

Overview of dark sector and dark QCD analyses at CMS

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On behalf of the CMS Collaboration

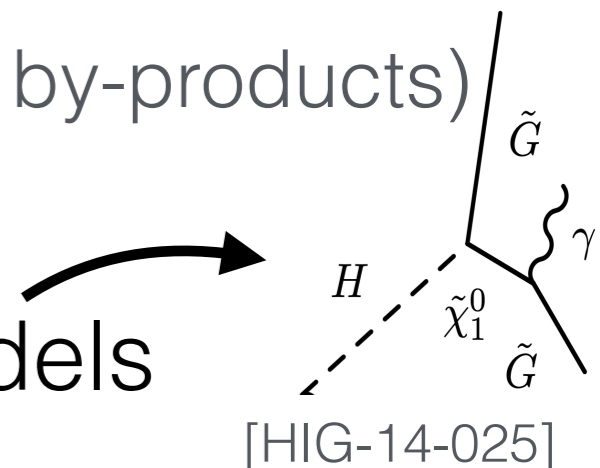
2021 LHC DM WG workshop

30 November 2021



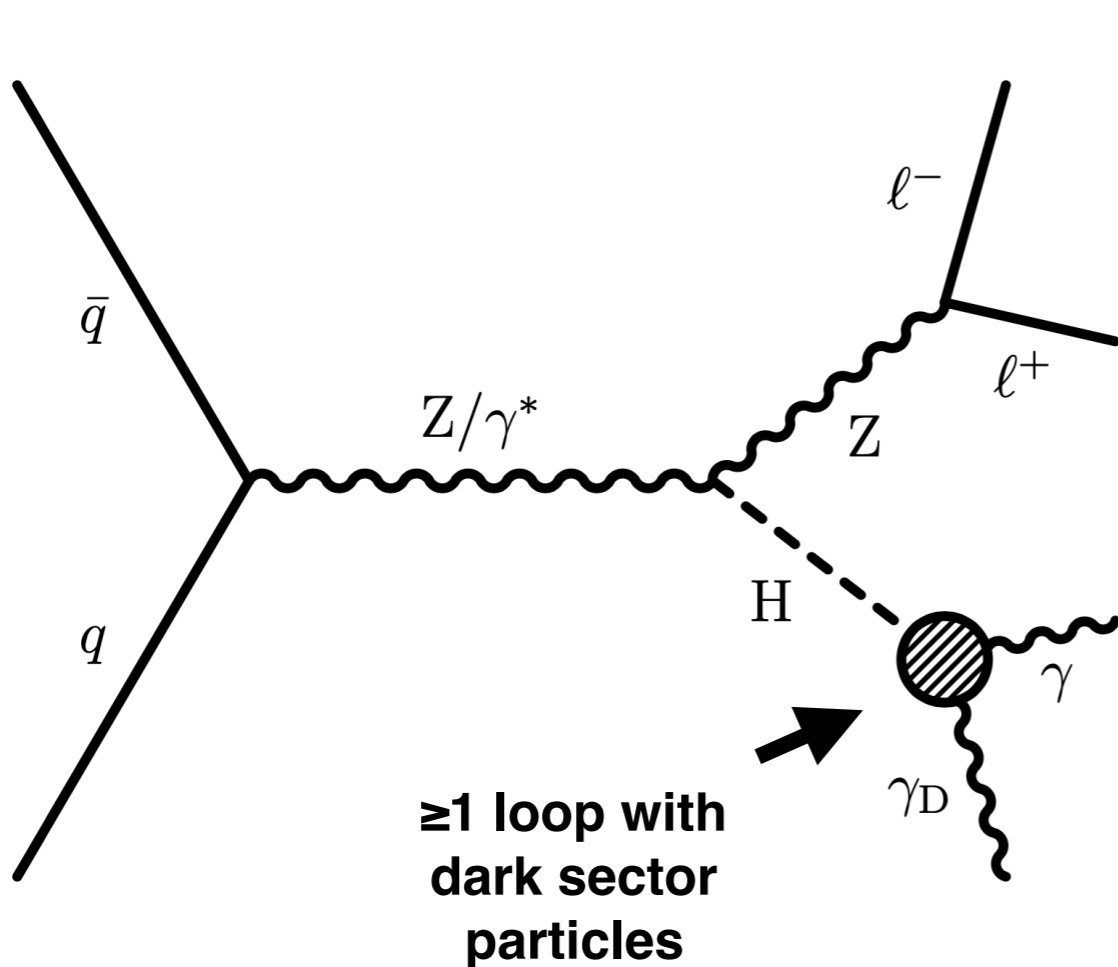
Dark photon searches

- A **dark photon**: A simple potential U(1) long-range mediator of a dark sector
- Proposed in several dark-sector BSM models (some of them really old)
- Could also help explain several open questions in cosmology (small-scale structure formation problems, PAMELA-Fermi-AMS2 positron anomaly, ...) [[1603.01377](#)]
- In HEP, decay channel **$H \rightarrow \gamma\gamma_D$** could help explain flavor hierarchy problem [[1310.1090](#)]
- Leads to a single photon + MET (+ H channel by-products) signature in the detector
- Signature γ +MET also for other types of models

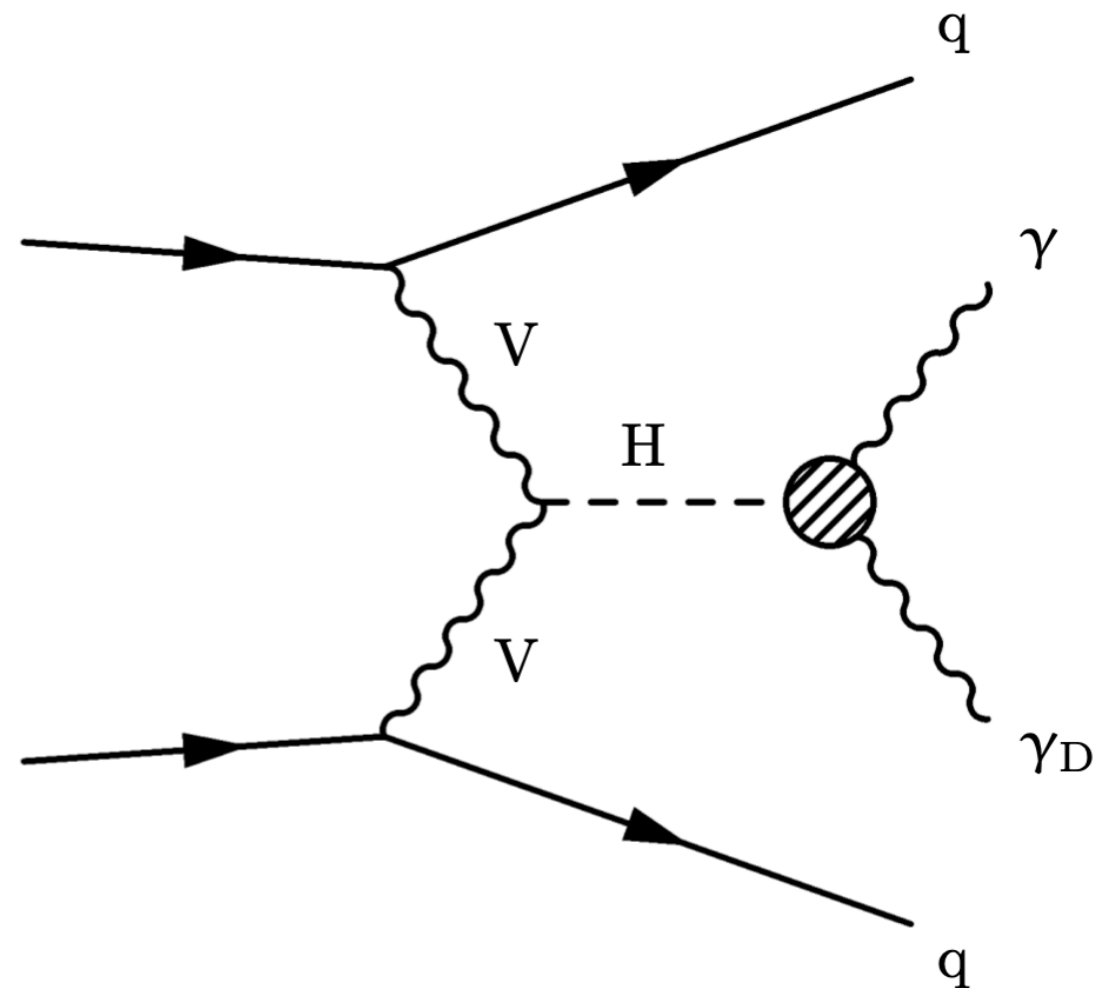


Dark photon searches

- Publications for two H production modes:



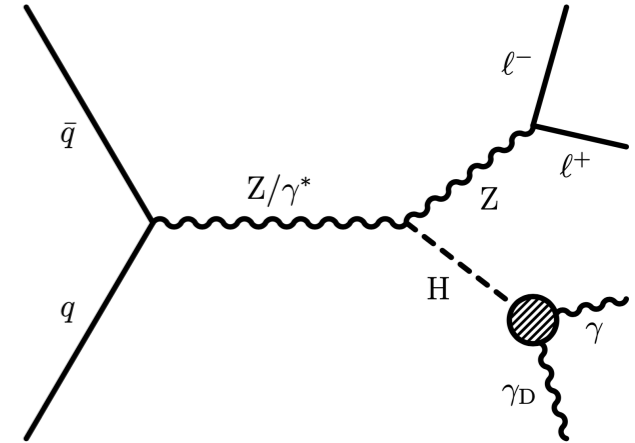
ZH; EXO-19-007
JHEP 10 (2019) 139



VBF; EXO-20-005
JHEP 03 (2021) 011

ZH \rightarrow $\Upsilon\Upsilon_D$

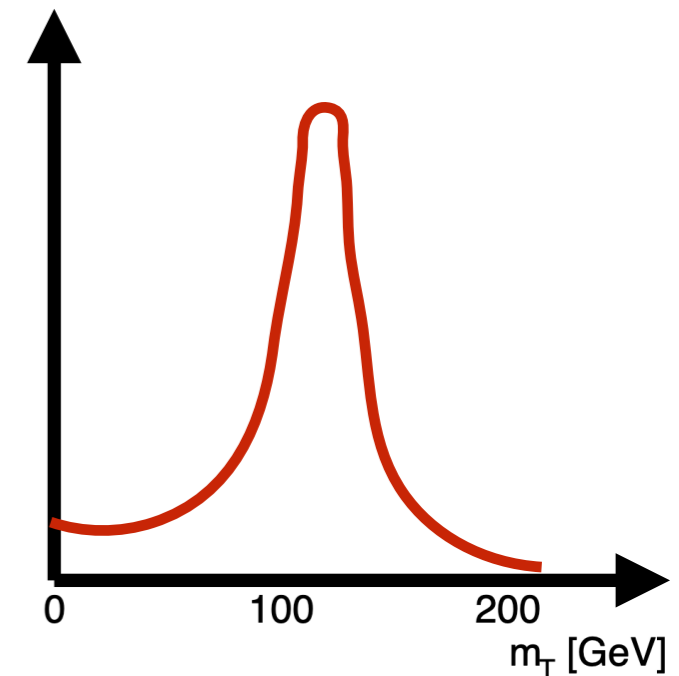
- **Final state:** 2 leptons (e/μ), 1 photon, MET
 - MET+ γ should be opposite to $\ell\ell$ system
 - $\ell\ell$ system should be compatible with Z
 - Little jet activity



- Bump (Jacobian peak) hunt in m_T of MET+ γ system, expected @ $m_T \sim m_H$

Main backgrounds:

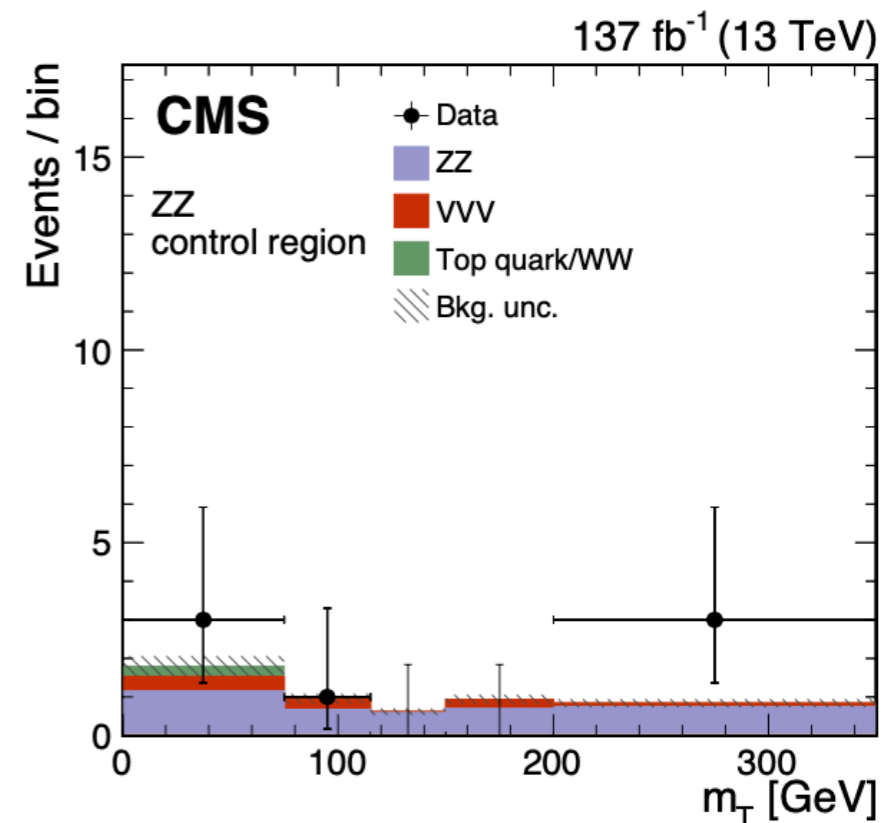
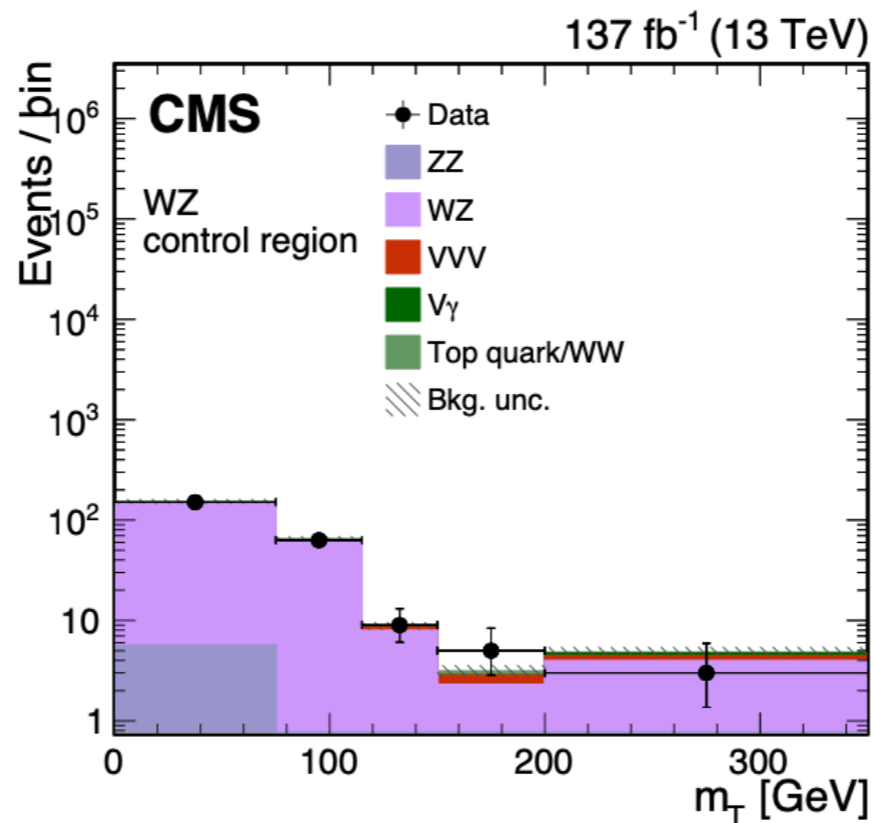
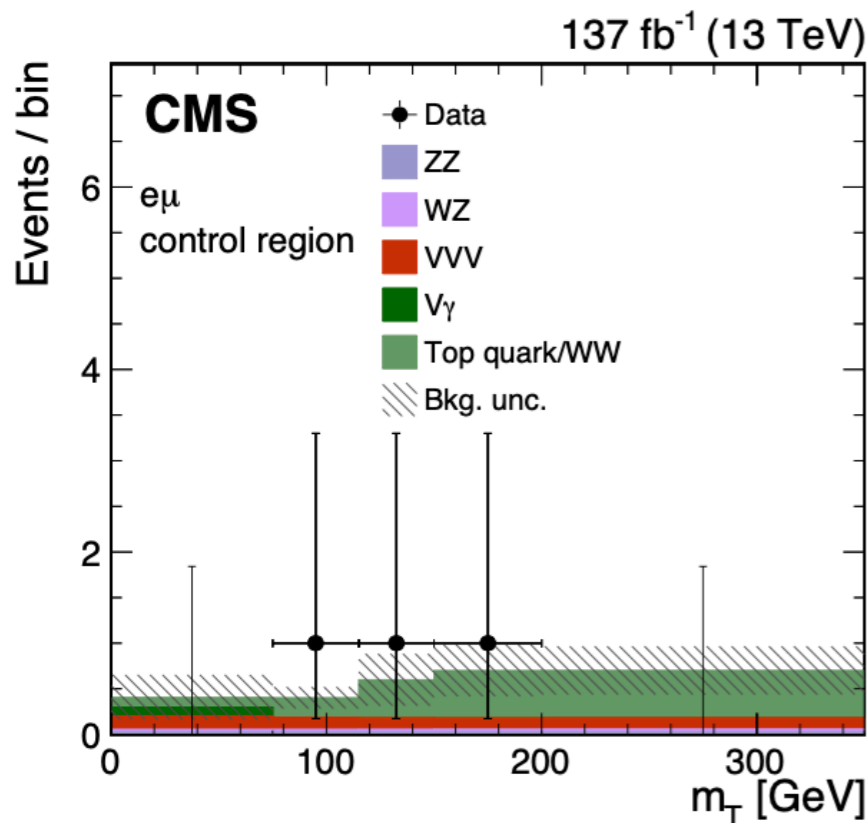
- **WZ**; e misidentified as γ
Reduce with medium lepton and photon ID & isolation
- **WW** and **top production**; non-resonant, real MET
Reduce by requiring low jet multiplicity, veto on b-quarks
- **Z γ** ; WZ γ /ZZ γ with missed lepton, or Z γ w/o real MET
Various kinematic cuts; enforce topology of MET+ γ balanced with $\ell\ell$ system in transverse plane, high MET, etc.

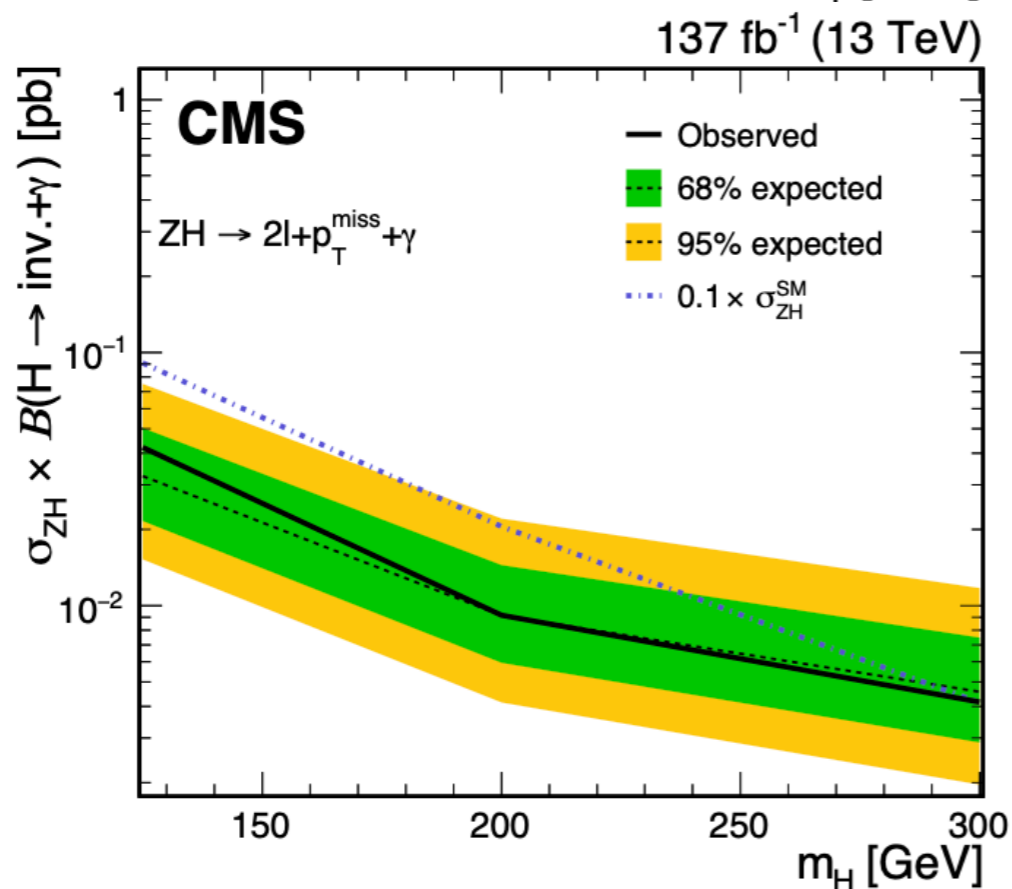
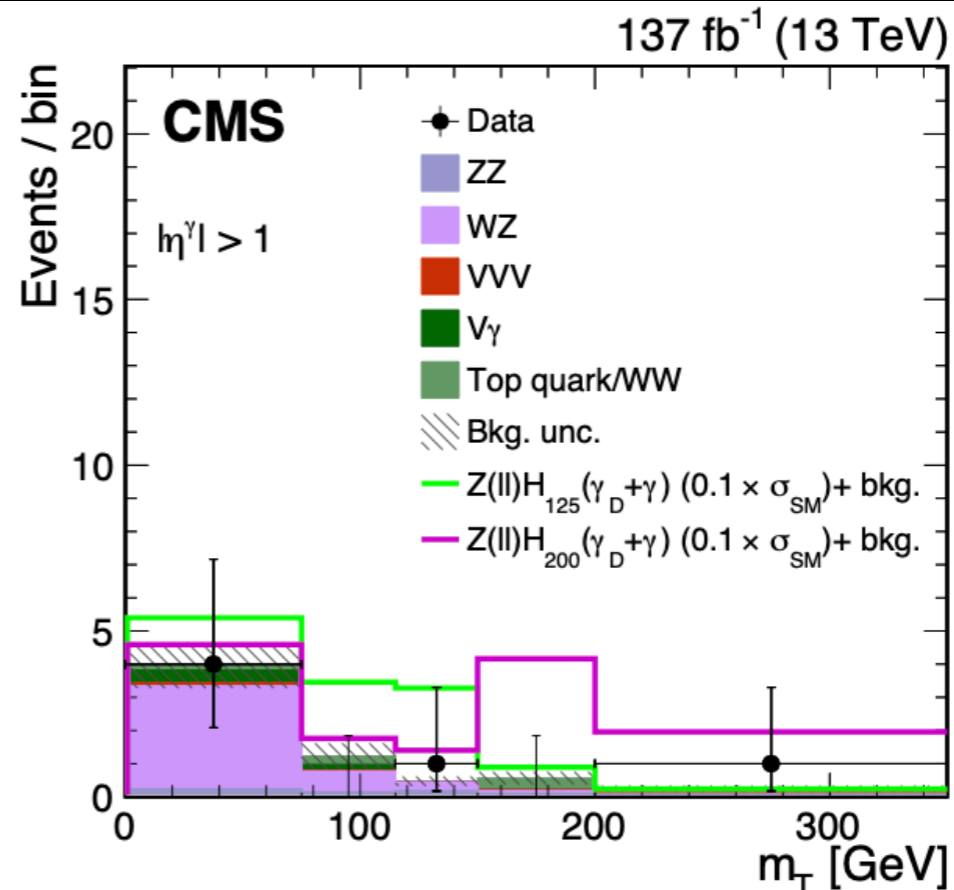
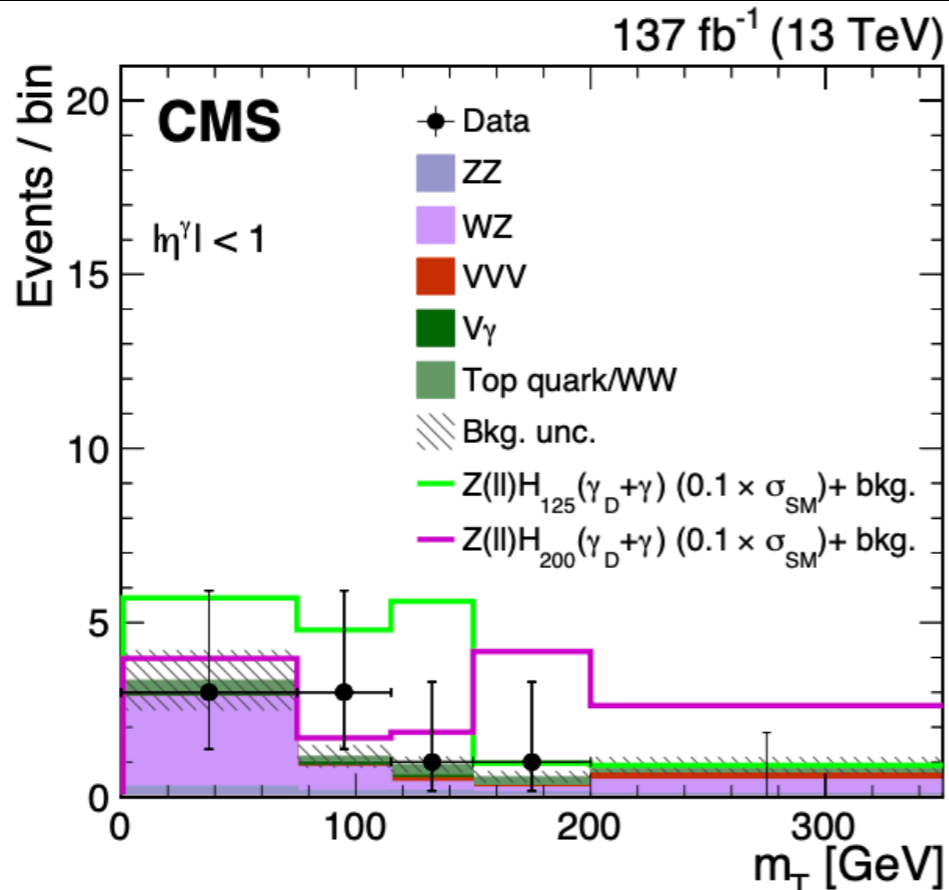


Background estimation

- Cleverly constructed control regions:

Region	Data	Prediction
$e\mu$: full selection, but $e\mu$ pairs	3	2.8 ± 0.5
WZ: replace photon by a third lepton	231	240.8 ± 3.8
ZZ: replace a photon by a dilepton pair	7	5.1 ± 0.2
WW: full selection, but $110 < m_{\ell\ell} < 200$ GeV	10	9.9 ± 1.8
B-tagged: full selection, but b-tagged event	4	8.7 ± 2.2
$Z\gamma$: loose selection	168	168.6 ± 17.8
WZ γ : 3 leptons and a photon	7	8.8 ± 1.3





@ $H = 125$ GeV:

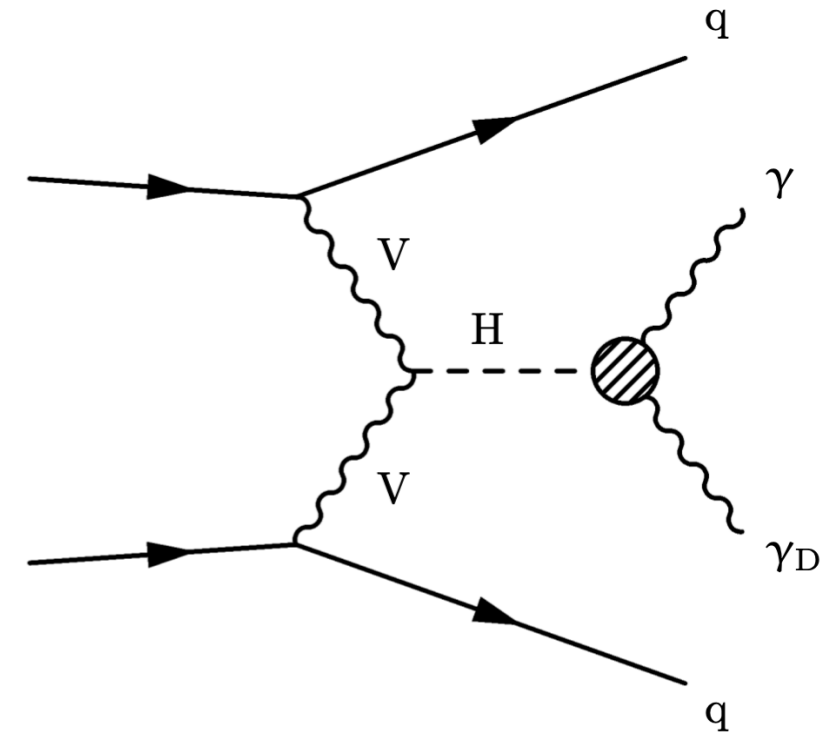
$B(H \rightarrow \text{invisible} + \gamma)$

