Performance e impatto sulla fisica Tracker Fase 2

CMS Italia - Piacenza
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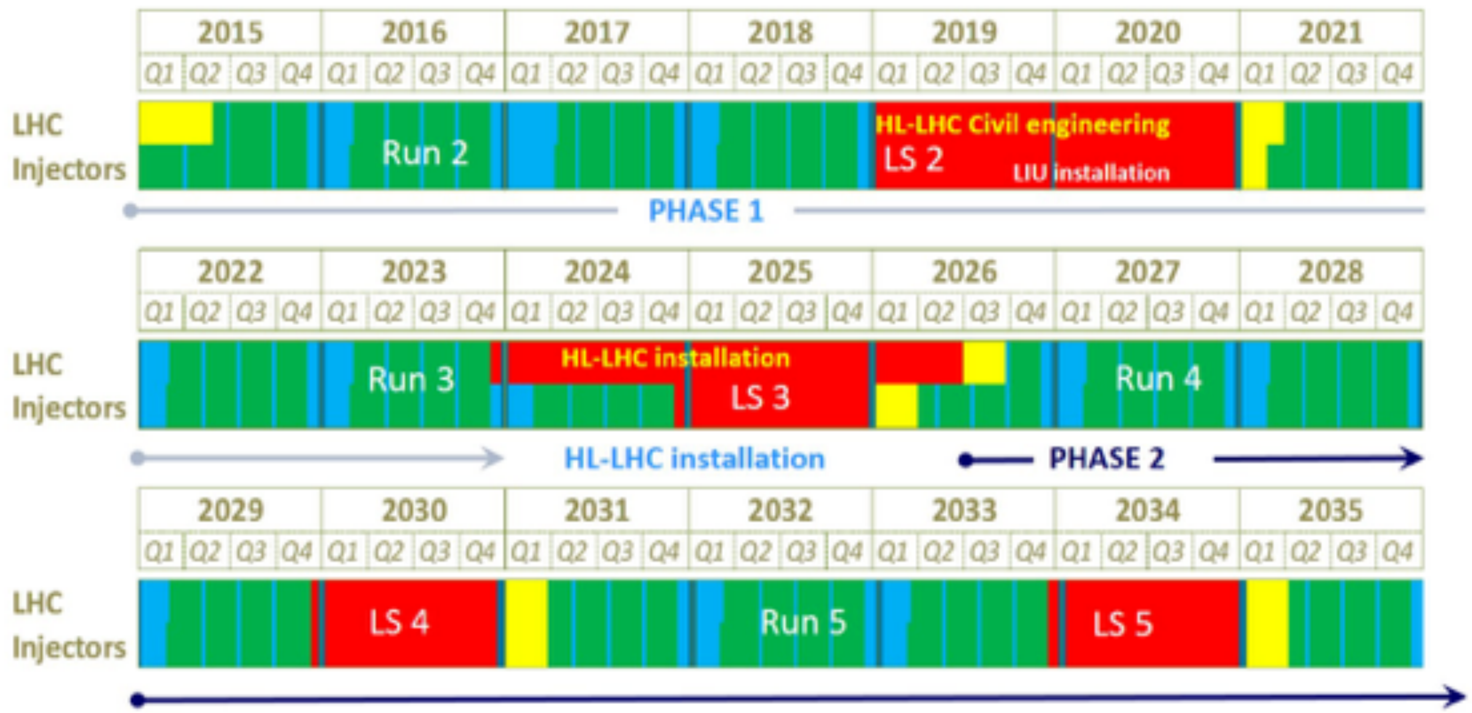
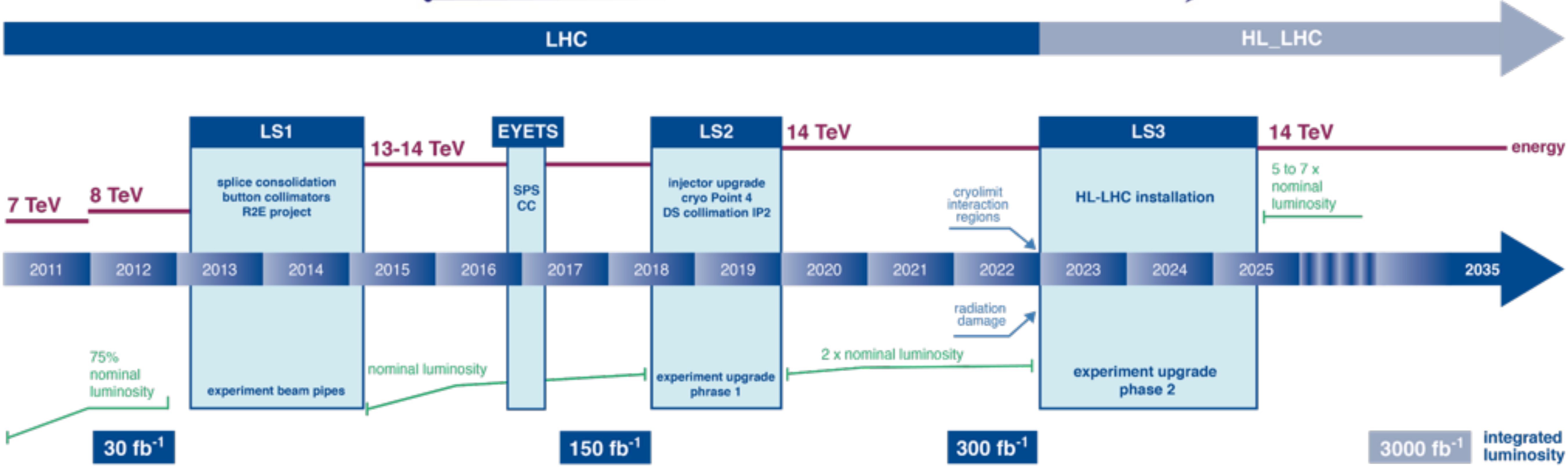
Giacomo Fedi
(Università di Pisa & INFN Pisa)

Timeline


2015
2016
2017
2018
2019
2020
2021
Q1 Q2 Q3 Q4
LHC
Injectors
Run 2
HL-LHC Civil engineering
LS 2
LIU installation
PHASE 1
2022
2023
2024
2025
2026
2027
2028
Run 3
HL-LHC installation
LS 3
Run 4
HL-LHC installation
PHASE 2
2029
2030
2031
2032
2033
2034
2035
LS 4
Run 5
LS 5


LHC
HL_LHC
LS1
splice consolidation
button collimators
R2E project
experiment beam pipes
13-14 TeV
EYETS
SPS
CC
LS2
injector upgrade
cryo Point 4
DS collimation IP2
experiment upgrade
phrase 1
14 TeV
LS3
HL-LHC installation
experiment upgrade
phase 2
14 TeV
energy
7 TeV
8 TeV
5 to 7 x
nominal
luminosity
cryolimit
interaction
regions
radiation
damage
2011
2012
2013
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2016
2017
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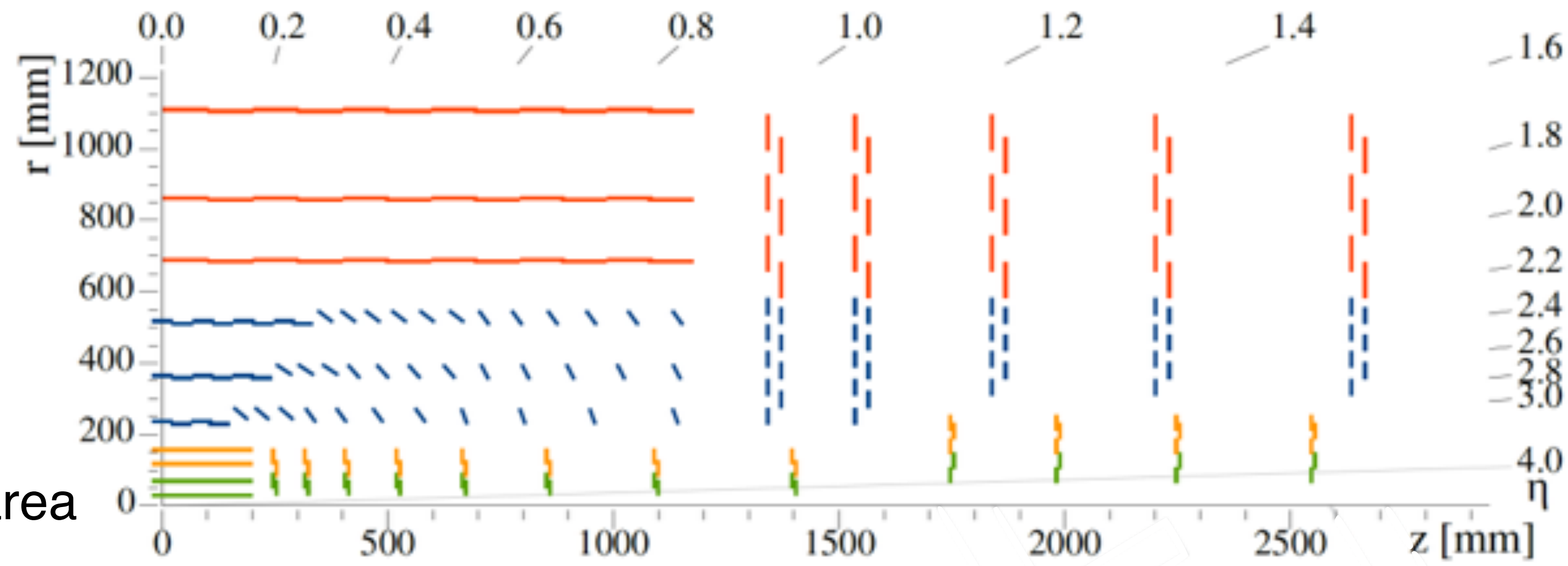
2019
2020
2021
2022
2023
2024
2025
2035
75%
nominal
luminosity
nominal luminosity
2 x nominal luminosity
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated
luminosity

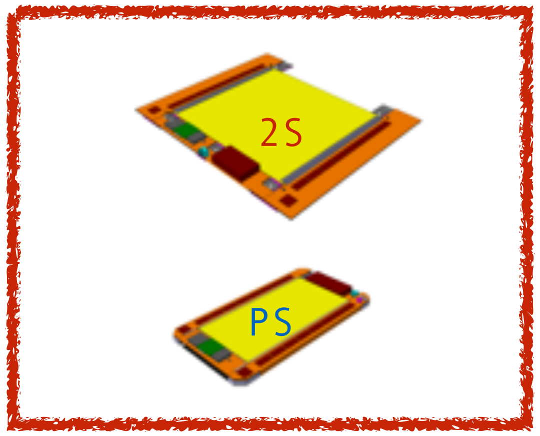
Introduction: tracking

HL-LHC phase: CMS tracker layout



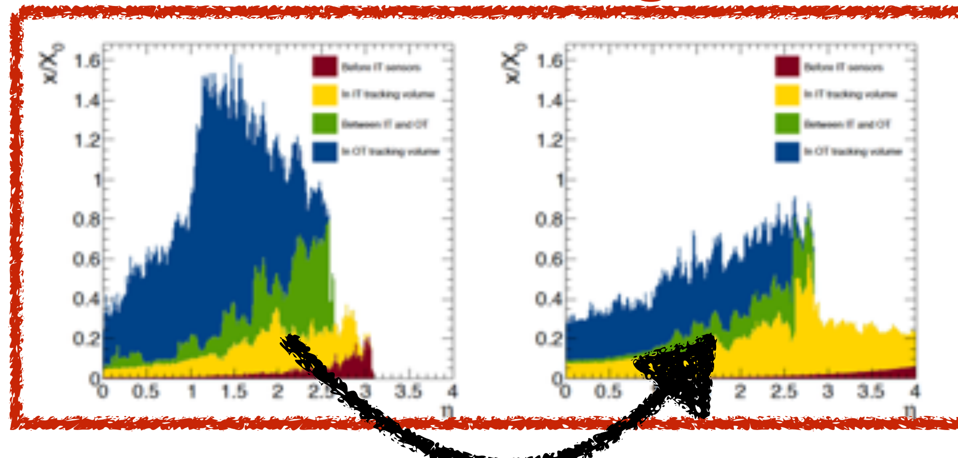
Pixel
(1x2 vs 2x2 chip modules) x6 pixel area reduction

Strips: p_T modules



- **Finer pixel pitches**
- **Wider acceptance**

Material budget

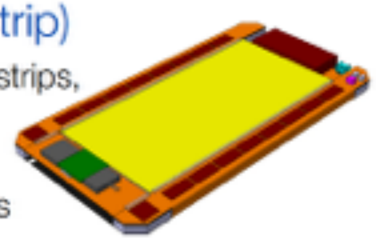


Challenges of tracking at the HL-LHC (2026):

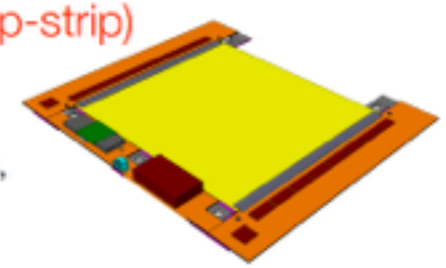
- **140-200 piled up p-p collisions**
- **~10 years of activity**

