Searching for dark sector at LHC through “dark jet”

Beyond the BSM workshop

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Hotel Tenbo 2018-10-03

Based on :
1712.07279(Myeonghun Park, MZ)

Outline

1.Introduction

2.How to tag a “Dark Jet”

3.An example at LHC

4.Conclusion and outlook

Motivation:Dark sector might be complicated

1.The simplest WIMP model maybe not enough: null results, small scale problem(cusp-problem, σ_8 $\cdots$)

2.We need to consider other paradigm(SIMP, asymmetric DM), or a different DM, like a composite particle originated from dark sector confinement.

3.There are some popular NP models that can give you such DM candidate, Mirror World, Dark QCD, Hidden Valley$\cdots$

These models look like…

the Standard Model	Mediator	Dark sector
$\gamma,\ g,\ l,\ q\ \ldots$ $\pi,\ \rho,\ p\ \ldots$	$X,\ Z'\ \ldots$	$\gamma',\ g',\ q'\ \ldots$ $\pi_d,\ \rho_d,\ p_d\ \ldots$
$SU(3) \times SU(2) \times U(1)$		$SU(N)'$ or $SU(N)' \times U(1)'$ or …

Dark quark can be produced at collider through mediator particles.
Once produced, dark parton => shower => hadronization
=> dark meson decay back to SM.

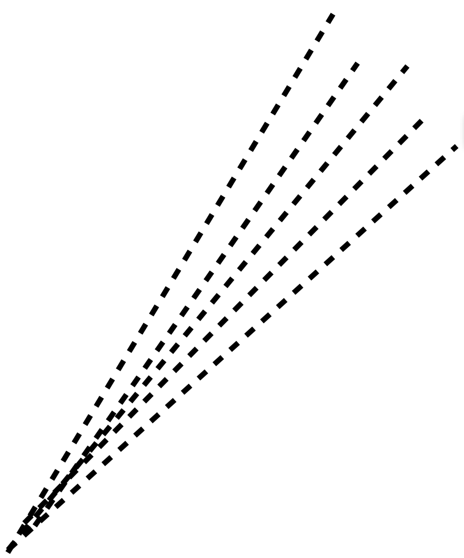
$$c\tau \approx 80\text{mm} \left(\frac{1}{\kappa^4}\right) \left(\frac{2\text{GeV}}{f_{\pi_d}}\right)^2 \left(\frac{0.1\text{GeV}}{m_q}\right)^2 \left(\frac{2\text{GeV}}{m_{\pi_d}}\right) \left(\frac{m_X}{1TeV}\right)^4$$

This kind of jet looks like….

It's very, very model dependent.

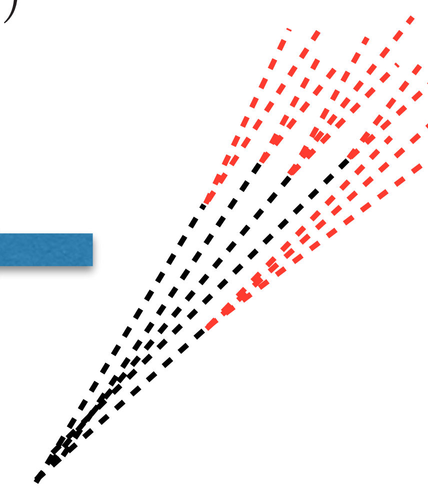
How long is lifetime of dark meson π_d, ρ_d…?

How much invisible particle inside a dark jet?



Most dark mesons are stable or stable enough.

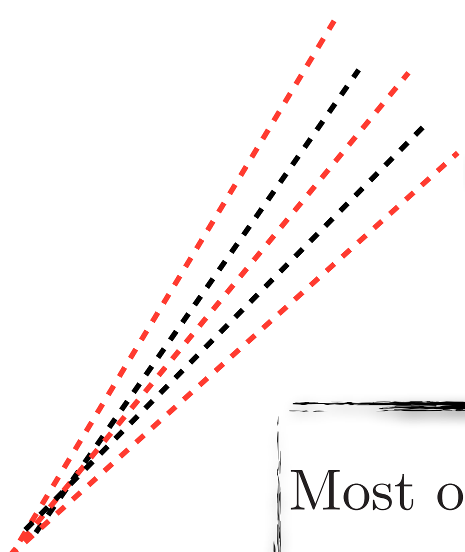
Invisible Jet (Missing Energy)



Most dark mesons are long-lived.

Emerging Jet (Displaced Track)

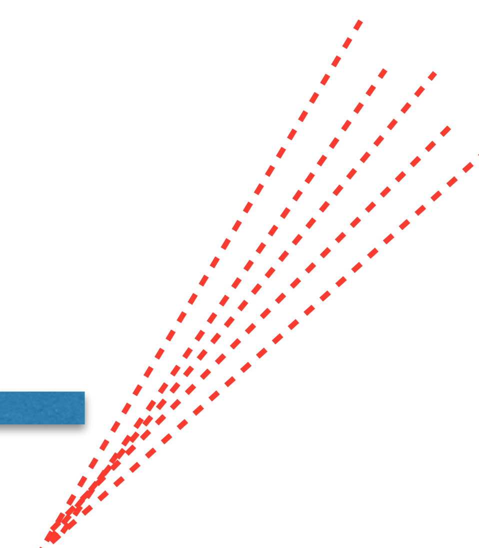
JHEP **1505**, 059 (2015)



A fraction of dark mesons are stable.

Semi-visible Jet (Transverse Mass)

Phys. Rev. Lett. **115**, no. 17, 171804 (2015)



Most of dark mesons decay to visible particles promptly.

"QCD-like" Dark Jet (What Can You Do?)

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2.How to tag a “Dark Jet”, when it looks like a QCD Jet

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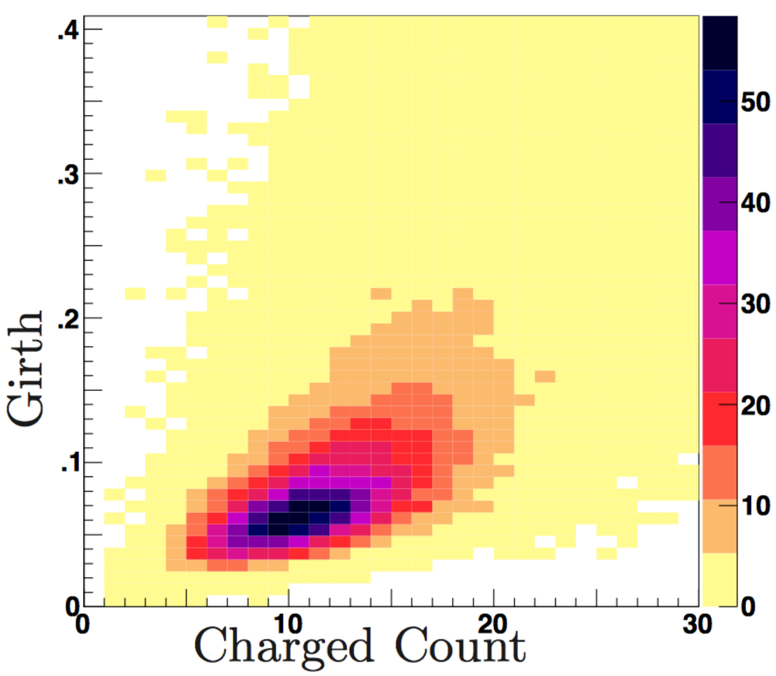
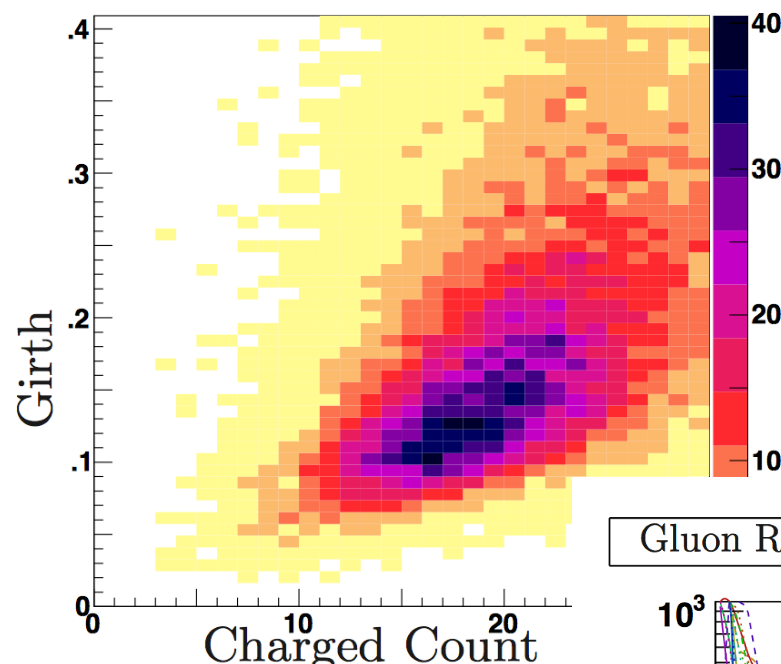
One example of one-prong jet tagging

Quark/Gluon Jet discrimination:

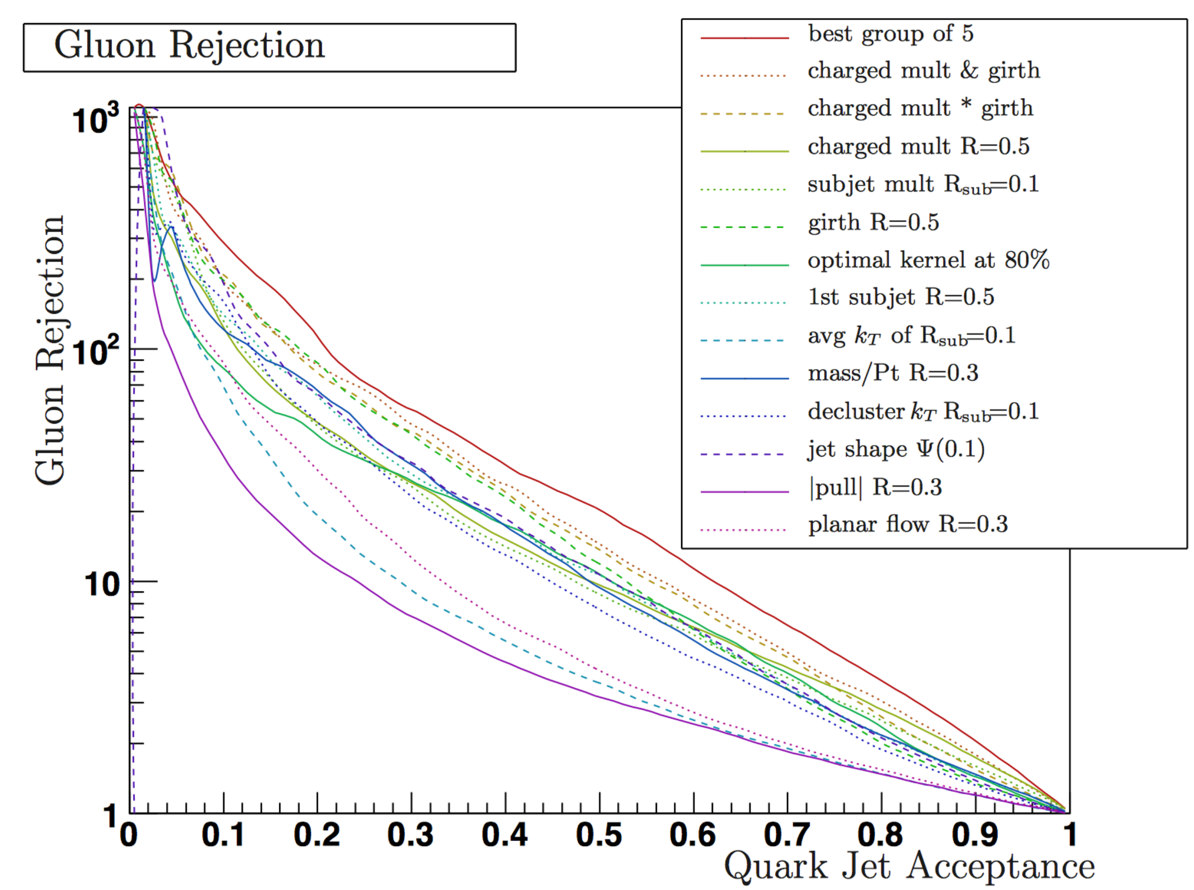
Quark



Gluon



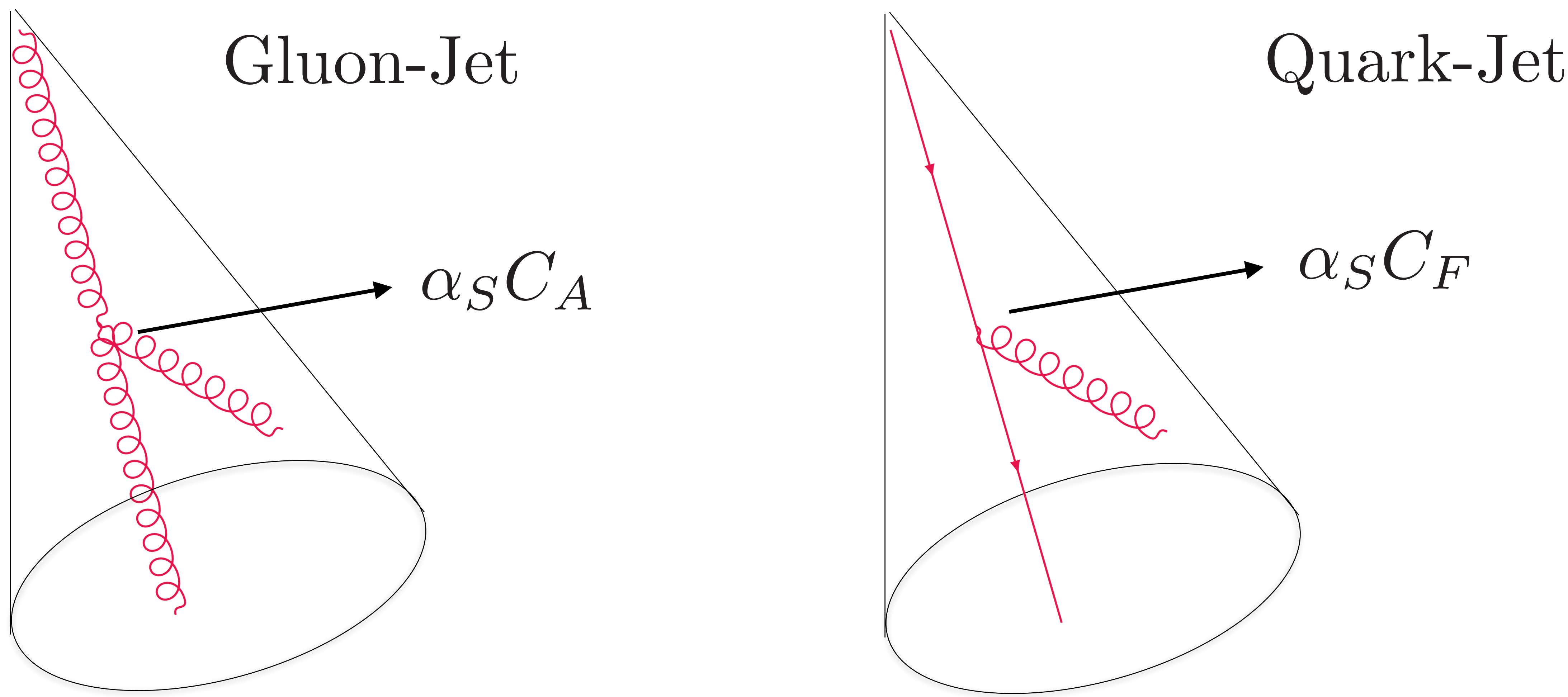
JHEP **1304**, 090 (2013)



quark-jet and gluon-jet are different,
even both of them are QCD-jet.

Why are they different? Casimir Scaling

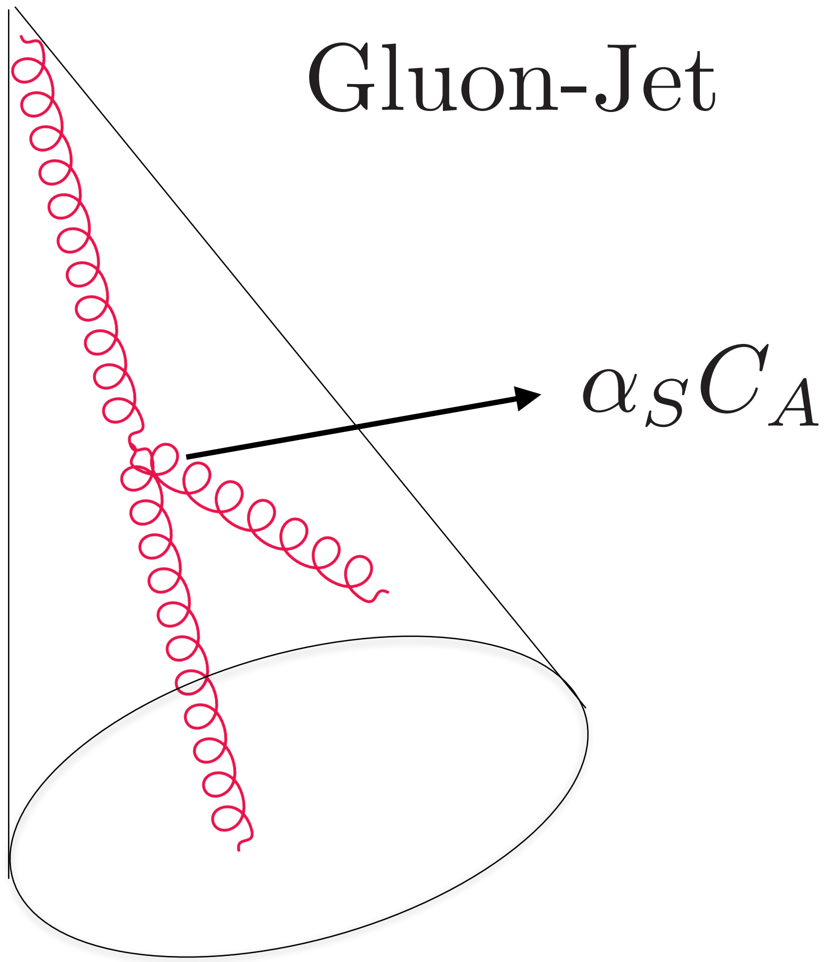
JHEP **1707**, 091 (2017)

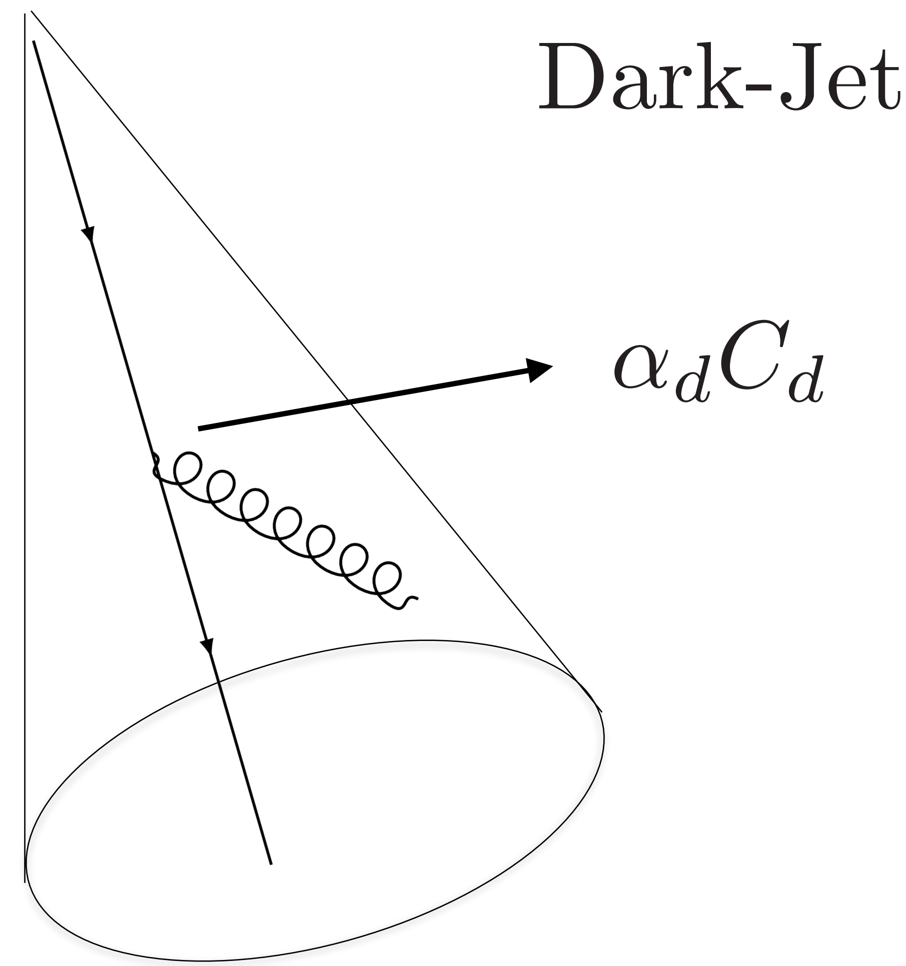


Strength of parton shower is controlled by this factor, so Gluon-Jet is broader than Quark-Jet, and there are more hadrons insider Gluon-Jet.

Their difference is decided by ratio C_A/C_F, it's called Casimir Scaling.

