Particle Flow at 40 MHz with the CMS L1 Trigger

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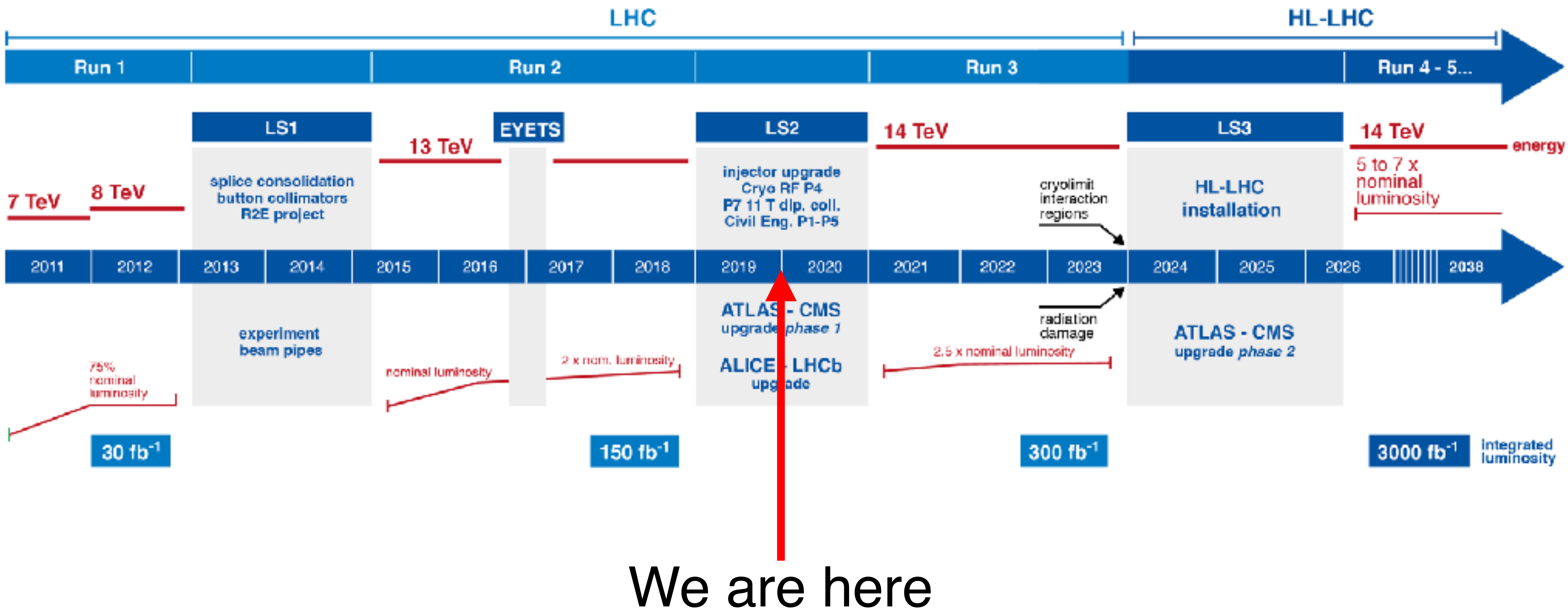
CPAD Instrumentation Frontier Workshop
December 8-10, 2019

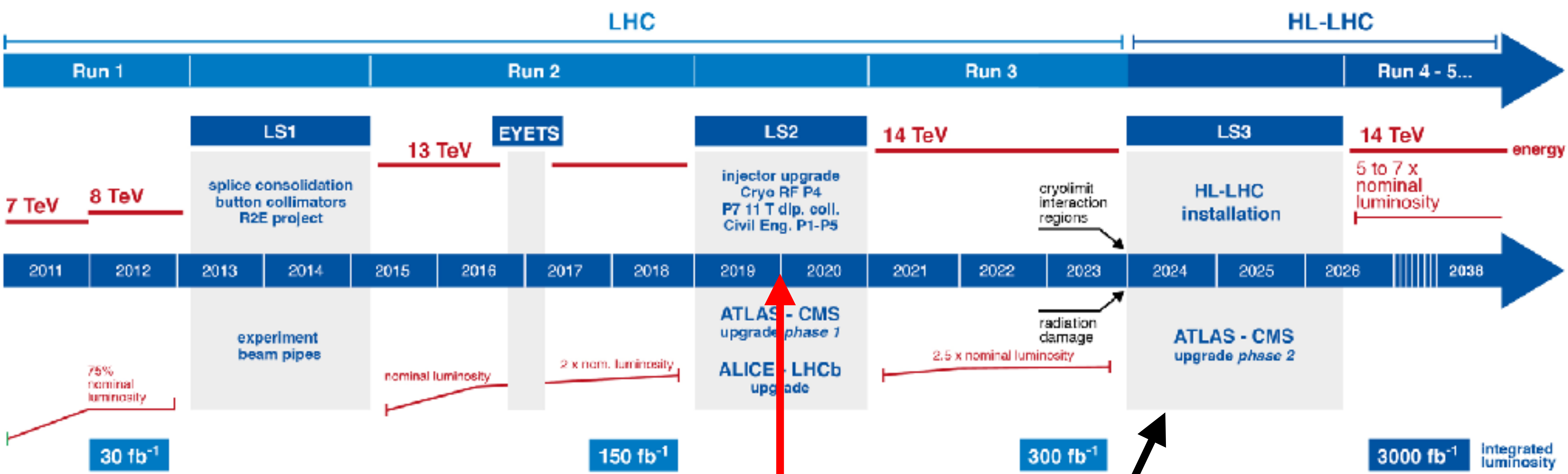
Outline

- Motivation and the High-luminosity LHC
- Particle Flow reconstruction
  - PUPPI Pileup subtraction
- The Phase-II Upgrade to the L1 CMS Trigger
- Progress of PF+PUPPI implementation

LHC / HL-LHC Plan



LHC / HL-LHC Plan

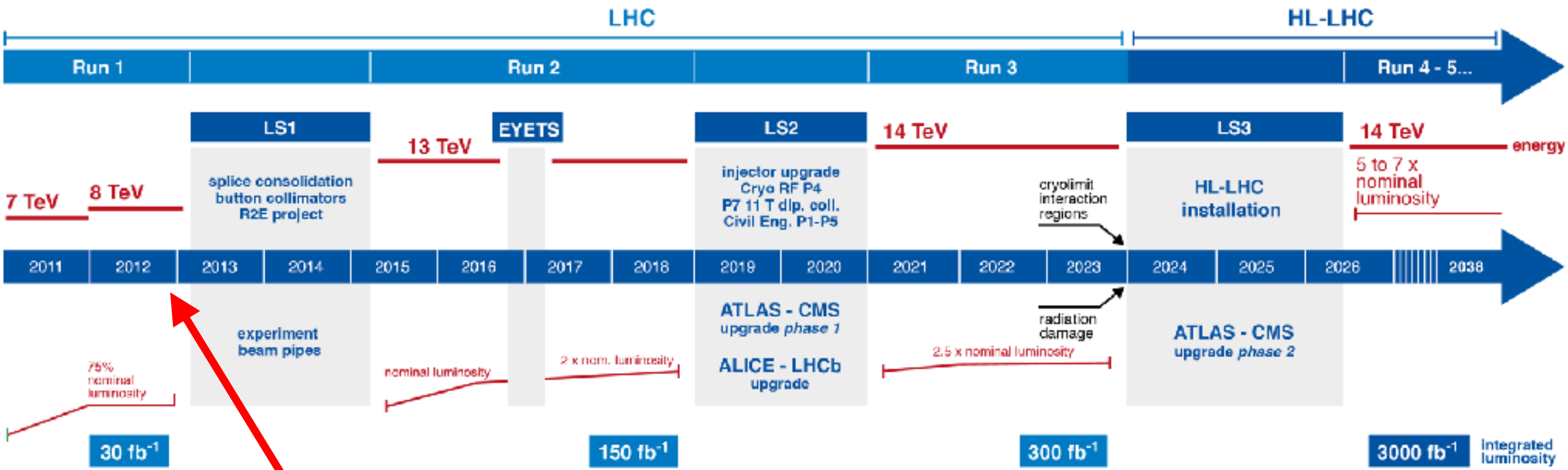


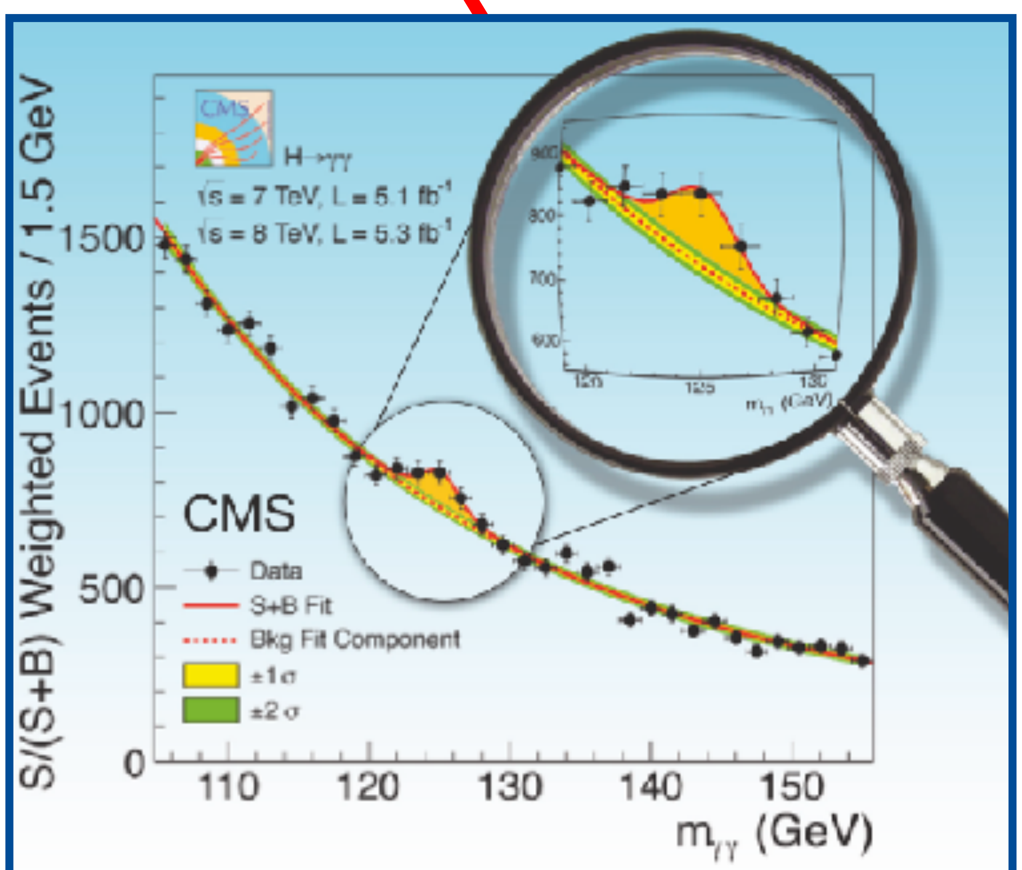
We are here

Phase-II upgrades

10x dataset increase

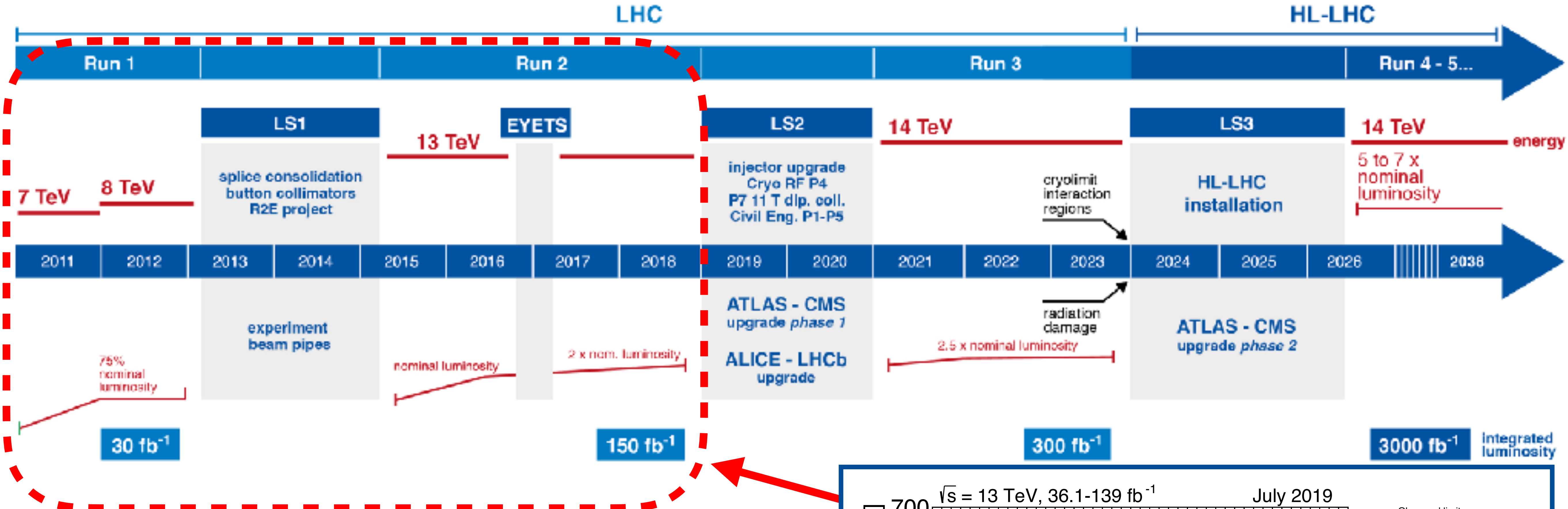
LHC / HL-LHC Plan





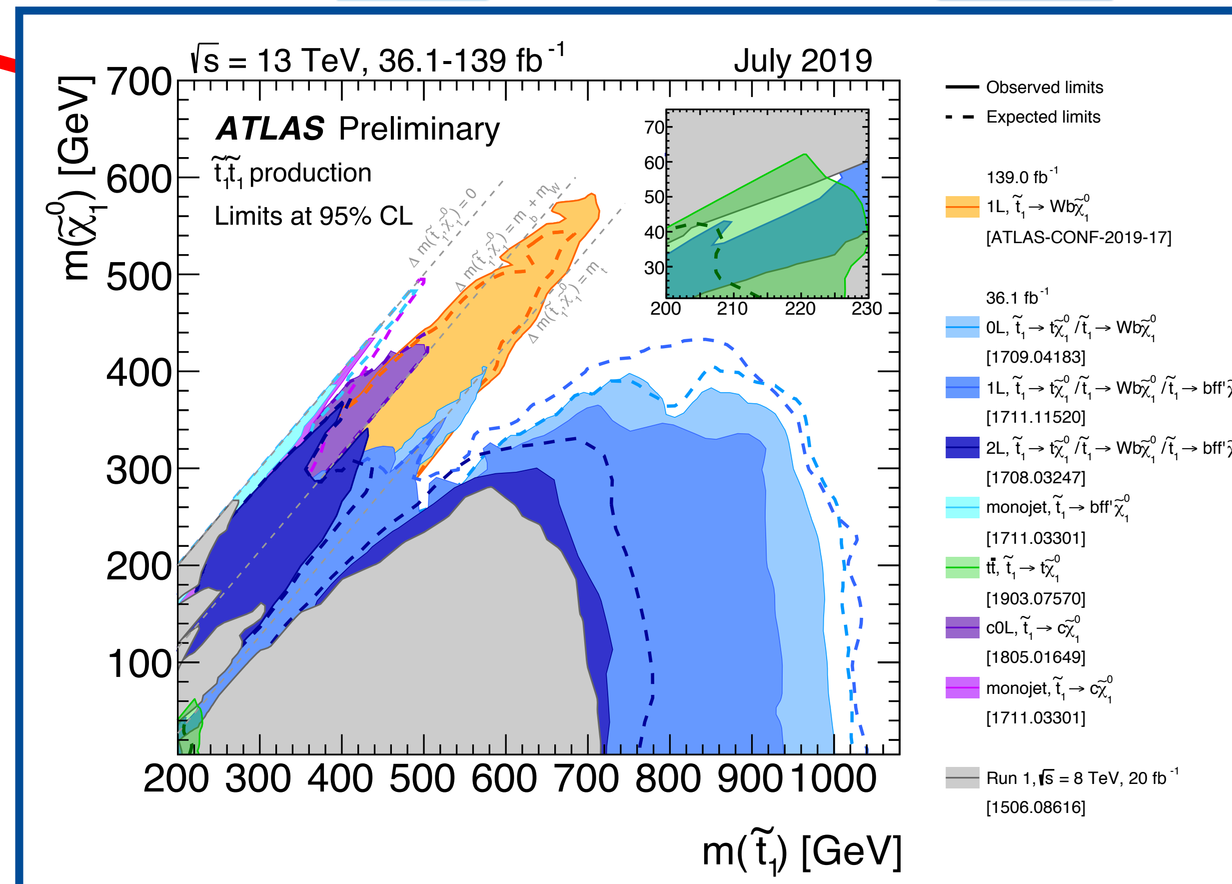
Discover Higgs!

LHC / HL-LHC Plan



Constraints on BSM Physics

(especially strongly produced)



