

Dark Sector Searches at the LHC

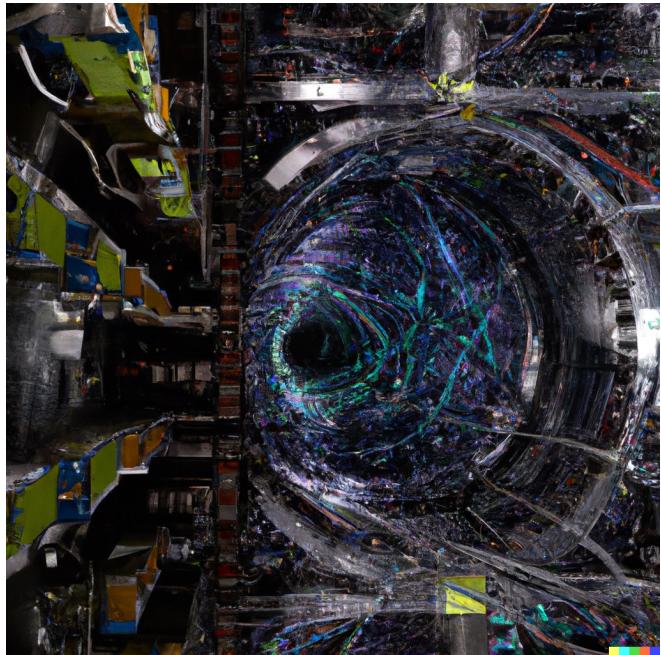
Tim Cohen

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

SM + gluino + neutralino

$$\mathcal{L} = \mathcal{L}_{SM} + ig\tilde{t}\tilde{t} + m_{\tilde{g}}\tilde{g}\tilde{g} + \frac{1}{\Lambda^2}\tilde{g}\tilde{g}\tilde{g}\tilde{g}$$



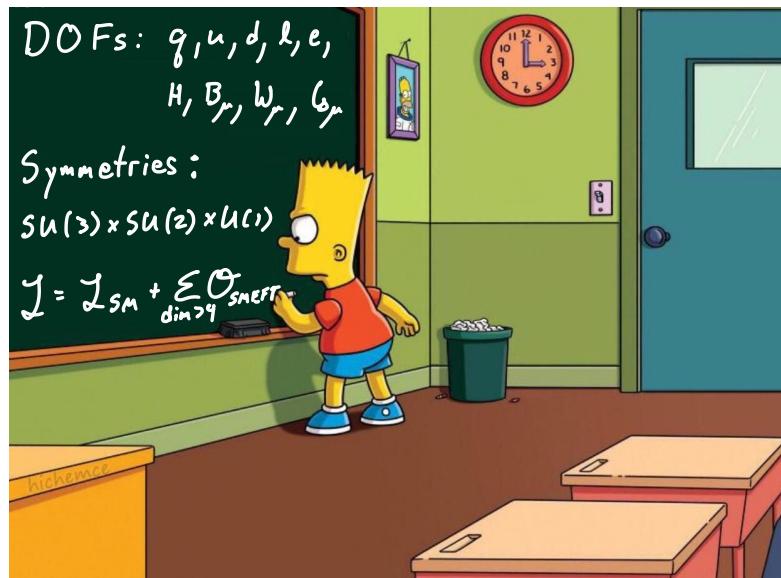
Effective Field Theory

DOFs: $q, u, d, l, e, H, B_r, W_r, \phi_r$

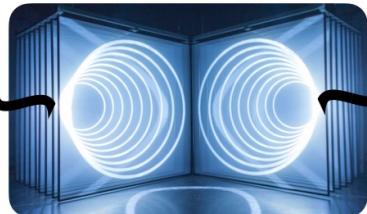
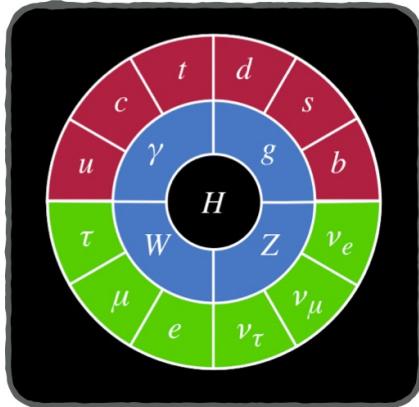
Symmetries:

$$SU(3) \times SU(2) \times U(1)$$

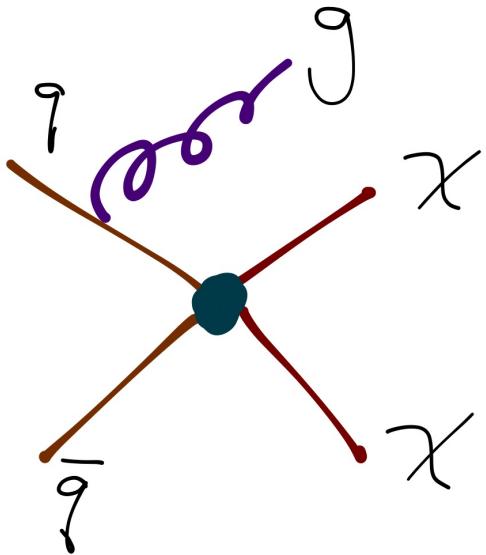
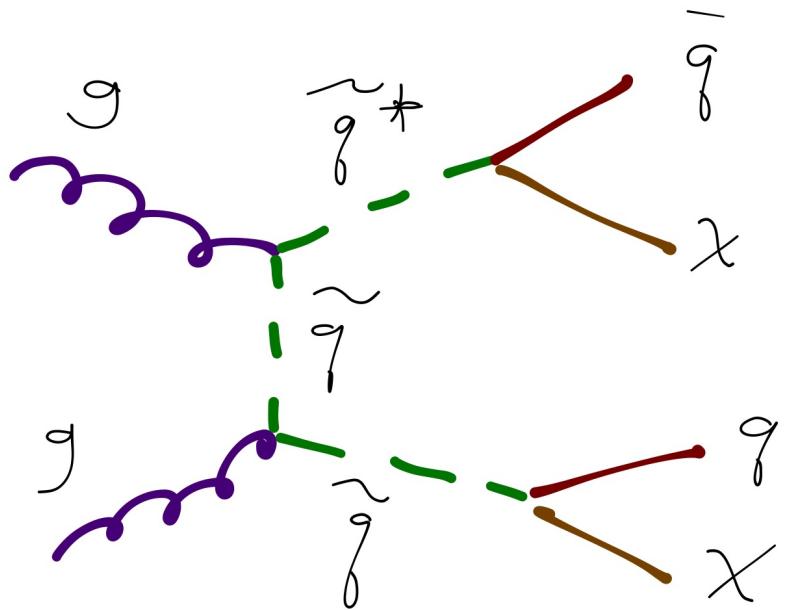
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{dim > 4} \mathcal{O}_{SMFT}$$