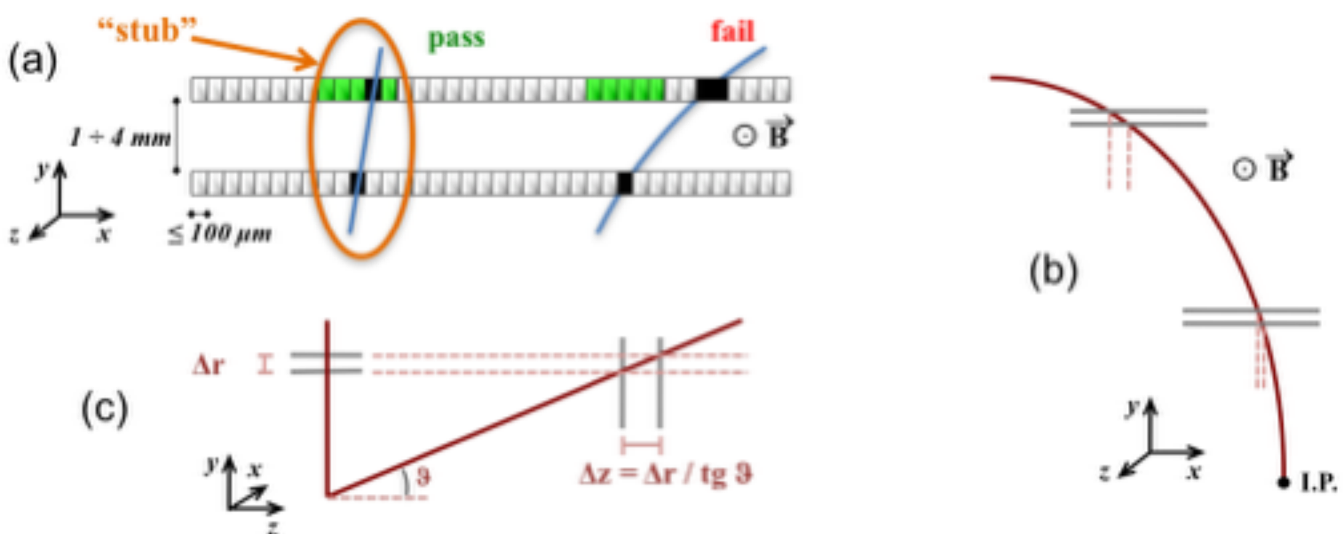
In situ data reduction

PS modules (pixel-strip)
- Top sensor: 2x2.5 cm strips, 100 μm pitch
- Bottom sensor: 1.5 mm x 100 μm pixels



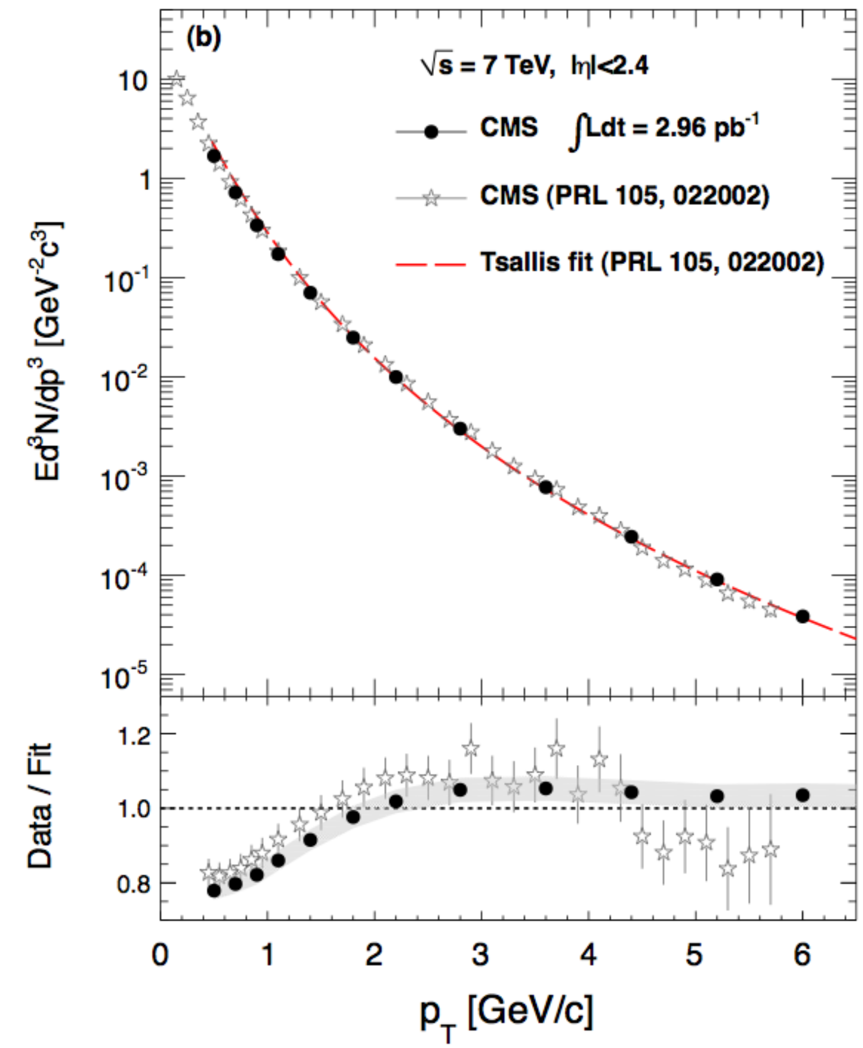
2S modules (strip-strip)
- Strip sensors 10x10 cm²
- 2x5 cm long strips, 90 μm pitch





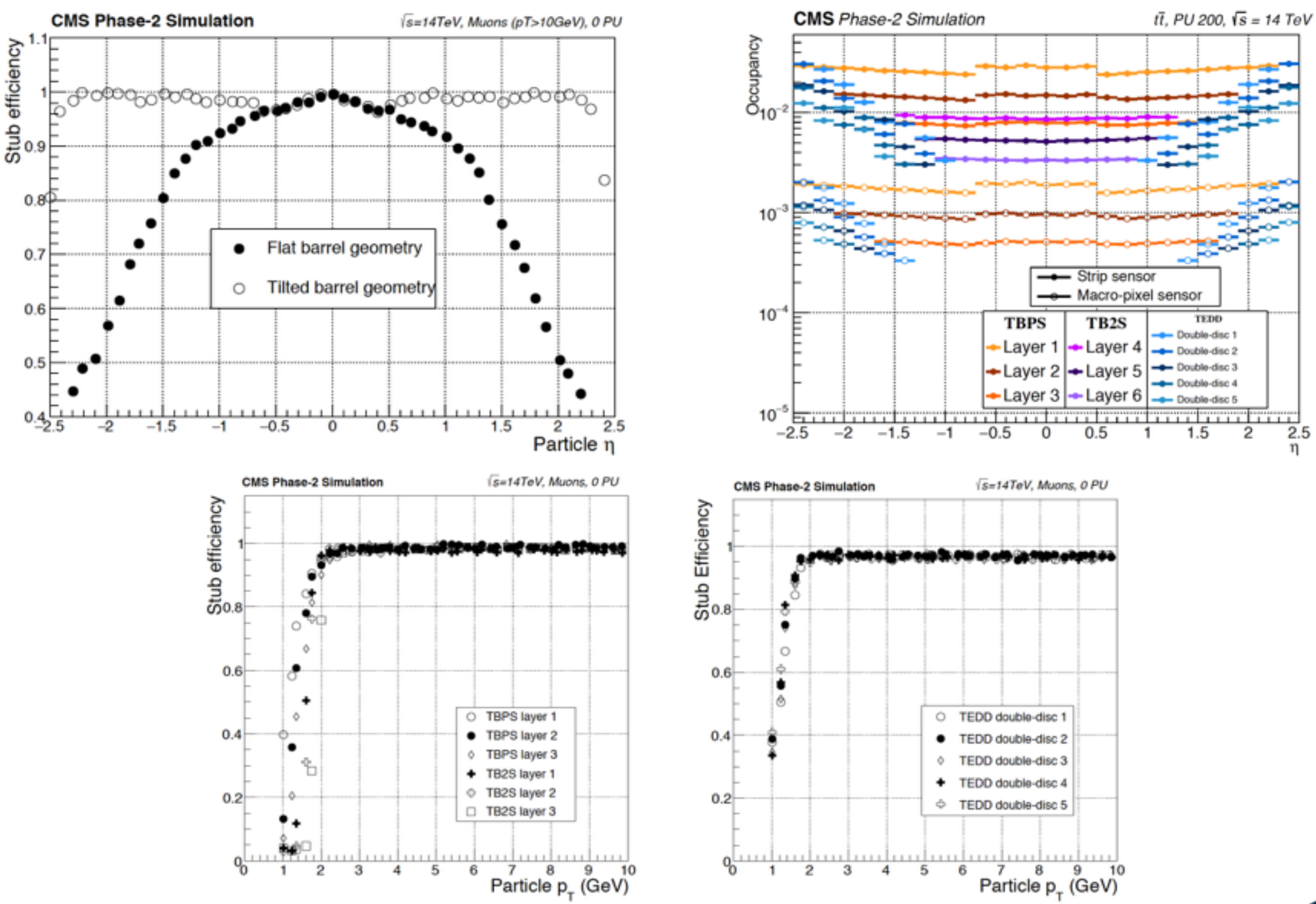
- Two silicon sensors separated by a small gap (a few mm)
- hits in two sensors correlated: stub
- tracks bend in strong magnetic field
- stubs with p_T <2 GeV rejected in real-time

Minimum bias tracks

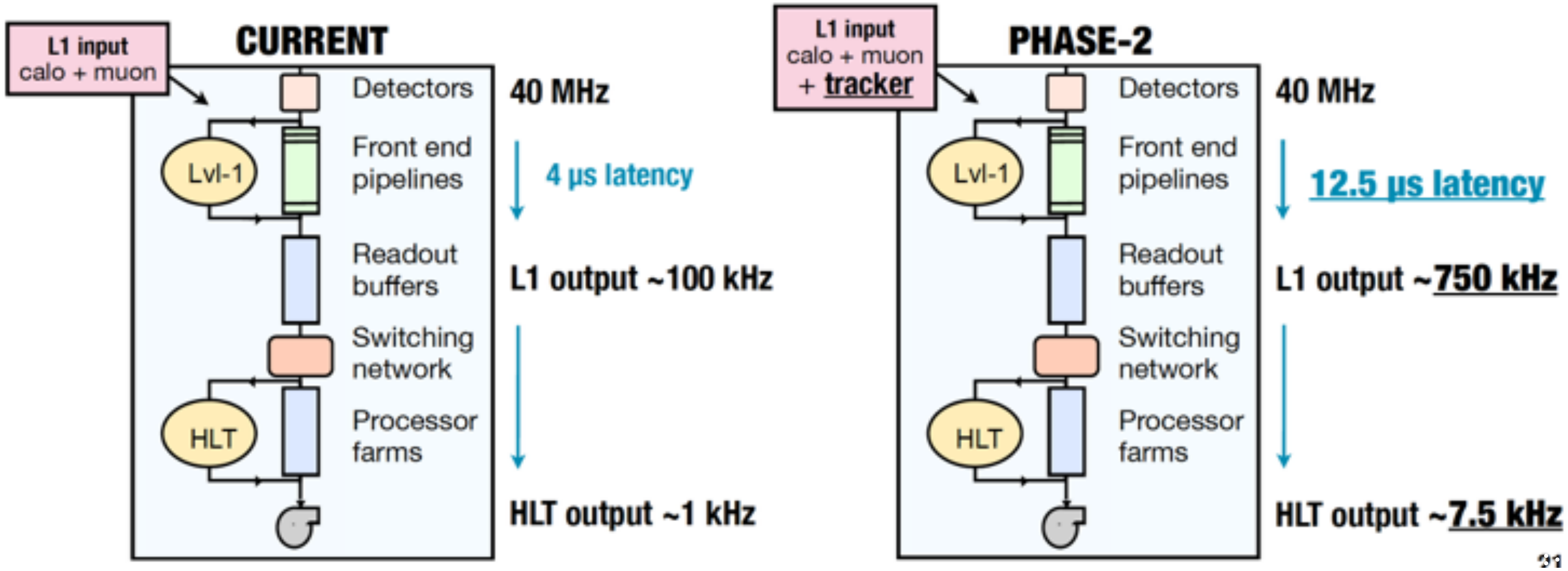


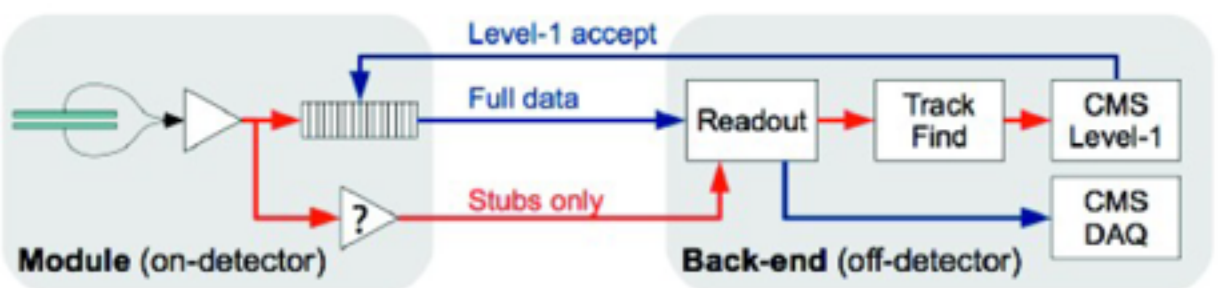
With two superimposed sensors per module we are able to filter low p_T tracks (>2 GeV). Big data transfer reduction O(10)

