Searches for Long-Lived SUSY Decays at CMS

Dylan Gilbert for the CMS Collaboration
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CMS Run II Dataset

- CMS integrated luminosity at 13 TeV exceeds 137/fb!
- With this 137/fb dataset, searches with ~0 background could be sensitive to impressively high mass superpartners.

<table>
<thead>
<tr>
<th>Physics Process</th>
<th>Mass for ~1 Event</th>
<th>Mass for ~10 Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluino pair production</td>
<td>~3.0 TeV</td>
<td>~2.5 TeV</td>
</tr>
<tr>
<td>Squark pair production</td>
<td>~2.1 TeV</td>
<td>~1.7 TeV</td>
</tr>
</tbody>
</table>

- Long-lived particle searches can achieve ~0 background at CMS.
- CMS has already released preliminary results from two 137/fb searches sensitive to long-lived SUSY particles.
CMS LLP Searches

- **Emerging** *(CMS PAS EXO-19-001)*
  - Search for delayed gluon jets *emerging* from decays of long-lived *gluinos*.

- **Disappearing** *(CMS PAS SUS-19-005)*
  - Search for long-lived *chargino* tracks *disappearing* after decay to a soft Standard Model particle and invisible neutralino LSP.
  - Charginos produced in gluino or squark decays.
  - Search includes an inclusive analysis (no LLP selection), allowing a direct comparison of sensitivity.
Search for long-lived particles using delayed jets and missing transverse momentum with proton-proton collisions at $\sqrt{s} = 13$ TeV
Gluons originating from a long-lived gluino decay are delayed relative to prompt jets. Why?

- Gluino is heavy $\Rightarrow$ it moves “slowly”.
- Path to ECAL is longer.

\[ L < \ell_1 + \ell_2 \]
Timing Delay as Observable of Choice

- Shouldn’t delayed jets produce displaced vertices and large impact parameters? What are the advantages of using timing delay instead?
  - Tracker-based observables aren’t very useful for decays near or even inside the ECAL.
  - Use of timing delay extends sensitivity to longer lifetimes (~0.5-1.5 meters).
- CMS ECAL timing performance is outstanding. (See backup)
- Timing delay backgrounds (see backup) are almost wholly reducible.
CMS LLP analyses can achieve nearly 0 background!

See backup for details.

But, only meaningful if signal efficiency is strong.

### Background Summary

<table>
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<th>Source</th>
<th>Estimate</th>
</tr>
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<tr>
<td>Beam halo muons</td>
<td>~0</td>
</tr>
<tr>
<td>Cosmic ray muons</td>
<td>~1</td>
</tr>
<tr>
<td>Satellite bunches</td>
<td>~0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1 ±2.5</strong></td>
</tr>
</tbody>
</table>

Table 2: Background prediction summary.
Results & Interpretation

- Observe 0 events in data signal region!

- Extract 95% CL limits based on background estimate of ~1 event.

As promised, use of timing as observable achieves complementary sensitivity to longer lifetimes with respect to tracker-based displaced jet search.
CMS Disappearing LLP Search

Searches for new phenomena in events with jets and high values of the $M_{T2}$ variable, including signatures with disappearing tracks, in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS PAS SUS-19-005
Disappearing Tracks

- Charged particle decaying to one neutral and one very low momentum charged daughter inside tracker “disappears”.
- Transverse decay length sensitivity is in the 10-100 cm range, due to CMS tracker geometry.
- In an inclusive analysis, such tracks are MET.

CMS pixel tracker was upgraded after 2016, for the 2017 & 2018 runs.
- 3 layers → 4, and generally improved efficiency.
- Requires separate background estimate for each period.
Background Sources

❖ Fake tracks, composed of hits that cannot be associated to any single real particle.
  ❖ Tend to be low $p_T$, while signal tends to be high $p_T$.
  ❖ Dominant background for shorter track lengths.
❖ Lost pions, especially 1-prong $\tau$ daughters.
  ❖ Isolated.
  ❖ Neutrino helps event pass MET/$M_{T2}$ selection.
❖ Dominant background for longer track lengths.
❖ Lost leptons.
  ❖ Lost electrons are a major background source before vetoing bad calorimeter regions using tag and probe.

