Dark showers in ATLAS and CMS

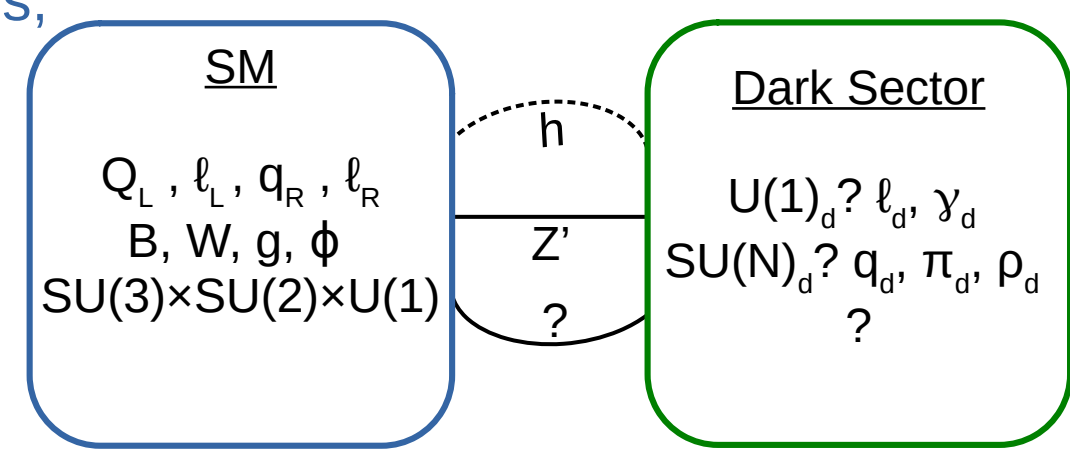
- Introduction
- Emerging jets
- Displaced jets
  - From ZH production with H decays
  - From pair production of neutral scalars
- RECAST from displaced jets: dark-photon jets
- Summary/Outlook

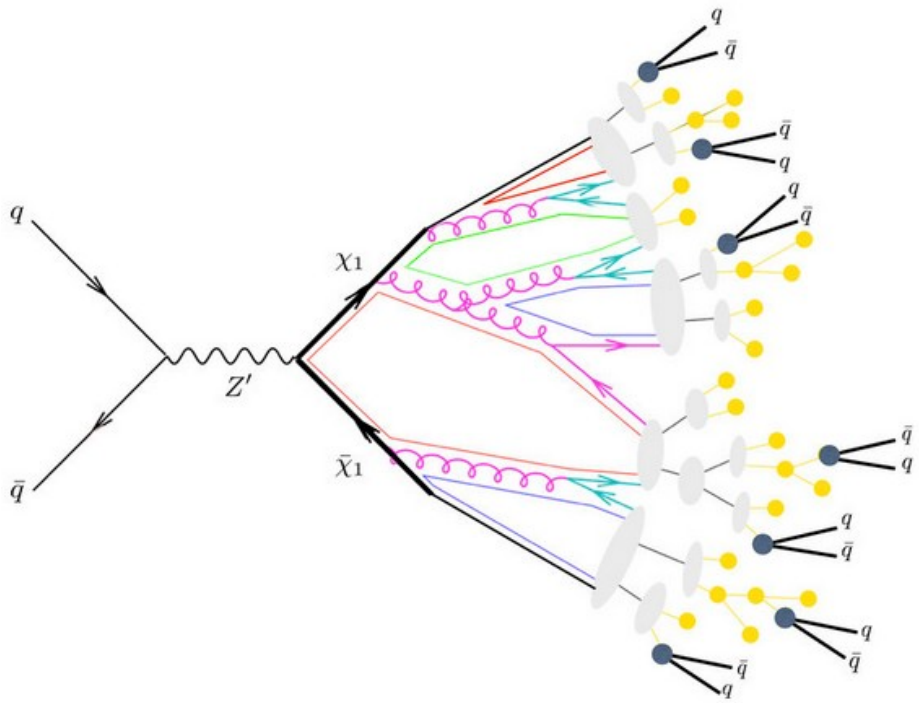
UNIVERSITY of ROCHESTER

Aran Garcia-Bellido
for the ATLAS and CMS collaborations

The dark sector

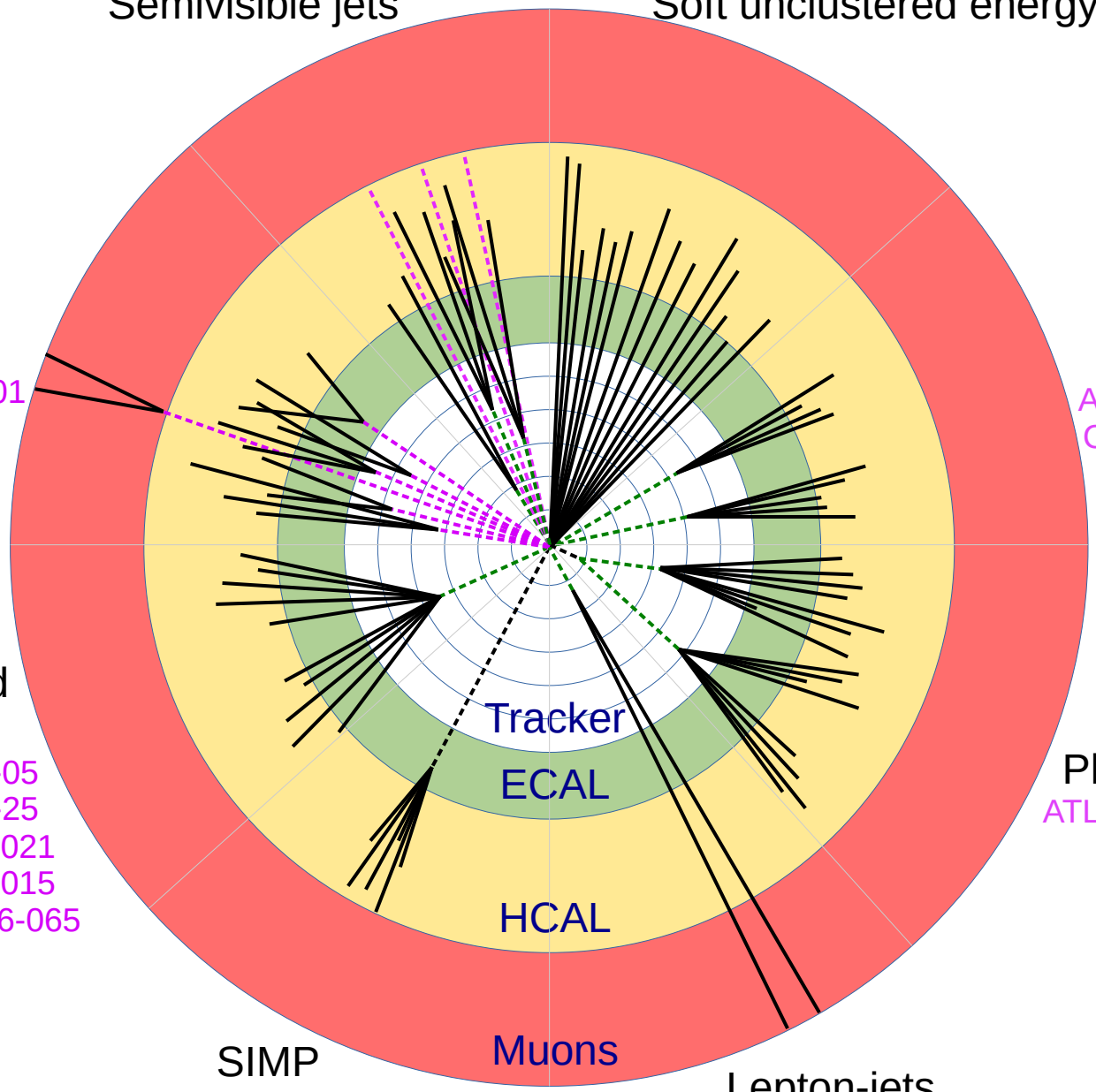
- A very rich phenomenology, depending on the underlying model (symmetries), mediator, couplings, number of families, and masses
  - Lepton-jets, photons, new hadronic showers
  - Multiplicity may be very high or low
  - May have boosted signals, missing energy...
- Lifetime: considered a free parameter
  - Prompt: hadronic exotic searches (resonant & non-resonant)
  - Long lived: striking new signatures
- Challenging analyses
  - Often need complex trigger strategies
  - Novel final states that require dedicated reconstruction techniques
    - New algorithms, taggers
  - Exciting challenges for experiments!





Lisanti

Many different signatures



Semivisible jets

Soft unclustered energy

Emerging jets
CMS-EXO-18-001

Higgs mediated DM
ATL-CONF-21-005
CMS EXO-20-003

Displaced Jets
ATL-EXO-17-05
ATL-EXO-17-25
CMS-EXO-19-021
CMS-EXO-20-015
LHCb-PAPER-16-065

Dark Photon jets
ATL-PUB-20-007

SIMP Trackless jets
CMS-EXO-17-010

Lepton-jets
ATL-EXO-14-09
LHCb-PAPER-2017-038

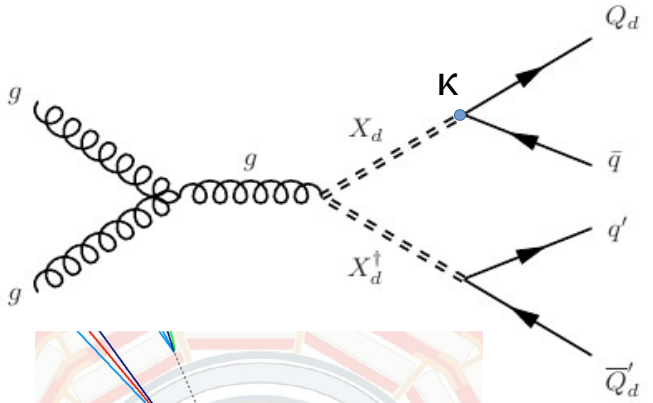
CMS: Emerging jets

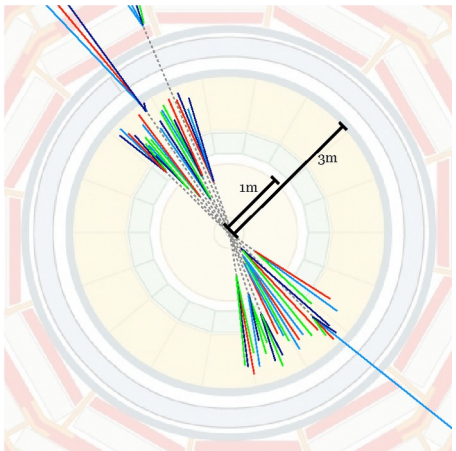
arXiv:1810.10069

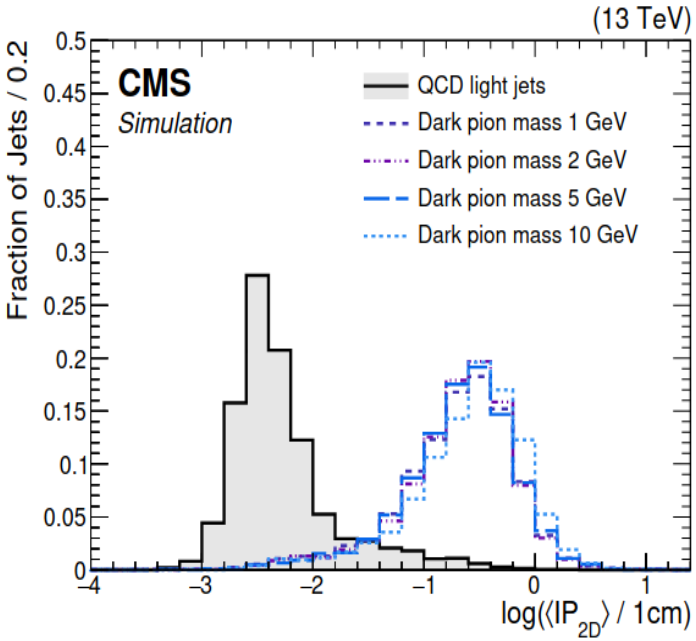
- Pair produced bifundamental scalars ($X_d \rightarrow Q_d\ q$)
- Dark quarks Q_d hadronize in hidden sector
  - Dark pions π_d have lifetime and then decay to SM