< 4.6% (95% CL) Observed

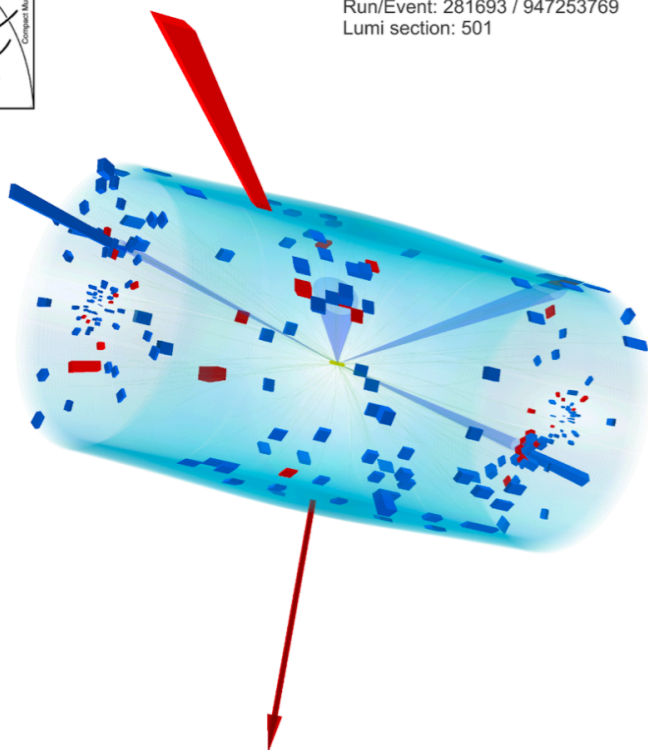
< 3.6% (95% CL) Expected

VBF $H \rightarrow \gamma\gamma_D$

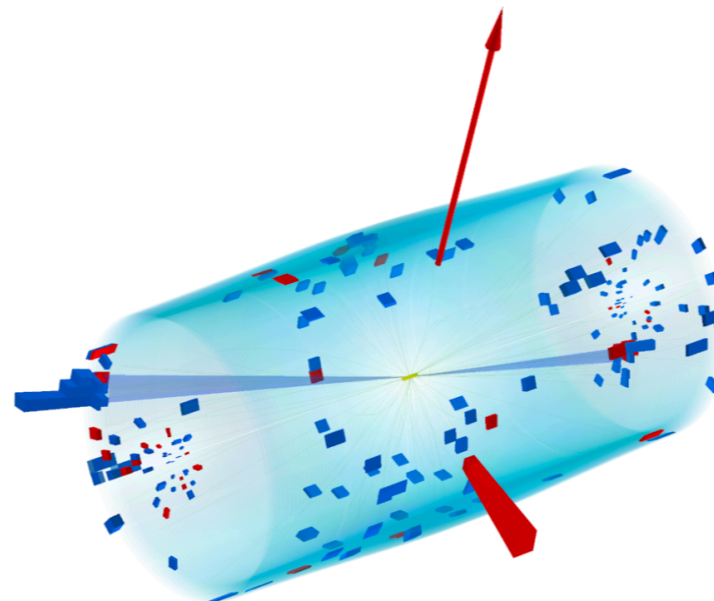
- Final state: 2 back-to-back jets, 1 γ , MET
- MET+ γ should be opposite to dijet system
- 2 jets have large $|\Delta\eta|$ and large dijet mass
- Event selection mostly enforcing VBF topology



CMS Experiment at LHC, CERN
Data recorded: Mon Sep 26 13:12:31 2016 PDT
Run/Event: 281693 / 947253769
Lumi section: 501



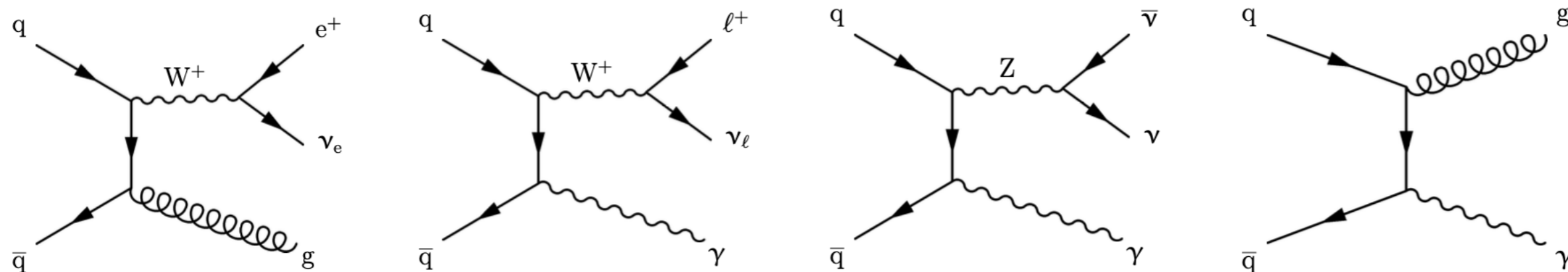
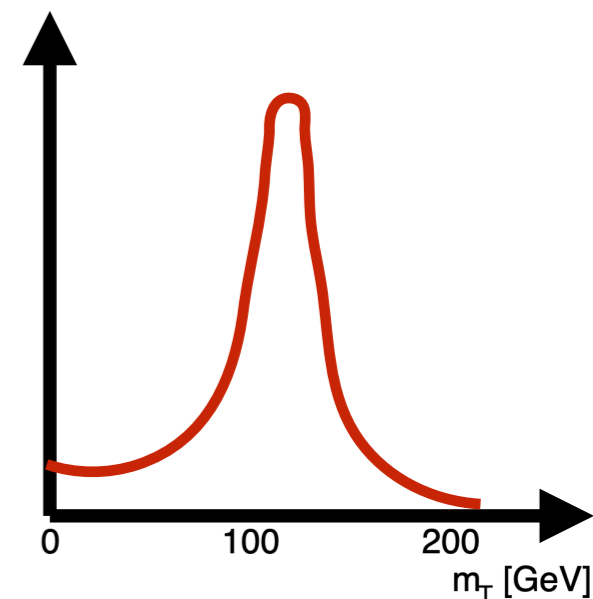
CMS Experiment at LHC, CERN
Data recorded: Wed Oct 19 16:20:18 2016 PDT
Run/Event: 283548 / 122756270
Lumi section: 198



Data-taking year	2016	2017/2018	
Trigger	VBF+ γ	Single-photon	p_T^{miss}
Number of photons		≥ 1 photon	
p_T^γ	> 80 GeV	> 230 GeV	> 80 GeV
Number of leptons		0	
$p_T^{j_1}, p_T^{j_2}$		> 50 GeV	
p_T^{miss}	> 100 GeV	> 140 GeV	> 140 GeV
Jet counting		2-5	
m_{jj}		> 500 GeV	
$ \Delta\eta_{jj} $		> 3.0	
η_{j_1}, η_{j_2}		< 0	
$\Delta\phi_{\text{jet}, \vec{p}_T^{\text{miss}}}$		> 1.0 radians	
z_γ^*		< 0.6	
p_T^{tot}		< 150 GeV	

VBF $H \rightarrow \gamma\gamma_D$

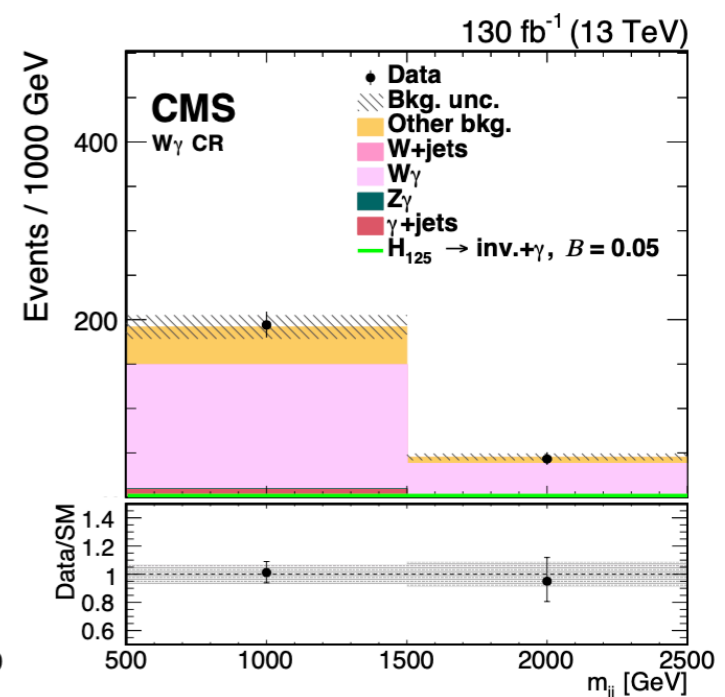
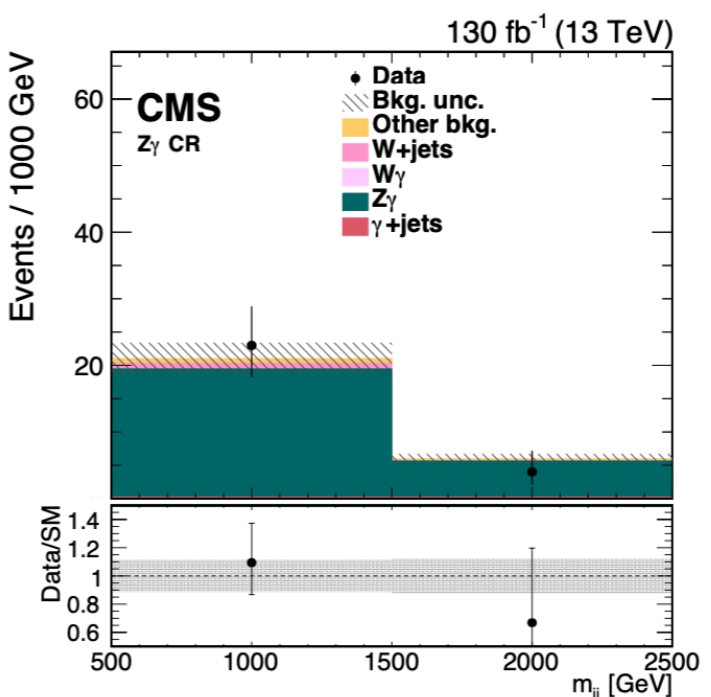
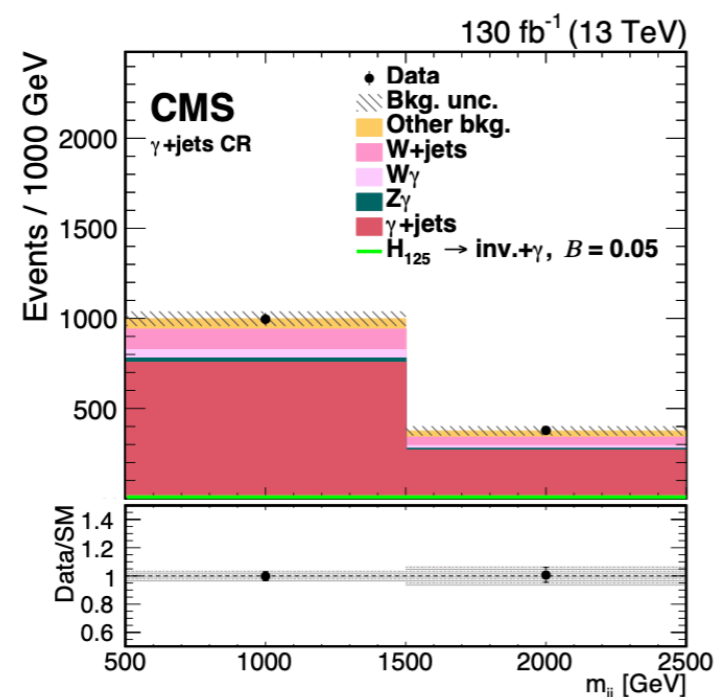
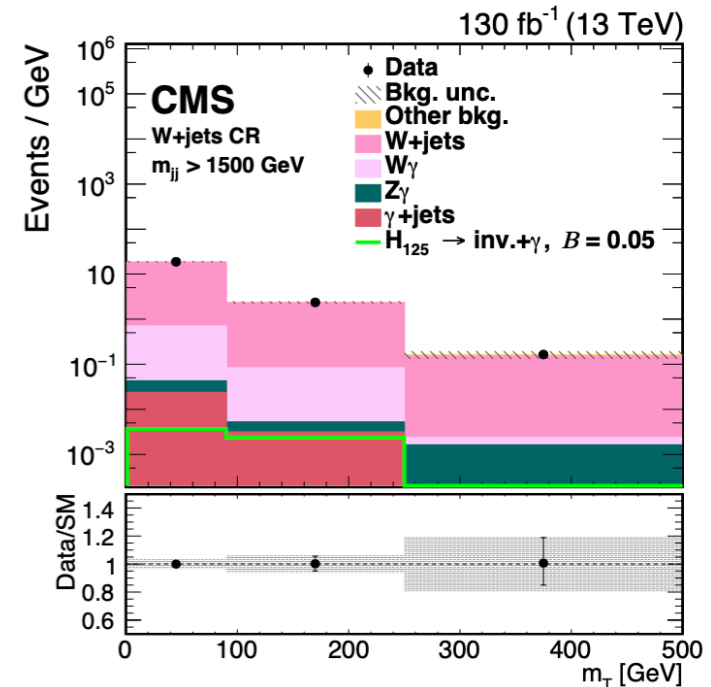
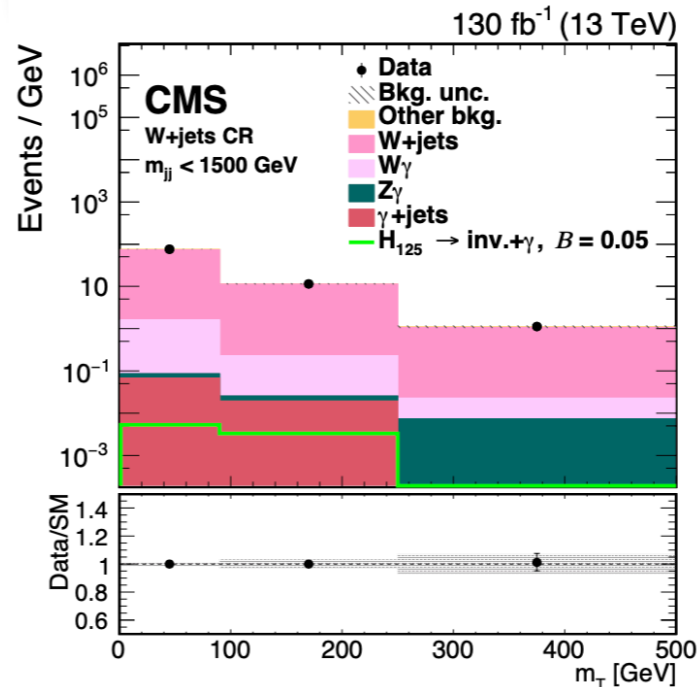
- Fit to m_T of MET+ γ system
 - A bump hunt at lower m_H
- Main **backgrounds**:
 - **Jets + $W(\rightarrow ev)$** ; $W \rightarrow ev$, e misID'd as γ
 - **Jets + γ + $Z(\rightarrow \nu\nu)$** ;
 - **Jets + γ + $W(\rightarrow lv)$** ; lepton from W out of acceptance
 - **Jets + γ + fake MET**;



