CMS Developments for Track-Triggers

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VERTEX 2015

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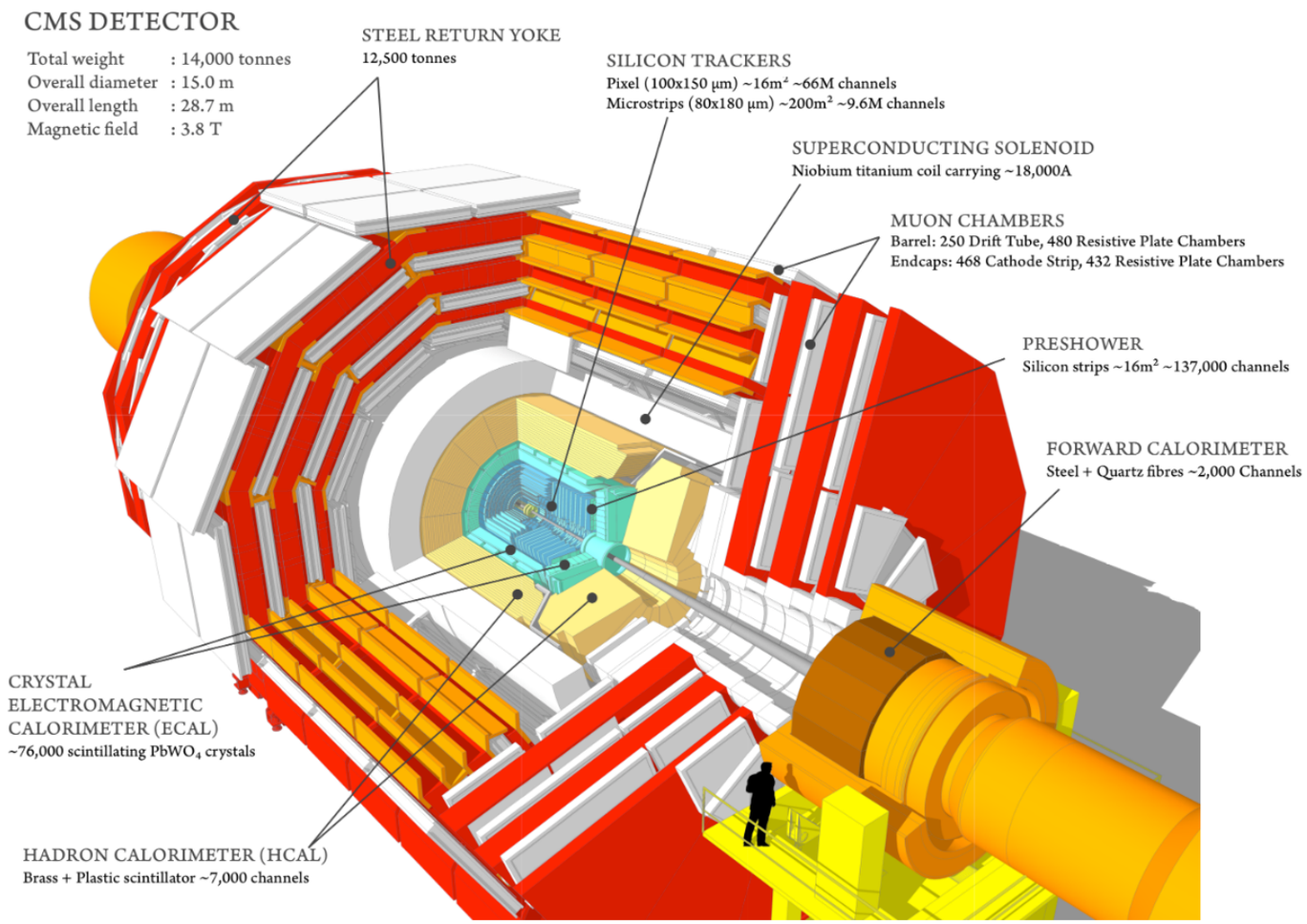
Introduction

- Upgrade to High-Luminosity LHC foreseen for Long Shutdown 3 in 2023-2025
  - Peak luminosity 5x10^{34} cm^{-2}s^{-1}
  - Goal to collect 3000 fb^{-1} over 10 years
  - Benchmark pileup <PU>=140
  - Very challenging environment for the LHC experiments
- New central tracker for CMS with triggering capabilities
  - Maintain high efficiency & keep rates under control for L1 objects
  - Different ideas for L1 track finding & fitting being studied by CMS

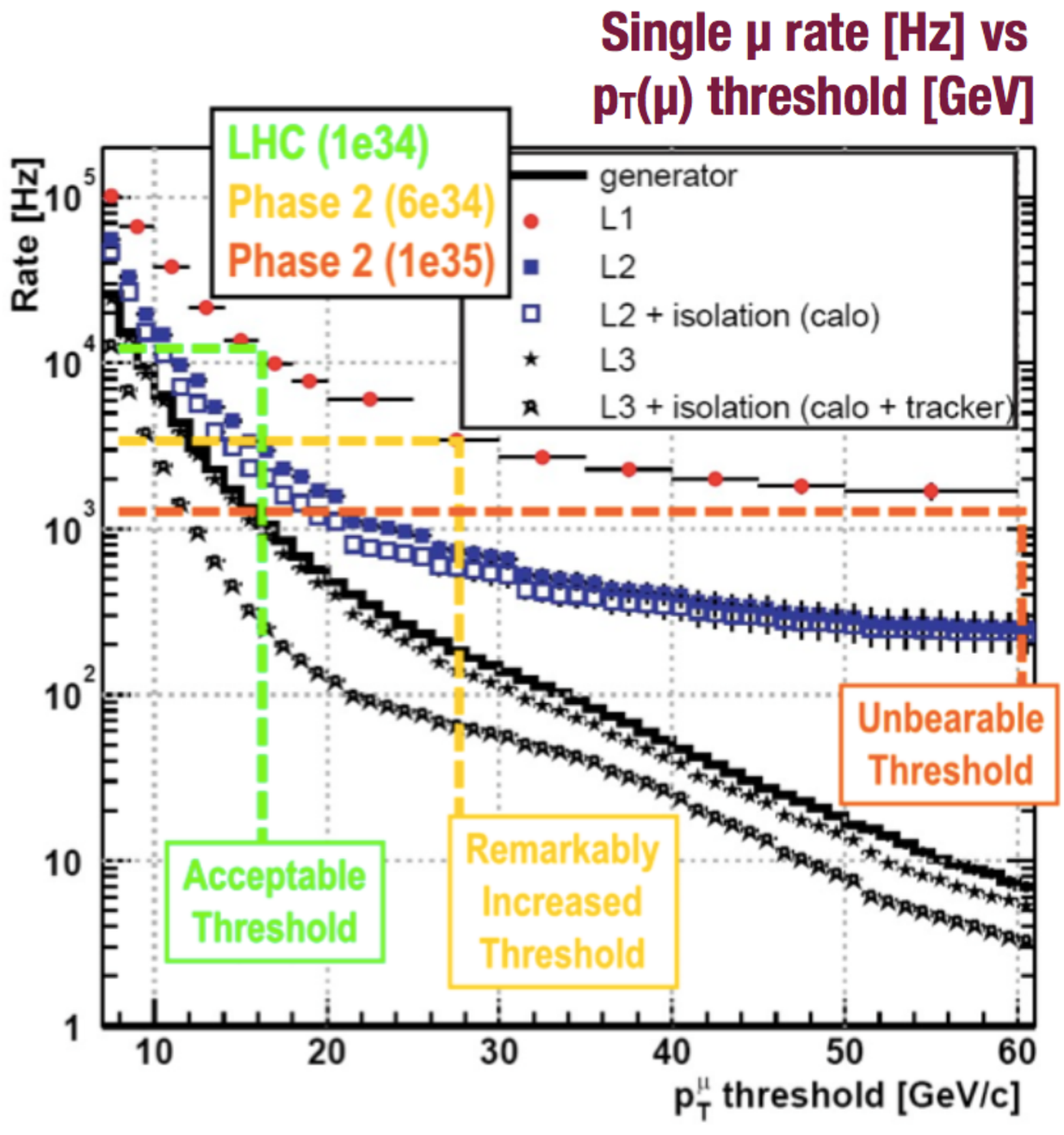


Outline

- Motivation for L1 track trigger at CMS
- Performing tracking at L1
    - Concept of track triggering
    - Overview of different approaches being investigated
- Expected performance of L1 tracking from simulation
    - Tracking efficiency
    - Track parameter resolutions
- Using tracks for L1 trigger
    - e/μ identification
    - Track isolation
    - Vertexing
    - Hadronic triggers

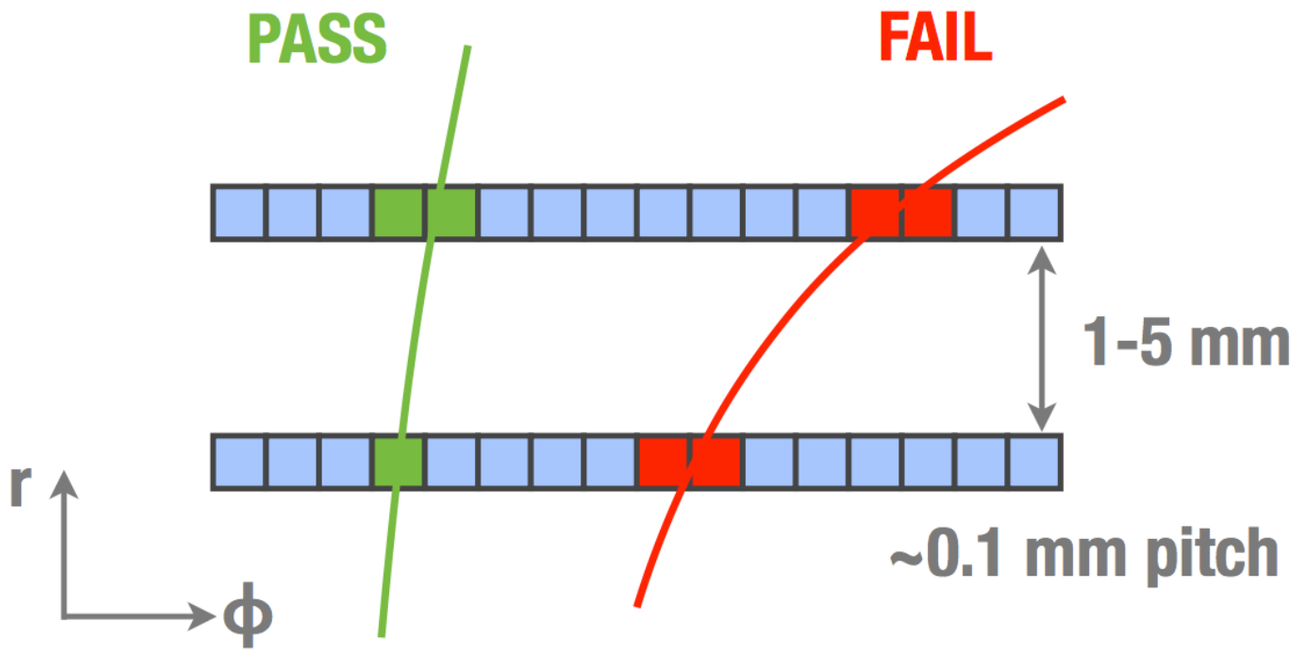
Motivation

- With HL-LHC, μ, e & jet rates would exceed 100 kHz
  - Increasing trigger thresholds restricts physics potential (+ alone not sufficient!)
  - Key goal for CMS to maintain similar physics performance as for 2012 operation
    - Precision measurements of Higgs properties
    - Sensitivity in searches for SUSY & other new physics scenarios
  - Including tracking @ L1 significantly reduces rates
- L1 track trigger
  - Precise momentum measurements for muons allow sharp turn-ons
  - Matching & isolation for electrons/taus, isolation for photons
  - Vertex association for hadronic triggers



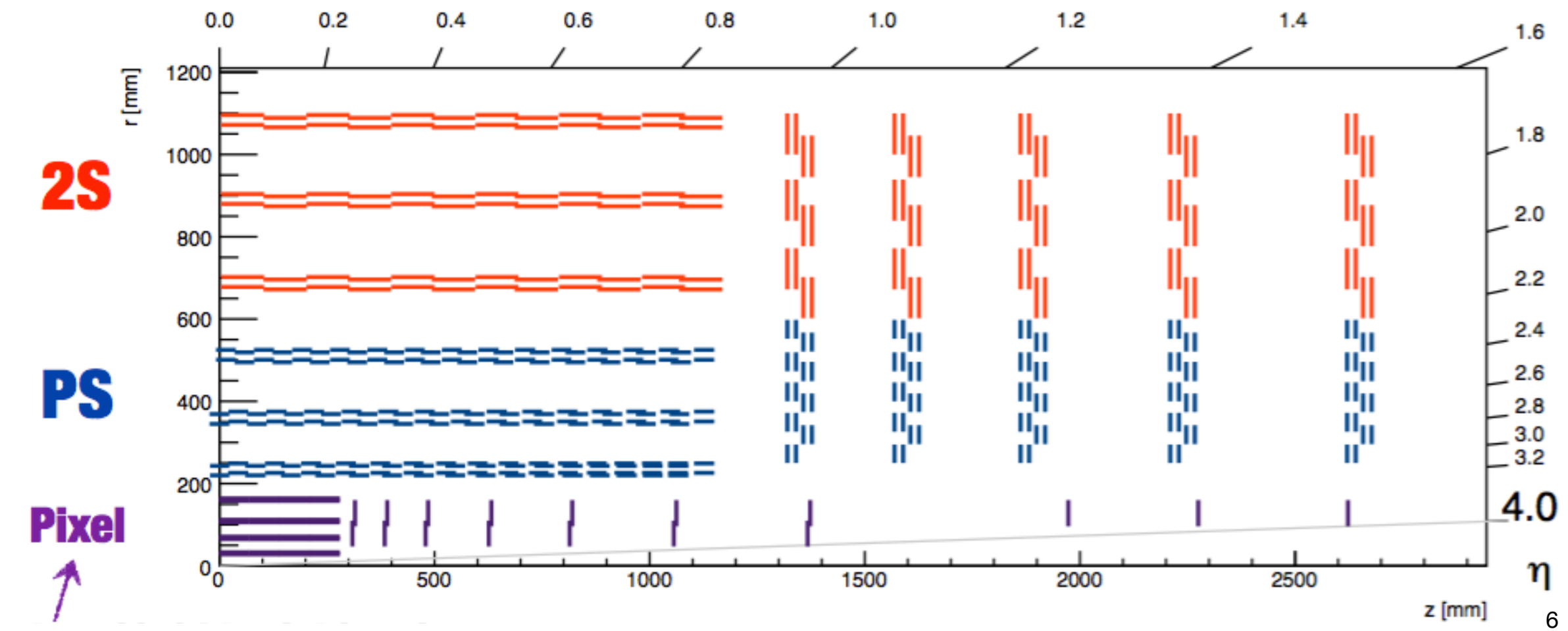
Track Trigger Concept

- Self-seeded L1 track trigger
  - Relies on local p_T reconstruction
  - Aim to reconstruct tracks with p_T > 2 GeV & identify z_0 position with ~1mm precision
    - Similar as average vertex separation at PU=140
- "p_T modules" provide p_T discrimination through hit correlation between closely spaced sensors
  - Stub: Correlated pairs of clusters, consistent with 2 GeV track
  - In minimum bias events, ~95% of tracks have p_T < 2 GeV



Upgraded CMS Tracker

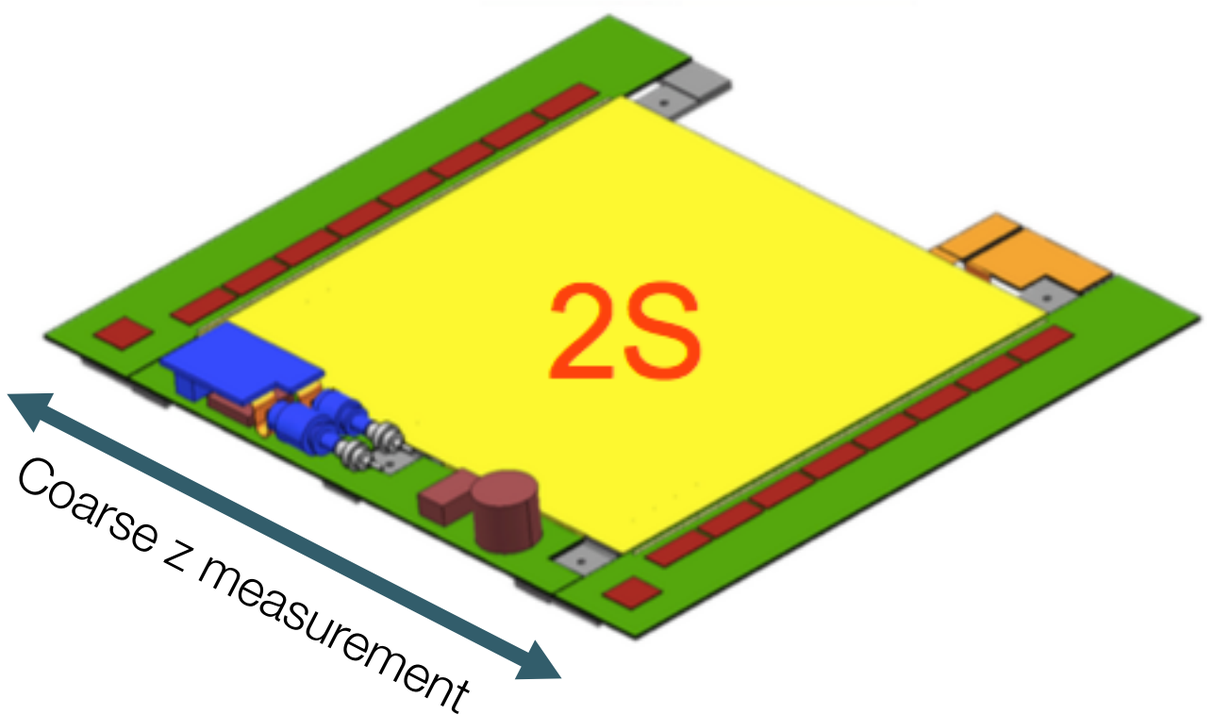
- Baseline geometry for upgraded tracker - barrel & endcaps with 5 disks
- Two types of p_T modules
  - 2S modules (strip-strip sensors)
  - PS modules (pixel-strip sensors)

