

Search for long-lived massive particles in CMS

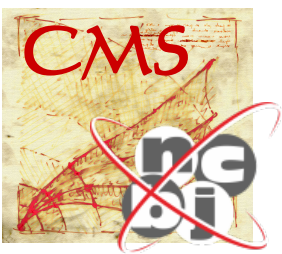
Małgorzata Kazana
on behalf of the CMS Collaboration

National Centre
for Nuclear Research
Warsaw, Poland



Compact Muon Solenoid
experiment at the CERN's LHC

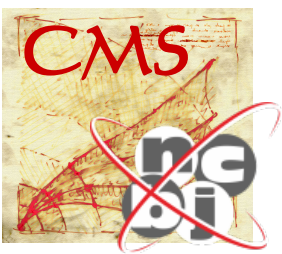
SUSY 2015
Lake Tahoe, California
August 23 – 29



Hunting for Long-Lived Particles

OUTLINE:

- **Various theoretical models** predict **naturally long-lived** particles: pMSSM, GMSB, AMSB, Split-SUSY (with R-hadrons), RPV SUSY, Hidden Valley (HV), Little Higgs and more
- **Challenging and interesting**
non-standard measurements and techniques of reconstructions, often difficult for triggering
- **Signature based searches**
interpreted in the context of different models
- **Review of EXOTIC LLP searches in the CMS**
 - Results from CMS data collected
in 2012 – **20/fb at 8TeV** and in 2011 – **5/fb at 7TeV**



Long-lived Signatures vs **Th. models**

- Lifetime categorization (studied so far in CMS):

- **Cross the detector**

GMSB
Spit-SUSY
PMSSM

- Heavy stable (fractionally, multi-, flip-) charged particles, **HSCP**
- High/low **ionisation** (dE/dx)
- **Delayed** → extended **time-of-flight** (TOF) vrt SM objects

- **Decay inside the detector**

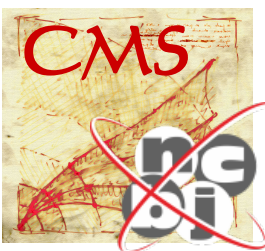
Not in this talk →

- charged LLP: **kinked** or **disappearing** tracks **AMSB** **RPV**
- neutral LLP: **non-pointing** or **displaced** objects or vertices **HV**

- **Stop inside the detector**

Spit-SUSY

- **Delayed decays** out-of-time in next bunch crossings



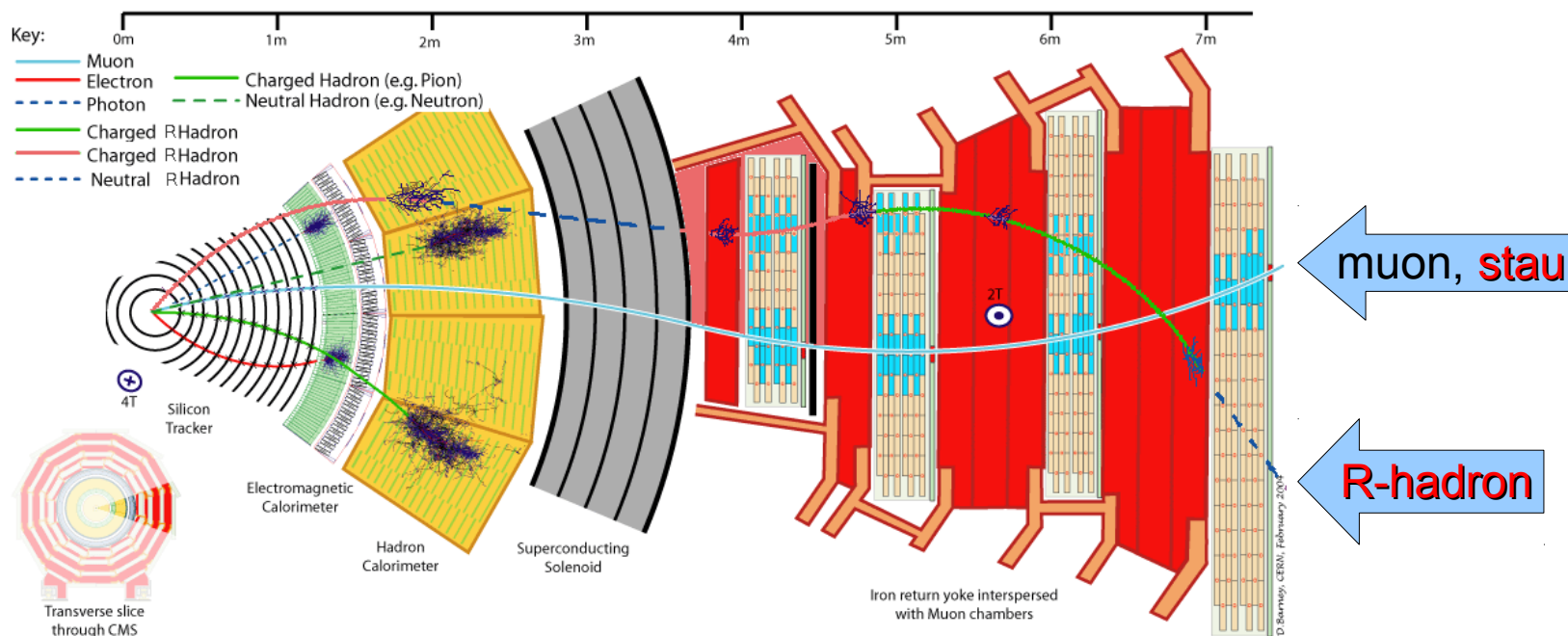
Heavy ^{QUASI} Stable Charged Particles

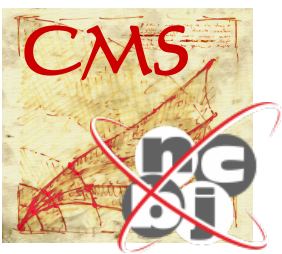
JHEP 07(2013)122

- **Cross the detector**

Signal: Long-Lived Particles from GMSB, Split-SUSY and others:

- lepton like (stau)
 - fractional charge ($Q = n \cdot 1/3e$)
 - multiple charge ($Q = n \cdot e$)
- R-hadrons formed from **gluino or stop**
 - charge can flip while crossing particle interacts with material

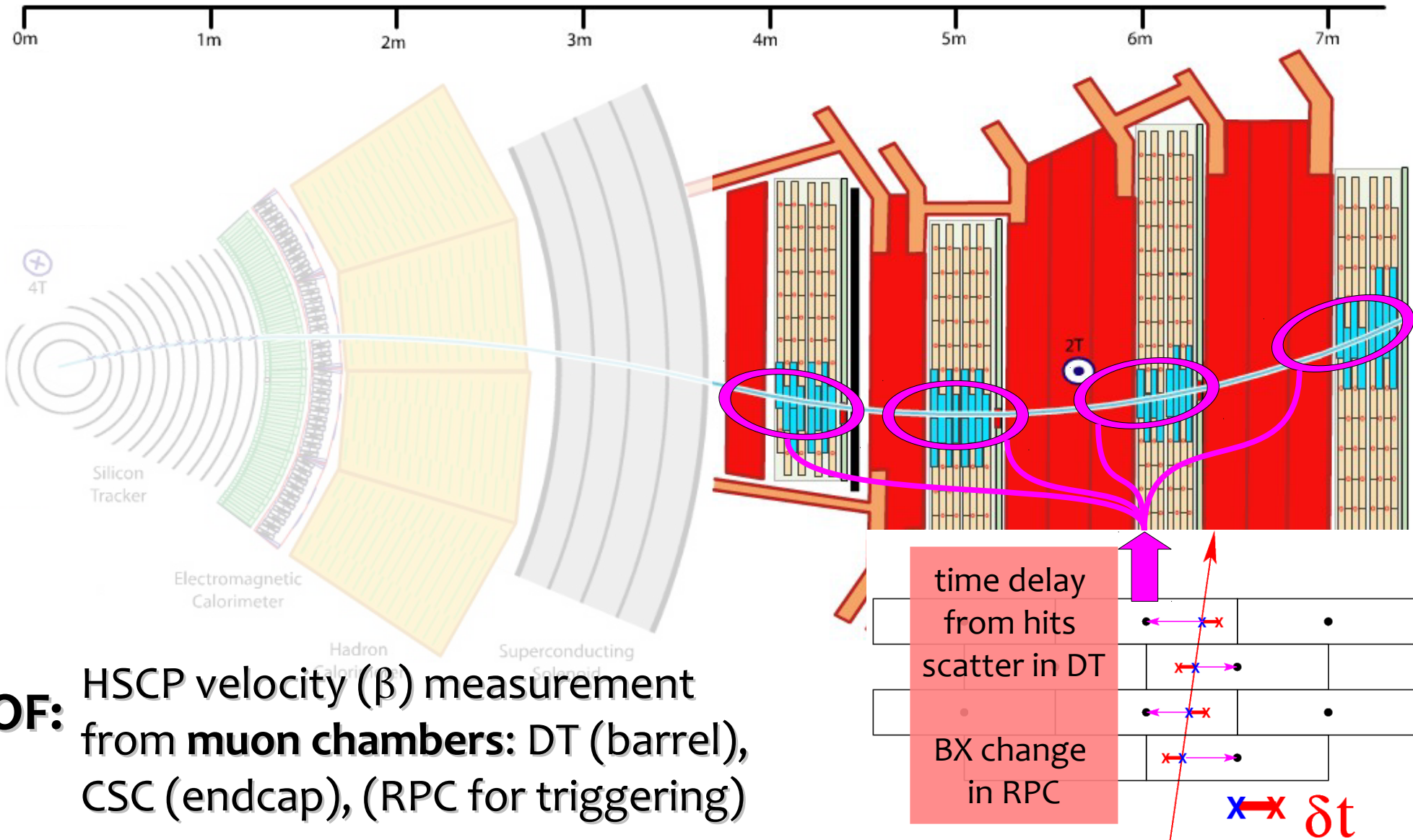




Idea of HSCP Search

HSCP can be **delayed** with respect to the *c*-speed SM particle

Muon System: Mass determination from β – TOF

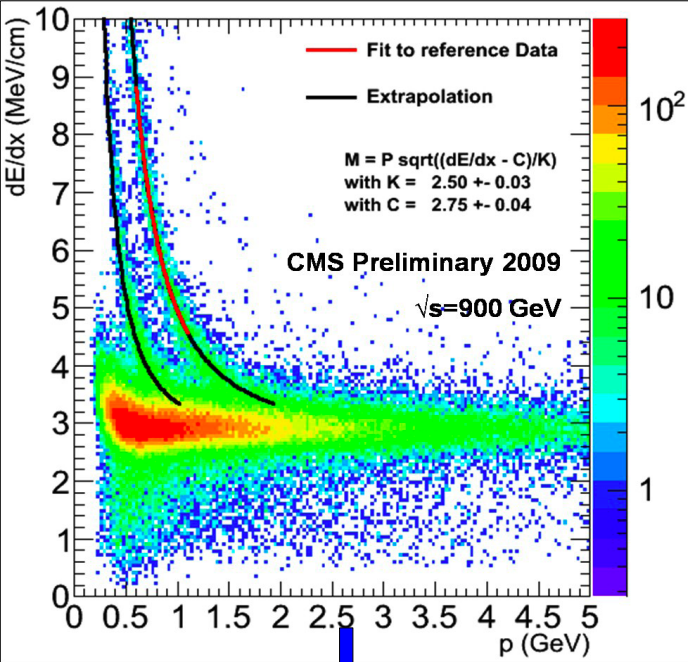


TOF: HSCP velocity (β) measurement from **muon chambers: DT (barrel), CSC (endcap), (RPC for triggering)**

