Triggering at collider experiments

Alex Tapper

Slides available at:

http://www.hep.ph.ic.ac.uk/~tapper/lecture/CMSIndia-2020.pdf

Imperial College London

Outline

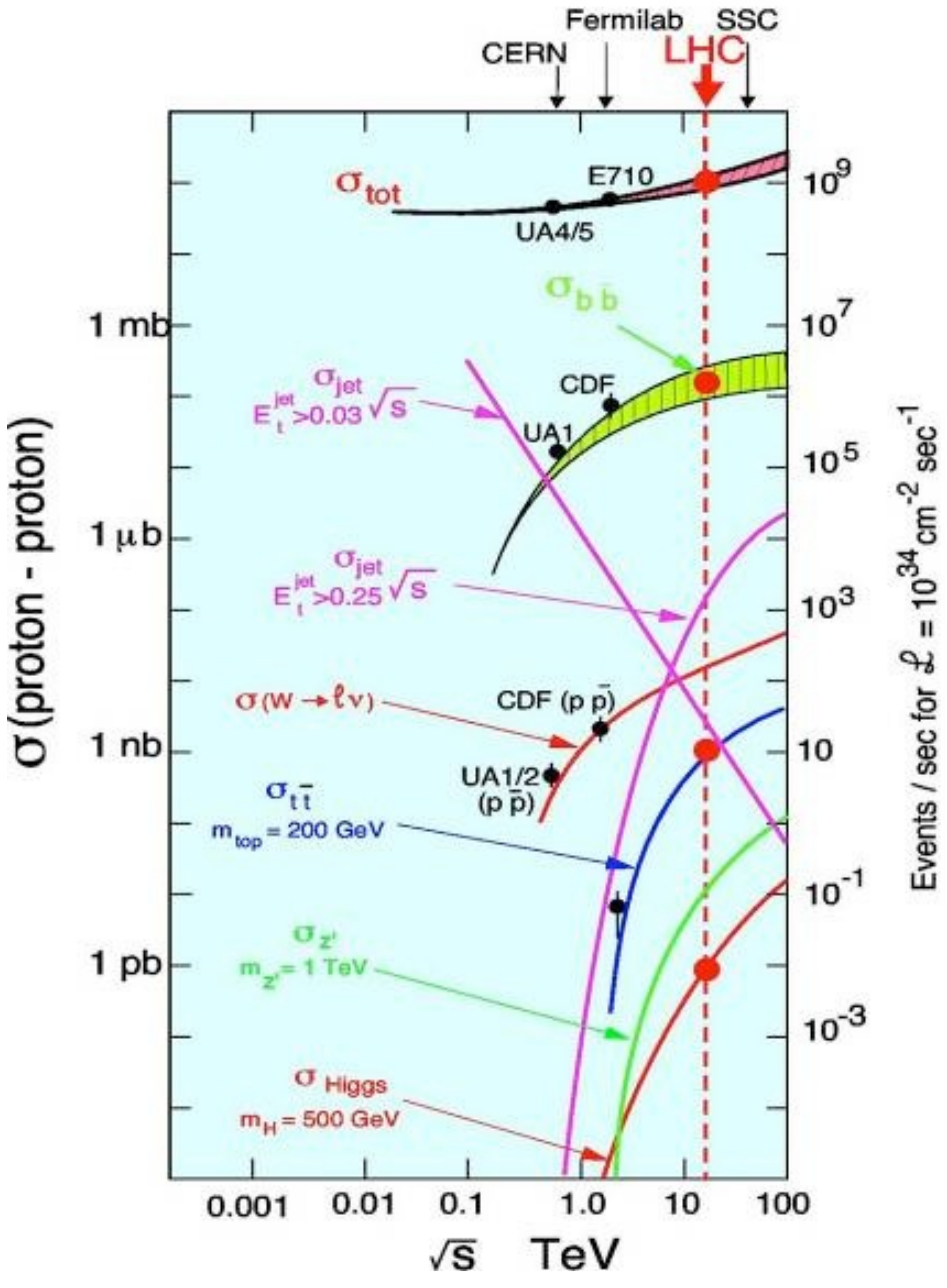
- Motivation and some important concepts
- Historical overview highlighting how challenges have driven development in the past
- Case study: current CMS trigger
- Case study: CMS trigger upgrade for HL-LHC
- Practical advice

Outline

- Motivation and some important concepts
- Historical overview highlighting how challenges have driven development in the past
- Case study: current CMS trigger
- Case study: CMS trigger upgrade for HL-LHC
- Practical advice

What and why?

- Enormous data rate:
  - 40 MHz * 1-2 MB
  - > 60 TB/s
  - Can't write this to tape!
- Just throw away events randomly?
  - Tiny cross sections for Higgs and new physics
  - Selection 1:10^{11}
- All online
  - Can't go back and fix it.
  - Don't screw up!



Challenges and constraints

- Constraints on trigger come from:
  - Accelerator: Bunch crossing rate, pile-up and multiple interactions, beam-gas interactions
  - Physics: What is required to make the decision to keep or reject an event? Simple objects like electrons and jets, track finding, matching objects together....
  - Output: How much data can you write to tape? How much can you reconstruct at an acceptable rate?

Some important definitions

- Good trigger will capture it's design physics and anything unexpected and reject common processes

- Deadtime
  - Trigger is not live for some reason so cannot take data
- Prescaling (downscaling)
  - Take every nth event that fires your trigger
  - Adjust n to allowed bandwidth
- Pass-through events (mark and pass)
  - Randomly select an event and allow it to pass the trigger regardless of any criteria
  - Useful to study and validate trigger systems

Outline

- Motivation and some important concepts
- Historical overview highlighting how challenges have driven development in the past
- Case study: current CMS trigger
- Case study: CMS trigger upgrade for HL-LHC
- Practical advice

The first trigger?

- Blackett pioneered a technique to trigger the camera of cloud chambers (and got the Nobel prize for this and other work)
- Just missed out on discovering the positron in 1932
- Stevenson and Street used this to confirm the discovery of the muon in 1937
- Can measure momentum and ionisation ($\sim 1/\beta^2$)
- Derive mass of particle - not electron or proton

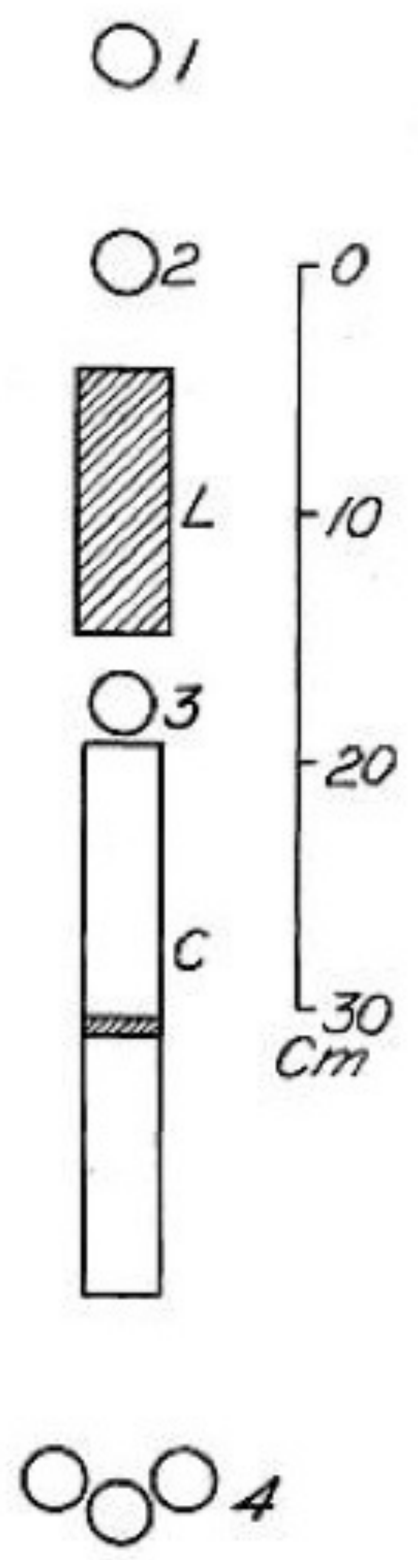
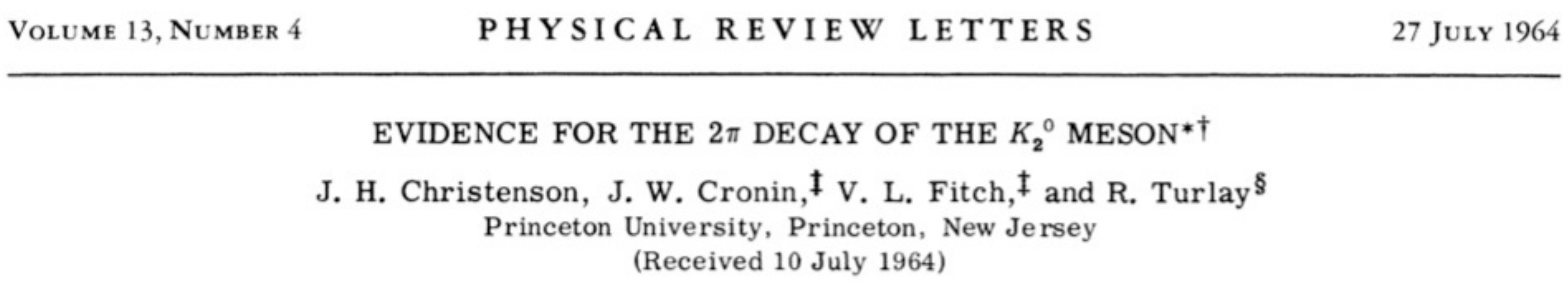


FIG. 1. Geometrical arrangement of apparatus.

Bubble chambers

- Accelerator gave a low-level trigger
  - Each expansion photographed
- DAQ was photographs
- Offline selection was human (looking at photographs)
- Only the most common processes observed
- Need to scan a huge number of photographs

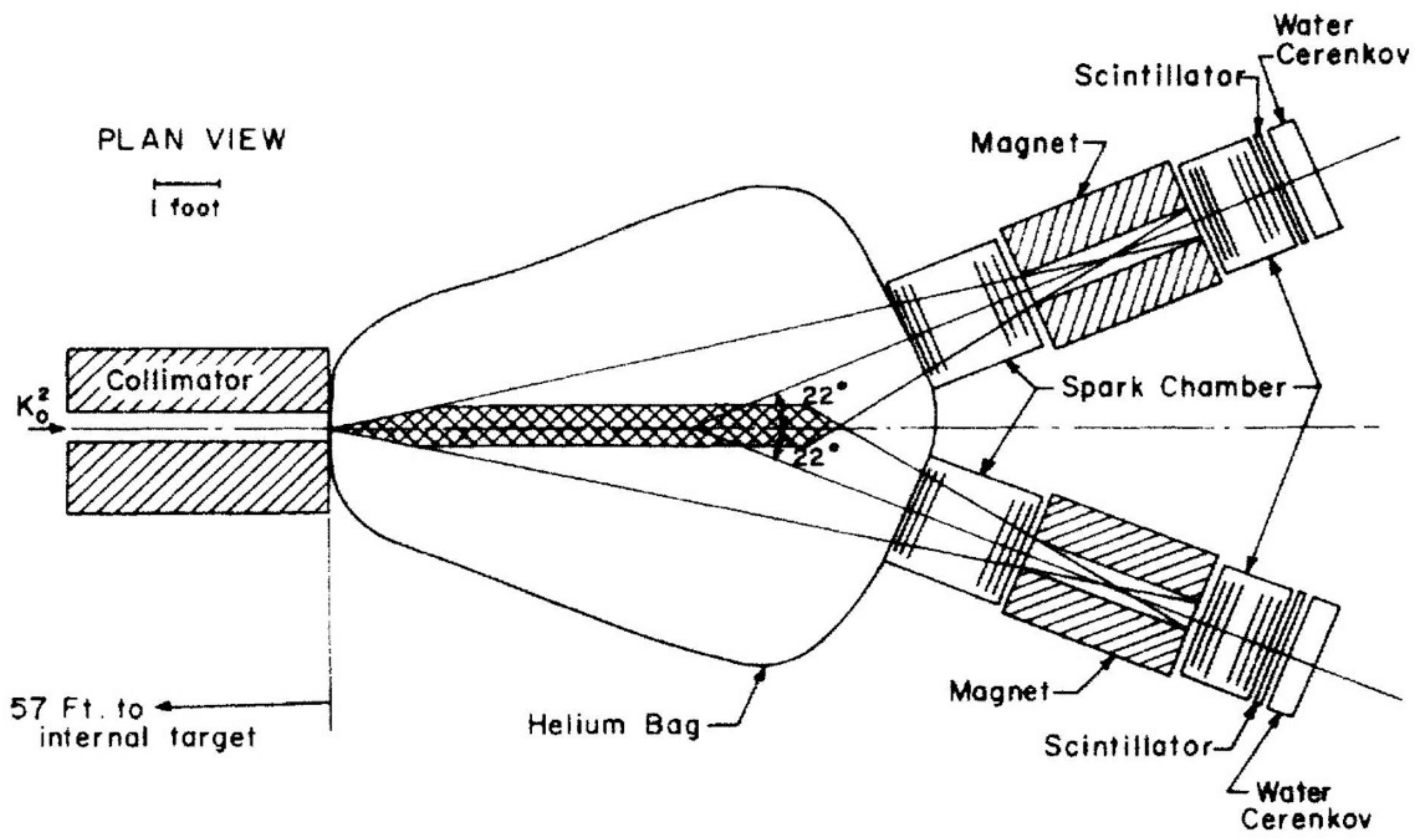
Fixed-target experiments



VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

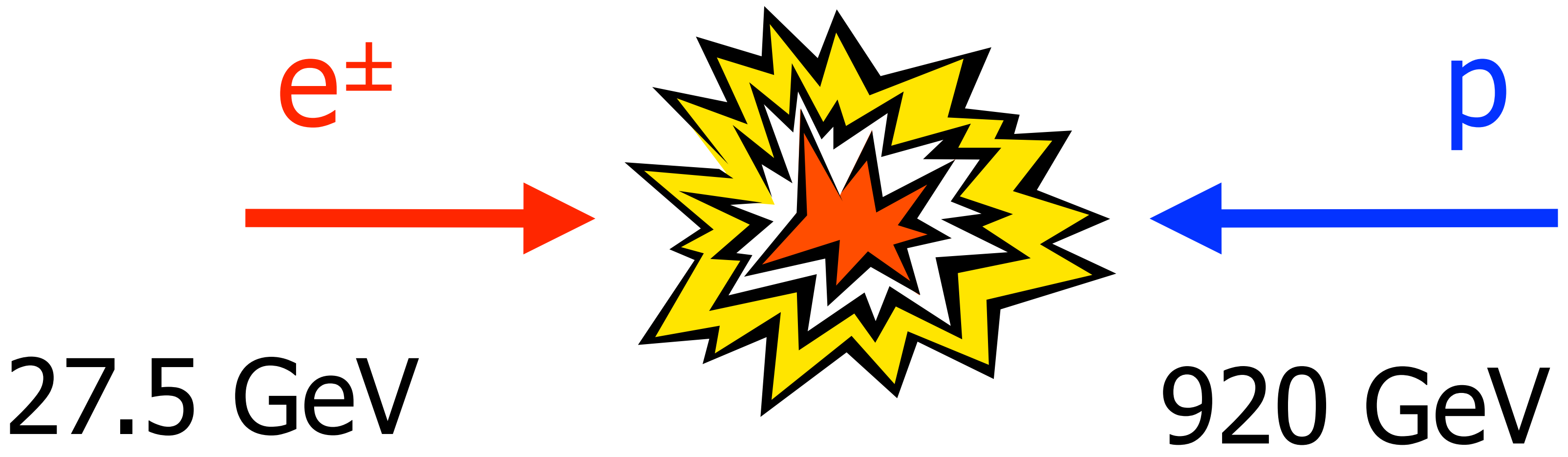
EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)



- Real physics triggers around in the '60s
- Discovery of CP violation
- Experiment triggered on coincidence of scintillators and Cerenkov detectors
- Small effect that they would not have seen otherwise (10^{-3})
- High dead time while detectors read out

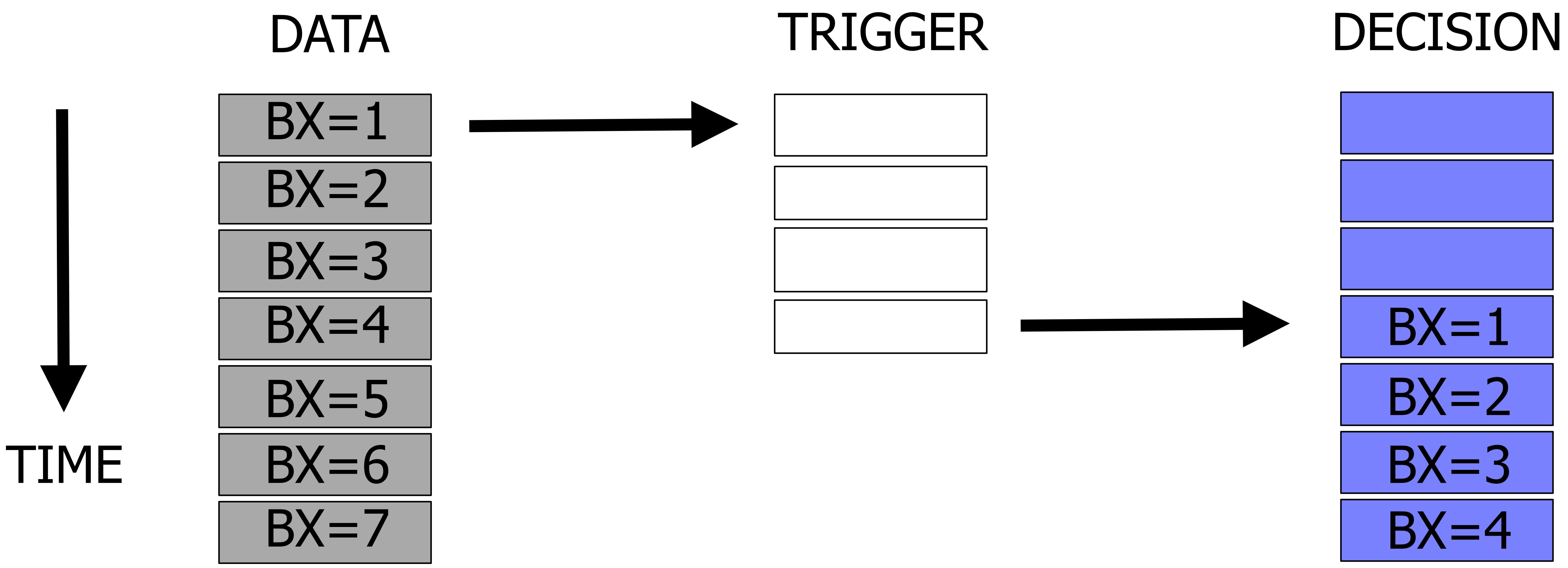
HERA



- 1992 - 2007
- Crossing rate 10 MHz (96 ns) very challenging
- Dominated by beam-gas interactions
- First use of pipelined trigger logic →

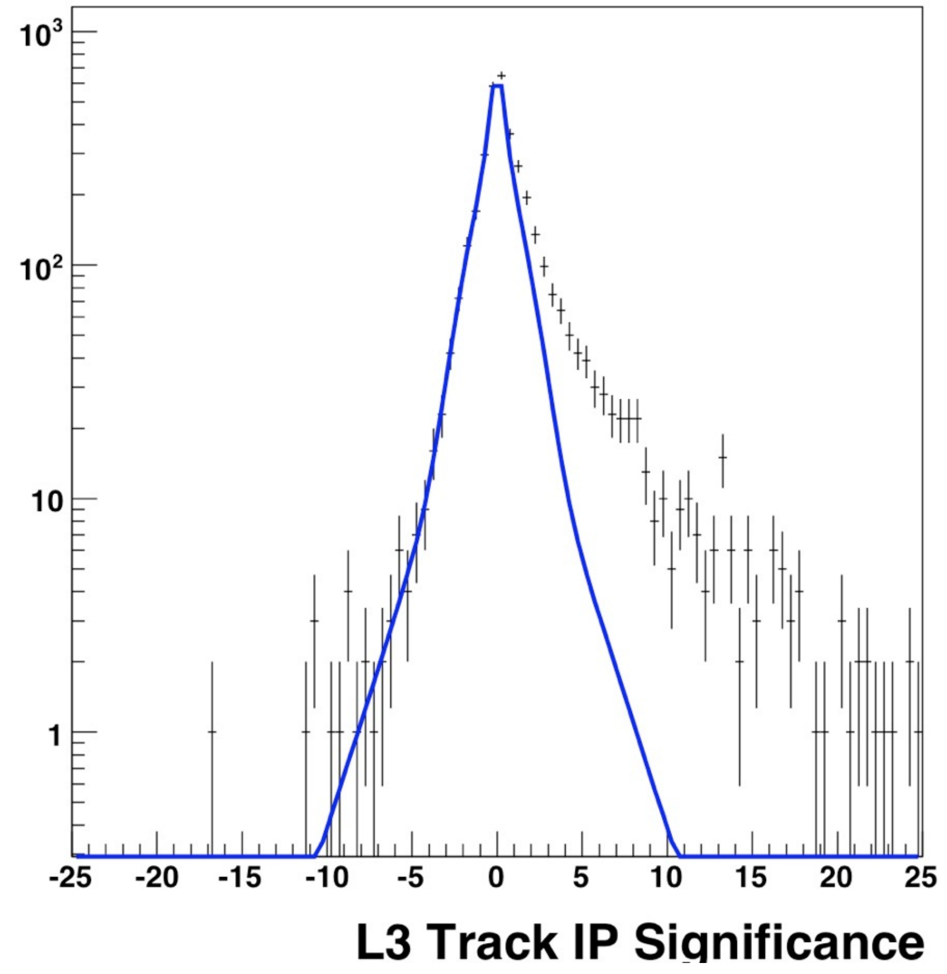
Pipelined trigger logic

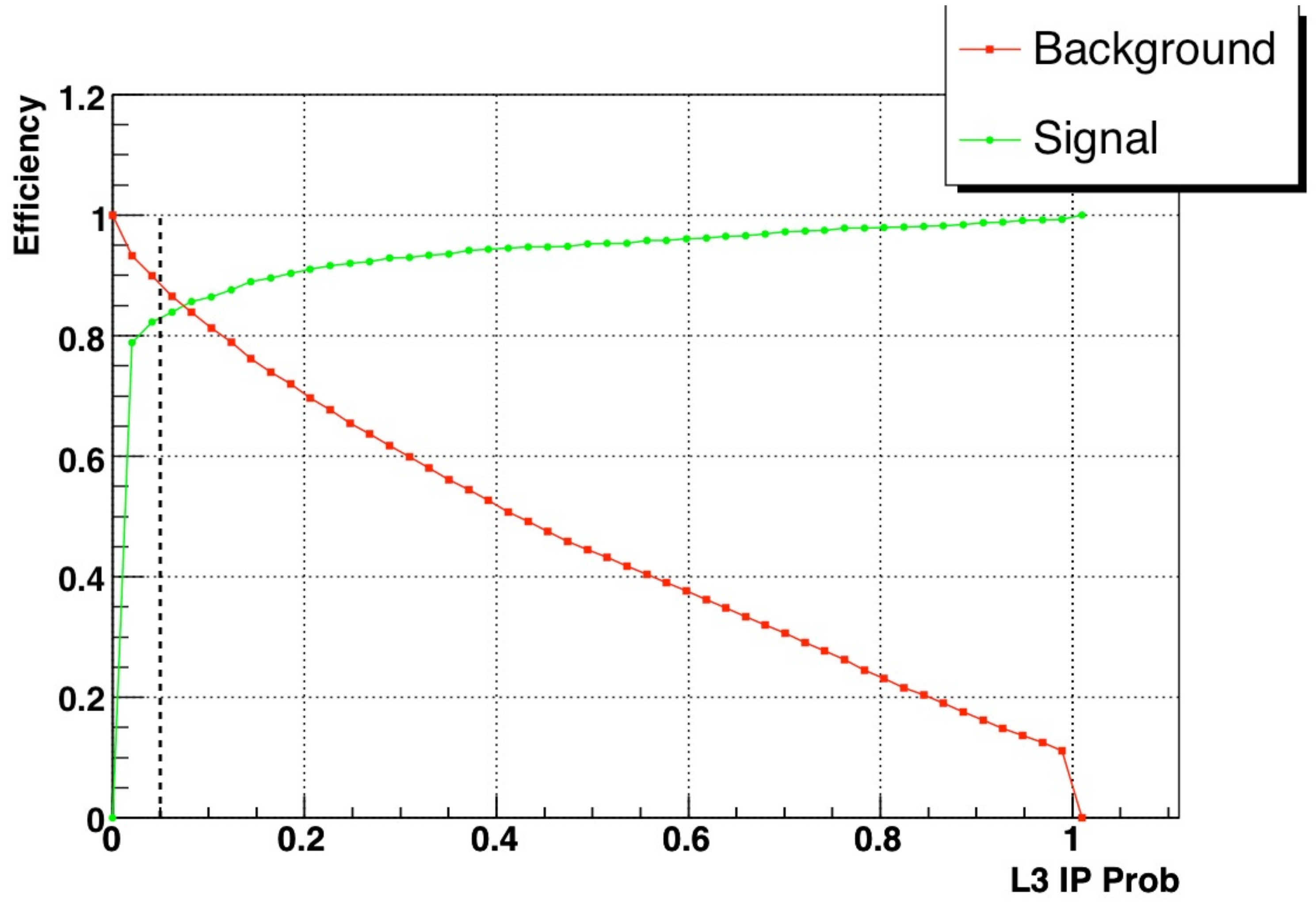
- Data stored in detector front-end pipeline
  - Pipelines deep enough for X BXs where X can be 100s
- Trigger analyses data and makes decision
- Decision used to signal readout or not
- Must give decision every BX to be dead time free
- Must have fixed latency (no iterative algorithms)



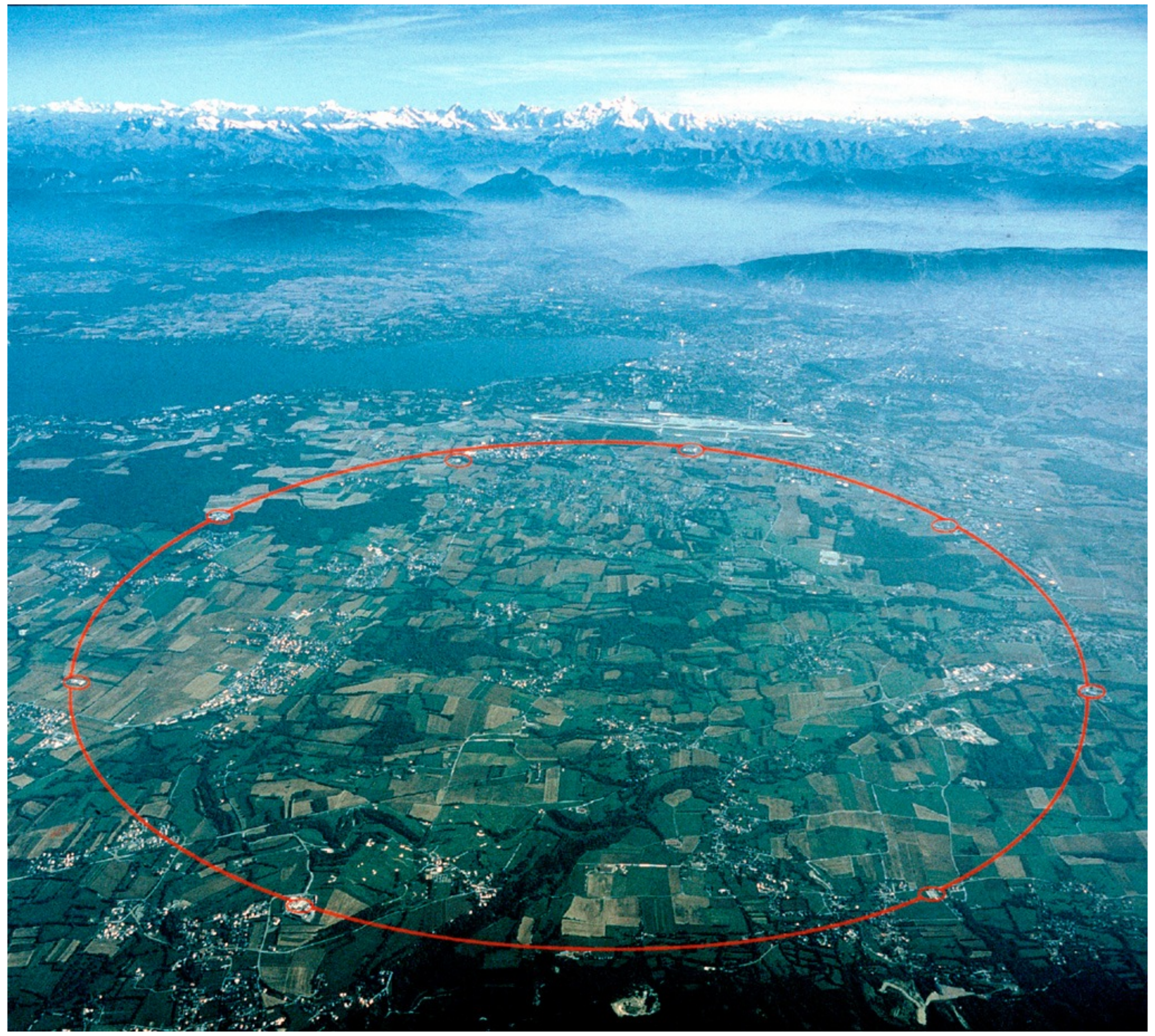
Tevatron and tracking triggers

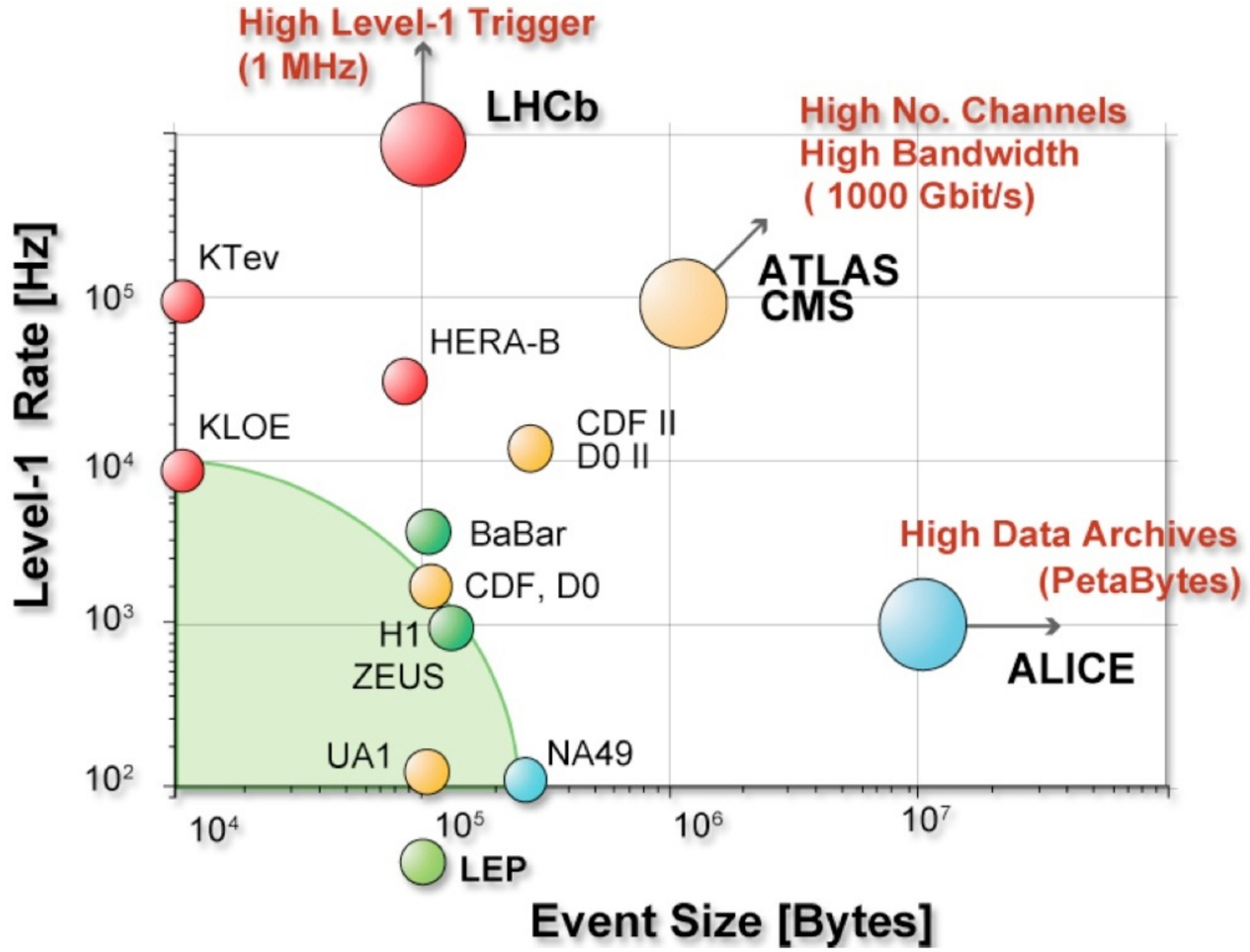
- Bunch spacing 396 ns
- Not as challenging as other colliders
- Challenge is to trigger B physics at an acceptable rate
- Huge amount of work went into developing tracking triggers
- Impact parameter Level 3 (software) trigger to select events with long-lived particles
- Developed at Imperial College 😀
- LHCb now use Boosted Decision Trees extensively





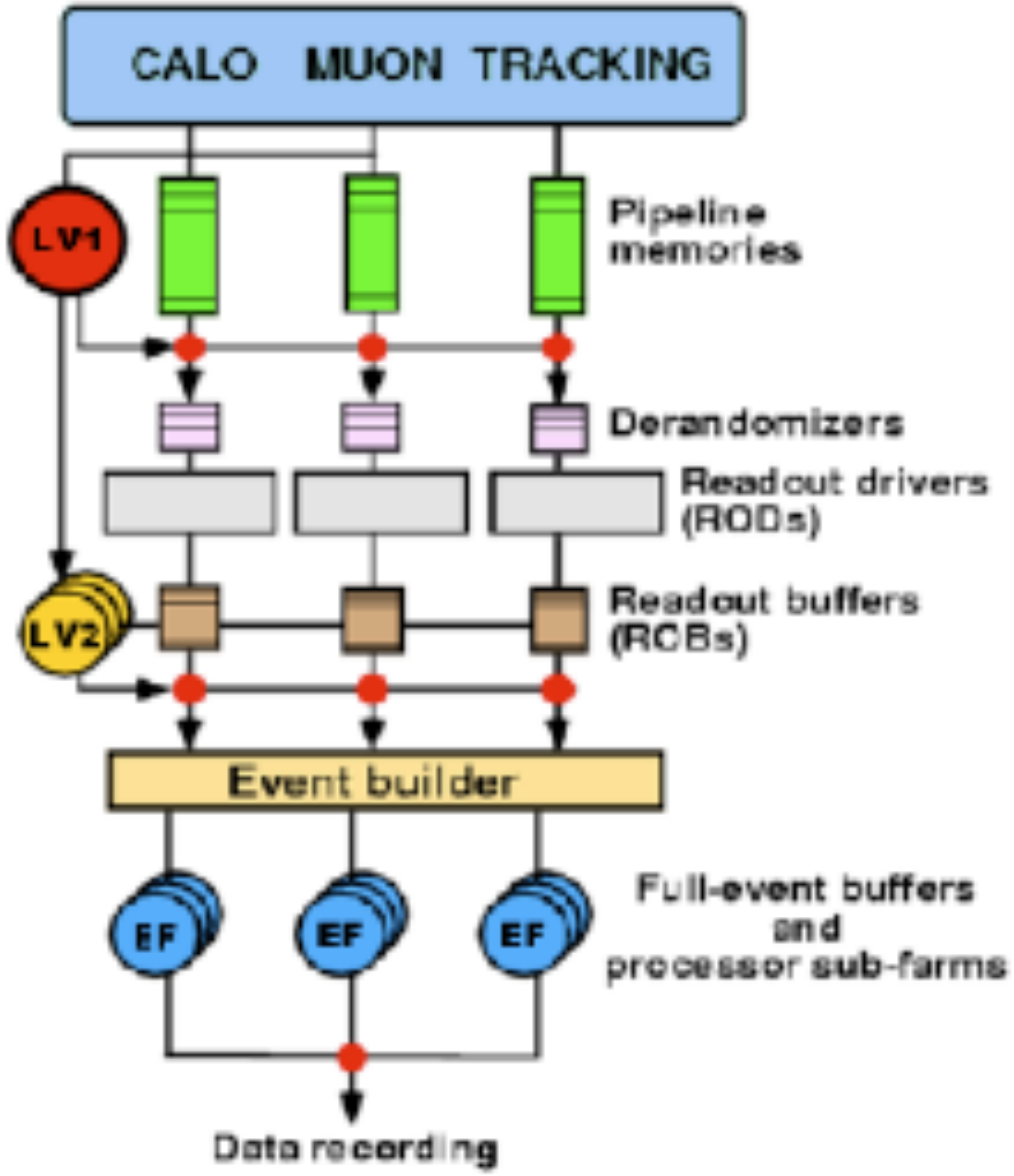
The LHC experiments





- Bigger detectors
- 40 MHz crossing rate
  → order of magnitude more challenging

Typical trigger design



- Three levels
- Level 1: hardware and firmware
  - Cannot keep up with bunch crossing rate
  - Pipelined and dead-timeless
- Level 2: composite of hardware and software
  - Can have hardware pre-processing
  - Can be regional processing
- Level 3: software
  - Farms of PCs
  - Full detector information
  - Close to offline algorithms

FPGAs

- FPGAs have been around in trigger systems for a while
- Latest large FPGAs give a huge amount of flexibility and are used in the LHC experiments
- Revolutionised trigger systems since the logic (algorithms) do not need to be fixed when the board is produced
- Can change the algorithms running in hardware, in light of better detector understanding, even physics discoveries
- Traditionally difficult to program, requiring low-level languages e.g. VHDL, recently huge progress in high-level language translation

Hardware algorithms

- Hardware is well suited to simple questions
- Cut out simple high-rate backgrounds
  - QCD at Tevatron and LHC
  - Beam-gas at HERA
- Capabilities are limited
  - Can extract objects like electrons, jets etc.
  - Can match and correlate these objects
- High speed and dead-timeless
- More difficult to modify algorithms (though higher-level languages improve)
- Possible algorithms tied to detector geometry

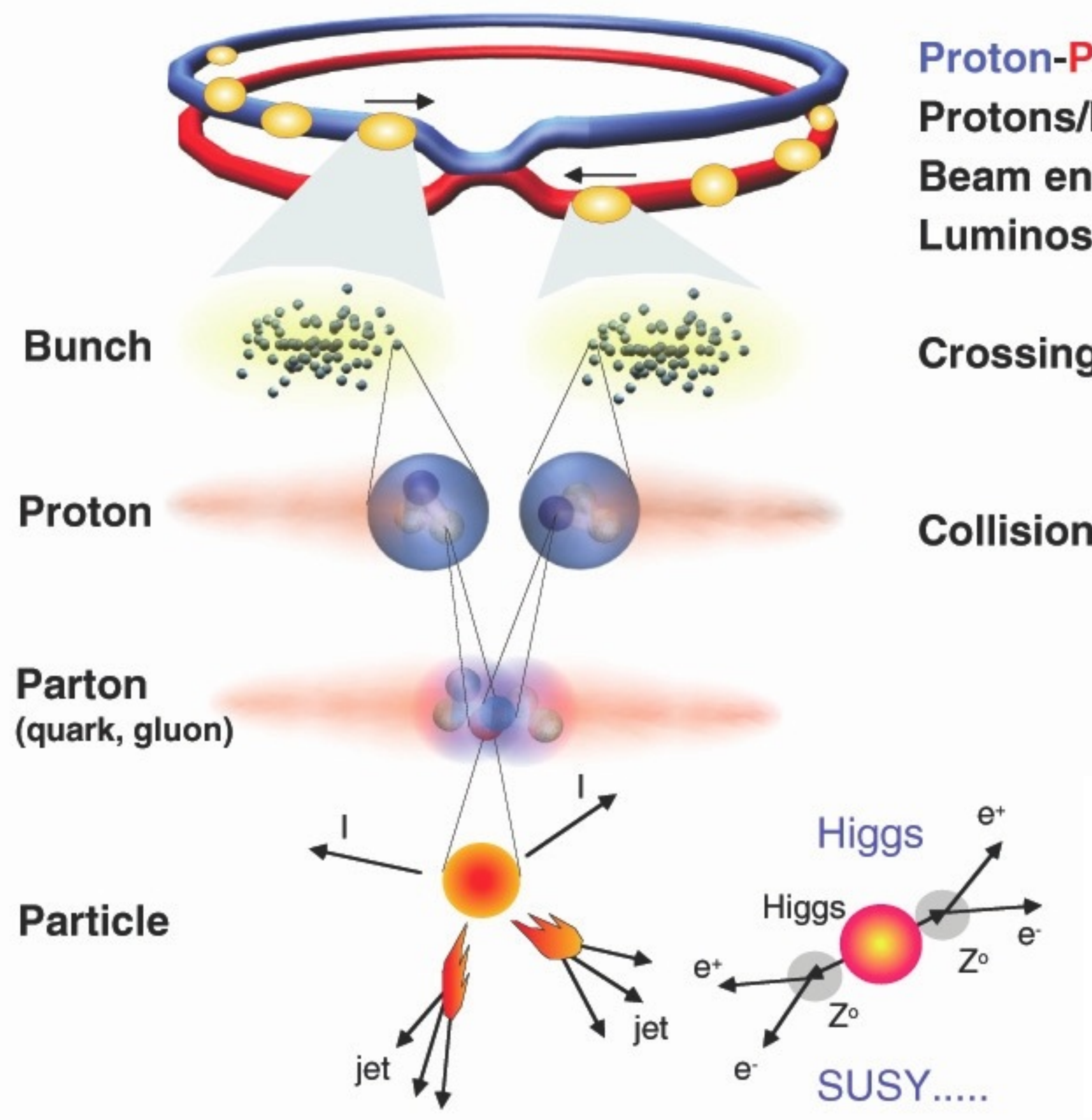
Software triggers and algorithms

- Hardware not well suited to complex algorithms with data from different detectors
- Track and vertex finding for example
  - Loop over hits and search
  - Iterative algorithms
- Software triggers are well suited to complex algorithms where full granularity data from the whole detector is necessary
- Higher level triggers are farms of PCs
- Distributed systems can have 1000s of nodes to be controlled

Outline

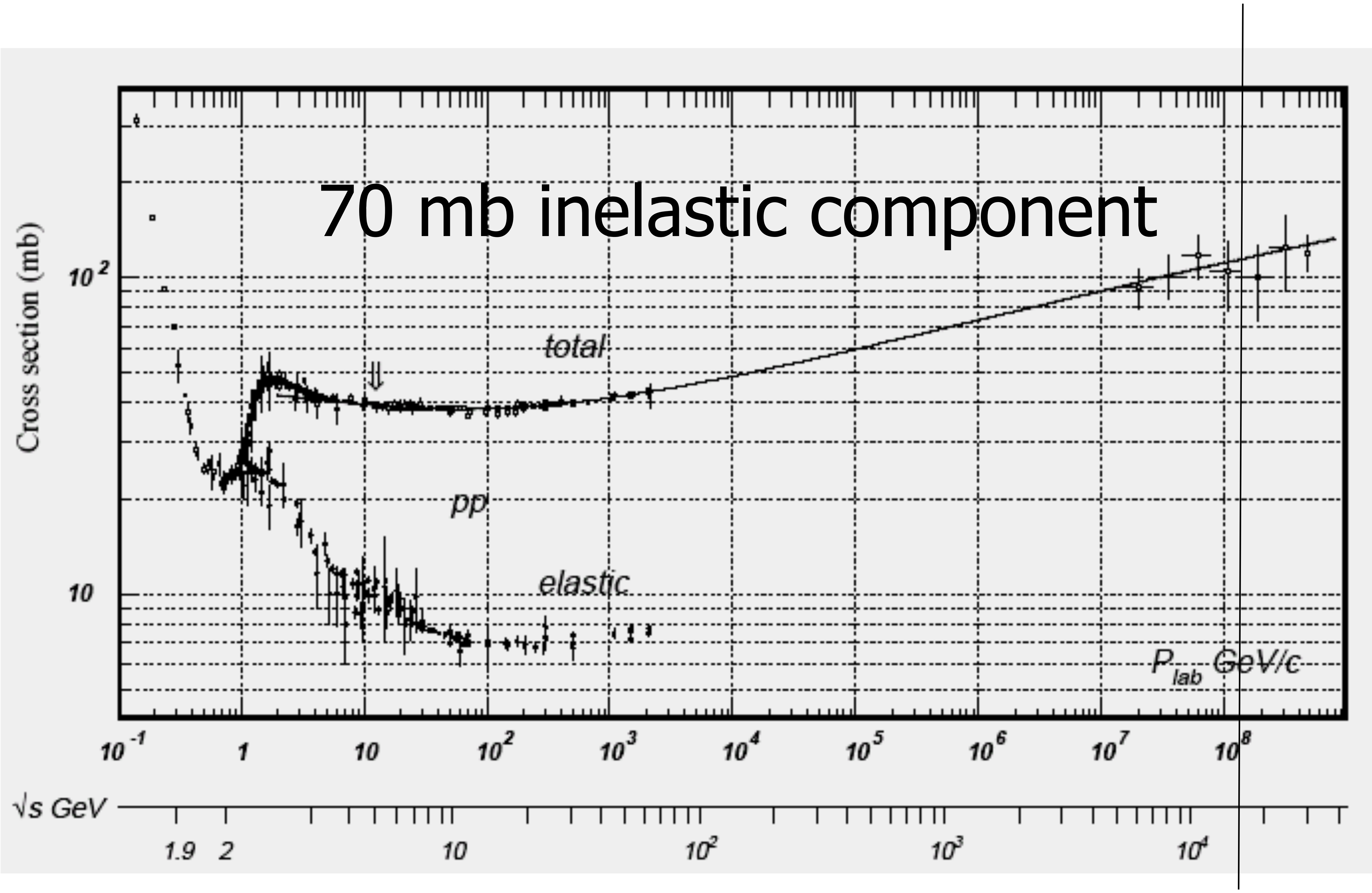
- Motivation and some important concepts
- Historical overview highlighting how challenges have driven development in the past
- Case study: current CMS trigger
- Case study: CMS trigger upgrade for HL-LHC
- Practical advice