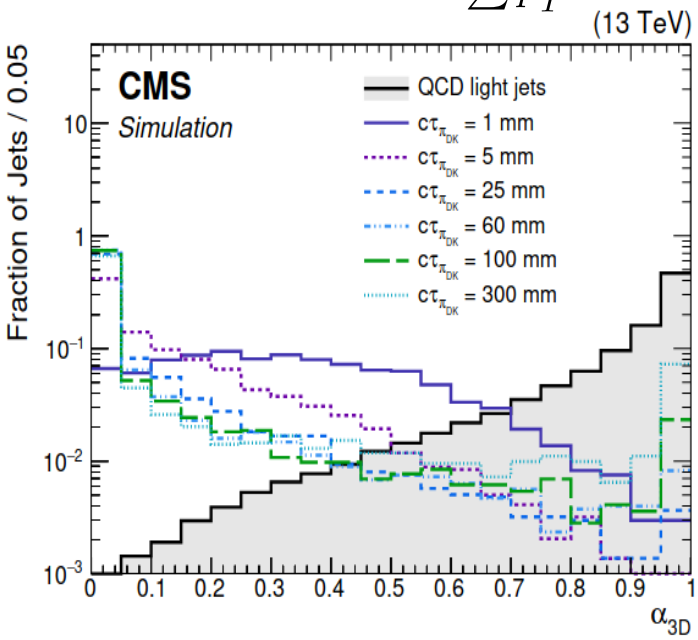
$$c\tau \approx 80\,\text{mm}\left(\frac{1}{\kappa^4}\right)\left(\frac{2\,\text{GeV}}{f_{\pi_\text{d}}}\right)^2\left(\frac{100\,\text{MeV}}{m_{down}}\right)^2\left(\frac{2\,\text{GeV}}{m_{\pi_\text{d}}}\right)\left(\frac{m_{X_\text{d}}}{1\,\text{TeV}}\right)^4$$

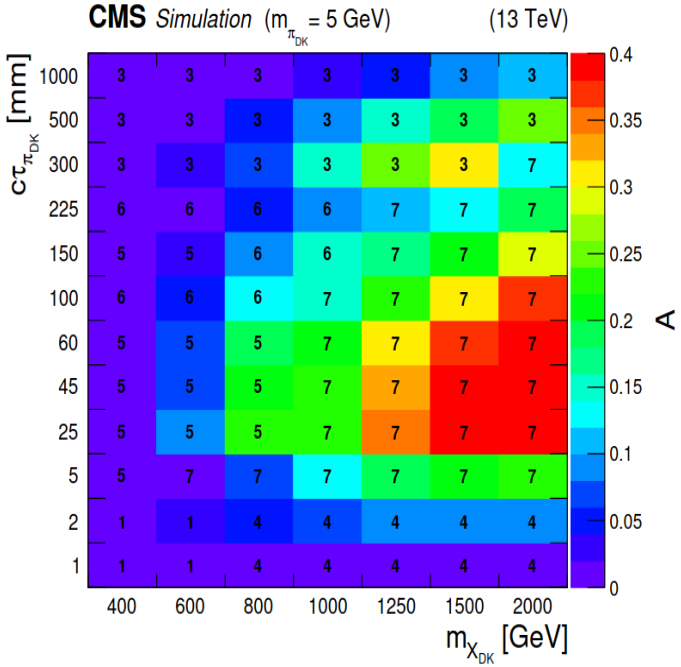
  - Multiple secondary vertices within same jet
- Signature: 2 emerging jets + 2 prompt jets
- Selection: 4 AK4 jets, $|\eta|<2$ with $H_T>900$ GeV
  - 7 signal regions based on:
    - Median of IP_{2D} of tracks within jet
    - p_T fraction of "prompt" tracks in jet $\alpha_{PV_i} = \frac{\sum_{trk\in PV_i} p_T^{trk}}{\sum p_T^{trk}}$











CMS: Emerging jets background estimate

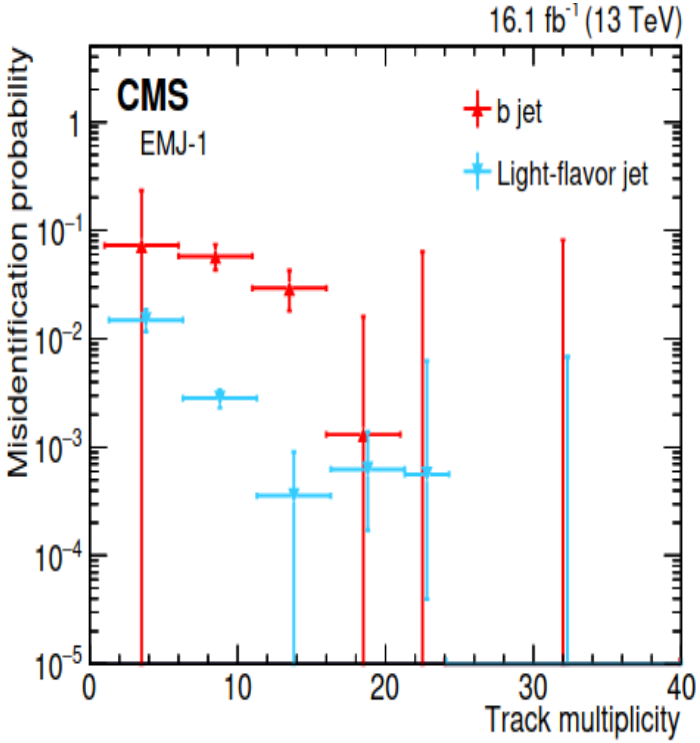
- Signal consists of tracks originating from several vertices at varying IP from PV
  - Sub-jet axes point out radially from PV
  - Heavy flavor jets could mimic the signature of short π_d lifetime
- Multijet QCD (light and b-jets) is the main background
- Estimate fake rate in two γ+jets CRs in data, one with heavy flavor and one without
  - The b-jet fraction of each CR (f_b) is fitted to two MC templates (light and b jets)

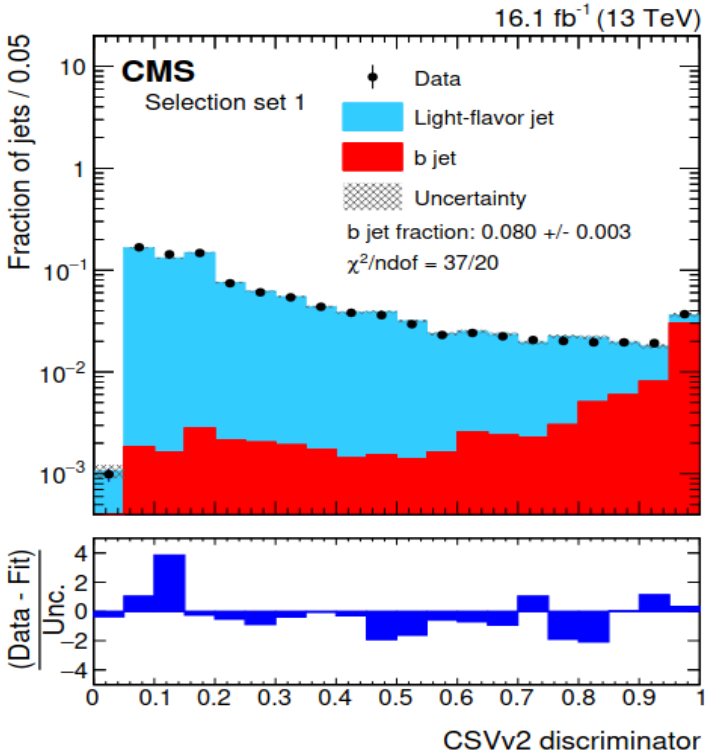
$$\begin{pmatrix}\epsilon_{f1}\\ \epsilon_{f2}\end{pmatrix} = \begin{pmatrix} f_{b1} & 1-f_{b1}\\ f_{b2} & 1-f_{b2}\end{pmatrix}\begin{pmatrix}\epsilon_{fb}\\ \epsilon_{fl}\end{pmatrix}$$

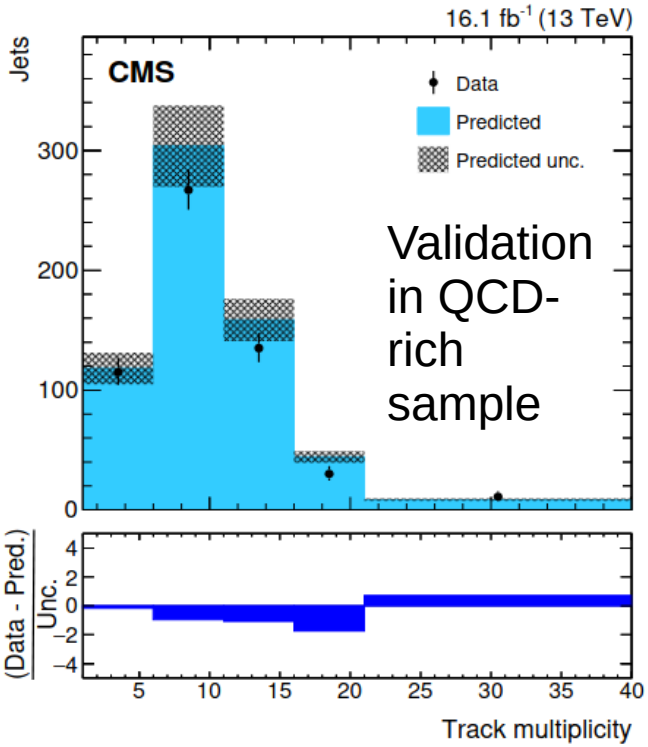
$$\begin{pmatrix}\epsilon_{fb}\\ \epsilon_{fl}\end{pmatrix} = \begin{pmatrix} \frac{1-f_{b2}}{f_{b1}-f_{b2}} & \frac{-(1-f_{b1})}{f_{b1}-f_{b2}}\\ \frac{-f_{b2}}{f_{b1}-f_{b2}} & \frac{f_{b1}}{f_{b1}-f_{b2}}\end{pmatrix}\begin{pmatrix}\epsilon_{f1}\\ \epsilon_{f2}\end{pmatrix}$$

the ϵ calculated bin-by-bin in n_{trk}

$$\epsilon_f = \epsilon_{fb} f_b + \epsilon_{fl}(1-f_b) \qquad P(EMJ) \propto \epsilon_f \epsilon_f (1-\epsilon_f)(1-\epsilon_f) + \ldots$$



