FERMILAB-SLIDES-19-073-E

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Particle Flow at 40 MHz with the CMS L1 Trigger

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CPAD Instrumentation Frontier Workshop
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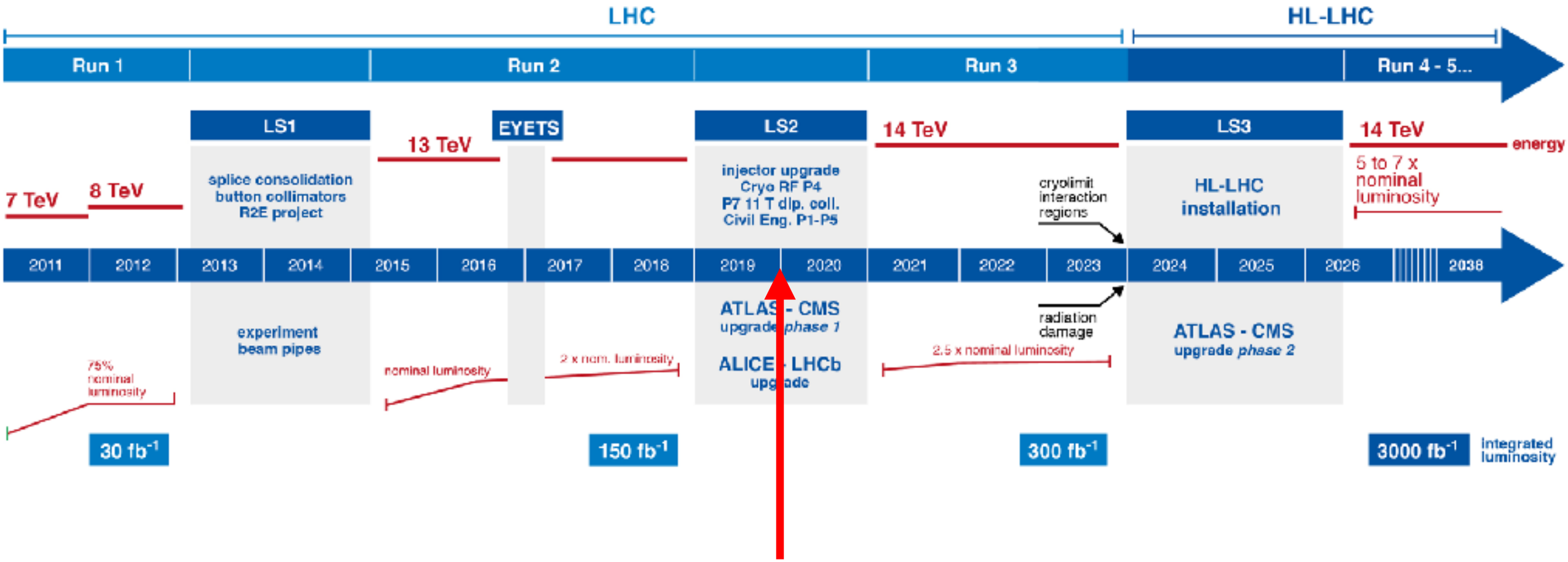
Outline

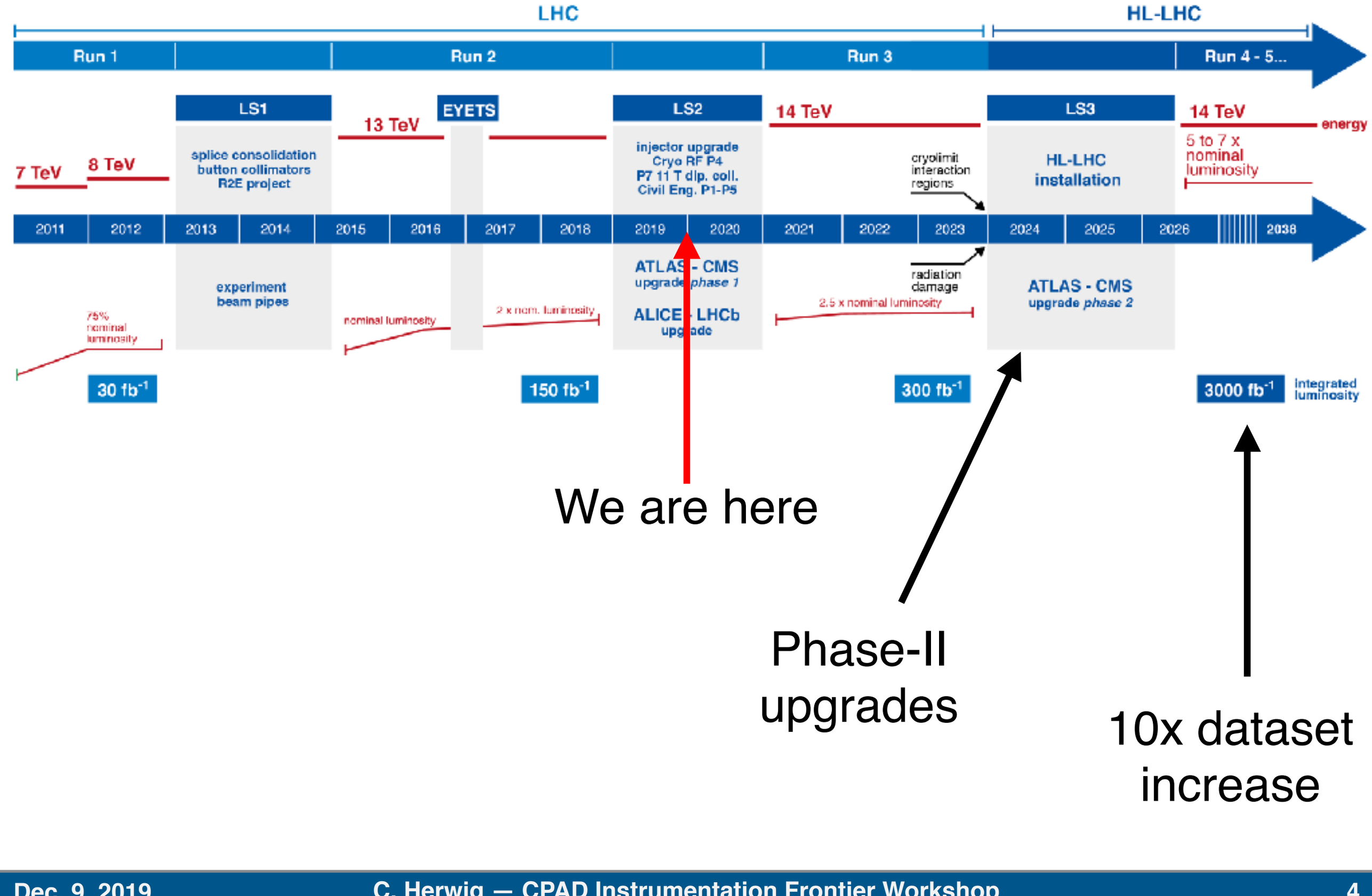
- Motivation and the High-luminosity LHC
- Particle Flow reconstruction
  - PUPPI Pileup subtraction
- The Phase-II Upgrade to the L1 CMS Trigger
- Progress of PF+PUPPI implementation

LHC / HL-LHC Plan



We are here

LHC / HL-LHC Plan



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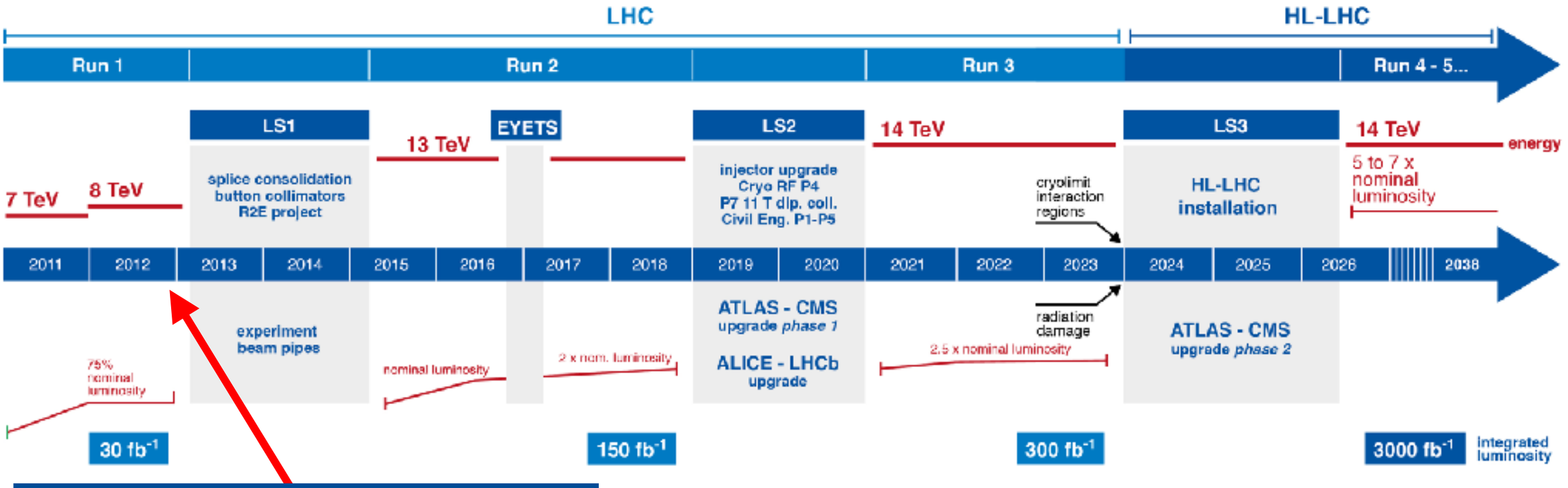
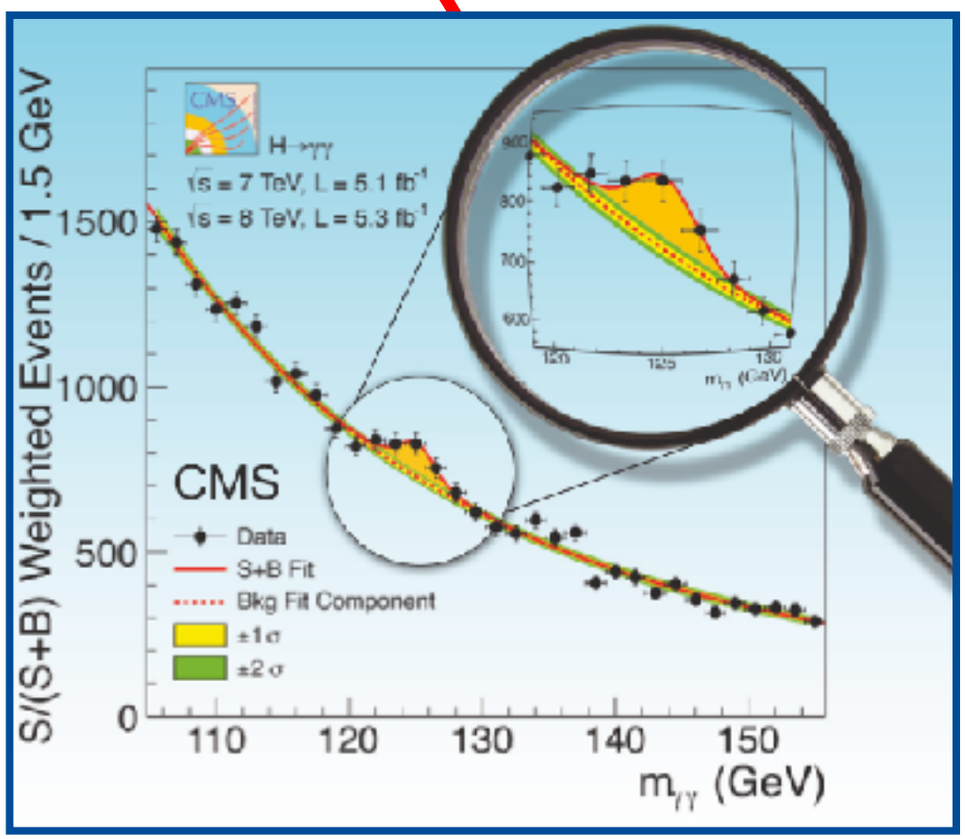
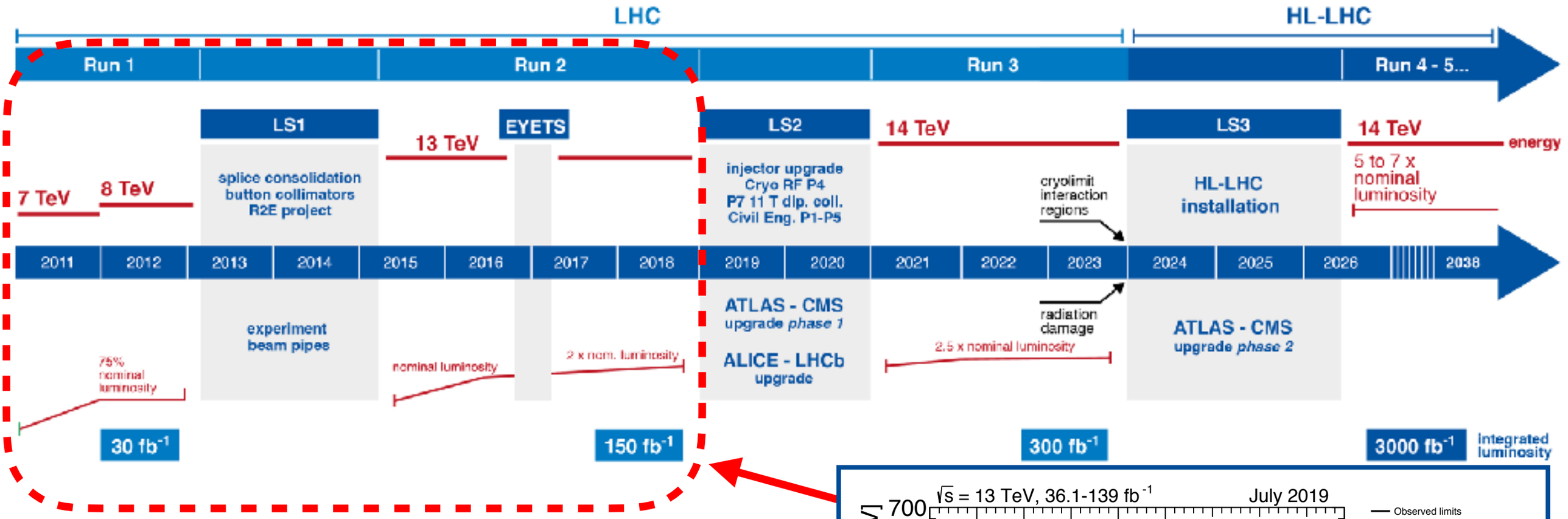




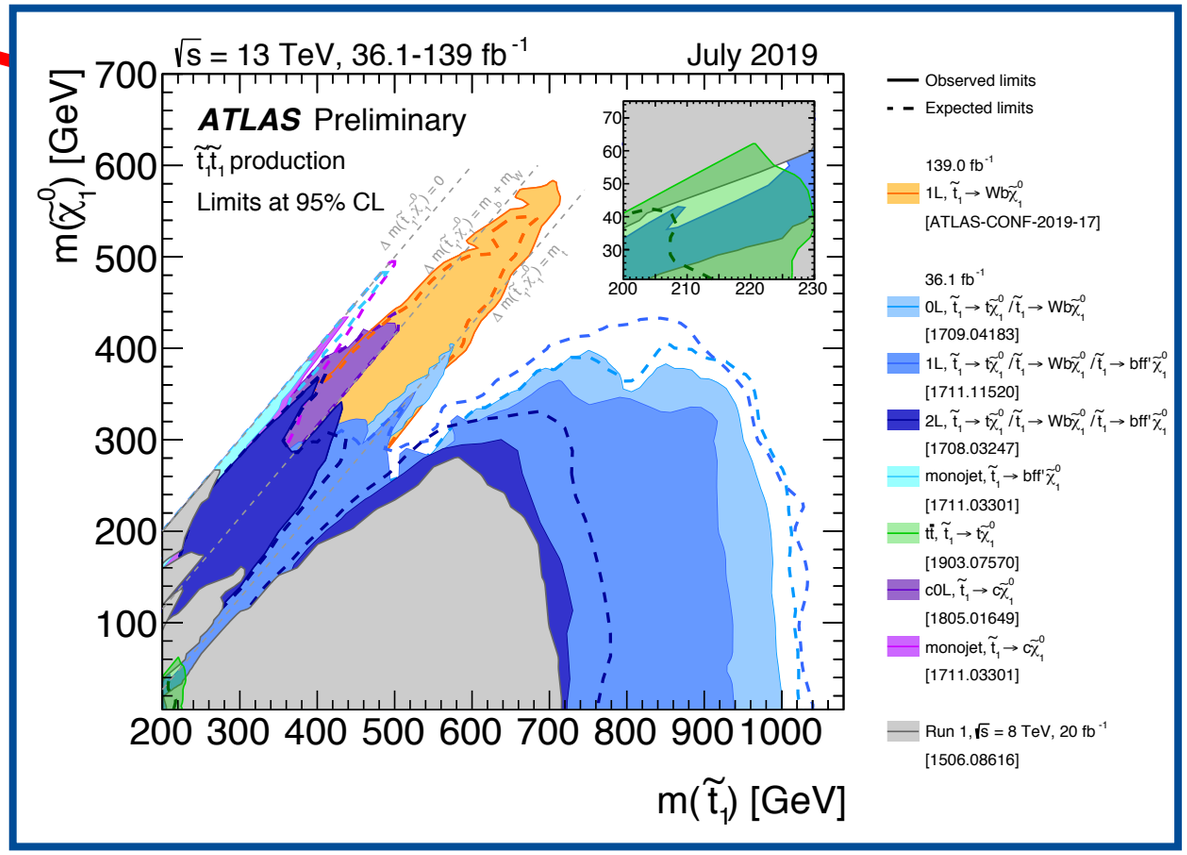
Discover Higgs!

