Karlsruher Institut für Technologie

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

Reinterpreting LHC Dark QCD results

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[3] The ATLAS Experiment (CERN), [4] Karlsruhe Institute of Technology (KIT), [5] University of Manchester

(Re)interpretation of the LHC results for new physics at CERN, February 25th 2025

Brief Introduction to Dark QCD

A hidden sector of SU(N_{cd}) structure

Dark bound states (mesons)

Pseudo-scalar : Call them π_d
Vector : Call them ρ_d

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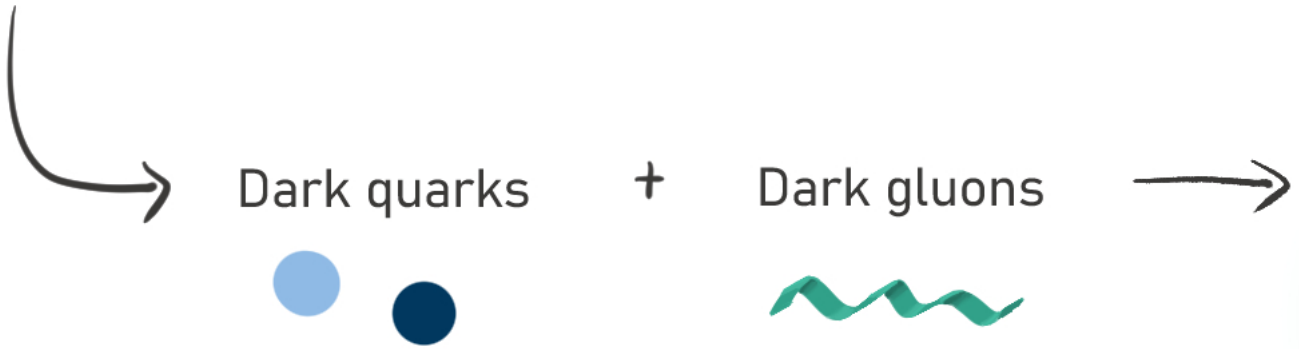


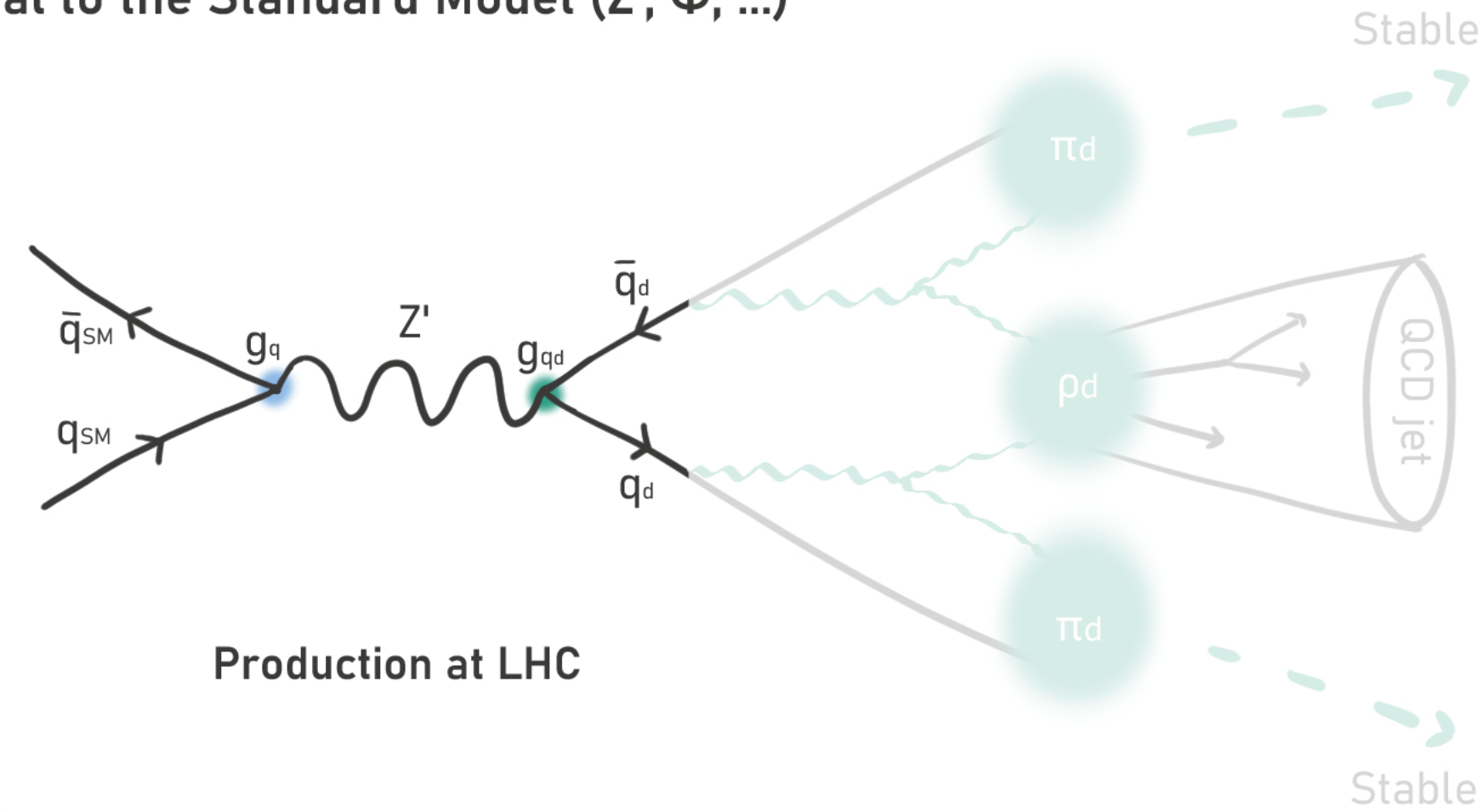
Dark bound states (mesons)

