CMS tracker & track-trigger impact

Workshop on the physics of the HL-LHC & perspectives at HE-LHC

CERN, November 1, 2017

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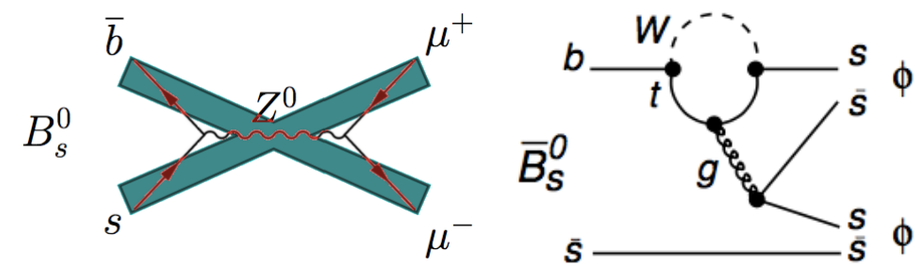
on behalf of the CMS Collaboration

HL-LHC opportunities & challenges

- Physics potential -- 3000 fb^{-1}
  - Extend discovery reach in searches for new physics & rare SM processes
  - Higgs boson precision measurements
  - Improved SM measurements
  - Precision measurement in **flavor sector**
    - *CP violation, rare B decays, top FCNC, ...*



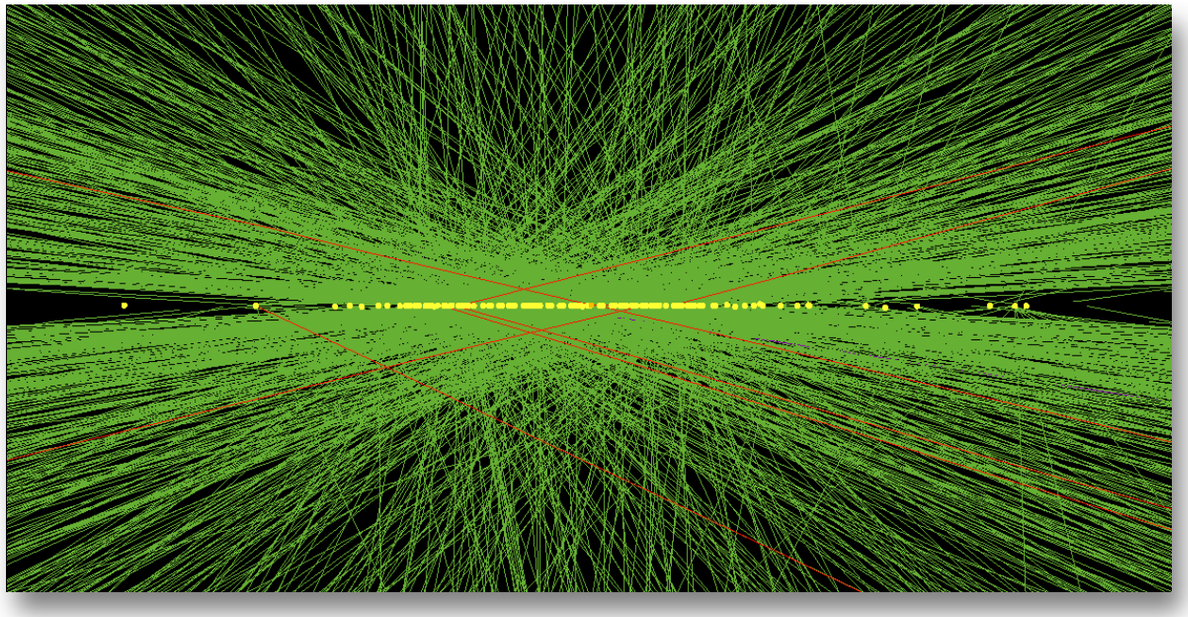
- Experimental challenges -- extreme conditions!
  - Expected average pileup of 200 with resulting increase in particle density
  - Radiation damages

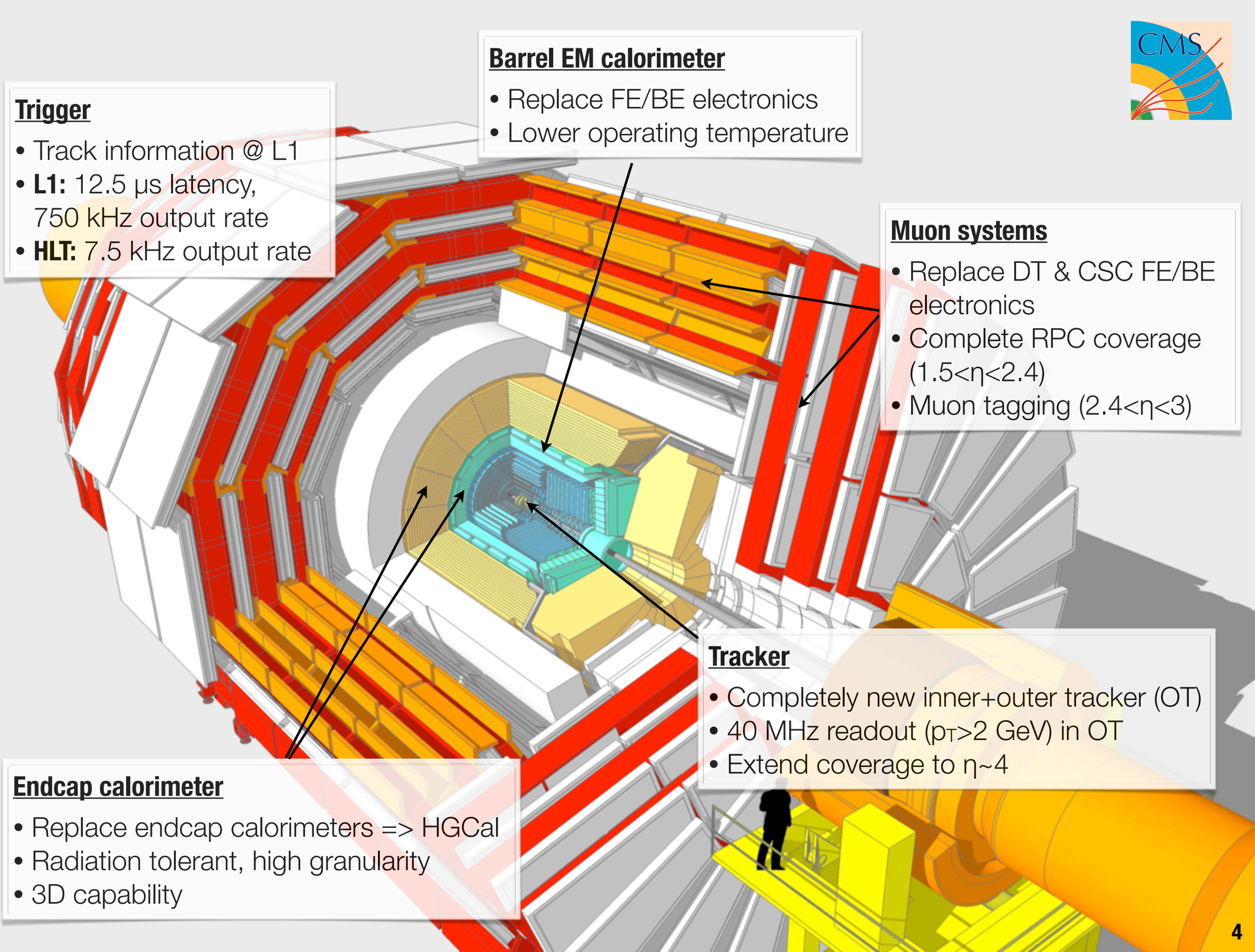
- *Physics goals rely on continued excellent detector performance & triggering!*

CMS detector upgrades

- HL-LHC conditions requires upgrade or replacement of several sub-systems

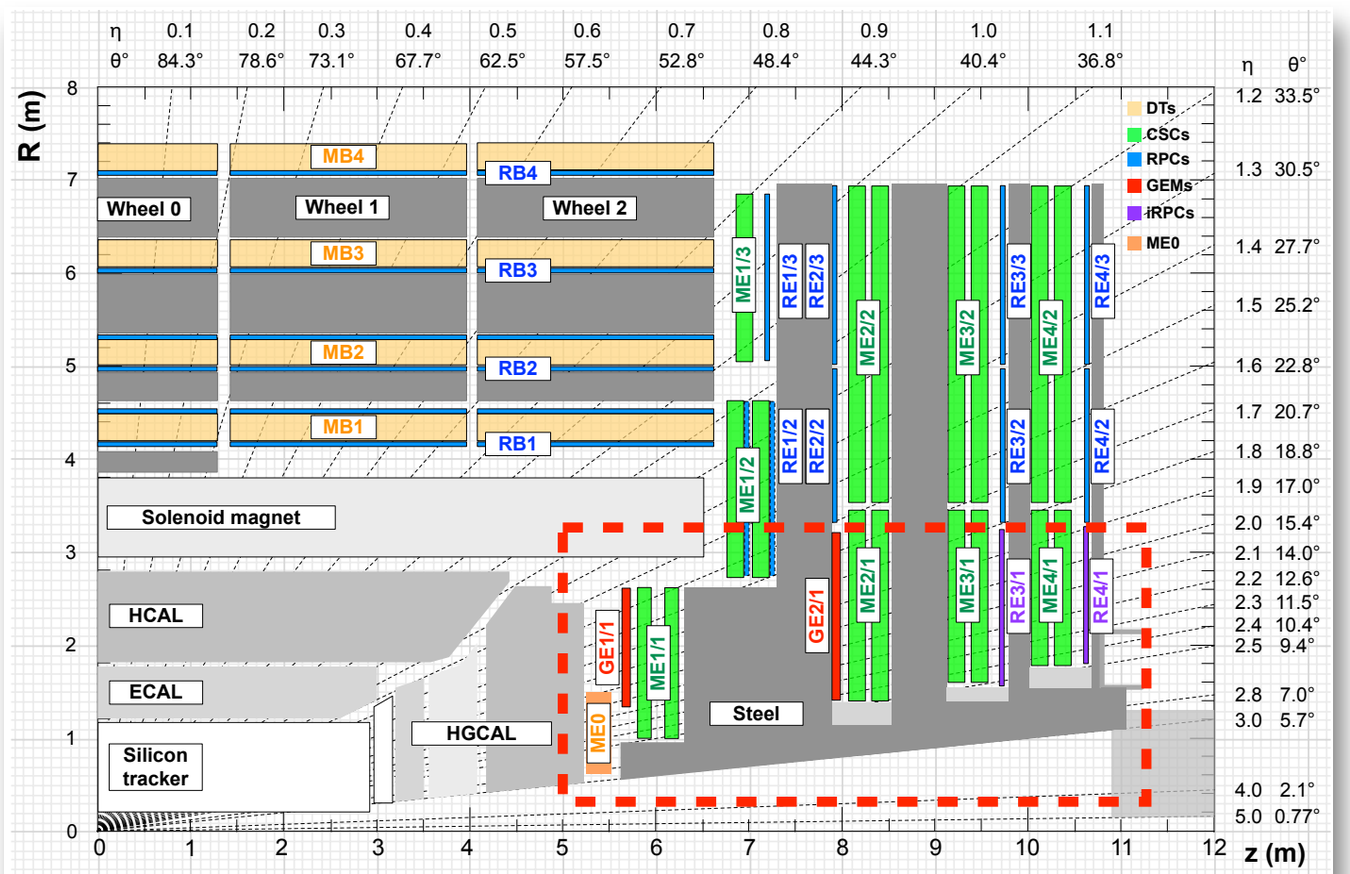
- Lifetime of detectors => replace inner tracker & forward calorimeter
- Increased readout bandwidth
  - Accommodate higher data rates
  - Requires replacing much of FE/BE electronics
    - *Also to improve radiation tolerance*
- PU mitigation
  - Higher detector granularity to reduce occupancy
  - Improved trigger capabilities
  - Precision timing