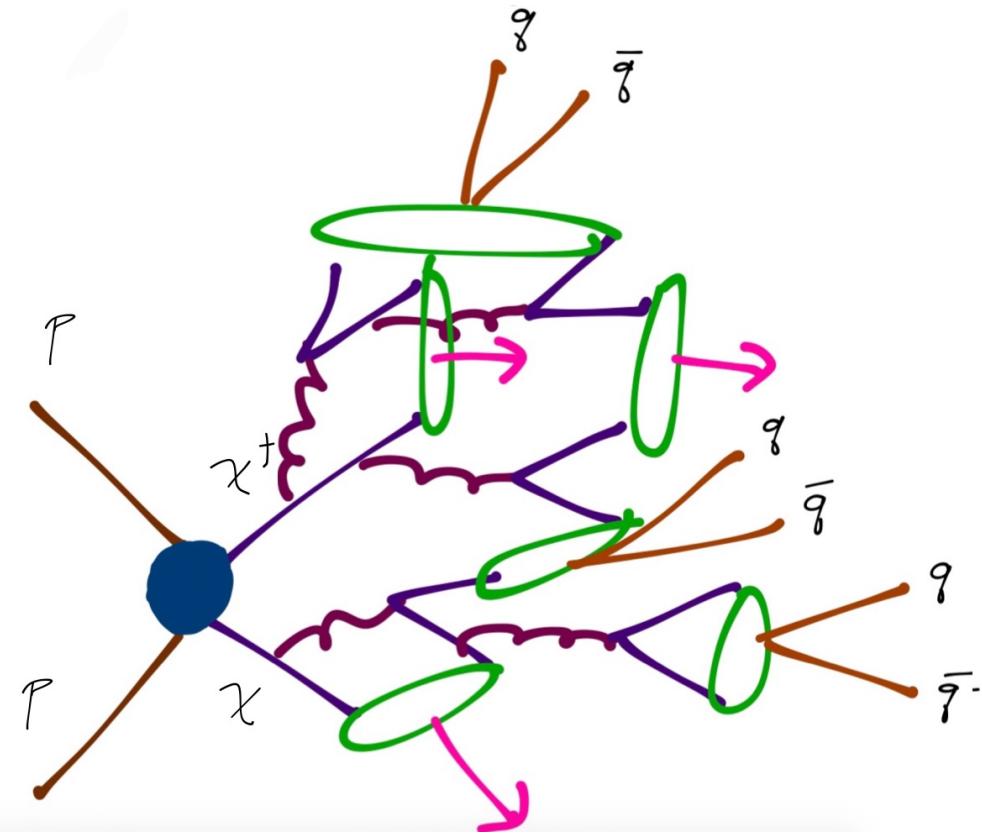
Dark Sector Paradigm



Weakly Coupled Dark Sector

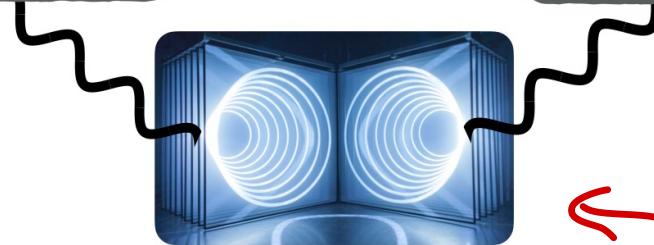
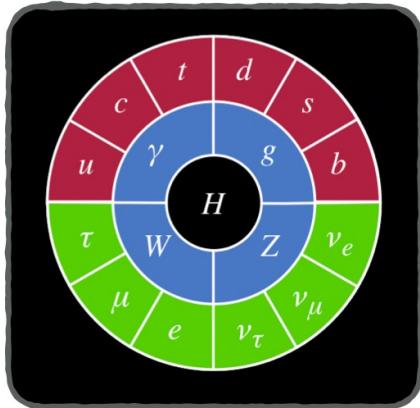


Strongly Coupled Dark Sector



Overwhelming Theory Space

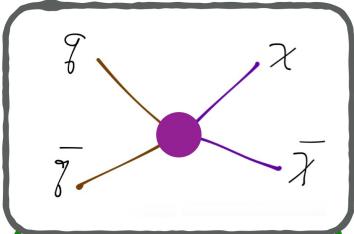
fixed →



← Finite
(renormalizable)
options

Portal to Quarks

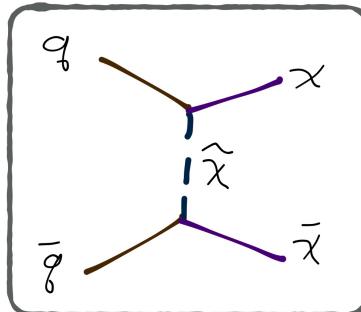
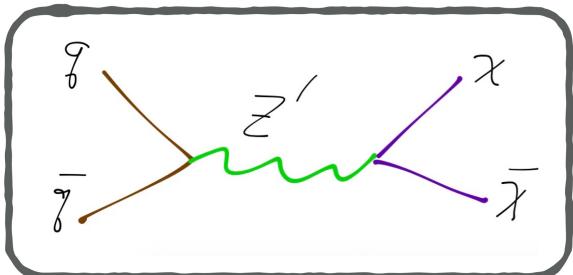
contact operator



s - channel



t - channel



Phenomena Driven

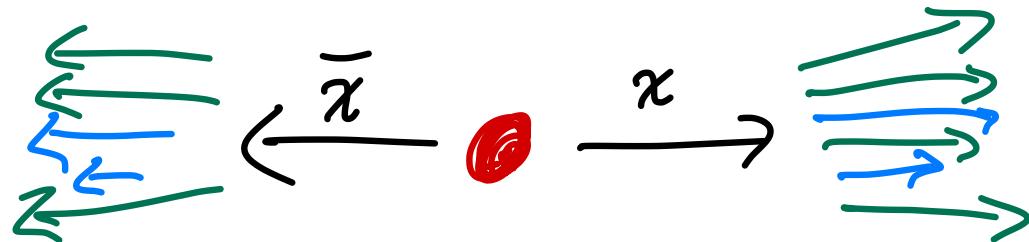
- Semi-visible jets
- Lepton jets
- Emerging jets
- Soft bombs
- Quirks
- Your awesome new idea?

Semi-visible Jets

Assume dark sector quarks χ dominantly interact with QCD.

Some dark mesons $\tilde{\pi}_D$ decay to QCD

Some dark mesons $\tilde{\pi}'_D$ are stable

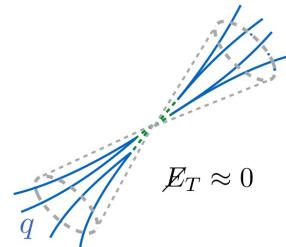


Missing energy aligned with jets

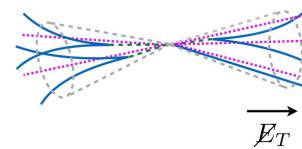
Semi-visible Jets

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

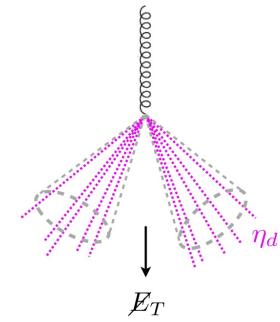
$$r_{inv} = 0$$



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



$$r_{inv} = 1$$

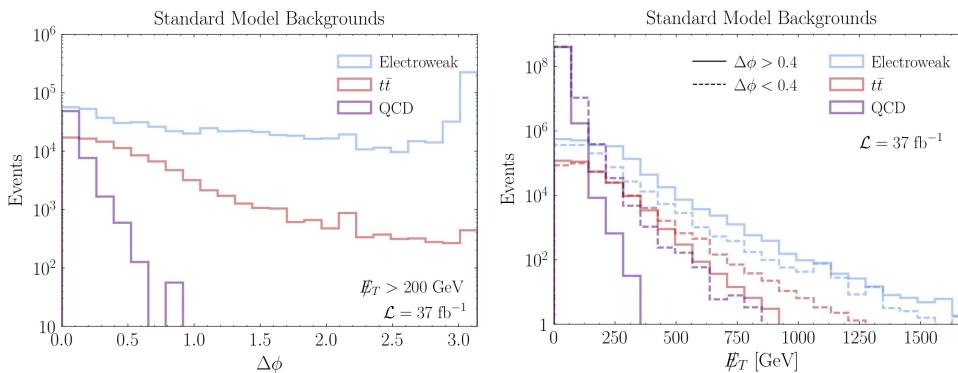
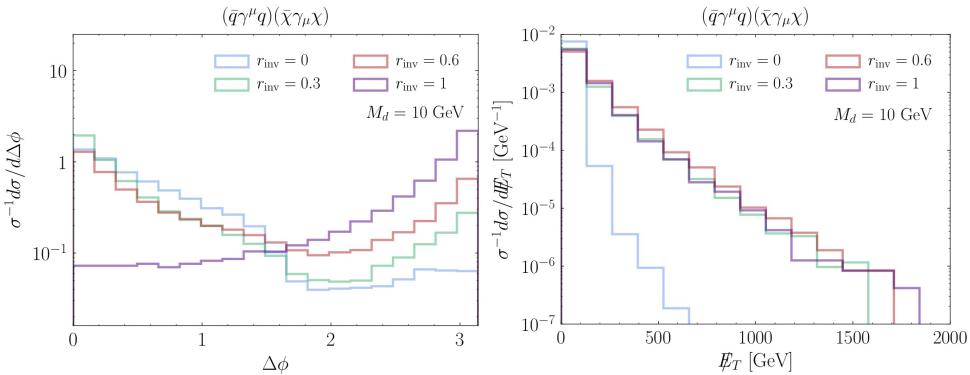


