Theory Overview

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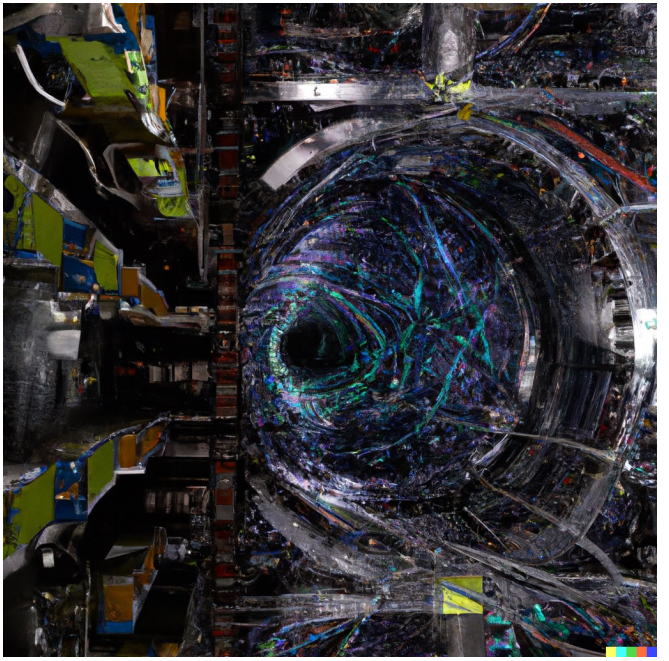
U Oregon

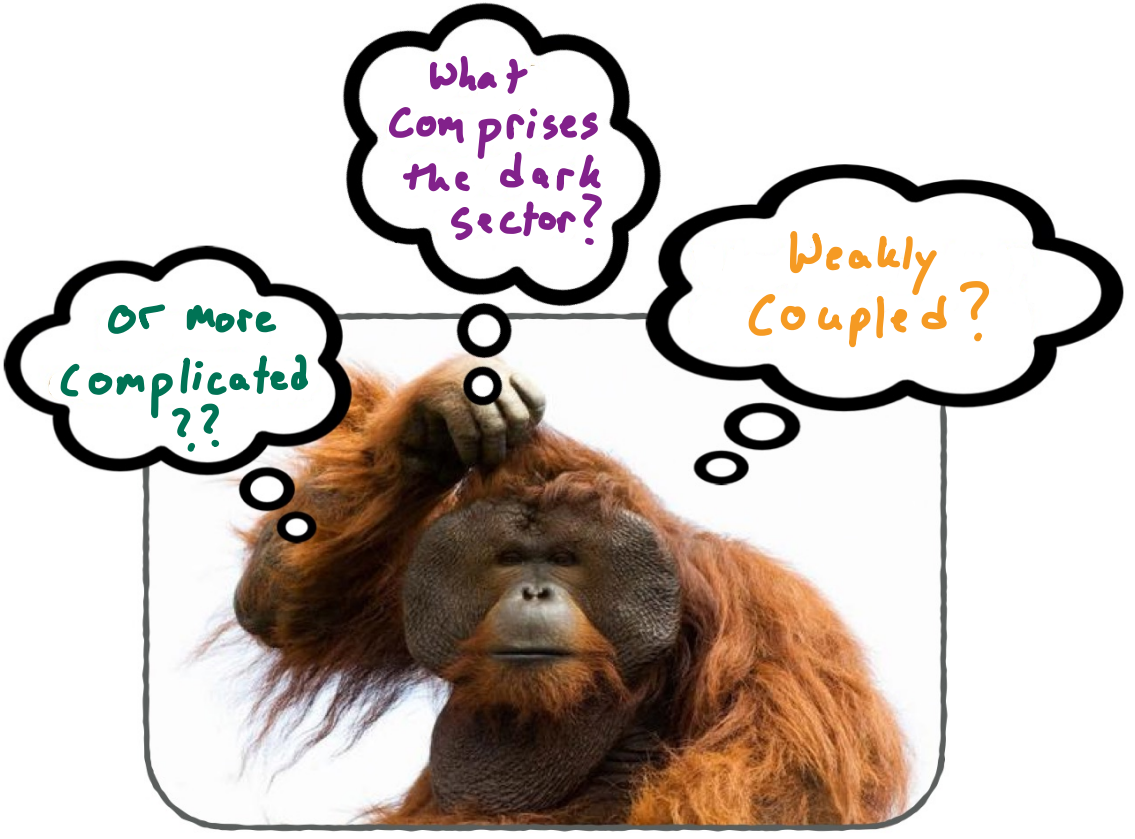
Dark Showers Workshop

Jan 21, 2025



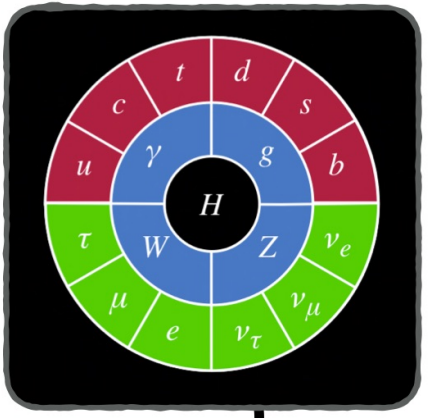
↑
"Large hadron collider dark sector"
interpreted by DALL-E

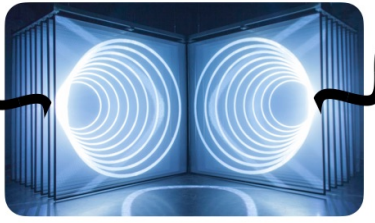
Deep Thoughts



Practical Thoughts

Dark Sector Paradigm

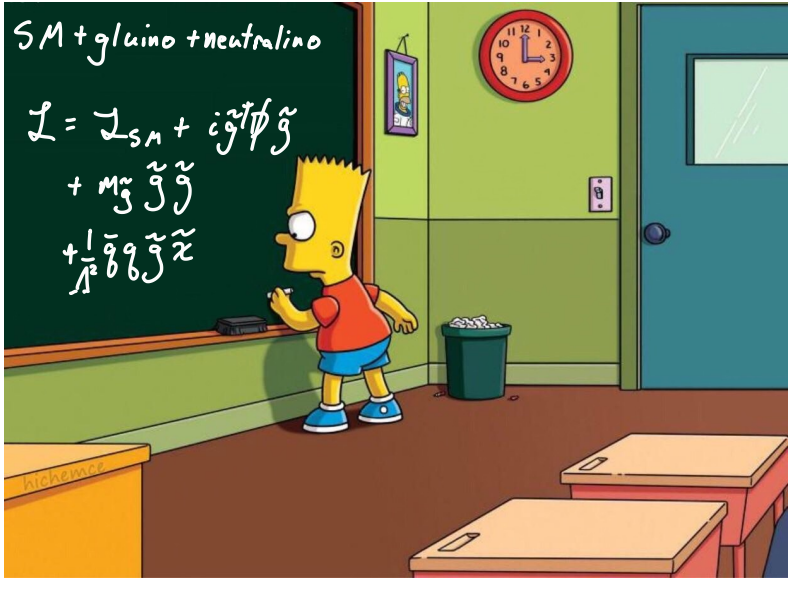




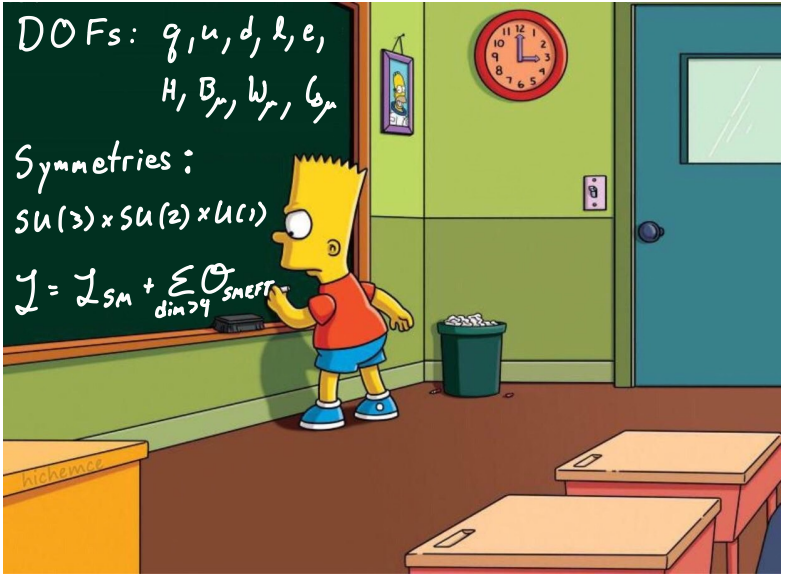
(aka "Hidden Valleys")

How to organize BSM predictions?

