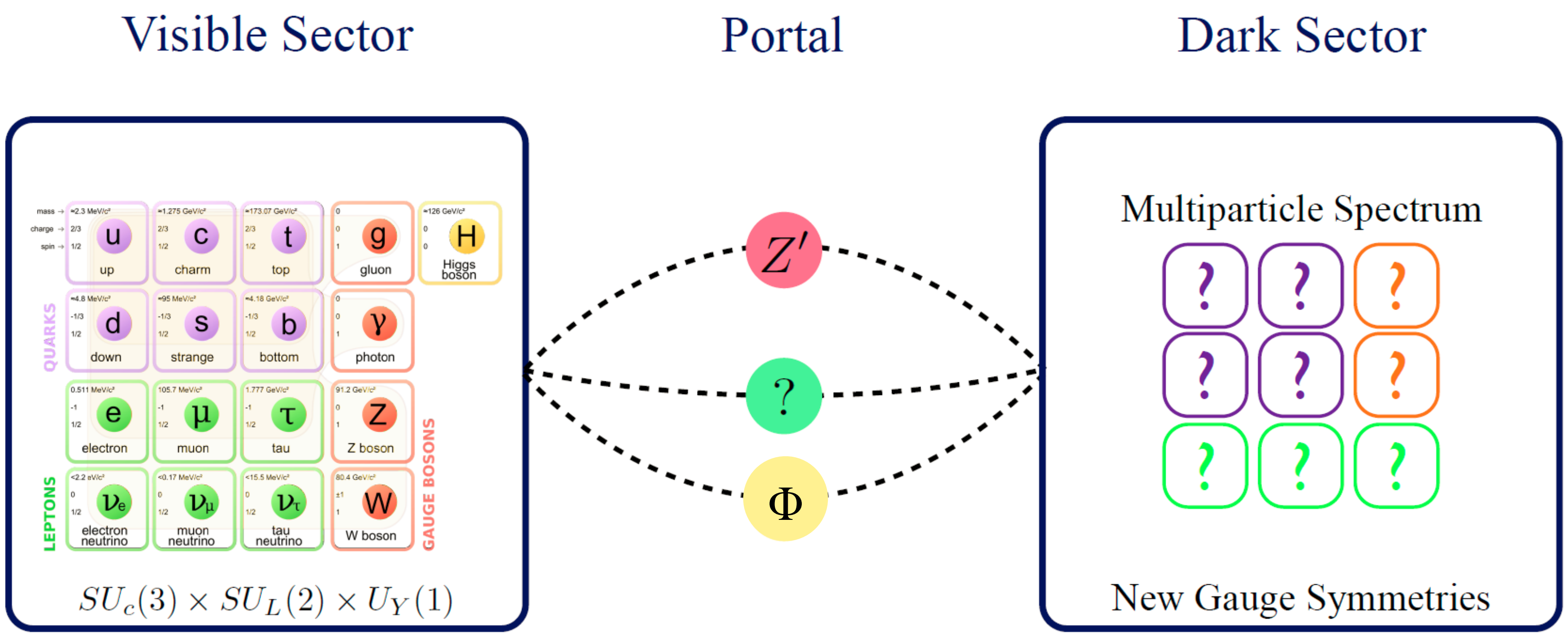
14th Conference on the Intersections of Particle and Nuclear Physics
(CIPANP 2022)

Search for dark matter with visible signatures

Thomas Klijnsma
On behalf of the CMS Collaboration

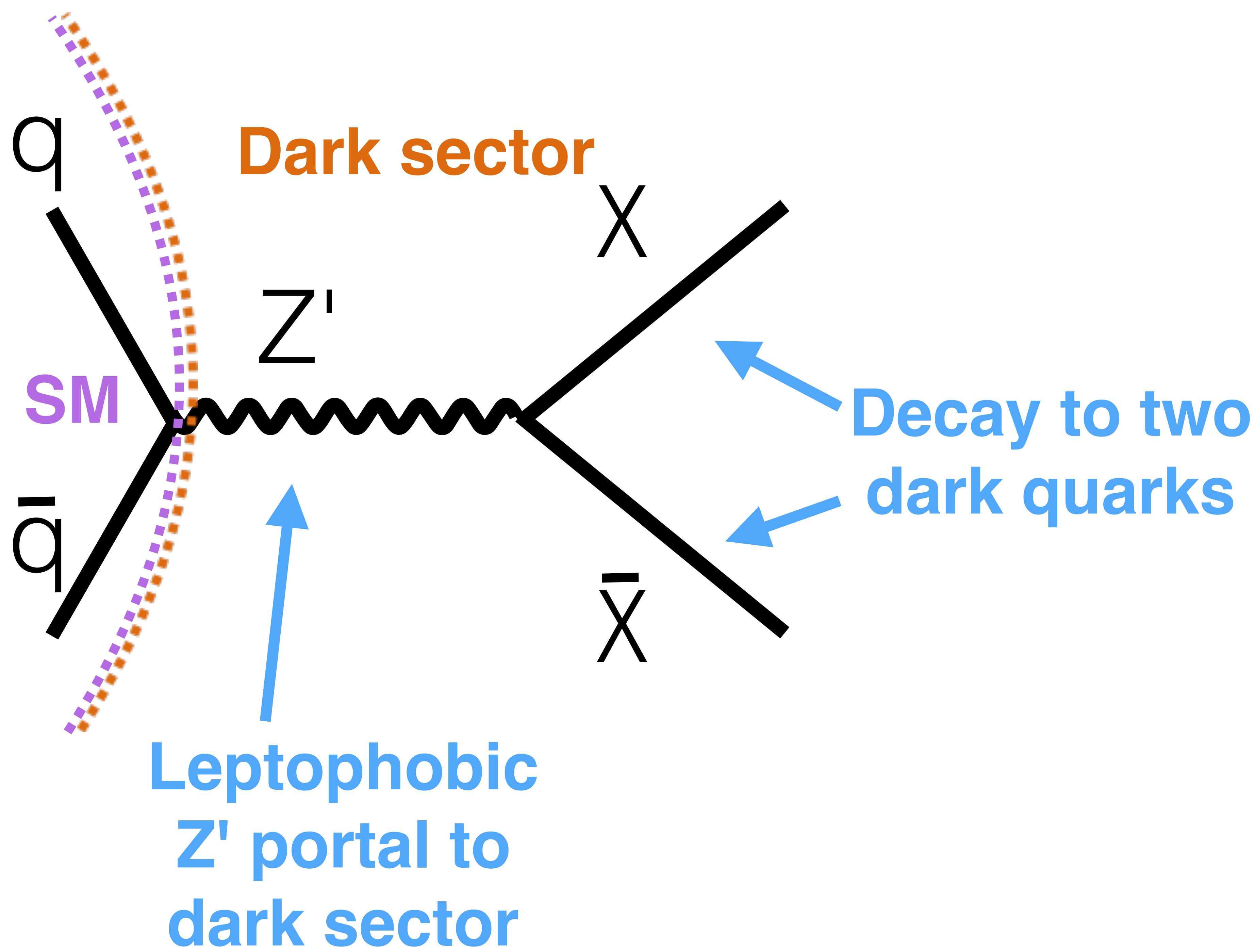
3 September 2022

About dark sectors

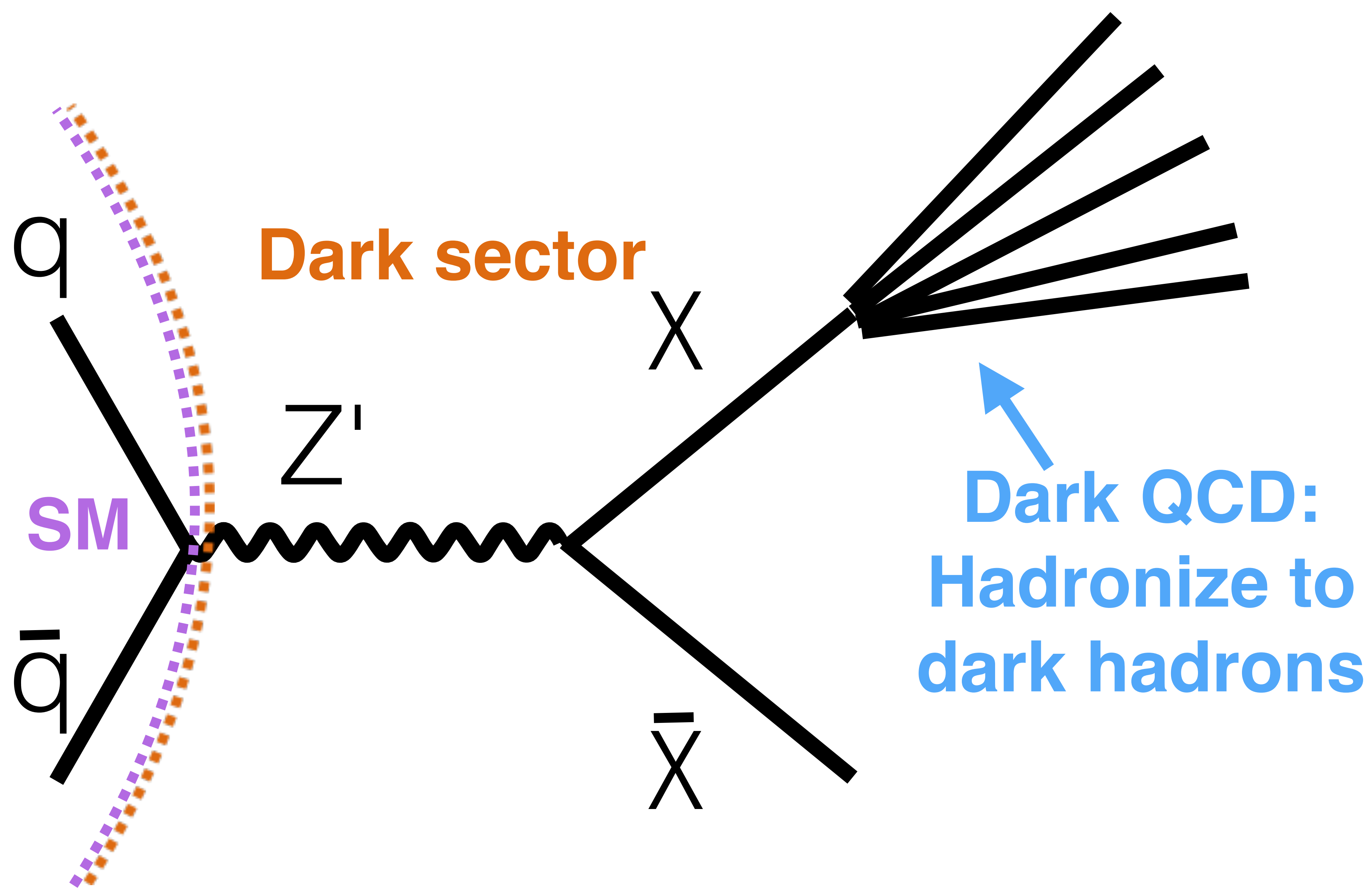


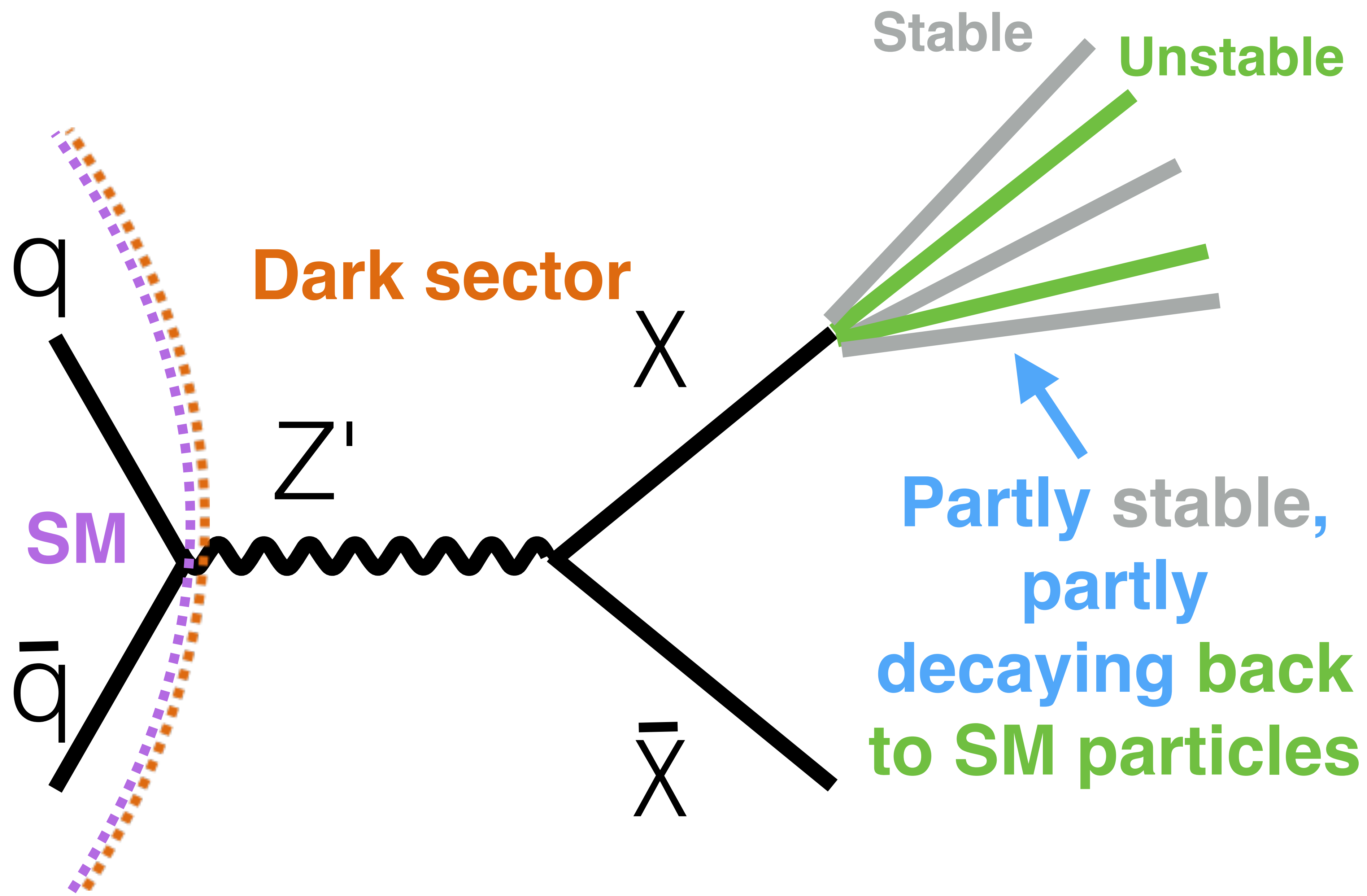
- What if dark matter is not a single particle?
  - Dark sector models more complex, but then again, so is ordinary matter
  - Alternative to WIMPs, detectable signatures
  - **Signature may be hiding in already-taken data**
  - This talk: **Semi-visible jets** [1503.00009] (one of the many signatures)
    - CMS search accepted for publication: [CMS-EXO-19-020]

Semi-visible jets in a nutshell

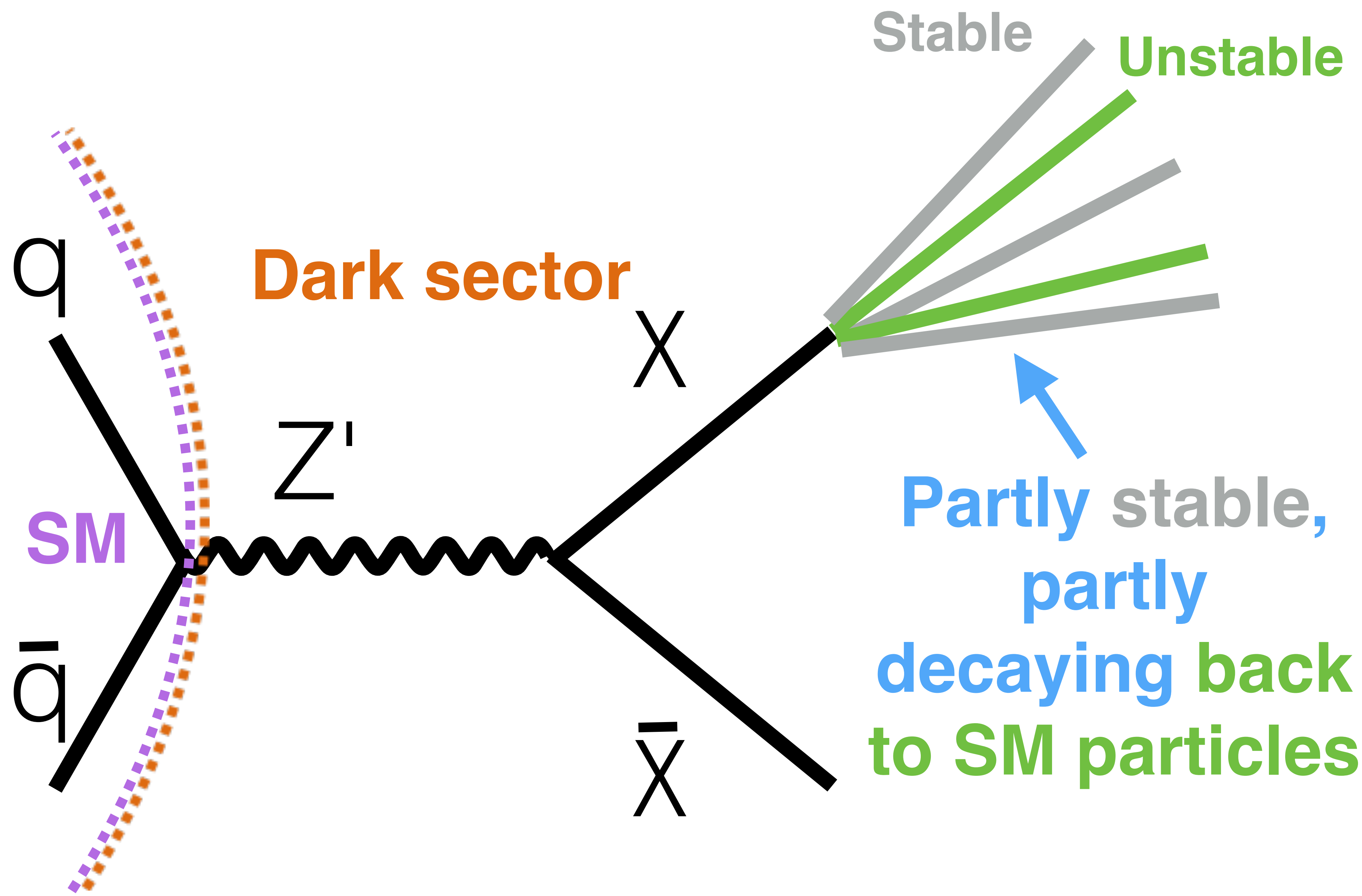


Semi-visible jets in a nutshell




Stable
Unstable
q
Dark sector
χ
Z'
SM
q̄
χ̄
Partly stable,
partly
decaying back
to SM particles