Typical Backgrounds:

Shorter Tracks
$Z \rightarrow \nu\nu$, + fake

Longer Tracks
$W \rightarrow \tau\nu$, isolated $\pi^\pm$
from $\tau$ lost in tracker

Data-driven background estimate

Validated bin-by-bin in data
Results

❖ See backup for description of selections and binning.

❖ Observe no significant excess above estimated background.

❖ Note that bins on the far right of each plot (longer tracks) have ~0 estimated background and 0 observed events.

❖ Another CMS LLP analysis achieves ~0 background, as promised! Signal is efficient.

❖ Models populating the long track bins are strongly constrained.

❖ Constraints from shorter track length bins are also significant.
Interpretation

- Preliminary results used to constrain pair-produced gluino decays to light jets.
- Other interpretations in progress for final result.
- "Democratic" decay, per gluino: 1/3 to neutralino, 1/3 to negative chargino, 1/3 to positive.
- So, 2/3 probability per gluino decay to produce a disappearing track.
- Gluino masses as large as nearly **2.5 TeV** are excluded at 95% CL, and (nearly degenerate) chargino and neutralino masses as large as **2.0 TeV**.

\[ \text{ct} = 10 \text{ cm} \quad \text{ct} = 50 \text{ cm} \quad \text{ct} = 200 \text{ cm} \]

Large mass splitting → large boosts → decays outside tracker → decreased sensitivity
Direct Look at CMS LLP Sensitivity

- A related analysis that does not use LLP methods produces leading generic constraints, allowing a direct comparison of sensitivity with and without use of LLPs.

No LLPs

LLP in $2/3$ decays, $c\tau = 50$ cm

- Constraint along $m_{\text{LSP}}$ axis improved by $\sim 800$ GeV.
- Constraint along $m_{\text{Gluino}}$ axis improved by more than $\sim 400$ GeV.
Summary

 Searches leveraging LLP signatures at CMS require creative techniques, but can achieve very small backgrounds while maintaining strong signal efficiency.

 Presented two searches in particular.

  “Emerging” gluinos ⇒ delayed jets.
  “Disappearing” charginos ⇒ short tracks.

 Mass reach improved by 100s of GeV or more.

 Many bins are ~empty. Sensitivity will significantly benefit from larger datasets in years to come.
Backup
CMS Detector, Briefly

- Tracker records hits from charged particles.
- Calorimeters, first electromagnetic (ECAL) then hadronic (HCAL), measure particle energies via showers.
- Muons penetrate to outermost system, the muon chamber.
- Neutrinos are invisible, as are potential weakly interacting superpartners.
Long Lived Particles (LLPs)

- Naively, particle lifetime decreases with increasing mass due to larger phase space, so one might expect any new physics at high energy scales will be very short lived.
  - Ex: top quark.

- But, decay rates can be suppressed by (incomplete list):
  - Tiny couplings.
    - Ex: $h \rightarrow ee$ is negligible despite large phase space.
  - Very heavy mediators / large difference in scales.
    - Ex: weak interaction.
  - Approximate symmetries causing small mass splittings relative to energy scale.
    - Ex: $m_{\text{proton}} \sim m_{\text{neutron}}$
LLPs from SUSY Models

- Gauge Mediated SUSY Breaking (GMSB):

\[ c\tilde{\tau} \sim 30\text{cm} \left( \frac{1 \text{ TeV}}{\tilde{m}} \right)^5 \left( \frac{\sqrt{F}}{10^4 \text{ TeV}} \right)^4 \]

Large energy scale of SUSY breaking extends lifetime

From arxiv: 1503.05923 (Eq 1)

