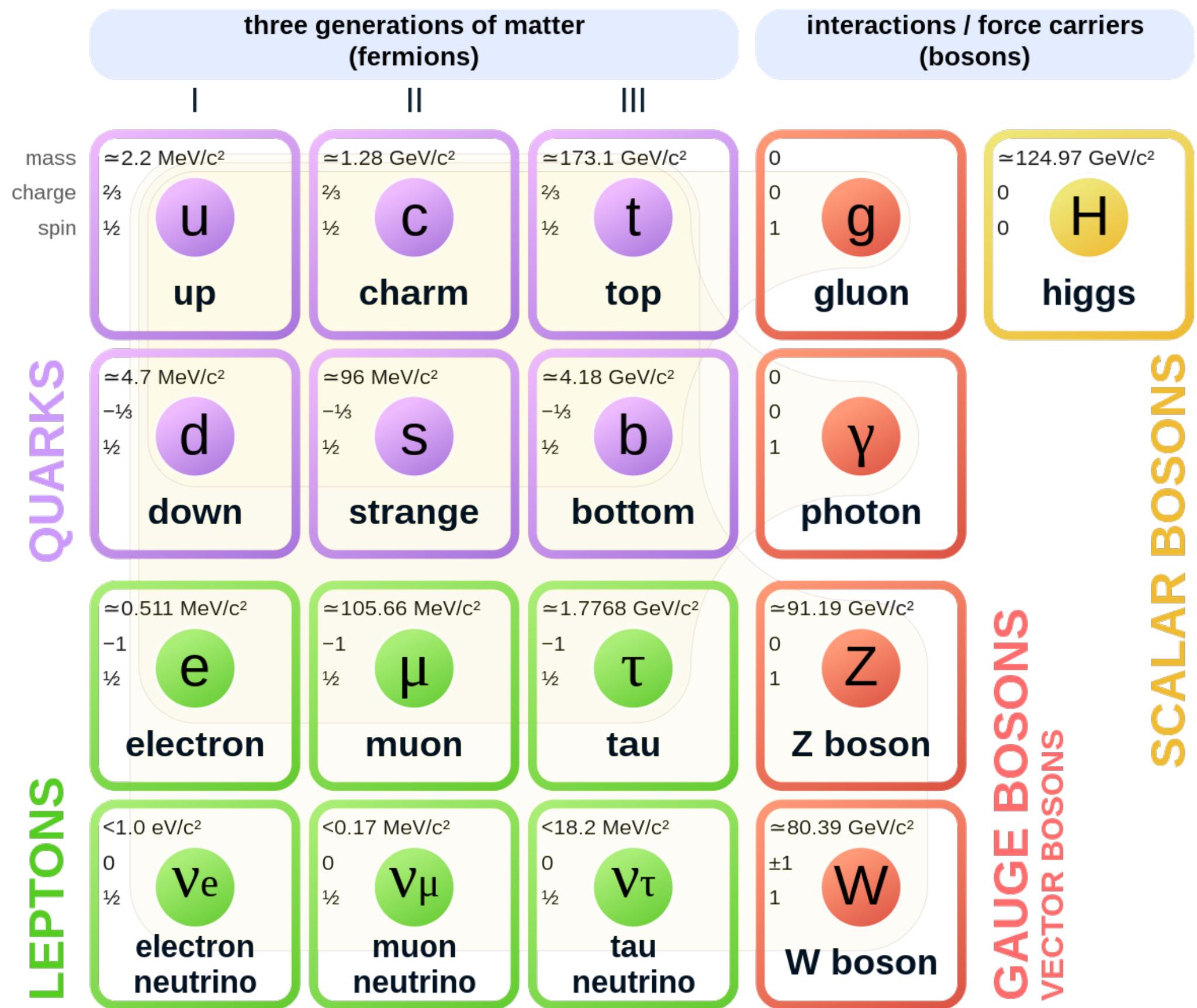


Annapaola de Cosa

# Hunting Dark Matter in Dark Showers

# Standard Model of Particle Physics

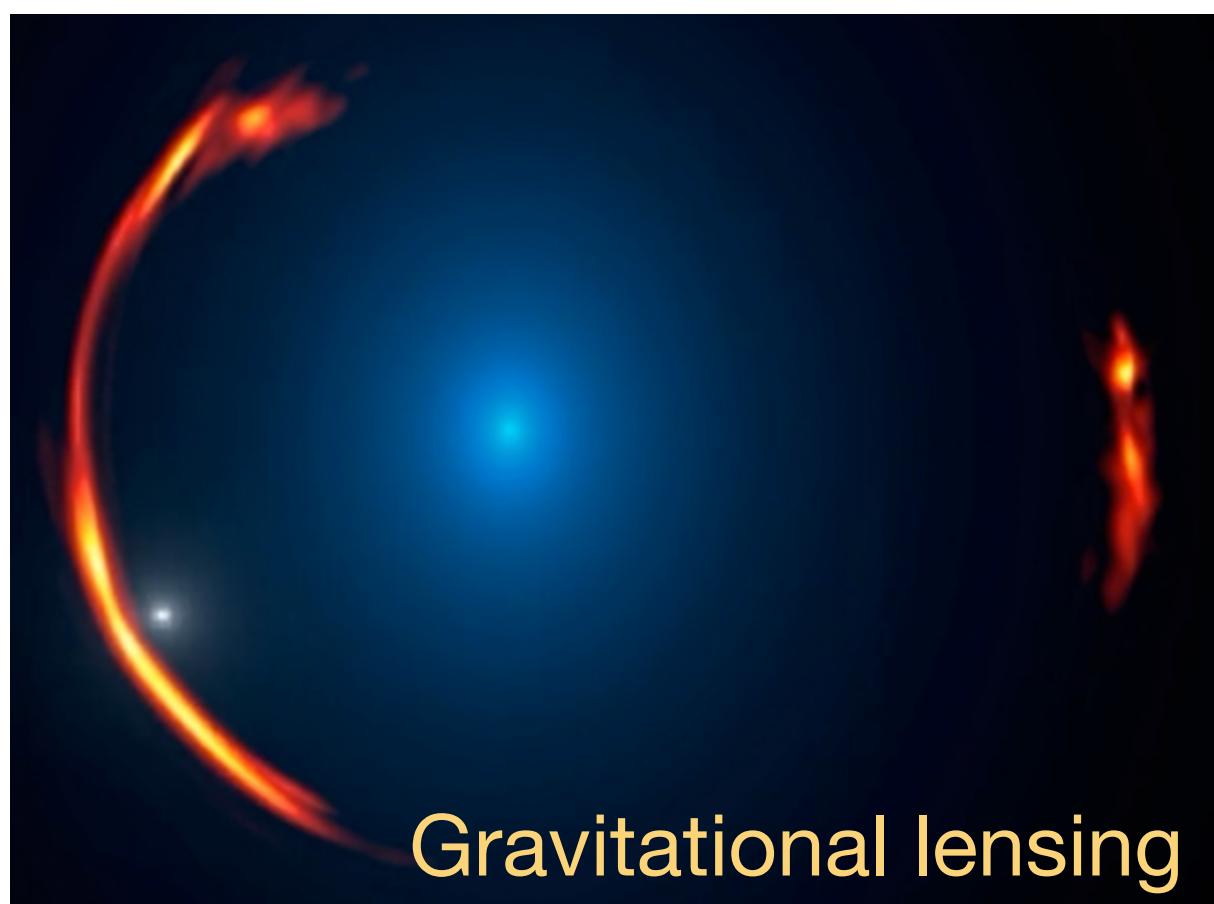
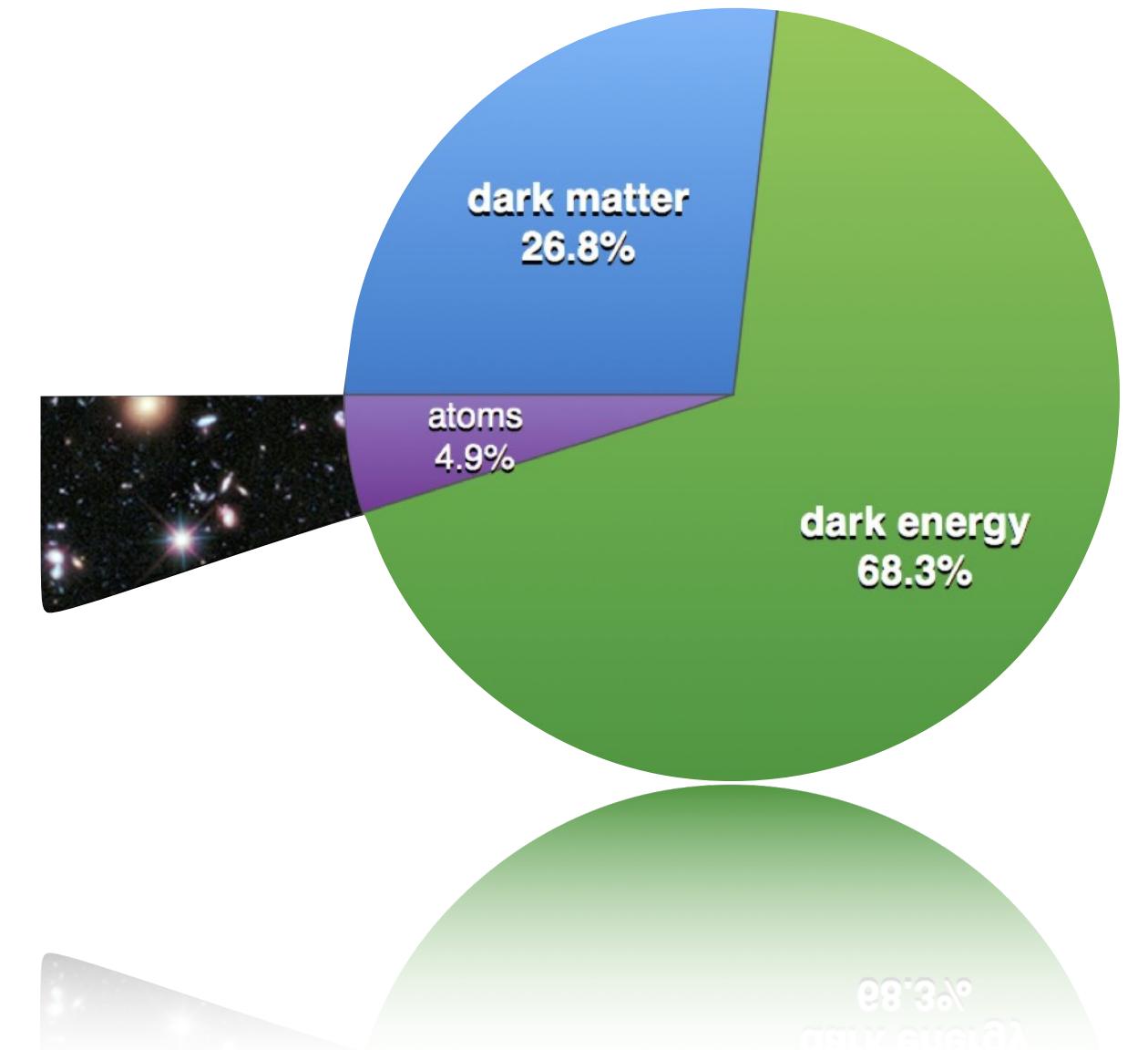
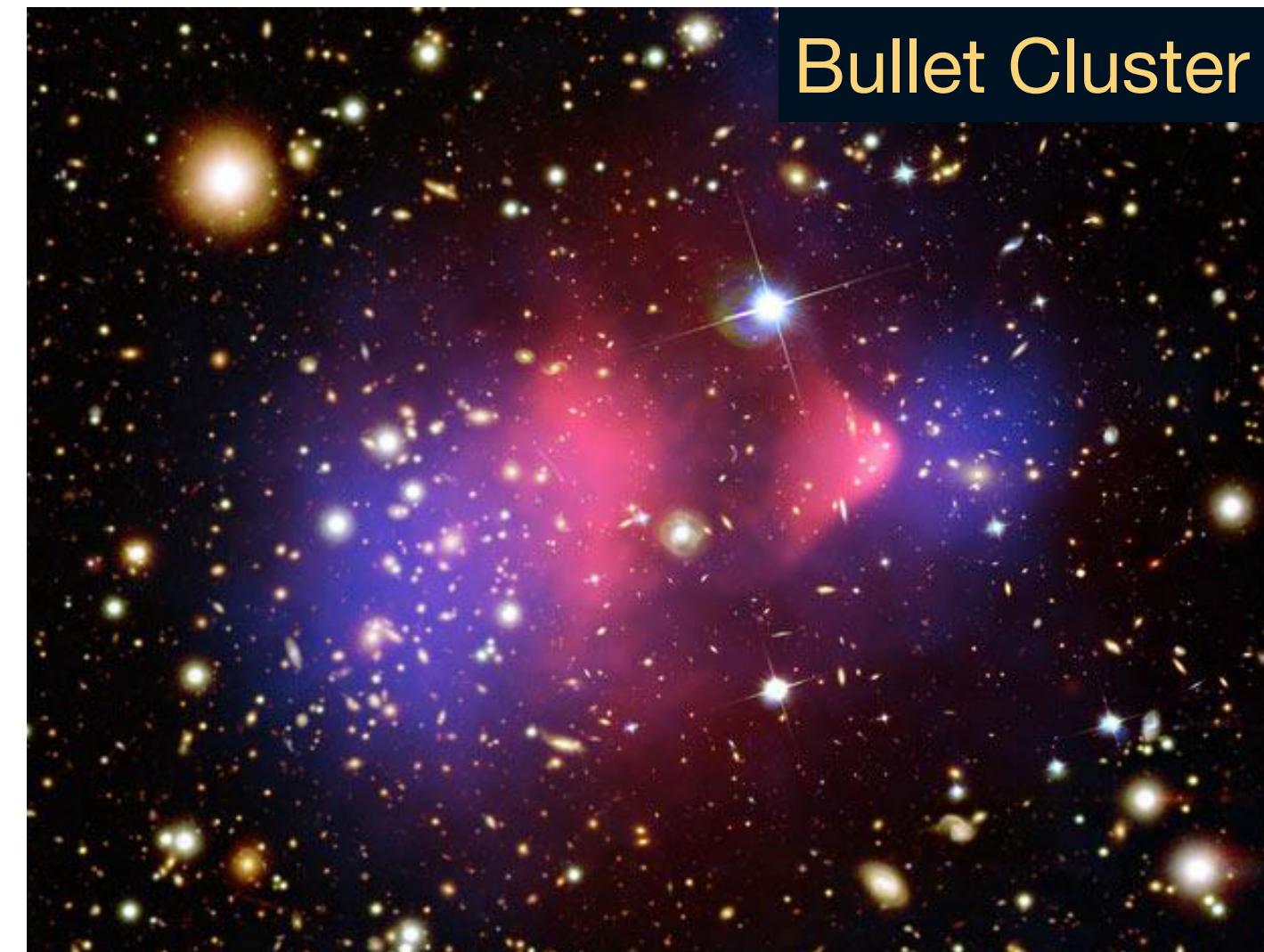
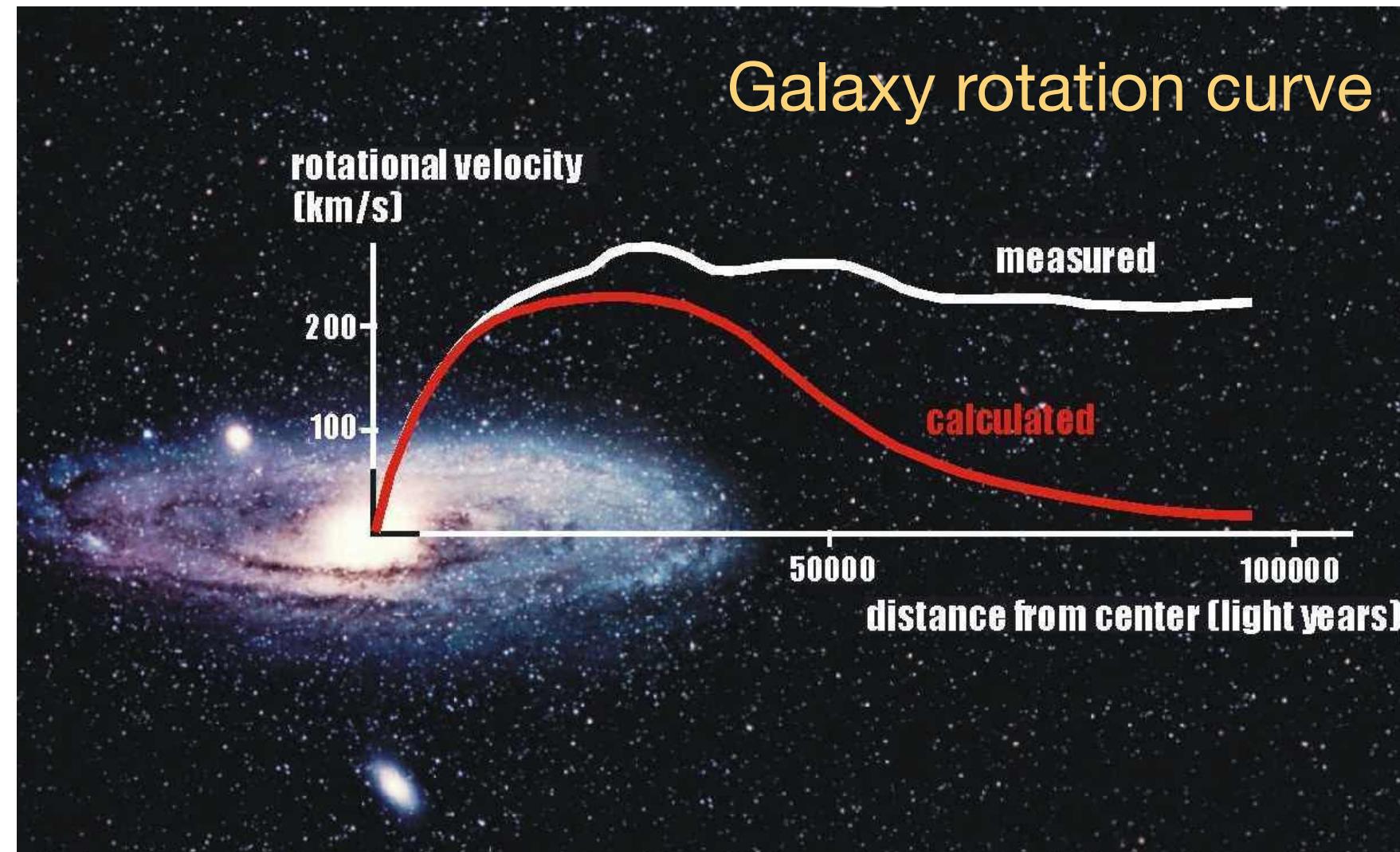
## Standard Model of Elementary Particles



### Some key open questions

- Can we fit gravity in the SM?
- Why are there three generations?
- What is the origin of particle mass hierarchy?
- Why do matter and antimatter behave differently?
- **What is Dark Matter made of?**

# Dark Matter evidence



What is Dark Matter made of?

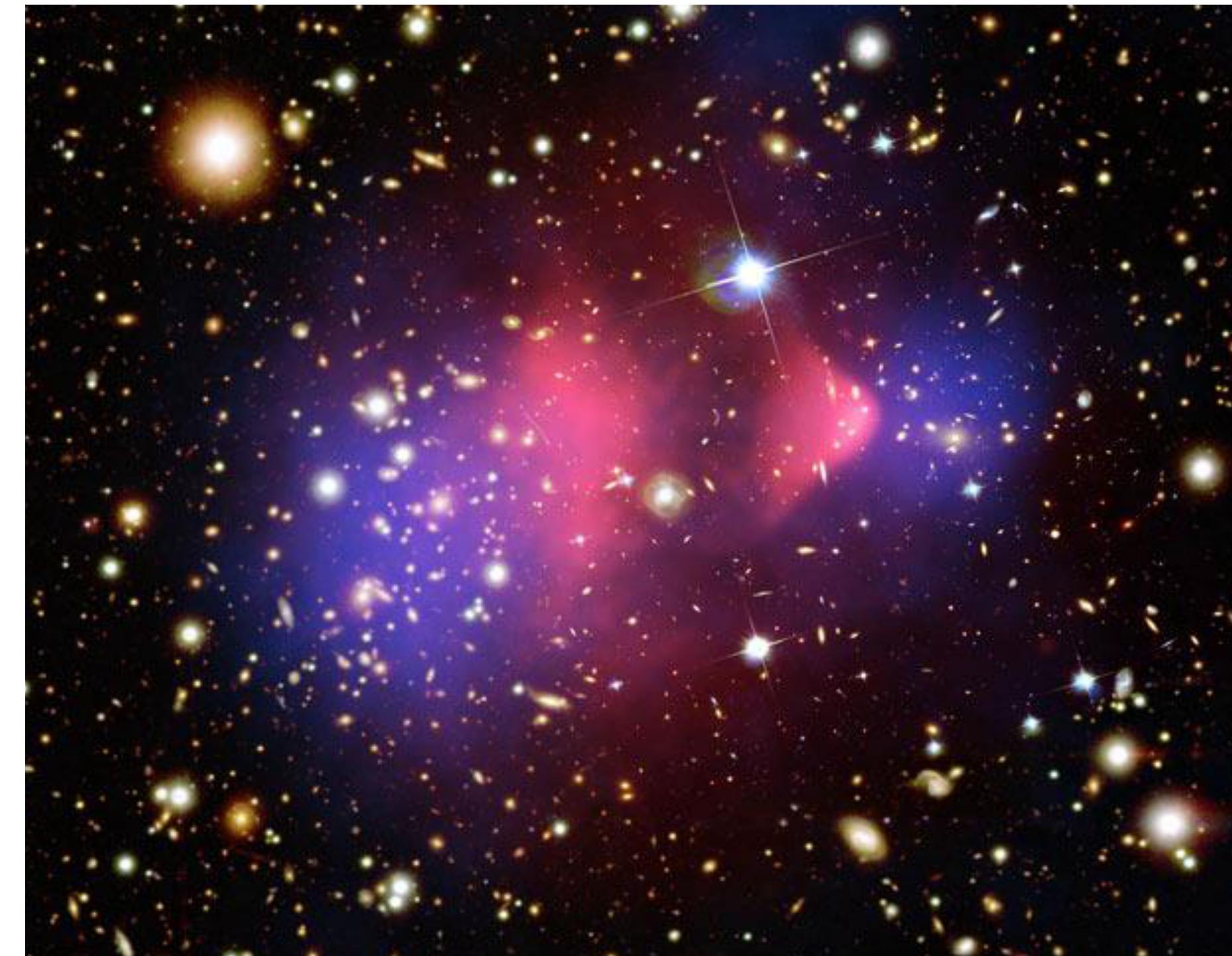
# Beyond the Standard Model

## Standard Model of Elementary Particles

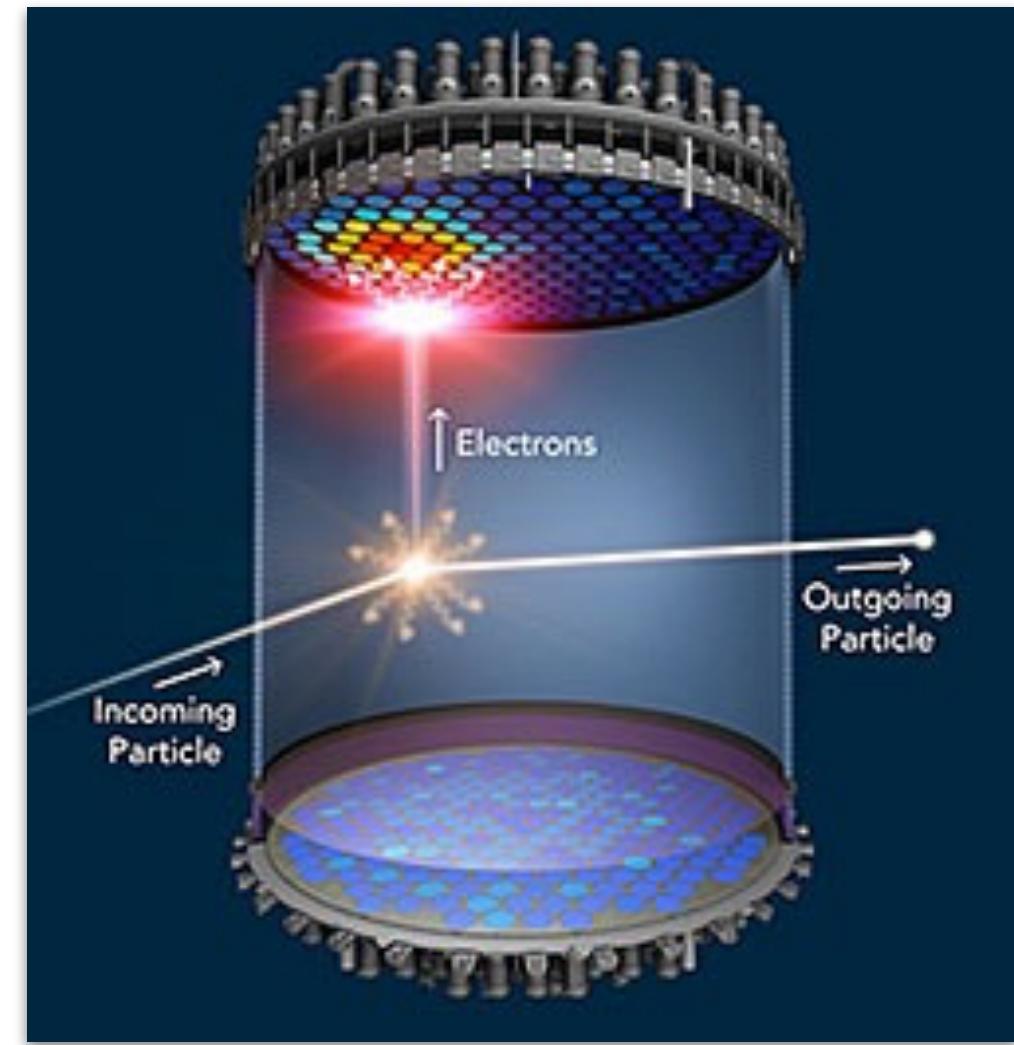
three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
mass $\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0 0 1	$\approx 124.97 \text{ GeV}/c^2$
charge $2/3$	$2/3$	$2/3$	g	H
spin $1/2$	$1/2$	$1/2$	up	charm
u	c	t	gluon	higgs
down	s	b	photon	
d	s	b		
electron	muon	tau	Z boson	
e	$\mu$	$\tau$	Z	
leptons				
electron neutrino	$\nu_\mu$	$\nu_\tau$	W boson	
$\nu_e$	$\nu_\mu$	$\nu_\tau$	W	