Tilted geometry benefits



L1 track trigger



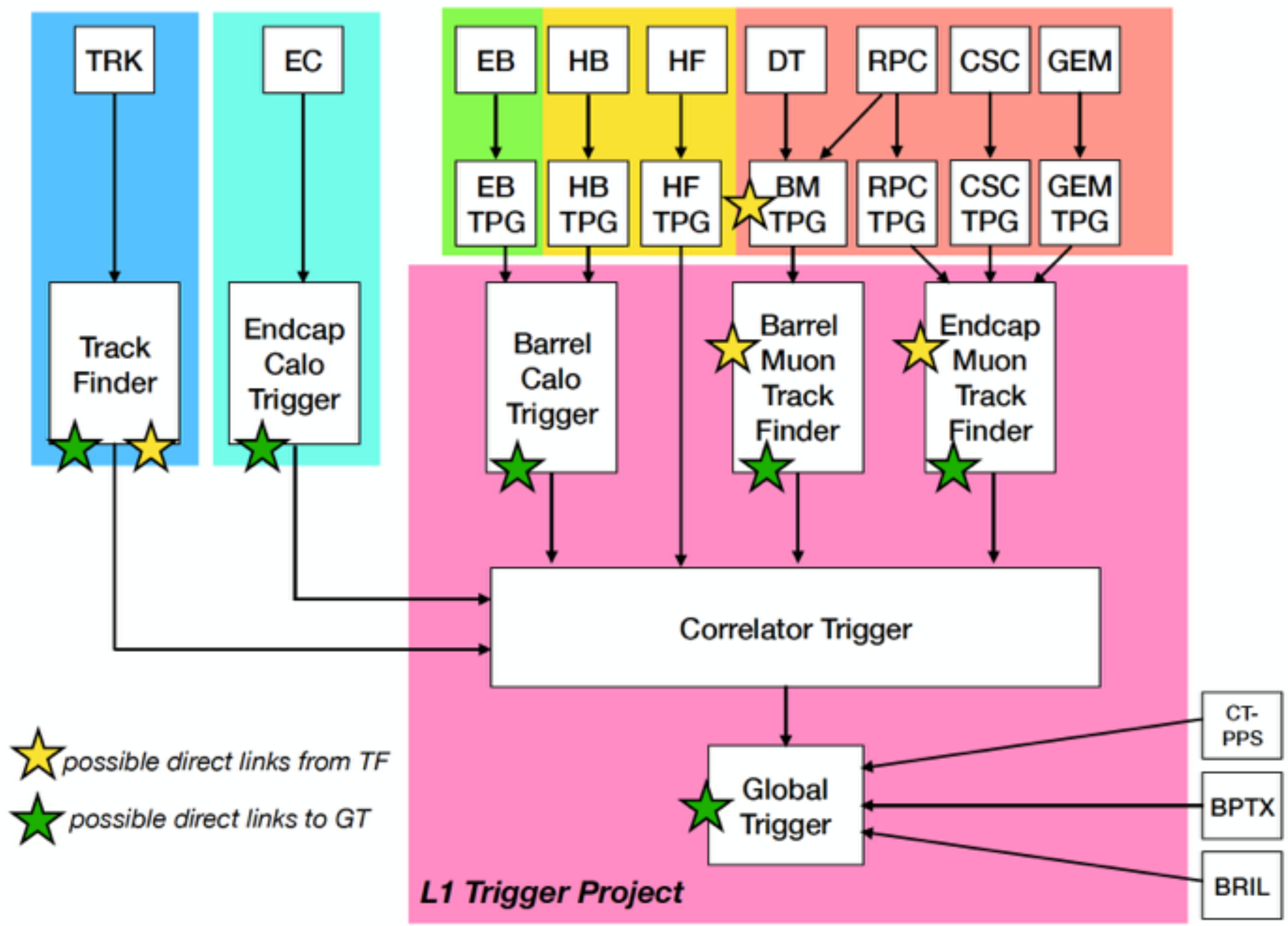


4 μs latency

L1 Track Trigger approaches:

- Fully FPGA Time multiplexing+Hough transform
- Fully FPGA Trackless
- FPGA+AM ASIC

L1 trigger



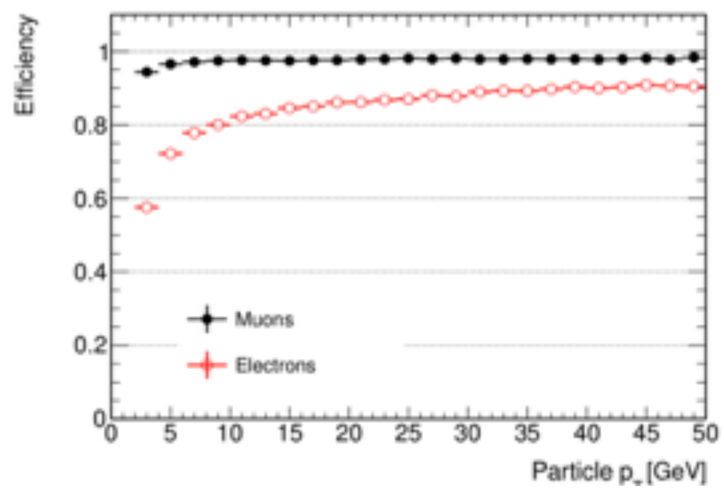
J. Brooke

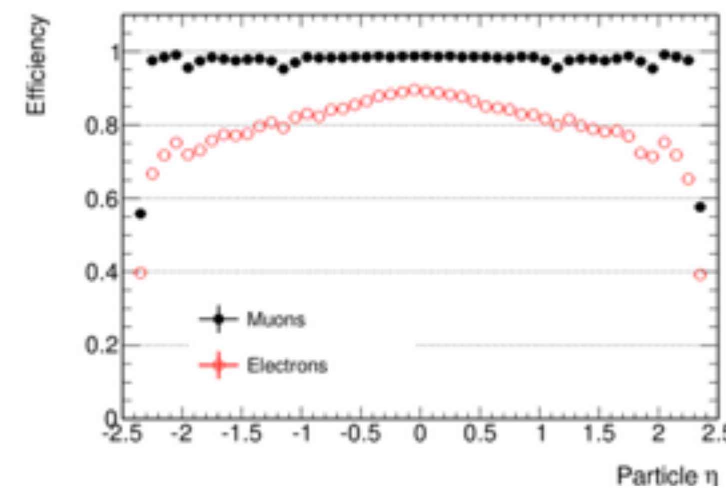
L1 track trigger performance

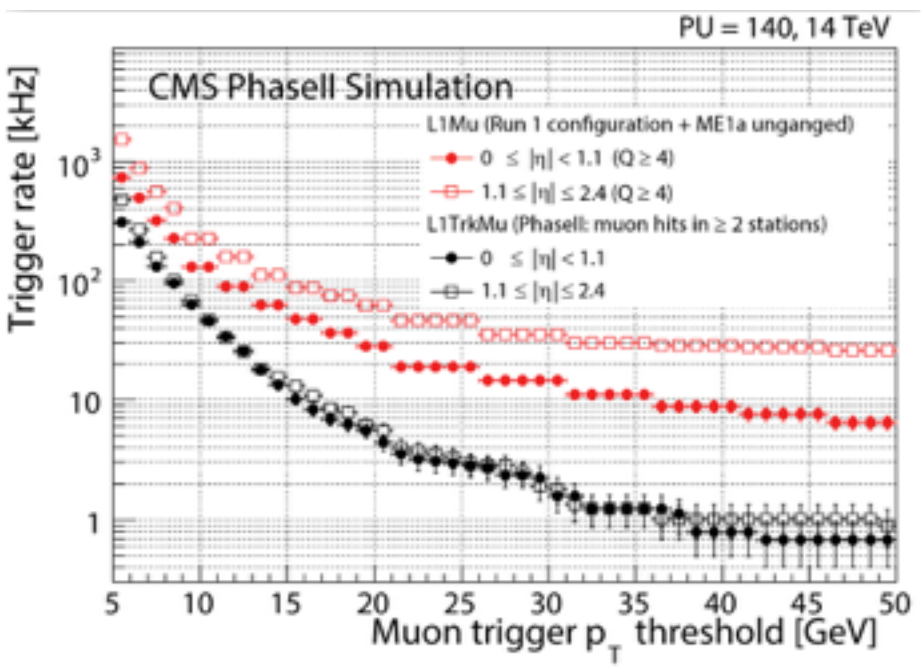
L1 Track Trigger:

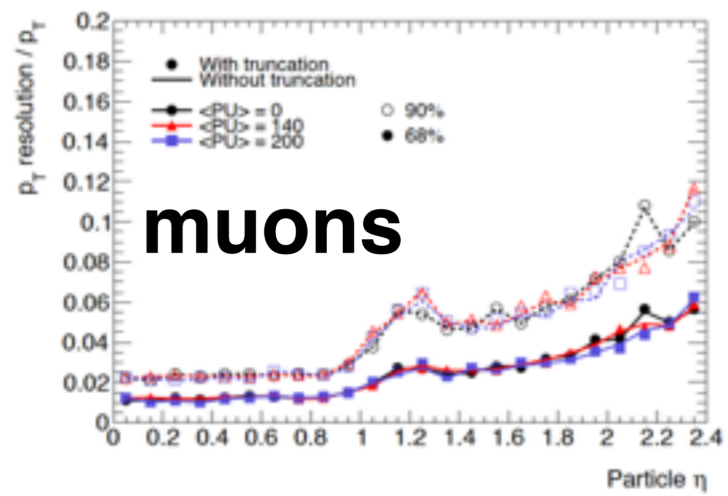
- **Improved lepton ID**
- **Track isolation**
- **Vertex determination**
- **Rate reduction**

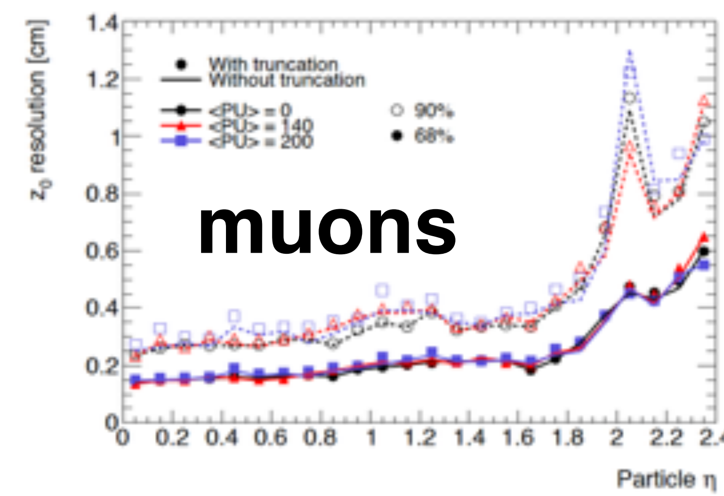
Caveats: flat geometry studies, p_T >3 GeV









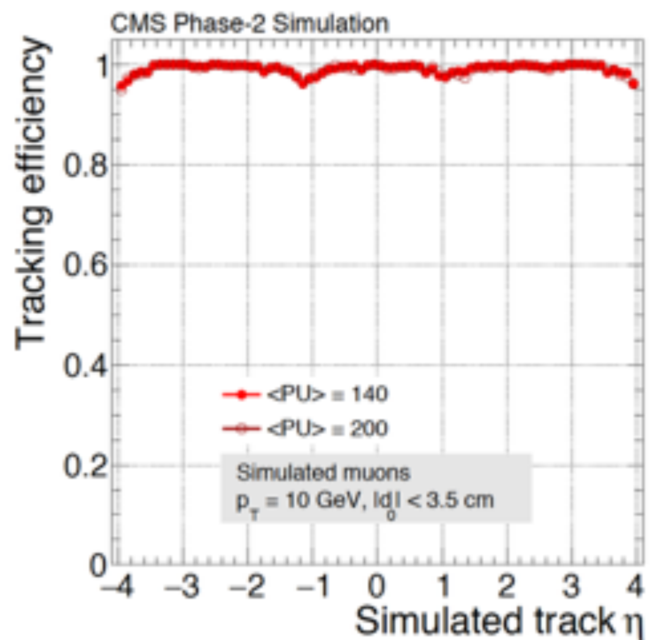


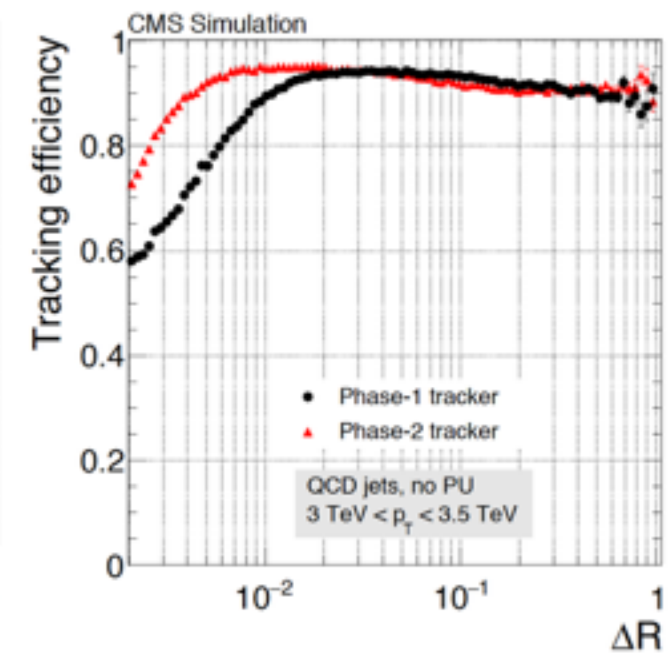
Offline tracking performance

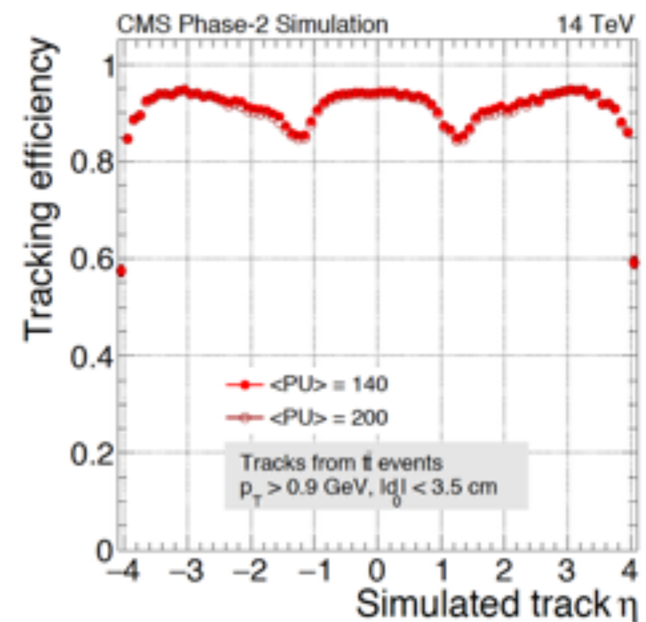
- 10 GeV muon efficiency ~100%
- Improved two-track separation in high-p_T jets