LHC / HL-LHC Plan



Constraints on BSM Physics

(especially strongly produced)



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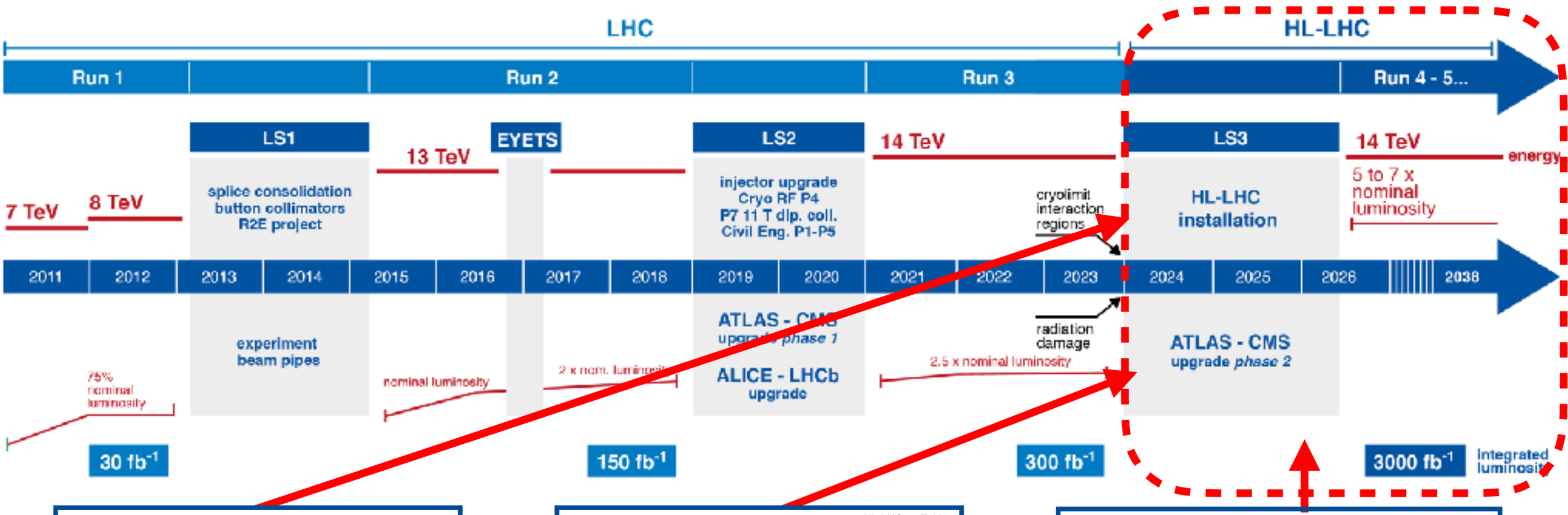
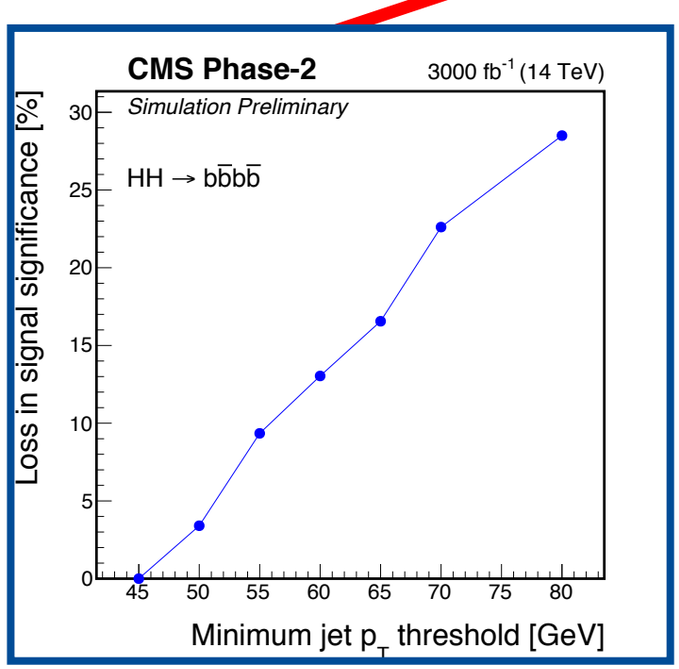
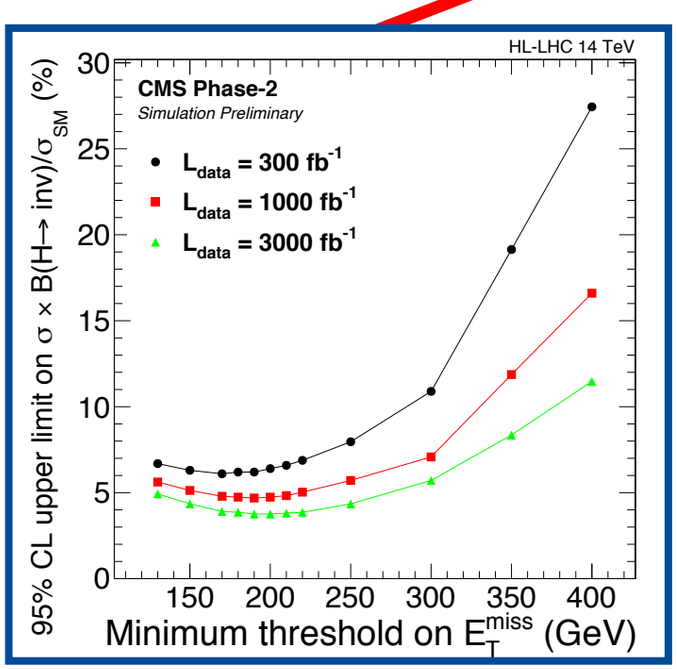
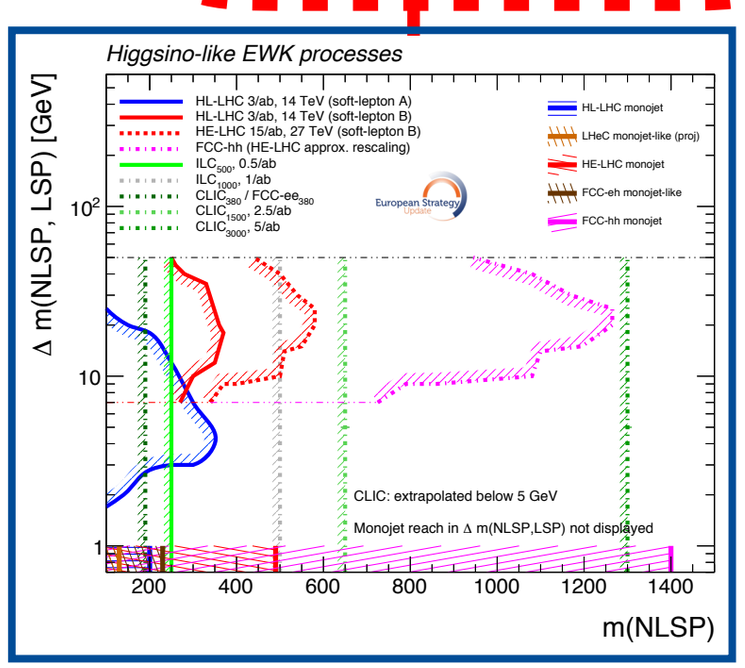




SM hh

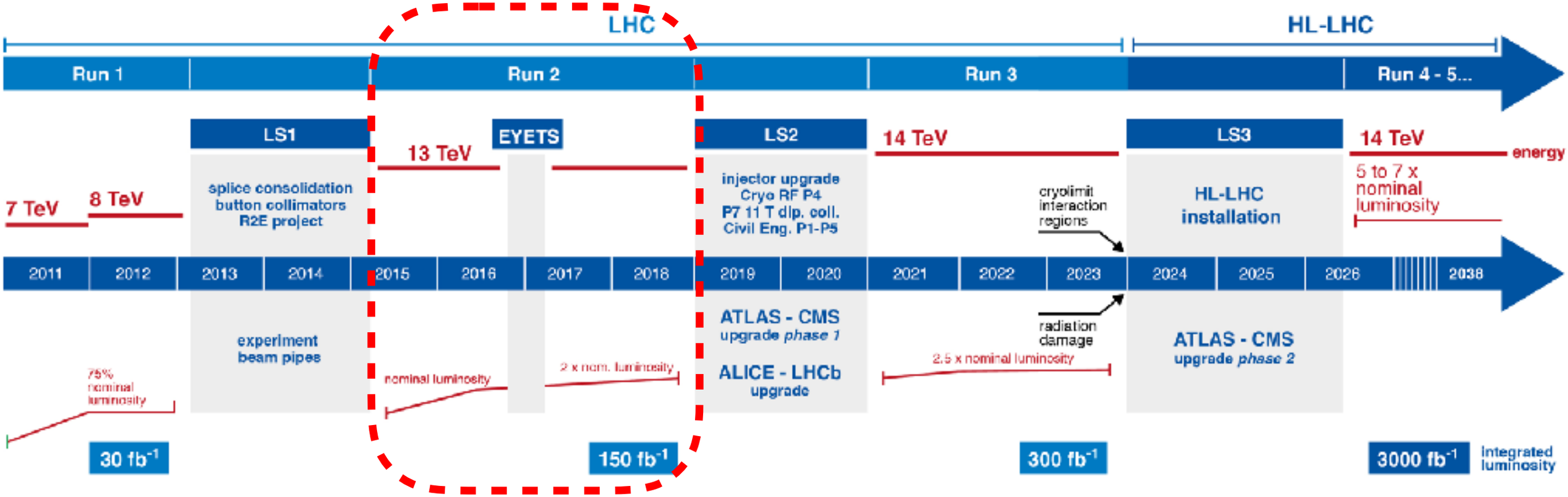


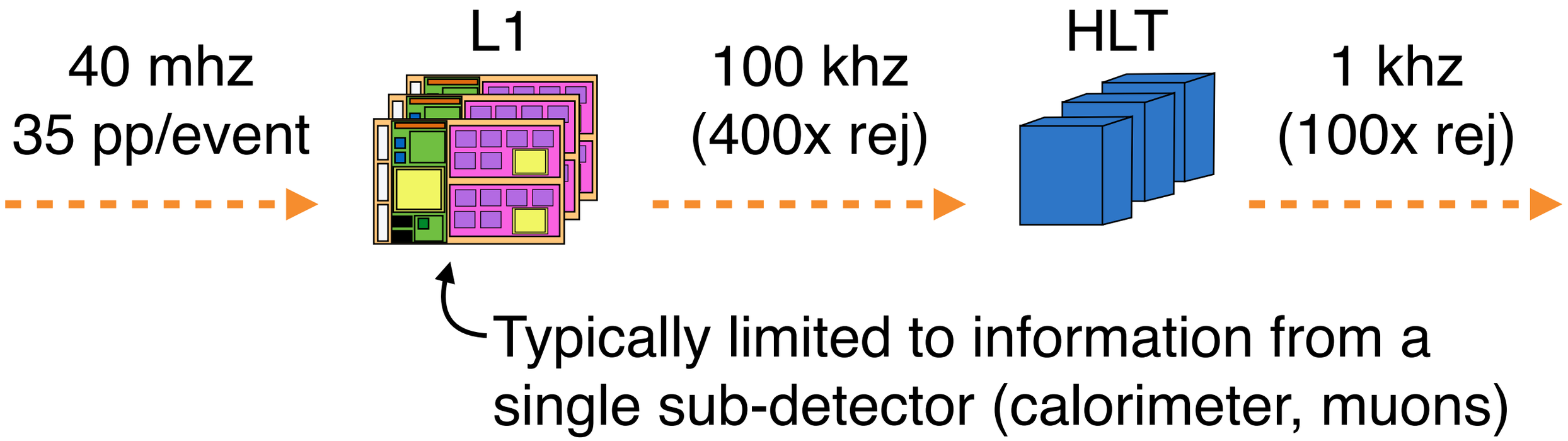
Rare+Exotic Higgs



EWK BSM

LHC / HL-LHC Plan





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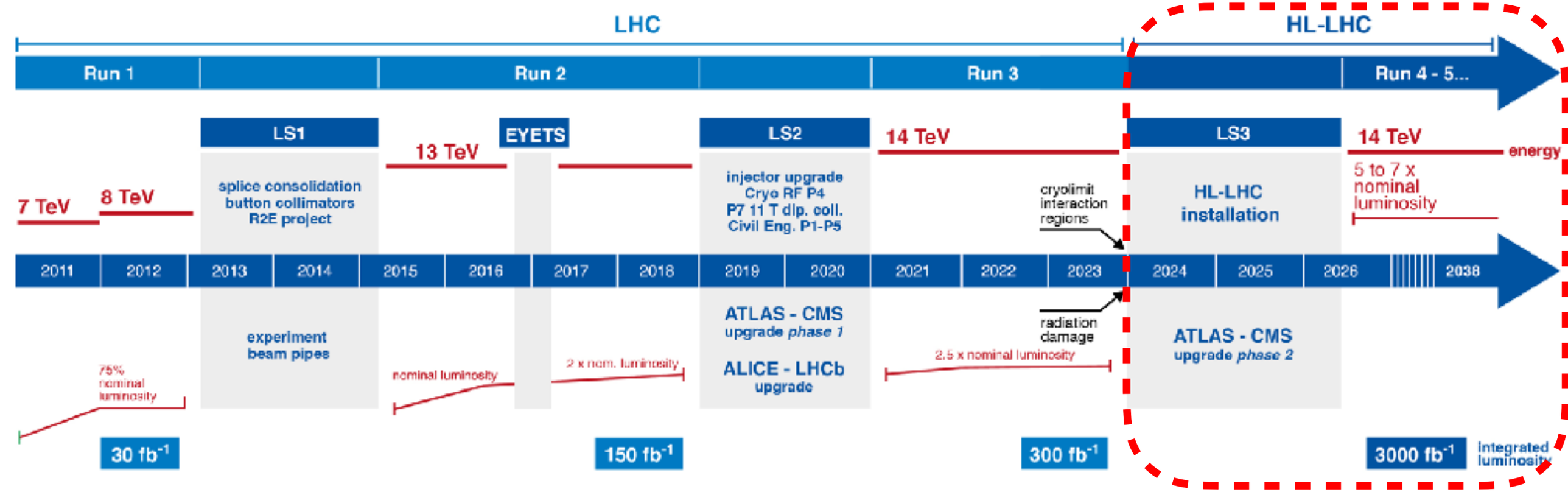
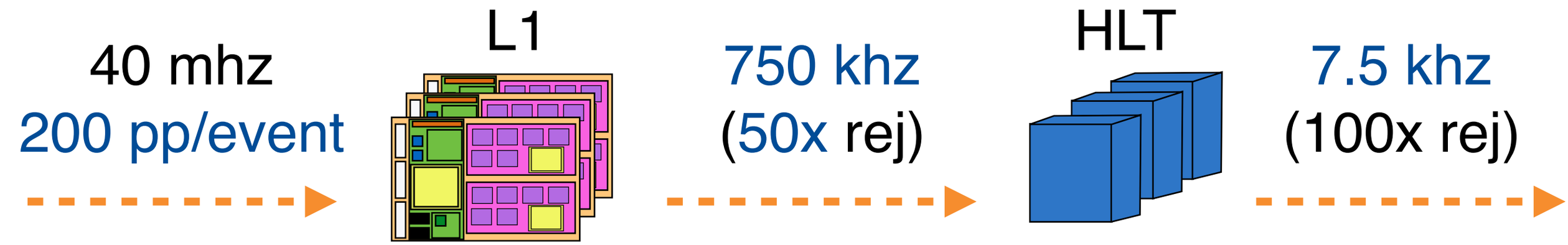
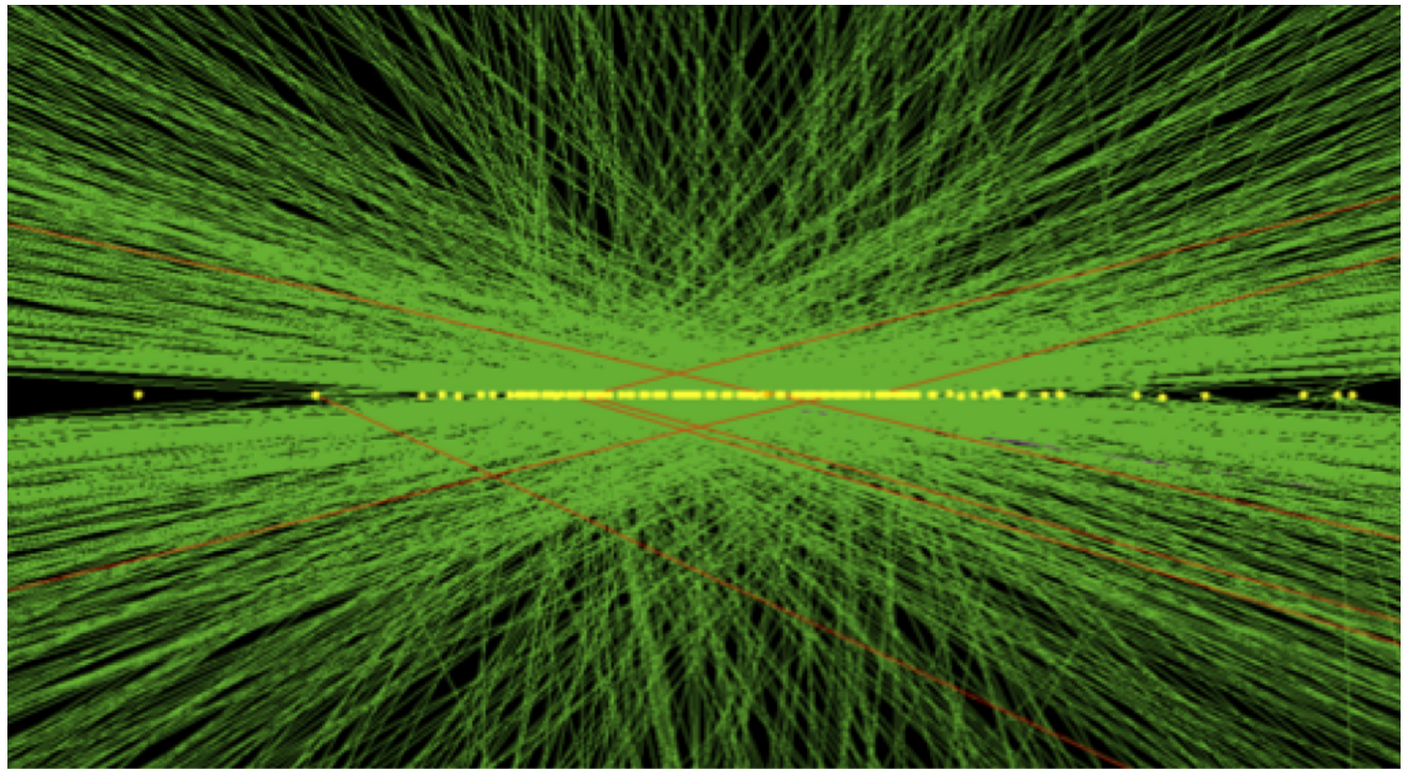




Naively scales with luminosity

Challenges to Phase-II L1 Trigger

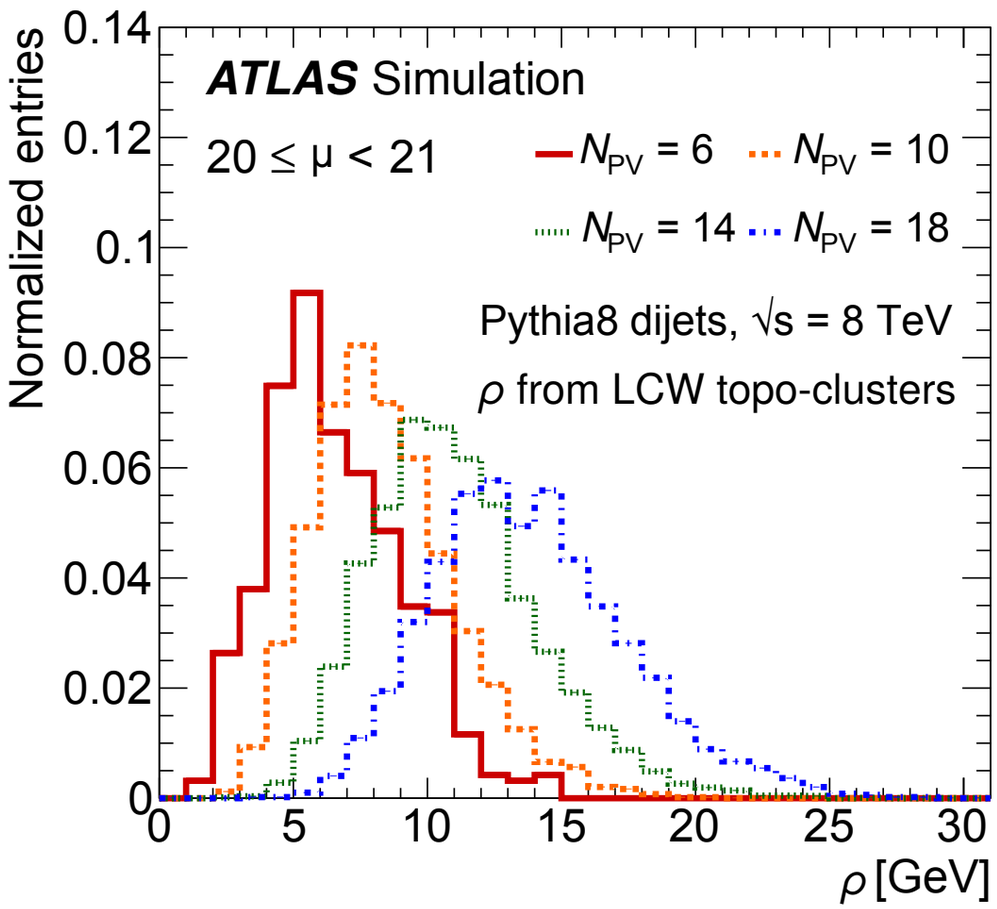
- L1 Accept rate scales ~ linearly with luminosity increase
  - Must maintain performance in hostile environment!



