Searches for Long-Lived SUSY Decays at CMS

Dylan Gilbert
for the CMS Collaboration
May 2019

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.

Physics Process	Mass for ~1 Event	Mass for ~10 Events
Gluino pair production	~3.0 TeV	~2.5 TeV
Squark pair production	~2.1 TeV	~1.7 TeV

- 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.

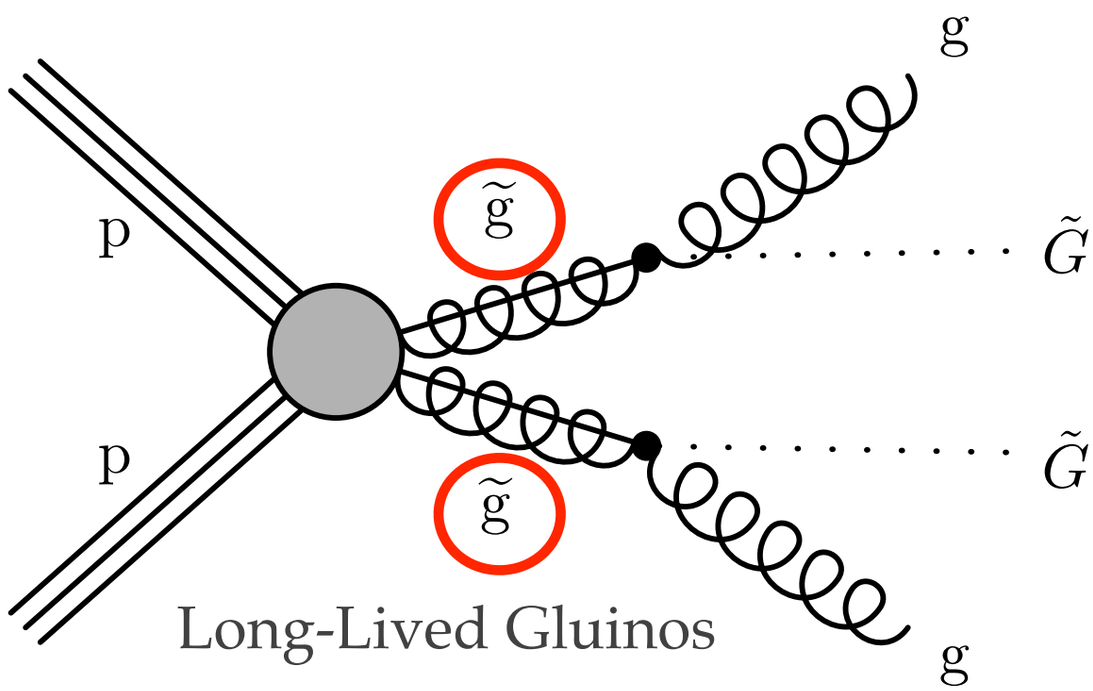
CMS LLP Searches

- **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.

CMS Emerging LLP Search

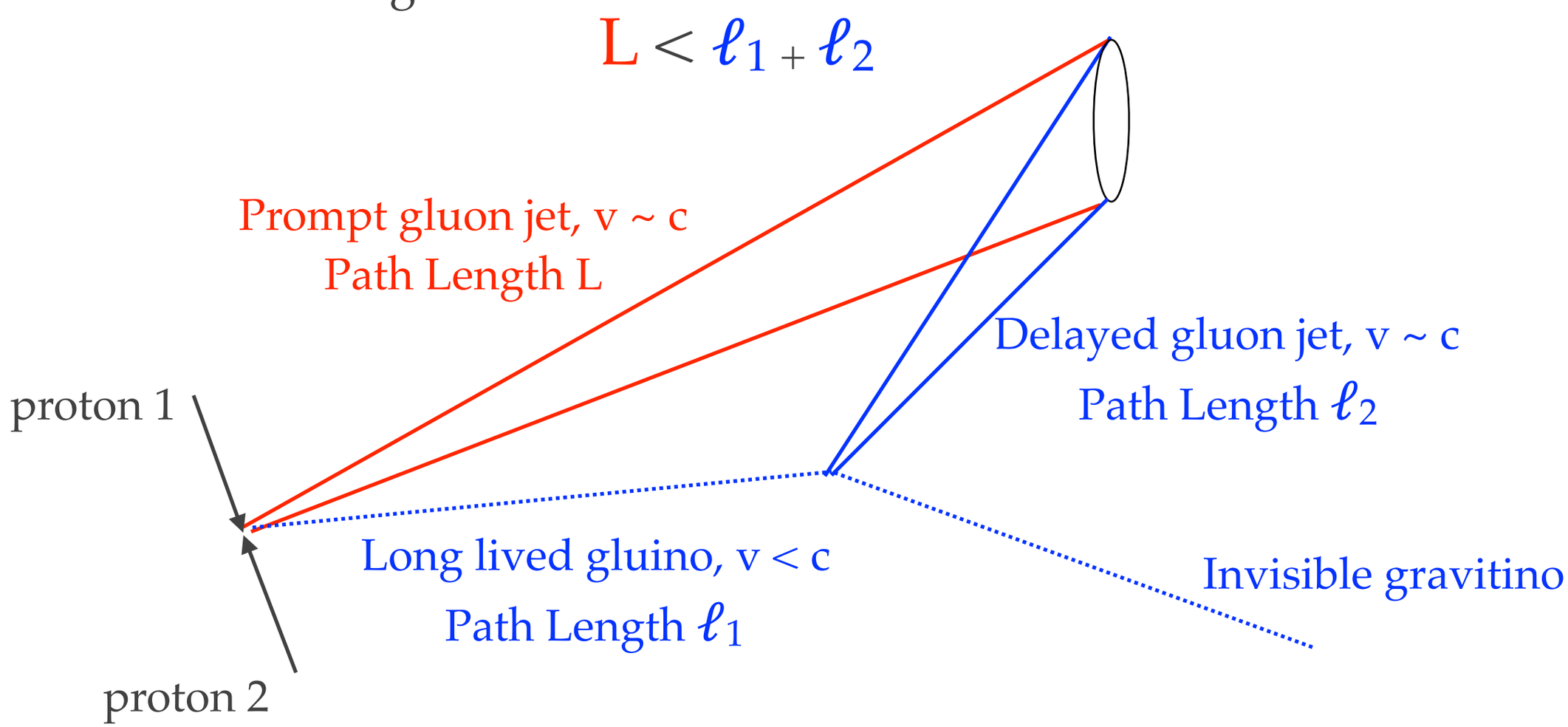
Search for long-lived particles using delayed jets and missing transverse momentum with proton-proton collisions at √s = 13 TeV



CMS PAS EXO-19-001

Delayed Gluon Jets

- Gluons originating from a long-lived gluino decay are <u>delayed</u> relative to prompt jets. Why?
  - Gluino is heavy $\Longrightarrow$ it moves "slowly".
  - Path to ECAL is longer.



Timing Delay as Observable of Choice

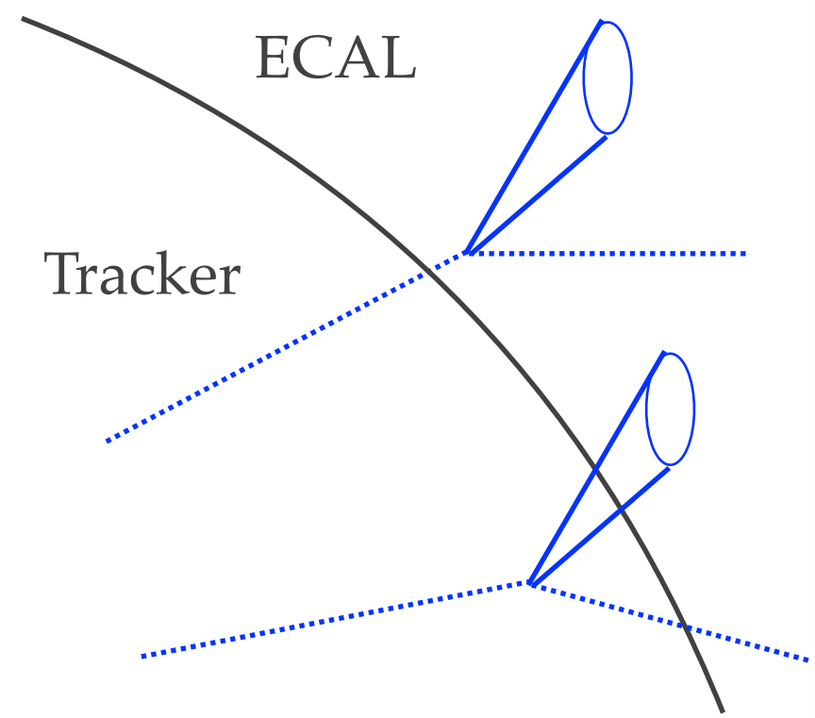
- Shouldn't delayed jets produce displaced vertices and large impact parameters? What are the advantages of using timing delay instead?
  - Tracker-based observables aren't very useful for decays **near or even inside the ECAL**.

  - 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.

