A search for new heavy particles in events with highly ionising, short tracks at the CMS experiment at 8 TeV

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FH Fellow Meeting (DESY)

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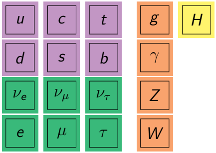
The Standard Model and beyond

- The Standard Model is a very successful theory, but suffers from shortcomings ...
  - Hierachy problem
  - Dark Matter
  - ...



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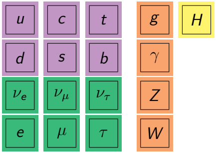
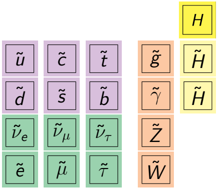


Possible solution:

$+$

The **M**inimal **S**upersymmetric **S**tandard **M**odel

$\rightarrow$ Doubling of particle content



Exotic supersymmetry signatures

- Many new particles predicted
- Wide SUSY parameter space already ruled out experimentally

→ Look for more exotic scenarios

$\tilde{u}$	$\tilde{c}$	$\tilde{t}$	$\tilde{g}$	$\tilde{A}^0$
$\tilde{d}$	$\tilde{s}$	$\tilde{b}$	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$
$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$
$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$	$\tilde{\chi}_1^\pm$	$\tilde{\chi}_2^\pm$

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Long-lived charginos

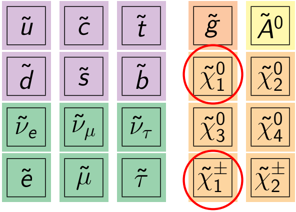
→ Lightest chargino almost mass degenerate with lightest neutralino:

$$m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_1^0}$$

→ Phase space suppression → long chargino lifetime

→ Occur naturally in the MSSM

Exotic supersymmetry signatures



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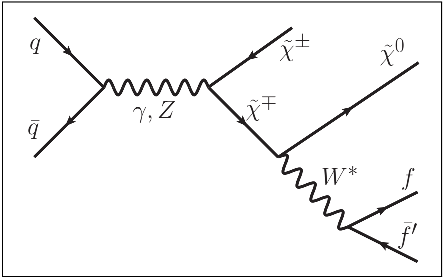
How to search for long-lived charginos?

Chargino signature in the detector

- Chargino decays to neutralino and $f\bar{f}'$ pair
- Signature dependent on the chargino lifetime



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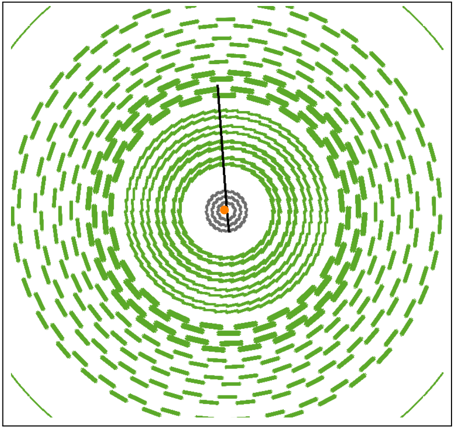
- **Intermediate lifetimes** ($c\tau \approx 1 - 30\,\text{cm}$): Short tracks inside the tracking system



$\longleftarrow \sim$ **2.2 m** $\longrightarrow$

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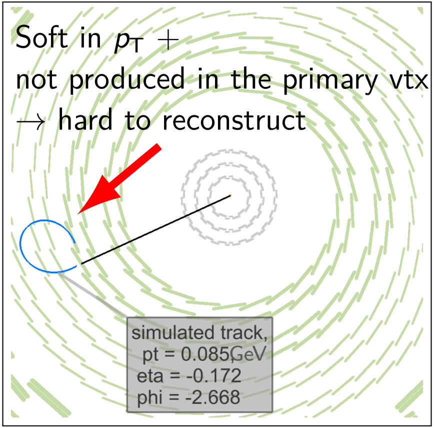

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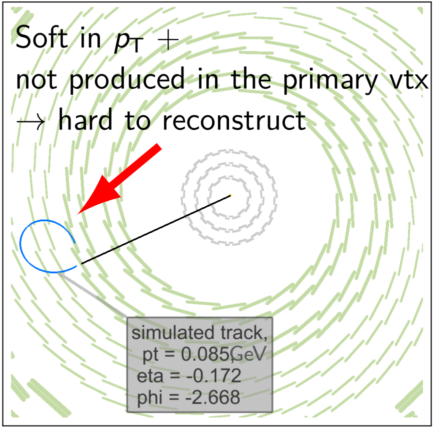
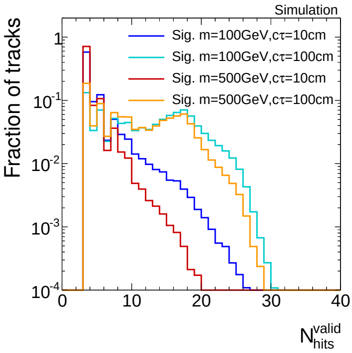


Non-standard search strategy

Twofold search strategy

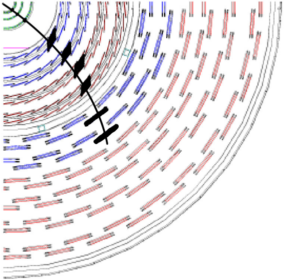
Search for highly ionising, short tracks

