Dark Sector Searches at the LHC

Tim Cohen
CERN/EPFL
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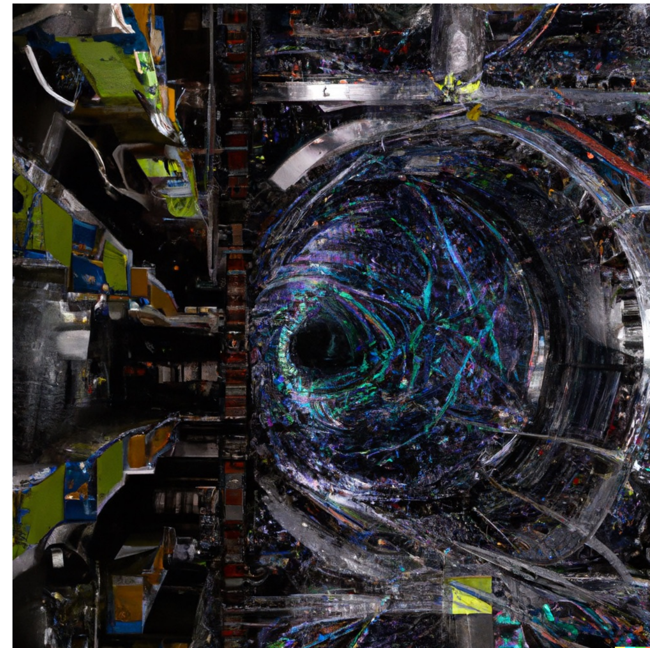
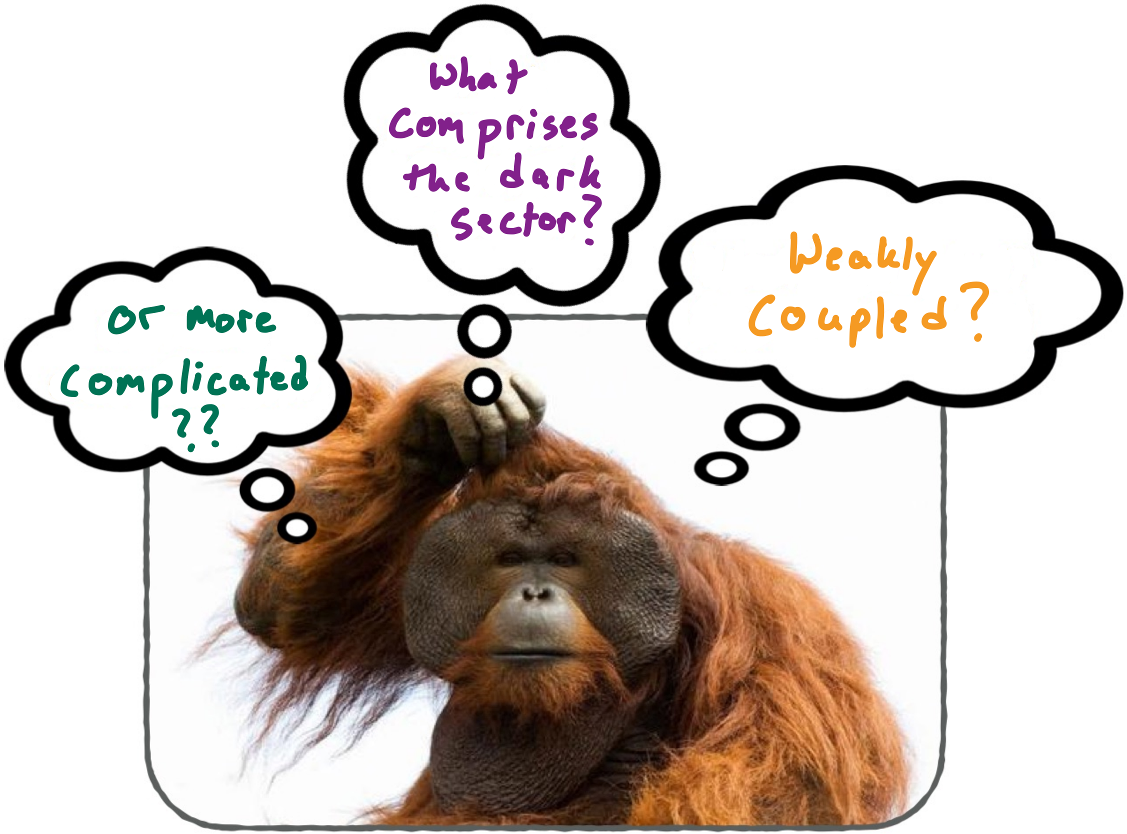
BSM Forum
+
Lund Jet Plane Institute

July 6, 2023



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

Deep Thoughts

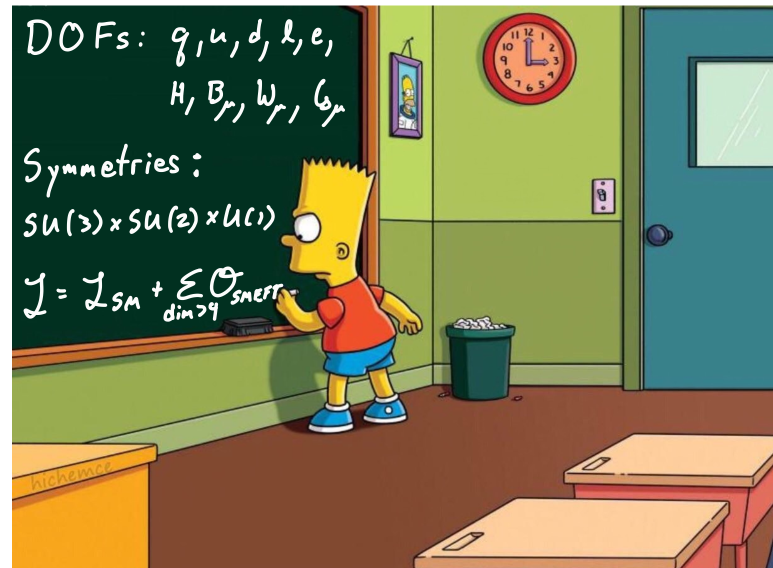


Practical Thoughts

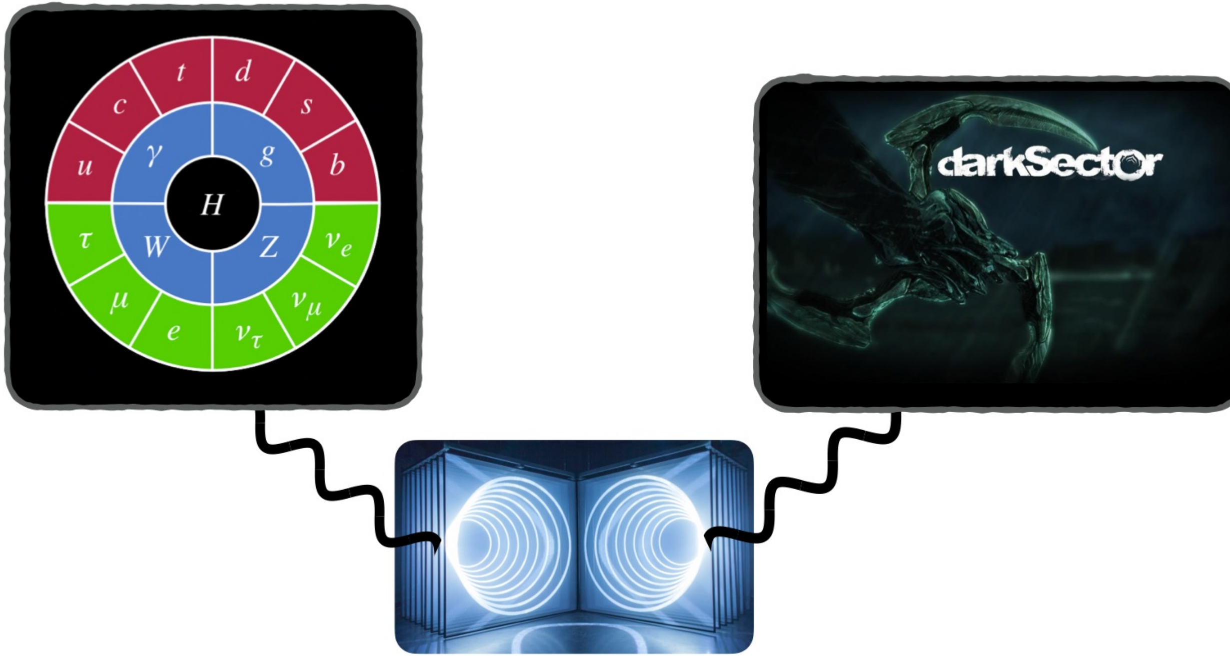
How to organize BSM predictions?

