Searches for long-lived particles at CMS

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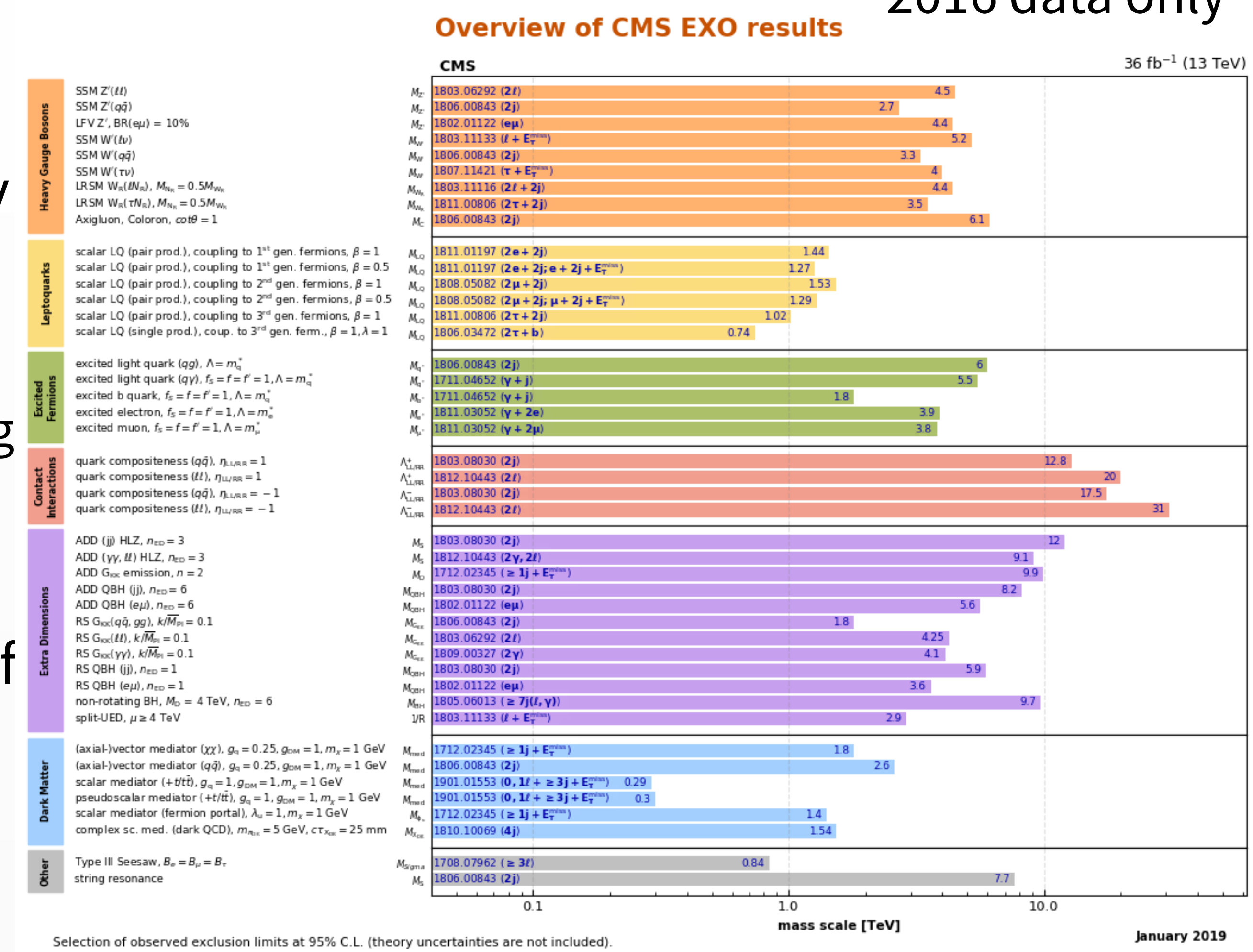
Conventional searches

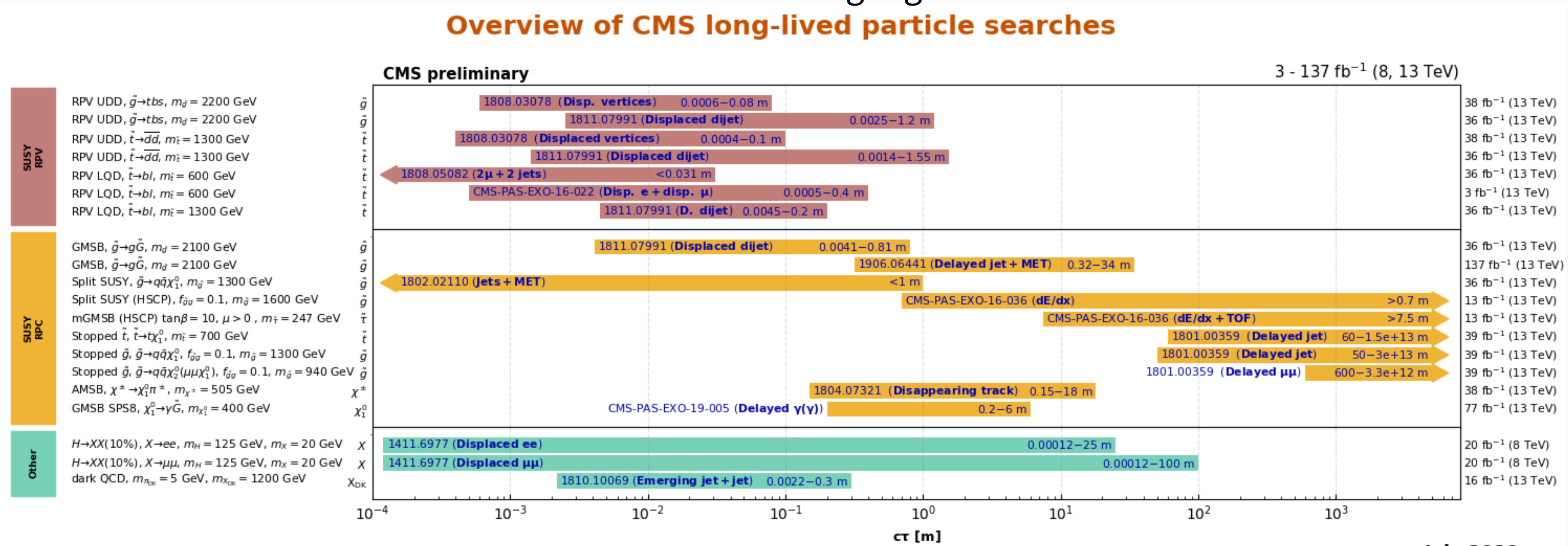
- CMS has performed numerous new physics searches, probing a large region of parameter space for a variety of BSM models:
  - In many cases, mass limits are now approaching or, in some cases, exceeding 10 TeV
- But remember, every search includes baked-in assumptions on the nature of new particles:
  - One of the most ubiquitous is that new particles will be short-lived

2016 data only



Long-lived particles

- Challenging these assumptions is more important than ever as we continue to find no significant evidence of BSM physics at the LHC
- Long-lived particles (LLP) in particular are predicted by a wide range of theoretical models:
  - Small coupling constants --- e.g., SUSY with R-parity violating couplings
  - Very off-shell intermediate decay products --- e.g., split SUSY where heavy intermediate squarks enhance the gluino lifetime
  - Limited decay phase space --- e.g., AMSB SUSY where the lightest neutralino and chargino are nearly degenerate
- CMS already has a rich programme of searches for LLPs with limits set on various signatures across more than eight orders of magnitude in lifetime
- Some of the most recent results from searches for LLPs will be highlighted in this talk