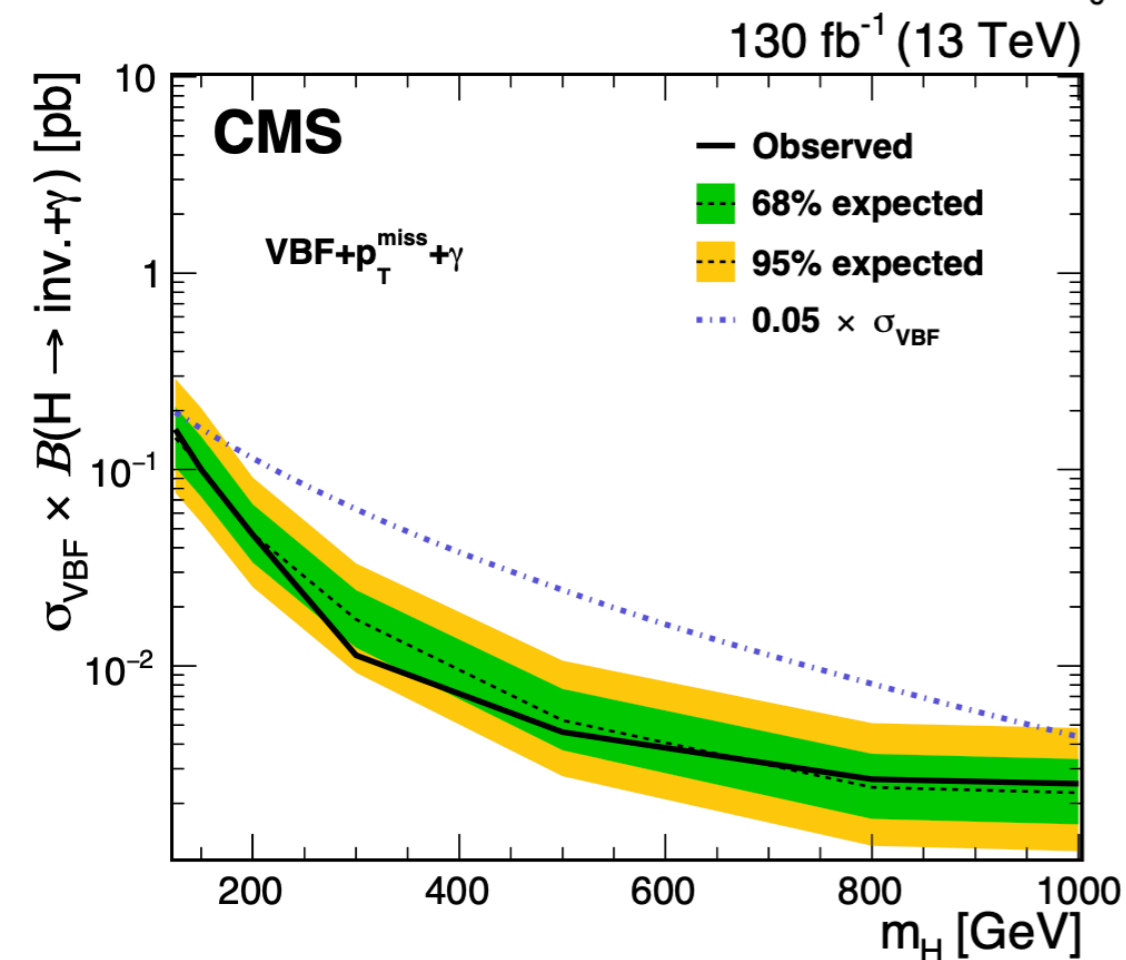
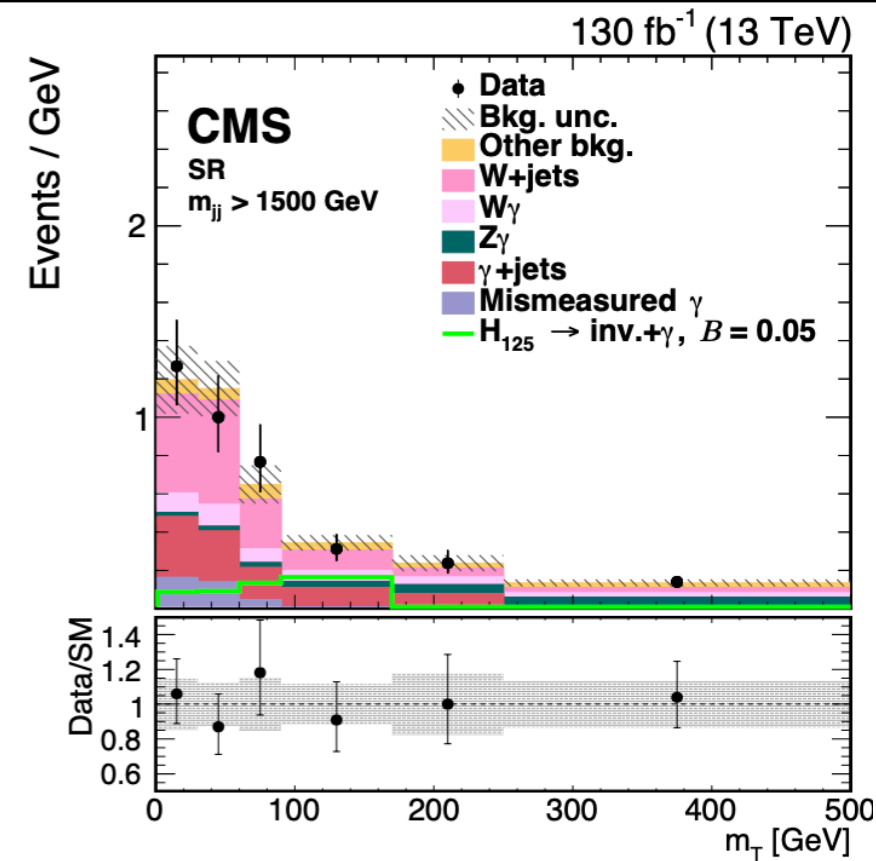
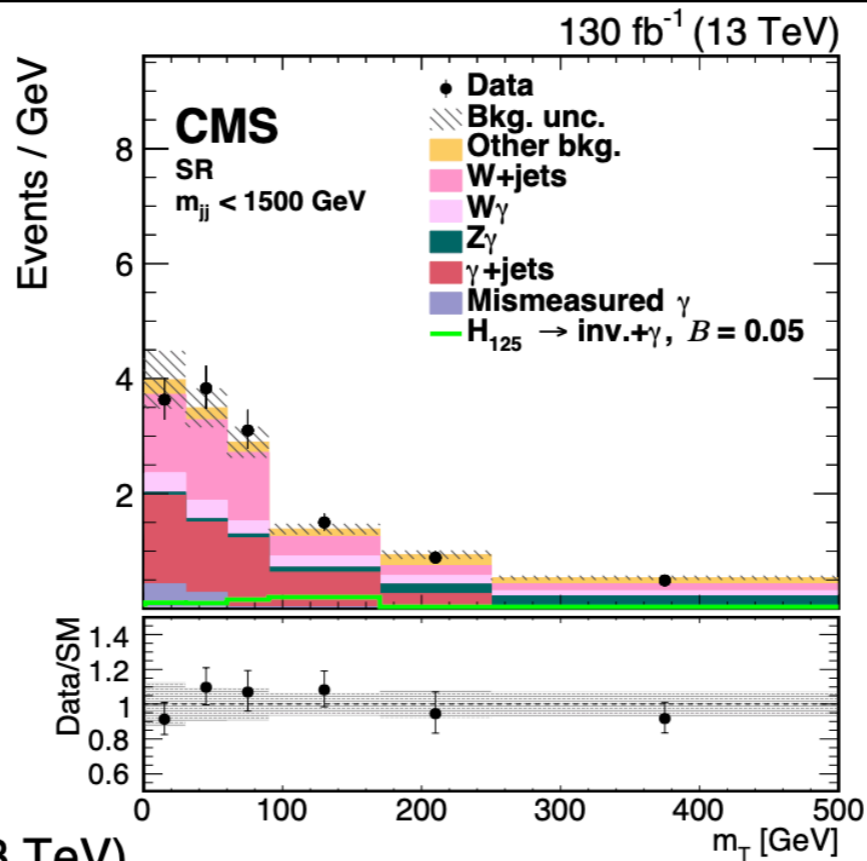
Background est.

- Similar idea, different regions
- Cleverly avoiding SR by tagging electrons and muons
- Remarkable agreement with data

- $W(\nu) + \text{jets}$ region: the full SR selection is applied, except that an electron must be selected and no photons found, and the electron is then used in place of the signal photon to build all kinematic variables.
- $Z(\mu^+\mu^-) + \gamma$ region: the full SR selection is applied, except that two muons must be selected together with a photon, and the $\Delta\phi_{\text{jet}, \vec{p}_T^{\text{miss}}}$ requirement is not considered. The muons are added to \vec{p}_T^{miss} to emulate the signal topology.
- $W(\mu\nu) + \gamma$ region: the full SR selection is applied, but a muon must be selected together with a photon, and the muon is added to \vec{p}_T^{miss} to emulate the signal topology.
- $\gamma + \text{jets}$ region: the full SR selection is applied, but $\Delta\phi_{\text{jet}, \vec{p}_T^{\text{miss}}}$ must be < 0.5 .



- Further constraining the possible branching of $H \rightarrow \gamma\gamma_D$:

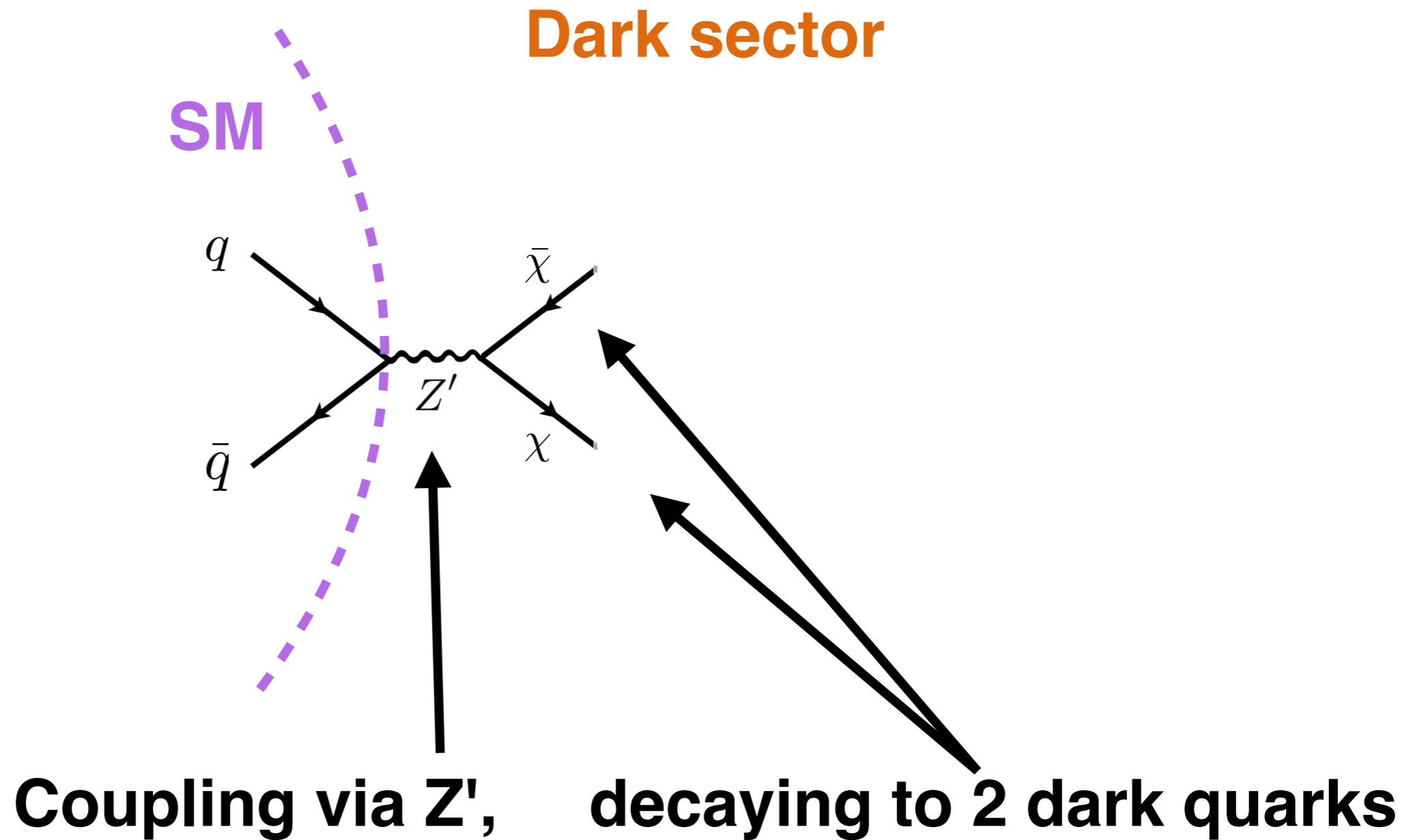


@ $H = 125$ GeV:
 $B(H \rightarrow \text{invisible} + \gamma)$

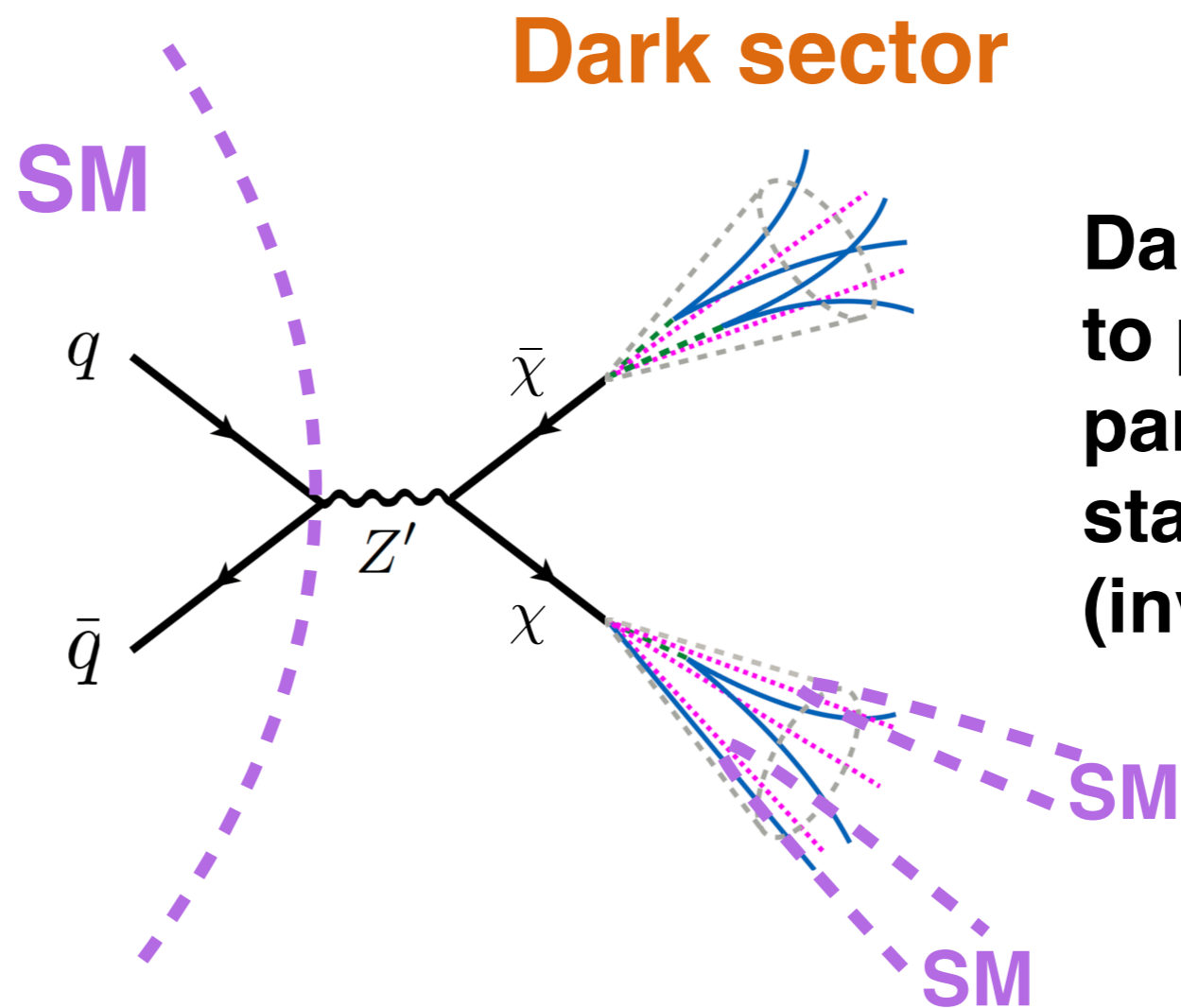
VBF		ZH		VBF+ZH	
Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)
3.5	$2.8^{+1.3}_{-0.8}$	4.6	$3.6^{+2.0}_{-1.2}$	2.9	$2.1^{+1.0}_{-0.7}$

Semi-visible jets

Switching gears...