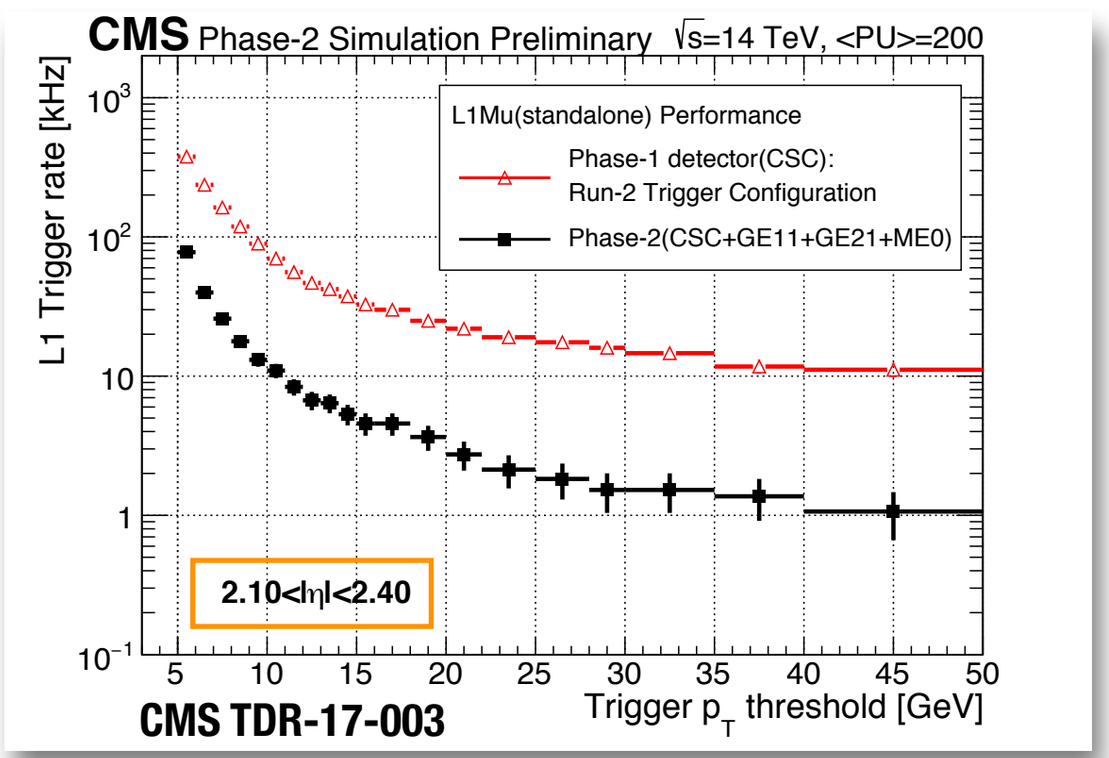



Trigger
• Track information @ L1
• L1: 12.5 μs latency, 750 kHz output rate
• HLT: 7.5 kHz output rate
Barrel EM calorimeter
• Replace FE/BE electronics
• Lower operating temperature
Muon systems
• Replace DT & CSC FE/BE electronics
• Complete RPC coverage (1.5<η<2.4)
• Muon tagging (2.4<η<3)
Tracker
• Completely new inner+outer tracker (OT)
• 40 MHz readout (pT>2 GeV) in OT
• Extend coverage to η~4
Endcap calorimeter
• Replace endcap calorimeters => HGCal
• Radiation tolerant, high granularity
• 3D capability

Muon upgrades

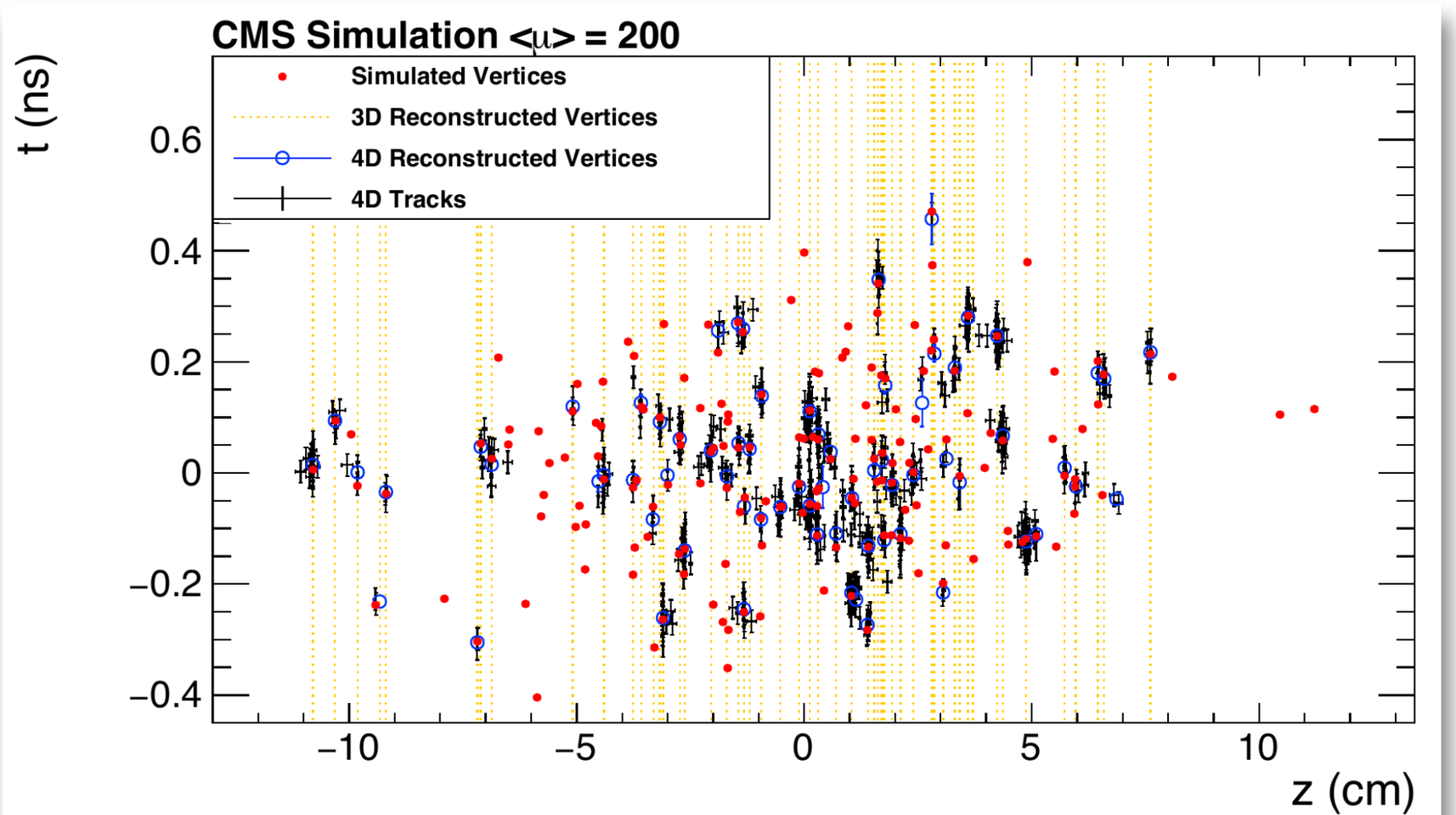
- New DT+CSC electronics for increased radiation tolerance & readout speed
- New forward detectors
  - Gas Electron Multipliers & (improved) RPC stations] enhance 1.6<|η|<2.4 region & reduce trigger rates
  - Forward extension (GEM) to |η| < 2.8] extend beyond |η|=2.4
- Maintain standalone muon trigger efficiency



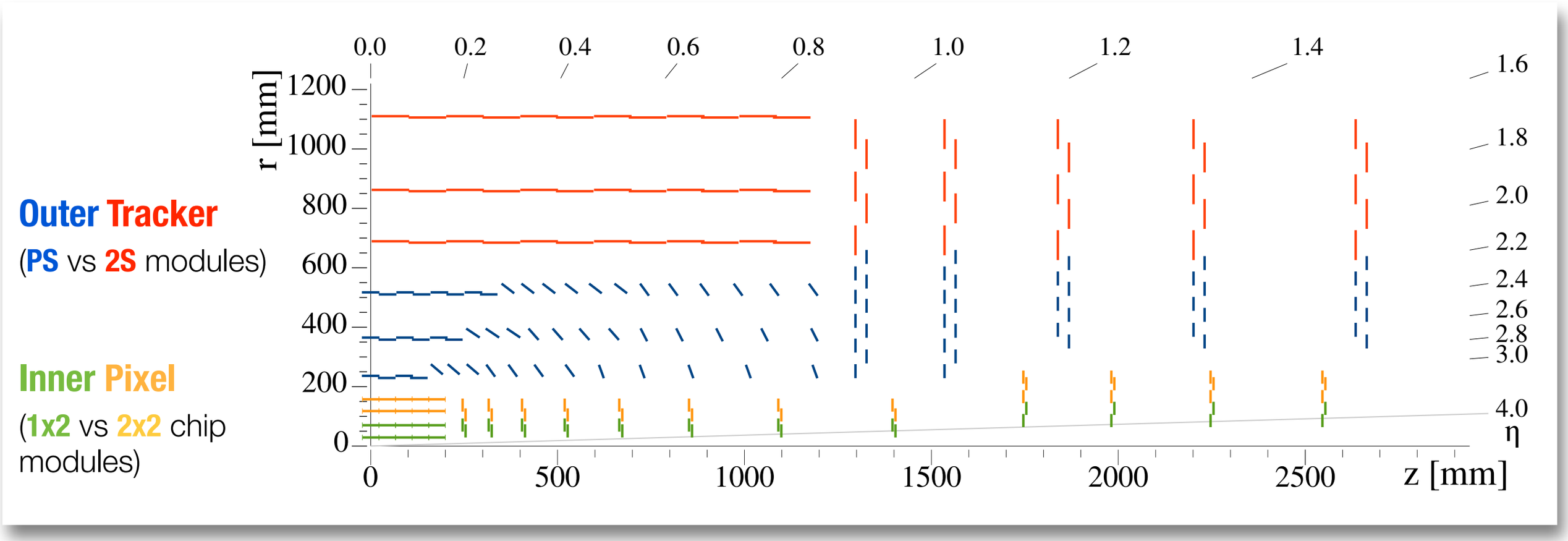


Precision timing

- ECAL barrel + HGCal upgrades => 30-50 ps timing resolution for moderate-energy photons & high-energy hadrons
- <u>Dedicated precision timing layer</u> ← under study!
  - Thin LYSO + SiPM, outside tracker barrel support tube
  - Precision timing for charged particles => useful for flavor analyses?

