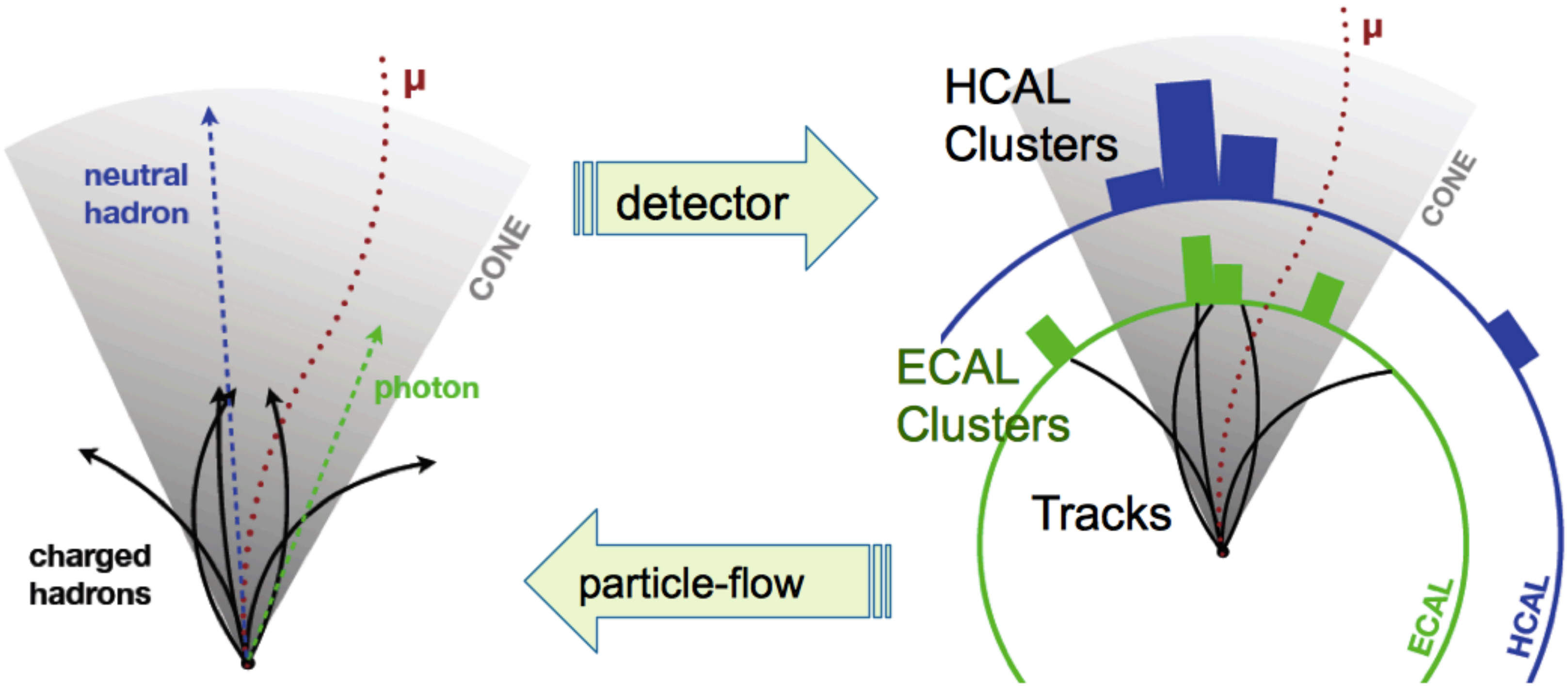
Particle Flow in the Level 1 Trigger for CMS Phase II

Giovanni Petrucciani (CERN)
on the behalf of the
CMS Collaboration

Particle Flow reconstruction



Goal: reconstruct and identify individually all particles produced in the CMS detector

Why Particle Flow?