The Large Hadron Collider



Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

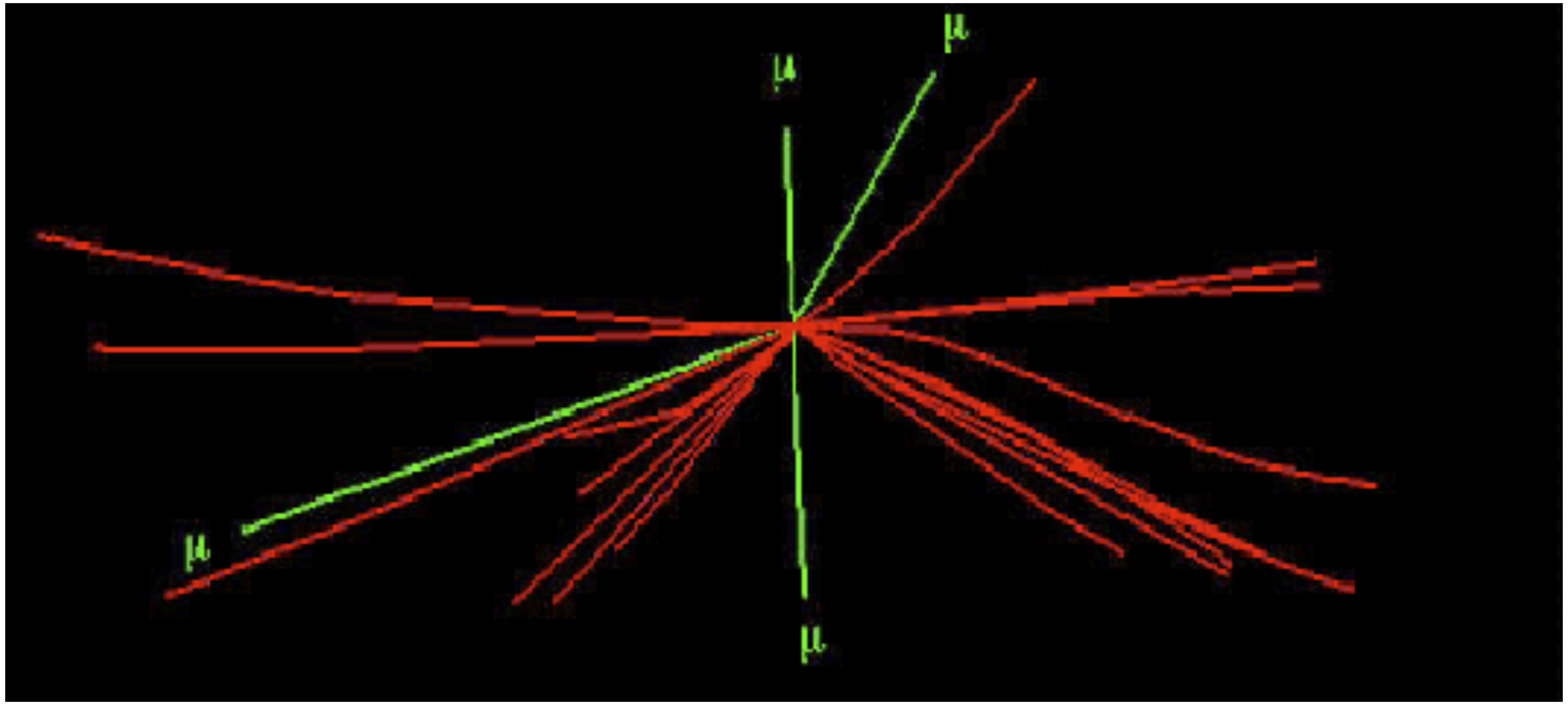
LHC challenges: data rate



- L = 10^{34} cm^{-2} s^{-1}=10^7 mb^{-1} Hz
- σ_{inel} (pp) ≈ 70 mb
  → **Event Rate = 7 x 10^8 Hz**
- Δt = 25 ns = 25 x 10^{-9} Hz^{-1}
  → **Events/25ns =7 x 2.5 = 17.5**
- Not all bunches full (2835/3564)
  → **Events/crossing = 23**

- At design LHC luminosity we have 22 events superimposed on any discovery signal
- 10^9 events per second x typical event size of 1-2 Mbytes >> TByte/sec
- Enormous data rate. Need super-fast algorithms to select interesting events while suppressing less interesting events

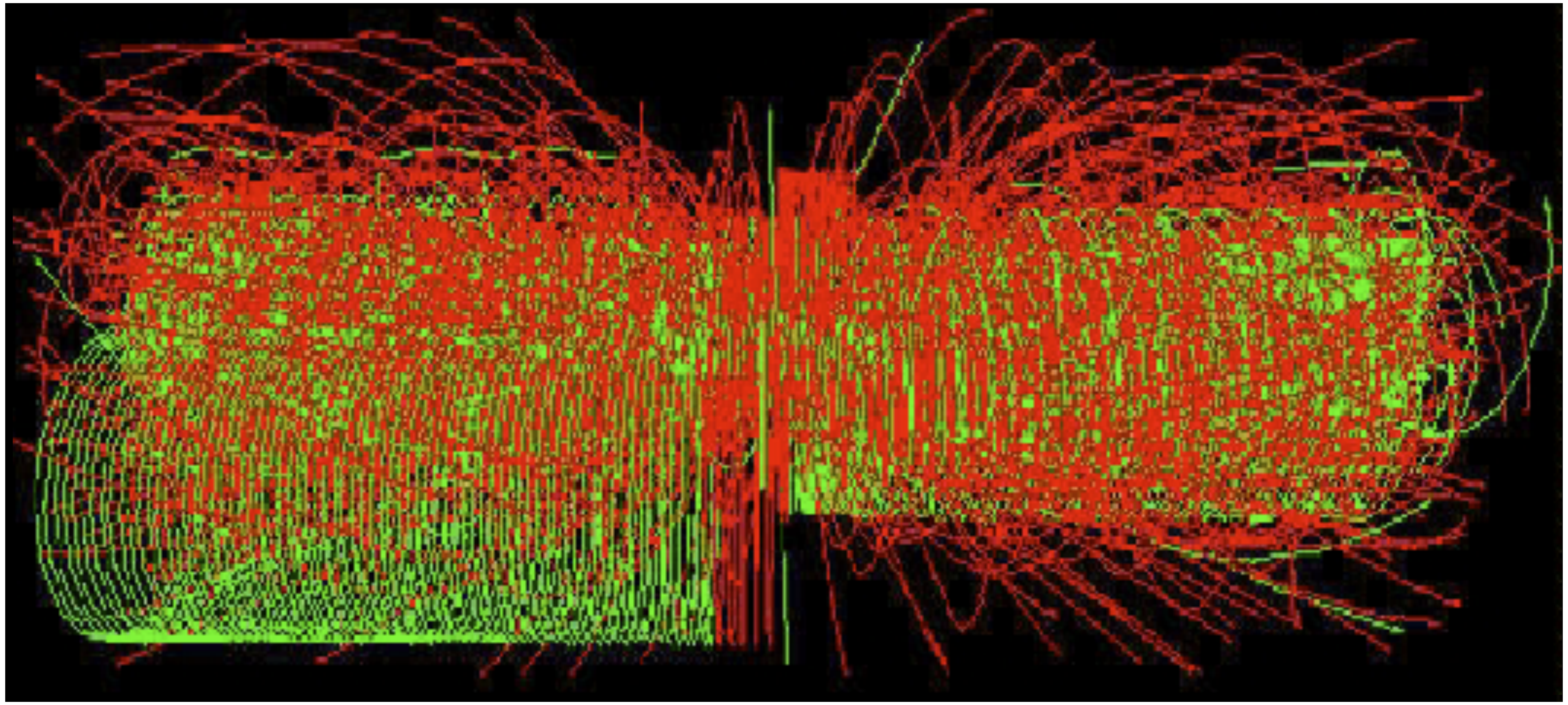
LHC trigger challenges - pile-up



Higgs -> 4μ

- We want to select this type of event for example Higgs to 4 muons....
  - which has this superimposed on it……
- Sophisticated algorithms necessary

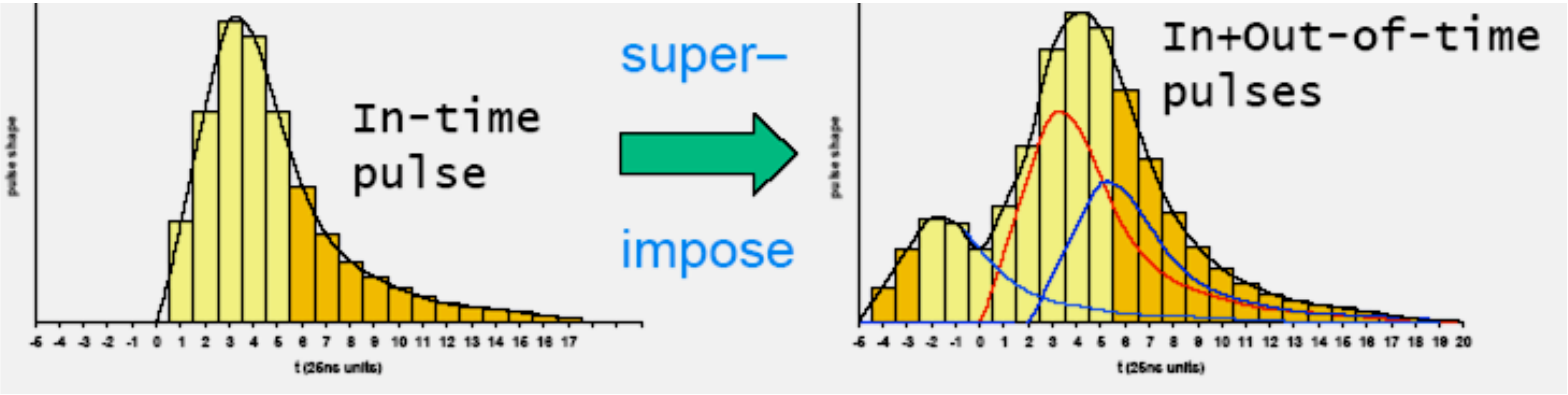
LHC trigger challenges - pile-up



Higgs -> 4μ +30 MinBias

- We want to select this type of event for example Higgs to 4 muons....
  - which has this superimposed on it……
- Sophisticated algorithms necessary

LHC trigger challenges - pile-up



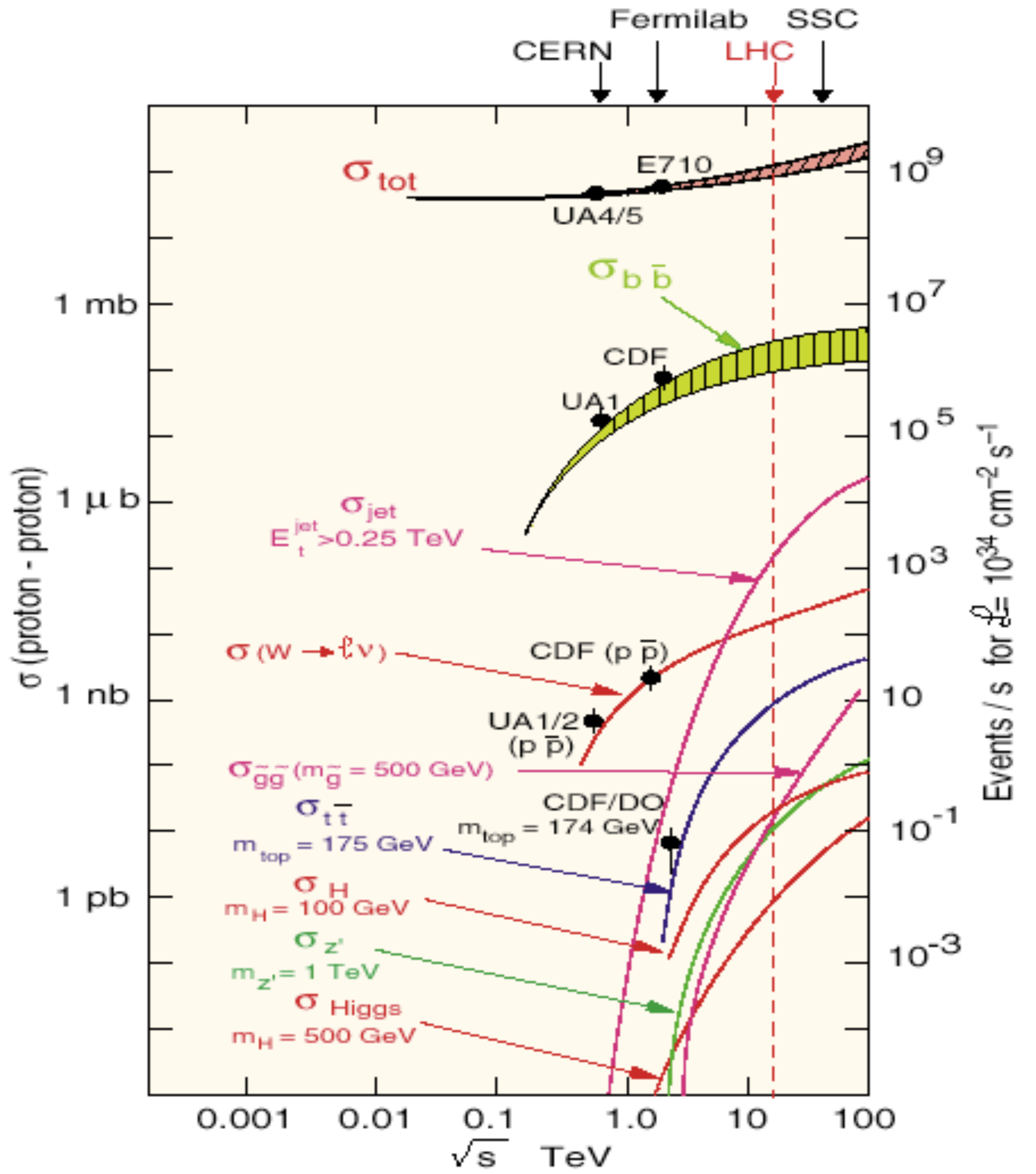
- In-time pile up: same crossing different interactions
- New events come every 25 nsec → 7.5 m separation
- Out-of-time pile up: due to events from different crossings
- Need a to identify the bunch crossing that a given event comes from

LHC challenges: needle in a haystack

- QCD cross sections are orders of magnitude larger than electroweak or any exotic channels

- Event rates:
  - Inelastic: 10^9 Hz
  - $W \to l\nu$: 100 Hz
  - t-tbar:10 Hz
  - H (125 GeV): 0.1 Hz
  - X (600 GeV): 0.01 Hz

$\Rightarrow$ Need to select events at the 1:10^{11} level



From the trigger design report

- High efficiency for hard scattering physics at the LHC
- Processes like
  - top decays, $H \rightarrow \gamma\gamma$, $H \rightarrow 4l$, W-W, SUSY…
- Need to efficiently reconstruct decay products from intermediate W and Z bosons
  - Sets scale for single lepton triggers from W decay $P_T > 40$ GeV
- For $H \rightarrow \gamma\gamma$
  - Sets scale for di-photon trigger of $P_T > 20$, 15 GeV
- Benchmark is that muon and isolated electron must have efficiency > 50% for W decays

From the trigger design report

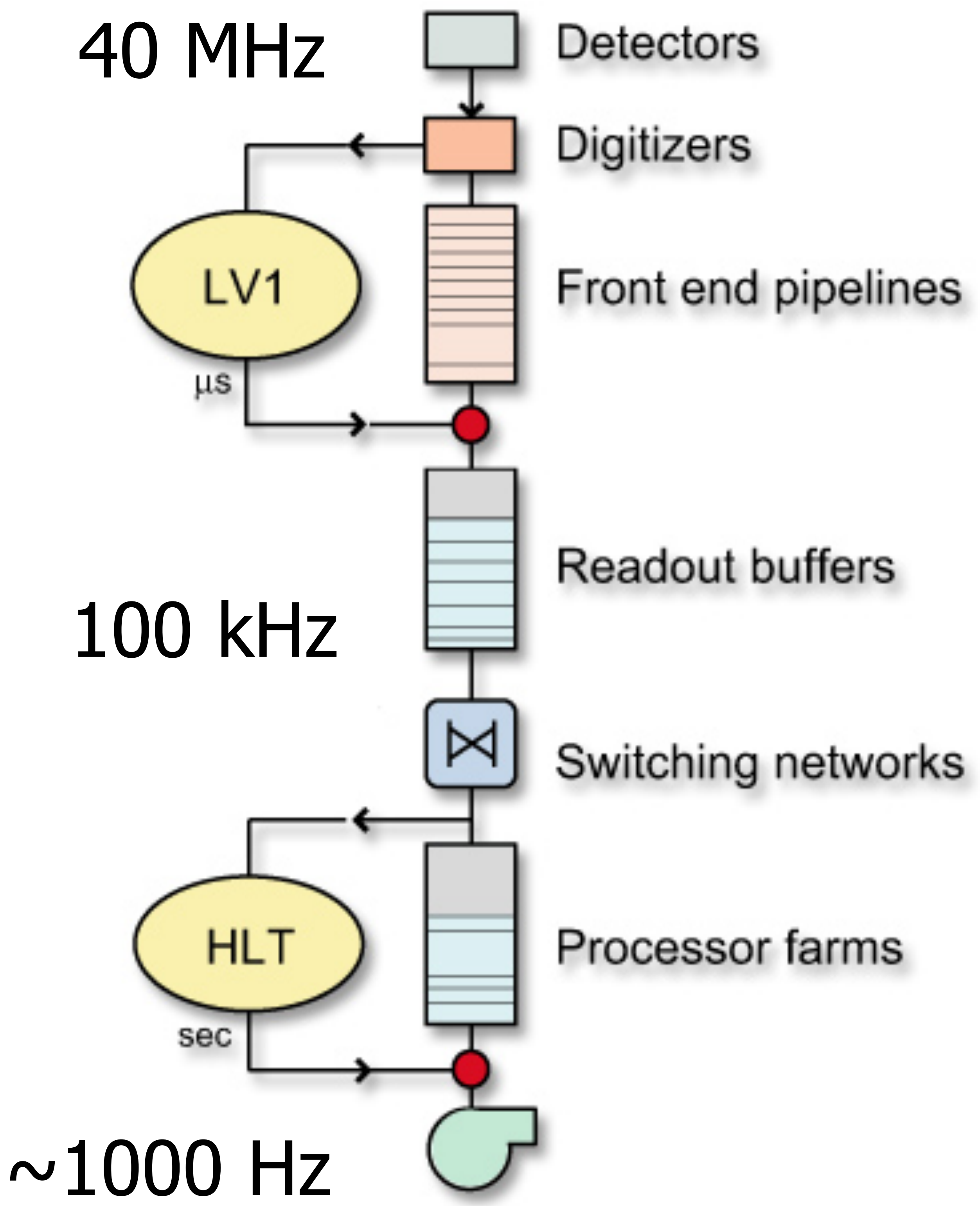
- Requirements
  - Leptons and jets $|\eta|<2.5$ with high efficiency above some p_T threshold
  - Single lepton triggers with high efficiency (>95%) $|\eta|<2.5$ $P_T>40$ GeV
  - Di-lepton triggers with high efficiency (>95%) $|\eta|<2.5$ $P_T>20$, 15 GeV
  - Di-photons similar to di-leptons
  - Jets continuous over $|\eta|<5$ for single and multi-jet topologies. High efficiency required for high-E_T jets
  - Missing E_T with threshold around 100 GeV

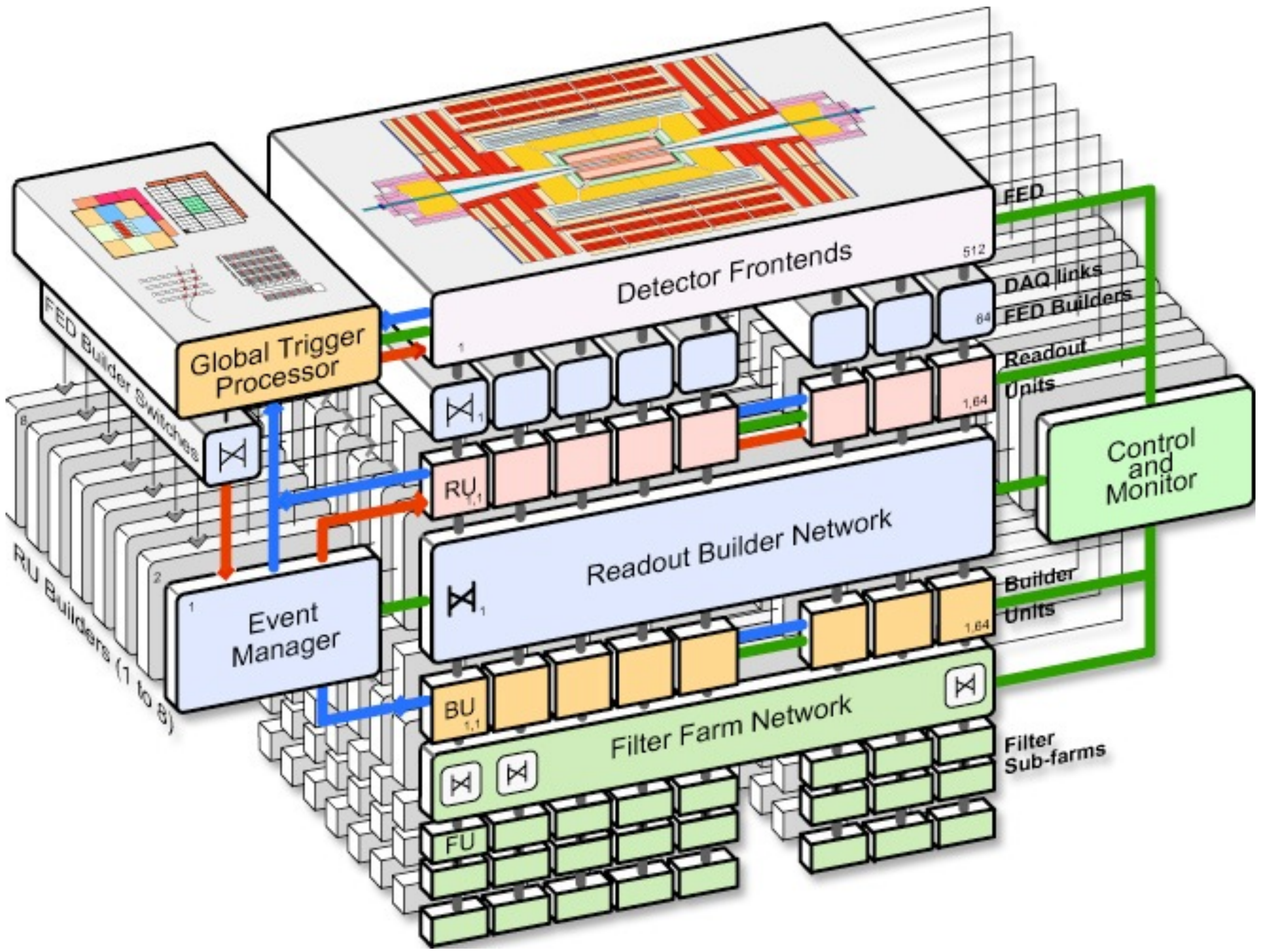
Backgrounds

What drives the rate for each type of trigger?

- Electrons and photons
  - High-E_T π^0 from jet fragmentation and direct photon processes
- Muons
  - Mis-measurement of low P_T muons
  - Hadronic decays
  - Punch through from jets
- Jets
  - Mis-measurement of low E_T QCD jets
- Tau
  - Narrow QCD jets fake hadronic tau decays
- Missing E_T
  - All sorts of mis-measurement, machine backgrounds etc.

CMS trigger and DAQ

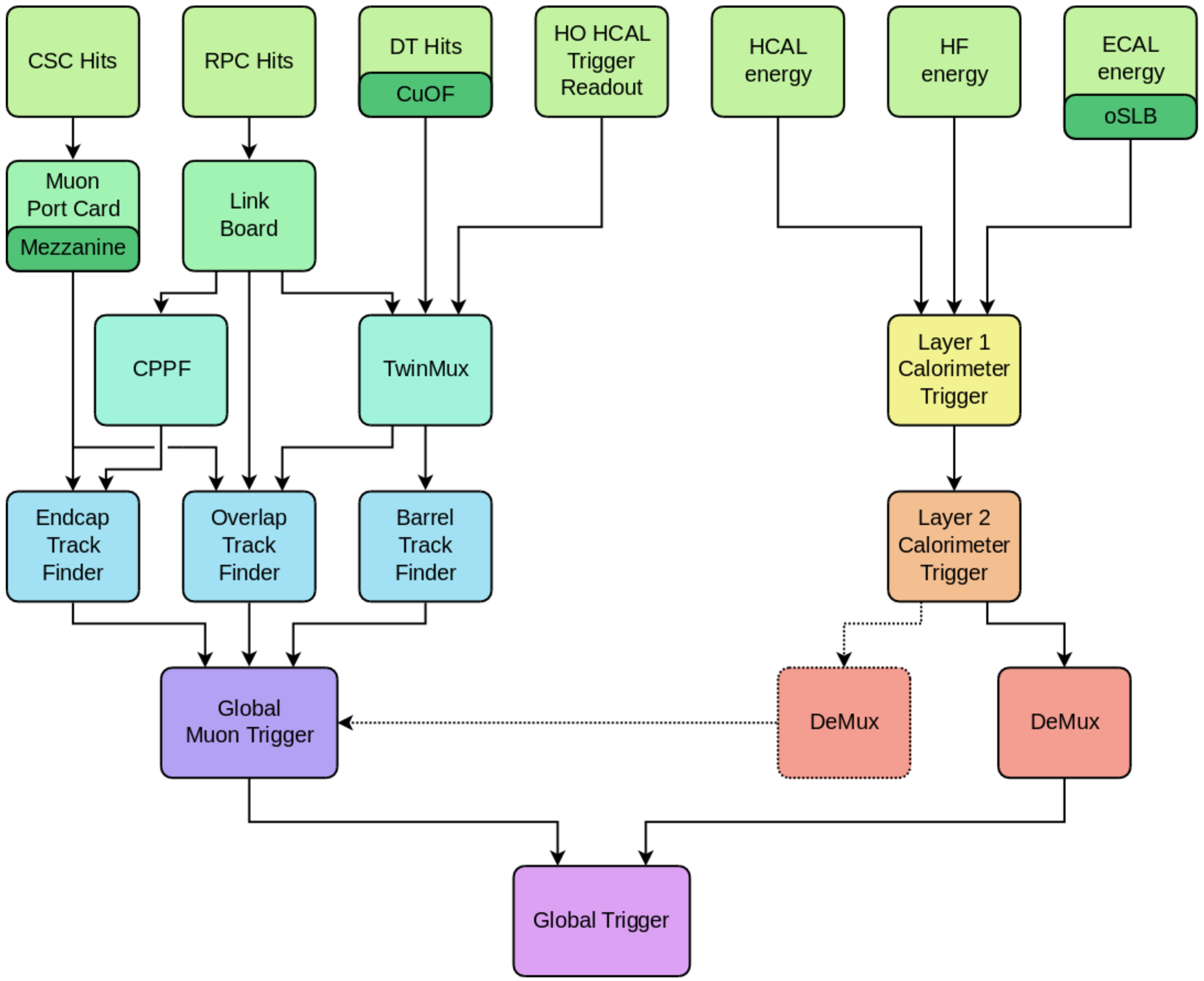




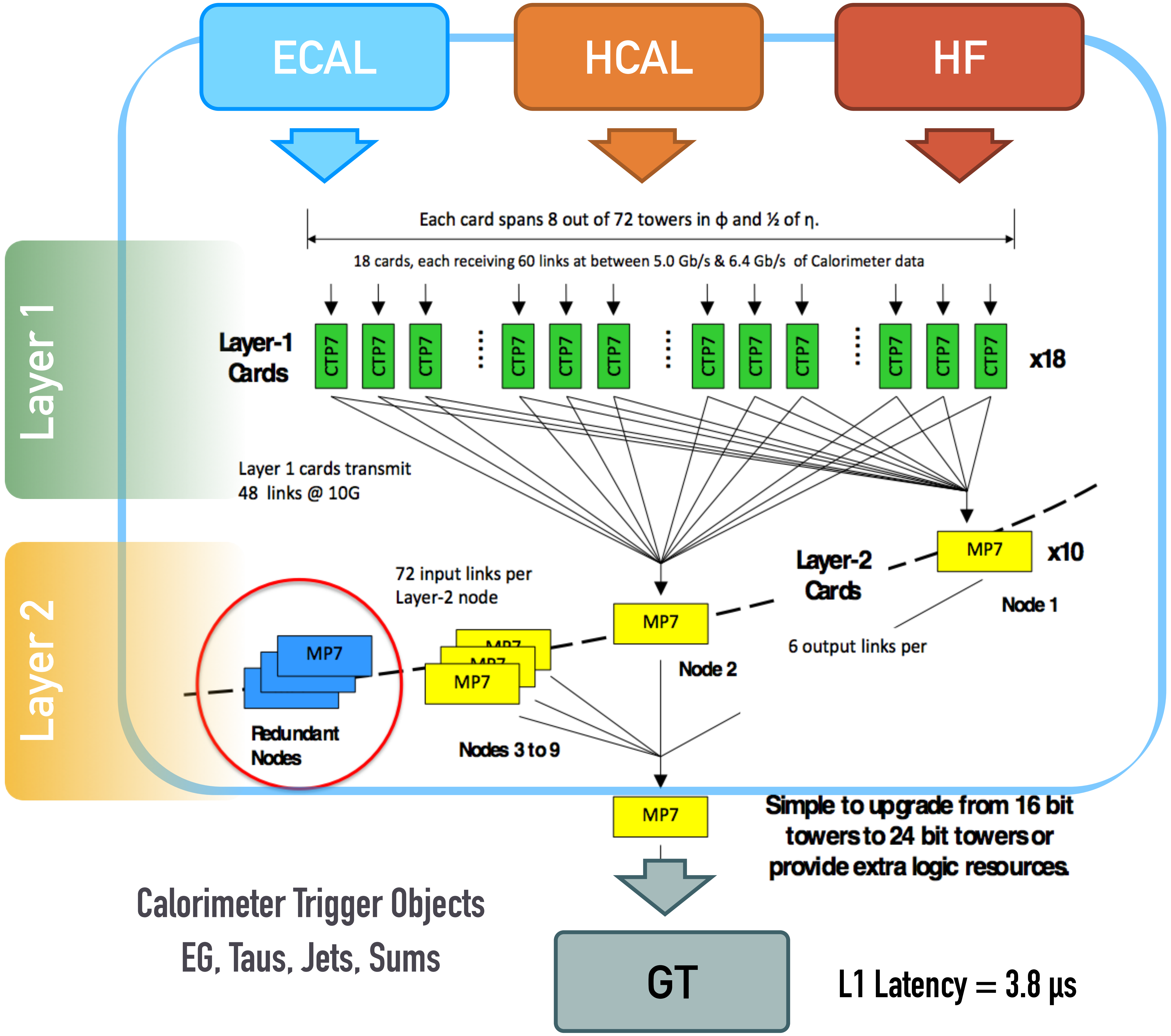
Level-1 trigger system overview

- Key concepts

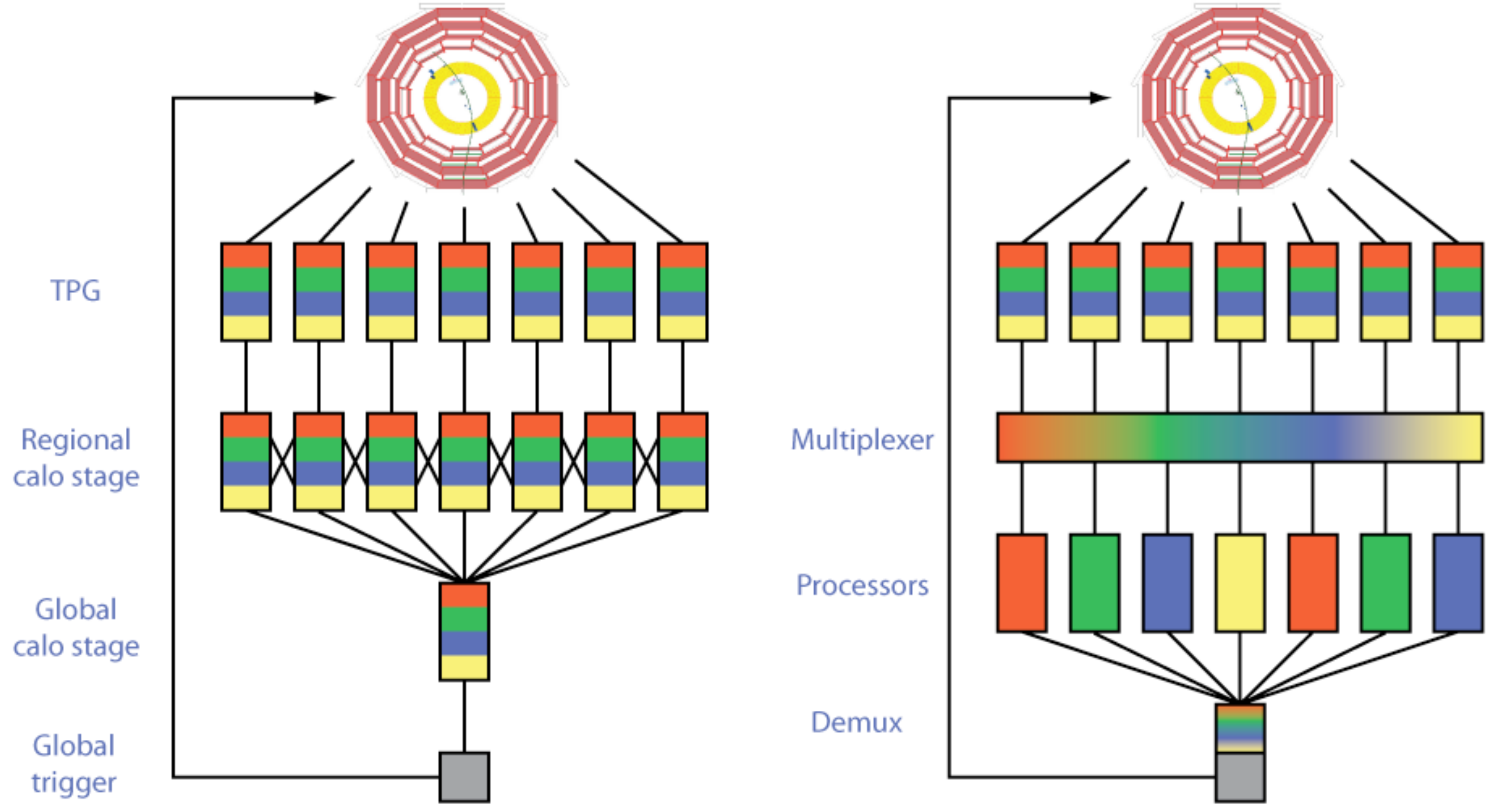
- Calorimeter system — remove boundaries by streaming data from single event into one FPGA
- Muon system — use redundancy of three muon detector systems early to make a high resolution muon trigger
- Global trigger — expandable to many possible conditions and more sophisticated quantities, to give a rich physics menu



System implementation



- Organised in two layers, implementing a **time-multiplexed** architecture



Fully pipelined trigger

Time-Multiplexed Trigger

Processors (examples)

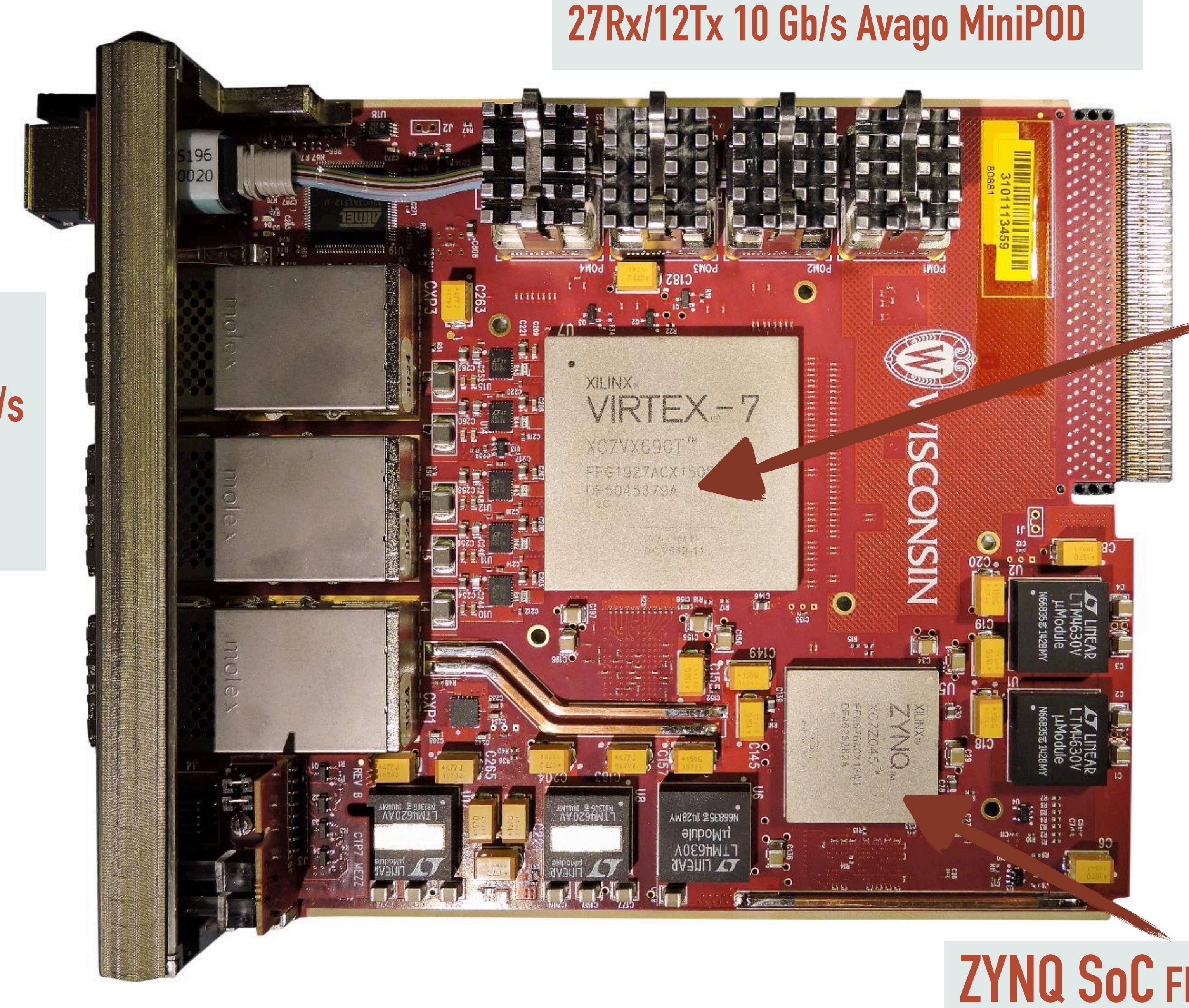
CTP7 Calorimeter Trigger Processor

Layer 1 - Pre-processing

- Aggregates & time-multiplexes calorimeter data
- DAQ readout for monitoring

Optical links
27Rx/12Tx 10 Gb/s Avago MiniPOD

Optical links
40Rx/36 Tx 10 Gb/s
Avago MicroPod
Pluggable CXP



Xilinx Virtex 7
690T

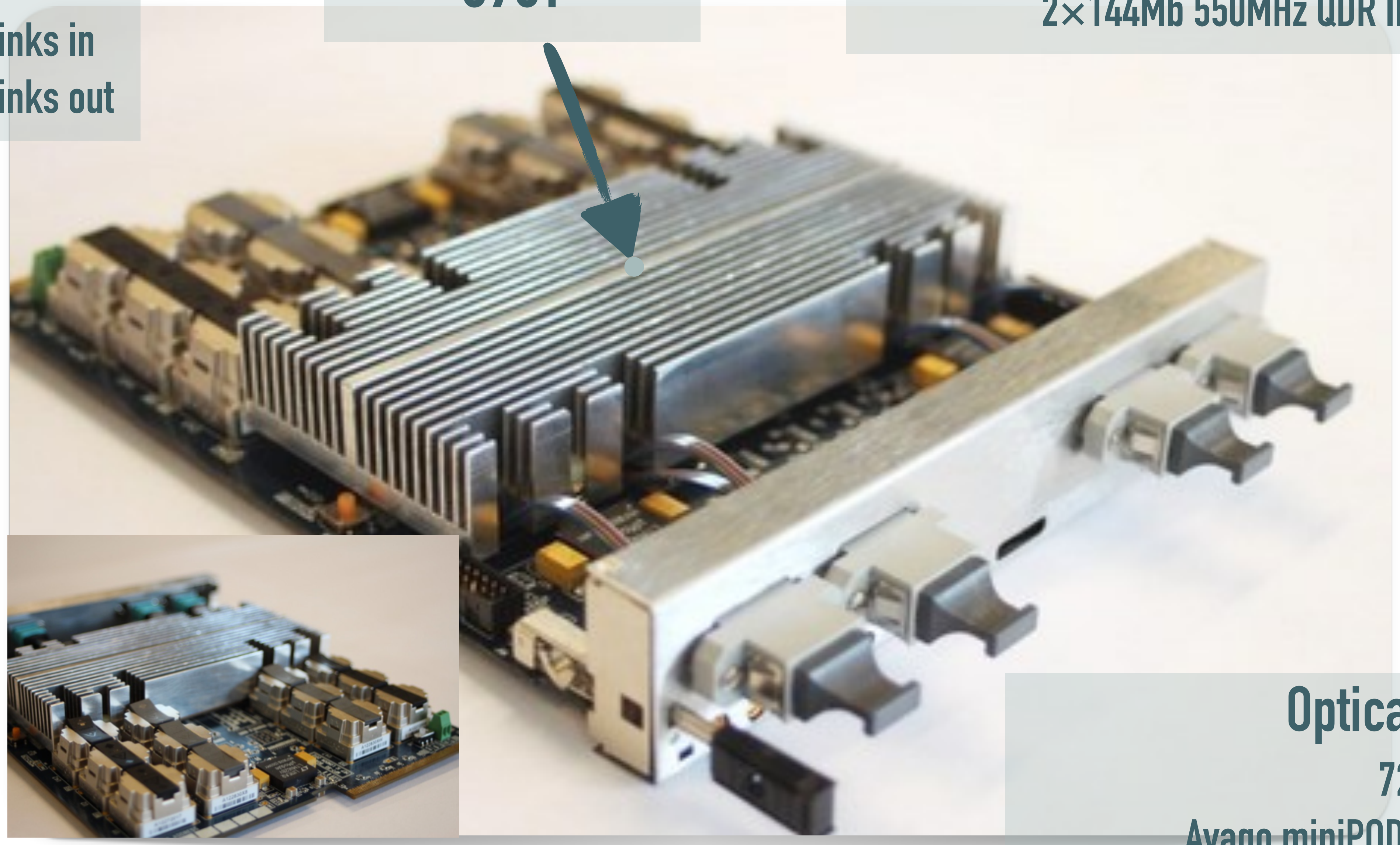
Backplane
8Rx/8Tx Rack fabric
4Rx/4Tx MCH1
DAQ Rx/Tx AMC13 in MCH2
GbE Tx/Rx MCH1 to AMC13

ZYNQ SoC FPGA Dual ARM Cortex-A9 CPU +
Linux. Communication & support functions

Backplane
Ethernet, PCIe×4
TTC, DAQ, SATA/SAS
11×1.8Gbps LVDS links in
11×1.8Gbps LVDS links out

Xilinx Virtex 7
690T

Atmel 32-bit MMC
supporting μSDHC interface firmware upload
2×144Mb 550MHz QDR II+ SRAM



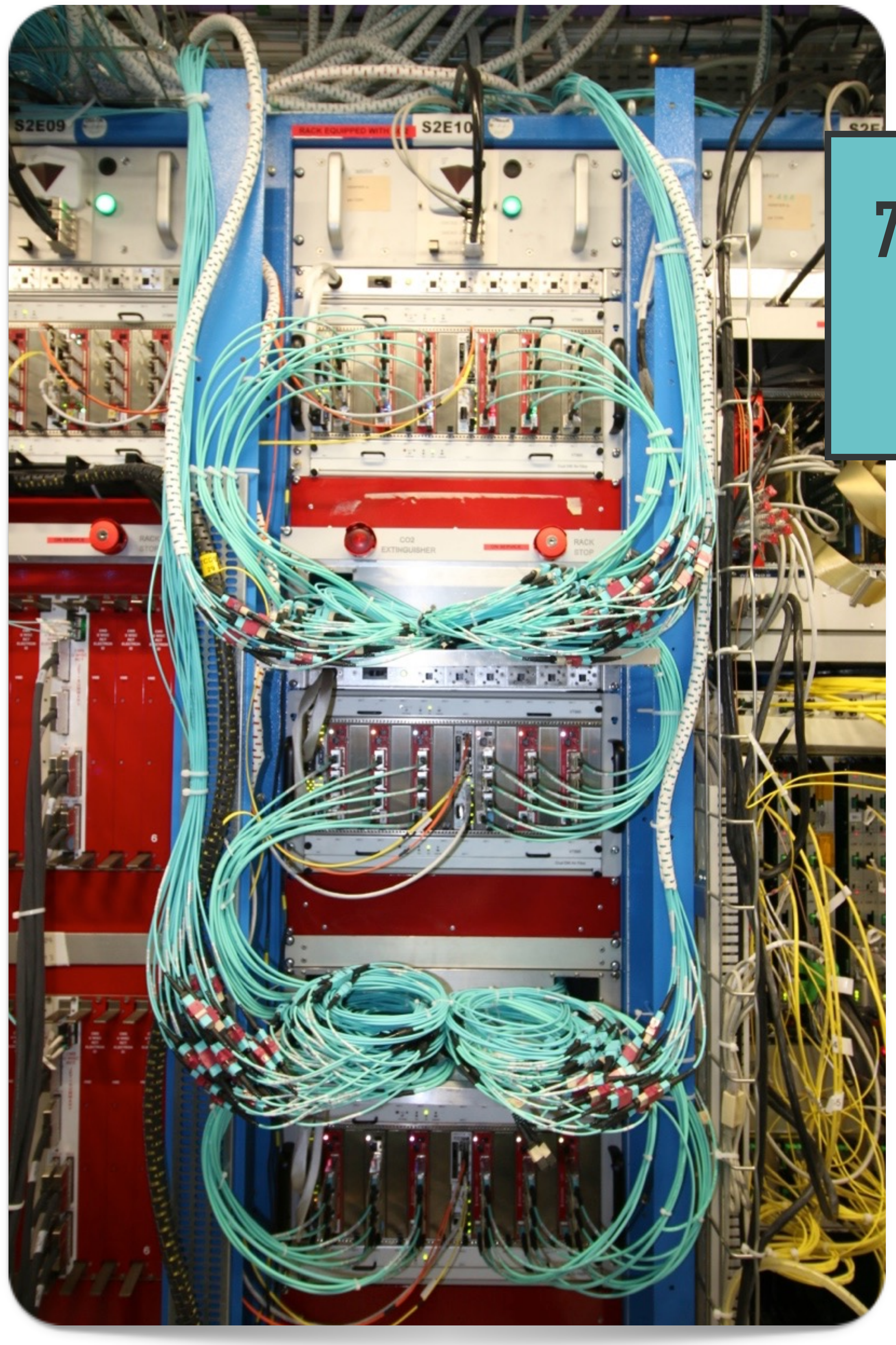
Optical links
72Rx/72Tx
Avago miniPOD 6Rx/6Tx
10.3 Gb/s each, 740 Gbps I/O

MP7 Master Processor

Layer 2 - Trigger Algorithms

- Hosts most of the algorithms
- DAQ readout for monitoring

System Integration

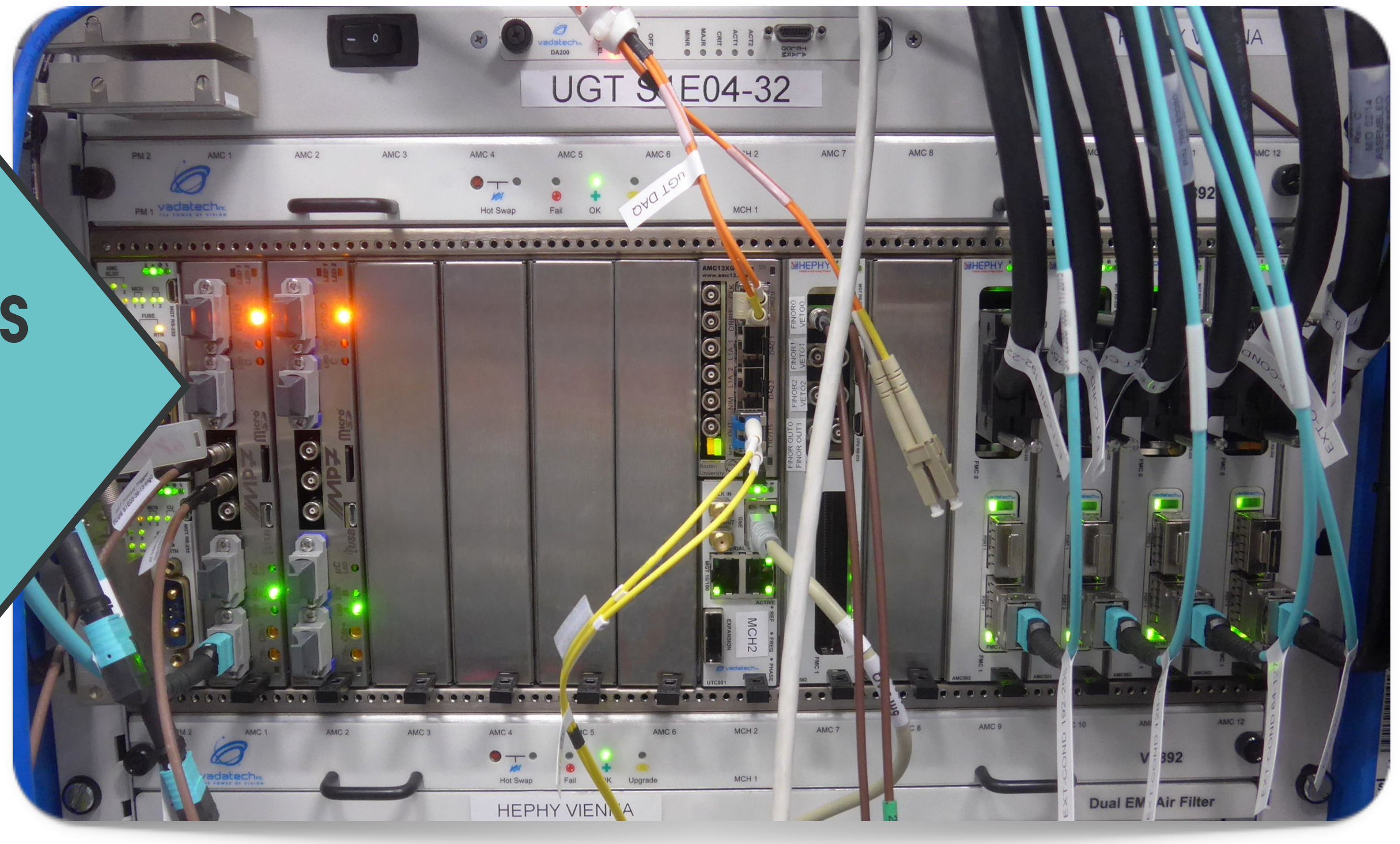


Layer 1
3 Vadatech VT894 Crate,18 CTP7 boards
6 bits ECAL+HCAL energy + veto & feature to Layer 2

720×10Gb/s links

Layer 2
1 Vadatech VT894 Crate, 10 MP7 boards

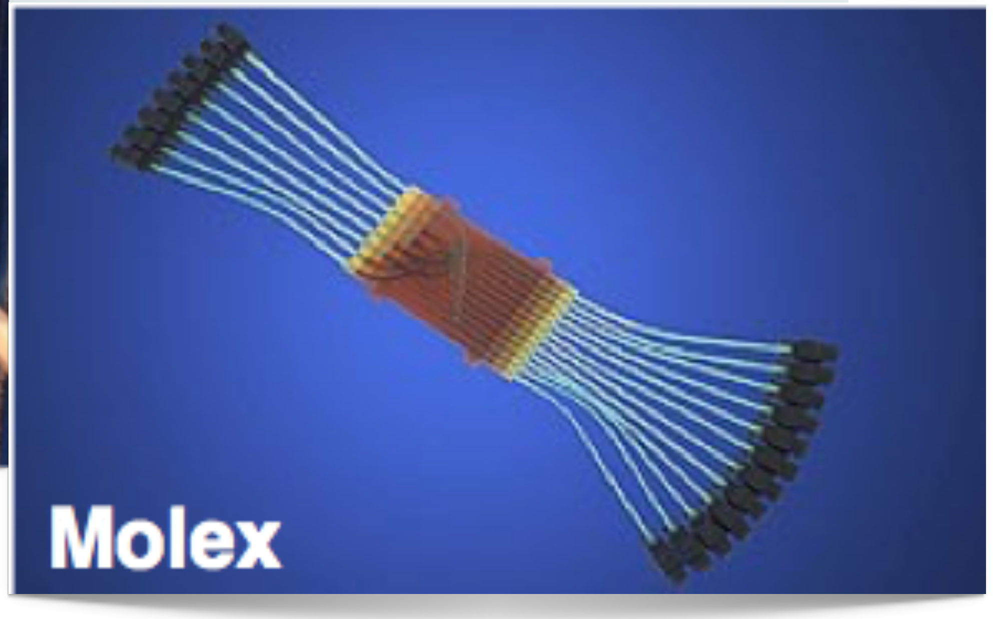
8×10 Gb/s links



Global Trigger
receives 12 electron/photon + 12 Tau iso/non-iso candidates + 12 Jets and sums.