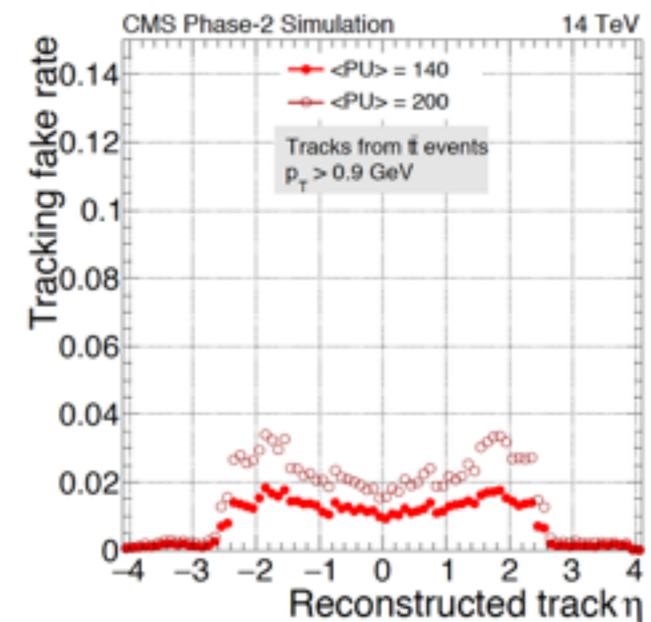
- High track efficiency
- Low track fake rate (performance @200PU in HL-LHC ~ @70PU now)

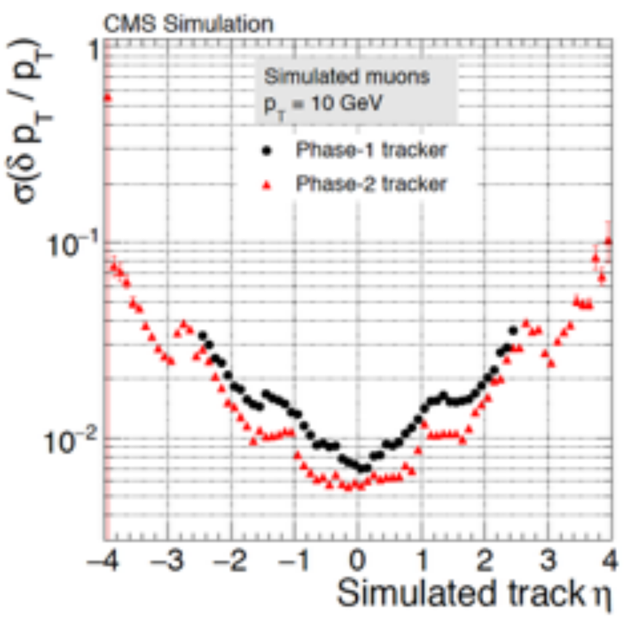
- Better momentum resolution

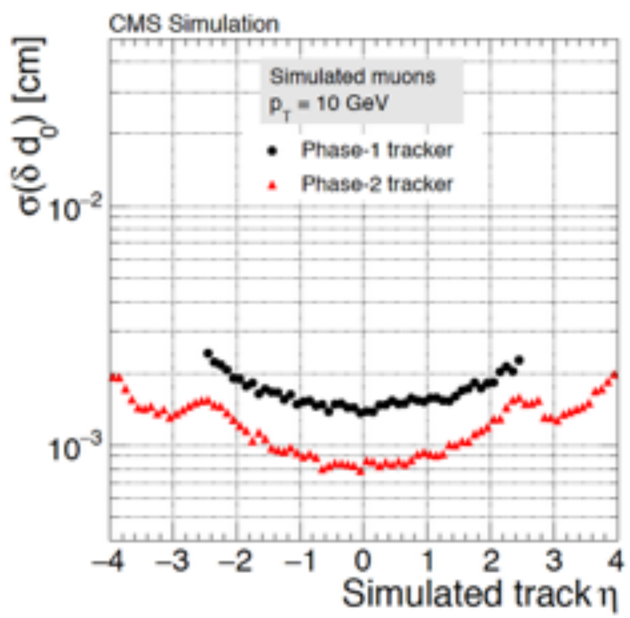






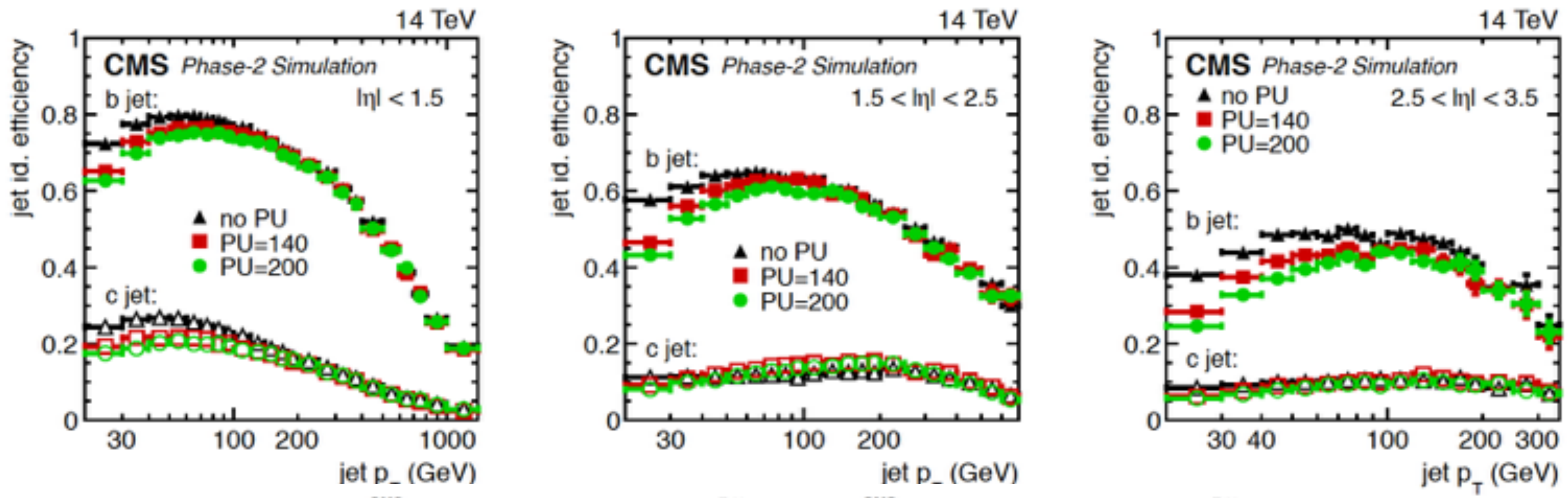




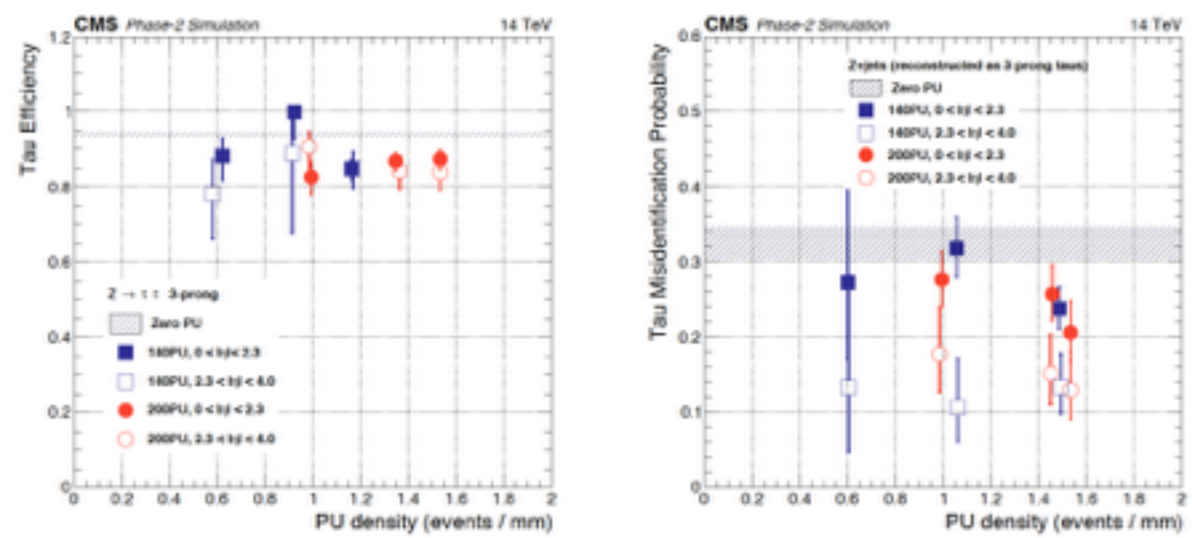


Physics objects

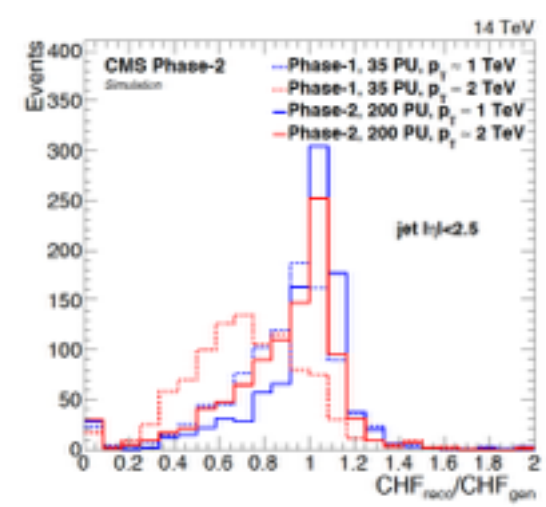
- **B-tagging**
- **Increased pixel acceptance b-tag for η>|2.5|**



- **τ-tagging**
- **τ p_T >22 GeV**



- **Jets**
- **CHF=Charge hadron energy fraction (fraction of energy within a jet that is reconstructed as charged hadrons)**



Effects on physics

Showing some case studies

Increased statistics 3000 fb^{-1} and HL-LHC:

- Exploration of multi-TeV physics (discovery)
  - Testing of BSM models
  - Discovery of rare processes
- Access to rare process (looking for deviations)
  - BR measurements
  - Precision measurements

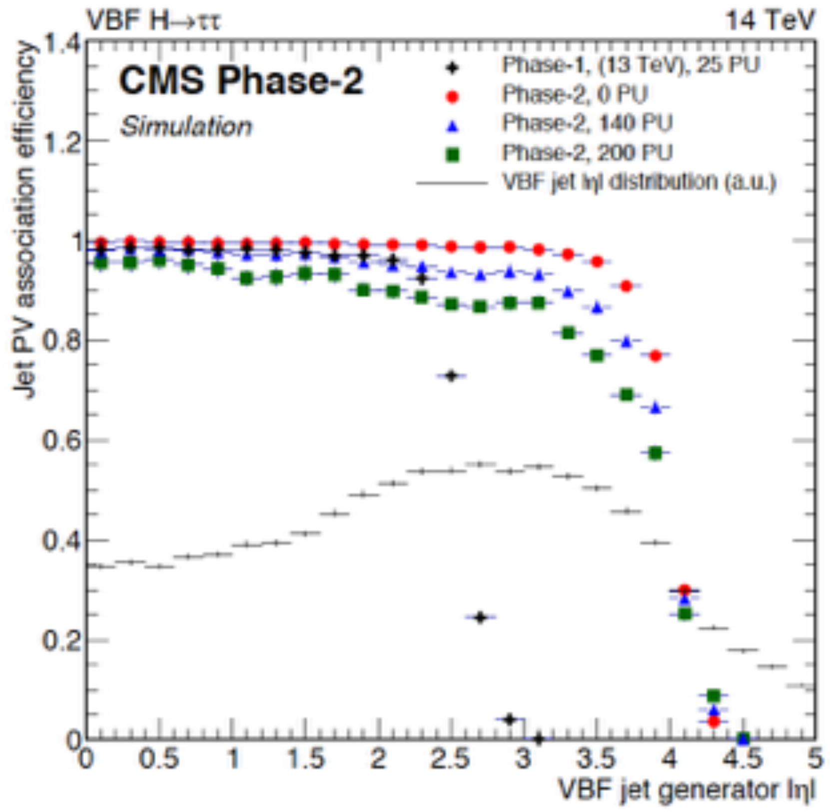
Effect of the Phase-2 tracker on physics