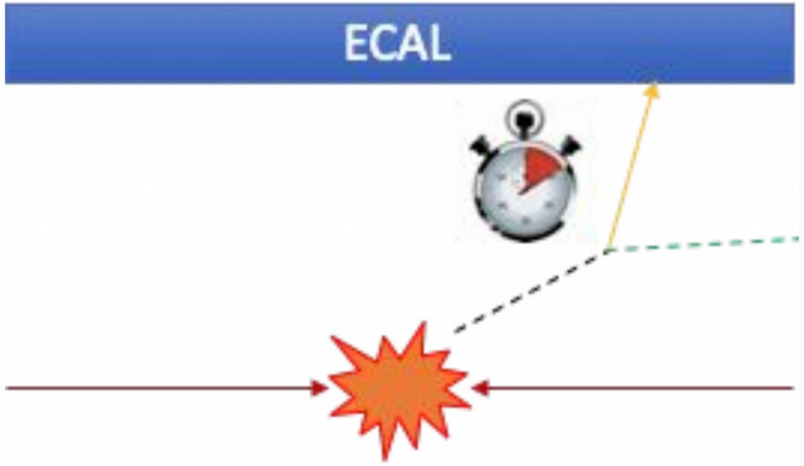


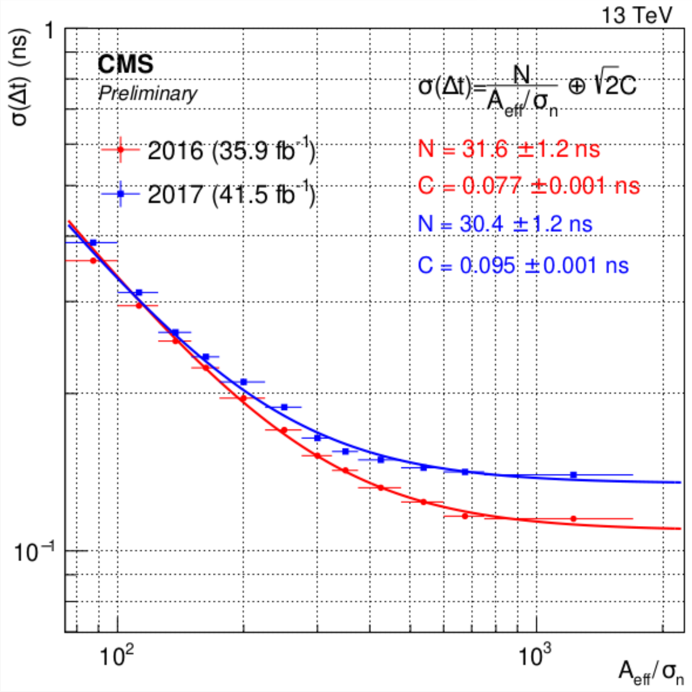
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Delayed photons

BRAND NEW!
EXO-19-005

- Search for neutral LLPs decaying to photons:
  - Photons arrive late at the ECAL
- Diphoton trigger used in 2016:
  - 95% efficient in signal after offline selection
- Dedicated displaced photon + H_T trigger used in 2017:
  - 99.9% efficient in signal after offline selection



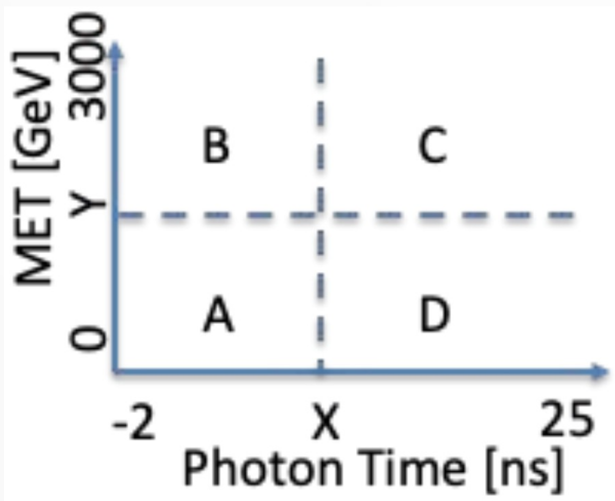


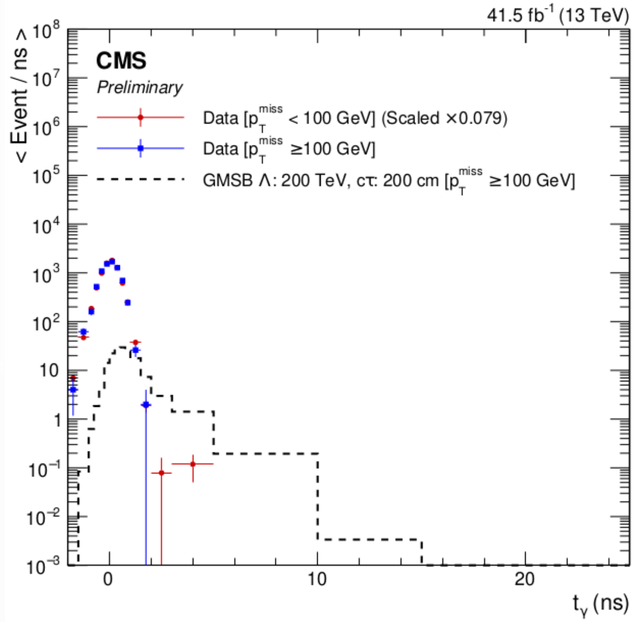
- Triggers determine offline selection categories:
  - 2016: at least two photons passing custom out-of-time photon identification
  - 2017: exactly one or at least two photons passing identification
- Photon arrival time (t_γ) is one of the main observables:
  - Weighted average of timestamps from each ECAL crystal in the photon cluster
  - Weighted by ECAL time resolutions obtained from dedicated measurement as a function of effective crystal amplitude

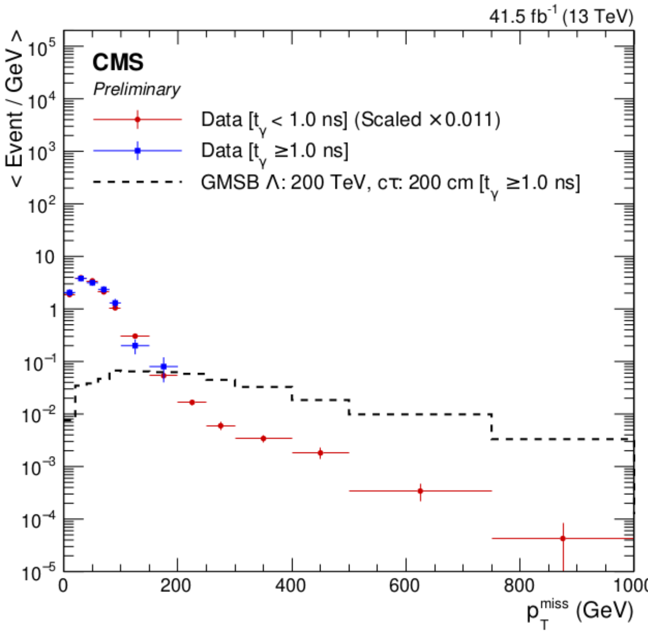
Delayed photons

BRAND NEW!
EXO-19-005

- The other main observable is missing transverse momentum (p_T^{miss})
- Background estimated using an ABCD method with t_γ and p_T^{miss}:
  - Fit for background yield and signal strength simultaneously in all four regions
  - Signal is roughly evenly distributed between regions
  - Background is lowest in region C (high t_γ, high p_T^{miss}), making it the most sensitive region
- The observation in each region is consistent with the expected background from the fit