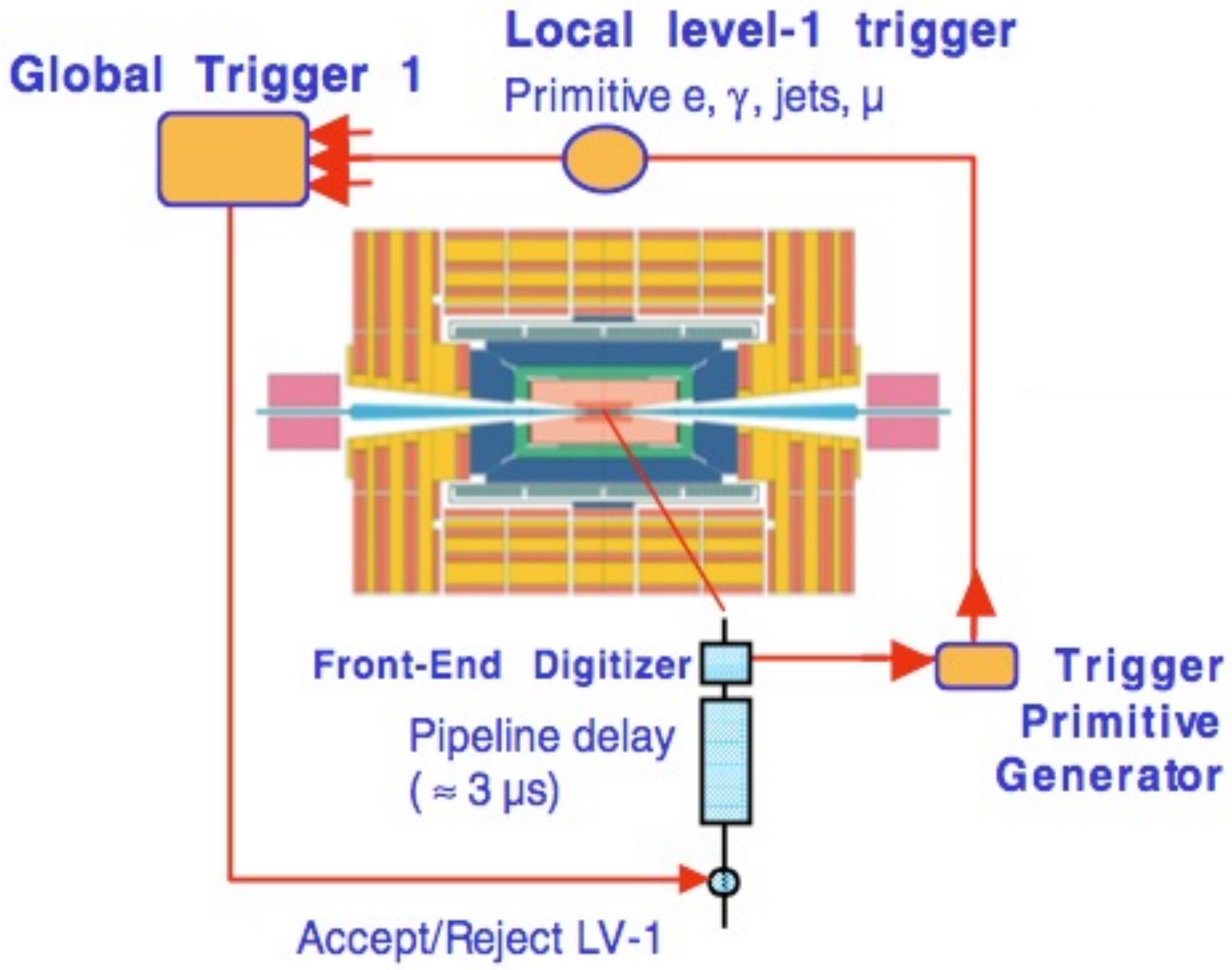
Time multiplexing routed through 72 to 72 12-fibre MPO connectors

Molex Enclosure
Flexplane (commercial)



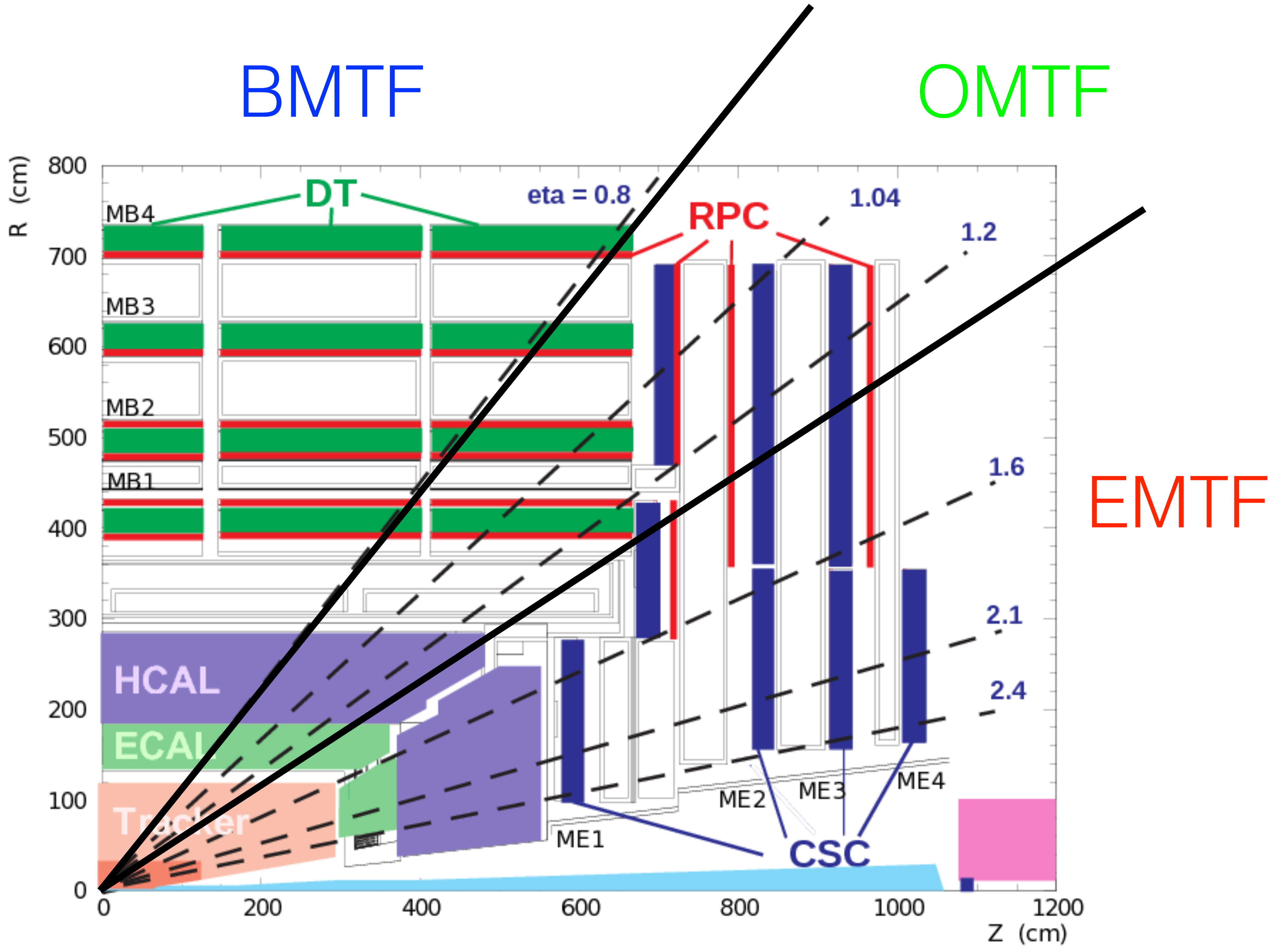
Level-1 Trigger latency

- Detector data stored in front-end pipelines
  - Pipelines deep enough for 128 bunch crossings (~3μs)
- Trigger decision derived from trigger primitives generated on the detector
- Trigger systems search for isolated e, γ, μ, jets and compute the transverse and missing energy of the event
- Event selection algorithms run on the global triggers
  - Must give a trigger decision every 25ns.



Muon track finder algorithms

- Muon track finding
  - Segment into Barrel, Overlap, and Endcap regional processors
    - Complementary detector strengths e.g. RPC timing
    - Improve robustness in the case of dead channels/ chambers and cracks
  - Pattern based track finding in endcap and overlap (with separate MVA LUT p_T assignment in endcap)
  - Road search extrapolation track finding in barrel
  - Global muon trigger takes muon tracks from regional finders, sorts by p_T and quality and cancels duplicates
  - Input from calorimeter trigger to apply isolation to muon candidates

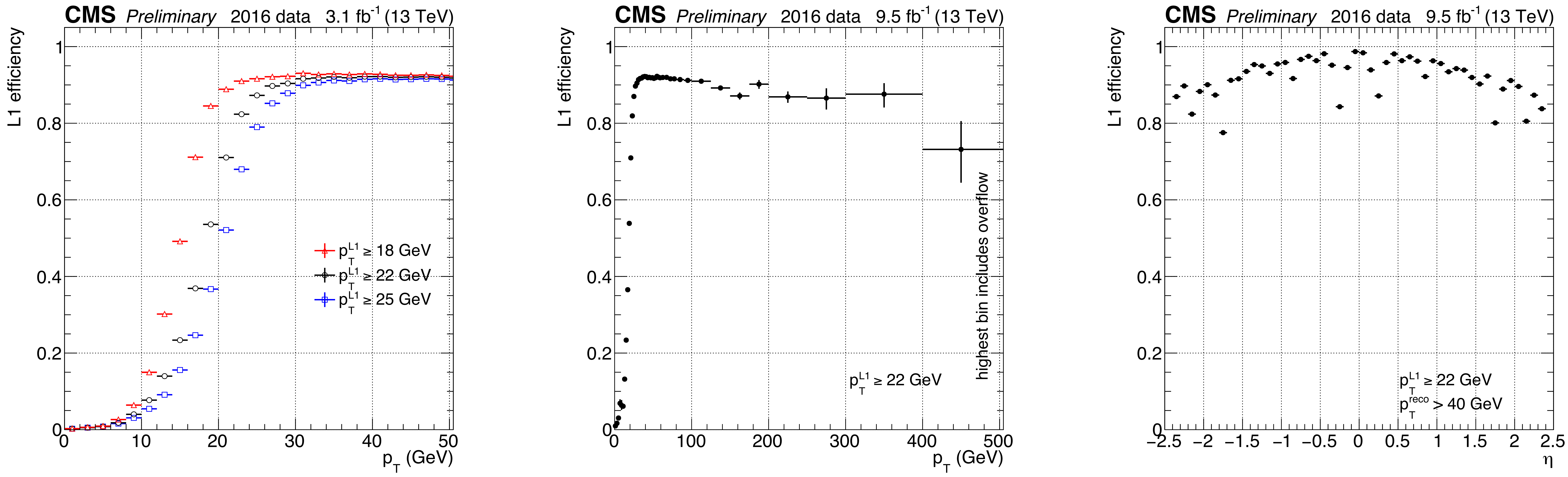


BMTF $|\eta| < 0.83$

OMTF $0.83 < |\eta| < 1.24$

EMTF $|\eta| > 1.24$

Muon trigger performance results



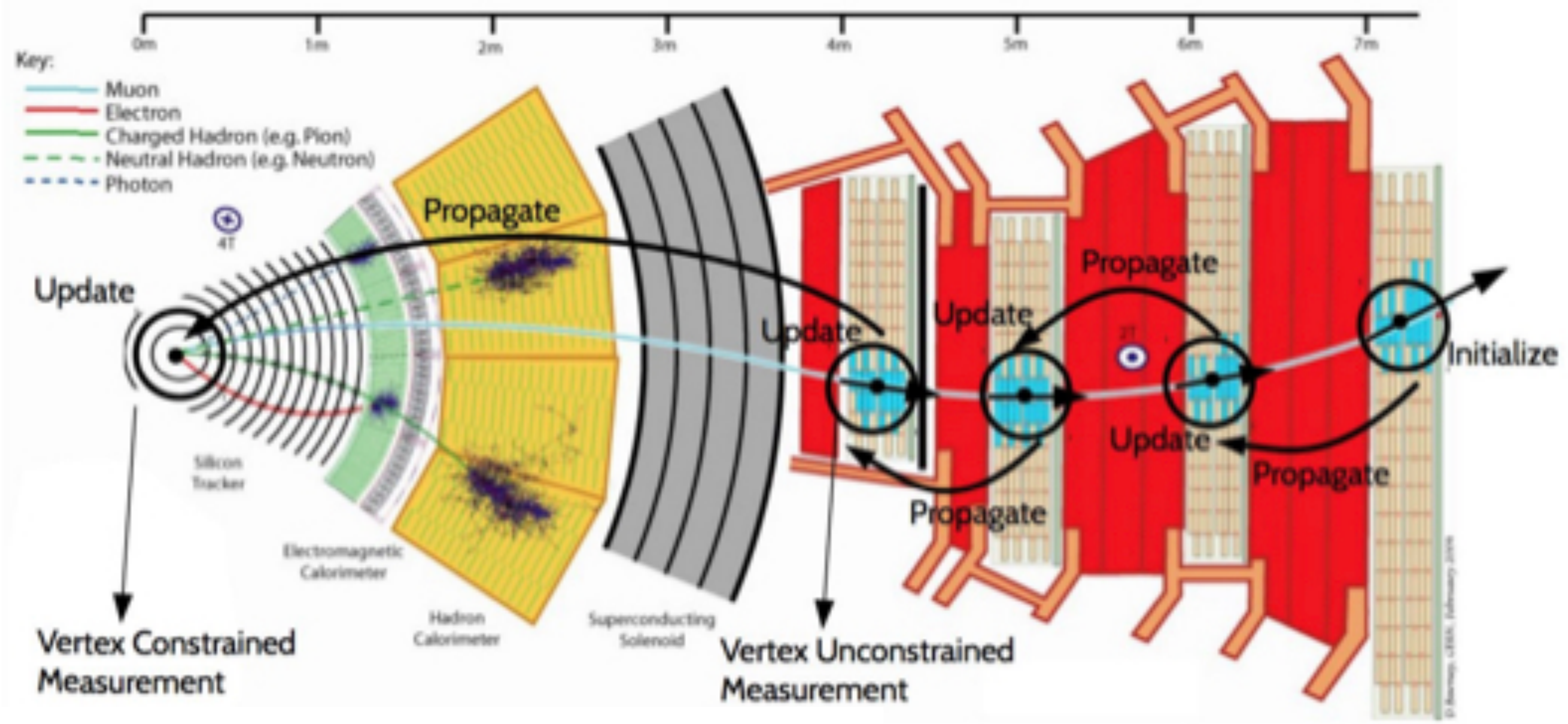
- Trigger efficiency for a single muon with p_T > 18, 22 and 25 GeV vs offline muon p_T and η
- Using tag and probe method on a dataset of $Z \longrightarrow \mu\mu$ events

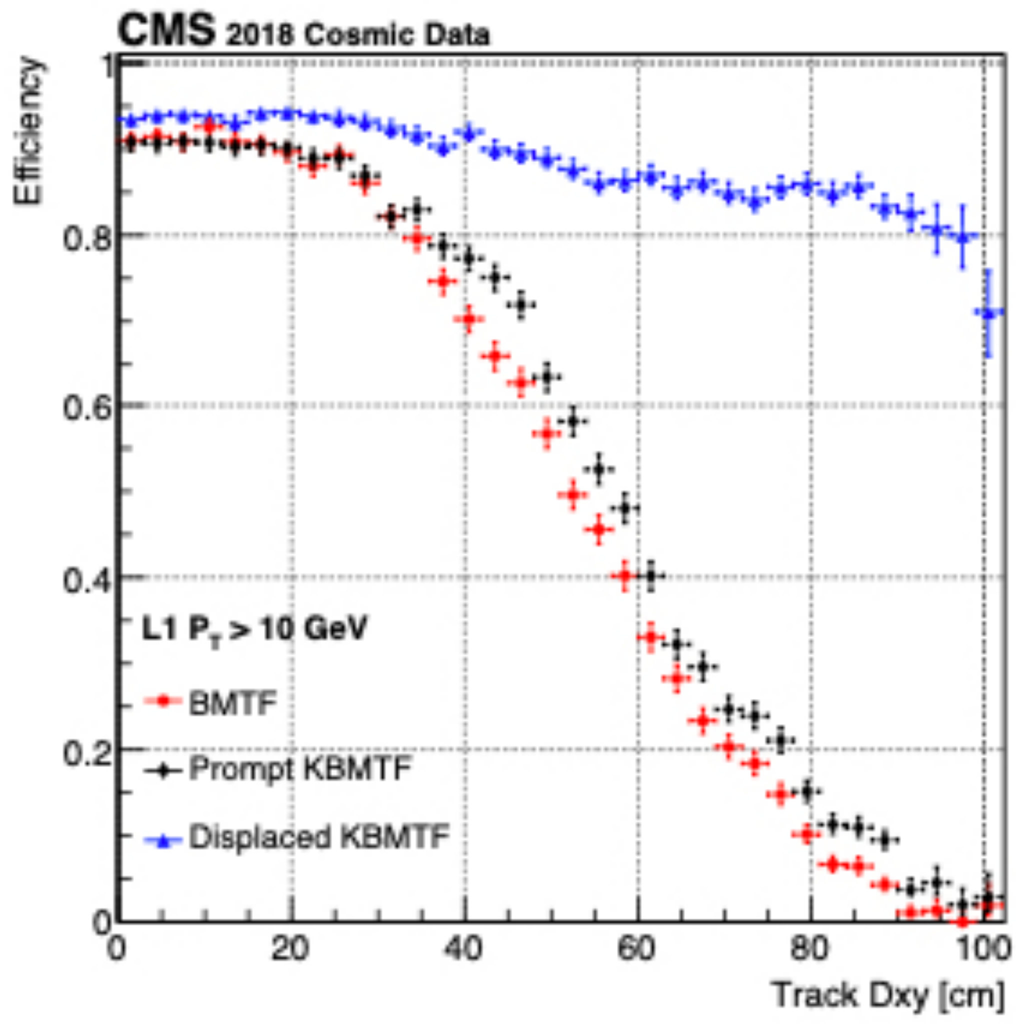
Muon track finder algorithms for Run 3

- Kalman filter algorithm will be used for barrel muons

  - Commissioned in late 2018 ready for Run 3

  - Gives two measurements of muon p_T:
    - Vertex constrained (traditional)
    - Unconstrained — suitable for displaced muons e.g. from long-lived exotic particles →





e/γ finder algorithm

Dynamic clustering

Improved energy containment
Showing electrons, photon conversions
Minimise effect of pile-up
Improved energy resolution

Cluster shape veto

Discriminate using cluster shape and EM energy fraction between e/γ and jets

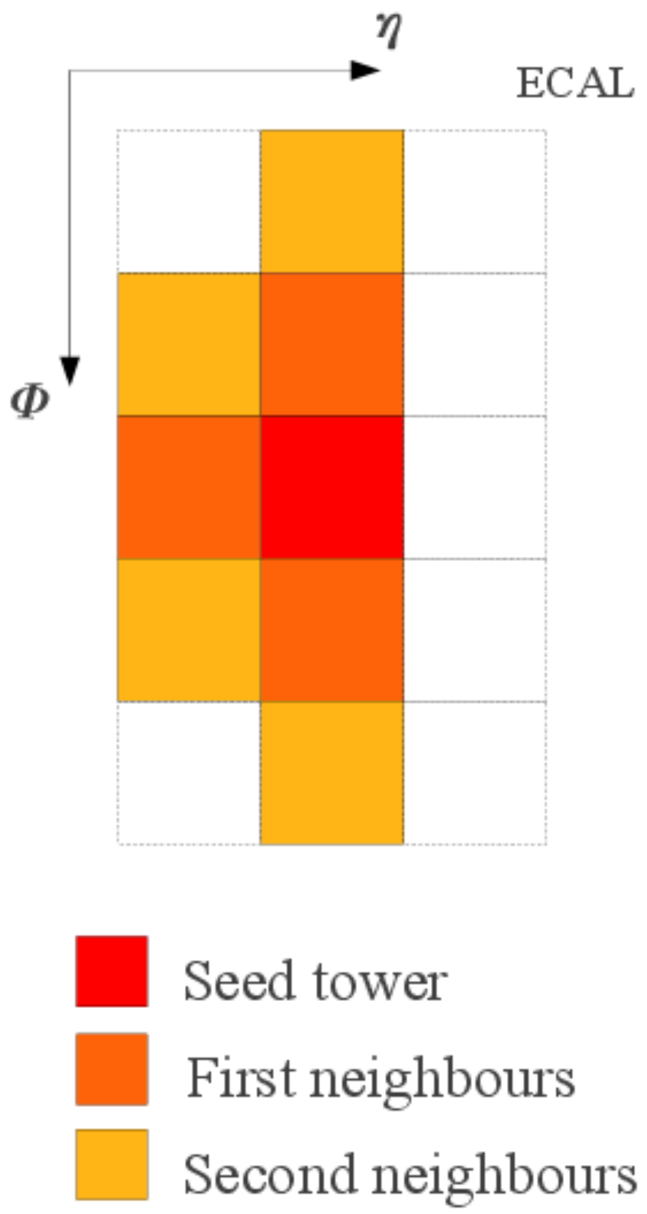
Calibration

e/γ cluster energy calibrated as fn. of E_T, η and cluster shape

Energy weighted position

Potential use in correlating objects e.g. invariant mass

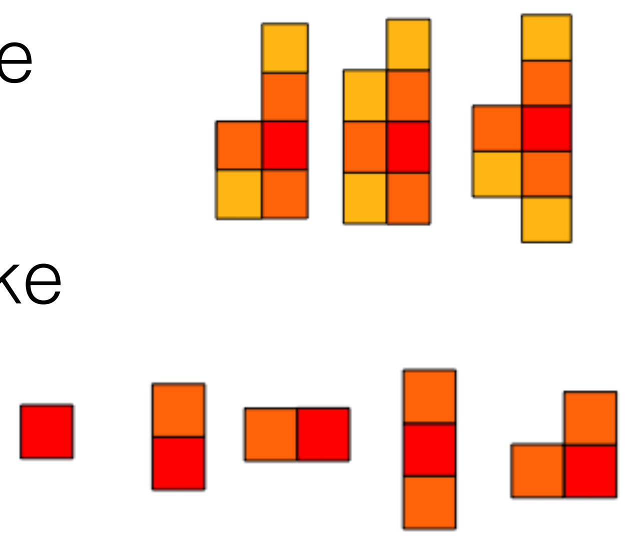
Cluster building

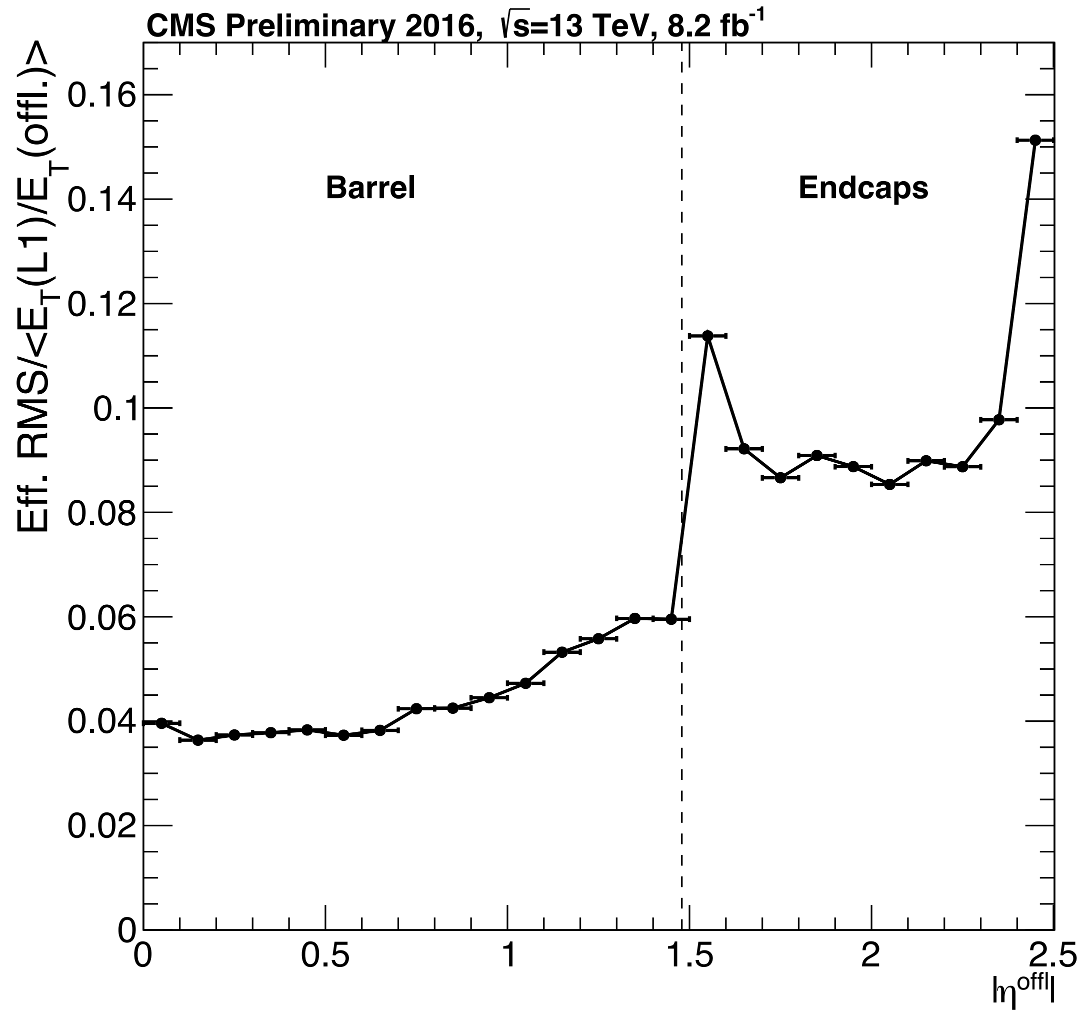


Cluster shapes

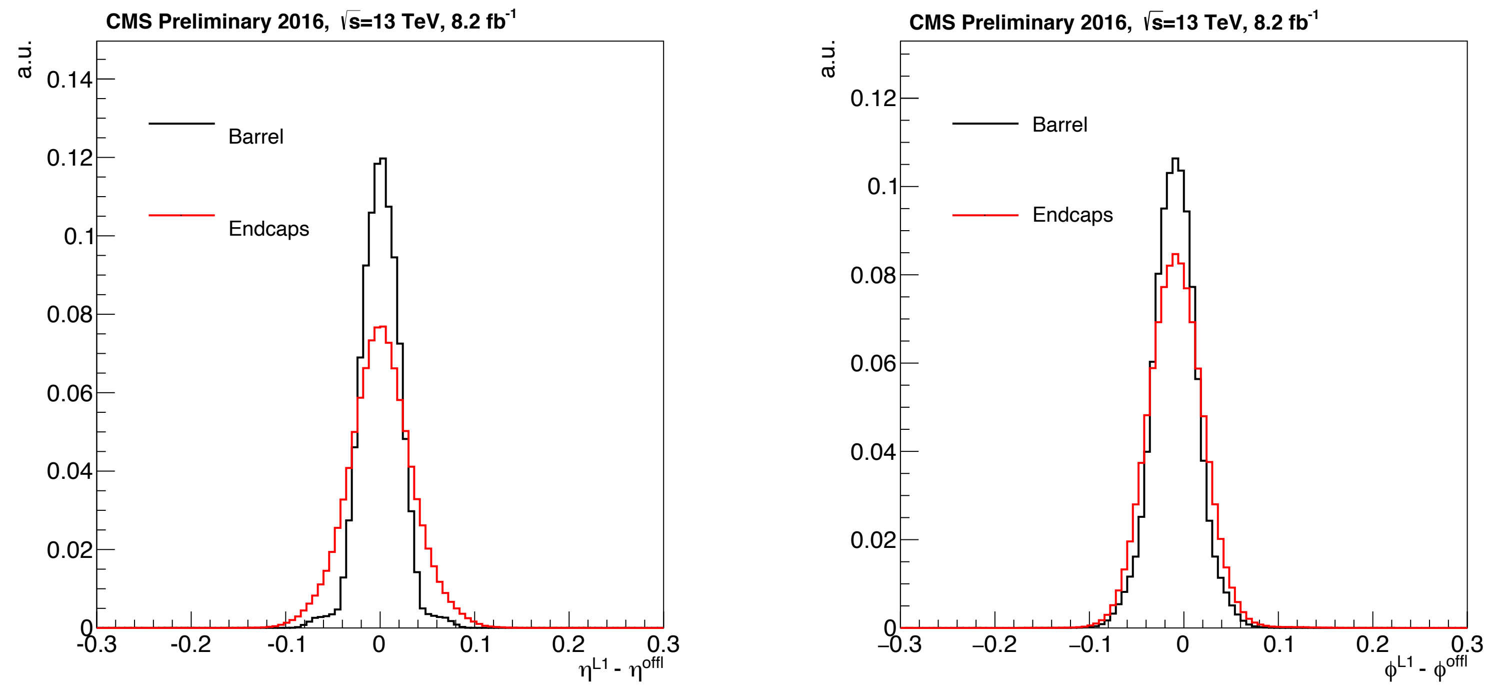
jet like

e/γ like





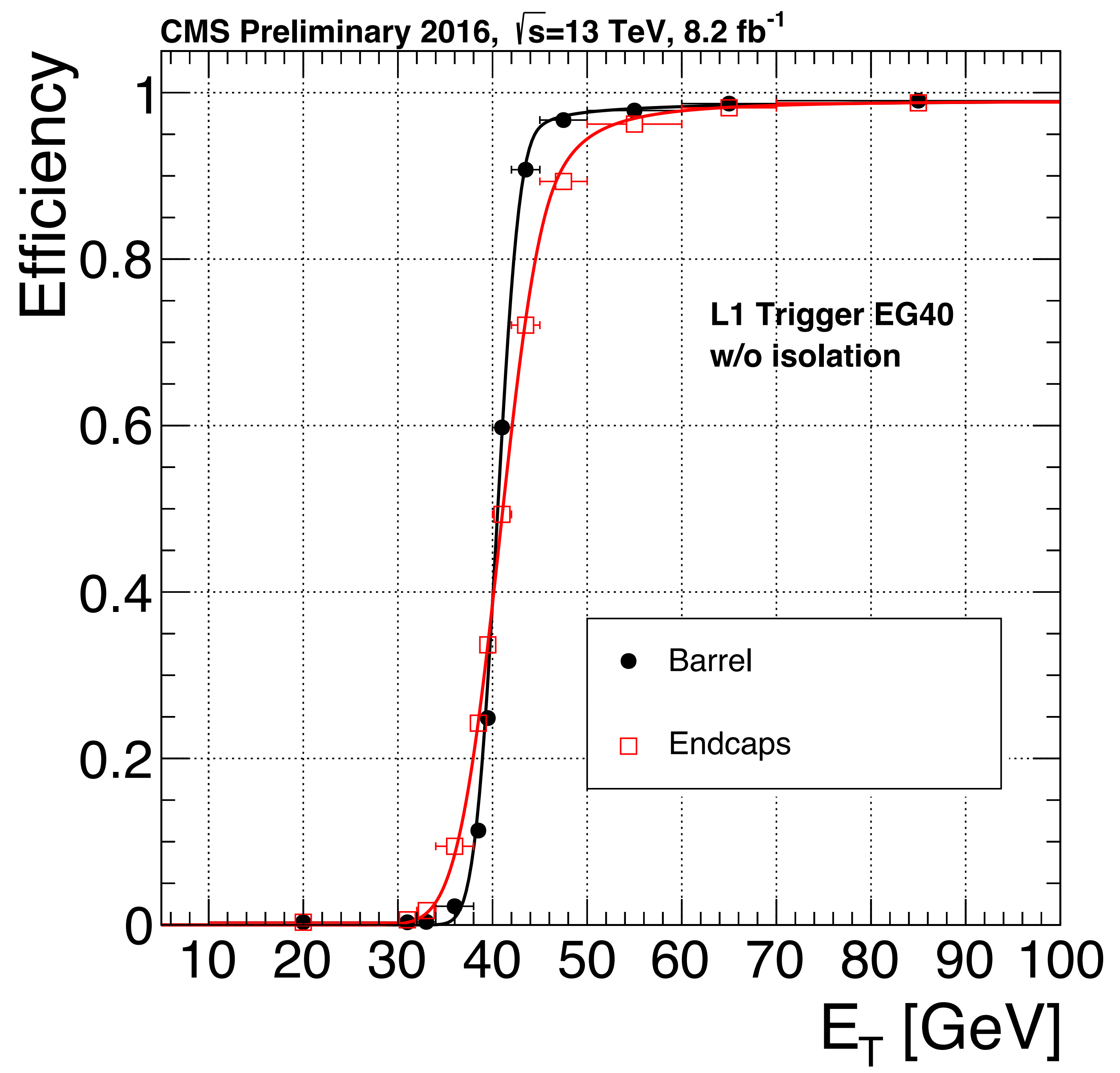
Energy comparison to offline



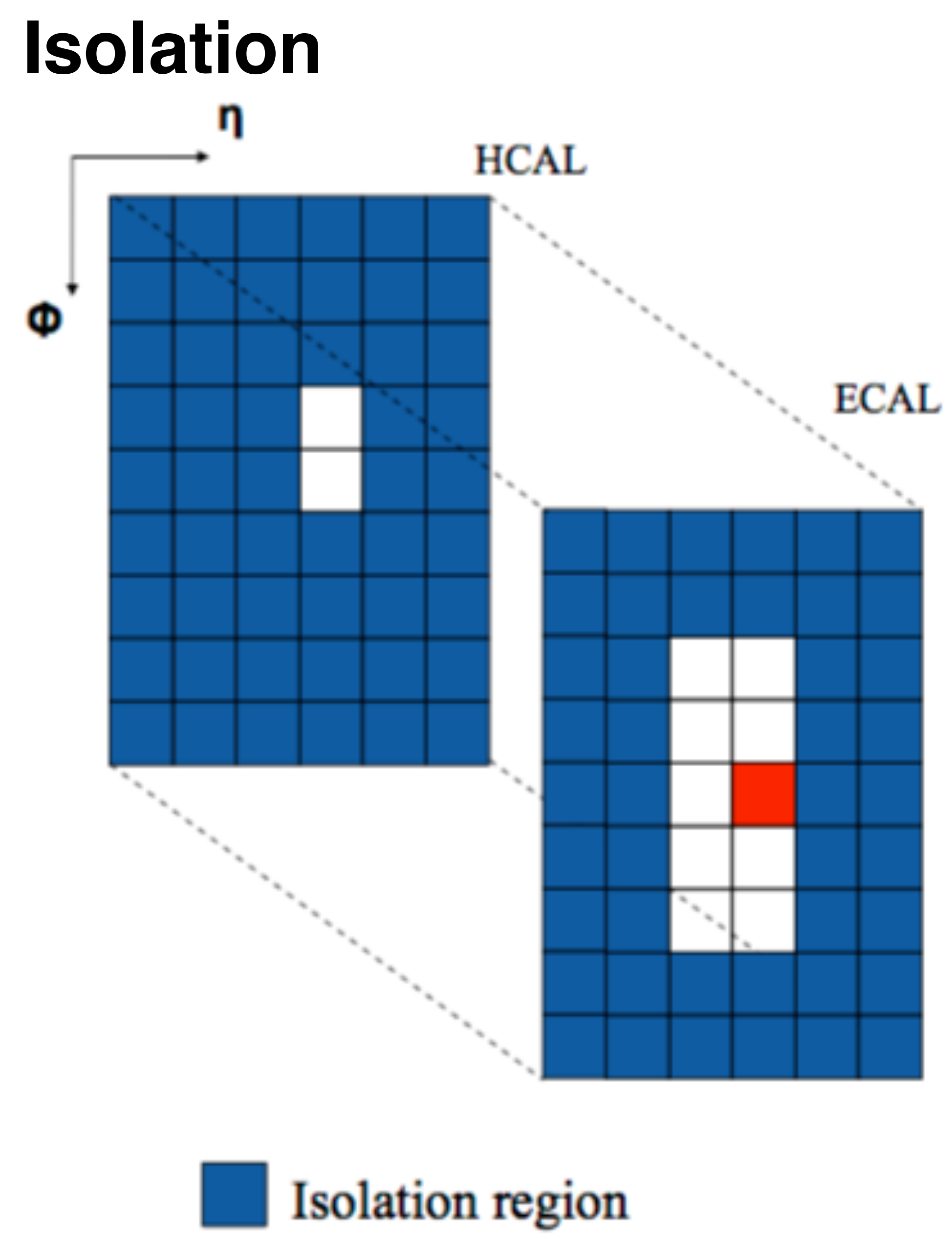
Position comparisons to offline

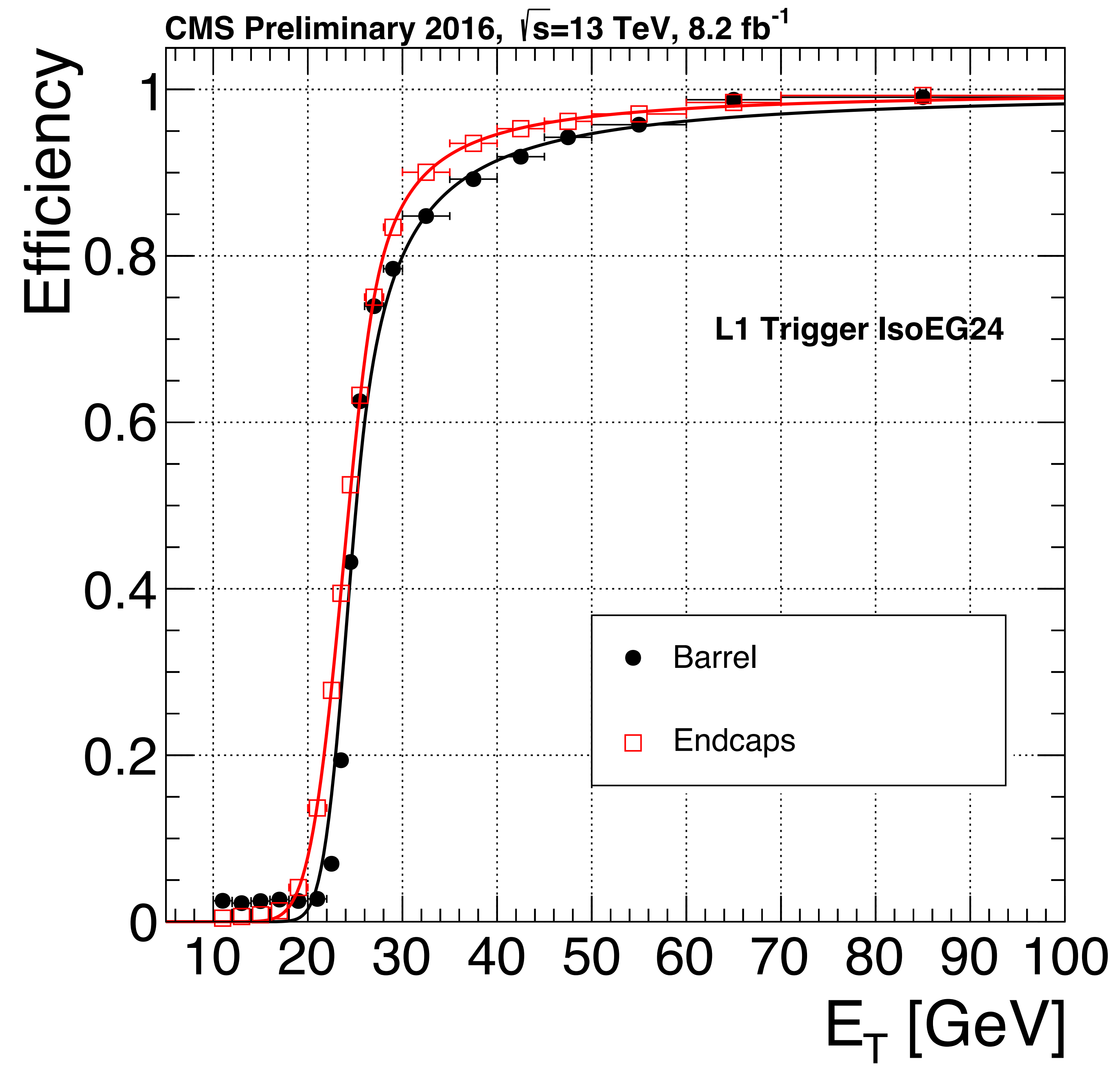
e/γ trigger performance results

- Trigger efficiency for a single e/γ with E_T > 40 GeV vs offline E_T
- Using tag and probe method on a dataset of Z⟶ee events



Isolation
Create isolation annuli (removing footprint) for ECAL and HCAL around cluster Isolation energy requirement fn. of PU and η

