

# Theory overview on dark showers

Christiane Scherb  
LBNL & UC Berkeley

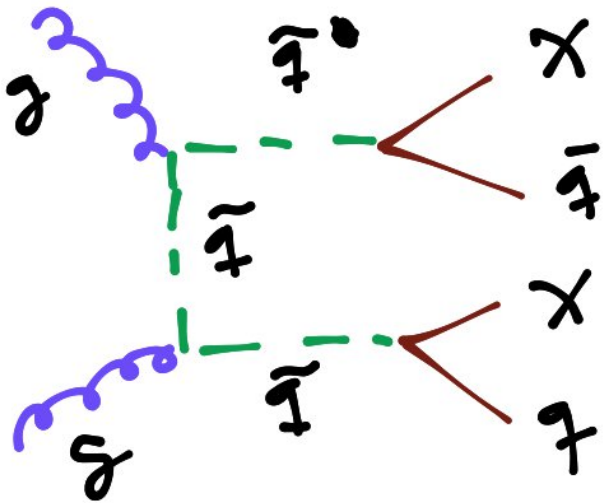
LHCP 2024



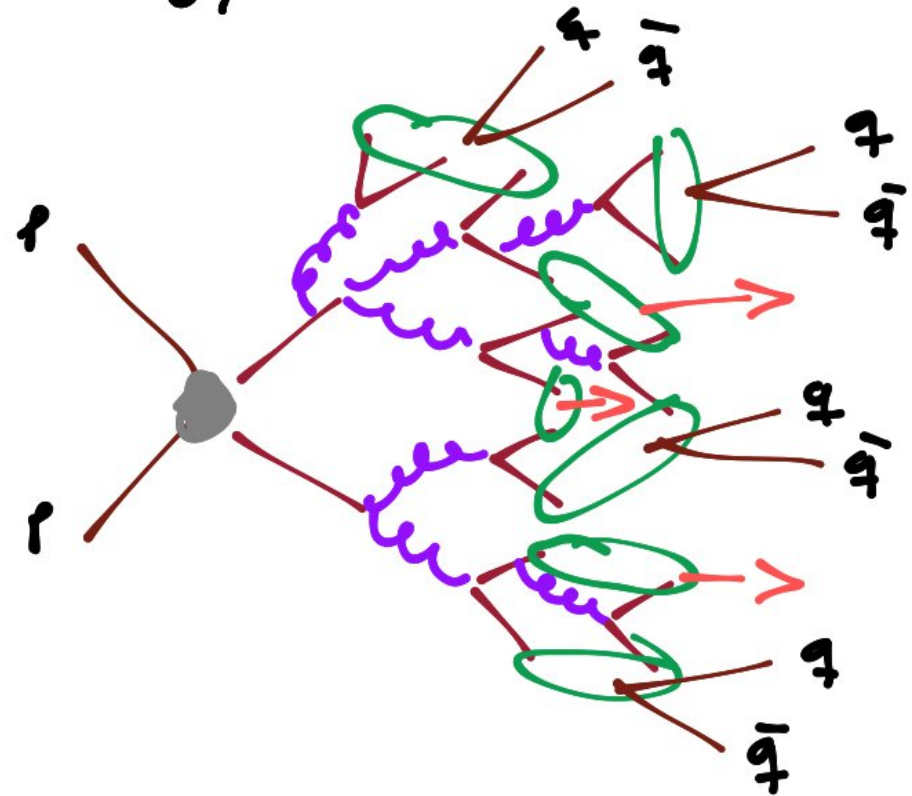
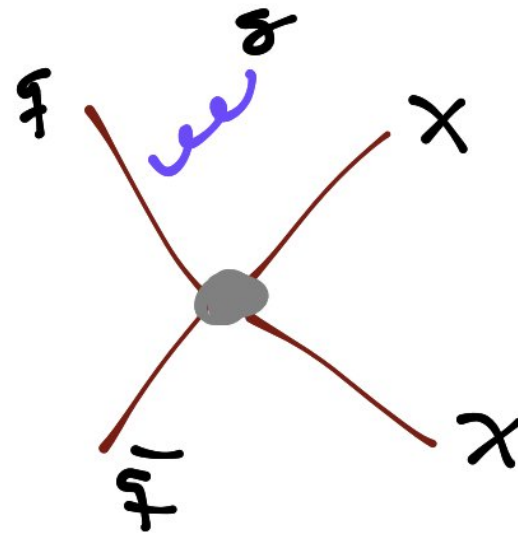
# Why dark showers?

dark showers are a feature/signature of confining dark sectors

weakly coupled dark sector



strongly coupled dark sector



# Why dark showers?

dark showers are a feature/signature of confining dark sectors

Hidden Valley models/QCD-like dark sectors

Strassler,  
Zurek '06

→ sector of SM neutral particles connected via a portal

- produced in SM collision
- include states that decay within 1 s lifetime
- have self interactions
- unusual collider pheno

# Hidden Valley models

Standard Model of Particle Physics

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
mass charge spin			0 1 1/2	0 0 0
$\bar{u}$ up +2.2 MeV/c <sup>2</sup>	$\bar{c}$ charm +1.28 GeV/c <sup>2</sup>	$\bar{t}$ top +173.1 GeV/c <sup>2</sup>	$\bar{g}$ gluon	$\bar{H}$ higgs +124.97 GeV/c <sup>2</sup>
$\bar{d}$ down +4.7 MeV/c <sup>2</sup>	$\bar{s}$ strange +98 MeV/c <sup>2</sup>	$\bar{b}$ bottom +4.18 GeV/c <sup>2</sup>	$\bar{\gamma}$ photon	
$\bar{e}$ electron +0.511 MeV/c <sup>2</sup>	$\bar{\mu}$ muon +105.66 MeV/c <sup>2</sup>	$\bar{\tau}$ tau +1.7768 GeV/c <sup>2</sup>	$\bar{Z}$ Z boson +91.19 GeV/c <sup>2</sup>	
$\bar{\nu}_e$ electron neutrino <1.0 eV/c <sup>2</sup>	$\bar{\nu}_\mu$ muon neutrino +0.17 MeV/c <sup>2</sup>	$\bar{\nu}_\tau$ tau neutrino +18.2 MeV/c <sup>2</sup>	$\bar{W}$ W boson +80.433 GeV/c <sup>2</sup>	
LEPTONS			GAUGE BOSONS VECTOR BOSONS	SCALAR BOSONS