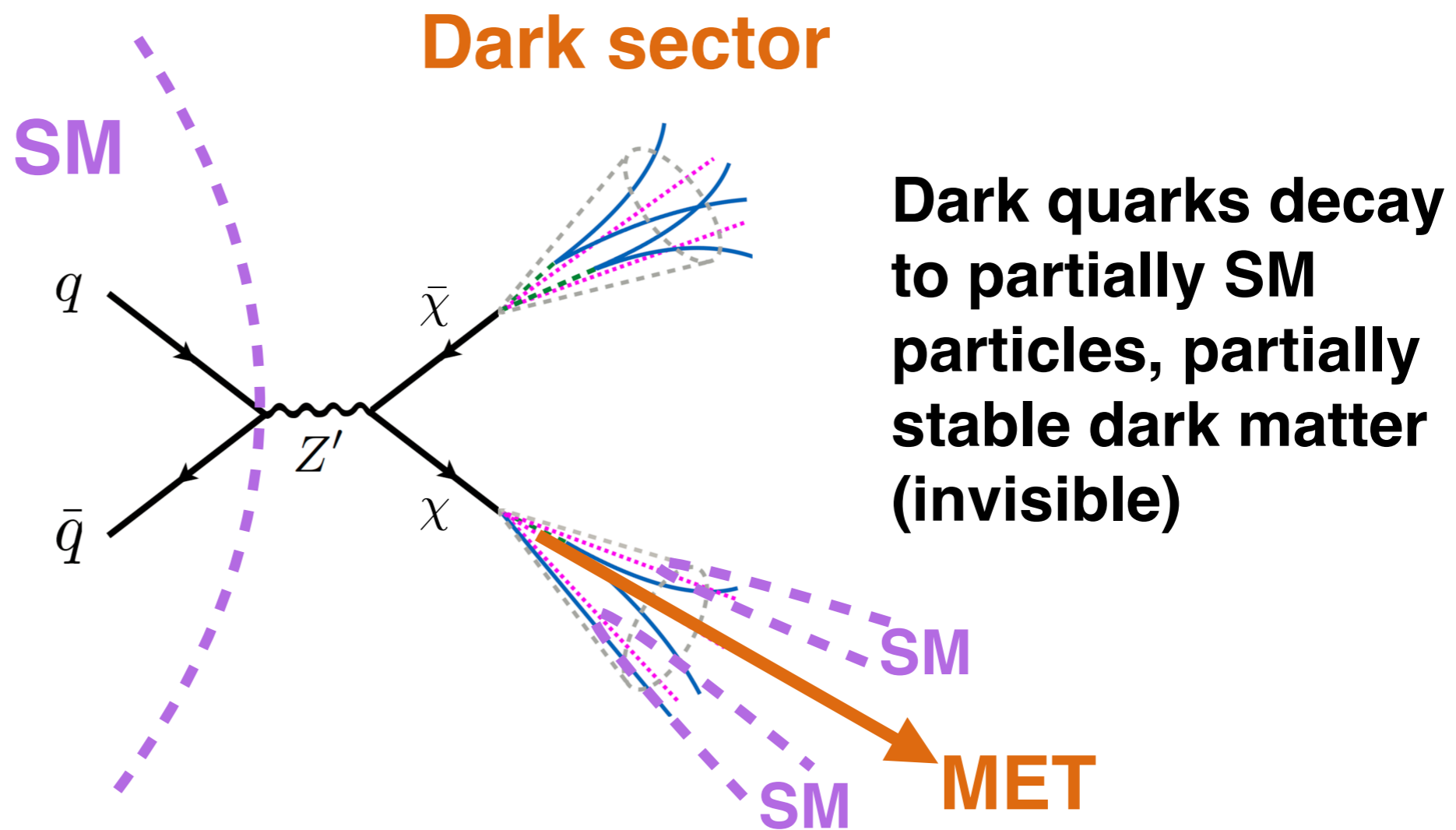


Semi-visible jets



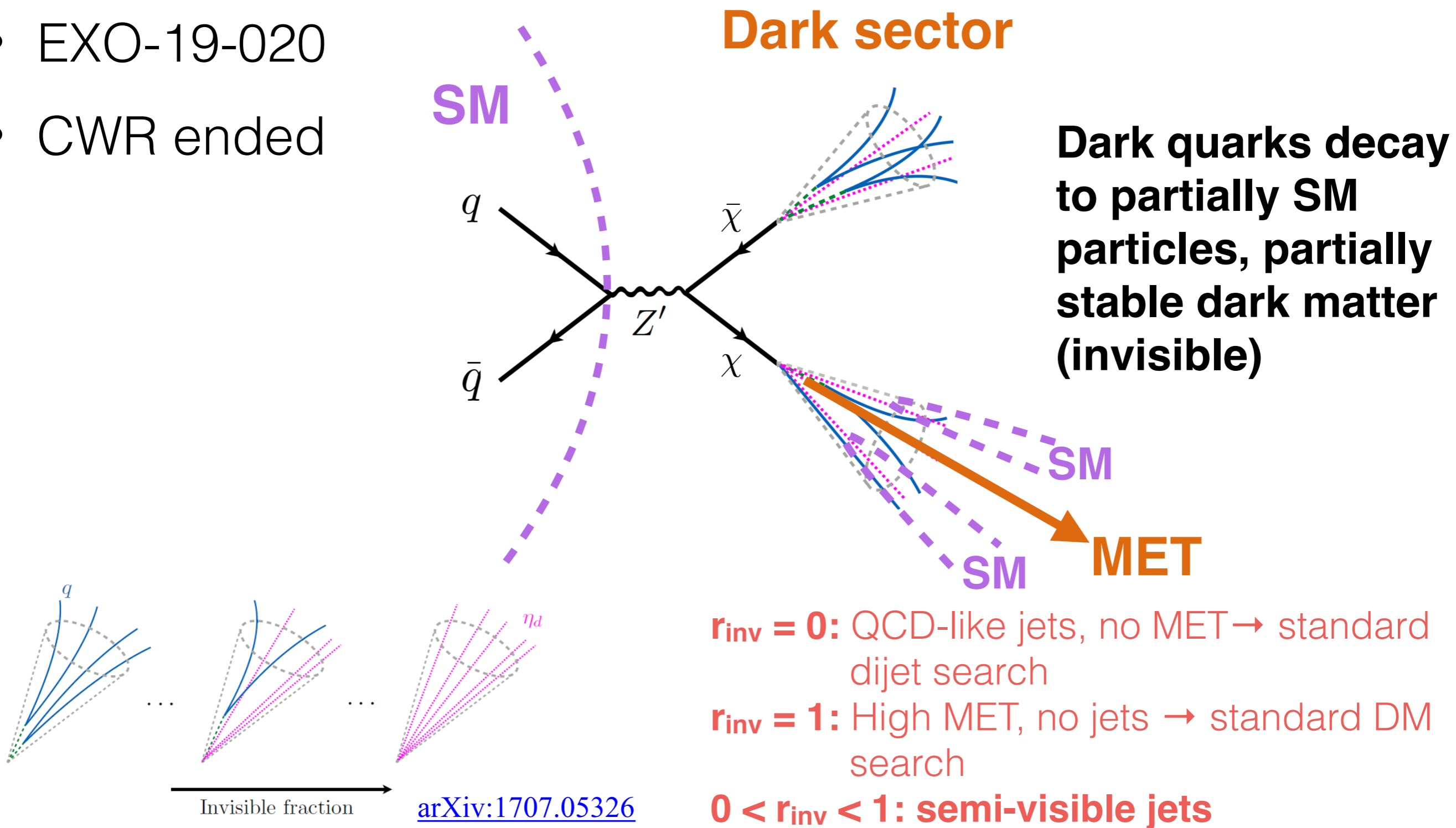
Dark quarks decay to partially SM particles, partially stable dark matter (invisible)

Semi-visible jets



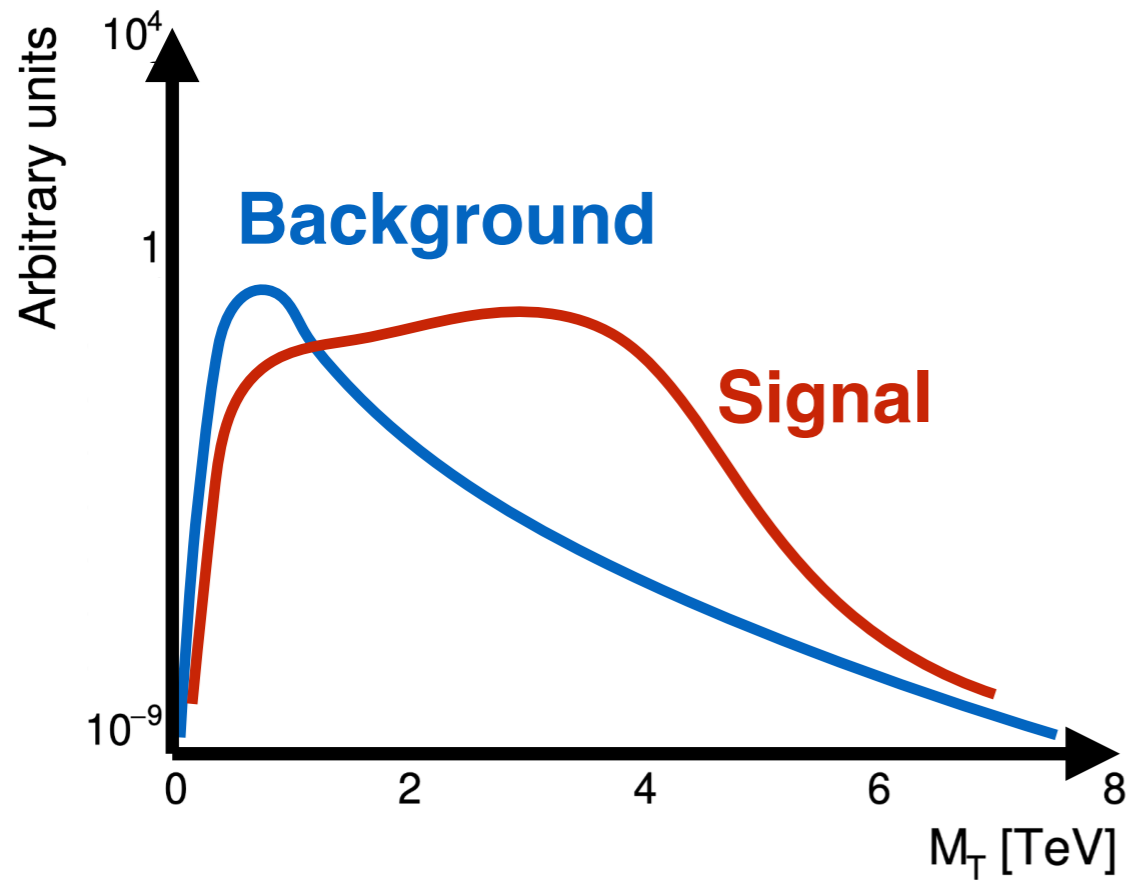
Semi-visible jets

- Precisely a signature that is not looked for by other searches
- EXO-19-020
- CWR ended



EXO-19-020: High mass Z' analysis

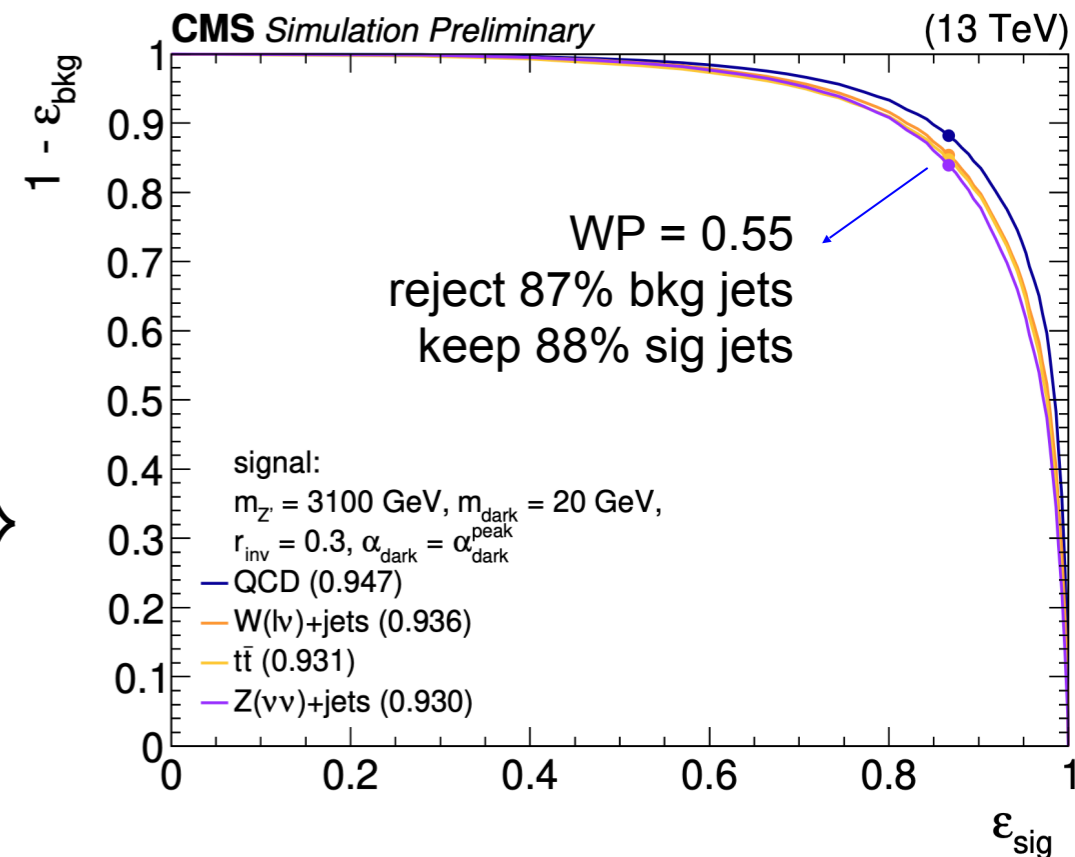
- **Bump hunt:** $M_T^2 = \left(\text{MET} + \sqrt{p_{T, \text{dijet}}^2 + m_{\text{dijet}}^2} \right)^2 - (\text{MET}_x + p_{x, \text{dijet}})^2 - (\text{MET}_y + p_{y, \text{dijet}})^2$