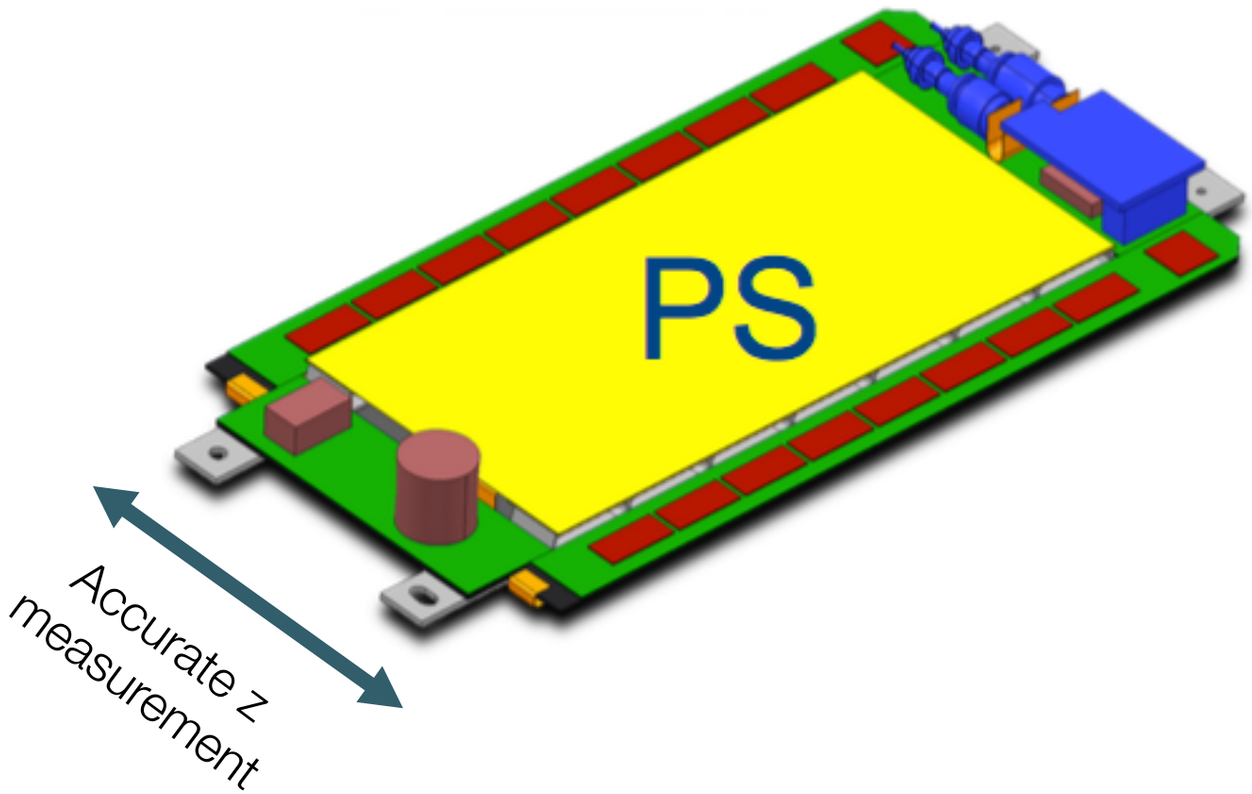


Not used in results shown here

Tracker Modules

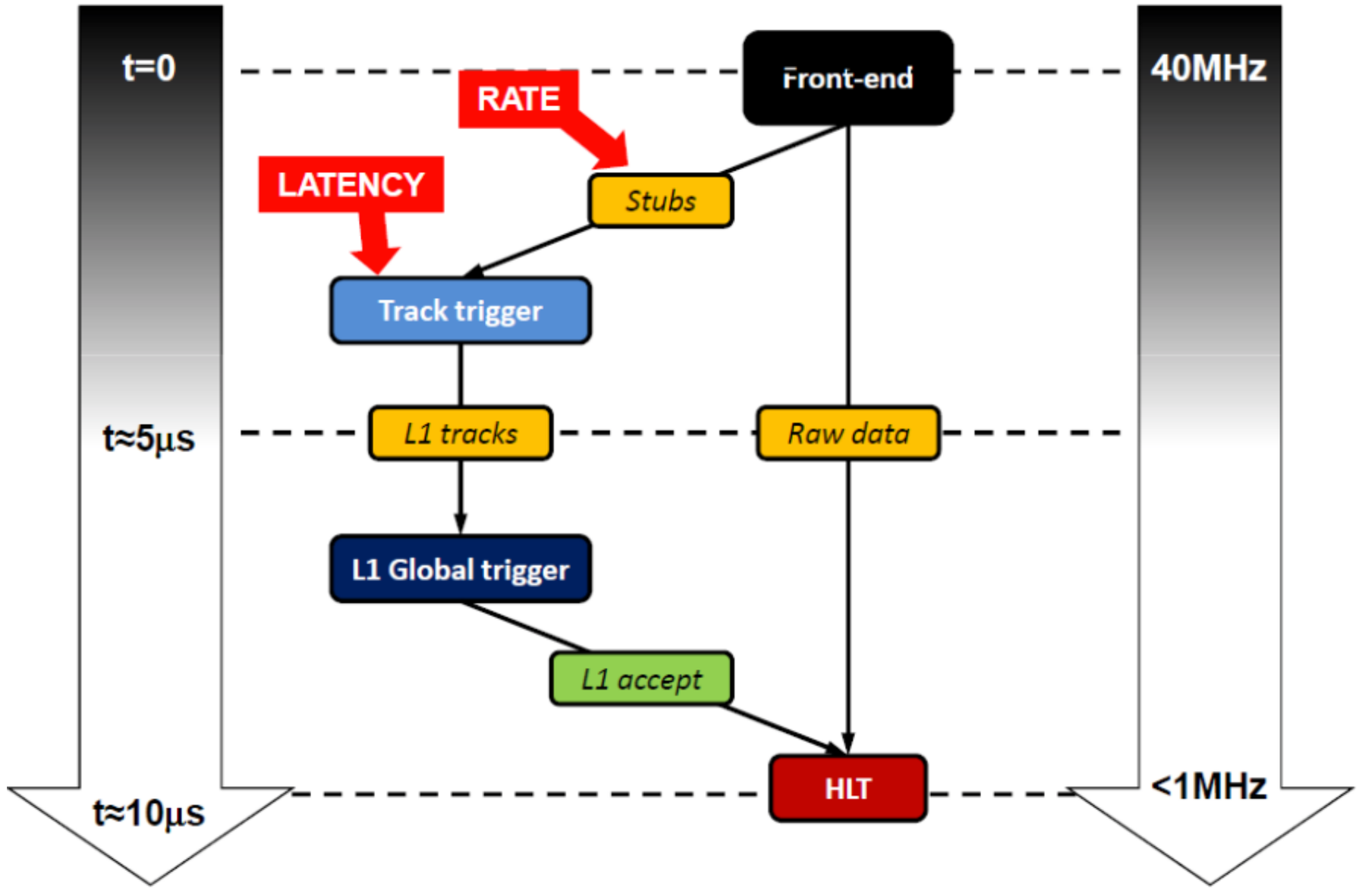
- Modules discriminate low-p_T tracks in FE electronics
- **2S modules**
  - Three outer layers of strip-strip modules
  - Strip sensors 10x10 cm2
    - 2x5 cm long strips
    - 90 µm pitch
- **PS modules**
  - Three inner layers of pixel-strip modules
  - Top sensor
    - 2x25 mm strips, 100 µm pitch
  - Bottom sensor
    - 1.5 mm x 100 µm pixels





L1 Tracking for CMS

- Starting from 50Tb/s of stubs (extracted from the tracker tracker at 40 MHz)
- Build all primary tracks in ~5μs (p_T > 2 GeV/c, $|d_0|$<5mm, $|\eta|$<2.5)



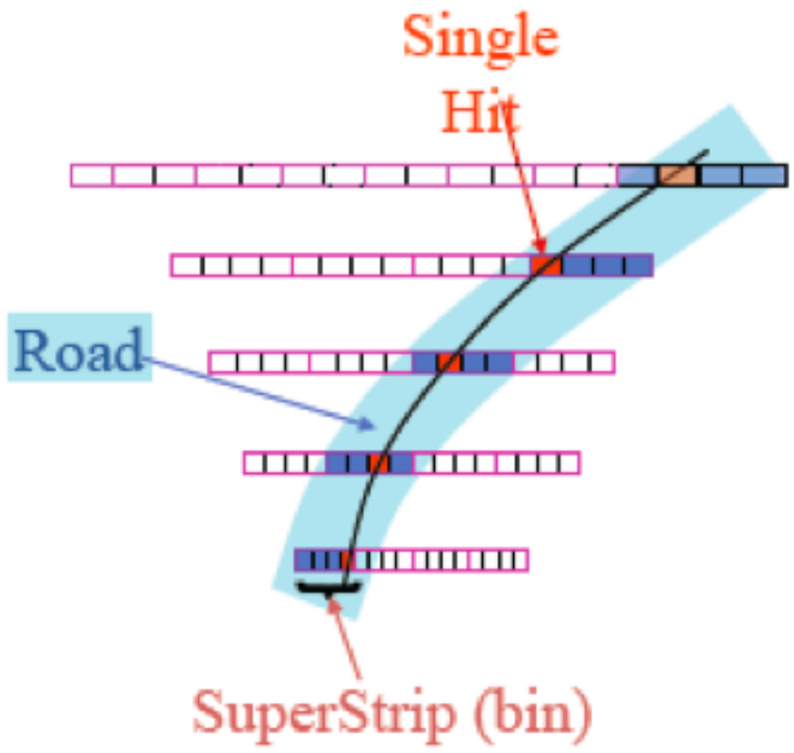
Pattern Recognition and Track Fitting

- The 2 steps of track reconstruction:
  - Step 1: Pattern recognition: very complicated in high PU conditions.
  - Step 2: Track fit (strongly depends on step 1 efficiency)
- Three main approaches being evaluated by CMS
  - **Associative Memory (AM) + FPGA**
    - Based on associative memories (ASIC) for pattern recognition and FPGA for track fitting
  - **Geometry-Based Time-Multiplexed Trigger**
    - FPGA Hough transform + track fit
  - **Tracklet-Based L1 Tracking**
    - Algorithmic approach, entirely based on FPGA

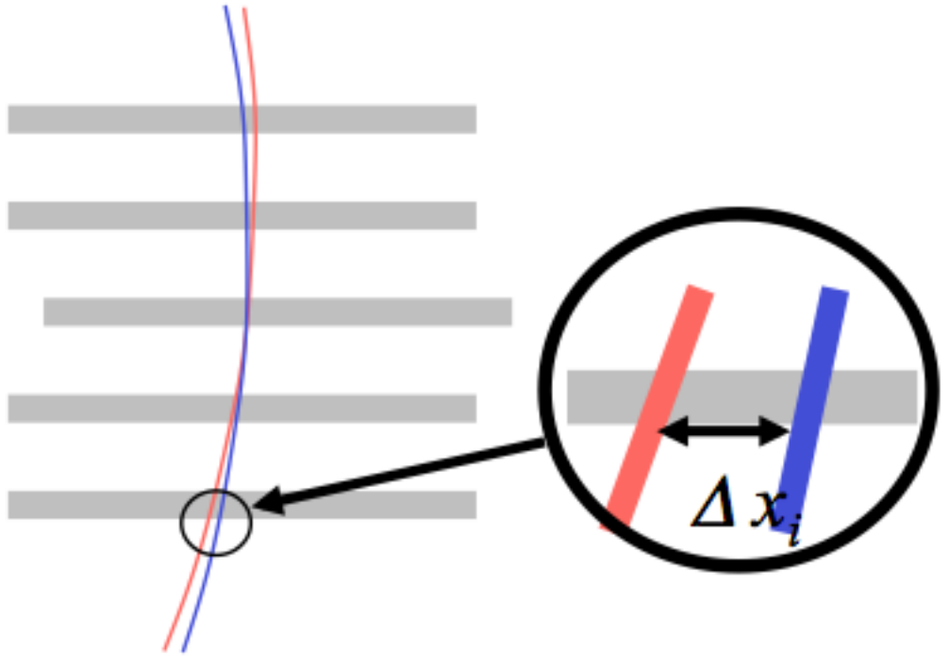
AM-Based L1 Tracking

- Track finding is solved in two stages
  - Stage 1: associative memory
    - Stored “roads” filled with matching stub data
  - Stage 2: track fitting
    - Several track fitting methods studied: principal component analysis (PCA)-based linearized track fit, Hough transform, Retina fit
- Use time multiplexing to reduce rate for each trigger board

Stage 1

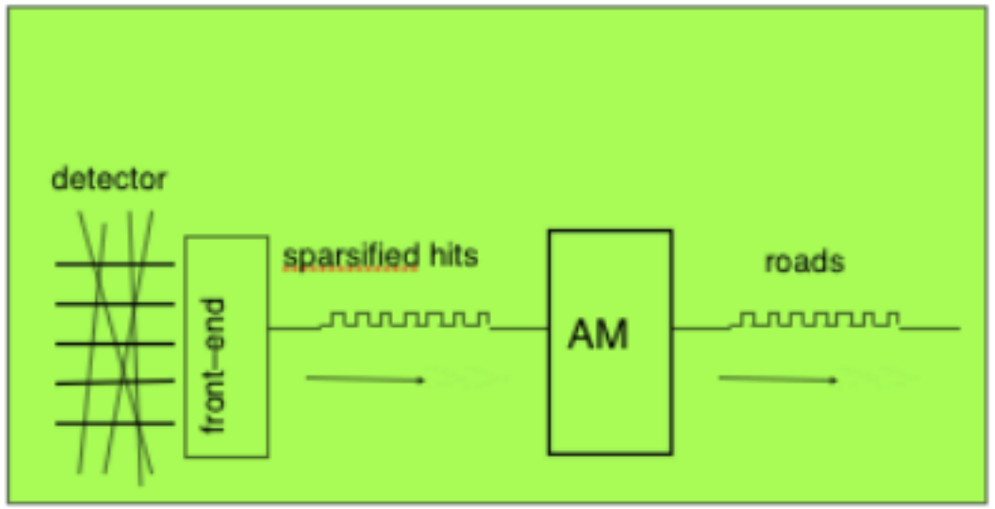


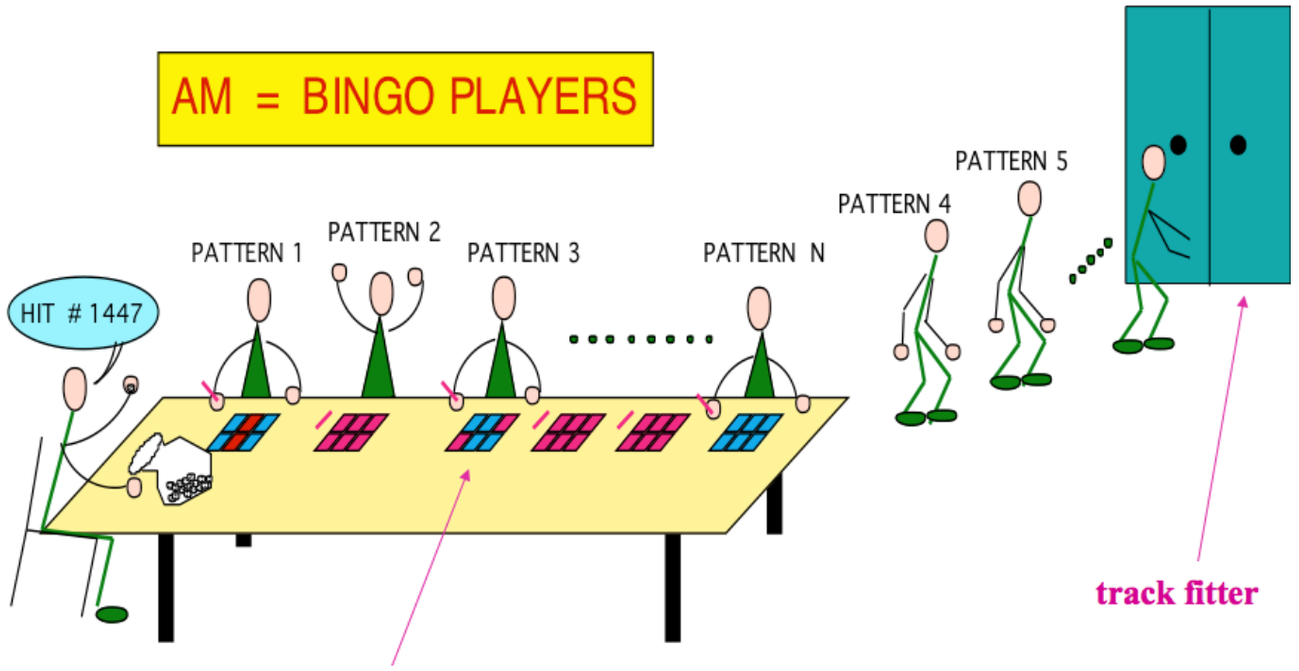
Stage 2



Associative Memory

- Set of patterns stored in Associative Memory (AM)
- Each pattern contains the coordinates of hit at each detector layer of a possible track
- Each coordinate is compared to all the patterns in parallel
- Pattern recognition is complete as soon as the last hit is read
- **Time dependence linear in number of stubs**
- Already used successfully in HEP experiments (CDF), will be installed in ATLAS (after L1) during LHC phase I (FTK system).

