Search for LLP using Delayed Photons at CMS

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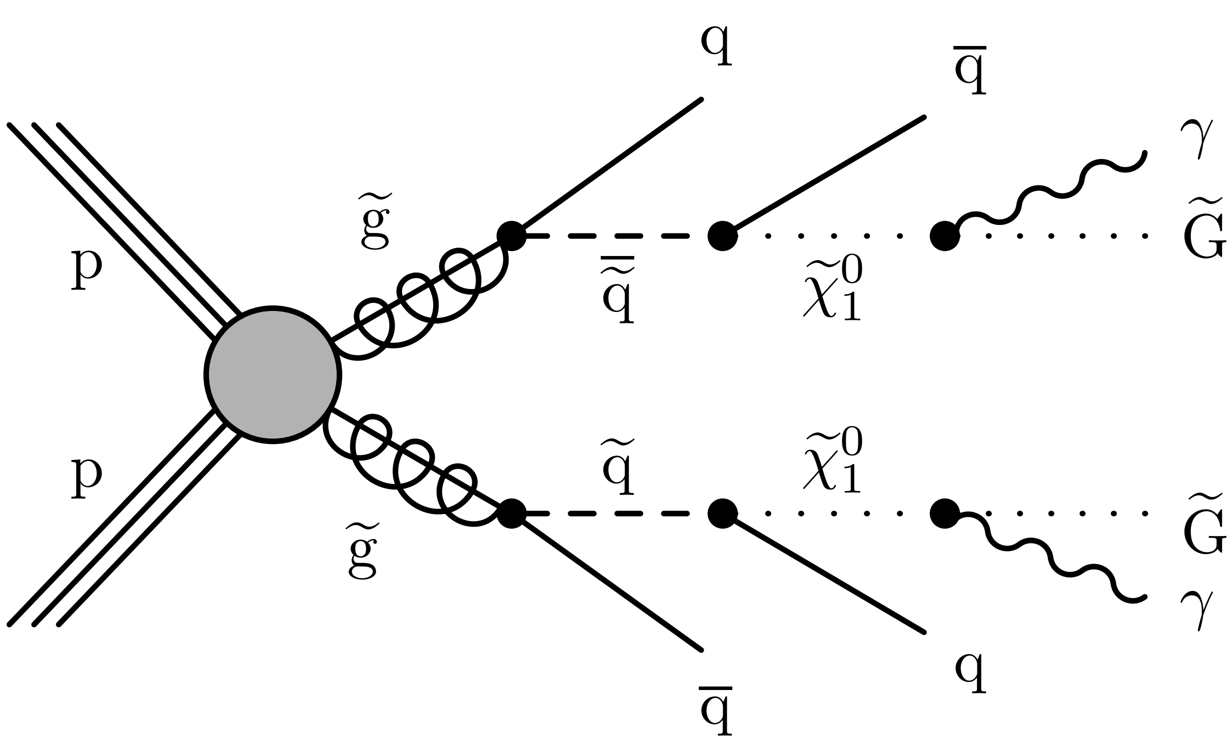
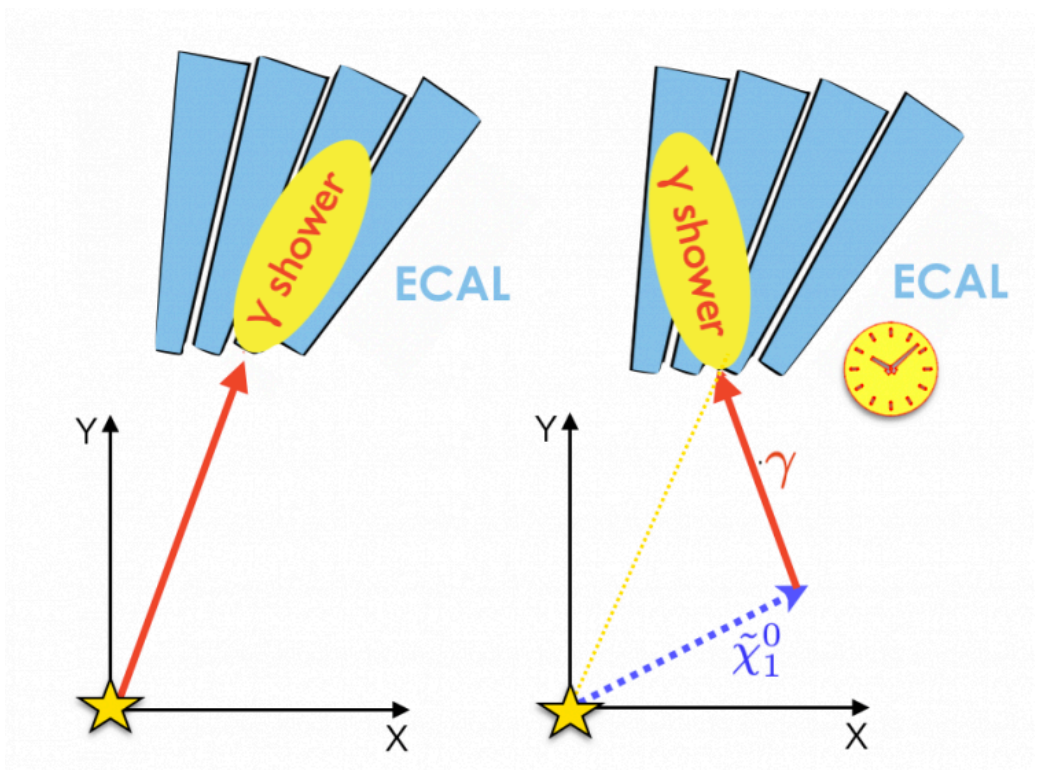
Unique and challenging signature





Final state

- 0, 1 or 2 photons (ɣ escape detector, or NLSP ($\tilde{\chi}_1$) decays to Z/W)
- MET ($\tilde{G}$, missing ɣ)
- Jets

