

Dark Sector Searches at the LHC

Tim Cohen

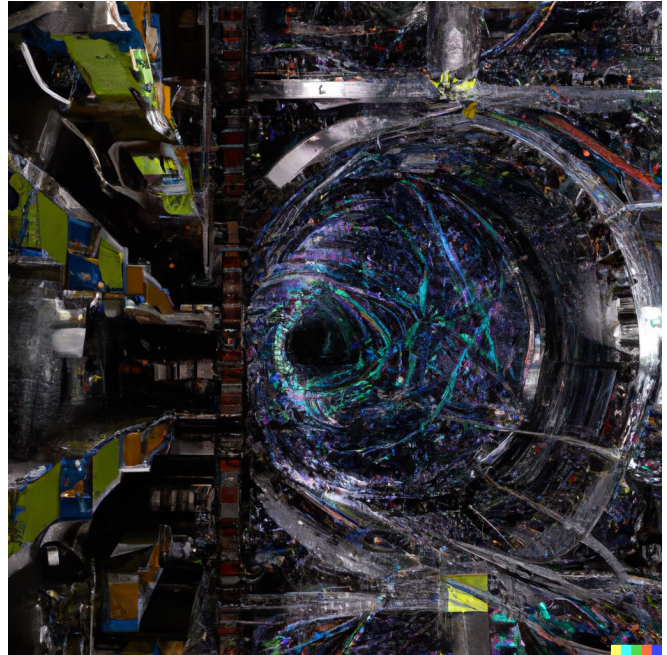
CERN/EPFL

U Oregon

Nanjing Normal U

PAC Webinar - 47

April 12, 2023



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

Deep Thoughts



Practical Thoughts

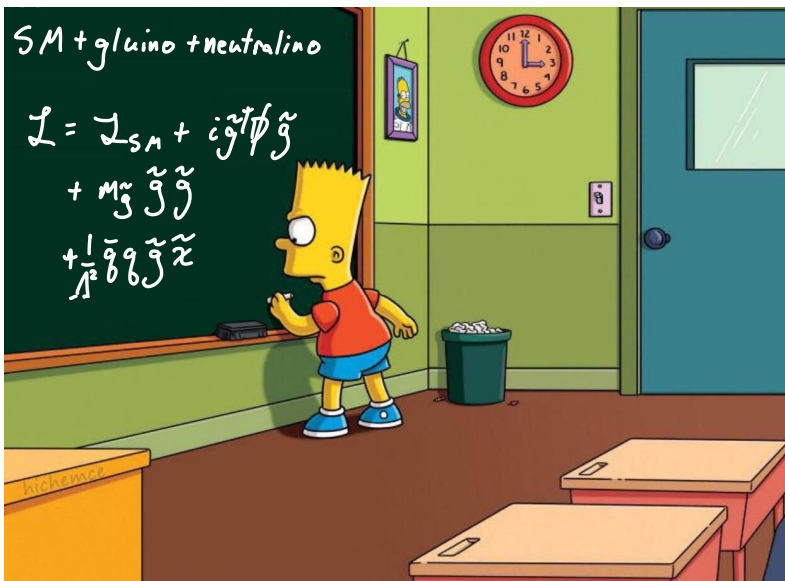
How do we ensure
discovery????

Can we better optimize
searches????

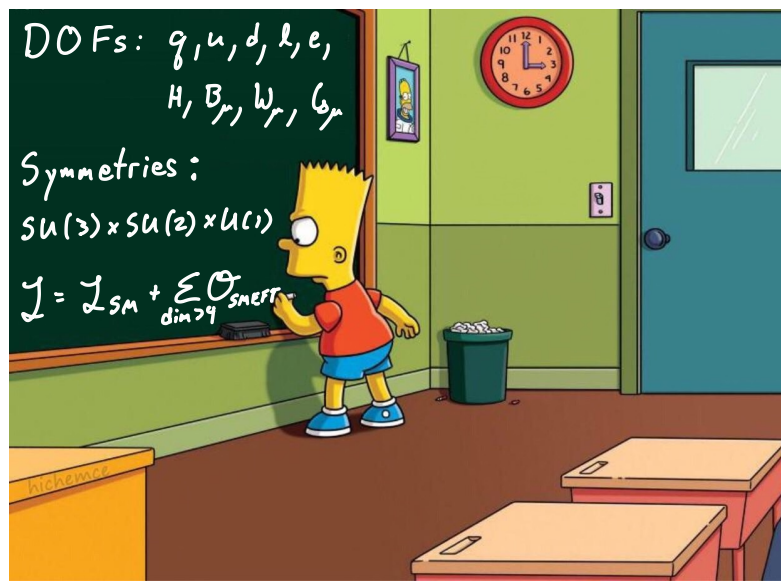


How to organize BSM predictions?

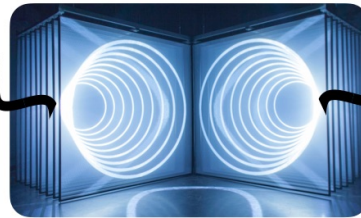
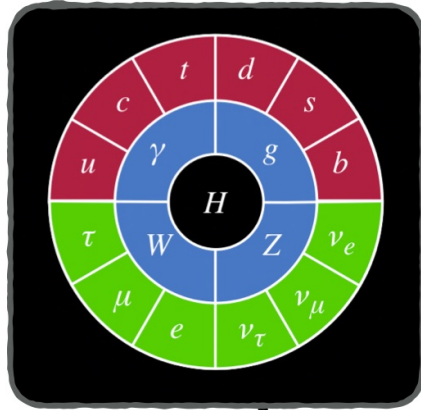
Simplified Models



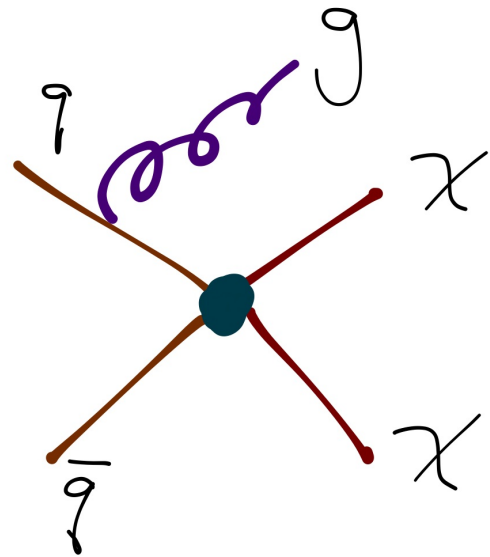
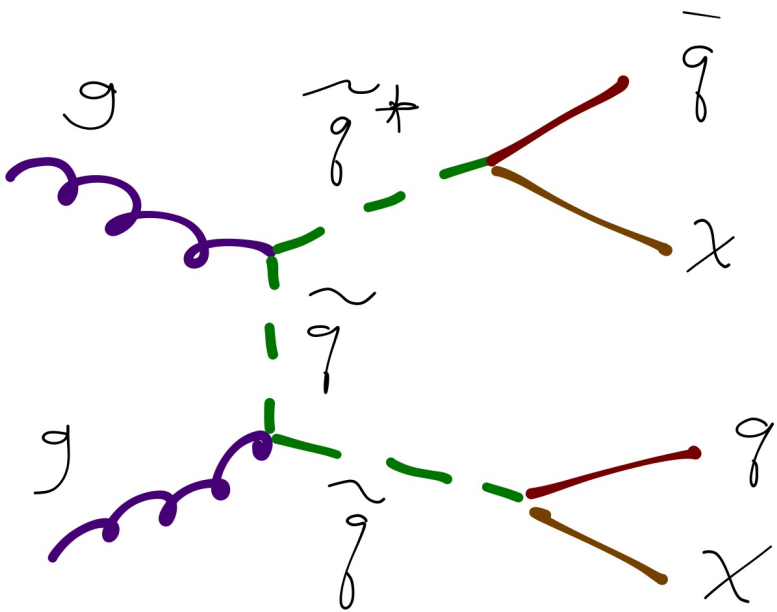
Effective Field Theory