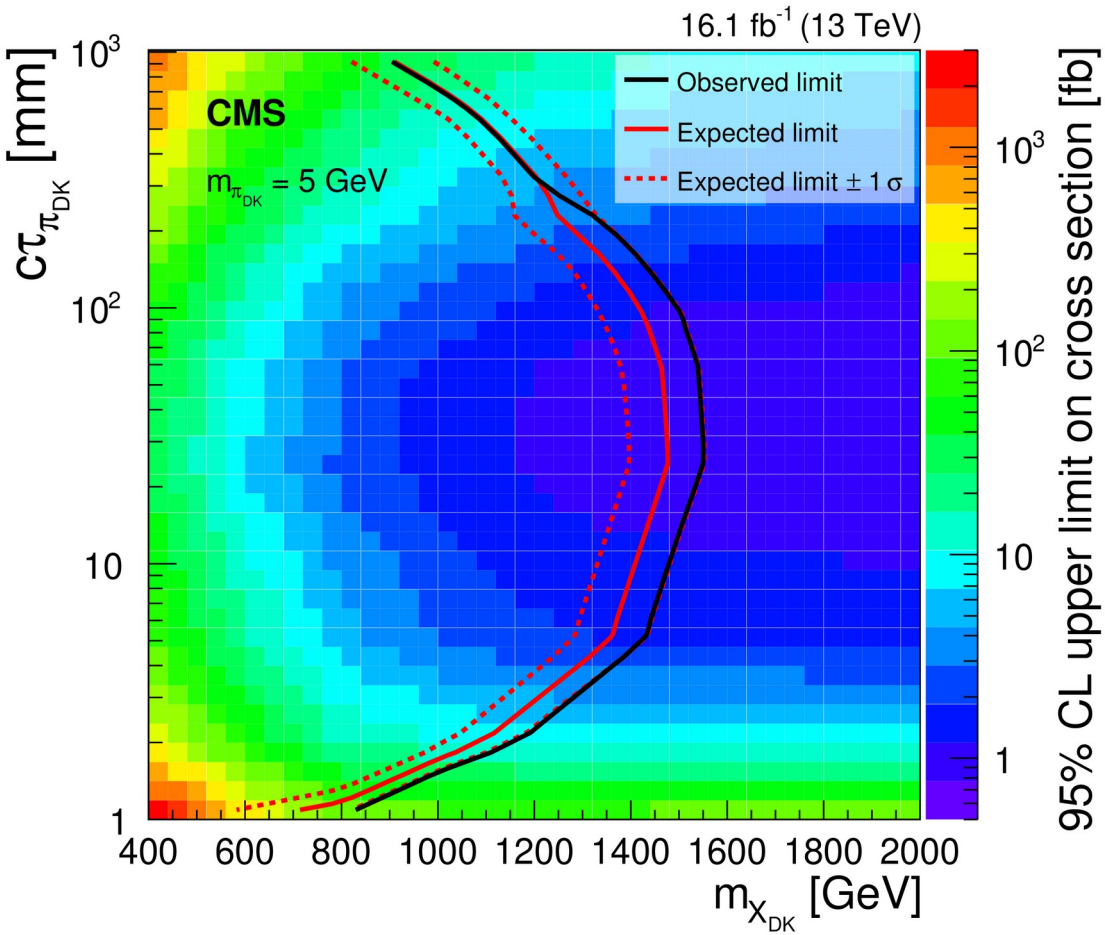




CMS: Emerging jets results

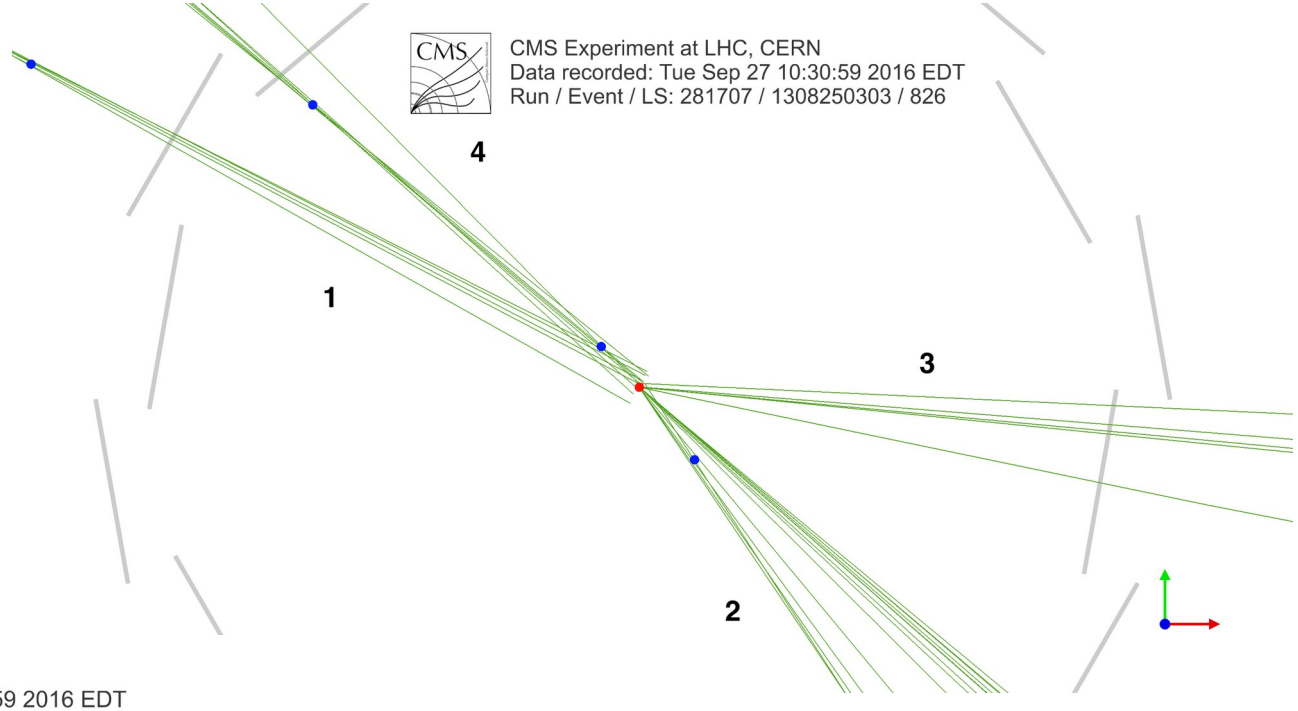
- Observed events in agreement with expected bkgd. in all 7 SR

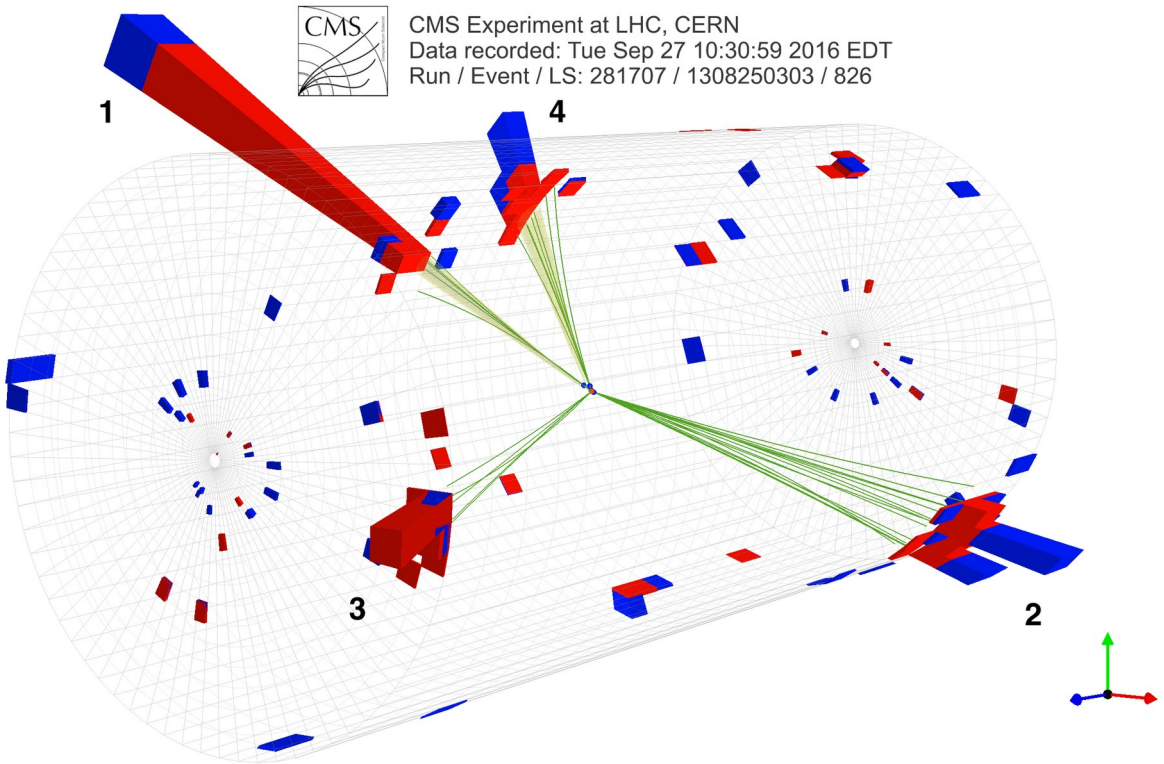
Set number	Expected	Observed	Signal	Model parameters		
				$m_{X_{DK}}$ [GeV]	$m_{\pi_{DK}}$ [GeV]	$c\tau_{\pi_{DK}}$ [mm]
1	$168 \pm 15 \pm 5$	131	36.7 ± 4.0	600	5	1
2	$31.8 \pm 5.0 \pm 1.4$	47	$(14.6 \pm 2.6) \times 10^2$	400	1	60
3	$19.4 \pm 7.0 \pm 5.5$	20	15.6 ± 1.6	1250	1	150
4	$22.5 \pm 2.5 \pm 1.5$	16	15.1 ± 2.0	1000	1	2
5	$13.9 \pm 1.9 \pm 0.6$	14	35.3 ± 4.0	1000	2	150
6	$9.4 \pm 2.0 \pm 0.3$	11	20.7 ± 2.5	1000	10	300
7	$4.40 \pm 0.84 \pm 0.28$	2	5.61 ± 0.64	1250	5	225



Emerging jet candidate

- Event passes SR1 and SR5
- Jets 1 and 4 pass the EMJ criteria





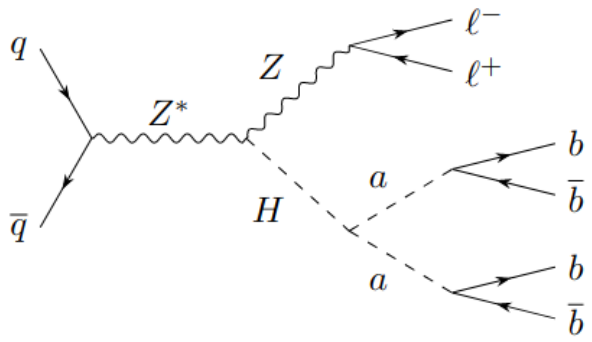
ATLAS: Higgs to displaced jets

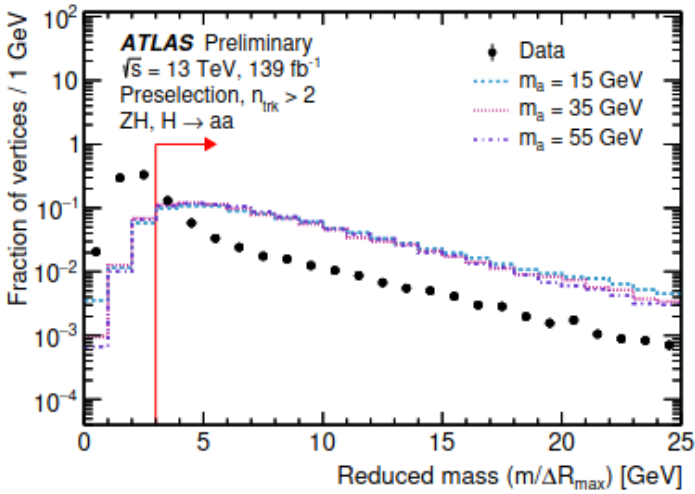
ATLAS-CONF-2021-005

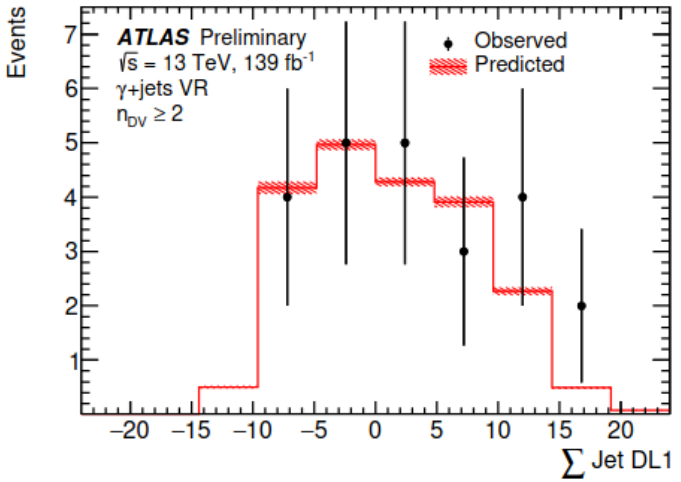
- New pseudoscalar boson a decaying exclusively to $b\bar{b}$, $Z \to \ell\ell$ used for trigger (allows reach to low jet p_T)
  - Sensitive to $2 < c\tau_a < 20$ mm
  - $M_a \in [15,55]$ GeV
- Extend std. reco. tracks to Large Radius Tracking
- Standard b-tag algos are ineffecient for long cτ
- DisplacedVertex algorithm: $N_{DVjets} \geq 2$
  - Prune for displaced tracks
  - $N_{trk}>2$, $m/\Delta R_{max}>3$GeV, $r/\sigma_r>100$, $\max|d_0|>3$mm
- At least one central jet with CHF<0.045 or $\alpha_{max}<0.05$

$$CHF = \frac{\sum p_T^{trk,|d_0|<0.5mm}}{p_T^{jet}} \qquad \alpha_{PV_i} = \frac{\sum_{trk \in PV_i} p_T^{trk}}{\sum p_T^{trk}}$$

- Bkg validation in orthogonal γ+jets sample
  - DV algo achieves similar efficiency as b-tagging DL1 algorithm