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

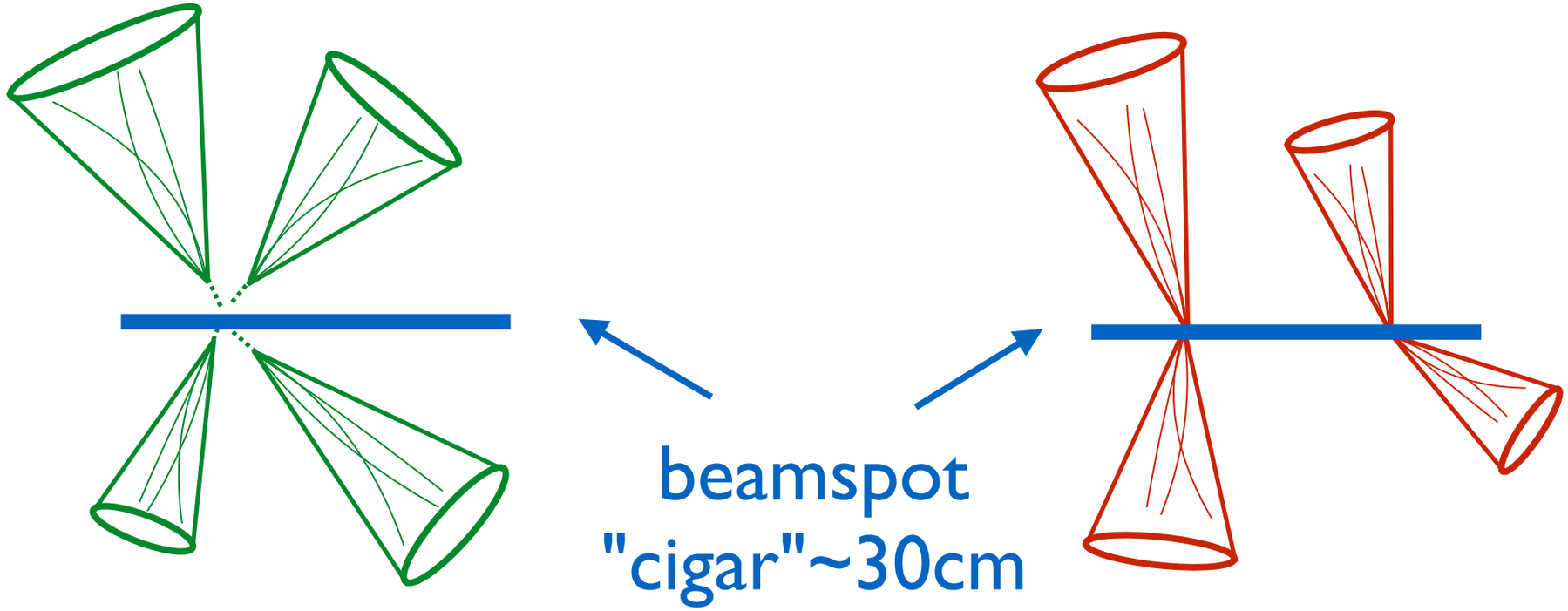
More low-p_T jets to "measure high" than vice versa
→ **Higher trigger rate**

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) ~ (lumi)^2



Not new problems, solved offline with Particle Flow Reco+

Particle Flow Reconstruction

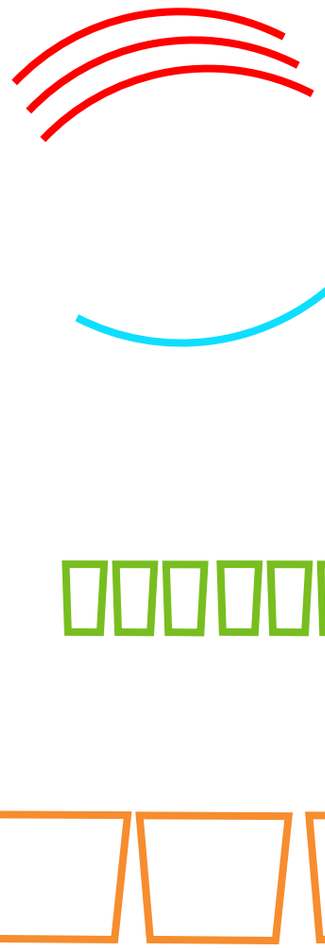
- Idea: **combine measurements** across all sub-detectors to achieve **best possible resolution per object**
  - Algorithm returns a list of single-particle candidates

