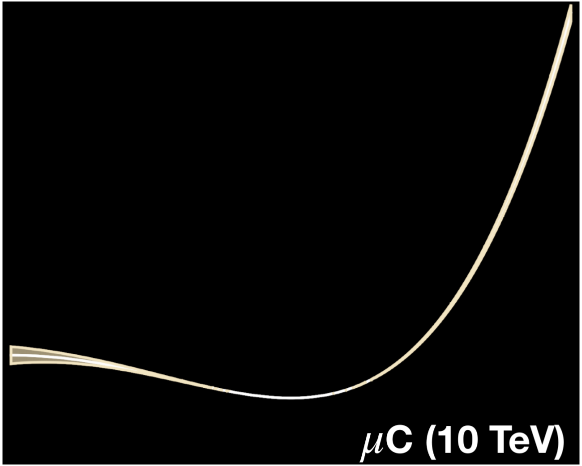
- Higgs looks Standard Model like, but **shape of potential** uncertain even after HL-LHC!





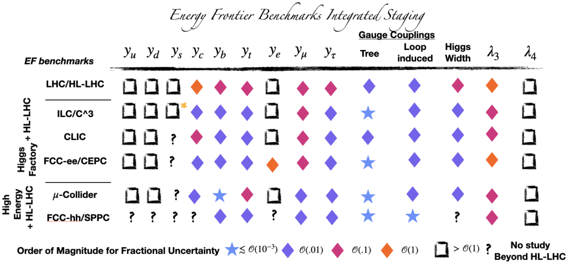
Nathaniel Craig

Higgs Couplings at a Muon Collider



Nathaniel Craig

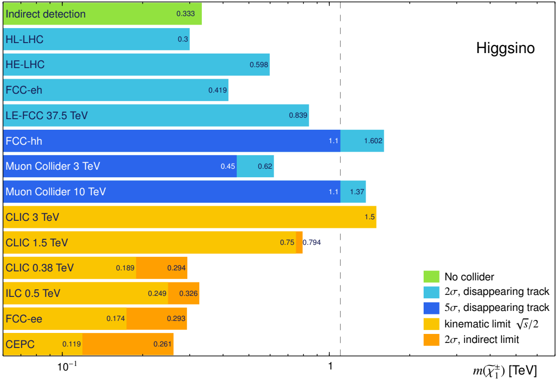
- 10 TeV muon collider will constrain potential shape to $O(1)\%$.
- Constraints on couplings **comparable** between muon collider, FCC-hh.

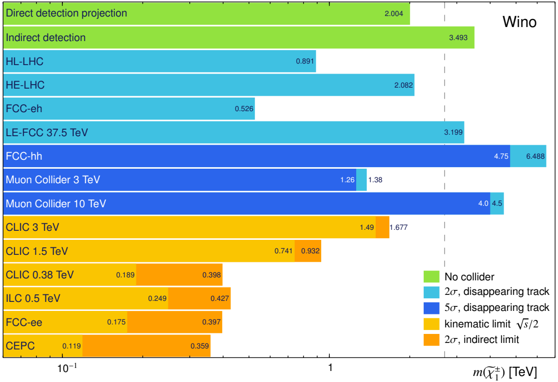


Snowmass Energy Frontier Report (2211.11084)

Dark Matter at Future Colliders

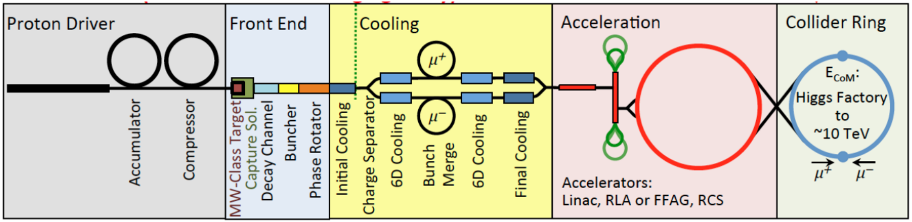
- Simplest WIMPs: "minimal dark matter" (0903.3381, 2203.07351):
  - No new interaction; add new scalar or fermionic multiplet charged under $SU(2)_L \times U(1)_Y$.
  - SUSY examples: doublet (Higgsino), triplet (Wino); higher order multiplets possible.
  - **Not excluded**; $10\,\mathrm{TeV}$ collider can reach relic density at 5σ for Higgsino/Wino-like DM.





R. Capdevilla et al. (10.1007/JHEP06(2021)133)

How to Collide Muons



- Main muon collider challenges all **accelerator** related:
  - 1-4 MW target for proton driver: alternatives to liquid mercury needed.
  - 6D ionization cooling: must focus beam as quickly as possible, reduce transverse emittance.
  - Fast ramping magnets to inject, accelerate beam: need $1000\,\mathrm{T/s}$, plus $16\,\mathrm{T}$ DC magnet.
  - Collider ring: 12-$16\,\mathrm{T}$ large aperture dipoles, 15-$20\,\mathrm{T}$ quadrupoles; **similar to FCC-hh**.
  - Neutrino radiation flux from decaying muons.
- Baseline design from US Muon Accelerator Program, updated by IMCC (2303.08533)