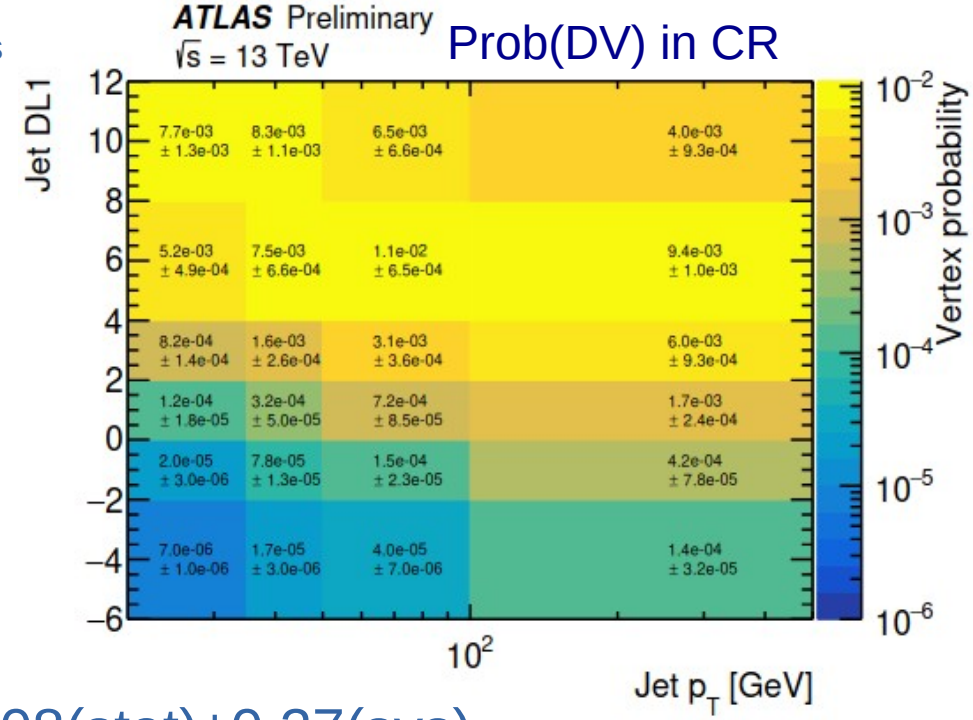




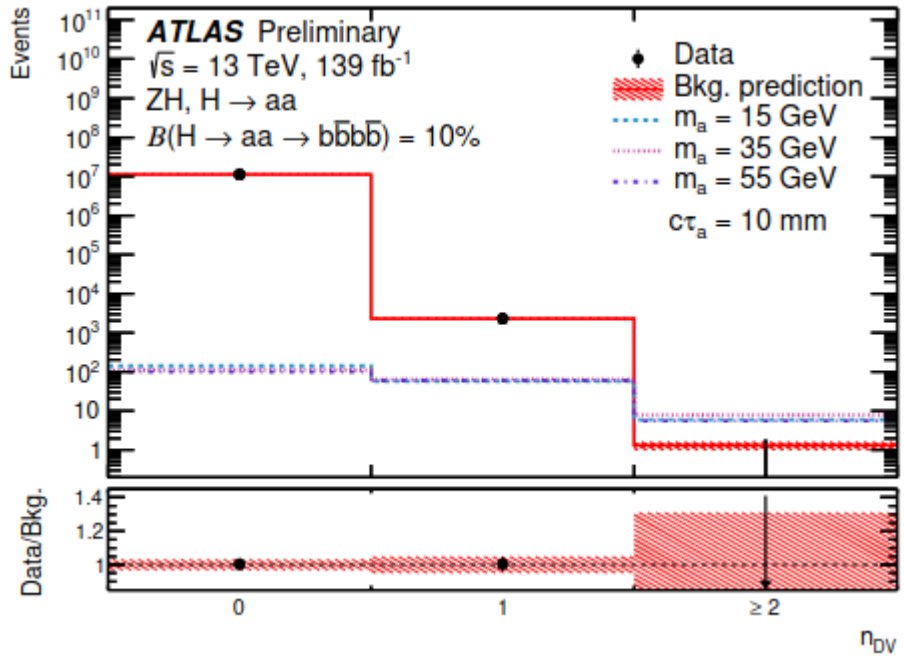


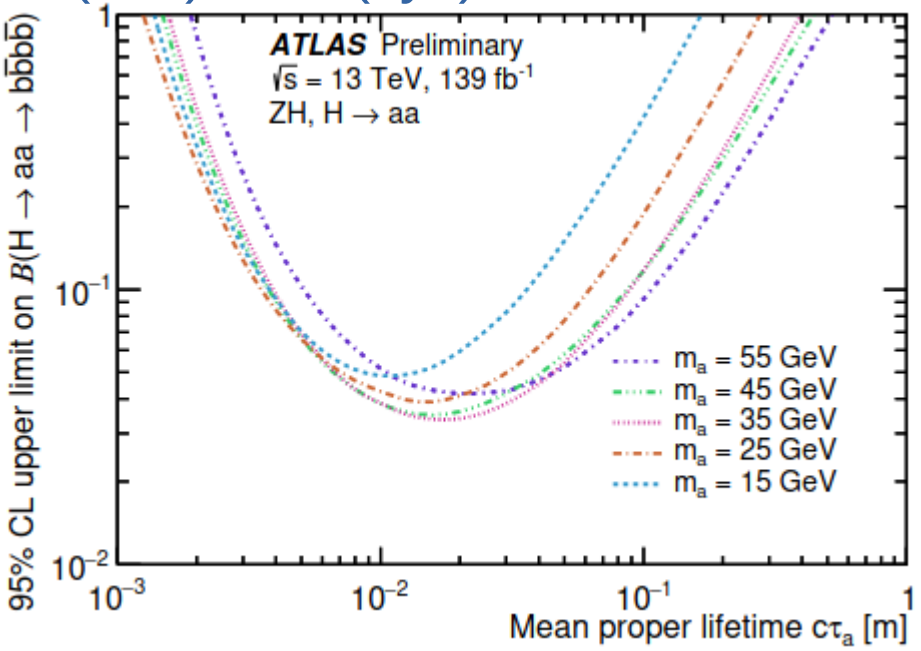
ATLAS: Higgs to displaced jets results

- Control regions defined based on N_{DVjets}
- Use CR to estimate bkgd in $n_{DV} \geq 2$



- No observed events, expected: 1.30±0.08(stat)±0.27(sys)

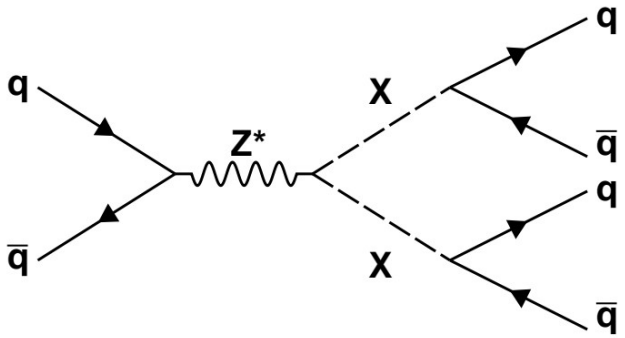




CMS: XX→qq qq displaced jets

1811.07991

- Pair-production of long-lived neutral scalar X with equal decays to u,d,c,s,b.
- Use displaced jet trigger (H_T and track IP reqs)
- Dijet candidates from all possible pairs of jets (AK4)
- Adaptive vertex fitter (annealing) to find SV applied to each dijet candidate
- Preselection based on SV χ^2/ndof, m_{vtx}, p_T(vtx), second largest IP_{sig}, vtx track energy fraction in dijet, and ζ



$$\frac{\sum_{\text{track}\in\text{SV}} E_{\text{track}}}{\sum_{\text{track}\in\text{dijet}} E_{\text{track}}}$$

Secondary-vertex/dijet variable	Requirement
Vertex χ^2/n_{dof}	<5.0
Vertex invariant mass	>4 GeV
Vertex transverse momentum	>8 GeV
Second largest two-dimensional IP significance	>15
Vertex track energy fraction in the dijet	>0.15
ζ (charged energy fraction associated with compatible primary vertices)	<0.20

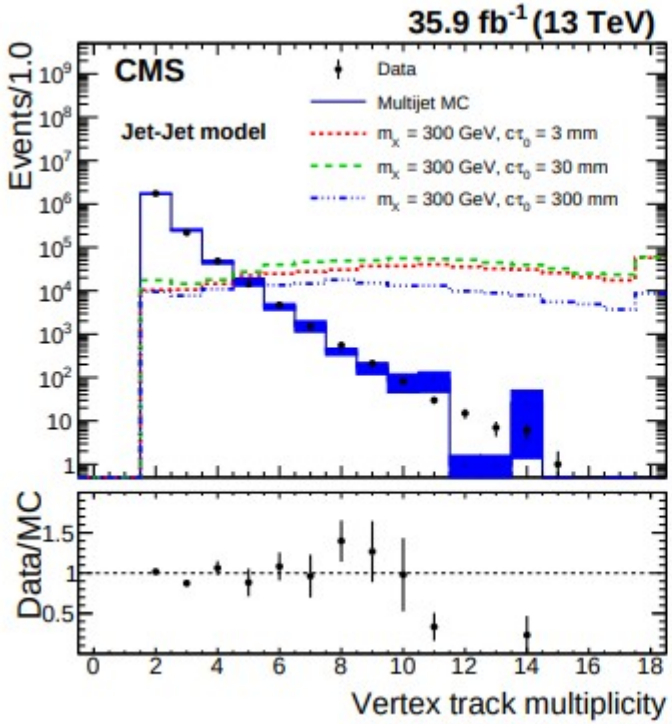
$$\zeta = \frac{\sum_{\text{track}\in\text{PV}_1} E^{\text{Jet}_1}_{\text{track}} + \sum_{\text{track}\in\text{PV}_2} E^{\text{Jet}_2}_{\text{track}}}{E_{\text{Jet}_1} + E_{\text{Jet}_2}}$$

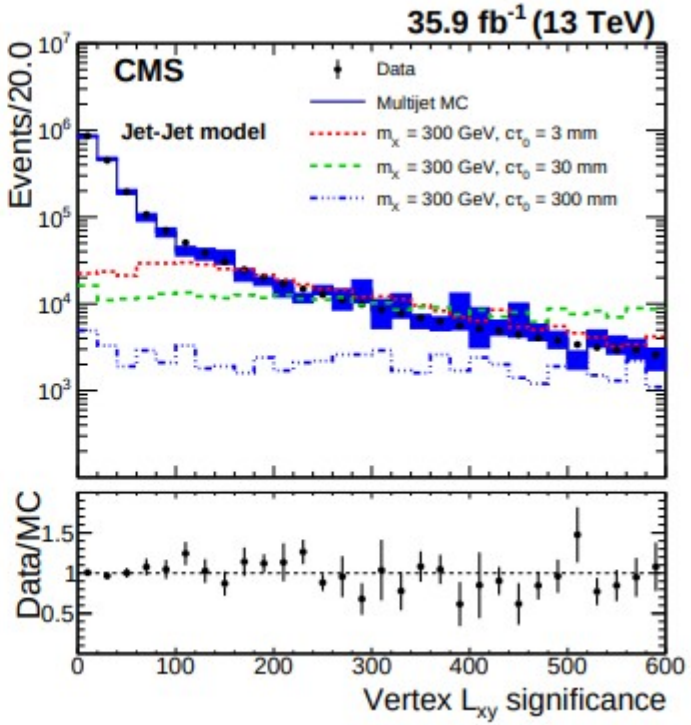
- Build likelihood discriminant based on: vertex track multiplicity; vertex L_{xy} significance; Cluster RMS

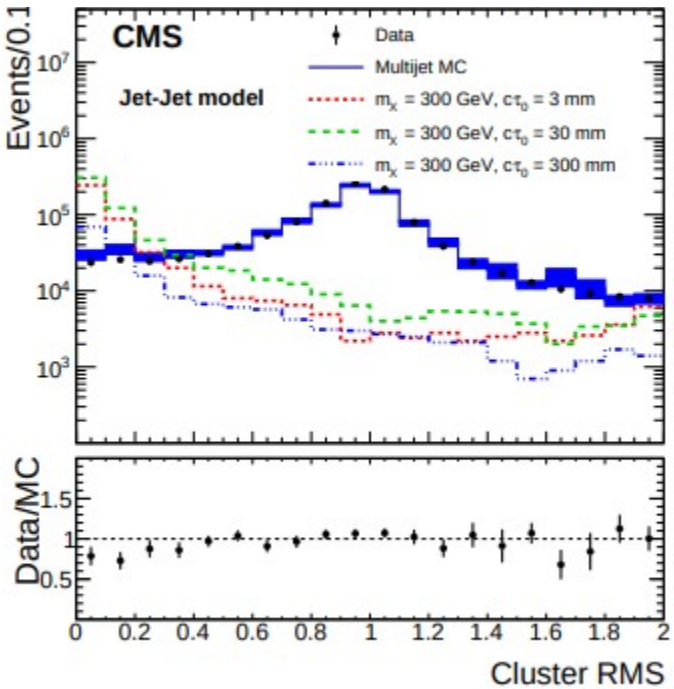
$$L^{\text{exp}}_{\text{xy}} = \frac{IP^{\text{track}}_{2D}}{\sin(\phi_{\text{track}} - \phi_{\text{dijet}})}\left(1 - \frac{|IP^{\text{track}}_{2D}|}{R}\right)$$

