Track Trigger at CMS for the High Luminosity LHC

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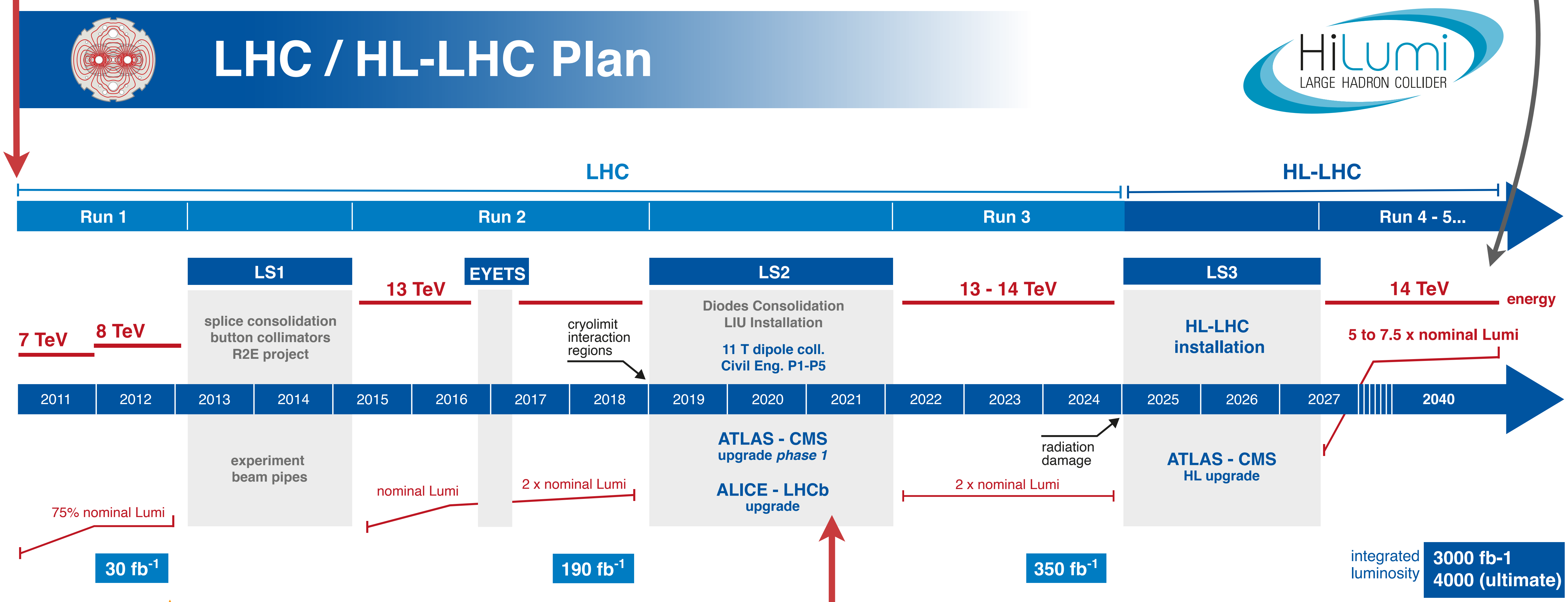
LBL RPM
April 8, 2021

