Phenomenology of dark gauge group at the LHC

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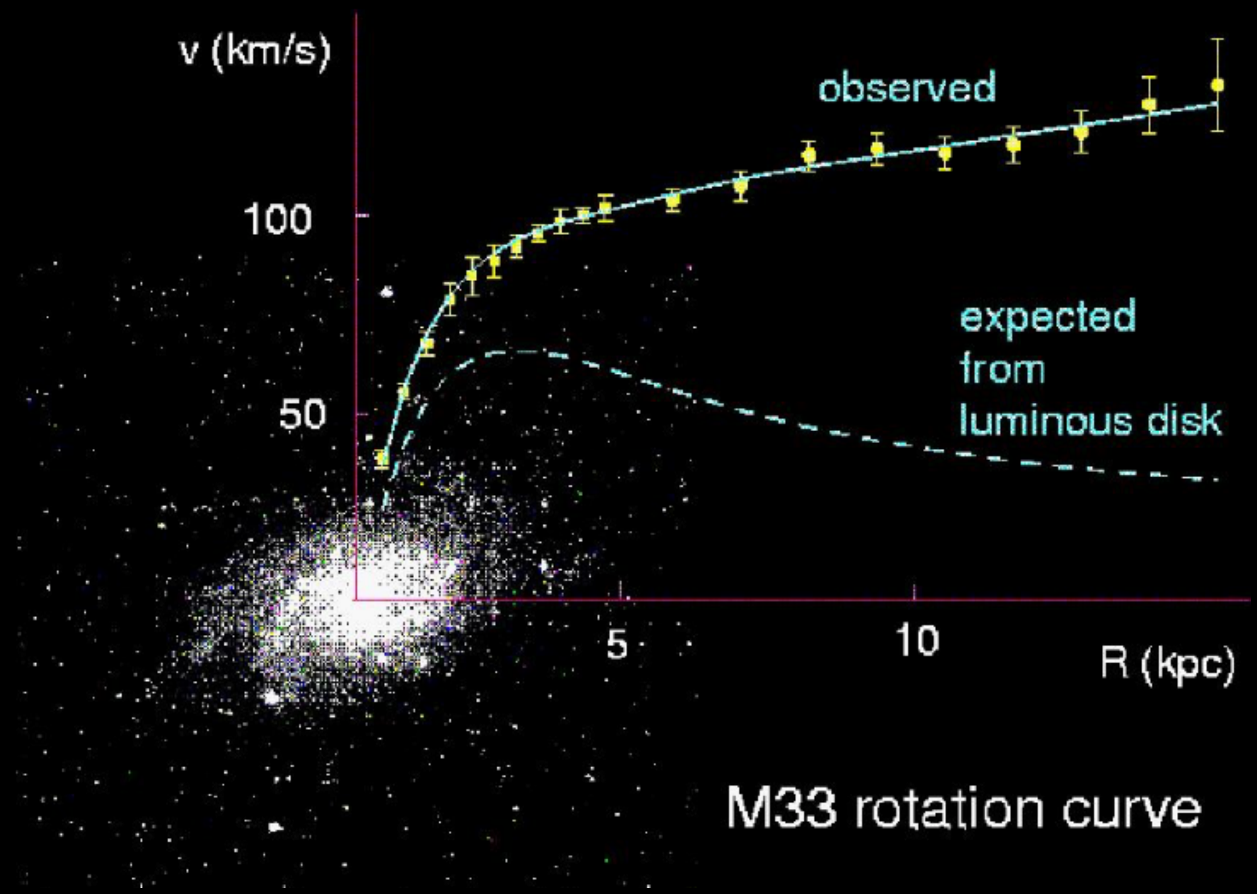
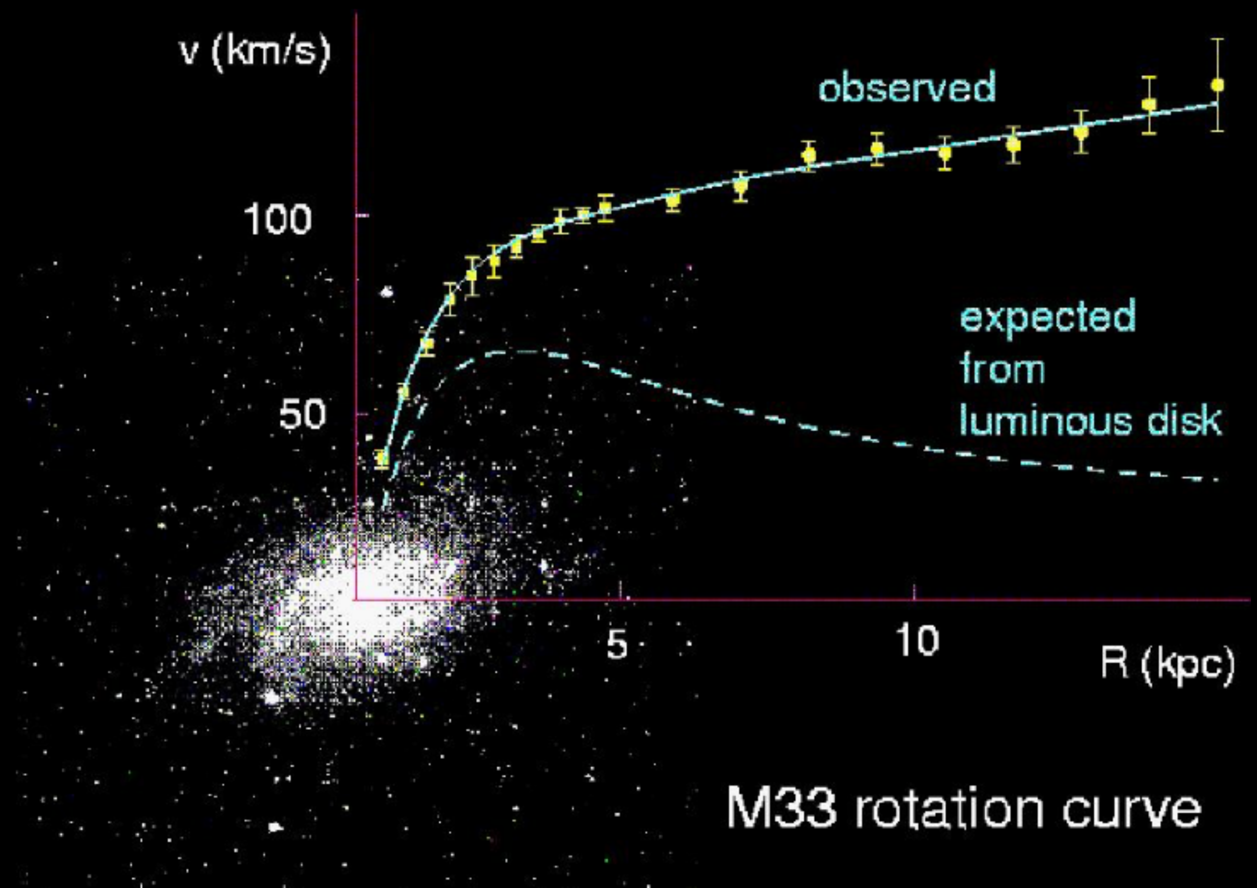
based on
1. arXiv: 1612.02850 (with Mengchao Zhang, HS Lee, MH Kim)
2. arXiv:1712.09279 (with Mengchao Zhang)

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

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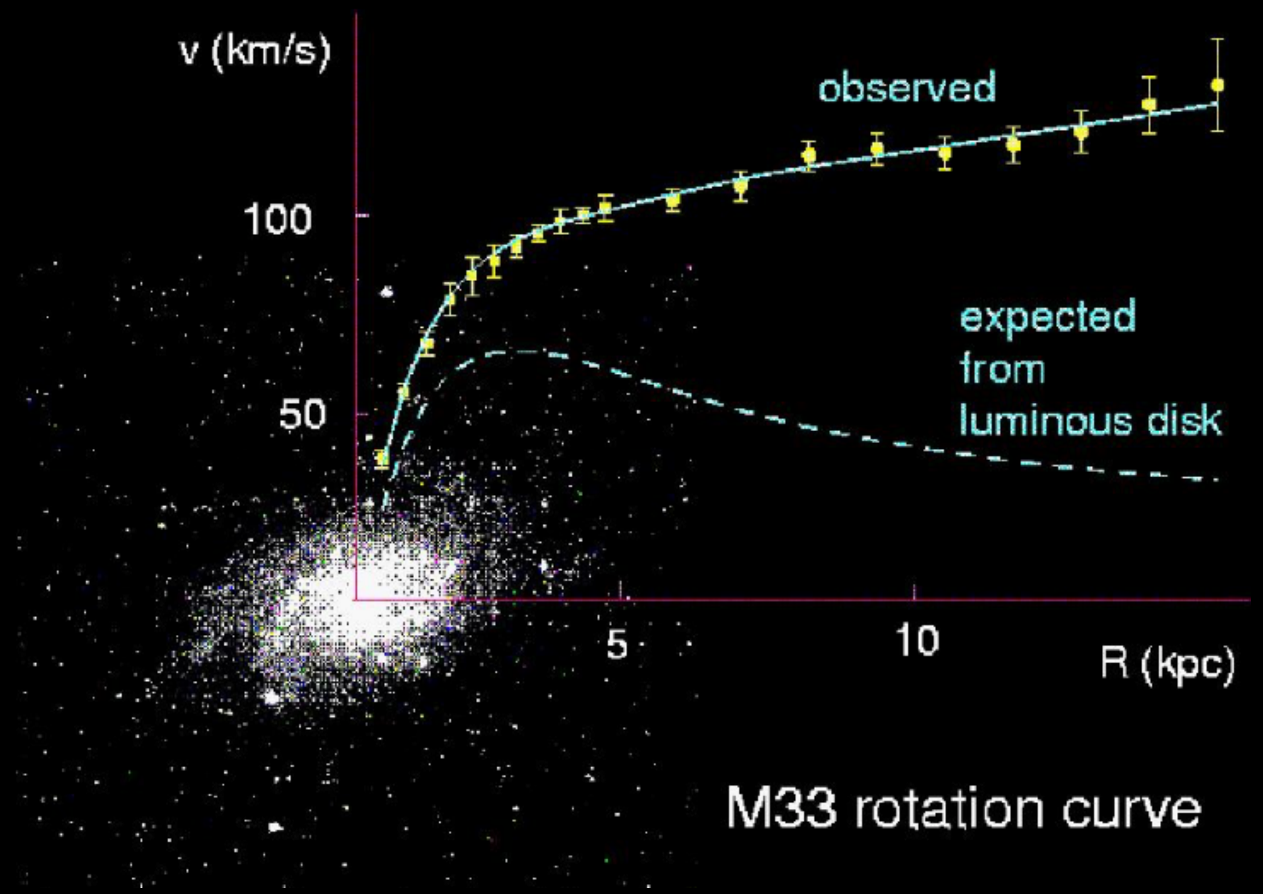
- Dark Matter is **Neutral** under **Standard Model U(1)$_{EM}$**

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 **weak gauge-charged and a Higgs**.
- 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