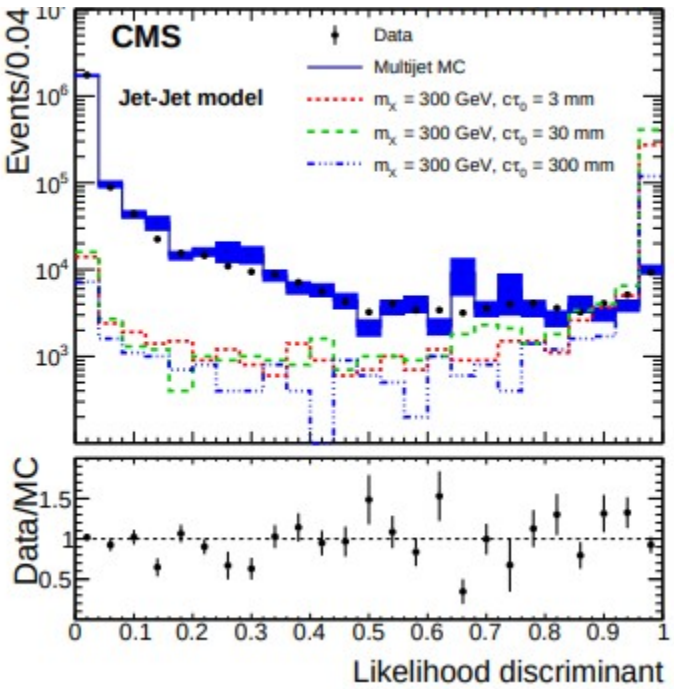
$$RMS_{\text{cluster}} = \sqrt{1/N_{\text{tracks}} \sum_{i=0}^{N_{\text{tracks}}} \frac{(L^{\text{exp}}_{\text{xy}}(i) - L_{\text{xy}})^2}{L^2_{\text{xy}}}},$$

CMS: XX→qq qq displaced jets Likelihood







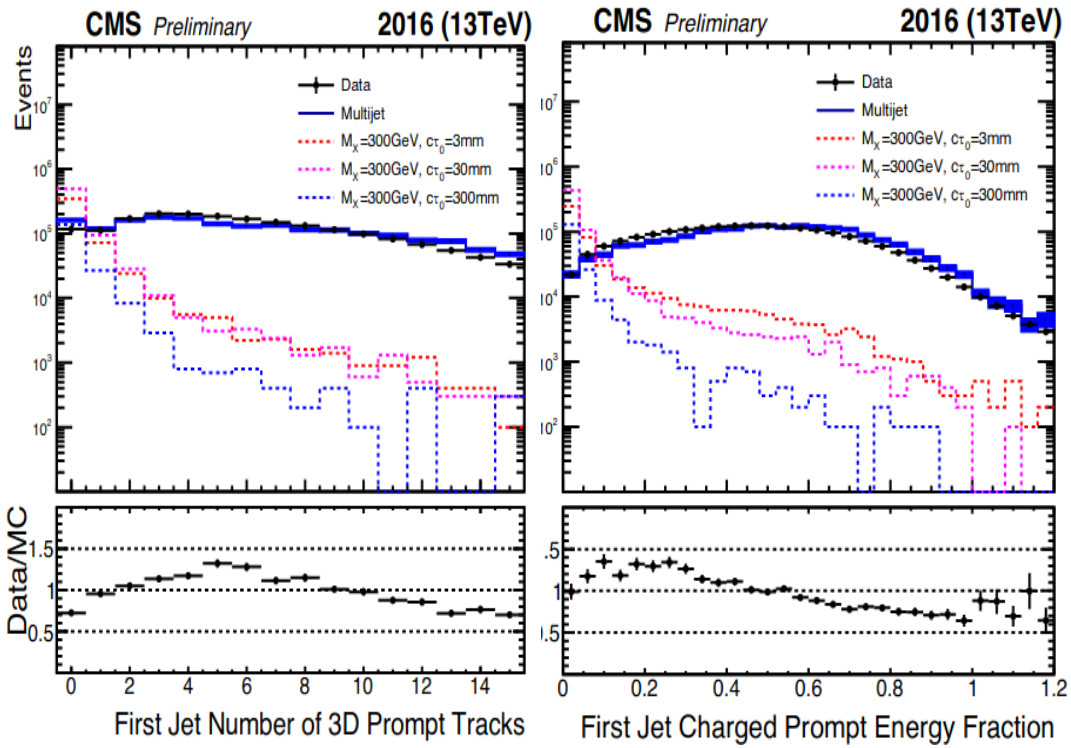


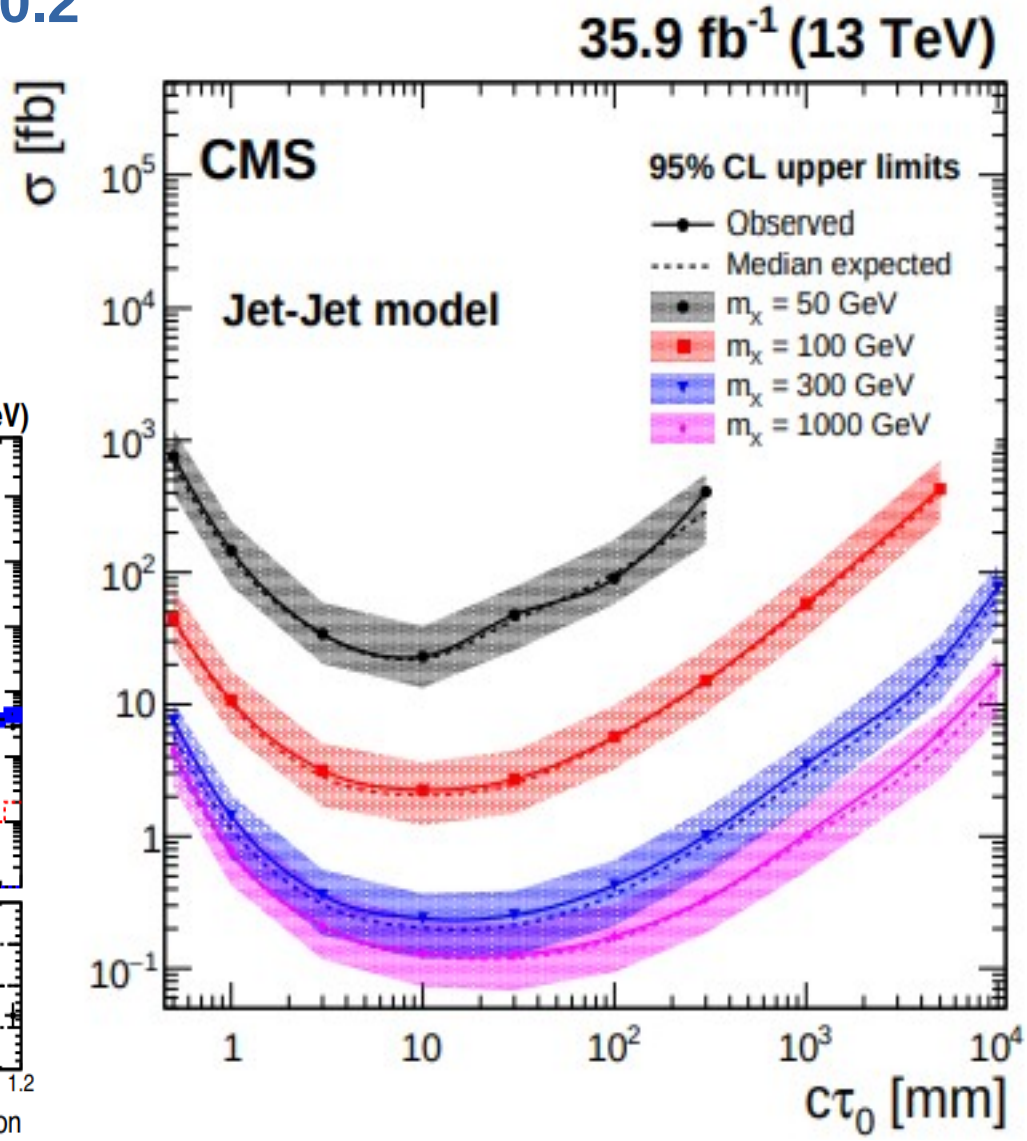
CMS: XX→qq qq displaced jets results

- Final selection also requires
  - For jet1: N(3D prompt tracks)≤1, CPEF<0.15
  - For jet2: N(3D prompt tracks)≤1, CPEF<0.13
  - Lhood>0.9993 → **N_{obs}=1; N_{exp}=1.0 ± 0.2**
- σ_{XX} > 0.2 fb are excluded for m_X > 1 TeV for $c\tau_0 \in [3, 130]$ mm
- The lowest σ_{XX} excluded is 0.13 fb, at $c\tau_0$ = 30 mm and m_X > 1 TeV

Charged prompt energy fraction:

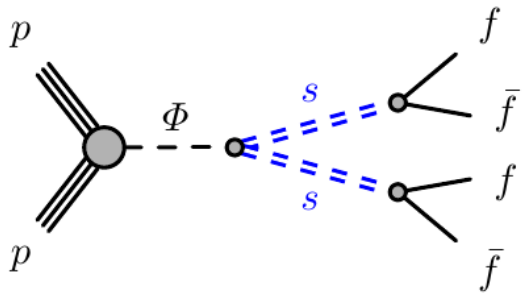
$$CPEF = \frac{\sum E^{trk,|d_0|<0.5mm}}{\sum E^{trk}}$$



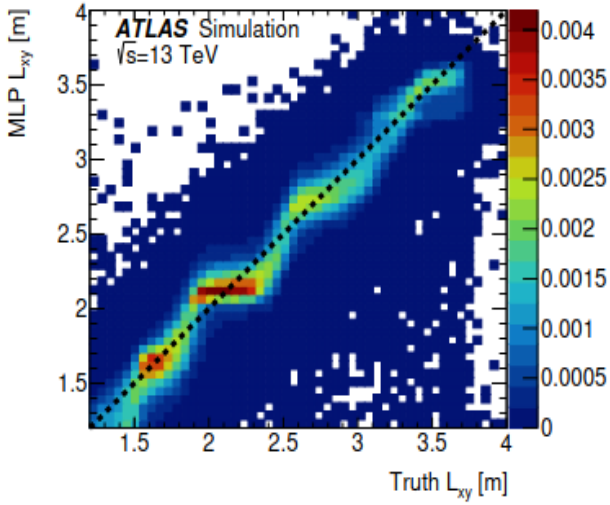


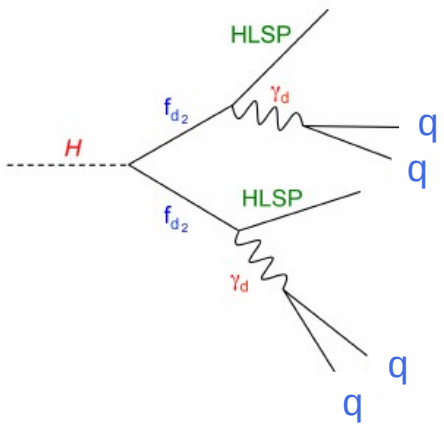
ATLAS: Displaced jets with RECAST

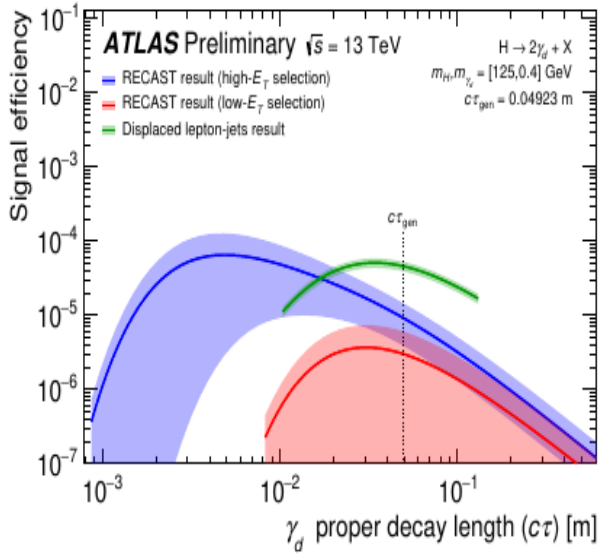
- Based on CalRatio displaced jets (decay in HCAL)
  - With dedicated CalRatio triggers for jets with high values of E_H/E_{EM}
    - Includes L1 topological selection → low m_Φ
  - Train NN with L_{xy}, L_z, E_H/E_{EM} to get L_{xy}, L_z for each jet
  - Then use BDT to classify each jet as LLP signal, SM multi-jet or Beam-Induced-Background
- Recast into Higgs mediator/dark photon production
  - Dark photons are boosted, decay into quarks
  - Validated with signal from original analysis
  - Powerful use of Analysis Preservation tools

