

Dark Sector Searches in CMS

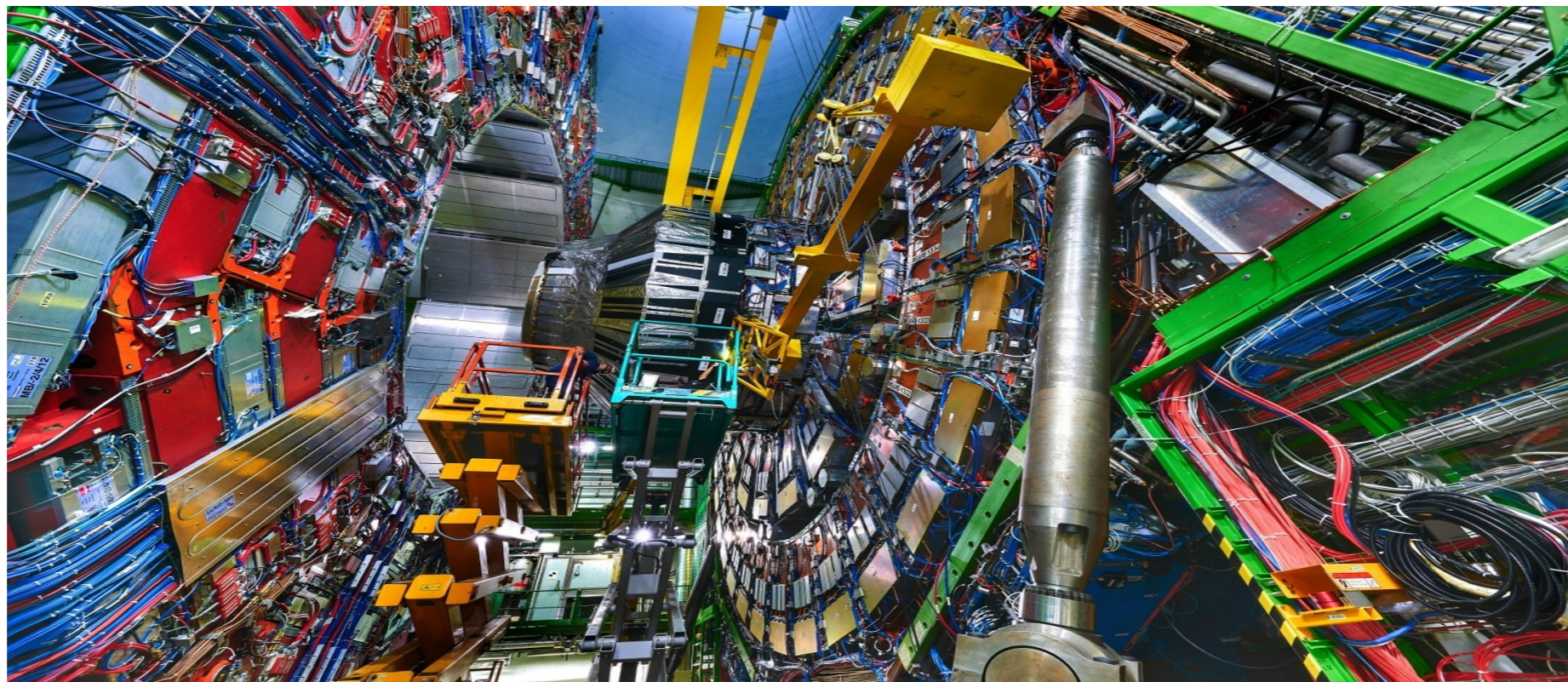


**SUSY-2021: 28th International Conference on SUSY and
Unification of Fundamental Interactions
(23-28 August 2021)**

Sushil S. Chauhan

Panjab University, Chandigarh, India

(On behalf of the CMS Collaboration)

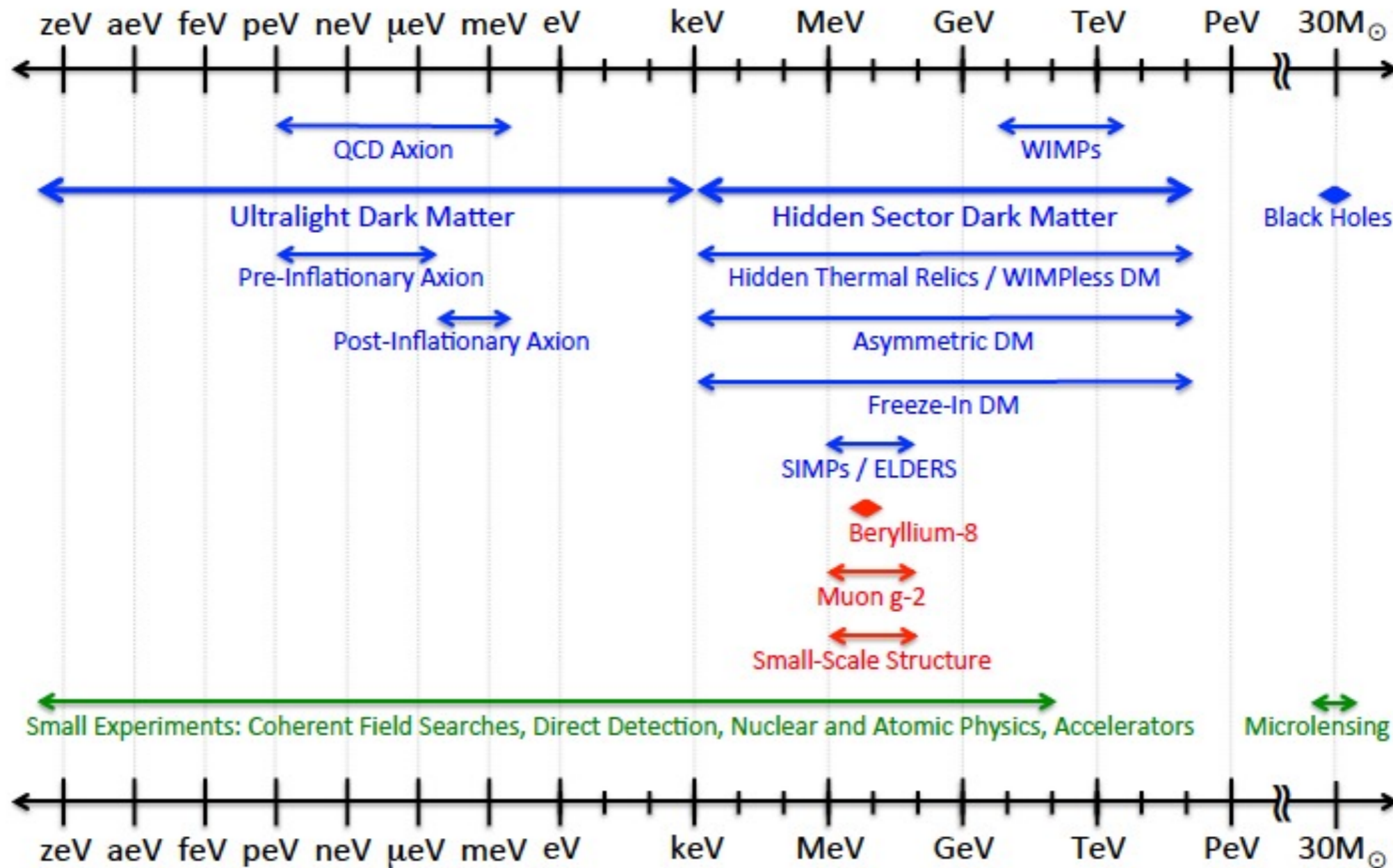


Dark Sector: Big Picture



From Battaglieri et al., arXiv:1707.04591

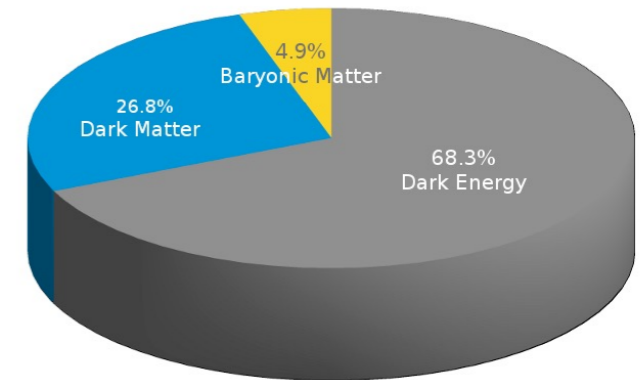
Dark Sector Candidates, Anomalies, and Search Techniques



The Hidden Dark Sector

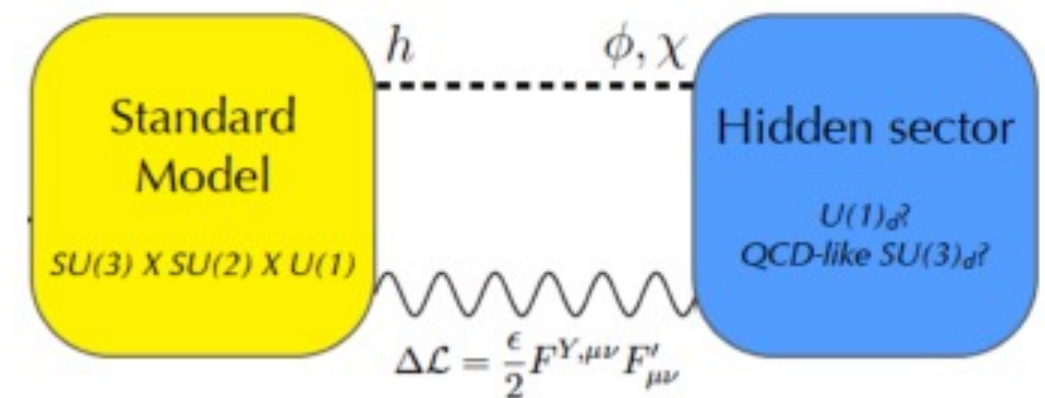


- ◉ The dark sector consists of particles that do not couple directly to known SM fields. They interact through some portals/mediators

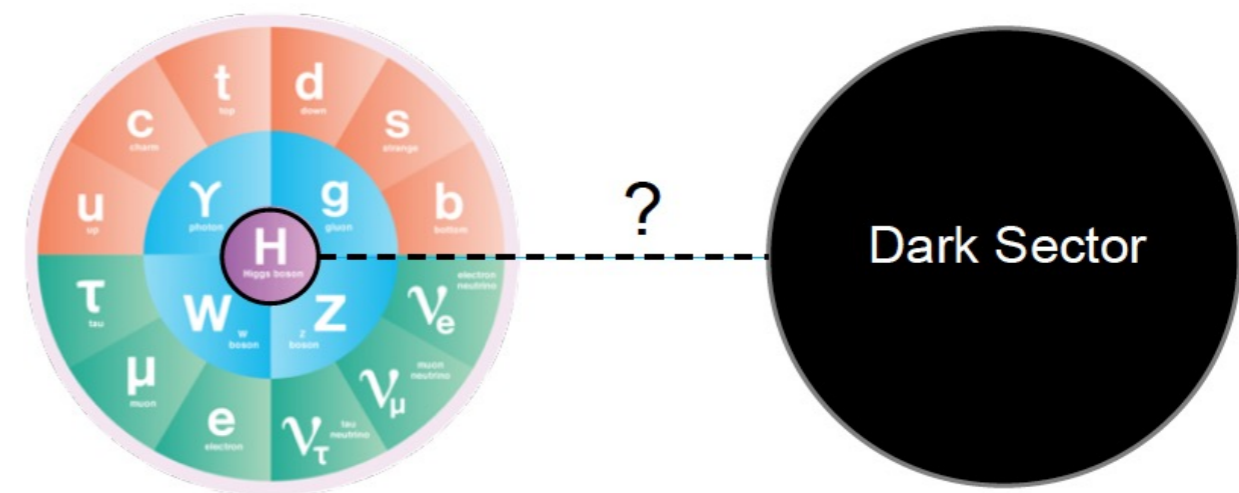


DM Candidates:

- ◉ dark photons (vector portal)
- ◉ dark scalars (Higgs portal, displaced jets)
- ◉ dark QCD sector (emerging jets)
- ◉ ALPs (axions)
- ◉ Sterile neutrinos
- ◉



- ◉ Higgs portal is used in many of these searches including dark photons



Focus of This talk



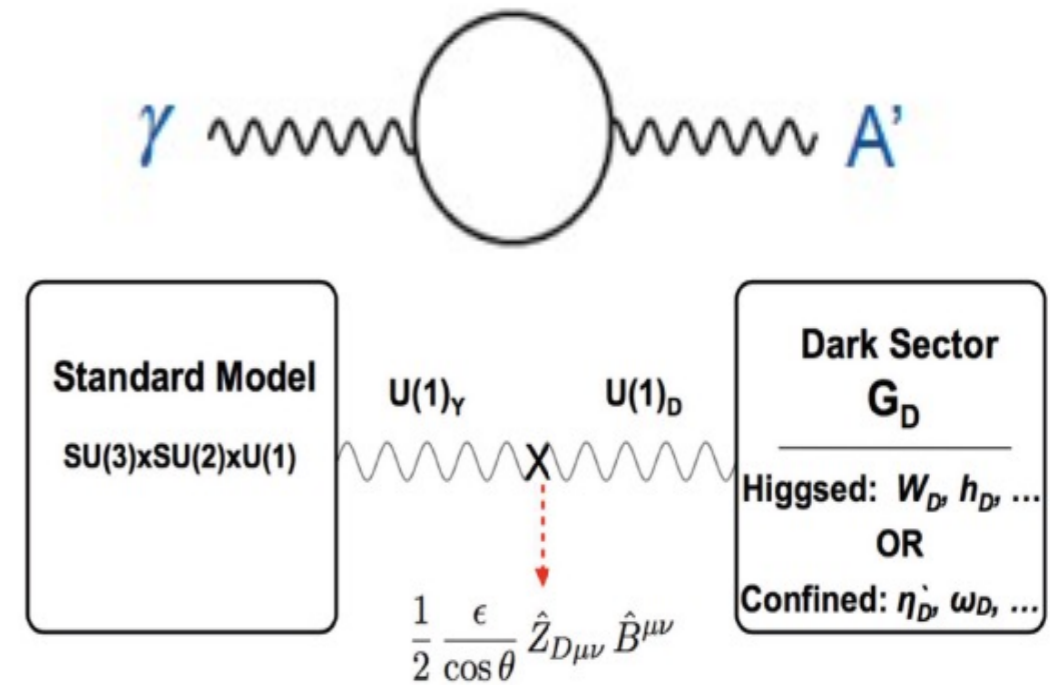
- ◉ **Main focus of this talk**
 - **Dark Photon**
 - **Higgs to Light BSM Boson**
 - **$\mu\mu$ Resonance Search**
 - **Displaced Di-Muon Search**
 - **Semi-Visible Jets**
 - **Displaced Jets**
 - **Emerging Jets**

- ◉ **Other Results for:**
 - **Mediator DM Searches (Plenary talk by [Zeynep Demiragli](#))**
 - **Dark Higgs Search (parallel talk by [Reham Aly Mohamed](#))**

