Ulrich Goerlach on behalf of the CMS collaboration
Many thanks for all the help and material available

Long-lived neutral particles decaying into leptons

CMS results from Run I, 8 TeV data

Beyond the Standard Model particles, that live long enough to decay inside the volume of the tracking detectors

- Motivation
- Secondary vertices, *arXiv: [hep-ex] 1411.6977, Nov 2014*
- Large impact parameters, *arXiv: [hep-ex] 1409.4789, Sept 2014*
- Conclusions

Physics motivations to search for new long lived particles

- **Cosmological motivations:**
  - Dark Matter candidates requires neutral particles
  - Possible Big Bang Nucleo-synthesis problem (^{6}Li and ^{7}Li abundances) example for a Heavy Stable Charged Particle (HSCP)
- **Many models predict naturally long-lived particles**
  - SUSY: pMSSM, GMSB, AMSB, Split-SUSY, RPV-SUSY, Displaced SUSY, Little Higgs, Hidden Valley, etc.
- **Unusual Signatures**
  - Highly ionizing tracks, or fractional charges
  - Disappearing or kinked tracks
  - Secondary vertices with large displacements
- **Non-standard event selection and reconstruction!**

Examples for long lived particles

This talk will concentrate on neutral particles decaying to leptons

$\rightarrow pMSSM:\quad H_{BSM} \rightarrow 2X;\ X \rightarrow \ell\ell;\quad X \rightarrow q\bar{q}$

$\rightarrow GMSB:\quad \tilde{\chi}^0 \rightarrow \gamma\,\tilde{G};\quad \tilde{\tau} \rightarrow \tau\,\tilde{G};$

$\tilde{\chi}^0$ and $\tilde{\tau}$ are long-lived because of small coupling to $\tilde{G}$

$\rightarrow AMSB:\quad \tilde{\chi}^+ \rightarrow \tilde{\chi}^0\pi^+$ via virtual $\tilde{q}$

$\tilde{\chi}^+$ is long-lived because NLSP and $\tilde{\chi}^0$ are close in mass

$\rightarrow Split-SUSY:\quad \tilde{g} \rightarrow g\tilde{\chi}^0$ via virtual $\tilde{q}$

$\tilde{g}$ is long-lived because $\tilde{q}$ is heavy

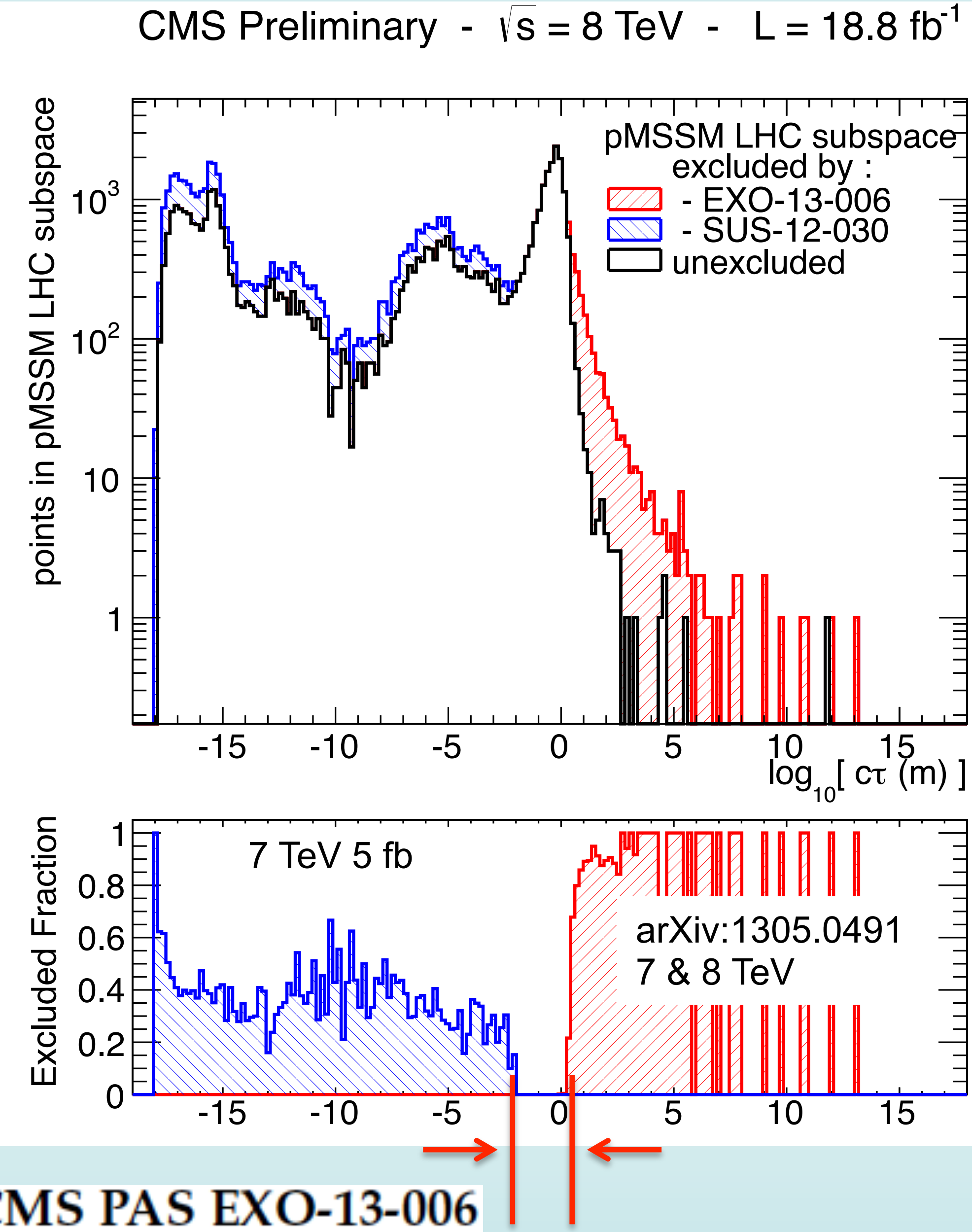
$\rightarrow RPV-SUSY:\quad \tilde{\chi}^0 \rightarrow \ell\ell\nu;\quad or\quad \tilde{\chi}^0 \rightarrow q\bar{q}'\ell\quad \lambda'_{221} \neq 0$

$$\tilde{\chi}^0 \xrightarrow{\lambda_{121}} \begin{cases} e^\pm\mu^\mp\nu_e \\ e^\pm e^\mp\nu_\mu \end{cases} \quad \text{or} \quad \tilde{\chi}^0 \xrightarrow{\lambda_{122}} \begin{cases} e^\pm\mu^\mp\nu_e \\ \mu^\pm\mu^\mp\nu_e \end{cases}$$

$\tilde{\chi}^0$ life time determined by coupling λ and masses

$\rightarrow Displaced-SUSY:\quad \tilde{t}\tilde{t} \rightarrow b\ell\, b\ell'\quad RPV-$stop decay

Limits in the framework of pMSSM



CMS PAS EXO-13-006

- **Standard SUSY (or BSM) searches concentrate on promptly decaying particles cτ < 1cm**
- **Searches for stable particles look for objects traversing most of the detectors cτ > 50cm**
- **Reinterpretation of limits within pMSSM**

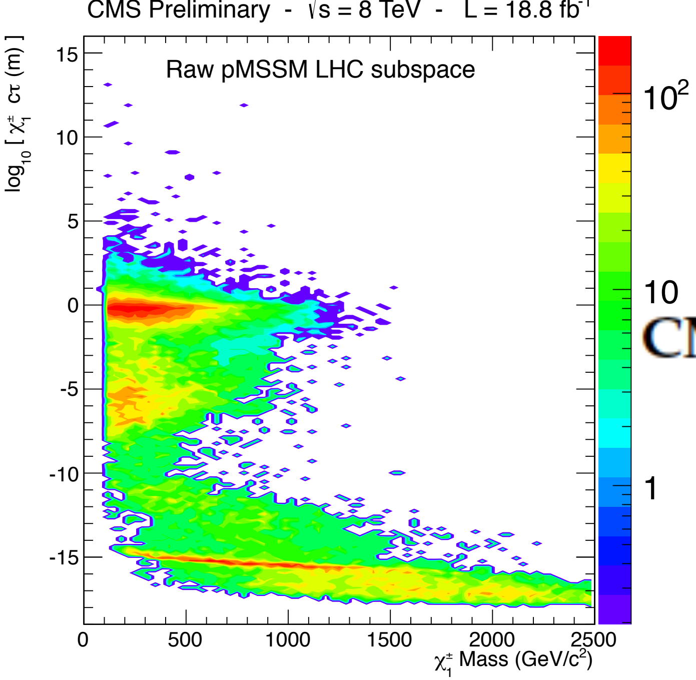
➔There is a gap to be investigated.

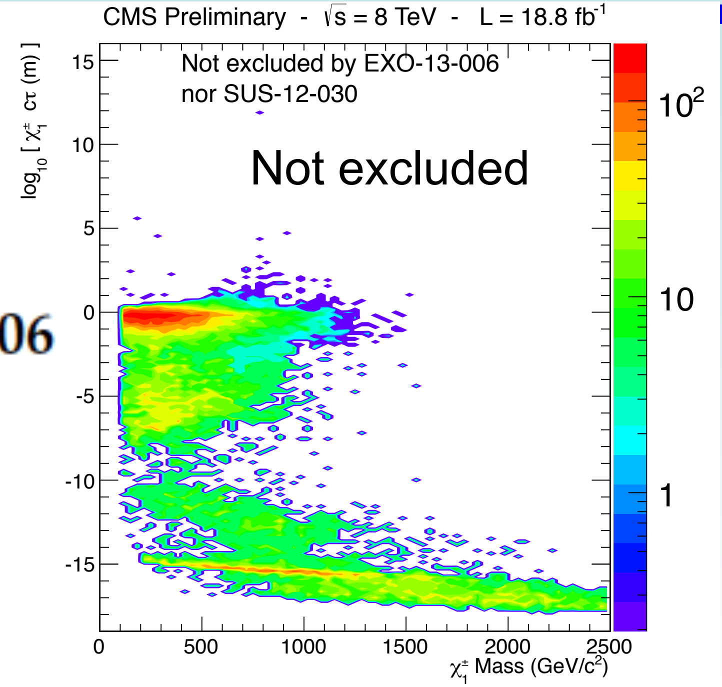
→ Look for decays of particles within CMS detector

→ Displaced vertices

→ Disappearing tracks

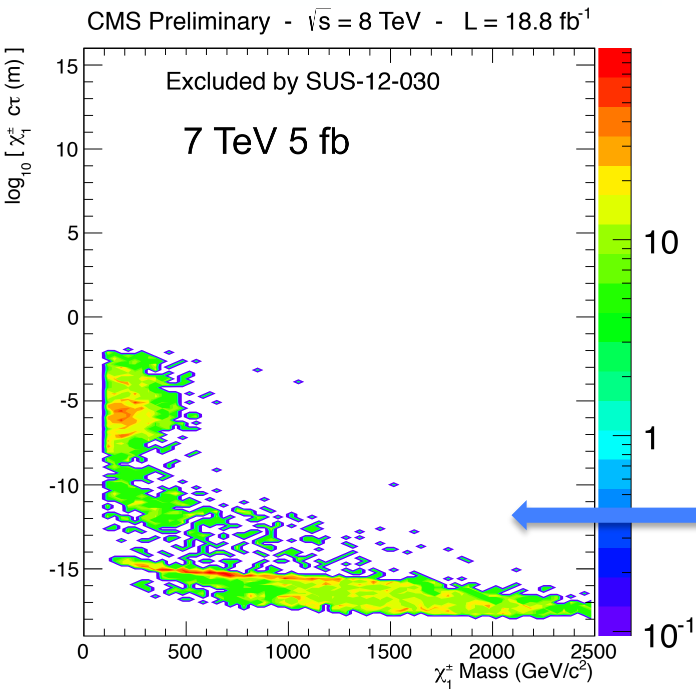
pMSSM points
19 parameters





CMS PAS EXO-13-006

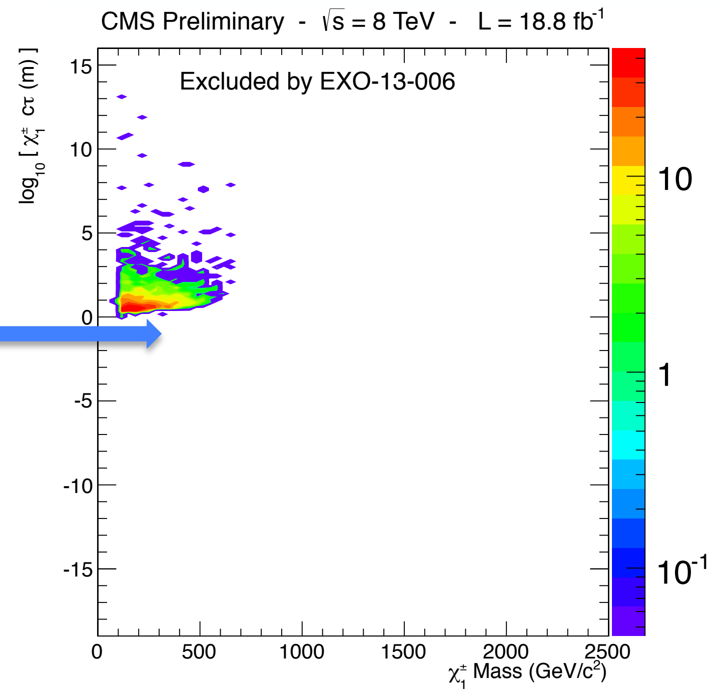
$$-3\,\text{TeV} \le M_1, M_2 \le 3\,\text{TeV}$$
$$0 \le M_3 \le 3\,\text{TeV}$$
$$-3\,\text{TeV} \le \mu \le 3\,\text{TeV}$$
$$0 \le m_A \le 3\,\text{TeV}$$
$$2 \le \tan\beta \le 60$$
$$0 \le \tilde{Q}_{1,2}, \tilde{U}_{1,2}, \tilde{D}_{1,2}, \tilde{L}_{1,2}, \tilde{E}_{1,2}, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3 \le 3\,\text{TeV}$$
$$-7\,\text{TeV} \le A_t, A_b, A_\tau \le 7\,\text{TeV},$$