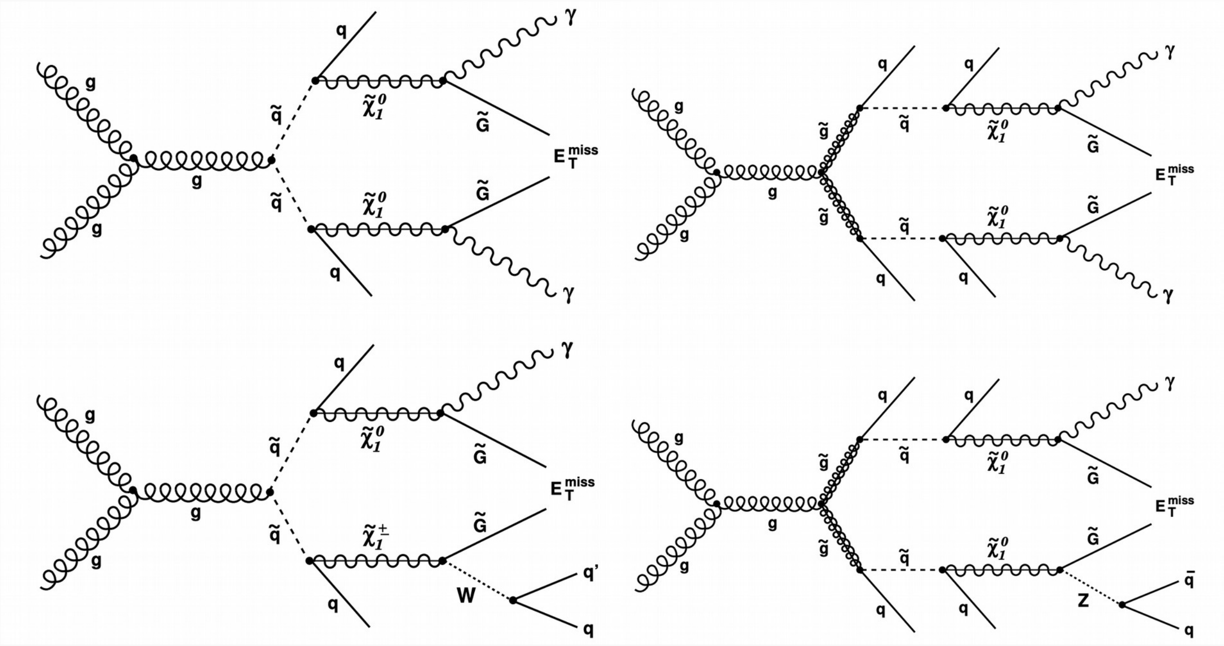


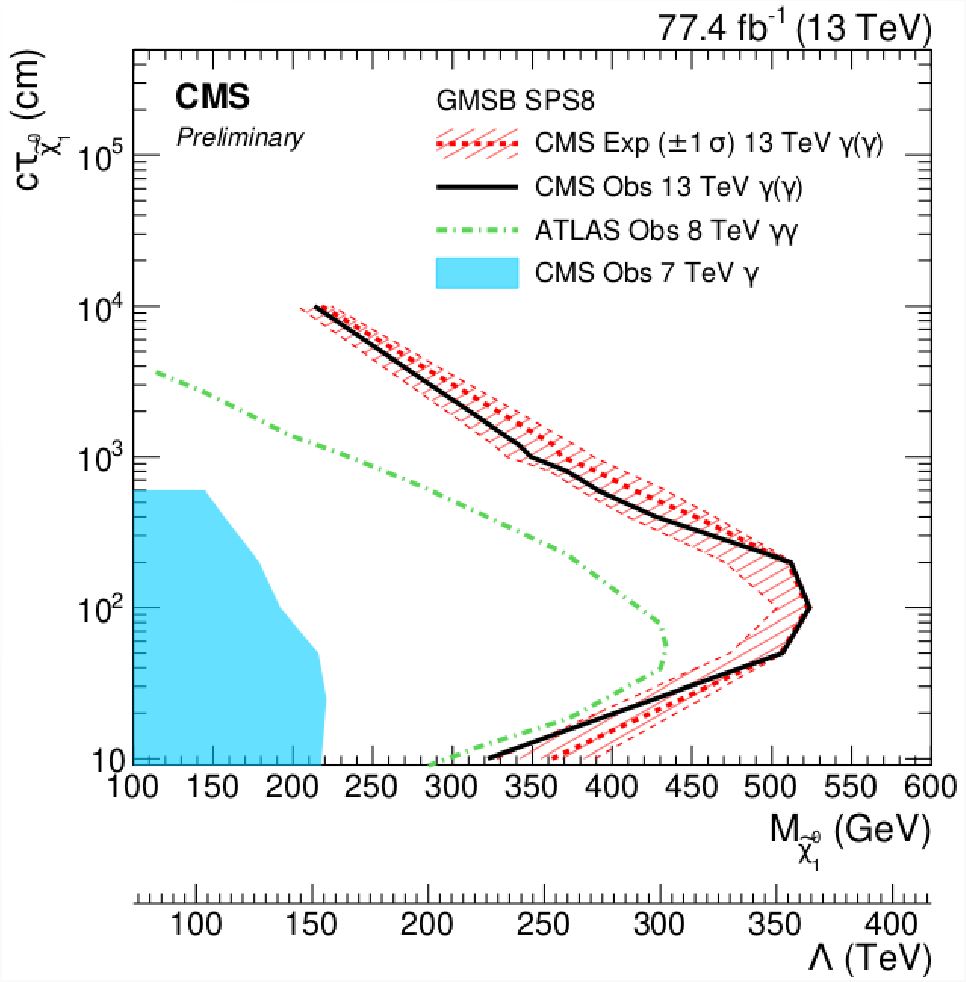


Delayed photons

BRAND NEW!
EXO-19-005

- Limits placed on long-lived neutralino production via gluino/squark pair production in the context of GMSB SUSY:
  - Limits extended by about an order of magnitude in lifetime and ~100 GeV in neutralino mass compared to best Run 1 results

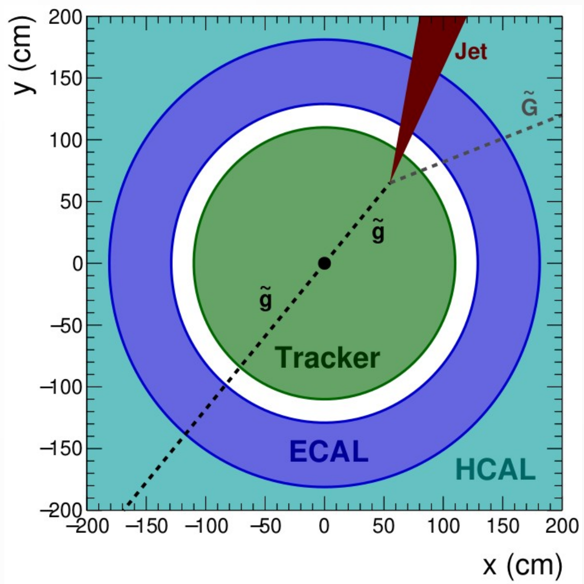


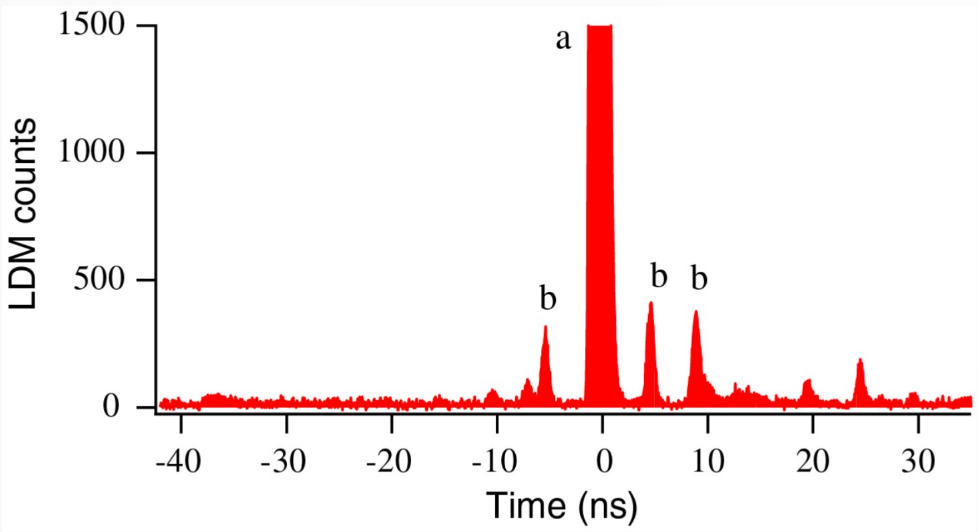


Delayed jets

Submitted to PLB
arXiv:1906.06441
HEPData entry

- Search for LLPs decaying to hadronic jets using the full Run 2 data set:
  - Shower would arrive late at the ECAL
  - Targeting decays beyond the acceptance of the tracker
- First search to look for this kind of topology, and the first to use ECAL timing to tag delayed jets
- Events collected with a trigger requiring p_T^{miss} > 120 GeV