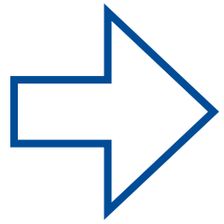
Tracks

Muon segments

ECal

HCal





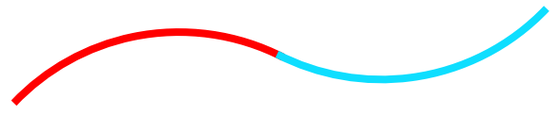
Muons

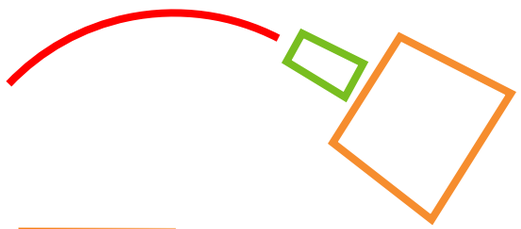
Electrons

(Isolated) photons

Charged hadrons

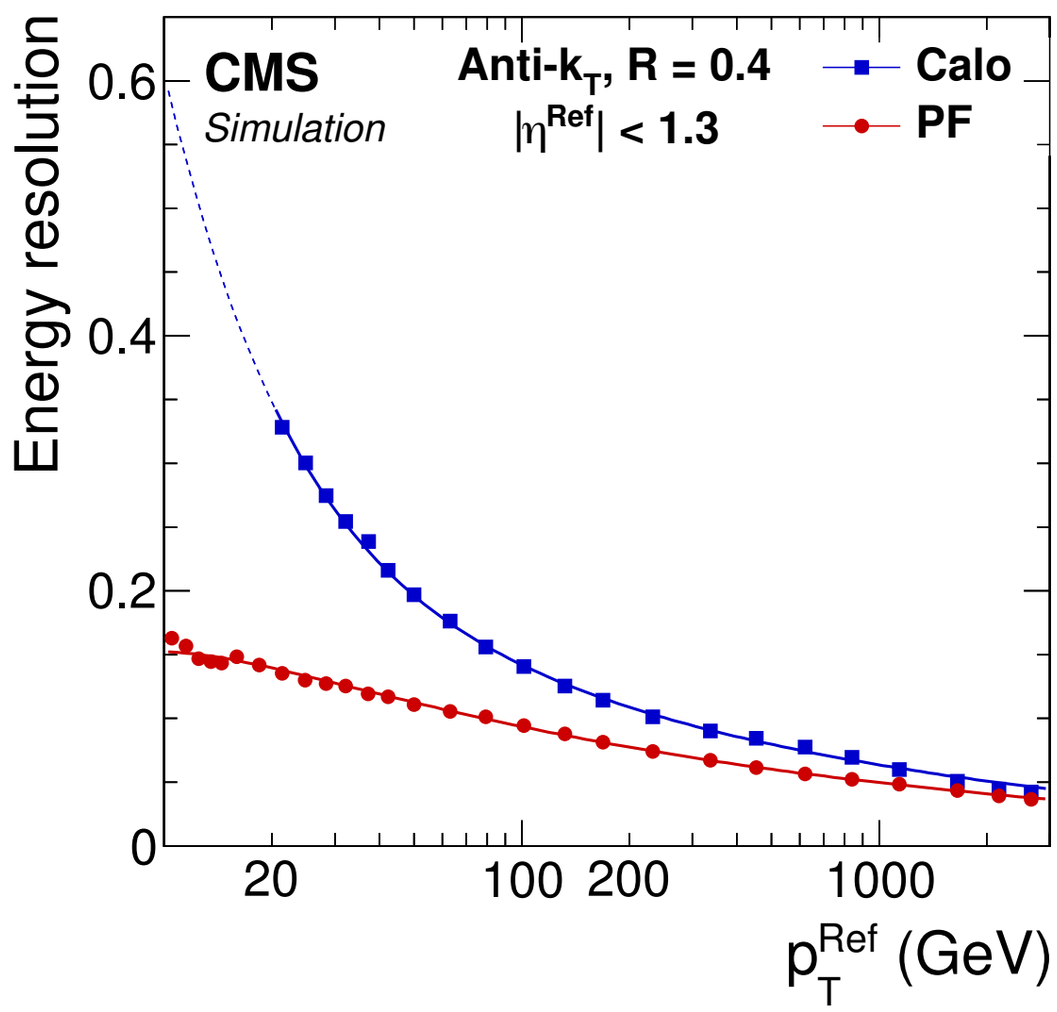
Neutral hadrons



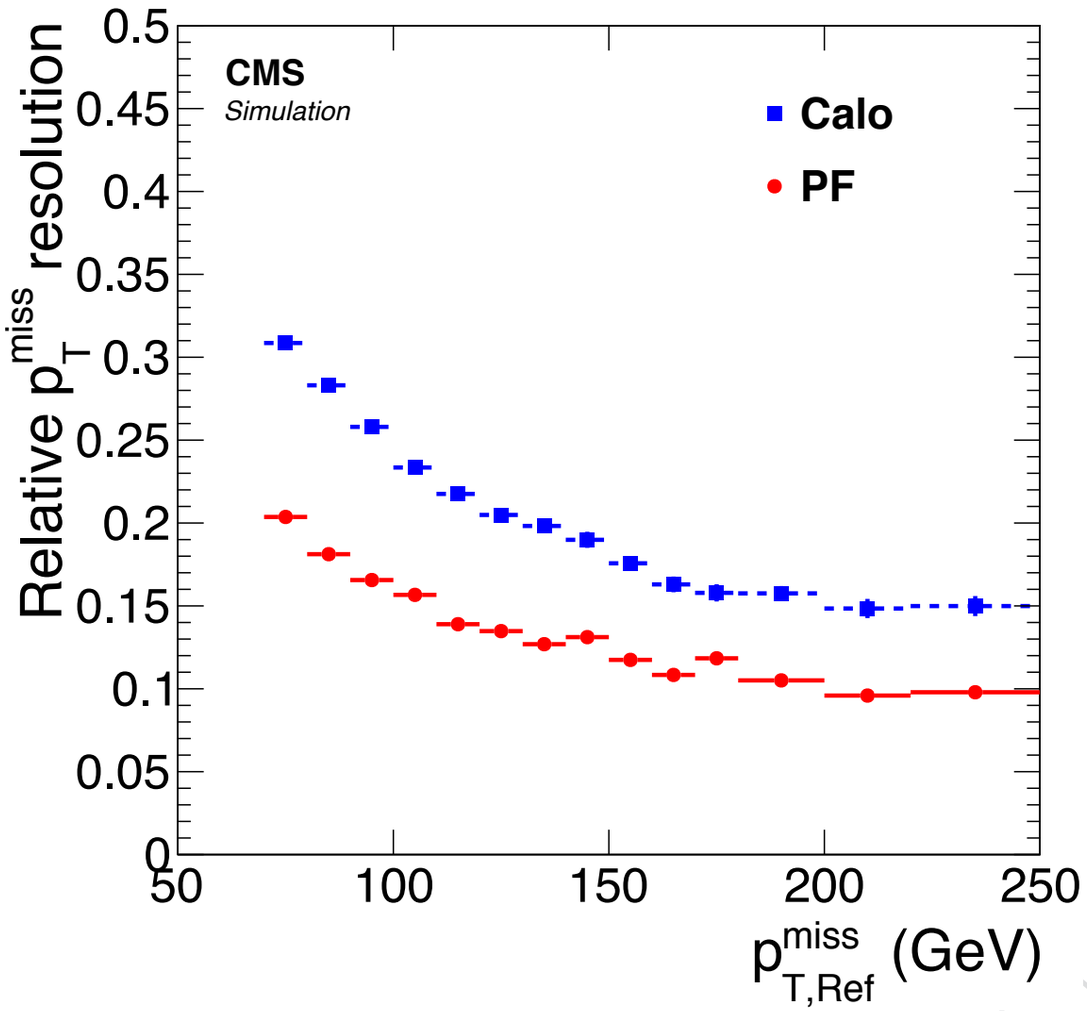


Particle Flow Reconstruction

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



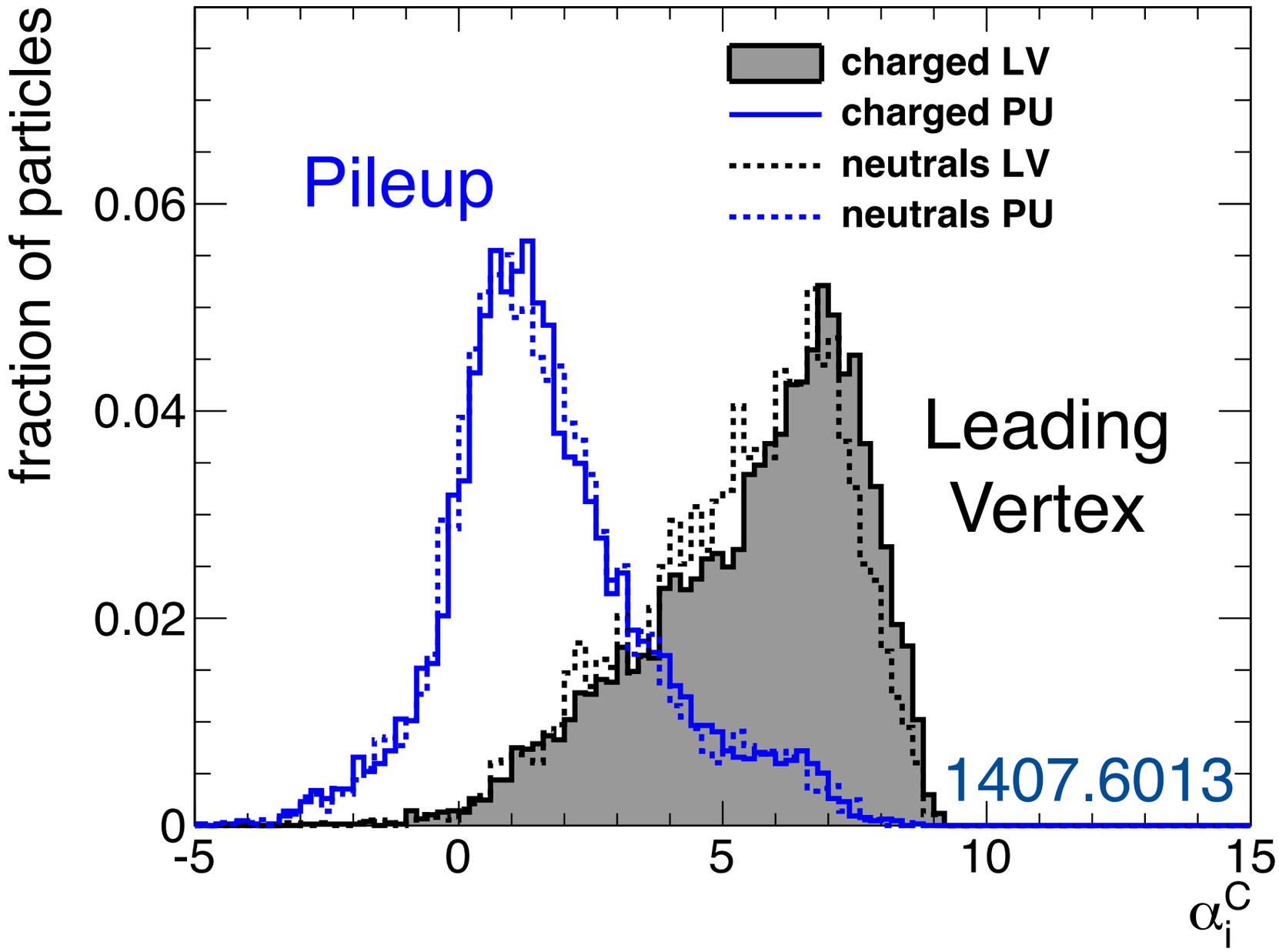
Improved Jet p_T resolution



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



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

Pileup Per Particle Identification

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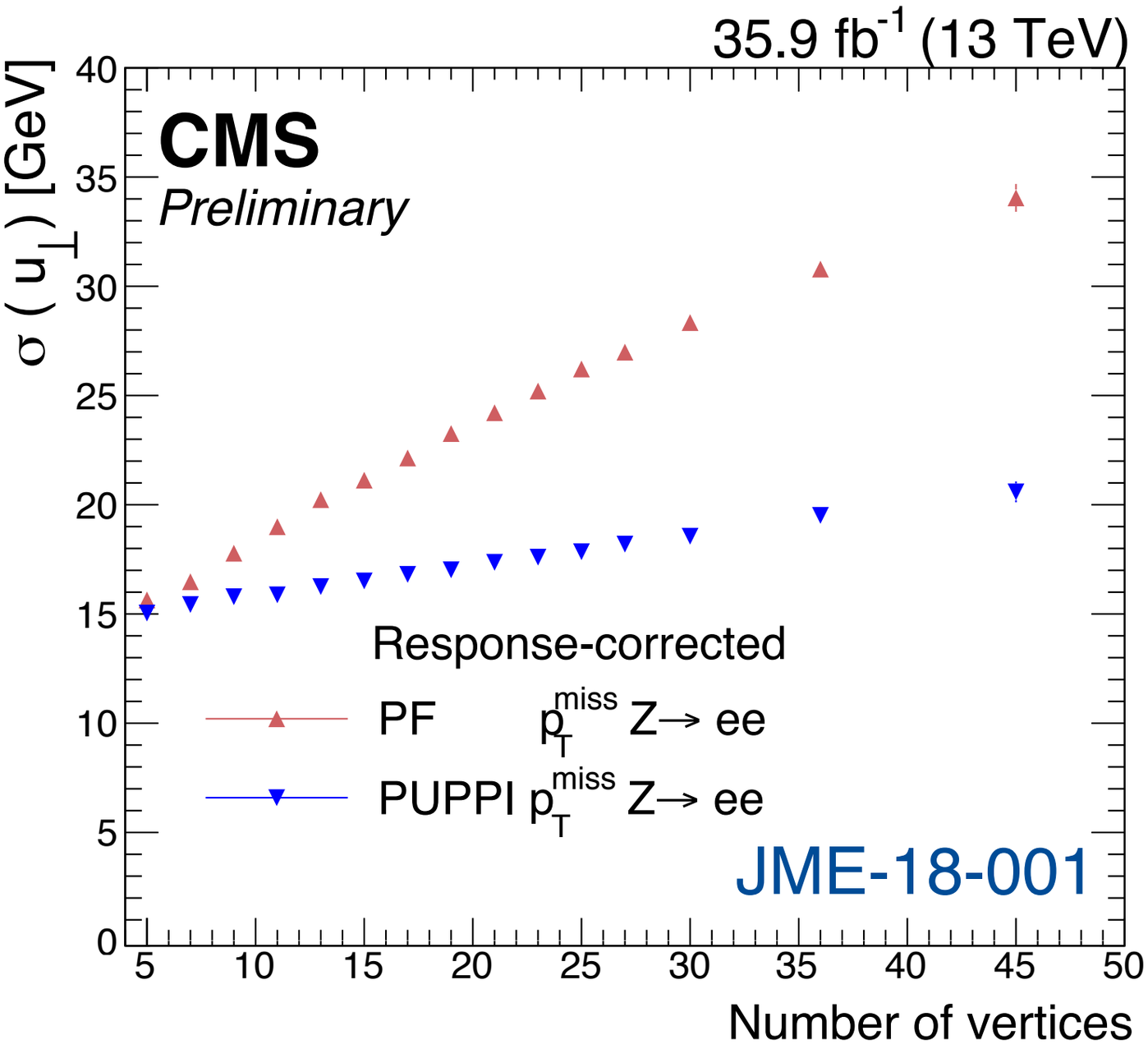
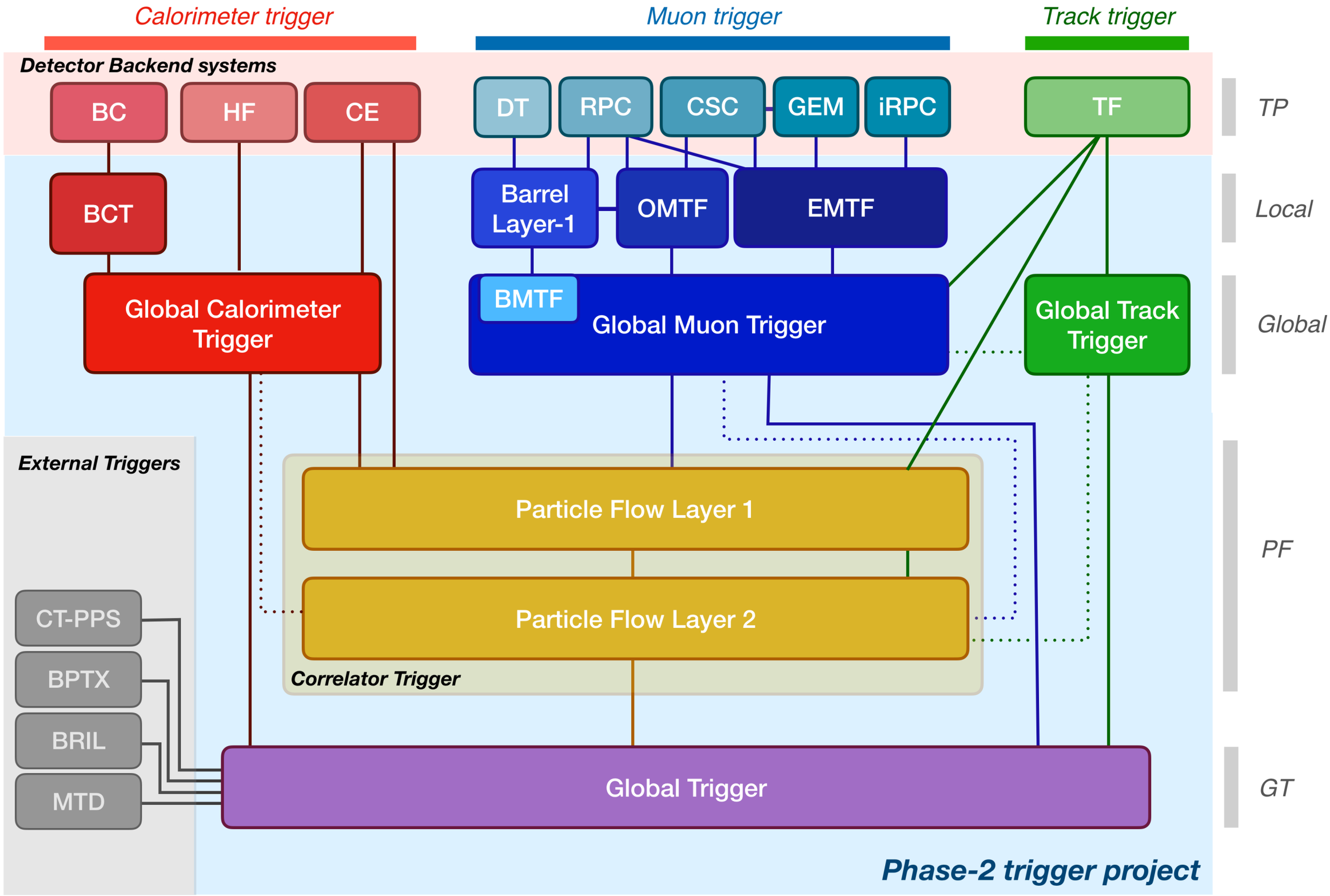


Improved p_T-miss resolution

Architecture of the Phase-II L1 Trigger



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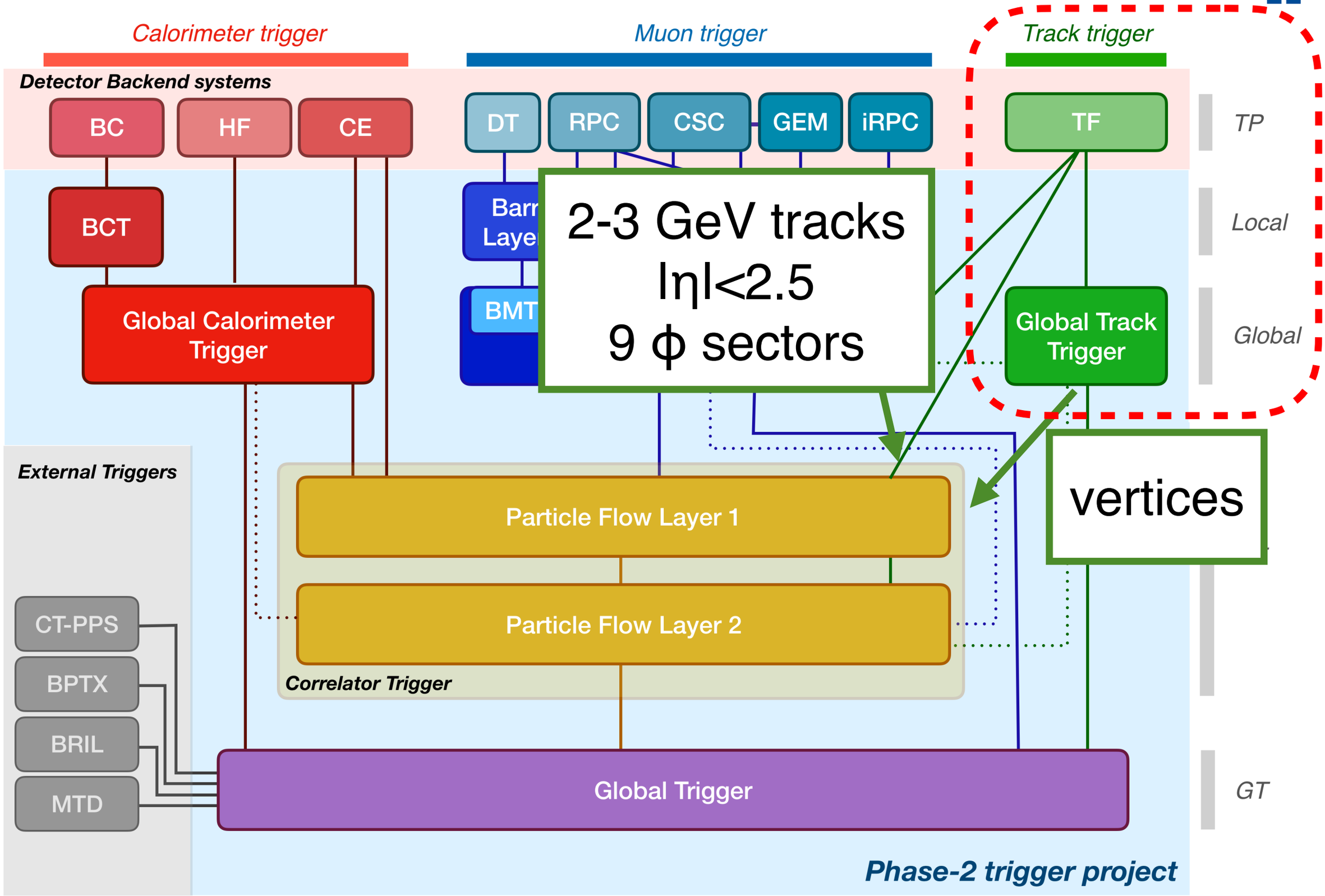

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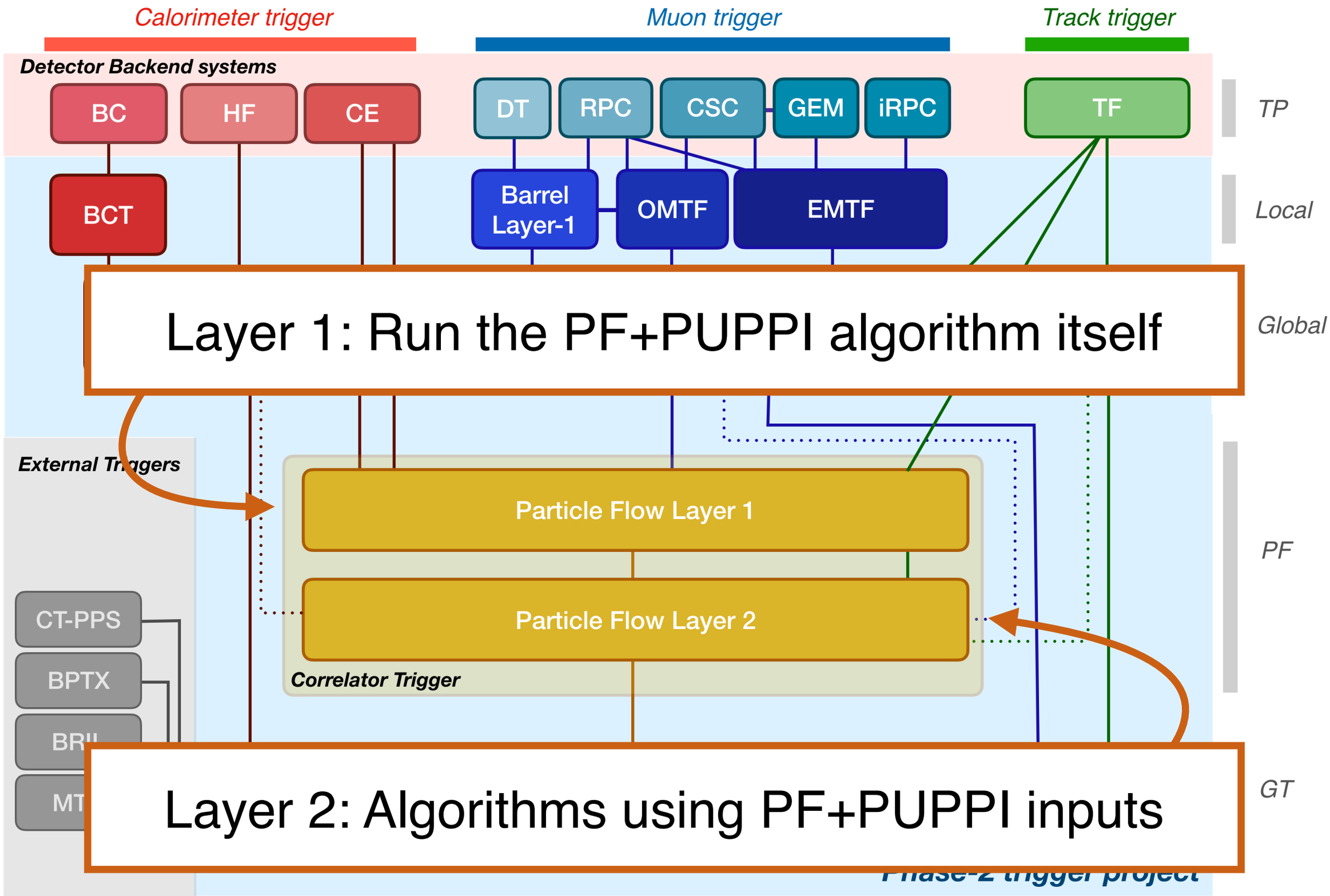