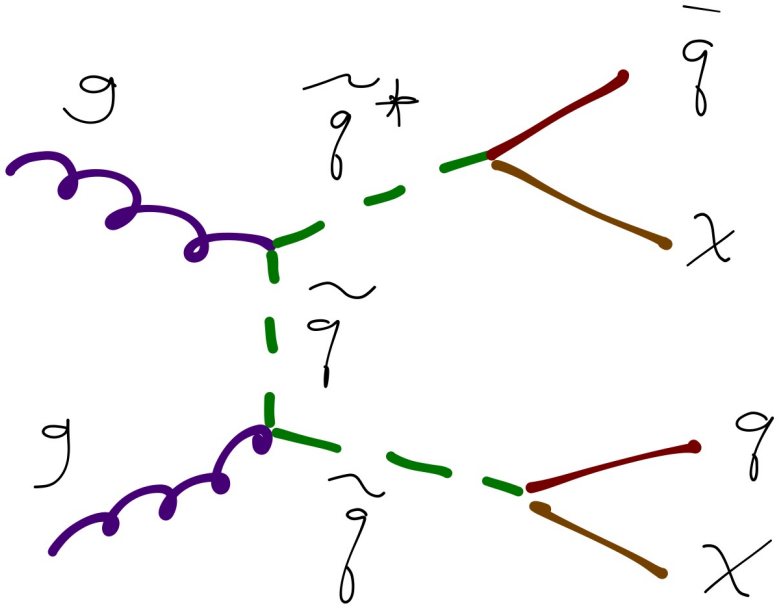
Simplified Models

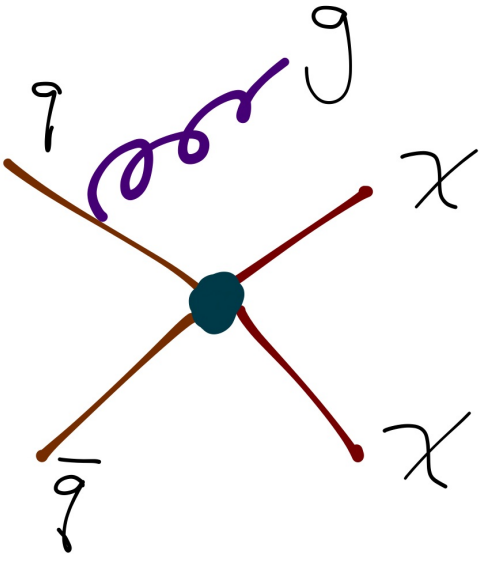


Effective Field Theory

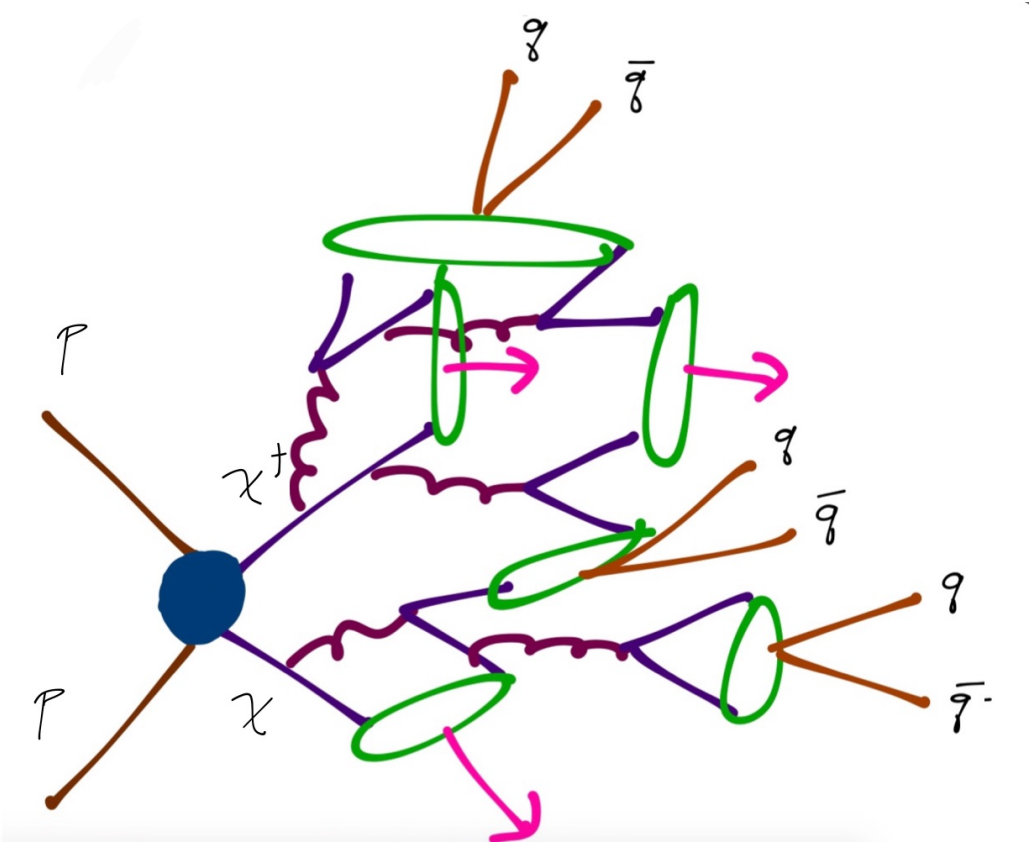


Weakly Coupled Dark Sector

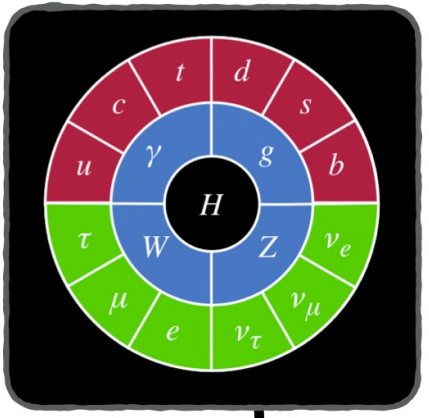




Strongly Coupled Dark Sector

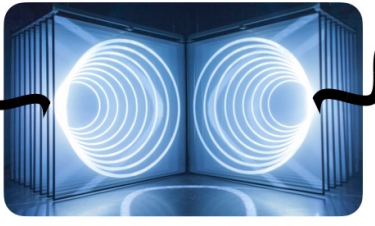


Overwhelming Theory Space



Fixed →

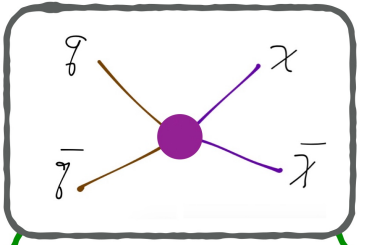
???



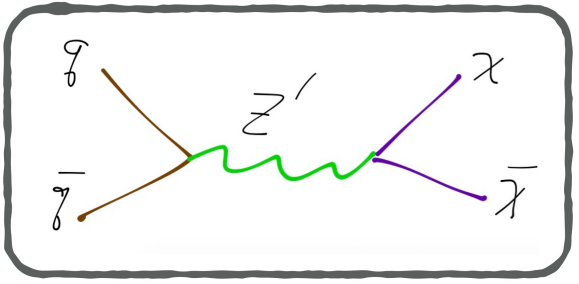
← Finite (renormalizable) options

Portal From Quarks to Dark Quarks

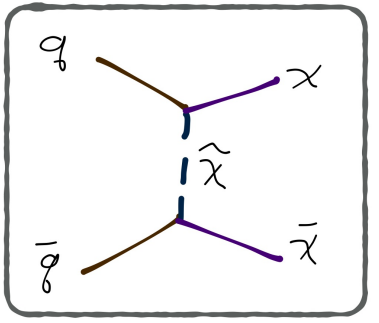
contact operator



s - channel



t - channel



Naturalness motivation for Higgs portal

Rich Phenomenology

- Semi-visible jets
- Lepton jets
- Emerging jets

} Dark jets

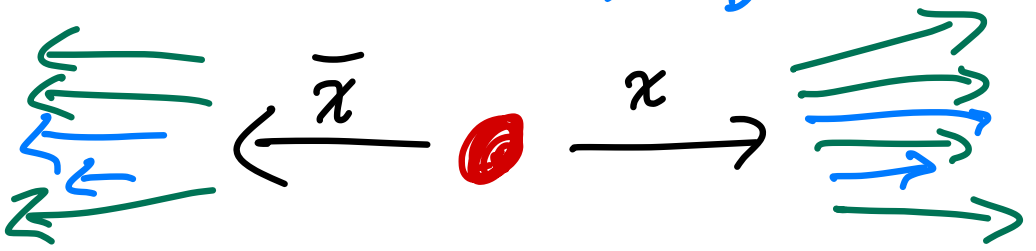
- Soft bombs / Soft Unclustered Energy Patterns
- Quirks
- Your awesome new idea?

Semi-visible Jets

Assume dark sector quarks x dominantly interact with QCD.