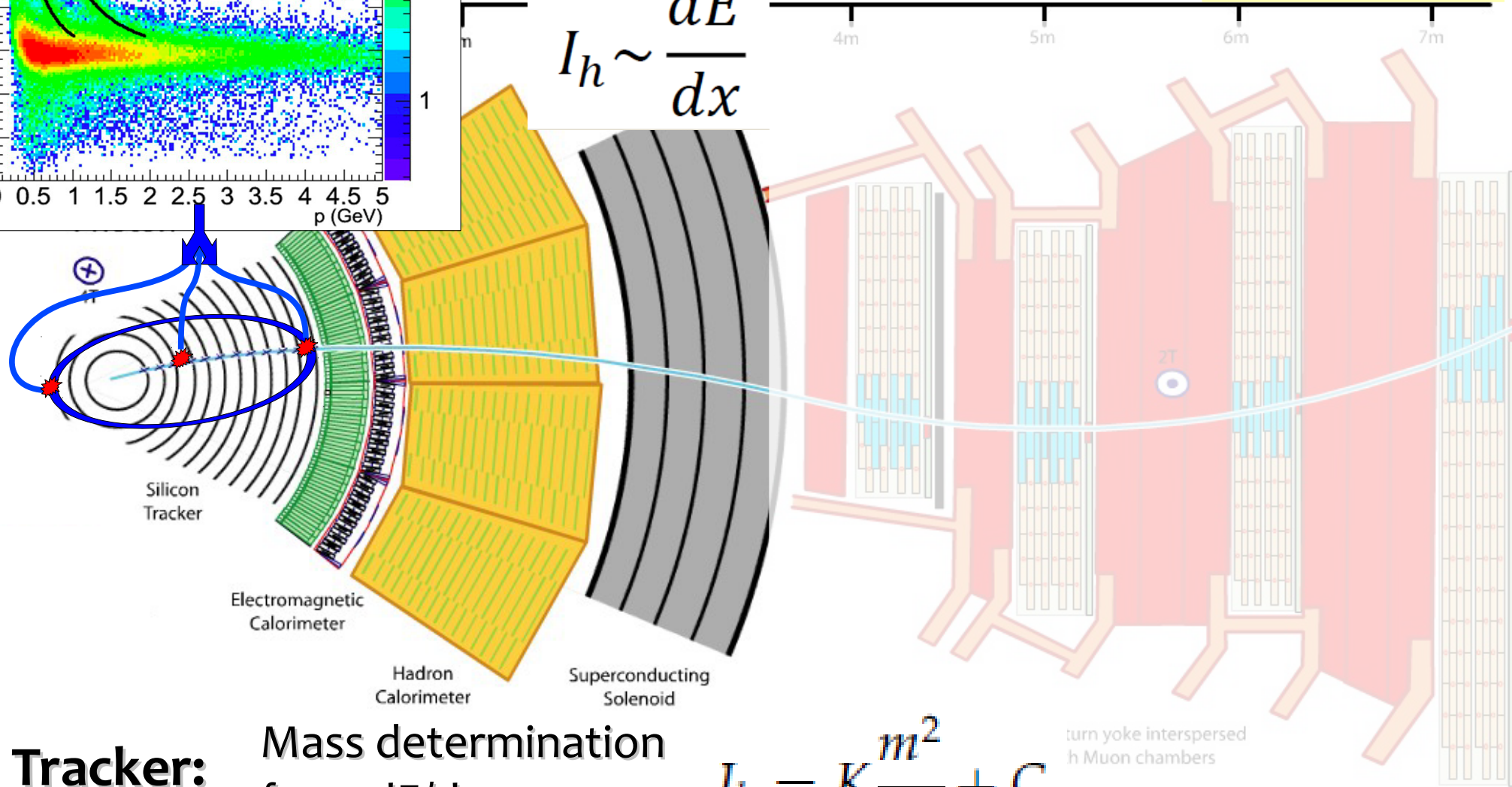
Idea of HSCP Search

HSCP has high unusual **ionization** related to its mass

JHEP 07(2013)122



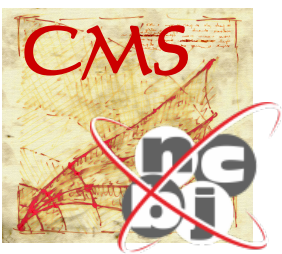
$$I_h \sim \frac{dE}{dx}$$



Tracker:

Mass determination
from dE/dx
discriminants

$$I_h = K \frac{m^2}{p^2} + C$$



HSCP Selection

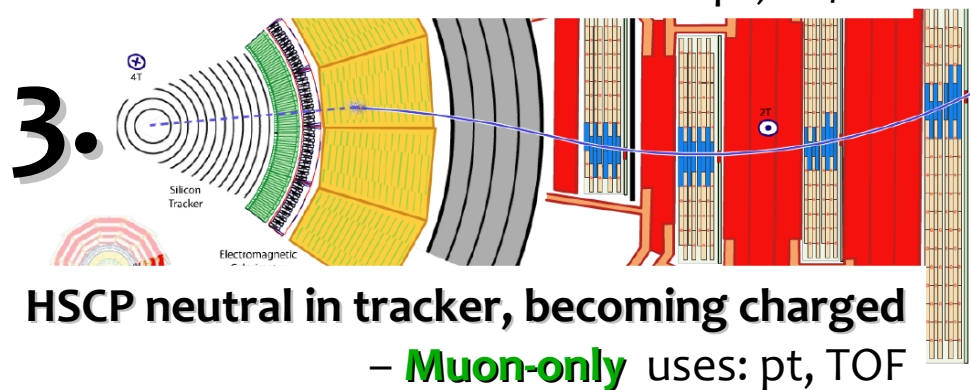
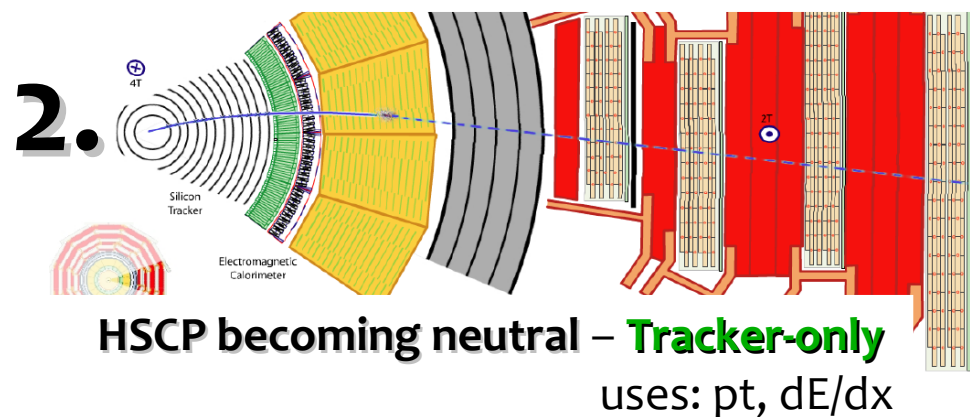
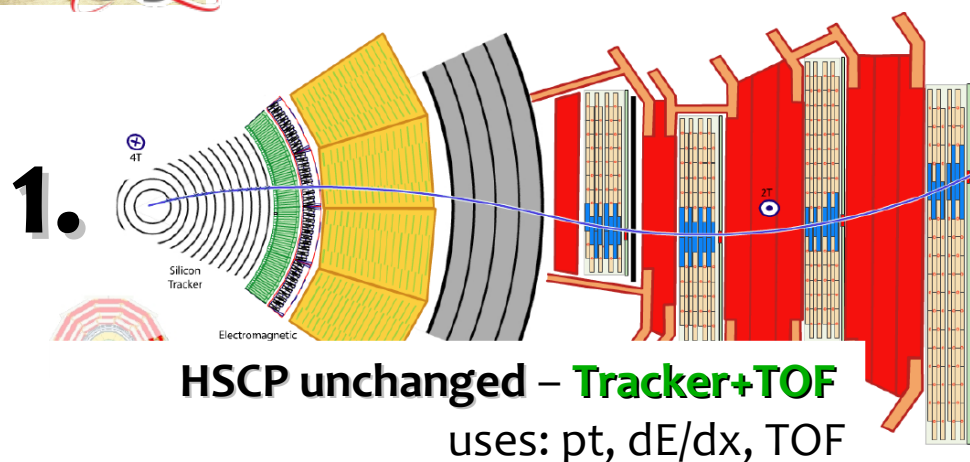
Event selection:

- **Trigger:** muon ($p_T > 40$ GeV) or MET > 150 GeV or mu $p_T > 60$ GeV & MET > 65 GeV
- **Basic pre-selection:**
 $p_T > 45$ GeV, $|\eta| < 2.1$, $|d_{xy}|$ and $|dz| < 0.5$ cm,
#Hits > 7 , very loose isolation, cosmic veto, etc
- **Selection optimised** to for the best discovery reach for each class of models using **track p_T , Muon $1/\beta$, Track I_{as}** (dE/dx discriminator)
- **Background** from ABCD method

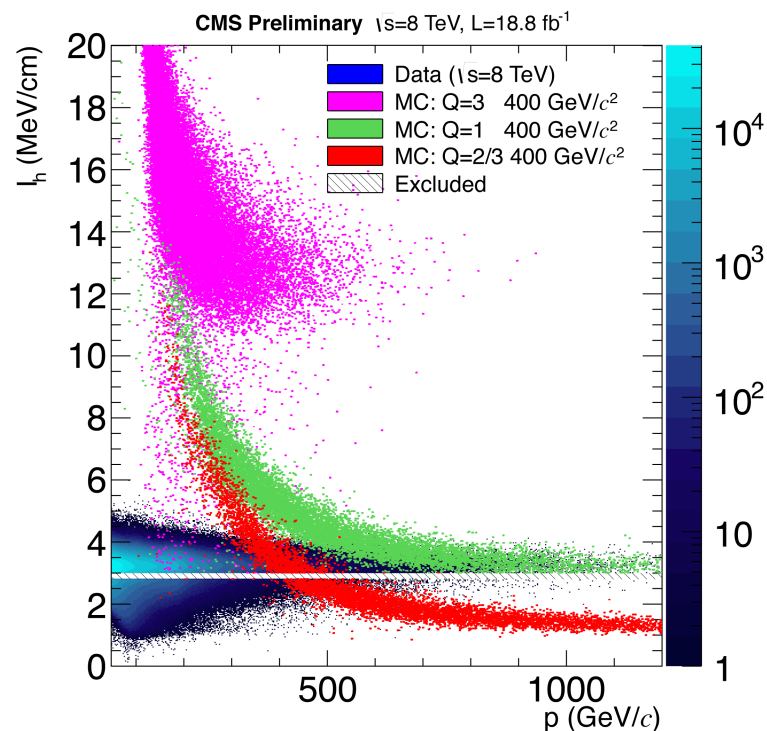


Five HSCP Search Paths

JHEP 07(2013)122



HSCP with $Q = n \cdot e$
4. Multiply Charged Particles
uses: dE/dx TOF, **do not use pt**,
because reco pt \sim true pt/Q



5. HSCP with $Q = n \cdot 1/3e$
Fractionally Charged Particles
uses: pt, dE/dx, no TOF to be inclusive



HSCP RESULTS

	Selection criteria				Number of events			
					$\sqrt{s} = 7 \text{ TeV}$		$\sqrt{s} = 8 \text{ TeV}$	
	p_T (GeV/c)	$I_{as}^{(t)}$	$1/\beta$	Mass (GeV/c ²)	Pred.	Obs.	Pred.	Obs.
2. Tracker-only	>70	>0.4	-	>0	7.1 ± 1.5	8	33 ± 7	41
				>100	6.0 ± 1.3	7	26 ± 5	29
				>200	0.65 ± 0.14	0	3.1 ± 0.6	3
				>300	0.11 ± 0.02	0	0.55 ± 0.11	1
				>400	0.030 ± 0.006	0	0.15 ± 0.03	0
1. Tracker+TOF	>70	>0.125	>1.225	>0	8.5 ± 1.7	7	44 ± 9	42
				>100	1.0 ± 0.2	3	5.6 ± 1.1	7
				>200	0.11 ± 0.02	1	0.56 ± 0.11	0
				>300	0.020 ± 0.004	0	0.090 ± 0.02	0
Muon-only 3.	>230	-	>1.40	-	-	-	6 ± 3	3
$ Q > 1e$ 4.	-	>0.500	>1.200	-	0.15 ± 0.04	0	0.52 ± 0.11	1
$ Q < 1e$ 5.	>125	>0.275	-	-	0.12 ± 0.07	0	1.0 ± 0.2	0

Mass (GeV/c²)