Dark matter? ← Pseudo-scalar : Call them π_d

Vector : Call them ρ_d

Brief Introduction to Dark QCD

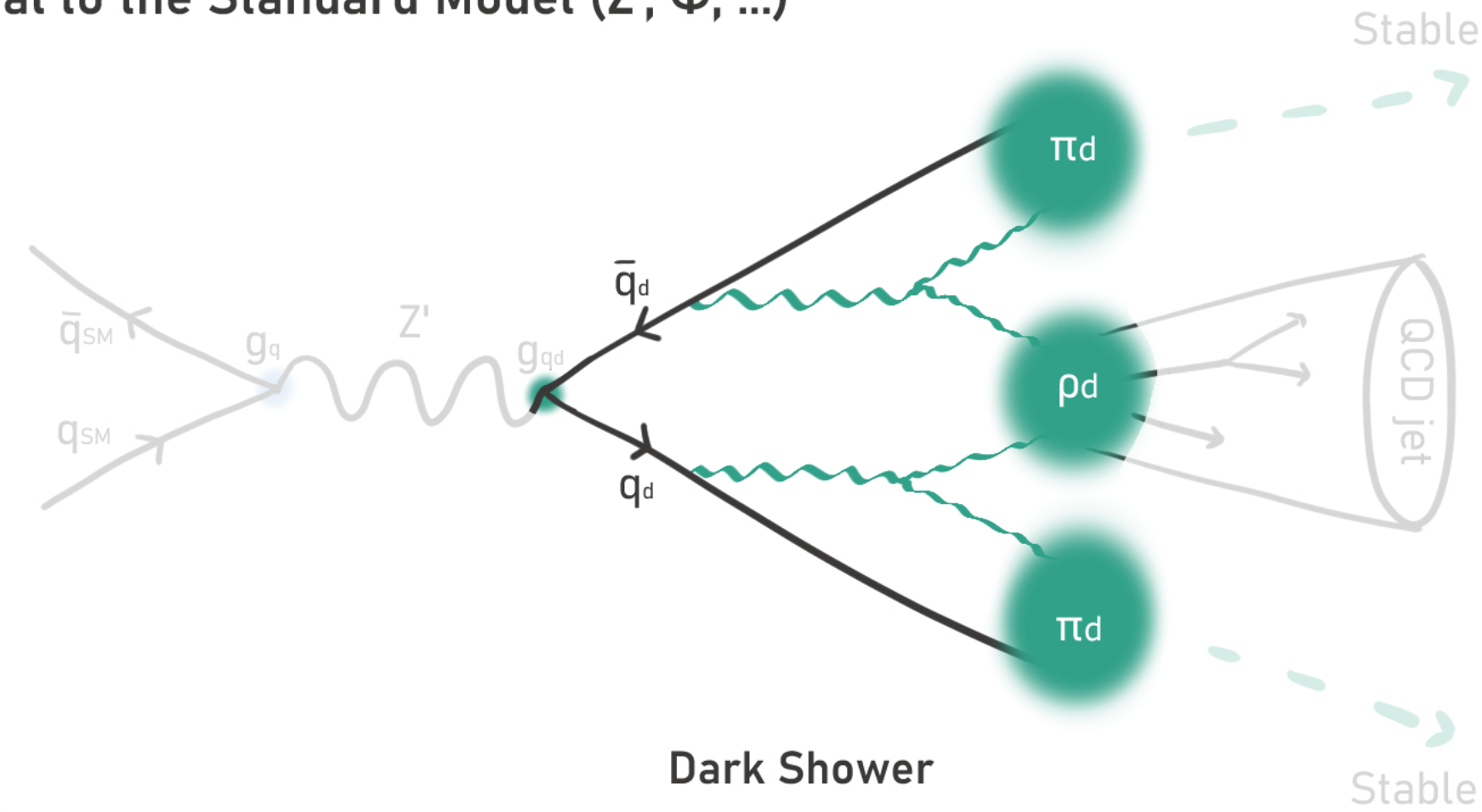
Portal to the Standard Model (Z', Φ, ...)



Production at LHC

Brief Introduction to Dark QCD

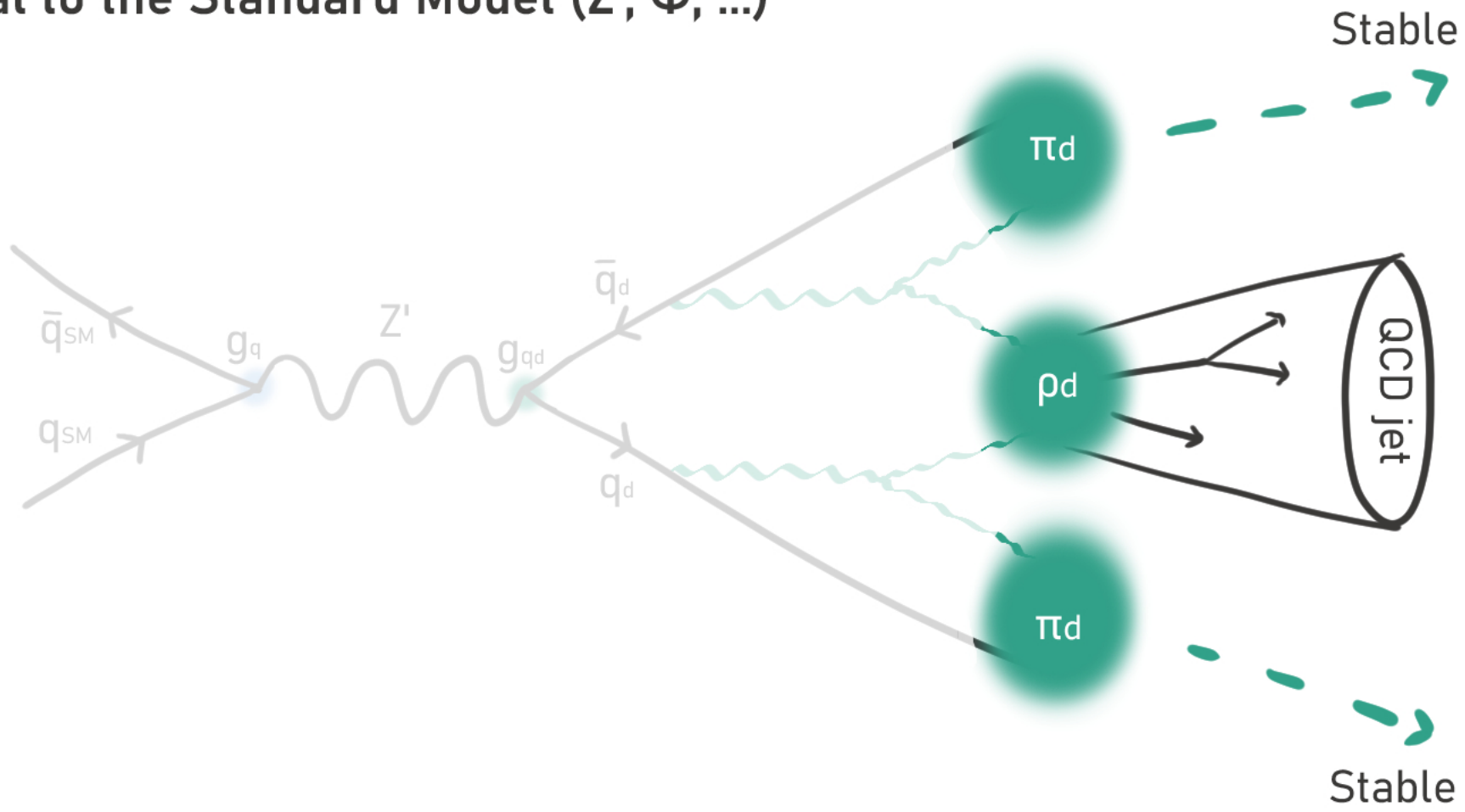
Portal to the Standard Model (Z', Φ, ...)