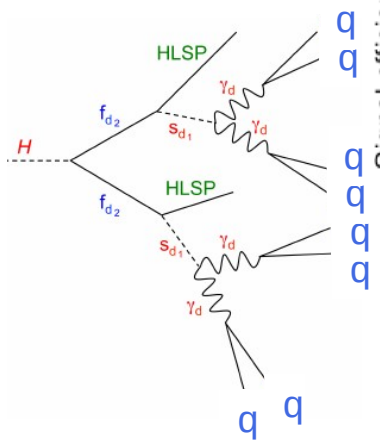


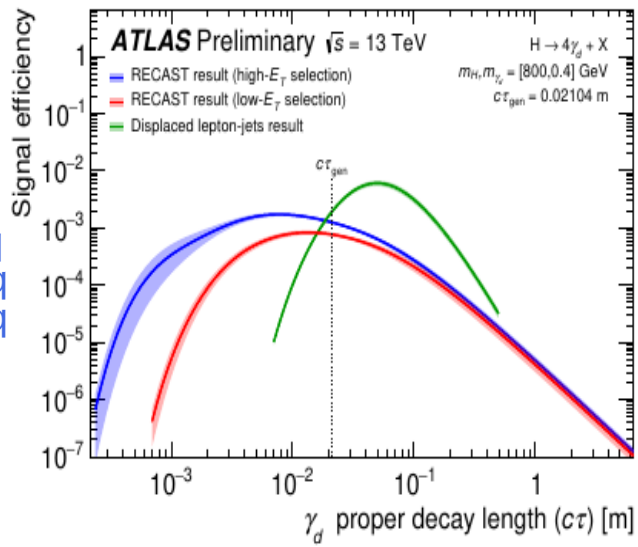
arXiv:1902.03094







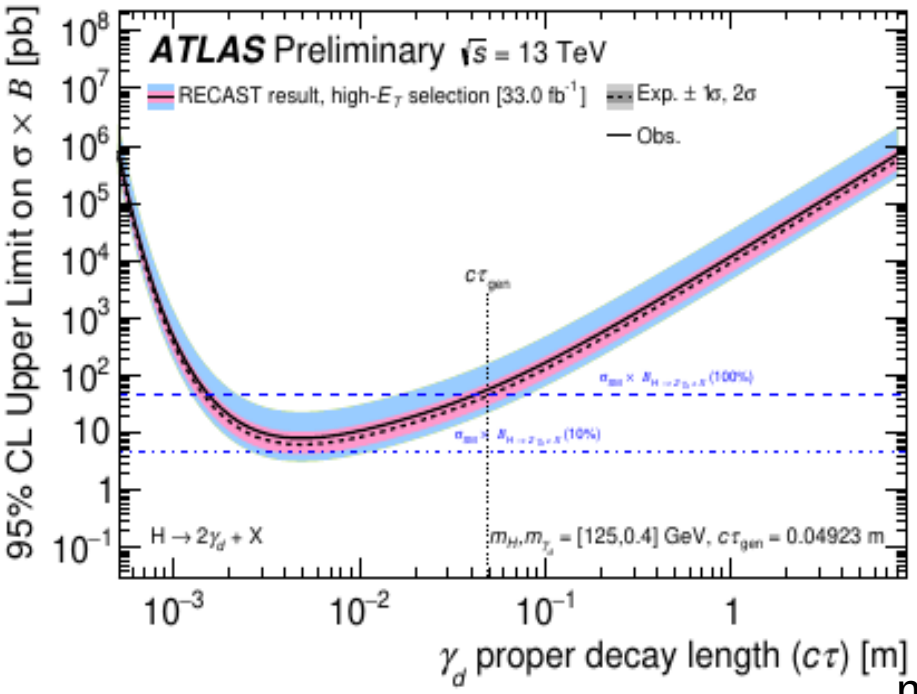


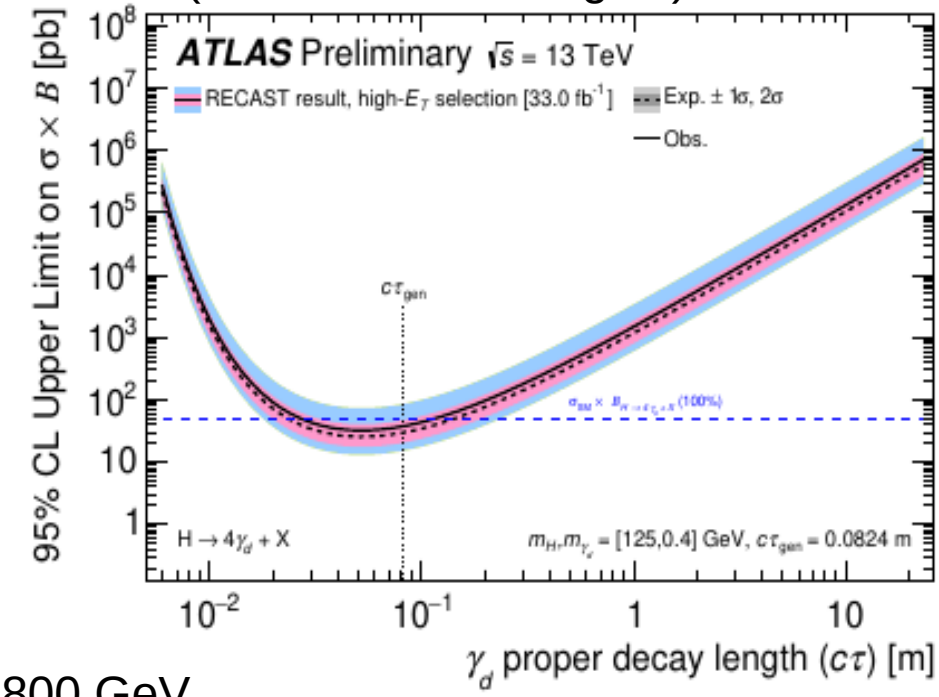


ATL-PHYS-PUB-2020-007

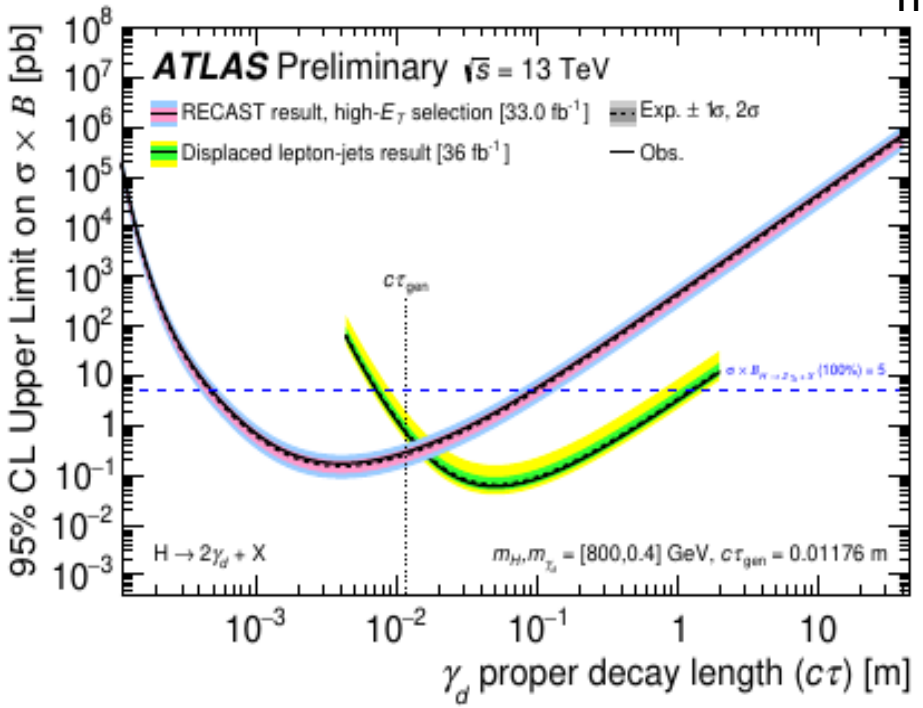
ATLAS: Dark-photon jets results

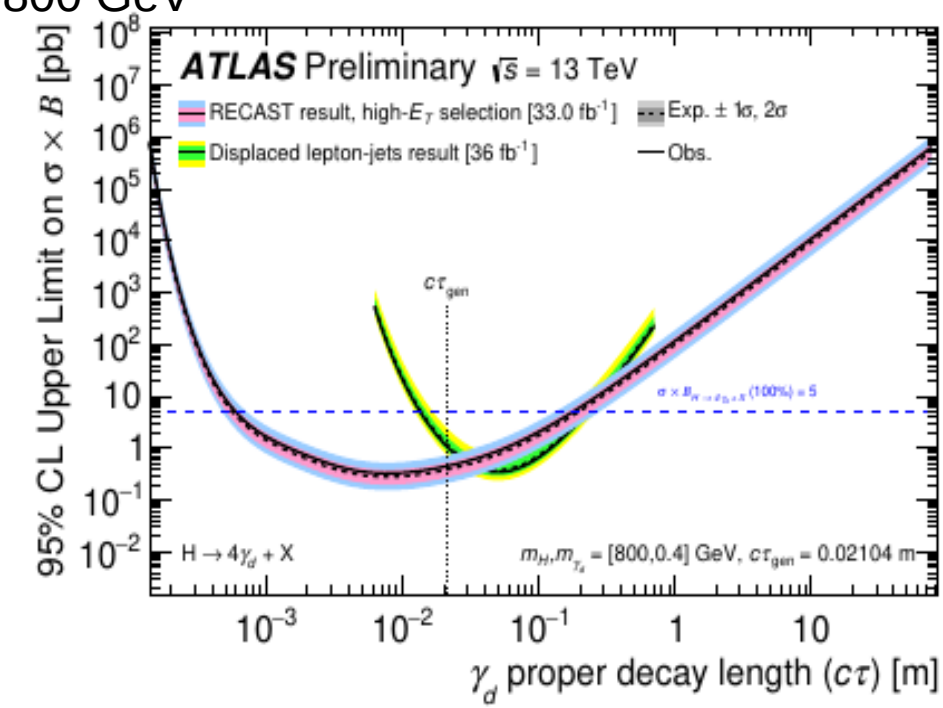
m_H=125 GeV (new limit in this region)





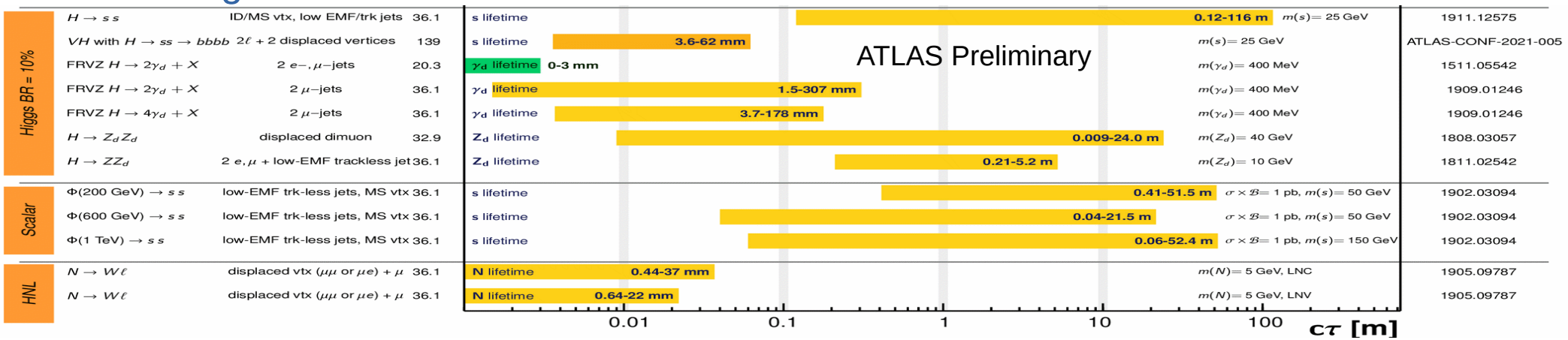
m_H=800 GeV

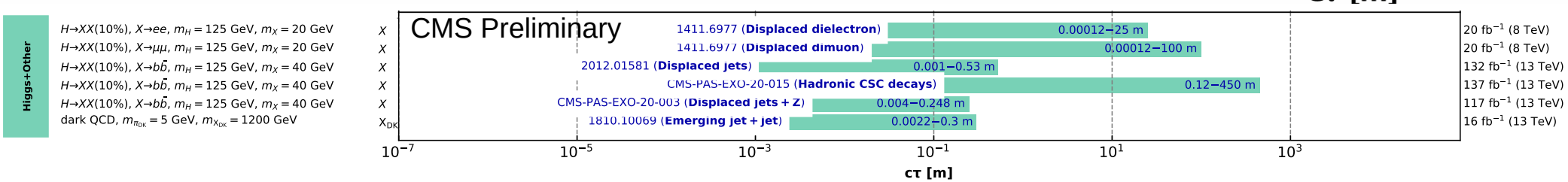




Summary/Outlook

- Exciting new signatures with dark shower phenomenology
  - No excess in the data so far
  - Investigating regions of parameter space for BSM previously unexplored at colliders
  - Still room for new searches in ATLAS and CMS
  - But stay tuned, several new analyses in the works!
- Strong collaboration with theorists to tune models, implement signal MC tools...
- Overlap with LLP searches can shed light on some models/final states
- Need to develop new triggers, reconstruction techniques, algorithms for jet tagging, and background estimation
- Detector upgrades will bring new trigger capabilities, better pointing calorimeters, more timing information...