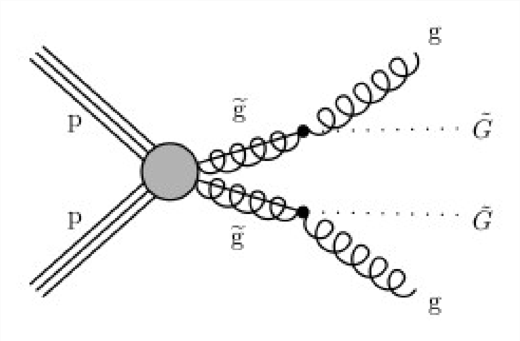
Phys. Rev. Spec. Top. Accel. Beams 15 (2012) 032803

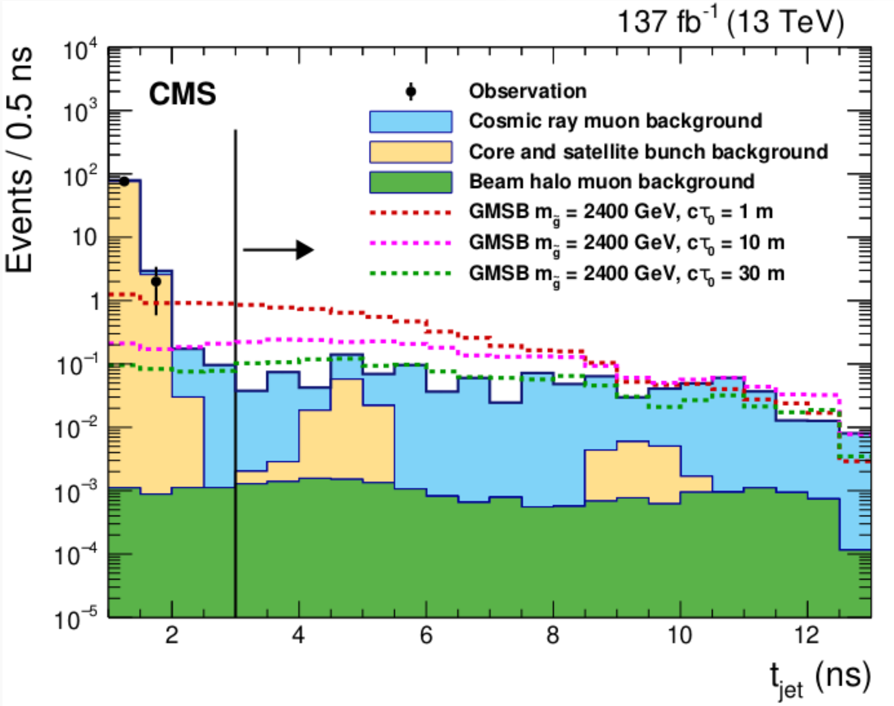
- Extensive quality selections remove a wide array of backgrounds:
  - Direct interactions with ECAL front-end
  - Satellite bunches
  - Beam halo deposits in ECAL
  - Cosmic muon deposits in ECAL
  - Noise deposits
- These selections reduce the background by many orders of magnitude

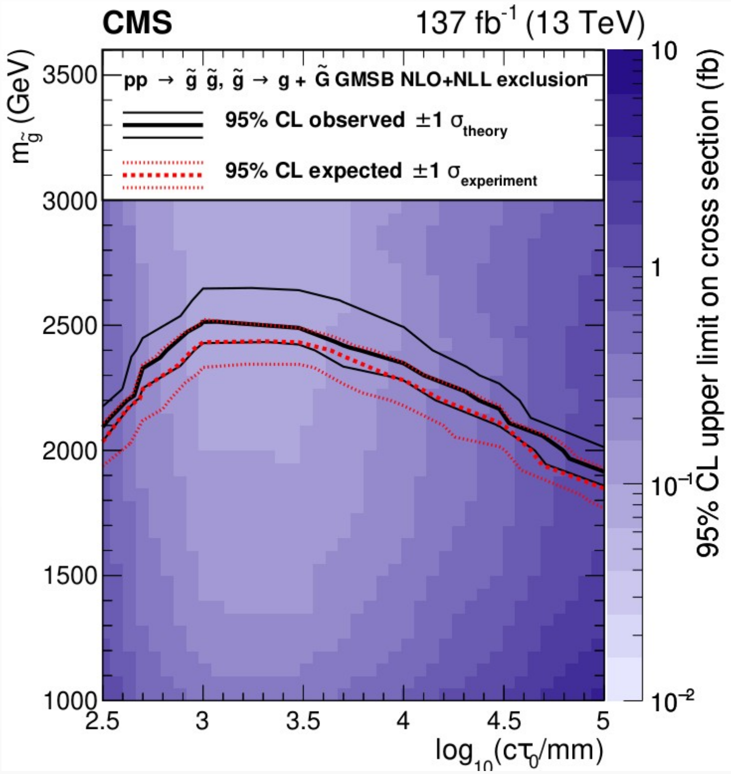
Delayed jets

Submitted to PLB
arXiv:1906.06441
HEPData entry

- Remaining background dominated by beam halo, satellite bunches, and cosmic muons:
  - Each predicted with independent ABCD methods defined with the cleaning variables targeting each background
- 1.1-1.1+2.5 events predicted in signal region ($t_{jet} > 3$ ns):
  - No events observed
- Limits placed on long-lived gluino production in the context of a GMSB model



