Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Collaborative Research Center TRR 257
P H
Particle Physics Phenomenology after the Higgs Discovery

General Framework for Flavored Dark Matter Models

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Dark Tools 2025

17.06.2025

Why Flavoured Dark Matter?

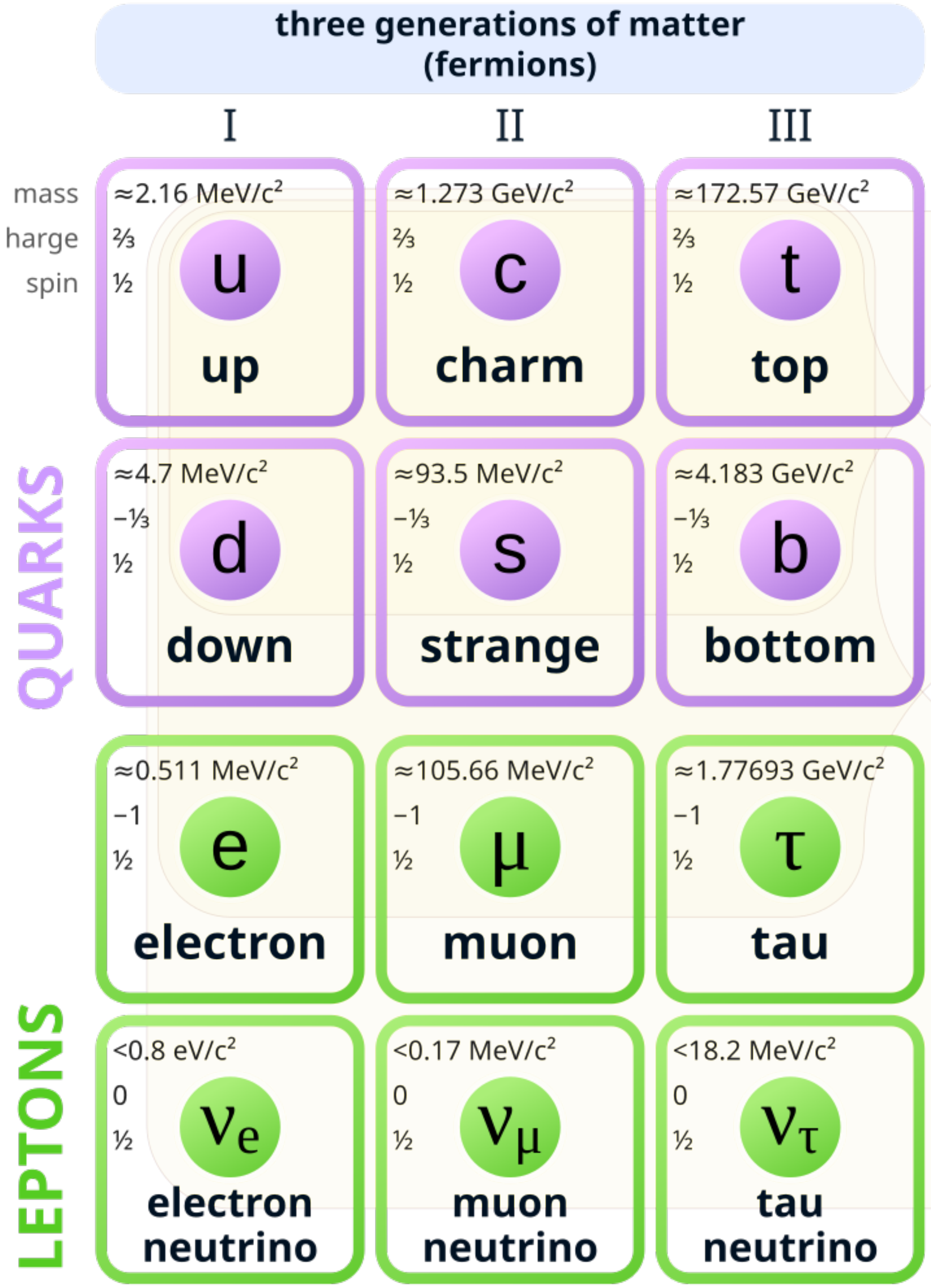
- Traditional weakly interacting massive particle (WIMP) models under severe pressure

  → Assume DM has non-trivial flavour structure like SM

- New source of flavour and CP violation

  → Different phenomenology

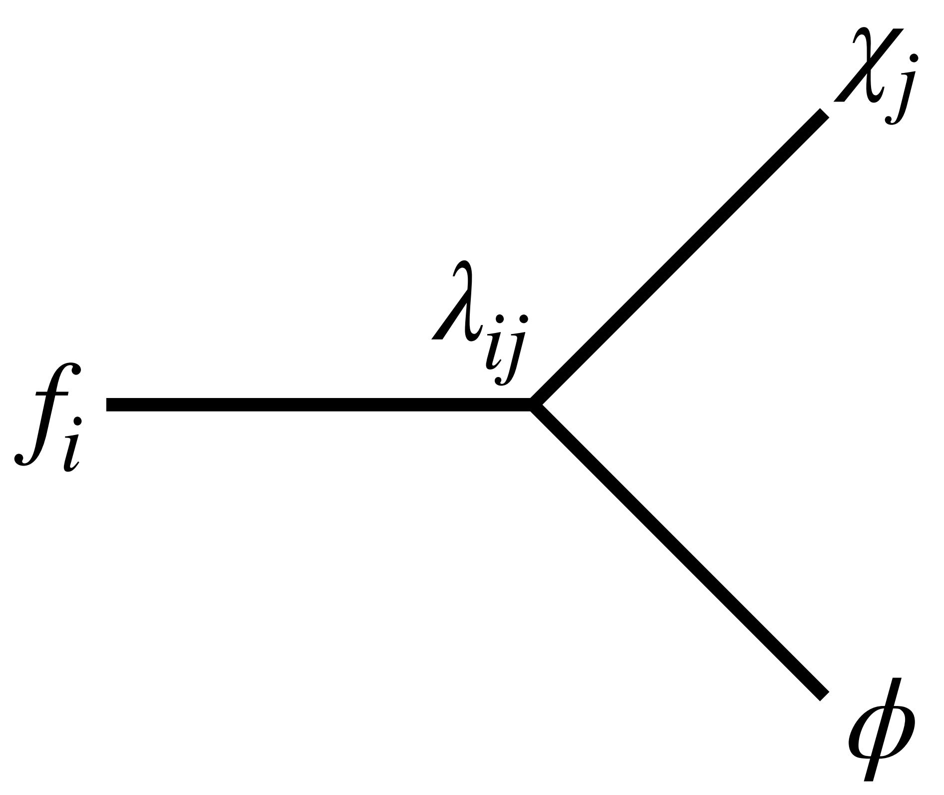
- Introduce dark minimal flavor violation (DMFV) concept to keep parameters minimal



[Wikipedia]

Dark Minimal Flavour Violation [Agrawal, Blanke, Gemmler 2014]

- Extend SM by single new flavour symmetry and new fields (DM flavour triplet $X = (X_1, X_2, X_3)^T$ and mediator Y)
- Couple to SM fermions f through complex 3×3 matrix λ
- Mass matrix M_X expanded in powers of λ



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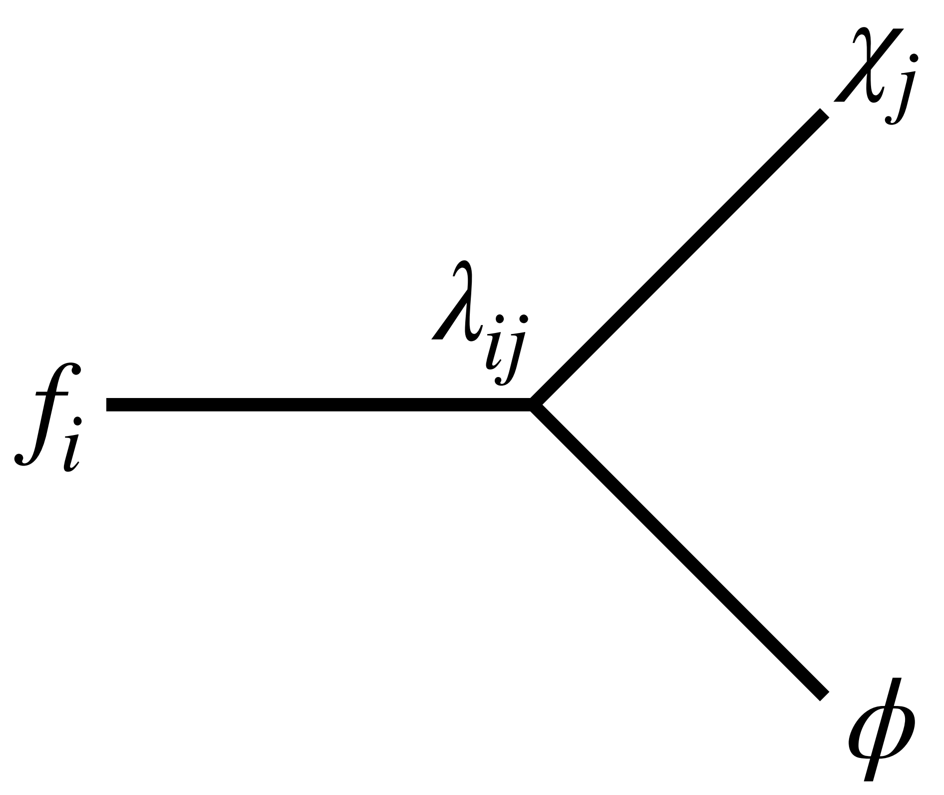

X_j	Y	f_i

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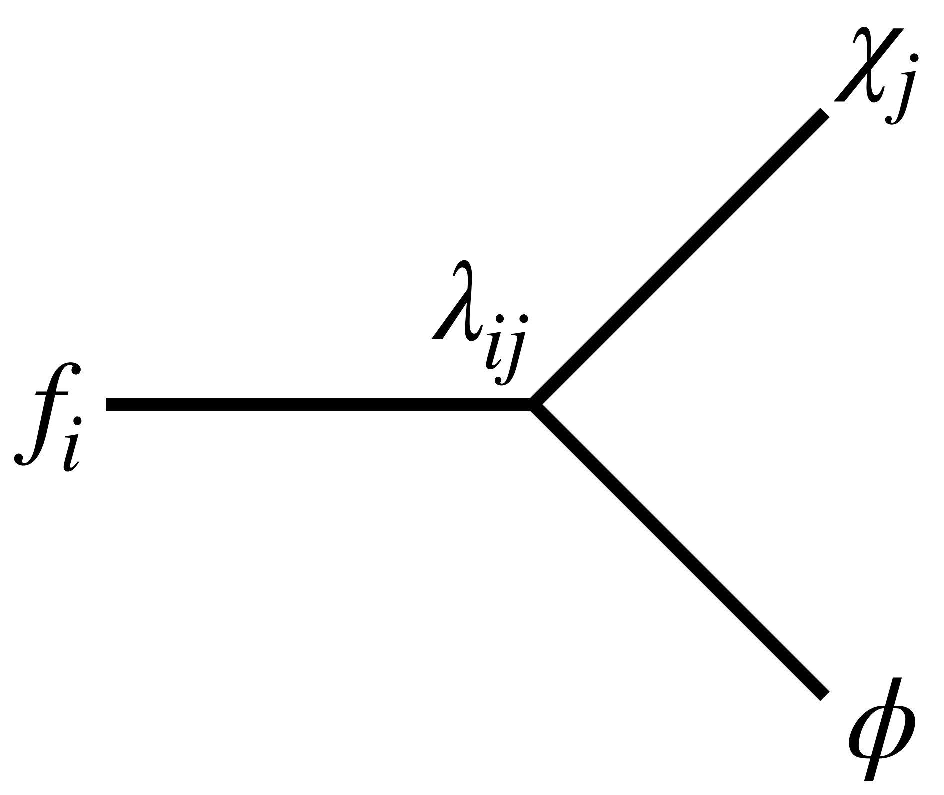

	X_j	Y	f_i
Spin 0	• Real scalar • Complex scalar	• Vector-like fermion	

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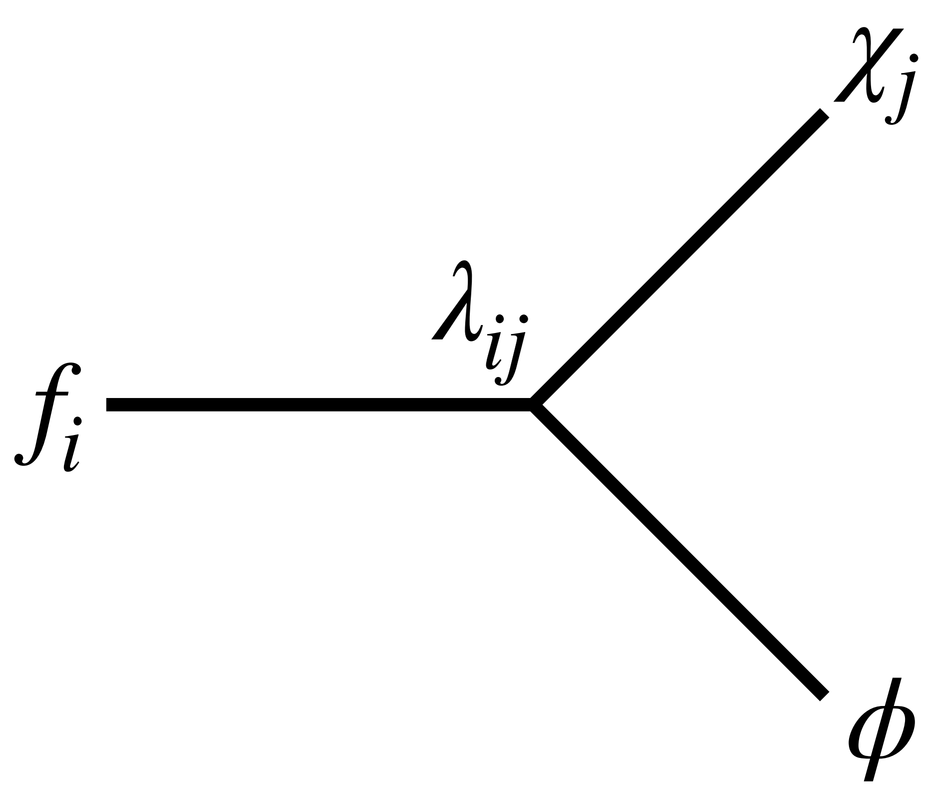

