

# Semi-visible Jet Phenomenology

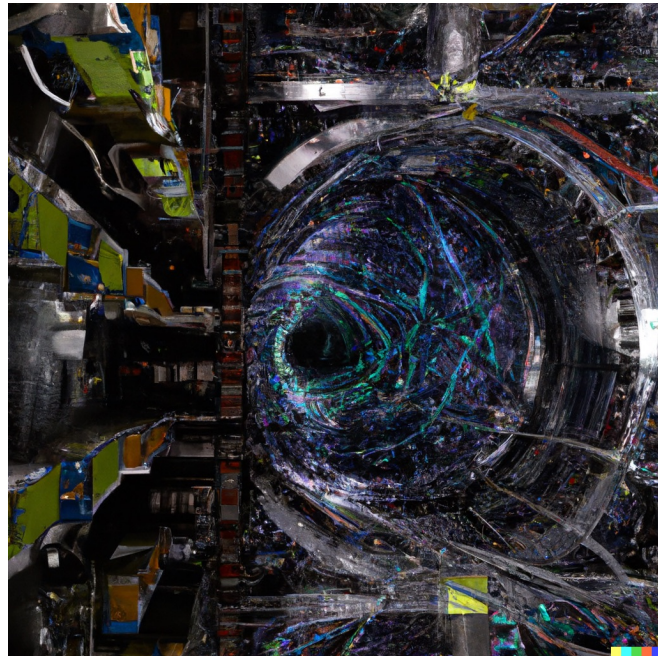
Tim Cohen

CERN/EPFL  
U Oregon

MITP YOUNGSTERS

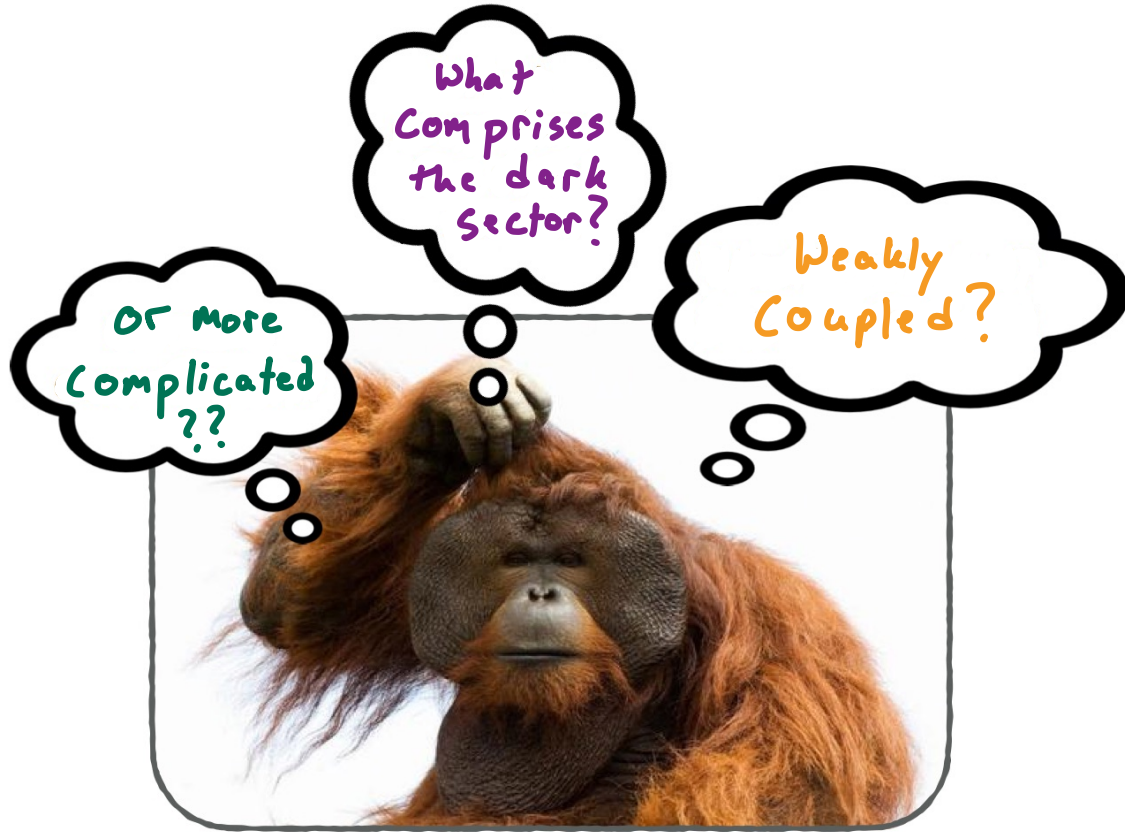
Colours in Darkness

Oct 18, 2023



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

# Deep Thoughts



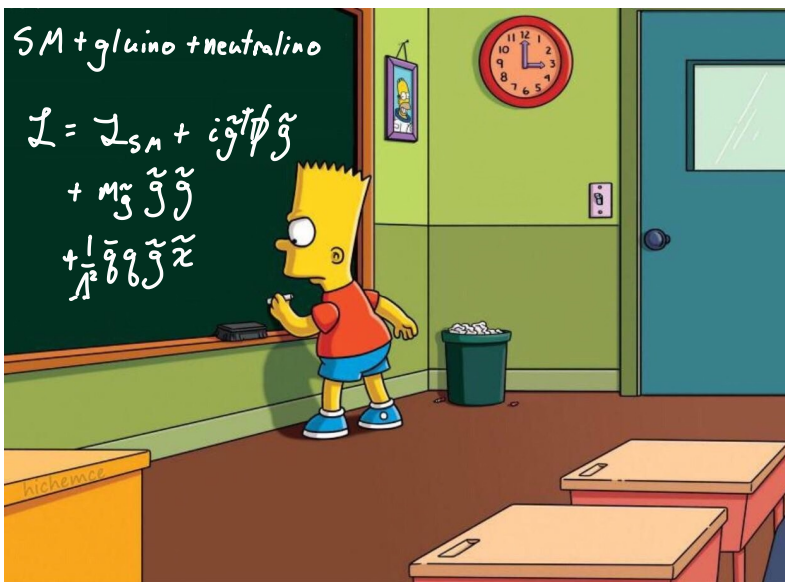
# Practical Thoughts

Optimize  
searches to  
ensure discovery  
!!!

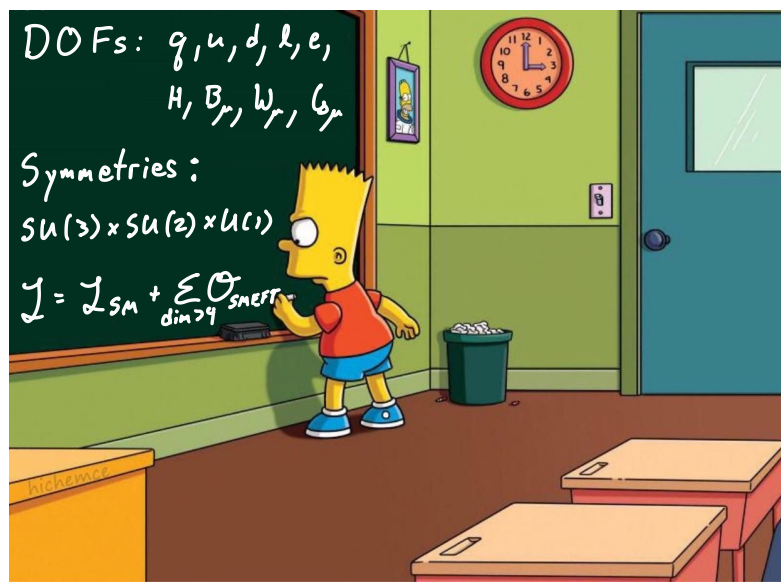


# How to organize BSM predictions?

## Simplified Models

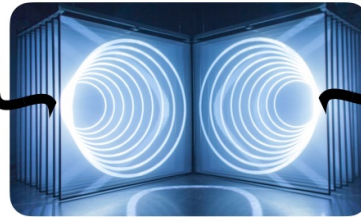
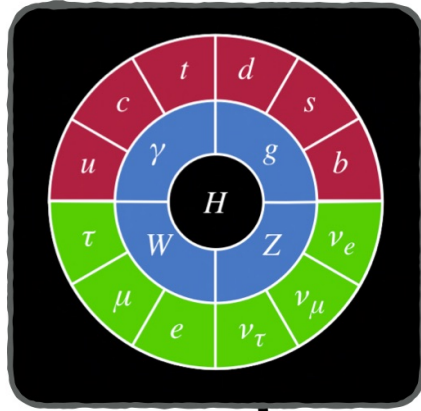