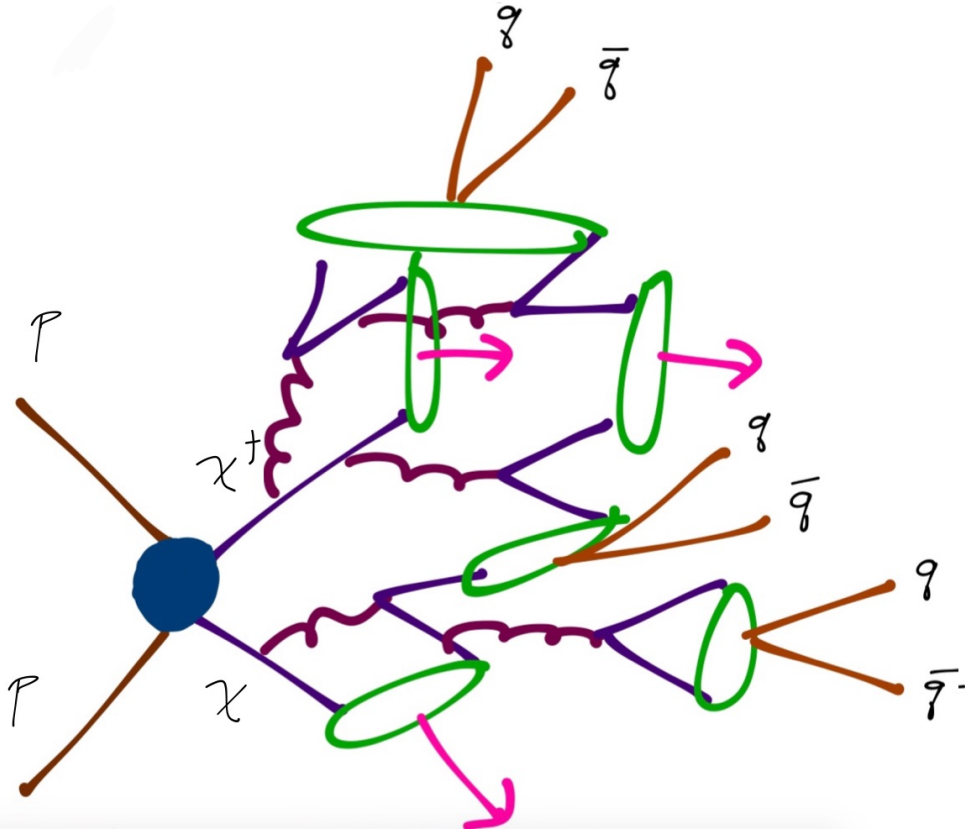
Dark Sector Paradigm



Weakly Coupled Dark Sector

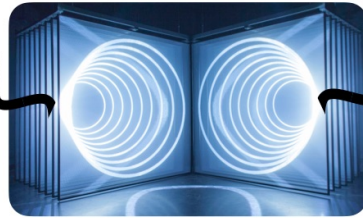
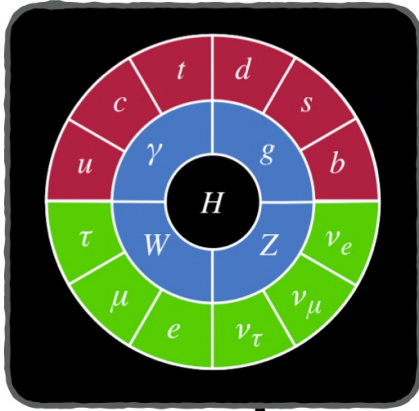


Strongly Coupled Dark Sector



Overwhelming Theory Space

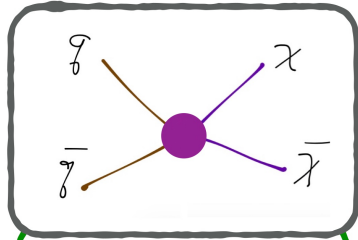
Fixed →



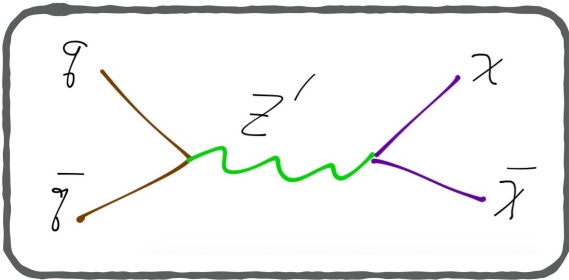
← Finite
(renormalizable)
options

Portal to Quarks

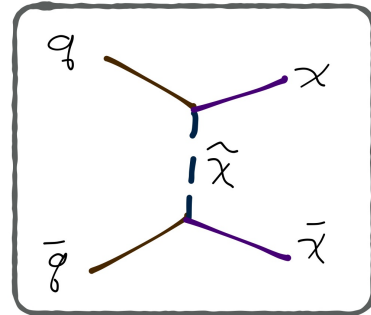
contact operator



s-channel



t-channel

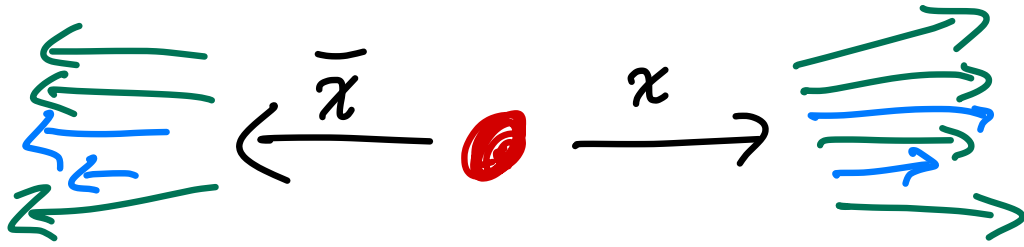


Phenomena Driven

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

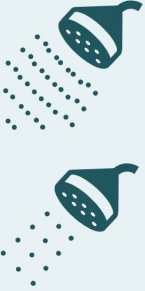

Semi-visible Jets

Assume dark sector quarks χ dominantly interact with QCD.
Some dark mesons Π_D decay to QCD
Some dark mesons Π_D' are stable

