Semivisible Jets at CMS

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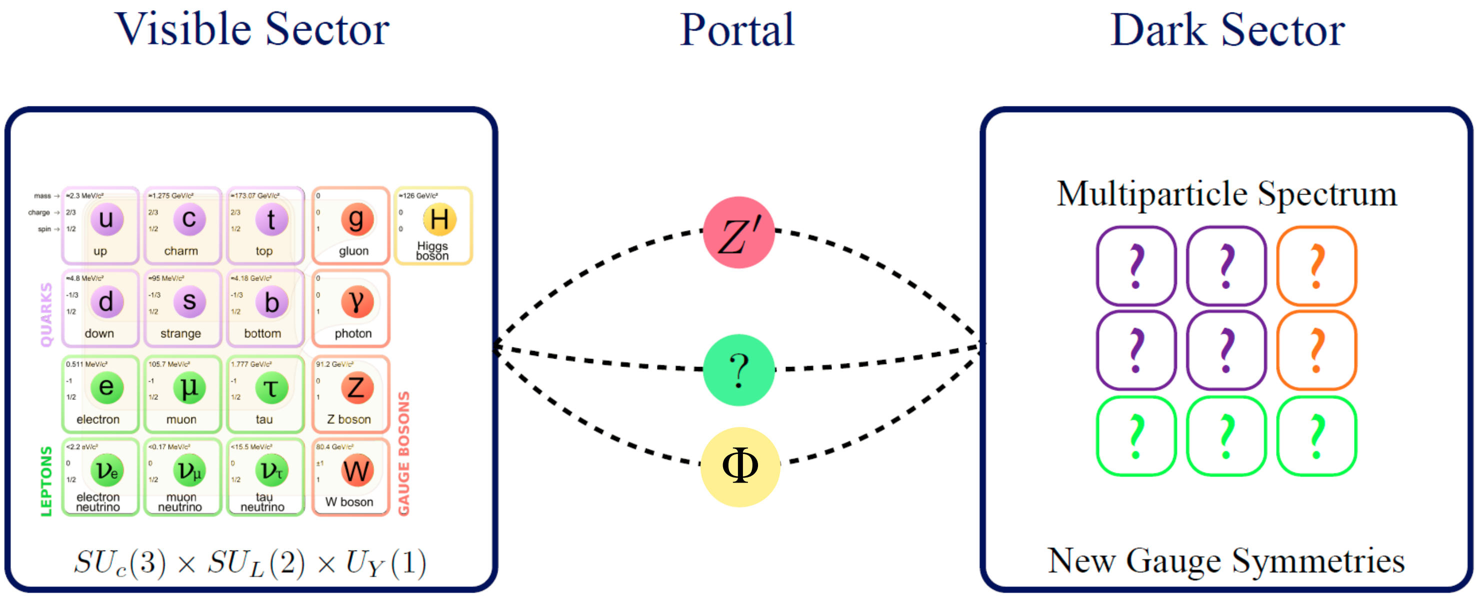
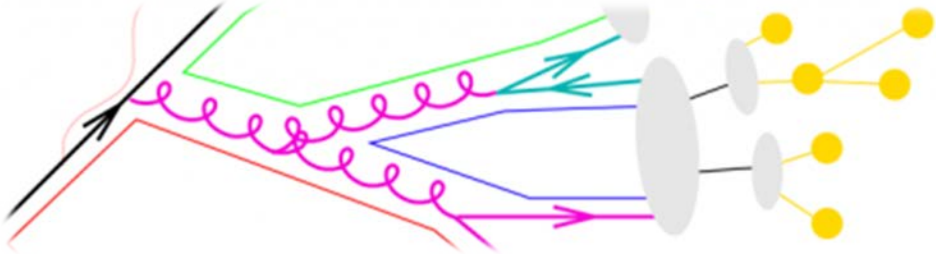
Hidden Sectors



- Simplest assumption: dark matter consists of a single species of weakly interacting massive particles
  - No observation of WIMPs → look for new models and phenomenology
- Dark matter may consist of multiple species of composite particles interacting via new, dark forces
  - Visible matter is mostly composite particles & has similar density to DM

Strongly Coupled Models

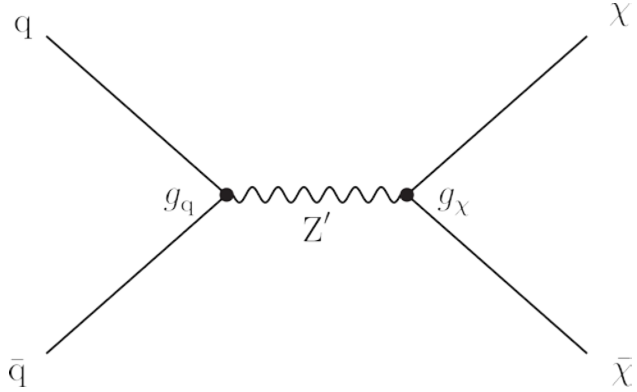
- New “dark QCD” force, $SU_{\text{dark}}(\boldsymbol{N_c^{\text{dark}}})$ (carried by dark gluons) with scale Λ_{dark}
- $\boldsymbol{N_f^{\text{dark}}}$ flavors of (fermionic) dark quarks χ_i (charged under $SU_{\text{dark}}(\boldsymbol{N_c^{\text{dark}}})$)
- Dark quarks *hadronize* to form dark mesons and baryons → “dark showers”



- Some dark hadrons may be *stable* because of conserved quantities
  - o Dark baryon number, dark isospin number, etc.
  - ➢ DM candidates!
- Other dark hadrons decay back to SM (through virtual mediators)
  - ➢ Leads to novel phenomenology

Production

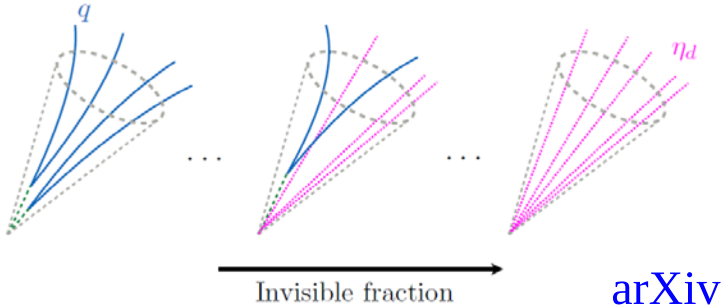
- Hidden sector couples to SM weakly via massive mediator:
  Z' from broken $U(1)$, vector, leptophobic, couplings g_q, g_χ



- Coupling choices aligned with LHC DM Working Group:
  - $g_q = 0.25$
  - $g_\chi = 1.0/\sqrt{(\boldsymbol{N_c^{\mathbf{dark}}}\boldsymbol{N_f^{\mathbf{dark}}})} = 0.5$
  - $B_{dark} = 47\%$, $\Gamma_{Z'}/m_{Z'} = 5.6\%$
    - Same as LHC DM models w/ $g_{DM} = 1.0$

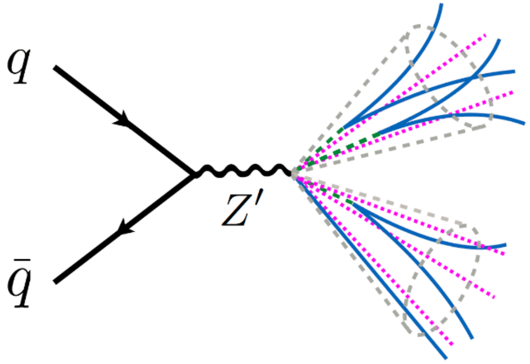
Decay

- Fraction of stable hadrons r_{inv} may vary from 0 to 1
  - Decreases w/ dark quark mass splitting, increases w/ N_f^{dark}
- ➢ Jets that contain *mix of visible and invisible particles* (prompt decays)
  - *Not covered* by existing searches for dijet resonances, p_T^{miss}+ISR



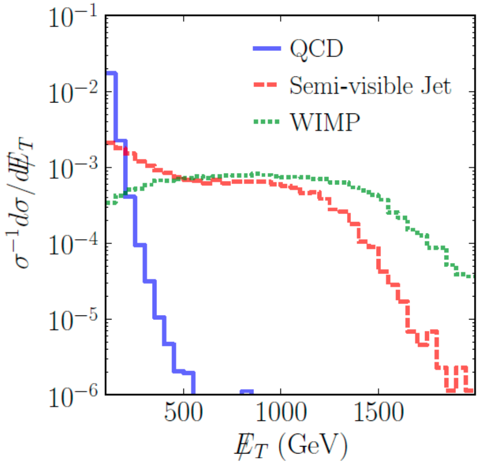
arXiv:1707.05326

- $Z' \rightarrow \chi\chi \rightarrow$ dark hadrons $\rightarrow$ SM quarks $\rightarrow$ SM hadrons
  - Decay to SM → two high-p_T, *wide* jets
  - ρ_{dark}: democratic decay
  - π_{dark}: mass insertion decay (prefer heavy flavor)
  - $N_c^{\mathrm{dark}} = 2$, $N_f^{\mathrm{dark}} = 2$, $m_\chi = \frac{1}{2} m_{\mathrm{dark}}$



Resonant Search

- Kinematic signature: Less missing energy than WIMPs, aligned w/ jet



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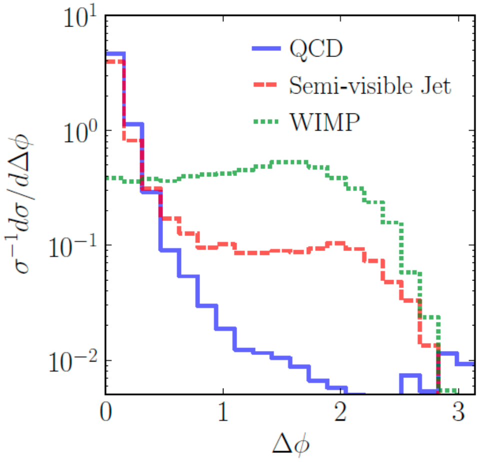
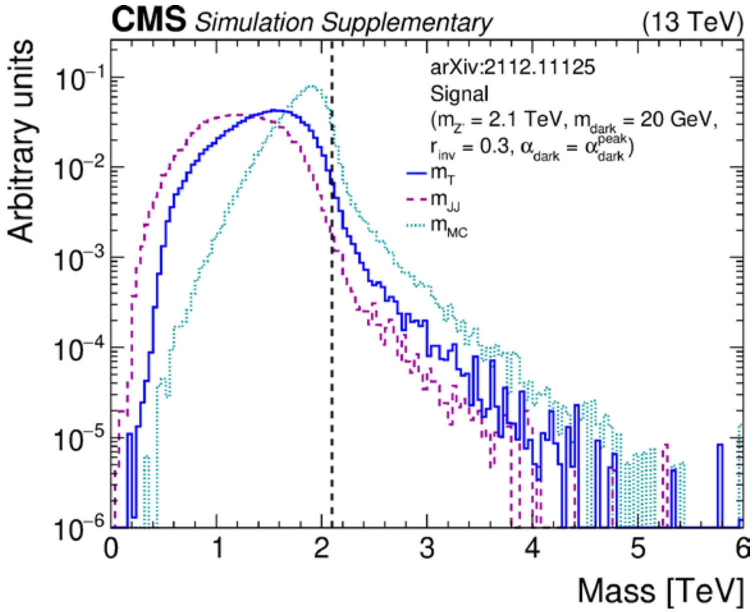
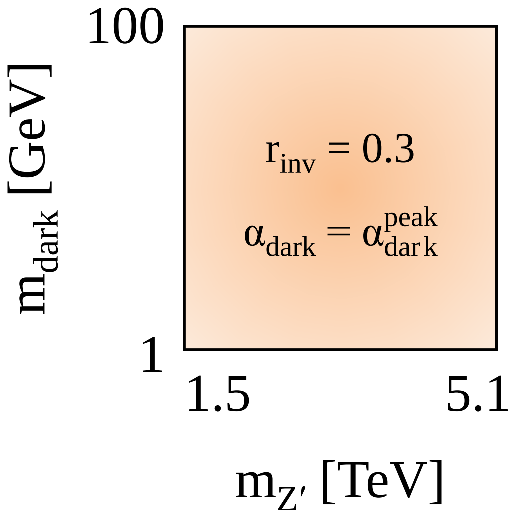


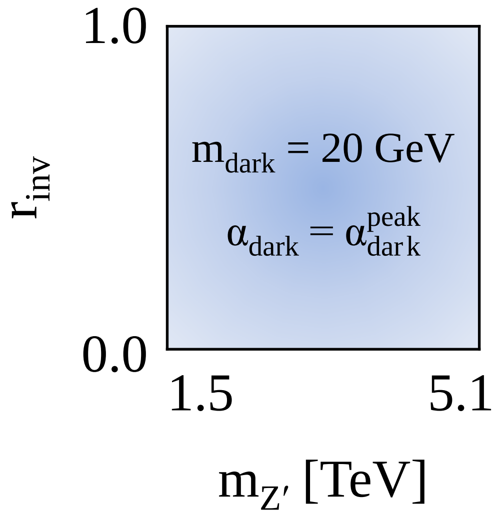
- Bump hunt in **$m_T(JJ, p_T^{miss})$**
  - Kinematic edge at **$m_{Z'}$**
  - Better resolution than **m_{JJ}**
  - SM backgrounds have steeply falling distributions

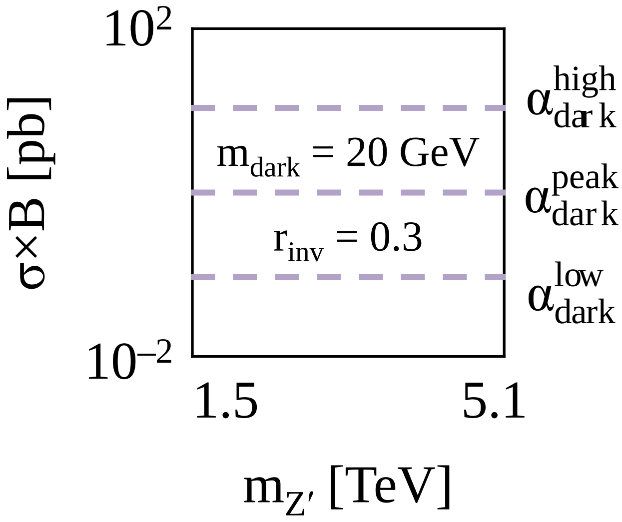


Signal Models

- Parameters varied: $m_{Z'}$, m_{dark} (dark hadron mass scale), r_{inv}, α_{dark}
  - α_{dark}: running coupling of dark QCD (alternate form of scale Λ_{dark})
  - $\alpha_{\text{dark}}^{\text{peak}}$ maximizes dark hadron multiplicity (depends on m_{dark})
    - "Empirical" relationship derived from Pythia
    - Variations: $\alpha_{\text{dark}}^{\text{high}} = \frac{3}{2}\alpha_{\text{dark}}^{\text{peak}}$, $\alpha_{\text{dark}}^{\text{low}} = \frac{1}{2}\alpha_{\text{dark}}^{\text{peak}}$
- Three 2D scans ($m_{Z'}$ vs. m_{dark}, r_{inv}, α_{dark}) ⟶ 475 points
  - Benchmark values: $m_{\text{dark}} = 20$ GeV, $r_{\text{inv}} = 0.3$, $\alpha_{\text{dark}} = \alpha_{\text{dark}}^{\text{peak}}$
- 4D scan with same grid of values would be 8208 points







Dual Strategy

- Dark QCD theories are very complicated
  - Need to make choices about numerous parameters
  - Plus modeling of hadronization/fragmentation, etc.
- First search for jets aligned with p_T^{miss} → maximize *generality* & *sensitivity*

"Inclusive" search

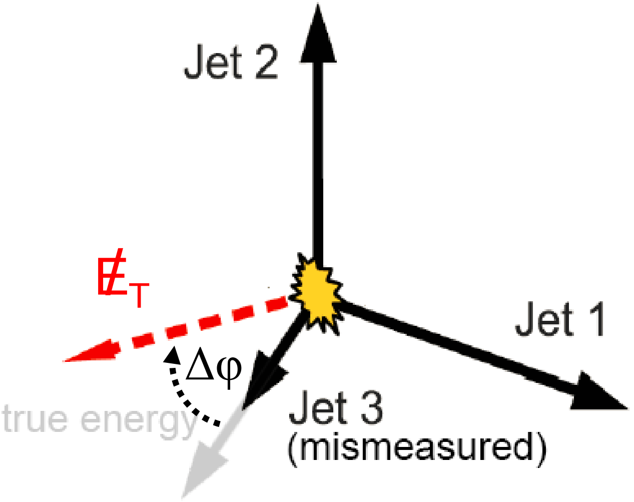
- Use only event-level kinematic variables
- Results apply to any model with similar kinematic behavior

"BDT-based" search

- Employ machine learning for optimized semivisible jet tagger
- Assumes chosen signal models are "correct"