## Effective Field Theory

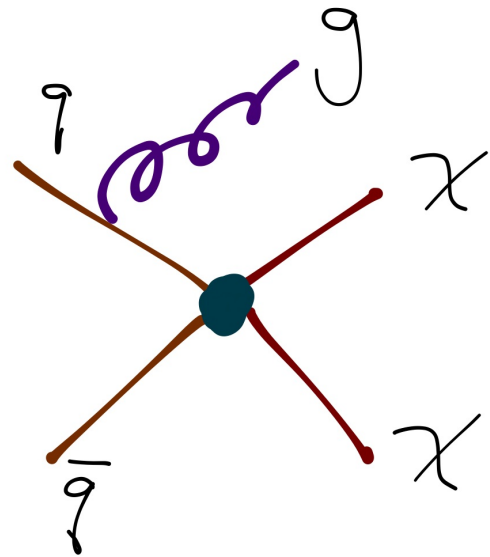
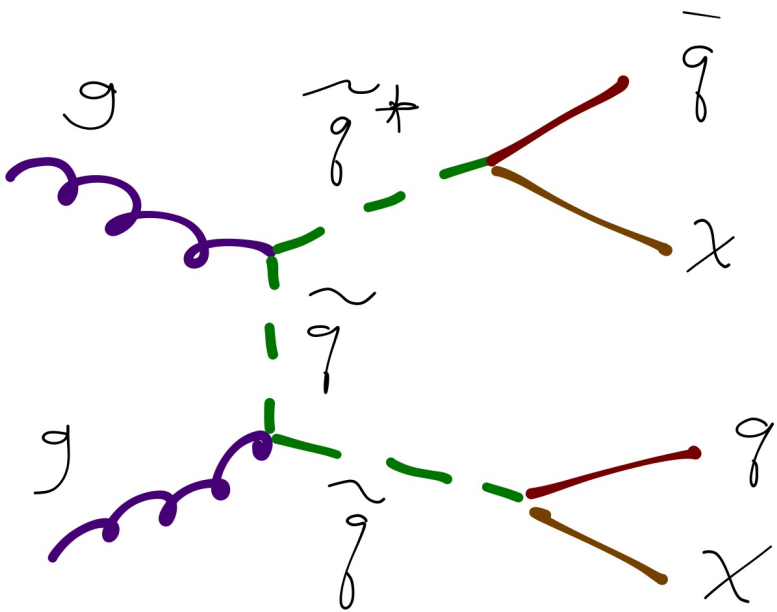




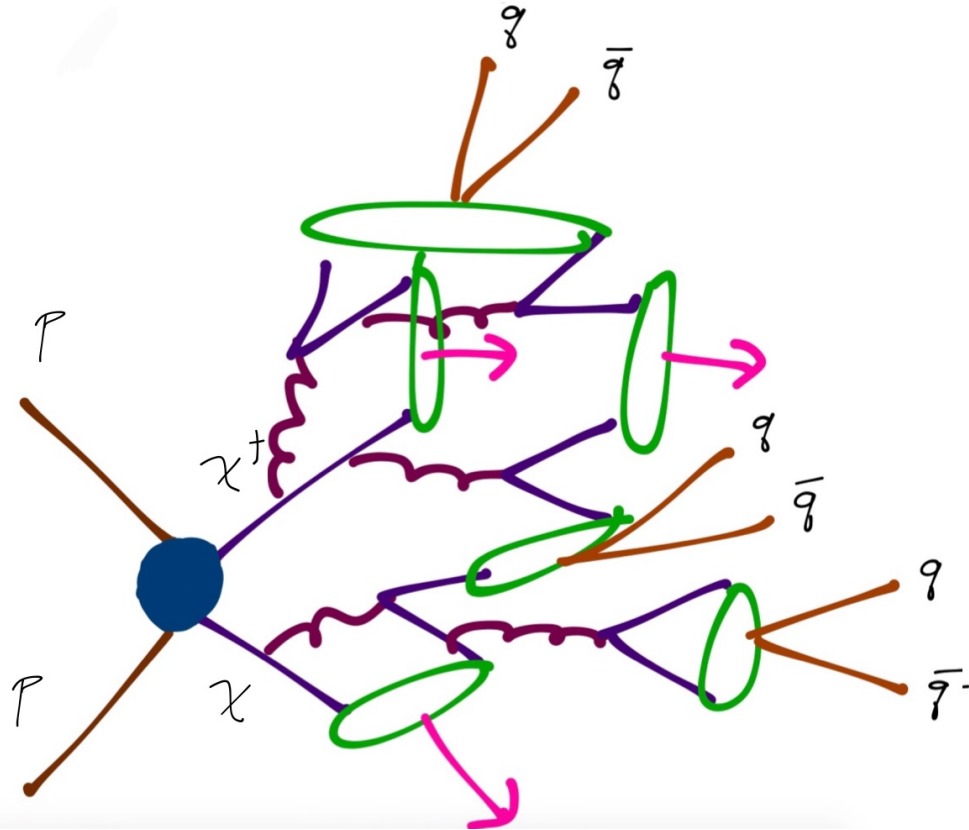
# Dark Sector Paradigm



# Weakly Coupled Dark Sector

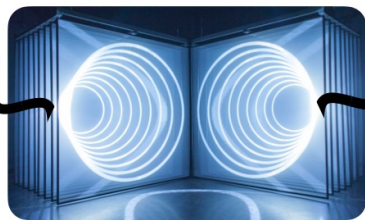
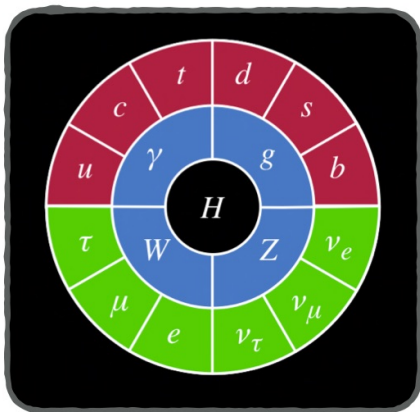


# Strongly Coupled Dark Sector



# Overwhelming Theory Space

Fixed  $\rightarrow$

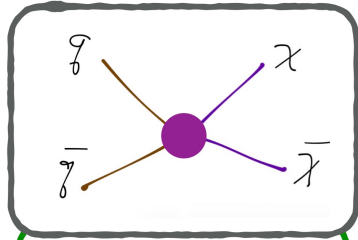


$\leftarrow$  Finite  
(renormalizable)  
options

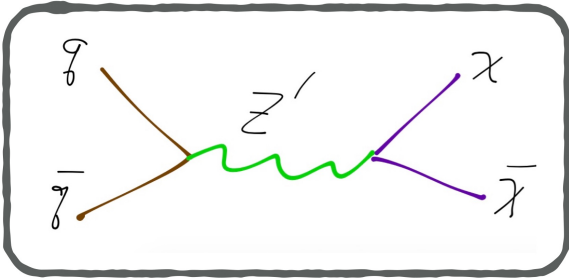


# Portal to Quarks

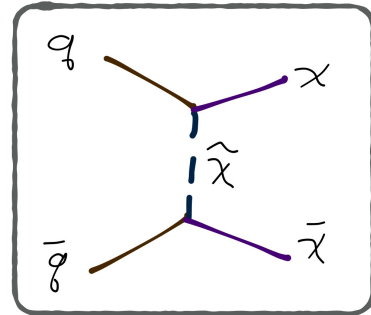
contact operator



s-channel



t-channel



# Phenomena Driven

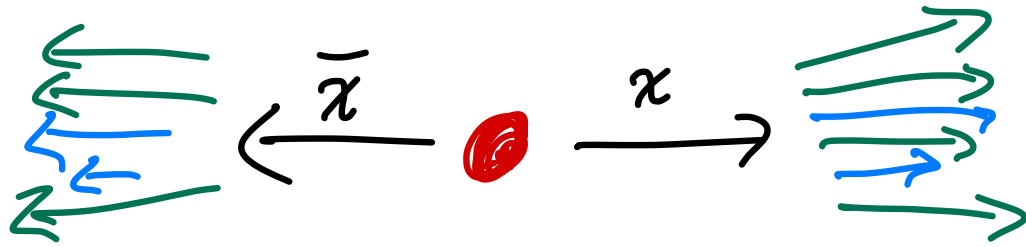
- Semi-visible jets
- Lepton jets
- Emerging jets
- Soft bombs
- Quirks
- Your awesome new idea?