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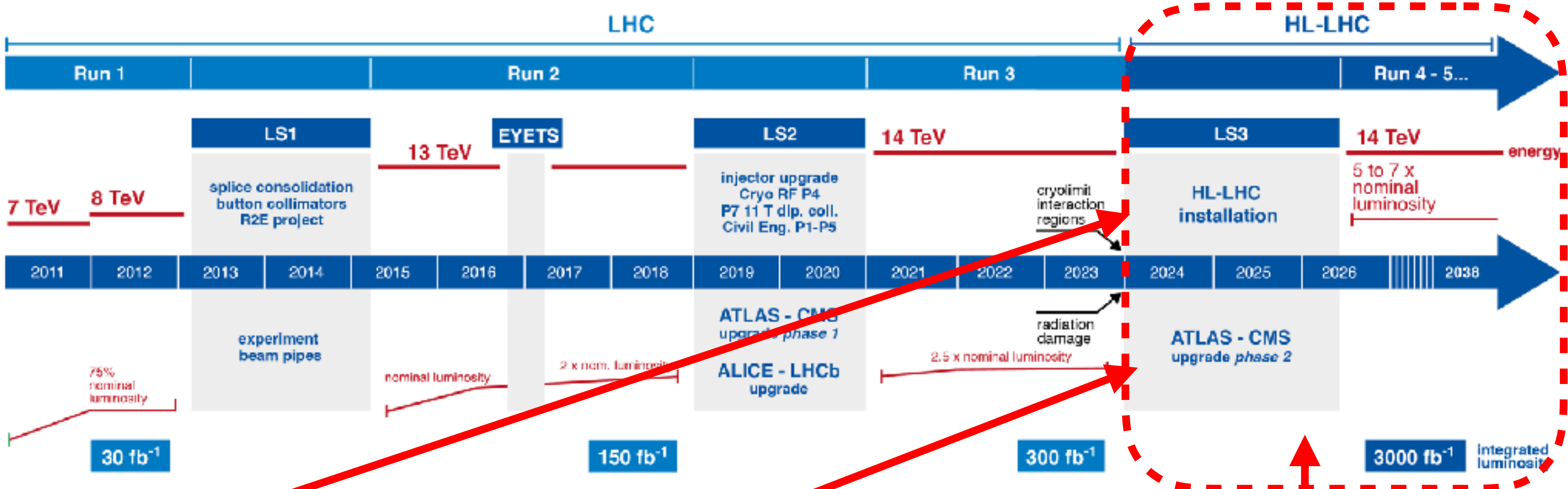
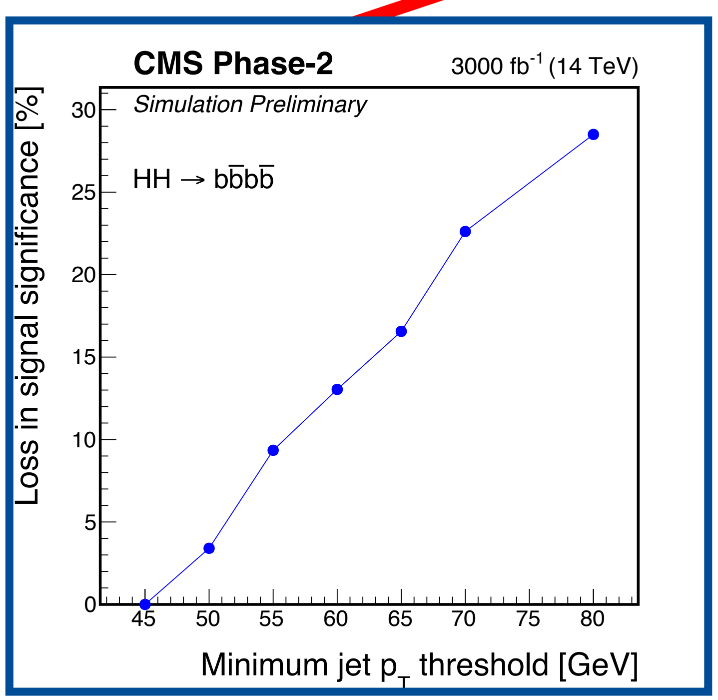
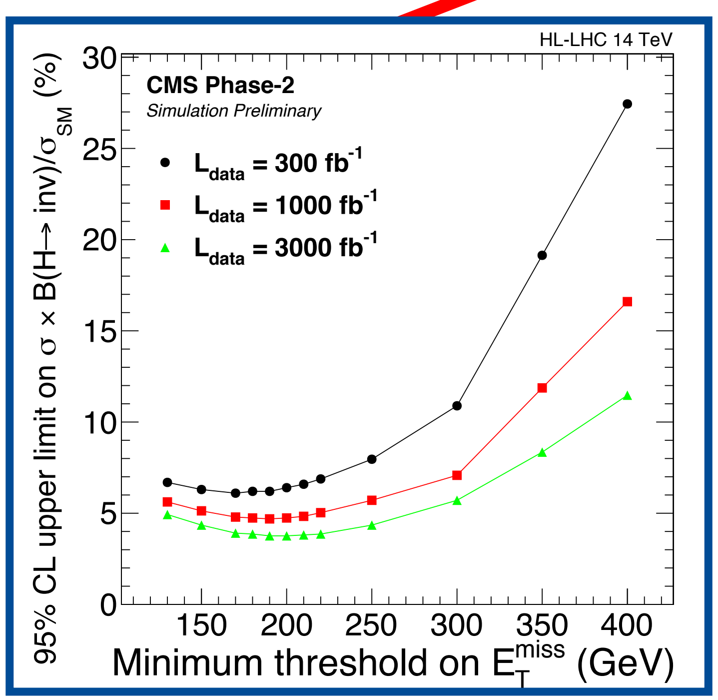
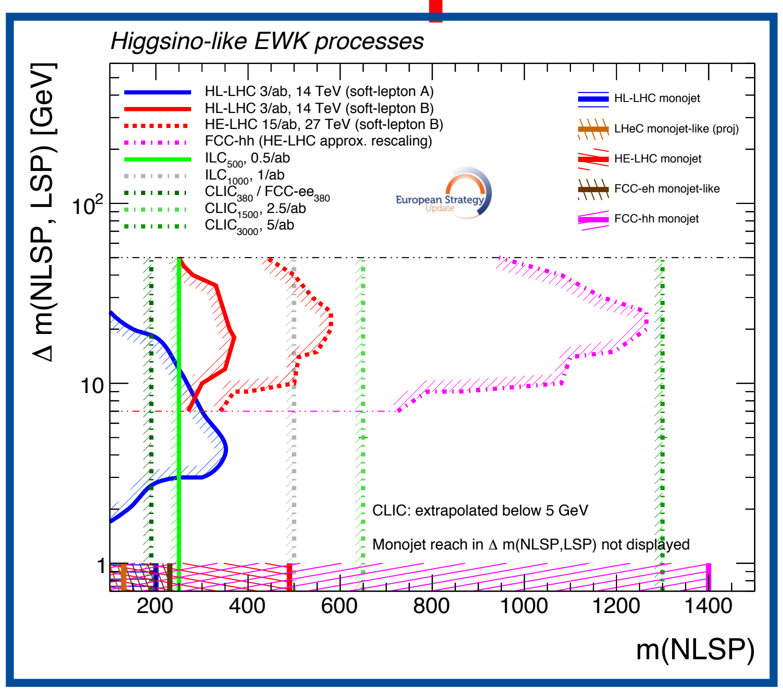




SM hh

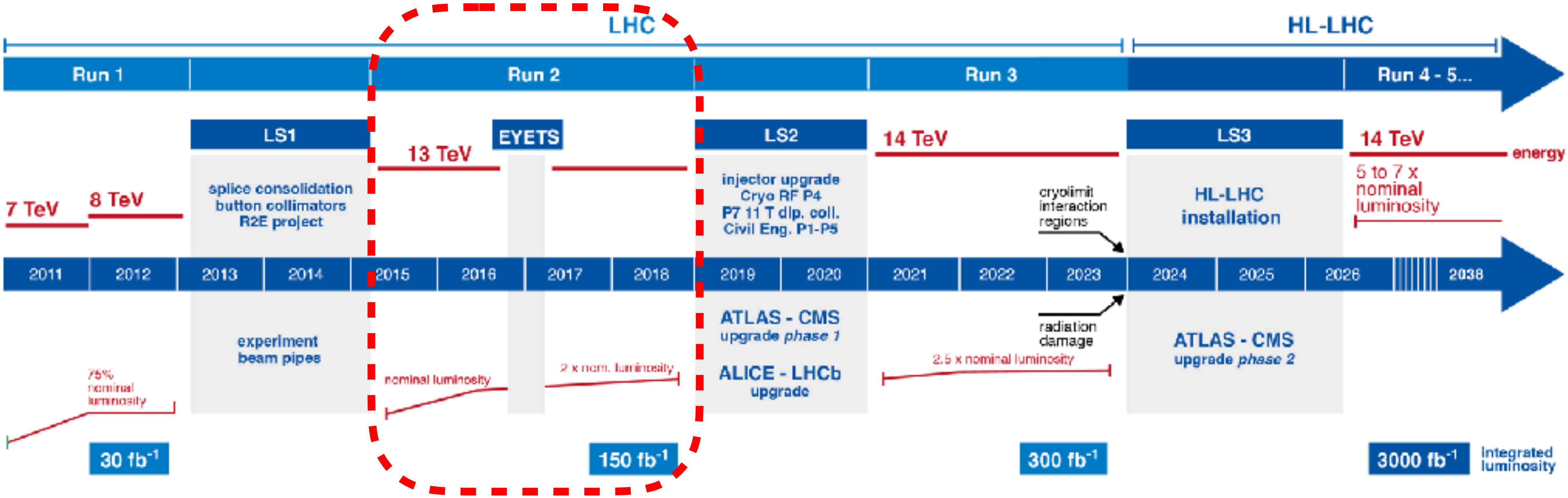


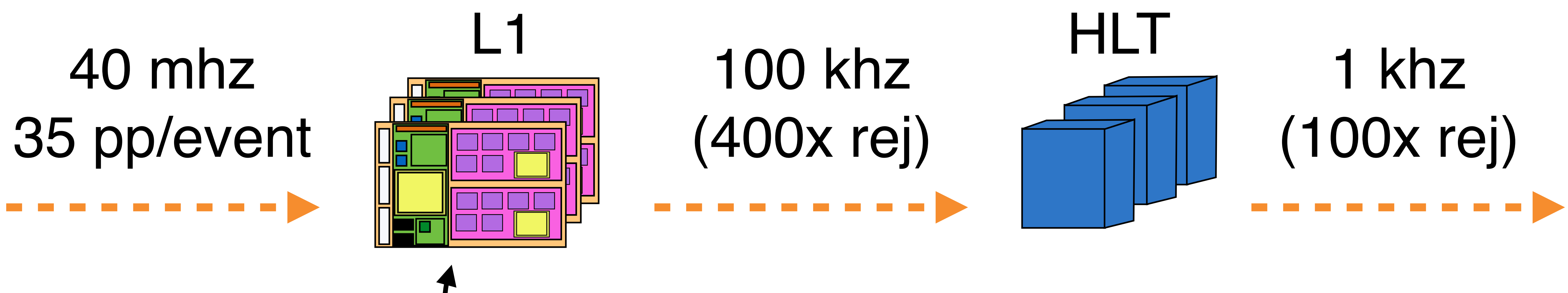
Rare+Exotic Higgs



EWK BSM

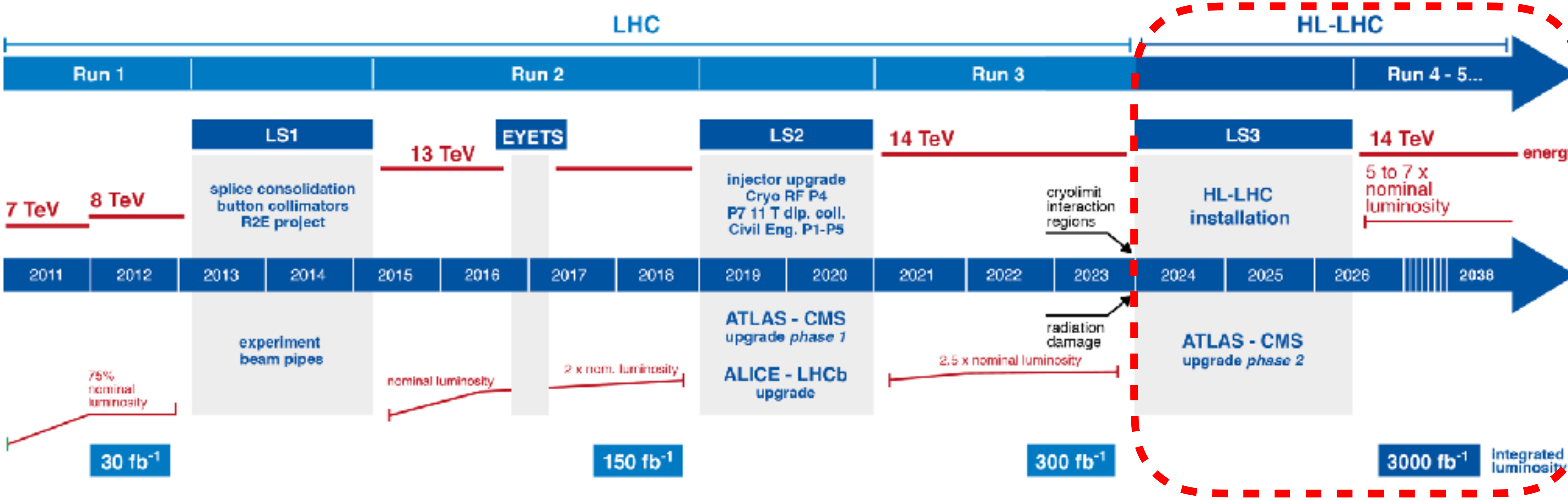
LHC / HL-LHC Plan





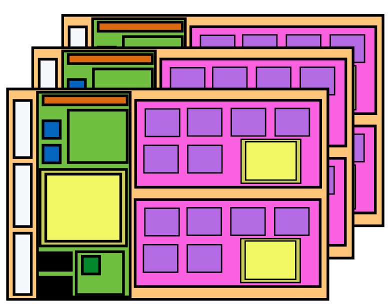
Typically limited to information from a single sub-detector (calorimeter, muons)

LHC / HL-LHC Plan



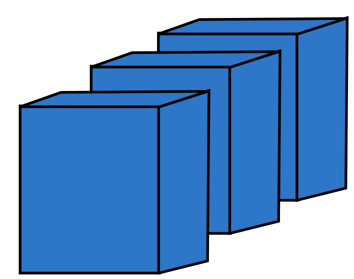
40 mhz
200 pp/event

L1



750 khz
(50x rej)

HLT

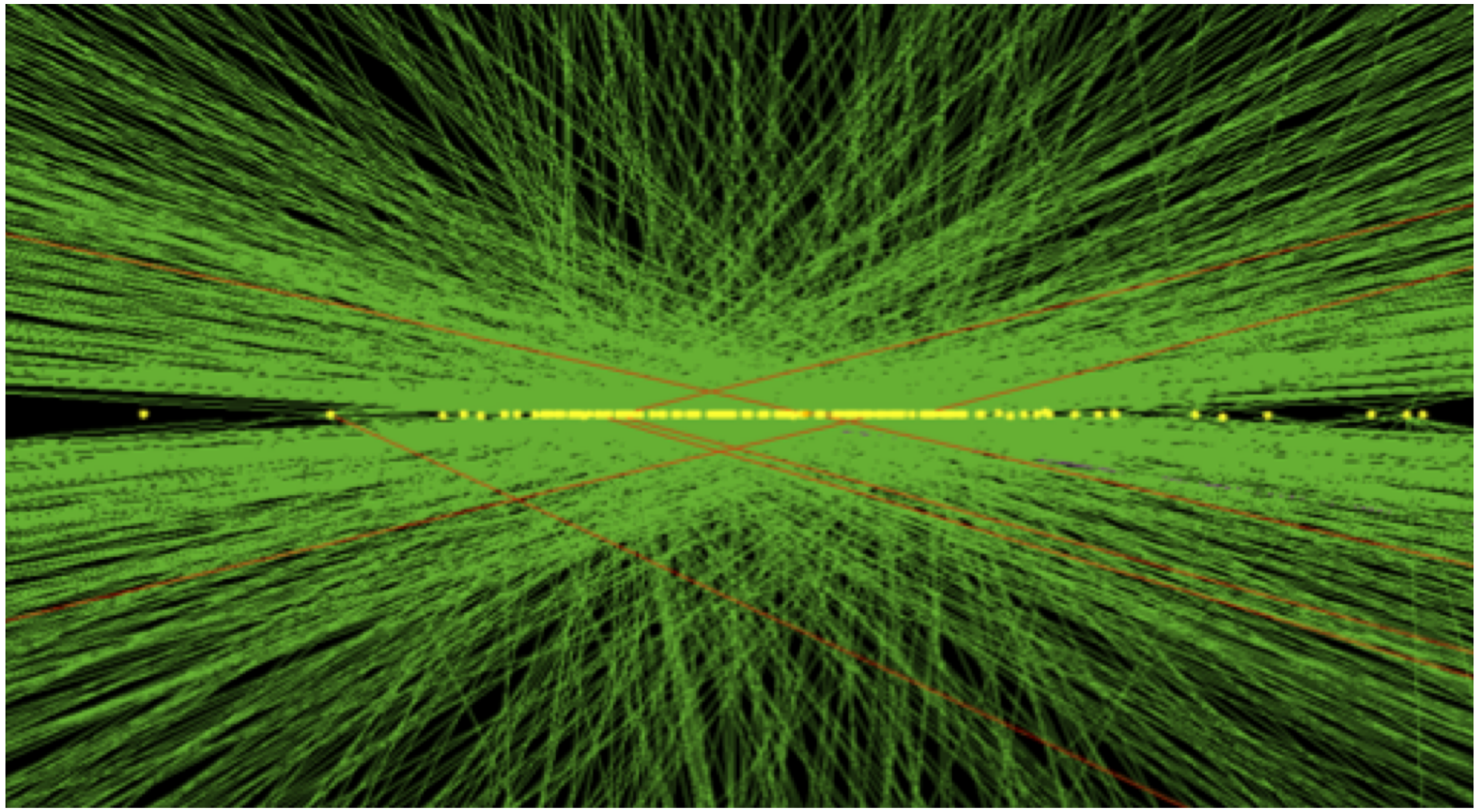


7.5 khz
(100x rej)

Naively scales with luminosity

Challenges to Phase-II L1 Trigger

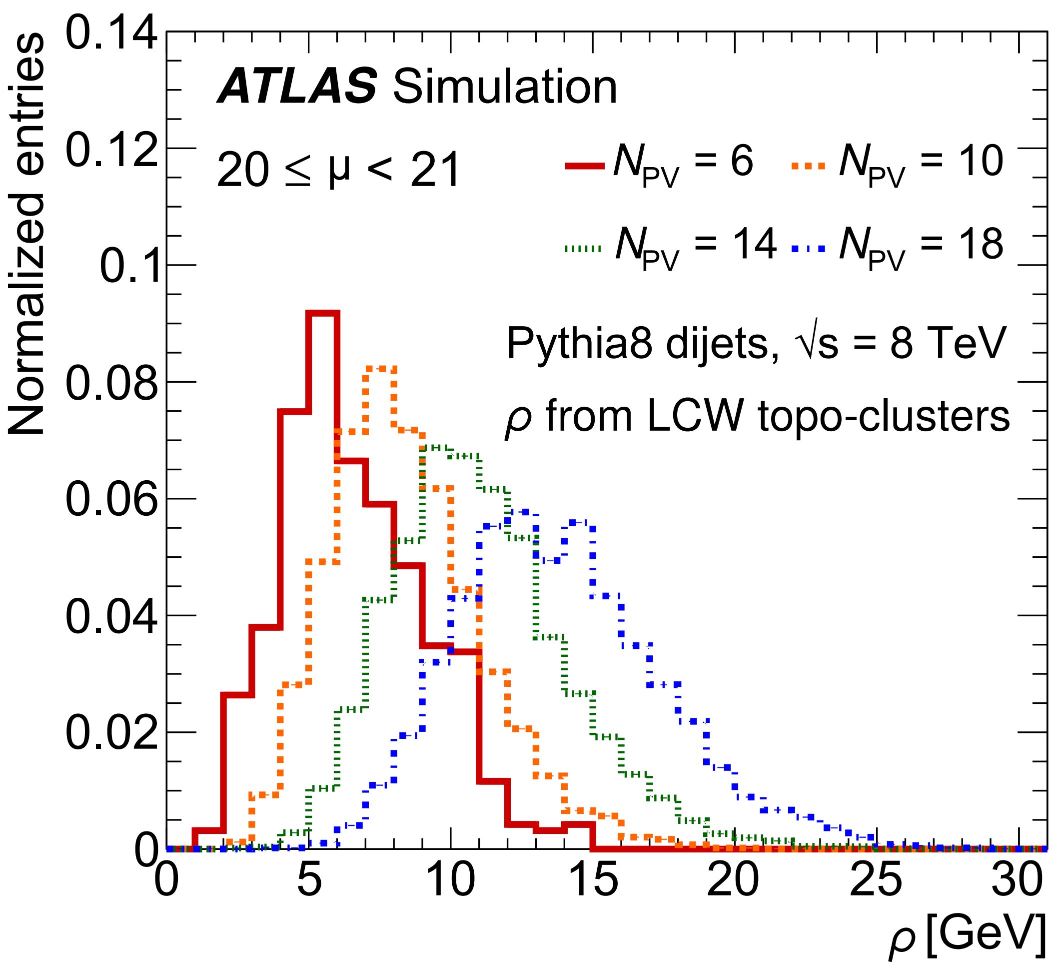
- L1 Accept rate scales ~ linearly with luminosity increase
  - Must maintain performance in hostile environment!



Challenges to Phase-II L1 Trigger

- L1 Accept rate scales ~ linearly with luminosity increase
  - Must maintain performance in hostile environment!