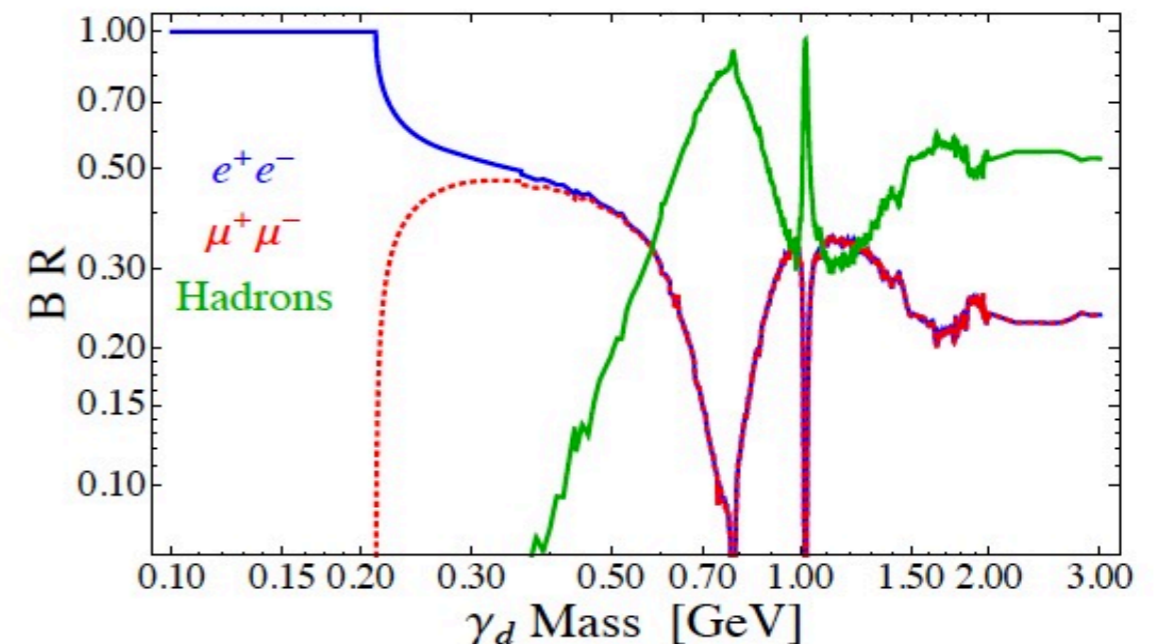
- ◉ **A complete list of CMS results:**
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>

Add $U(1)_d$ from hidden sector

- Connection between dark sector and SM
- Couple with SM via kinetic mixing, ϵ is kinetic mixing coefficient
- Massive gauge boson ($A/Z_d/\gamma_d$)
- ϵ and mass of ($A/Z_d/\gamma_d$) are key parameters



From arXiv:1002.2952



- Search based on life time of dark particles from hidden sector.
- The dark photon decays to SM particles through its kinetic mixing to visible spectrum

Dark Photon: ZH Channel

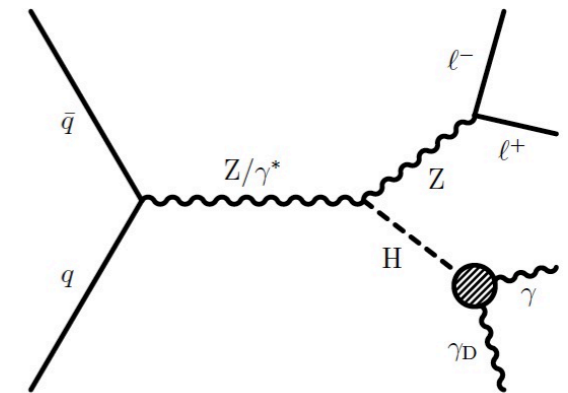


JHEP 10 (2019) 139

EXO-19-007

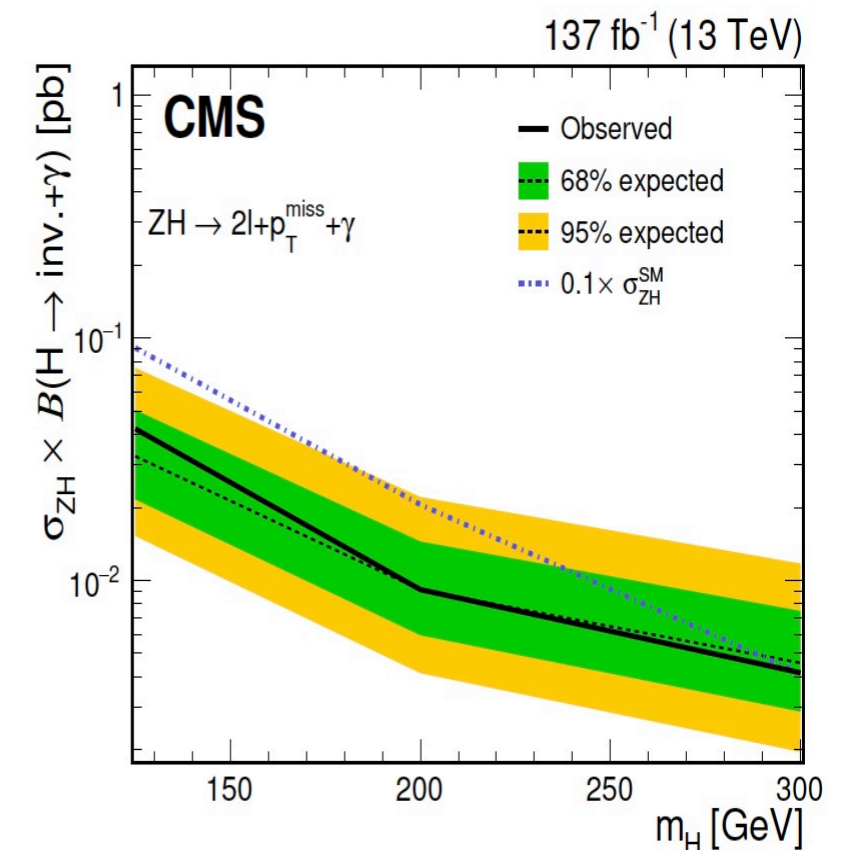
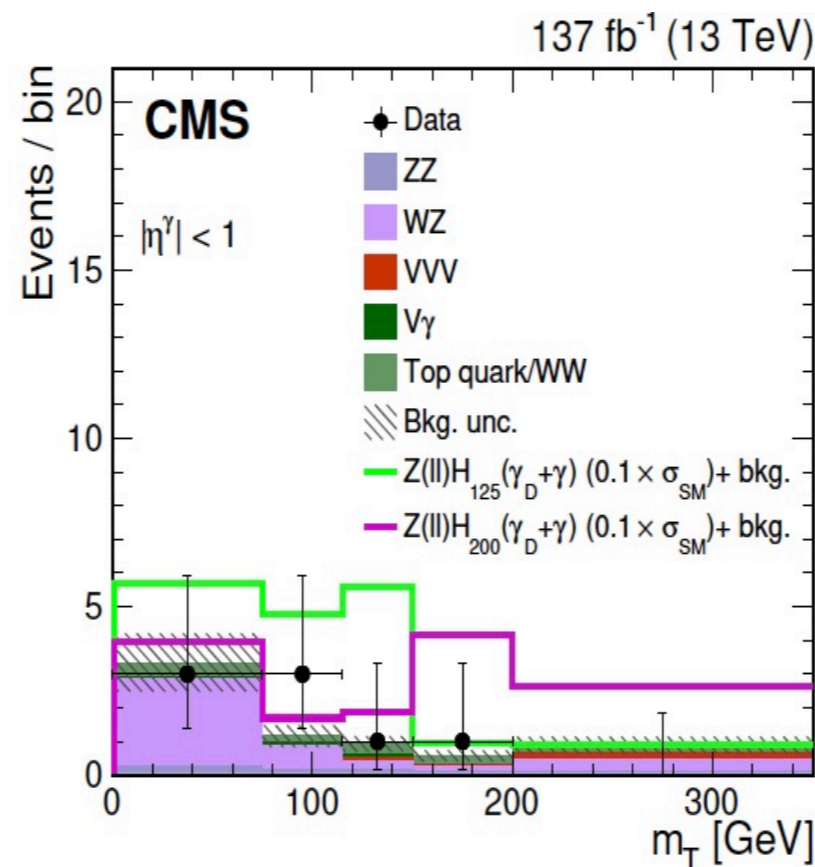
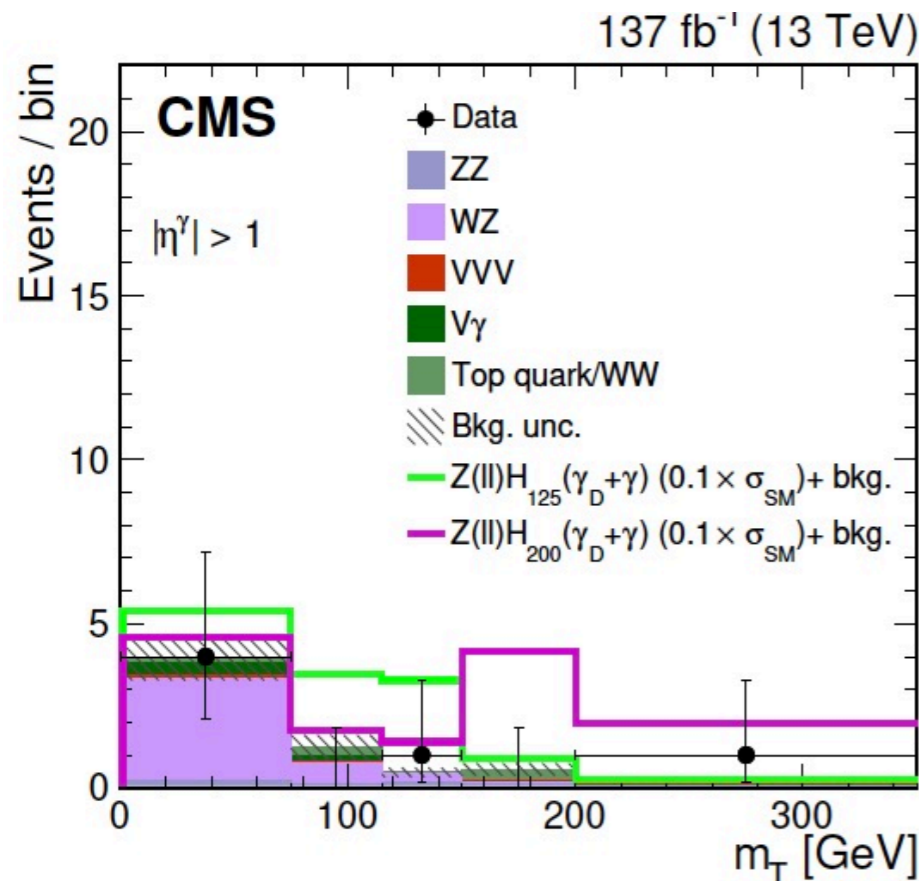
- Probing a Higgs portal model with dark sector
 - $H \rightarrow \gamma\gamma_d$ where γ_d is massless dark photon
 - γ_d couples to Higgs through hidden charge sector
 - M_T of photon-MET system is used as discriminating variable
 - Dominant background normalized in control region

$$m_T = \sqrt{2p_T^{\text{miss}}E_T^\gamma[1 - \cos(\Delta\phi_{\vec{p}_T^{\text{miss}}, \vec{E}_T^\gamma})]}$$



Relatively clean final state

Limit on $BR < 4.6\%$ at 95% CL for SM $H(\gamma + \text{Inv.})$



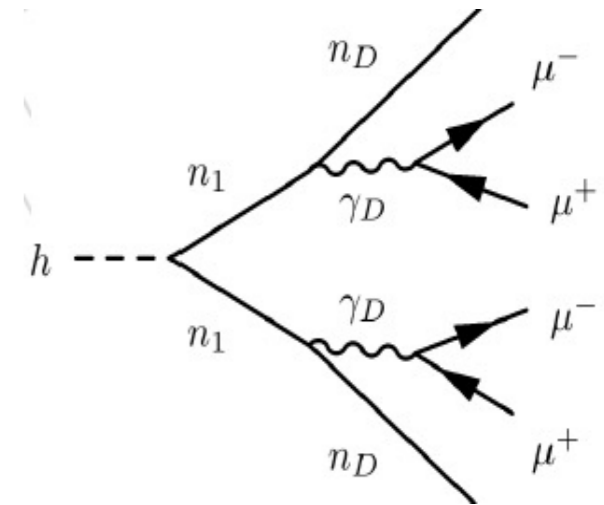
Higgs to Light BSM Boson



PLB 796 (2019) 131-154

CMS-HIG-18-003

- Search for $H \rightarrow 4\mu + X$ with Dark SUSY benchmark model
- n_d is dark neutralino that is remain undetected and n_1 is lightest non-dark neutralino



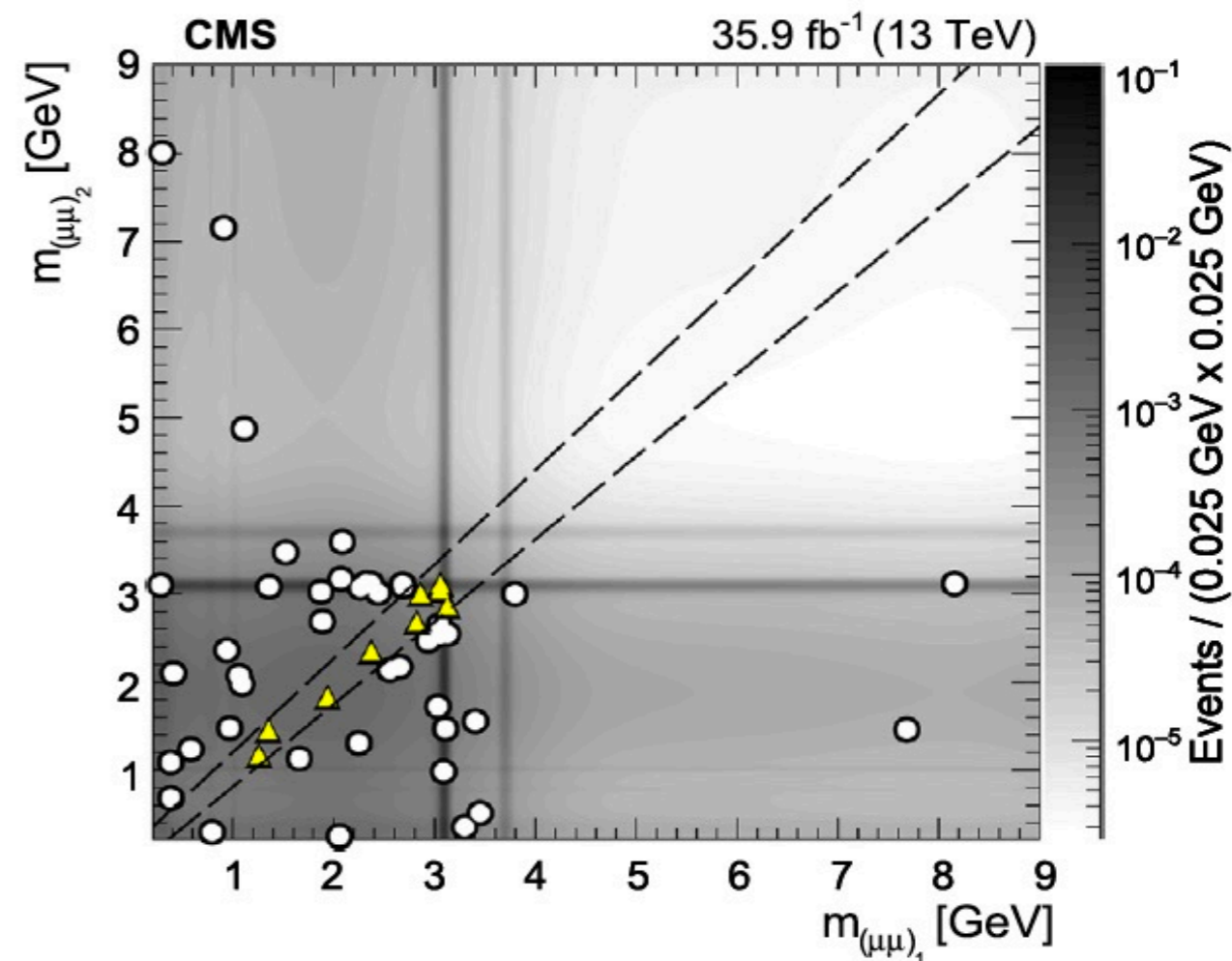
Signal Region:

- $M_{(\mu\mu)1} \sim M_{(\mu\mu)2}$
- $|M_{(\mu\mu)1} - M_{(\mu\mu)2}| < 5\sigma(M_{\mu\mu})$

Main Backgrounds:

- QCD b-pair production
- J/Ψ production (SPS, DPS)
- Electroweak contribution (mainly non-resonant)

Low total background

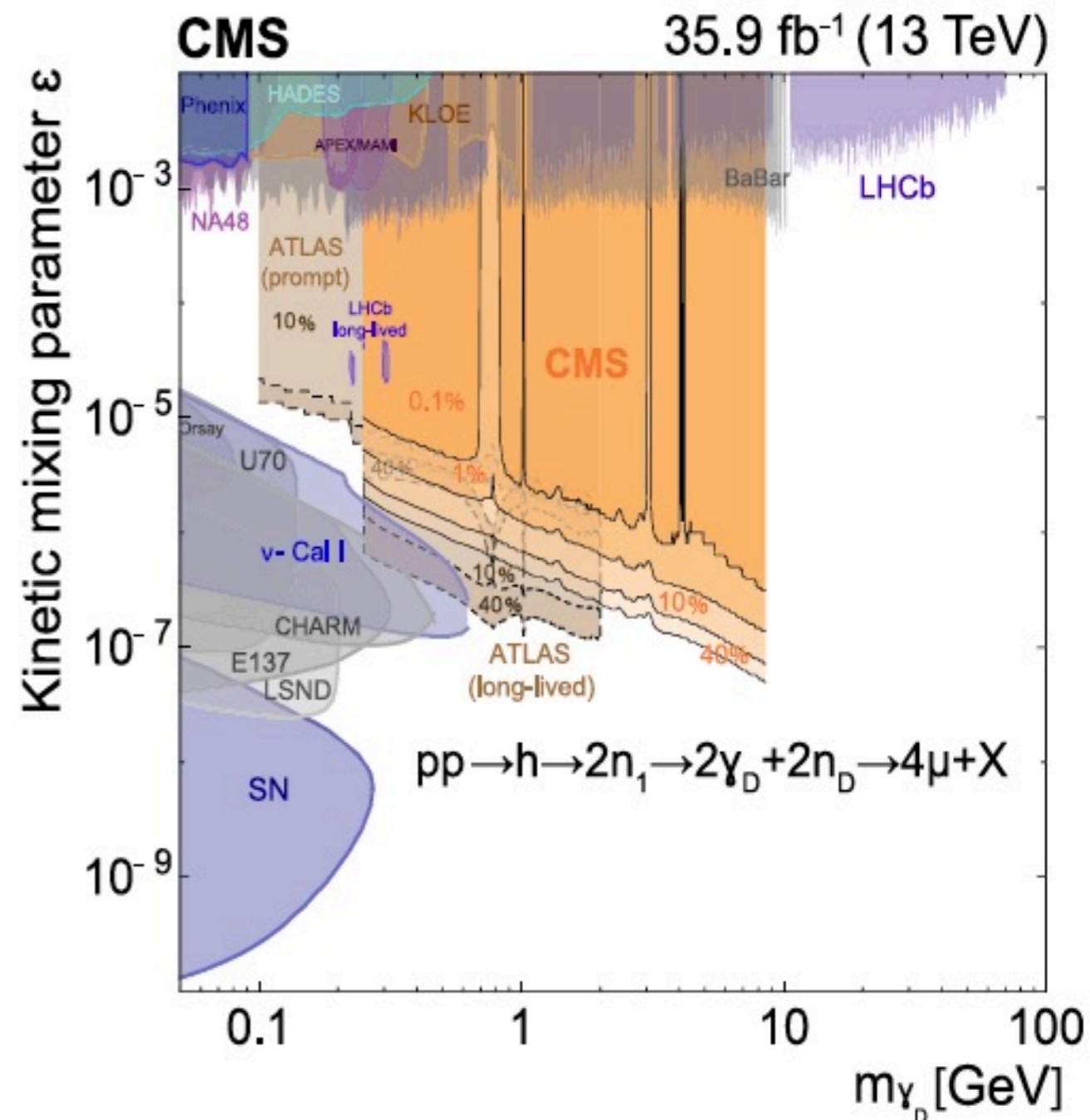


Higgs to Light BSM Boson



- Limits are interpreted in terms of kinetic mixing parameter ϵ and M_{γ_D}
- Limits are shown for $B(H \rightarrow 2\gamma_D + X)$ in the range of 0.1–40 %
- Upper limit set on:

$$\sigma(pp \rightarrow h \rightarrow 2n_1 \rightarrow 2\gamma_D + 2n_D) \times B(\gamma_D \rightarrow 2\mu)$$



Search for Narrow Resonance of $\mu^\pm\mu^\pm$



PRL 124, 131802

EXO-19-018

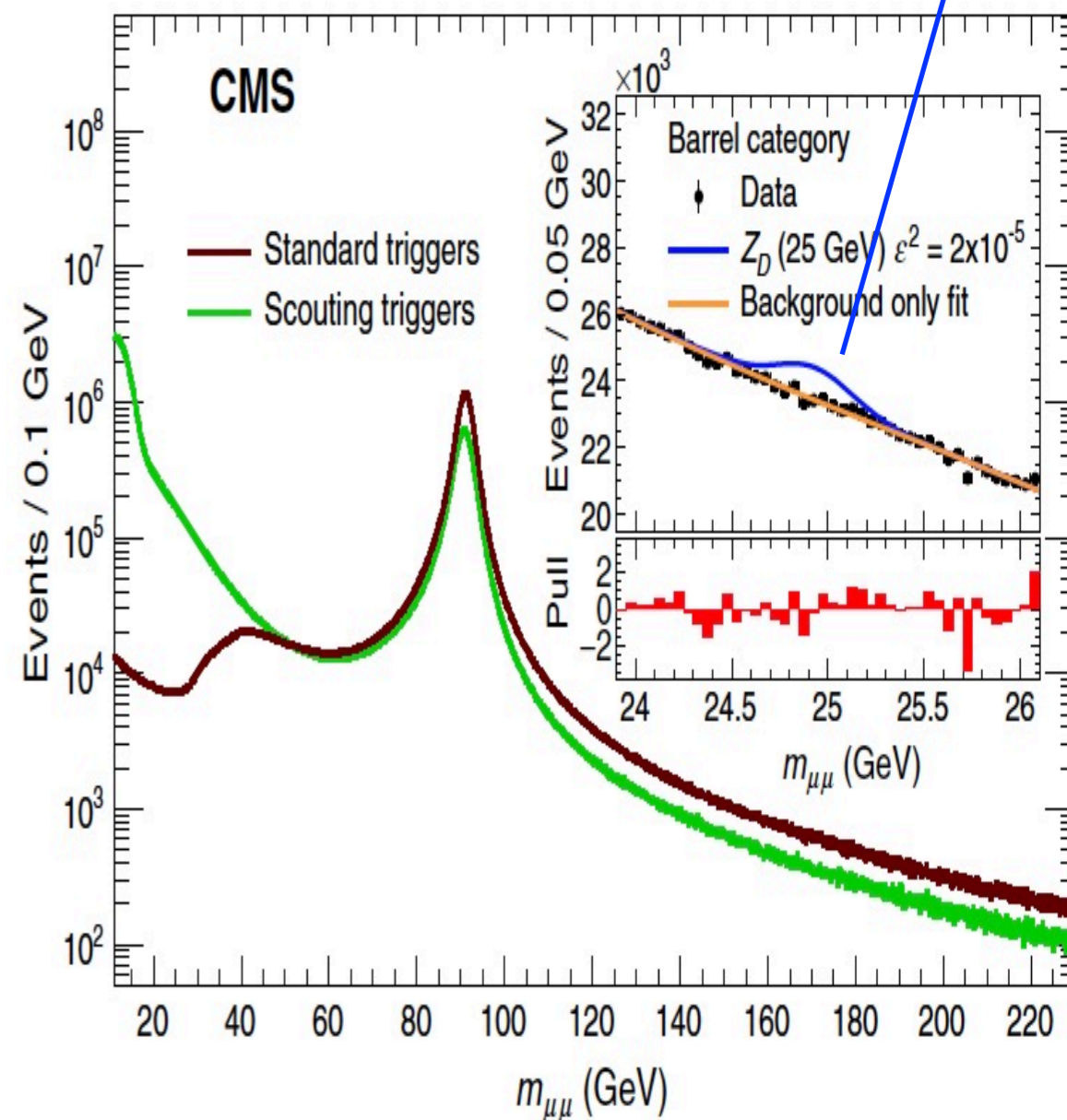
- Dedicated scouting triggers
- Data collected with increase rate but reduce trigger level information
 - increase acceptance below $M_{\mu\mu} < 45$ GeV

- Events are categorized based on resolution of $M_{\mu\mu}$

- ~1% in Barrel $|\eta| < 0.9$
- ~3% In Endcap $|\eta| > 1.2$

Sliding window resonance hunt in $M_{\mu\mu}$ distribution

Dark Photon Signal

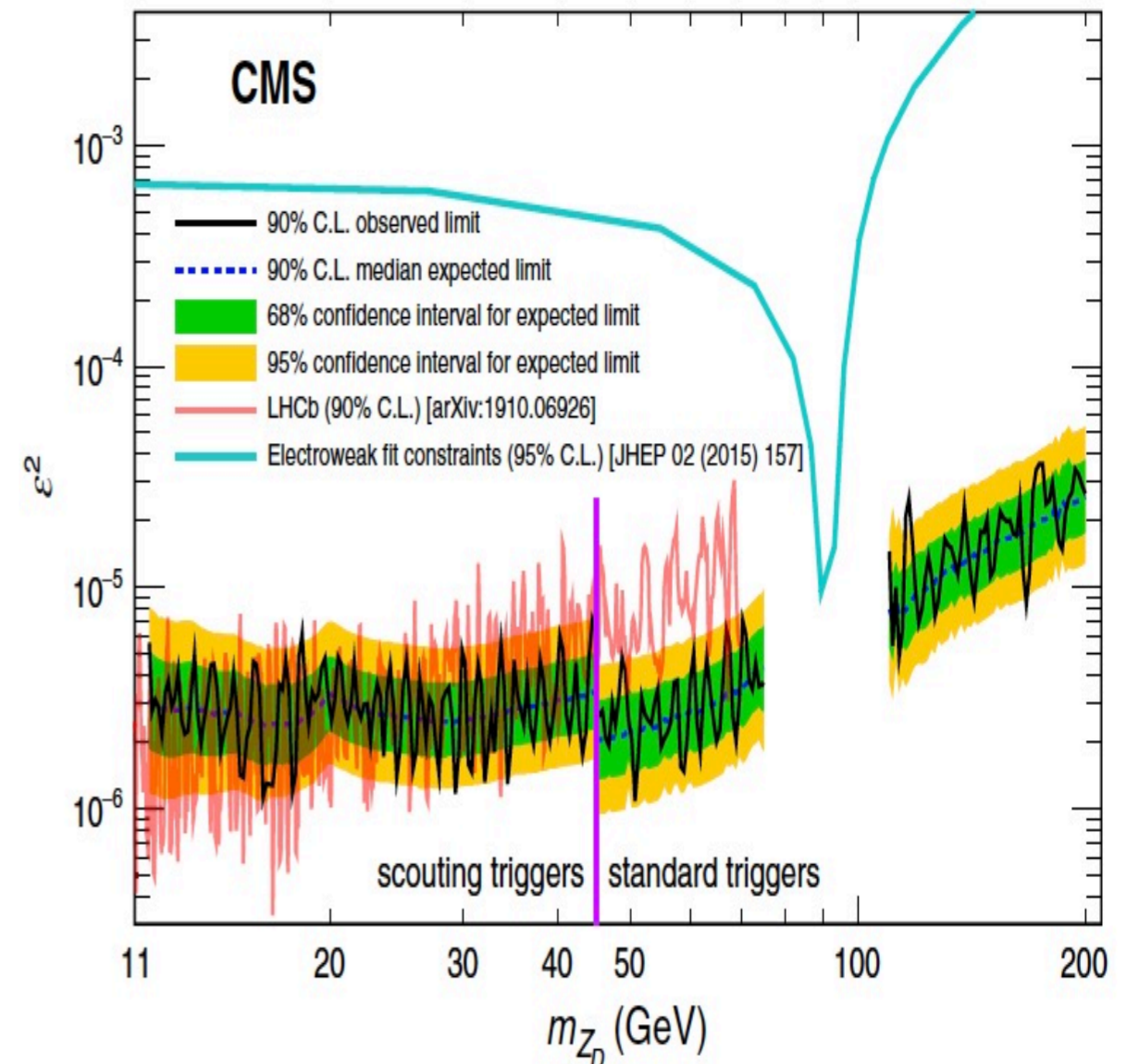
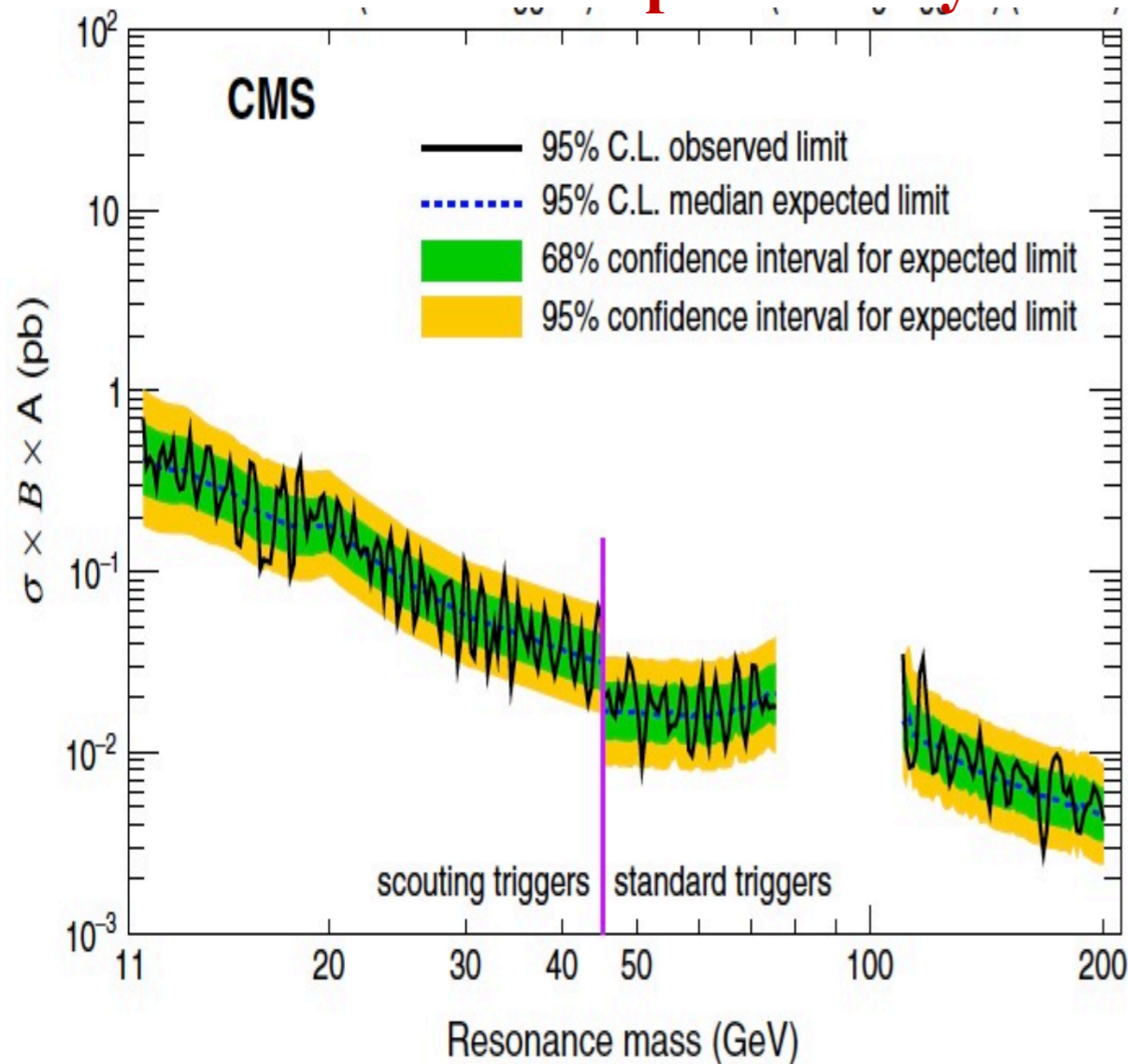