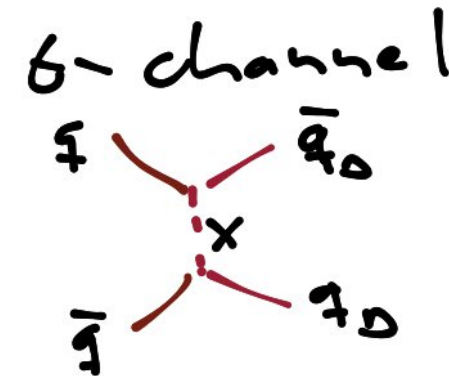
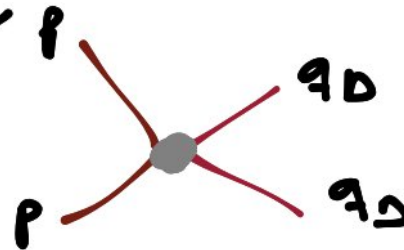
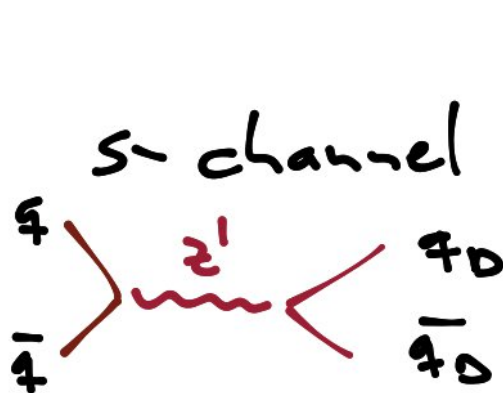
QCD-like Dark Sector

$$\mathcal{G}_{SM} \times SU(N_D)_D$$

$n_D$  dark quarks  $Q_D$

$N_D$  dark colours

Portal



# Hidden Valley models

Standard Model of Particle Physics

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
mass charge spin			0 1 1/2	0 0 1
$\pm 2.2 \text{ MeV}/c^2$ 2/3 1/2 <b>u</b> up	$\pm 1.28 \text{ GeV}/c^2$ 2/3 1/2 <b>c</b> charm	$\pm 173.1 \text{ GeV}/c^2$ 2/3 1/2 <b>t</b> top	<b>g</b> gluon	<b>H</b> higgs
$\pm 4.7 \text{ MeV}/c^2$ -1/3 1/2 <b>d</b> down	$\pm 98 \text{ MeV}/c^2$ -1/3 1/2 <b>s</b> strange	$\pm 4.18 \text{ GeV}/c^2$ -1/3 1/2 <b>b</b> bottom	<b>\gamma</b> photon	
$\pm 0.511 \text{ MeV}/c^2$ -1 1/2 <b>e</b> electron	$\pm 105.66 \text{ MeV}/c^2$ -1 1/2 <b>\mu</b> muon	$\pm 1.7768 \text{ GeV}/c^2$ -1 1/2 <b>\tau</b> tau	<b>Z</b> Z boson	
$< 1.0 \text{ eV}/c^2$ 0 1/2 <b>\nu_e</b> electron neutrino	$\pm 0.17 \text{ MeV}/c^2$ 0 1/2 <b>\nu_\mu</b> muon neutrino	$\pm 1.82 \text{ MeV}/c^2$ 0 1/2 <b>\nu_\tau</b> tau neutrino	<b>W</b> W boson	

QUARKS (left column), LEPTONS (right column), GAUGE BOSONS VECTOR BOSONS (bottom row), SCALAR BOSONS (right side)

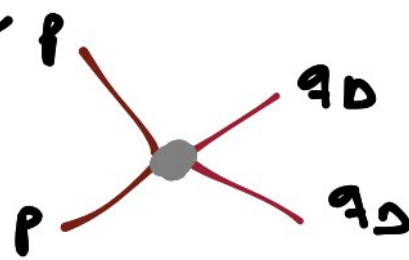
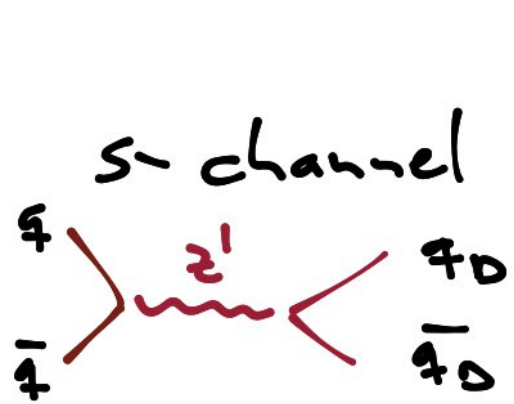
QCD-like Dark Sector

$$\mathcal{G}_{SM} \times SU(N_D)_D$$

$n_D$  dark quarks  $Q_D$

$N_D$  dark colours

Portal



t-channel  
→ connection to flavor

- neutral meson mixing
- $B \rightarrow K \pi_0, B \rightarrow \bar{u} \pi_0$
- $K \rightarrow \pi \pi_0, D \rightarrow \pi \pi_0$

# Hidden Valley Models: dark pions

$$\mathcal{L}_{dQCD} = \bar{Q}_\alpha (i\not{D} - m_{Q_D} \delta_{\alpha,\beta}) Q_\beta - \frac{1}{4} G_{D,\mu\nu}^A \tilde{G}_D^{\mu\nu A}$$

for small  $m_Q$ : approximate  $SU(3)_{d_L} \times SU(3)_{d_R}$

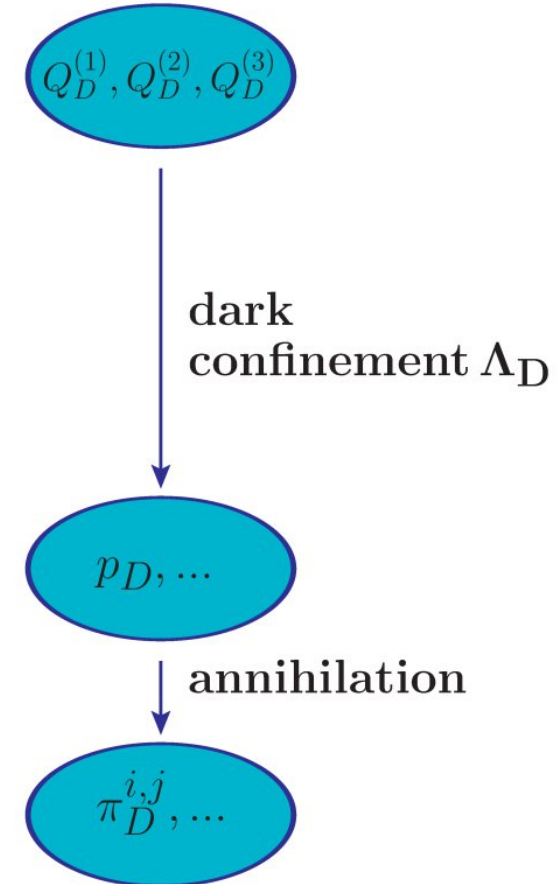


broken by dark quark condensate to  $SU(3)_V$

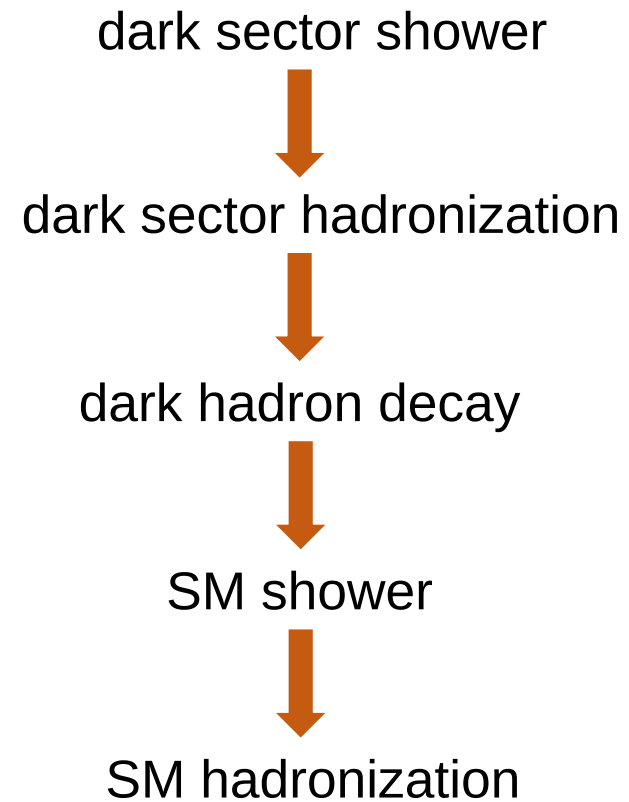
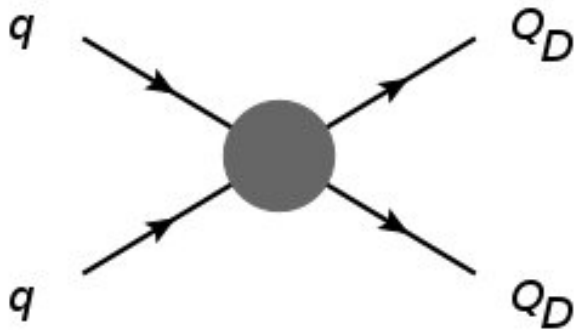


