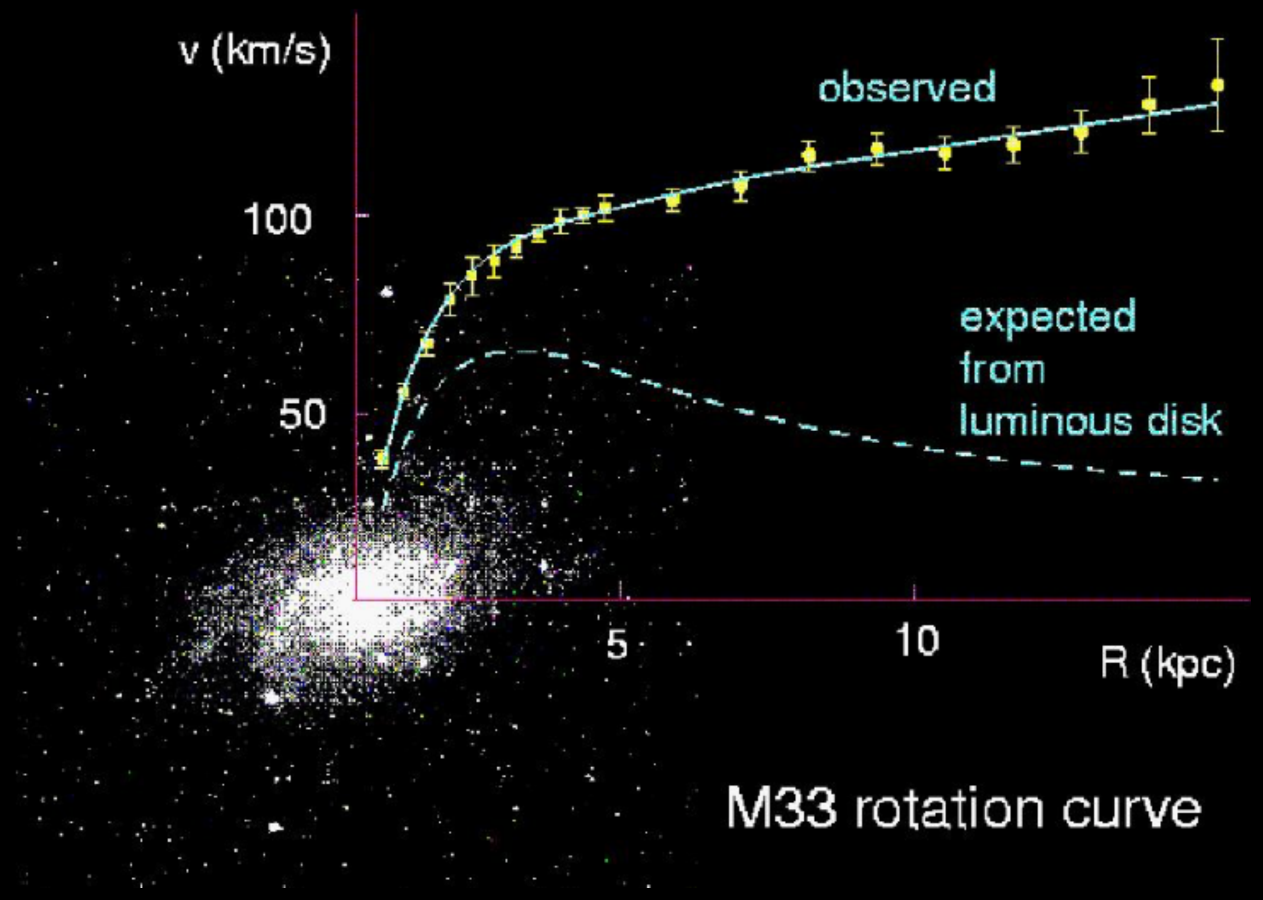
Phenomenology of dark gauge group at the LHC

박명훈

서울과학기술대학교
SEOUL NATIONAL UNIV. OF SCIENCE & TECHNOLOGY
1910

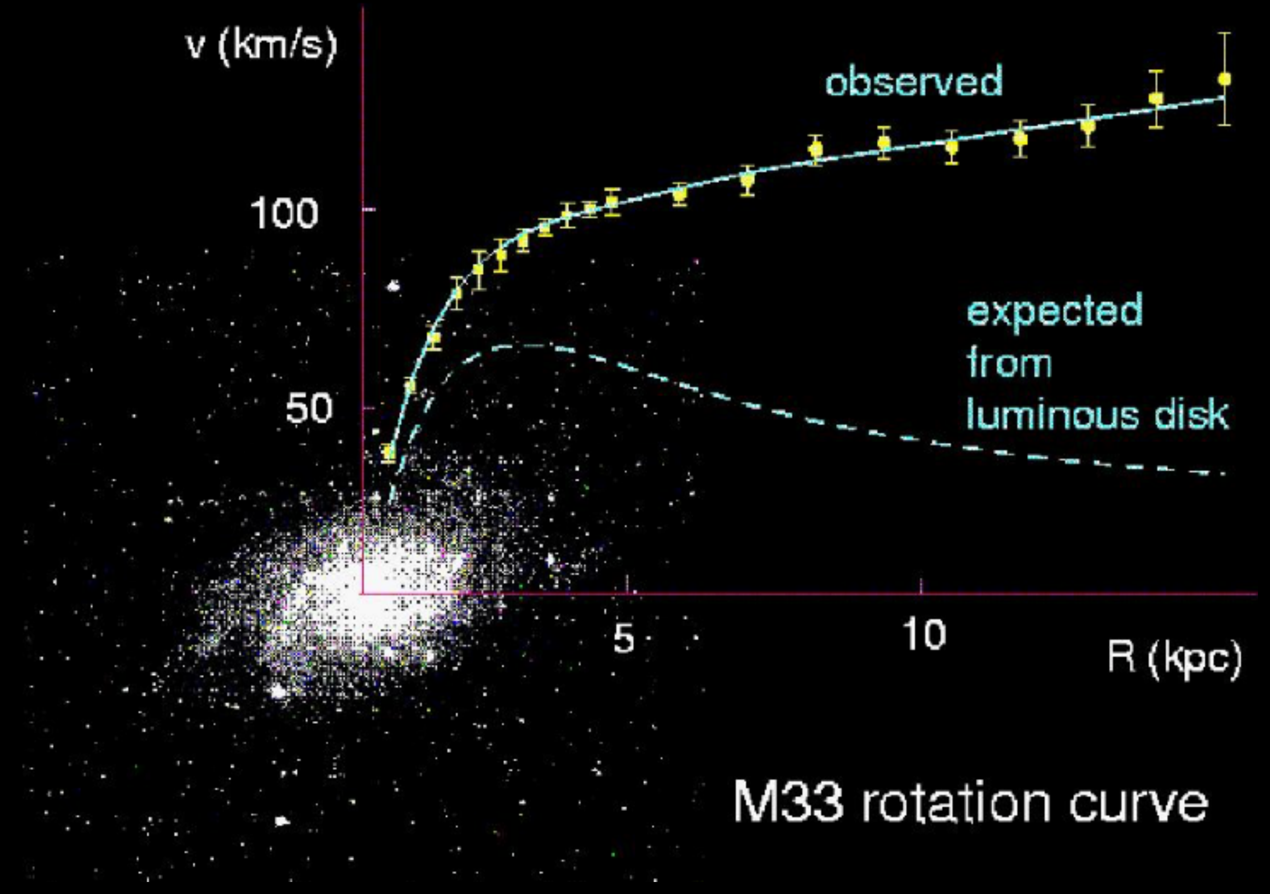
ibs Institute for Basic Science

Dark Matter is neutral



- We know that we **can not** see dark matter directly

Dark Matter is neutral

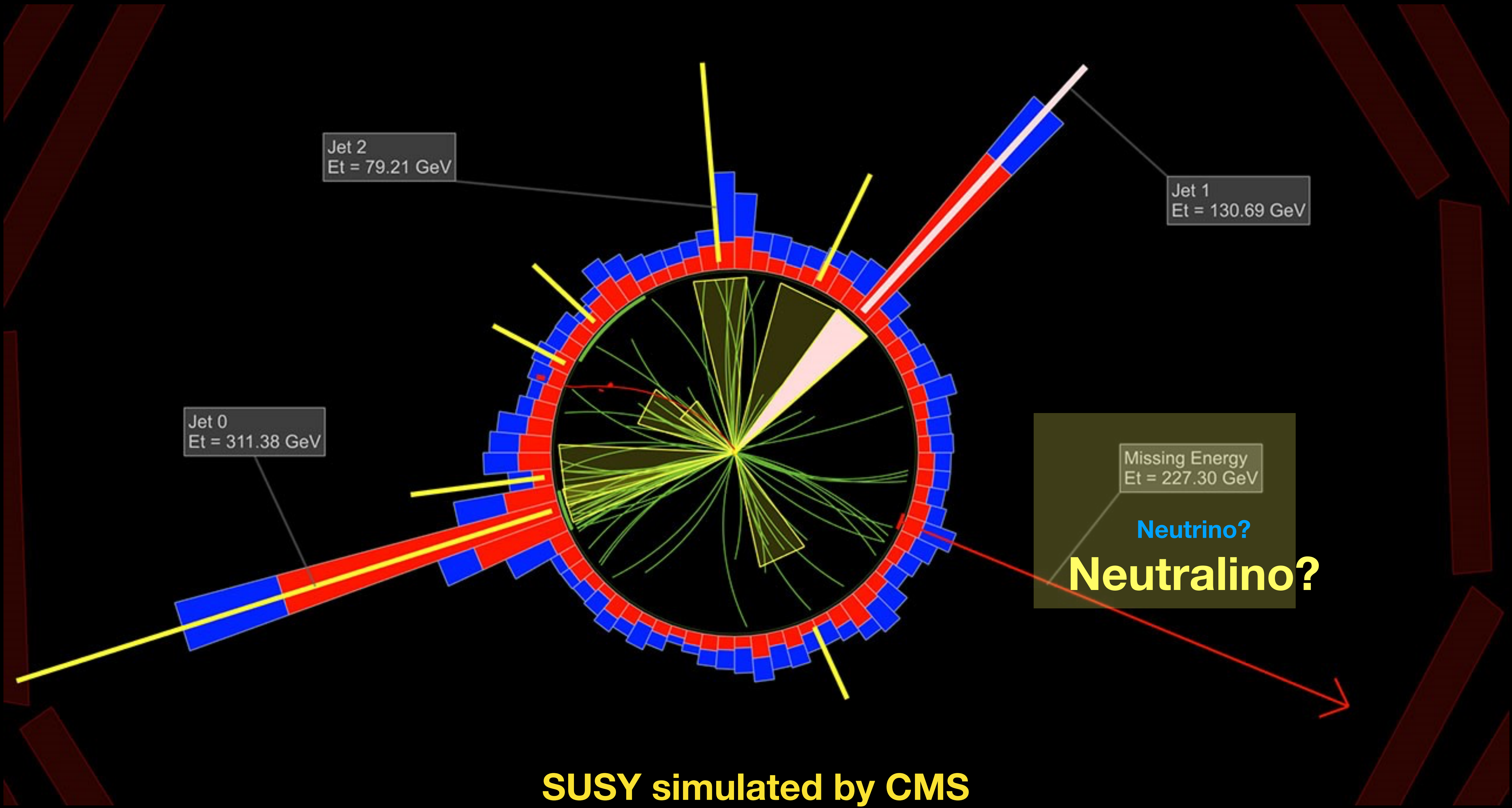


- We know that we **can not** see dark matter directly

↓

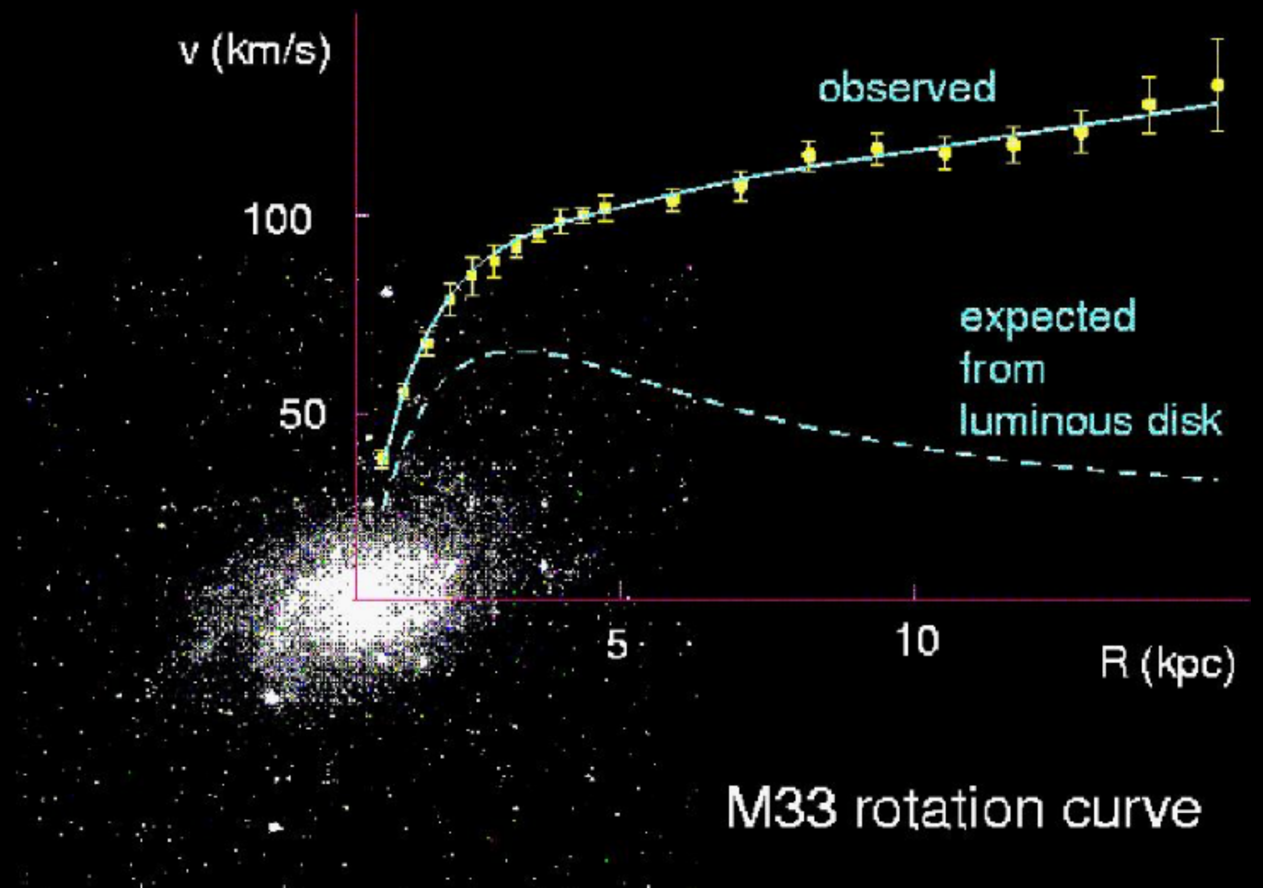
- Dark Matter is **Neutral** under **Standard Model U(1)$_{EM}$**

Collider signature for neutral Dark Matter



SUSY simulated by CMS

Is Dark Matter neutral under …?



- We know that we **can not** see dark matter directly

↓

- Dark Matter is Neutral under Standard Model $U(1)_{EM}$

- But it **does not** mean that Dark Matter is neutral under "**Dark Gauge Group(s)**"

- What would be the
  phenomenological consequences
  of “dark charged” dark matter ?

- How we can
  check
  whether dark matter is “dark charged” or not.

Particle under Gauge Group

- In the Standard Model, **fermions** get masses due to **a Higgs [designed to break SU(2)]**
- In the Standard Model, proton/neutron get masses due to **non-abelian gauge-charged**.

- Fermion, Gauge particle and Higgs

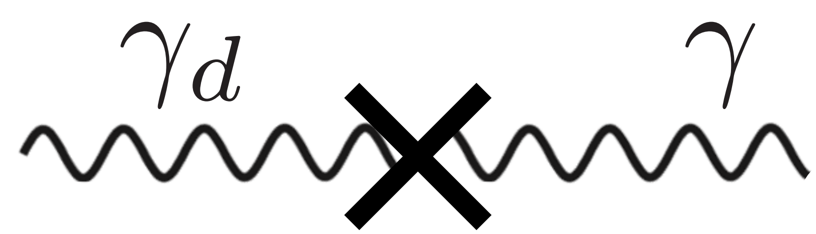
  - Dark Matter, Dark Gauge particle and Dark Higgs

U(1) Dark photon and DM

- Dark matter may have a dark-U(1) charge
  (good to have proper relic density)

- dark-U(1) can mix with SM U(1)-hyper through a Gauge-kinetic mixing : Gauge-invariant term

$$\mathcal{L} \ni \epsilon F'_{\mu\nu} F^{\mu\nu}_{Y}$$



- If dark-U(1) is massless (unbroken), then a dark matter can have a milli-charged under SM U(1)

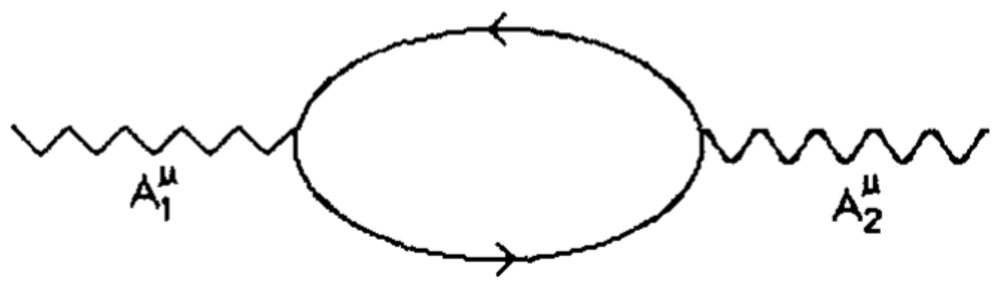
- If dark-U(1) is massive, dark matter would be totally neutral under SM U(1) (Holdom 1986)

- **If this additional U(1) exists, it can be a portal to DM sector**

Small mixing

- There may be loop-induced diagram, mediated particles charged under two U(1)

Holdom 1986

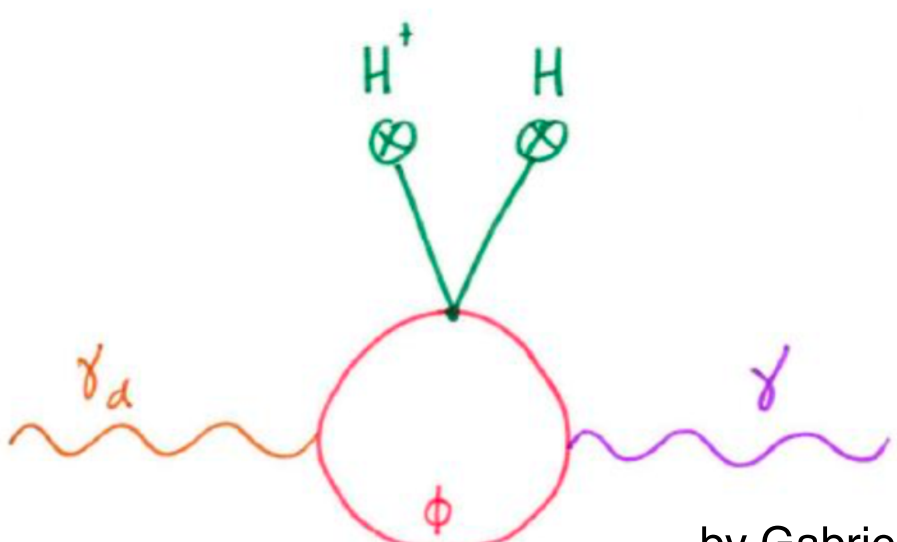


f_{12}, f'_{12}

$$\epsilon \propto \frac{Q_1 Q_2}{\pi^2} \ln\left(\frac{m'_{12}}{m_{12}}\right)$$

- Higher dimensional operator, induced from Standard Model SU(2) and dark U(1)