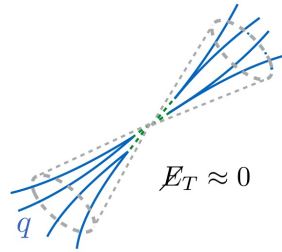


Missing energy aligned with jets

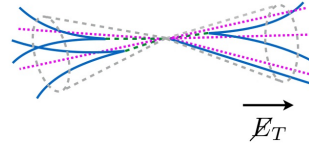
Semi-visible Jets

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

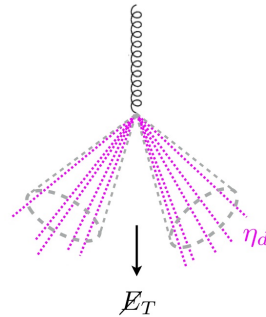
$$r_{inv} = 0$$



$$0 < r_{inv} < 1$$



$$r_{inv} = 1$$

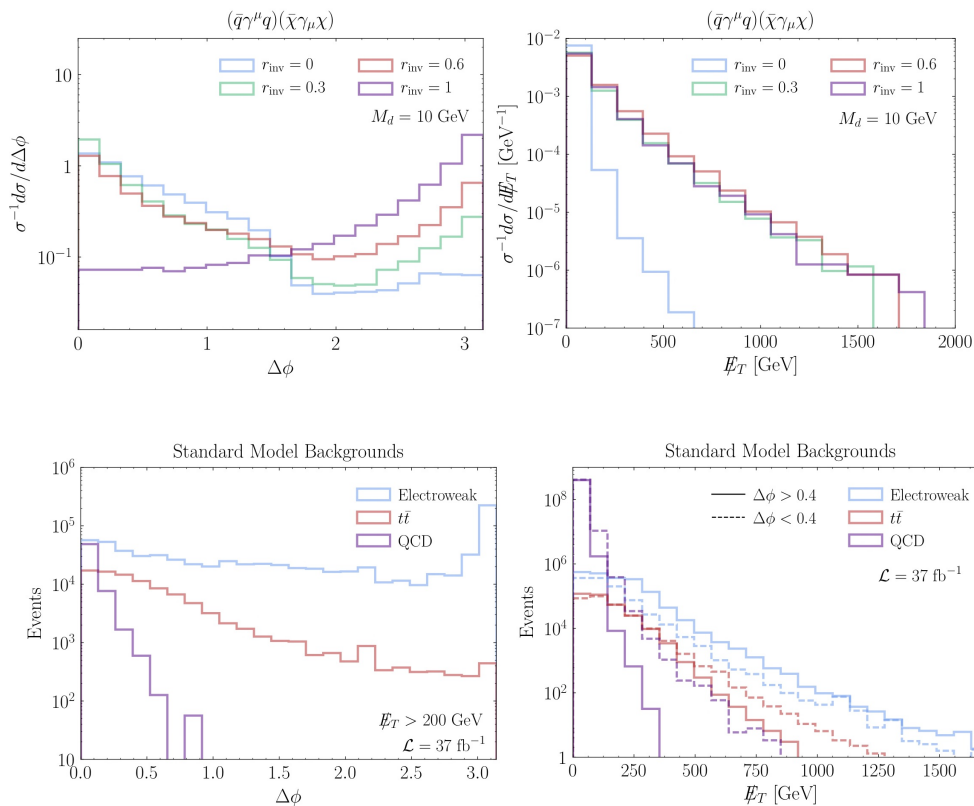


Pheno parametrization

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

- α_d (or Λ_d)
- Γ_{inv}
- M_d
- \mathcal{O}_{portal}

Signal vs Background

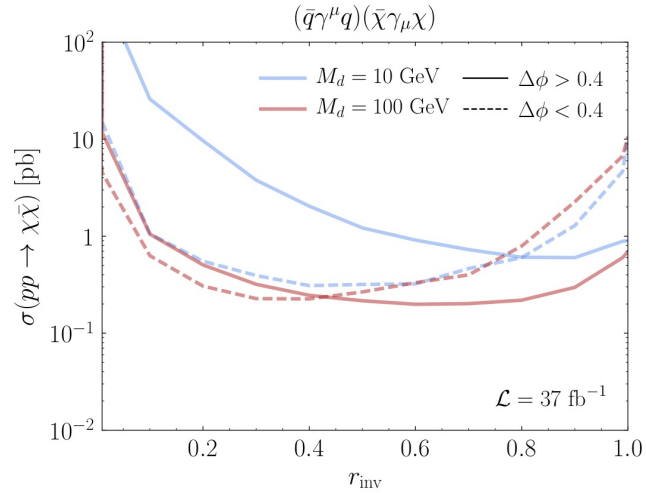
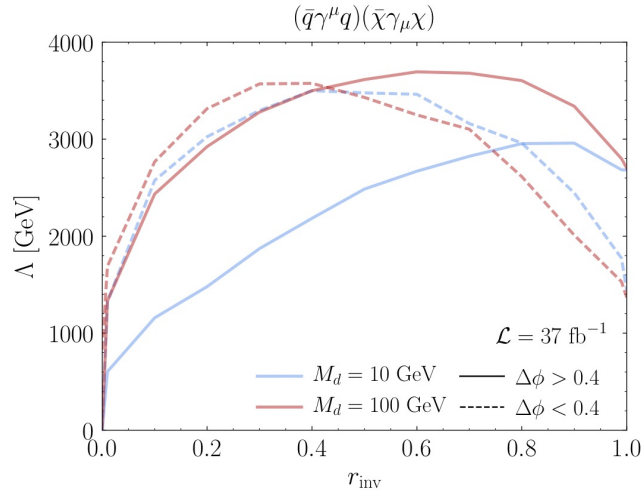


TL, M. Lisanti, H.-k. Lou, S. Mishra-Sharma [arXiv:1707.05326]

Benchmarking

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

Projected Limits



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

Model Dependence

Production Pick portal $\Rightarrow \mathcal{L} \Rightarrow$ Perturbative

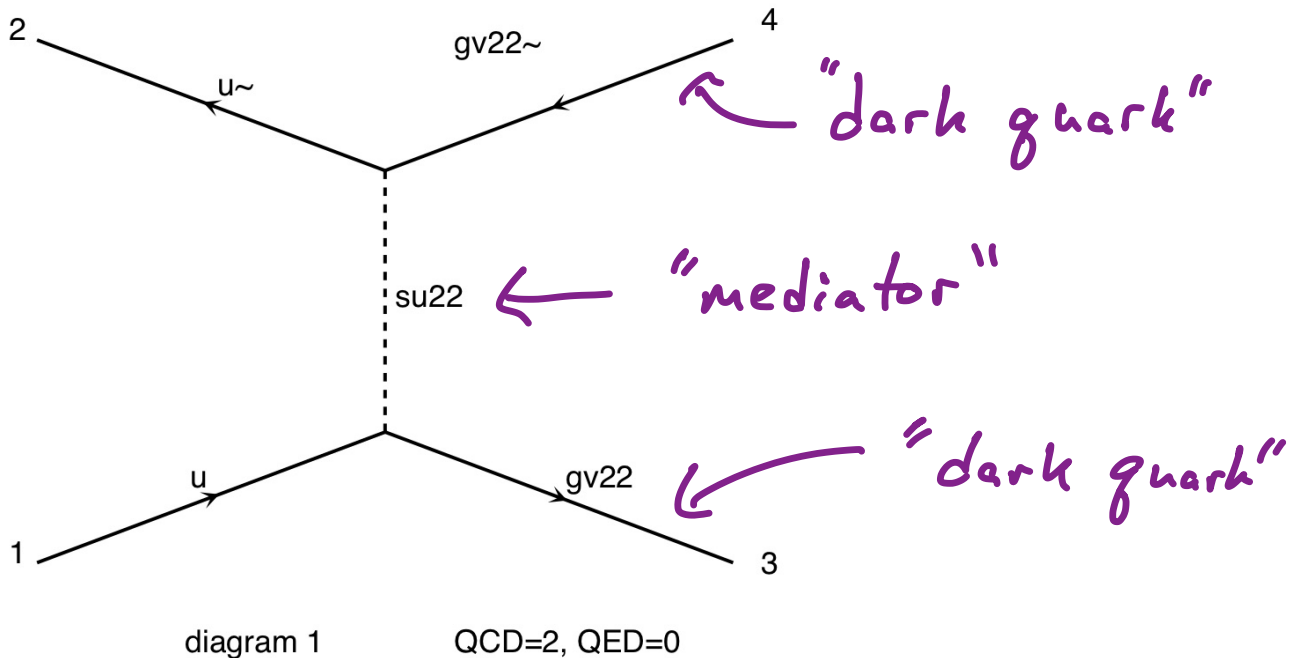
Showering Pick # colors and # flavors \Rightarrow
Sudakov factor \Rightarrow Parton shower

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"

