Performing precision measurements and new physics searches at the HL-LHC with the upgraded CMS Level-1 Trigger

a.k.a.

CMS' Adventures in the Level-1 Trigger Wonderland

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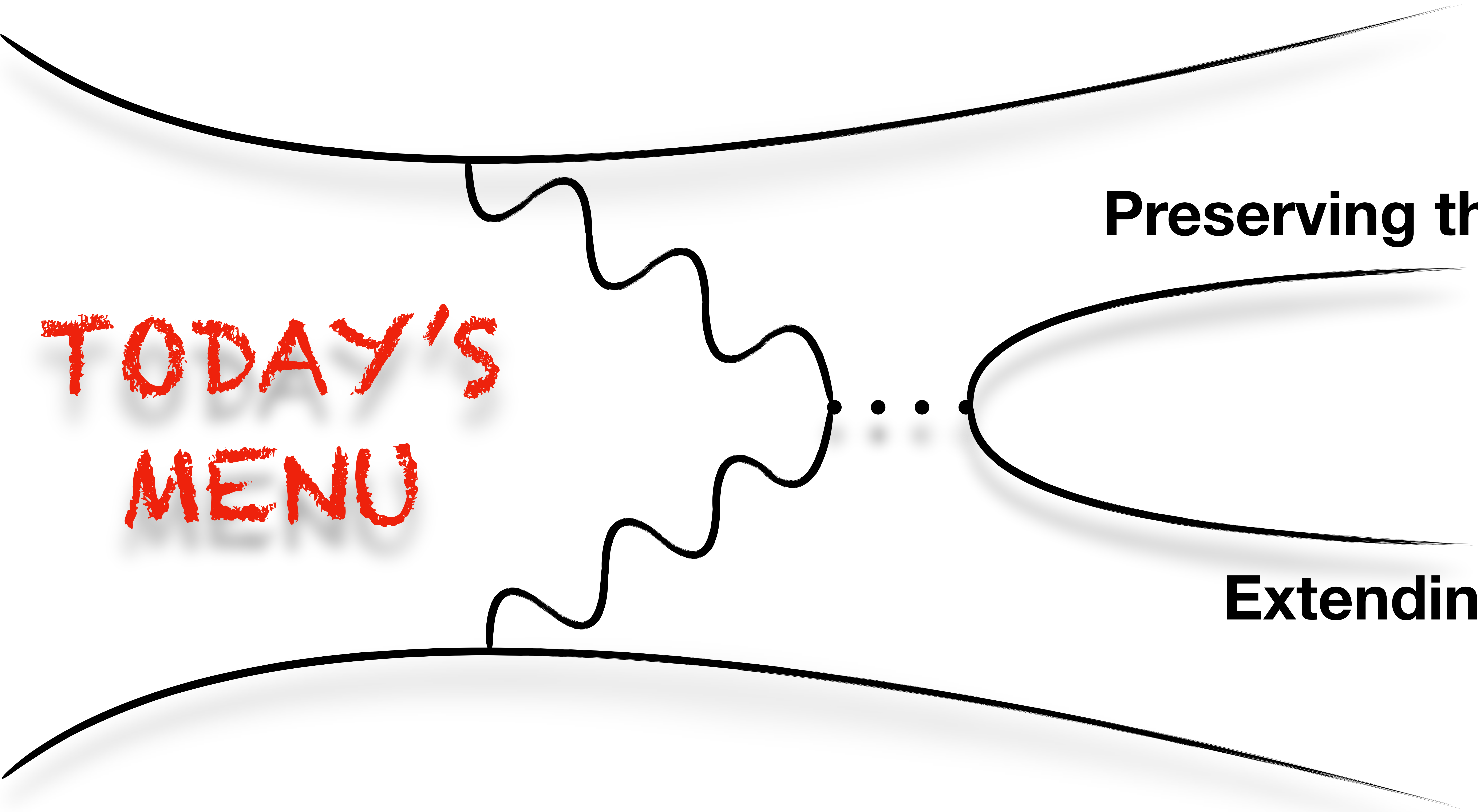
on behalf of the CMS Collaboration



HL-LHC and CMS Phase-2

Preserving the discovery potential
(with the Phase-2 Trigger)

Extending the physics reach
(with the Phase-2 Trigger)

Conclusions and outlook

HL-LHC and CMS Phase-2

High Luminosity LHC and CMS Phase-2 upgrade

- **High Luminosity LHC** will start in 2029 and will integrate **10 times the LHC luminosity**, and have an **instantaneous luminosity 3 times the Run 2 peak value**

⇛ **unprecedented** levels of radiation and **number of simultaneous collisions** (~70@LHC → ~200@HL-LHC)

Official schedule
Last updated: January 2022

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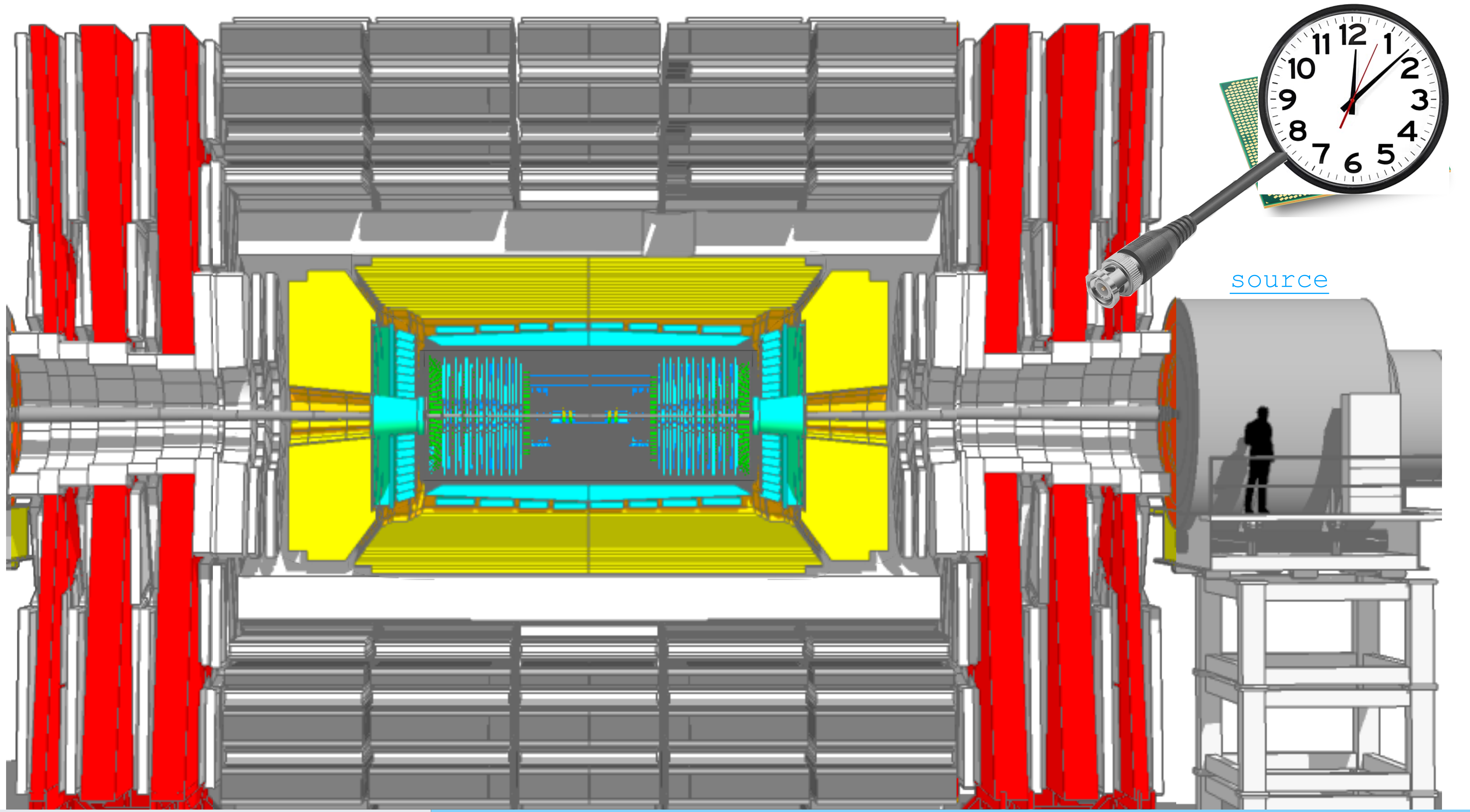
- The CMS experiment will be upgraded mainly (but not only) by:
  - ✱ replacing the **tracking detectors** TDR
  - ✱ replacing the **barrel calorimeters electronics** TDR
  - ✱ replacing the **endcap muon detectors** TDR
  - ✱ replacing the **endcap calorimeter** TDR
  - ✱ introducing the **timing detector** TDR
  - ✱ renewing the **Trigger** TDR **and the DAQ** TDR



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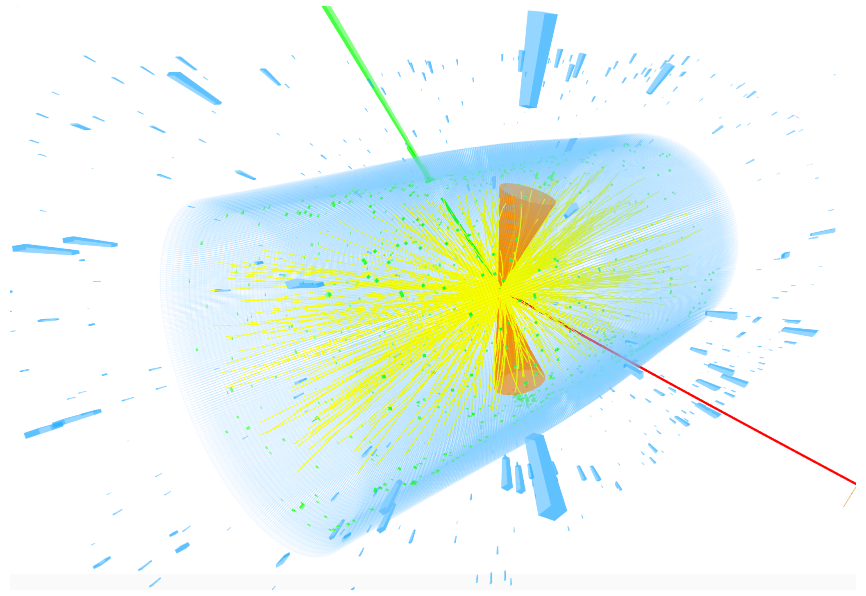
CMS Phase-2 Trigger

- The Phase-2 trigger system implements the well-established **two-level trigger architecture** with **Level-1 (L1)** and **High-Level-Trigger (HLT)**
- The **L1 trigger** will operate **at hardware level** implementing processor boards equipped with FPGAs and high-speed links
- The **HLT** will operate **at software level** using as input the CMS detector full-granularity information and more sophisticated algorithms



rate 40 MHz → **L1** (latency 12.5 μs) → rate 750 kHz → **HLT** (latency 500 ms) → rate 7.5 kHz → **Data storage**

The **main hardware features** for the Phase-2 L1 Trigger system will be:

* the use of **generic processor boards**
* the use of **high-speed optical links** *(28Gb/s against the 10Gb/s in Phase-1)*
* the extensive use of **state-of-the-art FPGAs** *(8 times more resources than in Phase-1)*
* the implementation of a **modular architecture**

CMS Phase-2 Level-1 Trigger architecture

Calorimeter trigger

* inclusion of the HGCAL detector information
* use of higher granularity (x25 in barrel ECAL)
* production of high resolution clusters

reconstructs candidates from calo deposits

Particle Flow trigger (aka Correlator Trigger)

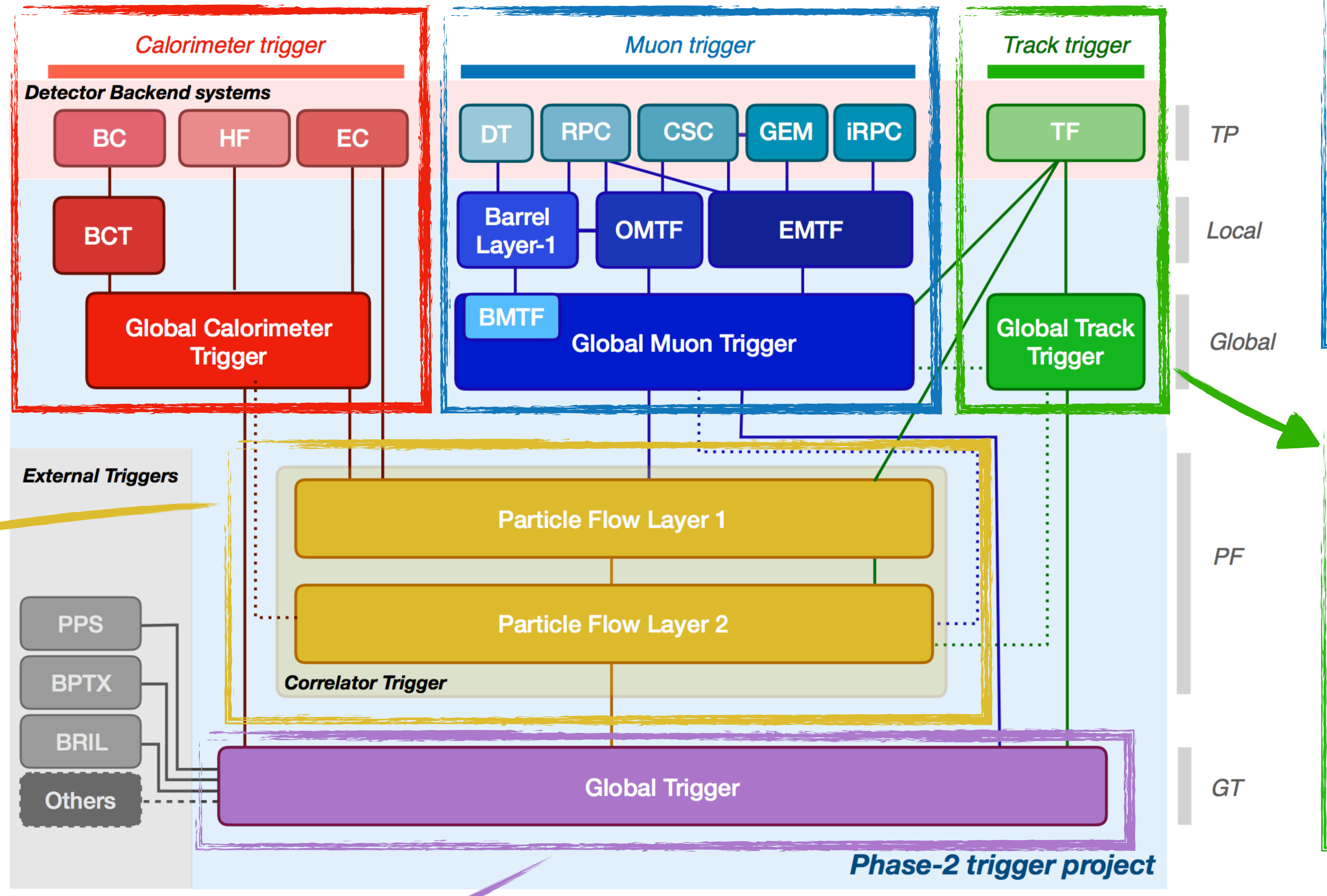
* match tracks to Calo and Muon objects
* Layer 1 produces the particle flow and PUPPI (slide 16) candidates
* Layer 2 builds and sorts the final trigger objects

reconstructs higher level variables and objects

Global trigger

* combine the outputs of all the triggers
* evaluate sophisticated correlation variables
* provide interface with external triggers
* implement the **L1physics menu: trigger algorithms (single/multi-objects trigger)**

calculates final decision



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Muon trigger

* three regions: barrel, endcap, overlap
* η coverage extension: $2.4<|\eta|<2.8$
* matching of muon candidates with tracks

reconstructs μ candidates

Track trigger

* first ever inclusion of tracks at L1 trigger
* precise vertex reconstruction
* reconstruct light resonances, displaced isolated tracks, displaced jets

reconstructs charged particle candidate

40MHz Scouting System

* enable trigger-less analysis at collision rate
* work with a subset of the triggers info
* use processing boards' spare optical outputs
* perform live diagnostics of the trigger system

targets bunch crossing rate analysis

⇛ this L1 Trigger architecture is capable of *Global Event Reconstruction* *closer to the offline performance* moving the trigger capabilities towards a *"Real-Time analysis"*

Preserving the discovery potential…

…with single-lepton trigger algorithms
…with double-γ trigger algorithms
…with double-τ trigger algorithms
…with multi-jet trigger algorithms

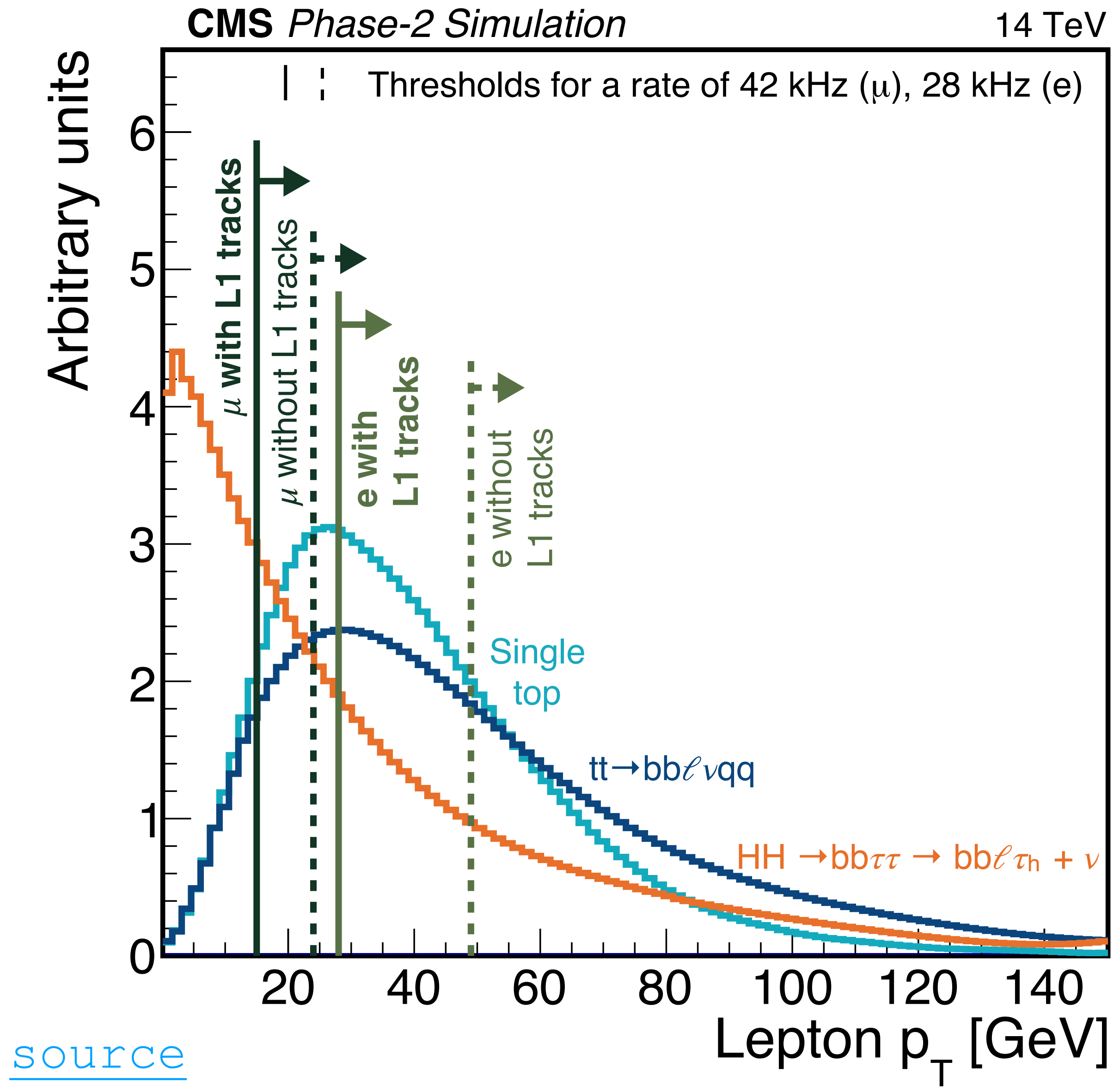
…with single-lepton trigger algorithms

Preserving Phase-1 lepton L1-thresholds with track information

The role of tracks for the lepton algorithms is threefold:

* they are **matched to the calorimeter deposits** to help in the identification of the e candidates
* they are **matched to the muon detectors hits** to help in the identification of the μ candidates
* they are **used to define an isolation variable** for both e and μ candidates

Using the tracks at L1 Trigger guarantees to set thresholds on e/μ as low as those used during Phase-1



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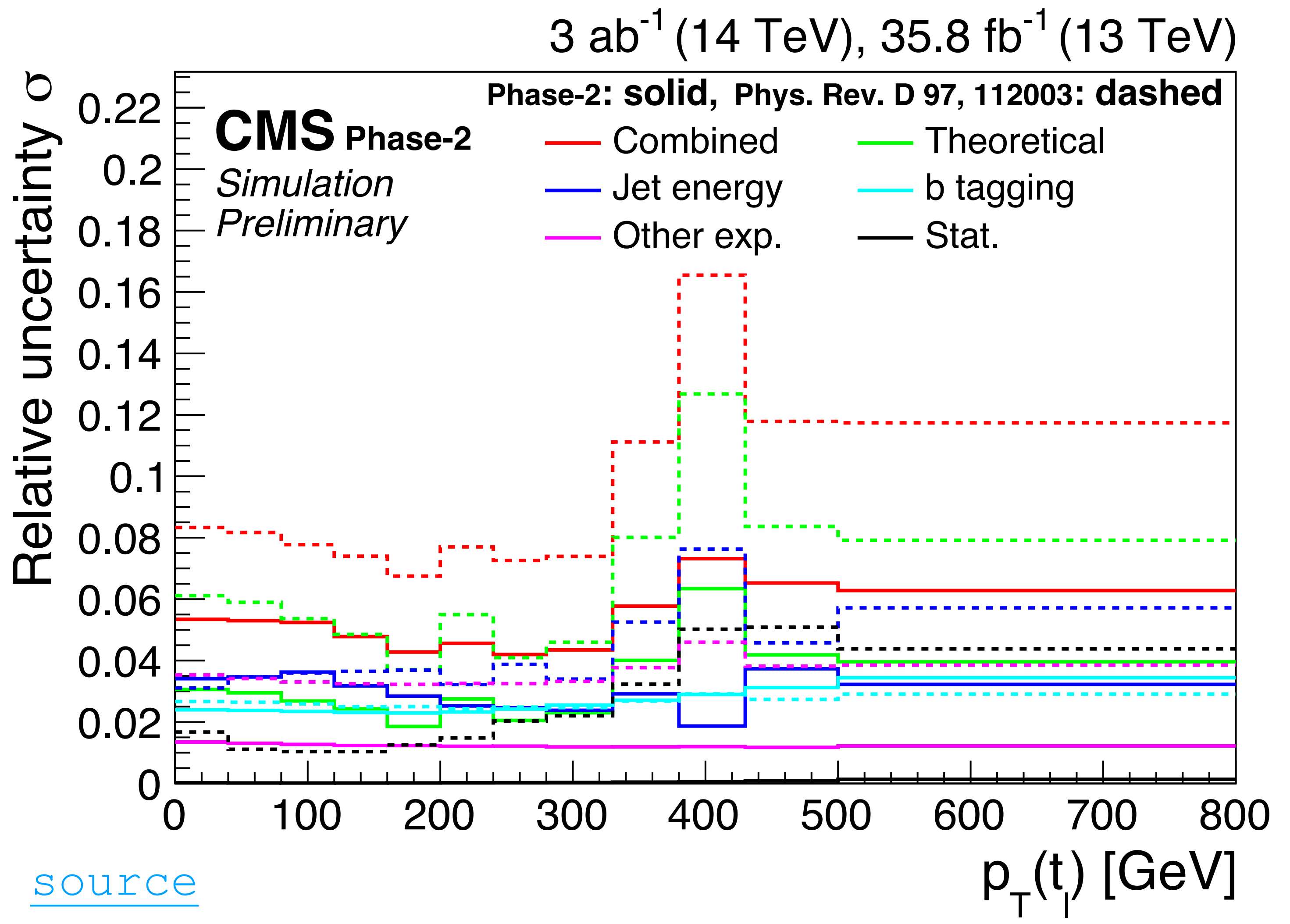
Differential tt→bblνqq