Spencer Chang et.al. 2015



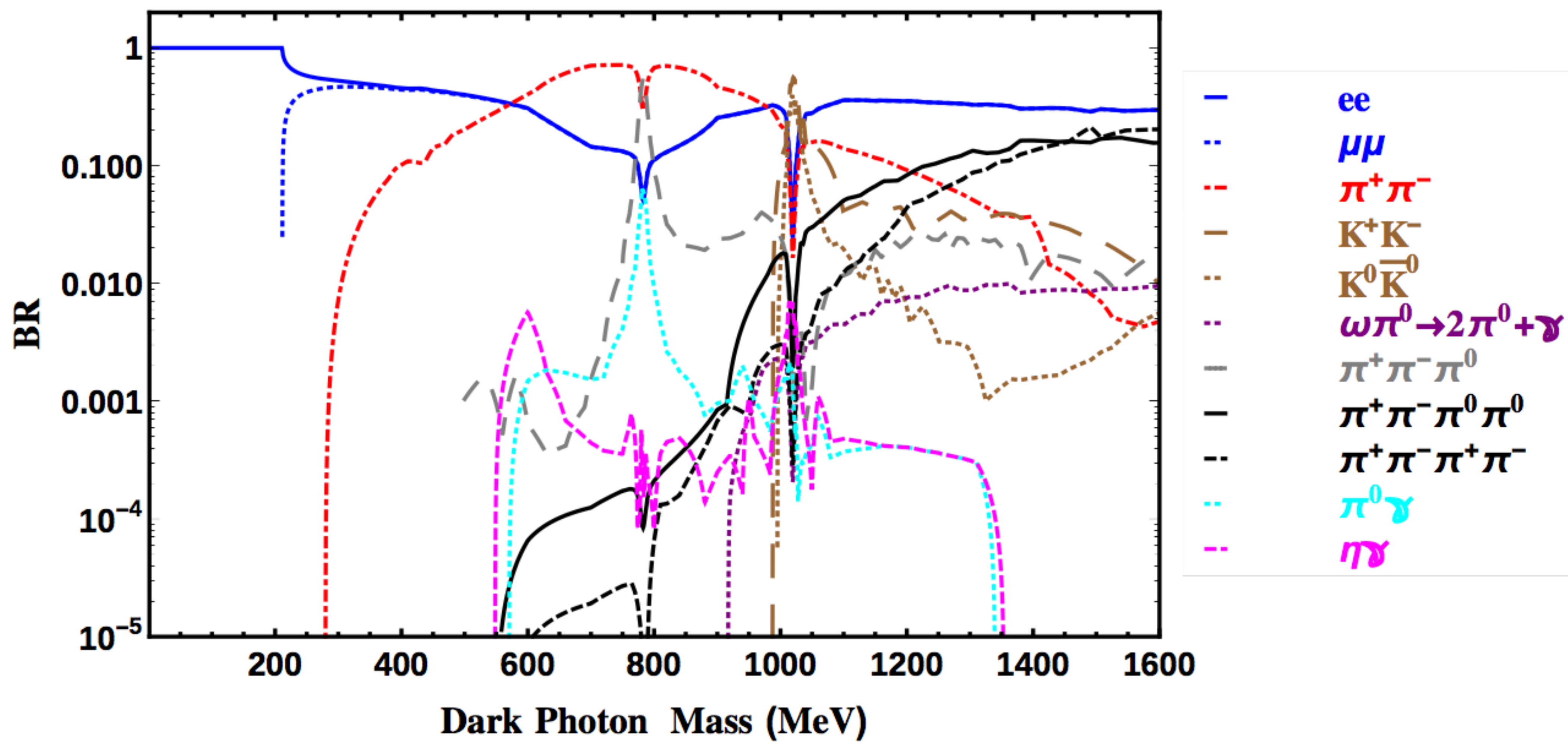
by Gabriel Barello

$$\frac{c}{16\pi^2 m_\phi^2} \left(H^\dagger \tau^a H\right) W^a_{\mu\nu} F_D^{\mu\nu}$$

- mediated by SU(2) triplet ϕ

Dark photon decay

The decay of dark photon only depend on its mass:



There are just two parameters in this simple extension:
kinetic mixing and **dark photon mass**.

life time

decay pattern

DM with dark charge and dark-Higgs

- For a minimality, abelian U(1)-gauge on DM

  - Dark Matter, Gauge field and Dark-Higgs

A'_μ	Φ	χ_L	χ_R
	Q'_Φ	Q'_{χ_L}	Q'_{χ_R}

• • •

$$\mathcal{L}_{\rm matter} \ni -g' Q'_V A'_\mu \bar{\chi}\gamma^\mu \chi - g' Q'_A A'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi$$

Yukawa for mass

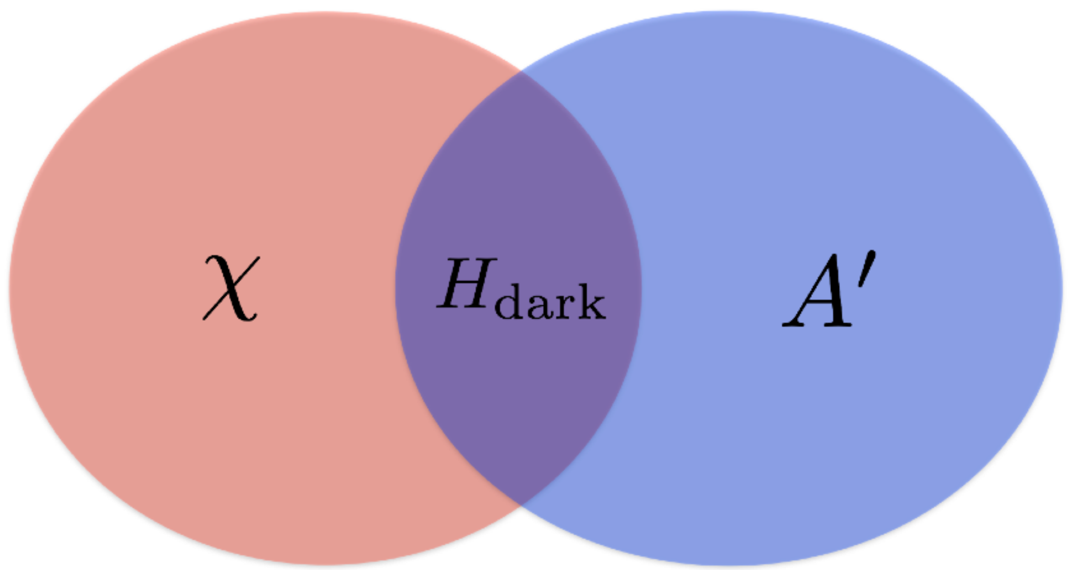
$$\mathcal{L} \ni y_\chi \bar{\chi}_L \Phi^* \chi_R + h.c.$$

$$Q'_{\chi_L} - Q'_{\chi_R} + Q'_\Phi = 0$$

$$Q'_A = \frac{1}{2}(Q'_{\chi_R} - Q'_{\chi_L}) = \frac{Q'_\Phi}{2}$$

$$Q'_V = \frac{1}{2}(Q'_{\chi_R} + Q'_{\chi_L}) = \frac{Q'_\Phi}{2} + Q'_{\chi_L}$$

- Dark matter and dark-photon **share the same origin** (**Dark Higgs**) for their mass



Yukawa Interaction

$$\mathcal{L} \ni y_\chi \bar{\chi}_L \Phi^* \chi_R + h.c.$$

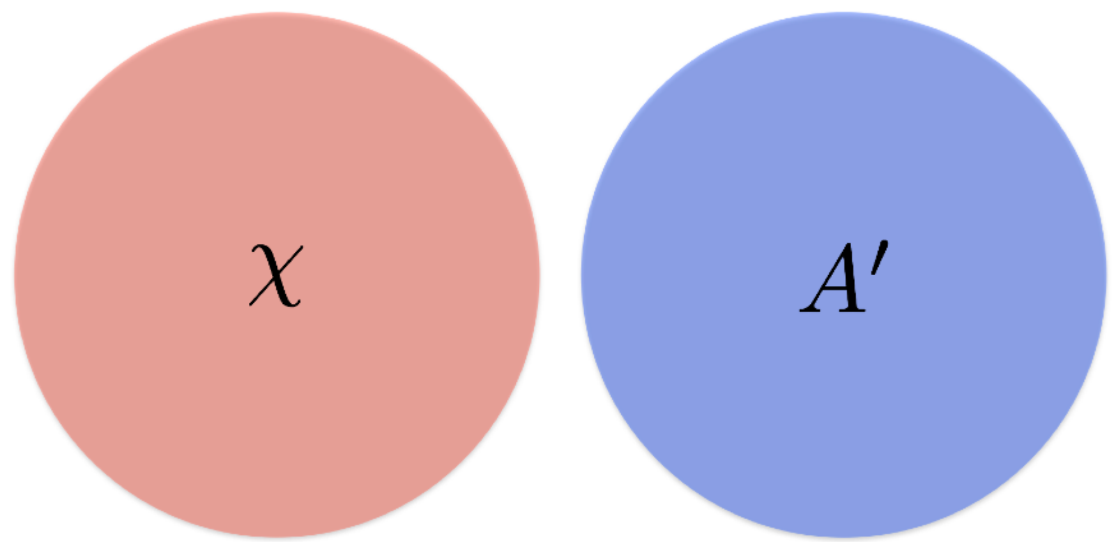
$$Q'_{\chi_L} - Q'_{\chi_R} + Q'_\Phi = 0$$

Dark-gauge breaking with non-zero charge Q'_Φ

- For maximal chirality: $Q'_{\chi_R} = 0$, $Q'_{\chi_L} = -Q'_\Phi$

$$Q'_A = \frac{1}{2}(Q'_{\chi_R} - Q'_{\chi_L}) = \frac{Q'_\Phi}{2}$$

- Dark matter and dark-photon **DO NOT share the a source** for their mass

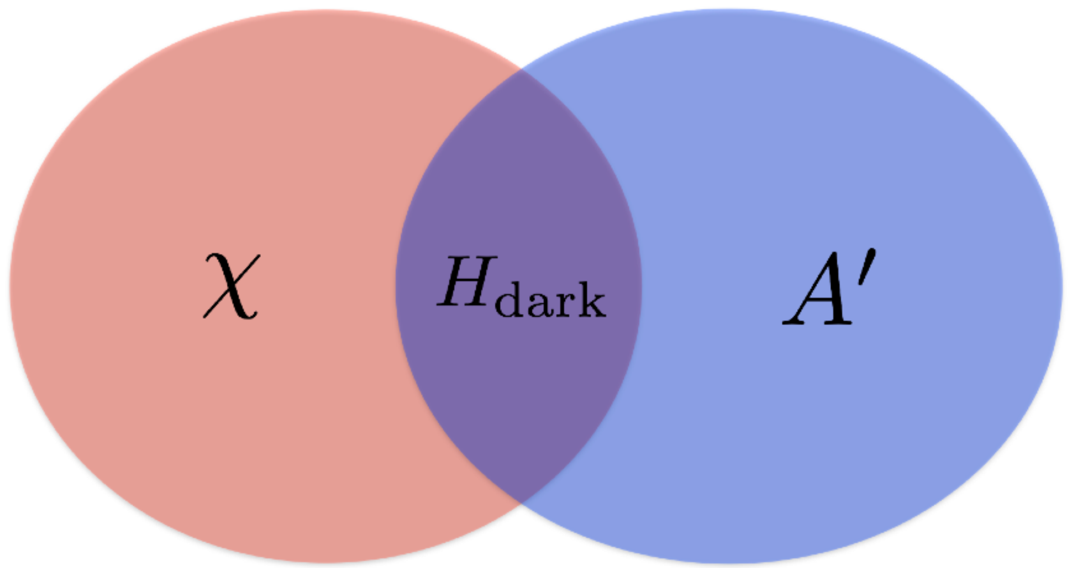


No Yukawa Interaction: **Vector-like DM**

$$Q'_{\chi_L} = Q'_{\chi_R}$$

- No axial vector coupling:

$$Q'_A = \frac{1}{2}\left(Q'_{\chi_R} - Q'_{\chi_L}\right) = 0$$



with Dark-Higgs
Chiral fermion

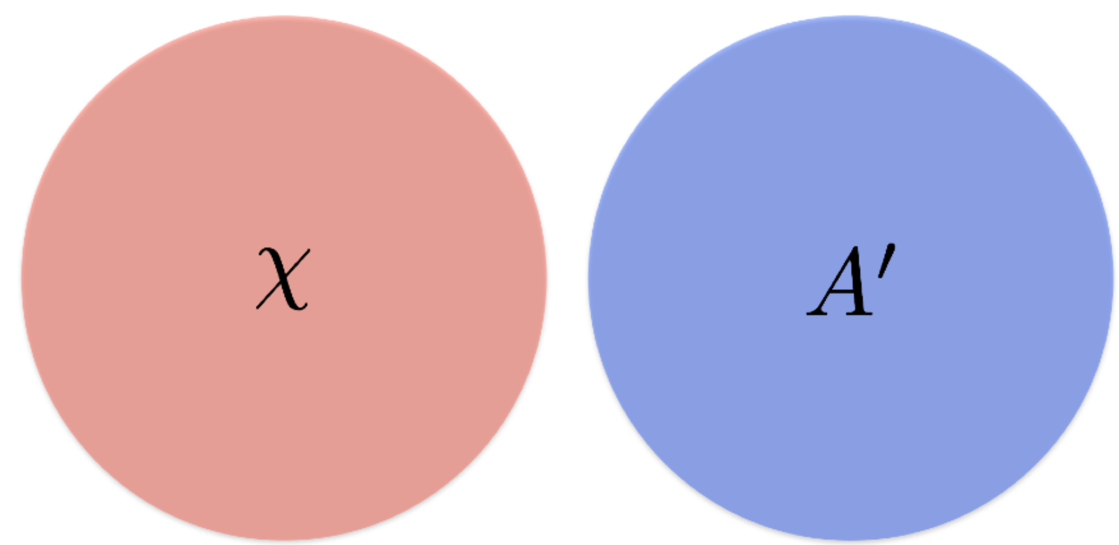
dark matter and dark-photon
share the same origin for their mass

$$Q'_A = \frac{1}{2}(Q'_{\chi_R} - Q'_{\chi_L}) = \frac{Q'_\Phi}{2}$$

Can we see difference @ LHC ?

dark matter and dark-photon
have their own mass mechanism

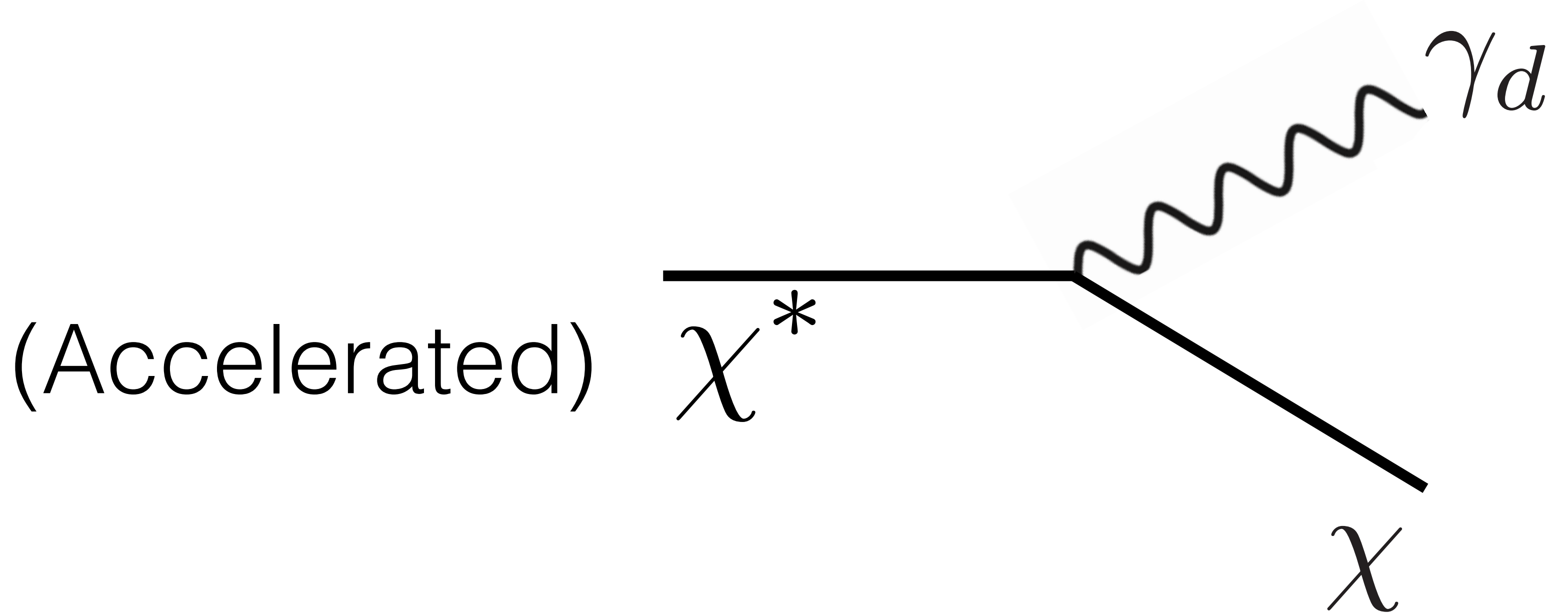
$$Q'_{\chi_L} = Q'_{\chi_R}$$



No Dark-Higgs
Vector-like fermion

How can we observe?

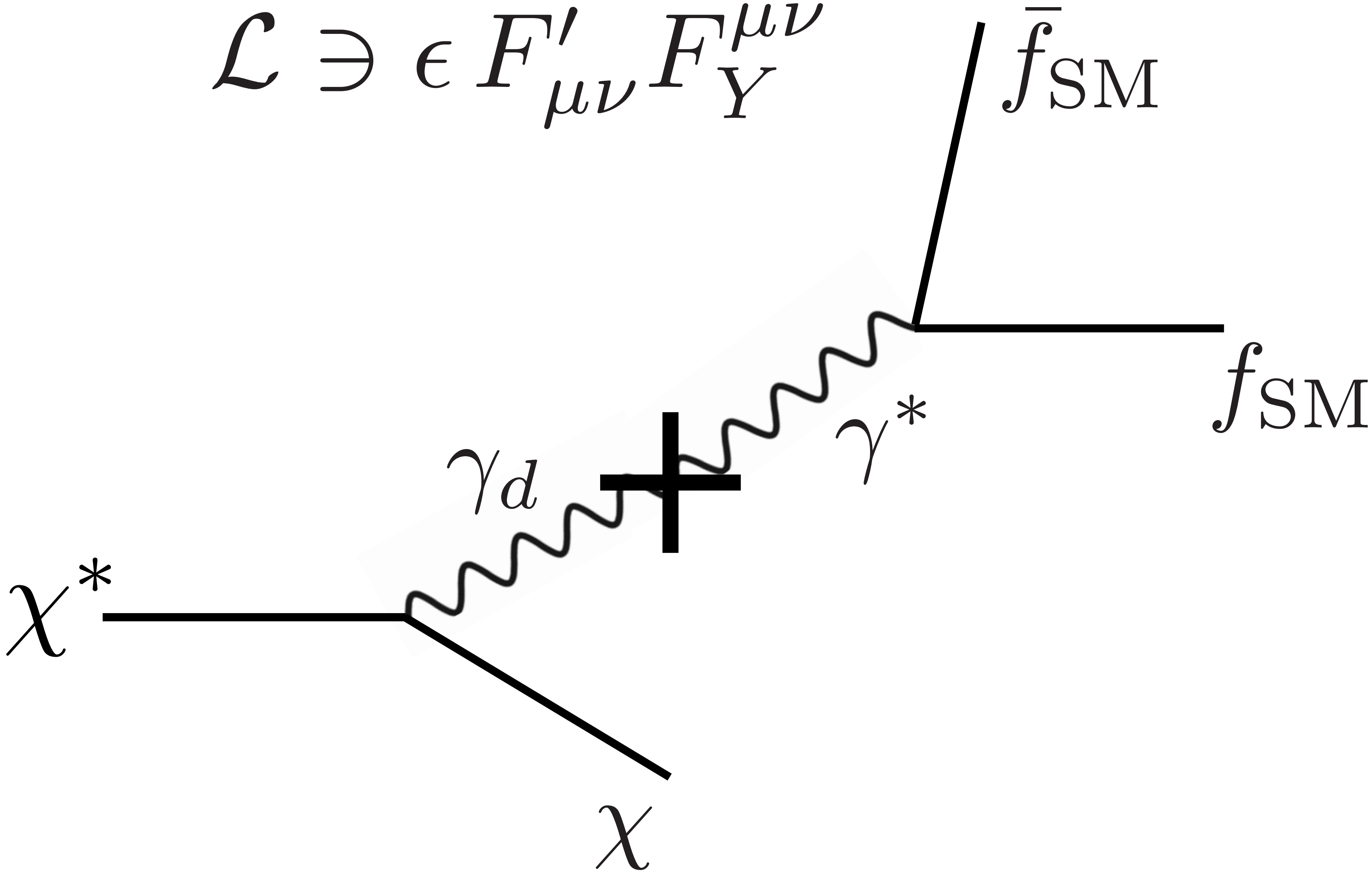
- **Dark Showering:** Accelerated "Dark Charged" particle radiates corresponding dark-gauge bosons



How can we observe?