8 pseudo-Nambu-Goldstone bosons

Dark Pion	Dark Quark Content
$\pi_D^{(1,2)}$	$\bar{Q}_{D2} Q_{D1}$
$\pi_D^{(1,3)}$	$\bar{Q}_{D3} Q_{D1}$
$\pi_D^{(2,3)}$	$\bar{Q}_{D3} Q_{D2}$
$\pi_D^3$	$\frac{1}{\sqrt{2}} [\bar{Q}_{D1} Q_{D1} - \bar{Q}_{D2} Q_{D2}]$
$\pi_D^8$	$\frac{1}{\sqrt{6}} [\bar{Q}_{D1} Q_{D1} + \bar{Q}_{D2} Q_{D2} - 2\bar{Q}_{D3} Q_{D3}]$



# Dark jets



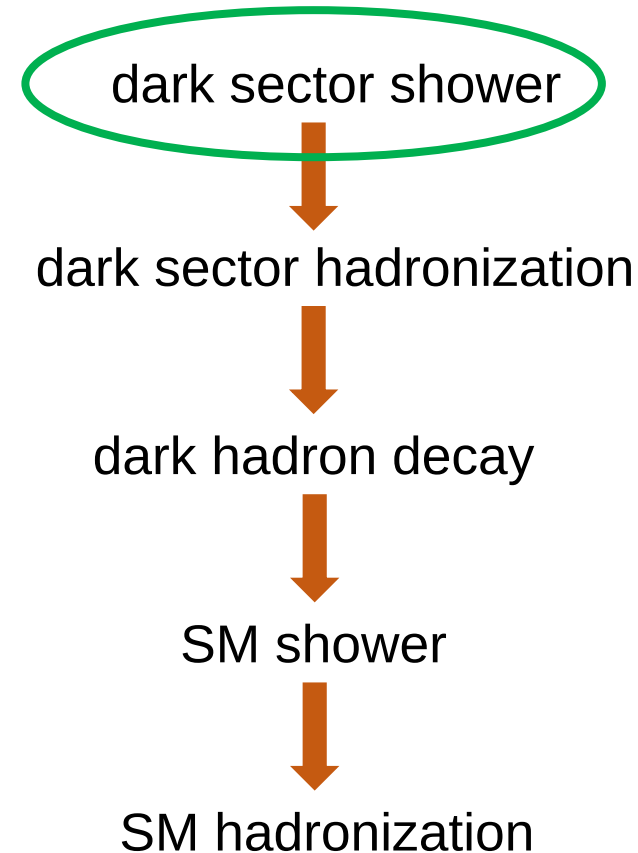
# Dark jets

QCD-like:  $SU(N)$  with  $F \ll 3N$

- $m \lesssim \Lambda \rightarrow$  understood, pythia fine
- $m \gtrsim \Lambda \rightarrow$  somewhat understood, not in pythia e.g. Curtin et al

less QCD-like:  $SU(N)$  with  $F \gg 3N$

- equal  $m \rightarrow$  somewhat understood, not in pythia
- unequal  $m$  (many large some small)  $\rightarrow$  understood, not in pythia yet poster by Joshua Lockyer





# Dark jets

- non-perturbative, unknown
- Lund string fragmentation in pythia

$$f(z) = \frac{1}{z^{1+r_{QD}} b_{m_{QD}^2}} (1-z)^{a_L} \exp\left(\frac{-b_{m_{QD}^2}^2}{z}\right)$$

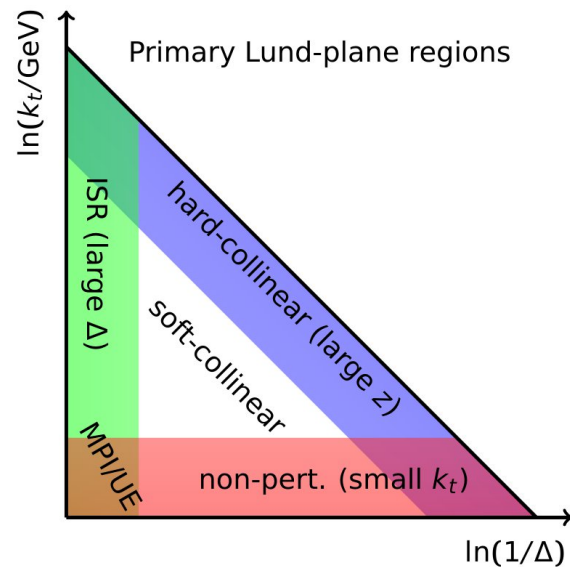
- observables can depend on hadronization parameter choice

Cohen, Roloff, CS '23'

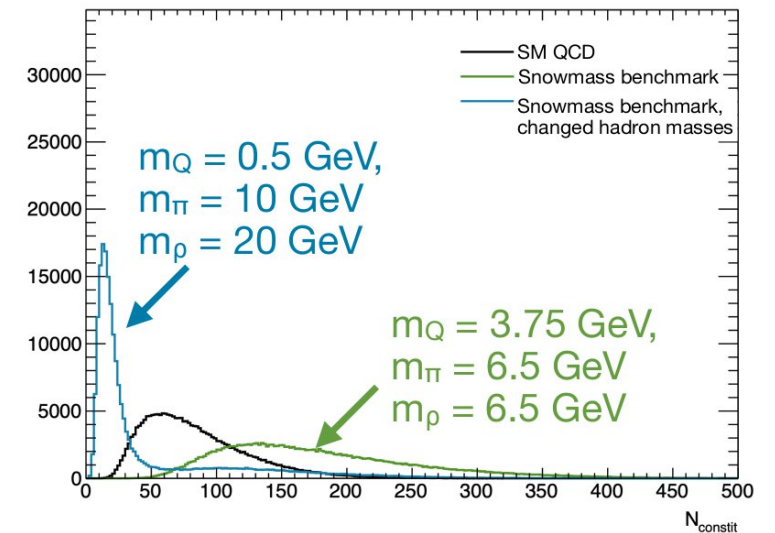
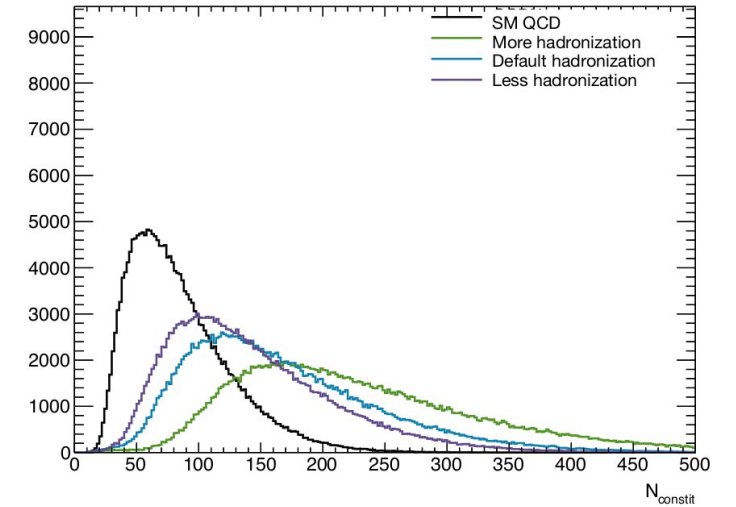