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}

• • •

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

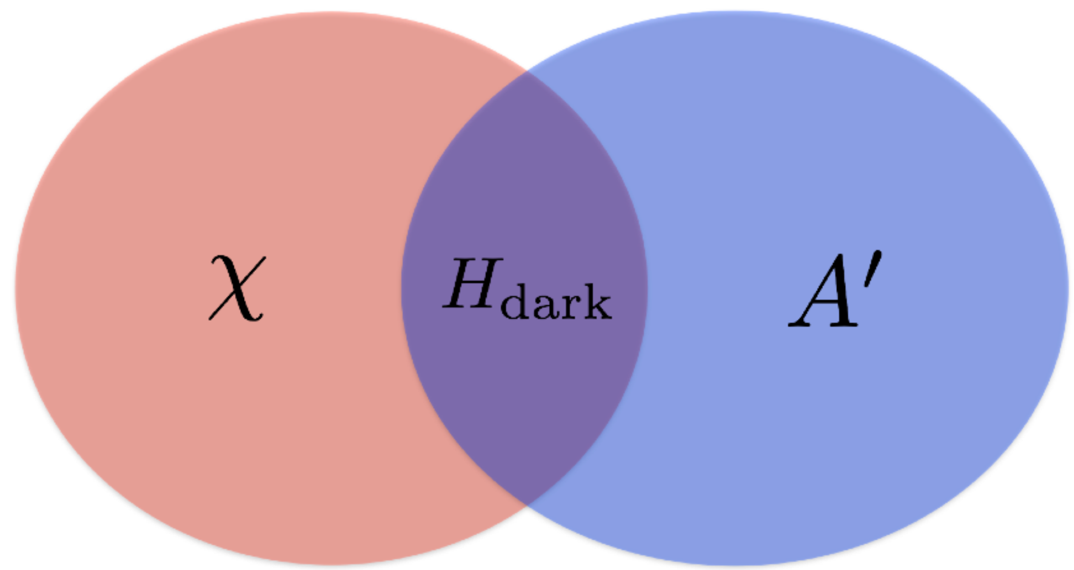
Yukawa for mass

$$Q'_A = \frac{1}{2}(Q'_{\chi_R} - Q'_{\chi_L}) = \frac{Q'_\Phi}{2} \quad \leftarrow \quad \mathcal{L} \ni y_\chi \bar{\chi}_L \Phi^* \chi_R + h.c.$$

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

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

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



Yukawa Interaction

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

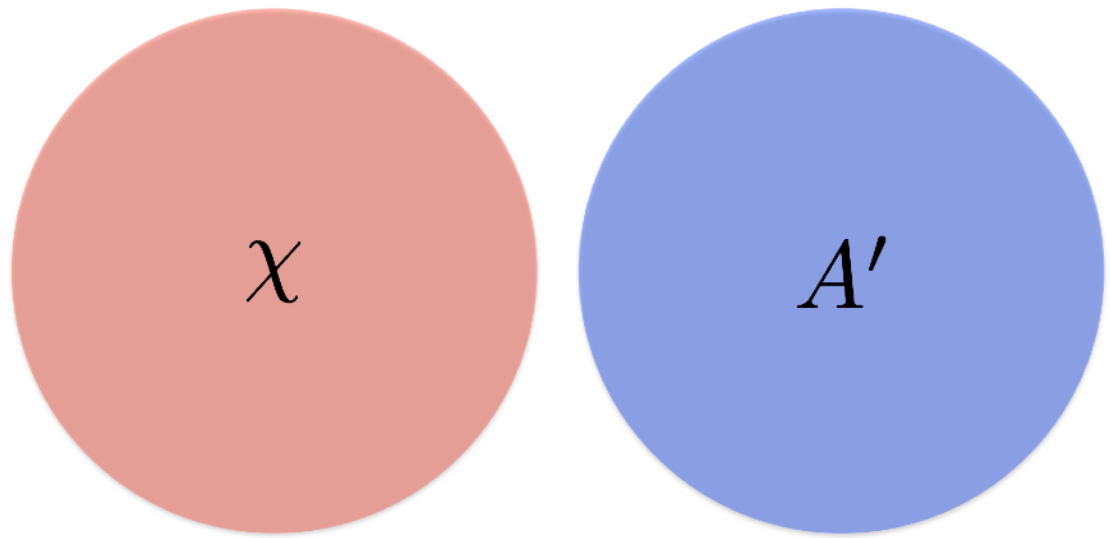
$$Q'_{\chi_L} - Q'_{\chi_R} + Q'_\Phi = 0$$

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

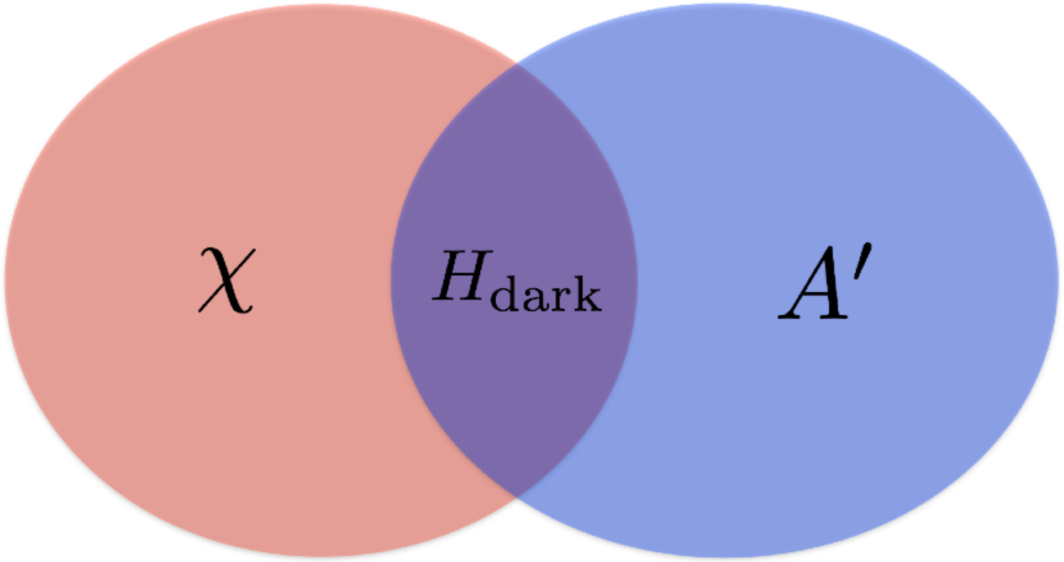


No Yukawa Interaction: **Vector-like DM**

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

- No axial vector coupling:

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



with Dark-Higgs
Chiral fermion

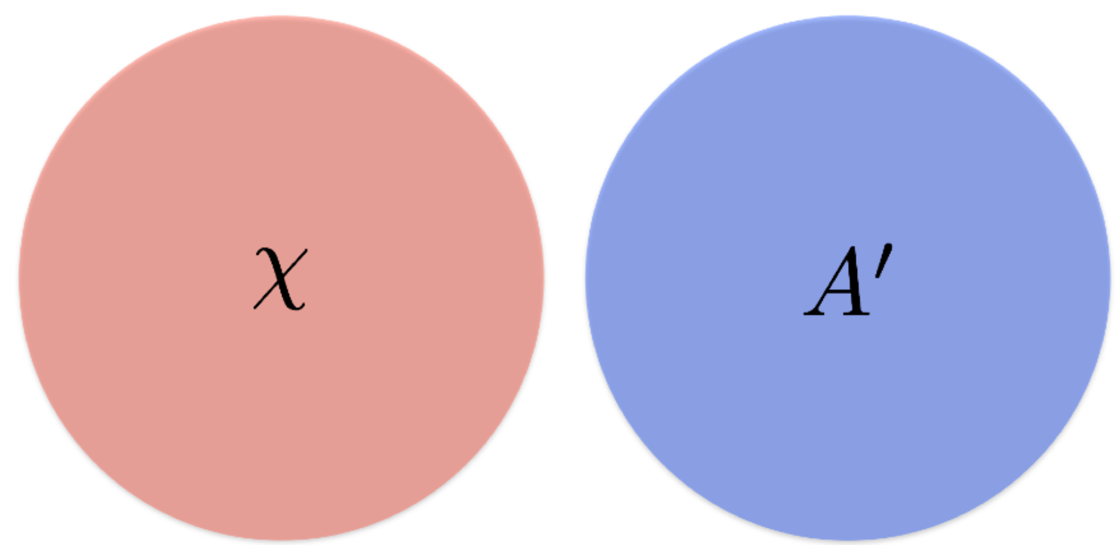
dark matter and dark-photon
share the same origin for their mass

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

Can we see difference @ LHC ?

dark matter and dark-photon
have their own mass mechanism

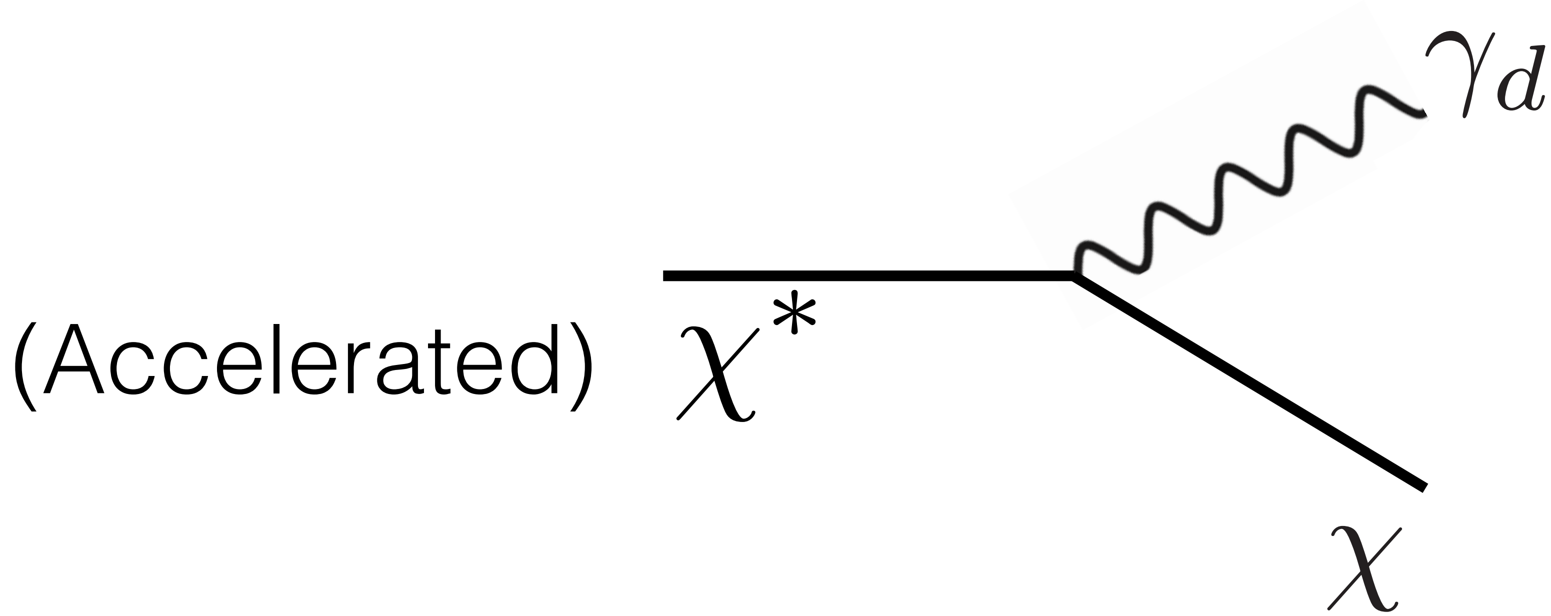
$$Q'_{\chi_L} = Q'_{\chi_R}$$



No Dark-Higgs
Vector-like fermion

How can we observe?

