Searches for **Electroweak SUSY** and for **Long-lived Particles** at the LHC

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on behalf of the ATLAS and CMS Collaborations
Introduction

- SUSY: hypothetical **fundamental** space–time symmetry between fermions and bosons.
- Presence of superpartners around the EW scale can mitigate the **hierarchy problem** of the SM.
- SUSY must be broken — how SUSY–breaking happens hints the physics of the very high–energy scale.
- If R–parity is exactly conserved, the lightest supersymmetric particle (LSP) can be a dark matter candidate.

- LHC Run 2 is over!
  — each of CMS and ATLAS collected ~140 fb$^{-1}$.
- Searches are actively in progress.
- Early full Run 2 results are coming out.

This talk covers selected recent search results of:
- Electroweak SUSY production
- Long–lived (SUSY and more…) scenarios
Electroweak SUSY production searches

MSSM mass params.

$\tilde{h}^0, \tilde{A}^0, \tilde{H}^{\pm}$ … $\mu$

$\tilde{W}^0, \tilde{W}^{\pm}$ … $M_2$

$\tilde{B}$ … $M_1$

Mass eigenstates

$\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^0_3$, $\tilde{\chi}^0_4$

$\tilde{\chi}^{\pm}_2$, $\tilde{\chi}^{\pm}_3$

Order of hierarchy and mixing depends on phenomenologies we want to focus on.

Most searches focus on pair production of lowest mass electroweakinos.

Examples of simplified models

“Wino–Bino”

$\tilde{W}^0, \tilde{W}^{\pm}$

$\tilde{B}$

$\Delta m$

“Higgsino”

$\tilde{h}^0, \tilde{A}^0, \tilde{H}^{\pm}$

$\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^0_3$, $\tilde{\chi}^0_4$
Electroweak SUSY production searches

MSSM mass params.

\( (\tilde{h}^0, \tilde{A}^0, \tilde{H}^{\pm}) \) ... \( \mu \)

\( (\tilde{W}^0, \tilde{W}^{\pm}) \) ... \( M_2 \)

\( \tilde{B} \) ... \( M_1 \)

Mass eigenstates

\( \tilde{\chi}^0_1 \)

\( \tilde{\chi}^0_2 \)

\( \tilde{\chi}^0_3 \)

\( \tilde{\chi}^0_4 \)

\( \tilde{\chi}^{\pm} \)

Order of hierarchy and mixing depends on phenomenologies we want to focus on.

Most searches focus on pair production of lowest mass electroweakinos.

Representative production

“C_{1N1}”

“C_{1C1}”

“C_{1N2}”

Stau/Slepton

Decays

Representative searches: \( Wh \) (e.g. 1L+bb) or \( WW \) (e.g. di-lepton) final states.
A large fraction of $C_2 \rightarrow N_1$ decay with higgs emission expected when $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) > m(h)$ and $m(\tilde{h}) > m(\tilde{W})$.

- **C$_1$ decay**: $W(qq)$ or $W(L\nu)$
- **C$_2$ decay**: Various higgs decay branches possible e.g.:
  - $h(bb)$
  - either $h(WW), h(ZZ), h(\tau\tau) \rightarrow 1L+X$
  - $h(\gamma\gamma)$

**Representative signatures**
- All-hadronic (0L) + 2b
- Exact 1L + 2b
- Exact 1L + 2$\gamma$
- Same-sign 2L or 3L

**Complementary sensitivities**

**Key search feature**: $h(125)$ mass
**Lepton-triggered → well-isolated lepton**

**Transverse mass \( m_T > 150 \text{ GeV} \)**

**Require large contransverse mass \( m_{CT} > 170 \text{ GeV} \) for \( t\bar{t} \) rejection.**

**h(bb) resonance at \( 90 \text{ GeV} < m(bb) < 150 \text{ GeV} \).**

**2 SRs: (1) \( 125 \text{ GeV} < \text{MET} < 200 \text{ GeV} \) and (2) \( \text{MET} > 200 \text{ GeV} \)**

**No significant excess observed.**

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### Low-MET SR

![Low-MET SR Data](image1.png)

### High-MET SR

![High-MET SR Data](image2.png)

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**Excluding \( C_1 \) 220–490 GeV for massless \( N_1 \)**

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**Equation:**

\[ m_{CT} = \sqrt{2p_T^{b_1}p_T^{b_2} (1 + \cos \Delta \phi_{bb})} \]
**MET trigger → offline MET > 200–250 GeV required.**