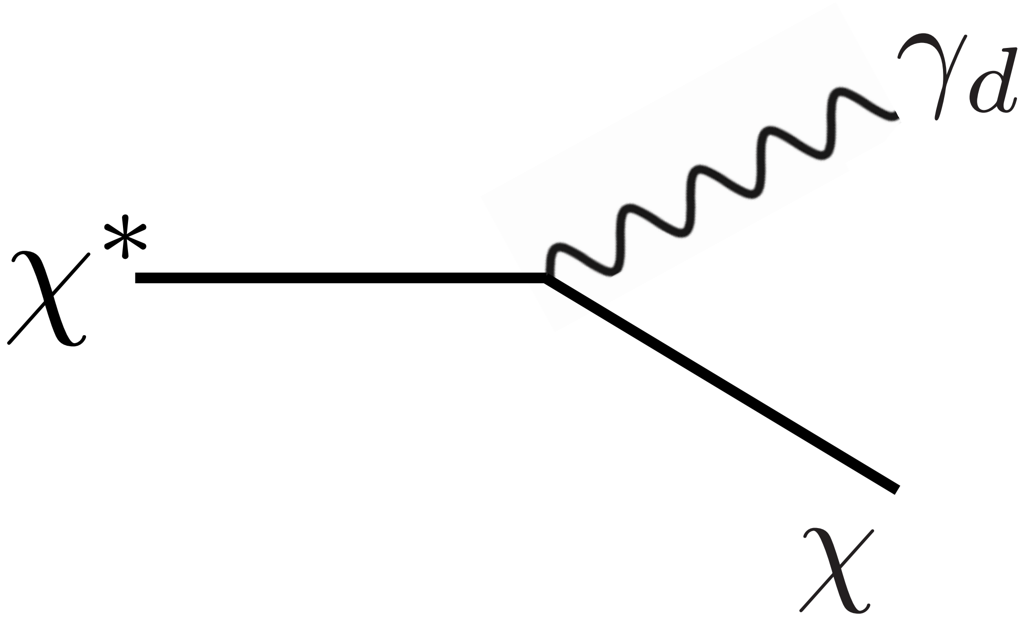
- dark-U(1) can mix with SM U(1)-hyper through a **Gauge-kinetic mixing** : Gauge-invariant term

$$\mathcal{L} \ni \epsilon\, F'_{\mu\nu} F_Y^{\mu\nu}$$



Showering process

Differential probability of a splitting process $\propto \frac{\alpha'}{2\pi} \mathrm{d}x \frac{\mathrm{d}t}{t} P_{\chi \to \chi\, \gamma_d}(x, t)$



With $x = \frac{E_{\chi,\mathrm{out}}}{E_{\chi^*}}$

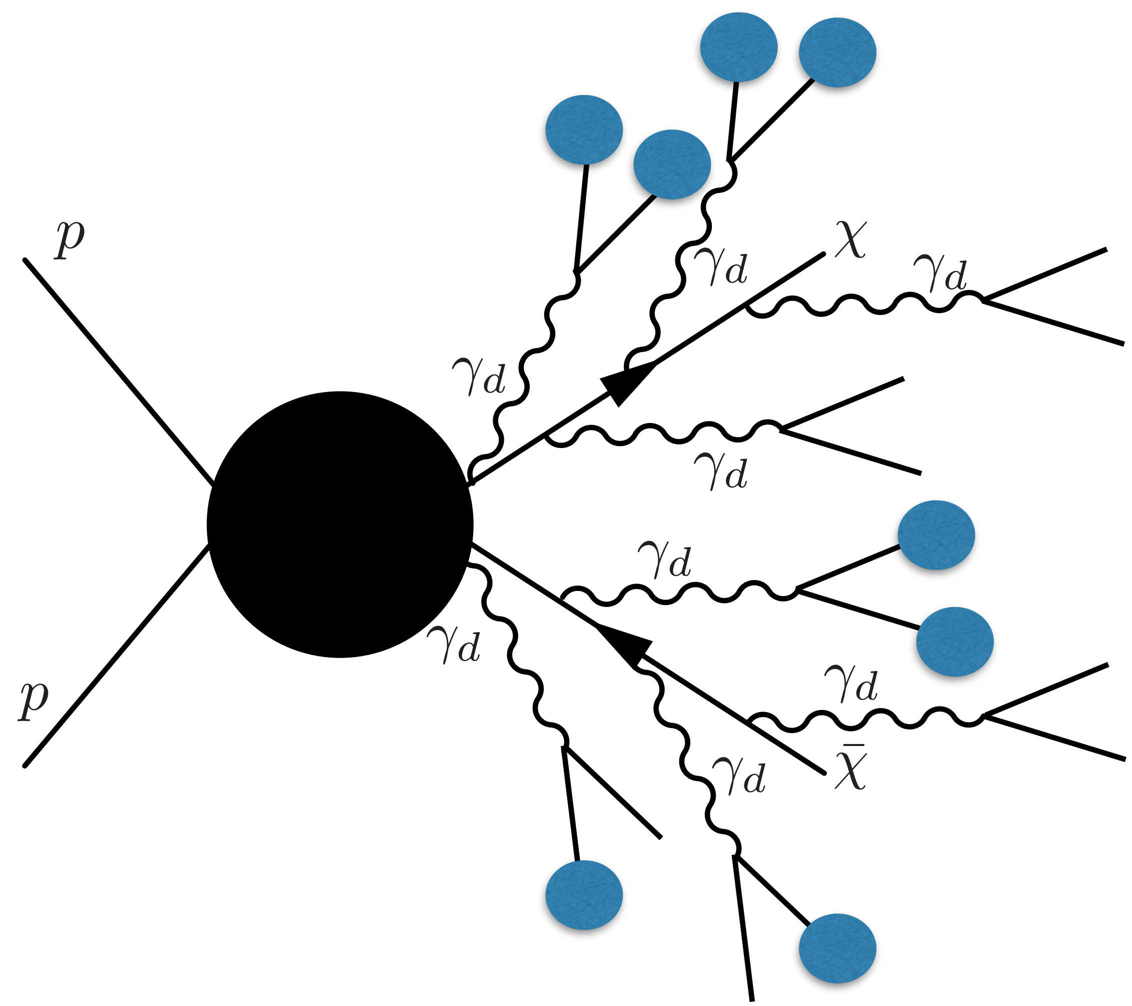
Splitting function

$$P_{\chi \to \chi\gamma_d}(x, t) \simeq Q_V'^2 \frac{1 + x^2}{1 - x}$$

- In a **chiral** case, the **longitudinal** component of a dark photon couples to a dark matter

$$P_{\chi \to \chi\gamma_d}(x, t) \simeq (Q_V'^2 + Q_A'^2) \frac{1 + x^2}{1 - x} + 2Q_A'^2 \frac{m_\chi^2}{m_{\gamma_d}^2}$$

Energetic DM @ Colliders

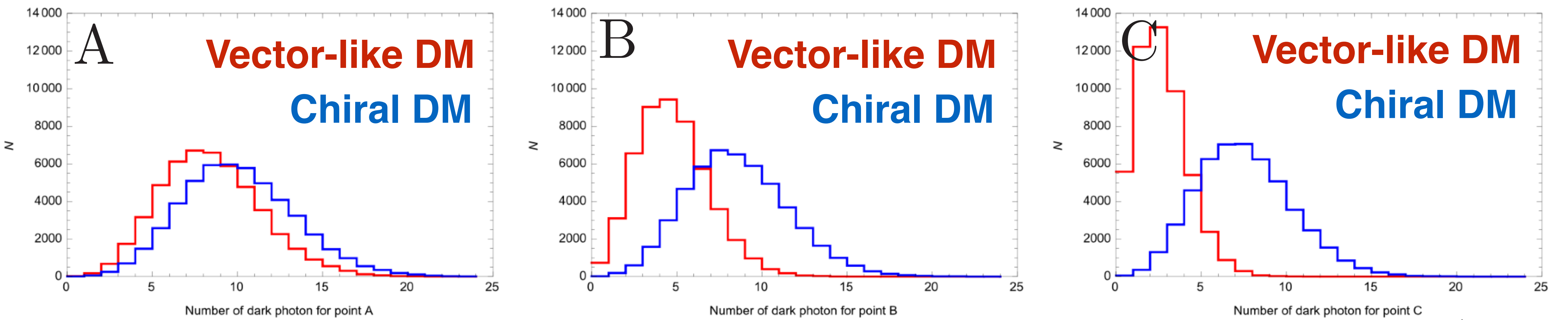


- **Radiations** from **Energetic** “dark charged” particles will acquire certain level of energy, enough to be “**<u>tagged</u>**”

(<u>detectable effect</u>)

Benchmark Points (BP)	A	B	C
α'	0.3	0.15	0.075
m_χ (GeV)	0.7	1.0	1.4
m_{γ_d} (GeV)	0.4		

- Number of showered dark photons



weak coupling limit

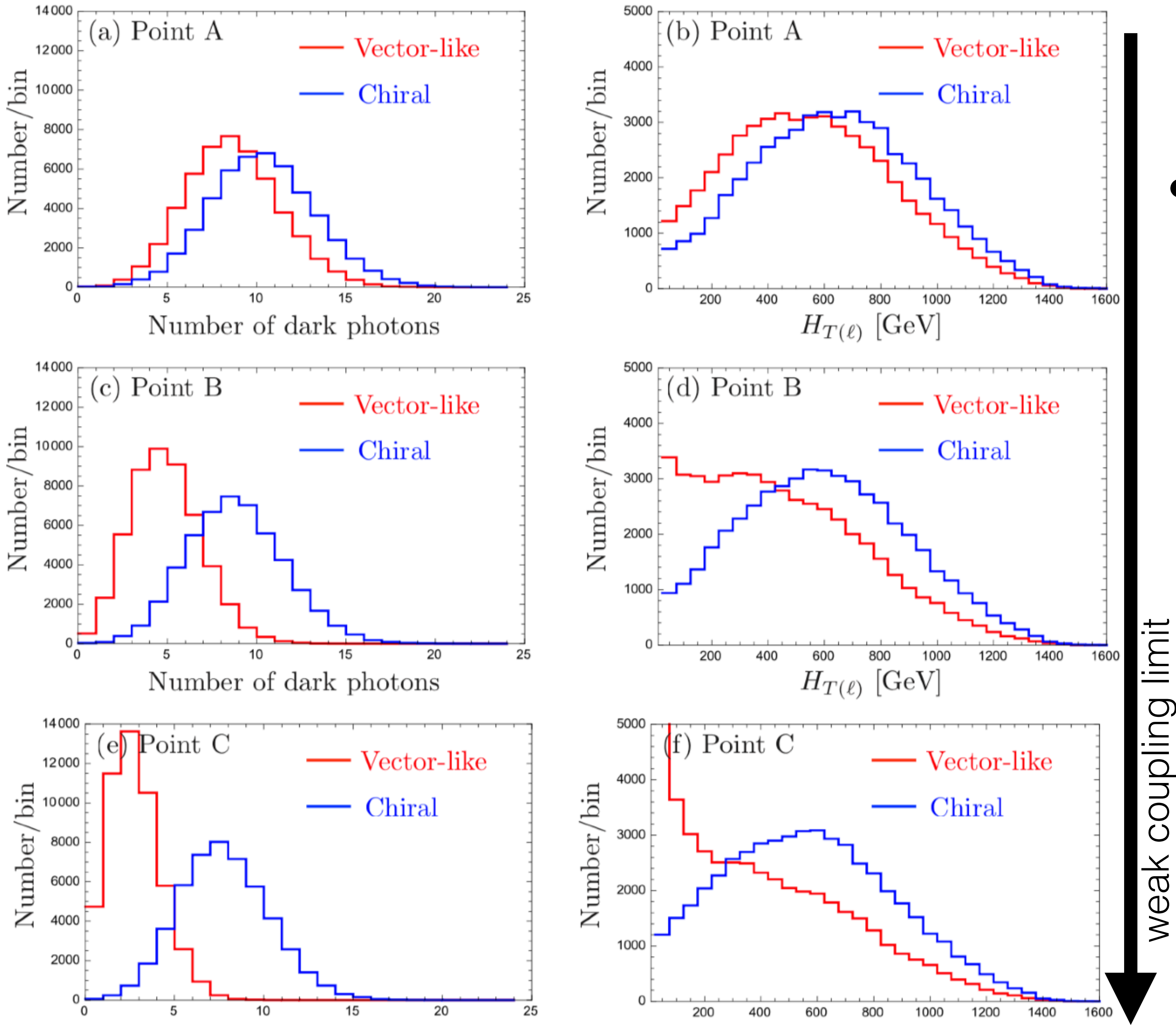
$$P_{\chi\to\chi\gamma_d}(x,t) \simeq (Q_V'^2 + Q_A'^2)\,\frac{1+x^2}{1-x} + 2Q_A'^2\,\frac{m_\chi^2}{m_{\gamma_d}^2}$$

- In the weak gauge coupling limit,

$$\lim_{\alpha'\ll 1} \alpha' P_{\chi\to\chi\gamma_d} \simeq \alpha' \cdot 2Q_A'^2 \frac{m_\chi^2}{m_{\gamma_d}^2} \propto \frac{m_{\gamma_d}^2}{v_S^2} \cdot \frac{m_\chi^2}{m_{\gamma_d}^2} \sim y_\chi^2$$

Quantify the difference

- We use the transverse energy deposits $H_{T(\ell)} = \sum_{i=\mu^\pm, e^\pm} |p_{T_i}|$



Number of dark photons $H_{T(\ell)}$ [GeV]

- In a splitting function

$$P_{\chi\to\chi\gamma_d}(x,t) \simeq Q_V'^2 \frac{1+x^2}{1-x}$$

$$x \simeq 1 : \text{Soft radiation}$$

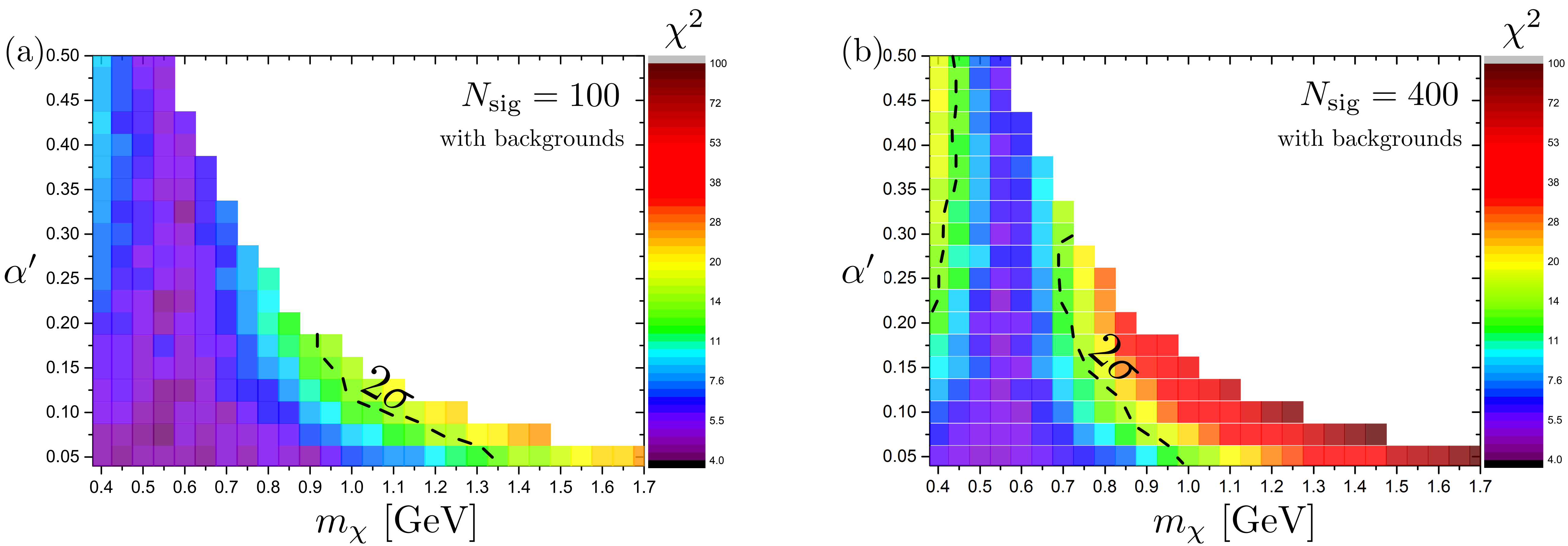
- In a chiral case, additional term:

$$P_{\chi\to\chi\gamma_d}(x,t) \ni 2Q_A'^2 \frac{m_\chi^2}{m_{\gamma_d}^2}$$

: **No singularity** at x~ 1

Checking chirality@ Collider

- After triggering signal events by tagging a collimated muon-jet (a jet only with muons)



with 100 , 400 signal events after cuts to reduce BKG

Number of BKG ~ O(1)

SU(N) dark sector

Where is from the stability of Dark matter ?

How does Dark matter become MASSIVE ?

= Dark "Baryon"

Dark Matter with SU(N)

- A new scale of confinement will be introduced Λ
- "Composite " particle (baryon) under non-abelian gauge group

  - "Composite" Dark Matter under dark non-abelian gauge group

Dark Matter with SU(2)

Timothy Cohen et.al 2015

- Dark sector in SU(2) with two fermionic quark flavors

$$\chi_i = \chi_{1,2}$$

- There are two accidental symmetries:
  - A dark-isospin number $U(1)_{1-2}$
  - A dark-baryon number $U(1)_{1+2}$

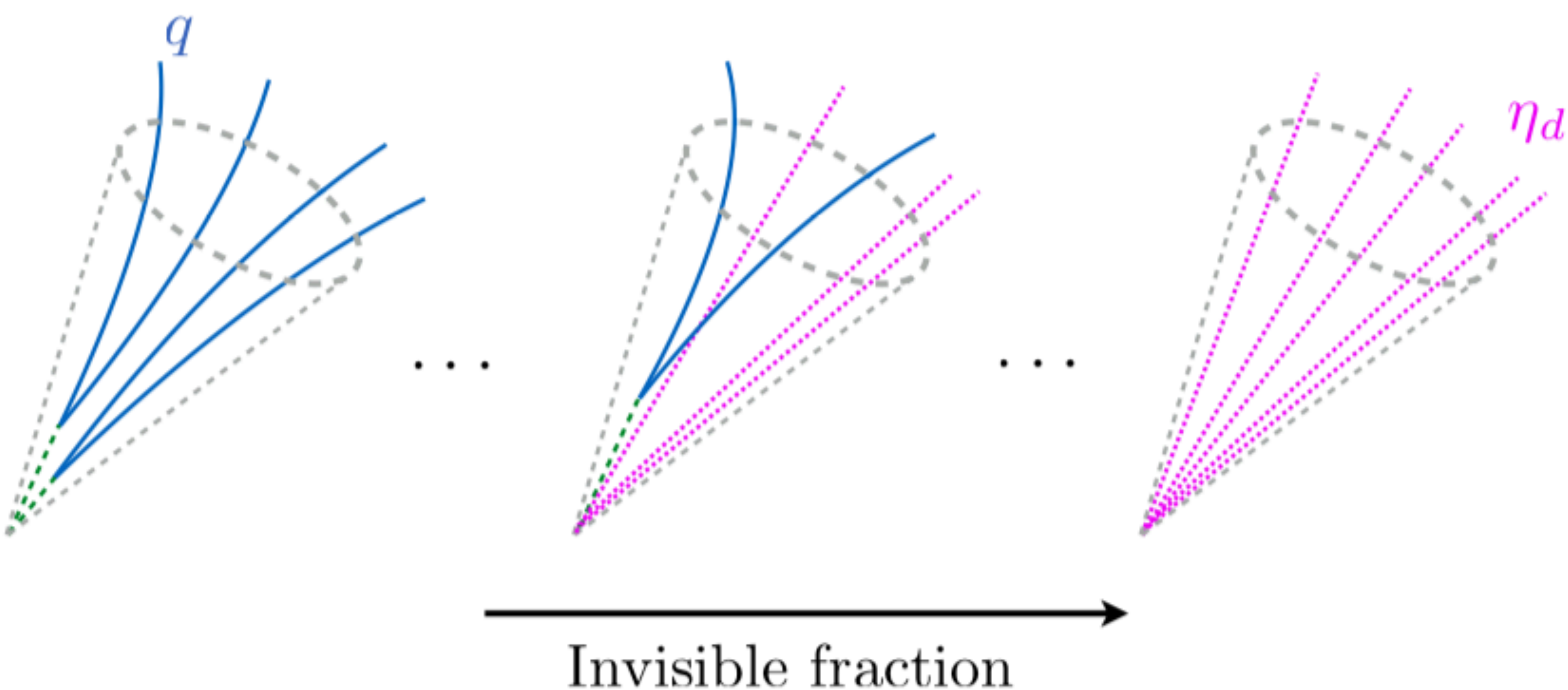
- Dark Matter is **Dark Baryon with two dark-quarks**

$$(\chi_1\chi_2, \chi_1^\dagger\chi_2^\dagger)$$

- Dark mesons are
  - Stable mesons $(\chi_1^\dagger\chi_2, \chi_1\chi_2^\dagger)$, charged under $U(1)_{1-2}$
  - Unstable mesons $(\chi_1^\dagger\chi_1, \chi_2^\dagger\chi_2)$, neutral under $U(1)_{1-2}$

Dark Matter with SU(2)