Semi-visible jets in a nutshell



$$r_{inv} = \frac{\text{Number of stable dark hadrons}}{\text{Number of total dark hadrons}}$$

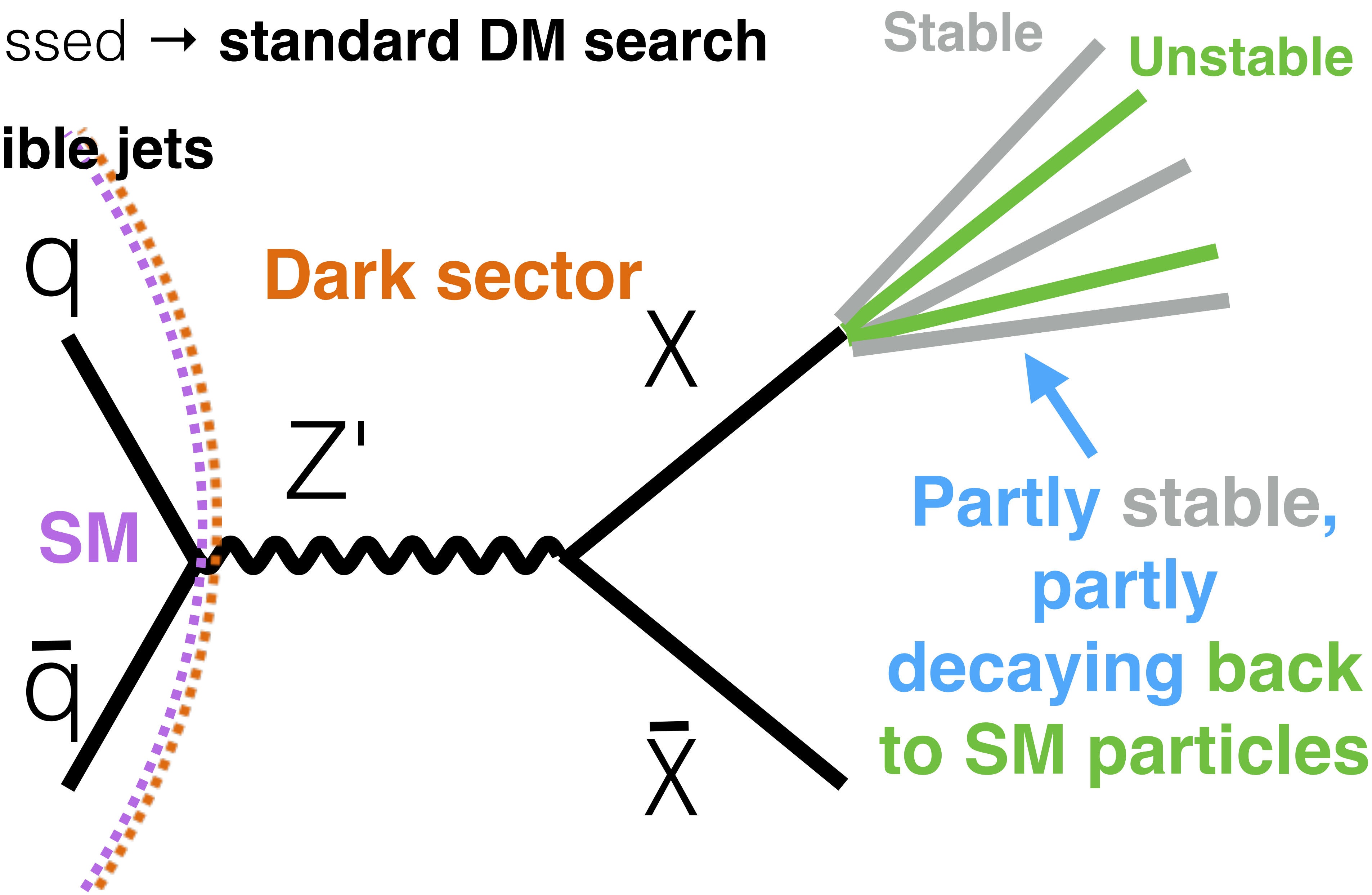
(stable + unstable)

Semi-visible jets in a nutshell

r_{inv}=0: Completely reconstructed → **standard dijet search**

r_{inv}=1: Completely missed → **standard DM search**

0 < r_{inv} < 1: **semi-visible jets**



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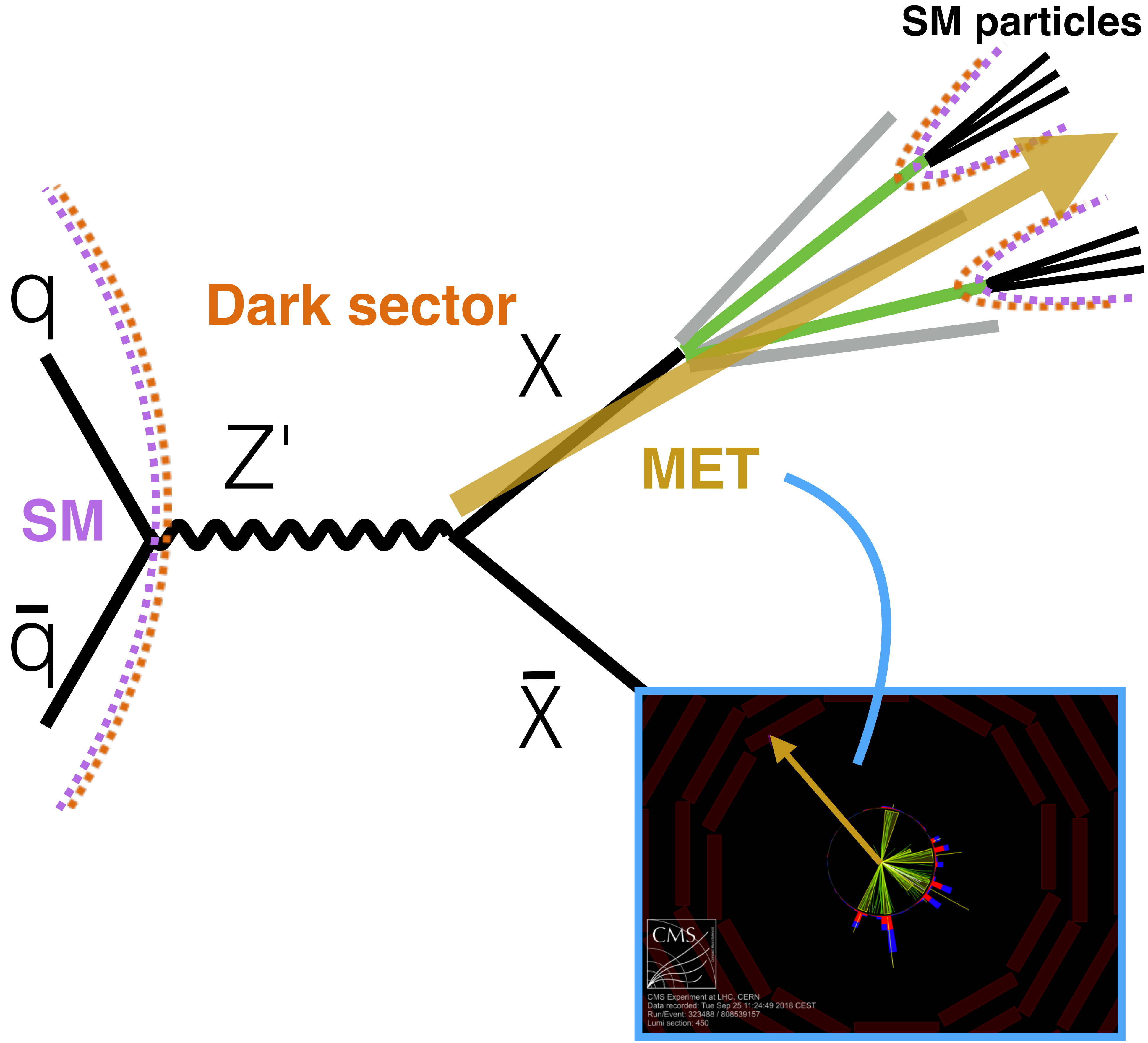
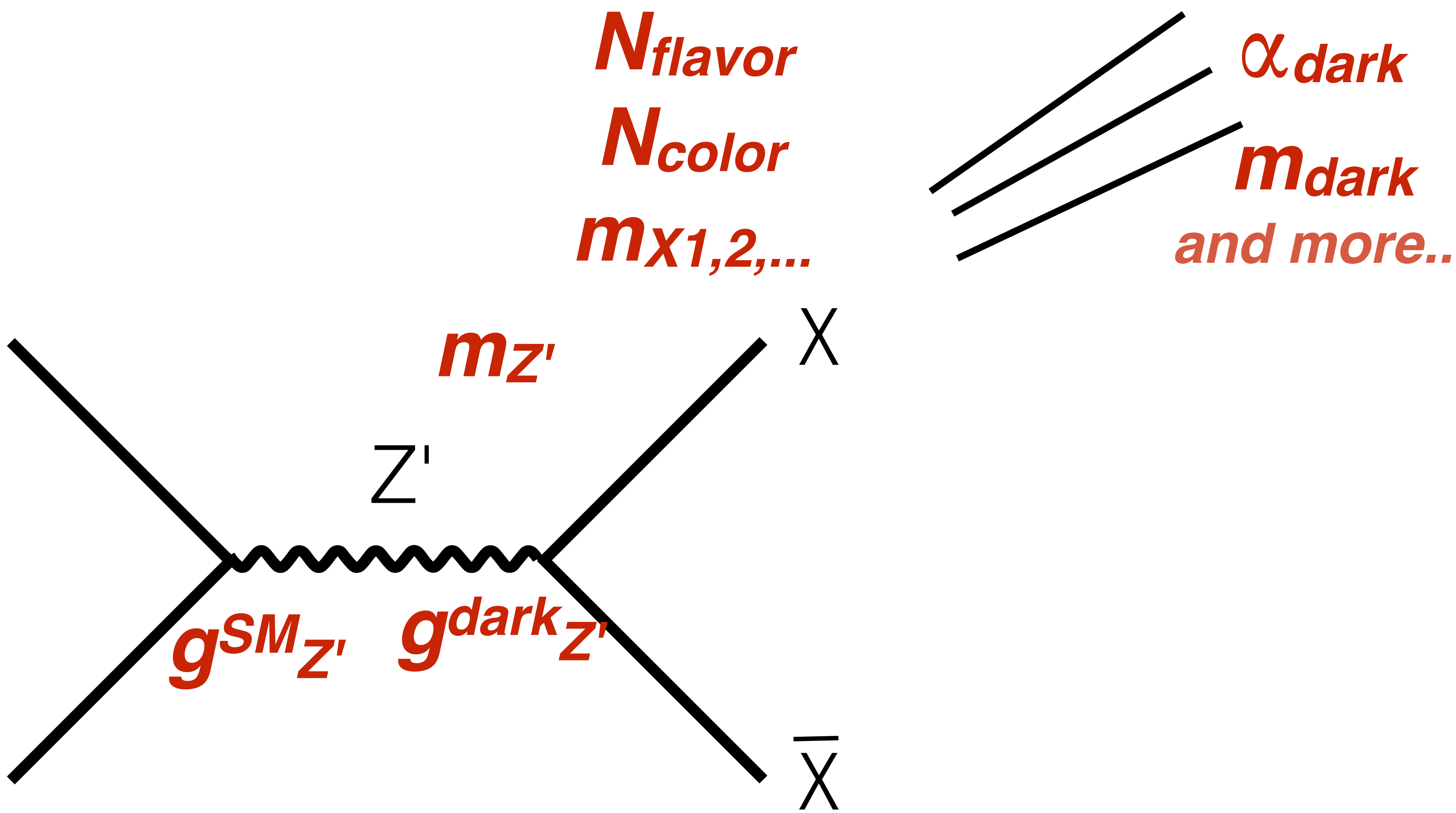
Semi-visible jets in a nutshell



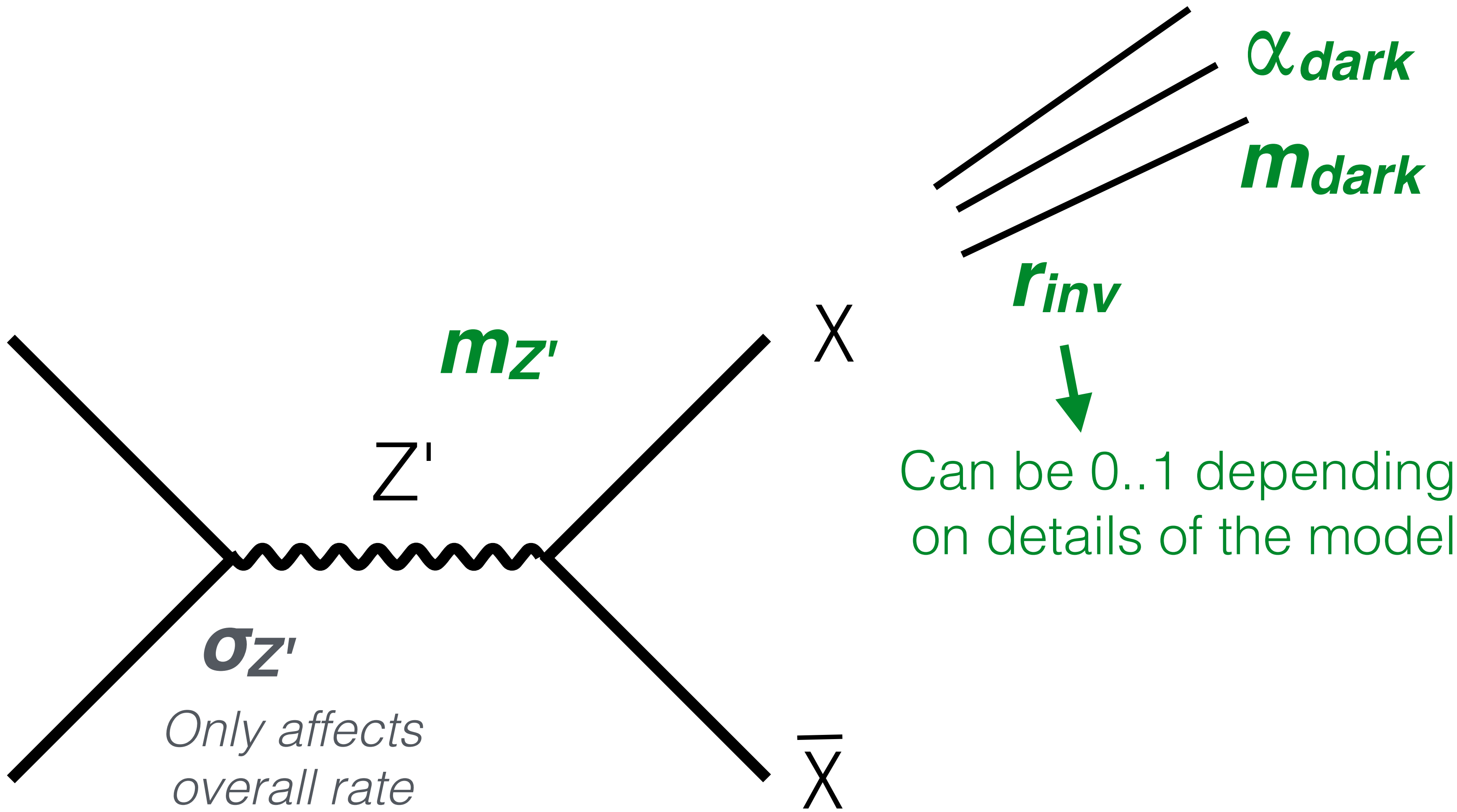
Model parameters

- Complete model parametrization can have many parameters
    - Some of these based on non-perturbative physics



Model parameters

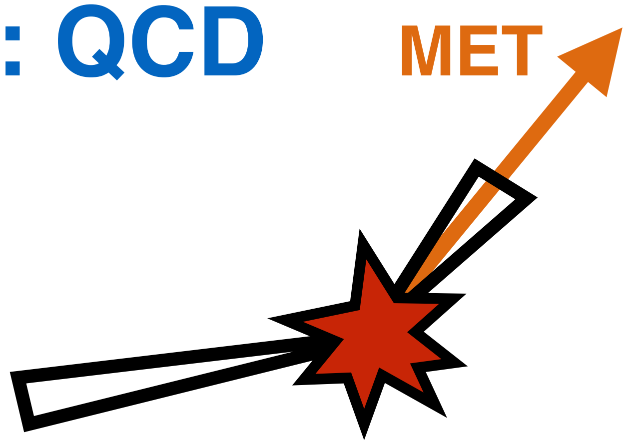
- Focus instead on **'effective' parameters** that have direct impact on jet observables and MET



- Dark hadrons decay promptly (no long lifetimes), dark QCD ($\Lambda_{dark} \ll m_{Z'}$), and no leptons in the dark hadron decays
  - Some alternative experimental signatures could be realized altering these details (displacement, leptons)