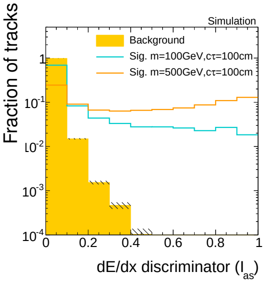
1. Selection of tracks
   - Including short tracks: $N_{hits} \geq 3$
   - Novel compared to other searches ($N_{hits} \geq 7/8$)
2. Selection of heavy particles
   - Using dE/dx (Energy loss per path length)
   - $\langle \frac{\mathbf{dE}}{\mathbf{dx}} \rangle \cong \mathbf{K} \frac{\mathbf{m^2}}{\mathbf{p^2}} + \mathbf{C}$

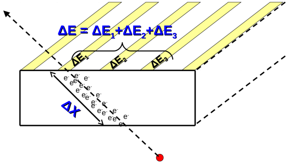


dE/dx measurement of short tracks

ΔE/Δx measurements ⟶ **dE/dx likelihood discriminator**







Short tracks:

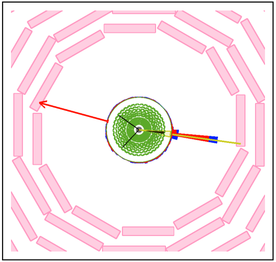
- Only few ΔE/Δx measurements
- Less discriminating power

So far:

- No ΔE/Δx pixel information

Novelty: Pixel energy calibration → first use of pixel dE/dx at CMS

Event selection



Event-based selection:

- Trigger on ISR (Jet + $\not{E}_T$)
- QCD-multijet suppression

Candidate track selection:

Event selection

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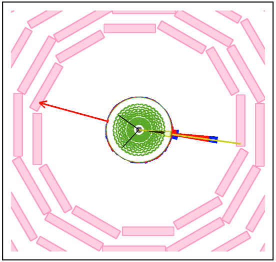
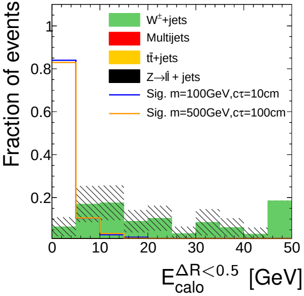
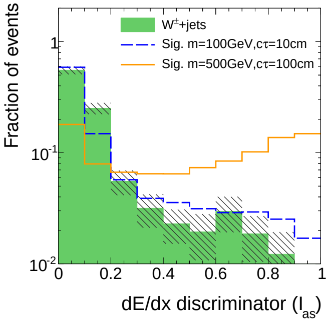


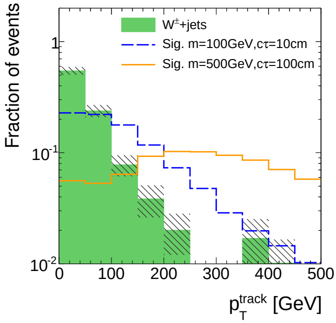
Candidate track selection: **N_{events}**

- Good quality track selection → $1.3 \cdot 10^6$
- Kinematic preselection → $9.5 \cdot 10^5$
- Lepton/jet veto → 616
- Isolation selection
  - Track isolation
  - $E_{calo}^{\Delta R<0.5} < 5$ GeV → 119

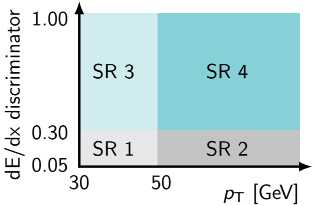


Main discriminating variables





Optimisation of search sensitivity in dE/dx and p_T
→ 4 signal regions

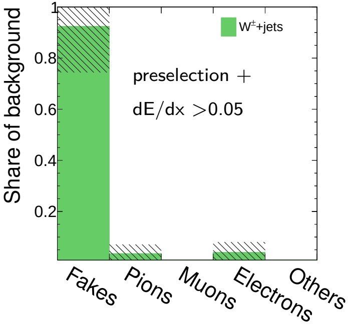


Background contributions

- **Fake tracks**:
  Reconstructed tracks, not produced by one single particle

- **Muons**
- **Electrons**
- **Pions**

} In case of non-reconstruction



Dominant background: Fake tracks

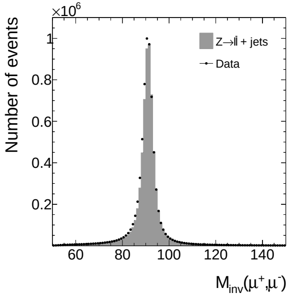
Fake background: Twofold estimation approach

Fully data-based

1. **Estimation of N_{fake} (inclusive in dE/dx):**

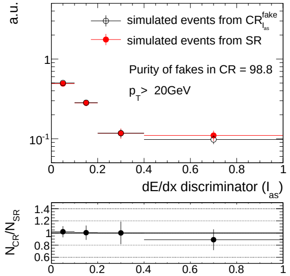
- Fake rate (ρ_{fake}):
  Selection of $Z \to \ell\ell$ events + Candidate track selection = Selection of fake tracks
- ρ_{fake} independent of underlying process

$\to$ $N_{\text{fake}} = \rho_{\text{fake}} \cdot N_{\text{event-based selection}}$