So for a Dark-Jet …





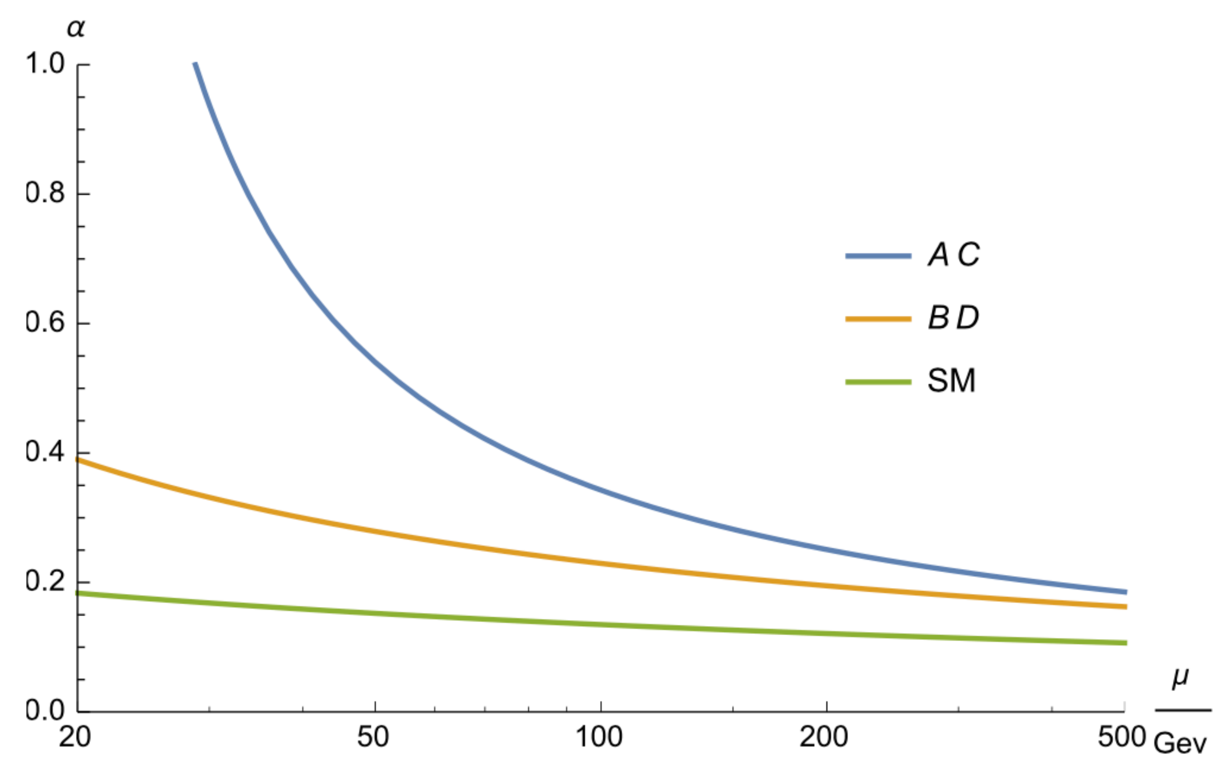
We have a modified Casimir Scaling in Gluon/Dark Jet discrimination,
C_A/C_F should be changed to $\alpha_S C_A/\alpha_d C_d$.
So, if α_d is very different with α_S ...

Our dark sector setting

Our four benchmark setting. High confinement scale is required by short dark meson lifetime.

	N_d	n_f	$\Lambda_d(GeV)$	$\tilde{m}_{q'}(GeV)$	m_{π_d}(GeV)	m_{ρ_d}(GeV)	π_d Decay Mode	ρ_d Decay Mode
A	3	2	15	20	10	50	$\pi_d \to c\bar{c}$	$\rho_d \to \pi_d \pi_d$
B	3	6	2	2	2	4.67	$\pi_d \to s\bar{s}$	$\rho_d \to \pi_d \pi_d$
C	3	2	15	20	10	50	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 4.0GeV$	$\rho_d \to \pi_d \pi_d$
D	3	6	2	2	2	4.67	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 0.7GeV$	$\rho_d \to \pi_d \pi_d$

Running coupling of different setting.



Variable 1: two points energy correlation function $C_1^{(\beta)}$

Definition: $$C_1^{(\beta)} = \sum_{i<j\in J} z_i z_j (R_{ij})^\beta$$

with $z_i = p_{T\,i} / \sum_{i\in J} p_{T\,i}$ **and** $R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$

Leading order re-summation result:

Casimir Scaling

$$\frac{1}{\sigma}\frac{d\sigma}{dC_1^{(\beta)}} = \frac{d}{dC_1^{(\beta)}} \exp\left(-\int_{C_1^{(\beta)}}^{R_0^\beta} \frac{2\alpha C}{\pi\beta\tilde{C}} L(\tilde{C}) d\tilde{C}\right) = \frac{2\alpha C}{\pi\beta C_1^{(\beta)}} L(C_1^{(\beta)}) \exp\left(-\int_{C_1^{(\beta)}}^{R_0^\beta} \frac{2\alpha C}{\pi\beta\tilde{C}} L(\tilde{C}) d\tilde{C}\right)$$

with

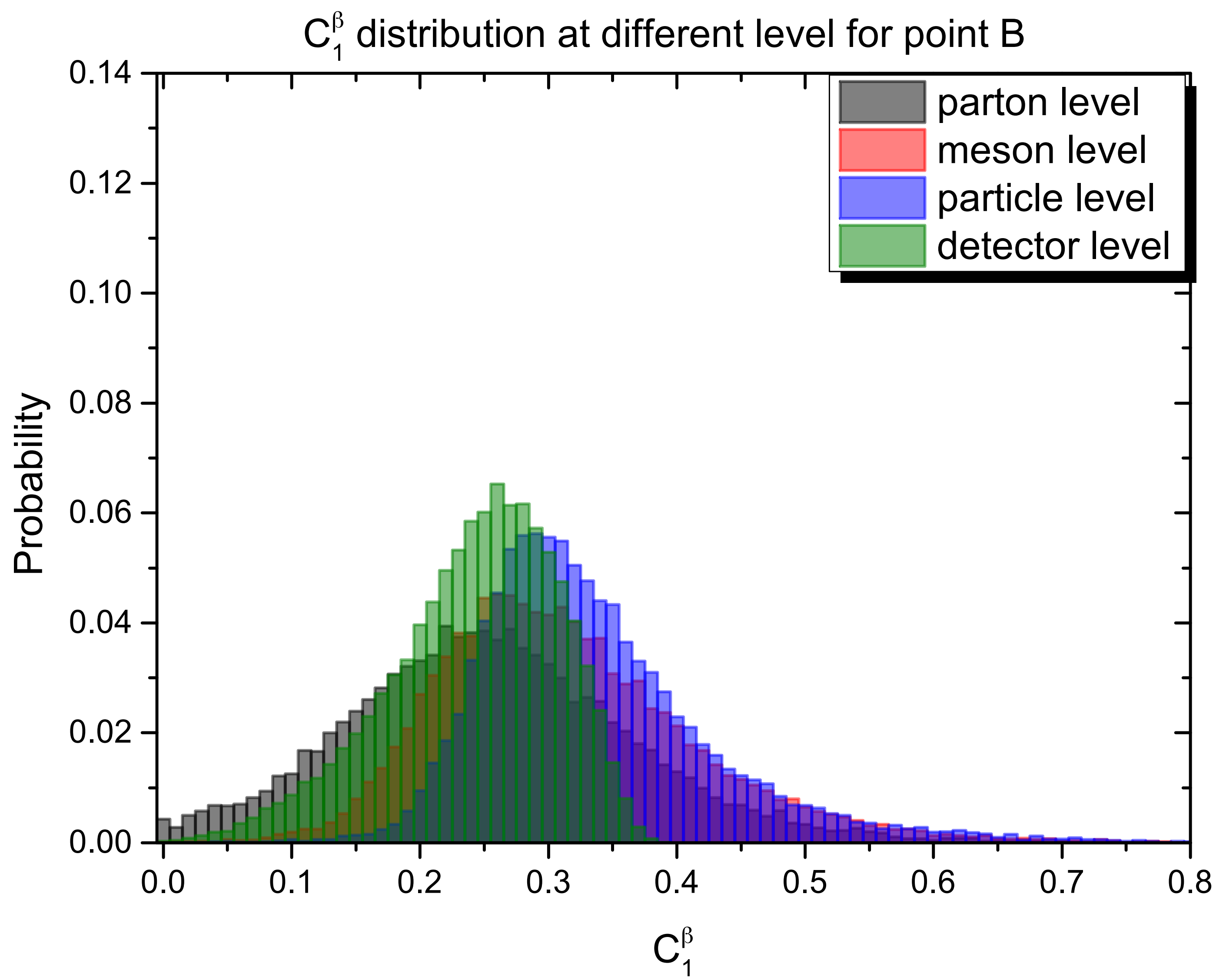
$$L(C_1^{(\beta)}) = \ln \frac{1 + \sqrt{1 - 4C_1^{(\beta)}/R_0^\beta}}{1 - \sqrt{1 - 4C_1^{(\beta)}/R_0^\beta}}$$

Variable 1: two points energy correlation function $C_1^{(\beta)}$

Meson level: parton level distribution convolute with a "shape function". And the mean value of shape function is proportional to Λ.