SCALAR BOSONS  
GAUGE BOSONS  
VECTOR BOSONS

## Dark Matter



# The quest for DM



## Direct detection

- DM-nucleon scattering

## Indirect detection

- DM annihilation products

## Particle colliders

- Direct production of DM

# The energy frontier

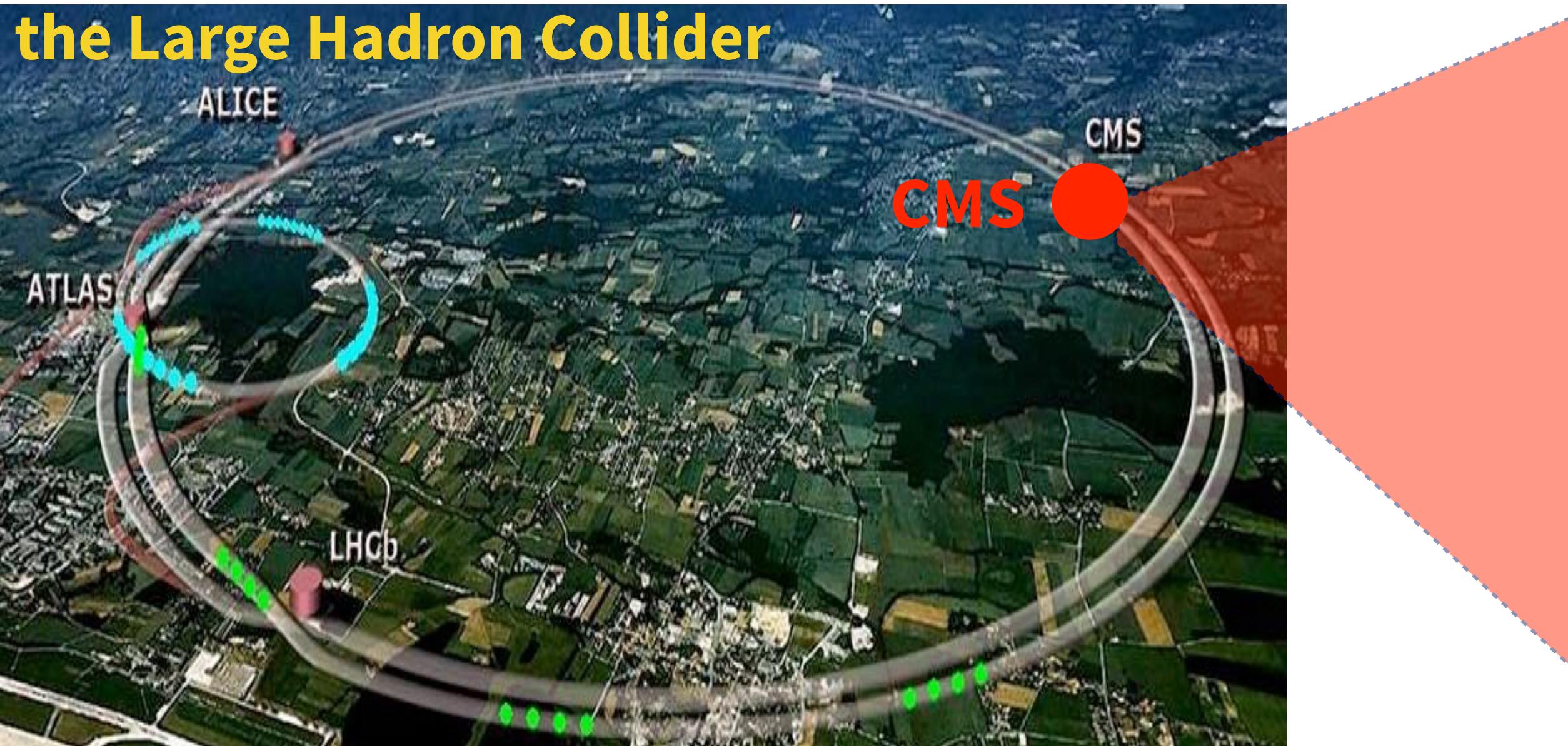
## the Large Hadron Collider

ALICE

ATLAS

LHCb

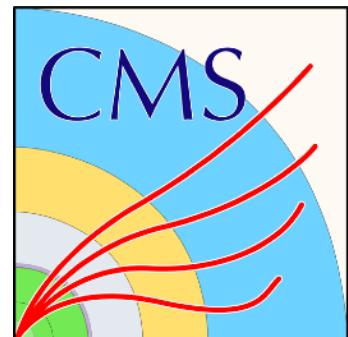
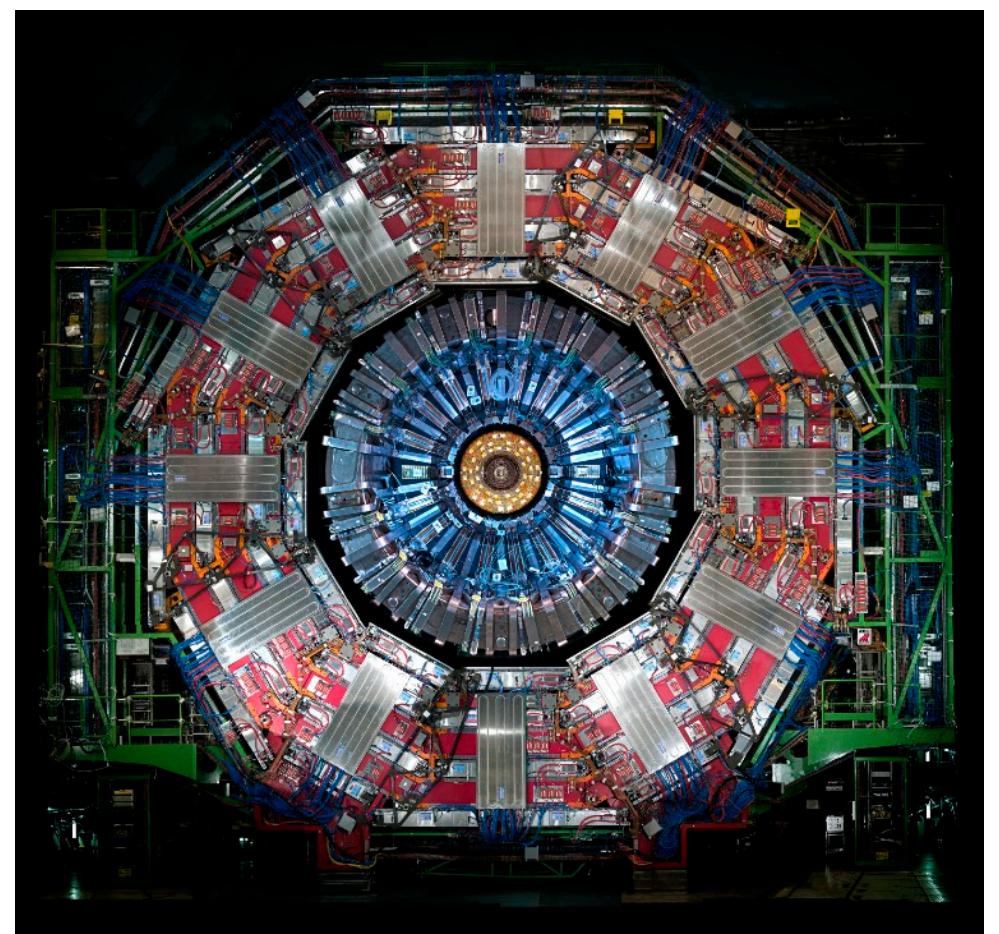
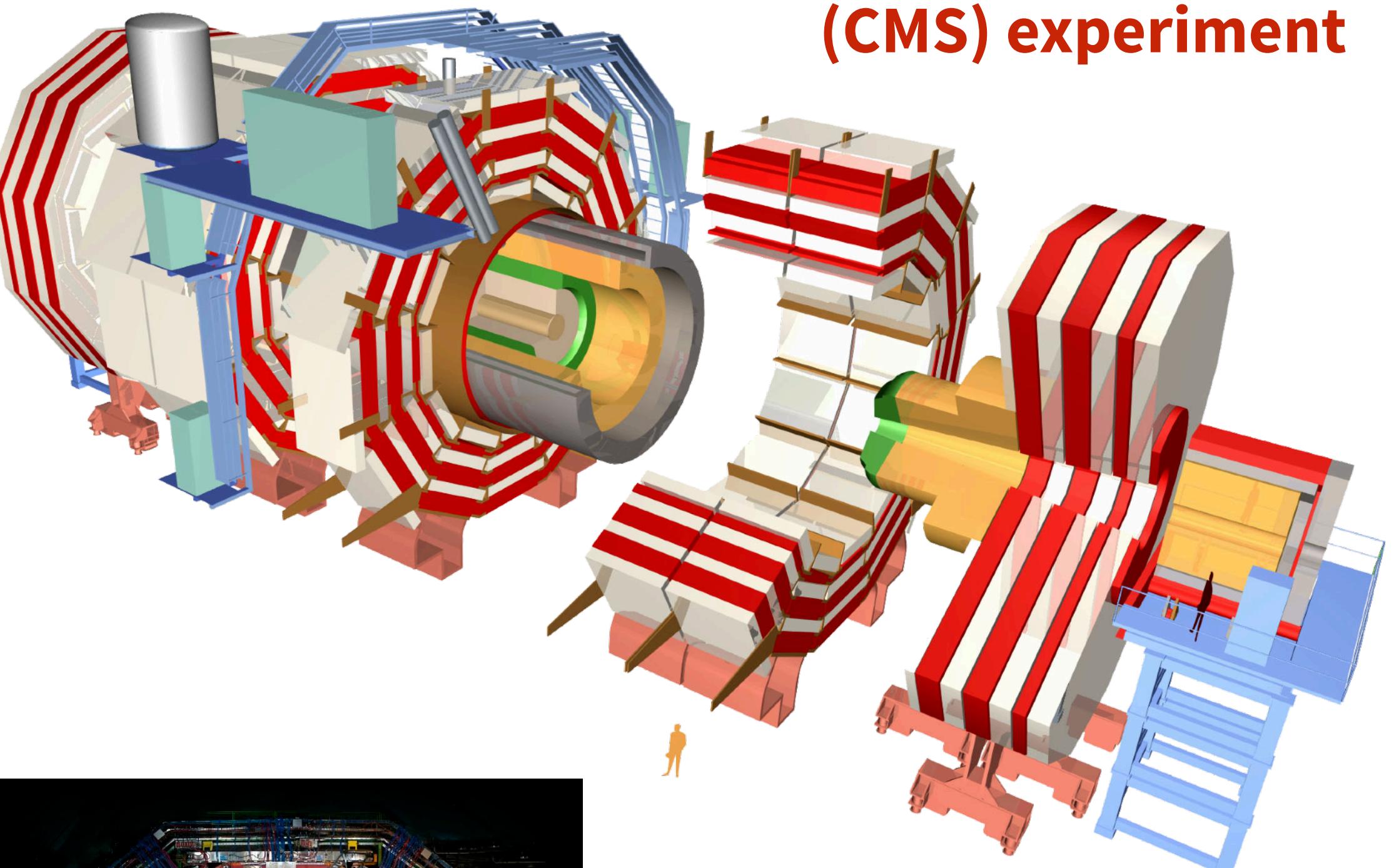
CMS



## The Large Hadron Collider

- **27 Km** circumference
- Proton-proton collisions at a centre of mass energy of **14 TeV**

## Compact Muon Solenoid (CMS) experiment



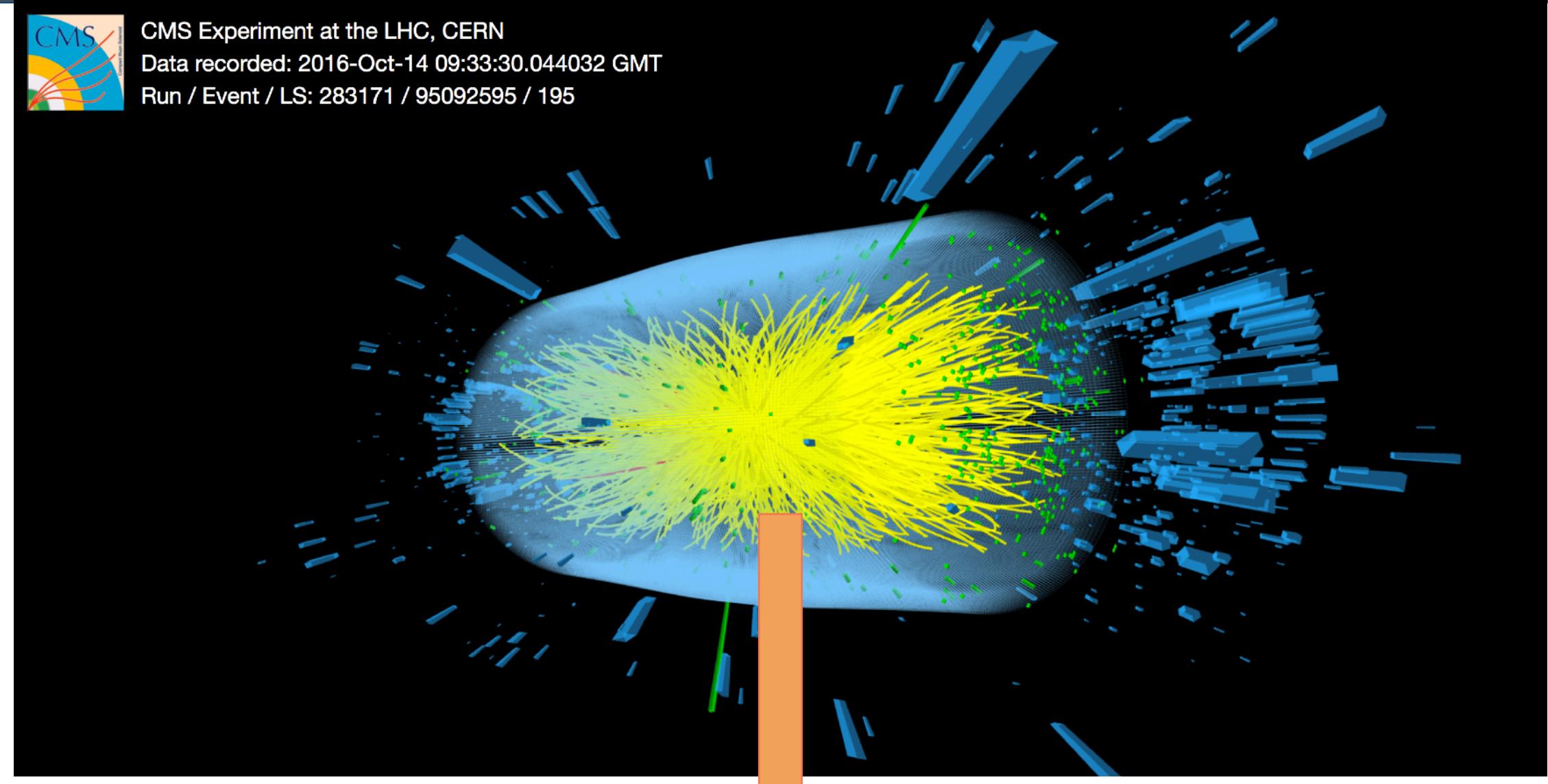
# The high intensity challenge

## New physics is very rare

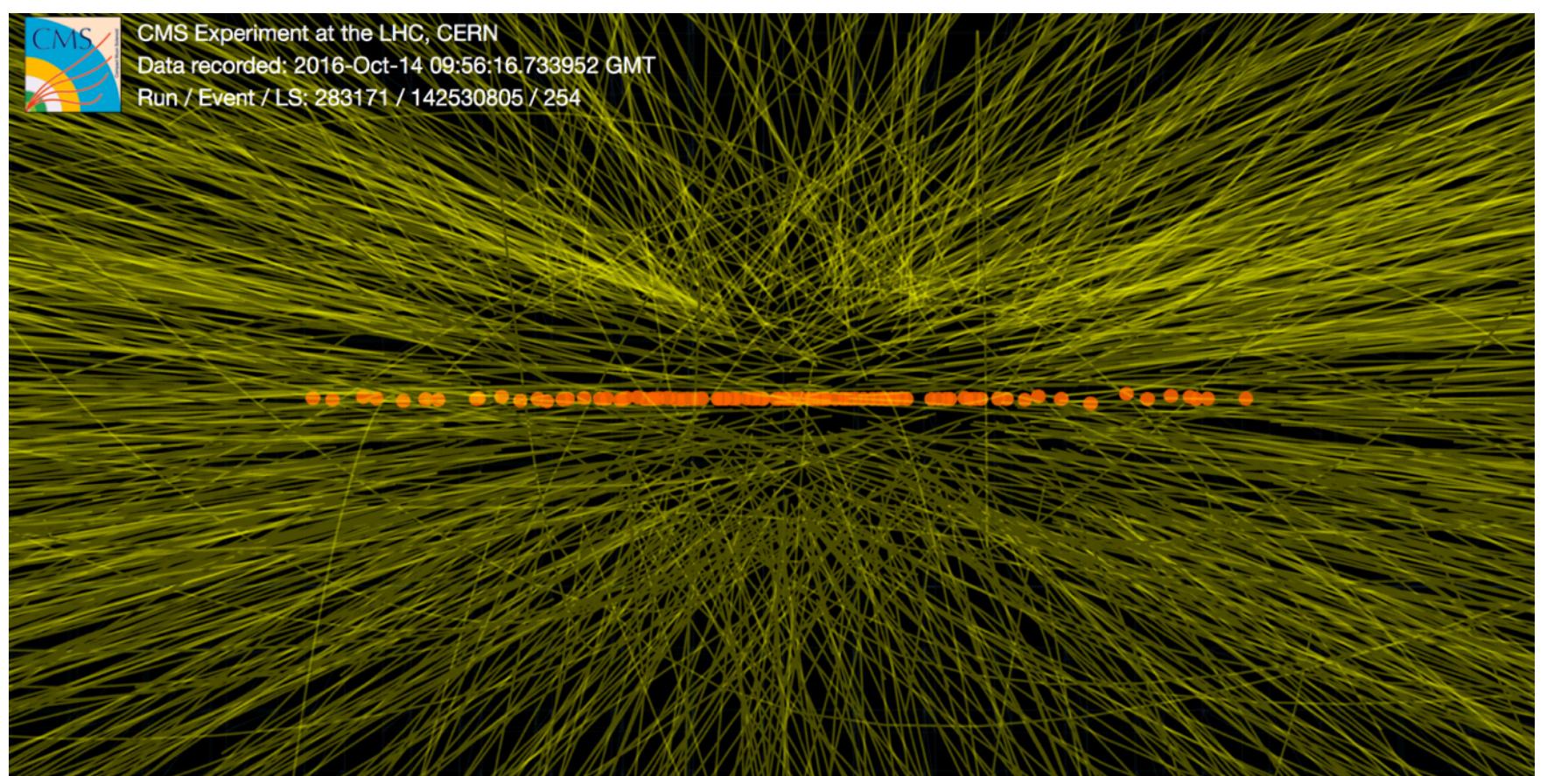
- Rates  $\sim$ **10-15 orders** of magnitude lower than most common SM processes

## High collision rate increases probability to find new particles

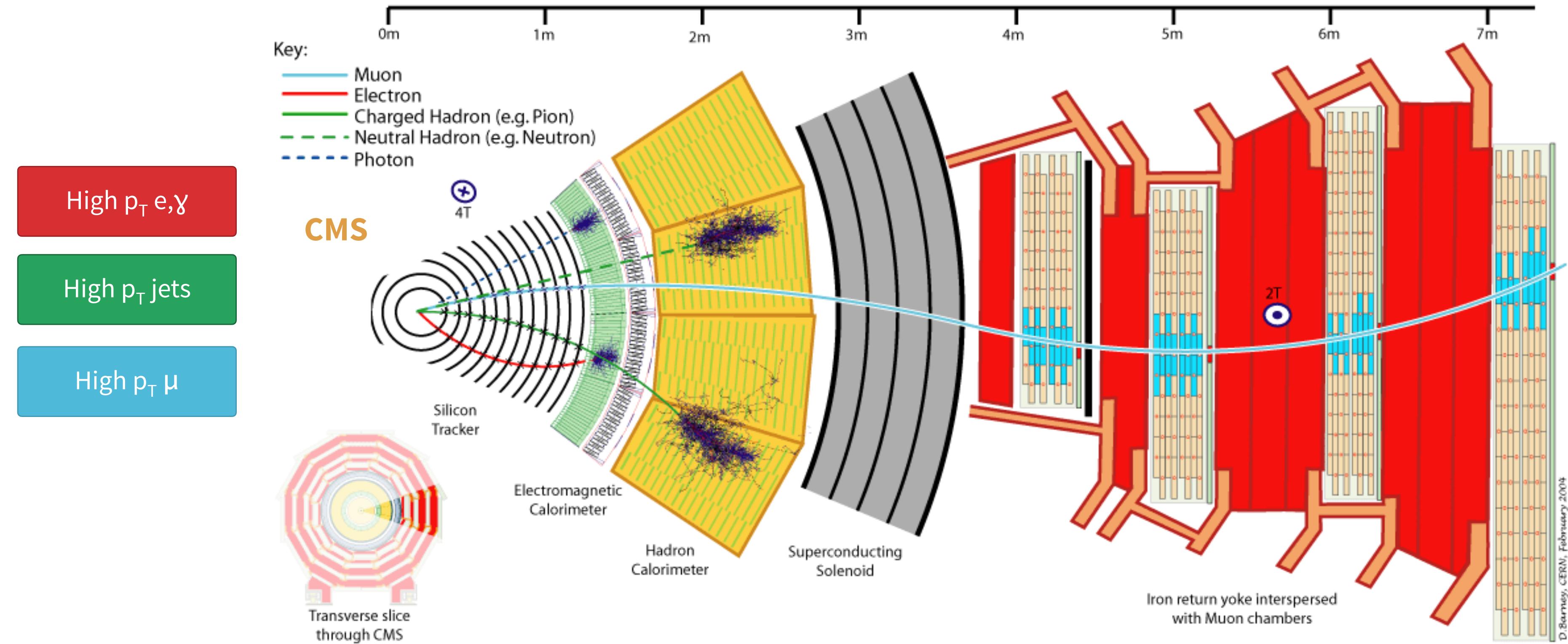
- **~600 million collisions/s**
- Just few containing interesting particles
- Tens overlapping collisions in one snapshot



100 overlapping collisions (**orange**)



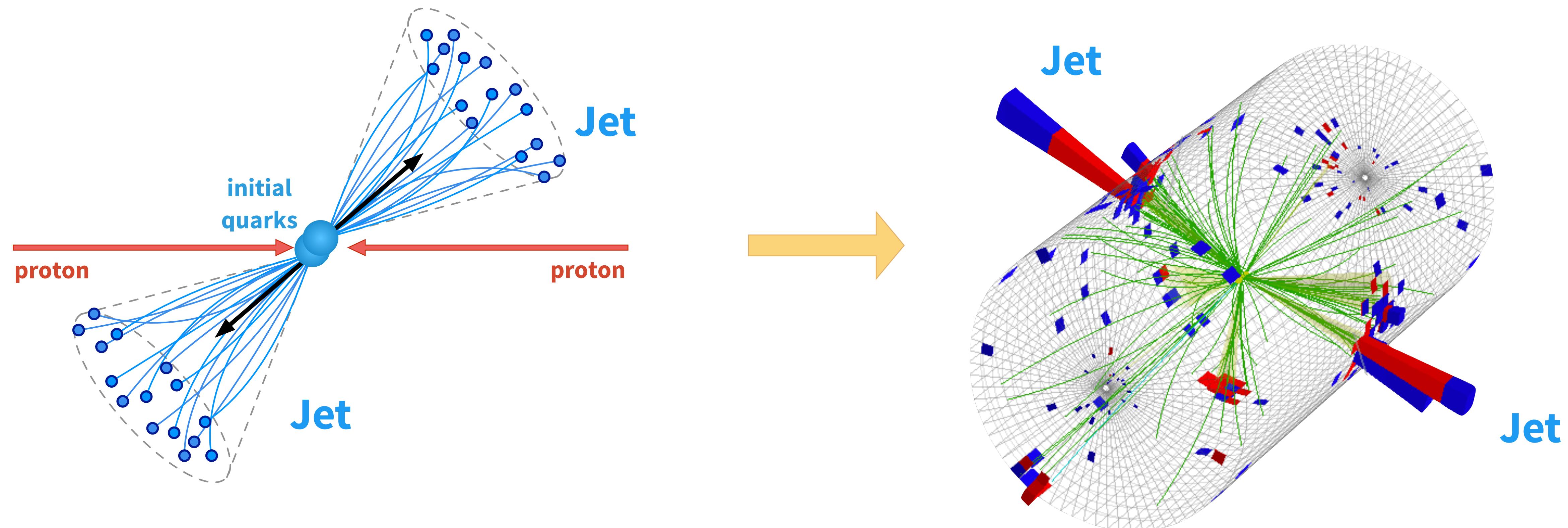
# Particle puzzle



**Visible particles are reconstructed from tracks and energy deposits in the detector**

Information from all subdetectors are combined to create a consistent set of reconstructed particles