Good sensitivity to decay scenarios with weak tracker input



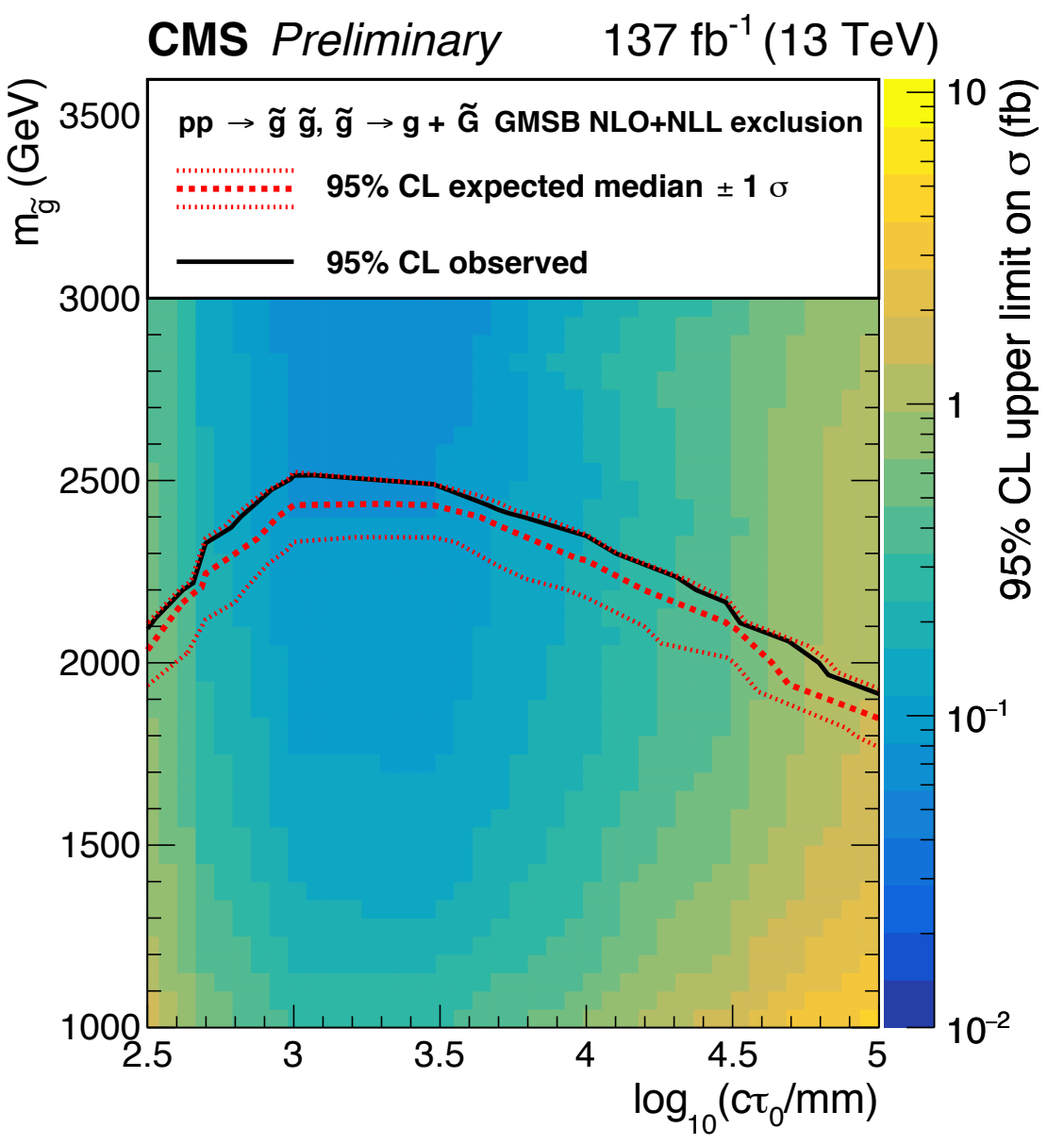
Background Summary

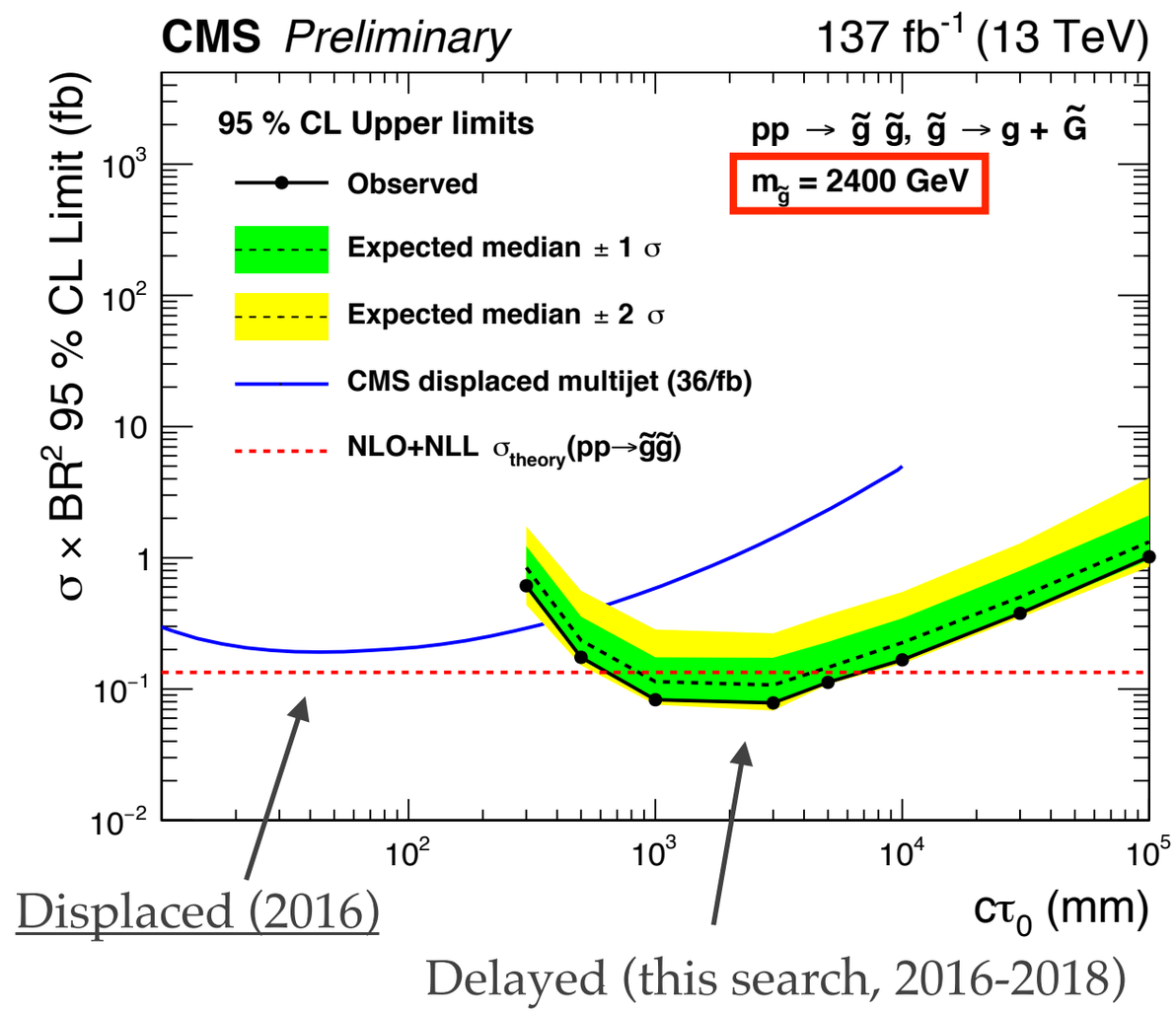
Source	Estimate
Beam halo muons	~0
Cosmic ray muons	~1
Satellite bunches	~0.1
Total	$1^{+2.5}_{-1}$

- CMS LLP analyses can achieve nearly 0 background!
  - See backup for details.
- But, only meaningful if signal efficiency is strong.

Results & Interpretation

- Observe 0 events in data signal region!
- Extract 95% CL limits based on background estimate of ~1 event.

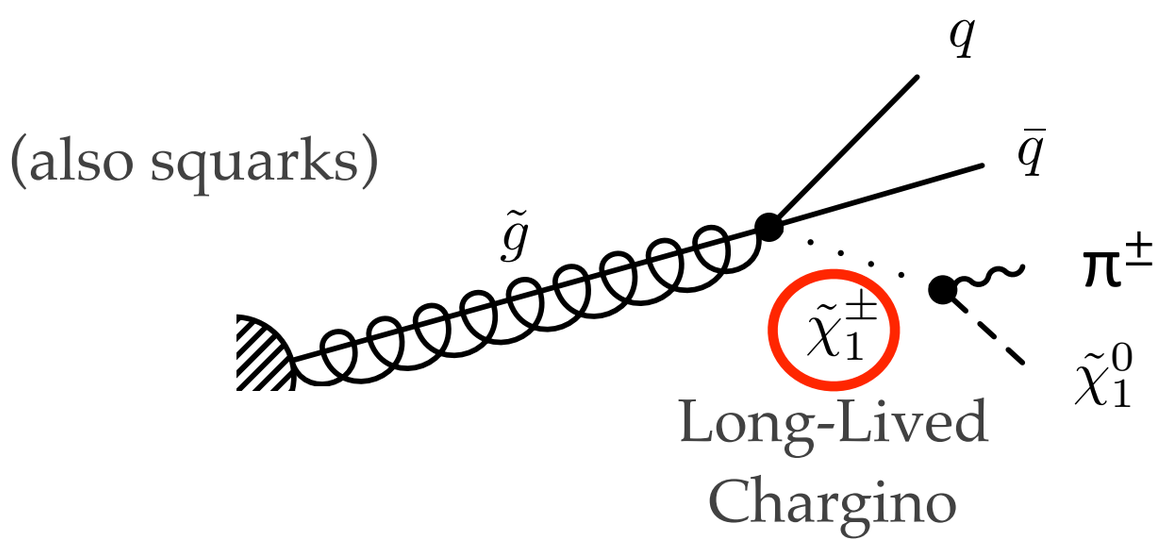




As promised, use of timing as observable achieves complementary sensitivity to longer lifetimes with respect to tracker-based displaced jet search.

CMS Disappearing LLP Search

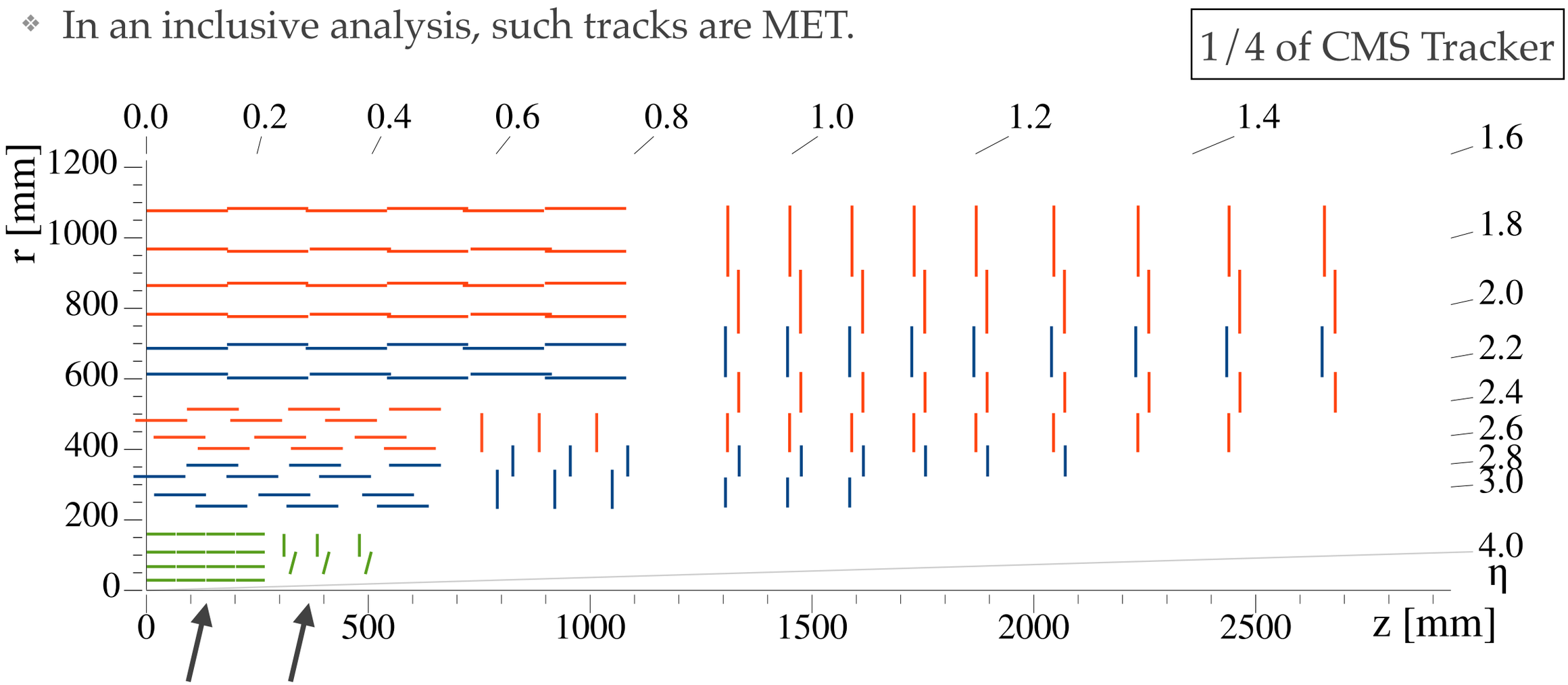
Searches for new phenomena in events with jets and high values of the M_{T2} variable, including signatures with disappearing tracks, in proton-proton collisions at $\sqrt{s} = 13$ TeV



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 τ 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.

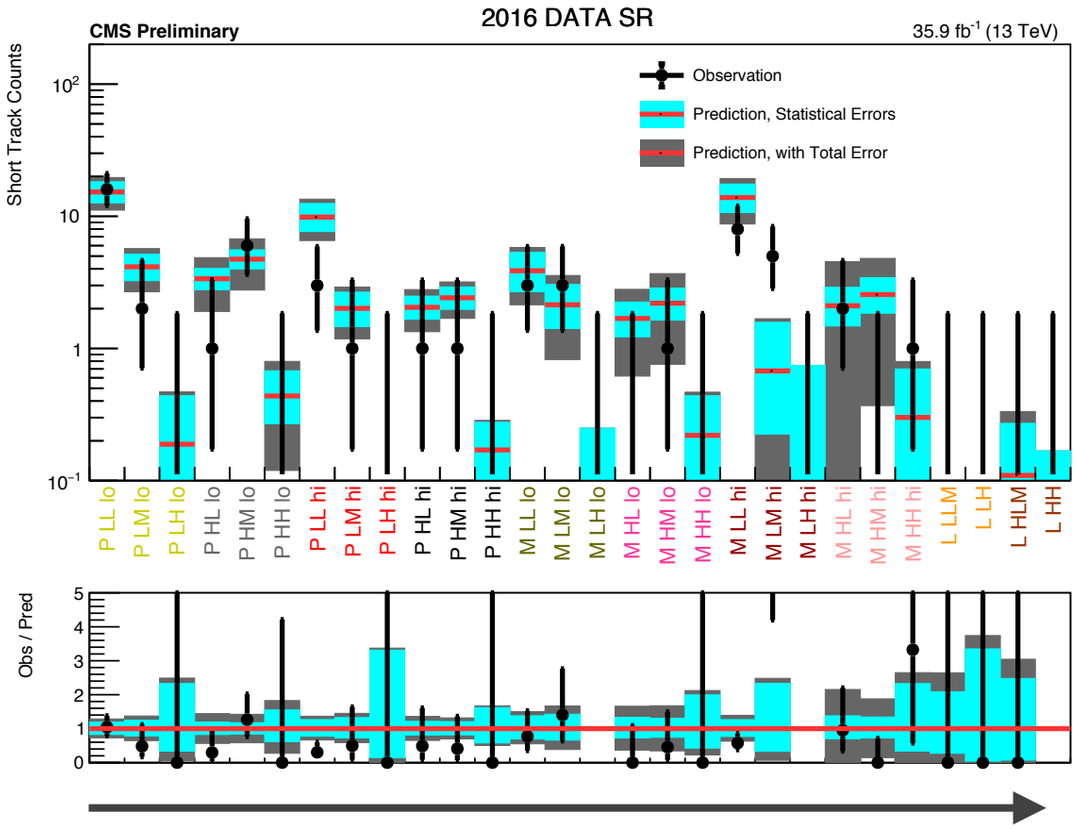
Typical Backgrounds:

Shorter Tracks ←	Longer Tracks →
$Z \to \nu\nu$, + fake	$W \to \tau\nu$, isolated $\pi^{\pm}$ from τ lost in tracker