**h(bb) resonance at 105 GeV < m(bb) < 135 GeV.**

**Require large contransverse mass \( m_{CT} \) for \( t\bar{t} \) rejection.**

**No excess observed in the signal region.**

**Exclusion up to ~690 GeV wino.**
**h(γγ) narrow peak search.**

**SM Wh process as an irreducible peaking background.** Estimated from NLO cross section

**Non–peaking contributions are estimated from side–band in 105 GeV < m(γγ) < 160 GeV.**

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**Discovered p_0 values**

**0.03 (~1.9σ)**

**0.09 (~1.3σ)**
Opposite-sign di-leptons. Same-flavor ($ee, \mu\mu; Z$-veto) and different-flavour ($e\mu$) categories.

Major backgrounds: $VV$ and $tt$ (irreducible)

Di-lepton trigger, both leptons offline $p_T > 25$ GeV

Di-lepton invariant mass $> 25$ GeV, $m(Z) \pm 30$ GeV vetoed for SS.

Allow up to single central light jet (signal region is classified)

Signal region:
- $E_T^{miss} > 110$ GeV, $E_T^{miss}$ signif. $> 10$
- Transverse mass $m_{T2} > 100$ GeV
- SR is binned in $m_{T2}$

No significant deviation from the background est.
Opposite-sign di-leptons. Same-flavor (ee, µµ; Z-veto) and different-flavour (eµ) categories.

Major backgrounds: VV and tt (irreducible)

Di-lepton trigger, both leptons offline $p_T > 25$ GeV

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- $E_T^{miss} > 110$ GeV, $E_T^{miss}$ signif. $> 10$
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- SR is binned in $m_{T2}$
LLP Search Classes

Direct LLP Detection
- Stable heavy charged particle
- Monopole/HIP
- Disappearing track
- Displaced leptons
- Non-prompt photons/jets
- Stopped particles
- Displaced jets (Calo-ratio)

Stable heavy charged particle

Metastable Vertex + X

ID Displaced Vertex

Emerging jets

Displaced vertex in MS

Dilepton displaced vertex

Lepton-jets

Displaced jets (Calo-ratio)

Disappearing track

Non-prompt photons/jets

Stopped particles

Displaced leptons

Monopole/HIP

Direct LLP Detection

LLP Decay Detection
## LLP Search Classes

<table>
<thead>
<tr>
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<td>SUSY-2016-31</td>
<td>Stable and meta-stable massive charged particles</td>
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<td>SUSY-2016-32</td>
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<td>EXOT-2017-13</td>
<td>Multi-charged particle searches</td>
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<td>SUSY-2016-08</td>
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<td>CONF-2019-006</td>
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<td>EXOT-2017-05</td>
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<td>EXOT-2017-03</td>
<td>Non-collimated muons</td>
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<td>SUS-19-005</td>
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<td>PAS-EXO-16-022</td>
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<td>PAS-EXO-19-001</td>
<td>Delayed jets</td>
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<tr>
<td>EXO-16-004</td>
<td>Stopped particles</td>
<td>39</td>
</tr>
</tbody>
</table>
Direct detection of massive charged particles

Lifetime coverage $>\mathcal{O}(0.1 \text{ ns})$ up to stable. Observables depending on lifetime

Short (disappearing) track

- Pixel $dE/dx$
- Calo or MS timing

Calo or MS timing

- ID + Calo
- Full detector
- 1 track
- 2 track

Pixel $dE/dx$

- Stable
- Stable
- Stable

Main Target Interpretations

- $\tilde{\chi}^\pm_1$
- $\tilde{g}$
- $\tilde{t}$
- $\tilde{b}$ (R-hadron)

Scenarios

- $p + \tilde{g}^{L}(LLP)$
- $p + \tilde{\chi}^0_1(LLP)$
- $p + \tilde{\chi}^+_1(LLP)$
- $p + \tilde{\tau}^+_1(LLP)$
- $p + \tilde{\tau}^-_1(LLP)$

LLP Observable

- Short Track
- $dE/dx$
- $dE/dx$ & ToF
- ToF

Target Lifetime

- $< 3 \text{ ns}$
- $< 50 \text{ ns}$
- Stable

Detector

- Inner Detector
- Inner Detector
- Inner & Muon Trackers
- ID + Calo
- Full Detector
- 1 track
- 2 track

Scenarios

- $p + \tilde{g}^{L}(LLP)$
- $p + \tilde{\chi}^0_1(LLP)$
- $p + \tilde{\chi}^+_1(LLP)$
- $p + \tilde{\tau}^+_1(LLP)$
- $p + \tilde{\tau}^-_1(LLP)$

Main Target Interpretations

- $\tilde{g}$
- $\tilde{t}$
- $\tilde{b}$ (R-hadron)
- $\tilde{\chi}^\pm_1$
- $\tilde{\tau}^\pm_1$
Direct detection of massive charged particles

**ATLAS-SUSY-2016-032, submitted to PRD, 36fb$^{-1}$**

- Recent update for stable charged particle search using ToF (and dE/dx) for 2015+2016 dataset.
- Various strong limits interpretations for R–hadron, charginos or sleptons depending on signal topologies.