# Dark hadronization

- changing hadronization parameters can change observables
- Lund jet plane useful to separate hadronization dependent region



Dreyer, Salam, Soyez '18

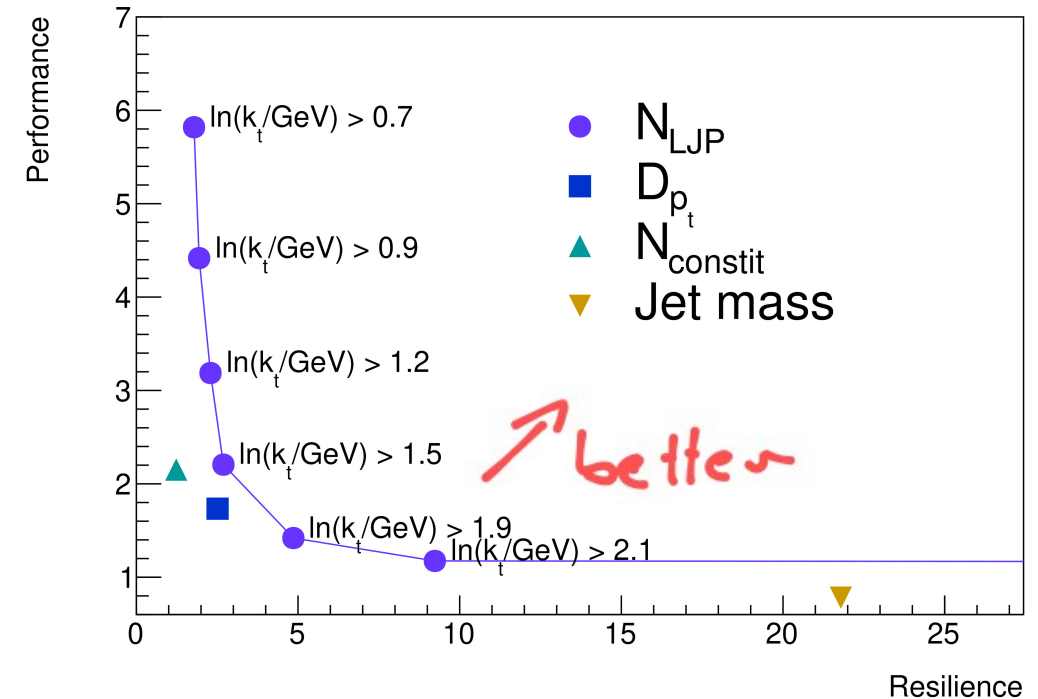


# Dark hadronization

- changing hadronization parameters can change signature
- Lund jet plane useful to separate hadronization dependent region

Dreyer, Salam, Soyez

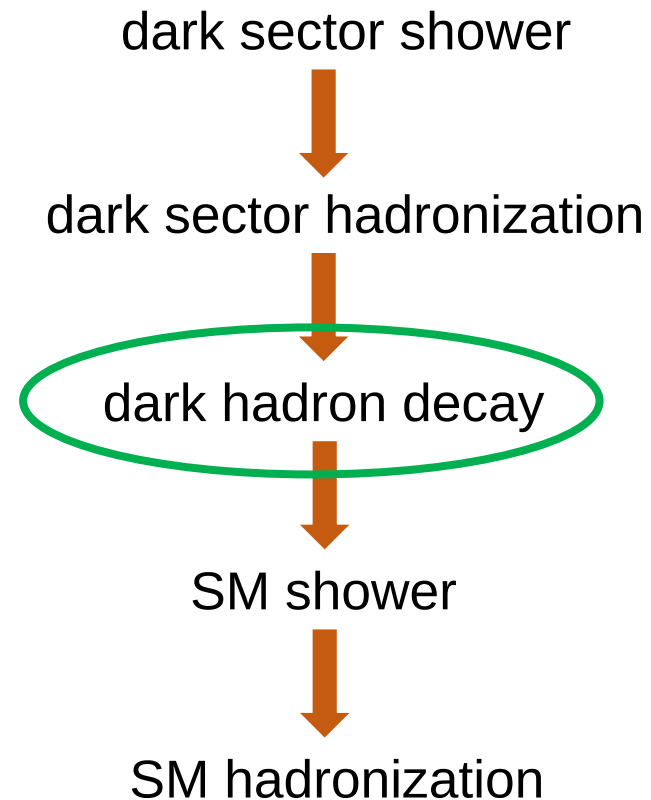
- allows to construct hadronization independent observables



Cohen, Roloff, CS '23

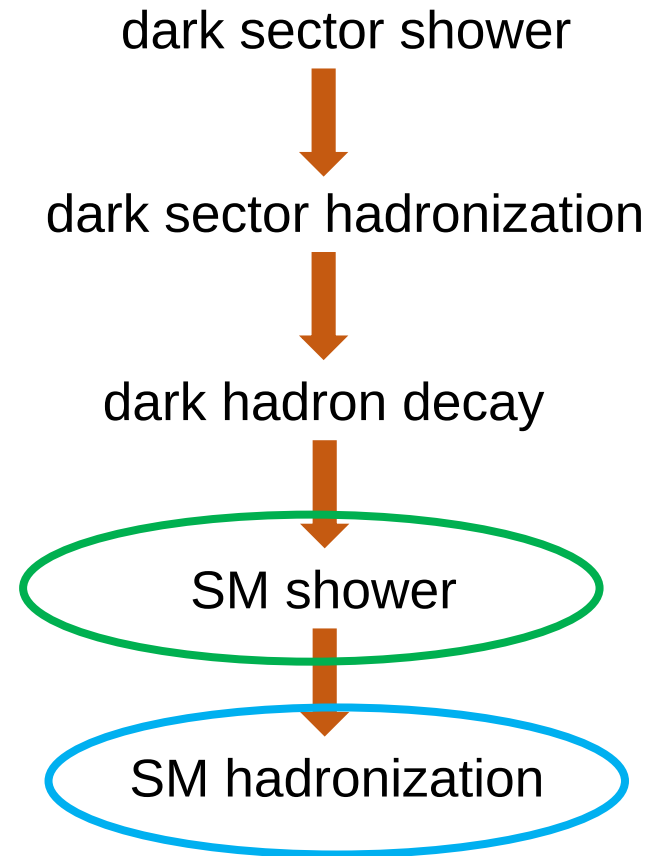
# Dark jets

- model dependent
- calculate and implement  
→ pythia ok



# Dark jets

- SM shower understood  
→ pythia ok
- SM hadronization non-perturbative,  
but (mostly) known  
→ pythia ok