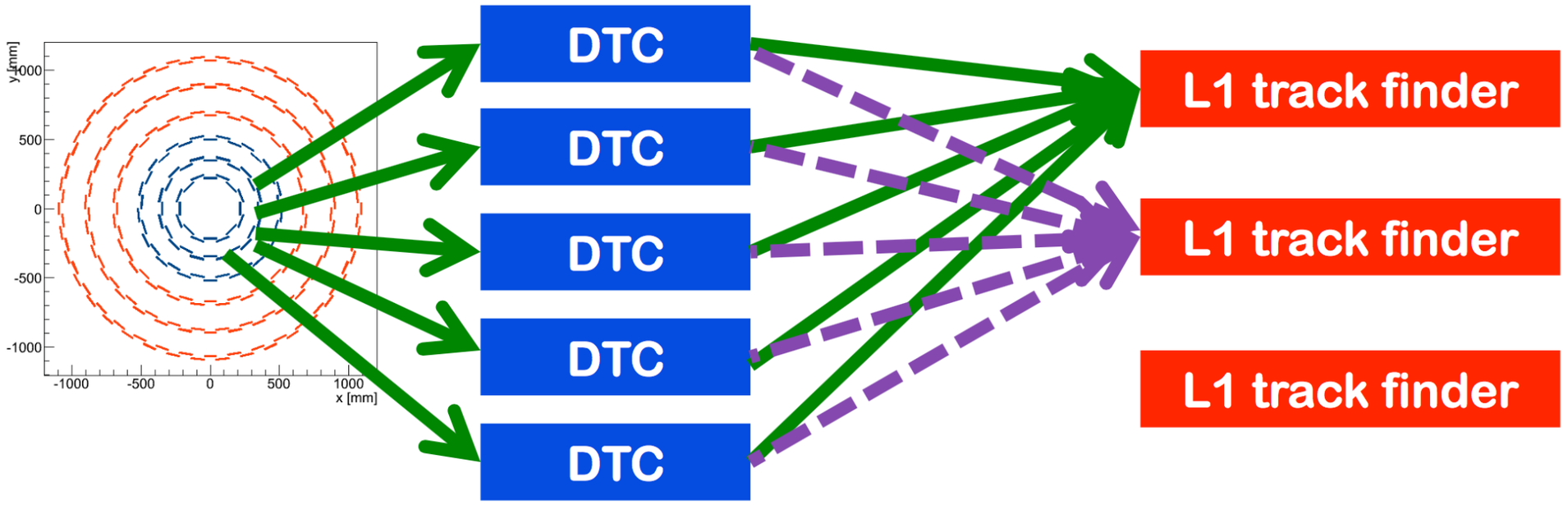




Lower granularity bins

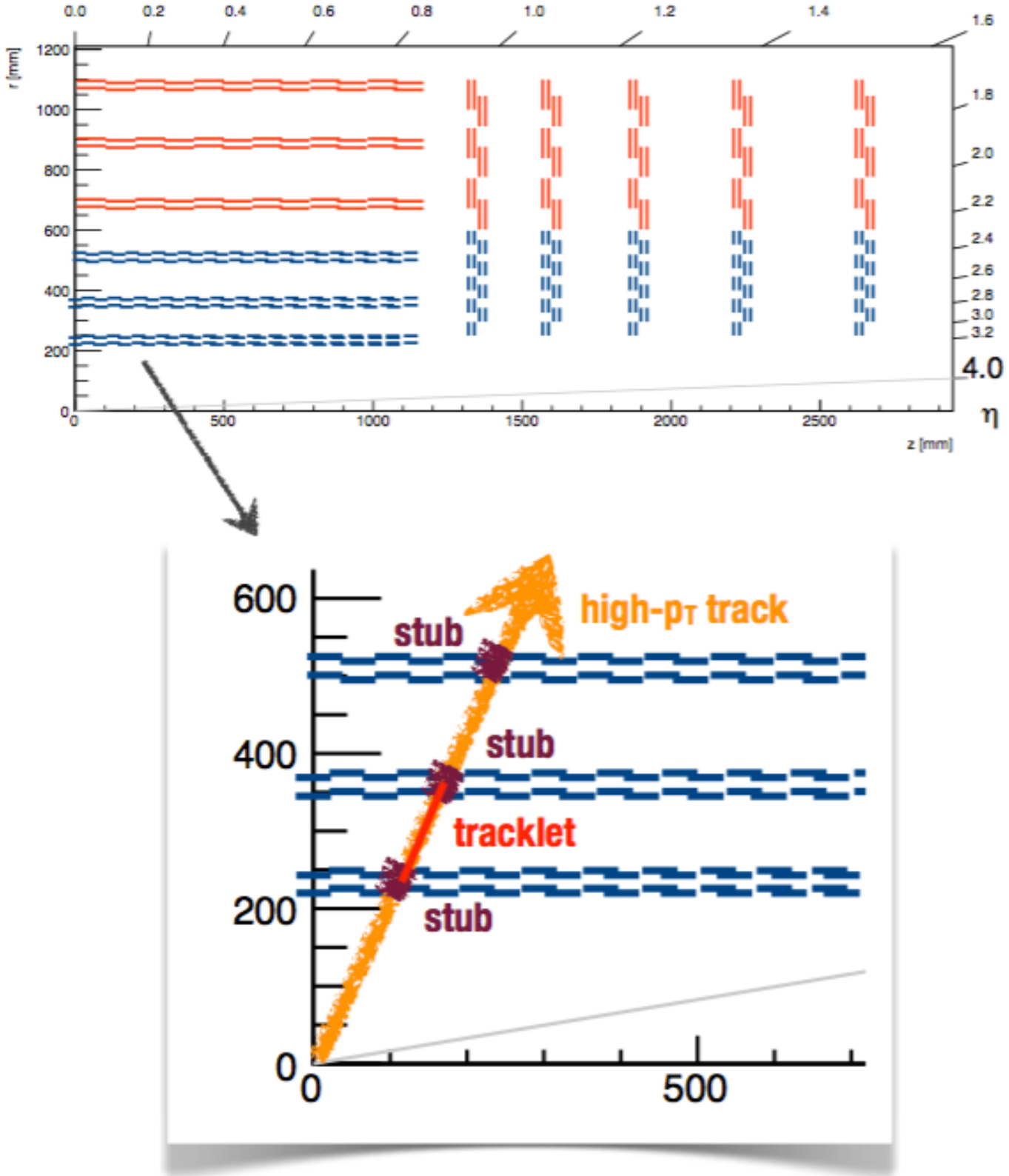
Geometry-Based Time-Multiplexed Trigger

- Same concept used for 2016 CMS calorimeter trigger upgrade
    - Build on foundation of design ideas and features known to work
- Multiple sources (DTC cards) send data to L1 track finders for complete event processing
    - Divide the tracker in 5 rapidity regions
    - Process each region with a time multiplexing factor of 24
- Pattern recognition: use Hough transform (in FPGA) to identify stub combinations loosely compatible with tracks
- Track fit: done in FPGA, flexible in the specific algorithm
    - e.g. PCA-based linearized track fit



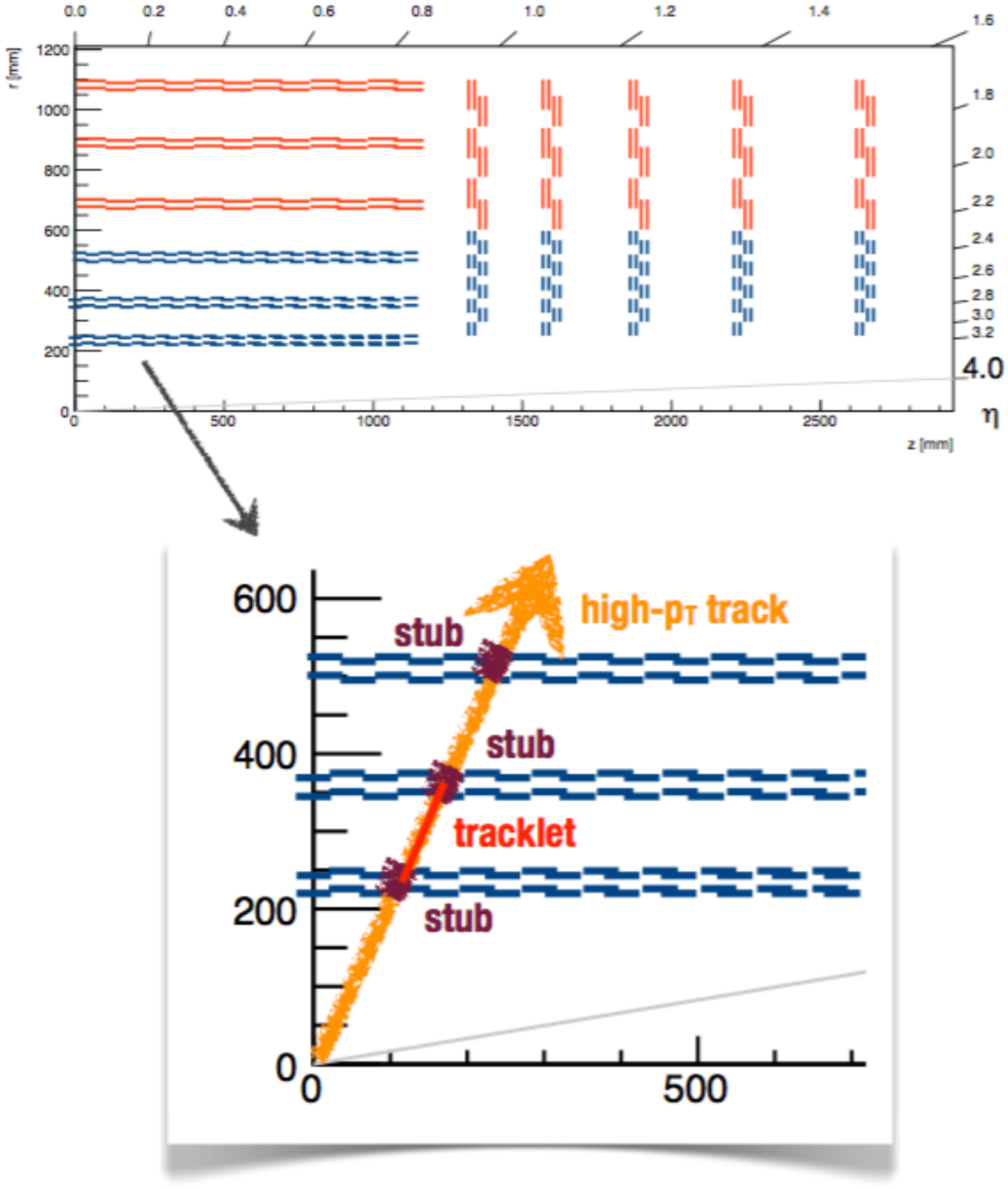
Tracklet-Based L1 Tracking

- Seed
  - Seed by forming tracklets from pairs of stubs in neighboring layers
    - Rough estimate of tracklet parameters from the two stubs + constraint to beamspot
    - Tracklet must be consistent with $p_T > 2$ GeV/c, $|z_0| < 15$ cm
  - Seed multiple times
    - L1+L2, L2+L3, L1+D1, …
- Project
  - Project tracklets to outer layers and disks to search for matching stubs
  - Both inside-out and outside-in
- Fit: Linearized Chi2 fit



Track Fitting

- Different solutions, similar basic ideas for all approaches
- Fit
  - Perform track fit of stubs matched to trajectory
    - e.g. Linearized Chi2 fit, PCA-based linearized track fit, Hough transform, Retina fit
  - Gives final track parameters (p_T, η, phi_0, z_0 and optionally d_0)
- Duplicate removal
  - A given track can be found many times
  - Ensures high efficiency
  - Removes duplicates, e.g. based on χ2

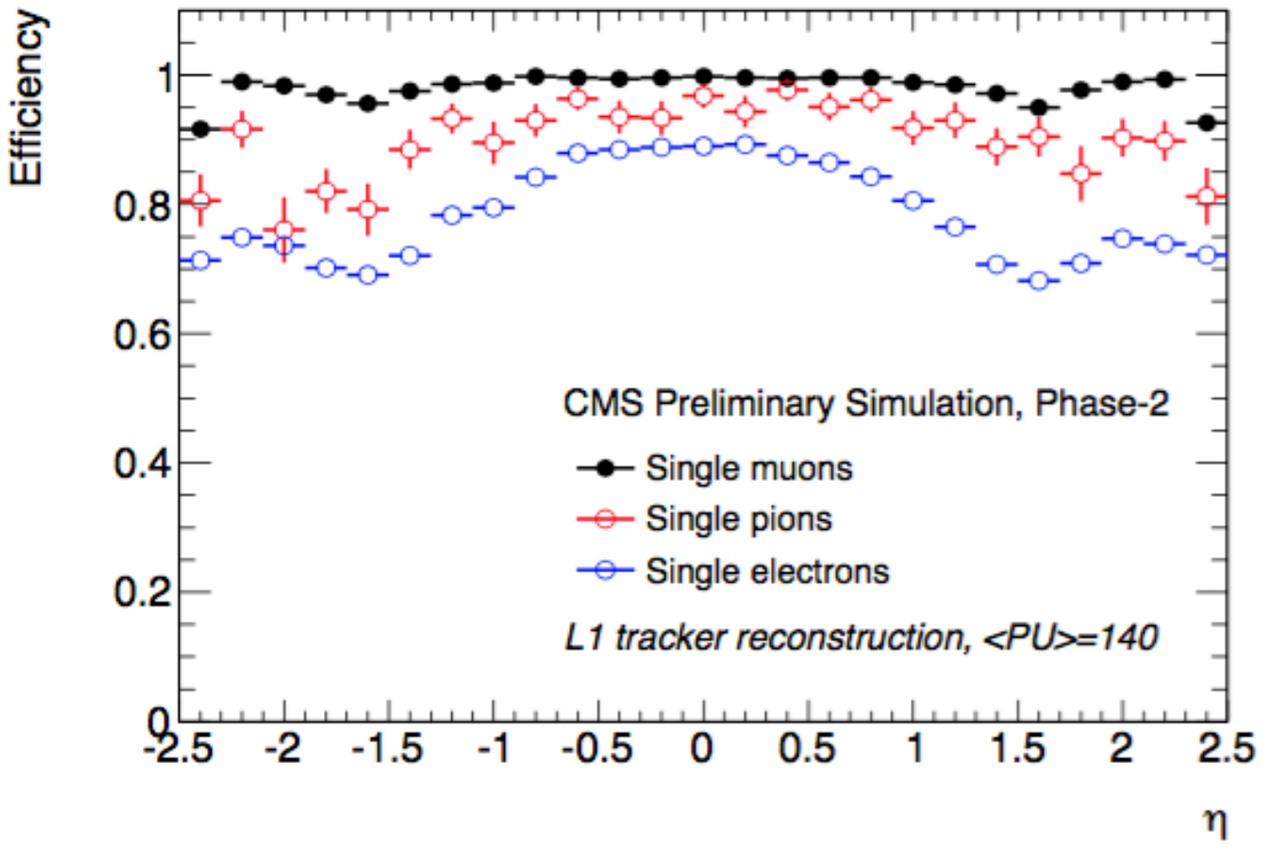


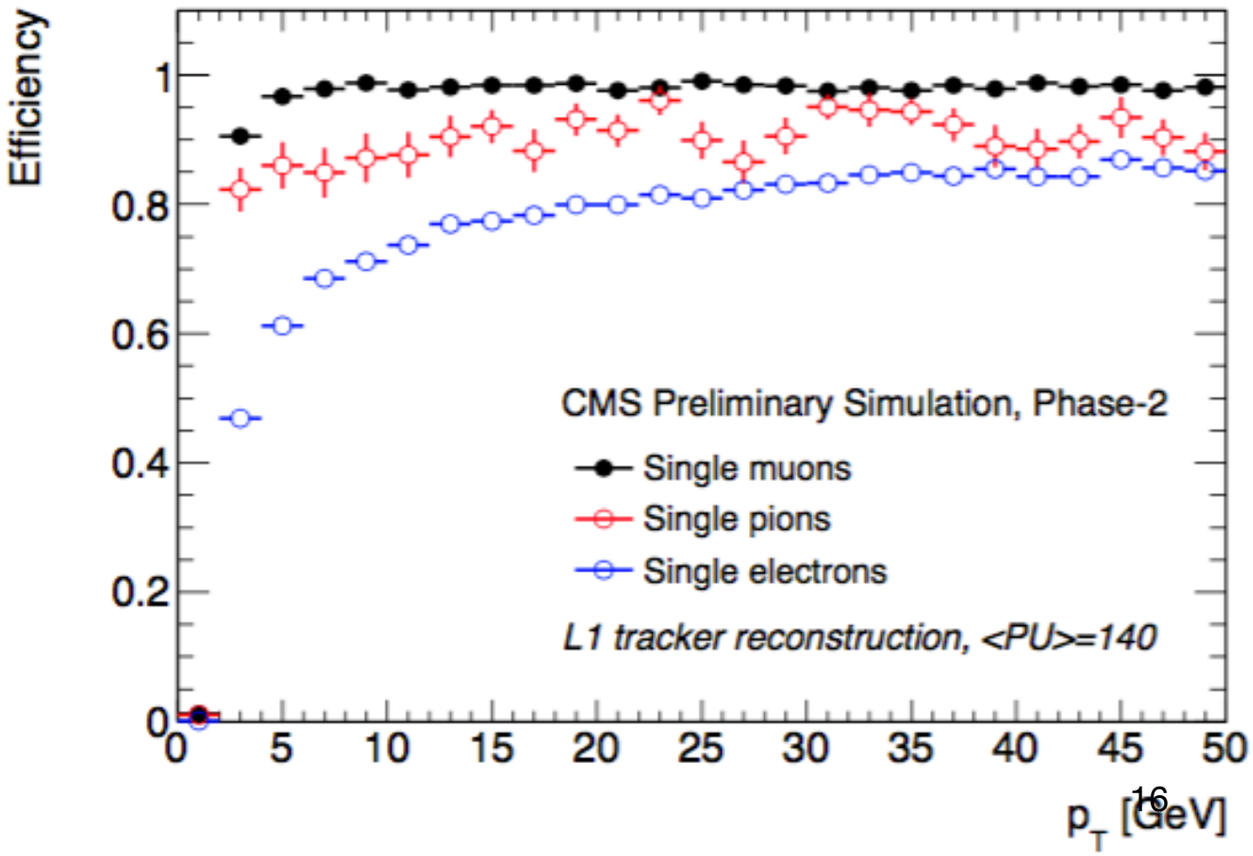
Tracking Performance

- Evaluate L1 tracking performance using simulation
- Results shown for floating-point implementation of algorithm
- Study performance for single-gun particles
  - Single μ, e, π of positive & negative charge
    - Generated with flat p_T spectrum
    - Events have <PU>=140 & bunch spacing = 25 ns @ 14 TeV
    - Efficiencies defined w.r.t. truth tracks corresponding to single-gun particle
- L1 track selection
  - Kinematics $p_T > 2$ GeV, $|\eta| < 2.5$
  - Quality $\chi 2 < 100$, track has ≥ 4 stubs
- Performances shown for tracklet-based tracking, similar performances are expected with AM+FPGA with linearized track fit

Tracking Efficiency

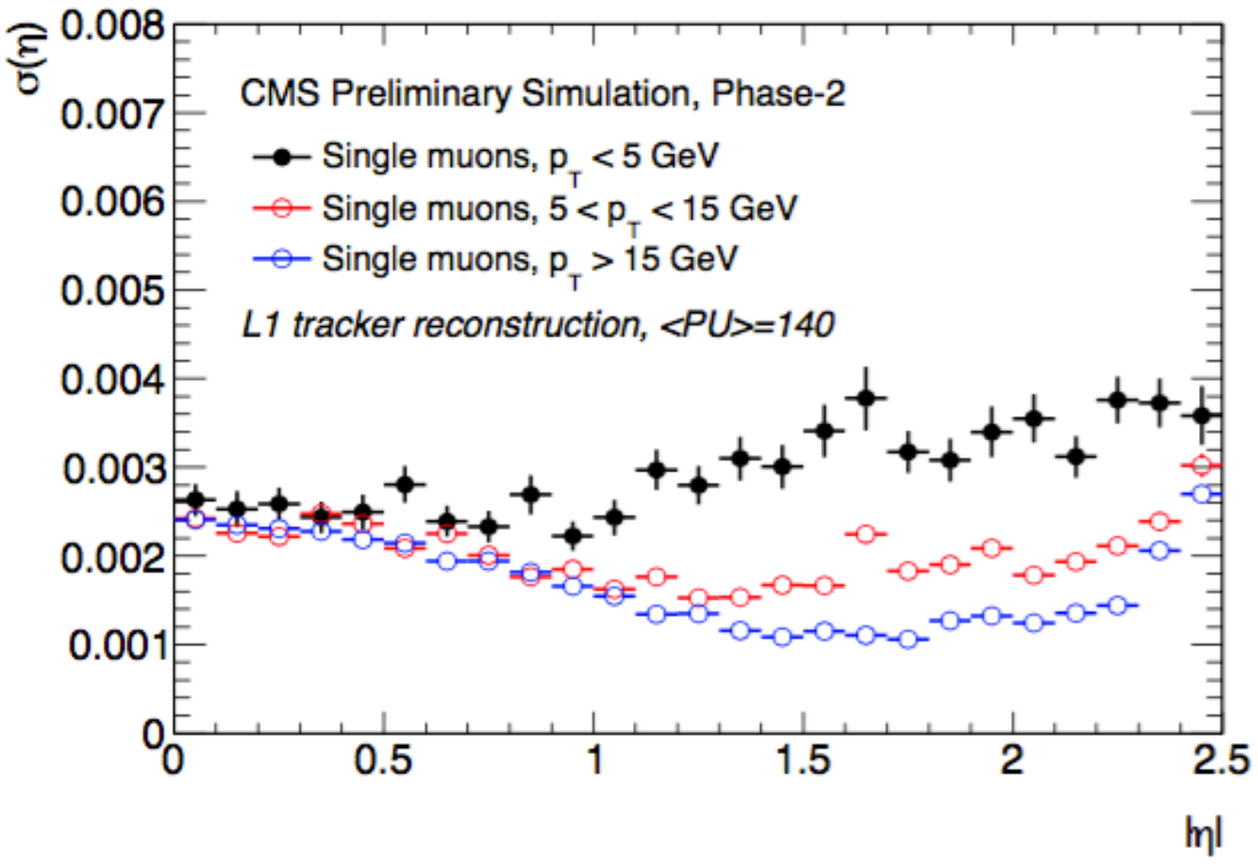
- L1 tracking efficiency as function of η & p_T for single μ, π, e with <PU>=140
  - Muons Sharp turn-on at 2 GeV & high efficiency across all η
  - Pions Somewhat lower efficiency due to higher interaction rate
  - Electrons Slower turn-on curve, efficiency reduced from bremsstrahlung
- For $|\eta| < 1.0$ & $p_T > 2$ GeV, efficiency for μ, π, e is >99%, 95%, 87%