Pheno parametrization

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

- α_d (or Λ_d)
- r_{inv}
- M_d
- O_{partial}

Signal vs Background



T.C., M. Lisanti, H.-k. Lou, S. Mishra-Sharma [[arXiv:1707.05326](https://arxiv.org/abs/1707.05326)]

Benchmarking

- Pick α_{portal} : contact operator

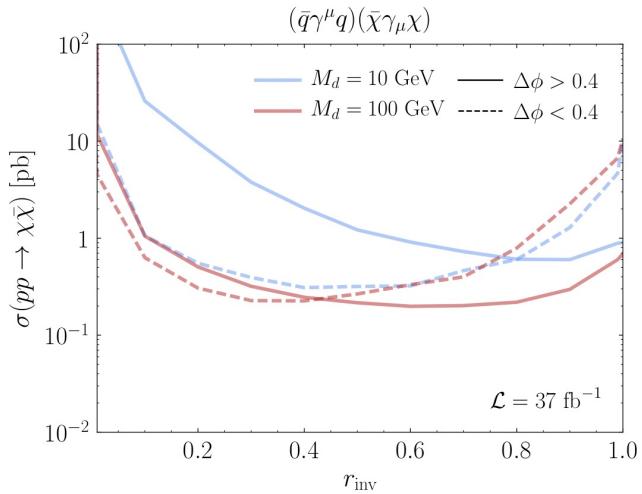
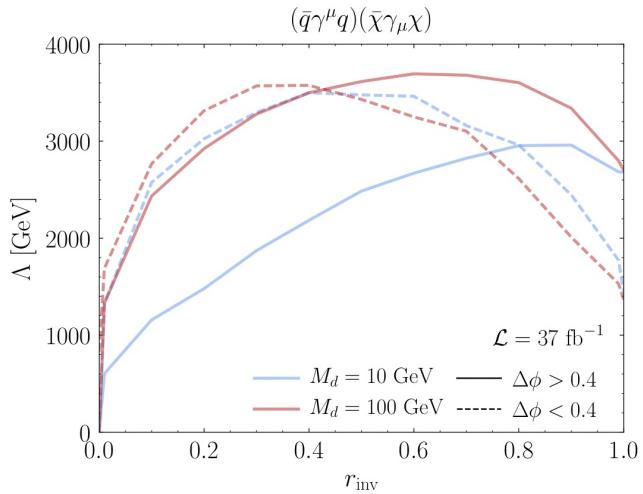
$$\Lambda_d = 20 \Lambda_{\text{QCD}}$$

- Pick some parameters: $f_{\text{inv}} = 0.5$

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

- 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

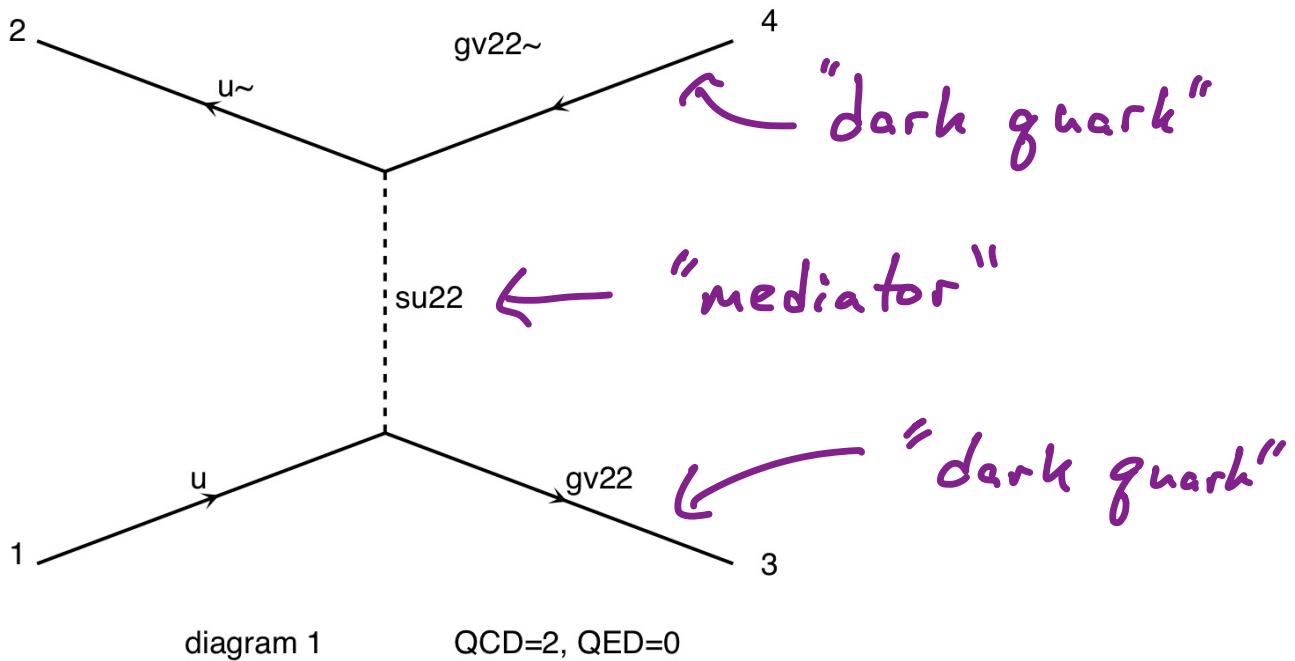
Showering Pick # colors and # flavors \Rightarrow
Sudakov factor \Rightarrow Parton Shower

Hadronization Need to know spectrum
 \Rightarrow Fragmentation functions
 \Rightarrow Non-perturbative

Decay Depends on spectrum + portal

Production in t -channel Model

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



Production in t -channel Model

Want higher body diagrams for "matching"