# Particle puzzle: quarks



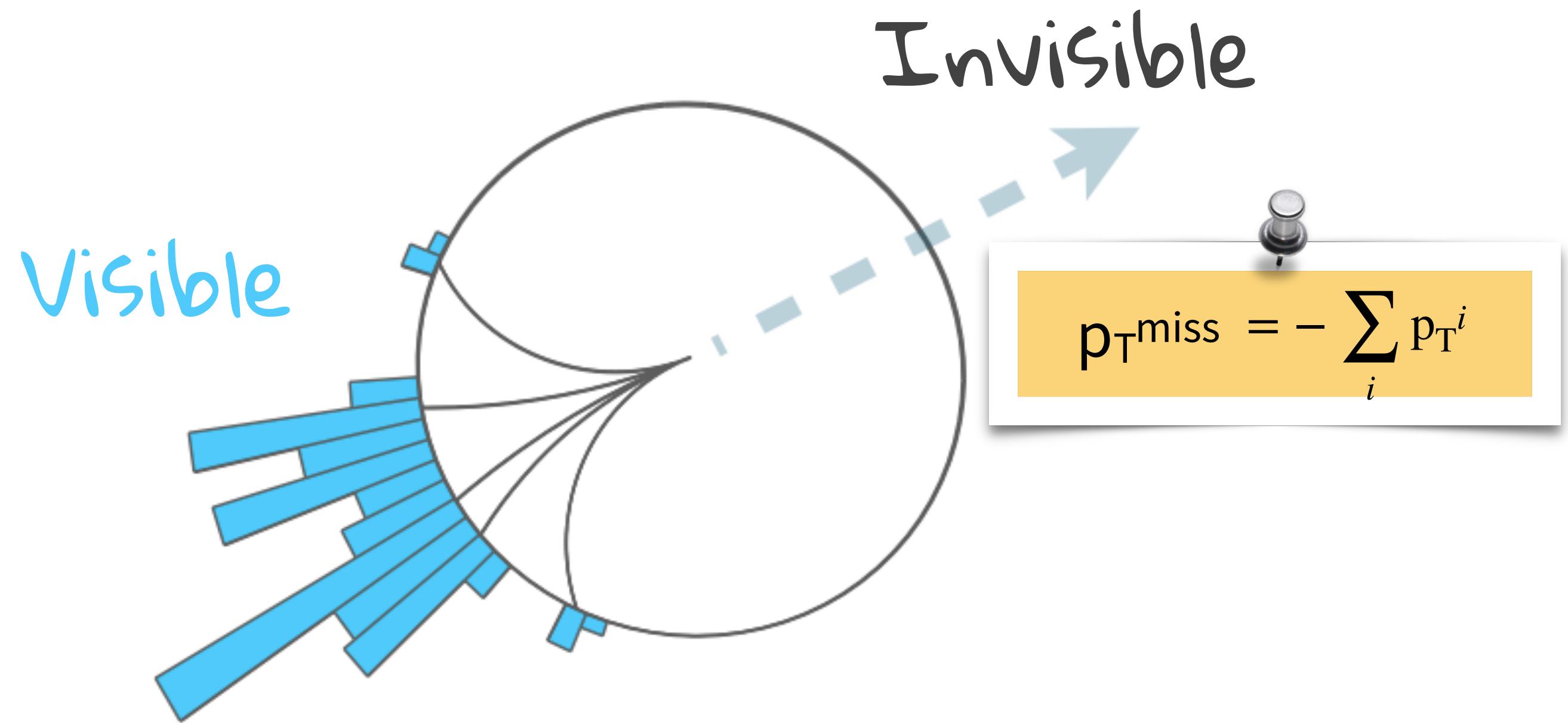
**Quarks confined into hadrons by strong interaction:**

- cannot be observed directly
- give rise to a **jet of collimated hadrons**

# Particle puzzle: Invisible particles

Invisible particles = not reconstructable

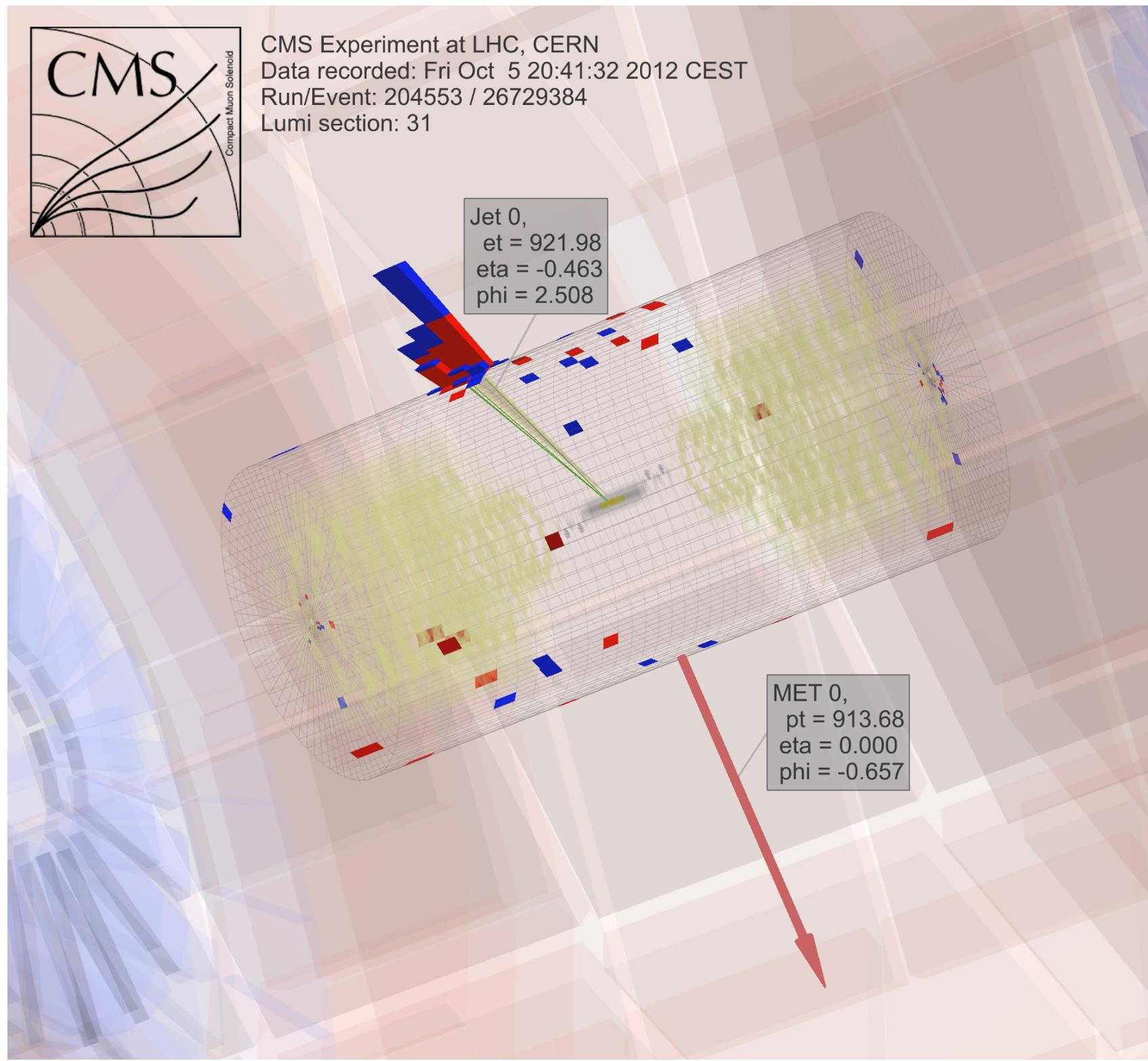
Momentum carried out by invisible particles quantified by an energy imbalance ( $p_T^{\text{miss}}$ ) in the event collision products



# Particle puzzle: Invisible particles

Invisible particles = not reconstructable

Momentum carried out by invisible particles quantified by an **energy imbalance** ( $p_T^{\text{miss}}$ ) in the event collision products



**Missing momentum reconstructed from all visible particles**

- **Genuine missing momentum** from neutrinos or new invisible particles
- **Artificial missing momentum** from instrumental effects

**Challenge: need good reconstruction of visible particles**

# DM hypotheses

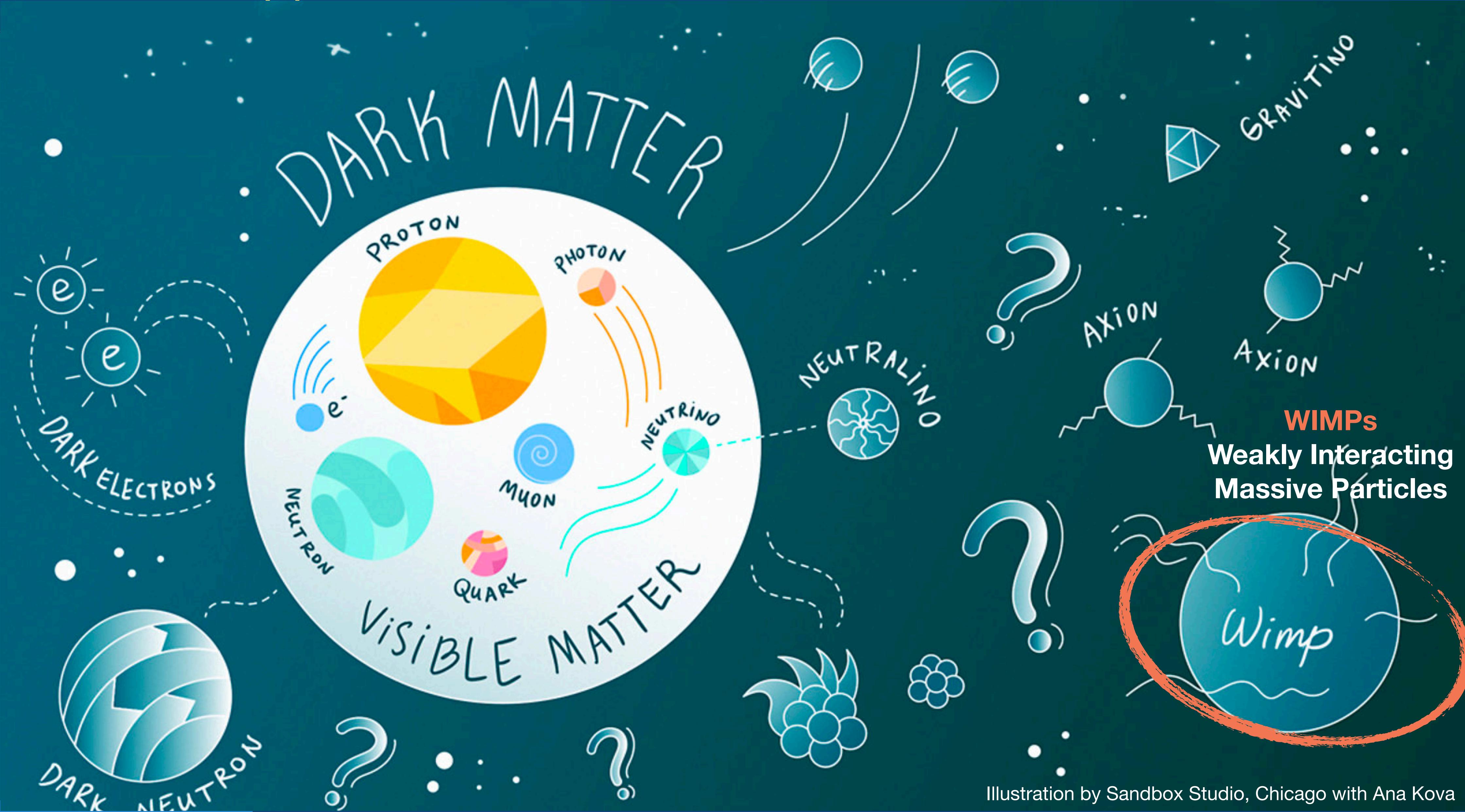
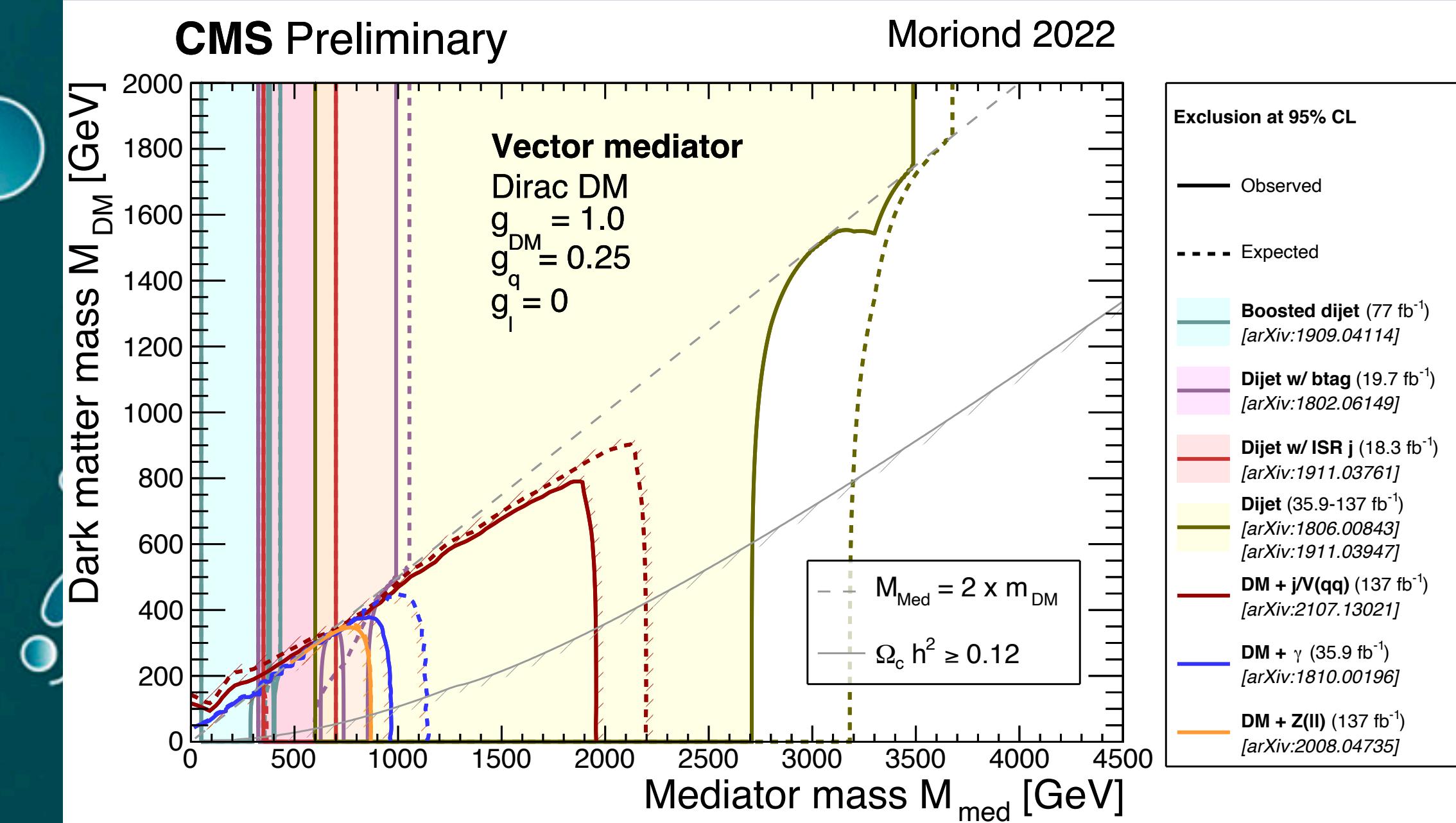


Illustration by Sandbox Studio, Chicago with Ana Kova

# DM searches at colliders

Illustration by Sandbox Studio, Chicago with Ana Kova



**Most popular DM hypotheses, like Weakly Interacting Massive Particles (WIMPs), largely excluded**

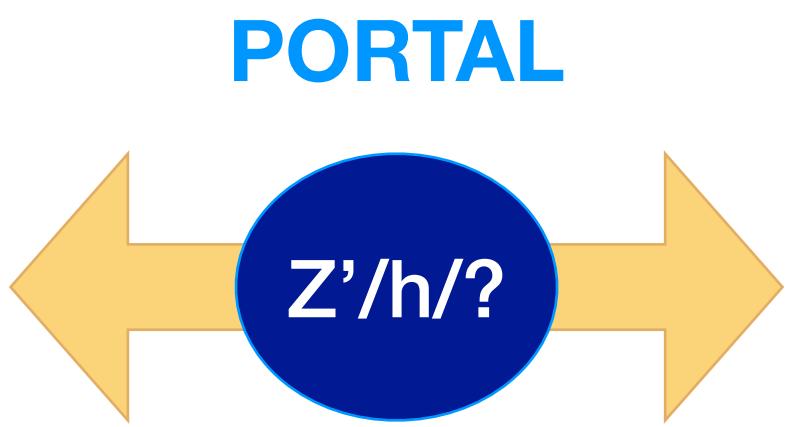
- Need to explore new models
- Use new experimental techniques

# Dark Matter in a Hidden Valley

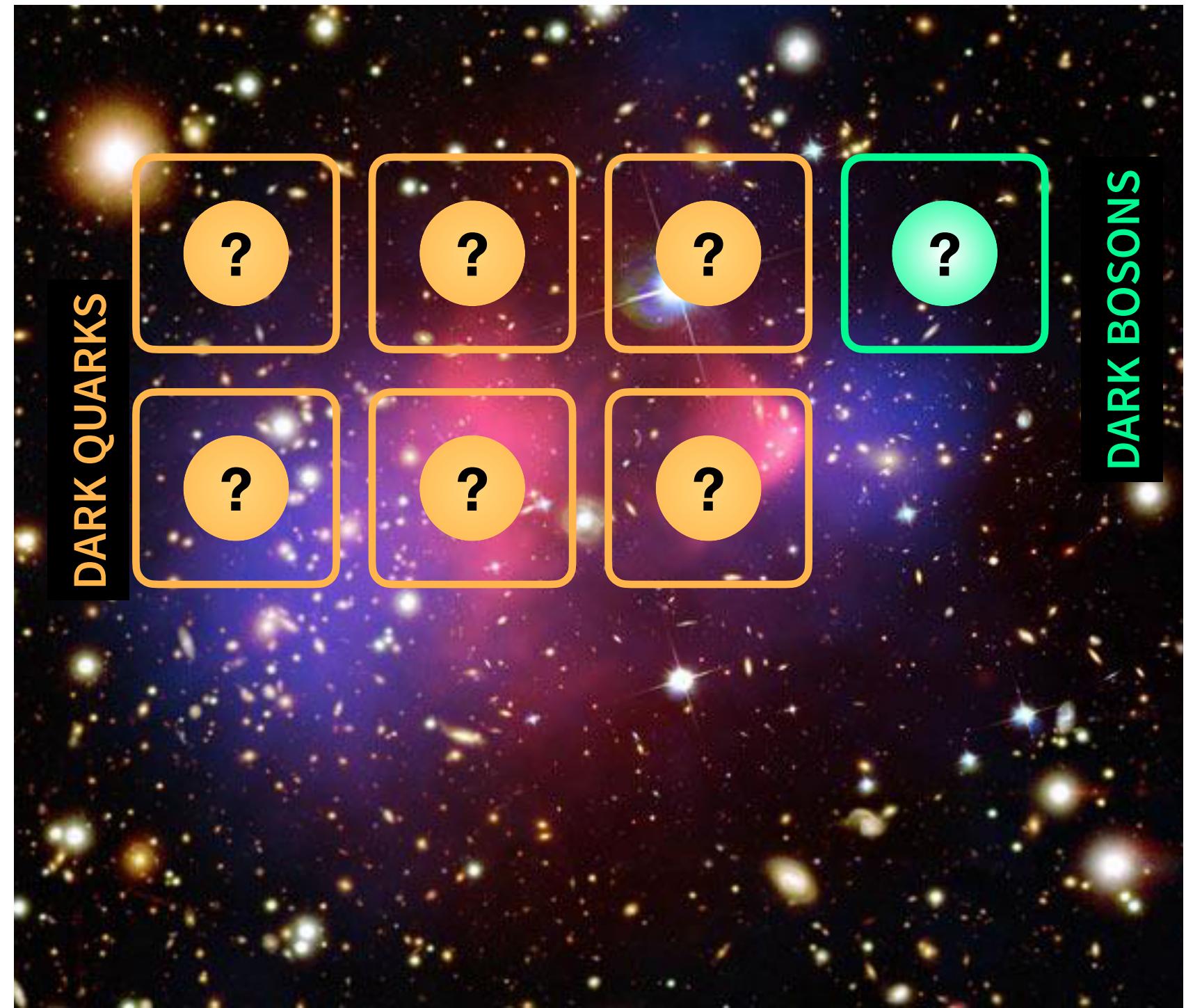
## Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
mass charge spin	$\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ U up	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ C charm	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 g gluon
mass charge spin	$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$\approx 96 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 $\gamma$ photon
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$ $-1$ $\frac{1}{2}$ e electron	$\approx 105.66 \text{ MeV}/c^2$ $-1$ $\frac{1}{2}$ $\mu$ muon	$\approx 1.7768 \text{ GeV}/c^2$ $-1$ $\frac{1}{2}$ $\tau$ tau	$\approx 91.19 \text{ GeV}/c^2$ $0$ 1 Z Z boson
	$<1.0 \text{ eV}/c^2$ 0 $\frac{1}{2}$ $\nu_e$ electron neutrino	$<0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ $\nu_\mu$ muon neutrino	$<18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ $\nu_\tau$ tau neutrino	$\approx 80.39 \text{ GeV}/c^2$ $\pm 1$ 1 W W boson

SCALAR BOSONS  
GAUGE BOSONS  
VECTOR BOSONS



## Dark Sector



# Dark QCD-like scenarios

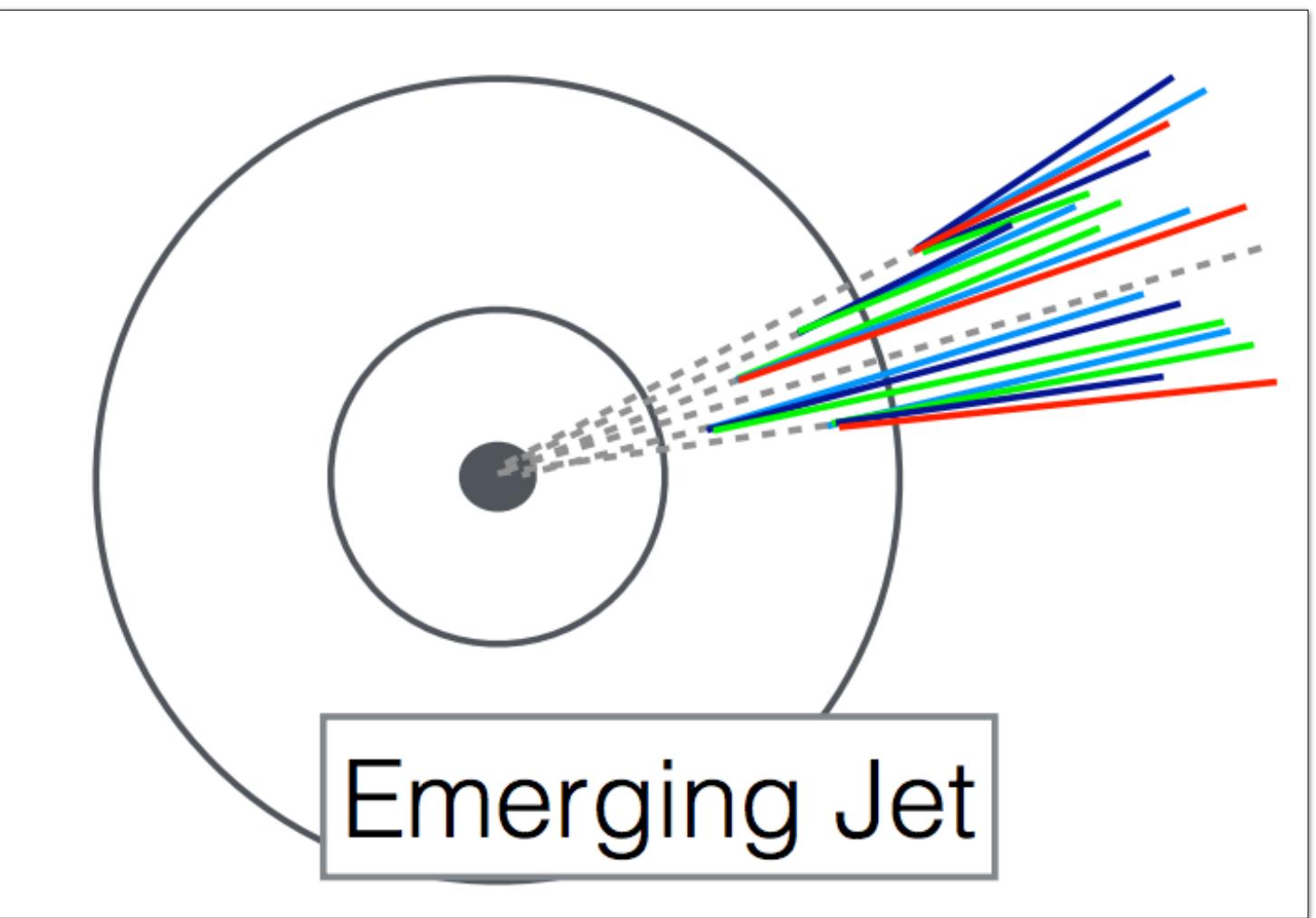
## In a Dark QCD-like scenario

- Dark sector confines below a confinement scale ( $\Lambda_{\text{cdark}}$ ) giving dark hadrons
- **Dark quarks undergo rapid hadronization**
- Dark hadrons **decay to SM particles** (at least in part) **with potentially sizeable lifetime**