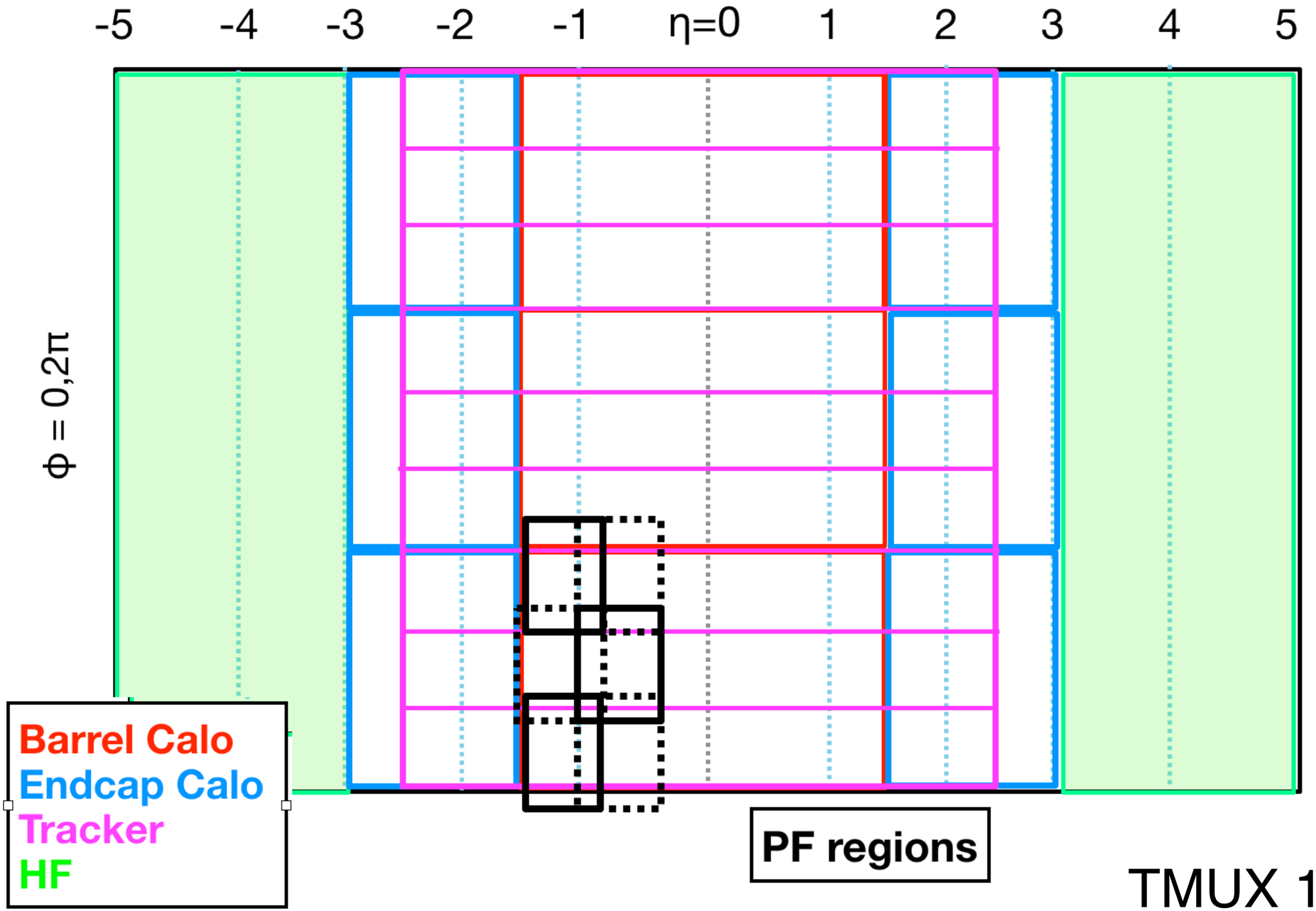
Strategy for L1 Implementation

- 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

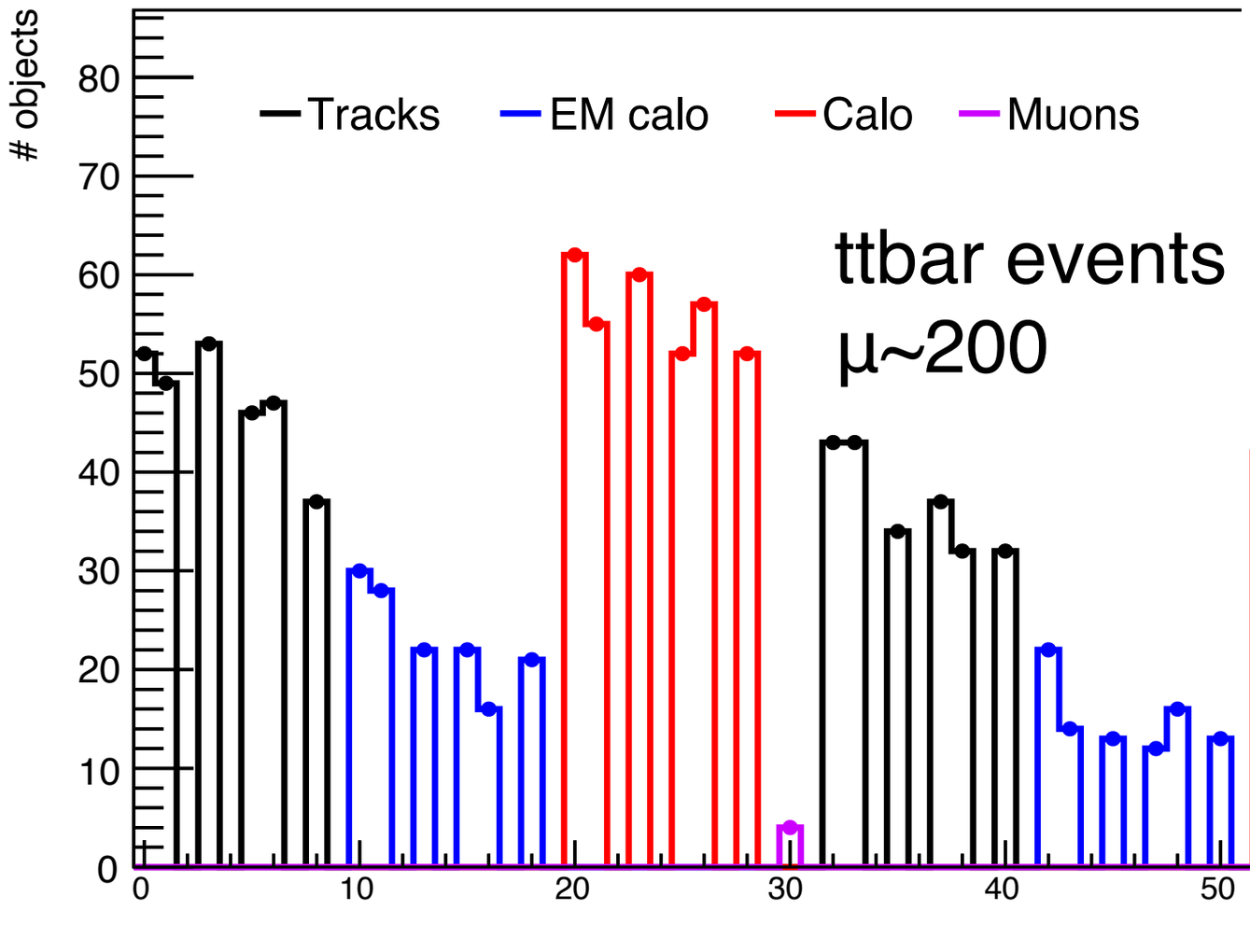
Inputs versus η, PF+PUPPI regions

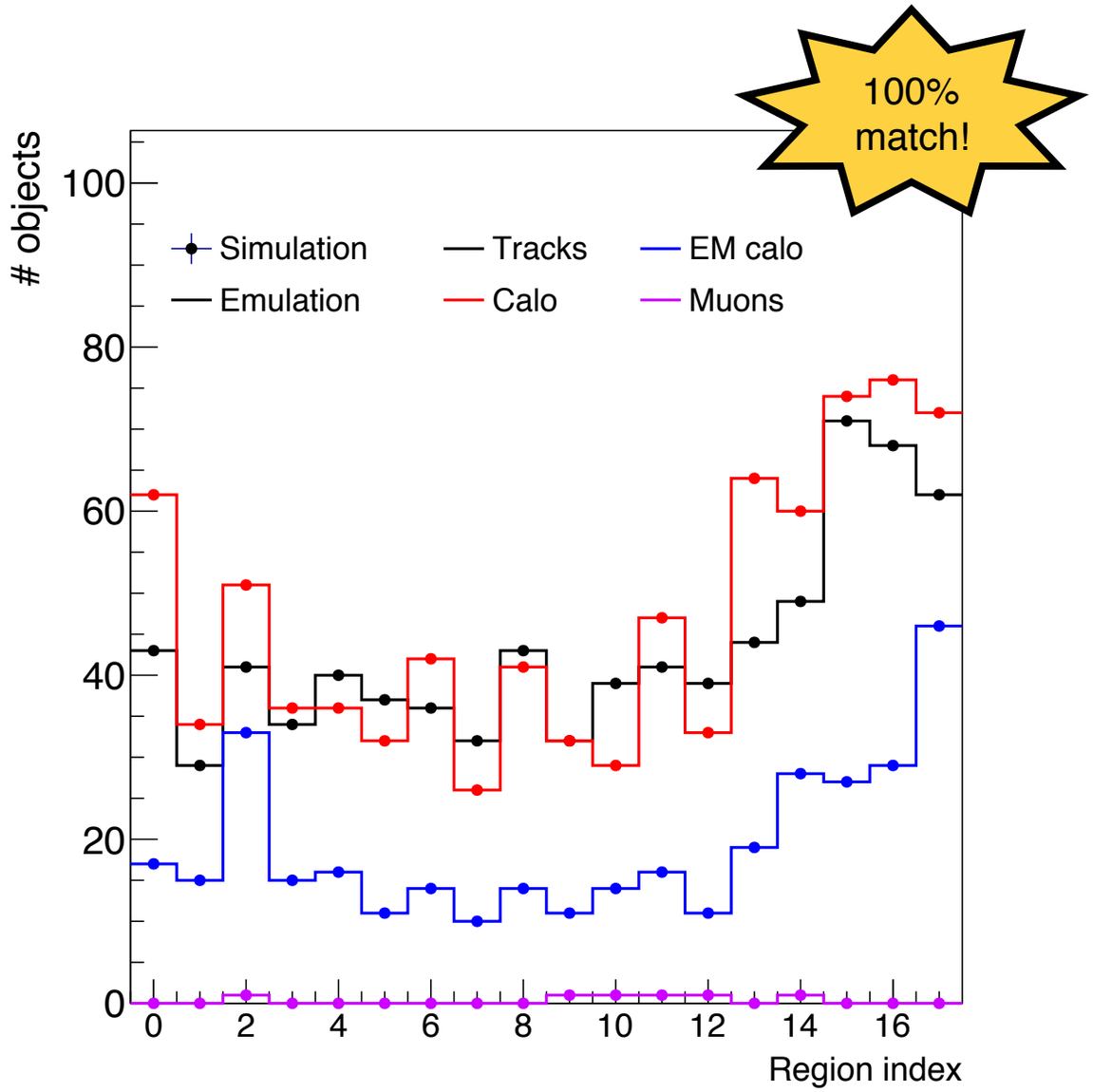


TMUX 18→6

Regionizer validation

VHDL algorithm validated with simulated data inputs

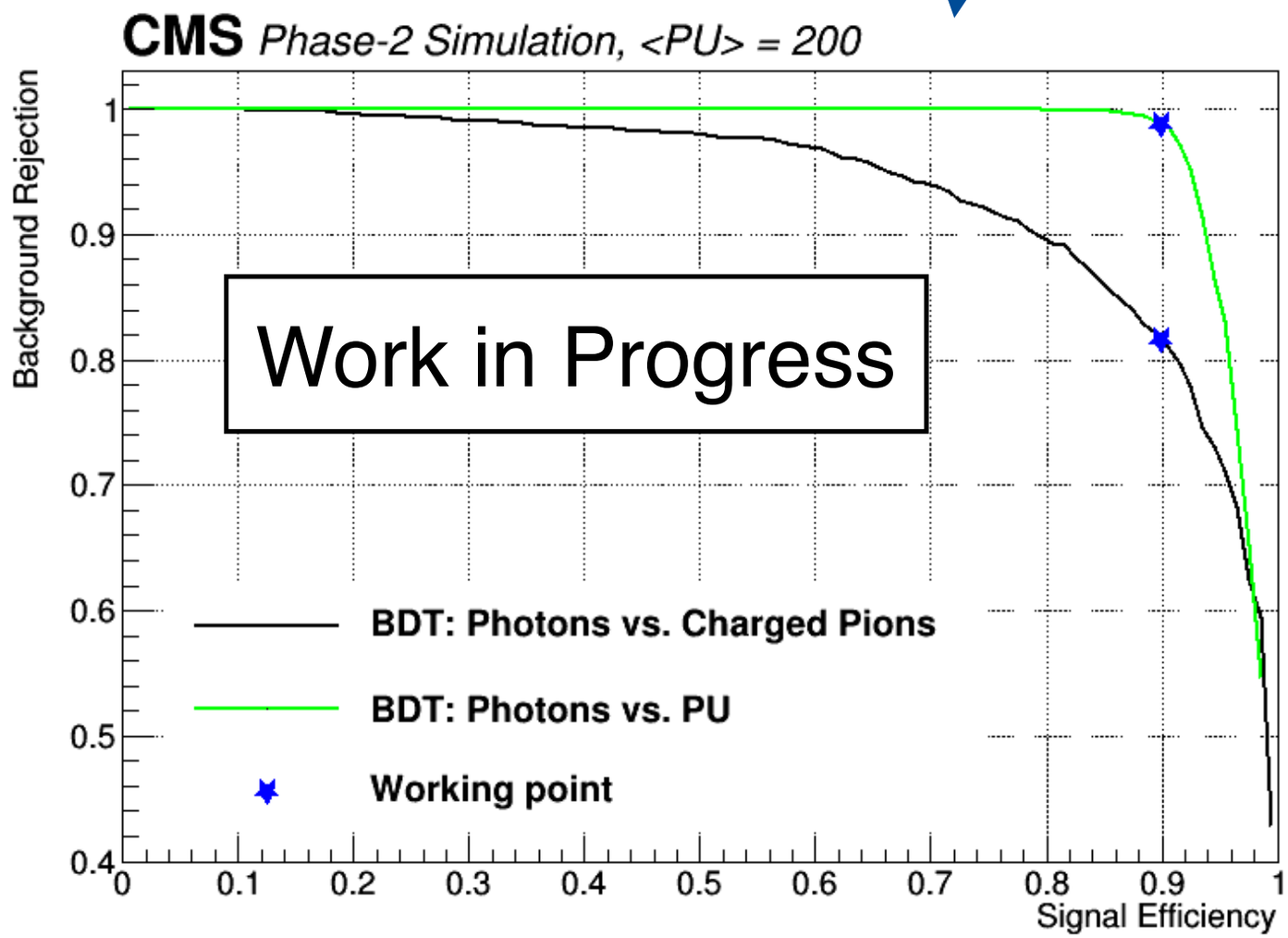




HW Particle Flow + PUPPI

- 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!



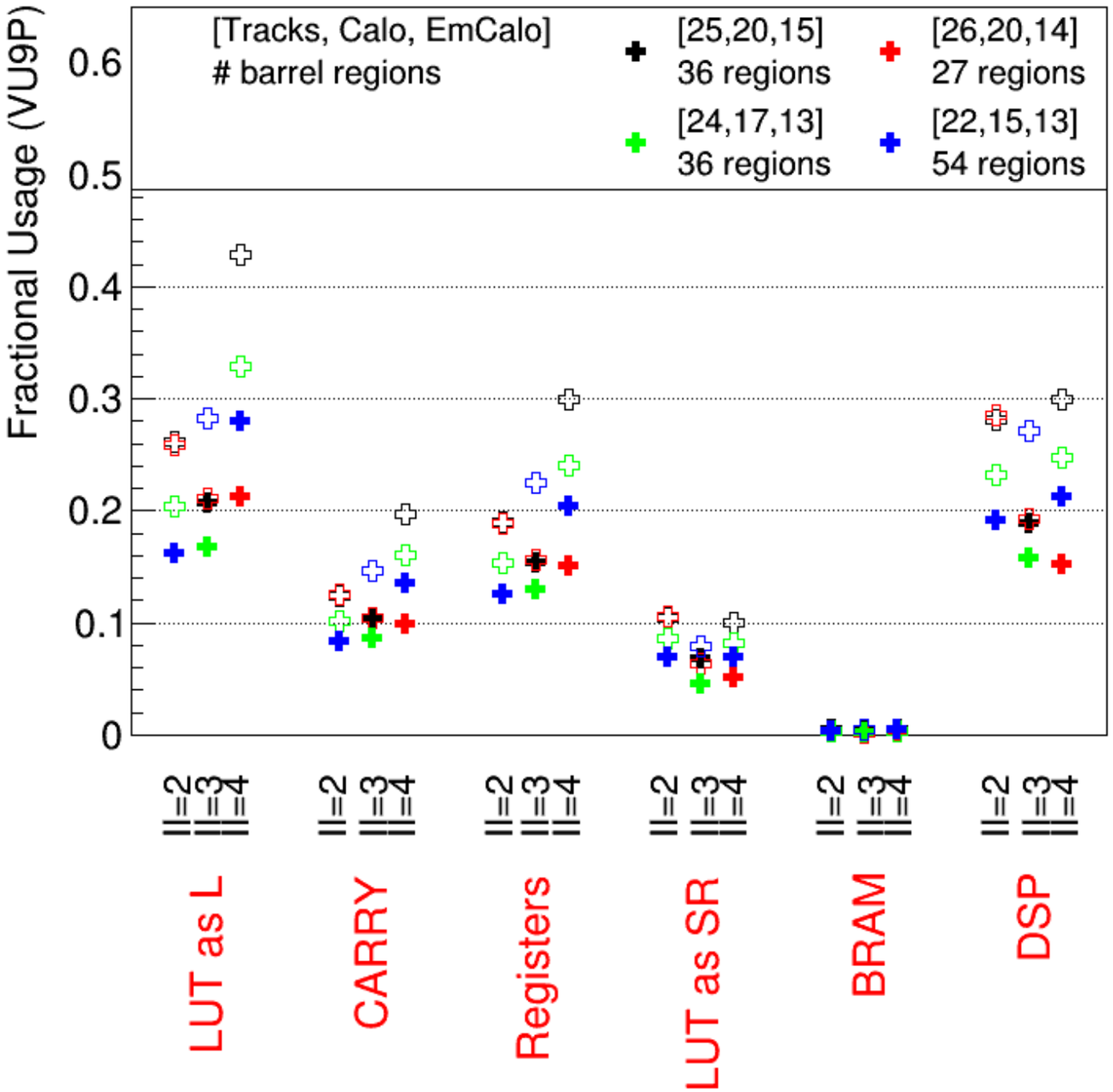
Resource drivers

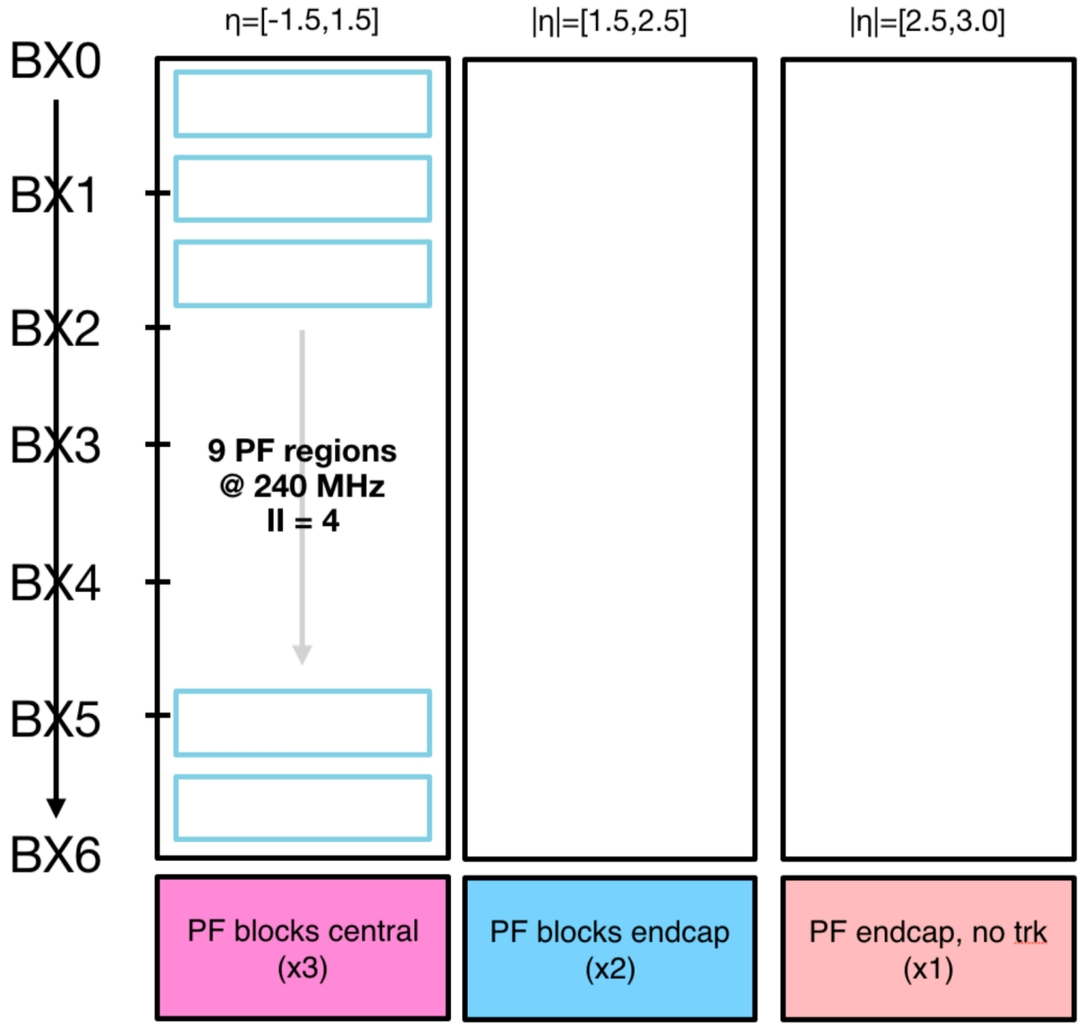
- Many ΔR calculations for track-calo linking drives DSP
  - Scales as (#tracks)*(#calo clusters)
- PUPPI weights drive BRAM usage
  - To compute $p_T/\Delta R$ quickly requires division tables
  - DSPs also used to map (p_T, ΔR) → PUPPI weights