Some dark mesons π_D promptly decay to QCD

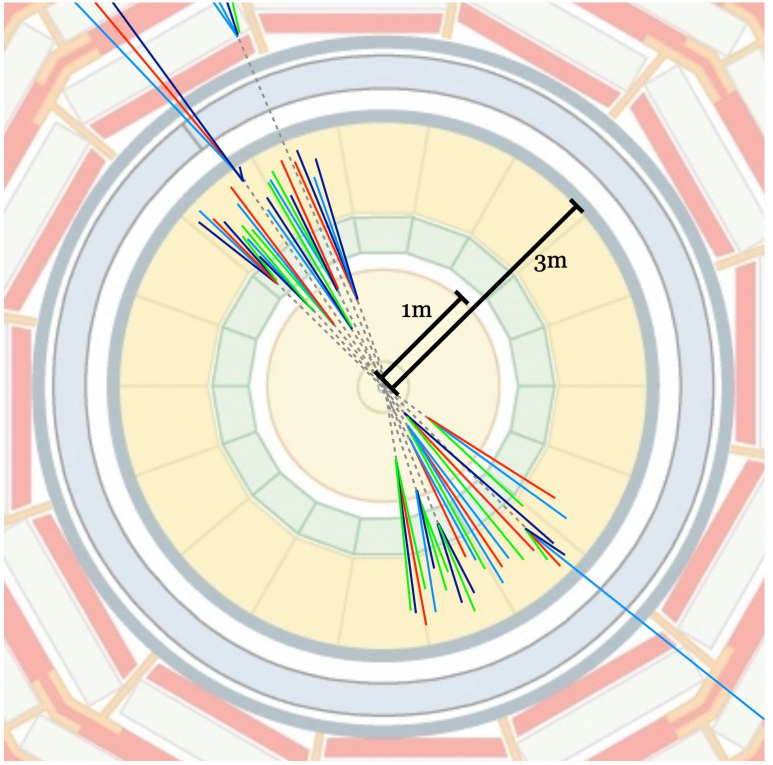
Some dark mesons π_D' are stable



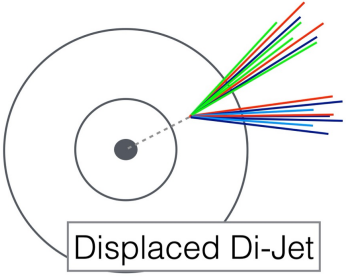
Missing energy aligned with jets

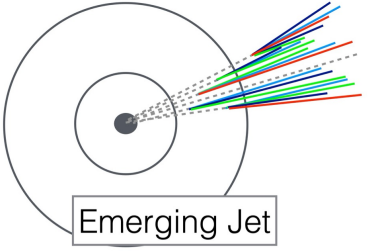
arXiv: 1503.00009

Emerging Jets



Dark mesons π_D have displaced decays to QCD

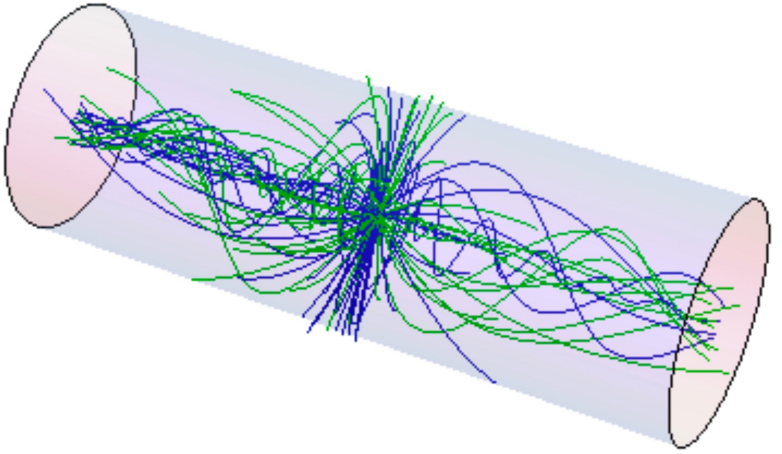




arXiv: 1502.05409

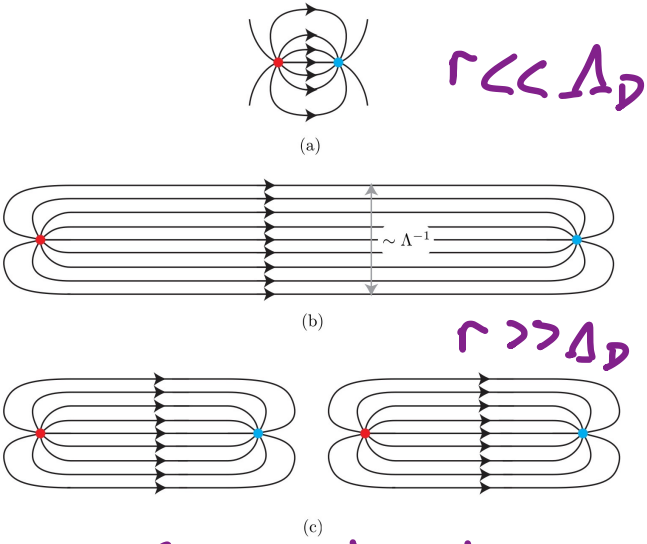
Soft Bombs

Nearly conformal (scale invariant) dark QCD sector at strong coupling



arXiv: 1612.00850

Quirks

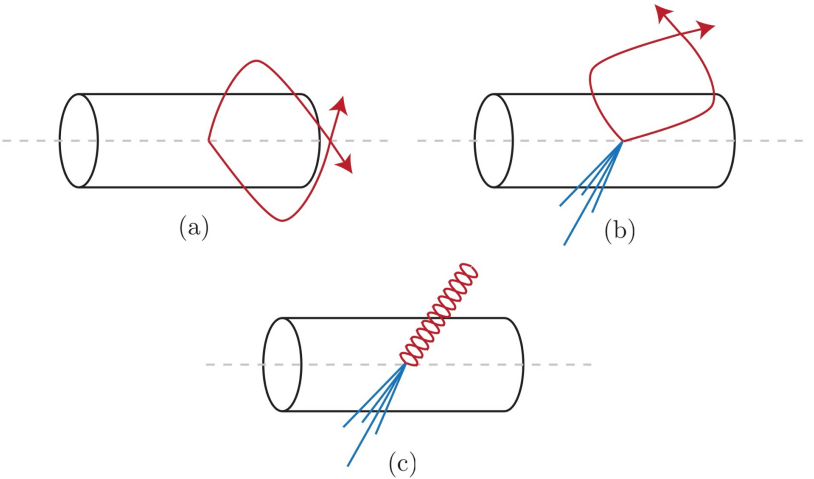


$r \ll \Lambda_D$

$r \gg \Lambda_D$

String breaking
$2m_Q \gg \Lambda_D$

Example signatures



arXiv: 0805.4642

Benchmarking / Parametrizations

Production portal

new particles / operators

⇒ couplings and mass scales

↓

Dark QCD: $E \gg \Lambda_D$

confinement scale Λ_D,

$N_c + N_f \Rightarrow$ rate for running coupling,

constituent quark masses

↓

Dark QCD: $E \ll \Lambda_D$

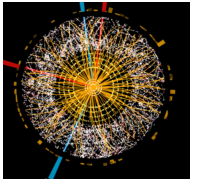
Hadronization, spectrum, decays → within dark sector

→ to SM

* How to trigger?

* Is it ruled out?

Simulation ???



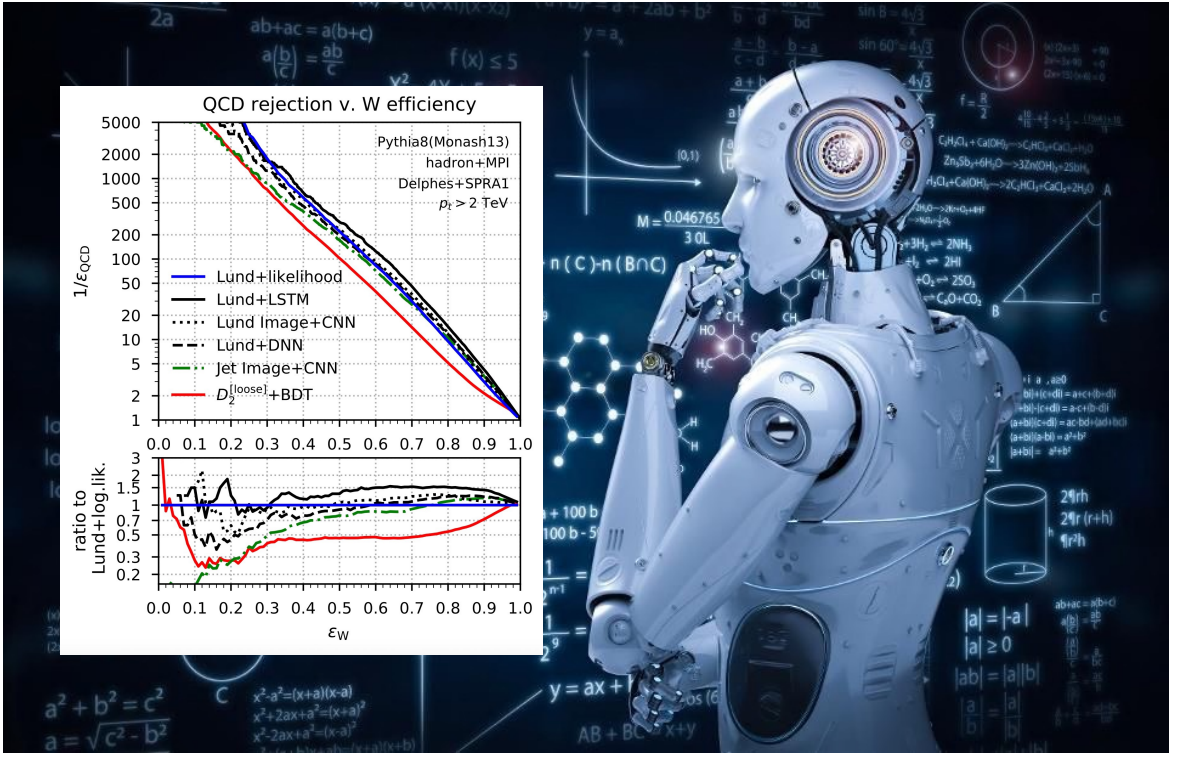
We now have Pythia and Herwig simulations!

Frontiers

New Phenomena?

Machine Learning

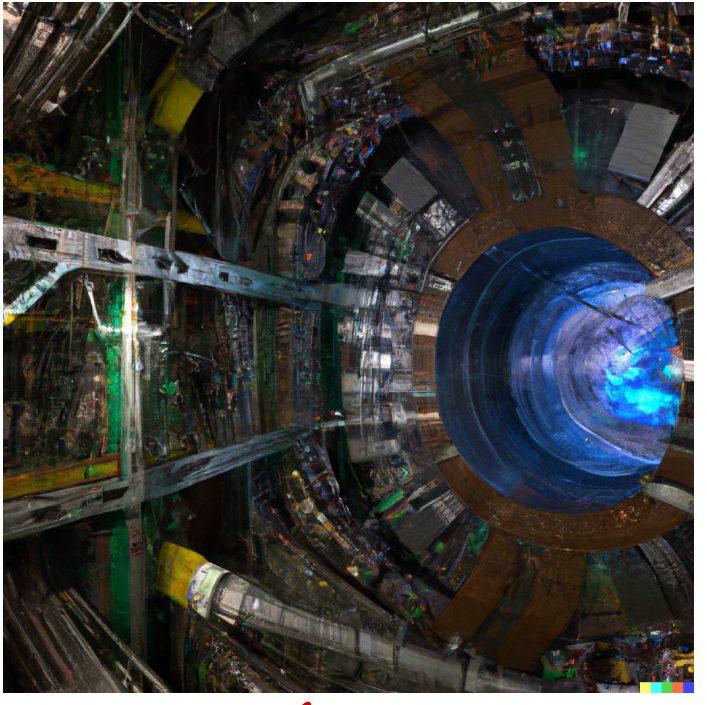
* Robust to simulation unknowns



arXiv: 1907 04758

Bright Future for Dark Showers

- More searches from CMS and ATLAS!
- Improvements to sims
- Robust predictions
- Machine learning
- Exploring model space
- New physics discovery??

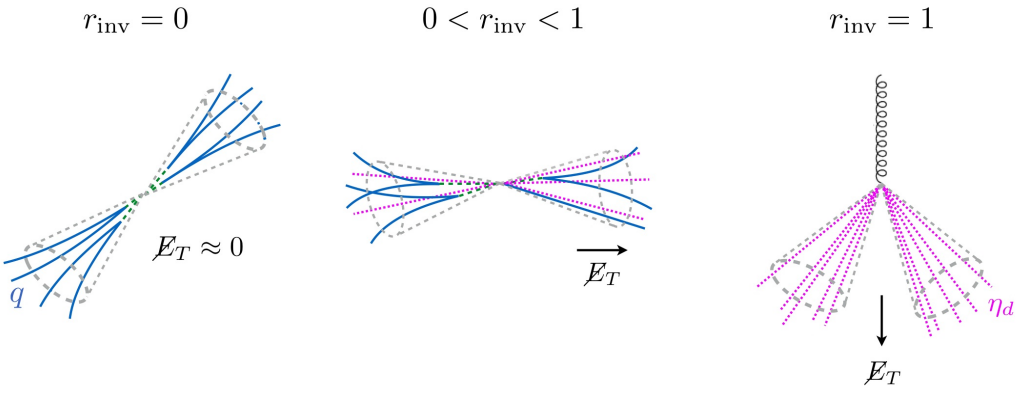


↑
Another DALL-E "original"

Example: SVJ

Semi-visible Jets

Shower Strength	Invisible ratio
$\alpha_d(1\text{TeV})$	r_{inv}
larger $\alpha_d(\Lambda)$	larger r_{inv}



- α_d (or Λ_d)
- r_{inv}
- m_d
- σ_{portal}

Pheno parametrization

TC, M. Lisanti, H.K. Lou
arXiv:1503.00009

Model Dependence

Production — Pick portal ⇒ Z ⇒ Perturbative

Showering — Pick # colors and # flavors ⇒ Sudakov factor ⇒ Parton shower

Hadronization — Need to know spectrum ⇒ Fragmentation functions ⇒ Non-perturbative

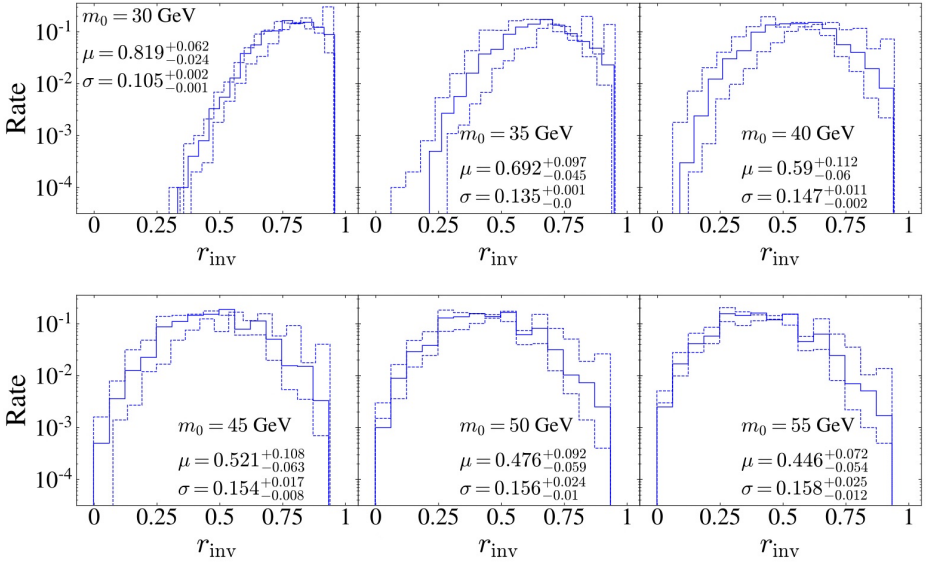
Decay — Depends on spectrum & portal

Semi-visible Jets from Glueballs

w/ Batz, Curtin, Gemmell, Kribs

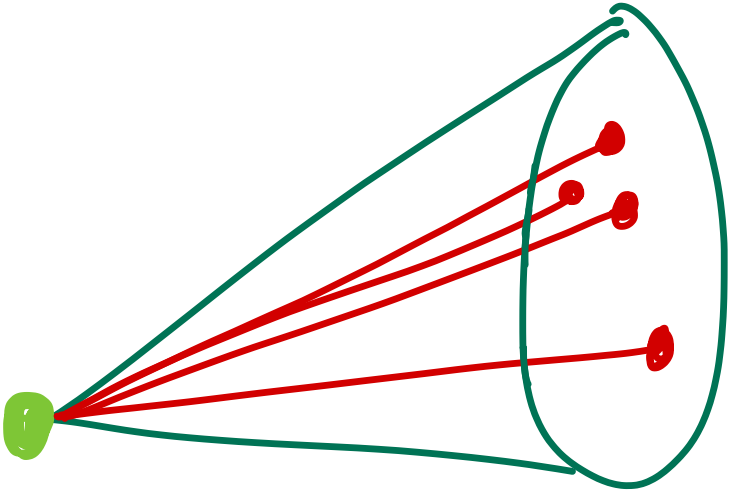
$pp \to Z' \to$ glueballs

Pure glue dark sector (N_c, Λ_{dark})



Better Observables?