- Important **test of SM, EWSB, and BSM**
- **Important bkg for many other analysis**
- **η-differential** studies accessible during Phase-2



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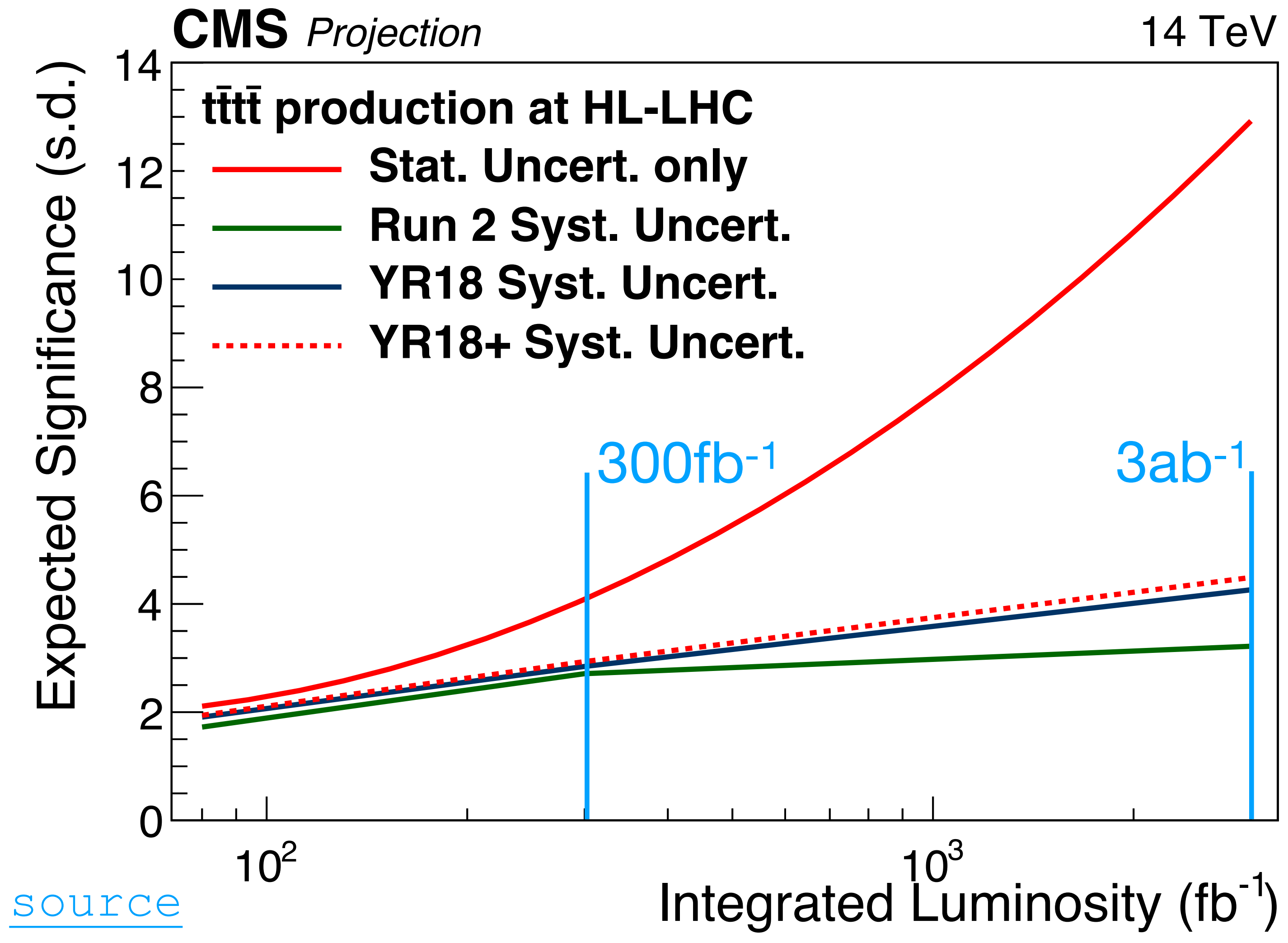
⇛ **x1.5 improvement compared to 2016**

tttt in leptonic final states

- **Rare SM process** used to **constrain** magnitude and **CP properties** of **top Yukawa coupling**, and to **probe BSM scenarios** (2HDM and DM)
- **Evidence possible already at 300fb^{-1}**



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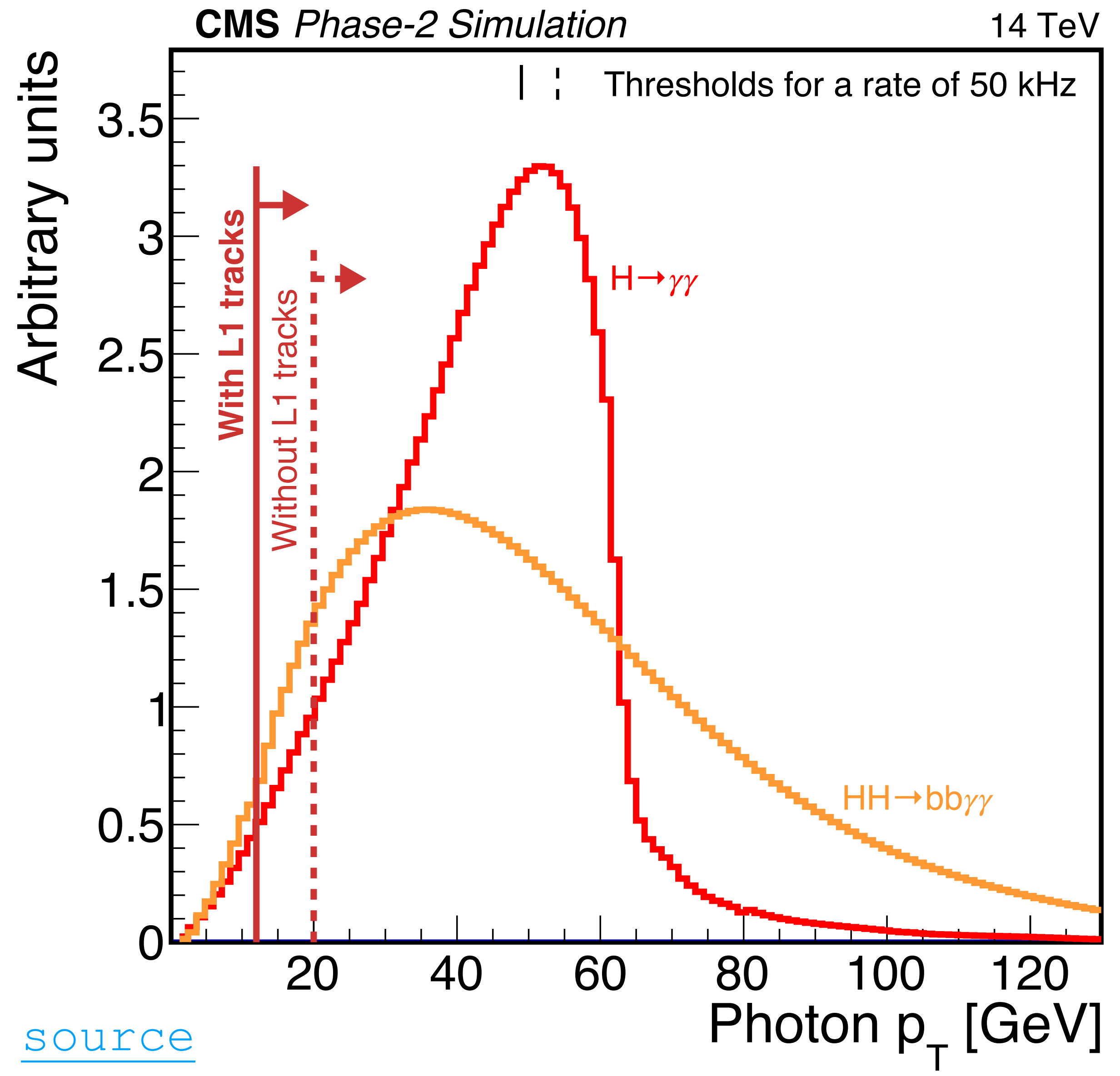
⇛ **x2 improvement compared to Run2**

…with double-γ trigger algorithms

Preserving Phase-1 photon L1-thresholds with track information

The role of tracks for the photon algorithms is that they are **used to define an isolation variable**: a photon is identified as an isolated standalone calorimeter objects satisfying the calorimeter-based γ ID for barrel and endcap, and the **track-based isolation cut (|η| < 2.4)** is enforced on the candidate

Using the tracks at L1 Trigger guarantees to set thresholds on γ as low as those used during Phase-1



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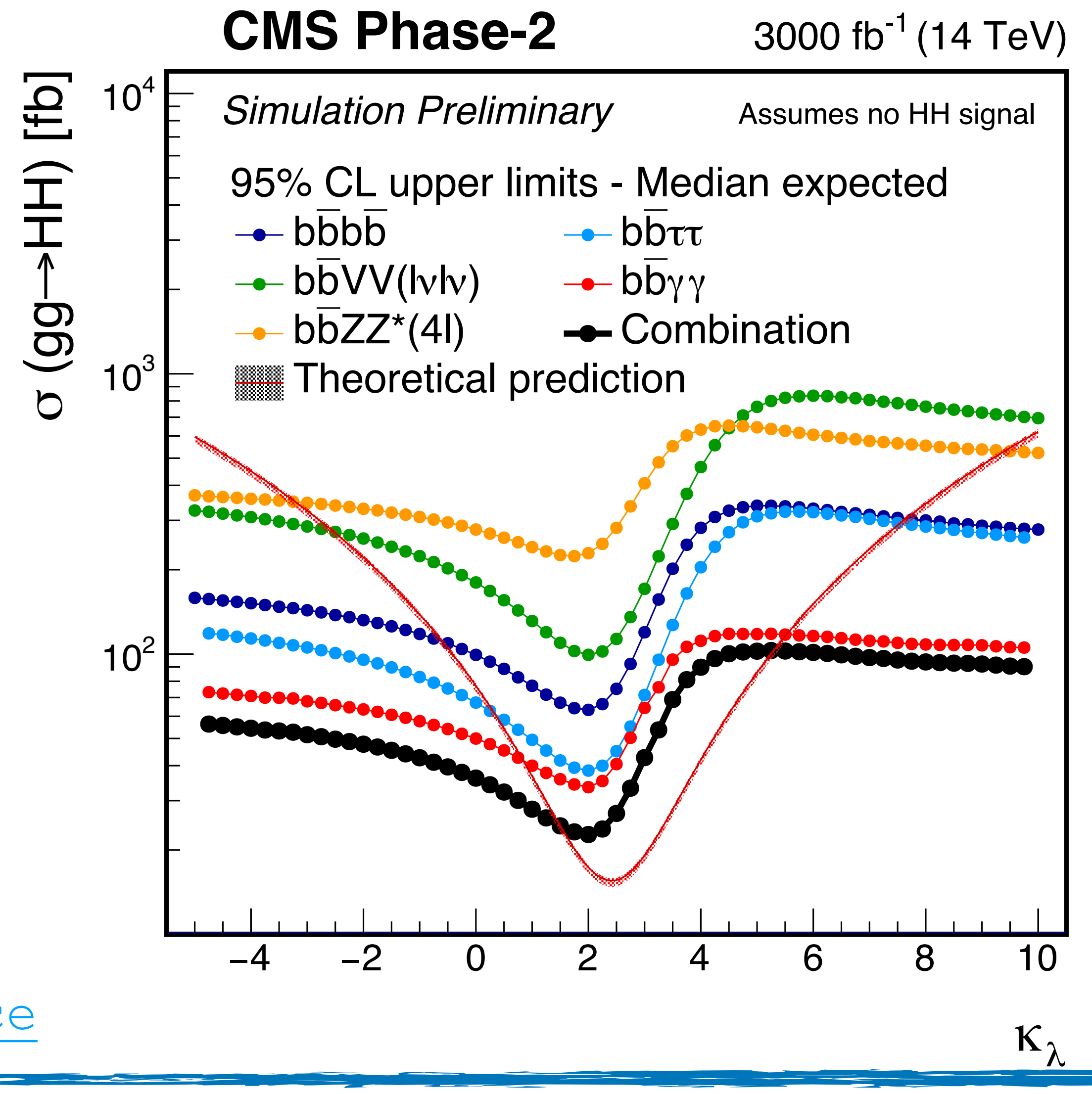
HH→bbγγ

- **bbγγ** final state **among most sensitive**
- **Upper limit @ 95% CL = 1.09 x SM**
- **Significance of HH signal 1.85σ**



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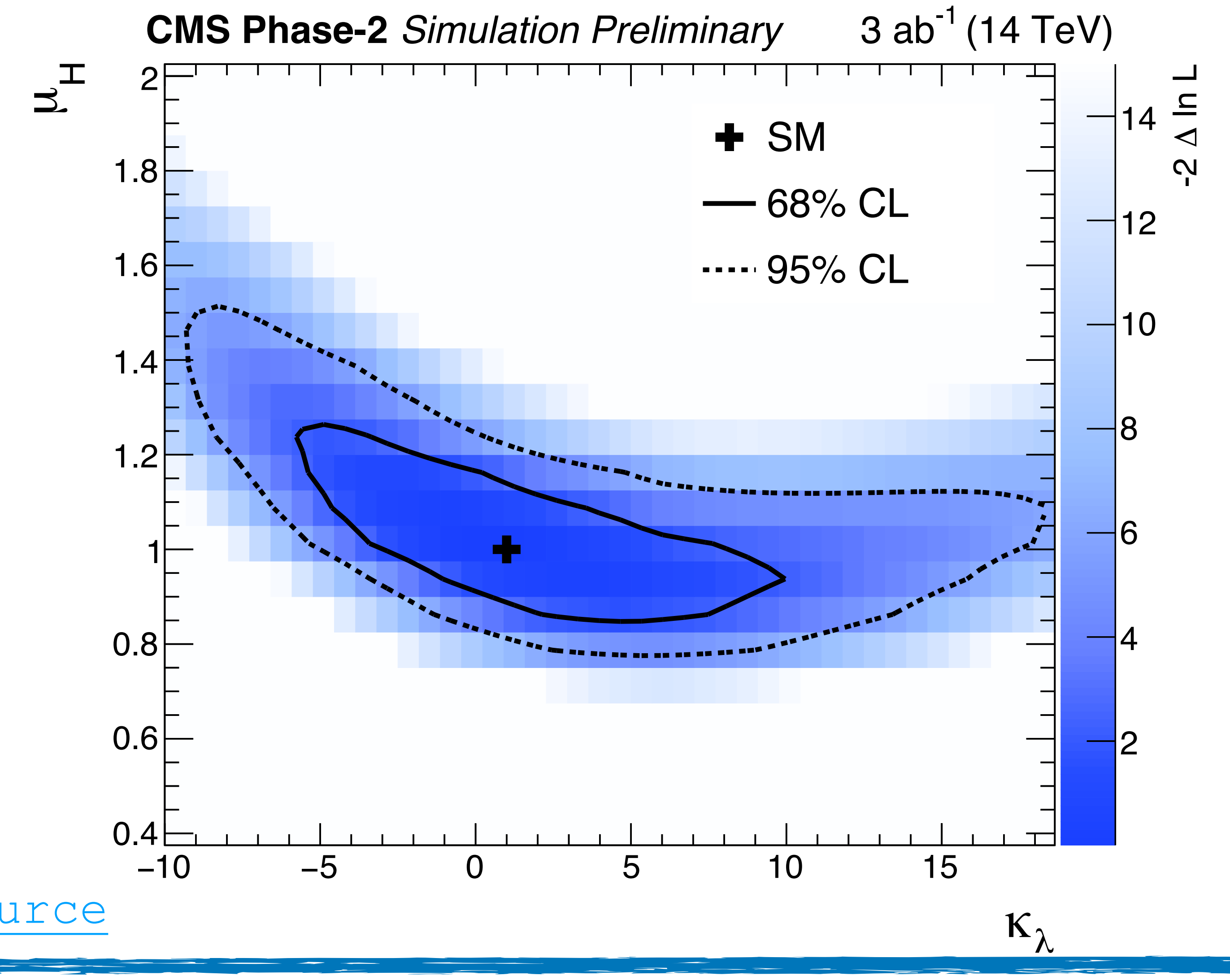
⇛ **x7 improvement compared to Run2**

λ_{HHH} constraints from ttH+tH

- **Radiative corrections** to ttH and th are **indirect probe for λ_{HHH}**
- Both **inclusive and differential σ(ttH/tH)**

⇛ **would be the first ever measurement of this kind**



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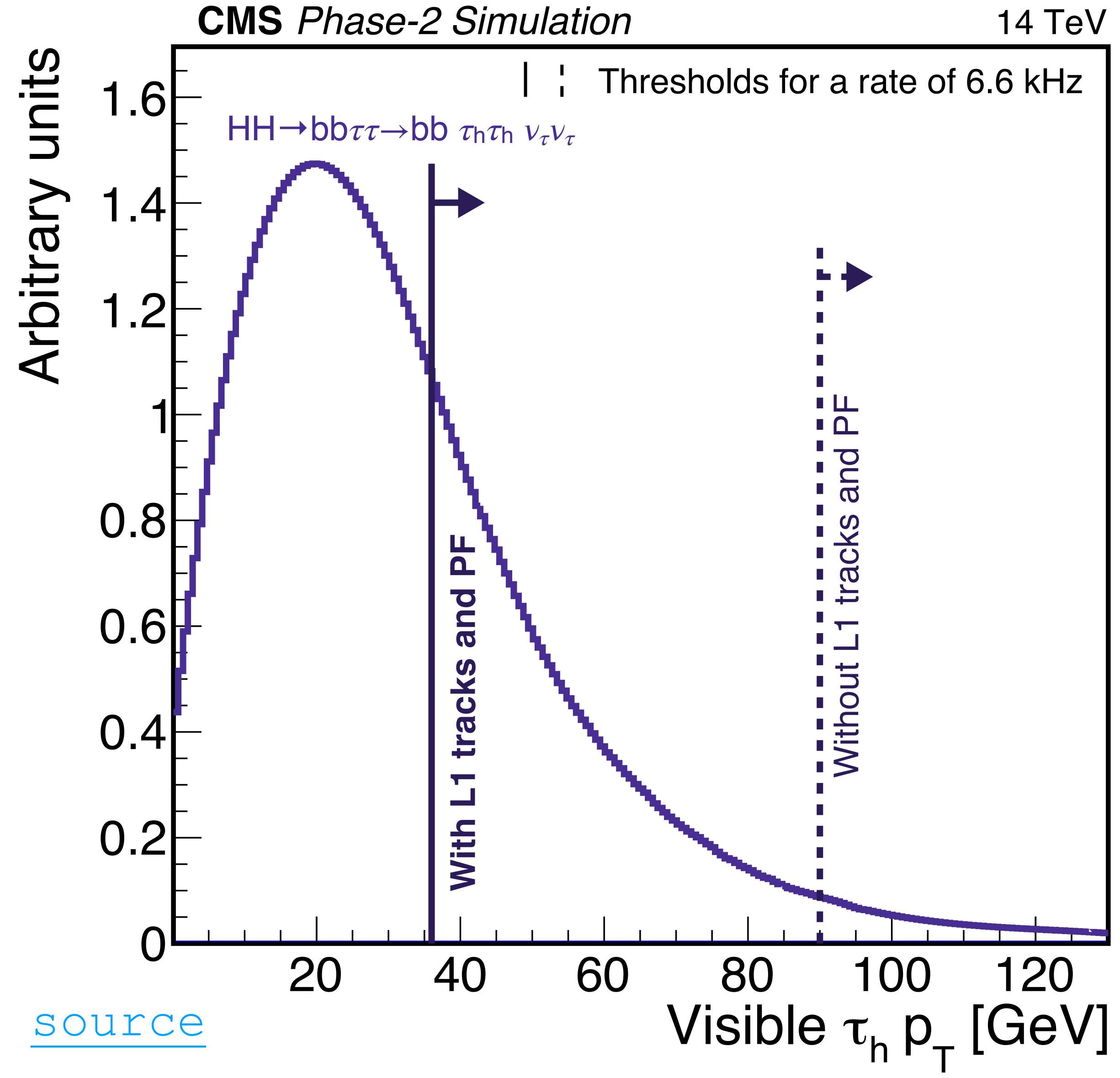
…with double-τ trigger algorithms

Preserving Phase-1 tau L1-thresholds with track information

Tau candidates are reconstructed at L1 Trigger with three different algorithm:

* **tower-based algorithm** → reconstructs and isolates taus using rectangular and square mask over calorimeter towers
* **HGCAL-based algorithm** → relies on multiple BDTs for the tasks of pileup rejection, τ recognition, and isolation
* **tracker+calo algorithm** → matches the calorimeter deposits with the tracks of the hadronic decay products

Using the tracks at L1 Trigger guarantees to set thresholds on tau as low as those used during Phase-1
The HGCAL-based algorithm complements the tracker-based algorithm to extend the coverage to η<3