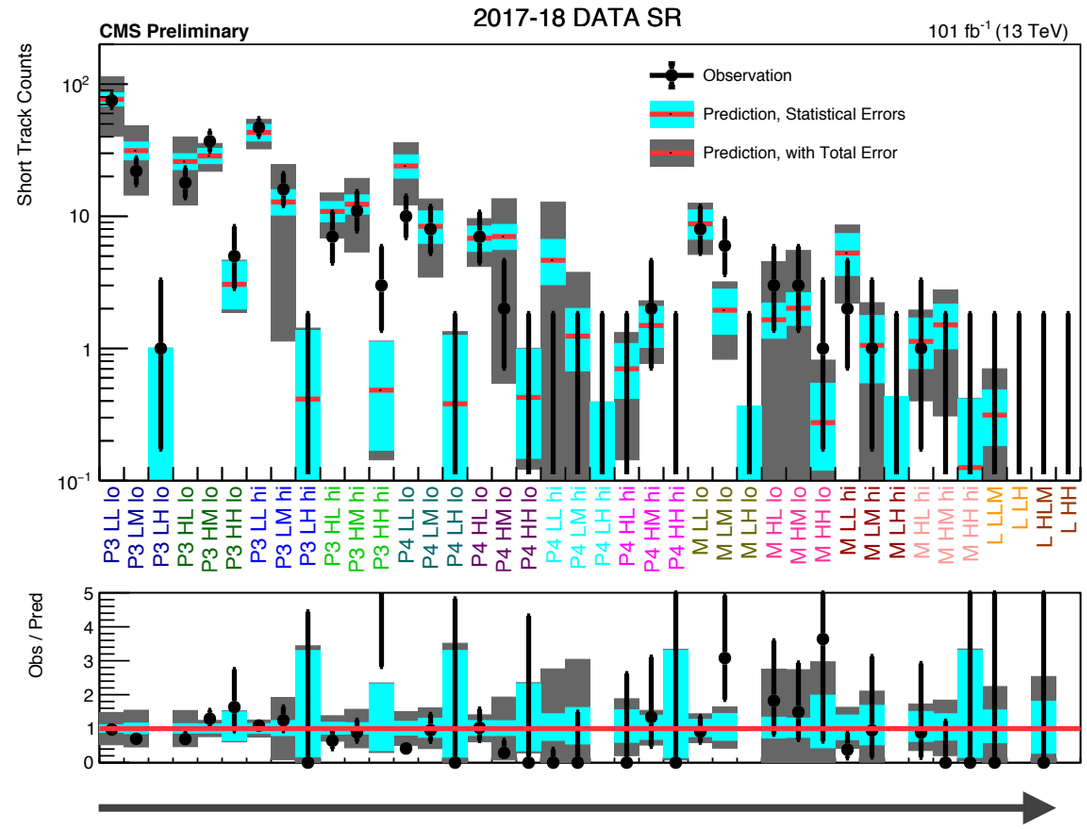
Data-driven background estimate

Validated bin-by-bin in data

Results



Increasing Track Length



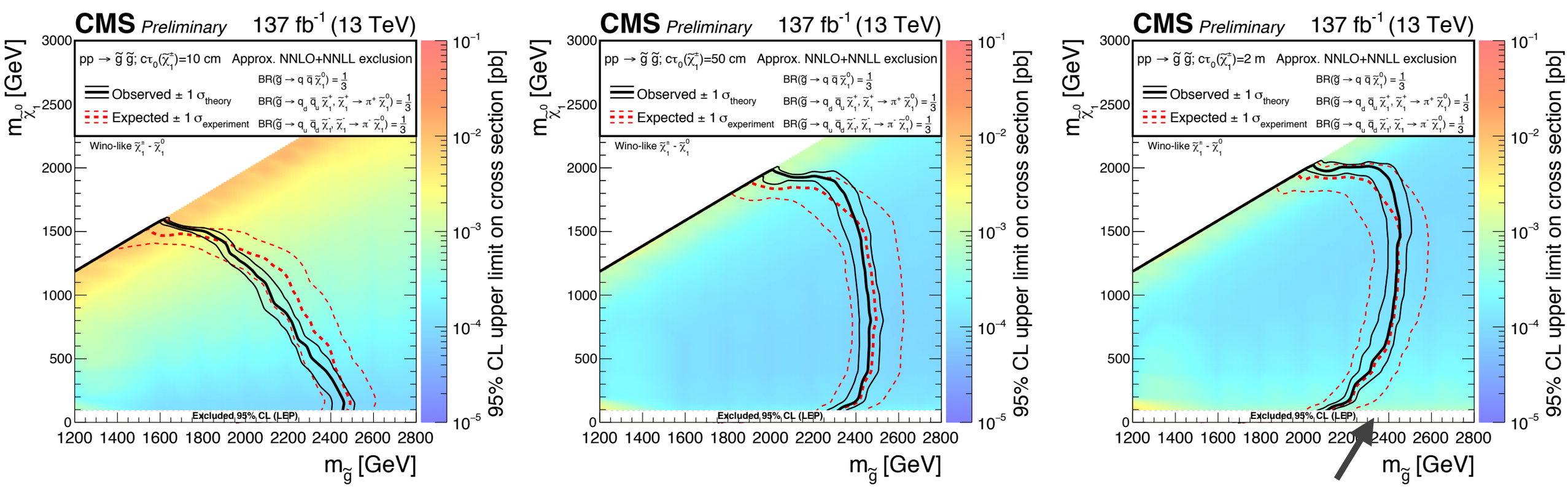
Increasing Track Length

- 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**.

$c\tau = 10$ cm $\qquad$ $c\tau = 50$ cm $\qquad$ $c\tau = 200$ cm

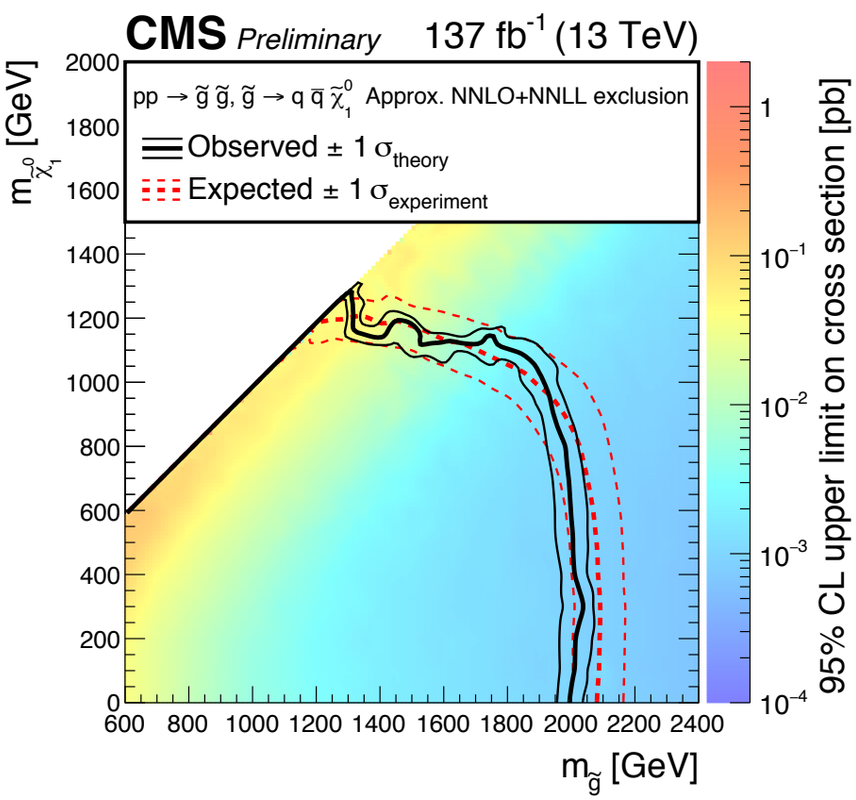


Large mass splitting → large boosts → decays outside tracker → decreased sensitivity

Direct Look at CMS LLP Sensitivity

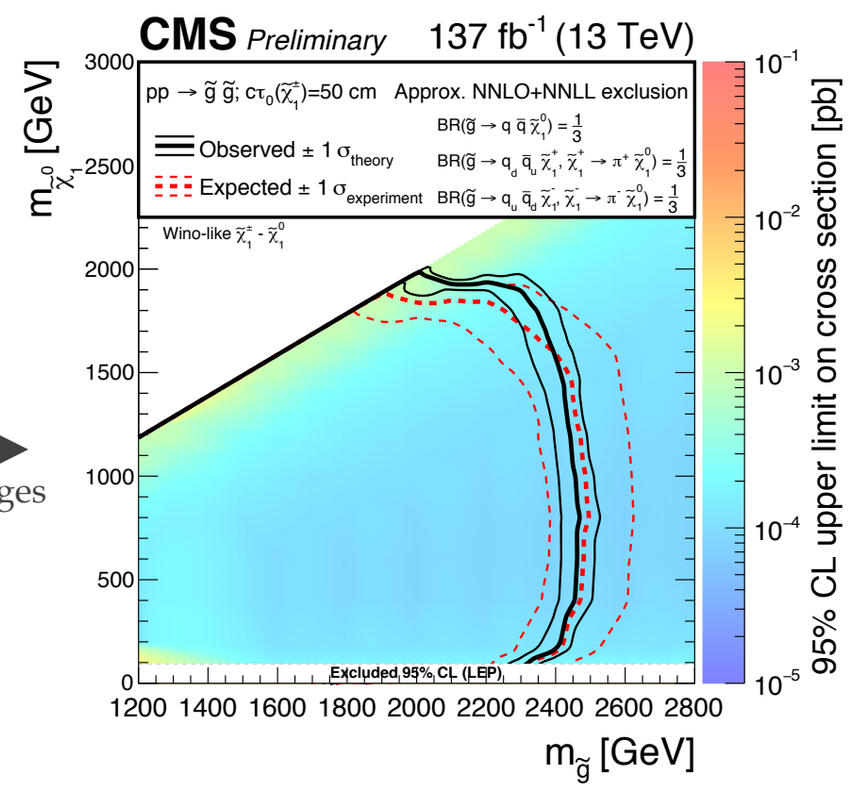
- A <u>related analysis</u> that does not use LLP methods produces leading generic constraints, allowing a direct comparison of sensitivity with and without use of LLPs.

No LLPs



Axis scale changes

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



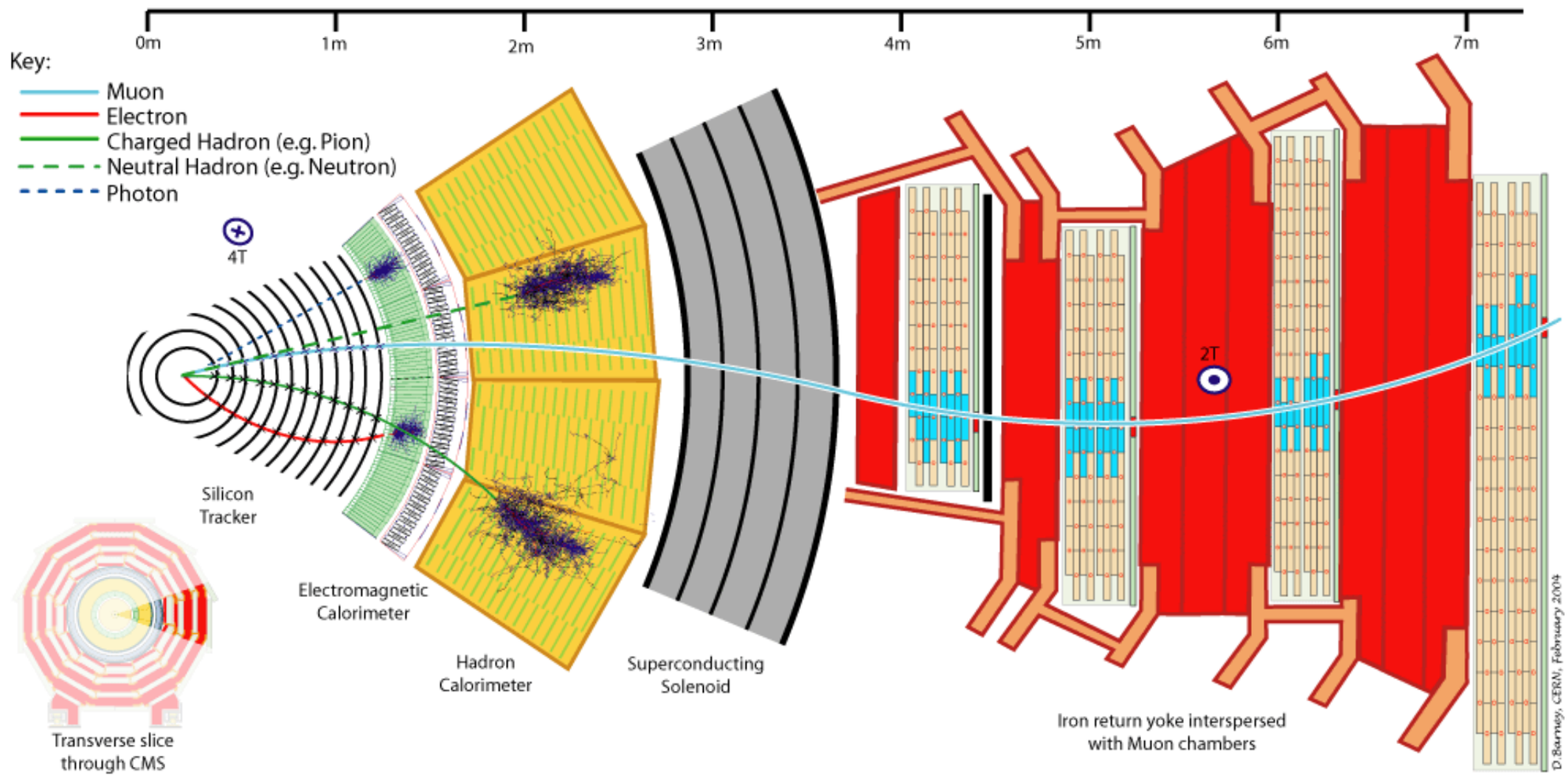
- Constraint along m_{LSP} axis improved by ~800 GeV.
- Constraint along m_{Gluino} axis improved by more than ~400 GeV.