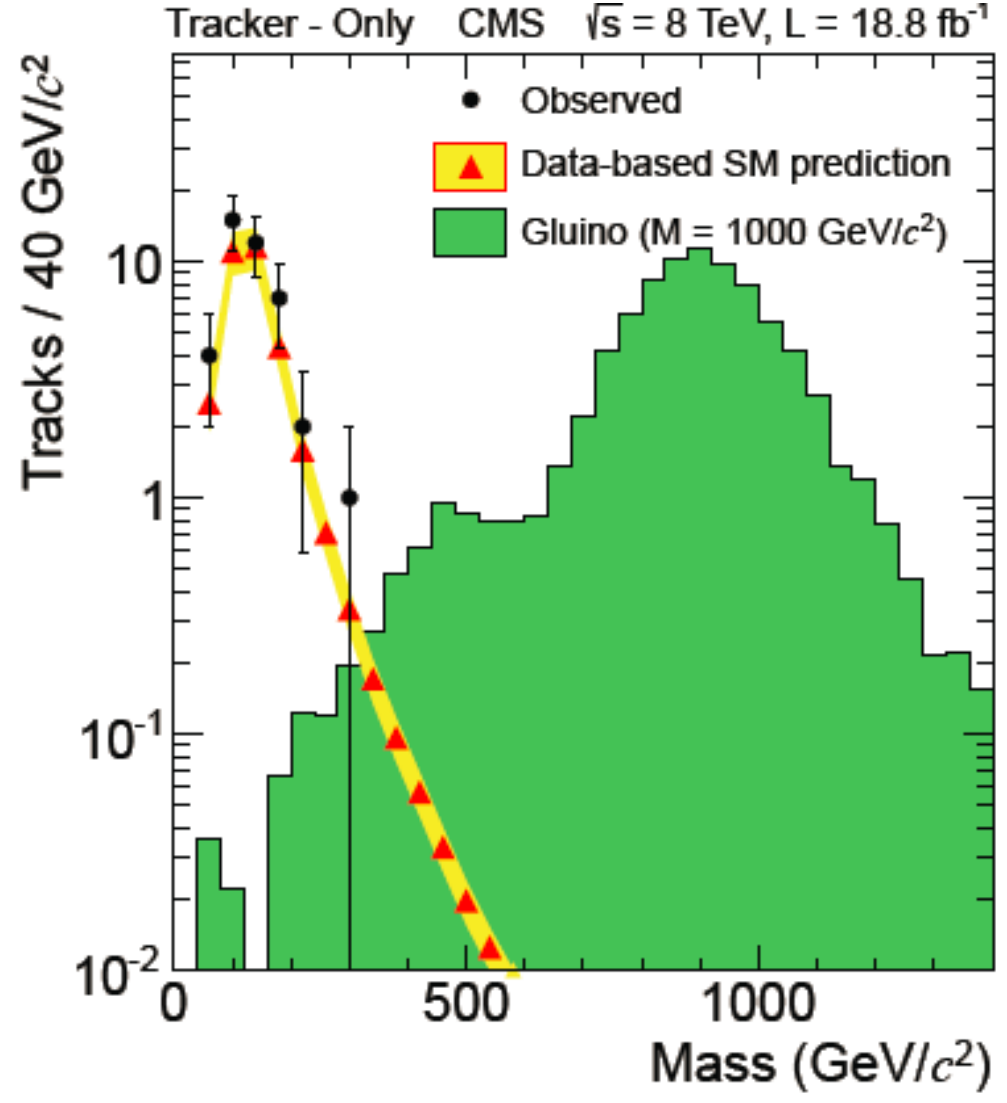
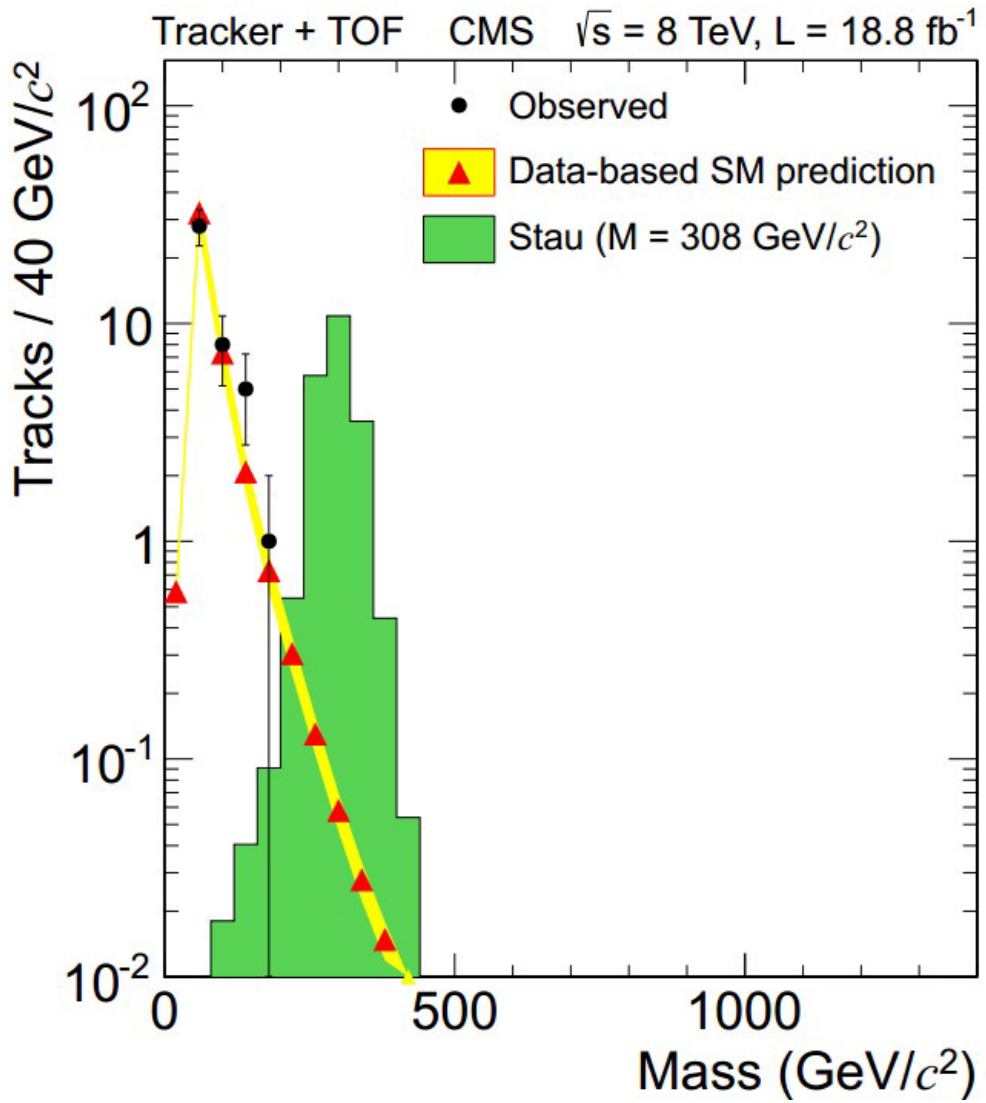


HSCP RESULTS

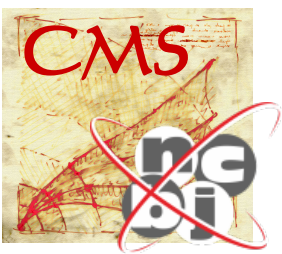
JHEP 07(2013)122

dE/dx + TOF

dE/dx

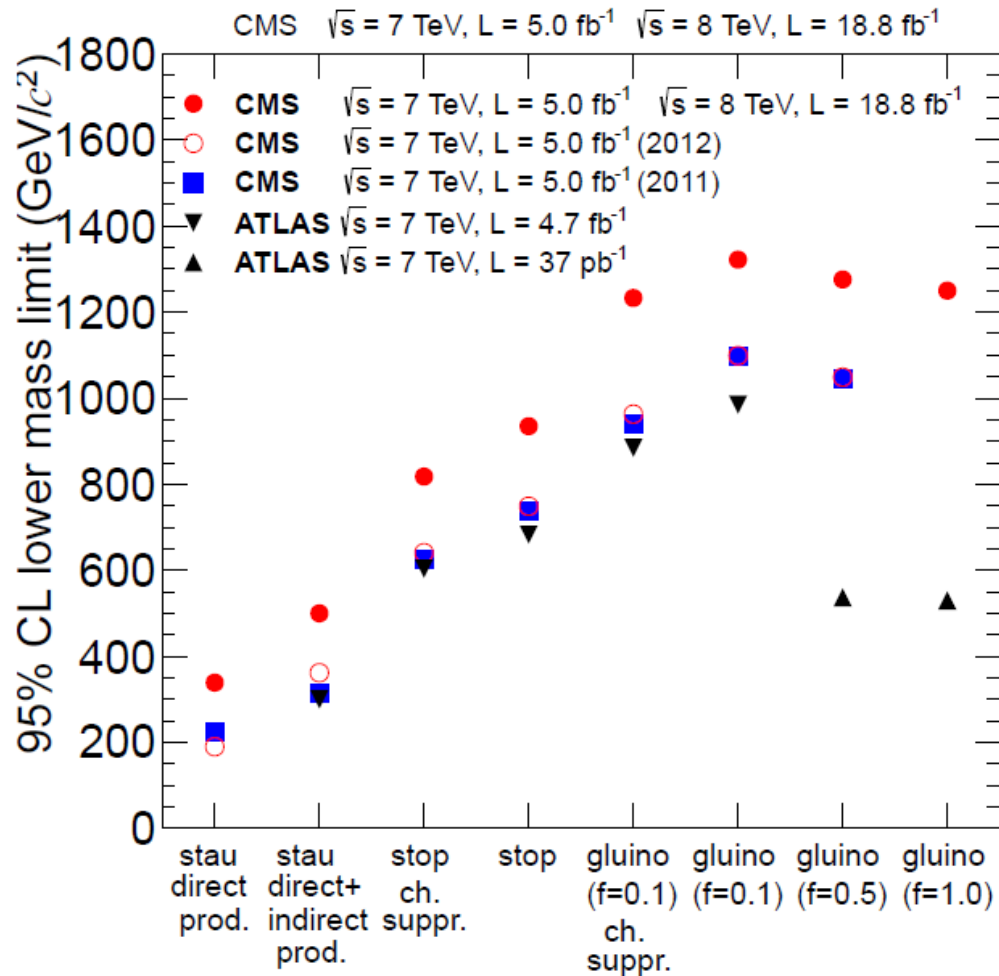


Mass determined from dE/dx

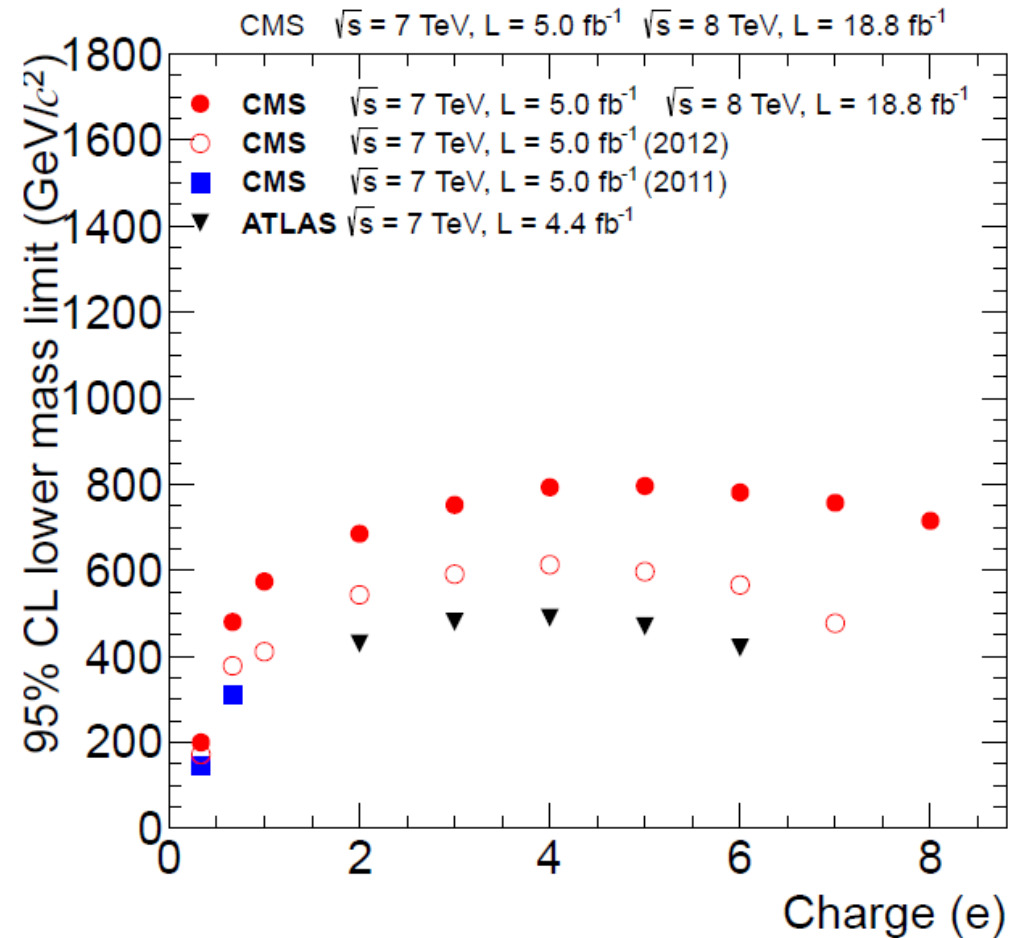


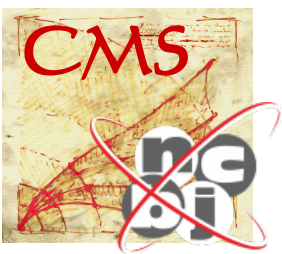
HSCP LIMITS

Stau R-hadrons (stop, gluino)



Multiply Charged Particles Fractionally Charged Particles



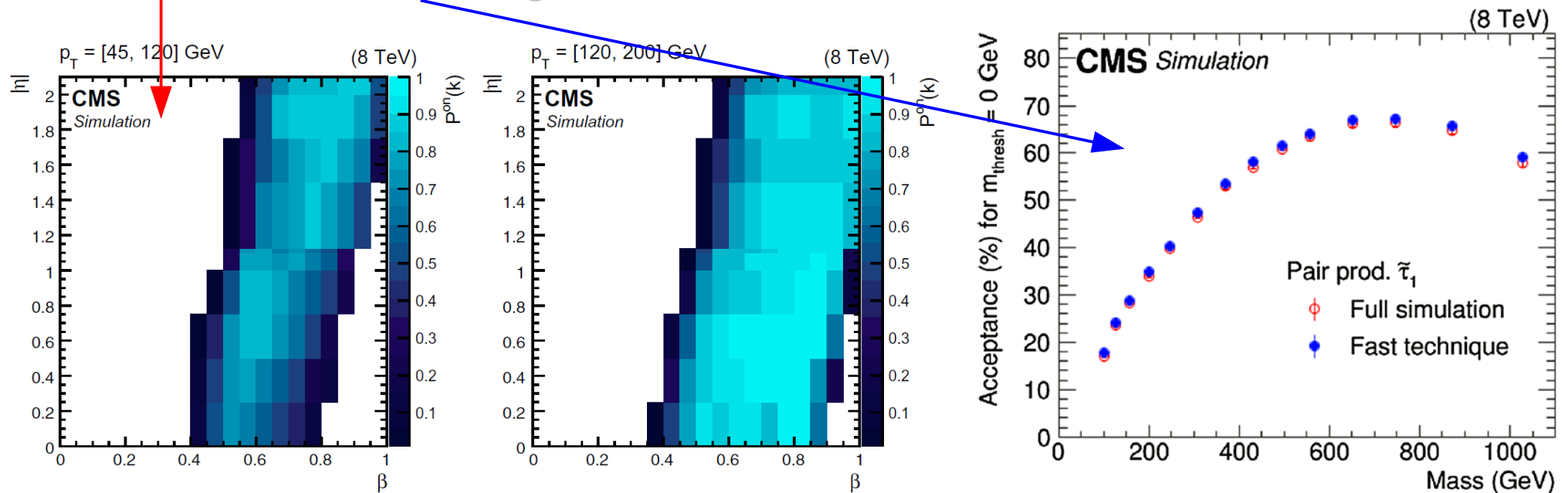


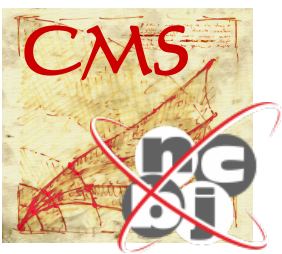
HSCP re-interpretation by CMS

EPJ C (2015) 75:325

- **Reinterpretation of the HSCP search results in context of pMSSM and AMSB**
- Developed a technique to allow anyone to assess CMS sensitivity to any model predicting long-lived lepton-like particles
- The efficiency for HSCP particles is given as a function of β and η in bins of p_T , it can be applied to any model if the kinematics is known