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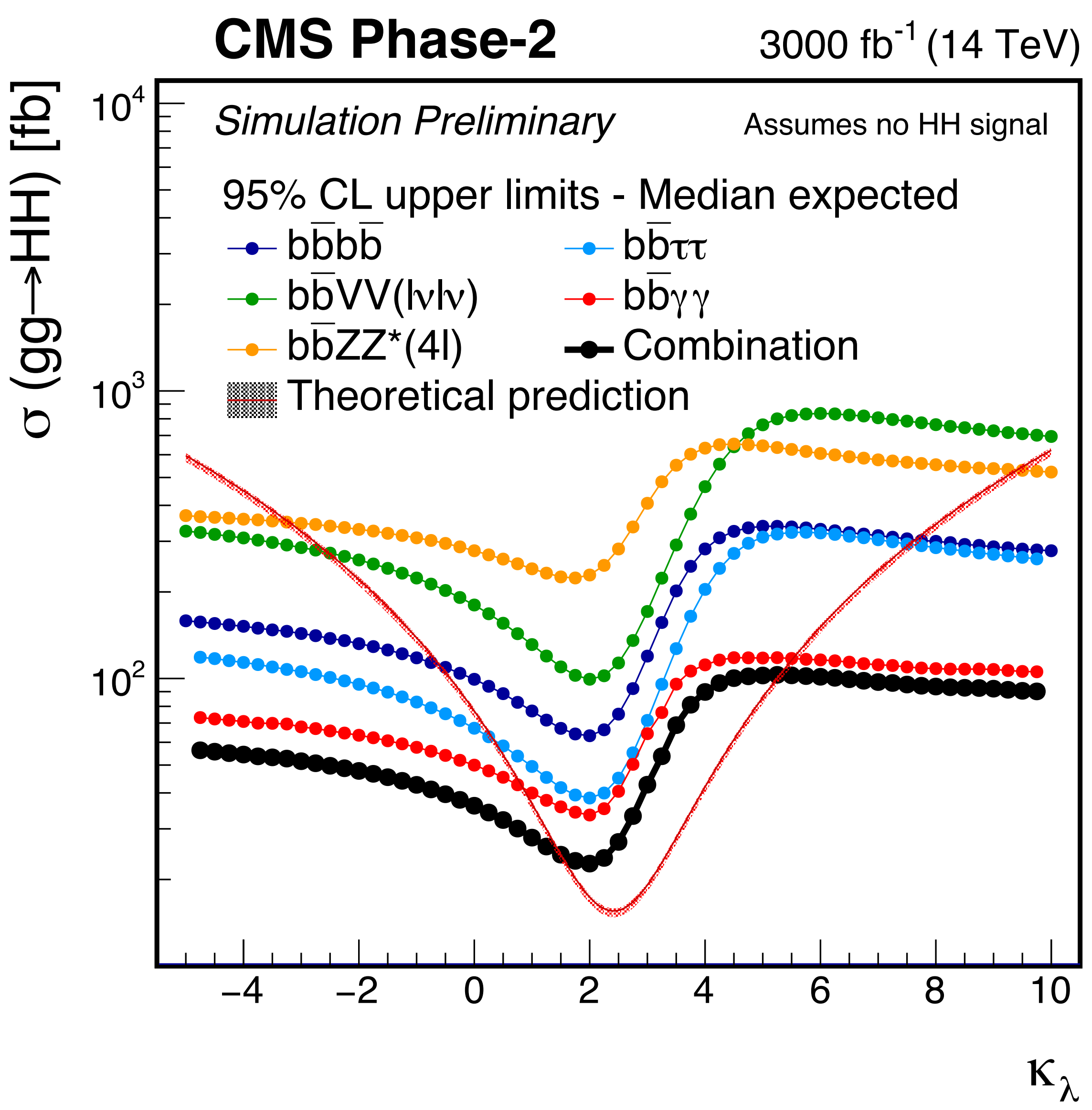
HH→bbττ

- bbττ **among most sensible final states** (thanks to ττ purity and bb large branching ratio)
- **Pseudorapidity coverage extension central for increasing acceptance**
- Upper limit @ 95% CL = **1.4 x SM**
- Significance of HH signal **1.4σ**

⇛ x30 improvement compared to 2016
(Run2 results not public yet)



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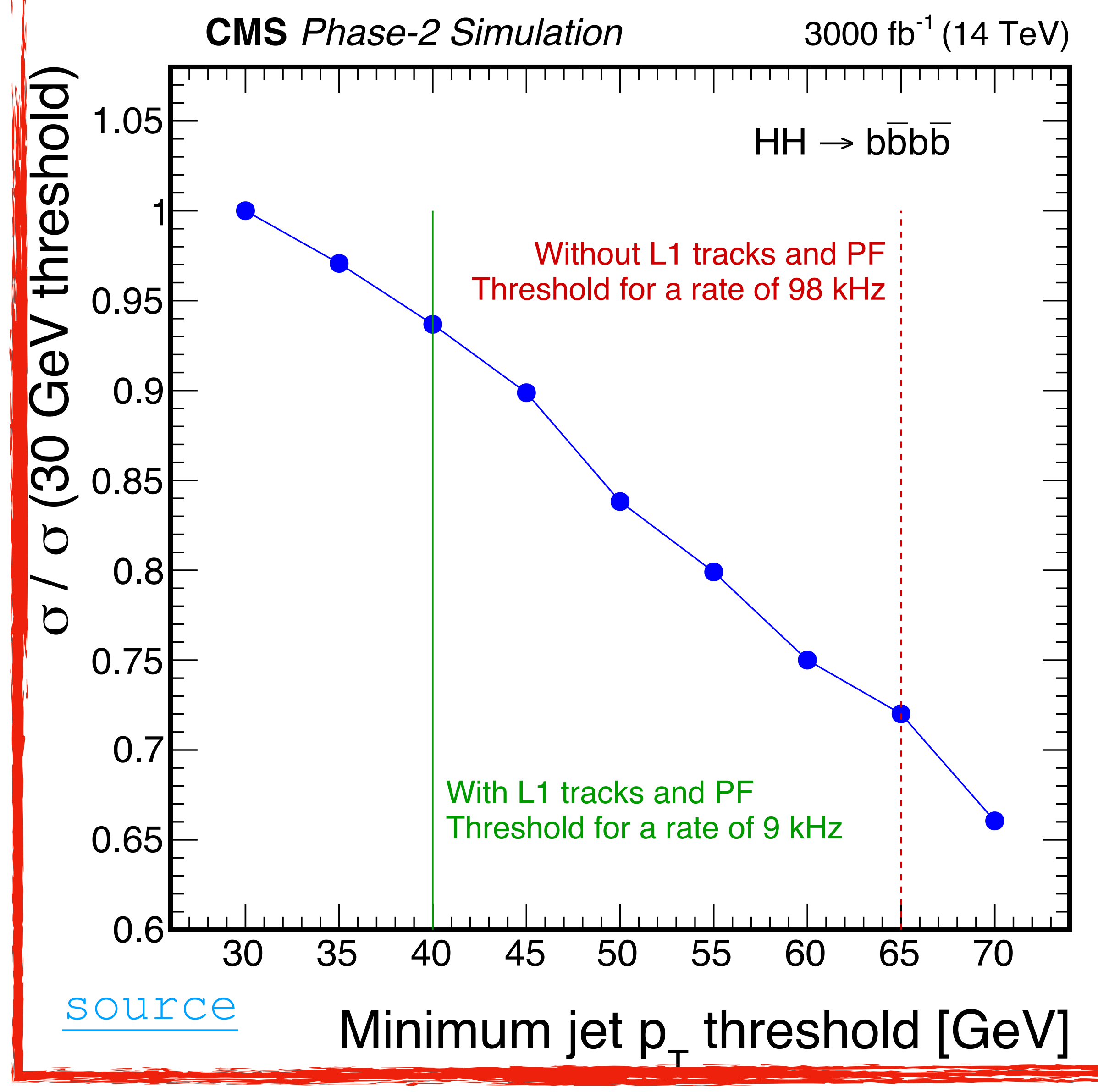
…with multi-jet trigger algorithms

Preserving Phase-1 jet L1-thresholds with track information

Jet candidates are reconstructed at L1 Trigger with three different algorithm:

* **calorimeter-based algorithm** → builds jets using rectangular and square mask over calorimeter towers
* **track-based algorithm** → builds jets based on tracks and clusters them with a nearest-neighbour approach
* **particle-flow algorithm** → builds jets based on PUPPI candidates (slide 16) and clusters them with fixed dimension windows

Using the tracks at L1 Trigger guarantees to set thresholds on jets as low as those used during Phase-1



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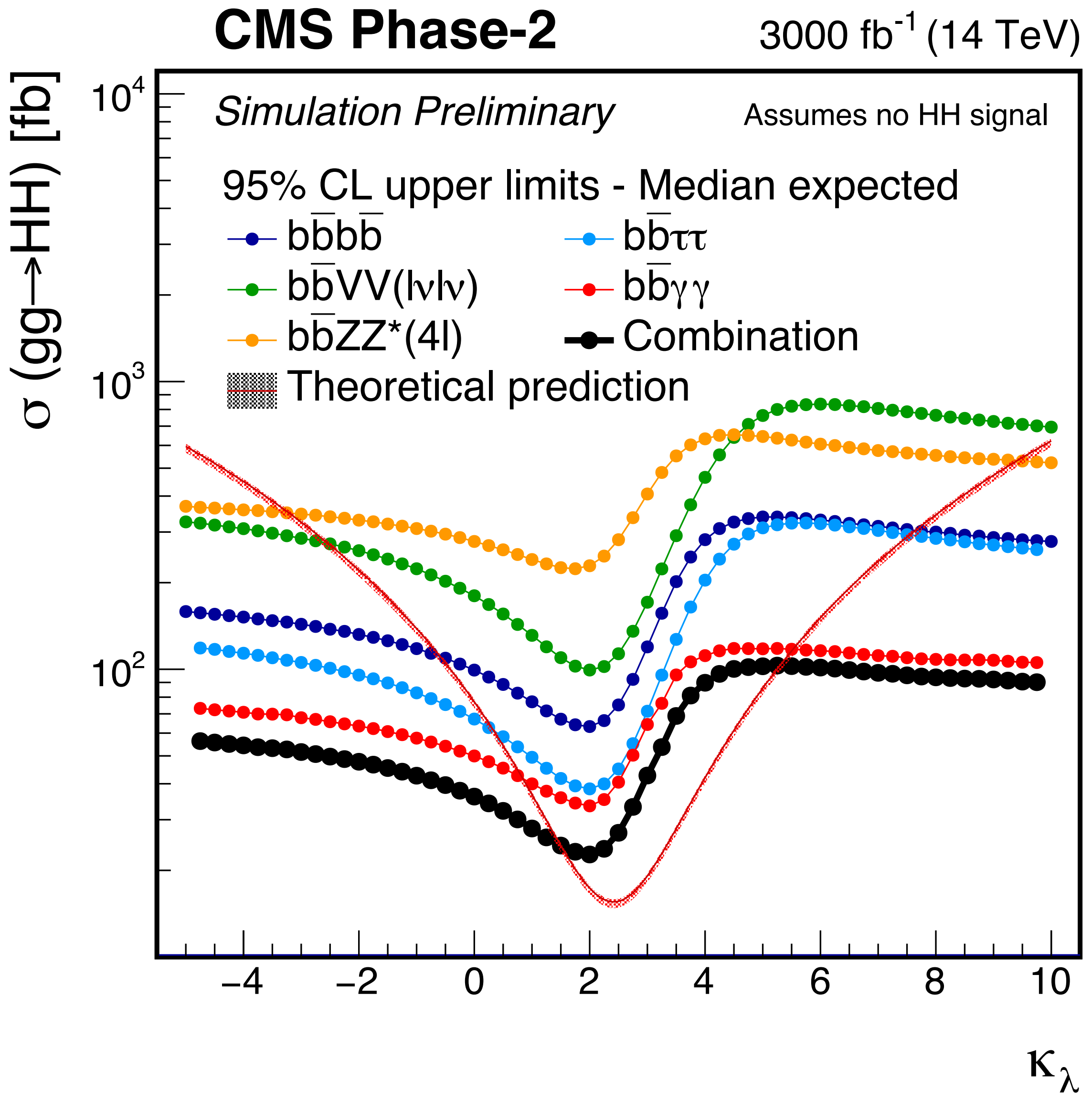
HH→bbbb

- bbbb **among most sensible final states** (thanks bbbb large branching ratio)
  → suffers from very large multi-jet background
- **Pseudorapidity coverage extension central for increasing acceptance**
- Upper limit @ 95% CL = **2.1 x SM**
- Significance of HH signal **0.95σ**

⇛ x3.5 improvement compared to Run2



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Extending the physics reach…

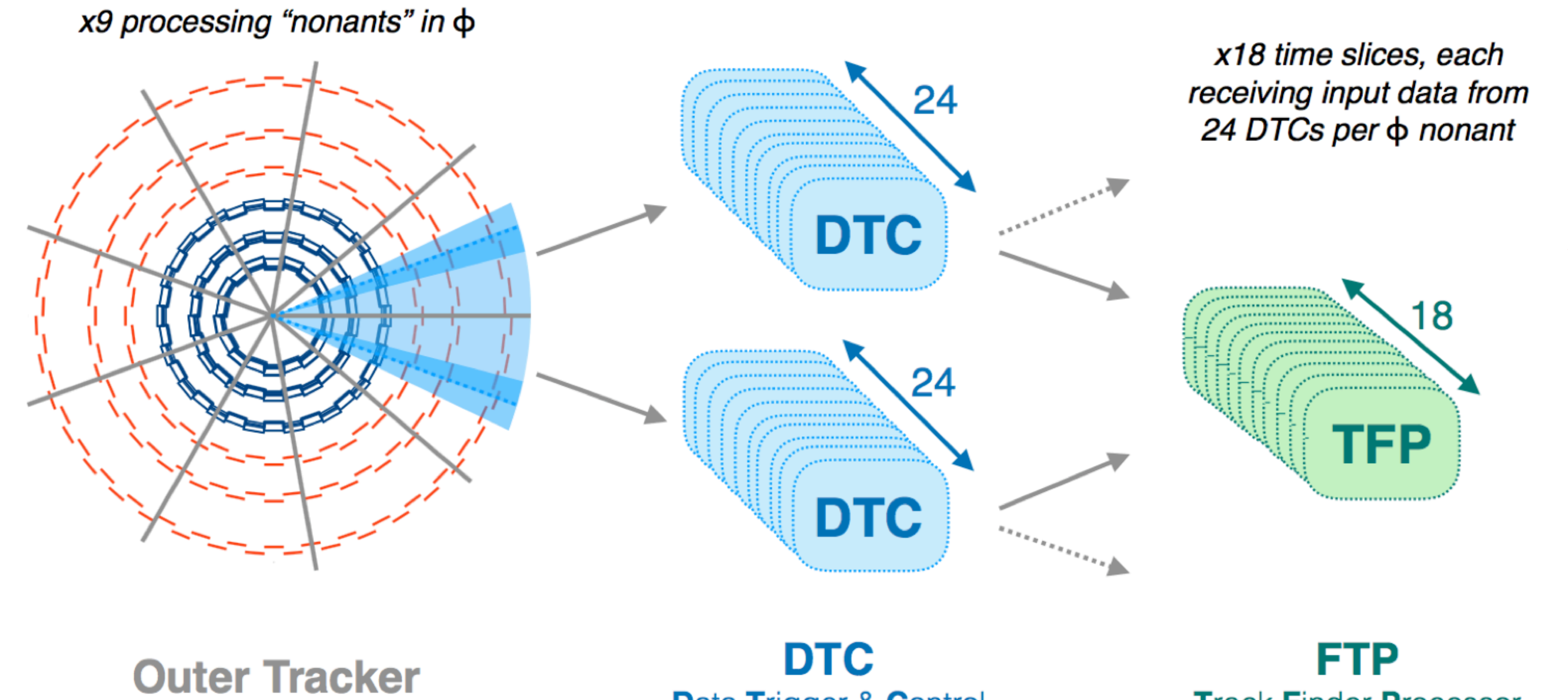
…<u>with tracking at Level-1 trigger</u>
…<u>with extended η coverage</u>
…<u>with displaced objects</u>
…<u>with ML-based trigger algorithms</u>

…with tracking at Level-1 trigger

First ever inclusion of track information at L1 Trigger

Using the **full outer tracker (η<2.4) volume** and a **time-multiplexed architecture (x18)**, the Track Trigger gives the ability to reconstruct charged particle tracks at the 40 MHz collision rate.
In combination with the **Correlator Trigger** gives the possibility to precisely reconstruct **primary and secondary vertexes** per each collision.

Using the L1 Track trigger guarantees to obtain unprecedented trigger capabilities



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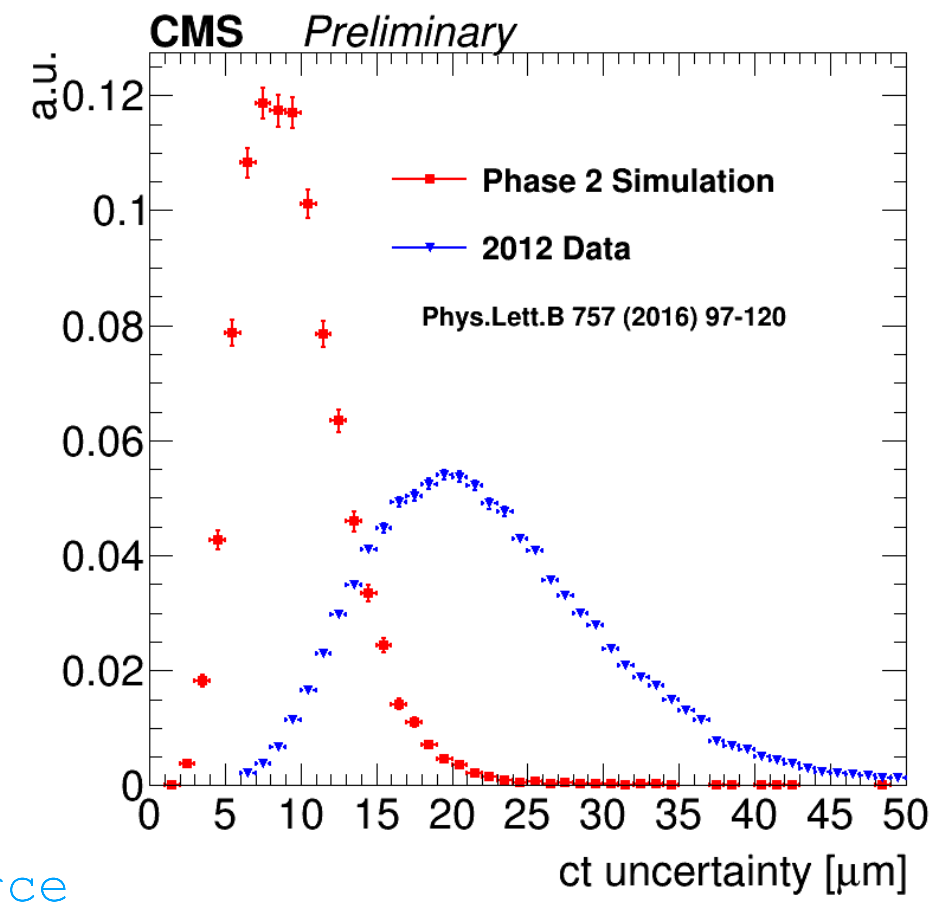
B physics and CP violation

- $B_s^0 \rightarrow J/\psi\phi(1020)$ **CP violation golden channel**
- Amazing ***ct*** **resolution reachable with Phase2 tracker**
- Expected uncertainty on CP-violating phase ϕ_s ~ 5-6 mrad



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⇛ x5 improvement compared to current world average

τ→μμμ lepton flavour violation

- No known symmetries strictly forbid **lepton-flavor violating (LFV) decays**
- At the LHC, the **τ→μμμ** decay is one of the **"cleanest" LFV decay** channel
- $\approx 10^{15}$ **τ** leptons will be **produced at HL-LHC**

- Main source **from** $D_s \rightarrow \tau\nu$

⇛ **very low momentum** τ's and μ's **(~1.3% have** $p > 2.5$ **GeV)**

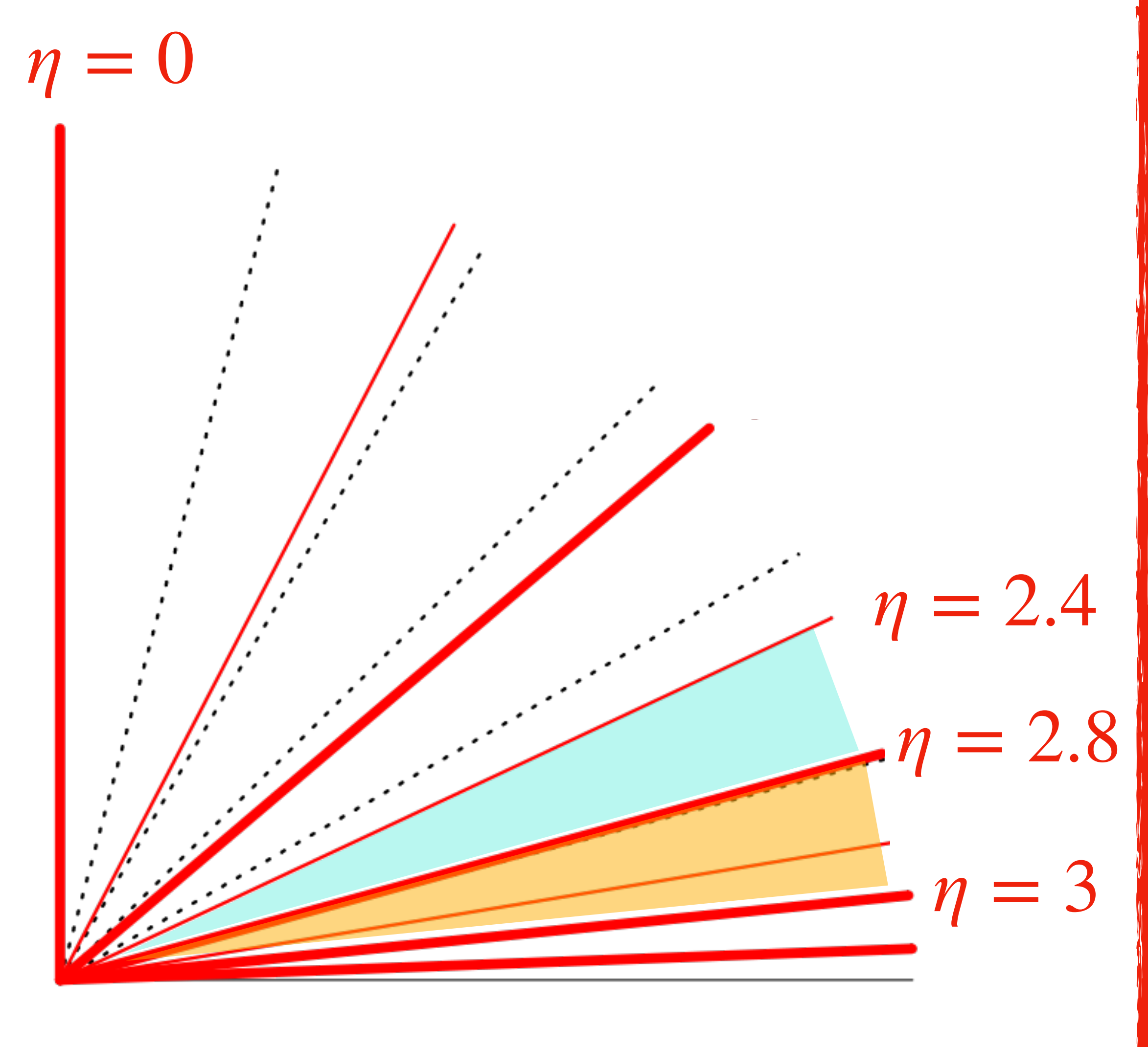
⇛ tracker necessary to retrieve at L1 the muons that do not reach the muon chambers