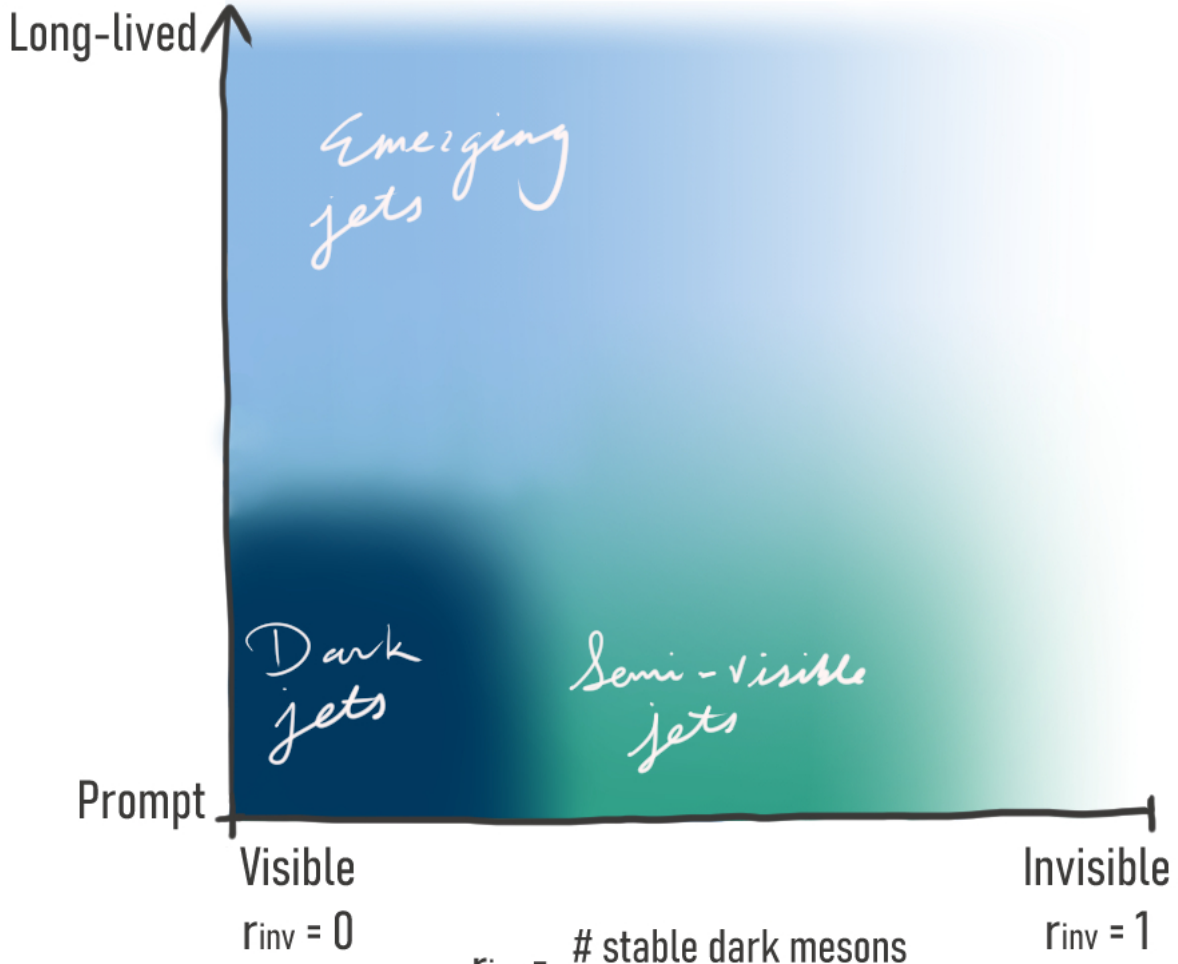
Dark Shower

Brief Introduction to Dark QCD

Portal to the Standard Model (Z', Φ, ...)