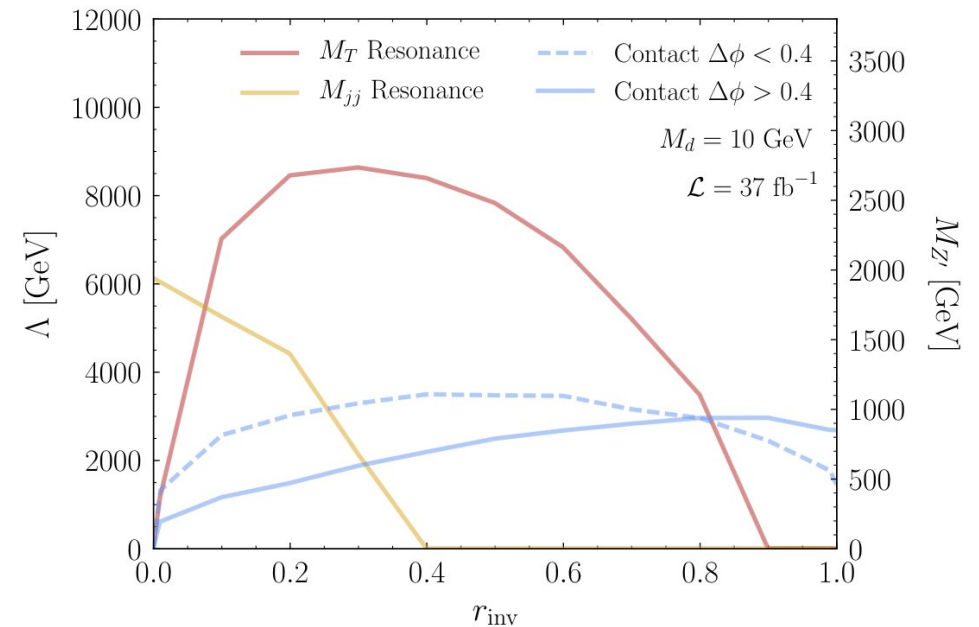
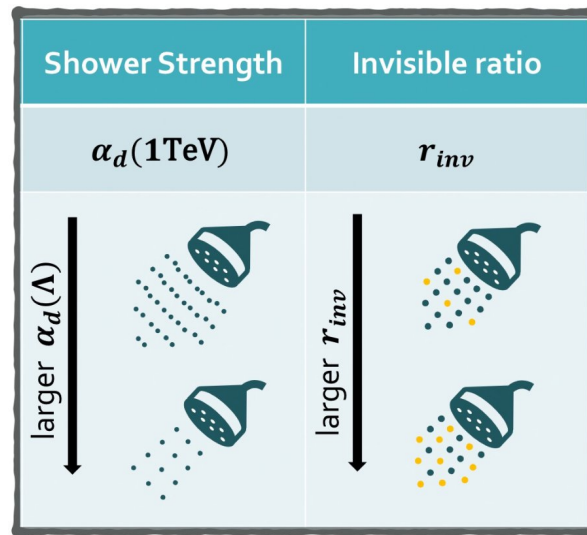
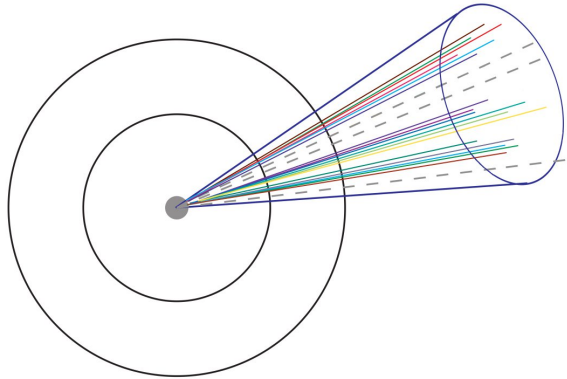


# Signatures

- semi-visible jets
- lepton jets
- emerging jets
- soft unclustered energy patterns (SUEPs)
- quirks
- ...

# Semi-visible jets

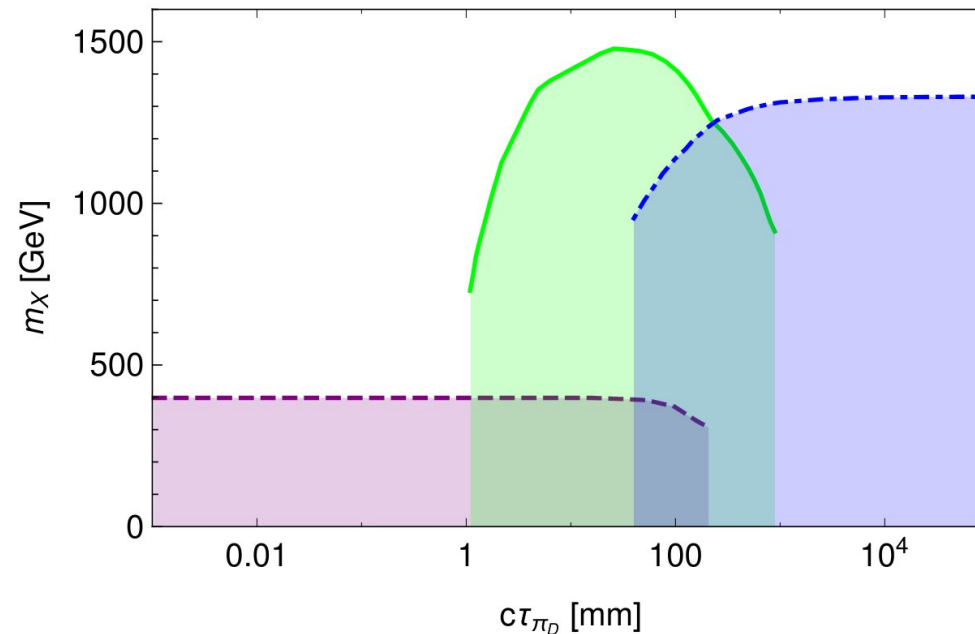
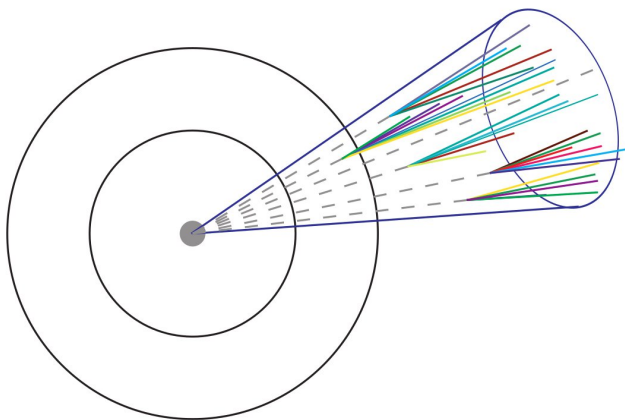
- multiple neutral particles decaying to SM
- stable ones  $\longrightarrow$  MET



Cohen, Lisanti, Lou '15  
Cohen et al '17

# Emerging jets

- multiple neutral particles decaying to SM
- stable ones  $\longrightarrow$  MET
- displaced vertices