…with extended η coverage

Extended pseudorapidity acceptance

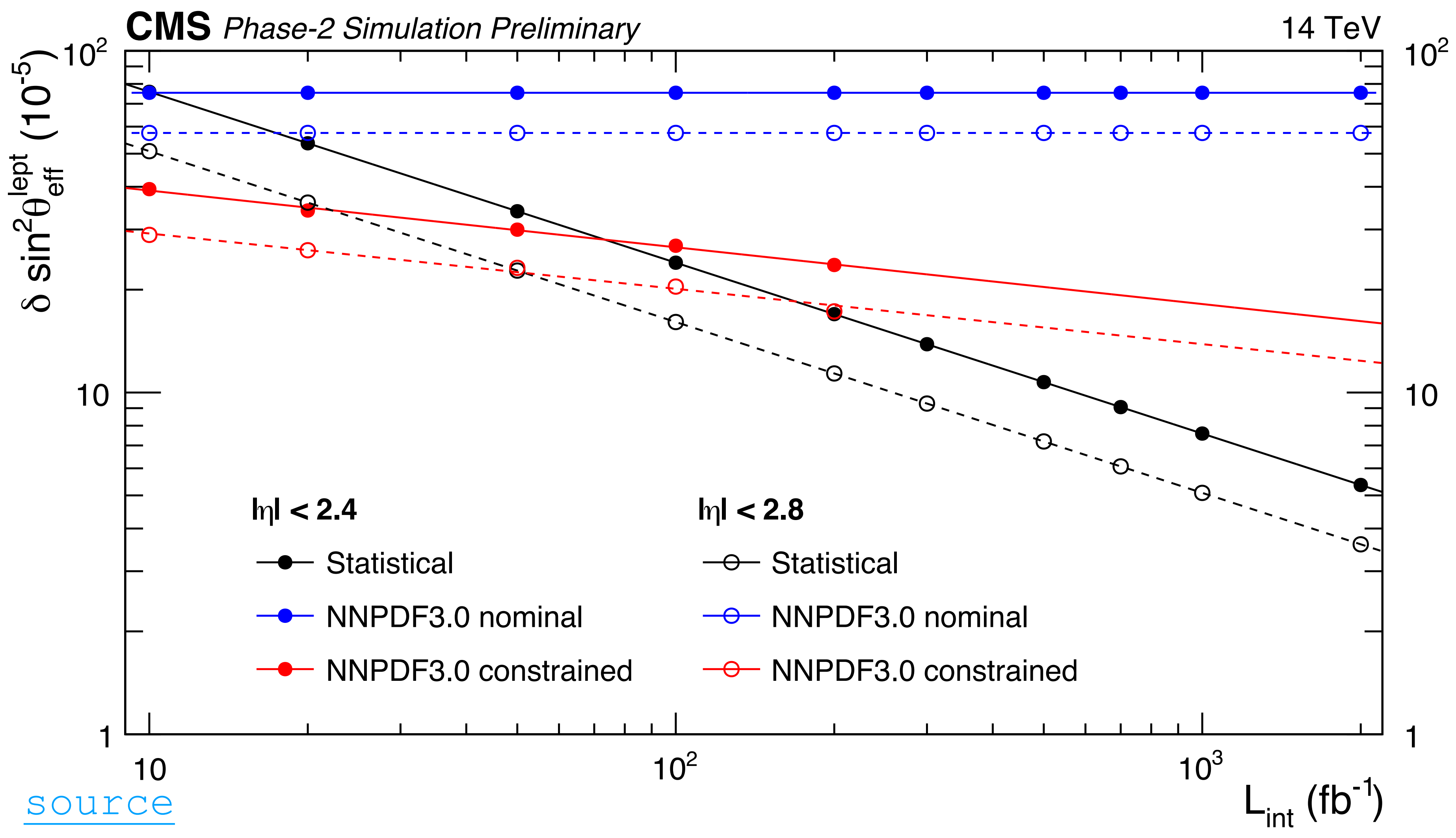
The L1 pseudorapidity coverage is increased thanks to:

* the upgraded **endcap μ detectors** ($|\eta| < 2.8$)
* the upgraded **endcap calorimeters** ($|\eta| < 3$)



Weak mixing angle measurement

- Part of the **precision measurements program of the HL-LHC**
- Done using the using **forward-backward asymmetry**
- Primary channel is **Drell-Yan decaying to μμ**
- **η extension decreases statistical uncertainties by ~30% and PDF by ~20%**



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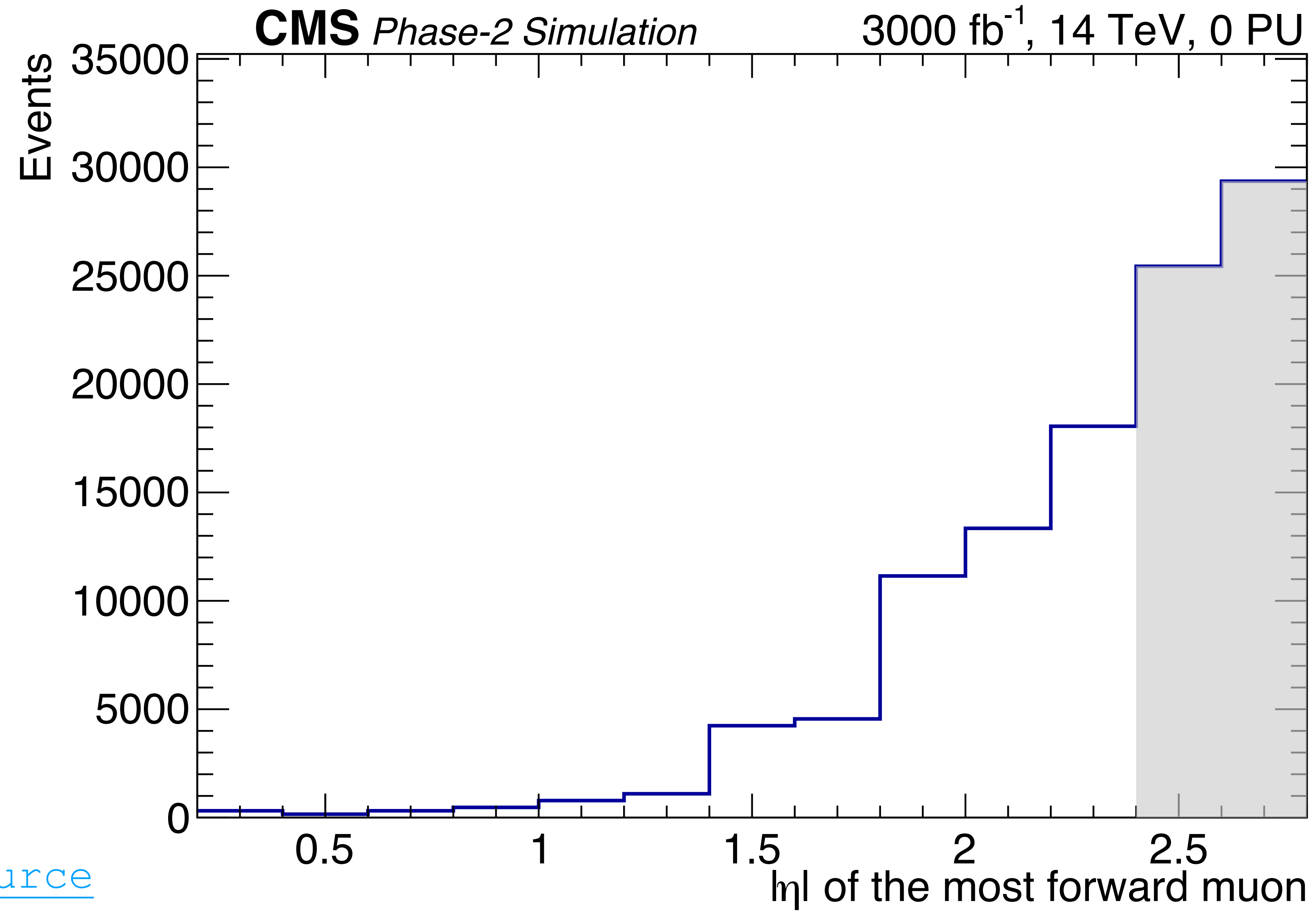
τ→μμμ lepton flavour violation

- Main source **from $D_s \rightarrow \tau\nu$**

⇛ **highly forward boosted τ**

⇛ extended η coverage will allow to drastically increase statistics



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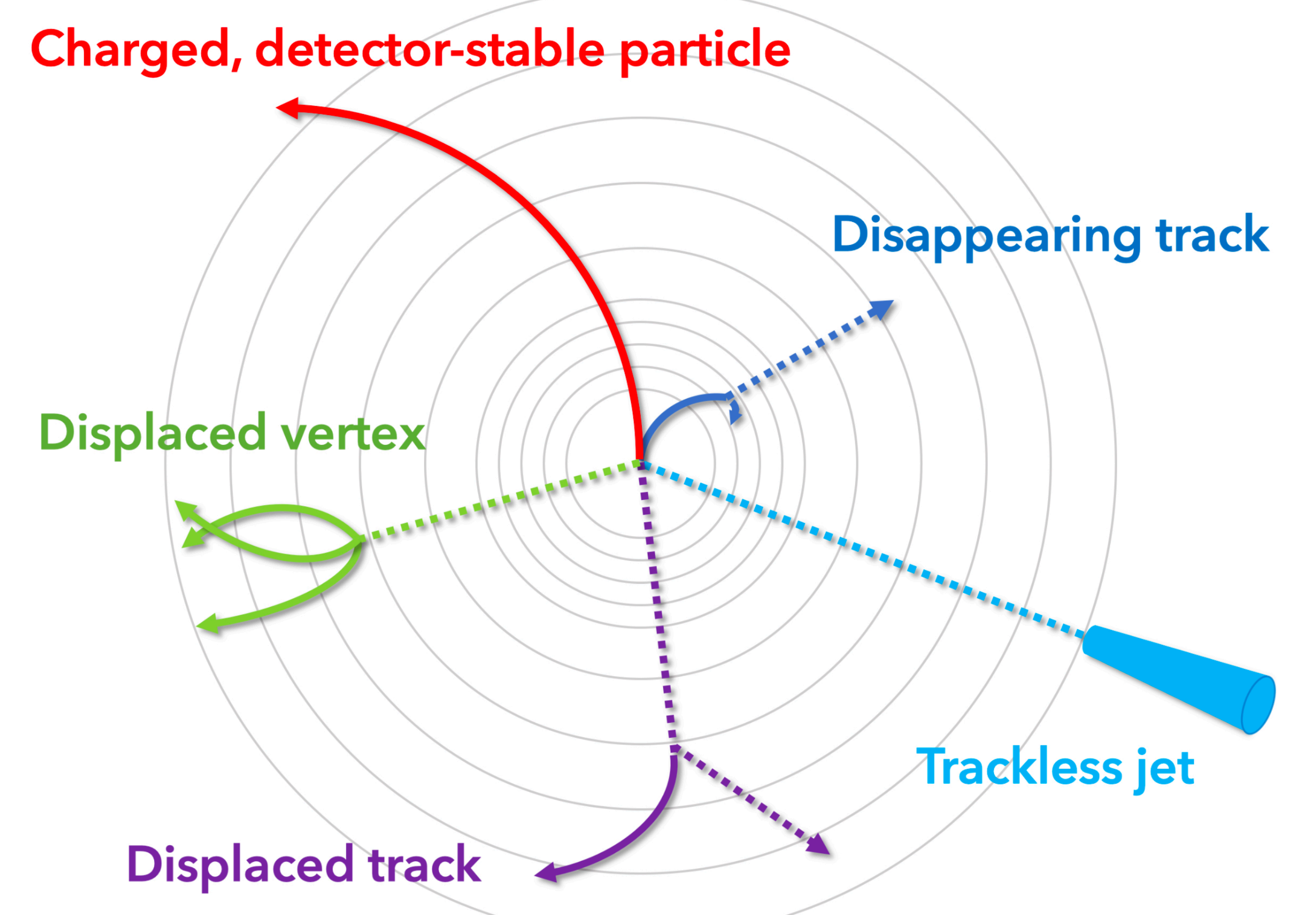
…with displaced objects

Extending displaced object capabilities w/ track information

Displaced objects reconstructed through:

- **Track Trigger** reconstructing tracks while removing interaction point constraint
- **Correlator Trigger** reconstructing secondary vertexes
- **Timig information** from the barrel

This Guarantees unprecedented capabilities in term of displace objects algorithms implementation



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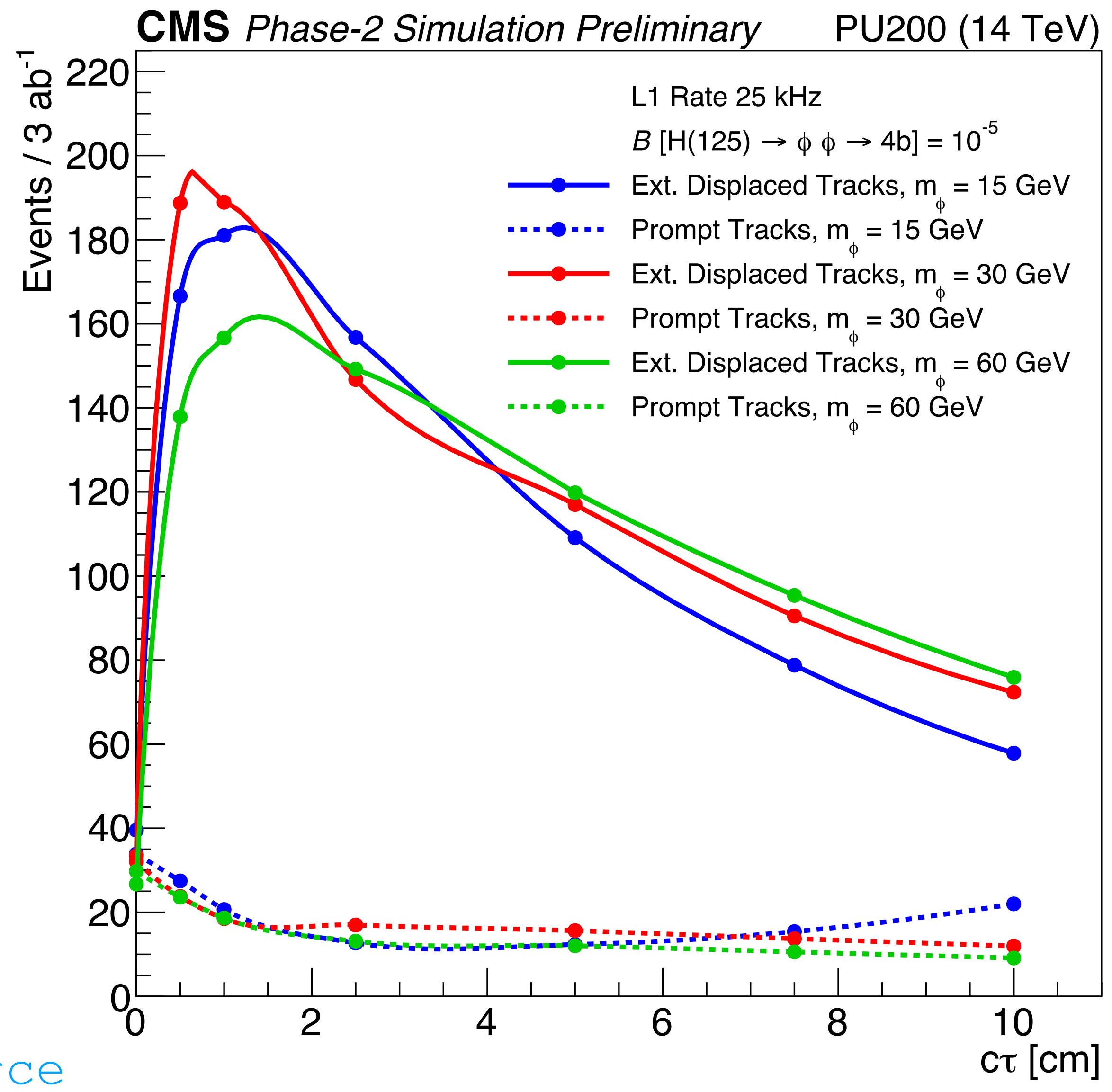
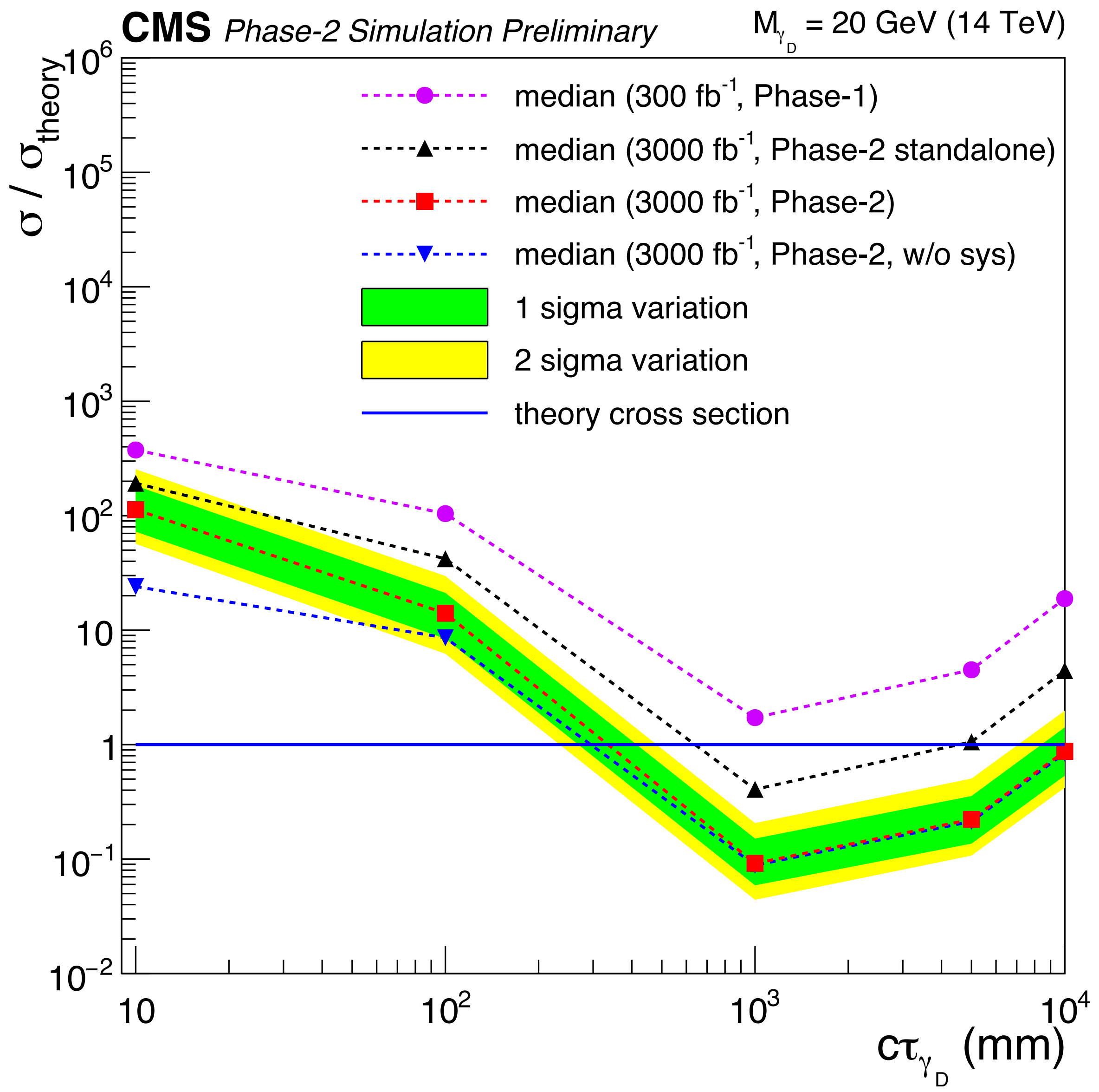
Long-lived particles searches

- Growing class of new physics models predicts **long-lived particles (LLPs)**
- Signature with emergence of **SM particles at a large distance from the collision point**





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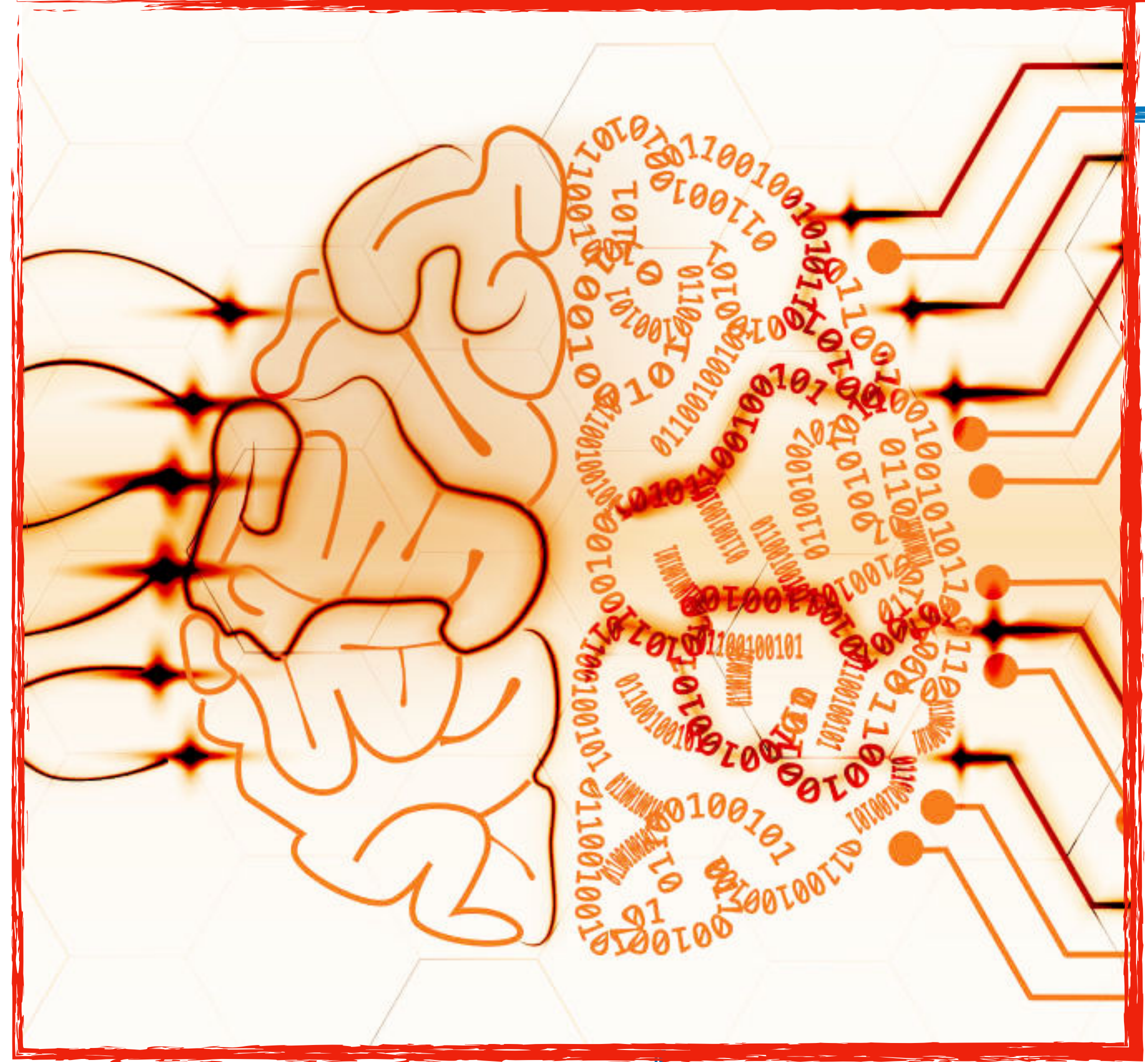
⇛ **unprecedented acceptance of displaced topology objects**