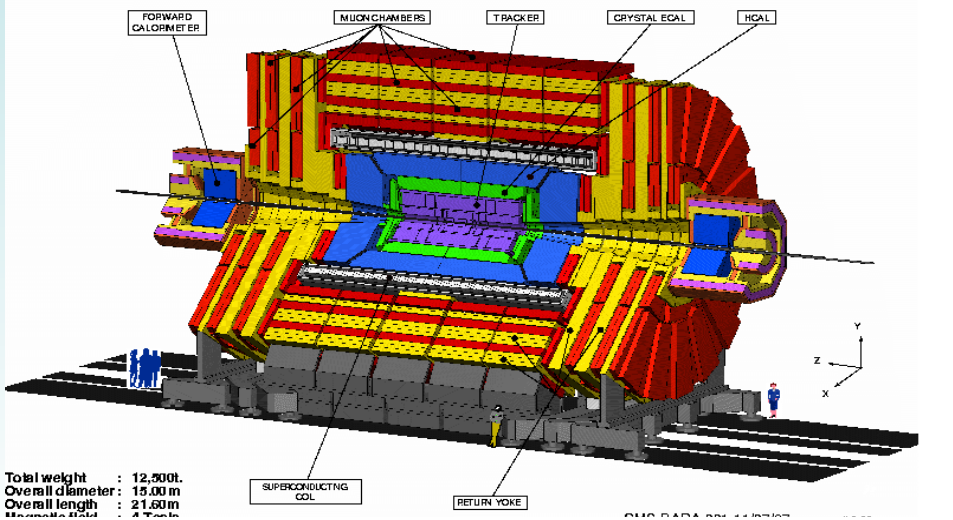
Re-interpretation of HSCP limits within pMSSM

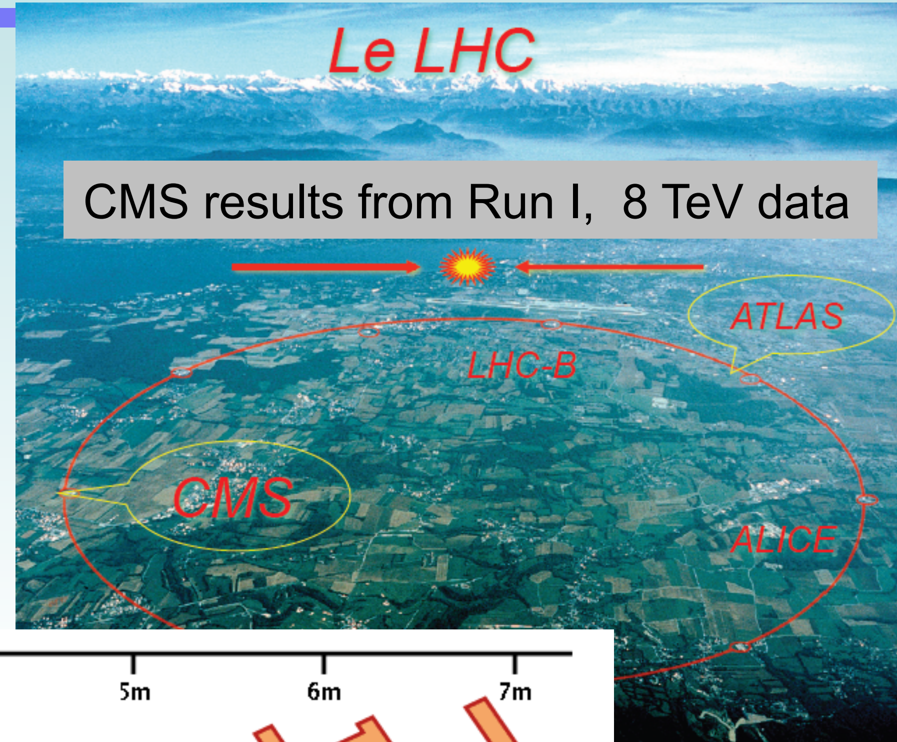
delayed exclusion

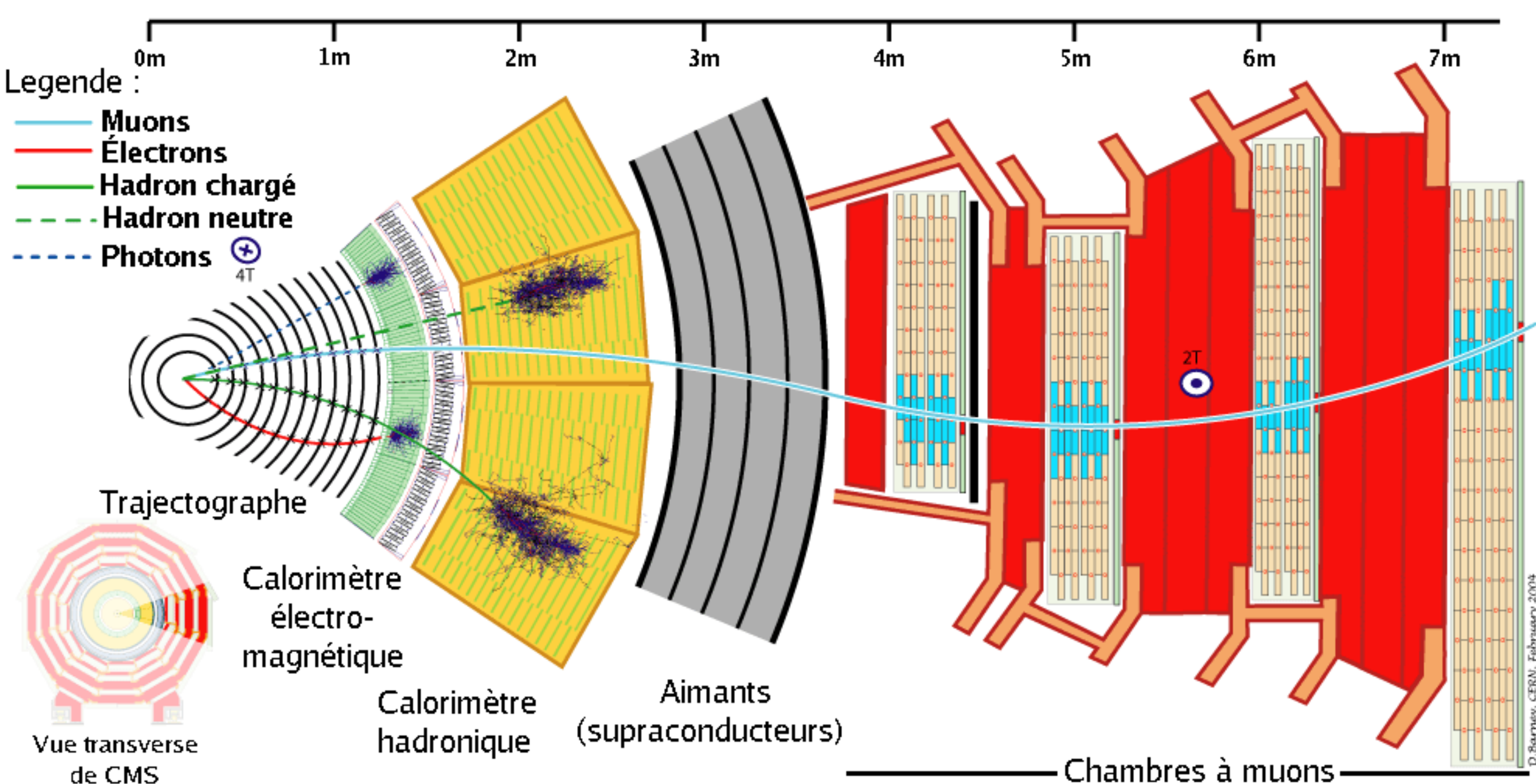
Prompt exclusion



CMS

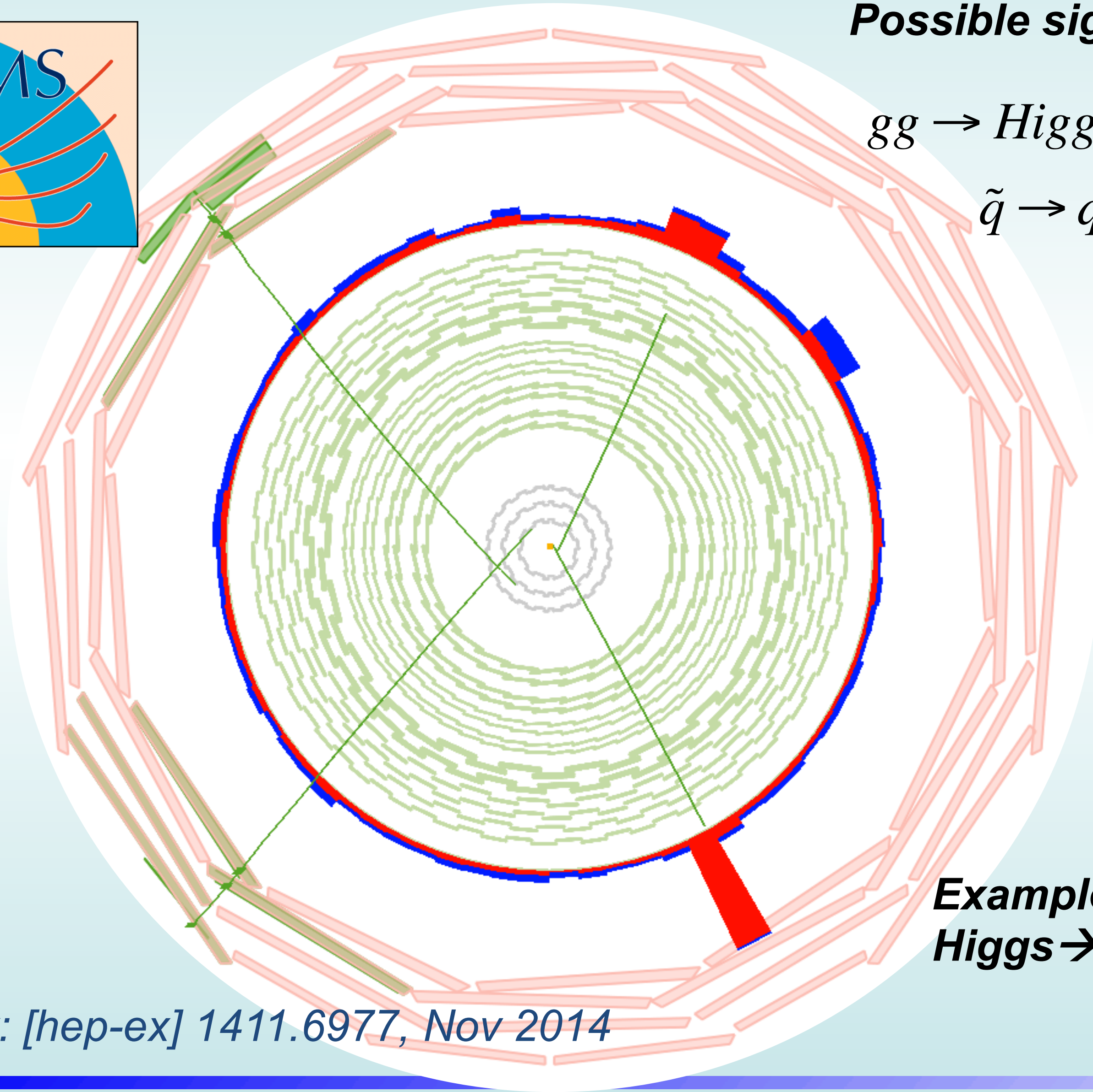

FORWARD CALORIMETER
MUON CHAMBERS
TRACKER
CRYSTAL ECAL
HCAL
SUPERCONDUCTNG COIL
RETURN YOKE
Y
Z
X
Total weight : 12,500t.
Overall diameter : 15.00 m
Overall length : 21.60m


Le LHC
CMS results from Run I, 8 TeV data
ATLAS
LHC-B
CMS
ALICE


0m
1m
2m
3m
4m
5m
6m
7m
Legende :
Muons
Électrons
Hadron chargé
Hadron neutre
Photons
4T
2T
Trajectographe
Calorimètre électro-magnétique
Calorimètre hadronique
Aimants (supraconducteurs)
Chambres à muons
Vue transverse de CMS
D.Barney, CERN, February 2004

Search for long-lived particles decaying to leptons

Look for displaced secondary vertices



Possible signals:

$$gg \rightarrow Higgs_{BSM} \rightarrow 2X;\ \ X \rightarrow \ell^+\ell^-$$

$$\tilde{q} \rightarrow q\tilde{\chi}^0;\ \ \tilde{\chi}^0 \rightarrow \nu\ell^+\ell^-$$

Very small standard model background

Example of a decay
Higgs→ 2X → 2 lepton pairs

arXiv: [hep-ex] 1411.6977, Nov 2014

Event selection

- **Trigger:**

  Many standard HLT use tracking information with vertex constraint so we have to use

  - Muon pairs: Two two tracks in outer muon chambers,

    $p_T > 23$ *GeV, opening angle < 2.5 radians*

  - Electron pairs: Two clusters in electromagnetic calorimeter

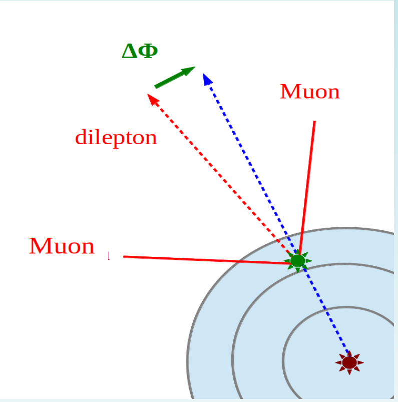
    $E_T > 36\ (22)$ *GeV*, compatible with electron of photon hypothesis