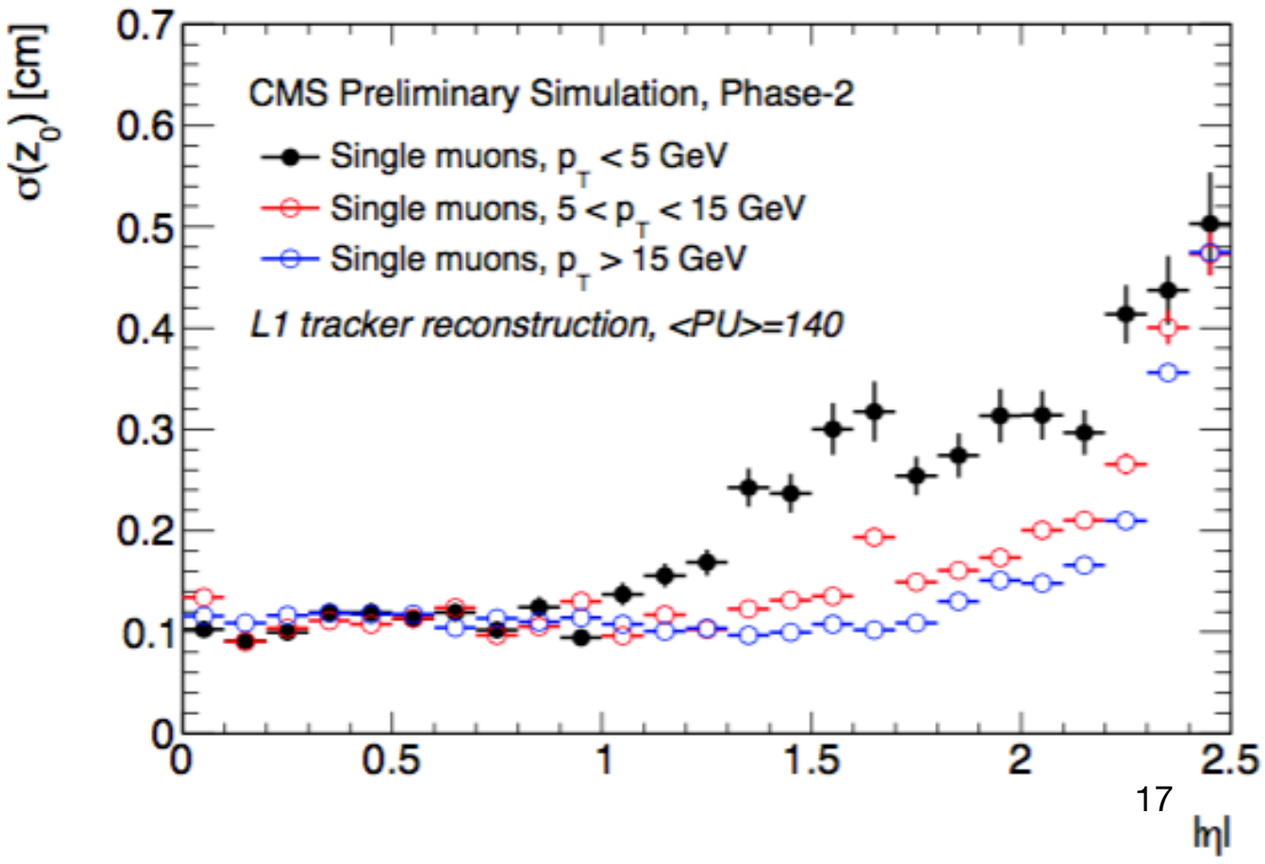




Track Resolutions

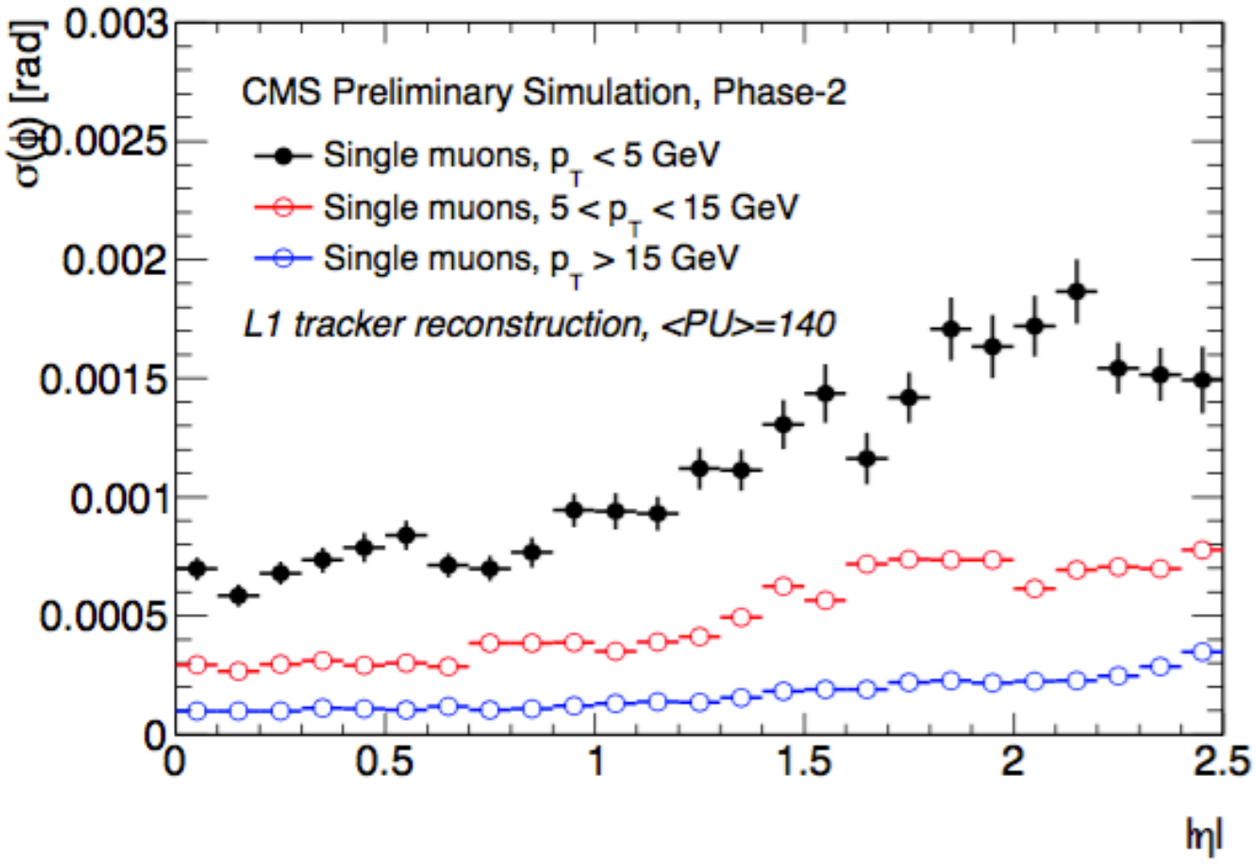
- L1 track parameter resolutions for single muons in events with <PU>=140
- Here, η & z_0 resolution vs |η| for three ranges of p_T
  - σ(η) ~0.002 for high p_T tracks
  - σ(z_0) ~1mm for a wide range of η despite large extrapolation distances thanks to PS modules

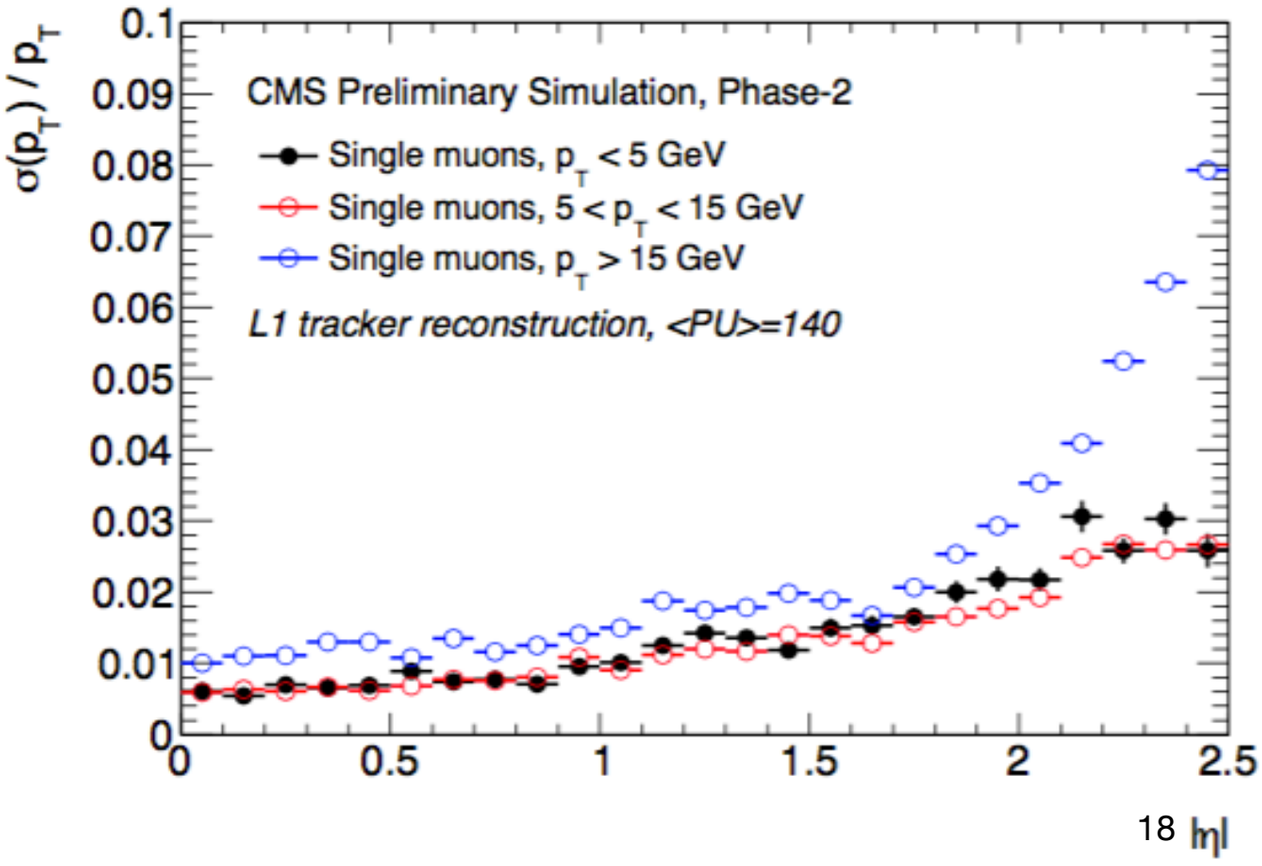




Track Resolutions

- L1 track parameter resolutions for single muons in events with <PU>=140
- Here, ϕ & p_T resolution vs |η| for three ranges of p_T
  - σ(ϕ) ~0.0003 for 10 GeV track at central η
  - $\sigma(p_T)/p_T$ ~1% at central η for high-p_T track

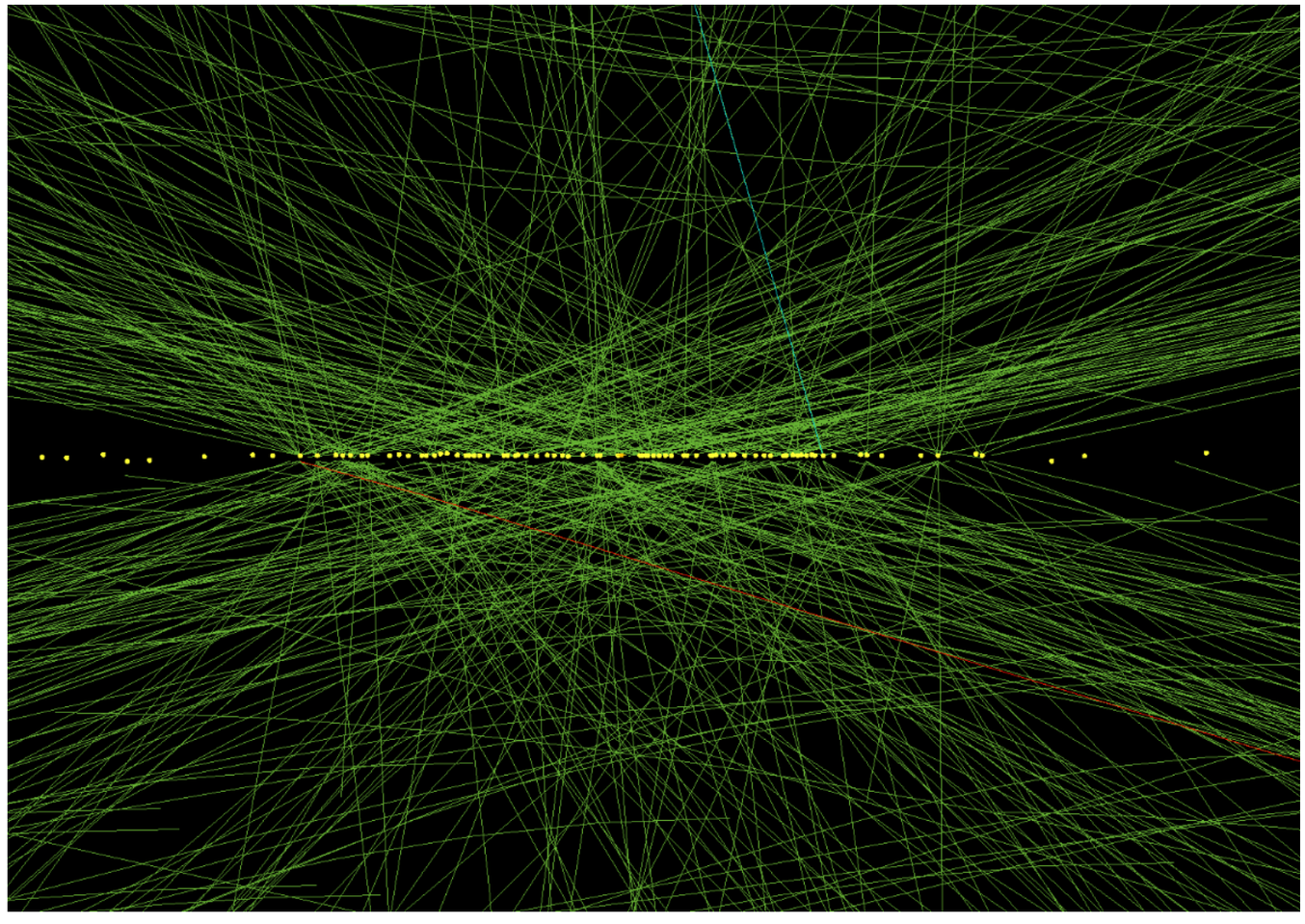




Toward Triggers

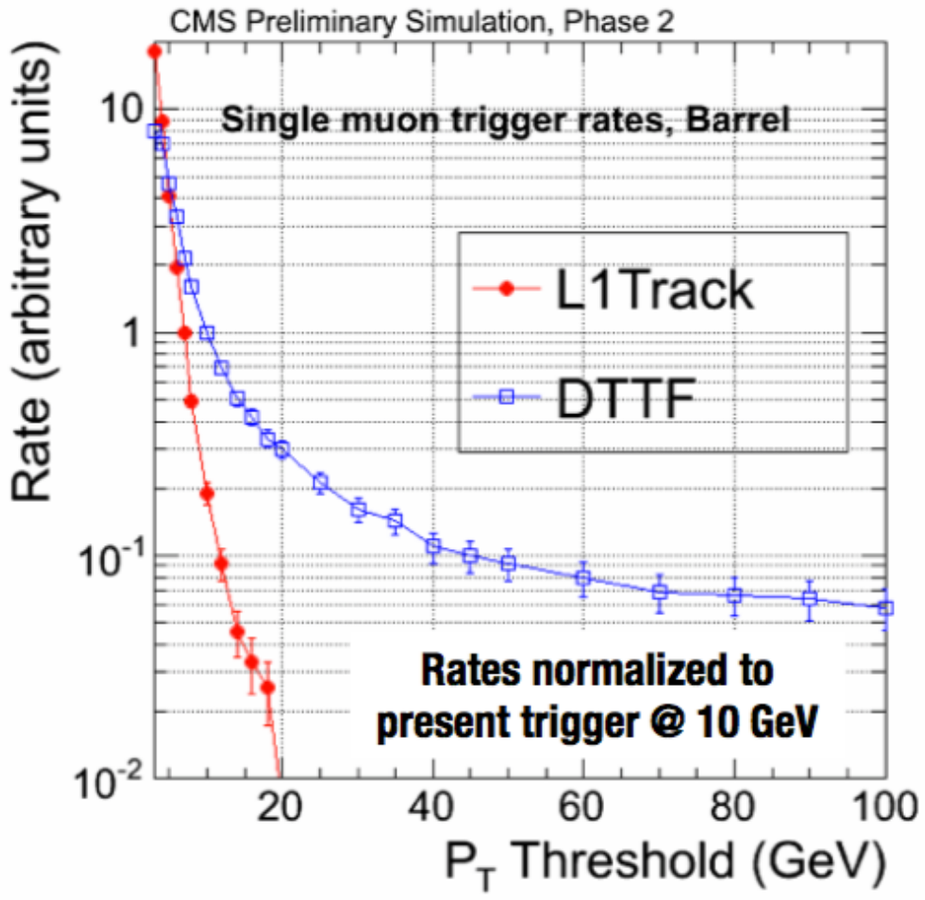
- To use the tracking, must combine L1 track information with L1 trigger objects
- The following assumes tracks with similar performance as previous slides
- How does track trigger help reduce rates?
- Leptons...
  - Add track isolation
  - Improved p_T measurement
  - Determine z position
- Photons...
  - Add track isolation
- Hadronic...
  - Determine z position & require jets to originate from common vertex to reject jets from PU interactions
  - Multijet, H_T (sum of transverse energies) & missing H_T triggers
- Primary vertex & track missing transverse energy (MET)

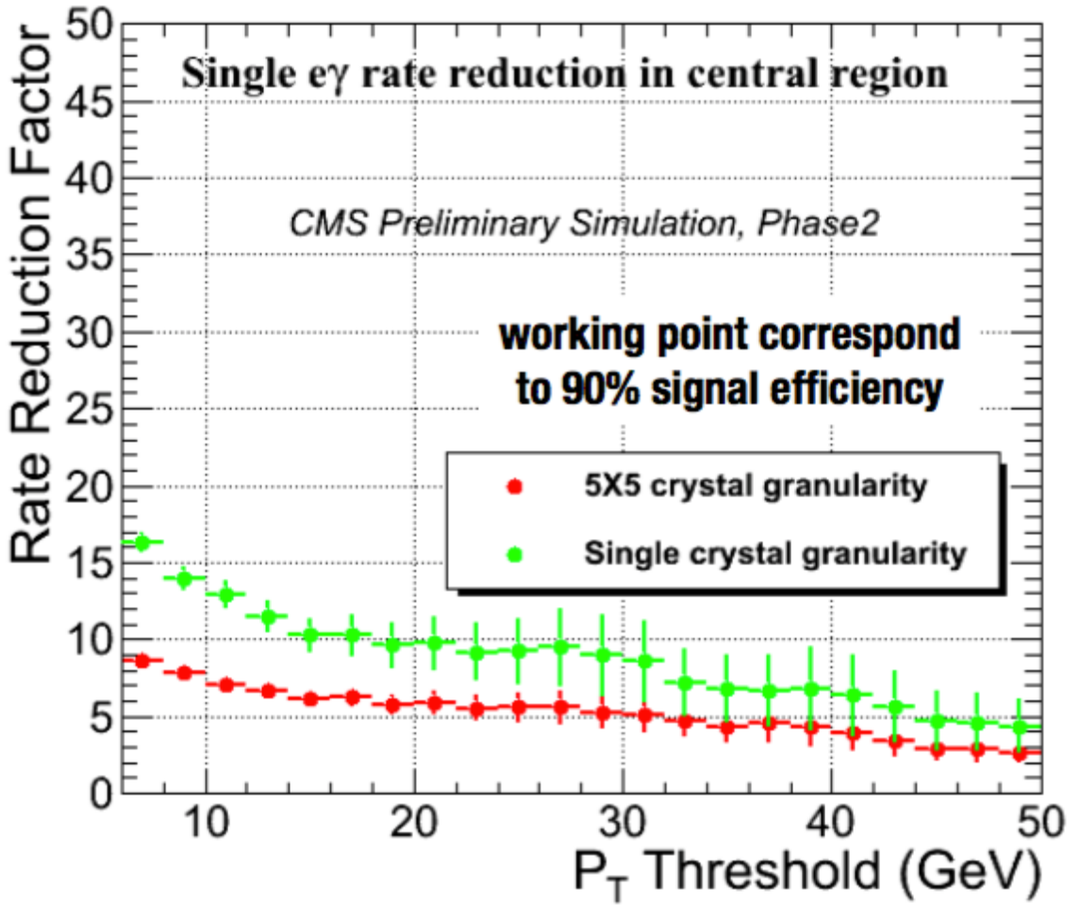
...