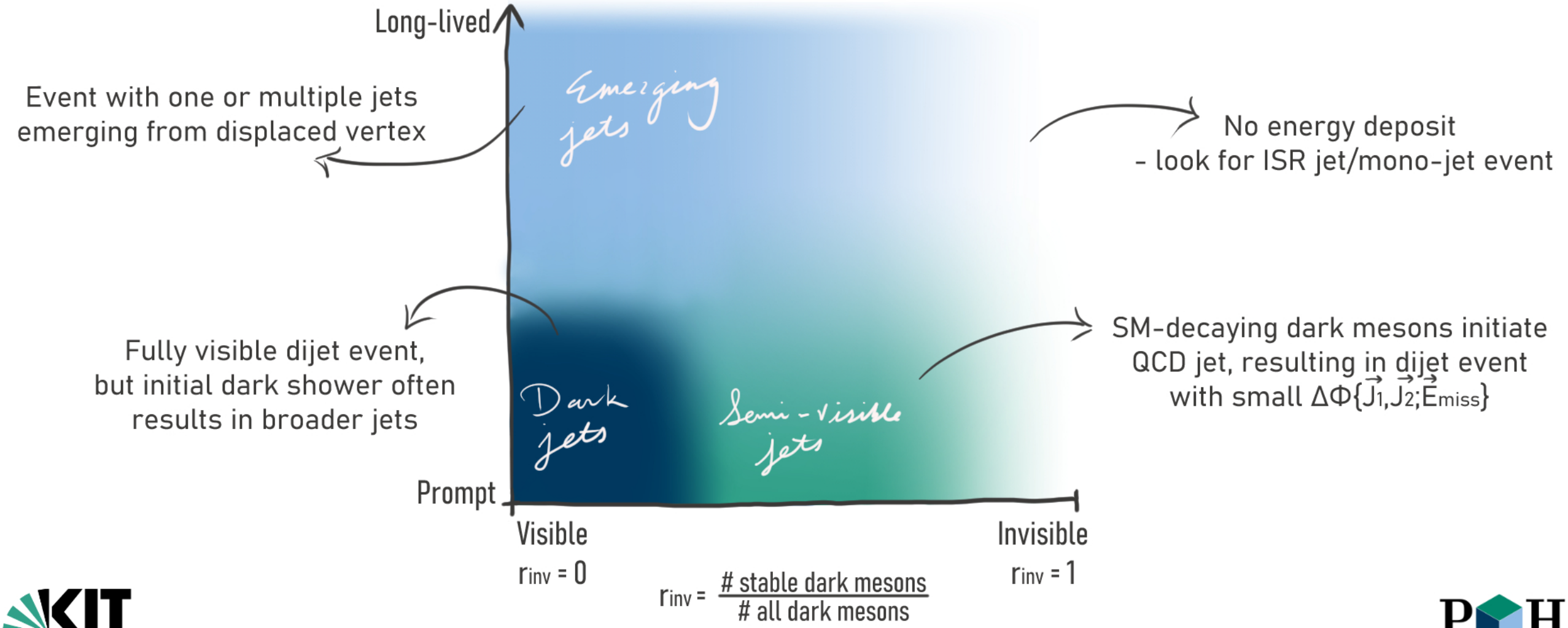
Dark Shower Signatures



$$r_{inv} = \frac{\text{\# stable dark mesons}}{\text{\# all dark mesons}}$$

Thanks to Caterina Doglioni for inspiration for figure

Dark Shower Signatures



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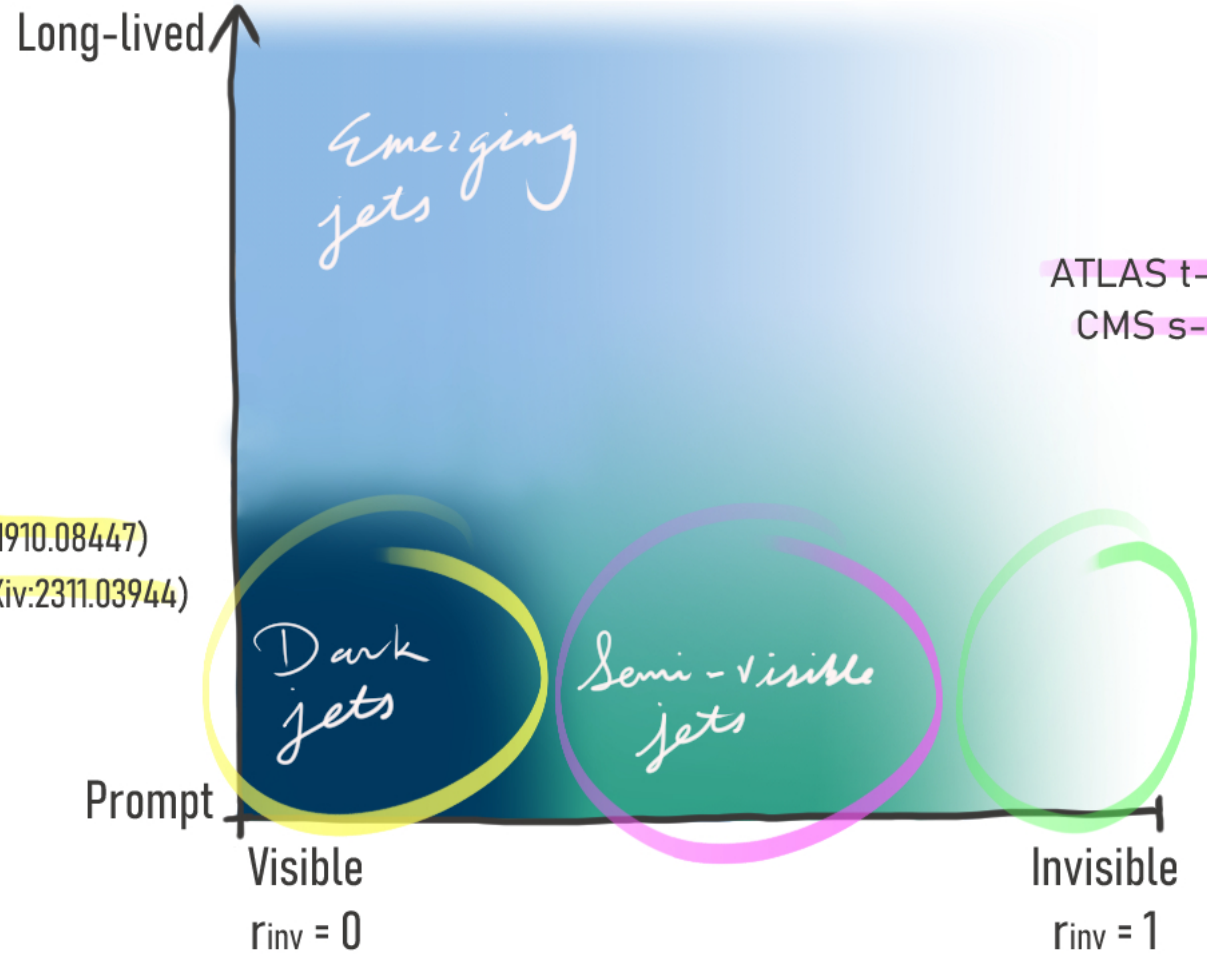


ATLAS t-channel SVJ analysis (arXiv:2305.18037)
CMS s-channel SVJ analysis (arXiv:2112.11125)

ATLAS dijet analysis (arXiv:1910.08447)
ATLAS dark jets analysis (arXiv:2311.03944)

CMS mono-jet analysis (arXiv:2107.12021)

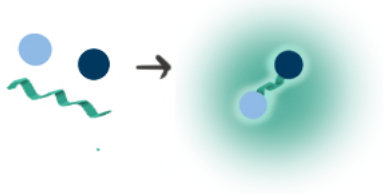
Dark Shower Signatures

Many parameters can be of importance to the signature

See more here: Snowmass Whitepaper 2021 (arXiv:2203.09503)

N_{cd}
Number of dark colours

Λ_d
Dark confinement scale

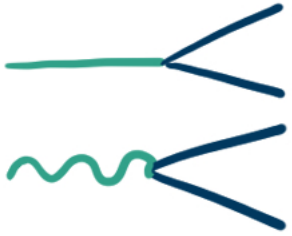


g_q, g_{qd}
Couplings

N_{fd}
Number of dark flavours

$m_{\pi d}$, $m_{\rho d}$, m_q, m_{med}
Mass spectrum

Decay modes & branching fractions



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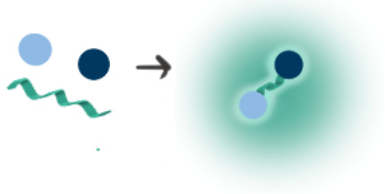

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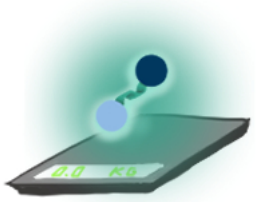

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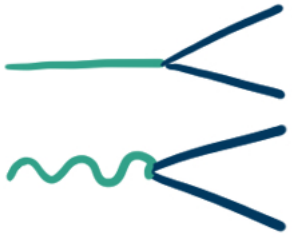

r_{inv}

- is not a fundamental parameter of theory
- varying it may require, for consistency, to vary some fundemental parameters

Dark Shower Signatures

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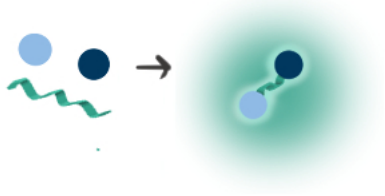

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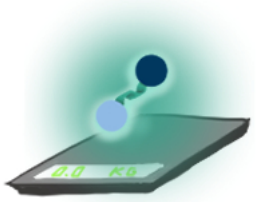

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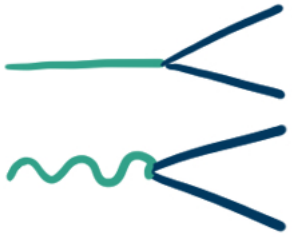

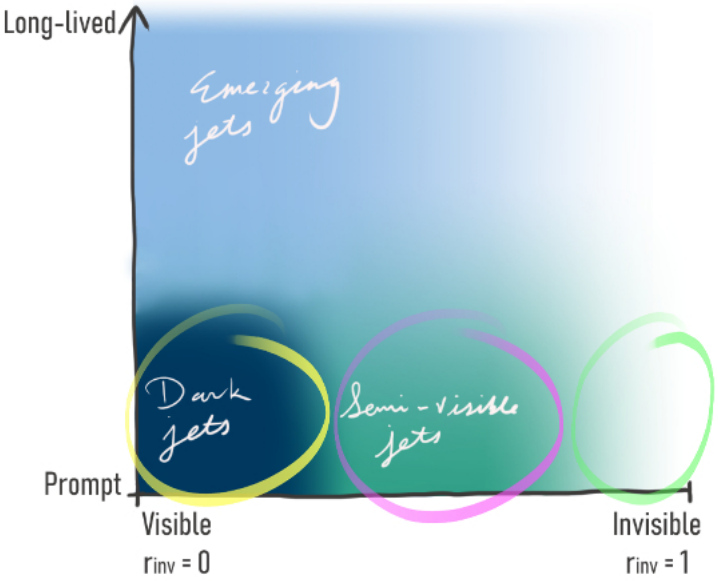

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Reinterpretation of LHC Results with MadAnalysis5

MadAnalysis5 as a tool for reinterpretation

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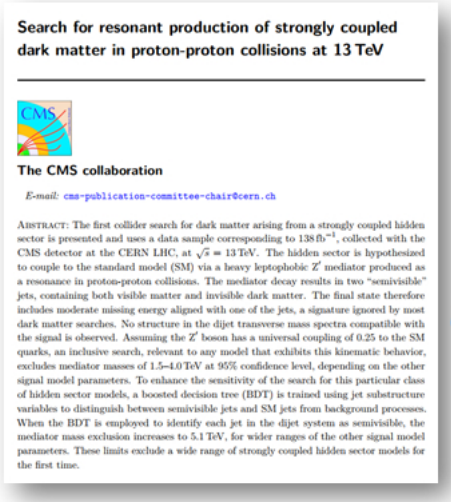
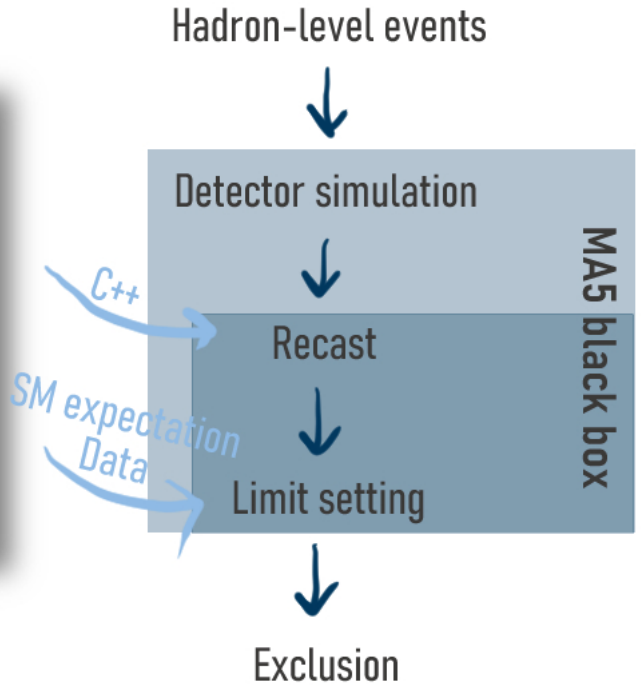