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: $m_{proton} \sim m_{neutron}$

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)

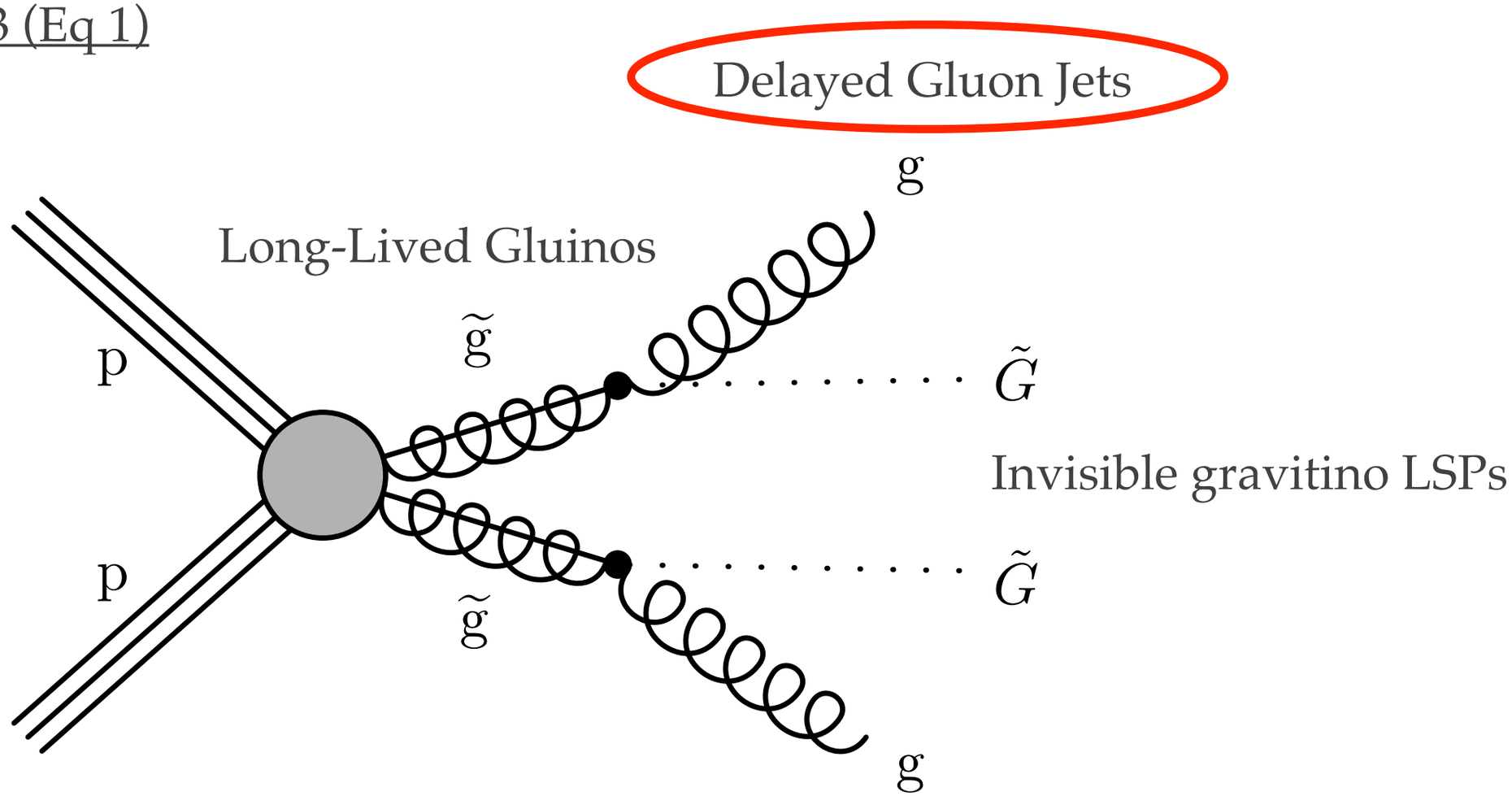


Fig. 1a from CMS PAS EXO-19-001

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)

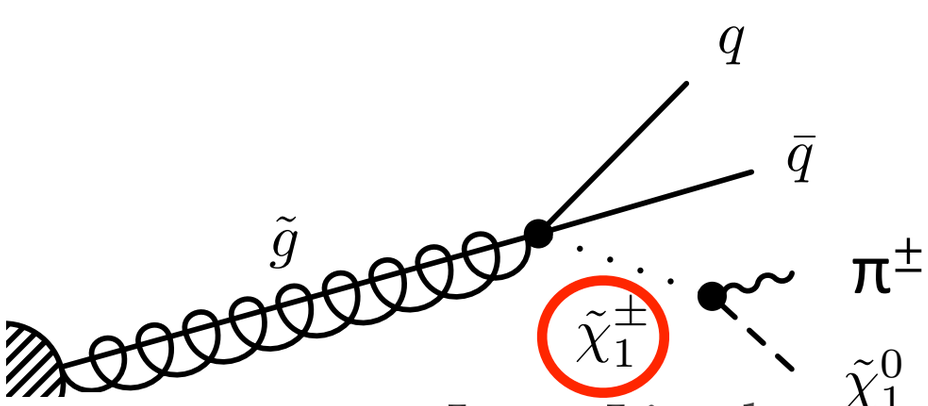
Parameter from SUSY higgs potential

  - Extends chargino lifetime:

$$c\tau_{\chi_1^\pm} \sim 1\text{m}\left(\frac{200\ \text{MeV}}{m_{\chi_1^\pm} - m_{\chi_1^0}}\right)^5$$

(Eq 64)

  - Gluinos can decay to intermediate long-lived chargino.



Small mass splitting, so pion is too soft to produce a track

Invisible neutralino LSP

Long-Lived Chargino

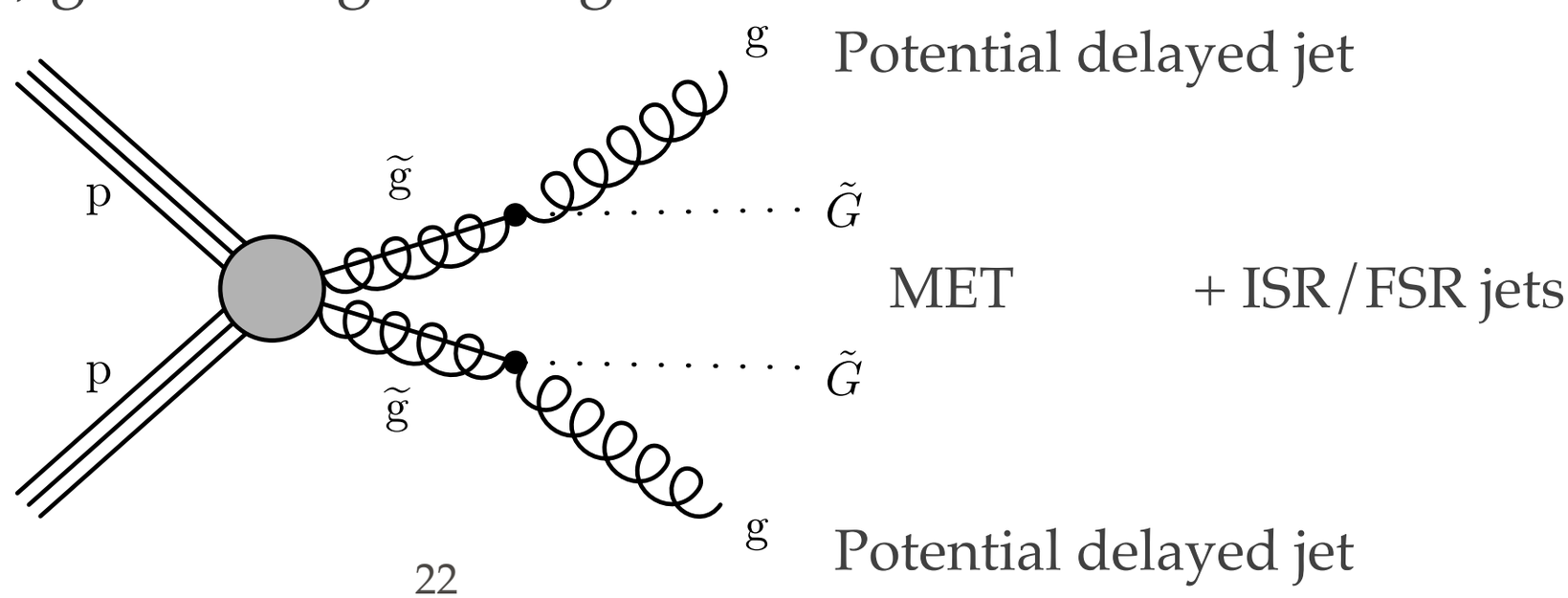
Chargino track disappears!

Fig. 8 from CMS PAS SUS-19-005

Emerging Jet Search

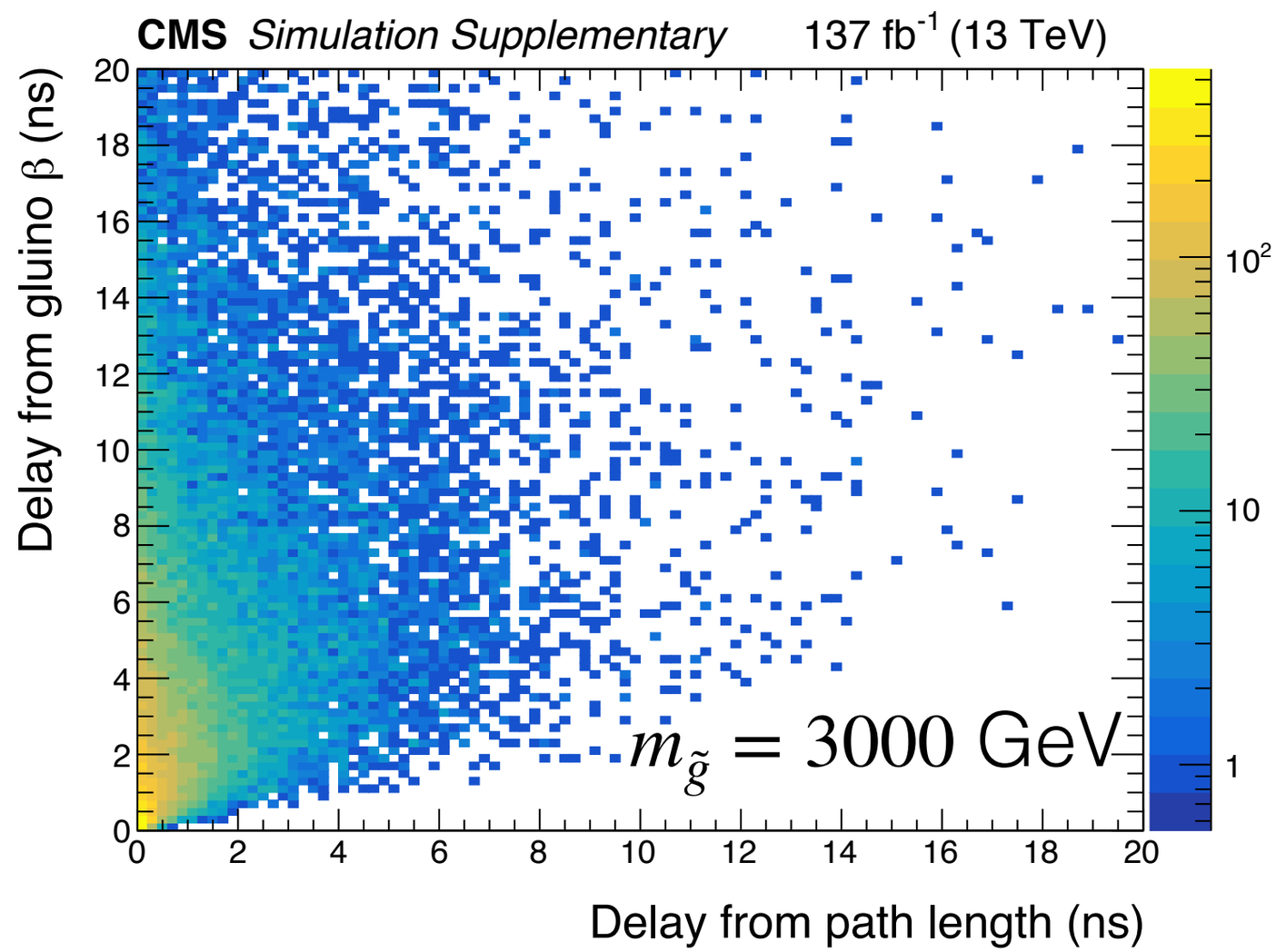
Analysis Strategy

- Jets + MET. For signal region, MET > 300 GeV.
- Define "jet delay" $t_{Jet} = 0$ for $t = L/c$. For signal region: $t_{Jet} > 3$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 → gluon + gravitino



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?



CMS ECAL Timing Performance

Noise contribution significant below ~20 GeV.

- Recall that a typical signal jet is delayed by only ~ns. Is the CMS ECAL so precise?
- Yes! ECAL timing resolution is ~0.2 ns in the barrel ($|\eta| < 1.48$)
  - ECAL deposit > ~20 GeV, easily satisfied by signal.