# Semi-visible Jets

Assume dark sector quarks  $\chi$  dominantly interact with QCD.

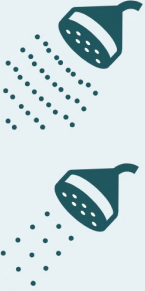

Some dark mesons  $\Pi_D$  decay to QCD

Some dark mesons  $\Pi_D'$  are stable

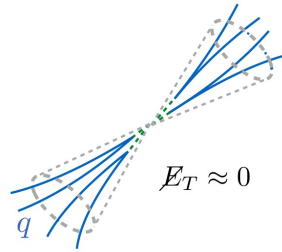


Missing energy aligned with jets

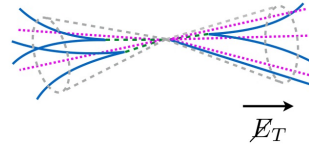
# Semi-visible Jets

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

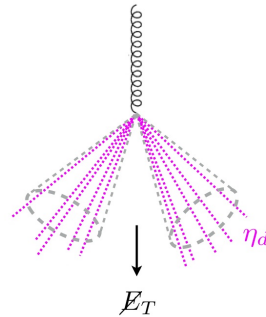
$$r_{inv} = 0$$



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



$$r_{inv} = 1$$



Pheno parametrization

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

- $\alpha_d$  (or  $\Lambda_d$ )
- $\Gamma_{inv}$
- $M_d$
- $\sigma_{portal}$



# 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

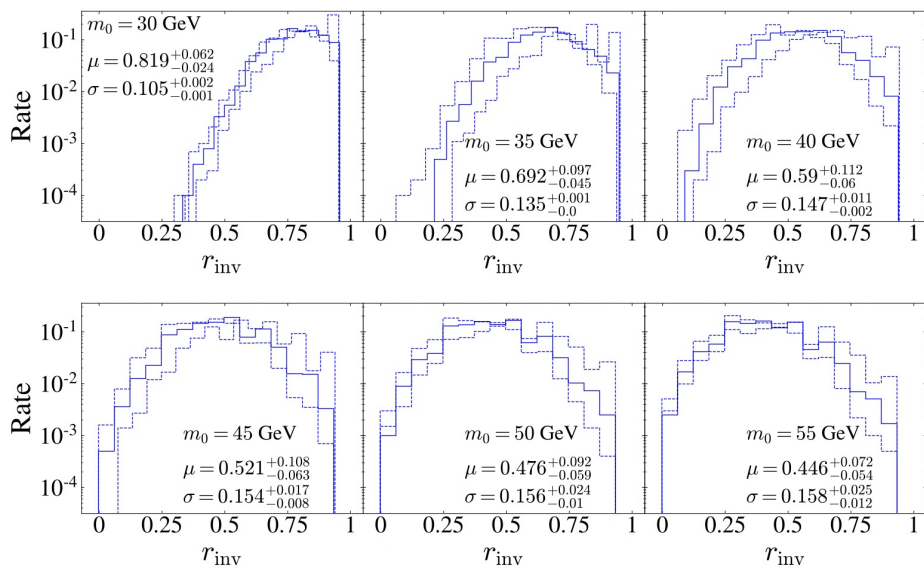
Decay Depends on spectrum & portal

# Semi-visible Jets from Glueballs

w/ Batz, Curtin, Gemell, Kribs

$pp \rightarrow Z' \rightarrow \text{glueballs}$

Pure glue dark sector ( $N_c, \Lambda_{\text{dark}}$ )

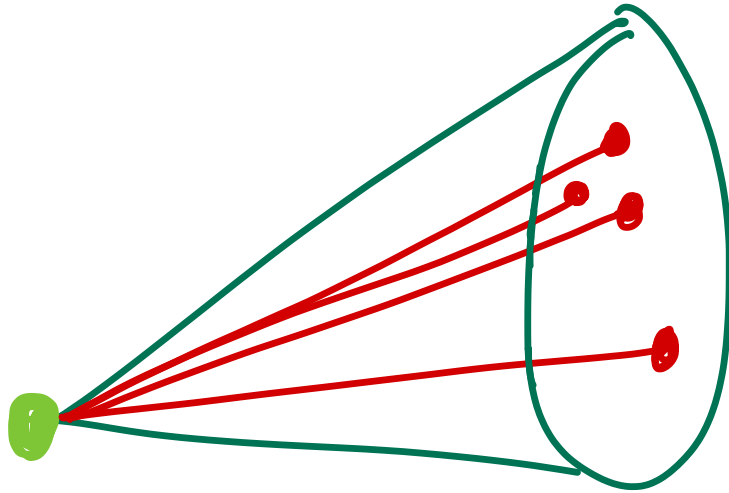


# Frontiers



Better Observables?

Jet substructure



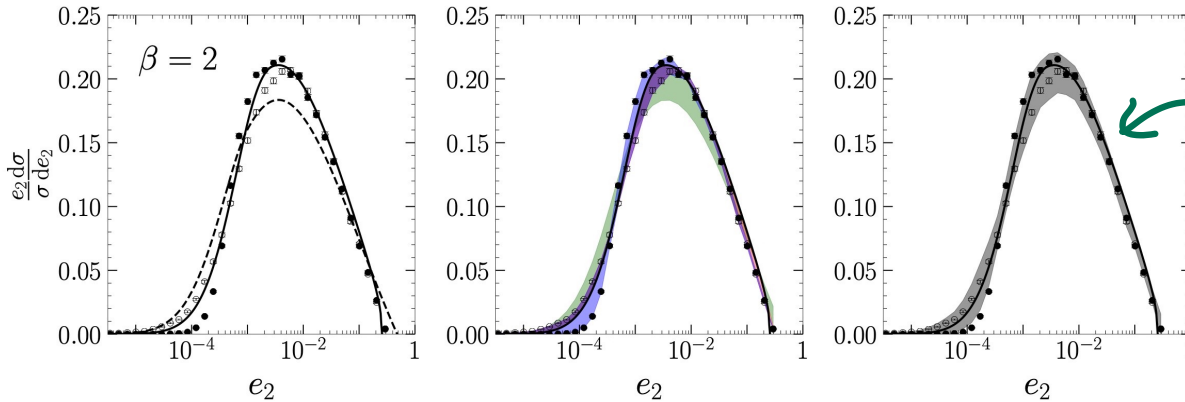


# Dark Substructure

z-point correlation function

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

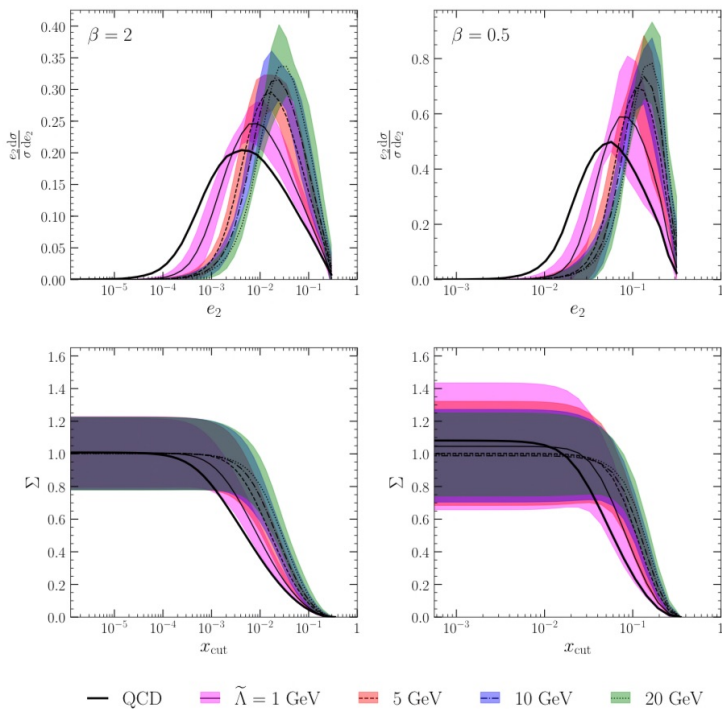
Generalization of jet mass ( $\beta=2$ )