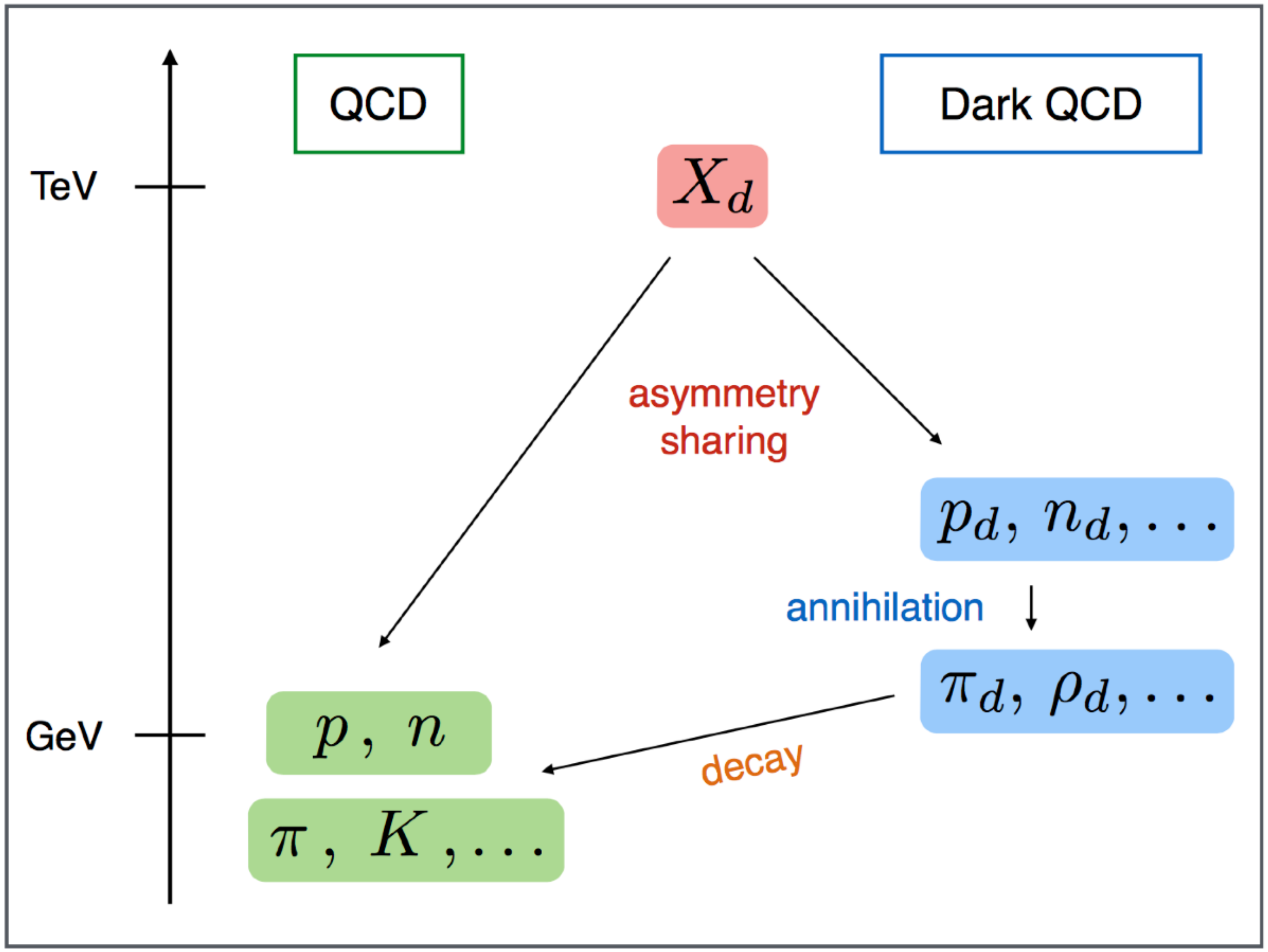
Timothy Cohen et.al 2015



$$r_{\text{inv}} \equiv \left\langle \frac{\#\text{ of stable hadrons}}{\#\text{ of hadrons}} \right\rangle$$

Dark Matter with SU(3)

- Hidden Valley type extension   Andreas Weiler et.al. 2015

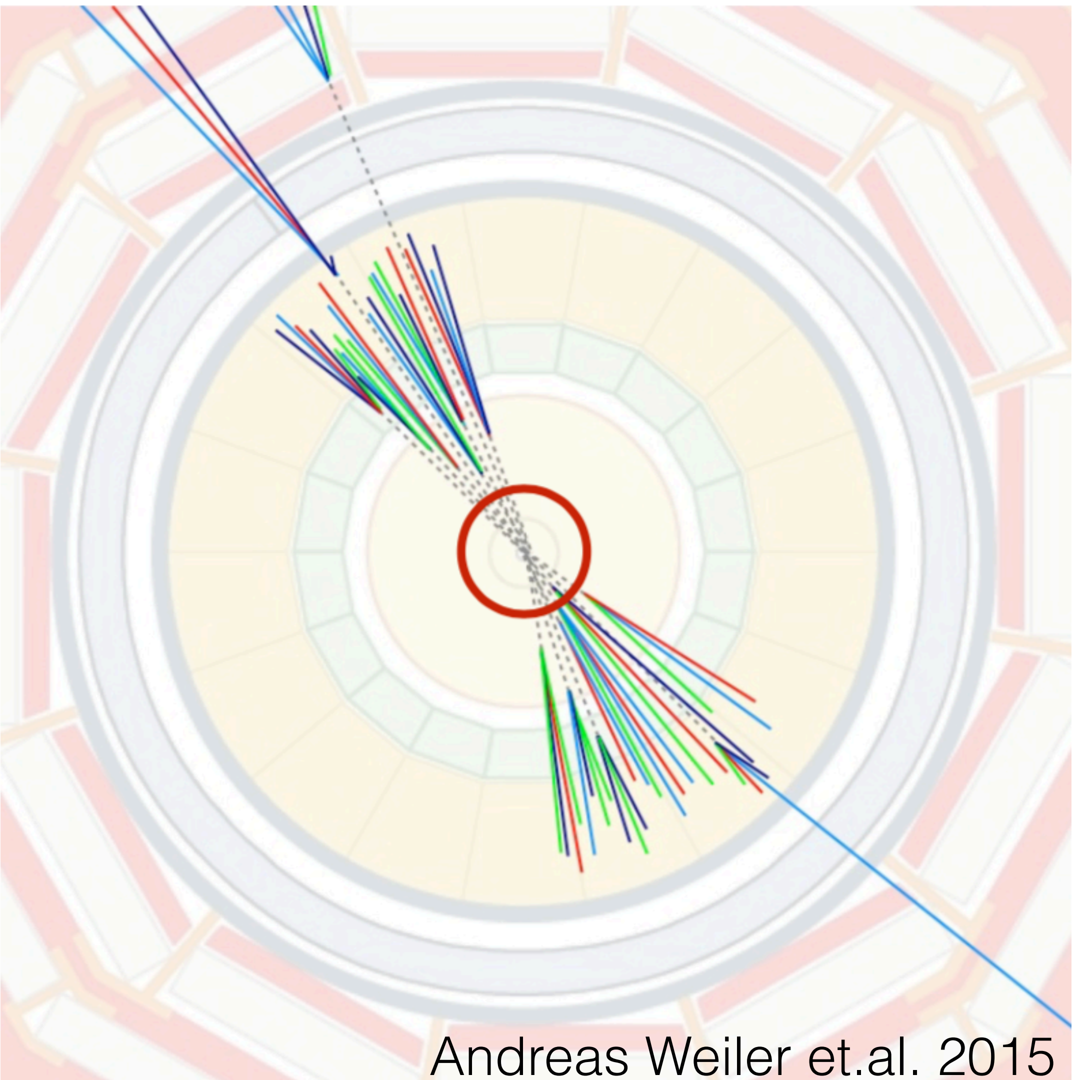


Field	$SU(3)\times SU(2)\times U(1)$	$SU(3)_{\mathrm{dark}}$	Mass	Spin
Q_d	$(1,1,0)$	(3)	m_d $\mathcal{O}(\mathrm{GeV})$	Dirac Fermion
X_d	$(3,1,\frac{1}{3})$	(3)	M_{X_d} $\mathcal{O}(\mathrm{TeV})$	Complex Scalar

- Dark Matter is **Dark Baryon with three dark-quarks**
- Dark mesons can be easily produced

Dark Matter with SU(3)

Andreas Weiler et.al. 2015

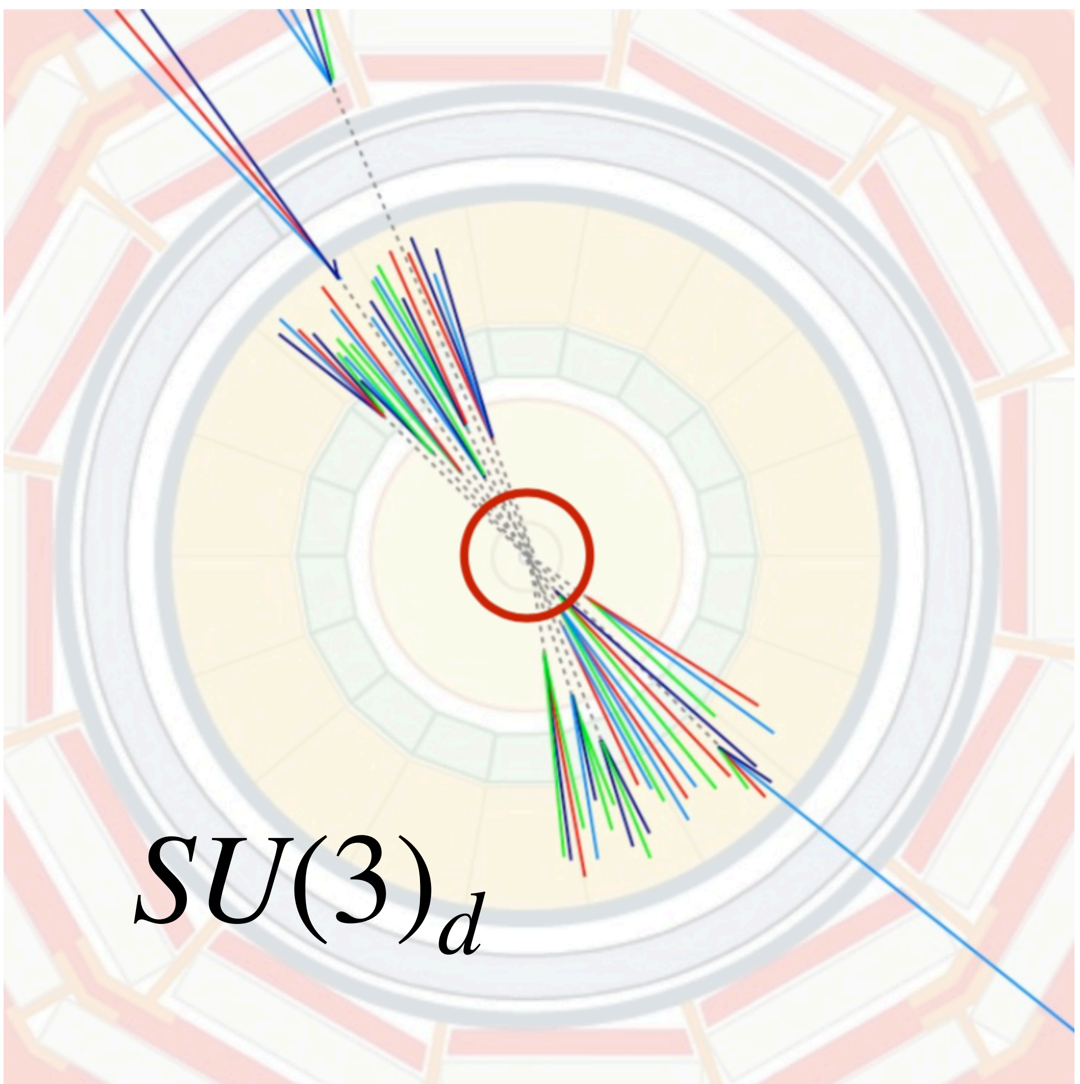


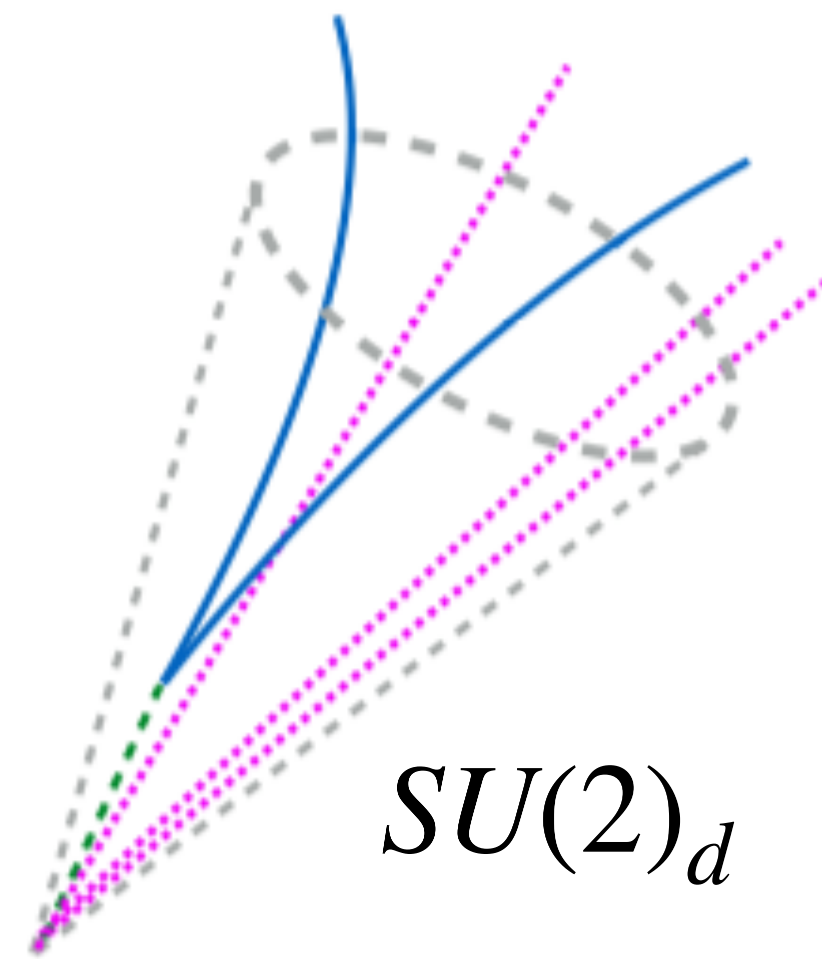
- Dark mesons can be easily produced and they will have a **finite life-time : Displaced Vertex**

$$\Gamma(\pi_d \to \bar{d}d) = \frac{\kappa^4 N_c f_{\pi_d}^2 m_{\text{down}}^2}{32\pi M_{X_d}^4} m_{\pi_d}$$

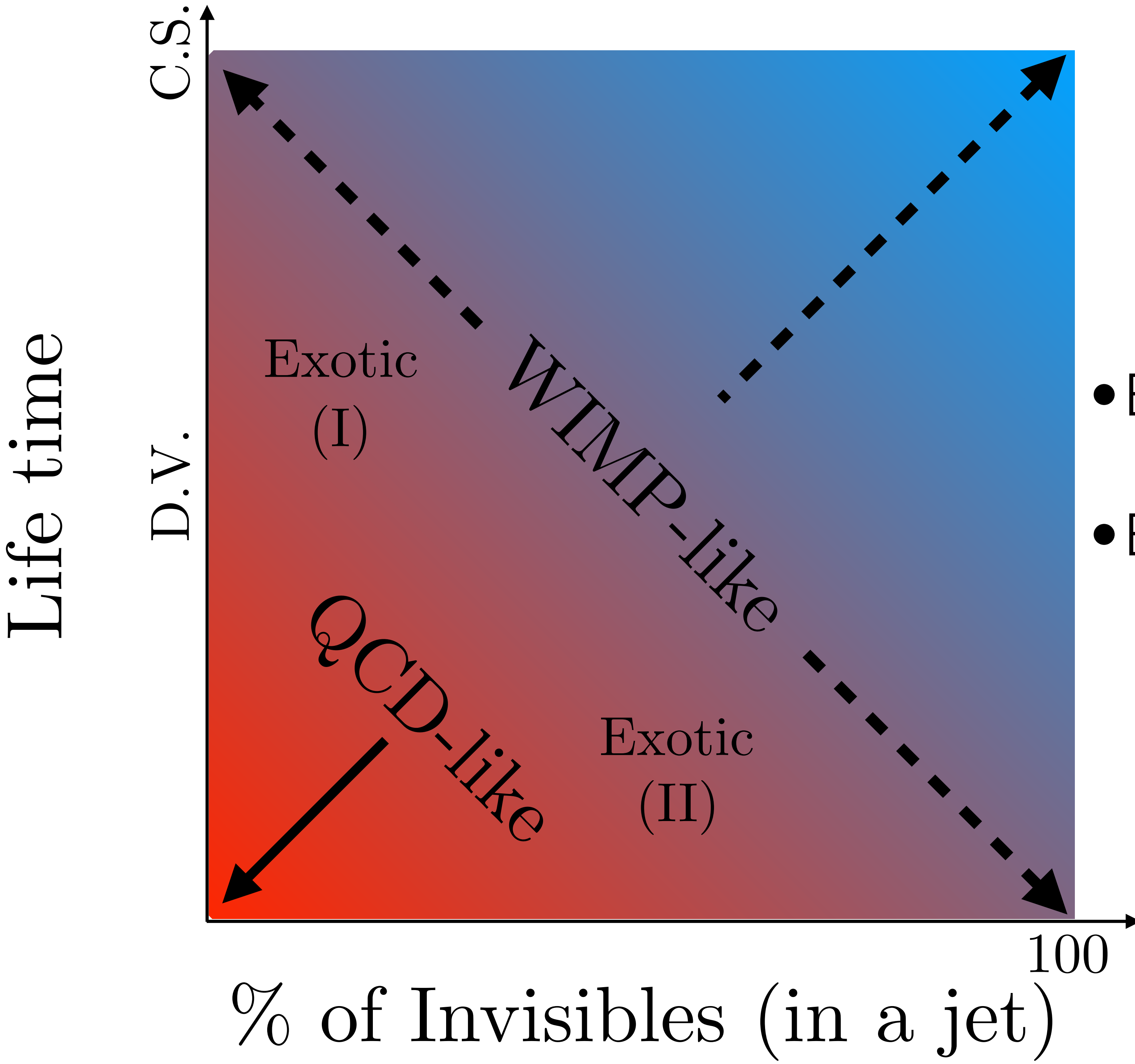
$$c\tau_0 = \frac{c\hbar}{\Gamma} \approx 80\,\text{mm} \times \frac{1}{\kappa^4} \times \left(\frac{2\text{ GeV}}{f_{\pi_d}}\right)^2 \left(\frac{100\text{ MeV}}{m_{\text{down}}}\right)^2 \left(\frac{2\text{ GeV}}{m_{\pi_d}}\right) \left(\frac{M_{X_d}}{1\text{ TeV}}\right)^4$$

Conventional-"exotic" searches for SU(N) charged DM?





- Exotic (I) : Emerging jet
- Exotic (II) : Semi-invisible jet



- Exotic (I) : Emerging jet
- Exotic (II) : Semin-invisible jet

Minimal setup

- Consider a minimal set up for Hadron Collider
  - SM Strong Sector - Mediator - Hidden Sector

  to produce and detect signatures at hadron colliders

$$\mathcal{L}_d = \bar{q}'(i\not{D} - m_{q'})q' - \frac{1}{4}G'^{\mu\nu}G'_{\mu\nu} \quad : SU(N_d)$$

- A mediator which couples SM part and Dark part

$$\mathcal{L}_{med} = (D^\mu X)^\dagger(D_\mu X) - M_X^2 X^\dagger X + \kappa X\,\bar{q}'q + h.c.$$

OR

$$\mathcal{L}_{med} = -\frac{1}{4}Z'^{\mu\nu}Z'_{\mu\nu} - \frac{1}{2}M_{Z'}^2 Z'^{\mu}Z'_{\mu} + Z'_{\mu}(\bar{q}'\gamma^\mu q' + \bar{q}\gamma^\mu q)$$

- Dark pion: spin-0 pseudo-scalar. Due to chiral flipping suppression, dark pion tends to decay a heavy SM quark pair.

$$\Gamma(\pi_d \to q\bar{q}) = \frac{3\kappa^4 f_{\pi_d}^2 m_q^2}{32\pi M_X^4} m_{\pi_d}$$

or if there is U(1), dark pion would like to decay into two dark photons promptly.

- Dark rho meson: spin-1 vector meson

- Dark baryon: In SU(3), population ratio of baryons over mesons is O(10) %.