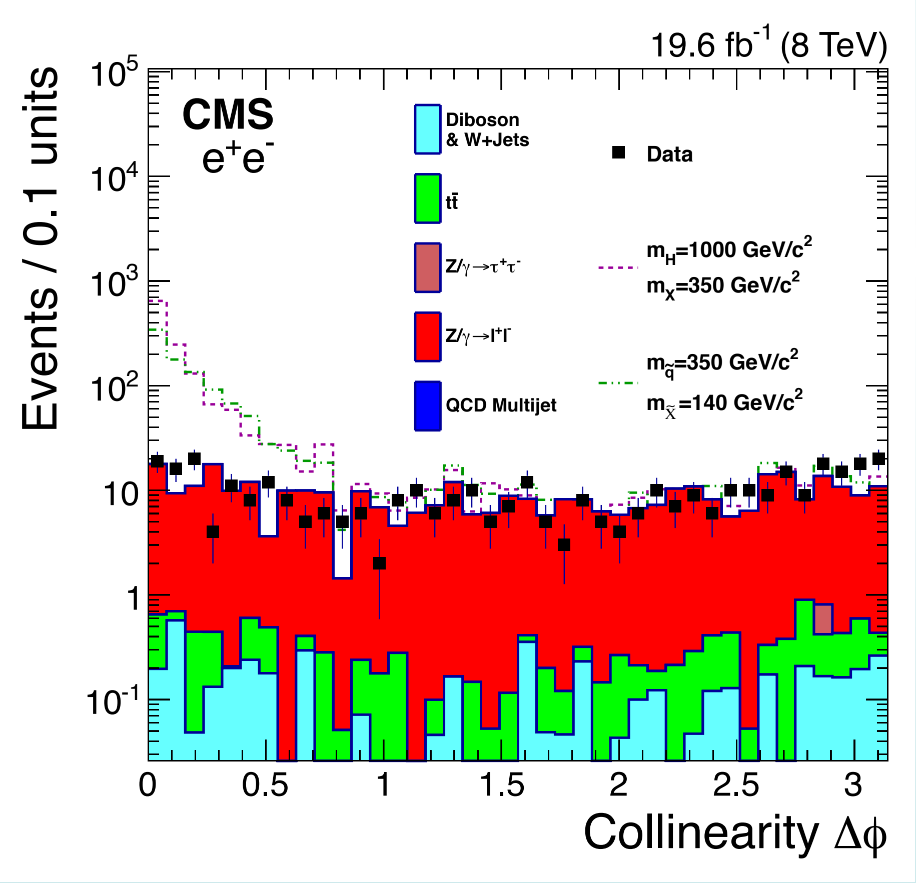
- **Displaced secondary vertex**
  - Good primary vertex required
  - Match ($\Delta R < 0.1$) high purity tracks ($\eta < 2.0$) to ecal trigger clusters or with muon track.
  - Electrons $E_T > 40\ (25)$ *GeV and* $p_T > 36(21)$ *GeV ;*
  - both Muons $p_T > 26$ *GeV,* $\Delta R > 0.2$
  - Hollow isolation cone ($0.04(3) < \Delta R < 0.3$) for muons(electrons) based on tracks
  - Transvers impact parameter of tracks $|d_0| / \sigma_d > 12$
  - Fit tracks to secondary vertex, $\chi^2 / dof < 10(5)$ for electrons (muons); limit the number of hits before vertex to 1 and number of missing hits behind vertex to 3(4)
  - The angle $\Delta\phi$ between dilepton momentum and vertex flight direction is used to define signal / control region.

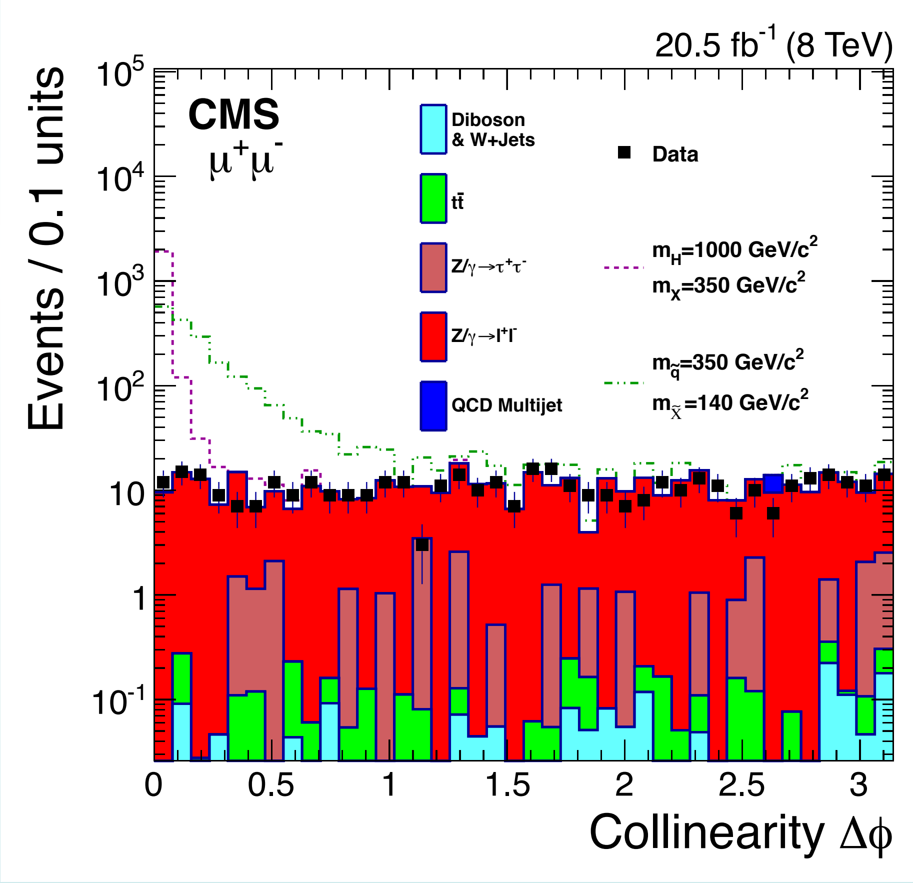
Control and signal region

$$\Delta\phi < \pi/2 \ = \ \textit{signal region}$$
$$\Delta\phi > \pi/2 \ = \ \textit{control region}$$

$$\left|d_0\right|/\sigma_d\Big|_{\ell\ell} > 4.5\,(3.0)$$
"loose selection"



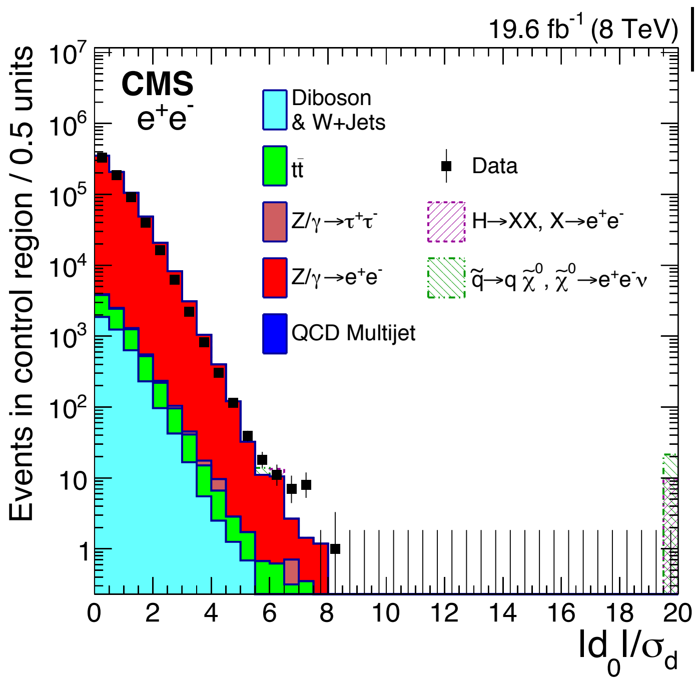


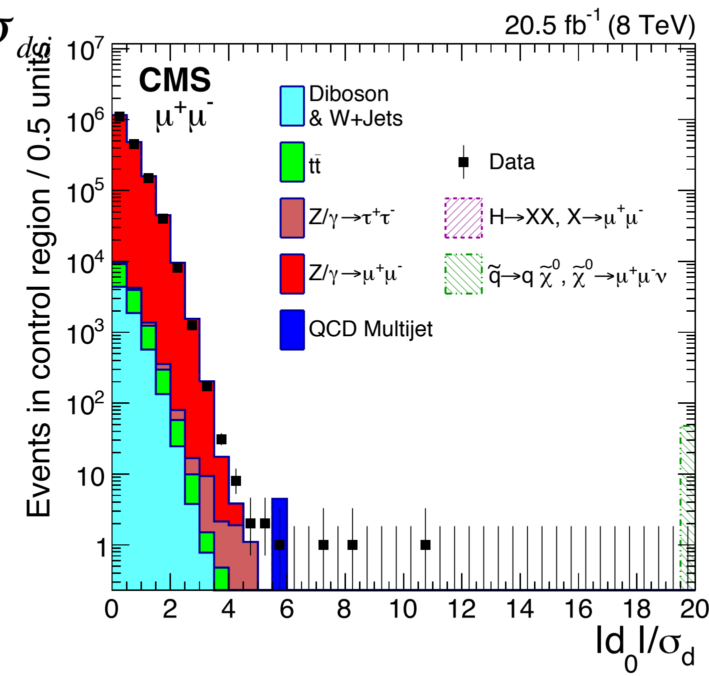


arXiv: [hep-ex] 1411.6977, Nov 2014

Pair impact parameter distributions

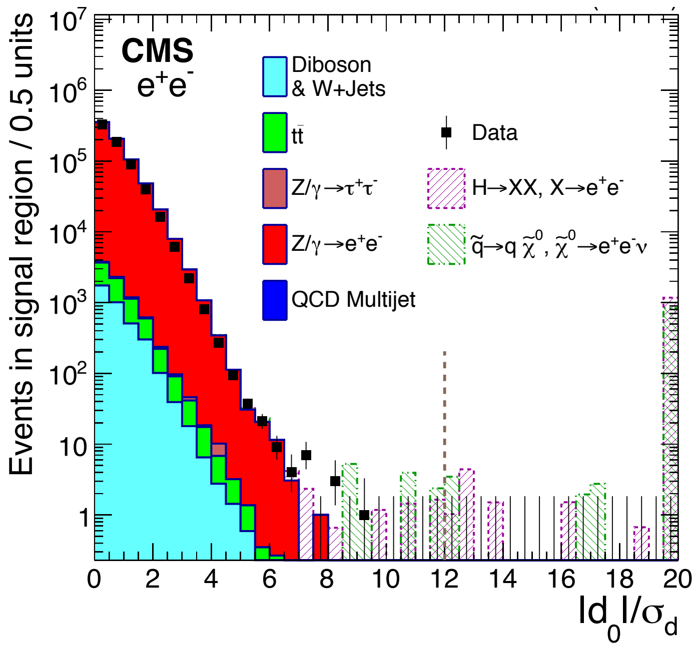
$$\left|d_0\right| / \sigma_d \Big|_{\ell\ell} = \min_{1,2} \left|d_{0,i}\right| / \sigma_{d,i}$$

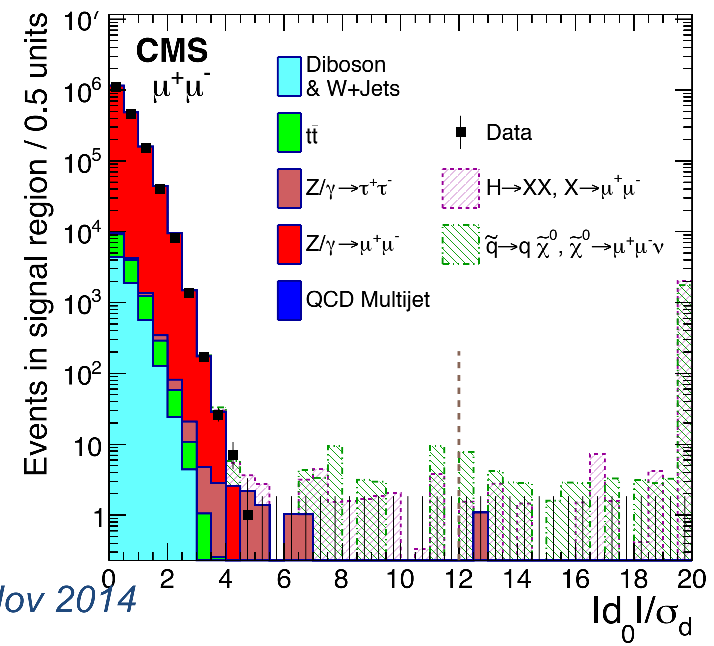




$\Delta\phi > \pi / 2$

control region





$\Delta\phi < \pi / 2$

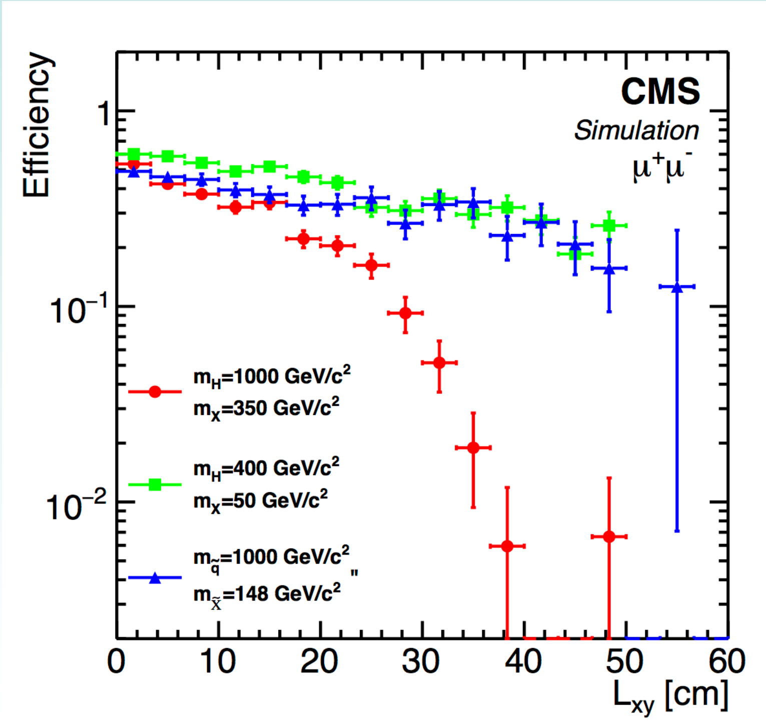
signal region

No event observed!