Fig. 1a from CMS PAS EXO-19-001
LLPs from SUSY Models

- Anomaly Mediated SUSY Breaking (AMSB):
  - Chargino-neutralino mass splitting is suppressed by largeness of SUSY scale relative to SM scale.
    \[
    \frac{\Delta m}{m} \sim \left(\frac{m_W}{\mu}\right)^4
    \]
    From arxiv: 9810155 (Eq 63)
  - Extends chargino lifetime:
    \[
    c\tau_{\chi_1^\pm} \sim 1m \left(\frac{200 \text{ MeV}}{m_{\chi_1^\pm} - m_{\chi_1^0}}\right)^5
    \]
    (Eq 64)
  - Gluinos can decay to intermediate long-lived chargino.

Fig. 8 from CMS PAS SUS-19-005

Invisible neutralino LSP
Small mass splitting, so pion is too soft to produce a track
Chargino track disappears!
Emerging Jet Search
Analysis Strategy

- Jets + MET. For signal region, MET > 300 GeV.
- Define “jet delay” \( t_{\text{Jet}} = 0 \) for \( t = L/c \). For signal region: \( t_{\text{Jet}} > 3\text{ns} \).
- Apply series of cleaning selections targeting background sources of delayed jets.
- Estimate residual background from data.
  - Sources of delayed jet backgrounds are not modelled in CMS simulations.
- Interpret in GMSB, gluino \( \rightarrow \) gluon + gravitino

![Diagram of potential delayed jets and MET + ISR/FSR jets]
Source of Delay

- For very heavy gluinos near the limit of cross section sensitivity, the “gluino slowness” delay tends to be larger, but both effects are significant.

- Notice that most delays are only on the order of ns! Can we be sensitive?
Recall that a typical signal jet is delayed by only $\sim$\,ns. Is the CMS ECAL so precise?

Yes! ECAL timing resolution is $\sim$\,0.2 \,ns in the barrel ($|\eta| < 1.48$)

ECAL deposit $> \sim$\,20 \,GeV, easily satisfied by signal.

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Noise contribution significant below $\sim$\,20 \,GeV.

Figure 4 from: \textit{Daniele del Re 2015 J. Phys.: Conf. Ser.}\,587\,012003
Background Sources

- ECAL timing failures.
  - Resolution tails.
  - Noise.
- Direct ECAL avalanche photodiode (APD) hit, skipping scintillation stage.
- External muons
  - Cosmic rays
  - “Beam halo” muons, produced by collisions with hardware upstream of detector. Travel parallel to beam.
- Satellite bunches
  - LHC has a “bucket” for proton bunches every 2.5 ns, but fills only 1 bucket in 10 for 25 ns bunch spacing. Some protons can leak into adjacent buckets.
- Note: in-time pileup can cause delay, but not enough: $t_{\text{Jet}} < \sim 1$ ns.
Cleaning

- **Many ECAL cells:** $N_{\text{Cell}} > 25$ rejects jets from noise and direct APD hits.

- **Large HCAL deposit:** HCAL energy fraction (HEF) > 0.2, $E_{\text{HCAL}} > 50$ GeV rejects noise and muon halo deposits.

- **Muon system veto:** Halo and cosmic ray muons typically leave hits in the muon system indicating their origin.

- **Small timing RMS:** $t_{\text{RMS}} / t_{\text{Jet}} < 40\%$ and $t_{\text{RMS}} < 2.5$ ns (RMS across all ECAL cells associated to a single jet) rejects jets affected by ECAL resolution issues.

- **Tracker veto:** targets satellite bunch jets.
  - Most jets have good high momentum tracks pointing back to the vertex.
  - Gluino jets “emerge” and so do not have this signature.
  - Reject jets with reconstructed track momentum exceeding $1/12$ of jet’s momentum.