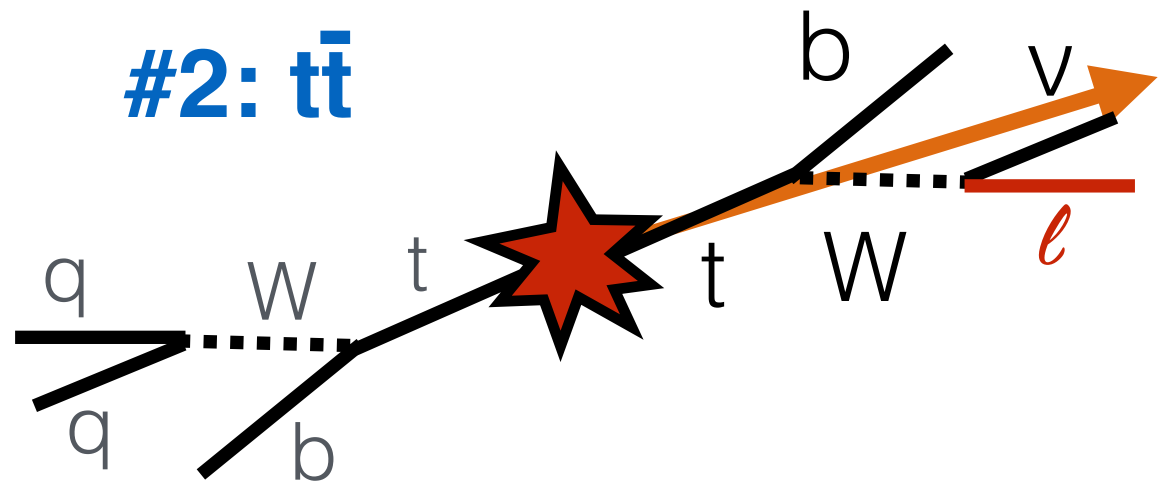
Backgrounds

#1: QCD



- **Dominant**; MET from misreconstruction

#2: $t\bar{t}$



- Mimics SVJ if lepton is missed

#3: W + jets

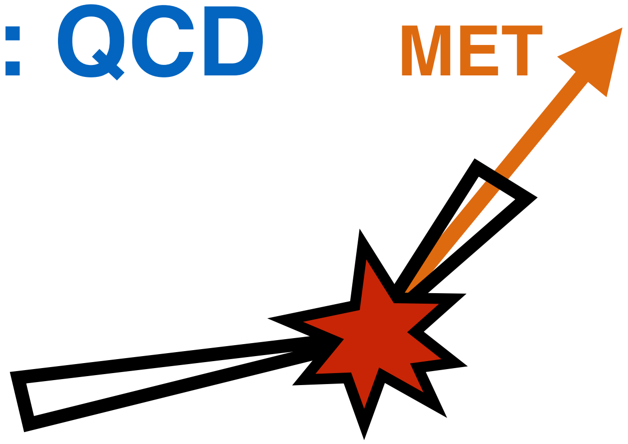
- MET from ν, missed lepton
- Not so likely to mimic SVJ but high σ

#4: Z + jets

- Least likely to have MET aligned with jet, but still noticeable background

Backgrounds

#1: QCD



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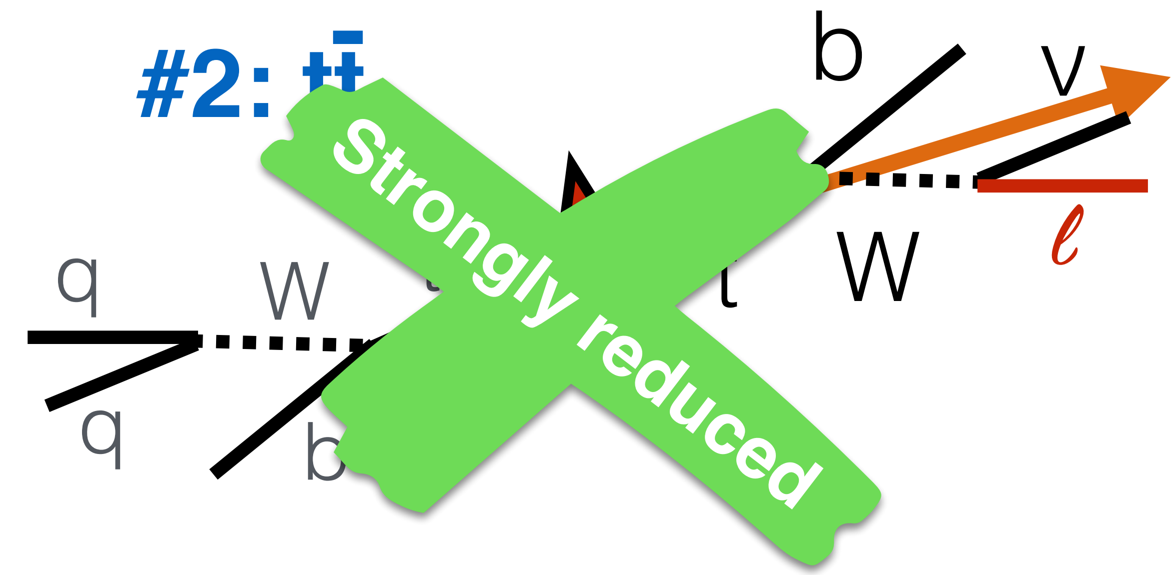
#2: $t\bar{t}$



- Mimics SVJ if lepton is missed

#3: W + jets

- MET from W missed lepton
- Not so likely to mimic SVJ but high σ

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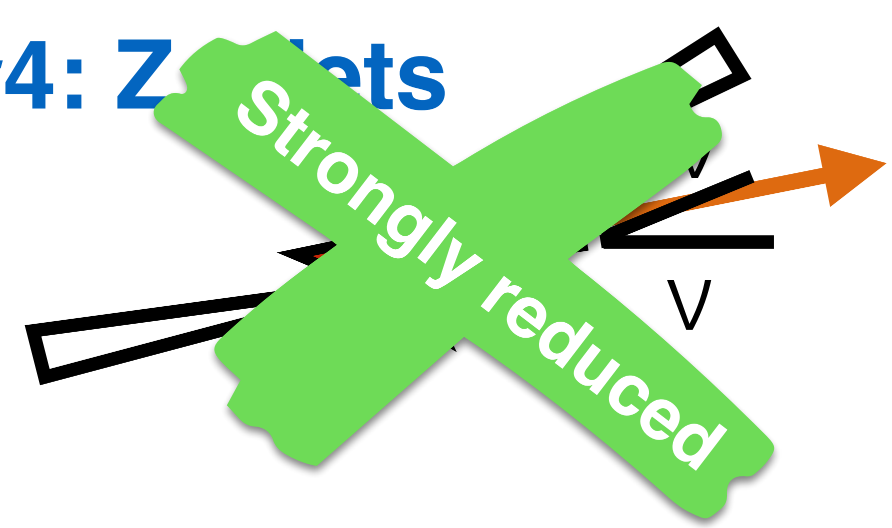


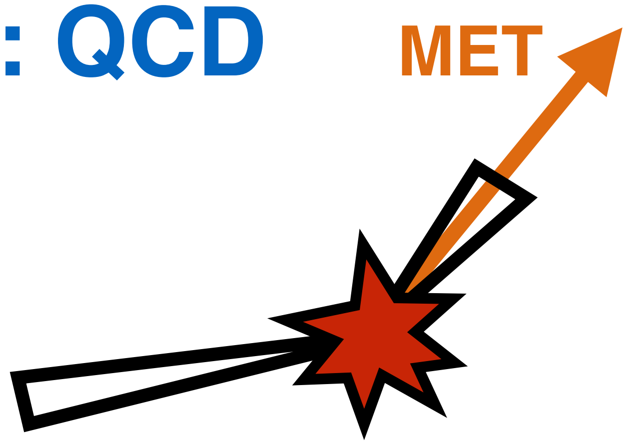
- Least likely to have MET aligned with jet, but still noticeable background

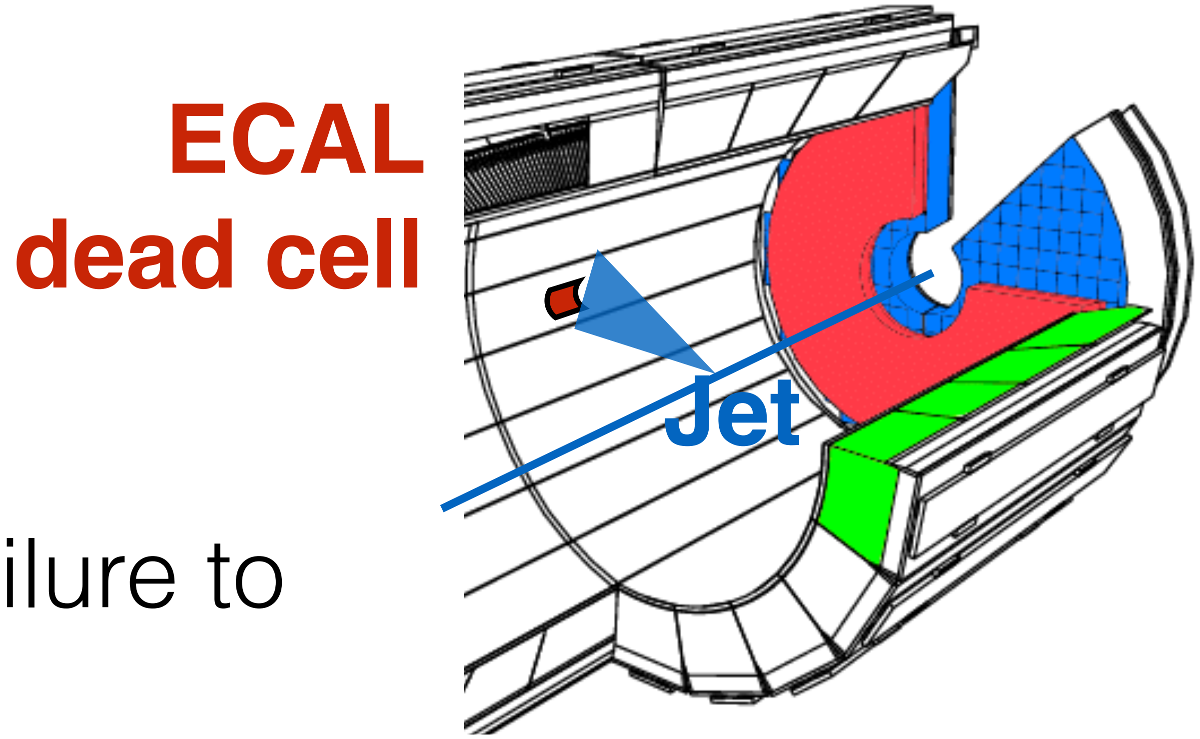
- **Veto leptons**
- **Require $\Delta\phi_{min}$ < threshold**
- Other less significant cuts

$\Delta\phi_{min} = \min(\Delta\phi(j_1, \text{MET}), \Delta\phi(j_2, \text{MET}))$

Backgrounds

#1: QCD

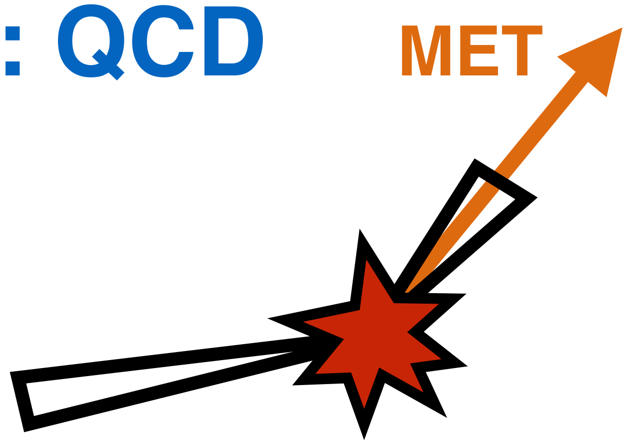


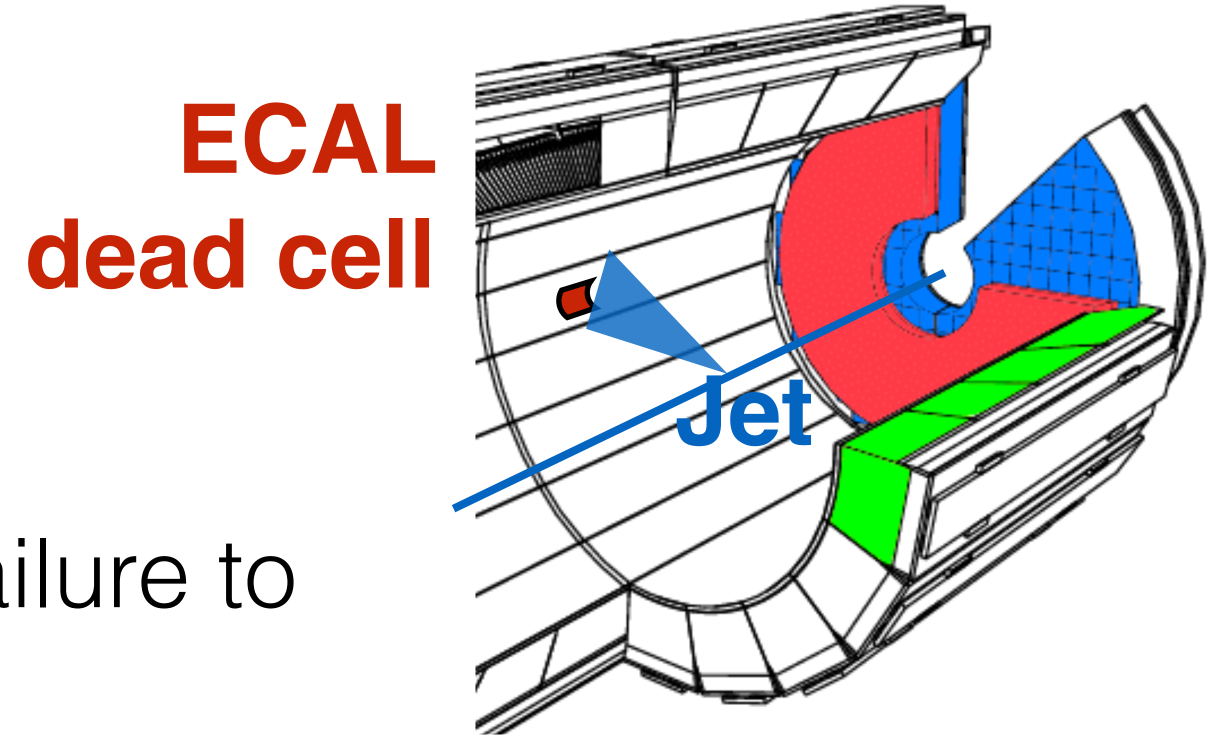


- Mostly **instrumental MET**, i.e. failure to reconstruct the whole jet
  - Example: ECAL dead cells
  - Custom filter put in place to reject an additional 40% QCD

Backgrounds

#1: QCD

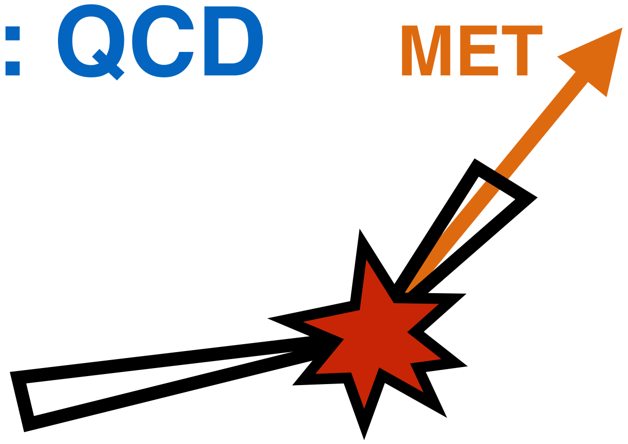


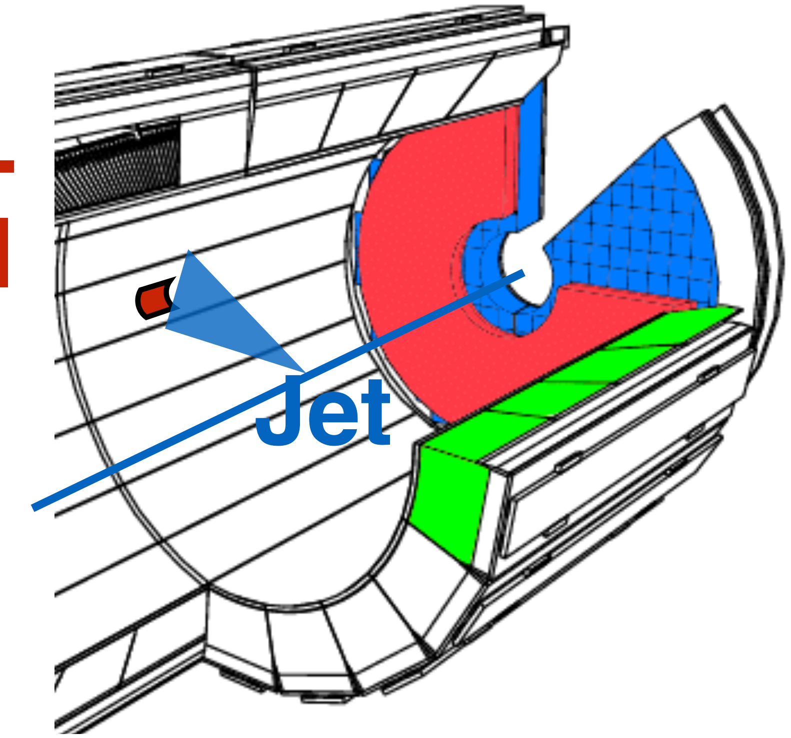


- Mostly **instrumental MET**, i.e. failure to reconstruct the whole jet
  - Example: ECAL dead cells
  - Custom filter put in place to reject an additional 40% QCD
- Main QCD rejection: require $\mathbf{R_T = MET/M_T > threshold}$
  - Good QCD rejection without sculpting M_T distribution