Motivation

Peak instantaneous luminosity: 5-7.5 x nominal

start of LHC operation

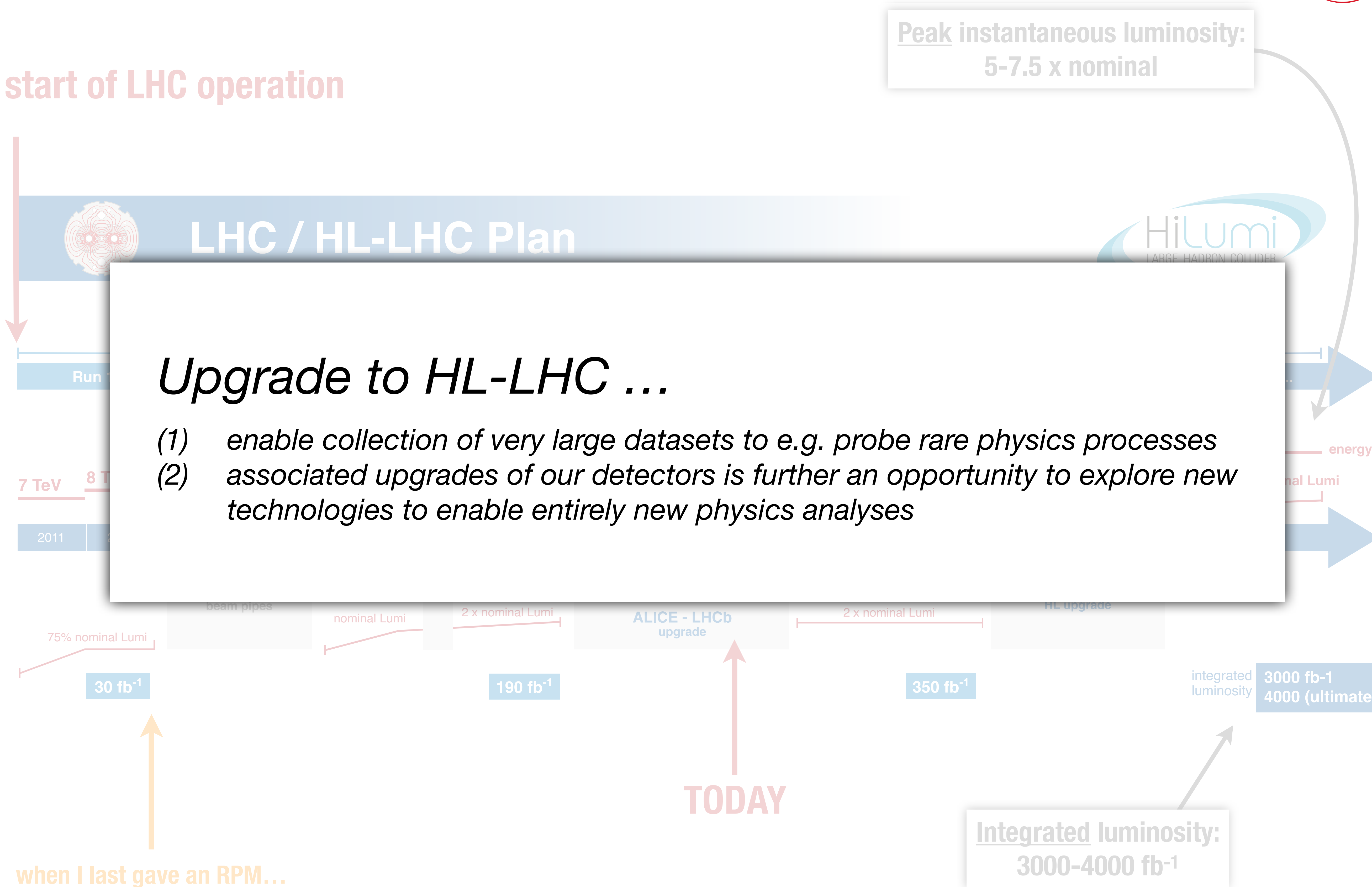


TODAY

when I last gave an RPM…

Integrated luminosity: 3000-4000 fb^{-1}

Motivation



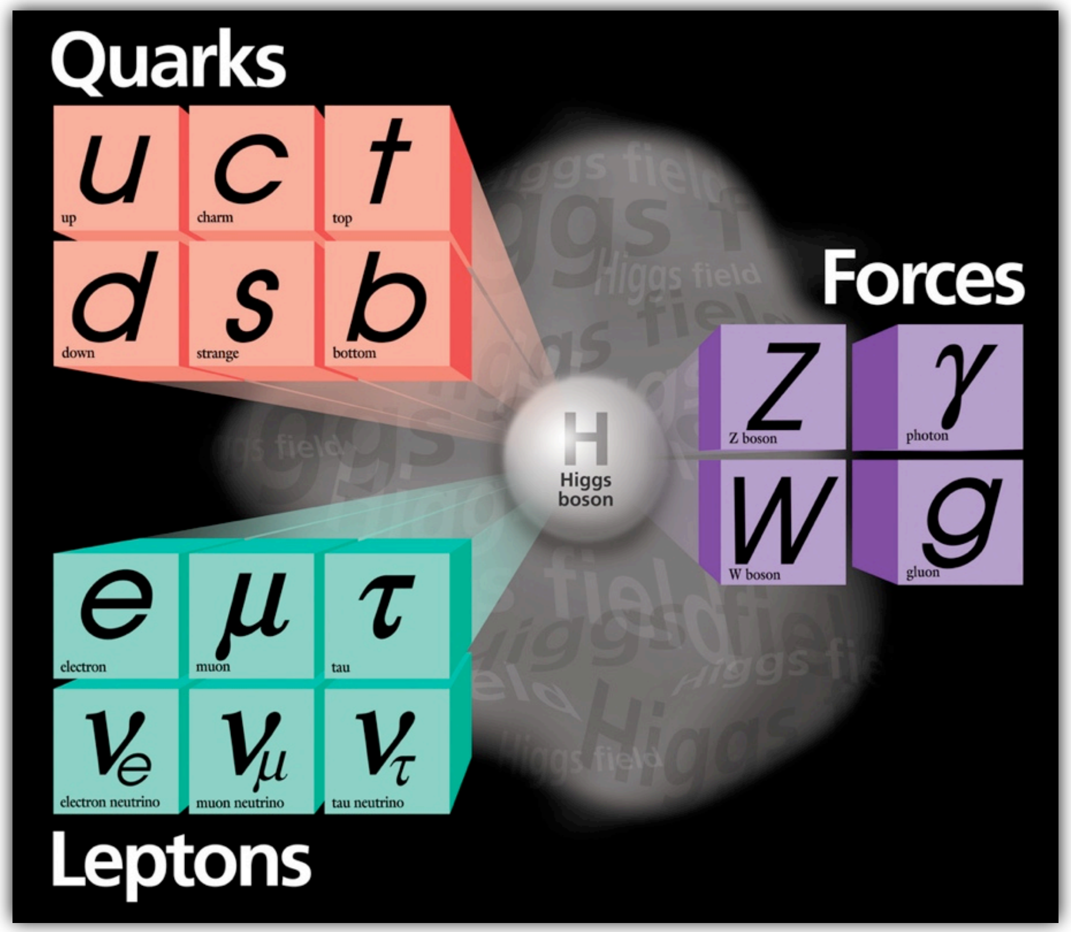
Upgrade to HL-LHC …

(1) enable collection of very large datasets to e.g. probe rare physics processes

(2) associated upgrades of our detectors is further an opportunity to explore new technologies to enable entirely new physics analyses

Standard Model

- Standard Model remarkably successful in explaining experimental data (*)



(*) *modulo possible recent "tensions"*

Standard Model … *and BEYOND*

- Standard Model remarkably successful in explaining experimental data
- Cannot explain:

Matter/anti-matter asymmetry?

Incorporating gravity?