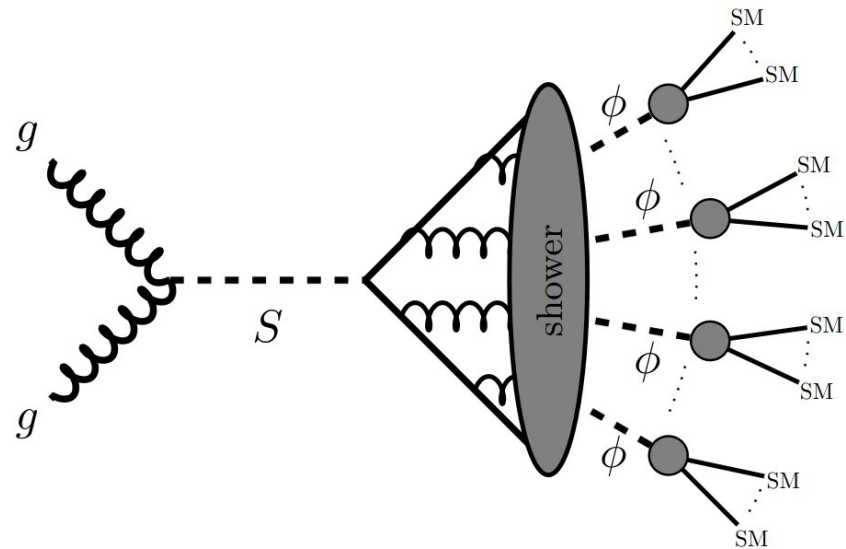
--- 4 jet search    — jet+emerging jet search    - - - MET search

Schwaller, Stolarski, Weiler '15  
Mies, CS, Schwaller '20



# SUEPs

- coupling close to confinement scale  
→ gluon radiation at larger angles



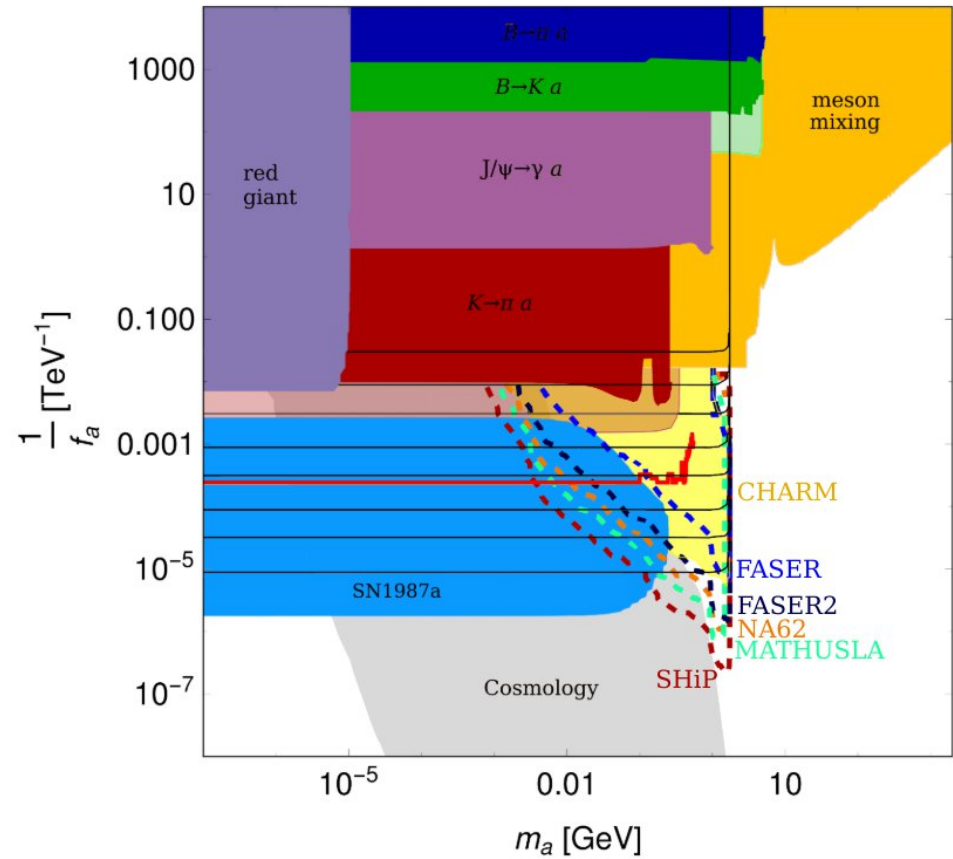
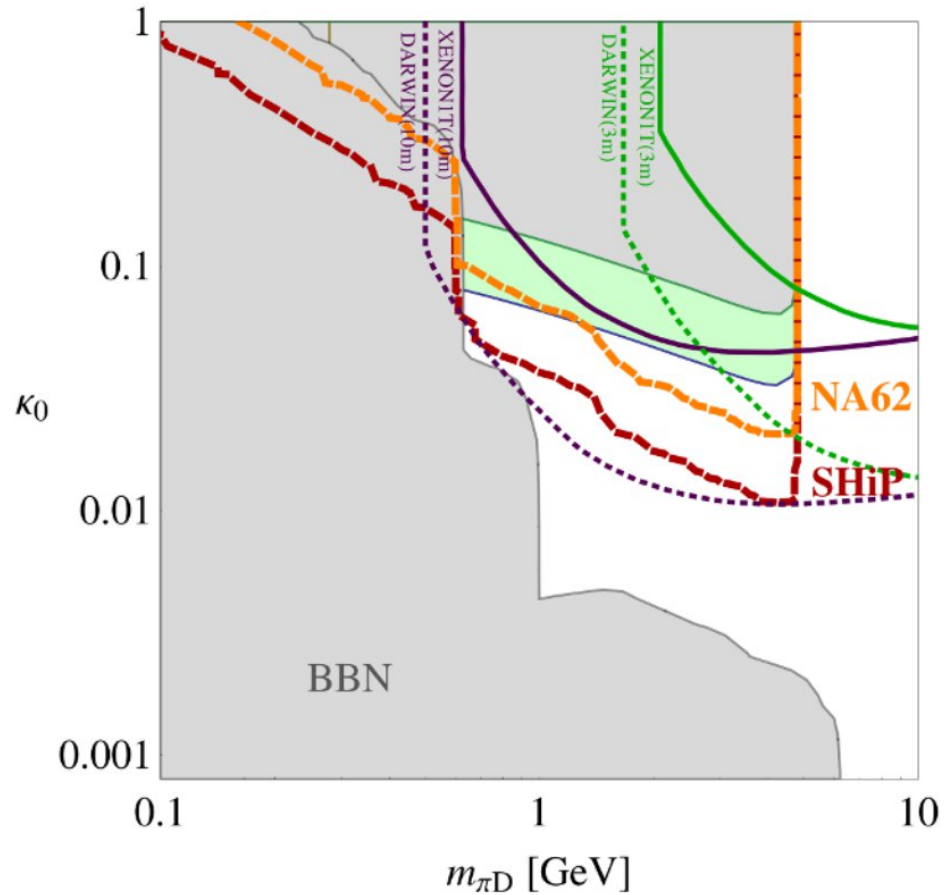
Knapen et al '16