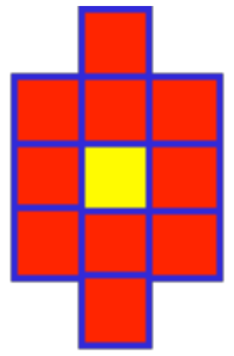




τ finder algorithm

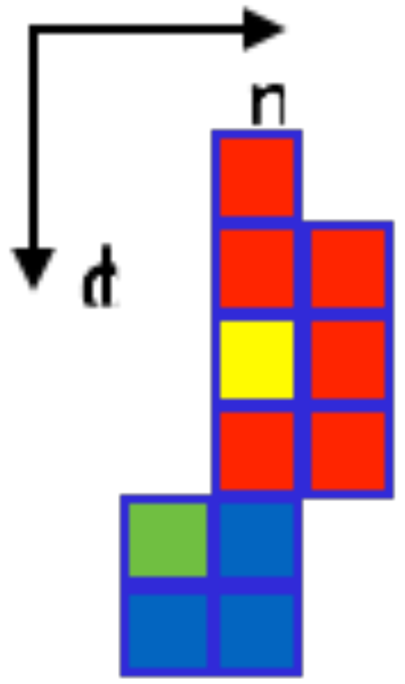
Clustering, shape and position

Very similar to e/γ — optimised for τ



Merging

Merge neighbouring clusters (~15% of clusters)
Recover multi-prong τ decays

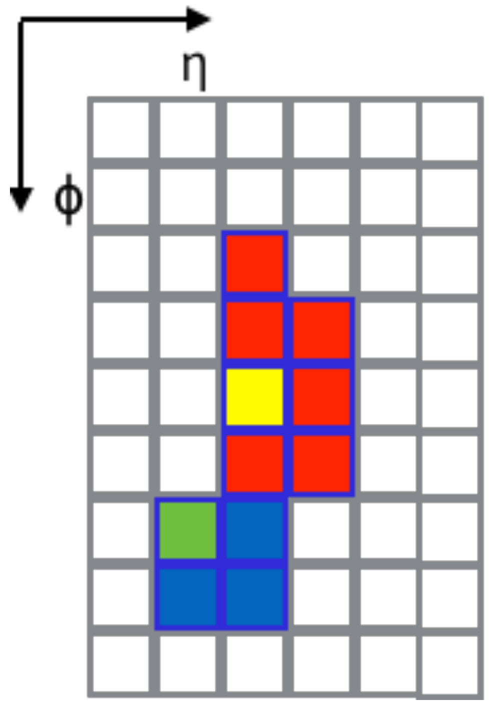


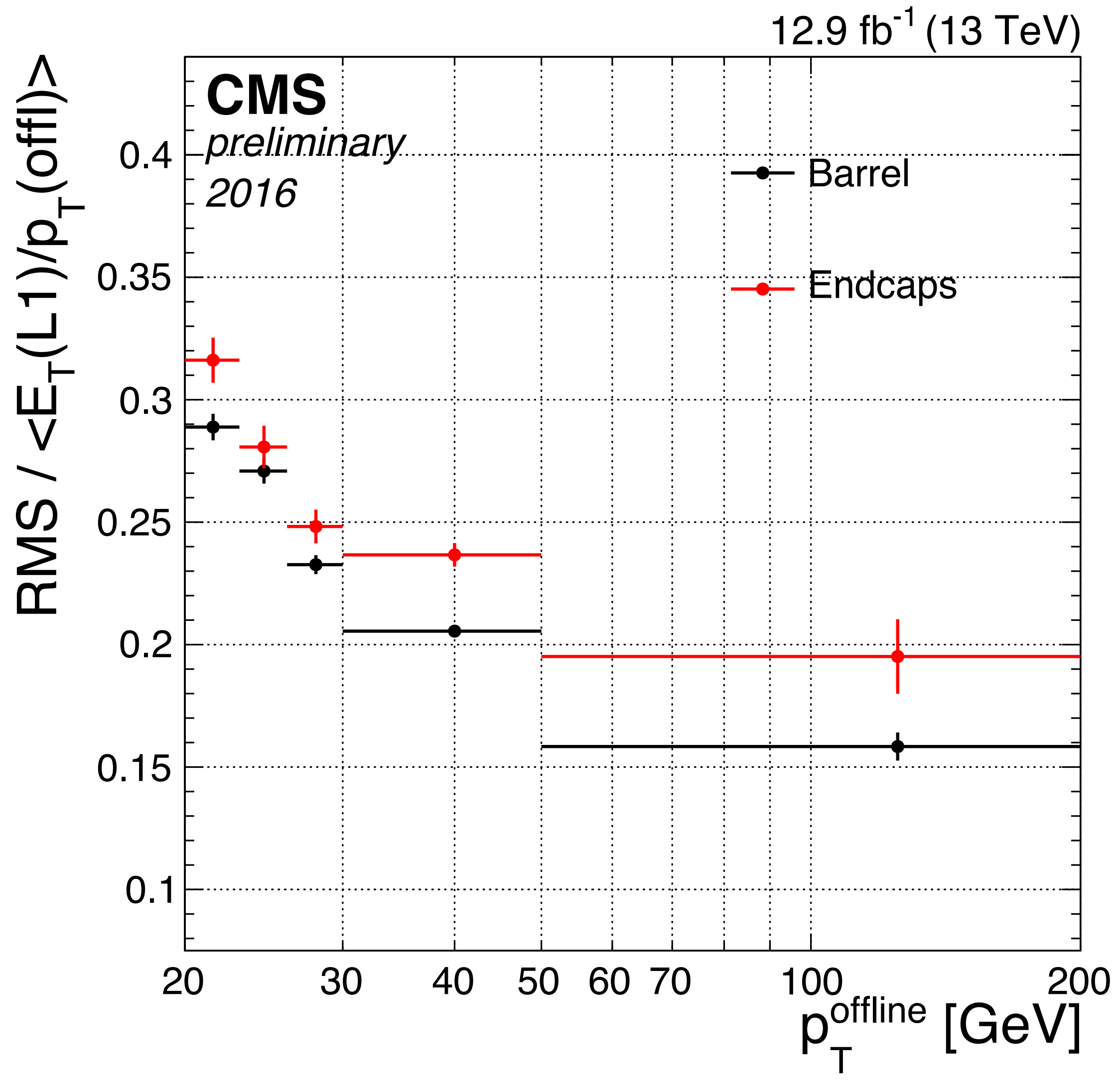
Calibration

τ cluster energy calibrated as fn. of E_T, η, merging and EM fraction

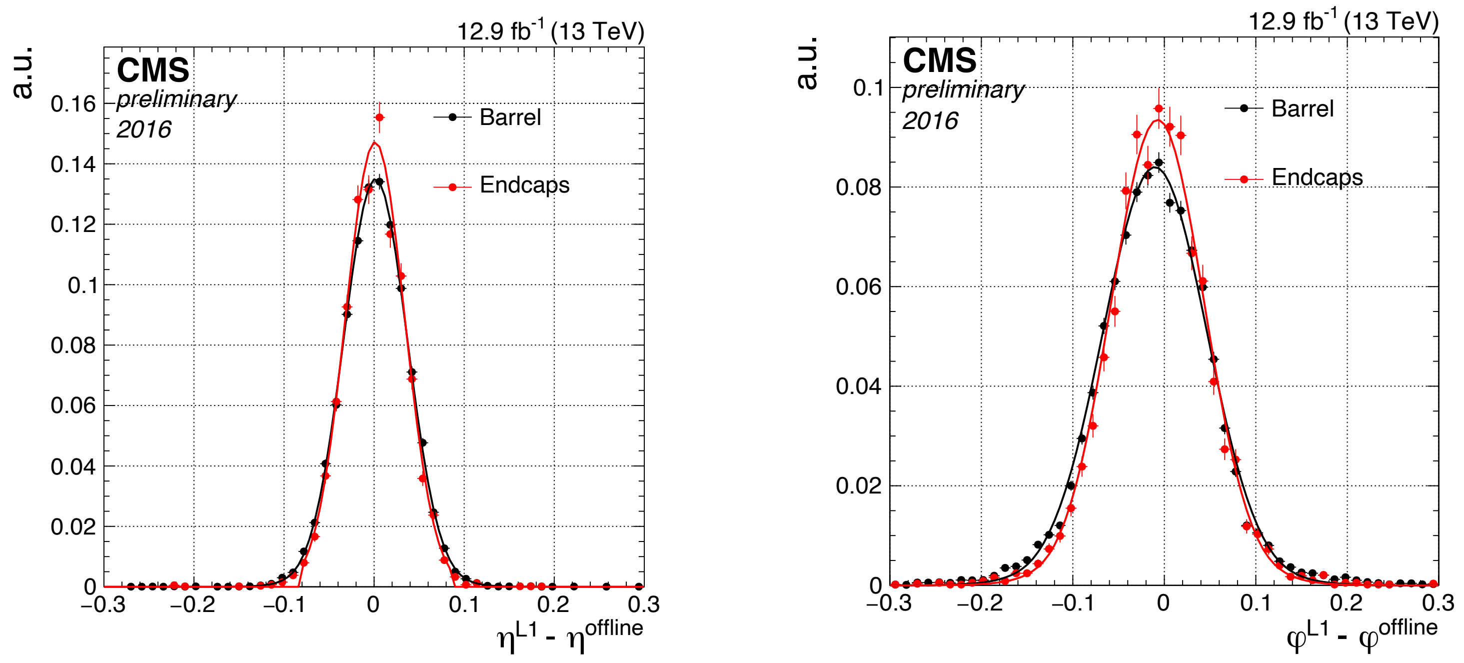
Isolation

Very similar to e/γ — optimised for τ including merging as input — two working points



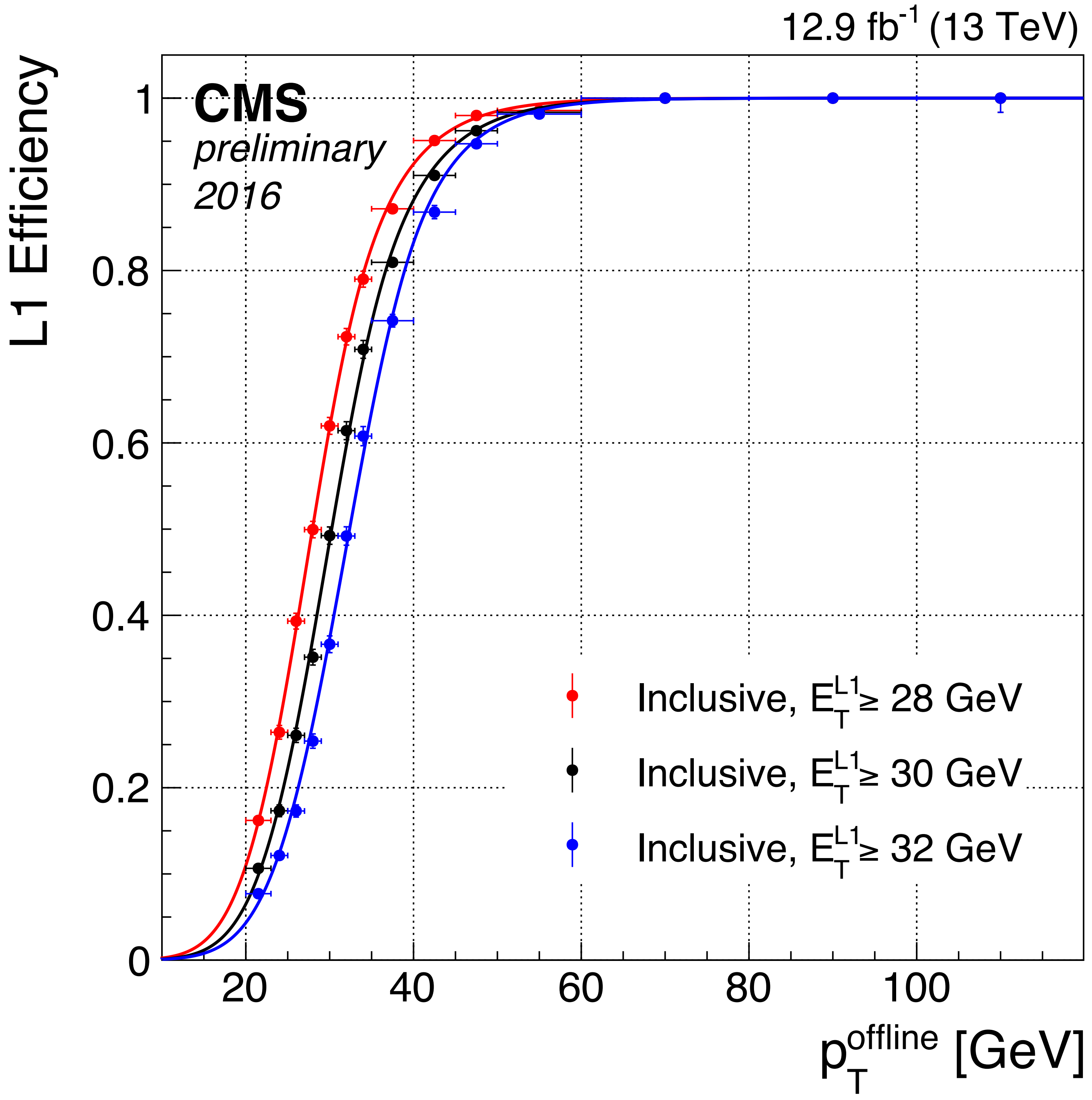


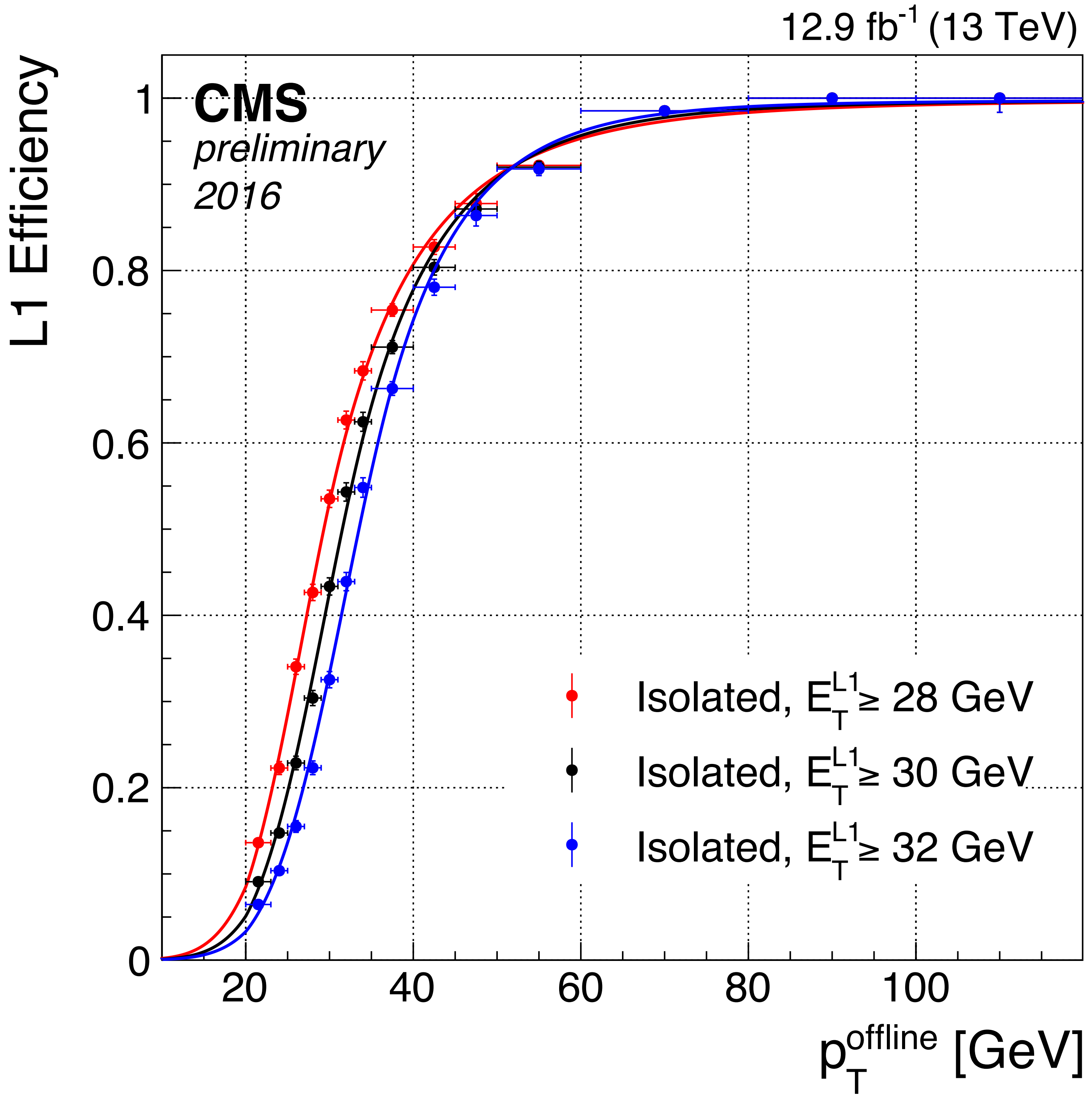
Energy comparison to offline



Position comparisons to offline

τ trigger performance results





- Trigger efficiency for a single τ with E_T > 28, 30 and 32 GeV vs offline τ p_T
- Using tag and probe method on a dataset of Z⟶μτ events

Jet finder algorithm

Input granularity

Access to higher granularity inputs than Run I

Sliding window jet algorithm

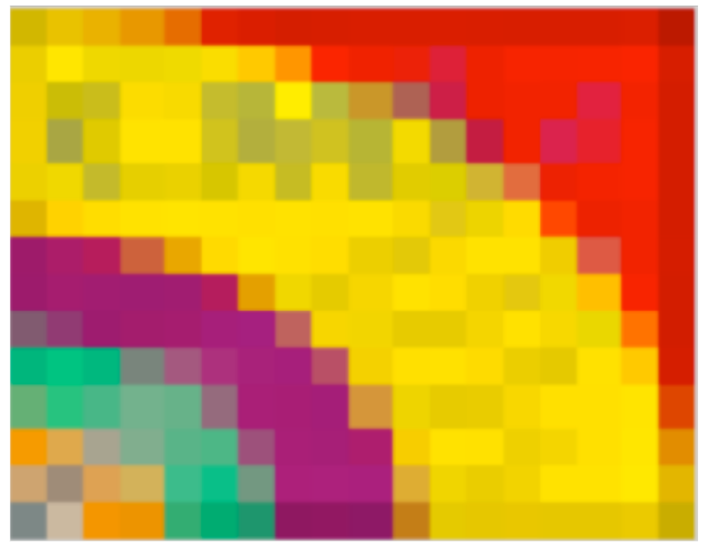
Search for seed energy above threshold
Apply veto mask to remove duplicates
Sum 9x9 trigger towers to approximate R=0.4 used offline

Pile-up subtraction

Consider four areas around jet window
Subtract sum of energy in lowest three from jet energy

Calibration

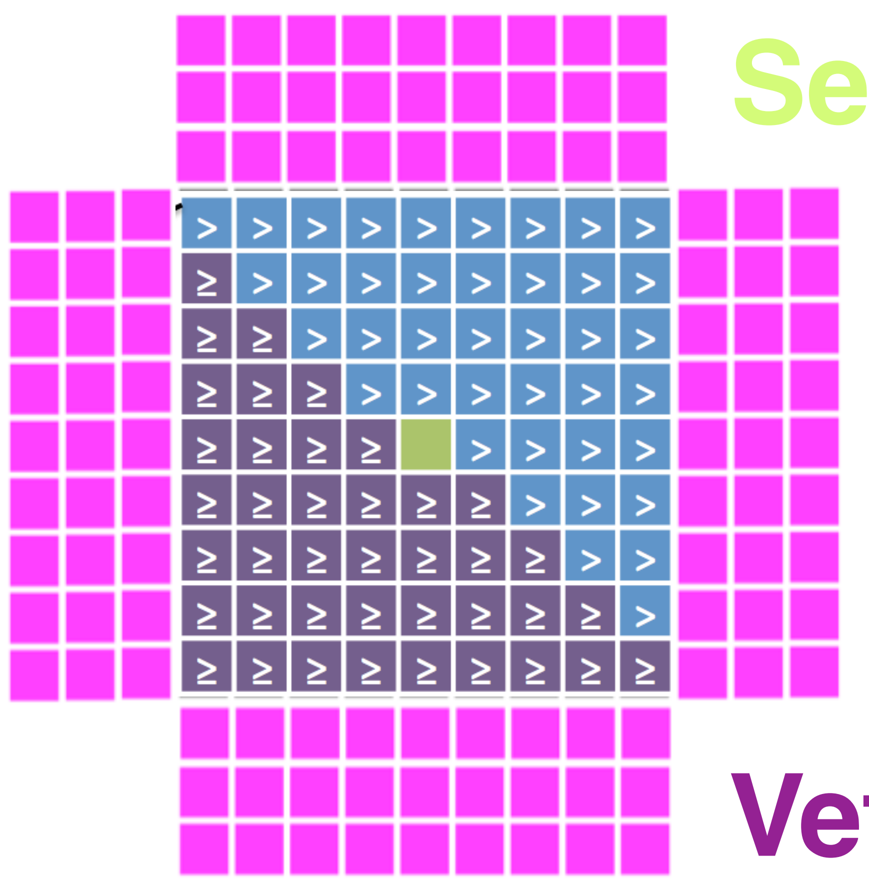
Correct jet energies as a function of jet E_T and η



14 (η) x 18 (ϕ)

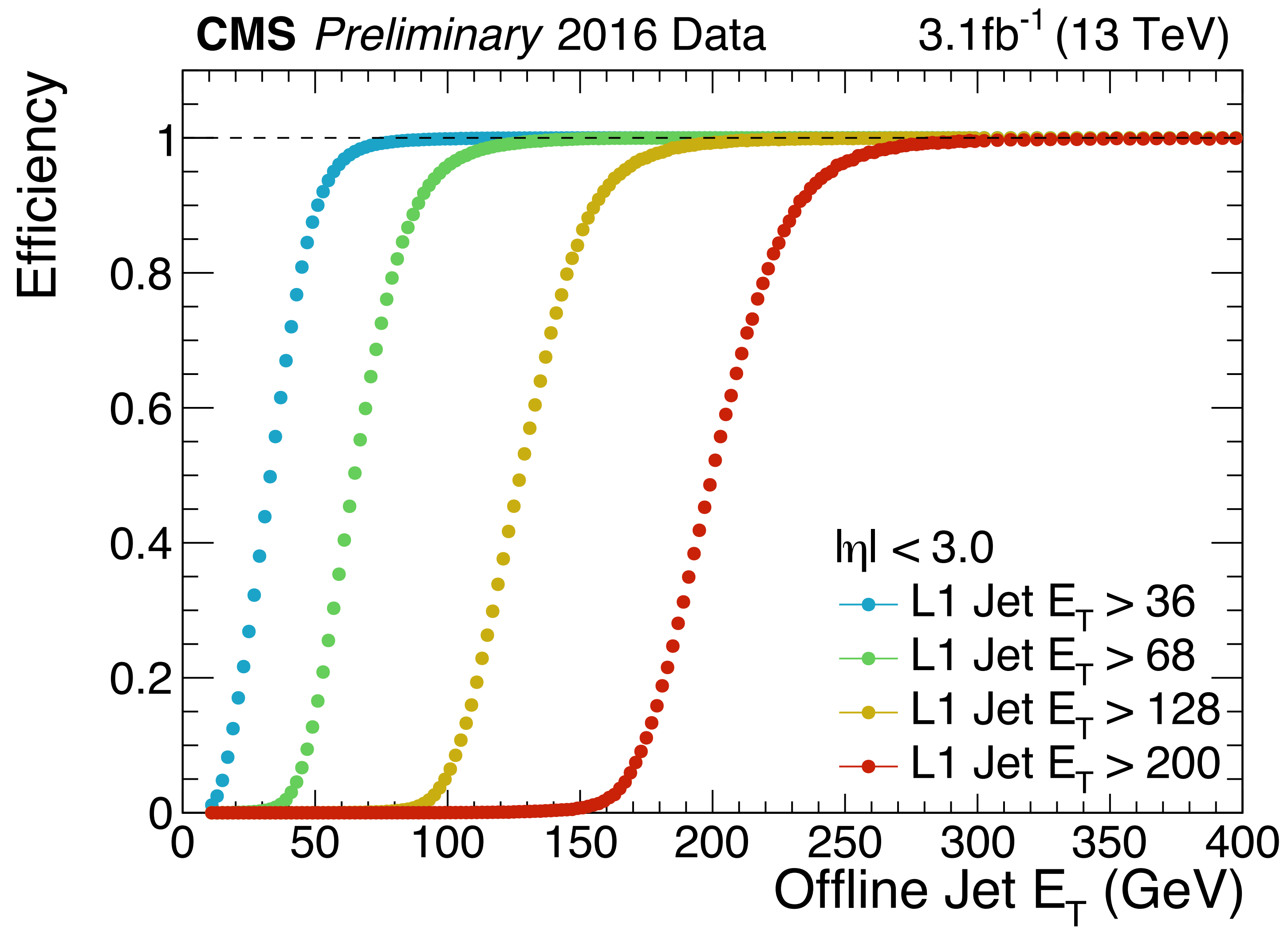
56 (η) x 72 (ϕ)

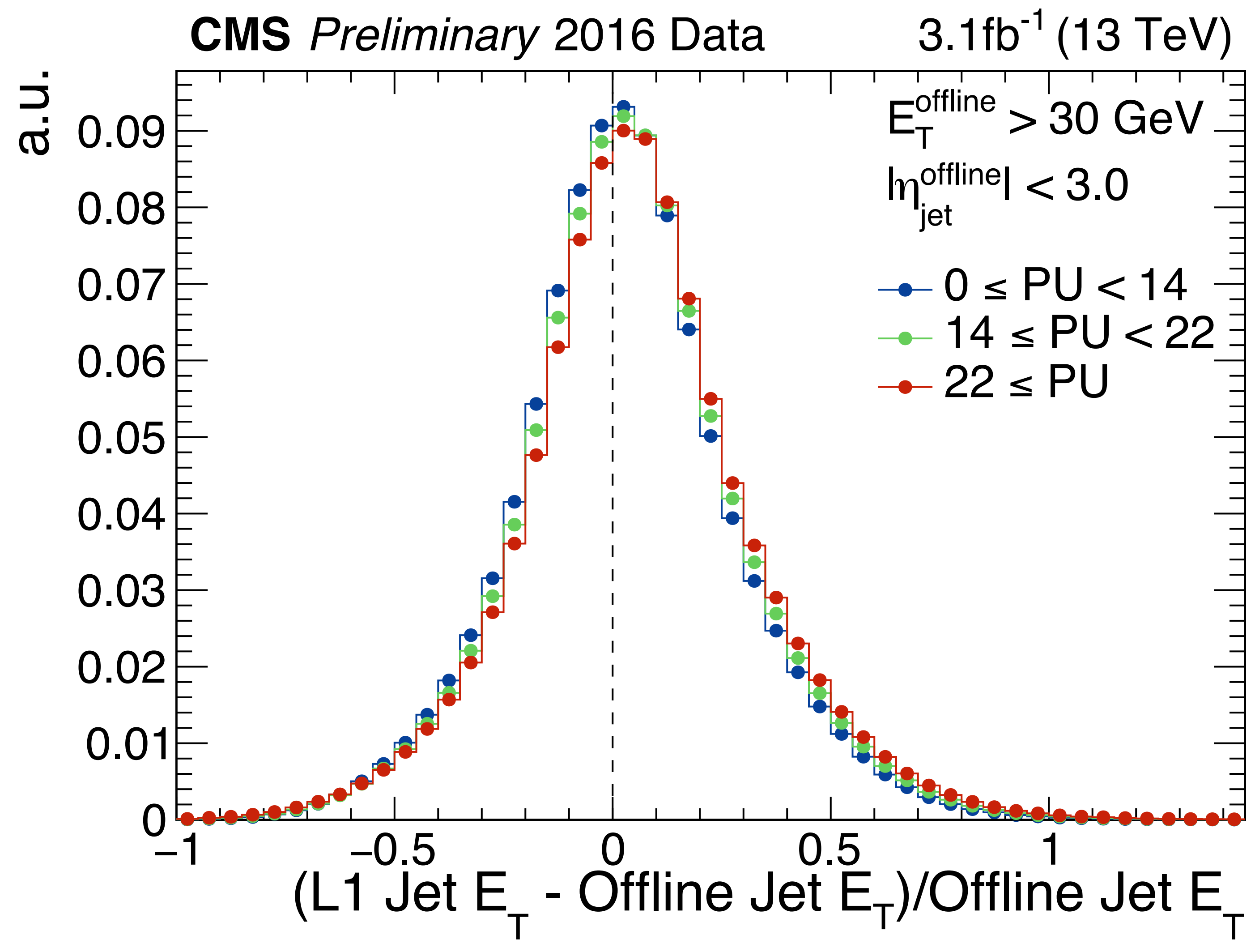
PUS areas

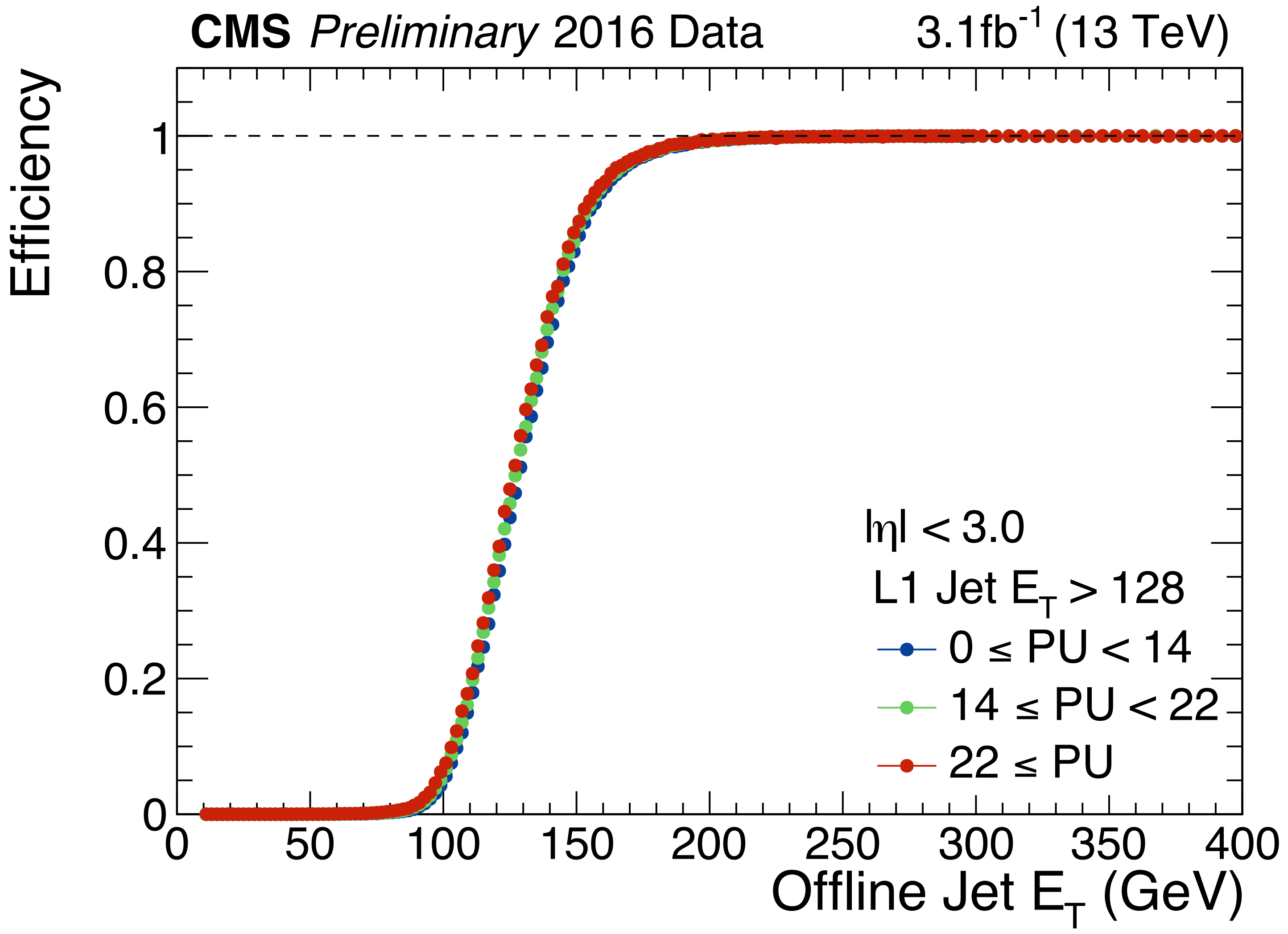


Jet trigger performance results

- Match Level-1 Trigger jets to offline (anti-k_t R = 0.4) jets using $\Delta R < 0.25$ in single muon data
- Compare energies and calculate efficiencies as a function of offline jet quantities



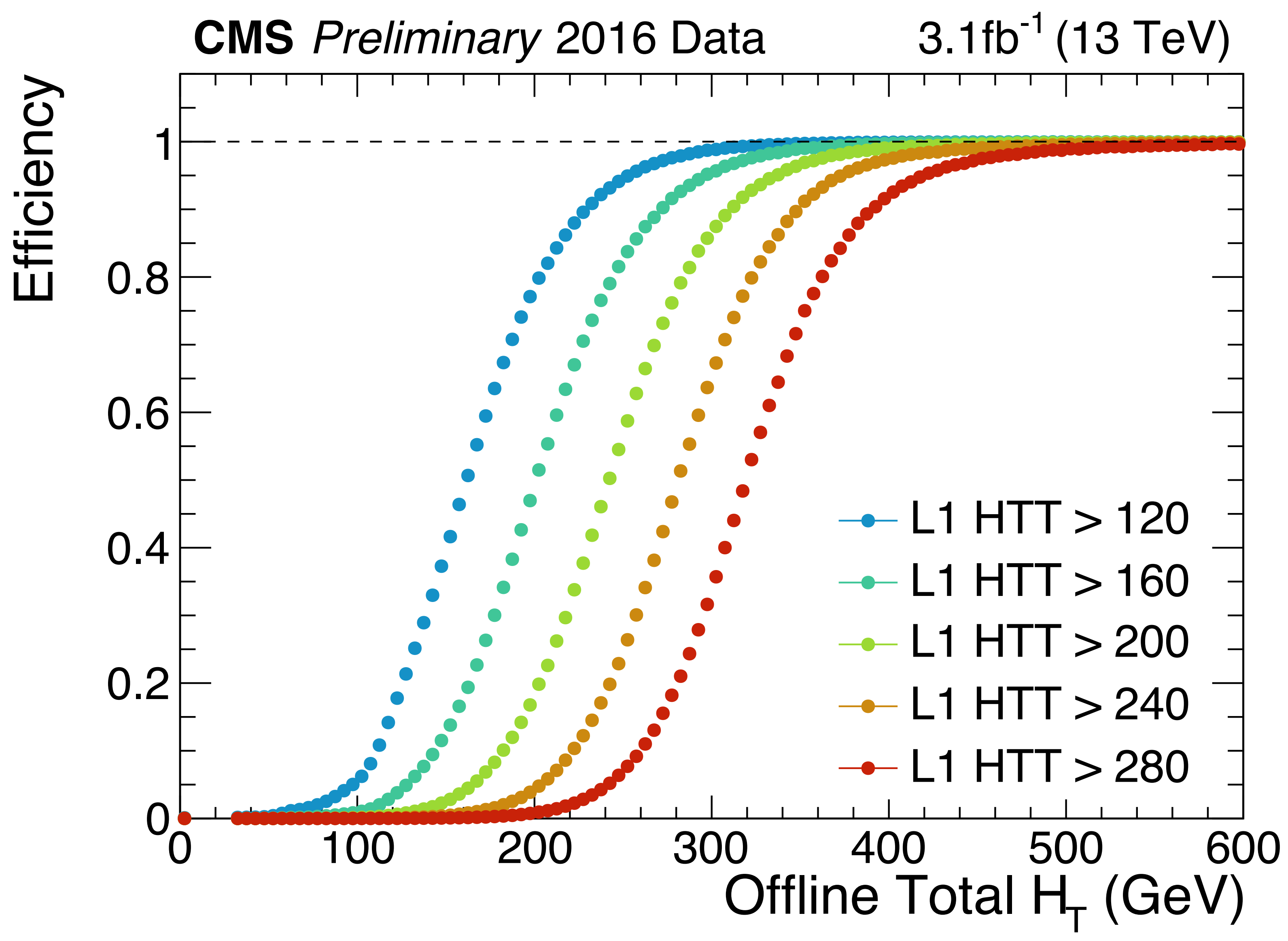


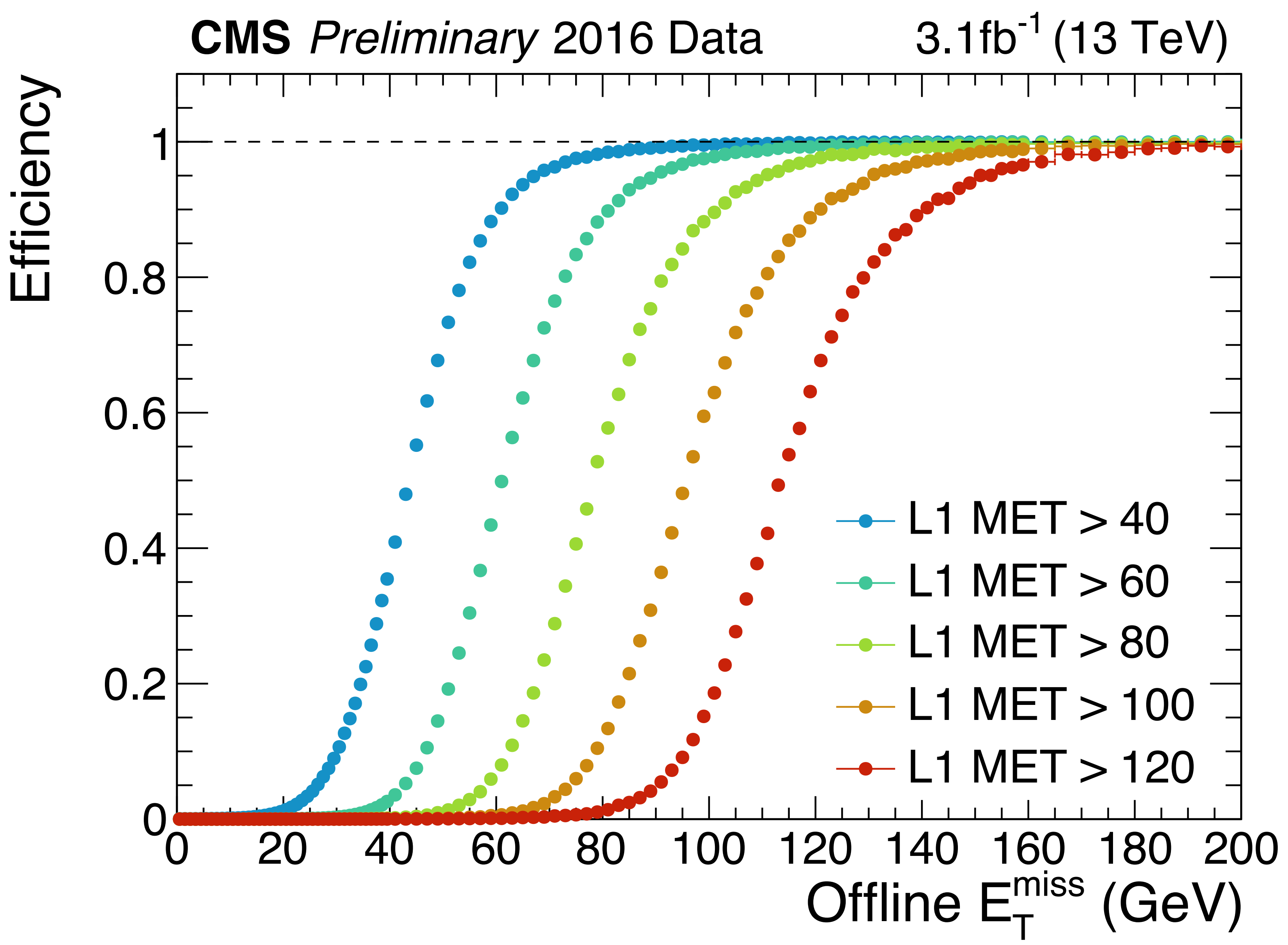


- Sharp efficiency turn-on with well calibrated E_T scale
- Insensitive to pile-up

Energy sum trigger performance results

- Use jets to calculate scalar sum $H_T = \Sigma E_{Tj}$ for $E_{Tj} > 30$ GeV and $|\eta| < 3$ using single muon data
- Vector sum of trigger towers with $|\eta| < 3$ to form E_T^{miss}

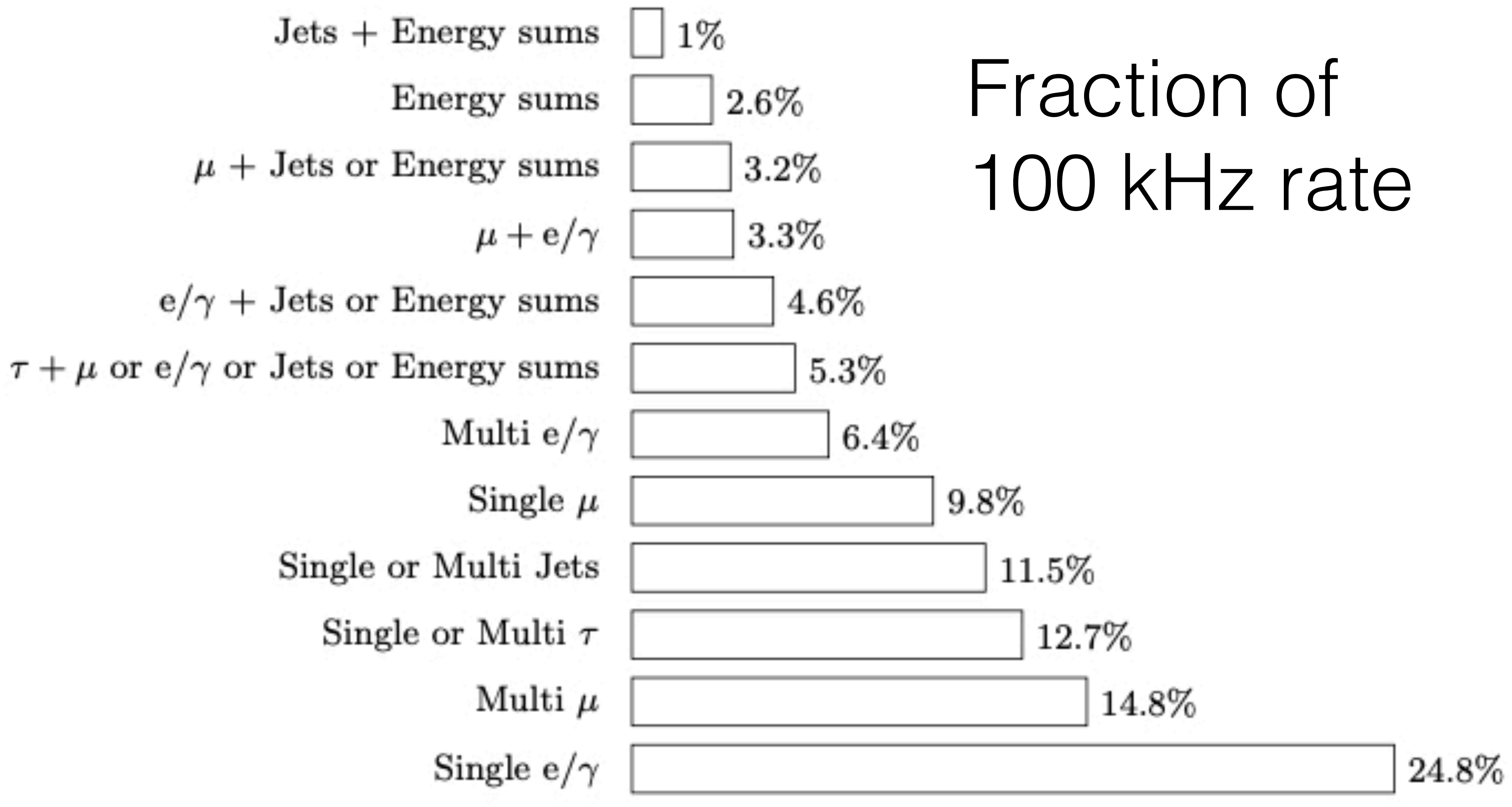




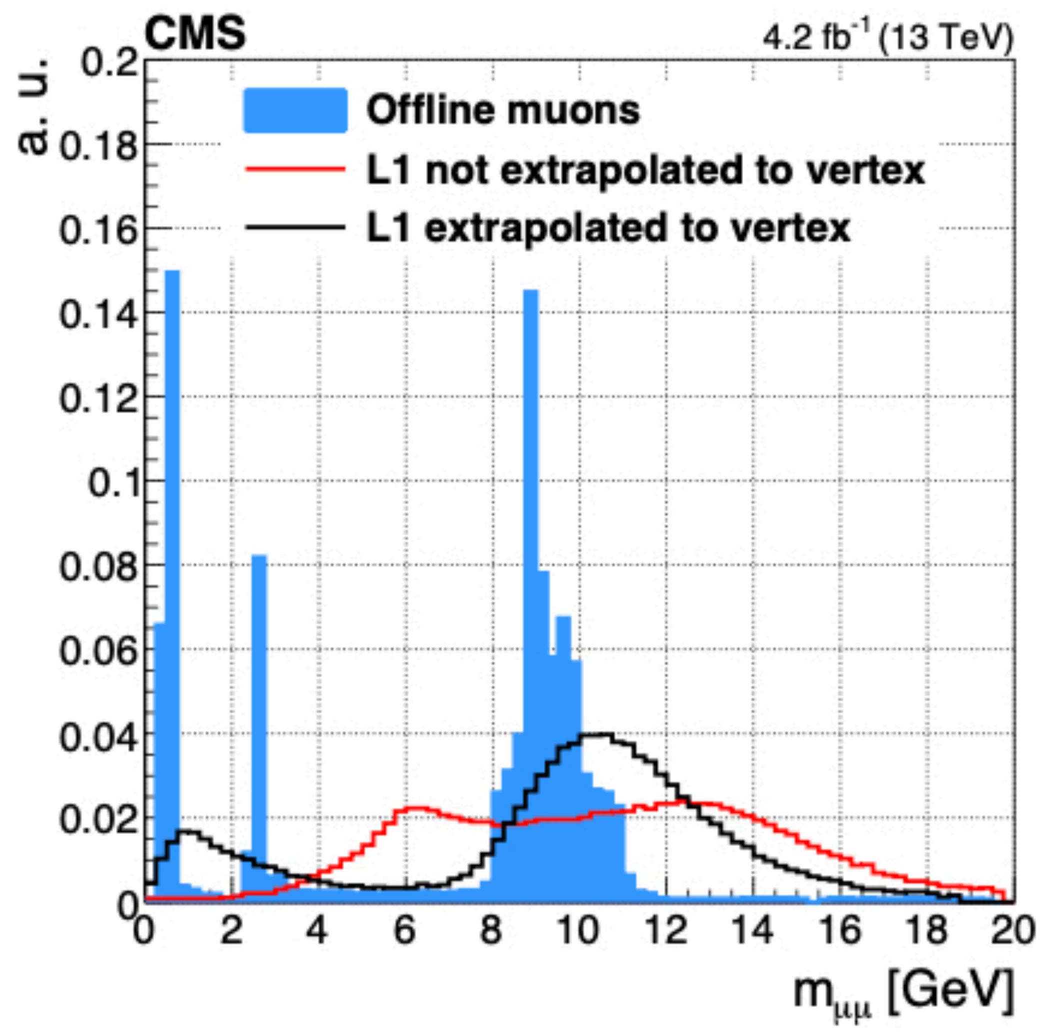
- Favourites with SUSY and exotics searches