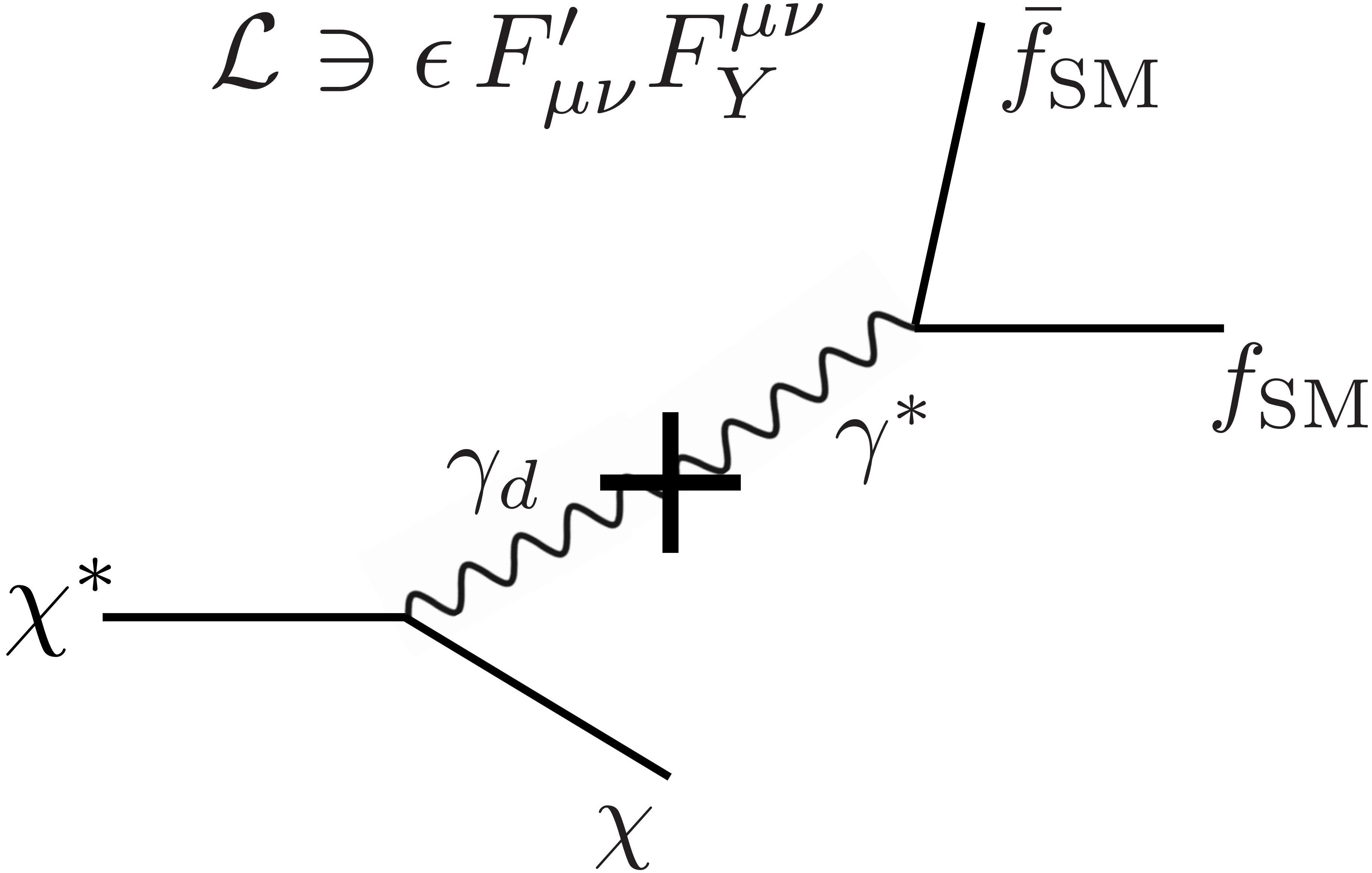
- **Dark Showering:** Accelerated "Dark Charged" particle radiates corresponding dark-gauge bosons



How can we observe?

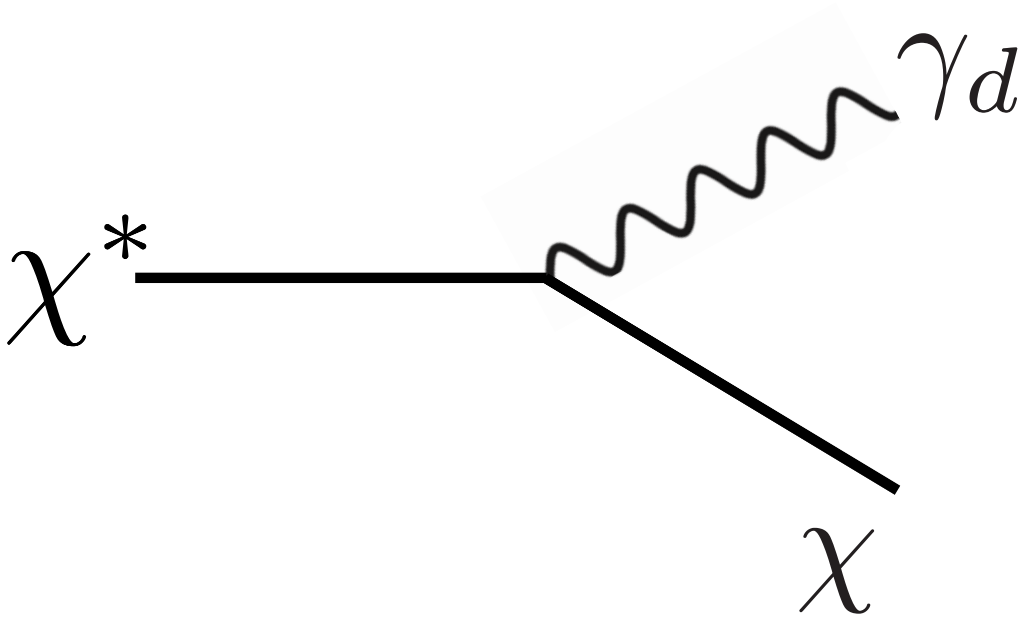
- dark-U(1) can mix with SM U(1)-hyper through a **Gauge-kinetic mixing** : Gauge-invariant term

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



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

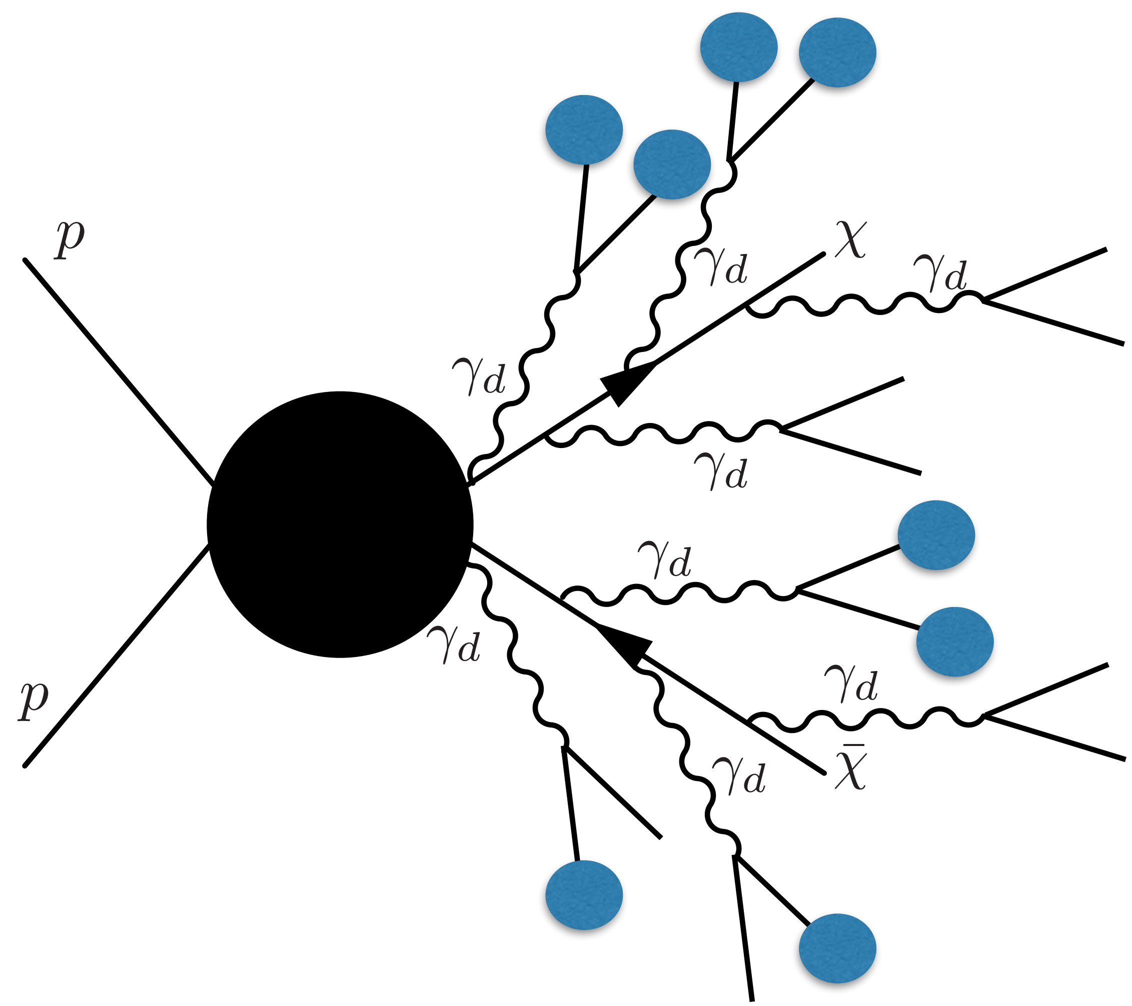
Splitting function

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

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

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

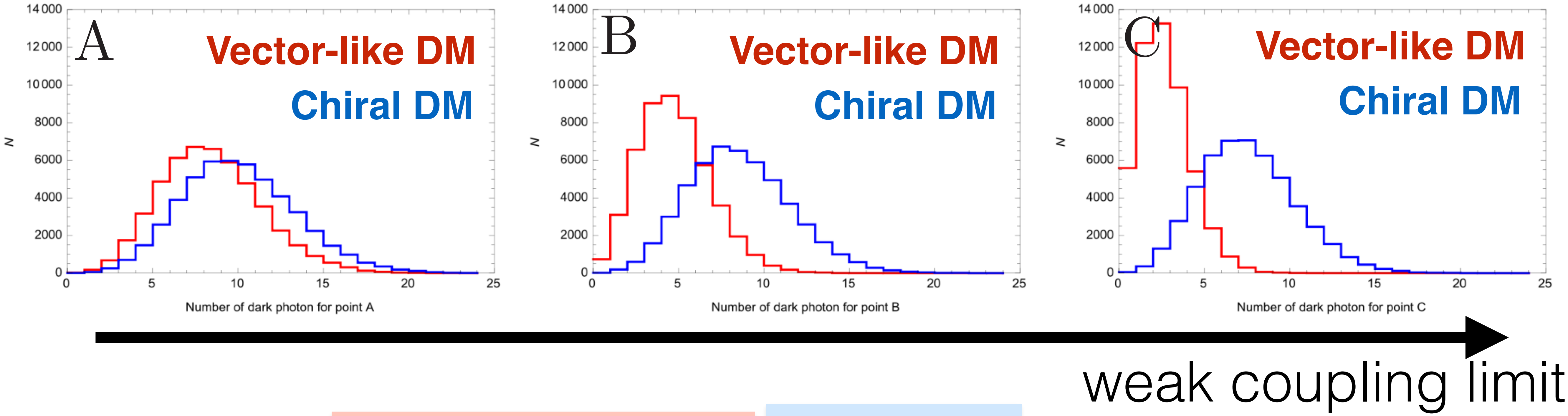
Energetic DM @ Colliders



- **Radiations** from **Energetic** "dark charged" particles will acquire certain level of energy, enough to be "**tagged**" (detectable effect)