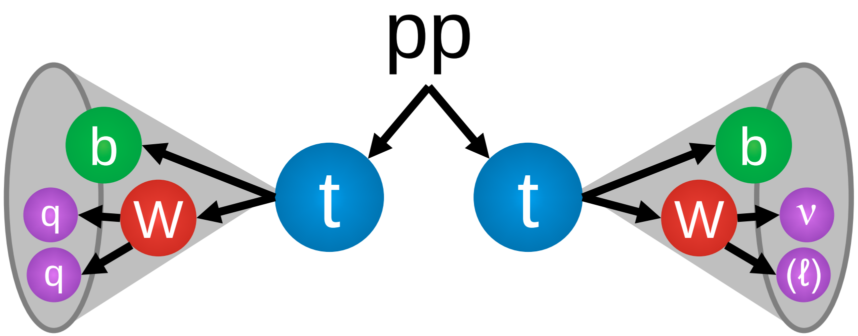
Backgrounds

QCD



- Jet mismeasurement induces $\not{E}_T$ aligned with jet
- Major background

$t\bar{t}$



- Wide, high-p_T jets: boosted tops
- "Lost" lepton ℓ: out of acceptance, can't veto (or hadronic τ)
- Neutrino aligned w/ wide jet: mimics semivisible jet

W(ℓν)+jets

- Lost lepton or hadronic τ
- Less likely than $t\bar{t}$ to mimic semivisible jet, but higher σ

Z(νν)+jets

- Real $\not{E}_T$ from νν, but least likely to align with jet

Event Selection

Preselection

- $N_J \geq 2$
- $p_T(J_1,J_2) > 200$ GeV, $|\eta(J_1,J_2)| < 2.4$, $J_{1,2}$ pass noise rejection
- $R_T \equiv p_T^{miss}/m_T > 0.15$
- $\Delta\eta(J_1,J_2) < 1.5$
- $m_T > 1500$ GeV
- e/μ veto ($p_T > 10$ GeV, $|\eta| < 2.4$)
- p_T^{miss} filters
- Nonfunctional ECAL cell filter: veto events w/ $\Delta R(j_{1,2}, c_{nonfunctional}) < 0.1$
- Inactive HCAL filter (2018 only): veto events w/ $p_T(j) > 30$ GeV, $-3.05 < \eta(j) < -1.35$, $-1.62 < \varphi(j) < -0.82$

Signal topology

Data quality

Reject QCD (w/o m_T sculpting)

Trigger efficiency

Reject $t\bar{t}$, $W(\ell\nu)$

Data quality

Process	Efficiency [%]
QCD	1.6×10^{-5}
$t\bar{t}$	0.0060
W+jets	0.0029
Z+jets	0.0085
Signal (benchmark)	17

Final Selection

- Gap jet filter: veto events w/ $p_T(j_1) > 1000$ GeV, $f_\gamma(j_1) > 0.7$
- $\Delta\varphi_{min}(J_{1,2},p_T^{miss}) < 0.80$

Data quality

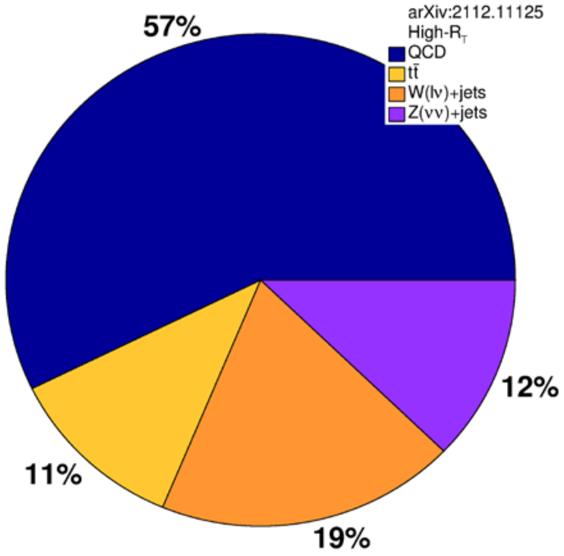
Reject $t\bar{t}$, $W(\ell\nu)$, $Z(\nu\nu)$

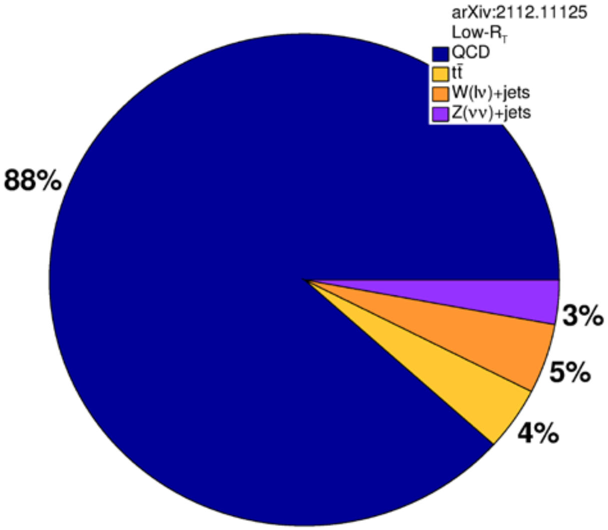
Inclusive Signal Regions

- With all inclusive selection requirements applied:

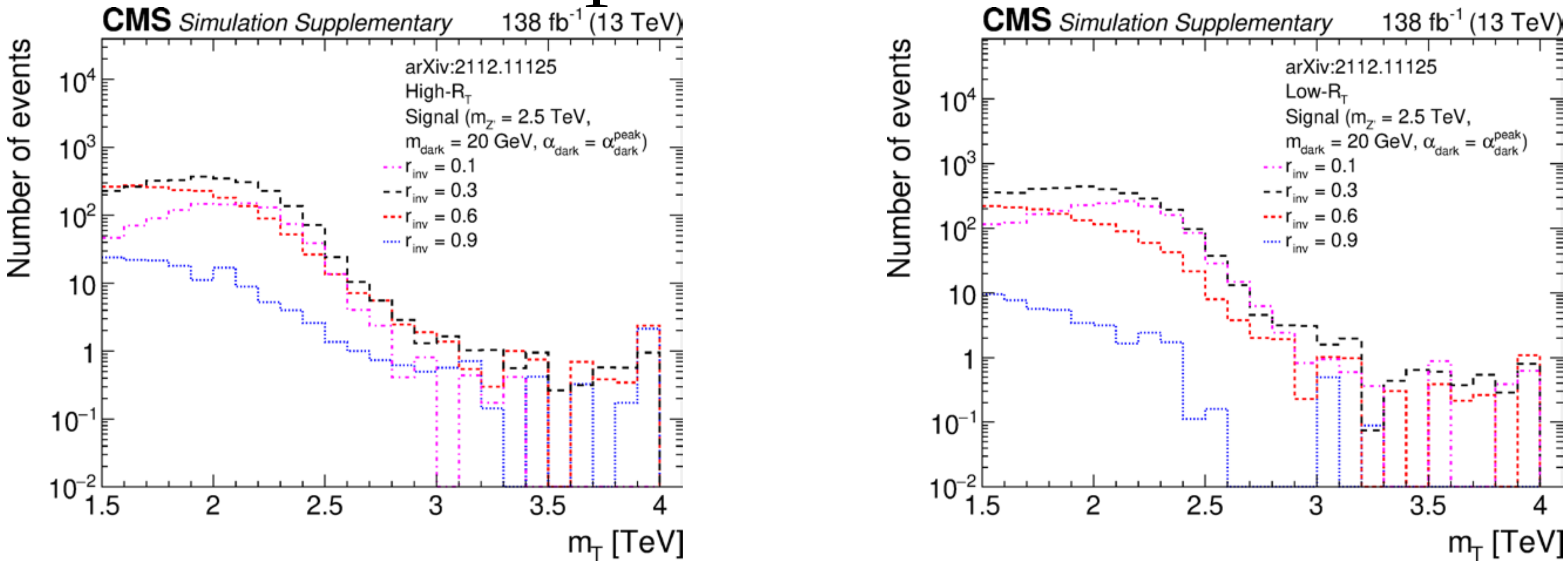
Process	**Efficiency [%]**
QCD	0.000016
$t\bar{t}$	0.0060
W(ℓν)+jets	0.0029
Z(νν)+jets	0.0085
signal	~17

- If only one signal region were defined, high-R_T ($R_T > 0.25$) would have optimal significance
- Adding separate region low-R_T ($0.15 < R_T < 0.25$) improves expected performance

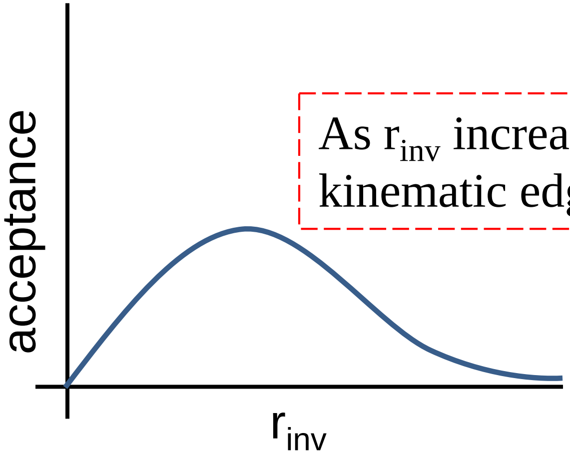




m_T Variations



- r_{inv} has largest impact on signal mass distributions
  - α_{dark} has minor impact; m_{dark} has very little impact



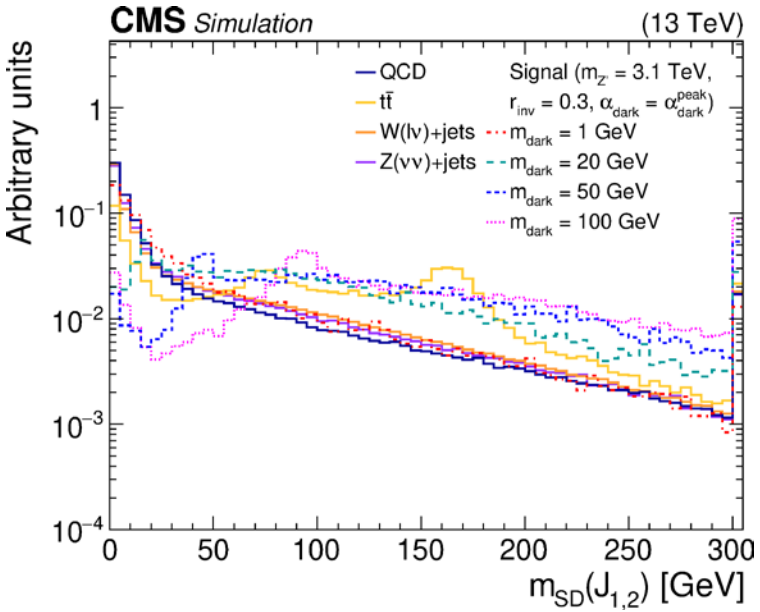
As r_{inv} increases, kinematic edge softens

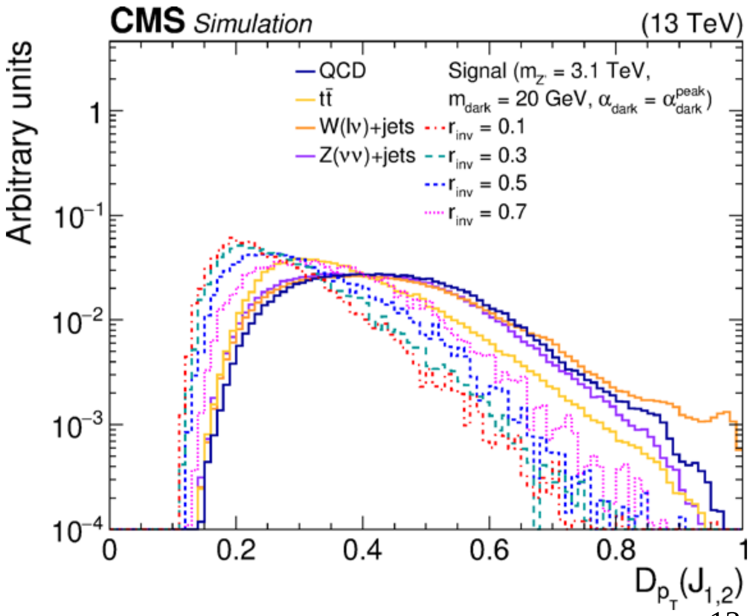
Low r_{inv} signals populate low-R_T signal region

Very high r_{inv} signals look like ISR

Tagging Semivisible Jets

- Various jet substructure variables (& $\Delta\varphi(\mathrm{J}, p_{\mathrm{T}}^{\mathrm{miss}})$) can weakly discriminate between semivisible jets and SM background jets
  - Heavy object tagging: m_{SD}, τ_{21}, τ_{32}, $N_2^{(1)}$, $N_3^{(1)}$
  - Quark-gluon discrimination: $D_{p_{\mathrm{T}}}$, σ_{major}, σ_{minor}, girth
  - Flavor (energy fractions): f_{γ}, $f_{h\pm}$, f_{h0}, f_e, f_{μ}
- ➢ Combine useful variables into a BDT for strong discrimination!
  - Background: equal mix of QCD and $t\bar{t}$; signal: mix of many models
  - Reweight background jet p_{T} spectrum to match signal: avoid sculpting

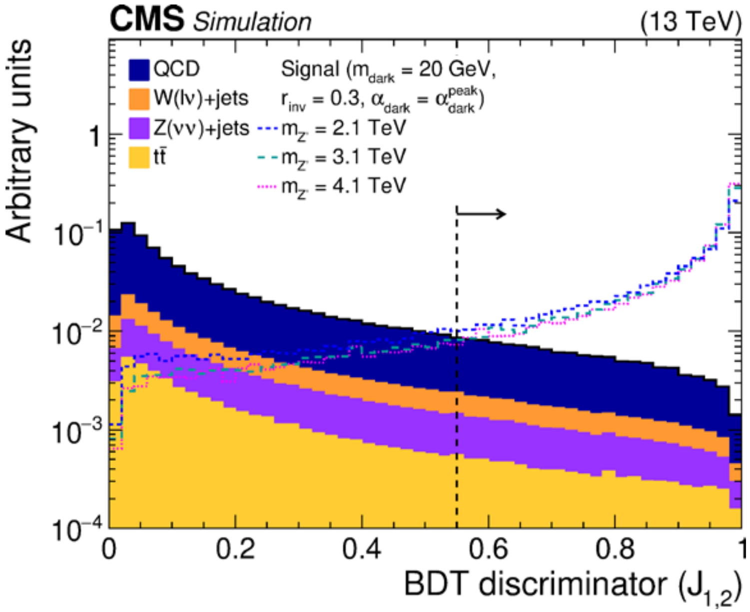


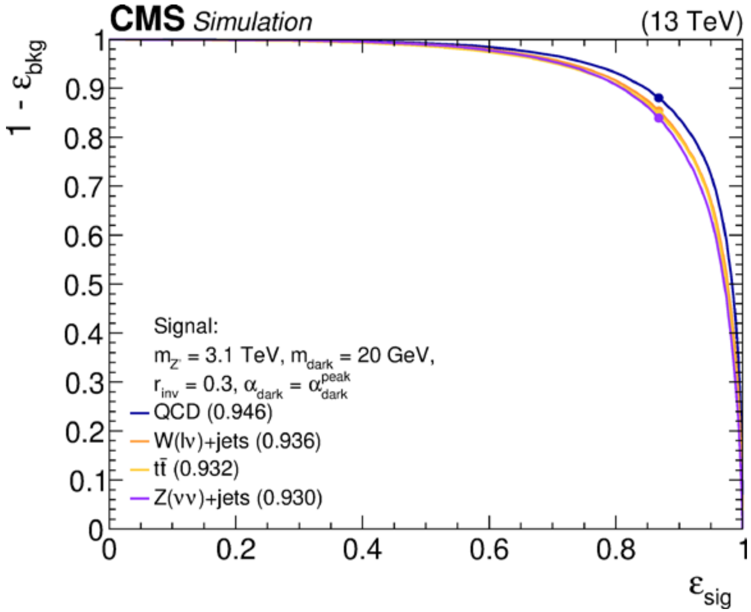


Tagger Performance

	$m_{Z'}$ = 3.1 TeV, m_{dark} = 20 GeV, r_{inv} = 0.3, $\alpha_{dark} = \alpha_{dark}^{peak}$		
	Acc (WP = 0.5)	AUC	$1/\varepsilon_B$ (ε_S = 0.3)
QCD	0.881	0.947	651.4
$t\bar{t}$	0.881	0.931	270.6
W(ℓν)+jets	0.881	0.936	441.5
Z(νν)+jets	0.881	0.930	420.7

- Strong and consistent performance
  - Training on only QCD ($t\bar{t}$) caused misclassification of $t\bar{t}$ (QCD) jets at rate of 10–20%
  - Some inefficiency for signals with high or low m_{dark}
- Working point 0.55 chosen based on background estimation