Level-1 Trigger menu

- Global trigger provides selection based on object algorithms
    - Simple algorithms like single lepton, jet etc.
    - Also complex algorithms including invariant masses, topology conditions like ΔR, overlap removal …
    - Up to 512 algorithms supported
    - Prepared in conjunction with physics groups with tutorials on tools and development

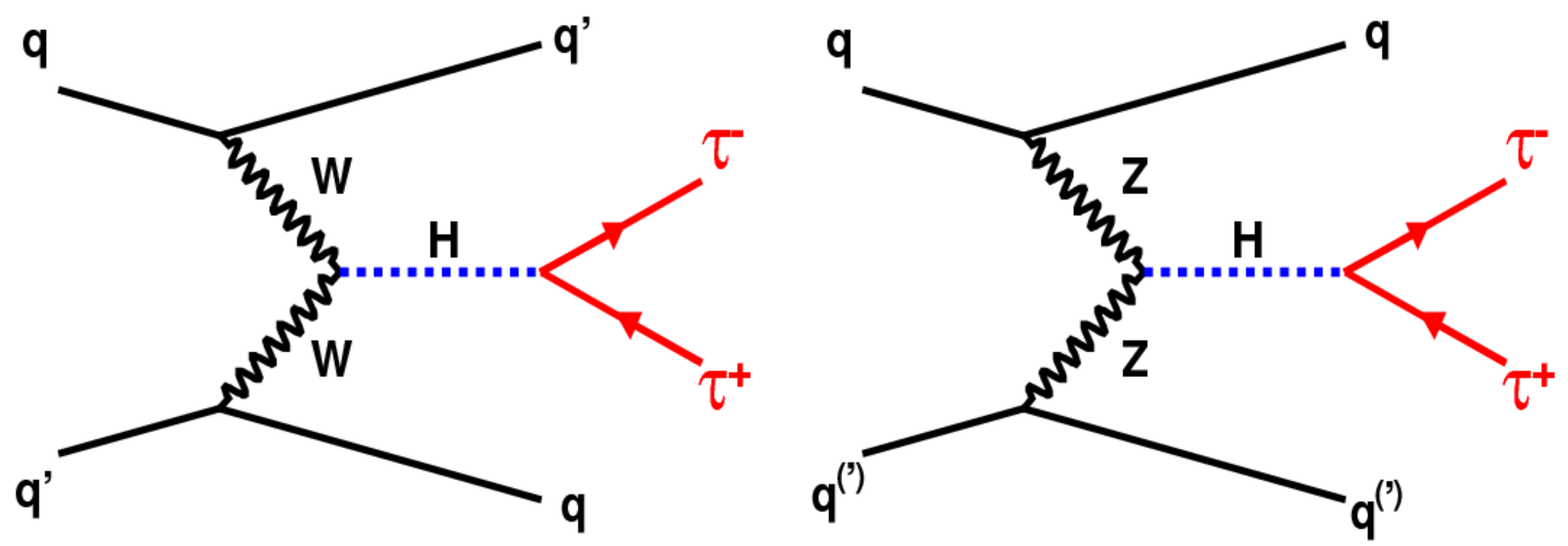


Fraction of 100 kHz rate



Example: invariant mass

- Example VBF Higgs to di-tau decays:
  - **Two low E_T jets, separated by large η gap**
  - **Central high p_T τ-lepton pair from Higgs decay**



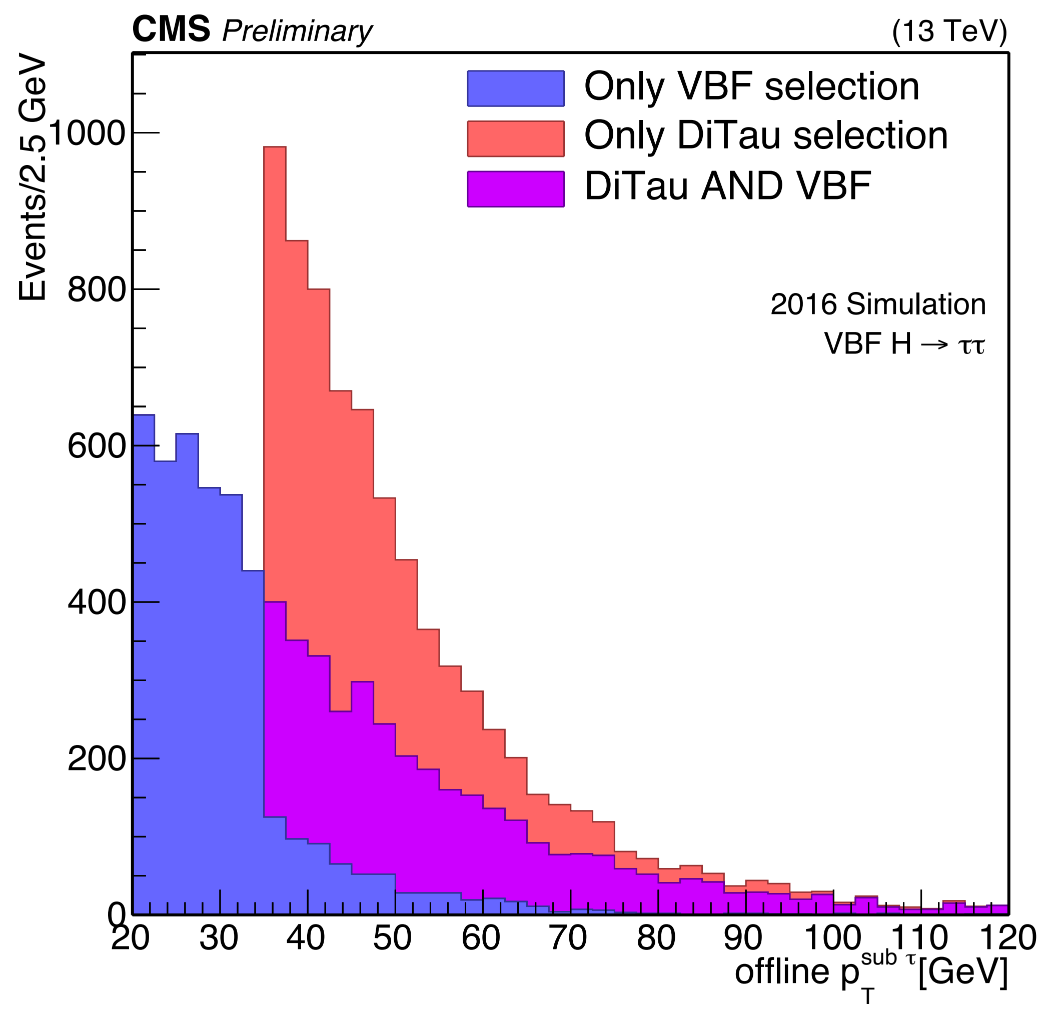
Di-jet selection with jet $E_T > 35$ GeV & $m_{jj} > 620$ GeV

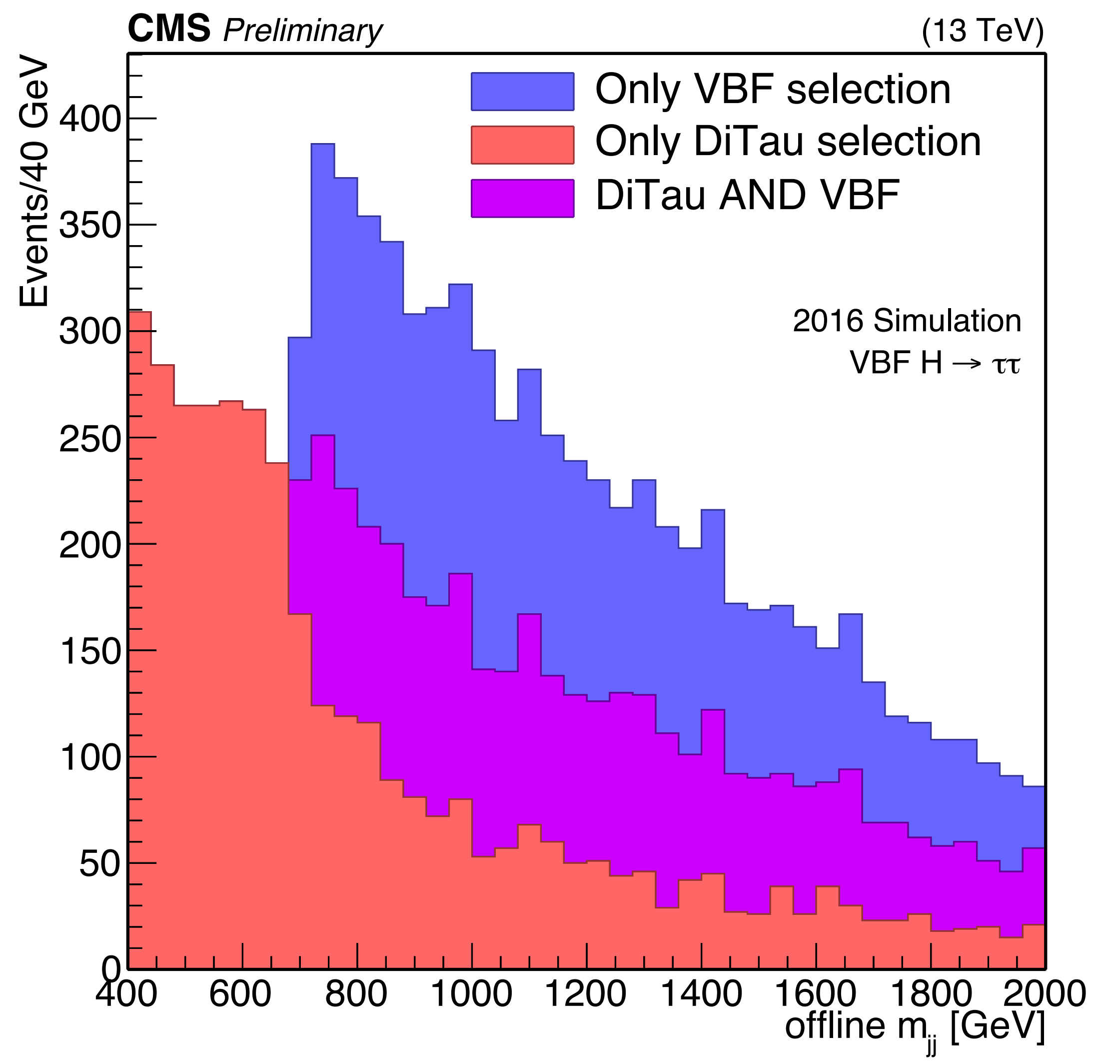
Single jet $E_T > 110$ GeV

Di-τ selection with $|\eta| < 2.1$ & $P_T > 32$ GeV

Use of invariant mass allowed the jet threshold to be kept low

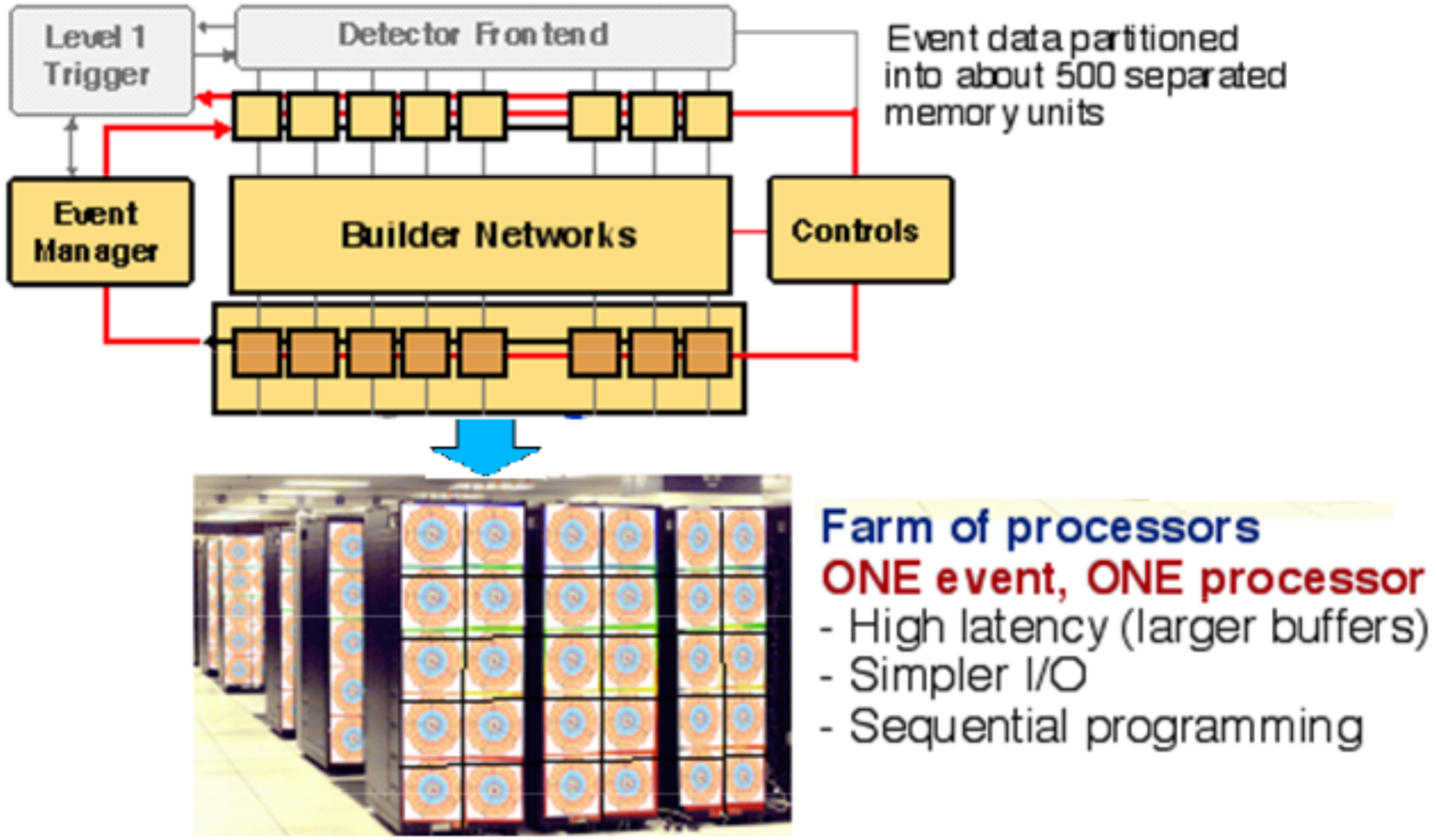
Combination of leptonic and hadronic selections adds ~**60% efficiency** for the Higgs signal





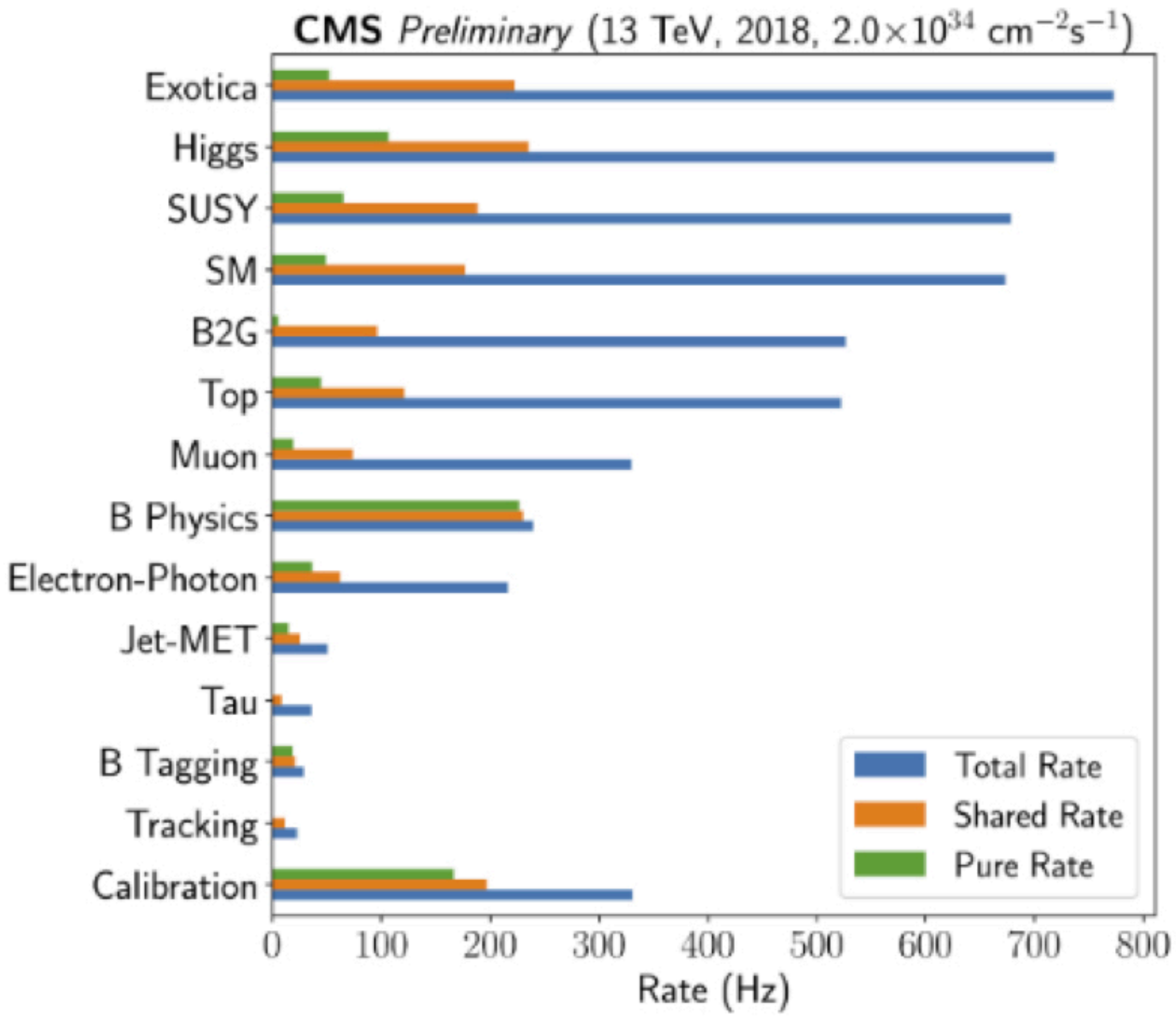
CMS High Level Trigger

- Traditional L2 and L3 merged into High Level Trigger (HLT)
  - 100kHz input rate from L1 trigger
  - ~30 000 CPU cores (Intel Haswell, Broadwell and Skylake)
  - Few hundred ms average per event
  - Multi-threaded version of CMS software used, where events share non-event data — 20% improvement in performance



High-level trigger menu

- Similarly to Level-1 Trigger, high-level trigger selects events based on reconstructed objects
  - Reconstruction algorithms similar to offline (full detector granularity) same code base but simplified in some cases and approx. calibrations
  - Key metric is CPU time — algorithms that take a long time (e.g. particle flow) must be run on subset of input events
  - Prepared in conjunction with physics groups with tutorials on tools and development



High-level trigger for Run 3

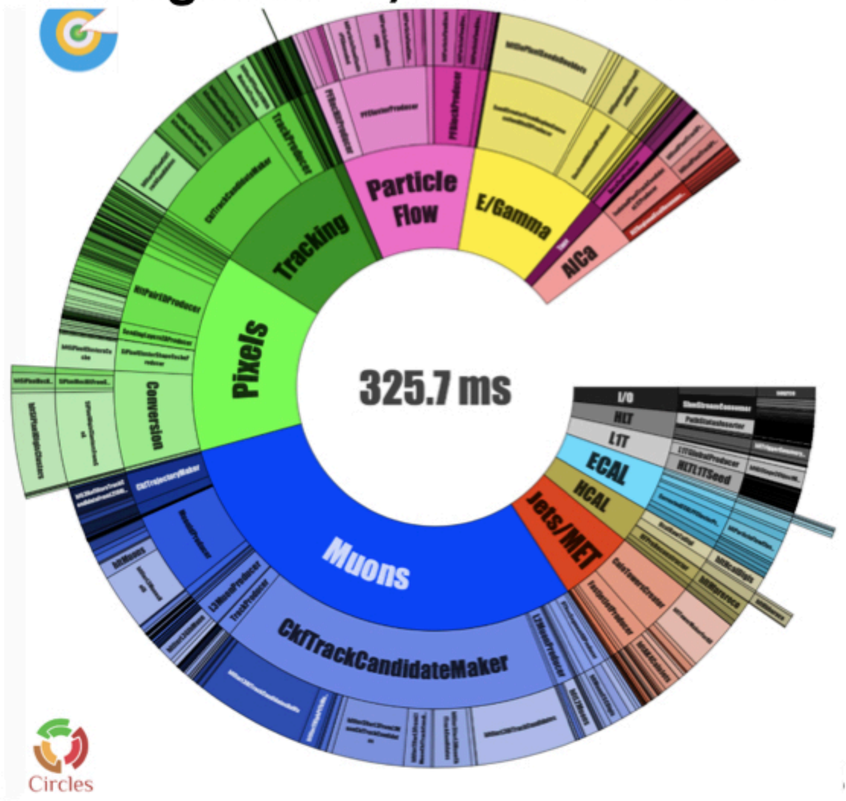
- Proposed plan for Run 3 is to equip the HLT farm with GPUs
  - Trial for HL-LHC upgrade where accepted that some sort of acceleration necessary
  - 20% fewer CPUs so need at least 20% improvement in performance to break even
  - Goal: Offload as much as possible part of HLT reconstruction to GPU's.
    ECAL, HCAL and pixel track reconstruction can now run on GPU's, decreasing the time spent per event reconstruction by ~25%
  - Opens doors to other options like wider use of Machine Learning, improved scouting …

CPU-only, 2018 Menu Latest Run-3 configuration, multi-threaded

25% decrease

Using GPUs

CPU+GPU, 2018 Menu Latest Run-3 configuration, multi-threaded



Outline

- Motivation and some important concepts
- Historical overview highlighting how challenges have driven development in the past
- Case study: current CMS trigger
- Case study: CMS trigger upgrade for HL-LHC
- Practical advice

Why upgrade the LHC?

- New Physics at the weak-scale could still be hiding in the difficult corners of phase space or in small deviations of the SM predictions
  - Direct searches targeting hard to identify signatures
    - Compressed spectra, small couplings or heavy off-shells mediators
    - Rare events with soft objects or long lived objects in the final state
  - Indirect searches through small deviations in SM properties
    - Less well known SM properties: Higgs boson couplings need $\mathcal{O}(1\%)$ on couplings
- Require the high statistical power dataset to have at least the same physics acceptance as currently i.e. same trigger thresholds
- Require to open a door to the uncharted land: several blind spots in current searches are due to trigger limitations. New trigger design to cover extended forward regions, full hadronic final states, LLP, soft leptons, etc...

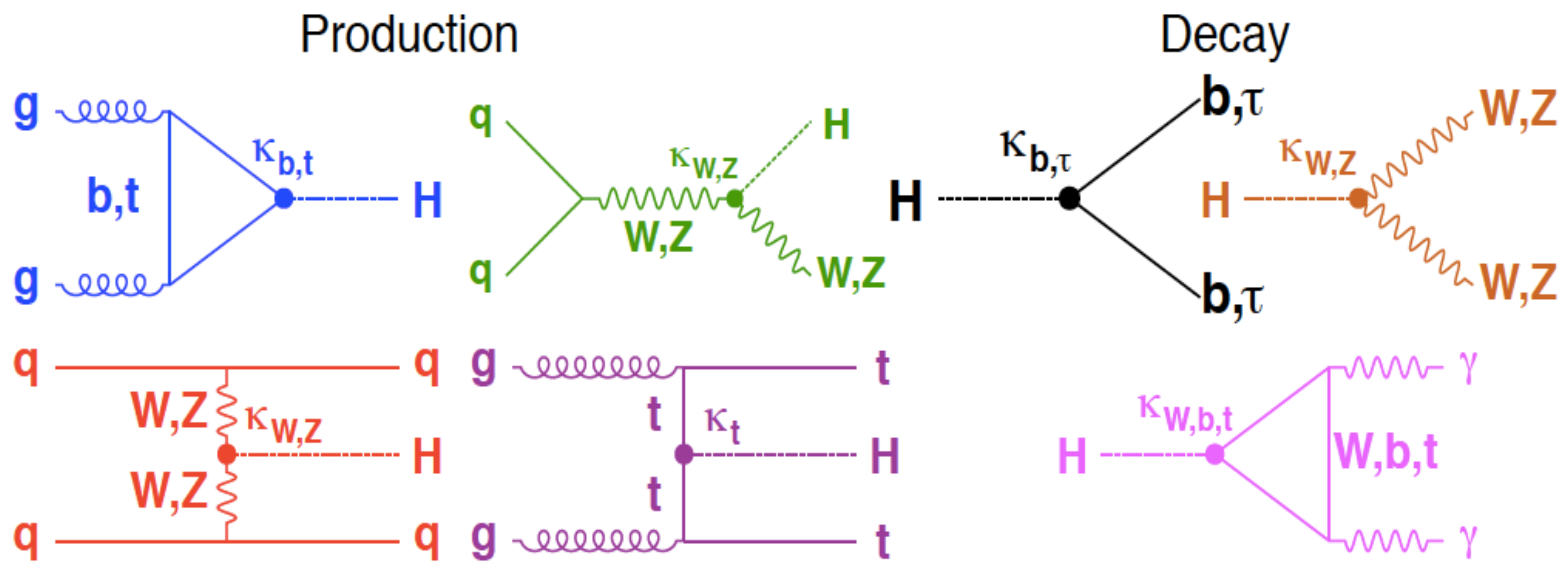
Future physics: Higgs

- Measurements of Higgs will play a big role in future
- Upgraded LHC is a *Higgs factory*
  - Run 1 $\mathcal{O}(1000)$ Higgs bosons at LHC
  - Upgrade factor 4-10 better measurements than today
  - Millions of events in all production modes
  - Access to rare decays of Higgs

	Total Higgs Bosons
LHC Run 1	**660k**
HL-LHC, 3000 fb^{-1}	**170M**
VBF (all decays)	13M
ttH (all decays)	1.8M
$H \rightarrow \gamma\gamma$	390k
$H \rightarrow Z\gamma$	230k
$H \rightarrow \mu\mu$	37k
$H \rightarrow J/\psi\gamma$	400
HH (all)	121K
$HH \rightarrow WWWW$	9200
$HH \rightarrow bb\gamma\gamma$	320
$HH \rightarrow \gamma\gamma\gamma\gamma$	1

Future physics: Higgs

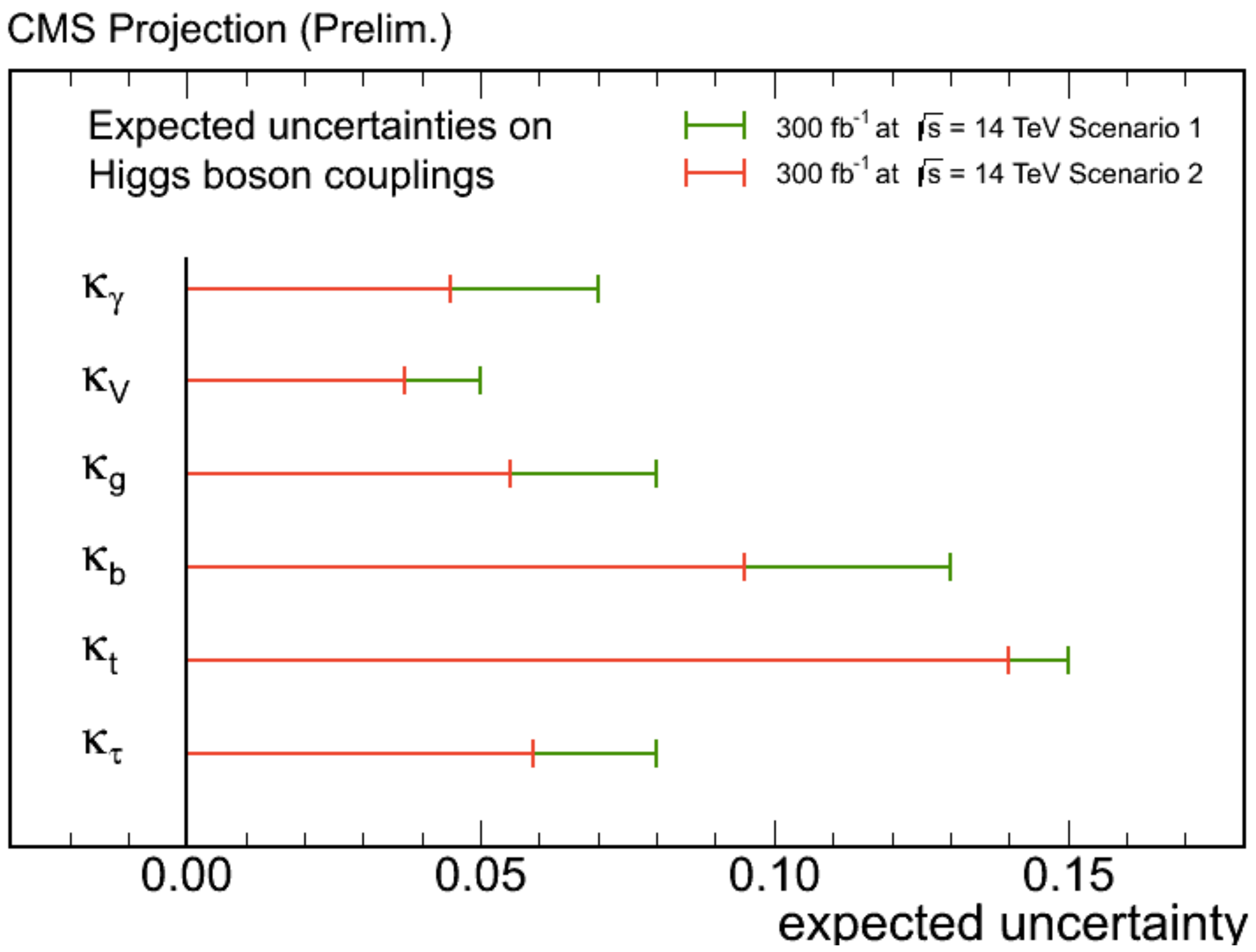
- Measurements of Higgs couplings
  - Answering the question, *is this the SM Higgs?*
  - Express the production and decay of the Higgs in terms of deviation from SM coupling

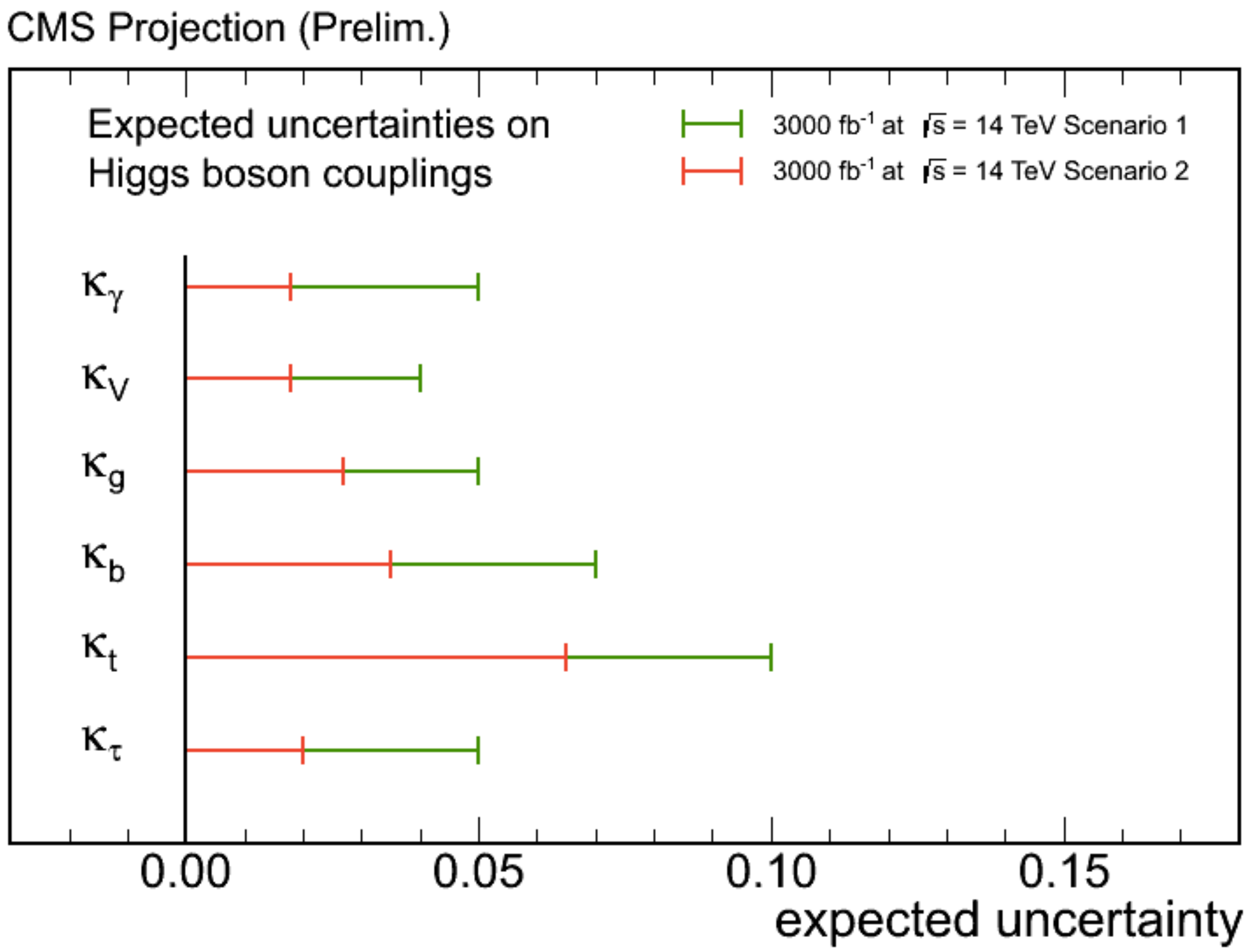


  - Requires great performance across the board
    - Electrons, muons, taus, forward jets, b-tagging, trigger, MET….

Future physics: Higgs

- Scaling of signal and background yields as:
  - **Scenario1** - systematic uncertainties remain the same: conservative
  - **Scenario 2** - theoretical uncertainties scaled by ½: expt. systematic uncertainties scaled by 1/√L

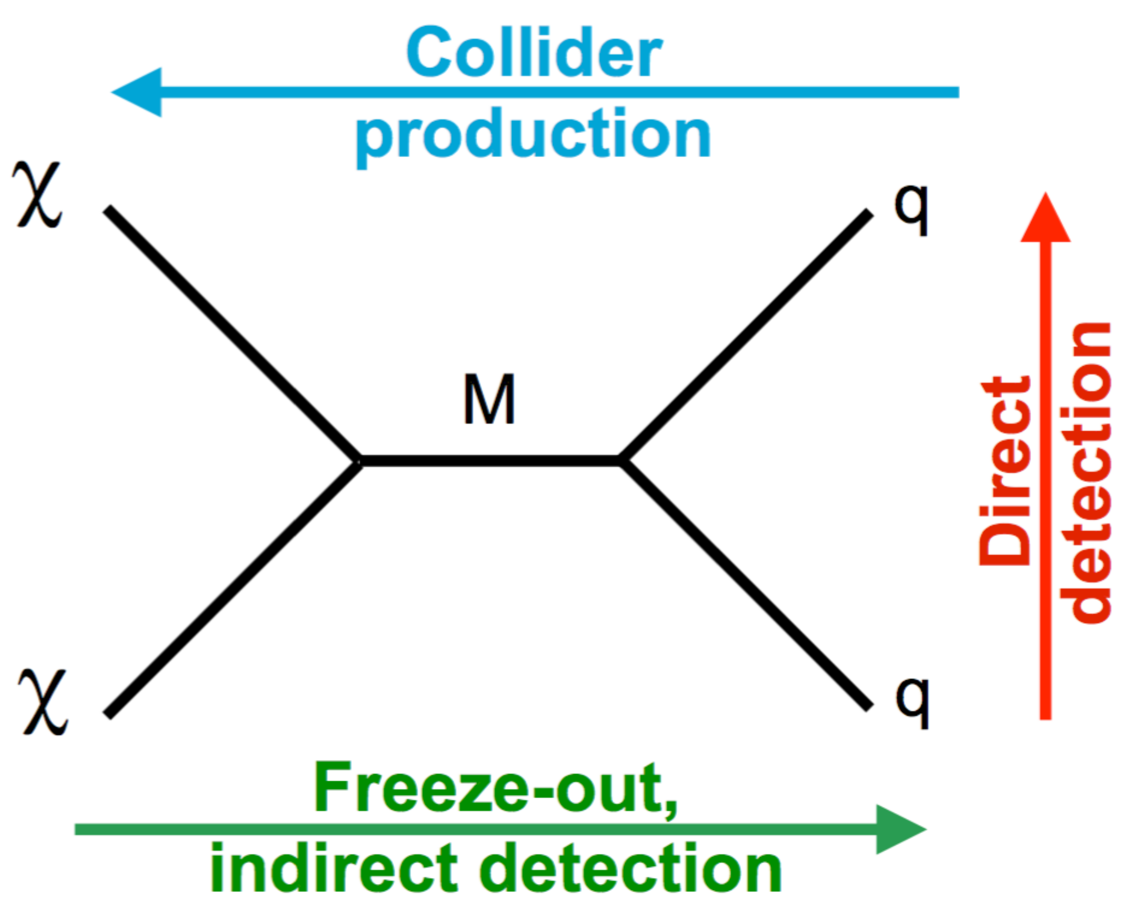




  - Example beyond the Standard Model theories predict up to ~5% deviation

Future physics: Dark Matter

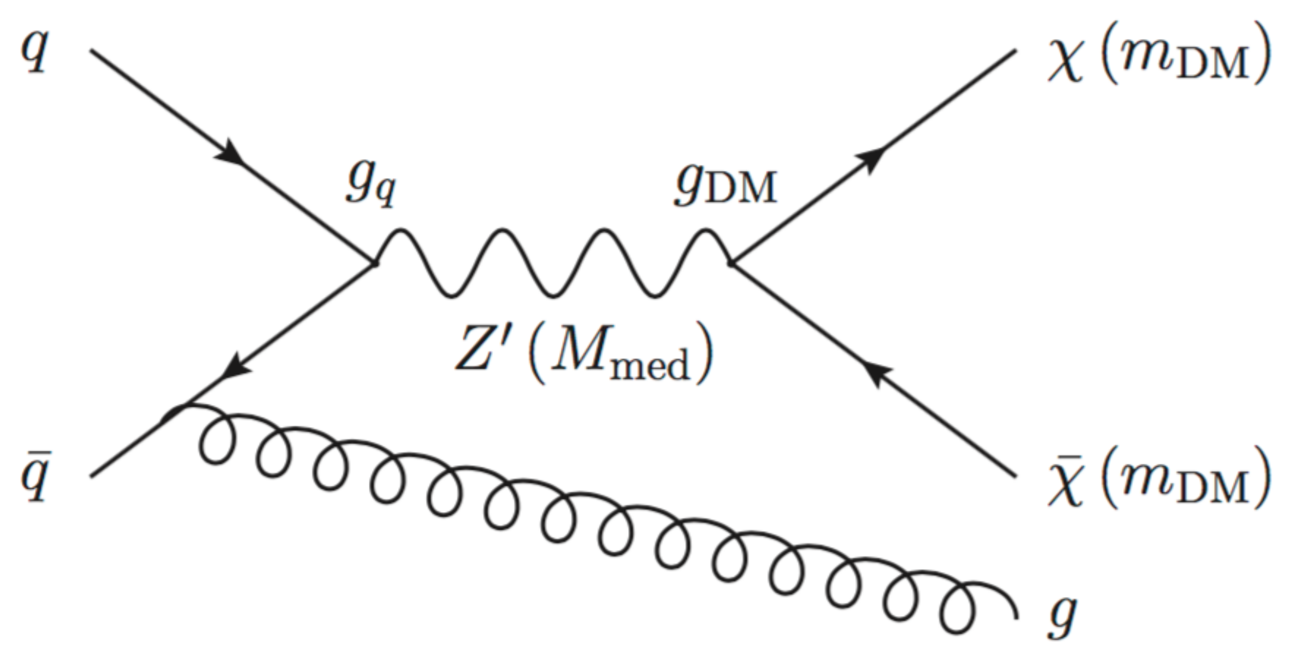
- What can the LHC contribute?
  - Complementary to direct detection experiments and observations

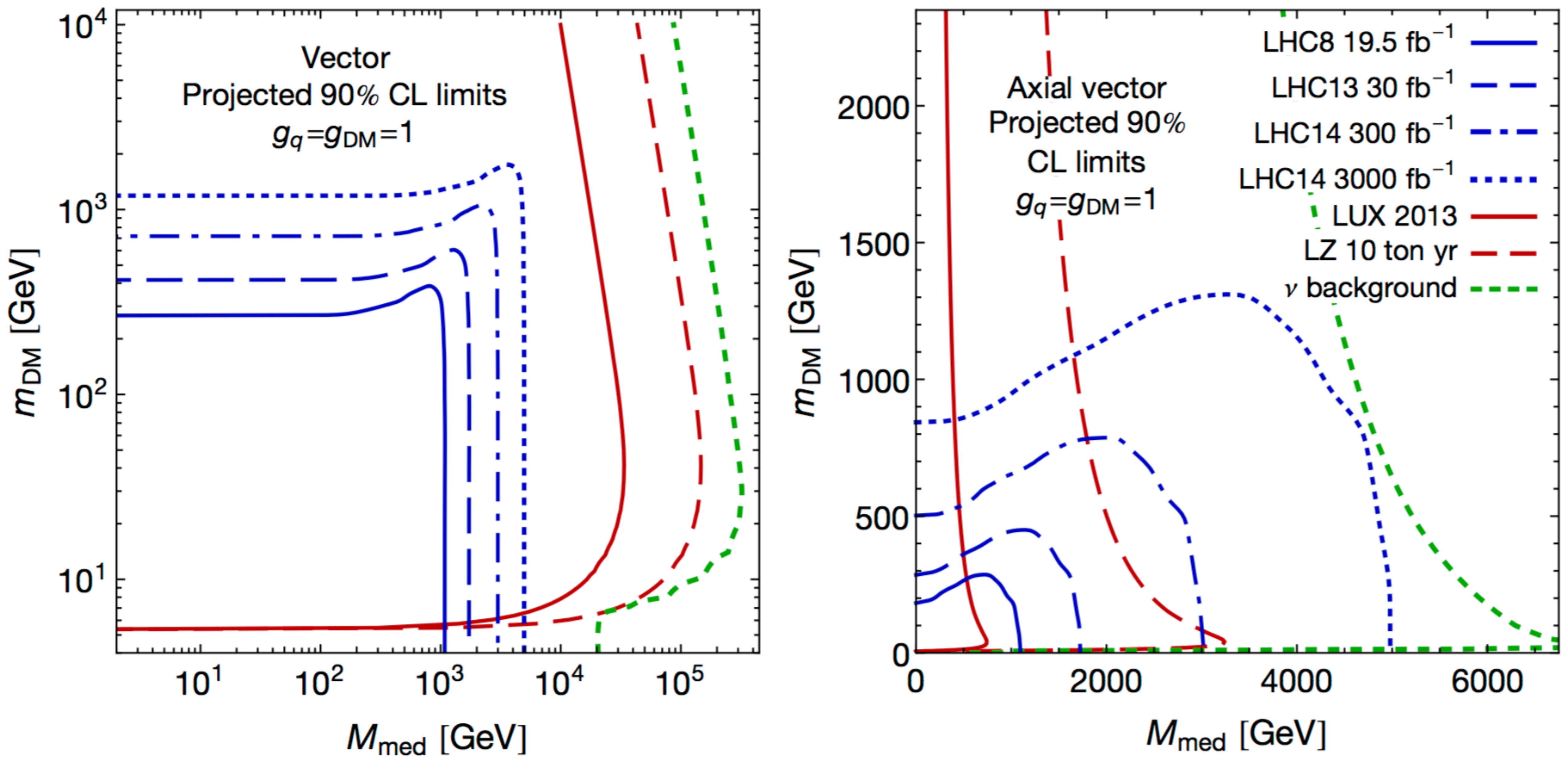


Future physics: Dark Matter

- How do you observe something invisible?