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Spin 1/2	• Majorana fermion • Dirac fermion	• Complex scalar	

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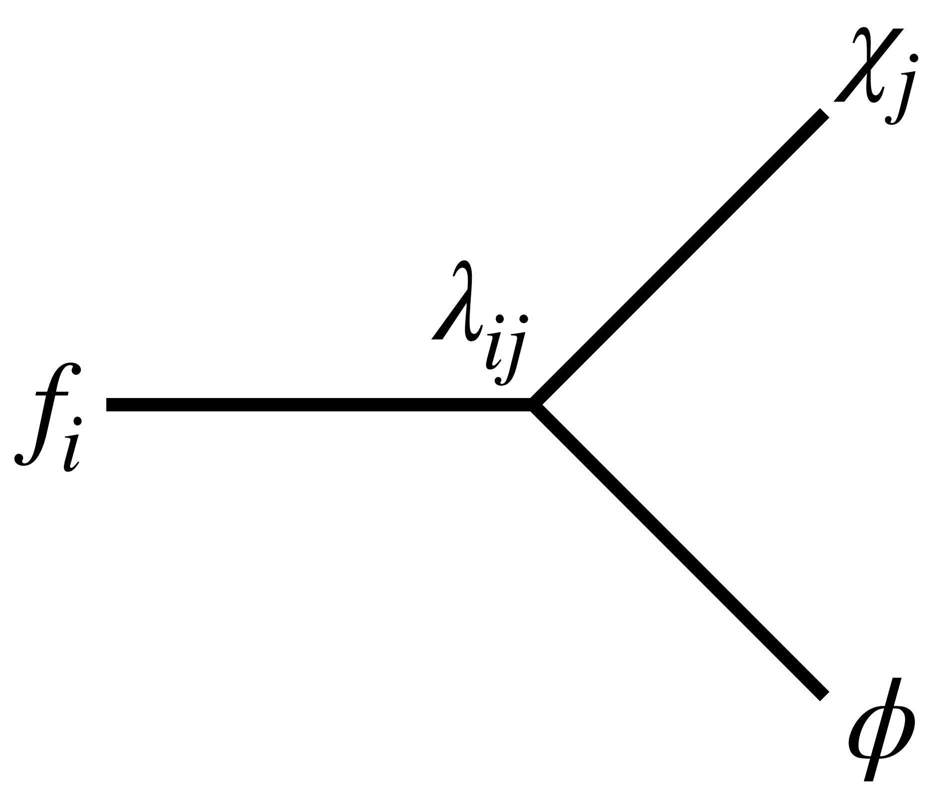

	X_j	Y	f_i
Spin 0	• Real scalar • Complex scalar	• Vector-like fermion	• Up-type quarks u_R • Down-type quarks d_R • Charged leptons e_R
Spin 1/2	• Majorana fermion • Dirac fermion	• Complex scalar	• Quark doublet q_L • Lepton doublet ℓ_L

Previously Studied Models

	u_R	d_R	q_L	e_R	ℓ_L
Real scalar DM	✗	✗	✗	✗	✗
Complex scalar DM	✗	✗	✗	[Acaroglu, Agrawal, Blanke 2022] [Acaroglu, Blanke, Tabet 2022] [Acaroglu, Agrawal, Blanke 2023]	[Acaroglu, Agrawal, Blanke 2022]
Dirac fermion DM	[Blanke, Kast 2017] [Jubb, Kirk, Lenz 2017] [Blanke et al. 2021]	[Agrawal, Blanke, Gemmler 2022] [Bensalem, Stolarski 2022]	[Blanke, Das, Kast 2018] [Blanke et al. 2021]	[Chen, Huang, Takhistov 2016]	✗
Majorana fermion DM	[Acaroglu, Blanke 2022] [Acaroglu, **LR** et al. 2024]	✗	✗	✗	✗

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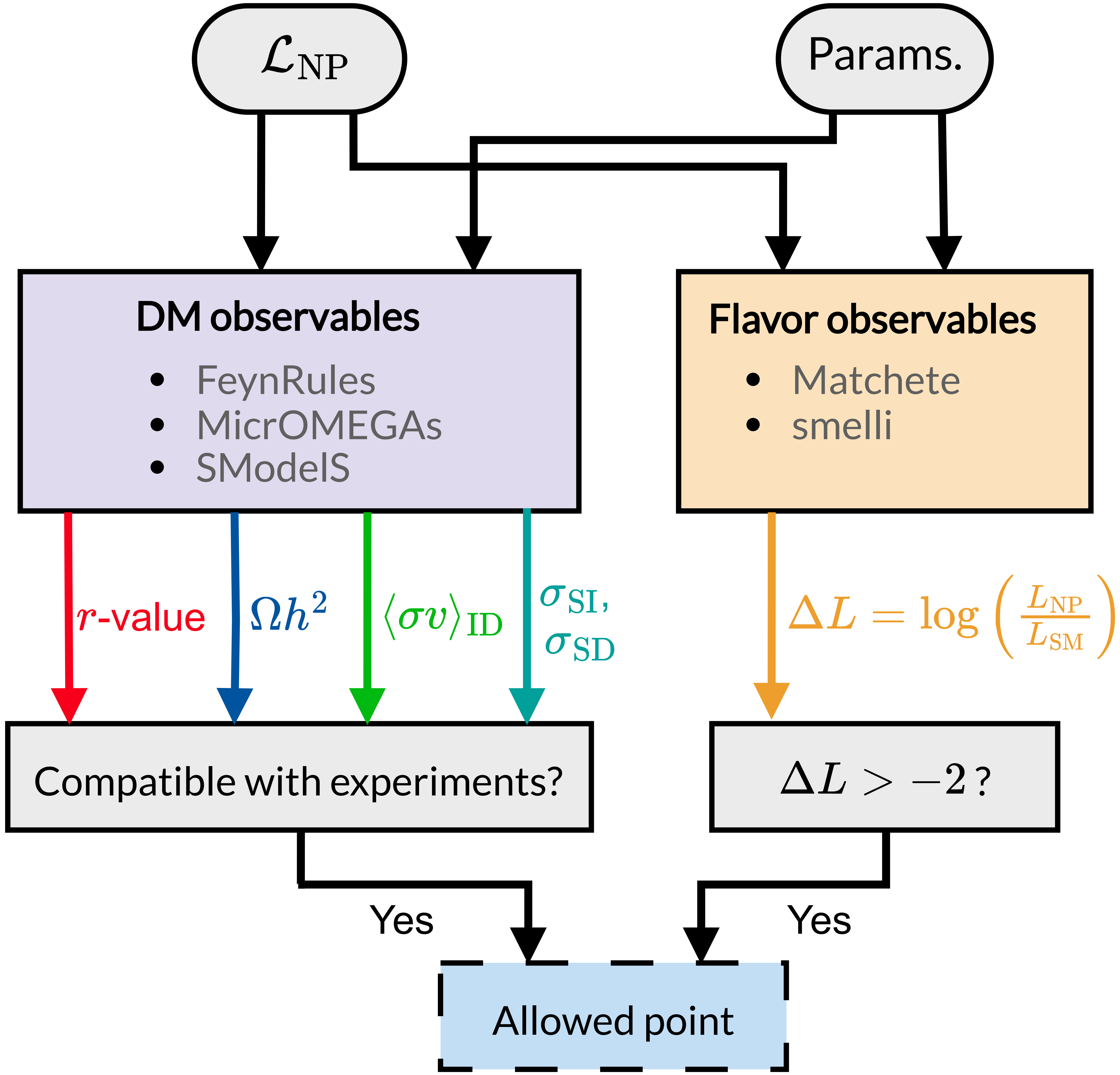
Majorana fermion DM	[Acaroglu, Blanke 2022] [Acaroglu, **LR** et al. 2024]	✗	✗	✗	✗

→ Develop framework to study phenomenology of all possible models

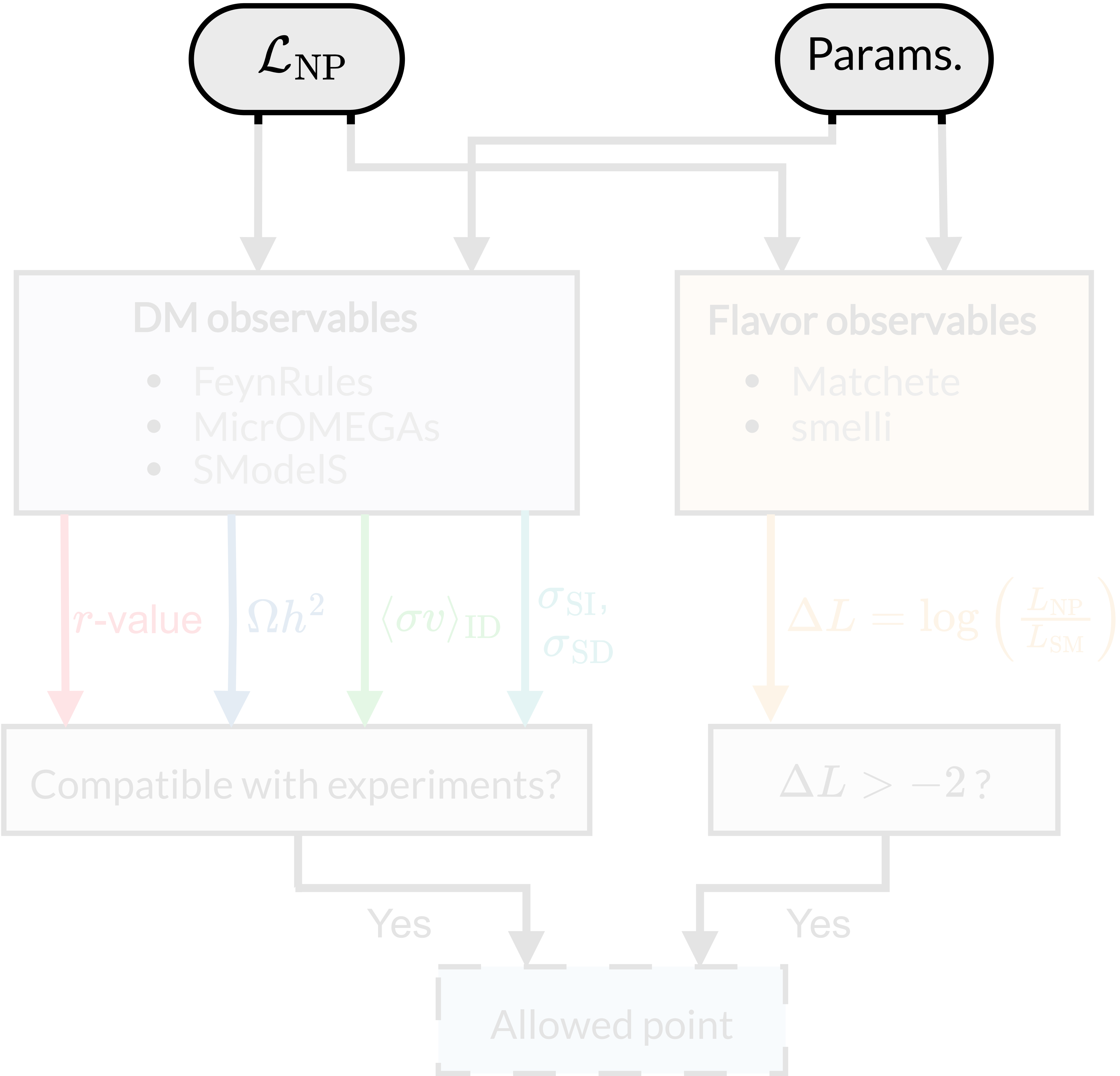
Tool-Chain



$\mathcal{L}_{\rm NP}$
Params.
DM observables
FeynRules
MicrOMEGAs
SModelS
Flavor observables
Matchete
smelli
r-value
Ωh^2
$\langle \sigma v \rangle_{\rm ID}$
$\sigma_{\rm SI}$,
$\sigma_{\rm SD}$
$\Delta L = \log\left(\frac{L_{\rm NP}}{L_{\rm SM}}\right)$
Compatible with experiments?
$\Delta L > -2\,?$
Yes
Yes
Allowed point