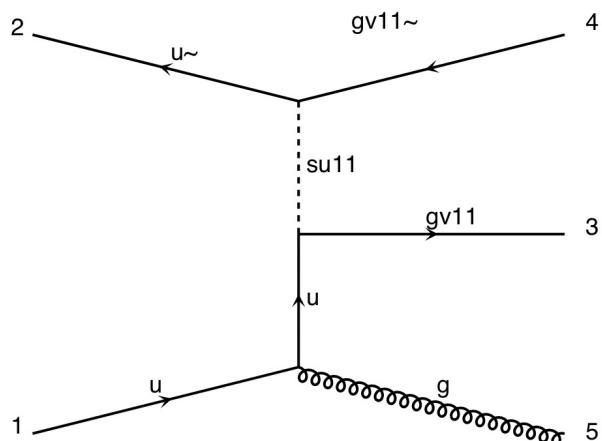


diagram 1

QCD=3, QED=0

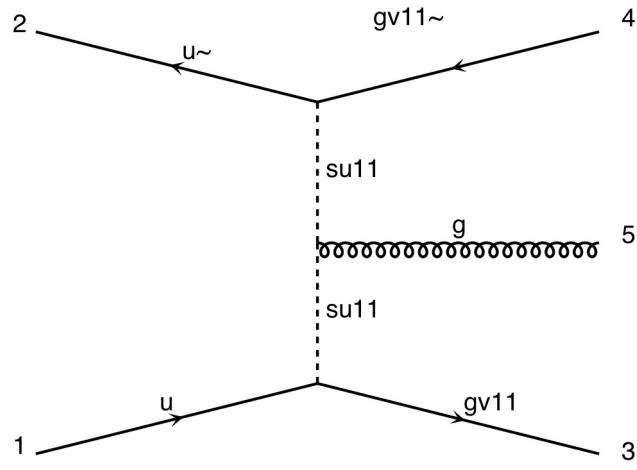


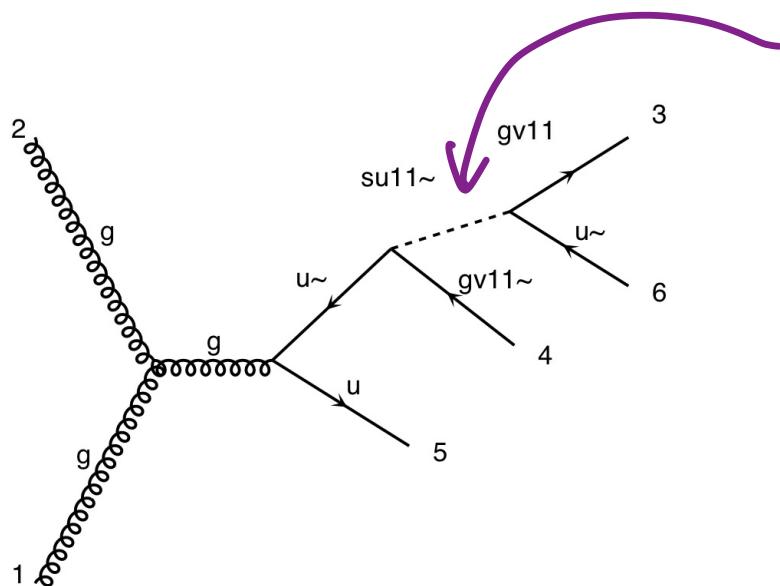
diagram 3

QCD=3, QED=0

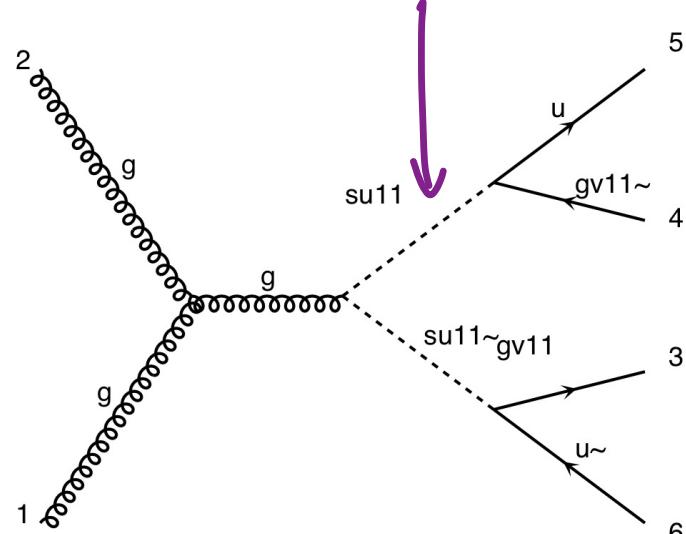
+ ...

Production in t -channel Model

Want higher body diagrams for "matching"

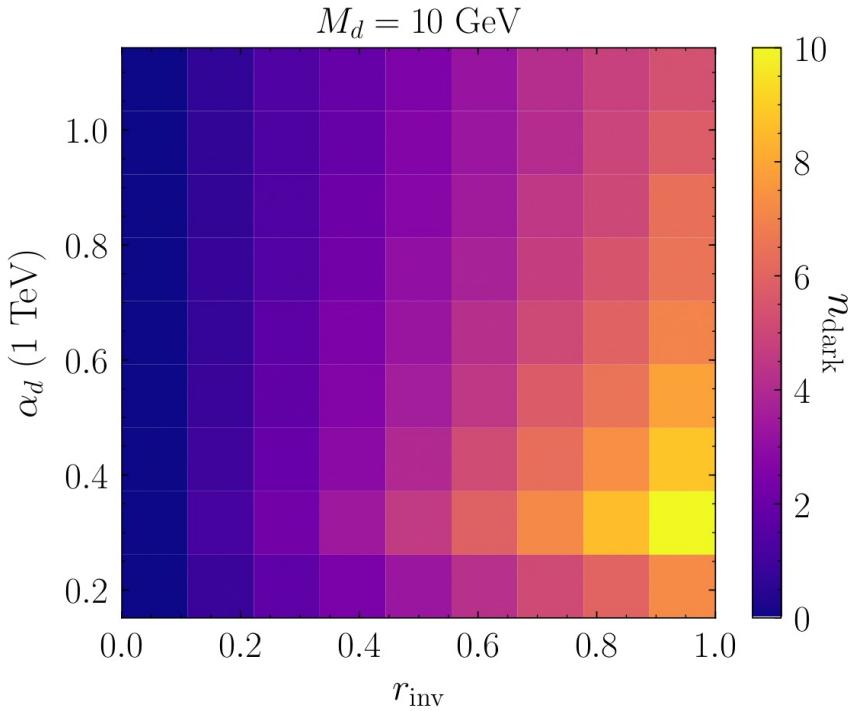


"on-shell" mediators



+ . . .

Showering Under reasonable theoretical control



Hadronization & Decay

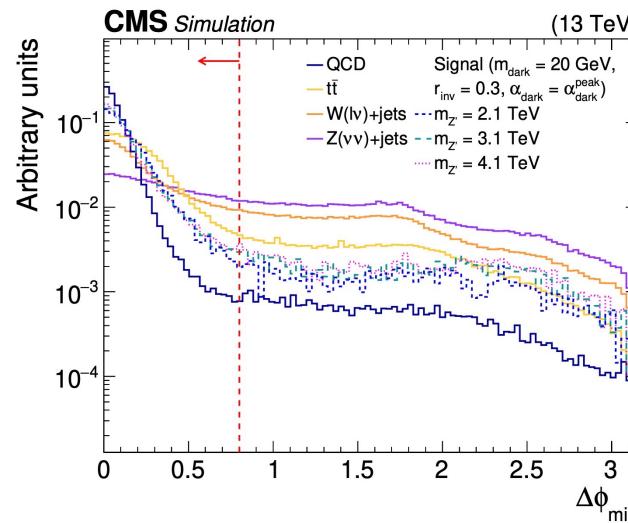
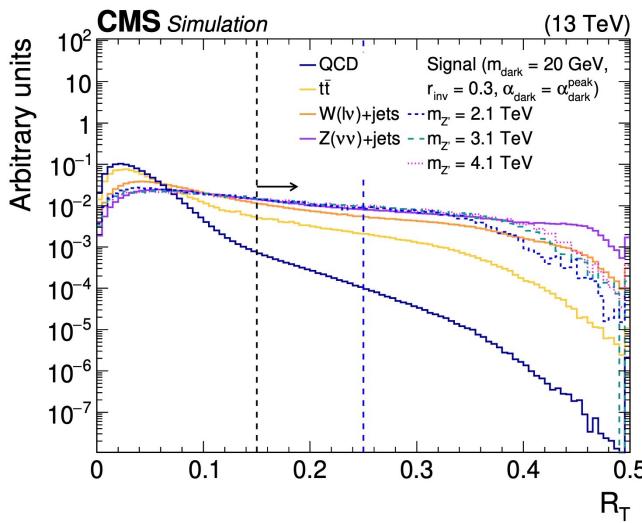
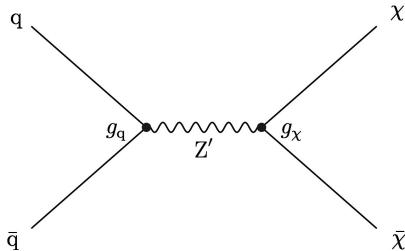
Phenomenological model