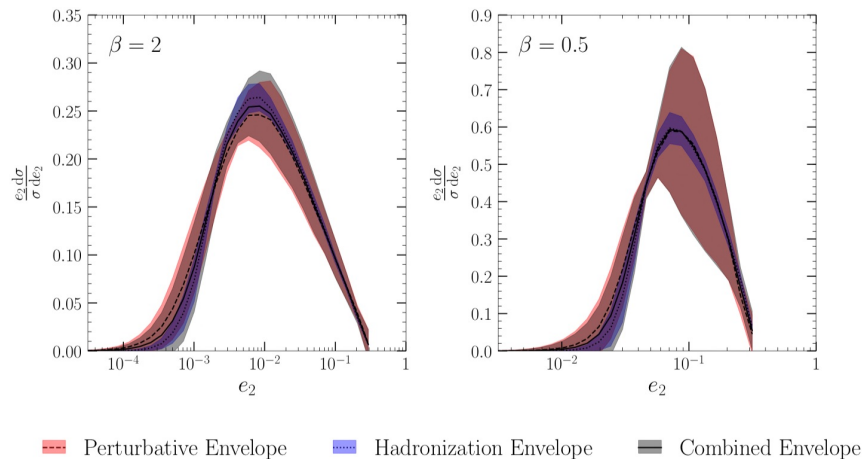
--- LL    — MLL    ◦ Pythia Parton    • Pythia Hadron

TC, Doss, Freytsis  
arXiv: 2004.00631

# Theoretical Errors



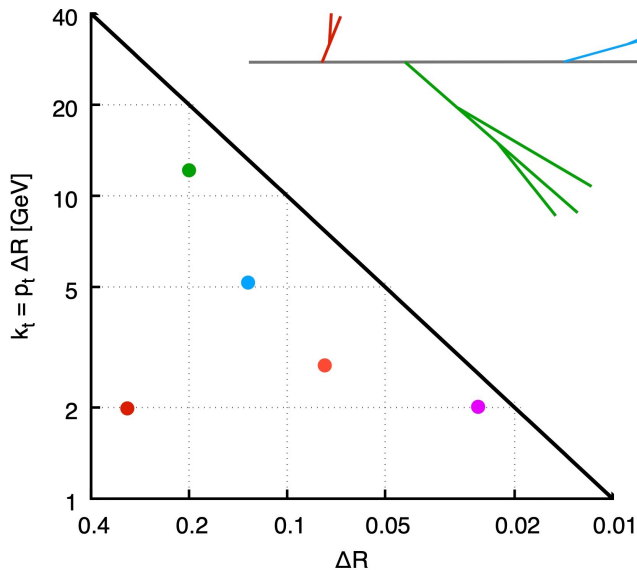
## Hadronization



TC, Doss, Freytsis  
 arXiv: 2004.00631

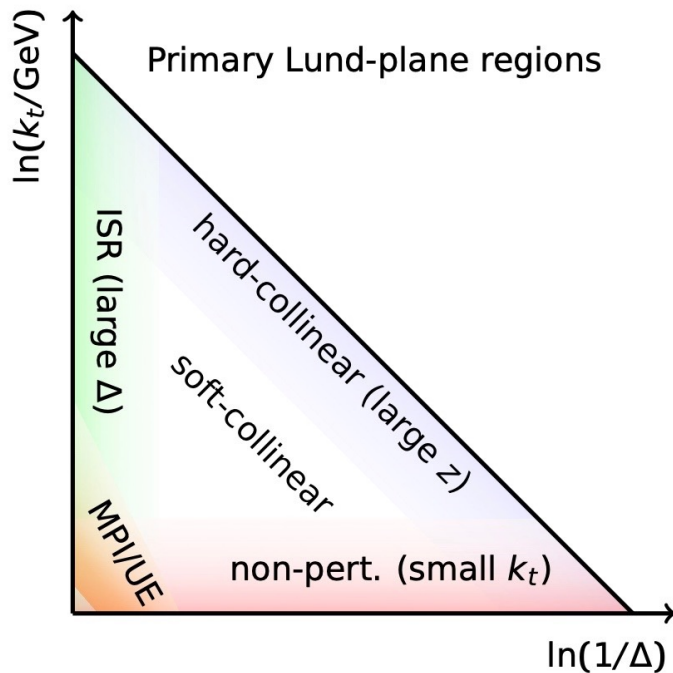
# Lund Jet Plane

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



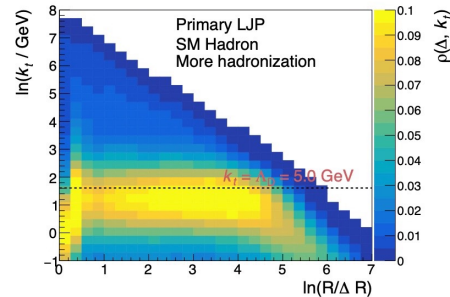
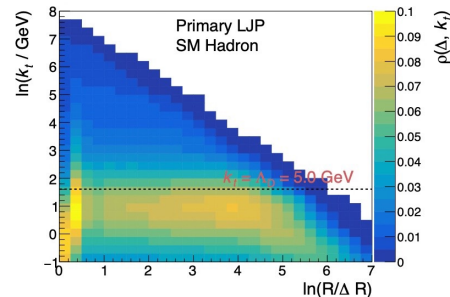
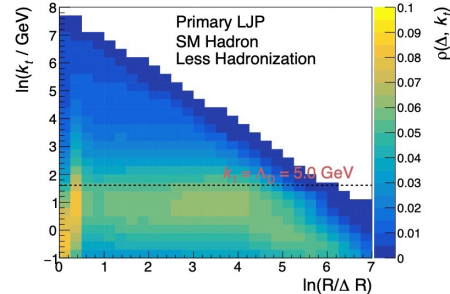
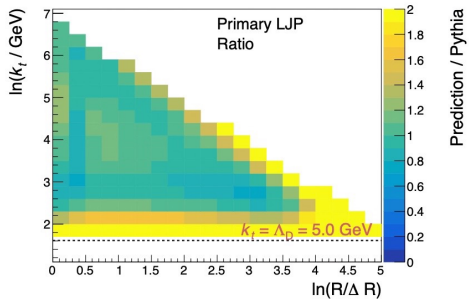
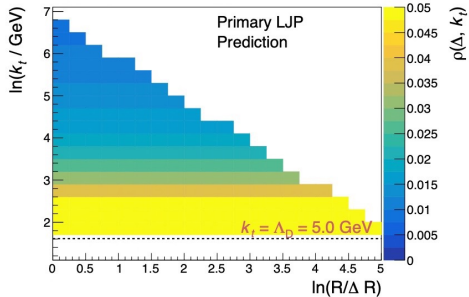
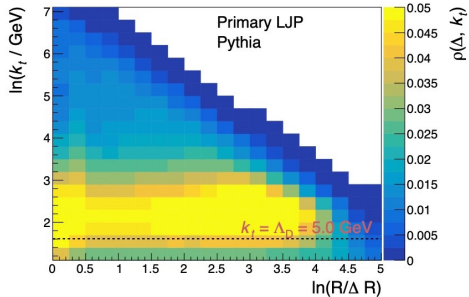
↑  
from talk by G. Salam