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



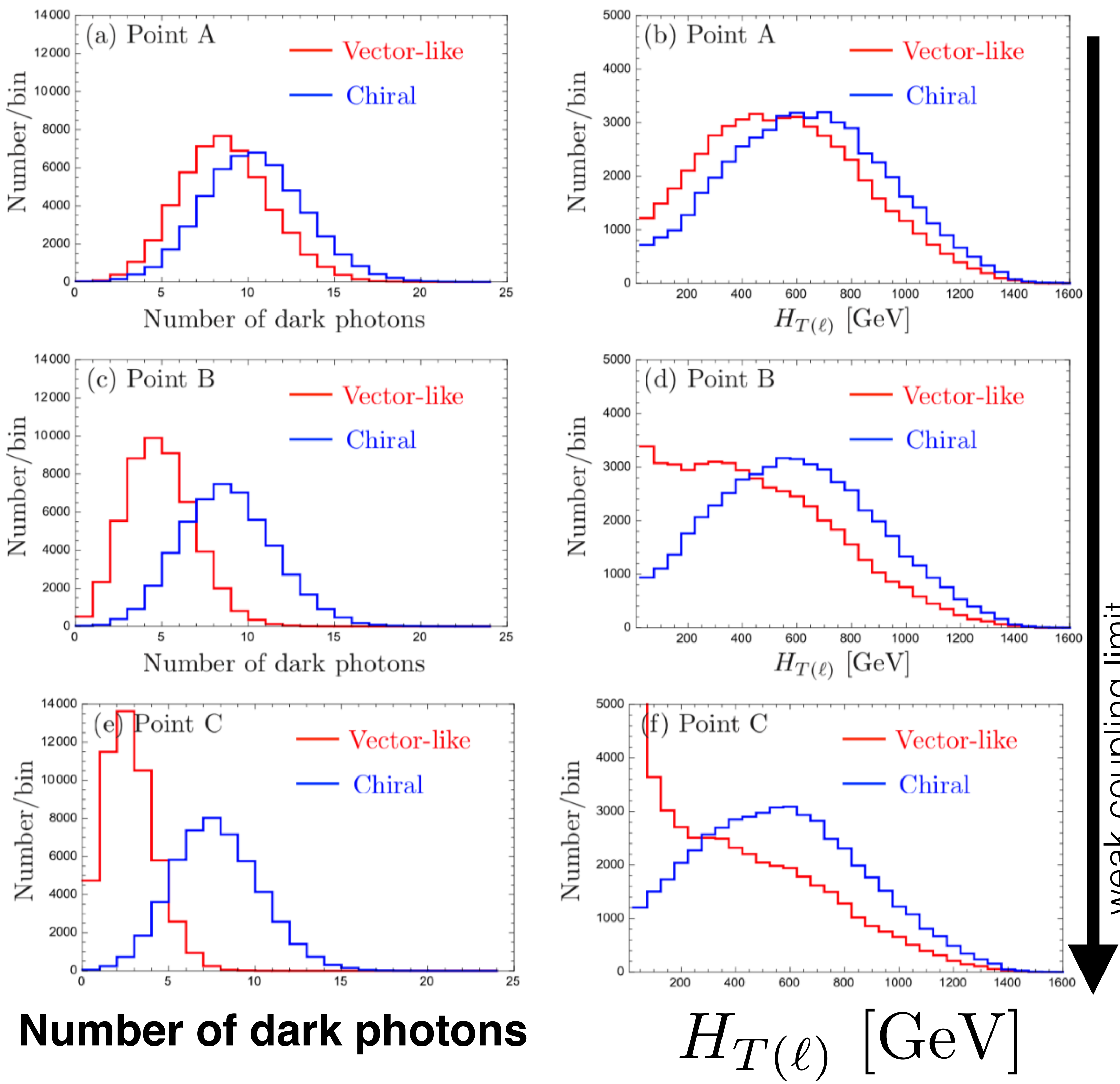
$$P_{\chi\to\chi\gamma_d}(x,t) \simeq (Q_V'^2 + Q_A'^2)\,\frac{1+x^2}{1-x} + 2Q_A'^2\,\frac{m_\chi^2}{m_{\gamma_d}^2}$$

- 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 $H_{T(\ell)} = \sum_{i=\mu^\pm, e^\pm} |p_{T_i}|$



- In a splitting function

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

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

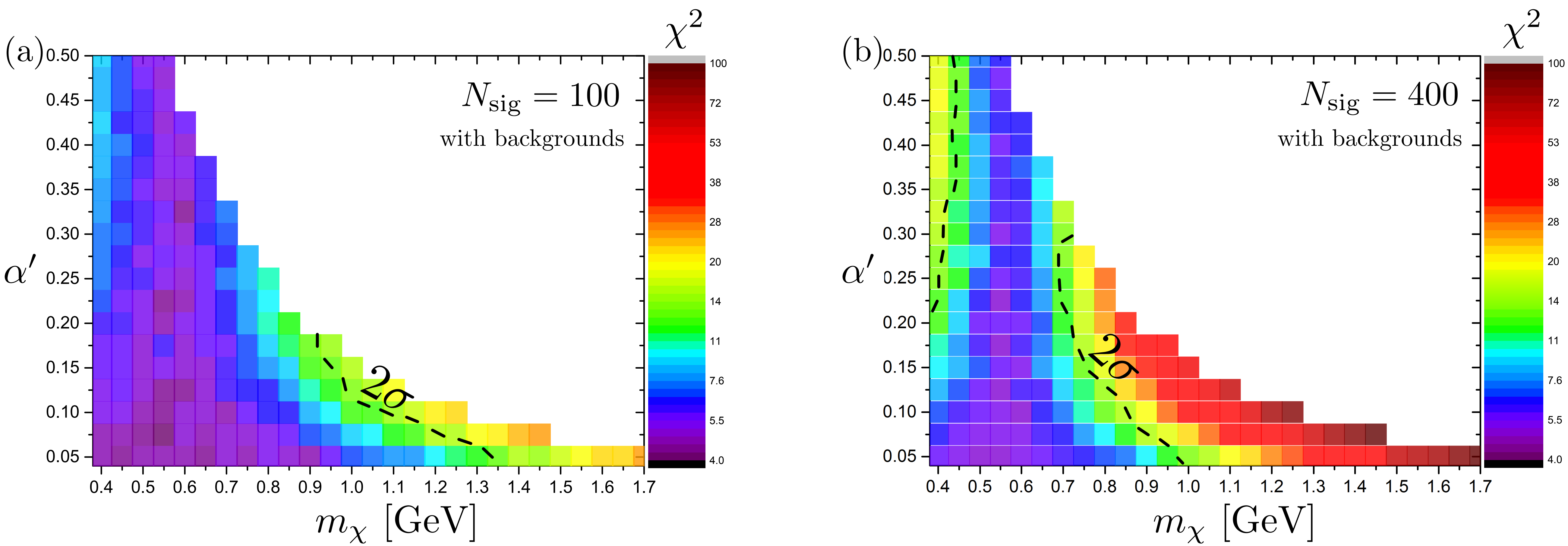
- In a chiral case, additional term:

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

: **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)

- "Composite " particle (baryon) under non-abelian gauge group

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

Minimal setup

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

  to produce and detect signatures at hadron colliders

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

- 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

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

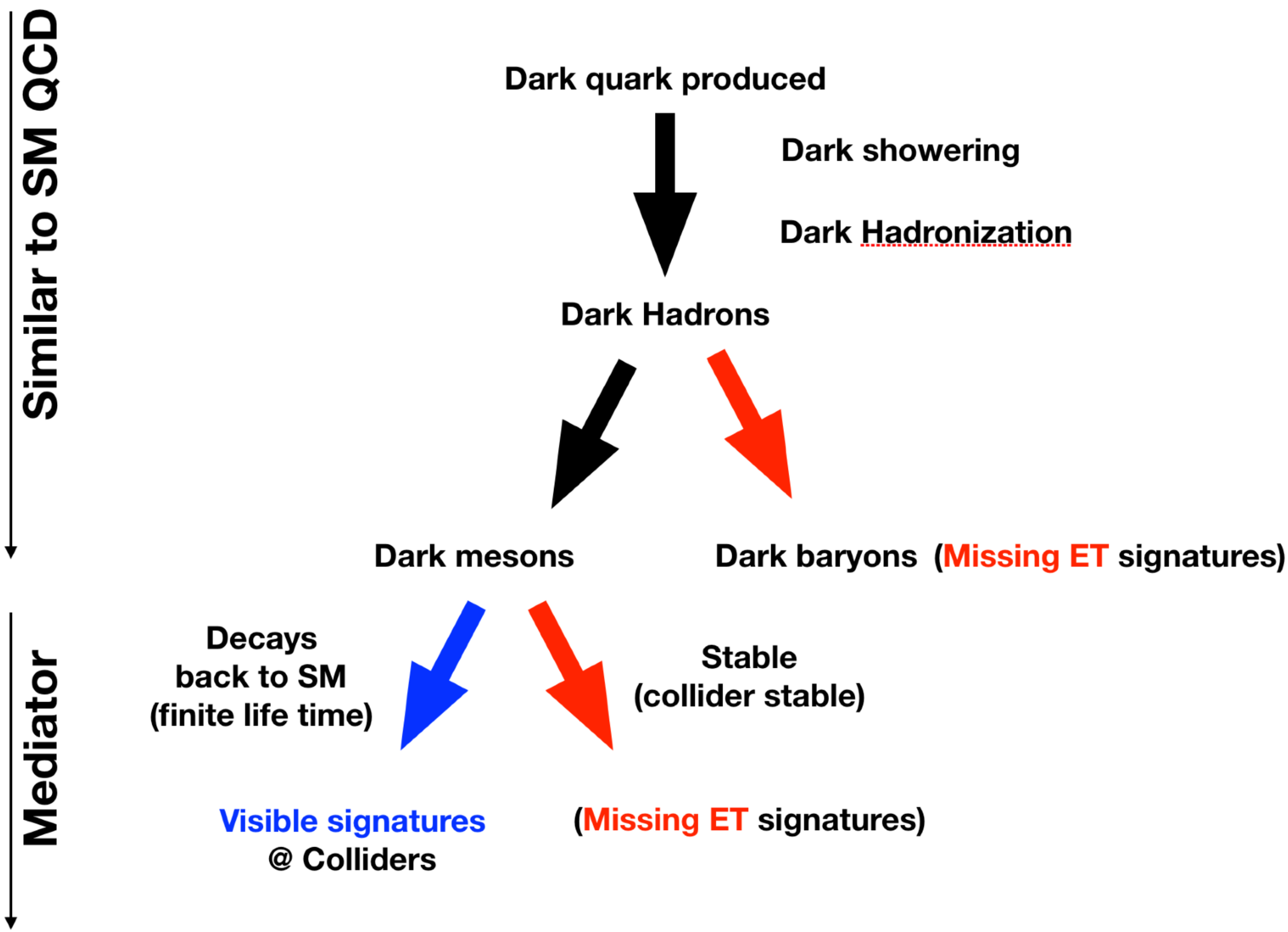
SU(N) dark sector

Where is from the stability of Dark matter ?