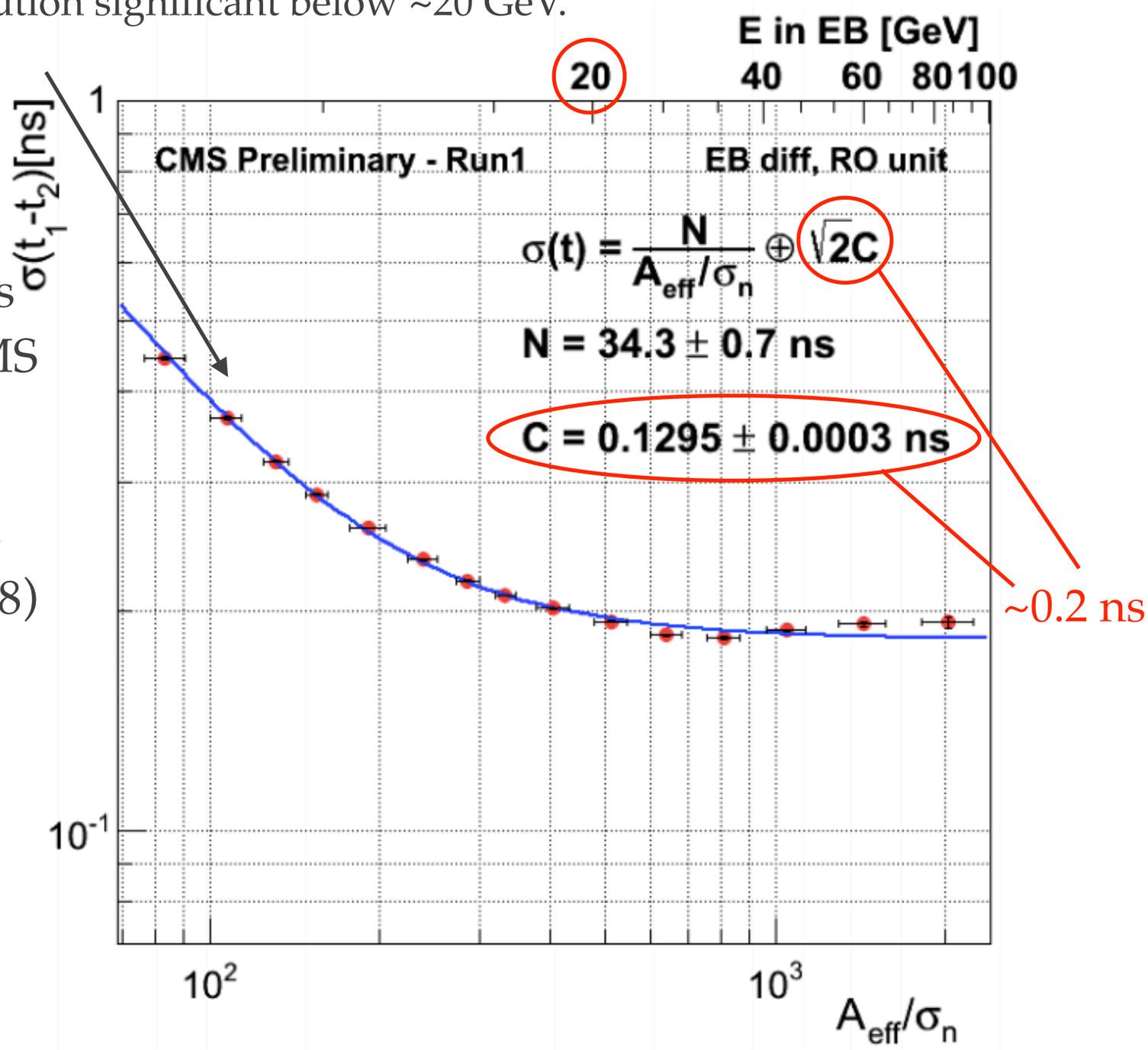


Figure 4 from: Daniele del Re 2015 J. Phys.: Conf. Ser.587 012003

Background Sources

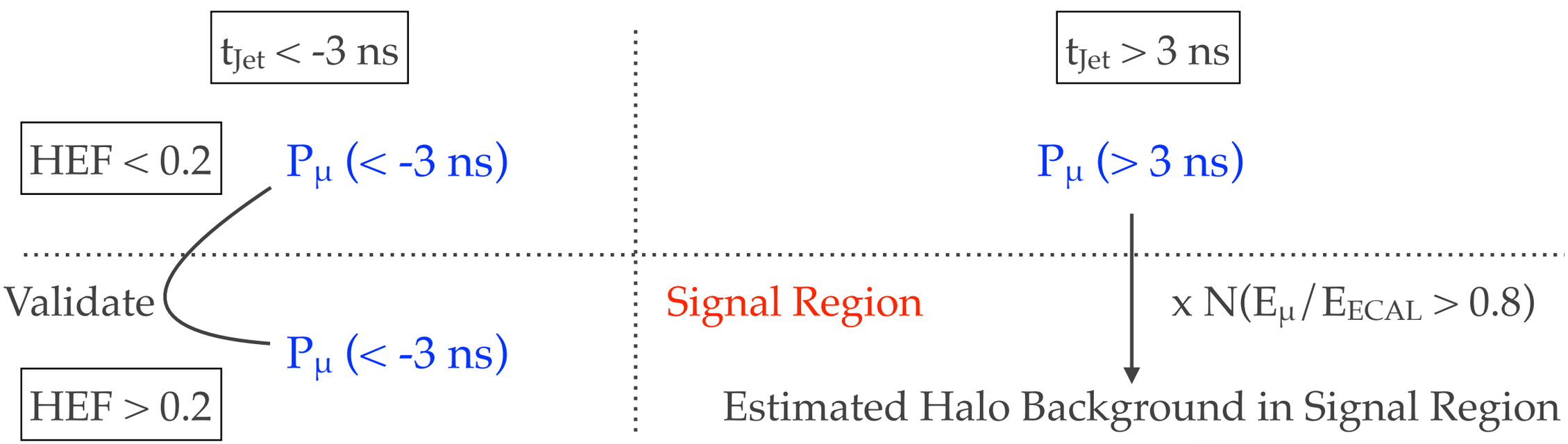
- ECAL timing failures.
  - Resolution tails.
  - Noise.
  - Direct ECAL avalanche photodiode (APD) hit, skipping scintillation stage.
- External muons
  - Cosmic rays
  - "Beam halo" muons, produced by collisions with hardware upstream of detector. Travel parallel to beam.
- Satellite bunches
  - LHC 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: $t_{Jet} < \sim 1$ ns.

Cleaning

- **Many ECAL cells**: $N_{Cell} > 25$ rejects jets from noise and direct APD hits.
- **Large HCAL deposit**: HCAL energy fraction (HEF) > 0.2, $E_{HCAL} > 50$ 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**: $t_{RMS}/t_{Jet} < 40\%$ and $t_{RMS} < 2.5$ 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 HEF > 0.2 **and** E_{HCAL} > 50 GeV **and** $E_\mu / E_{ECAL} < 0.8$.
- **Invert** HEF > 0.2 requirement and remove E_{HCAL} > 50 GeV selection.
- Measure $E_\mu / E_{ECAL} < 0.8$ pass/fail ratio $P_\mu = N(E_\mu / E_{ECAL} < 0.8) / N(> 0.8)$ in this region.
- Confirm that P_μ is independent of HEF using a validation region populated by <u>early</u> jets, $t_{Jet} < -3$ ns.
  - To protect against cosmic ray muon pollution, consider only horizontal jets.
- Estimated halo background is $N_{Halo} = P_\mu \times N(t_{Jet} > 3\text{ns}; E_\mu / E_{ECAL} > 0.8)$.

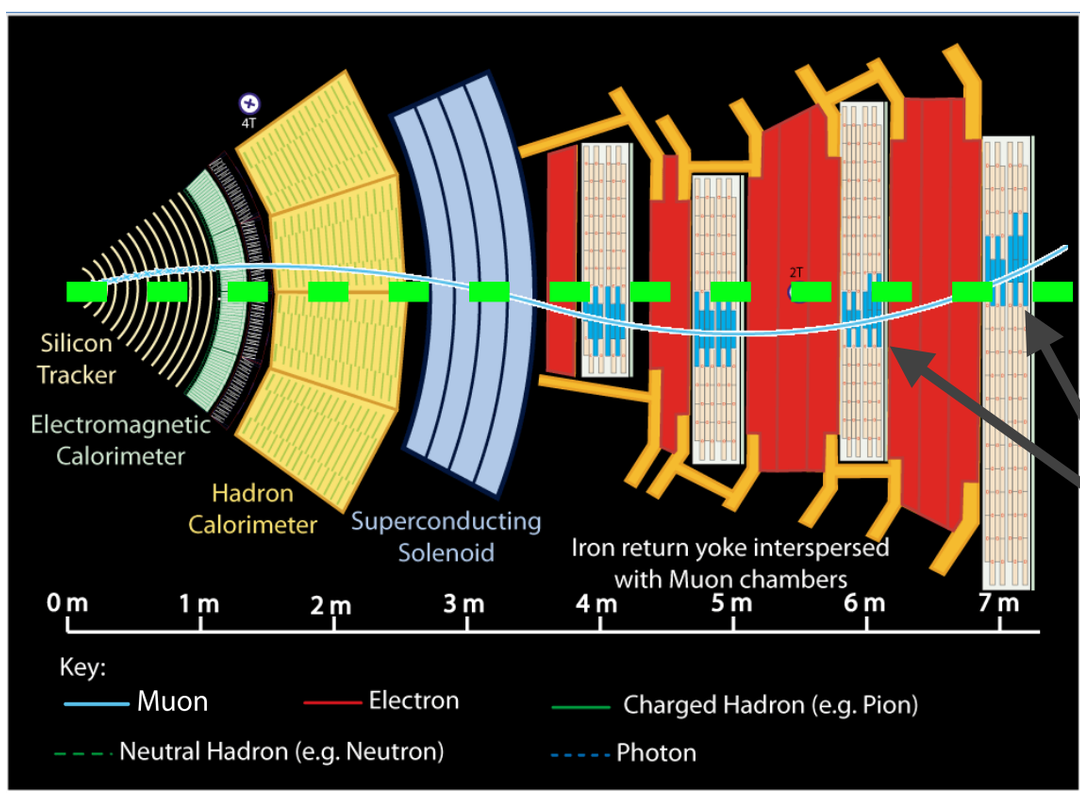


$0.02^{+0.06}_{-0.02}$ (stat) $^{+0.05}_{-0.01}$ (syst)

Background Estimate: Cosmics

- Muons from beam collisions have roughly constant CMS coordinate ϕ.
- Cosmics trajectories tend not to have constant ϕ.
- 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 $\Delta\phi$.

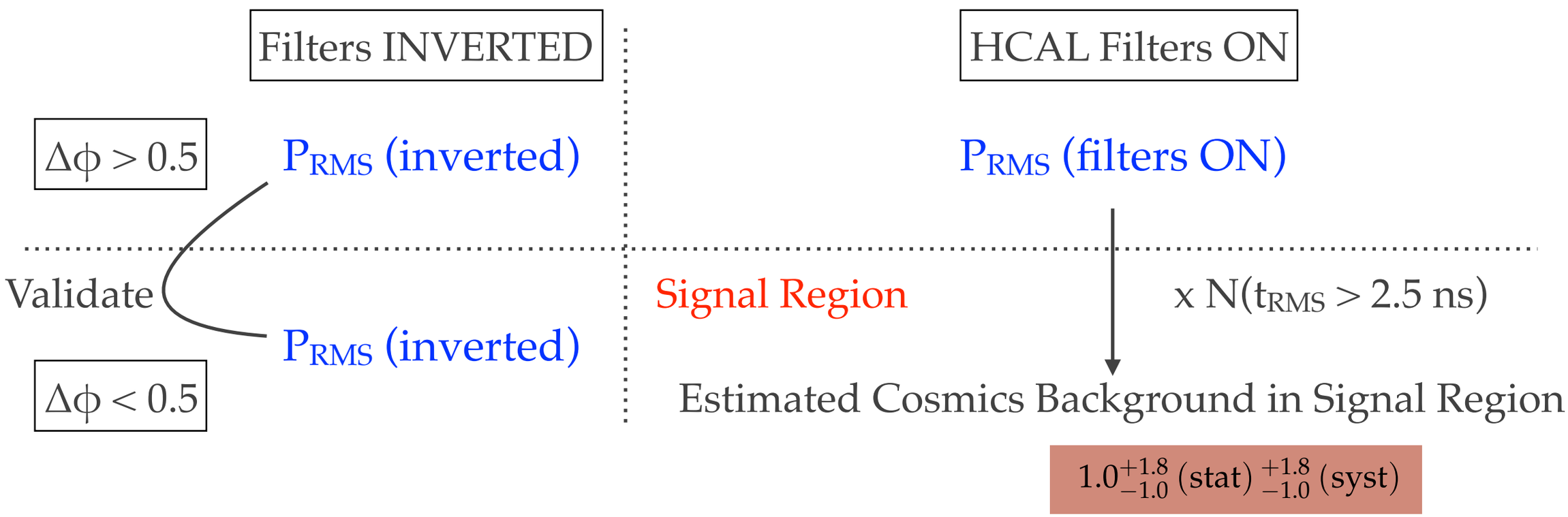
$$N_{Cosmics} = P_{RMS} \times N(t_{RMS} > 2.5\text{ ns})$$



Genuine beam muon hits follow a line of roughly constant ϕ

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

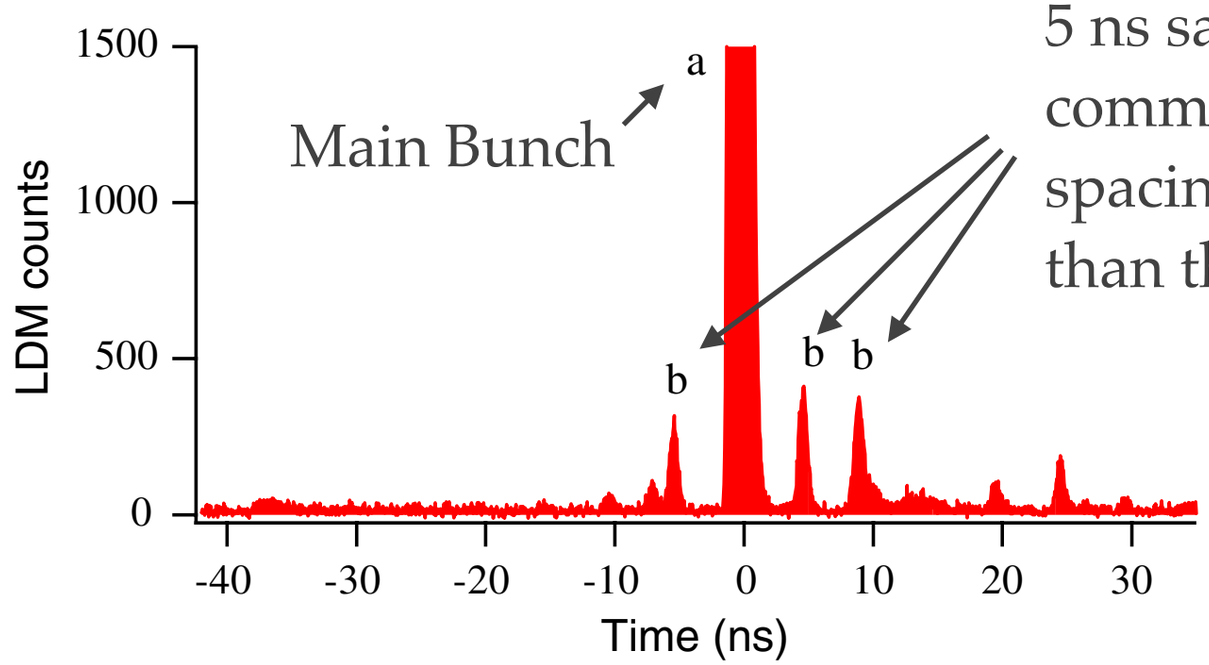
Background Estimate: Cosmics



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.