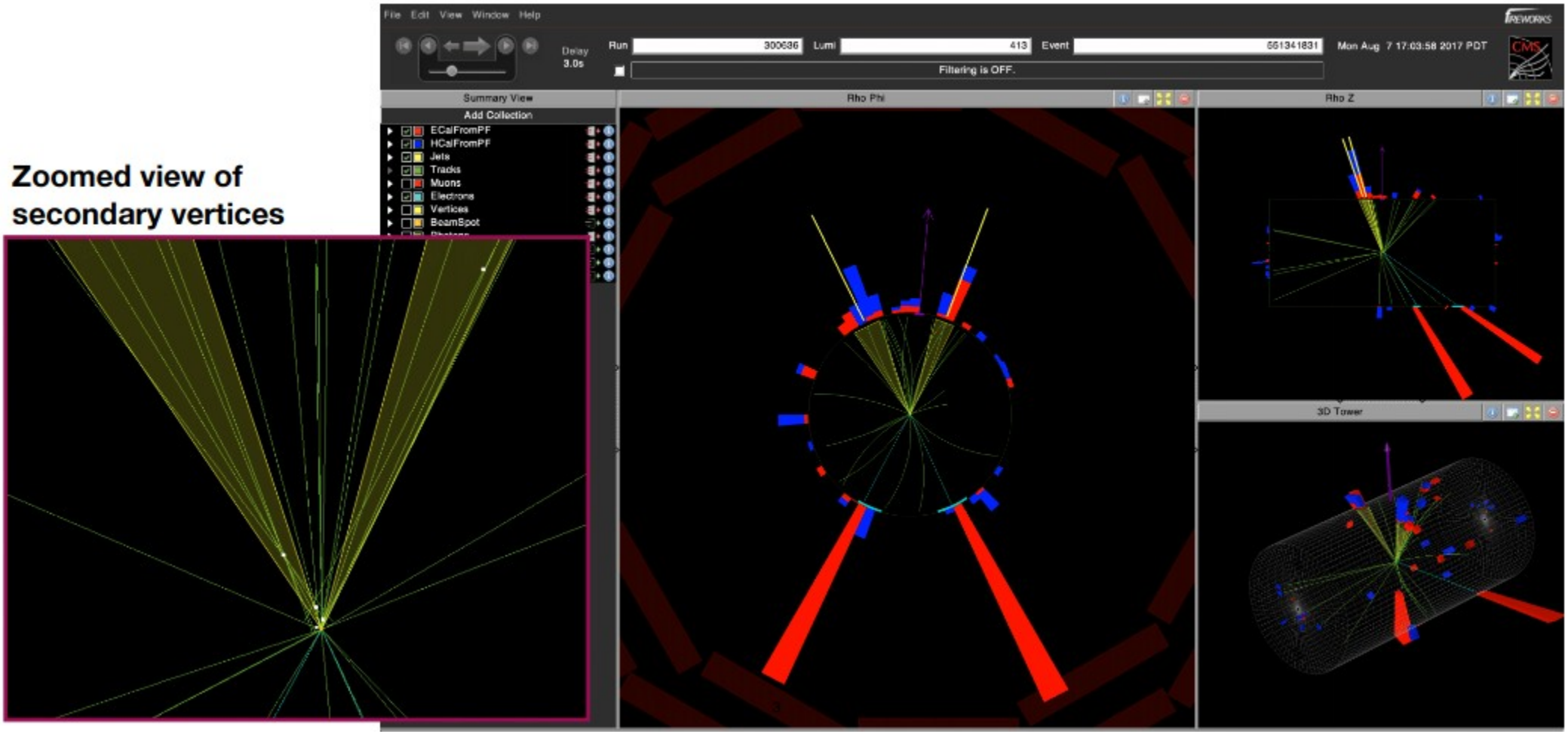
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

LHCP 2021

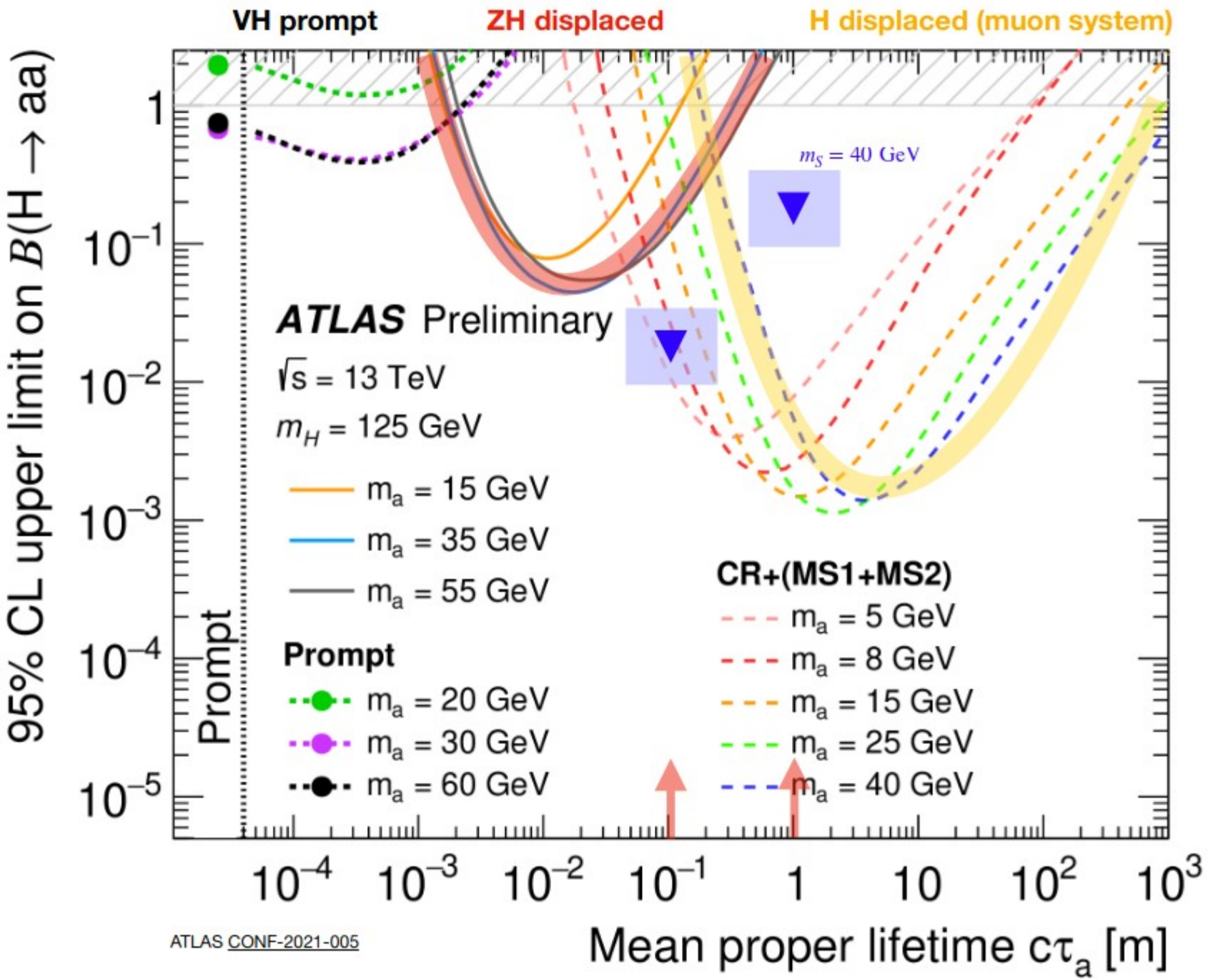
Extra material

- Z(ℓℓ)H, Higgs to displaced jets

CMS EXO-20-003



Complementarity of H decay searches



CMS: XX→qq qq displaced jets

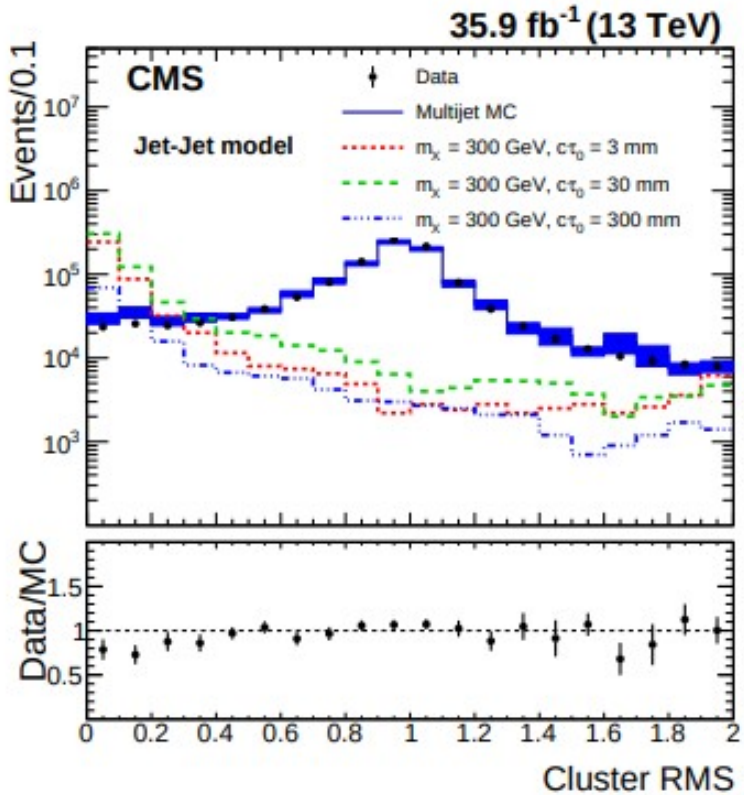
1811.07991

- By assuming the flight direction of the SV is aligned with the dijet direction, we can estimate the position of the SV using track parameters
  - Vertex L_{xy} can be estimated based on the track IP_{2D}, track curvature R and the dijet direction:

$$L_{xy}^{exp} = \frac{IP_{2D}^{track}}{\sin(\phi_{track} - \phi_{dijet})}\left(1 - \frac{|IP_{2D}^{track}|}{R}\right)$$

- Then tracks are clustered based on the similarity in L_{xy}^{exp} using hierarchical agglomerative clustering algorithm
- The cluster that is closest to the reconstructed vertex (i.e. AVF vertex) is chosen.

$$RMS_{cluster} = \sqrt{1/N_{tracks}\sum_{i=0}^{N_{tracks}} \frac{(L_{xy}^{exp}(i) - L_{xy})^2}{L_{xy}^2}},$$