Take *hh* production in 4*b* (or *bb*ττ) decay mode



Higher pileup
→ Extra stochastic energy enters into the jet cone

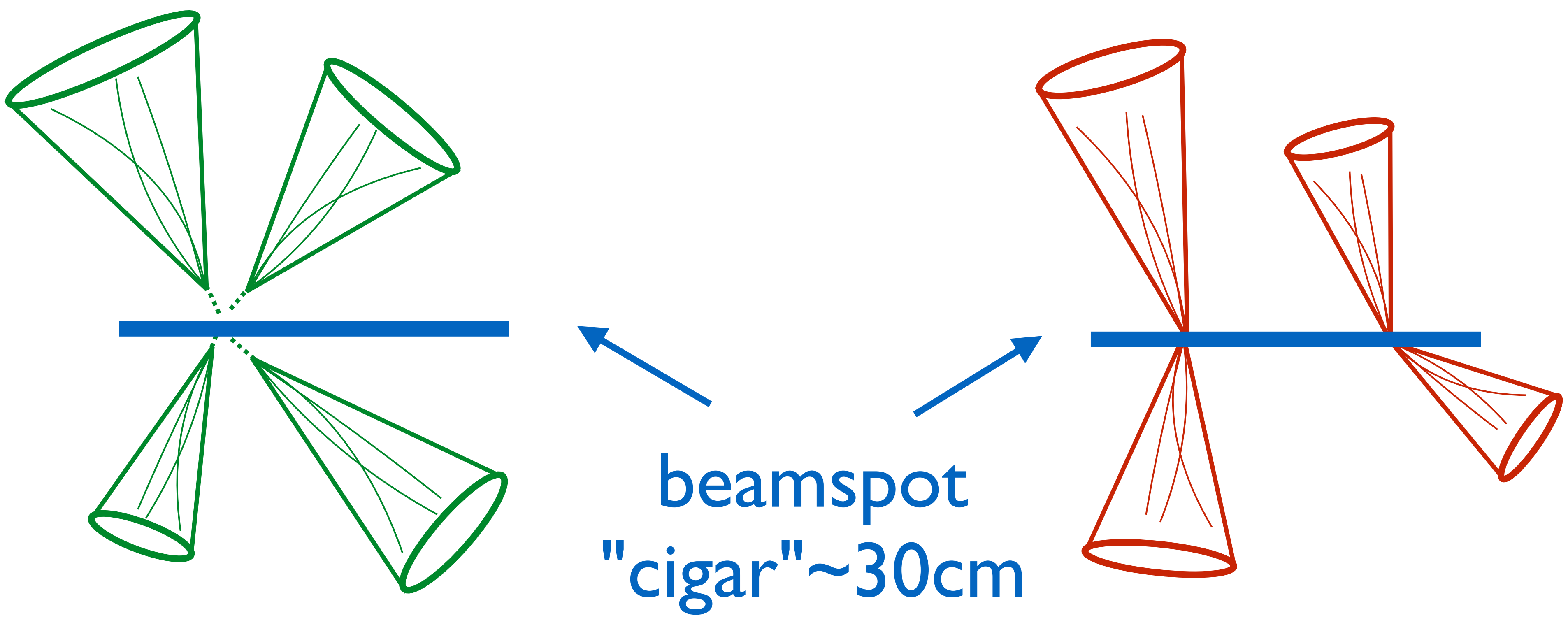
More low-p_T jets to "measure high" than vice versa
→ **Higher trigger rate**

Challenges to Phase-II L1 Trigger

- L1 Accept rate scales ~ linearly with luminosity increase
  - Must maintain performance in hostile environment!

It gets worse !!

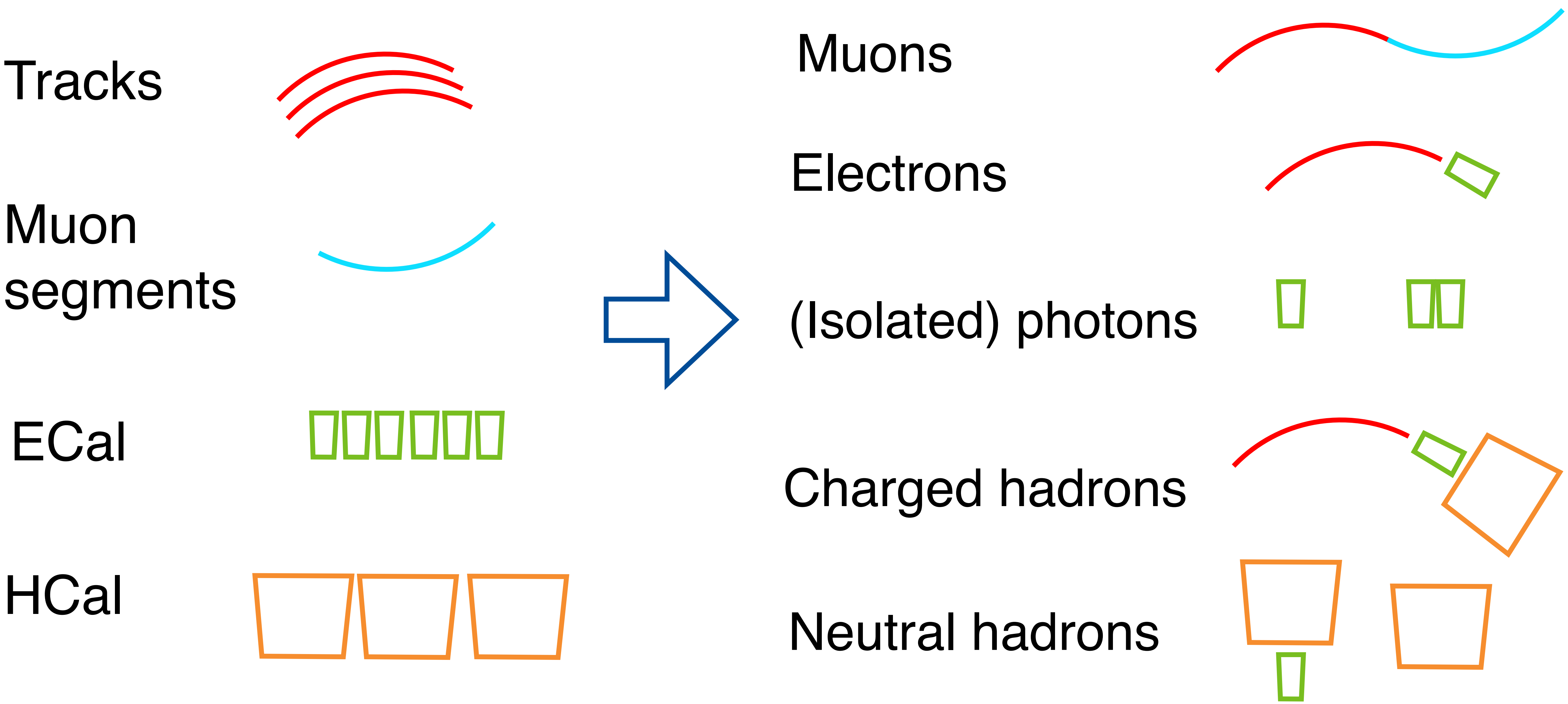
Background (uncorrelated coincidences) ~ $(\text{lumi})^2$



Not new problems, solved offline with Particle Flow Reco+

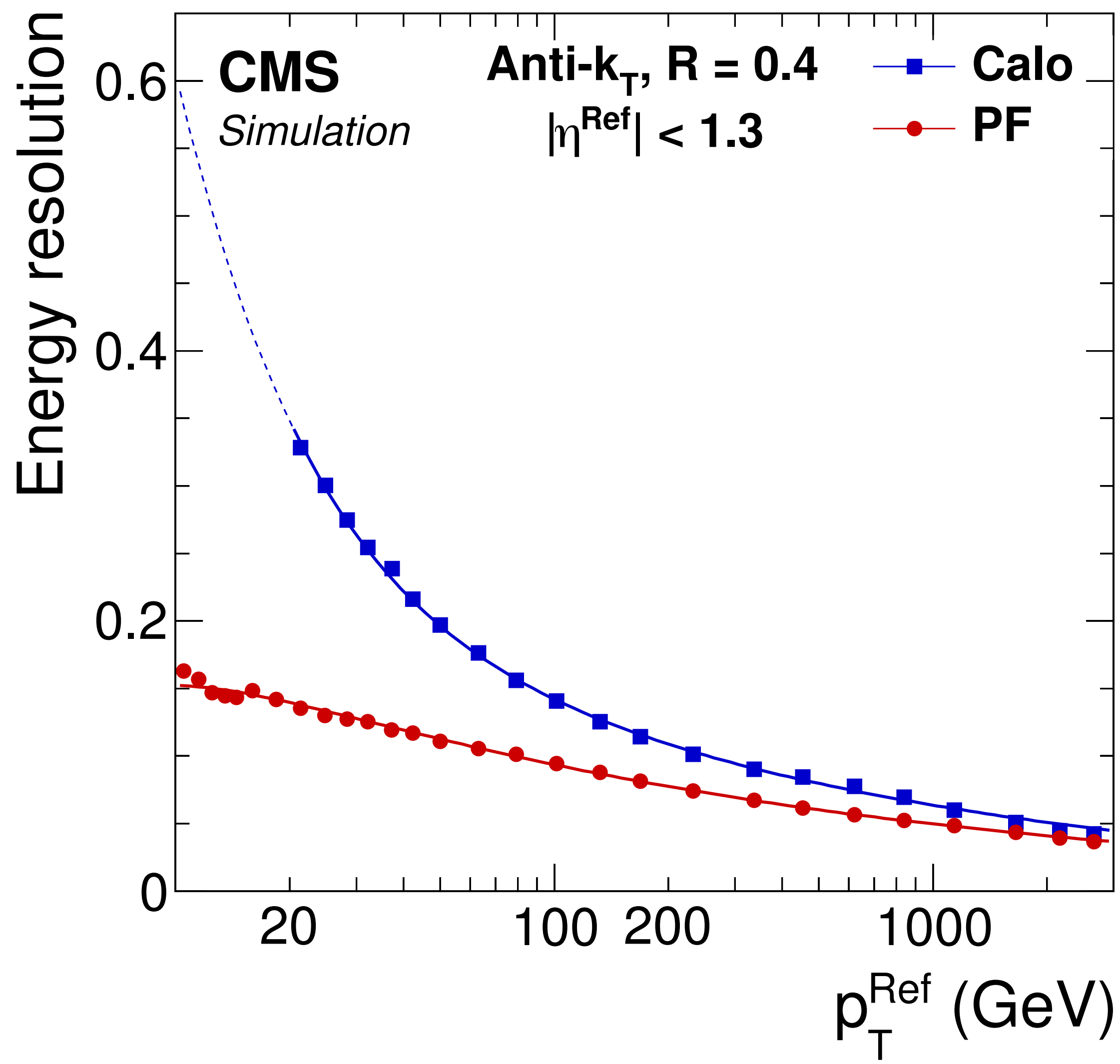
Particle Flow Reconstruction

- Idea: **combine measurements** across all sub-detectors to achieve **best possible resolution per object**
  - Algorithm returns a list of single-particle candidates

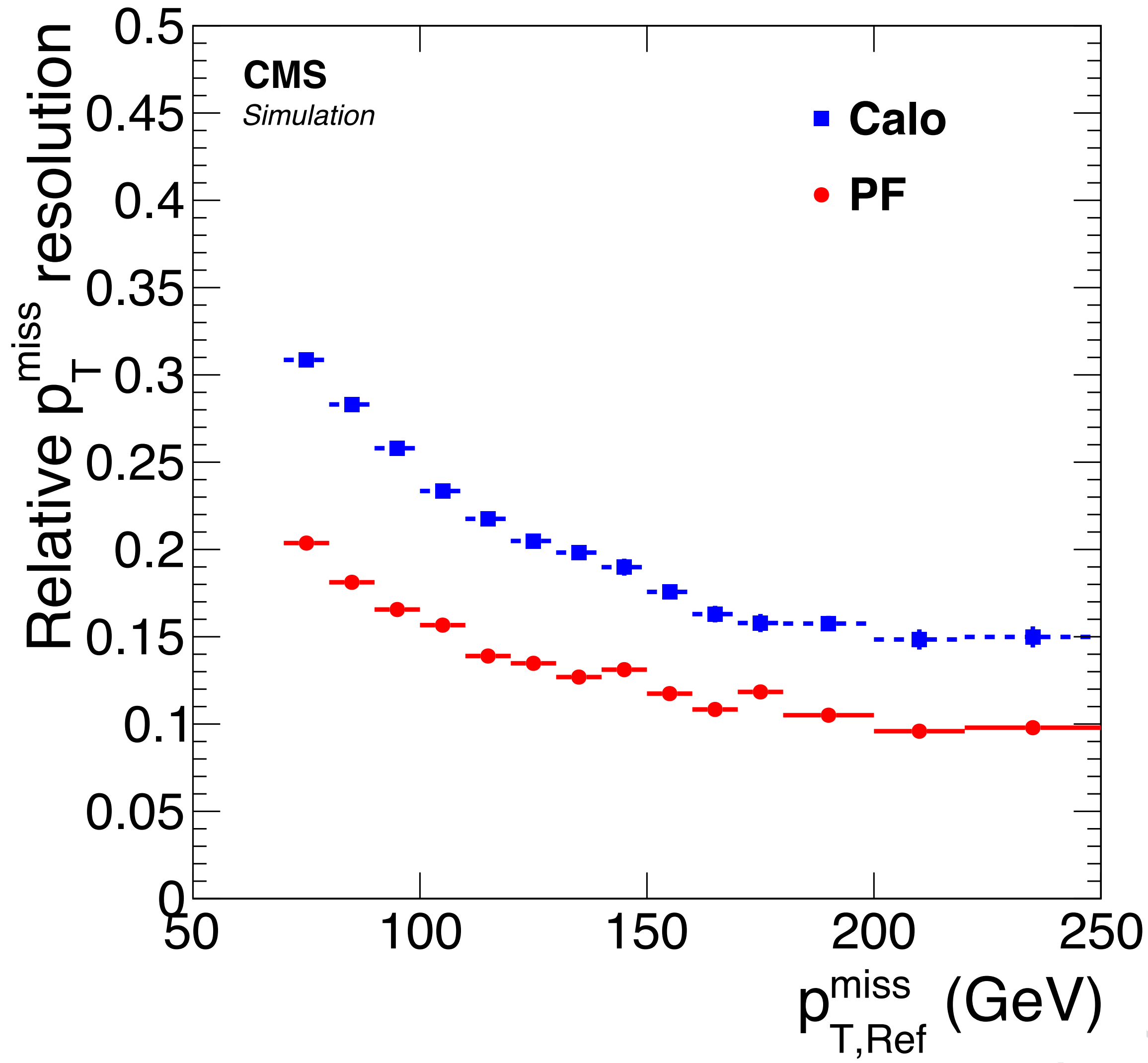


Particle Flow Reconstruction

- Idea: **combine measurements** across all sub-detectors



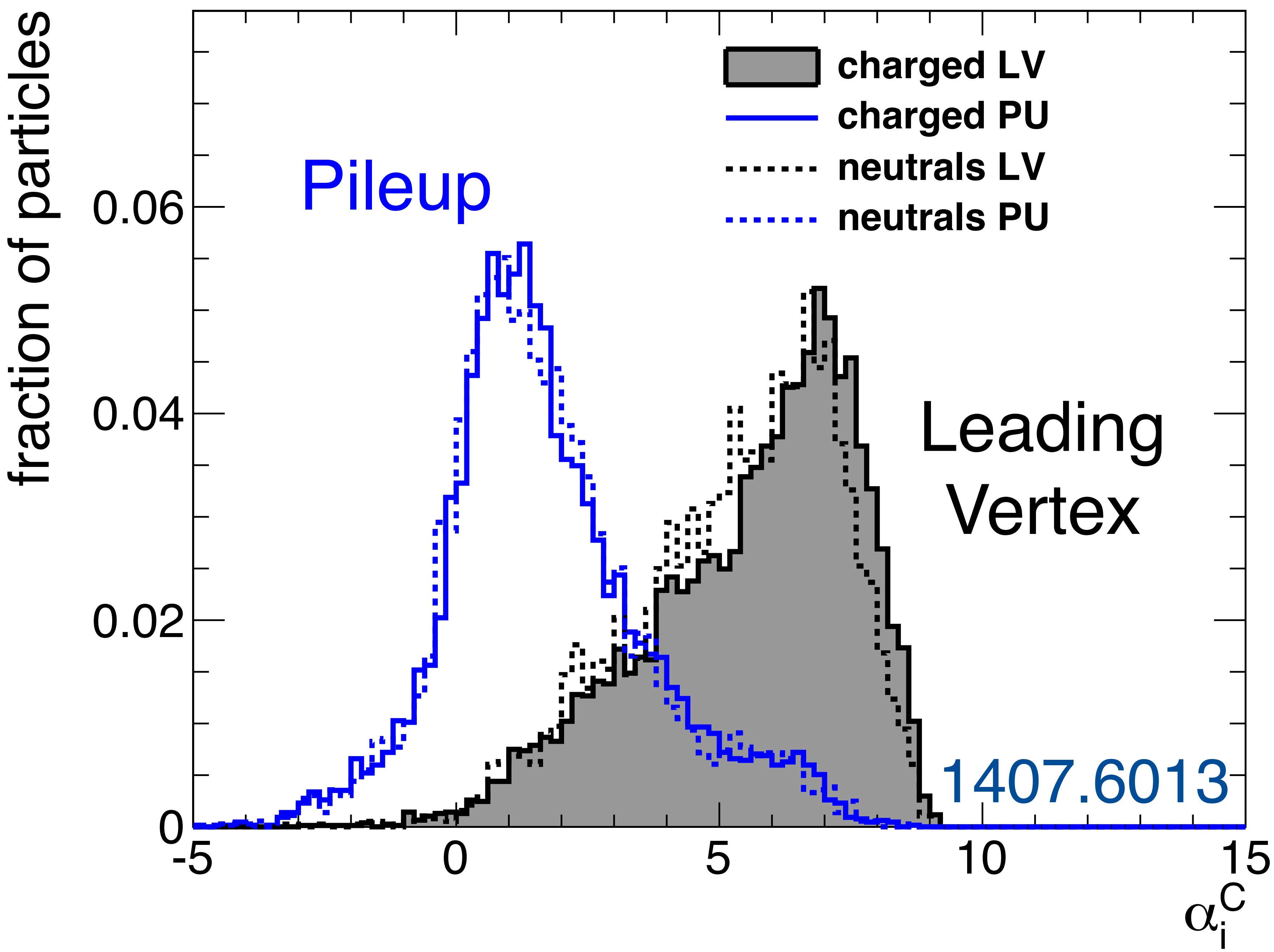
Improved Jet p_T resolution



Improved p_T-miss resolution

Pileup Per Particle Identification

- Idea: get probability that a neutral PF candidate is pileup based on local activity from the leading vertex