Muons and Electrons

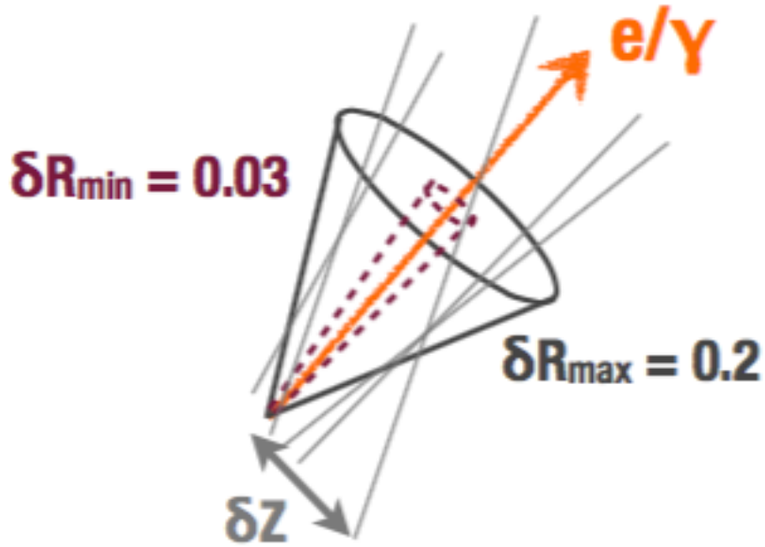
- Muons
  - Rates flatten at high thresholds
  - Matching to L1 tracks → factor >10 reduction for p_T > 14 GeV (w/o track isolation)
- Electrons
  - Match L1 e/γ objects to stubs
  - Factor ~10 (~6) rate reduction for single (current 5x5) crystal granularity @ 20 GeV
- Additional factor ~2 rate reduction with L1 track-based isolation



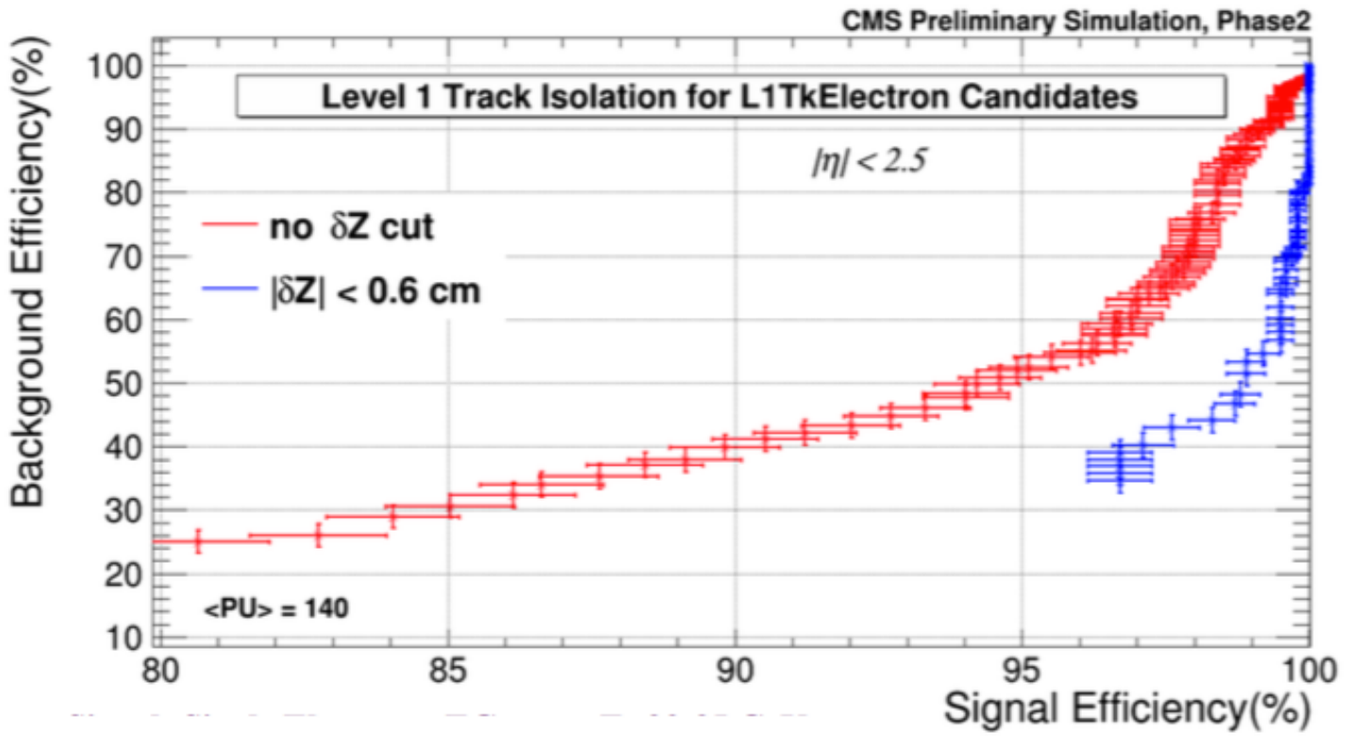


Track Isolation

- Track-based isolation for electrons
- Define relative isolation =
  $\sum p_T$(track) / E_T(e/gamma)
  - Sum over tracks with $p_T > 2$ GeV
  - Without or with δZ cut

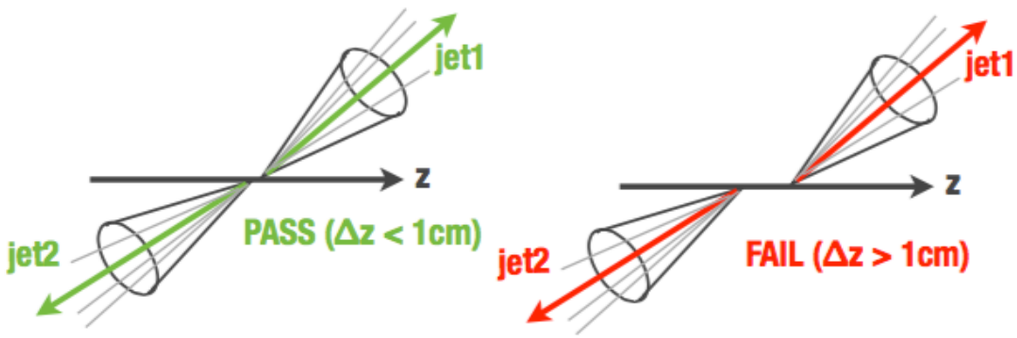


- Isolation efficiency shown for events in which a L1 track-electron candidate with $E_T > 20$ GeV was found
  - Signal is single electron events (<PU> = 140) with E_T = 20-25 GeV
- Can achieve factor 2 rejection for 99% signal efficiency

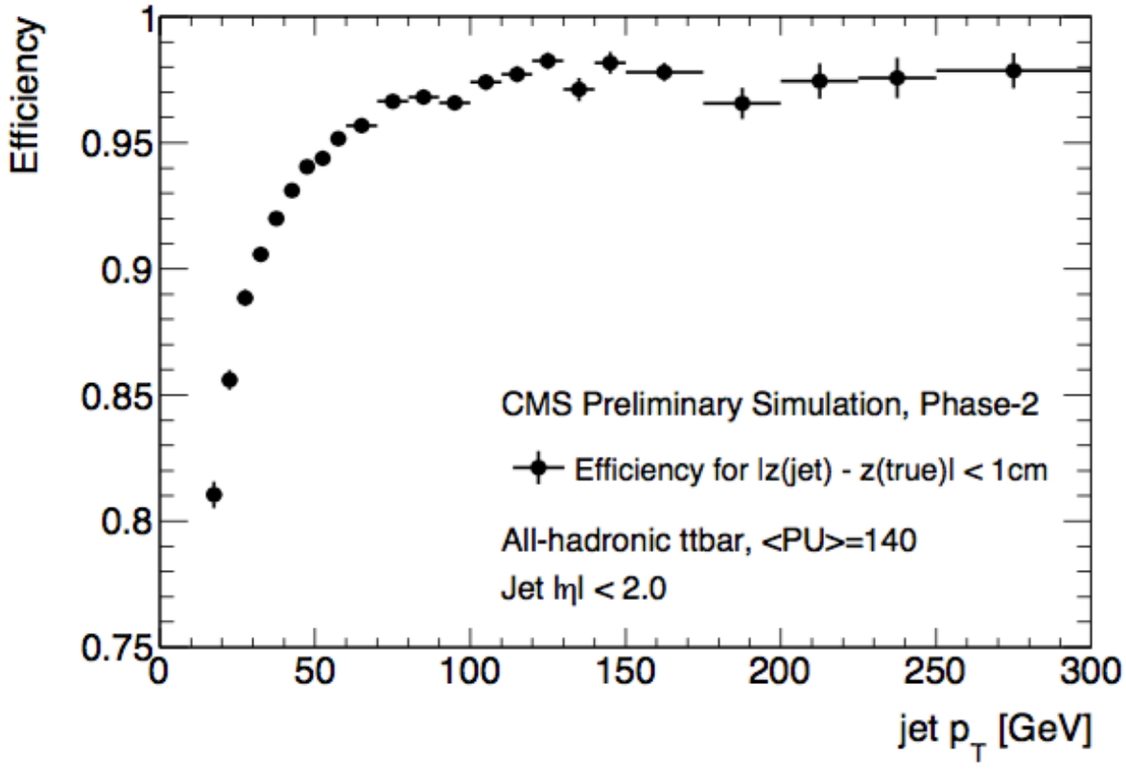


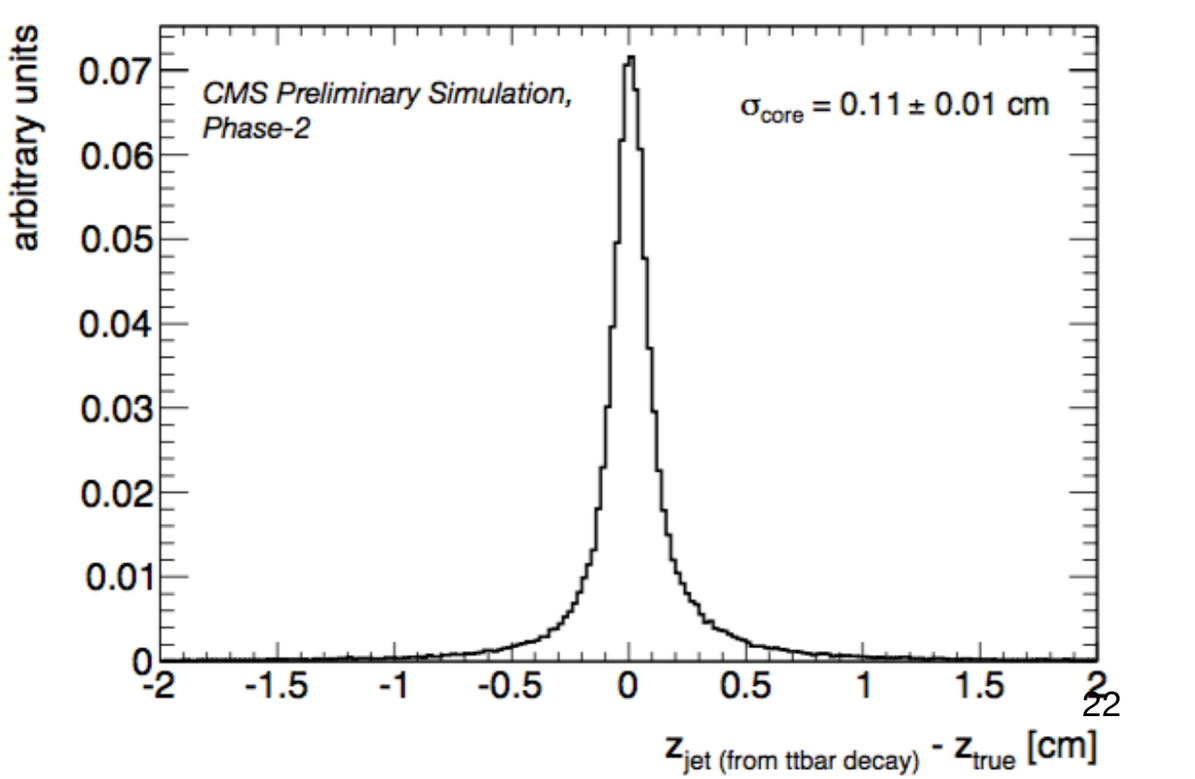
Jets

- Associating jets to nearby L1 tracks to measure z position
- Define hadronic triggers requiring jet vertex consistency
  - Multijet triggers
  - H_T (missing H_T) triggers



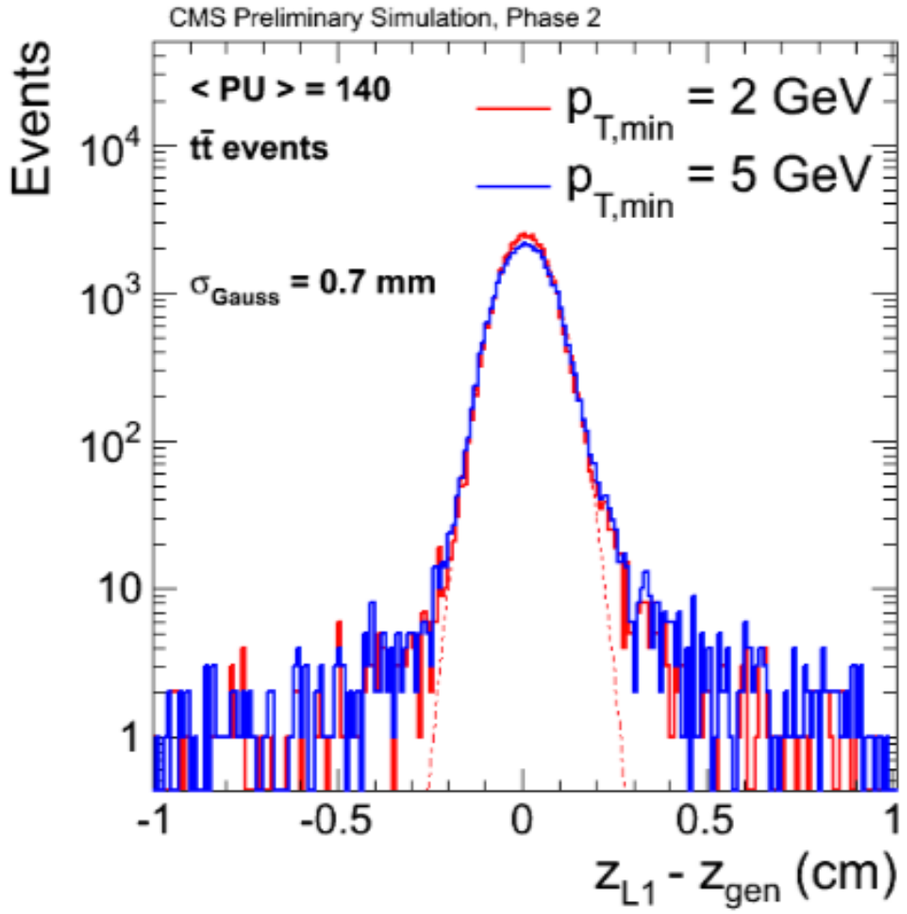
- High efficiency to measure z position & ~1mm resolution (all-hadronic ttbar)



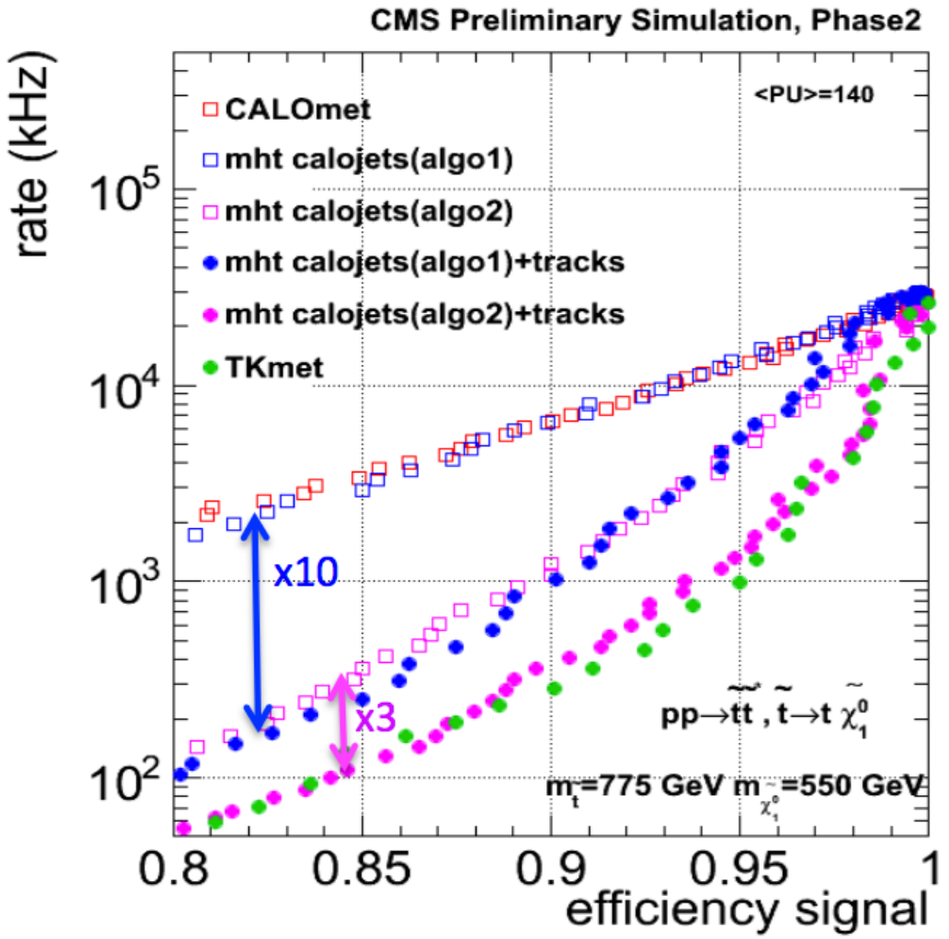


Track-Based MET

- Use L1 tracks to reconstruct primary vertex
- <1mm resolution for events with high track multiplicity
- Define L1 “track MET” variable using L1 tracks from primary vertex



- Rate reductions for SUSY signal
  - Stop pair production with hadronic top decays
  - Missing H_T determined with/without vertex association
    - Two L1 calorimeter jet algorithms, different PU subtraction methods
  - Sizable rate reductions