Backgrounds

#1: QCD



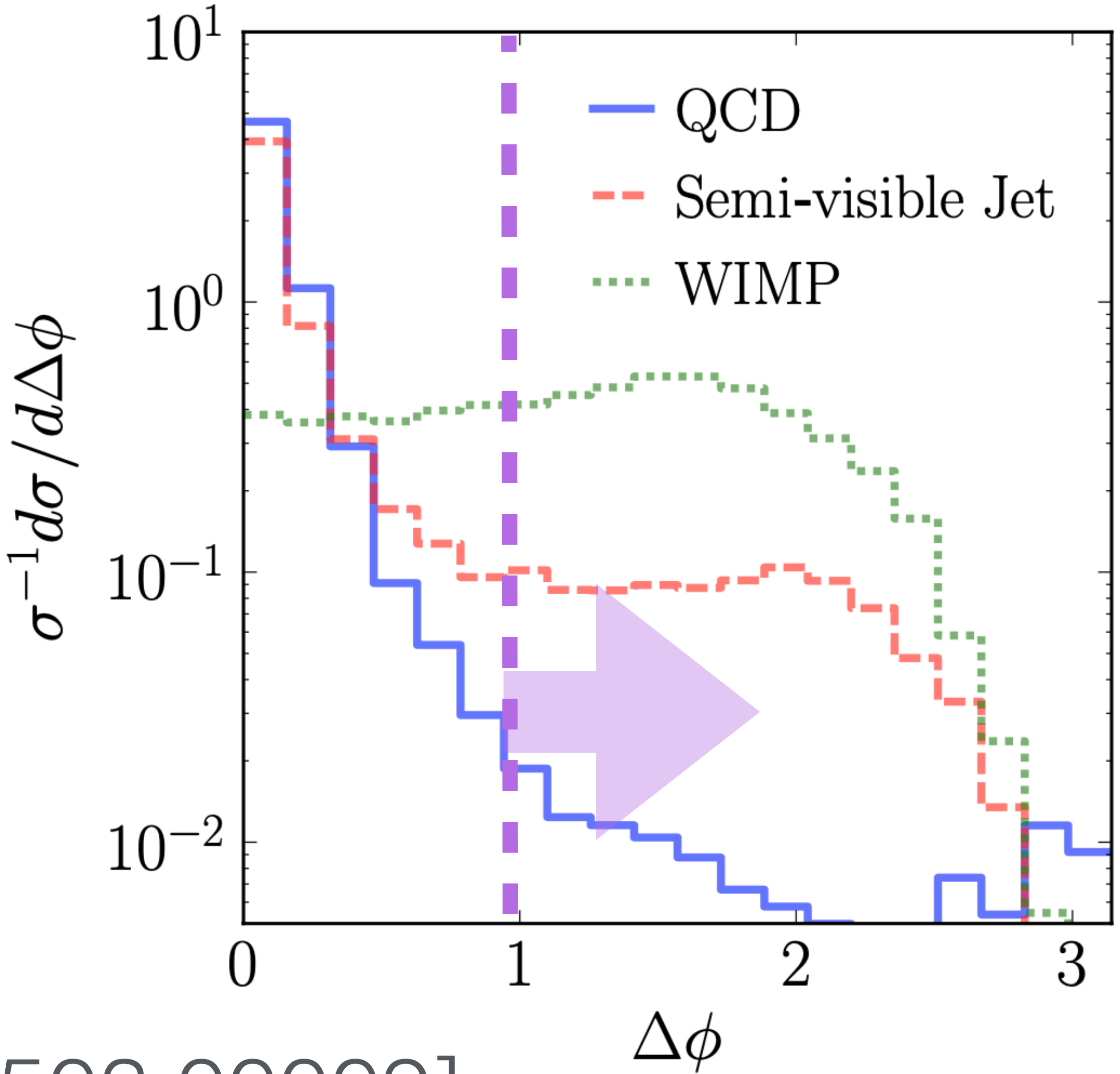


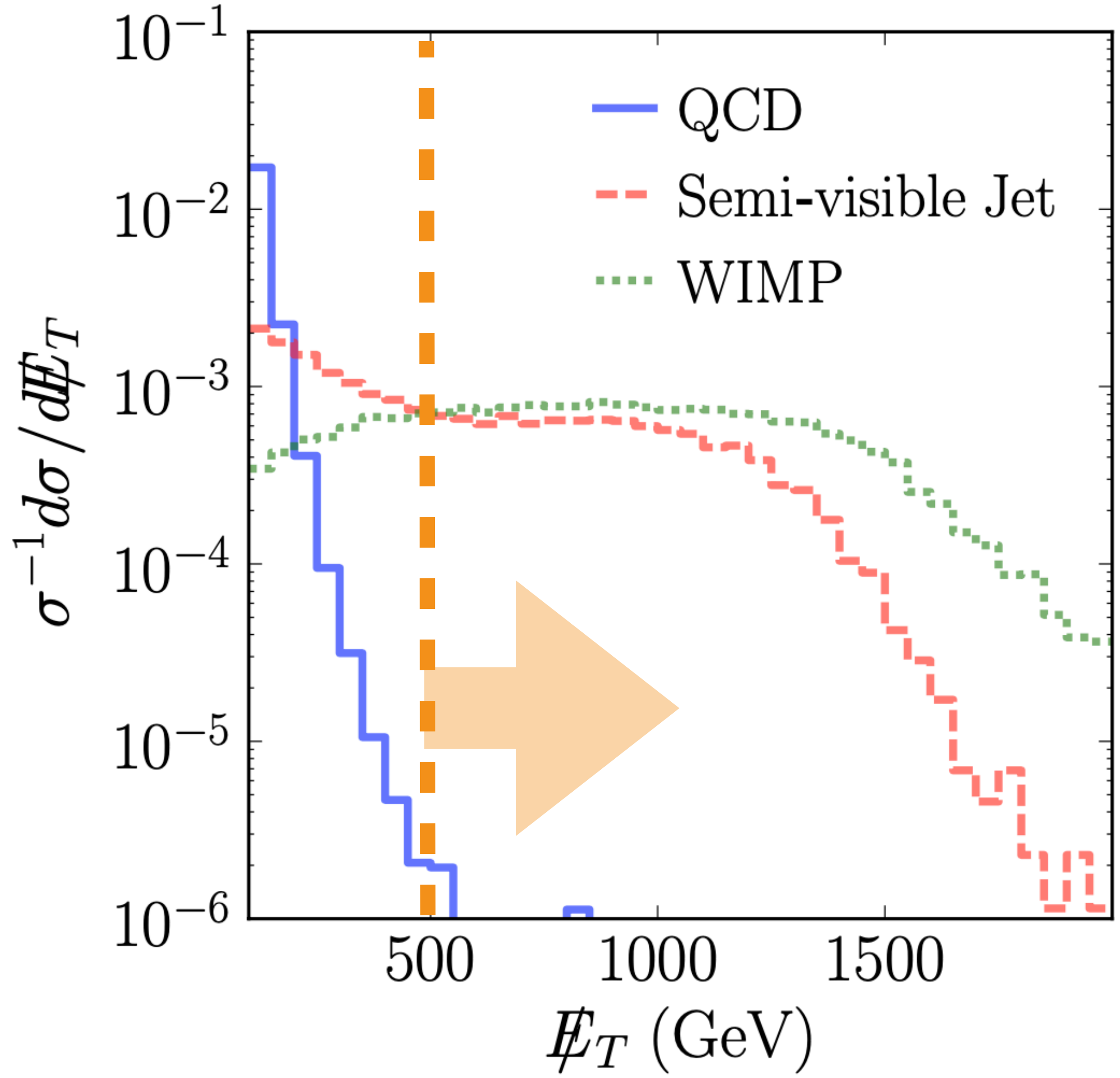
- Mostly **instrumental MET**, i.e. failure to reconstruct the whole jet
  - Example: ECAL dead cells
  - Custom filter put in place to reject an additional 40% QCD
- Main QCD rejection: require **R_T = MET/M_T > threshold**
  - Good QCD rejection without sculpting M_T distribution
- Further reduction via a **BDT** based on jet variables
  - **Model dependent!**
  - Perform final fits **without BDT** too; weaker limits, but no model dependence

Phenomenology of SVJs

Δϕ cut very inefficient for SVJs

Cut on MET kills more than for WIMP case

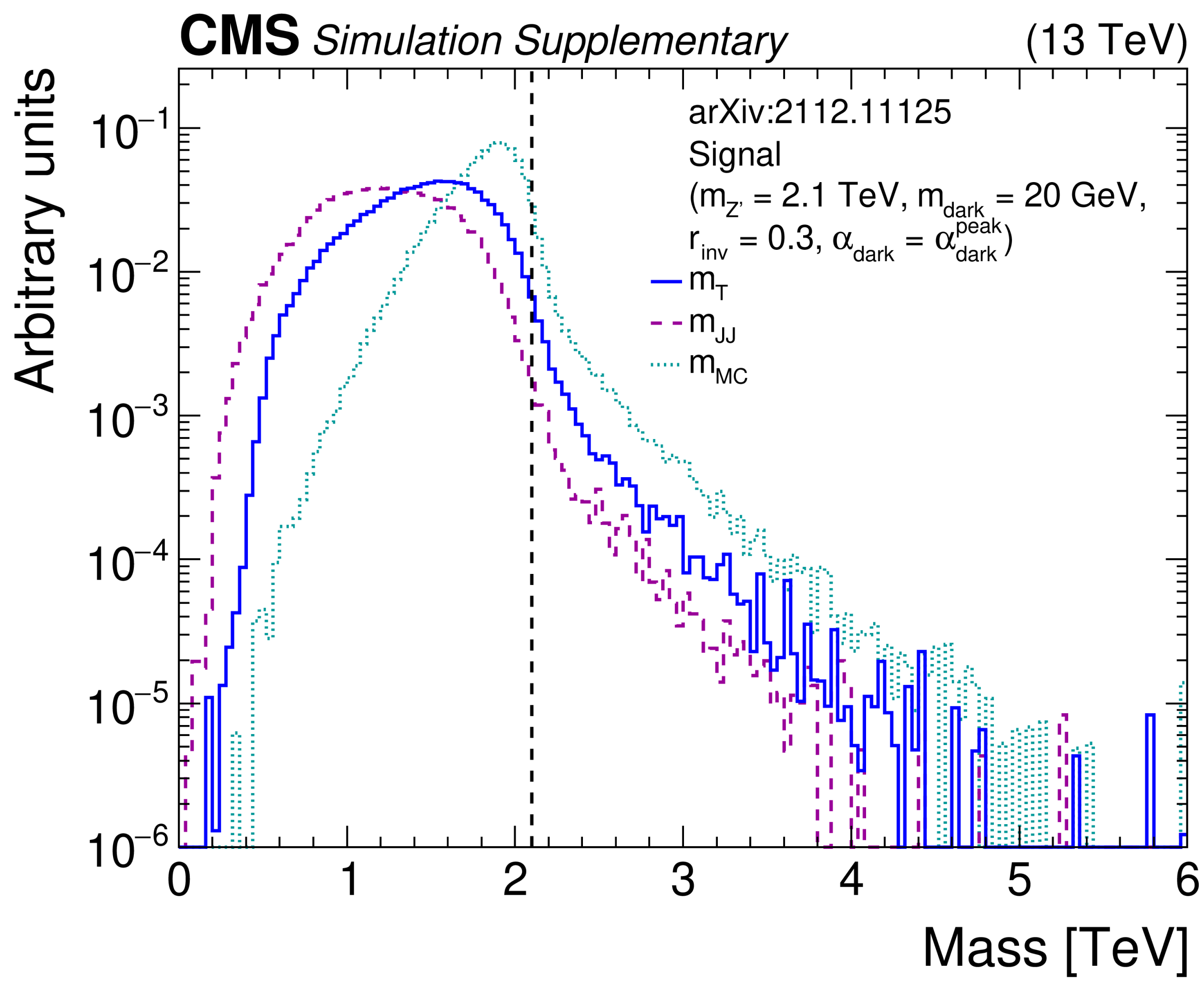




[1503.00009]

- **Semi-visible jet searches not covered by current searches**

Search strategy: Bump hunt



- High-mass Z' ($m_{Z'}$ > ~1000 GeV) leads to a **resonance** in the mass spectrum
- Searching in **M_T(JJ, MET):**

$$M_{\mathrm{T}}^2 = \left(\mathrm{MET} + \sqrt{p_{\mathrm{T,\,dijet}}^2 + m_{\mathrm{dijet}}^2}\right)^2 - (\mathrm{MET}_x + p_{x,\,\mathrm{dijet}})^2 - (\mathrm{MET}_y + p_{y,\,\mathrm{dijet}})^2$$

  - Kinematic **edge** @ $m_{Z'}$
  - Better resolution than m_{JJ}
- SM backgrounds smoothly falling

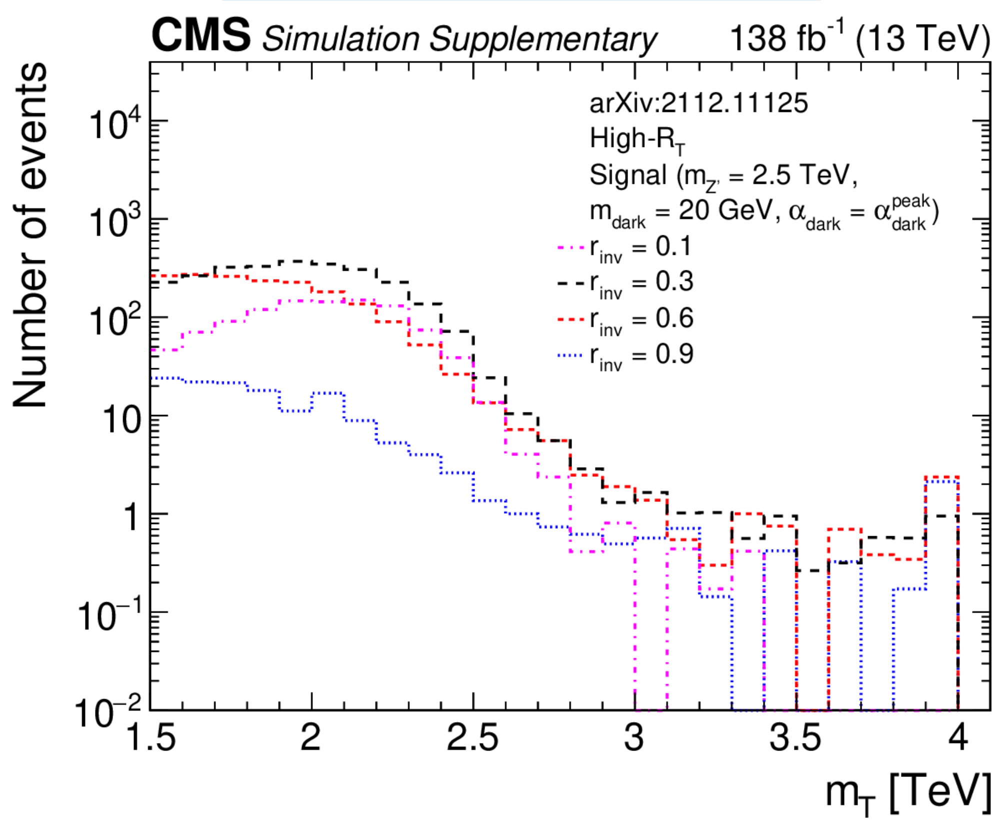
Signal regions

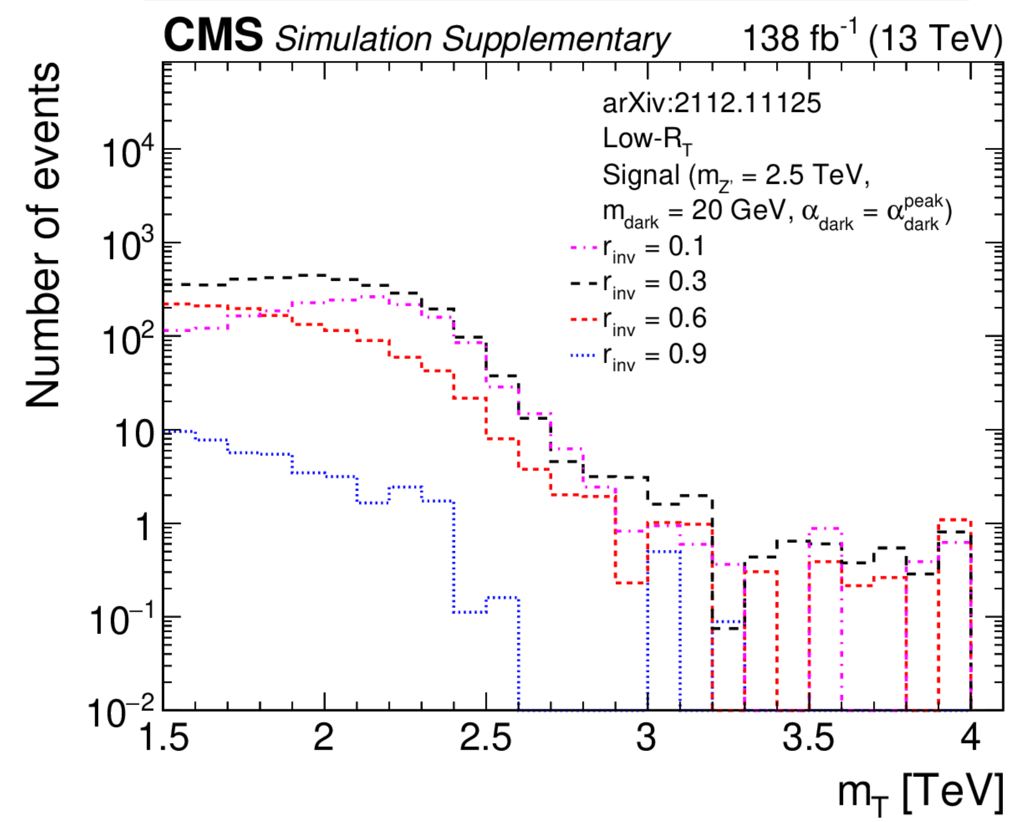
$R_T = MET/M_T$

- Low and high 'purity' regions are constructed to enhance sensitivity:

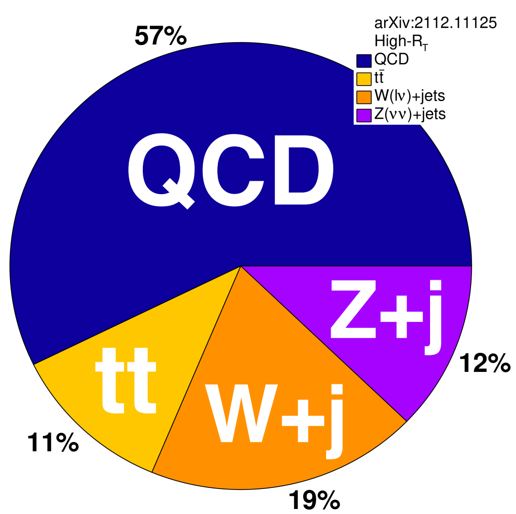
High: $R_T > .25$

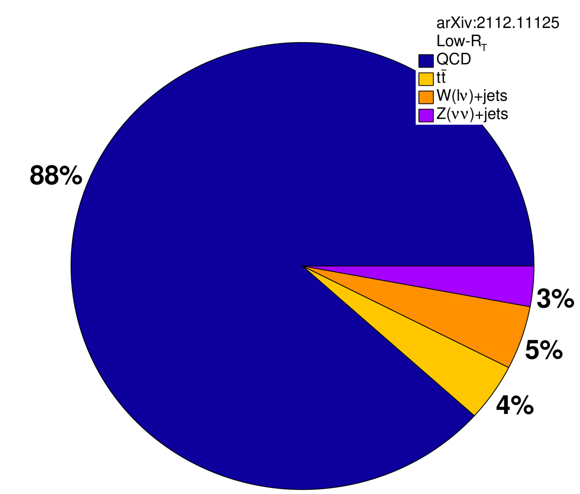
Low: $.15 < R_T < .25$





- Kinematic edge somewhat degraded in low purity region
- Pronounced effect of r_{inv} on M_T spectrum