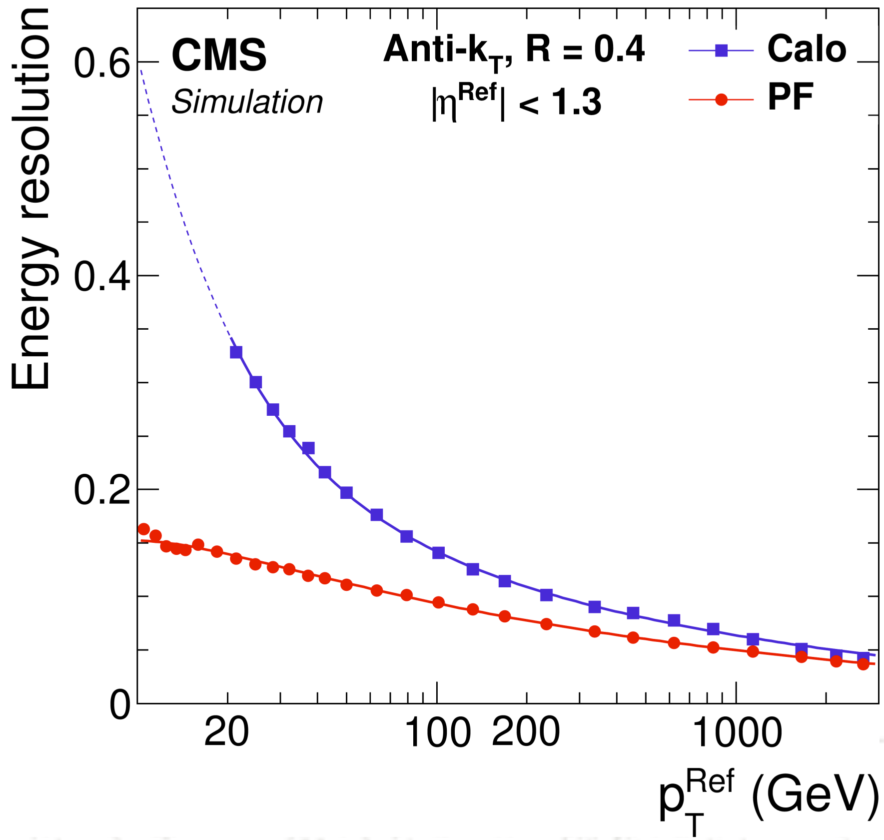
Several use cases where benefits from PF were proven in offline or HLTrigger reconstruction:

- **Jet performance**, especially at low p_T's relevant for e.g. top quark physics, ttH, compressed supersymmetry, ..
- **τ_h identification**
- **p_T^{miss}** performance
- as input to **pileup mitigation** strategies, e.g. per-particle pileup identification (PUPPI)