Conclusions

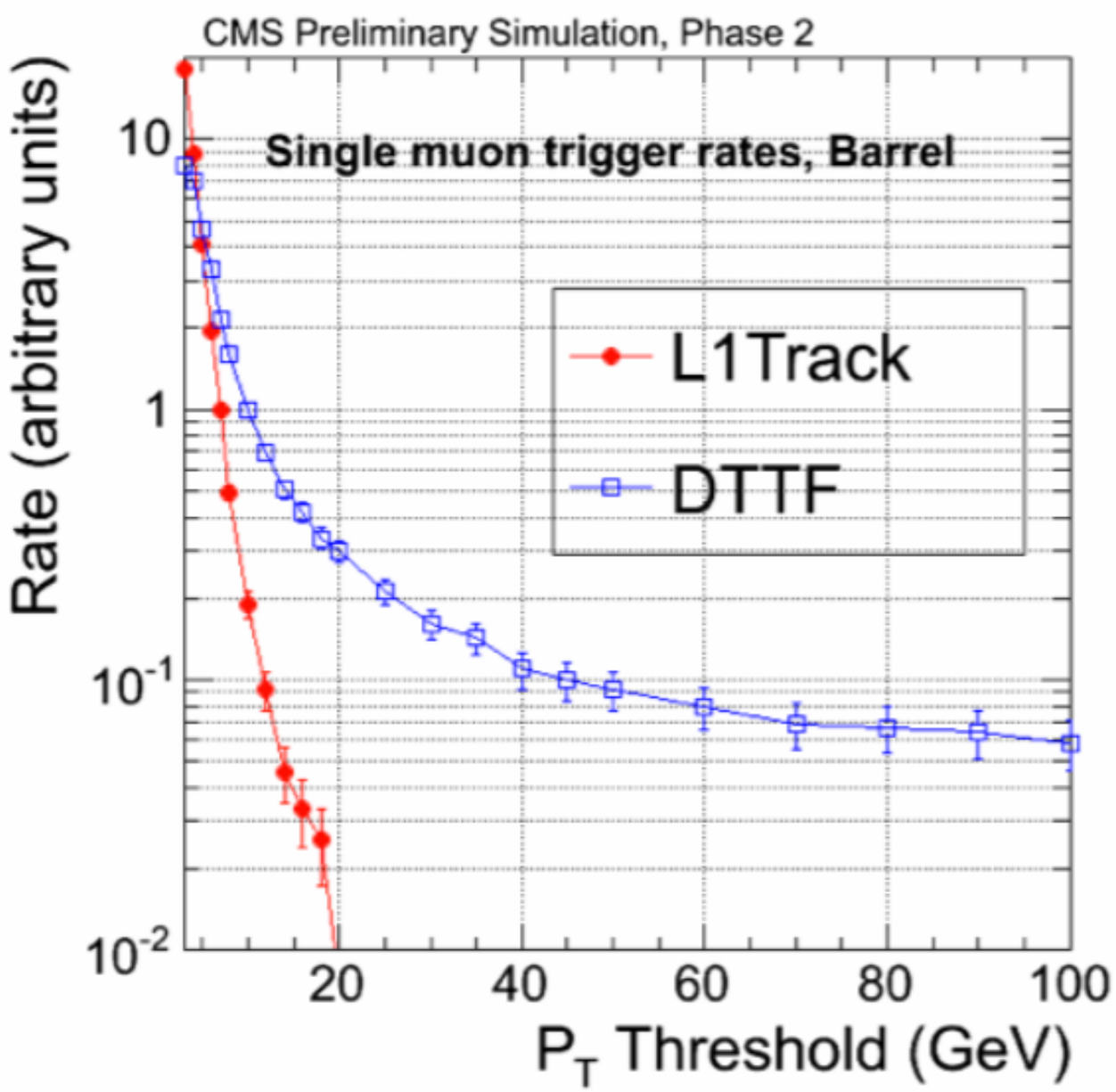
- New central tracker with triggering capabilities for CMS for phase-2 upgrade
  - Different approaches to tracking at L1 studied in parallel
  - Simulation of algorithms integrated to CMS software framework
  - Studies of their performance show very promising results!
    - High efficiency & precise track parameters achieved E.g. $\sigma(z_0) \sim 1$mm & $\sigma(p_T)/p_T \sim 1\%$ for wide range of η
- Incorporating L1 track information to L1 trigger gives sizable rate reductions
  - Factor ~10 in e/μ identification
  - Factor ~2 in track isolation
  - Large rate reductions also for hadronic triggers
- Including tracking information at the L1 trigger important to achieve necessary rate reductions as driven by the physics!

Thank You

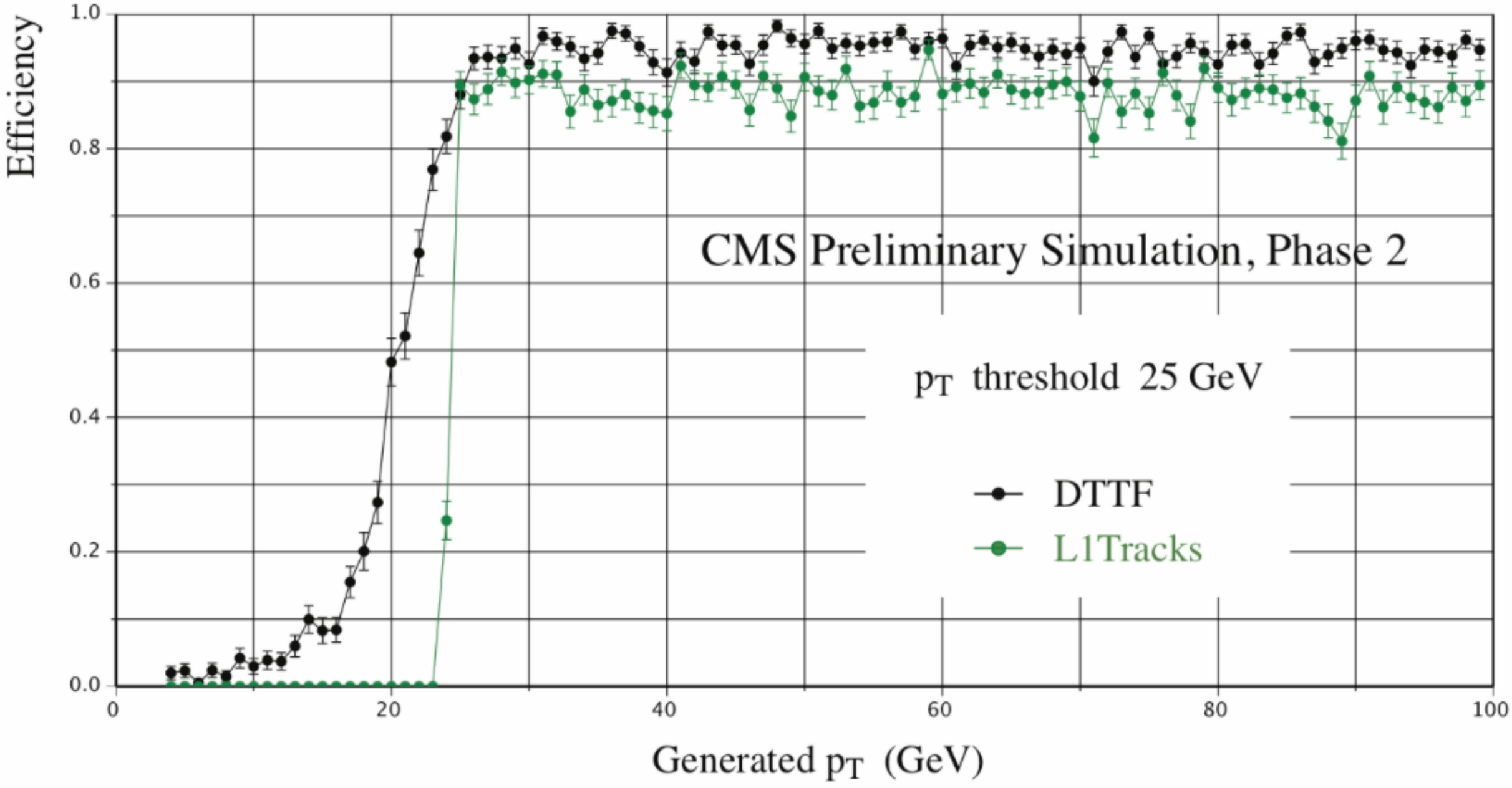
Backup

Muons

- Rates for drift tube trigger primitives (DTTF) flattens at high thresholds
- Matching DT trigger primitives with L1 tracks gives large rate reduction
- Factor >10 reduction for p_T thresholds above ~14 GeV
  - Not including tracker isolation
- Rates normalized to present trigger at 10 GeV



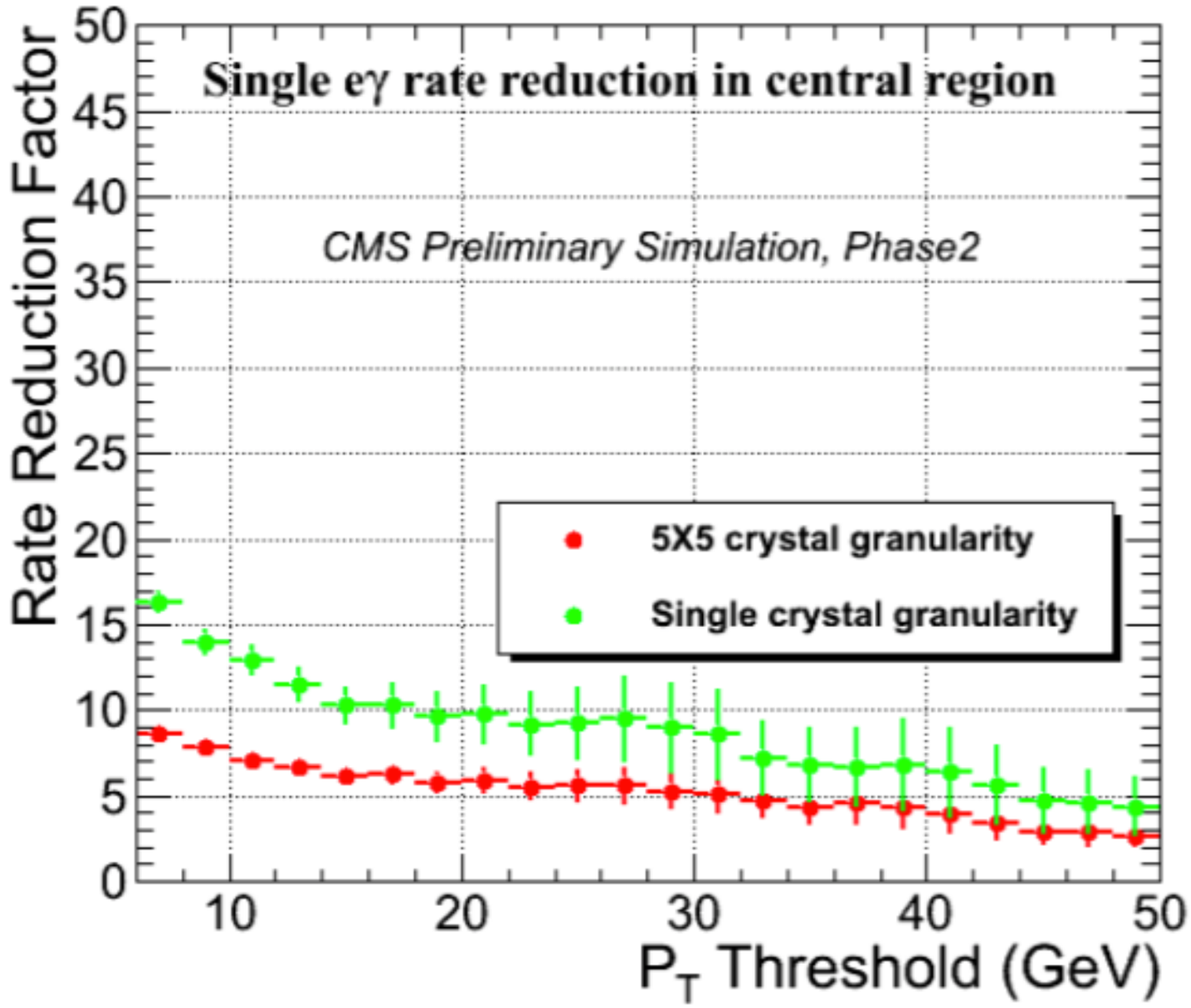
Muons : turn-on curves



Much sharper turn-on curves w.r.t. DTTF, as expected from the much better PT resolution. Hence the contribution from mis-measured low PT muons (which makes most of the DTTF rate) is dramatically reduced.

Electrons

- Matching L1 e/γ objects to L1 track stubs for |η| < 1
- Red curve Current (5x5 crystal) L1 calorimeter granularity Green curve Single crystal-level position resolution
- Better position resolution → improved performance matching L1 e/γ object to tracker
- Working-point corresponding to 90% signal efficiency
- Rate reduction factor ~10 (~6) for single (5x5) crystal granularity for ET > 20 GeV



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  - Without or with δZ cut
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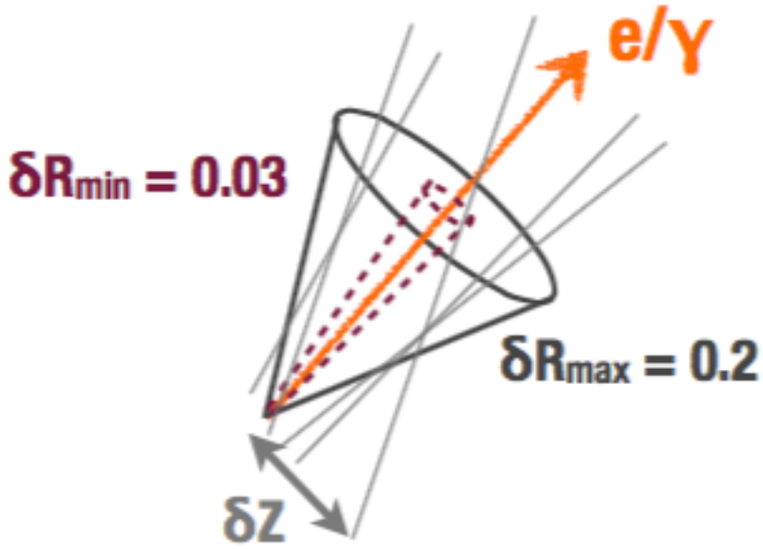
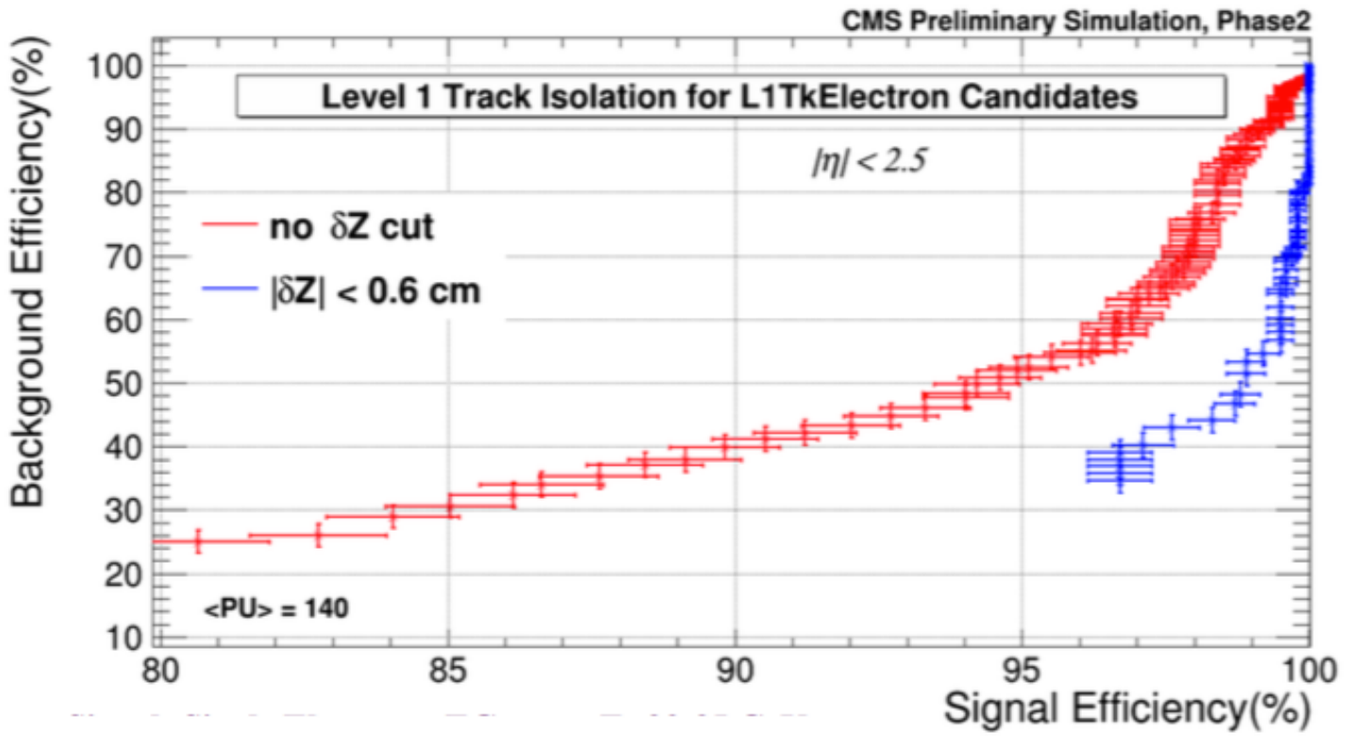
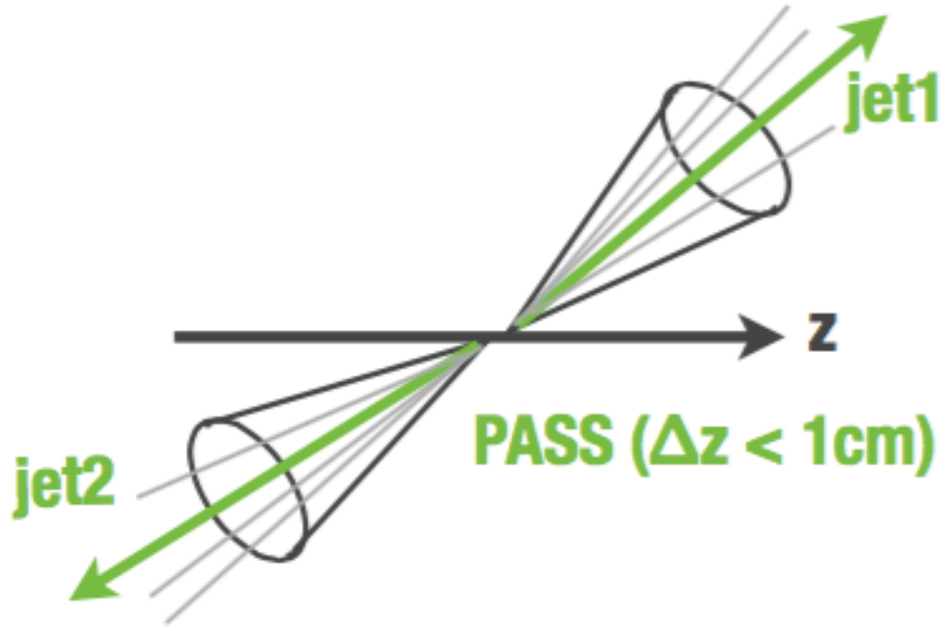
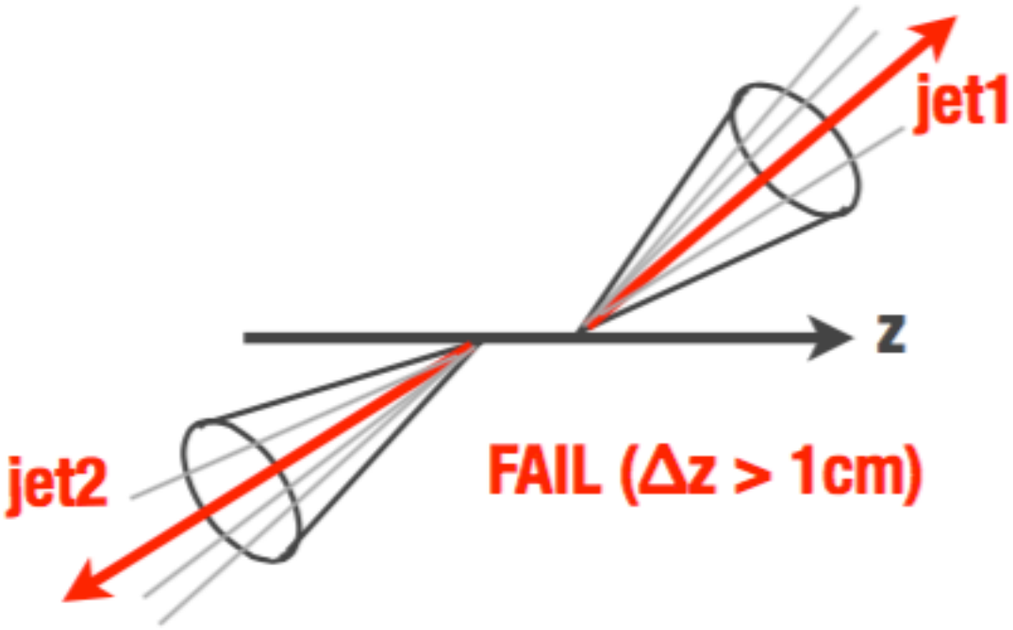