Tool-Chain - Input

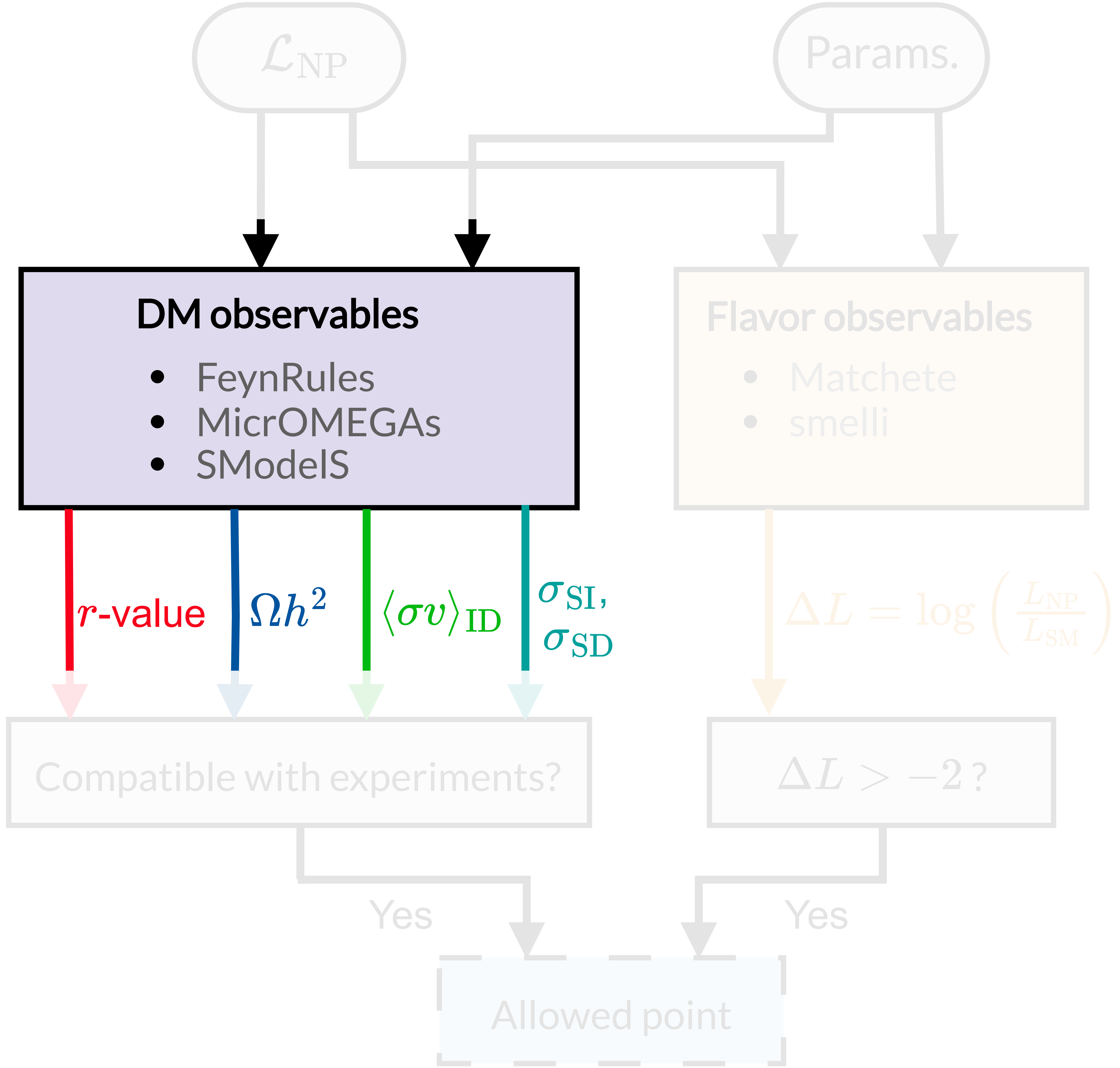
- Lagrangian $\mathscr{L}_{\rm NP}$ describing all new physics (NP) interactions of DM model
- Values for masses M_{X_i} and M_Y
- Values for couplings to SM particles



Tool-Chain - DM Observables

[Alloul et al. 2014]

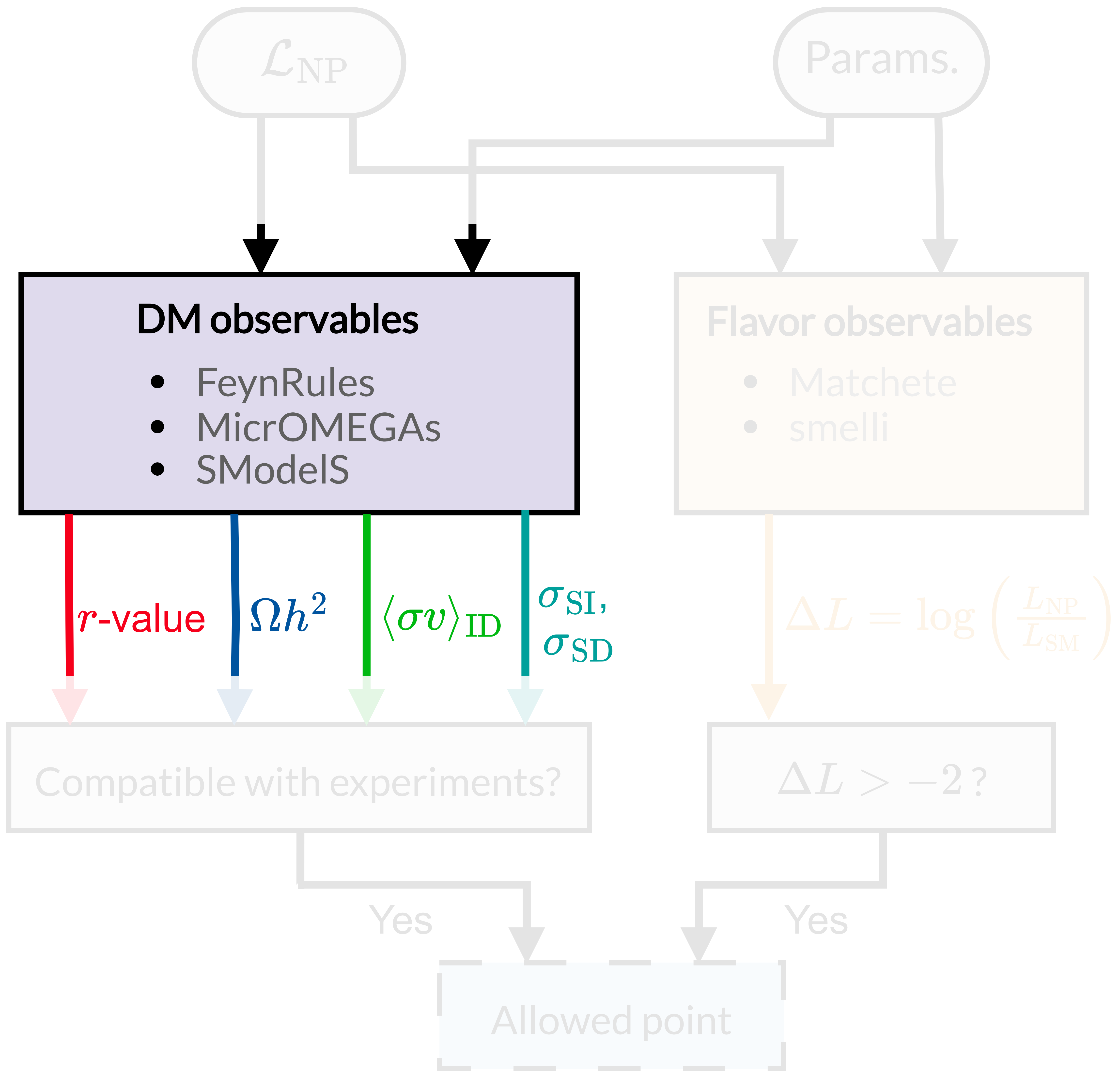
- Implemented all models in FEYNRULES
- All FeynRules, CalcHEP and UFO model files available on GitHub in lena-ra/Flavored-Dark-Matter
- CalcHEP files used for implementation in MicrOMEGAs



Tool-Chain - DM Observables

[Bélanger et al. 2018]
[Altakach et al. 2024]

- MicrOMEGAs computes DM properties:
  - Relic abundance Ωh^2
  - Annihilation cross section $\langle \sigma v \rangle$ for every annihilation channel for indirect detection
  - Spin (in)dependent DM-nucleon cross section $\sigma_{\text{SI/SD}}$



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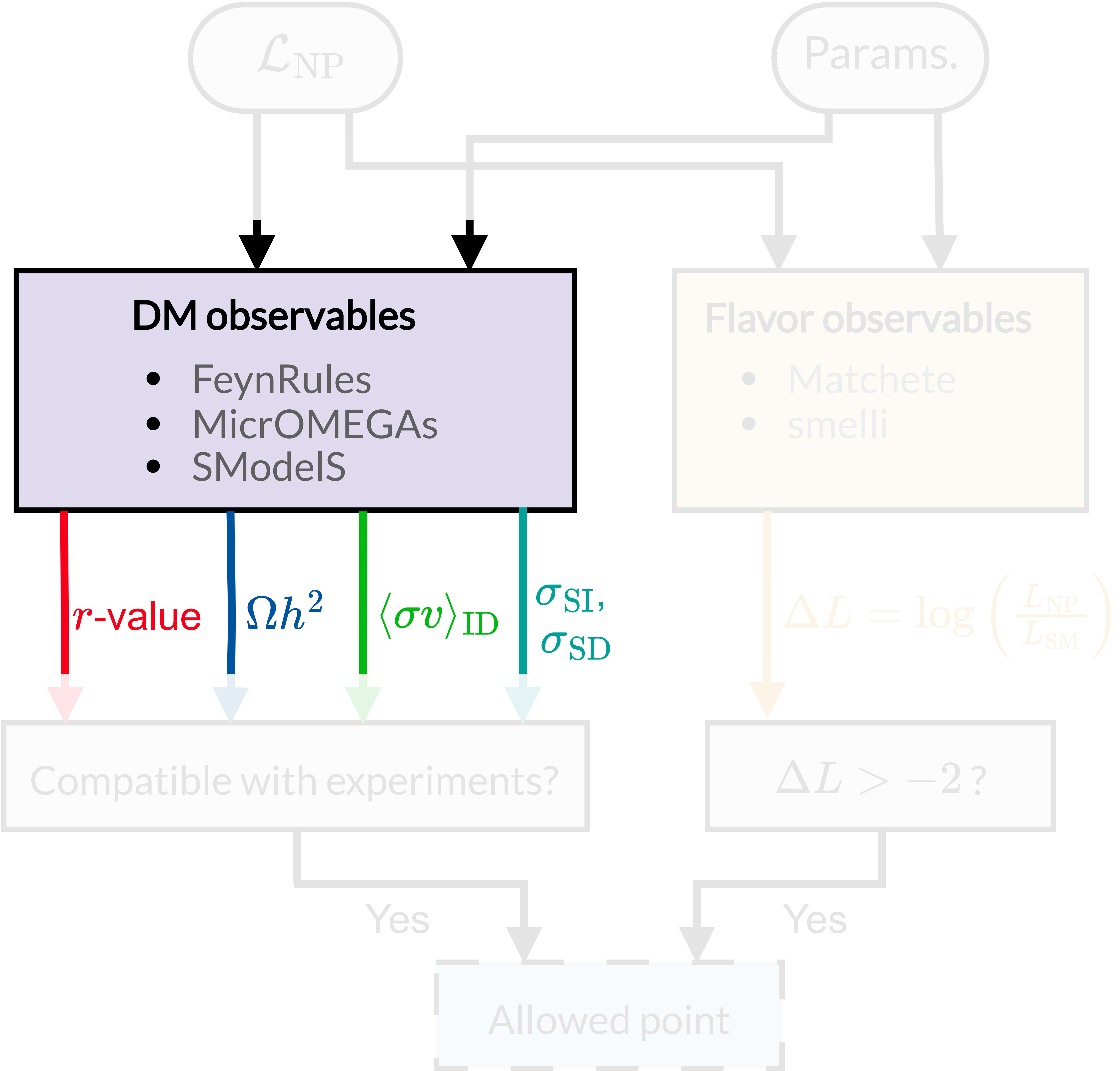
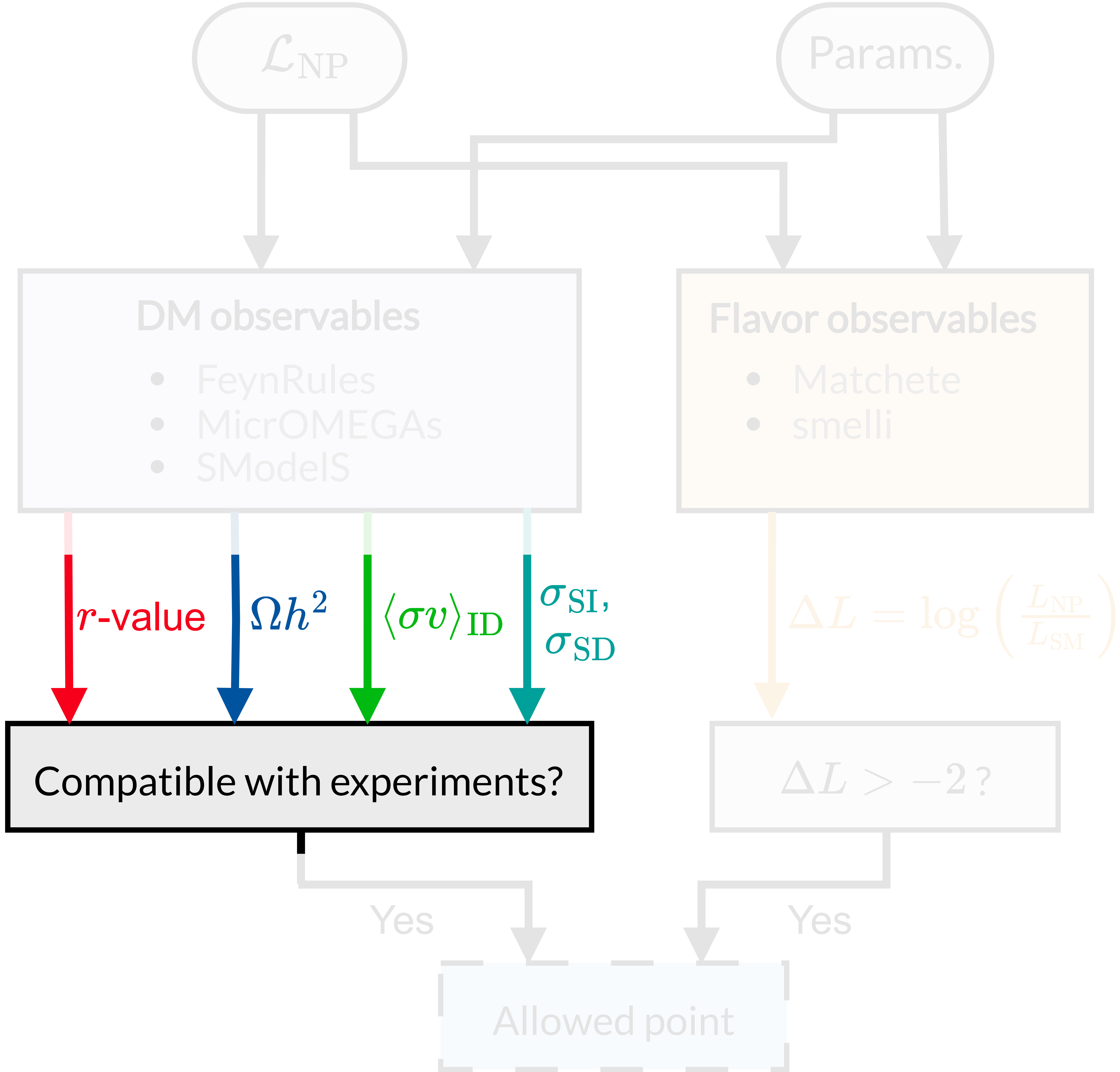
- SMODELS computes constraints from colliders, returns

$$r\text{-value} = \frac{\text{signal cross section}}{\text{experimental upper limit}}$$