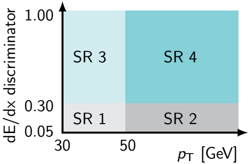
2. **dE/dx shape:**

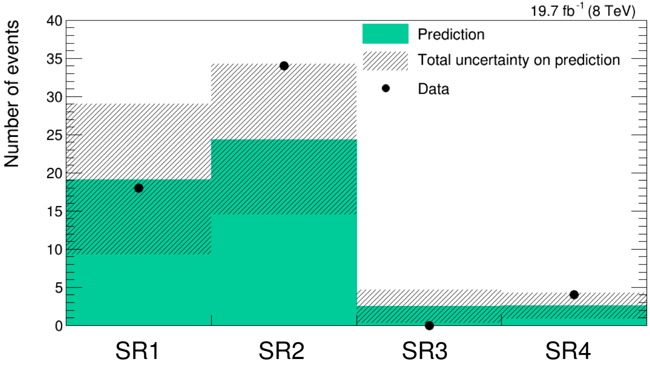
- From fake enriched control region in data
- Same dE/dx shape in signal region and **control region**



Results

→ Four different signal regions

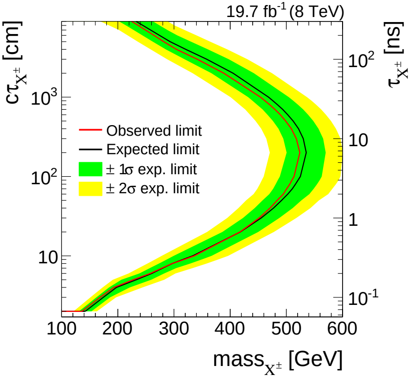




→ No excess

Interpretation in the MSSM

- CL_s exclusion limits
- Combination of four signal regions



Exclusion up to masses of 500 GeV and down to lifetimes of 2 cm

Conclusion

A search for new heavy particles
in events with highly ionising, short tracks

- Targets mass-degenerate chargino - neutralino scenarios
- Novelties:
  - Inclusion of tracks down to three hits
  - Use of energy information from pixel tracker
  - Offline energy calibration of pixel silicon tracker

- No sign of physics beyond the Standard Model
- Stronger limits for intermediate chargino lifetimes compared to previous analyses

Thank you

Backup

Search for highly ionising, short tracks

Dominant systematic uncertainties

Background uncertainty	Min [%]	Max [%]
Uncertainty on fake rate	32.1	45.2
Uncertainty on fake dE/dx shape	18.7	65.2

Signal uncertainty	Min [%]	Max [%]
Theoretical x-section	4.5	12.1
Simulation of ISR	9.2	12.6
Simulation of trigger efficiency	1.9	4.4
Simulation of PDF	2.6	6.8
Simulation of calorimeter isolation	3.0	12.1
Simulation of missing middle/inner hits	2.2	3.7
Simulation of dE/dx	6.0	6.0
Track reconstruction efficiency simulation	4.6	6.0

Long-lived charginos in the MSSM

Back

$$\Psi_i^+ = \left(-i\tilde{W}^+, \tilde{h}_u^+\right) \qquad \Psi_i^0 = \left(-i\tilde{B}, -i\tilde{W}^0, \tilde{h}_u^0, \tilde{h}_d^0\right)$$

$$\mathcal{M}_{\chi^\pm} = \begin{pmatrix} M_2 & gv_d \\ gv_u & \mu \end{pmatrix} \qquad \mathcal{M}_{\chi^0} = \begin{pmatrix} M_1 & 0 & \frac{g'v_u}{\sqrt{2}} & -\frac{g'v_d}{\sqrt{2}} \\ 0 & M_2 & -\frac{gv_u}{\sqrt{2}} & \frac{gv_d}{\sqrt{2}} \\ \frac{g'v_u}{\sqrt{2}} & -\frac{gv_u}{\sqrt{2}} & 0 & -\mu \\ -\frac{g'v_d}{\sqrt{2}} & \frac{gv_d}{\sqrt{2}} & -\mu & 0 \end{pmatrix}$$

Wino-like lightest chargino and neutralino if $M_2 < M_1, \mu$

pMSSM parameter scans reveal (*Cahill-Rowley et.al.,Phys.Rev.D88,2013*):

- If $\tilde{\chi}_1^0$ DM candidate + current observations fulfilled

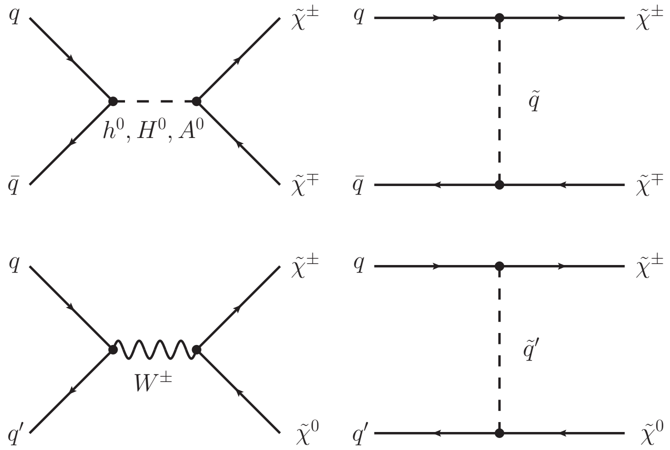
$\rightarrow$ NLSP is usually wino-like chargino

$\rightarrow$ $m_{\tilde{\chi}_1^\pm, \tilde{\chi}_1^0} \approx 160\,\text{MeV}$

$\rightarrow$ In 25% of these scenarios: $\tilde{\chi}_1^\pm$ decays inside detector