Simplified Models

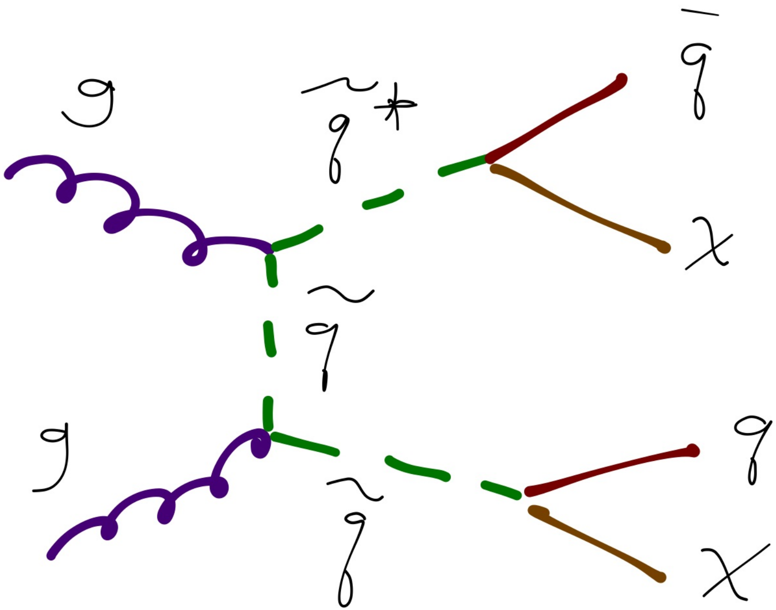
Effective Field Theory

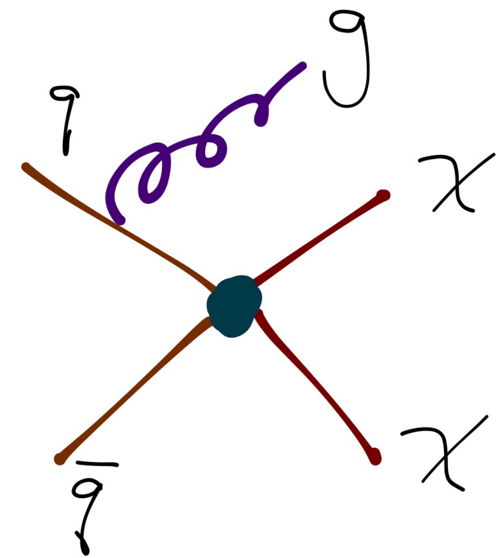


Dark Sector Paradigm

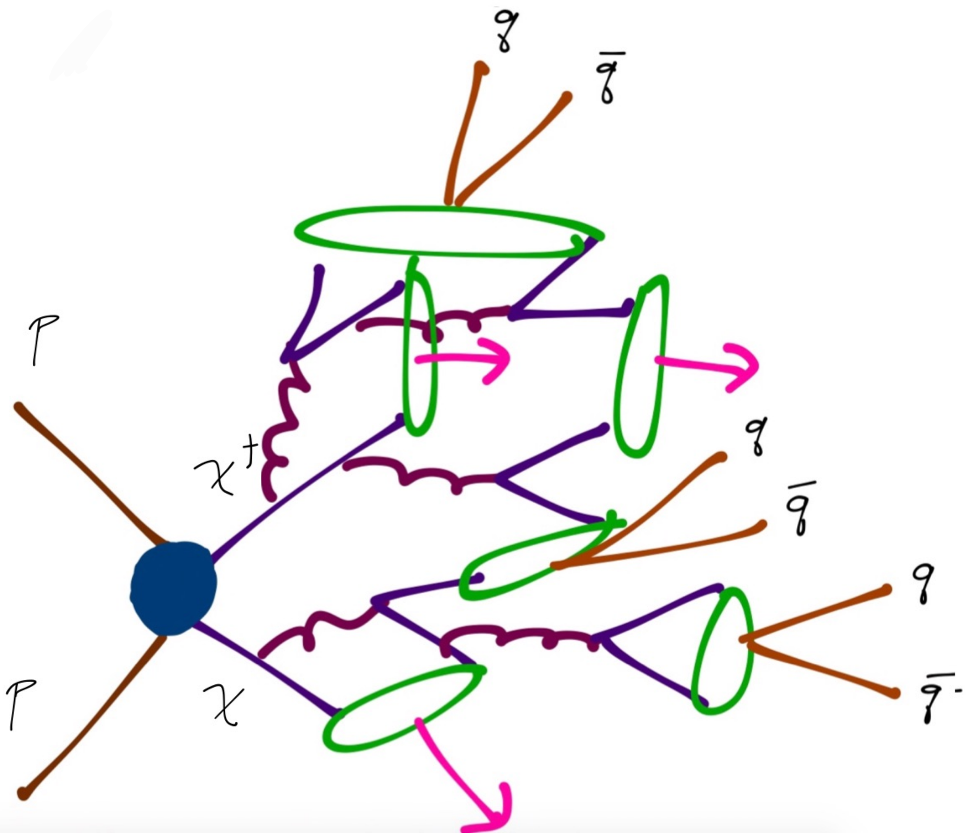


Weakly Coupled Dark Sector



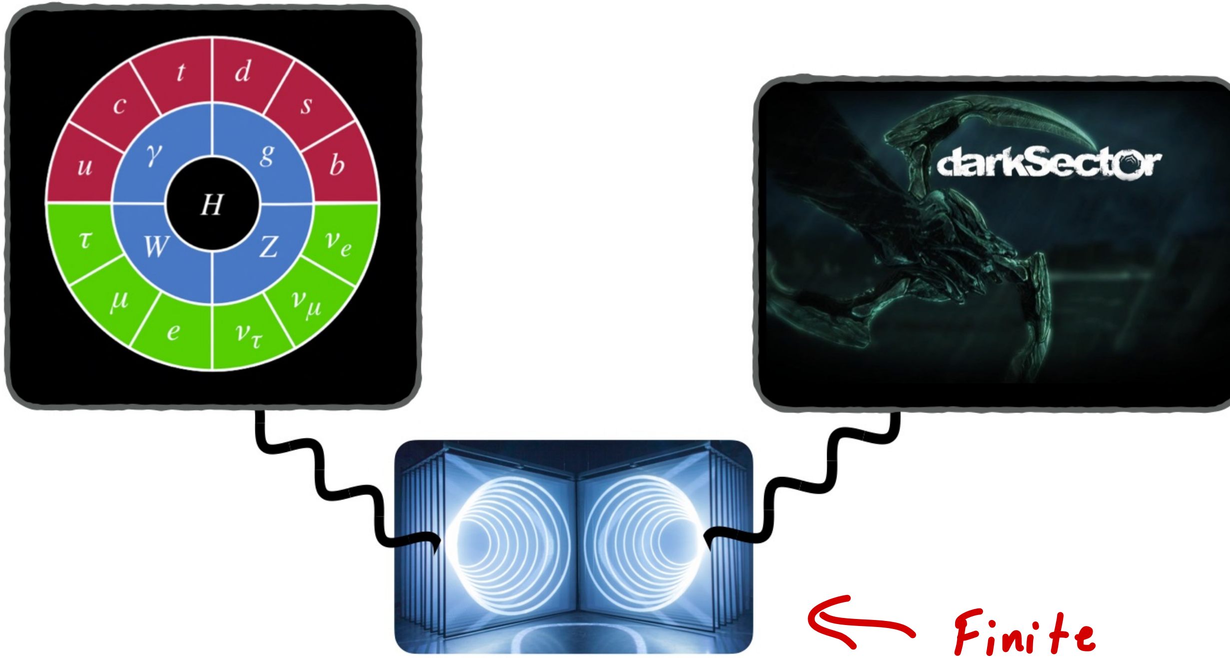


Strongly Coupled Dark Sector



Overwhelming Theory Space

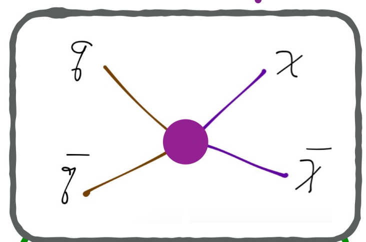
Fixed →



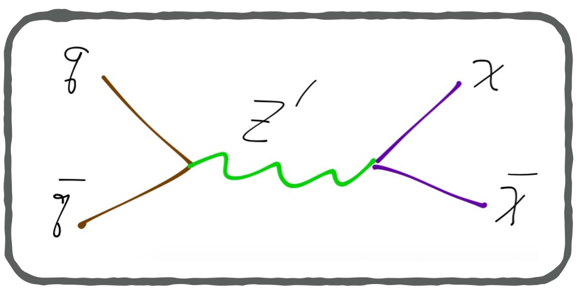
← Finite (renormalizable) options

Portal to Quarks

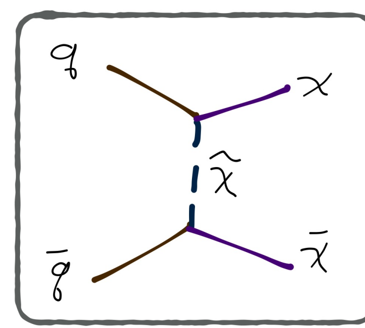
contact operator



s - channel



t - channel



Phenomena Driven

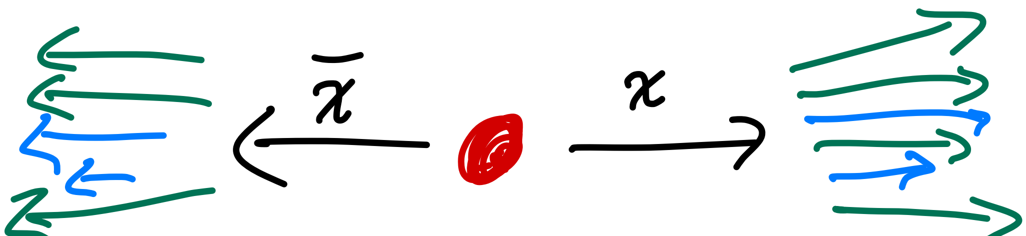
- Semi-visible jets
- Lepton jets
- Emerging jets
- Soft bombs
- Quirks
- Your awesome new idea?

Semi-visible Jets

Assume dark sector quarks χ dominantly interact with QCD.