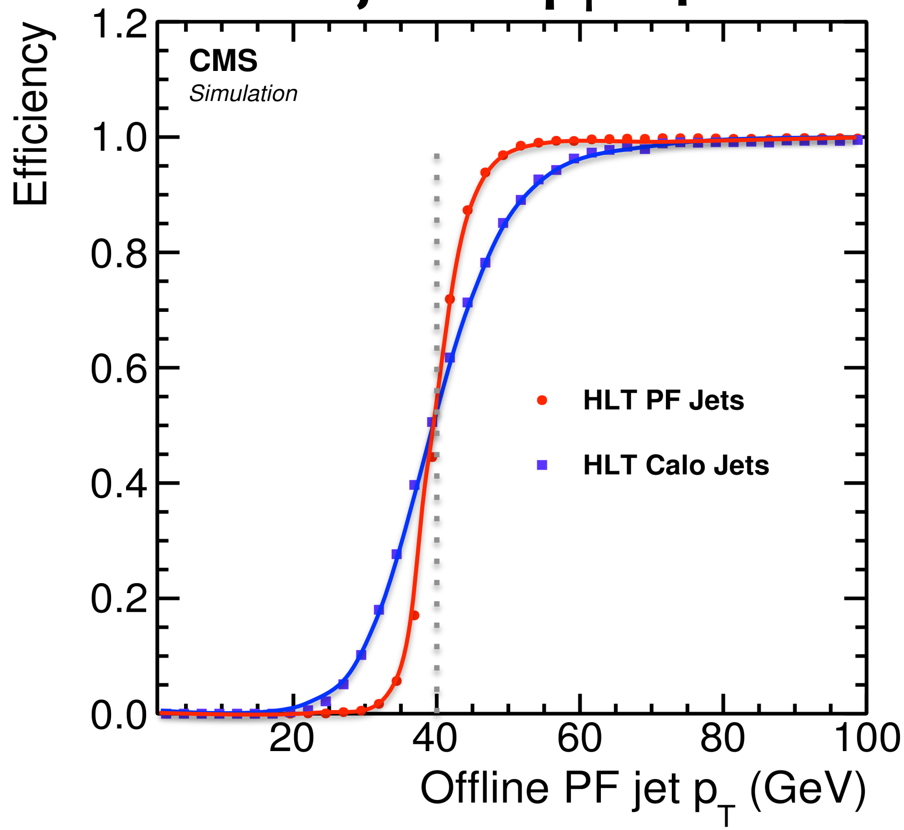
in other talks

PF Jet performance: Offline, HLT

Offline jet energy resolution: Calo vs PF



HLT turn-on curve for jets of $p_T > 40$



JINST 12 (2017) P10003 (lines added by hand in right plot for readability)]

Requirements for PF algo

1. efficient track reconstruction to identify and measure charged hadrons
   – Available at the L1 for the first time with the Phase II upgrade (for $p_T > 2$ GeV, $|\eta| < 2.4$)
2. finely segmented calorimeters, to separate individual particles
   – Phase II upgrade: crystal-level Ecal info at L1, and new high granularity Endcap Calorimeter.
3. enough processing resources