- Residual backgrounds after cleaning from beam halo, cosmic muons, and satellite bunches each have separate data-driven estimate.
Background Estimate: Beam Halo

- Signal region jets must have \( \text{HEF} > 0.2 \) and \( E_{\text{HCAL}} > 50 \text{ GeV} \) and \( E_\mu / E_{\text{ECAL}} < 0.8 \).
- **Invert** HEF > 0.2 requirement and remove \( E_{\text{HCAL}} > 50 \text{ GeV} \) selection.
- Measure \( E_\mu / E_{\text{ECAL}} < 0.8 \) pass/fail ratio \( P_\mu = N(E_\mu / E_{\text{ECAL}} < 0.8) / N(> 0.8) \) in this region.
- Confirm that \( P_\mu \) is independent of HEF using a validation region populated by early jets, \( t_{\text{Jet}} < -3 \text{ ns} \).
- To protect against cosmic ray muon pollution, consider only horizontal jets.
- Estimated halo background is \( N_{\text{Halo}} = P_\mu \times N(t_{\text{Jet}} > 3 \text{ ns}; E_\mu / E_{\text{ECAL}} > 0.8) \).

### Diagram

- **HEF < 0.2**
  - \( P_\mu (< -3 \text{ ns}) \)
  - \( t_{\text{Jet}} < -3 \text{ ns} \)
- **HEF > 0.2**
  - \( P_\mu (< -3 \text{ ns}) \)
  - \( t_{\text{Jet}} > 3 \text{ ns} \)
  - **Signal Region**
  - \( E_\mu / E_{\text{ECAL}} > 0.8 \)
  - \( x N(E_\mu / E_{\text{ECAL}} > 0.8) \)
  - **Estimated Halo Background in Signal Region**
    - \( 0.02^{+0.06}_{-0.02} \text{ (stat)} +^{0.05}_{-0.01} \text{ (syst)} \)
Background Estimate: Cosmics

- Muons from beam collisions have roughly constant CMS coordinate $\phi$.
- Cosmics trajectories tend not to have constant $\phi$.
- Selection: $\Delta \phi < 0.5$ for connected muon chamber hits.
- Inverting selection to $\Delta \phi > 0.5$ produces a cosmics-enriched control region.
- Use $t_{RMS} < 2.5$ ns pass/fail ratio: $P_{RMS} = N(t_{RMS} < 2.5 \text{\,ns})/N(>2.5 \text{\,ns})$.
- Invert HCAL filters that suppress cosmic muons to produce a validation region, and establish independence of $t_{RMS}$ and muon system $\Delta \phi$.

$$N_{\text{Cosmics}} = P_{RMS} \times N(t_{RMS} > 2.5 \text{\,ns})$$

Genuine beam muon hits follow a line of roughly constant $\phi$

For signal region, require outermost muon system hits to have $\Delta \phi < 0.5$. 
Background Estimate: Cosmics

The discriminating variables used for the cosmic prediction are the $t_{\text{RMS}}$ jet of the jet and the $\max(D_{ij}^{\text{DT}})$ and $\max(D_{ij}^{\text{RPC}})$, labelled as $\max(D_{ij}^{\text{DT}}/\text{RPC})$. The pass/fail ratio of the $t_{\text{RMS}} < 2.5$ ns selection is measured for events with $\max(D_{ij}^{\text{DT}}/\text{RPC}) > \frac{p}{2}$ and applied to events with $\max(D_{ij}^{\text{DT}}/\text{RPC}) < \frac{p}{2}$. Cosmic muons passing through the HCAL will typically only deposit significant energy in a single isolated cell. The HCAL noise rejection quality filters are designed to veto events containing such isolated deposits and so inverting these filters, with all other selections applied, provides a validation region enriched in events with cosmic muons.

The correlation between $t_{\text{RMS}}$ jet and $\max(D_{ij}^{\text{DT}}/\text{RPC})$ in the validation sample is consistent with zero, meaning they can be used to form an unbiased prediction. The prediction in the validation region for the number of events passing signal thresholds on $t_{\text{RMS}}$ jet and $\max(D_{ij}^{\text{DT}}/\text{RPC})$ is $1.1^{+1.9}_{-1.1}$, in agreement with the 1 event observed. An additional systematic uncertainty is applied from the statistical power of the validation region. The final prediction in the signal region is $1.0^{+1.8}_{-1.0} (\text{stat})^{+1.8}_{-1.0} (\text{syst})$.