…with ML-based trigger algorithms

Using advanced Machine Learning technique at L1 Trigger

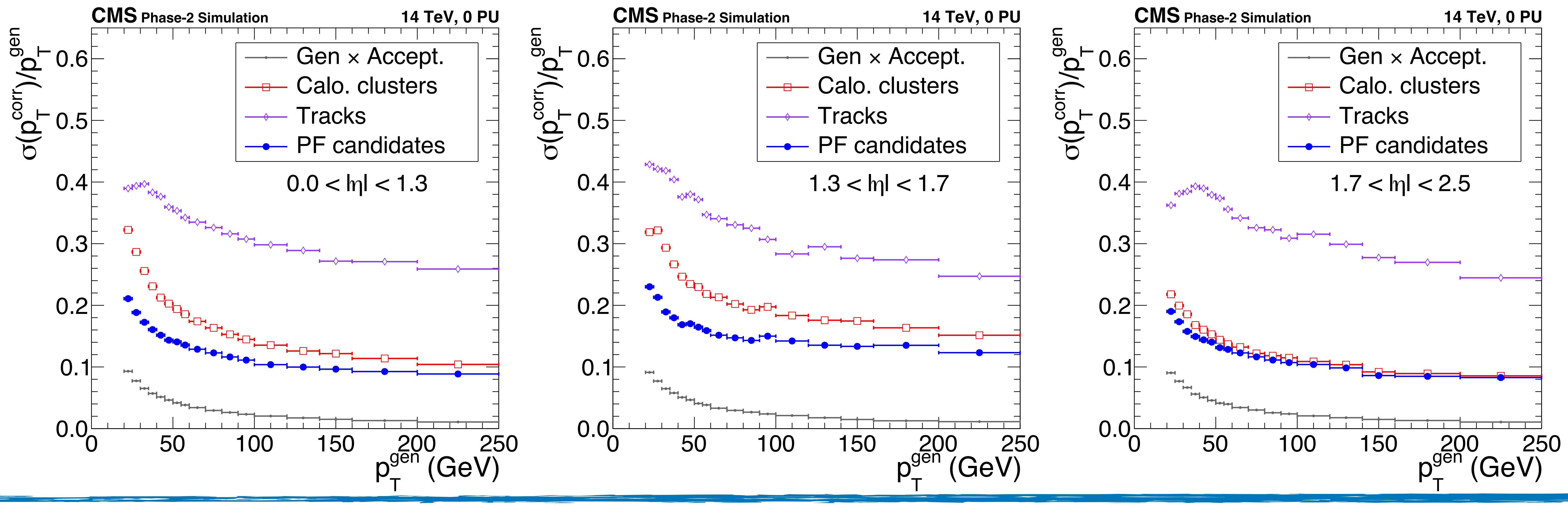
The many hardware improvements of the Phase-2 L1 Trigger architecture give the possibility to **implement ML techniques (DNNs, BDTs, etc)** to perform fast but precise real-time event reconstruction



PUPPI algorithm (as a representative of many algorithms)

- The Pileup Per Particle Identification (**PUPPI**) is based on a **Neural Network using the particle-flow approach** (it originated from an offline tool redesigned to fit trigger requirements)
- The Phase 2 upgrade ensures the possibility of **implementing such an algorithm inside the L1 trigger FPGAs boards**
- PUPPI relies on the use of **vertexing to reduce the contribution of pileup at the particle level**

⇛ unprecedented possibilities coming from ML implementability at L1 trigger level



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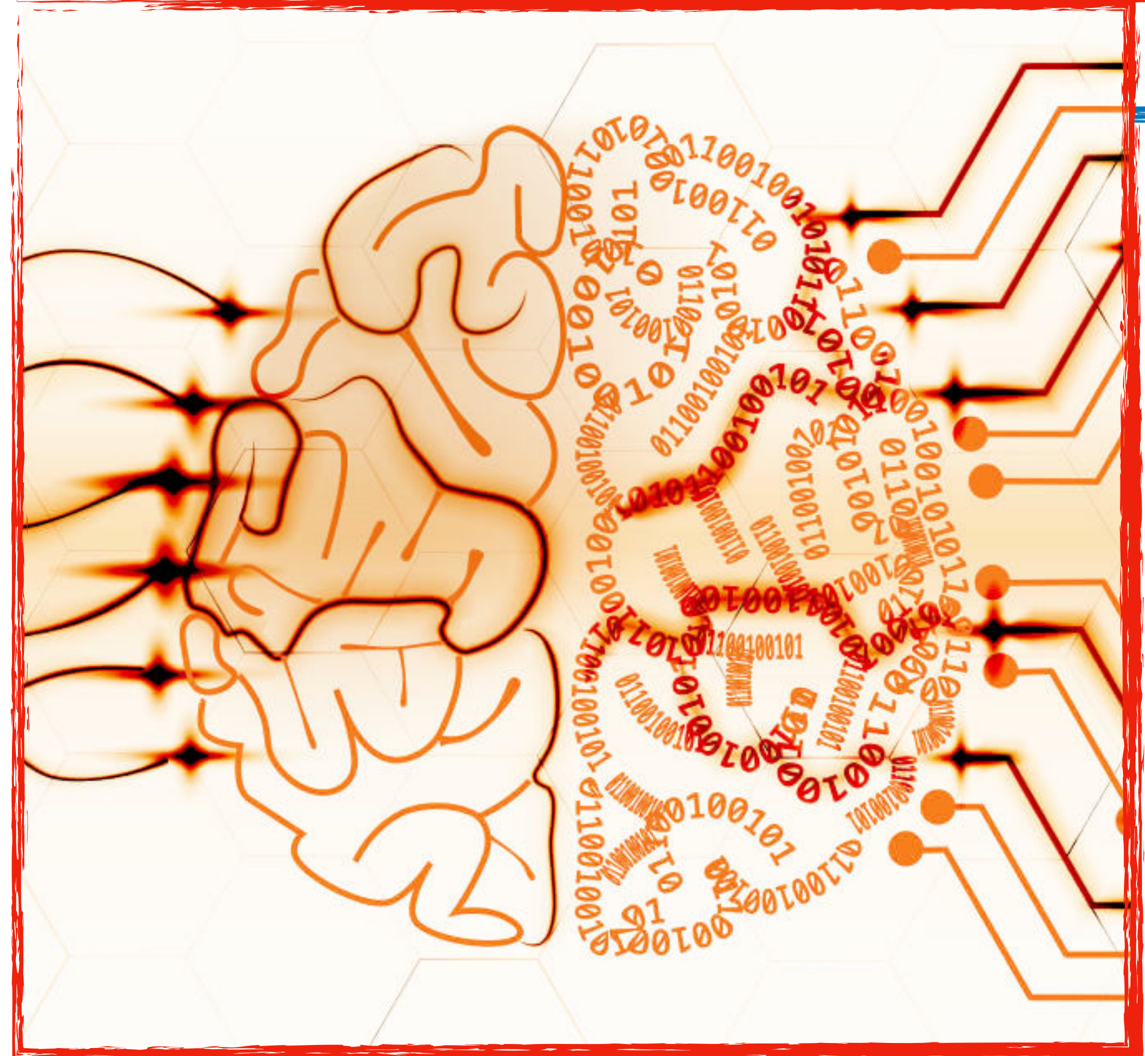
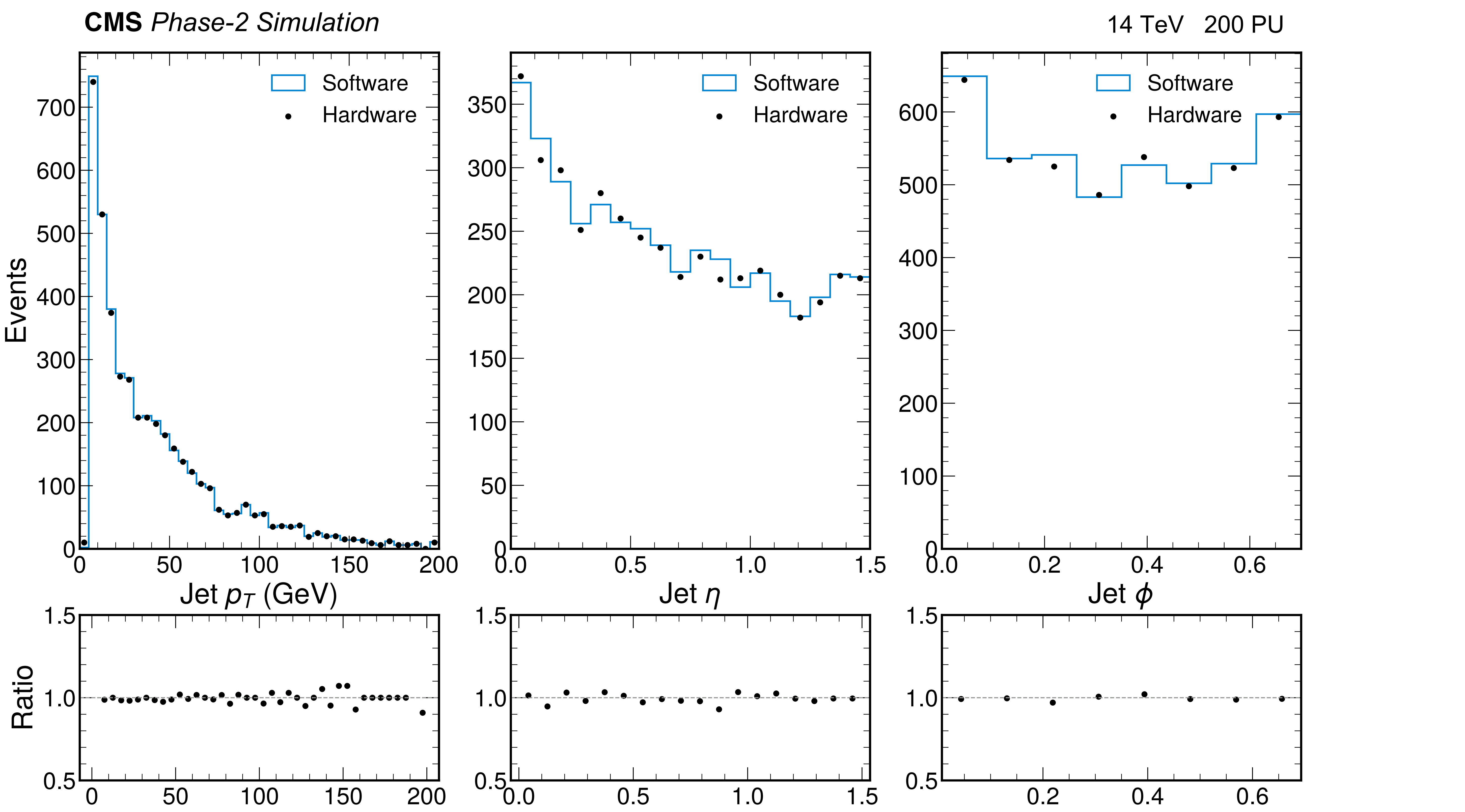


PUPPI algorithm (as a representative of many algorithms)



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⇛ almost perfect (98%) match between hardware demonstration and software emulation

Conclusions and outlook

Conclusions and outlook

- **HL-LHC** will pose **big challenges for CMS experiment** ⇒ **experiment wide upgrade**, **both hardware and software**
- Today we focused on the **Phase-2 Level-1 Trigger upgrade** and we saw:

* **L1 trigger main hardware** features…
  …high speed links
  …state-of-the-art FPGAs

* **Preserve the discovery potential…**
  …with single-lepton trigger algorithms
  …with double-γ trigger algorithms
  …with double-τ trigger algorithms
  …with multi-jet trigger algorithms

* **L1 trigger architecture** main upgrades…
  …inclusion of the Track Trigger
  …the new Correlator Trigger

* **Extend the physics reach…**
  …with tracking at Level-1 trigger
  …with extended η coverage
  …with displaced objects
  …with ML-based trigger algorithms

- **All analyses that can be envisaged will benefit from the Phase-2 L1 trigger**
- The prospects for the full Phase-2 dataset analyses foresee **very large improvements** in their results

- During the coming years the **L1 Trigger Team** will keep on pushing the boundaries of triggering at CMS and will **continue** in the **hardware demonstration of the trigger algorithms** (**many demonstrations already done!!**)…

…till our *adventures* will lead us ***Through the Looking-Glass***

Thanks for your kind attention!

BACKUP

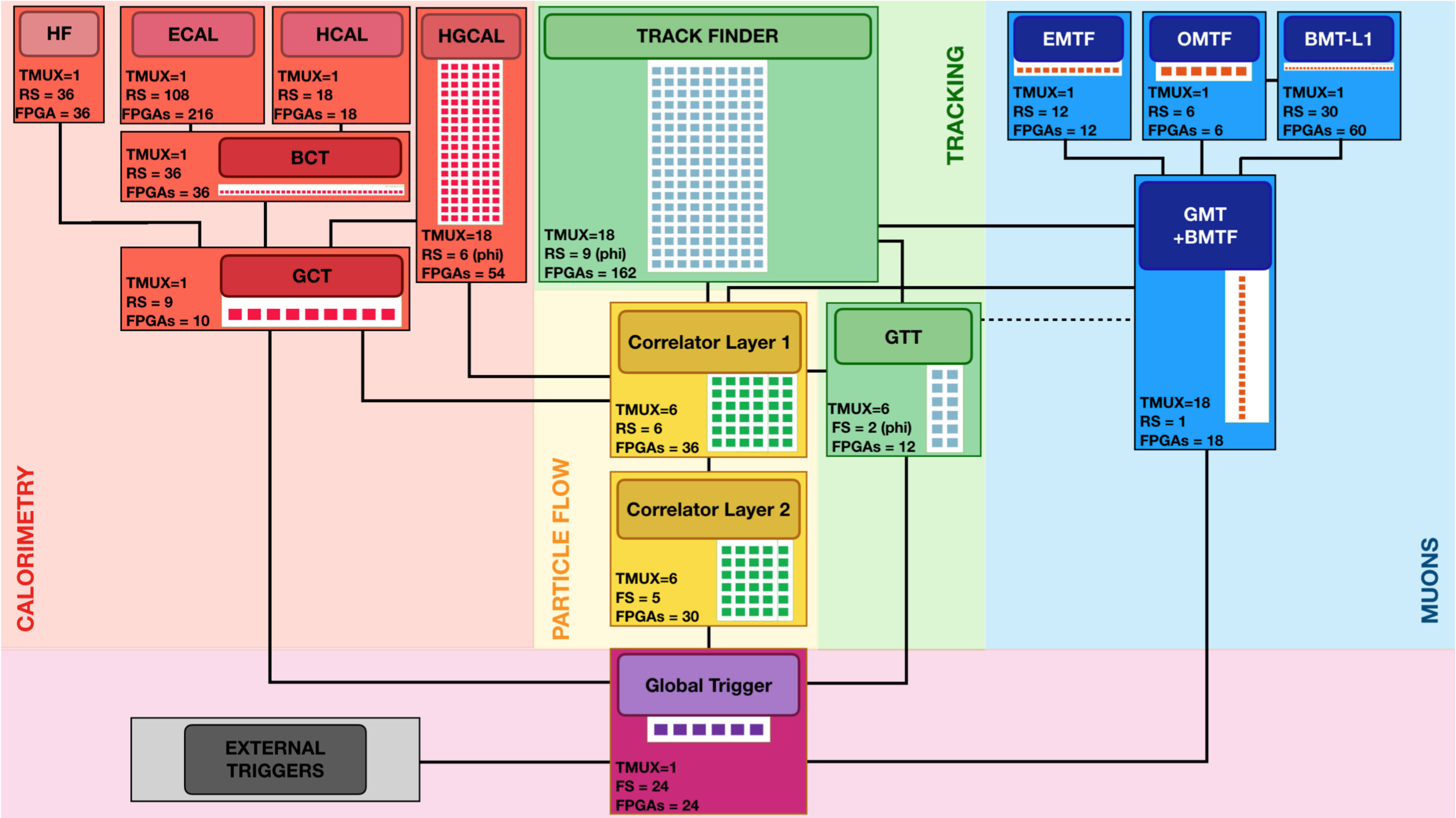
source of everything hereafter

BACKUP:
L1 Trigger menu

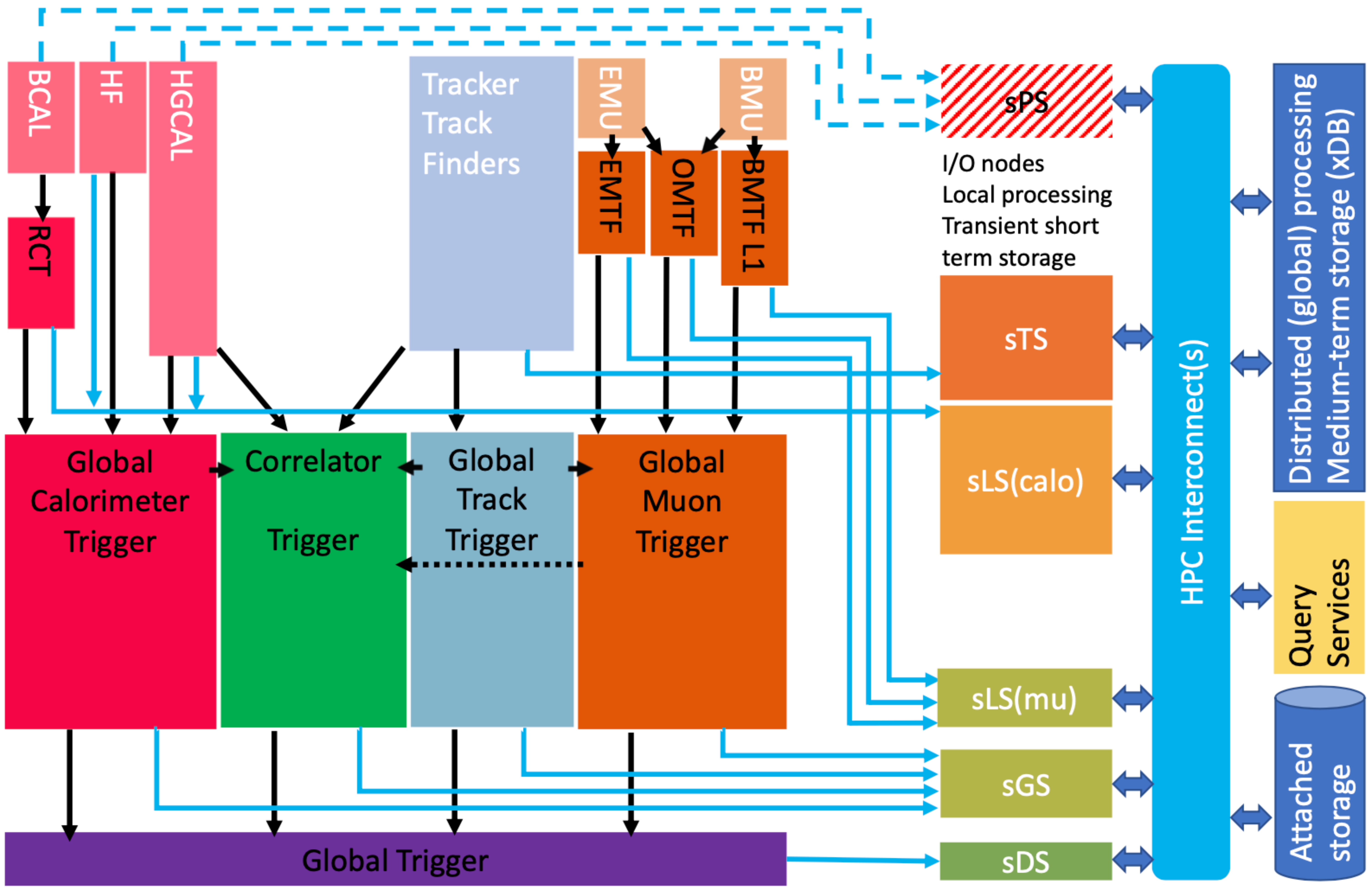
L1 Trigger seeds	Offline Threshold(s) at 90% or 95% (50%) [GeV]	Rate $\langle PU \rangle = 200$ [kHz]	Additional Requirement(s) [cm, GeV]	Objects plateau efficiency [%]
Single/Double/Triple Lepton (electron, muon) seeds				
Single TkMuon	22	12	$\|\eta\| < 2.4$	95
Double TkMuon	15,7	1	$\|\eta\| < 2.4$, $\Delta z < 1$	95
Triple TkMuon	5,3,3	16	$\|\eta\| < 2.4$, $\Delta z < 1$	95
Single TkElectron	36	24	$\|\eta\| < 2.4$	93
Single TkIsoElectron	28	28	$\|\eta\| < 2.4$	93
TkIsoElectron-StaEG	22, 12	36	$\|\eta\| < 2.4$	93, 99
Double TkElectron	25, 12	4	$\|\eta\| < 2.4$	93
Single StaEG	51	25	$\|\eta\| < 2.4$	99
Double StaEG	37,24	5	$\|\eta\| < 2.4$	99
Photon seeds				
Single TkIsoPhoton	36	43	$\|\eta\| < 2.4$	97
Double TkIsoPhoton	22, 12	50	$\|\eta\| < 2.4$	97
Taus seeds				
Single CaloTau	150(119)	21	$\|\eta\| < 2.1$	99
Double CaloTau	90,90(69,69)	25	$\|\eta\| < 2.1$, $\Delta R > 0.5$	99
Double PuppiTau	52,52(36,36)	7	$\|\eta\| < 2.1$, $\Delta R > 0.5$	90
Hadronic seeds (jets,H_T)				
Single PuppiJet	180	70	$\|\eta\| < 2.4$	100
Double PuppiJet	112,112	71	$\|\eta\| < 2.4$, $\Delta\eta < 1.6$	100
PuppiH_T	450(377)	11	jets: $\|\eta\| < 2.4$, $p_T > 30$	100
QuadPuppiJets-PuppiH_T	70,55,40,40,400(328)	9	jets: $\|\eta\| < 2.4$, $p_T > 30$	100,100
E_T^{miss} seeds				
PuppiE_T^{miss}	200(128)	18		100
Cross Lepton seeds				
TkMuon-TkIsoElectron	7,20	1	$\|\eta\| < 2.4$, $\Delta z < 1$	95, 93
TkMuon-TkElectron	7,23	3	$\|\eta\| < 2.4$, $\Delta z < 1$	95, 93
TkElectron-TkMuon	10,20	1	$\|\eta\| < 2.4$, $\Delta z < 1$	93, 95
TkMuon-DoubleTkElectron	6,17,17	0.1	$\|\eta\| < 2.4$, $\Delta z < 1$	95, 93
DoubleTkMuon-TkElectron	5,5,9	4	$\|\eta\| < 2.4$, $\Delta z < 1$	95, 93
PuppiTau-TkMuon	36(27),18	2	$\|\eta\| < 2.1$, $\Delta z < 1$	90, 95
TkIsoElectron-PuppiTau	22,39(29)	13	$\|\eta\| < 2.1$, $\Delta z < 1$ $\Delta R > 0.3$	93, 90