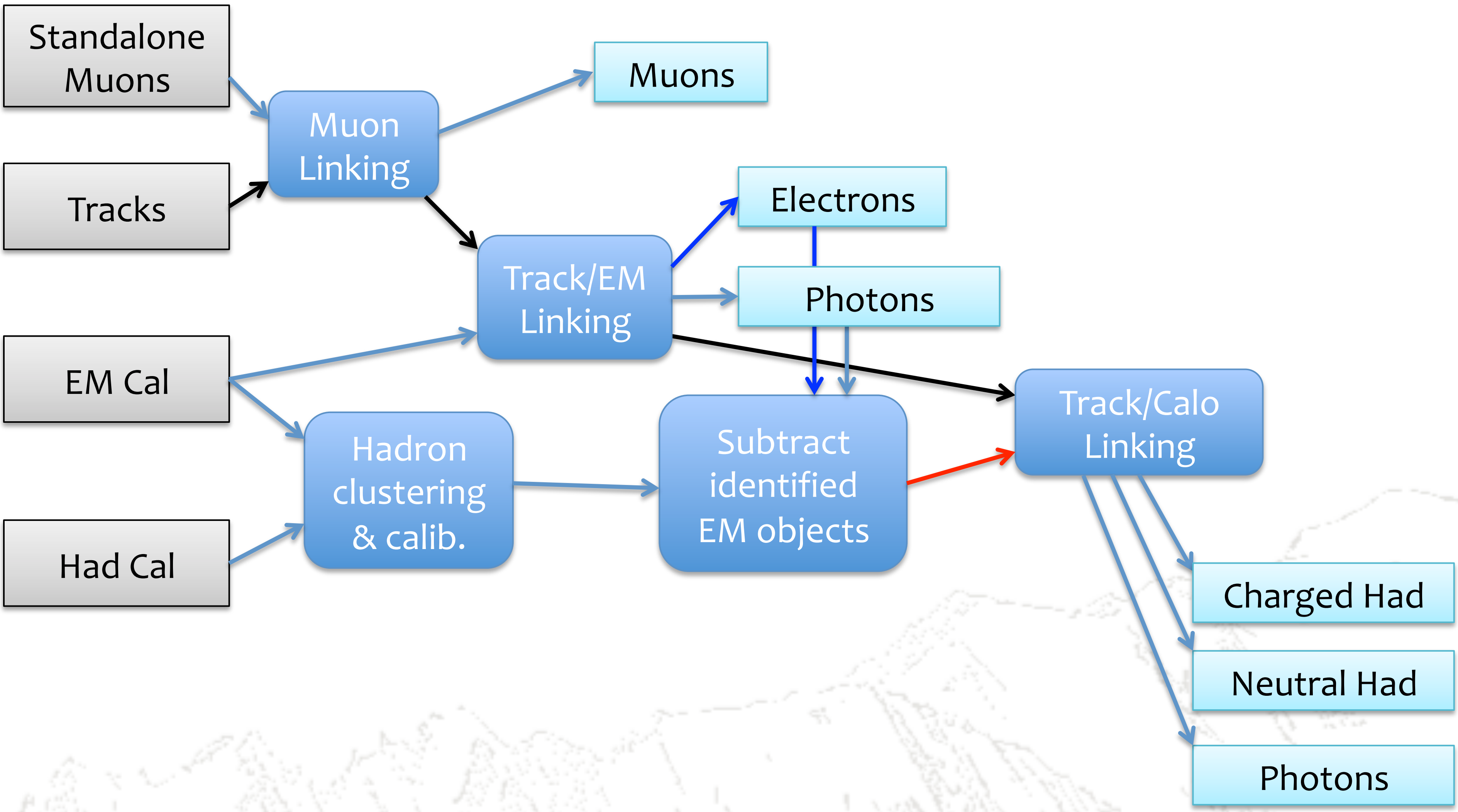
Constraints

- L1 receives input events at rate of 40 MHz, must output events after a fixed latency < 1μs
  - For comparison, the current PF @ H L Trigger, runs at O(20) kHz, taking O(100) ms/event
- FPGA architecture very different from a CPU
  - large number of processing components that can all work in parallel, but with much less flexibility
- Developed PF@L1 from first principles rather than adapting the very complex offline PF algo
  - Today presenting first prototype algorithm

L1 PF Inputs

- The current prototype L1 PF algorithm uses:
  - tracks from the L1 track trigger
  - clusters from the calorimeter triggers:
    - fine granularity clusters for photons & electrons
    - coarser granularity clusters for hadrons
  - muons from the muon system
- The algorithm for now is only relying on basic information on the inputs (position, energy, …)
  - Improvements possible in the future exploiting more inputs, e.g. cluster timing, shower shapes, …

L1 PF Algorithm chart

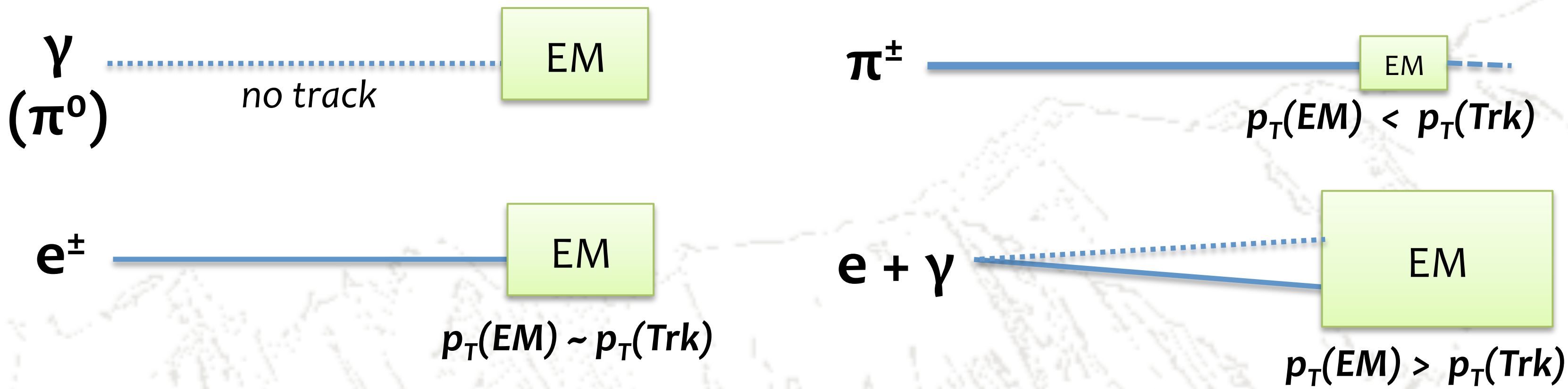


L1 PF Algo: muons

1. Link tracker tracks to muon detector tracks
   - for each muon reconstructed in the muon subdetector, look for the best matching track, in the inner tracker, in direction and momentum
   - call that track a muon
   - mask it out from further PF algorithm steps

L1PF Algo: $e^{\pm}$, γ

- Select narrow clusters in the EM calorimeter
- Link each track to the nearest EM cluster
  - require tight matching in position, exploiting the fine granularity of the EM calorimeters
- Compare p_T(EM) vs p_T(Trk)
  - Define photons and electrons
  - For pion-like tracks, keep the track for further PF steps, and discard the EM cluster