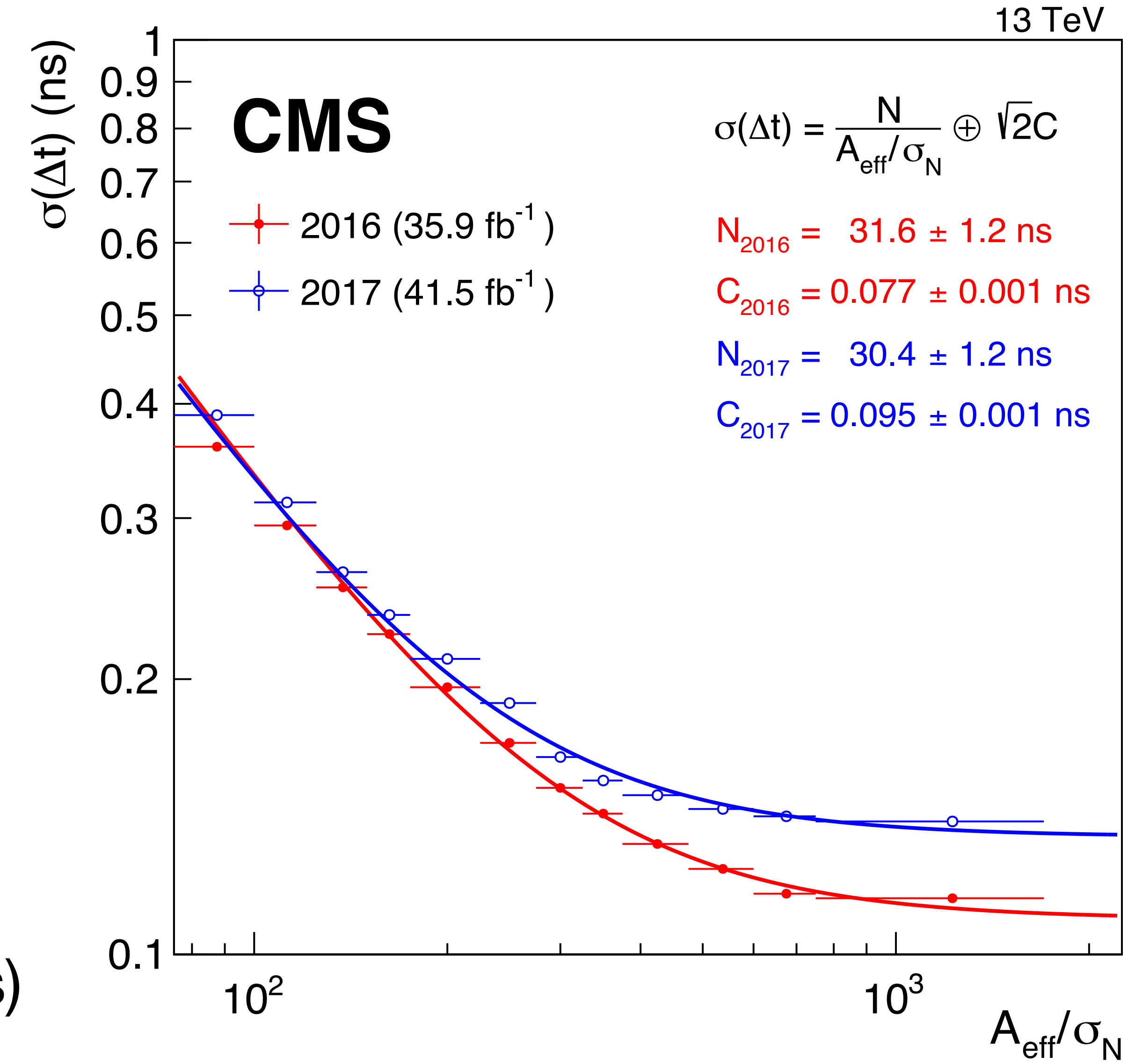
Experimental tool

- ɣ arrival time at ECAL
- MET
- Jets; ɣ shower shape; ~~ɣ vertex~~ (works for ATLAS; not CMS)

CMS ECAL time resolution

- e/ɣ timestamp: resolution weighted average time of all hits in the shower

- Time resolution for e/ɣ object
  - Intrinsic timing resolution in pulse reconstruction (<100ps)
  - Clock jitter of different readout units (~150ps)
  - Beam spot time spread (180-200ps)
  - …
  - Overall resolution: about 300-400ps

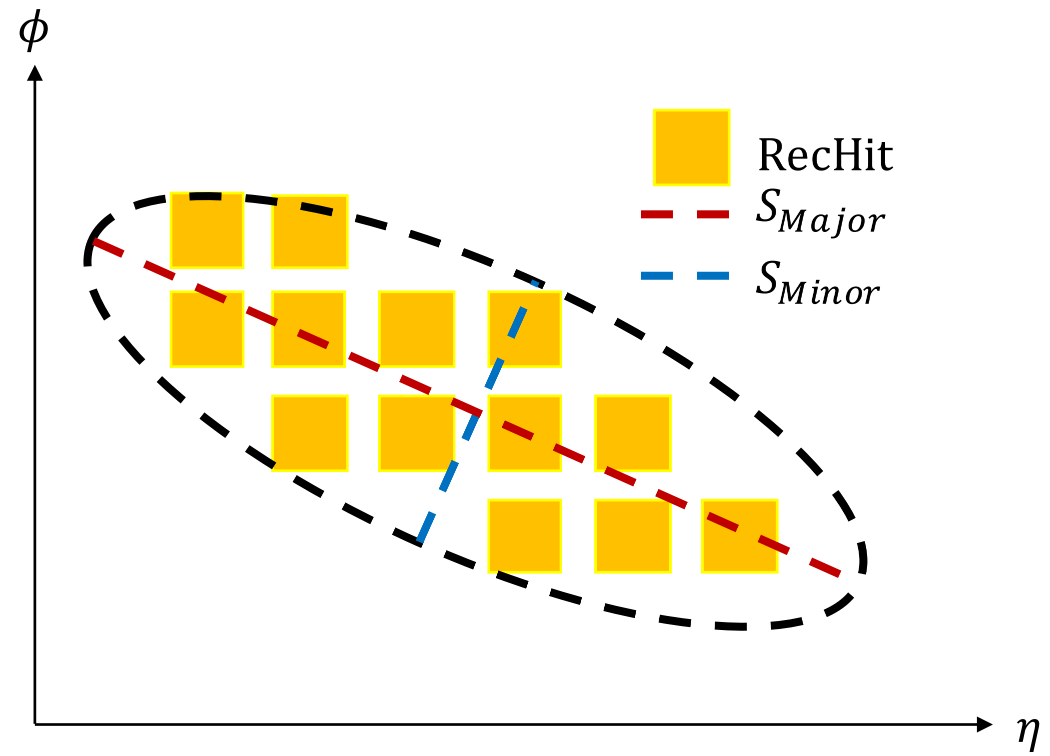


Intrinsic timing resolution
(Δt of two neighboring crystals)