- Dark glue ball: In the case of $m_{q_d} \gg \Lambda_d$, the lightest dark hadron would be a "glue-ball"

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

A, C : Large Lambda QCD

B, D : Small Lambda QCD

A, B : meson decays into HF

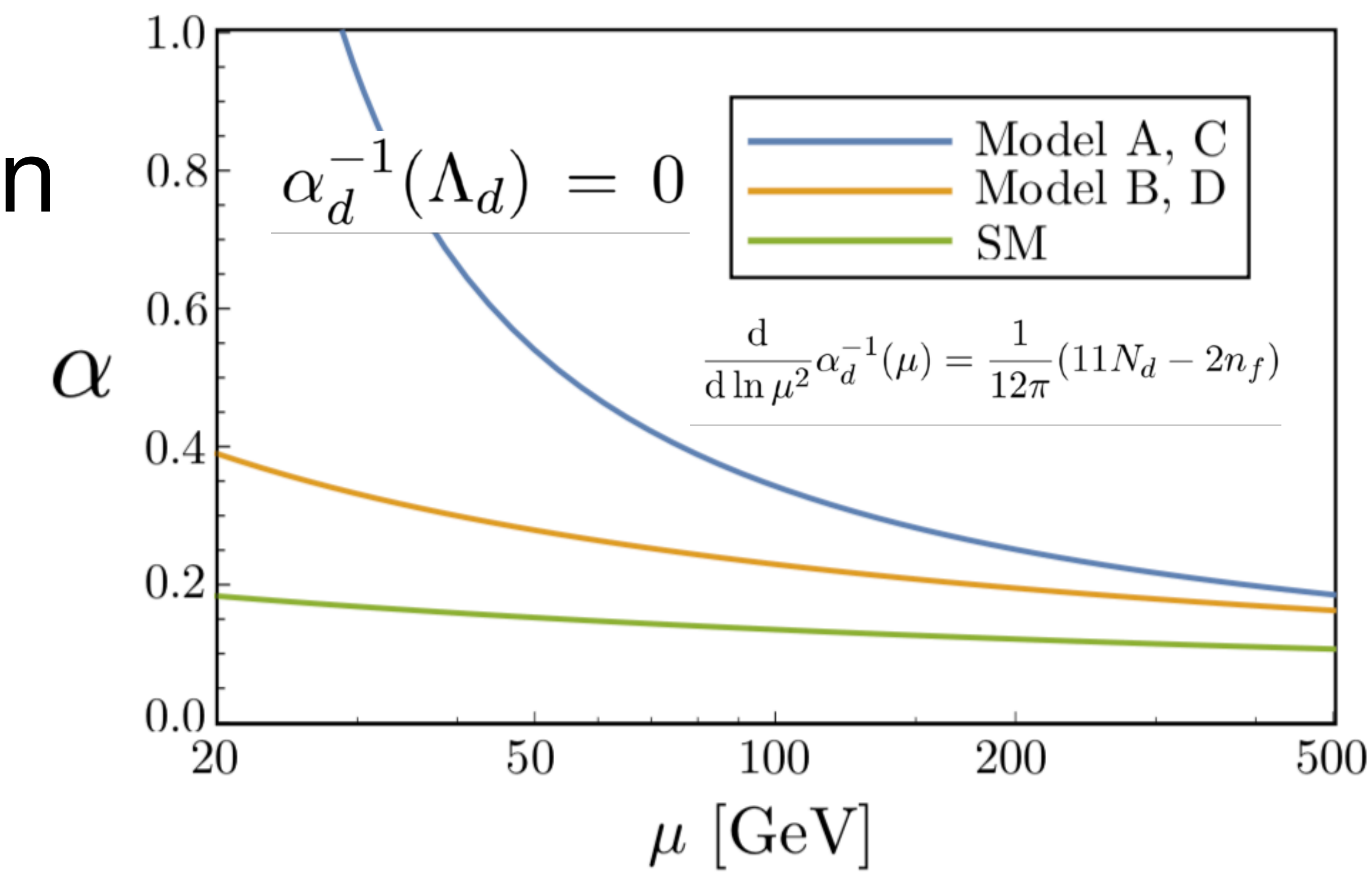
C, D : additional meson decay

Jet evolution depends on

1. Color factor
2. Coupling

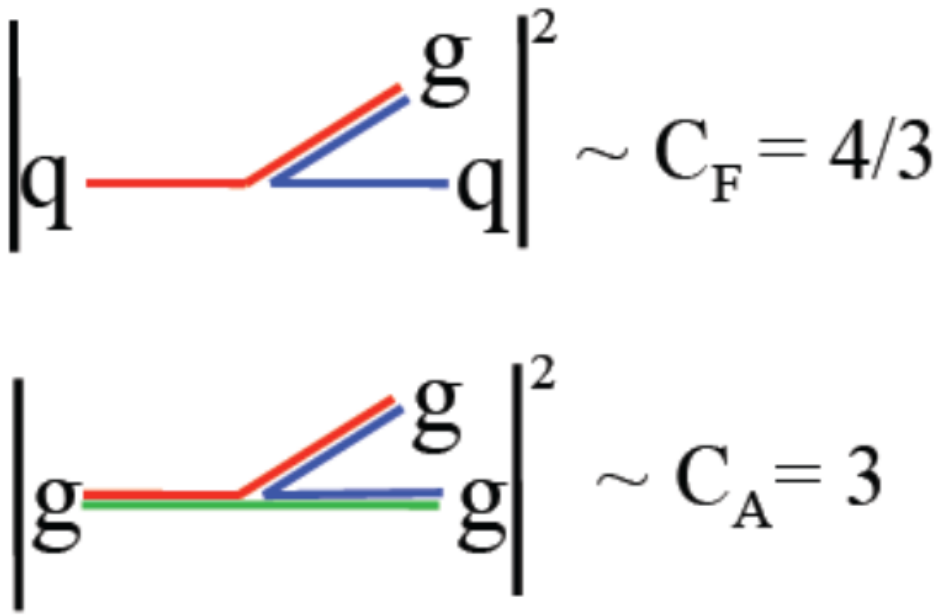
Jet components depends on

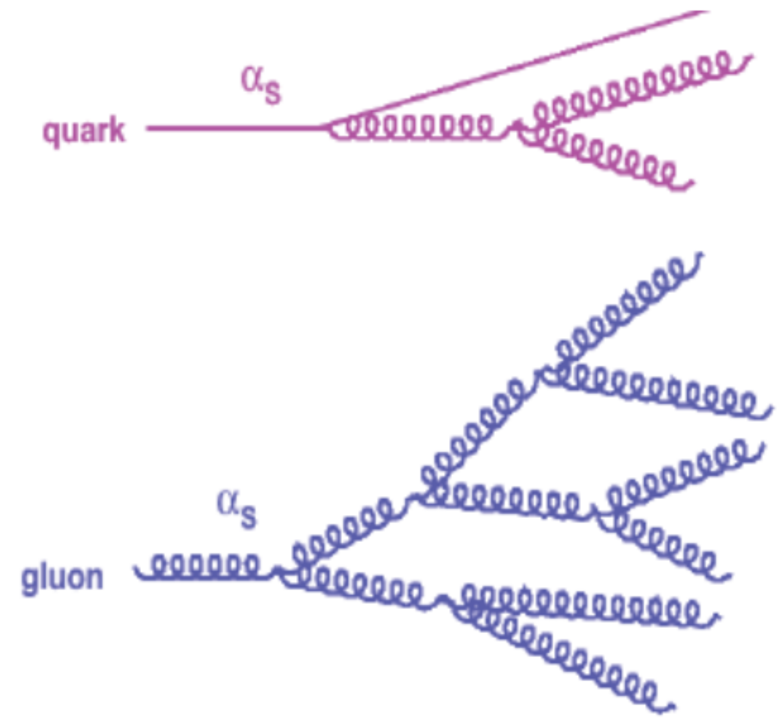
- decay mode.



Color factor

- What is the most significant difference between quark and gluon ?





quark jets

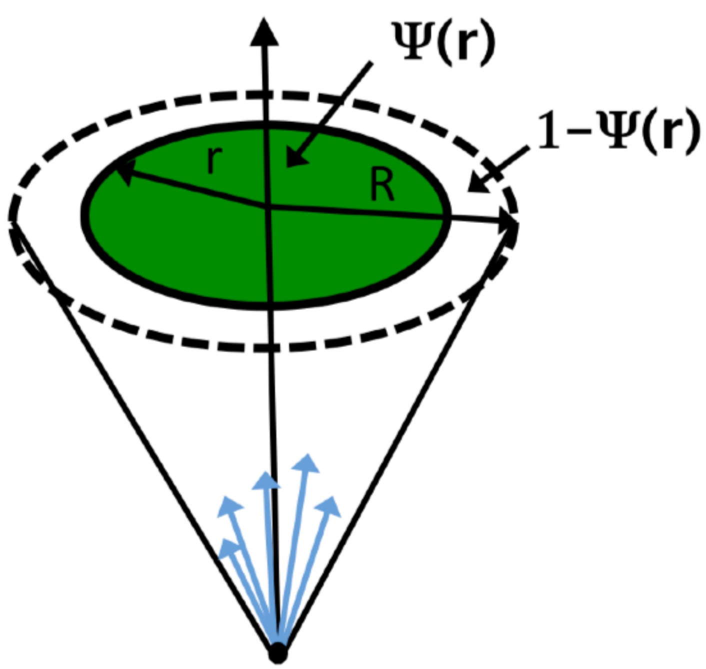
gluon jets

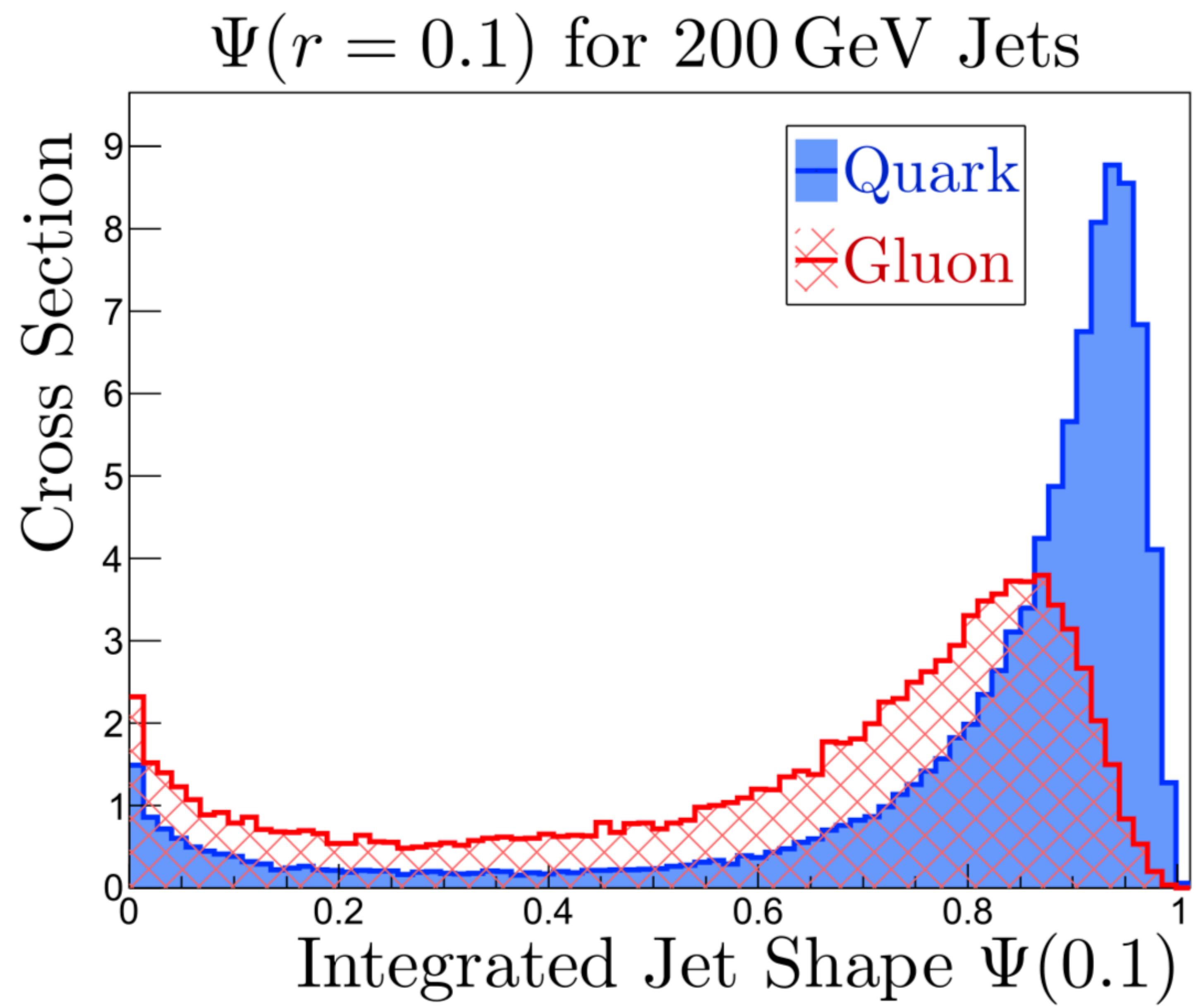
$$F_{q\to g}(z,\theta) = \frac{4}{N_c}\frac{\alpha_s}{\pi}\frac{1+(1-z)^2}{z}\frac{1}{\sin^2\theta}$$

$$F_{g\to q}(z,\theta) = \frac{4}{N_c^2-1}\frac{\alpha_s}{\pi}\frac{z^2+(1-z)^2}{\sin^2\theta}$$

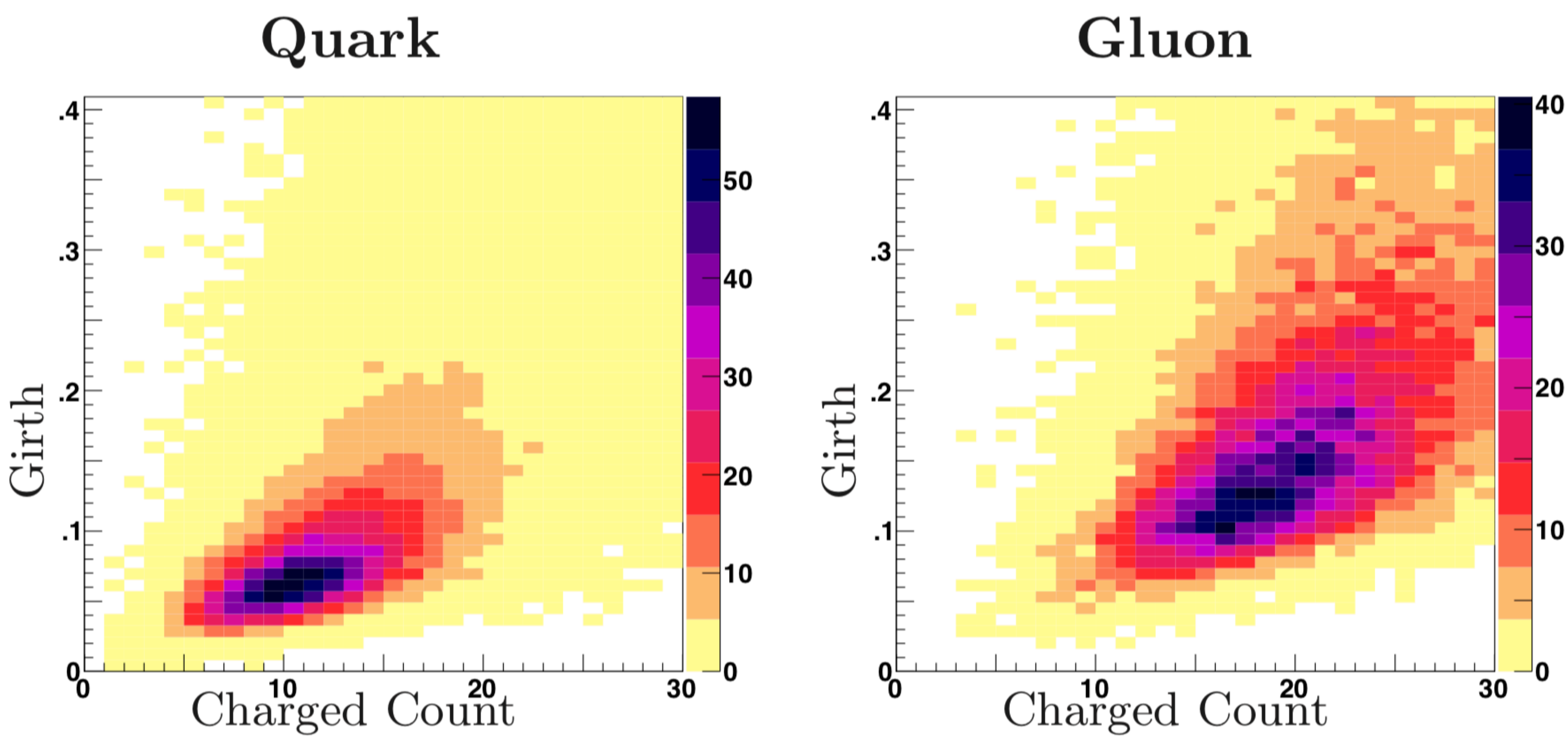
pencil (q) v.s. wide (g)

$$\Psi(r) = \frac{1}{N}\sum_{J}\sum_{i\in J}\frac{p_T(0<r_i<r)}{p_{T,J}}$$





Thin & Simple (q) v.s. Fat & Busy (g)

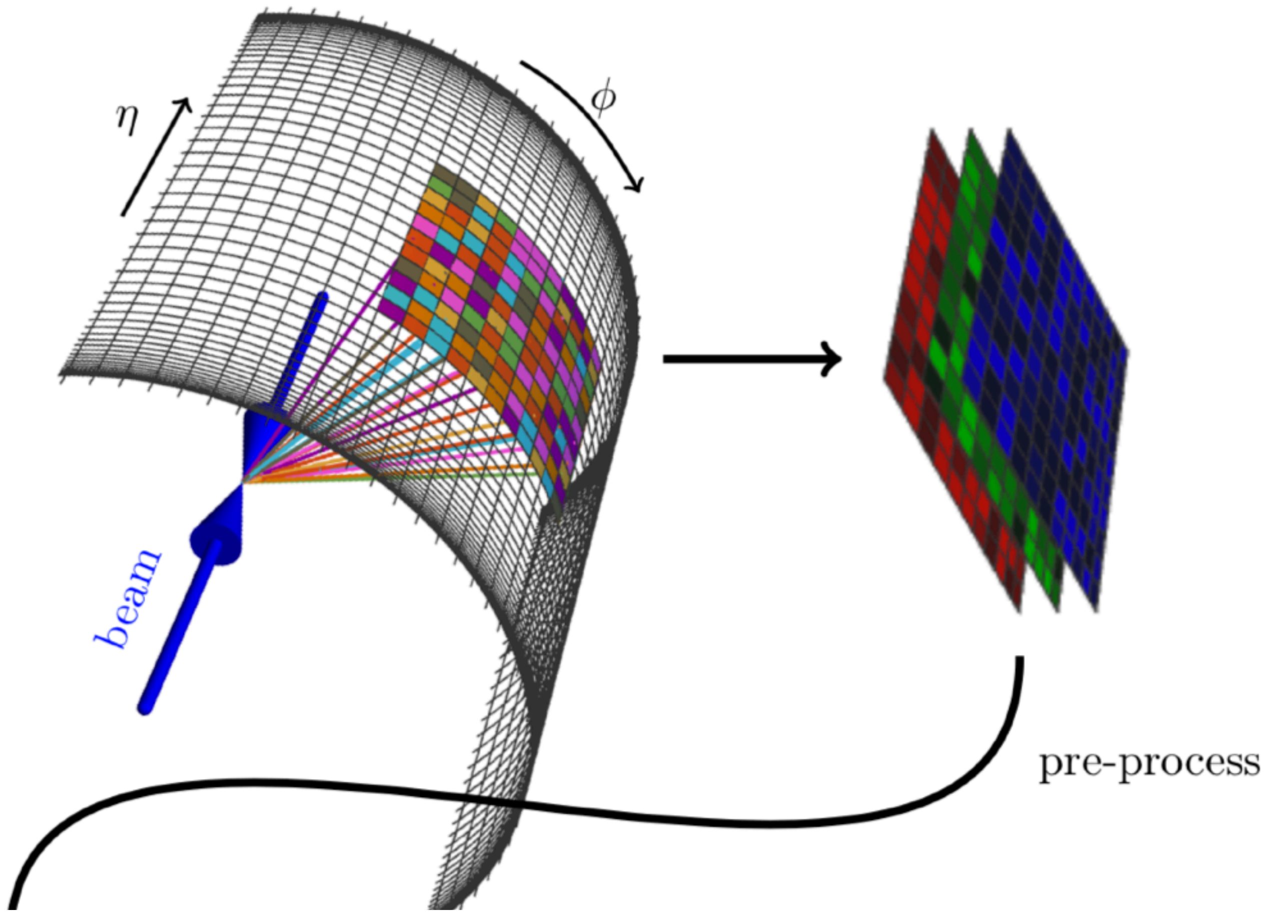


Matthew D. Schwartz et. al 2013

$$\text{girth} = \sum_{i \in J} \frac{p_{T_i}}{P_{T_J}} |r_i|$$

Jet shape can be interpreted by image analysis

by Schwartz et.al. 2017



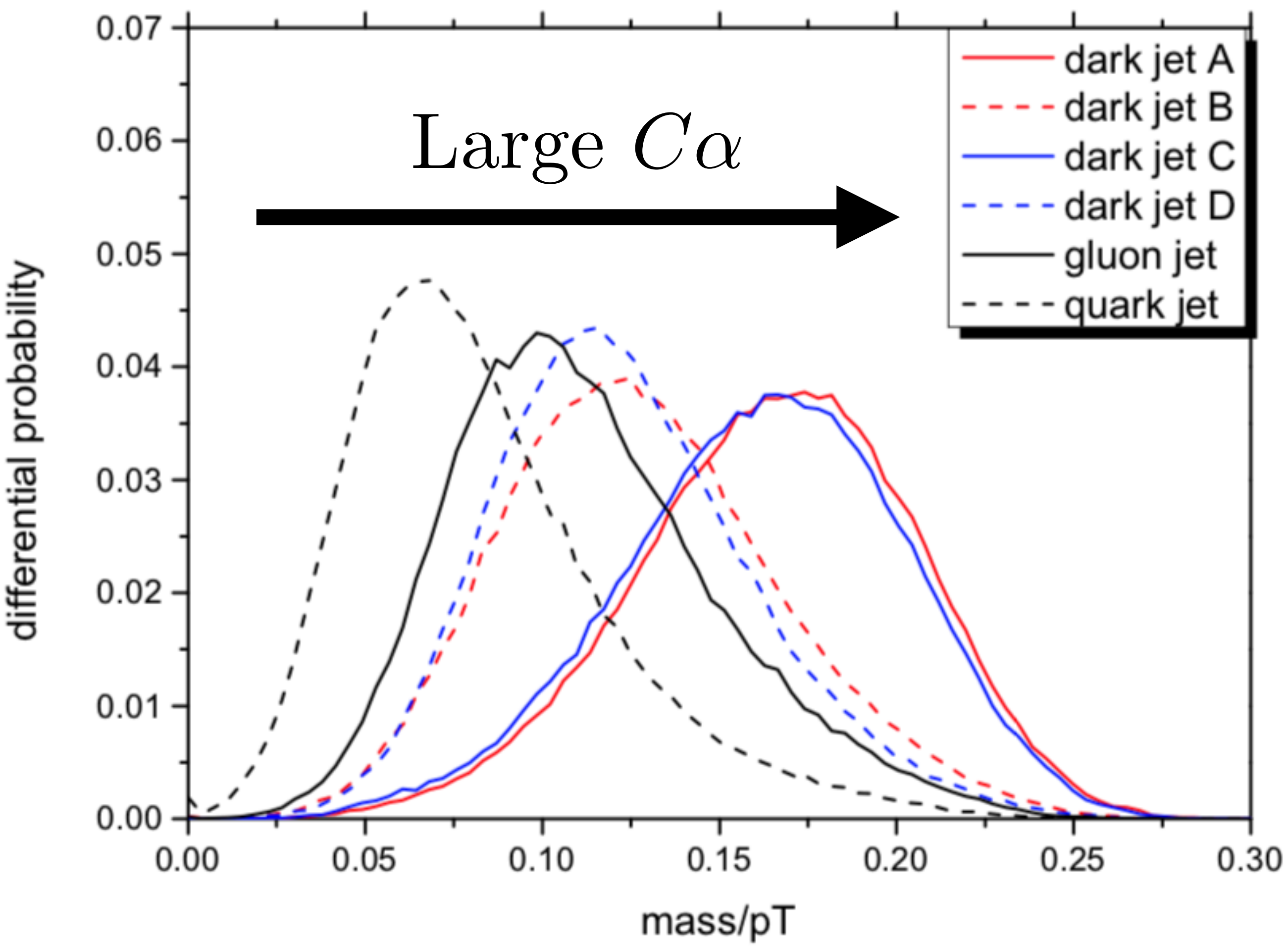
$\texttt{red}$ = transverse momenta of charged particles