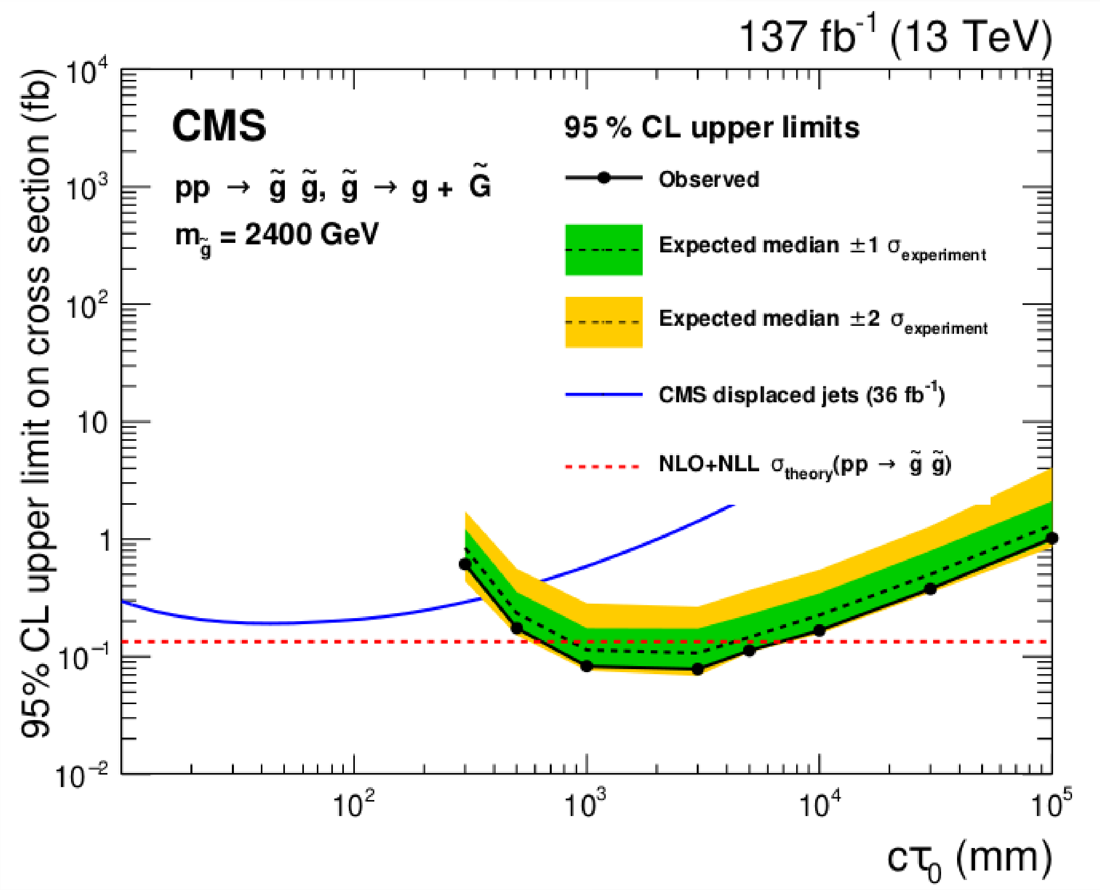




Delayed jets

Submitted to PLB
arXiv:1906.06441
HEPData entry

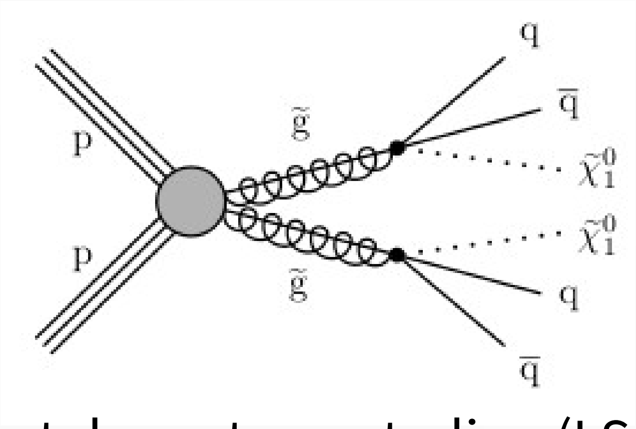
- Beautifully complements the previous displaced jets search from CMS:
  - The current search extends sensitivity to longer lifetimes that are outside the acceptance of the tracker



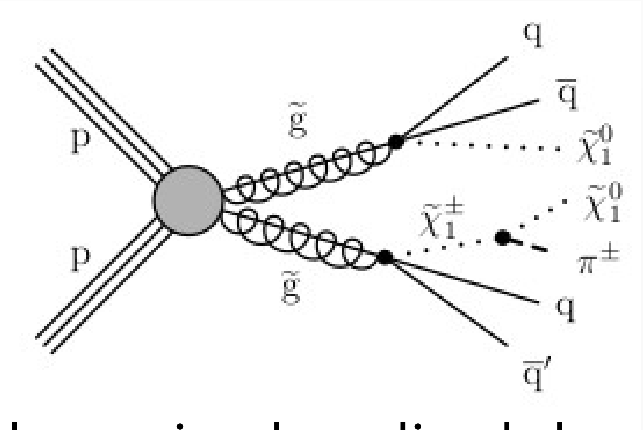
M_{T2} + disappearing track

SUS-19-005

- The M_{T2} variable has been used to search for BSM physics in hadronic final states:
  - See L. Thomas's talk from yesterday for details on the inclusive analysis
- Inclusive M_{T2} analysis already signal dominated if gluino/squark is much heavier than LSP:
  - In compressed scenario, we need another handle to improve sensitivity
- If the gluinos/squarks decay via an intermediate chargino that is nearly degenerate with the neutralino LSP, then the chargino can be metastable, decaying within the tracker volume to invisible products:
  - This is the striking disappearing track signature that has the potential to reduce backgrounds by several orders of magnitude
- Triggers and preselection identical to inclusive M_{T2} analysis with at least two jets



Direct decay to neutralino (LSP)



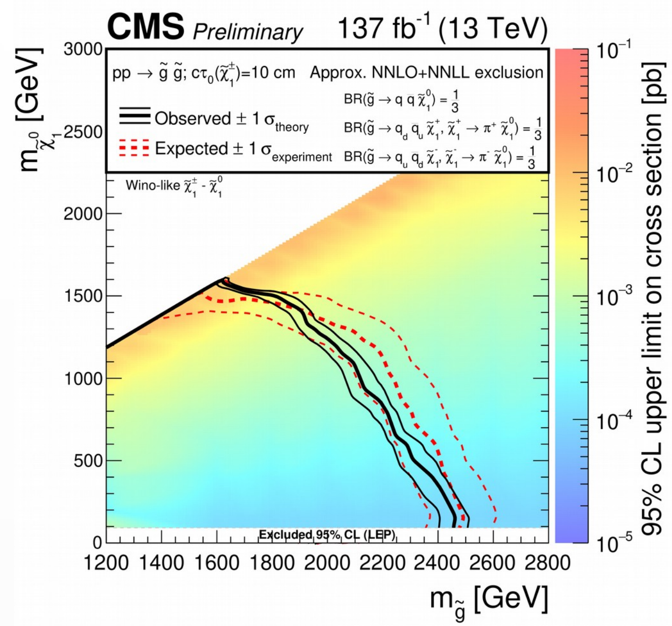
One decay via a long-lived chargino

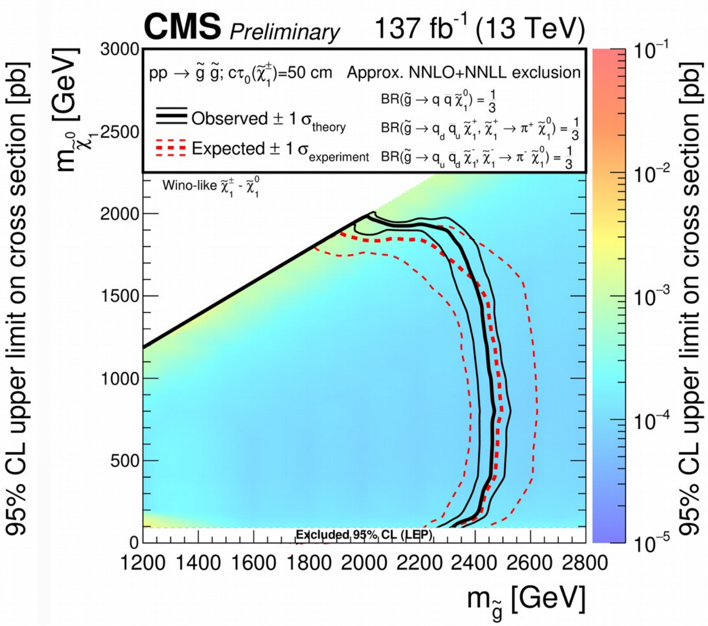
M_{T2} + disappearing track

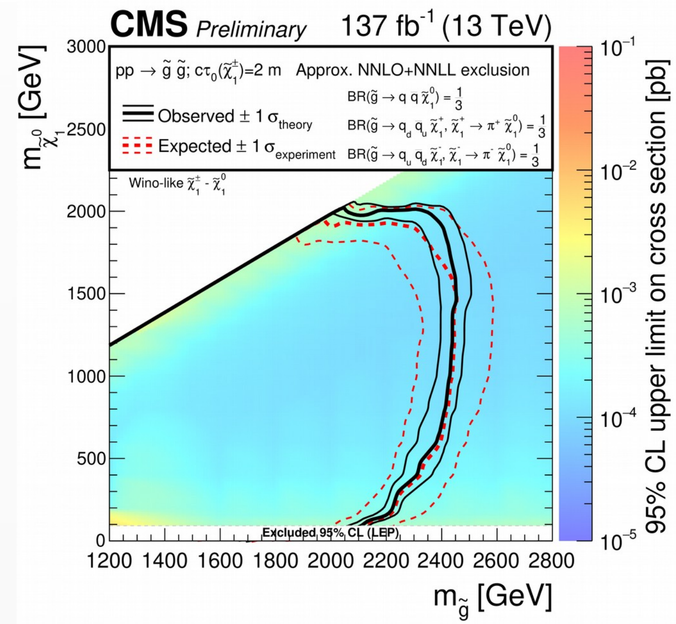
- Disappearing tracks are selected by requiring a high quality, isolated track that:
  - Is not associated with any leptons
  - Is not associated with significant calorimeter energy
  - Has at least 2 missing outer hits
- Selected events categorized into 28 (40) search regions in 2016 (2017+2018) based on:
  - Track length
  - Track p_T
  - Number of jets
  - H_T