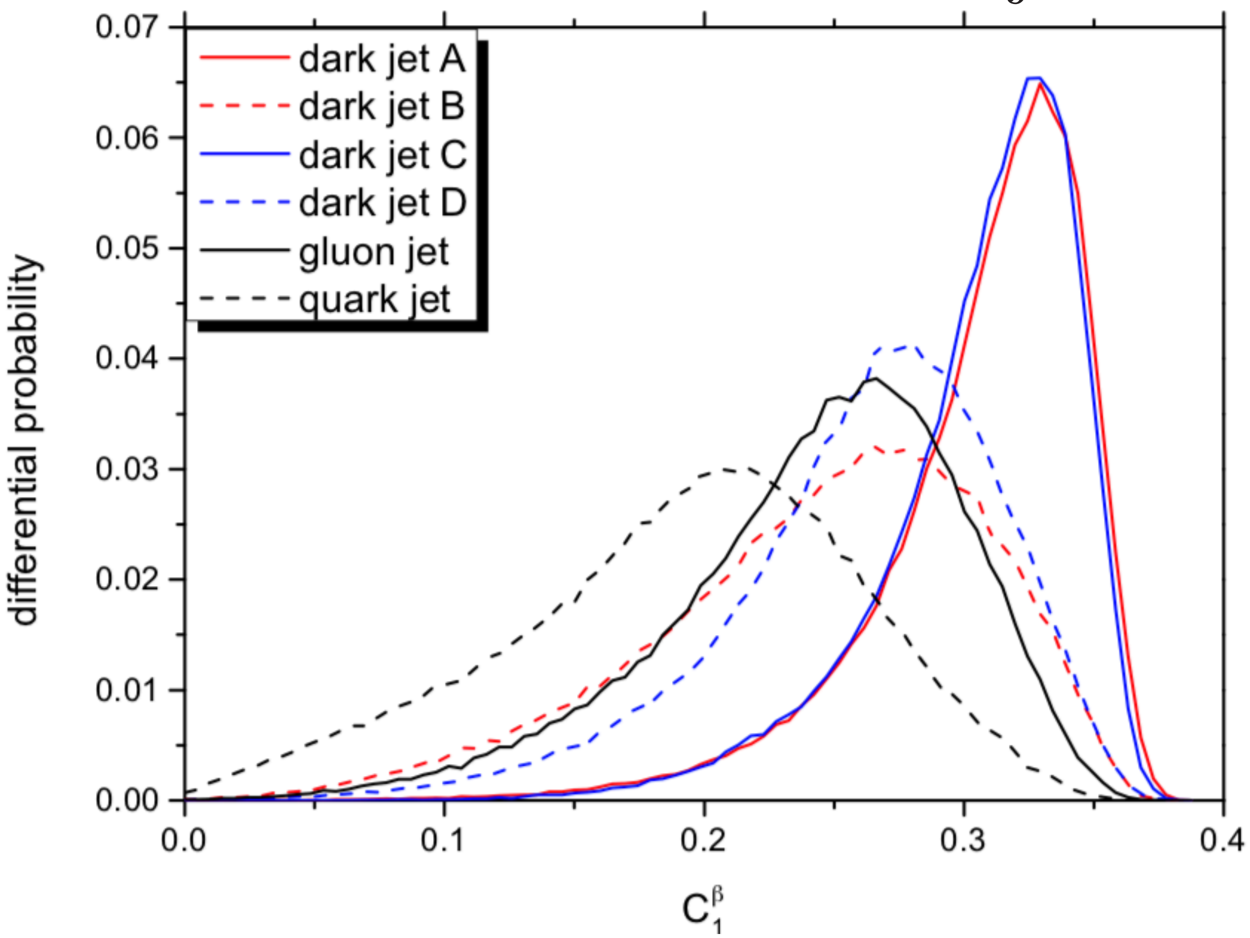
Dark meson decay: push up $C_1^{(\beta)}$ further:

$$z_1 z_2 \theta^\beta \to \frac{1}{4}(z_1 + z_2)^2 \left(\frac{m_{\pi_d}}{p_T}\right)^\beta$$

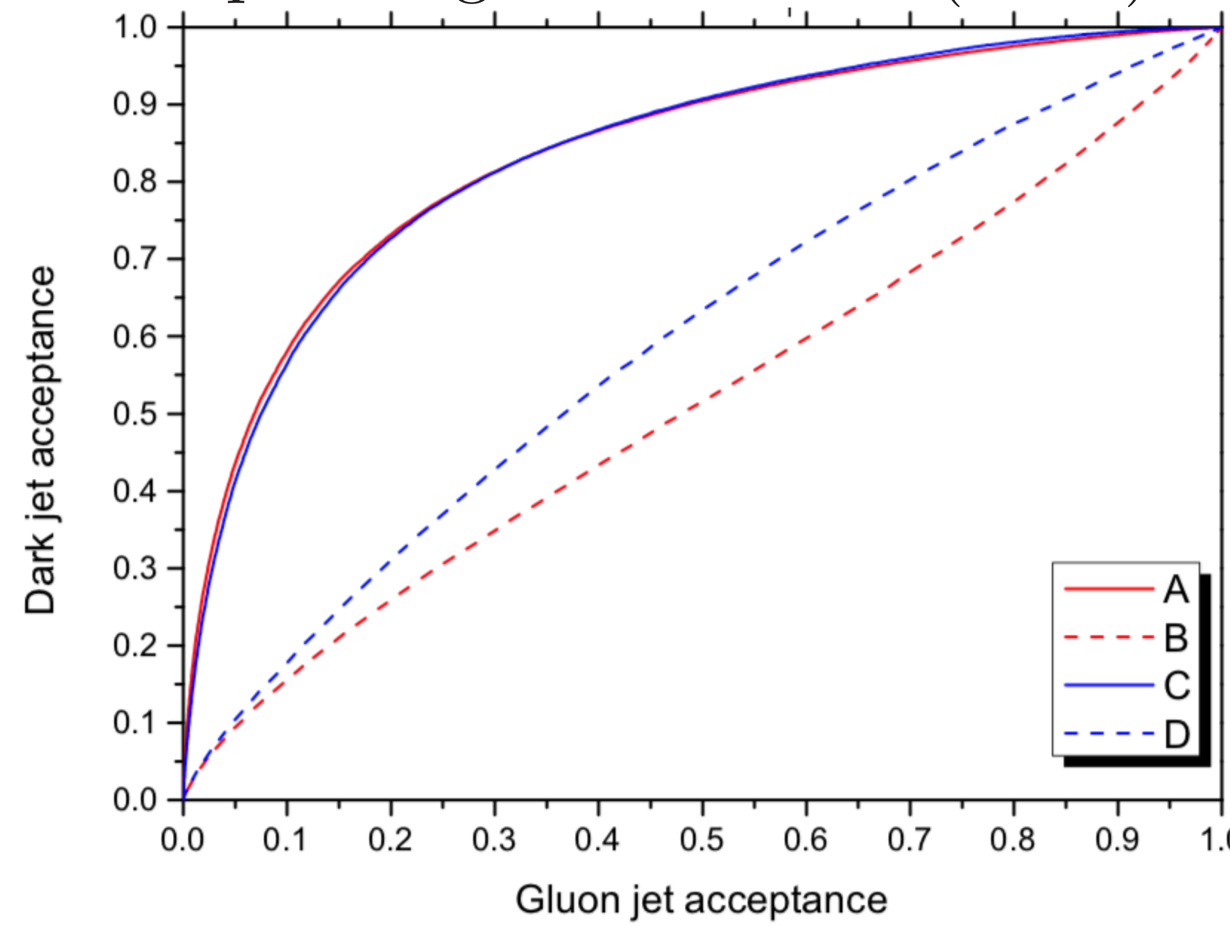


Variable 1: two points energy correlation function $C_1^{(\beta)}$

Distribution of different jets



receiver operating characteristic(ROC) curve



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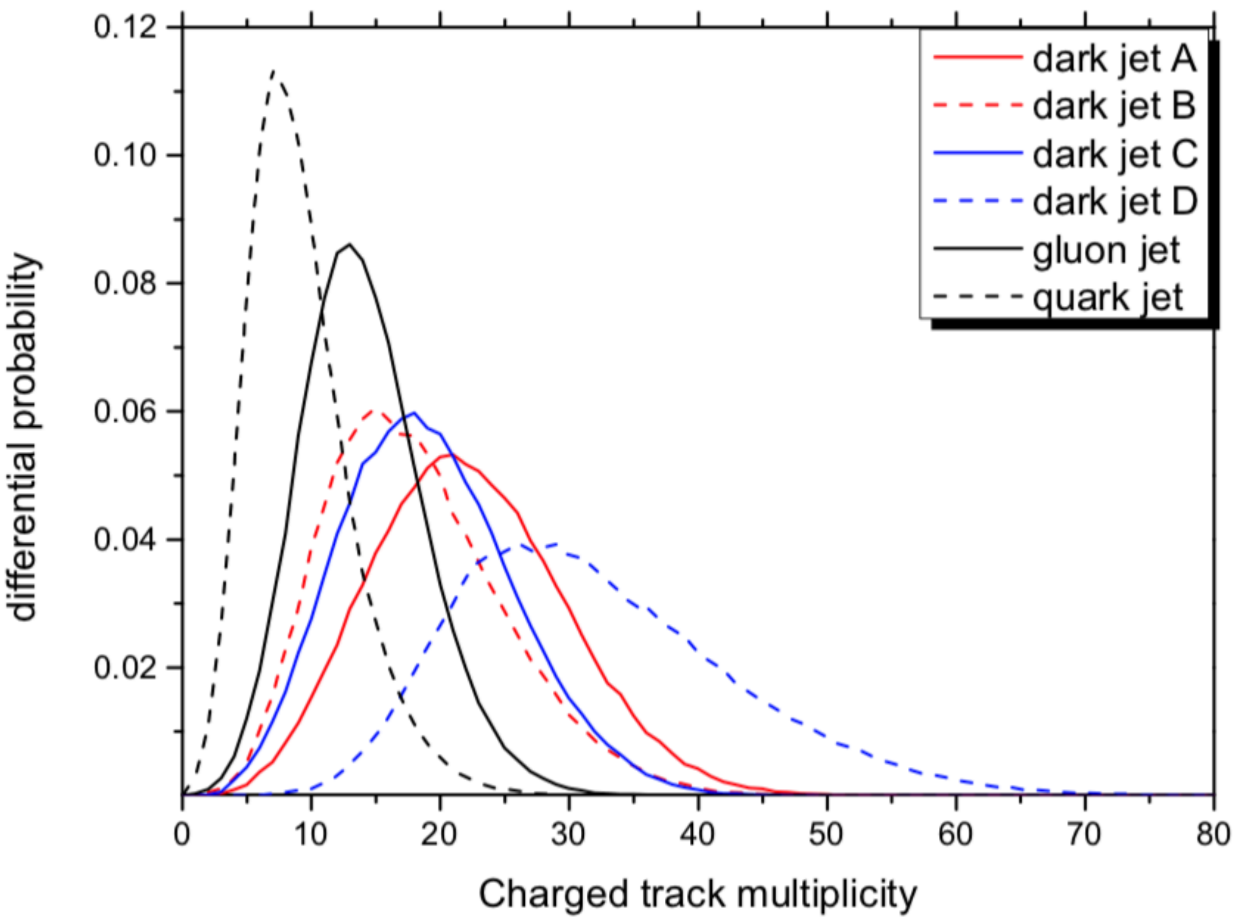
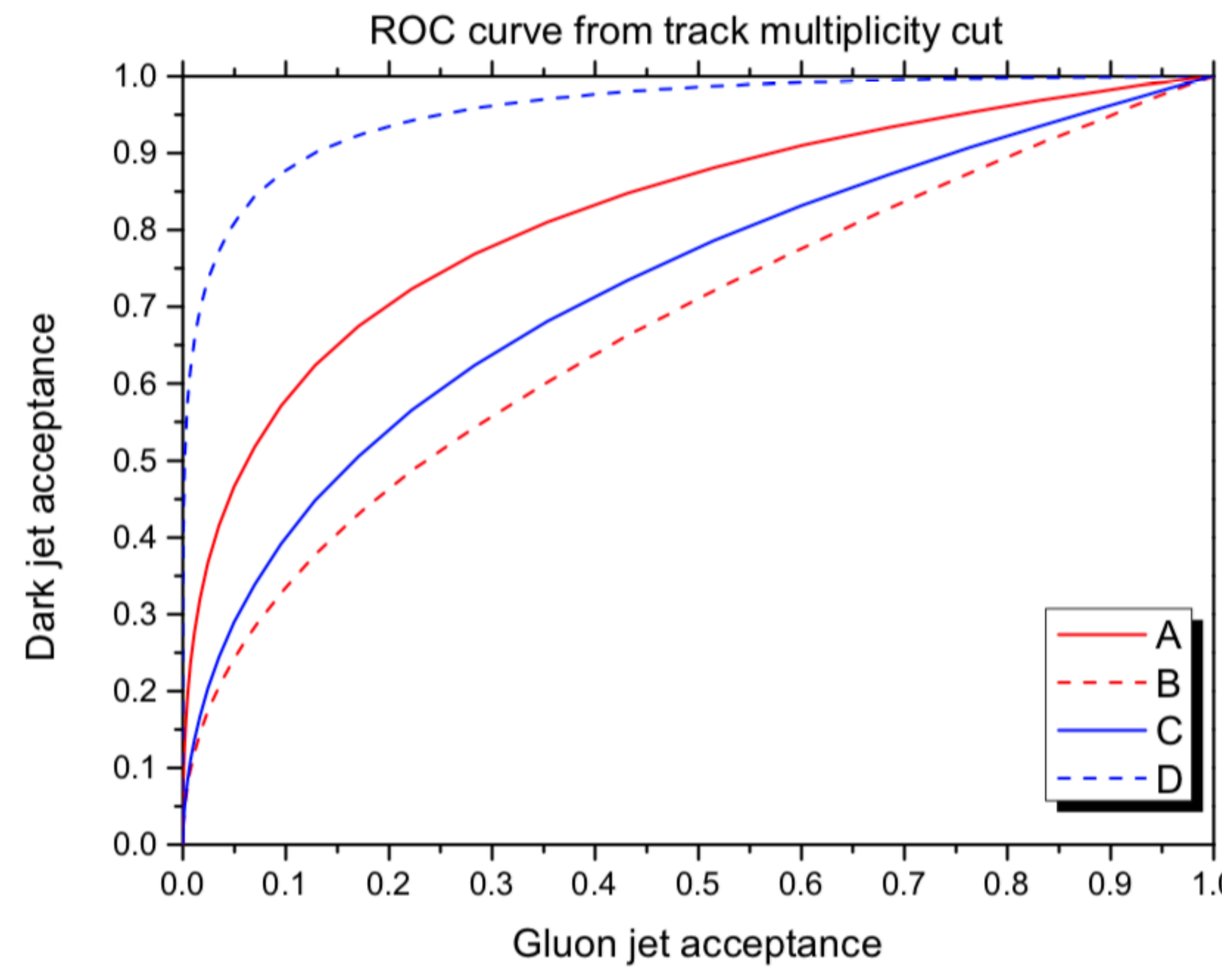
Variable 2: Charged Track multiplicity