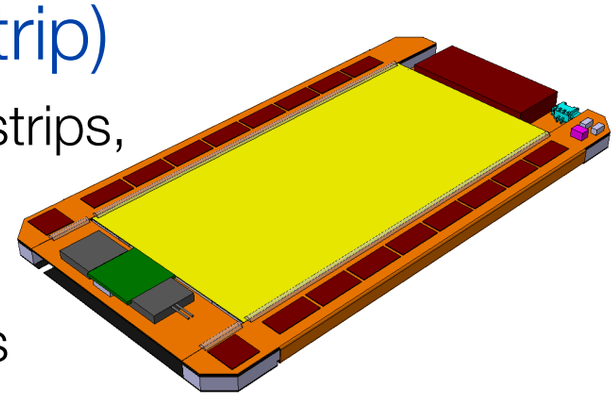


Tracker system



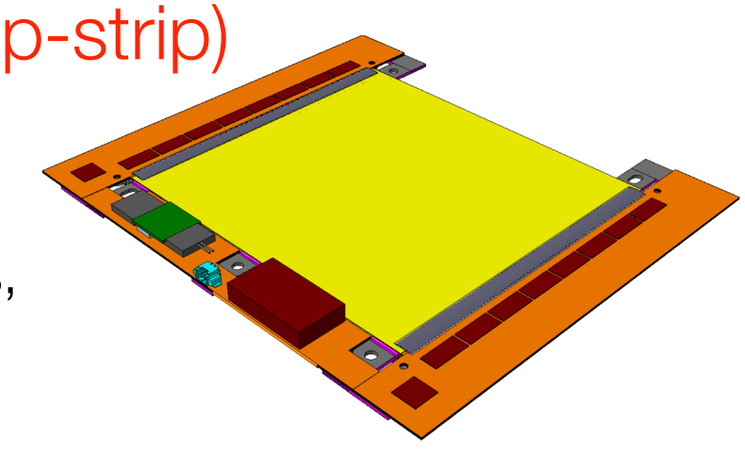
PS modules (pixel-strip)

- Top sensor: 2x2.5 cm strips, 100 μm pitch
- Bottom sensor: 1.5 mm x 100 μm pixels



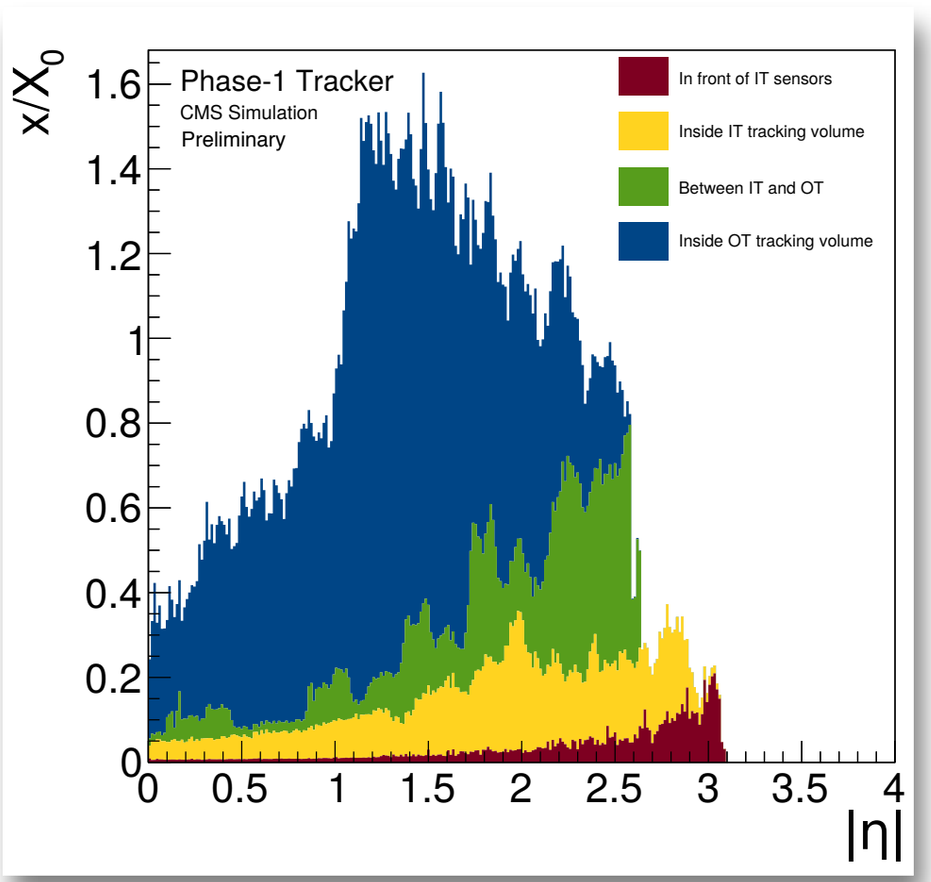
2S modules (strip-strip)

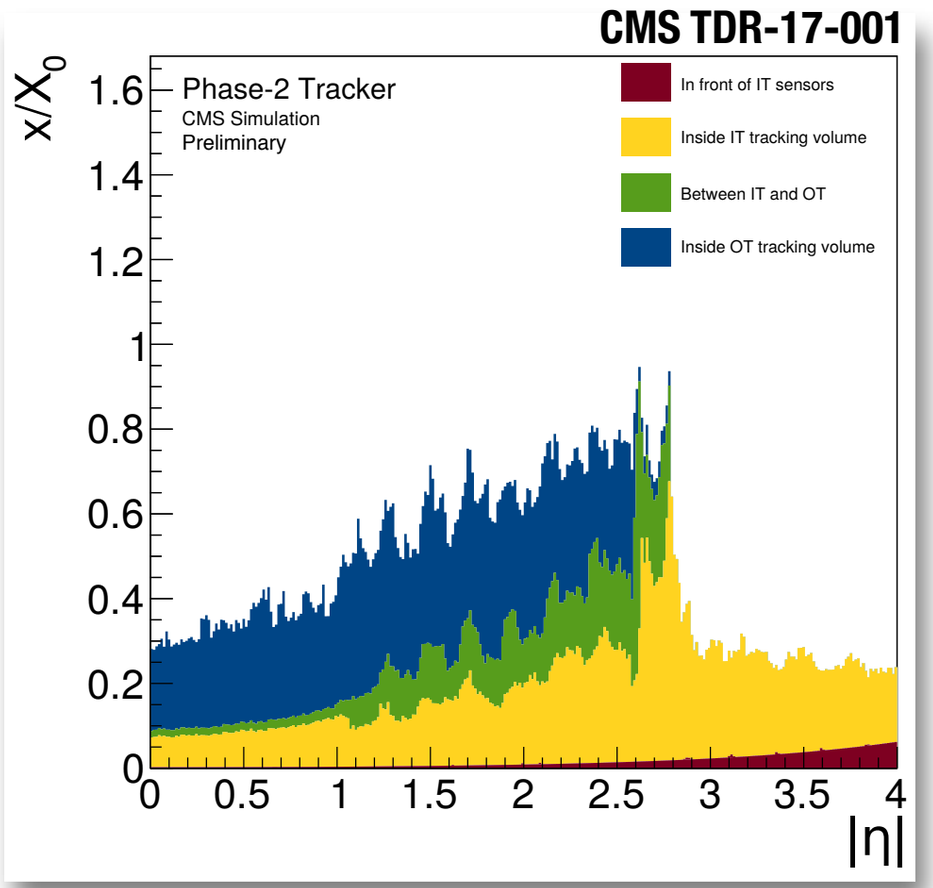
- Strip sensors 10x10 cm^2
- 2x5 cm long strips, 90 μm pitch



Tracker system

- Requirements driving design
  - Radiation tolerance
  - Increased granularity to cope with PU=200
  - Extended coverage at high |η|
  - Reduced amount of material => improved momentum resolution (combined with better hit resolution)
  - Track finding @ 40 MHz

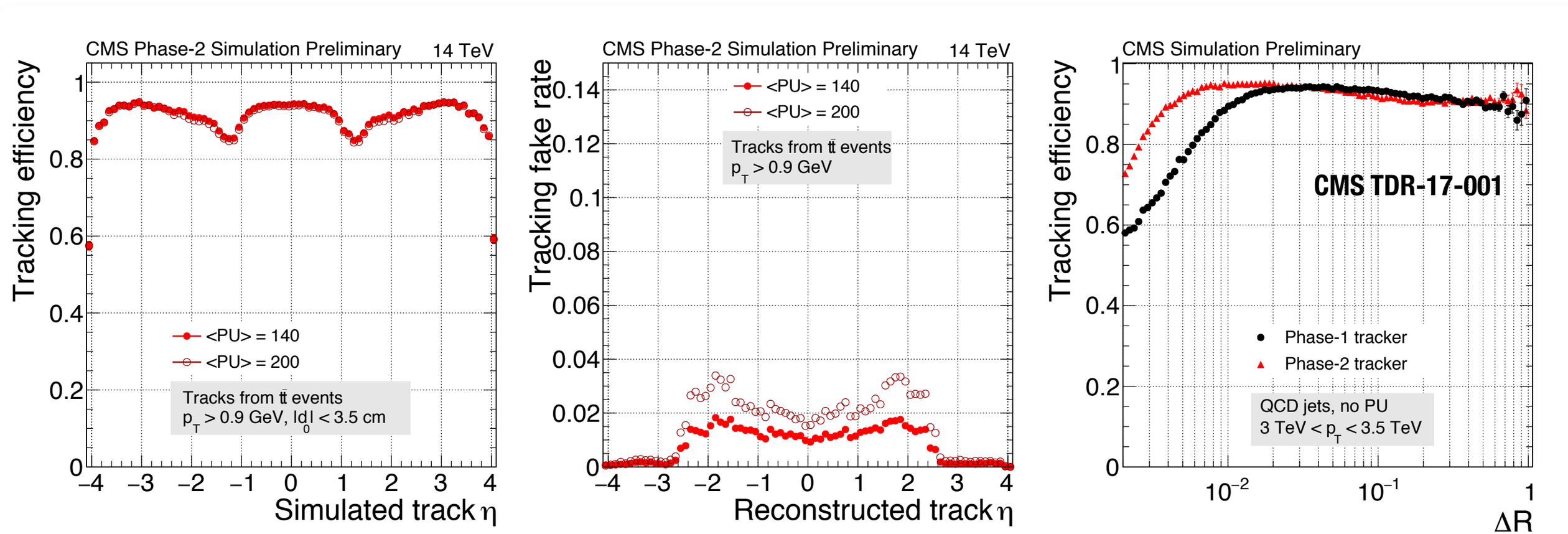




Tracking performance

See also poster by E. Brondolin!

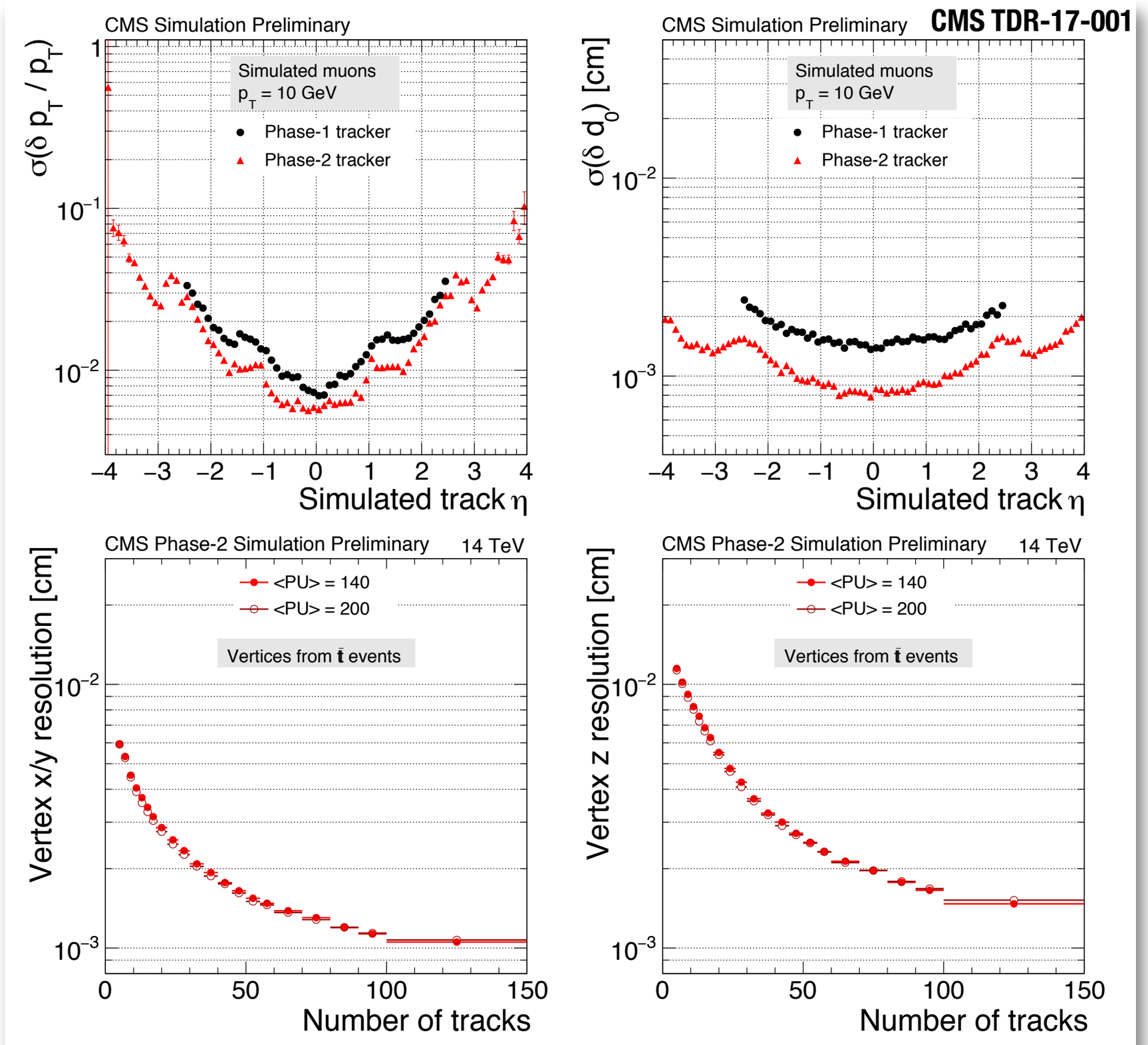
- Iterative track finding: seeding - track finding - track fitting - track selection
  - At PU=200, about 6000 charged particles per event!
- High efficiency & low fake rates
- Improved two-track separation in high-p_T jets