CMS ECAL Run II timing: CMS-DP-2019-021

Event selection

- Trigger:
  - 2016: diphoton trigger (p_T > 42/25 GeV)
  - 2017: dedicated displaced one photon trigger (p_T > 60 GeV, cut on S_{major} and S_{minor}, HT > 350 GeV)
  - > 95% efficient
  - Different triggers result to slightly different event selections between years



Selection: 2016

- ≥2 photons: p_T > 70/40 GeV, leading ɣ in barrel
- ≥3 jets (p_T > 30 GeV)
- Efficiency x acceptance: 10% to 0.15% depending on $c\tau$ (0.1 to 100 m)

Selection: 2017

- 2ɣ category: p_T > 70/40 GeV, leading ɣ in barrel
- 1ɣ category: p_T > 70 GeV in barrel
- ≥3 jets (p_T > 30 GeV); HT > 400 GeV
- Efficiency x acceptance (1ɣ): 10% to 0.65%

complementary

- 1ɣ: higher efficiency for large $c\tau$ models
- 2ɣ: 10 times less background than 1ɣ

Backgrounds

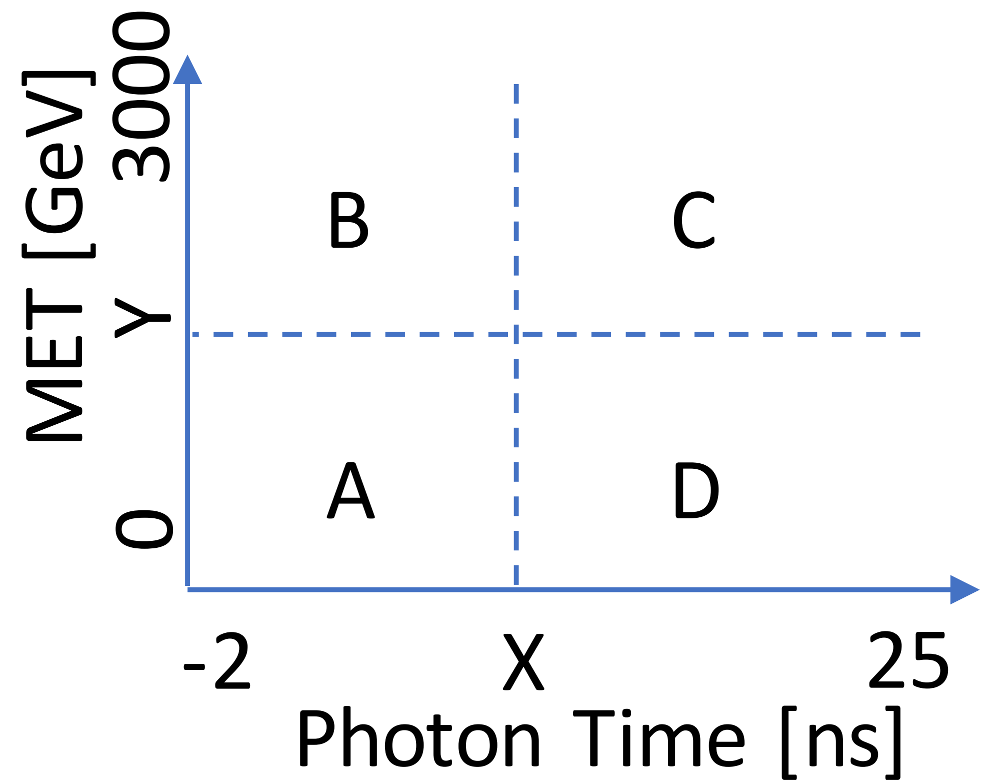
- Non-collisional backgrounds: negligible after offline selection (mainly because of nJets requirement)
  - Conventional backgrounds that are known to have non-zero photon time, like beam halo events, are checked to be small in the negative time region, and negligible when scaled to positive time region

- Collisional backgrounds:
  - From pp collision with high MET and jets, including collisions from satellite bunches spaced ~ 2.5 ns apart
  - Appealing feature: γ time distributions are the same for low MET and high MET events (verified in CRs)

Background estimation

- Purely **data-driven** ABCD method to perform background estimation and signal extraction

- **Observables**: photon time and MET
  - They are uncorrelated for backgrounds; background in bin C can be constrained by backgrounds in bin A, B and D
  - Bin boundaries X and Y optimized to maximize sensitivity for different signal models



$$\mathrm{N_A} = \mathrm{Bkg_A} + \mu \times \mathrm{Sig_A}$$

$$\mathrm{N_B} = c_1 \times \mathrm{Bkg_A} + \mu \times \mathrm{Sig_B}$$

$$\mathrm{N_C} = c_1 \times c_2 \times \mathrm{Bkg_A} + \mu \times \mathrm{Sig_C}$$