Probability maps of that LLP passes all HSCP cuts are expressed as a $f(\beta, p_T, \eta)$
Pure **GenLevel MC** enough to verify results of HSCP analysis



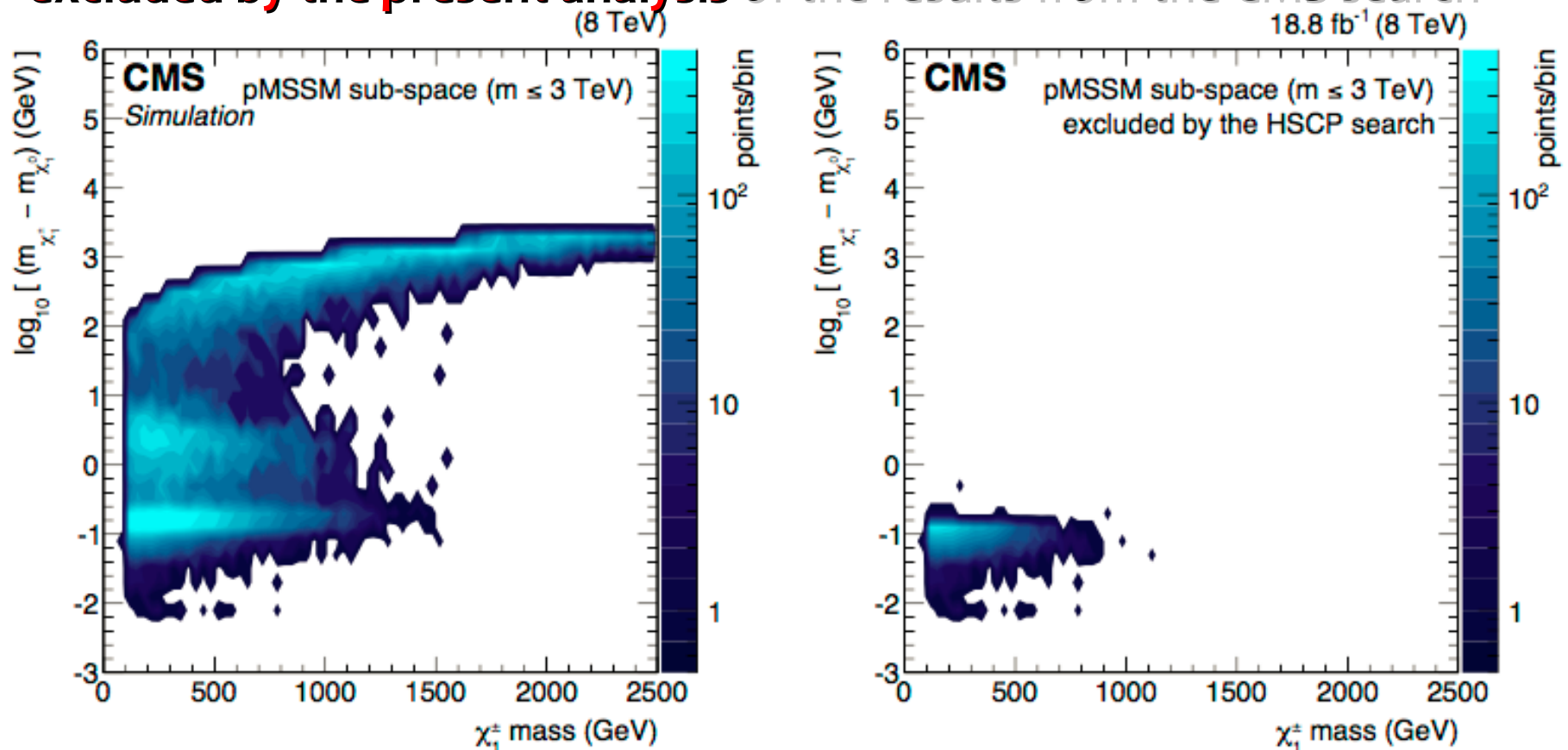


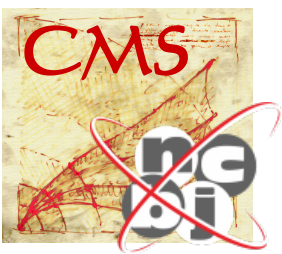
HSCP re-interpretation by CMS

EPJ C (2015) 75:325

- Limits on the long-lived sector of the pMSSM sub-space for SUSY particle masses < 3 TeV:

95.9% (100%) of the points with a chargino lifetime $\tau \geq 10$ ns (1000 ns) are **excluded by the present analysis** of the results from the CMS search

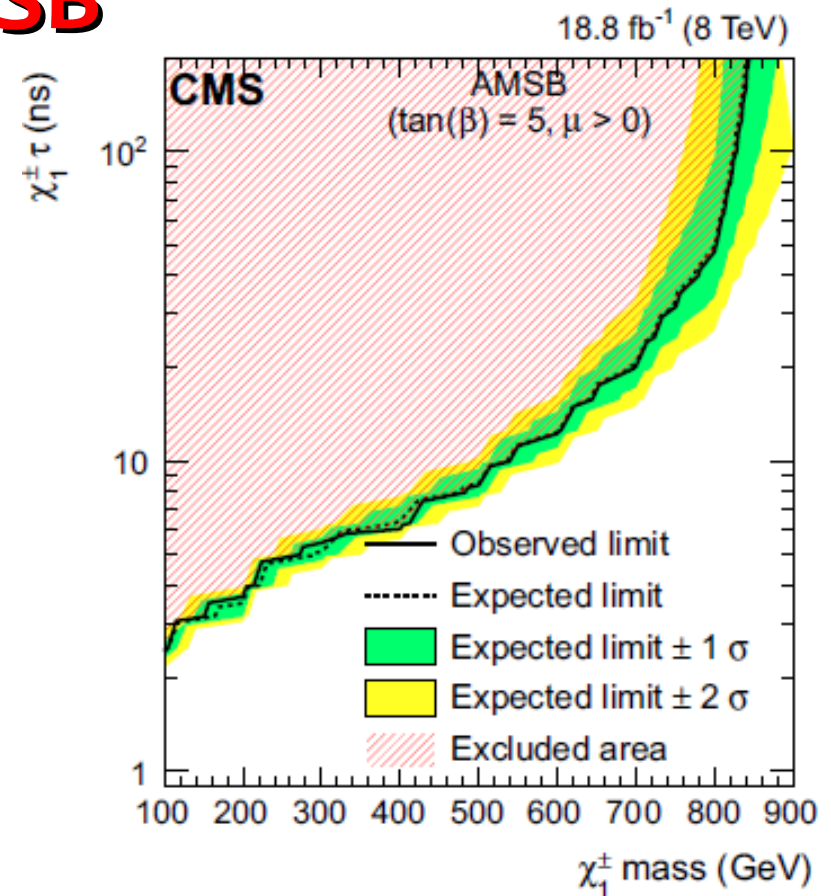
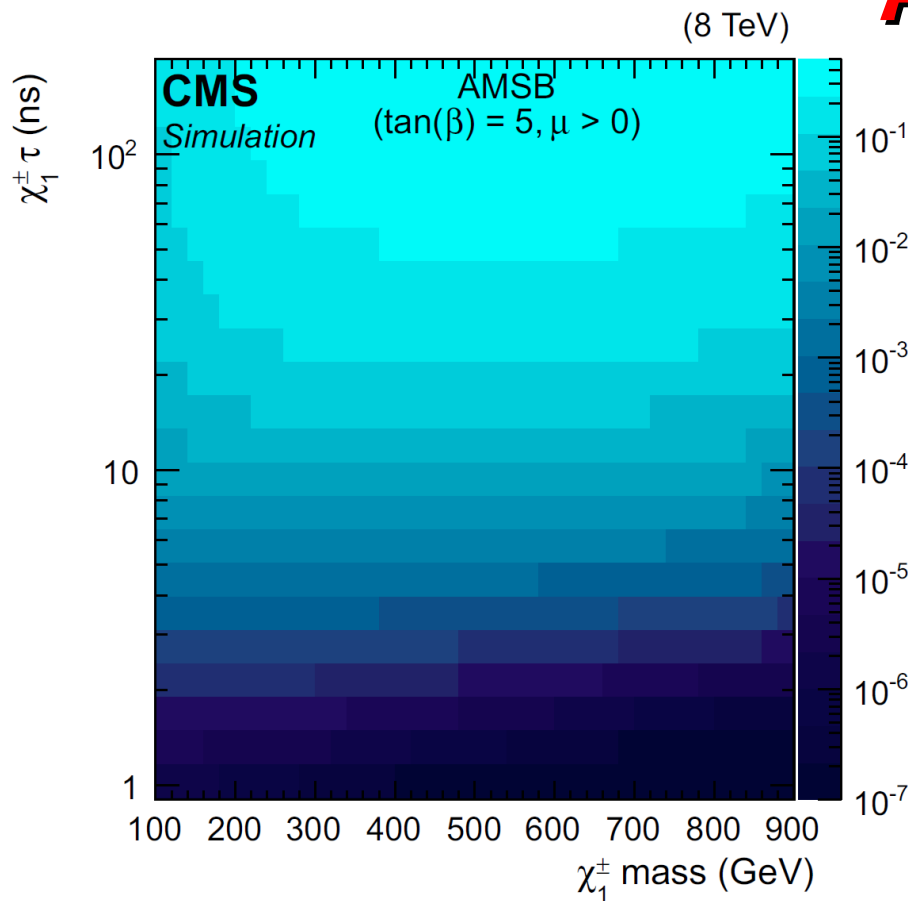




HSCP re-interpretation by CMS

EPJ C (2015) 75:325

AMSB



- Signal acceptance as a function of chargino mass for the AMSB model as predicted by the fast technique

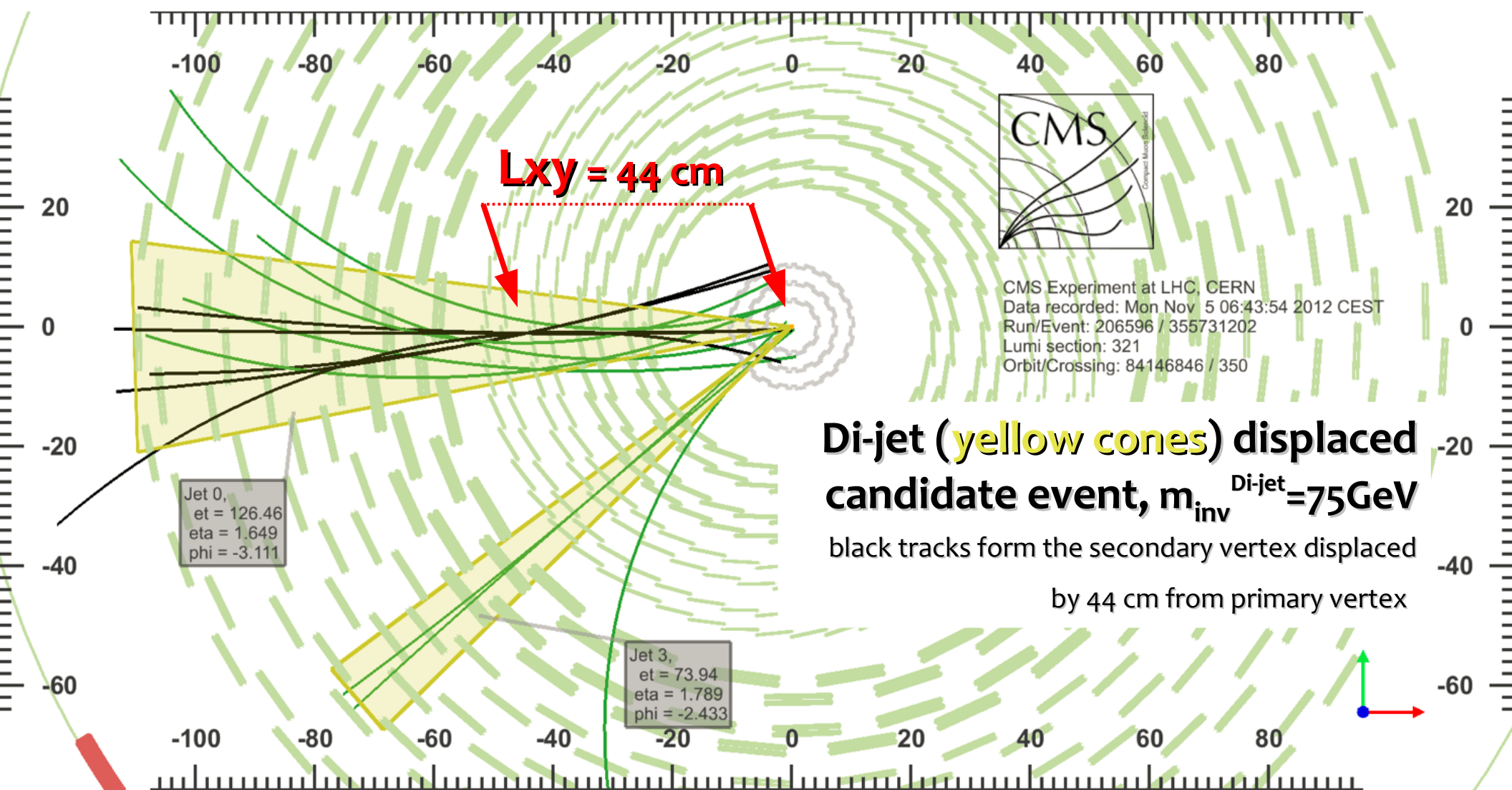
- Observed and expected excluded region on the chargino mass and lifetime parameter space in the context of the AMSB model with $\tan \beta = 5$ and $\mu \geq 0$.