$\texttt{green}$ = the transverse momenta of neutral particles

$\texttt{blue}$ = charged particle multiplicity

What's the case of jet evolved from Dark QCD ?

eg: jet mass



Large $C\alpha$ pushes a distribution to the right

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma}{\mathrm{d}(p^2/Q^2)} \approx \frac{C\alpha}{\pi}\frac{Q^2}{p^2}\ln\frac{Q^2}{p^2}\exp\left\{-\frac{C\alpha}{2\pi}\left(\ln\frac{Q^2}{p^2}\right)^2\right\}$$

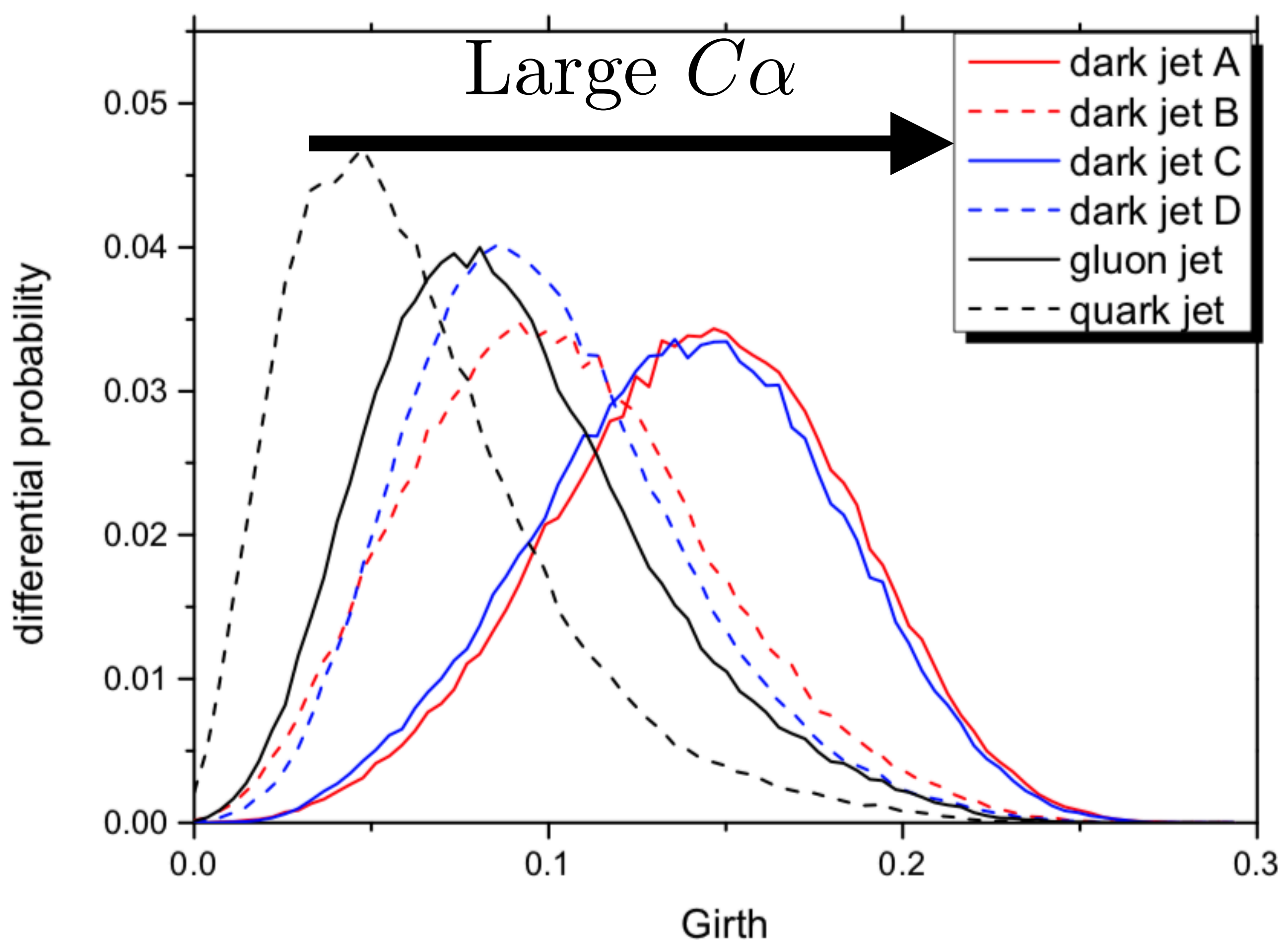
Gluon: C= 3
Quark: C= 4/3

: Coupling strengths of A and C are larger than the case of B and D

eg: Girth

- A radial "spread", called girth is a good discriminator

$$\text{girth} = \sum_{i \in J} \frac{p_{T_i}}{P_{T_J}} |r_i|$$



eg: Energy correlation

- Correlations among constitute particles would be interesting

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

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

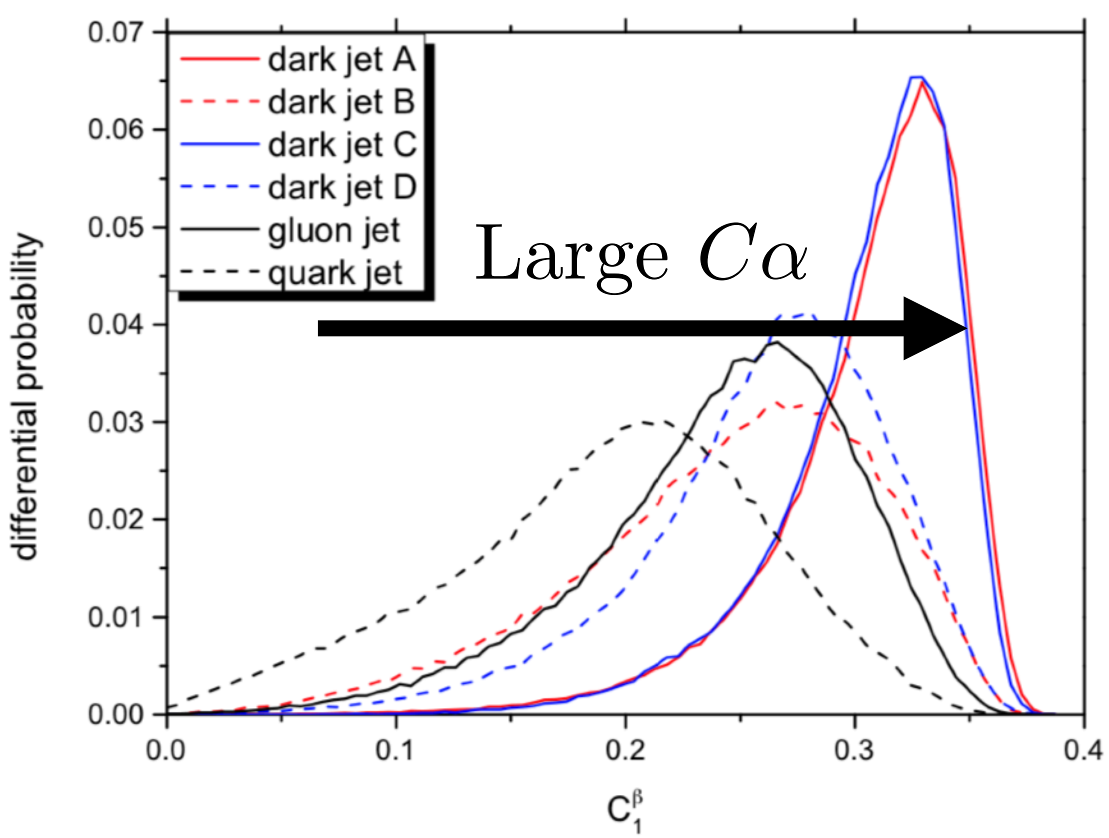
- As the mass of dark mesons $>$ SM QCD Λ, dark mesons contributes large E-correlation for $\beta > 0$

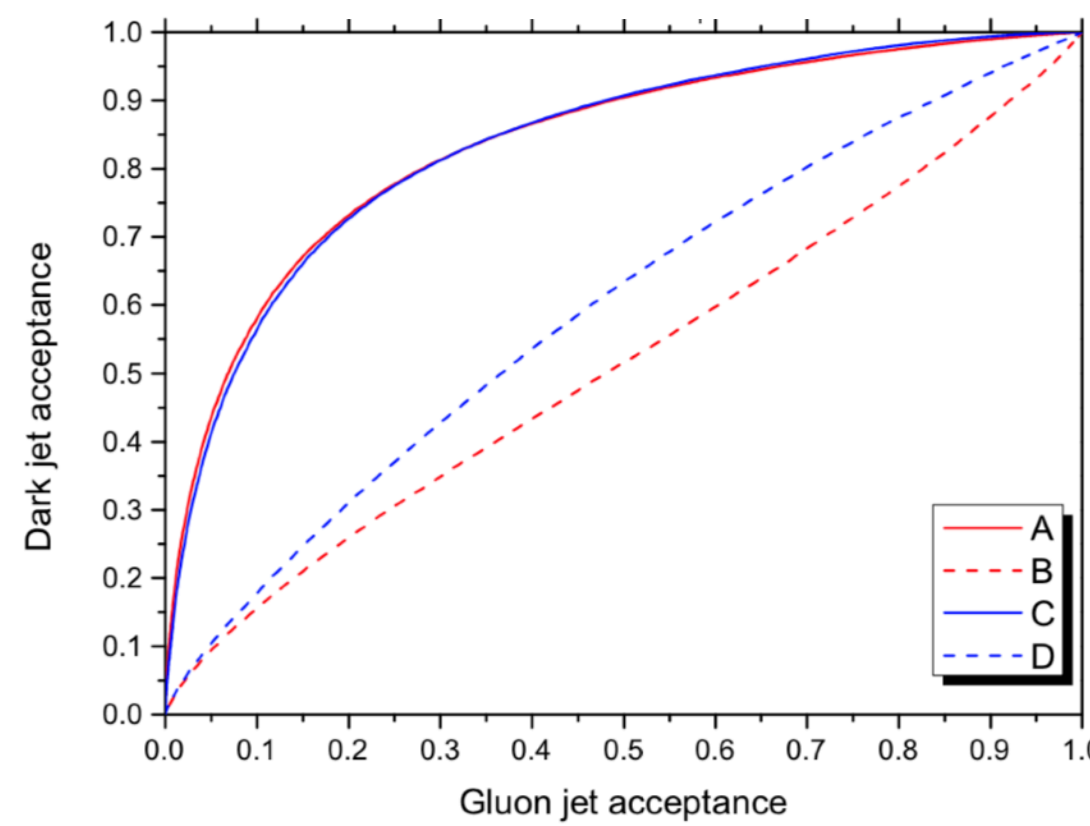
$$z_1 z_2\, \theta^\beta \to \frac{1}{4}(z_1 + z_2)^2 \left(\frac{m_{\pi_d}}{p_T}\right)^\beta$$

eg: Energy correlation

- Correlations among constitute particles would be interesting

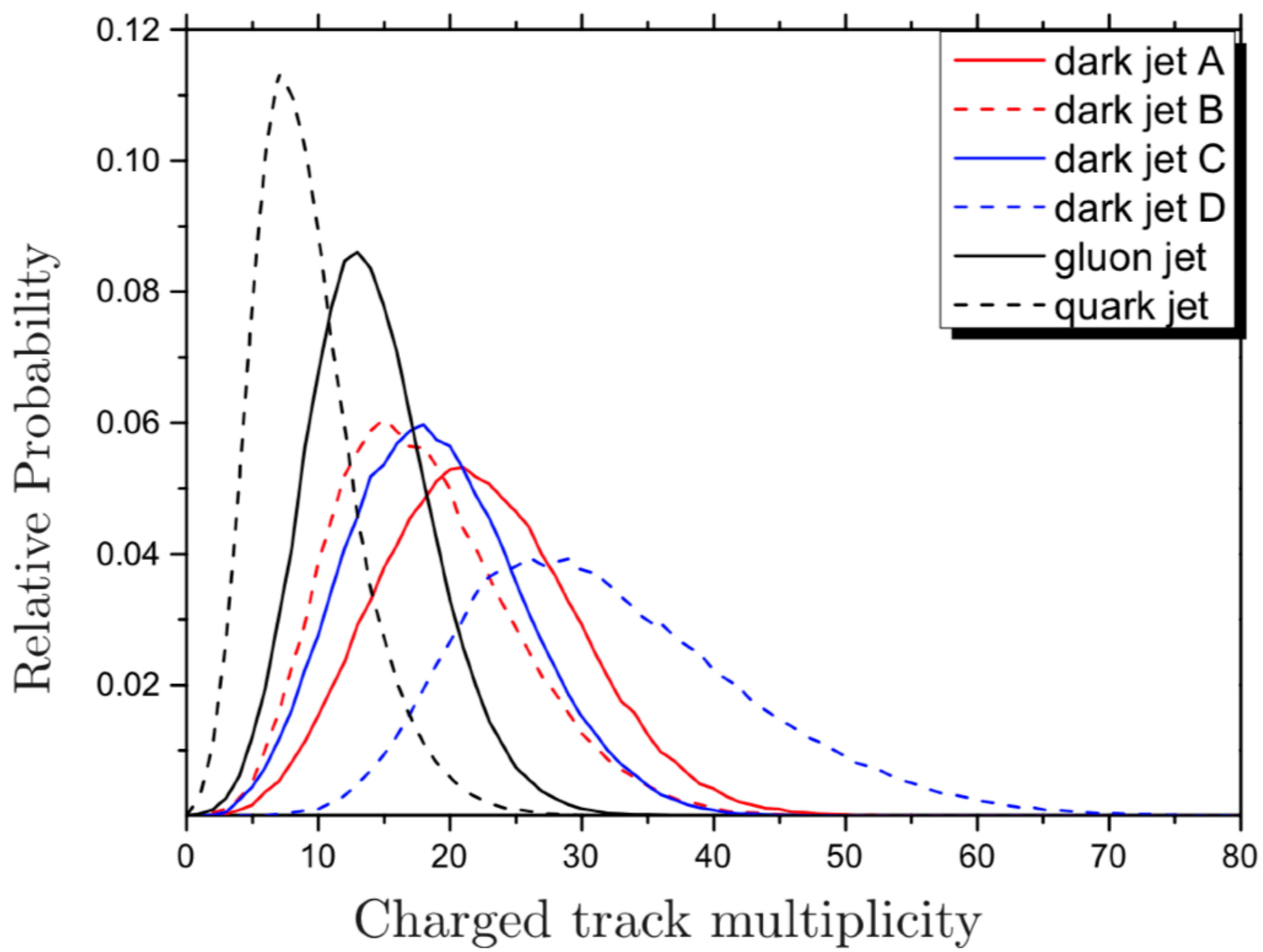
$$C_1^{(\beta)} = \sum_{i<j\in J} z_i z_j (R_{ij})^\beta$$

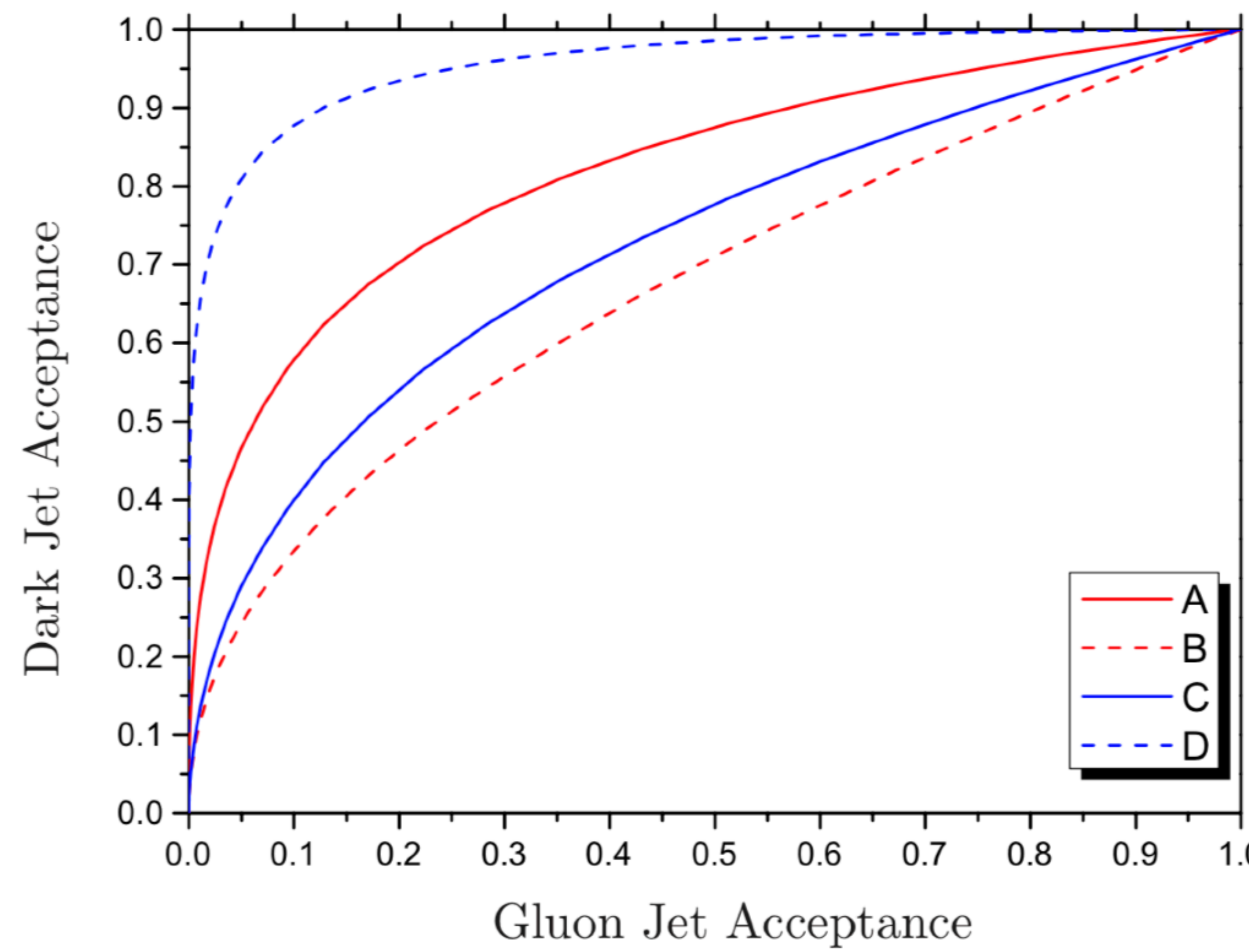




eg: Charged track multiplicity

- Analyses with charged track multiplicity get benefits from the LHC track reconstruction performance.
- IRC-unsafe variables, but cut on pt > 0.5 GeV