- The tracker detector was designed to maintain (at least) the same performance at Phase-1 conditions in the Phase-2 high-pileup environment
- Evaluating just the effect of the tracker (no full detector simulation yet available)

Higgs decays (1/2)

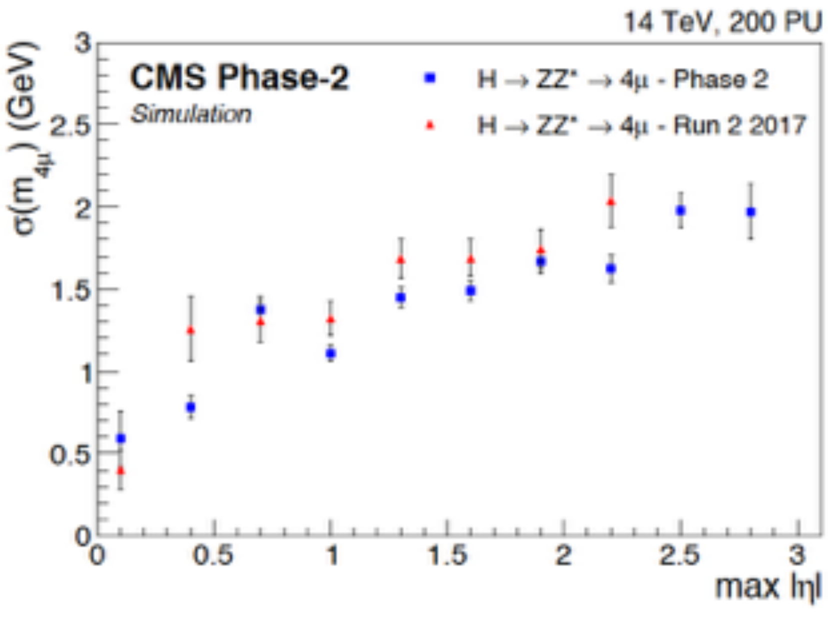
VBF H → ττ

- **Motivation:** Yukawa coupling between the Higgs boson and fermions, sensitivity reached in HL-LHC at the same level of deviations due to some BSM models
- **Benefits:** increased tracker acceptance
  - +10.5% in hadronic tau acceptance
  - increased VBF jets acceptance (Higher signal ID x1.5, higher S/N ratio)



H → ZZ* → 4l

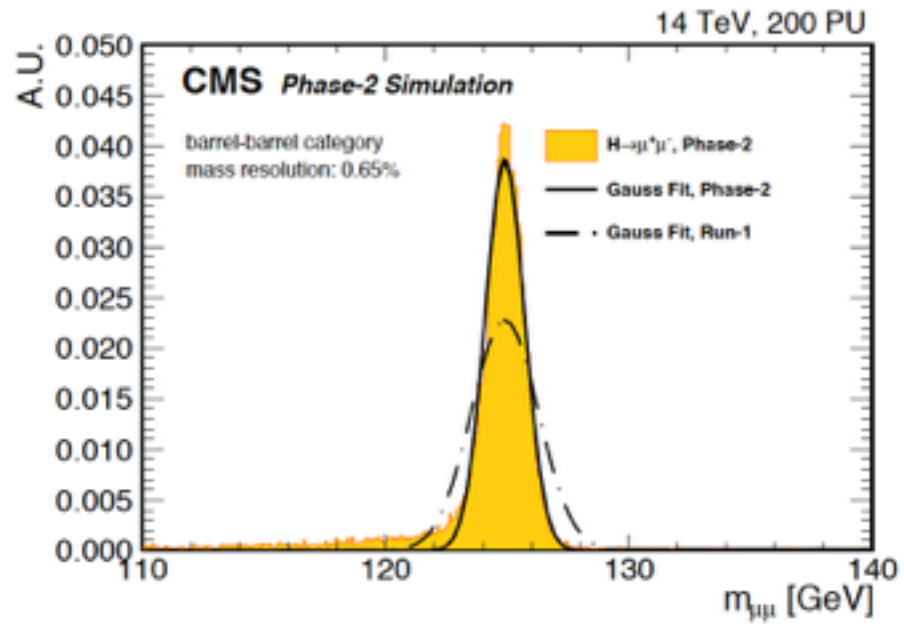
- **Motivation:** golden decay channel, fully reco → measurement of CP quantum numbers and diff x-section, anomalies in couplings
- **Benefits:**
  - Triggering on low p_T leptons
  - Increased acceptance (from η <2.4| to <|3.0| → +15% 4l acceptance)
  - Increased p_T resolution improves the S/N ratio



Higgs decays (2/2)

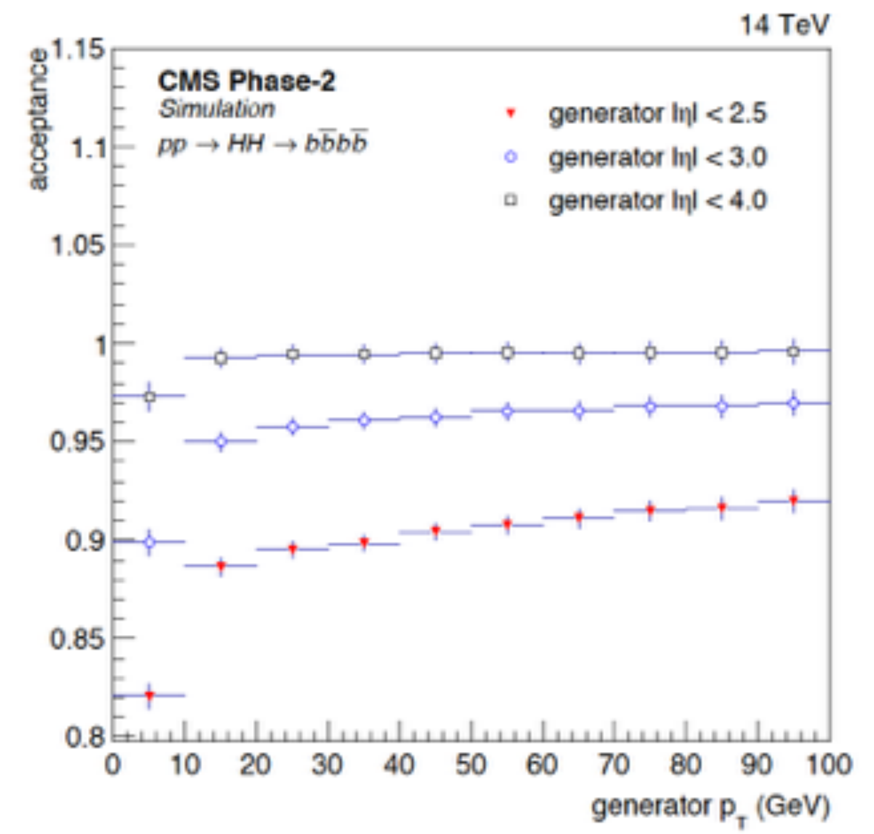
H → μμ

- **Motivation:** measurement of H coupling to muons
- **Benefits:** increase tracking performance increases the signal sensitivity over a large Drell-Yan di-muon production
- 65% better mass resolution
- **Sensitivity:** 5% uncertainty on Higgs-muon coupling



HH → $b\bar{b}b\bar{b}$

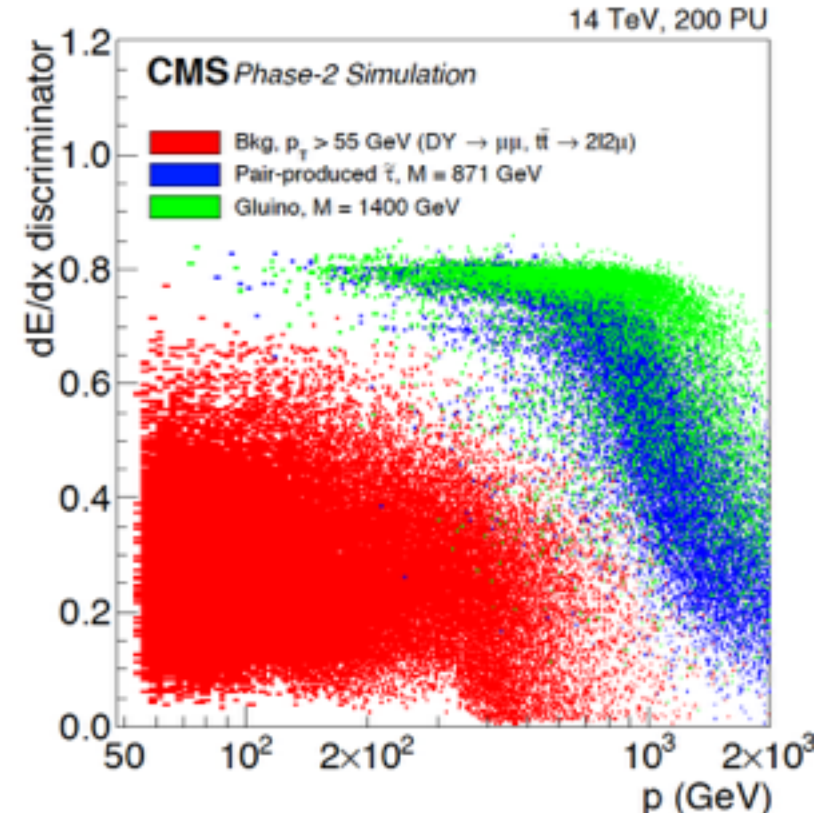
- **Motivation:** study the nature of electroweak symmetry breaking, extremely rare process
- **Benefits:** increase momentum resolution, excellent b-tagging capabilities
- Fraction of generated b jets from signal as function of p_T and η



Exotic and top

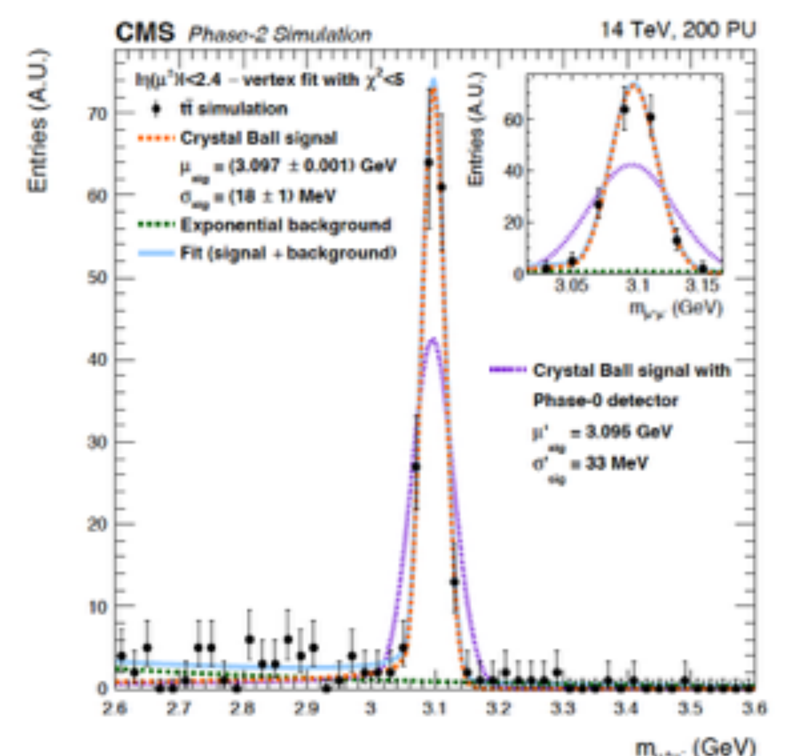
Exotic

- **Motivation:** search for BSM particles, e.g. Split SUSY particles stau and gluino
- **~Benefits:** inner tracker will keep on providing dE/dx presence of extra bit in the outer tracker output enabling a programmable over the threshold flag (HIP flag)
- **Sensitivity:** Phase-1 sensitivity will be reached in 4 times the int lumy of Phase-2 with dE/dx+HIP flag