Average over many jets



# Lund Dark Jet Plane

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



leading log density

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

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

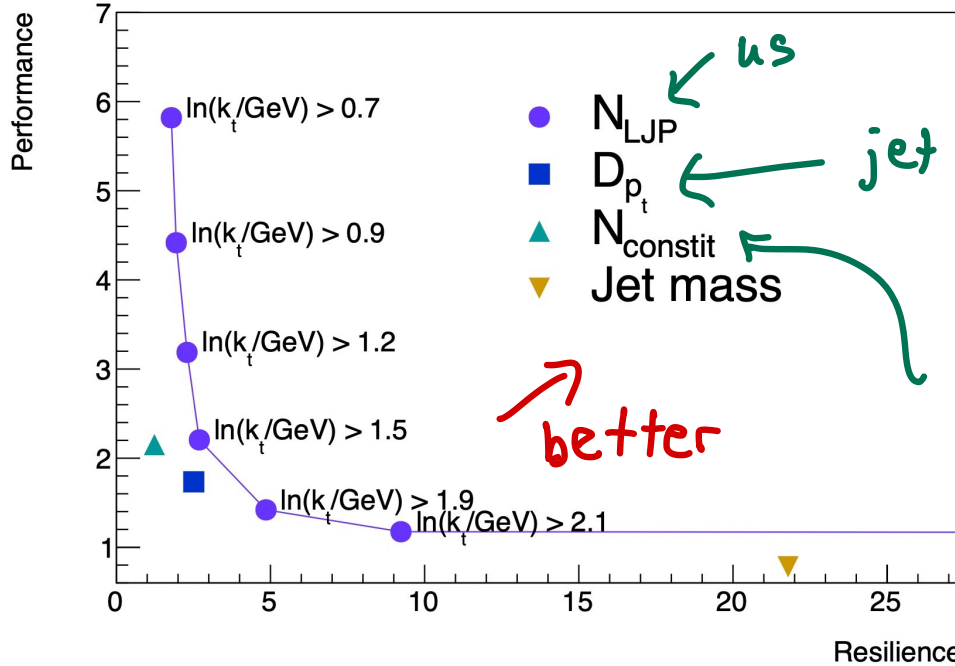
for  $SU(N)$

Varying  
hadronization



# Performance vs Resilience

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



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

better

Next step is to design search

Variation wrt hadronization

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

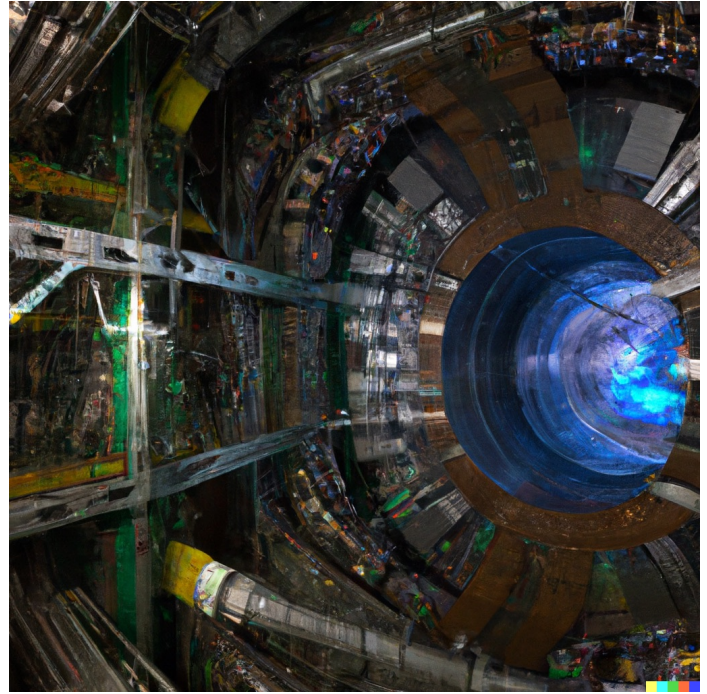


# New Phenomena?



# Bright Future for Dark Showers

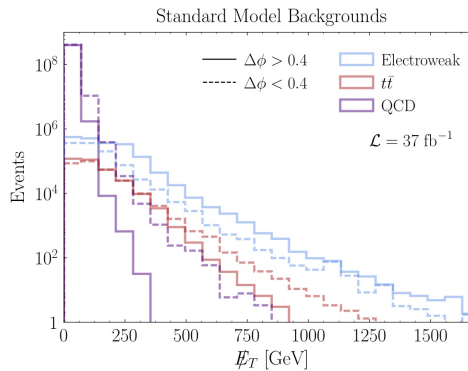
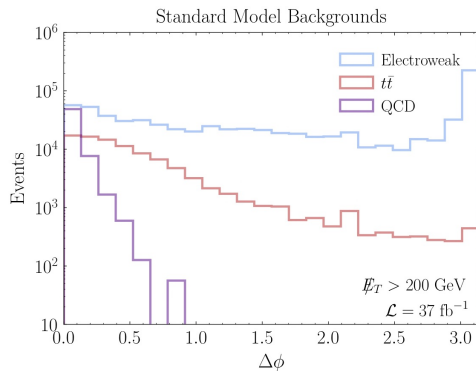
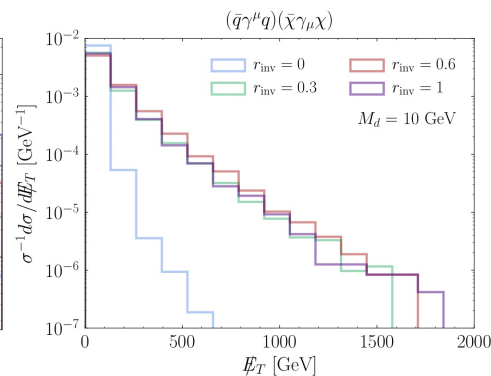
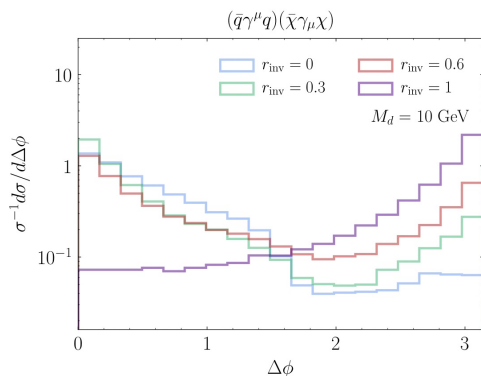
- More searches from CMS and ATLAS!
- Improvements to sims
- Robust predictions
- Machine learning
- Exploring model space
- New physics discovery??



↑  
Another DALL-E "original"

Backups

# Signal vs Background

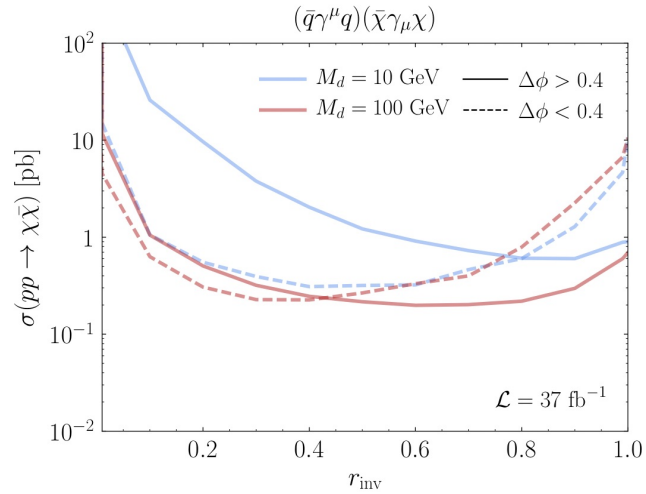
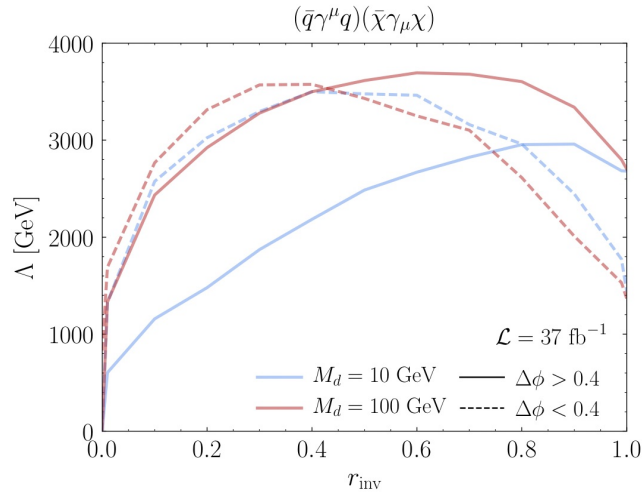


TL, M. Lisanti, H.-k. Lou, S. Mishra-Sharma [arXiv:1707.05326]