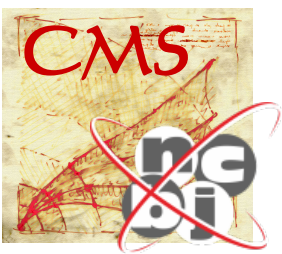


Displaced Jets

Phys. Rev. D 91, 012007 (2015)

- **Decay inside the detector**
- Long-lived massive neutral particles decaying to quark-antiquark pairs
- Distinctive topology of a pair of jets originating at a secondary vertex





Displaced Jets

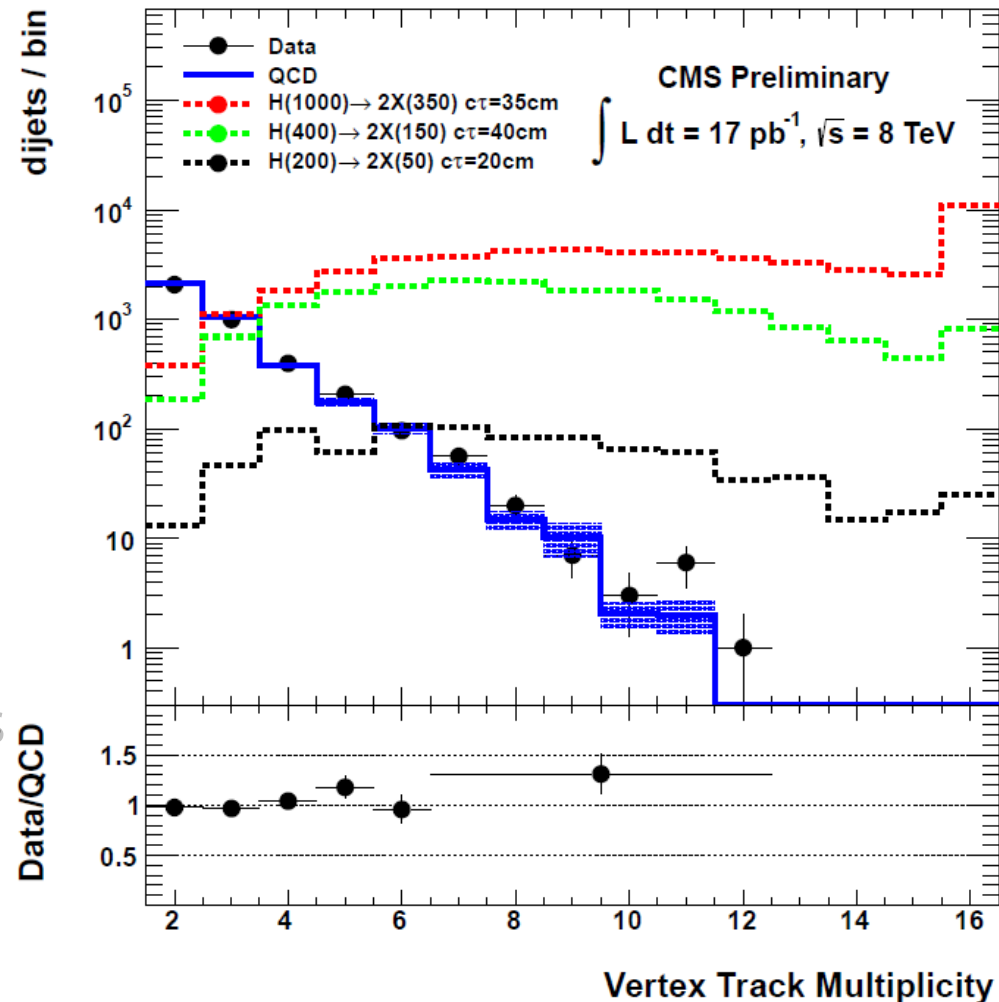
Phys. Rev. D 91, 012007 (2015)

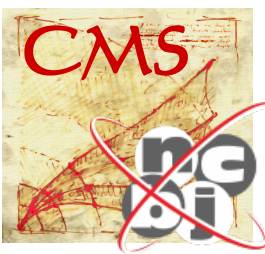
Signal: $gg \rightarrow (\text{non-SM}) H \rightarrow 2X, X \rightarrow qq$

- originating from Hidden Valley model, Split SUSY, RPV SUSY, GMSB, etc.
- Benchmark points
 $M_H = [200, 400, 1000] \text{ GeV}$,
 $M_X = [50, 150, 350] \text{ GeV}$,
 $c\tau_X = [3, 20, 35, 40, 300] \text{ cm}$

Event selection:

- Trigger: $HT > 300 \text{ GeV}$ and > 1 jets with small fraction of prompt tracks
- **Multivariate discriminant** based on vertex track multiplicity, fraction of tracks with positive d_0 , and variables from a dedicated track cluster algorithm





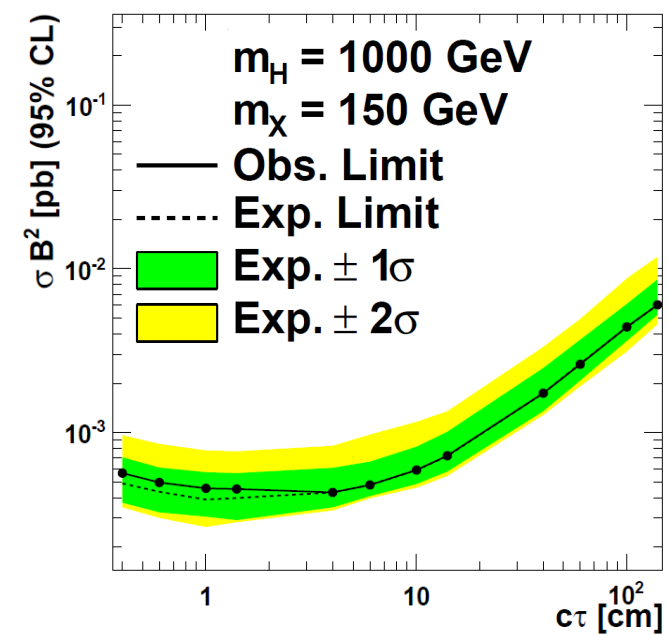
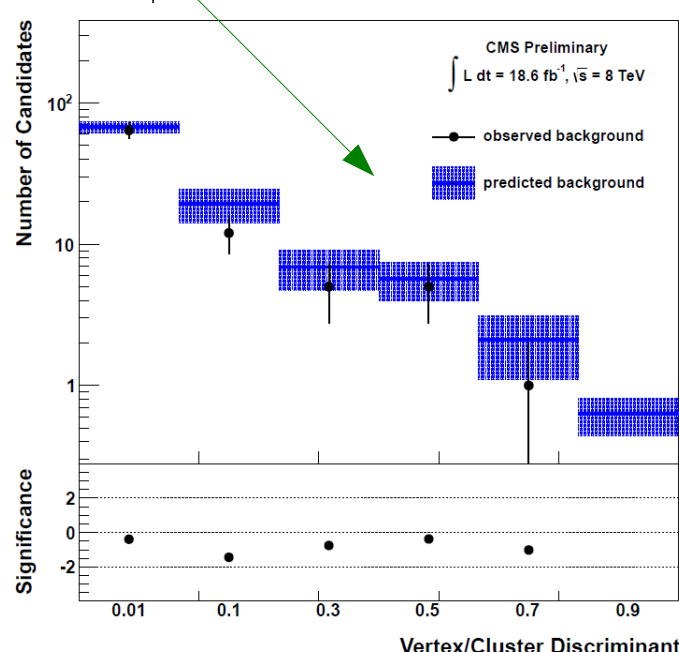
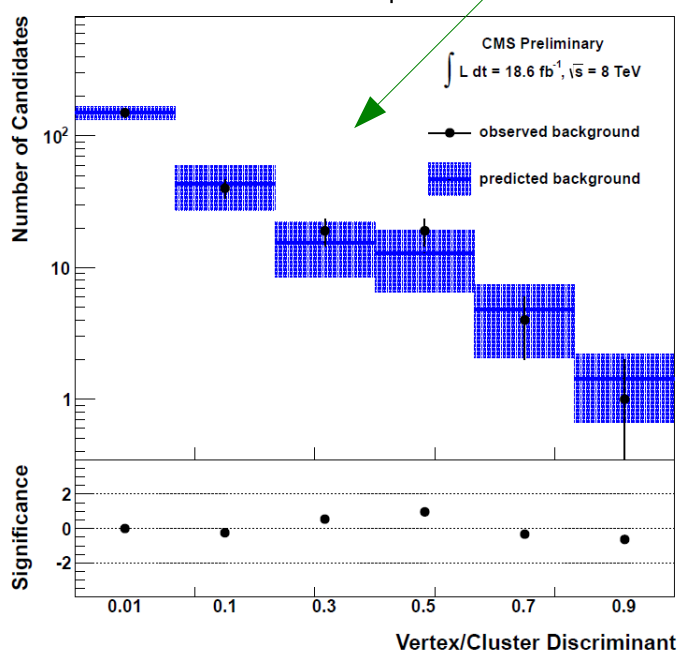
Displaced Jets RESULTS & LIMITS

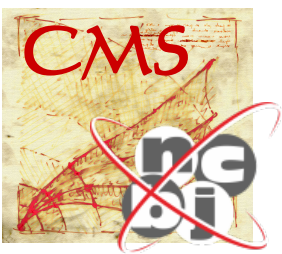
Phys. Rev. D 91, 012007 (2015)

- Background:** ABCD prediction using jet variables and vertices infos
- Search optimised for two regions $L_{xy} < 20$ or $L_{xy} > 20$ cm
- For X mean lifetimes of **0.1 to 200 cm**, the upper **cross-section $\times B^2$** ($X \rightarrow qq$) limits are typically **0.3-300 fb**

L_{xy}	< 20 cm(low)	> 20 cm(high)
prompt tracks	≤ 1	≤ 1
prompt energy fraction	< 0.15	< 0.09
vertex/cluster disc.	> 0.9	> 0.8
expected background	$1.60 \pm 0.26(stat.) \pm 0.51(syst.)$	$1.14 \pm 0.15(stat.) \pm 0.52(syst.)$
observed	2	1

$\int L dt = 18.6 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV}$





Stopped gluinos

JHEP 08(2012)026

Strategy: Stopped inside the detector

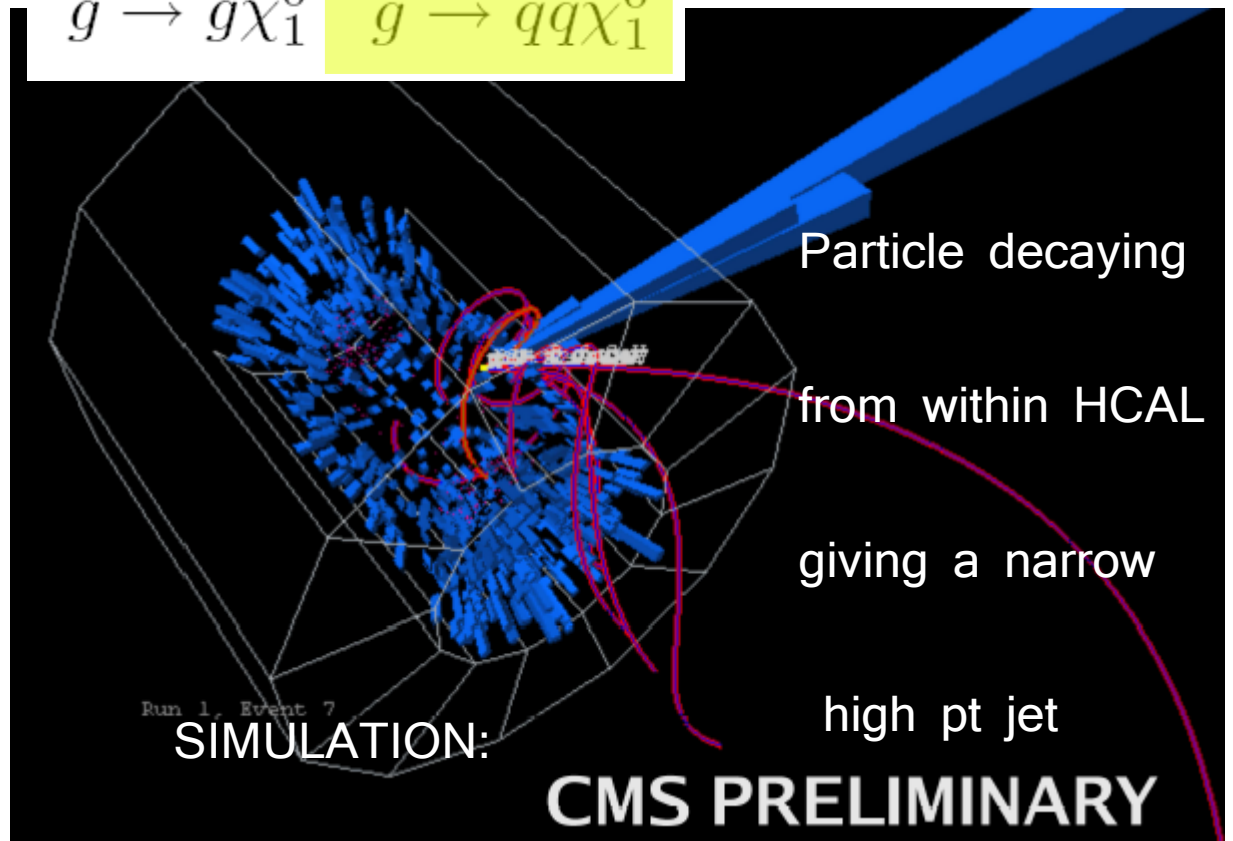
- Search for LLPs (gluino from Split-SUSY with high energy losses) that have stopped in the CMS detector, during 7 TeV pp operations
- Stopped R-hadron can decay after a while (μsec , sec or days, months)
- Search in GAPS between LHC beam crossing