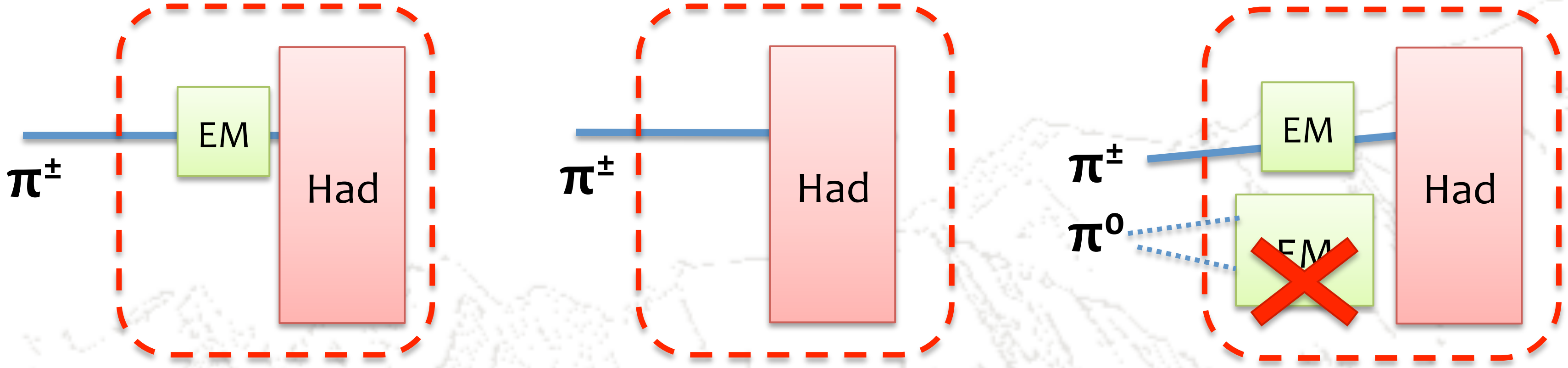


L1 PF Algo: hadrons

1. Combine EM and Had calorimeter to make hadron clusters (possibly already in the calo trigger)
   – Apply energy calibration as function of p_T, η and EM/(EM+Had), derived for pions
   – Remove EM clusters from photons and electrons identified by the PF algorithm
2. Link each tracks to the "best" cluster
   – look also at the matching in p_T during linking
   – forbid high p_T tracks to match to low p_T clusters (and then discard unlinked high p_T tracks: ~ fakes)
3. Compare calo p_T to sum of linked track p_T's
   – Promote significant energy excess to neutral particles