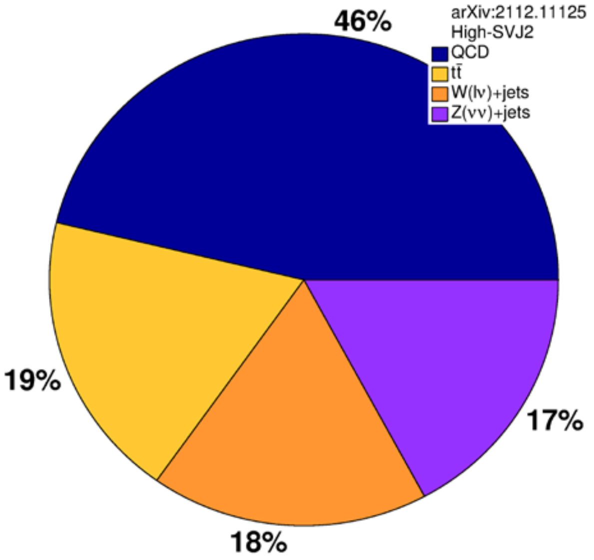


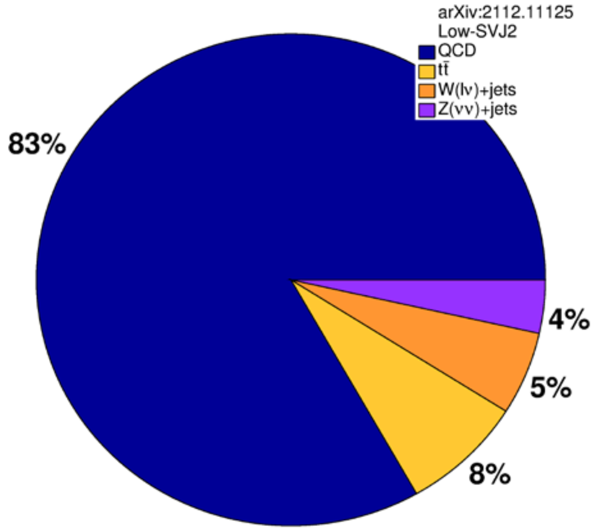


BDT-based Signal Regions

- Start from inclusive signal regions (high-R_T, low-R_T)
- Require both leading wide jets to be tagged as semivisible
  - high-SVJ2, low-SVJ2 regions: strict subsets of inclusive regions

➢ Reduce background by factor ~60 while preserving signal





Background Estimation

- Estimate smoothly-falling SM backgrounds via analytic fit to m_T data
- Primary fit function:

$$x = m_{\mathrm{T}}/\sqrt{s}$$

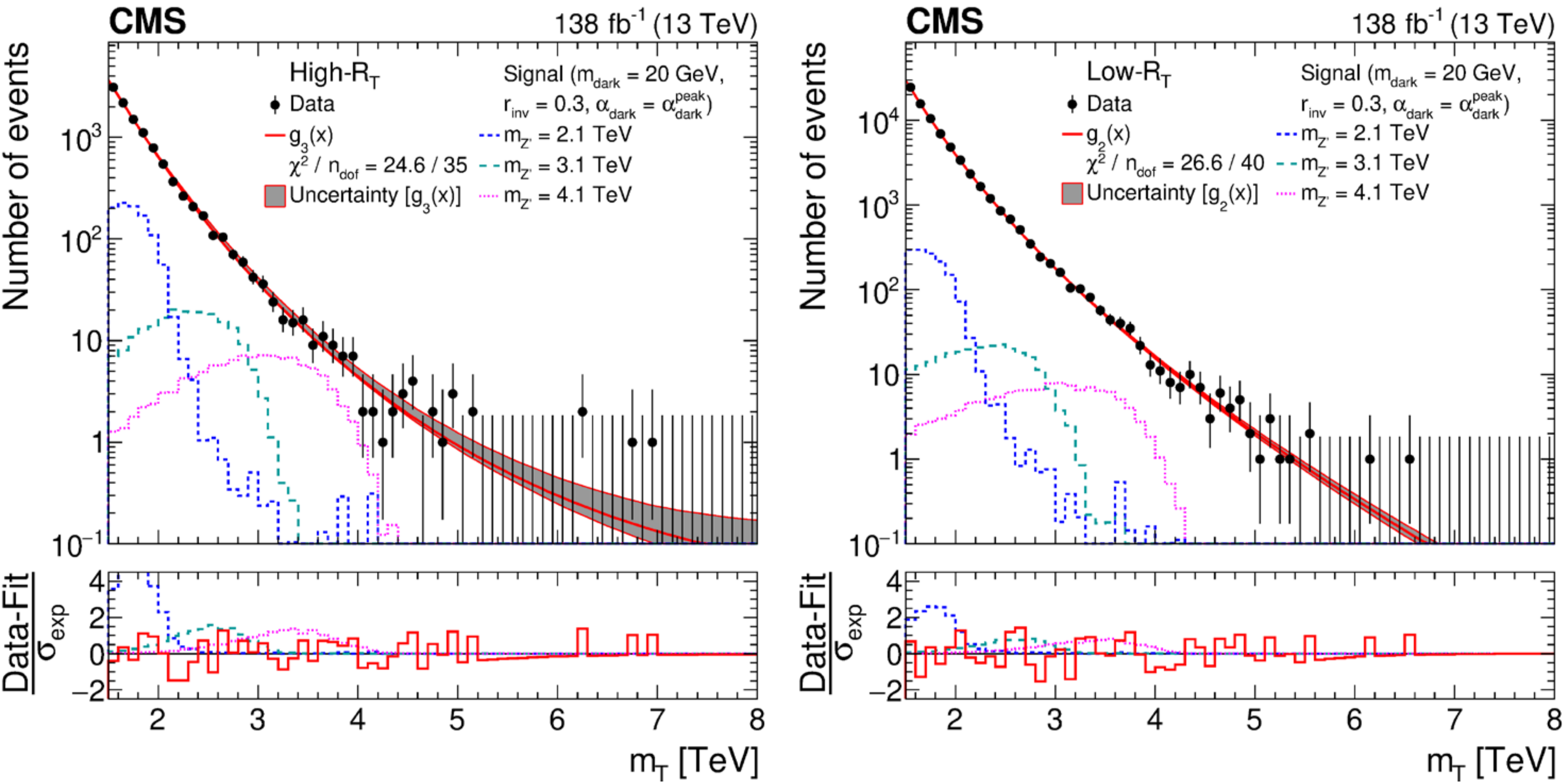
$$g(x) = \exp(p_1 x) x^{p_2(1+p_3 \log(x)(1+p_4 \log(x)(\cdots)))}$$

  - Perform fits varying sign and magnitude of initial parameter values (necessary to escape false minima)
  - Optimal # parameters for each signal region determined w/ Fisher test
- Several secondary functions (from other resonant searches) employed for bias studies:
  - Ensure that chosen function can fit different possible data distributions
  - Generate toy data with secondary functions, fit w/ primary function
  - $b = (\sigma_{\mathrm{ext}} - \sigma_{\mathrm{inj}})/\varepsilon_{\sigma_{\mathrm{ext}}}$ should be normally distributed ($\mu = 0$, $\sigma = 1$)
  - $|\langle b \rangle| \leq 0.5$ in all cases → fits are sufficiently unbiased

Optimal # Parameters

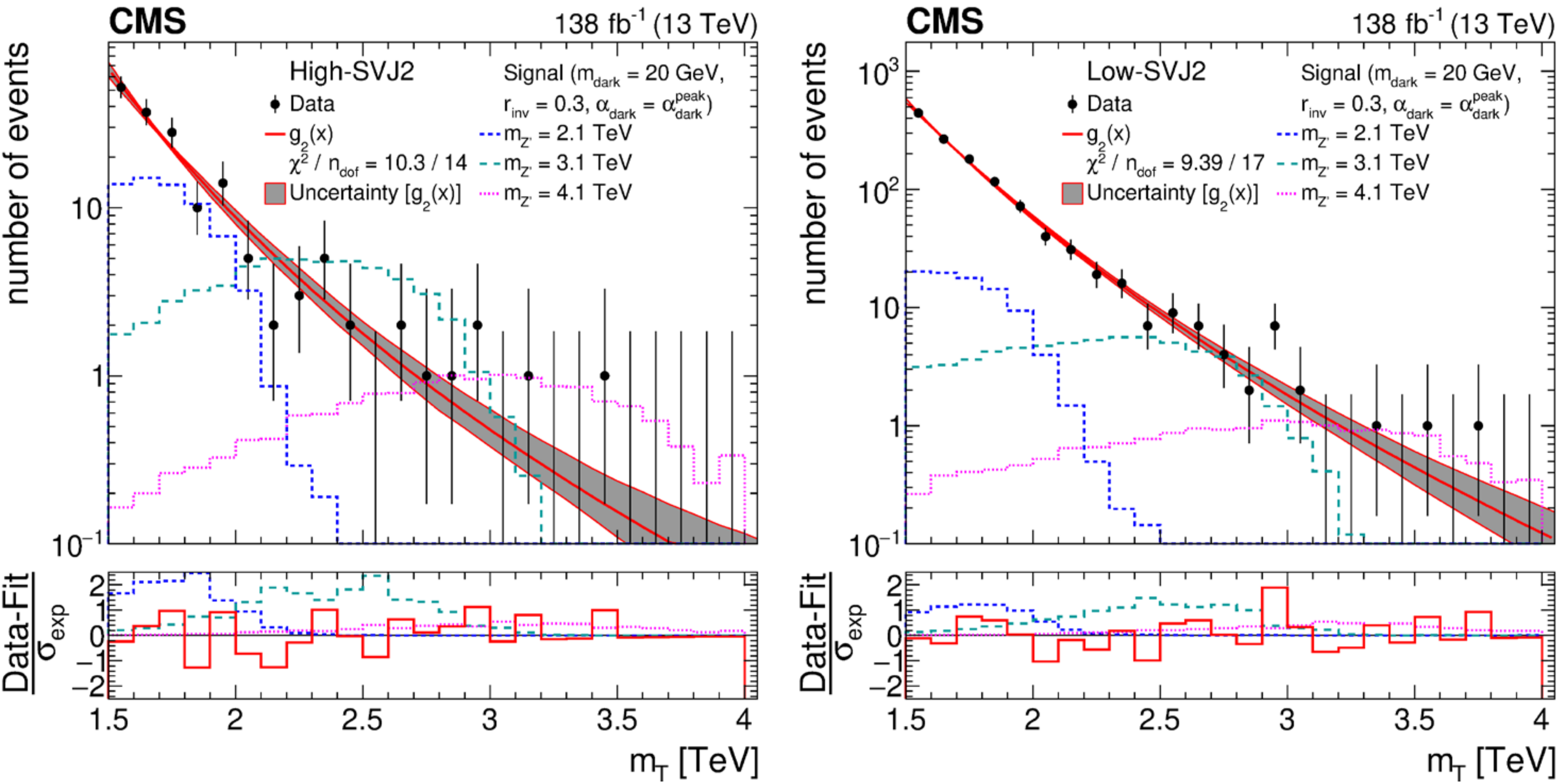
region	$\boldsymbol{g(x)}$
high-R_T	3
low-R_T	2
high-SVJ2	2
low-SVJ2	2

Background Fits (inclusive)



- No significant deviations from SM
  - o Small pulls, few if any cases of several contiguous pulls > 0
- Signals shown w/ cross section at observed limit

Background Fits (BDT-based)

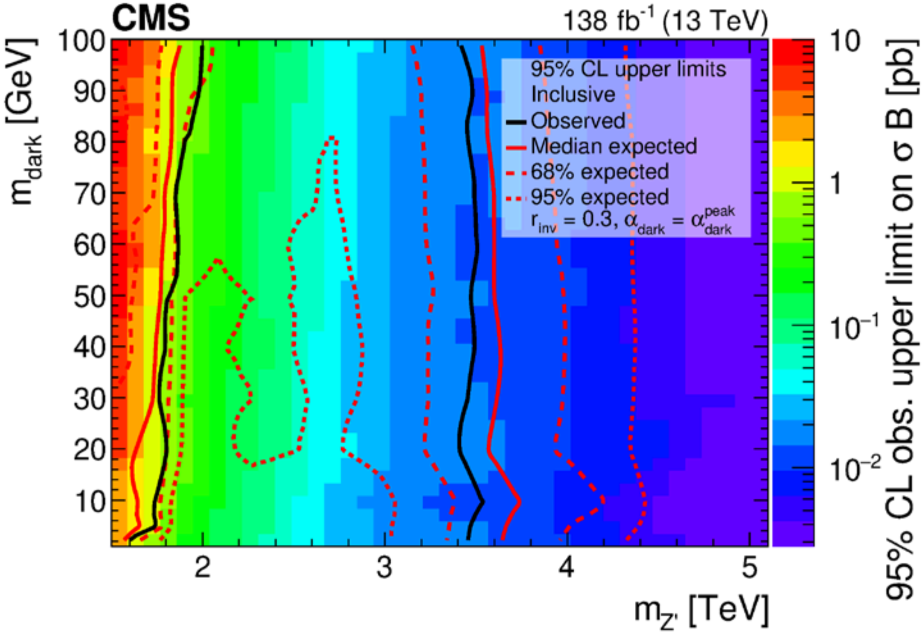


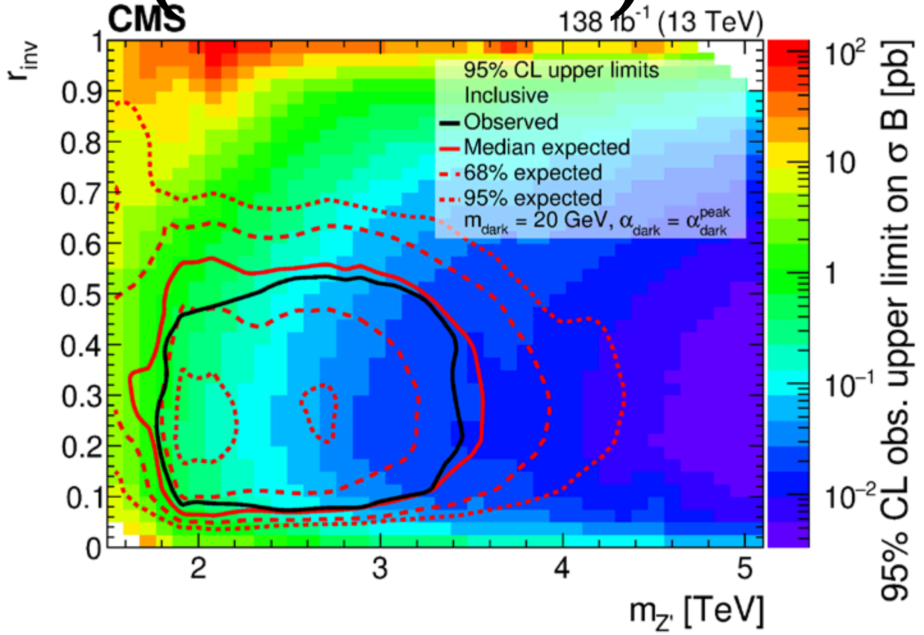
- No significant deviations from SM
  - Small pulls, few if any cases of several contiguous pulls > 0
- Signals shown w/ cross section at observed limit

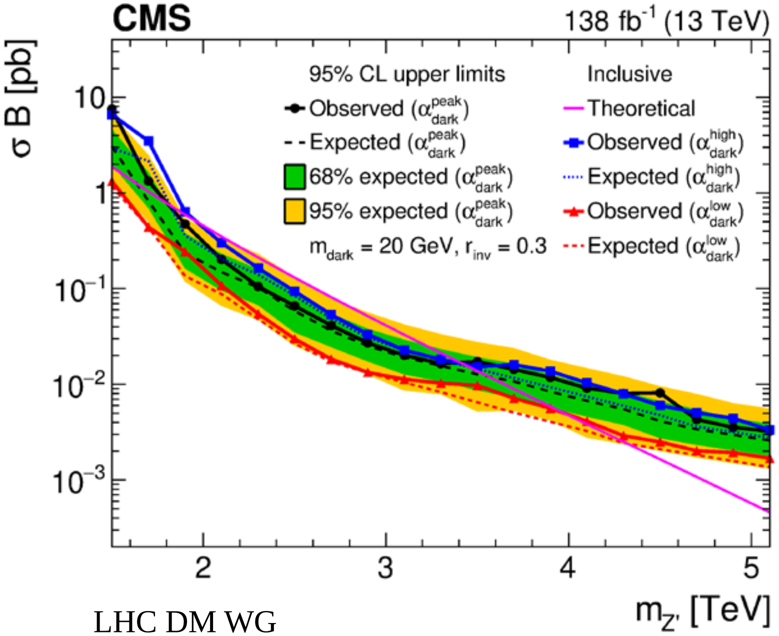
Systematic Uncertainties

- 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*

Observed Limits (inclusive)