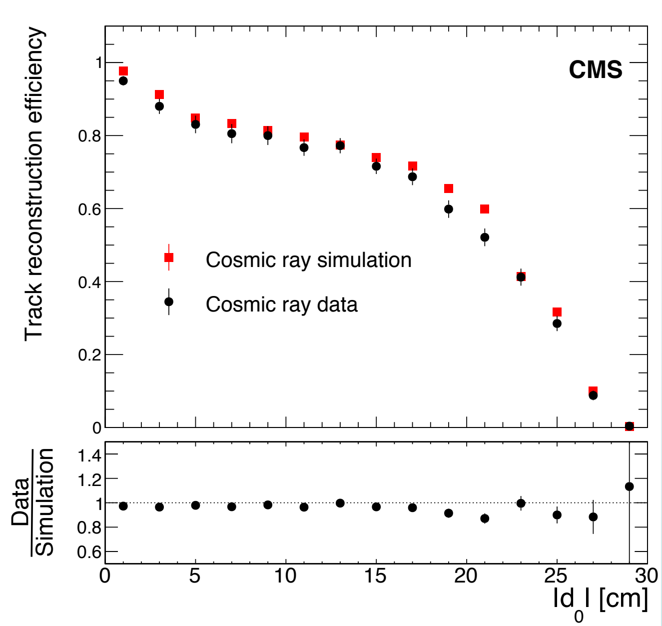
arXiv: [hep-ex] 1411.6977, Nov 2014

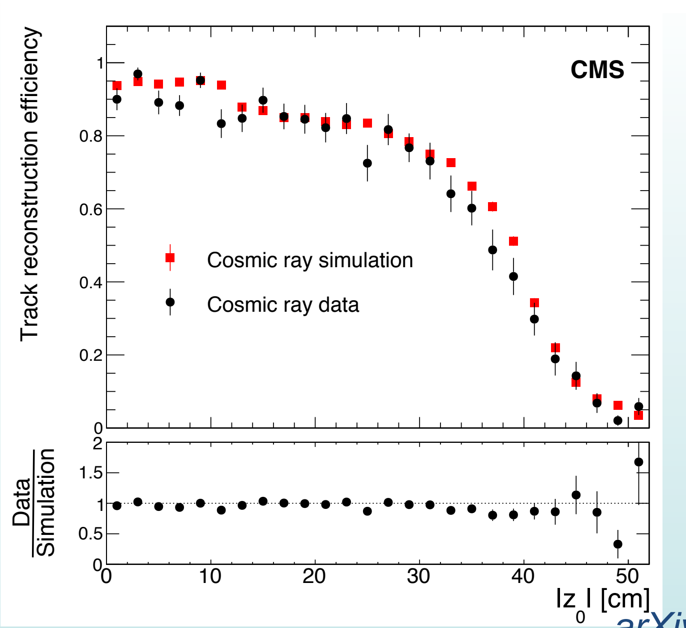
$$p_T^{\mu} > 26\,GeV;\;\; \eta < 2.0;\;\; L_{xy} < 50cm$$

cτ = 20cm



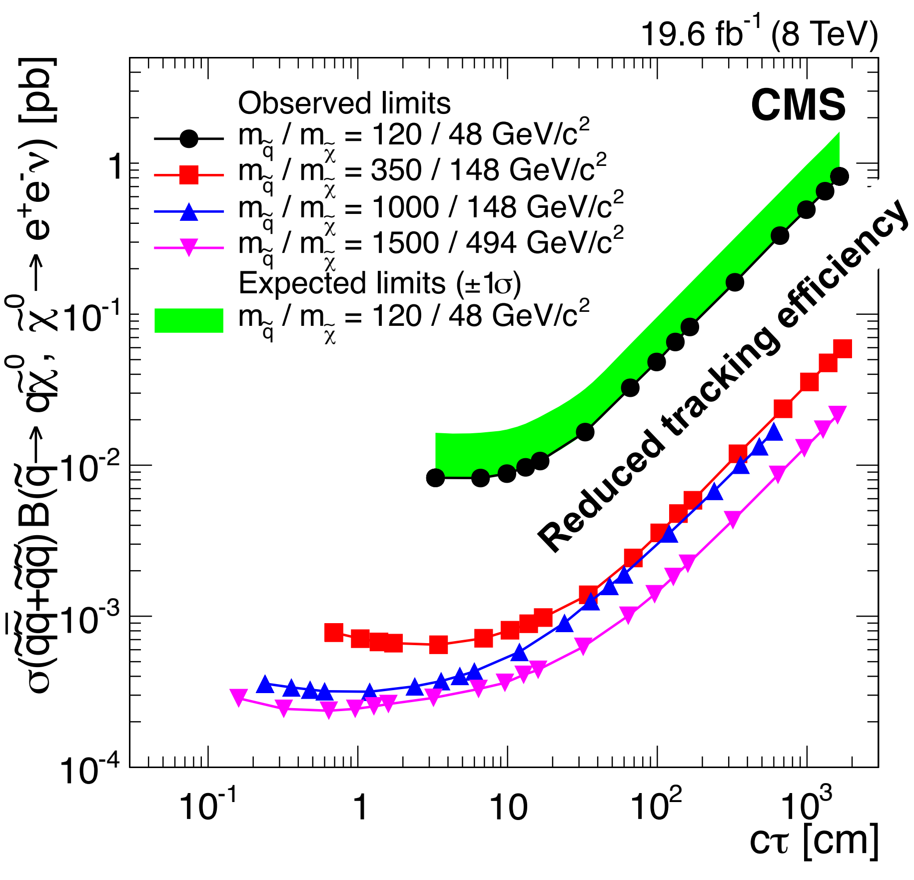
Track finding efficiency simulation and comparison with cosmic ray data

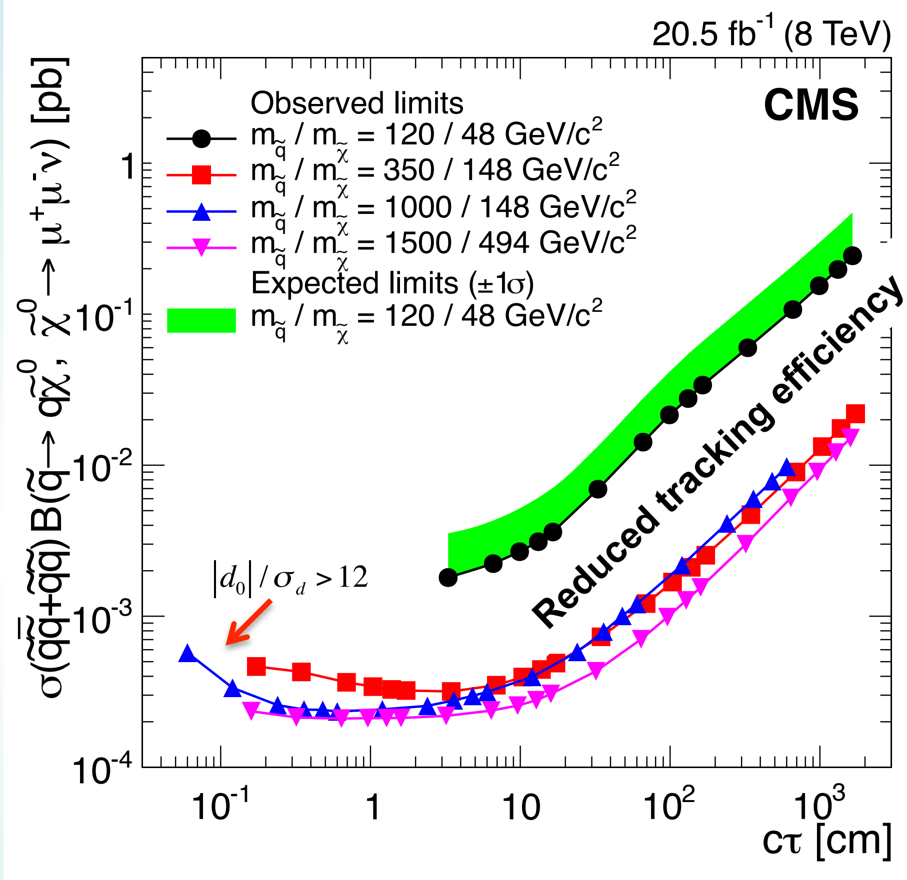




arXiv: [hep-ex] 1411.6977, Nov 2014

Results (neutralino RPV-decay) $\tilde{\chi}^0 \rightarrow \ell\ell\nu$





No events found on signal region
Place limits on x-section x Branching ratio
Depends on kinematics / masses

$$\Delta\phi < \pi / 2 \quad ; \quad \ell\ell : \min\left|d_0^{\ell}\right| / \sigma_d > 12$$

$$c\tau(\mathrm{cm}) \simeq \frac{0.3}{|\lambda_{ijk}|^2} \cdot \left(\frac{m_{\tilde{f}}}{100\ \mathrm{GeV}}\right)^4 \cdot \left(\frac{1\ \mathrm{GeV}}{m_{\tilde{\chi}_1^0}}\right)^5$$

arXiv: [hep-ex] 1411.6977, Nov 2014

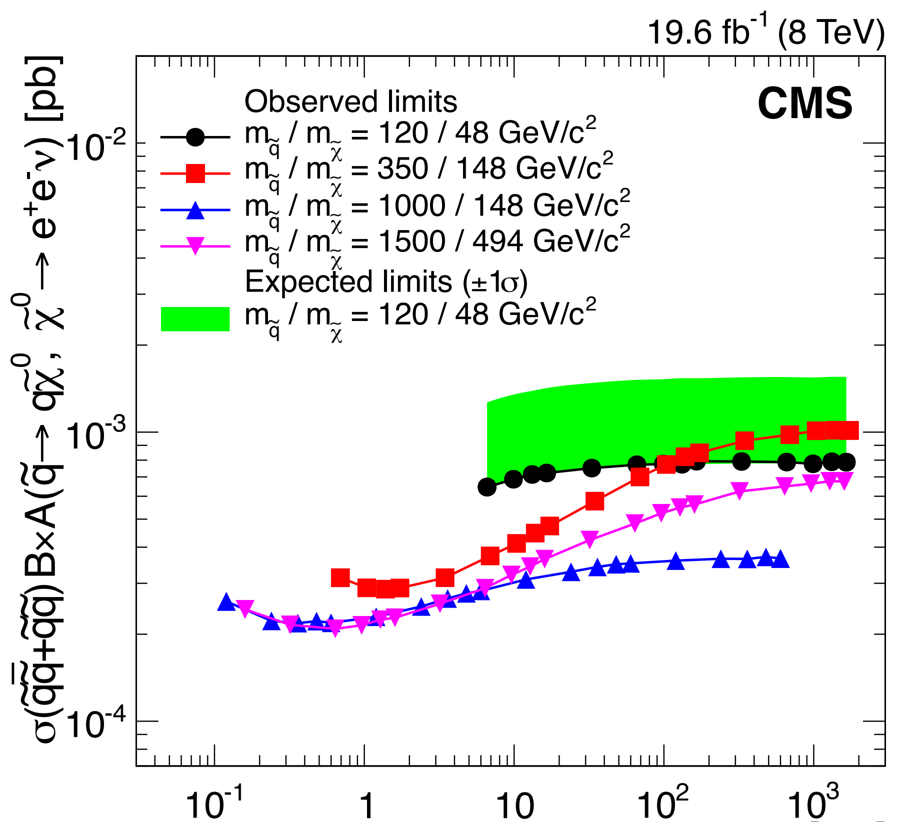
Results (neutralino RPV-decay)

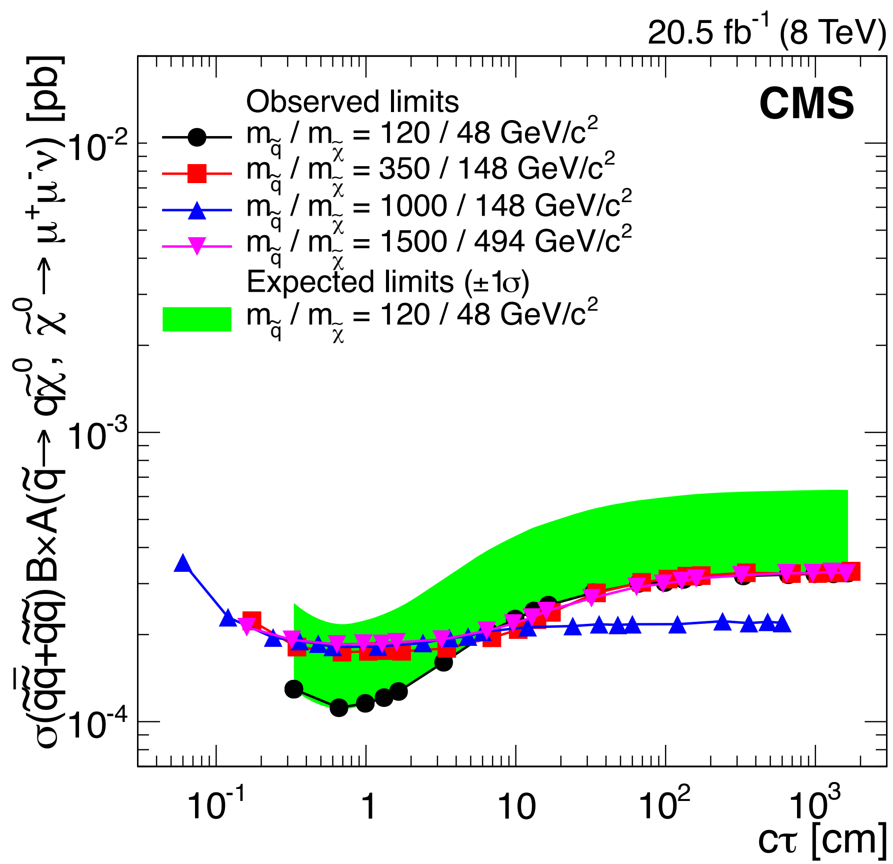
Acceptance region with "good" efficiency: $p_T^{\ell} > 26 - 40\ GeV;\ \eta < 2.0;\ L_{xy} < 50cm$