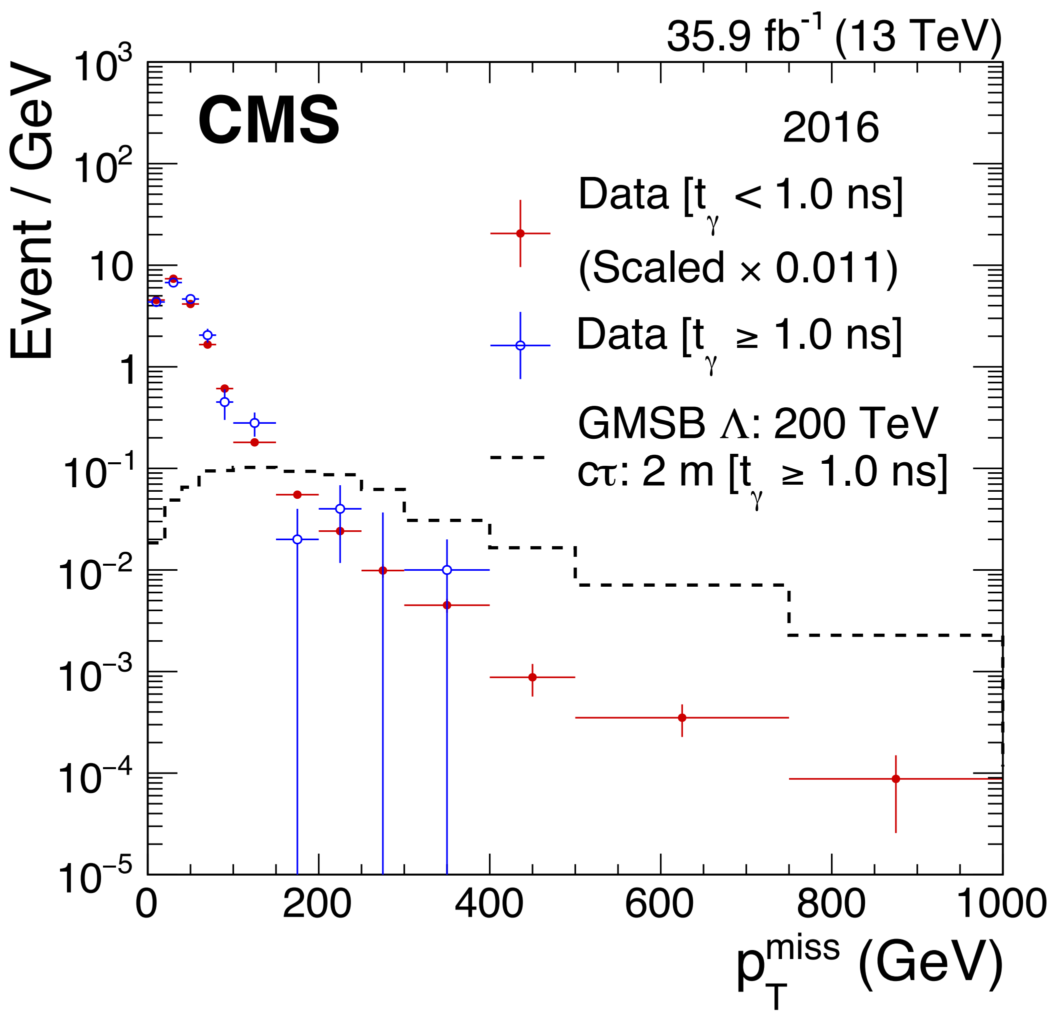
$$\mathrm{N_D} = c_2 \times \mathrm{Bkg_A} + \mu \times \mathrm{Sig_D}$$

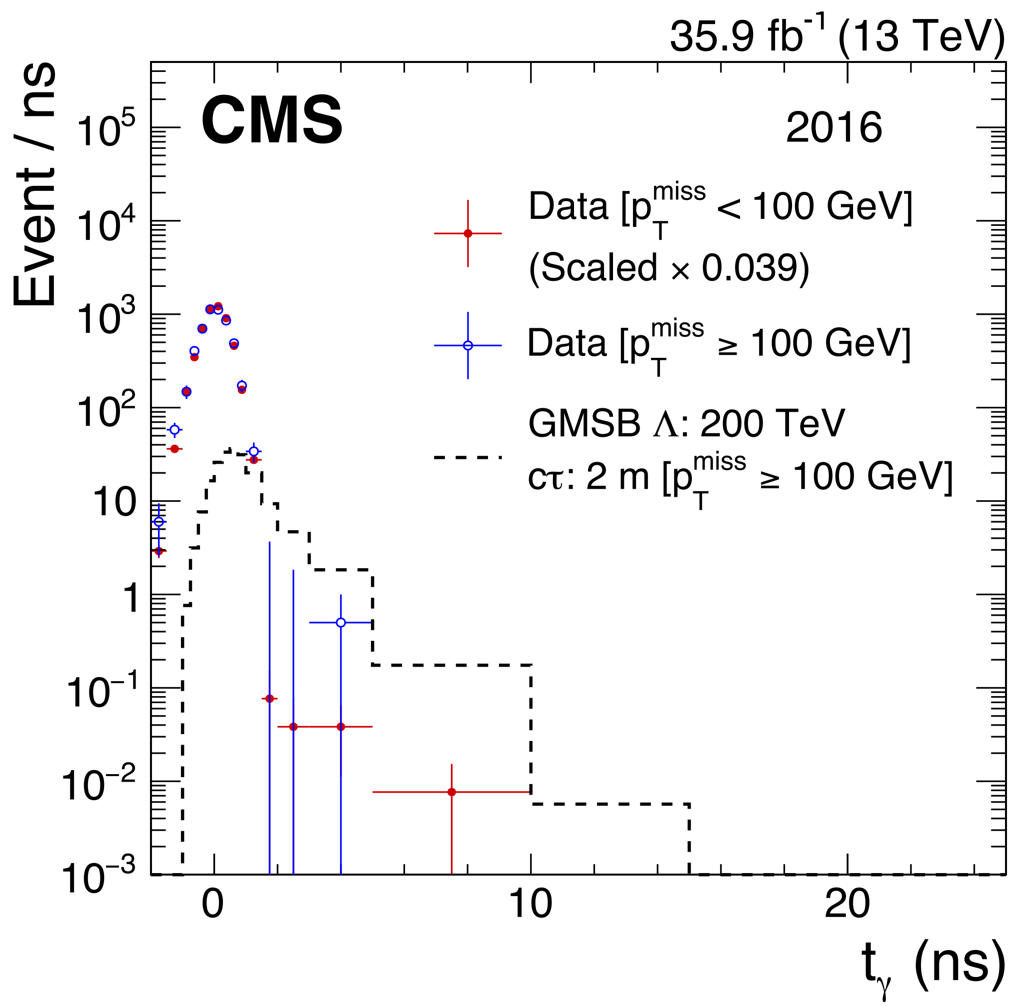
4 equations
4 unknowns ($\mathrm{Bkg_A}$, c_1, c_2, μ)

bin boundaries (X, Y)

$c\tau$ (m)	$\Lambda \leq 300$ TeV			$\Lambda > 300$ TeV		
	2016	2017γ	2017$\gamma\gamma$	2016	2017γ	2017$\gamma\gamma$
(0, 0.1)	0 , 250	0.5 , 300	0.5 , 150	0 , 250	0.5 , 300	0.5 , 200
(0.1 , 100)	1.5 , 100	1.5 , 200	1.5 , 150	1.5 , 150	1.5 , 300	1.5 , 200