Tool-Chain - Check Constraints

- Exclude parameter point if one of the following is true:
  - r-value ≥ 1
  - Ωh^2 not within [0.11, 0.13]
  - $\langle \sigma v \rangle_{\text{ID}}$ > experimental limit from γ-ray, $\bar{p}$, e^+ and ν data
  - σ_{SI} or σ_{SD} > experimental limits from CRESST-III, LZ, XENON1T, DarkSide-50, PICO-60



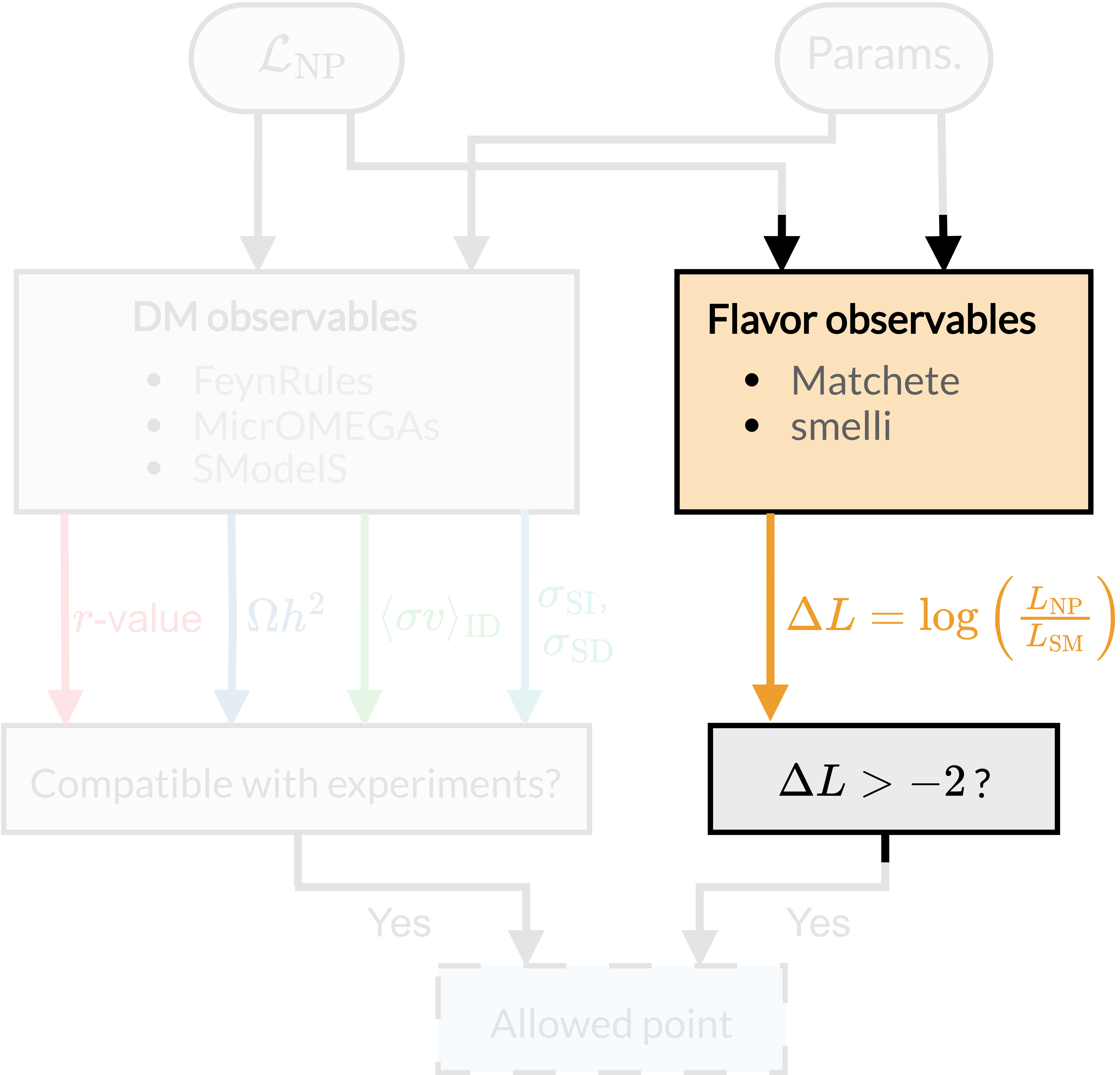
Tool-Chain - Flavor Observables

[Fuentes-Martín et al. 2023]
[Aebischer et al. 2019]

- MATCHETE computes matching of DM model to SM Effective Field Theory
- SMELLI evolves SMEFT Wilson coefficients from high energy scale to low energy scale where flavor observables are measured
- Computes flavor observables
- Provides log-likelihood ratio

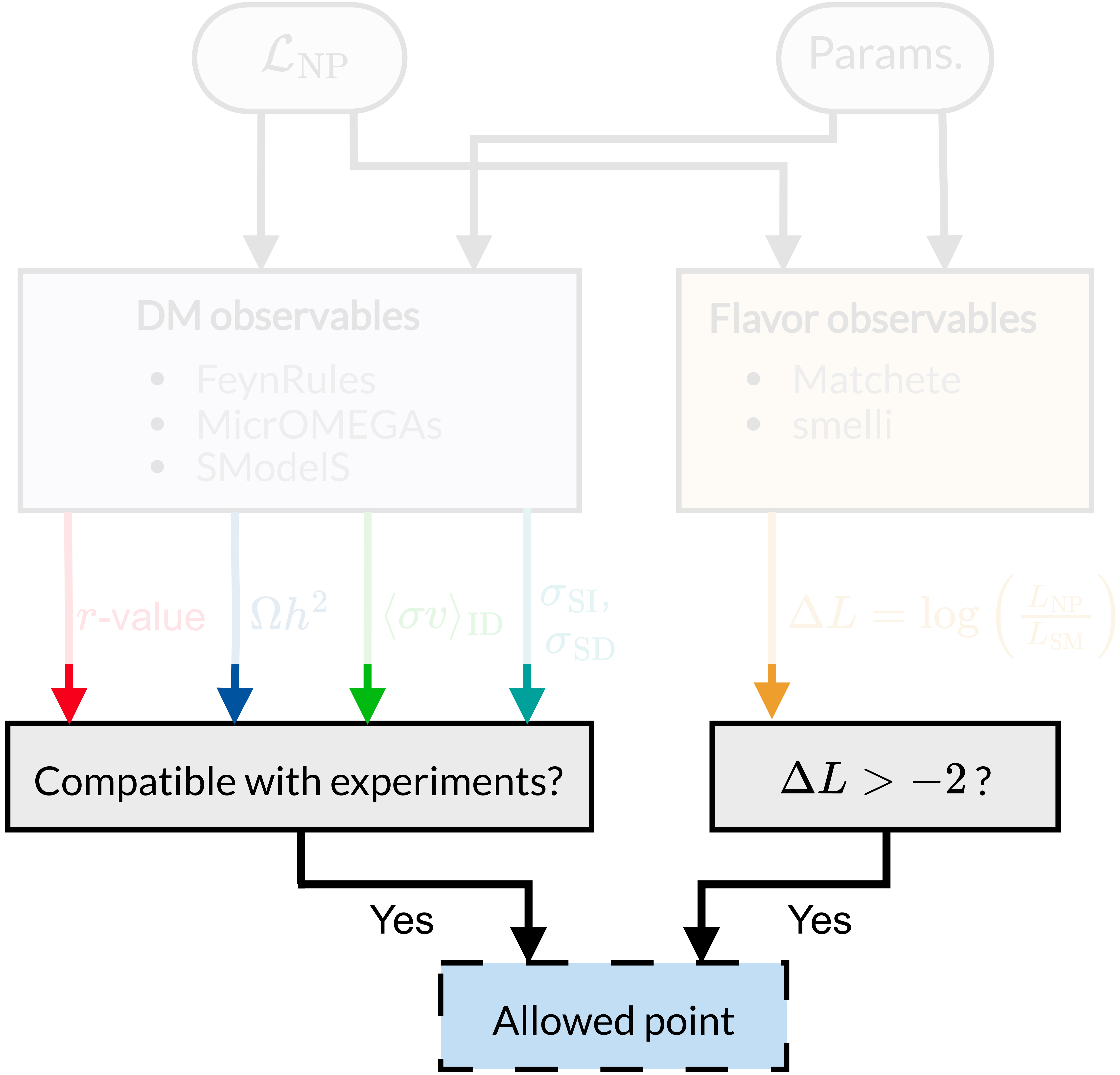
$$\Delta L = \log\left(\frac{L_{\rm NP}}{L_{\rm SM}}\right)$$

- Keep point if $\Delta L > -2$



Tool-Chain - Allowed Parameters

- Perform random parameter scan
- Keep point if not excluded by any observable
- Obtain viable parameter space for any of the flavored DM models



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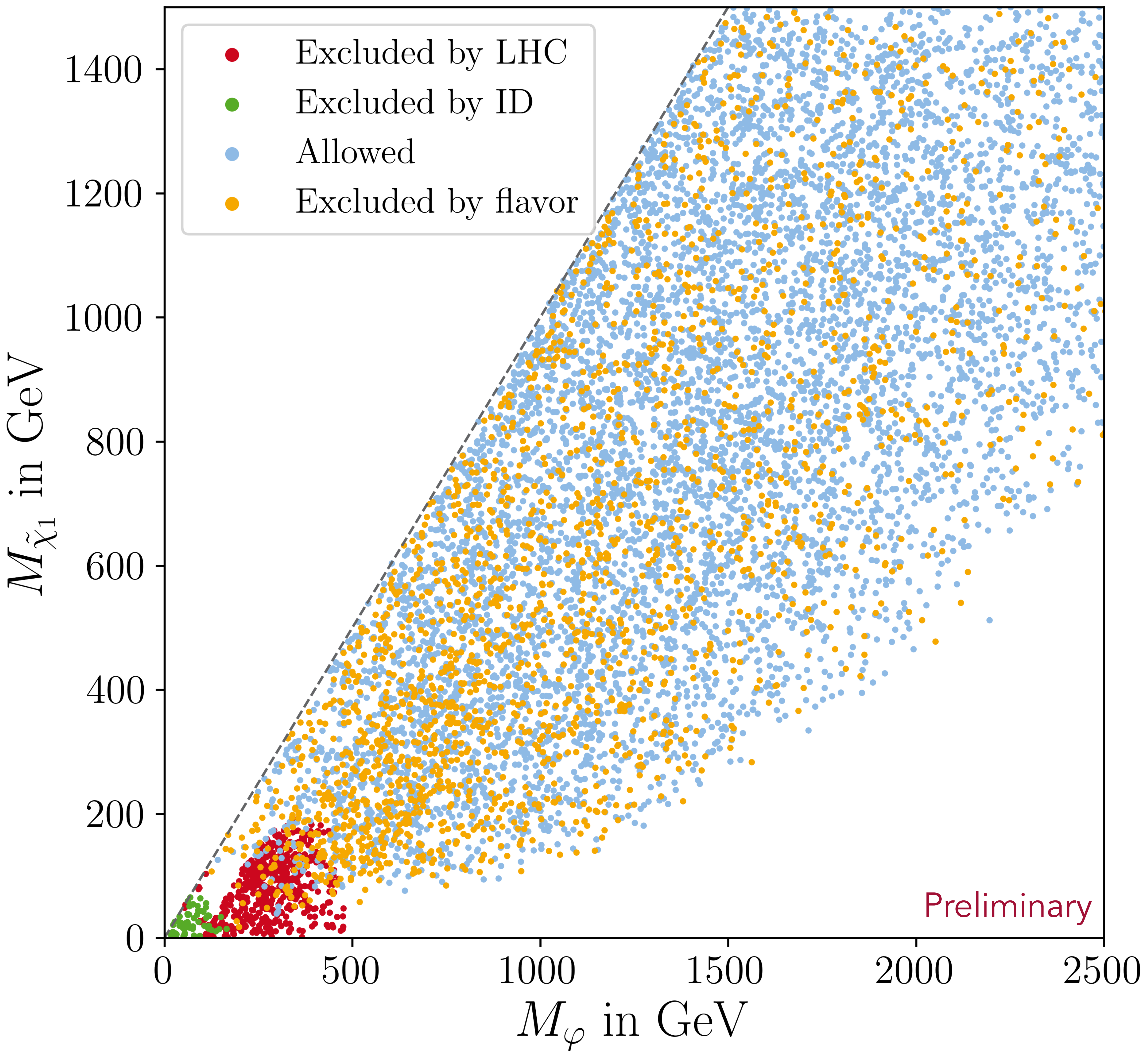
- Dark matter flavor triplet $\tilde{\chi}$, mediator φ