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



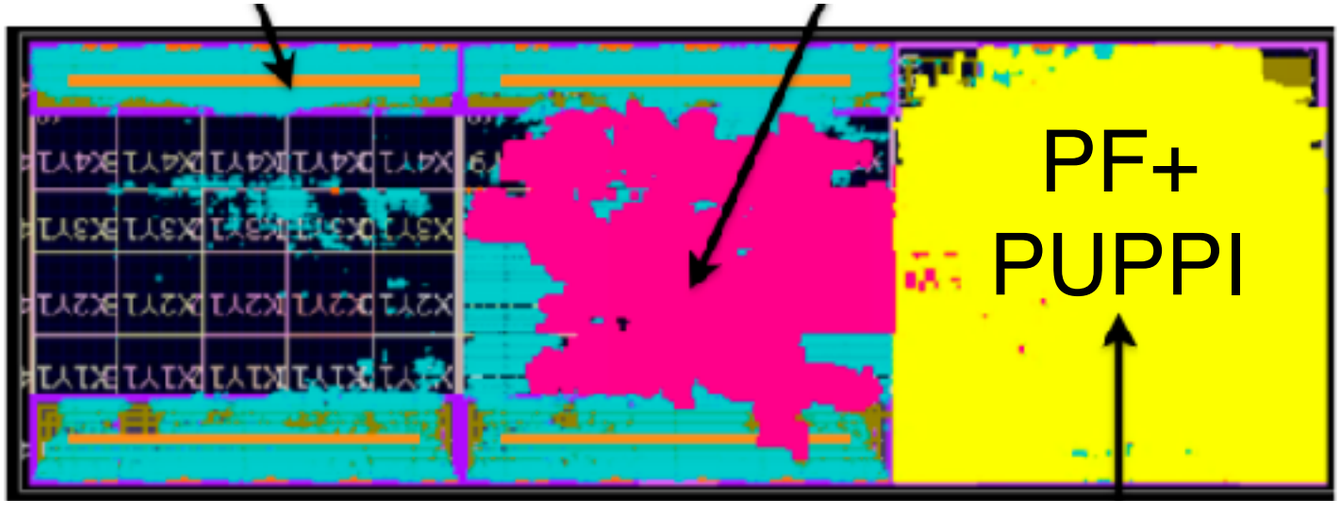


Resources vs. various initiation intervals and region sizes

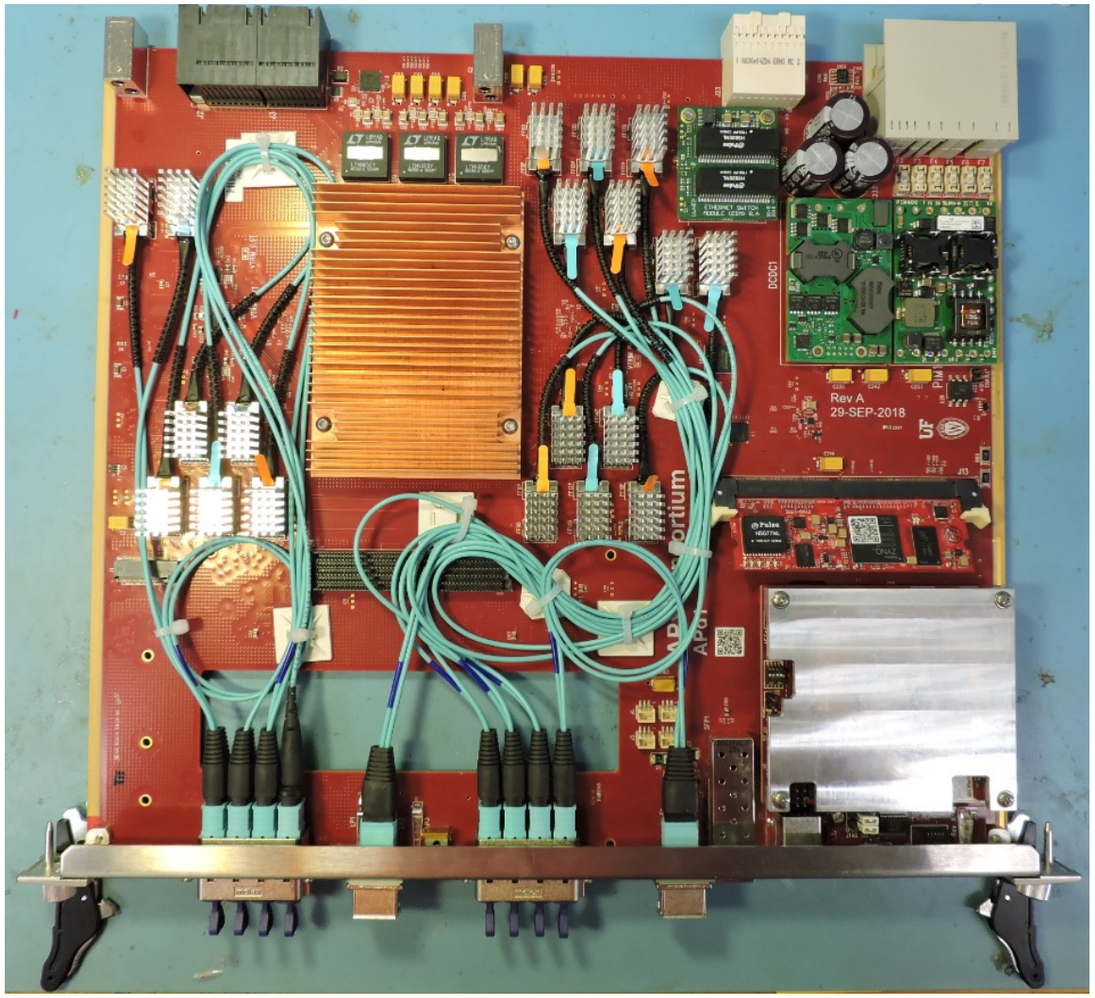
Hardware Prototype

Link infra

Regional sorting



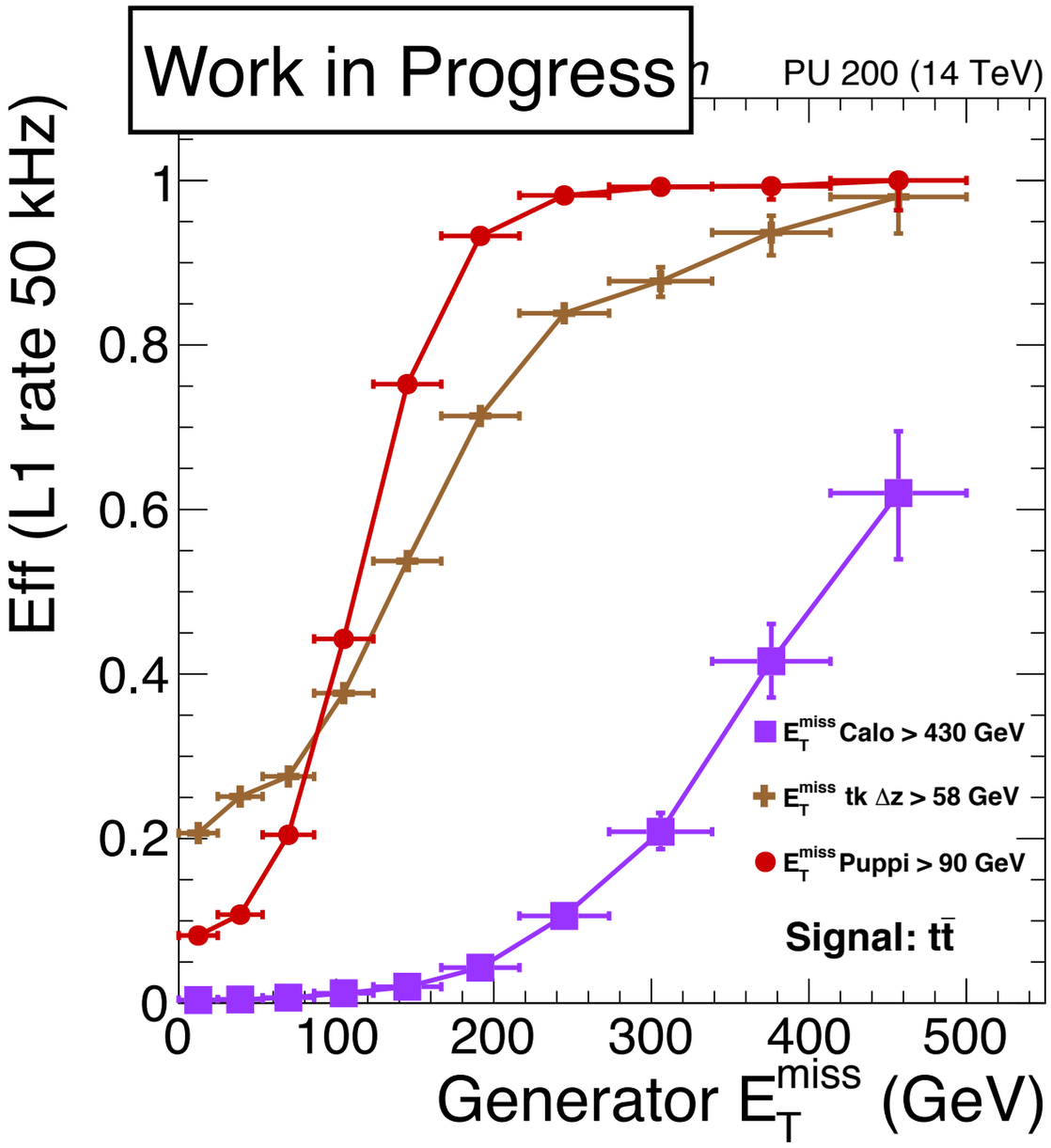
Placed preliminary algorithm on VU9P

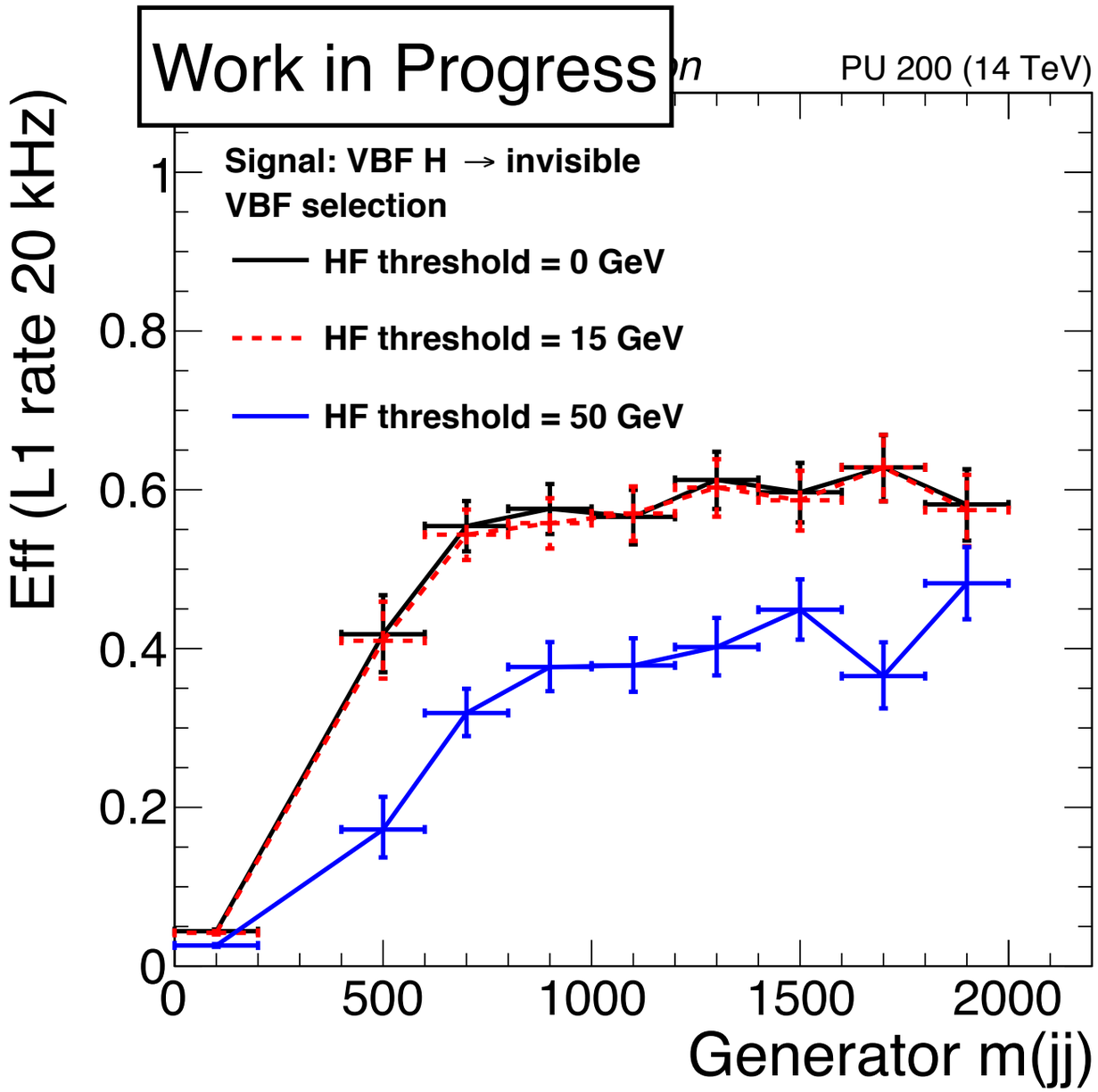


ATCA carrier card development lead by APx consortium

Layer 2 algorithms — Jets and MET

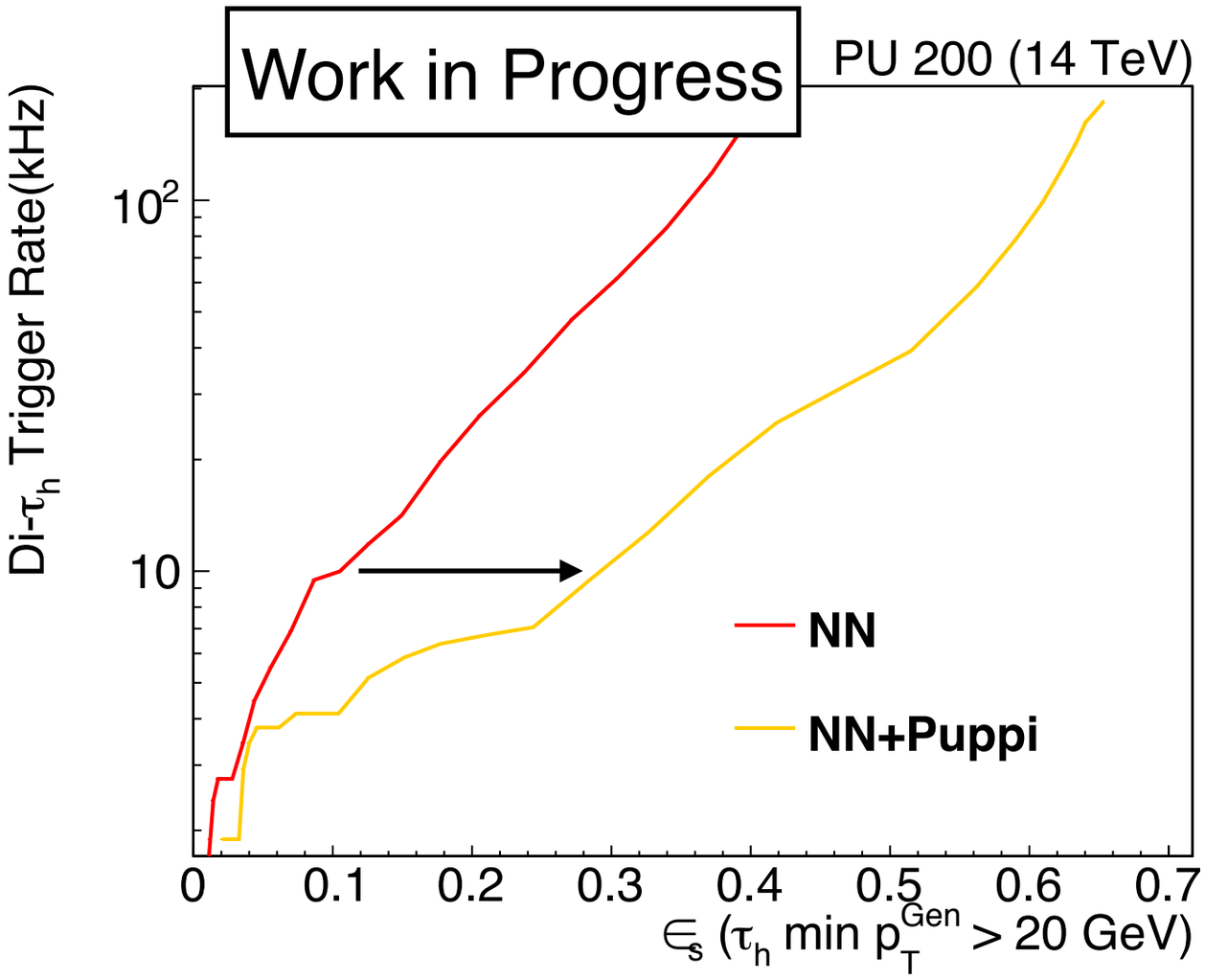
- Use PF+PUPPI candidates to build jets, energy sums





Layer 2 algorithms — Tau ID NN

- Identify hadronic tau decays using PF+PUPPI candidates



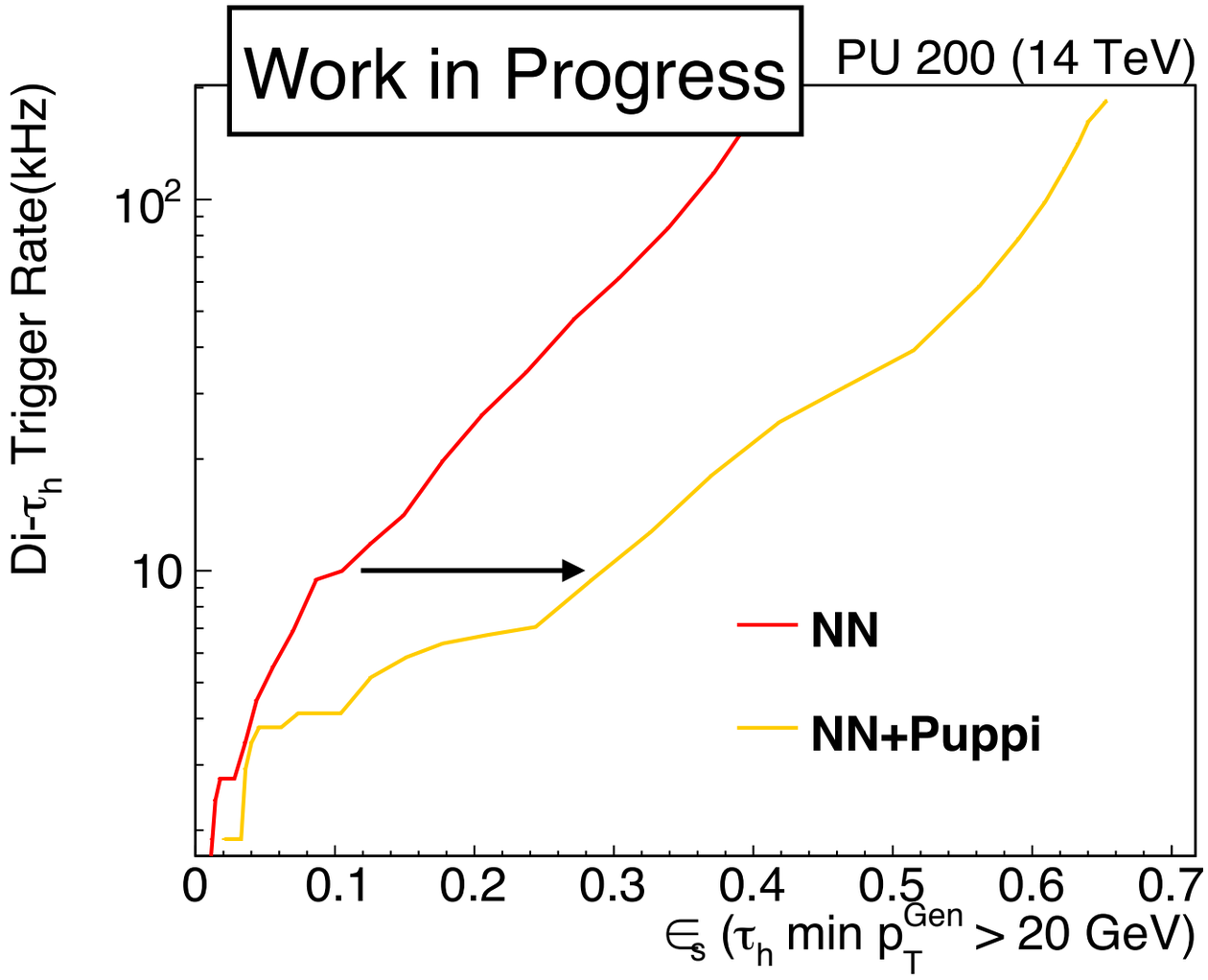
- Inputs: 10 nearby PF candidates (p_T,η,ϕ,id)
- Dense w/ 3 hidden layers (25,25,10) → 1 MVA ID
- This implementation:
  - Up to 18 PF+PUPPI candidates / event

A proof-of-principle prototype
Developed using hls4ml

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

Layer 2 algorithms — Tau ID NN

- Identify hadronic tau decays using PF+PUPPI candidates



A proof-of-principle prototype
Developed using hls4ml

- Inputs: 10 nearby PF candidates (p_T,η,ϕ,id)
- Dense w/ 3 hidden layers (25,25,10) → 1 MVA ID
- hls4ml