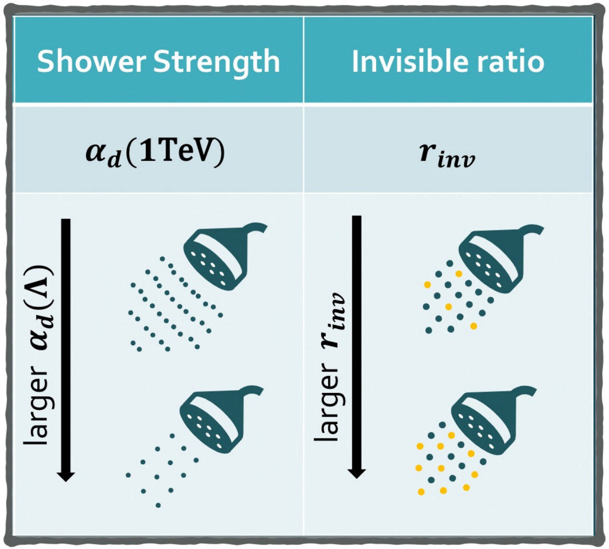
Some dark mesons π_D decay to QCD

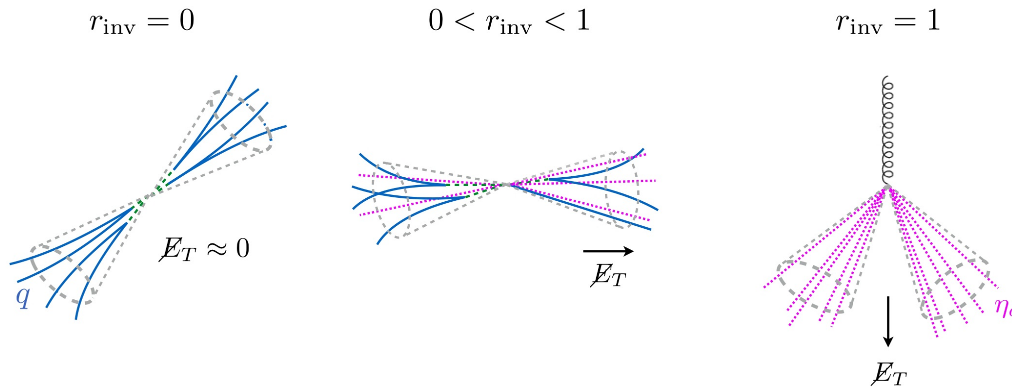
Some dark mesons π_D' are stable



Missing energy aligned with jets

Semi-visible Jets



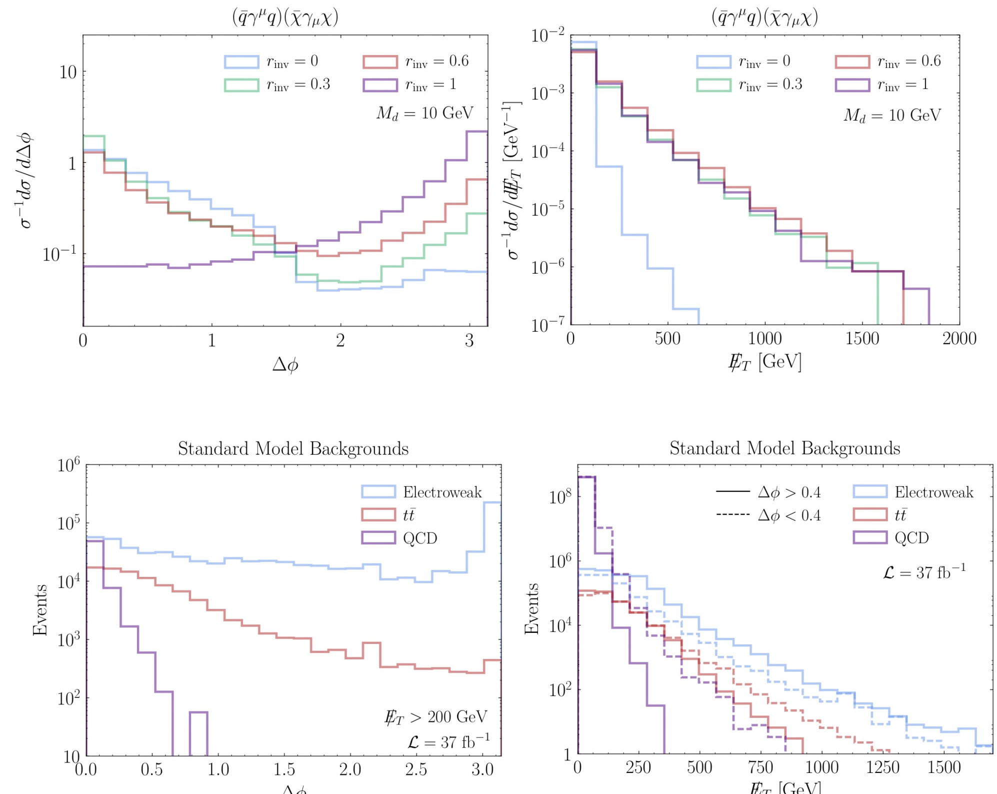


Pheno parametrization

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

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

Signal vs Background

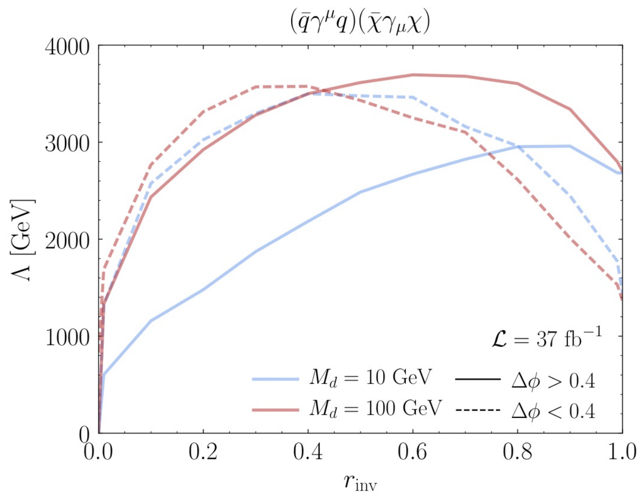


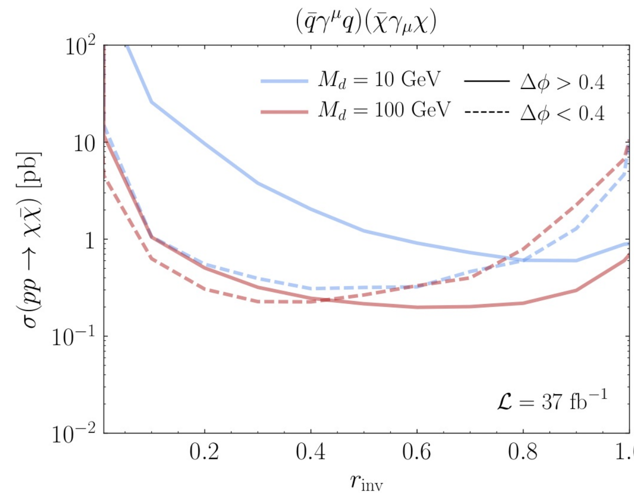
TC, M. Lisanti, H.K. Lou, S. Mishra-Sharma [arXiv:1707.05326]

Benchmarking

- Pick a portal: contact operator
- Pick some parameters: $\Lambda_d = 20\Lambda_{QCD}$
  $r_{inv} = 0.5$
  $m_d = 10$ GeV
- Determine limit on σ_{portal}

Projected Limits





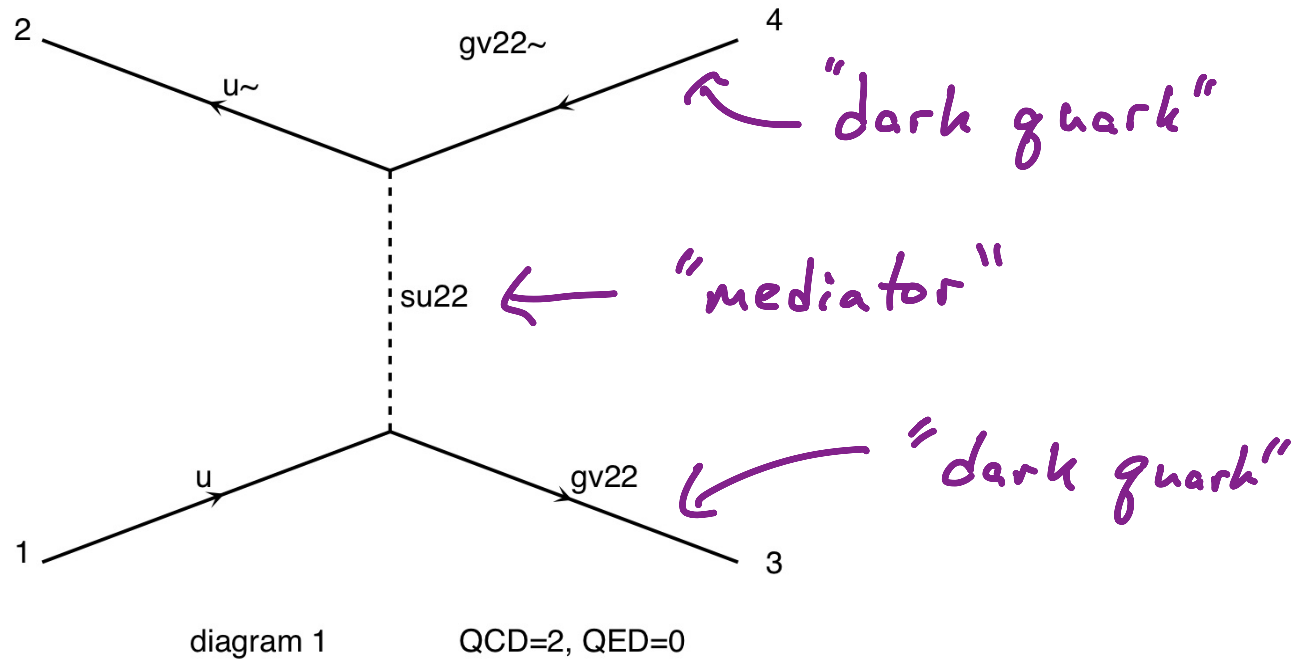
s-channel + t-channel models
see arXiv: 1707.05326

Model Dependence

Production	Pick portal $\Rightarrow \mathcal{L} \Rightarrow$ Perturbative
Showering	Pick # colors and # flavors $\Rightarrow$ Sudakov factor $\Rightarrow$ Parton shower
Hadronization	Need to know spectrum $\Rightarrow$ Fragmentation functions $\Rightarrow$ Non-perturbative
Decay	Depends on spectrum & portal

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"