M_{T2} + disappearing track

- Backgrounds are estimated by measuring the number of tracks passing loosened isolation and quality selections:
  - Normalized using ratio measured in a low-M_{T2} control region
- No significant excess is observed in any search region in the full Run 2 data set
- Limits are placed on gluino production with an intermediate long-lived chargino in the decay:
  - Addition of disappearing track improves expected cross section limits by up to 100 times for chargino lifetimes greater than a few centimeters







Conclusion

- CMS has a very extensive and rich programme of searches for new long-lived particles:
  - A few of the most recent results were highlighted here
- These searches often challenge our technical skills and creativity, but they are also very rewarding:
  - Considering "unconventional" signatures, making full use of the excellent capabilities of our detectors and introducing new analysis techniques, lets us probe previously unexplored regions of phase space, and hence significantly increase our discovery potential!
  - As seen here, timing information is one tool that is starting to be exploited by more searches, leading to results that nicely complement those from other approaches
  - Also, more conventional searches are being reinterpreted in the context of models with LLPs to understand their sensitivity to such signatures and their complementarity with dedicated LLP searches
- Stay tuned for more LLP results from the full Run 2 data set and beyond!
  - The systematic exploration of the vast LLP landscape is really beginning in earnest, and this will be a key feature of the hunt for BSM physics in Run 3

Backup

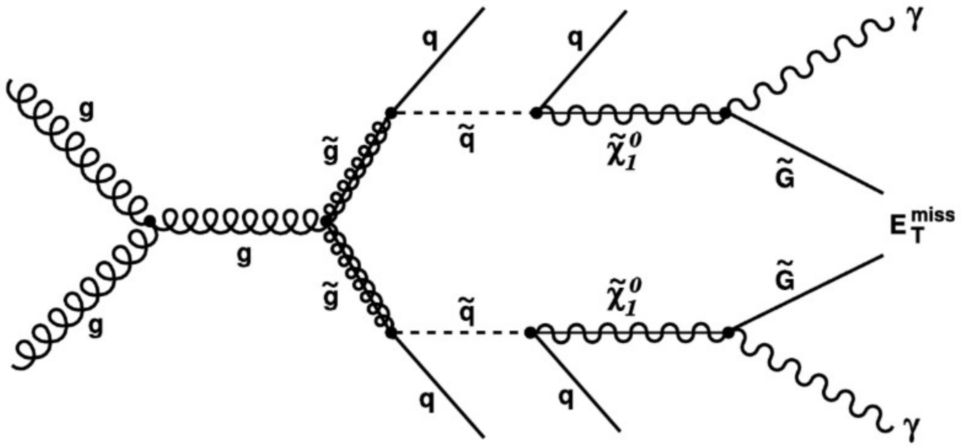
Delayed photons ABCD bins

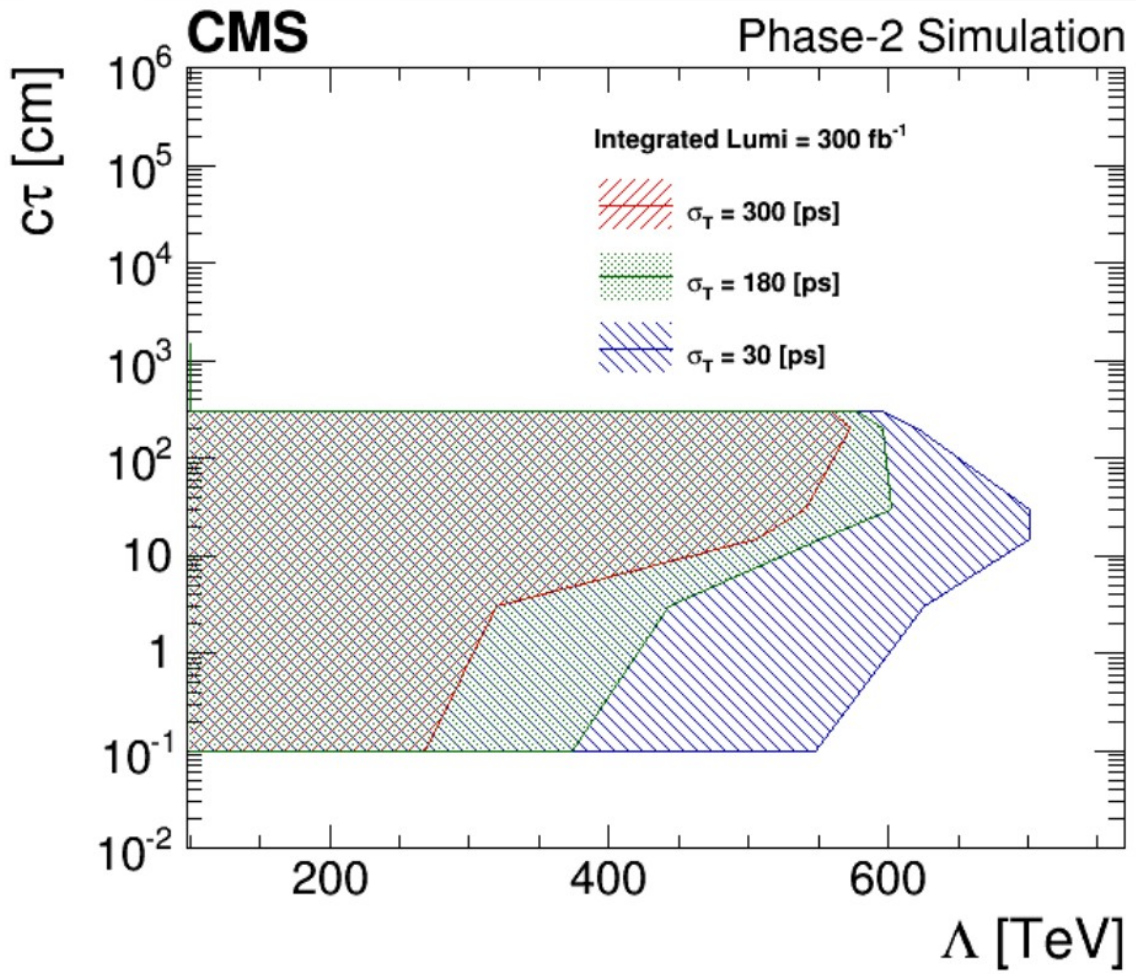
$c\tau$ (cm)	$\Lambda \leq 300$ TeV			$\Lambda > 300$ TeV		
	2016	2017γ	2017$\gamma\gamma$	2016	2017γ	2017$\gamma\gamma$
(0,10]	0, 250	0.5, 300	0.5, 150	0, 250	0.5, 300	0.5, 200
(10, 10000]	1.5, 100	1.5, 200	1.5, 150	1.5, 150	1.5, 300	1.5, 200