Fig. 6 (upper)



5 ns satellites are more common, due to larger bucket spacing in the injector chain than the LHC itself.

- 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}.

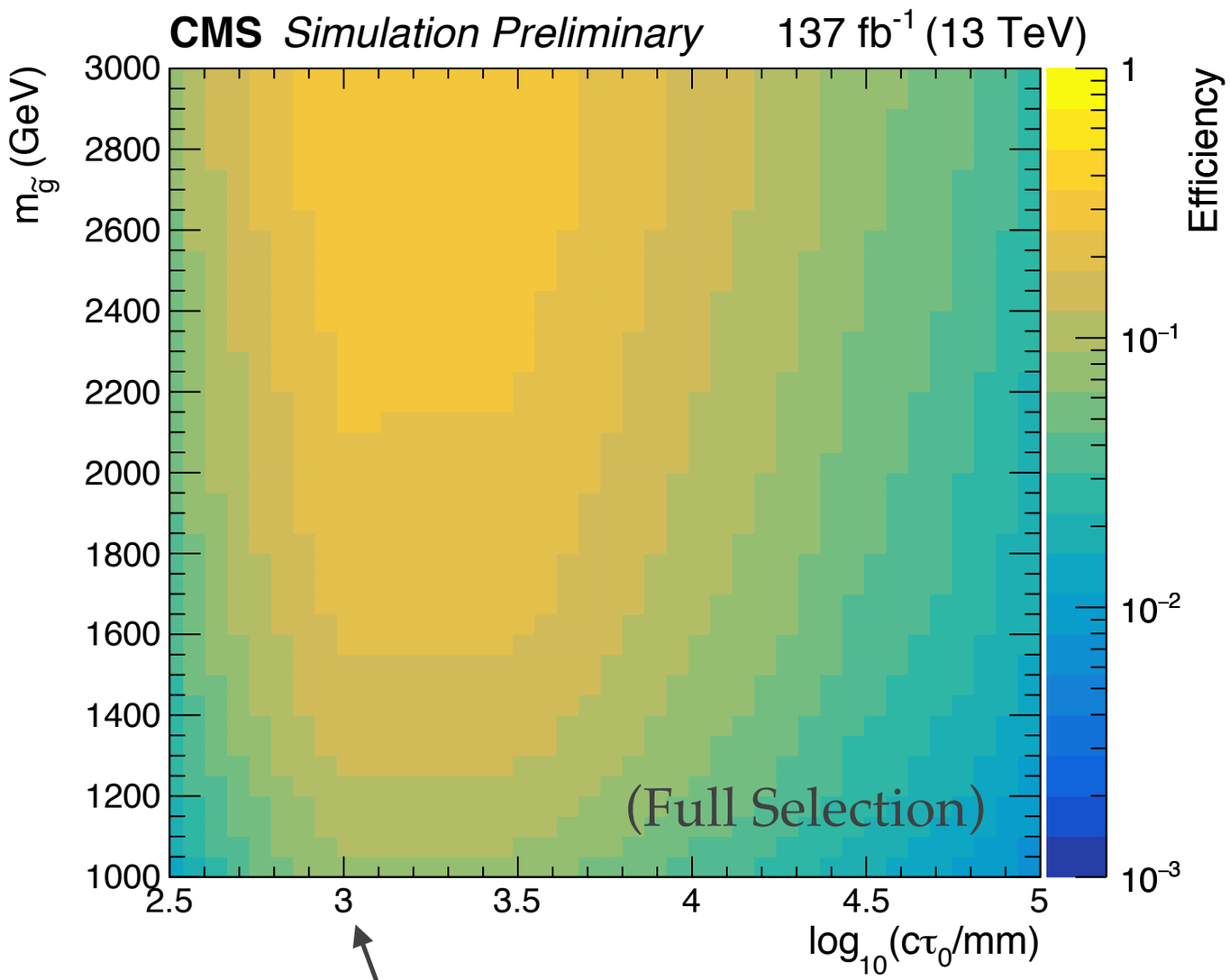
Background Estimate: Satellite Bunches

Measure P_{PV} $P_{PV} = N(E_{PV\ Tracks}/E < 1/12)\ /\ N(> 1/12)$	Apply P_{PV} $P_{PV} \times N(> 1/12)$
$-3 < t_{Jet} < -1$ ns, MET > 300 GeV	$t_{Jet} < -3$ ns, MET > 300 GeV
$-3 < t_{Jet} < -1$ ns, MET < 300 GeV	$t_{Jet} < -3$ ns, MET < 300 GeV
$1 < t_{Jet} < 2$ ns, MET > 300 GeV	$2 < t_{Jet} < 3$ ns, MET > 300 GeV
$1 < t_{Jet} < 3$ ns, MET > 300 GeV	Signal Region $1 < t_{Jet} < 3$ ns, MET > 300 GeV

$0.11^{+0.09}_{-0.05}\,(\text{stat})\,^{+0.02}_{-0.02}\,(\text{syst})$

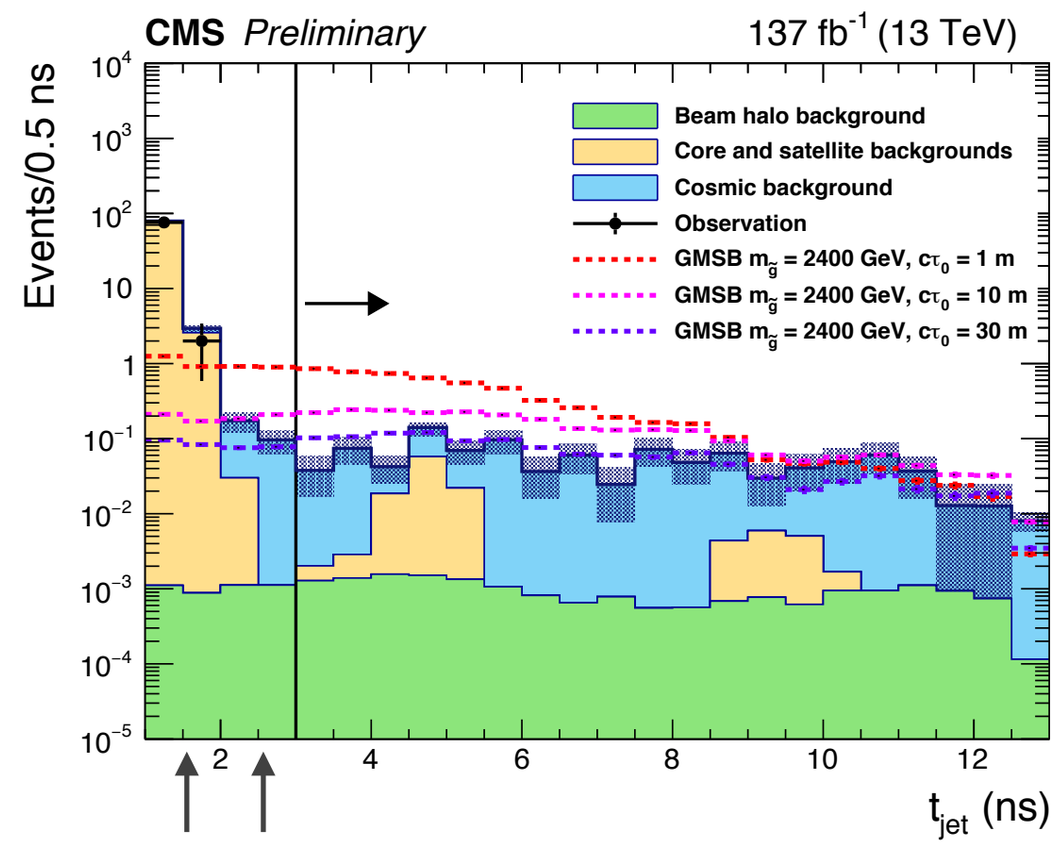
Also check timing invariance of P_{PV}' in inverted MET validation region, $t_{Jet} > 2$ ns.

Signal Efficiency



Targeting O(1m) decay lengths.

t_{Jet} Distribution



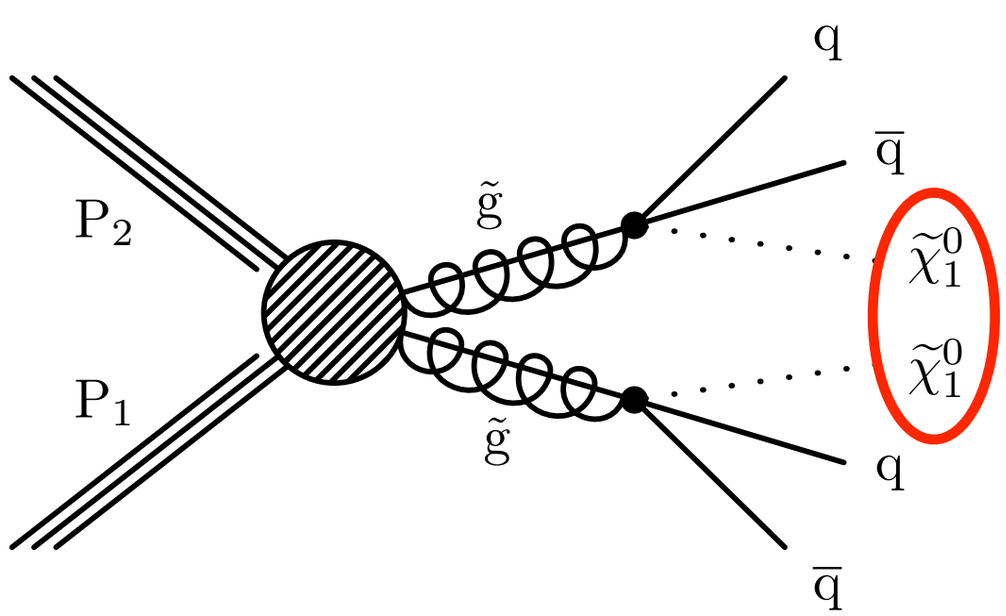
Inefficiency

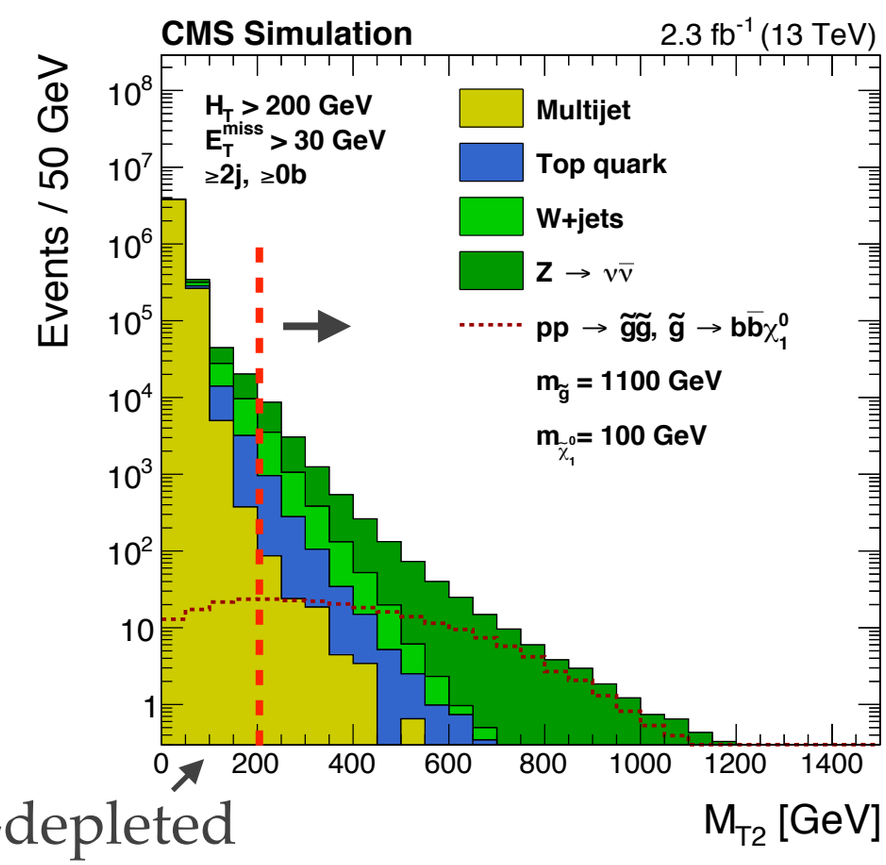
- Recall: expect ~1 event in CMS dataset for ~3.0 TeV gluino pair production.
- For signal models of interest, total selection efficiency is very roughly ~20-40%.
- Inefficiency largely from $t_{Jet} > 3$ ns selection.