Tracking performance

- Excellent track resolutions with even improved performance beyond current tracker system

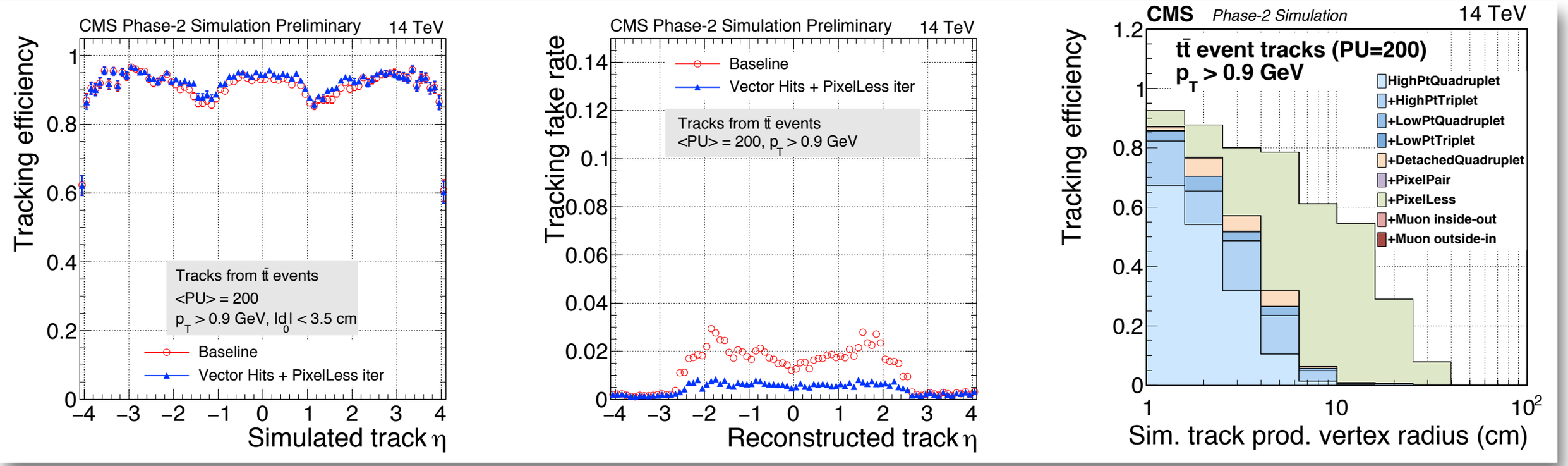
- Very high vertex efficiency (~93% at PU=200) & precise vertex resolutions



Tracking performance

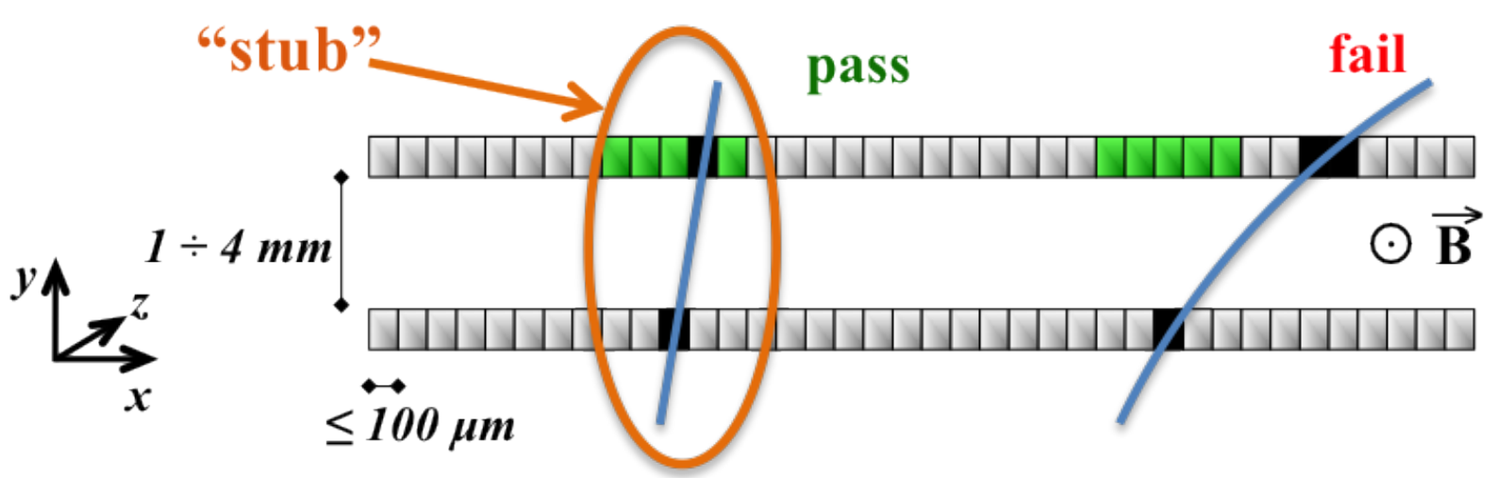
See also poster by E. Brondolin!

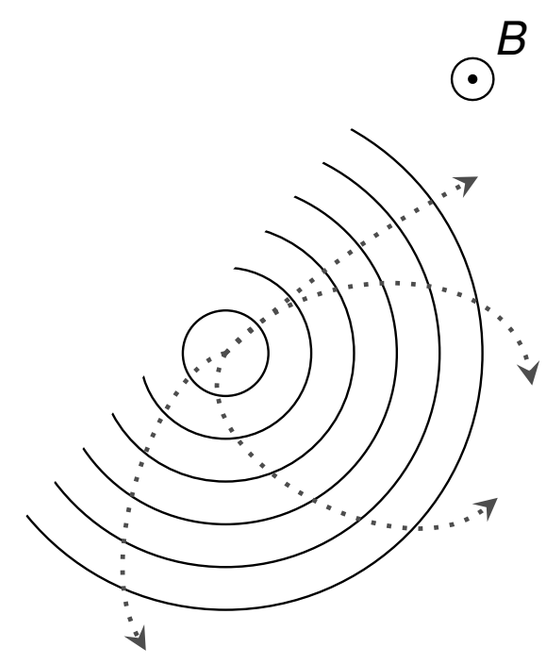
- Further optimization under study
  - Using “vector hits” -- hit pairs that provide both position & direction
  - Additional dedicated iteration targeting displaced tracks
- Promising results
  - Improved efficiency with reduced fake rate
  - Computational consumption under study



Track trigger concept

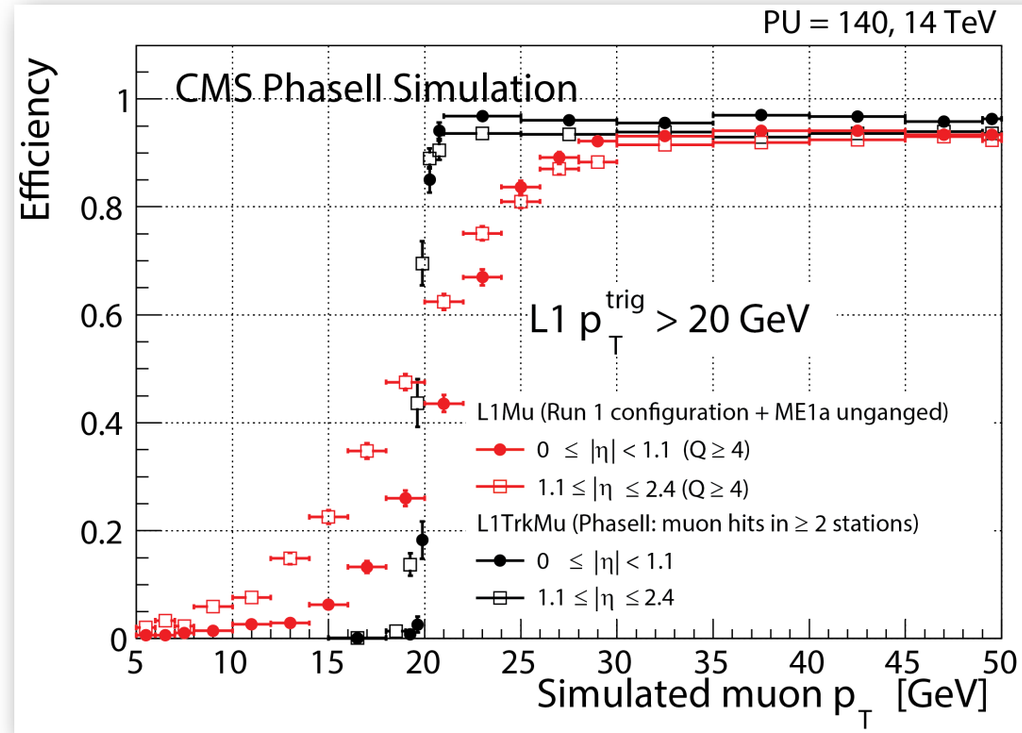
- Self-seeded L1 track trigger
  - Local p_T reconstruction
  - Reconstruct tracks with $p_T > 2$ GeV & identify z_0 with ~1mm precision
- Outer tracker modules provide p_T discrimination in FE electronics through hit correlations between closely spaced sensors
- **Stubs:** Correlated pairs of clusters, consistent with ≥ 2 GeV track
  - Data reduction at trigger readout (by a factor 10-20)
  - <u>*Stubs form input to track finding*</u>