- M_T seemingly best resolution (better than M_{JJ})
- Smoothly falling background
- Kinematic edge @ $M_T \sim m_{Z'}$

- Combine jet substructure variables in **BDT**

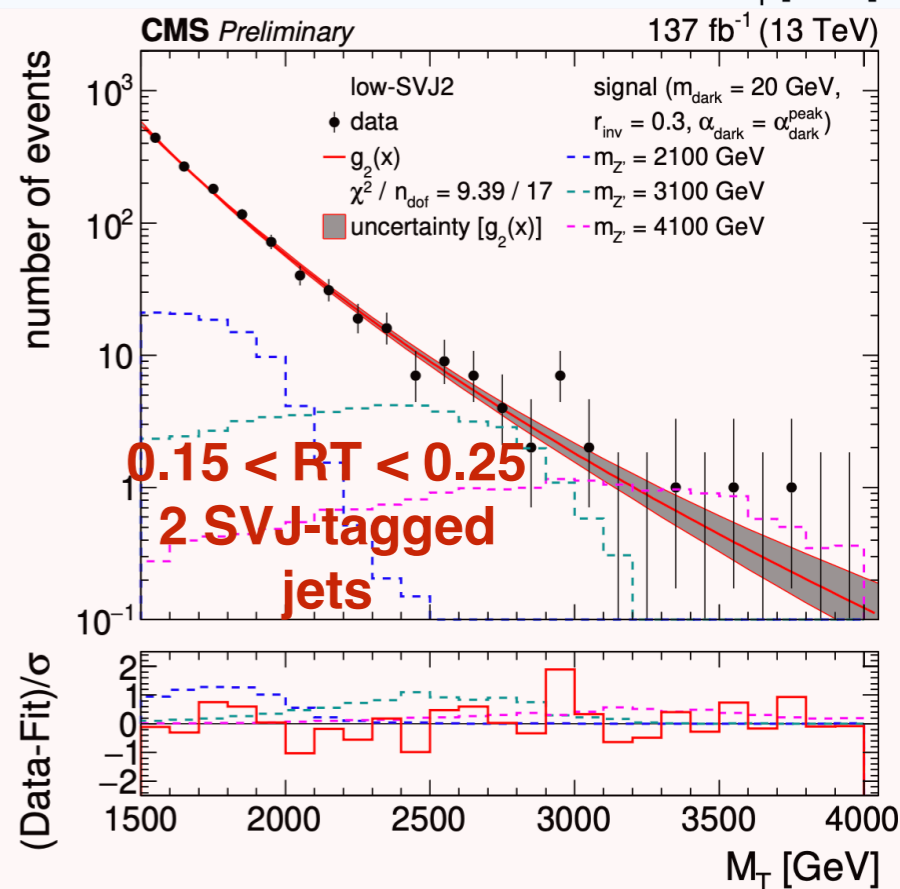
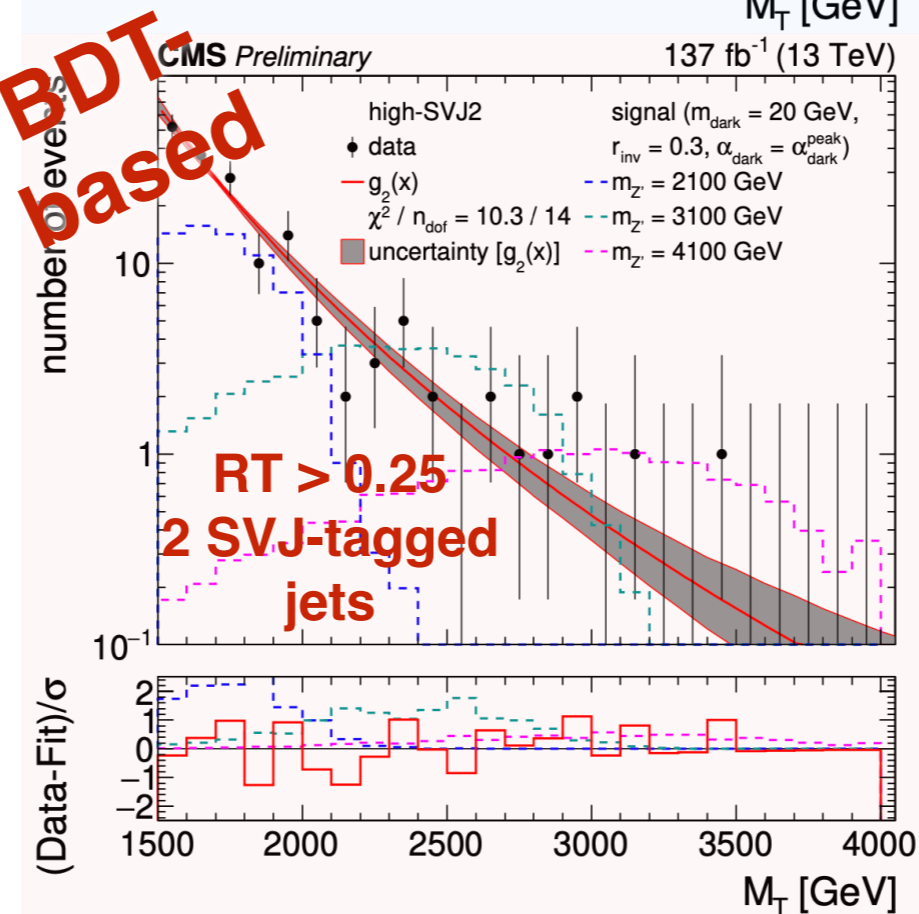
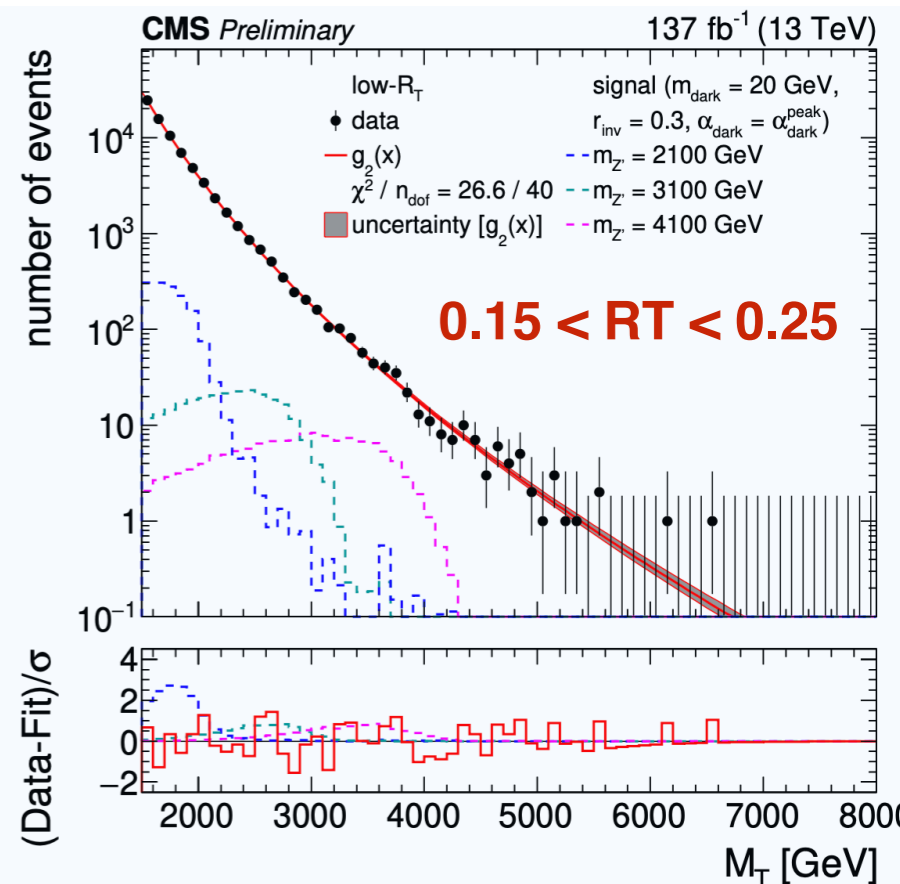
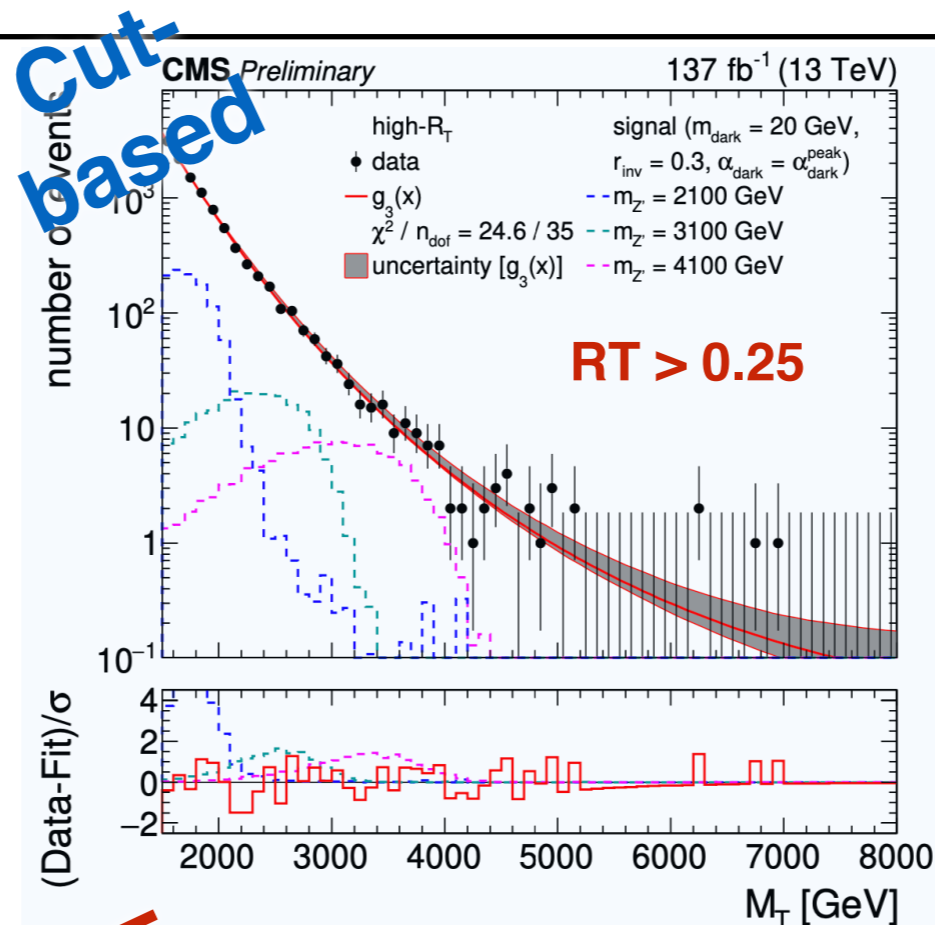
Heavy-object tagging
Quark-gluon discrimination
Flavor