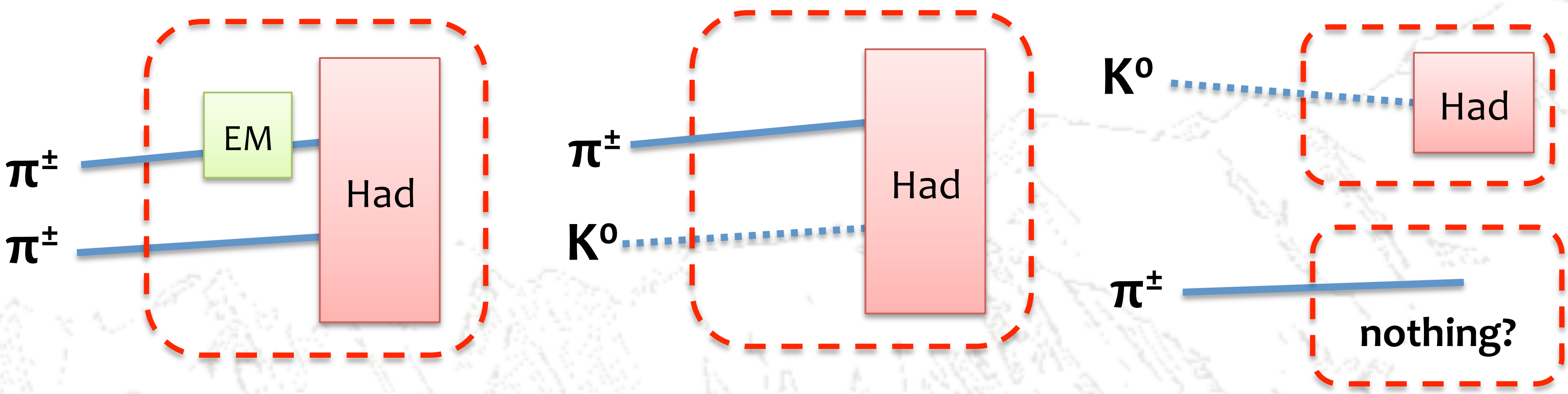
L1 PF Algo: hadrons / 1

1. Combine EM and Had calorimeter to make hadron clusters (possibly already in the calo trigger)
   – Apply energy calibration as function of p_T, η and EM/(EM+Had), derived for pions
2. Remove energy from EM clusters of photons and electrons identified by the PF algorithm



L1 PF Algo: hadrons / 2

3. Link each tracks to the “best” cluster
   - look also at the matching in p_T during linking
   - forbid high p_T tracks to match to low p_T clusters (and then discard unlinked high p_T tracks: ~ fakes)
4. Compare calo p_T to sum of linked track p_T’s
   - Promote significant energy excess to neutral particles

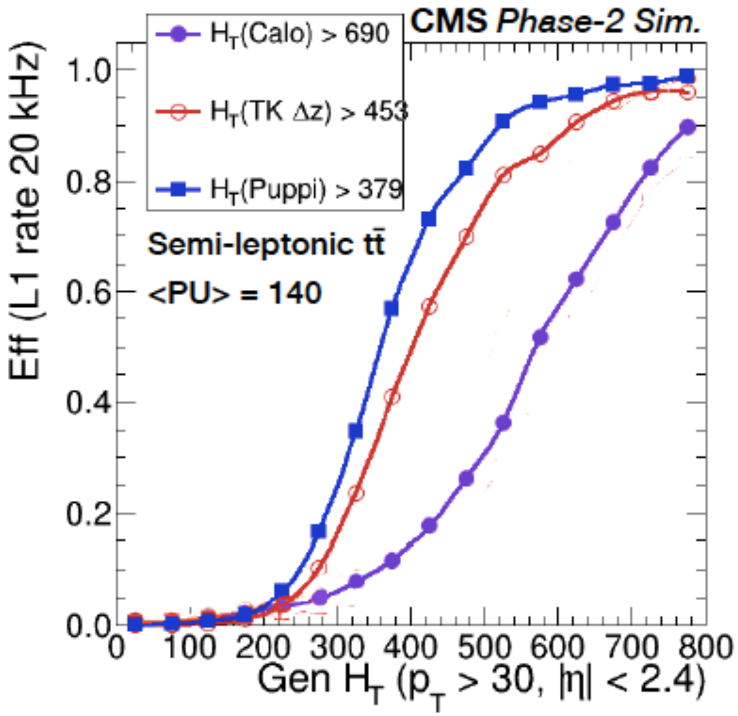


FPGA Implementation

- Rely on Vivado High Level Synthesis framework to compile C++ code into HDL and firmware
  - C++ code optimized to yield an efficient firmware
  - output of optimized code validated for bitwise identity with original reference version
  - firmware deployed and validated on spares of existing CMS Phase I L1T boards (Virtex-7 based)
- Extrapolate from Virtex-7 to newer FPGAs proposed for the Phase II upgrade
  - latency prototype algorithm ~ 0.5μs, with reasonable FPGA resource usage

Performance

- Performance of an H_T trigger using jets made from:
  - Calorimeters alone
  - L1 Tracks (with PV constraint)
  - PF (+Puppi pileup mitigation)
- In all cases, use ak4 jets with corrected p_T > 30 GeV, |η| < 2.4
- Compare turn-on curve at a fixed background rate:
  - PF has lowest theshold (best rate reduction)
  - PF has best turn on shape (best correlation with true H_T)