Performance





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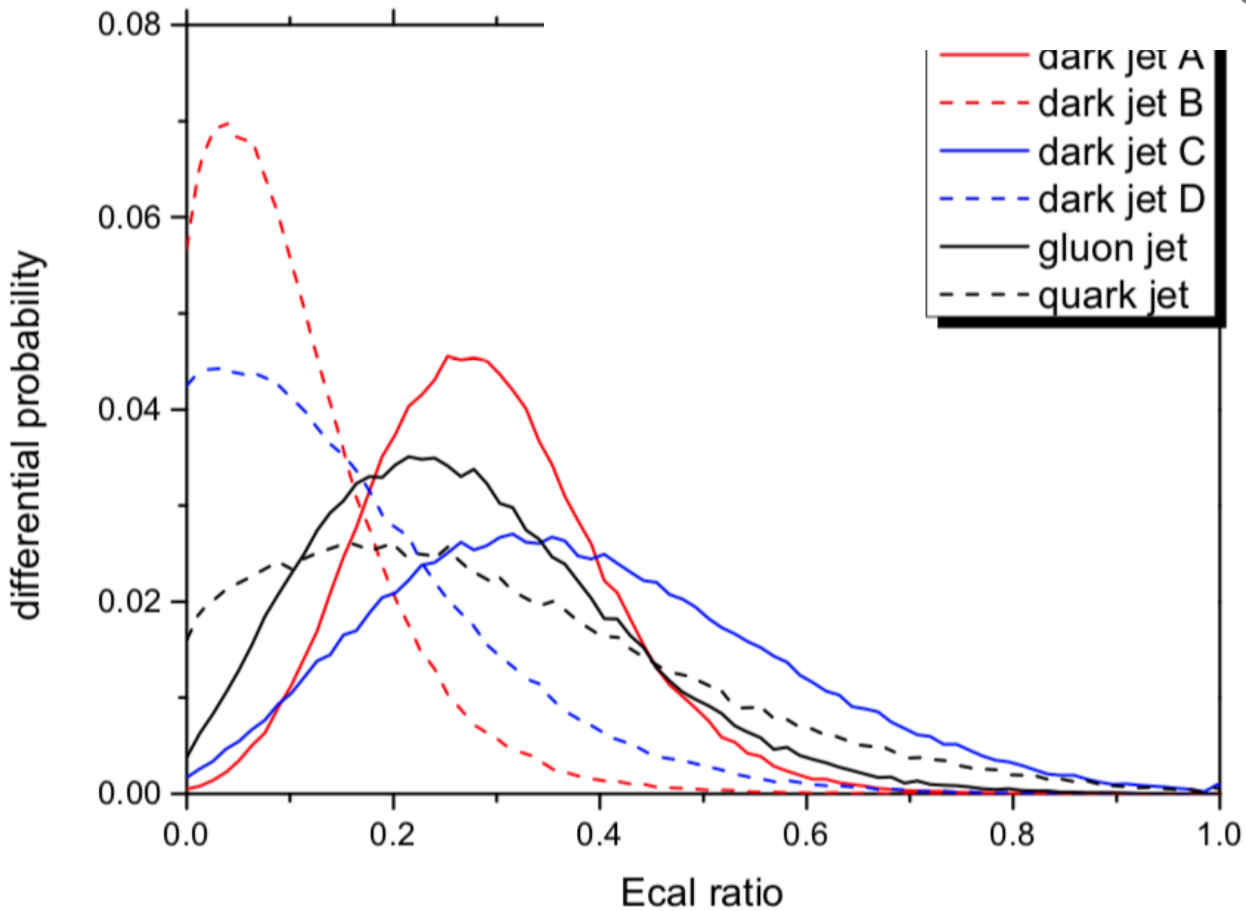
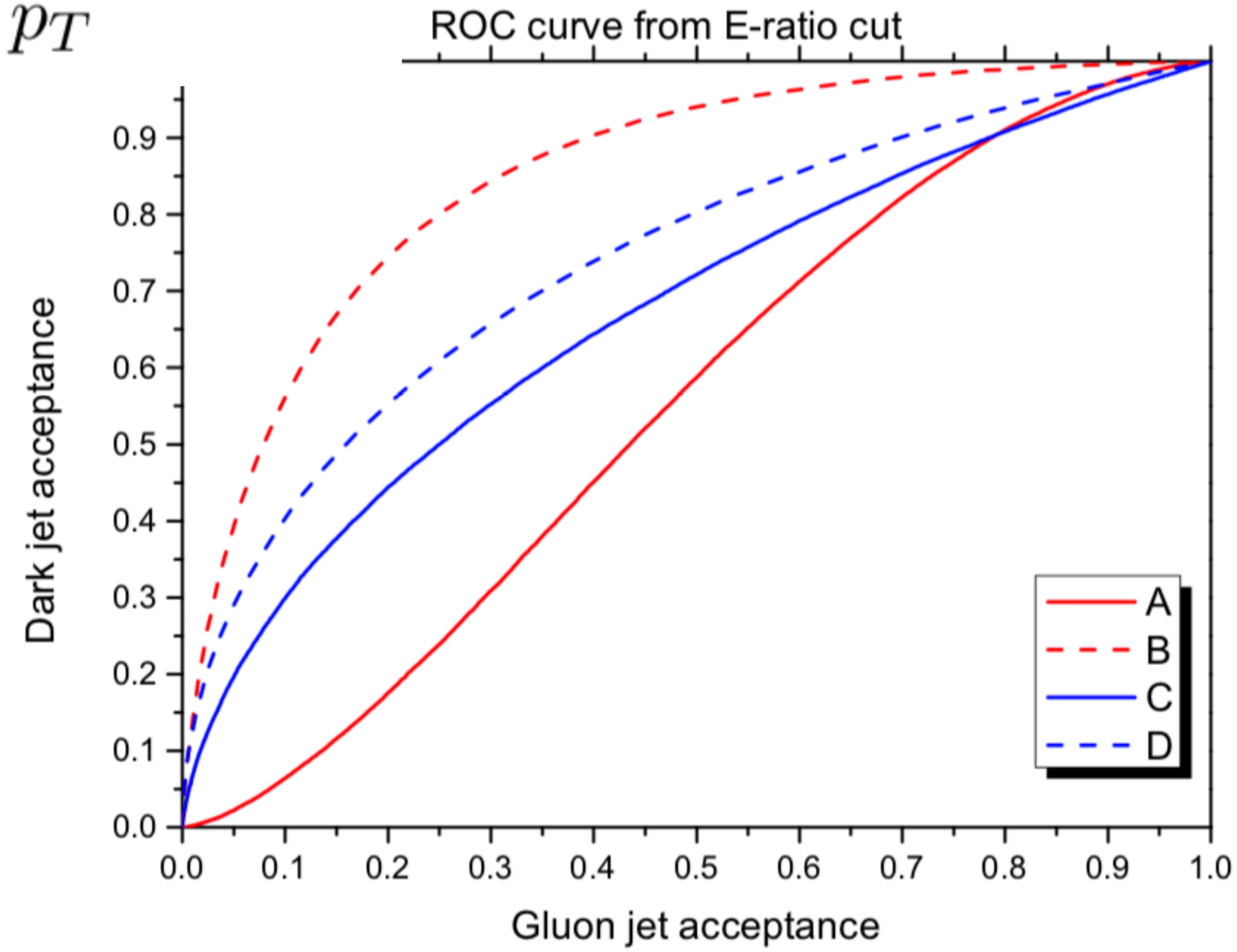
Variable 3: E-ratio

Useful to some special final states, defined as:

$$\text{E-ratio} = \frac{\text{Energy deposit on Ecal}}{\text{Jet } p_T}$$





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Kaons inside dark jet B is very important

Multiple variables analysis

How to combine the discriminant ability of different variables? We use boosted decision tree(BDT).