L1 Trigger seeds	Offline Threshold(s) at 90% or 95% (50%) [GeV]	Rate $\langle PU \rangle = 200$ [kHz]	Additional Requirement(s) [cm, GeV]	Objects plateau efficiency [%]
Cross Hadronic-Lepton seeds				
TkMuon-PuppiH_T	6,320(250)	4	$\|\eta\| < 2.4$, $\Delta z < 1$	95,100
TkMuon-DoublePuppiJet	12,40,40	10	$\|\eta\| < 2.4$, $\Delta R_{j\mu} < 0.4$, $\Delta\eta_{jj} < 1.6$, $\Delta z < 1$	95,100
TkMuon-PuppiJet-PuppiE_T^{miss}	3,100,120(55)	14	$\|\eta\| < 1.5$, $\|\eta\| < 2.4$, $\Delta z < 1$	95,100, 100
DoubleTkMuon-PuppiJet-PuppiE_T^{miss}	3,3,60,130(64)	4	$\|\eta\| < 2.4$, $\Delta z < 1$	95,100, 100
DoubleTkMuon-PuppiH_T	3,3,300(231)	2	$\|\eta\| < 2.4$, $\Delta z < 1$	95,100
DoubleTkElectron-PuppiH_T	10,10,400(328)	0.9	$\|\eta\| < 2.4$, $\Delta z < 1$	93,100
TkIsoElectron-PuppiH_T	26,190(124)	9	$\|\eta\| < 2.4$, $\Delta z < 1$	93,100
TkElectron-PuppiJet	28,40	34	$\|\eta\| < 2.1$, $\|\eta\| < 2.4$, $\Delta R > 0.3$, $\Delta z < 1$	93,100
PuppiTau-PuppiE_T^{miss}	55(38),190(118)	4	$\|\eta\| < 2.1$	90,100
VBF seeds				
Double PuppiJets	160,35	40	$\|\eta\| < 5$, $m_{jj} > 620$	100
B-physics seeds				
Double TkMuon	2,2	12	$\|\eta\| < 1.5$, $\Delta R < 1.4$, $q1 * q2 < 0$, $\Delta z < 1$	95
Double TkMuon	4,4	21	$\|\eta\| < 2.4$, $\Delta R < 1.2$ $q1 * q2 < 0$, $\Delta z < 1$	95
Double TkMuon	4.5,4	10	$\|\eta\| < 2.0$, $7 < m_{\mu\mu} < 18$, $q1 * q2 < 0$, $\Delta z < 1$	95
Triple TkMuon	5,3,2	7	$0 < m_{\mu 5 \mu 3, q1*q2<0} < 9$ $\|\eta\| < 2.4$, $\Delta z < 1$	95
Triple TkMuon	5,3,2.5	6	$5 < m_{\mu 5 \mu 2.5, q1*q2<0} < 17$ $\|\eta\| < 2.4$, $\Delta z < 1$	95
Rate for above Trigger seeds				346
Total Level-1 Menu Rate (+30%)				**450**