$$\alpha \sim \sum_{i \in \text{cone}} \frac{p_{\text{T},i}}{\Delta R_i}$$

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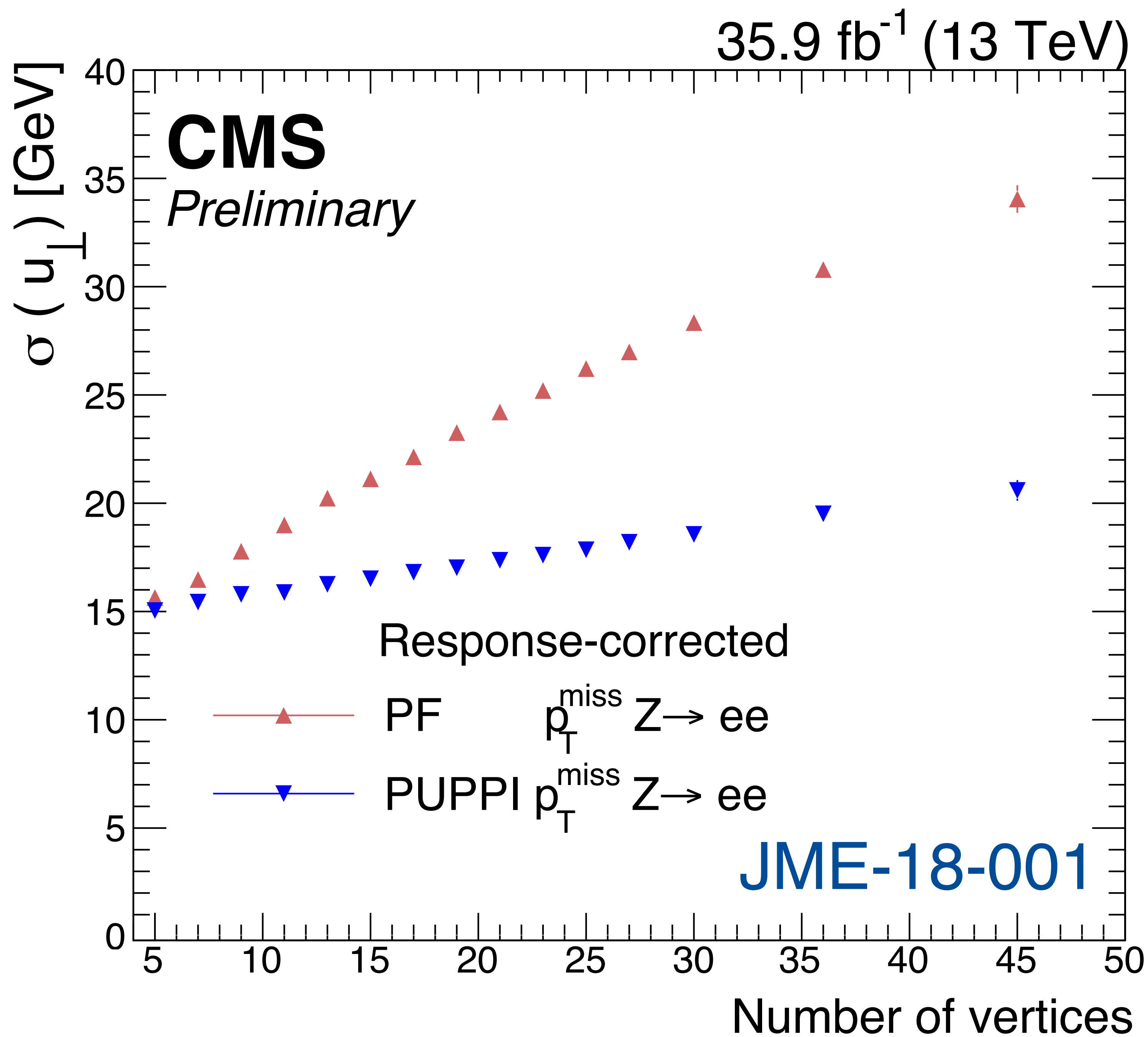
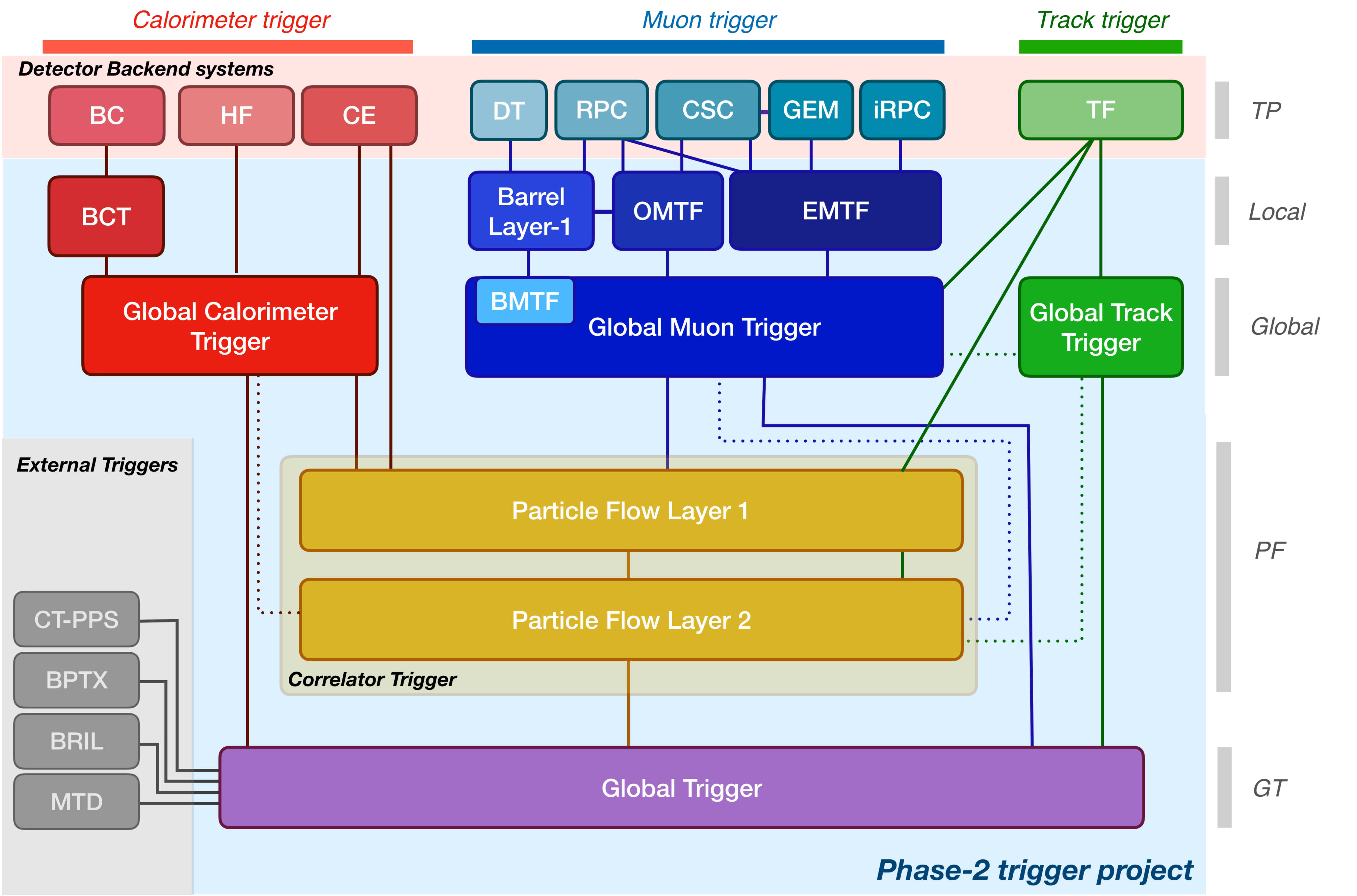
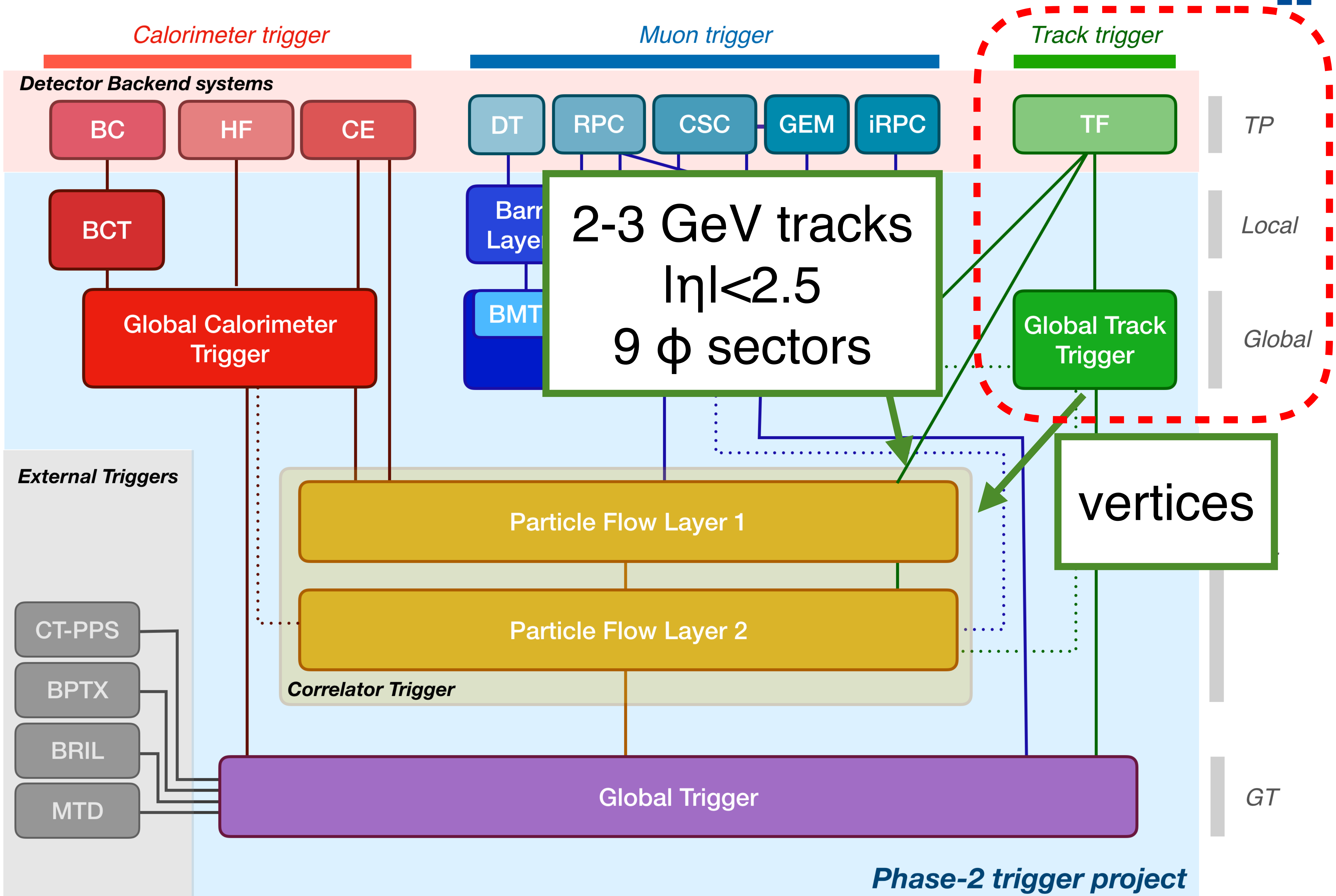


Improved p_T-miss resolution

Architecture of the Phase-II L1 Trigger



Architecture of the Phase-II L1 Trigger



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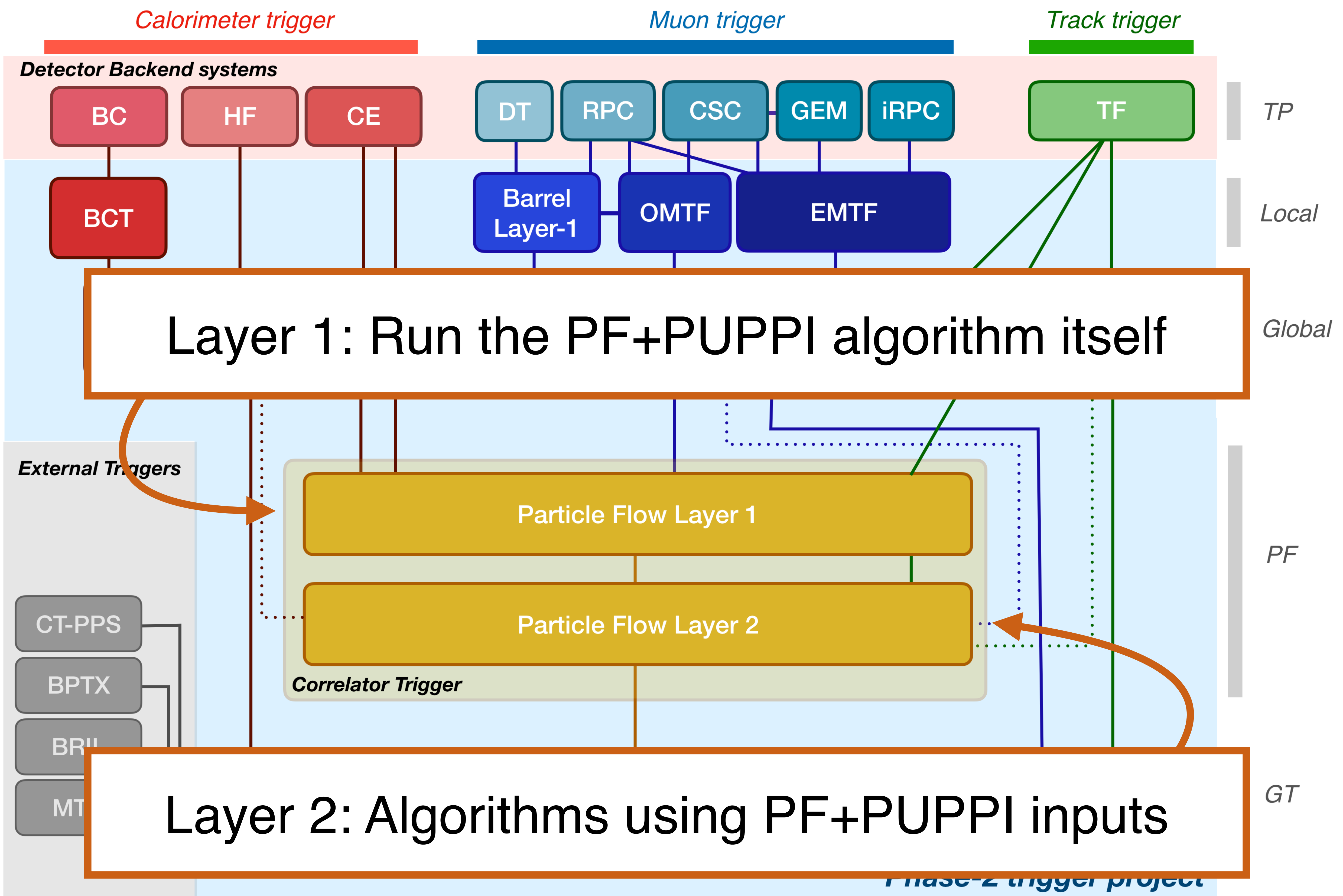


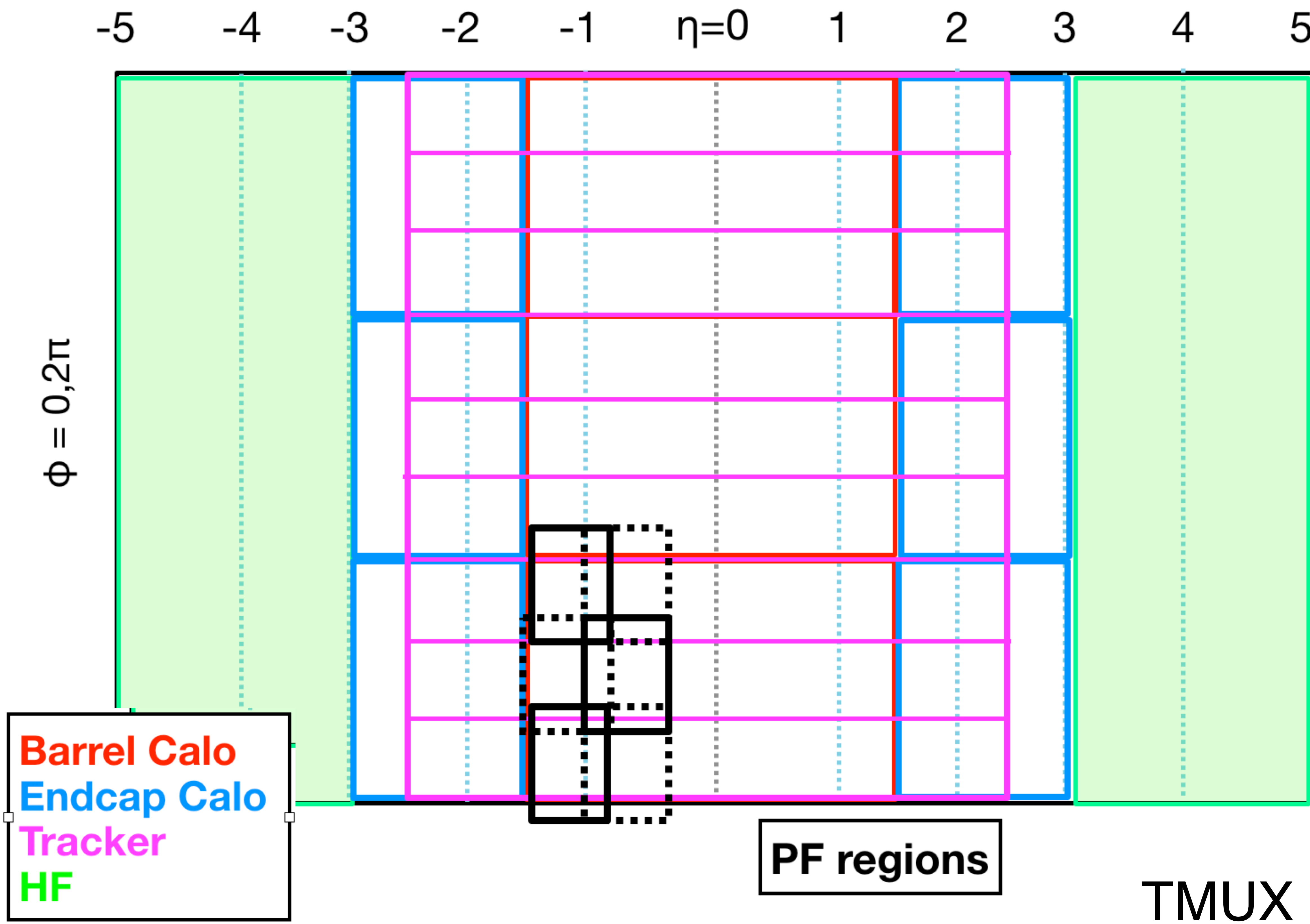
Strategy for L1 Implementation

- Take advantage of the **inherent locality** of PF+PUPPI
  - Distribute computation across many processing units

- Processing is divided into three main steps:
  - Regionalization (VHDL) **Layer 1**
  - PF+PUPPI calculation (High Level Synthesis C++)
  - Algorithms using PF+PUPPI inputs (HLS C++) **Layer 2**

- HLS: no expertise required!
  - Fast prototyping, debugging, comparison of alg variants