Search for Narrow Resonance of $\mu^\pm\mu^\pm$



- Model independent upper limit as a function of resonance mass
- Dark photon interpretation with upper limit on ϵ^2 as a function of dark photon mass between 11.5 – 200 GeV

- Limits are complimentary to LHCb results

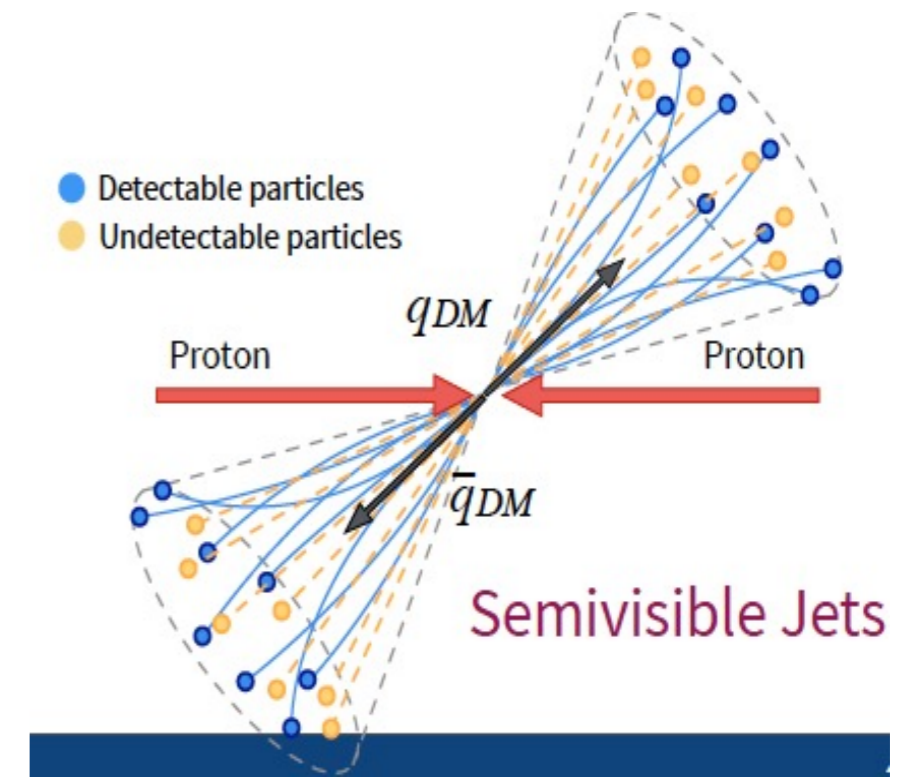
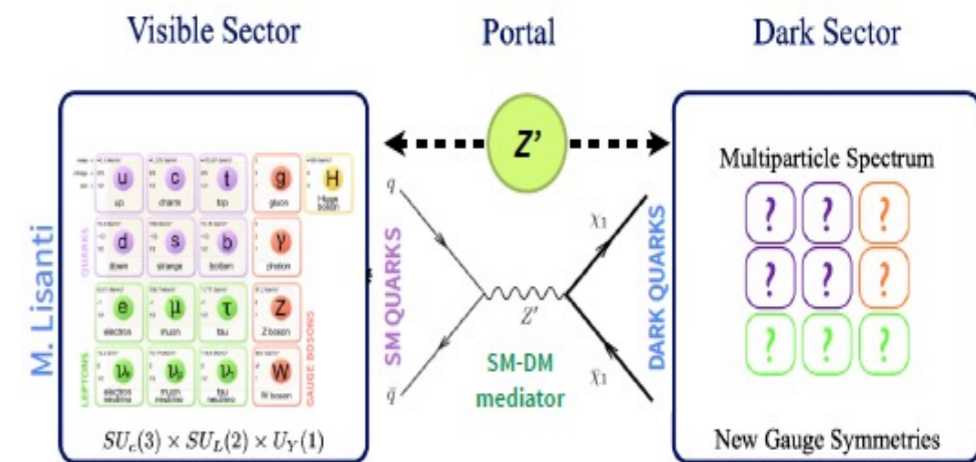


Semi-Visible Jets (SVJ)

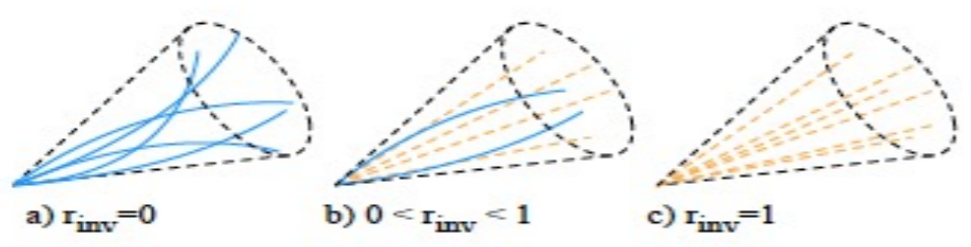


EXO-19-020

- **Strongly coupled hidden sector**
- **New $SU_{\text{dark}}(N)$ force: Dark QCD and associated particles**
- **Connected to SM by weakly coupled mediators: scalars, vector etc..**
- **Stable dark hadron remains invisible**
- **Unstable dark hadron decays resulting in visible fraction of dark energy**



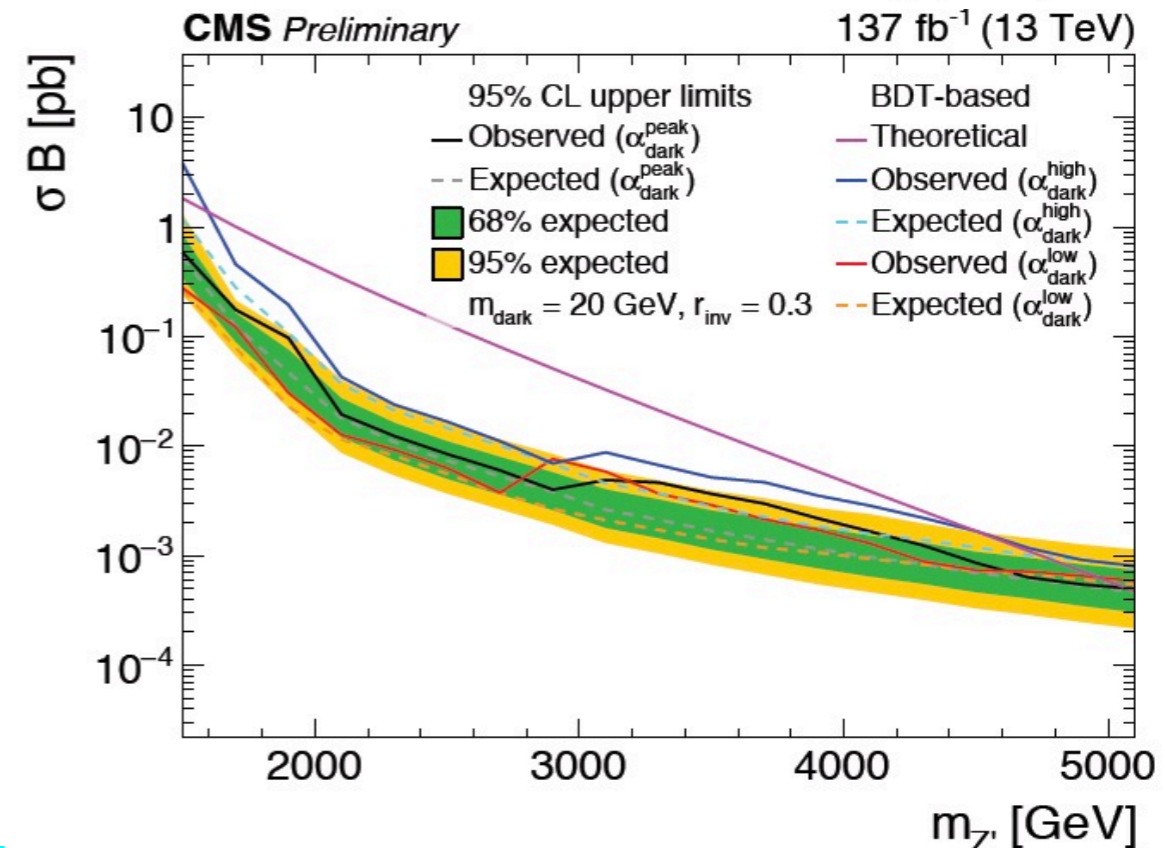
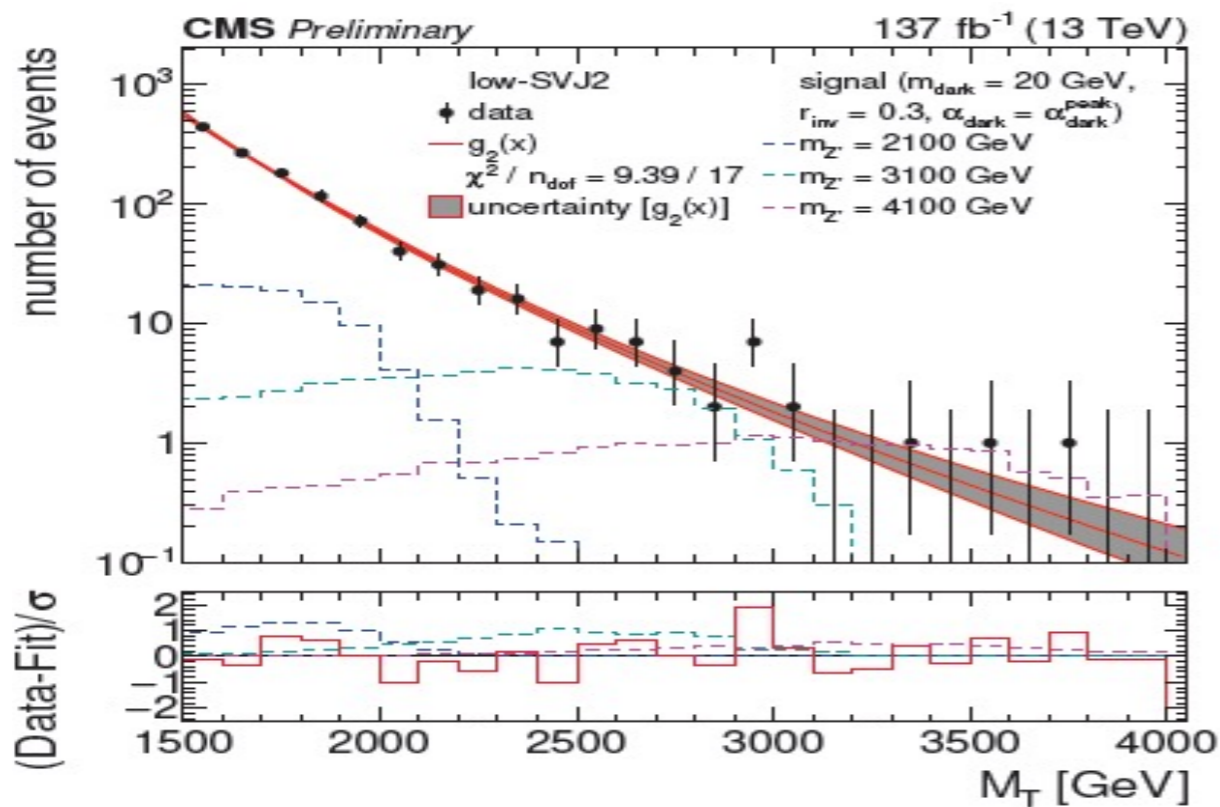
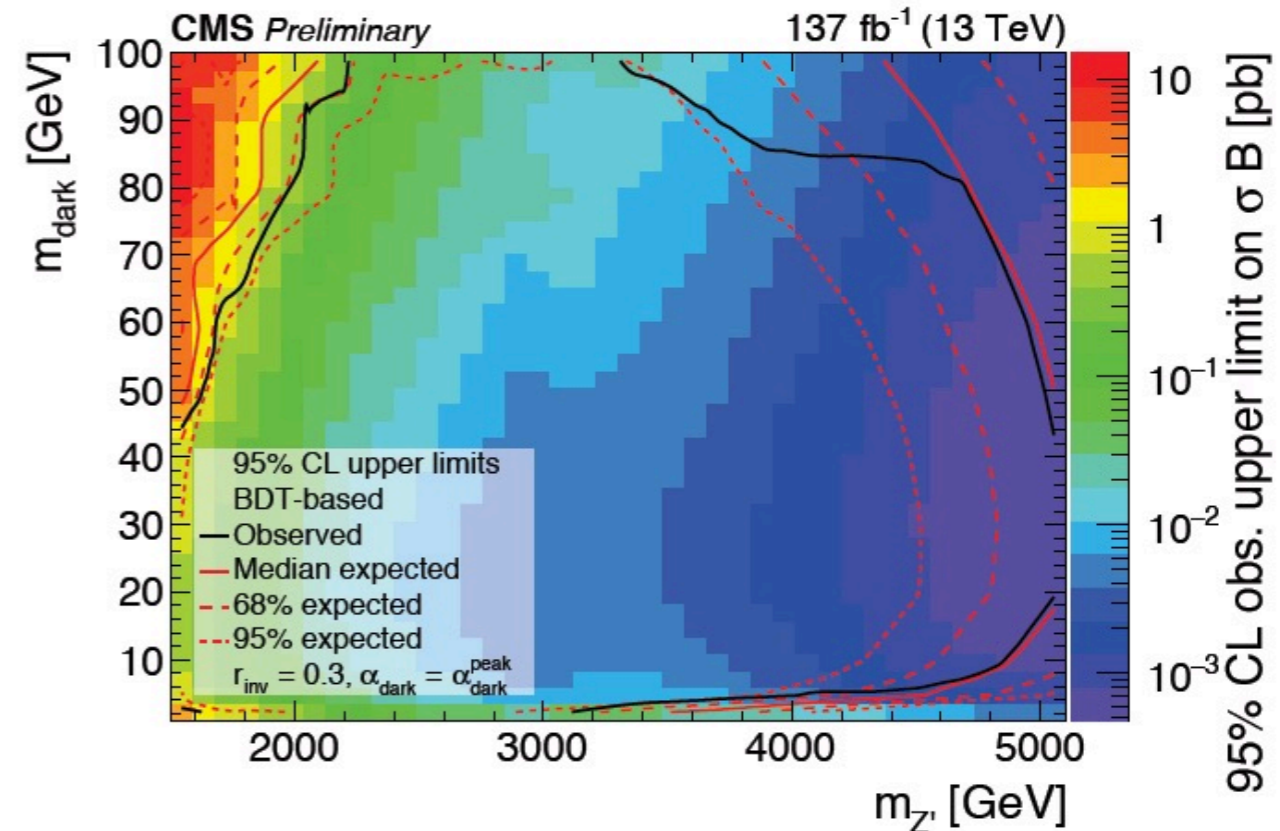
$$r_{inv} = \left\langle \frac{N \text{ stable dark hadrons}}{N \text{ dark hadrons}} \right\rangle$$