# 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

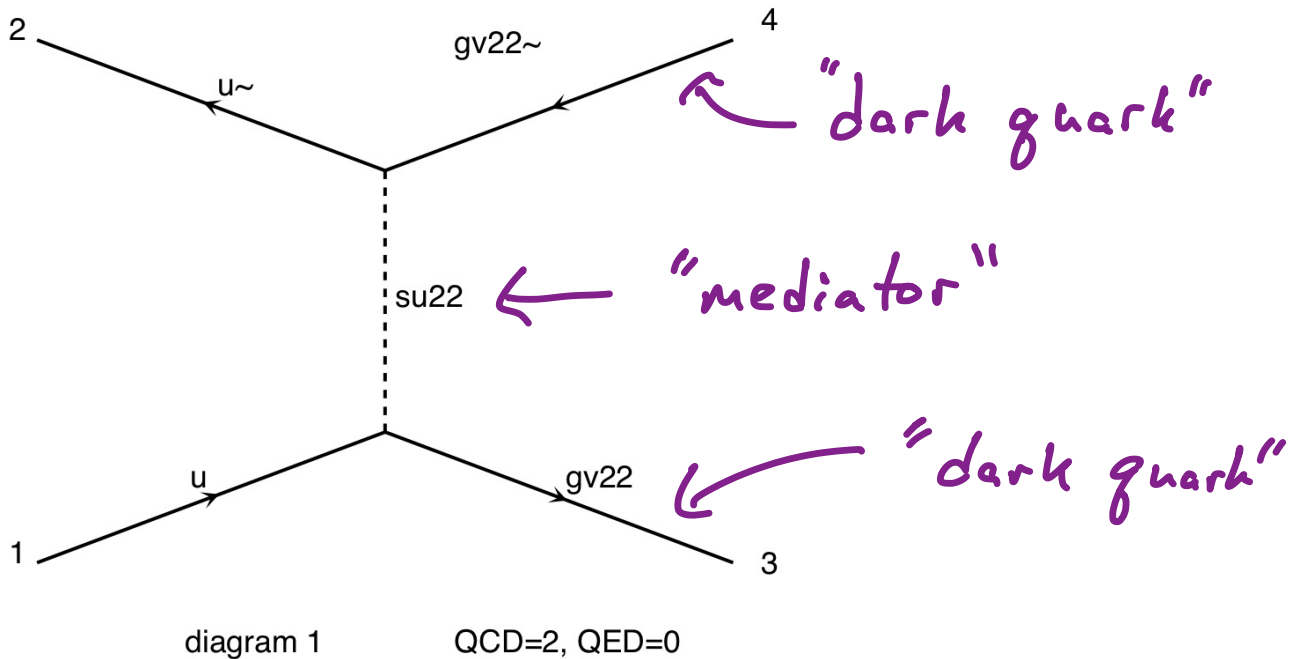


s-channel + t-channel models  
see arXiv:1707.05326



# 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"

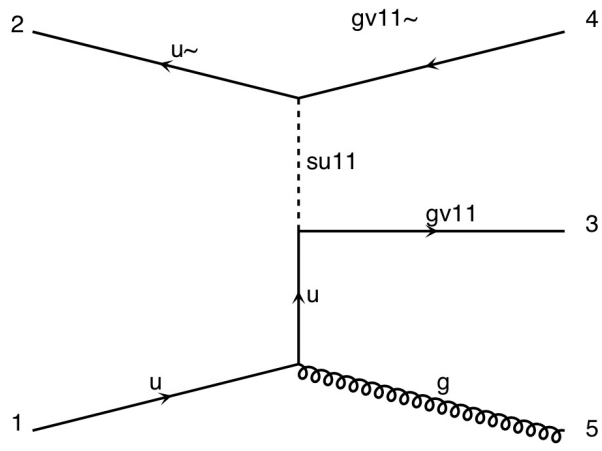


diagram 1      QCD=3, QED=0

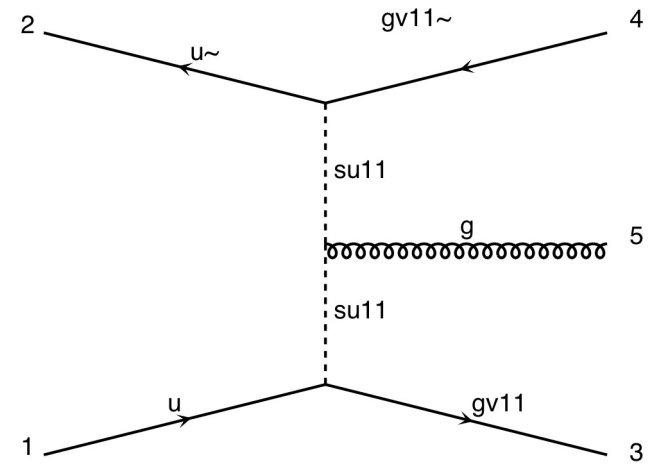


diagram 3      QCD=3, QED=0

+ ...

# Production in $t$ -channel Model

Want higher body diagrams for "matching"

"on-shell" mediators

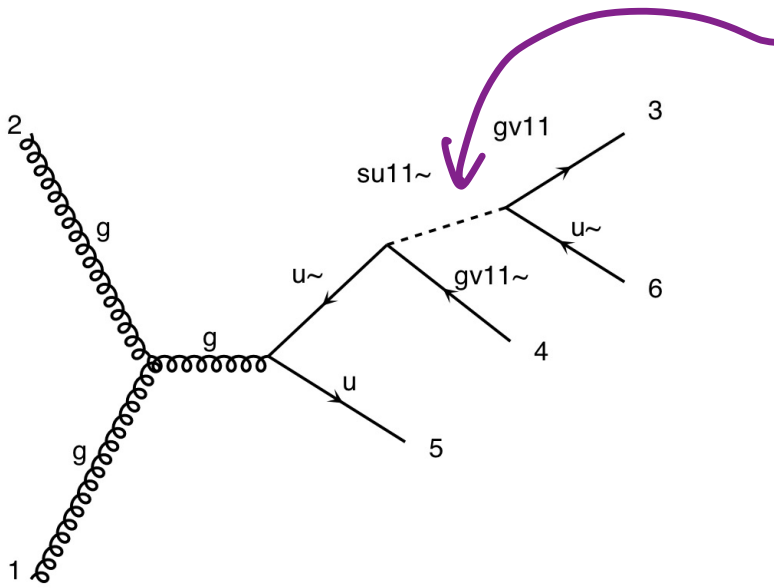


diagram 1

QCD=4, QED=0

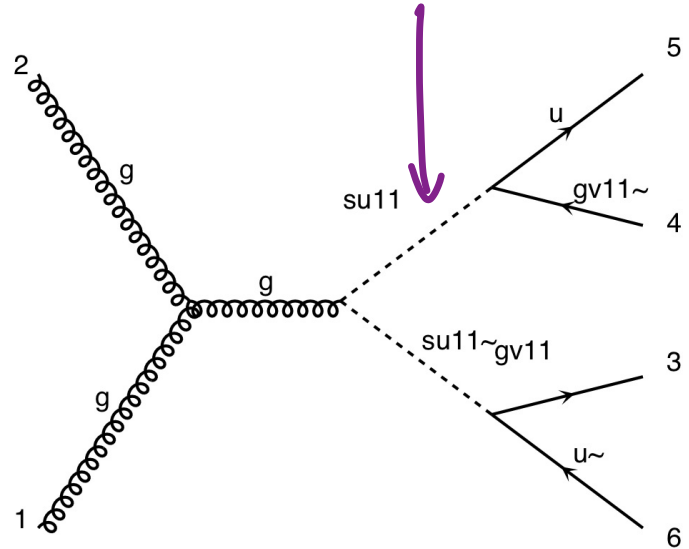


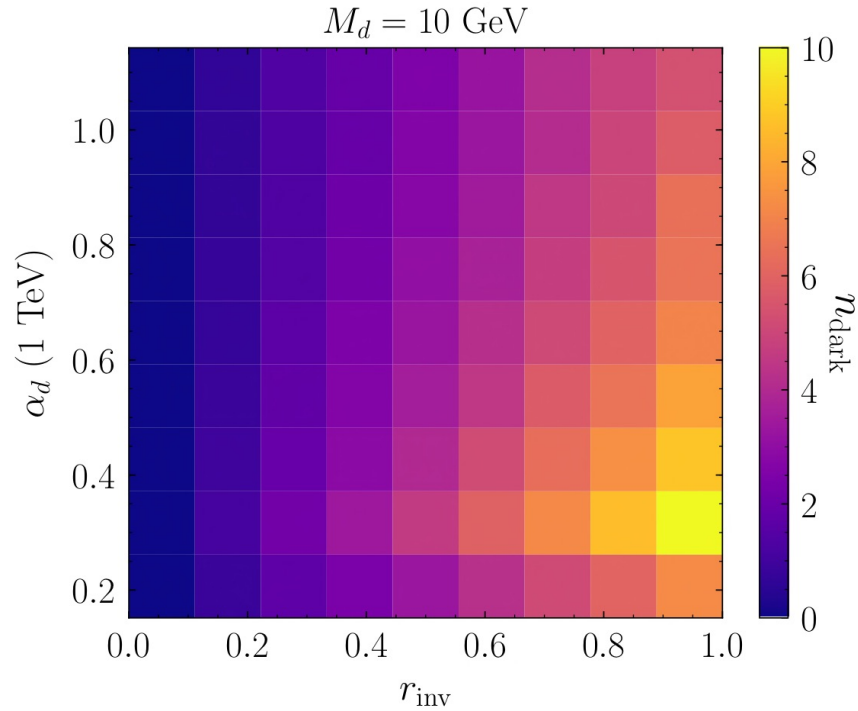
diagram 2

QCD=4, QED=0

+ . . .