Hadronic Triggers

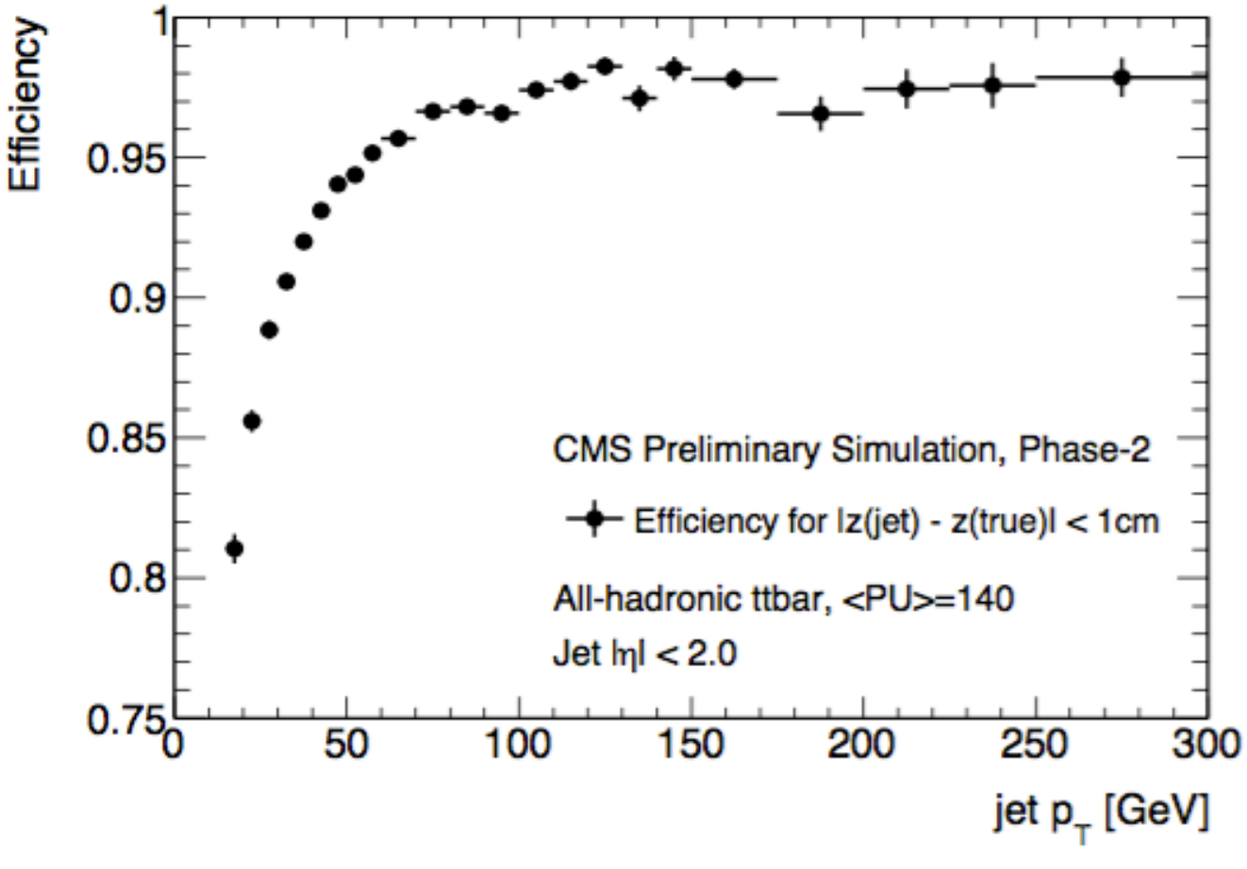
- Jet's z position measured by associating the jet to nearby L1 tracks
- Define hadronic triggers requiring vertex consistency
  - Multijet triggers
    - n jets from same vertex (|z(jet) - zEVT| < 1cm)
- HT (missing HT) triggers
  - No vertex association: HT = sum(jet pT) for all jets (pT > 15 GeV & |η| < 2.0)
  - Vertex association: HT = sum(jet pT) for jets with |z(jet) - zEVT| < 1cm

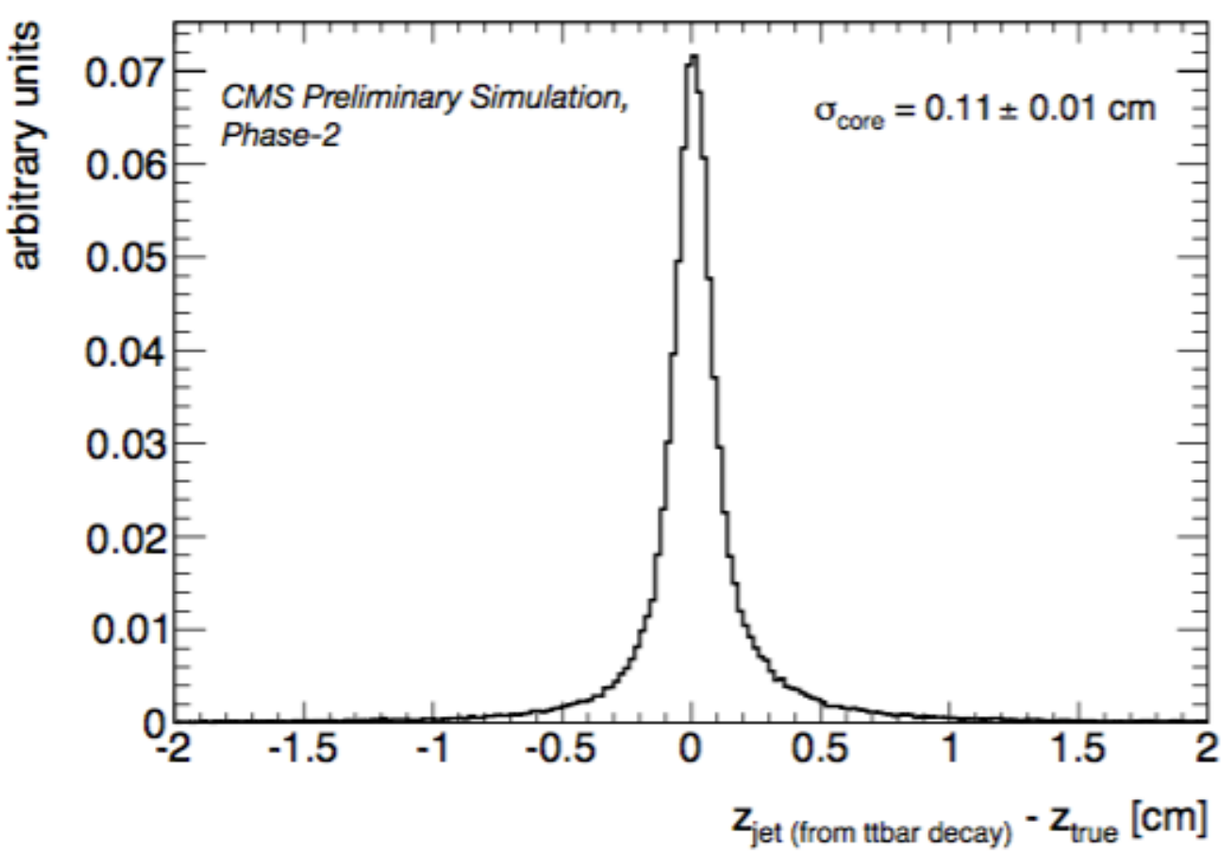




Jet z Position

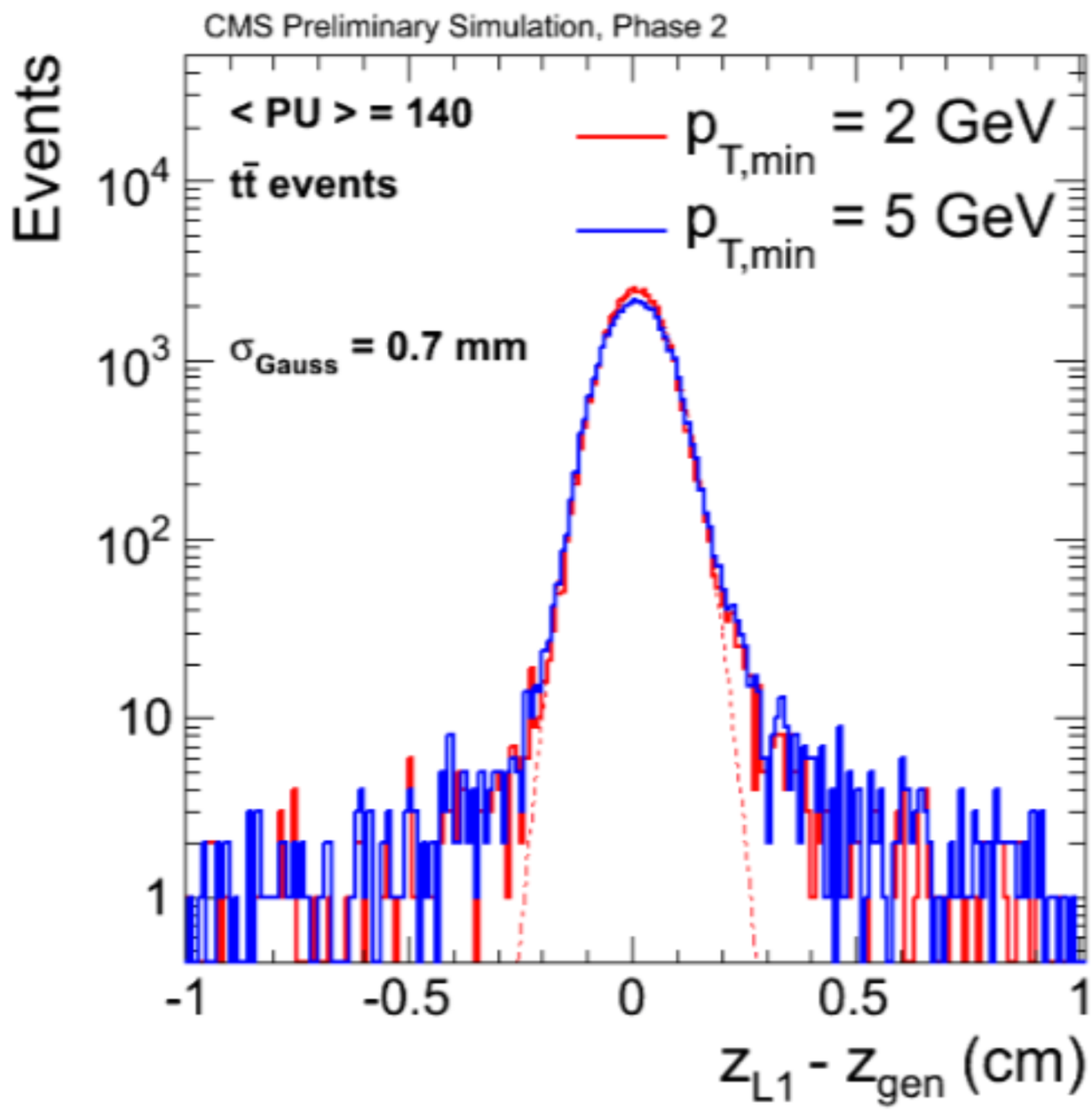
- Jet vertex performance in all-hadronic ttbar events (<PU>=140)
- High efficiency to accurate measure z position (|zjet - ztrue| < 1cm) ~1mm resolution (Gaussian core)





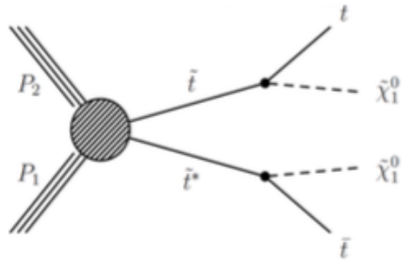
Primary Vertex & Track MET

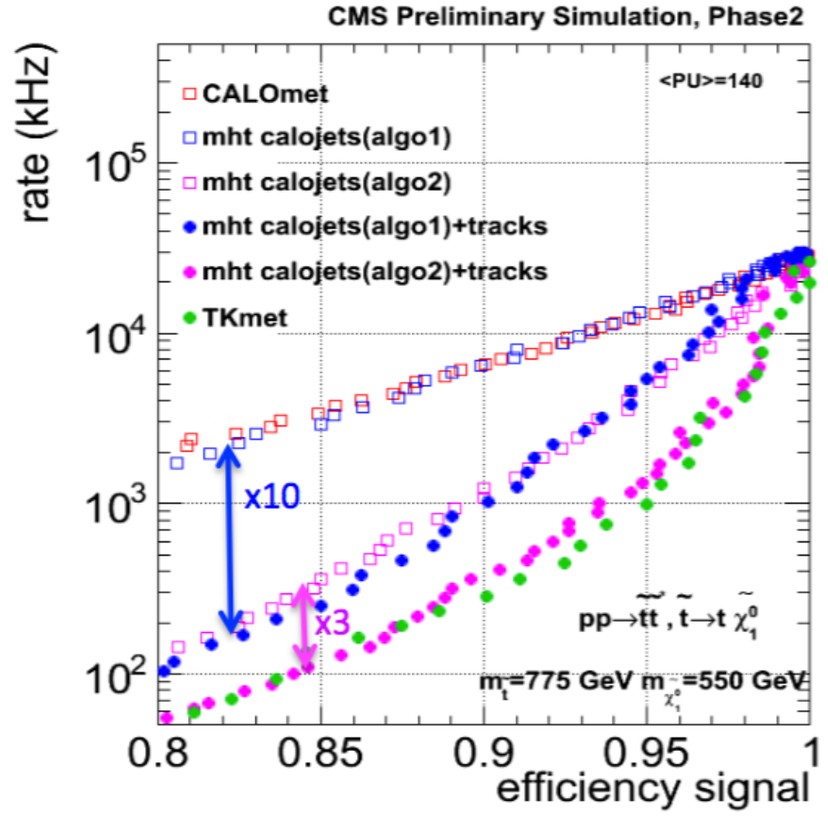
- L1 tracks can also be used to reconstruct primary vertex of event
- Resolution of primary vertex using L1 tracks with pT > 2 GeV or 5 GeV
  - <1mm for events with large track multiplicity
    - Here: ttbar <PU>=140
  - Similar performance with the higher track pT threshold
- Track “MET”
- Define L1 track-based missing transverse momentum from L1 tracks coming from primary vertex

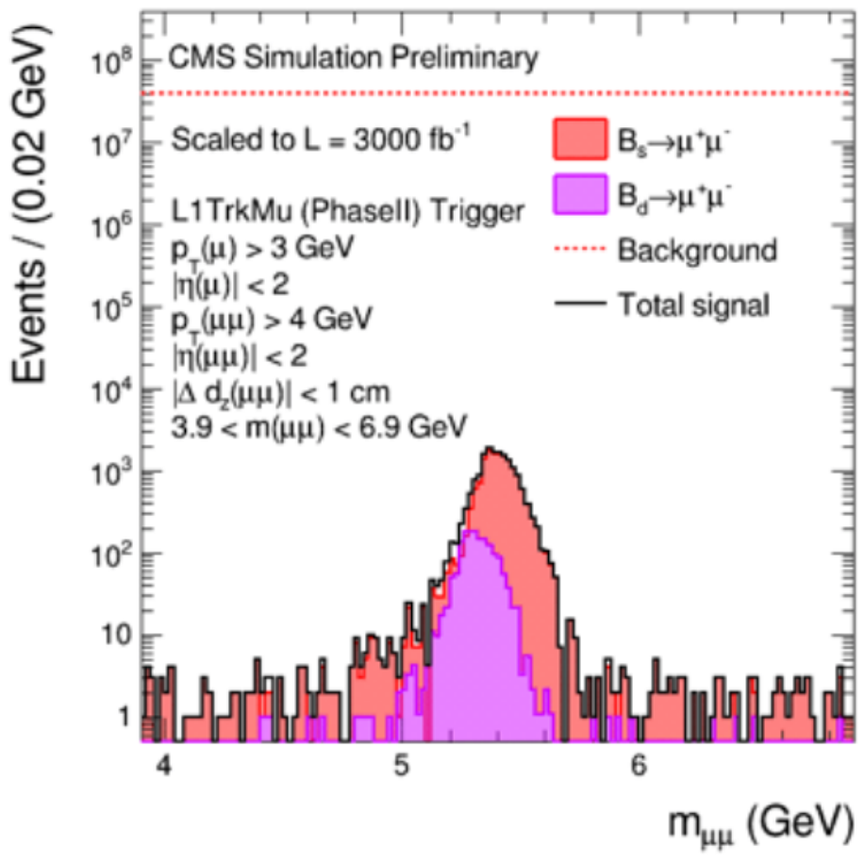


Impact on Physics

- SUSY Signal Point Rate reductions using L1 tracks for SUSY signal
- Stop pair production with hadronic top decays (stop=775 GeV, LSP=550 GeV) Signal defined by genMET > 100 GeV
- Missing HT determined with/without vertex association
  - Algo1 & Algo2: Calorimeter-based L1 jet algorithms with different PU subtraction methods
- Sizable rate reductions achieved with tracking information
- Bs(d)->μμ
  - Approximately current HLT to L1
  - ~ 70 MeV mass resolution
  - Trigger rate (average of 140 PU events) a few hundred Hz
  - Tiny fraction of bandwidth
  - Expected L1 track trigger performance more than sufficient to preserve Run 1 acceptance



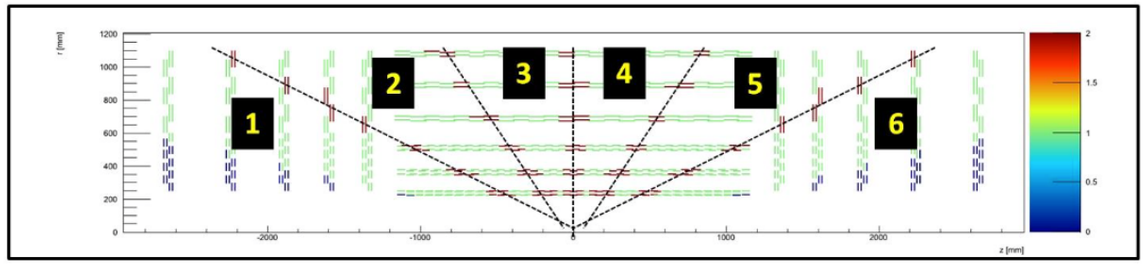




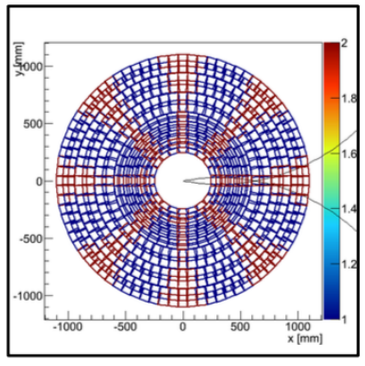
AM-Based L1 Tracking

- Fast
  - Processing time independent of the numbers of hits
  - Robust against PU
  - Provides a clean environment to any track fit method
- Already used successfully in HEP experiments (CDF), will be installed in ATLAS (after L1) during LHC phase I (FTK system)
- To cope with the huge amount of L1 data (50 Tb/s), the tracker is subdivided into 48 trigger towers: 8(r-ϕ)x6(r-z)
  - Each sector will receive in average 200 stubs per event (and up to 500 in some case) so around 400- 600 Gb/s per trigger towers
  - Patterns bank are generated per sector. 48 sectors -> ≈ 60 M patterns for the full tracker