Photon time and MET





MET in small and large photon time slices

Photon time in low and high MET slices

Systematic uncertainties

- The dominant uncertainty comes from the background estimation
- A closure test is performed to validate the MET-time uncorrelated assumption, and assign uncertainties
  - Define two control regions: ɣ+jets CR (invert nJets cut); QCD CR (invert isolation on leading photon)
  - Count observed events in bin C: NC
  - Calculate predicted events in bin C: $NC_{predict}$ = NB*ND/NA
  - Compare NC with $NC_{predict}$, and assign systematics uncertainty on bin C background estimation based on this difference

- For ABCD binning corresponds to **$c\tau \leq$ 0.1m: less than 4%**
- For **larger $c\tau$: assign 90%** (limited by statistics of CR yields in bin C)

Result of fit

Bin boundary [t_γ (ns), p_T^{miss} (GeV)]		2016 category A	B	C	D
(0, 250)	N_{obs}^{data}	16 139	41	62	18 826
	$N_{bkg}^{post\text{-}fit}$	$16\,130 \pm 110$	47.5 ± 4.8	55.6 ± 5.6	$18\,830 \pm 130$
	$N_{bkg(no\ C)}^{post\text{-}fit}$	$16\,140 \pm 110$	41.0 ± 6.5	47.8 ± 7.7	$18\,830 \pm 130$
(1.5, 100)	N_{obs}^{data}	33 760	1302	1	5
	$N_{bkg}^{post\text{-}fit}$	$33\,760 \pm 160$	1303 ± 37	0.29 ± 0.28	5.7 ± 2.2
	$N_{bkg(no\ C)}^{post\text{-}fit}$	$33\,760 \pm 160$	1302 ± 37	0.19 ± 0.21	5.0 ± 2.1
(1.5, 150)	N_{obs}^{data}	34 595	467	0	6
	$N_{bkg}^{post\text{-}fit}$	$34\,600 \pm 170$	467 ± 22	0.08 ± 0.08	5.9 ± 2.3
	$N_{bkg(no\ C)}^{post\text{-}fit}$	$34\,600 \pm 170$	467 ± 22	0.08 ± 0.09	6.0 ± 2.3

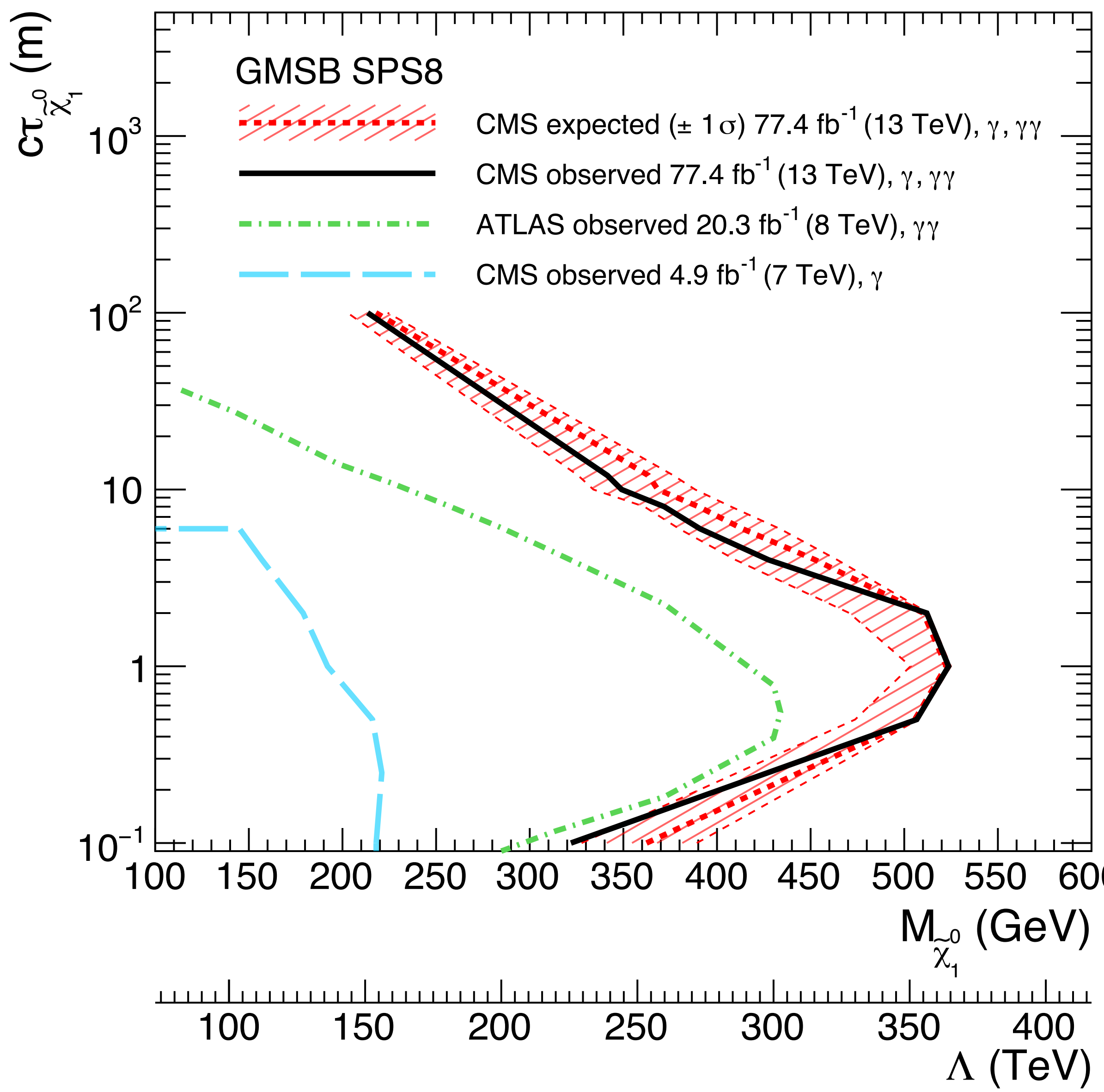
$N_{bkg}^{post-fit}$: predicted background yields from the background-only fit