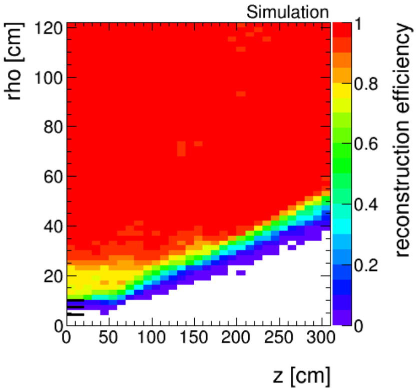
Production feynman diagrams

Back



Chargino track reconstruction effiency

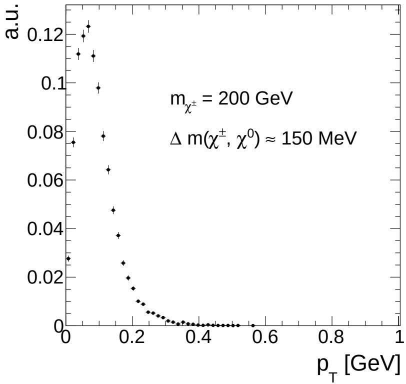
Back

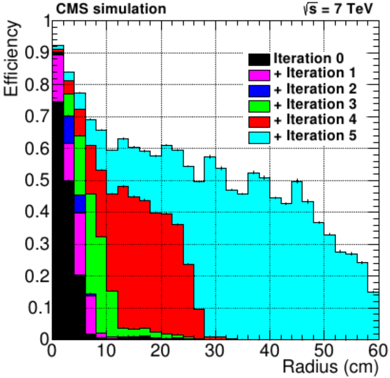


- Track reconstruction efficiency for very short tracks $20 - 40\%$
- Fully efficient reconstruction at 30 cm

Reconstruction of low p_T pions

Back



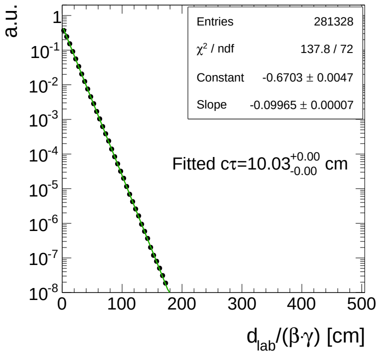


- Reconstruction efficiency for 100 MeV pions $\sim$ 40%
- Displaced track reconstruction efficiency between 10-50%

Chargino lifetime reweighting

Back

- Calculation of event weights
- Weights depend on
  - Generated mean lifetime in particle rest frame(τ_{gen})
  - Individual proper lifetime of the chargino (t)
  - Targeted mean lifetime (τ_{target})
  - Number of charginos in the event (i)



$$w = \prod_{i=1}^{n} \frac{\tau^{\text{gen}}}{\tau^{\text{target}}} \cdot \exp\left[t_i \cdot \left(\frac{1}{\tau^{\text{gen}}} - \frac{1}{\tau^{\text{target}}}\right)\right]$$

Cutflow

Back

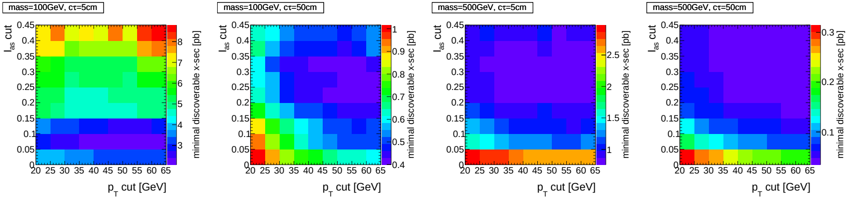
	Simulated background samples				Simulated signal samples				Data
Selection	W + jets	$t\bar{t}$ + jets	$Z \to \ell\bar{\ell}$	Multijet	m=100GeV $c\tau$=10 cm	m=100GeV $c\tau$=100 cm	m=500GeV $c\tau$=10 cm	m=500GeV $c\tau$=100 cm	MET data
After skim	$9.16 \cdot 10^{7}$	$1.04 \cdot 10^{6}$	$2.21 \cdot 10^{7}$	$1.38 \cdot 10^{11}$	$3.41 \cdot 10^{5}$	$3.41 \cdot 10^{5}$	$3.46 \cdot 10^{2}$	$3.46 \cdot 10^{2}$	$1.07 \cdot 10^{7}$
Event-based selection:									
Trigger	$4.31 \cdot 10^{6}$	$1.15 \cdot 10^{5}$	$4.23 \cdot 10^{3}$	$4.32 \cdot 10^{6}$	$1.55 \cdot 10^{4}$	$1.49 \cdot 10^{4}$	46.2	46.2	$1.07 \cdot 10^{7}$
Trigger selection	$1.89 \cdot 10^{6}$	$5.31 \cdot 10^{4}$	$6.26 \cdot 10^{2}$	$9.63 \cdot 10^{5}$	$1.09 \cdot 10^{4}$	$9.83 \cdot 10^{3}$	36.3	35.7	$3.94 \cdot 10^{6}$
QCD suppression	$1.11 \cdot 10^{6}$	$6.76 \cdot 10^{3}$	$1.32 \cdot 10^{2}$	$9.55 \cdot 10^{3}$	$7.90 \cdot 10^{3}$	$6.98 \cdot 10^{3}$	27.6	27.1	$1.38 \cdot 10^{6}$
Track-based selection:									
Good quality selection	$1.07 \cdot 10^{6}$	$6.63 \cdot 10^{3}$	$1.32 \cdot 10^{2}$	$9.55 \cdot 10^{3}$	$2.80 \cdot 10^{3}$	$5.38 \cdot 10^{3}$	5.07	20.0	$1.30 \cdot 10^{6}$
Kinematic selection	$8.14 \cdot 10^{5}$	$5.63 \cdot 10^{3}$	$1.32 \cdot 10^{2}$	$5.48 \cdot 10^{3}$	$2.54 \cdot 10^{3}$	$4.93 \cdot 10^{3}$	4.73	18.9	$9.51 \cdot 10^{5}$
Lepton/jet veto	$5.02 \cdot 10^{2}$	5.88	0	0	$1.99 \cdot 10^{3}$	$3.67 \cdot 10^{3}$	3.83	15.0	616
Isolation selection	31.9	0.67	0	0	$1.67 \cdot 10^{3}$	$3.04 \cdot 10^{3}$	3.39	12.6	119