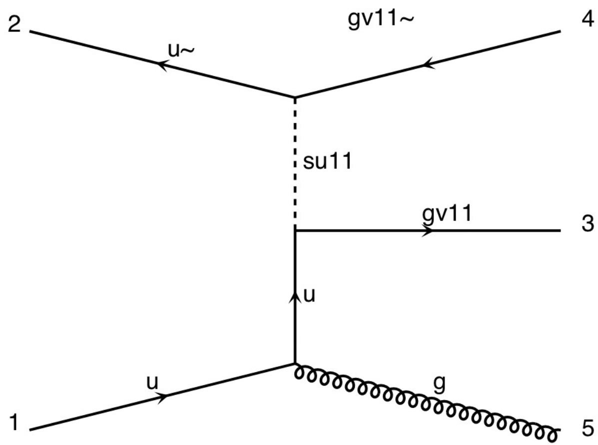


diagram 1 QCD=3, QED=0

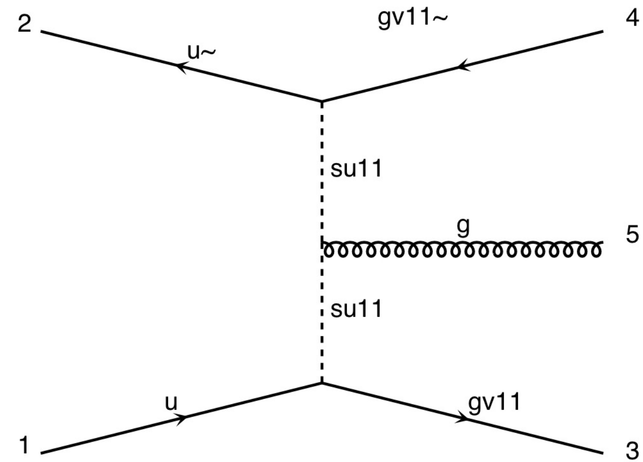


diagram 3 QCD=3, QED=0

+ ...

Production in t-Channel Model

Want higher body diagrams for "matching"

"on-shell" mediators

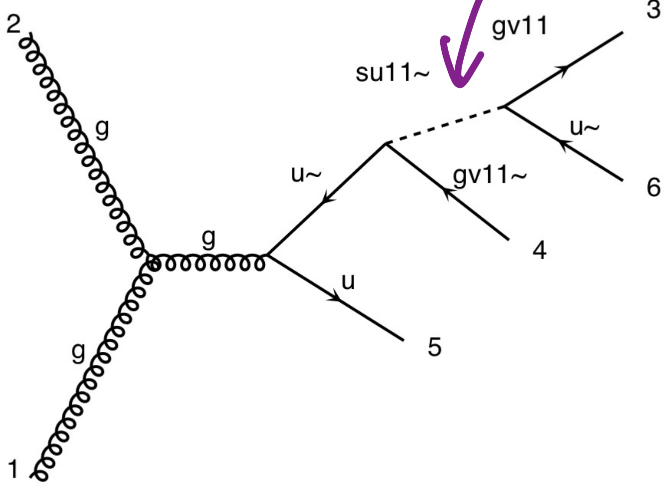


diagram 1 QCD=4, QED=0

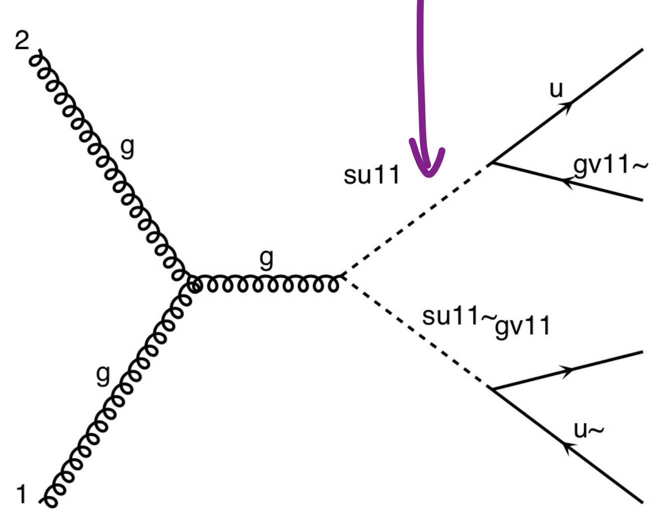
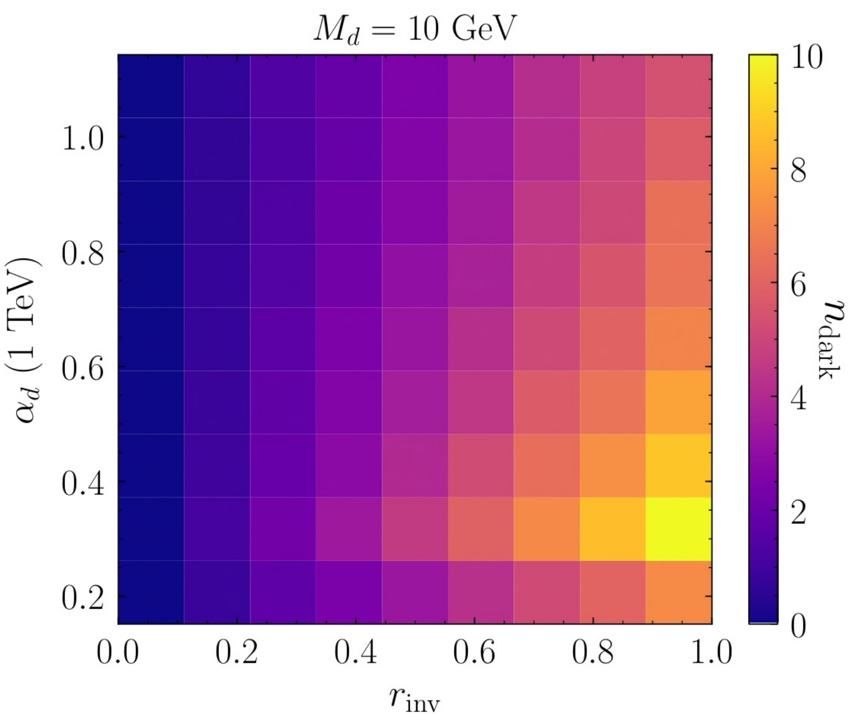


diagram 2 QCD=4, QED=0

+ . . .