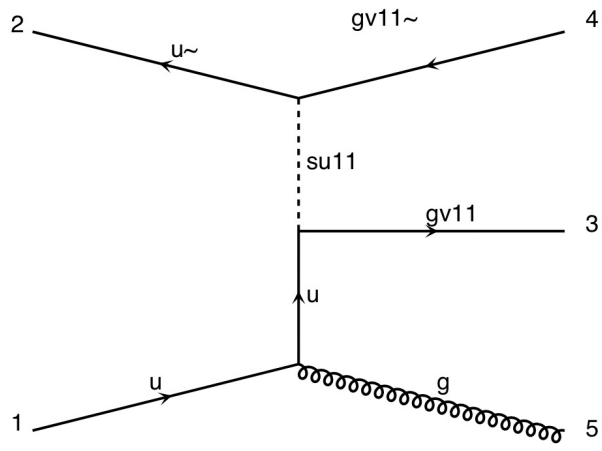


diagram 1 QCD=3, QED=0

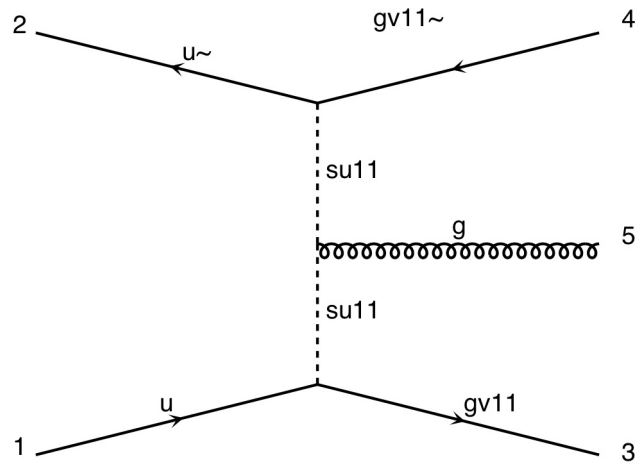


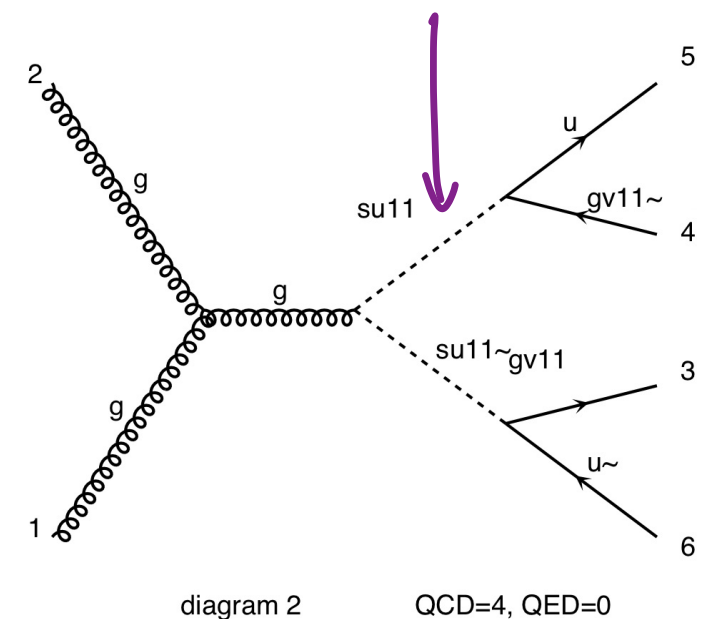
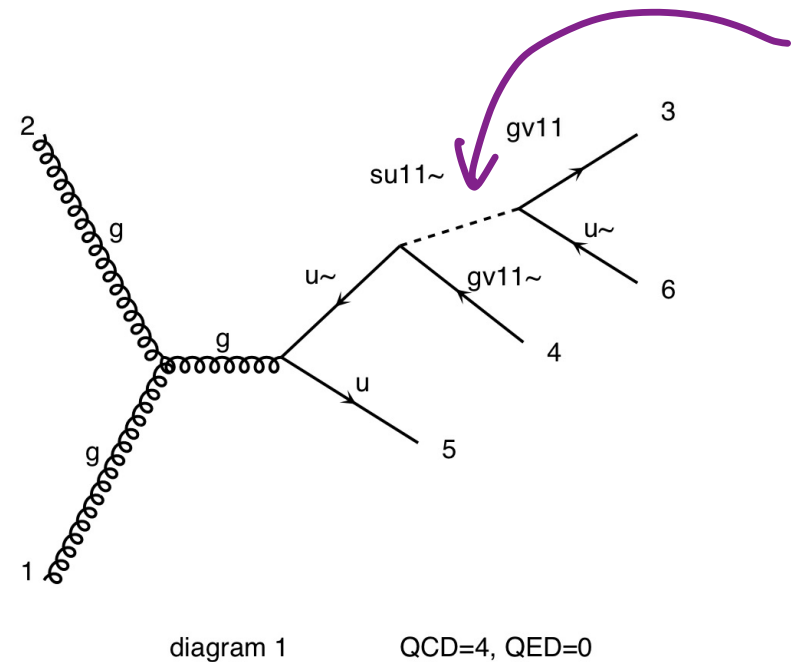
diagram 3 QCD=3, QED=0

+ ...

Production in t -channel Model

Want higher body diagrams for "matching"

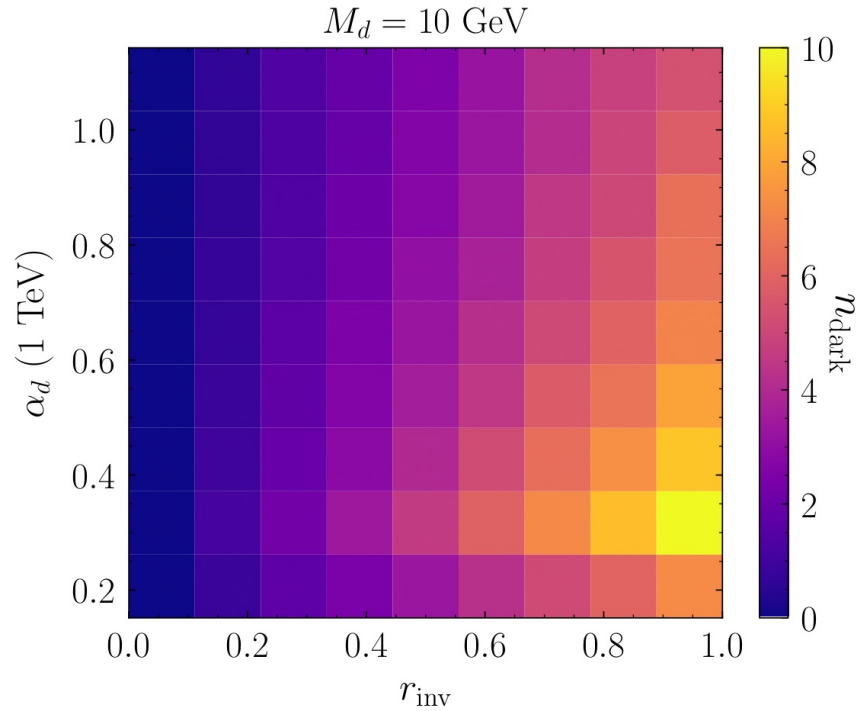
"on-shell" mediators



+ ...

Showering

Under reasonable theoretical control



Hadronization & Decay

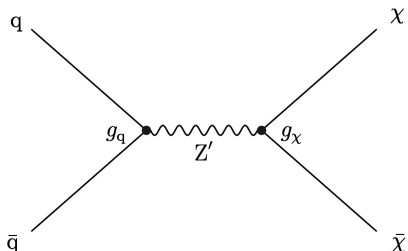
Phenomenological model

- Spectrum is non-perturbative
- Fragmentation is non-perturbative
but exponential suppression for producing heavy states
⇒ only care about lightest
- Decay: Vector mesons decay fast
Scalar mesons chirality suppressed

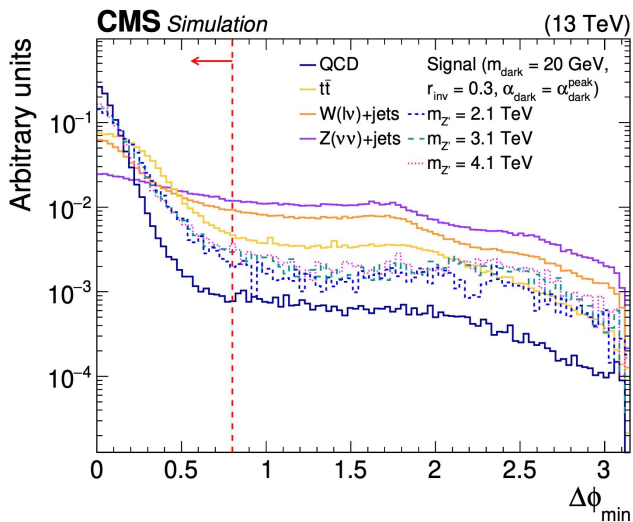
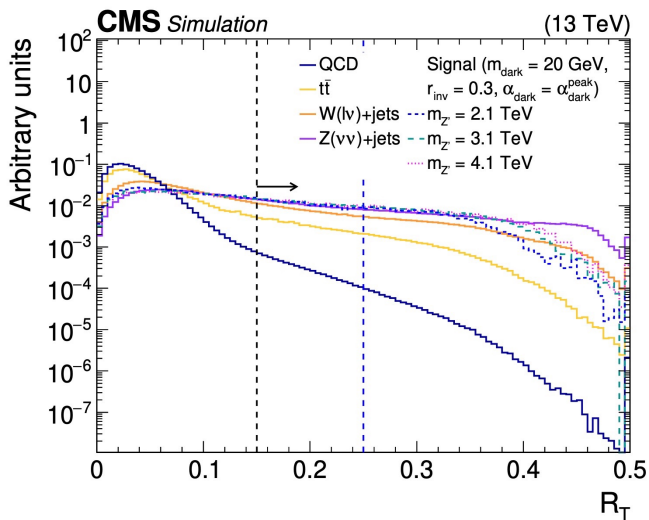
S-channel
model