Optimisation of search sensitivity

Back

- Optimisation for various benchmark signal models
- For each selection in p_T and dE/dx:

$$Z = \frac{\alpha_{\min} \cdot N_S(\text{mass}, c\tau, p_T^{\text{cut}}, I_{\text{as}}^{\text{cut}})}{\Delta B(p_T^{\text{cut}}, I_{\text{as}}^{\text{cut}})} = 5. \qquad \text{with } \alpha_{\min} = \frac{\sigma_{\min}}{\sigma_S}.$$



Optimisation of search sensitivity

Back

Mass [GeV]	Lifetime $c\tau$ [cm]	Optimal p_T cut [GeV]	Optimal I_{as} cut	σ_{min} [pb]
100	1	30	0.05	61.596
200	1	20	0.05	43.414
300	1	n/a	n/a	n/a
400	1	n/a	n/a	n/a
500	1	n/a	n/a	n/a
100	10	30	0.05	1.531
200	10	30	0.30	0.561
300	10	30	0.30	0.354
400	10	30	0.30	0.238
500	10	50	0.30	0.201
100	50	50	0.30	0.435
200	50	50	0.30	0.110
300	50	50	0.30	0.063
400	50	50	0.30	0.045
500	50	50	0.30	0.037

Event selection for ρ_{fake} determination in $Z \to \mu\bar{\mu}$ events

Back

Event-based selection	Two global muons with	$p_T > 25\,\text{GeV}$
		$\lvert\eta\rvert < 2.4$
		$\sum_{\Delta R<0.4} p_T^{\text{PF particle}} / p_T(\mu) < 0.12$
		$\left.\frac{\chi^2}{n_{\text{dof}}}\right\rvert_{\text{global track}} < 10$
		$\lvert d0\rvert < 0.2\,\text{cm}$
		$\lvert dz\rvert < 0.5\,\text{cm}$
		$\geq$ 1 hit in the muon detector considered in global fit
		$\geq$ 2 hits in different muon stations
		$\geq$ 1 hit in the pixel detector
		$\geq$ 6 hits in the tracker system
	Muons opposite in charge	
	$80\,\text{GeV} < M_{\text{inv}}(\mu_1, \mu_2) < 100\,\text{GeV}$	
Candidate track selection	Good quality selection	
	Kinematic selection	
	Lepton/jet veto	
	Isolation selection	

Event selection for ρ_{fake} determination in $Z \to e\bar{e}$ events

Back

Event-based selection	Two Electrons with	$p_T > 25\,\text{GeV}$
		$\lvert\eta\rvert < 2.5$
		$\sum_{\Delta R<0.4} p_T^{\text{PF particle}}/p_T(e) < 0.15$
		pass conversion veto
		no missing inner tracker hits
		good MVA electron as defined in
	Electrons opposite in charge	
	$80\,\text{GeV} < M_{\text{inv}}(e_1, e_2) < 100\,\text{GeV}$	
Candidate track selection	Good quality selection	
	Kinematic selection	
	Lepton/jet veto	
	Isolation selection	

Results for preselection

Channel	$N_{Z\to ll}^{\text{cand trk selection}}$	$N_{Z\to ll}$	ρ_{fake}
$Z \to \mu\bar{\mu}$	403	$6.17 \cdot 10^6$	$(6.53 \pm 0.33) \cdot 10^{-5}$
$Z \to e\bar{e}$	369	$5.08 \cdot 10^6$	$(7.26 \pm 0.38) \cdot 10^{-5}$

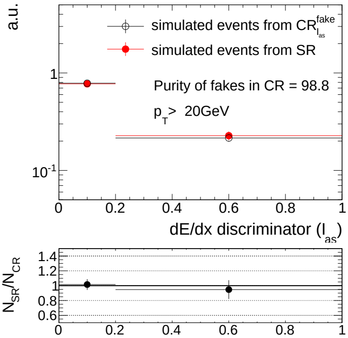
Systematic uncertainties - fake background

1.) Fake rate uncertainty

- Comparison of ρ_{fake} between $Z \rightarrow \ell\ell$+fake and $W + jets$ (full analysis selection) with simulated events.
- Uncertanties mainly driven by statistical limitation of simulated samples.
- Lower trigger cuts and remove QCD-multijet cuts

2.) dE/dx shape uncertainty

- Comparison of shape differences in CR and SR in simulated events.
- Uncertainties mainly driven by statistical limitations of simulated samples
- Only candidate track selection applied.