### Background summary

The predicted background yields are summarised in Table 2. The overall background prediction is $1^{+2.5}_{-1}$ events.

**Table 2: Background prediction summary.**

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<td><strong>Beam halo</strong></td>
<td>$0.02^{+0.06}_{-0.02}$</td>
<td>$0.11^{+0.09}_{-0.05}$</td>
<td>$1.0^{+1.8}_{-1.0}$</td>
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7 Results

Figure 2 shows the timing distribution for events with jets passing all signal region selections. The templates are for illustration purposes only and are not used for the statistical interpretation. The overall prediction for the signal region is $1^{+2.5}_{-1}$ events which is consistent with the observation of 0 events.

8 Interpretation

The model used for the interpretation is the GMSB SUSY model in which gluinos are pair produced and form R-hadrons. The long-lived gluinos then decay to a gluon and gravitino producing a delayed jet and missing energy. The experimental acceptance times efficiency ($A#_\mu$), shown in Figure 3, is evaluated independently for each model point, defined in terms of gluino mass ($m_{\tilde{g}}$) and lifetime ($c_t\tau_0$). The efficiency is maximised for high gluino masses and
Satellite Bunches

- The LHC has a “bucket” for protons every 2.5 ns, and nominally fills 1 bucket in 10 to maintain a 25 ns bunch spacing.

- Inevitably, some protons “leak” into unintended buckets.

![Figure 6 (upper)](image)

- Standard Model jets tend to contain charged tracks pointing back to primary vertex (PV). Signal jets do not.

- Satellite bunch jets are no exception ⇒ reject delayed jets from satellite bunches by requiring jets to have little energy from tracks extrapolating to PV: $E_{PV}/E < 1/12$.

- Of course, some unusual background jets escape this veto.
Background Estimate: Satellite Bunches

- Use pass/fail ratio of $E_{PV}/E < 1/12$ selection: $P_{PV} = N(>1/12)/N(<1/12)$.

$$N_{Satellite} = P_{PV} \times N(E_{PV}/E < 1/12)$$

- Measure $P_{PV}$ in events with $1 < t_{Jet} < 3$ ns and apply to $t_{Jet} > 3$ ns signal region events.

- Multiple validation regions:
  - Measure $P_{PV}$ in $-3 < t_{Jet} < -1$ ns events and apply to $t_{Jet} < -3$ ns events.
    - Mild underprediction (slightly over 1σ), ~0 estimated and 1 observed.
  - Statistical fluke? Invert the MET > 300 GeV selection, and repeat.
    - ~2 estimated and 1 observed ⇒ validated at $t_{Jet} < 0$, within statistics.
  - Measure $P_{PV}$ in $1 < t_{Jet} < 2$ ns events and apply to $2 < t_{Jet} < 3$ ns events.
    - Predict ~0, observe 0.
  - Invert MET selection for $t_{Jet} > 2$ ns events and measure $P_{PV}' = N(>0.5)/N(<0.5)$ as function of $t_{Jet}$ to confirm that track reconstruction issues do not cause $P_{PV}$ to vary with $t_{Jet}$. 