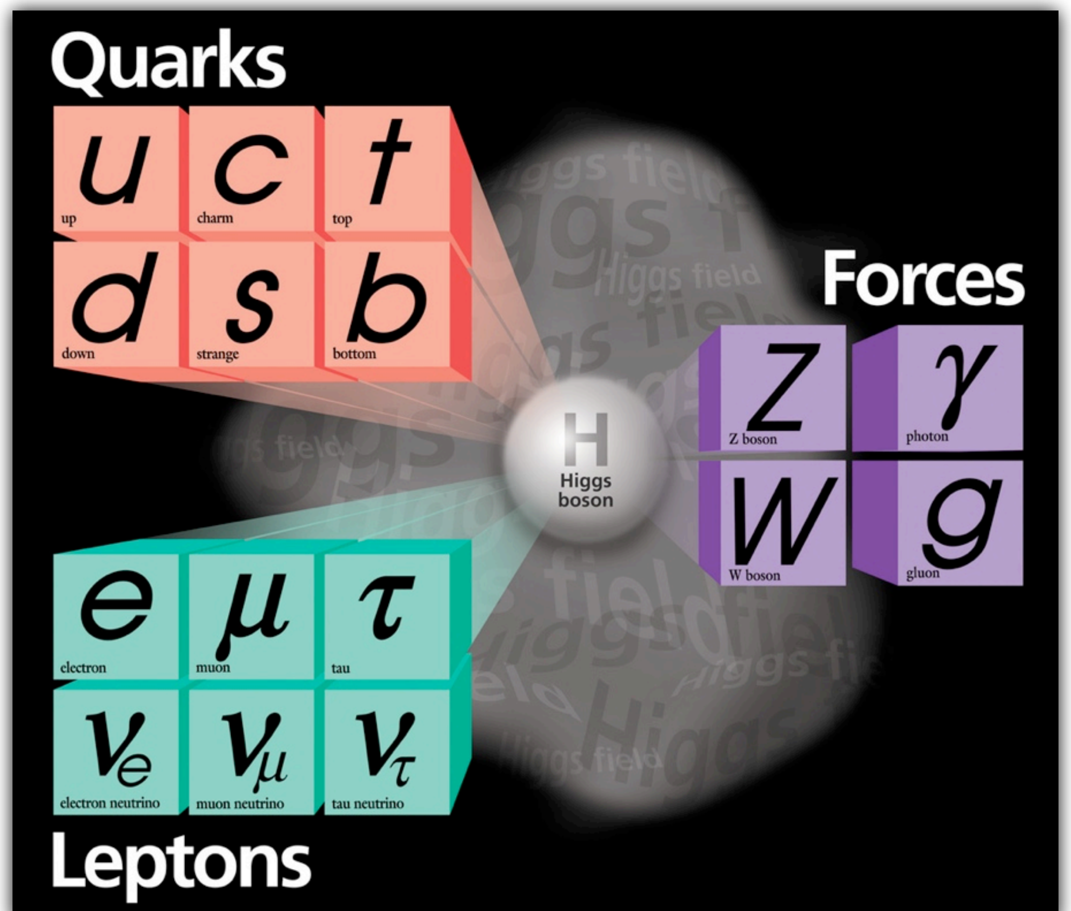
Dark matter?

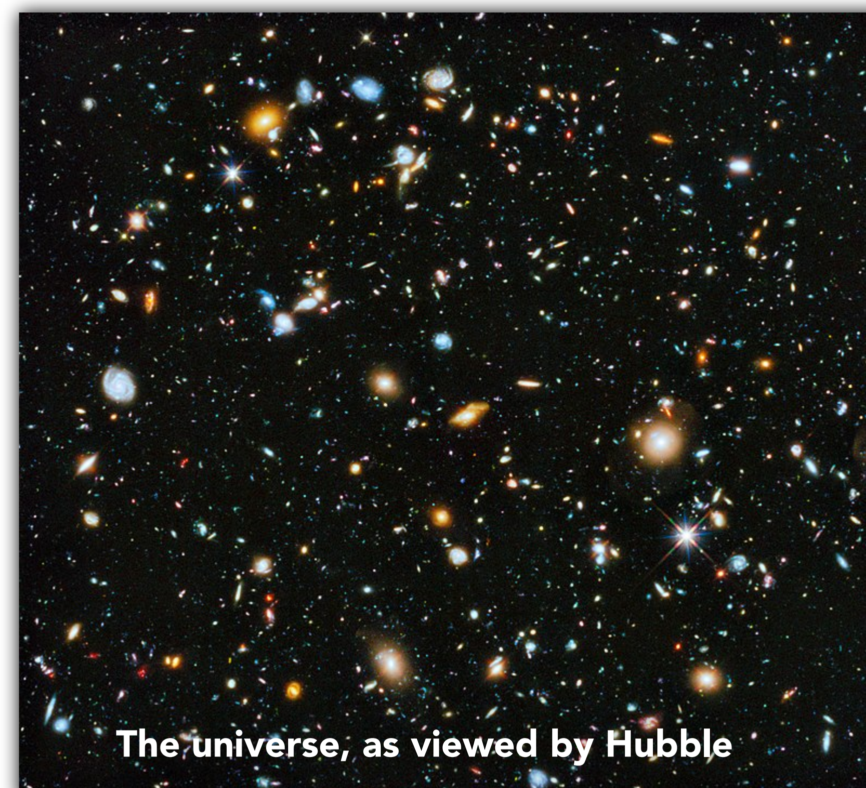
Why three generations?