  - Monojet (and other) events





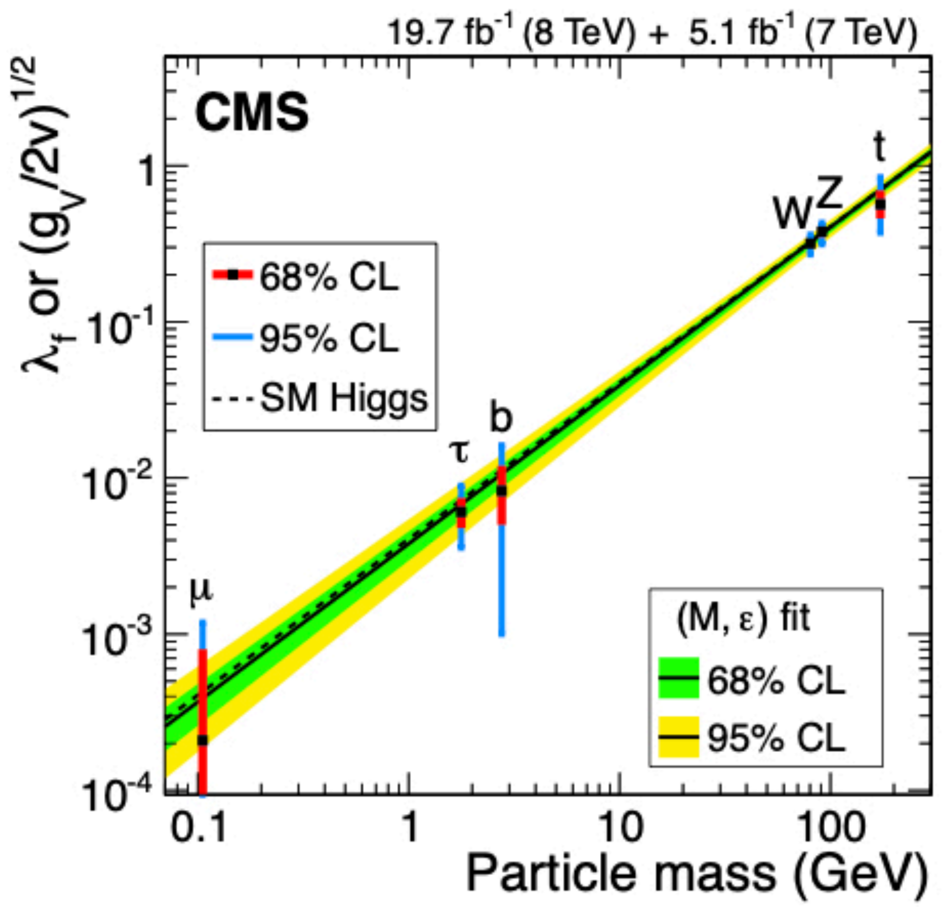
  - Large gains with 300 fb^{-1} to 3000 fb^{-1}

Buchmüller et al.
arXiv:1407.8257

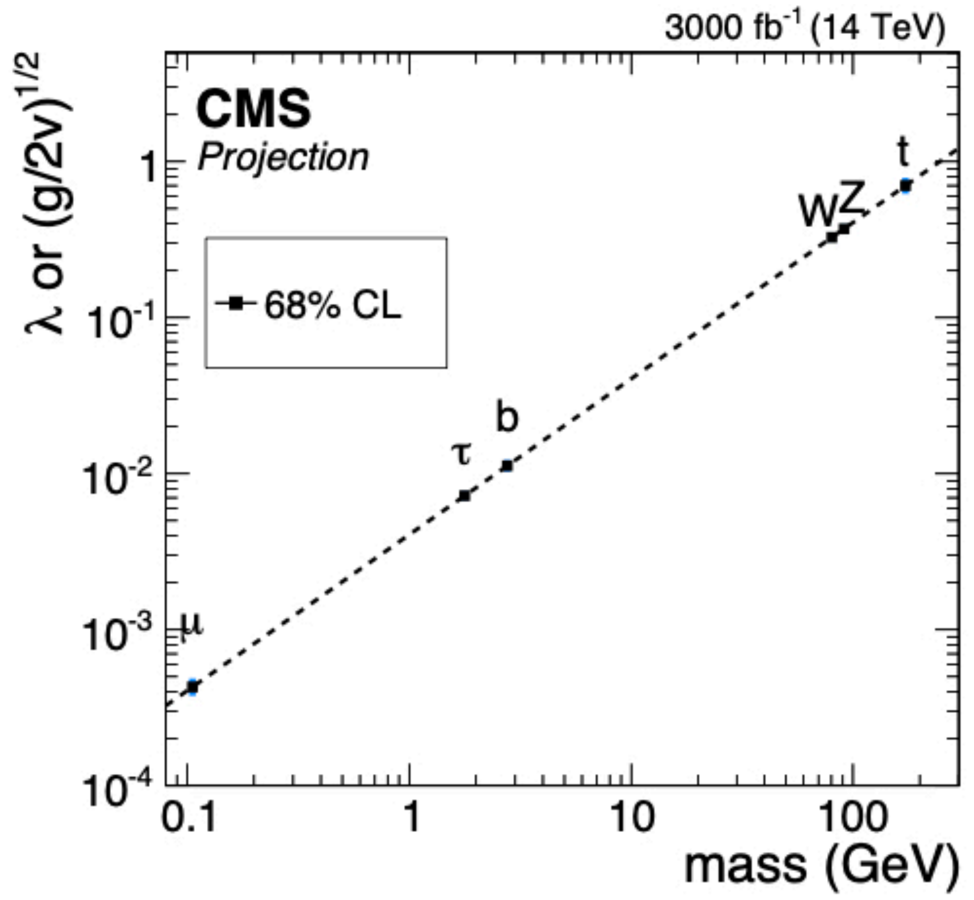
  - Requires excellent performance for jets and missing energy

Physics summary

- Broad physics programme
  - Precision SM (including Higgs) measurements
  - Searches for new physics



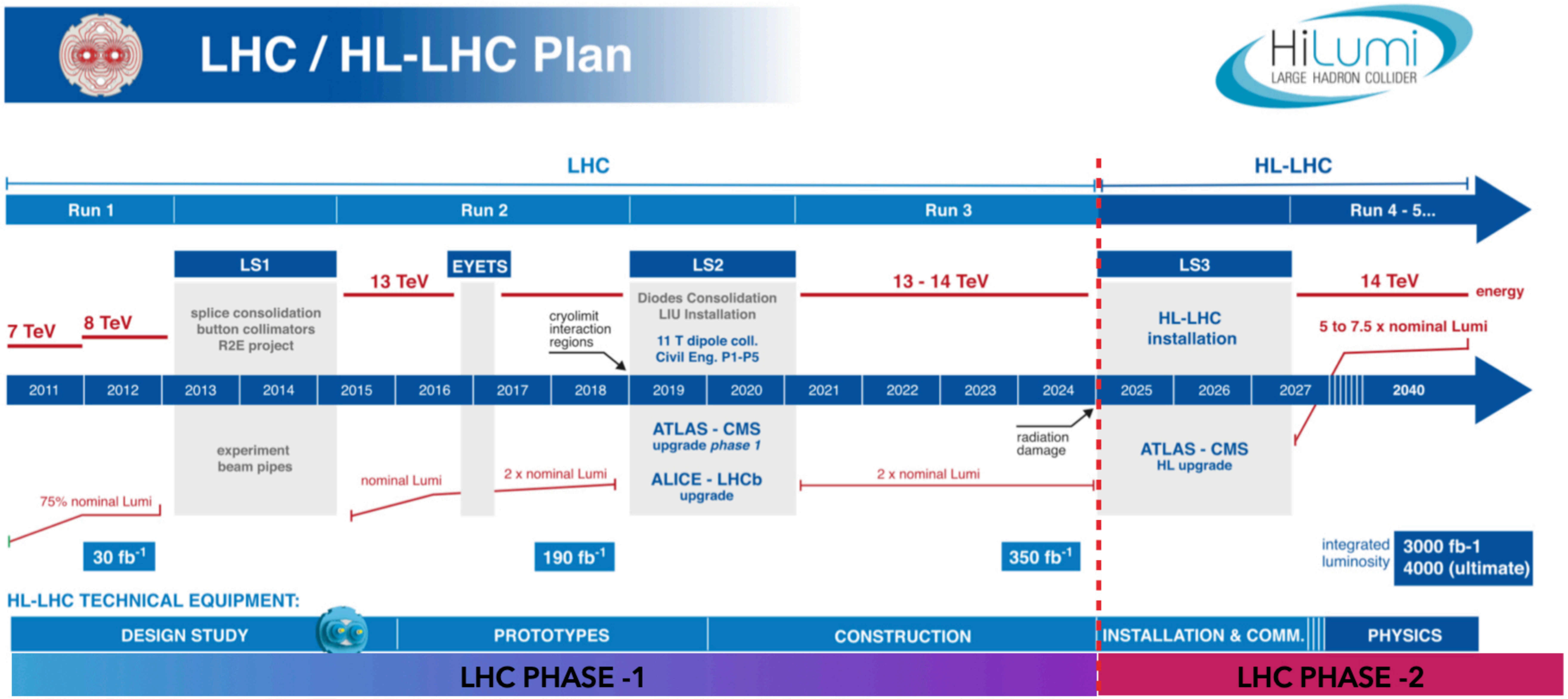
- Complementary to other (potential) colliders



- Highlighted key areas for detector performance

- **Bottom line**: will need to maintain current high level of detector performance and improve in some areas, for example long-lived particles

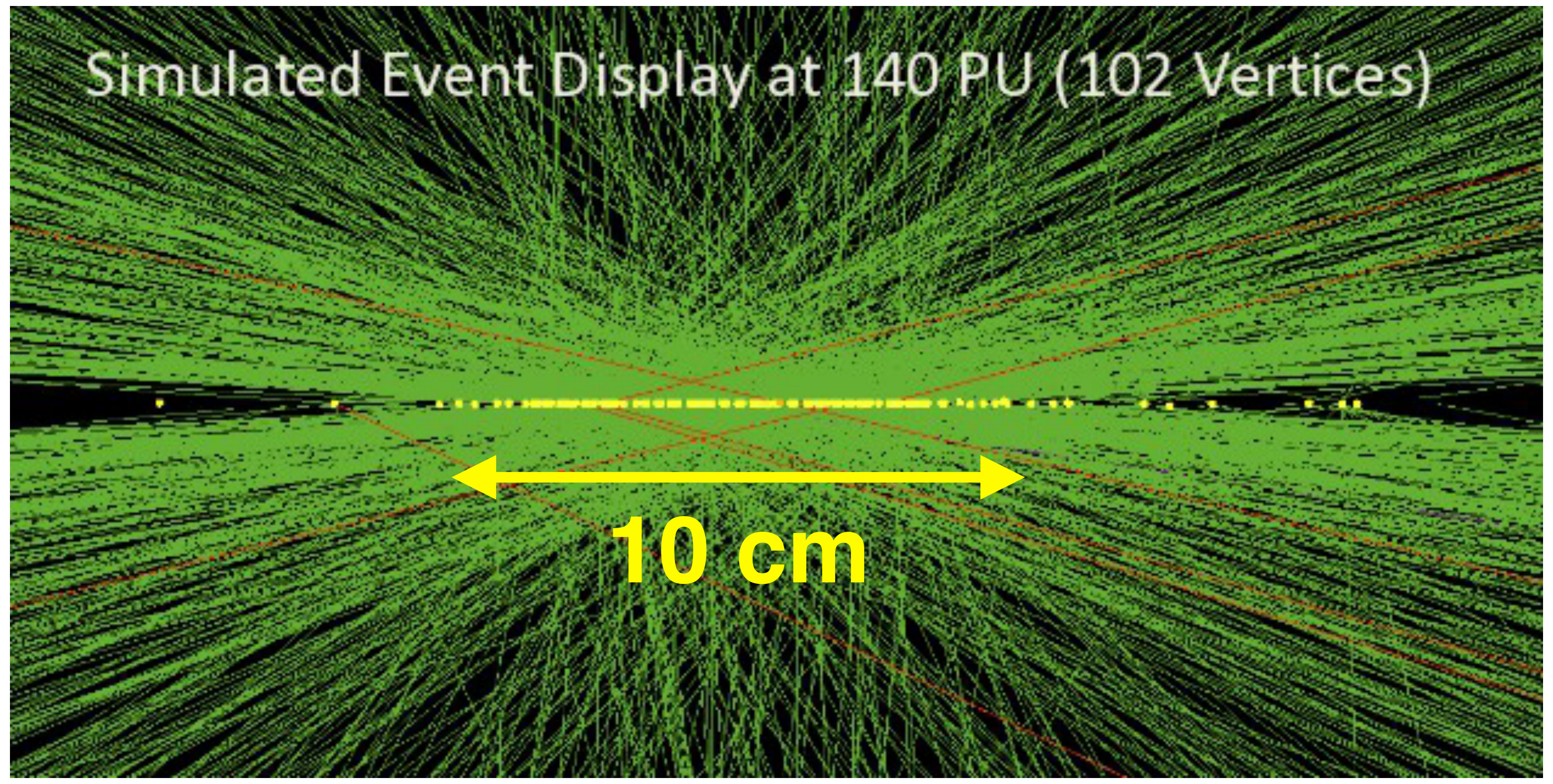
LHC: Running conditions



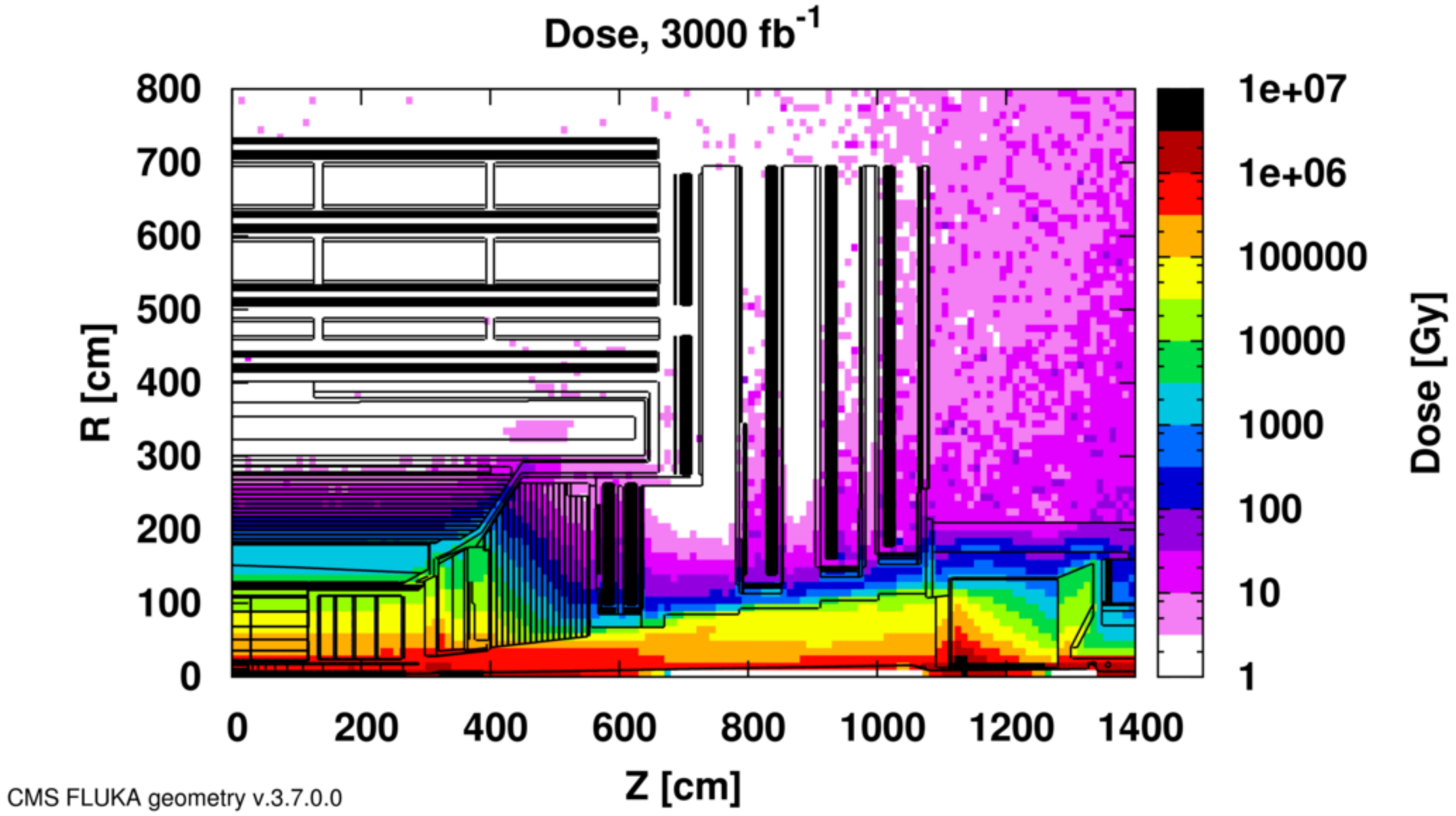
- Nominal : 5×10^{34} cm^{-2} s^{-1} 140 PU, Int Lumi = 3000 fb^{-1}
- Ultimate: 7.5×10^{34} cm^{-2} s^{-1} 200 PU, Int Lumi = 4000 fb^{-1}

Detector challenges

- Pileup
  - Detector performance degraded (e.g. pattern recognition)
  - Offline reconstruction complexity



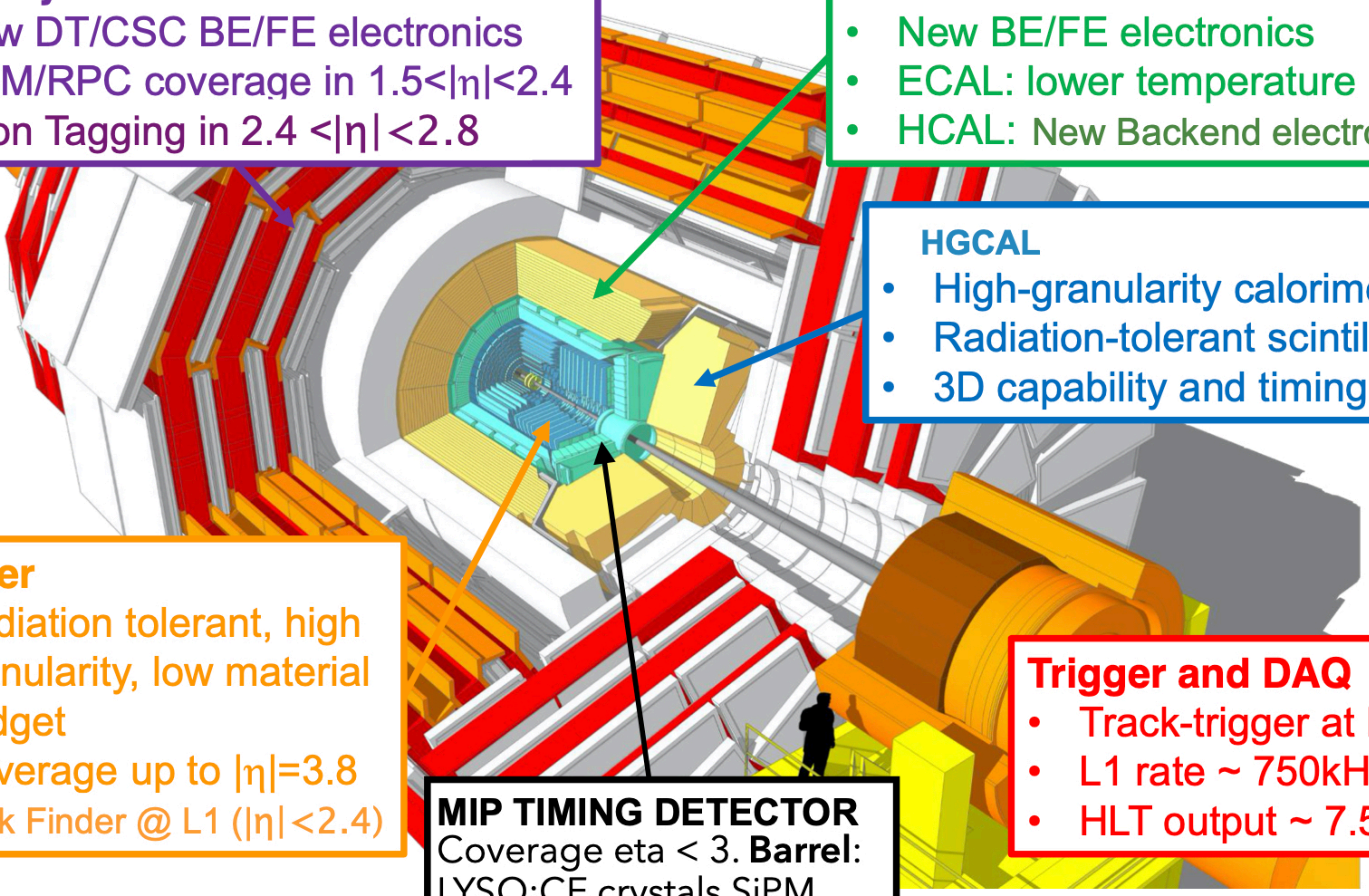
- Radiation
  - High fluencies and high doses for trackers and endcap calorimeters
  - Degraded performance



- Rates
  - Trigger rates increase with instantaneous luminosity and performance degrades with pileup (e.g. isolation)
  - Current L1 trigger 4 MHz!

Run period	W→lν rate
Run1	80 Hz
Run 2	200 Hz
Run 3	400-600 Hz
HL-LHC	1KHz

Detector upgrades



Muon System
- New DT/CSC BE/FE electronics
- GEM/RPC coverage in $1.5<|\eta|<2.4$
- Muon Tagging in $2.4 <|\eta|<2.8$

Barrel Calorimeter
- New BE/FE electronics
- ECAL: lower temperature
- HCAL: New Backend electronics

HGCAL
- High-granularity calorimeter
- Radiation-tolerant scintillator
- 3D capability and timing

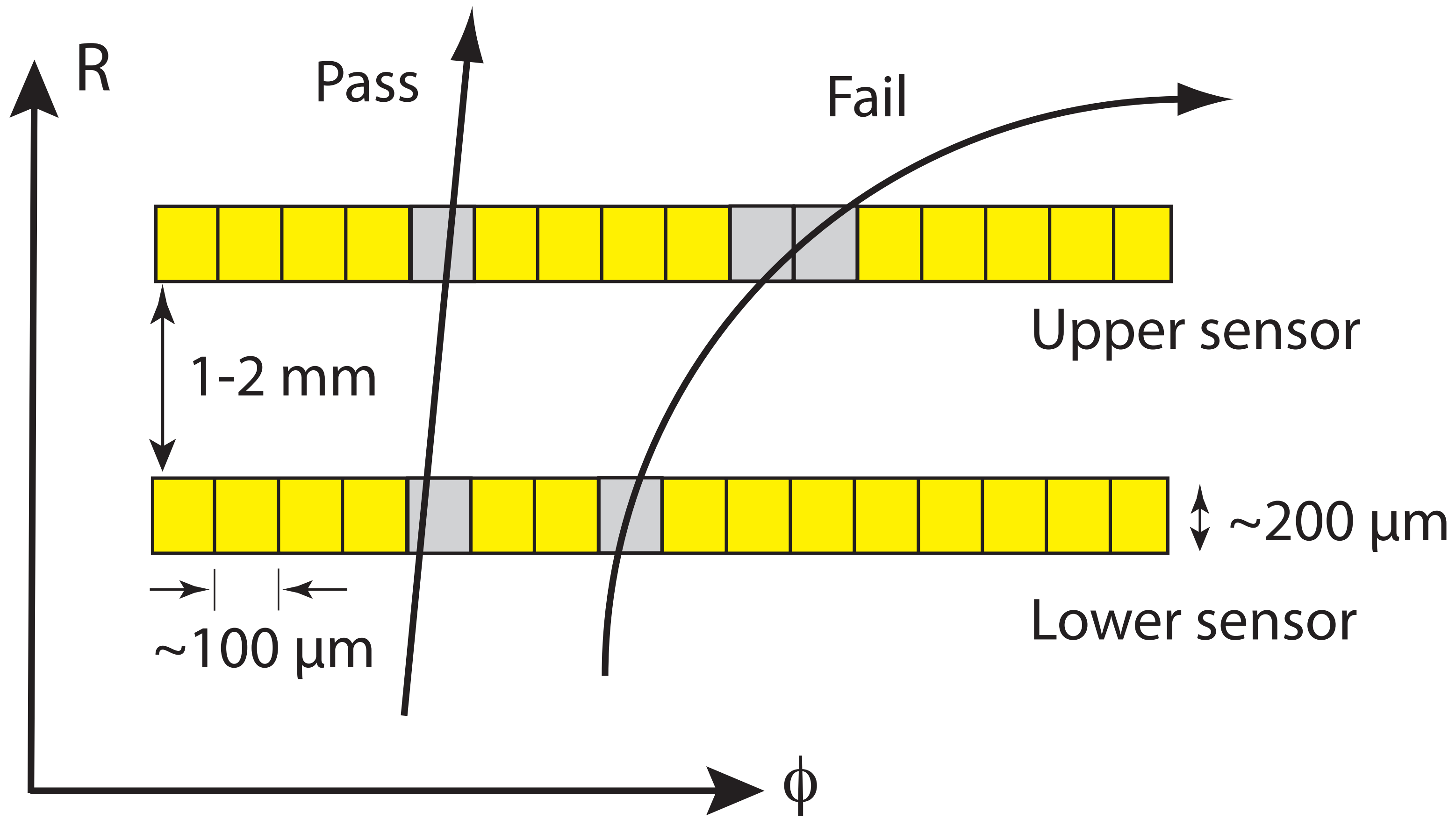
Tracker
- Radiation tolerant, high granularity, low material budget
- Coverage up to $|\eta|=3.8$
- Track Finder @ L1 ($|\eta|<2.4$)

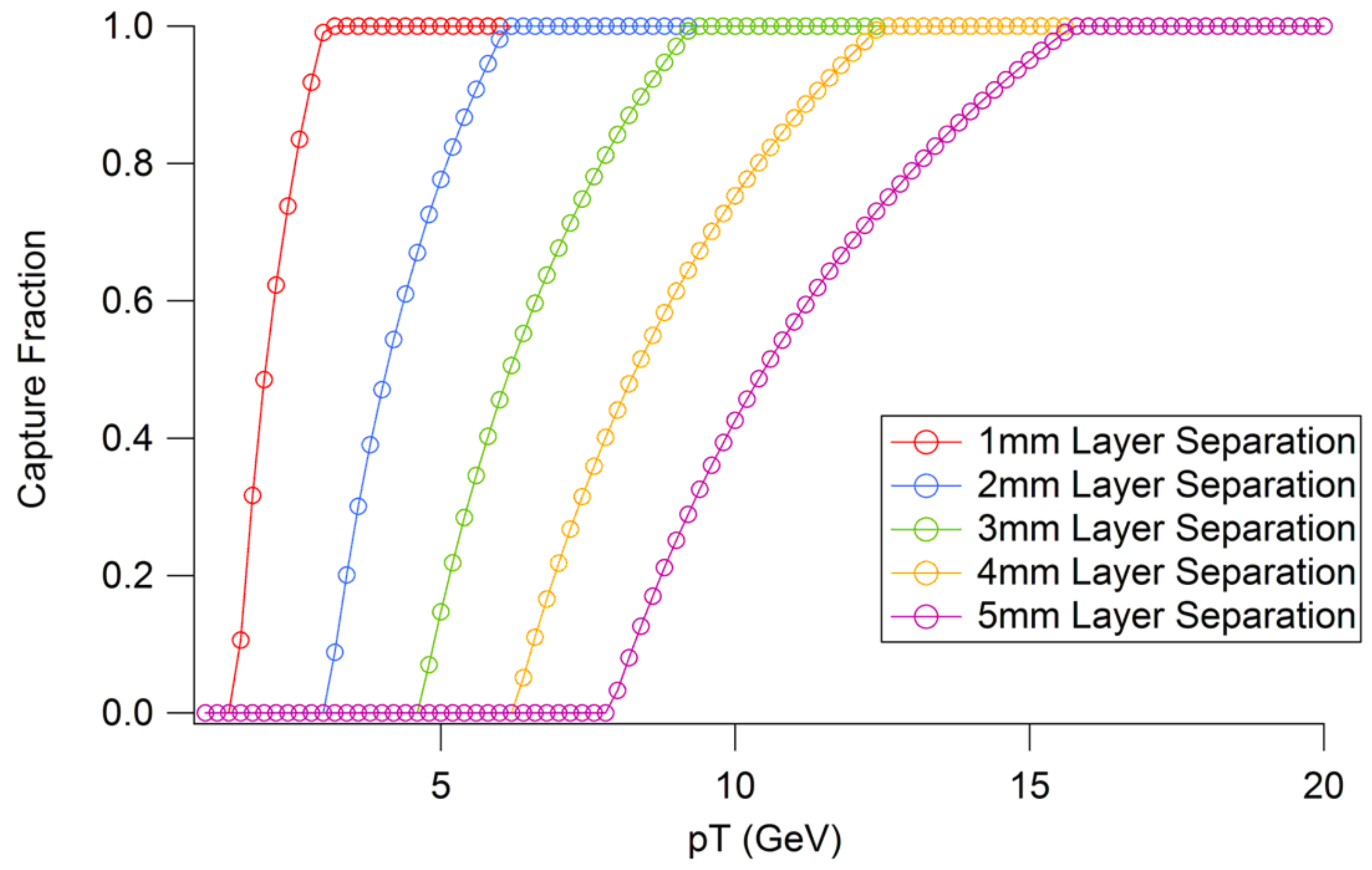
MIP TIMING DETECTOR
Coverage eta < 3. **Barrel**: LYSO:CE crystals SiPM. **EndCap**: Silicon Sensors (LGAP). **Timing ~ 30-40ps**

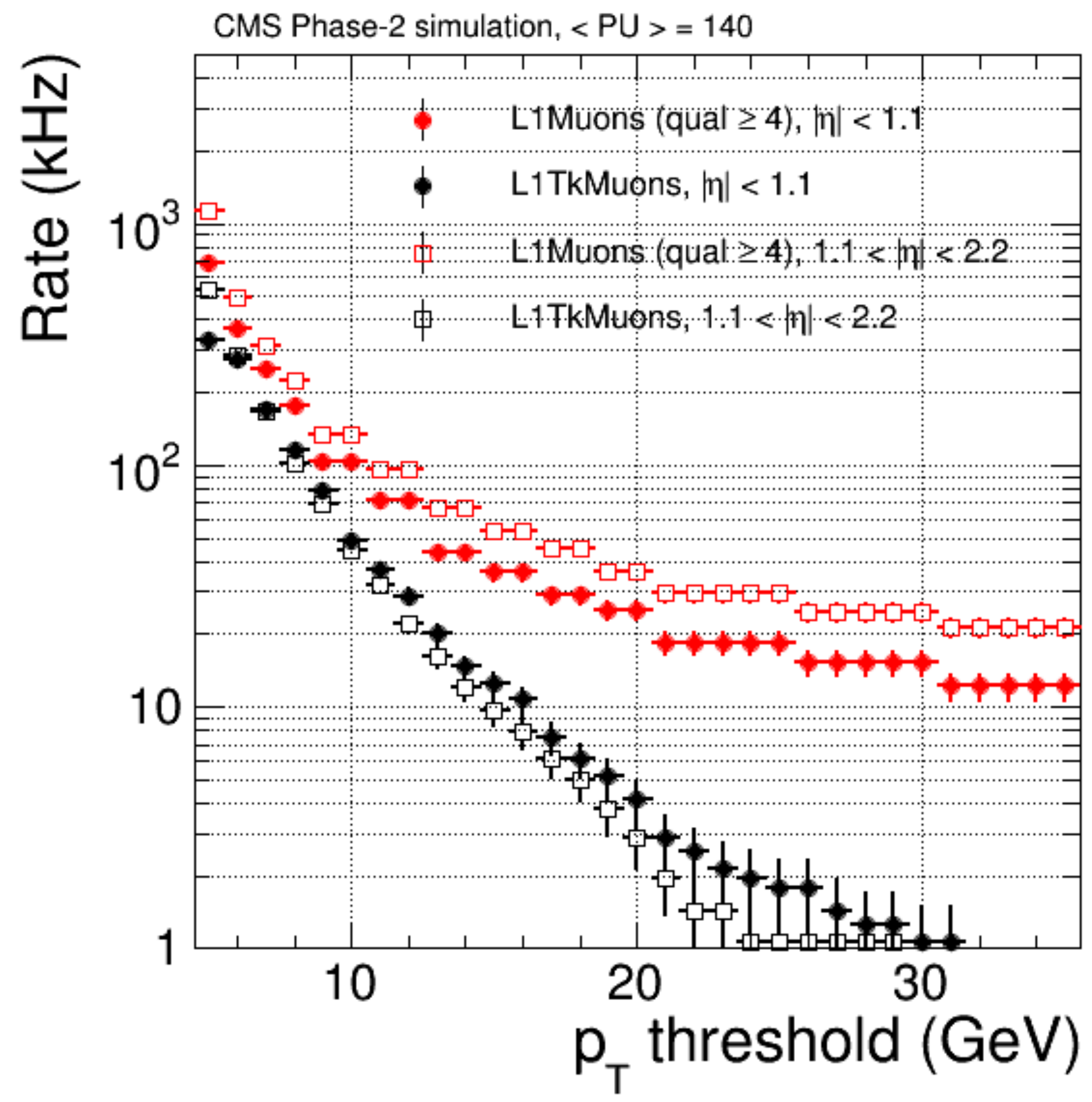
Trigger and DAQ
- Track-trigger at L1
- L1 rate ~ 750kHz
- HLT output ~ 7.5kHz

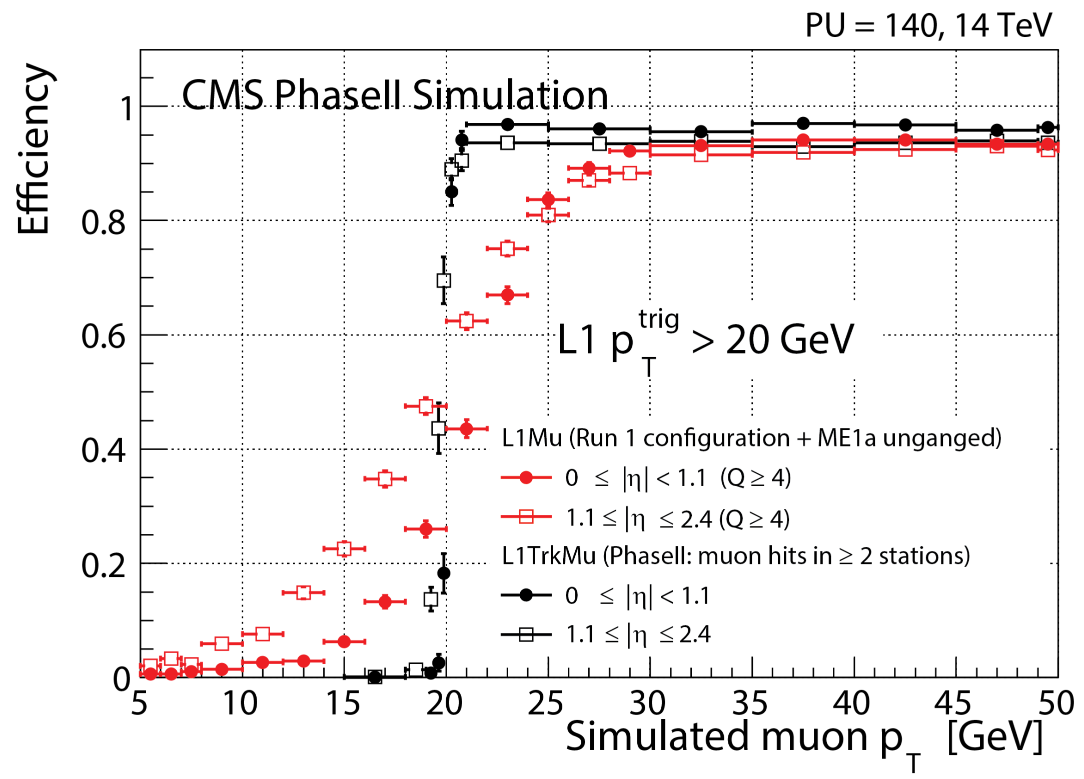
Tracker upgrade

- Outer tracker
  - P_T-modules → doublet sensors with common electronics to correlate hits and form stubs for trigger
  - Distance between sensors give track p_T lower cut





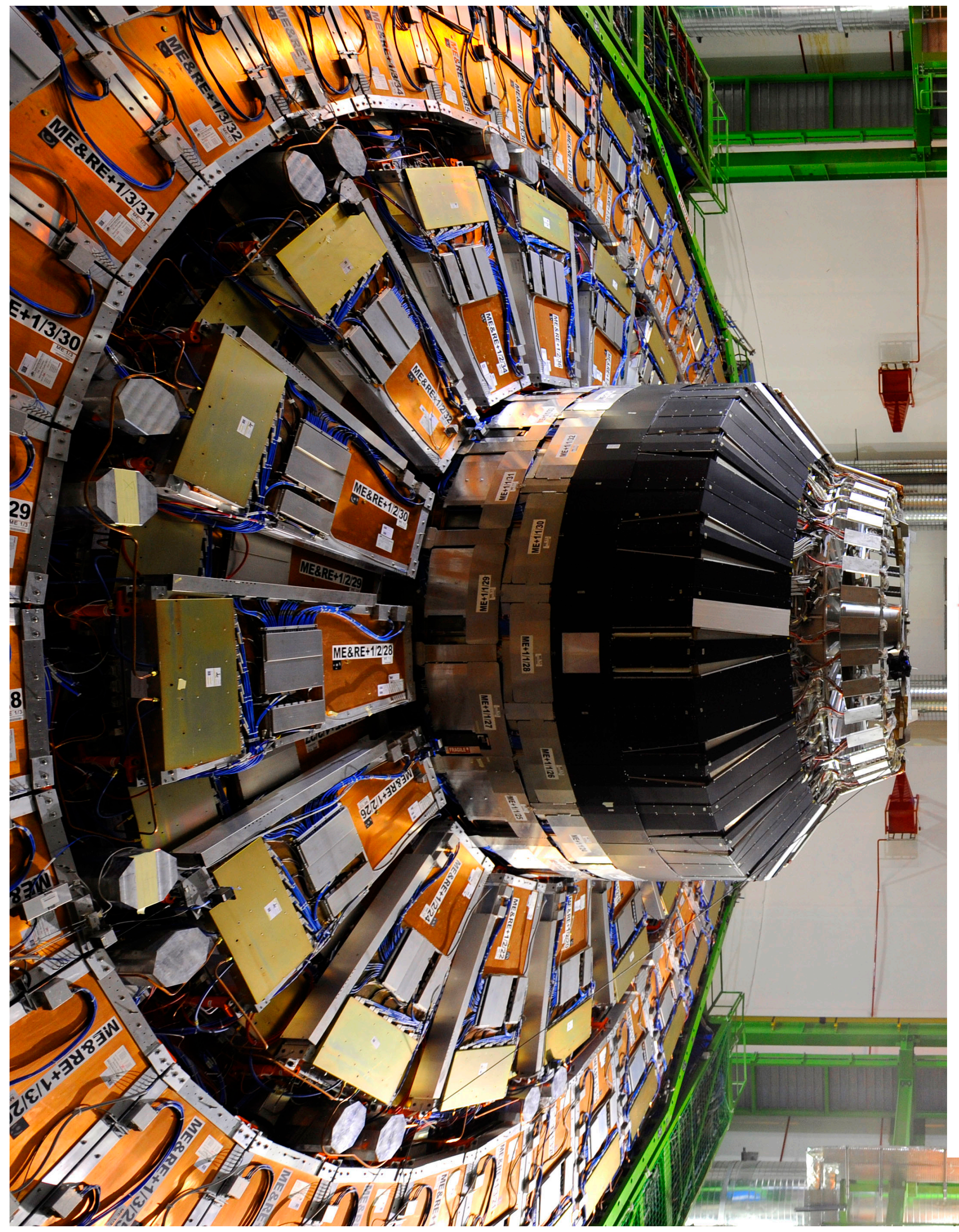


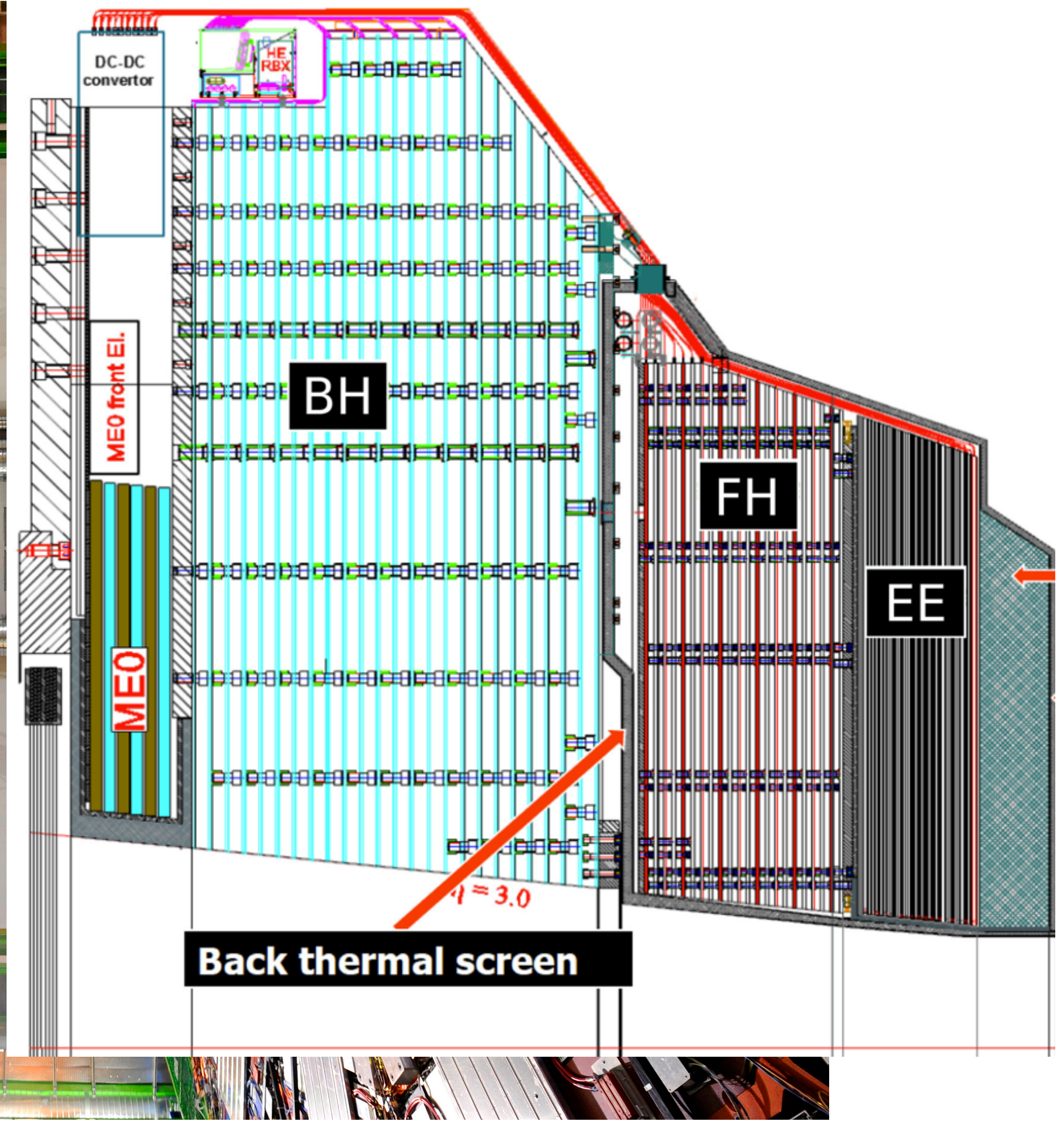


  - Allows control of trigger rates
  - FPGA based track finding proven

Endcap calorimeter upgrade

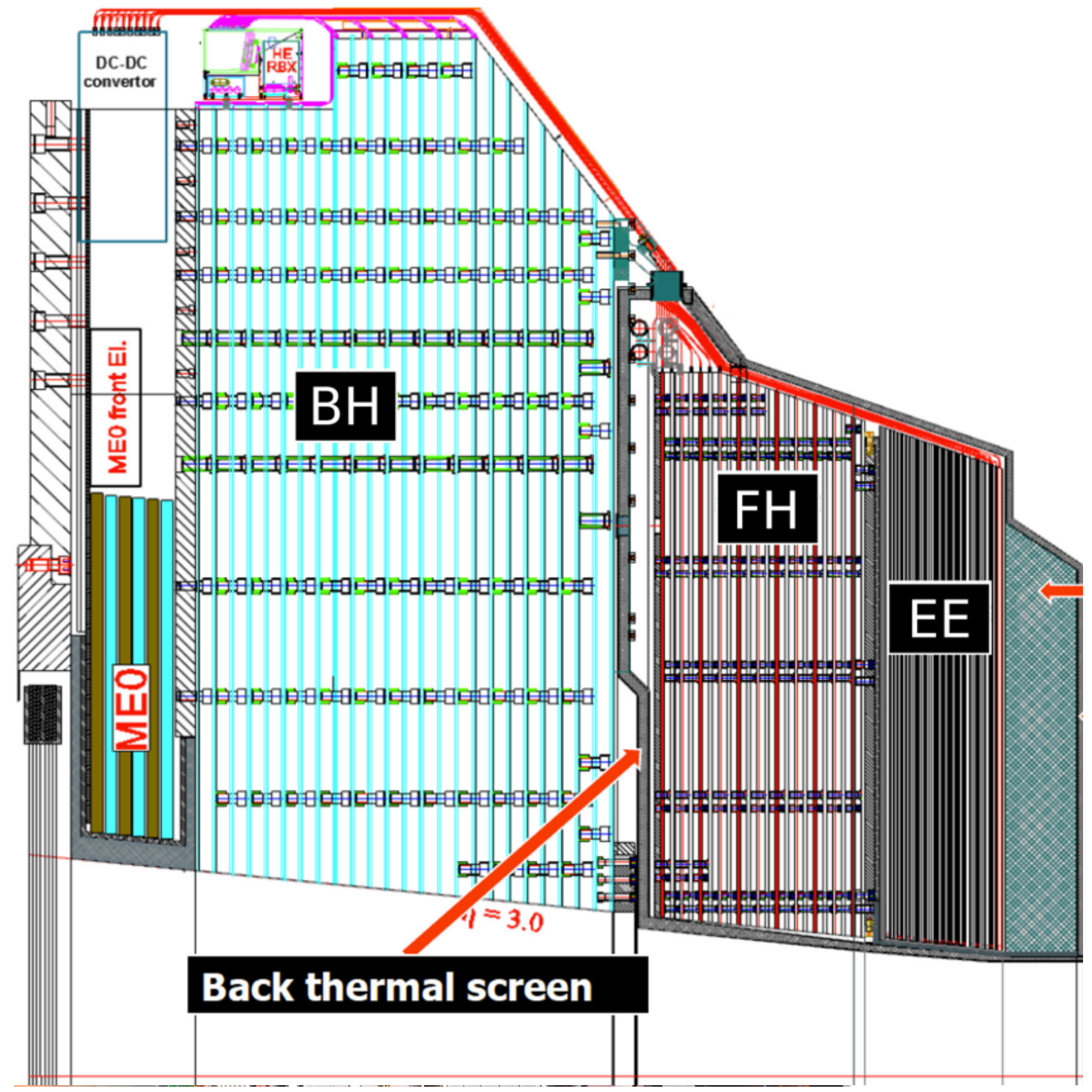
- Current endcap calorimetry will not remain performant after LS3
  - Combination of radiation damage and high pile up conditions
- Plan to replace by integrated high-granularity calorimeter
  - Sampling calorimeter with silicon sensors, optimised for high pile up
  - High granularity readout (~1 cm^2) and precision timing capability (<50ps)



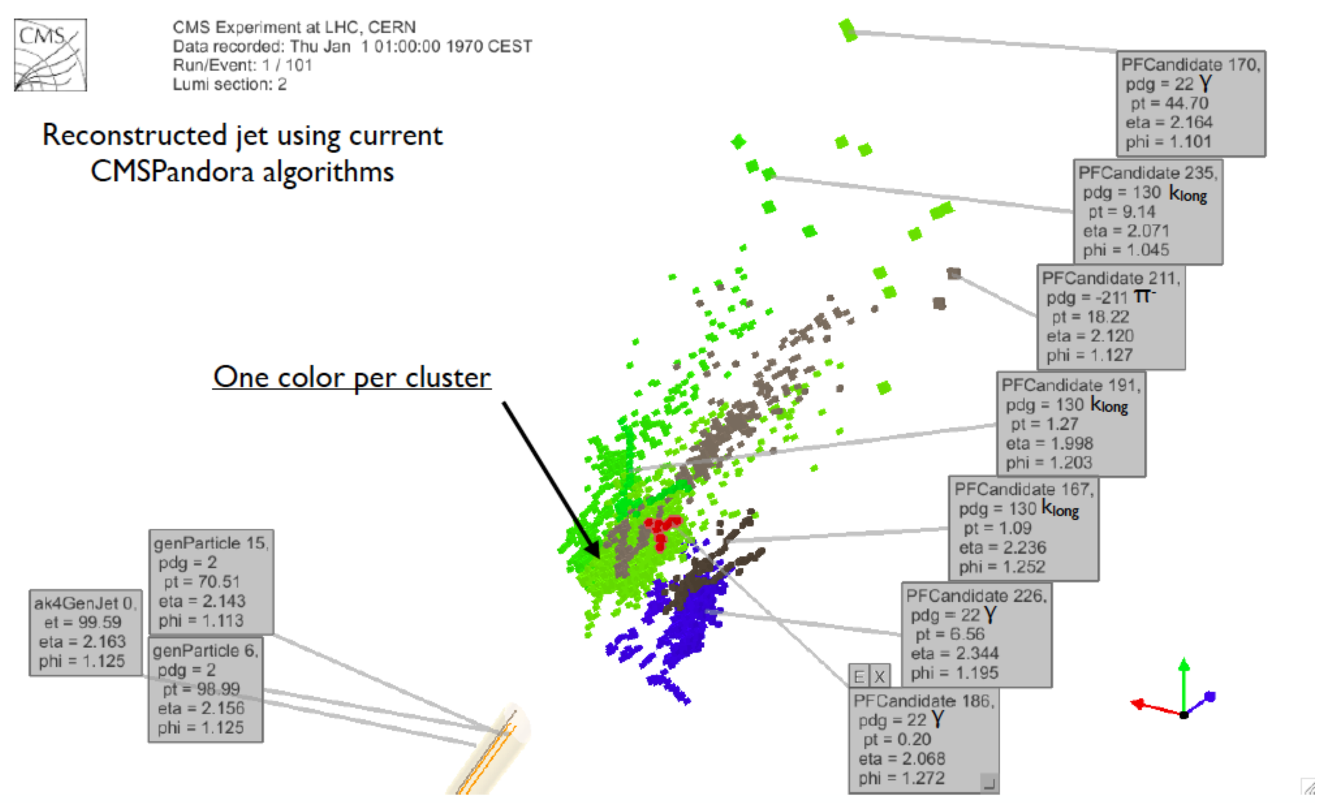


Endcap calorimeter upgrade

- High Granularity Calorimeter with 4D (space-time) shower measurement
  - Electromagnetic section (26 X0, 1.5λ): 28 layers of Silicon-W/Cu absorber
  - Front Hadronic section (3.5 λ): 12 layers of Silicon/Brass or Stainless Steel
  - Back Hadronic Calo. (BH) - radiation tol. - granularity
  - BH (5 λ): 12 layers of Scintillator/Brass or Stainless Steel (2 depth readout)