Jet substructure

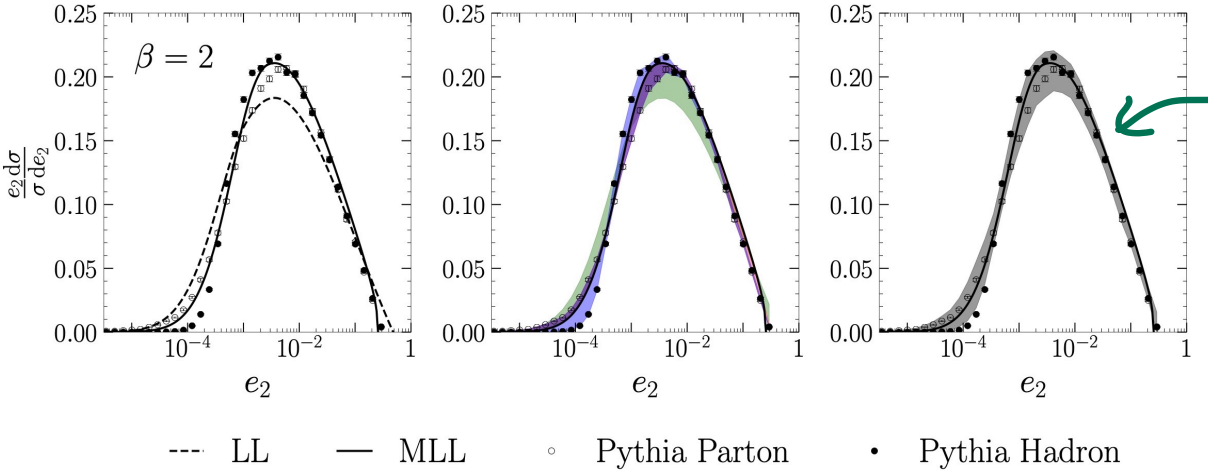


Dark Substructure

2-point correlation function

$$e_2^{(\beta)} = \sum z_i z_j (\theta_{ij})^\beta$$

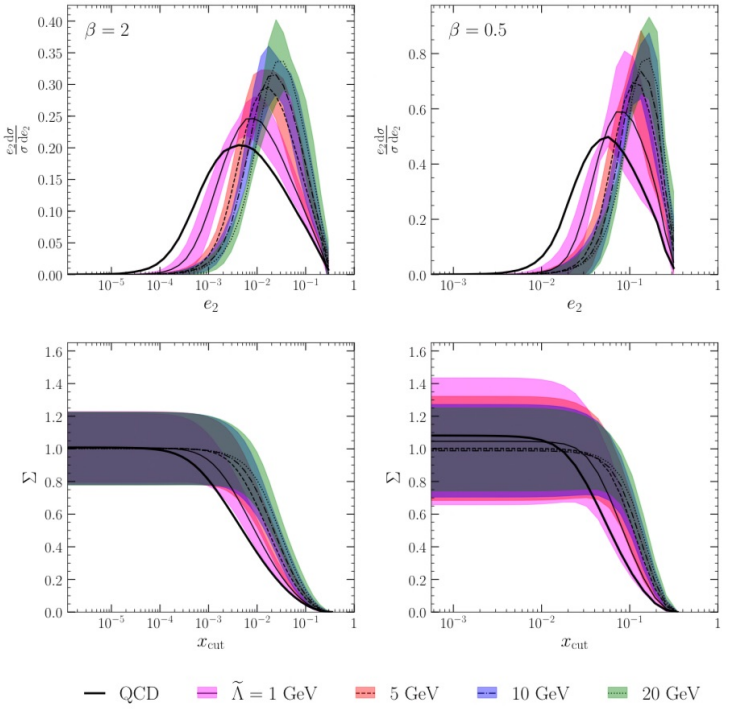
Generalization of jet mass ($\beta=2$)



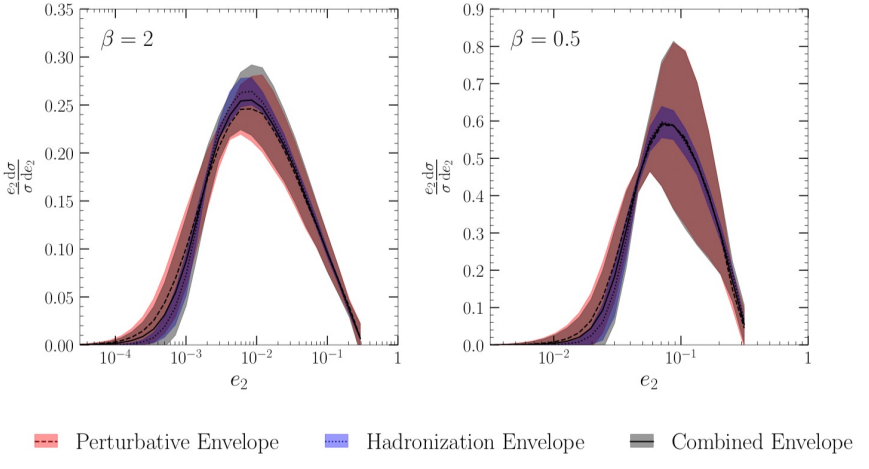
error envelope theory systematic

TC, Doss, Freytsis
arXiv: 2004.00631

Theoretical Errors

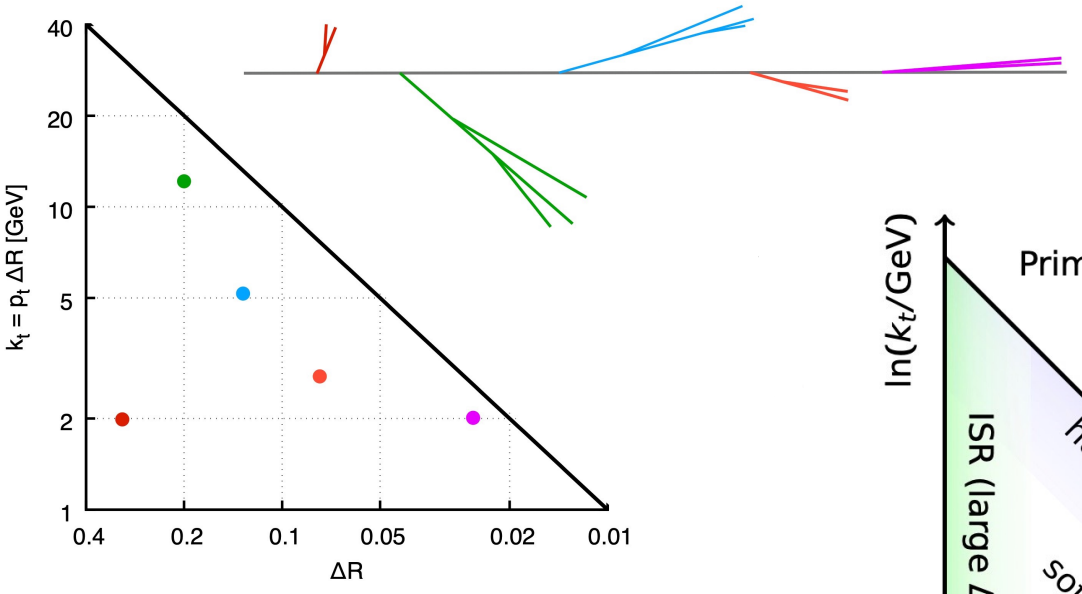


Hadronization



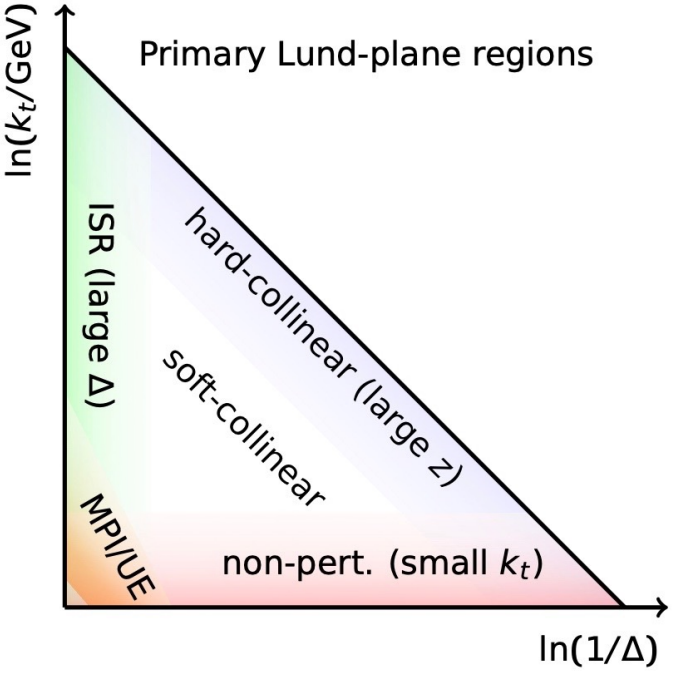
TC, Doss, Freytsis
arXiv: 2004.00631

Lund Jet Plane



from talk by G. Salam

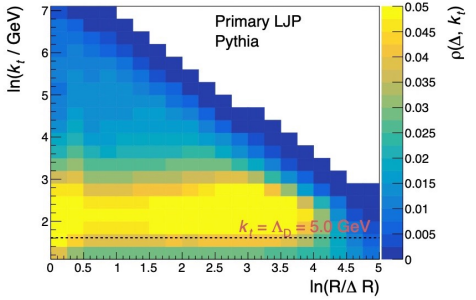
F. Dreyer, G. Salam, G. Soyez
arXiv: 1807.04758