Majorana DM coupling to e_R



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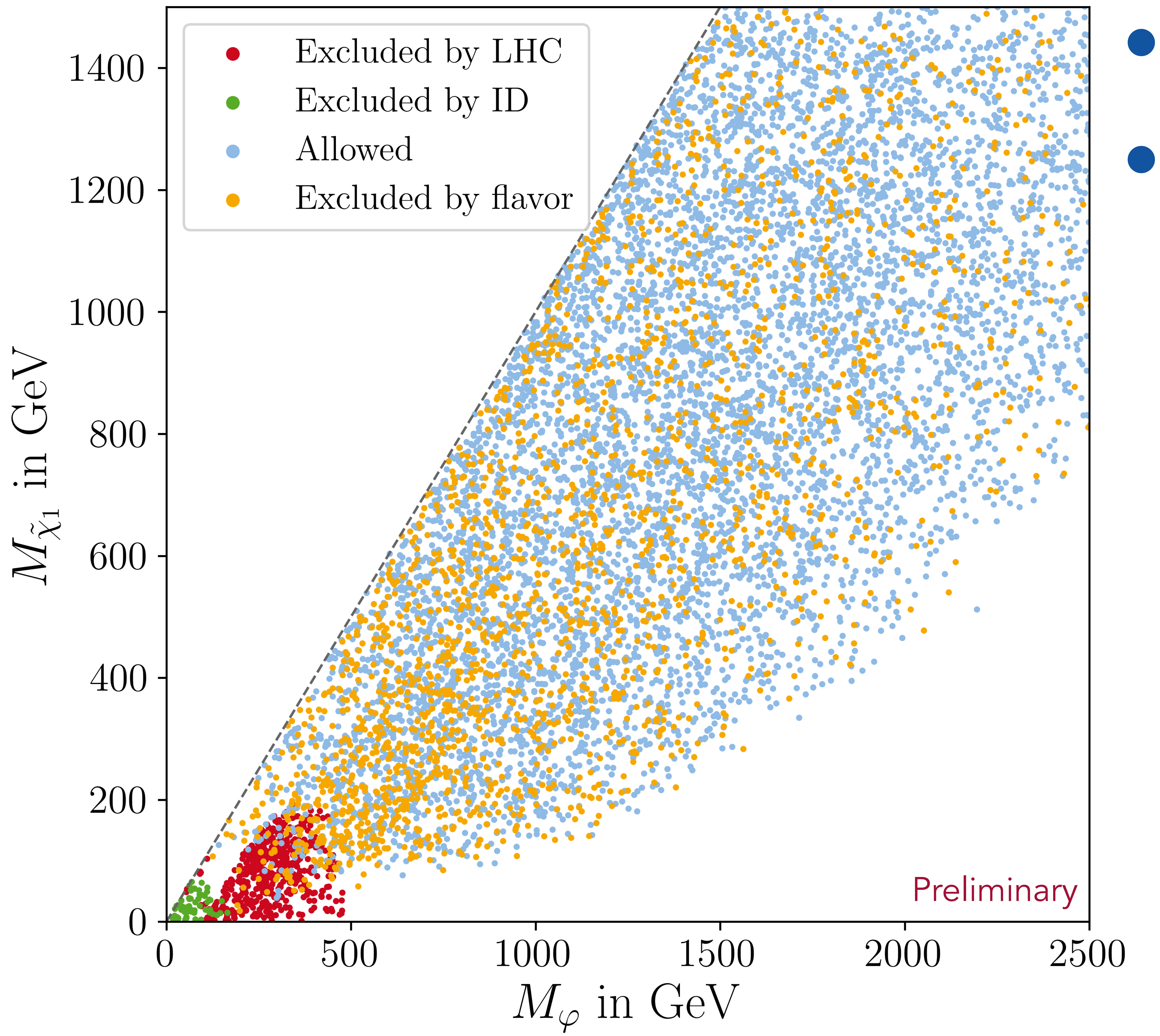

- Relic abundance most constraining
- Lower bound on DM mass because of upper limit on coupling

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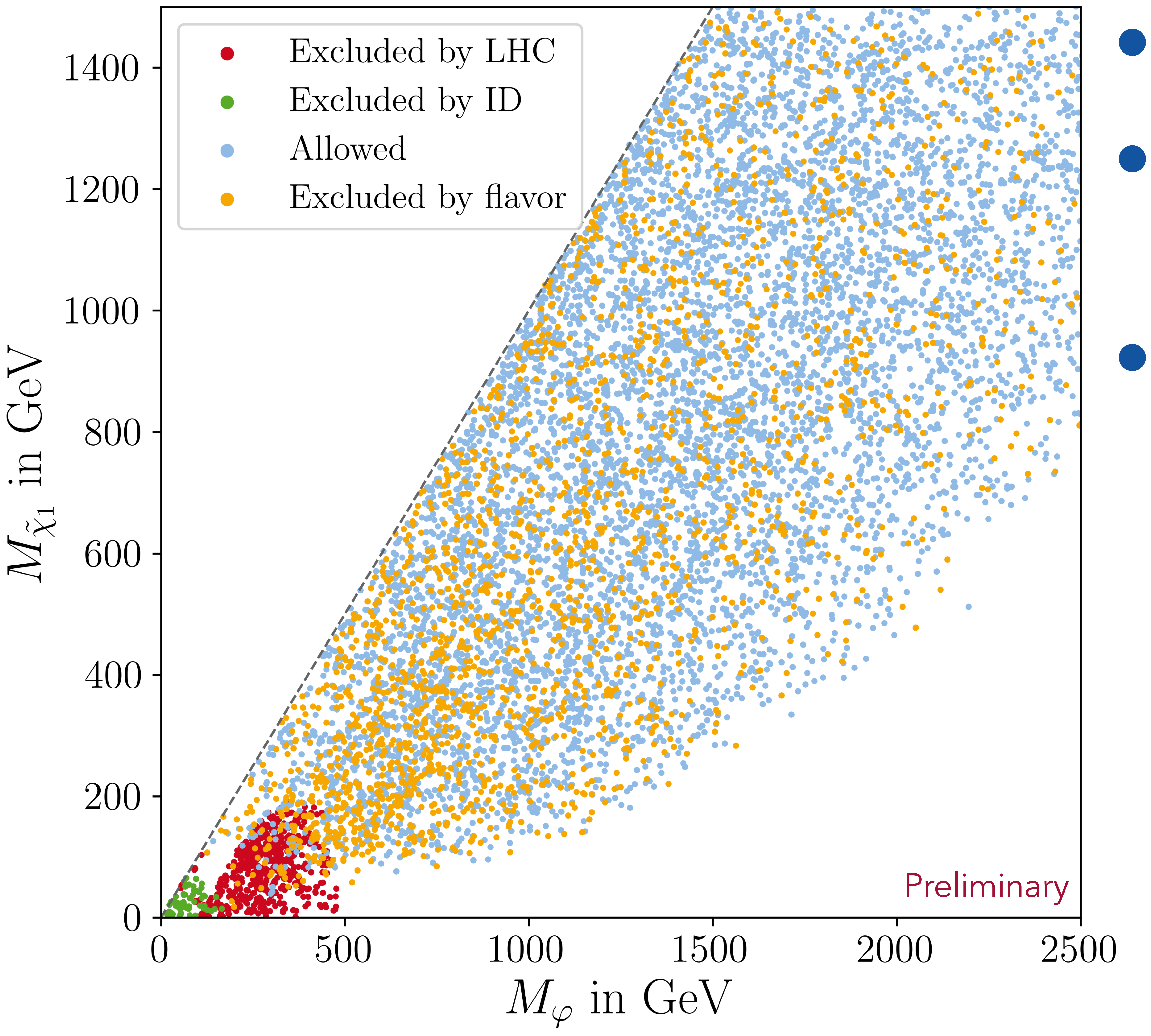

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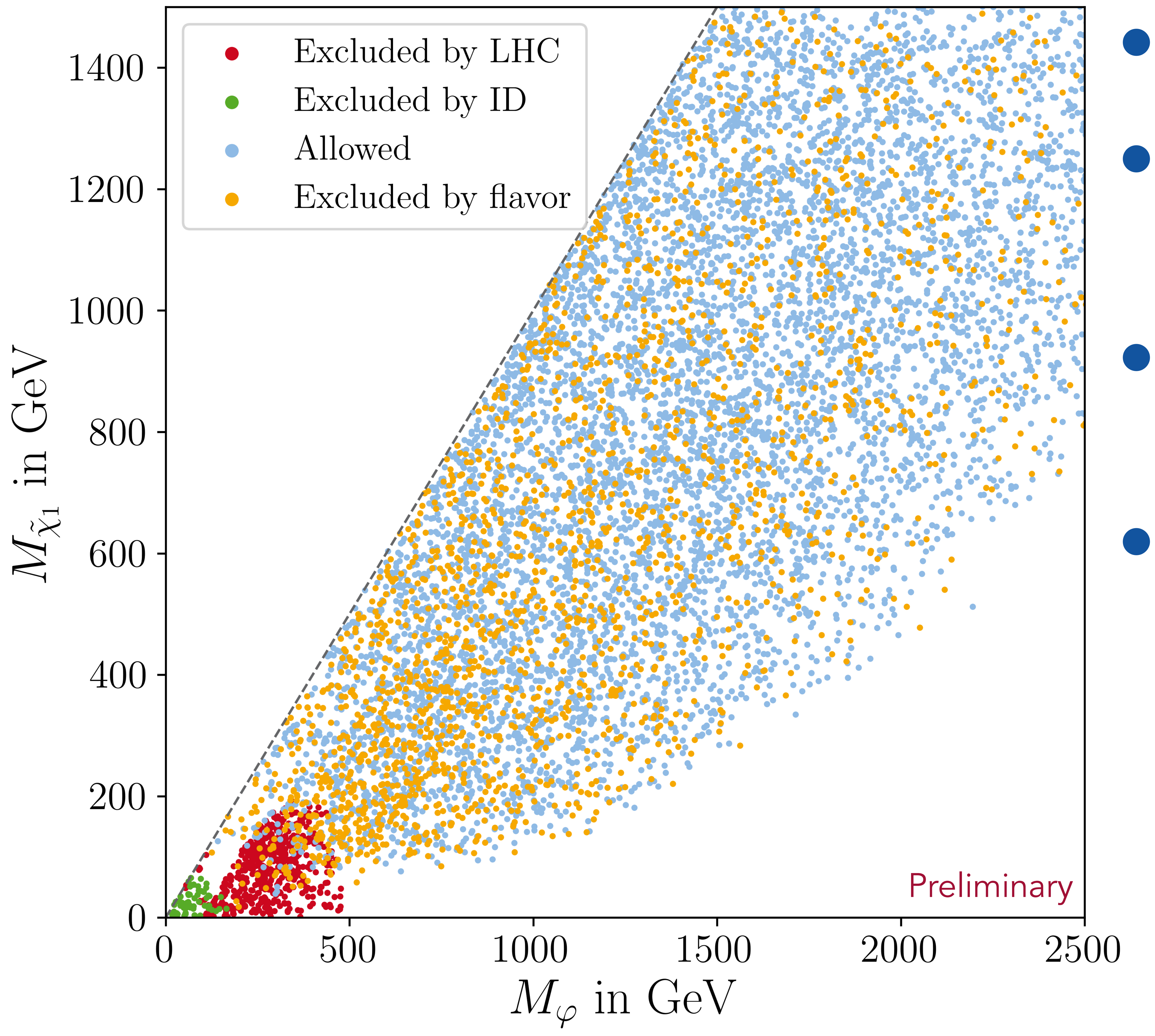

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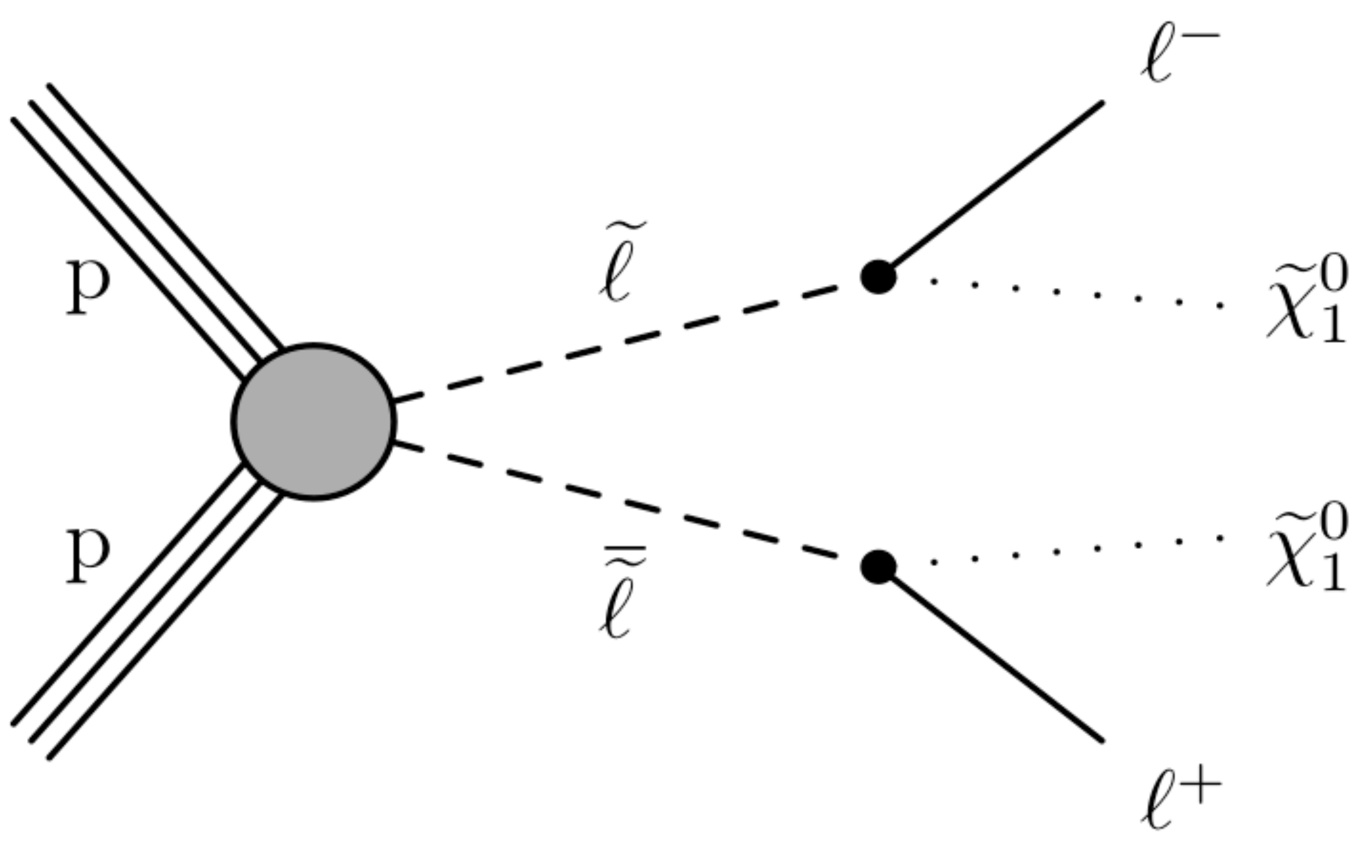
- Drell-Yan production of mediator pair decaying into leptons + $\not{E}_T$ is dominant LHC signal