- Major new areas of R&D
  - Level-1 Trigger, reconstructions algorithms, analogue and digital electronics…

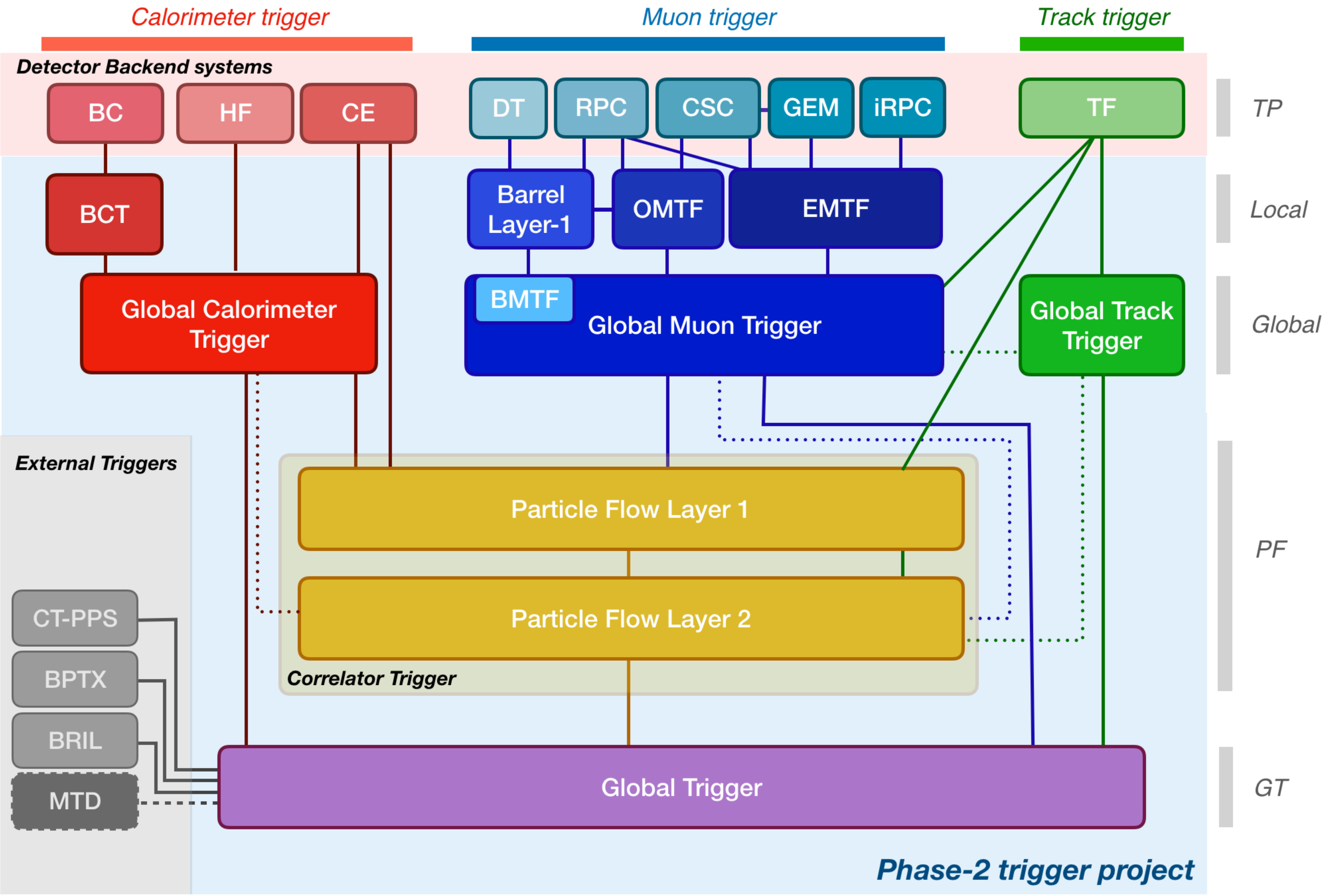


CMS trigger upgrade

Retain two-level triggering approach: L1 & HLT

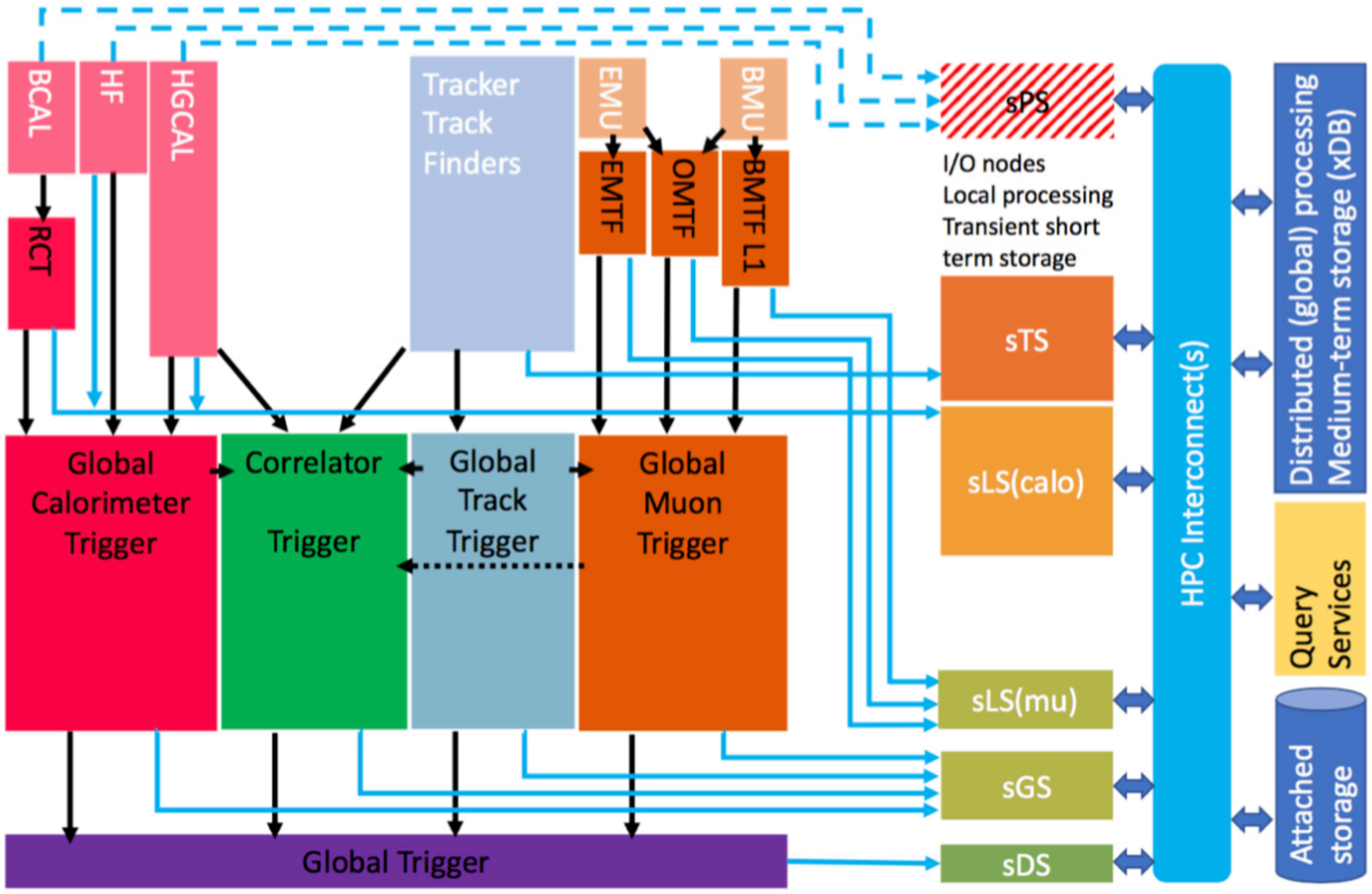
- Level-1 (hardware) system
  - Increase bandwidth 100 kHz → 750 kHz
  - Increase latency 3.8 μs → 12.5 μs
  - Include high-granularity detector information and tracker information (first time!)
  - Add dedicated scouting system @ 40 MHz
- High-Level (software) Trigger
  - Keep rejection (100:1) 1 kHz → 7.5 kHz (18xCPU)
  - Data throughput 2.5 GB/s → 61 GB/s (25x)
  - Optimise reconstruction software: balance efficiency/ rate and event size/timing
  - Strategy: benefit from modern processor tech (heterogenous architecture CPU/GPU/FPGA…)

New Level-1 Trigger system



- Provides robust independent triggers for **calorimeter**, **muon** and **tracking** systems separately, and a ***Particle Flow*** trigger, which combines all information

40 MHz scouting system

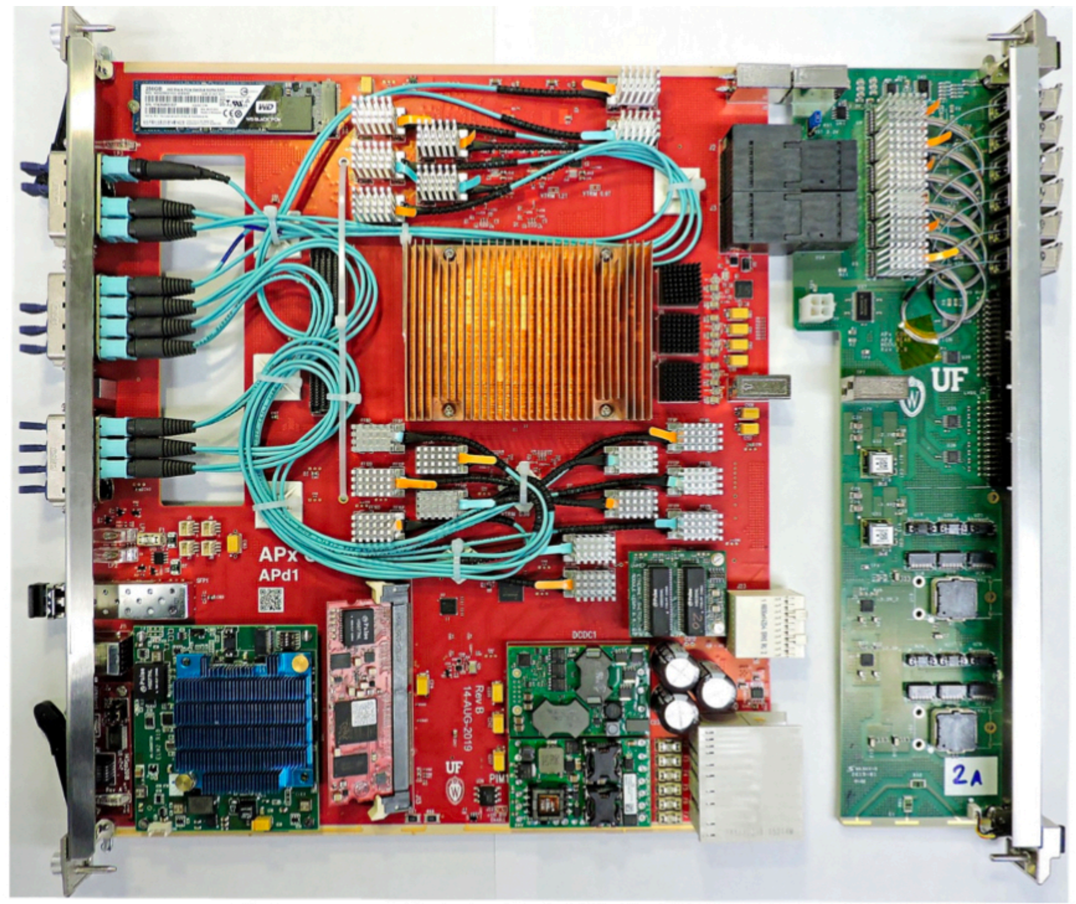


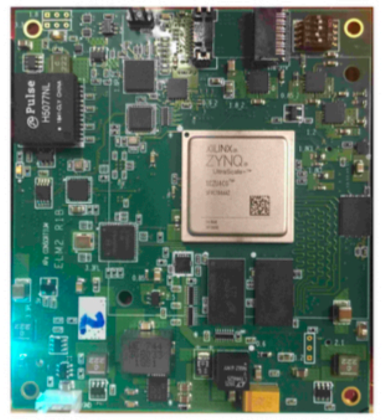
- Provide real-time diagnostics, monitoring, testing new algorithms and developing menus, selecting an reconstructing physics objects without rate limitation → physics potential too!

Processors (examples)

APx consortium

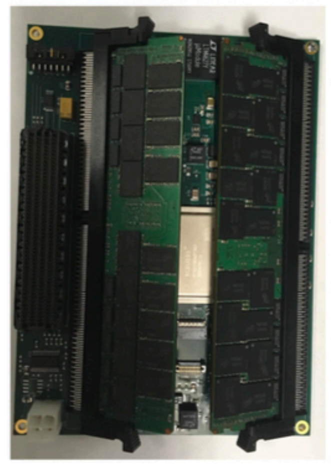
- Powered by a VU9P FPGA with 2.5M logic cells
- 100 bidirectional links up to 28 Gbps
  - 76 to the front directly connected to mid-board optics
  - 24 to the rear transmission module via high density connector
    - Rear transmission module supports interfaces for legacy links and generic serial I/O
- Control, management, and monitoring by an embedded linux mezzanine (ELM) on-board
  - Featuring a ZYNQ system-on-chip with dual core ARM processor and FPGA logic
- Large 128GB memory mezzanine for look-up table applications
- Shelf management via custom IPMI mezzanine running real time OS





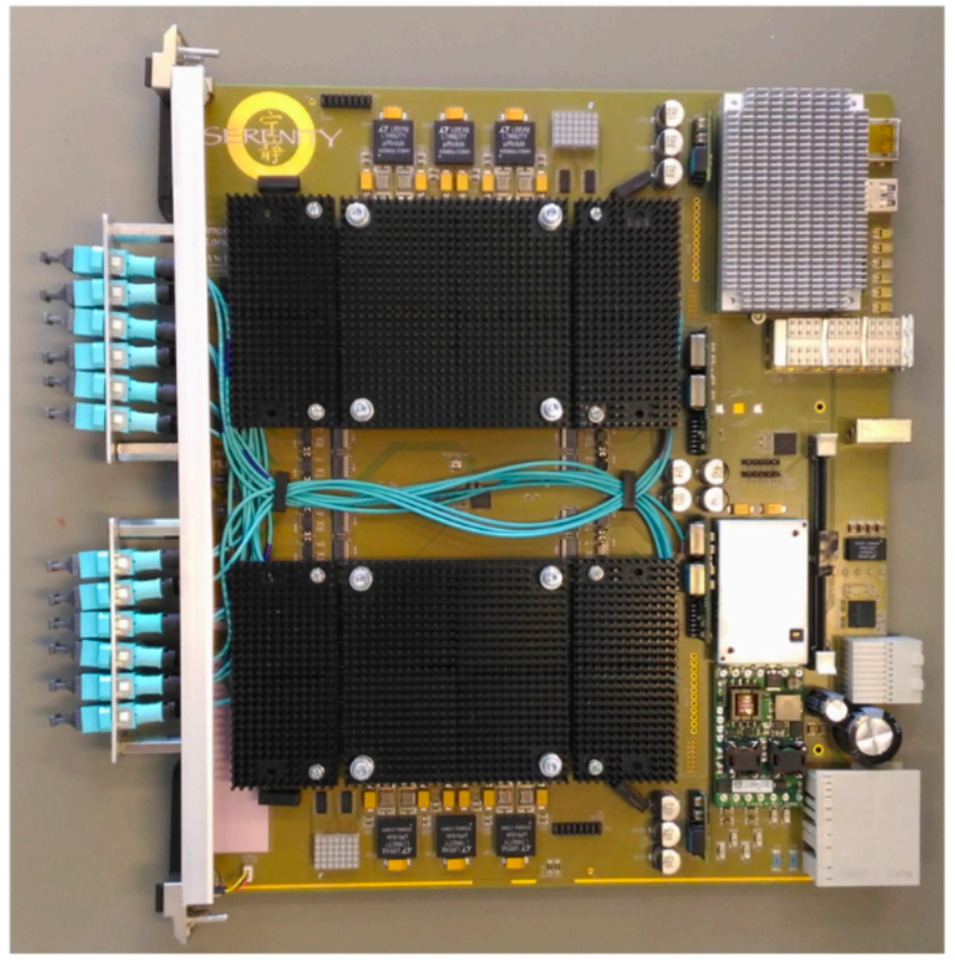
ELM

IPMC



Memory LUT

- Carrier board supporting two sites hosting daughter cards
- Up to 144 bidirectional links (extendable to 192) through mid-board optics connected to both sites
  - Up to 72 (96) links per FPGA that can run at 16 or 28 Gbps
- Daughter cards with FPGAs mount on the carrier through ultra-dense low profile interposer
  - Provides the flexibility to design daughter cards with any combination of FPGAs that fit the ATCA shelf power budget
- Control & Monitoring performed via a commercial COM express mezzanine featuring a standard x86 processor
  - That communicates with daughter cards and service Artix 7 FPGA
- IPMI management through CERN IPMC mezzanine

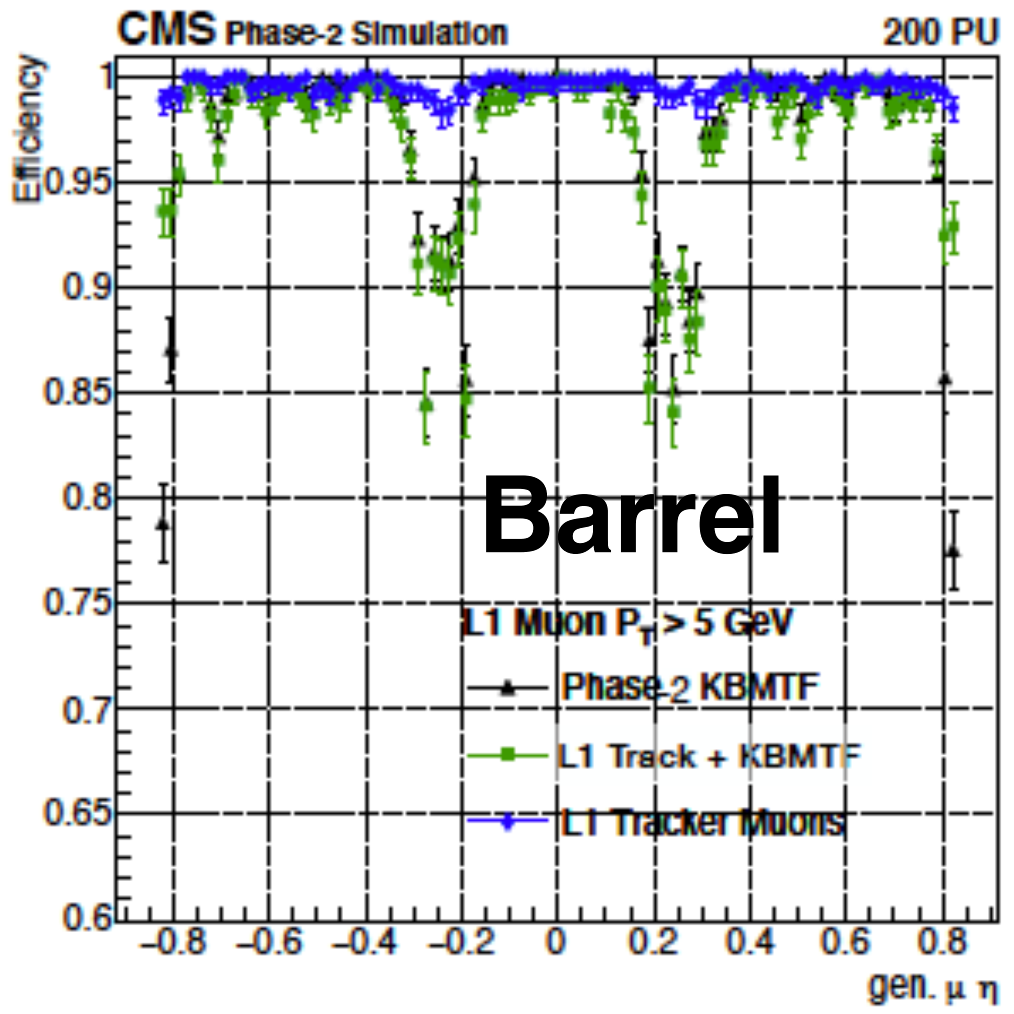


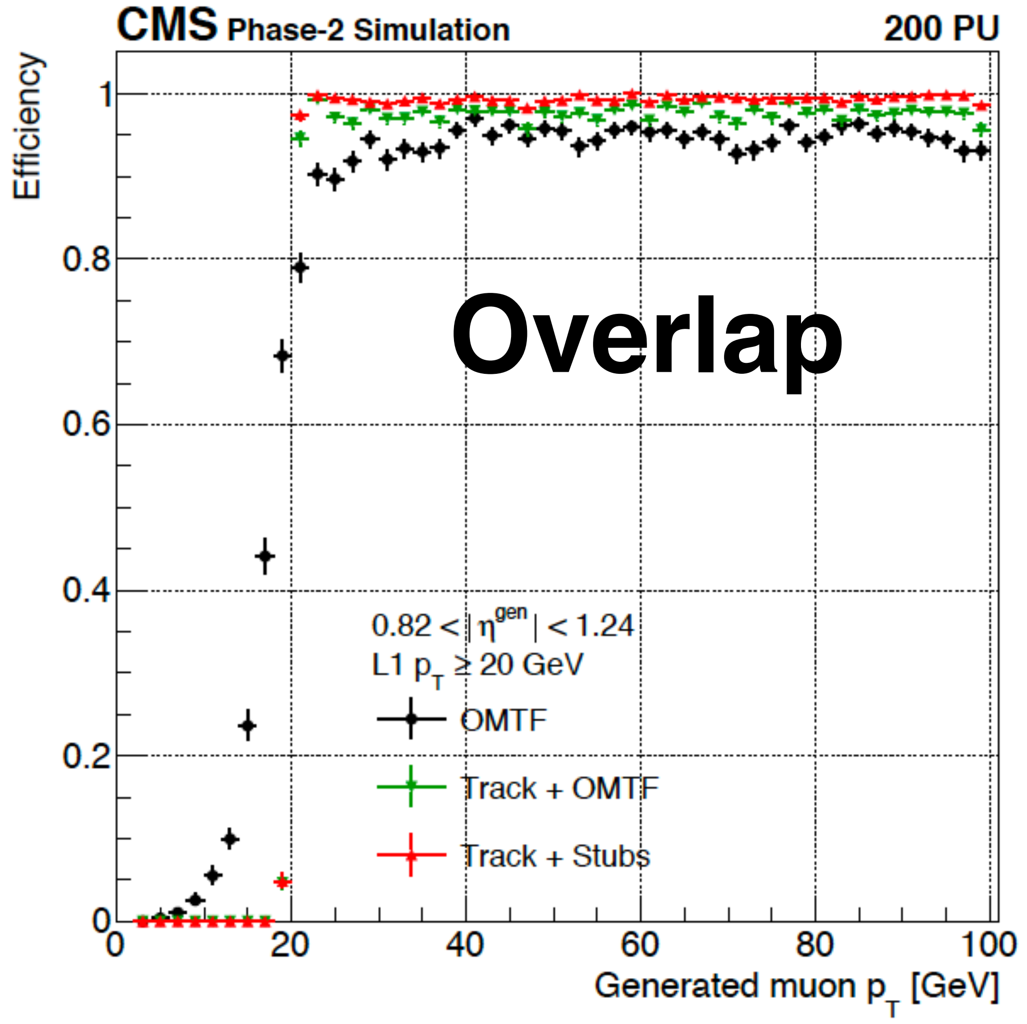
Daughter card with FPGA

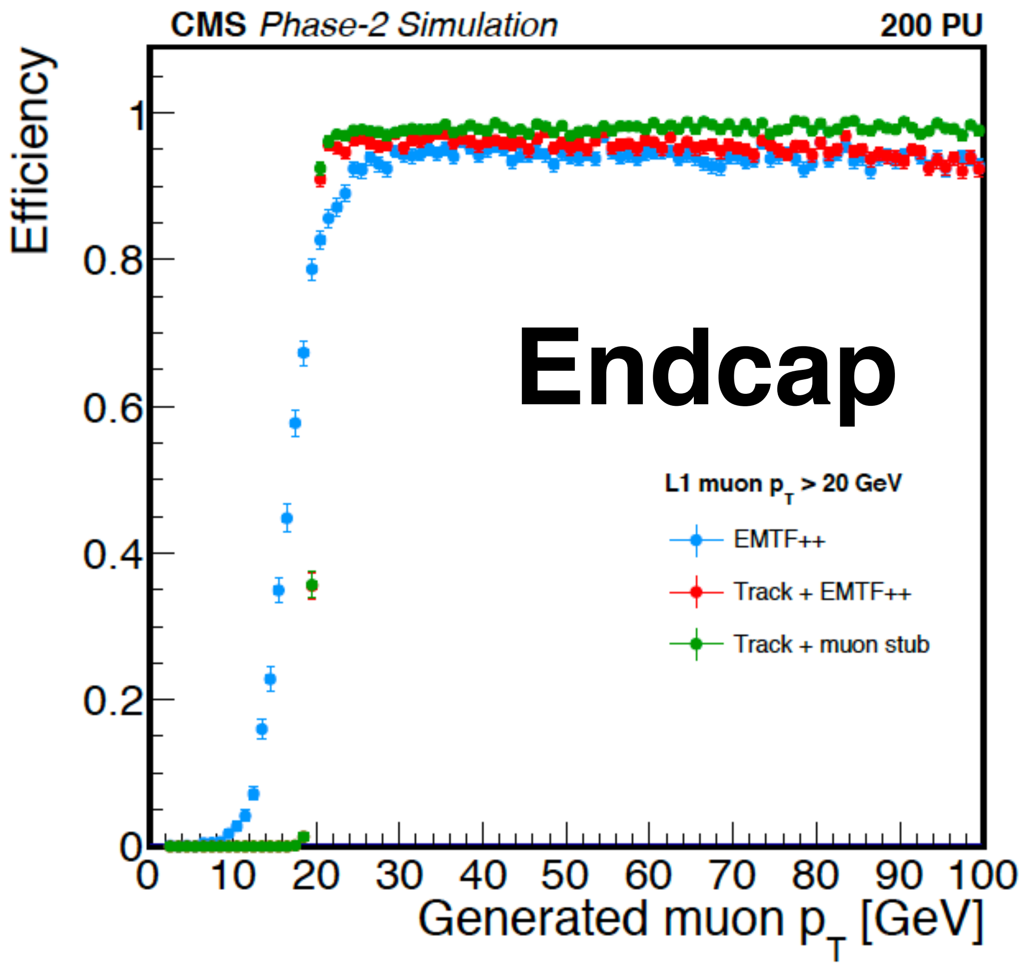
Serenity collaboration

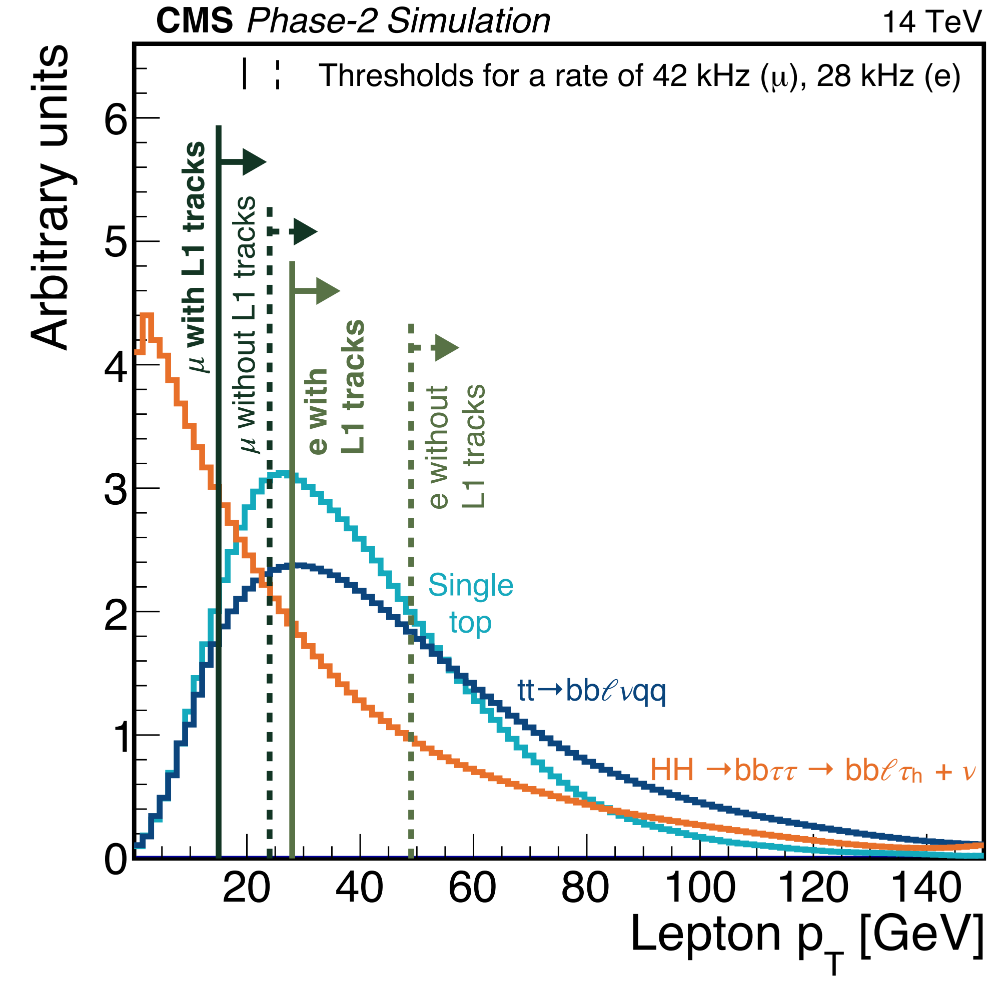
Level-1 Trigger algorithms: muons

- Standalone muons
  - Similar to current trigger conceptually
    - Kalman filter in barrel
    - Naive Bayes Classifier in overlap
    - NN, including new GEM and iRPC chambers in endca
- Track matched muons
  - Match with standalone muon
    - Use track p_T measurement for sharper efficiency
  - Match with muon stubs
    - Recover some efficiency in muon chamber “gaps"



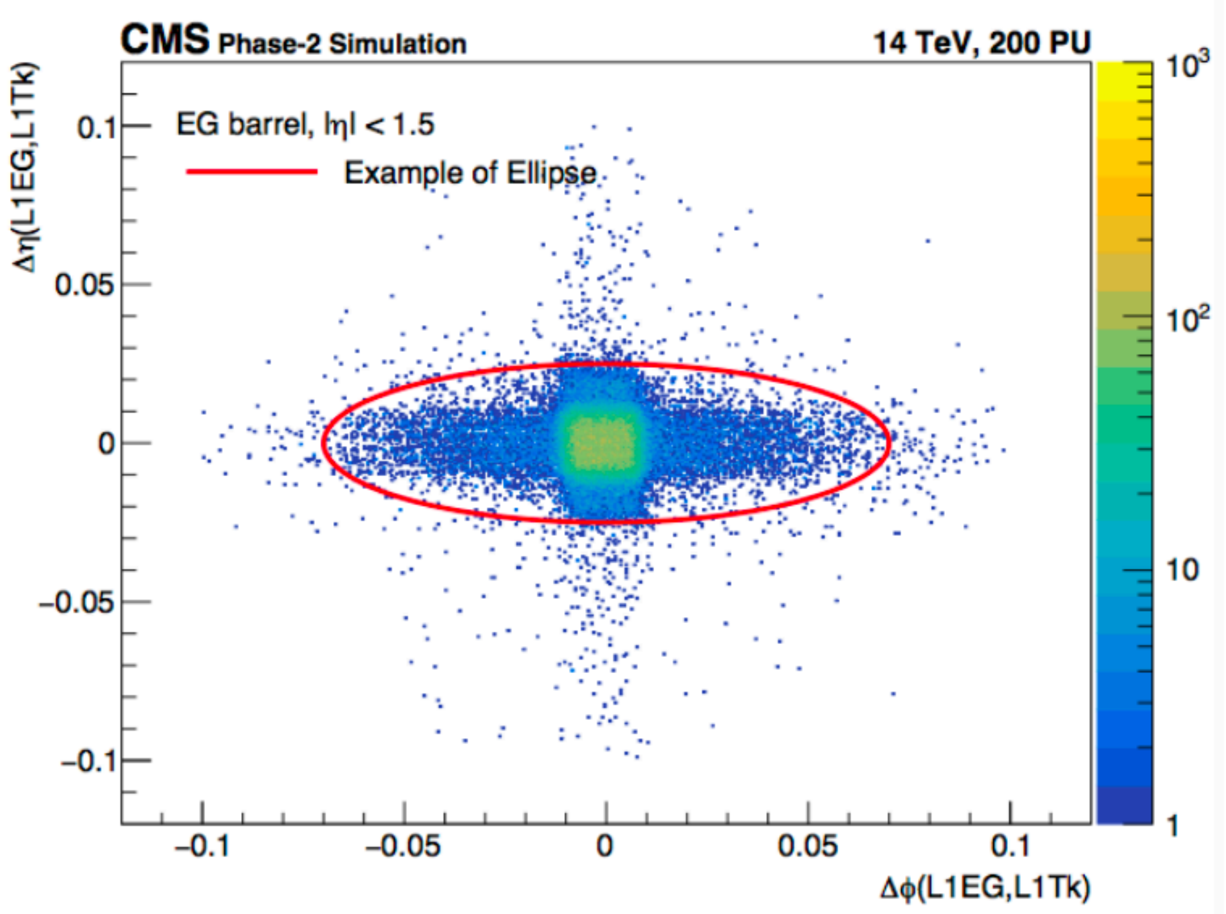




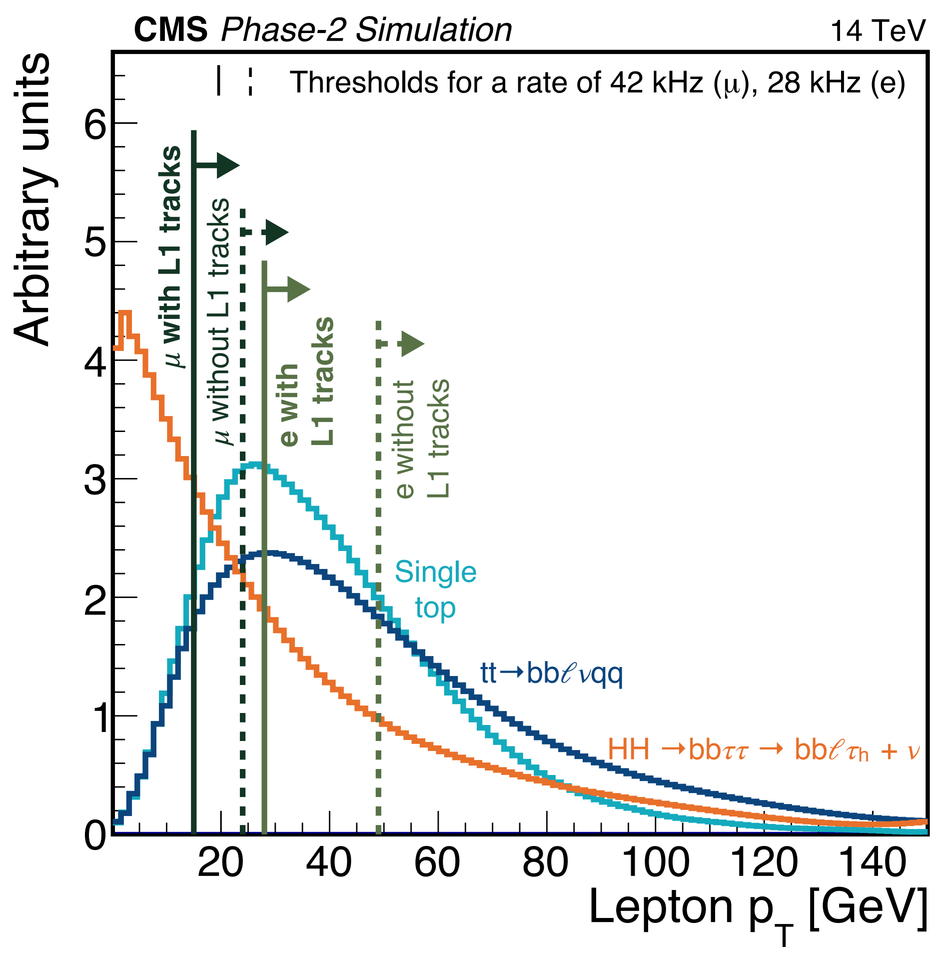


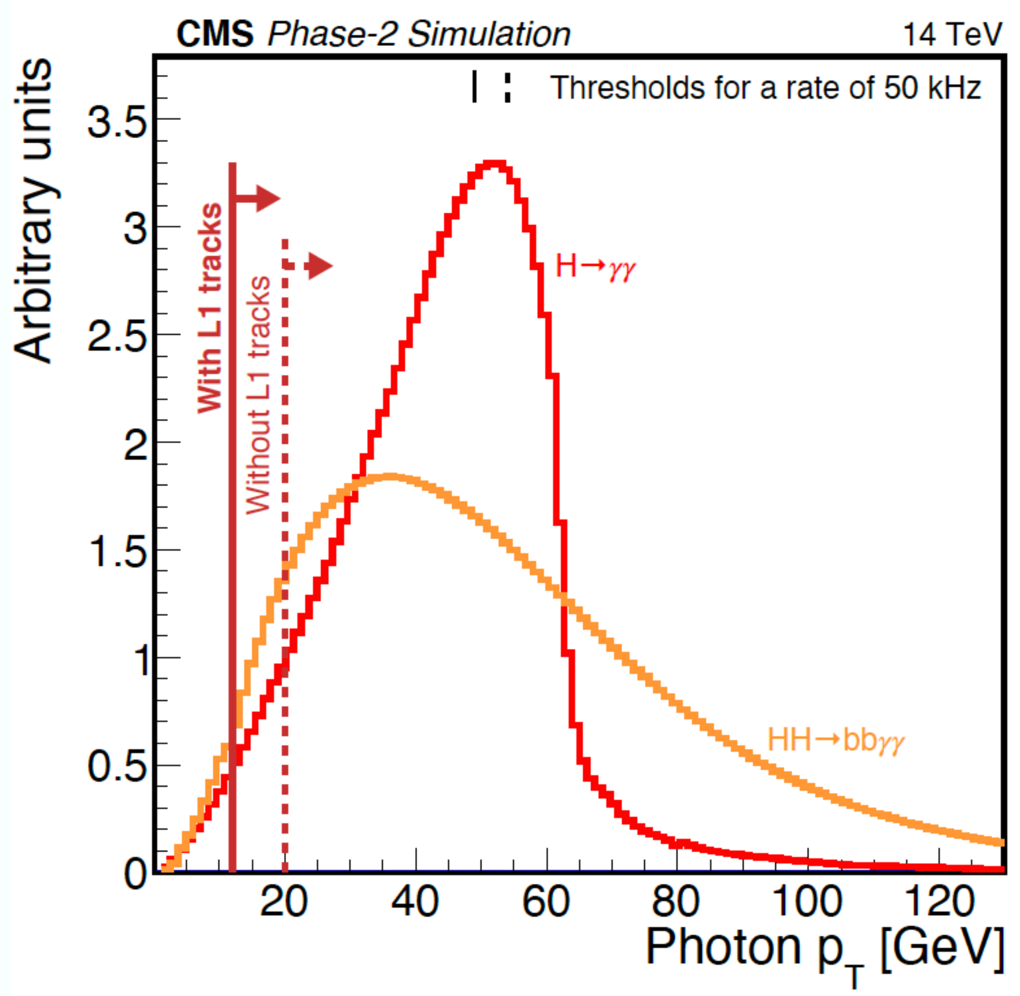
Level-1 Trigger algorithms: e/γ

- Standalone
  - Barrel
    - Individual ECAL crystals available for first time!
  - Endcap
    - 3D clusters from high-granularity calorimeter



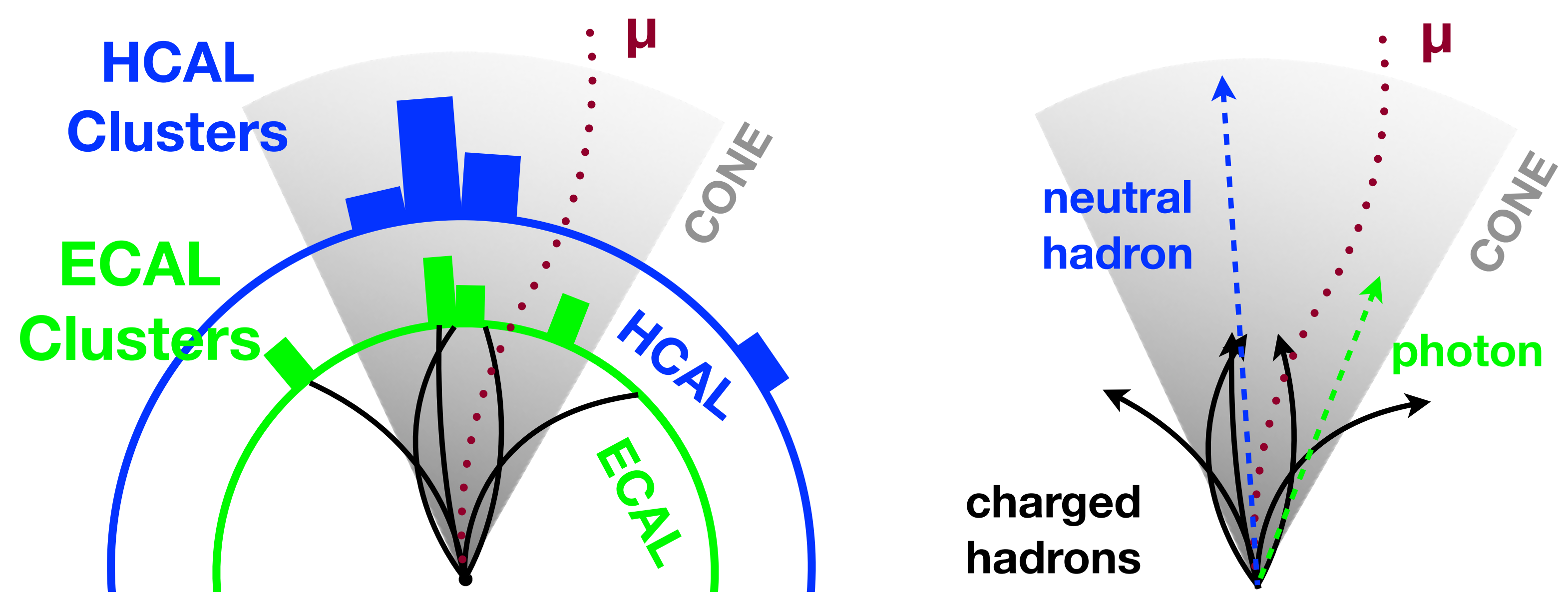
- Track matched
  - Match track to cluster
  - Optimised elliptical matching
  - Tracks can also be used for isolation



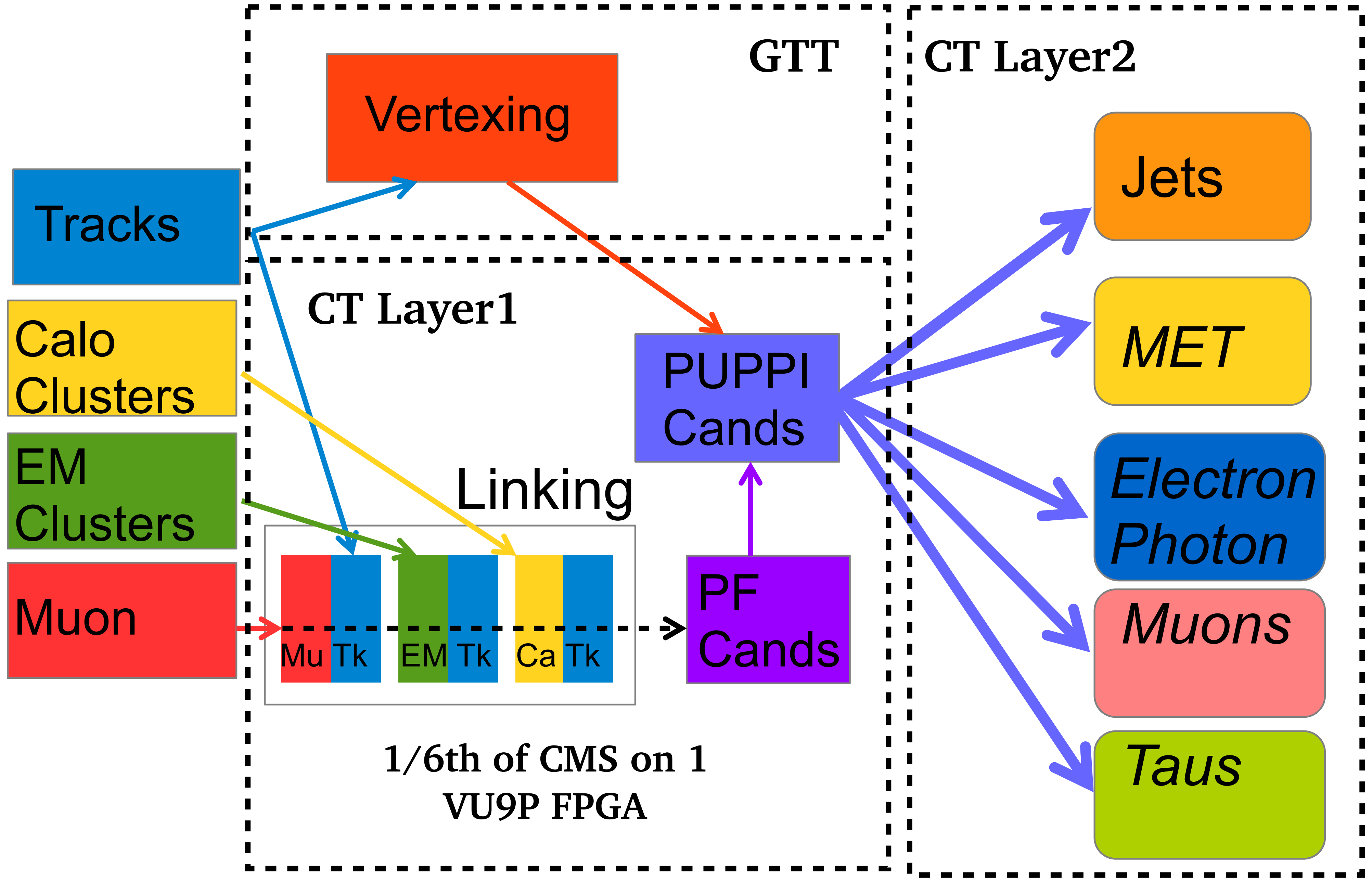


Level-1 Trigger algorithms: Particle Flow

- PF reconstruction aim at reconstruct and identify all particles in an event using all sub-detector information
  - Implementable for the first time at L1 thanks to:
    - Efficient reconstruction of charged particles in the tracker
    - Fine granularity calorimetry to resolve the contributions from neighbouring particles