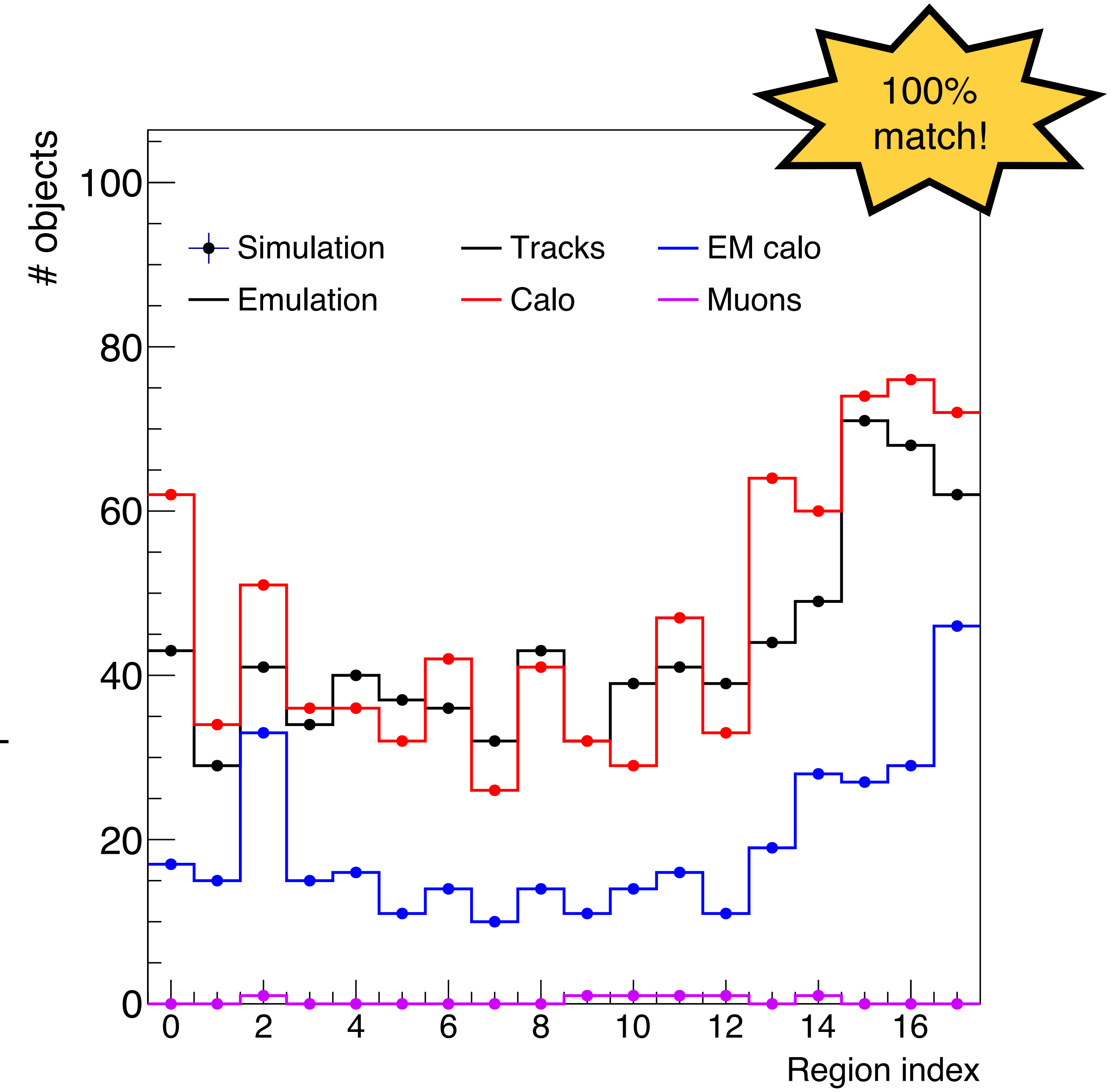
Inputs versus η, PF+PUPPI regions



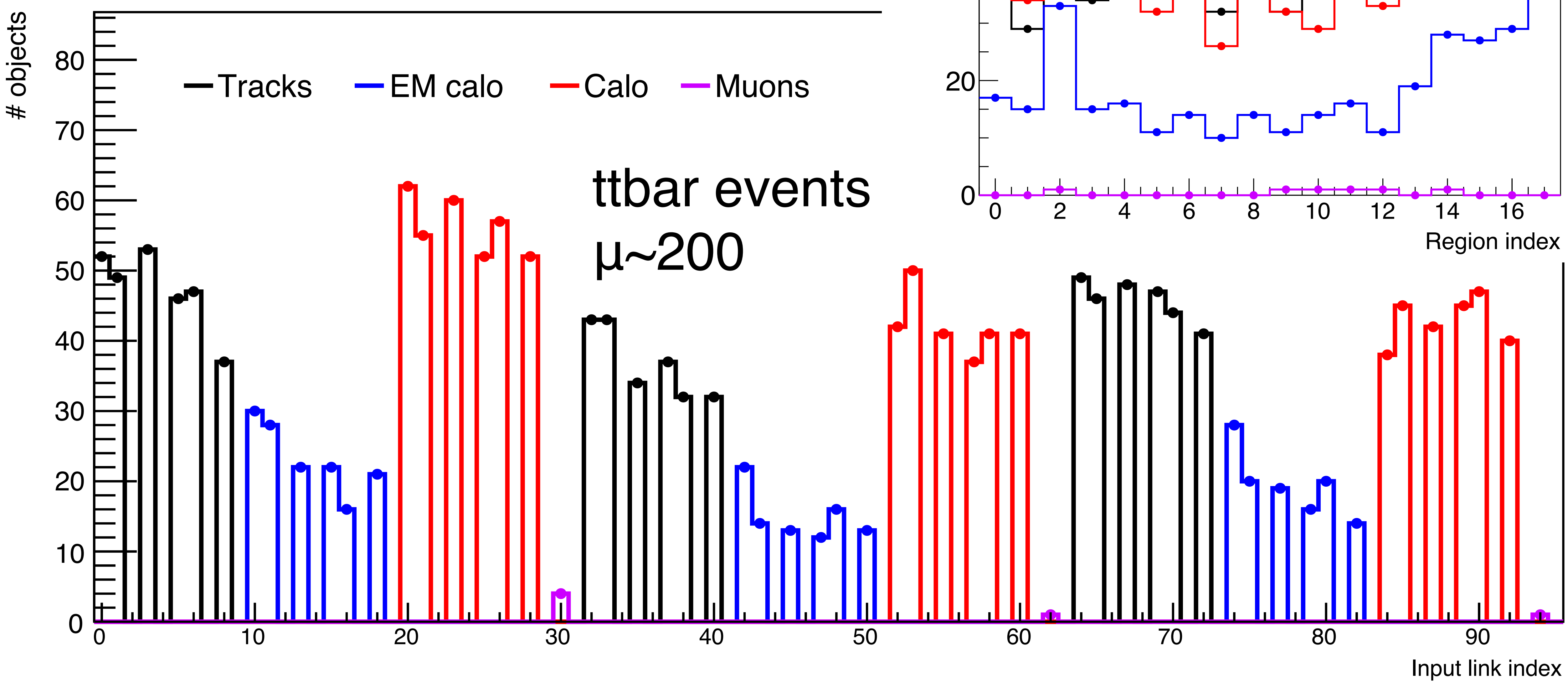
TMUX 18→6

Regionizer validation

VHDL algorithm validated with simulated data inputs

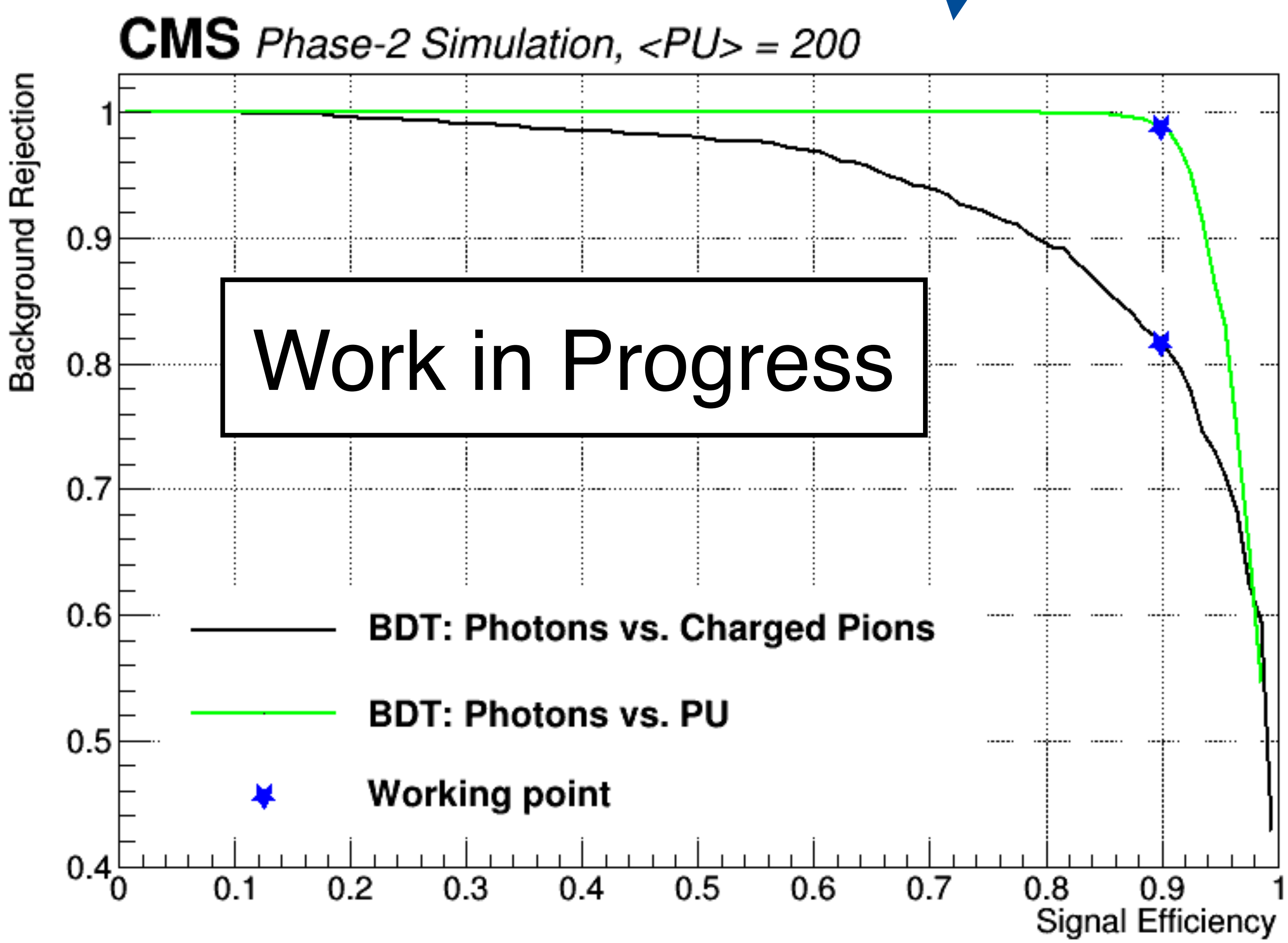


ttbar events
μ~200



HW Particle Flow + PUPPI

- Regionalization → small # of objects to link (truncation)
- Cluster input pre-processing: exploit shapes
- PUPPI 'linearized'; smaller cone size



- Classify cluster:
  - Hadronic or EM-like?
- Remove pileup deposits
  - Less work for PUPPI!

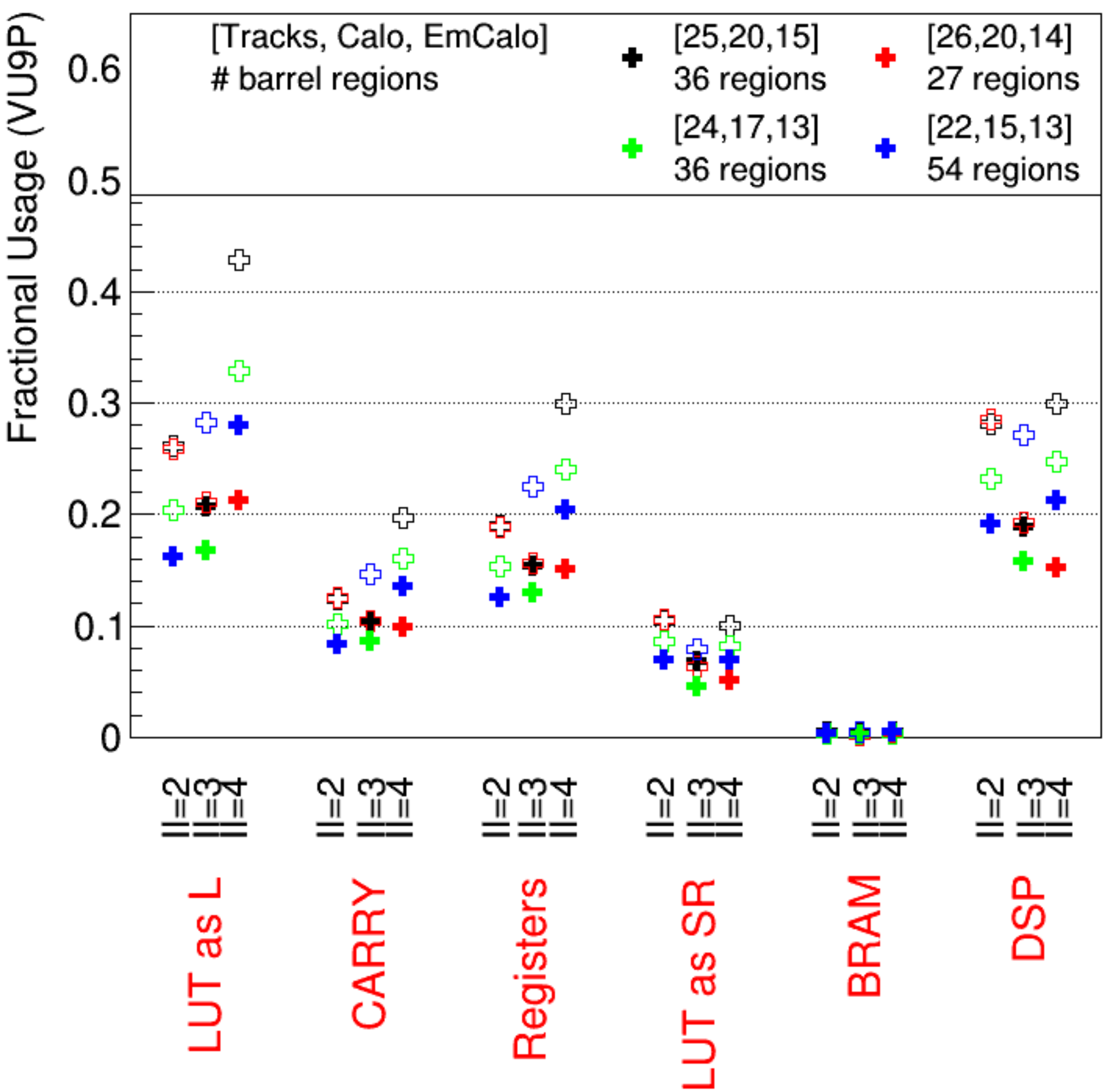
Resource drivers

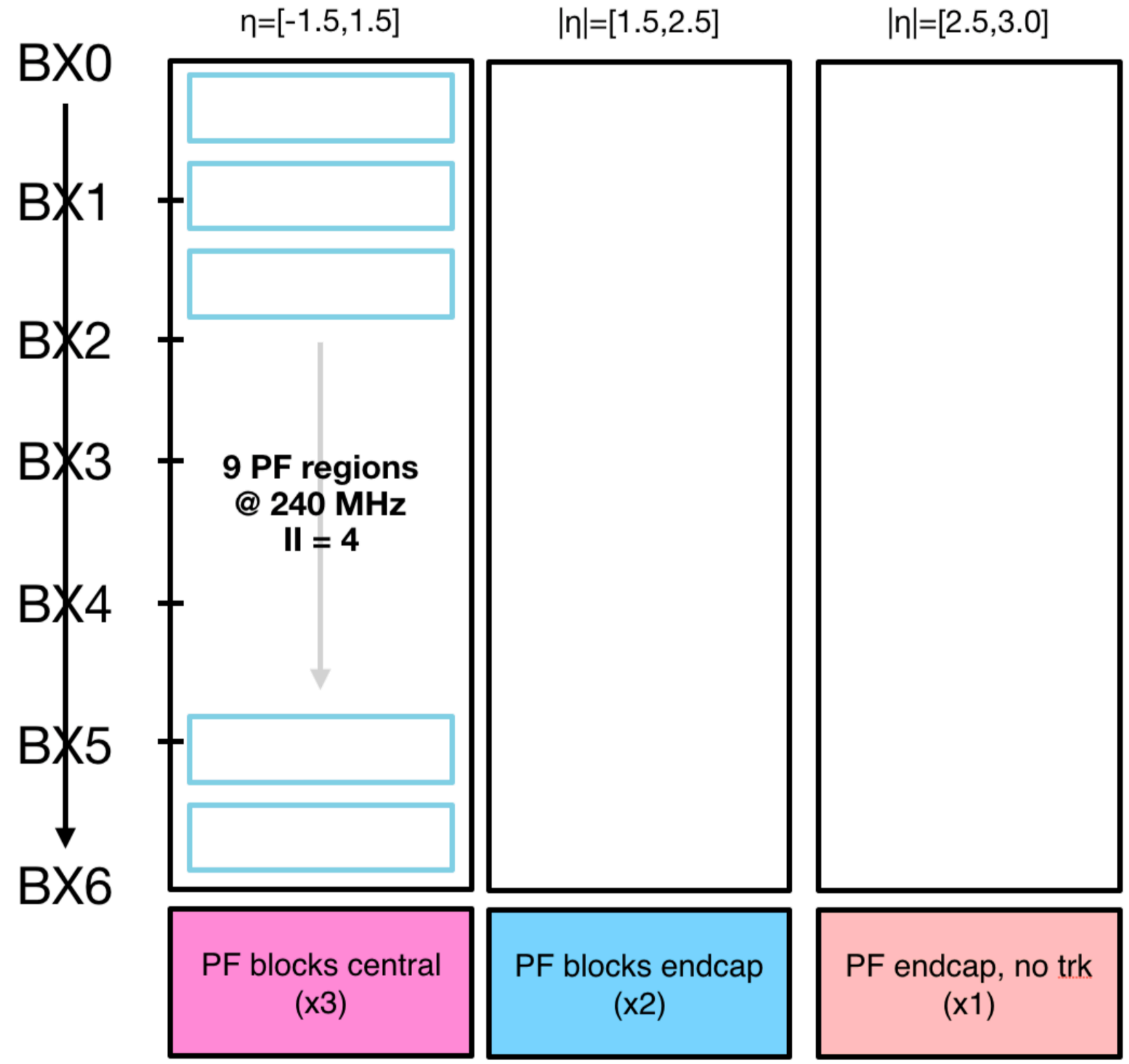
- Many ΔR calculations for track-calo linking drives DSP
  - Scales as (#tracks)*(#calo clusters)
- PUPPI weights drive BRAM usage
  - To compute $p_T/\Delta R$ quickly requires division tables
  - DSPs also used to map (p_T, ΔR) → PUPPI weights