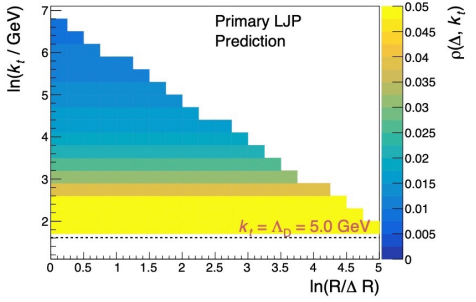


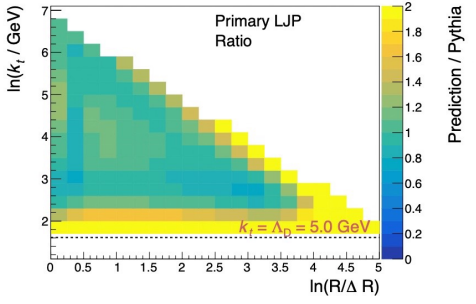
Average over many jets

Lund Dark Jet Plane

TC, J. Roloff, C. Scherb
arXiv: 2301.07732







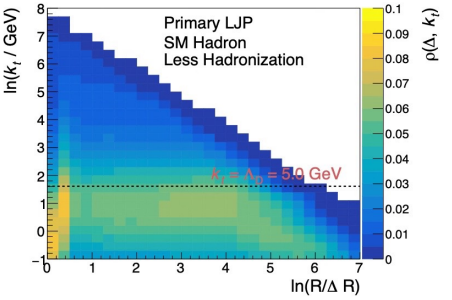
leading log density

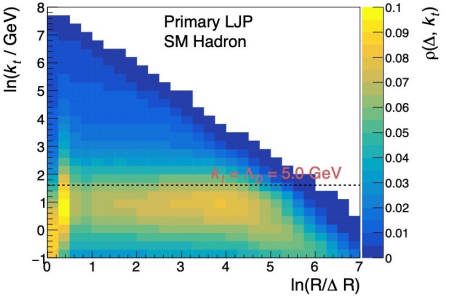
$$\sim \frac{2\alpha_D(k_t) C_F}{\pi}$$

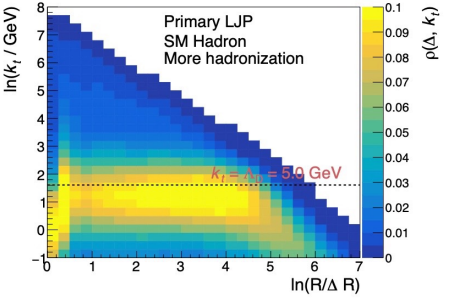
$$C_F = \frac{N^2-1}{2N}$$

for SU(N)

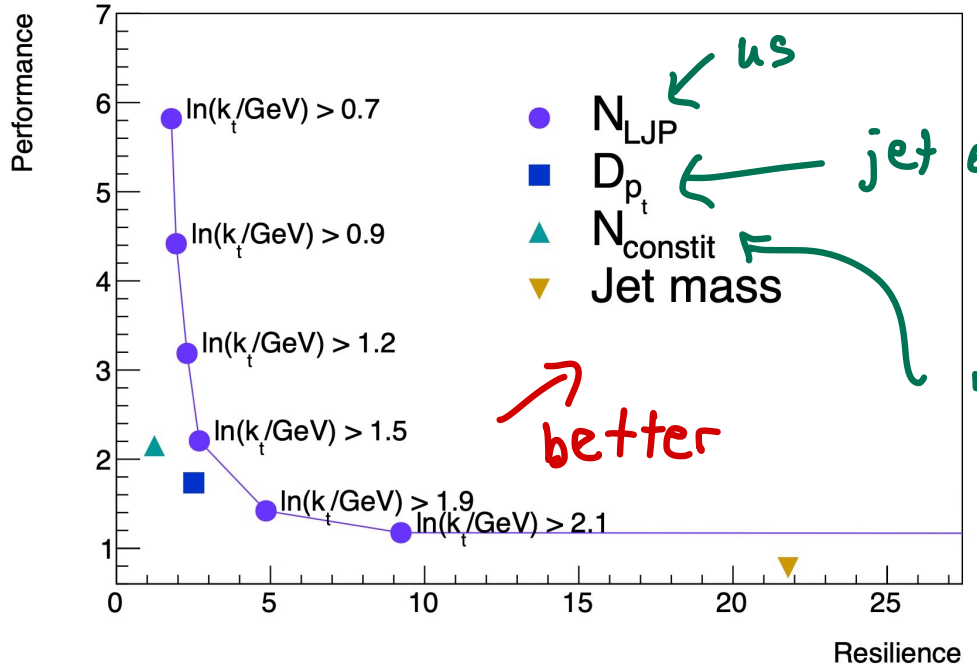
Varying hadronization







Performance vs Resilience



vs

jet energy sharing

$\sqrt{\Sigma p_T^2}/\Sigma p_T$

number of constituents

$\frac{\varepsilon_{dark}}{\sqrt{\varepsilon_{QCD}}}$

better

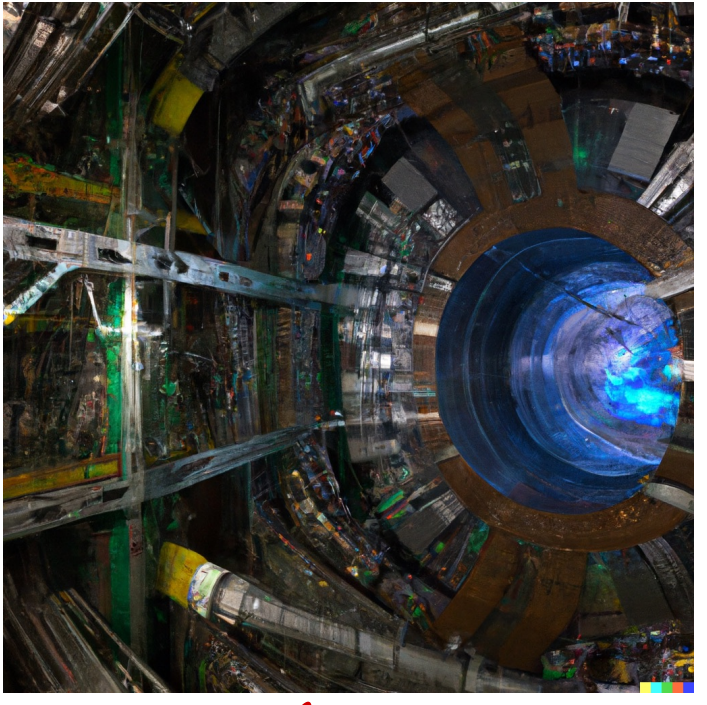
Next step is to design search

variation wrt hadronization

$\left(\frac{\Delta\varepsilon_{dark}}{\langle\varepsilon_{dark}\rangle}\right)^2$

Bright Future for Dark Showers

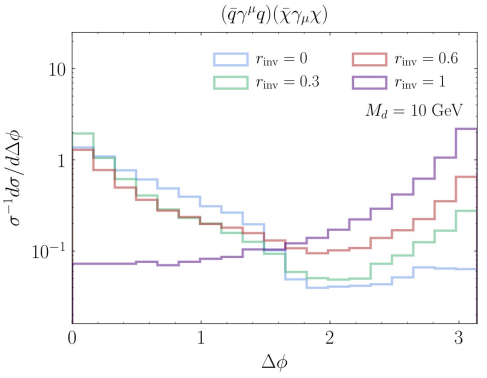
- More searches from CMS and ATLAS!
- Improvements to sims
- Robust predictions
- Machine learning
- Exploring model space
- New physics discovery??

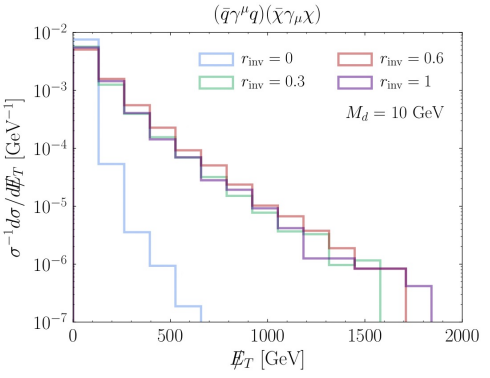


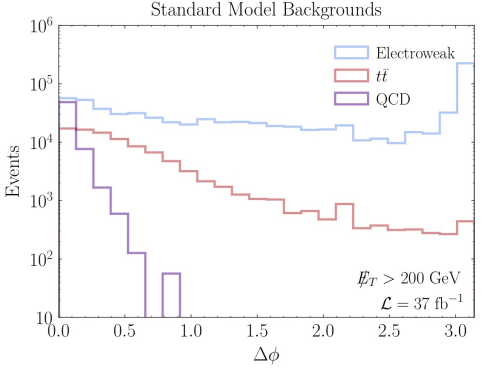
↑
Another DALL-E "original"

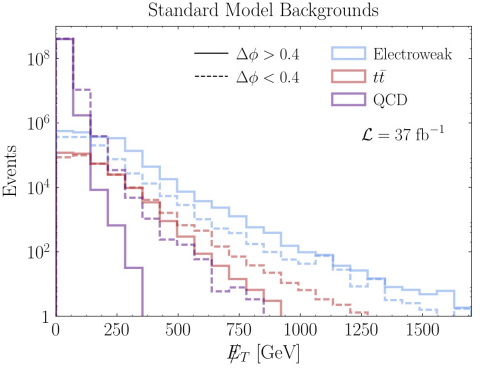
Backups

Signal vs Background









TC, M. Lisanti, H.K. Lou, S. Mishra-Sharma [arXiv: 1707.05326]