# Dark QCD-like scenarios

## In a Dark QCD-like scenario

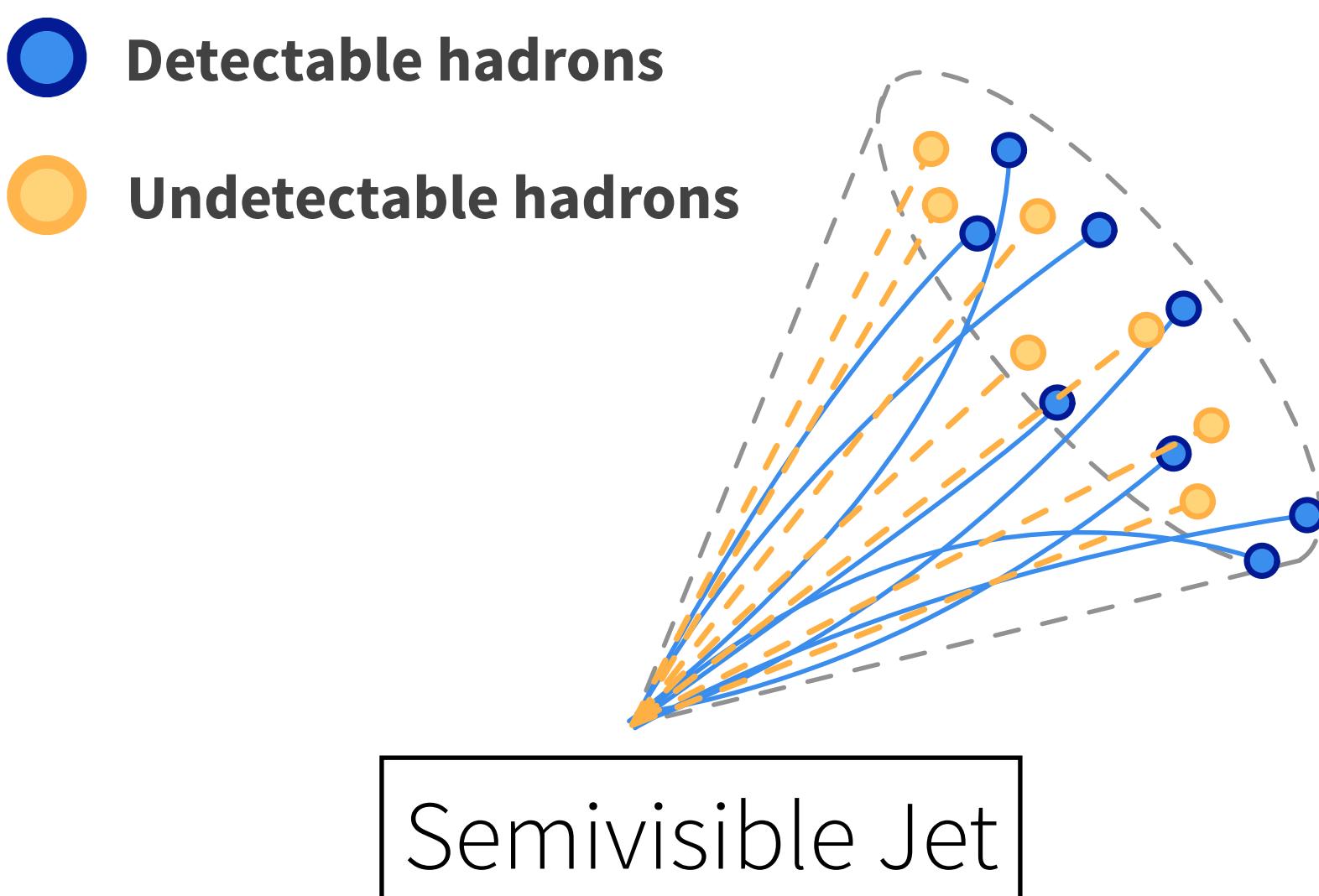
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- **Dark quarks undergo rapid hadronization**
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## LHC phenomenology very much dependent on model details

- Dynamic of dark sector shower define the phenomenology
- Can lead to **semivisible jets** or **emerging jets** signatures (if  $m_{\text{dark}} < \Lambda_{\text{cdark}} < \sqrt{s}$ )

## Signatures poorly or not at all explored

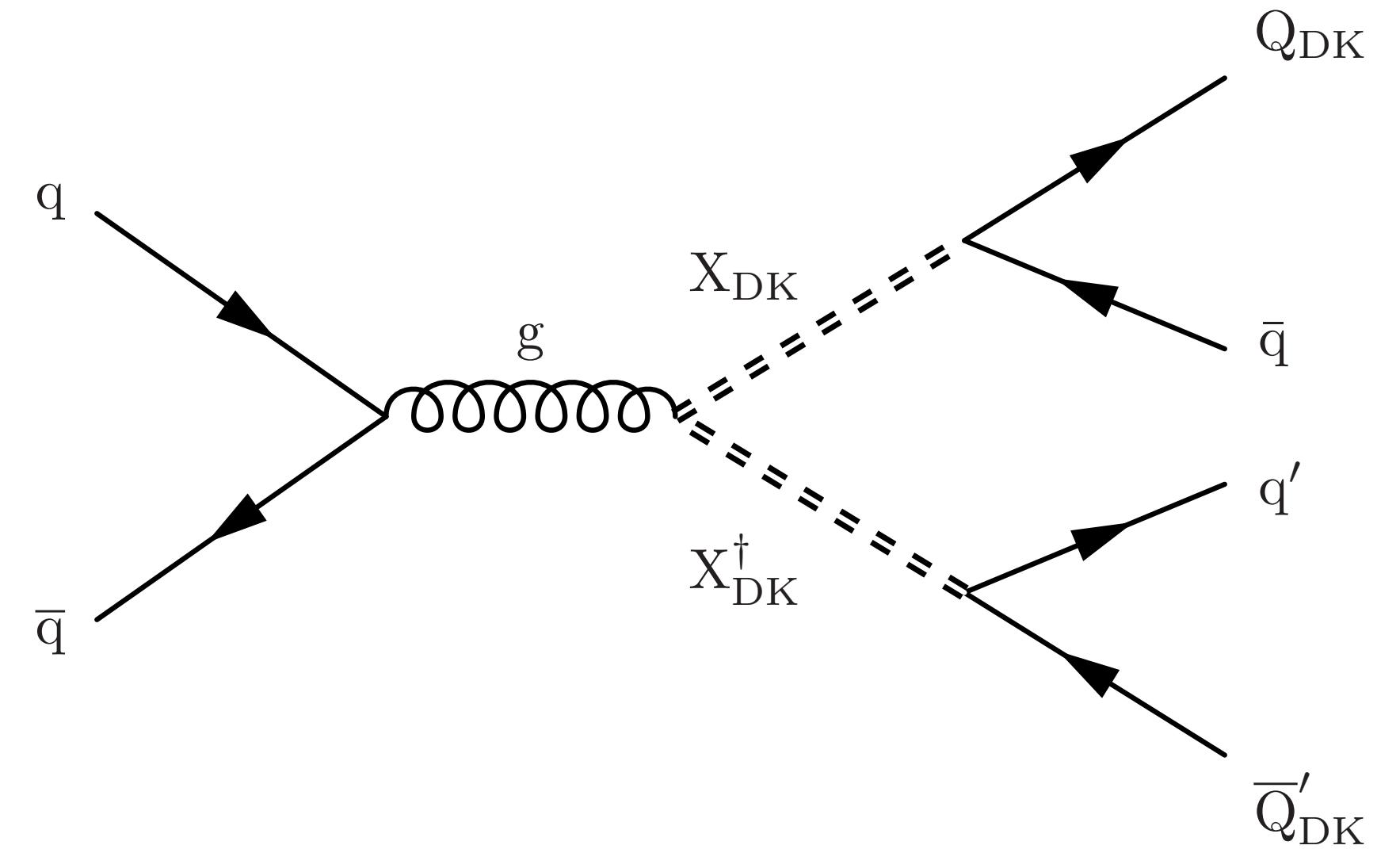


# Particle Puzzle: Emerging jets

## Electrically neutral dark quarks ( $Q_{DK}$ )

- Self interacting within the dark sector via a new **QCD-like fundamental force**
- **Dark quarks bound into dark hadrons**
- SM-DS interaction mediated by a scalar bifundamental ( $X_{DK}$ ) charged under both SM and dark QCD

## DM baryons as DM candidate



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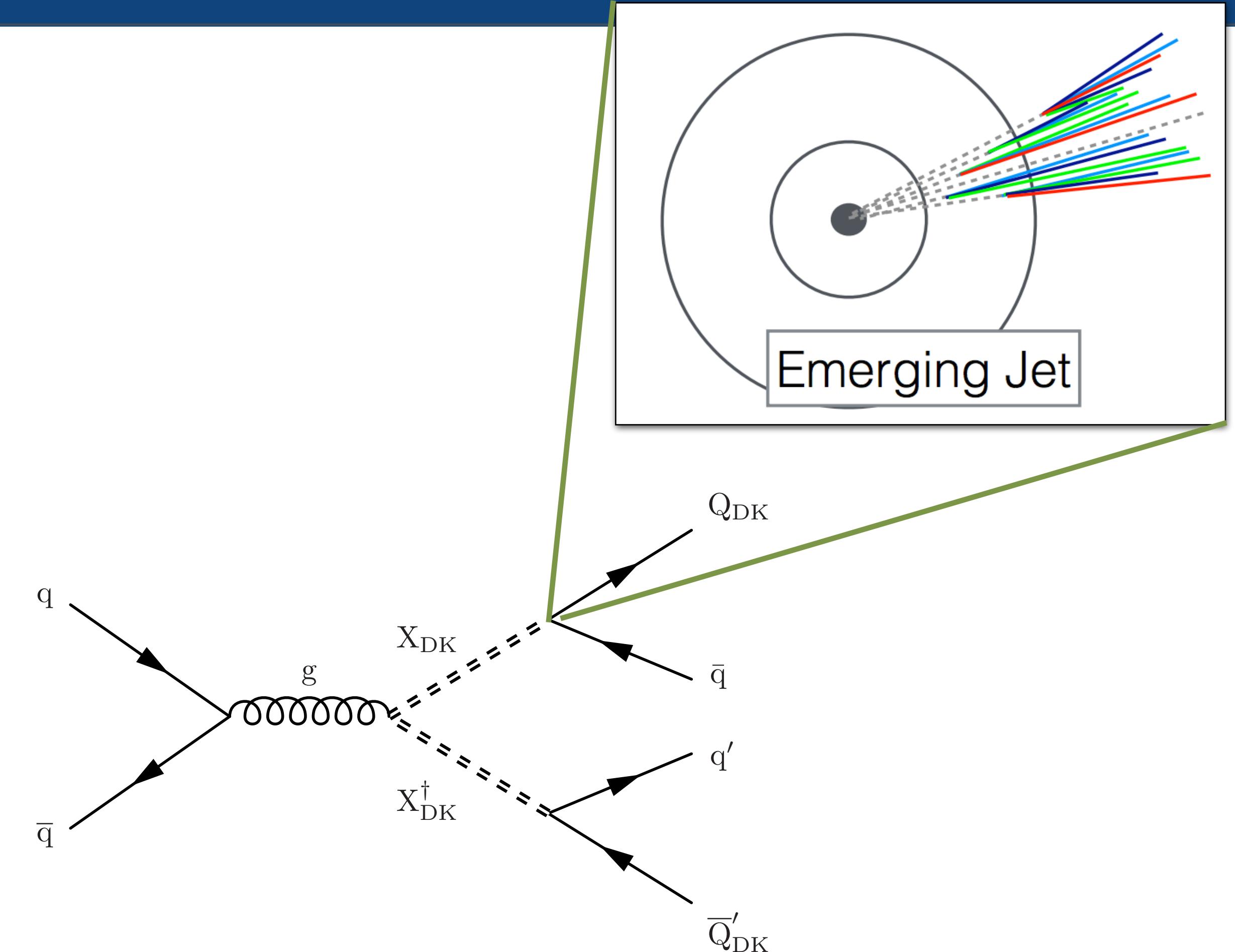
## DM baryons as DM candidate

## Emerging jets from dark shower

- Dark pion decay length define phenomenology
  - EJ look like normal jets but contain **multiple displaced vertices** from dark pion decays

## Dark Pion decay length –

$$c\tau \approx 80 \text{ mm} \left( \frac{1}{\kappa^4} \right) \left( \frac{2 \text{ GeV}}{f_{\pi_{DK}}} \right)^2 \left( \frac{100 \text{ MeV}}{m_{\text{down}}} \right)^2 \left( \frac{2 \text{ GeV}}{m_{\pi_{DK}}} \right) \left( \frac{m_{X_{DK}}}{1 \text{ TeV}} \right)^4$$



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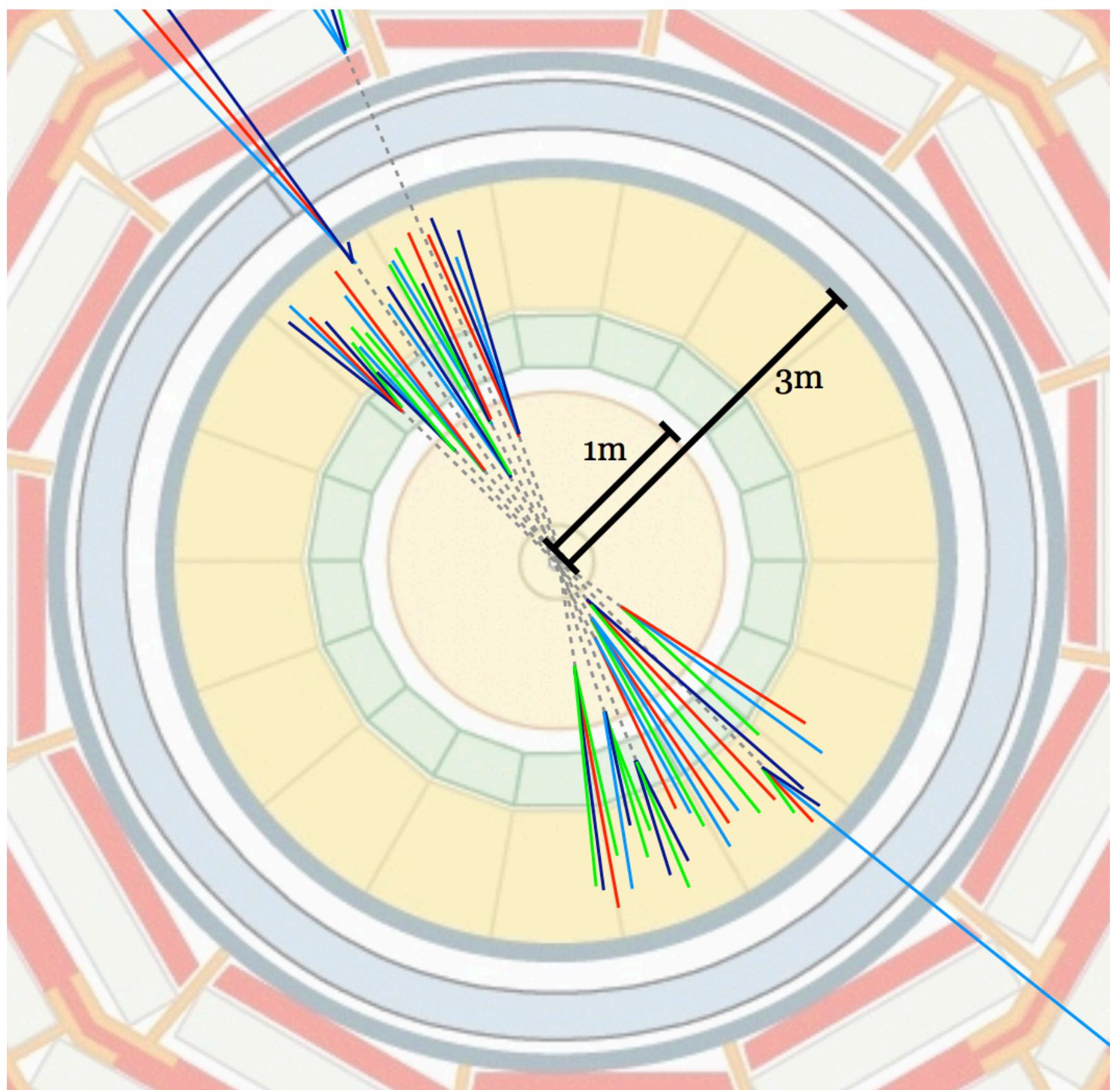
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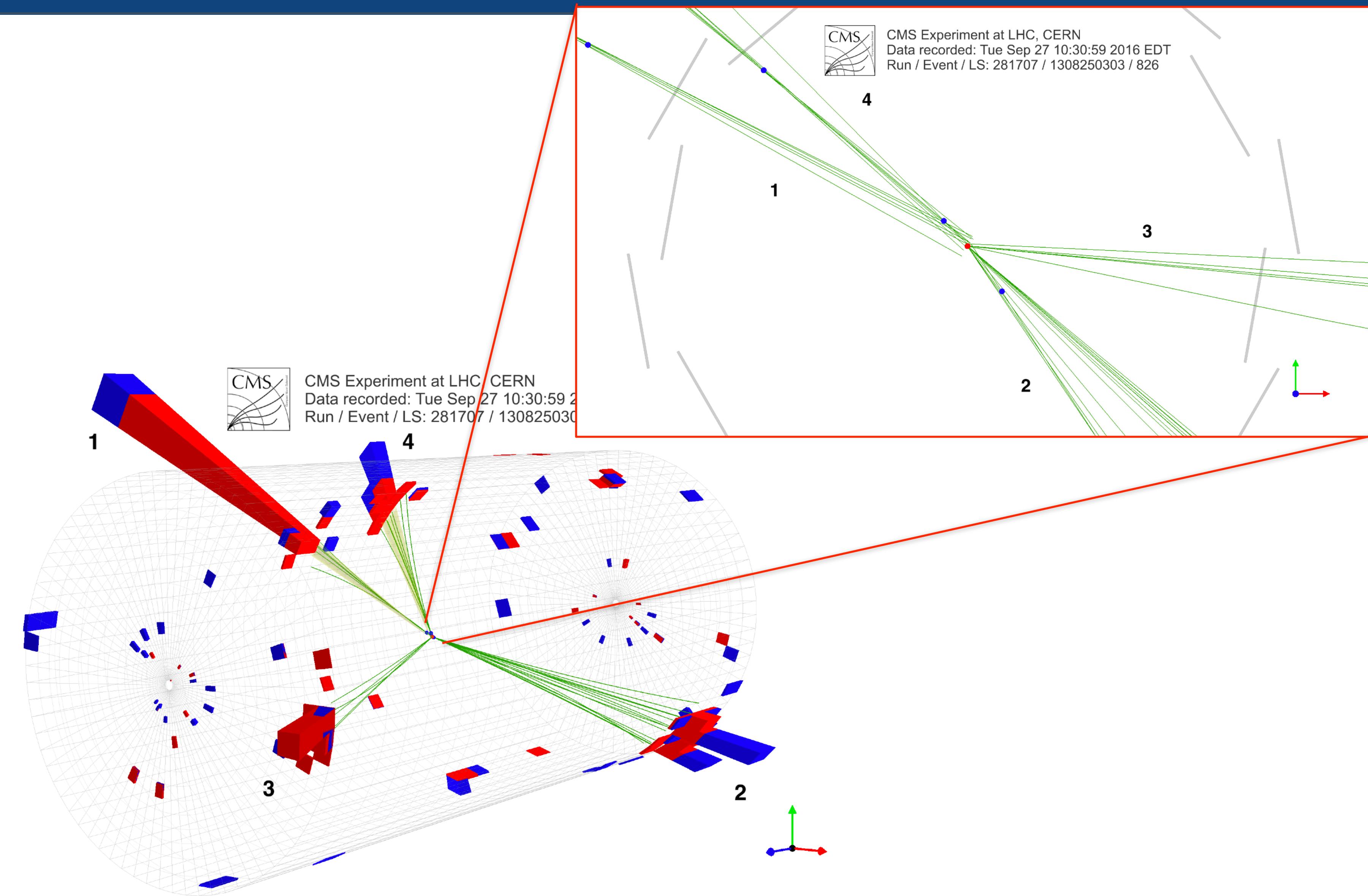
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**Signature: 2 SM jets + 2 Emerging jets**

Can have large  $p_T^{\text{miss}}$  if  $c\tau_\pi$  large

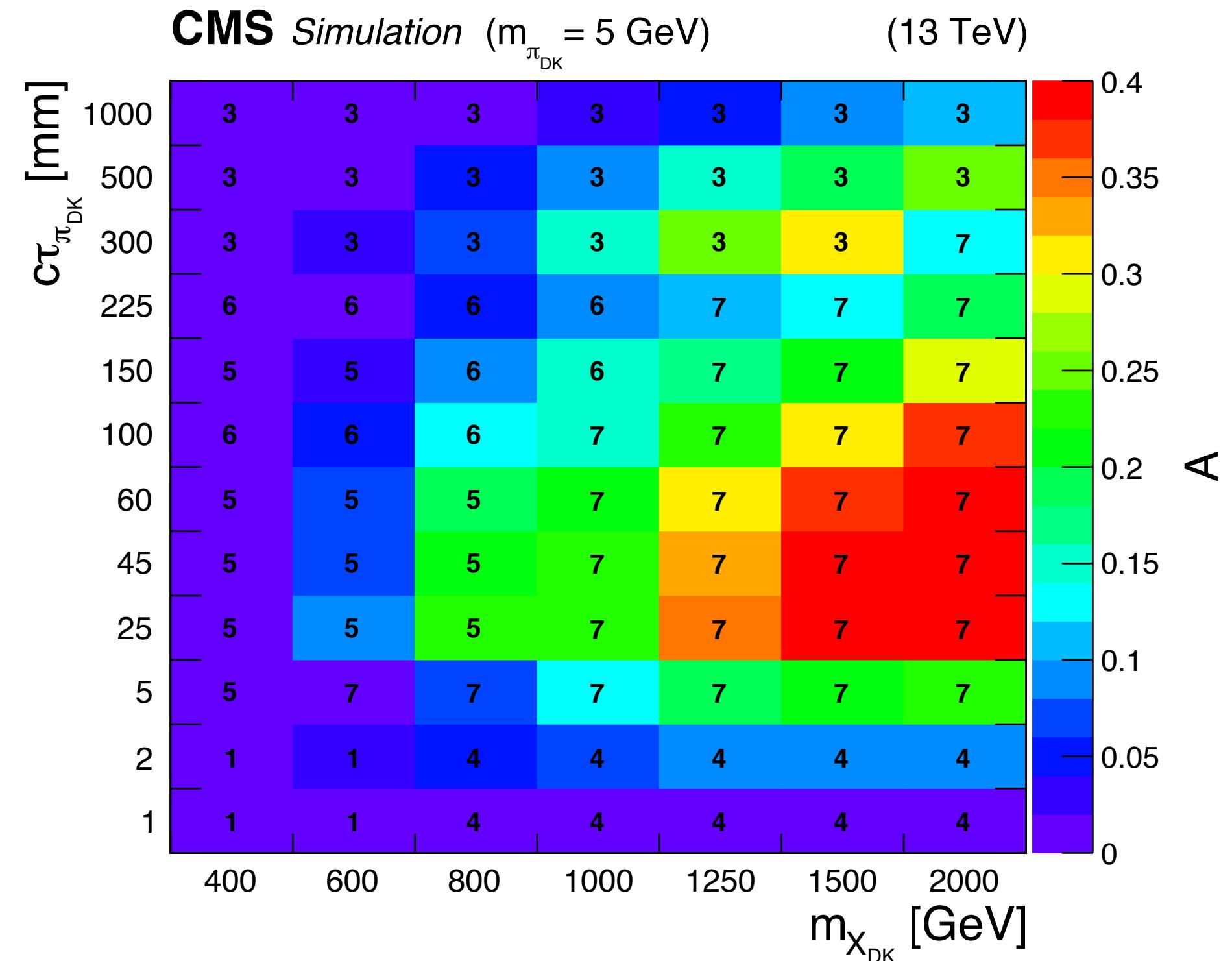
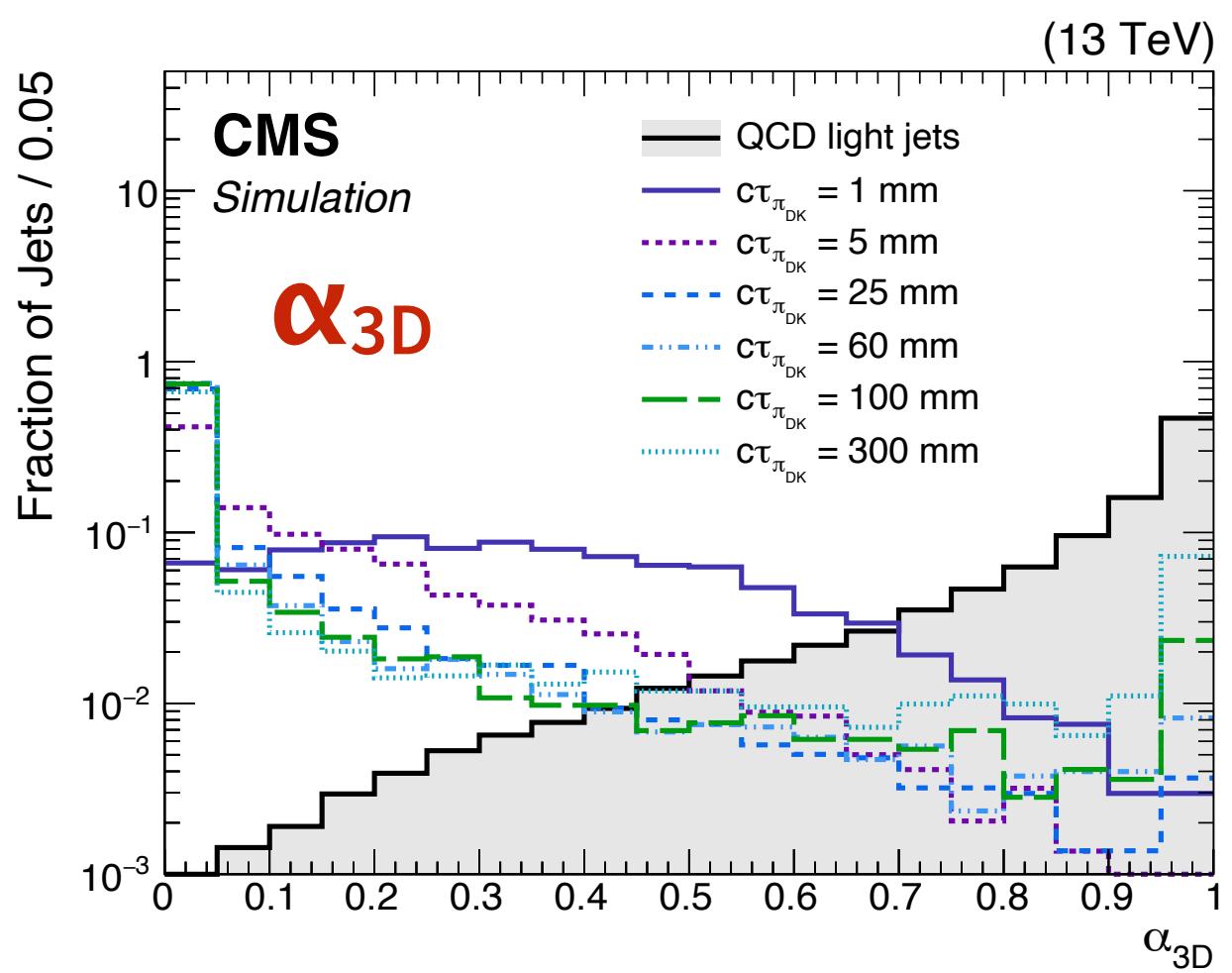
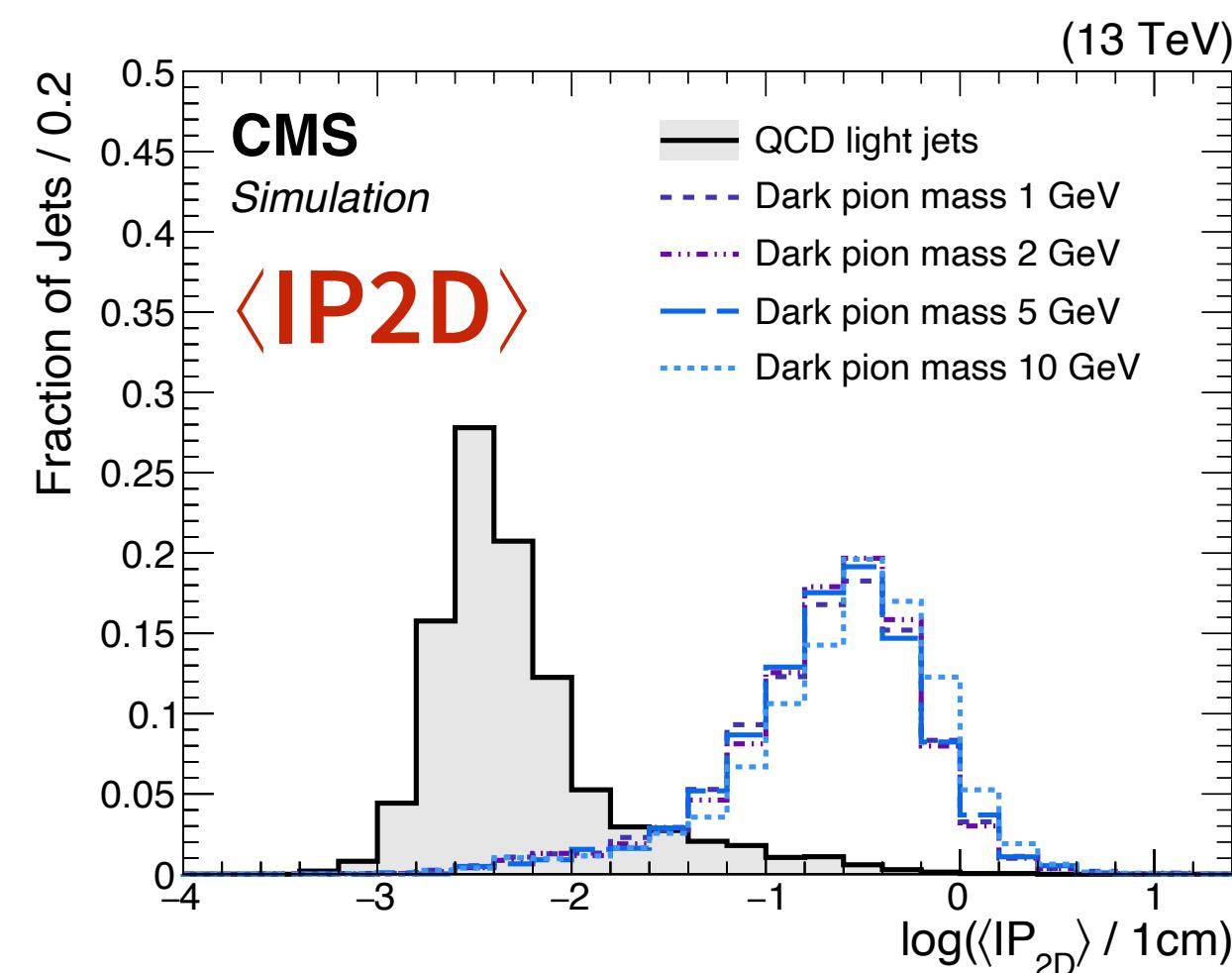
# Emerging jets signature