# Showering

Under reasonable theoretical control



# Hadronization & Decay

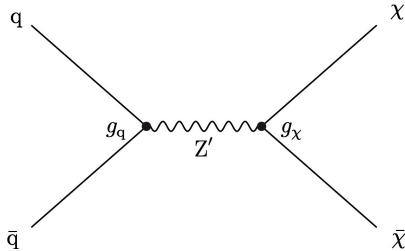
## Phenomenological model

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

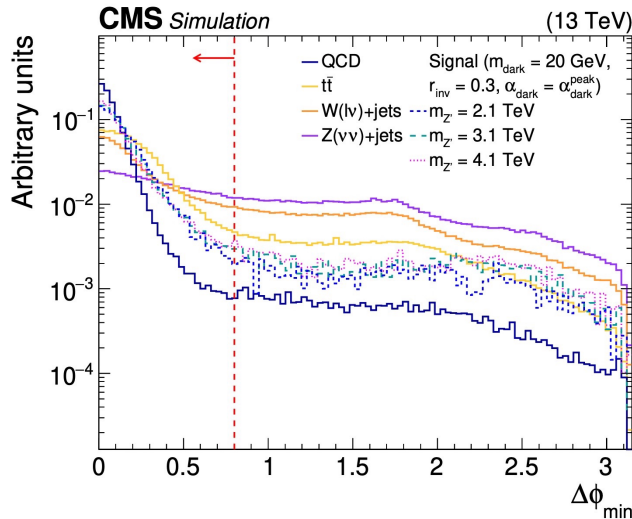
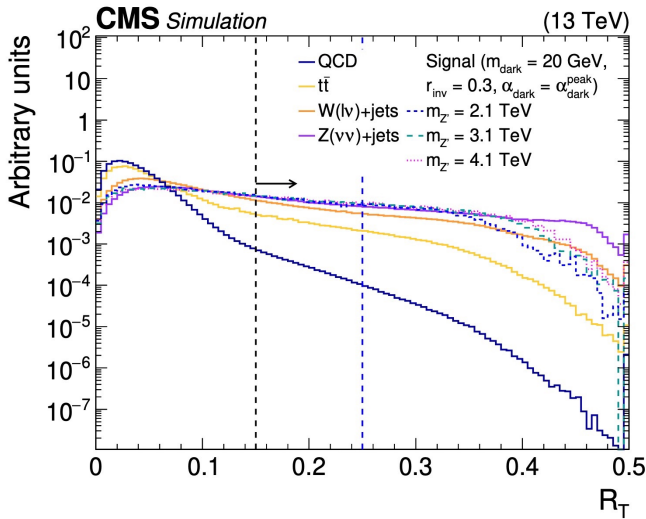
S-channel  
model

# CMS Search

arXiv: 2112.11125



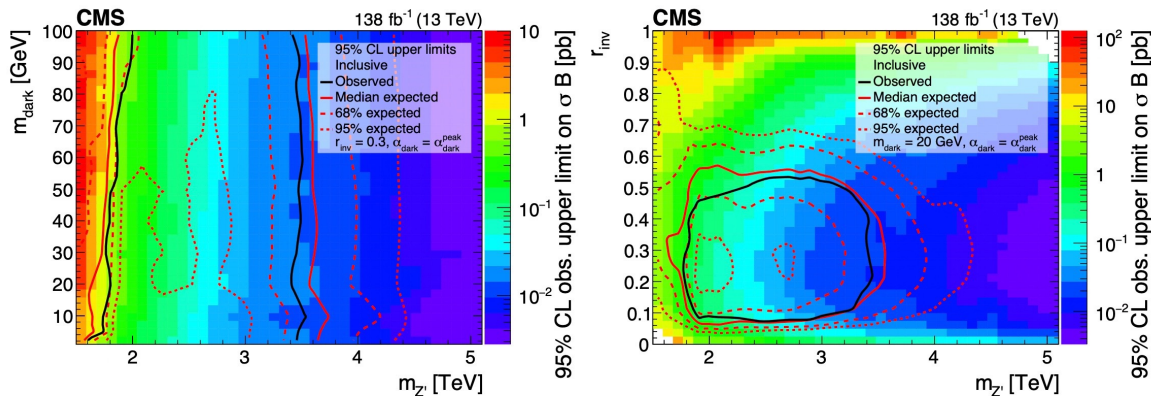
Scan	$m_{Z'}$ [TeV]	$m_{\text{dark}}$ [GeV]	$r_{\text{inv}}$	$\alpha_{\text{dark}}$
1	1.5–5.1	1–100	0.3	$\alpha_{\text{dark}}^{\text{peak}}$
2	1.5–5.1	20	0–1	$\alpha_{\text{dark}}^{\text{peak}}$
3	1.5–5.1	20	0.3	$\alpha_{\text{dark}}^{\text{low}} - \alpha_{\text{dark}}^{\text{high}}$



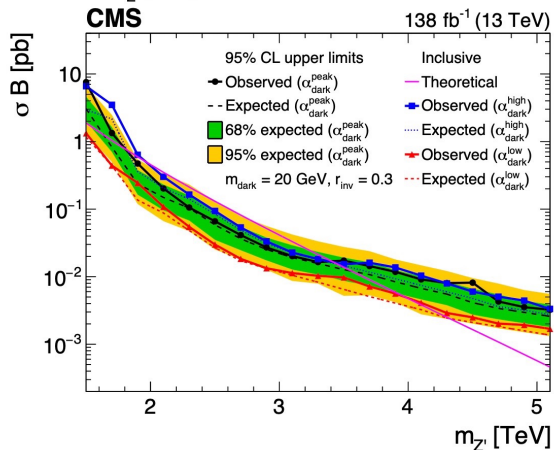
$$R_T = \frac{p_T^{\text{miss}}}{m_T}$$

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

# 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

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

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

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

# CMS Search

## Preselection requirements

---

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

$$R_T > 0.15$$

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

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

$$N_\mu = 0$$

$$N_e = 0$$

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

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

## Final selection requirements

---

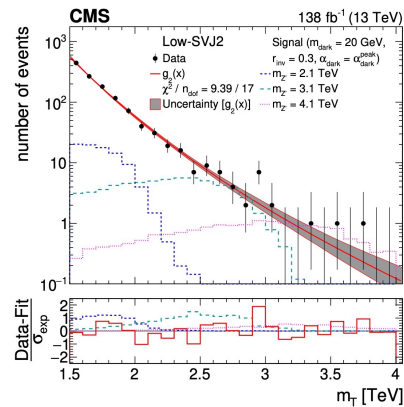
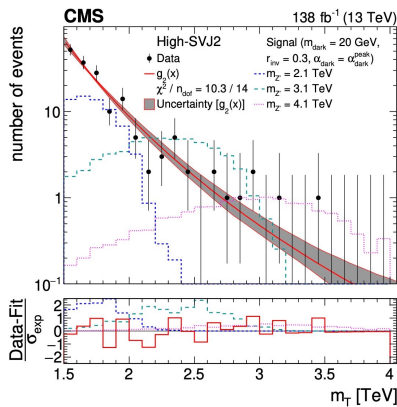
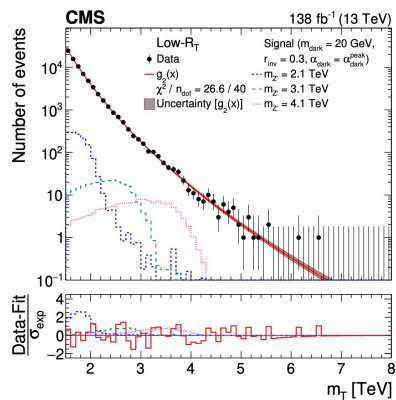
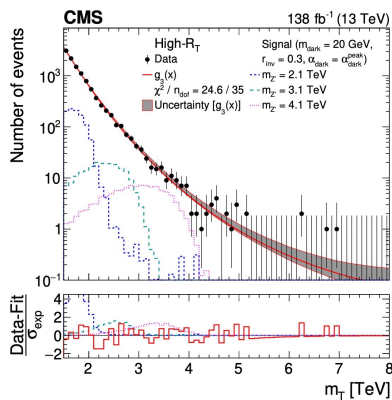
$$\text{veto } f_\gamma(j_1) > 0.7 \ \& \ p_T(j_1) > 1.0 \text{ TeV}$$