J/ψ in top events

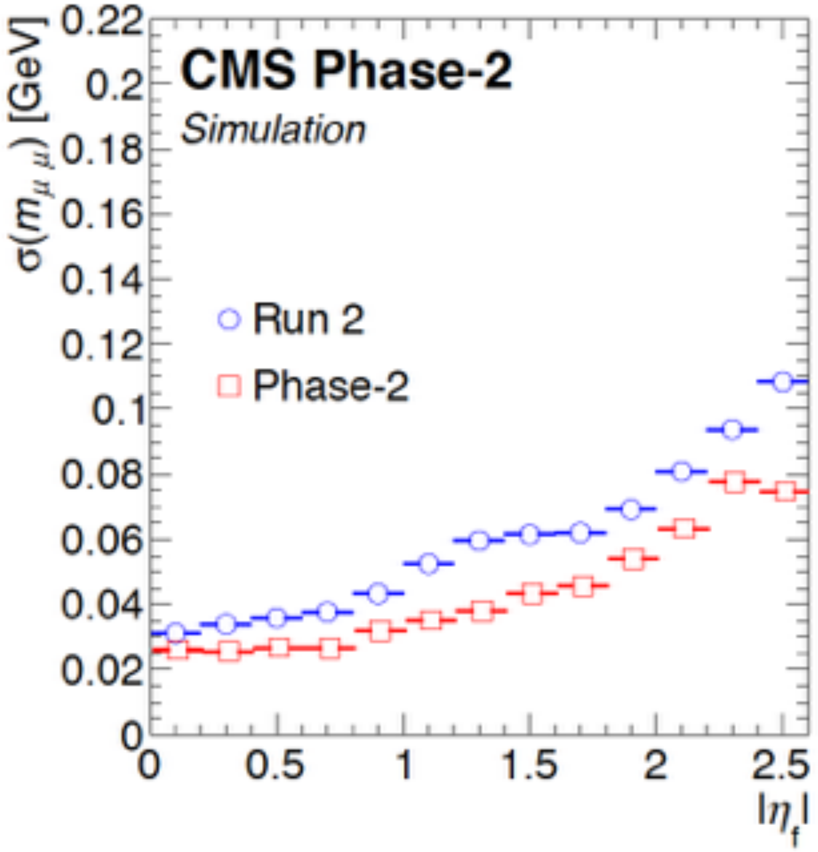
- **Motivation:** measurement of top mass, based on its partial reconstruction from final states containing J/ψ→μμ decays from b fragmentation *reconstructing J/ψ +(l from W decay)*
- **Benefits:** mainly on the J/ψ mass resolution ~50% improvement, better S/N discrimination
- **Expectations @3ab^{-1}:** 6e5 signal events against 2e5 BG events, no PU dependence
- **Caveats:** muons limited in the η<|2.4| region



B-physics

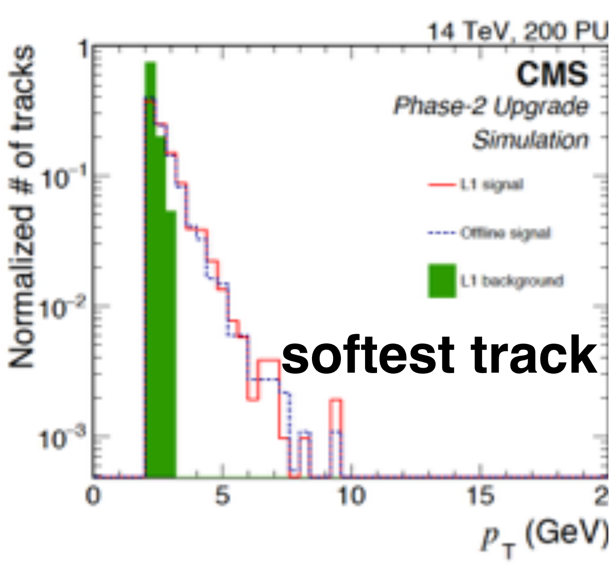
$B_{0,s} \to \mu\mu$

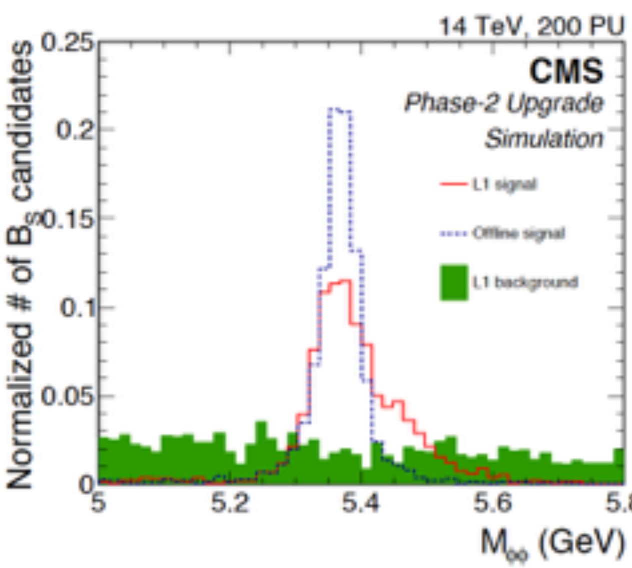
- **Motivation: FCNC forbidden at tree level in the SM. Deviations in BR measurement can be hint of NP such as leptoquarks or extra Higgs doublets**
- **Benefits: L1 tracking capability and momentum resolution**
- **Expectations: 40% improvements in the mass resolution, improved B_s vs B_0 separation**



$B_s \to \varphi\varphi \to 4K$

- **Motivation: measurement of CP violation phase in the CKM matrix, FCNC suppressed (possible enhancement due to NP particles)**
- **Benefits: accessible thanks to the L1 tracking capabilities**
- **Expectations: 30-35% efficiency @L1**





Conclusions

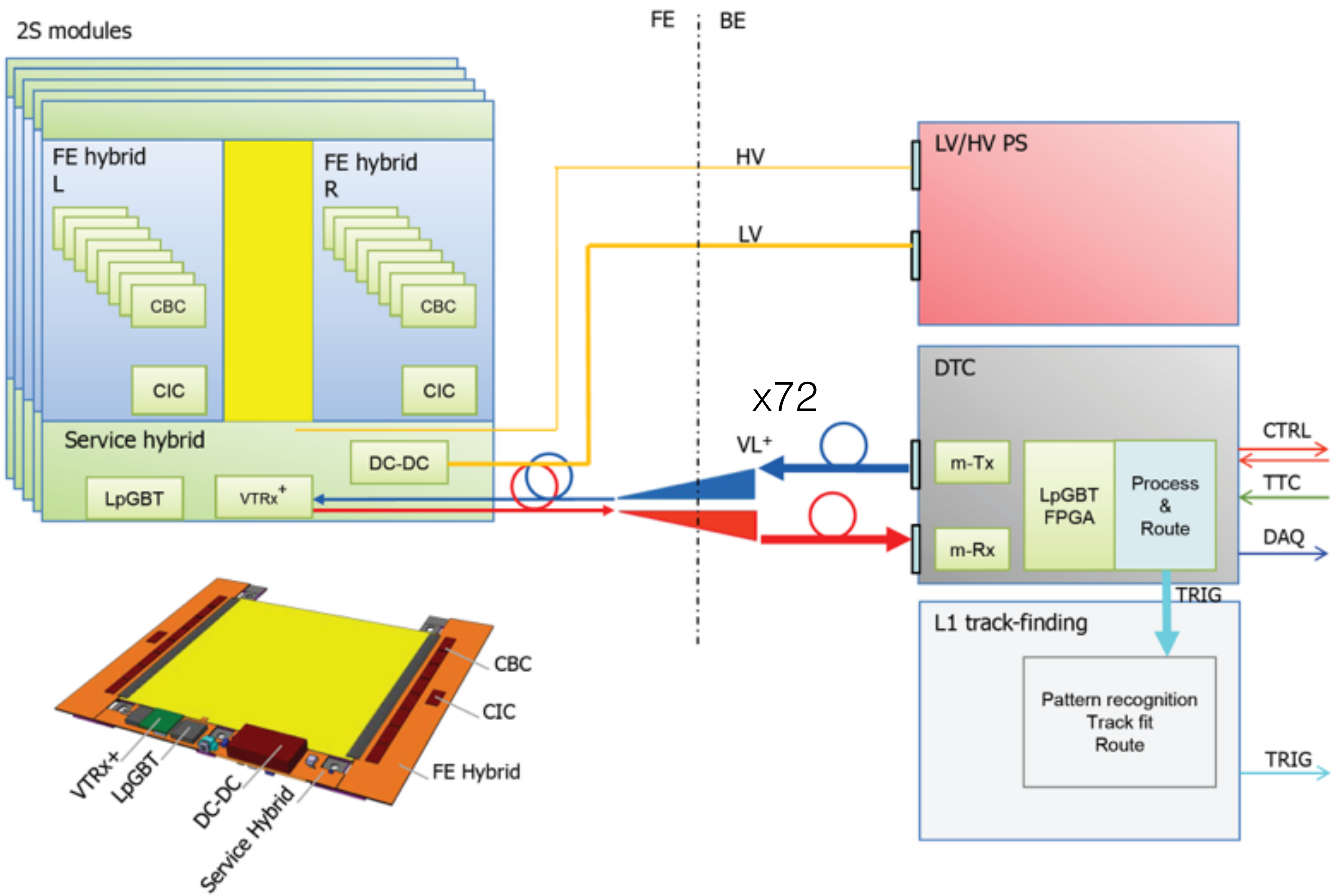
- Main goal of the Phase-2 tracker is to maintain the same performance of the current tracker in a harsh environment (PU200)
- Various improvements are expected:
  - Increased η acceptance from <|2.5| to <|4.0|
  - Less material budged
  - L1 tracking capabilities
  - Increased track parameter precision
- The expected final integrated luminosity (3000 fb^{-1}) and the good performance of the tracker allow us to access new physics channels and to improve precision measurements
- The physics decay channels which has been analyzed consider mainly the improved tracker performance and not the overall detector improvements.

Extra

Future developments

- **Tracking iterations targeting physics objects: e.g. tracks inside jets**
- **Multiple algorithms: This exploits the concept of using different algorithms specialized for certain tasks in different iterations**
- **Tracking in the Outer Tracker: profit from the L1 track finder information at the offline tracking level**
- **Tracking at HLT using GPUs**

Readout electronics



650 Gbps
to Trig

Pixel modules

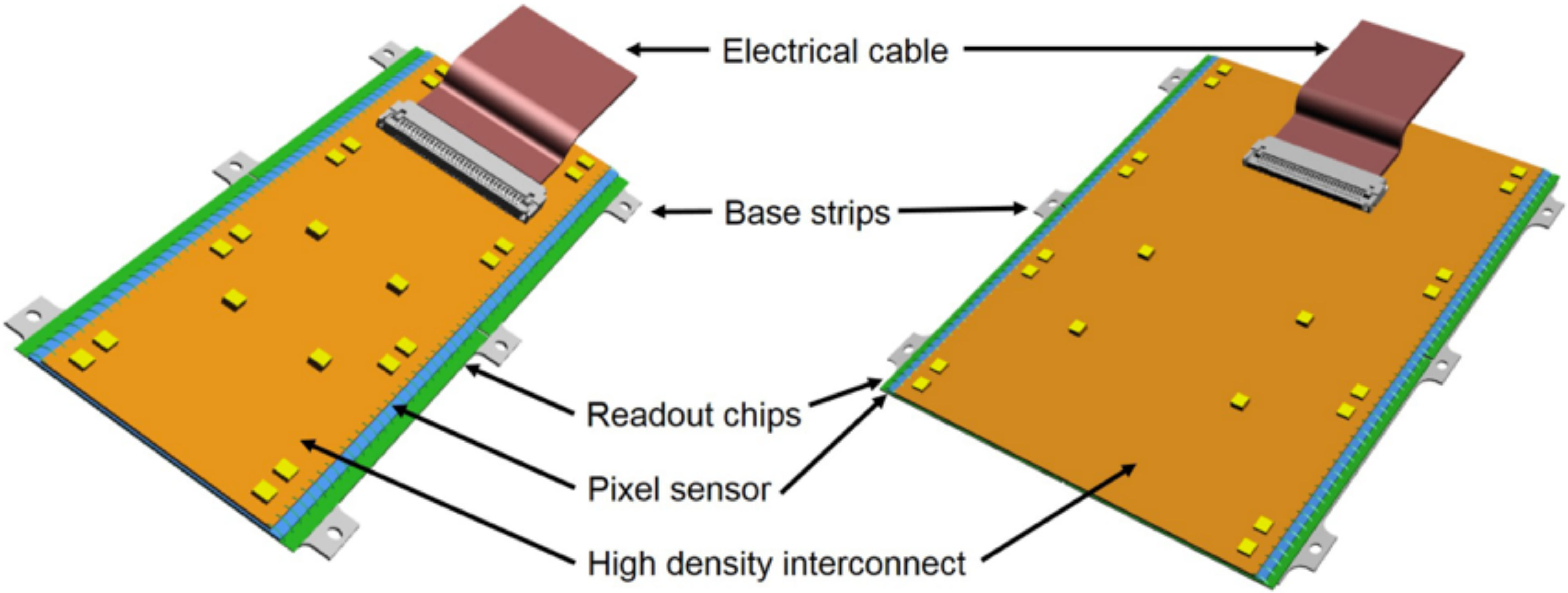
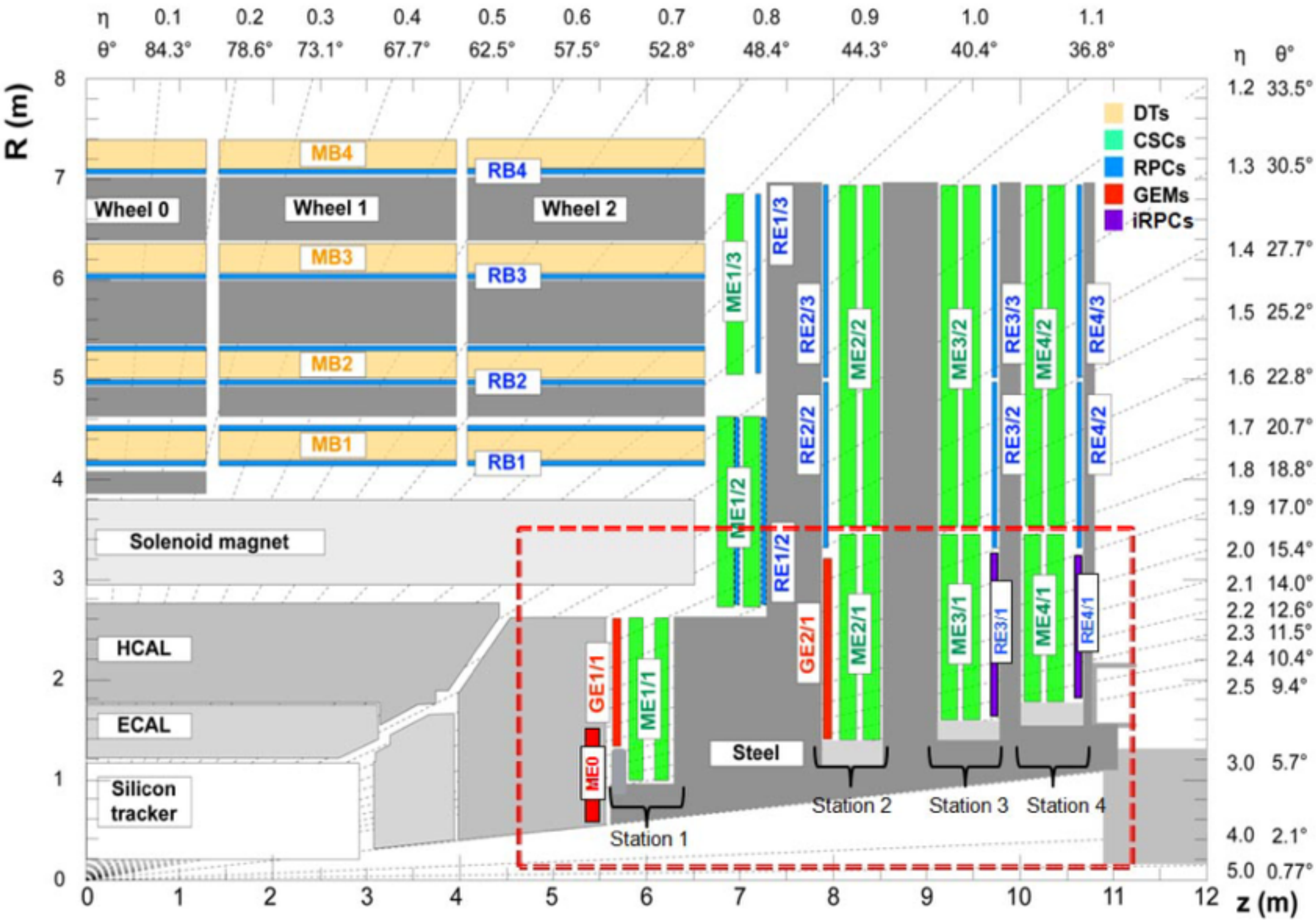