How does Dark matter become MASSIVE ?

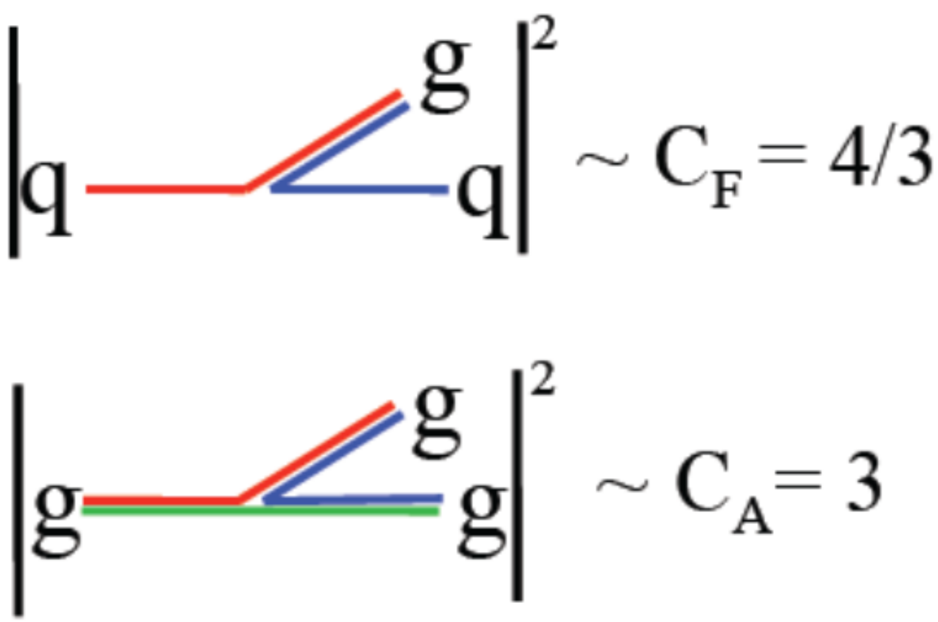
= Dark "Baryon"

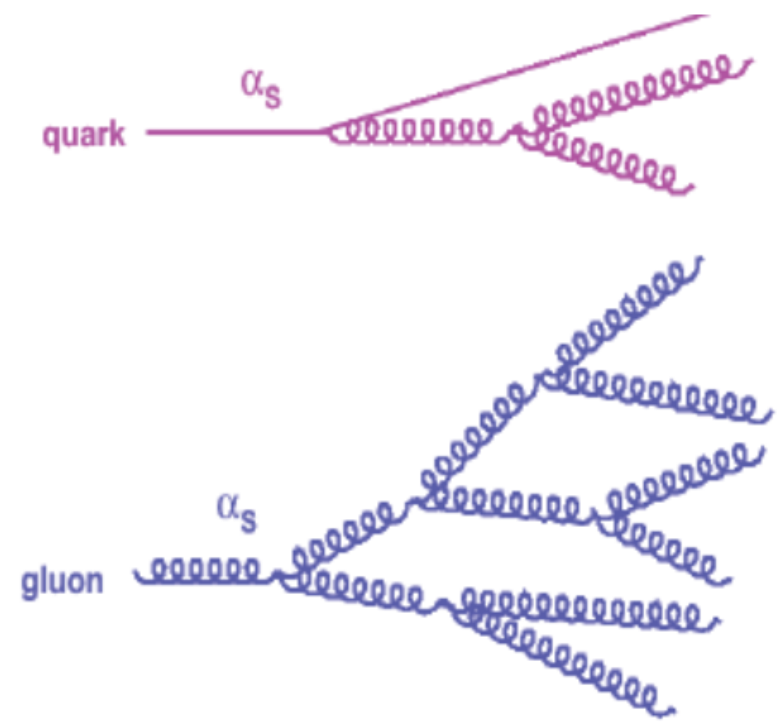
Activities at Collider



Color factor

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





quark jets

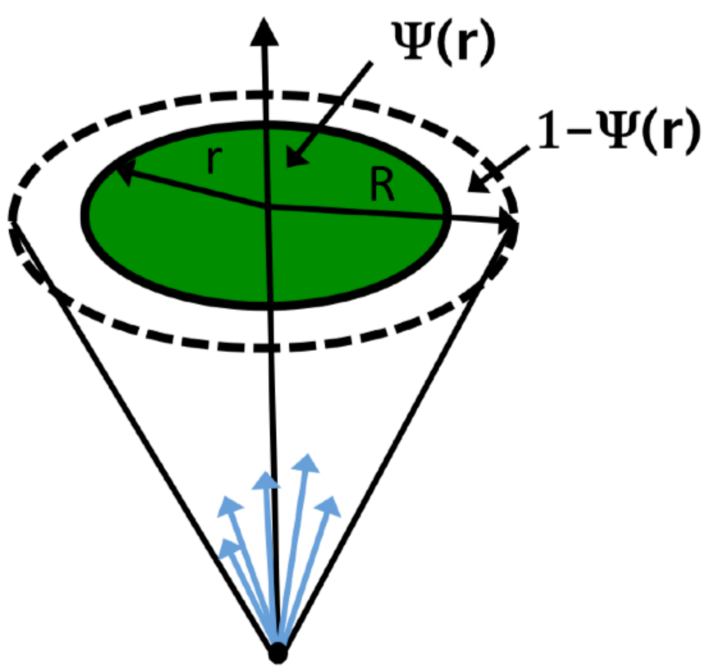
gluon jets

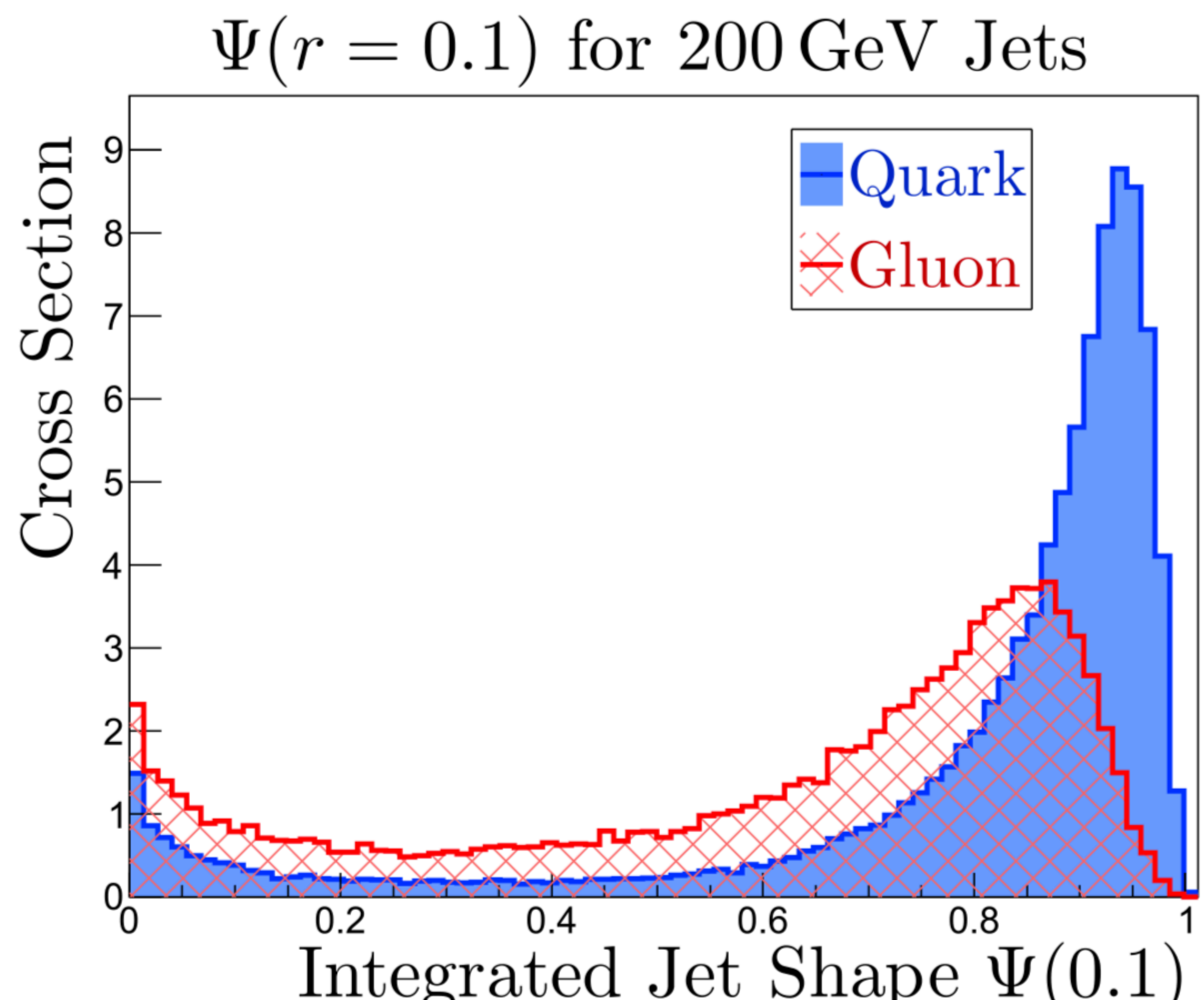
$$F_{q\to g}(z,\theta) = \frac{4}{N_c}\frac{\alpha_s}{\pi}\frac{1+(1-z)^2}{z}\frac{1}{\sin^2\theta}$$

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

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

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





What's the case of Dark QCD ?