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**Background Estimate: Satellite Bunches**

<table>
<thead>
<tr>
<th>Measure $P_{PV}$</th>
<th>Apply $P_{PV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{PV} = \frac{N(E_{PV \text{ Tracks}}/E &lt; 1/12)}{N(&gt; 1/12)}$</td>
<td>$P_{PV} \times N(&gt; 1/12)$</td>
</tr>
</tbody>
</table>

- $-3 < t_{Jet} < -1 \text{ ns, MET > 300 GeV}$  
  - $t_{Jet} < -3 \text{ ns, MET > 300 GeV}$
- $-3 < t_{Jet} < -1 \text{ ns, MET < 300 GeV}$  
  - $t_{Jet} < -3 \text{ ns, MET < 300 GeV}$
- $1 < t_{Jet} < 2 \text{ ns, MET > 300 GeV}$  
  - $2 < t_{Jet} < 3 \text{ ns, MET > 300 GeV}$
- $1 < t_{Jet} < 3 \text{ ns, MET > 300 GeV}$  
  - $1 < t_{Jet} < 3 \text{ ns, MET > 300 GeV}$

**Signal Region**

Also check timing invariance of $P_{PV}'$ in inverted MET validation region, $t_{Jet} > 2 \text{ ns}$.

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**Results**

Figure 2 shows the timing distribution for events with jets passing all signal region selections. The templates are for illustration purposes only and are not used for the statistical interpretation. The overall prediction for the signal region is $1^{+2.5}_{-1.0}$ events which is consistent with the observation of 0 events.

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**Interpretation**

The model used for the interpretation is the GMSB SUSY model in which gluinos are pair produced and form R-hadrons. The long-lived gluinos then decay to a gluon and gravitino producing a delayed jet and missing energy. The experimental acceptance times efficiency ($A_{#}$), shown in Figure 3, is evaluated independently for each model point, defined in terms of gluino mass ($m_{\tilde{g}}$) and lifetime ($\tau_0$). The efficiency is maximised for high gluino masses and
Targeting O(1m) decay lengths.

- Recall: expect ~1 event in CMS dataset for ~3.0 TeV gluino pair production.
- For signal models of interest, total selection efficiency is very roughly ~20-40%.
- Inefficiency largely from $t_{\text{jet}} > 3$ ns selection.
Disappearing Track Search
\[ M_{T2} \]

- In events with 1 invisible particle, transverse momentum can be directly inferred from the visible content.
- In events with 2 invisible particles, only vector sum of the transverse momenta can be inferred.
- "M\[T2\]" generalizes transverse mass \( M_T \) to events containing 2 invisible particles.
  - 2 invisible neutralino LSPs in gluino or squark pair production.
- Strong rejection of multijet mismeasurement background.

Note: \( M_{T2} < 200 \text{ GeV} \) is signal-depleted
All Hadronic Search using $M_{T2}$

- Inclusive (no LLPs) jets + MET analysis leveraging $M_{T2}$ to suppress jet mismeasurement background.
- Edition based on 35.9/fb 2016 dataset (13 TeV) produced some of the most stringent constraints on squark and gluino pair production.
- Updated with full 137/fb 2016-2018 dataset.
  - Extends inclusive limits $\Rightarrow$ strongest available.
  - Added NEW complementary disappearing track regions targeting long-lived charginos in the gluino and squark decay chains.

Inclusive Gluino to Light Jet Limits

![Graph showing gluino to light jet limits](image)

Inclusive Squark to Light Jet Limits

![Graph showing squark to light jet limits](image)
Track Selections

- Disappearing: At least 2 missing outer hits and weak calorimeter deposits associated to track.
  - Veto suspect calorimeter regions using Drell-Yan lepton tag and probe.
- $p_T > 15$ GeV.
- High track quality (e.g., small impact parameter) for fake rejection.
- Lepton veto.
  - For longer tracks, require $M_T(\text{Track}, \text{MET}) > 100$ GeV or $p_T > 150$ GeV for enhanced lepton rejection.
- Isolated.