BACKUP:
L1 trigger architecture

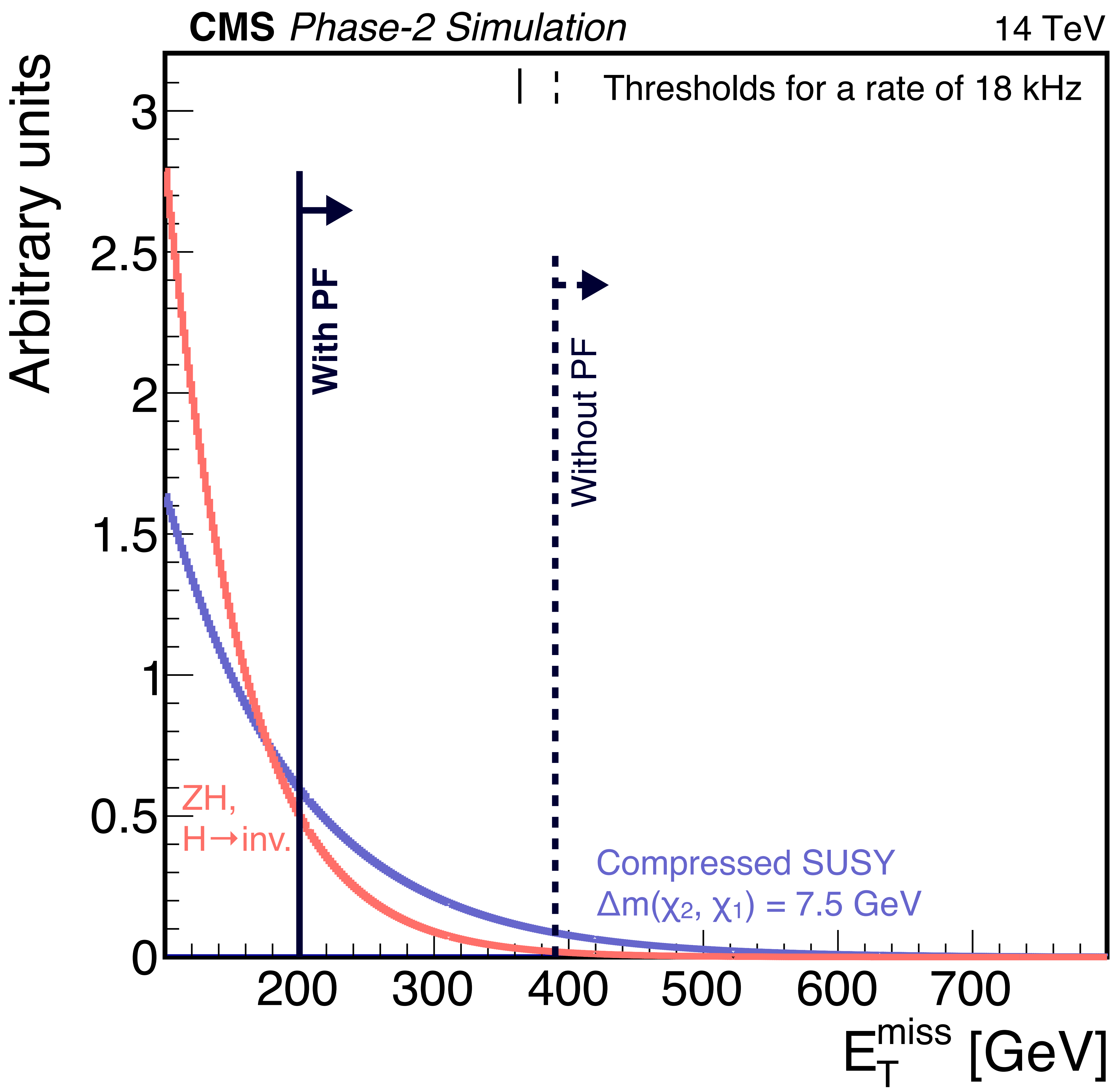


BACKUP:
L1 trigger architecture w/ 40MHz scouting

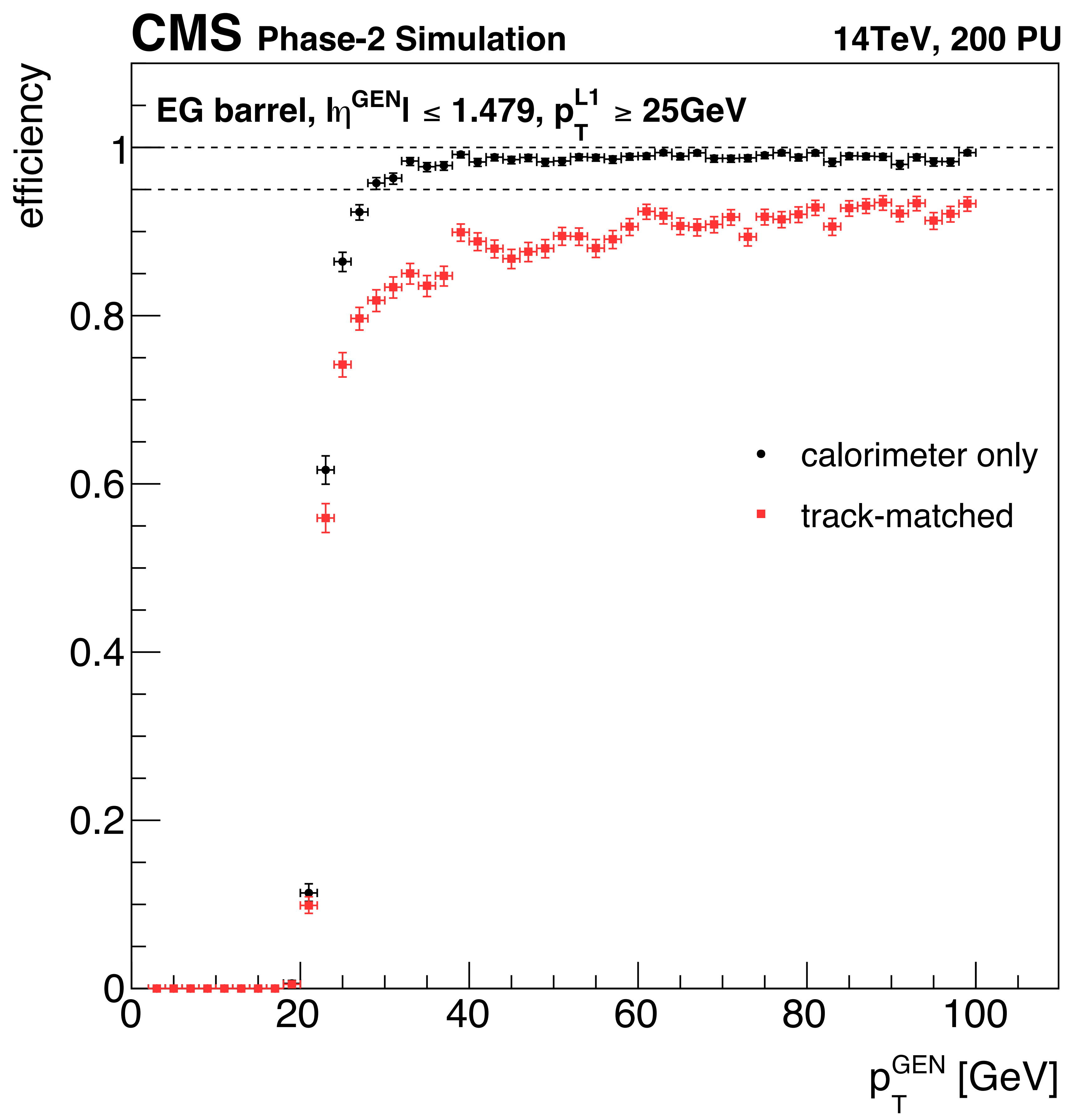


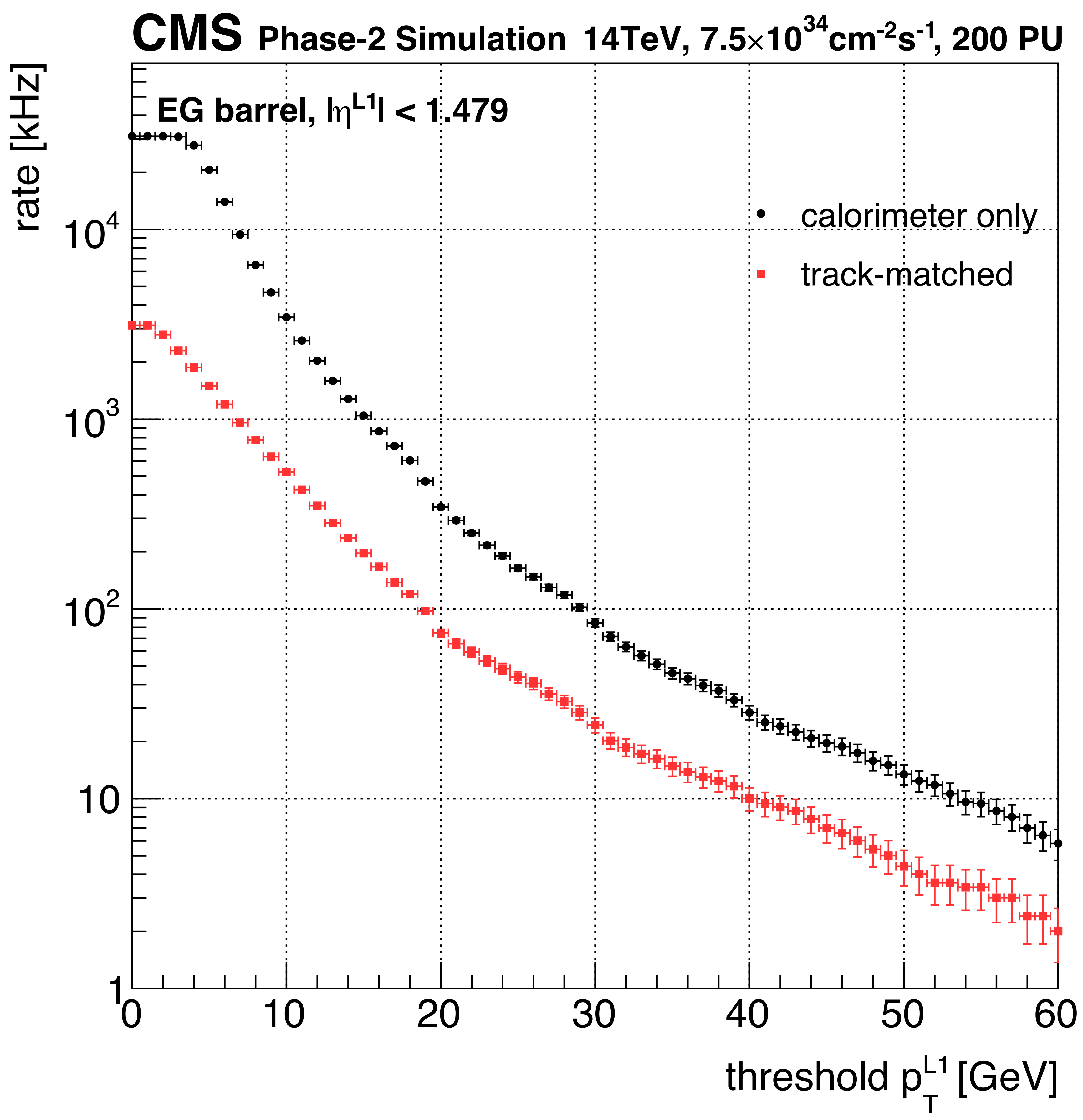
BACKUP

E_T^{miss} trigger algorithms

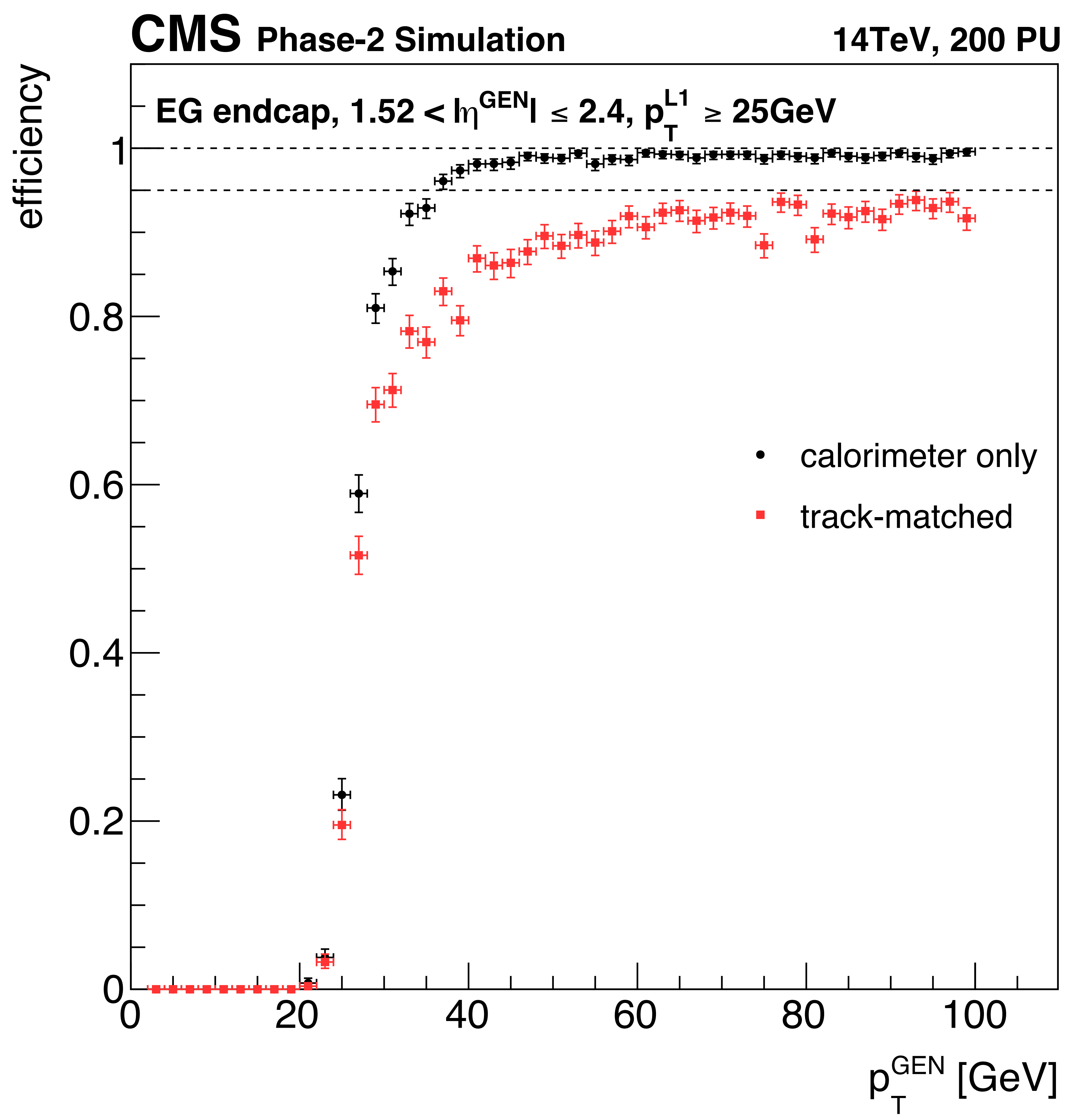


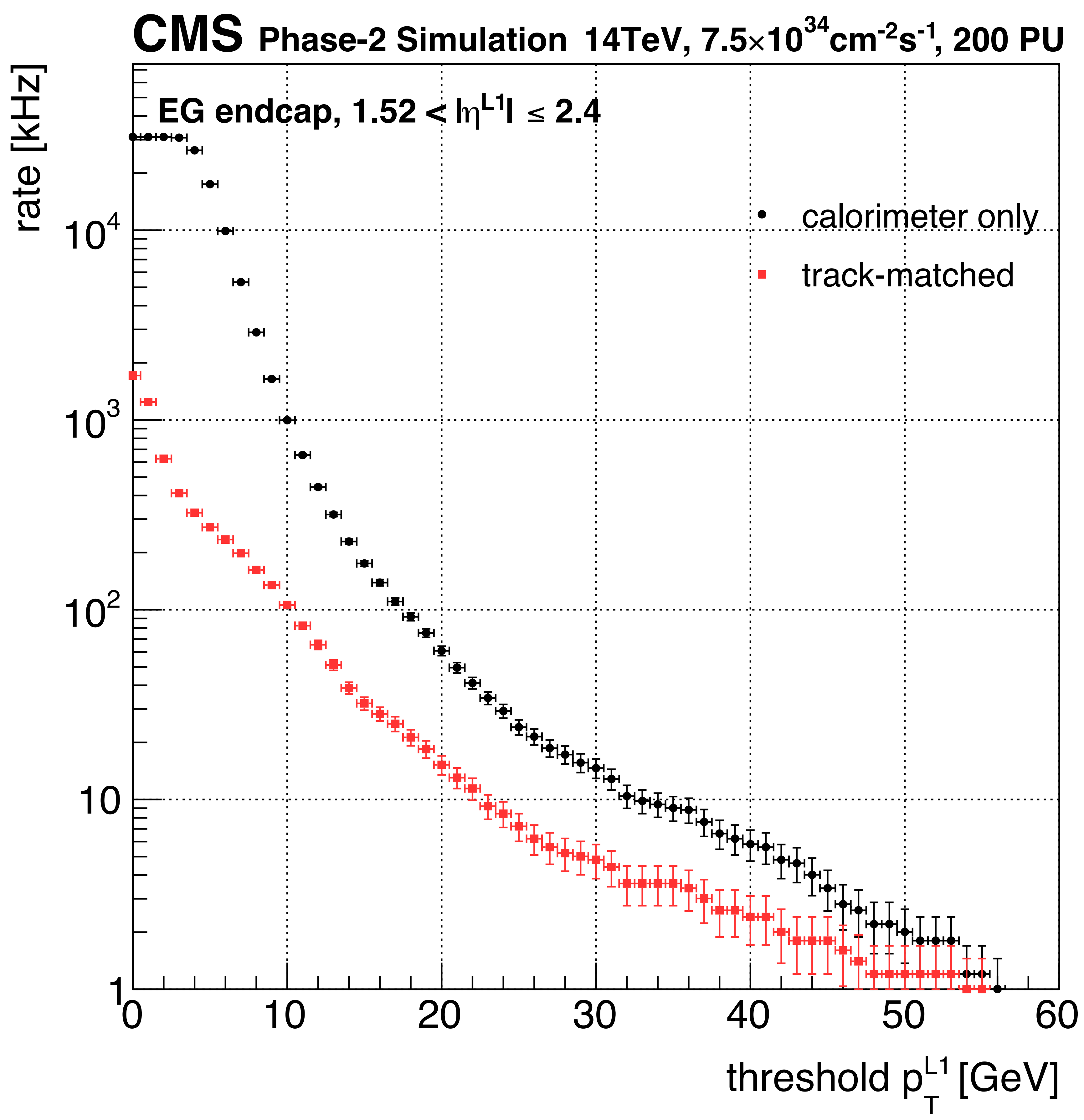
BACKUP:
e/γ barrel performances



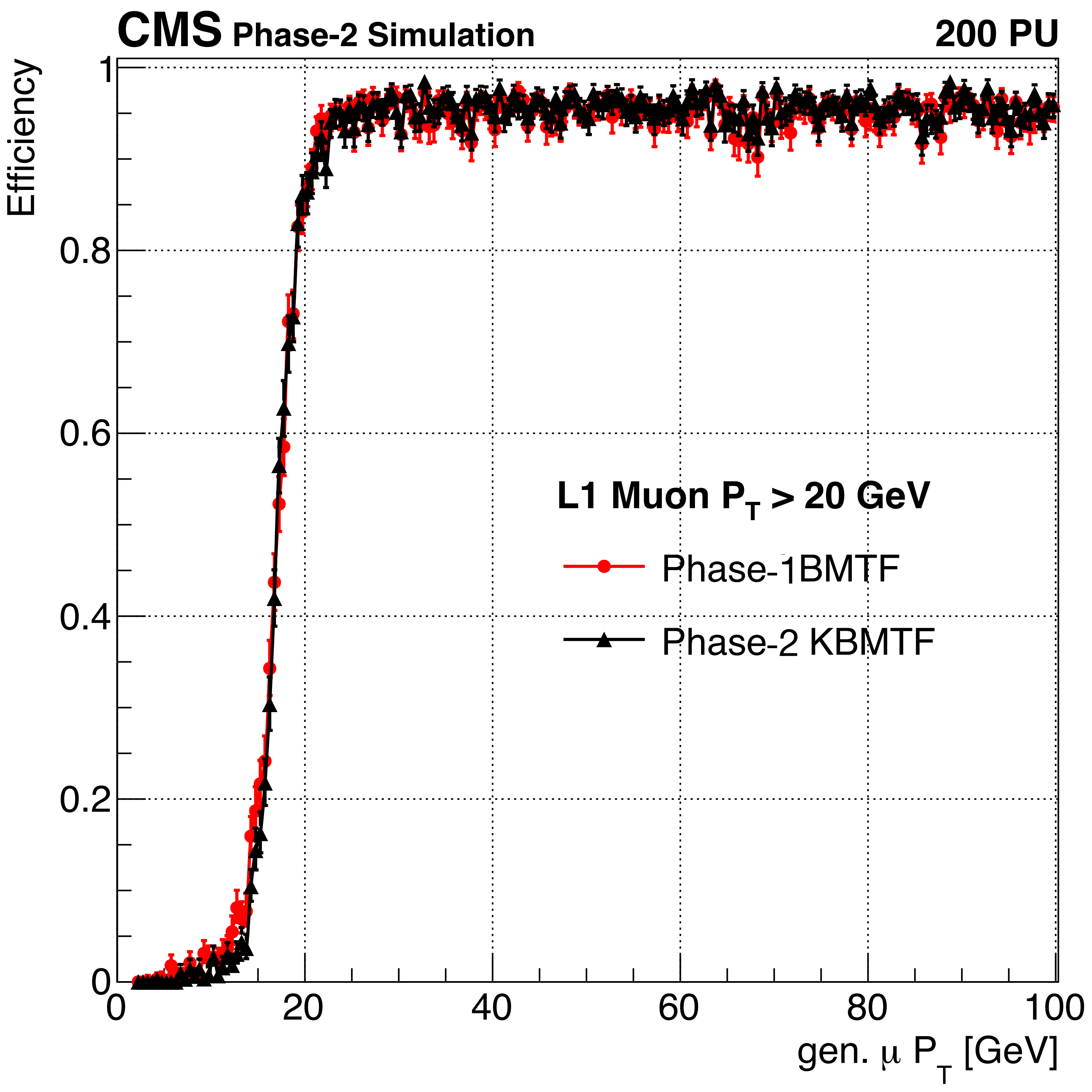


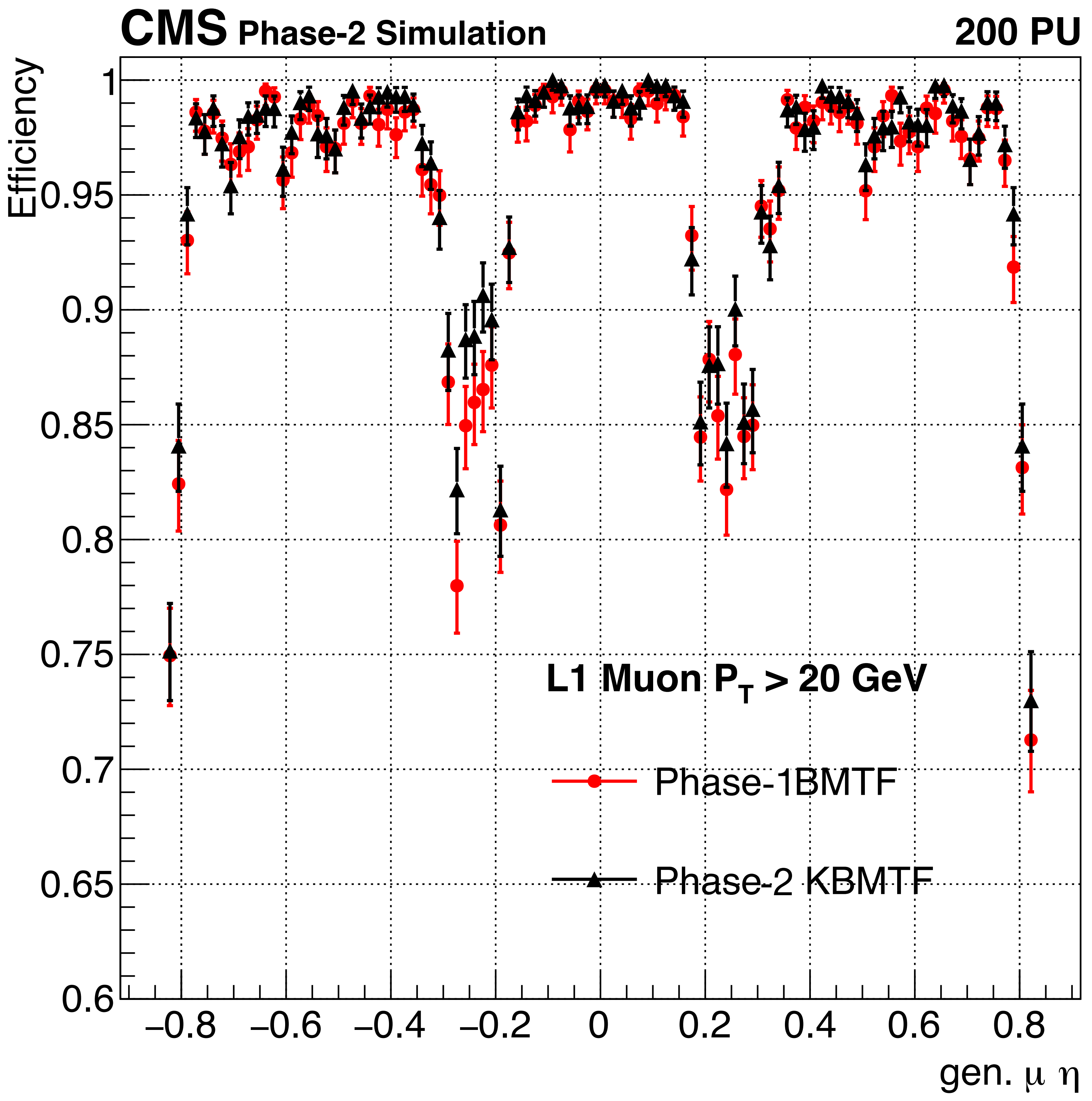
BACKUP:
e/γ endcap performances

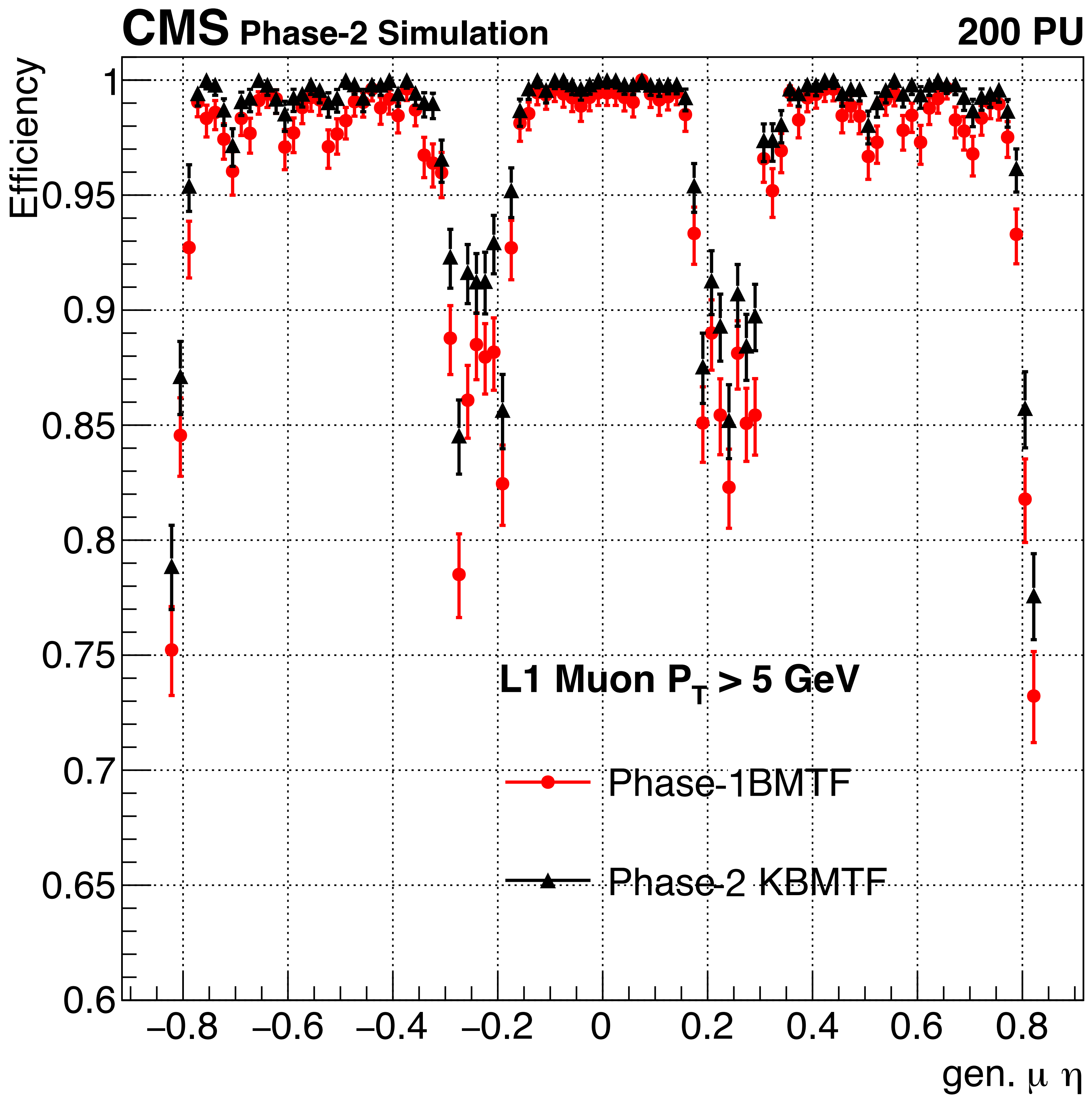




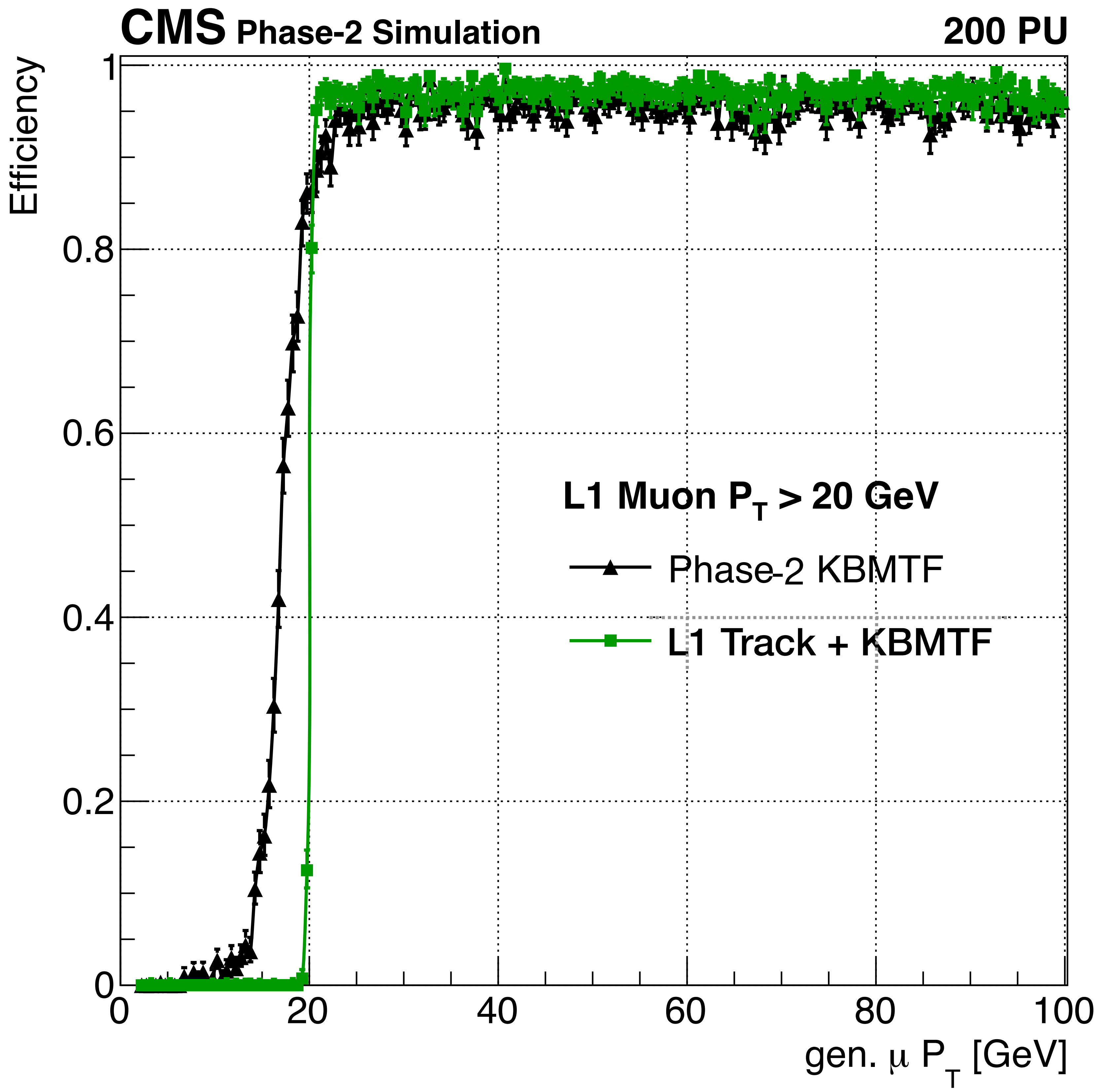
BACKUP:
μ barrel performances

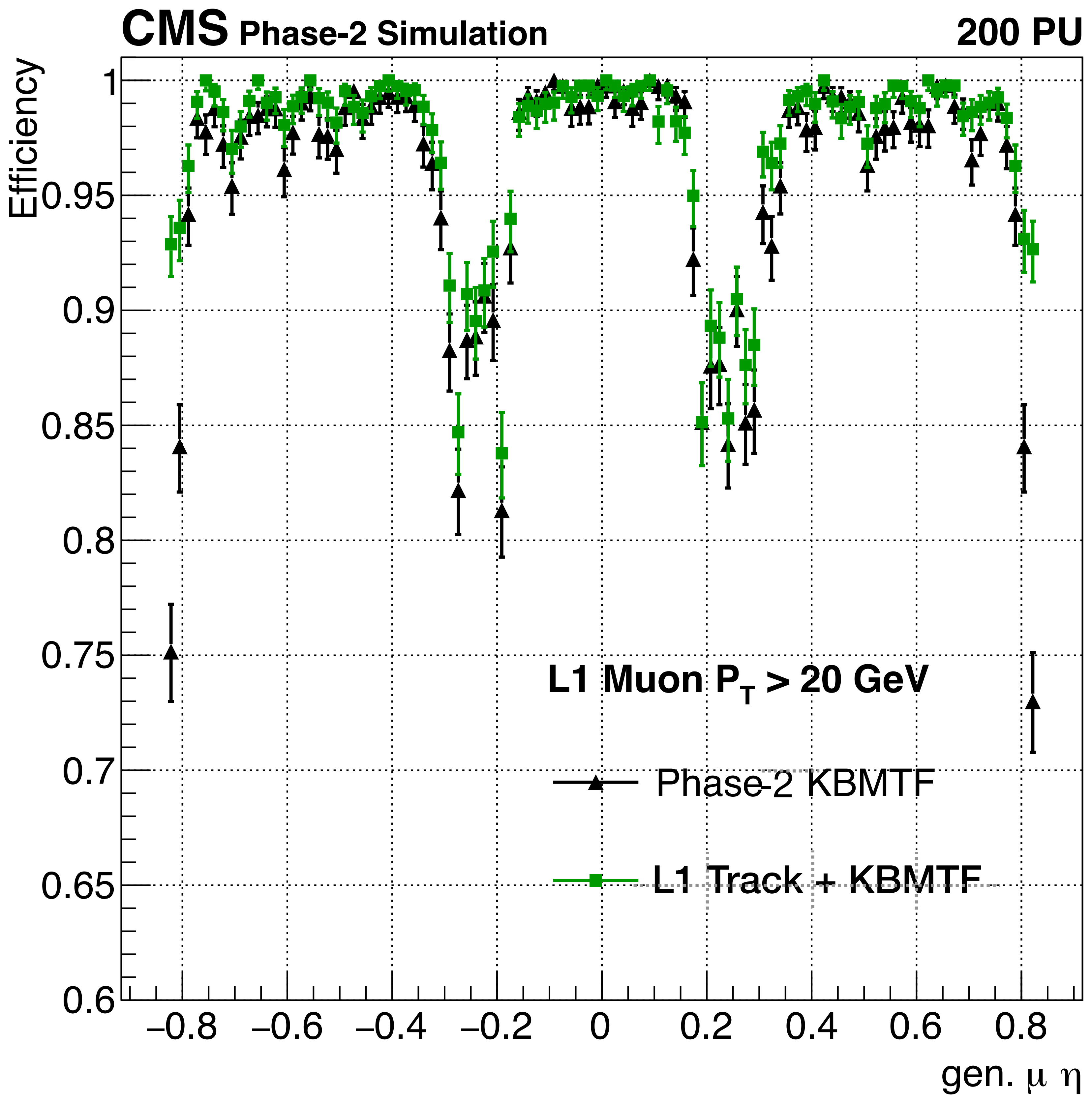


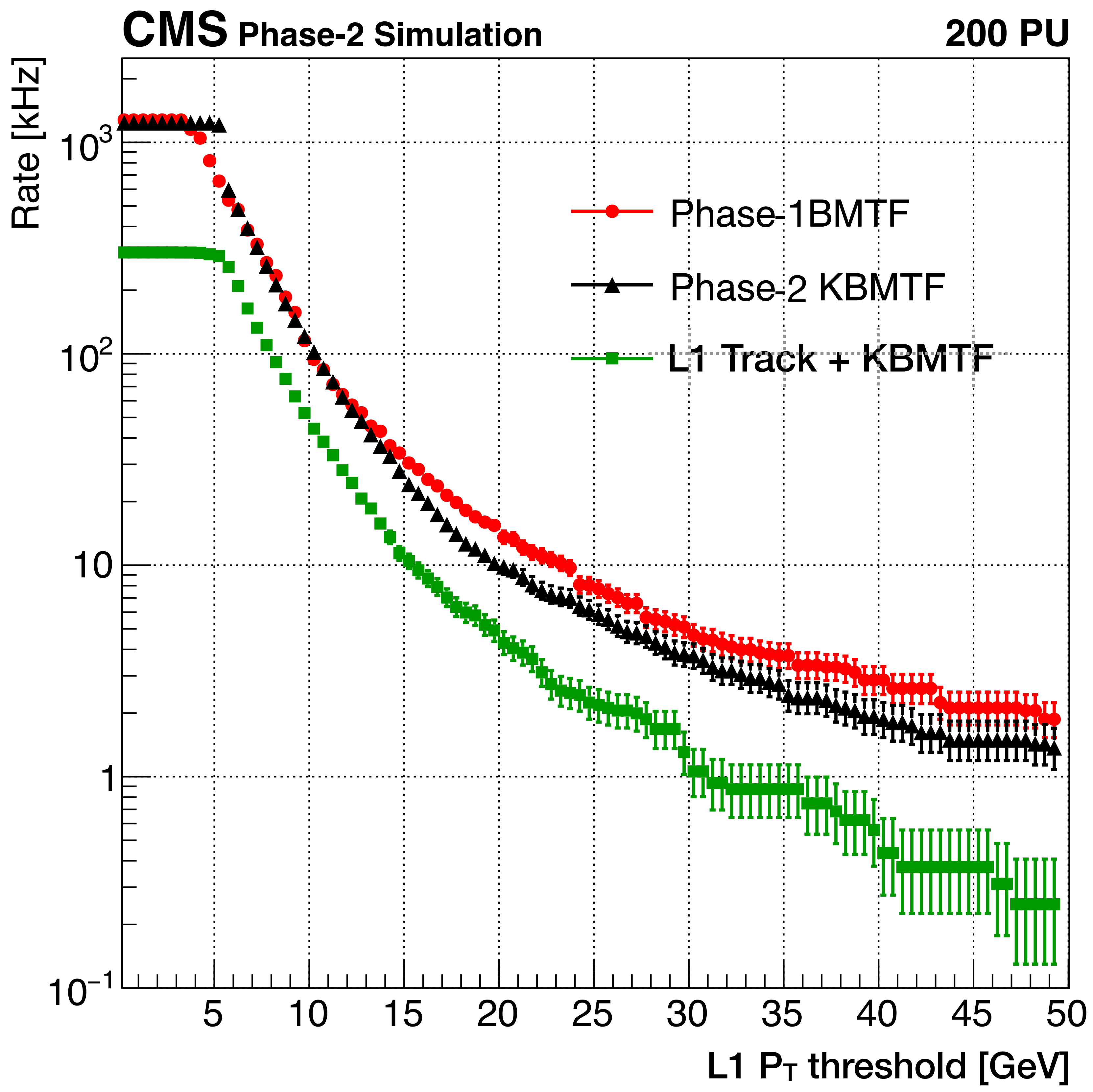




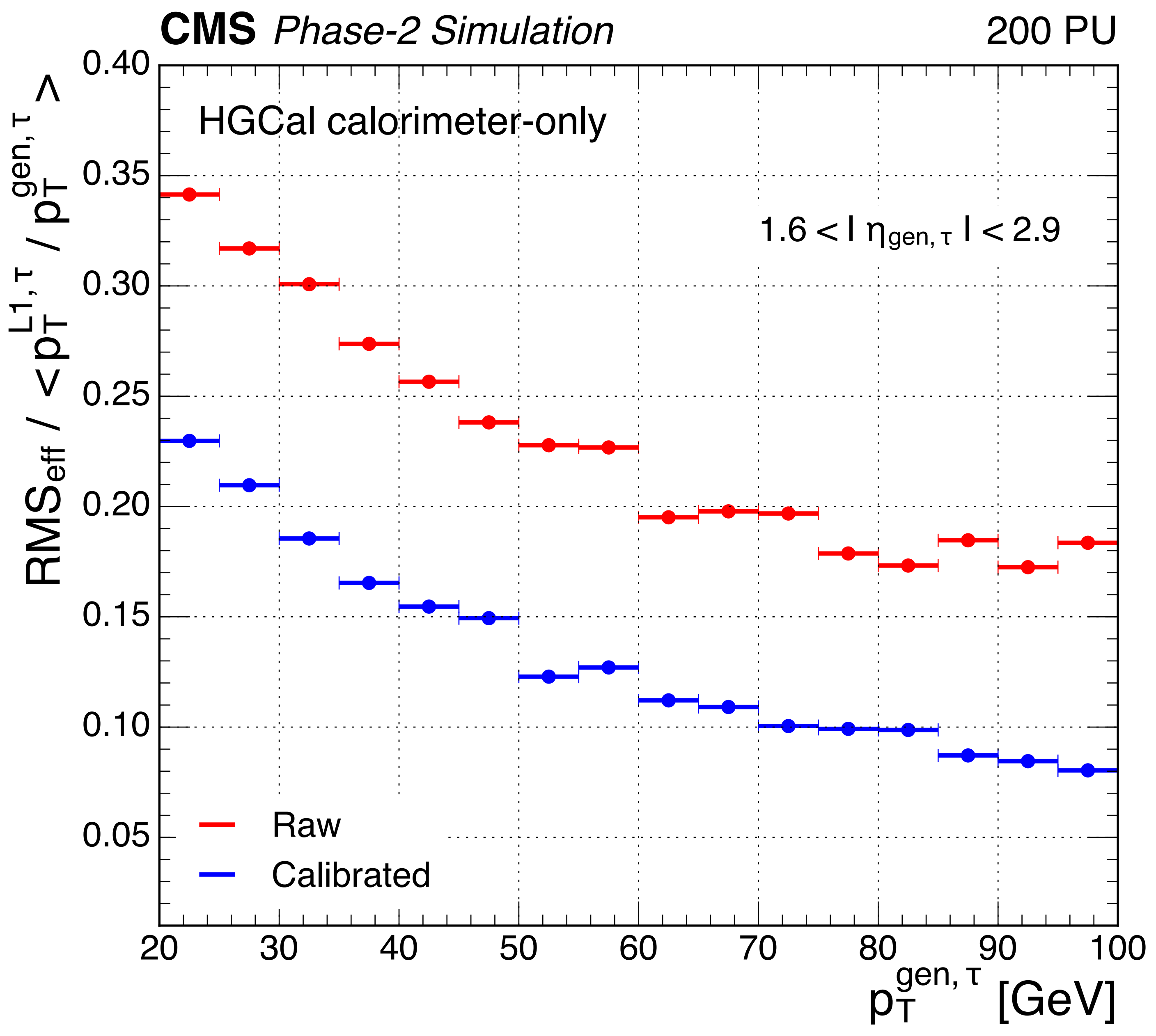
BACKUP:
μ barrel+track performances

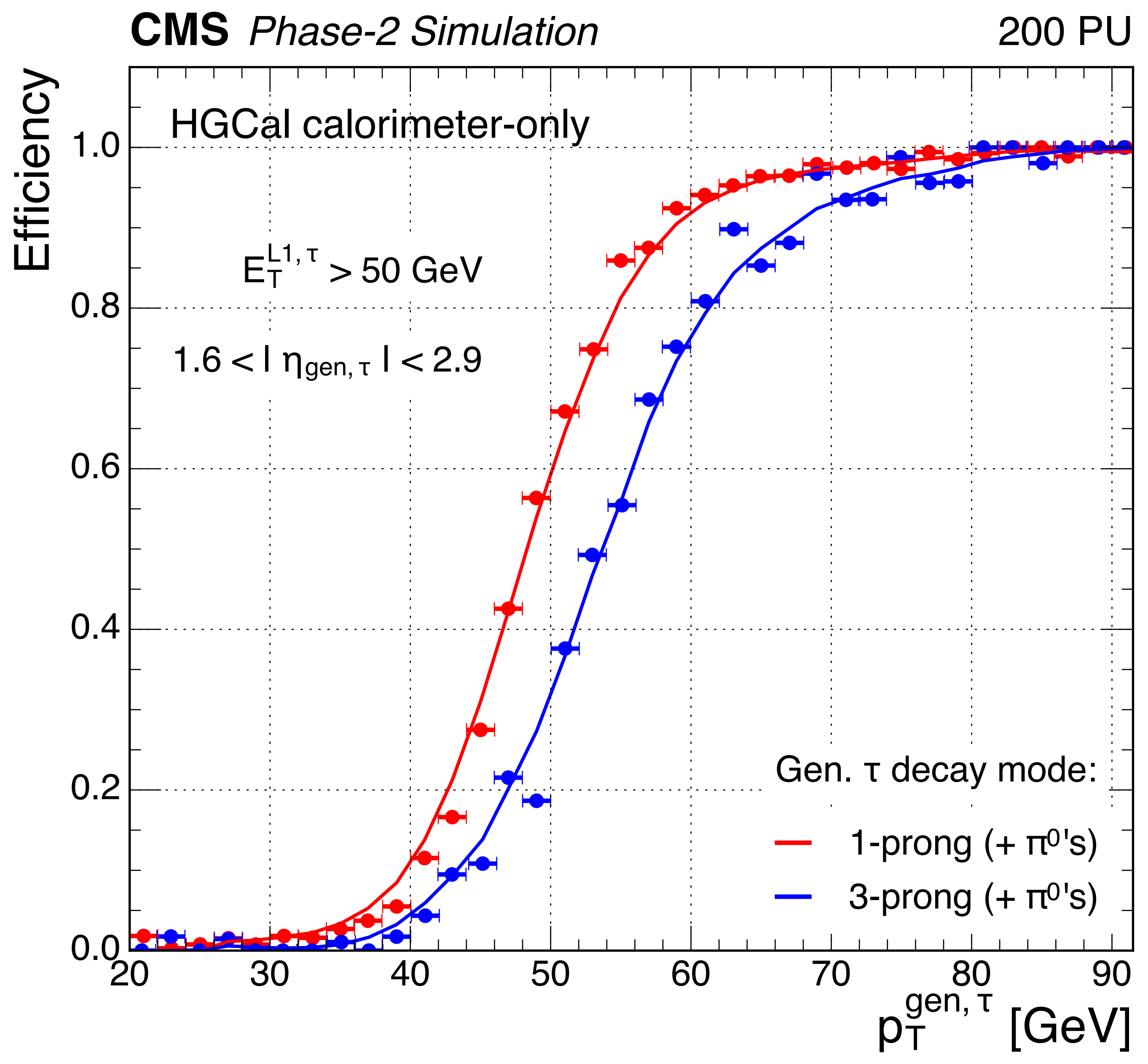