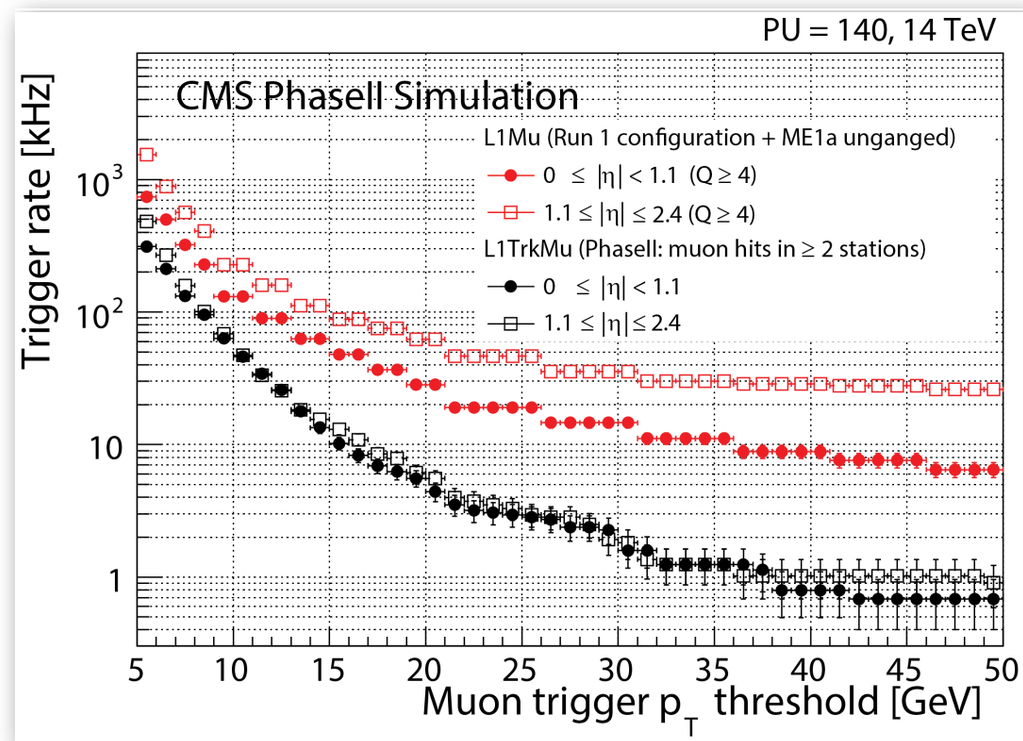




Tracking @ L1

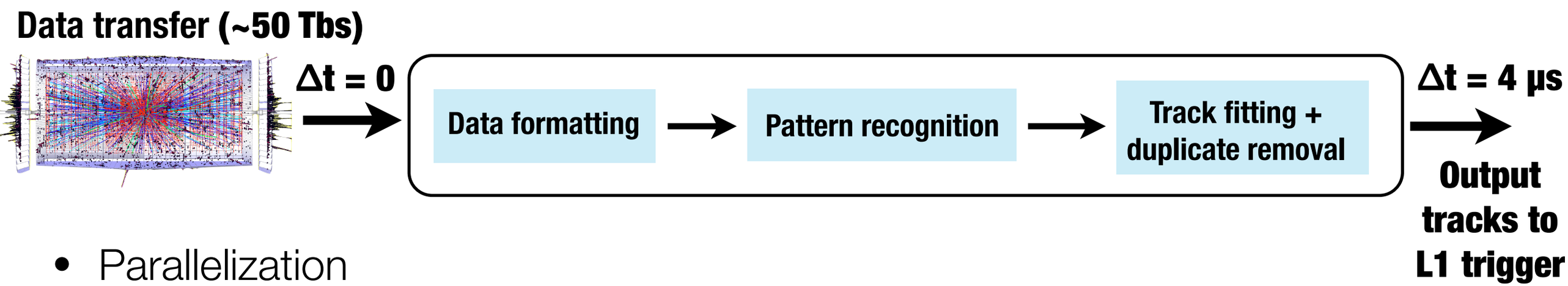
- HL-LHC conditions
  - 6-7K charged particles/BX at PU=200
  - ~200 tracks with p_T > 2 GeV
- Resulting challenges
  - Combinatorics => 15-20K input stubs/BX
  - Data volumes => up to ~50 Tbits/s
  - L1 trigger decision within 12.5 μs => time available for track finding ~4 μs
- Benefits
  - Improved lepton identification and p_T measurements
  - Track isolation
  - Vertex determination
  - **Large rate reductions possible!**





CMS Phase-2 Technical Proposal

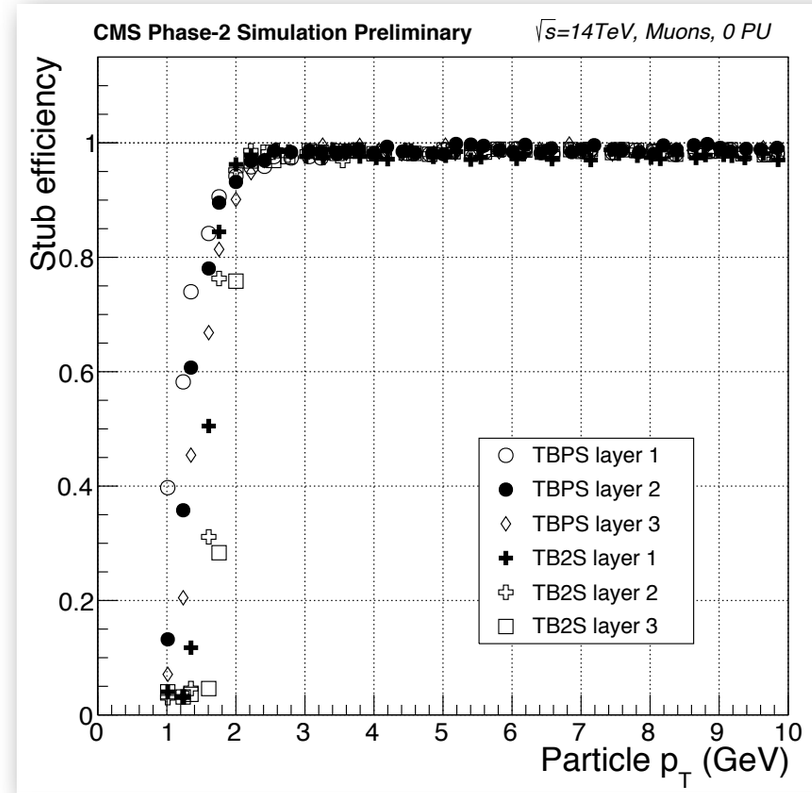
Track trigger strategy

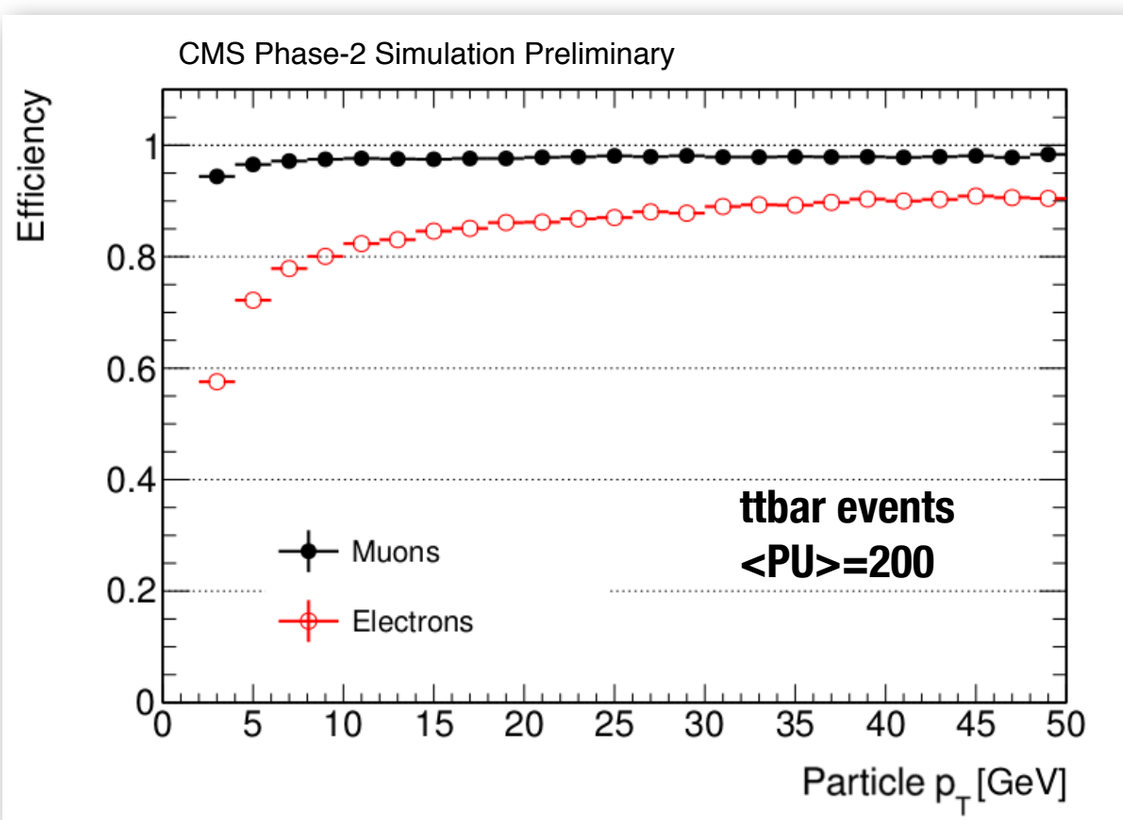


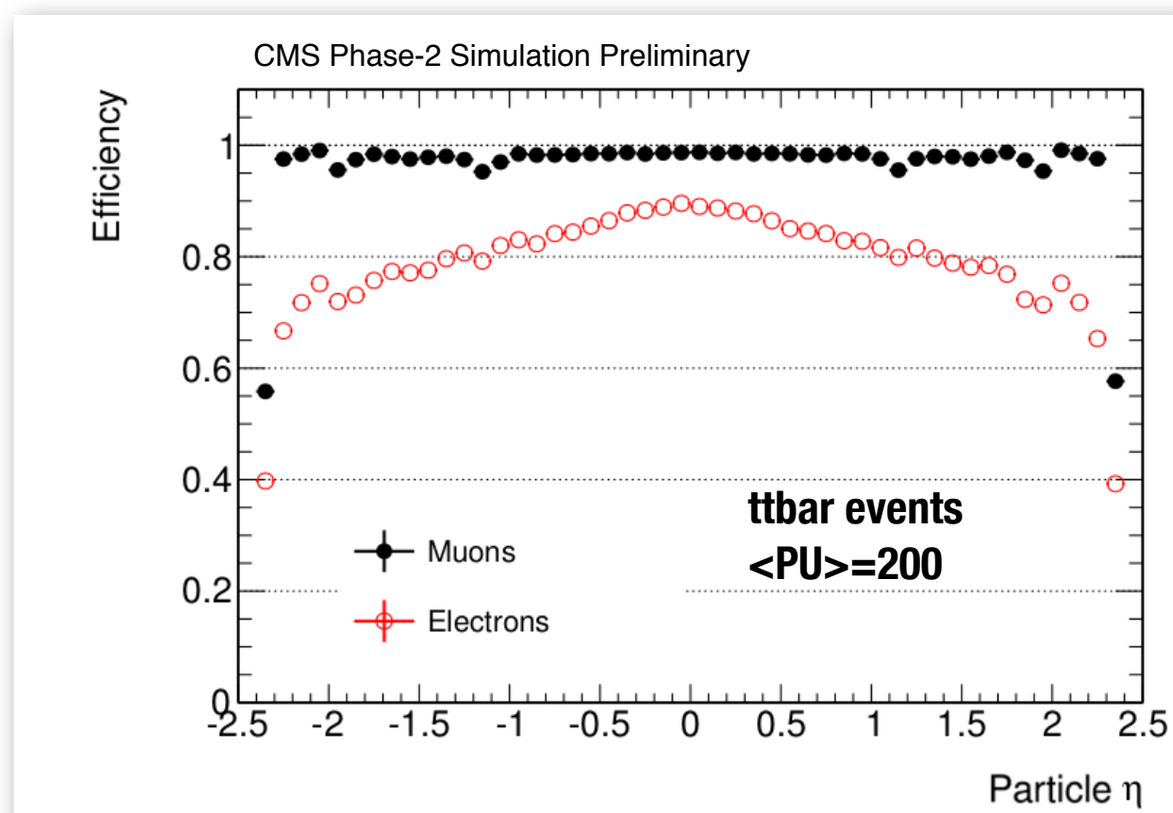
- Parallelization
  - Divide tracker in segments in ϕ / z
  - Time-multiplexed systems -- process several BX simultaneously
- Several approaches studied to attack combinatorics & occupancies
  - CMS baseline a fully FPGA-based system
    - *Off-the-shelf hardware*
    - *Programmable => flexibility*
  - Tracklet road search algorithm with full hit precision
  - Hough transform with large time-multiplexing