Resource	LUT	FF	BRAM	DSP
Usage	528k	785k	871	1020
% VU9P	45%	33%	40%	15%

PF+PUPPI resources for 22 tracks, 15+13 calo clusters

Regionalization schemes



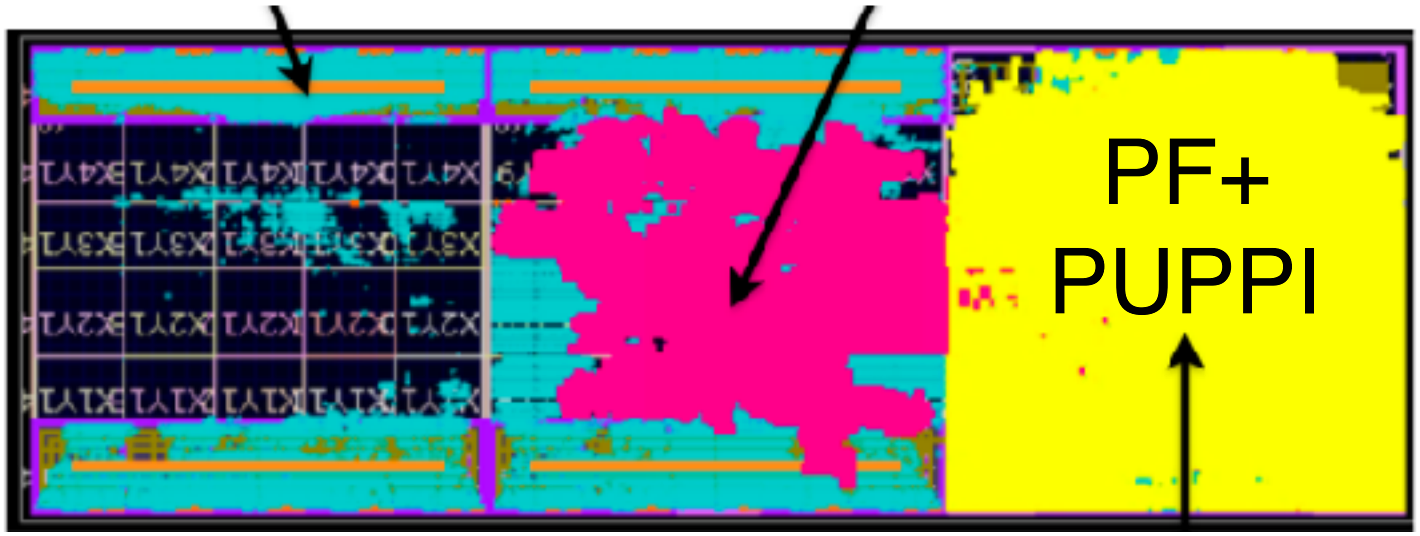


Resources vs. various initiation intervals and region sizes

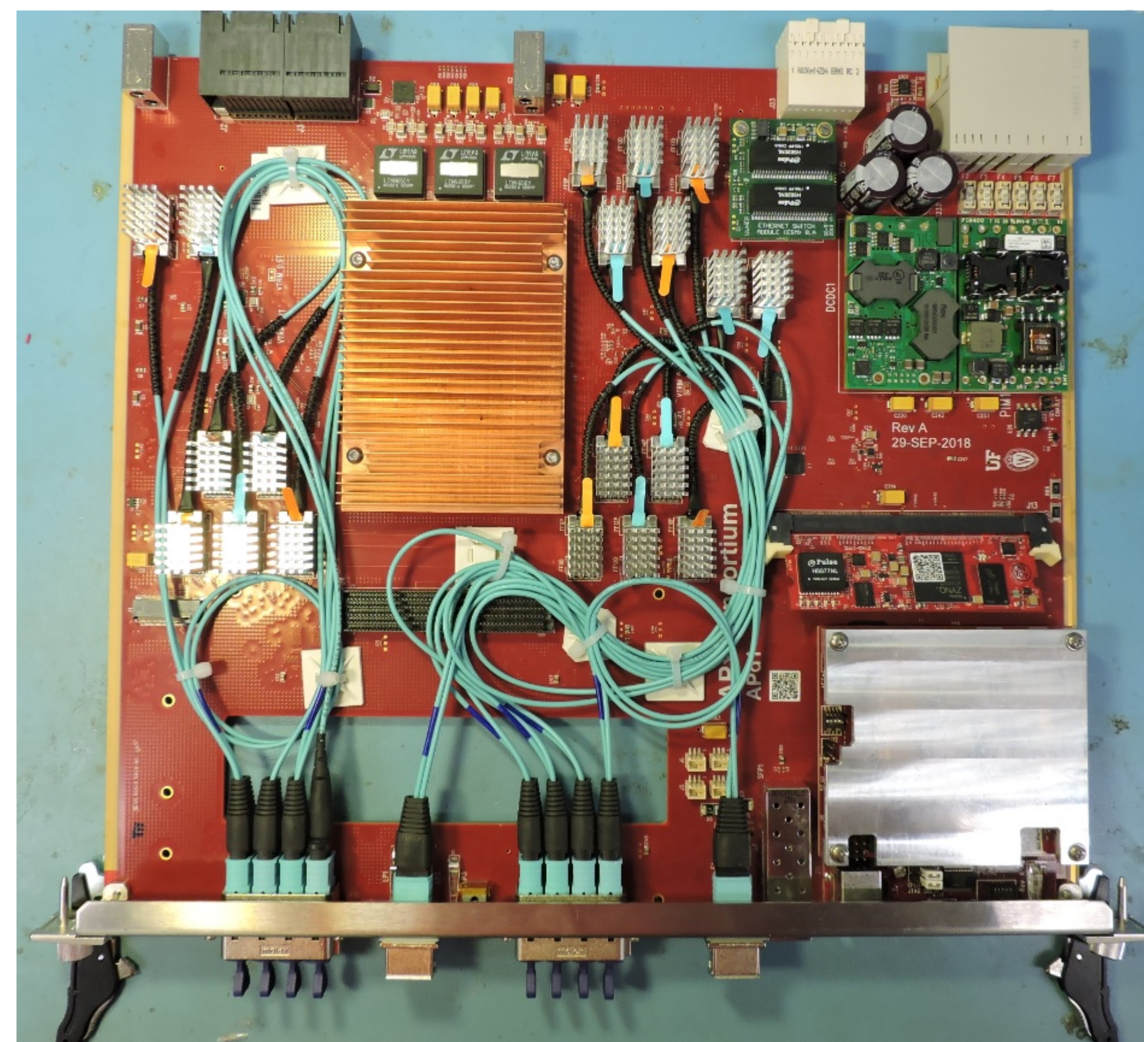
Hardware Prototype

Link infra

Regional sorting



Placed preliminary algorithm on VU9P



WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

UF
UNIVERSITY of FLORIDA

Fermilab

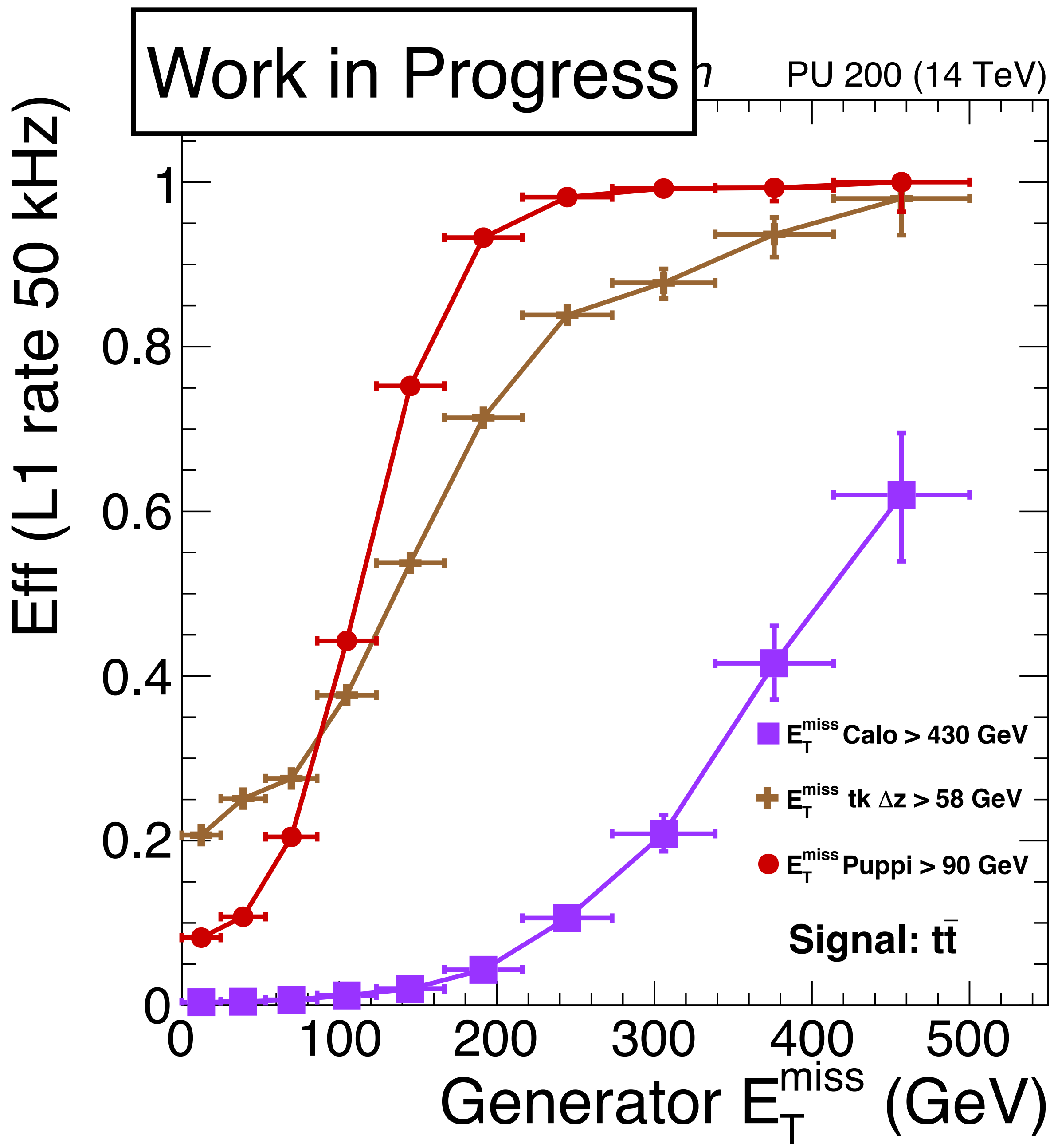
UNIVERSITY of VIRGINIA

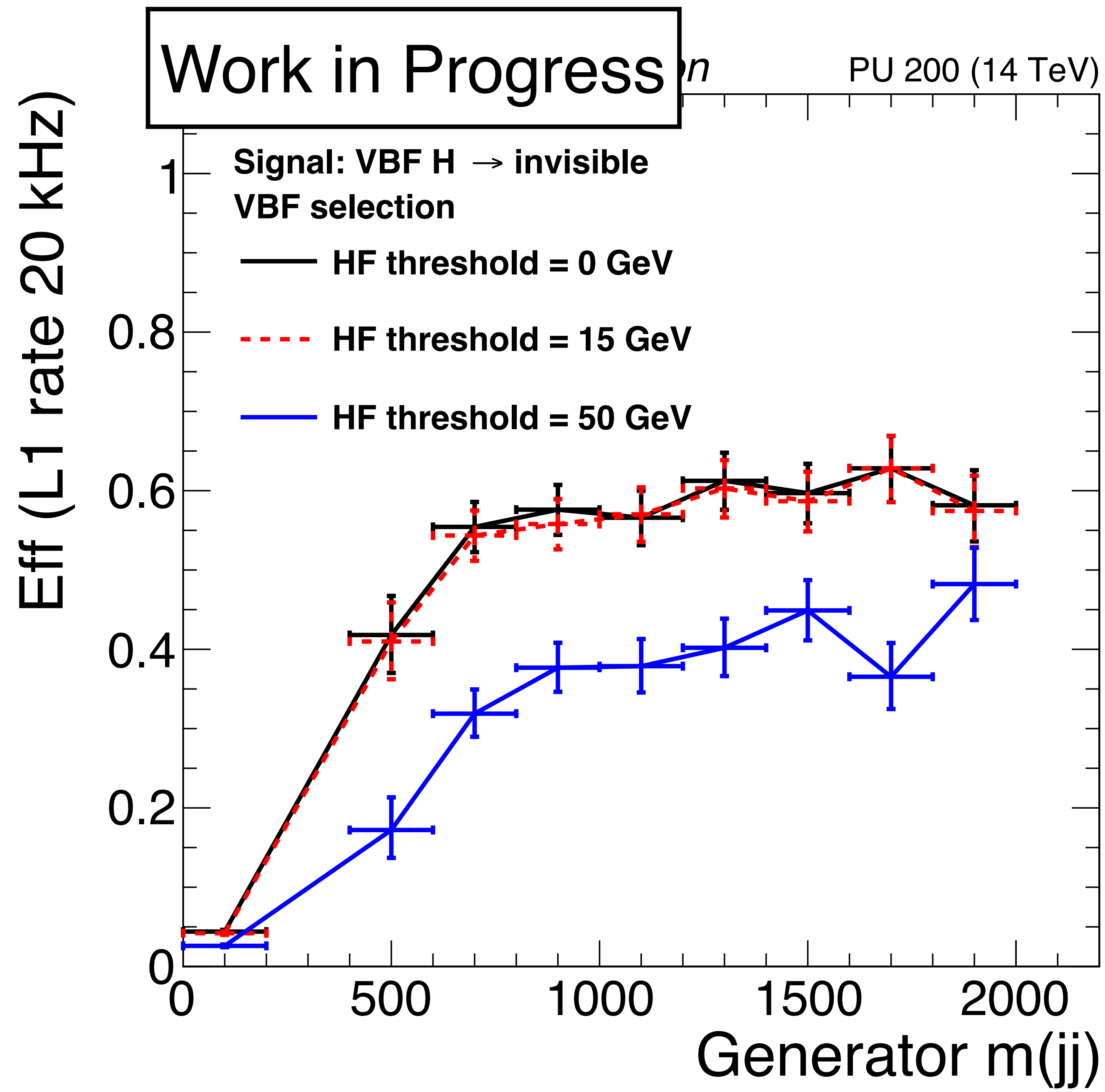
THE UNIVERSITY OF ILLINOIS AT CHICAGO

ATCA carrier card development lead by APx consortium

Layer 2 algorithms — Jets and MET

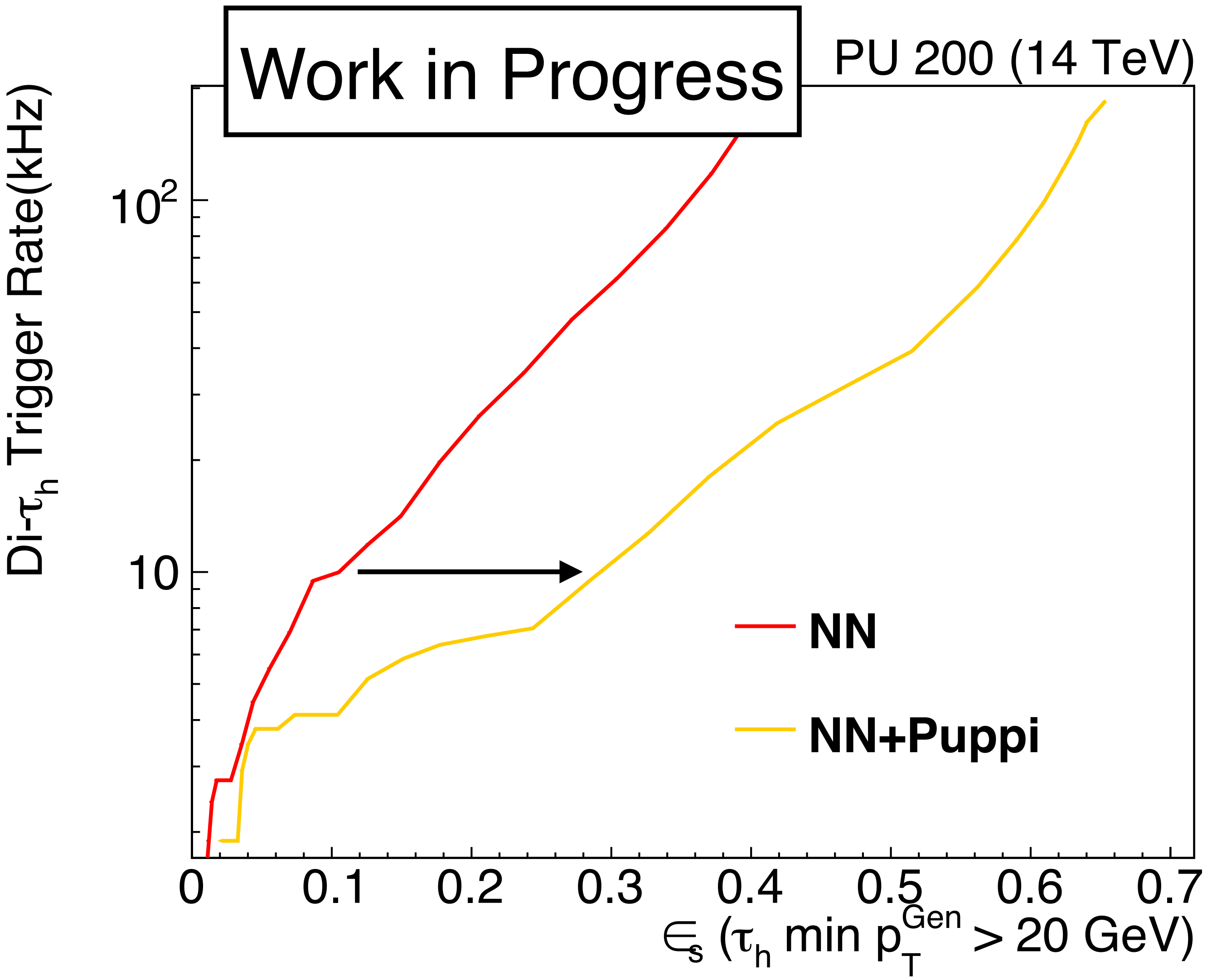
- Use PF+PUPPI candidates to build jets, energy sums





Layer 2 algorithms — Tau ID NN

- Identify hadronic tau decays using PF+PUPPI candidates



- Inputs: 10 nearby PF candidates (p_T,η,ϕ,id)
- Dense w/ 3 hidden layers (25,25,10) → 1 MVA ID
- This implementation:
  - Up to 18 PF+PUPPI candidates / event

LUT	FF	DSP	Latency
90k	150k	1400	210ns
7%	6%	20%	

A proof-of-principle prototype
Developed using hls4ml

Layer 2 algorithms — Tau ID NN

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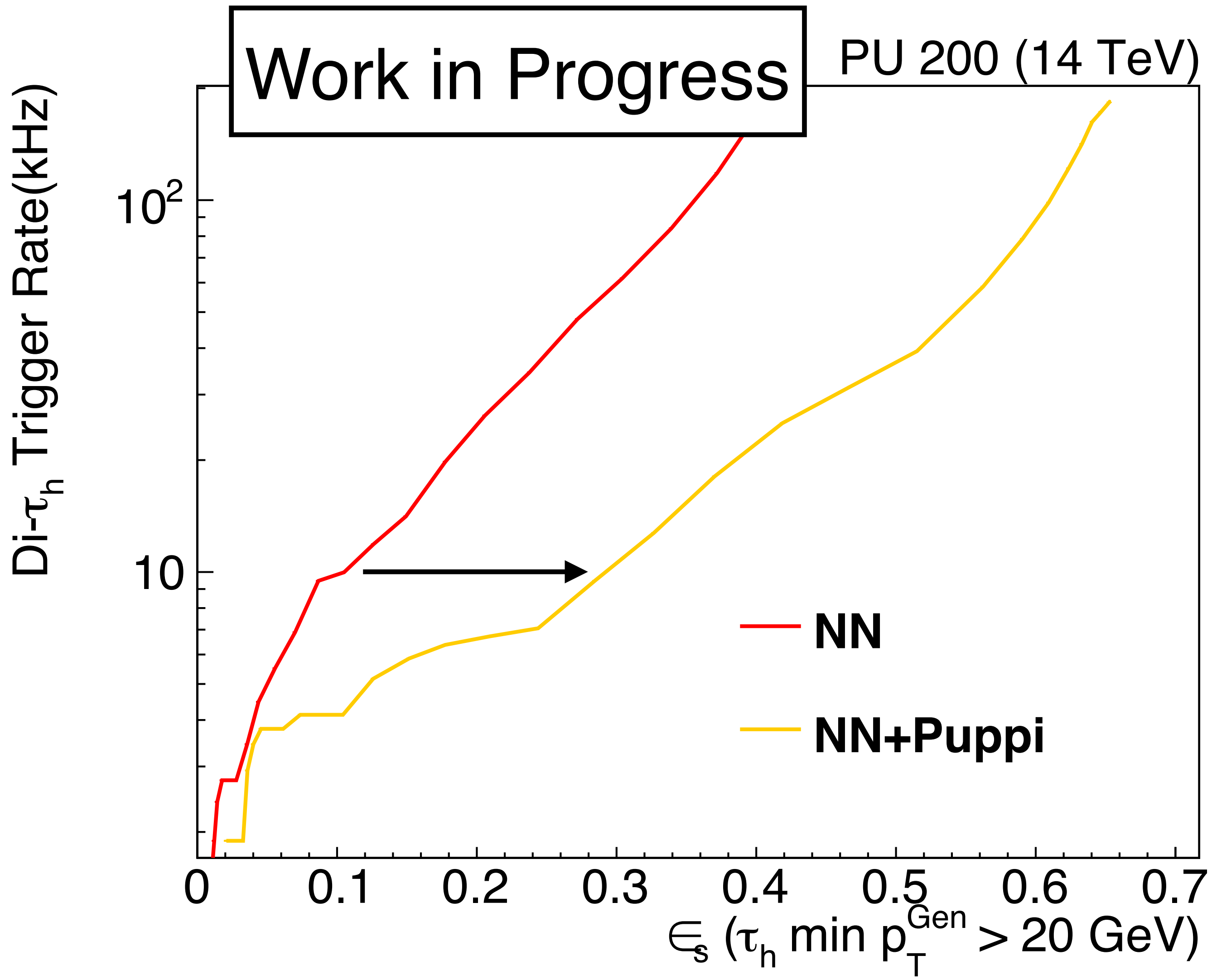

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-

See hls4ml talk / Sergo
+ L1 Muon / Jia Fu
+ ML trigger / Zhenbin

A proof-of-principle prototype
Developed using hls4ml

Conclusion

- The Level-1 Particle Flow Trigger is an ambitious addition to the Phase-II upgrade
- Correlation of all major sub-detectors allows unprecedented event reconstruction at 40mhz
- Capability promises to significantly enhance CMS sensitivity to interesting weak-scale physics