Stable R–hadron lifetime excluded up to ~2 TeV. Overall quite complementary searches.
An inclusive search for displaced jets with displaced vertex.

- CMS approach: define displacement likelihood

Displaced vertices with jets

CMS-EXO-18-007, 36fb⁻¹
Displaced vertices with jets

- Dedicated displaced jet HLT:
  - $H_T > 350$ GeV, $\geq 2$ displaced jets w/ $p_T > 40$ GeV and $|\eta| < 2.0$
  - (*) displaced jets: associating $\leq 2$ prompt tracks, $\geq 1$ displaced tracks
- Offline $H_T > 400$ GeV
- Jet-seeded displaced vertex reconstruction
  - Seed tracks: associated to a di-jet pair, IP signif. $> 5$ or $|d_0| > 0.5$ mm
  - Vertex mass $> 4$ GeV and $p_T > 8$ GeV
  - Track’s second largest IP signif. $> 15$
  - Charged energy fraction of the di-jet associated with the most compatible primary vertices (sort of displaced version of “jet-vertex fraction”).
- Displaced jet likelihood score $> 0.9993$

<table>
<thead>
<tr>
<th>Selection on $H_T$</th>
<th>Number of dijets</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$400 &lt; H_T &lt; 450$ GeV</td>
<td>1</td>
<td>$0.42 \pm 0.14$ (stat) $\pm 0.01$ (syst)</td>
<td>0</td>
</tr>
<tr>
<td>$450 &lt; H_T &lt; 550$ GeV</td>
<td>1</td>
<td>$0.23 \pm 0.08$ (stat) $\pm 0.07$ (syst)</td>
<td>0</td>
</tr>
<tr>
<td>$H_T &gt; 550$ GeV</td>
<td>1</td>
<td>$0.19 \pm 0.07$ (stat) $\pm 0.05$ (syst)</td>
<td>1</td>
</tr>
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</tr>
<tr>
<td>$&gt;1$</td>
<td></td>
<td>$0.16 \pm 0.11$ (stat) $\pm 0.06$ (syst)</td>
<td>0</td>
</tr>
</tbody>
</table>

Observed events in the SRs are consistent with data–driven estimated QCD background yields.

Excluded $\sim 2.3$ TeV GMSB $\tilde{g}_{\text{LLP}} \to g\tilde{G}$

$\sim 2.4$ TeV RPV (UDD) $\tilde{g}_{\text{LLP}} \to tbs$
Displaced vertices with muons

Benchmark model:
A tiny RPV coupling would make stop alive for O(1ns)

$$\tau(\tilde{t}) \sim \left( \frac{500 \text{ GeV}}{m(\tilde{t})} \right) \left( \frac{10^{-7}}{\lambda'_{23k}} \right)^2 \left( \frac{0.12}{\cos^2 \theta_t} \right) \times 10^{-3} \text{ ns}$$

Signal DV: \( r > 4 \text{ mm}, \geq 3 \text{ tracks}, m_{\text{vis}} > 20 \text{ GeV} \) and isolated non-prompt muon (decent cosmic ray veto)

Resembling BGs: cosmic, b–jets, instrumental fakes
Displaced vertices with muons

For full Run-2 DV analyses: a significant improvement in the vertex reconstruction algorithm in enriching vertex properties of multiplicity and mass.

For DV+μ: around 20–30% of the signal efficiency recovery.
**Displaced vertices with muons**

- MET or displaced muon trigger; exclusive 2 SRs. Cosmic ray veto + hadronic interaction veto.
- Robust data-driven background estimation for 3 exclusive categories (transfer factor from CR to SR for each of cosmic, heavy-flavor, fake Bkg components)
- SR yields are consistent with background estimation.
- Excluding stop mass up to **1.75 TeV** around ~0.1 ns lifetime.