$N_{bkg(noC)}^{post-fit}$: background-only fit when masking bin C

No excess over SM background. Will set upper limits on the signal cross sections

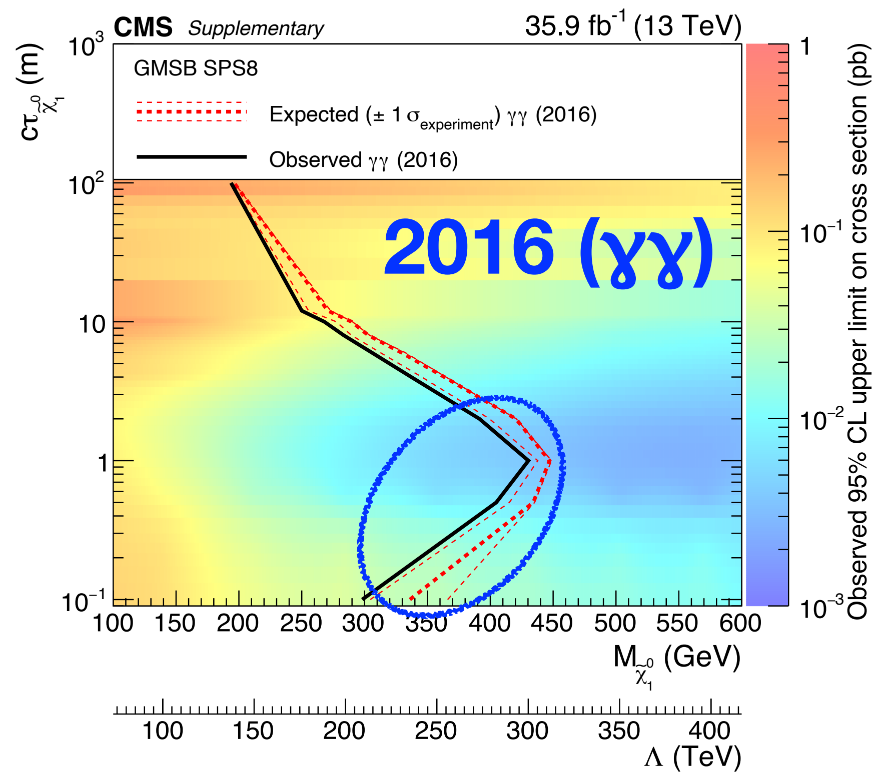
Upper limits

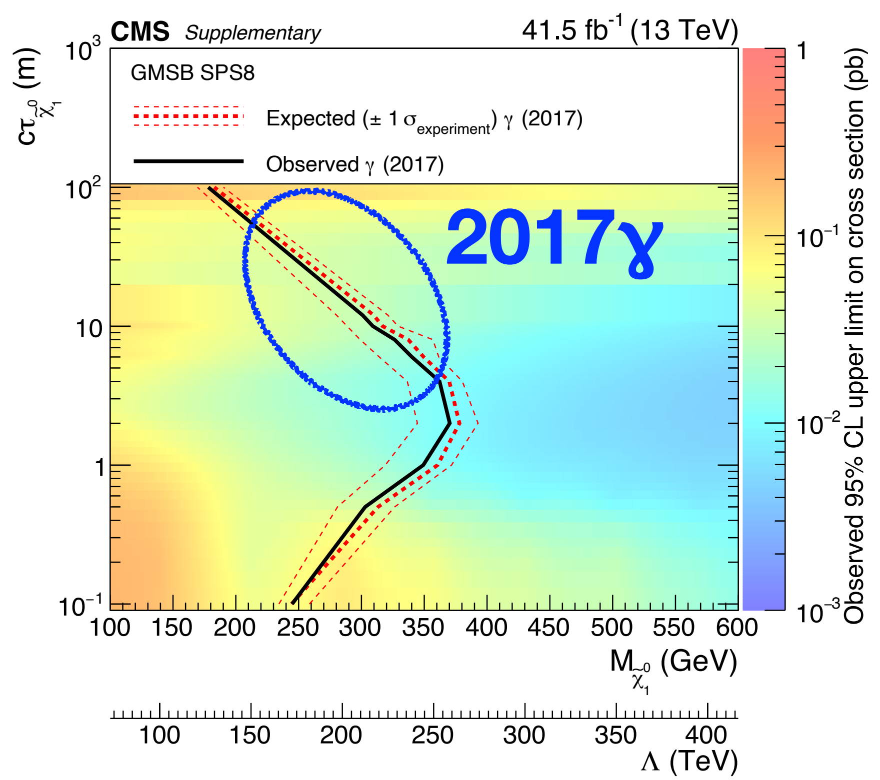
- Extended the previous limits
  - One order of magnitude in neutralino $c\tau$
  - About 100 GeV in neutralino mass
- Most sensitive $c\tau$: about 1 m (ECAL radius)

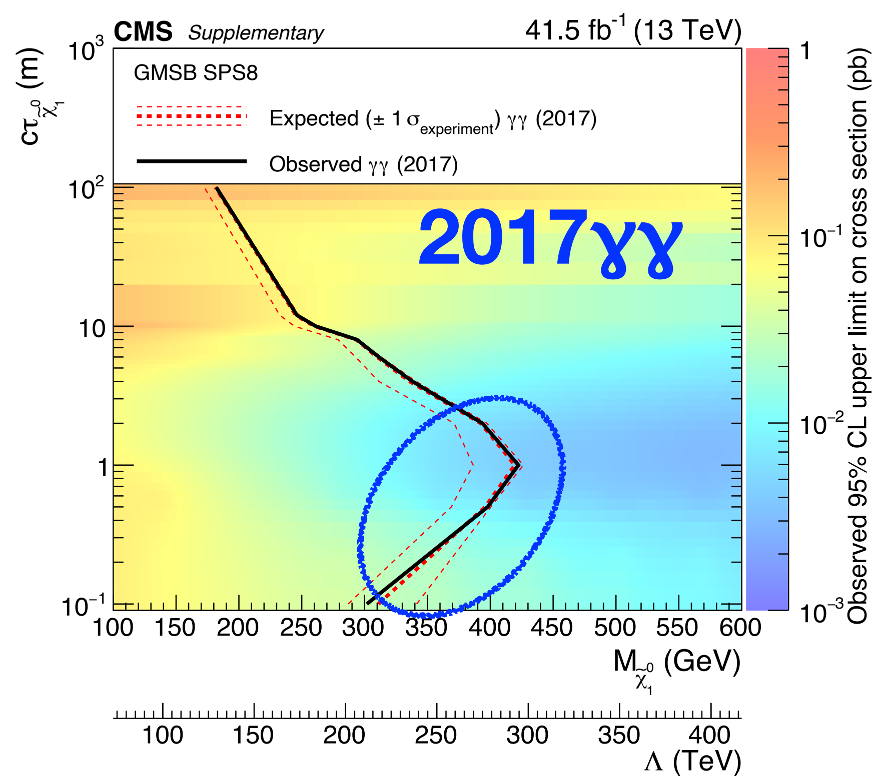


Categories comparison

- ɣ and ɣɣ categories are complementary
- ɣ: for larger $c\tau$
- ɣɣ: for smaller $c\tau$