	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

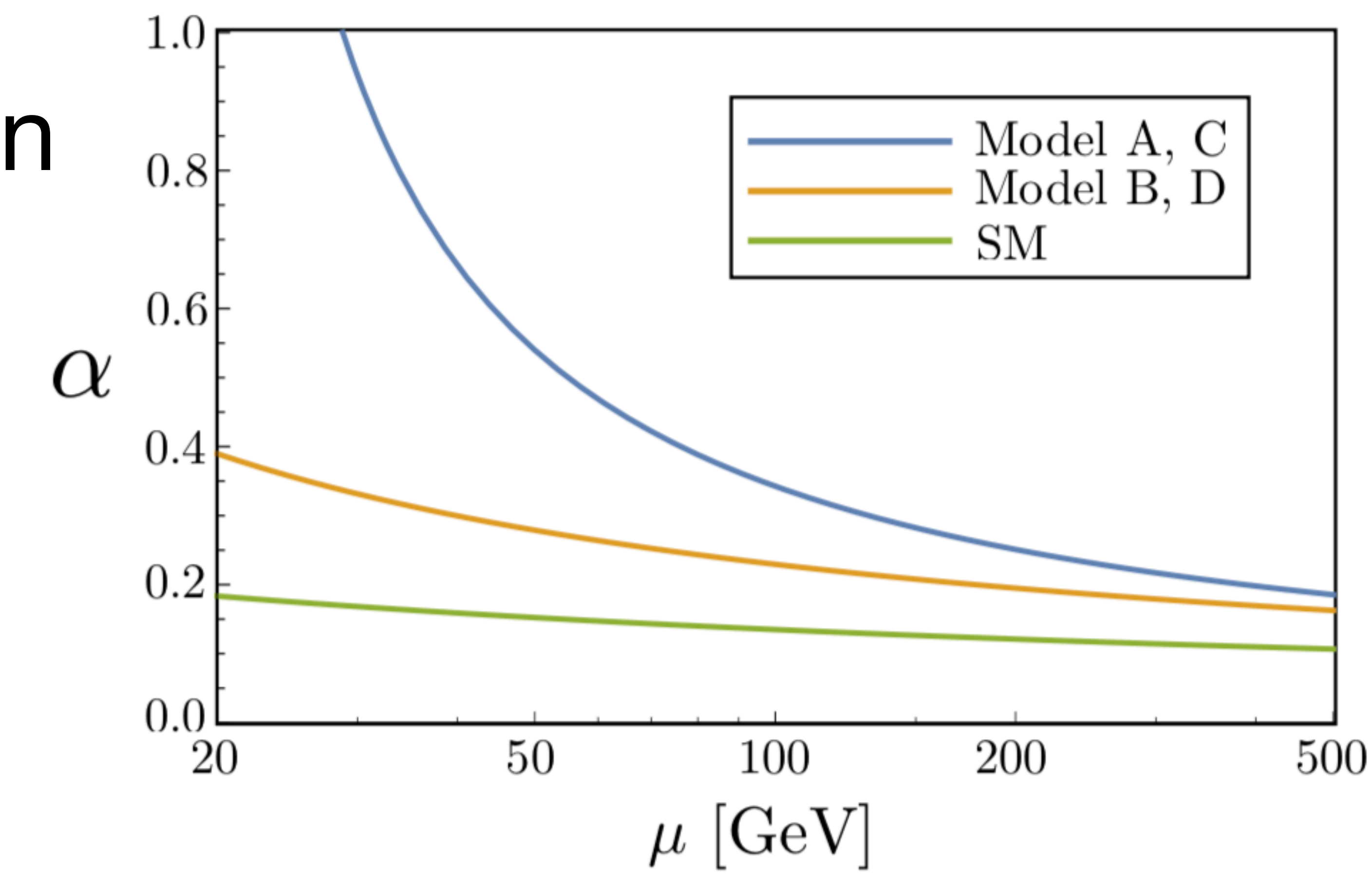
C, D : additional meson decay

Jet evolution depends on

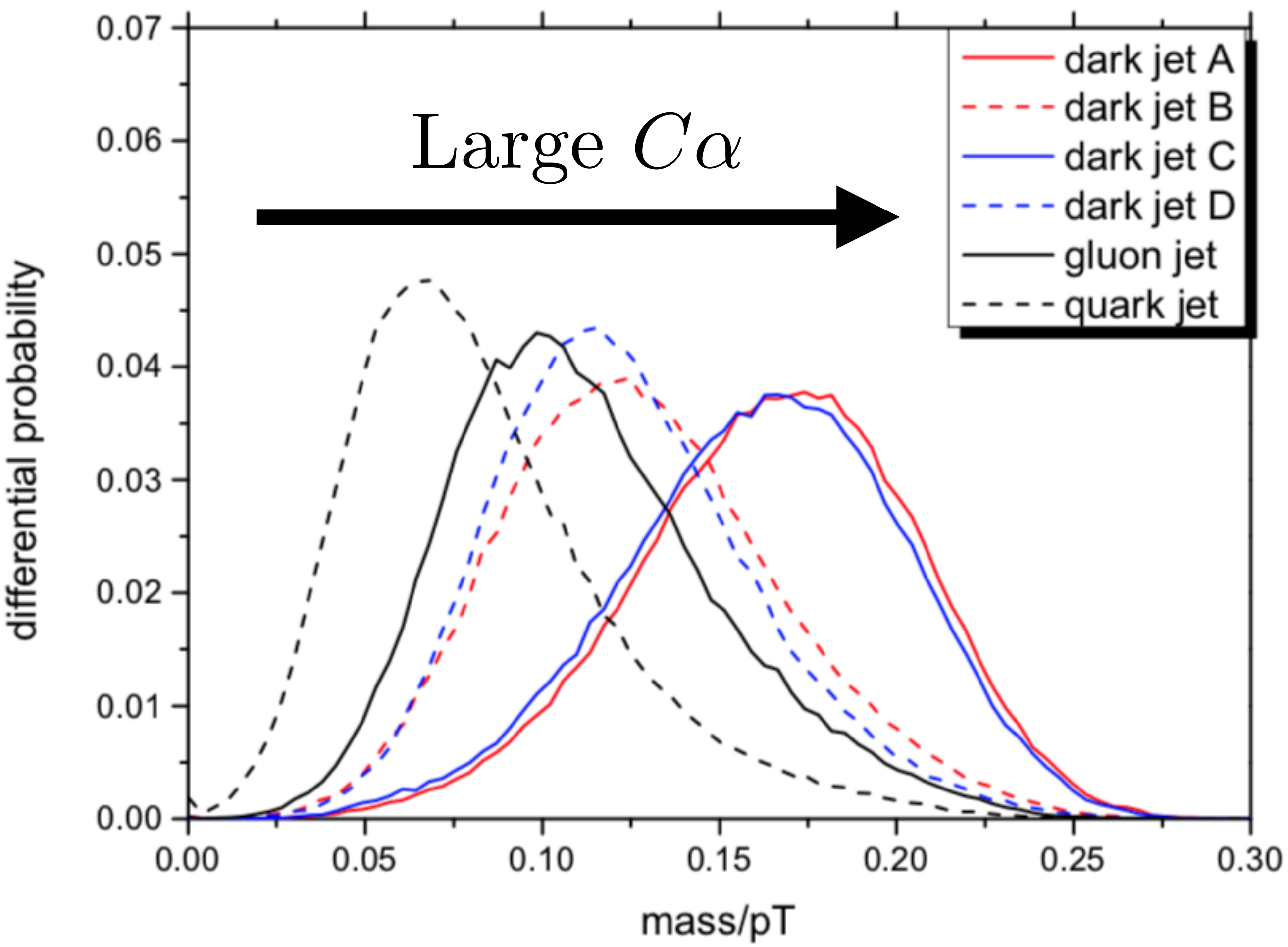
1. Color factor
2. Coupling

Jet components depends on

- decay mode.