Search for resonant production of strongly coupled dark matter in proton-proton collisions at 13 TeV

The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

Abstract: The first collider search for dark matter arising from a strongly coupled hidden sector is presented and uses a data sample corresponding to 138 fb^{-1}, collected with the CMS detector at the CERN LHC, at $\sqrt{s} = 13$ TeV. The hidden sector is hypothesized to couple to the standard model (SM) via a heavy leptophobic Z′ mediator produced as a resonance in proton-proton collisions. The mediator decay results in two "semivisible" jets, containing both visible matter and invisible dark matter. The final state therefore includes moderate missing energy aligned with one of the jets, a signature ignored by most dark matter searches. No structure in the dijet transverse mass spectra compatible with the signal is observed. Assuming the Z′ boson has a universal coupling of 0.25 to the SM quarks, an inclusive search, relevant to any model that exhibits this kinematic behavior, excludes mediator masses of 1.5–4.0 TeV at 95% confidence level, depending on the other signal model parameters. To enhance the sensitivity of the search for this particular class of hidden sector models, a boosted decision tree (BDT) is trained using jet substructure variables to distinguish between semivisible jets and SM jets from background processes. When the BDT is employed to identify each jet in the dijet system as semivisible, the mediator mass exclusion increases to 5.1 TeV, for wider ranges of the other signal model parameters. These limits exclude a wide range of strongly coupled hidden sector models for the first time.



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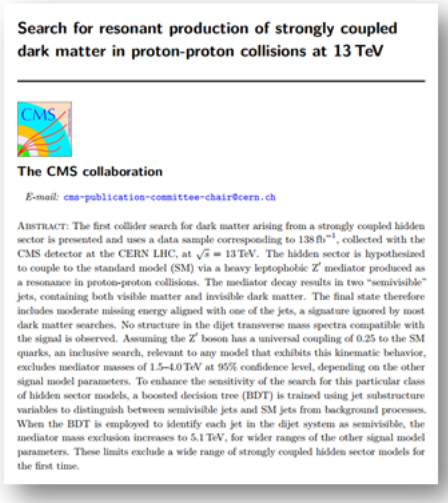

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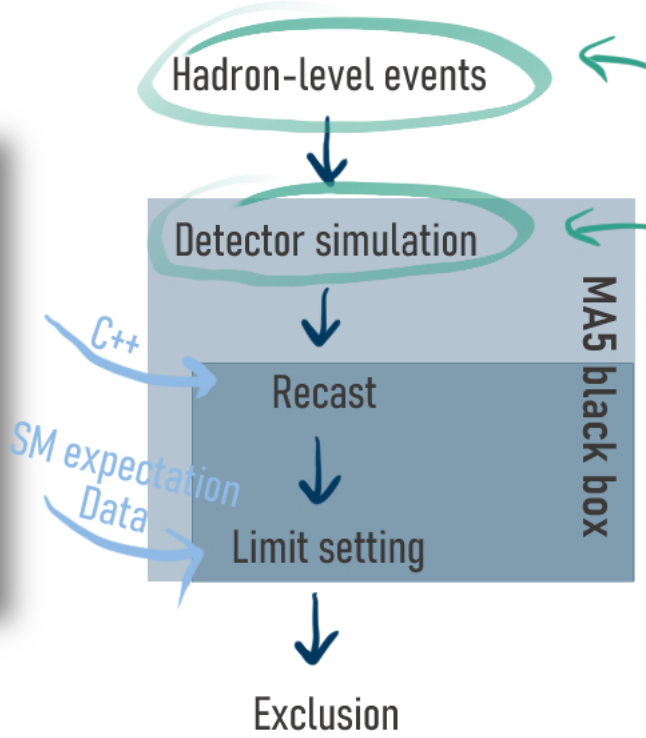

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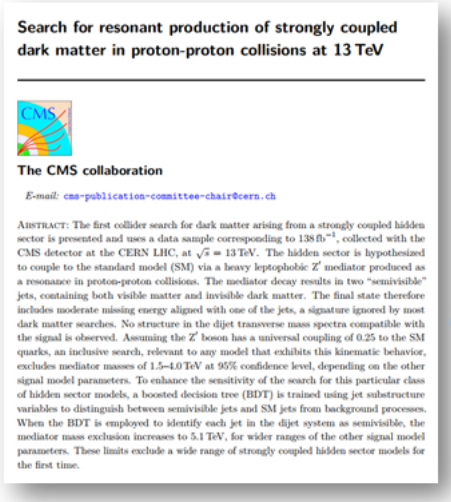

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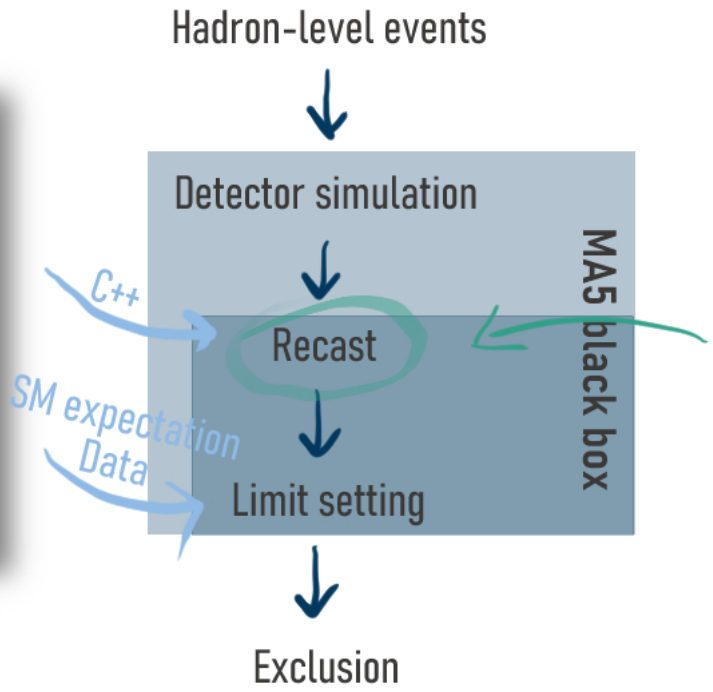

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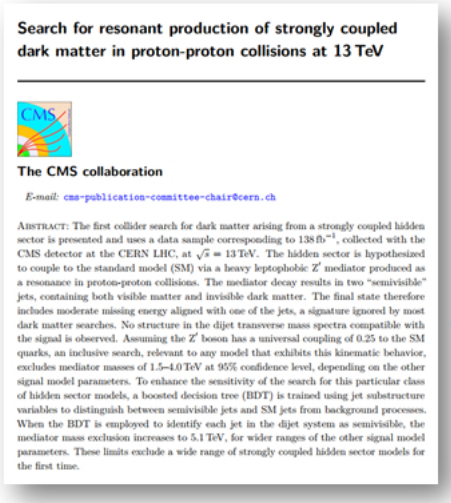