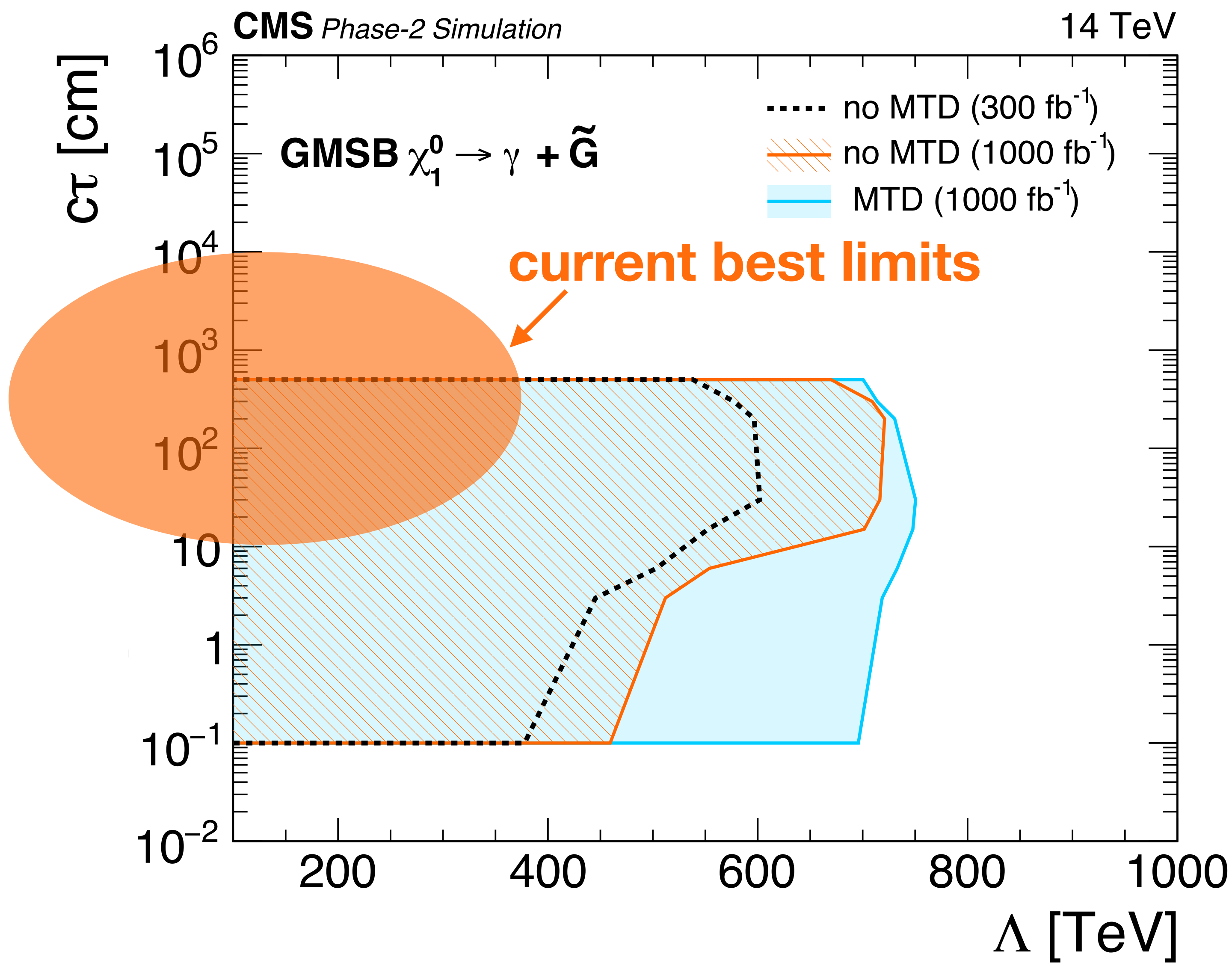




Towards Phase-2

- With upgraded ECAL
  - ECAL time resolution reduced to 30 ps (vs. current 100 ps intrinsic + 150 ps clock jitter)
  - Limited by beam spot time spread (180 ps)
- With Mip Timing Detector (MTD)
  - Can measure the primary vertex time with up to 30 ps resolution (eliminates the 180 ps spread)
  - Can also measure arrival time for converted photons

- **Significant extended reach for low $c\tau$ models**



See details in: [CMS-TDR-020](CMS-TDR-020)

Miscellaneous

- **Out-of-time (OOT) photon reconstruction:**
  - To reject spikes, CMS has a time cut on photons (~ 3 ns) in the standard reconstruction
  - We had to go back to RAW data to save those OOT photons…
  - (Non-standard object reconstruction, potential challenge for other LLP searches)