L1 tracking performance

- Stub finding performance
  - Sharp turn-on & high efficiency
- L1 tracking efficiency
  - Very high & flat tracking efficiency
  - Low-p_T electrons challenging
  - Here shown for $p_T > 3$ GeV
    - *Benchmark studied for TDR*

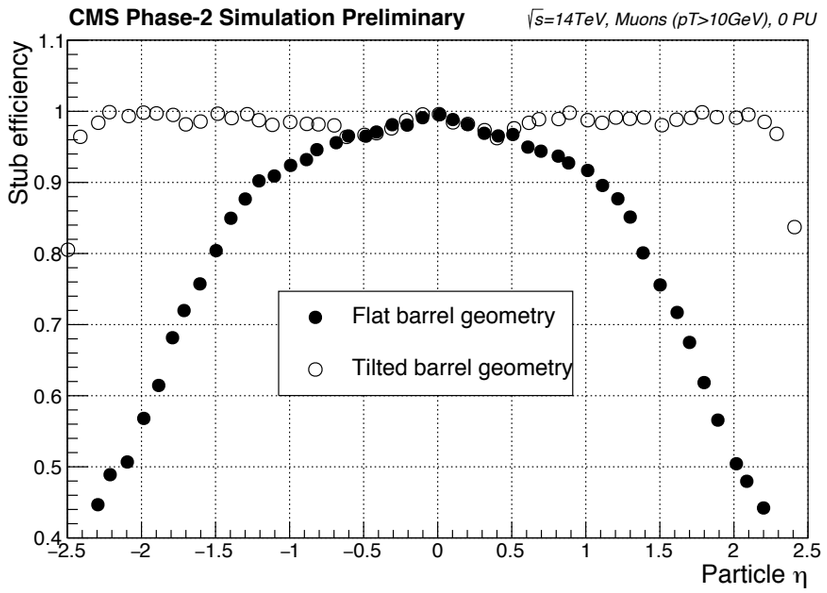


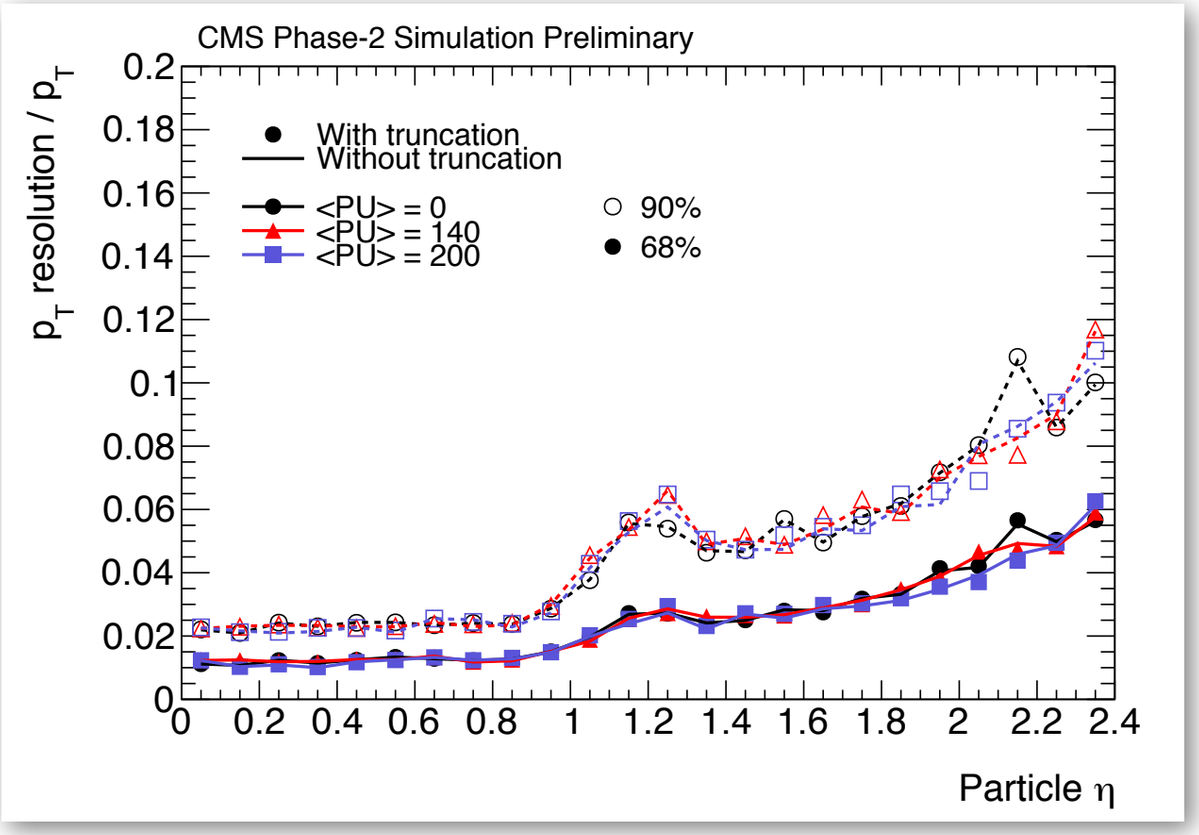


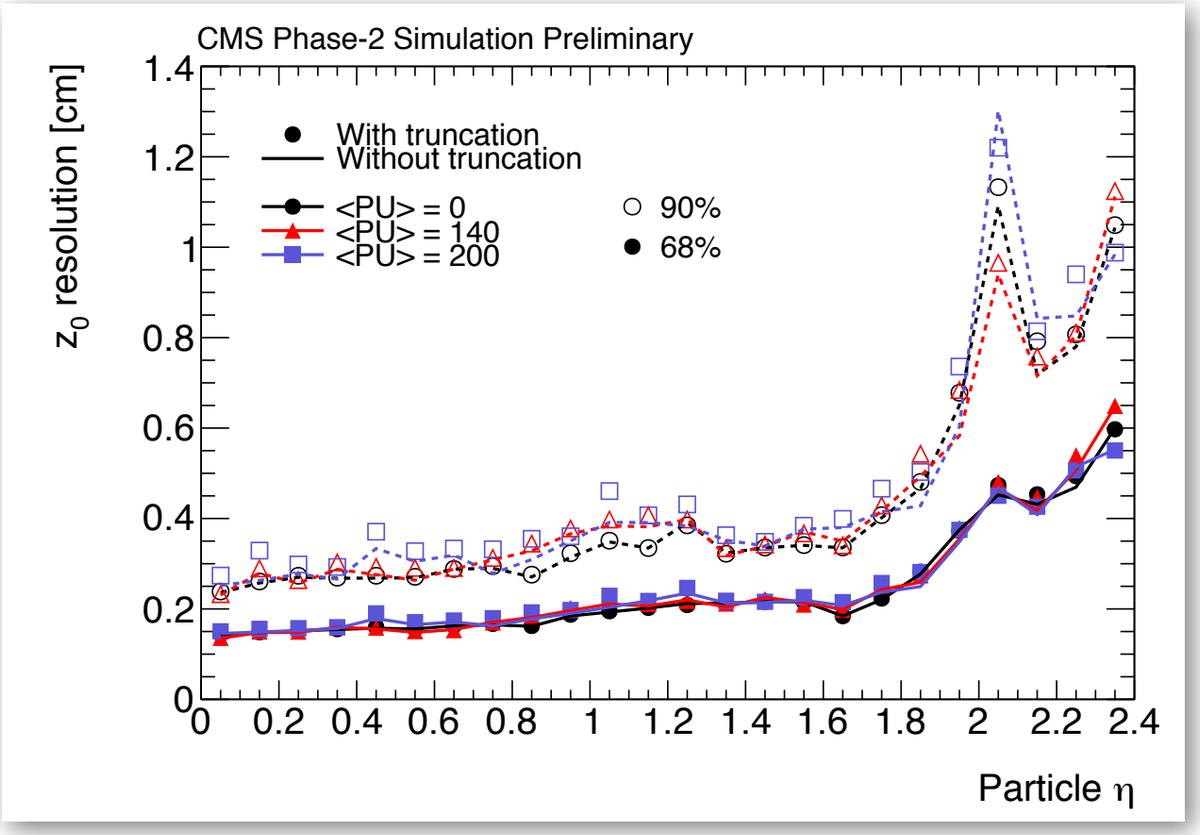


L1 tracking performance

- Precise track parameter resolutions
- Note: Plots assume an earlier ("flat") version of tracker geometry
  - Current geometry => slightly worse z_0 resolution at intermediate/forward η
  - Necessary to avoid inefficiencies from lack of communication between PS module halves