# Emerging jets identification

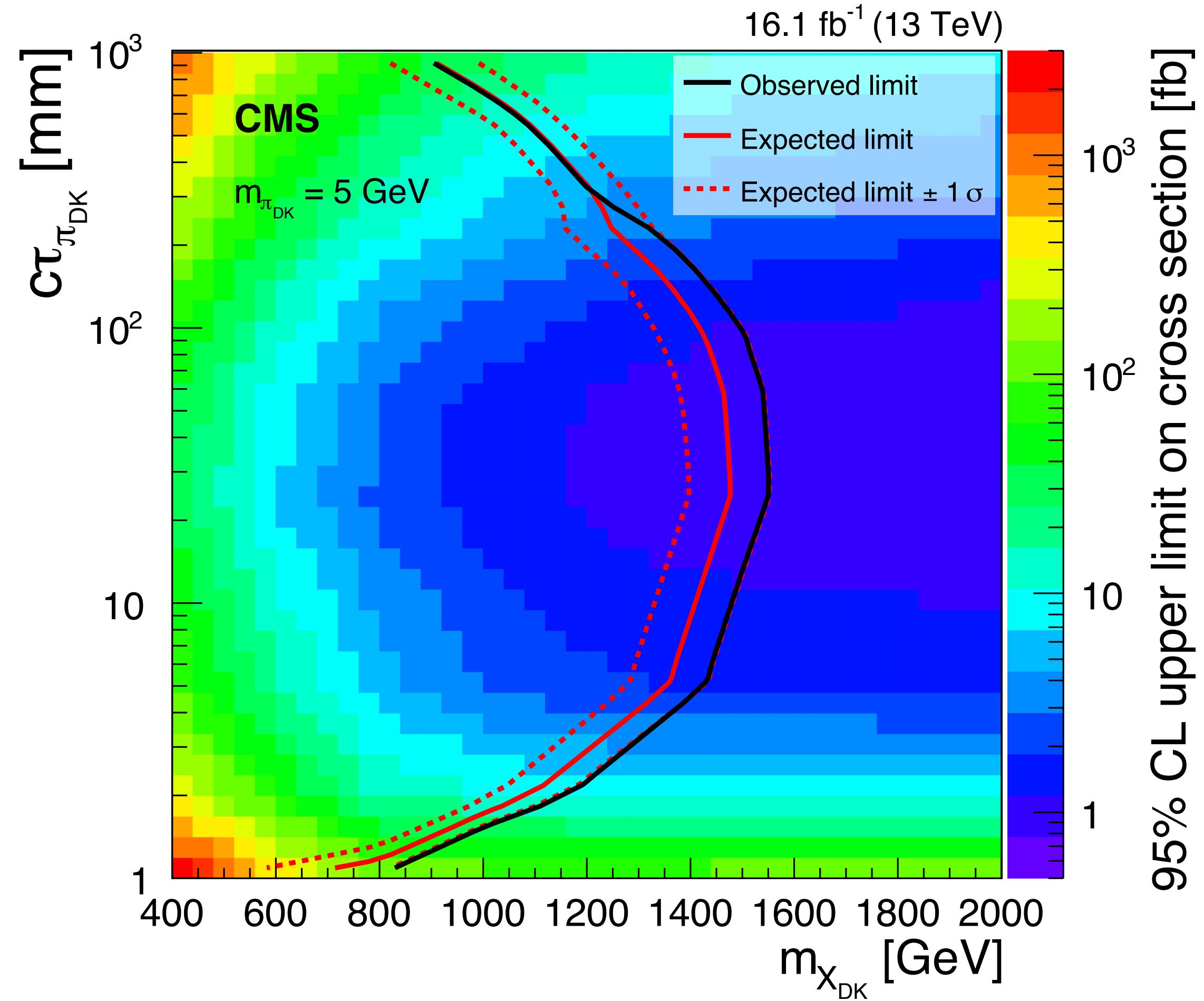
## EJ selection based on multiple displaced vertices identification

- Transverse impact parameter ( $\langle \text{IP2D} \rangle$ ) of associated tracks correlated to dark meson proper decay length
- Jet pT fraction associated to prompt tracks ( $\alpha_{3D}$ )
- 7 sets of selection requirements, addressing different models



Acceptance of selection criteria ranges from few % to 48% for massive mediators

# Emerging jets



No significant excess observed over SM background expectation

- DM mediators with mass between 400 and 1250 GeV and dark pion decay lengths between 5 and 225 mm excluded
- Weak dependence on dark pion mass

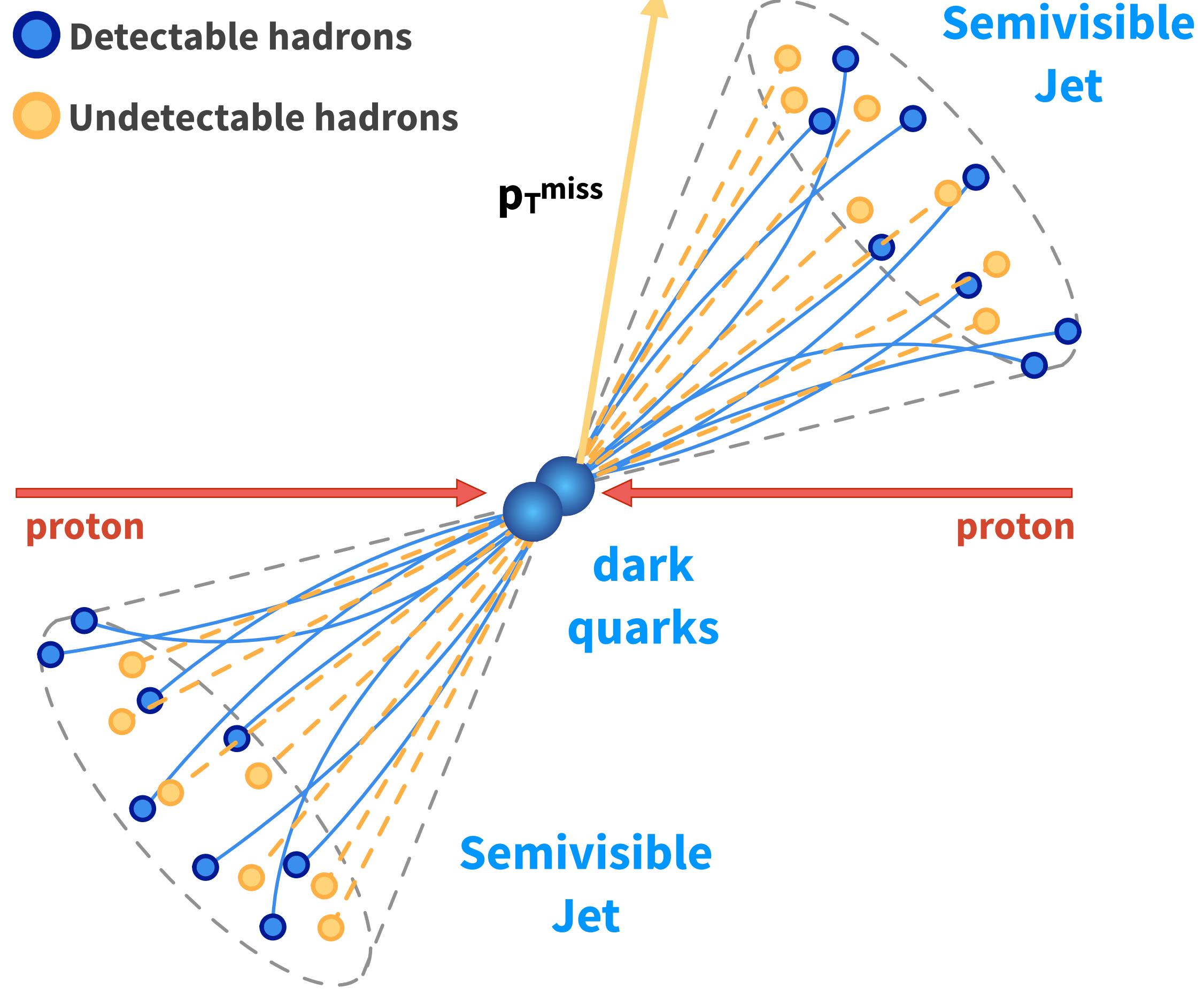
# Particle puzzle: Semivisible jets

## Dark quarks hadronise in the dark sector

- **Unstable** dark hadrons can decay to visible particles
- **Stable** ones will remain invisible to the detector

## Challenging experimental signature:

- Missing momentum collinear to visible jets



# Unexplored territory @ LHC

**Semivisible jets data lay in a region discarded by common searches**

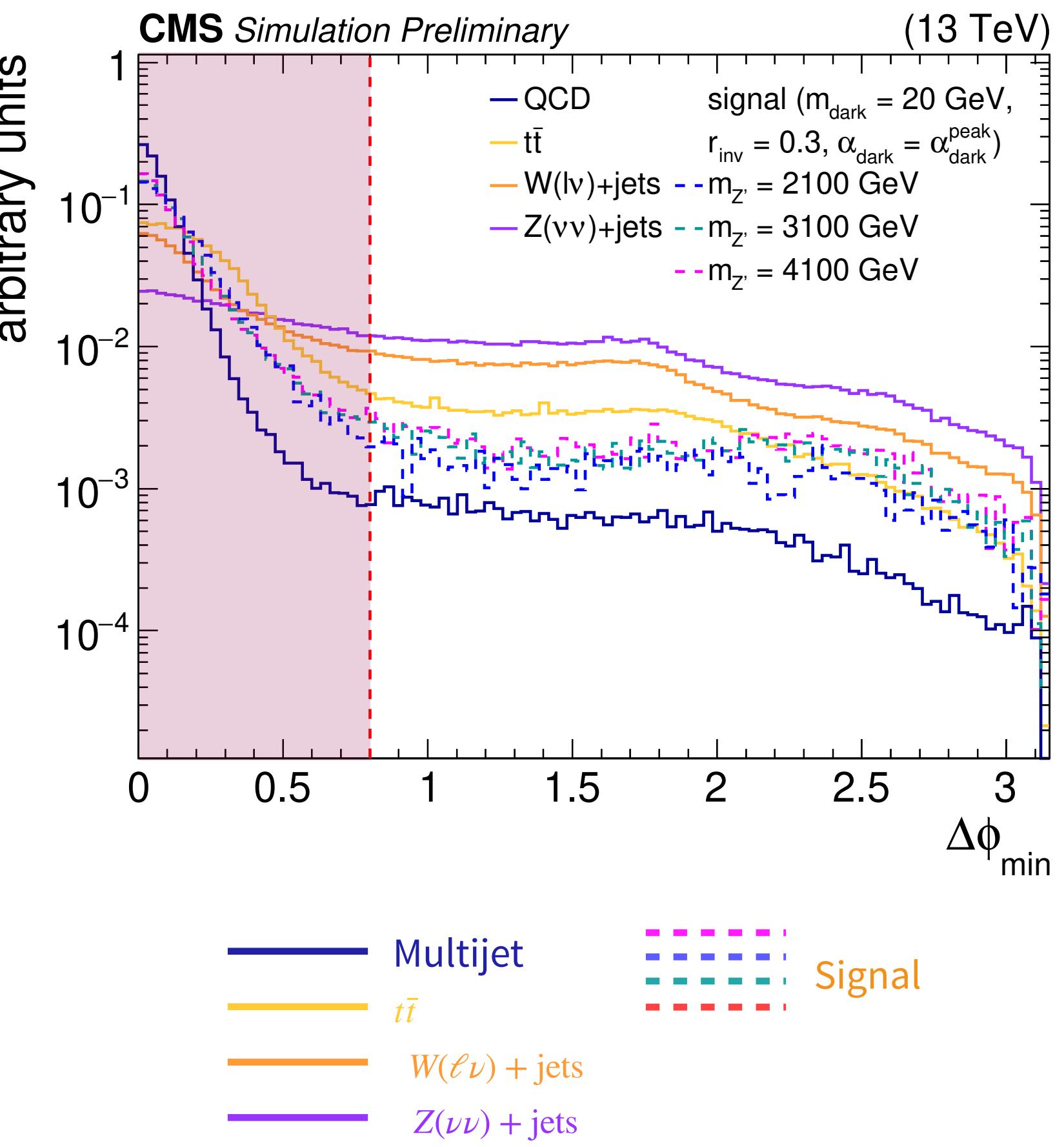
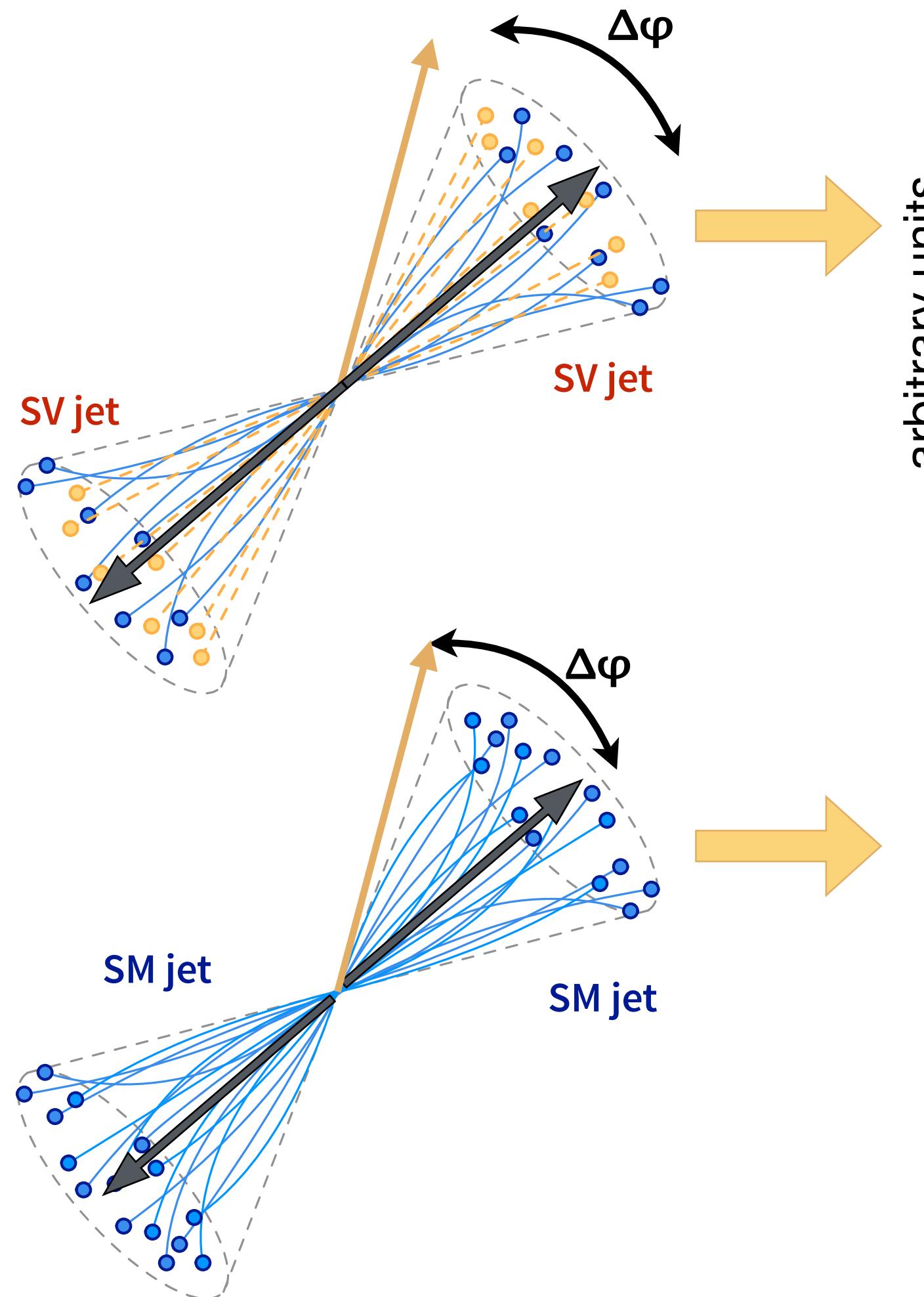
- **Missing momentum collinear to visible jet**
- Overwhelming background
- Complex event topology
- Need suitable algorithms to search for New Physics here



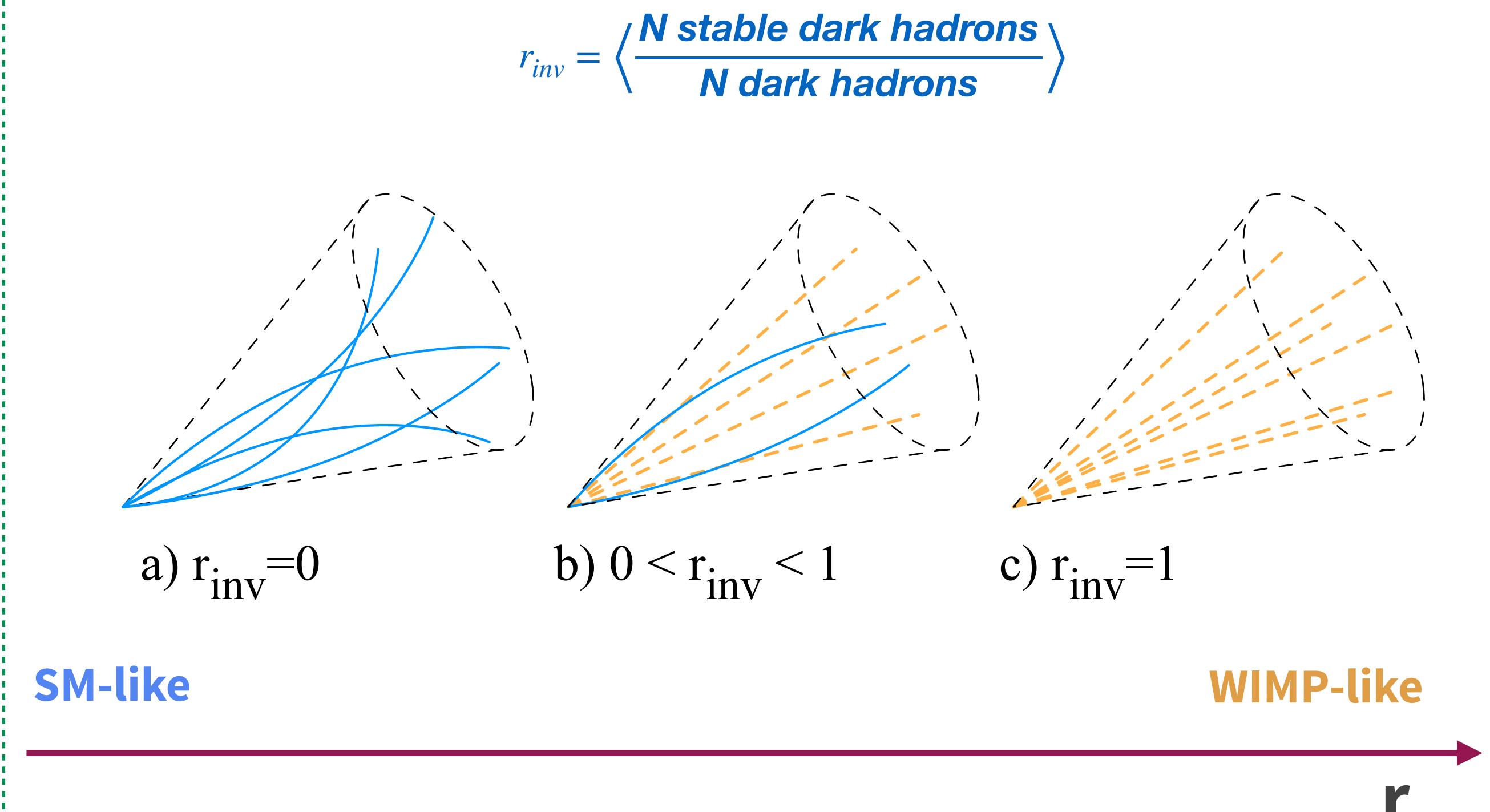
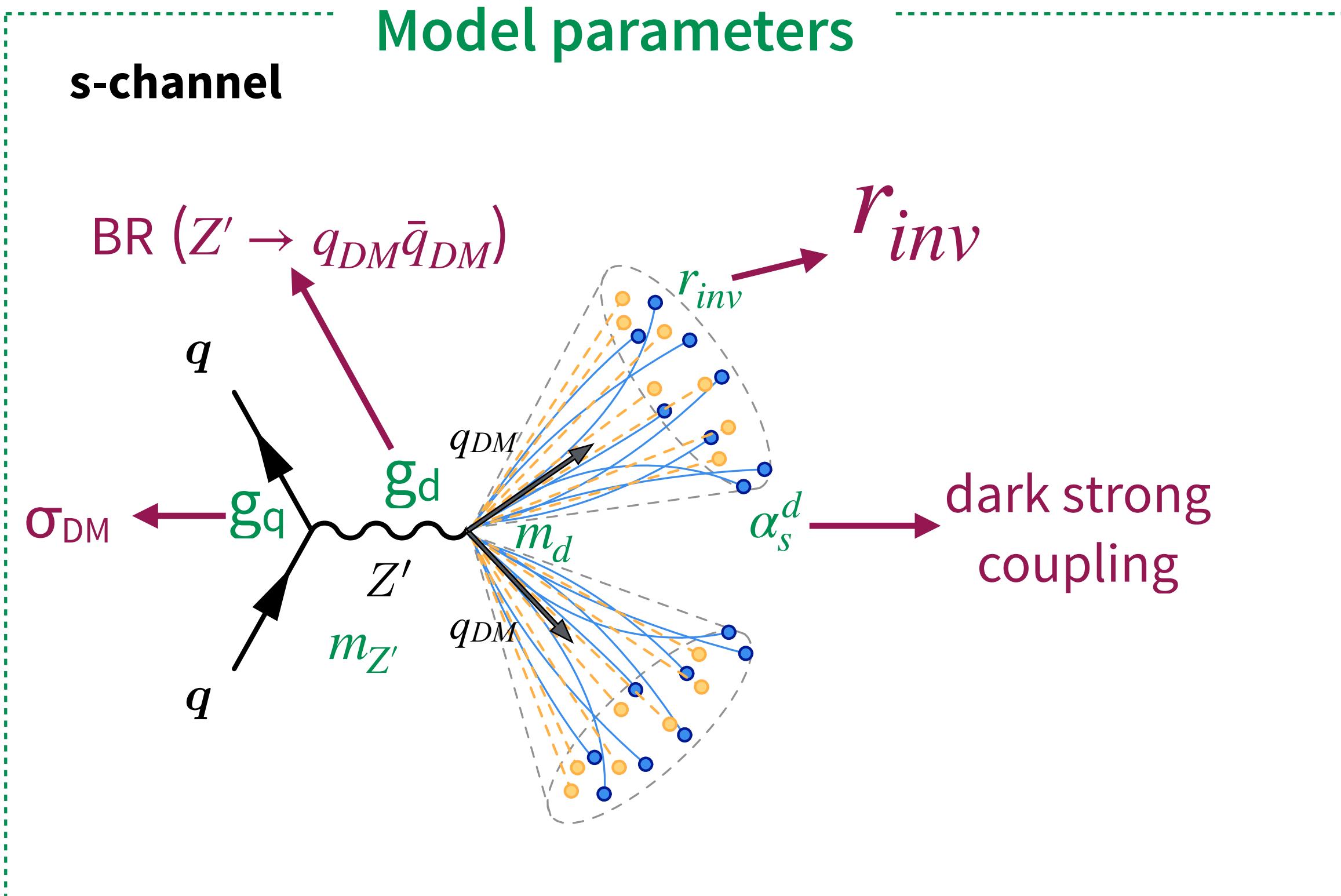
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- Missing momentum collinear to visible jet
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# Interpretation framework