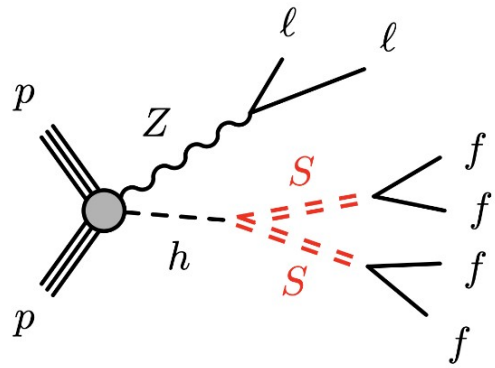


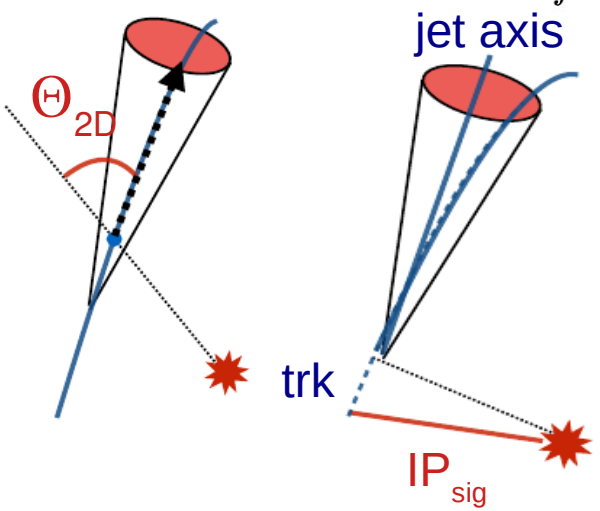
CMS: Higgs to displaced jets

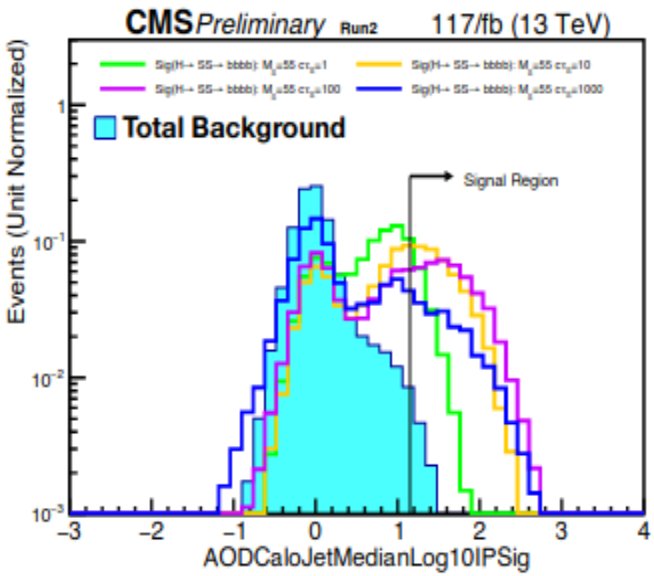
CMS EXO-20-003

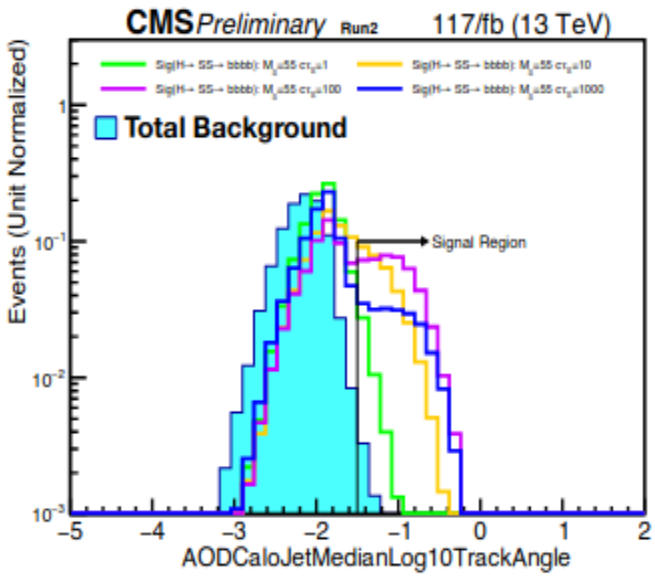
- Backgrounds:
  - 90% $Z \rightarrow \ell\ell$+jets: estimated in low Z p_T CR
  - 10% tt: estimated in eμ+jets CR
- Tagging variables for DV algorithm:
  - Track IP_{sig} in xy ; α_{max}
  - Track angle Θ_{2D}: between ray from PV to track innermost hit and jet direction
  - Jets are DV: $\log(IP_{sig})>1.25$, $\log(\Theta_{2D})>-1.5$, $\alpha_{max}<0.45$

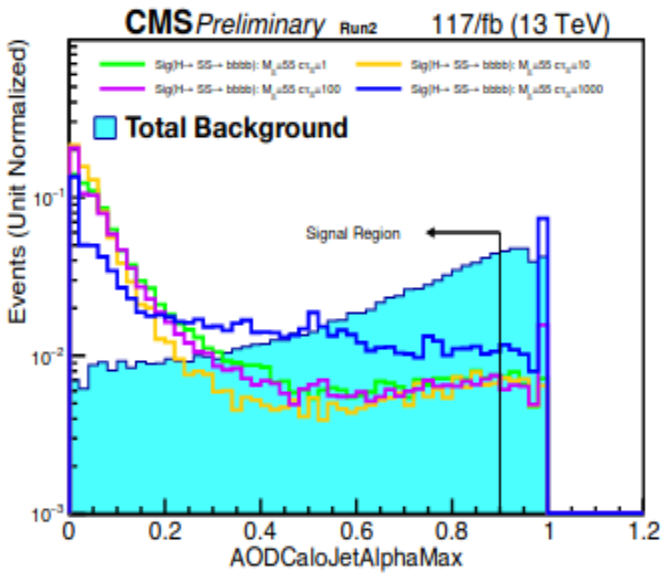
$$\alpha_{vtx_i} = \frac{\sum_{tracks \in vtx_i} p_T^{tracks}}{\sum_{tracks} p_T^{tracks}}$$





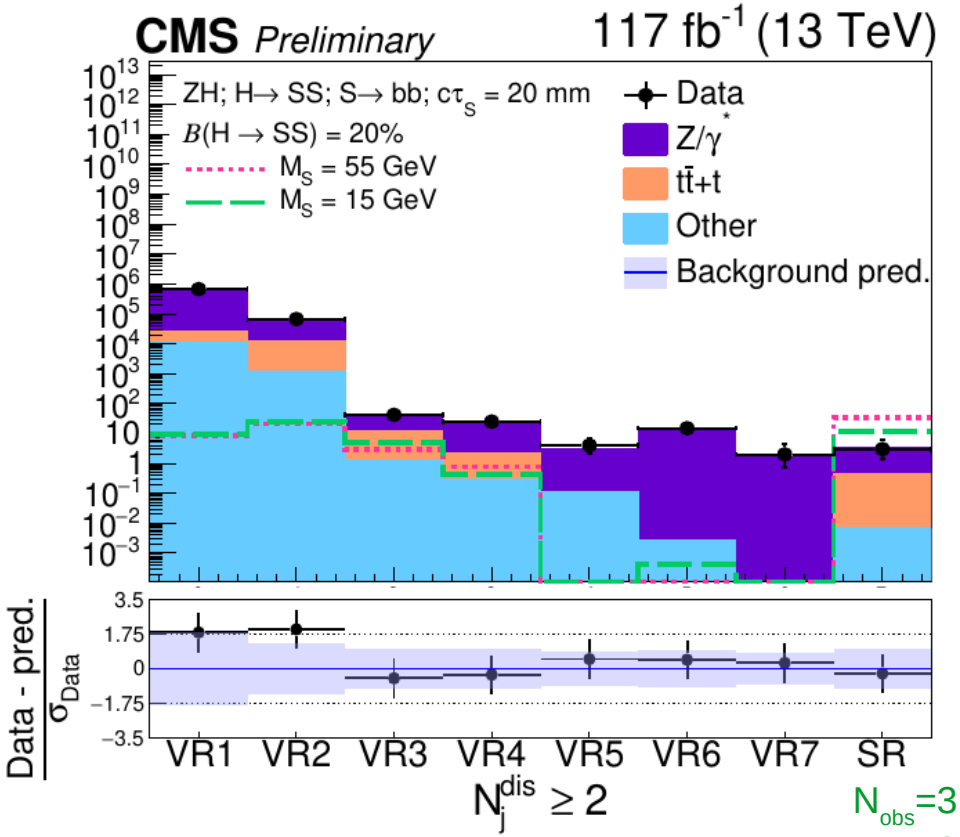




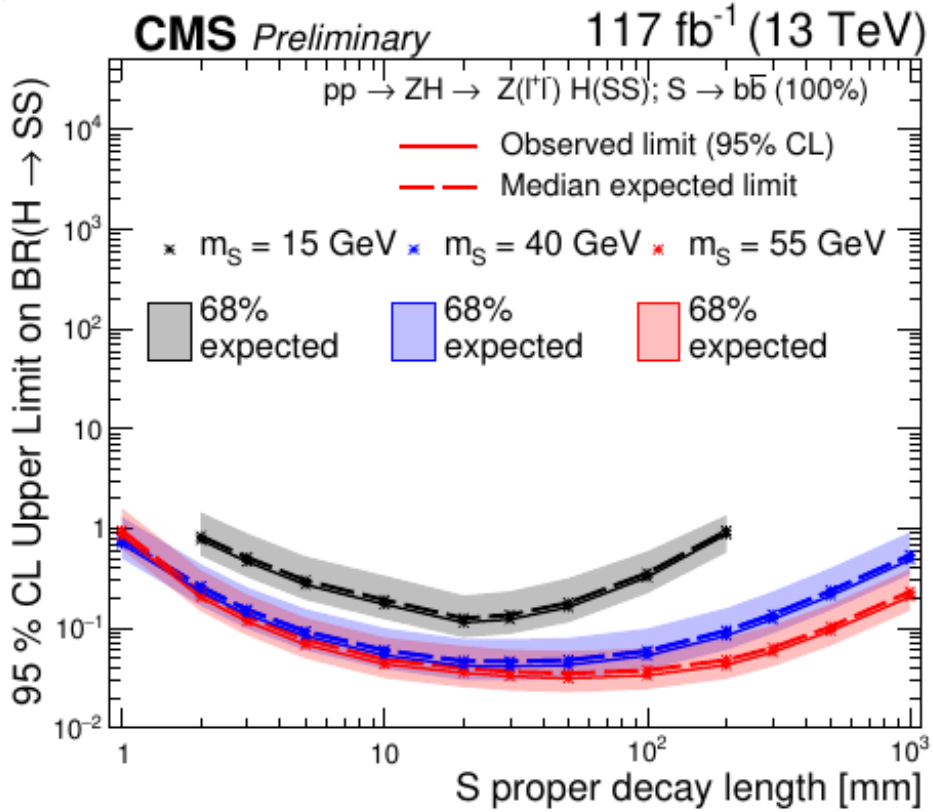


CMS: Higgs to displaced jets results

- Global fit to CR(tt)+CR(Z+jets)+SR: get bkgs with scale factors
  - Largest systematic uncertainty assigned to SFs
- 7 validation regions defined by inverting one or more tag vars.
  - Perform fit in VRs as well
  - Fit closes within uncertainty for all validation samples
- Results also include $S \to d\bar{d}$ search

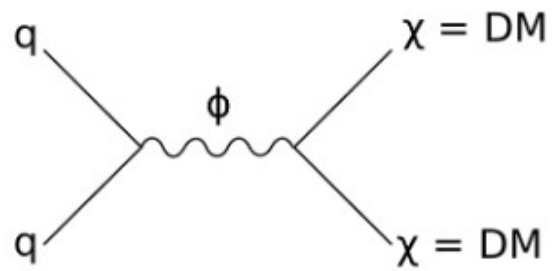


N_{obs}=3
N_{bkg}=3.5±1.8



CMS: Strongly Interacting massive particles

- Signature: pair of narrow neutral jets (neutron-like)
  - Large χ cross-section yields early showers in ECAL
  - Small χ cross-section yields punch-through and MET
- Selection:
  - $N_{jets} = 2$, $p_T > 550$ GeV, $\Delta\varphi(j_1,j_2)>2$
  - Photon & conversion veto, MET filters
  - $N_{vtx} \geq 2$, $ChF_{j1,j2} < 0.05$
  - Use data CR to estimate $ChF(p_T,\eta)$
- SIMP-nucleon interactions are uncertain for m_χ>100 GeV



CMS-EXO-17-010

ChF selection criterion	Background prediction from data	Obs.	SIMP signal [m_χ] 1 GeV	100 GeV	1000 GeV
< 0.20	898 ± 30 (stat) ± 33 (syst)	969	1300 ± 58	634 ± 44	2.25 ± 0.07
< 0.15	209 ± 10 (stat) ± 17 (syst)	229	1269 ± 57	613 ± 43	2.18 ± 0.07
< 0.10	26.6 ± 2.2 (stat) ± 9.3 (syst)	30	1197 ± 56	589 ± 42	2.09 ± 0.07
< 0.07	5.1 ± 0.6 (stat) ± 4.1 (syst)	4	1153 ± 55	568 ± 41	2.00 ± 0.07
< 0.05	$1.27 \pm 0.22\,(\text{stat})^{+3.40}_{-1.27}$ (syst)	0	1101 ± 53	544 ± 40	1.90 ± 0.06