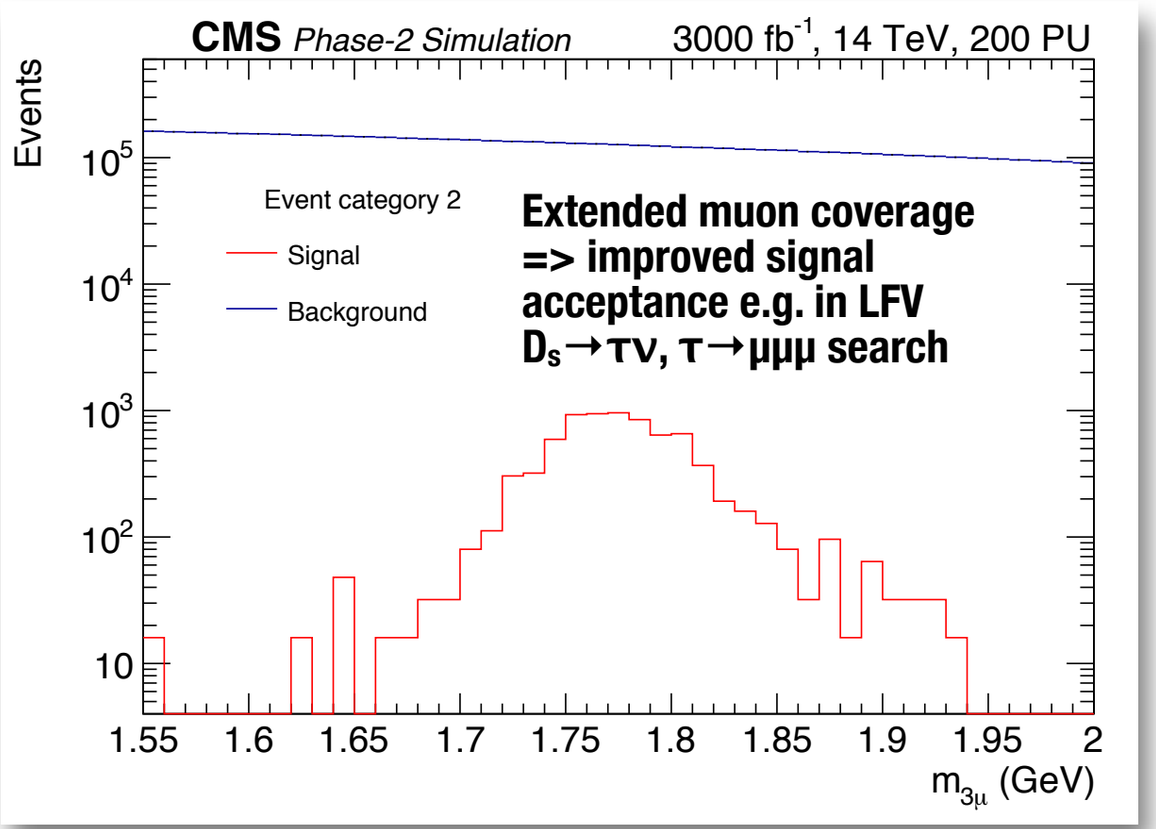


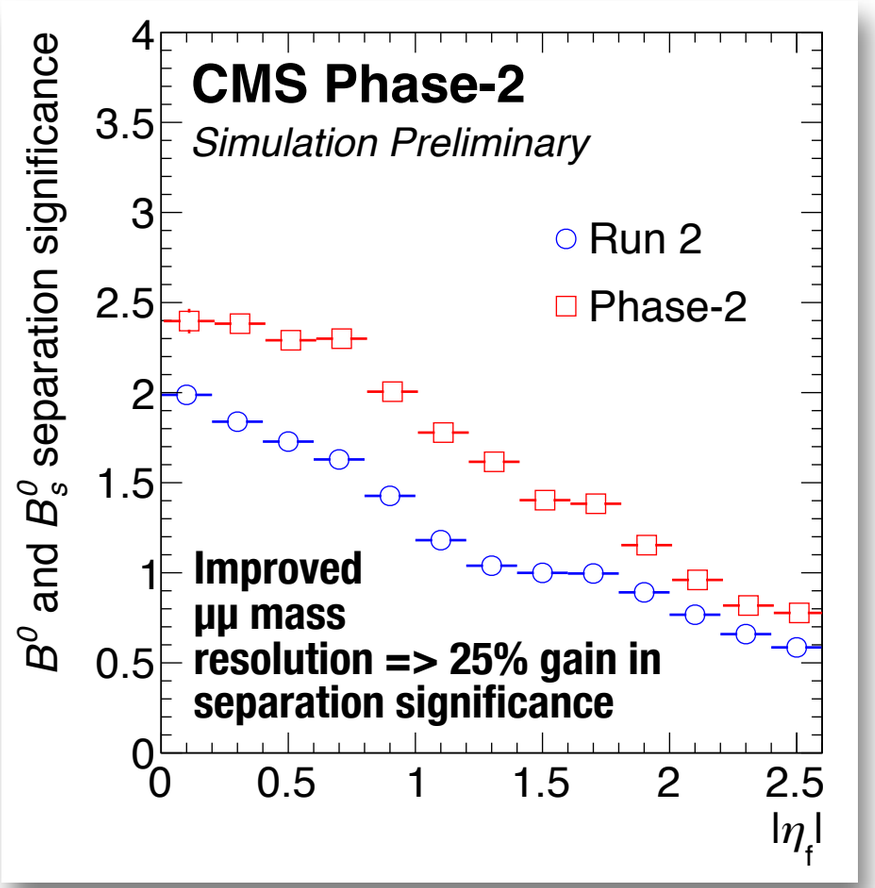


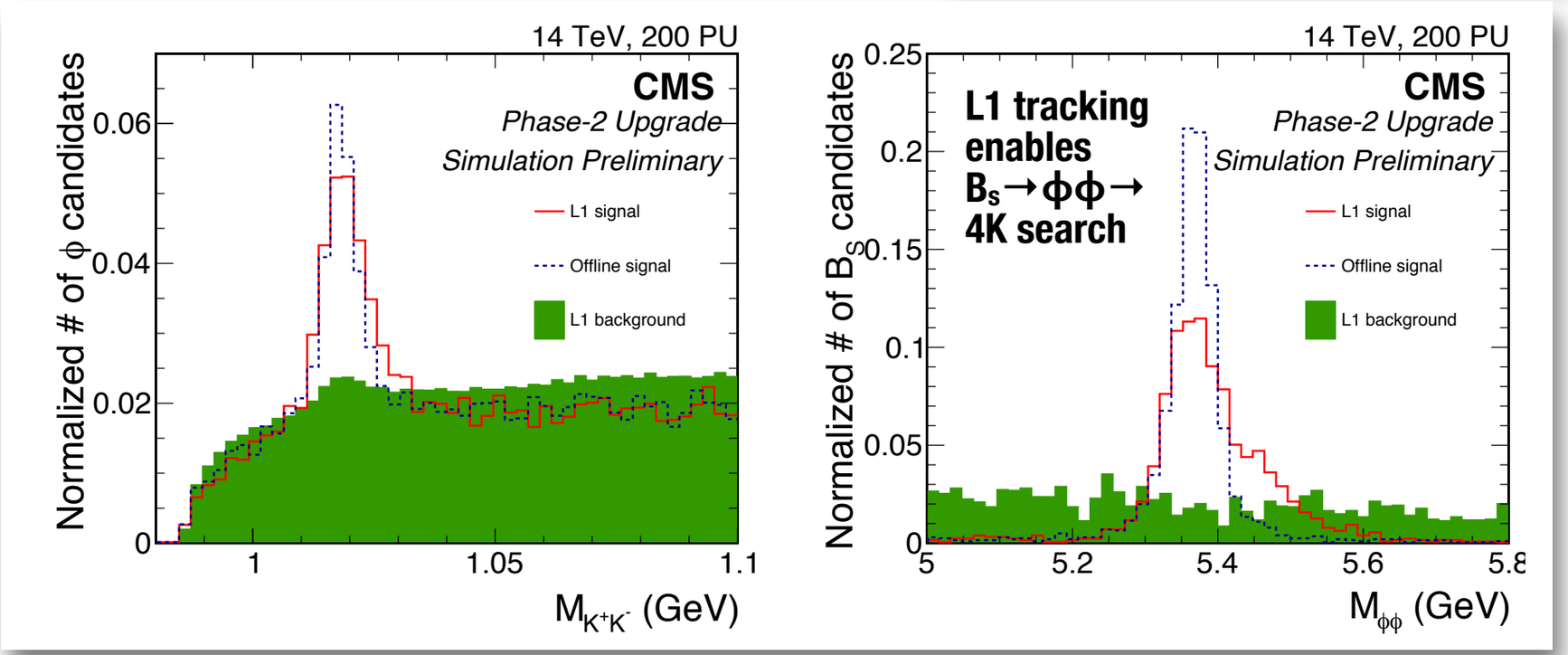


Physics examples

Details in presentation
by S. Sarkar







Conclusions

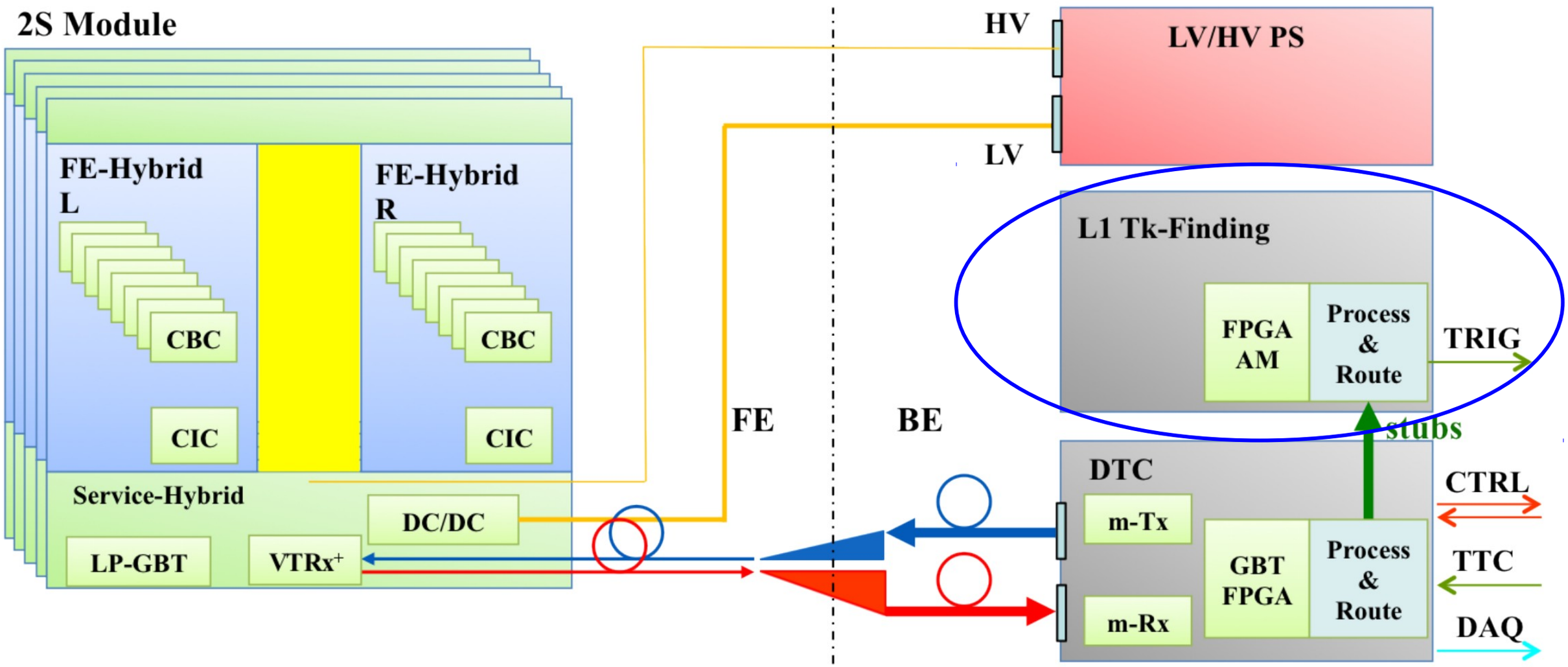
- Achieving full physics potential of HL-LHC requires significant upgrades to CMS detector systems

- Of particular relevance to flavor physics
  - New inner pixel + outer tracker system
    - *Higher granularity & improved momentum resolutions*
    - *Capability of tracking @ 40 MHz => can enable signatures otherwise unattainable*
  - Improvements also from...
    - *Upgraded muon system => reduced trigger rates & extended η acceptance*
    - *Potential to benefit from precision timing (under study)?*