- 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

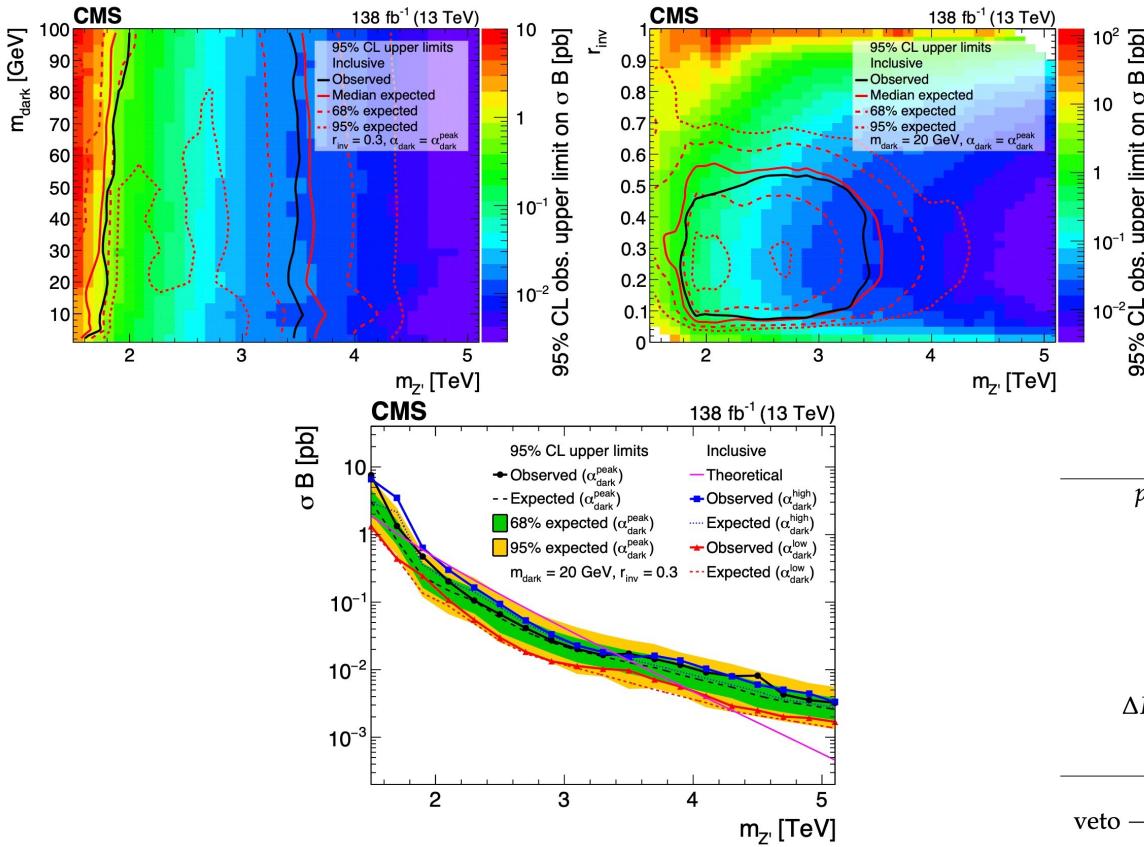
arXiv: 2112.11125



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

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

CMS Search



Also provided
stronger
limits using
BDT tagger

Preselection requirements

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

$$R_T > 0.15$$

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

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

$$N_\mu = 0$$

$$N_e = 0$$

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

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

Final selection requirements

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

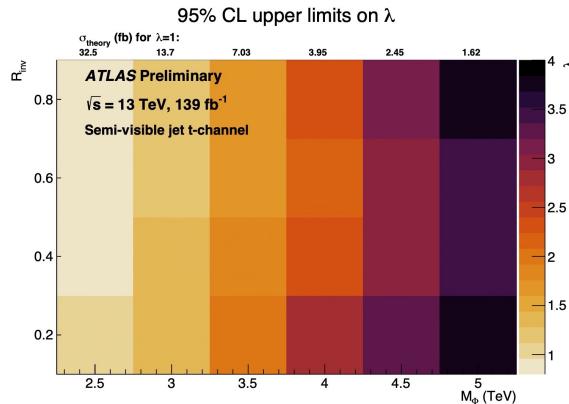
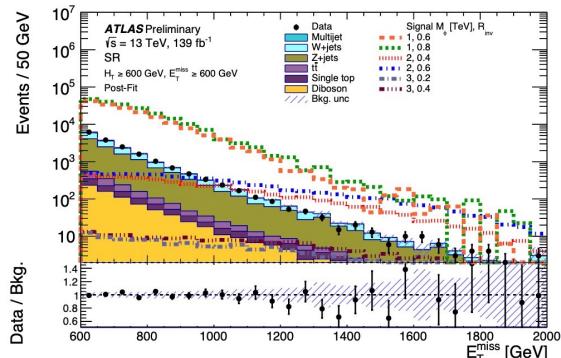
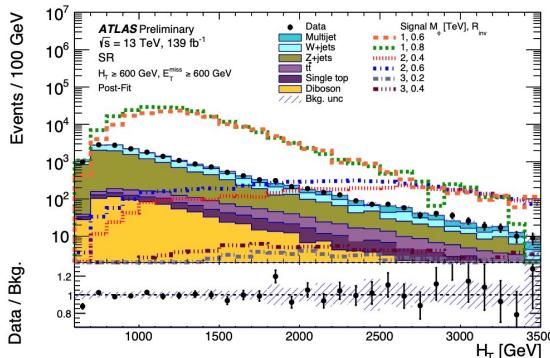
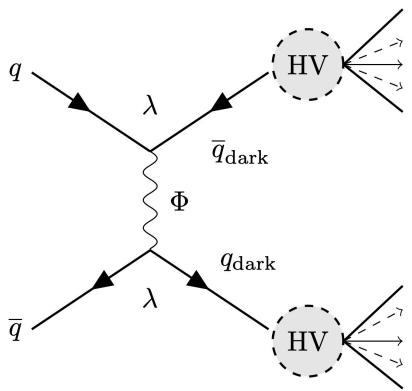
$$\text{veto } -3.05 < \eta_j < -1.35 \text{ \& } -1.62 < \phi_j < -0.82 *$$

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

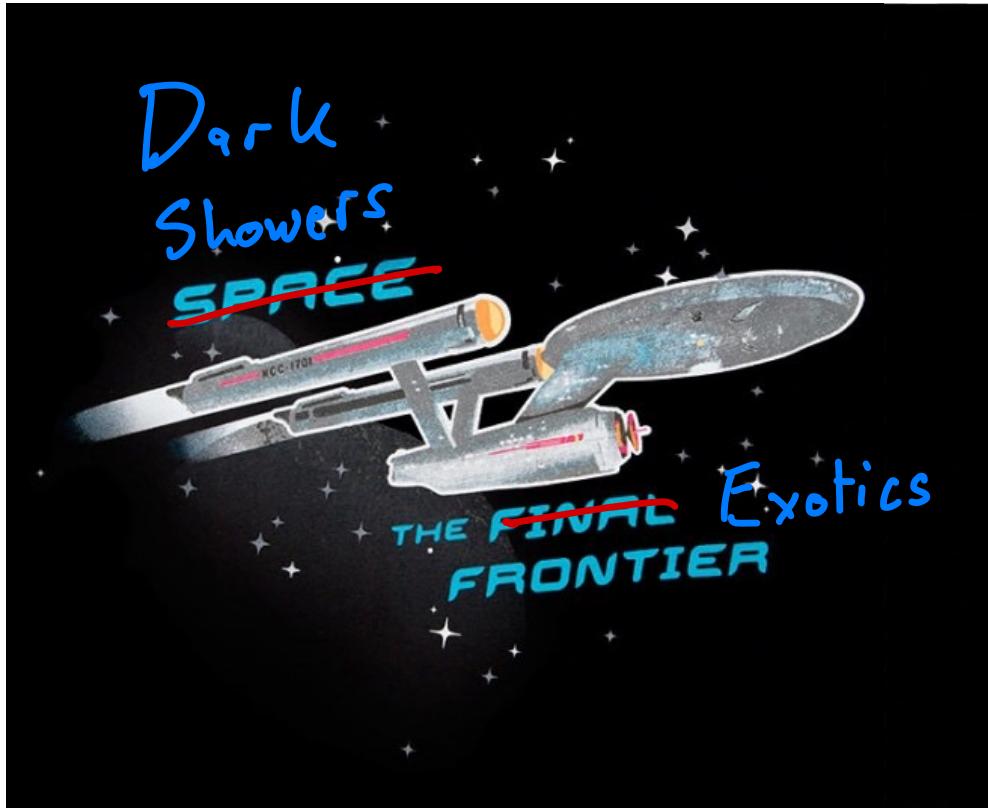
ATLAS Search

ATLAS - CONF - 2022 - 038

t-channel model



Frontiers

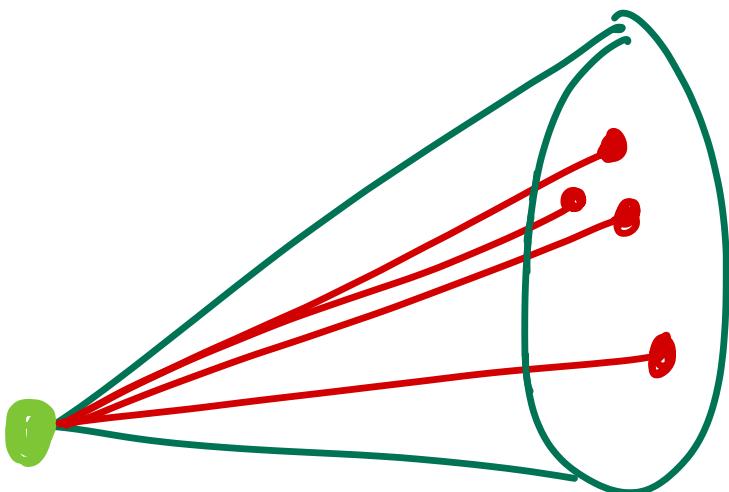


New Phenomena?