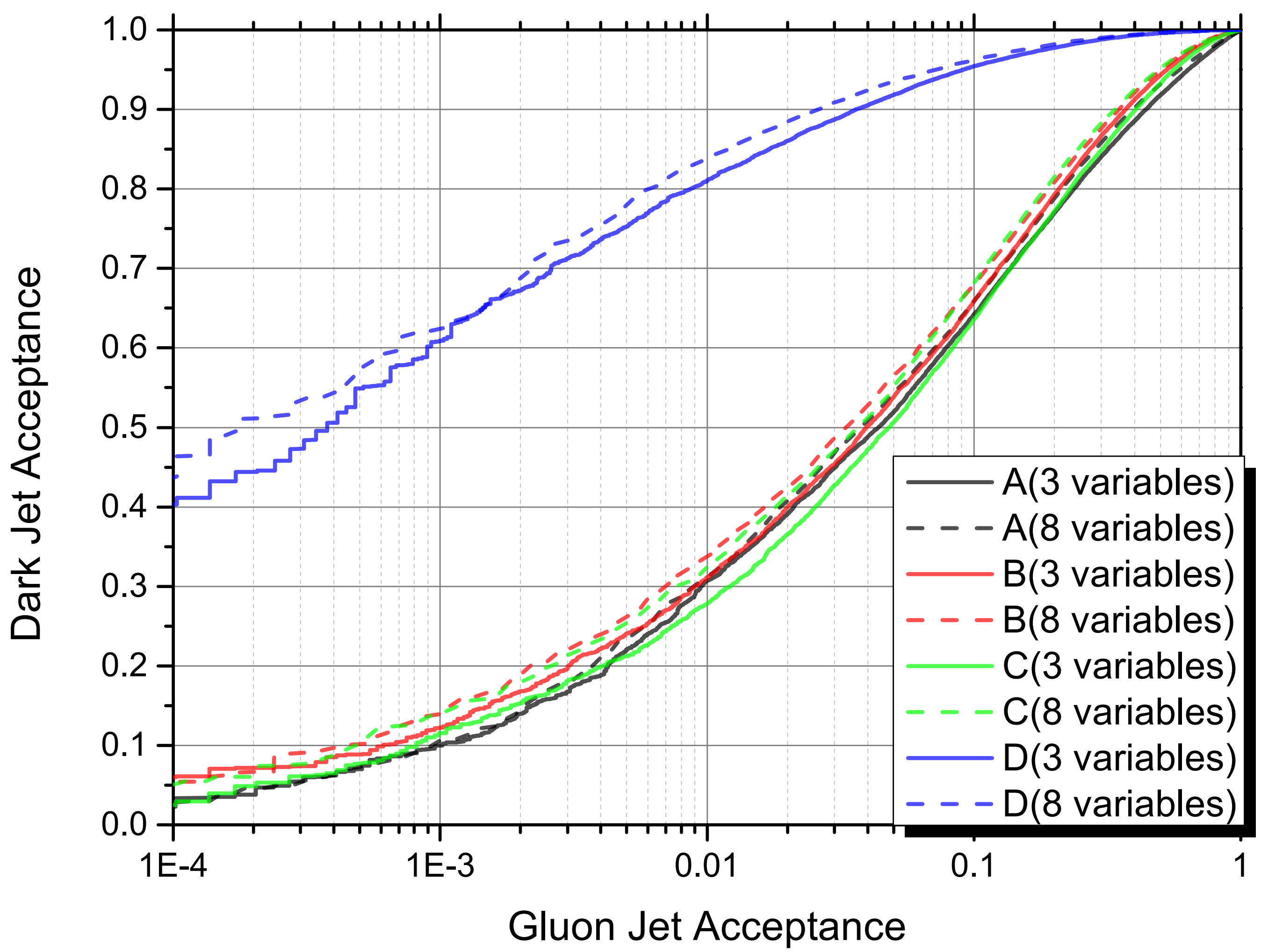
BDT gives you a mapping from a set of variables to a BDT score:

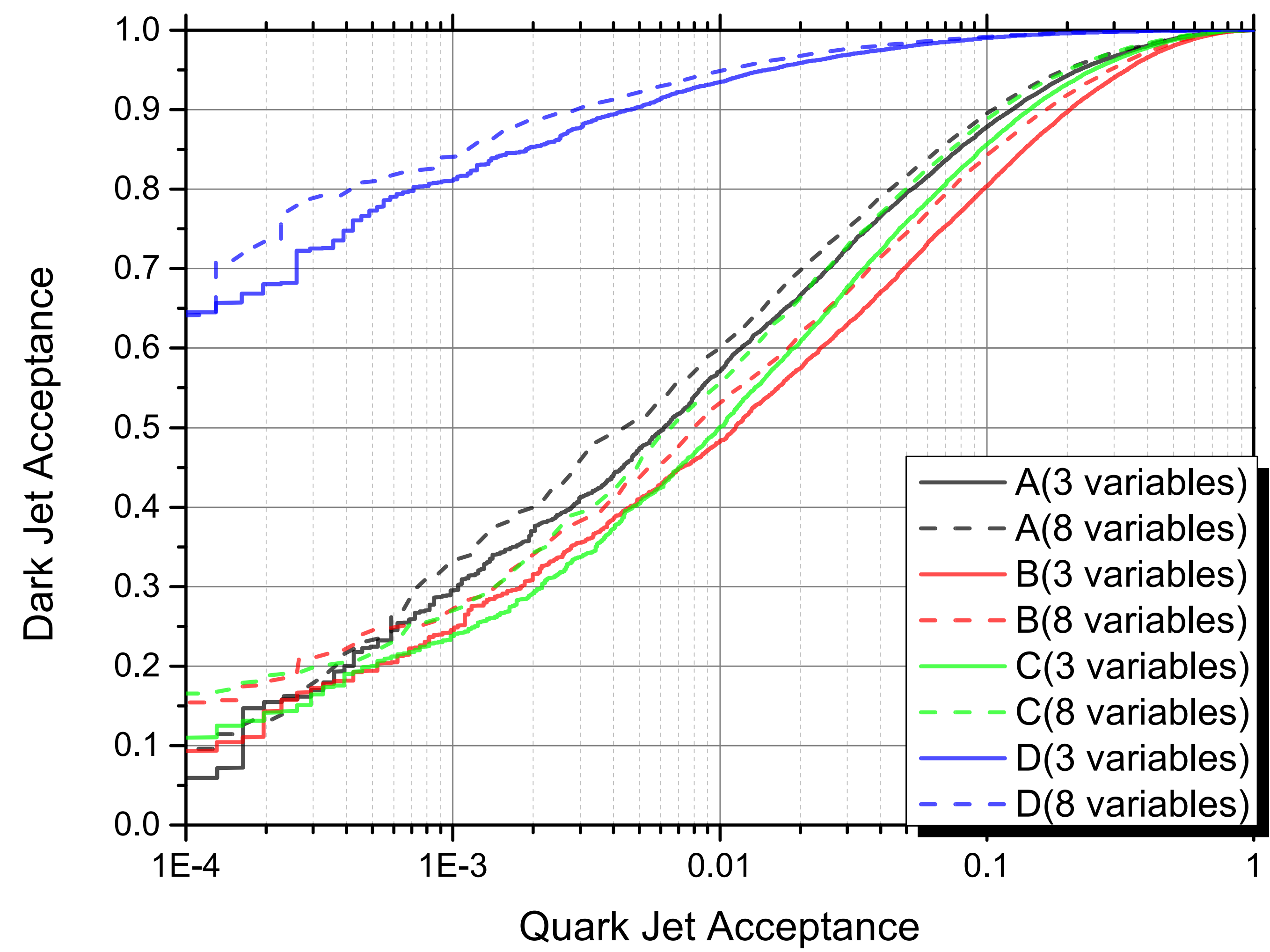
$$\{\text{var1,var2,var3,...}\} \rightarrow \text{BDT score}$$

Final discriminant performance

You can combine multiple variables to enhance the discriminant performance. Here we use boosted decision tree(BDT).

Combination of $C_1^{(\beta)}$, track Multi, and E-ratio is good enough.



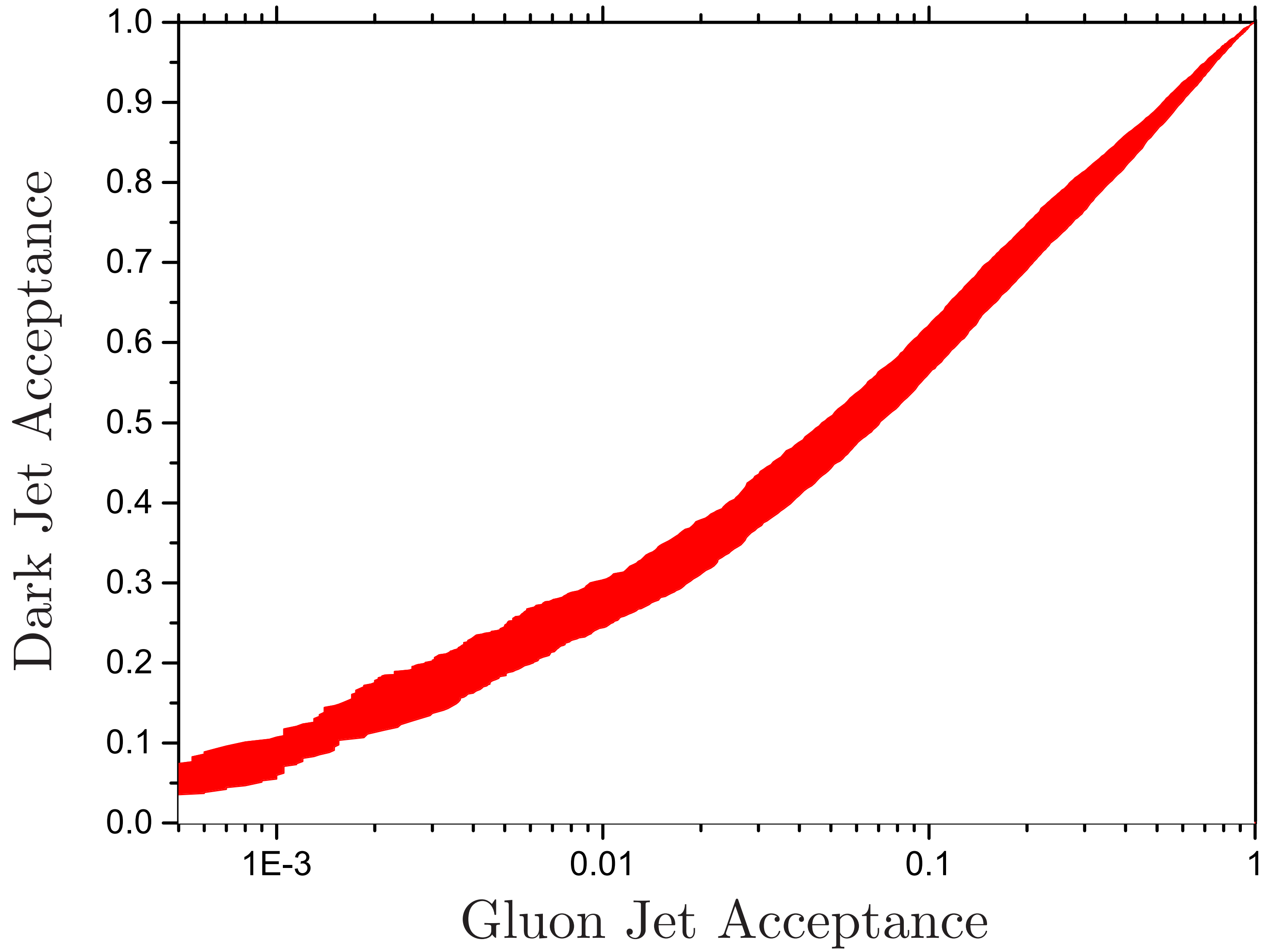


Exclude 99% Gluon-Jet, reserve >30% Dark-Jet.