---

**ATLAS** Preliminary

\[ \sqrt{s} = 13 \text{ TeV}, \; 136 \text{ fb}^{-1} \]

- **Data**
- **Heavy Flavor**
- **Fakes**
- **Cosmics**

**E_T^m** Trigger Selection

- \((m, \tau) = (1.7 \text{ TeV}, 0.01 \text{ ns})\)
- \((m, \tau) = (1.7 \text{ TeV}, 0.1 \text{ ns})\)

**Full Muon Selection**

---

**ATLAS** Preliminary

\[ \sqrt{s} = 13 \text{ TeV}, \; 136 \text{ fb}^{-1} \]

- **Expected Excl. Limit** \((\pm 1, 2 \sigma_{\text{exp}})\)
- **Observed Limit** \((\pm 1 \sigma_{\text{SUSY}})\)

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Stop R-Hadron, \(p p \to \tilde{t} \tilde{t}, \tilde{t} \to \mu j\)
CMS and ATLAS have been performing wide-range SUSY searches.

Today I focused on most-recent results.

Quite strong limits have been set so far, including R-parity-violating or long-lived scenarios (incl. other BSM scenarios).

Unfortunately, no SUSY/BSM discovery so far…

Early preliminary full Run–2 dataset results were presented, with new ideas or techniques.

More of full dataset analyses expected to come…

Stay Tuned!
Backup
SUSY searches in LHC

★ Usual to assume $R$-parity is conserved: a *pair-production* of sparticles results in final states with 2x LSPs, yielding a **significant** $E_T^{\text{miss}}$.

★ Can suppose versatile sparticle mass spectra: branch search analyses depending on the characteristic of the visible (SM) final-state objects.

★ On top of general/comprehensive searches, dedicated searches for specifically interesting phenomenological scenarios.
Most classically, select/optimize the signal regions where the SM backgrounds deplete while a good SUSY acceptance is ensured.

Estimate the background yields using various control regions.

Validate the BG estimation of each enriched sub-component in the vicinity of signal regions (VRs).

Unblinding SRs after validating the BG estimation.

Exclusion limits are drawn if no significant excess is observed.
The \( R \)-parity violation

\( R \)-parity-violating (RPV) superpotential

- No fundamental reasons to prohibit RPV from QFT — if \( R \)-parity conserves, it’s \textit{accidental}.
- Large constraints from low-energy limits e.g. proton decay at Super KamiokaNDE.

\[
W_{\text{RPV}} = \mu_i l_i h_u + \lambda_{ijk} l_i l_j \bar{e}_k + \lambda'_{ijk} l_i q_j \bar{d}_k + \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k
\]

- Different topologies compared to \( R \)-parity-conserving (e.g. not always \( E_T^{\text{miss}} \)).
- In LHC searches, usually assume only a specific RPV term and search for it.
- Some signatures are similar to lepto-quark pair production or RPC-SUSY scenarios.
Many BSM scenarios have a possibility of creating a BSM particle with a macroscopic or stable lifetime (i.e. very narrow decay width) in the LHC.

Given that comprehensive searches are demanded, the importance of long-lived particle searches have been highlighted in recent years.

Pros:
- A unique probe to super-compressed or small coupling BSM scenarios.
- In many cases, zero or small SM backgrounds can be achieved; can expect extension of search sensitivity as luminosity gains.

Cons:
- The LHC experiment program isn’t primarily designed/optimized to perform long-lived scenarios. Sensitivity is largely determined by the geometry.
- Often dedicated techniques are needed, and cares are needed in understanding of reconstruction and specialized data flow.
- Backgrounds are often instrumental, cosmic ray: hard to predict using common MC simulations. Need to know your instruments, and in many cases data-driven background estimation is required.
# ATLAS Long-lived Particle Searches* - 95% CL Exclusion