# Summary

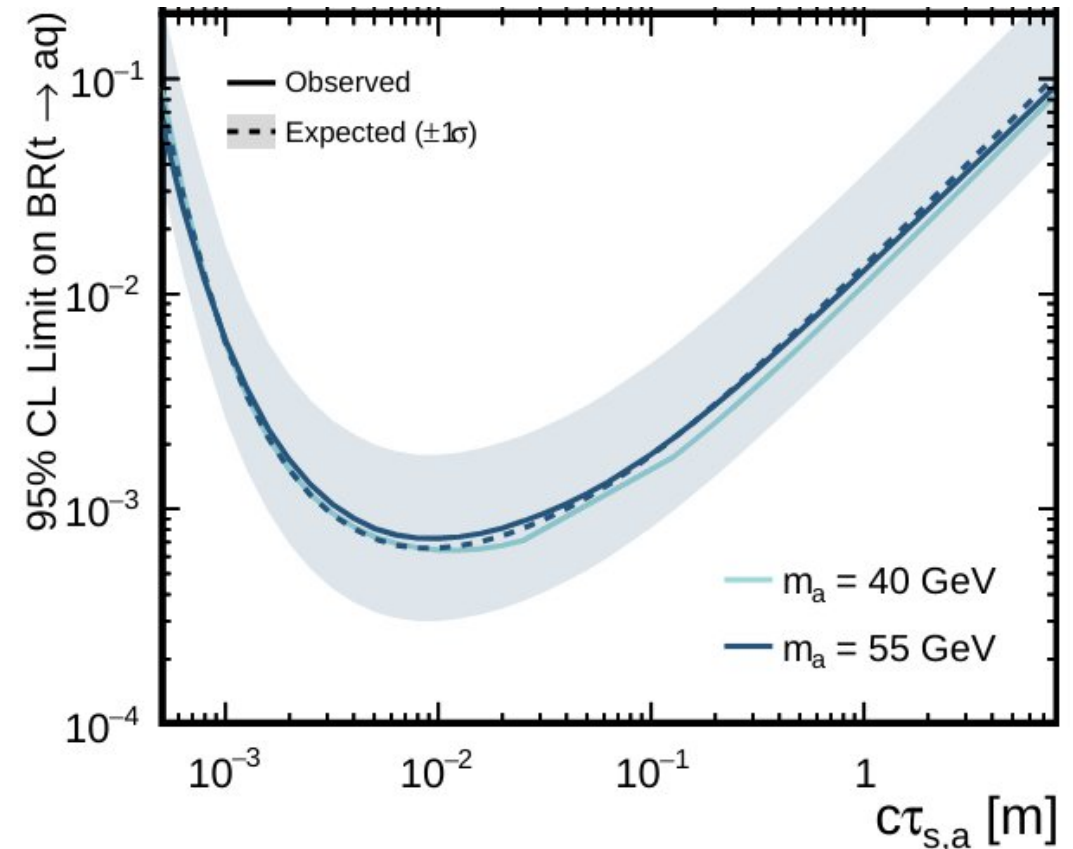
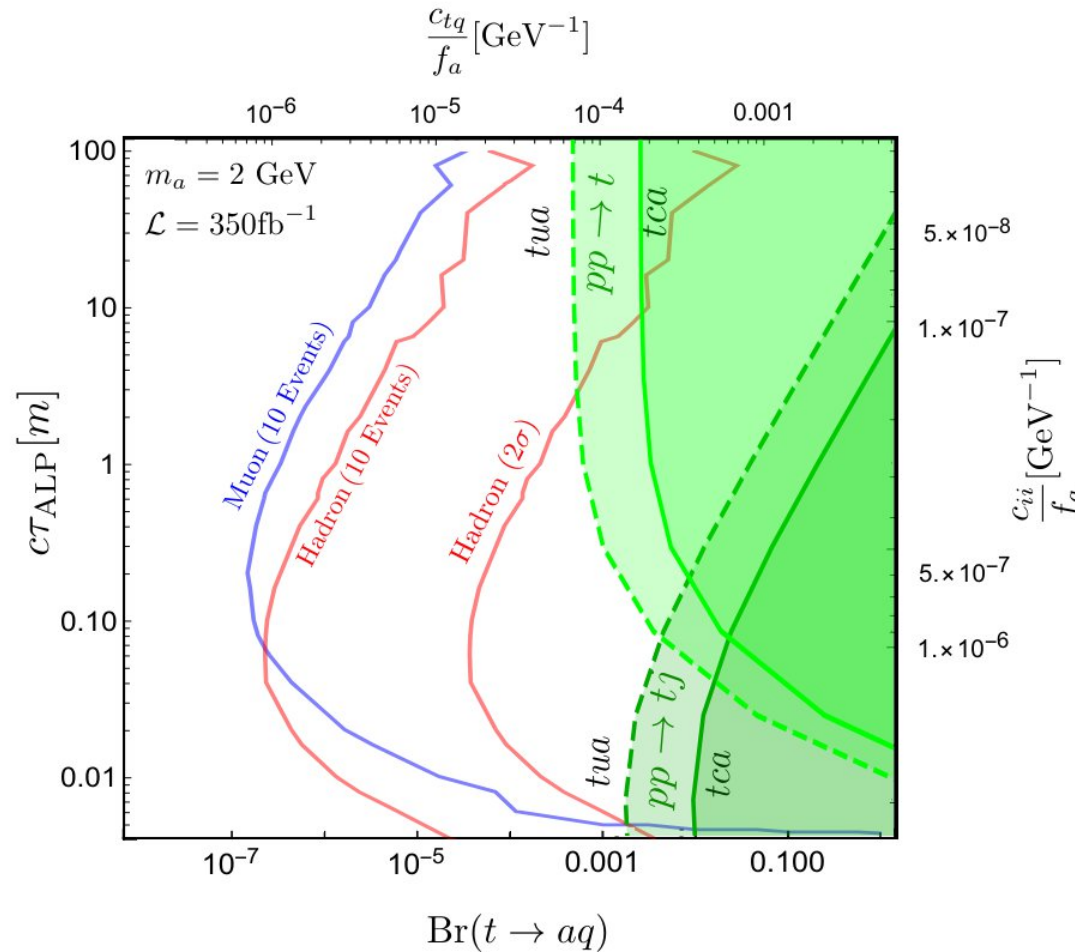
- realistic dark sectors are rich, but complicated
- collider pheno done piecewise
- difficult to capture full breadth
  
- great progress on simulation and experimental side!