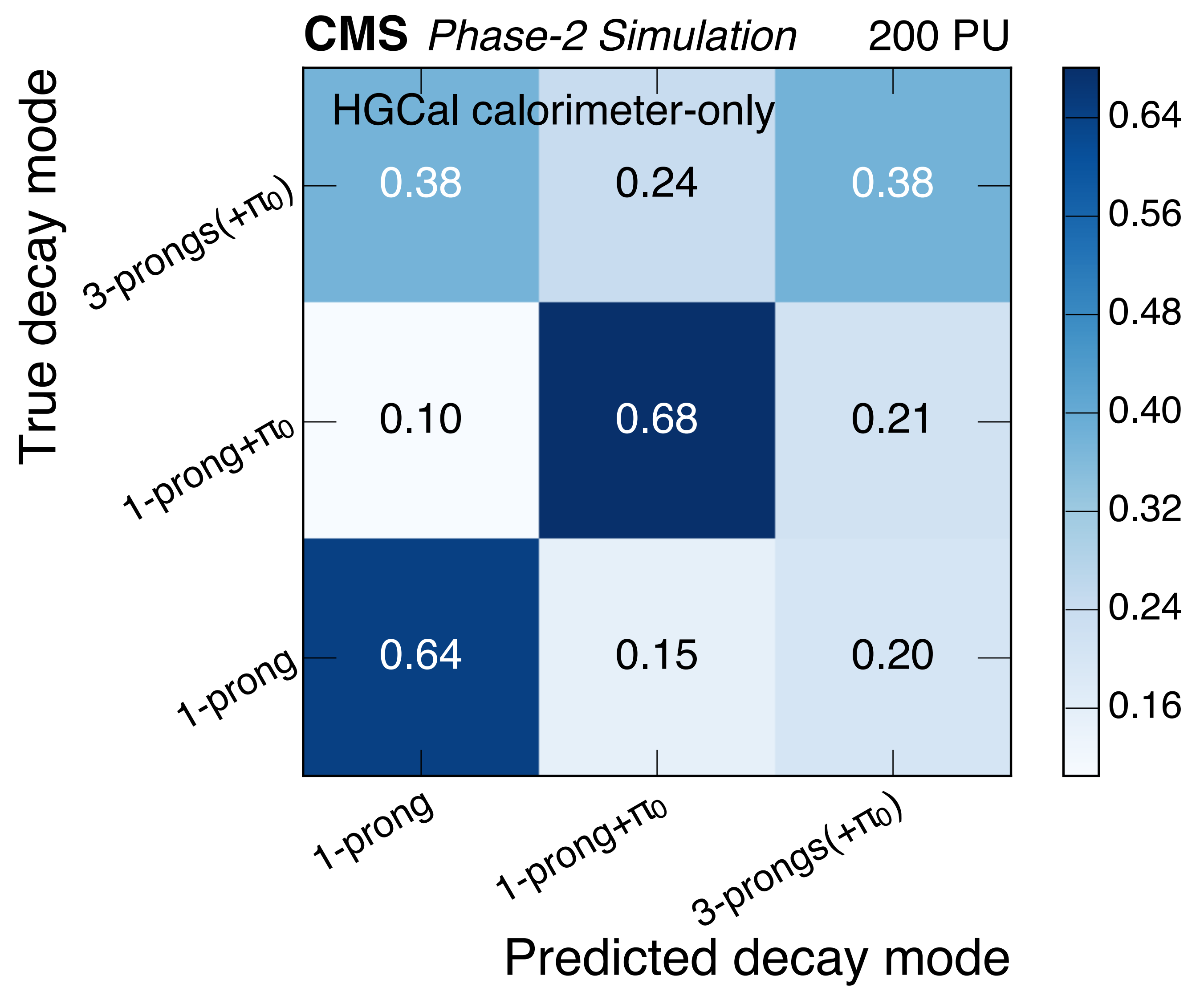


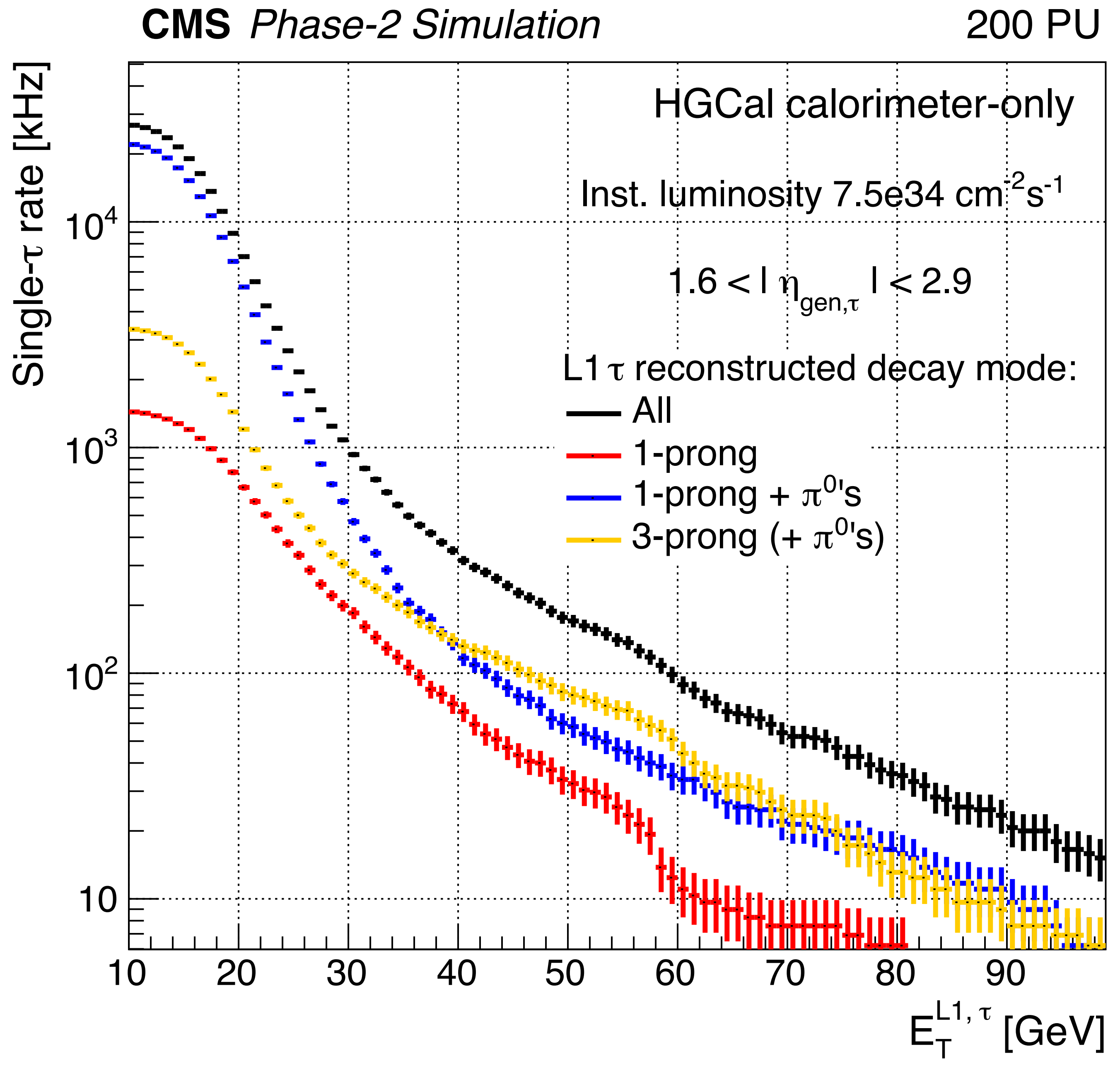


BACKUP:
HGCAL τ algorithm performance









BACKUP:
EMTF demonstrator

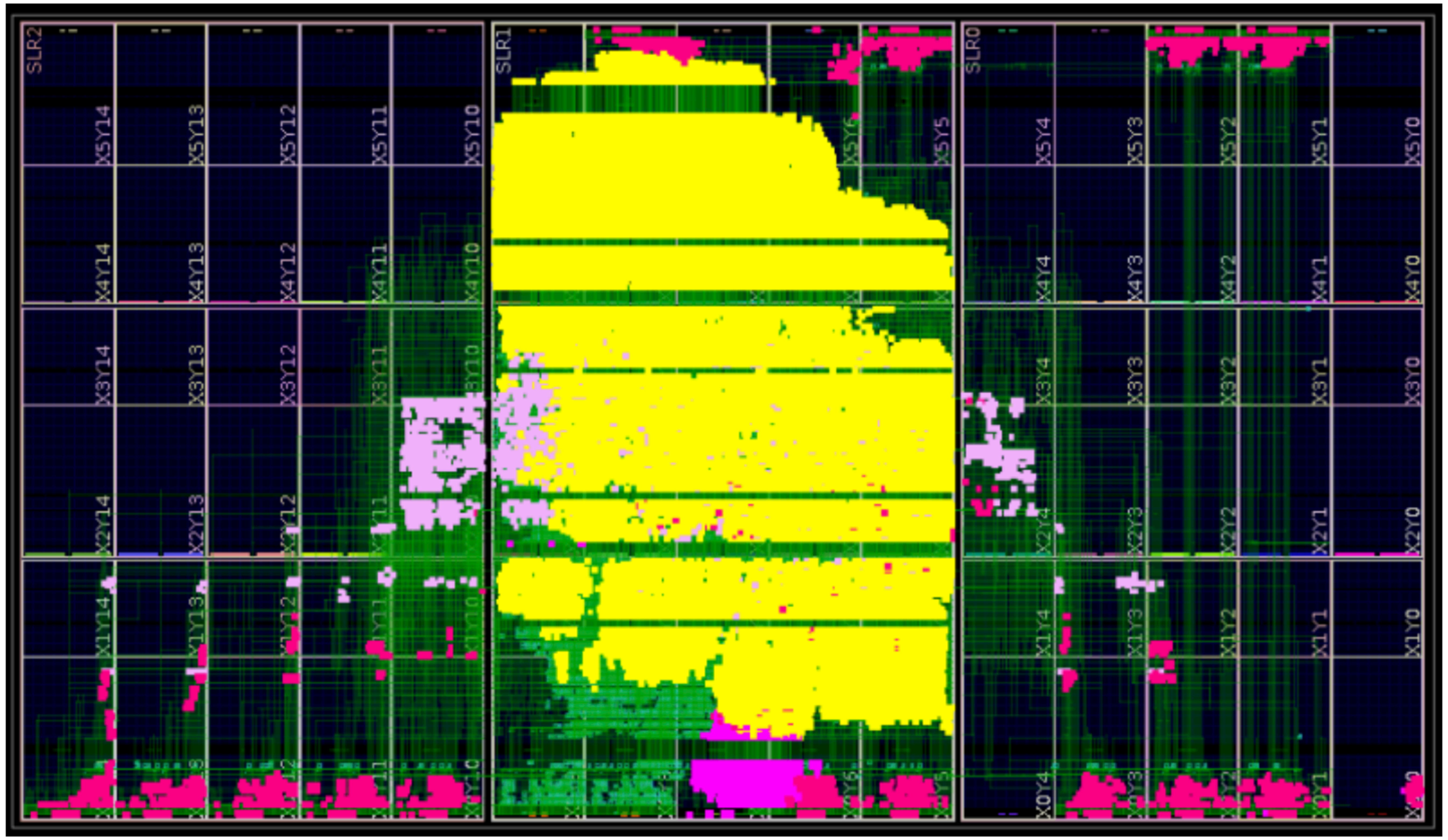


Figure 6.45: Image of the EMTF firmware usage in the Virtex 9 Ultrascale+ FPGA. Shown are the EMTF logic core (yellow), input links (red), input link data deframers (light pink), control link to the ELM2 (magenta), and other logic (green).

BACKUP:
GTT demonstrator

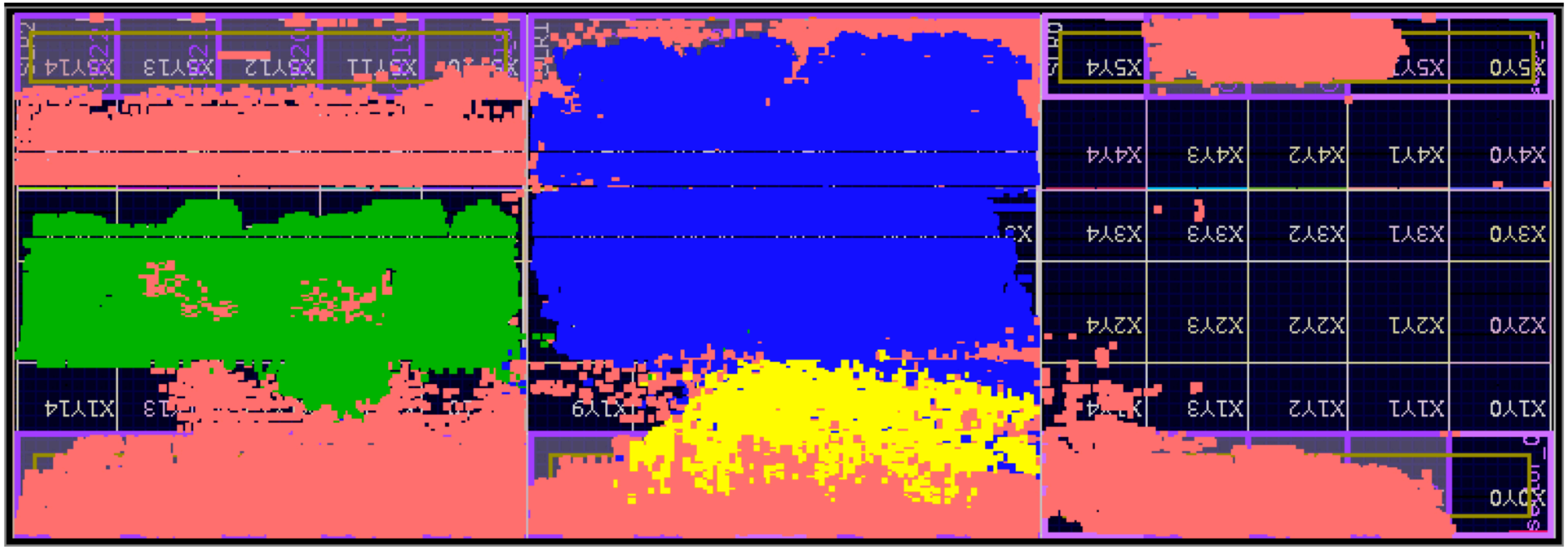


Figure 6.51: Resource placement on VU9P FPGA for the GTT demonstration. Red shows the firmware shell plus track conversion modules, green shows the primary vertex finding algorithm, blue is the track jet finding algorithm, and yellow is the track E_T^{miss} algorithm.