Semi-Visible Jets (SVJ)



- Use of jet internal structure to tag SVJ using BDT
- Background estimation: analytical fit to M_T distribution
- Backgrounds: QCD, t-tbar, Z(vv)+jets, W(lv)+jets
- $R_T = MET/M_T$ is used for signal selection e.g., QCD has low R_T
- **Challenges:** artificial MET e.g., ECAL dead cells

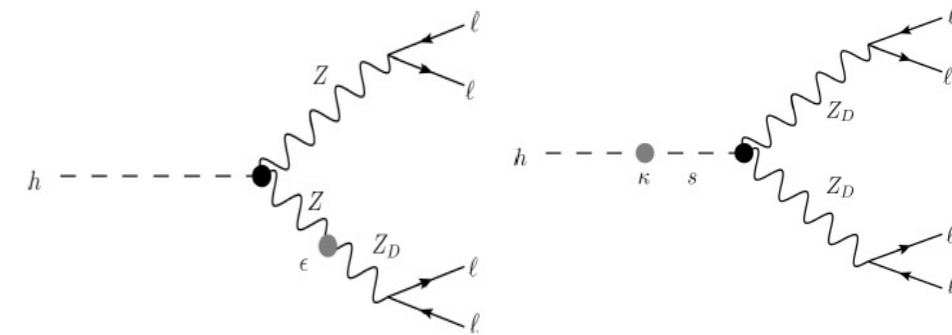


Displaced Low Mass Di-Muon Search



- 2 displaced muons with associated displaced vertex
- Low muon P_T calo scouting trigger used
- Event categorization based on transverse displacement (l_{xy}), P_T , and no. of isolated muons
 - One additional bin of $H \rightarrow Z_D Z_D \rightarrow 4\mu$ (background free)
- Binned likelihood fit in each of event category

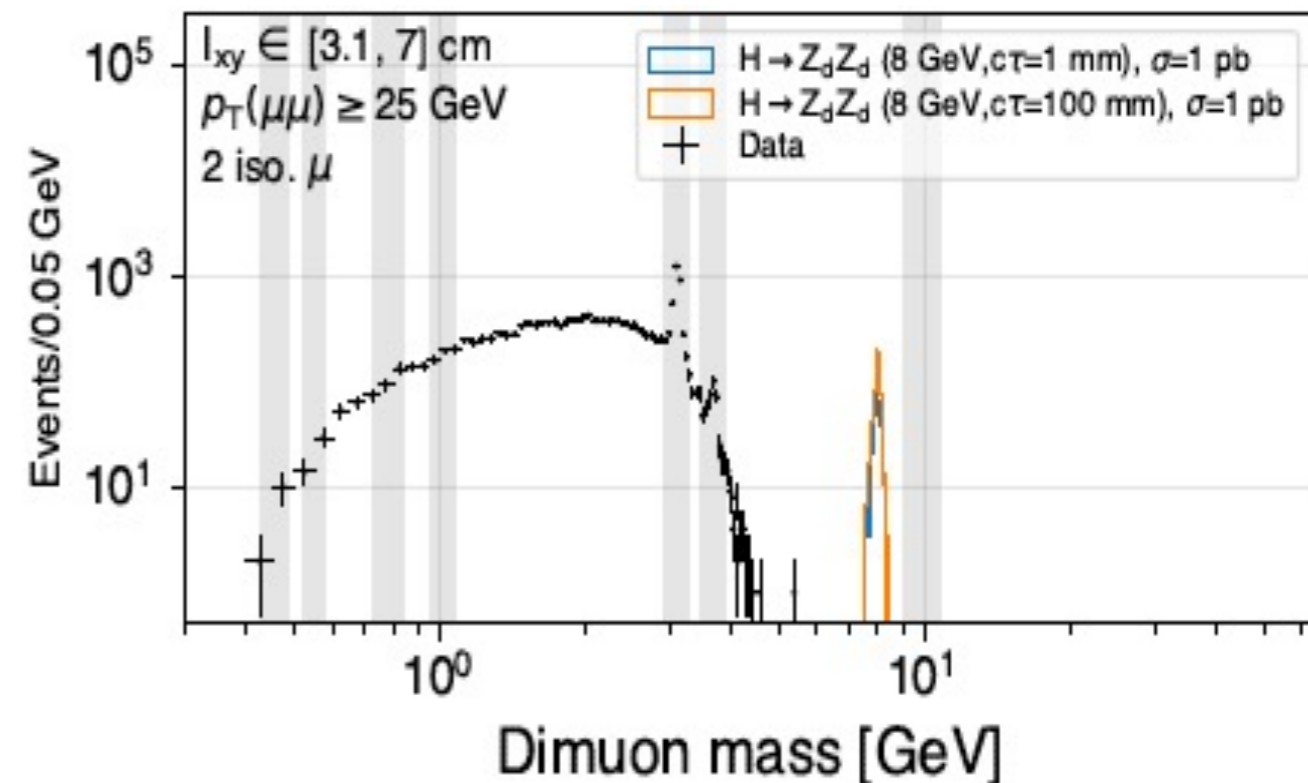
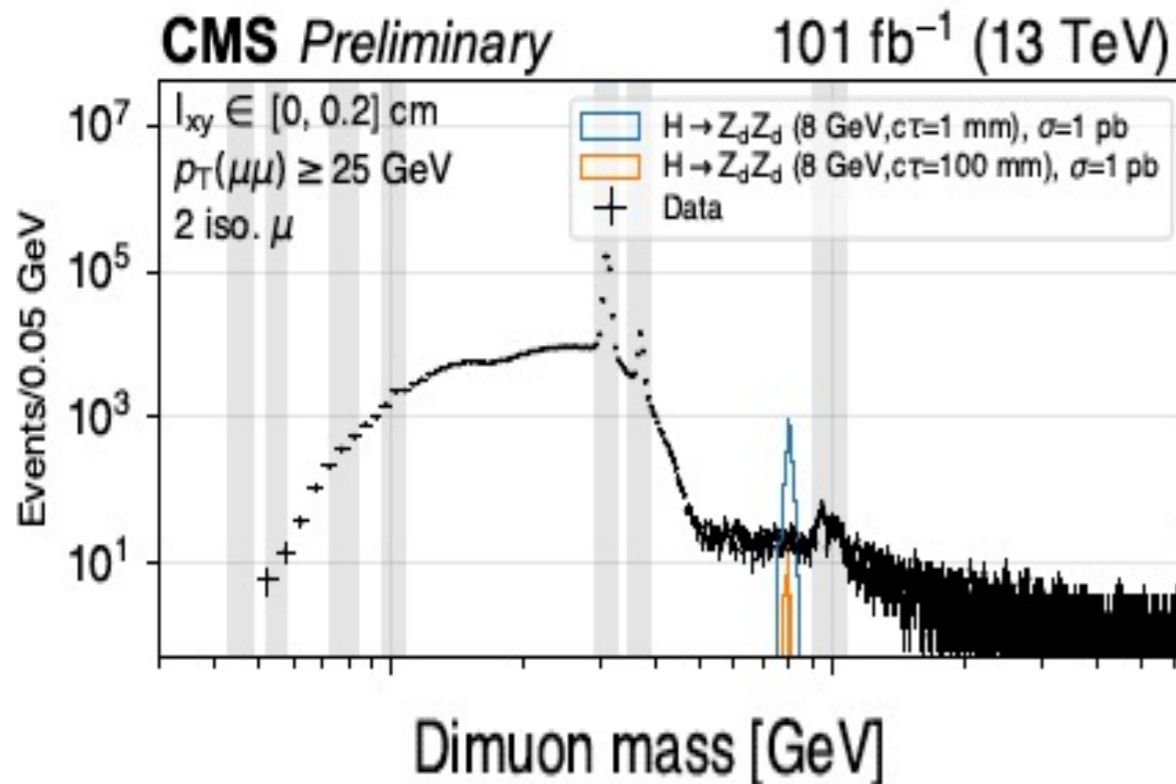
EXO-20-014