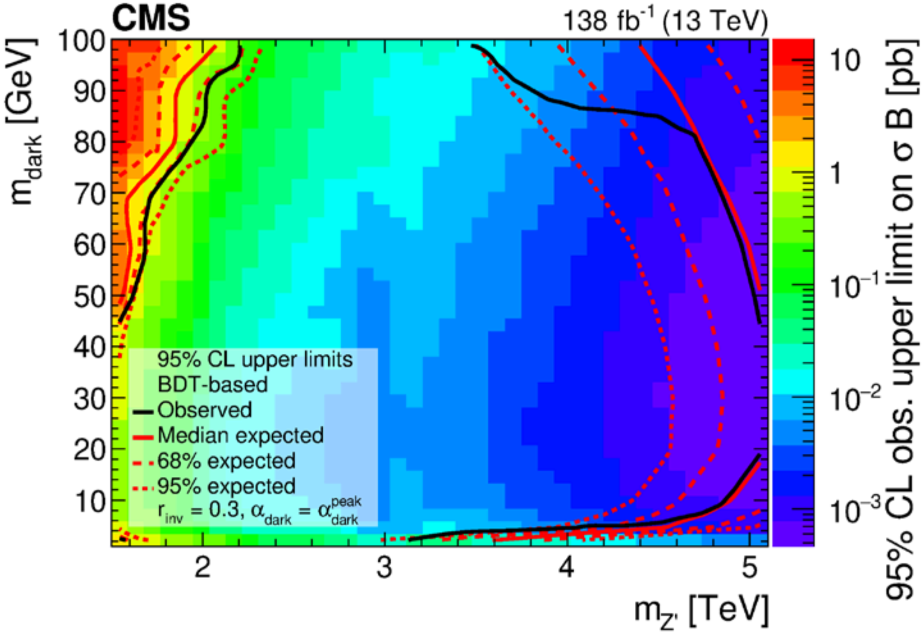


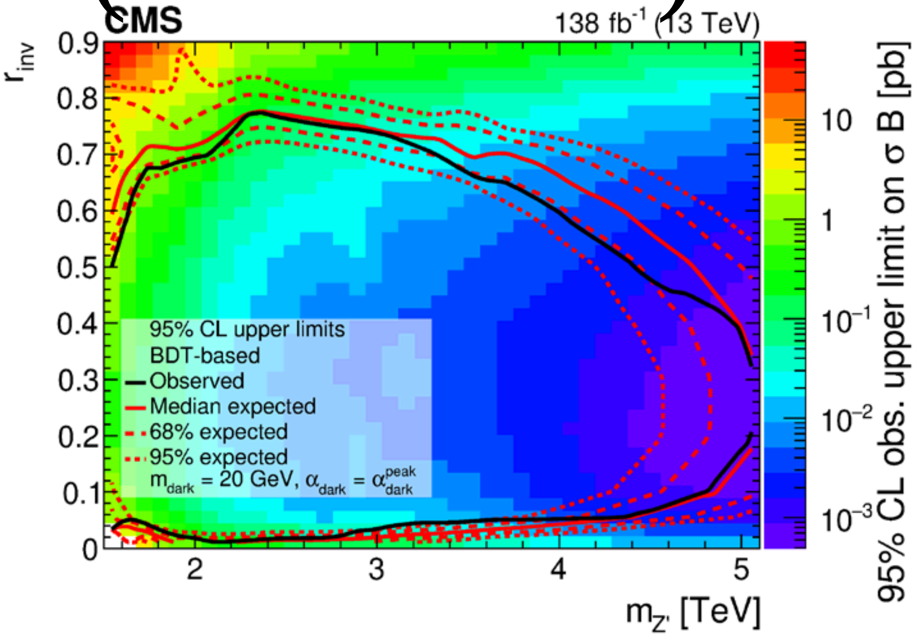


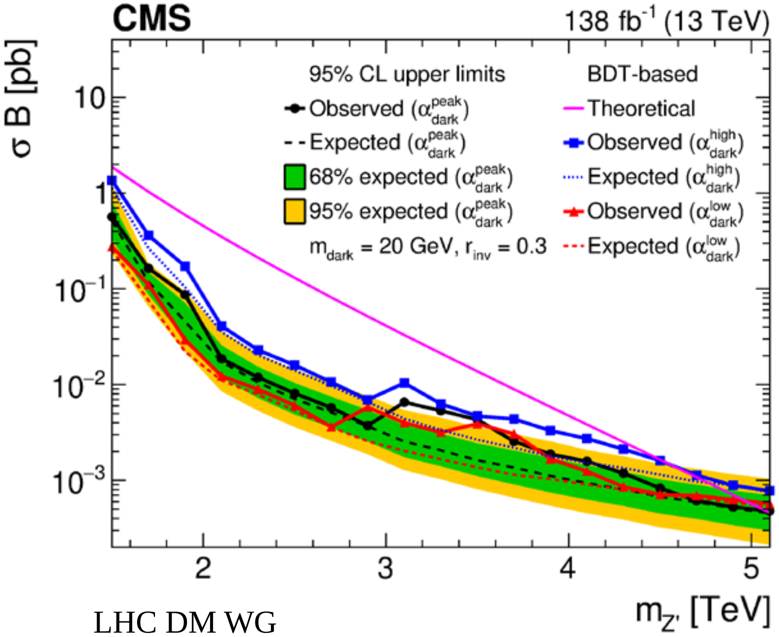
Observed (expected) exclusions:

- $1.5 < m_{Z'} < 4.0$ TeV ($1.5 < m_{Z'} < 4.3$ TeV)
- Depending on $m_{Z'}$:
  - o $0.07 < r_{inv} < 0.53$ ($0.06 < r_{inv} < 0.57$)
  - o All m_{dark}, α_{dark} variations

Observed Limits (BDT-based)







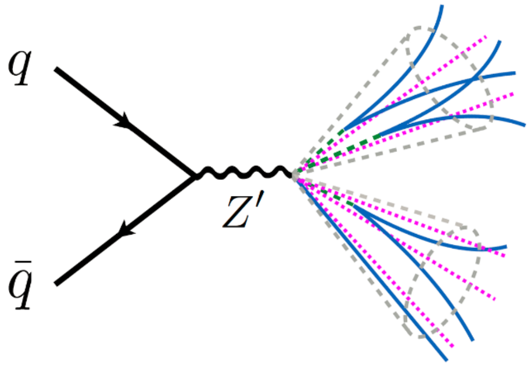
Observed (expected) exclusions:

- 1.5 < $m_{Z'}$ < 5.1 TeV (1.5 < $m_{Z'}$ < 5.1 TeV)
- Depending on $m_{Z'}$:
  - o 0.01 < r_{inv} < 0.77 (0.01 < r_{inv} < 0.78)
  - o All m_{dark}, α_{dark} variations

➢ Signal parameters excluded for wider range in $m_{Z'}$ vs. inclusive search

Conclusions

- CMS search directly excludes a large portion of semivisible jet model space for the first time
  - Sensitivity to a broad range of $m_{Z'}$, m_{dark}, r_{inv} values
- Dual strategy provides both generality and sensitivity
  - Inclusive search can be reinterpreted for any kinematically similar signal
  - BDT-based search improves background rejection by almost two orders of magnitude (first SVJ tagger applied to data)
- Stay tuned for more SVJ results from CMS!



Backup

Strongly-Coupled Hidden Sector References

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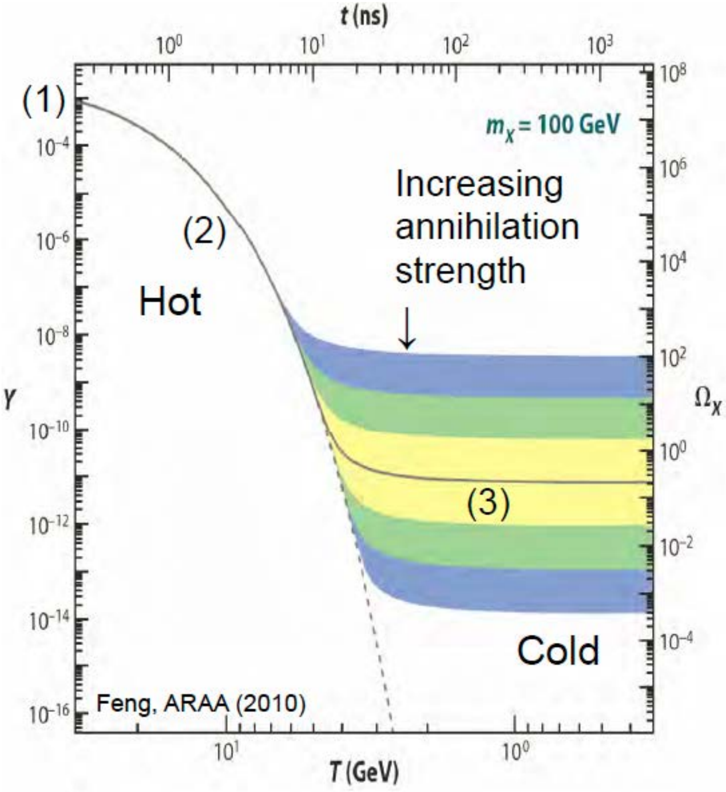
Dark Matter Relic Abundance

- Dark matter production, annihilation at equilibrium in early universe
- Universe expands and cools: stops DM production, then annihilation
- WIMPs imply fixed DM abundance (bottom)



Feng, ARAA (2010)

$$\Omega_{\mathrm{DM}} h^2 = 0.12$$

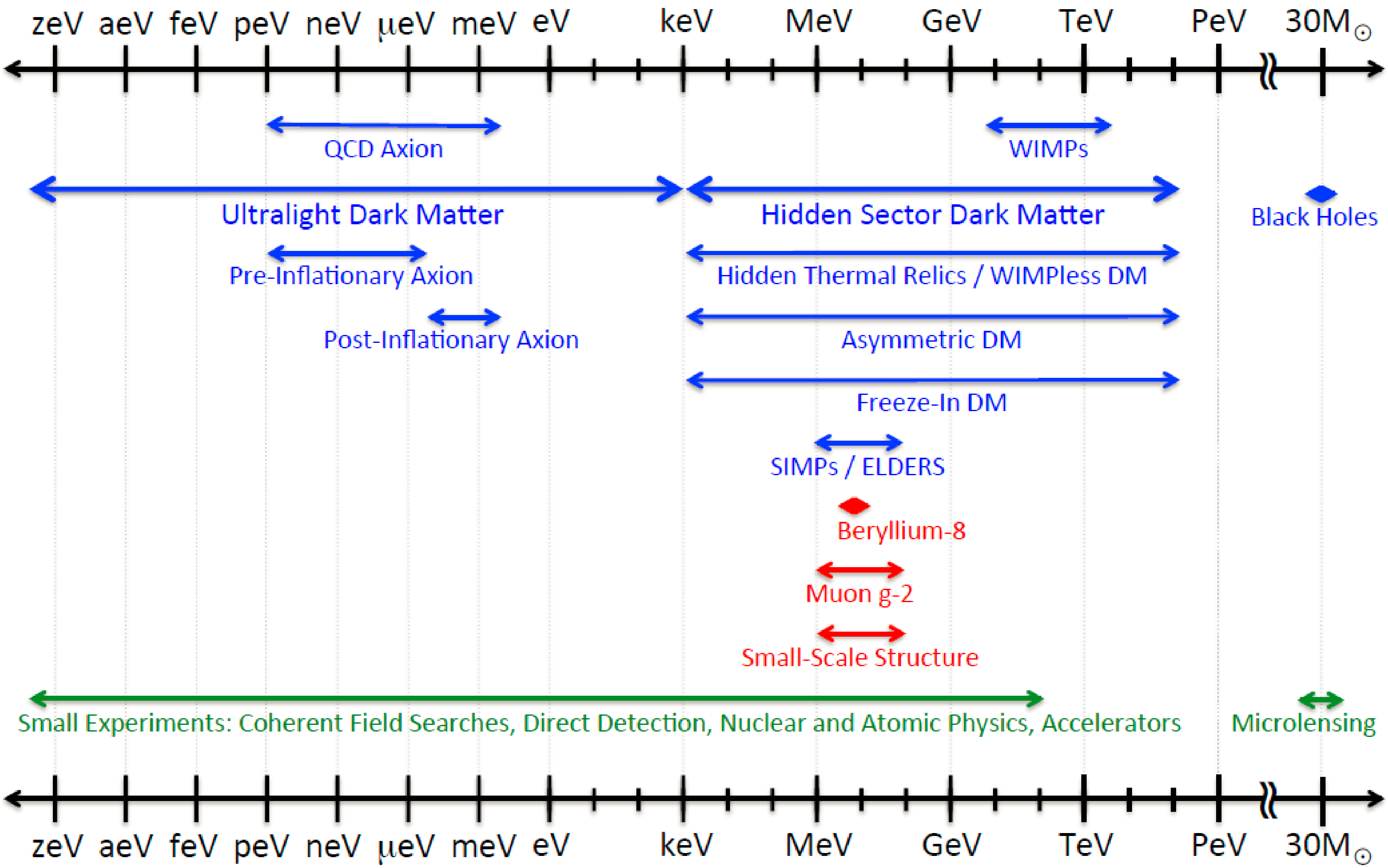
$$\Omega_{\mathrm{DM}} h^2 = \frac{0.2 \times 10^{-9} \mathrm{GeV}^{-2}}{\langle \sigma v \rangle}$$

$$\Omega_{\mathrm{DM}} \sim 0.2$$

$\langle \sigma v \rangle \sim 10^{-9} \mathrm{GeV}^{-2}$ (weak cross section)

Dark Matter Landscape

Dark Sector Candidates, Anomalies, and Search Techniques



QCD Axion

WIMPs

Ultralight Dark Matter

Hidden Sector Dark Matter

Black Holes

Pre-Inflationary Axion

Hidden Thermal Relics / WIMPless DM

Post-Inflationary Axion

Asymmetric DM

Freeze-In DM

SIMPs / ELDERS

Beryllium-8

Muon g-2

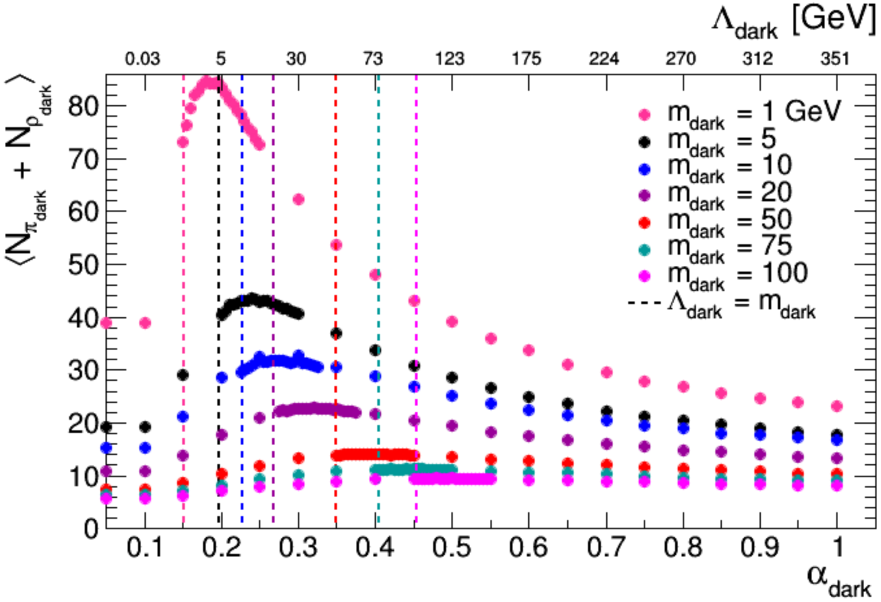
Small-Scale Structure

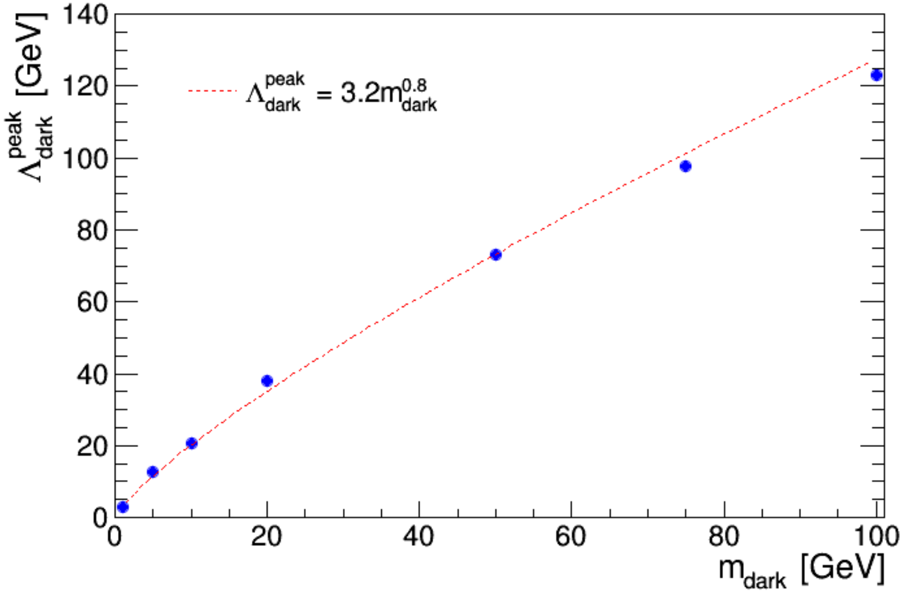
Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators

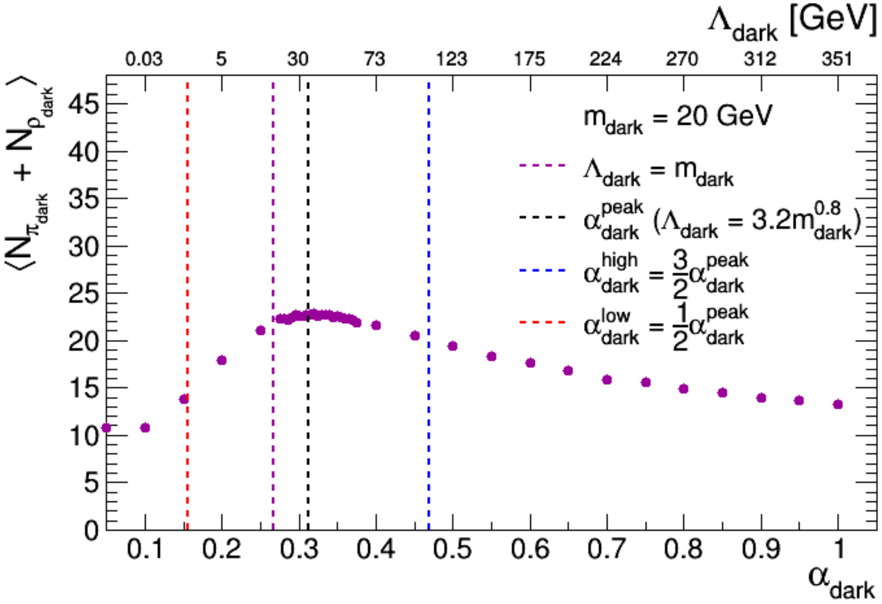
Microlensing

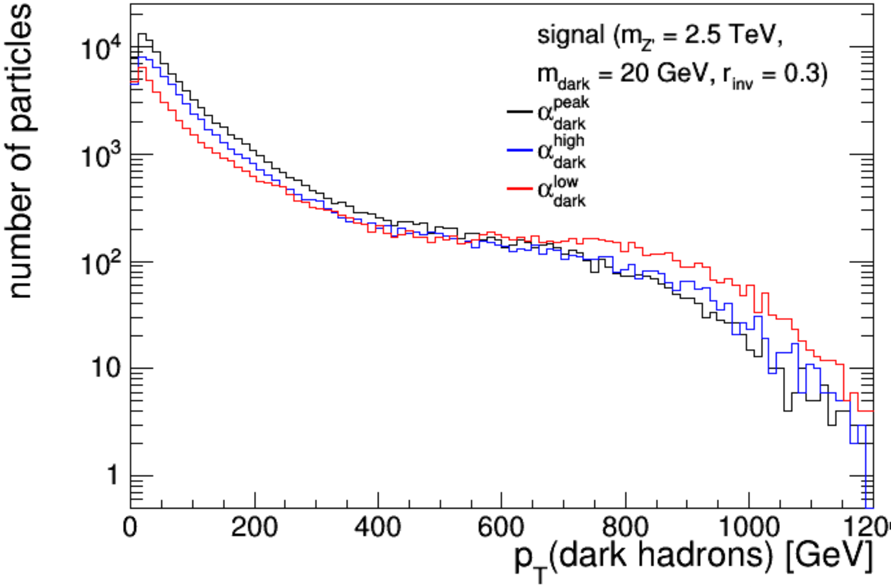
arXiv:1707.04591, G. Landsberg

α_{dark} variations

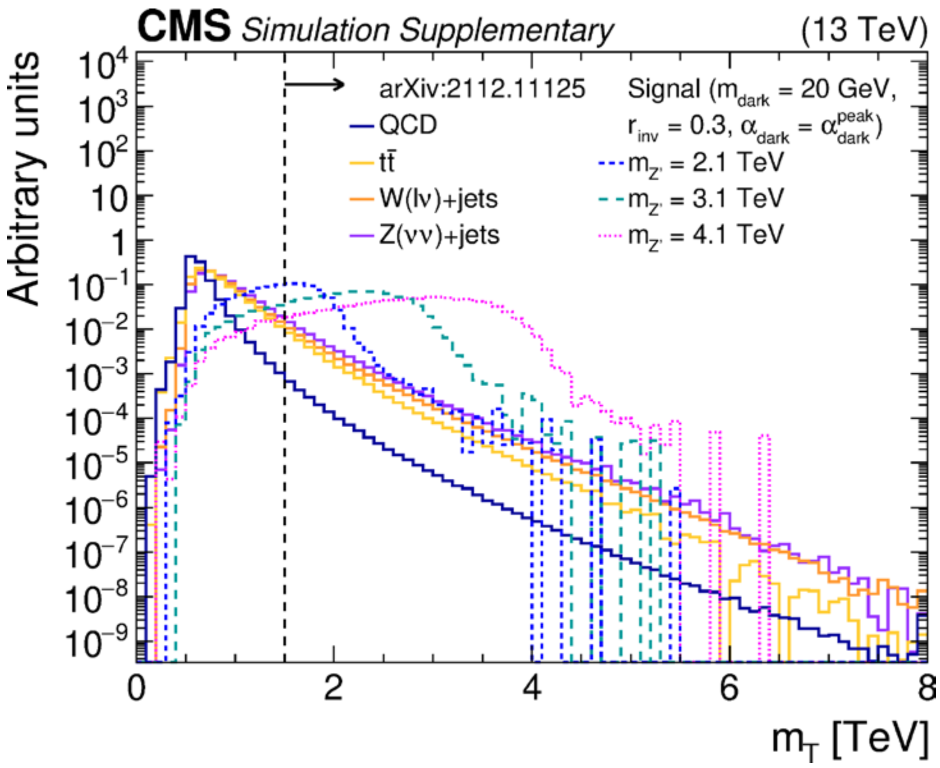


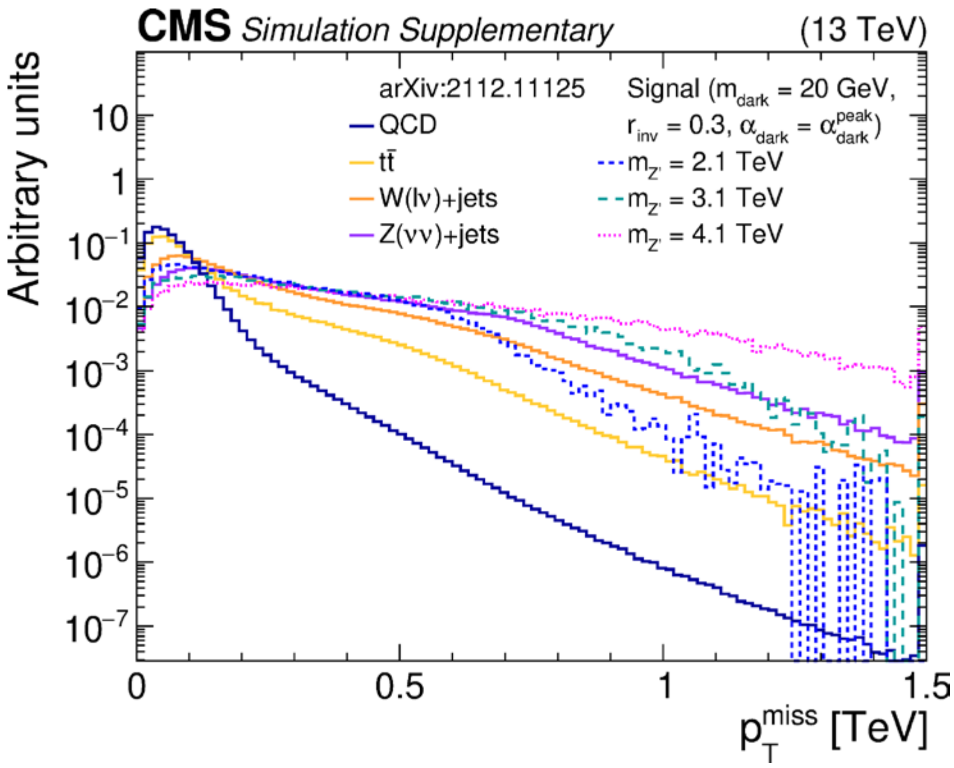




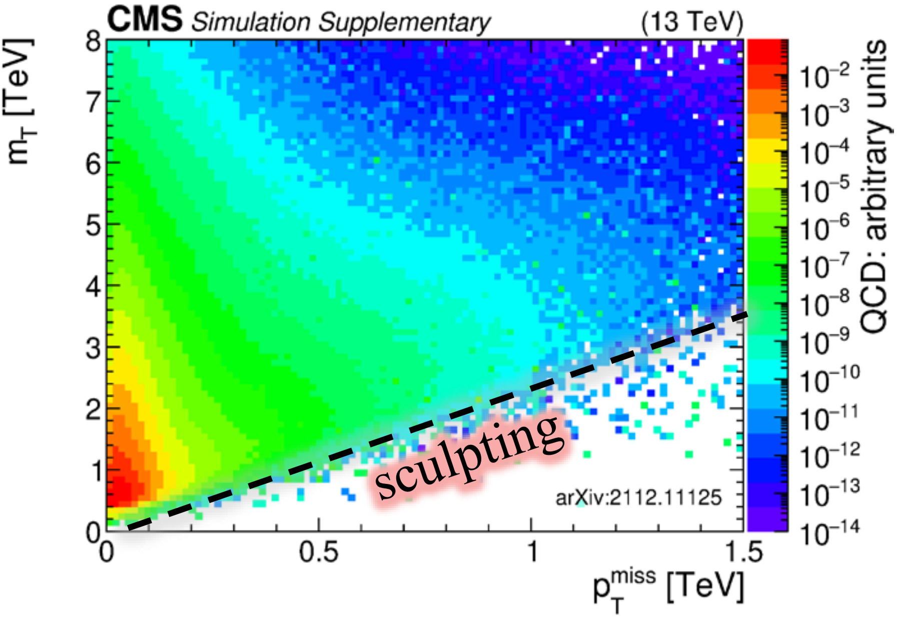


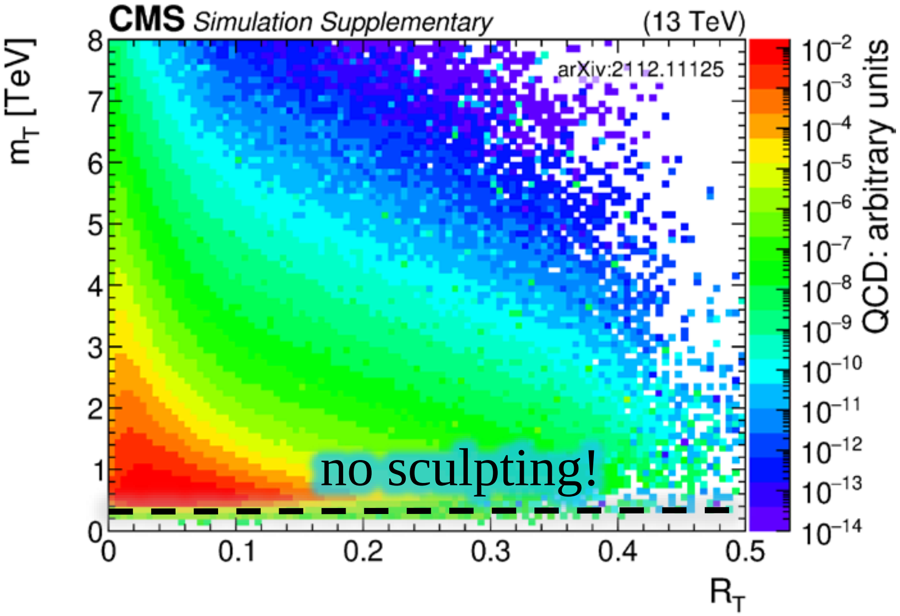
Semivisible Jet Kinematics





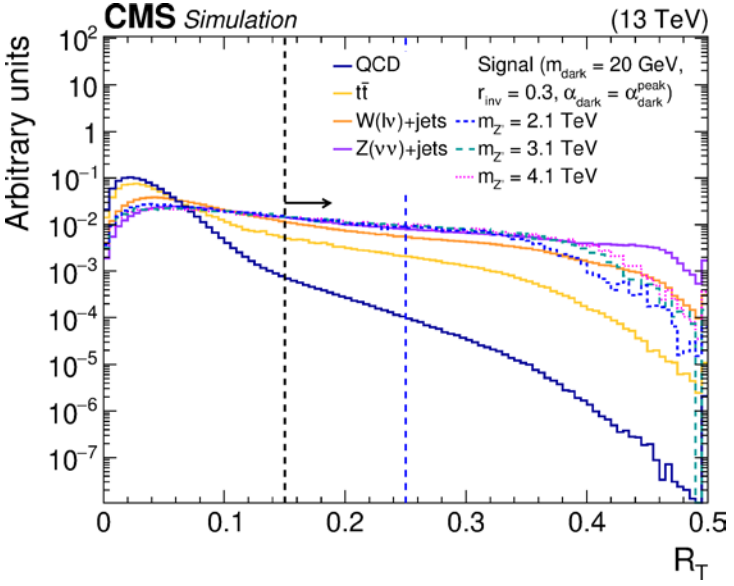
Mass Sculpting





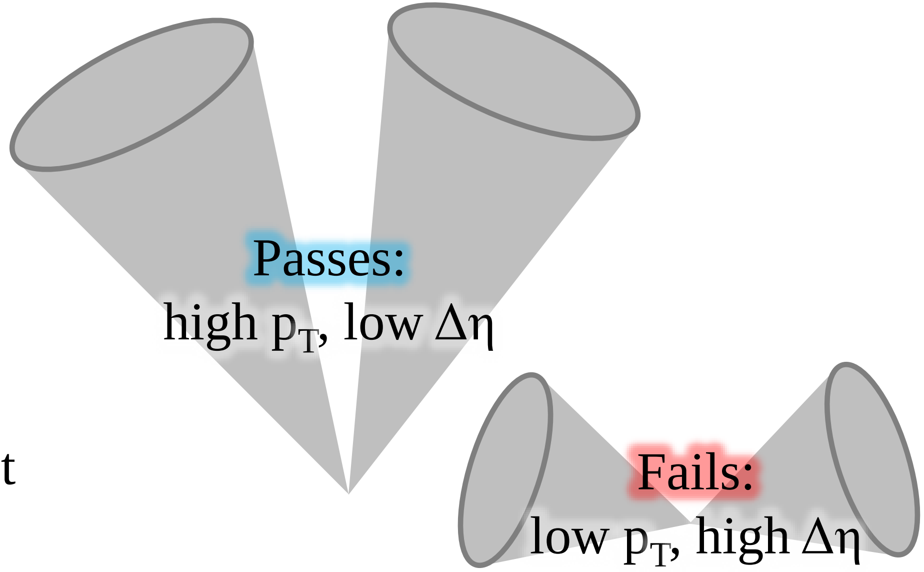
- Avoid/minimize direct cuts on m_T ingredients: p_T^{miss}, jet p_T
  - o Relative variable (“transverse ratio”): $R_T = p_T^{miss}/m_T$