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

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…

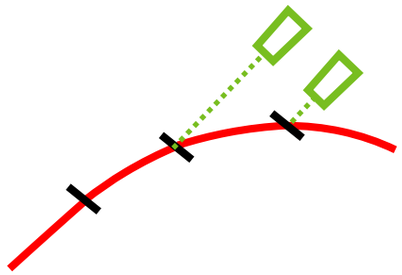
Mu… seg…

EC…

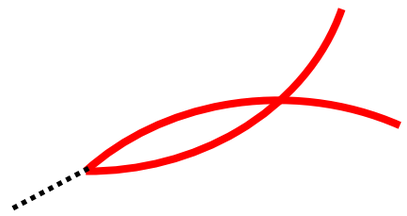
HCal…

The full story is a bit more complicated…

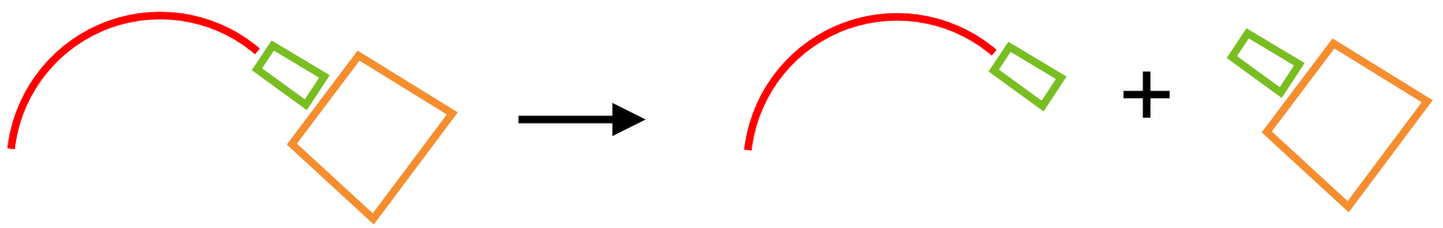
Kinked tracks, brem recovery



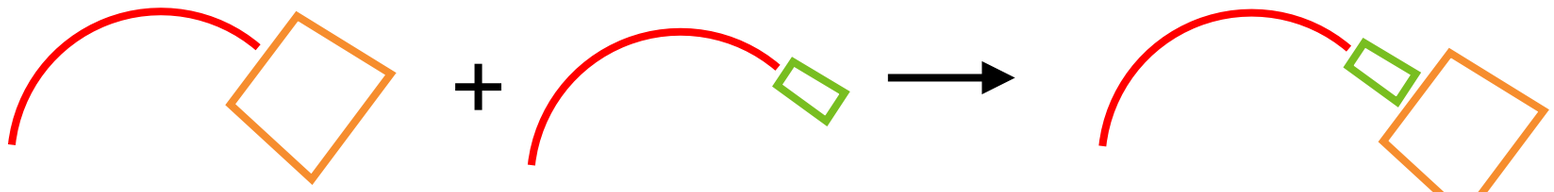
Secondary vertices



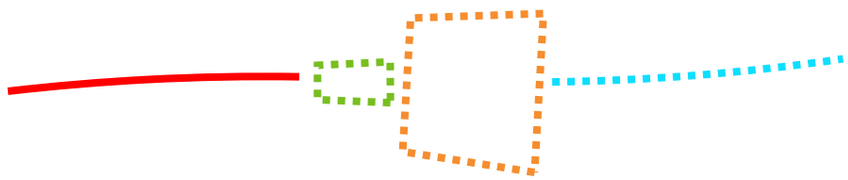
Cluster splitting



"Indirect linking"



Fake tracks



Neutral hadrons

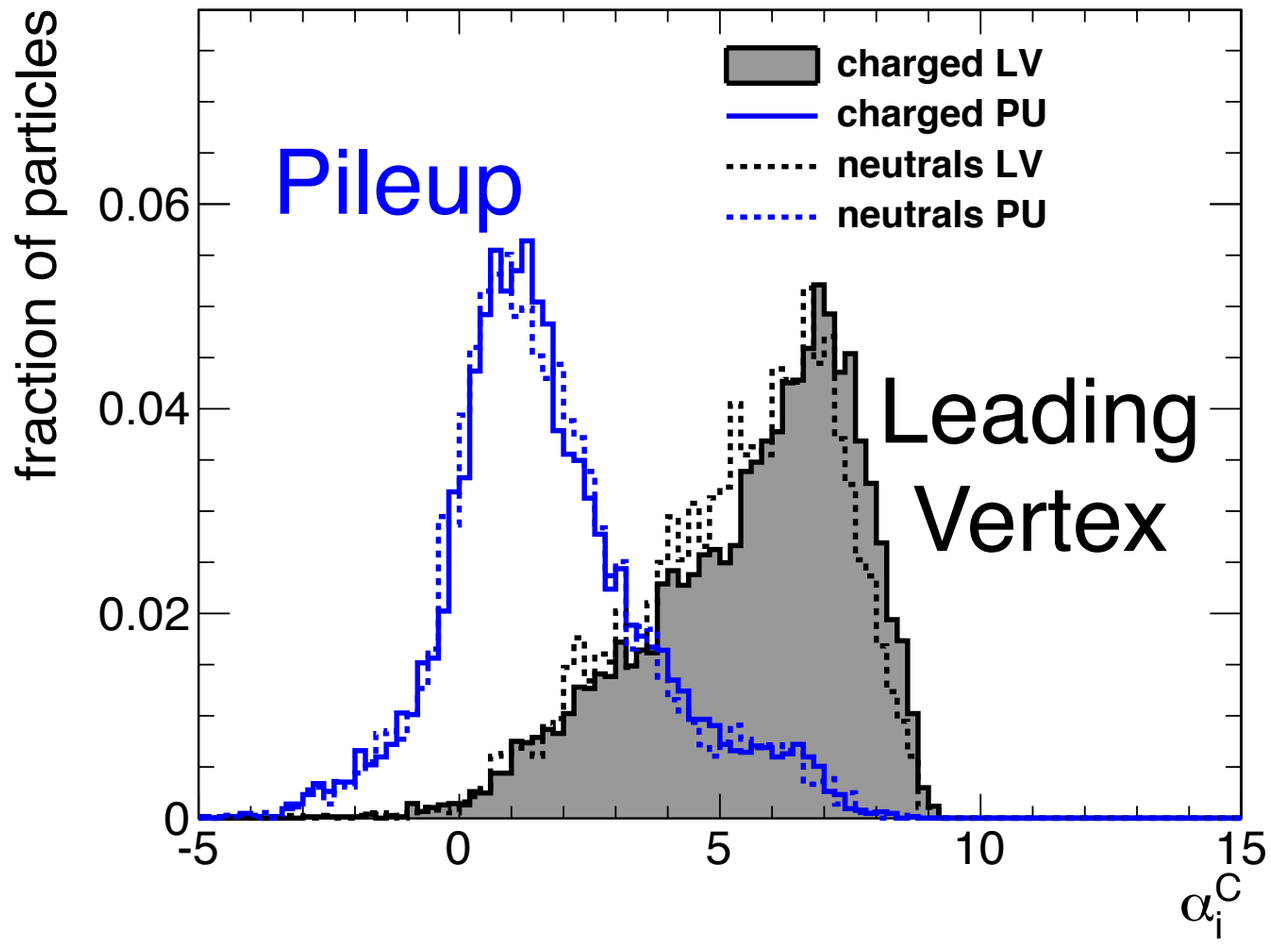
Pileup Per Particle Identification

- 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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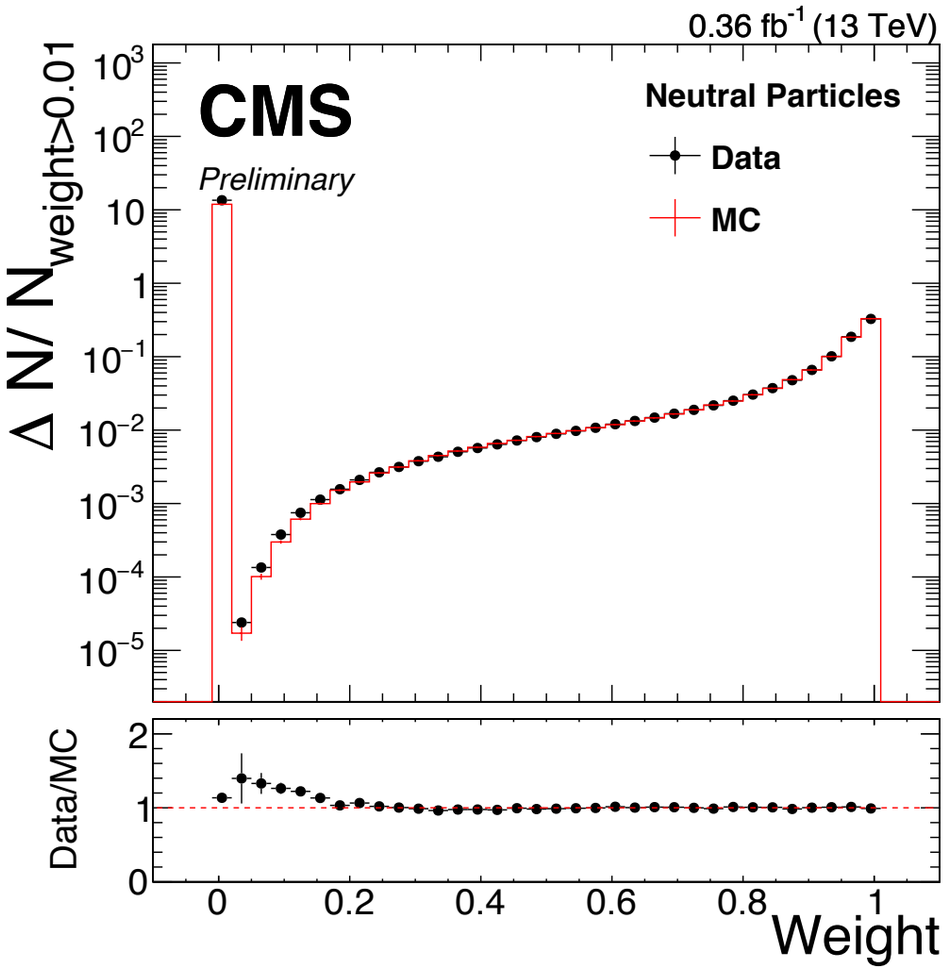
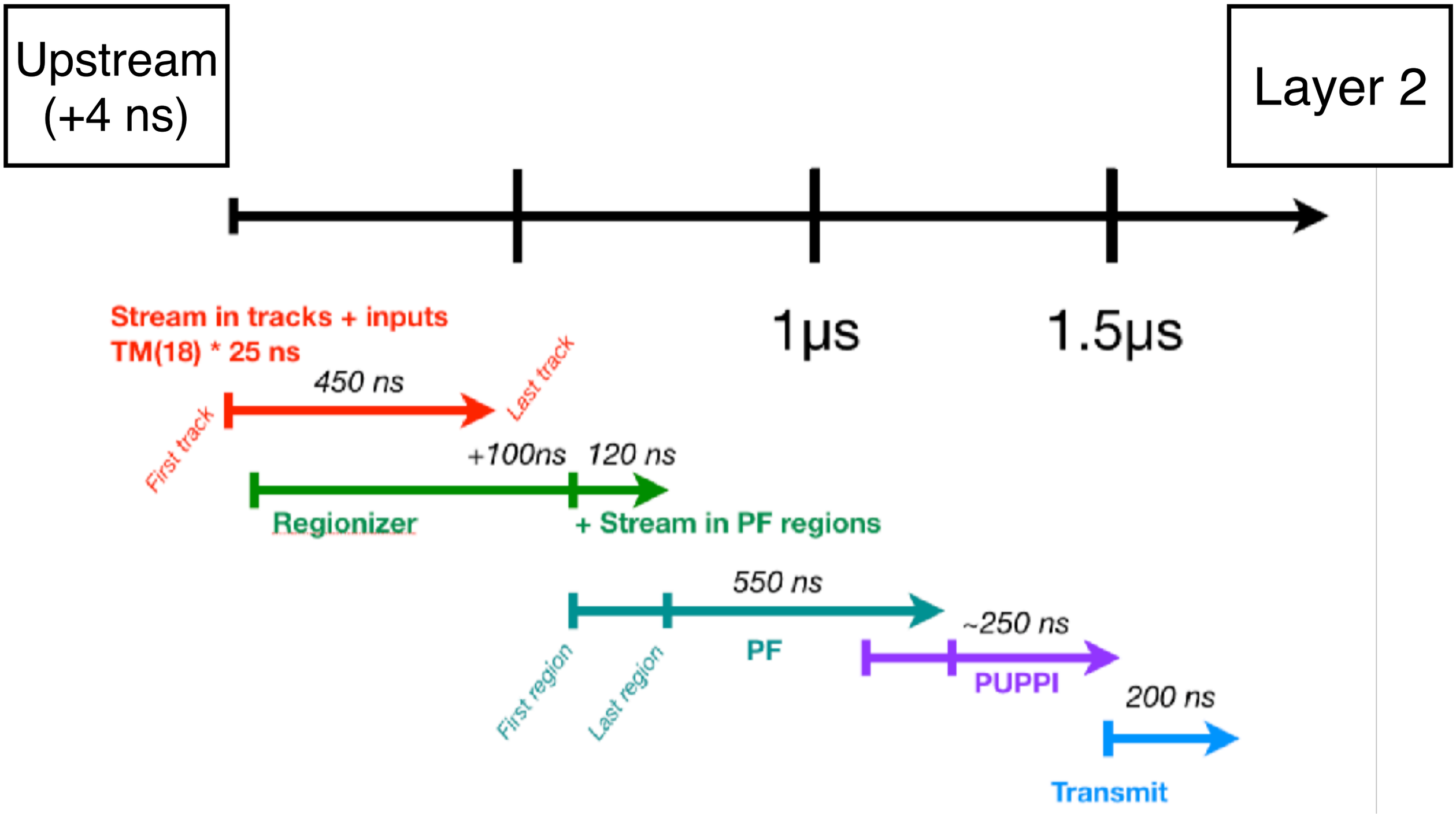


Compare α w/ expected distribution, given the level of pileup (chi2 test)

← obtain weights!

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

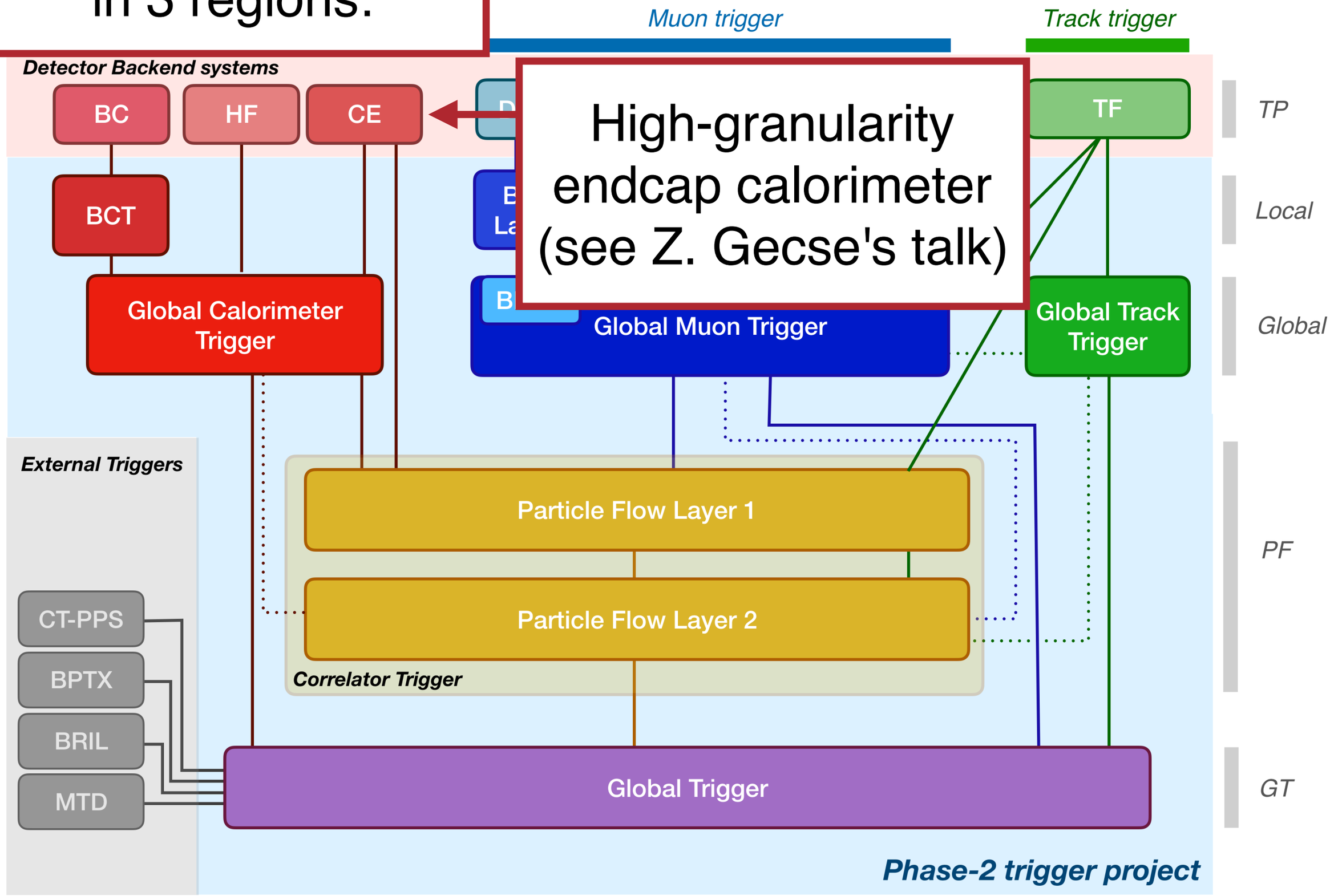
Latency budget



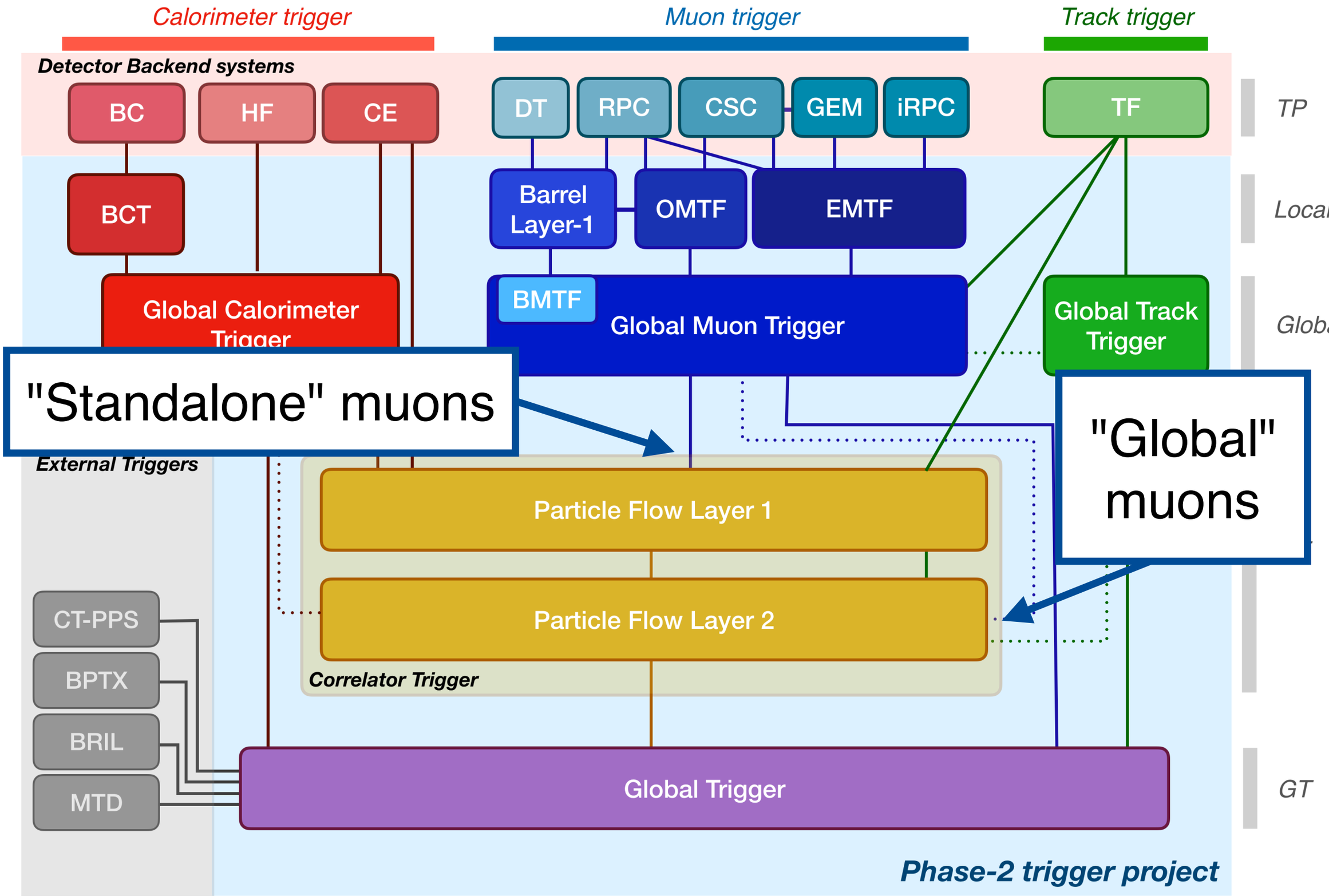
the Phase-II L1 Trigger

Calorimeter clusters in 3 regions:

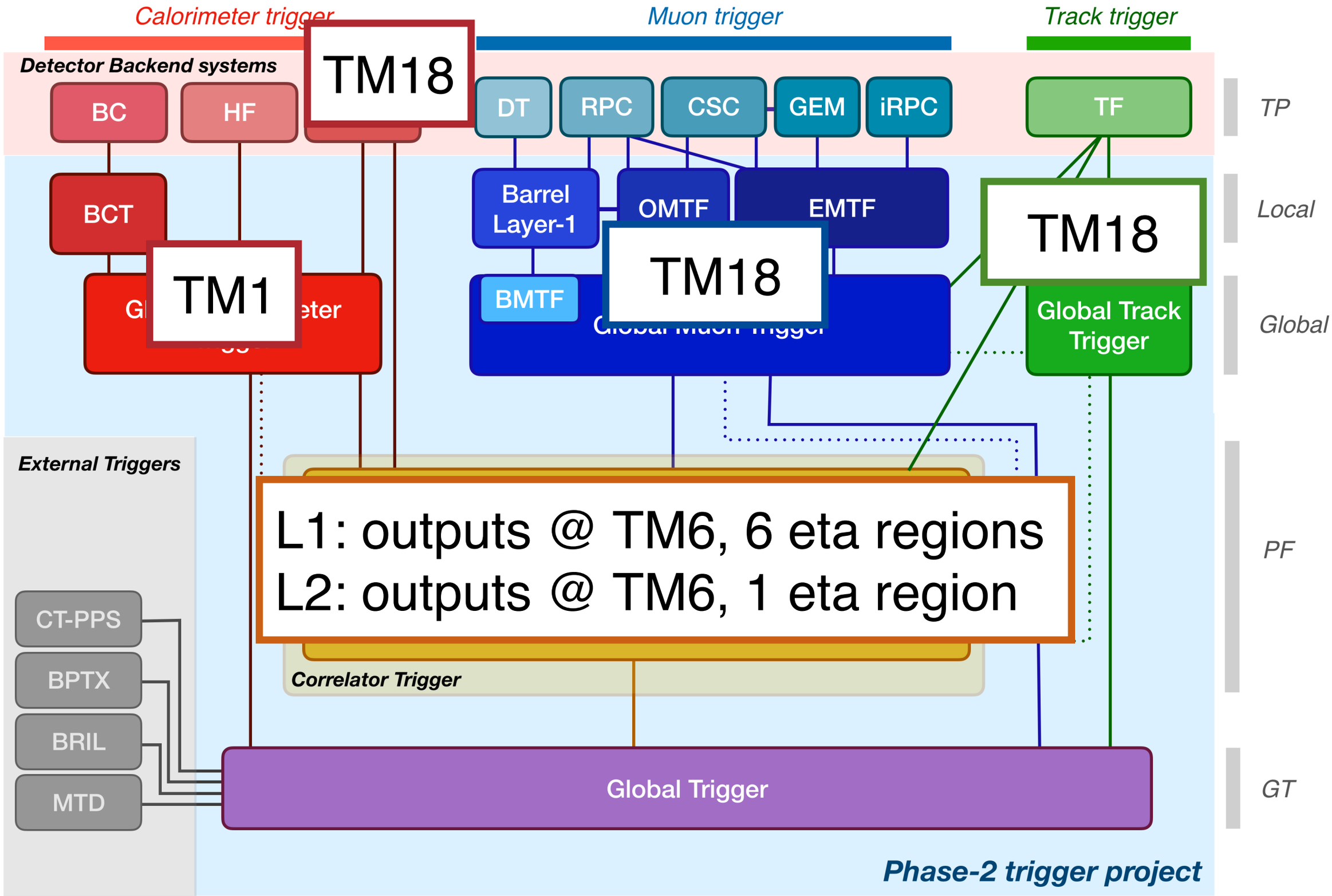
High-granularity endcap calorimeter (see Z. Gecse's talk)



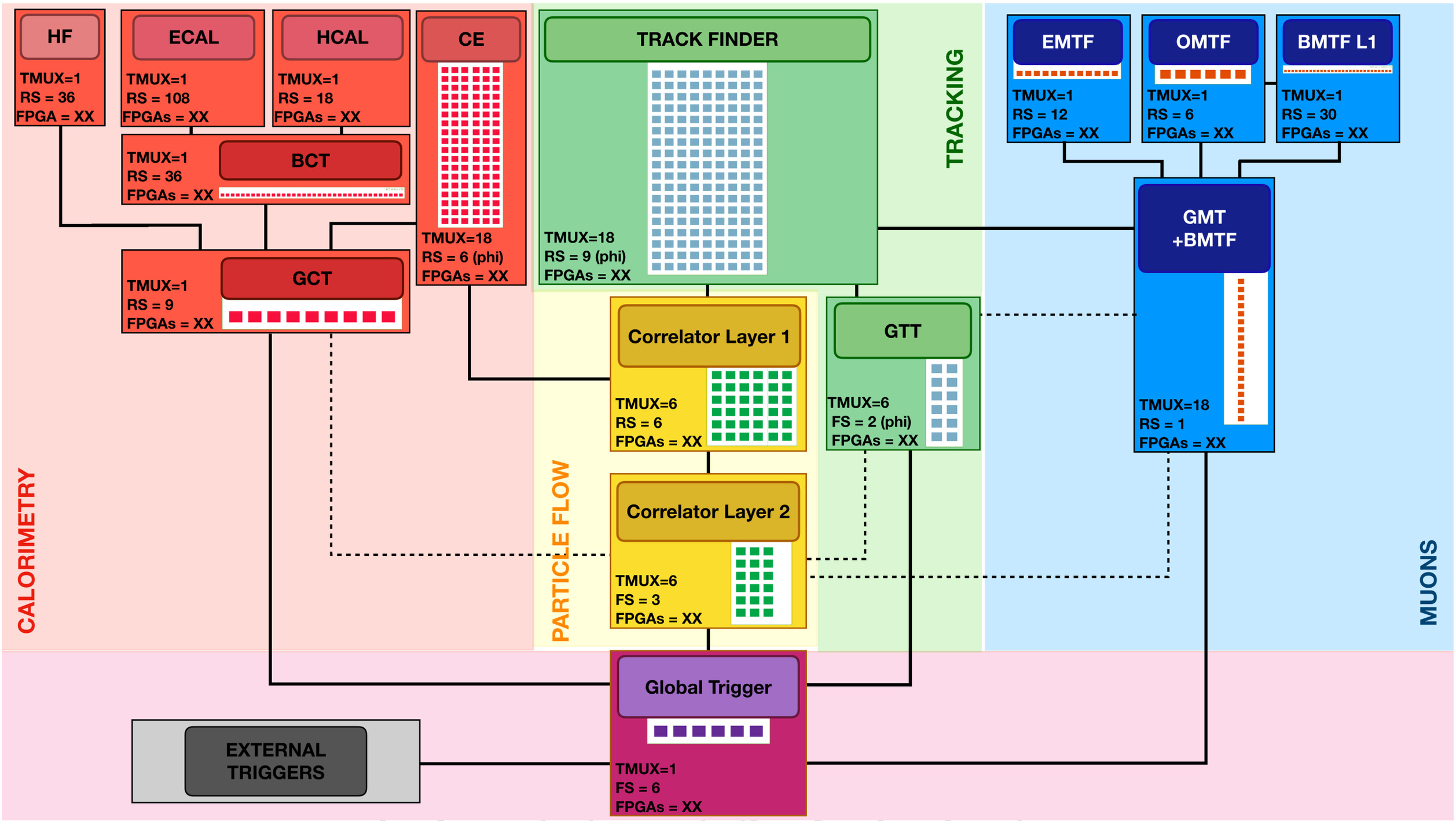
Architecture of the Phase-II L1 Trigger



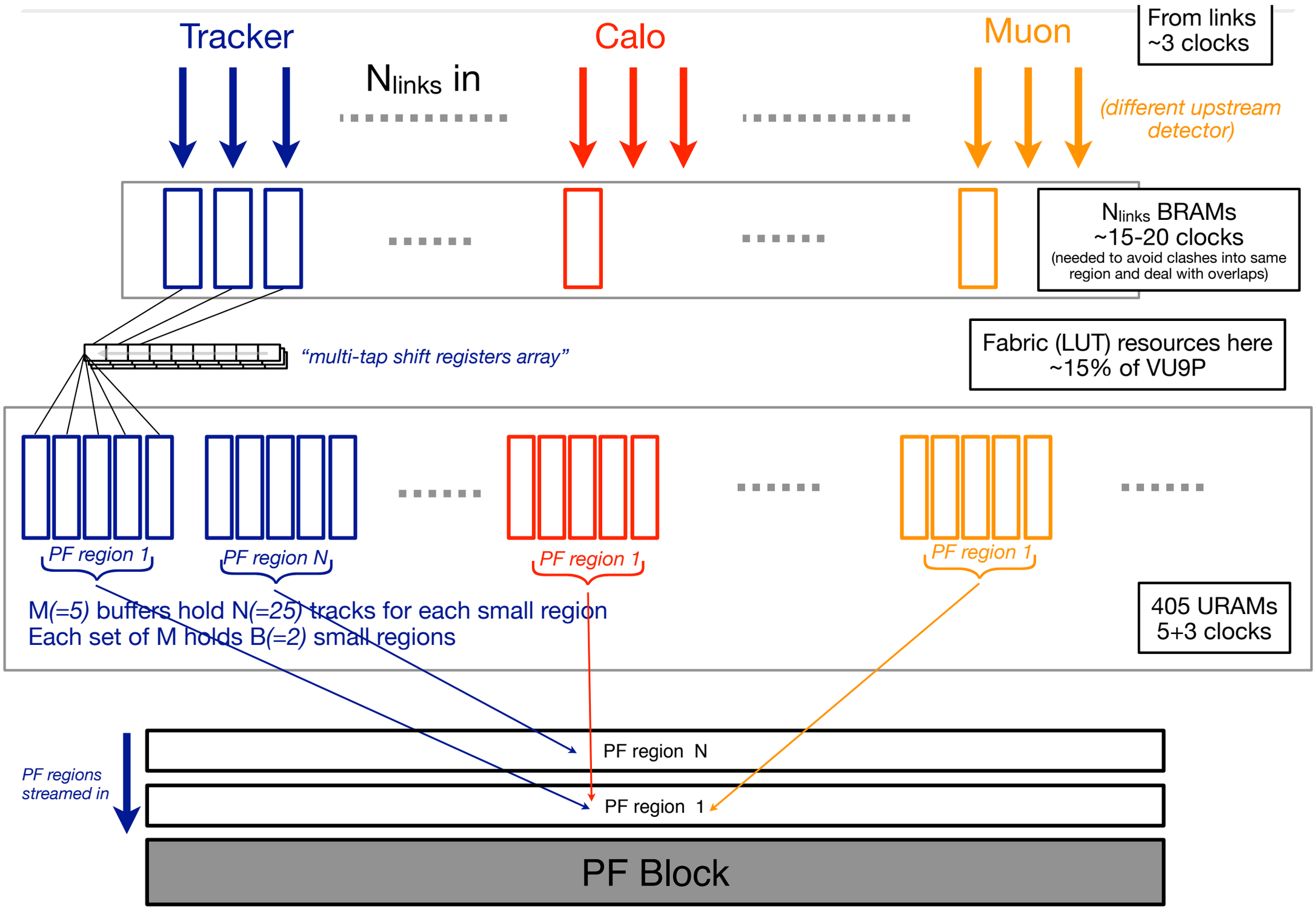
Architecture of the Phase-II L1 Trigger



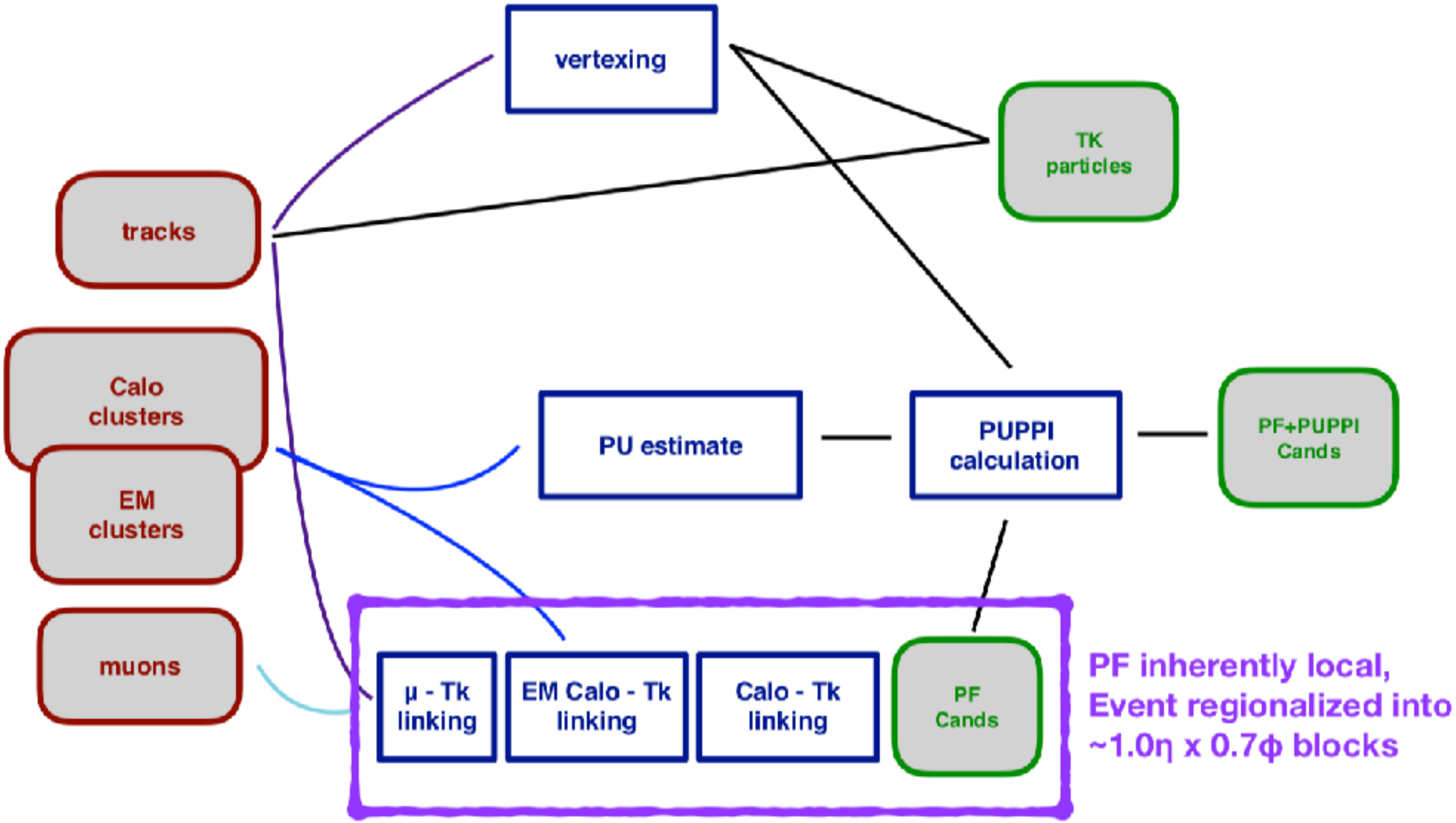
FPGA / TMUX / Region view



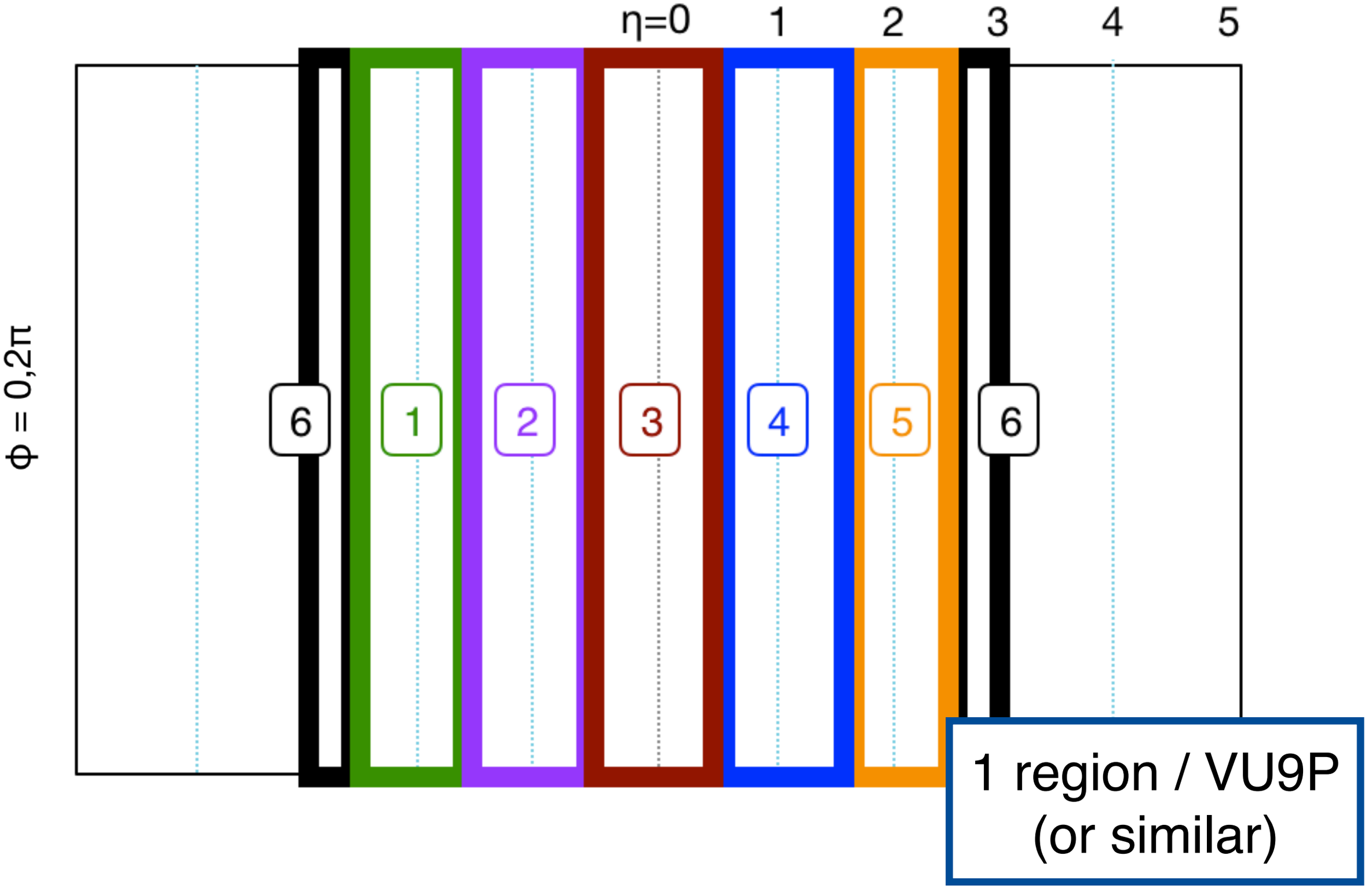
Firmware - Regionalization



PF+PUPPI algo



Regionalization — 'board regions'



1 region / VU9P
(or similar)