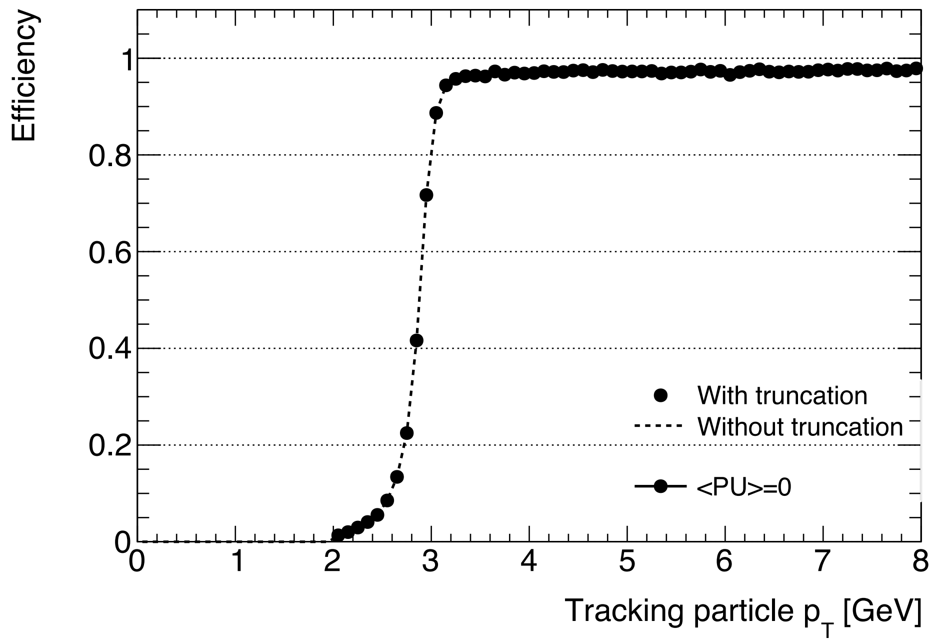
Figure 4.3: Sketch of the 1×2 (left) and 2×2 (right) pixel modules. The dimensions are roughly $1.8 \times 4.4\,\mathrm{cm}^2$ and $3.7 \times 4.4\,\mathrm{cm}^2$ for the 1×2 and 2×2 modules, respectively. The yellow elements symbolize passive electrical components.

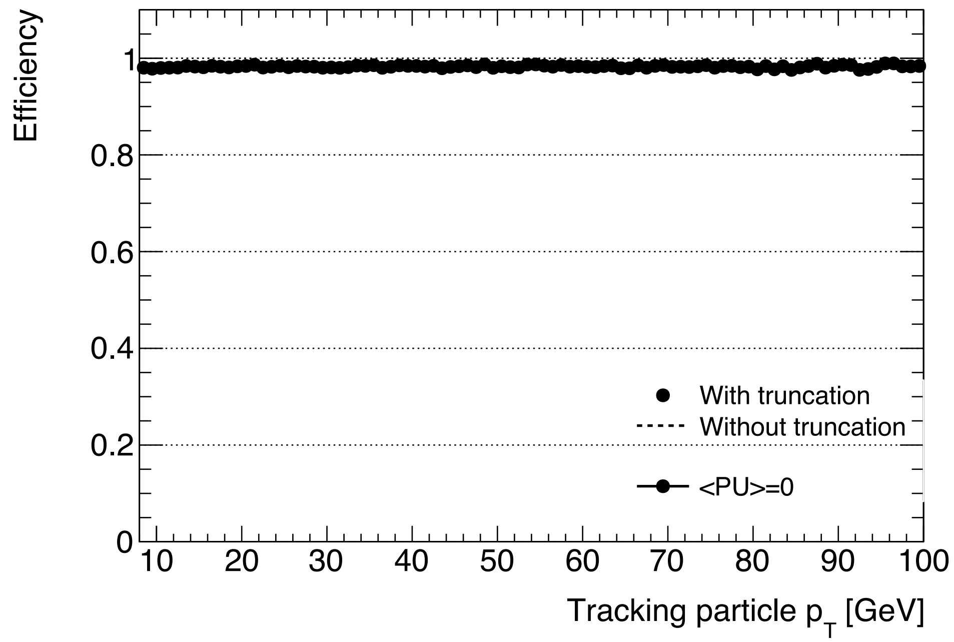
Muon chambers



System performance - Single muons

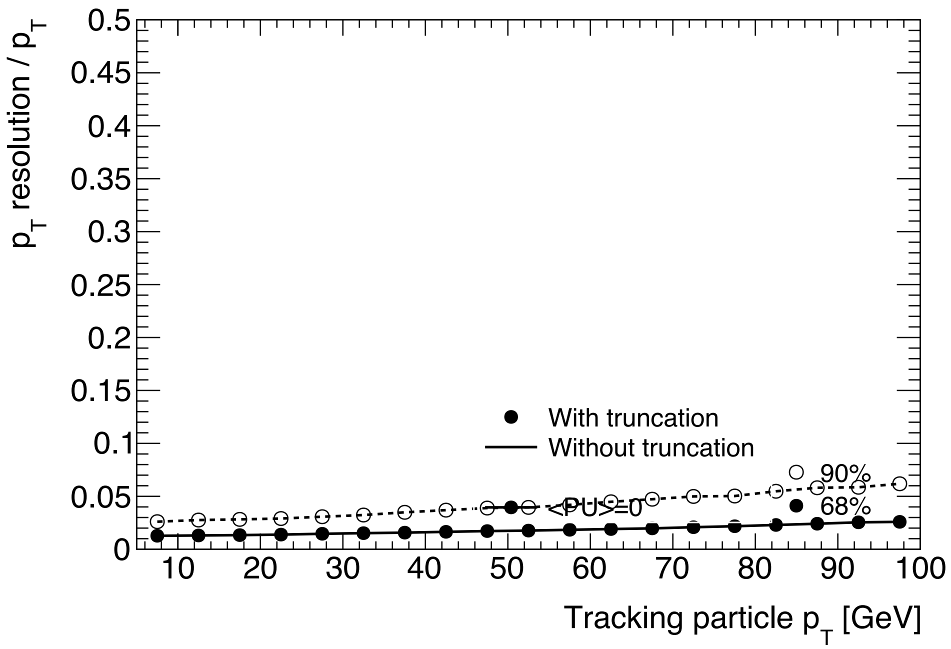
Efficiency vs pT: 2-8 GeV, 8-100 GeV





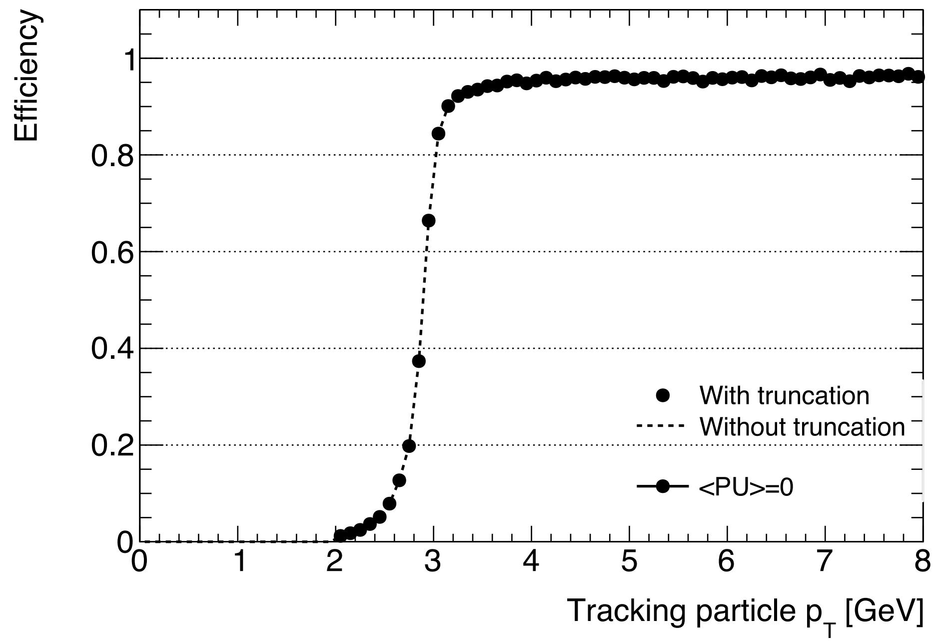
ptres/pt vs pt: 2-100 GeV

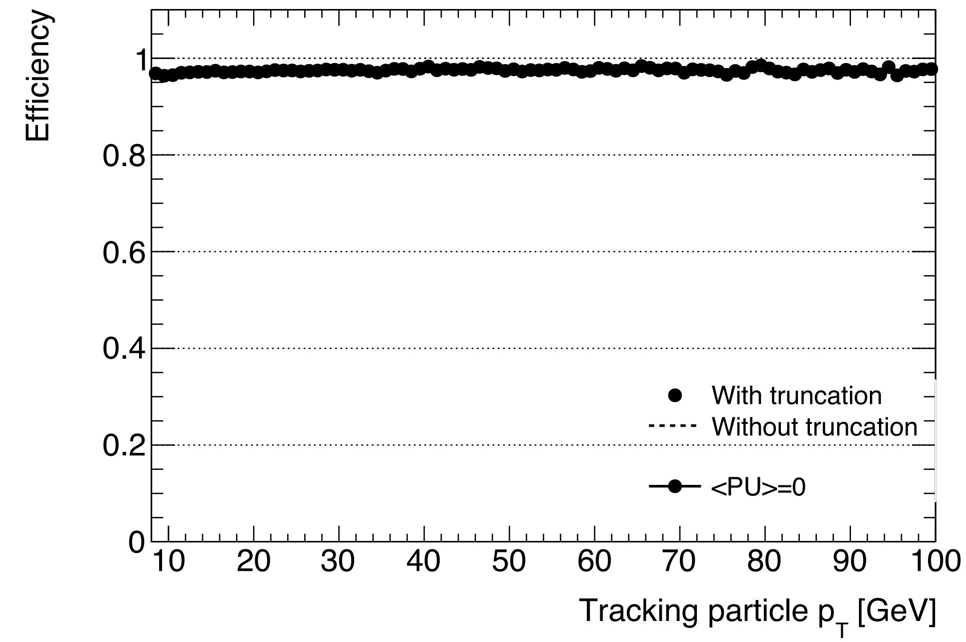
Demonstrator accepts stubs with pt>3 GeV