## Lifetime Summary

**Status:** March 2019

### ATLAS Preliminary

$\sqrt{s} = 8, 13$ TeV

$\mathcal{L} = (3.4 - 36.1)$ fb$^{-1}$

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>$\mathcal{L} \cdot dt$ [fb$^{-1}$]</th>
<th>Lifetime Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV $\chi^0_1 \rightarrow \ell^+ \ell^- \ell^0$</td>
<td>displaced lepton pair</td>
<td>20.3</td>
<td>$\chi^0_1$ lifetime</td>
</tr>
<tr>
<td>GGM $\chi^0_1 \rightarrow Z \chi^0_1$</td>
<td>displaced v+jets</td>
<td>20.3</td>
<td>$\chi^0_1$ lifetime</td>
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<tr>
<td>GGM $\chi^0_1 \rightarrow Z \chi^0_1$</td>
<td>displaced dimuon</td>
<td>32.9</td>
<td>$\chi^0_1$ lifetime</td>
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<tr>
<td>CMSB non-pointing or delayed $\gamma$</td>
<td>non-pointing or delayed $\gamma$</td>
<td>20.3</td>
<td>$\chi^0_1$ lifetime</td>
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<tr>
<td>AMSB $pp \rightarrow \chi^0_1 \gamma, \chi^0_1 \tau^+ \tau^-$</td>
<td>disappearing track</td>
<td>20.3</td>
<td>$\chi^0_1$ lifetime</td>
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<td>AMSB $pp \rightarrow \chi^0_1 \gamma, \chi^0_1 \tau^+ \tau^-$</td>
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<td>AMSB $pp \rightarrow \chi^0_1 \gamma, \chi^0_1 \tau^+ \tau^-$</td>
<td>large pixel dE/dx</td>
<td>18.4</td>
<td>$\chi^0_1$ lifetime</td>
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<td>Stealth SUSY</td>
<td>2 ID/MS vertices</td>
<td>19.5</td>
<td>$\chi^0_1$ lifetime</td>
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<tr>
<td>Split SUSY</td>
<td>large pixel dE/dx</td>
<td>36.1</td>
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<td>displaced v+jets $\rightarrow E_T^{miss}$</td>
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<tr>
<td>Split SUSY</td>
<td>0 $\ell$, 2-6 jets $\rightarrow E_T^{miss}$</td>
<td>36.1</td>
<td>$\chi^0_1$ lifetime</td>
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### Reference

- ATLAS-CONF-2018-003
- ATLAS-CONF-2016-042
- ATLAS-CONF-2016-042
- ATLAS-CONF-2016-042

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<td>$\sigma_{BR} = 1 \text{ pt, } m(\chi^0_1) = 50$ GeV</td>
</tr>
</tbody>
</table>

*Only a selection of the available lifetime limits is shown.*
LLP searches complete what we can do with the collider experiments.
Disappearing track: a highly-compressed spectrum

A specific SUSY scenario (pure wino) like AMSB.

$C_1-N_1$ masses splitting arises only by dynamical loop running correction ($\sim 150$ MeV)

Long-lived $C_1$ production via strong interaction.

Long-lived $C_1$ decays to almost degenerated $N_1$, emitting a soft pion which is hard to be visible in the reconstruction.

Signature in $\Sigma$:
(isolated high-$p_T$ track with no presence of hits in the outermost 2 layers.

(Short track) — further classified by track length.

$\Delta m \sim \mathcal{O}(100 \text{ MeV})$
CMS-SUS-19-005-PAS, 137 fb⁻¹

- **Trigger**: mixture of $H_T$, MET, $H_T^{\text{miss}}$ and jet $p_T$.
- **Backgrounds**: fake (combinatorial), charged hadrons, leptons.
- **Transfer factor**: for each component estimated mostly pure data-driven, for longer track case, assisted by MC simulation.
- **Signal region**: defined separately for 2016 and 2017+2018 (pixel detector upgrade in between)

![Comparison of estimated (pre-fit) background and observed data events in (upper) each of the 2016 search regions, and in (lower) each of the 2017–2018 search regions, in the search for disappearing tracks. The red histogram represents the predicted background, while the black points are the actual observed data counts. The cyan band represents the statistical uncertainty on the prediction. The gray band represents the total uncertainty. The labels on the x-axes are explained in Tables 7–8 of Appendix B.2. Regions whose predictions use the same measurement of $f_{\text{short}}$ are identified by the colors of the labels. Bins with no entry in the ratio have zero (pre-fit) predicted background.](image)

No significant excess observed in multiple SRs
Disappearing track: a highly-compressed spectrum

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Excluding gluino mass up to 2.46 TeV at the most sensitive lifetime (50 cm)
Assume a BSM particle yields a displaced jet before reaching the calorimeter.

A heavy BSM long-lived particle flies with significantly small $\beta$.

The total flight path length can be longer than prompt jets due to presence of kinks.

A displaced jet may arrive later than prompt jets.

e.g. a $\beta=0.5$ gluino decaying at the outer surface of the CMS tracker at $|\eta|=0$: $\Delta t \sim 4$ ns.

CMS ECAL timing resolution: down to $\sim 0.2$ ns.

Ecal timing: median of the each cell timing comprising the jet, after cleaning $|t| > 20$ ns clusters.

Various backgrounds

- Timing resolution tail
- Electronic noises
- Direct APD hits (skipping scintillation $\sim 11$ ns)
- In/Out–time pileup
- Satellite bunches (at $\pm 5$ ns)
- Beam halo, or “non–collision backgrounds”
- Cosmic muon hits
Background estimation for 3 different categories (cosmic, core/satellite collision, non-collision backgrounds)

No events observed in the delayed signal region.

Limit to gluino mass up to ~2.5 TeV.
(most sensitive for around 1000 mm/c lifetime)