Benchmarking

- Pick a portal: contact operator

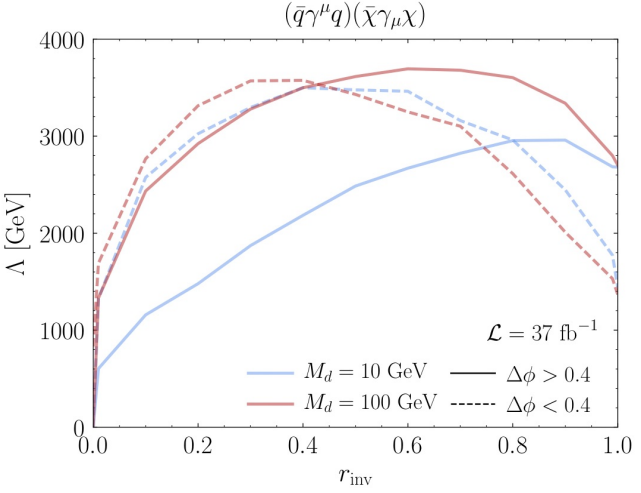
$$\Lambda_d = 20 \Lambda_{QCD}$$

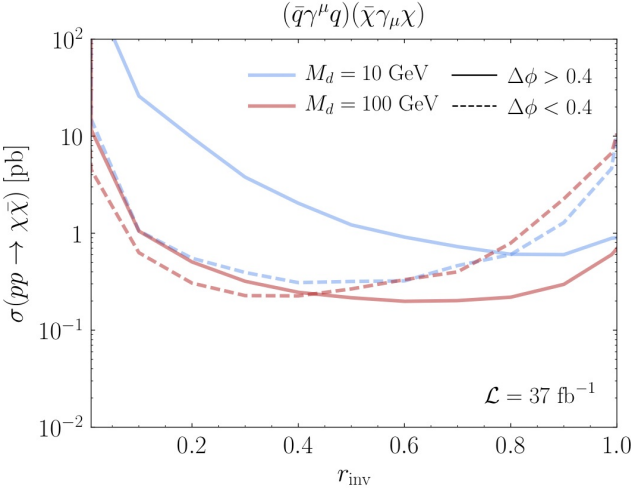
- Pick some parameters: $r_{inv} = 0.5$

$$m_d = 10\ \text{GeV}$$

- Determine limit on σ_{portal}

Projected Limits

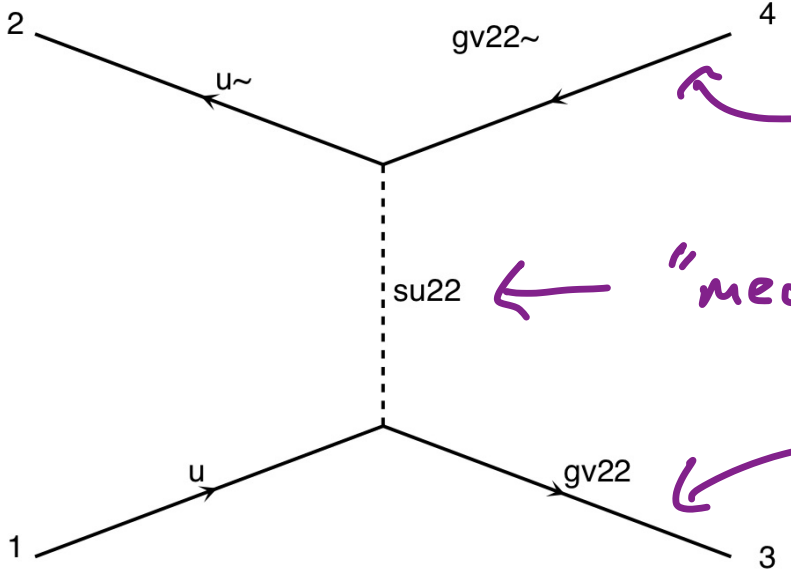




s-channel + t-channel models
see arXiv: 1707.05326

Production in t-channel Model

$q\bar{q} \rightarrow q_D \bar{q}_D$



Production in t-channel Model

Want higher body diagrams for "matching"

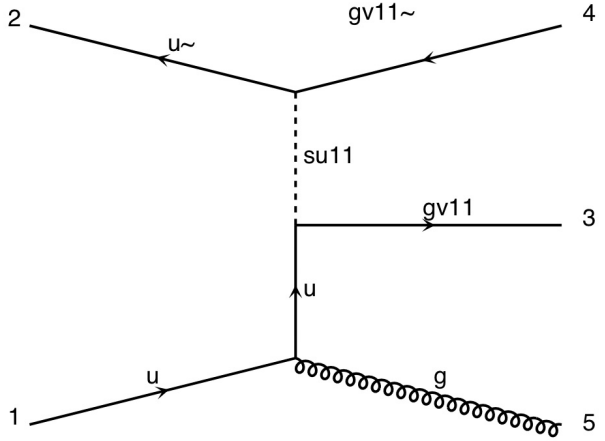


diagram 1 QCD=3, QED=0

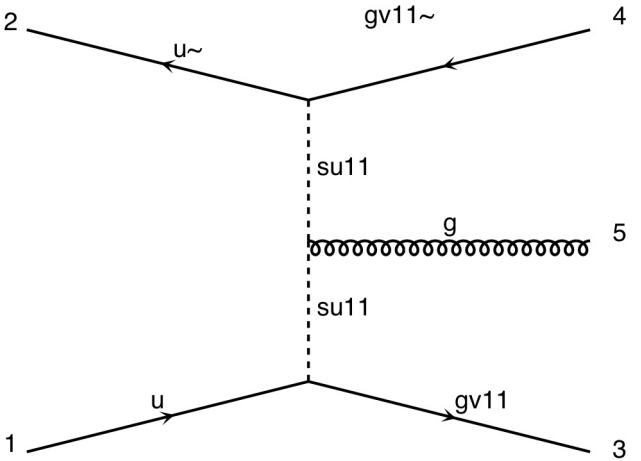


diagram 3 QCD=3, QED=0

+ ...

Production in t-channel Model

Want higher body diagrams for "matching"

"on-shell" mediators

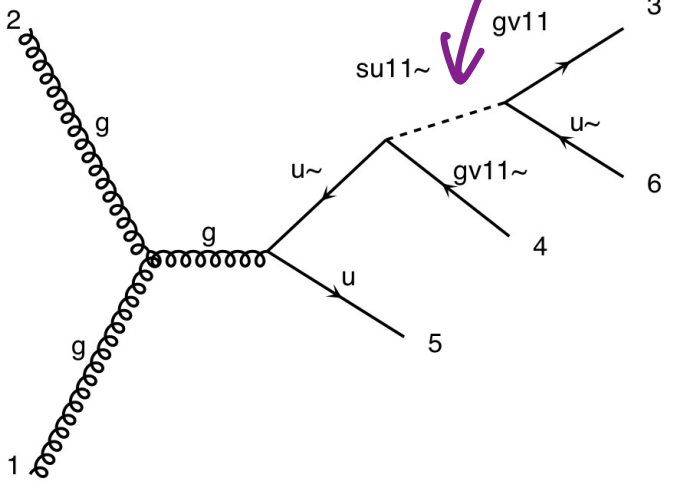


diagram 1 QCD=4, QED=0

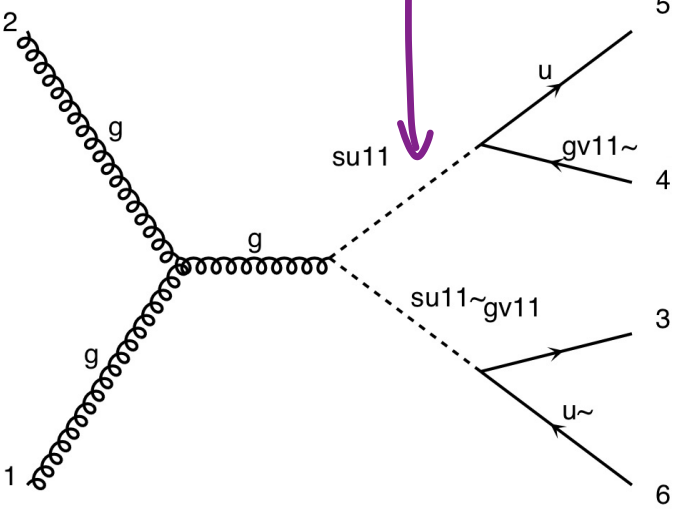
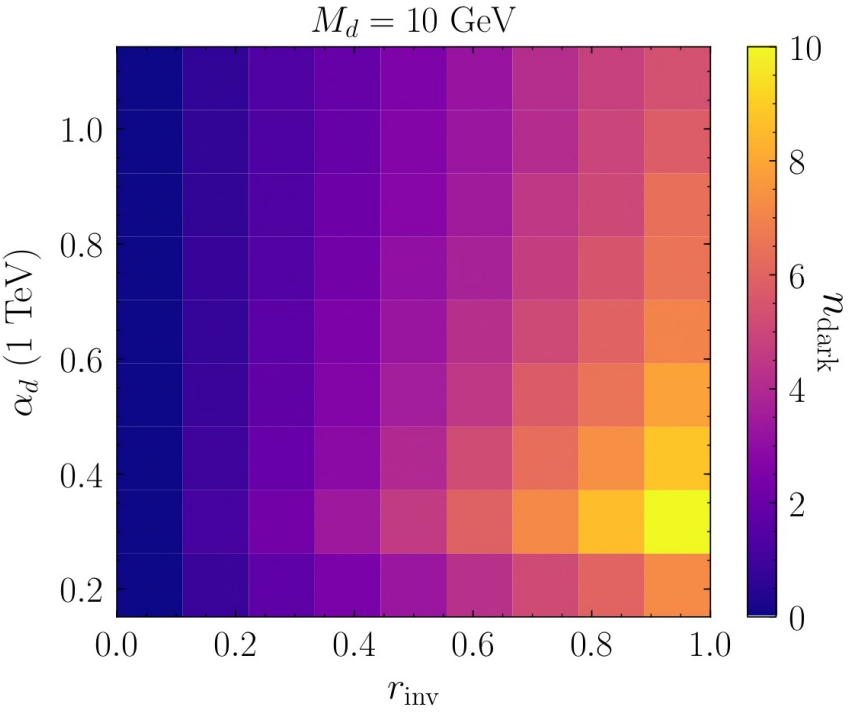


diagram 2 QCD=4, QED=0

+ ...

Showering

Under reasonable theoretical control



Hadronization & Decay

Phenomenological model

- Spectrum is non-perturbative
- Fragmentation is non-perturbative

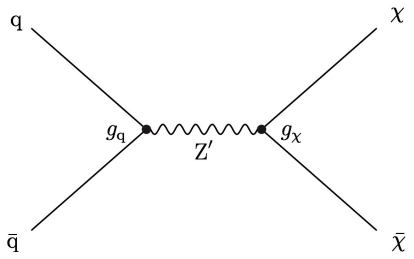
  but exponential supression for producing heavy states
  ⇒ only care about lightest

- Decay: Vector mesons decay fast
  Scalar mesons chirality supressed

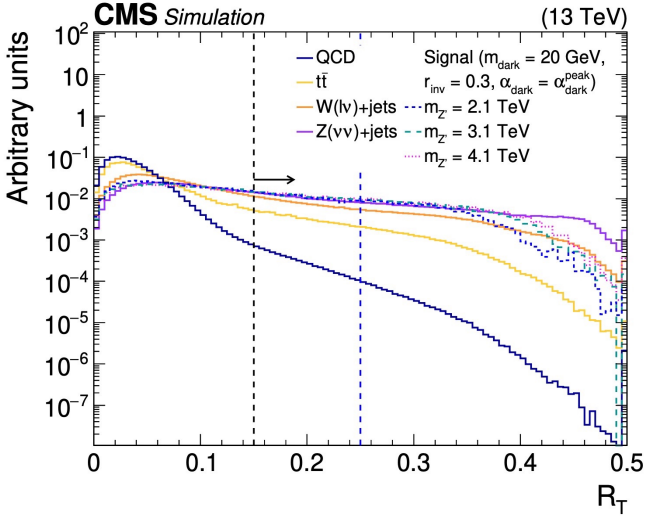
CMS Search

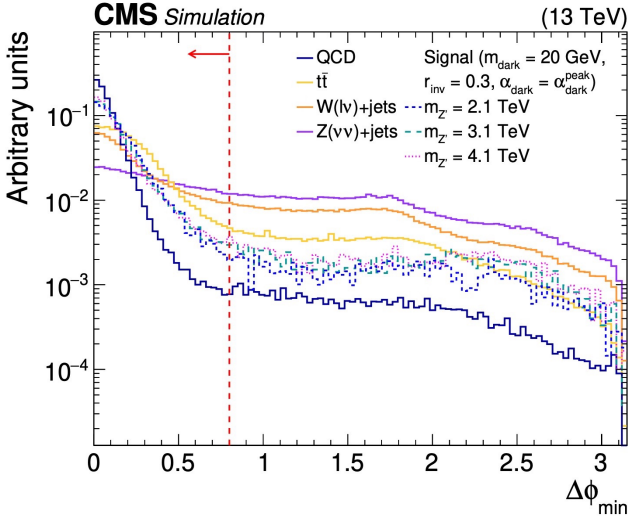
arXiv: 2112.11125

s-channel model



Scan	$m_{Z'}$ [TeV]	m_{dark} [GeV]	r_{inv}	α_{dark}
1	1.5–5.1	1–100	0.3	α_{dark}^{peak}
2	1.5–5.1	20	0–1	α_{dark}^{peak}
3	1.5–5.1	20	0.3	α_{dark}^{low}–α_{dark}^{high}