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.

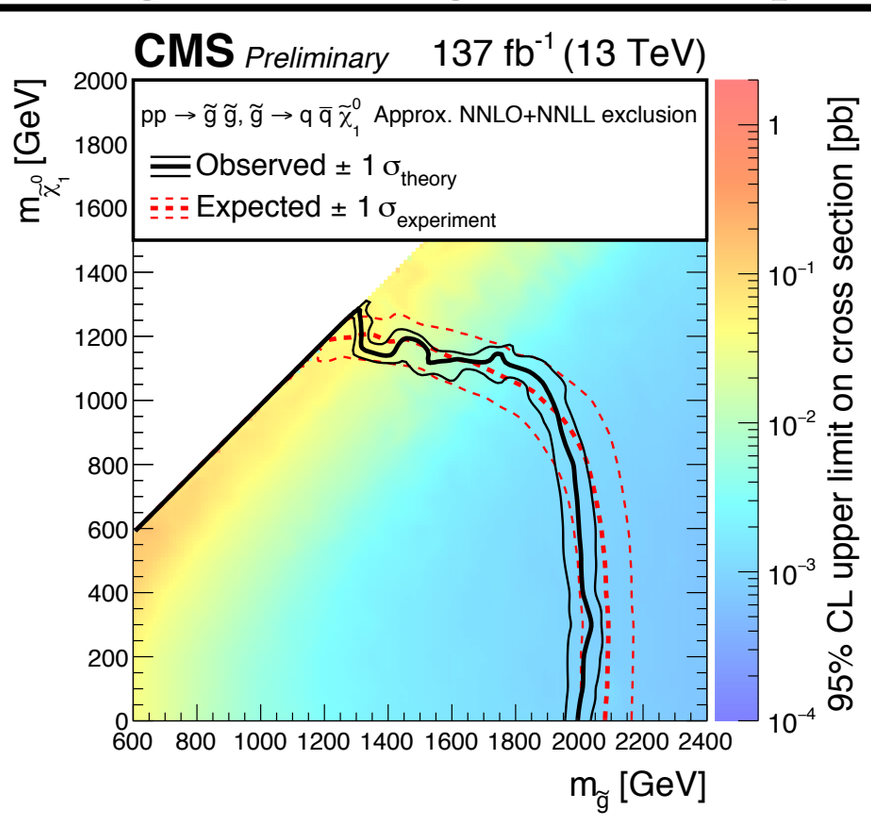




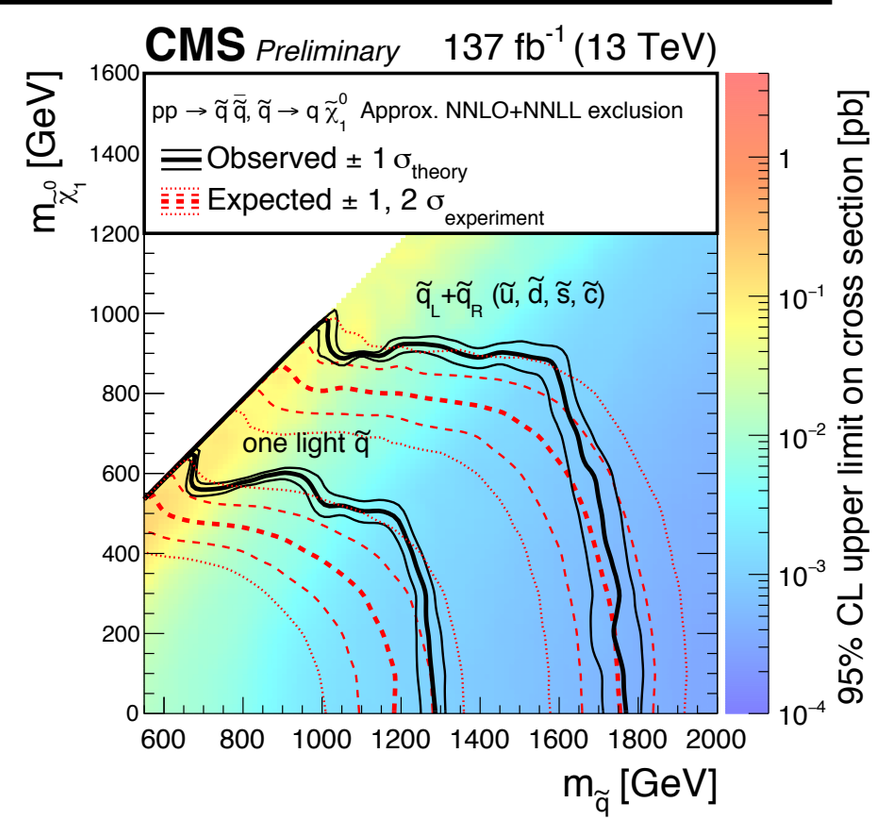
Note: $M_{T2} < 200$ GeV is signal-depleted

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 ⇒ 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

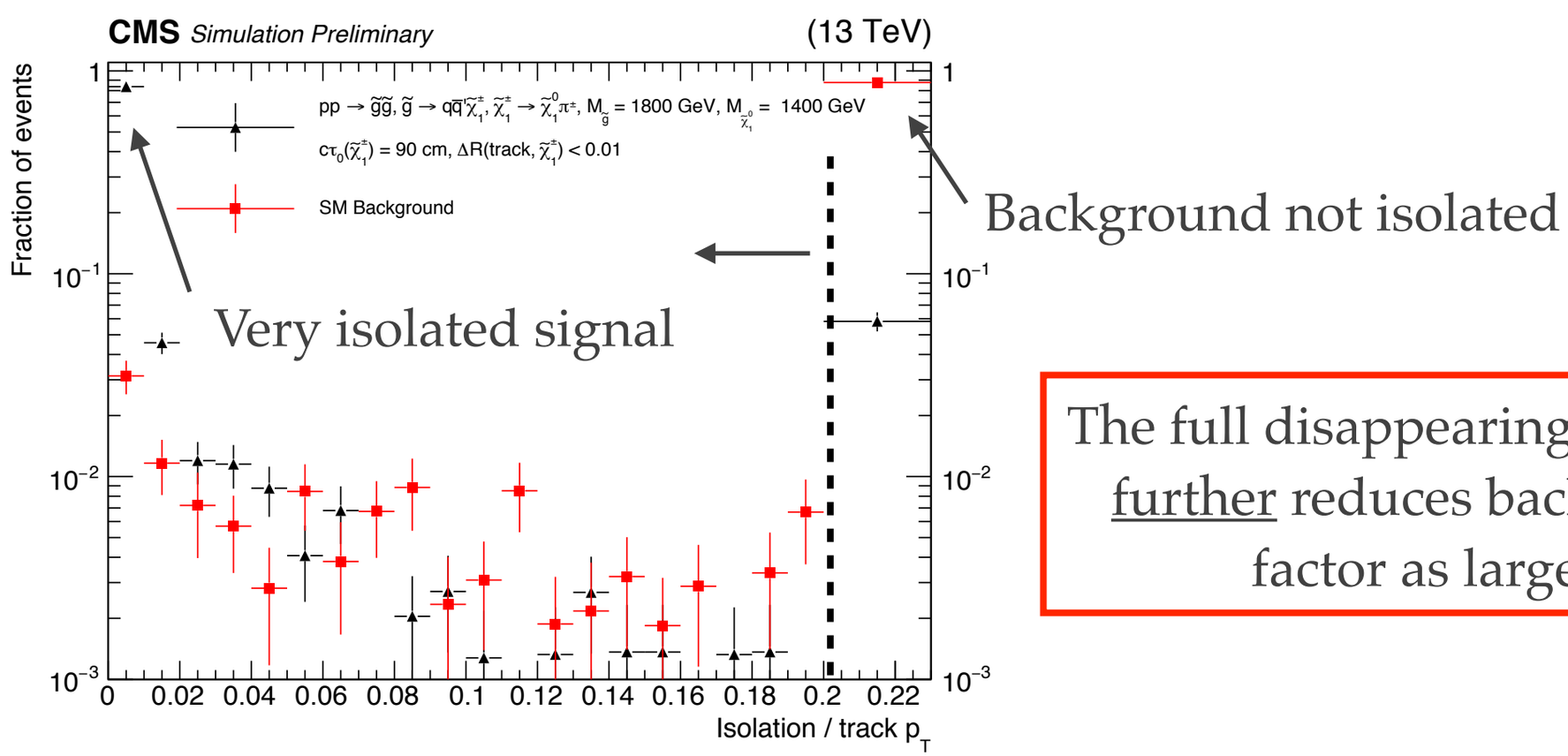


Inclusive Squark to Light Jet Limits

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 (eg small impact parameter) for fake rejection.
- Lepton veto.
  - For longer tracks, require M_T(Track,MET) > 100 GeV or $p_T > 150$ GeV for enhanced lepton rejection.
- Isolated.

Ex: Relative Isolation



The full disappearing track selection <u>further</u> 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.

$\Rightarrow$ 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 $p_T < 50$ GeV ("lo") and $p_T > 50$ 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_{Jet} and H_T.
  - N_{Jet} = 2-3 (“L”, squark-like) and 4+ (“H”, gluino-like).
  - H_T = [250, 450] GeV (“L”), [450, 1200] GeV (“M”), and 1200+ GeV (“H”).
    - Merge “L” and “M” H_T into “LM” for Long tracks.
- Regions are given as:

  Track-length $N_{Jet}H_T$ p_T

  - Ex: **P HH lo** is Pixel-only tracks, $N_{Jet} \geq 4$, $H_T > 1200$ 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.

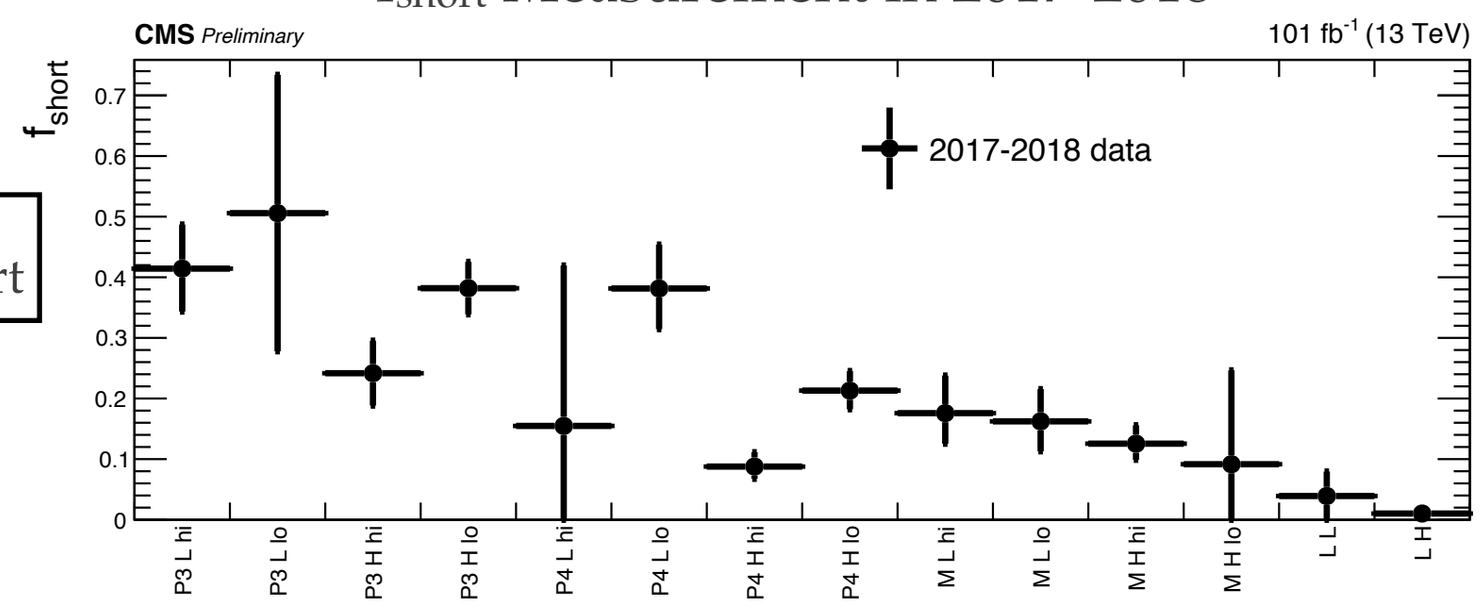
Background Estimation

- 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 $f_{short} = N_{ST} / N_{STC}$ and measure separately for every signal region.
  - Except inclusively in H_T, exploiting empirical invariance to improve statistics.
- Measure f_{short} in data control region at $60 < M_{T2} < 100$ GeV.
  - Recall major advantage of M_{T2}: low M_{T2} is signal-depleted.
  - For L tracks only, use data $f_{short}(M)$ adjusted by simulation $f_{short}(L)/f_{short}(M)$ due to poor statistics.
- f_{short} systematic assessed by varying H_T and MET selections in measurement region.