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

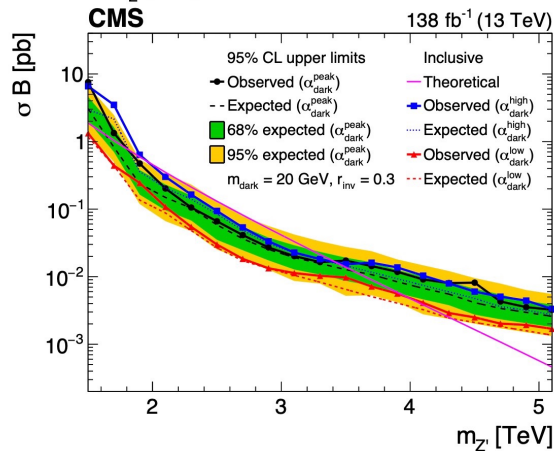
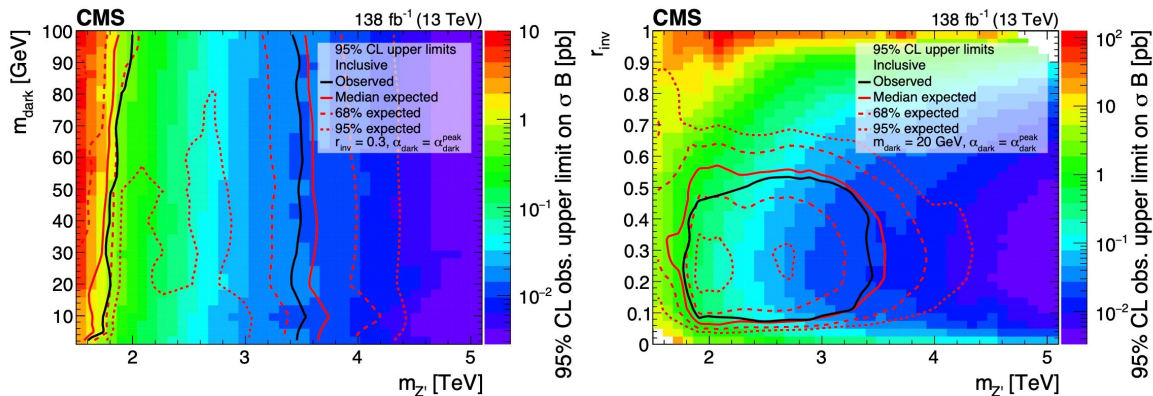
$$\Delta\phi_{\text{min}} < 0.8$$



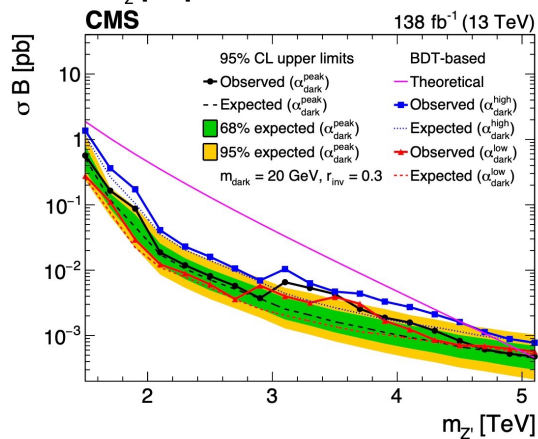
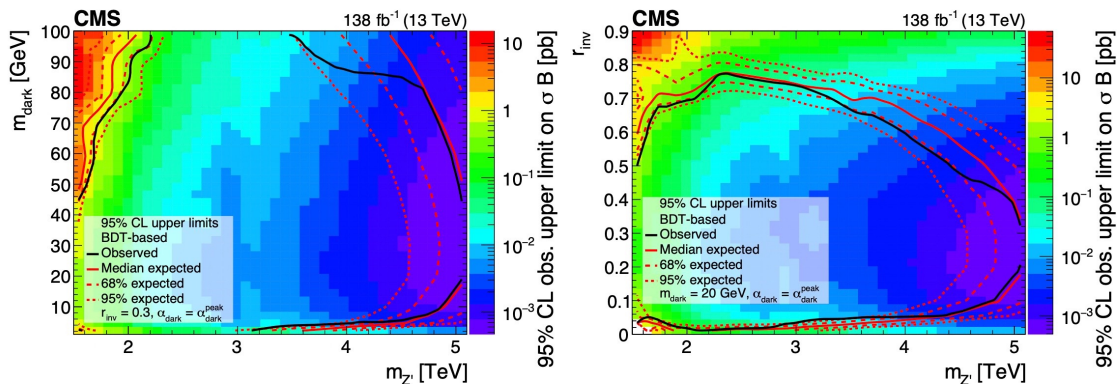
# CMS Search



# CMS Search



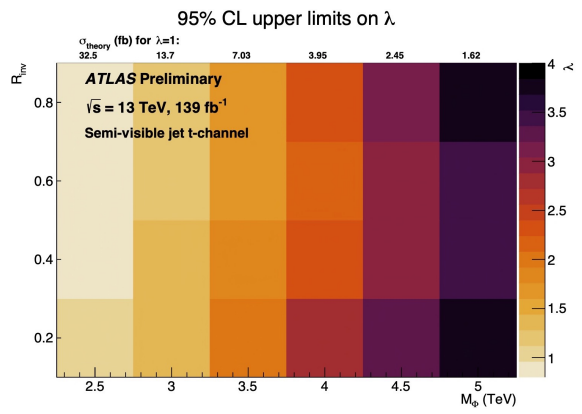
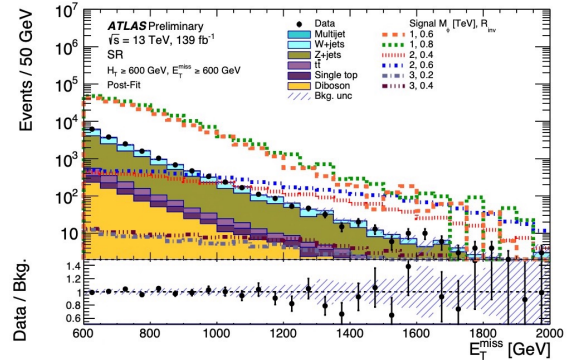
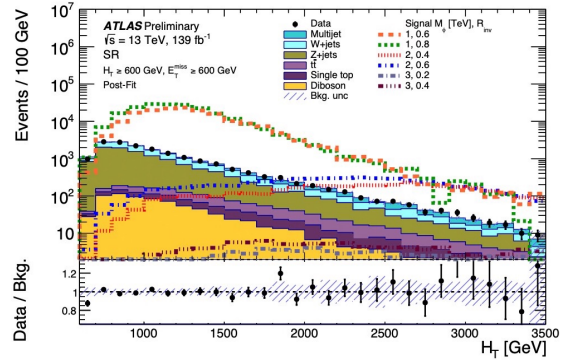
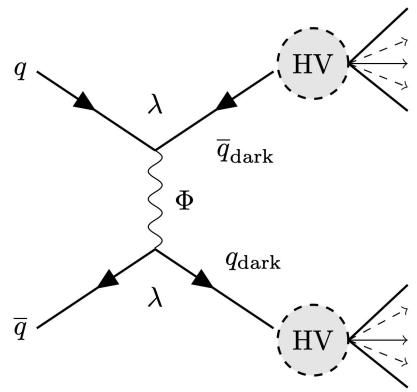
# CMS Search



# ATLAS Search

## ATLAS-CONF-2022-038

*t*-channel model



# Lund Jet Plane

Tool to isolate hadronization effects

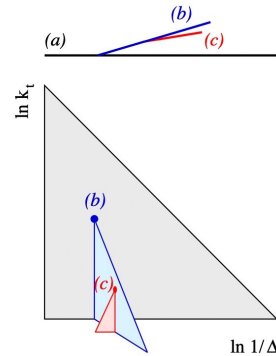
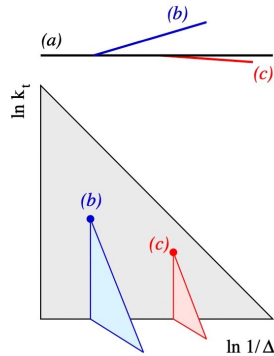
Recluster jet using Cambridge - Aachen algorithm  
(Clusters according to distance in rapidity and  $\varphi$ )

Plot branchings in Lund Plane: angle  $\Delta$  and  
transverse momentum  $k_T$  of emission wrt emitter

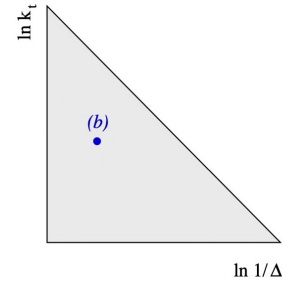
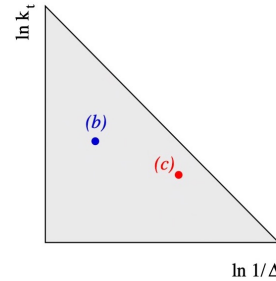
F. Dreyer, G. Salam,  
G. Soyez  
arXiv:1807.04758

JET

LUND DIAGRAM



PRIMARY LUND PLANE



# Lund 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