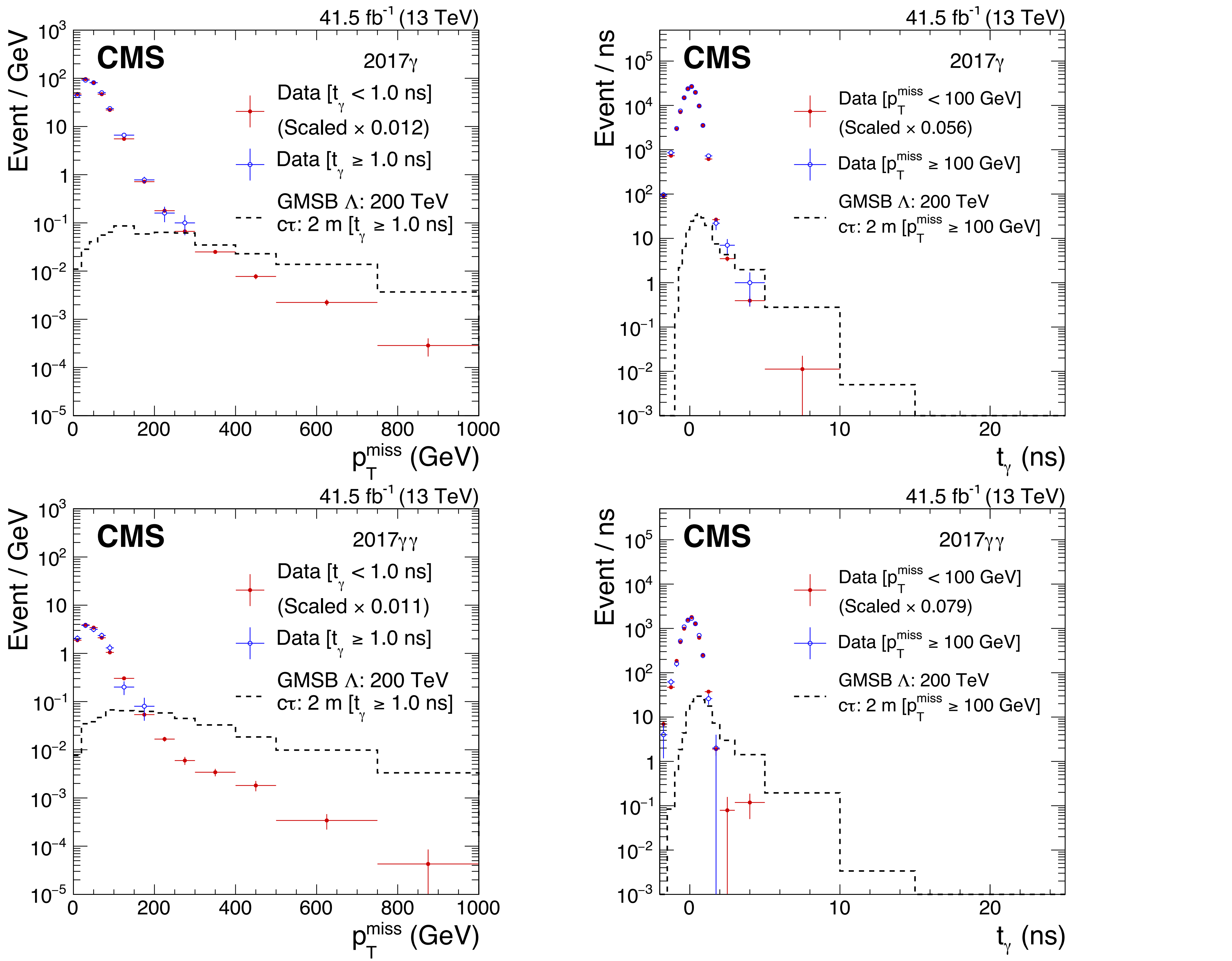
- When one of the signal photons is produced outside ECAL and deposits energy in outer detector (HCAL, muon system), it will **look like an isolated noise**
  - Hits in HCAL, nothing in ECAL
  - (up to 10% of) our photon signals will be killed by the filters designed to kill such isolated noise
  - This is a potential issue for other LLP searches as well

Summary

- A search for LLP using delayed photon using photon arrival time at ECAL and MET is presented
- Extended the previous best limits by one order of magnitude of proper decay length and about 100 GeV of mass of the NLSP
- Limitations:
  - For small $c\tau$: limited by ECAL time resolution - will be significantly improved in Phase-2
  - For large $c\tau$: limited by ECAL geometry acceptance

BACK UP

Photon time and MET (2017)



Result of fit (2017)

Bin boundary $[t_\gamma$ (ns), p_T^{miss} (GeV)]		A	B	C	D
		2017γ category			
(0.5, 300)	N_{obs}^{data}	458 372	281	41	67 655
	$N_{bkg}^{post\text{-}fit}$	458 370 ± 660	281 ± 15	41.4 ± 2.4	67 660 ± 280
	$N_{bkg(no\ C)}^{post\text{-}fit}$	460 369 ± 660	281 ± 16	41.5 ± 2.7	67 660 ± 280
(1.5, 200)	N_{obs}^{data}	524 652	1364	1	332
	$N_{bkg}^{post\text{-}fit}$	524 650 ± 710	1364 ± 36	0.9 ± 0.8	330 ± 20
	$N_{bkg(no\ C)}^{post\text{-}fit}$	524 650 ± 700	1364 ± 35	0.9 ± 1.0	330 ± 20
(1.5, 300)	N_{obs}^{data}	525 694	322	0	333
	$N_{bkg}^{post\text{-}fit}$	525 690 ± 700	322 ± 17	0.19 ± 0.21	330 ± 20
	$N_{bkg(no\ C)}^{post\text{-}fit}$	525 690 ± 700	322 ± 17	0.20 ± 0.24	330 ± 20
		2017$\gamma\gamma$ category			
(0.5, 150)	N_{obs}^{data}	21 640	362	56	3201
	$N_{bkg}^{post\text{-}fit}$	21 640 ± 140	364 ± 17	54.0 ± 3.0	3200 ± 60
	$N_{bkg(no\ C)}^{post\text{-}fit}$	21 640 ± 140	362 ± 18	53.6 ± 3.3	3200 ± 60
(0.5, 200)	N_{obs}^{data}	21 863	139	24	3233
	$N_{bkg}^{post\text{-}fit}$	21 860 ± 140	142 ± 11	21.1 ± 1.7	3240 ± 60
	$N_{bkg(no\ C)}^{post\text{-}fit}$	21 860 ± 140	139 ± 11	20.6 ± 1.8	3230 ± 60
(1.5, 150)	N_{obs}^{data}	24 824	418	0	17
	$N_{bkg}^{post\text{-}fit}$	24 820 ± 150	420 ± 20	0.25 ± 0.28	16.7 ± 4.4
	$N_{bkg(no\ C)}^{post\text{-}fit}$	24 820 ± 150	420 ± 20	0.29 ± 0.36	17.0 ± 4.4
(1.5, 200)	N_{obs}^{data}	25 079	163	0	17
	$N_{bkg}^{post\text{-}fit}$	25 080 ± 150	163 ± 12	0.11 ± 0.12	16.9 ± 4.4
	$N_{bkg(no\ C)}^{post\text{-}fit}$	25 080 ± 150	163 ± 12	0.11 ± 0.14	17.0 ± 4.4