Exclude 99% Quark-Jet, reserve >50% Dark-Jet.

Uncertainty estimation

You can only use Pythia8 to do Dark QCD simulation.
So we rescale the renormalization scale in parton shower process to estimate the theoretical uncertainty.



$(0.5\mu^2 \to 2.0\mu^2)$

Dark sector setting A is used here, which has a large running coupling.

Our result looks quite robust.

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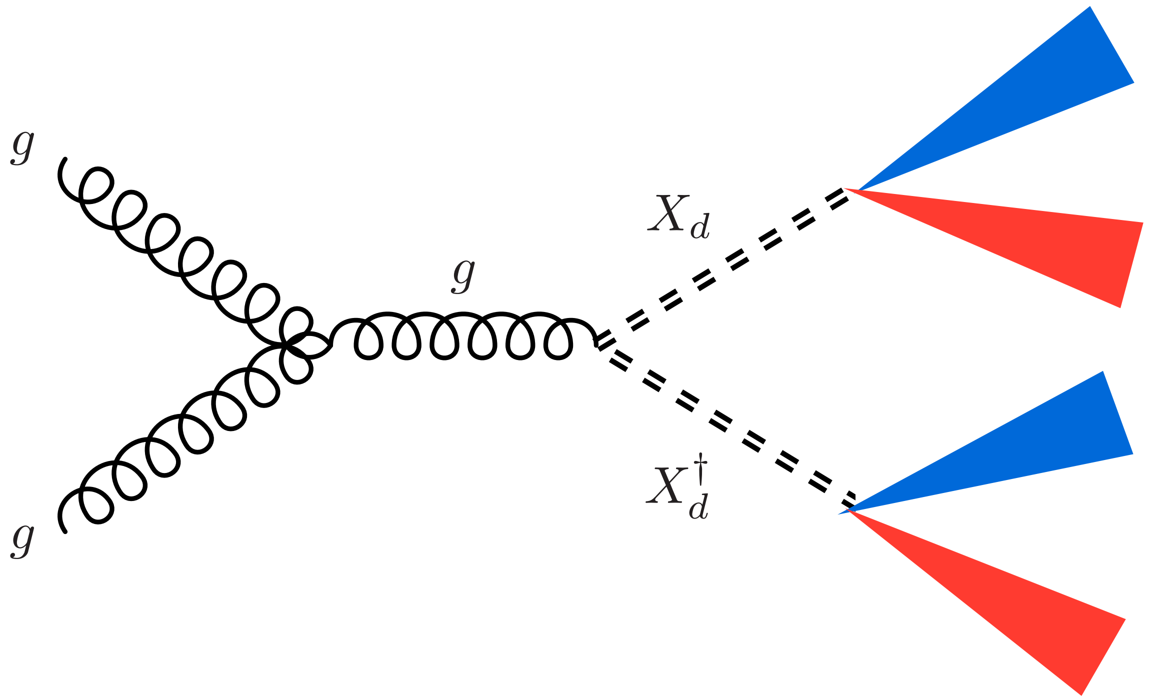
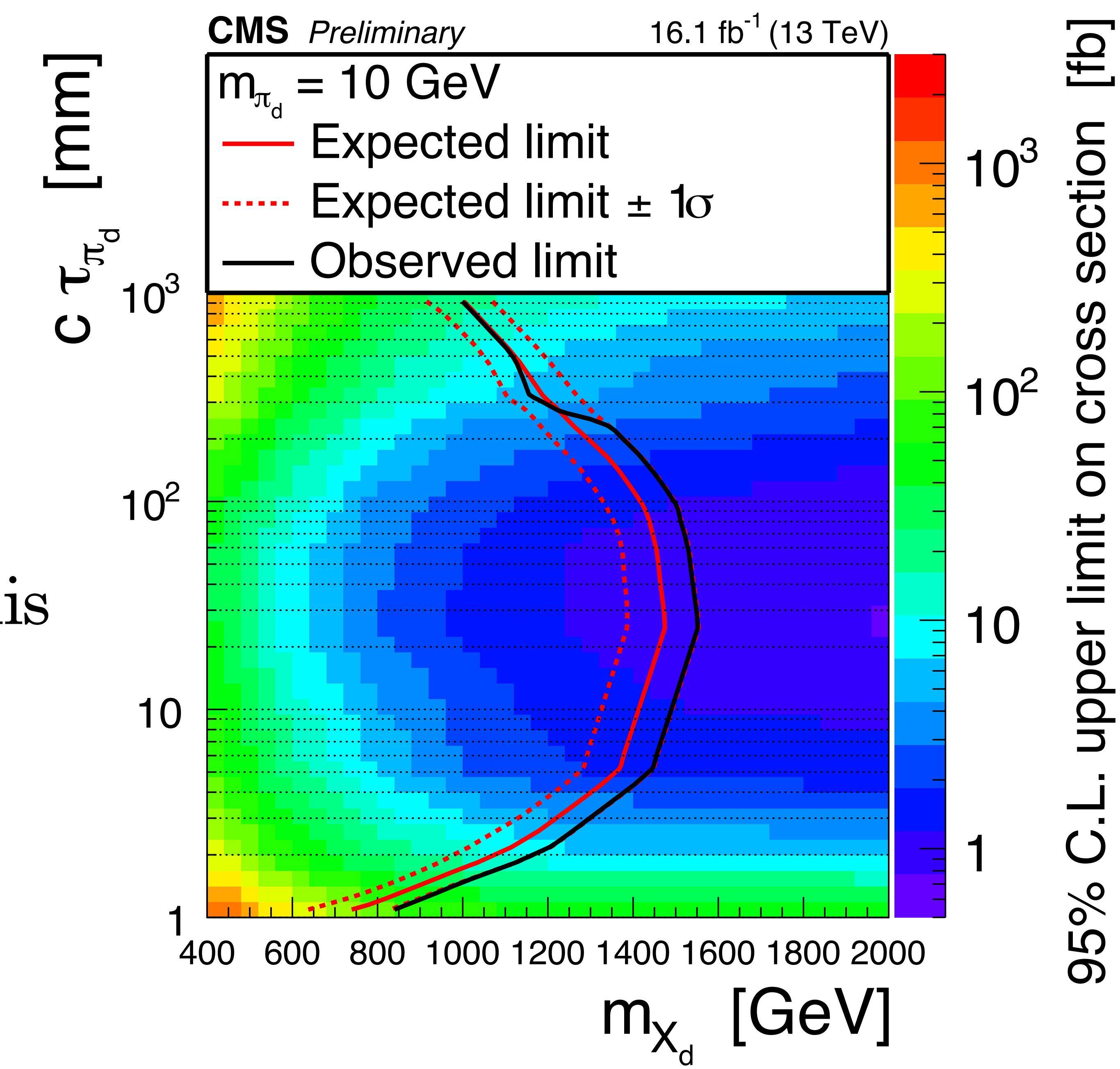
CMS report: based on displaced vertex



CMS report use displaced vertex to search for mediator particles.

If dark meson decay promptly, this method lose its effect.



Tagging the QCD-like "Dark jet"

Our analysis ins based on ATLAS report: search for pair-produced resonances in 4-jets final state

- Events are required to have at least 4 jets with $p_{\mathrm{T}} > 120\mathrm{GeV}$ and $|\eta| < 2.4$.
- These 4 jets are paired by minimizing $\Delta R_{\min} = \sum_{i=1,2} |\Delta R_i - 1|$, with ΔR_i the angular distance between two jets in a pair.
- Define m_{avg} as the average of the invariant masses of these two jets pair as $m_{\mathrm{avg}} = \frac{1}{2}(m_1 + m_2)$ with m_1 and m_2 are the invariant masses of two resonances. Discard events with large angular separation according to a resonant mass:

$$\Delta R_{\min} > -0.002 \times (m_{\mathrm{avg}}/\mathrm{GeV} - 225) + 0.72 \qquad \text{if } m_{\mathrm{avg}} < 225\mathrm{GeV}$$
$$\Delta R_{\min} > +0.0013 \times (m_{\mathrm{avg}}/\mathrm{GeV} - 225) + 0.72 \qquad \text{if } m_{\mathrm{avg}} > 225\mathrm{GeV}$$

- Boosting the system of these two resonances (two jets pairs) to their centre-of-mass frame. $\cos\theta^*$ is defined as the cosine of the angle between one of the resonance and the beam-line in the centre-of-mass frame. The mass asymmetry $\mathcal{A}$ is defined as:

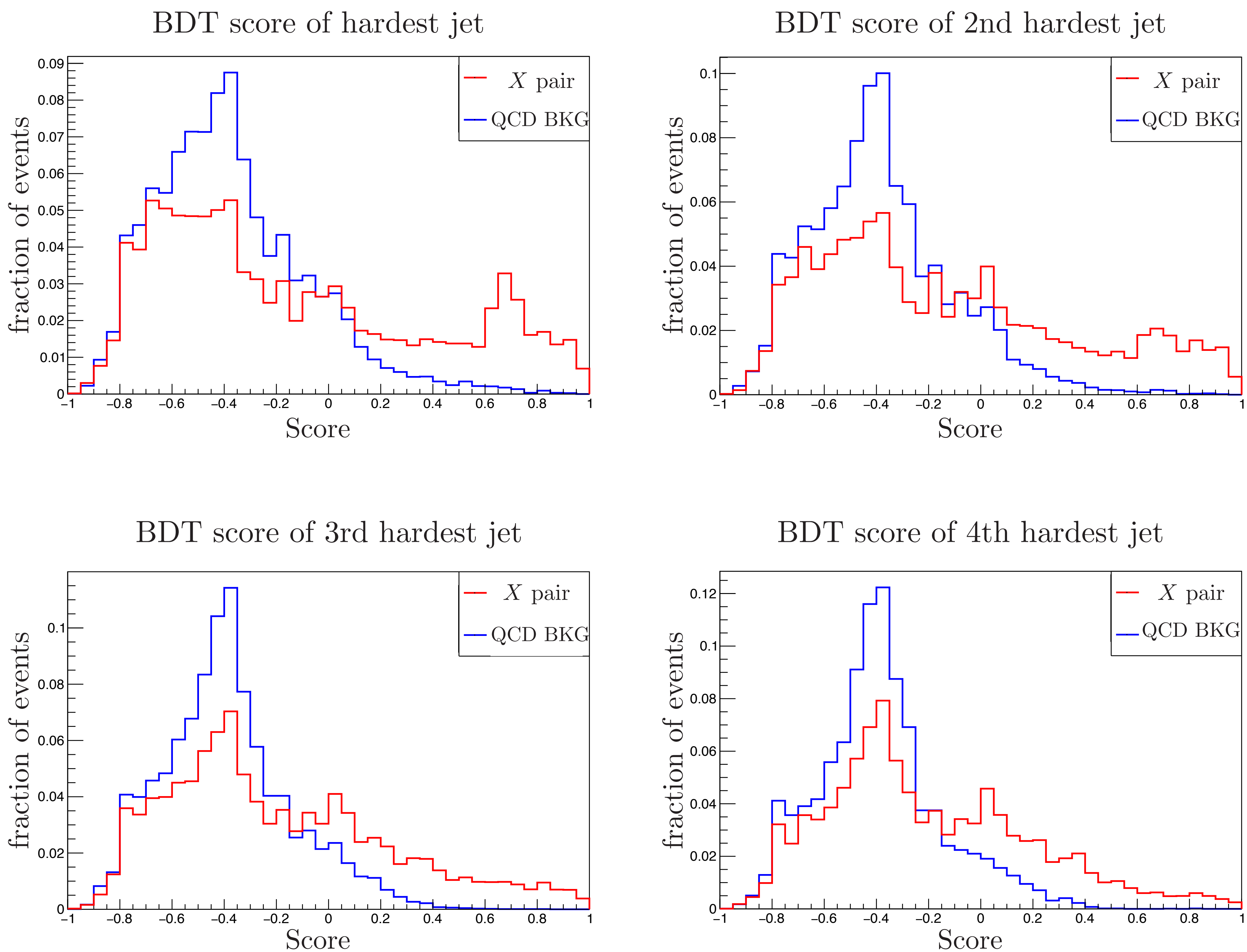
$$\mathcal{A} = \frac{|m_1 - m_2|}{m_1 + m_2}, \tag{4.2}$$