Leptonic background estimation

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Inclusive background estimate

- Determine scaling factors from CR (lepton veto inverted region) to SR in simulation.
- $\rho_{MC}^{lepton_i} = \frac{N_{SR}^{\text{trk matched to lepton}_i}}{N_{\text{lepton}_i\text{ veto inverted}}}$
- $\mathrm{N}_{bkg}^{\text{lepton}_i\text{, inclusive in I}_{as}} = \mathrm{N}_{data}^{\text{lepton}_i\text{ veto inverted}} \cdot \rho_{MC}^{lepton_i}$

	$\rho_{\mathrm{MC}}^{\mathrm{lep}_i}$	$\mathrm{N}_{\text{CR,data}}^{\text{veto inverted}}$	$\mathrm{N}_{\text{predicted}}^{\text{inclusive in I}_{\text{as}}}$
electrons	$1.25^{+1.70}_{-0.77} \cdot 10^{-4}$	60067	$7.49^{+10.19}_{-4.63}$
muons	$2.17^{+1.65}_{-0.93} \cdot 10^{-4}$	76664	$16.64^{+12.64}_{-7.12}$
taus	$< 2.13 \cdot 10^{-2}$	445	< 9.46

dE/dx shape

- Take I_{as} also from MC (large systematic uncertainties, but..)

Systematic uncertainties - leptonic background

1.) Leptonic scale factor uncertainty

- Derived by tag-and-probe method comparing data and simulation
- Selection of $Z \to \ell\bar{\ell}$ events with one well reconstructed lepton (tag) and one candidate track (probe)
- For μ and e: $80\,\mathrm{GeV} < M_{\mathrm{inv}}\,(\mathrm{lepton}, \mathrm{cand.\ trk}) < 100\,\mathrm{GeV}$
- For τ: $40\,\mathrm{GeV} < M_{\mathrm{inv}}\,(\mu, \mathrm{cand.\ trk}) < 75\,\mathrm{GeV}$ and $m_T\,(\mu, \not{E}_{\mathrm{T}}) < 40\,\mathrm{GeV}$
- $\rho^{\mu} = \frac{N_{\mathrm{SR}}^{\mathrm{T\&P}\mu}}{N_{\mathrm{CR,}\ \mu\ \mathrm{veto\ inverted}}^{\mathrm{T\&P}}}$

		Muons	Electrons	Taus
Data	$N_{\mathrm{SR}}^{\mathrm{T\&Plep}_i}$	211	319	19
	$N_{\mathrm{CR,\ lep}_i\ \mathrm{veto\ inverted}}^{\mathrm{T\&P}}$	$4.10 \cdot 10^{6}$	$3.74 \cdot 10^{6}$	33
	ρ^{lep_i}	$(5.14 \pm 0.35) \cdot 10^{-5}$	$(8.52 \pm 0.48) \cdot 10^{-5}$	$(5.76 \pm 1.66) \cdot 10^{-1}$
Simulation	$N_{\mathrm{SR}}^{\mathrm{T\&Plep}_i}$	153.9 ± 15.4	125.1 ± 15.8	9.1 ± 4.0
	$N_{\mathrm{CR,\ lep}_i\ \mathrm{veto\ inverted}}^{\mathrm{T\&P}}$	$(4.284 \pm 0.003) \cdot 10^{6}$	$(4.112 \pm 0.003) \cdot 10^{6}$	30.9 ± 7.8
	ρ^{lep_i}	$(3.59 \pm 0.36) \cdot 10^{-5}$	$(3.04 \pm 0.39) \cdot 10^{-5}$	$(2.95 \pm 1.49) \cdot 10^{-1}$

Systematic uncertainties - leptonic background

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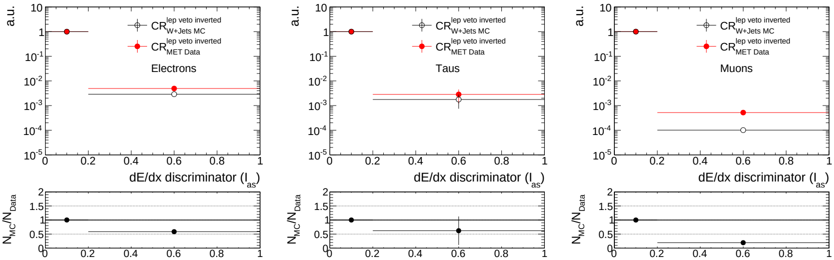
1.) Leptonic dE/dx shape uncertainty

- Comparison of dE/dx shape between data and simulation in lepton-veto inverted control region



Tau background - visualisation

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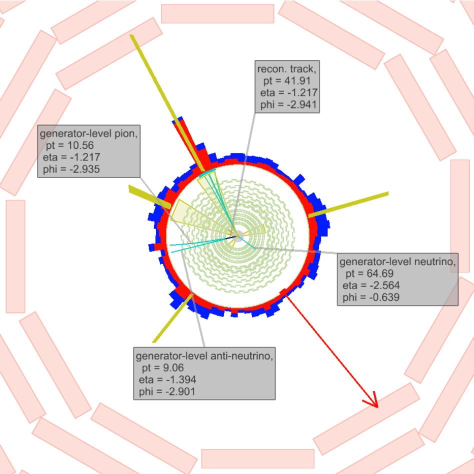