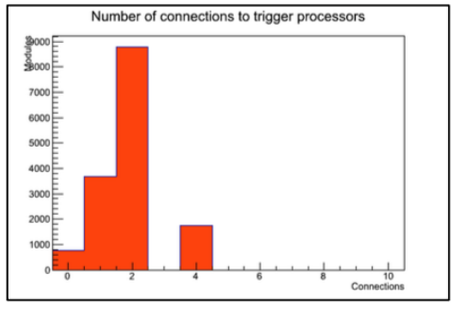
6 divisions in η



8 divisions in ϕ



➢ We don't need to send stubs in more than 4 sectors



Linearized Track Fit

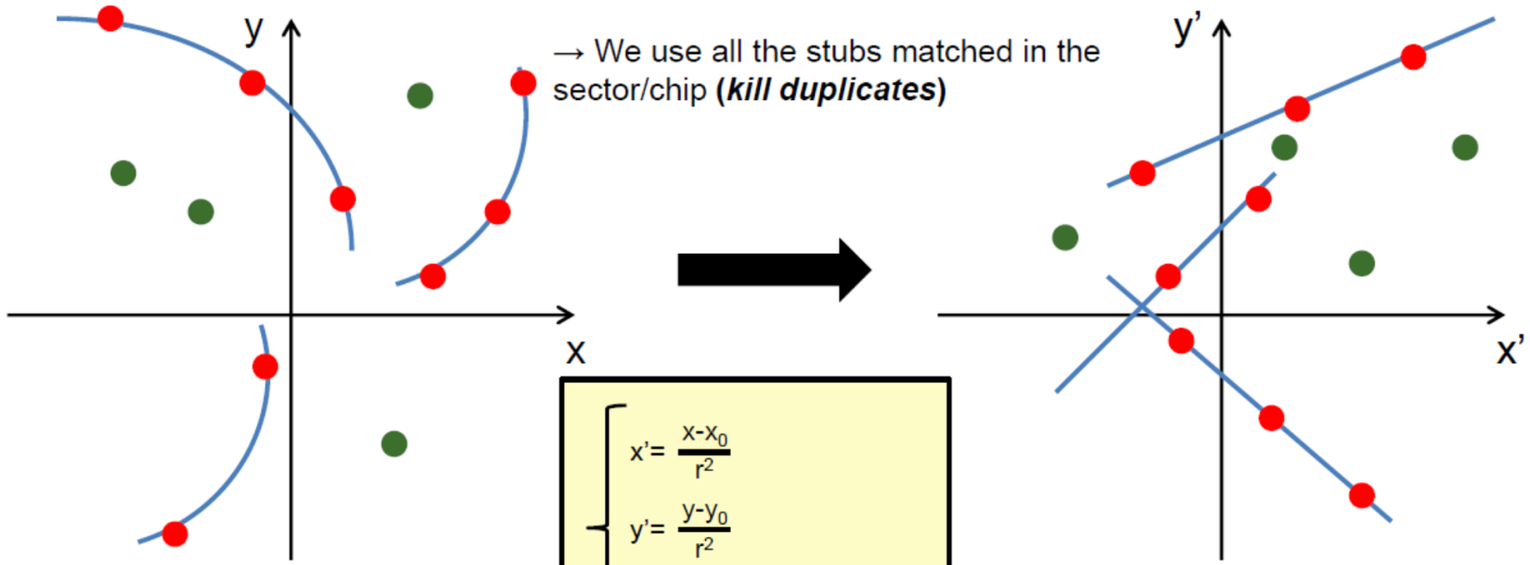
- Various methods of track fitting are being developed
- One example is the linearized track fit which obtains track parameters and χ2 from linear combination of hit coordinates
  - Optimal parameters are estimated from principal component analysis
- Was was used at the CDF SVT
  - New to CMS: 3D fit (SVT was transverse plane only)
  - New to CMS: Endcap region (disk geometry)
- To be implemented in FPGA

Hough Transform

→ **Fast hough transform step 1:** ***conformal space mapping***

→ Transform circles into lines. Need one hit on the circle (x_0,y_0).

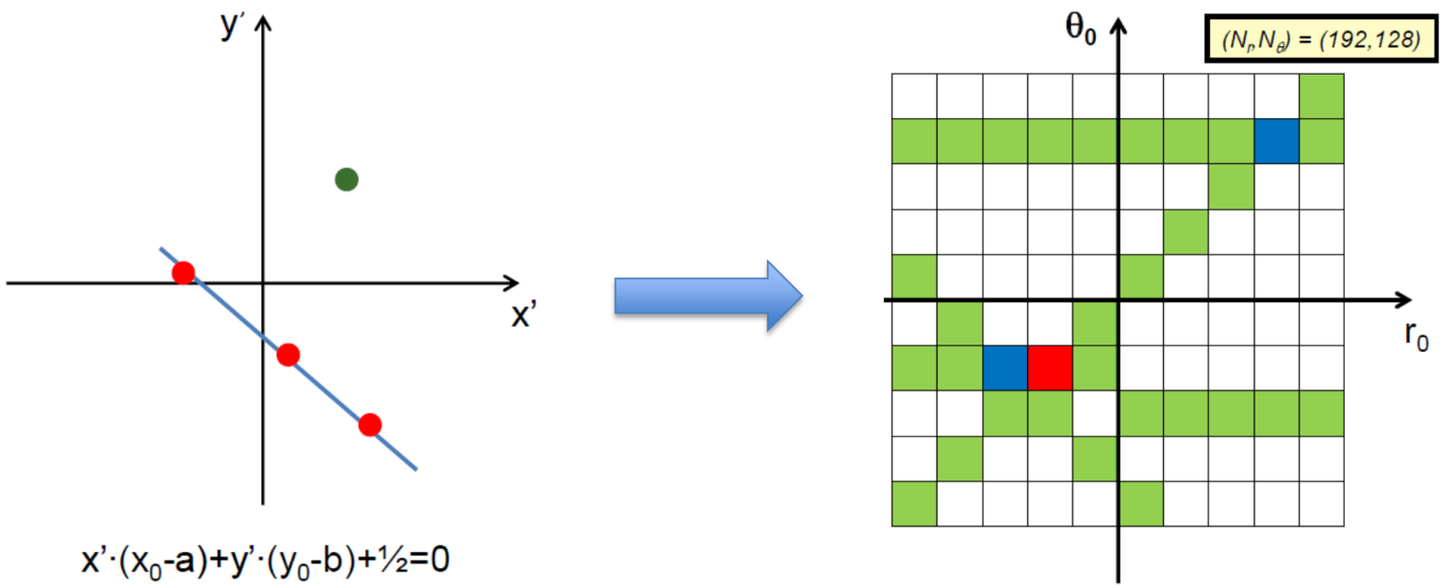
→ We use all the stubs matched in the sector/chip (***kill duplicates***)



$(x-a)^2+(y-b)^2=R^2$

$x'\cdot(x_0-a)+y'\cdot(y_0-b)+½=0$

→*If you only want primaries (**our case**), you can consider* ***$(x_0,y_0)=(0,0)$***



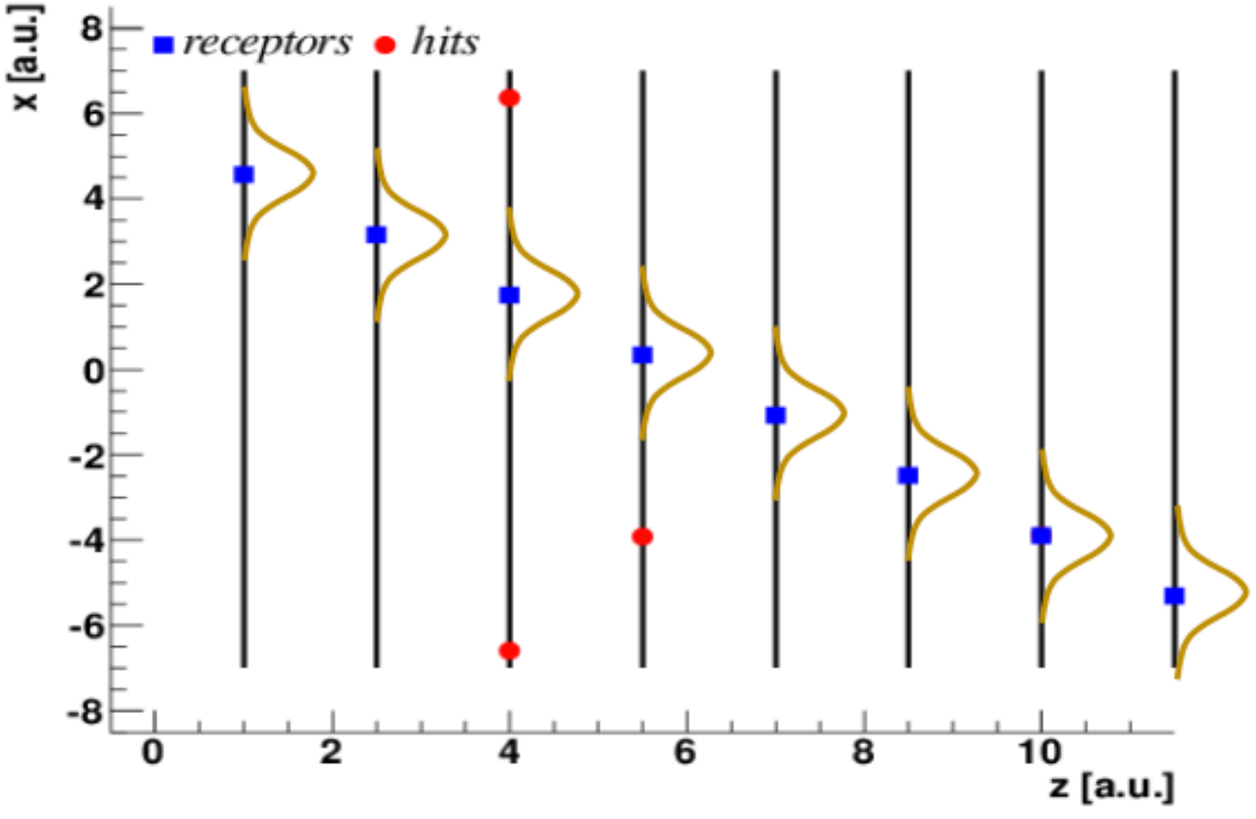
$x'\cdot(x_0-a)+y'\cdot(y_0-b)+½=0$

$x'\cdot\cos(\theta_0)+y'\cdot\sin(\theta_0)=r_0$

$x'\cdot\cos(\theta_0^i)+y'\cdot\sin(\theta_0^i)=r_0^i$

Retina Fit - Basic Principle

For all the hits in the detector layers $(z_n, x_n)_k$ (due to real particles going through the detector or noise), the response R_{ij} of the (m_i, q_j) cellular unit is calculated summing over all hits and layers



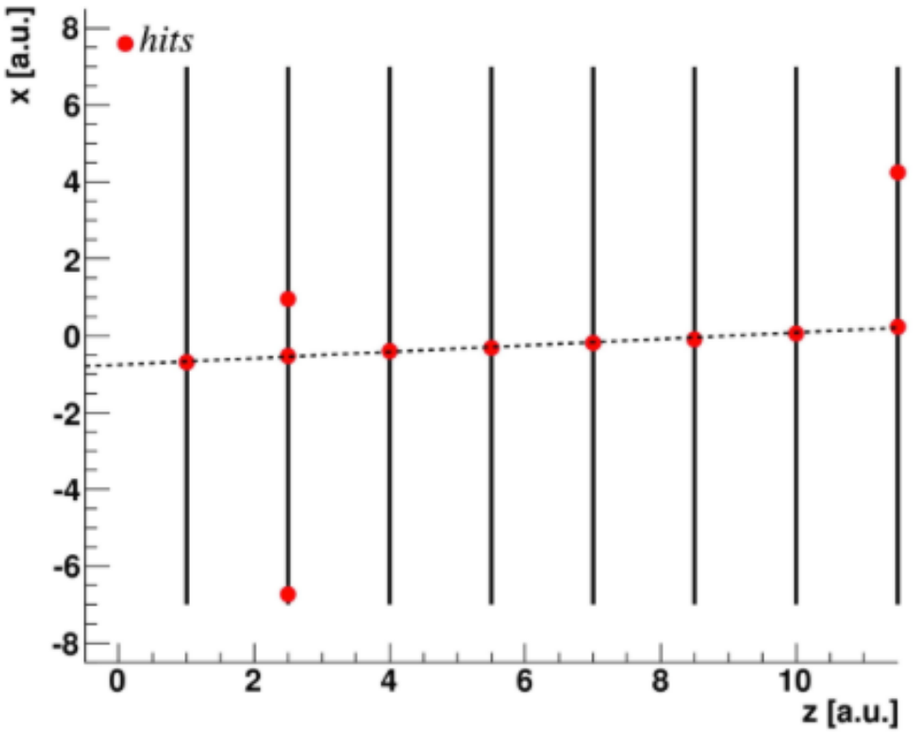
$$s^2_{ijkr} = (x^k_n - x^{ij}_r)^2$$

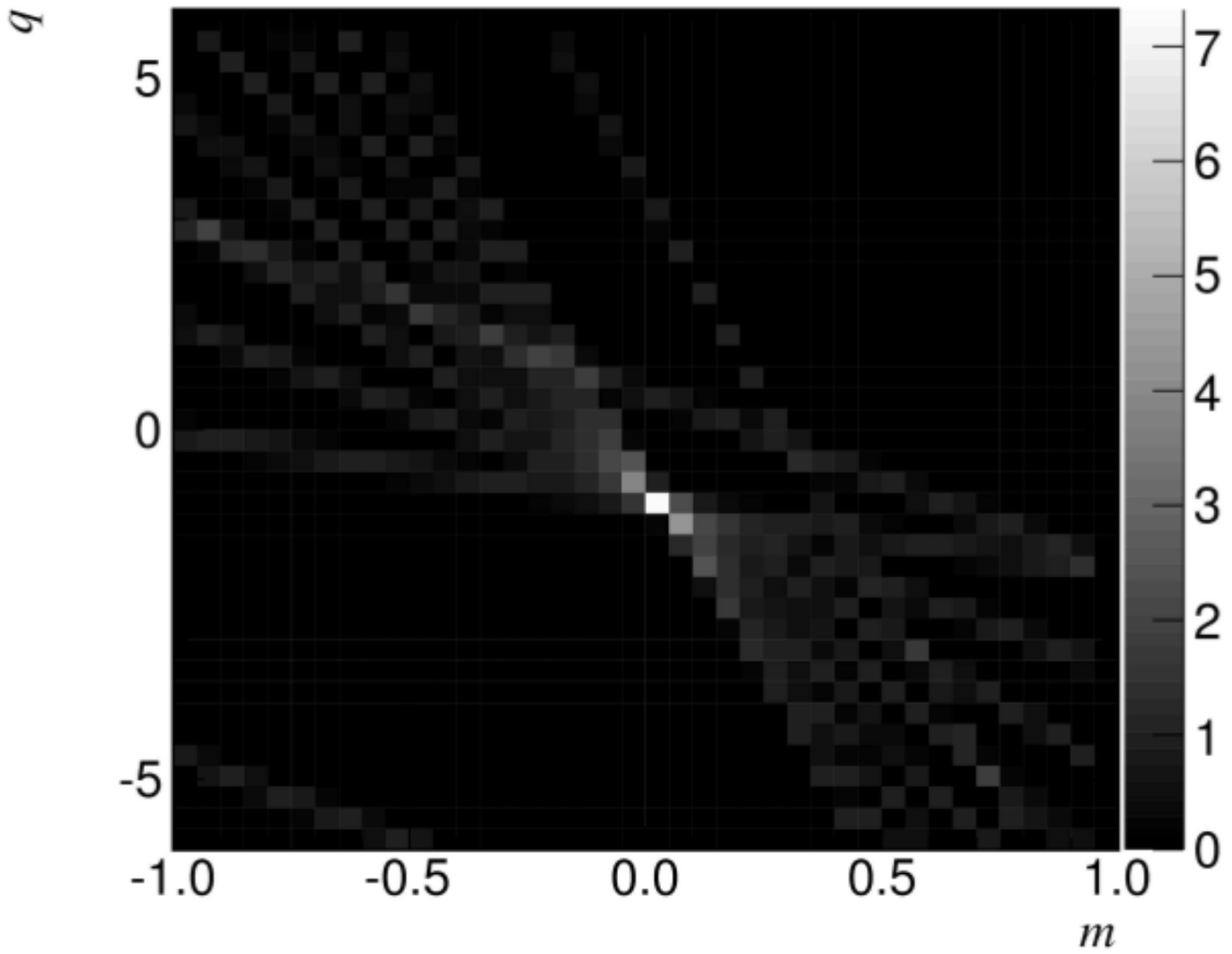
$$R_{ij} = \sum_{kr} \exp\left(-\frac{s^2_{ijkr}}{2\sigma^2}\right)$$

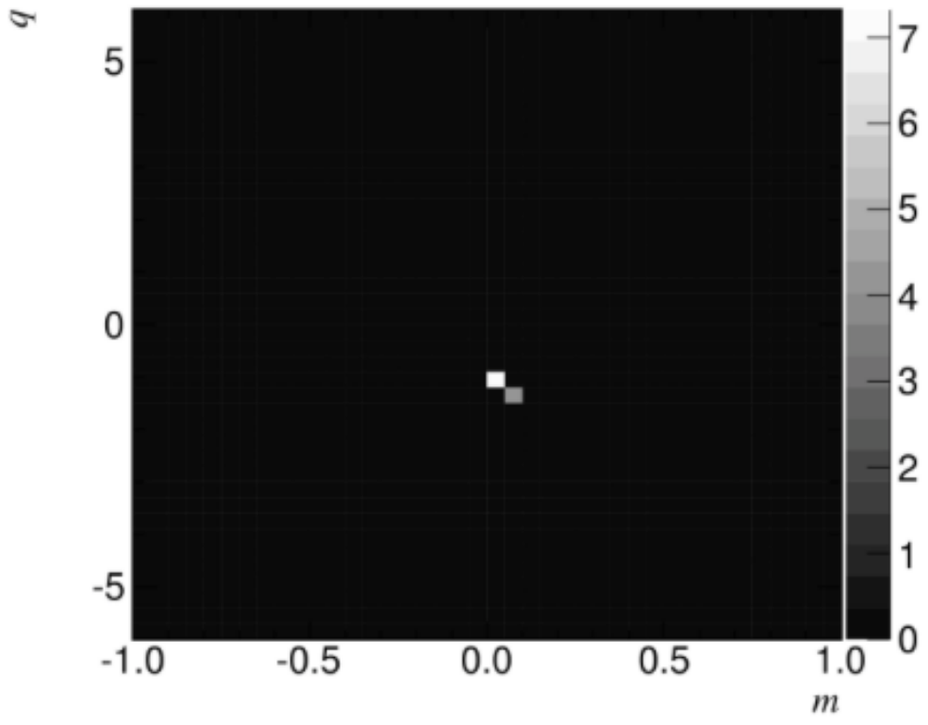
R_{ij} represents the "excitation" of the the receptive field.

Retina Fit

Once all cells are excited with the R_{ij} , a track is identified by a local maximum (in the parameter space).







over threshold