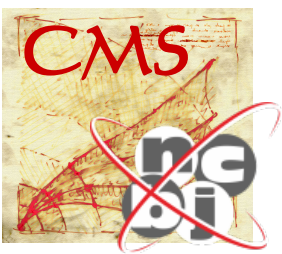
$$\tilde{g} \rightarrow g\tilde{\chi}_1^0$$

$$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$$

Trigger:

- Decays inside calorimeters could give trigger when there is no BX





Stopped gluinos RESULTS

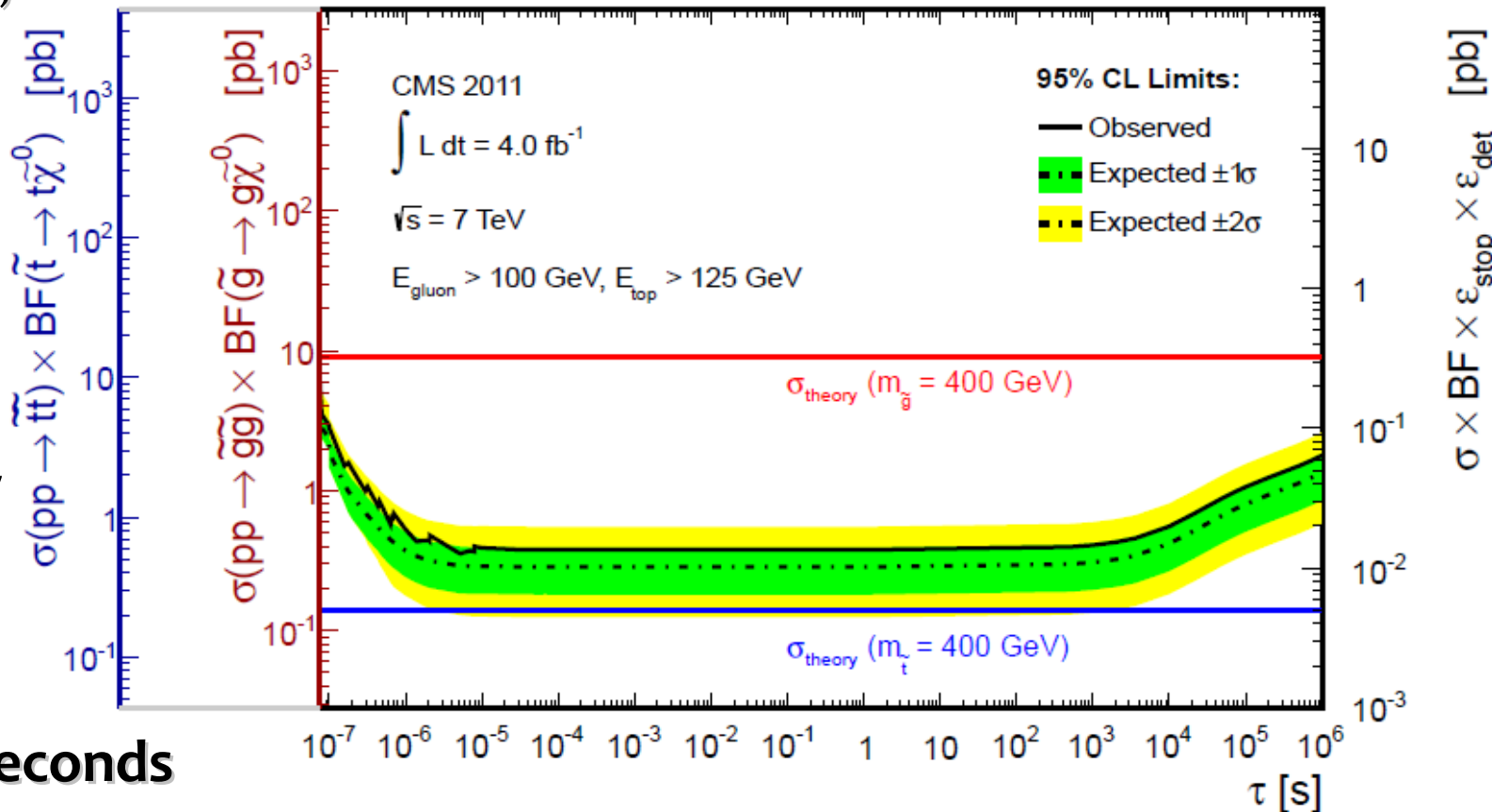
JHEP 08(2012)026

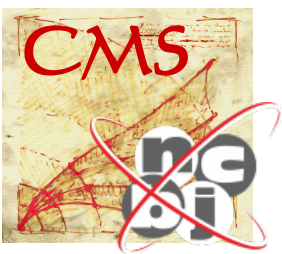
- **Data set:** 4/fb @ 7TeV & search interval of 246 hours of trigger live time
- **12 events observed,** expected bkg: 8.6 ± 2.4

95% CL limits on LL gluino and stop production, over 13 orders of magnitude of particle lifetime

For R-hadron "cloud model",
gluino < 640 GeV
stop < 340 GeV
 are excluded for lifetimes:

$10 \mu\text{s} < \tau < 1000 \text{ seconds}$





Conclusions

- **No evidence** for new exotic long-lived particles... **yet**
- Data **significantly constrains** many models of BSM
- 2015 pp @ 13 TeV – **hunting for LLPs restarted**
 - Higher energy → wider mass reach
 - More challenging searches with higher luminosity (tracks, isolation, triggering, etc.)
 - 25 ns collision mode → changes in L1 triggers



Work supported by Polish National Science Center
UMO-2014/14/WST2/00428 & UMO-2014/15/B/ST2/03998



List of included publications

References:

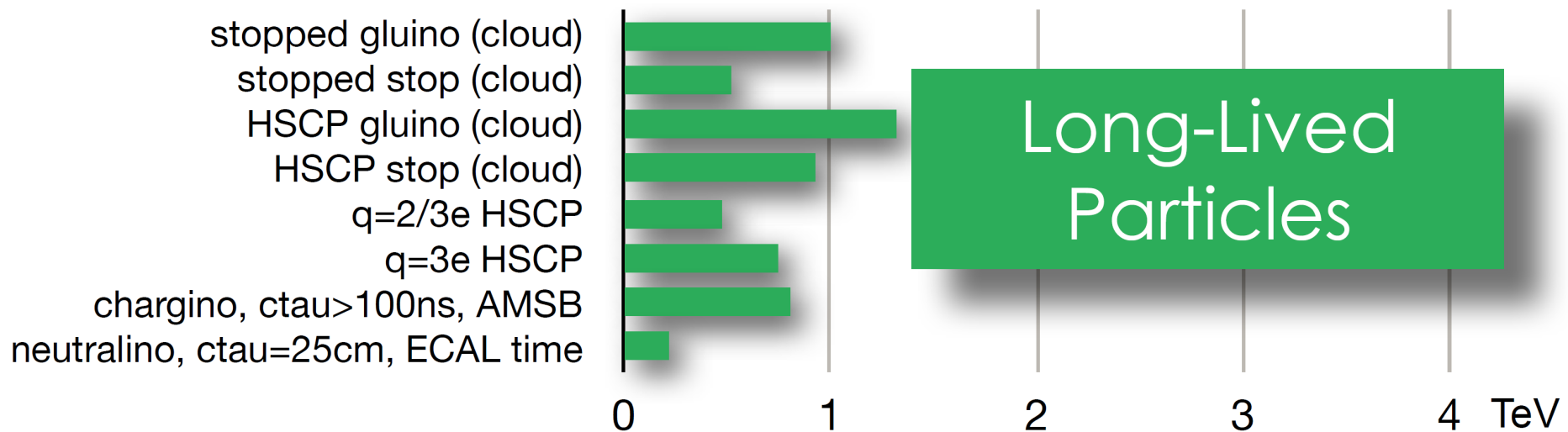
- Heavy stable charged particles (HSCP) JHEP 07(2013)122
EPJ C (2015) 75:325
- Long-lived neutral particles
 - Displaced jet pairs Phys. Rev. D 91, 012007 (2015)
 - Displaced lepton pairs Phys. Rev. D 91, 052012 (2015)
- Displaced supersymmetry Phys. Rev. Lett. 114 (2015) 061801
- Stopped particles JHEP 08(2012)026

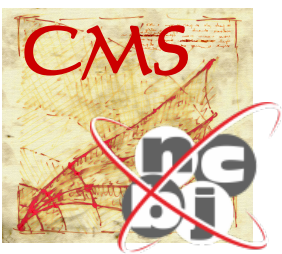
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>



CMS limits on LLP

- Status on March 2015





Displaced leptons

- Decay inside the detector

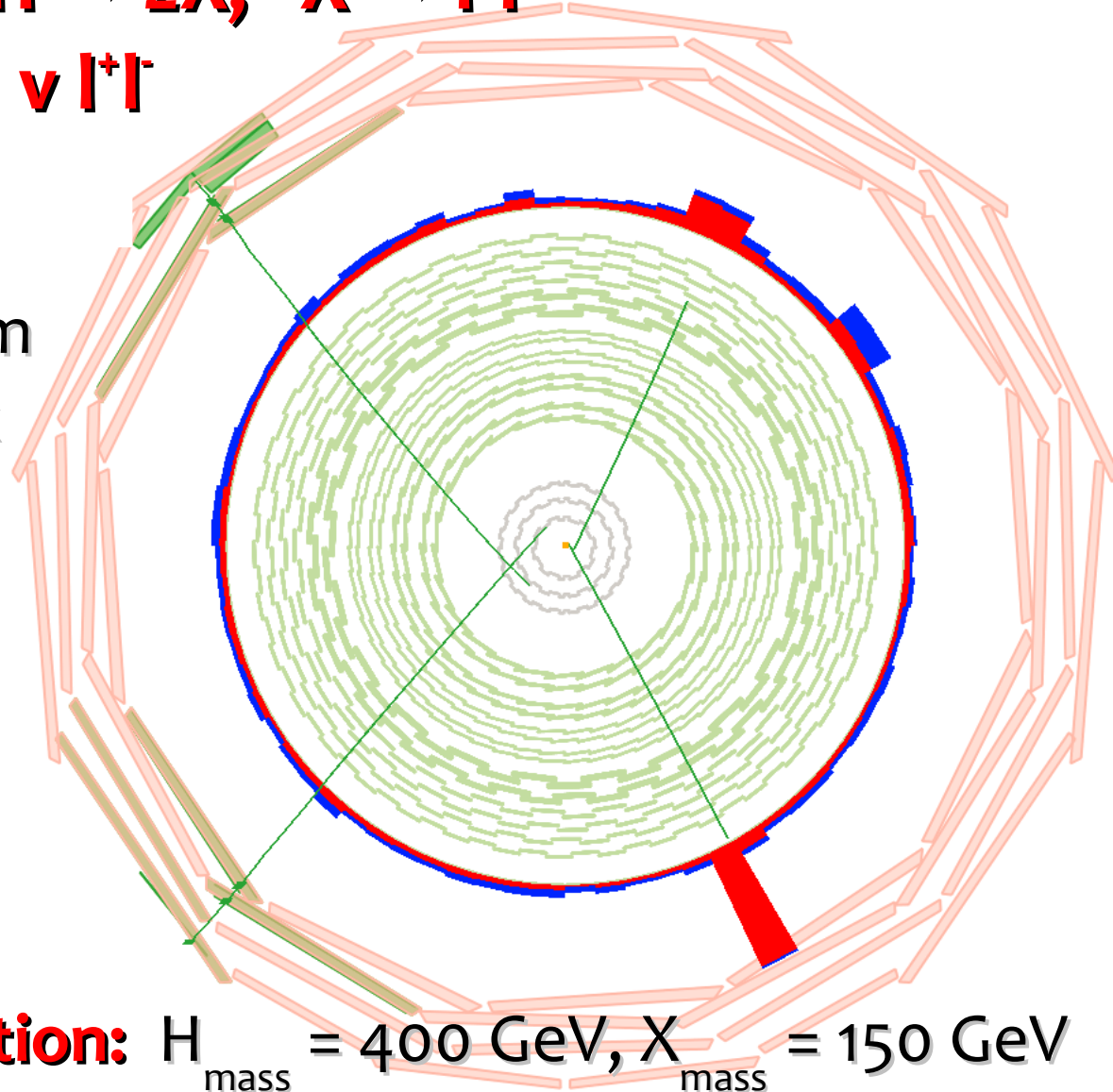
Signal: $gg \rightarrow (\text{non-SM}) H \rightarrow 2X, X \rightarrow l^+l^-$
 $\tilde{q} \rightarrow q \tilde{\chi}_0, \tilde{\chi}_0 \rightarrow \nu l^+l^-$

Signature:

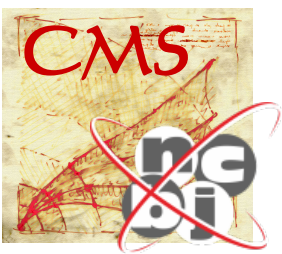
Lepton pair originating from displaced secondary vertex

Model:

Split-SUSY,
weak RPV SUSY,
Hidden Valley,
Z' with LL neutrinos



MC simulation: $H_{\text{mass}} = 400 \text{ GeV}, X_{\text{mass}} = 150 \text{ GeV}$