$$0.5 \text{ GeV} \leq m(Z_D) \leq 50 \text{ GeV}$$

$$0.1 \text{ mm} \leq c\tau_0(Z_D) \lesssim 1000 \text{ mm}$$

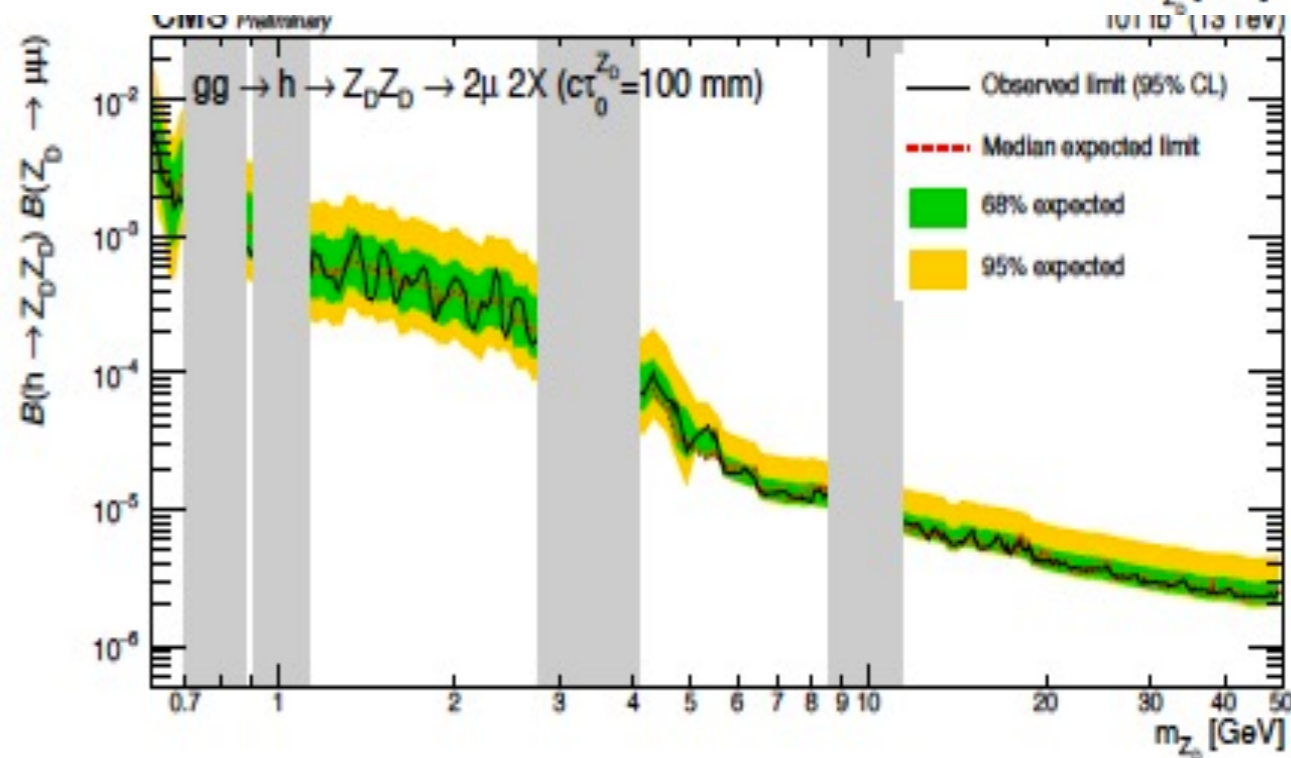
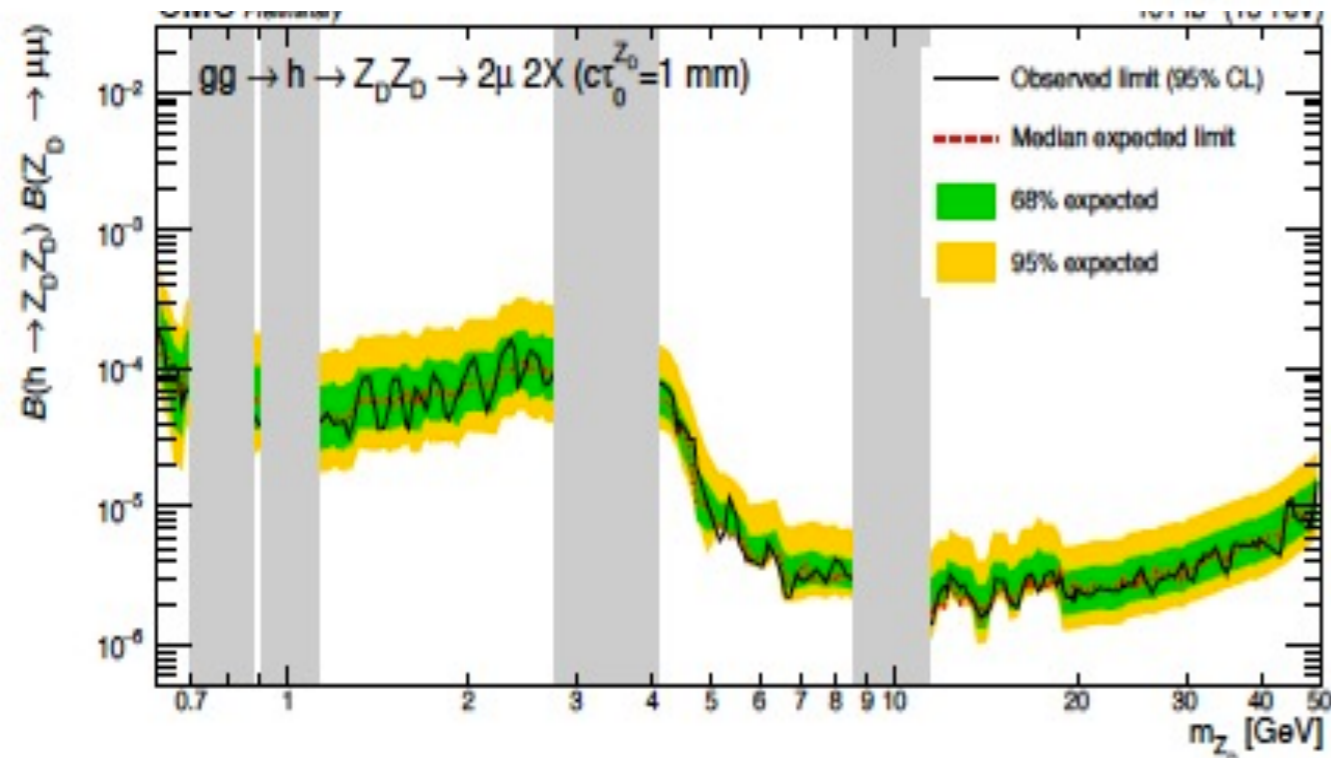
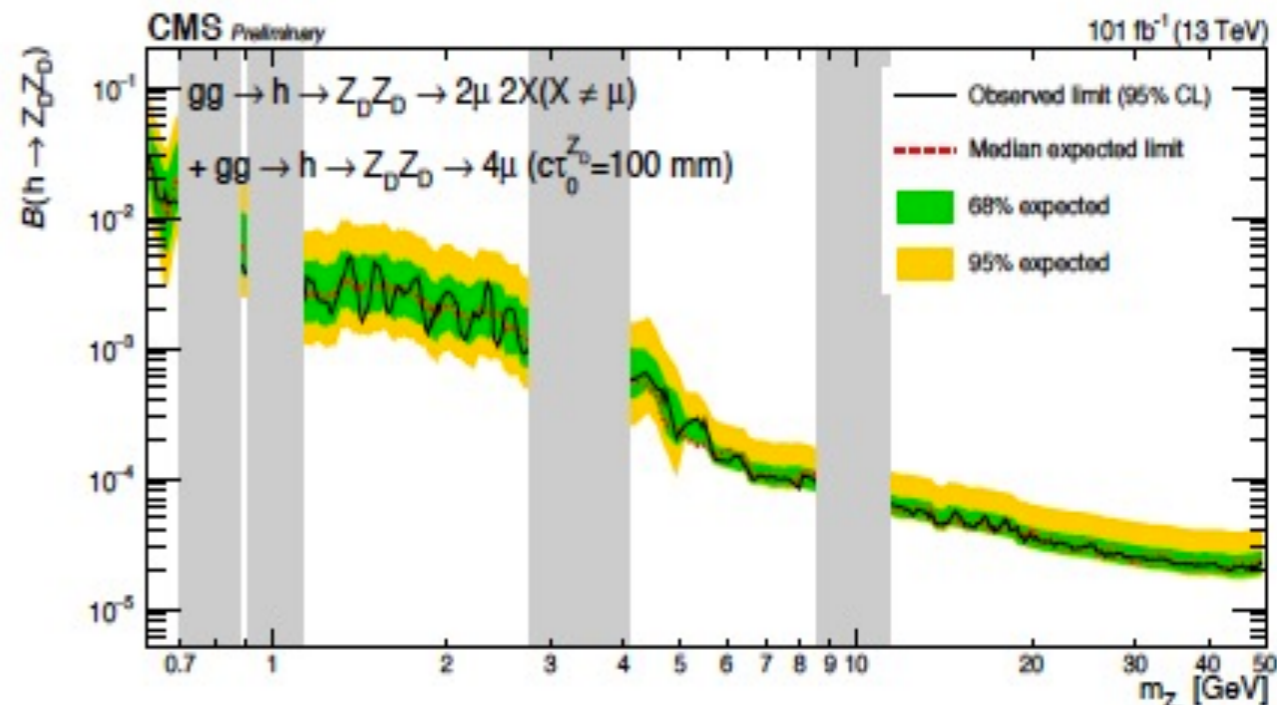
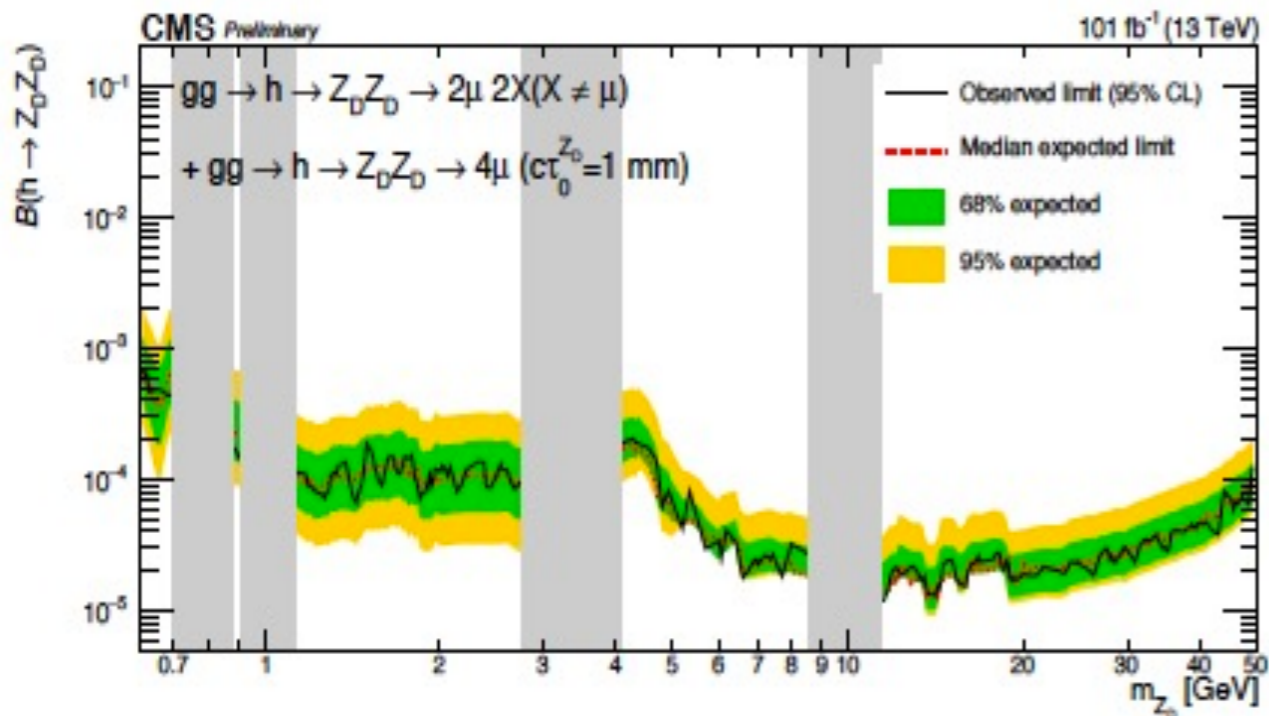
$$\text{Constrain: BR}(H \rightarrow Z_D Z_D) \cdot \text{BR}(Z_D \rightarrow \mu\mu)$$



Displaced Low Mass Di-Muon Search



- 4μ dominates the sensitivity at small life time and at low mass, assuming $BR(Z_D \rightarrow \mu\mu) = 100\%$



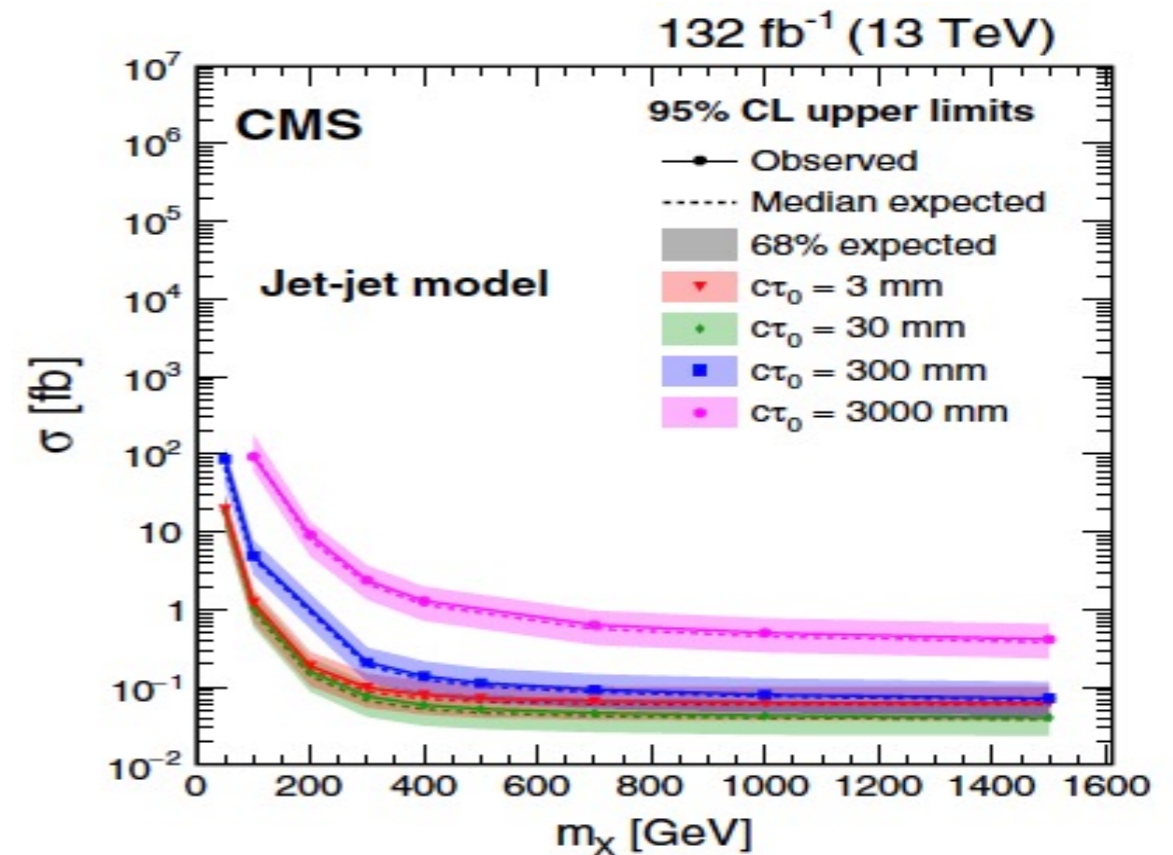
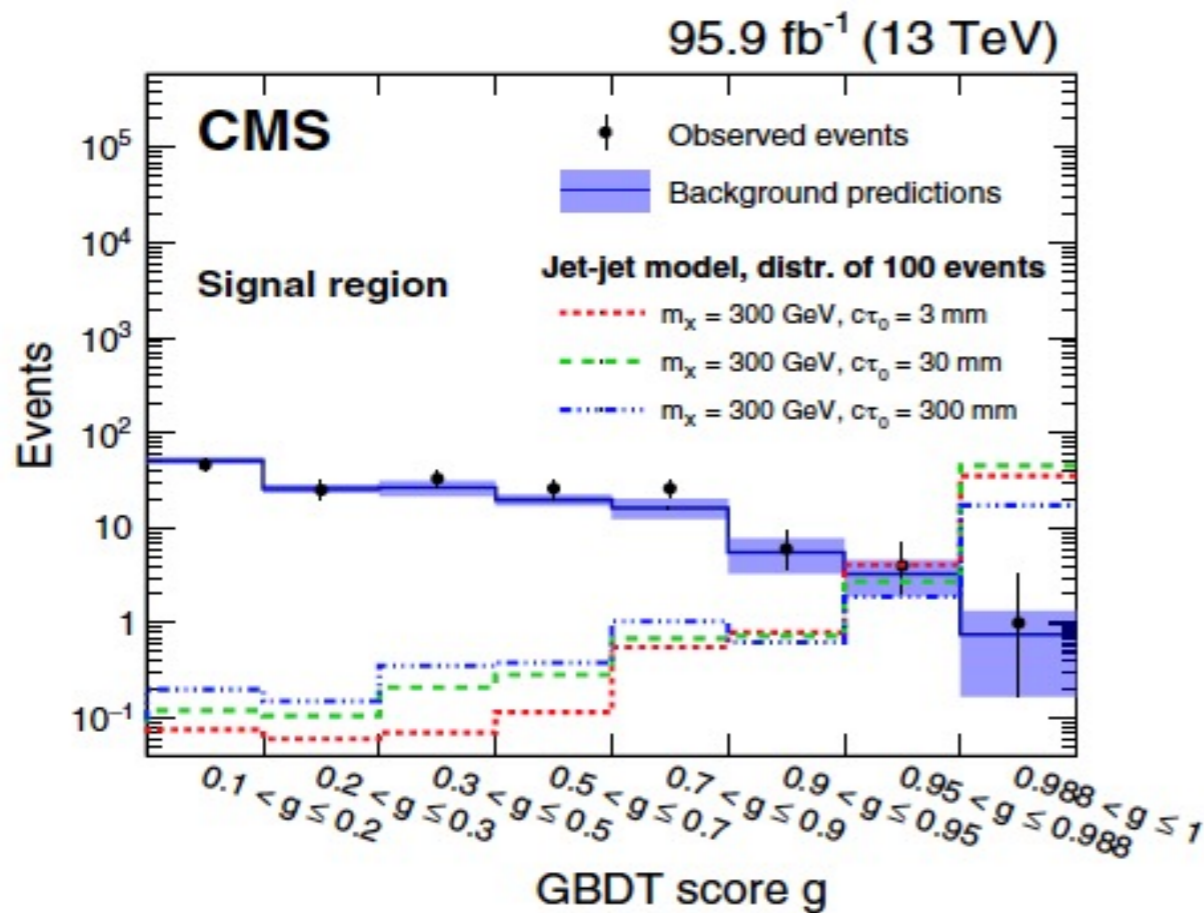
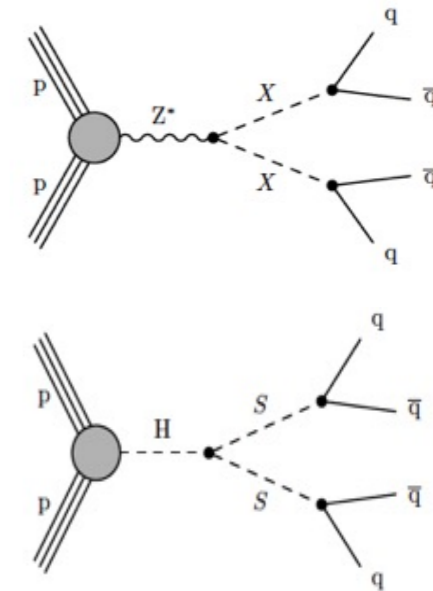
Displace Jet