Delayed photons yields

Year / Category	Bin Split [t_γ (ns), p_T^{miss} (GeV)]		A	B	C	D
2016$\gamma\gamma$	(0, 250)	N_{obs}^{data}	16139	41	62	18826
		$N_{bkg}^{post-fit}$	16133 ± 114	47.5 ± 4.8	55.6 ± 5.6	18832 ± 130
		$N_{bkg(mask)}^{post-fit}$	16139 ± 114	41.0 ± 6.5	47.8 ± 7.7	18826 ± 130
	(1.5, 100)	N_{obs}^{data}	33760	1302	1	5
		$N_{bkg}^{post-fit}$	33759 ± 164	1303 ± 37	0.29 ± 0.28	5.7 ± 2.2
		$N_{bkg(mask)}^{post-fit}$	33761 ± 165	1302 ± 37	0.19 ± 0.21	5.0 ± 2.1
	(1.5, 150)	N_{obs}^{data}	34595	467	0	6
		$N_{bkg}^{post-fit}$	34596 ± 166	467 ± 22	0.08 ± 0.08	5.9 ± 2.3
		$N_{bkg(mask)}^{post-fit}$	34596 ± 167	467 ± 22	0.08 ± 0.09	6.0 ± 2.3
2017γ	(0.5, 300)	N_{obs}^{data}	458372	281	41	67655
		$N_{bkg}^{post-fit}$	458368 ± 660	281 ± 15	41.4 ± 2.4	67656 ± 280
		$N_{bkg(mask)}^{post-fit}$	458369 ± 662	281 ± 16	41.5 ± 2.7	67657 ± 281
	(1.5, 200)	N_{obs}^{data}	524652	1364	1	332
		$N_{bkg}^{post-fit}$	524653 ± 706	1364 ± 36	0.9 ± 0.8	332 ± 20
		$N_{bkg(mask)}^{post-fit}$	524653 ± 704	1364 ± 35	0.9 ± 1.0	332 ± 20
	(1.5, 300)	N_{obs}^{data}	525694	322	0	333
		$N_{bkg}^{post-fit}$	525694 ± 707	322 ± 17	0.19 ± 0.21	333 ± 20
		$N_{bkg(mask)}^{post-fit}$	525694 ± 704	322 ± 17	0.20 ± 0.24	333 ± 20
2017$\gamma\gamma$	(0.5, 150)	N_{obs}^{data}	21640	362	56	3201
		$N_{bkg}^{post-fit}$	21638 ± 143	364 ± 17	54.0 ± 3.0	3203 ± 61
		$N_{bkg(mask)}^{post-fit}$	21639 ± 143	362 ± 18	53.6 ± 3.3	3201 ± 61
	(0.5, 200)	N_{obs}^{data}	21863	139	24	3233
		$N_{bkg}^{post-fit}$	21860 ± 144	142 ± 11	21.1 ± 1.7	3236 ± 61
		$N_{bkg(mask)}^{post-fit}$	21863 ± 144	139 ± 11	20.6 ± 1.8	3233 ± 61
	(1.5, 150)	N_{obs}^{data}	24824	418	0	17
		$N_{bkg}^{post-fit}$	24824 ± 154	418 ± 20	0.25 ± 0.28	16.7 ± 4.4
		$N_{bkg(mask)}^{post-fit}$	24824 ± 154	418 ± 20	0.29 ± 0.36	17.0 ± 4.4
	(1.5, 200)	N_{obs}^{data}	25079	163	0	17
		$N_{bkg}^{post-fit}$	25079 ± 154	163 ± 12	0.11 ± 0.12	16.9 ± 4.4
		$N_{bkg(mask)}^{post-fit}$	25079 ± 154	163 ± 12	0.11 ± 0.14	17.0 ± 4.4

Delayed photons Phase II projection with timing detector





TECHNICAL PROPOSAL FOR A MIP TIMING DETECTOR IN THE CMS EXPERIMENT PHASE 2 UPGRADE

Delayed jets selection

Baseline jet selection
$\lvert\eta\rvert < 1.48$
$p_{\mathrm{T}} > 30\,\mathrm{GeV}$
Signal jet selection
$E_{\mathrm{ECAL}} > 20\,\mathrm{GeV}$
$N_{\mathrm{ECAL}}^{\mathrm{cell}} > 25$
HEF > 0.2 and $E_{\mathrm{HCAL}} > 50\,\mathrm{GeV}$
$t_{\mathrm{jet}}^{\mathrm{RMS}}/t_{\mathrm{jet}} < 0.4$ and $t_{\mathrm{jet}}^{\mathrm{RMS}} < 2.5\,\mathrm{ns}$
$\mathrm{PV}_{\mathrm{track}}^{\mathrm{fraction}} < 0.083$
$E_{\mathrm{ECAL}}^{\mathrm{CSC}}/E_{\mathrm{ECAL}} < 0.8$
$t_{\mathrm{jet}} > 3\,\mathrm{ns}$
Event level selection
At least one signal jet
$p_{\mathrm{T}}^{\mathrm{miss}} > 300\,\mathrm{GeV}$
Quality filters
$\max(\Delta\phi_{\mathrm{DT}}) < \pi/2$
$\max(\Delta\phi_{\mathrm{RPC}}) < \pi/2$

Delayed jets backgrounds

Background source	Events predicted
Beam halo muons	$0.02^{+0.06}_{-0.02}\,(\mathrm{stat})^{+0.05}_{-0.01}\,(\mathrm{syst})$
Core and satellite bunch collisions	$0.11^{+0.09}_{-0.05}\,(\mathrm{stat})^{+0.02}_{-0.02}\,(\mathrm{syst})$
Cosmic ray muons	$1.0^{+1.8}_{-1.0}\,(\mathrm{stat})^{+1.8}_{-1.0}\,(\mathrm{syst})$

M_{T2} + disappearing track preselection

Trigger	2016: $p_T^{miss} > 120\,GeV$ and $H_T^{miss} > 120\,GeV$ or $H_T > 300\,GeV$ and $p_T^{miss} > 110\,GeV$ or $H_T > 900\,GeV$ or jet $p_T > 450\,GeV$ 2017 and 2018: $p_T^{miss} > 120\,GeV$ and $H_T^{miss} > 120\,GeV$ or $H_T > 60\,GeV$ and $p_T^{miss} > 120\,GeV$ and $H_T^{miss} > 120\,GeV$ or $H_T > 500\,GeV$ and $p_T^{miss} > 100\,GeV$ and $H_T^{miss} > 100\,GeV$ or $H_T > 800\,GeV$ and $p_T^{miss} > 75\,GeV$ and $H_T^{miss} > 75\,GeV$ or $H_T > 1050\,GeV$ or jet $p_T > 500\,GeV$
Jet selection	$R = 0.4$, $p_T > 30\,GeV$, $\lvert\eta\rvert < 2.4$
b tag selection	$p_T > 20\,GeV$, $\lvert\eta\rvert < 2.4$
p_T^{miss}	$p_T^{miss} > 250\,GeV$ for $H_T < 1200\,GeV$, else $p_T^{miss} > 30\,GeV$ $\Delta\phi_{min} = \Delta\phi\left(p_T^{miss}, j_{1,2,3,4}\right) > 0.3$ $\lvert\vec{p}_T^{miss} - \vec{H}_T^{miss}\rvert / p_T^{miss} < 0.5$
M_{T2}	Inclusive M_{T2} search (if $N_j \geq 2$): $M_{T2} > 200\,GeV$ for $H_T < 1500\,GeV$, else $M_{T2} > 400\,GeV$ Search for disappearing tracks (if $N_j \geq 2$): $M_{T2} > 200\,GeV$
Veto muon Veto muon track	$p_T > 10\,GeV$, $\lvert\eta\rvert < 2.4$, $p_T^{sum} < 0.2\,p_T^{lep}$ $p_T > 5\,GeV$, $\lvert\eta\rvert < 2.4$, $M_T < 100\,GeV$, $p_T^{sum} < 0.2\,p_T^{lep}$
Veto electron Veto electron track	$p_T > 10\,GeV$, $\lvert\eta\rvert < 2.4$, $p_T^{sum} < 0.1\,p_T^{lep}$ $p_T > 5\,GeV$, $\lvert\eta\rvert < 2.4$, $M_T < 100\,GeV$, $p_T^{sum} < 0.2\,p_T^{lep}$
Veto track	$p_T > 10\,GeV$, $\lvert\eta\rvert < 2.4$, $M_T < 100\,GeV$, $p_T^{sum} < 0.1\,p_T^{track}$
p_T^{sum} cone (isolation)	Veto e or μ: $\Delta R = \min(0.2, \max(10\,GeV / p_T^{lep}, 0.05))$ Veto track: $\Delta R = 0.3$

M_{T2} + disappearing track selection

Observable	Selection	Track length	STC factor
p_T [GeV]	> 15	All	
$\|\eta\|$	< 2.4 and not $1.38 < \|\eta\| < 1.6$	All	
$\sigma(p_T)$ / p_T^2 [GeV^{-1}]	< 0.2; < 0.02; < 0.005	P; M; L	$\times 3$
d_{xy} (from primary vertex) [cm]	< 0.02 (< 0.01)	P (M, L)	$\times 3$
d_z (from primary vertex) [cm]	< 0.05	All	$\times 3$
Neutral isolation ($\Delta R < 0.05$) [GeV]	< 10	All	$\times 6$
Neutral isolation / p_T	< 0.1	All	$\times 6$
Isolation ($\Delta R < 0.3$) [GeV]	< 10	All	$\times 6$
Isolation / p_T	< 0.2	All	$\times 6$
Number of pixel layers	≥ 3 (≥ 2)	P, M† (M, L)	
Number of lost inner hits	$= 0$	All	
Number of lost outer hits	≥ 2	M, L	
Is a PF candidate?	No	All	
PF lepton veto ($\Delta R < 0.1$)	Yes	All	
Lepton veto ($\Delta R < 0.2$)	Yes	All	
Bad calorimeter module veto	Yes	All	
M_T (track, $\vec{p}_T^{\,miss}$) [GeV]	> 100, if $p_T < 150$ GeV	L	