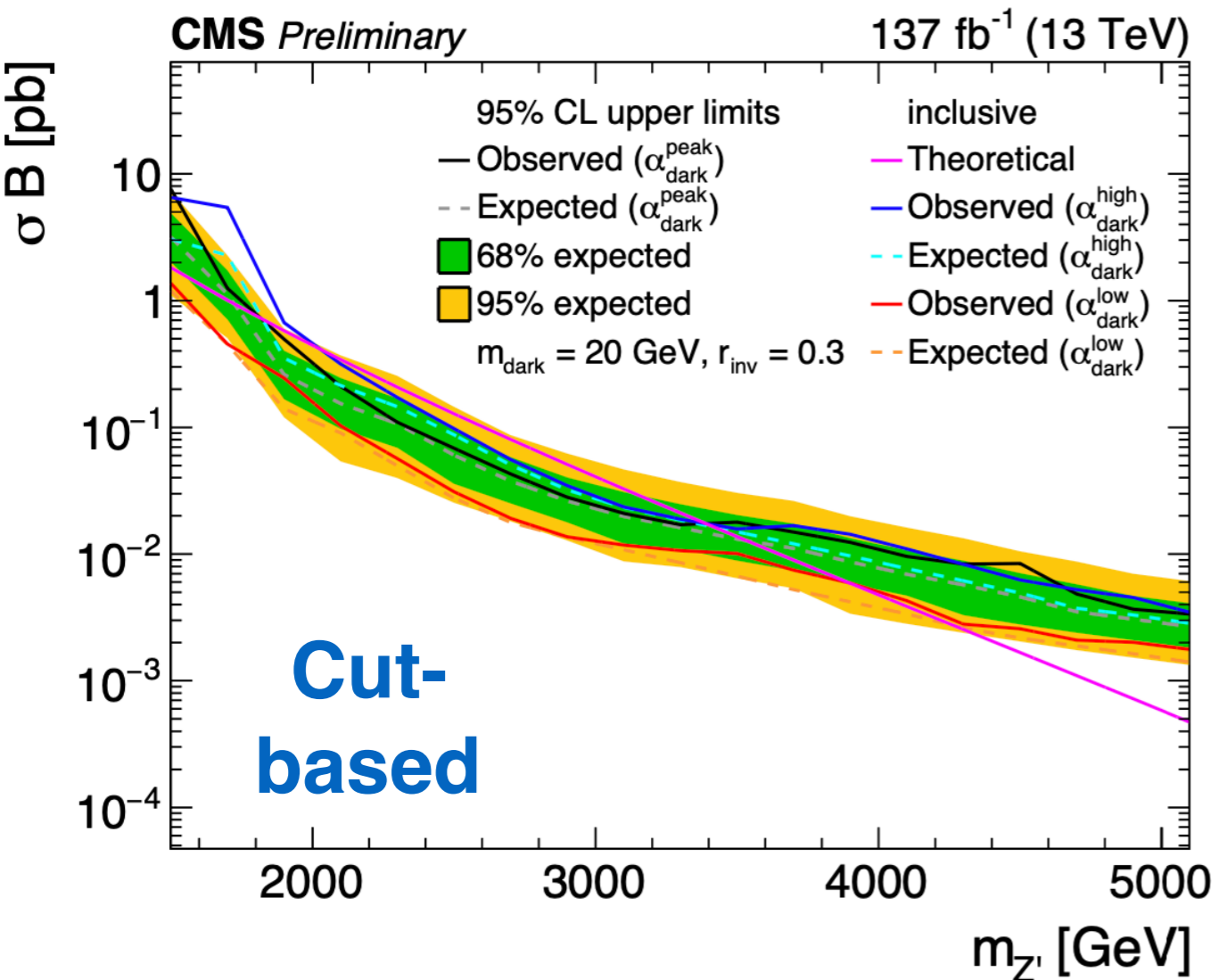


Fit strategy

$$R_T = \frac{\text{MET}}{M_T}$$

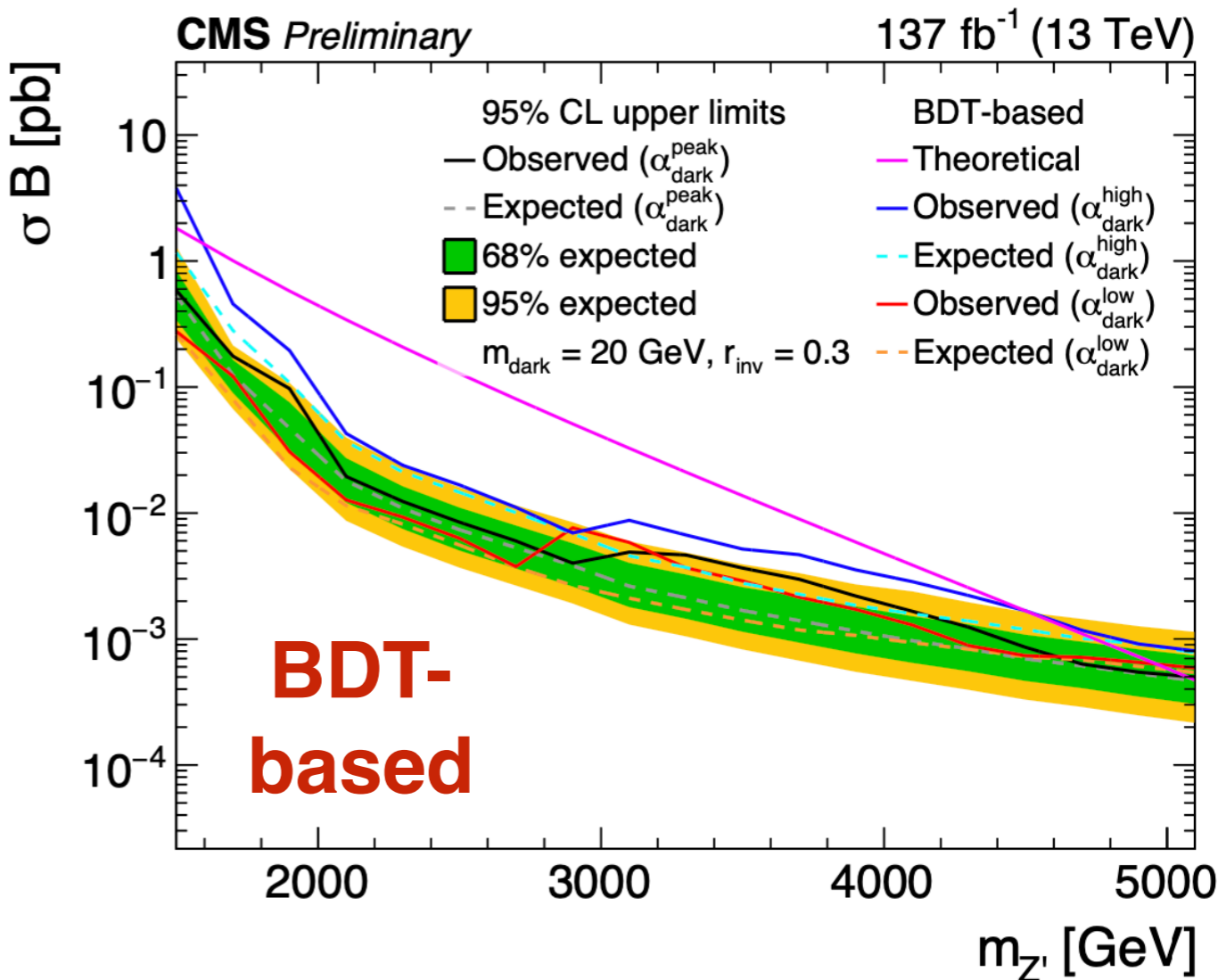
- **$RT > 0.25$** has optimal significance when doing a **cut-based search**
- adding $0.15 < RT < 0.25$ improves expected limit
- BDT-based subset of cut-based, **require 2 SVJ-tagged jets**





exclude

$1.5 < m_{z'} < 3.9 \text{ TeV}$
 $0.08 < r_{\text{inv}'} < 0.53$

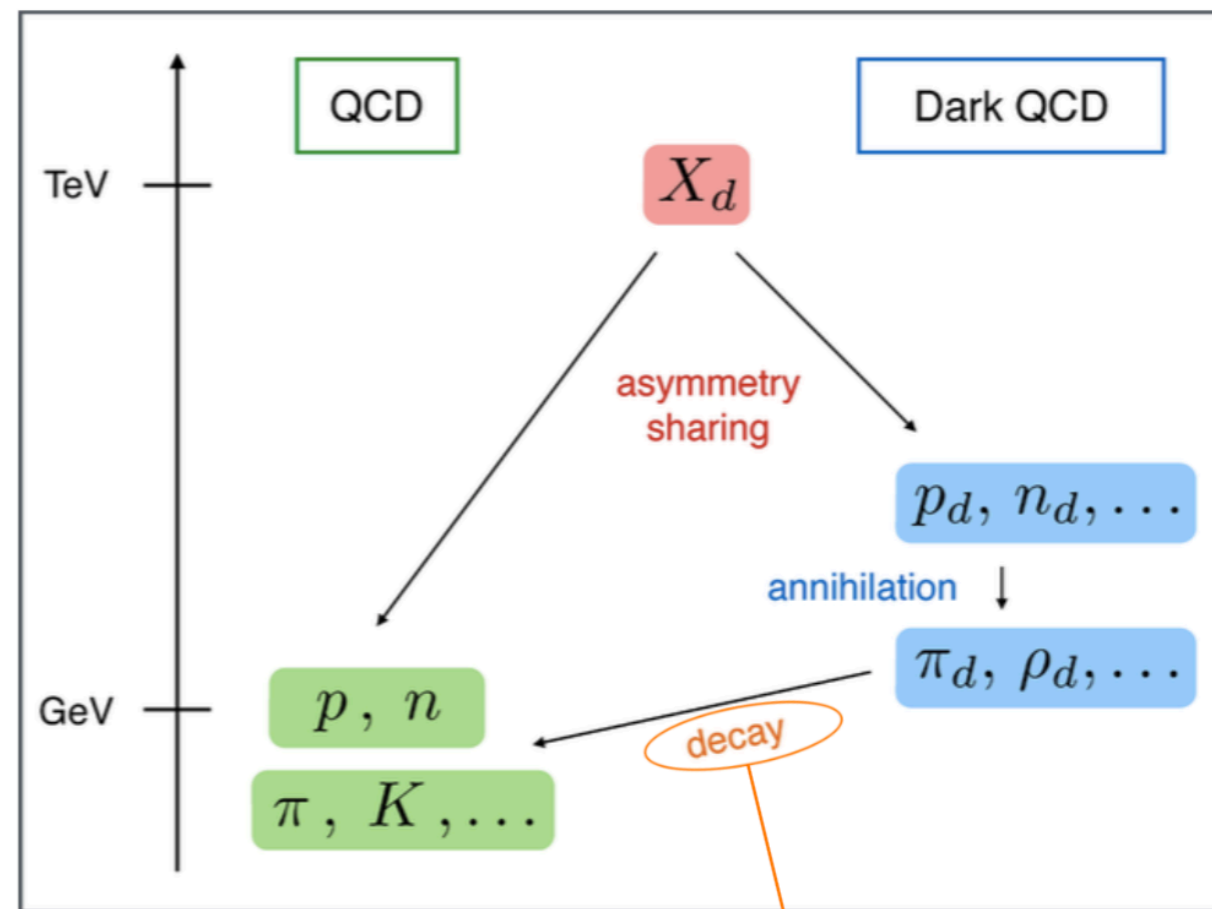
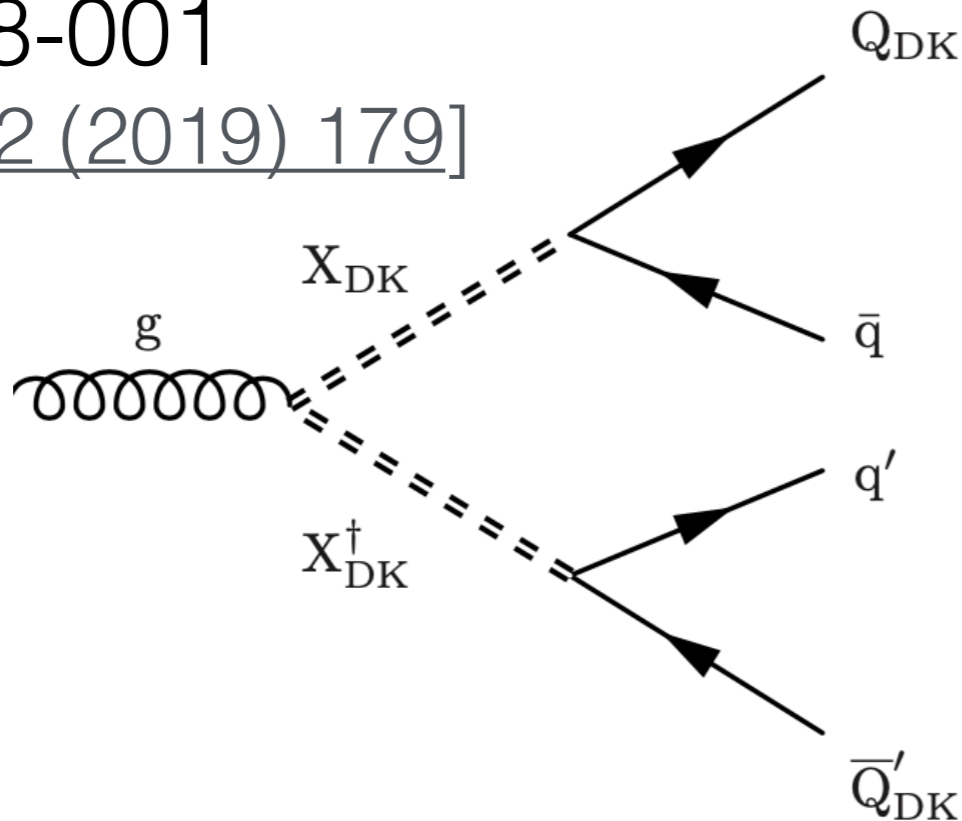


exclude

$1.5 < m_{z'} < 5.1 \text{ TeV}$
 $0.01 < r_{\text{inv}} < 0.77$

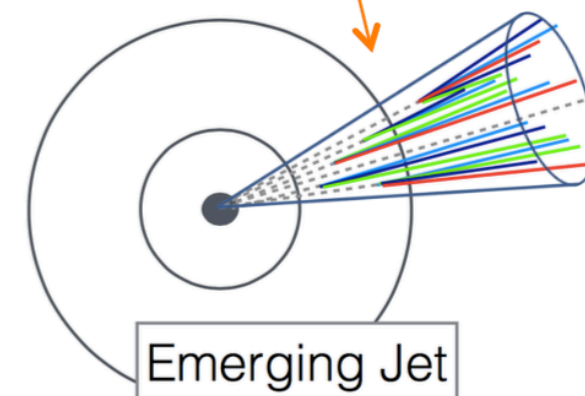
Emerging jets

- EXO-18-001
[[JHEP 02 \(2019\) 179](#)]



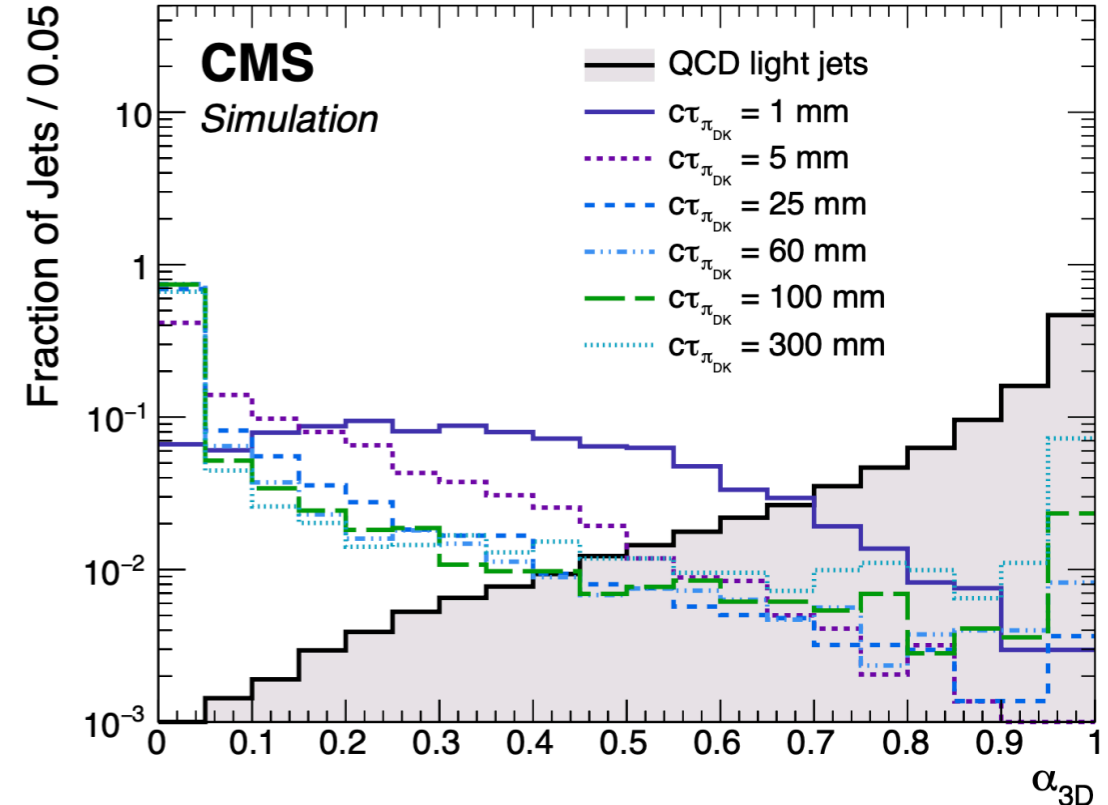
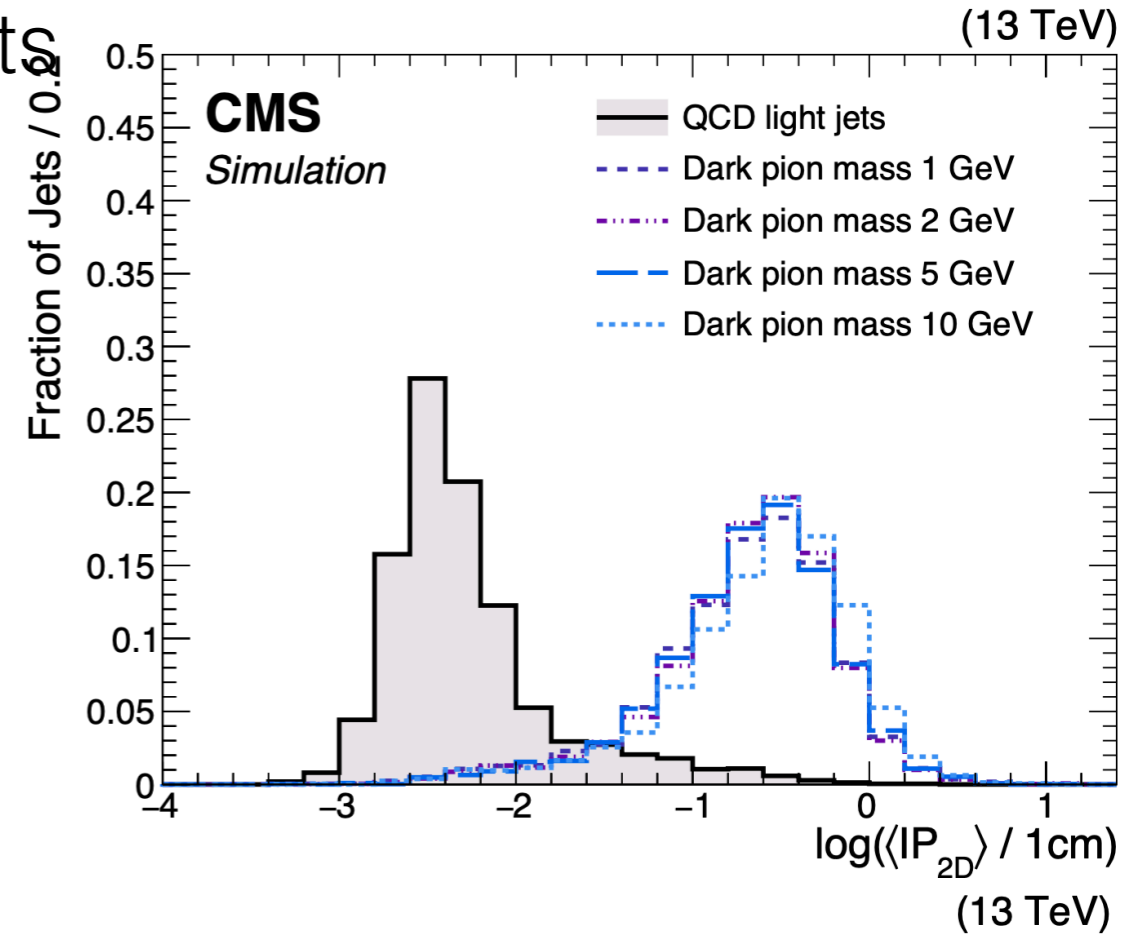
- Long decay chain via a dark QCD model [[1502.05409](#)]