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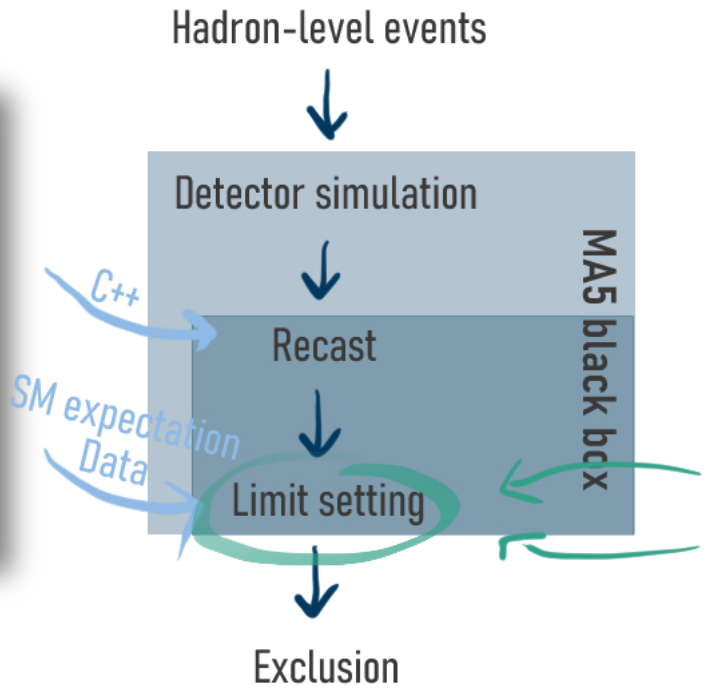

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- Selection cuts and cutflow tables
- Data and simulation results
- Statistical analysis approach

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Reinterpretation of LHC Results with MadAnalysis5

CMS s-channel SVJ analysis (JHEP 06 (2022) 156, CMS-EXO-19-020)

Heavy leptophobic vector mediator Z' and $m_{\pi d}=m_{\rho d}=m_{dark}$, $m_{qd}=m_{dark}/2$

Final state with ≥2 jets (R=0.8) and $\Delta\Phi<0.8$

Limits on $\sigma_{Z'}\times BR[Z'\rightarrow q_d\bar{q}_d]$ as function of $m_{Z'}$ and exclusion contours in $\{m_{Z'}, m_{dark}\}$ and in $\{m_{Z'}, r_{inv}\}$ planes

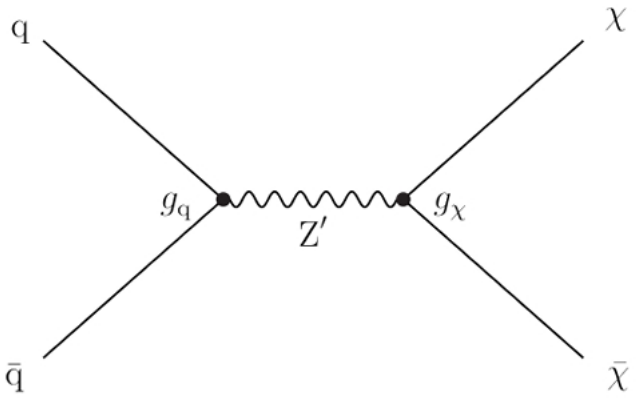

Figure from arXiv:2112.11125

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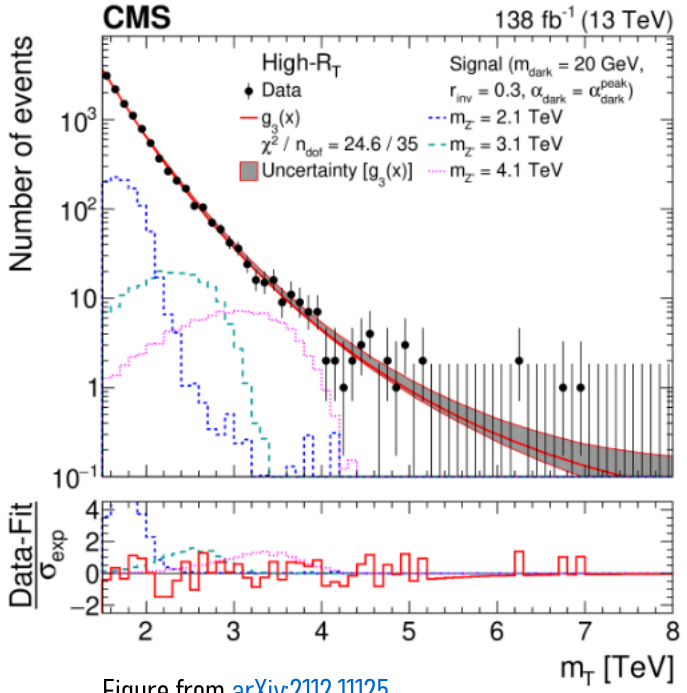
CMS s-channel SVJ analysis (JHEP 06 (2022) 156, CMS-EXO-19-020)

Pythia card provided on HEPData.net

Delphes card provided upon request
(many thanks to Kevin Pedro and Cesare Cazzinga)

No background estimate - instead fitting function for smooth background



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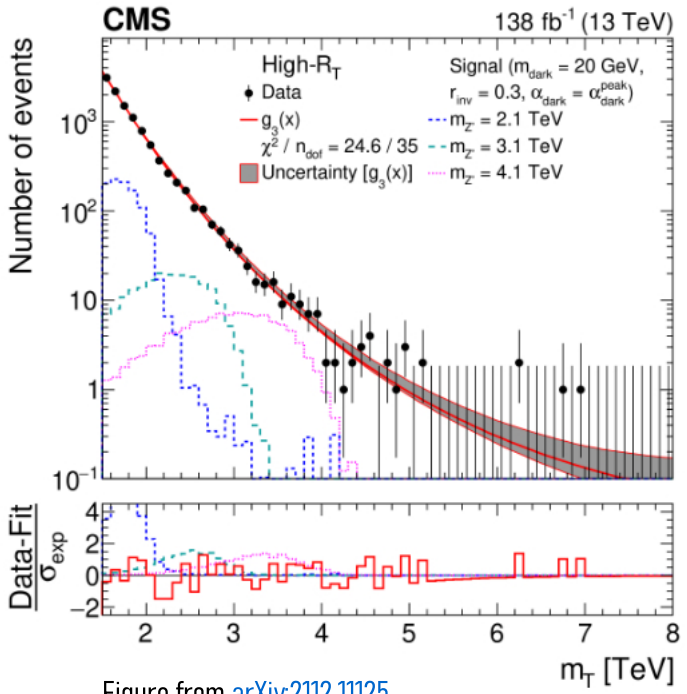
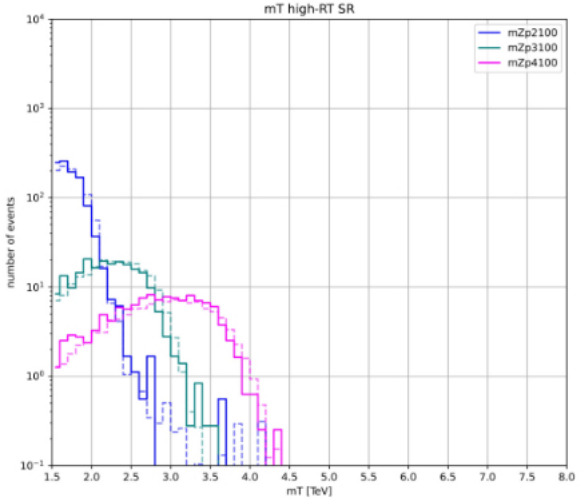