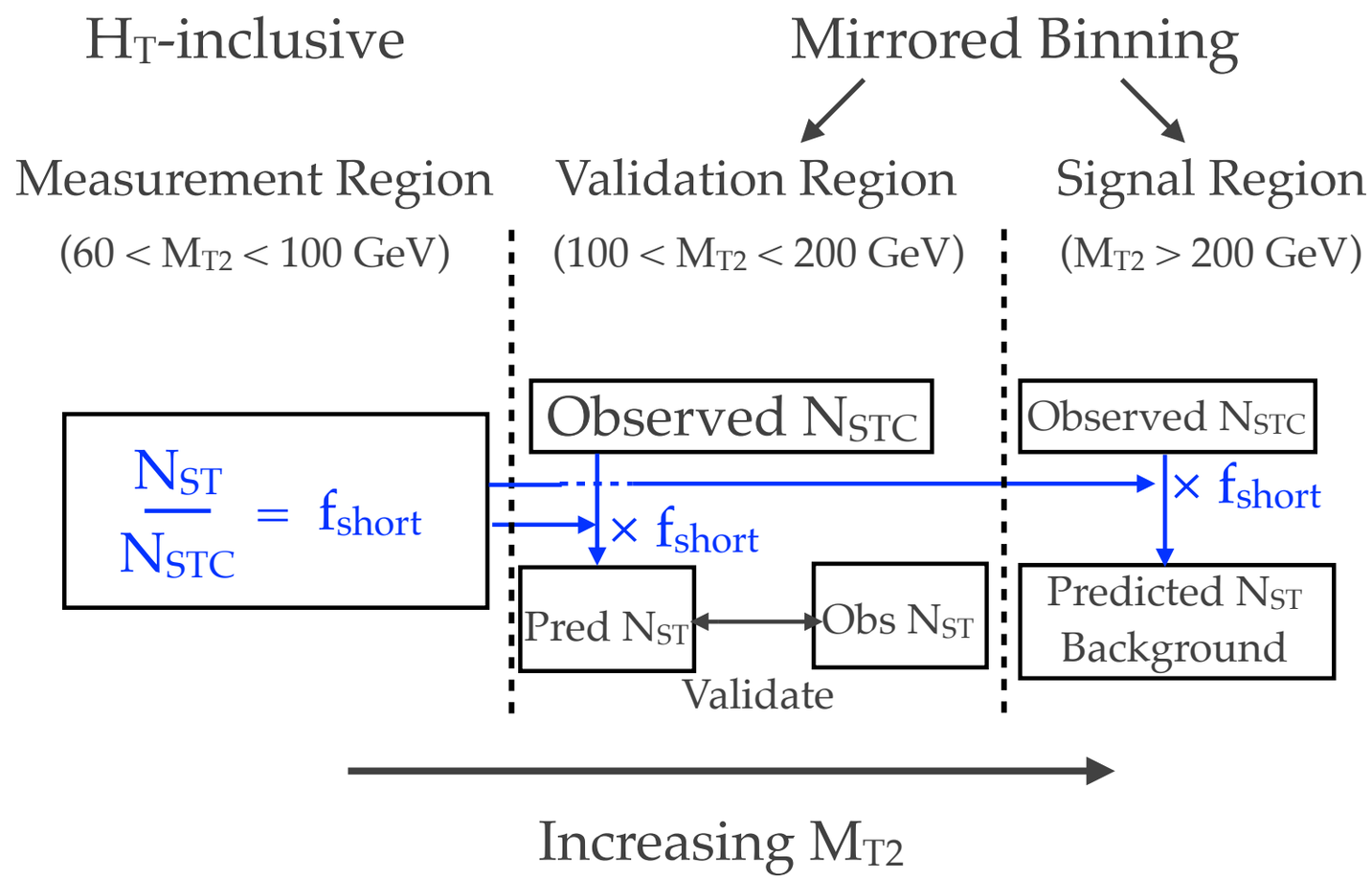
For each bin:

$$N_{ST}(Est) = N_{STC}(Obs) \times f_{short}$$

f_{short} Measurement in 2017-2018

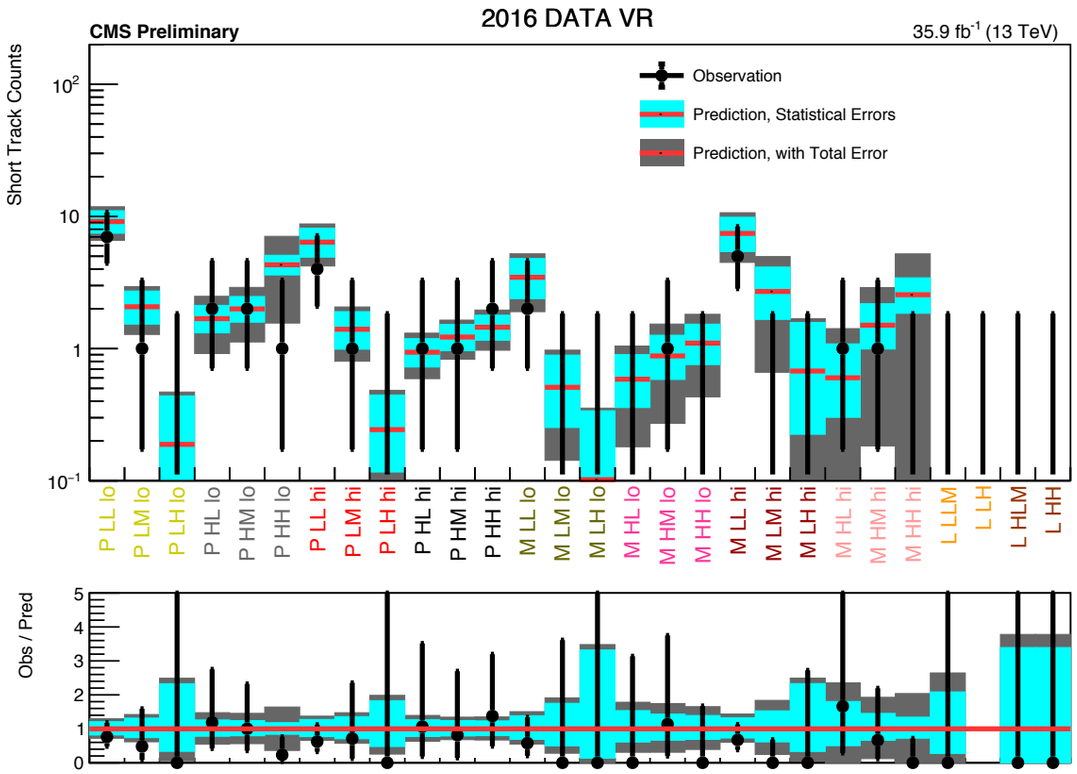


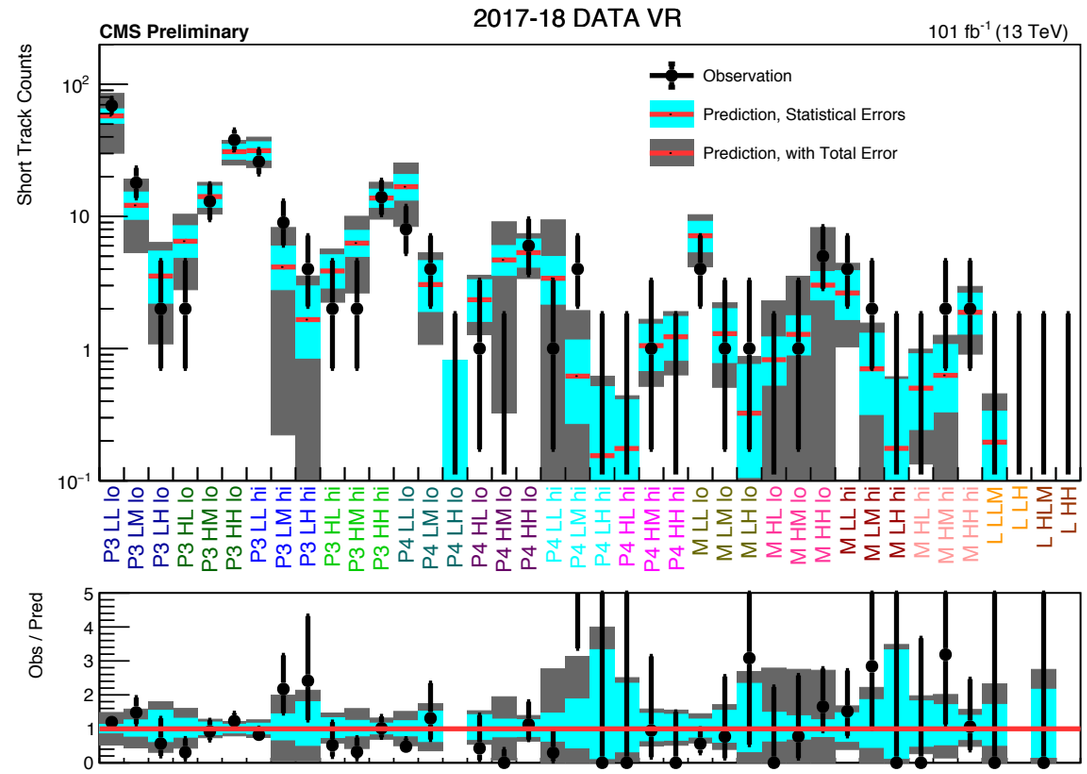
Procedure Summary



- Measure f_{short} at low M_{T2}, $60 < M_{T2} < 100$ GeV separately for each bin, except inclusively in H_T.
- Validate background estimate bin-by-bin at intermediate M_{T2}, $100 < M_{T2} < 200$ GeV.
- Estimate background using f_{short} and observed N_{STC} at $M_{T2} > 200$ GeV and search for signal.

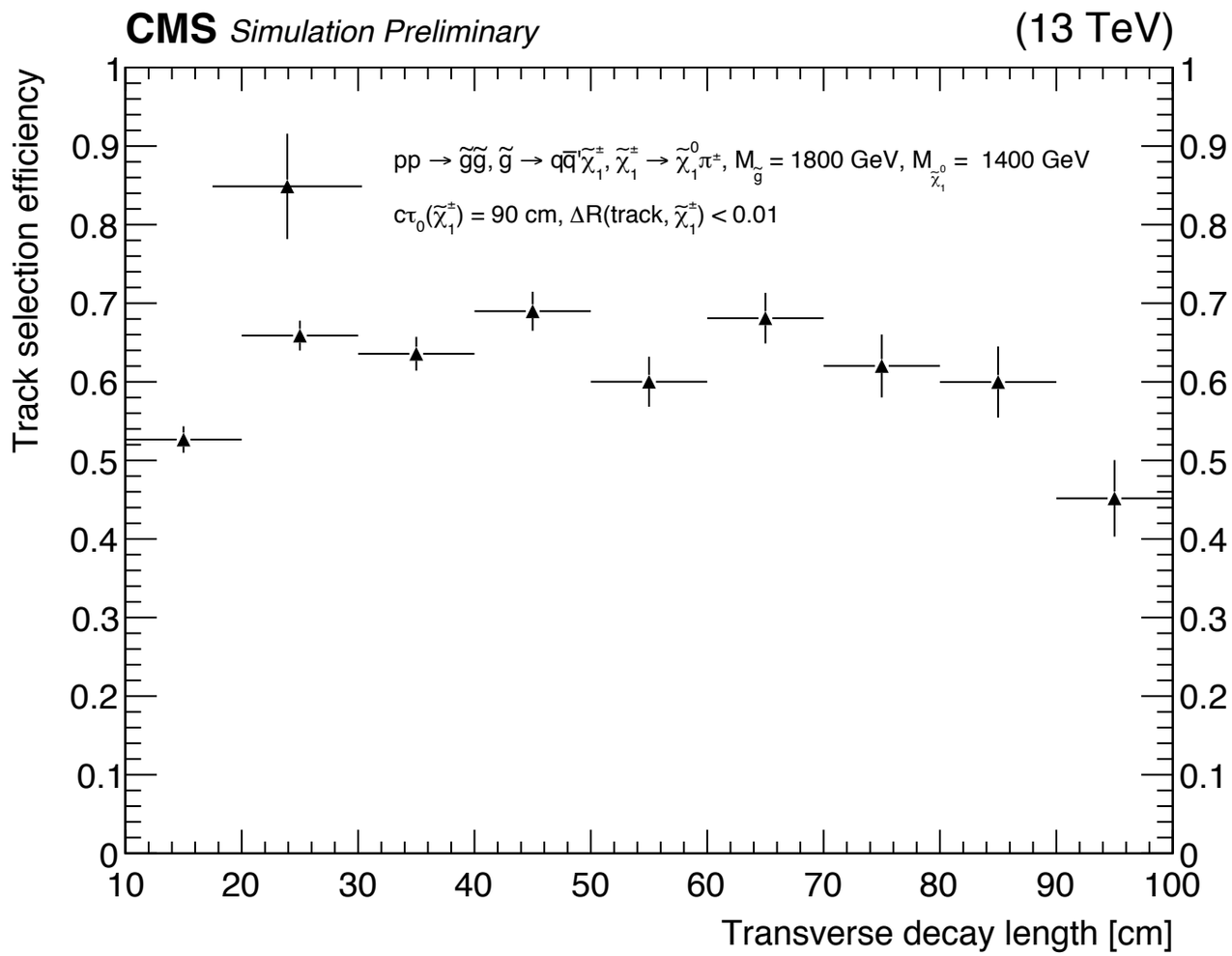
Validation





- 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_{short} (ie differing only in H_T), indicated by a shared label color, have highly correlated uncertainties.

Track Selection Efficiency



- Signal tracks pass the short track selection at roughly ~65% efficiency, per track.
- Only 1 short track required to enter signal region.