- Hadronization of a dark quark that decays back to SM particles
- Sub-jet axes point out radially from collision points
- 2 ordinary jets, 2 emerging jets with many displaced vertices
- Some intermediate dark hadrons have medium-long lifetime



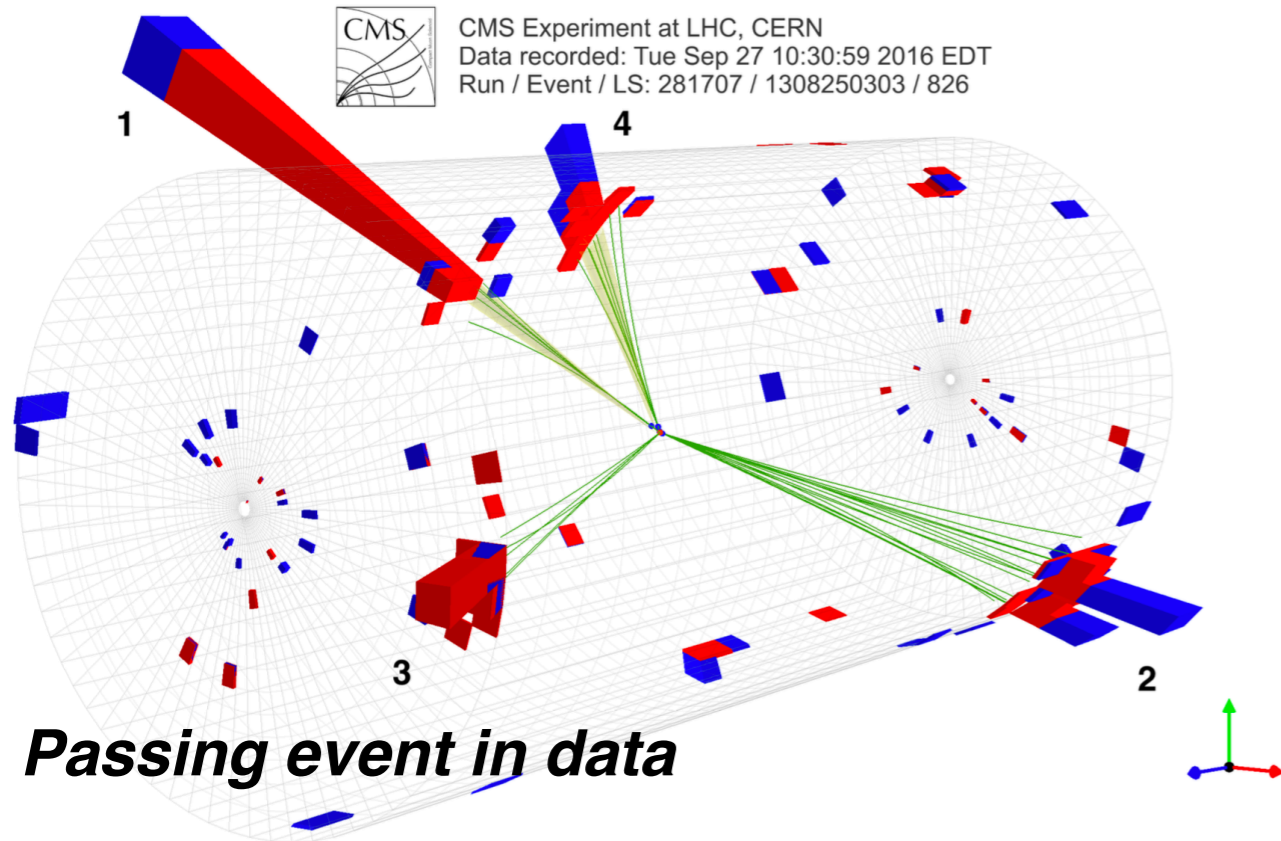
Emerging jets

- Signature: 2 ordinary jets, 2 emerging jets
 - Sub-jet axes point out radially from collision points
 - Emerging jets have many displaced vertices
 - If decay lengths \sim size of detector: MET
- Main background: **SM four-jet production**
 - MET from jet mismeasurement
 - **fake emerging jets** from long-lived B mesons or track misreconstruction
 - Control region: **γ + jets**
- Cut & count analysis with multiple signal regions



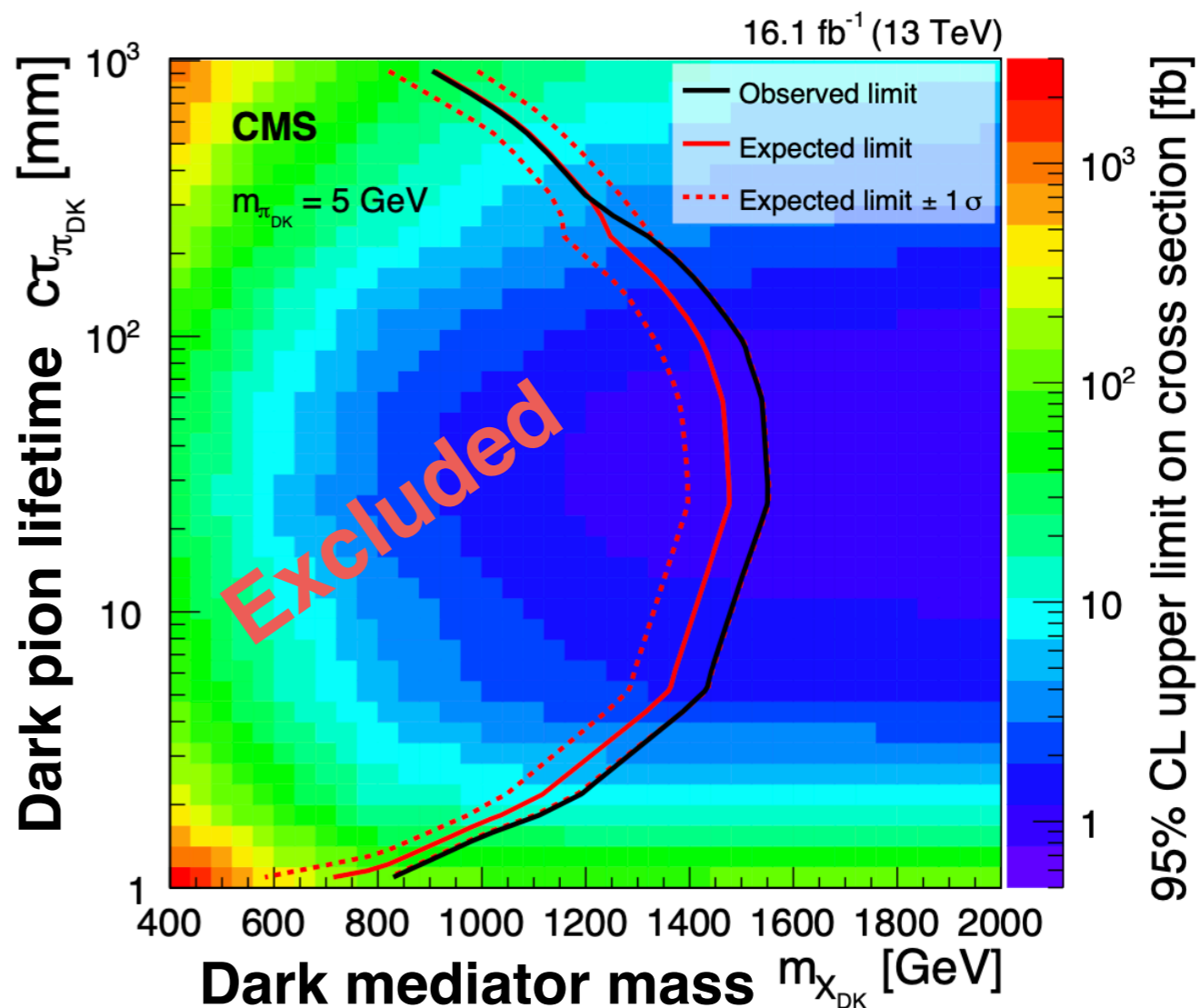


CMS Experiment at LHC, CERN
 Data recorded: Tue Sep 27 10:30:59 2016 EDT
 Run / Event / LS: 281707 / 1308250303 / 826

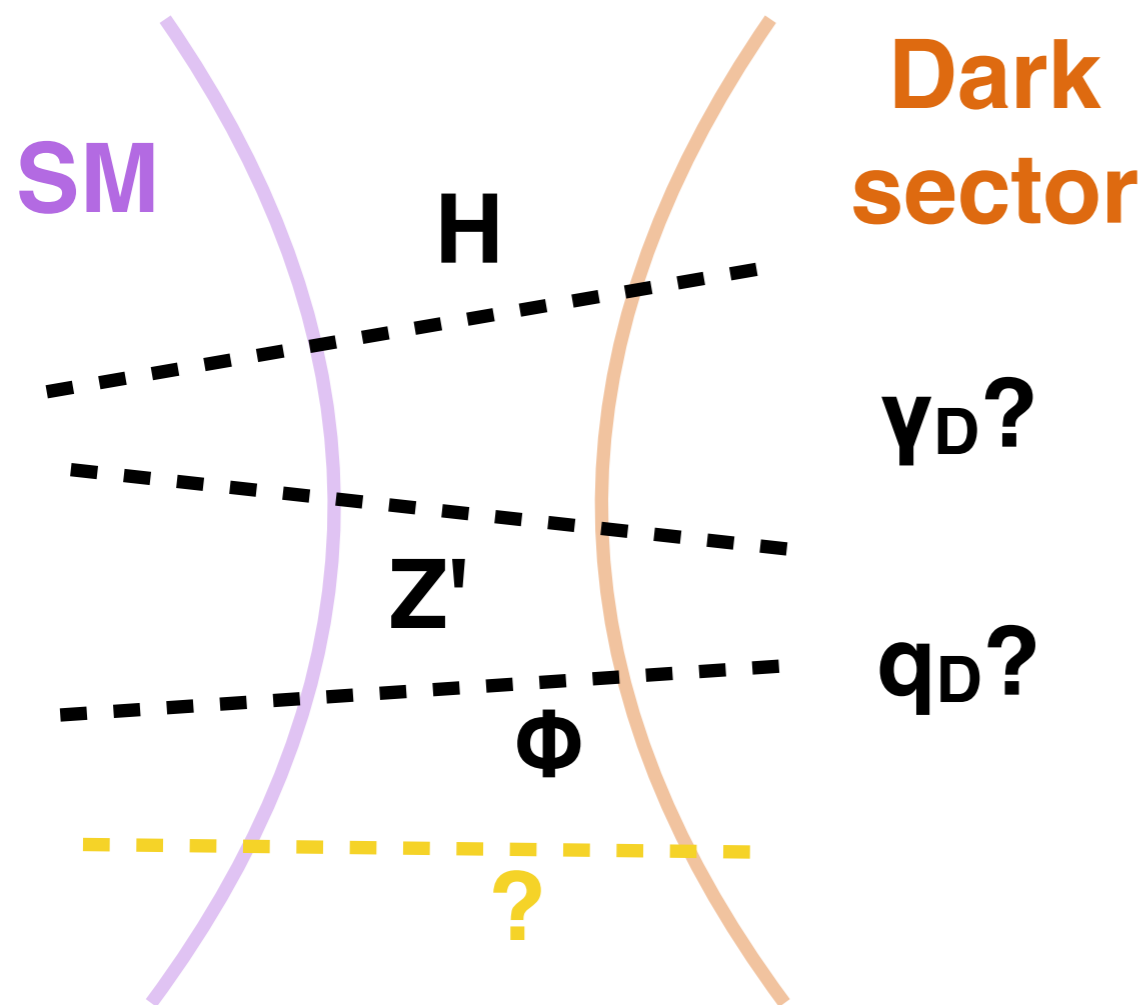


Passing event in data

- No deviation from SM observed
- First experimental limits on a QCD model with emerging jets



Conclusion



- So far no evidence of a dark sector!
- Is there a portal, and can we see it?

- In this talk, covered potential final states with a dark photon, semi-visible jets, and emerging jets
- Lots of space still for the dark sector to hide in
- Exciting field to keep an eye on

Backup

SVJ 2D limit plots