Muon background - visualisation

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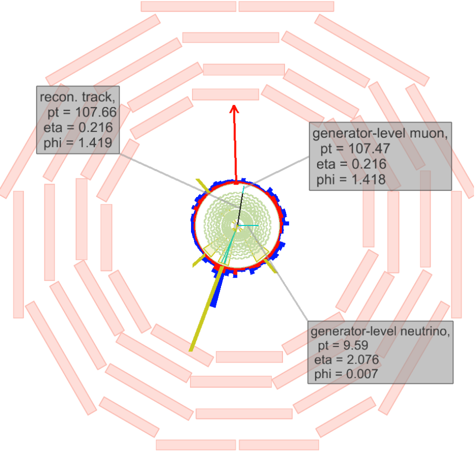

Electron background - visualisation

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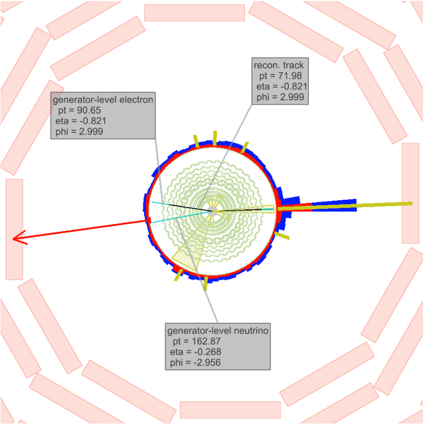

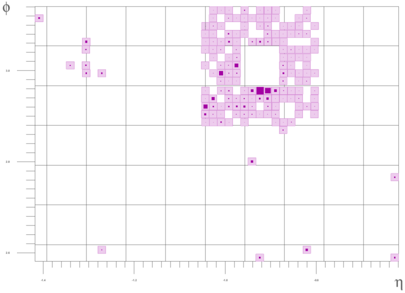

dE/dx simulation uncertainty

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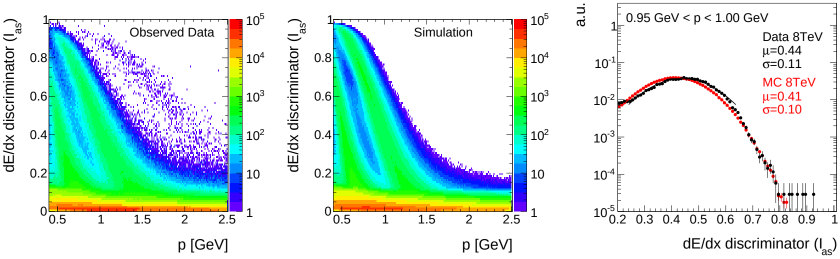
Comparison of low momentum protons



Other signal uncertainties

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- **Simulation of ISR:**
  - Recipe from SUSY group (https://twiki.cern.ch/twiki/bin/viewauth/CMS/SUSYApprovalProcedures)
  - ISR weights are applied in the main analysis
  - Weights are varied up and down by up to 25%
- **Simulation of trigger efficiency**
  - Done with same method used in Disappearing track search
  - Differences between MC and data in trigger turn-on applied as sys. uncertainty
  - Trigger turn-on curves measured with SingleMu dataset
- **Simulation of calorimeter isolation**
  - Measured in fake enriched control region
  - CR well suited because fake tracks are not correlated to calorimeter deposits
  - Comparison of of simulated and measured selection efficiencies

Other signal uncertainties

Back

- **Simulation of missing middle/inner hits**
  - Estimated in the muon-veto inverted control region
  - CR well suited because muons do not have intrinsic sources of missing hits (cf. electrons and pions)
  - Comparison of of simulated and measured selection efficiencies
- **Simulation of the track reconstruction efficiency**
  - Worst case estimation
  - All hits after third hit are removed for well reconstructed muons
  - Track reconstruction is performed again and track reconstruction efficiencies in MC and data are compared

Exemplary limit plots

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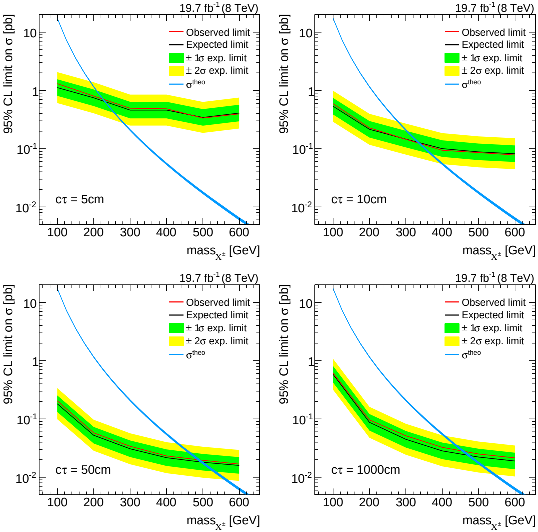

Exclusion in chargino mass vs. mass splitting

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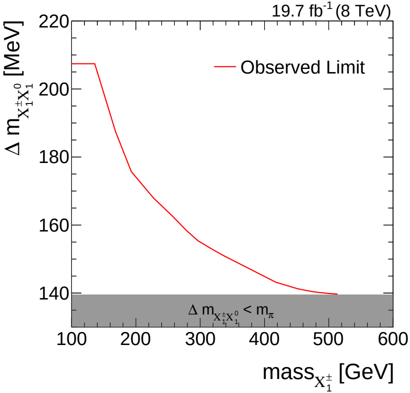

- Mathematical expression used for decay width from arXiv:hep-ph/9902309
- Decay width expressed in terms of $m_{\tilde{\chi}_1^\pm}$, $m_{\tilde{\chi}_1^0}$ and m_π
- Translation from decay width $\rightarrow$ mass splitting