eg: jet mass



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

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

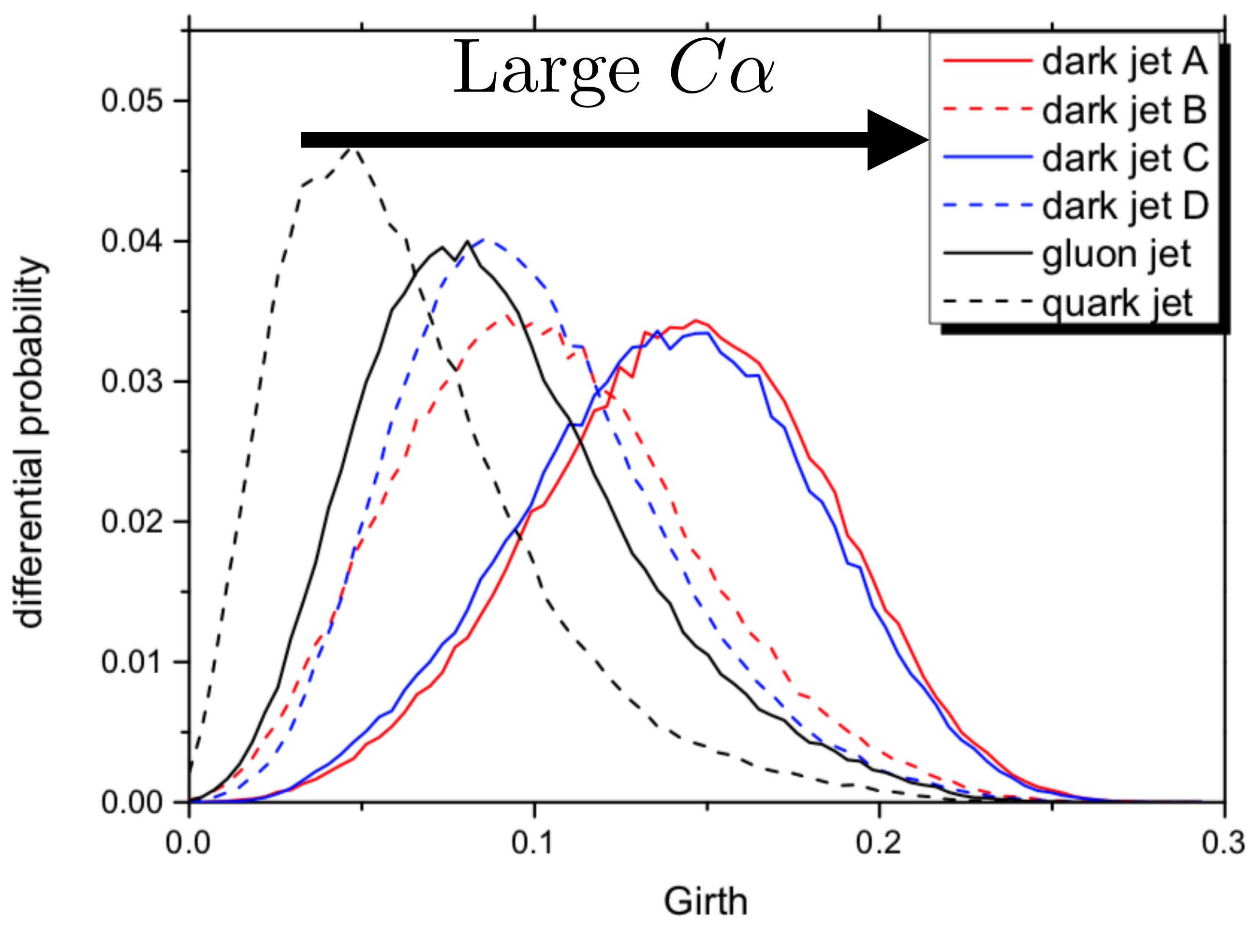
Gluon: C= 3
Quark: C= 4/3

: 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

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

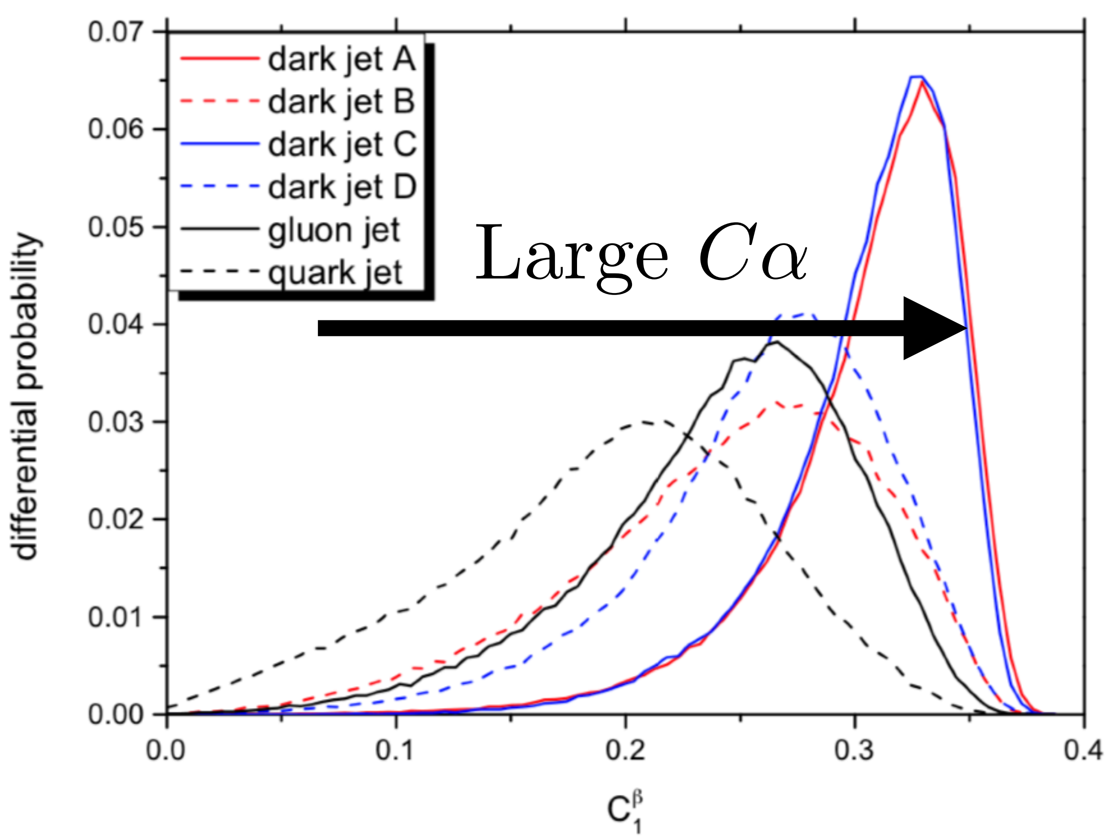


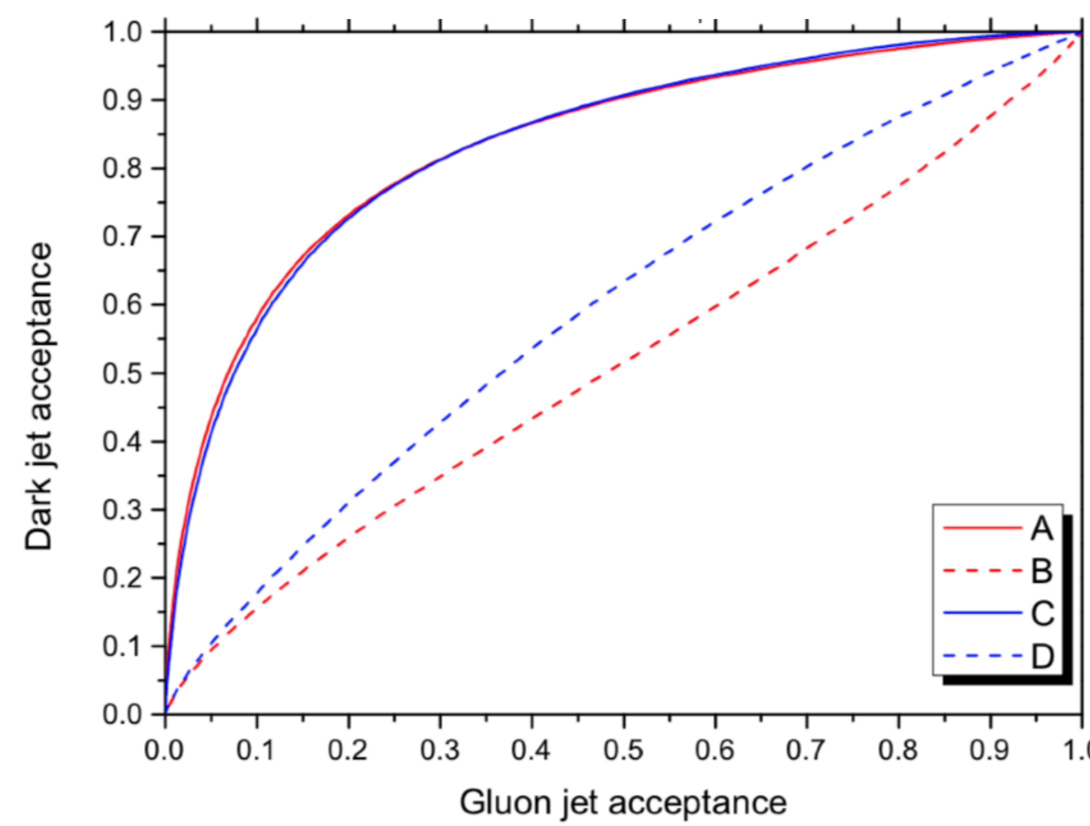
eg: Energy correlation

- Correlations among constitute particles would be interesting

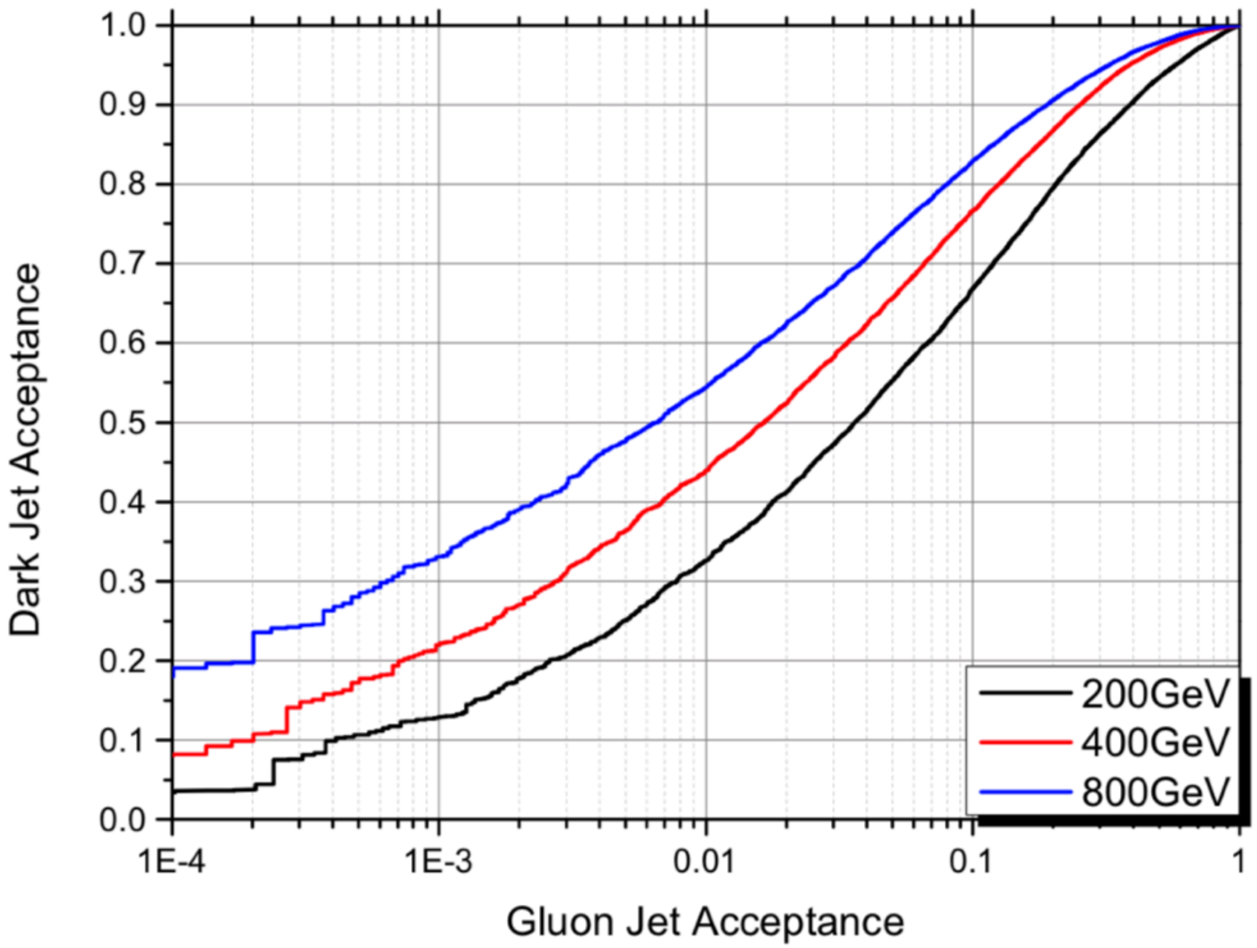
$$C_1^{(\beta)} = \sum_{i<j\in J} z_i z_j (R_{ij})^\beta$$

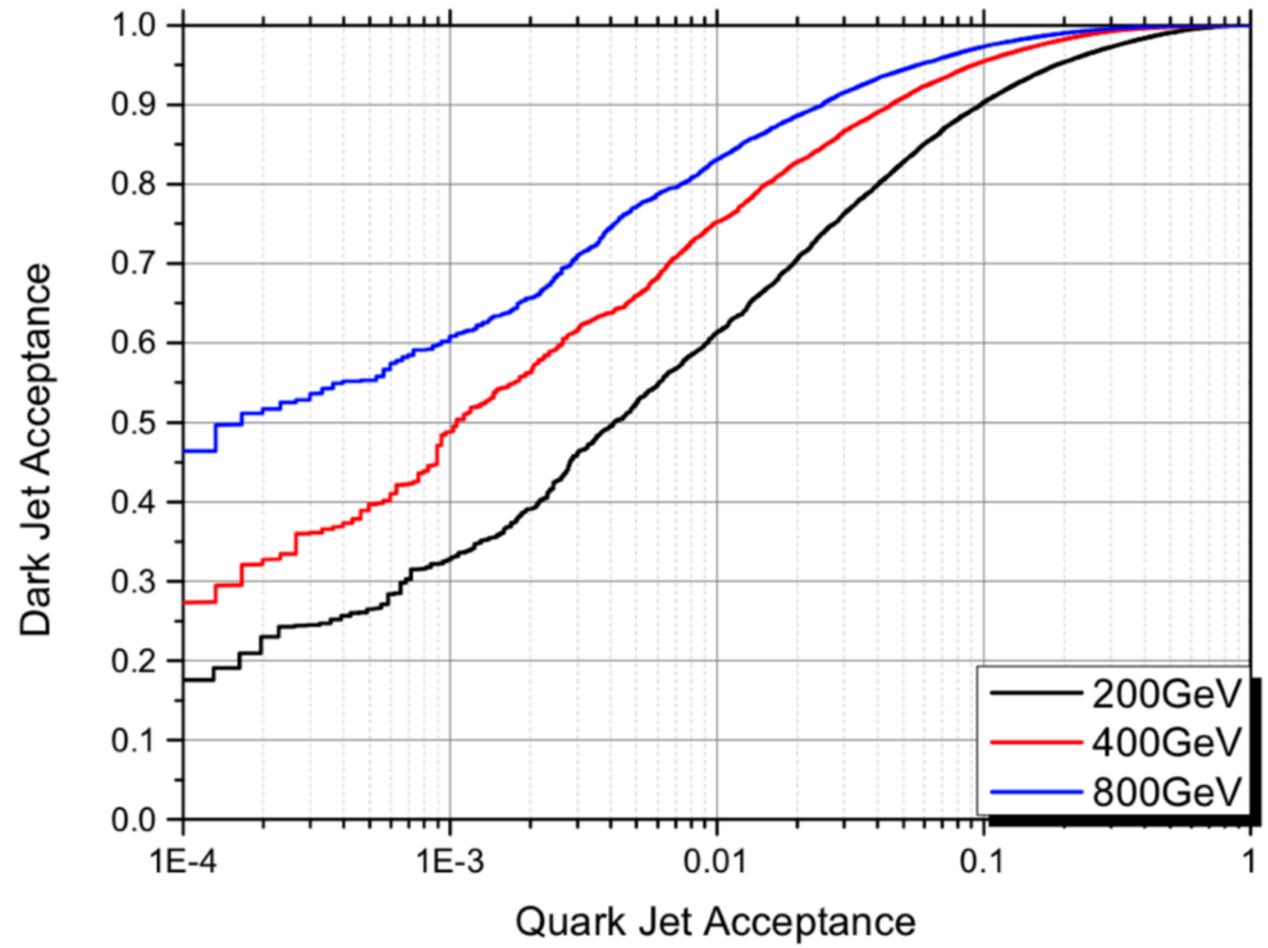
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}C_1^{(\beta)}} = \frac{2\alpha C}{\pi\beta C_1^{(\beta)}} L(C_1^{(\beta)}) \exp\left(-\int_{C_1^{(\beta)}}^{R_0^\beta} \mathrm{d}\tilde{C}\, \frac{2\alpha C}{\pi\beta\tilde{C}} L(\tilde{C})\right)$$