Plot instead: $\sigma \times B \times A$

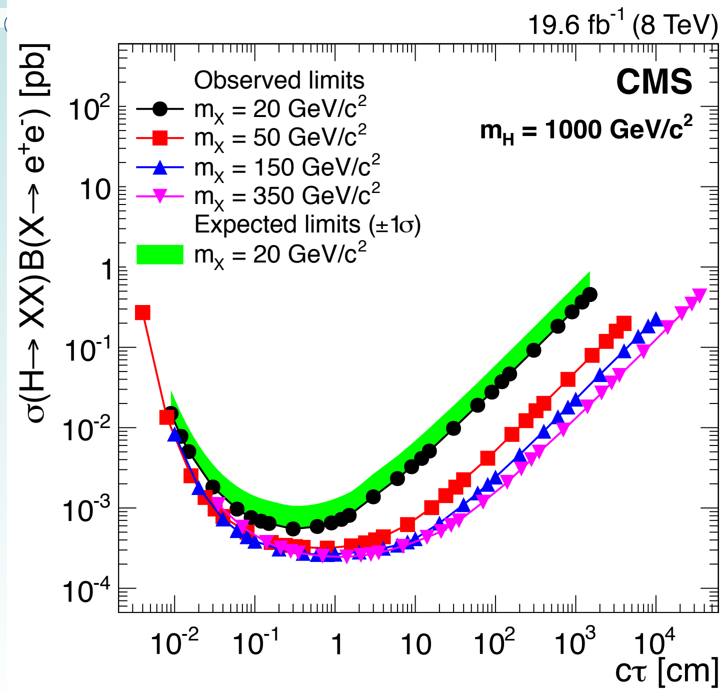
A = fraction of generated LL-particles, which pass these acceptance cuts

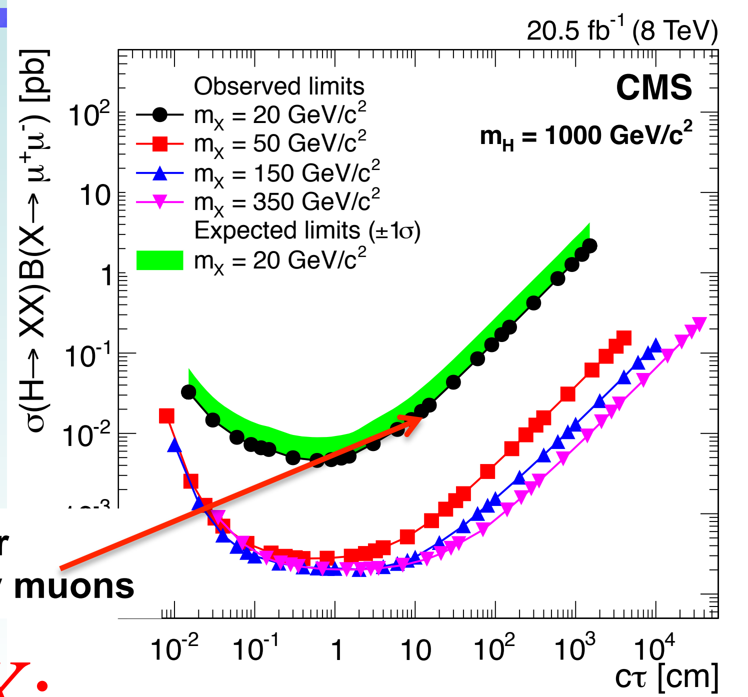
Less dependant on cτ and on model





arXiv: [hep-ex] 1411.6977, Nov 2014

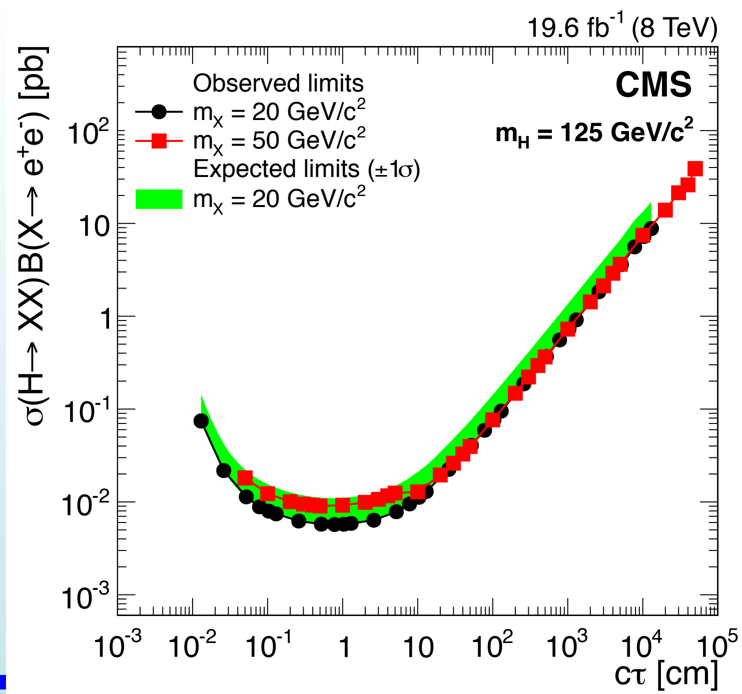




Reduced muon trigger efficiency for close by muons

$$H_{BSM} \to 2X;$$

$$X \to \ell\ell$$



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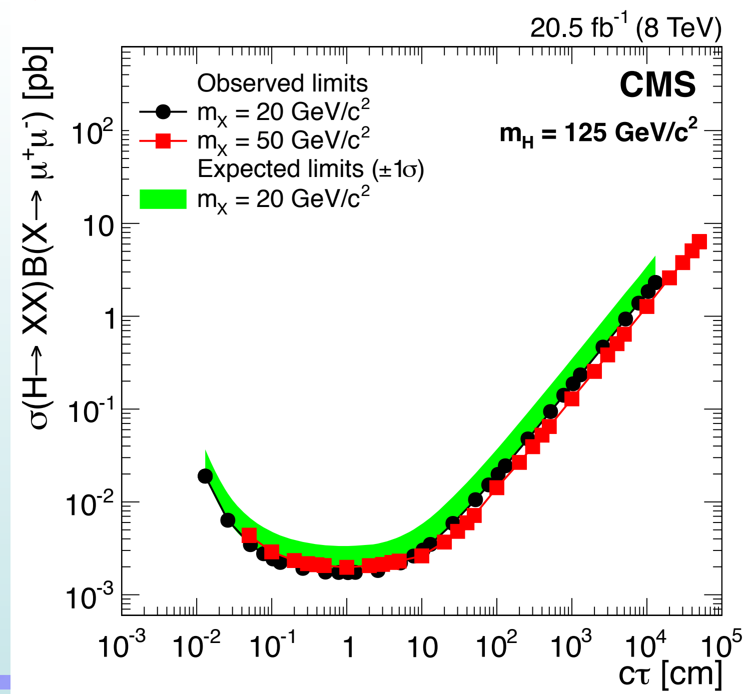
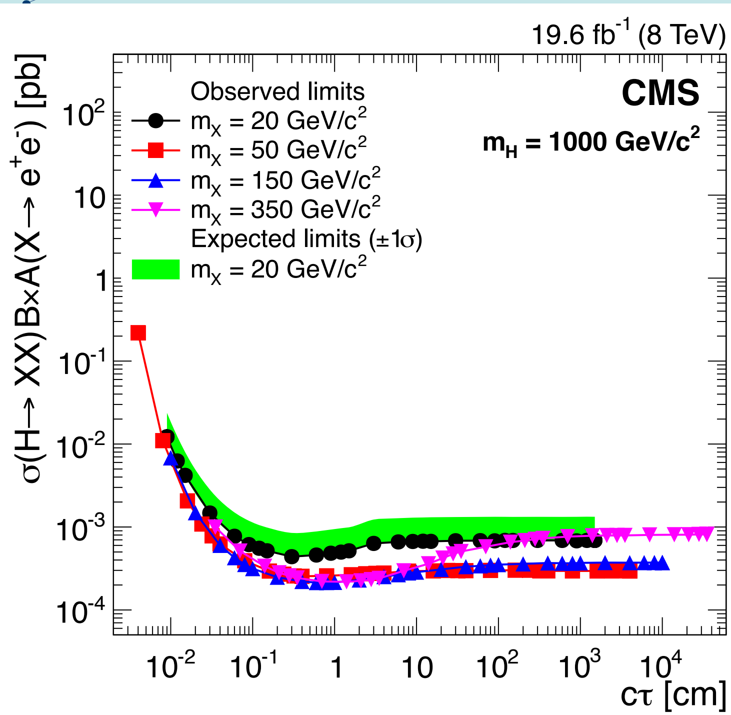
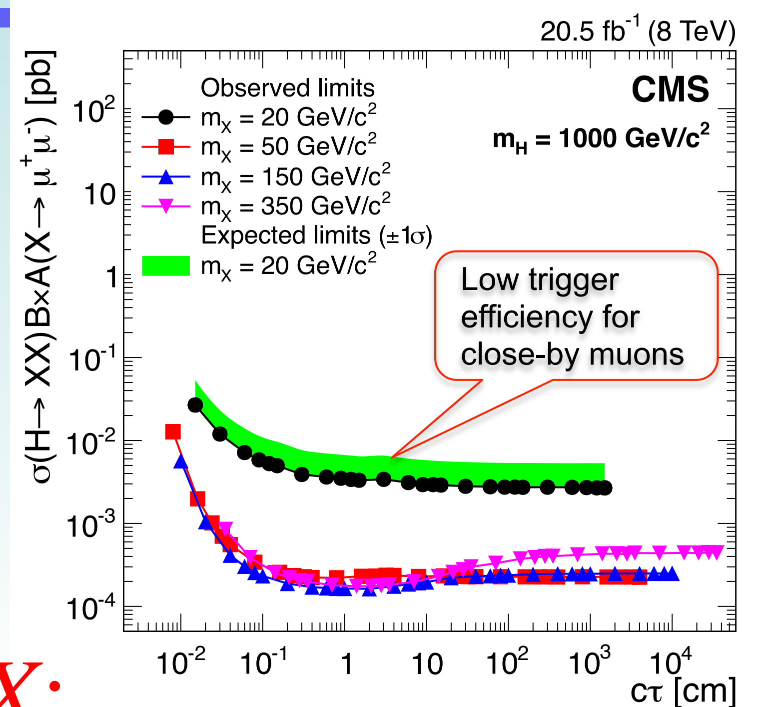
arXiv: [hep-ex] 1411.6977, Nov 2014