CMS Search

arXiv: 2112.11125



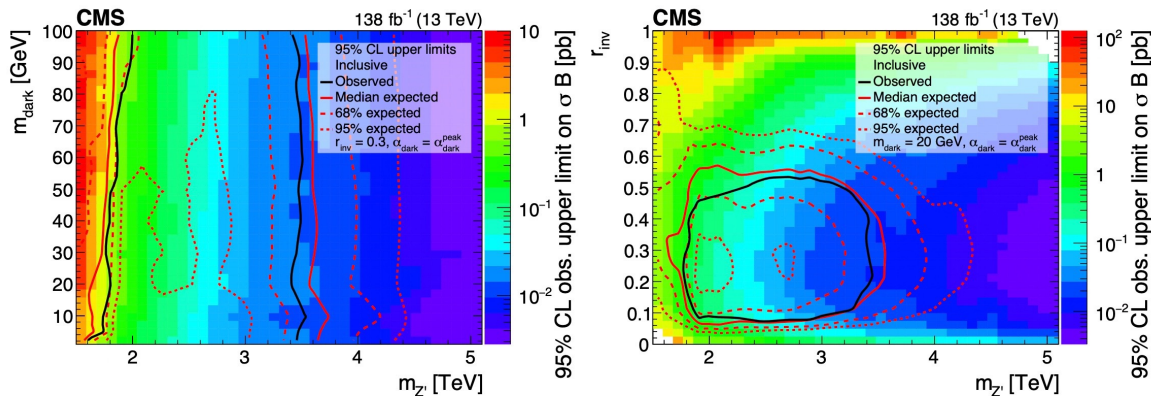
Scan	$m_{Z'}$ [TeV]	m_{dark} [GeV]	r_{inv}	α_{dark}
1	1.5–5.1	1–100	0.3	$\alpha_{\text{dark}}^{\text{peak}}$
2	1.5–5.1	20	0–1	$\alpha_{\text{dark}}^{\text{peak}}$
3	1.5–5.1	20	0.3	$\alpha_{\text{dark}}^{\text{low}} - \alpha_{\text{dark}}^{\text{high}}$



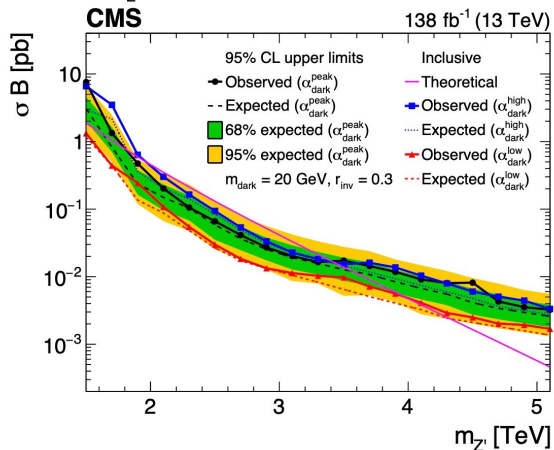
$$R_T = \frac{p_T^{\text{miss}}}{m_T}$$

$\Delta\phi_{\text{min}}$ is
min angle
between
jets and
 p_T^{miss}

CMS Search



Also provided
 stronger
 limits using
 BDT tagger



Preselection requirements

$$p_T(J_{1,2}) > 200 \text{ GeV}, \eta(J_{1,2}) < 2.4$$

$$R_T > 0.15$$

$$\Delta\eta(J_1, J_2) < 1.5$$

$$m_T > 1.5 \text{ TeV}$$

$$N_\mu = 0$$

$$N_e = 0$$

$$p_T^{miss} \text{ filters}$$

$$\Delta R(j_{1,2}, c_{nonfunctional}) > 0.1$$

Final selection requirements

$$\text{veto } f_\gamma(j_1) > 0.7 \text{ \& } p_T(j_1) > 1.0 \text{ TeV}$$

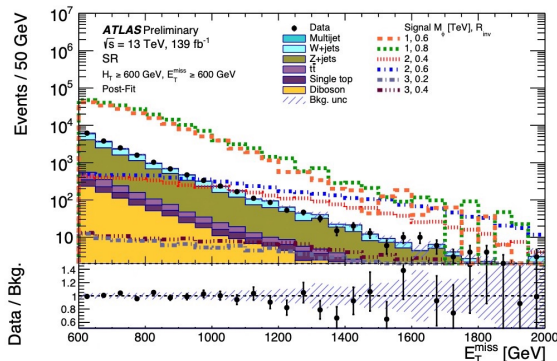
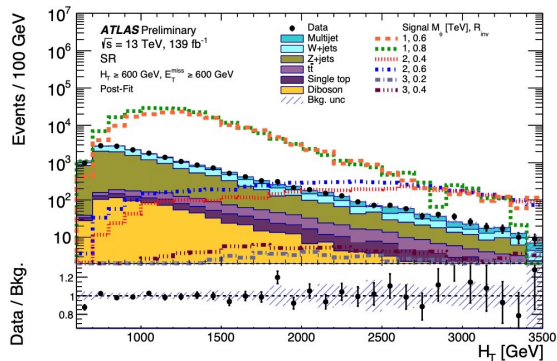
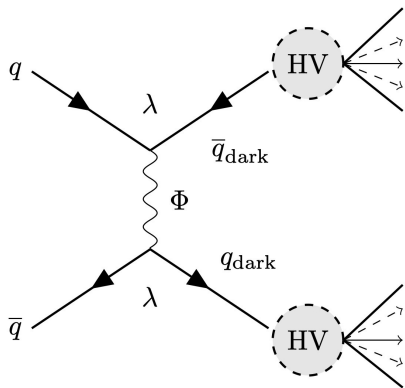
$$\text{veto } -3.05 < \eta_j < -1.35 \text{ \& } -1.62 < \phi_j < -0.82^*$$

$$\Delta\phi_{min} < 0.8$$

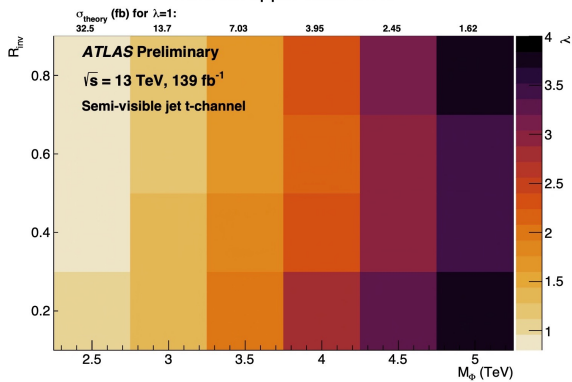
ATLAS Search

ATLAS-CONF-2022-038

t-channel model



95% CL upper limits on λ .



Frontiers

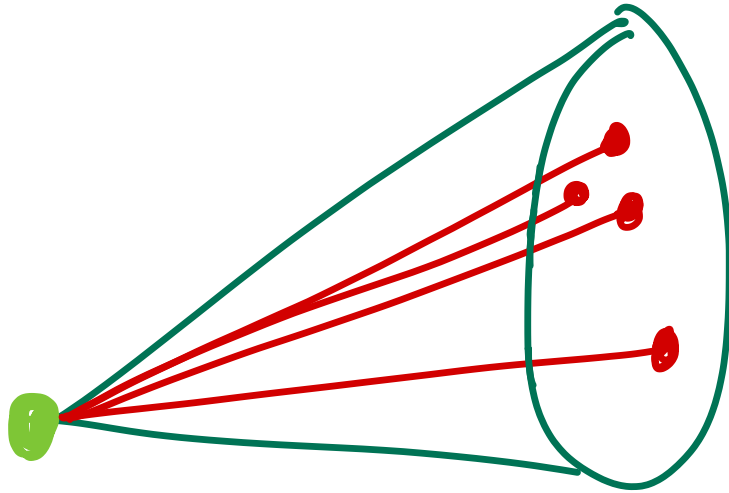


New Phenomena?