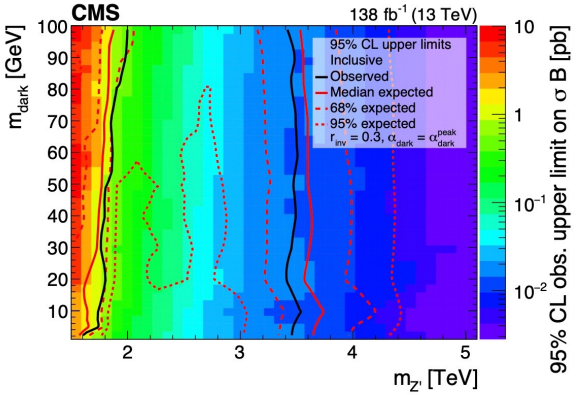


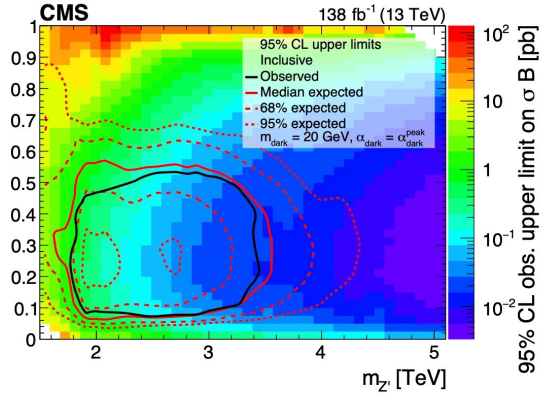


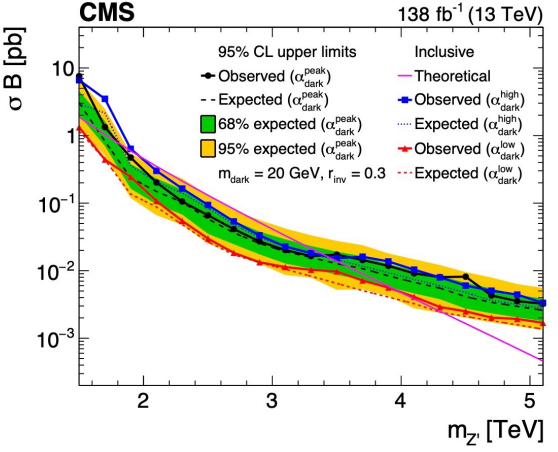
$$R_T = \frac{p_T^{miss}}{m_T}$$

$\Delta\phi_{min}$ is min angle between jets and $\vec{p}_T^{\,miss}$

CMS Search







Also provided stronger limits using BDT tagger

Preselection requirements
$p_T(j_{1,2}) > 200\,\text{GeV},\ \eta(j_{1,2}) < 2.4$
$R_T > 0.15$
$\Delta\eta(j_1, j_2) < 1.5$
$m_T > 1.5\,\text{TeV}$
$N_\mu = 0$
$N_e = 0$
p_T^{miss} filters
$\Delta R(j_{1,2}, c_{nonfunctional}) > 0.1$

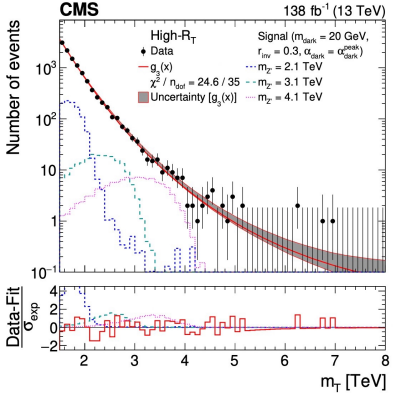
Final selection requirements
veto $f_\gamma(j_1) > 0.7$ & $p_T(j_1) > 1.0\,\text{TeV}$
veto $-3.05 < \eta_j < -1.35$ & $-1.62 < \phi_j < -0.82$ *
$\Delta\phi_{min} < 0.8$

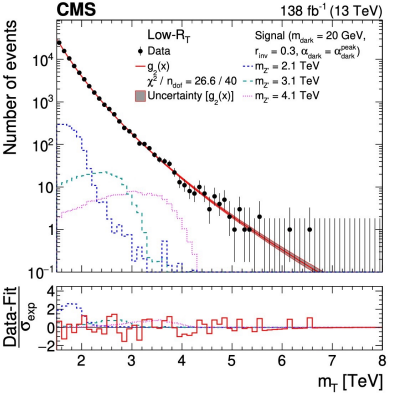
CMS Search

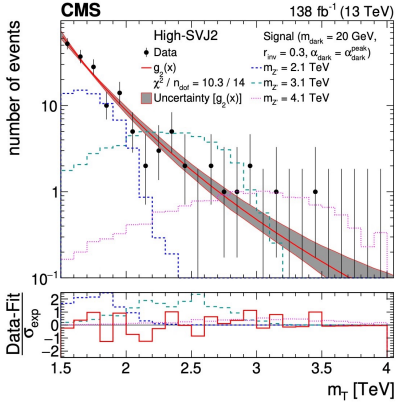
Preselection requirements
$p_{\mathrm{T}}(\mathrm{J}_{1,2}) > 200\,\mathrm{GeV},\ \eta(\mathrm{J}_{1,2}) < 2.4$
$R_{\mathrm{T}} > 0.15$
$\Delta\eta(\mathrm{J}_1, \mathrm{J}_2) < 1.5$
$m_{\mathrm{T}} > 1.5\,\mathrm{TeV}$
$N_{\mu} = 0$
$N_{\mathrm{e}} = 0$
$p_{\mathrm{T}}^{\mathrm{miss}}$ filters
$\Delta R(\mathrm{j}_{1,2}, c_{\mathrm{nonfunctional}}) > 0.1$

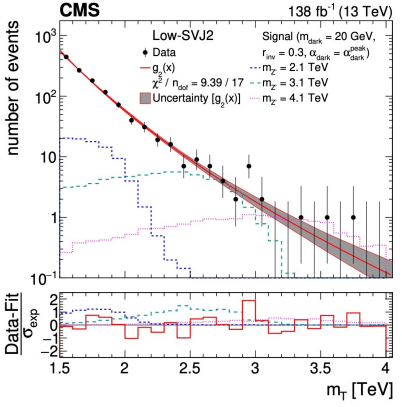
Final selection requirements
veto $f_{\gamma}(\mathrm{j}_1) > 0.7$ & $p_{\mathrm{T}}(\mathrm{j}_1) > 1.0\,\mathrm{TeV}$
veto $-3.05 < \eta_{\mathrm{j}} < -1.35$ & $-1.62 < \phi_{\mathrm{j}} < -0.82$ *
$\Delta\phi_{\mathrm{min}} < 0.8$

CMS Search

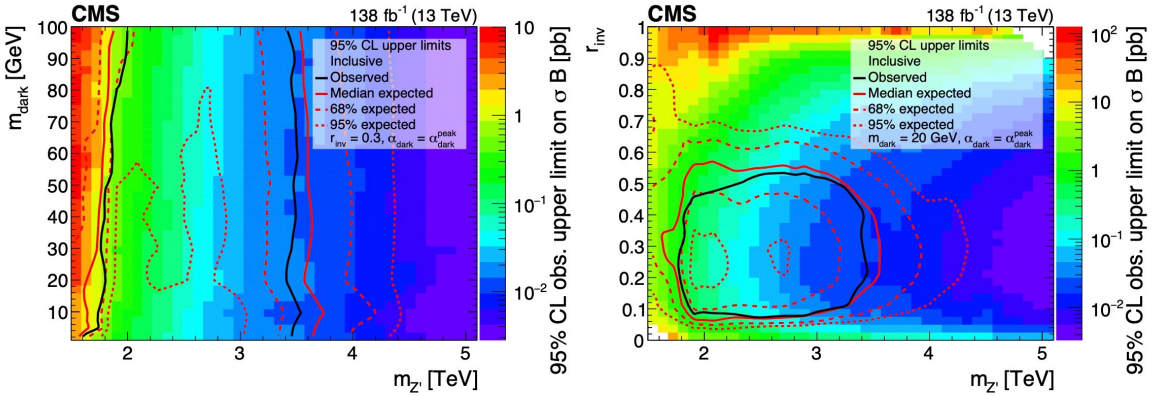

CMS
138 fb^{-1} (13 TeV)
High-R_T
Data
$g_3(x)$
χ^2 / n_{dof} = 24.6 / 35
Uncertainty [$g_3(x)$]
Signal (m_{dark} = 20 GeV, r_{inv} = 0.3, α_{dark} = α_{dark}^{peak})
$m_{Z'}$ = 2.1 TeV
$m_{Z'}$ = 3.1 TeV
$m_{Z'}$ = 4.1 TeV
Number of events
Data-Fit / σ_{exp}
m_T [TeV]

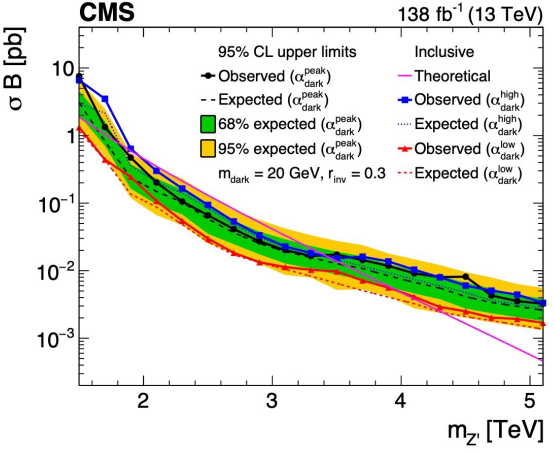

CMS
138 fb^{-1} (13 TeV)
Low-R_T
Data
$g_2(x)$
χ^2 / n_{dof} = 26.6 / 40
Uncertainty [$g_2(x)$]
Signal (m_{dark} = 20 GeV, r_{inv} = 0.3, α_{dark} = α_{dark}^{peak})
$m_{Z'}$ = 2.1 TeV
$m_{Z'}$ = 3.1 TeV
$m_{Z'}$ = 4.1 TeV
Number of events
Data-Fit / σ_{exp}
m_T [TeV]