Neutrino masses?

Why is the Higgs boson so light?

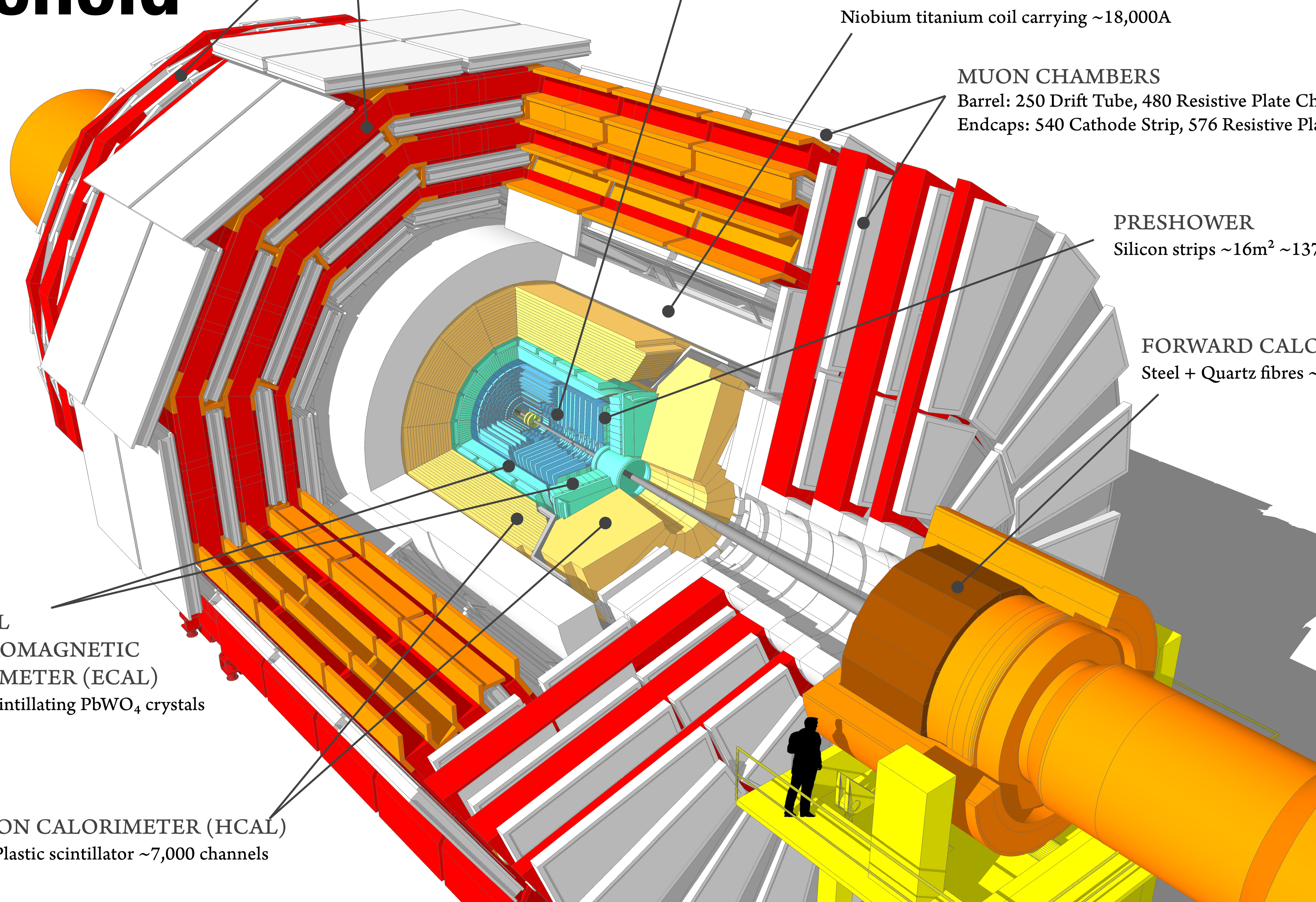
…