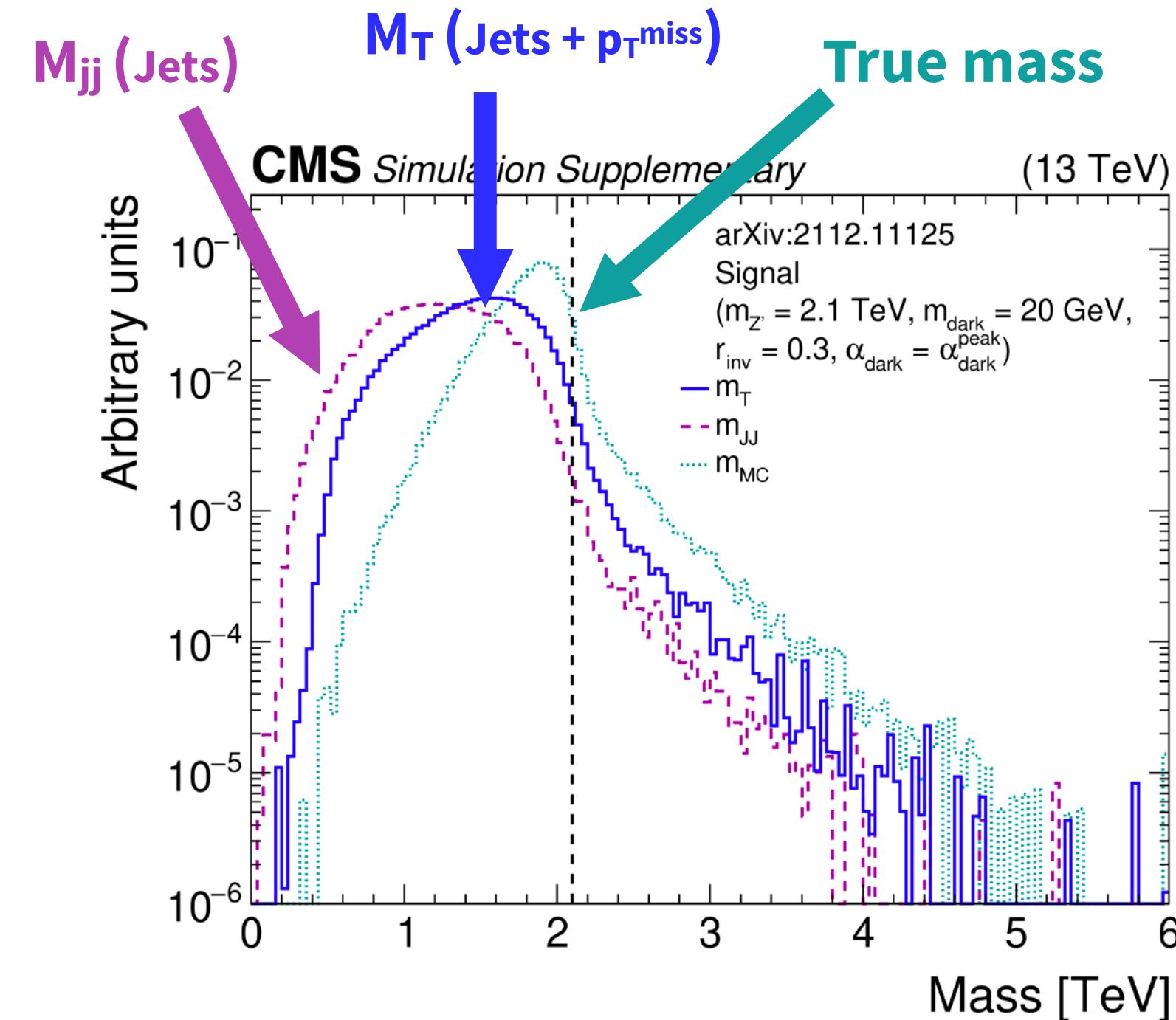


# Mediator reconstruction

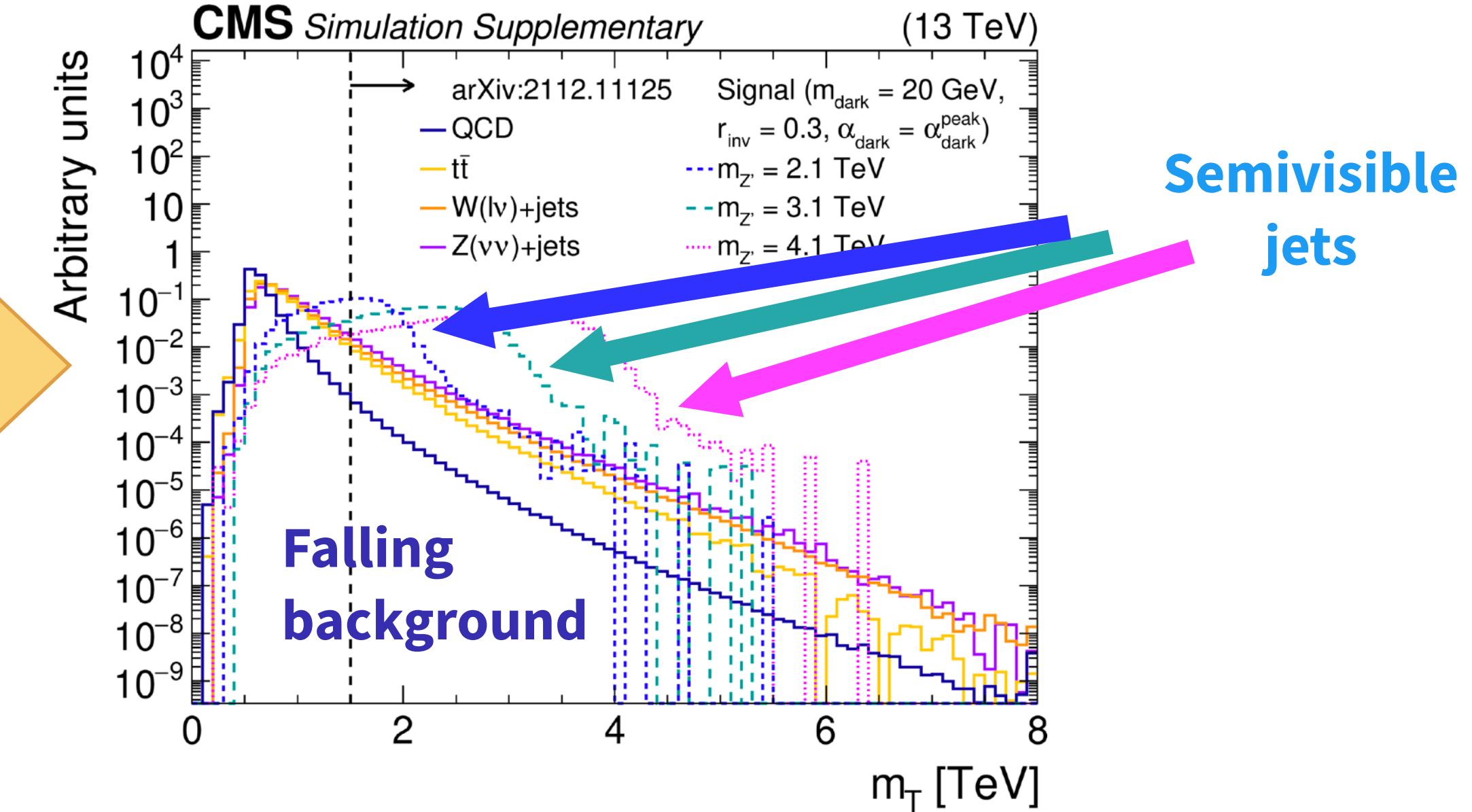
In the s-channel we can access the mediator

- Reconstruction of mediator mass from visible jets and  $p_T^{\text{miss}}$  (resonant channel)

$$M_T^2 = M_{jj}^2 + 2 \left( \sqrt{M_{jj}^2 + p_{T,jj}^2 p_T^{\text{miss}}} - \vec{p}_{T,jj} \cdot \vec{p}_T^{\text{miss}} \right)$$



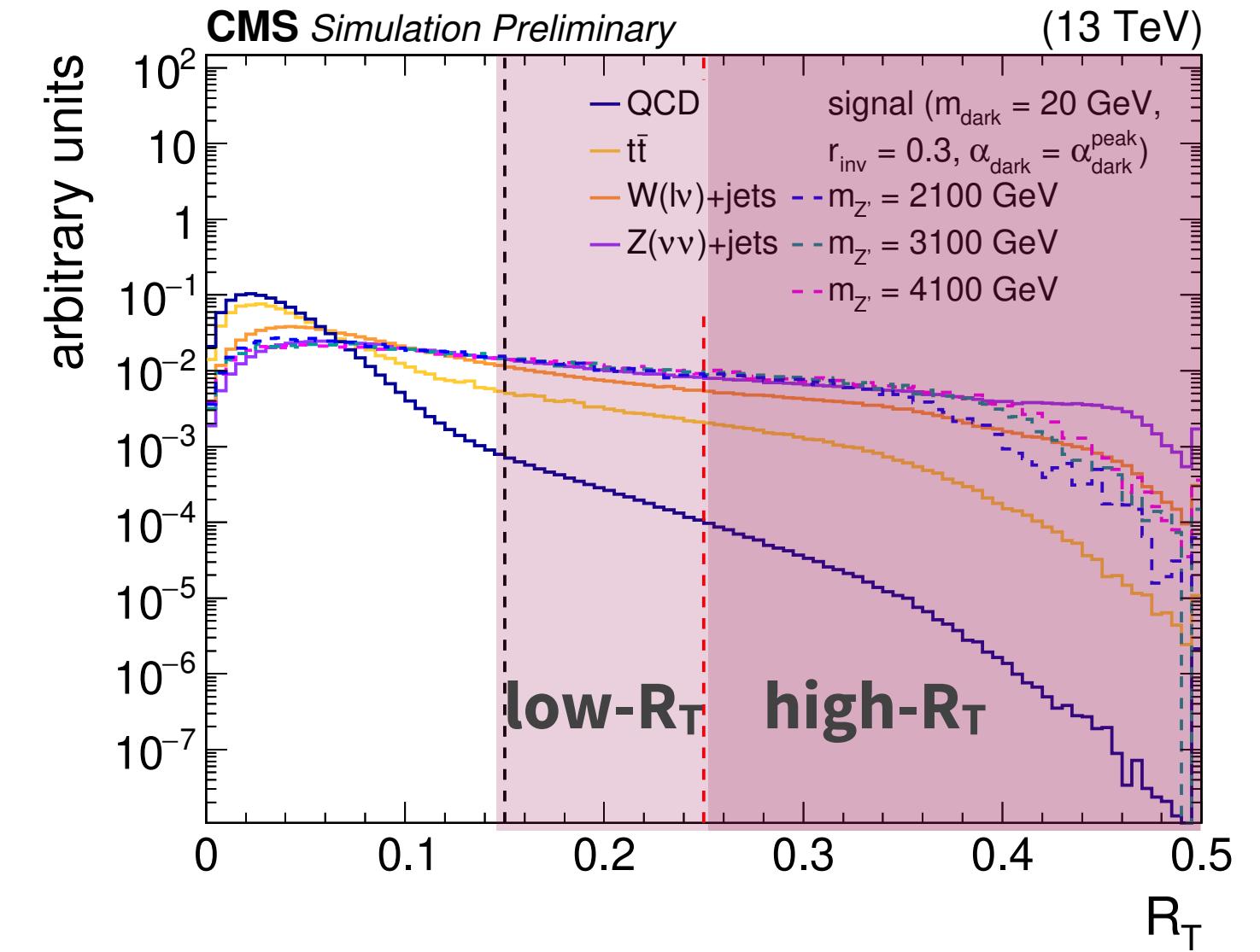
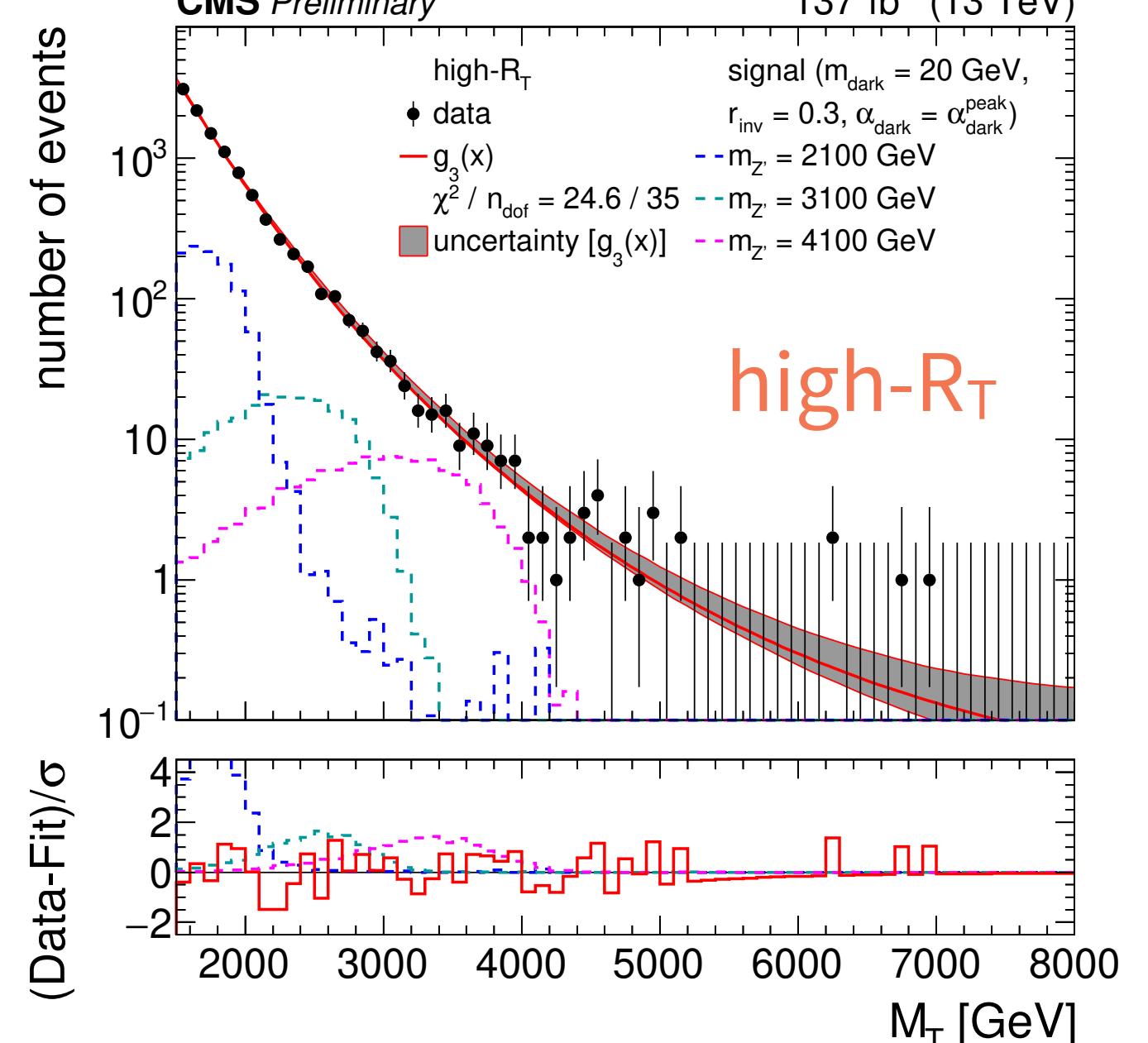
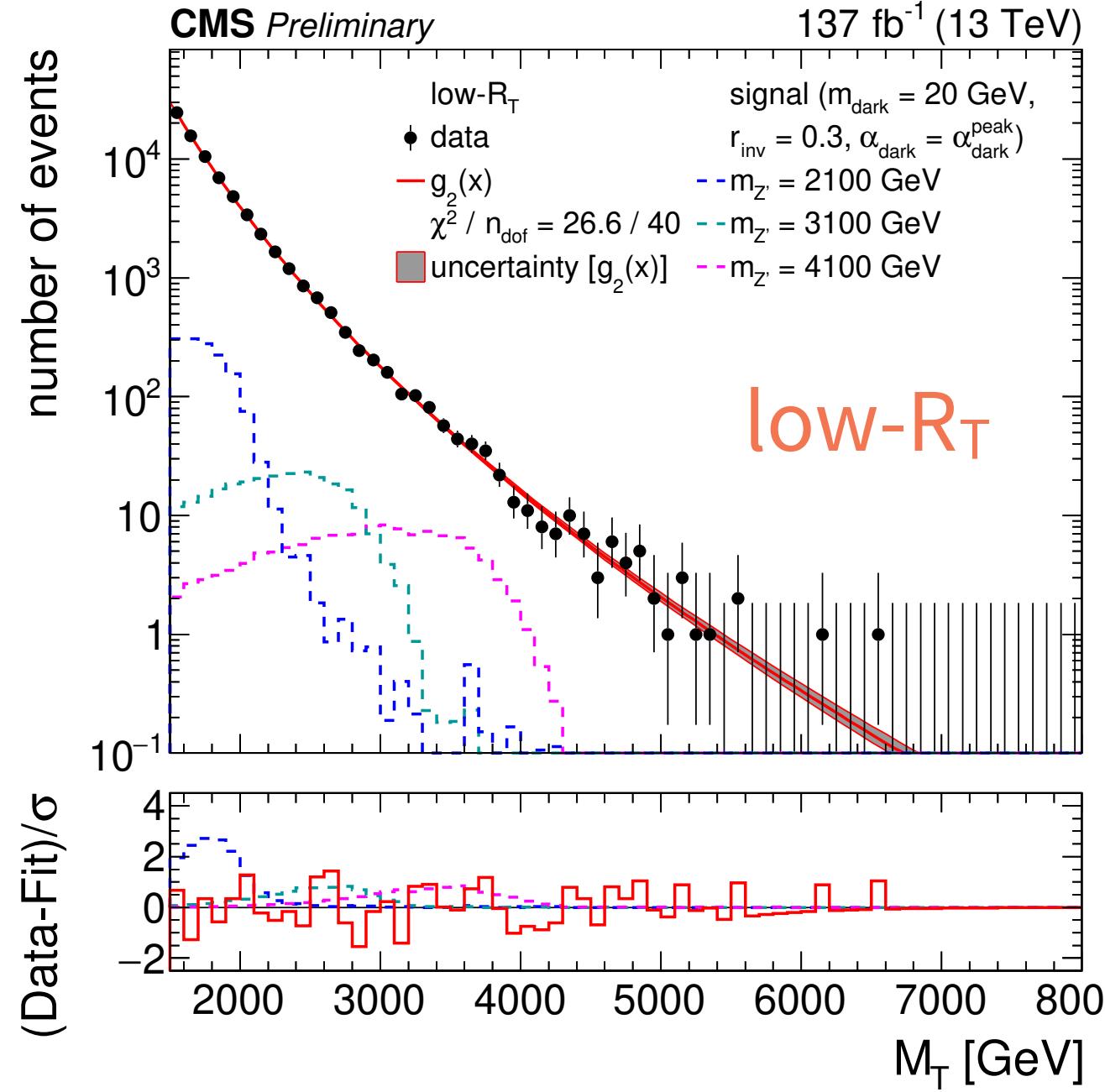
$M_T$  has a better resolution than  
 $M_{jj}$  endpoint at  $M_{Z'}$



# Background mitigation

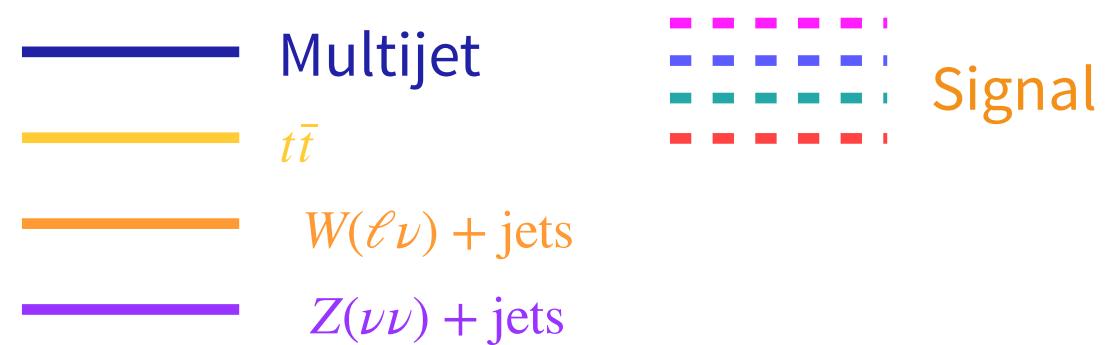
## Signal topology: At least 2 jets and large missing momentum

- Reject **multiphoton bkg**:  $R_T = p_T^{\text{miss}}/M_T > 0.15$
- Reject  $W(l\nu)$  and  $t\bar{t}$  **bkg**: Lepton veto
- Reject  $W(l\nu)$ ,  $Z(\nu\nu)$  and  $t\bar{t}$  **bkg**:  $\Delta\phi_{\min}(J_{1,2}, p_T^{\text{miss}}) < 0.80$