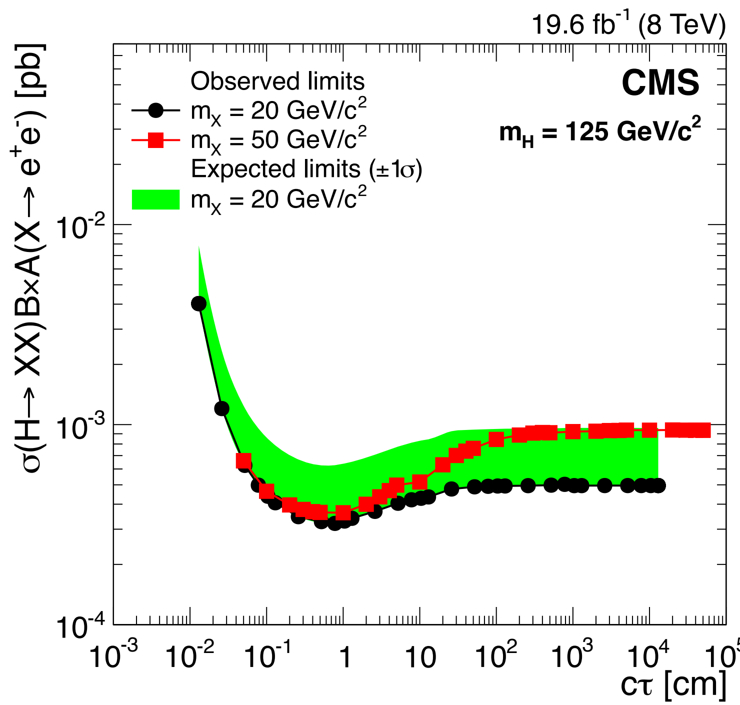




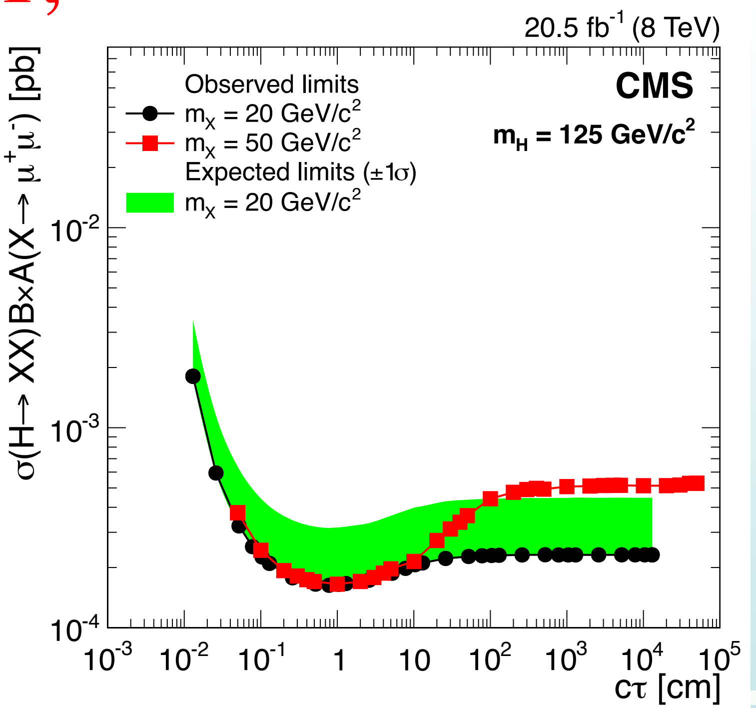


$$H_{BSM} \to 2X;$$

$$X \to \ell\ell$$

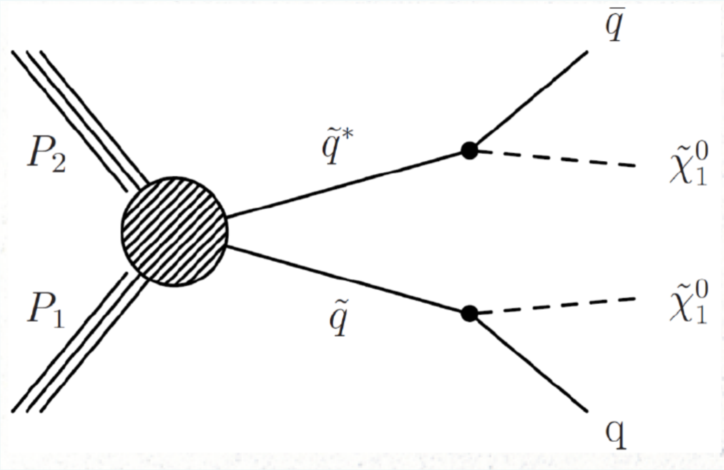


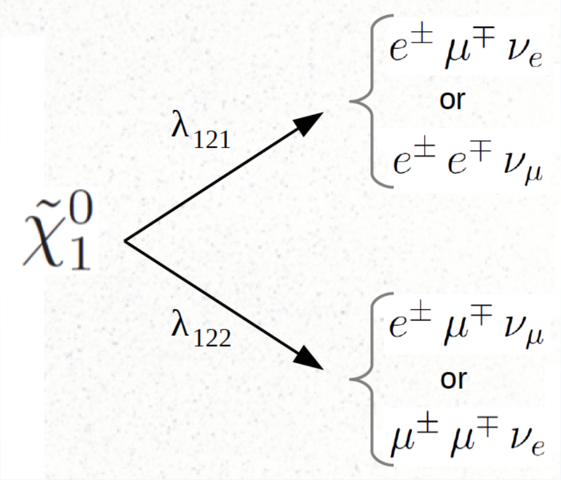
arXiv: [hep-ex] 1411.6977, Nov 2014



Extension to e-mu pairs

- Thesis of Christophe Goetzmann,
  defended 26 Nov 2014, co-supervisor E. Conte
- Look for RPV decays of Neutralinos:

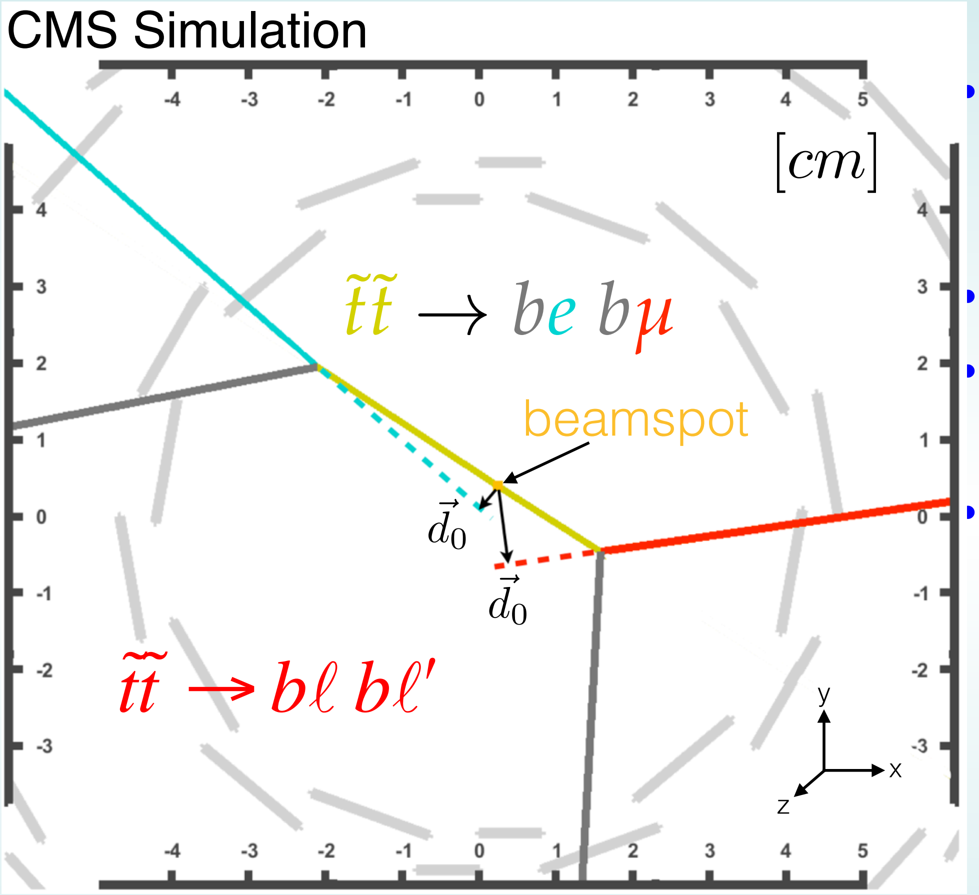




- Analysis follows the same line as the ee/μμ analysis
- Except the choice of trigger was more complicated
- Results not yet public, work in progress

CMS-B2G-12-024

Long-lived stops



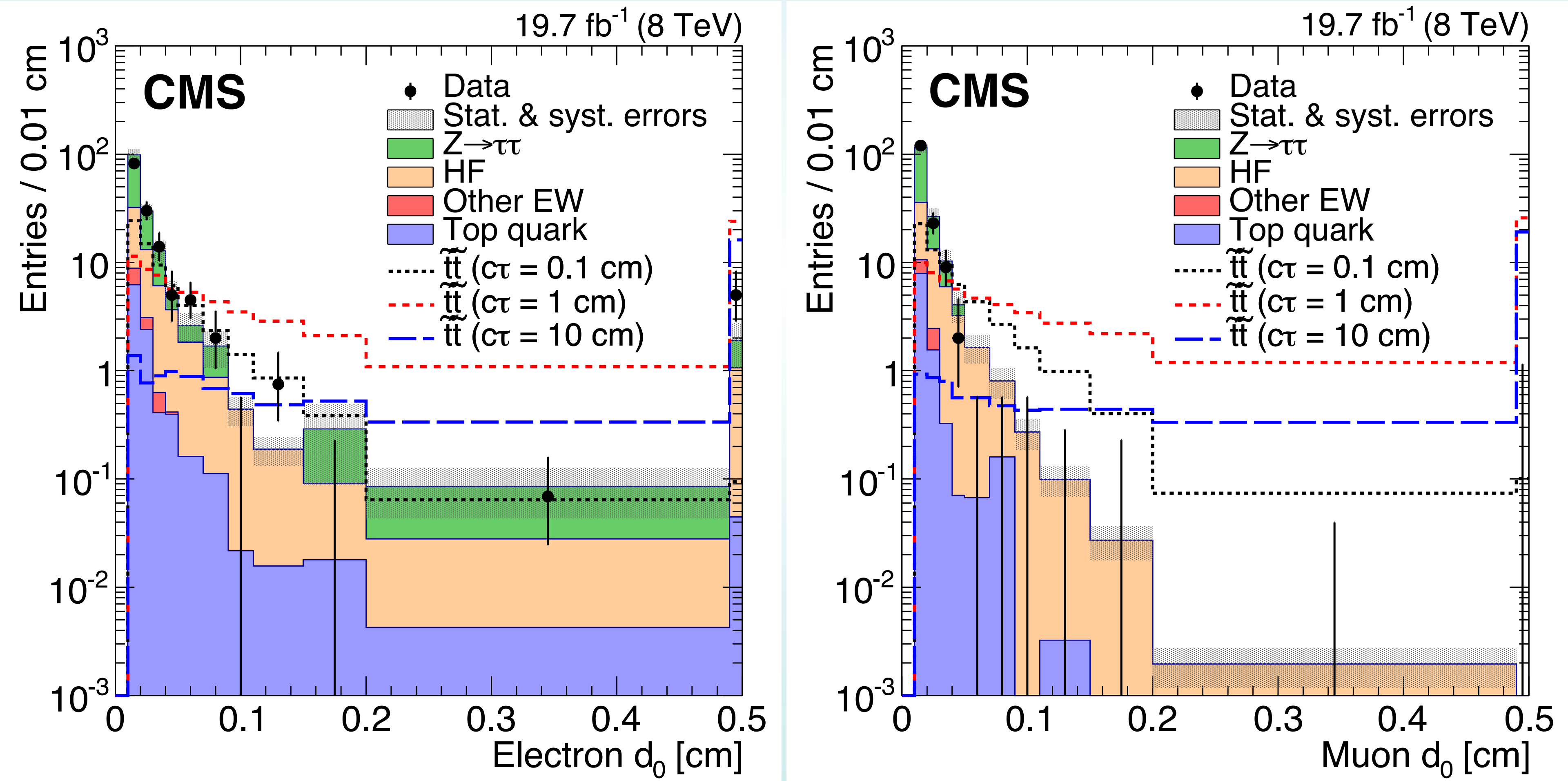
- **Search for final state with an electron-muon pair of opposite sign and both isolated.**
- **p_T > 25 GeV; η < 2.5**
- **No secondary vertex required, but** $|d_0| > 100\ \mu m.$
- **Three signal regions:**
  - SR3: 0.1cm < d_0 < 2cm both
  - SR2: d_0 > 0.05cm both .not. In SR3
  - SR1: d_0 > 0.02 cm both .not. In SR2 or SR3

Control region built from SS non isolated lepton pairs to control backgrounds

arXiv: [hep-ex] 1409.4789, Sept 2014

CMS-B2G-12-024

Search for Long-lived stops produced in pairs

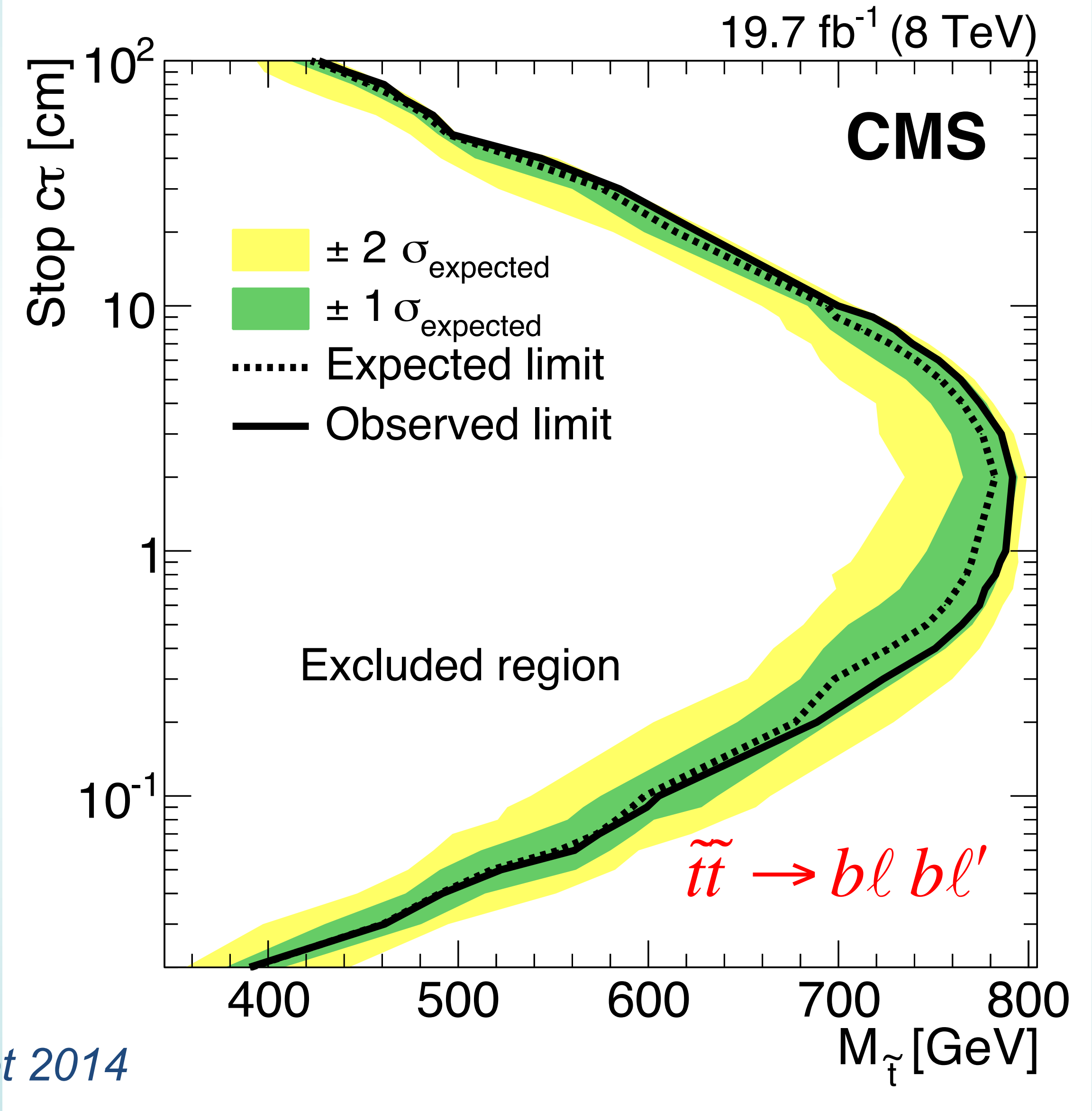


arXiv: [hep-ex] 1409.4789, Sept 2014

CMS-B2G-12-024

Long-lived stops

For life time hypothesis in the range of cτ = 2 cm stops up to 790 GeV are excluded



arXiv: [hep-ex] 1409.4789, Sept 2014

Conclusions

- The search for long-lived particles is a promising way to look for BSM physics
- Complementary to prompt searches
- This presentation (CMS only) concentrated on particles decaying in the difficult region of $c\tau$ < detector
- In all the searches no excess of candidate events has been found → placed upper limits on cross sections and branching ratios
- Experimental data are presented in a way that a large range of models can be tested