Fake - signal comparison

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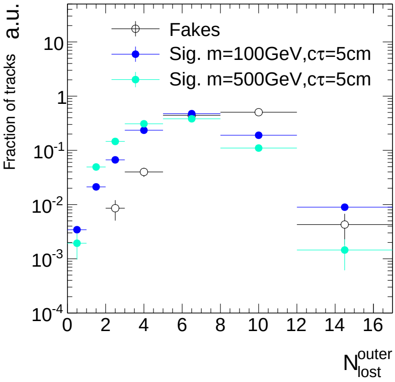

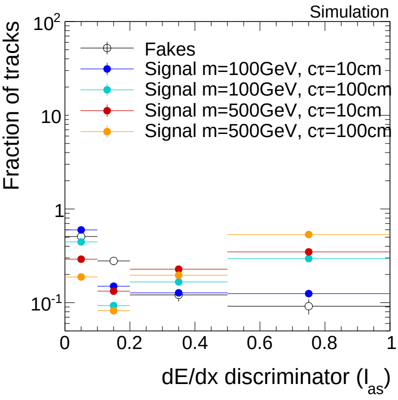

Asymmetric Smirnov-Cramer-von Mises discriminator

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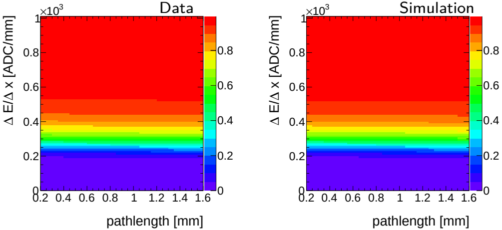
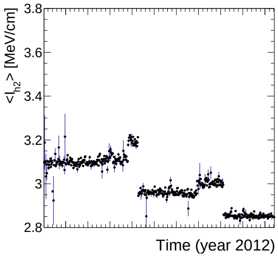
Comparison of observed measurements to a hypothesis distribution.

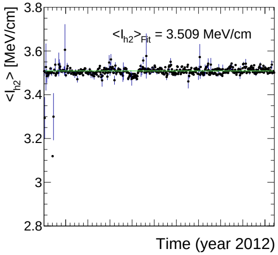
- Test statistics derived from integral of squared differences

$$I_{\text{as}} = \frac{3}{N} \cdot \left(\frac{1}{12N} + \sum_{i=1}^{N} \left[P_i \cdot \left(P_i - \frac{2i-1}{2N} \right)^2 \right] \right).$$



Pixel energy calibration



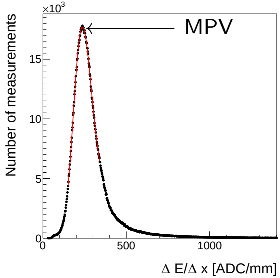


Method:

- Selection of minimally ionising particles.

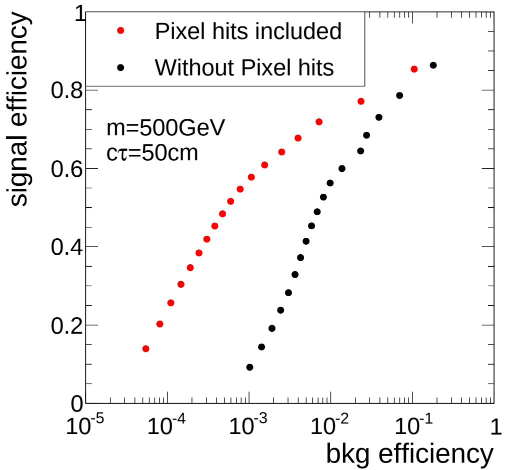
For each

- module
- time interval



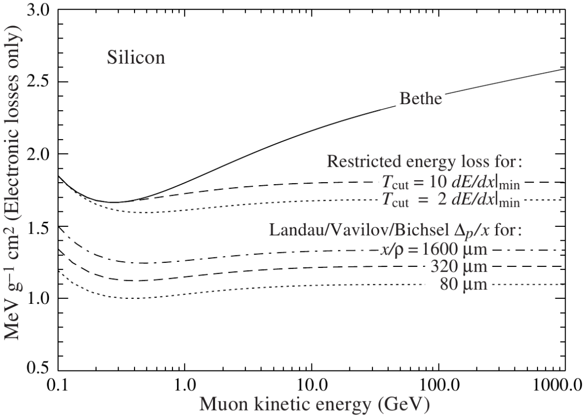
- Calibration factor: $c = \frac{\text{MPV}_{\text{target}}}{\text{MPV}_i}$
- Landau $\otimes$ Gaussian function fitted
- Absolute calibration with silicon strip energy measurements.

Pixel energy calibration



Improvement of background suppression up to an order of magnitude

Mean and most probable energy loss



Comparison to ATLAS results

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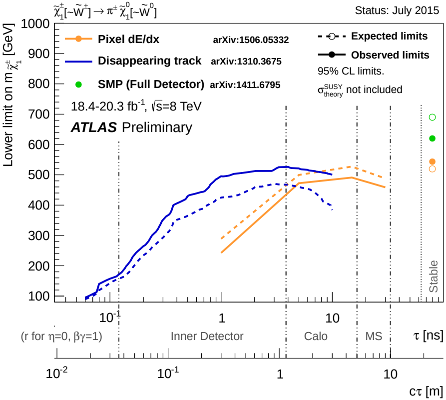

- Interpretation done in the same models
- Very similar sensitivity in the low lifetime region