Better Observables?

Jet substructure

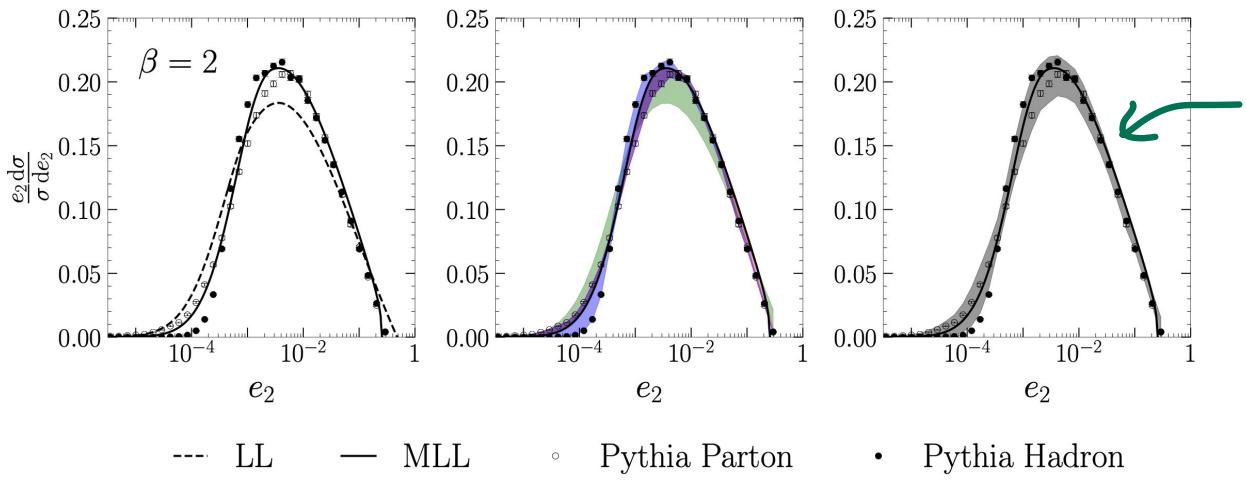


Dark Substructure

2-point correlation function

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

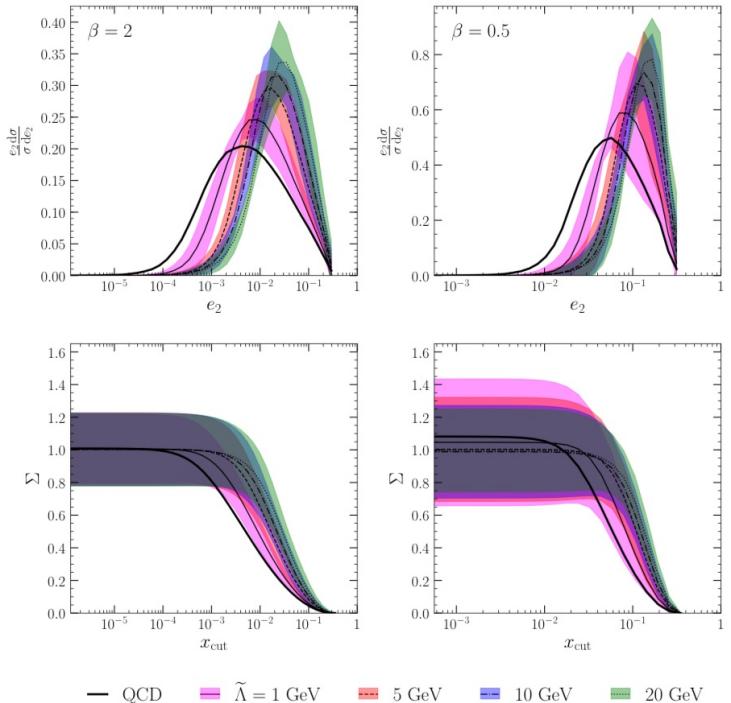
Generalization of jet mass ($\beta=2$)



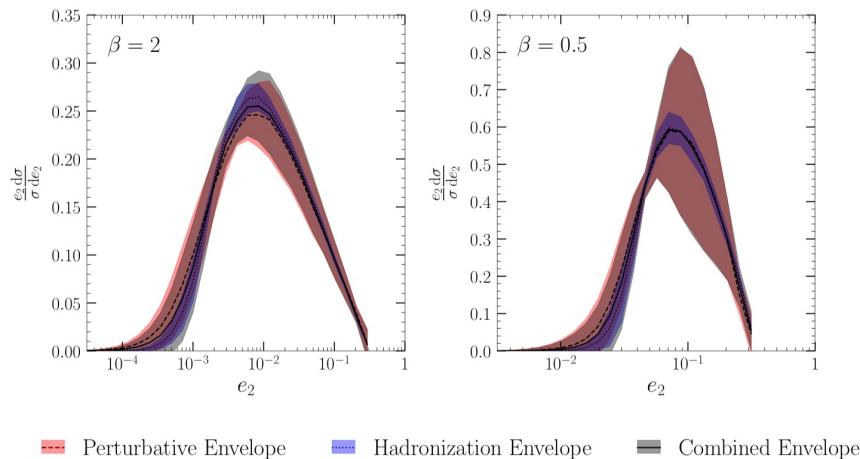
error
envelope
theory
systematic

TC, Doss, Freytsis
arXiv: 2004.00631

Theoretical Errors



Hadronization



TC, Doss, Freytsis
arXiv: 2004.00631

Lund Jet Plane

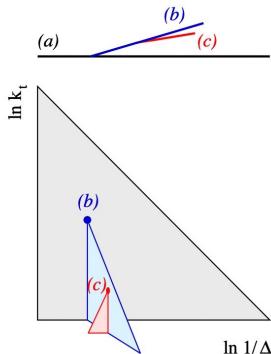
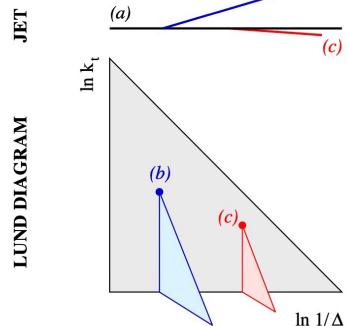
Tool to isolate hadronization effects

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

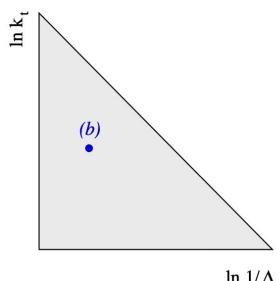
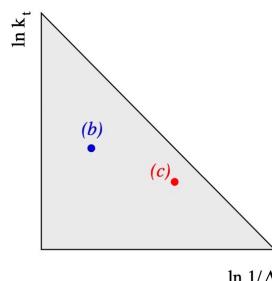
Plot branchings in Lund Plane : angle Δ and
transverse momentum k_T of emission wrt emitter