➢ Reject QCD background without shifting m_T peak



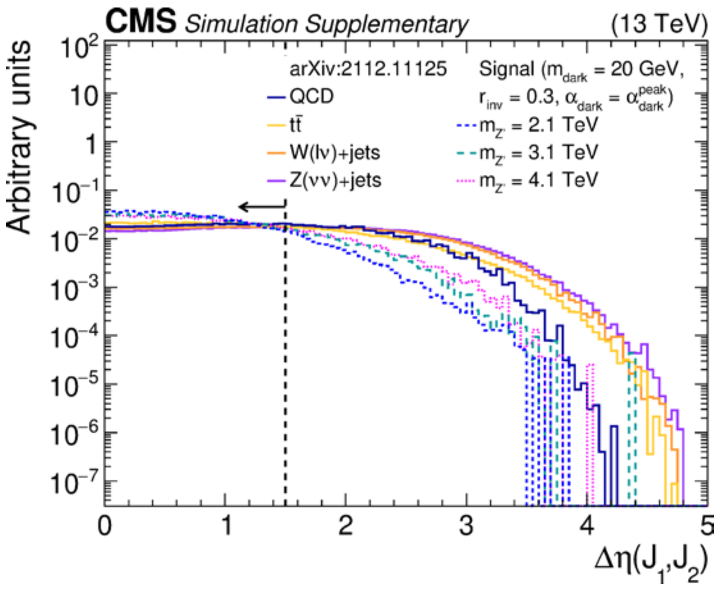
Triggering

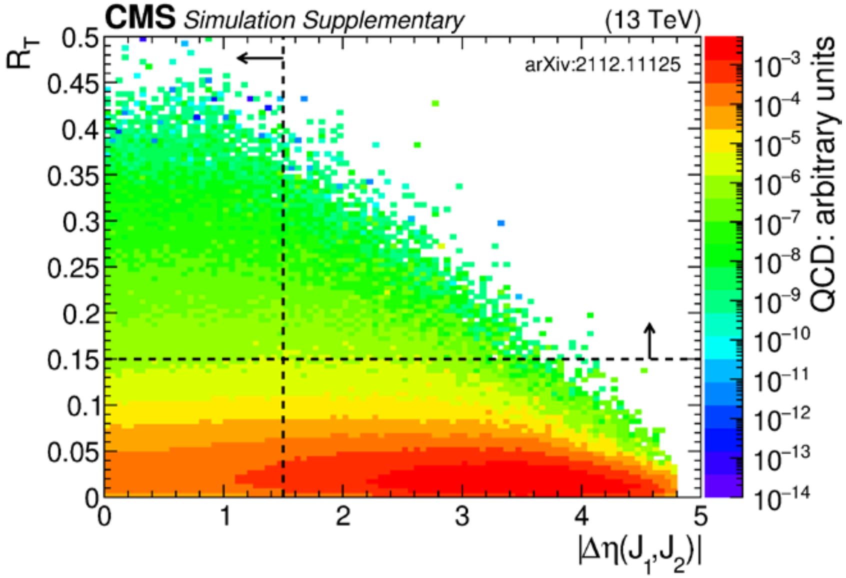
- Trigger on jet p_T, H_T
  - ➢ Require low $\Delta\eta(J_1,J_2)$ for high efficiency
- Usually improves signal sensitivity
  - ➢ Most *t*-channel QCD events already rejected by R_T requirement
- m_T > 1500 GeV for trigger efficiency



Passes:
high p_T, low $\Delta\eta$

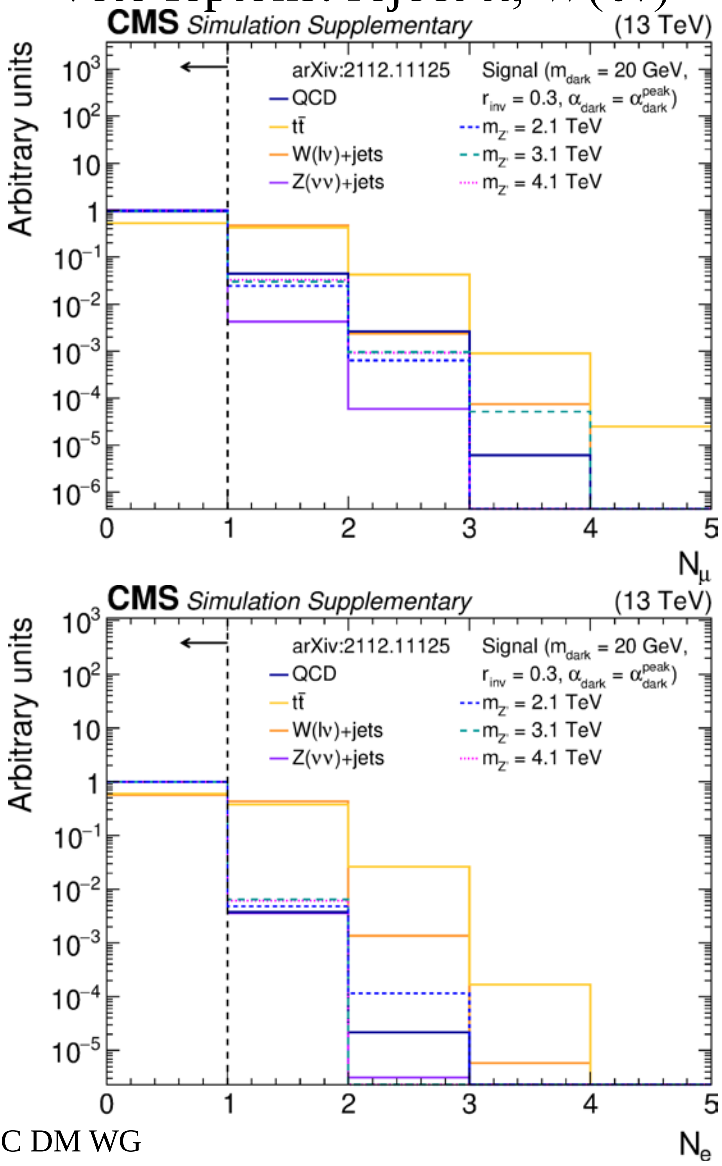
Fails:
low p_T, high $\Delta\eta$



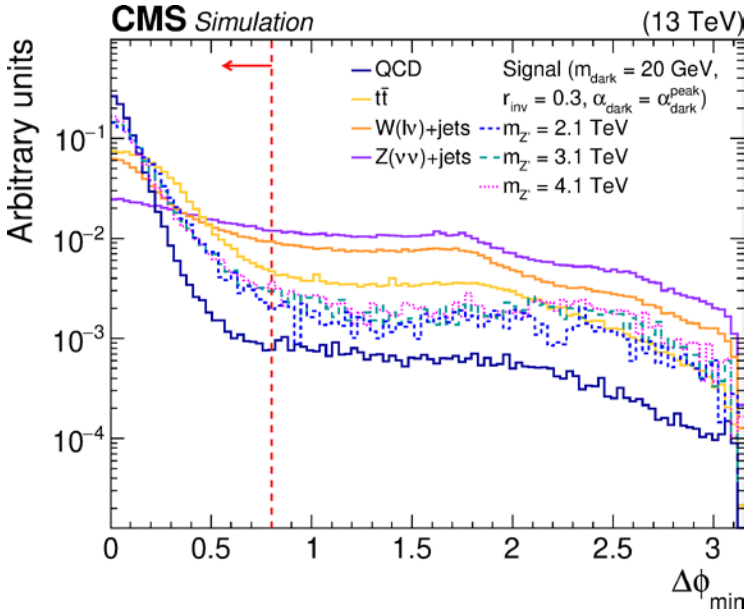


Electroweak Rejection

Veto leptons: reject $t\bar{t}$, W(ℓν)



Require low $\Delta\varphi_{\min}(J_{1,2},p_T^{\text{miss}})$:
Reject $t\bar{t}$, W(ℓν), Z(νν)



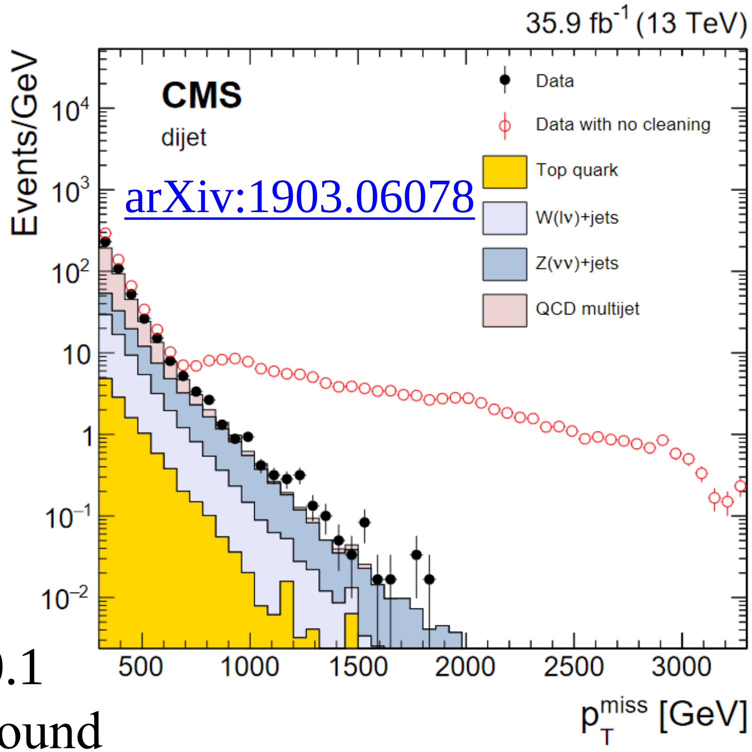
Instrumental Backgrounds

- Centrally-maintained filters reject *most* instrumental sources of artificial high-p_T^{miss} events
  - But low-Δφ region ignored by almost all analyses: filters not tuned here
- Major source of jet mismeasurement: nonfunctional ECAL readout channels (“dead” or “hot” cells)

➢ Custom filter vetoing events w/ narrow (AK4) jets w/ $\Delta R(j_{1,2}, \text{nonfunctional}) < 0.1$ → reject additional 40% of QCD background

  - Signal efficiency 95%

- Misreconstructed jets near barrel-endcap gap in ECAL
  - Appear at high p_T^{miss} and high m_T
  - Veto events w/ $p_T(j_1) > 1000$ GeV and $f_\gamma(j_1) > 0.7$



arXiv:1903.06078

Control Regions

Single Muon

- $N_J \geq 2$
- $p_T(J_1,J_2) > 200$ GeV, $|\eta(J_1,J_2)| < 2.4$, $J_{1,2}$ pass noise rejection
- $R_T \equiv p_T^{miss}/m_T > 0.15$
- $\Delta\eta(J_1,J_2) < 1.5$
- e veto ($p_T > 10$ GeV, $|\eta| < 2.4$)
- $N_\mu \geq 1$ ($p_T > 50$ GeV, $|\eta| < 2.4$, medium ID, $I_{mini} < 0.2$, HLT match)

- Used for trigger efficiency measurement
- Corresponding Single Muon High-$\Delta\eta$ region used for CR trigger efficiency measurement

---

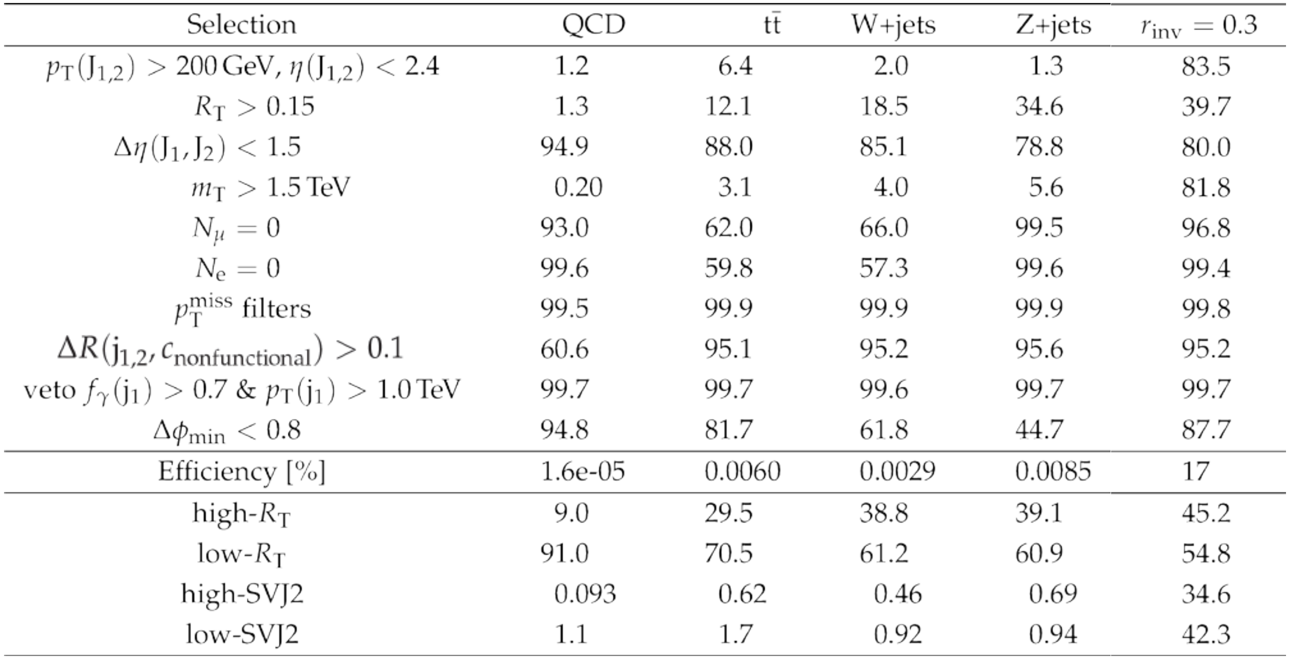
- Used for data quality studies
  - Statistically limited, but otherwise kinematically similar to signal region
- $\Delta\eta$ range maximizes data yield (in fully efficient region, $m_T > 1850$ GeV)
  - $1500 < m_T < 1850$ GeV can be used w/ trigger efficiency correction applied

High-$\Delta\eta$

Preselection, except:

- $1.5 < \Delta\eta(J_1,J_2) < 2.2$
- $m_T > 1850$ GeV

Cutflows



Selection	QCD	$t\bar{t}$	W+jets	Z+jets	$r_{\mathrm{inv}} = 0.3$
$p_{\mathrm{T}}(\mathrm{J}_{1,2}) > 200\,\mathrm{GeV}$, $\eta(\mathrm{J}_{1,2}) < 2.4$	1.2	6.4	2.0	1.3	83.5
$R_{\mathrm{T}} > 0.15$	1.3	12.1	18.5	34.6	39.7
$\Delta\eta(\mathrm{J}_1, \mathrm{J}_2) < 1.5$	94.9	88.0	85.1	78.8	80.0
$m_{\mathrm{T}} > 1.5\,\mathrm{TeV}$	0.20	3.1	4.0	5.6	81.8
$N_{\mu} = 0$	93.0	62.0	66.0	99.5	96.8
$N_{\mathrm{e}} = 0$	99.6	59.8	57.3	99.6	99.4
$p_{\mathrm{T}}^{\mathrm{miss}}$ filters	99.5	99.9	99.9	99.9	99.8
$\Delta R(\mathrm{j}_{1,2}, c_{\mathrm{nonfunctional}}) > 0.1$	60.6	95.1	95.2	95.6	95.2
veto $f_{\gamma}(\mathrm{j}_1) > 0.7$ & $p_{\mathrm{T}}(\mathrm{j}_1) > 1.0\,\mathrm{TeV}$	99.7	99.7	99.6	99.7	99.7
$\Delta\phi_{\mathrm{min}} < 0.8$	94.8	81.7	61.8	44.7	87.7
Efficiency [%]	1.6e-05	0.0060	0.0029	0.0085	17
high-R_{T}	9.0	29.5	38.8	39.1	45.2
low-R_{T}	91.0	70.5	61.2	60.9	54.8
high-SVJ2	0.093	0.62	0.46	0.69	34.6
low-SVJ2	1.1	1.7	0.92	0.94	42.3

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

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

- Energy correlation functions:

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

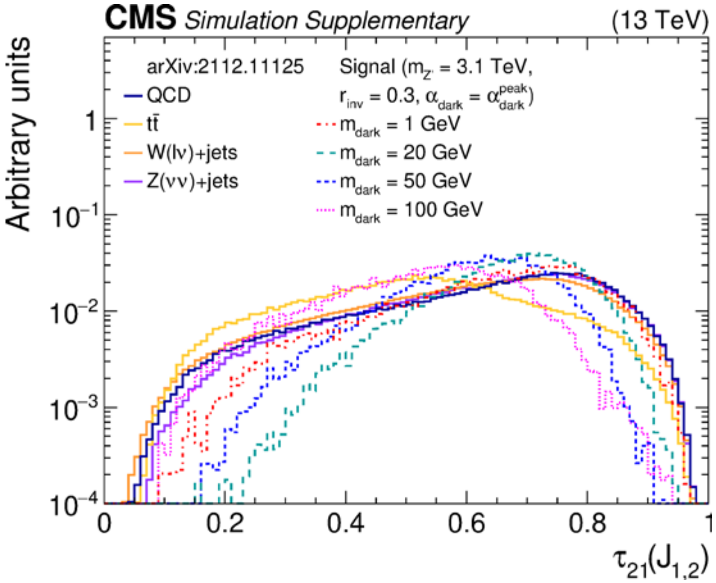
$$N_2^{(1)} = \frac{{}_2e_3^{(1)}}{\left({}_1e_2^{(1)}\right)^2} \qquad N_3^{(1)} = \frac{{}_2e_4^{(1)}}{\left({}_1e_3^{(1)}\right)^2}$$