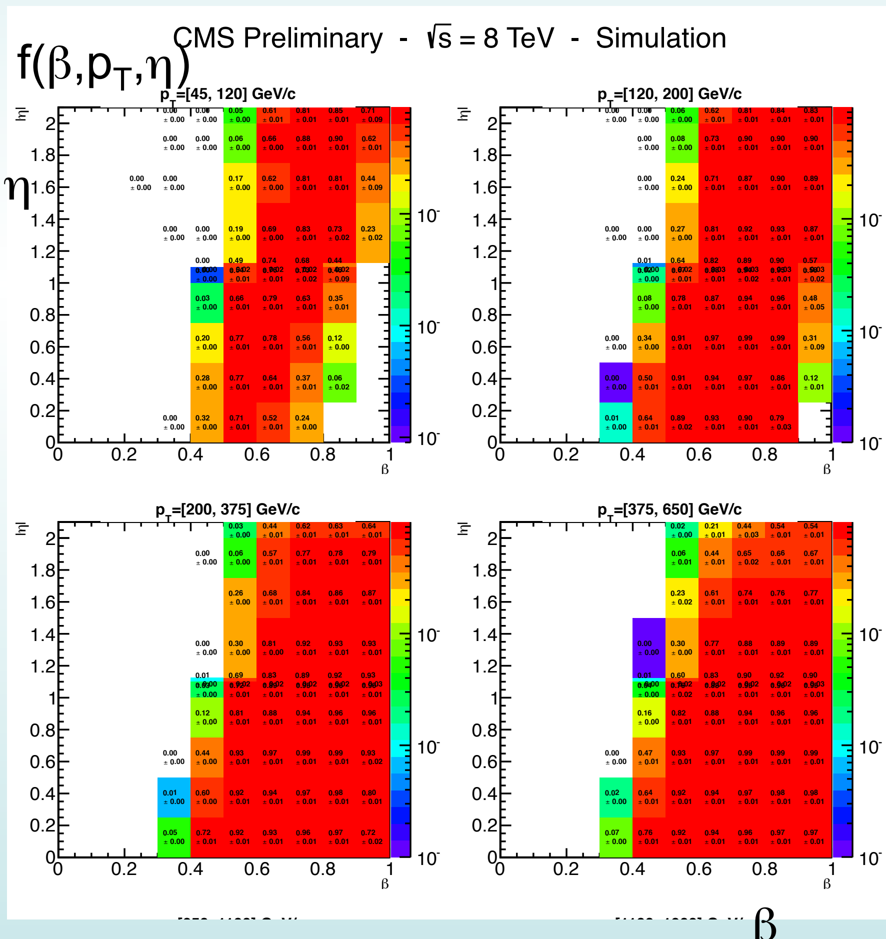
spares

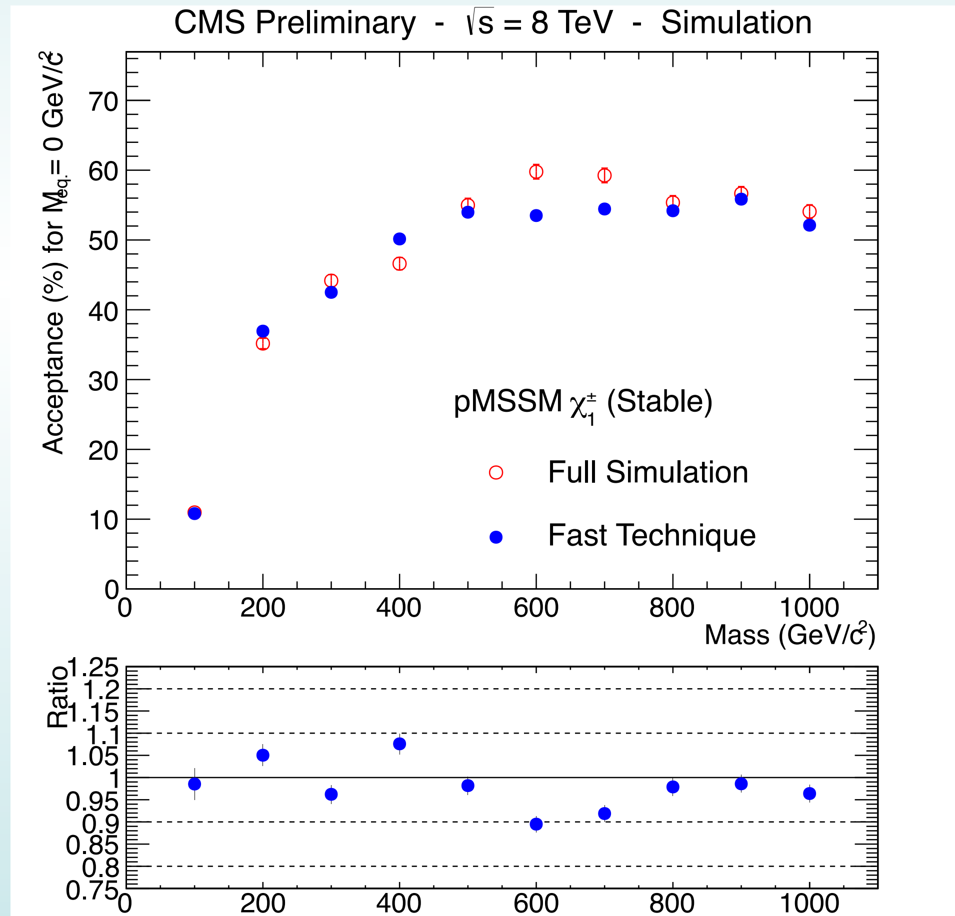
Re-interpretation of HSCP limits within pMSSM

HSCP analysis cuts are expressed as function of p_T, *dE/dx*, *ToF* and mass

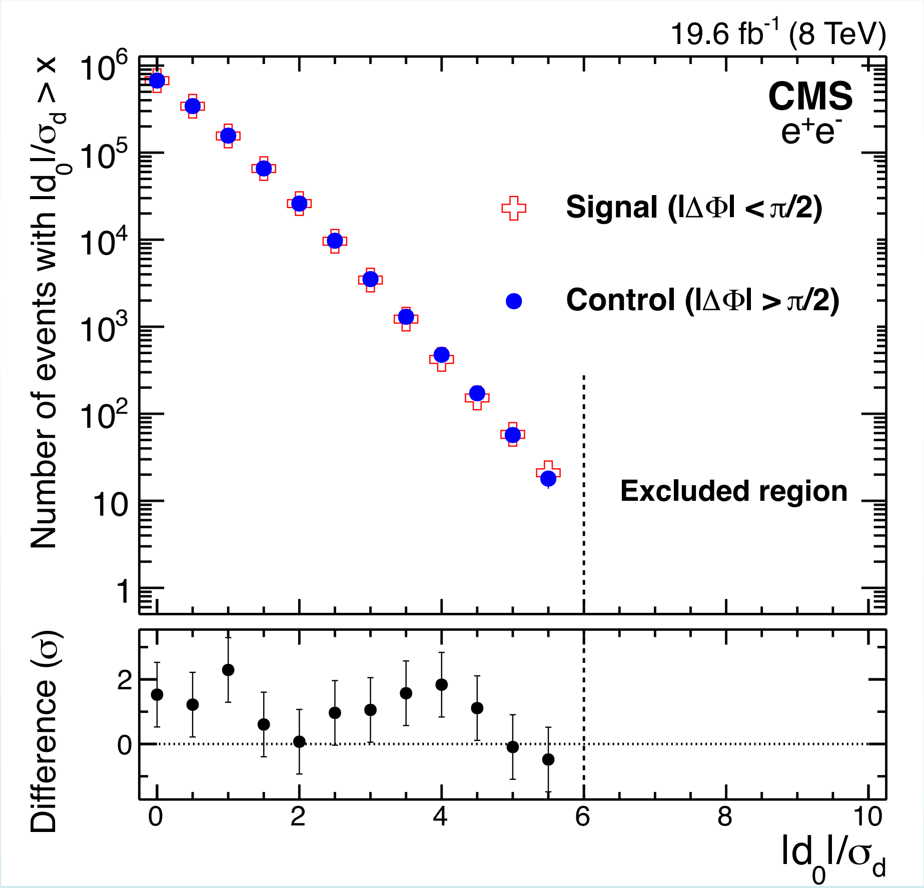
Probability to pass all cuts → $f(\beta, p_T, \eta)$

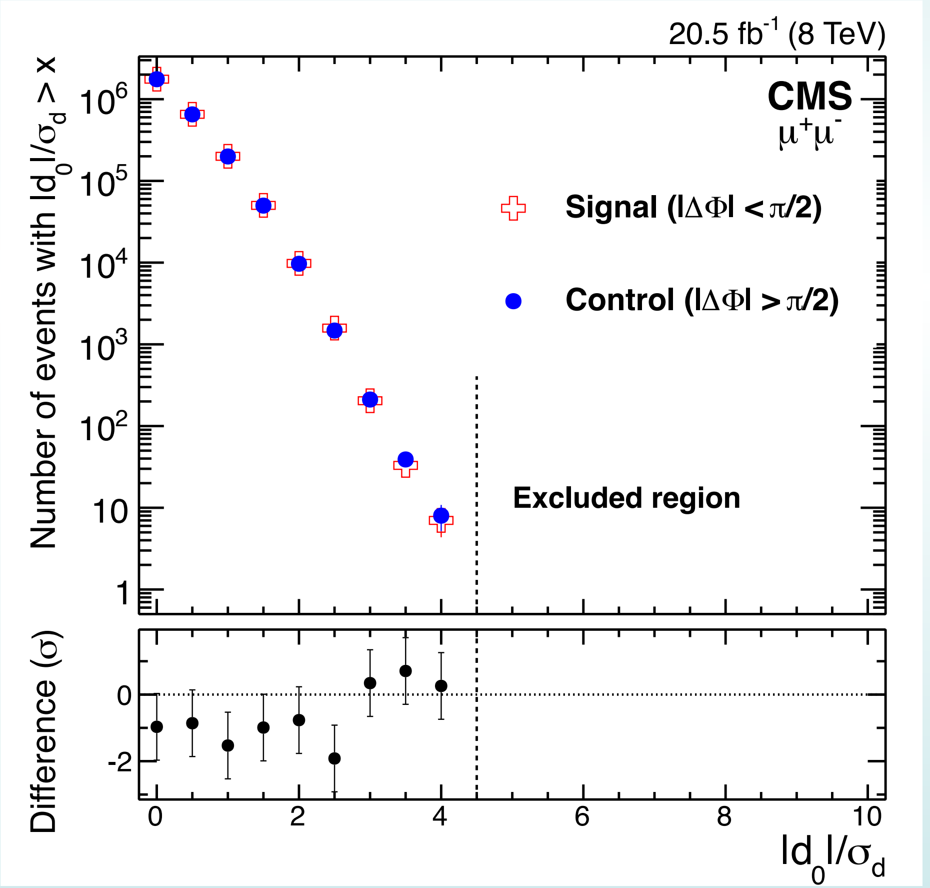
MC at generator level reproduces acceptance value of full simulation





Tail-cumulative distributions control plot lepton pair analysis





arXiv: [hep-ex] 1411.6977, Nov 2014

Systematics lepton pair analysis

Table 1: Systematic uncertainties affecting the signal efficiency over the two signal models and all mass values considered. In all cases, the uncertainty specified is a relative uncertainty. The NLO uncertainty is significant only for the H → XX model with $m_{\mathrm{H}} = 125\,\mathrm{GeV}/c^2$. The relative uncertainty in the integrated luminosity is 2.6%.