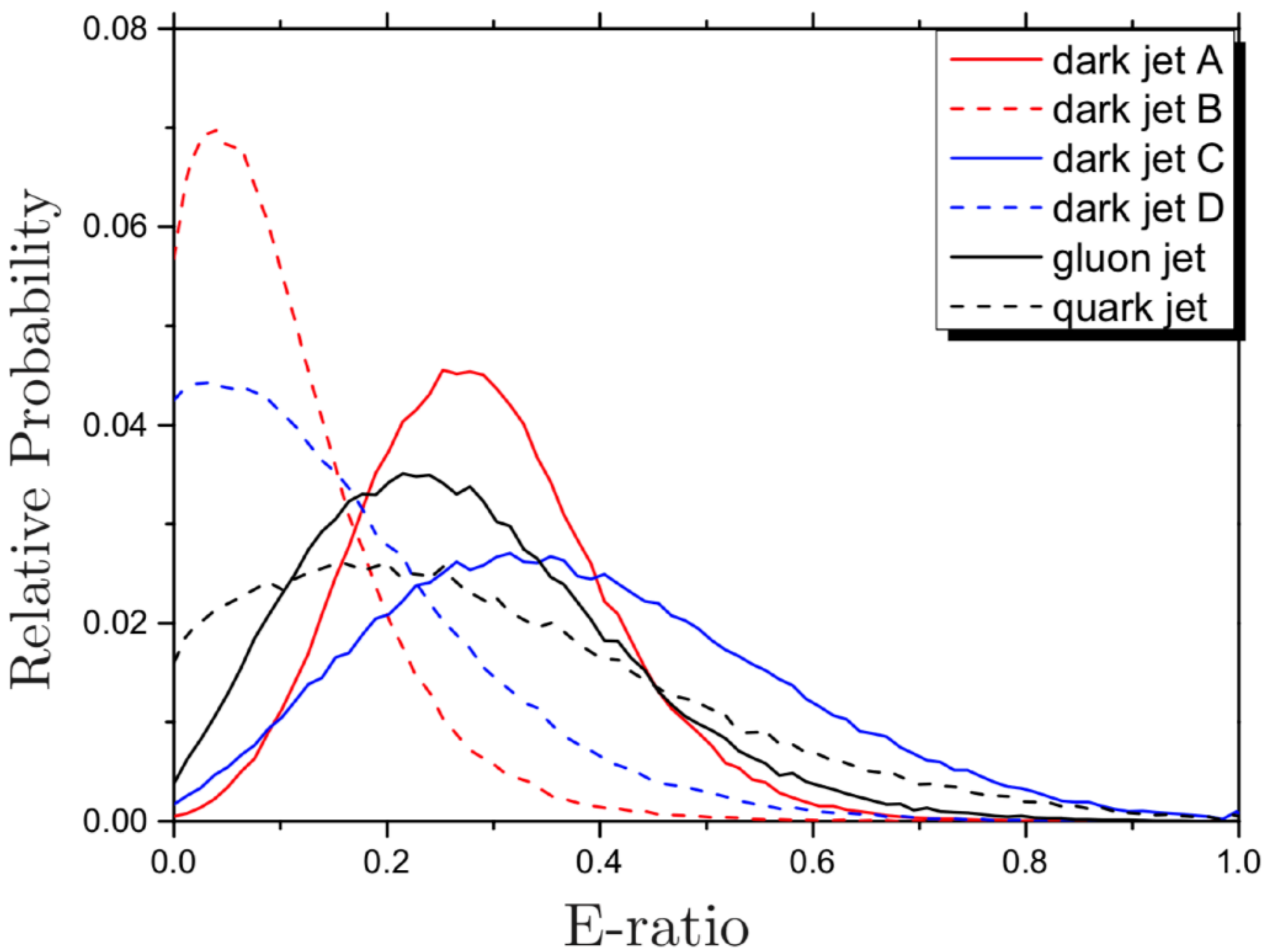


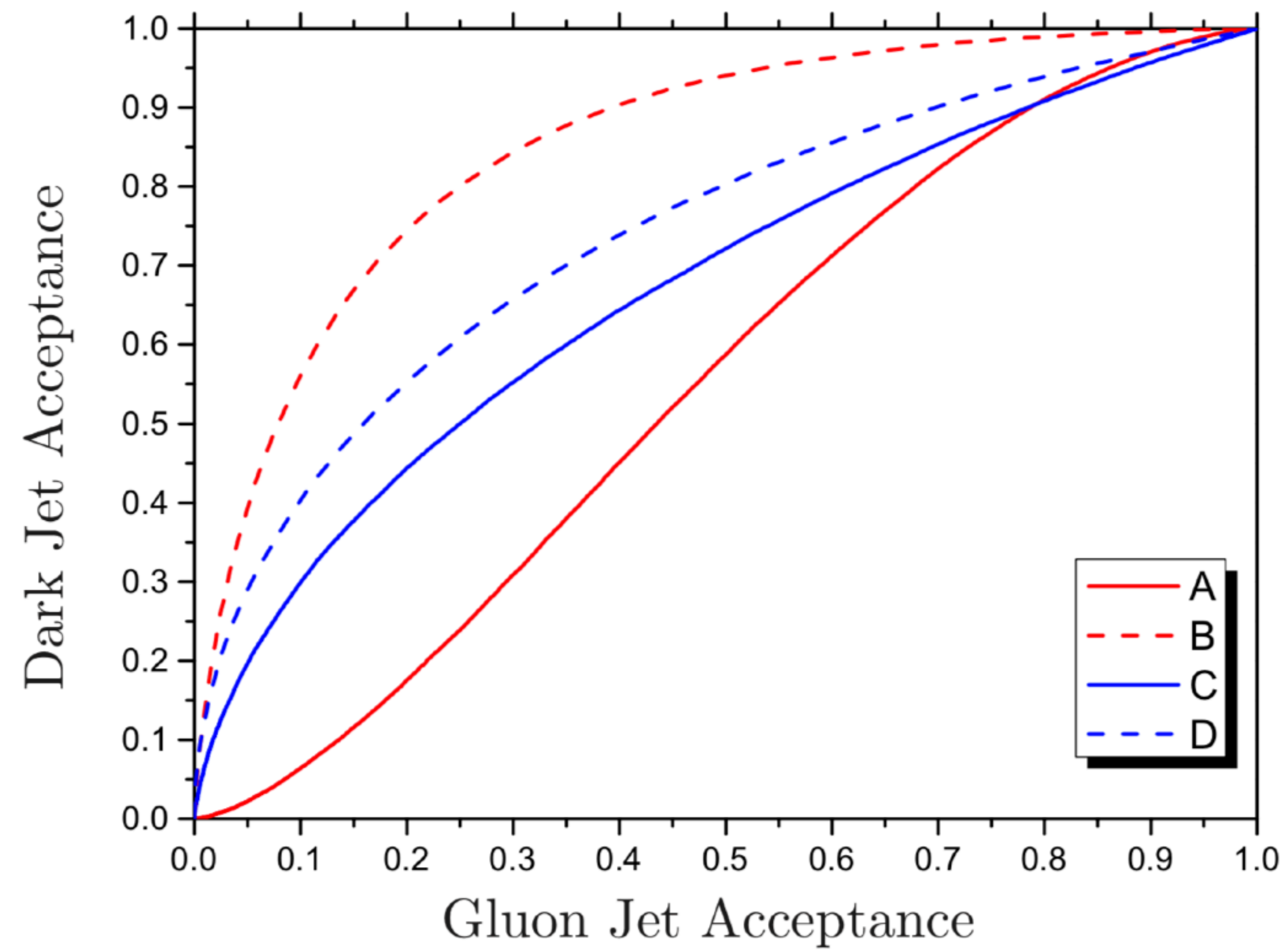


eg: E-ratio

- A variable which depends on the life-time of hadron;

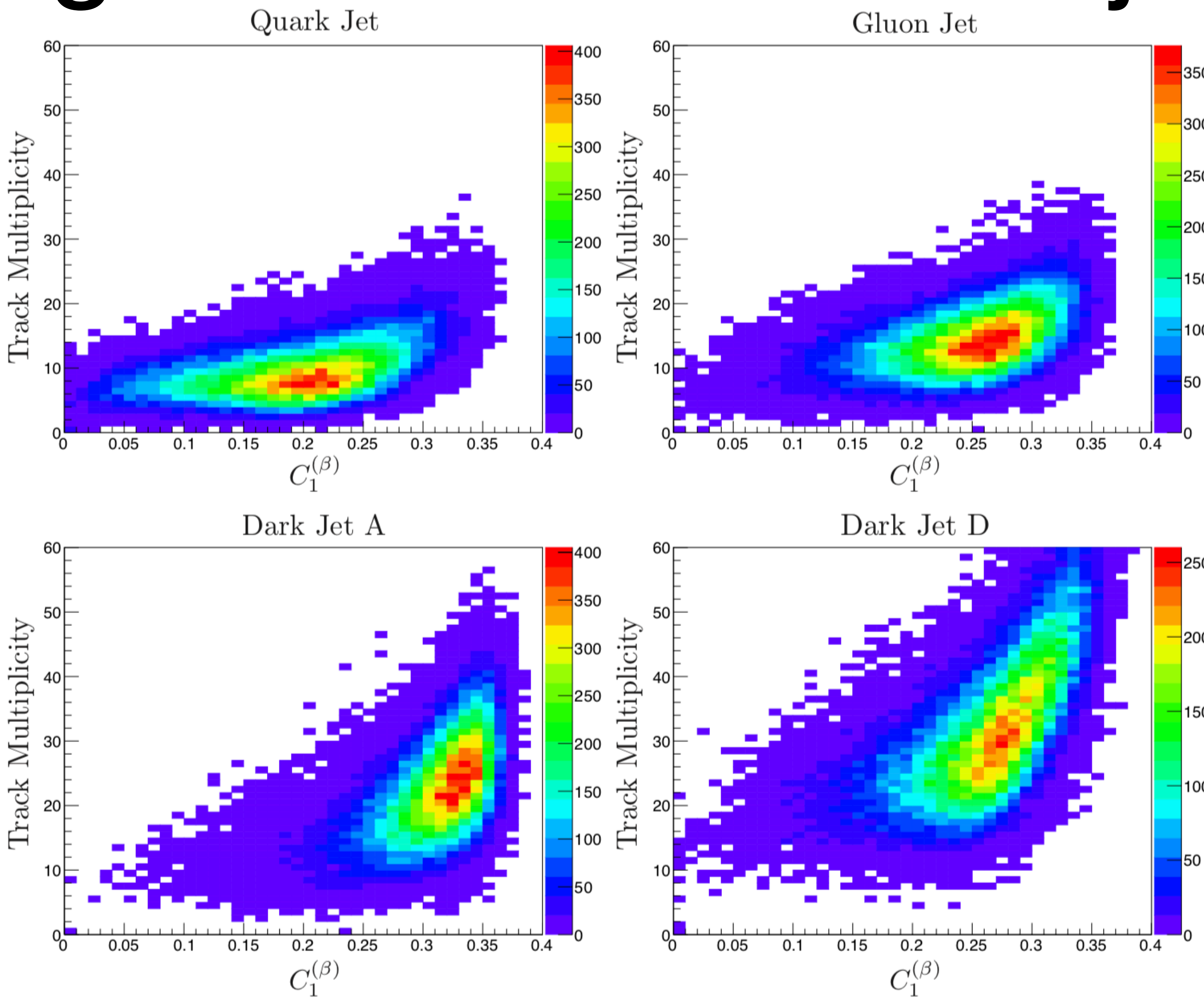
$$\text{E-ratio} = \frac{\text{Energy deposit on ECAL}}{\text{Jet's } p_T}.$$



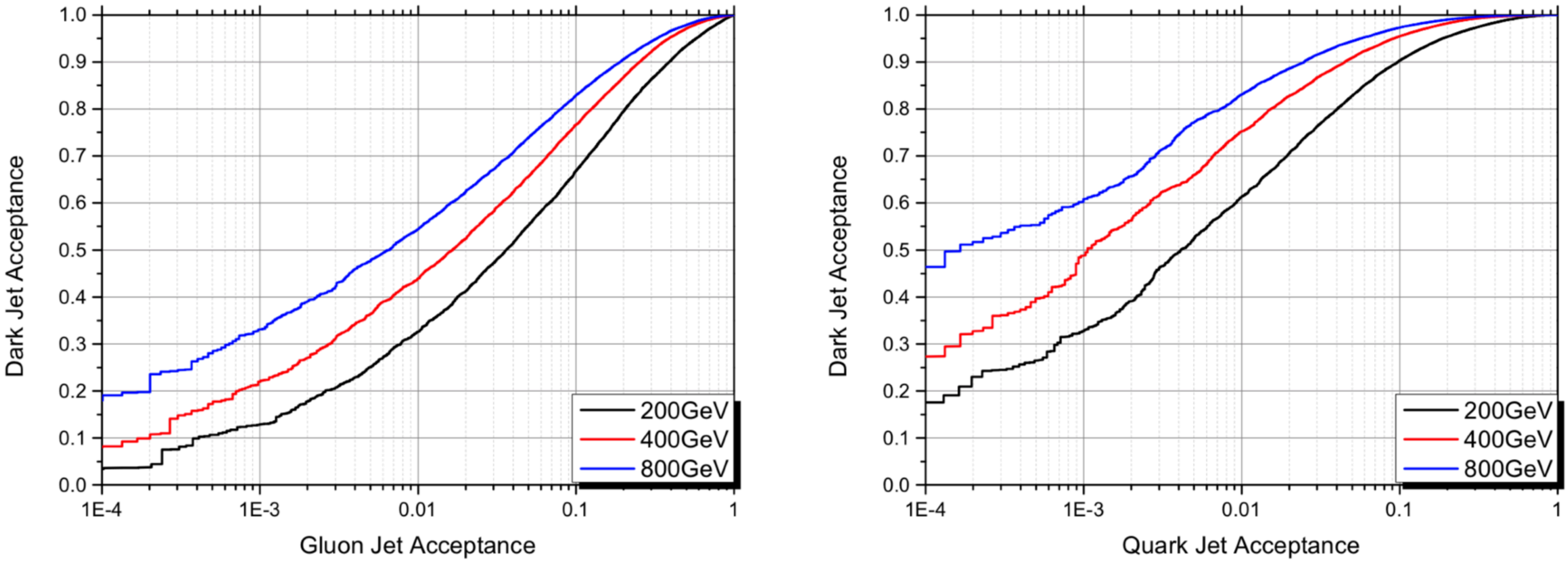


- A model with $\pi_d \to s\bar{s}$, which leads to K-Long.

Different behavior of jet signals from dark QCD jet

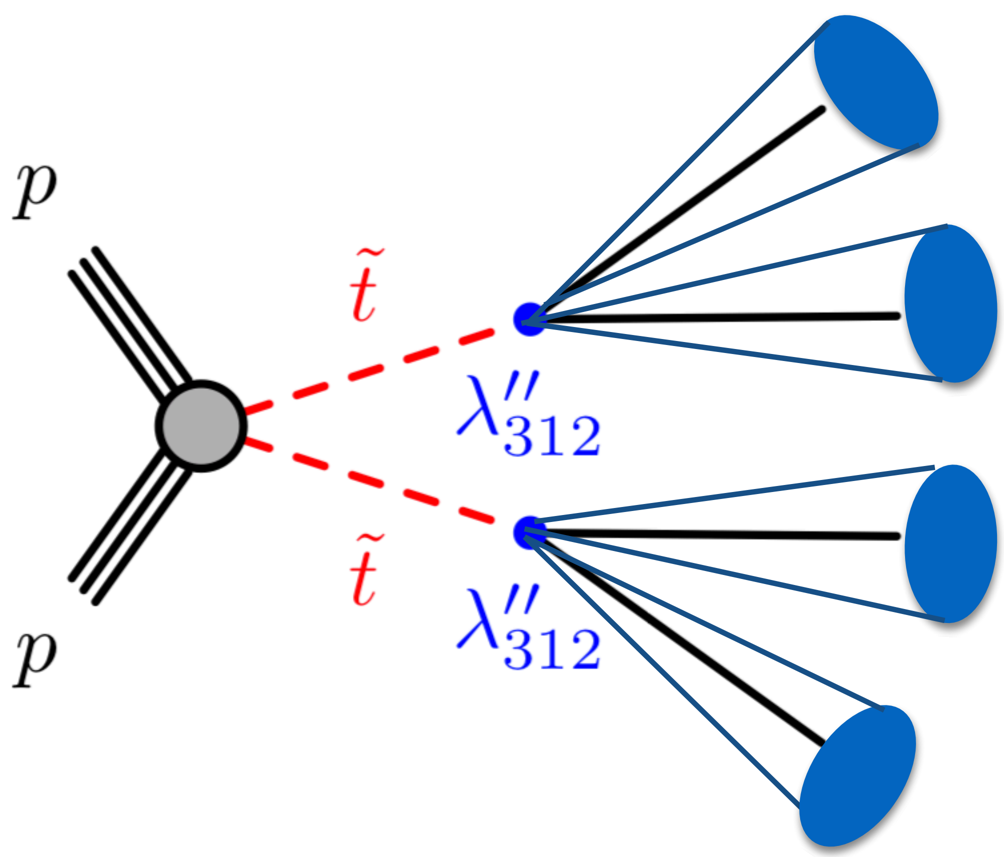


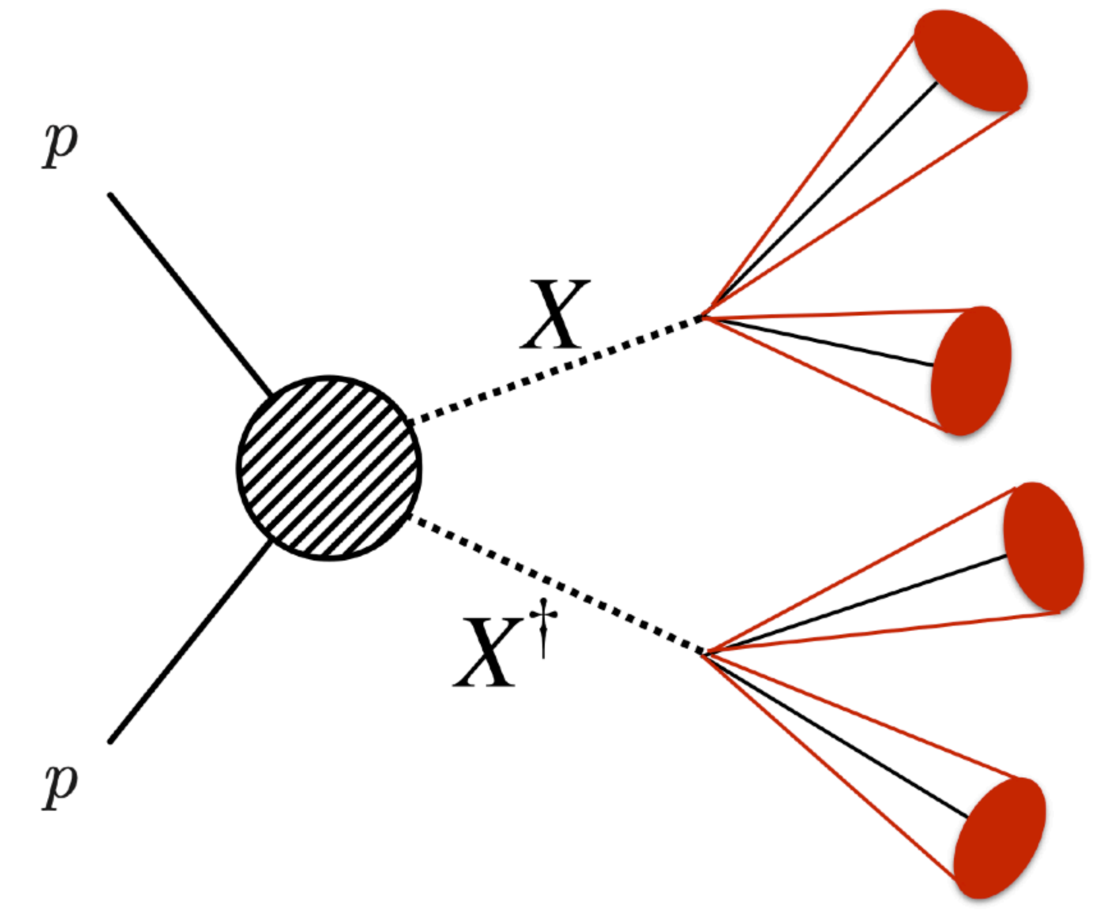
Identify dark jet



- Combining : Jet mass, Energy correlation function, girth, charged track multiplicity, # of subjects, ...
- High PT jet would be better to separate dark jet from SM QCD jets

Comparison between conventional search and jet substructure method





Normal QCD jet

Jet from Dark QCD

Conventional cuts

- 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 $\Delta R_{\mathrm{min}} = \sum_{i=1,2} |\Delta R_i - 1|$, 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:

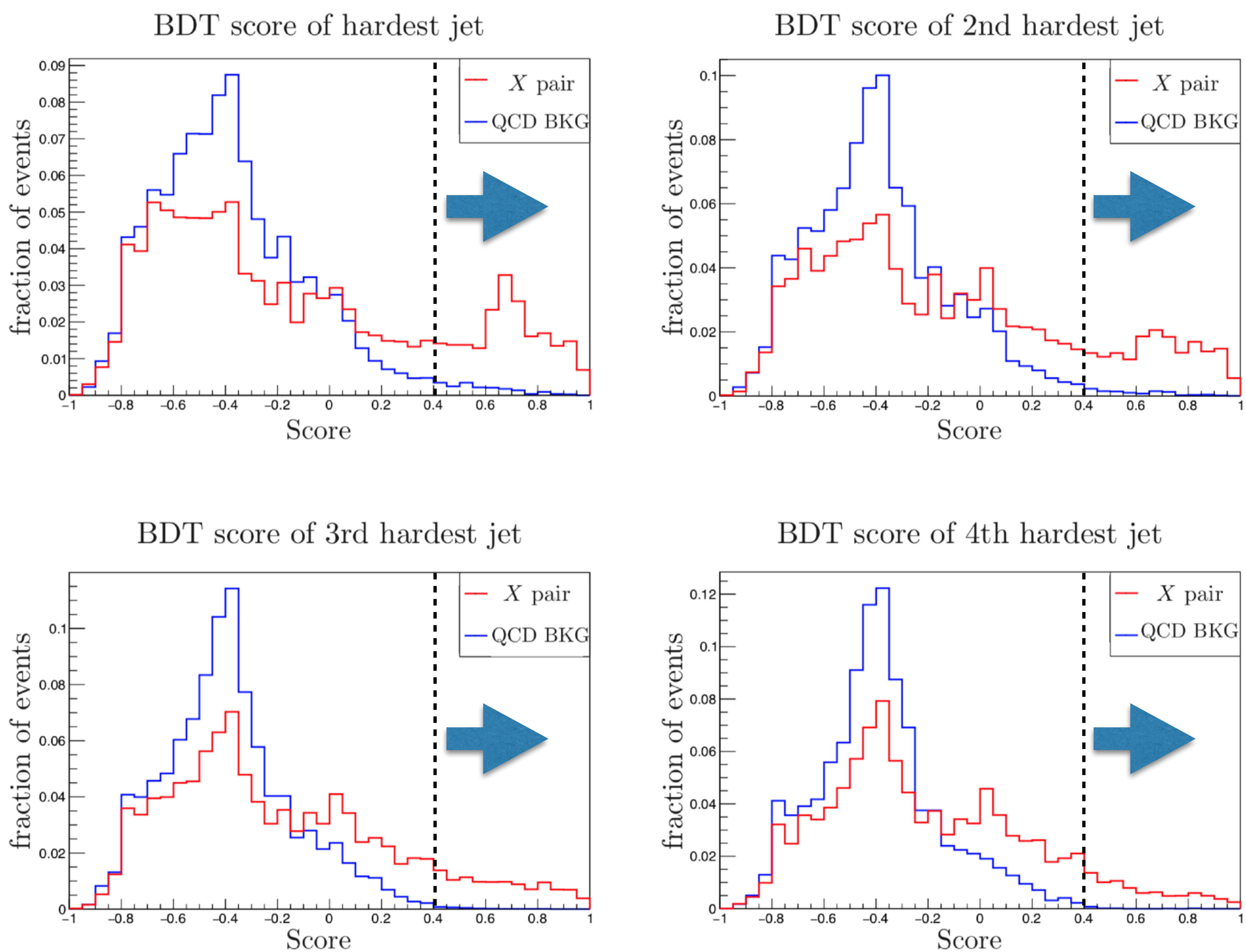
$$\Delta R_{\mathrm{min}} > -0.002 \times (m_{\mathrm{avg}}/\mathrm{GeV} - 225) + 0.72 \qquad \text{if } m_{\mathrm{avg}} < 225\mathrm{GeV}$$
$$\Delta R_{\mathrm{min}} > +0.0013 \times (m_{\mathrm{avg}}/\mathrm{GeV} - 225) + 0.72 \qquad \text{if } m_{\mathrm{avg}} > 225\mathrm{GeV}$$

- 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:

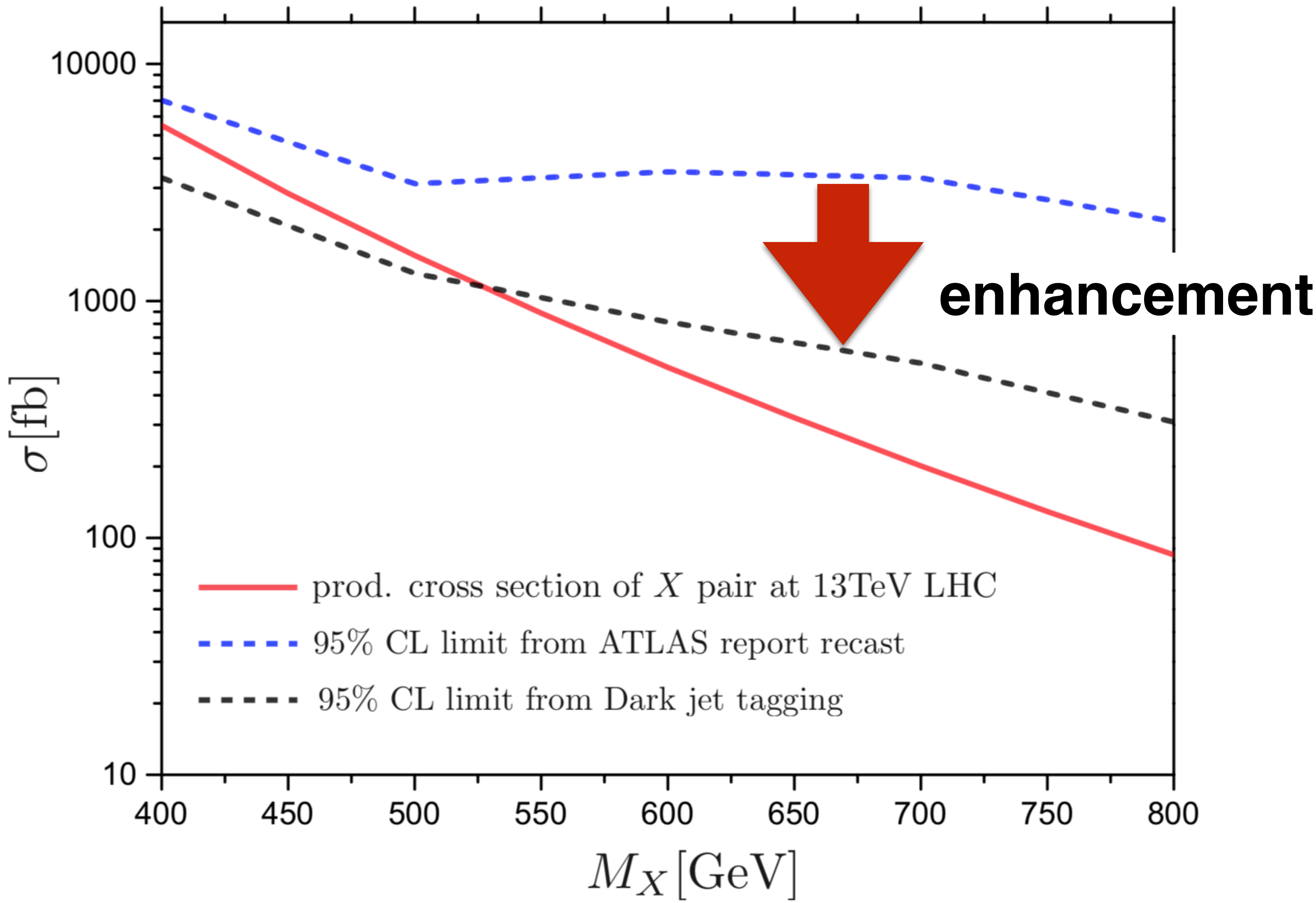
$$\mathcal{A} = \frac{|m_1 - m_2|}{m_1 + m_2},$$

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

BDT with $\{C_1^{(\beta)}$, E-ratio, Track Multiplicity$\}$



Comparison between conventional search and jet substructure method



Conclusion

- LHC program is an **active** experiment
  - to find dark sector (dark matter).
  - to measure properties of a dark sector.

- The **mass origin** in dark sector (like SM-Higgs mechanism) can strongly affect the dark photon showering in "**Energetic**" dark matter.

- Collider can probe the nature of dark matter by examine the **pattern** of dark photon **showering**

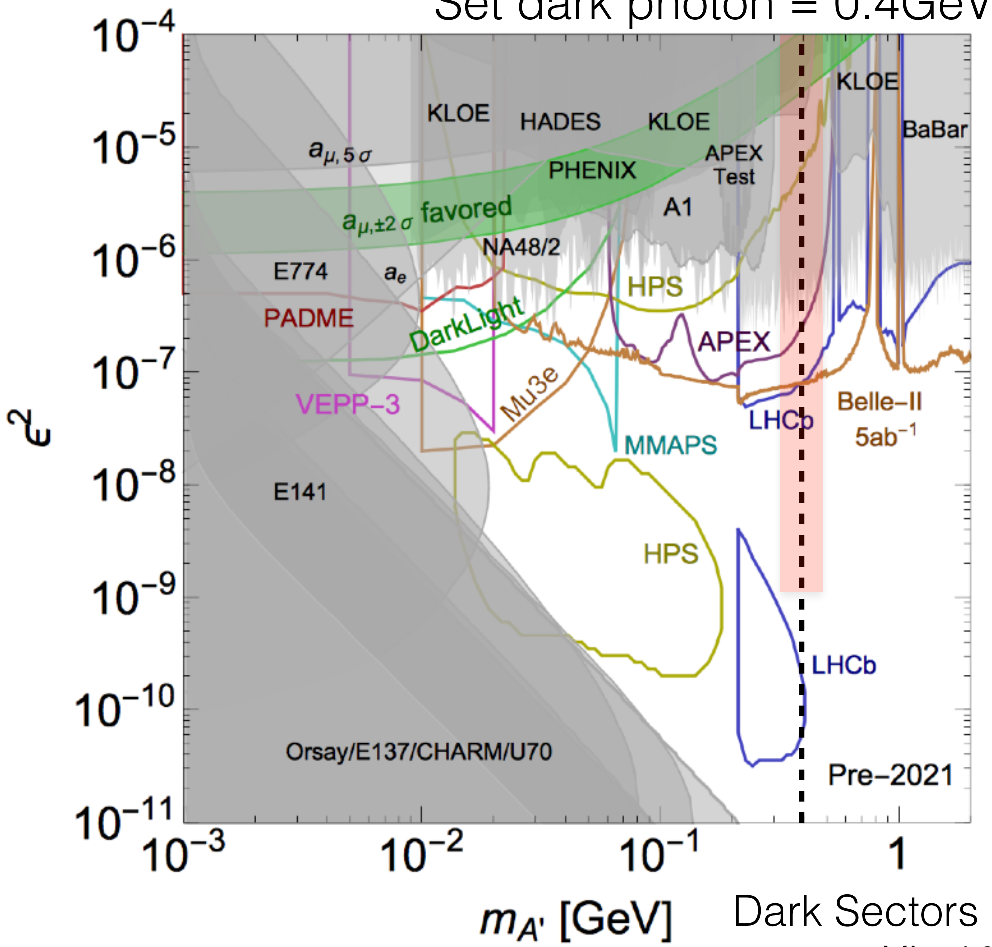
- LHC can probe the compositeness of dark matter using sophisticated **jet-substructure** techniques.

Back up

Benchmark points

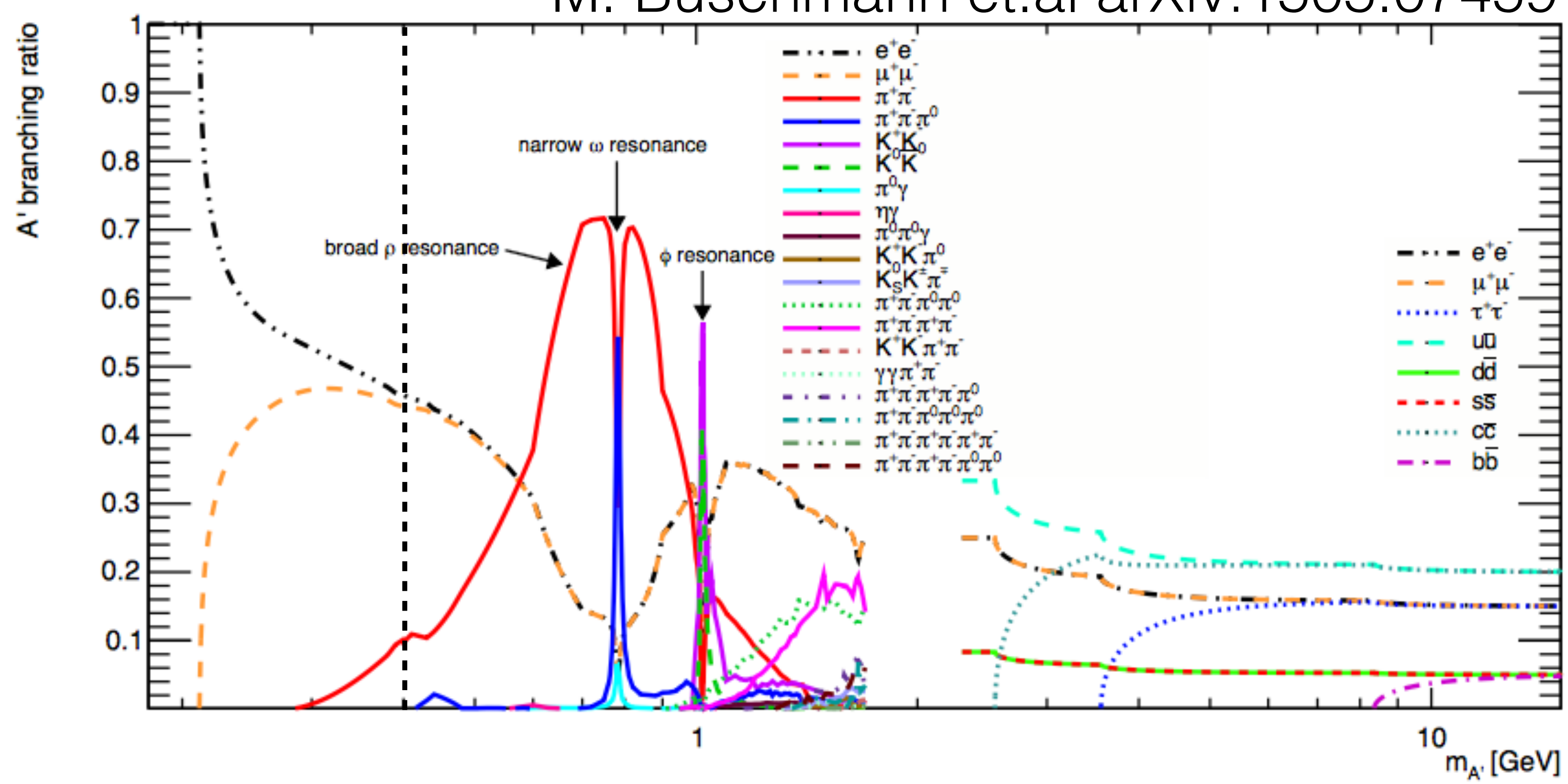
- We choose a bench mark point for
  - the prompt decays of a dark photon
  - Non-negligible decay mode into muons-pair to tag!

Set dark photon = 0.4GeV



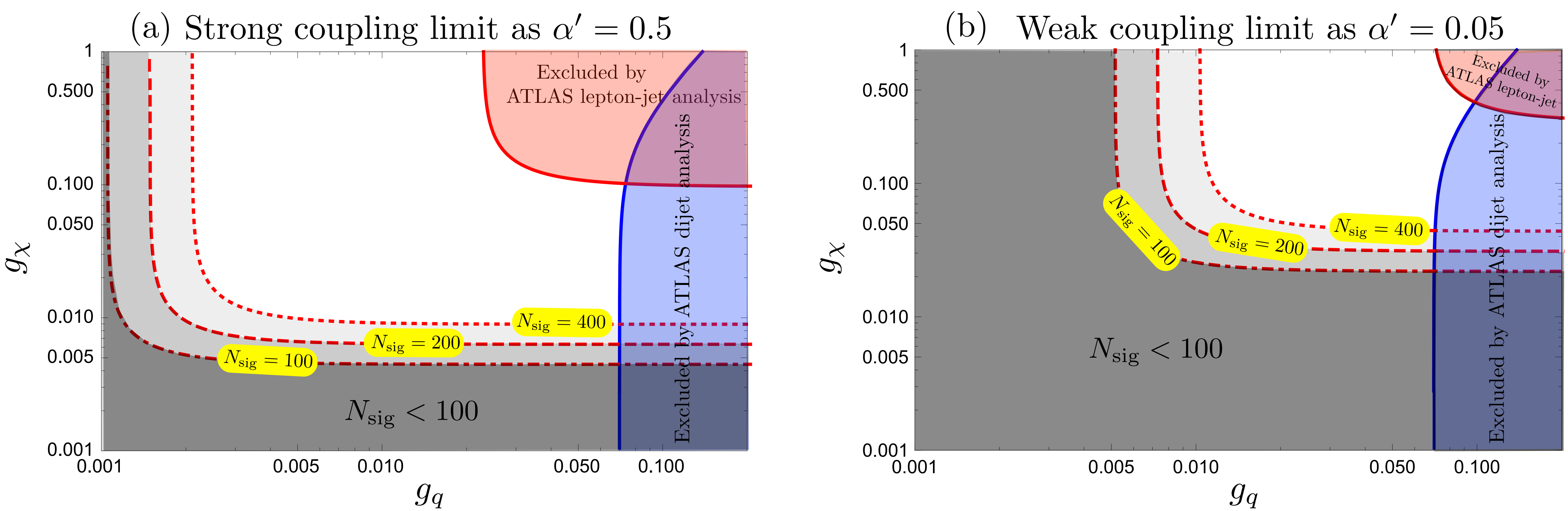
Dark Sectors 2016 Workshop
arXiv:1608.08632

M. Buschmann et.al arXiv:1505.07459



Constraints from LHC

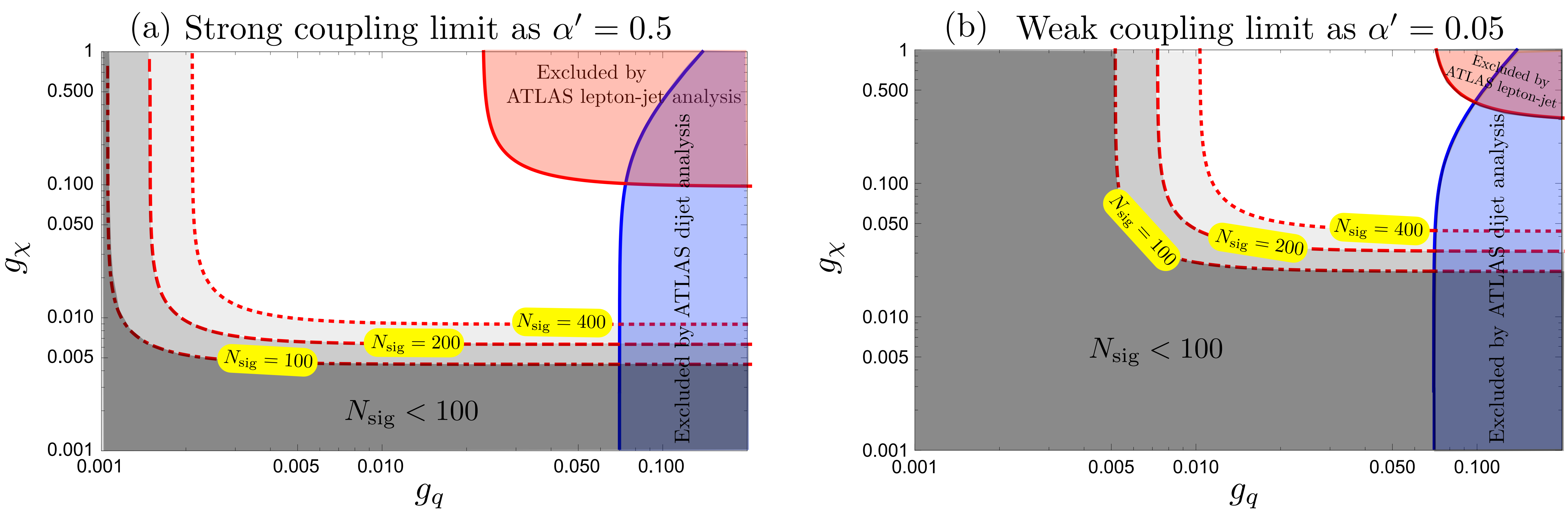
with $M_{Z'} = 1.5\ \text{TeV}$ and $m_{\gamma_d} = 0.4\ \text{GeV}$



Benchmark case	α'	m_χ(GeV)	Model	ϵ_S(%)
(a) strong coupling limit	0.50	0.5	vector-like	3.68
(b) weak coupling limit	0.05	0.45	chiral	0.41

Constraints from LHC

with $M_{Z'} = 1.5$ TeV and $m_{\gamma_d} = 0.4$ GeV



Benchmark case	α'	m_χ(GeV)	Model	$\epsilon_S(\%)$
(a) strong coupling limit	0.50	0.5	vector-like	3.68
(b) weak coupling limit	0.05	0.45	chiral	0.41