- Preliminary studies show excellent offline & L1 tracking performance

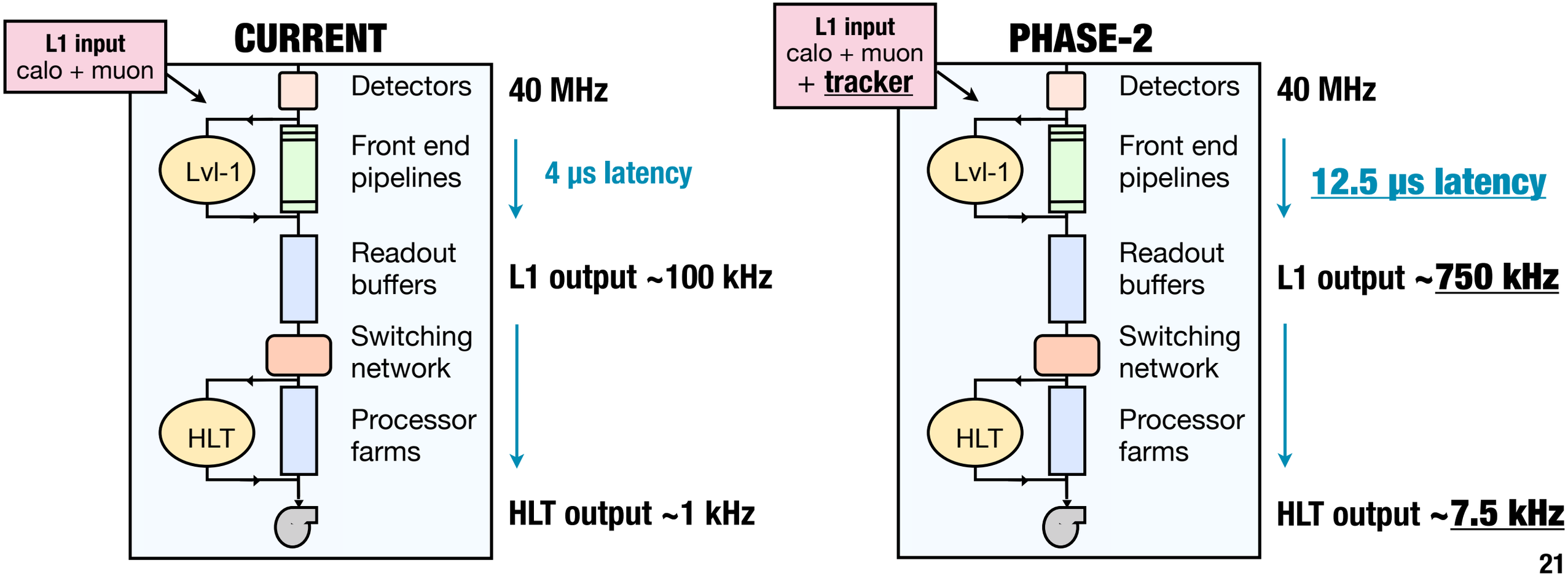
backup

Tracker FE / BE system overview



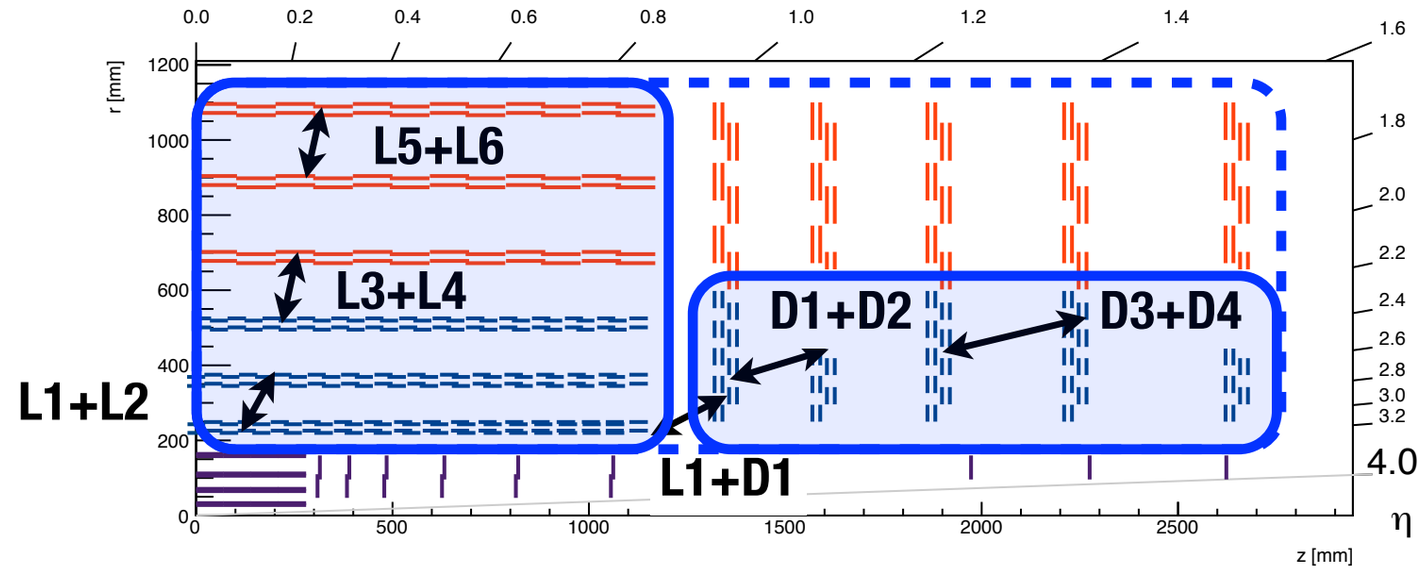
Phase-2 trigger system

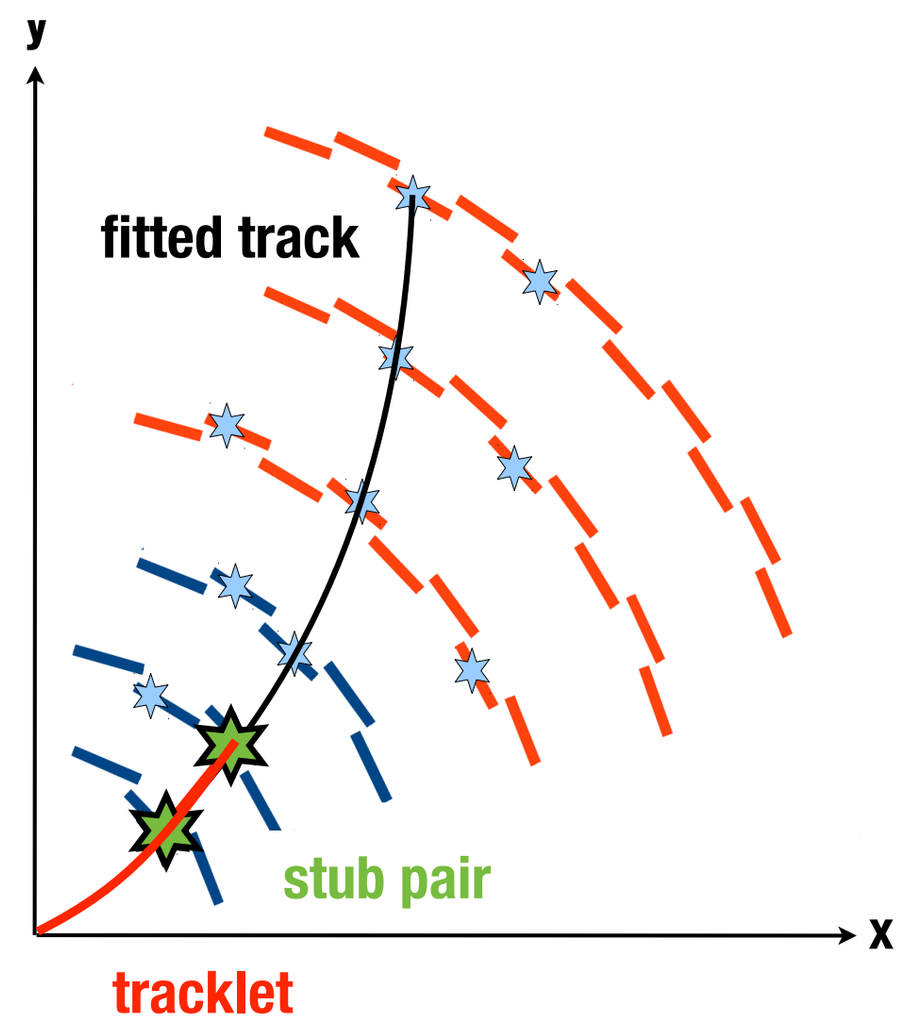
- Current L1 trigger uses information from calorimeters & muon system
- Planned upgrades
  - Replace ECAL barrel + endcap front-end electronics
  - Increased latency & L1 accept rate
  - L1 tracking + global track-trigger correlator



Tracklet-based method

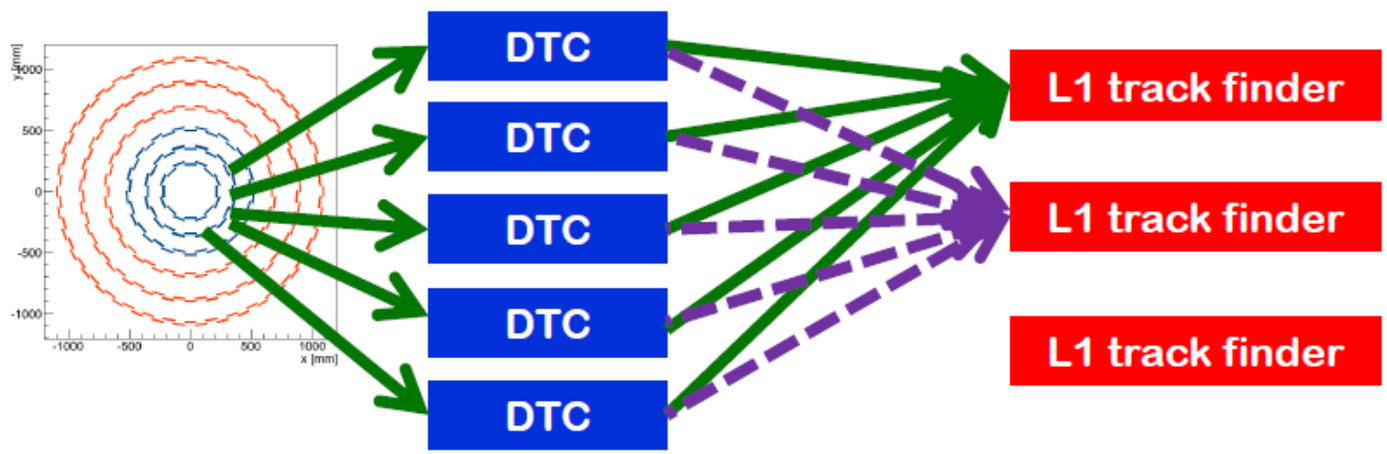
- **Seed** by forming tracklets
  - Pairs of stubs in adjacent layers/disks
  - Initial tracklet parameters from stubs + beamspot constraint
- **Project** to other layers/disks & match with stubs
  - Inside-out & outside-in
  - Calculate residuals used in fit
- **Fit** stubs matched to trajectory
  - Linearized X^2 fit
- Remove **duplicate** tracks based on shared stubs



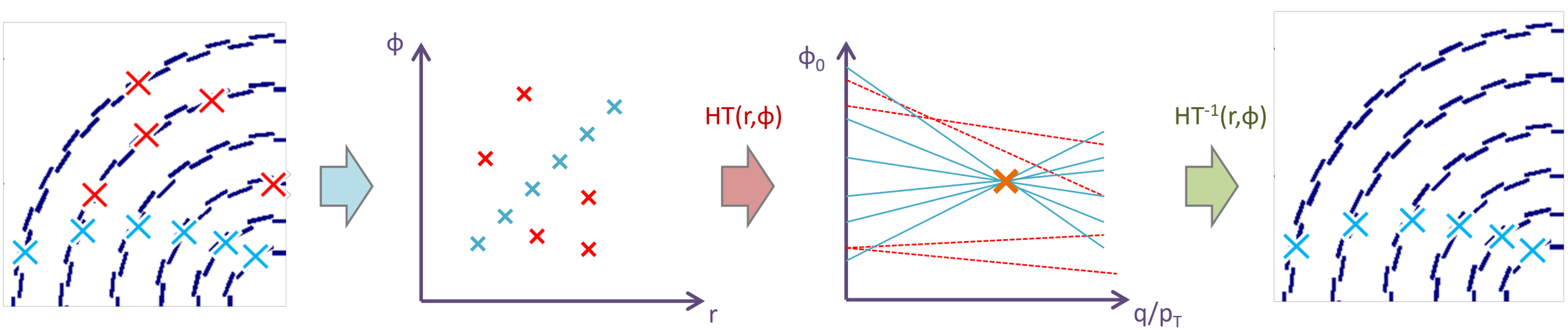


Time-multiplexed + Hough transform

- Fully time-multiplexed architecture where all module data for given BX send to a single track finder processor board



- Pattern recognition using Hough transform + track fitting (all in FPGA)



Associative memory (AM) approach

- Tackle combinatorics through massive parallel processing using ASIC
  - Filters out ~80% of stubs not associated with high-p_T particles
- Pattern Recognition Associate Memory = content addressable memory (CAM) + majority logic (ML)
- Pattern recognition with narrow roads, match preloaded patterns in AM chip
  - Time roughly proportional to # stubs
  - **(1) <u>Find roads</u>** -- low-resolution track candidates
  - **(2) <u>Fit tracks</u>** (linearized X^2) inside roads using FPGA