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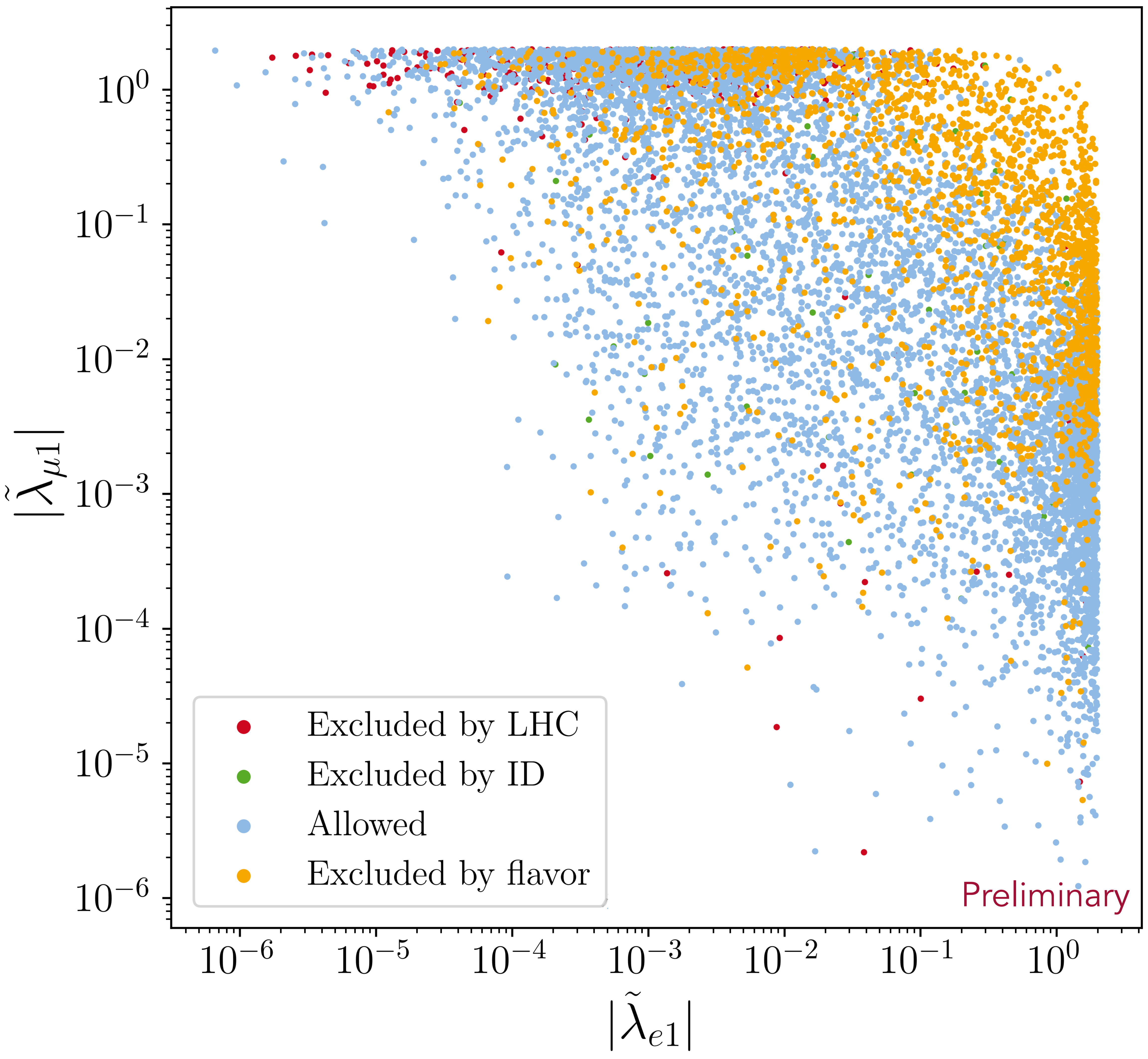

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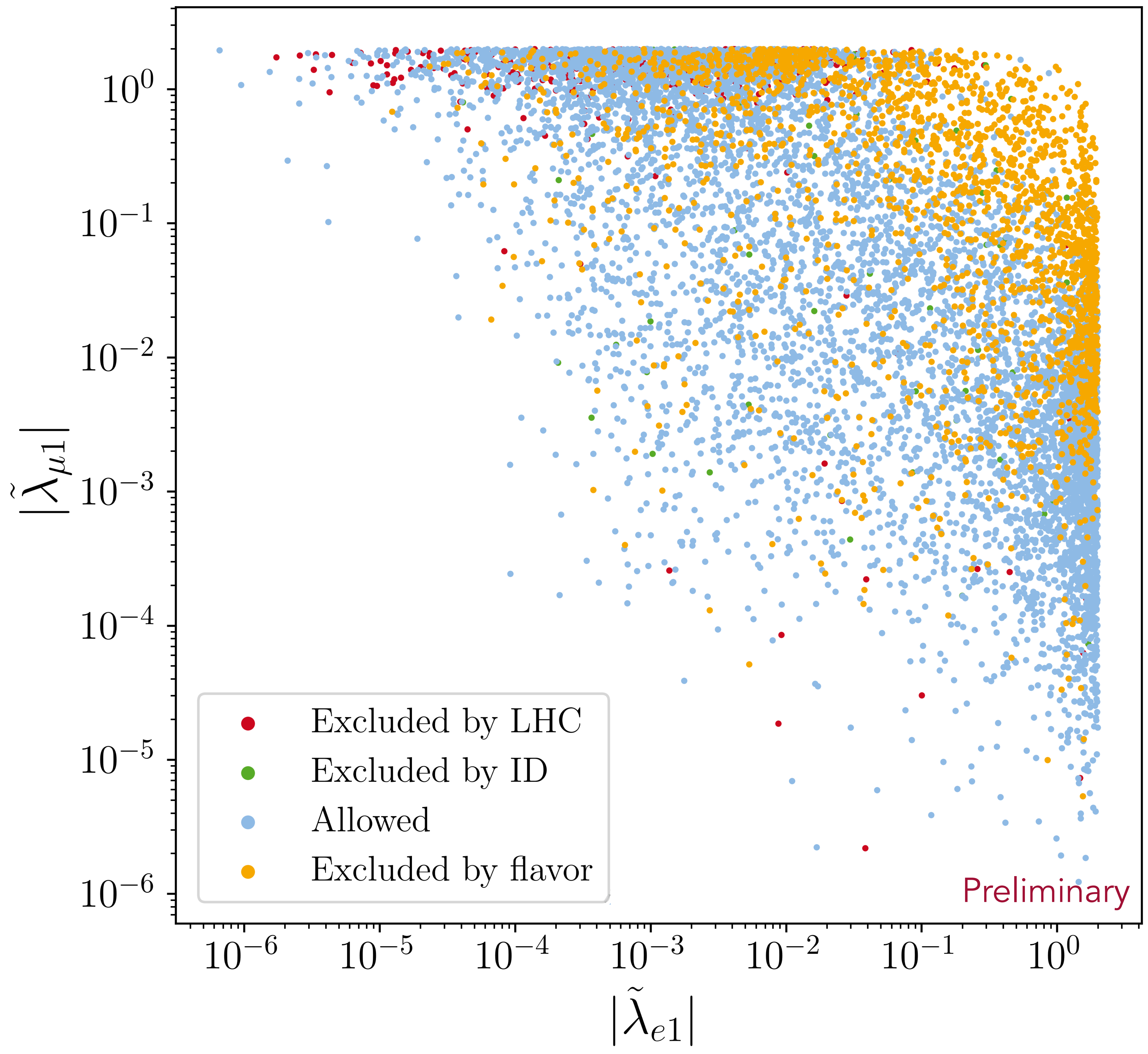
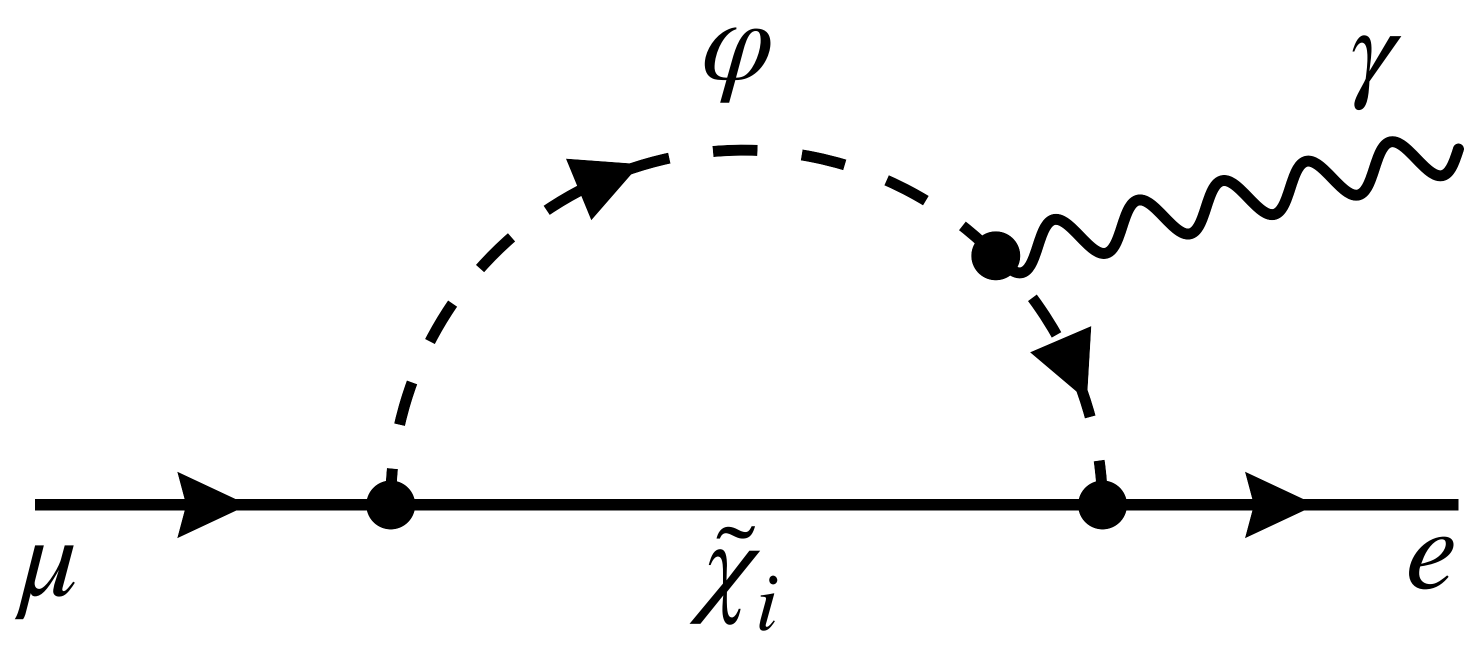