System perf. - Single pions

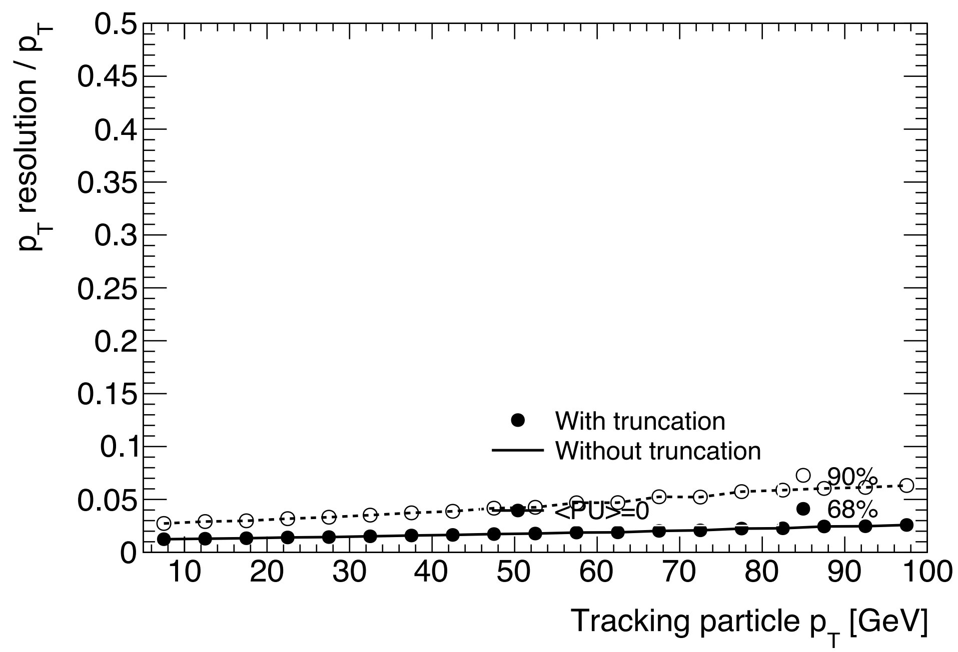
Efficiency vs pT: 2-8 GeV, 8-100 GeV





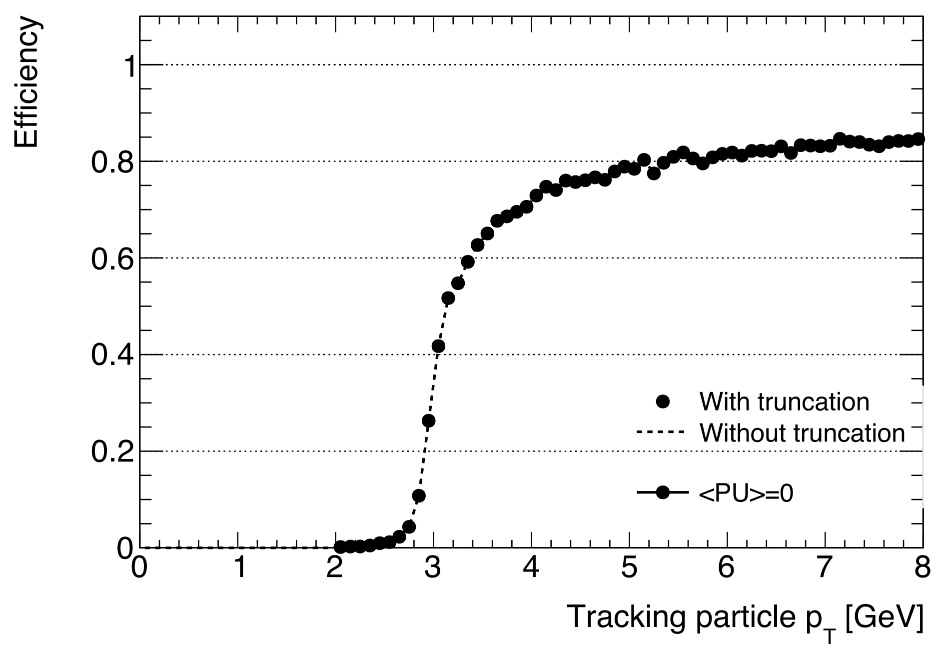
ptres/pt vs pt: 2-100 GeV

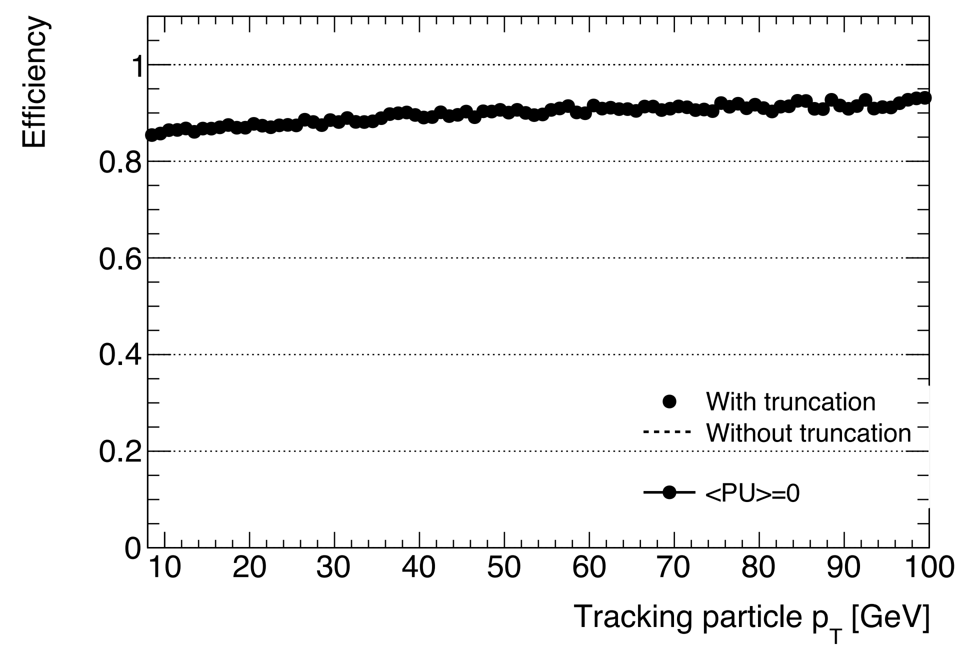
Demonstrator accepts stubs with pt>3 GeV



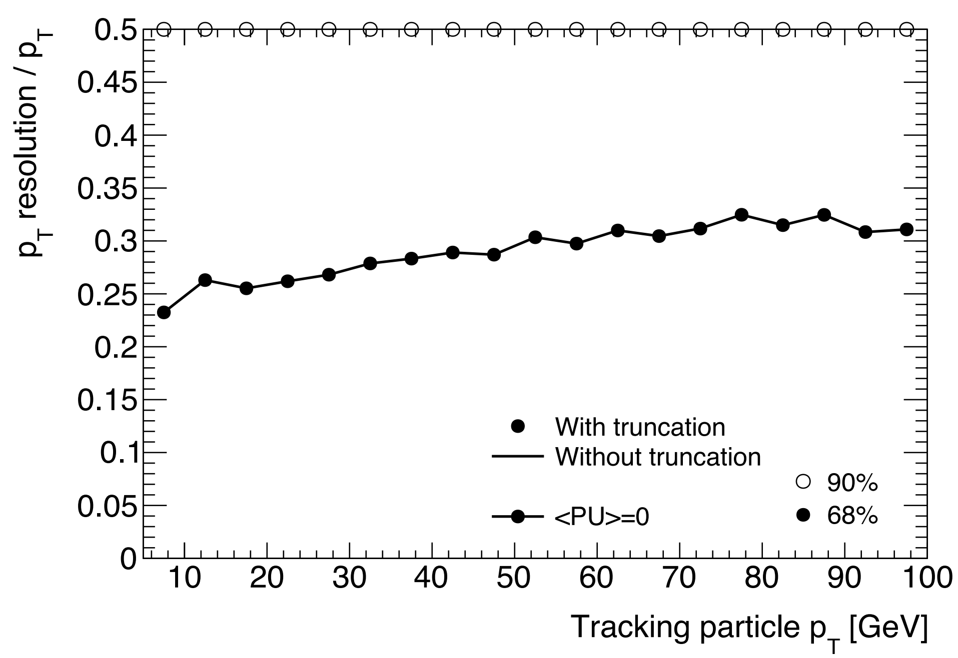
System perf. - Single electrons

Efficiency vs pT: 2-8 GeV, 8-100 GeV





ptres/pt vs pt: 2-100 GeV



Demonstrator accepts stubs with p_T >3 GeV

Physics objects at L1

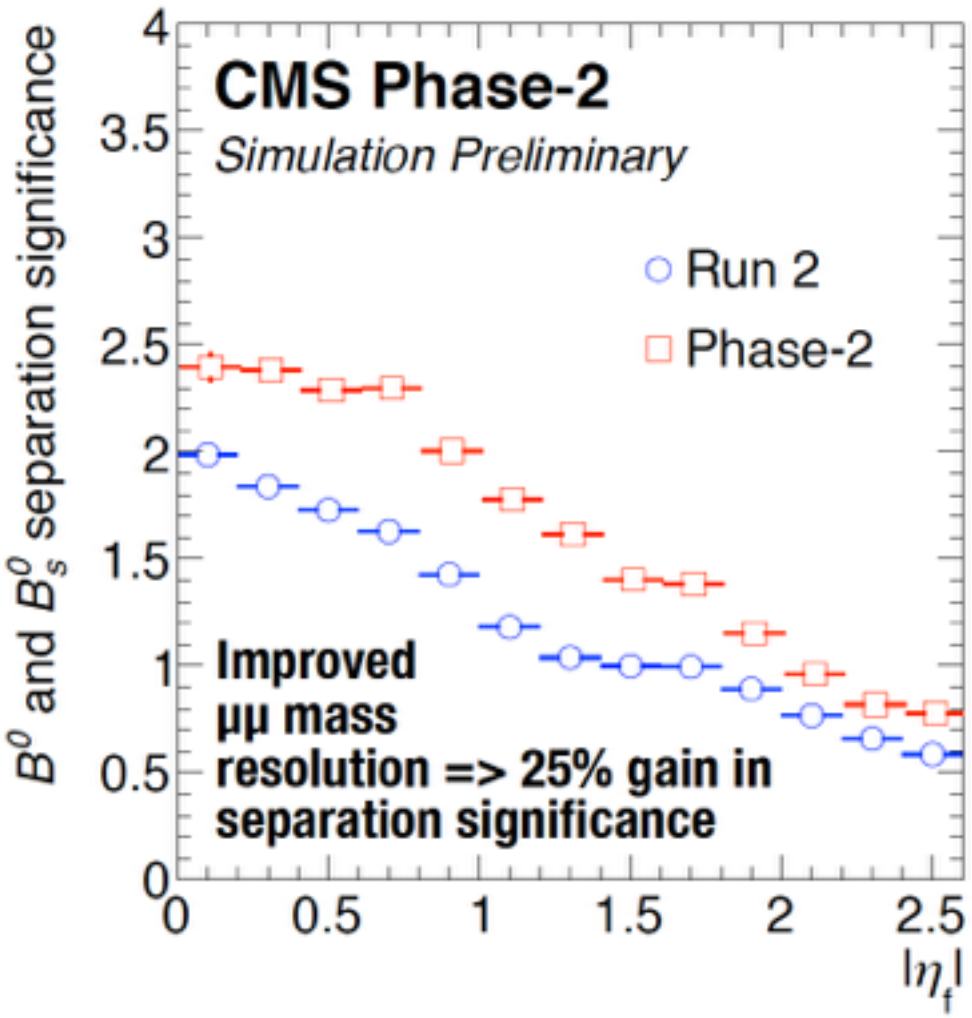
Motivation for Track Jet Finding

- For L1 Tracks, we already have good enough resolution in z to separate the prompt tracks from the PU
  - Use the tracks with a consistent z and cluster in η-ϕ to build L1 track jets
  - This gives some rejection for fake tracks from stub combinatorics which don't have a consistent z with other tracks and tend to be isolated in η-ϕ
  - L1 Jet pT from clustered tracks gives a strong discriminant from the softer pileup jets. Can optimize the algorithm so that it also preserves the efficiency for low pT jets
  - Jets further away in z from the prompt candidates can give a measure of the average track multiplicity and energy density from PU
- From the L1 tracks as input, we can already make L1 trigger objects like HT, MHT, Number of jets
- Further downstream, track jets can be combined with the ECAL clusters to calibrate for the neutrals further refining the L1 Jet object
- Finally, with a simple algorithm the jet clustering will not result in overconsumption of resources and a large latency

Rishi Patel

BMM

Improved
μμ mass
resolution => 25% gain in
separation significance



$D_s \to \tau\nu$, $\tau \to \mu\mu\mu$

Extended muon coverage
=> improved signal
acceptance e.g. in LFV
$D_s \to \tau\nu$, $\tau \to \mu\mu\mu$ search