Showering

Under reasonable theoretical control



Hadronization + Decay

Phenomenological model

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

  <u>but</u> exponential supression for producing heavy states

  ⇒ only care about lightest

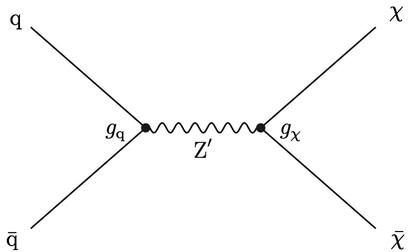
- Decay: Vector mesons decay fast

  Scalar mesons chirality supressed

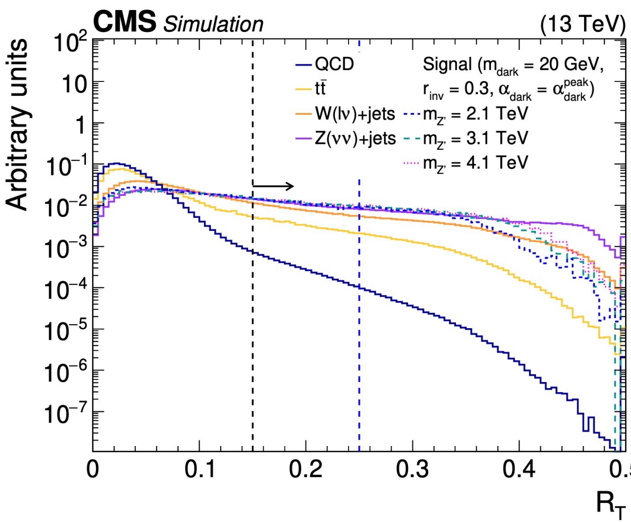
CMS Search

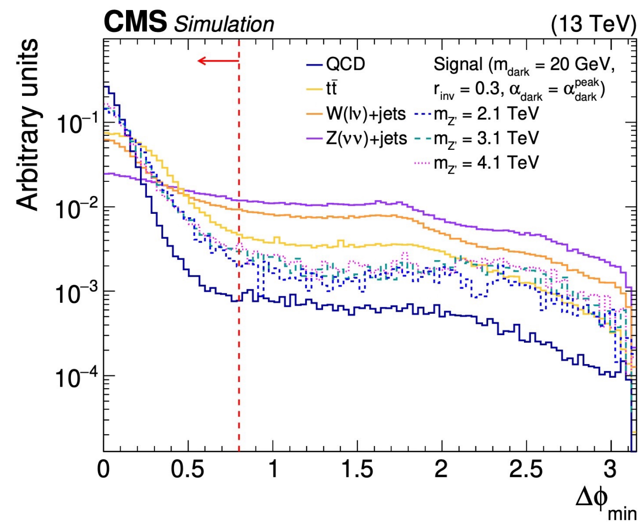
arXiv: 2112.11125

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}

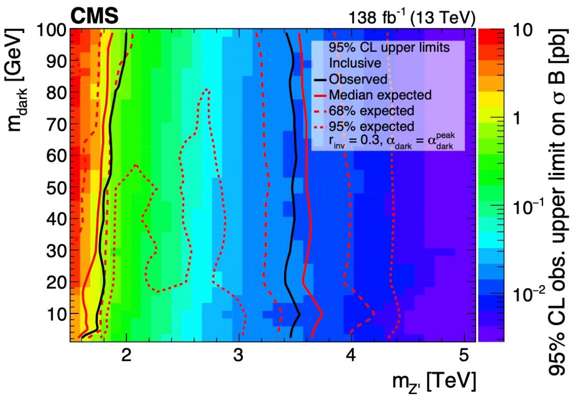


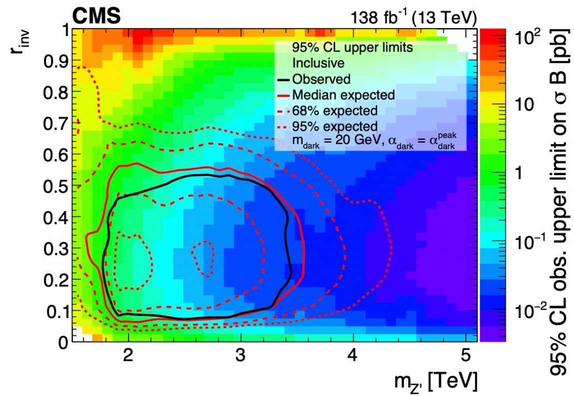


$$R_T = \frac{p_T^{miss}}{m_T}$$

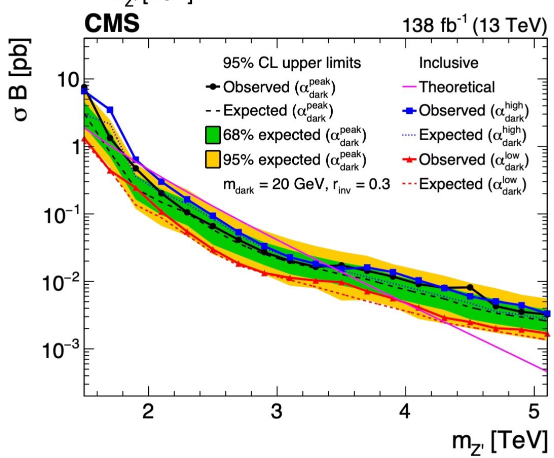
$\Delta\varphi_{min}$ is min angle between jets and $\vec{p}_T^{\,miss}$

CMS Search





Also provided stronger limits using BDT tagger



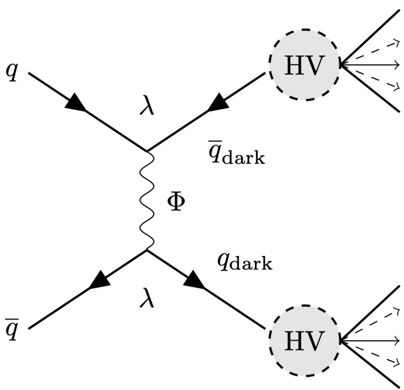
Preselection requirements
$p_T(J_{1,2}) > 200\,\text{GeV},\ \eta(J_{1,2}) < 2.4$
$R_T > 0.15$
$\Delta\eta(J_1, J_2) < 1.5$
$m_T > 1.5\,\text{TeV}$
$N_\mu = 0$
$N_e = 0$
p_T^{miss} filters
$\Delta R(j_{1,2}, c_{nonfunctional}) > 0.1$

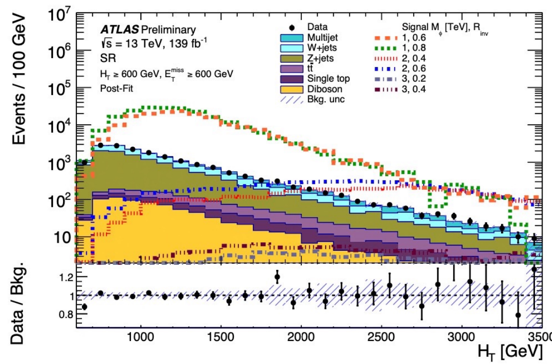
Final selection requirements
veto $f_\gamma(j_1) > 0.7$ & $p_T(j_1) > 1.0\,\text{TeV}$
veto $-3.05 < \eta_j < -1.35$ & $-1.62 < \phi_j < -0.82$ *
$\Delta\phi_{min} < 0.8$

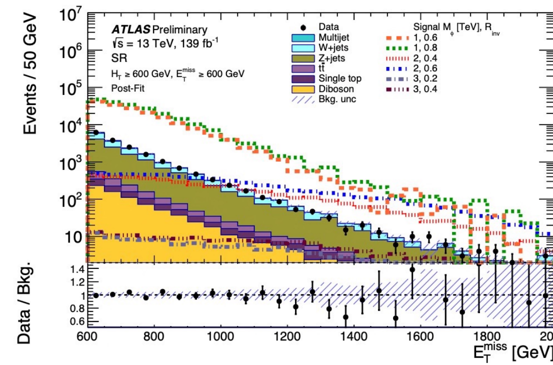
ATLAS Search

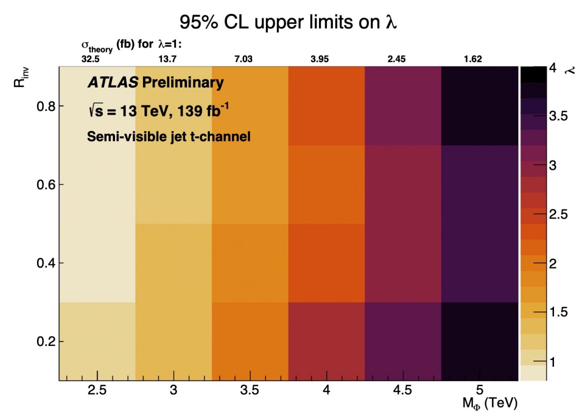
ATLAS-CONF-2022-038

t-channel model





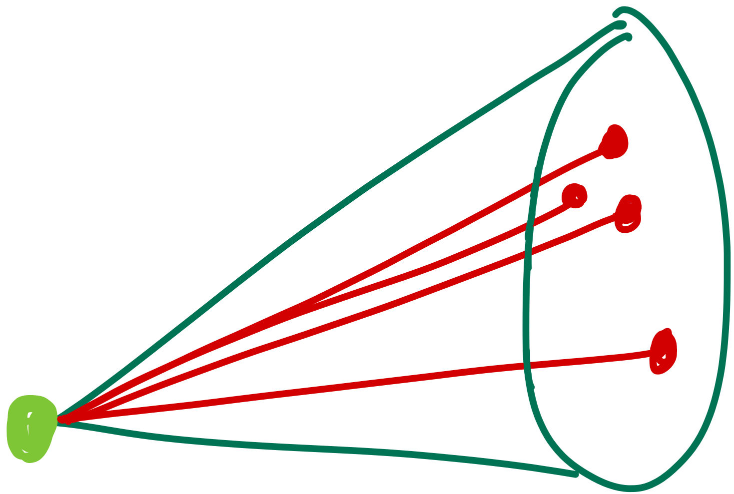




Frontiers

Better Observables?

Jet Substructure

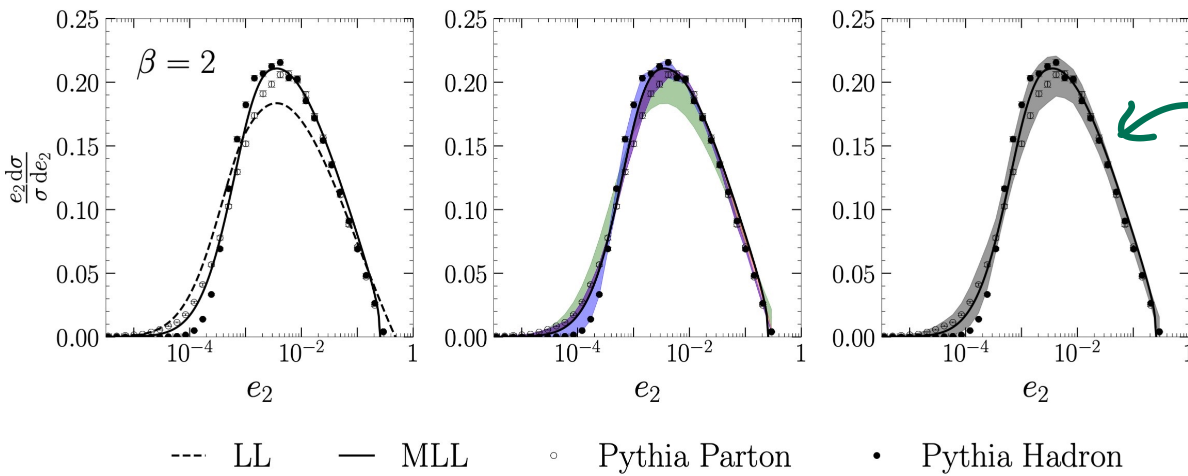


Dark Substructure

2-point correlation function

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

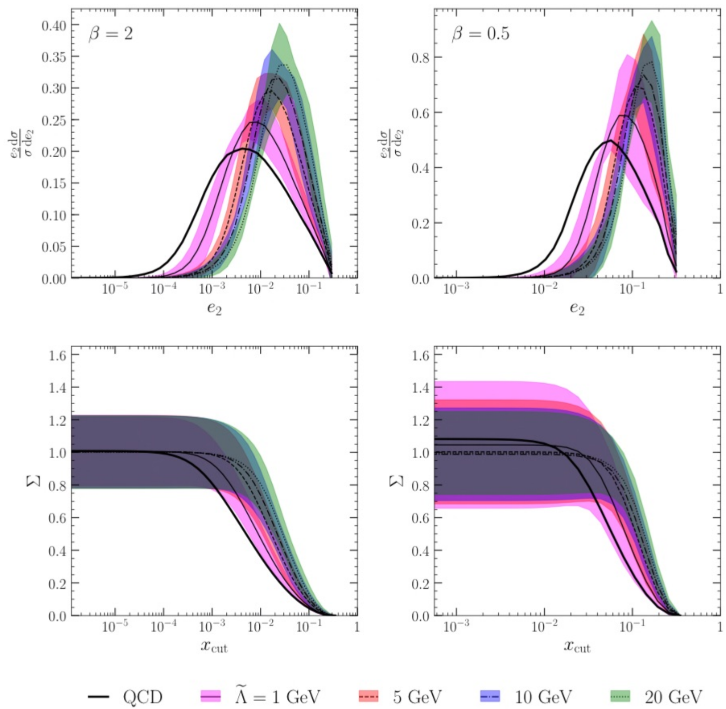
Generalization of jet mass ($\beta = 2$)