Better Observables?

Jet substructure

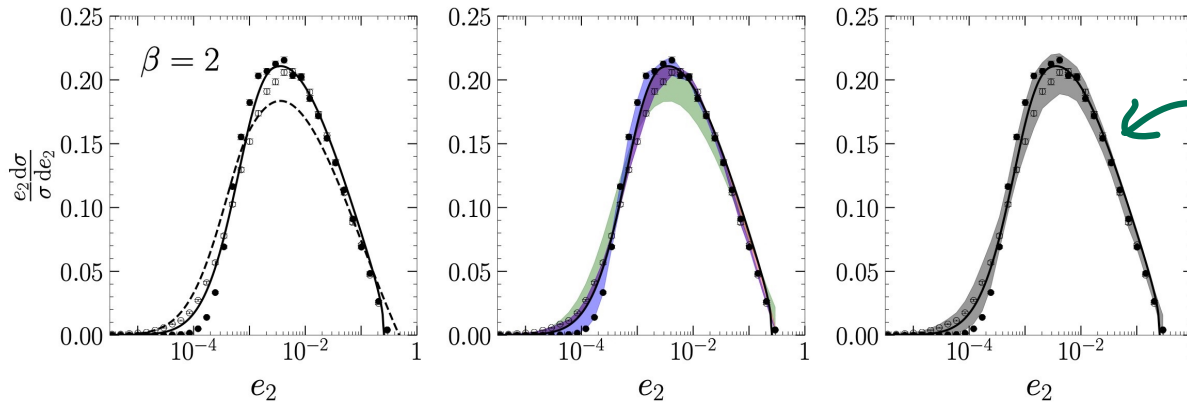


Dark Substructure

2-point correlation function

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

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

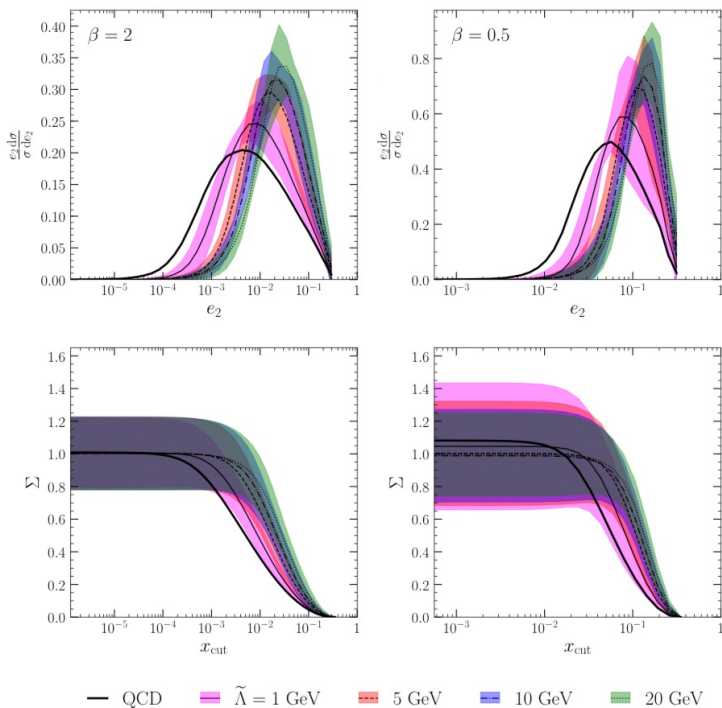


error envelope
theory
systematic

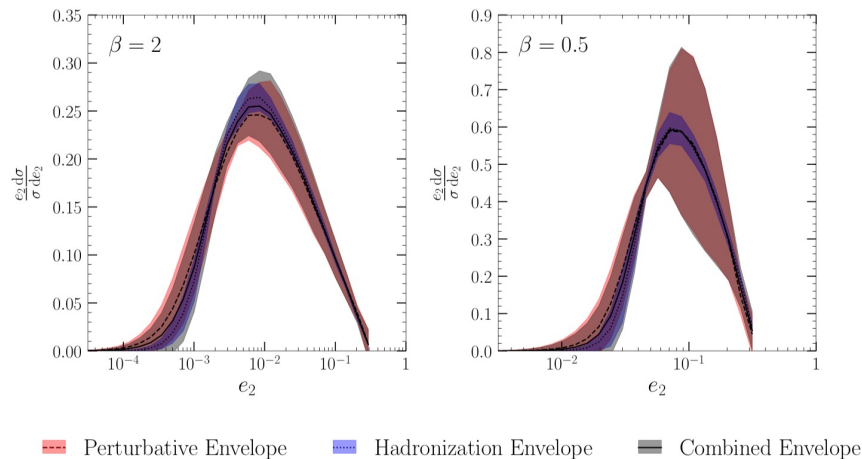
--- LL — MLL ◦ Pythia Parton • Pythia Hadron

TC, Doss, Freytsis
arXiv: 2004.00631

Theoretical Errors



Hadronization



TC, Doss, Freytsis
 arXiv: 2004.00631

Lund Jet Plane

Tool to isolate hadronization effects

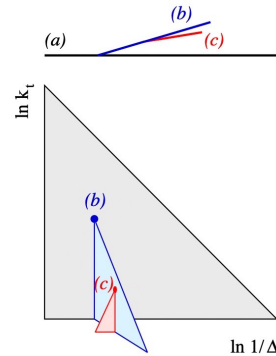
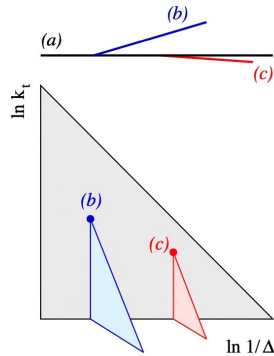
Recluster jet using Cambridge - Aachen algorithm
(Clusters according to distance in rapidity and φ)

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

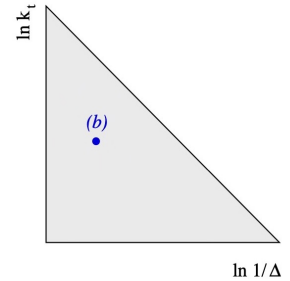
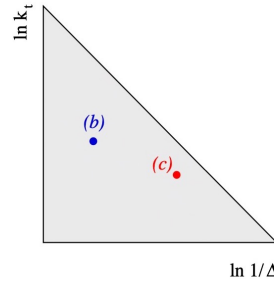
F. Dreyer, G. Salam,
G. Soyez
arXiv:1807.04758