Backup

Particle Flow Reconstruction

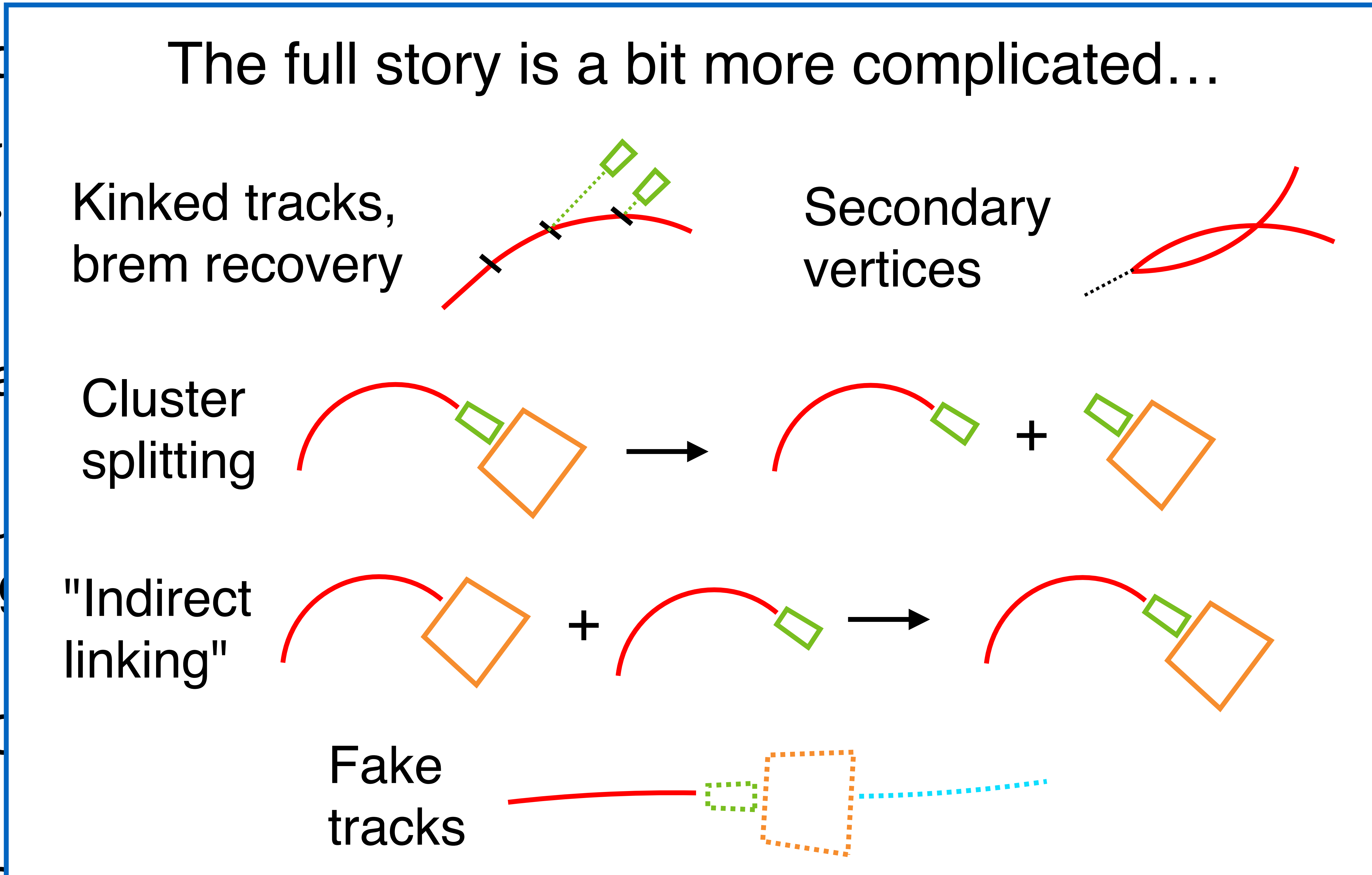
• Id ... to
a
•

Tra

Mu
seg

EC

HCal



Neutral hadrons

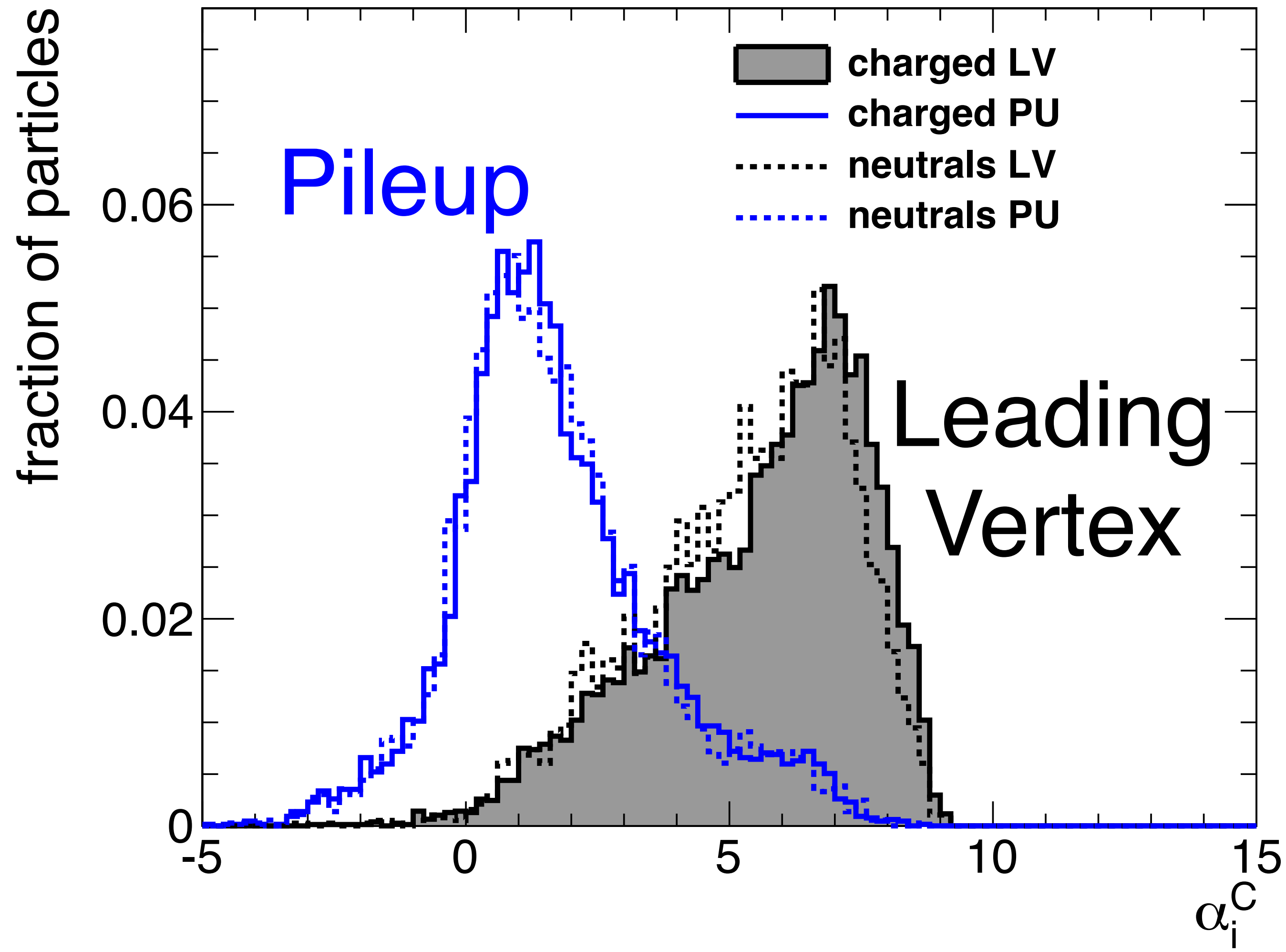
Pileup Per Particle Identification

- Idea: assign a probability that a neutral PF candidate is pileup based on local activity from the leading vertex
  - Discriminant favor nearby, high-p_T particles (in cone)
    - QCD is collinear, while pileup is diffuse

$$\alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < R_0} \left(\frac{p_{Tj}}{\Delta R_{ij}} \right)^2$$

sum over nearby charged particles

$$\Delta R_{ij}^2 = \Delta\eta_{ij}^2 + \Delta\phi_{ij}^2$$



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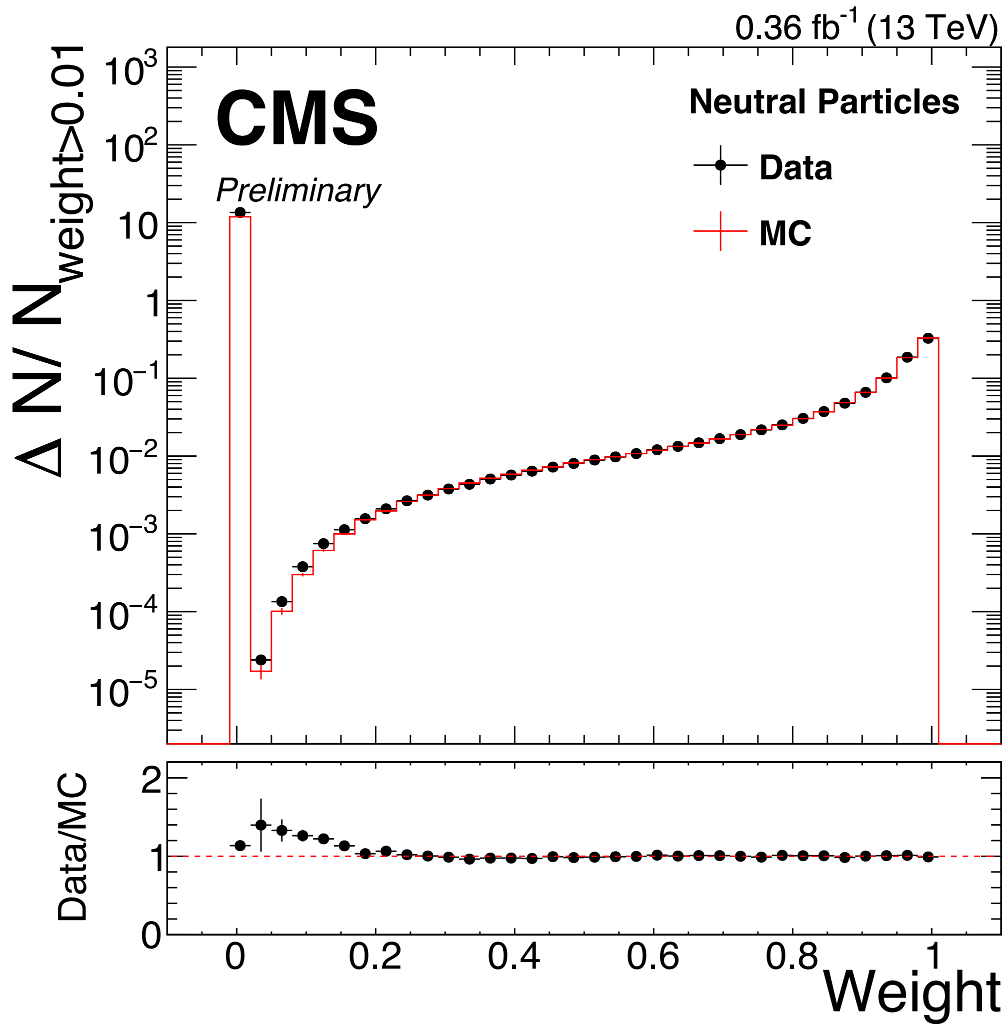
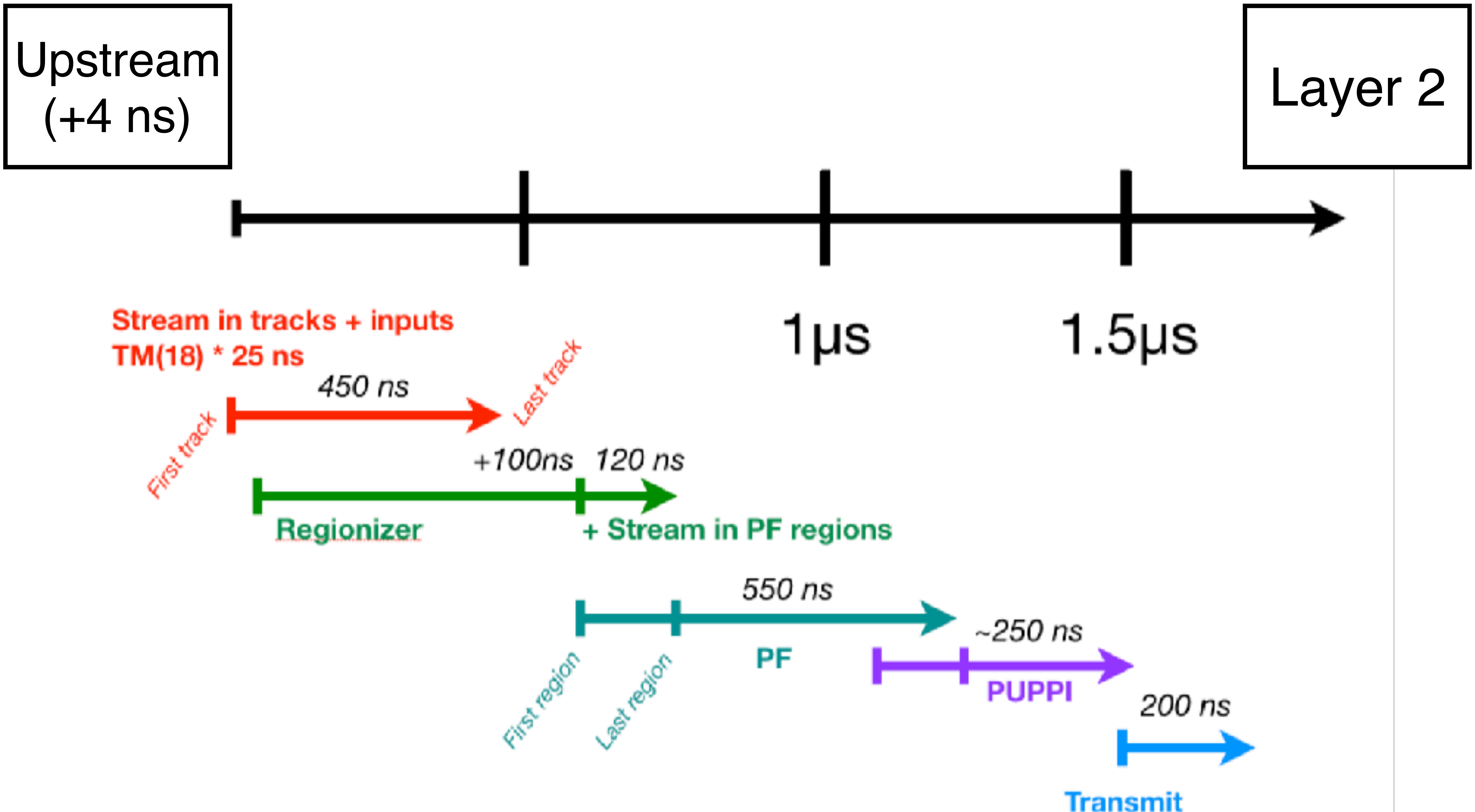


Compare α w/ expected distribution, given the level of pileup (chi2 test)

← obtain weights!

Re-scale 4-vectors:
50 GeV particle w/ 0.4 PUPPI weight considered as a 20 GeV particle

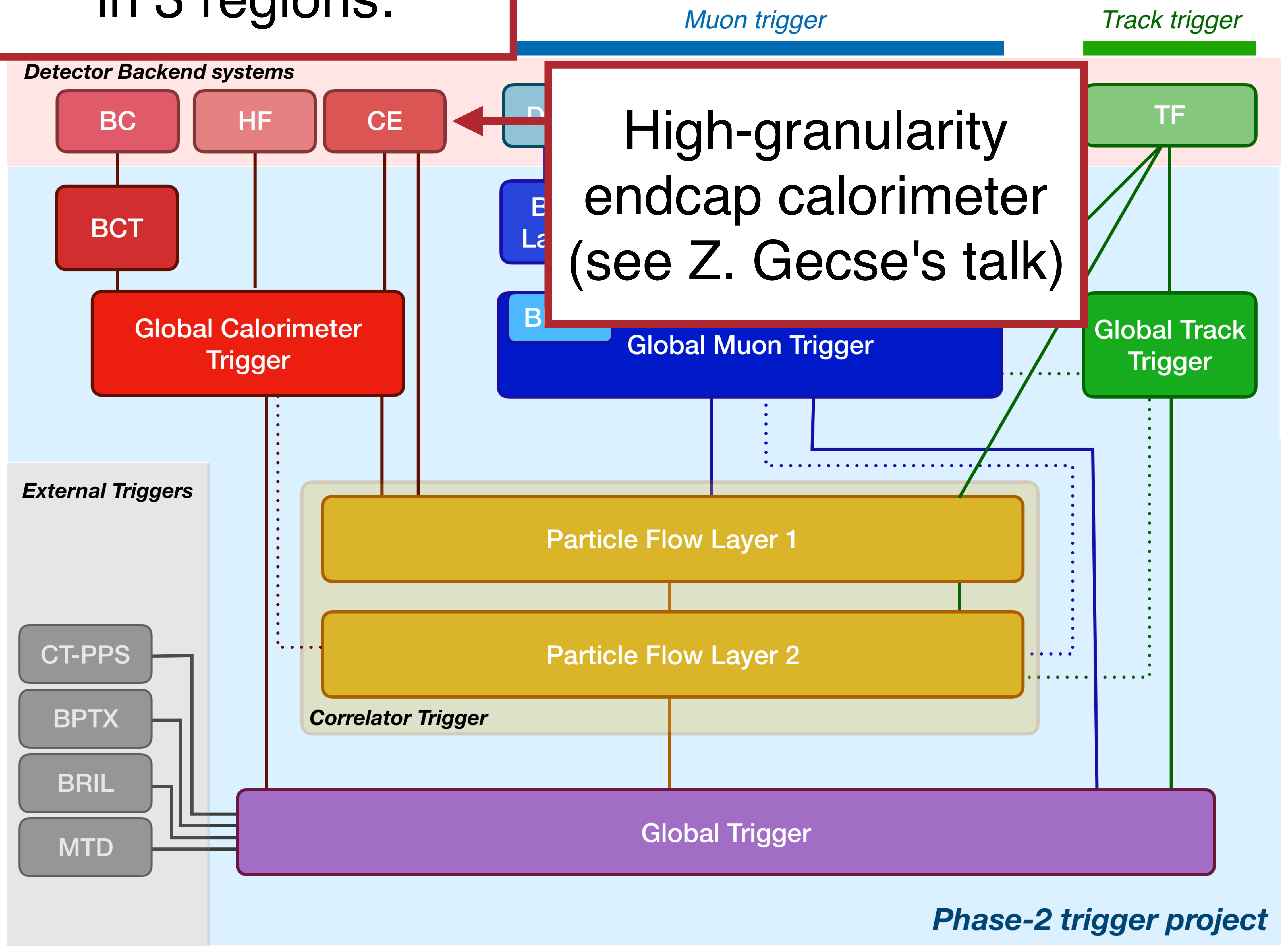
Latency budget



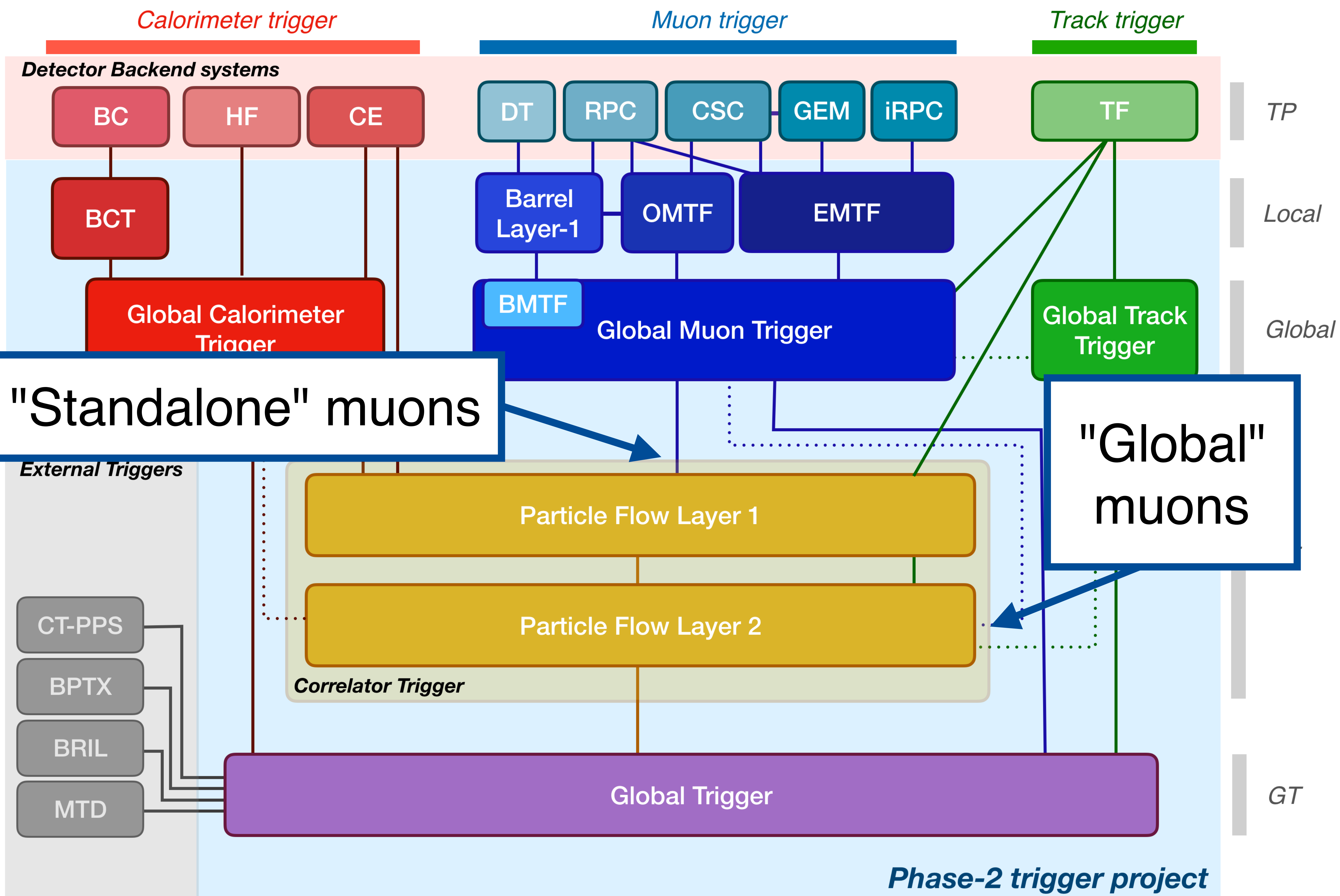
the Phase-II L1 Trigger

Calorimeter clusters in 3 regions:

High-granularity endcap calorimeter (see Z. Gecse's talk)



Architecture of the Phase-II L1 Trigger



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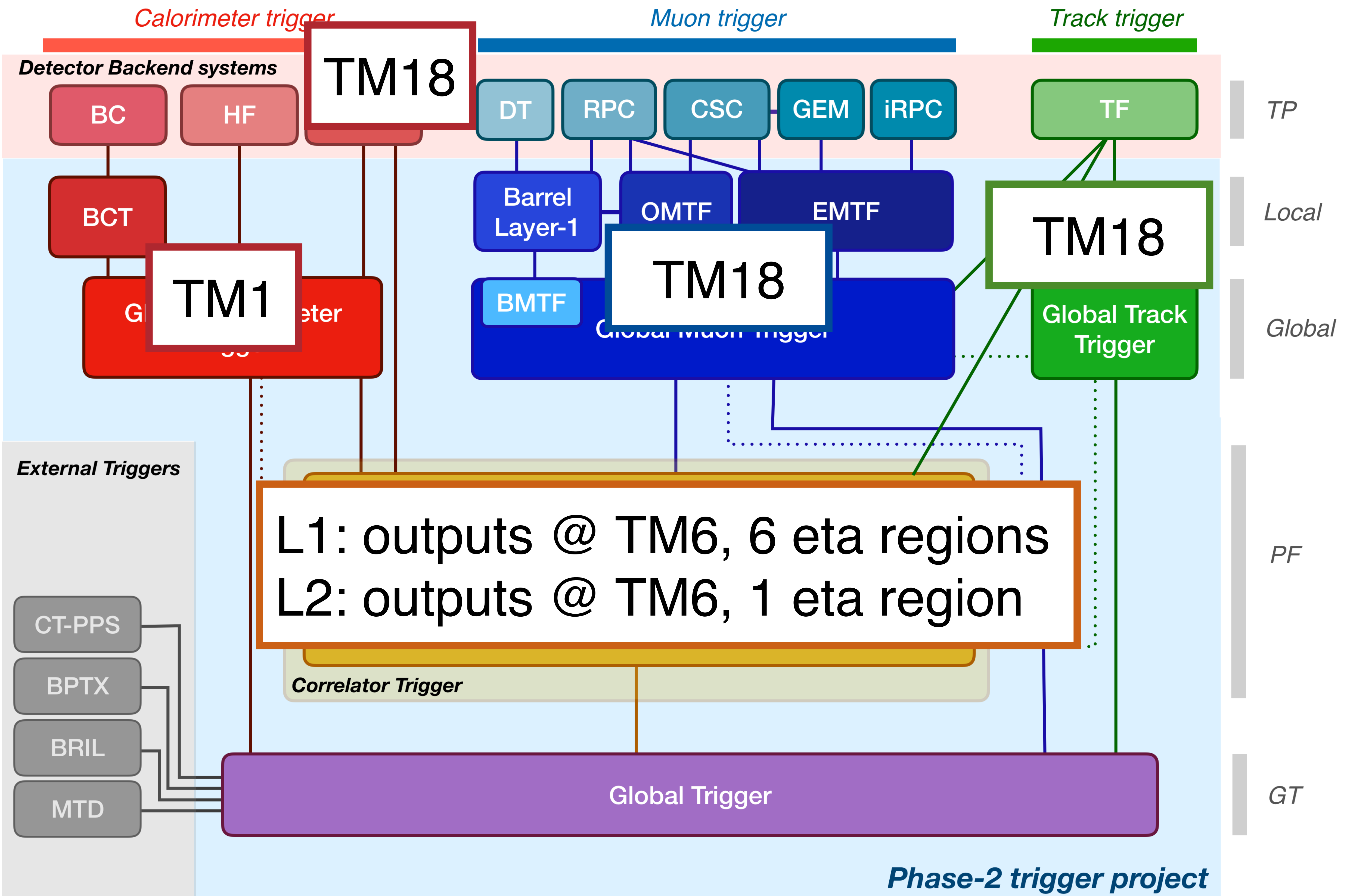
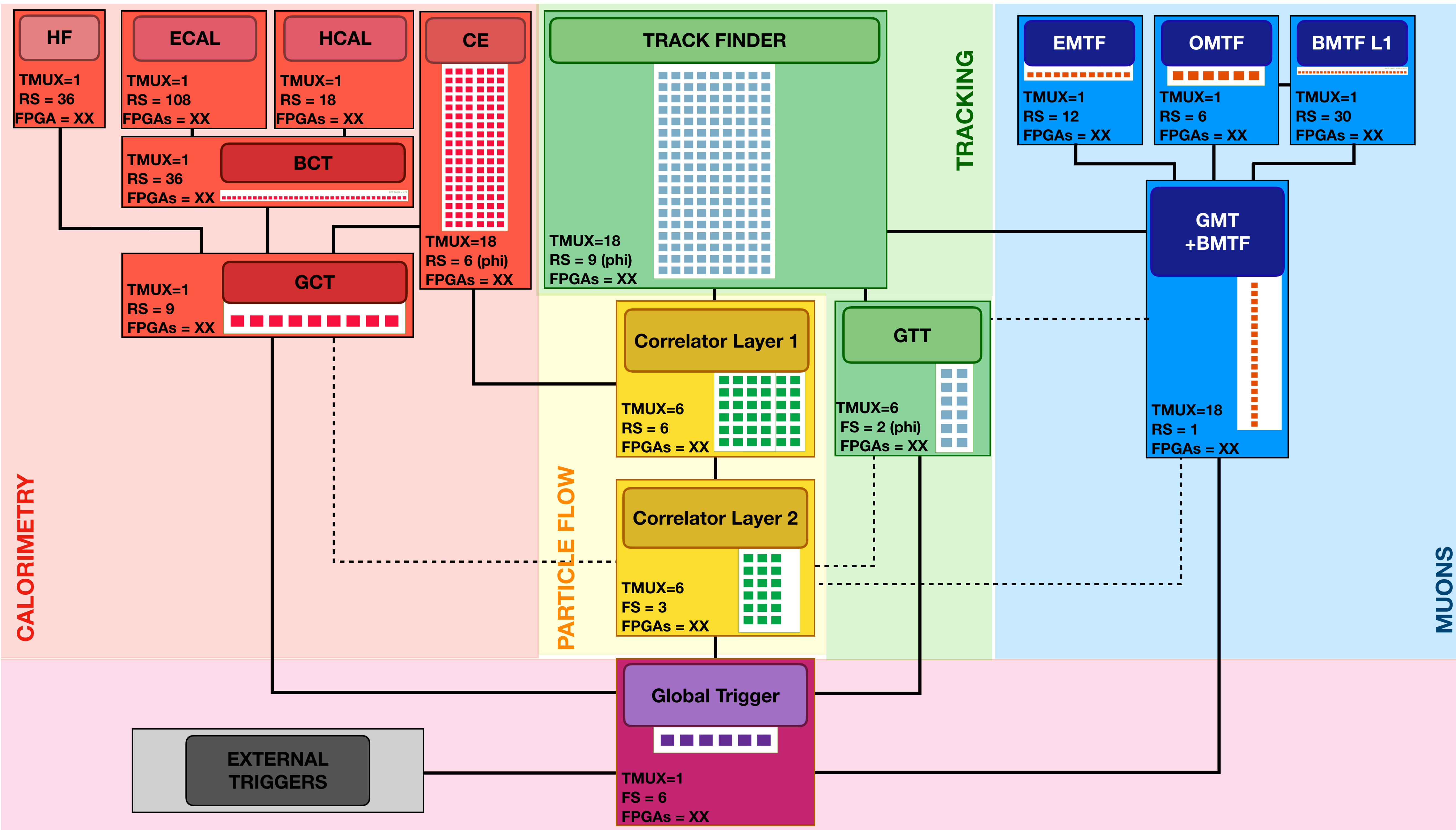
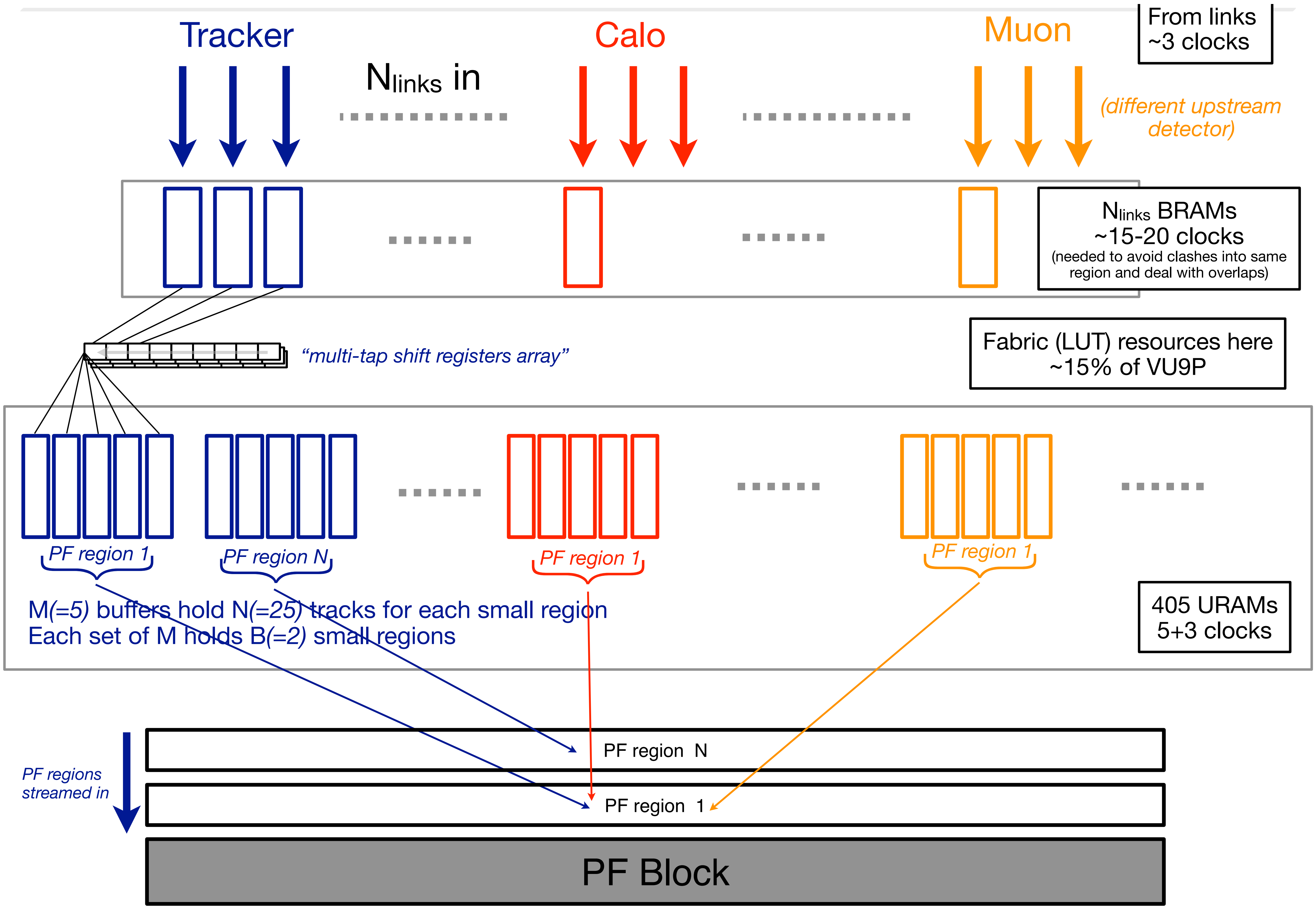


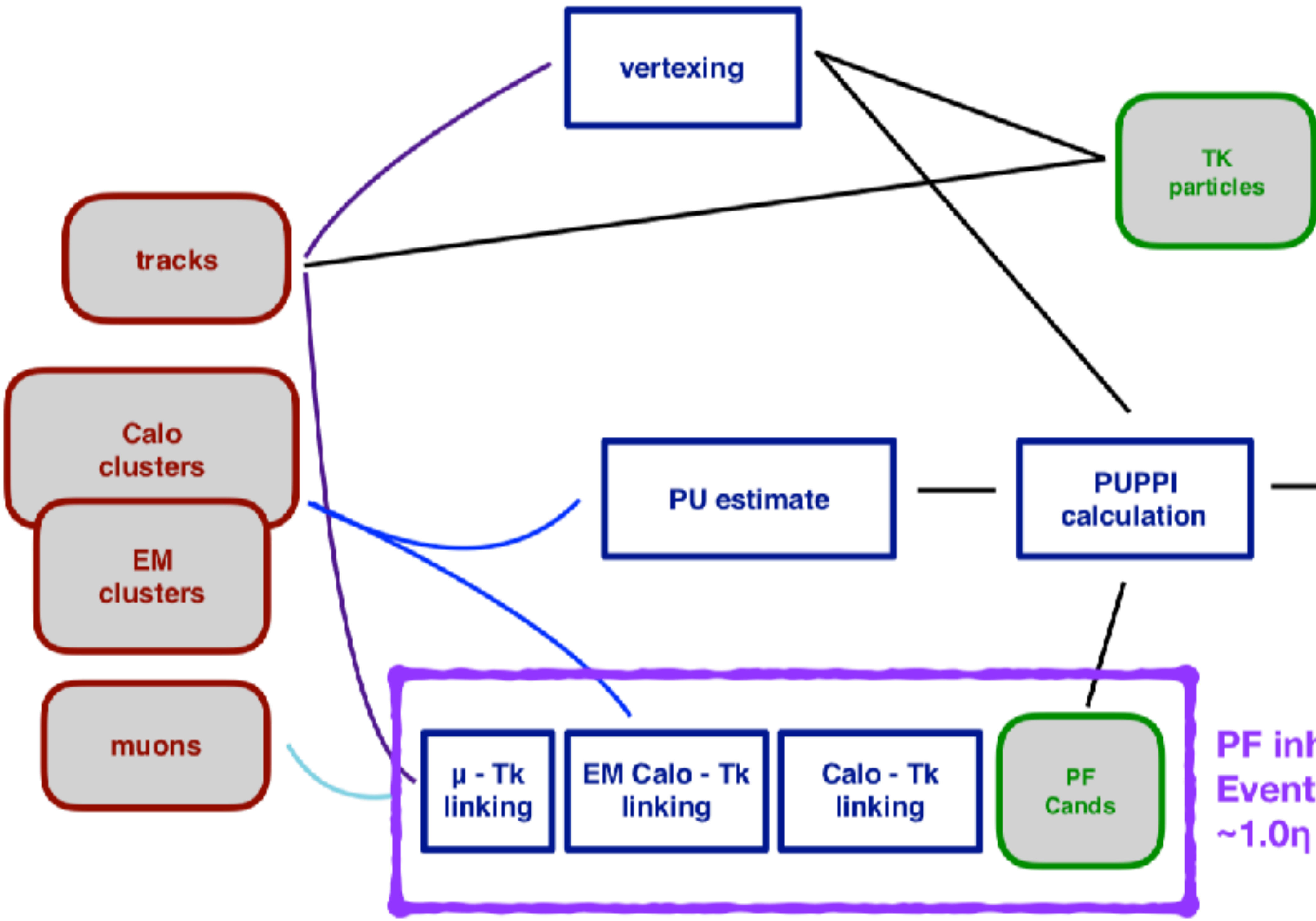
FPGA / TMUX / Region view



Firmware - Regionalization

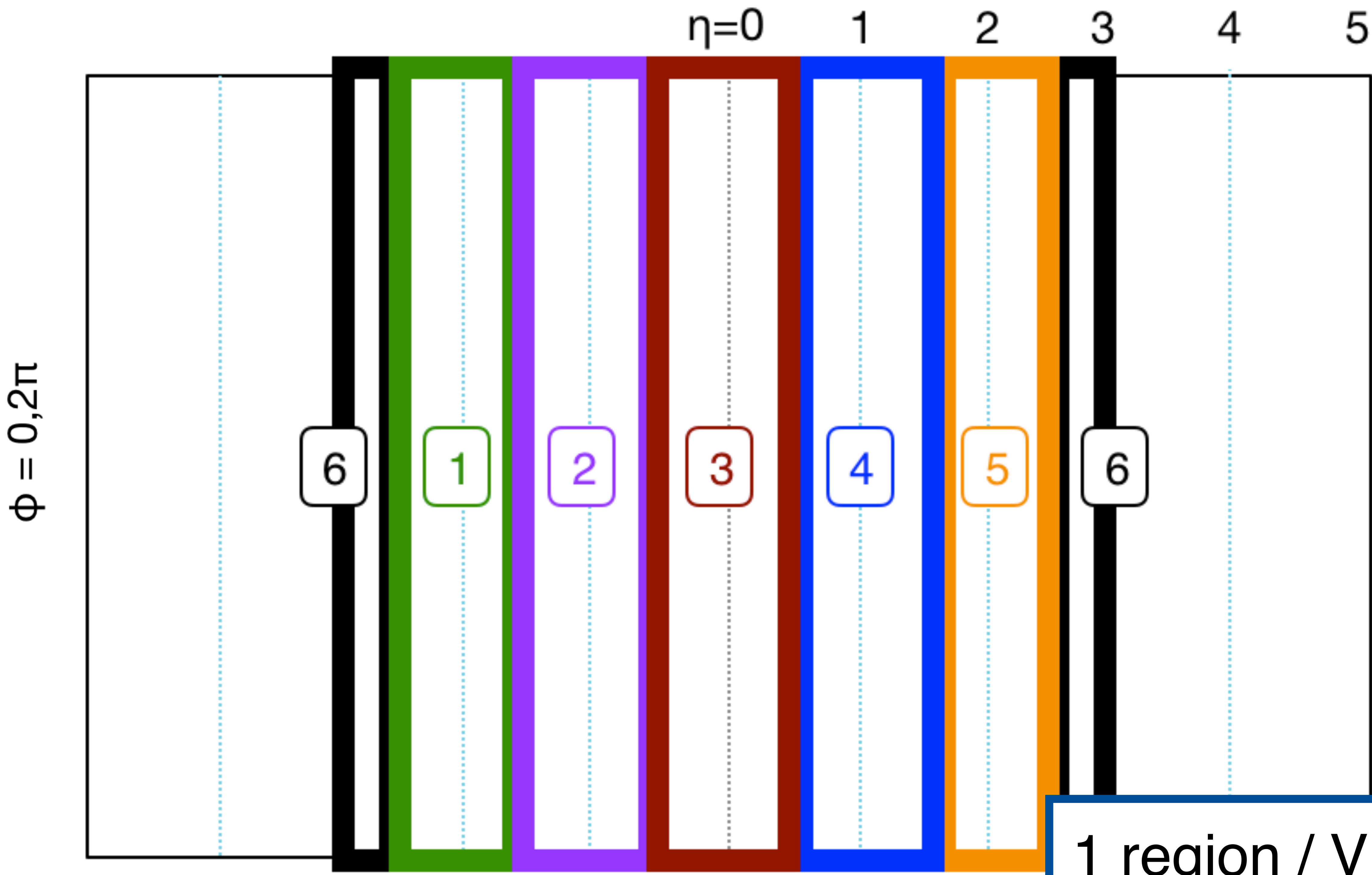


PF+PUPPI algo



PF inherently local,
Event regionalized into
~1.0η x 0.7ϕ blocks

Regionalization — 'board regions'



1 region / VU9P
(or similar)