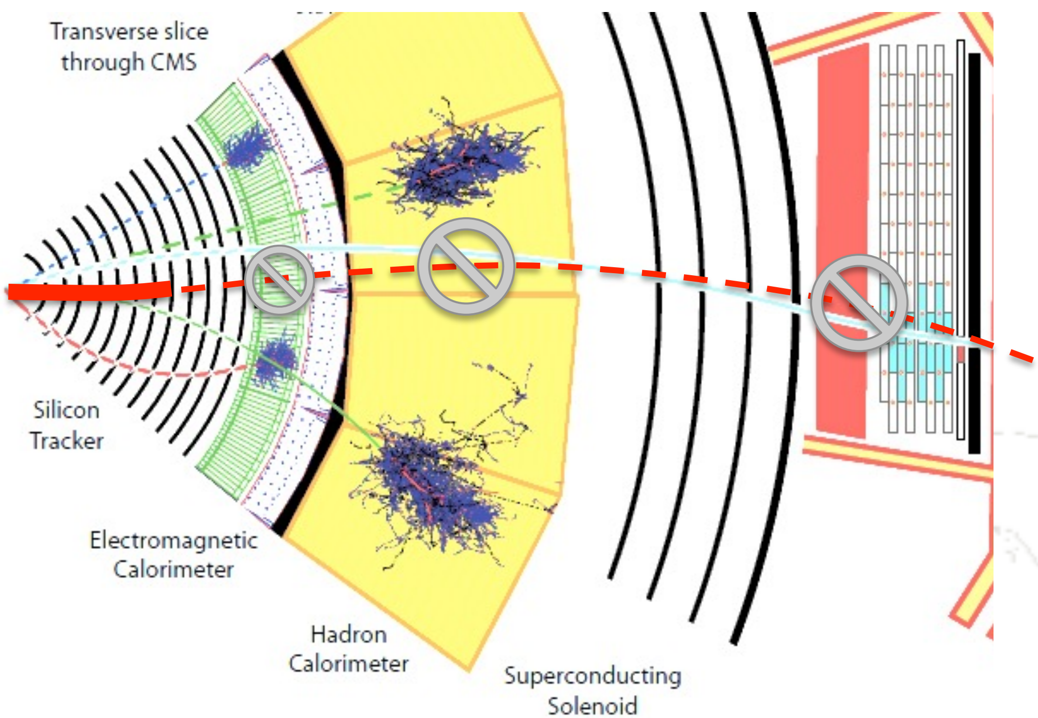
[CMS TDR 17-004]

Physics implications?

- Expect PF to improve L1 reconstruction performance especially for jets, p_T^{miss}, τ
  - Important in selecting BSM physics decaying to SM particles, or produced in association with SM particles
  - Should be able to preserve efficiency for events with many moderate p_T jets (e.g. ttH, tttt, …)
- Could it provide new handles to trigger directly on some exotic signatures?
  - "Yes if you could select those events offline without pixel subdetector and without a custom tracking" would be my best guess at a generic answer.

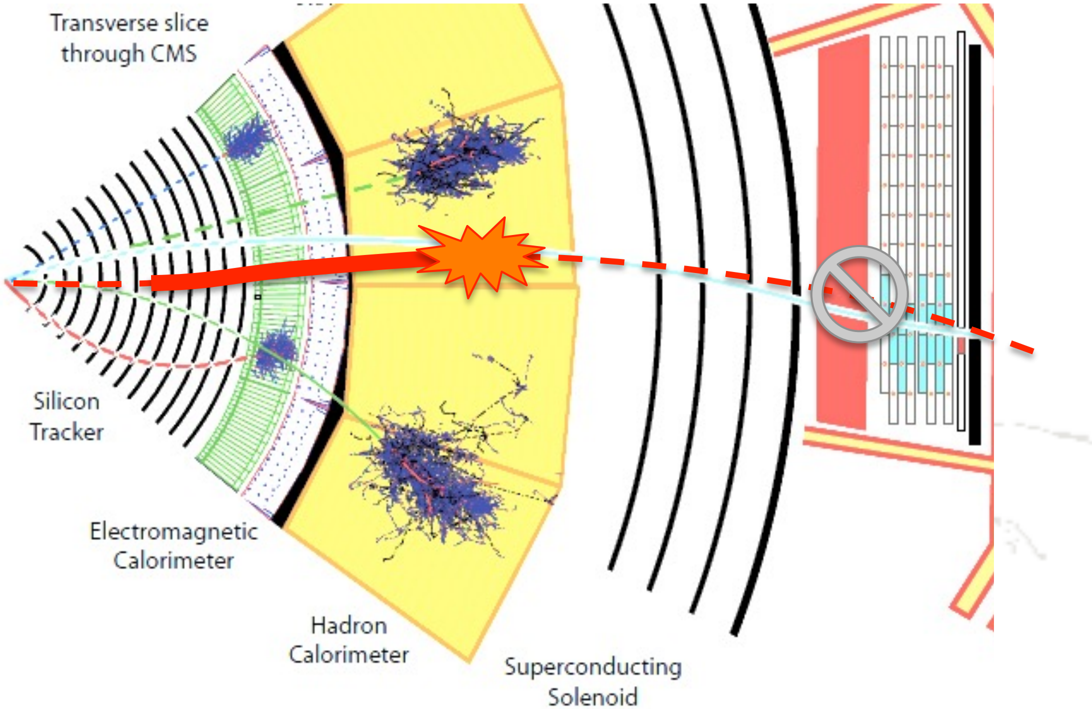
PF response to BSM signals: disappearing charged particle