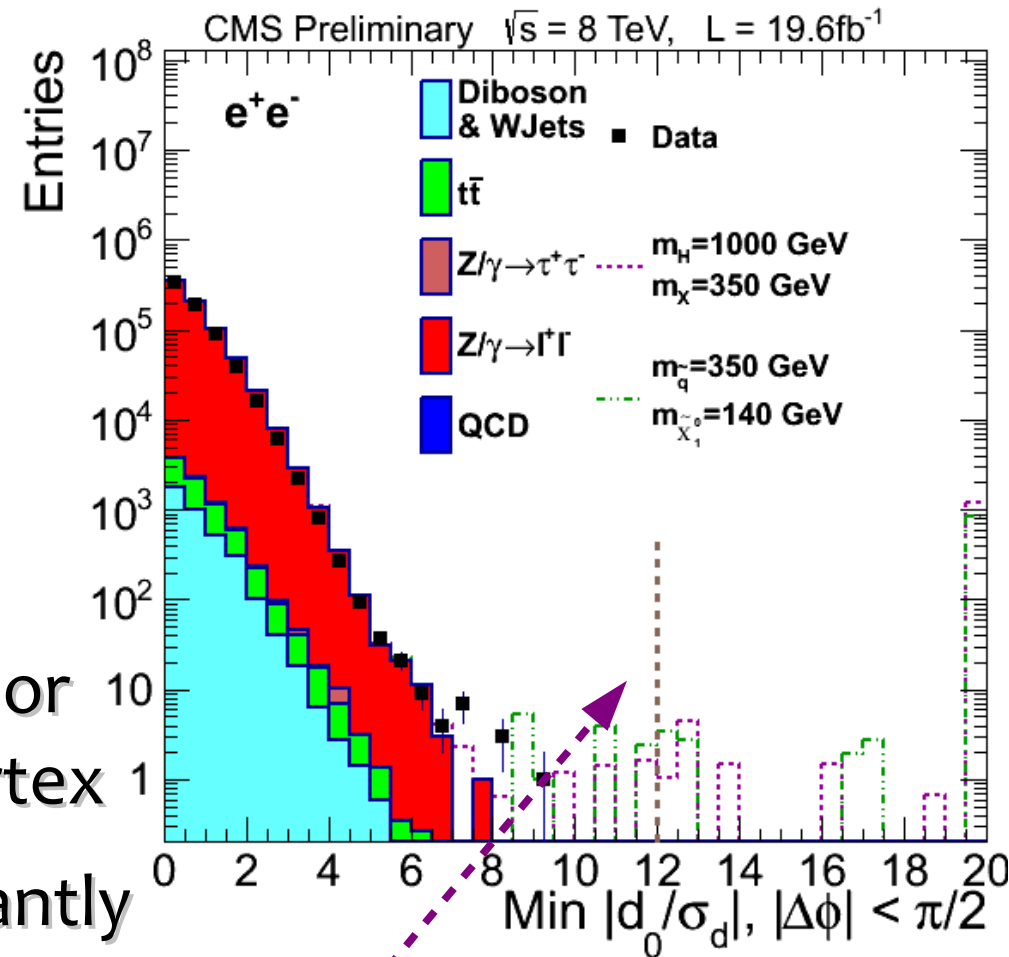
Displaced Leptons

- Trigger:**

- ECAL & Muon System only, reconstructing of displaced tracks in Tracker not possible in online trigger

- Selection:**

- 2 isolated, electrons (40,26 GeV) or muons (26 GeV) with a good vertex
- Require both leptons significantly displaced from primary vertex: $d_0/\sigma(d_0) > 12$
- Angle $\Delta\phi$ between vertex flight direction and dilepton momentum used to define signal/control region for background estimation





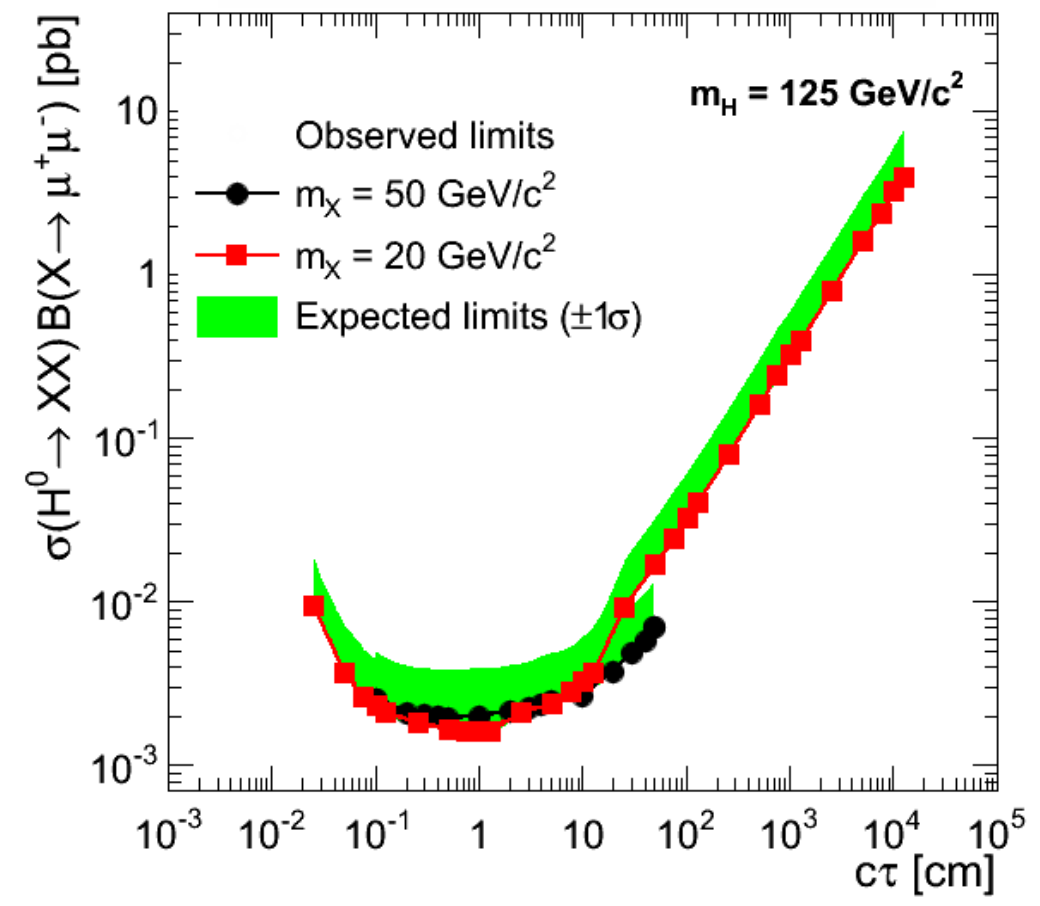
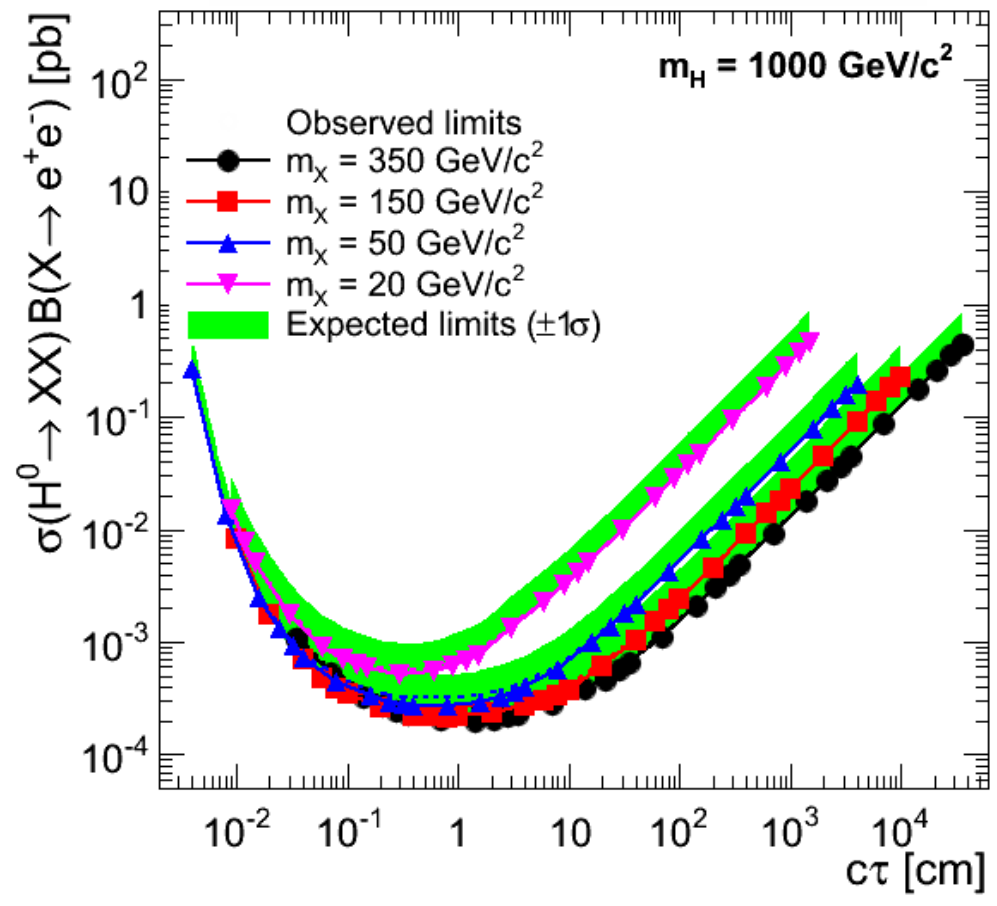
Displaced Leptons RESULTS

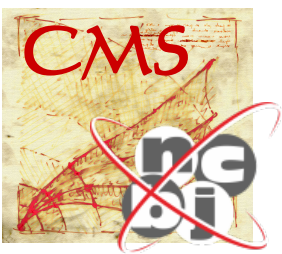
Phys. Rev. D 91, 052012 (2015)

- Background **Expected**: 0 events – **Observed**: 0 in signal region with $L_{xy} > 50$ cm

$X \rightarrow l^+l^-$
 CMS Preliminary $\sqrt{s} = 8$ TeV $L = 19.6$ fb $^{-1}$

$\tilde{\chi}_0 \rightarrow \nu l^+l^-$
 CMS Preliminary $\sqrt{s} = 8$ TeV $L = 20.5$ fb $^{-1}$





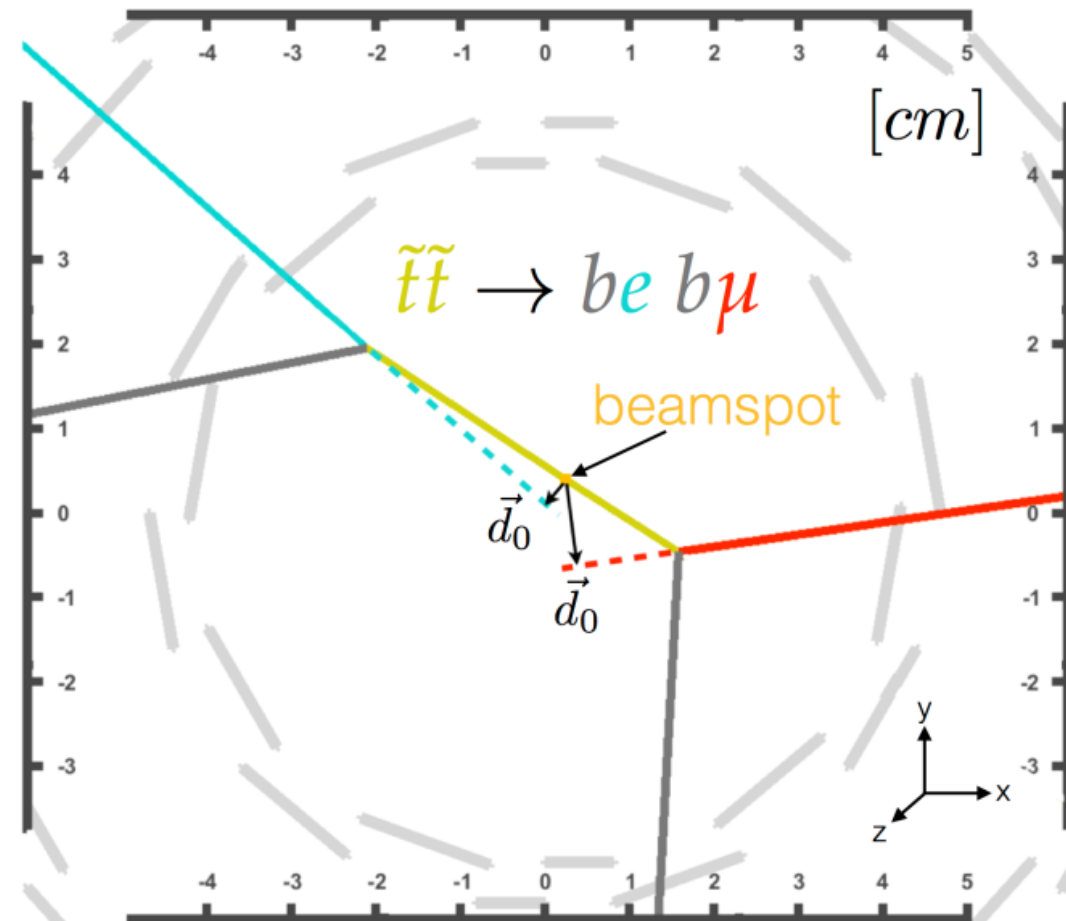
Displaces stops

“Displaced SUSY” with R-parity violating stop decays

Signal: $\tilde{t}\tilde{t} \rightarrow 2(b\ell)$ with $c\tau \sim 100\mu\text{m} - 1\text{m}$