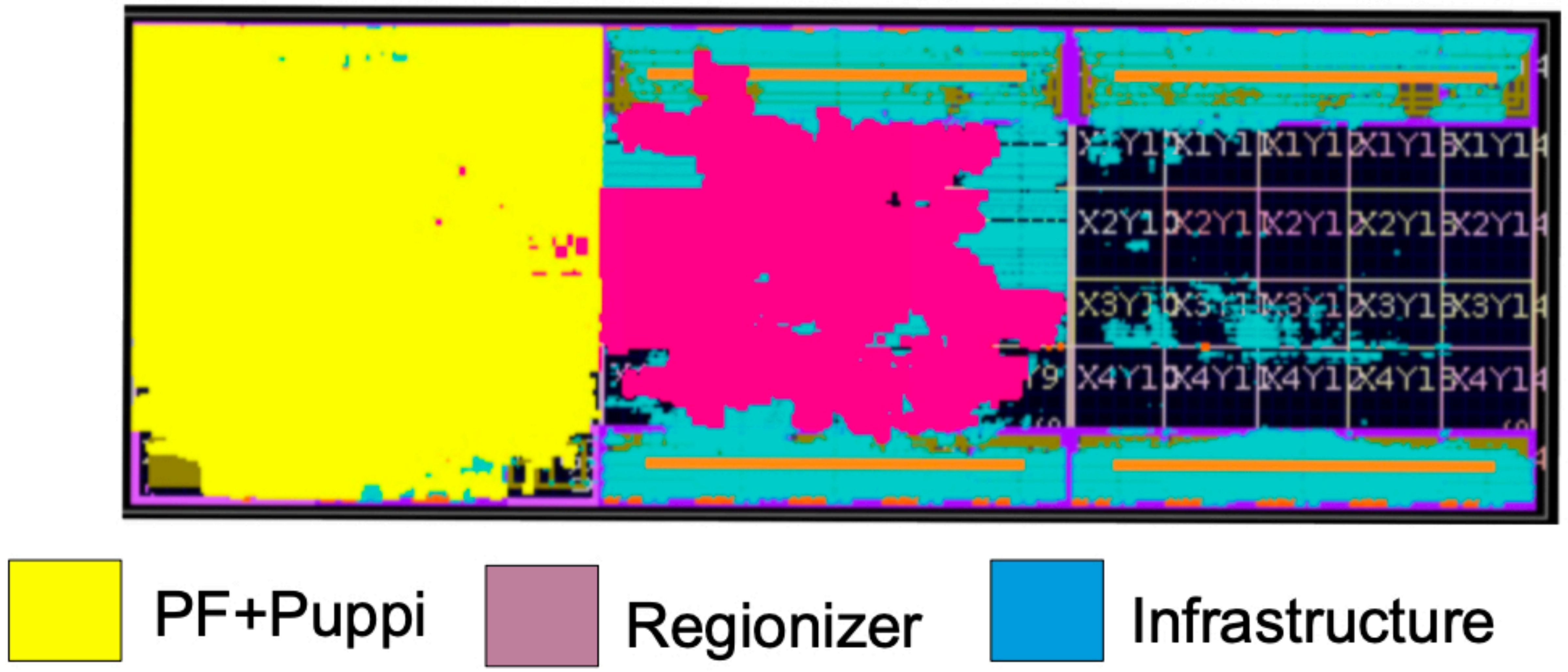


- PF candidates are then filtered with the PUPPI algorithm
  - Uses vertex to define a particle weight
  - Basically a probability of being prompt



Particle flow demonstrator

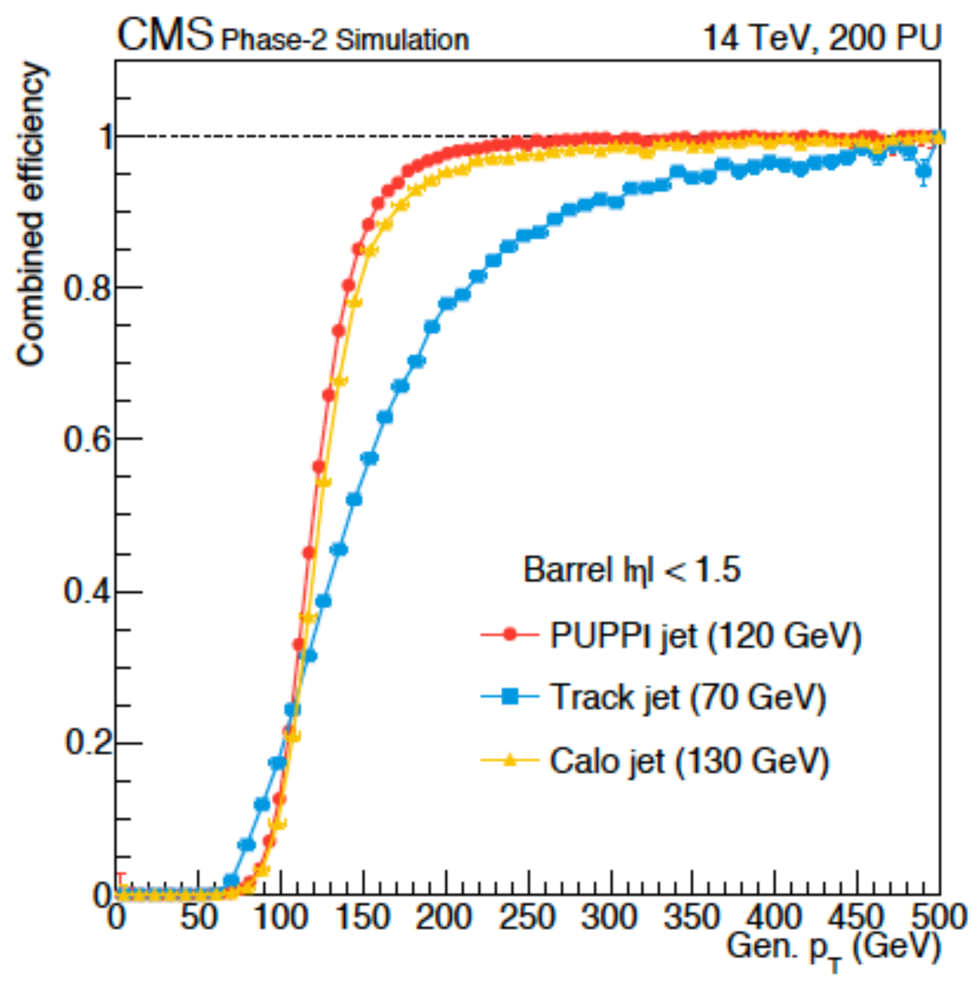
- Most ambitious aspect of the upgrade design
  - Important to demonstrate it can be implemented
  - Resource utilisation and latency fits within the requirements proving that complicated algorithms such as Particle Flow are possible in CMS Phase-2 Trigger

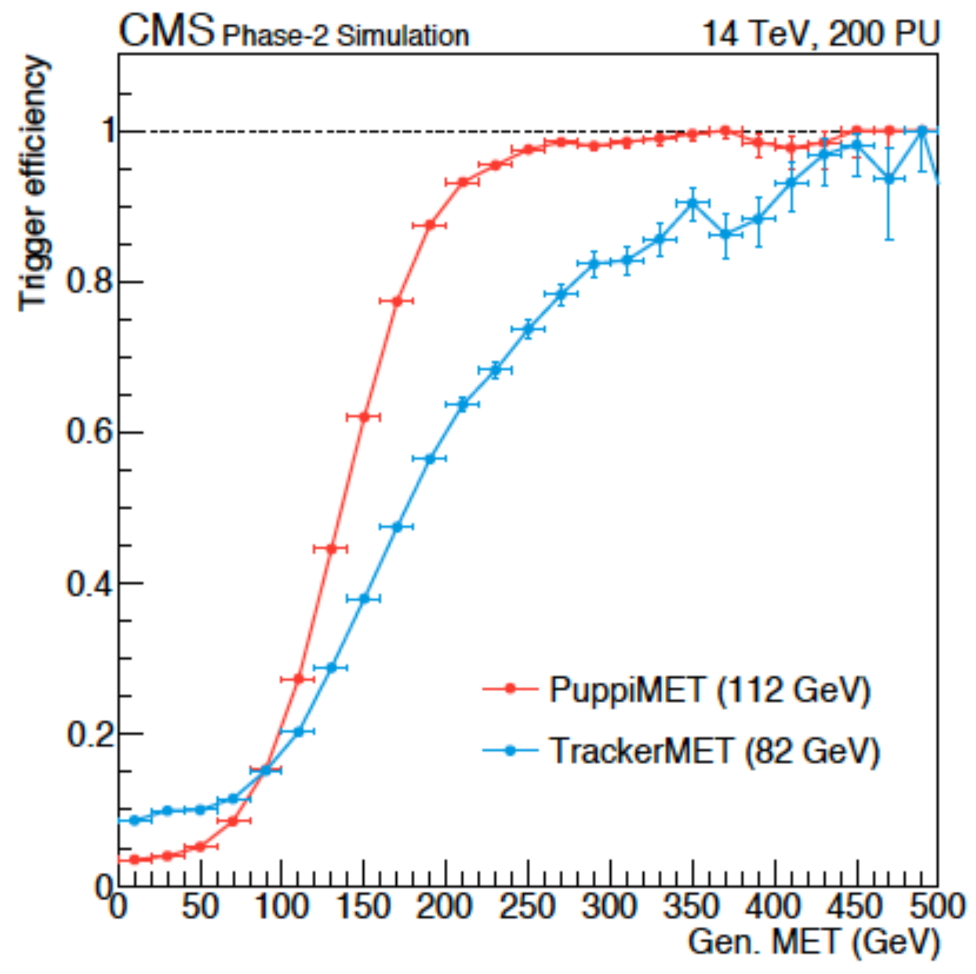


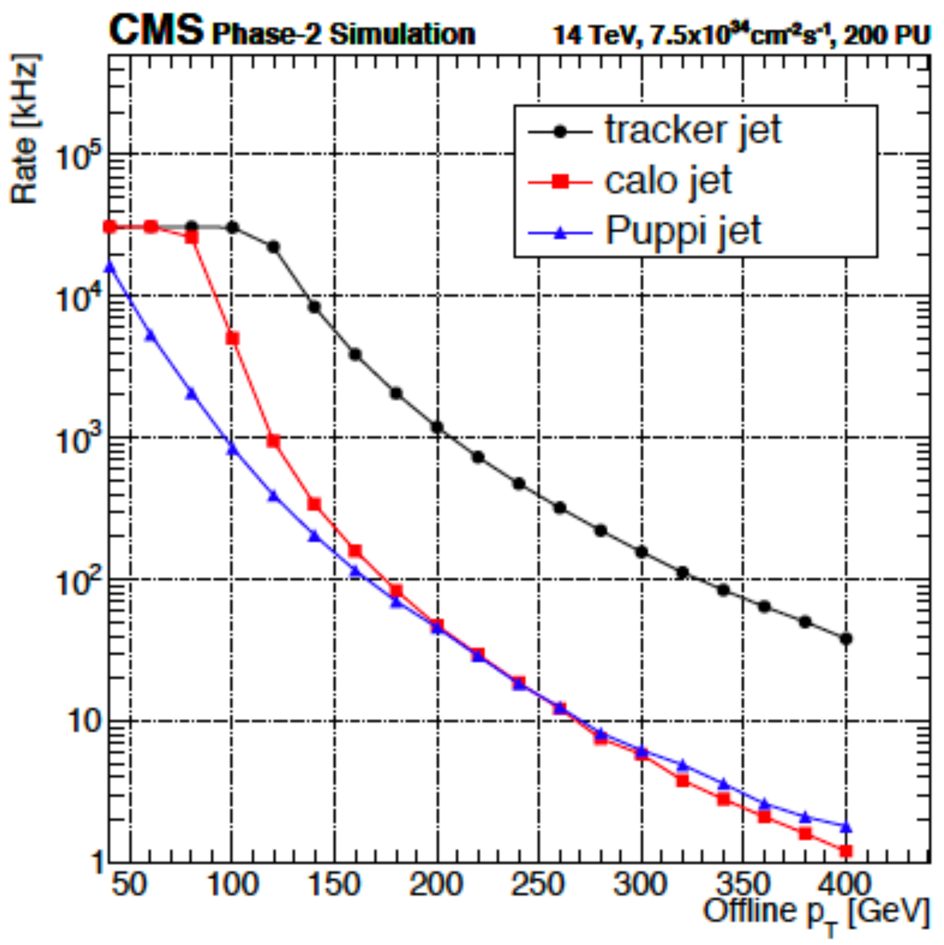
	APx
FF	33%
LUT	**45%**
BRAM	40%
UltraRAM	25%
DSP	15%
Latency (µs)	**0.7**

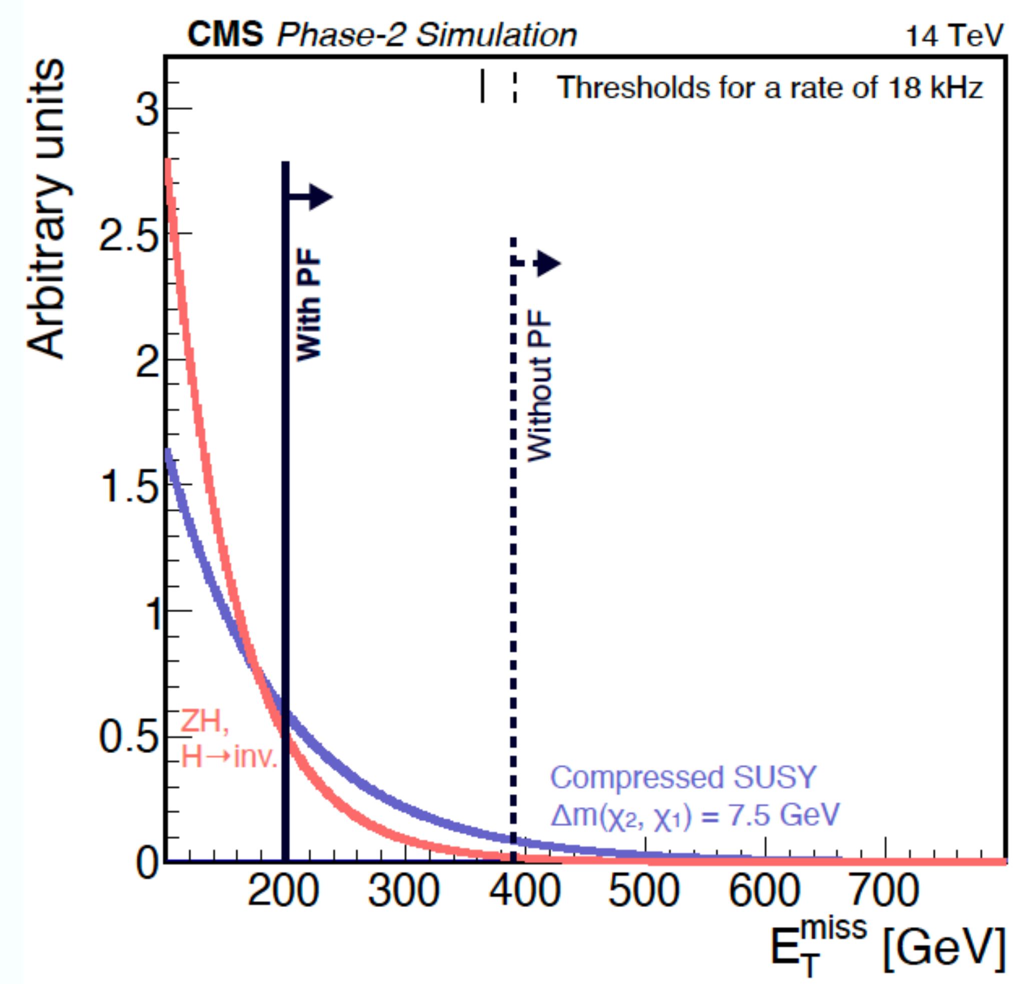
Level-1 Trigger algorithms: Jets & MET

- **Standalone**
  - Calorimeter only jets/MET
    - Simple and robust at high E_T
    - Similar algorithm to current trigger
  - Track jets/MET
    - Using only charged tracks
    - Robust against pileup
- **Combined**
  - PUPPI jets/MET
    - Sophisticated algorithm removing pileup and optimally using different detector inputs



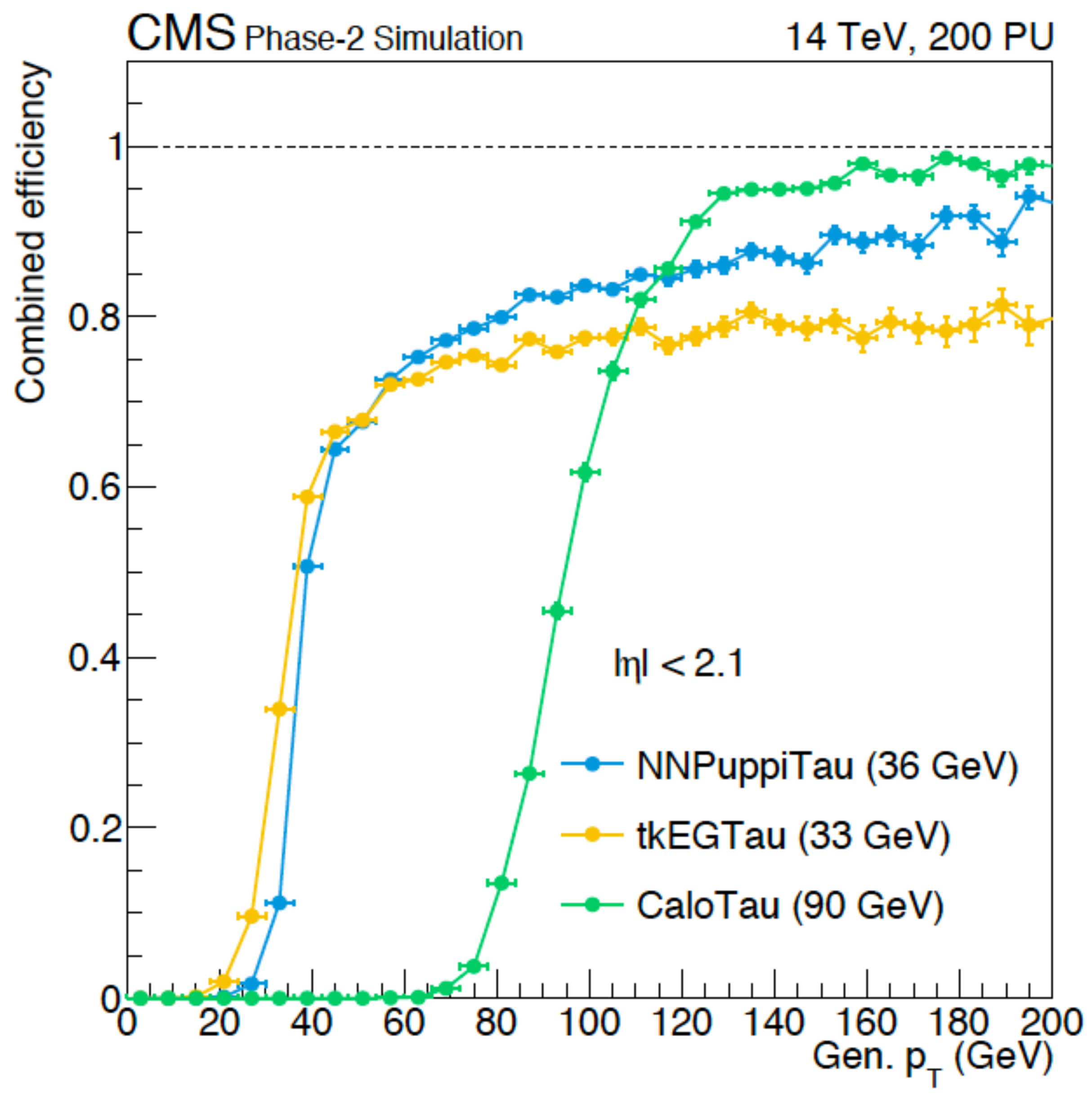


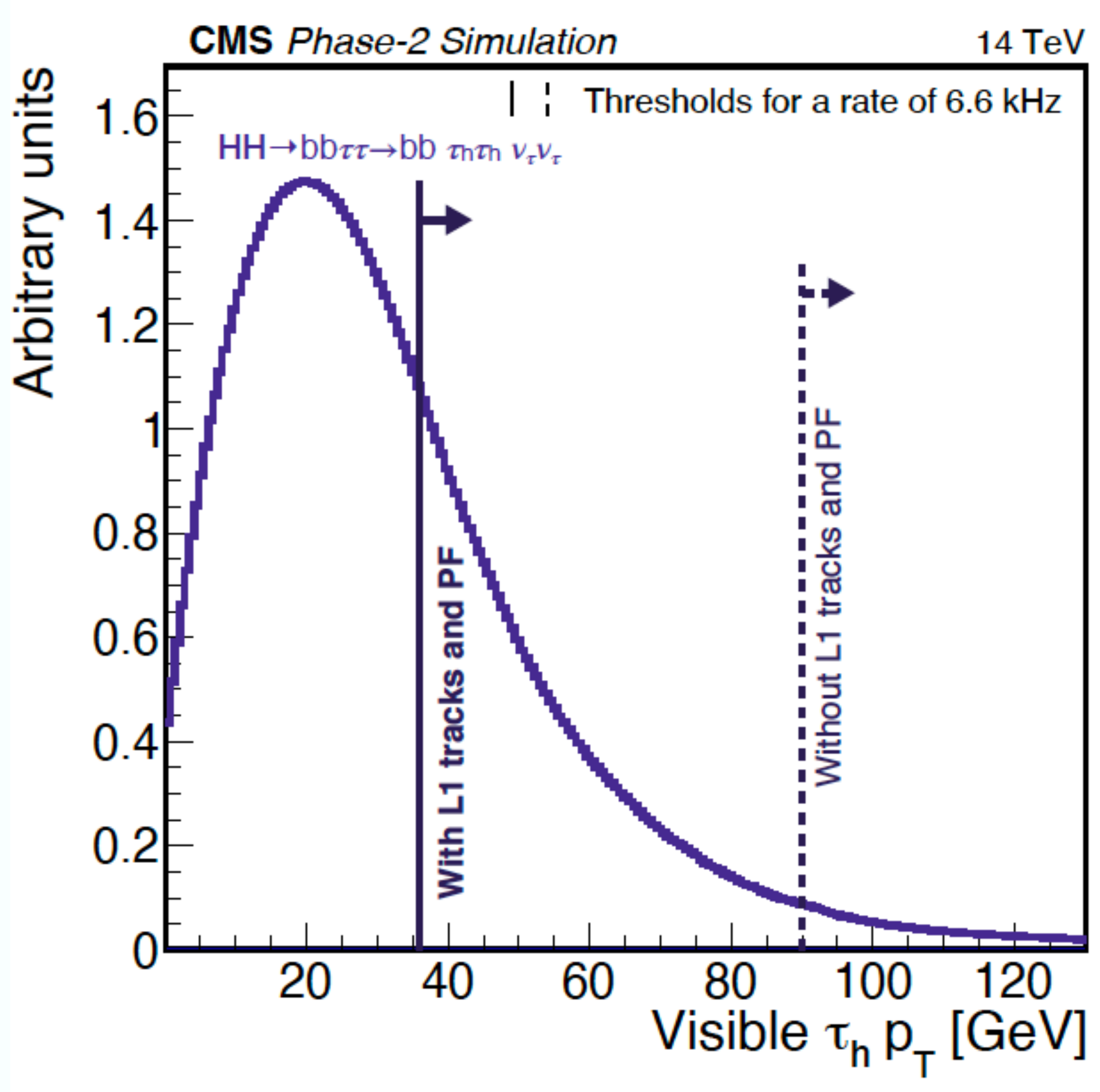




Level-1 Trigger algorithms: τ_h

- NN PUPPI τ algorithm
  - Input: iteratively seed from highest p_T charged PUPPI particle with $\Delta R>0.4$ from each other, from each seed take all PUPPI candidates within $\Delta R<0.4$
  - p_T, $\Delta\eta$seed, $\Delta\phi$seed, particle ID of 10 highest p_T particles in cone input to dense NN: different working points from NN output
  - Other (simple) algorithms can recover efficiency in plateaux or provide robustness





Level-1 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	$\lvert\eta\rvert < 2.4$	95
Double TkMuon	15,7	1	$\lvert\eta\rvert < 2.4$, $\Delta z < 1$	95
Triple TkMuon	5,3,3	16	$\lvert\eta\rvert < 2.4$, $\Delta z < 1$	95
Single TkElectron	36	24	$\lvert\eta\rvert < 2.4$	93
Single TkIsoElectron	28	28	$\lvert\eta\rvert < 2.4$	93
TkIsoElectron-StaEG	22, 12	64	$\lvert\eta\rvert < 2.4$	93, 99
Double TkElectron	25, 12	4	$\lvert\eta\rvert < 2.4$	93
Single StaEG	51	25	$\lvert\eta\rvert < 2.4$	99
Double StaEG	37,24	5	$\lvert\eta\rvert < 2.4$	99
Photon seeds				
Single TkIsoPhoton	36	43	$\lvert\eta\rvert < 2.4$	97
Double TkIsoPhoton	22, 12	50	$\lvert\eta\rvert < 2.4$	97
Taus seeds				
Single CaloTau	150(119)	21	$\lvert\eta\rvert < 2.1$	99
Double CaloTau	90,90(69,69)	25	$\lvert\eta\rvert < 2.1$, $\Delta R > 0.5$	99
Double PuppiTau	52,52(36,36)	7	$\lvert\eta\rvert < 2.1$, $\Delta R > 0.5$	90
Hadronic seeds (jets,H_T)				
Single PuppiJet	180	70	$\lvert\eta\rvert < 2.4$	100
Double PuppiJet	112,112	71	$\lvert\eta\rvert < 2.4$, $\Delta\eta < 1.6$	100
PuppiH_T	450(377)	11	jets: $\lvert\eta\rvert < 2.4$, $p_T > 30$	100
QuadPuppiJets-PuppiH_T	70,55,40,40,400(328)	9	jets: $\lvert\eta\rvert < 2.4$, $p_T > 30$	100,100
E_T^{miss} seeds				
PuppiE_T^{miss}	200(128)	18		100
Cross Lepton seeds				
TkMuon-TkIsoElectron	7,20	2	$\lvert\eta\rvert < 2.4$, $\Delta z < 1$	95, 93
TkMuon-TkElectron	7,23	3	$\lvert\eta\rvert < 2.4$, $\Delta z < 1$	95, 93
TkElectron-TkMuon	10,20	1	$\lvert\eta\rvert < 2.4$, $\Delta z < 1$	93, 95
TkMuon-DoubleTkElectron	6,17,17	0.1	$\lvert\eta\rvert < 2.4$, $\Delta z < 1$	95, 93
DoubleTkMuon-TkElectron	5,5,9	4	$\lvert\eta\rvert < 2.4$, $\Delta z < 1$	95, 93
PuppiTau-TkMuon	36(27),18	2	$\lvert\eta\rvert < 2.1$, $\Delta z < 1$	90, 95
TkIsoElectron-PuppiTau	22,39(29)	29	$\lvert\eta\rvert < 2.1$, $\Delta z < 1$ $\Delta R > 0.3$	93, 90

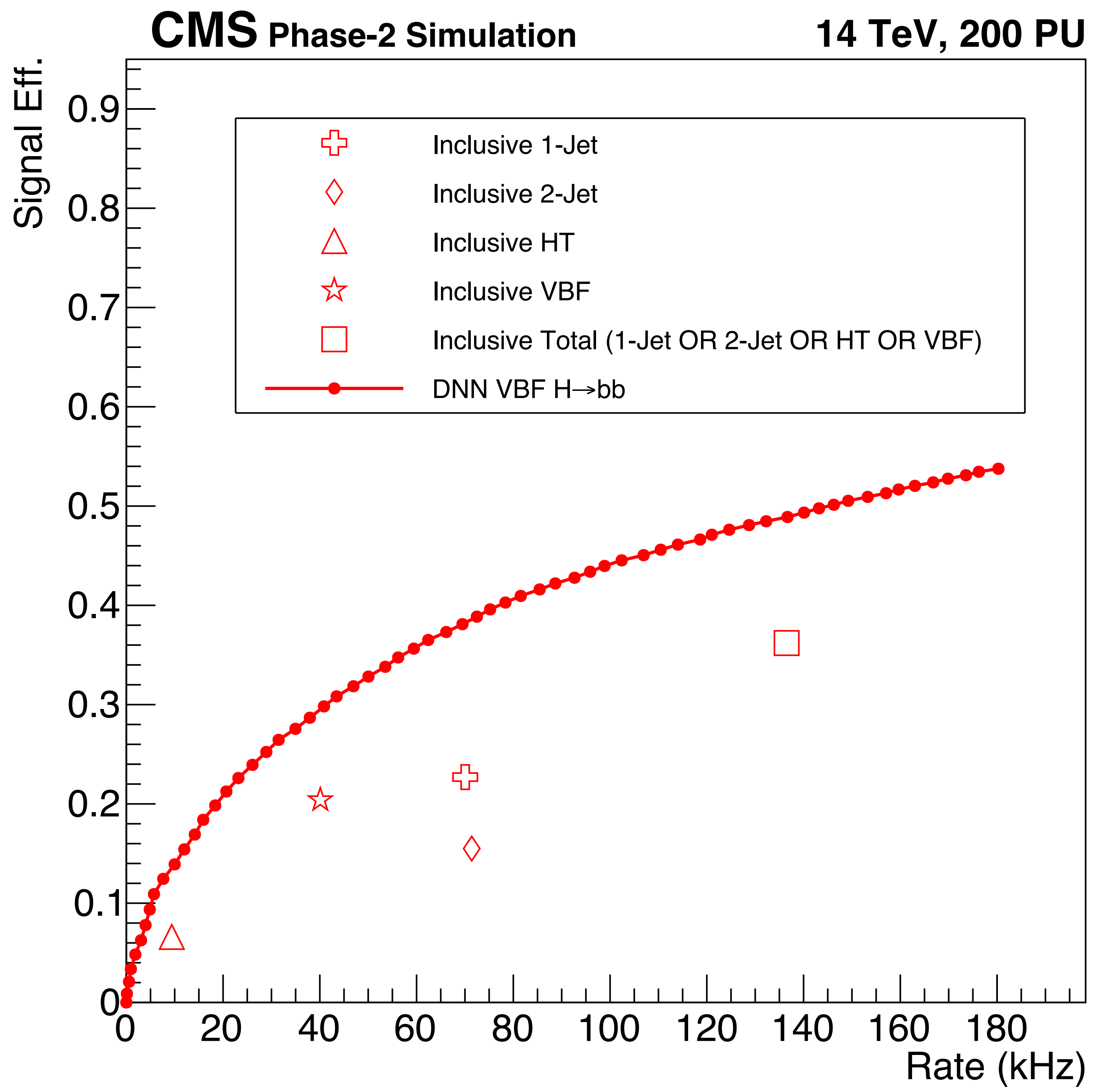
L1 Trigger seeds	Offline Threshold(s) at 90% or 95% (50%) [GeV]	Rate $\langle PU \rangle = 200$ [kHz]	Additional Requirement(s) [cm, GeV]	Objects plateau efficiency [%]
Cross Hadronic-Lepton seeds				
TkMuon-PuppiH_T	6,320(250)	4	$\lvert\eta\rvert < 2.4$, $\Delta z < 1$	95,100
TkMuon-DoublePuppiJet	12,40,40	10	$\lvert\eta\rvert < 2.4$, $\Delta R_{j\mu} < 0.4$, $\Delta\eta_{jj} < 1.6$, $\Delta z < 1$	95,100
TkMuon-PuppiJet-PuppiE_T^{miss}	3,100,120(55)	14	$\lvert\eta\rvert < 1.5$, $\lvert\eta\rvert < 2.4$, $\Delta z < 1$	95,100, 100
DoubleTkMuon-PuppiJet-PuppiE_T^{miss}	3,3,60,130(64)	4	$\lvert\eta\rvert < 2.4$, $\Delta z < 1$	95,100, 100
DoubleTkMuon-PuppiH_T	3,3,300(231)	2	$\lvert\eta\rvert < 2.4$, $\Delta z < 1$	95,100
DoubleTkElectron-PuppiH_T	10,10,400(328)	0.9	$\lvert\eta\rvert < 2.4$, $\Delta z < 1$	93,100
TkIsoElectron-PuppiH_T	26,190(124)	22	$\lvert\eta\rvert < 2.4$, $\Delta z < 1$	93,100
TkElectron-PuppiJet	28,40	34	$\lvert\eta\rvert < 2.1$, $\lvert\eta\rvert < 2.4$, $\Delta R > 0.3$, $\Delta z < 1$	93,100
PuppiTau-PuppiE_T^{miss}	55(38),190(118)	4	$\lvert\eta\rvert < 2.1$	90,100
VBF seeds				
Double PuppiJets	160,35	40	$\lvert\eta\rvert < 5$, $m_{jj} > 620$	100
B-physics seeds				
Double TkMuon	2,2	12	$\lvert\eta\rvert < 1.5$, $\Delta R < 1.4$, $q1 * q2 < 0$, $\Delta z < 1$	95
Double TkMuon	4,4	21	$\lvert\eta\rvert < 2.4$, $\Delta R < 1.2$ $q1 * q2 < 0$, $\Delta z < 1$	95
Double TkMuon	4.5,4	10	$\lvert\eta\rvert < 2.0, 7 < m_{\mu\mu} < 18$, $q1 * q2 < 0$, $\Delta z < 1$	95
Triple TkMuon	5,3,2	7	$0 < m_{\mu 5 \mu 3, q1*q2<0} < 9$ $\lvert\eta\rvert < 2.4$, $\Delta z < 1$	95
Triple TkMuon	5,3,2.5	6	$5 < m_{\mu 5 \mu 2.5, q1*q2<0} < 17$ $\lvert\eta\rvert < 2.4$, $\Delta z < 1$	95
Rate for above Trigger seeds				363
Total Level-1 Menu Rate (+30%)				**472**

- Able to maintain current performance at 7.5x10^{34} cm^{-2} s^{-1} and 200 PU — with contingency for new ideas

Level-1 Trigger algorithms: NN

- In current trigger possibility to apply requirements on correlations between multiple objects (masses, $\Delta\varphi$…)
- Natural continuation: instead of simple 1D cuts on objects and object correlations, use modern ML tools to build more powerful multivariate discriminators
  - Software tools to synthesize such algorithms into FPGA firmware now exist
  - FPGAs resources now allow it

- Performed full exercise for VBF H→invisible/bb
  - L1 design, signal acceptance/rates, feasibility study for firmware implementation
  - L1Seed design with DNN (feasibility study for firmware implementation performed) with input variables: pT and η of 3 leading jets, pT(jj), m(jj), ΔR(jj), Δη(jj), Zeppenfeld variables, MET, $\Delta\varphi$(MET,jj)…



High level trigger

- Challenges:
  - Achieve rejection factor 100:1 (while tracking available @ L1)
  - Keep CPU time < 500 ms
  - Reconstruction : more complex detector (HGCAL, tracking, timing layer, etc.)
  - Timing : increase with inst luminosity (7.5x input event rate), but also with pile-up

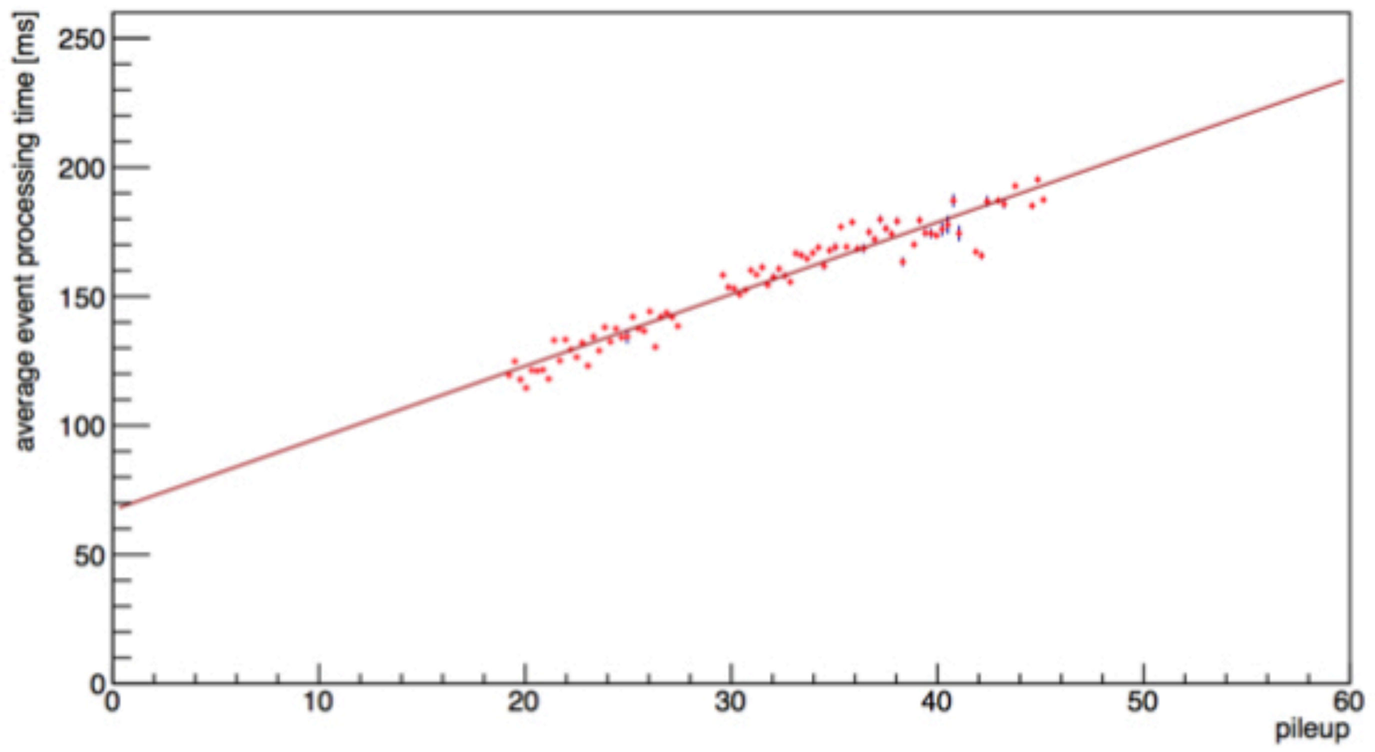
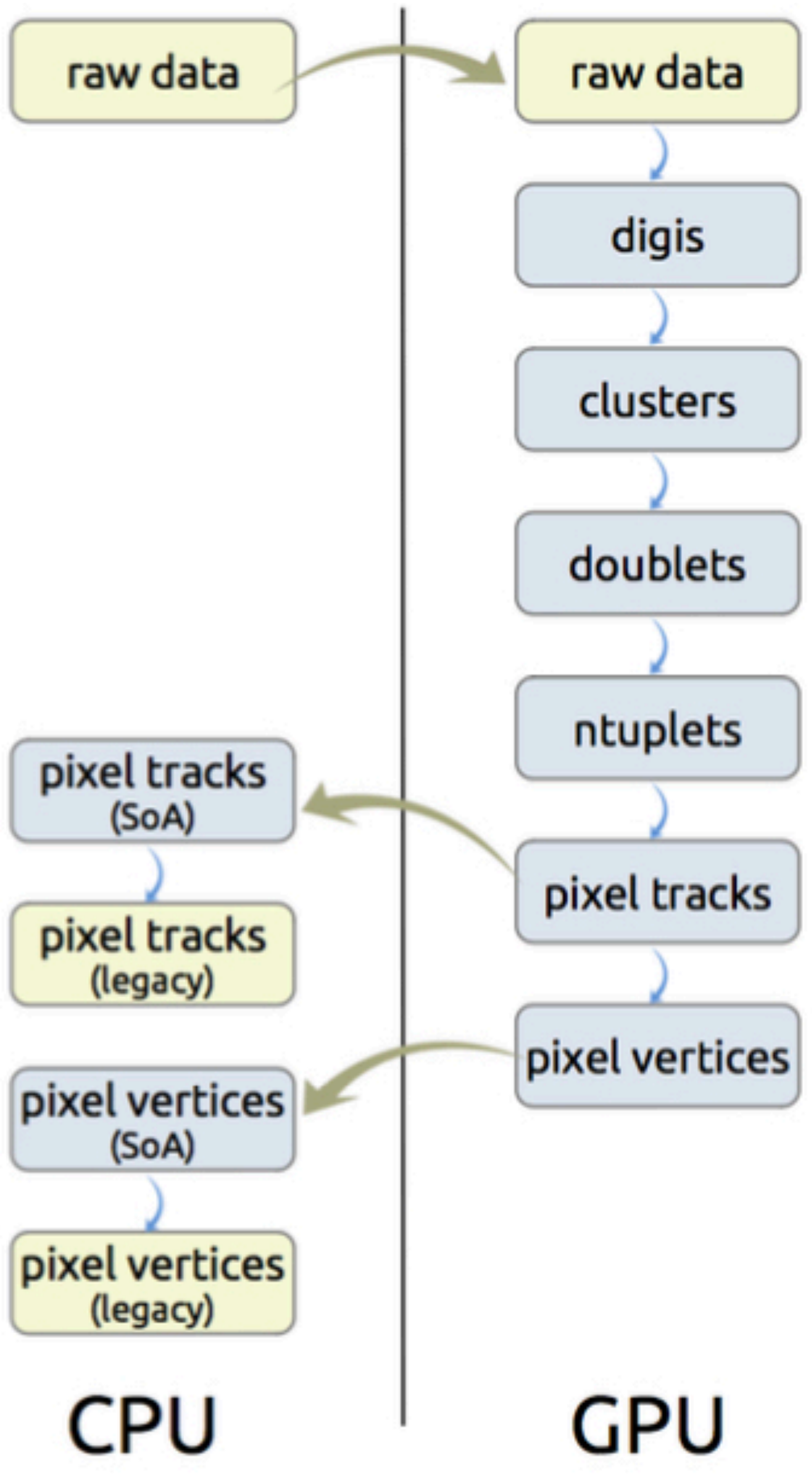


Figure 1.3: Average HLT CPU time per event[24] as a function of pile-up during 2017 data taking.

- Requirements
  - 18x more computing power
  - 25x more data throughput
  - No achievable by extrapolating current approach — need paradigm shift — heterogeneous approach accepted (?)

High level trigger

- Main strategic choice: same framework and algorithms used offline
  - As current trigger which has served CMS well — allows rapid deployment of new triggers etc.
- Current HLT R&D co-processors as off-load engines for specific algorithms
  - Demonstrator with GPU for Run 3 — gain experience in CMS
  - Pixel based tracking, ECAL and HCAL reconstruction prototyped
- Various architectures/processors possible
  - Coprocessor equipped nodes, network offload service …



Patatrack
https://patatrack.web.cern.ch/patatrack/

Outline

- Motivation and some important concepts
- Historical overview highlighting how challenges have driven development in the past
- Case study: current CMS trigger
- Case study: CMS trigger upgrade for HL-LHC
- Practical advice

Practical advice

- You might well have to design a trigger for some physics channel you are interested in

- Not as unusual as you might imagine!

- Some things to remember....

Practical advice

- Generally
  - Keep it as simple as possible
  - Easy to commission
  - Easy to debug
  - Easy to understand

Practical advice

- Generally
  - Be as inclusive as possible
  - One trigger for several similar analyses
  - Your trigger should be able to discover the unexpected as well as the signal you intended it for!

Practical advice

- Generally
  - Make sure your trigger is robust
  - Triggers run millions of times a second so any strange condition WILL occur, make sure you are prepared for it
  - Detectors don’t work perfectly ever! make sure your trigger is immune to detector problems
  - Beam conditions change - be prepared

Practical advice

- Generally
  - Build in redundancy
  - Make sure your signal can be selected by more than one trigger
  - Helps to understand biases and measure efficiencies
  - Also for safety, if rates are too high or there’s some problem you still get your events

Practical advice

- Finally

  - Taking your signal events is only part of the game
  - You might well also need background samples
  - You will need to measure the efficiency of your trigger using a redundant trigger path
  - You will need to know if it works! Monitoring.

Outline

- Motivation and some important concepts
- Historical overview highlighting how challenges have driven development in the past
- Case study: current CMS trigger
- Case study: CMS trigger upgrade for HL-LHC
- Practical advice

Summary

- Trigger is essential at (hadron) colliders
- Must have a huge rejection of unwanted events if we are to see low cross section processes
- Trigger is not there to do analysis, just get the events written to tape at an acceptable rate
- In real life there are many more details to consider than discussed

The future

- Triggers driven by physics needs and accelerator environment

- Easy future: ILC
  - No trigger!
  - 200 μs between trains
  - Buffer and readout everything

- Difficult future: HL-LHC/FCC-hh …
  - Up to 200 interactions per bunch crossing
  - Need to keep trigger thresholds as LHC
  - Need to incorporate sophisticated detector into hardware algorithms e.g. tracking

Summary

- LHC is a very challenging environment to search for new physics and measure the properties of the Higgs boson
  - High instantaneous luminosity, high pileup etc.
  - Requires excellent performance online and offline
- CMS trigger tackles these challenges
  - FPGA based, very high bandwidth processors with sophisticated, programmable algorithms
  - Flexible to evolve with CMS physics programme e.g. GPUs for LHC Run 3
- Designing CMS trigger upgrade for HL-LHC
  - Based on experience from current trigger system
  - Integrating tracking and high-granularity detectors into Level-1 trigger and co-processors in HLT

References

- Level-1 Trigger:
  - Legacy TDR: https://cds.cern.ch/record/706847
  - Run I performance paper: https://arxiv.org/abs/1609.02366
  - Phase 1 upgrade TDR: https://cds.cern.ch/record/1556311
  - Run 2 performance paper: https://arxiv.org/abs/2006.10165
  - Phase 2 upgrade TDR: http://cds.cern.ch/record/2714892

- High Level Trigger:
  - Legacy TDR: http://cds.cern.ch/record/578006
  - Phase 2 upgrade interim TDR: https://cds.cern.ch/record/2283193