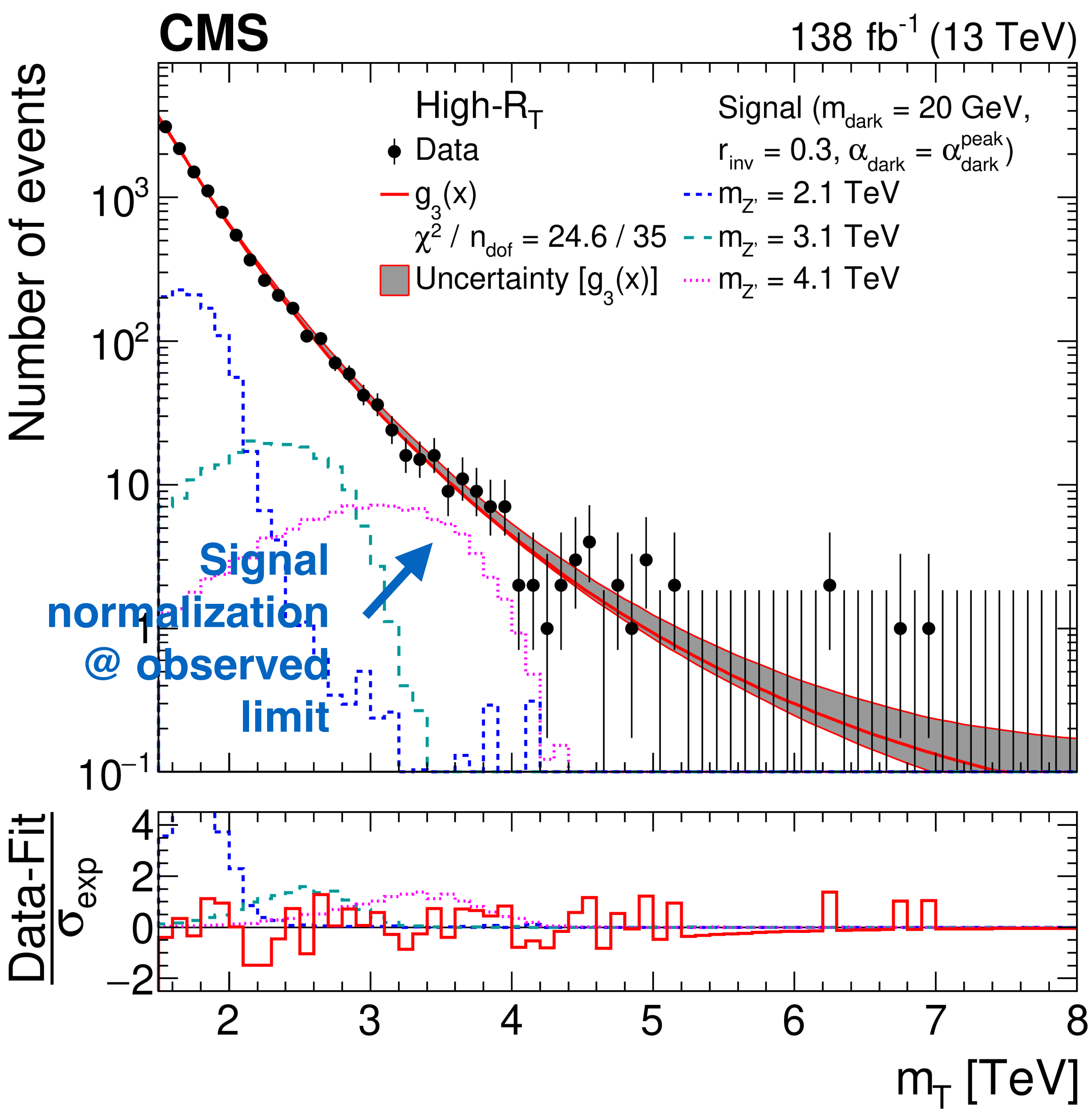


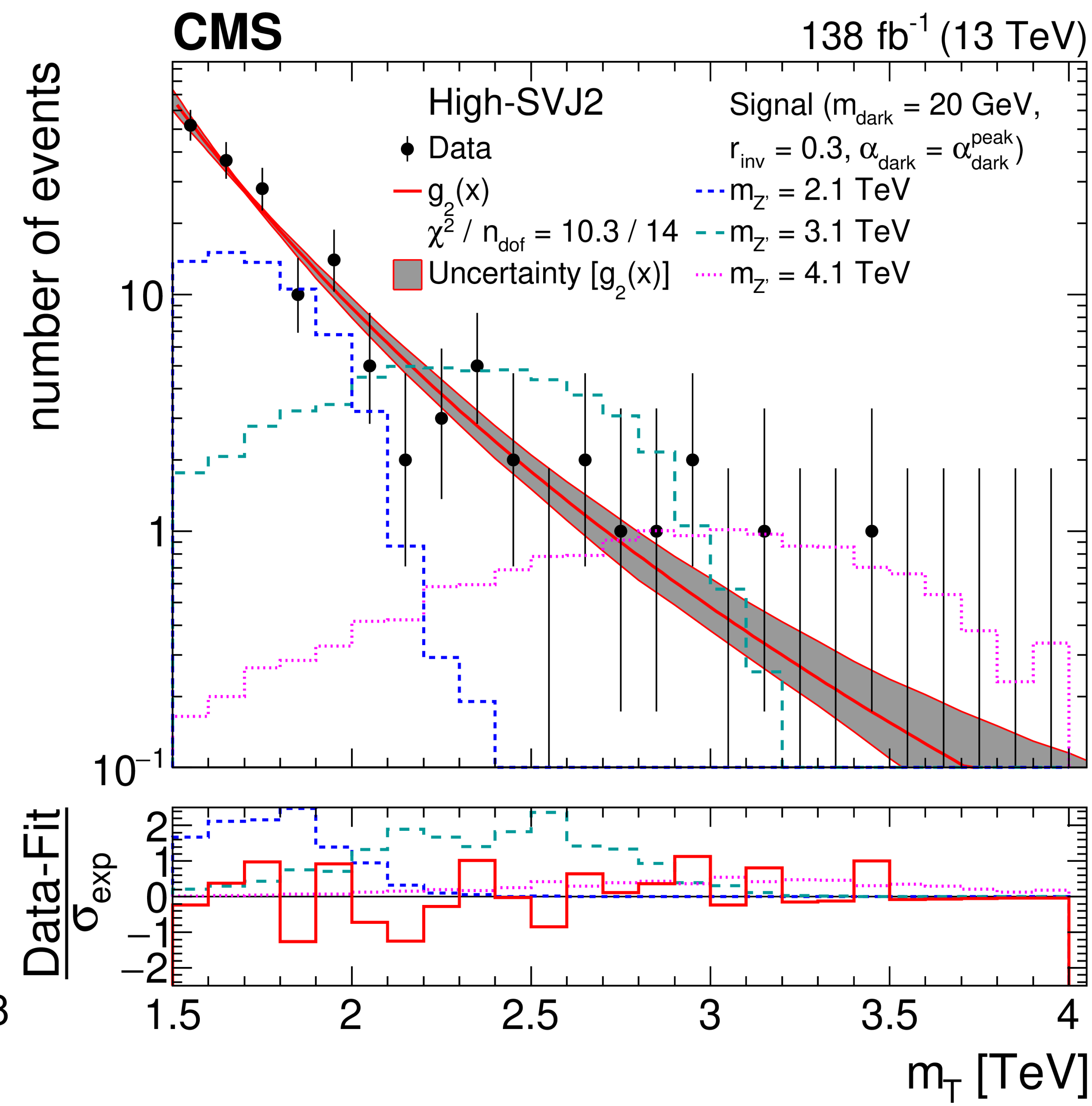


Results

High purity region only: $R_T > .25$

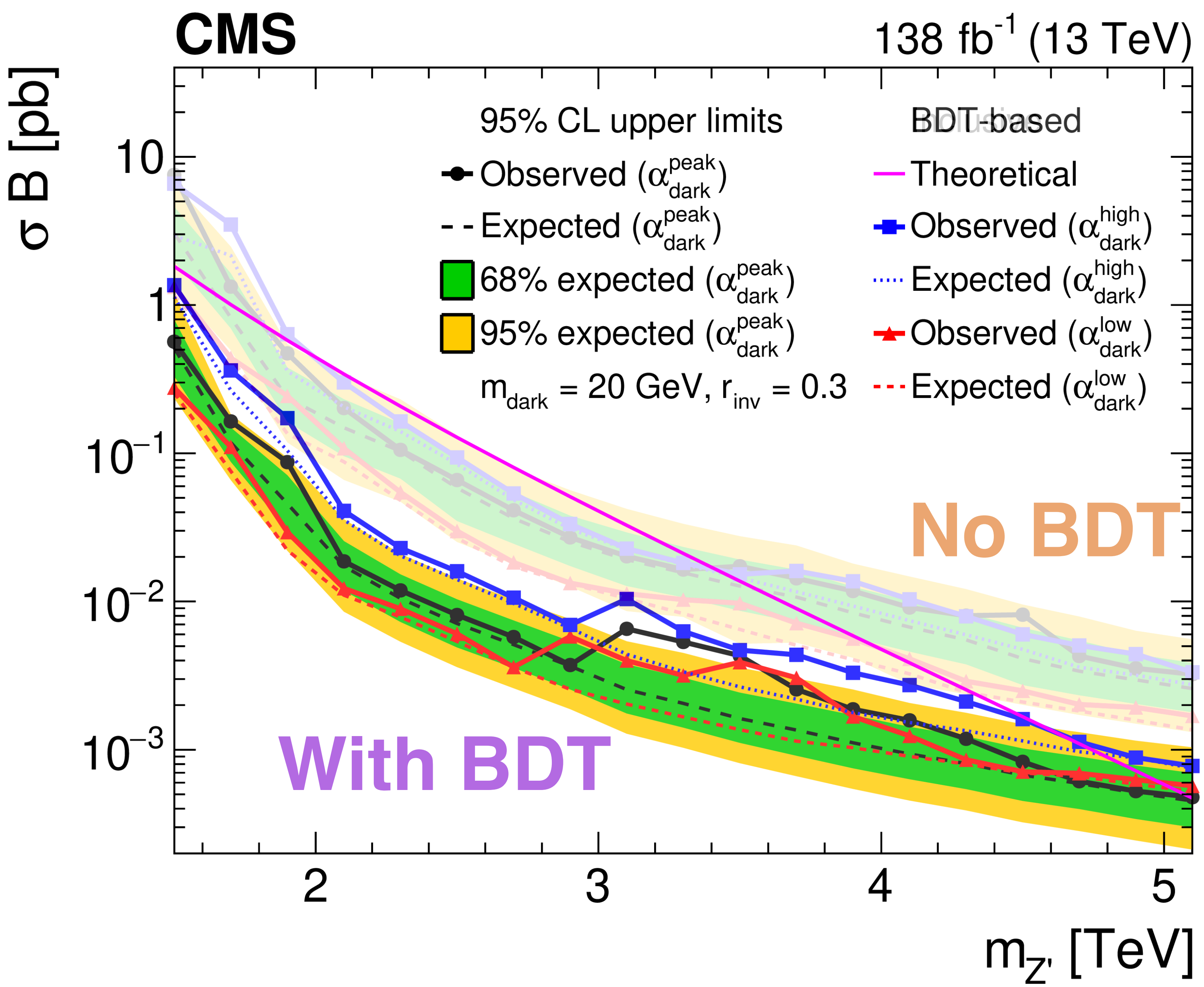
- Background estimation relies on fit to data





- No significant deviations from data

Limits



No BDT

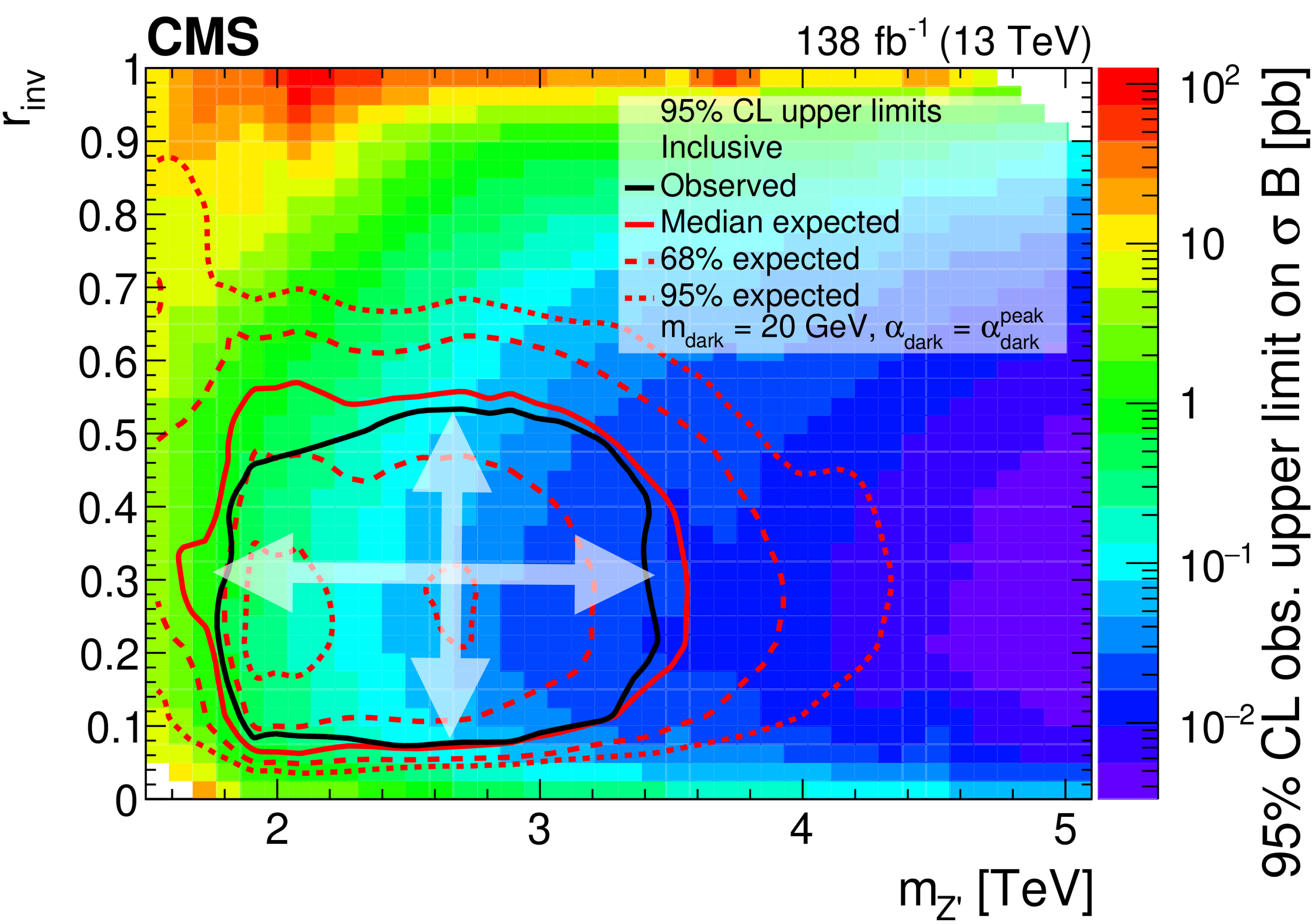
$1.5 < m_{Z'} < 4.0$ TeV (95% CL)

With BDT

$1.5 < m_{Z'} < 5.1$ TeV (95% CL)

Limits in ($m_{Z'}$, r_{inv})-plane

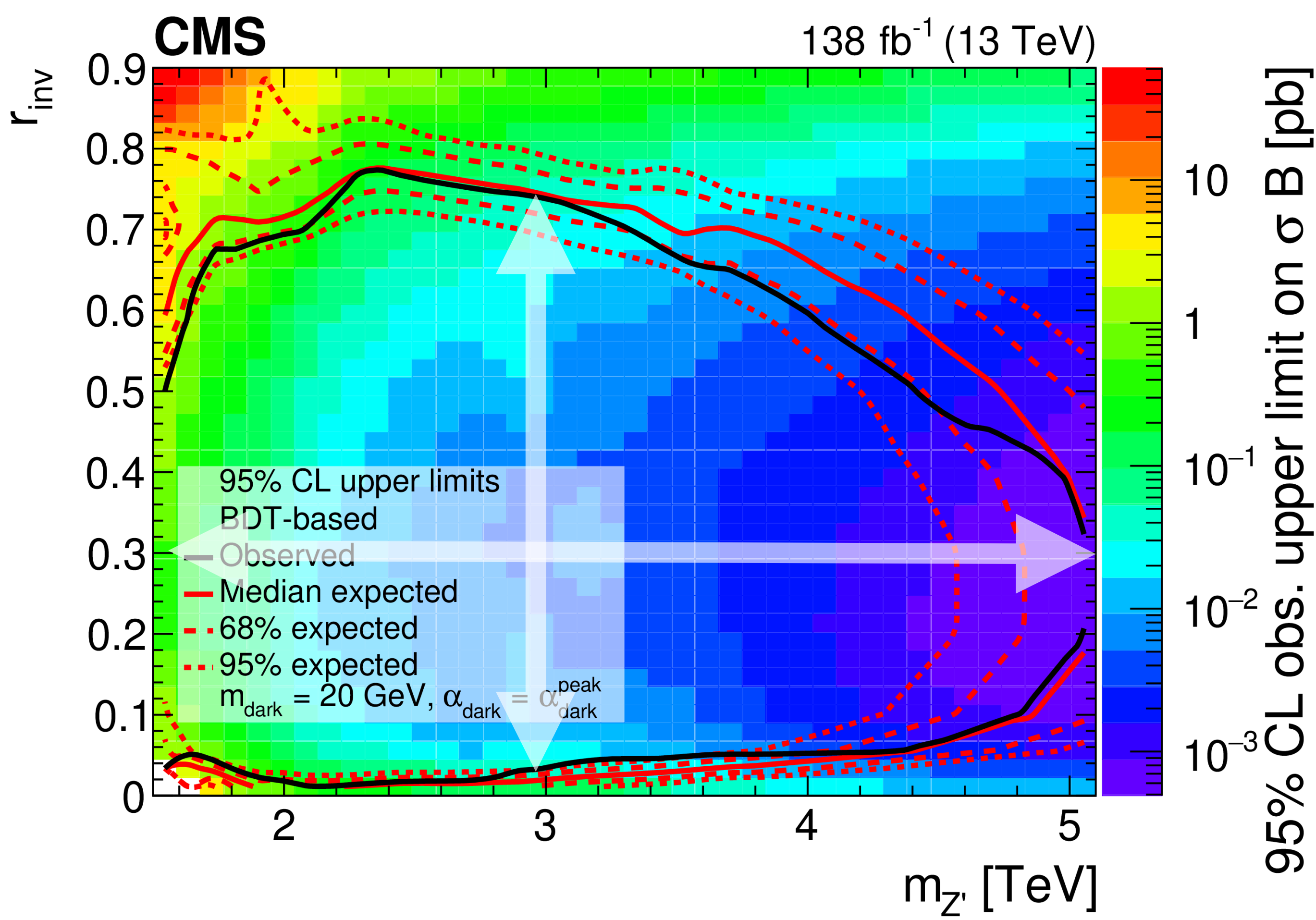
No BDT



$1.5 < m_{Z'} < 4.0$ TeV (95% CL)