- Strong flavor constraints from lepton-flavor violating decays



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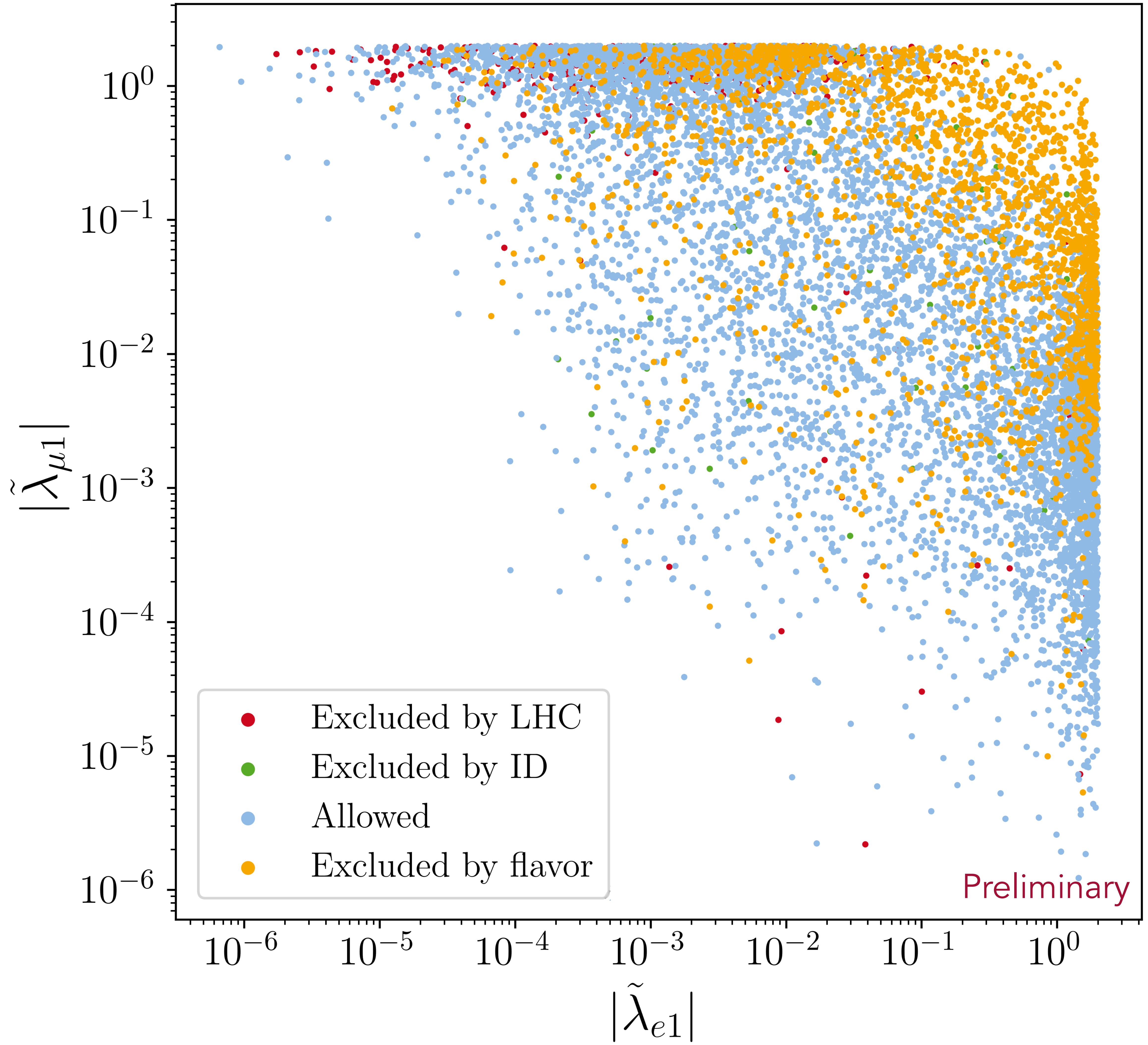

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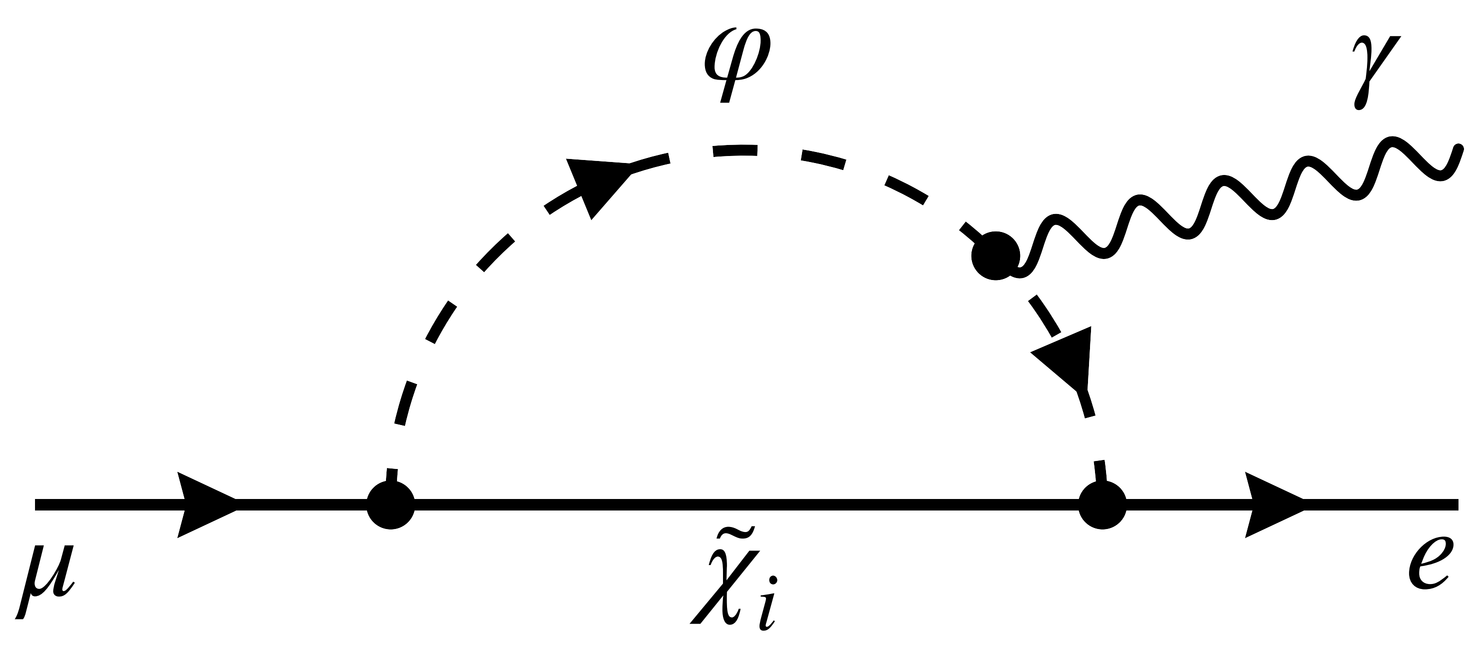
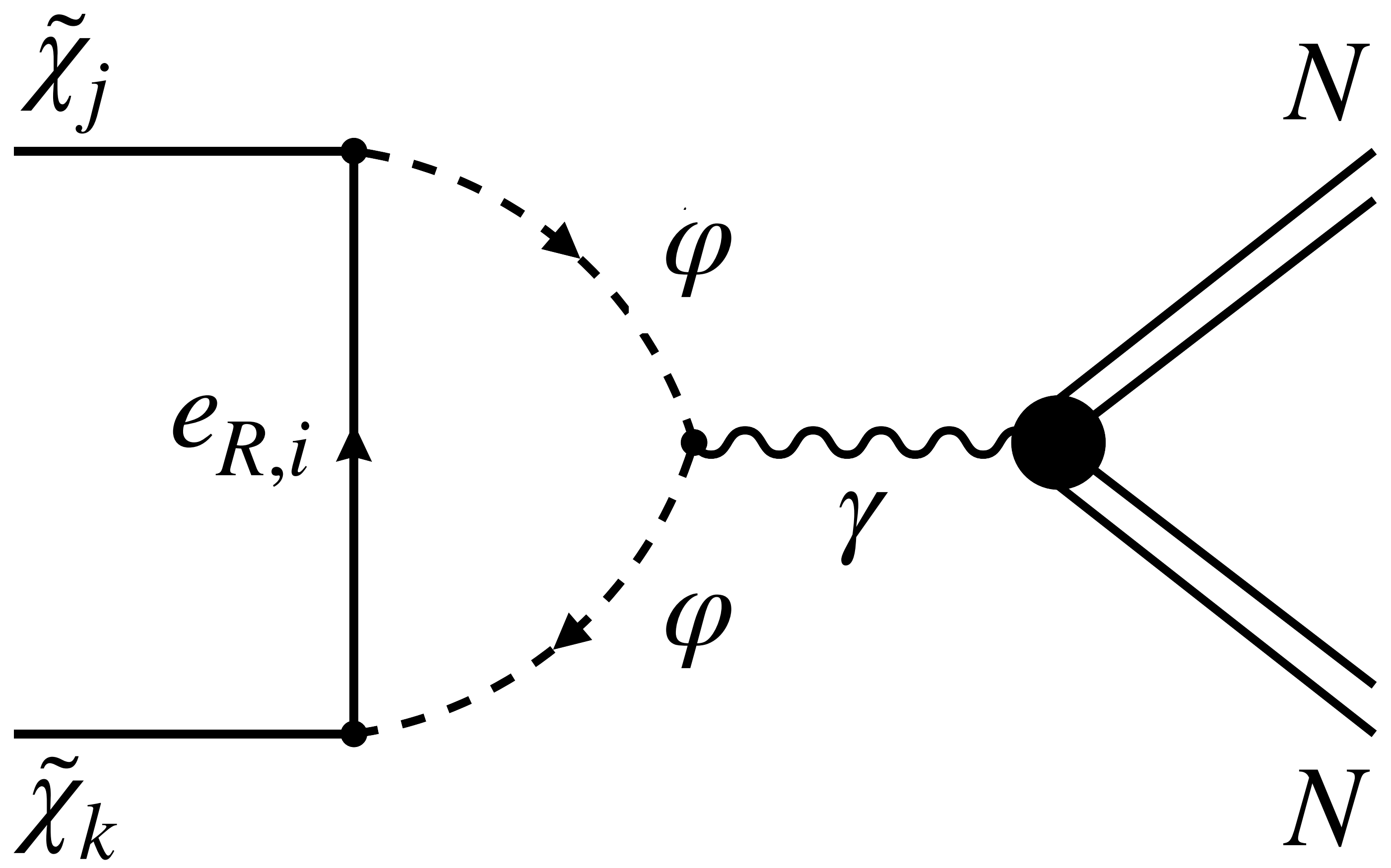


- DD constraints absent as only possible contribution is very suppressed



Conclusions

- Flavored DM models have rich phenomenology but many models have not been studied
- Developed framework to study different flavored DM models including constraints from relic density, direct & indirect detection, collider and flavor observable
- Showed constraints on Majorana DM coupling to e_R
- Strongest constraints from correct relic abundance and lepton-flavor violating decays, collider and ID constraints only relevant for small DM masses
- Outlook: Study other missing models

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Thank you!

Backup Slides

Majorana DM coupling to e_R

- Dark matter flavor triplet $\tilde{\chi}$, mediator φ
- New physics contribution with flavour and CP violating interaction:

$$\mathscr{L}_{\text{NP}} \supset \frac{1}{2}\bar{\tilde{\chi}}(i\not\partial - M_{\tilde{\chi}})\tilde{\chi} + (D_\mu\varphi)^\dagger(D^\mu\varphi) - m_\varphi^2\varphi^\dagger\varphi + (\lambda_{ij}\,\bar{e}_{R,i}\,\tilde{\chi}_j\,\varphi + \text{h.c.})$$
$$+\lambda_{\varphi\varphi}(\varphi^\dagger\varphi)^2 + \lambda_{\varphi H}(\varphi^\dagger\varphi)(H^\dagger H)$$

- Mass matrix cannot be generic → expand mass matrix in powers of λ:

$$M_{\tilde{\chi}} = m_{\tilde{\chi}}\left[\mathbf{1} + \frac{\eta}{2}(\lambda^\dagger\lambda + \lambda^T\lambda^*) + \mathcal{O}(\lambda^4)\right] \xrightarrow{\text{Diagonalize}} M_{\tilde{\chi}}^D = \text{diag}(M_{\tilde{\chi}_1}, M_{\tilde{\chi}_2}, M_{\tilde{\chi}_3})$$

Parameterization of λ

$$\lambda = U\,\mathrm{diag}(D_1, D_2, D_3)\,O\,d$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c^\theta_{23} & s^\theta_{23}e^{-i\delta_{23}} \\ 0 & -s^\theta_{23}e^{i\delta_{23}} & c^\theta_{23} \end{pmatrix} \begin{pmatrix} c^\theta_{13} & 0 & s^\theta_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s^\theta_{13}e^{i\delta_{13}} & 0 & c^\theta_{13} \end{pmatrix} \begin{pmatrix} c^\theta_{12} & s^\theta_{12}e^{-i\delta_{12}} & 0 \\ -s^\theta_{12}e^{i\delta_{12}} & c^\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$O = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c^\phi_{23} & s^\phi_{23} \\ 0 & -s^\phi_{23} & c^\phi_{23} \end{pmatrix} \begin{pmatrix} c^\phi_{13} & 0 & s^\phi_{13} \\ 0 & 1 & 0 \\ -s^\phi_{13} & 0 & c^\phi_{13} \end{pmatrix} \begin{pmatrix} c^\phi_{12} & s^\phi_{12} & 0 \\ -s^\phi_{12} & c^\phi_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$d = \mathrm{diag}(e^{i\gamma_1}, e^{i\gamma_2}, e^{i\gamma_3})$$

Sampling of Parameters

- D_i in $[0,2]$, linearly
- θ_{12} and ϕ_{12} in $[10^{-6},10^{-2}]$, logarithmically
- Remaining angles in $[10^{-4}, \pi/4]$, logarithmically.
- δ_{ij} and γ_i in $[0,2\pi)$, linearly
- $M_{\tilde{\chi}}$ in $[100,1500]$ GeV, linearly
- M_φ in $[M_{\tilde{\chi}_1}, M_{\tilde{\chi}_1} + 2000]$ GeV, linearly
- $\lambda_{\phi H}$ and η in $\pm[10^{-3},1]$, logarithmically

Indirect detection

Final state	Gamma rays	Antiprotons	Positrons	Neutrinos
e^+e^-	[50, 51]	–	[52]	–
$\mu^+\mu^-$	[53]	–	[52]	[53]
$\tau^+\tau^-$	[54, 55]	–	[52]	–
$q\bar{q}$ (light)	–	[56]	–	–
$c\bar{c}$	[50]	–	–	–
$b\bar{b}$	[57]	[56]	–	–
$t\bar{t}$	[50, 58]	–	–	–
W^+W^-	[53, 59]	[56]	–	–
ZZ	[50, 60]	–	–	–
hh	–	[56]	–	–
$\nu\bar{\nu}$ (any flavor)	–	–	–	[61, 62]

Treatment of limit for mixes final states AB:

$$\langle \sigma v \rangle_{AB} = \frac{1}{2}\left(\langle \sigma v \rangle_{AA} + \langle \sigma v \rangle_{BB}\right)$$

[50] S. Archambault, A. Archer, W. Benbow, R. Bird, E. Bourbeau, et al., *Dark matter constraints from a joint analysis of dwarf spheroidal galaxy observations with veritas,* *Physical Review D* **95** (Apr., 2017).

[51] A. Acharyya, C. B. Adams, P. Bangale, J. T. Bartkoske, P. Batista, et al., *An indirect search for dark matter with a combined analysis of dwarf spheroidal galaxies from veritas,* 2024.