- short high p_T track, no energy in calo, no muon signal
  - if the track is reconstructed it will be rejected by PF algo as fake
- Short track likely not reconstructed at L1
  - need ≥4 layers of outer tracker for a decent L1 track
- **Will look like p_T^{miss}**



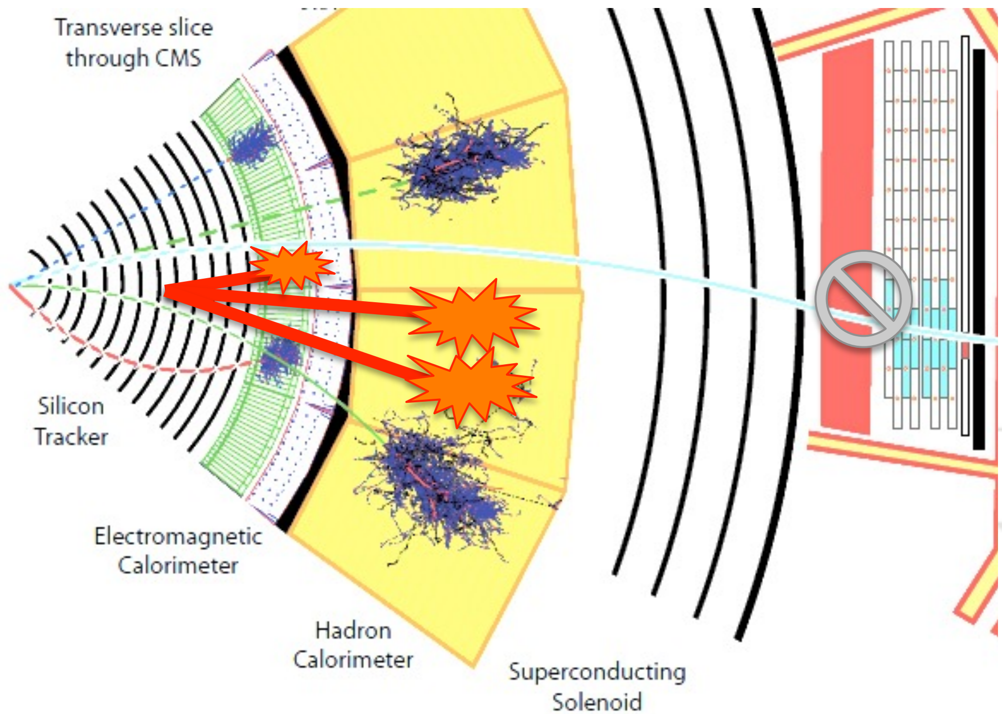
PF response to BSM signals: appearing charged particle

- track starting late + signal in the calo.
- early decay: track will look ordinary
  - L1 can't notice the lack of pixel hits
- late decay: track may be missed
- **Will look like a charged hadron, or a neutral one**



PF response to BSM signals: appearing jets

- signal will be seen in the calorimeters
  - **PF will reconstruct the visible energy**
- if tracks are found, they will likely not point to the PV
  - pile-up removal algorithms may reject them
  - Jet ID may dislike jets with no charged particles inside



PF response to BSM signals: heavy stable charged particle

- long high p_T track, ~ no energy in calo, a muon signal
  - will look like an isolated muon (dE/dx info not available in L1T)
- If it's too slow, the muon stub may be out of time
  - but it could still be available for PF to use in L1 reco