JET

LUND DIAGRAM

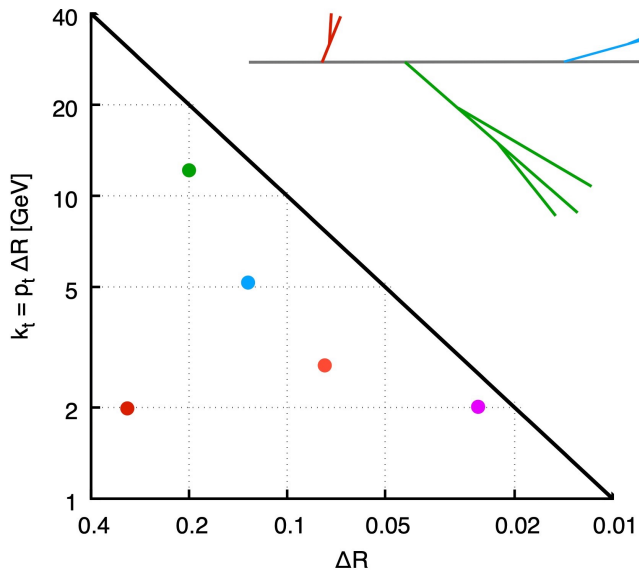


PRIMARY LUND PLANE



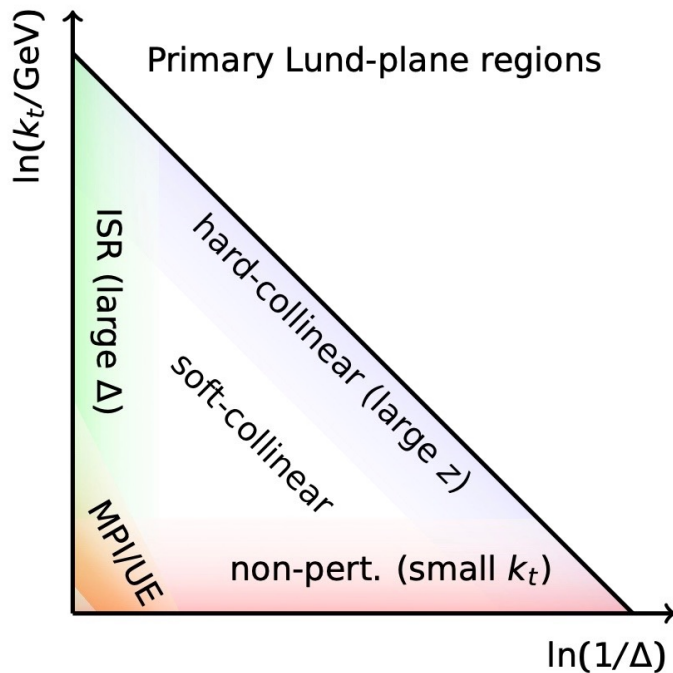
Lund Jet Plane

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



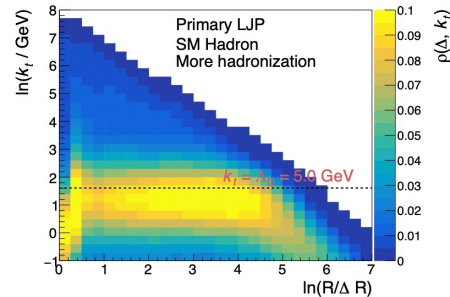
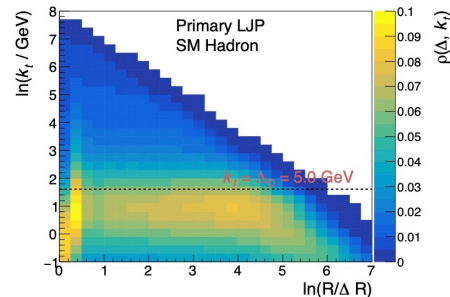
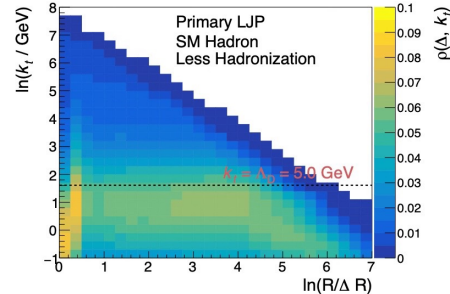
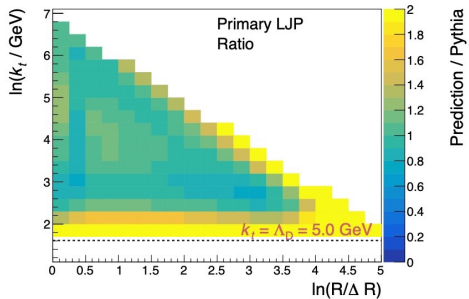
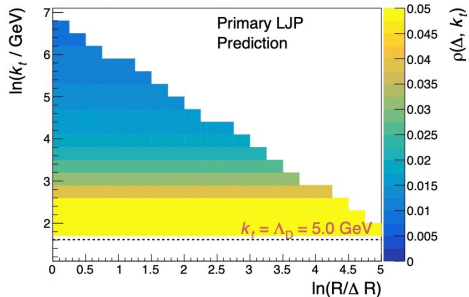
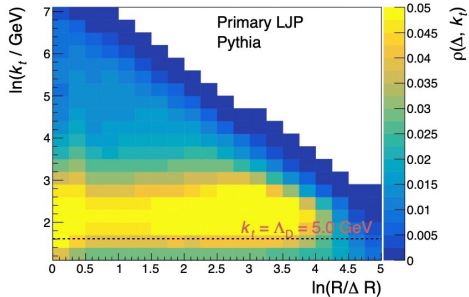
↑
from talk by G. Salam