## 2 signal regions

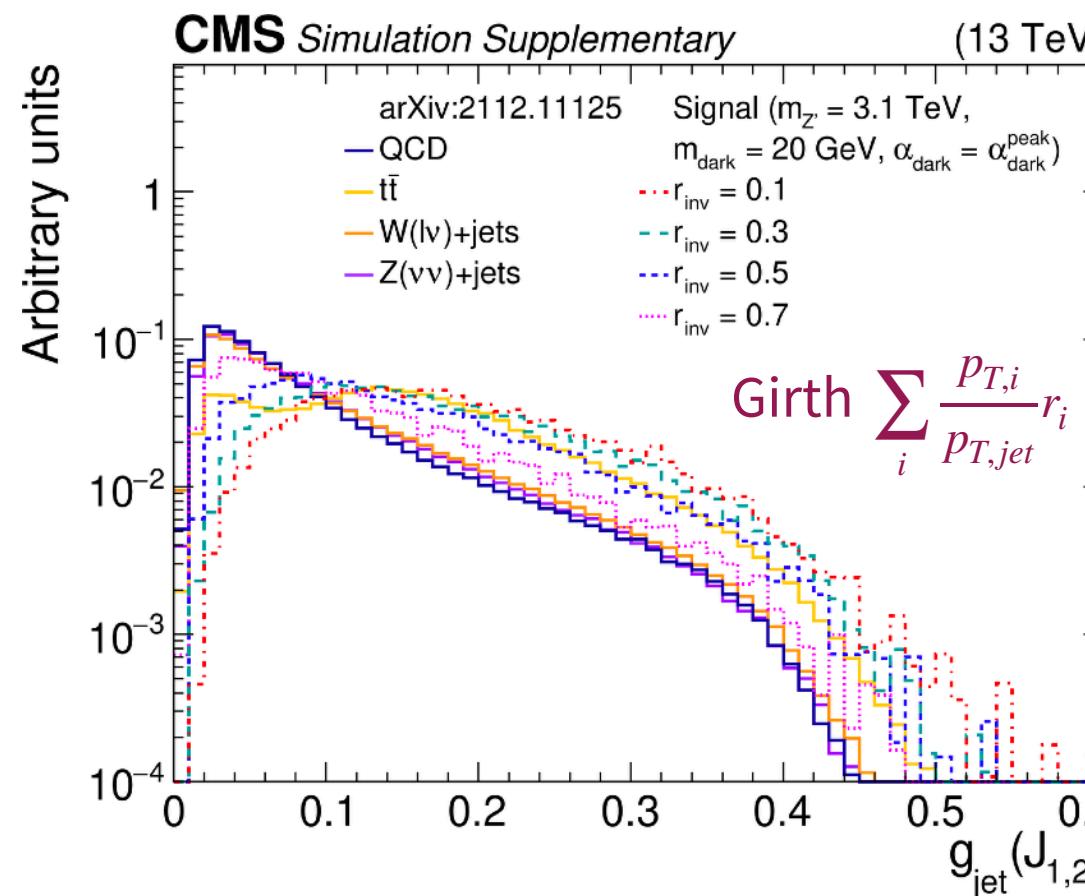
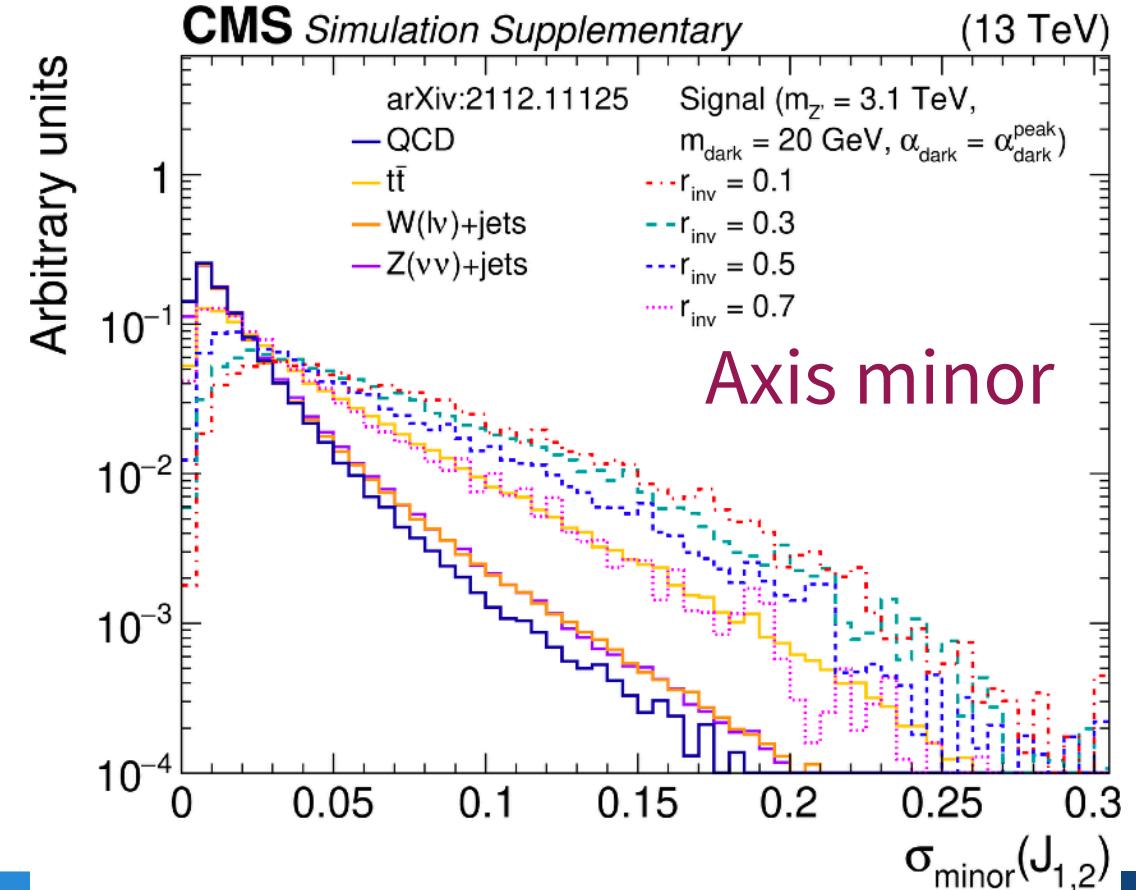
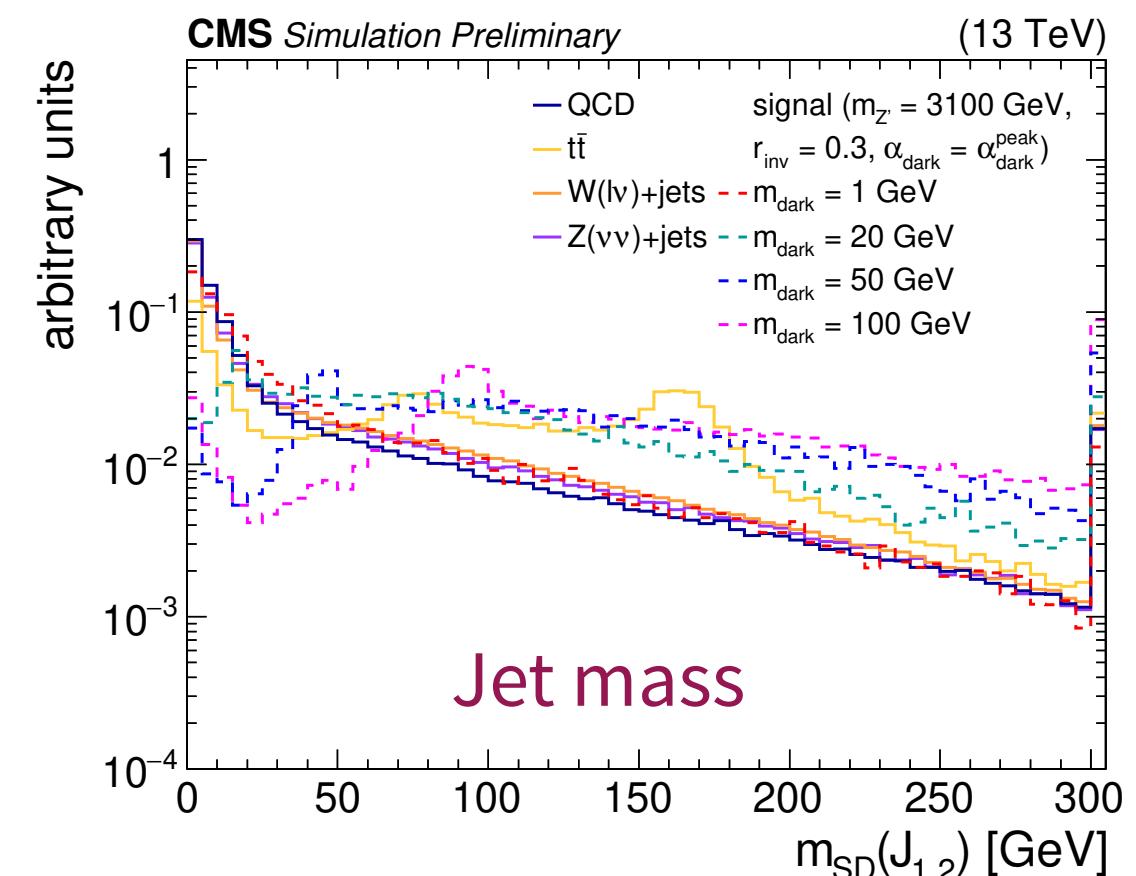
- **low- $R_T$** :  $0.15 < R_T < 0.25$
- **high- $R_T$** :  $R_T > 0.25$



# A look inside semivisible jets

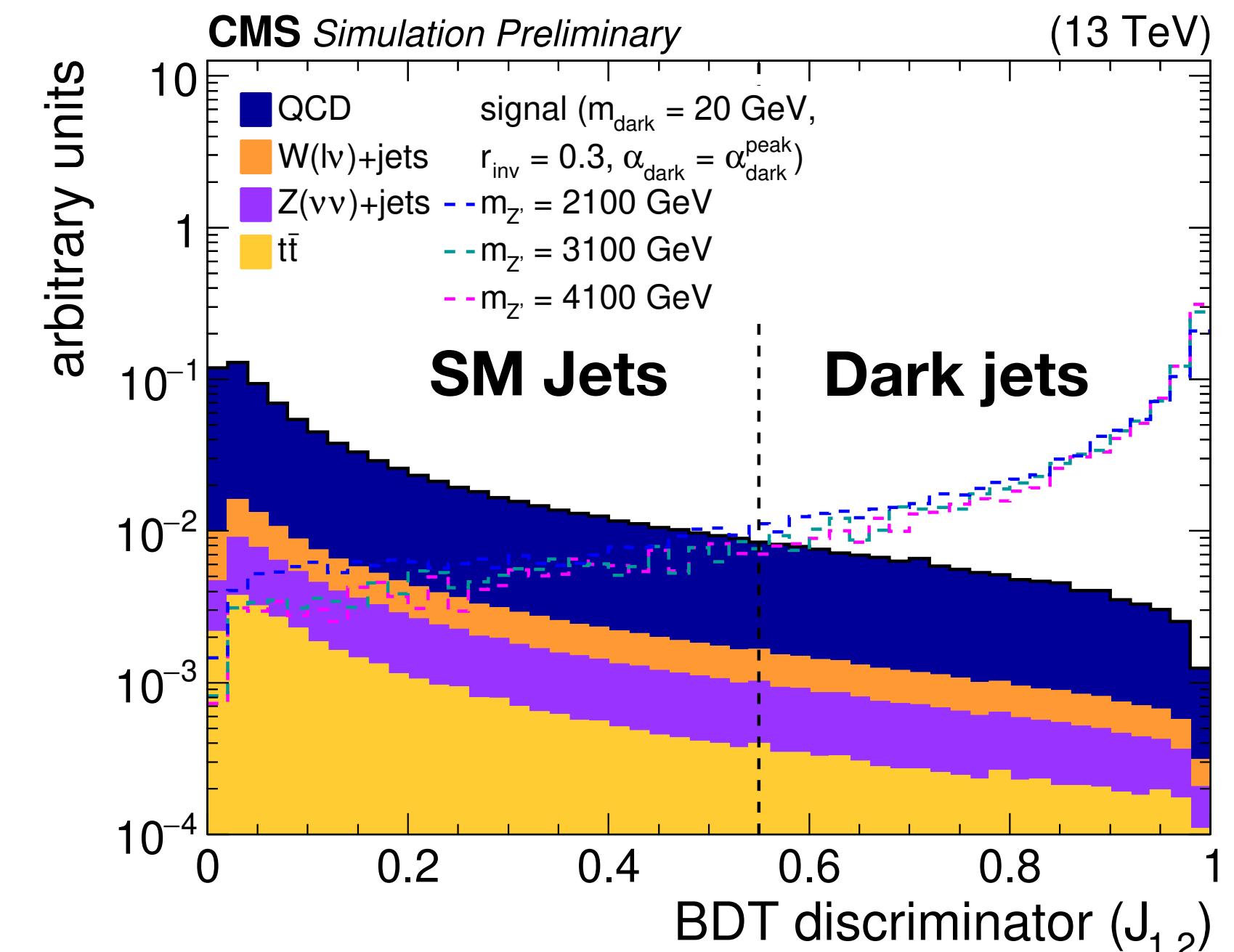
## Look inside the jet

- Underlying interaction affects the hadronization process
- Dedicated algorithms enable investigation of dark jets



**Multijet**  
 **$t\bar{t}$**   
 **$W(\ell\nu) + \text{jets}$**   
 **$Z(\nu\nu) + \text{jets}$**   
**Signal**

## Semivisible jets identification algorithm

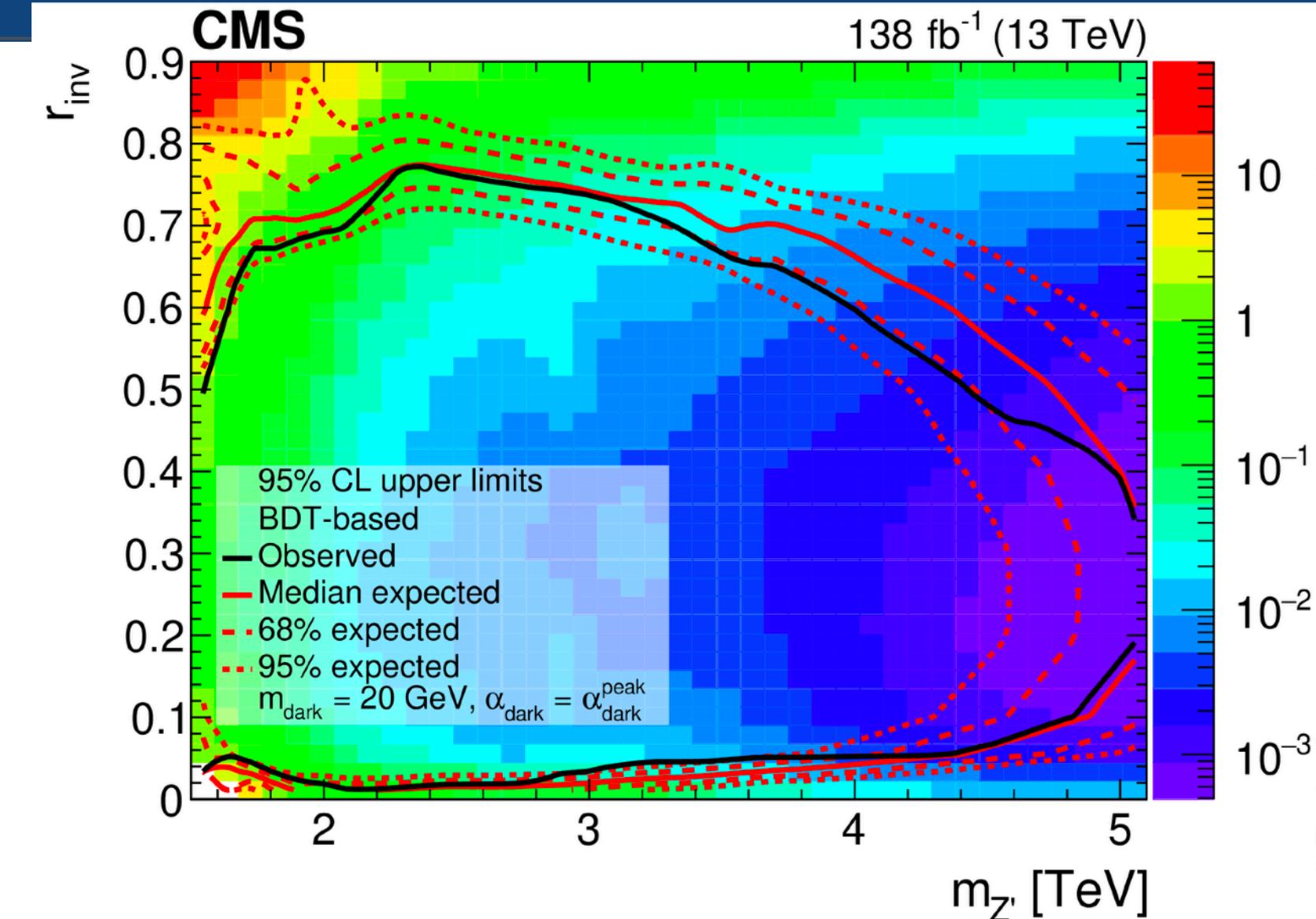
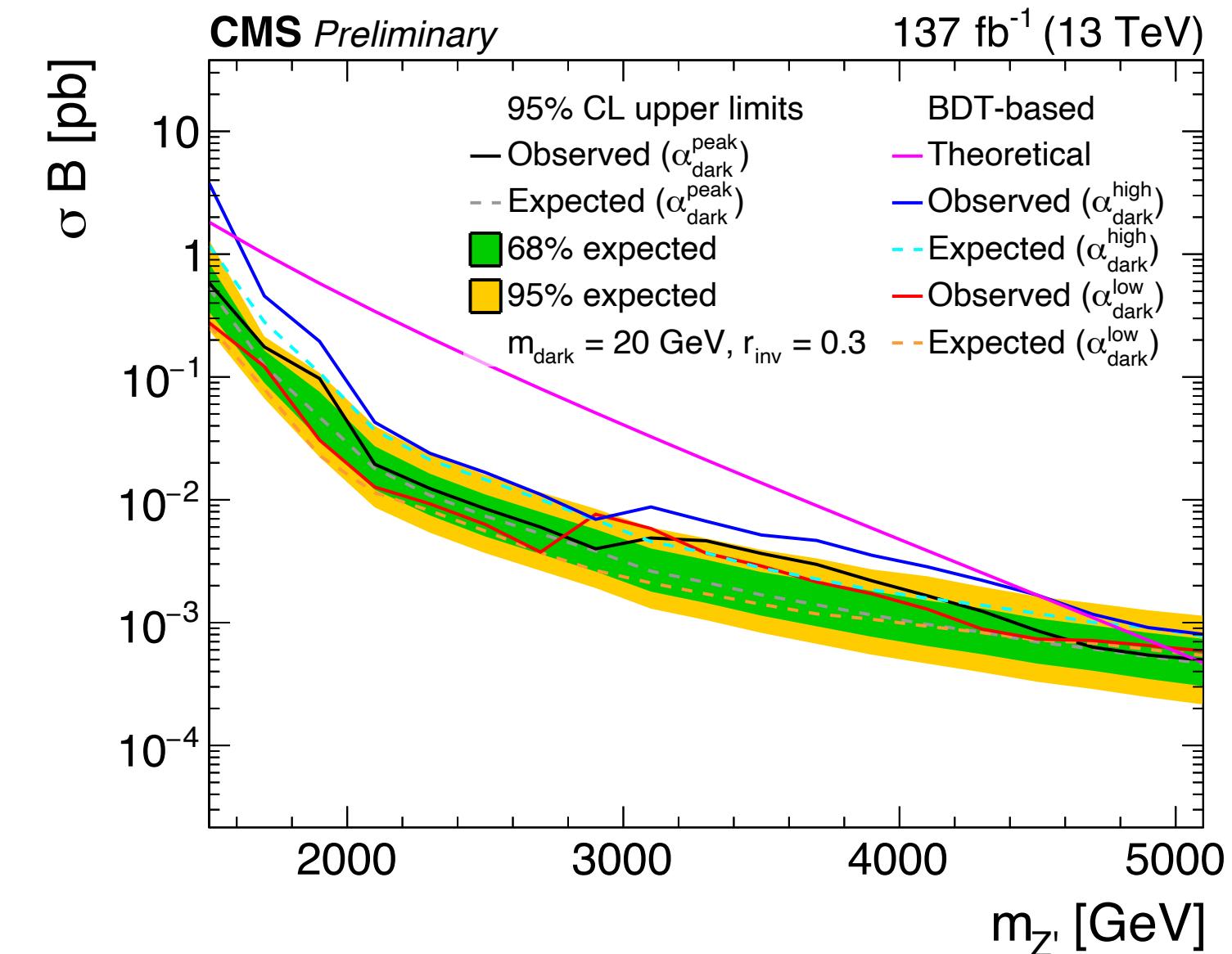
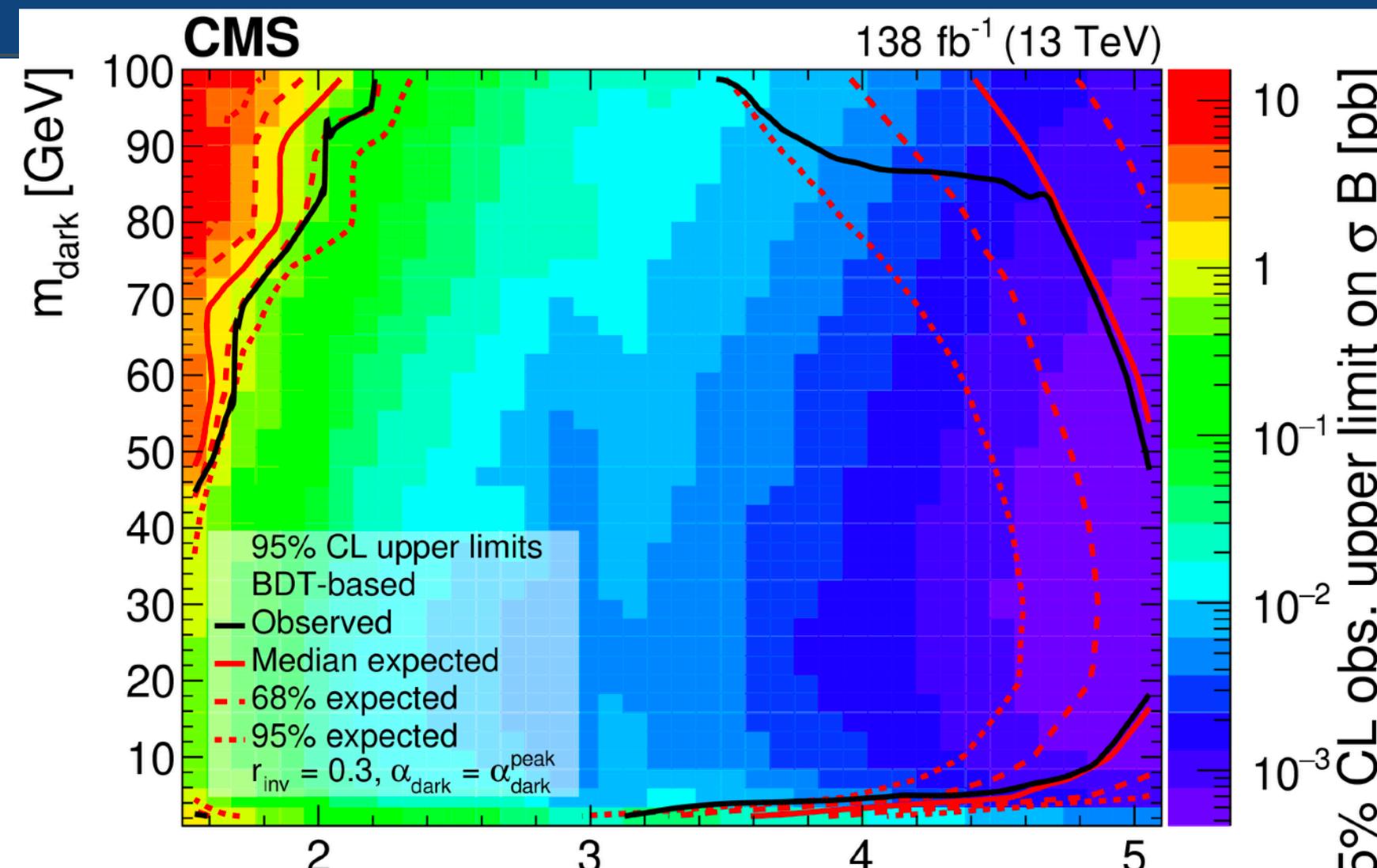
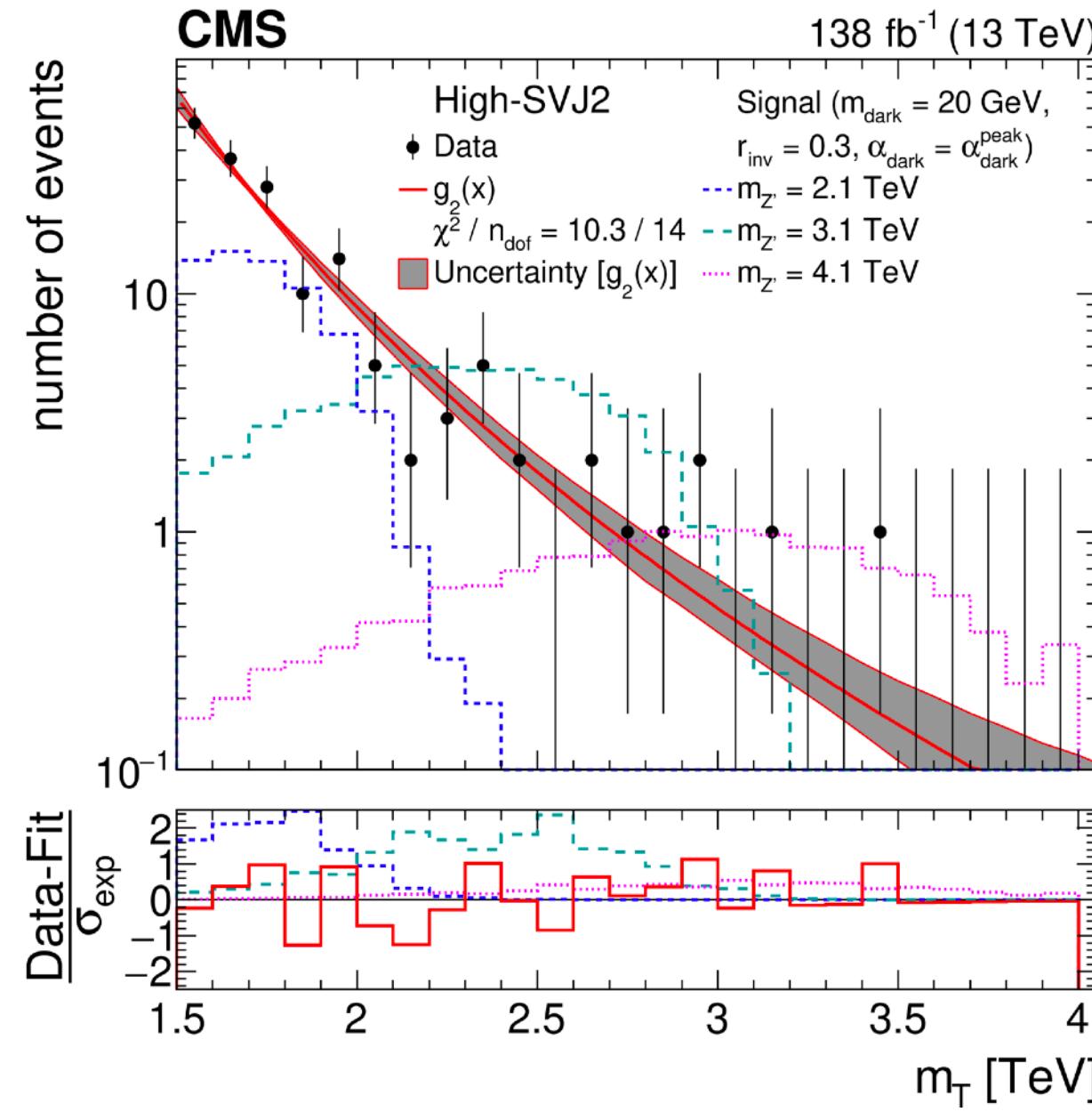