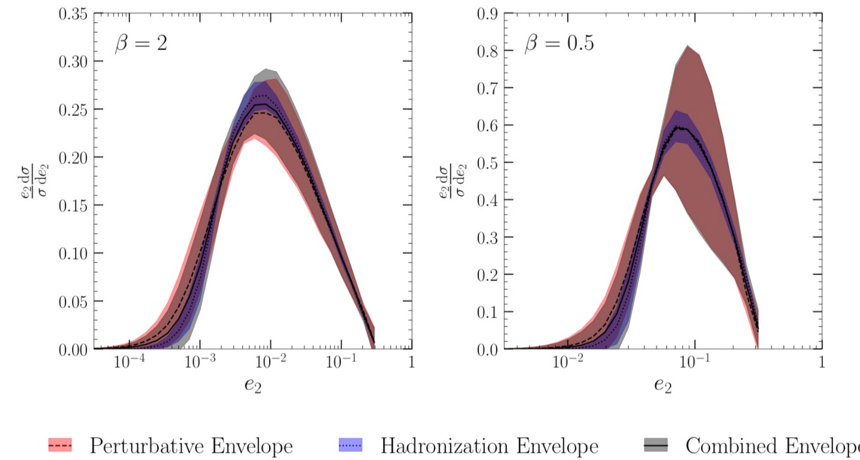
error envelope theory systematic

TC, Doss, Freytsis
arXiv: 2004.00631

Theoretical Errors



Hadronization



TC, Doss, Freytsis
arXiv: 2004.00631

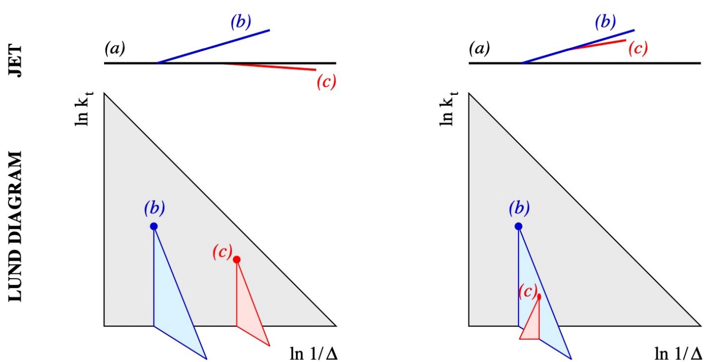
Lund Jet Plane

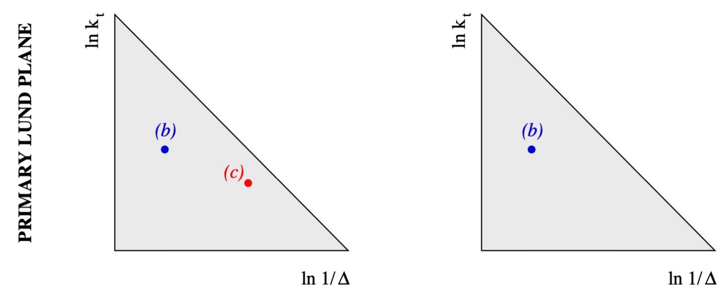
Tool to isolate hadronization effects

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

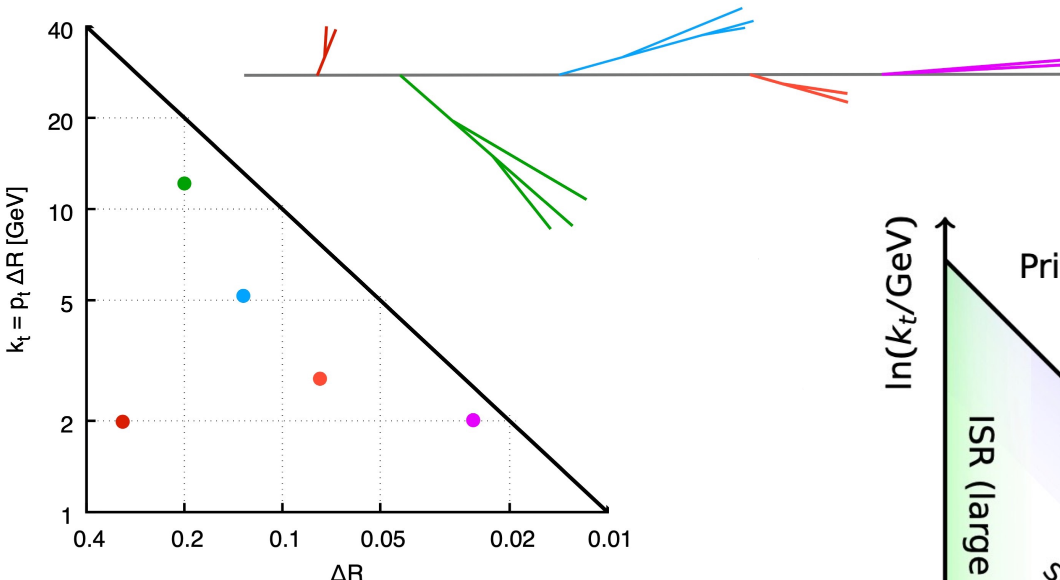
F. Dreyer, G. Salam,
G. Soyez
arXiv: 1807.04758



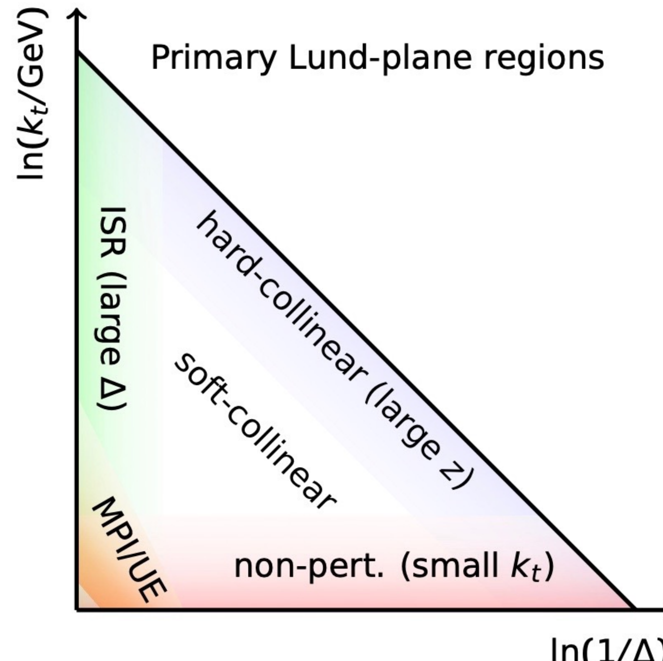


Lund Jet Plane

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



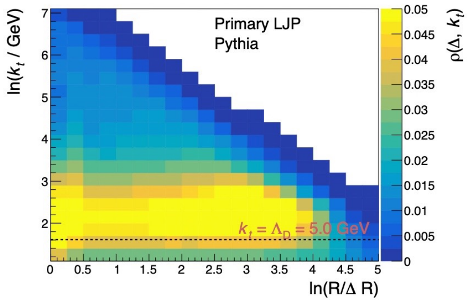
from talk by G. Salam

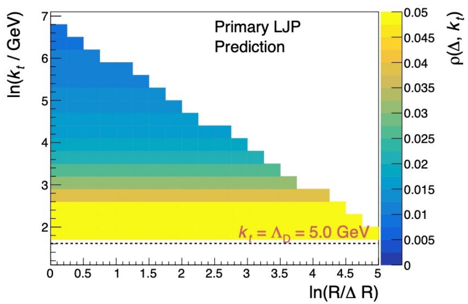


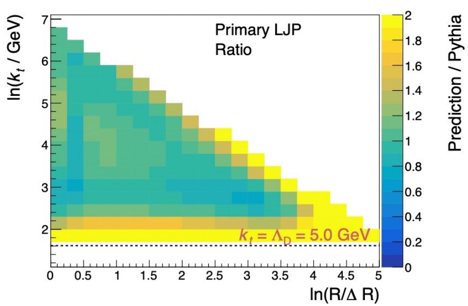
Average over many jets

Lund Dark Jet Plane

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





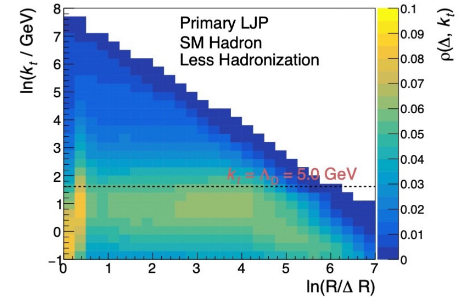


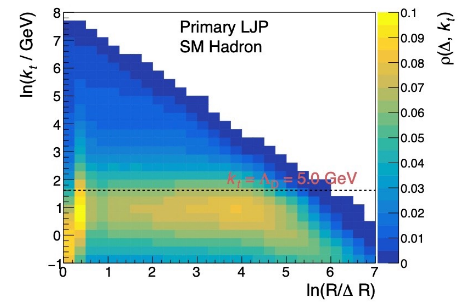
leading log density

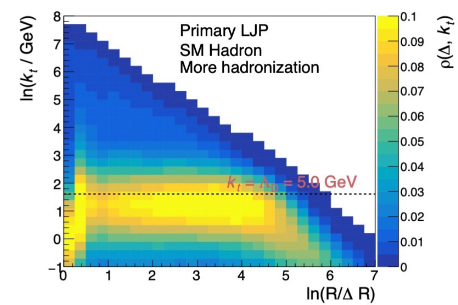
$$\sim \frac{2\alpha_D(k_t)\, C_F}{\pi}$$