[52] I. John and T. Linden, *Cosmic-ray positrons strongly constrain leptophilic dark matter,* *Journal of Cosmology and Astroparticle Physics* **2021** (Dec., 2021) 007.

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[54] A. Albert, B. Anderson, K. Bechtol, A. Drlica-Wagner, M. Meyer, et al., *Searching for dark matter annihilation in recently discovered milky way satellites with fermi-lat,* *The Astrophysical Journal* **834** (Jan., 2017) 110.

[55] M. collaboration, *Limits to dark matter annihilation cross-section from a combined analysis of magic and fermi-lat observations of dwarf satellite galaxies,* *Journal of Cosmology and Astroparticle Physics* **2016** (Feb., 2016) 039–039.

[56] F. Calore, M. Cirelli, L. Derome, Y. Genolini, D. Maurin, et al., *AMS-02 antiprotons and dark matter: Trimmed hints and robust bounds,* *SciPost Phys.* **12** (2022), no. 5 163, [2202.03076].

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[58] H. Abdallah, A. Abramowski, F. Aharonian, F. Ait Benkhali, A. Akhperjanian, et al., *Search for dark matter annihilations towards the inner galactic halo from 10 years of observations with h.e.s.s.,* *Physical Review Letters* **117** (Sept., 2016).

[59] M. Ackermann, A. Albert, B. Anderson, W. Atwood, L. Baldini, et al., *Searching for dark matter annihilation from milky way dwarf spheroidal galaxies with six years of fermi large area telescope data,* *Physical Review Letters* **115** (Nov., 2015).

[60] J. Aleksić, S. Ansoldi, L. Antonelli, P. Antoranz, A. Babic, et al., *Optimized dark matter searches in deep observations of segue 1 with magic,* *Journal of Cosmology and Astroparticle Physics* **2014** (Feb., 2014) 008–008.

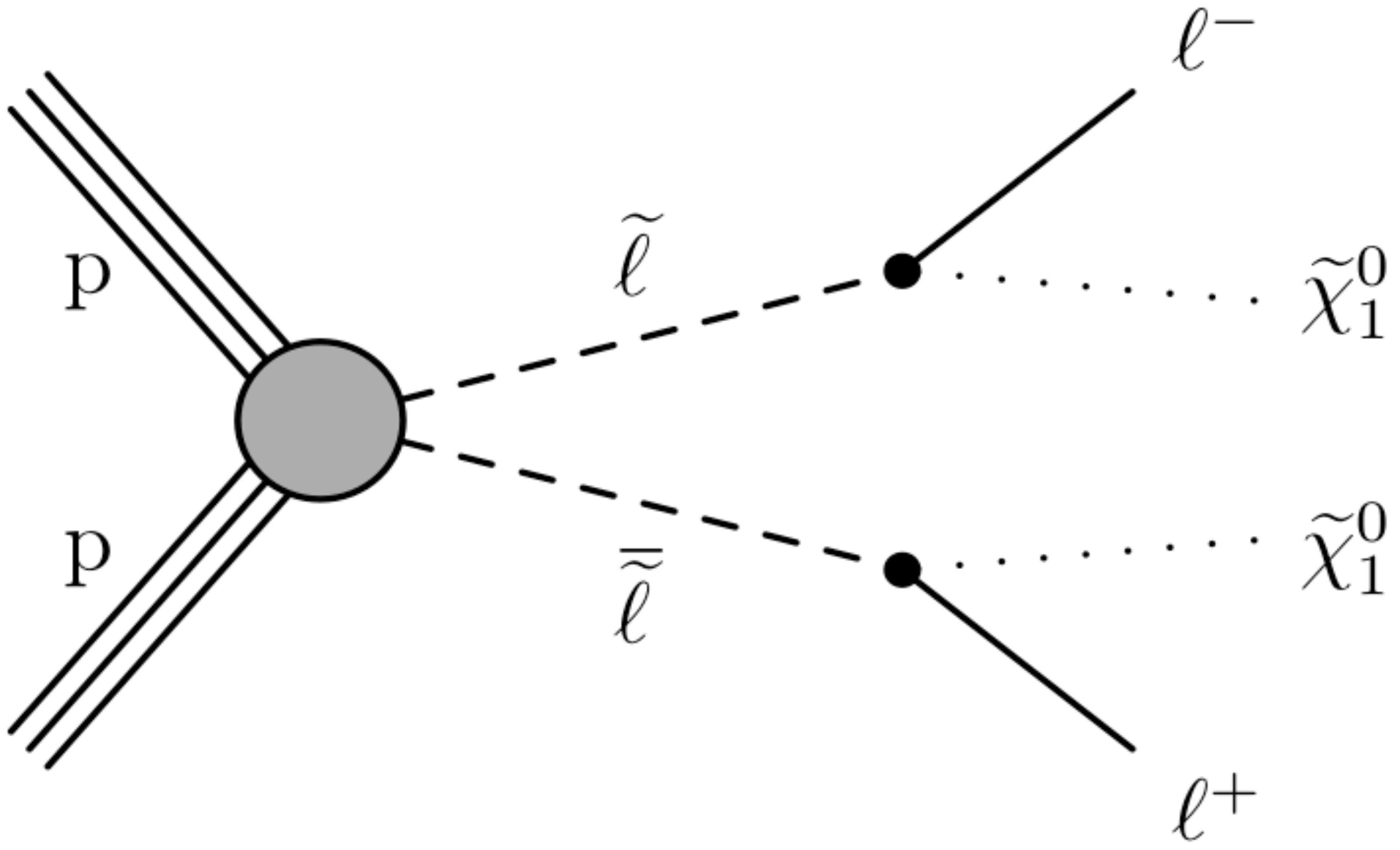
[61] T. I. Collaboration, R. Abbasi, M. Ackermann, J. Adams, S. K. Agarwalla, et al., *Search for neutrino lines from dark matter annihilation and decay with icecube,* 2023.

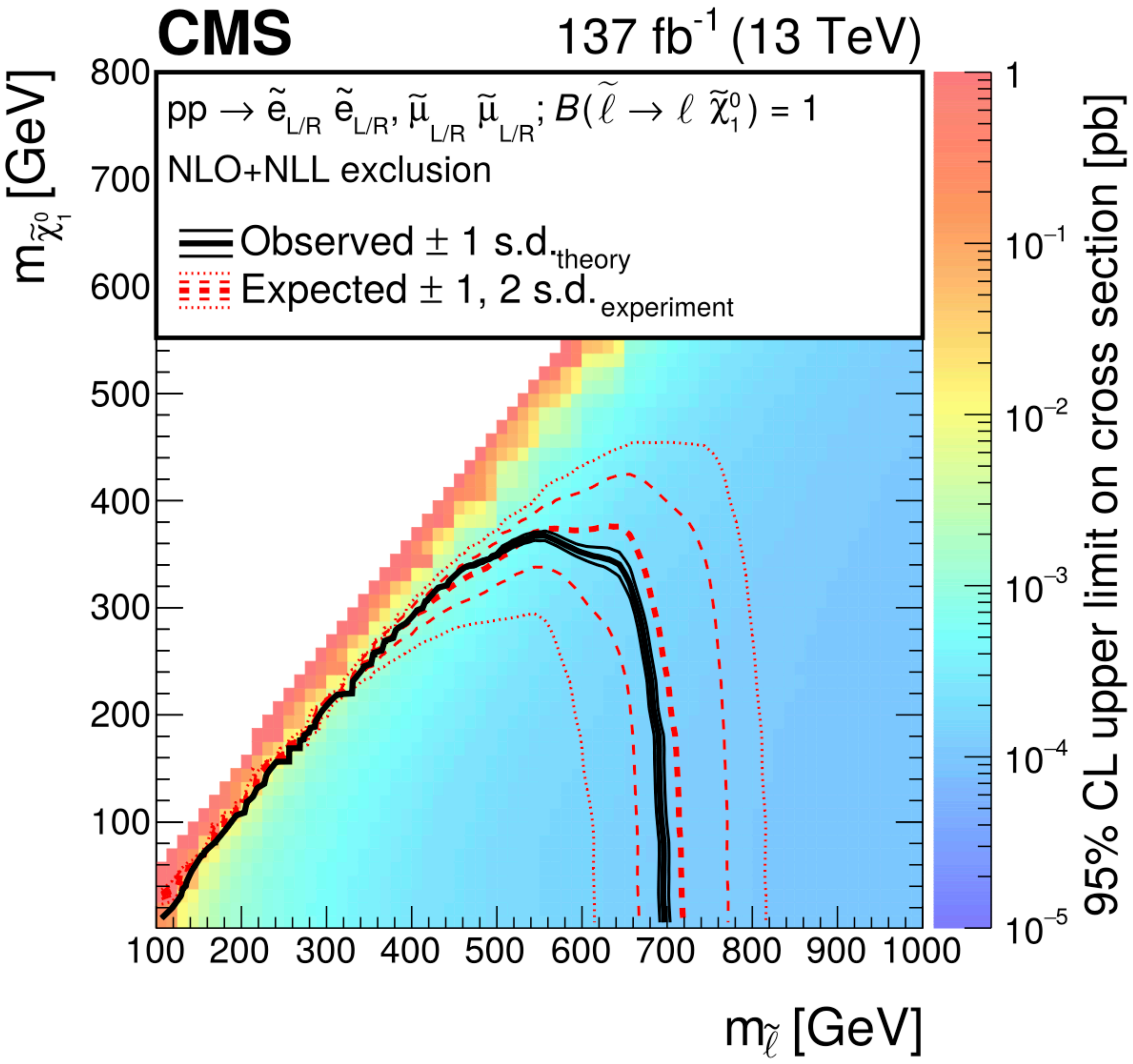
[62] A. Albert, M. André, M. Anghinolfi, G. Anton, M. Ardid, et al., *Search for dark matter towards the galactic centre with 11 years of antares data,* *Physics Letters B* **805** (June, 2020) 135439.

Collider constraints

[Sirunyan et al. 2021]

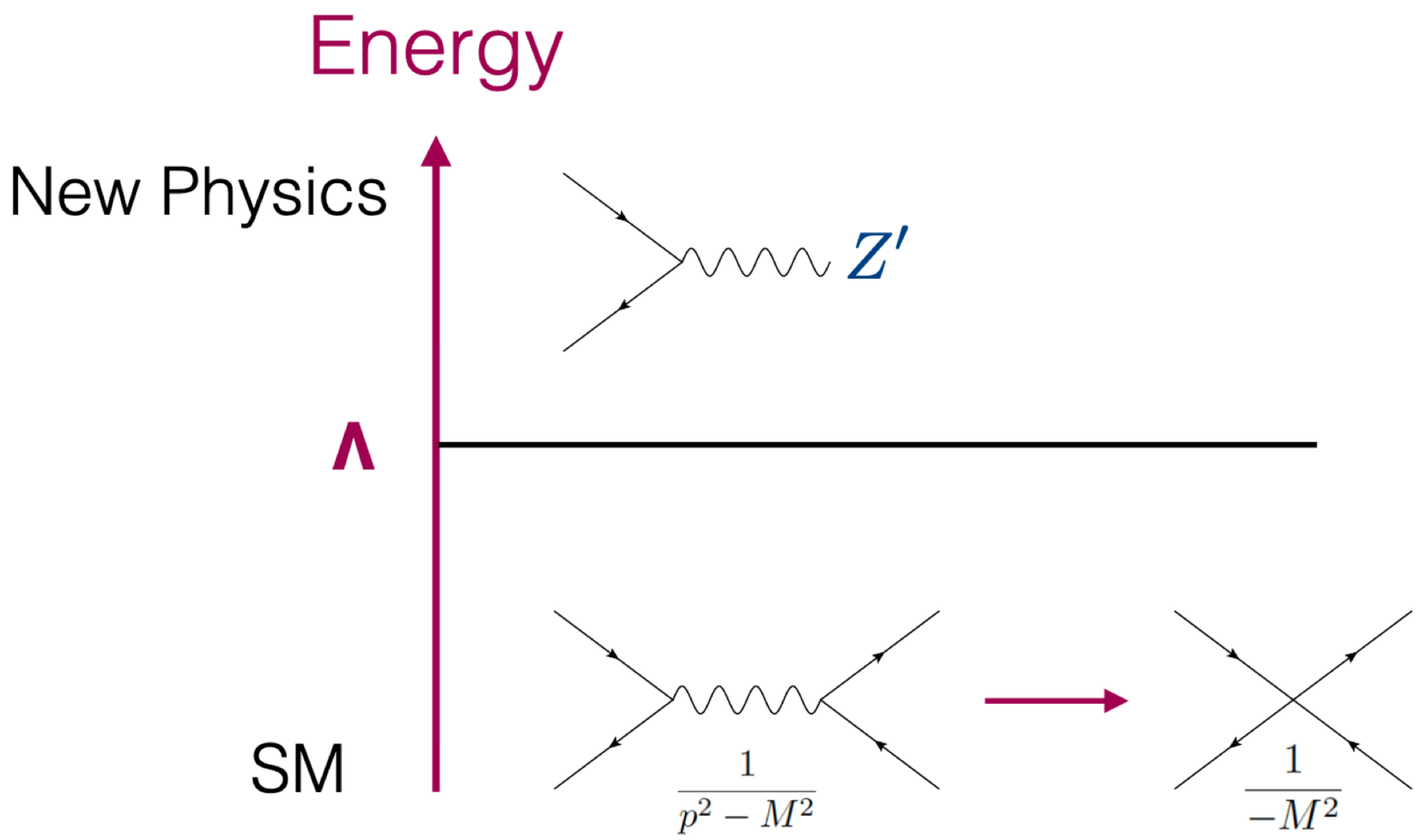
- Most sensitive CMS search





SMEFT

- SM Effective Field Theory $\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda}\mathcal{O}_i^{d=5} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i^{d=6}$
- Need to compute Wilson coefficients C_i



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Example: Majorana DM coupling to e_R