Average over many jets



Lund Dark Jet Plane

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



leading log density

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

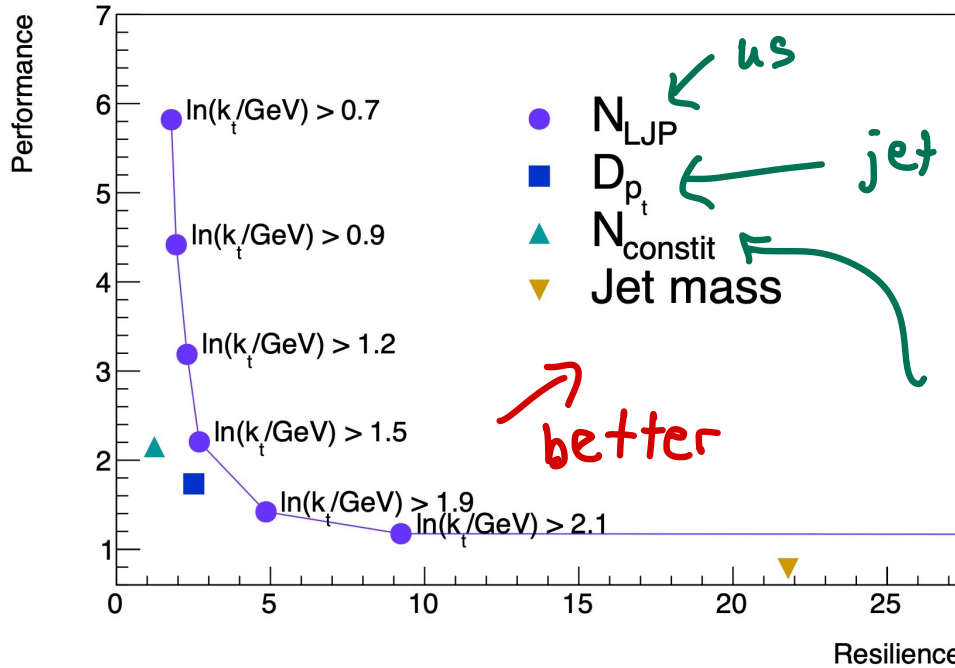
$$C_F = \frac{N^2 - 1}{2N}$$

for $SU(N)$

Varying
hadronization

Performance vs Resilience

$$\frac{\epsilon_{\text{dark}}}{\sqrt{\epsilon_{\text{QCD}}}}$$



$\sqrt{\epsilon_{P_T^2}} / \epsilon_{P_T}$
 number of constituents

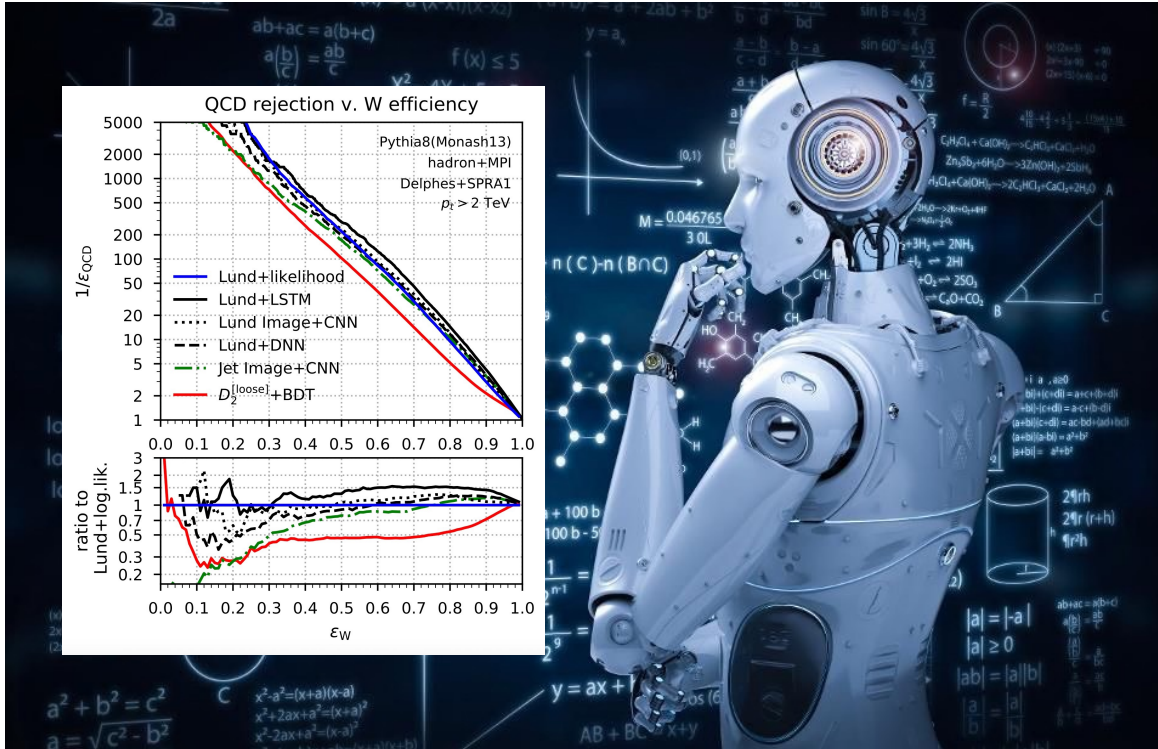
better

Next step is to design search

variation wrt hadronization

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

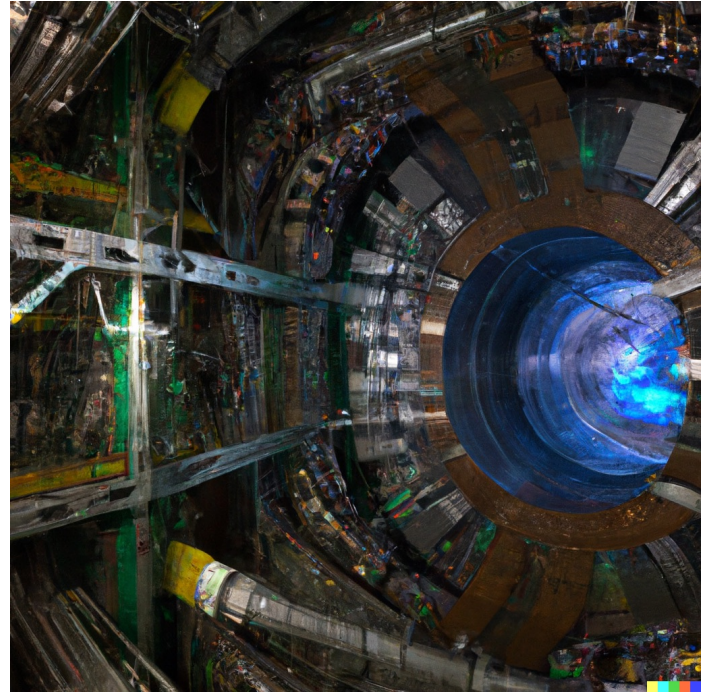
Machine Learning



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

Bright Future for Dark Showers

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



↑
Another DALL-E original

Backups

CMS Search

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$$R_T > 0.15$$

$$\Delta\eta(J_1, J_2) < 1.5$$

$$m_T > 1.5 \text{ TeV}$$

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p_T^{miss} filters

$$\Delta R(j_{1,2}, c_{\text{nonfunctional}}) > 0.1$$

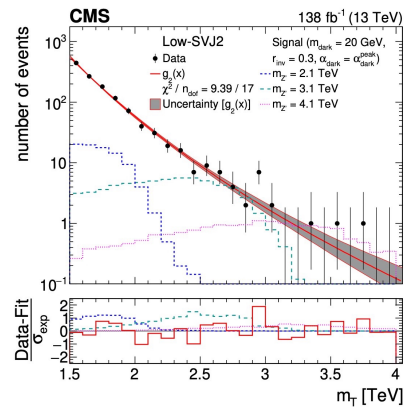
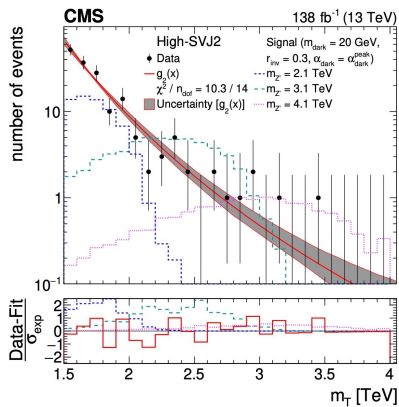
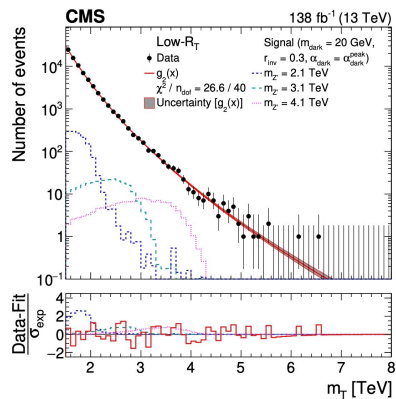
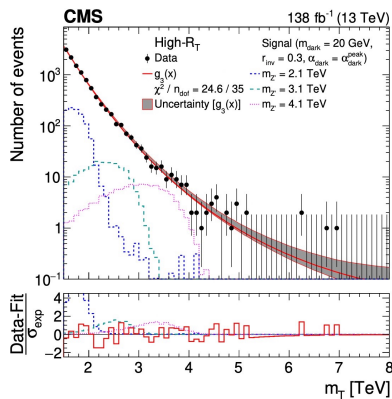
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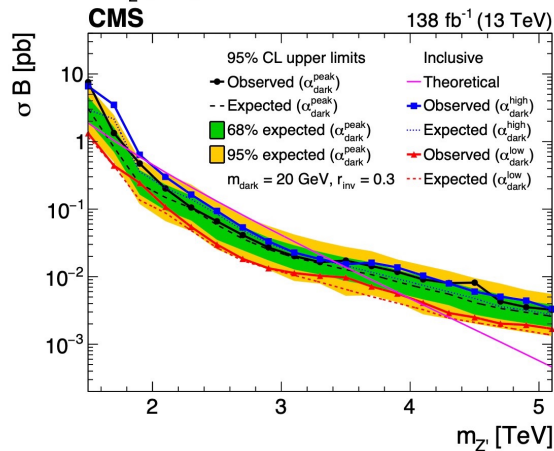
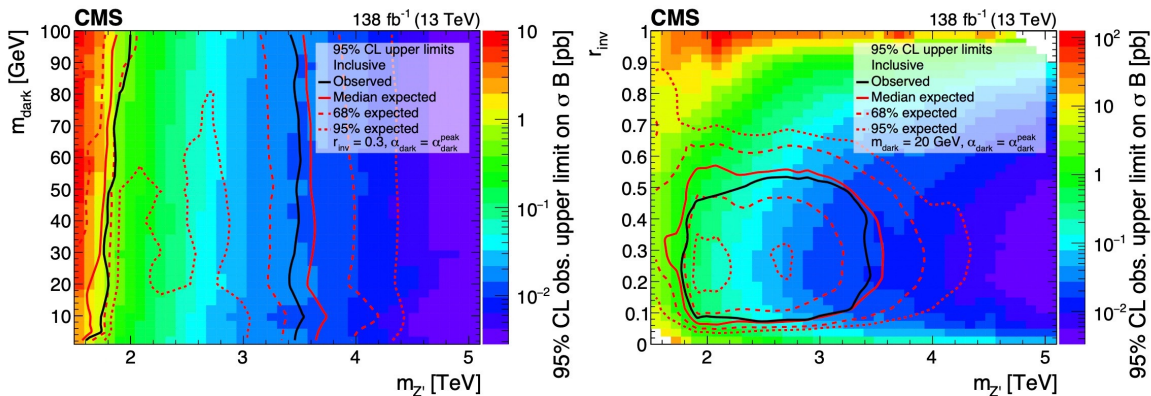
$$\text{veto } -3.05 < \eta_j < -1.35 \ \& \ -1.62 < \phi_j < -0.82 \ *$$

$$\Delta\phi_{\text{min}} < 0.8$$

CMS Search



CMS Search



CMS Search