F. Dreyer, G. Salam,
G. Soyez

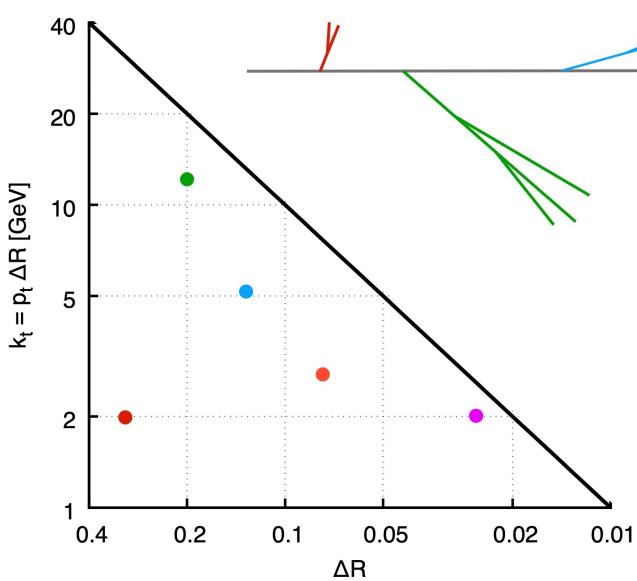
arXiv: 1807.04758



PRIMARY LUND PLANE



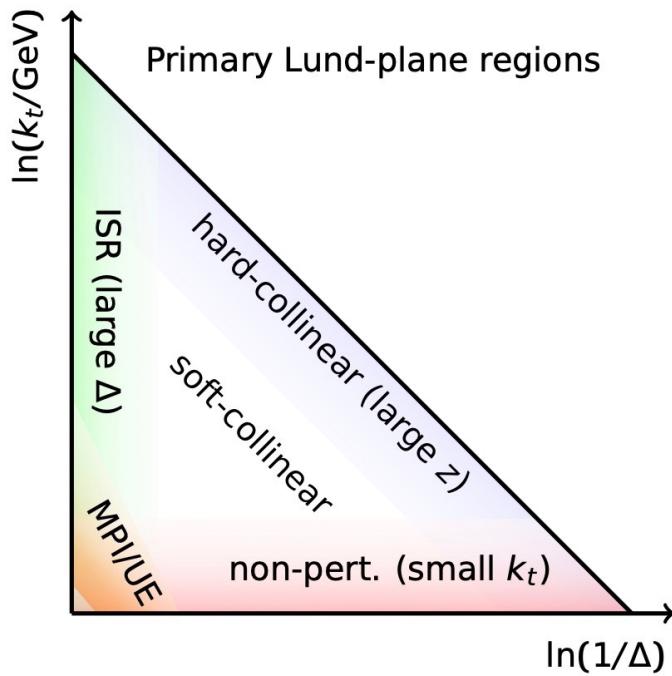
Lund Jet Plane



↑
from talk by G. Salam

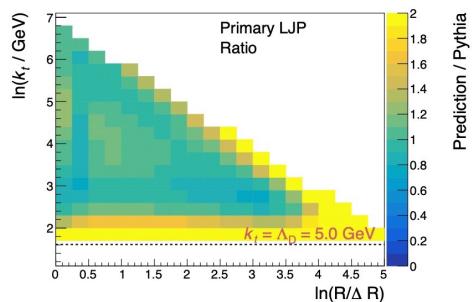
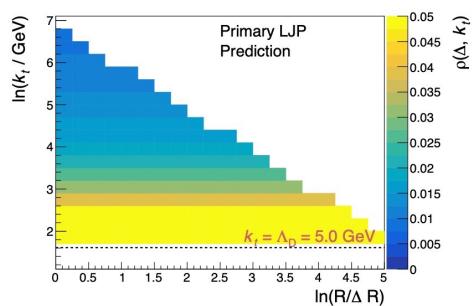
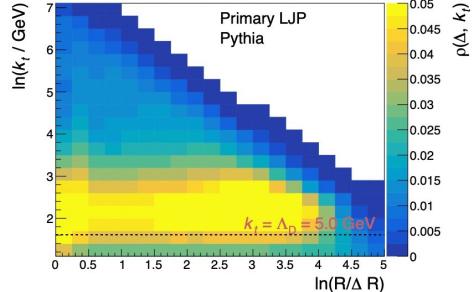
Average over many jets

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



Lund Dark Jet Plane

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



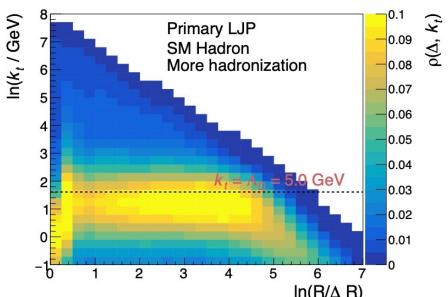
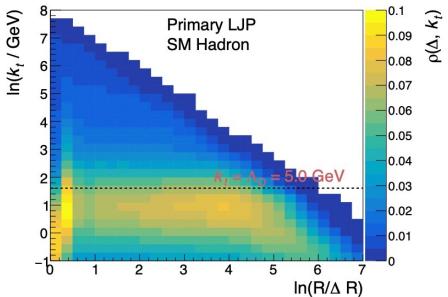
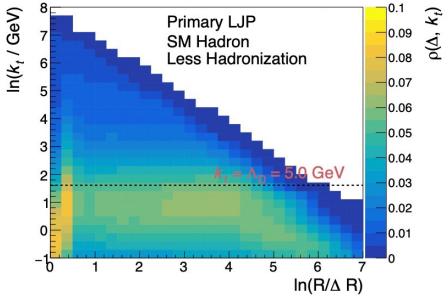
leading log density