# Signal region

**Jet Identifier proved to be  
key to probe Semivisible Jets**

- Improvement in sensitivity by almost a **factor 10**

high- $R_T$  2 SVJ



**Observed exclusions (maximum range)**

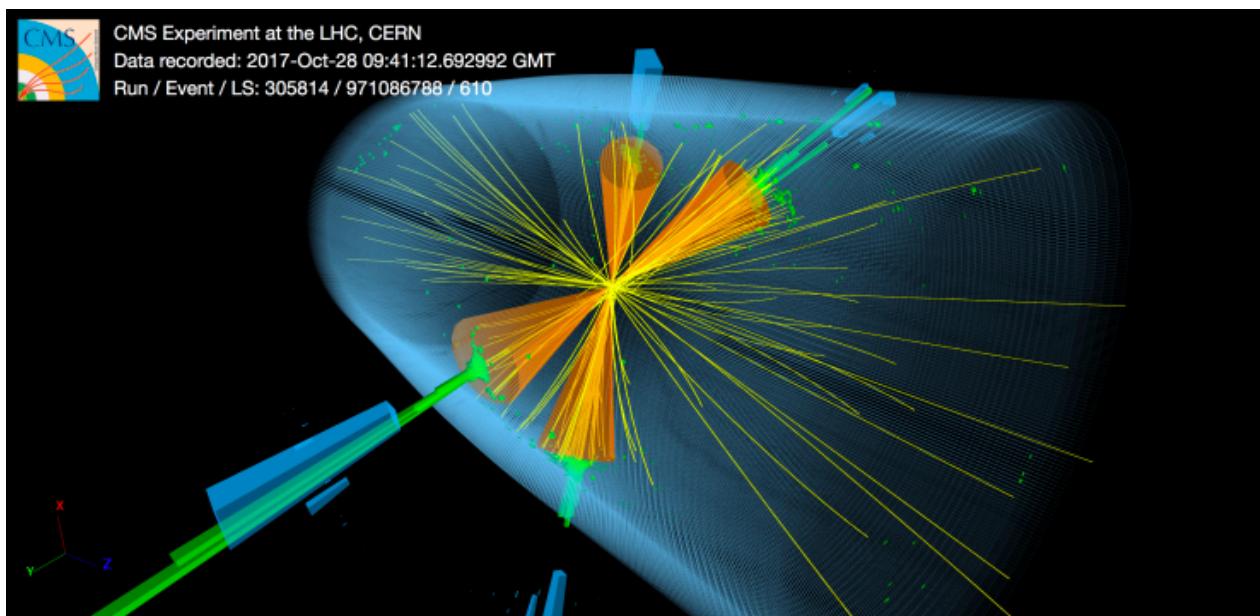
- $1.50 < m_{Z'} < 5.10 \text{ TeV}$
- $0.01 < r_{\text{inv}} < 0.77$
- all  $m_{\text{dark}}, \alpha_{\text{dark}}$  variations

# Paving the way for discovery

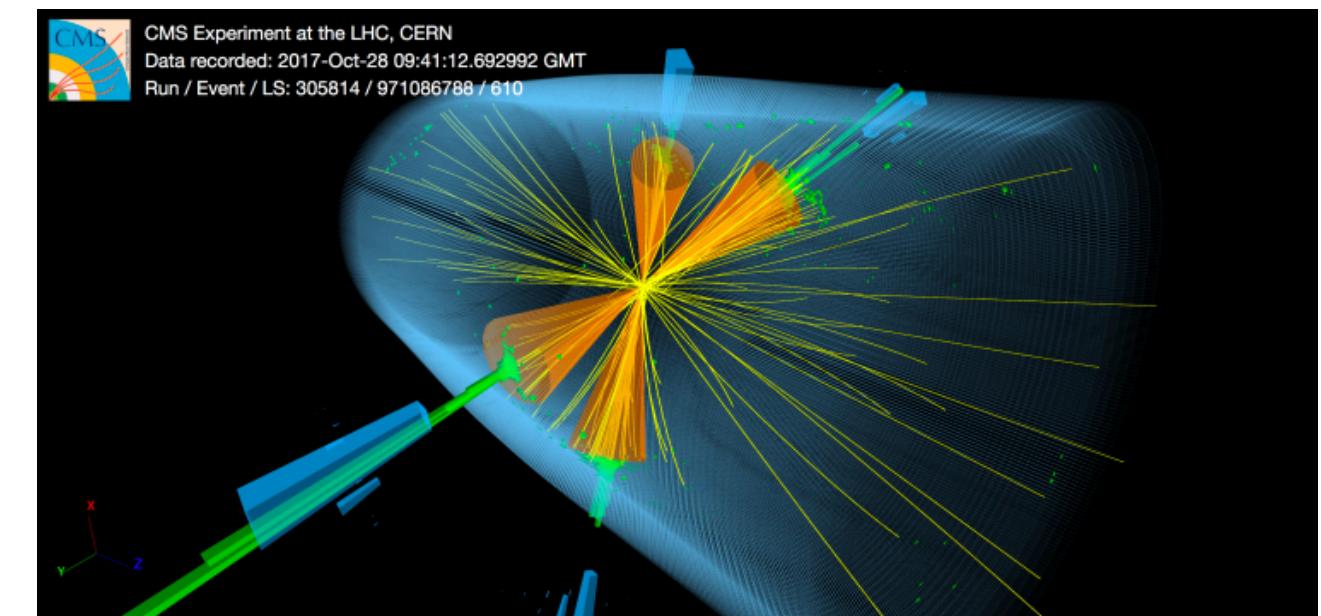
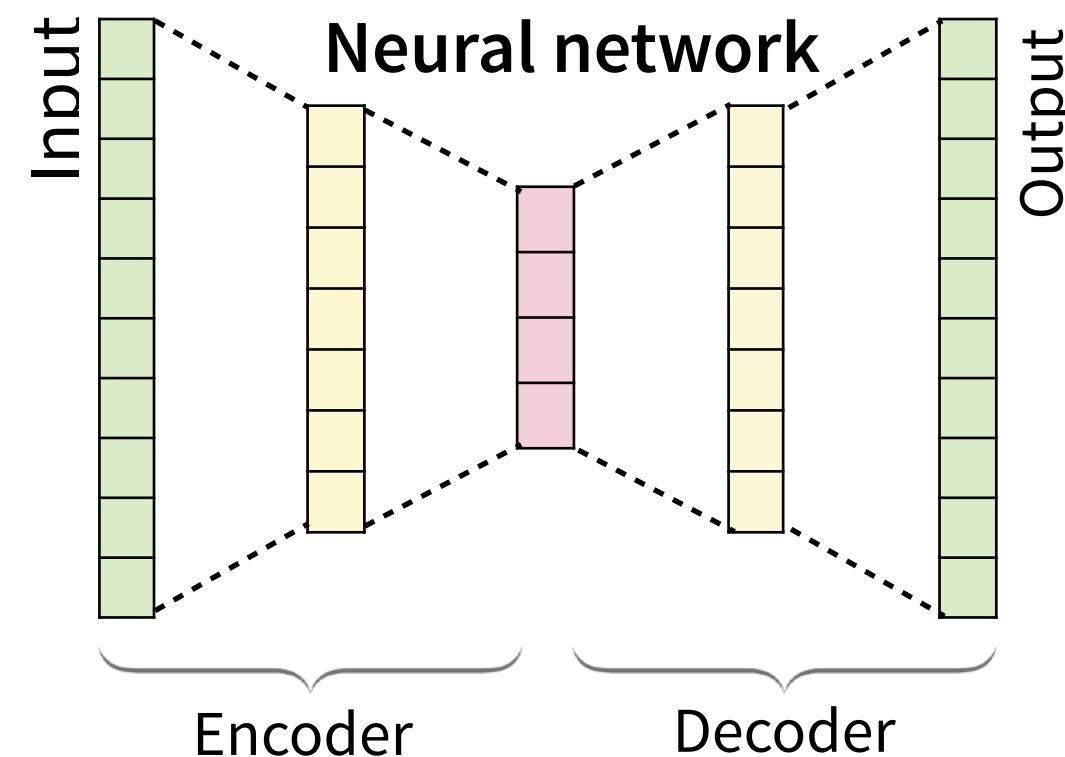
## Building new ways to look for DM

### Experimental methods

- Model-independent approach: Anomaly detection with autoencoders
- Learns to compress and reconstruct data
- Trained on known physics (SM jets) to identify anomalous data
- Unsupervised learning

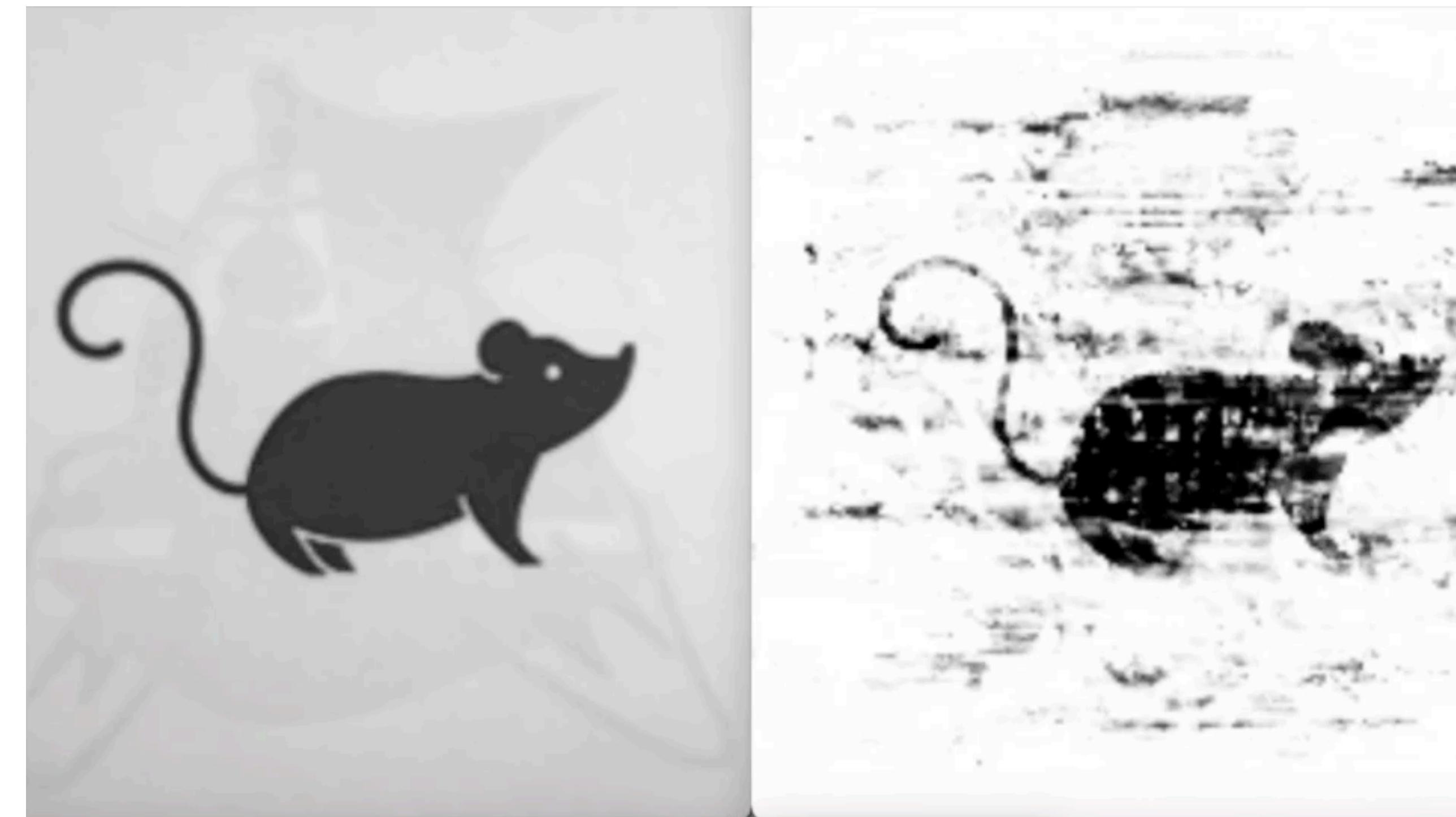


Input: Real Data - SM jets



Output: Reconstructed Data - SM jets

# Autoencoder demo



Input: Real Data

Output: Reconstructed Data

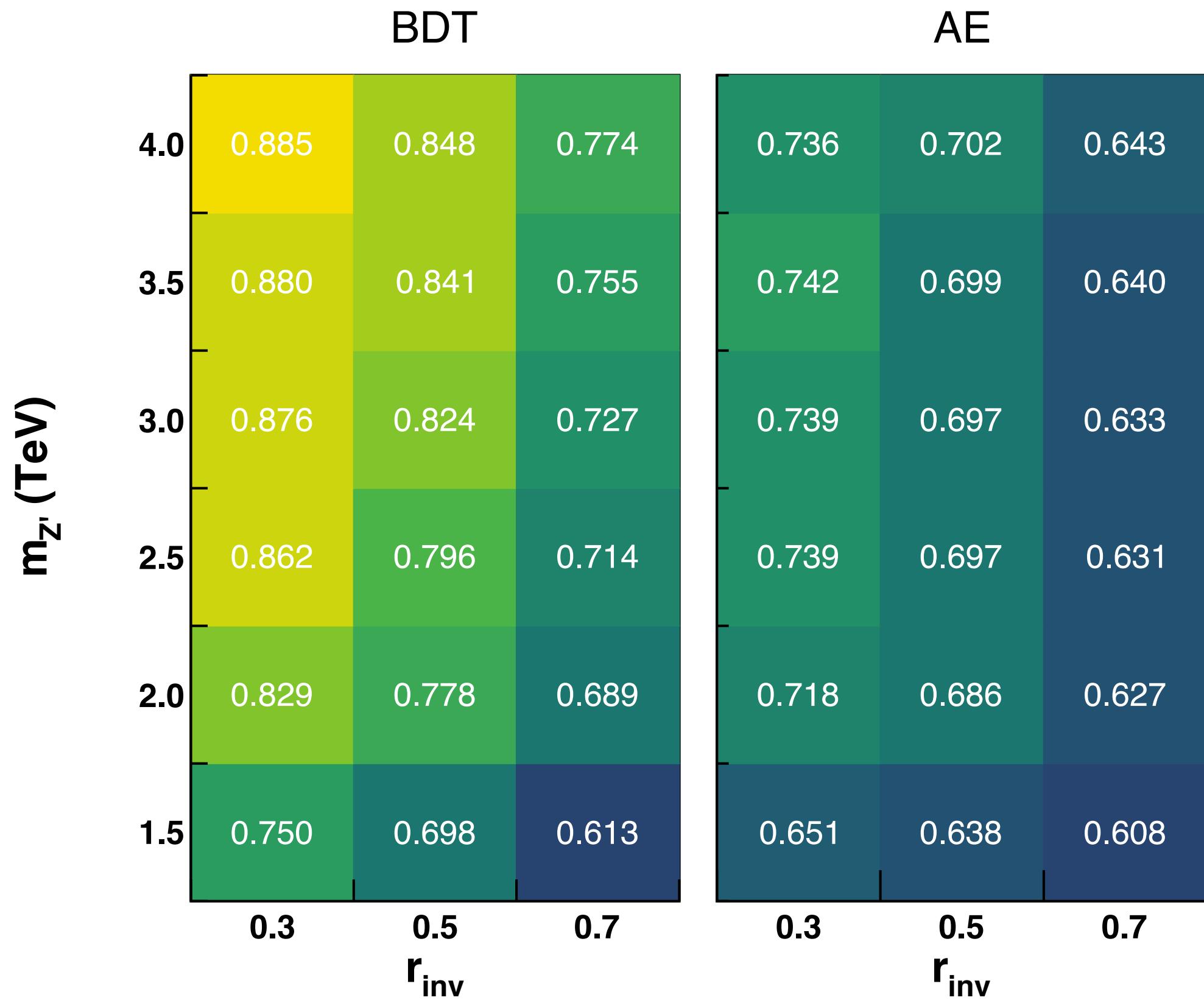
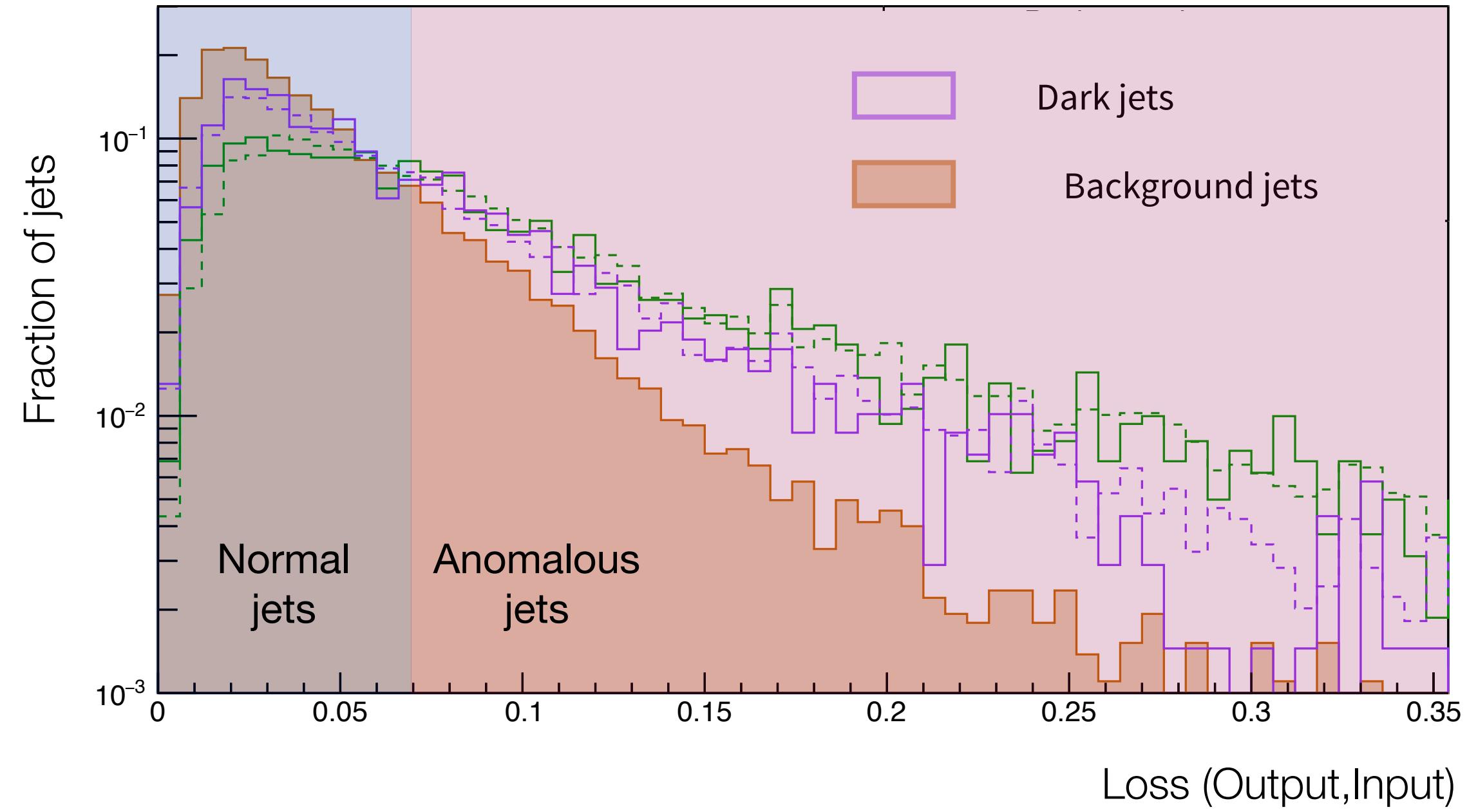
[Video from Jeremi Niedziela](#)

# Paving the way for discovery

A. de Cosa et al, “Autoencoders for Semivisible jet detection”  
JHEP Vol 2022, 74 (2022)

## Building new ways to look for DM

- Autoencoders trained on SM jets unable to reconstruct SV jets
- Training independent on background and signal modelling



# Paving the way for discovery

## Building new ways to look for DM

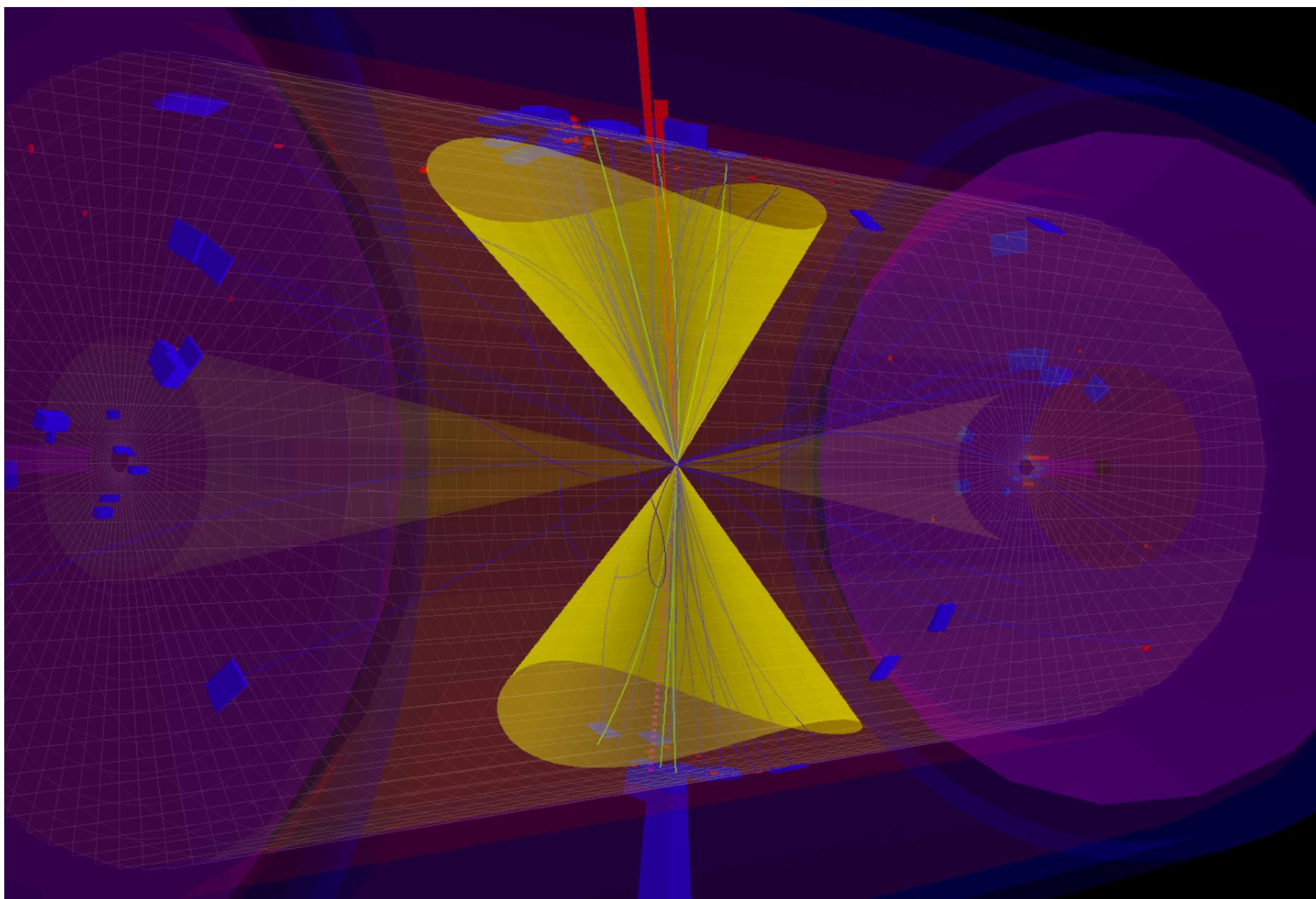
### Theoretical predictions

- Building consistent sets of benchmarks models
- Expand to novel signatures with leptons or heavy quark within the dark jets

Snowmass report from Dark Shower group: “Theory, phenomenology, and experimental avenues for dark showers: a Snowmass 2021 report”

**Semivisible Jet Workshop**  
**ETH Zurich, 5-7 July 2022**

Example of simulated lepton-enriched dark jet  
(Green and red tracks indicate leptons)



Picture from Cesare Cazzaniga (work in progress)

# Conclusions

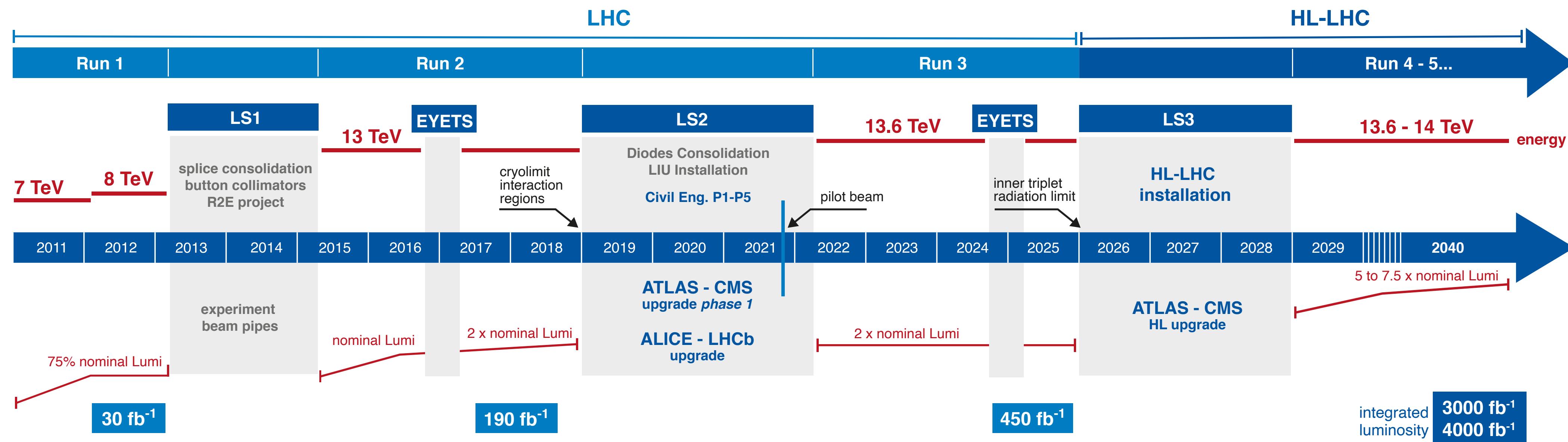
**Most obvious and accessible signatures have been explored**

- Constraining the space of possibilities

**Time to look into new, though more challenging possibilities**

- Searching for DM at colliders is a multi-dim problem
- DM searches can benefit from new trigger, identification and reconstruction strategies

**Take the best out of this era of big data**



# Thank you