- **Strategy:** Search for electron and muon final states without requirements on jets and MET
- **Trigger:** single muon and cluster in ECAL
- **Selection:**
 - isolated 1 mu & 1 ele
 - $p_t > 25\text{ GeV}$, $|\eta| < 2.5$
 - opposite charges
 - not inside jet $p_t > 10\text{ GeV}$
 - no common vertex
 - $0.1\text{ mm} < d_0 < 20\text{ mm}$
- **Decay inside the detector**

CMS Simulation

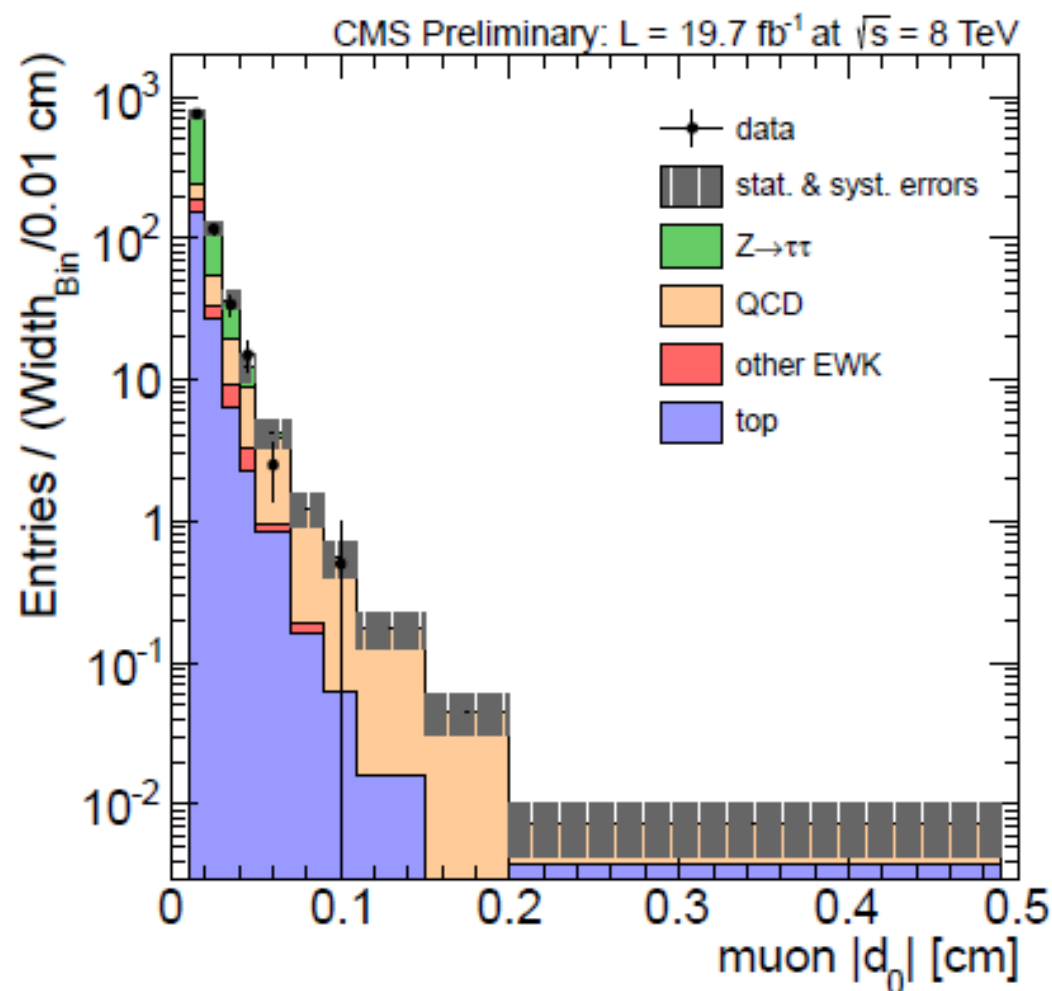
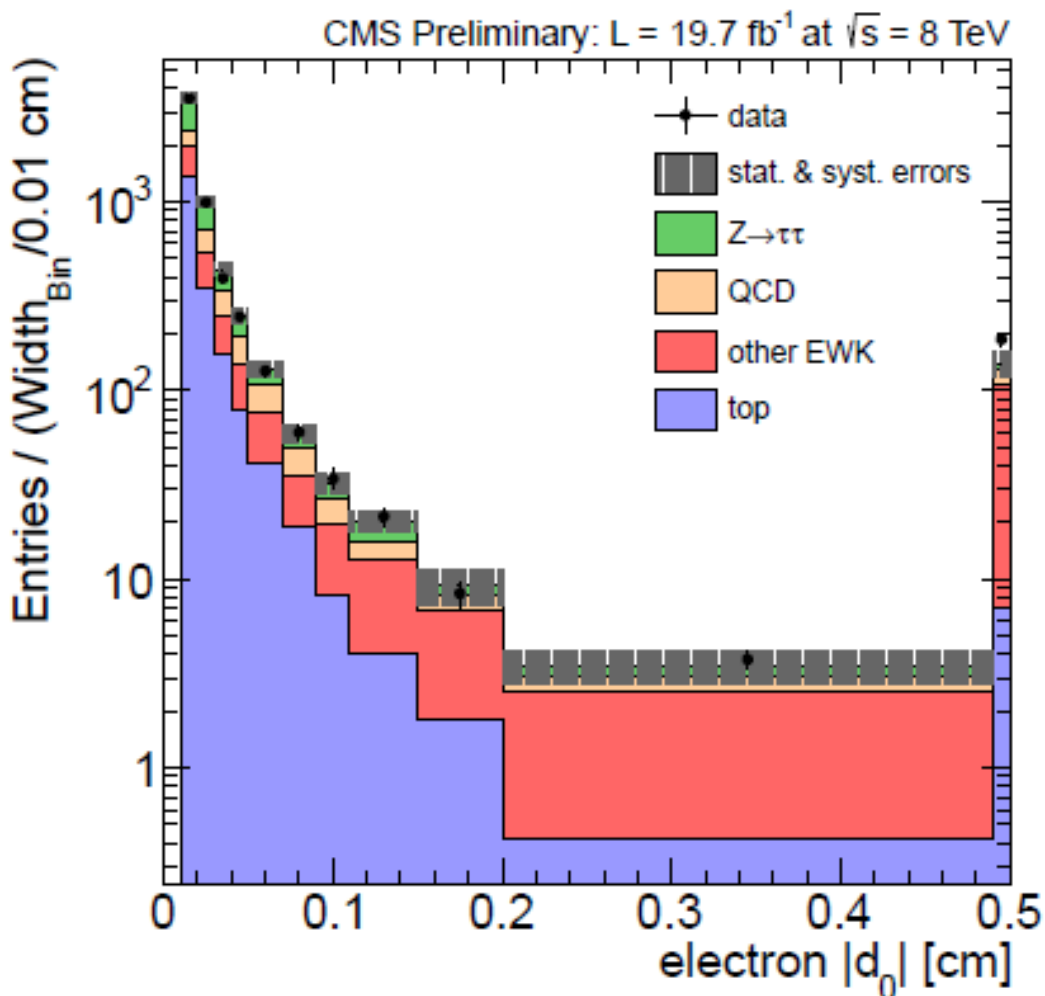


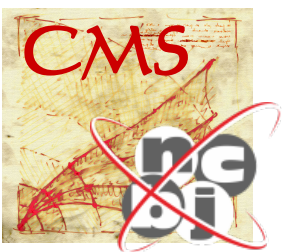


Displaced stops RESULTS

Phys. Rev. Lett. 114 (2015) 061801

- QCD background estimation:
Use same-sign and non-isolated regions to derive it
and validate it in control regions with smaller d_0





Displaced stops RESULTS

- QCD background estimation:
Use same-sign and non-isolated regions to derive it and validate it in control regions with smaller d_0

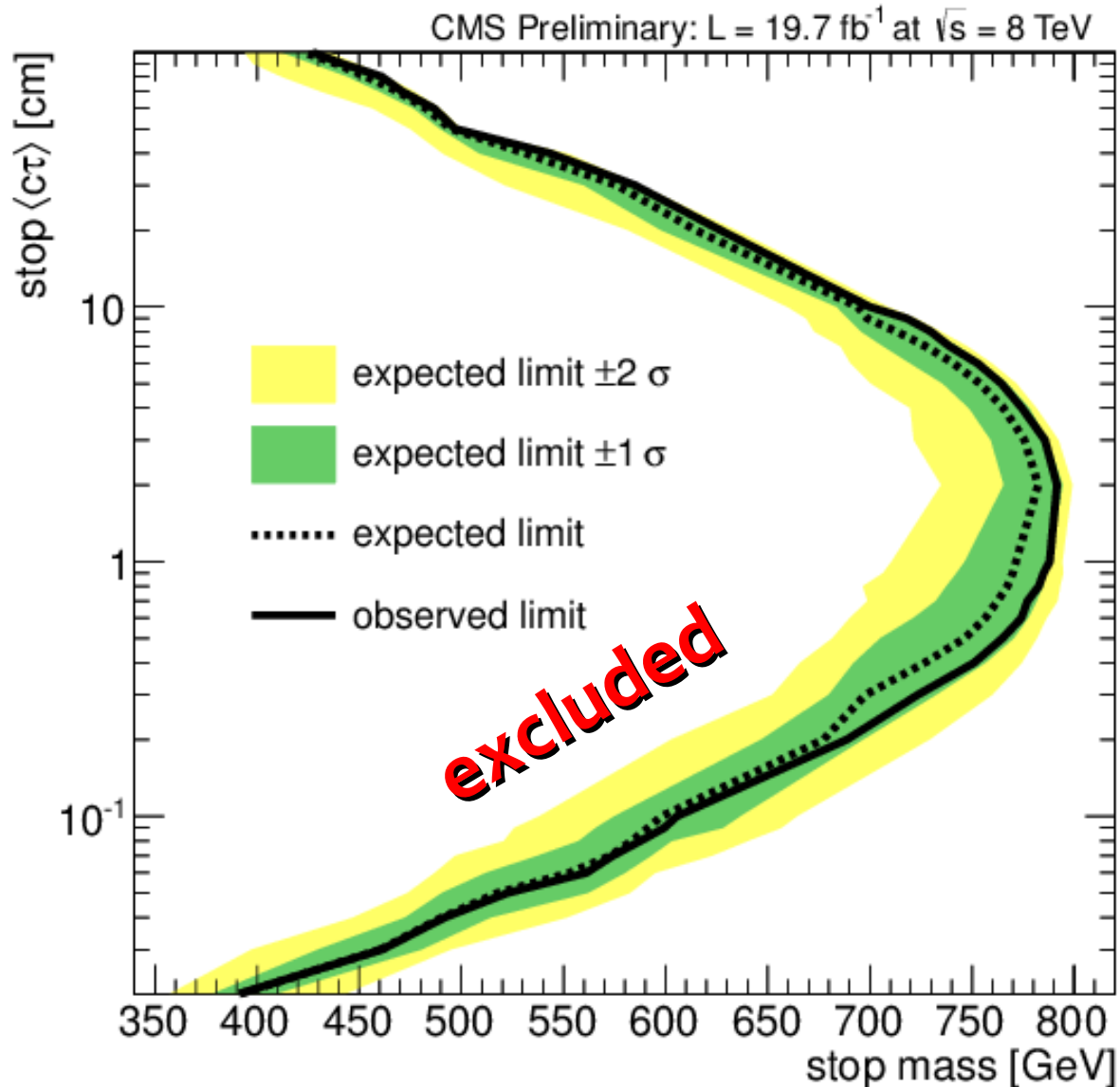
Event Source	$0.02 \text{ cm} < d_0 < 0.05 \text{ cm}$	$0.05 \text{ cm} < d_0 < 0.1 \text{ cm}$	$ d_0 > 0.1 \text{ cm}$
other EWK	$0.65 \pm 0.13 \pm 0.08$	$(0.89 \pm 0.53 \pm 0.11) \times 10^{-2}$	$< (89 \pm 53 \pm 11) \times 10^{-4}$
top	$0.767 \pm 0.038 \pm 0.061$	$(1.25 \pm 0.26 \pm 0.10) \times 10^{-2}$	$(2.4 \pm 1.3 \pm 0.2) \times 10^{-4}$
$Z \rightarrow \tau\tau$	$3.93 \pm 0.42 \pm 0.32$	$(0.73 \pm 0.73 \pm 0.06) \times 10^{-2}$	$< (73 \pm 73 \pm 6) \times 10^{-4}$
QCD	$12.7 \pm 0.2 \pm 3.8$	$(98 \pm 6 \pm 30) \times 10^{-2}$	$(340 \pm 110 \pm 100) \times 10^{-4}$
Total expected background	$18.0 \pm 0.5 \pm 3.8$	$1.01 \pm 0.06 \pm 0.30$	$0.051 \pm 0.015 \pm 0.010$
Observation	19	0	0
$pp \rightarrow \tilde{t}_1 \tilde{t}_1^*$			
$M = 500 \text{ GeV}, \langle c\tau \rangle = 1 \text{ mm}$	$30.1 \pm 0.7 \pm 1.1$	$6.54 \pm 0.34 \pm 0.24$	$1.34 \pm 0.15 \pm 0.05$
$M = 500 \text{ GeV}, \langle c\tau \rangle = 1 \text{ cm}$	$35.3 \pm 0.8 \pm 1.3$	$30.3 \pm 0.7 \pm 1.1$	$51.3 \pm 1.0 \pm 1.9$
$M = 500 \text{ GeV}, \langle c\tau \rangle = 10 \text{ cm}$	$4.73 \pm 0.30 \pm 0.17$	$5.57 \pm 0.32 \pm 0.20$	$26.27 \pm 0.70 \pm 0.93$

- **No excess**



Displaced stops LIMITS

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“Displaced SUSY”

For a lifetime hypothesis of **$c\tau = 2 \text{ cm}$** , stops up to **790 GeV** are excluded