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

for $SU(N)$





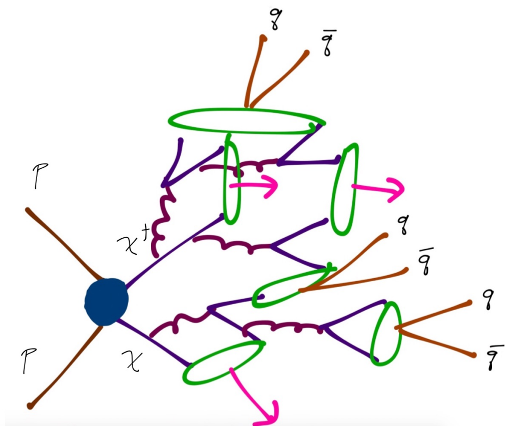


Varying hadronization

Lund Dark Jet Plane

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

Impact of Stages

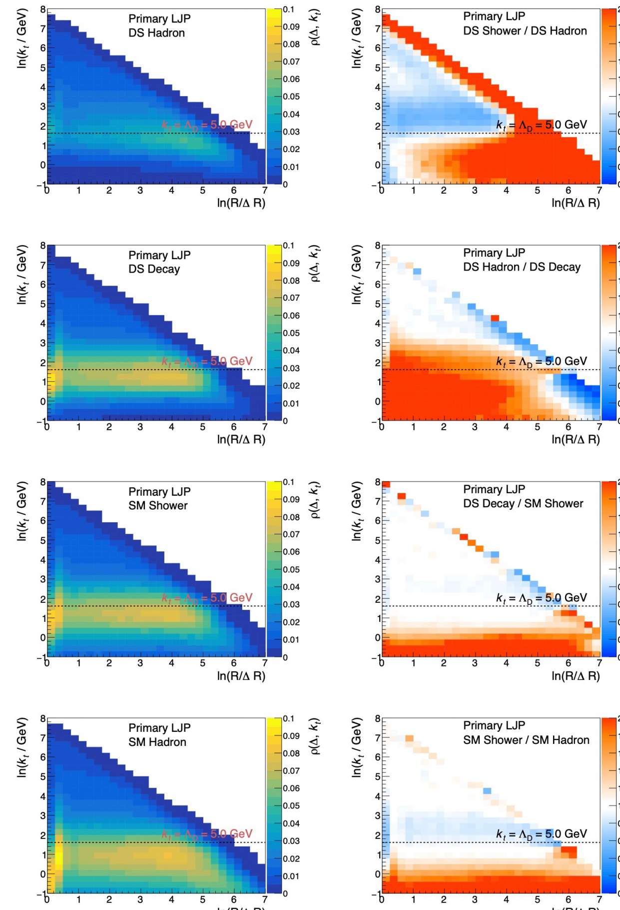


Dark hadrons

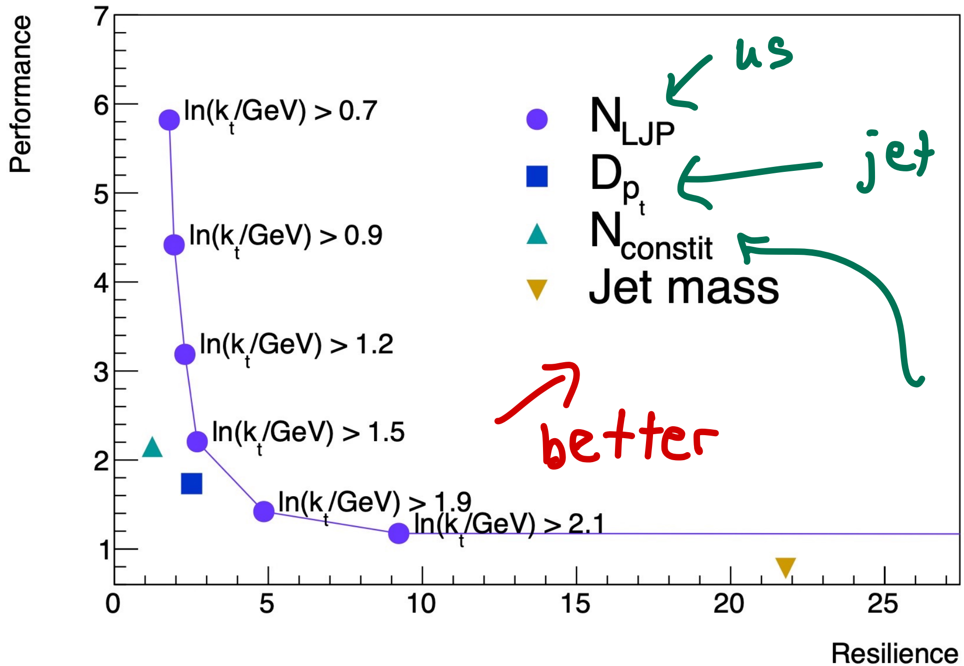
Decay to SM quarks

SM parton shower

SM hadrons



Performance vs Resilience



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

jet energy sharing

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

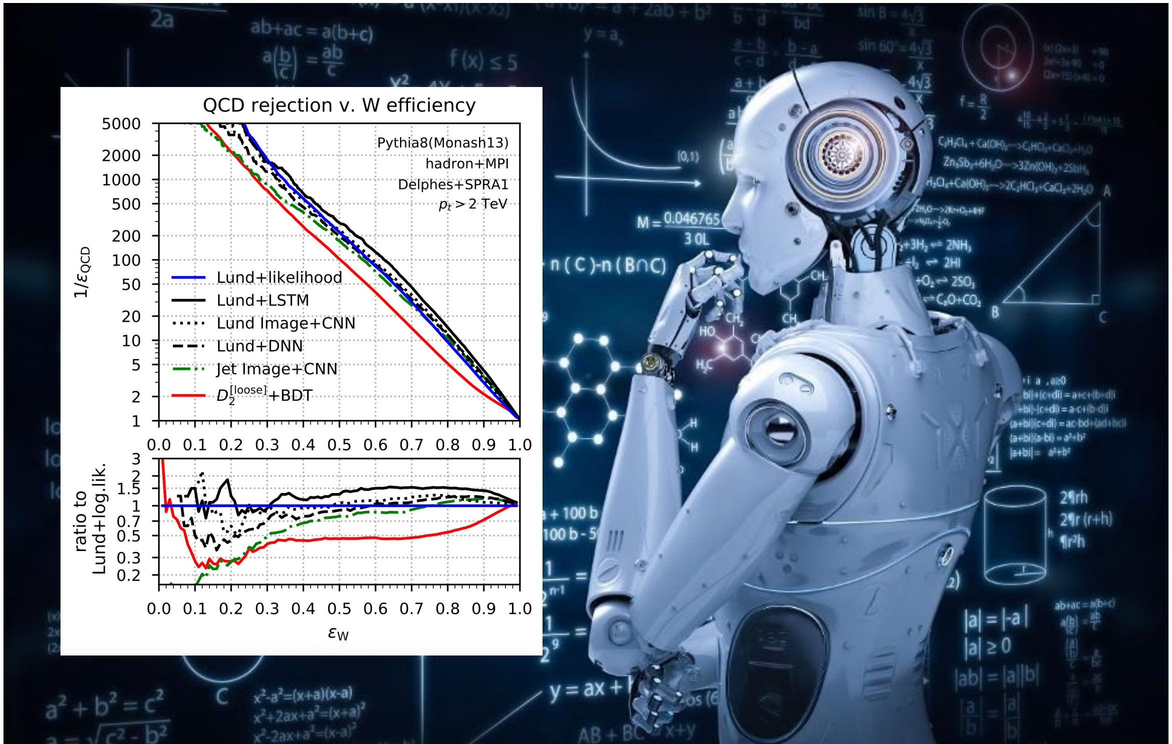
number of constituents

variation wrt hadronization →

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

Next step is to design search

Machine Learning

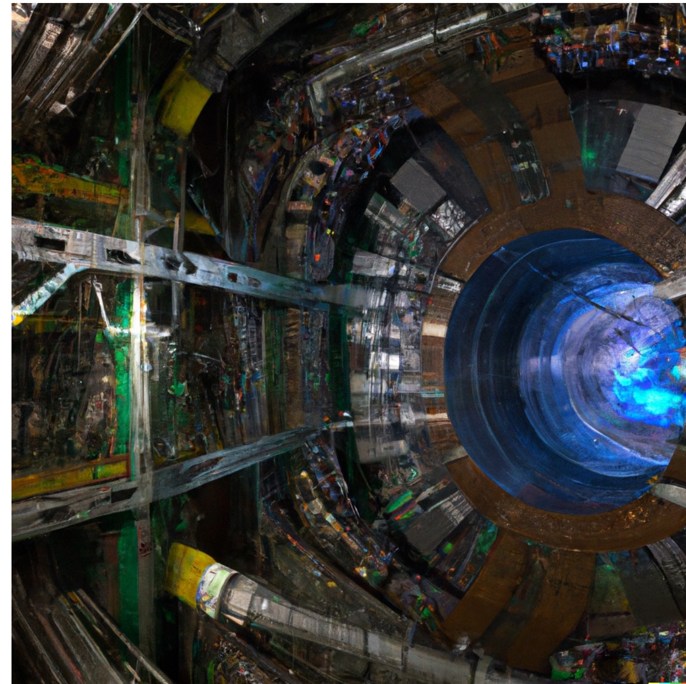


F. Dreyer, G. Salam,
G. Soyez
arXiv: 1807 04758

New Phenomena?