Ex: Relative Isolation

The full disappearing track selection further reduces background by a factor as large as $10^4$. 
Track Categorization

- Different track lengths have different background sources and are measured by different detector subsystems.
- Signals with different decay lengths populate different track length bins, and signal tracks tend to have higher \( p_T \) than background.

\[ \Rightarrow \text{categorize tracks based on length and } p_T \]

- Due to pixel tracker upgrade after 2016, separate 2016 from 2017 & 2018.
- Pixel-only (P) tracks have hits **only in the pixel tracker**.
  - In 2017-18, subcategorize into P3 and P4 tracks, which have hits in 3 layers and 4+ layers, respectively.
- Medium (M) tracks have hits outside the pixel tracker, but **fewer than 7 layers** with a measurement.
- Long (L) tracks have **7+ layers** with a measurement (but still disappear).
- For P and M tracks, split by \( p_T < 50 \text{ GeV} \) (“lo”) and \( p_T > 50 \text{ GeV} \) (“hi”).
  - L track background is so small that no further categorization is warranted.
- Treat each track category separately in all stages of the analysis.
Signal Region Binning

- Begin with inclusive analysis signal regions.
  - That is, Jets + MET with selections to reject jet mismeasurement.
- For each track category, bin in $N_{\text{Jet}}$ and $H_T$.
  - $N_{\text{Jet}} = 2-3$ ("L", squark-like) and $4+$ ("H", gluino-like).
  - Merge "L" and "M" $H_T$ into "LM" for Long tracks.
- Regions are given as:

  \[ \text{Track-length} \quad N_{\text{Jet}} H_T \quad p_T \]

- Ex: $\mathbf{P \; HH \; lo}$ is Pixel-only tracks, $N_{\text{Jet}} \geq 4$, $H_T > 1200$ GeV, track $p_T > 50$ GeV.
- Signal Region is $M_{T2} > 200$ GeV.
- Define a Validation Region mirroring SR bin-by-bin at $100 < M_{T2} < 200$ GeV.
Data-driven estimate.

Call a track passing all selections a “Short Track” (ST).

Call a track passing loosened isolation and quality cuts a “Short Track Candidate” (STC).

“Loose-not-tight”: cannot be both a STC and ST.

Define \( f_{\text{short}} = \frac{N_{\text{ST}}}{N_{\text{STC}}} \) and measure separately for every signal region.

Except inclusively in \( H_T \), exploiting empirical invariance to improve statistics.

Measure \( f_{\text{short}} \) in data control region at \( 60 < M_{T2} < 100 \text{ GeV} \).

Recall major advantage of \( M_{T2} \): low \( M_{T2} \) is signal-depleted.

For L tracks only, use data \( f_{\text{short}}(M) \) adjusted by simulation \( f_{\text{short}}(L)/f_{\text{short}}(M) \) due to poor statistics.

\( f_{\text{short}} \) systematic assessed by varying \( H_T \) and MET selections in measurement region.

For each bin:

\[
N_{\text{ST}}(\text{Est}) = N_{\text{STC}}(\text{Obs}) \times f_{\text{short}}
\]
Procedure Summary

\( \frac{N_{ST}}{N_{STC}} = f_{\text{short}} \)

Measurement Region
\((60 < M_{T2} < 100 \text{ GeV})\)

Validation Region
\((100 < M_{T2} < 200 \text{ GeV})\)

Signal Region
\((M_{T2} > 200 \text{ GeV})\)

Increasing \(M_{T2}\)

- Measure \(f_{\text{short}}\) at low \(M_{T2}\), \(60 < M_{T2} < 100 \text{ GeV}\) separately for each bin, except inclusively in \(H_T\).
- Validate background estimate bin-by-bin at intermediate \(M_{T2}\), \(100 < M_{T2} < 200 \text{ GeV}\).
- Estimate background using \(f_{\text{short}}\) and observed \(N_{STC}\) at \(M_{T2} > 200 \text{ GeV}\) and search for signal.
• Estimate performs well in validation region.
• Observed nonclosure used to assess additional systematic bin-by-bin.
  • Not less than the statistical uncertainty, to protect against “accidental” closure.
  • Highly conservative.
• Note that bins sharing the same $f_{\text{short}}$ (ie differing only in $H_T$), indicated by a shared label color, have highly correlated uncertainties.
Signal tracks pass the short track selection at roughly ~65% efficiency, per track.

Only 1 short track required to enter signal region.