PRD 104, 012015 (2021)

EXO-19-021

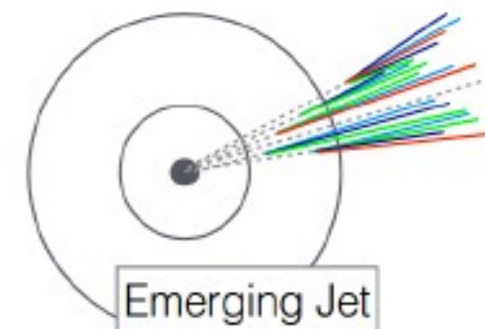
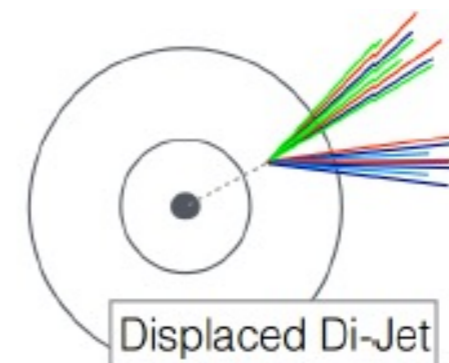
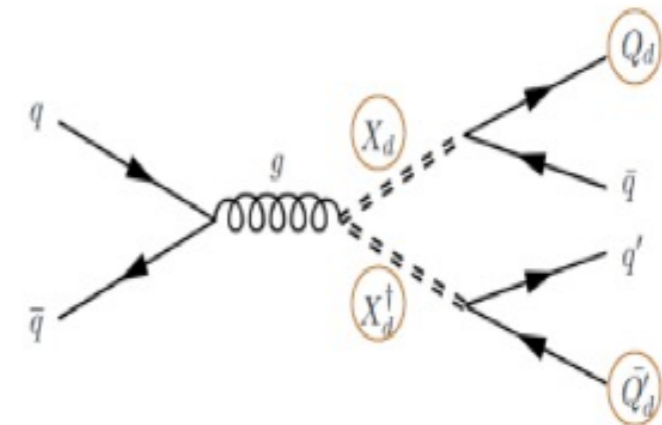
- **Pair of jets originating at secondary vertex**
- **Signal Models: LLPs decaying to jets/exotic decay of Higgs**
- **$c\tau$: 1 mm – 3m**
- **Dedicated trigger and secondary vertex reconstruction**
- **GBDT is used to for signal : vertex track multiplicity and IP2D variables are used**



PLB 797 (2019) 134876

EXO-18-001

- **Dark QCD sector with dark fermions (Q_d) and mediator X_d**
- **Emerging jets are produced in hadronization of Q_d and dark jet contain dark hadron e.g. long lived dark π_d**
 - π_d decay to SM particles
- **These jets contains multiple displaced vertices**
- **7 different SR targeting 336 signal hypothesis**
- **Dedicated emerging jet tagger**

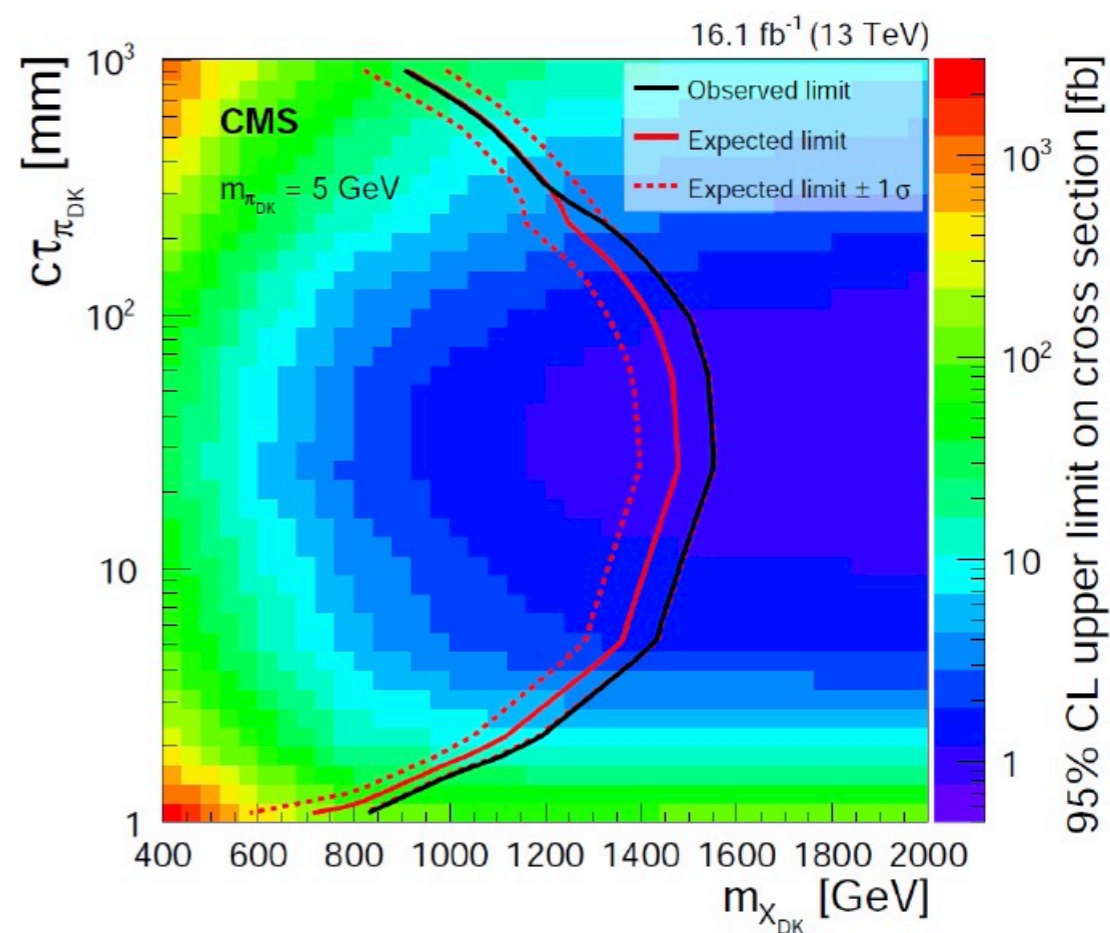
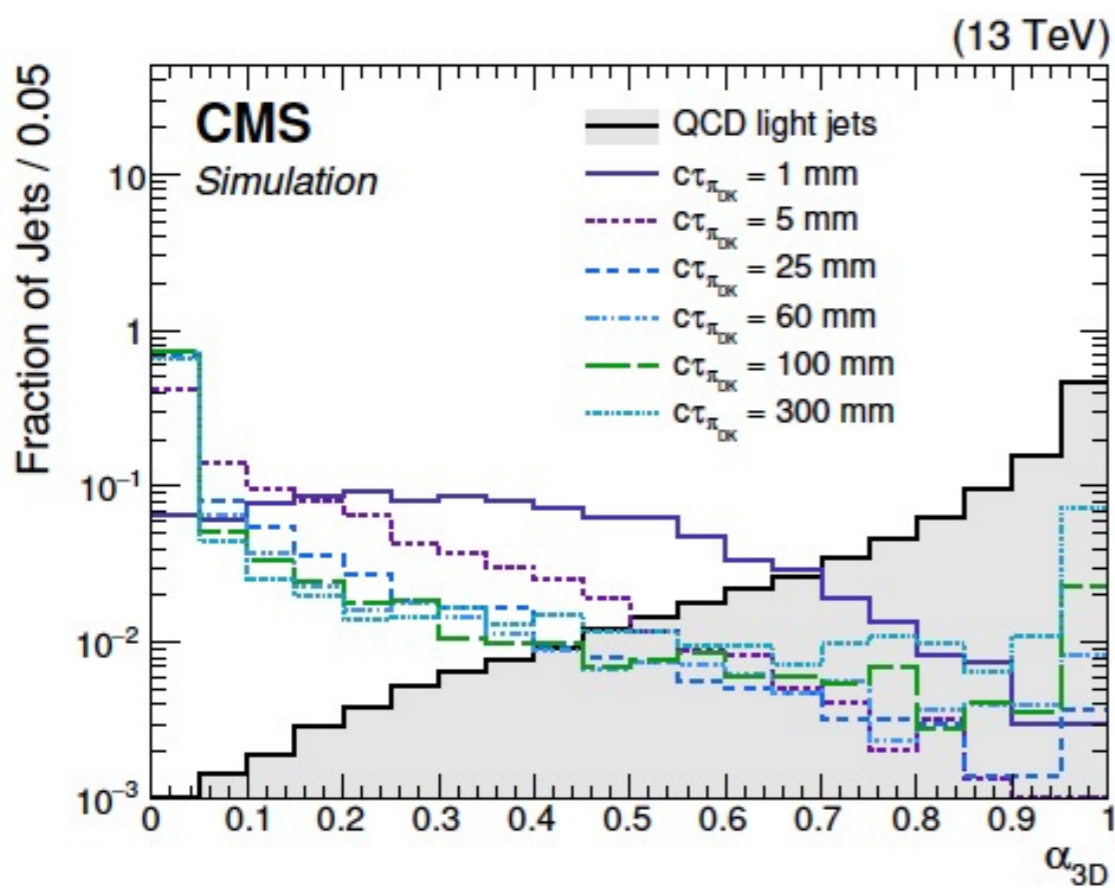


Signal model parameters	List of values
Dark mediator mass $m_{X_{DK}}$ [GeV]	400, 600, 800, 1000, 1250, 1500, 2000
Dark pion mass $m_{\pi_{DK}}$ [GeV]	1, 2, 5, 10
Dark pion decay length $c\tau_{\pi_{DK}}$ [mm]	1, 2, 5, 25, 45, 60, 100, 150, 225, 300, 500, 1000

Emerging Jets



Set number	H_T	$p_{T,1}$	$p_{T,2}$	$p_{T,3}$	$p_{T,4}$	p_T^{miss}	$n_{\text{EMJ}}(\geq)$	EMJ group	no. models
1	900	225	100	100	100	0	2	1	12
2	900	225	100	100	100	0	2	2	2
3	900	225	100	100	100	200	1	3	96
4	1100	275	250	150	150	0	2	1	49
5	1000	250	150	100	100	0	2	4	41
6	1000	250	150	100	100	0	2	5	33
7	1200	300	250	200	150	0	2	6	103
8	900	225	100	100	100	0	2	7	SM QCD-enhanced
9	900	225	100	100	100	200	1	8	



Summary & Conclusions



- ◉ **No evidence of dark sector yet at the LHC**
 - **More results are expected from Run-2 full data**
- ◉ **Extensive and broad dark sector search program at the CMS experiment and at the LHC**
- ◉ **Exciting Run-3 ahead of LHC and beyond...**



Thank You!!