# Flavor pheno

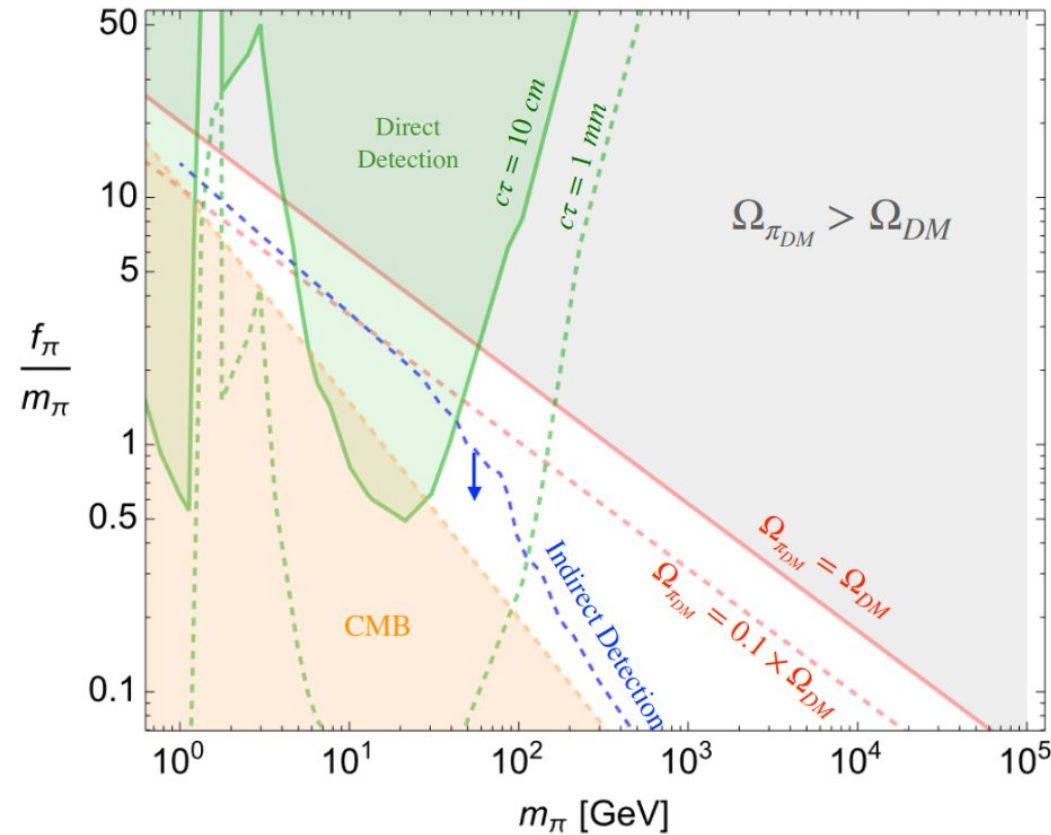


# Dark pions from top decays

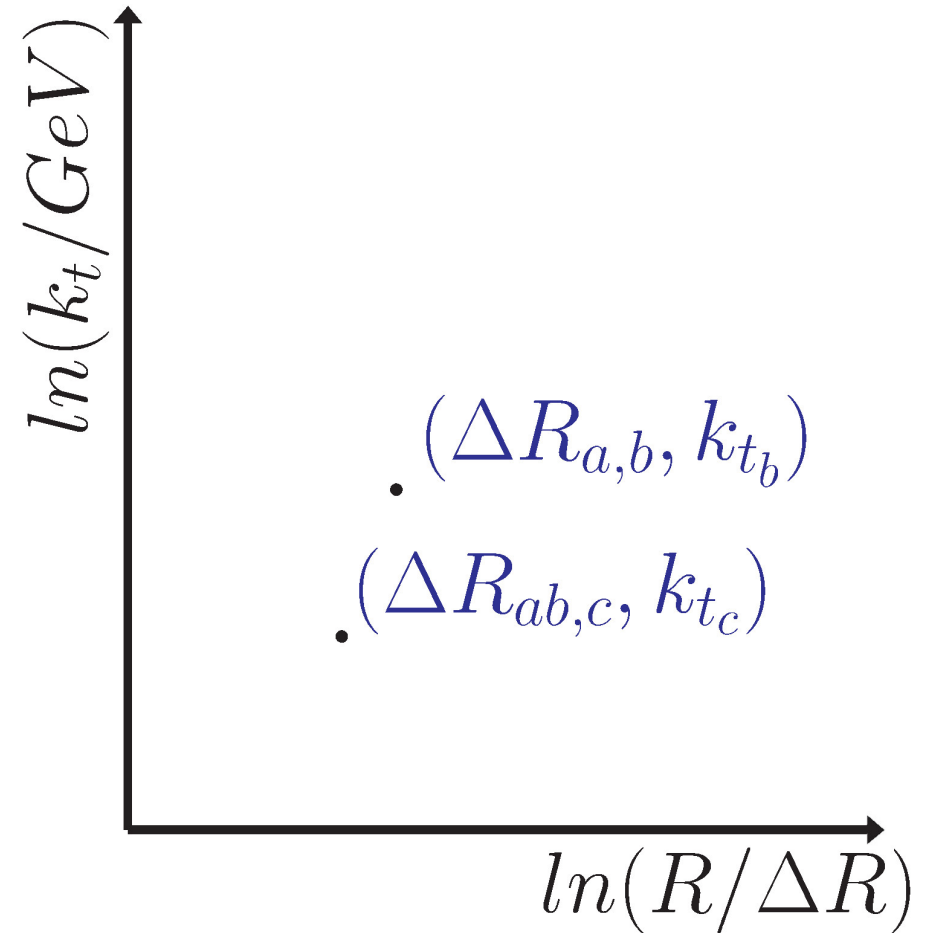
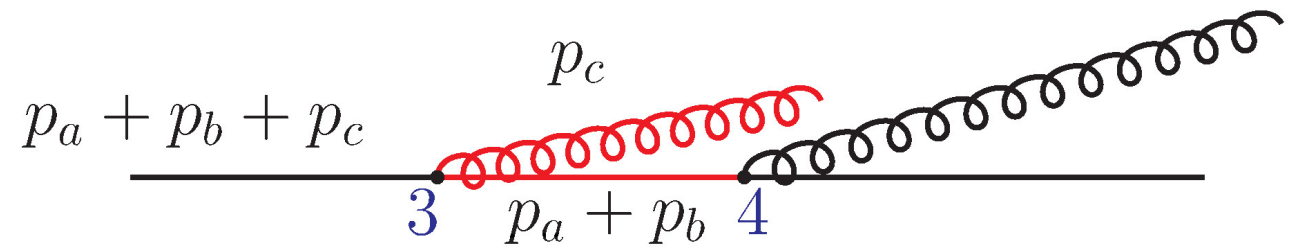
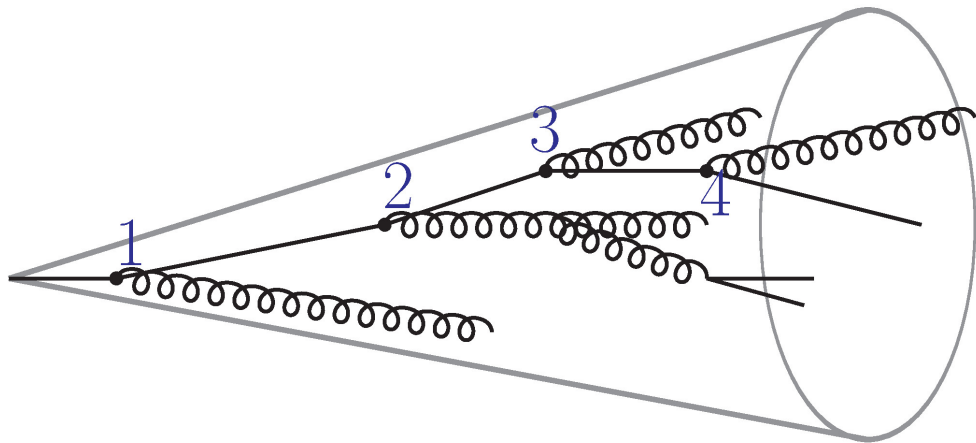


# Dark pion dark matter

$F = 4 \rightarrow$  stable dark pions in t-channel models



# Lund Jet Plane



# Using Lund Jet Plane for searches

different hadronization parameter choices give very different Lund Jet Planes

→ can translate into large differences in variables, e.g. number of tracks