Figure from arXiv:2112.11125

Reinterpretation efforts:

	$m_{Z'}$ = 3.1 TeV	
Selection cut	MA5	CMS
$N_{jets} > 1$	99.9%	------
$p_T(J_{1,2}) > 200$ GeV & $\eta(J_{1,2}) < 2.4$	84.17%	83.5%
$R_T = MET/m_T > 0.15$	32.4%	33.1%
$\Delta\eta(J_1,J_2) < 2.4$	25.5%	26.5%
$m_T > 1.5$ TeV	20.5%	21.7%
$N_\mu = 0$, $N_e = 0$, Veto/filter	-------	19.8%
$\Delta\Phi_{min} < 0.8$	18.3%	17.0%



Solid lines: MA5 analysis
Dashed lines: Original CMS analysis

Statistical tool is being implemented

Analysis will be available in database soon

Reinterpretation of LHC Results with MadAnalysis5

ATLAS t-channel SVJ analysis (Phys. Lett. B 848 (2024) 138324, ATLAS-EXOT-2022-37)

Scalar mediator Φ, non-resonant production

Final state with ≥2 jets (R=0.4), ΔΦ<2 and E_{miss}>250 GeV

Results are exclusion contours in {m_Φ, r_{inv}} plane

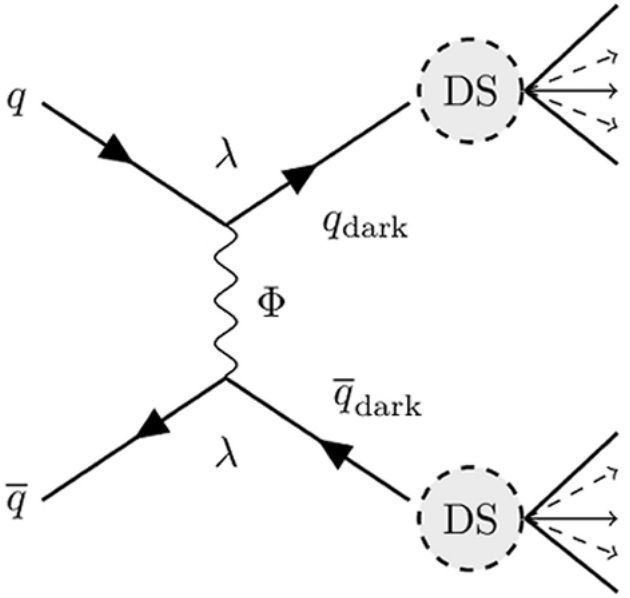


Figure from arXiv:2305.18037

Analysis implemented in MA5 (by T. Wojtkowski & S. Sinha)

Validated, will be available in MA5 Dataverse soon

$m_\Phi = 1$ TeV, $R_{inv} = 0.6$	ATLAS	MA5	Relative difference [%]	ATLAS cut efficiency [%]	MA5 cut efficiency [%]
Pre-selection	844520.2	802004.396	5.03		
$\Delta\phi < 2.0$	816341.4	773773.493	5.21	96.66	96.48
$p_{T,\ leading\ jet} > 250$ GeV	791042.5	747516.248	5.50	96.90	96.61
$N_{b-jet} < 2$	707151.0	747516.248	5.71	89.39	100
τ jet veto	701537.9	724219.427	3.23	99.21	96.88
$E_T^{miss} > 600$ GeV	101378.1	108504.199	7.03	14.45	14.98
$H_T > 600$ GeV	101235.2	108504.199	7.18	99.86	100

Reinterpretation of LHC Results with MadAnalysis5

ATLAS dark jets analysis (JHEP 02 (2024) 128, ATLAS-HDBS-2018-45)

Vector mediator Z', different π_d decay modes (see table)

Final state with ≥2 jets (R=1.0)

Results are limits on $\sigma_{Z'} \times BR[Z' \to q_d \bar{q}_d]$ as function of $m_{Z'}$ and Bumphunter test in m_{jj} between 1.3-5.0 TeV

Model	n_f	Λ_d (GeV)	$\tilde{m}_{q'}$ (GeV)	m_{π_d} (GeV)	m_{ρ_d} (GeV)	π_d decay mode
A	2	15	20	10	50	$\pi_d \to c\bar{c}$
B	6	2	2	2	4.67	$\pi_d \to s\bar{s}$
C	2	15	20	10	50	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 4.0$ GeV
D	6	2	2	2	4.67	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 0.7$ GeV

Table from arXiv:2311.03944

Analysis implemented in MA5 (by T. Wojtkowski)

Available in MA5 Dataverse @ https://doi.org/10.14428/DVN/AFYF5Y

Model C, $m_{Z'} = 2.5$ TeV	**ATLAS**	**MadAnalysis**
Trigger, $m_{jj} > 1.3$ TeV	65.8	66.8
$m_{j1,2} > 50$ GeV, $p_{T,j1} > 500$ GeV, $p_{T,j2} > 400$ GeV	81.3	79.8
$\lvert\eta_{j1,2}\rvert < 2$	100.0	98.5
$m_{j1,2} < 600$ GeV, $p_{T,j1,2} < 3000$ GeV	99.9	99.9
$n^{\epsilon}_{track,\ j1,2} > 0$	11.6	11.6
Total	6.2	6.1

Reinterpretation of LHC Results with MadAnalysis5

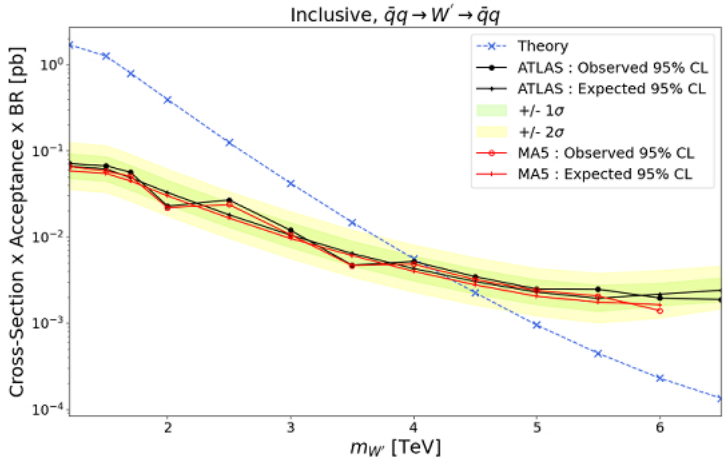
ATLAS dijet resonance analysis (JHEP 03 (2020) 145, ATLAS-EXOT-2019-03)

Can be sensitive to vector mediator Z'

Looking for final state with ≥2 energetic jets (R=0.4)

Results are limits on σ×A×BR as function of mass of particle

Analysis implemented in MA5 (by T. Wojtkowski)
Available in MA5 Dataverse @ https://doi.org/10.14428/DVN/KHJ1MW



Reinterpretation of LHC Results with MadAnalysis5

CMS mono-jet analysis (JHEP 11 (2021) 153, CMS-PAS-EXO-20-004)

Can be sensitive to vector mediator Z' and fully invisible dark shower

Final state with ≥1 energetic jets (R=0.4) and E_{miss}>250 GeV

Results are exclusion contours in $\{m_{med}, m_d\}$ plane or limits on coupling as function of m_{med}