Events are cut by requiring $\mathcal{A} < 0.05$ and $|\cos\theta^*| < 0.3$. This cut defines the inclusive signal region (SR) selection.

This report only use p_{T}, η, ϕ of jets.

Let's do something more.

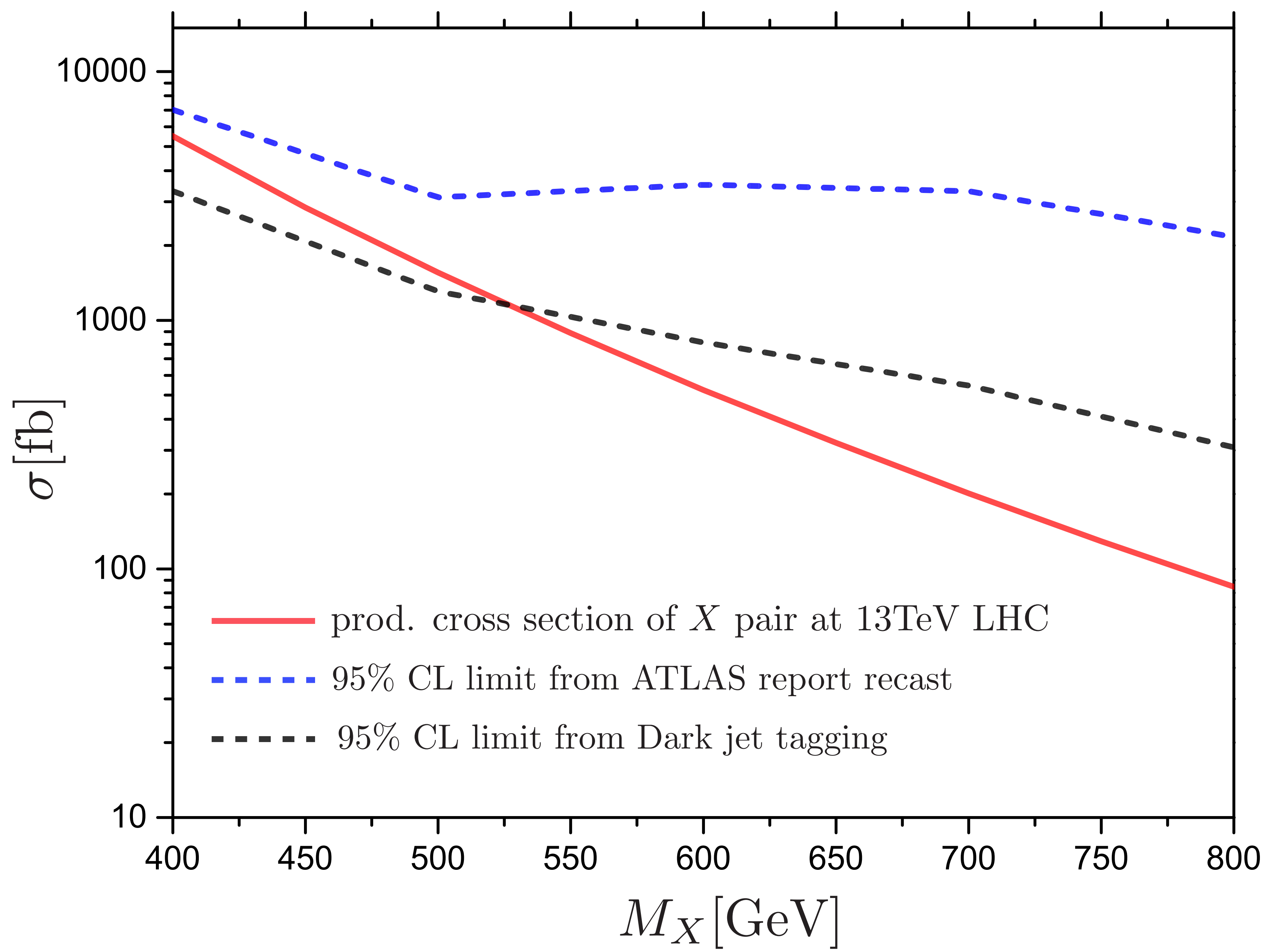
Tagging the QCD-like “Dark jet”



BDT score > 0.4 ==> Tagged as “Dark Jet”

Tagging the QCD-like “Dark jet”

	BKG	$M_X = 500\text{GeV}$	$M_X = 700\text{GeV}$	$M_X = 900\text{GeV}$
Inclusive selection	154,750	360	82	22
Require 1 dark jet	5,133	163	55	16
Require 2 dark jets	162	49	16	6
Significance	-	2.38	0.78	0.29



Conclusion and outlook

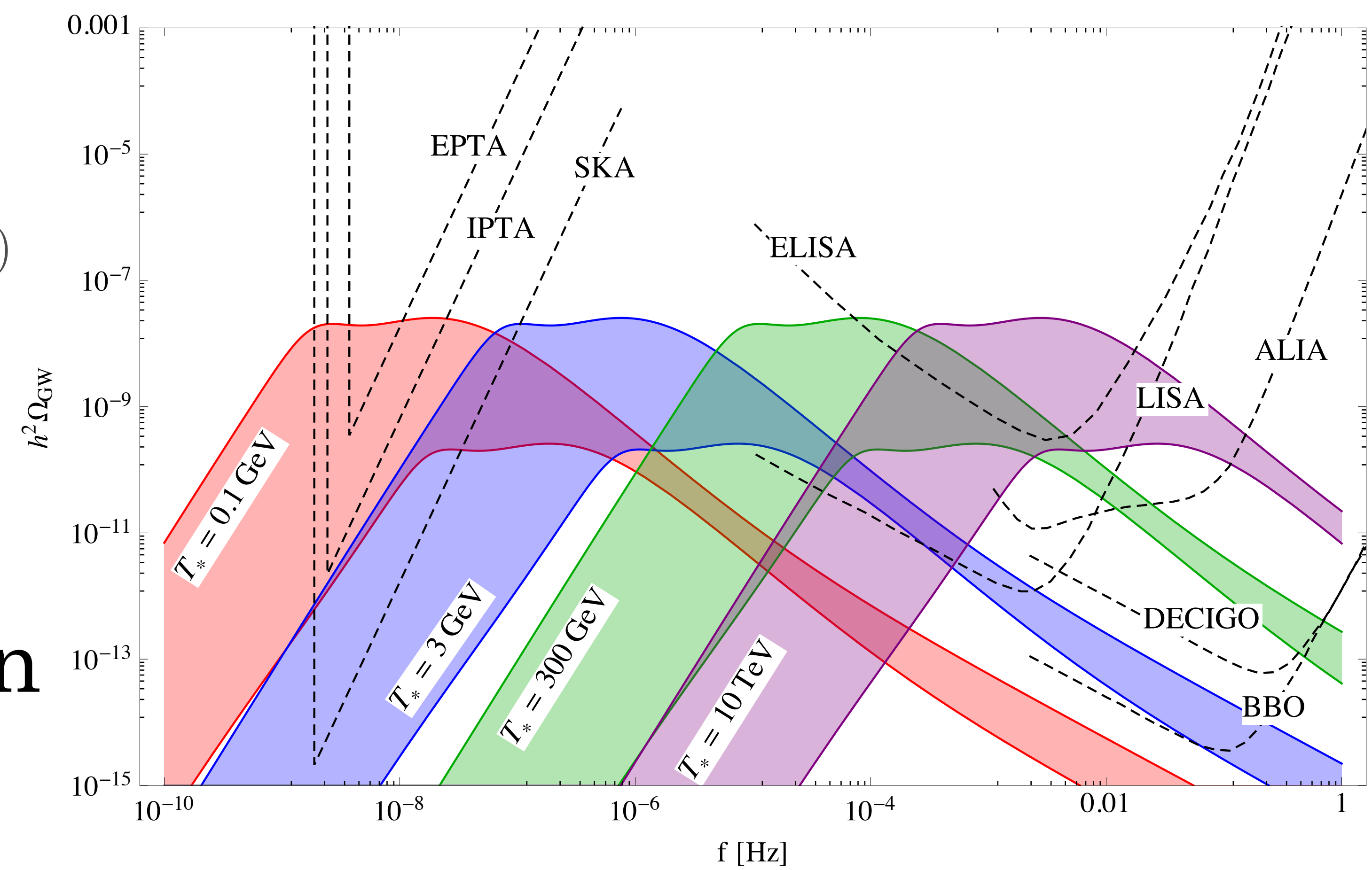
Jet is not only (η, ϕ, p_T), by looking inside a jet you can get more. Jet-substructure have been used in boosted object tagging and quark/gluon jet discrimination.

In this work, we indicate that if a dark sector can produce jet-like signal at collider, then it is possible to show the property of dark sector by jet-substructure directly.

Combination with cosmology will be more interesting:

Asymmetric Dark Matter: $\Omega_{DM}/\Omega_B \approx 5$

Confinement in Dark sector may trigger SFOPT, thus:



Phys. Rev. Lett. **115**, no. 18, 181101 (2015)

Thanks for your attention