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

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

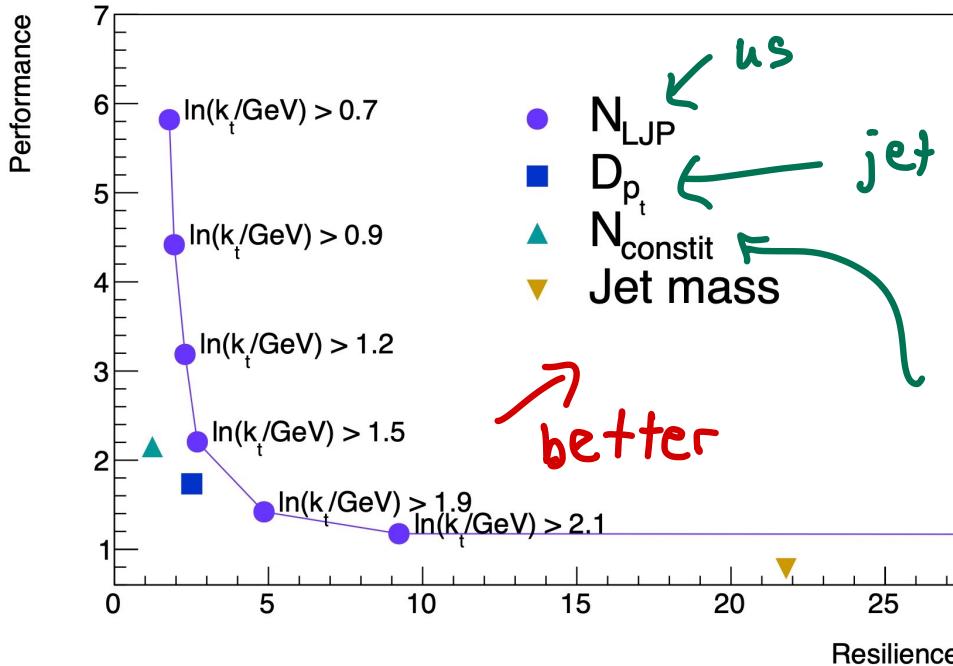
for $SU(N)$

Varying hadronization



Performance vs Resilience

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



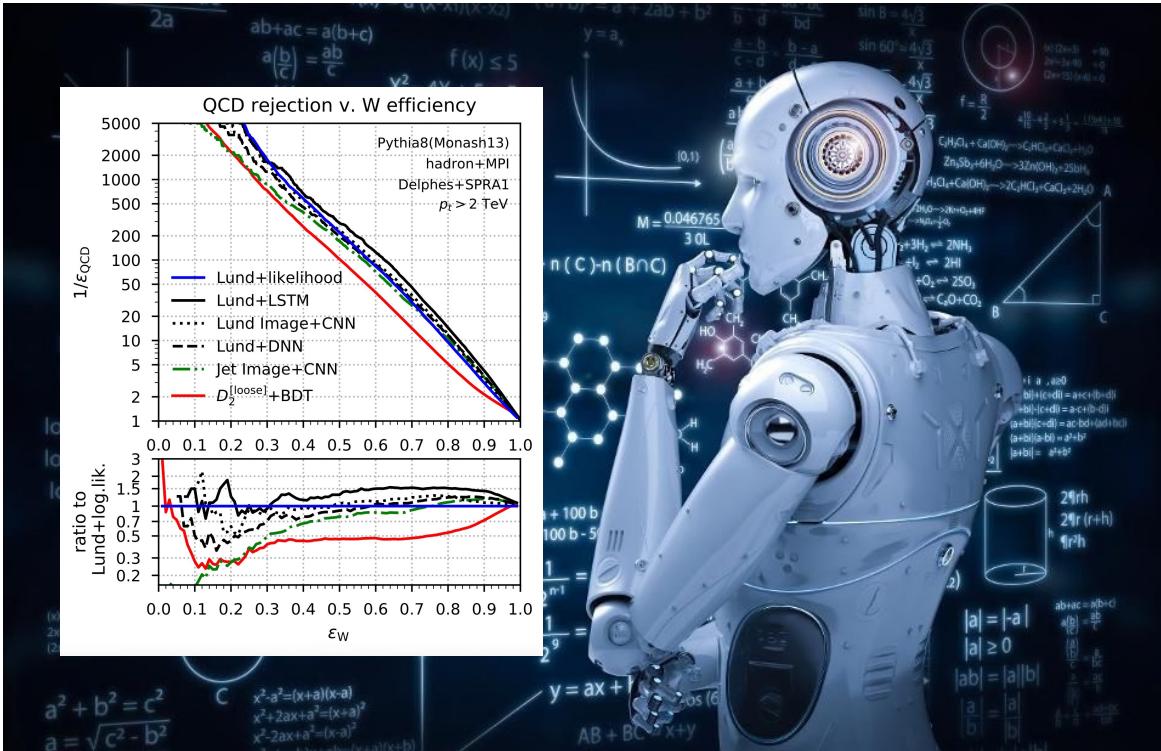
Next step is to design search

Variation wrt hadronization

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

jet energy sharing
 $\sqrt{\epsilon p_T^2 / \epsilon p_T}$
 number of constituents

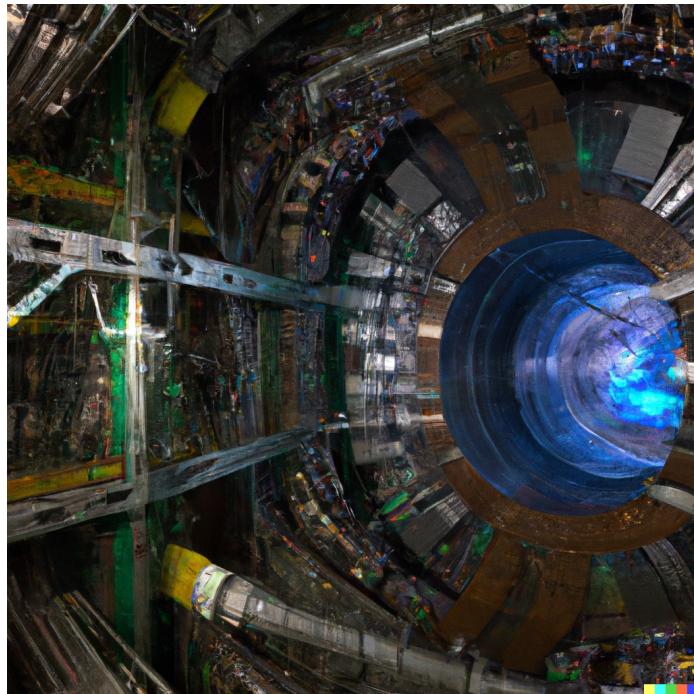
Machine Learning



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

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

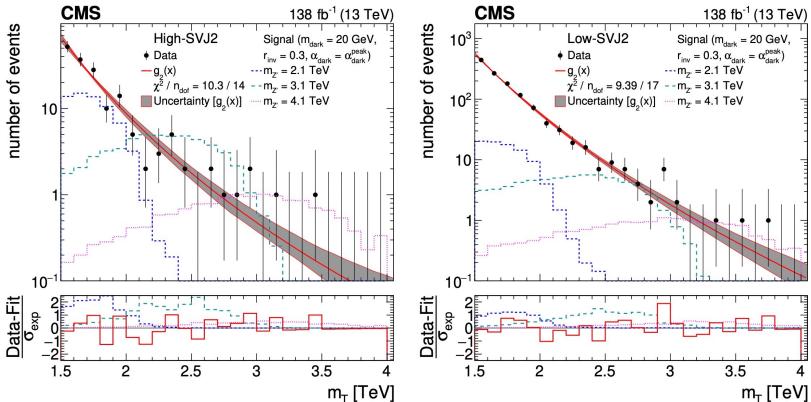
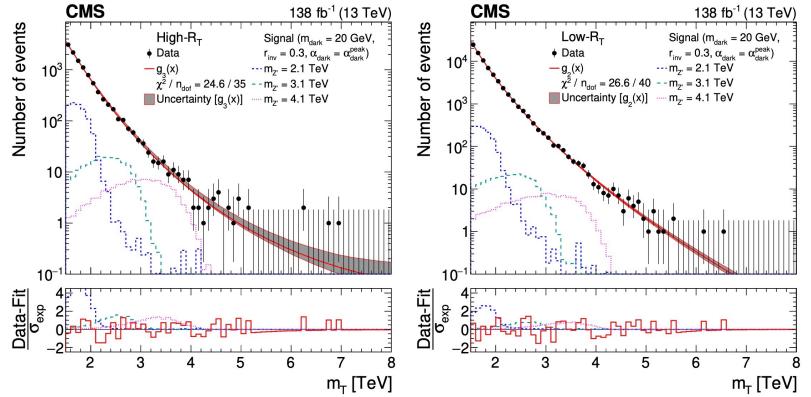
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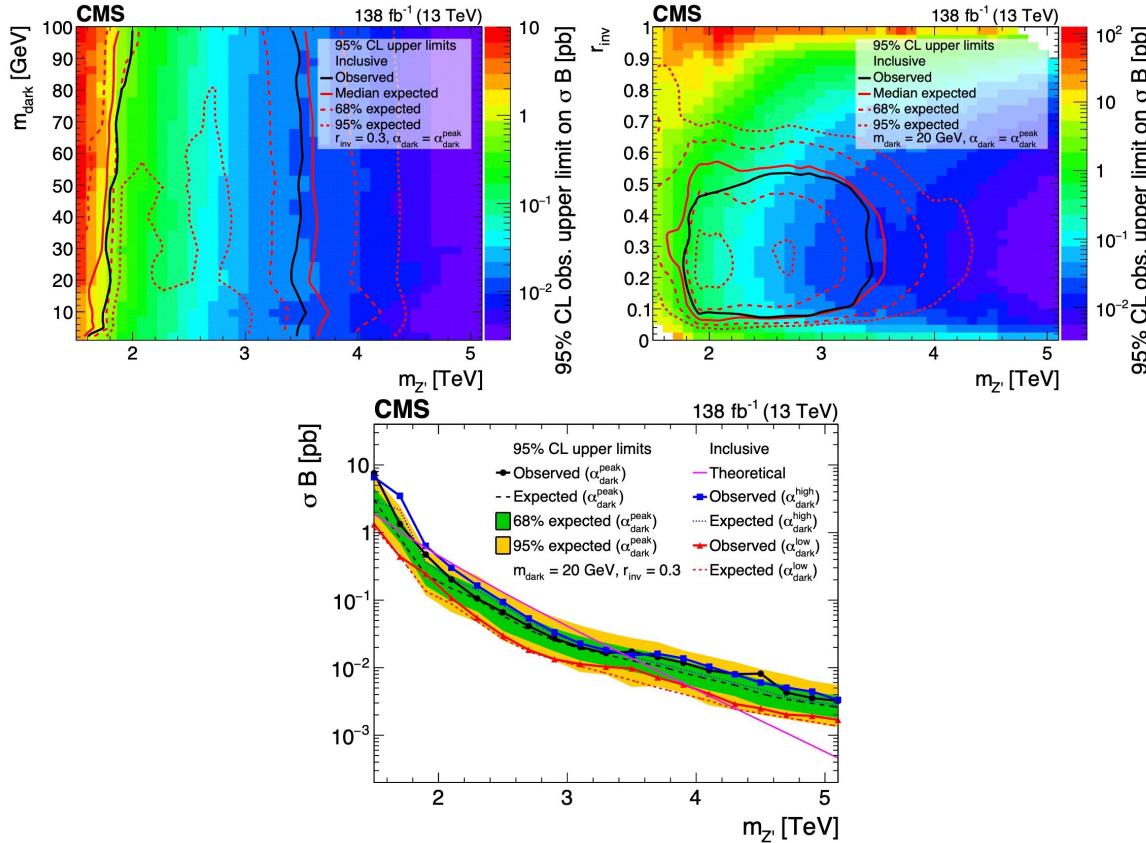
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CMS Search



CMS Search



CMS Search