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

CMS Search

Preselection requirements
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$R_T > 0.15$
$\Delta\eta(J_1, J_2) < 1.5$
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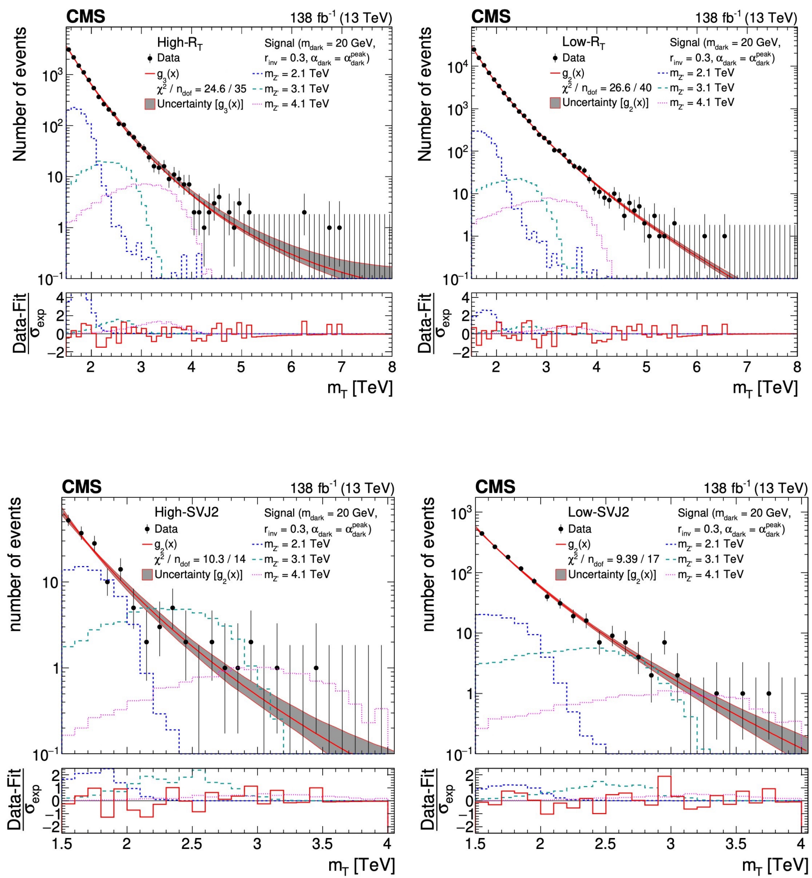
$N_\mu = 0$
$N_e = 0$
p_T^{miss} filters
$\Delta R(j_{1,2}, c_{\text{nonfunctional}}) > 0.1$

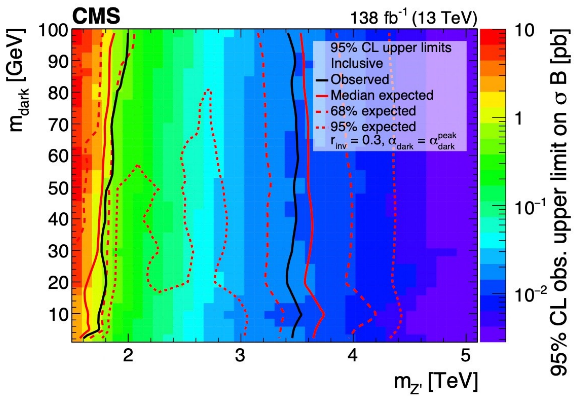
Final selection requirements
veto $f_\gamma(j_1) > 0.7$ & $p_T(j_1) > 1.0\,\text{TeV}$
veto $-3.05 < \eta_j < -1.35$ & $-1.62 < \phi_j < -0.82$ *
$\Delta\phi_{\text{min}} < 0.8$

CMS Search

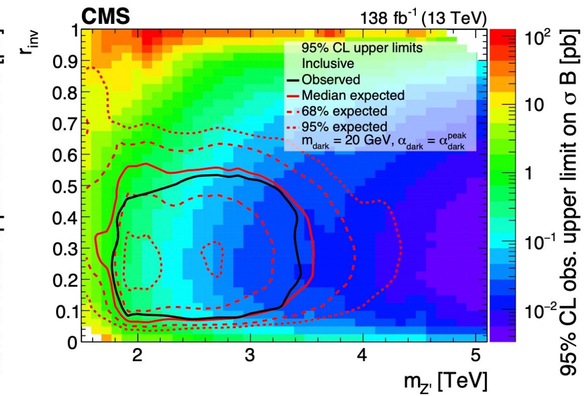


CMS
138 fb^{-1} (13 TeV)
High-R_T
Data
$g_3(x)$
χ^2 / n_{dof} = 24.6 / 35
Uncertainty [$g_3(x)$]
Signal (m_{dark} = 20 GeV, r_{inv} = 0.3, $\alpha_{dark} = \alpha_{dark}^{peak}$)
$m_{Z'}$ = 2.1 TeV
$m_{Z'}$ = 3.1 TeV
$m_{Z'}$ = 4.1 TeV
Number of events
$\frac{\text{Data-Fit}}{\sigma_{exp}}$
m_T [TeV]
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, $\alpha_{dark} = \alpha_{dark}^{peak}$)
$m_{Z'}$ = 2.1 TeV
$m_{Z'}$ = 3.1 TeV
$m_{Z'}$ = 4.1 TeV
Number of events
$\frac{\text{Data-Fit}}{\sigma_{exp}}$
m_T [TeV]
CMS
138 fb^{-1} (13 TeV)
High-SVJ2
Data
$g_2(x)$
χ^2 / n_{dof} = 10.3 / 14
Uncertainty [$g_2(x)$]
Signal (m_{dark} = 20 GeV, r_{inv} = 0.3, $\alpha_{dark} = \alpha_{dark}^{peak}$)
$m_{Z'}$ = 2.1 TeV
$m_{Z'}$ = 3.1 TeV
$m_{Z'}$ = 4.1 TeV
number of events
$\frac{\text{Data-Fit}}{\sigma_{exp}}$
m_T [TeV]
CMS
138 fb^{-1} (13 TeV)
Low-SVJ2
Data
$g_2(x)$
χ^2 / n_{dof} = 9.39 / 17
Uncertainty [$g_2(x)$]
Signal (m_{dark} = 20 GeV, r_{inv} = 0.3, $\alpha_{dark} = \alpha_{dark}^{peak}$)
$m_{Z'}$ = 2.1 TeV
$m_{Z'}$ = 3.1 TeV
$m_{Z'}$ = 4.1 TeV
number of events
$\frac{\text{Data-Fit}}{\sigma_{exp}}$
m_T [TeV]

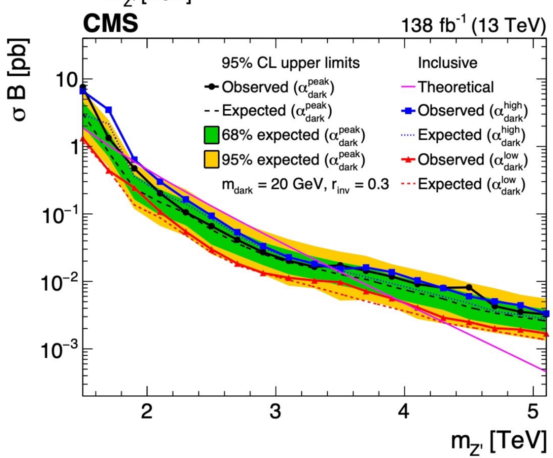
CMS Search



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]

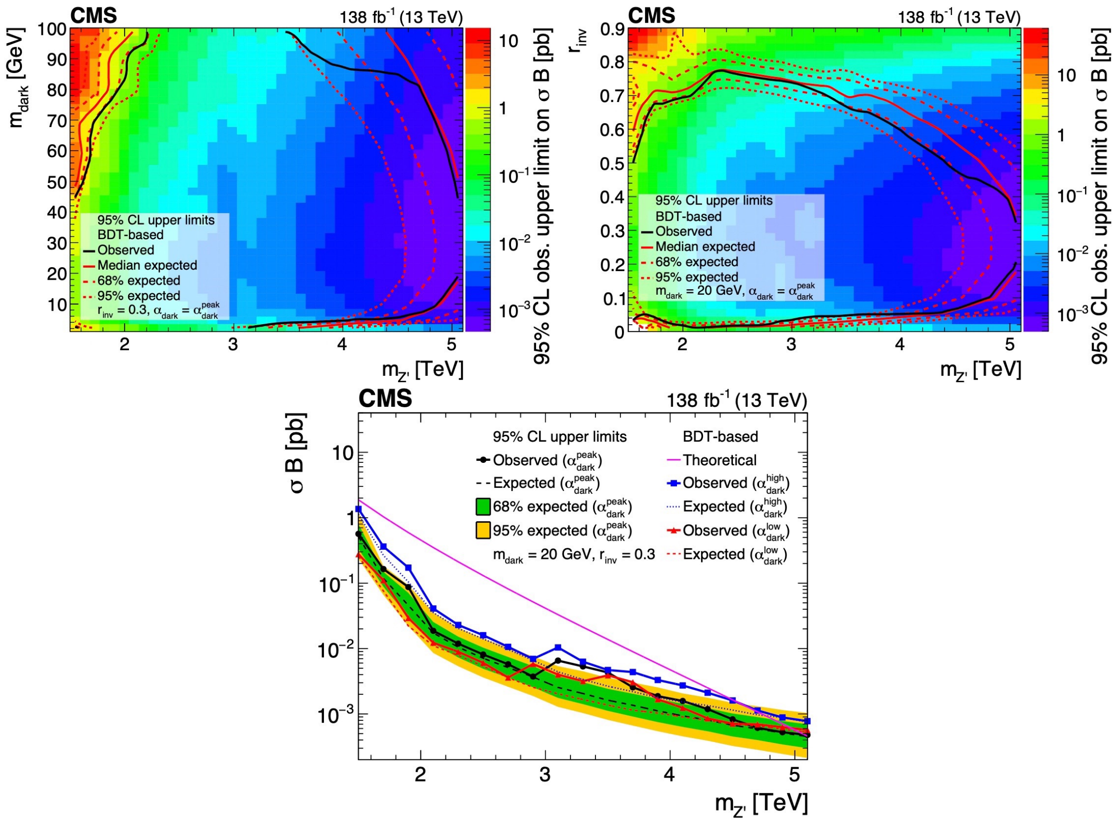


CMS
138 fb^{-1} (13 TeV)
95% CL upper limits
Inclusive
Observed
Median expected
68% expected
95% expected
m_{dark} = 20 GeV, $\alpha_{dark} = \alpha_{dark}^{peak}$
r_{inv}
$m_{Z'}$ [TeV]
95% CL obs. upper limit on σ B [pb]



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})
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})
σ B [pb]
$m_{Z'}$ [TeV]

CMS Search


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