CMS
138 fb^{-1} (13 TeV)
High-SVJ2
Data
$g_6(x)$
χ^2 / n_{dof} = 10.3 / 14
Uncertainty [$g_6(x)$]
Signal (m_{dark} = 20 GeV, r_{inv} = 0.3, α_{dark} = α_{dark}^{peak})
$m_{Z'}$ = 2.1 TeV
$m_{Z'}$ = 3.1 TeV
$m_{Z'}$ = 4.1 TeV
number of events
Data-Fit / σ_{exp}
m_T [TeV]

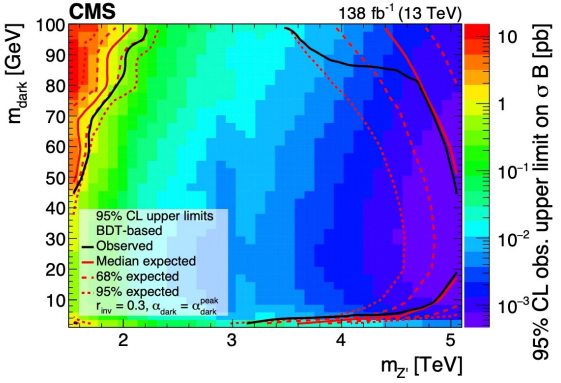

CMS
138 fb^{-1} (13 TeV)
Low-SVJ2
Data
$g_5(x)$
χ^2 / n_{dof} = 9.39 / 17
Uncertainty [$g_5(x)$]
Signal (m_{dark} = 20 GeV, r_{inv} = 0.3, α_{dark} = α_{dark}^{peak})
$m_{Z'}$ = 2.1 TeV
$m_{Z'}$ = 3.1 TeV
$m_{Z'}$ = 4.1 TeV
number of events
Data-Fit / σ_{exp}
m_T [TeV]

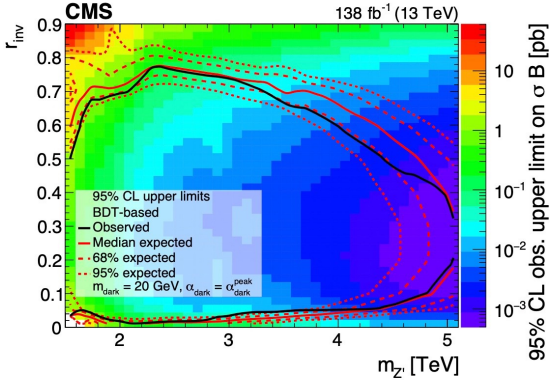
CMS Search

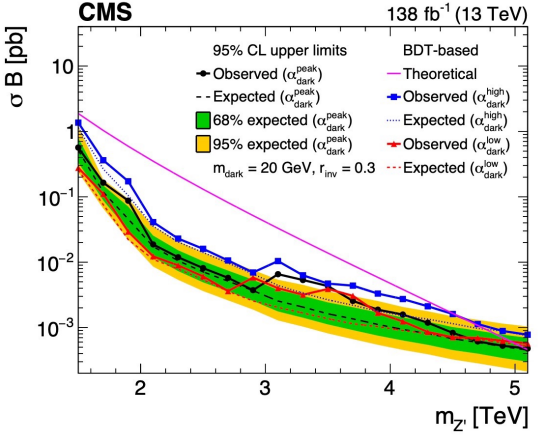

CMS
138 fb^{-1} (13 TeV)
95% CL upper limits
Inclusive
Observed
Median expected
68% expected
95% expected
r_{inv} = 0.3, $\alpha_{dark} = \alpha_{dark}^{peak}$
m_{dark} [GeV]
$m_{Z'}$ [TeV]
95% CL obs. upper limit on σ B [pb]
r_{inv}
m_{dark} = 20 GeV, $\alpha_{dark} = \alpha_{dark}^{peak}$


CMS
138 fb^{-1} (13 TeV)
95% CL upper limits
Inclusive
Observed (α_{dark}^{peak})
Expected (α_{dark}^{peak})
68% expected (α_{dark}^{peak})
95% expected (α_{dark}^{peak})
Theoretical
Observed (α_{dark}^{high})
Expected (α_{dark}^{high})
Observed (α_{dark}^{low})
Expected (α_{dark}^{low})
m_{dark} = 20 GeV, r_{inv} = 0.3
σ B [pb]
$m_{Z'}$ [TeV]

CMS Search


CMS
138 fb^{-1} (13 TeV)
m_{dark} [GeV]
$m_{Z'}$ [TeV]
95% CL obs. upper limit on σ B [pb]
95% CL upper limits
BDT-based
Observed
Median expected
68% expected
95% expected
r_{inv} = 0.3, $\alpha_{dark} = \alpha_{dark}^{peak}$

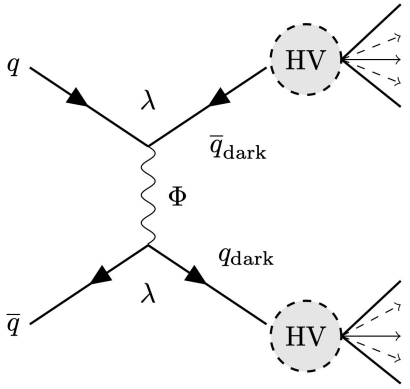

CMS
138 fb^{-1} (13 TeV)
r_{inv}
$m_{Z'}$ [TeV]
95% CL obs. upper limit on σ B [pb]
95% CL upper limits
BDT-based
Observed
Median expected
68% expected
95% expected
m_{dark} = 20 GeV, $\alpha_{dark} = \alpha_{dark}^{peak}$

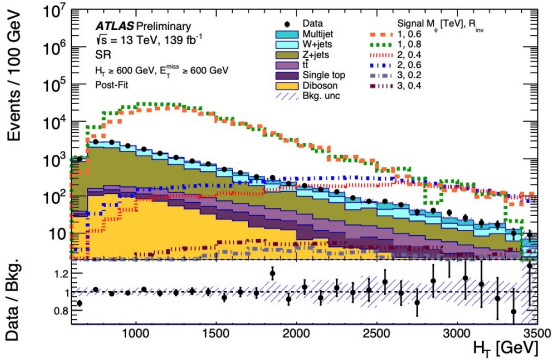

CMS
138 fb^{-1} (13 TeV)
σ B [pb]
$m_{Z'}$ [TeV]
95% CL upper limits
BDT-based
Observed (α_{dark}^{peak})
Expected (α_{dark}^{peak})
68% expected (α_{dark}^{peak})
95% expected (α_{dark}^{peak})
m_{dark} = 20 GeV, r_{inv} = 0.3
Theoretical
Observed (α_{dark}^{high})
Expected (α_{dark}^{high})
Observed (α_{dark}^{low})
Expected (α_{dark}^{low})

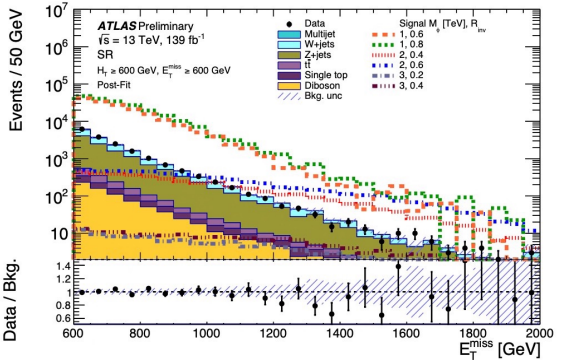
ATLAS Search

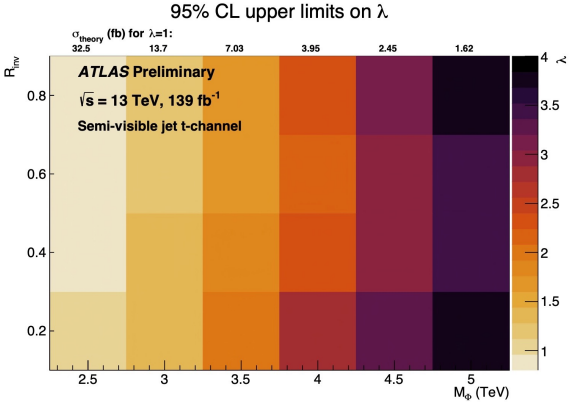
ATLAS-CONF-2022-038

t-channel model









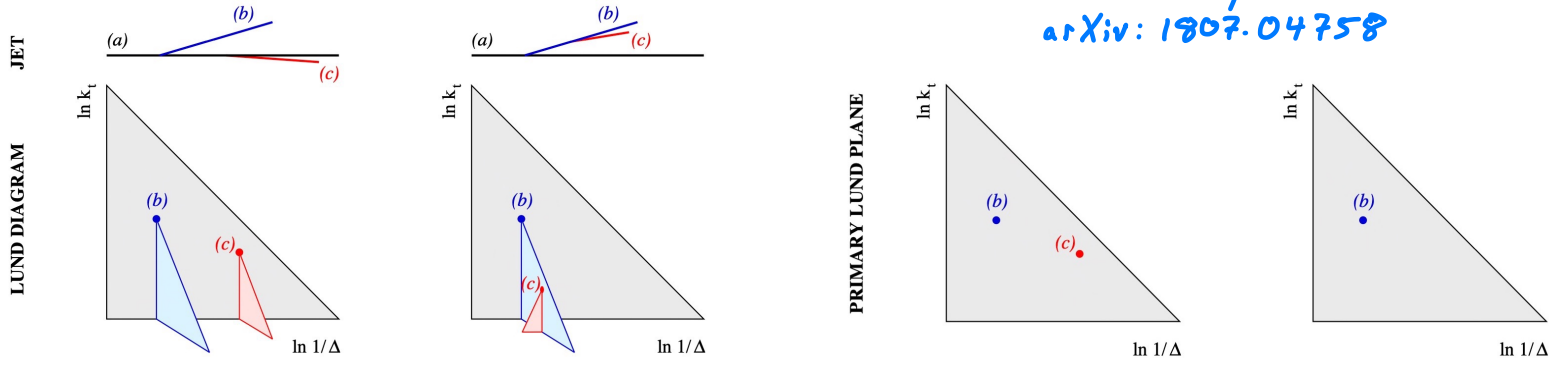
Lund Jet Plane

Tool to isolate hadronization effects

Recluster jet using Cambridge-Aachen algorithm (clusters according to distance in rapidity and φ)

Plot branchings in Lund Plane: angle Δ and transverse momentum k_T of emission wrt emitter

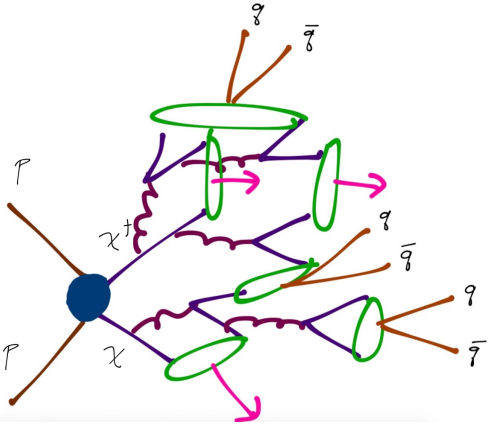
F. Dreyer, G. Salam, G. Soyez
arXiv: 1807.04758



Lund Dark Jet Plane

TC, J. Roloff, C. Scherb
arXiv: 2301.07732

Impact of Stages



Dark hadrons

Decay to SM quarks

SM parton Shower

SM hadrons