Analysis implemented in MA5 by CMS (by A. Albert)
Available in MA5 Dataverse @ https://doi.org/10.14428/DVN/IRF7ZL

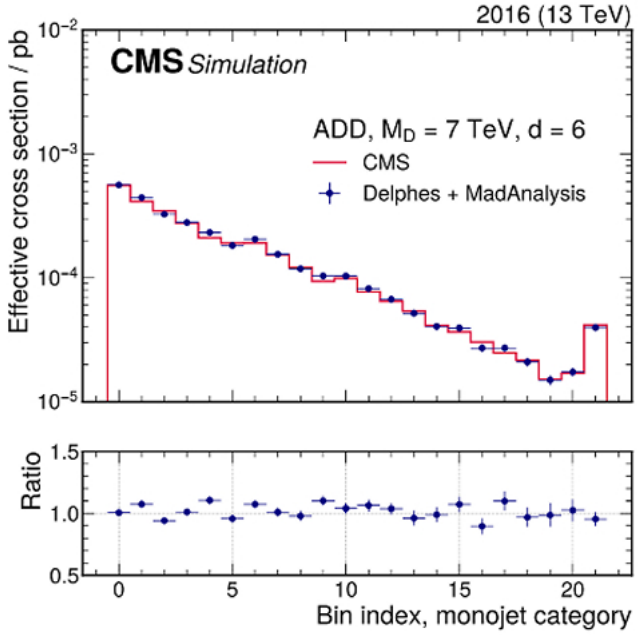
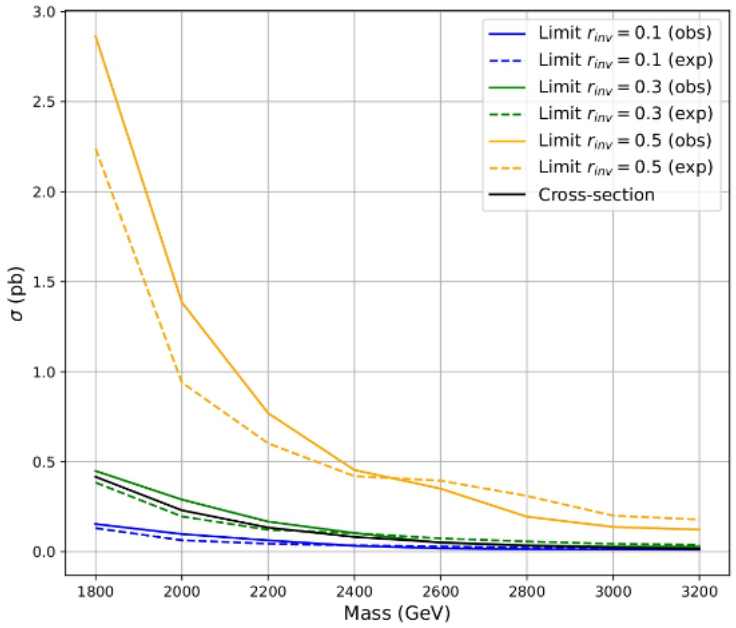


Figure from arXiv:2107.13021

Reinterpretation of LHC Results with MadAnalysis5

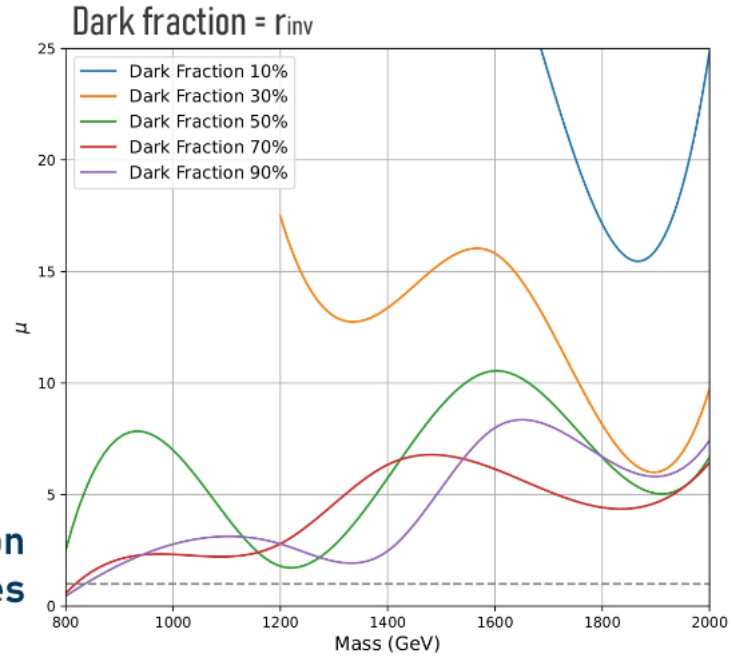
First results (preliminary):



From ATLAS-HDBS-2018-45
(vector mediator Z', dijet event)

Dark jets analysis has some exclusion power for $r_{inv} \in \{0.1, 0.3\}$ and for higher masses

SVJ t-channel analysis has some exclusion power for higher r_{inv} and for lower masses



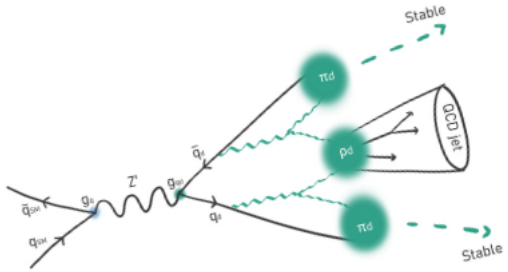
From ATLAS-EXOT-2022-37
(scalar mediator Φ, dijet event)

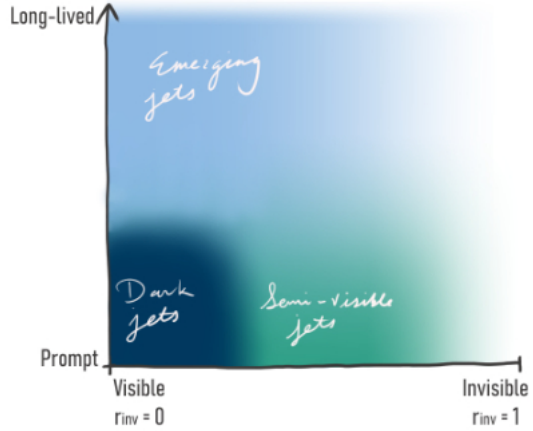
Summary

Dark QCD models/dark showers yield a broad range of phenomenology with non-trivial, and at times, model-dependent parameter correlations

To cover the most parameter space, it is key to reinterpret experimental analyses - we don't want to miss unexpected unconstrained areas of parameter space

Accessibility of all materials (cards/settings, statistical analysis etc.) from experimental analysis is necessary to enable us to reinterpret





We look forward to sharing our results with you in the near future!

Backup Slide

Plans for scan

- Fixing N_{cd}
- Varying $m_{Z'}$
- Varying Λ_d using (from Snowmass Whitepaper)

$$\frac{m_{\pi_D}}{\tilde{\Lambda}_D} = 5.5\sqrt{\frac{m_{q_D}}{\tilde{\Lambda}_D}} \qquad \frac{m_{\rho_D}}{\tilde{\Lambda}_D} = \sqrt{5.76 + 1.5\frac{m_{\pi_D}^2}{\tilde{\Lambda}_D^2}}$$

- Varing m_{qd}

=> Start from our benchmark and then study each variation one by one otherwise it will be too big a scan

Additionally, we want to study Pythia parameters

- probVector has some limiting values (from Snowmass Whitepaper)
- Check if aLund and bLund parameters have an effect

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