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

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**

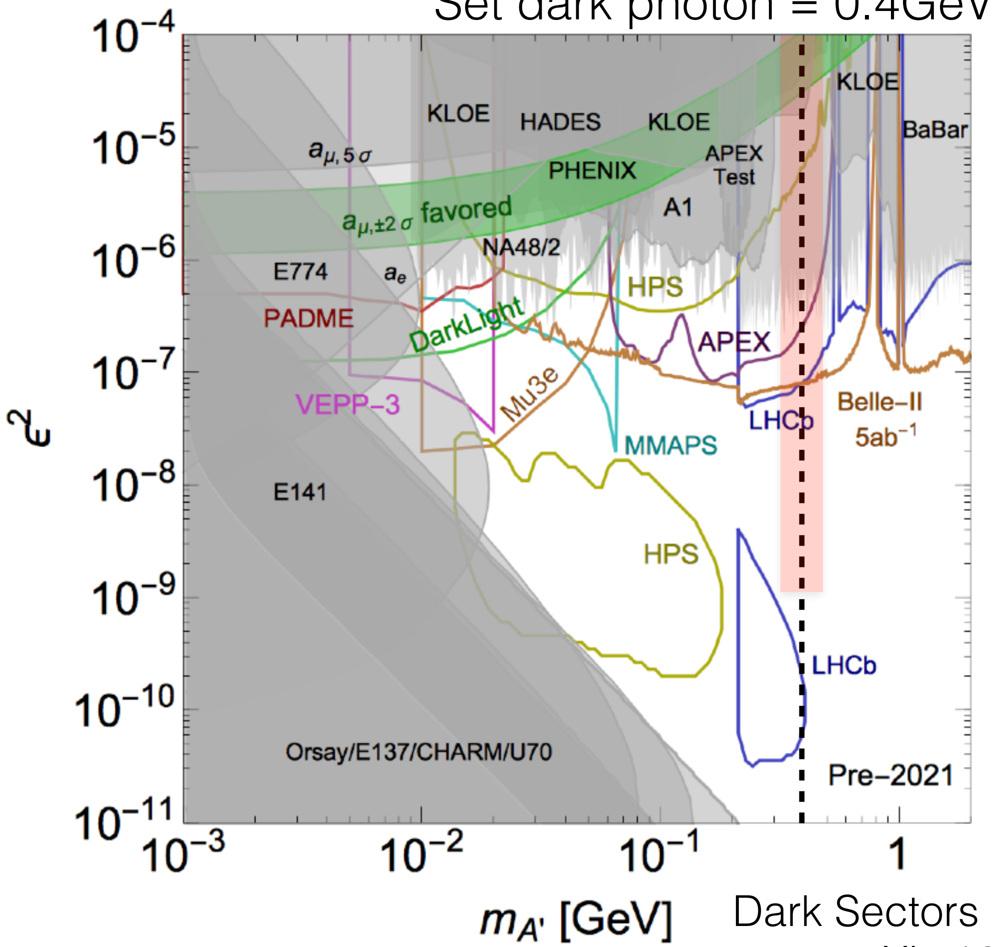
- LHC can probe the compositeness of dark matter using sophisticated **jet-substructure** techniques.

Back up

Benchmark points

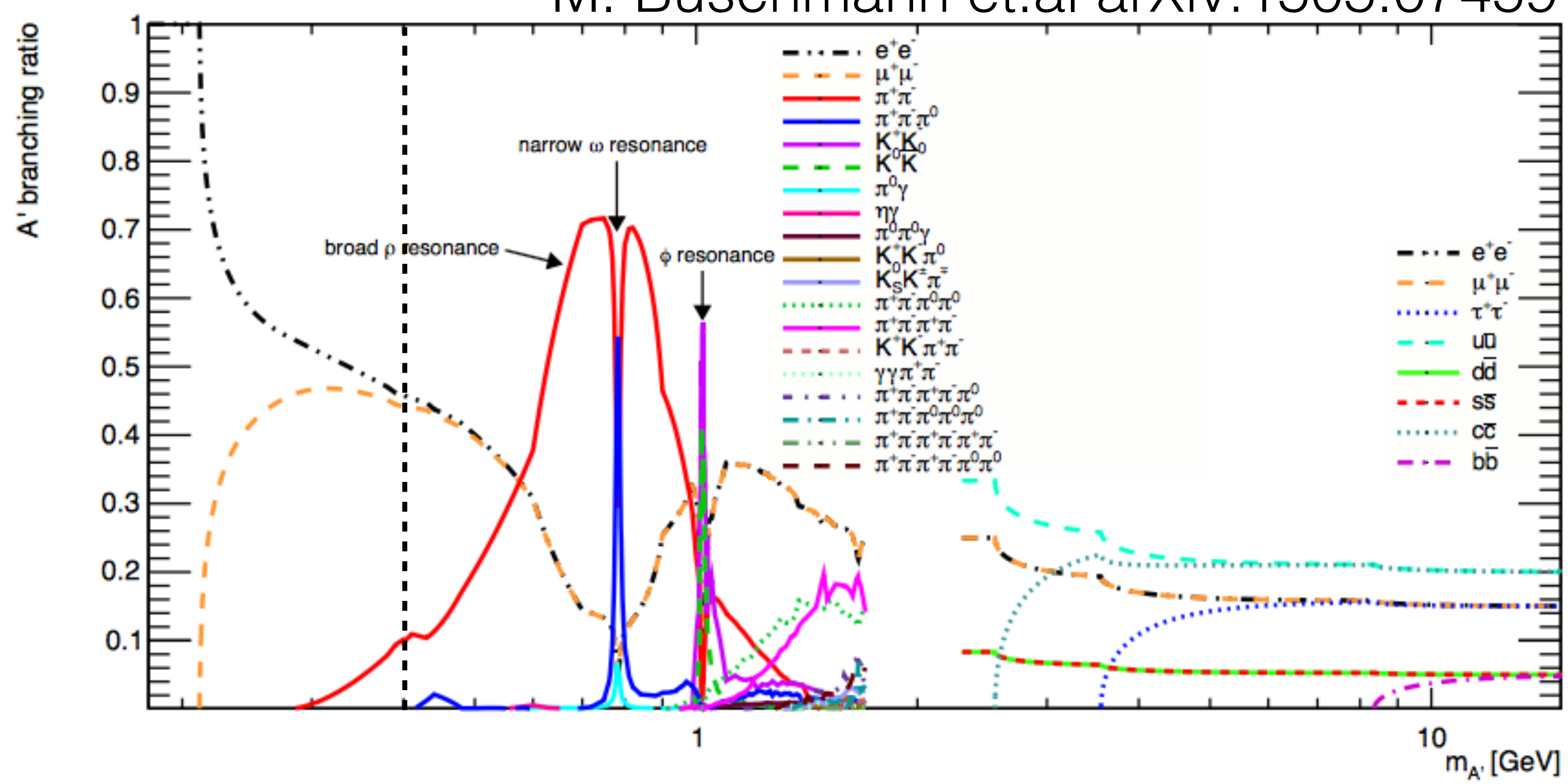
- We choose a bench mark point for
  - the prompt decays of a dark photon
  - Non-negligible decay mode into muons-pair to tag!

Set dark photon = 0.4GeV



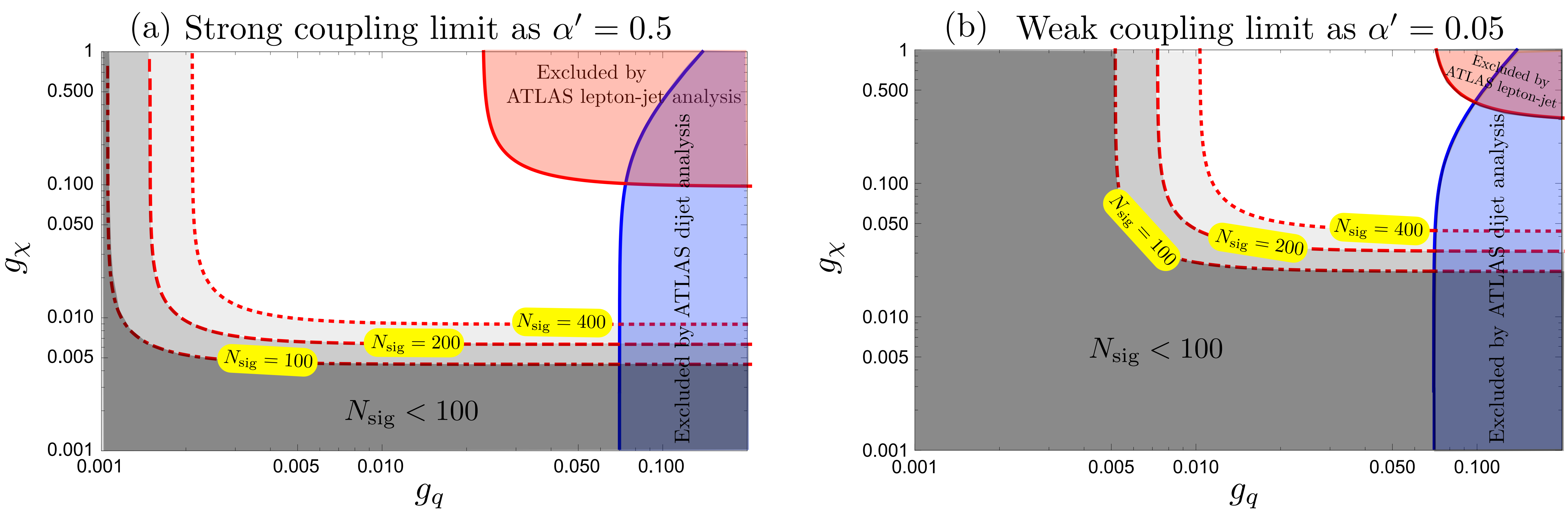
Dark Sectors 2016 Workshop
arXiv:1608.08632

M. Buschmann et.al arXiv:1505.07459



Constraints from LHC

with $M_{Z'} = 1.5$ 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