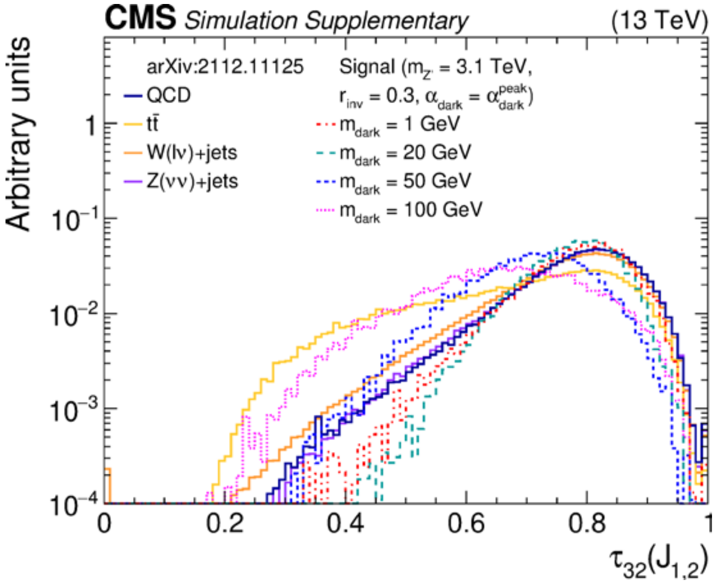
$$\begin{aligned} m_{\mathrm{T}}^2 &= \left[E_{\mathrm{T,JJ}} + E_{\mathrm{T}}^{\mathrm{miss}}\right]^2 - \left[\vec{p}_{\mathrm{T,JJ}} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right]^2 \\ &= m_{\mathrm{JJ}}^2 + 2p_{\mathrm{T}}^{\mathrm{miss}} \left[\sqrt{m_{\mathrm{JJ}}^2 + p_{\mathrm{T,JJ}}^2} - p_{\mathrm{T,JJ}}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

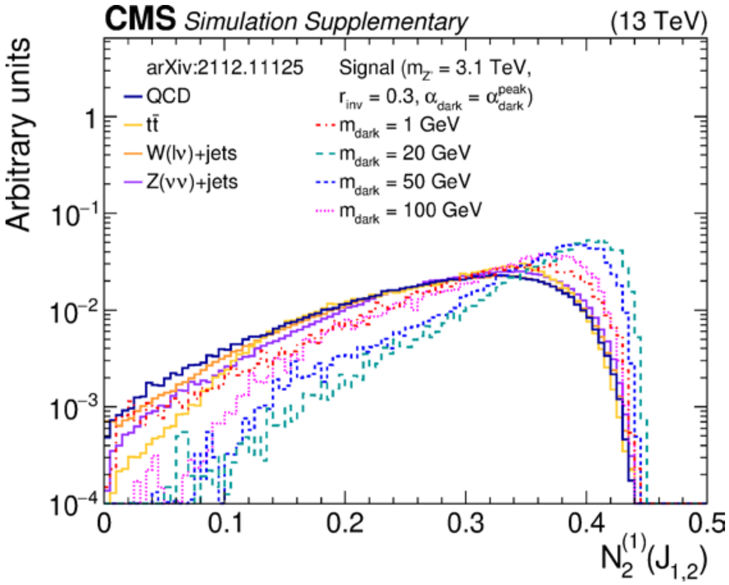
Soft Drop Mass

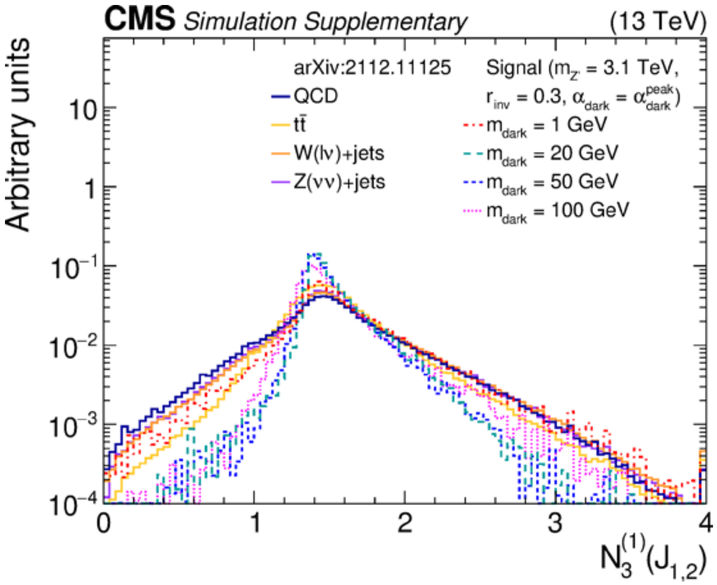
- Start w/ jet clustered by anti-k_t algorithm w/ $R = 0.8$
- Recluster jet constituents w/ Cambridge-Aachen algorithm
    - o Undo clustering one step at a time
    - o Get two subjets j_1, j_2
    - o Check condition: $\frac{\min(p_{Tj1}, p_{Tj2})}{p_{Tj1} + p_{Tj2}} > z_{cut} \times \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$
    - o If met, then keep whole jet and stop
    - o If not met, keep higher p_T subjet and repeat
- CMS uses $z_{cut} = 0.1$, $\beta = 0$
- See arXiv:1402.2657
- Effect: drop soft constituents (at wide angles)
  → remove ISR, underlying event, pileup
- Mass calculation: find invariant mass from softdrop subjet 4-vectors

BDT Input Variables (1)









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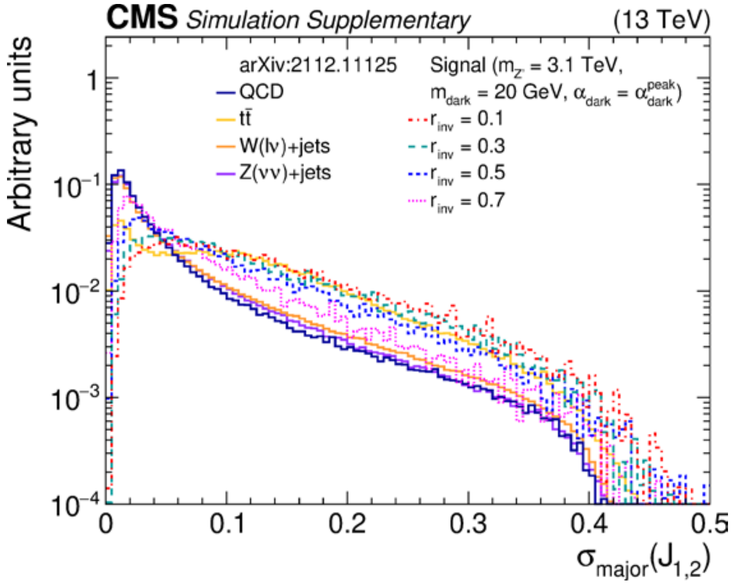

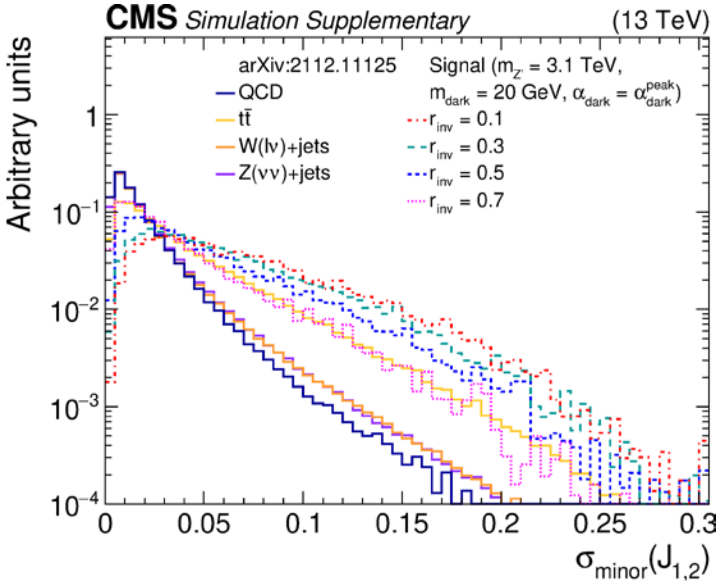

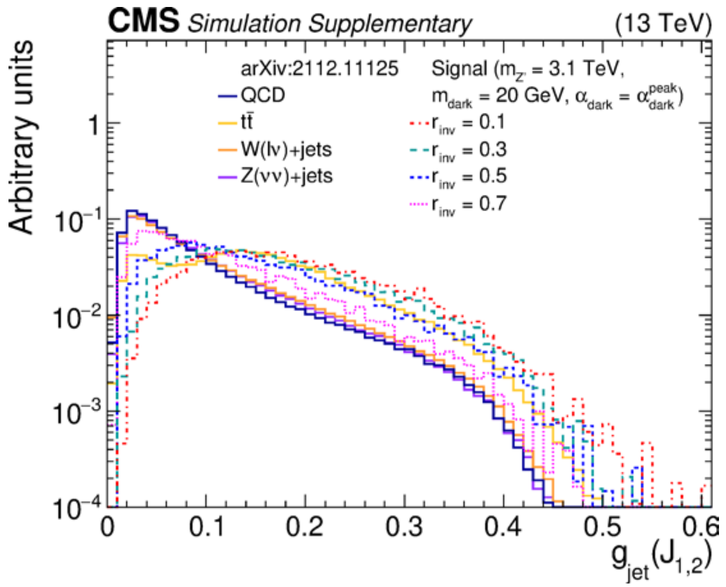

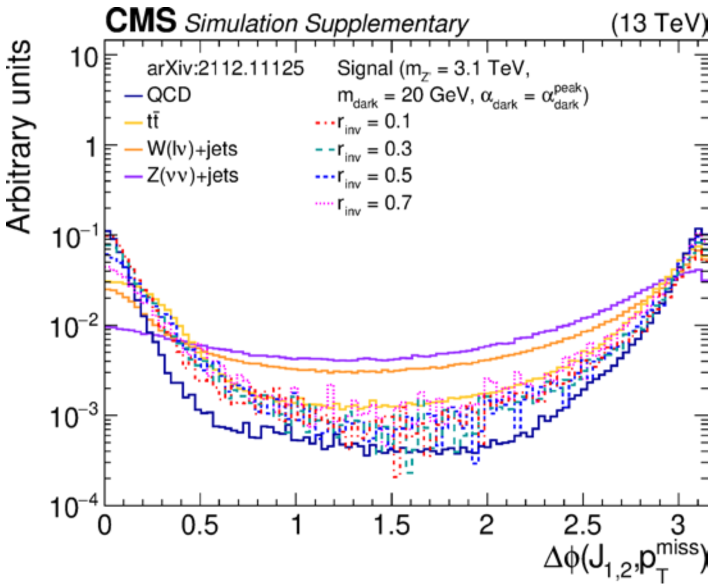

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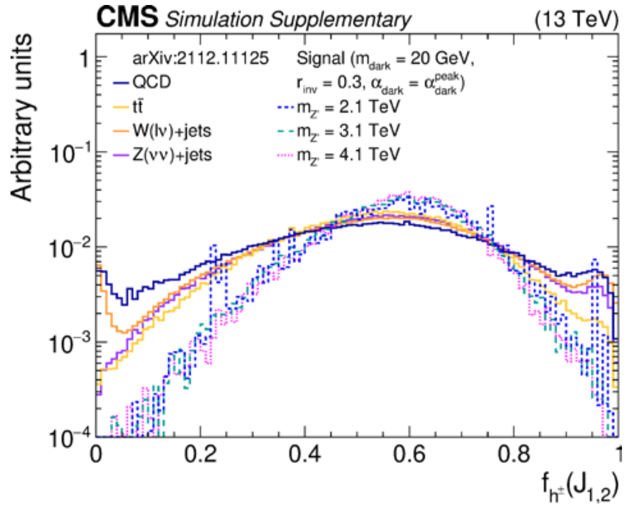
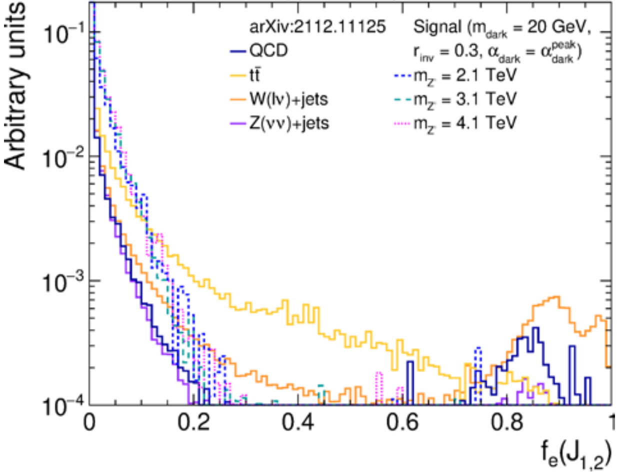
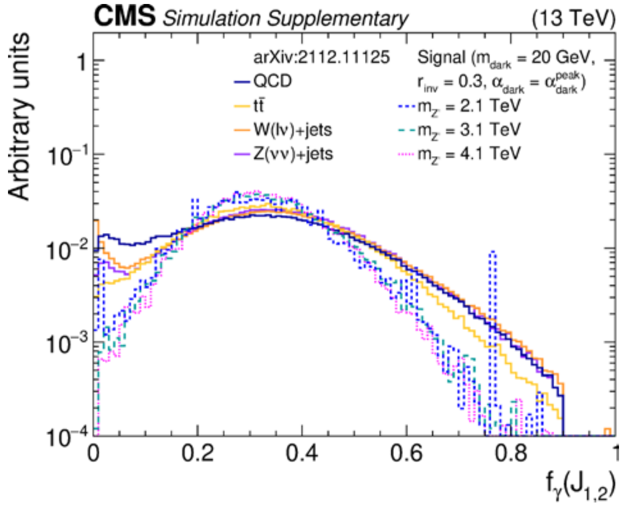
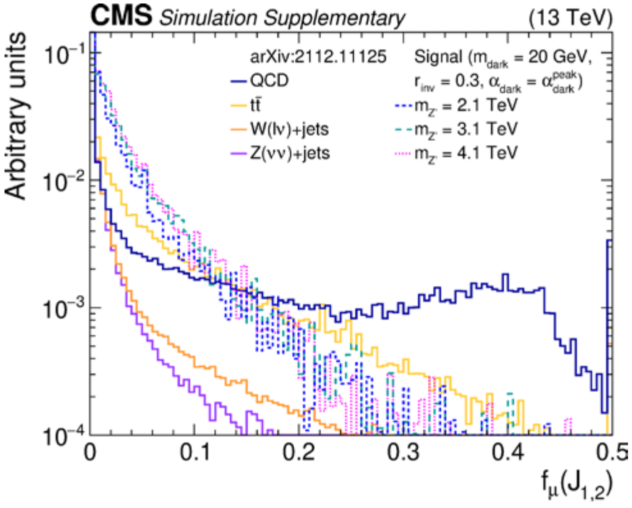
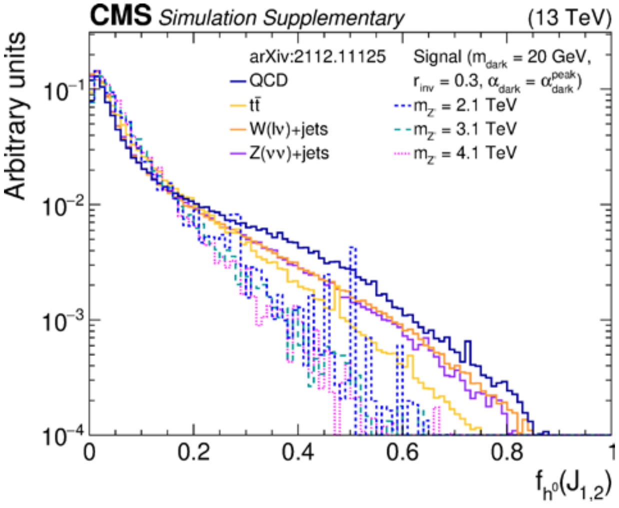