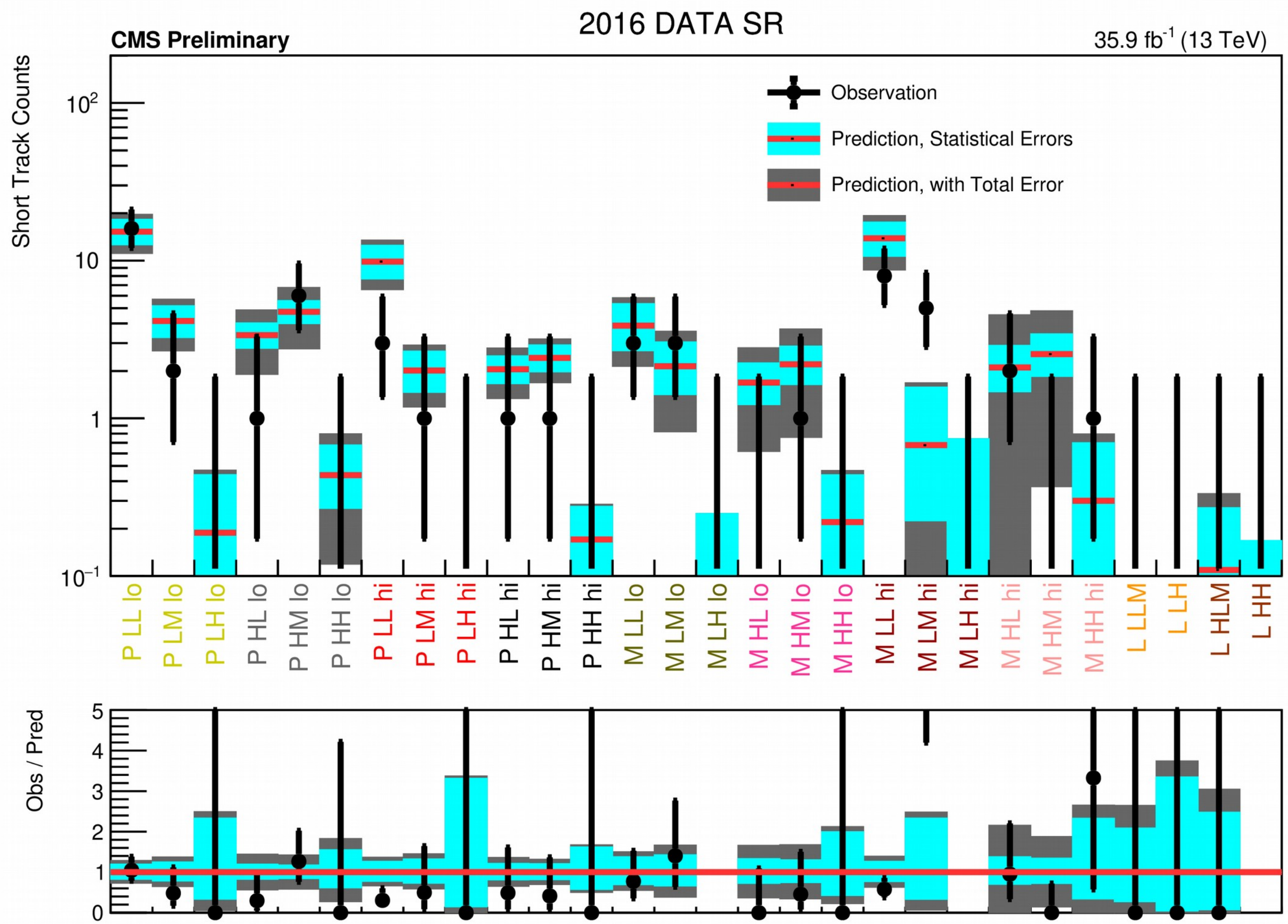
M_{T2} + disappearing track signal regions (2016)

Track length	N_j	H_T range [GeV]	Track p_T [GeV]	Label
P	2–3	[250, 450)	[15, 50)	P LL lo
			[50, ∞)	P LL hi
		[450, 1200)	[15, 50)	P LM lo
			[50, ∞)	P LM hi
		[1200, ∞)	[15, 50)	P LH lo
			[50, ∞)	P LH hi
	≥ 4	[250, 450)	[15, 50)	P HL lo
			[50, ∞)	P HL hi
		[450, 1200)	[15, 50)	P HM lo
			[50, ∞)	P HM hi
		[1200, ∞)	[15, 50)	P HH lo
			[50, ∞)	P HH hi
M	2–3	[250, 450)	[15, 50)	M LL lo
			[50, ∞)	M LL hi
		[450, 1200)	[15, 50)	M LM lo
			[50, ∞)	M LM hi
		[1200, ∞)	[15, 50)	M LH lo
			[50, ∞)	M LH hi
	≥ 4	[250, 450)	[15, 50)	M HL lo
			[50, ∞)	M HL hi
		[450, 1200)	[15, 50)	M HM lo
			[50, ∞)	M HM hi
		[1200, ∞)	[15, 50)	M HH lo
			[50, ∞)	M HH hi
L	2–3	[250, 1200)	[15, ∞)	L LLM
		[1200, ∞)	[15, ∞)	L LH
	≥ 4	[250, 1200)	[15, ∞)	L HLM
		[1200, ∞)	[15, ∞)	L HH

M_{T2} + disappearing track signal regions (2017+2018)

Track length	N_j	H_T range [GeV]	Track p_T [GeV]	Label
P3	2–3	[250, 450)	[15, 50)	P3 LL lo
			[50, ∞)	P3 LL hi
		[450, 1200)	[15, 50)	P3 LM lo
			[50, ∞)	P3 LM hi
		[1200, ∞)	[15, 50)	P3 LH lo
			[50, ∞)	P3 LH hi
	≥ 4	[250, 450)	[15, 50)	P3 HL lo
			[50, ∞)	P3 HL hi
		[450, 1200)	[15, 50)	P3 HM lo
			[50, ∞)	P3 HM hi
		[1200, ∞)	[15, 50)	P3 HH lo
			[50, ∞)	P3 HH hi
P4	2–3	[250, 450)	[15, 50)	P4 LL lo
			[50, ∞)	P4 LL hi
		[450, 1200)	[15, 50)	P4 LM lo
			[50, ∞)	P4 LM hi
		[1200, ∞)	[15, 50)	P4 LH lo
			[50, ∞)	P4 LH hi
	≥ 4	[250, 450)	[15, 50)	P4 HL lo
			[50, ∞)	P4 HL hi
		[450, 1200)	[15, 50)	P4 HM lo
			[50, ∞)	P4 HM hi
		[1200, ∞)	[15, 50)	P4 HH lo
			[50, ∞)	P4 HH hi
M	2–3	[250, 450)	[15, 50)	M LL lo
			[50, ∞)	M LL hi
		[450, 1200)	[15, 50)	M LM lo
			[50, ∞)	M LM hi
		[1200, ∞)	[15, 50)	M LH lo
			[50, ∞)	M LH hi
	≥ 4	[250, 450)	[15, 50)	M HL lo
			[50, ∞)	M HL hi
		[450, 1200)	[15, 50)	M HM lo
			[50, ∞)	M HM hi
		[1200, ∞)	[15, 50)	M HH lo
			[50, ∞)	M HH hi
L	2–3	[250, 1200)	[15, ∞)	L LLM
		[1200, ∞)	[15, ∞)	L LH
	≥ 4	[250, 1200)	[15, ∞)	L HLM
		[1200, ∞)	[15, ∞)	L HH

M_{T2} + disappearing track yields (2016)



M_{T2} + disappearing track yields (2017+2018)