$0.07 < r_{inv} < 0.53$ (95% CL)

With BDT



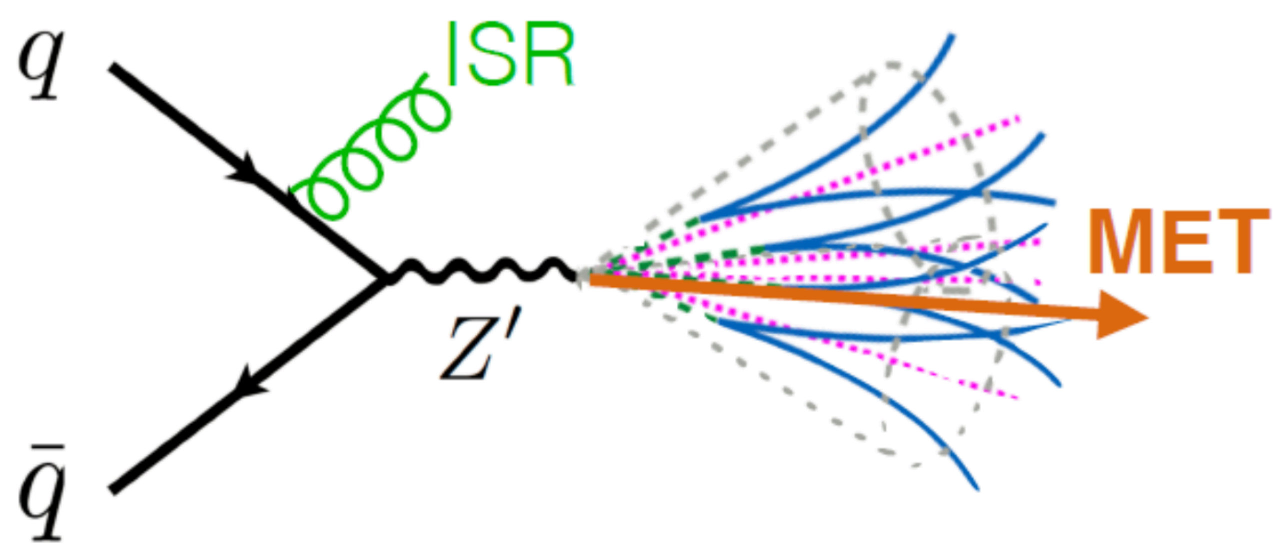
$1.5 < m_{Z'} < 5.1$ TeV (95% CL)

$0.01 < r_{inv} < 0.77$ (95% CL)

Other dark QCD analyses in the pipeline

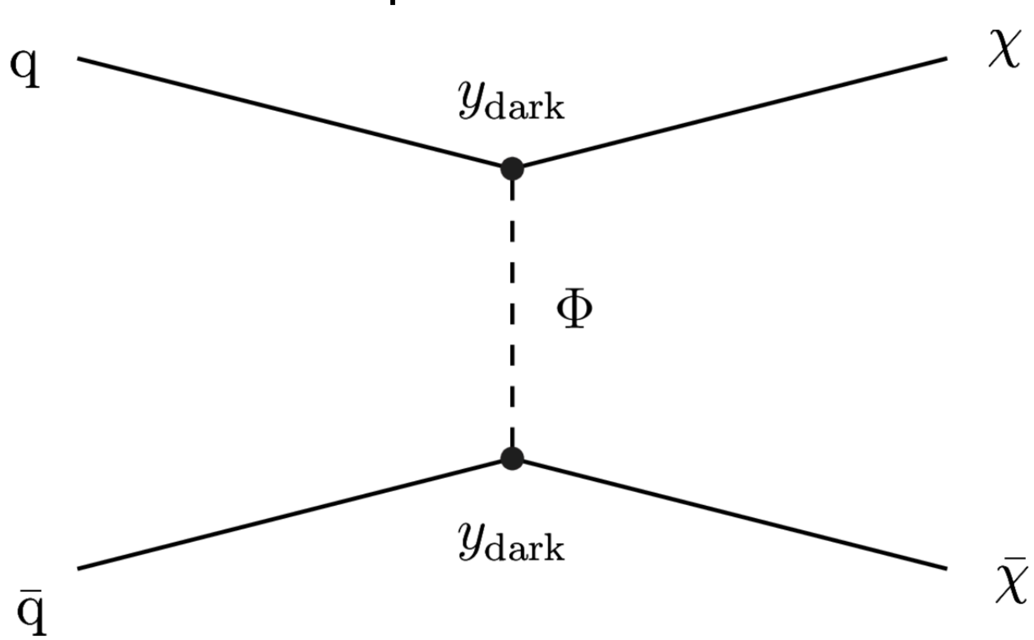
Boosted SVJs

What if $m_{Z'}$ is low and the Z' system is boosted?



t-channel

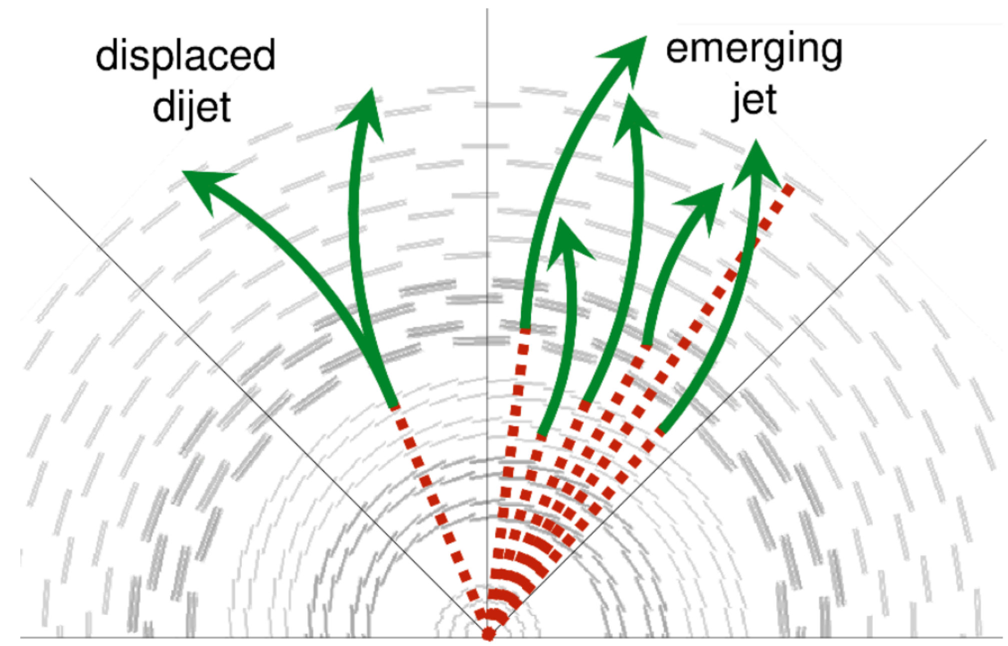
Alternative production modes



Emerging jets

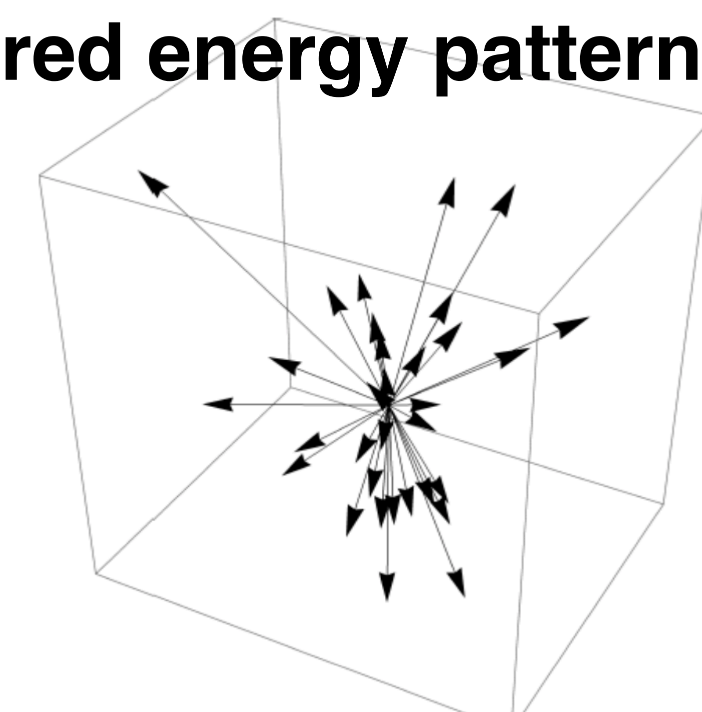
What if the dark hadrons have a non-negligible lifetime?

Published: [JHEP 02 (2019) 179]



Soft unclustered energy patterns (SUEPs)

Large 't Hooft coupling causing a spherical spray



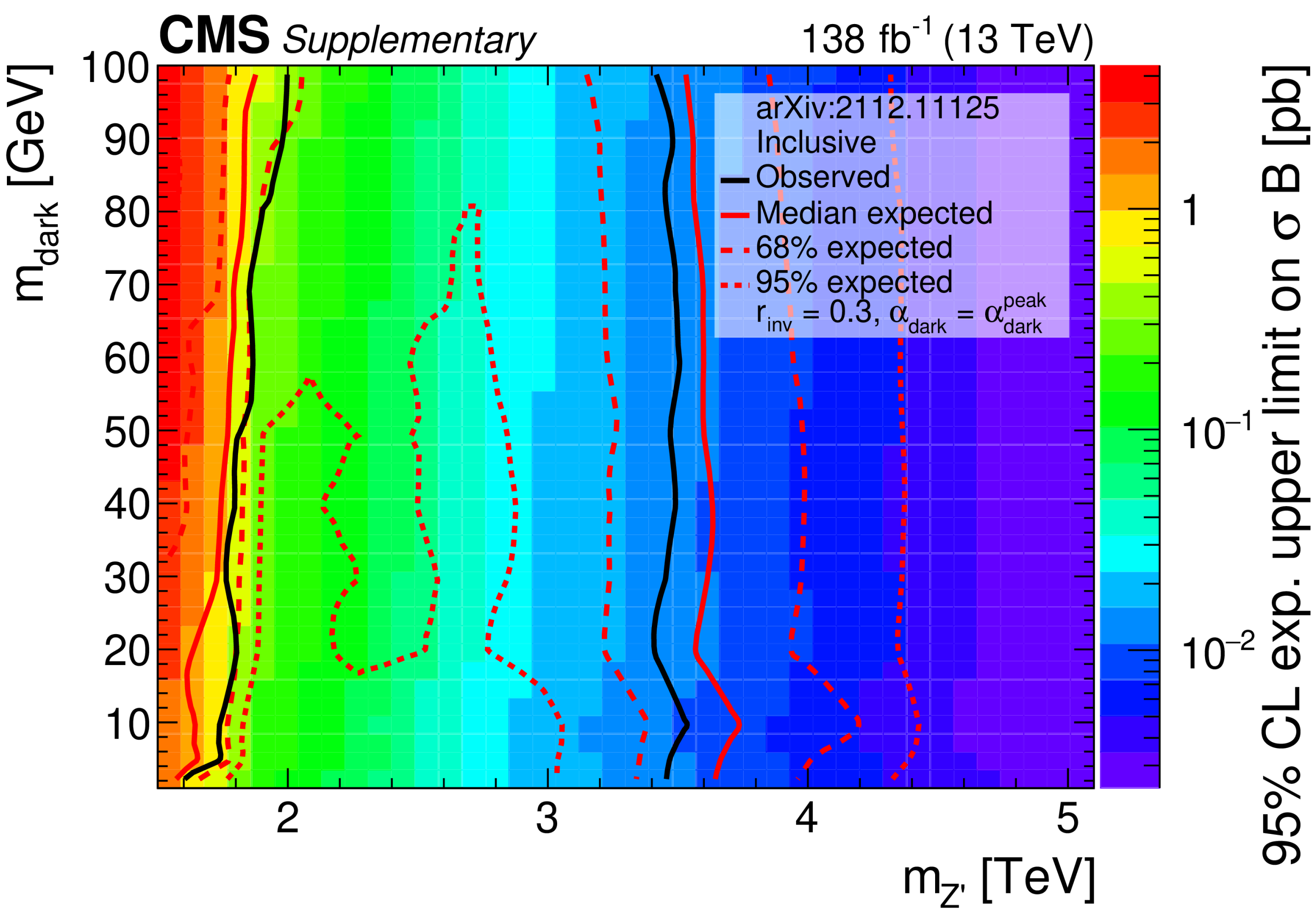
Conclusion

- Dark sector models can have interesting new signatures in particle detectors
  - These signatures may be hiding in already taken data
- Presented a search for semivisible jets in the CMS detector
  - First direct search for strongly-coupled composite dark matter at colliders
  - Both model independent and model specific results
- Many other interesting signatures possible - stay tuned!