Source	Uncertainty
Pileup modelling	2%
Parton distribution functions	<1%
Renormalization and factorization scales	<0.5%
Track reconstruction efficiency from cosmic ray muons	6.1%
Track reconstruction efficiency in high hit occupancy environment	3.5%
Track reconstruction efficiency loss due to bremsstrahlung (e only)	5.8%
Trigger efficiency	1.7% (e), 6.2% (μ)
NLO effects (only for the $m_{\mathrm{H}} = 125\,\mathrm{GeV}/c^2$ case)	5–7%

arXiv: [hep-ex] 1411.6977, Nov 2014

Spare, stops

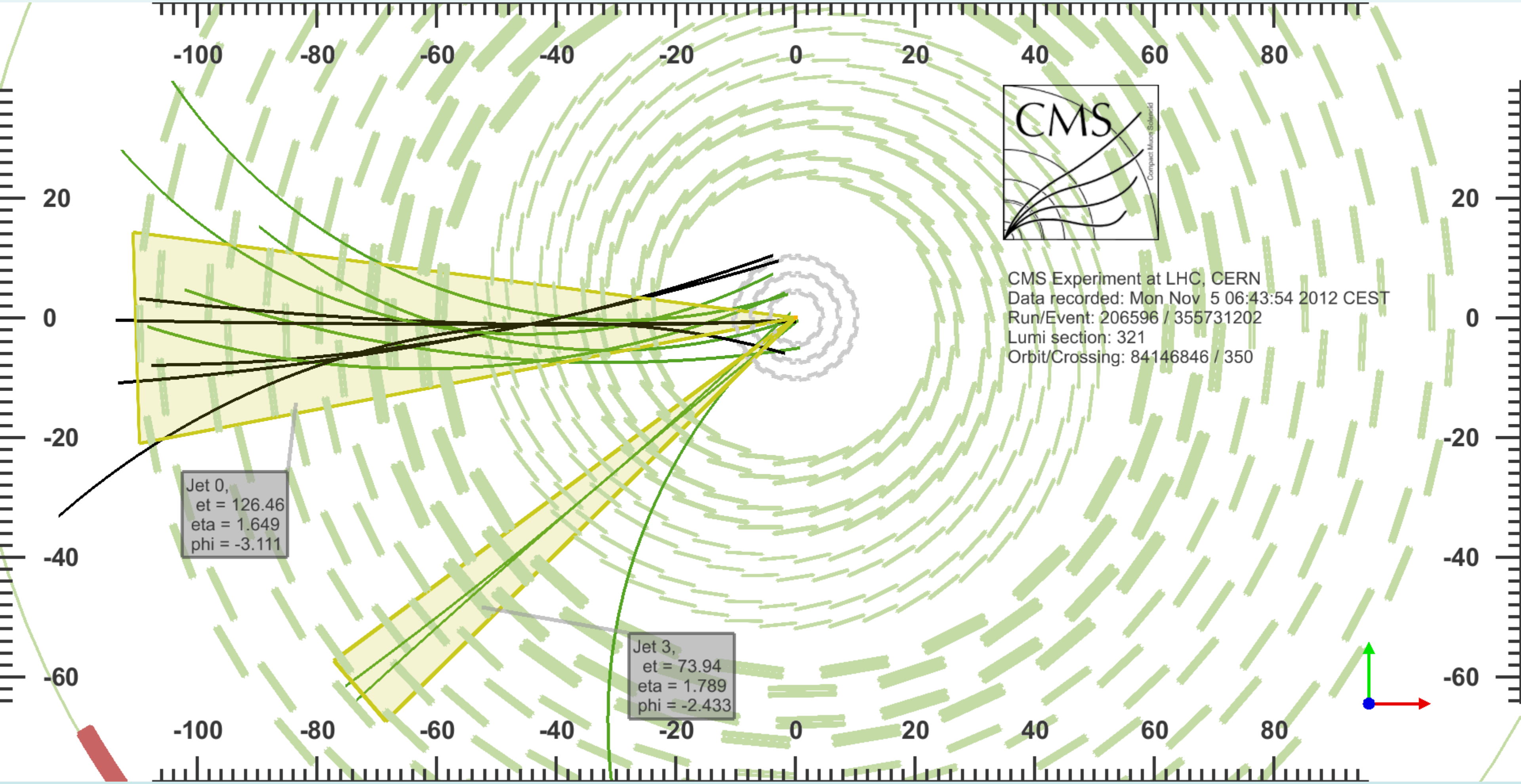
Event source	SR1	SR2	SR3
Other EW	$0.65 \pm 0.13 \pm 0.09$	$(0.89 \pm 0.53 \pm 0.12) \times 10^{-2}$	$<(89 \pm 53 \pm 12) \times 10^{-4}$
Top quark	$0.77 \pm 0.04 \pm 0.08$	$(1.25 \pm 0.26 \pm 0.12) \times 10^{-2}$	$(2.4 \pm 1.3 \pm 0.2) \times 10^{-4}$
$Z \to \tau\tau$	$3.93 \pm 0.42 \pm 0.39$	$(0.73 \pm 0.73 \pm 0.07) \times 10^{-2}$	$<(73 \pm 73 \pm 7) \times 10^{-4}$
HF	$12.7 \pm 0.2 \pm 3.8$	$(98 \pm 6 \pm 30) \times 10^{-2}$	$(340 \pm 110 \pm 100) \times 10^{-4}$
Total expected bkgd.	$18.0 \pm 0.5 \pm 3.8$	$1.01 \pm 0.06 \pm 0.30$	$0.051 \pm 0.015 \pm 0.010$
Observed	19	0	0

Table 2: Numbers of expected and observed events in the three search regions for the displaced SUSY analysis. Background and signal expectations are quoted as $N_{\rm exp} \pm 1\sigma(\text{stat.}) \pm 1\sigma(\text{syst.})$. If the estimated background is zero in a particular search region, the estimate is instead taken from the preceding region. Since this should always overestimate the background, it is denoted by a preceding "<".

arXiv: [hep-ex] 1409.4789, Sept 2014

Displaced jets

- **Neutral massive particles decaying into two jets**



Displaced jets (not sure if I will show it)

- **Pair of high-momentum jets forming a vertex**
- **Identify displaced jets by**
  - Few prompt tracks
  - High fraction of energy carried by displaced tracks d_0>0.5mm
  - Form secondary vertex from displaced tracks ch2/dof<5 Lxy/ sig>8
  - Clustering based discriminant

Table 2: Optimized selection criteria and the corresponding background expectations with their statistical (first) and systematic (second) uncertainties. The low $\langle L_{xy} \rangle$ selection is optimized for signal models with $\langle L_{xy} \rangle < 20$ cm, while the high $\langle L_{xy} \rangle$ selection is optimized for signal models with higher $\langle L_{xy} \rangle$.

	low $\langle L_{xy} \rangle$ selection	**high $\langle L_{xy} \rangle$ selection**
Number of prompt tracks for each jet	≤ 1	≤ 1
Prompt track energy fraction for each jet	< 0.15	< 0.09
Vertex/Cluster discriminant	> 0.9	> 0.8
Expected background	$\mathbf{1.56 \pm 0.25 \pm 0.47}$	$\mathbf{1.13 \pm 0.15 \pm 0.50}$

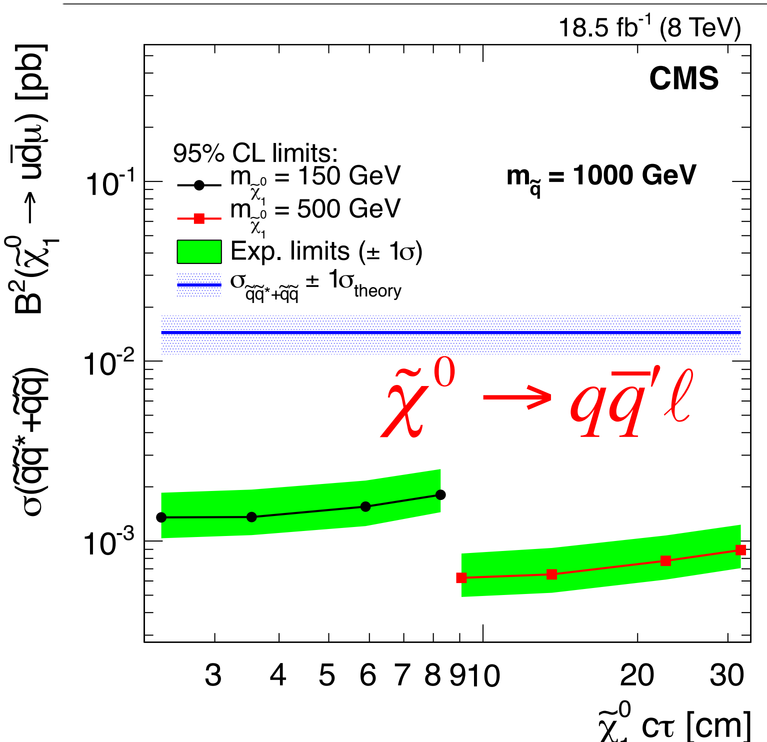
arXiv: [hep-ex] s ubmit/ 1121946, Nov 2014

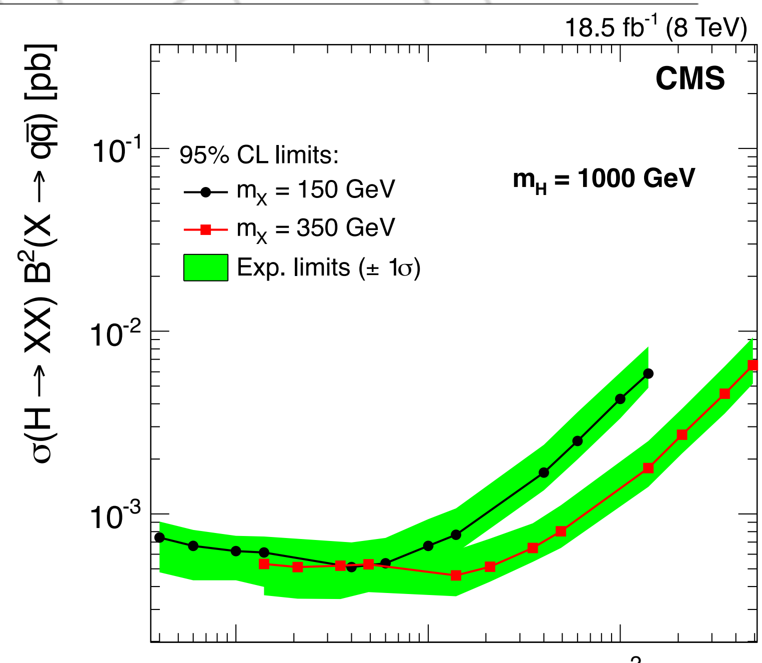
CMS-EXO-12-038

Displaced jets analysis *arXiv: [hep-ex] s ubmit/ 1121946, Nov 2014*

Dijets from common secondary vertex reconstructed from displaced tracks
Event: HT > 325 GeV; Jets: pT > 60 GeV, η < 2.0
Sec. vertex reco from tracks d0 > 0.5 mm, X/dof < 5
Hierarchical cluster algorithm and likelihood discriminant

	low $\langle L_{xy} \rangle$ selection	high $\langle L_{xy} \rangle$ selection
Number of prompt tracks for each jet	≤ 1	≤ 1
Prompt track energy fraction for each jet	< 0.15	< 0.09
Vertex/Cluster discriminant	> 0.9	> 0.8
Expected background	$\mathbf{1.56 \pm 0.25 \pm 0.47}$	$\mathbf{1.13 \pm 0.15 \pm 0.50}$





$H_{BSM} \rightarrow 2X;\ X \rightarrow q\bar{q}$

Disapearing tracks

$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \pi^\pm.$

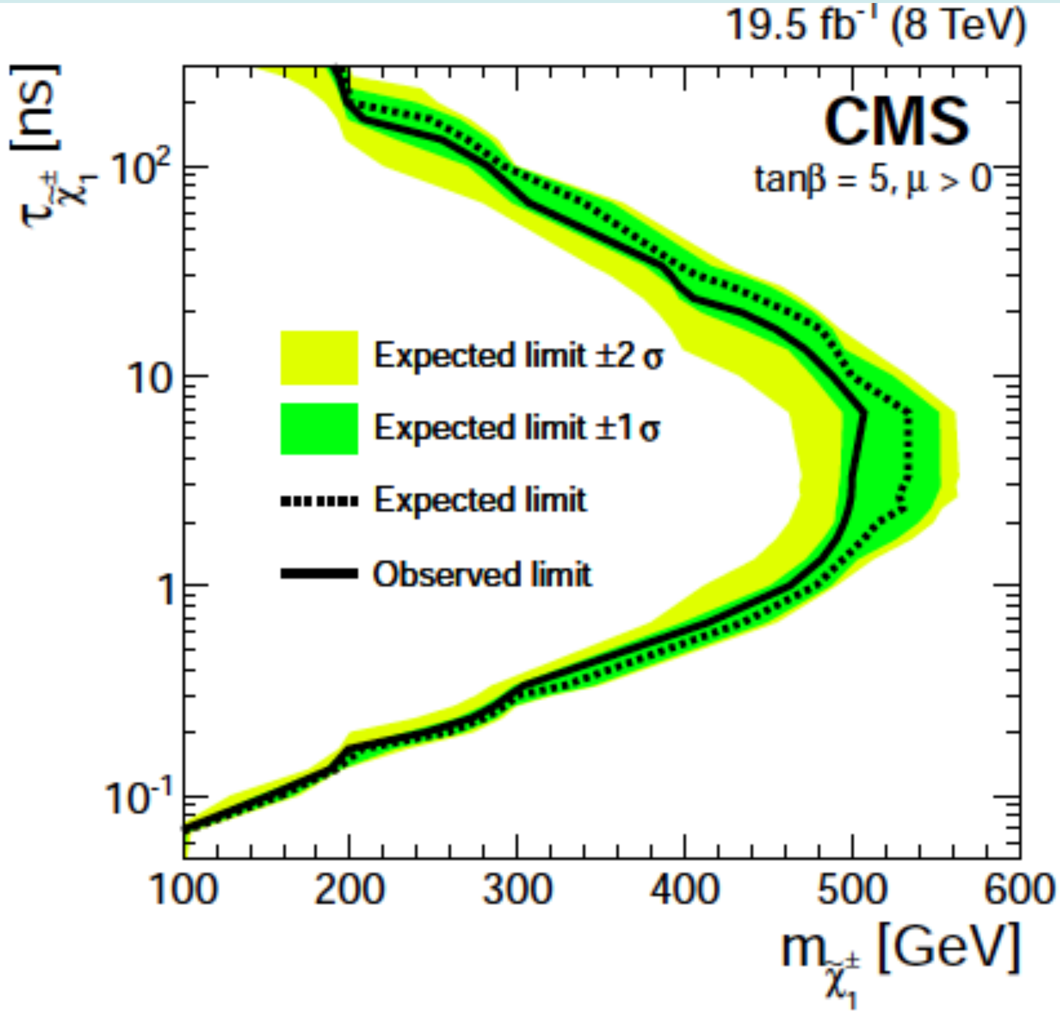


Figure 4: The expected and observed constraints on the chargino mean proper lifetime and mass. The region to the left of the curve is excluded at 95% CL.

arXiv:1411.6006v1

$\pi^\pm$ ≈100 MeV, typically too low for its track to be reconstructed.