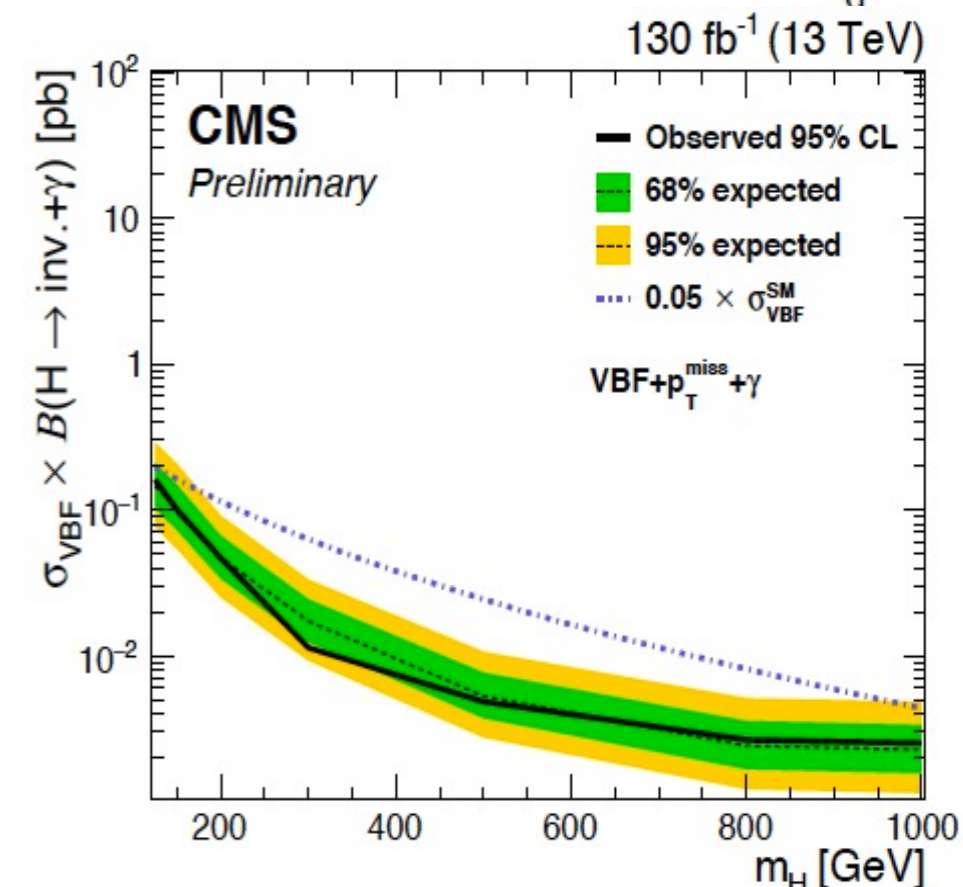
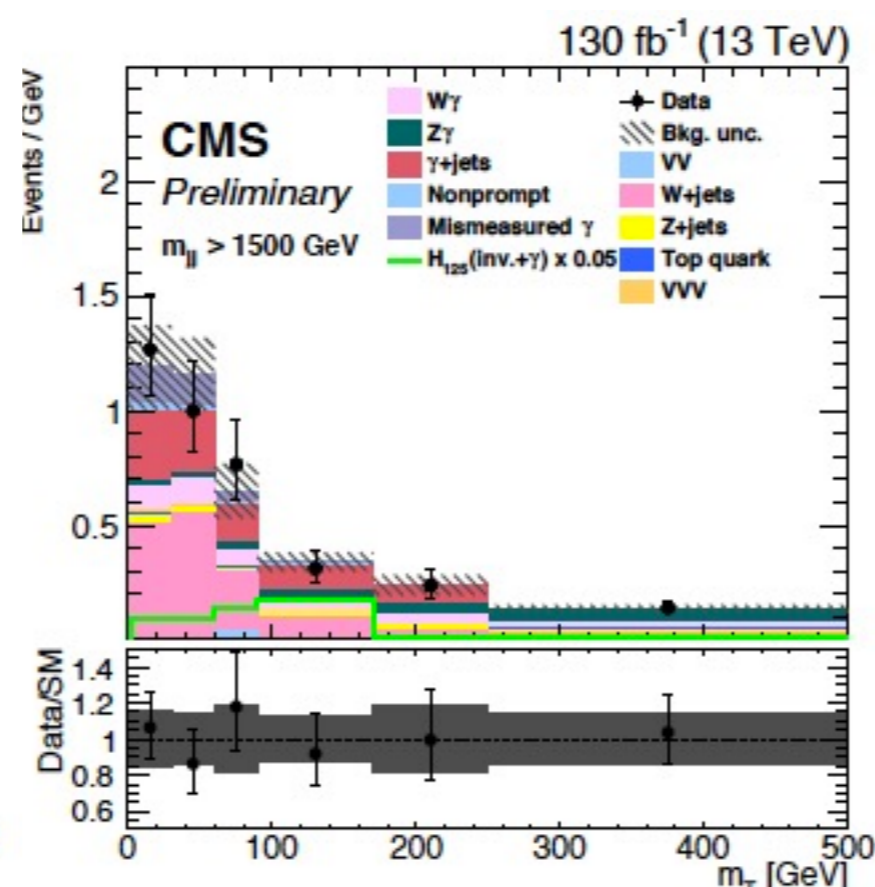
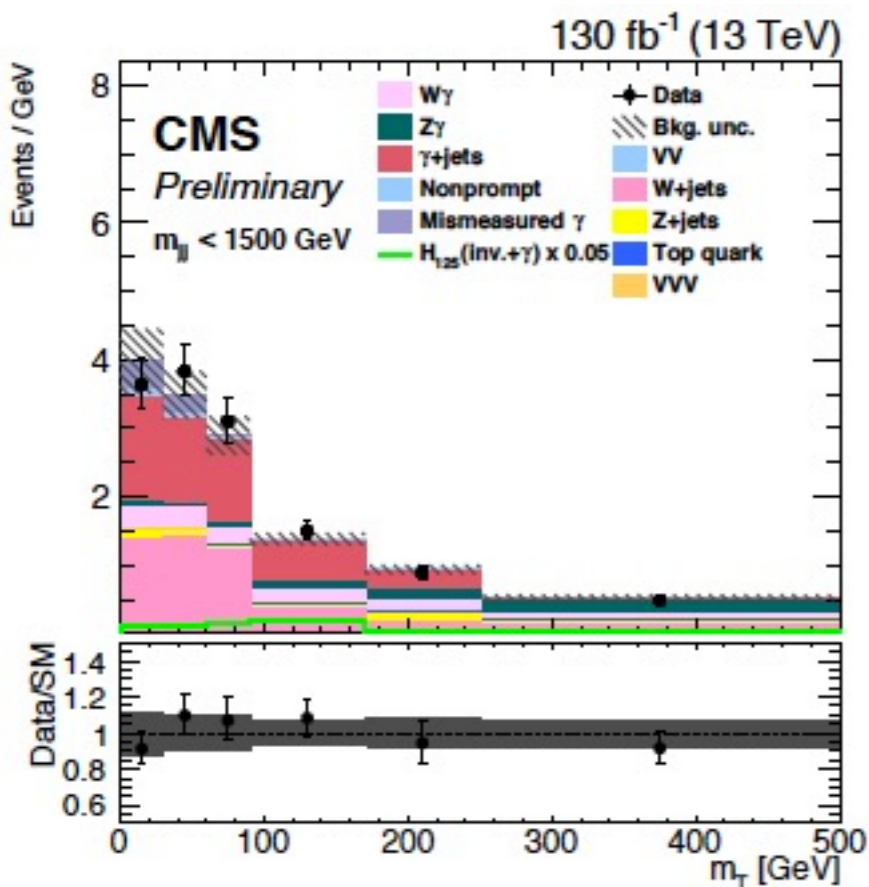
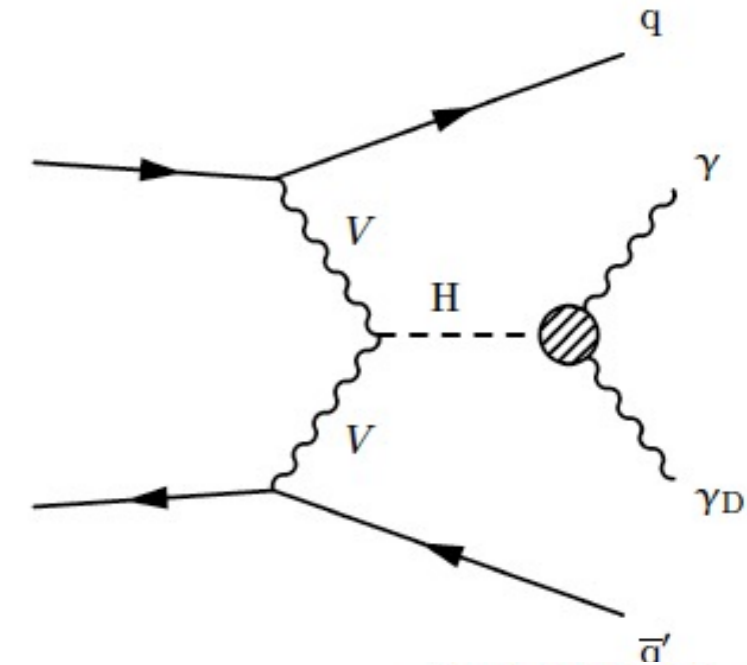
Dark Photon: Higgs VBF Channel

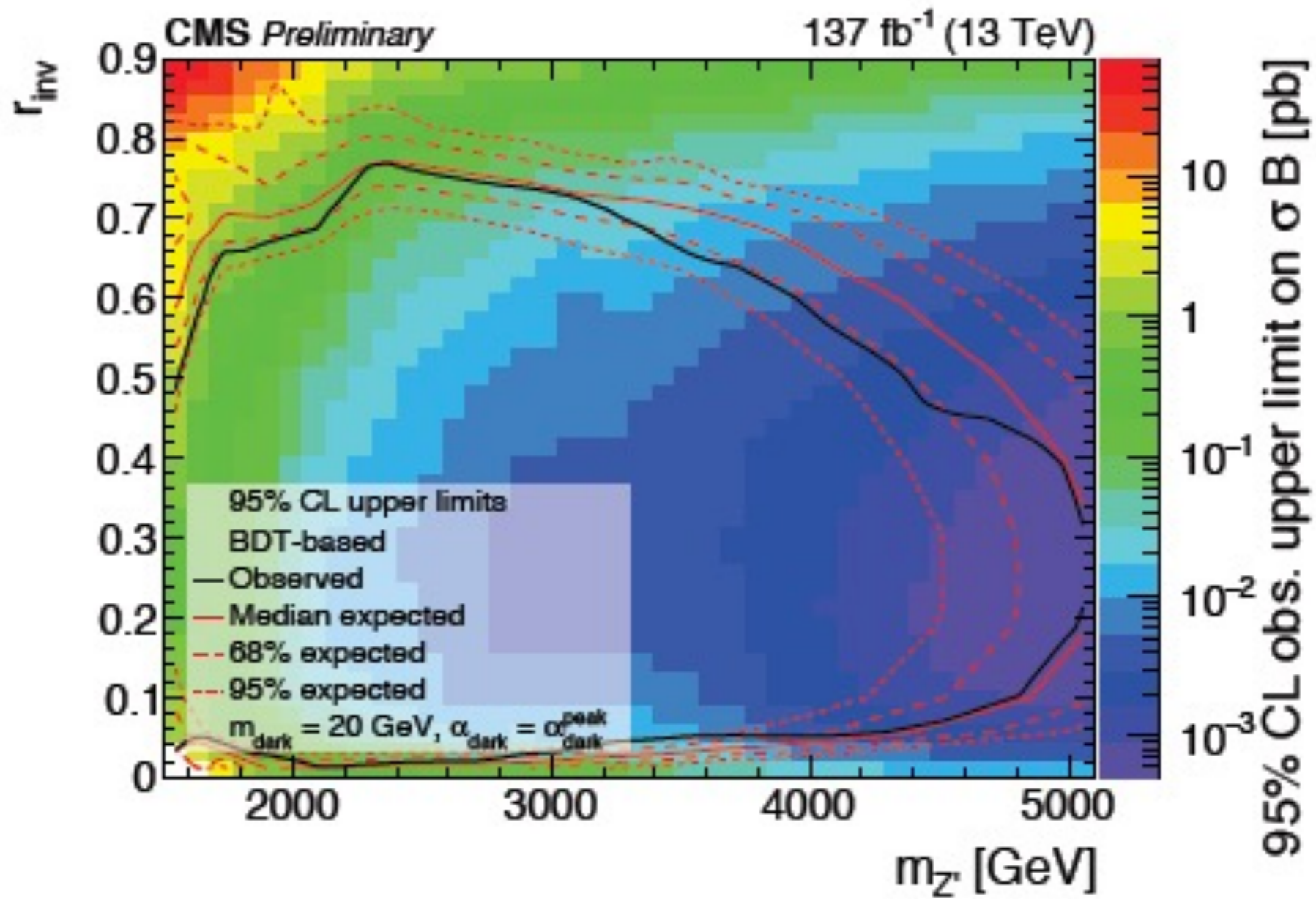


JHEP 03(2021) 011

EXO-20-005

- Isolated single photon, dark photon remains undetected
- Two high P_T VBF jets with high mass (> 500 GeV), large MET
- Backgrounds: $W(l\nu)+\gamma$, $Z(\nu\nu)+\gamma$, γ +jet are the largest
- Fit to M_T distribution for discrimination





Displaced Low Mass Di-Muon Search



L1 trigger seeds

- ▶ DoubleMu(4/4p5)_SQ_OS_dR_Max1p2 (2017/2018)
- ▶ DoubleMu0er1p4_SQ_OS_dR_Max1p4
- ▶ DoubleMu_15_7

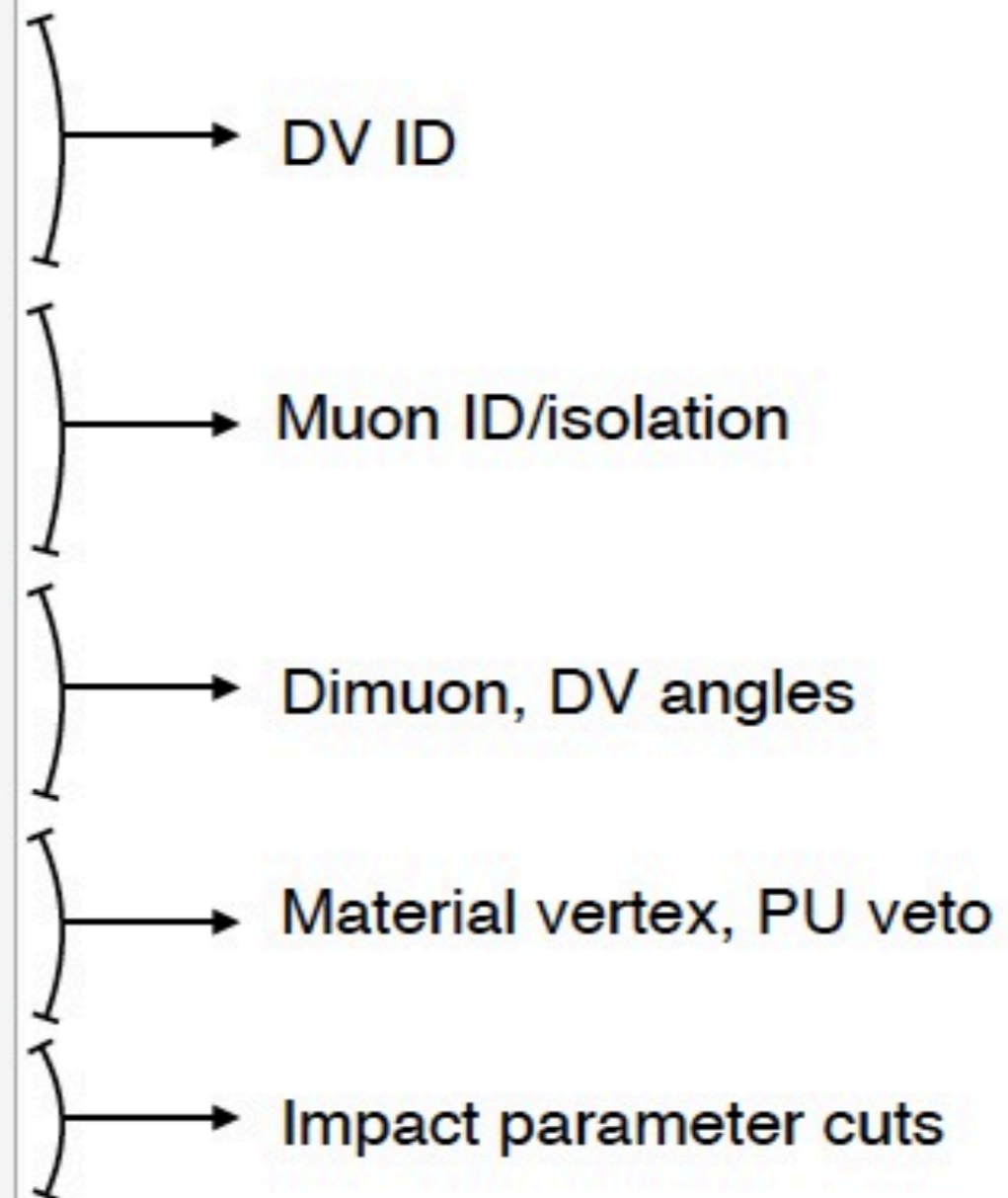
Baseline selections

At least 2 OS muons and 1 DV in collections, then

- ▶ **DV**
 - ▶ (x, y, z) errors $< (0.05, 0.05, 0.1)$ cm
 - ▶ $\chi^2/\text{ndof} < 5$
 - ▶ $l_{xy} < 11$ cm
- ▶ **Muon** ($p_T > 3$ GeV, $|\eta| < 2.4$)
 - ▶ **ID**
 - ▶ Num. tracker layers with meas. > 5
 - ▶ $\chi^2/\text{ndof} < 3$
 - ▶ **Isolation**
 - ▶ Relative track iso. < 0.1
 - ▶ ΔR with closest jet > 0.3
- ▶ **Dimuon kinematics**
 - ▶ $|\Delta\phi(\mu_1, \mu_2)| < 2.8$
 - ▶ $|\Delta\phi(\mu\mu, \overline{DV})| < 0.02$

Additional selections

- distance(DV, pixel modules) > 0.05 cm
- expected \geq observed pixel hits
- $\log_{10} |\Delta\eta_{\mu\mu} / \Delta\phi_{\mu\mu}| < 1.25$
- muon $|d_{xy} / \sigma_{d_{xy}}| > 2$
- muon $|d_{xy}| / (l_{xy} m_{\mu\mu} / p_T^{\mu\mu}) > 0.1$



Dark Sector: Big Picture

From Battaglieri et al., arXiv:1707.04591

Dark Sector Candidates, Anomalies, and Search Techniques