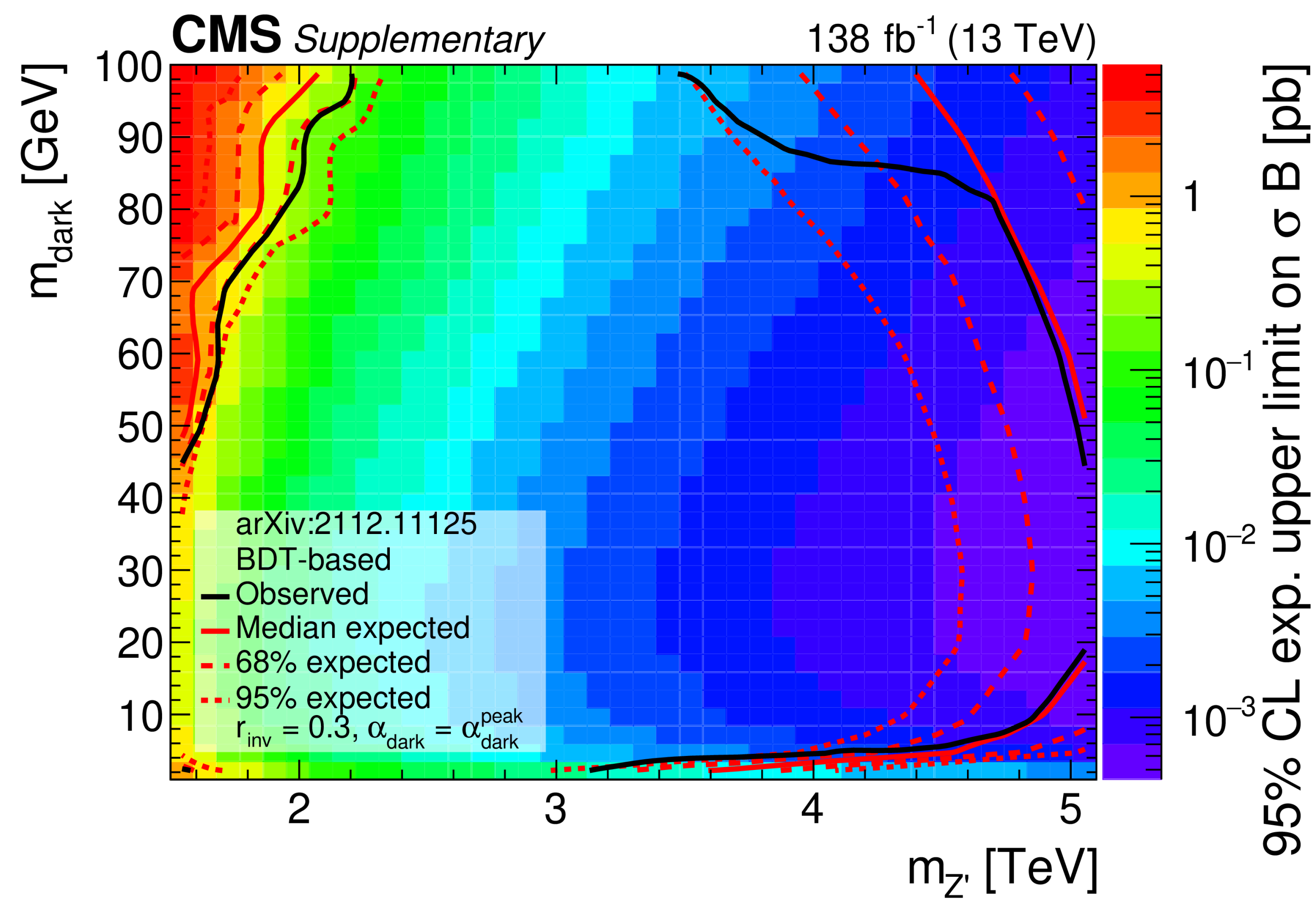
Back up

2D exclusion limits vs. m_{dark}

No BDT



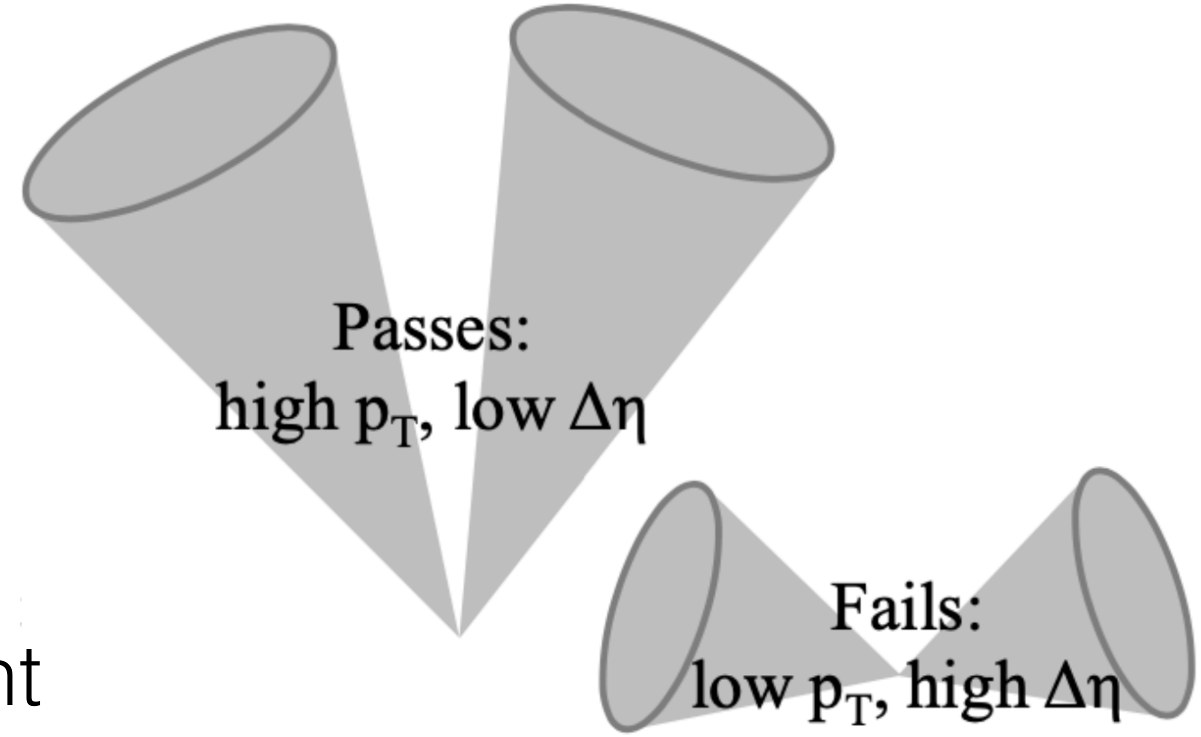
With BDT

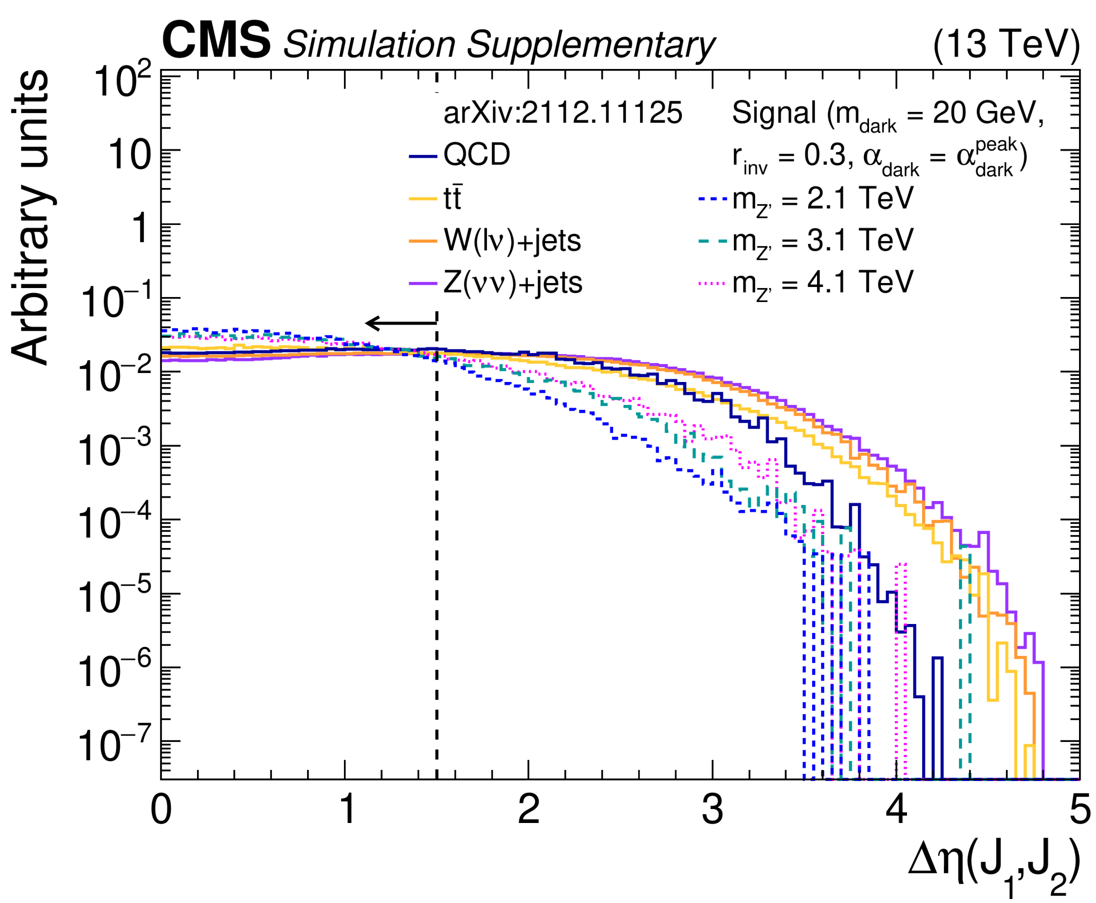


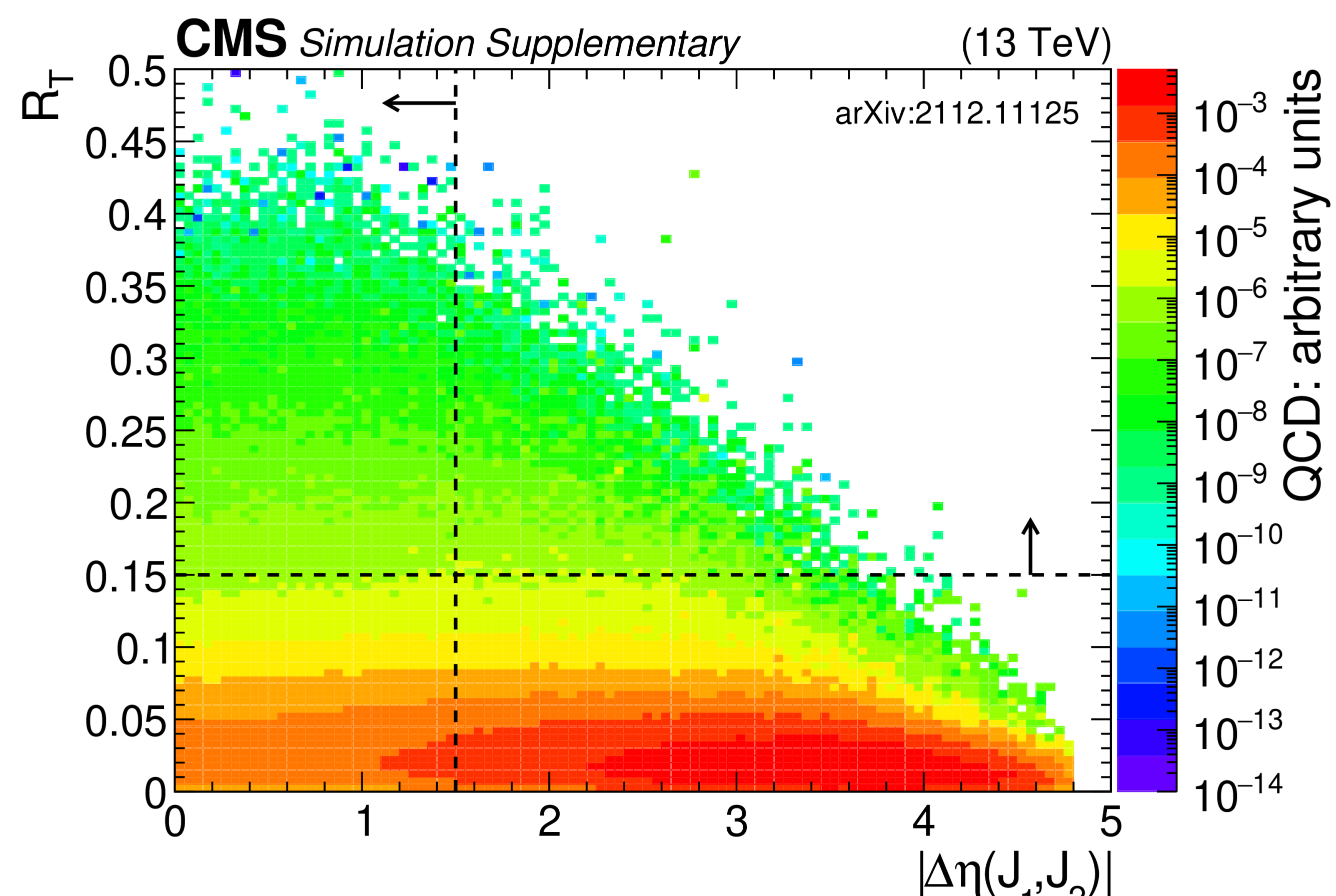
CMS

Triggering

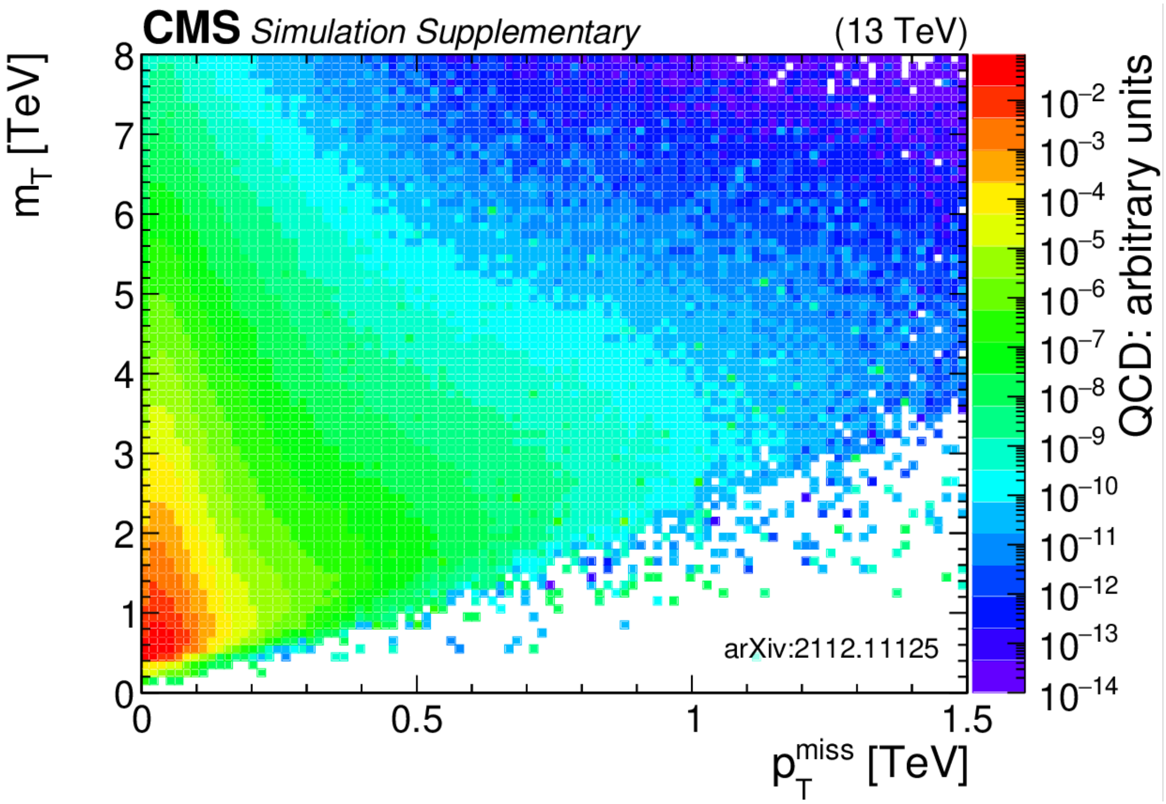
- Trigger on jet p_T, H_T
  - Require low $\Delta\eta(J_1,J_2)$ for high efficiency
- Usually improves signal sensitivity
  - Most t-channel QCD events already rejected by R_T requirement
- M_T>1500 GeV for trigger efficiency

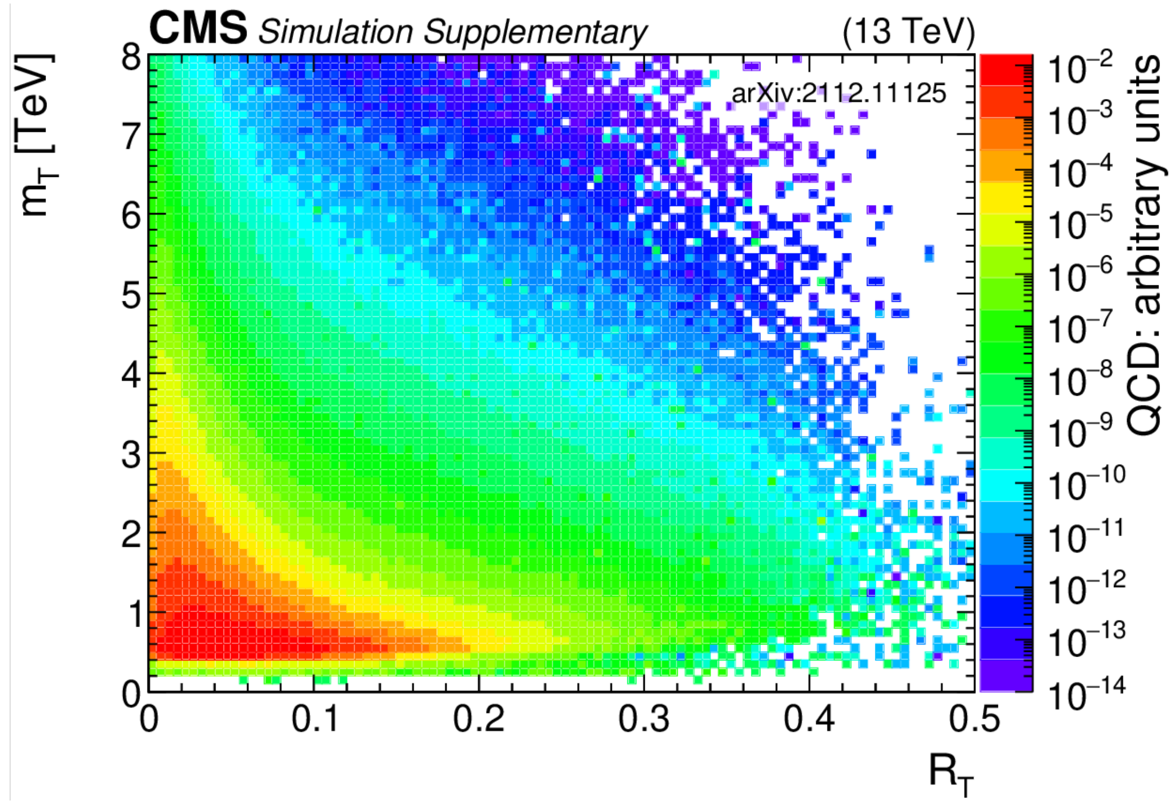




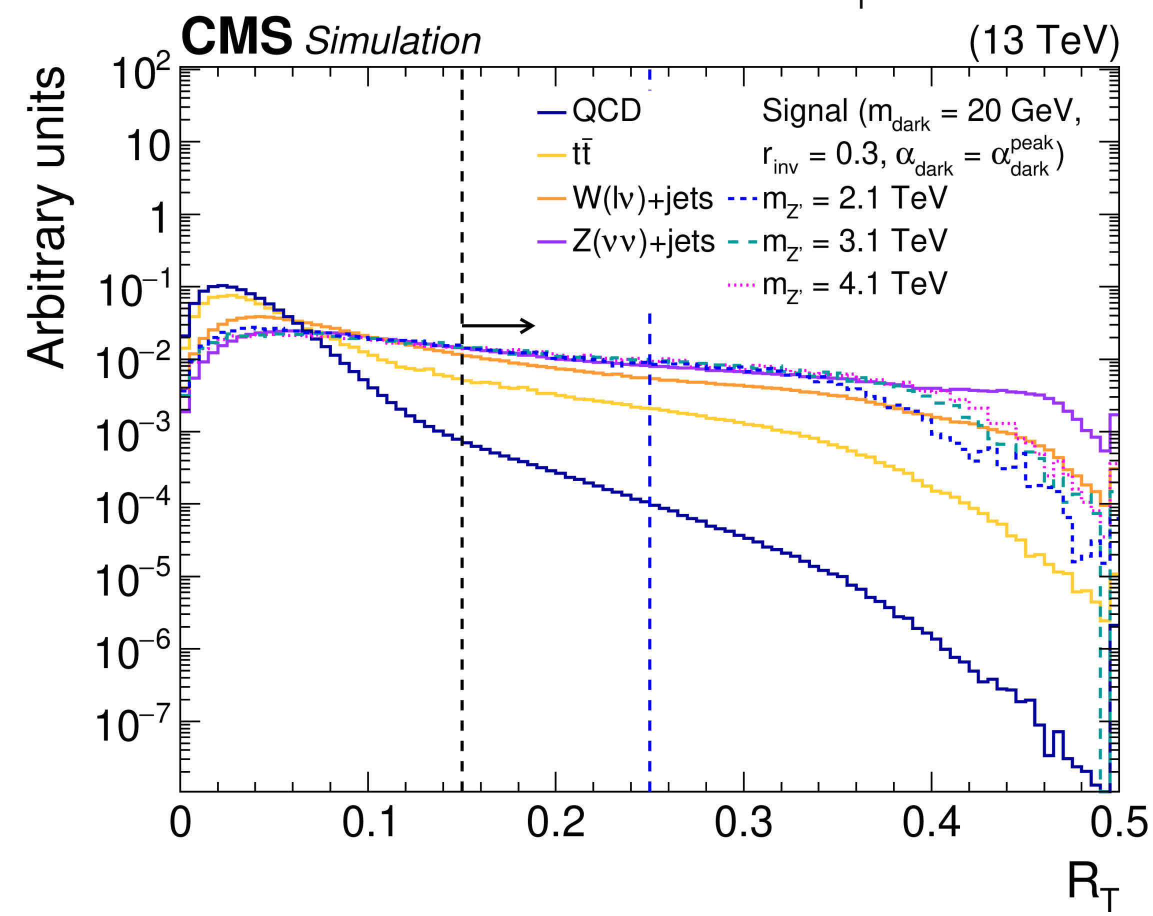


Mass sculpting





- Avoid/minimize direct cuts on M_T ingredients: p_T^{miss}, jet p_T
  - Relative variable ('transverse ratio') $R_T = p_T^{miss}/M_T$
  - Reject QCD background without shifting M_T peak