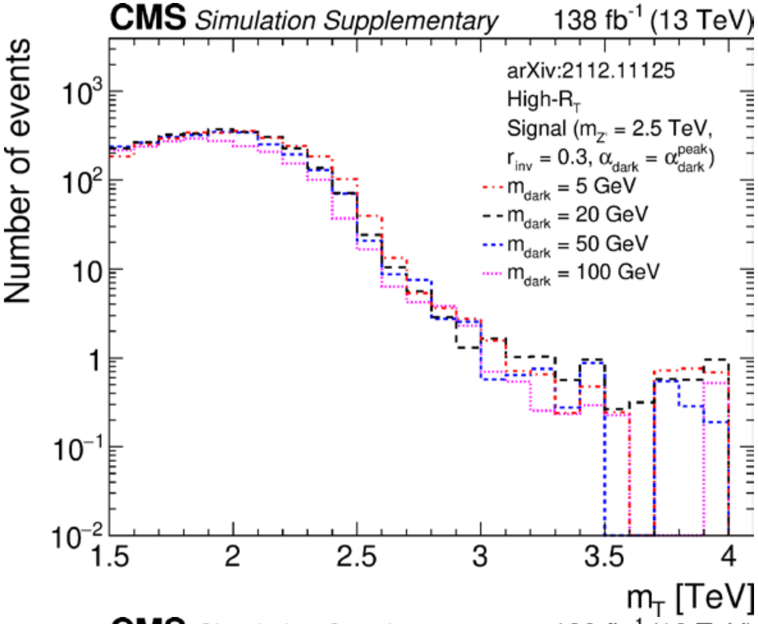




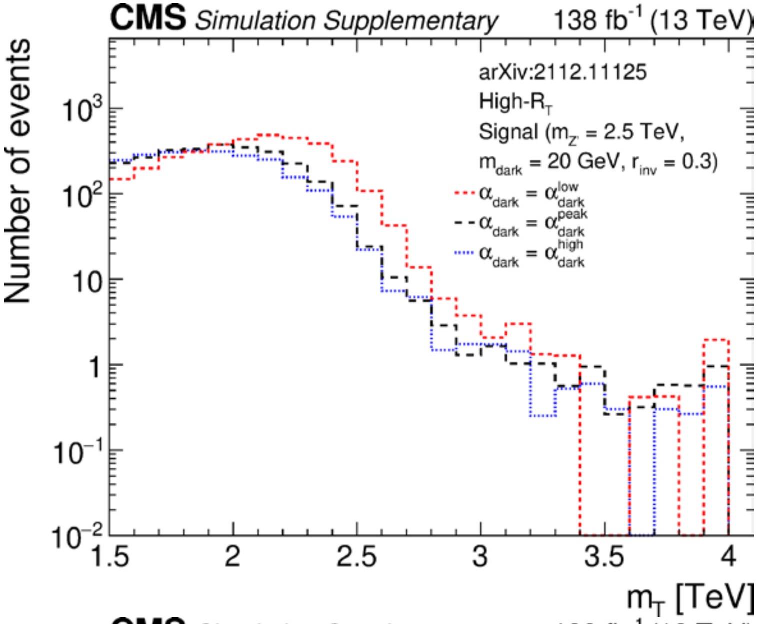


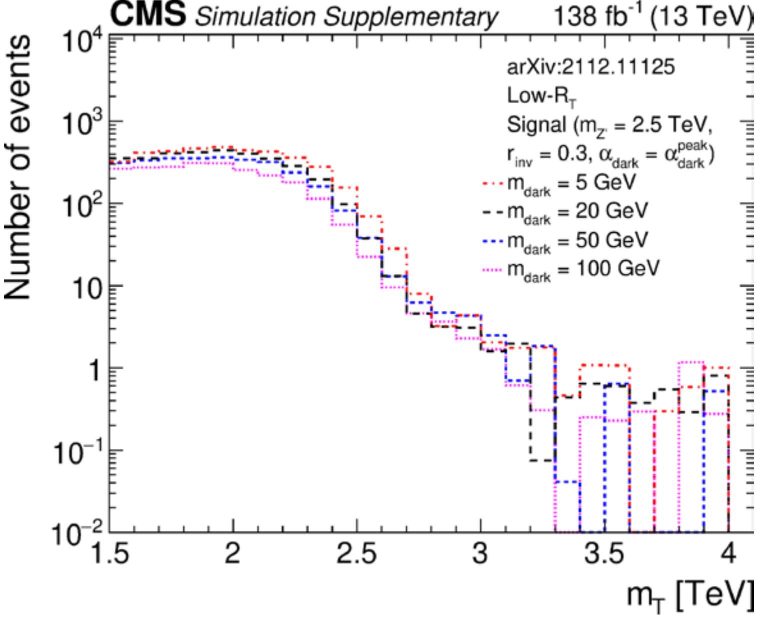


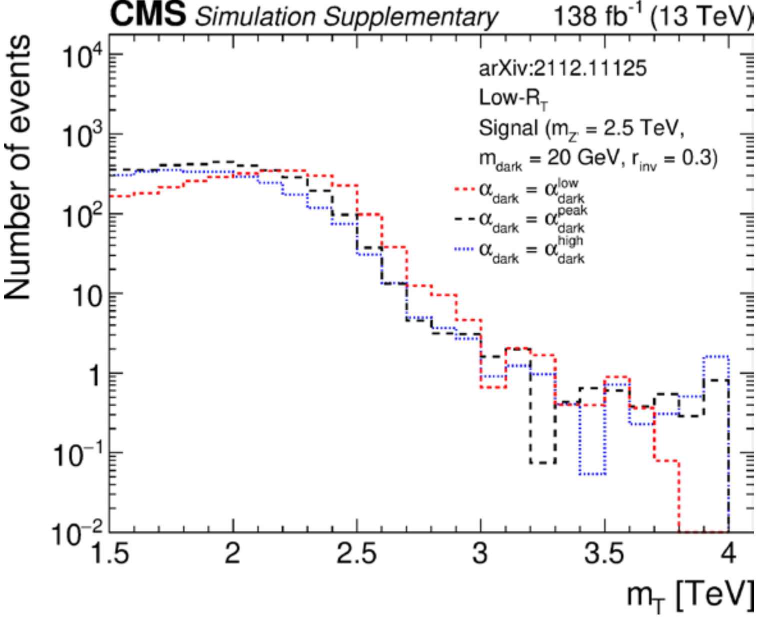
More m_T Variations



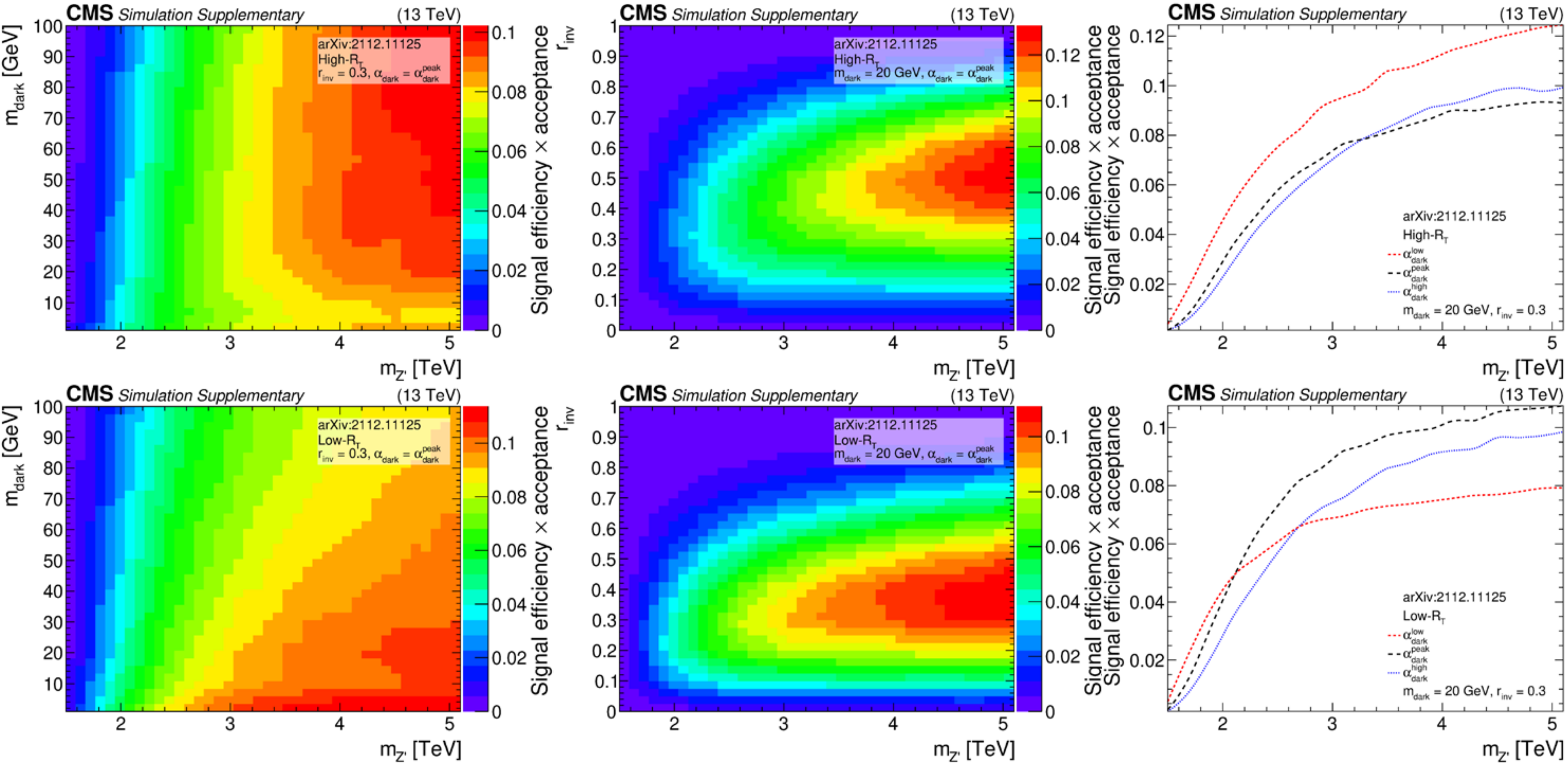
- α_{dark} has non-trivial impact
- m_{dark} has very little impact



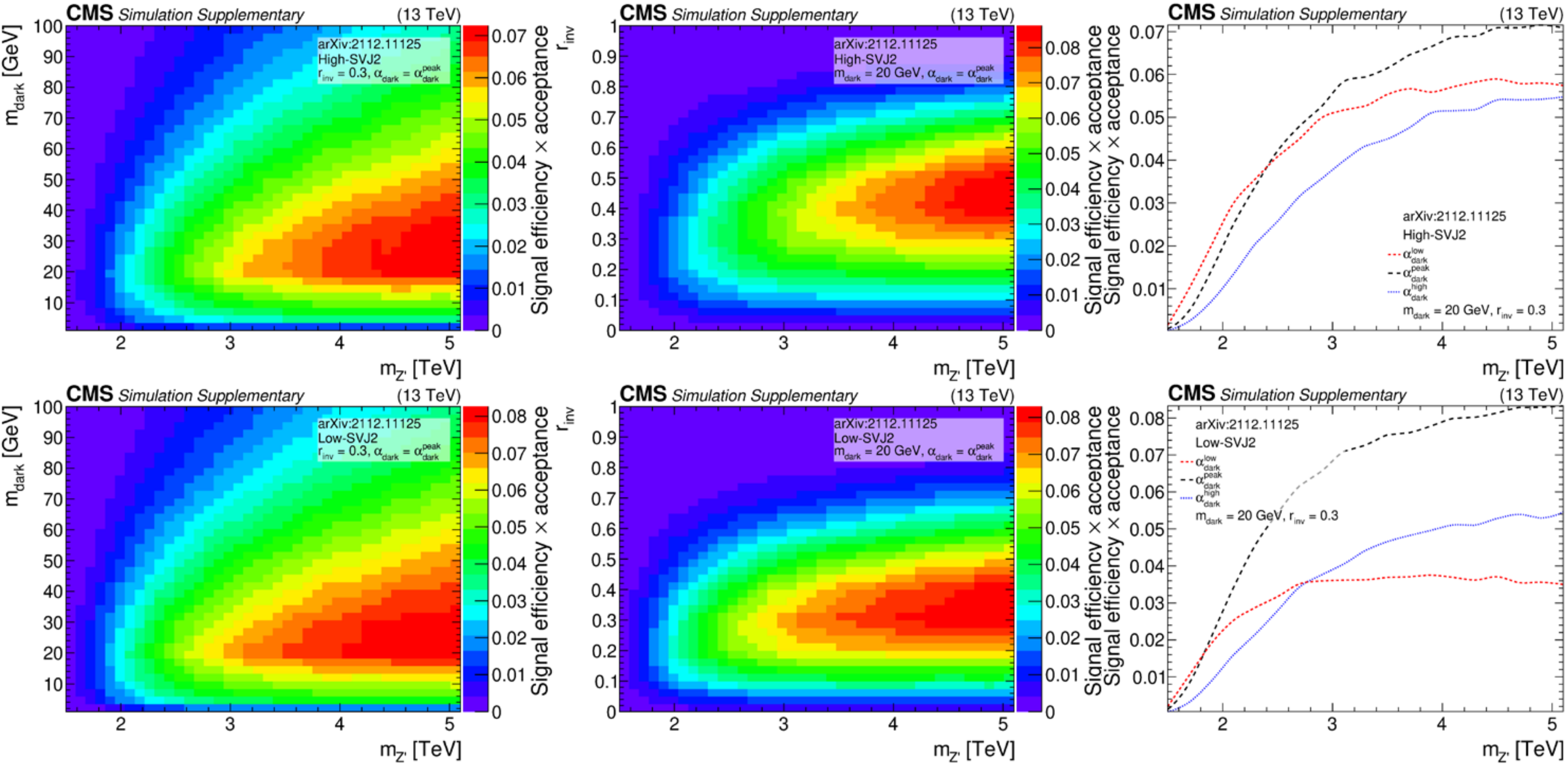




Signal Efficiency (inclusive)



Signal Efficiency (BDT-based)



Secondary Functions

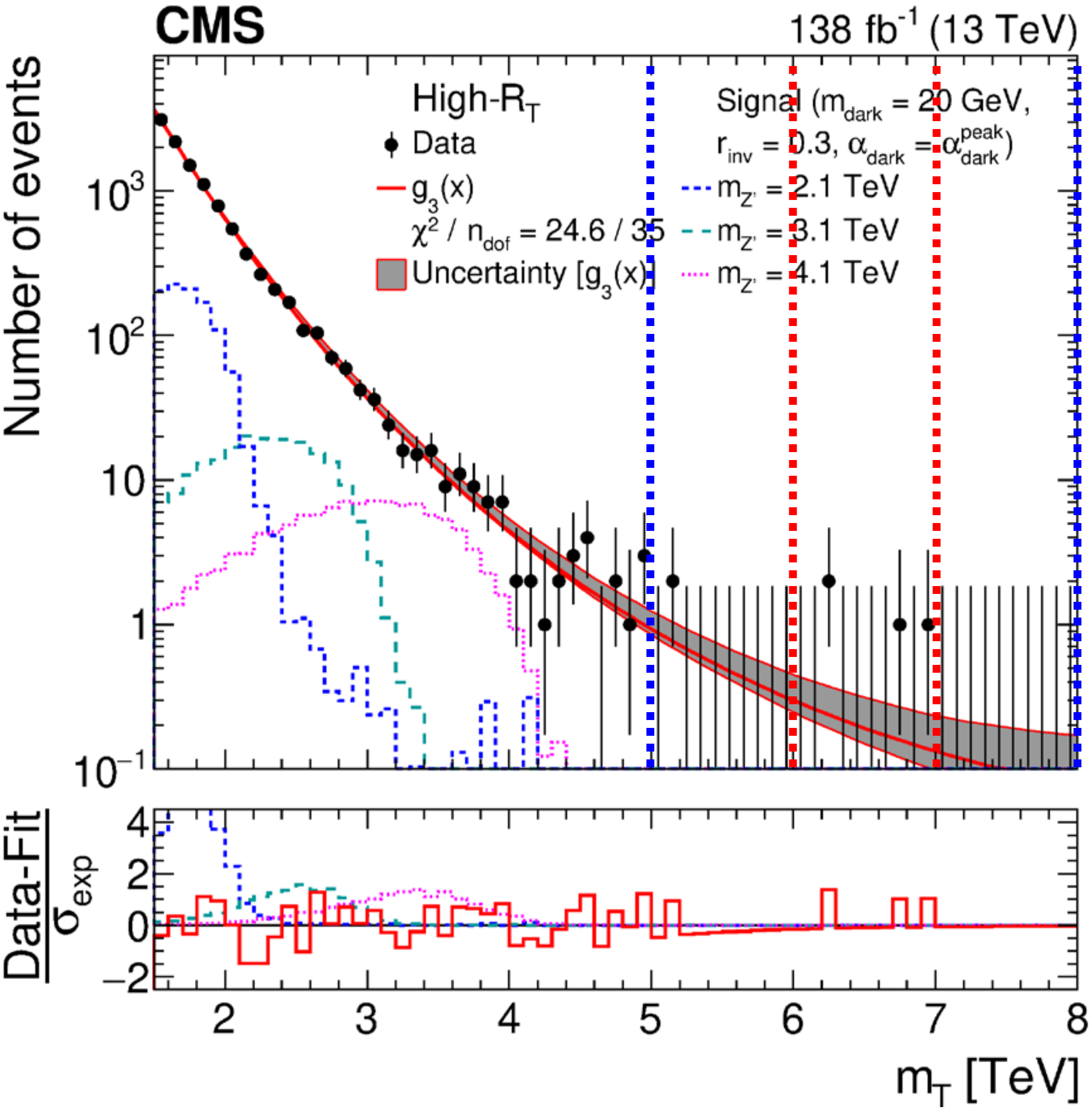
$$x = m_{\mathrm{T}}/\sqrt{s}$$

$$f(x) = (1-x)^{p_1}(x)^{p_2+p_3\log(x)}$$

$$h(x) = (x)^{-p_1}\exp(-p_2 x - p_3 x^2)$$

- *f*(*x*) from CMS dijet searches e.g. arXiv:1911.03947
- *h*(*x*) from UA2 dijet searches: Z. Phys. C **49** (1991) 17, Nucl. Phys. B **400** (1993) 3

High-R_T Tail Counts



m_T [TeV]	Obs.	Pred.
5–8	6	$8.4^{+2.1}_{-1.4}$
6–7	4	$2.0^{+0.6}_{-0.4}$

- Predicted counts and uncertainties obtained from integrating background fit