Systematic uncertainties

- Signal:
  - Experimental: (uncorrelated between years of data-taking)
    - Luminosity, trigger efficiency, **jet energy corrections** (up to 12%), jet energy resolution, pileup, statistical uncertainties in simulated samples
  - Theoretical: (correlated between years of data-taking)
    - PDFs, renormalization/factorization scale, parton shower modeling (ISR/FSR), **jet energy scale/composition** (up to 21%)
- Background:
  - Fit parameters: freely floating, uncertainties arise from statistical uncertainty in data
  - **Fit normalizations**: also freely floating, can change by up to 10% → most impactful uncertainty

Event selection

Preselection

- $N_J \geq 2$
- $p_T(J_1,J_2) > 200$ GeV, $|\eta(J_1,J_2)| < 2.4$, → Signal topology
  $J_{1,2}$ pass noise rejection → Data quality
- $R_T \equiv p_T^{miss}/M_T > 0.15$ → Reject QCD
- $\Delta\eta(J_1,J_2) < 1.5$
- $M_T > 1500$ GeV → Trigger efficiency
- e/μ veto ($p_T > 10$ GeV, $|\eta| < 2.4$) → Reject $t\bar{t}$, $W(\ell\nu)$
- p_T^{miss} filters
- Custom dead ECAL cell filter: veto events w/ $\Delta R(j_{1,2}, c_{dead}) < 0.1$
- Inactive HCAL filter (2018 only): veto events w/ $p_T(j) > 30$ GeV, $-3.05 < \eta(j) < -1.35$, $-1.62 < \varphi(j) < -0.82$

→ Data quality

Final Selection

- Gap jet filter: veto events w/ $p_T(j_1) > 1000$ GeV, $f_\gamma(j_1) > 0.7$ → Data quality
- $\Delta\varphi_{min}(J_{1,2}, p_T^{miss}) < 0.80$ → Reject $t\bar{t}$, $W(\ell\nu)$, $Z(\nu\nu)$

Cutflows

Selection	QCD	$t\bar{t}$	W+jets	Z+jets	signal
$p_T(J_{1,2}) > 200\,\text{GeV}$, $\eta(J_{1,2}) < 2.4$	1.2 ± 0.0	6.4 ± 0.0	2.0 ± 0.0	1.3 ± 0.0	83.0 ± 0.1
$R_T > 0.15$	1.3 ± 0.0	12.1 ± 0.0	18.5 ± 0.0	34.6 ± 0.0	39.7 ± 0.2
$\Delta\eta(J_1, J_2) < 1.5$	94.9 ± 0.0	88.0 ± 0.0	85.1 ± 0.0	78.8 ± 0.0	79.7 ± 0.2
$M_T > 1500\,\text{GeV}$	0.2 ± 0.0	3.1 ± 0.0	4.0 ± 0.0	5.6 ± 0.0	80.9 ± 0.2
$N_\mu = 0$	93.0 ± 1.8	62.0 ± 0.1	66.0 ± 0.0	99.5 ± 0.0	96.0 ± 0.1
$N_e = 0$	99.6 ± 0.0	59.8 ± 0.1	57.3 ± 0.1	99.6 ± 0.0	99.4 ± 0.1
p_T^{miss} filters	99.5 ± 0.0	99.9 ± 0.0	99.9 ± 0.0	99.9 ± 0.0	100.0 ± 0.0
$\Delta R(j_{1,2}, c_{dead})^2 > 0.01$	60.6 ± 0.3	95.1 ± 0.2	95.2 ± 0.0	95.6 ± 0.0	94.3 ± 0.2
veto $f_\gamma(j_1) > 0.7$ & $p_T(j_1) > 1000\,\text{GeV}$	99.7 ± 0.0	99.7 ± 0.0	99.6 ± 0.0	99.7 ± 0.0	100.0 ± 0.0
$\Delta\phi_{min} < 0.8$	94.8 ± 0.1	81.7 ± 0.1	61.8 ± 0.1	44.7 ± 0.1	87.7 ± 0.2
Efficiency [%]	1.6e-05	0.006	0.0029	0.0085	17
high-R_T	9.0 ± 0.1	29.5 ± 0.2	38.8 ± 0.1	39.1 ± 0.1	45.0 ± 0.4
low-R_T	91.0 ± 0.1	70.5 ± 0.2	61.2 ± 0.1	60.9 ± 0.1	54.7 ± 0.4
high-SVJ2	0.1 ± 0.0	0.6 ± 0.0	0.5 ± 0.0	0.7 ± 0.0	34.9 ± 0.4
low-SVJ2	1.1 ± 0.0	1.7 ± 0.2	0.9 ± 0.0	0.9 ± 0.0	43.2 ± 0.4

ECF definitions

$$ {}_v e_n^{(\beta)} = \sum_{1\le i_1 < i_2 < \cdots < i_n \le n_J} z_{i_1} z_{i_2} \ldots z_{i_n} \prod_{m=1}^{v} \min_{s<t\in\{i_1,i_2,\ldots,i_n\}}^{(m)} \left\{ \theta_{st}^{\beta} \right\} $$

$$ N_2 = \frac{{}_2 e_3^{(\beta)}}{({}_1 e_2^{(\beta)})^2} $$

$$ C_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^2} $$

$$ D_2^{(\alpha,\beta)} = \frac{{}_3 e_3^{(\alpha)}}{({}_1 e_2^{(\beta)})^{3\alpha/\beta}} $$

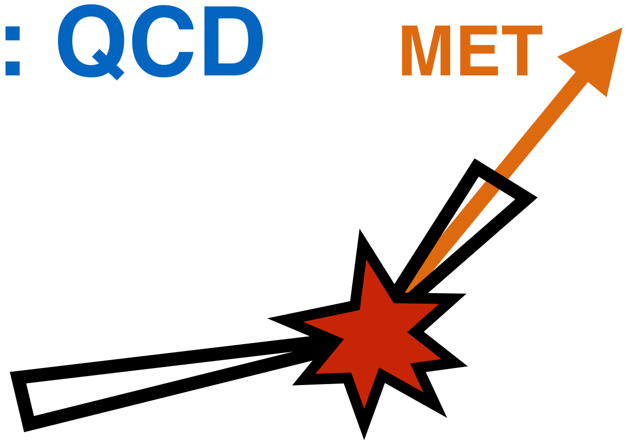
$$ M_2^{(\beta)} = \frac{{}_1 e_3^{(\beta)}}{{}_1 e_2^{(\beta)}} $$

```python
def e(particles: Particles, v, n, beta=1.):
    '''Raw "e" function from Angles paper'''
    s = 0.
    if n==0: return 1.
    if len(particles) < n: return 0.
    ptsum =  particles.pt.sum()
    for combination in particle_combinations(particles, n):
        z_product = (combination.pt / ptsum).prod()
        thetas = r(*particle_combinations_columns(combination, 2))
        thetas.sort()
        theta_product = thetas[:v].prod()
        s += z_product * (theta_product**beta)
    return s

def N_series(particles, i, beta=1.):
    try:
        return e(particles, 2, i+1) / ( e(particles, 1, i)**2 )
    except ZeroDivisionError:
        return -1.
```

Backgrounds

#1: QCD



- Some standard filters for instrumental MET
  - Not tuned for low Δϕ(j, MET) region

- Large source: Broken cells in the electromagnetic calorimeter
  - Custom filter put in place to reject an additional 40% QCD
- Main work horse: require **R_T = MET/M_T > threshold**
  - Good QCD rejection without sculpting M_T distribution
- Further reduction via a **BDT** trained on jet variables
  - **Model dependent!**
  - Perform final fits **without BDT** too; weaker limits, but no model dependence

Variable definitions

- **Girth:** $g = \sum_i \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}} r_i$
- **Major/minor axes:**

$$\mathcal{M} = \begin{bmatrix} \sum_i p_{\mathrm{T},i}^2 \Delta\eta_i^2 & -\sum_i p_{\mathrm{T},i}^2 \Delta\eta_i \Delta\phi_i \\ -\sum_i p_{\mathrm{T},i}^2 \Delta\eta_i \Delta\phi_i & \sum_i p_{\mathrm{T},i}^2 \Delta\phi_i^2 \end{bmatrix}$$

$$\sigma_{\mathrm{major}} = \sqrt{\lambda_1 / \sum_i p_{\mathrm{T},i}^2}$$

$$\sigma_{\mathrm{minor}} = \sqrt{\lambda_2 / \sum_i p_{\mathrm{T},i}^2}$$

- **p_TD:** $p_T D = \frac{\sqrt{\sum_i p_{\mathrm{T},i}^2}}{\sum_i p_{\mathrm{T},i}}$
- **Nsubjettiness:** $\tau_{21} = \tau_2/\tau_1$, $\tau_{32} = \tau_3/\tau_2$

$$\tau_N^{(\beta)} = \frac{1}{\sum_k p_{\mathrm{T},k} R_0} \sum_k p_{\mathrm{T},k} \min\{\Delta R_{1,k}^{(\beta)}, \Delta R_{2,k}^{(\beta)}, \dots, \Delta R_{N,k}^{(\beta)}\}$$

- $${}_v e_n^{(\beta)} = \sum_{1 \le i_1 < \cdots < i_n \le n_{\mathrm{const.}}} z_{i_1} \dots z_{i_n} \prod_{m=1}^{v} \min_{s<t \in \{i_1,\dots,i_n\}}^{(m)} \left\{ \theta_{st}^{\beta} \right\}$$

$$N_2^{(1)} = \frac{{}_2e_3^{(1)}}{\left({}_1e_2^{(1)}\right)^2} \qquad N_3^{(1)} = \frac{{}_2e_4^{(1)}}{\left({}_1e_3^{(1)}\right)^2}$$

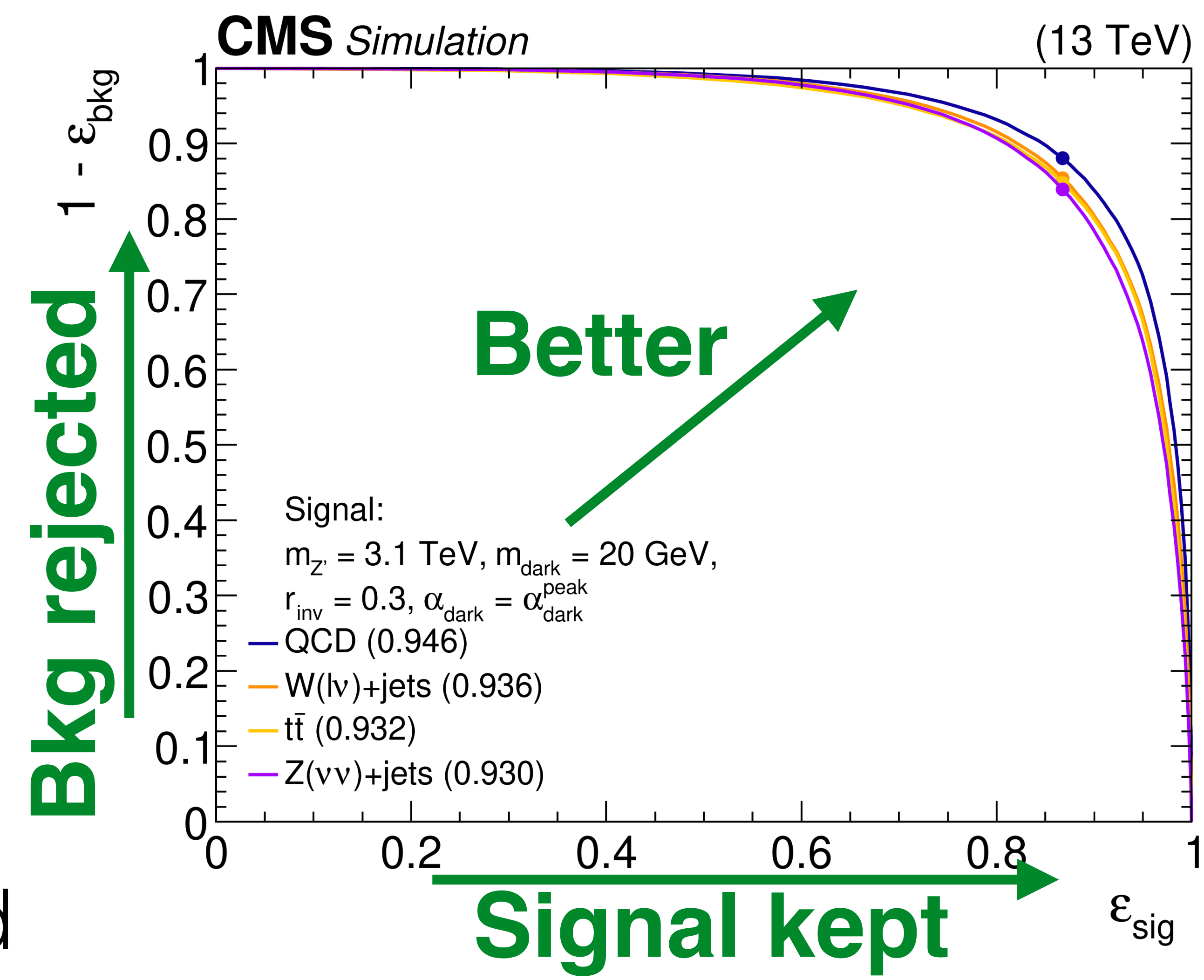
$$M_{\mathrm{T}}^2 = [E_{\mathrm{T},JJ} + E_{\mathrm{T}}^{\mathrm{miss}}]^2 - [\vec{p}_{\mathrm{T},JJ} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}}]^2$$
$$= M_{JJ}^2 + 2p_{\mathrm{T}}^{\mathrm{miss}} \left(\sqrt{M_{JJ}^2 + p_{\mathrm{T},JJ}^2} - p_{\mathrm{T},JJ} \cos(\phi_{JJ,\mathrm{miss}}) \right)$$

Tagging semi-visible jets

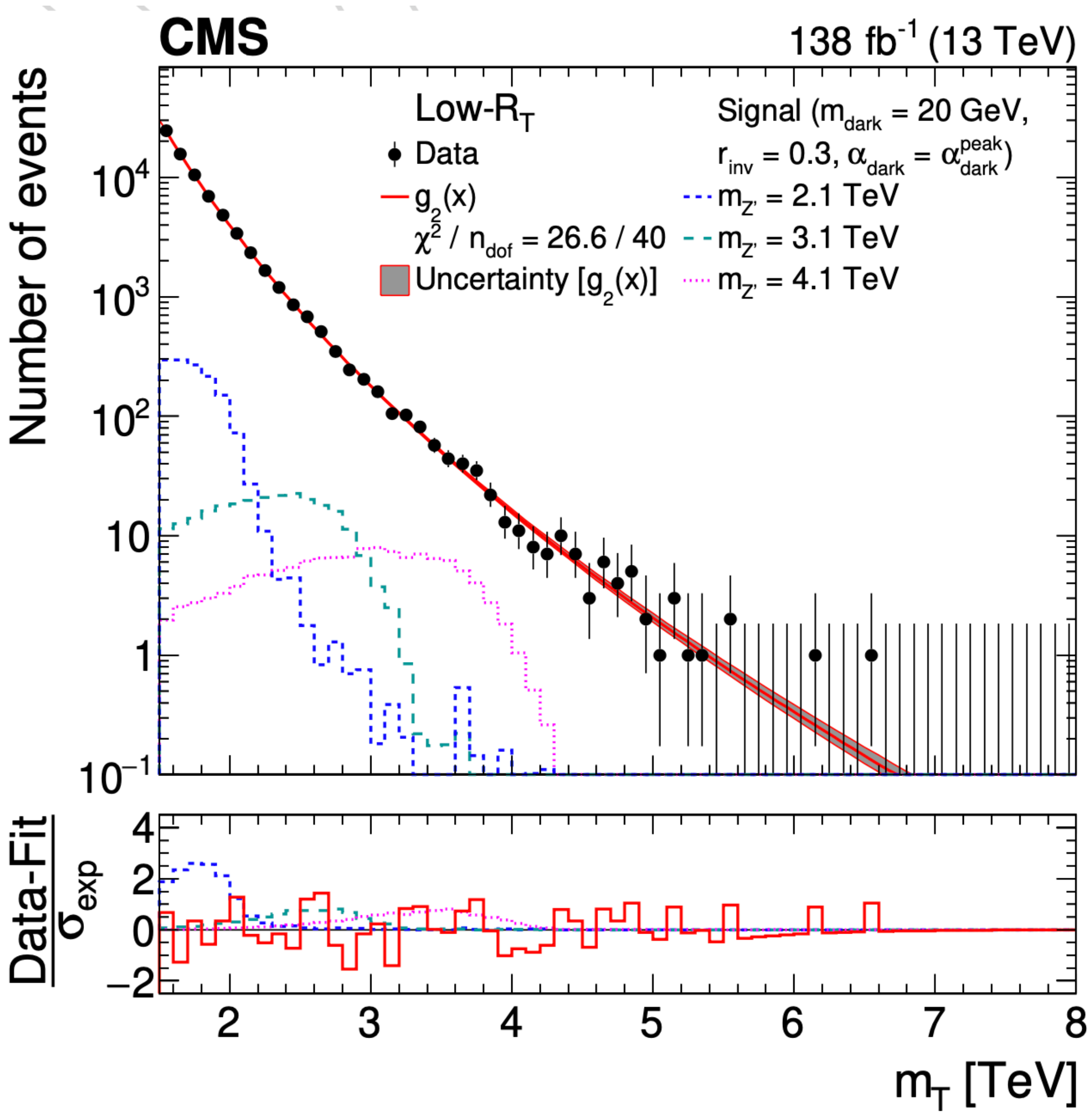
- Using a Boosted Decision Tree based on 15 jet-specific variables discriminate between SVJs and SM jets:

Heavy object ID	Quark vs. gluon	Flavor tagging	Other
N-subjettiness τ_{12}, τ_{32}	Jet girth	Jet energy fractions: $f_{\text{charged hadron}}$, $f_{\text{neutral hadron}}$, f_{electron}, f_{muon}, f_{photon}	$\Delta\phi$(j, MET)
Energy correlation fns N_2^1, N_3^1	Axis minor/major		
Soft drop mass m_{SD}	p_T dispersion		

  - No variable strongly discriminating by itself
- Trained on various signal model parameter variations
- Working point of **score > .55**
  - Reject **84-88% of background jets**
  - Keep 87% of signal jets
    - AUC of .946 w.r.t. QCD
- Two leading jets must be tagged



Low: .15 < R_T < .25



Low: .15 < R_T < .25