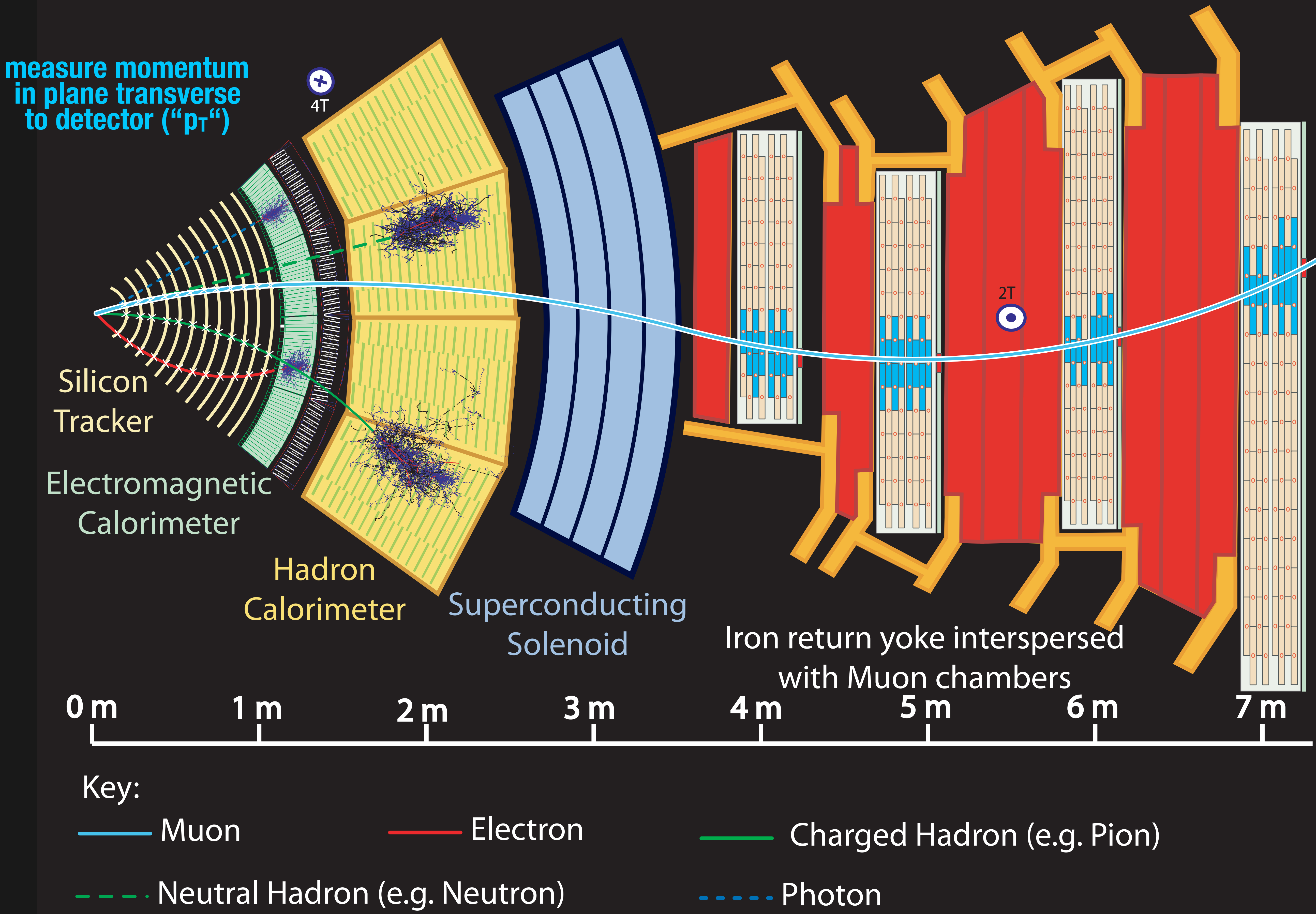


Compact Muon Solenoid

22m long
15m diameter
14,000 tonnes
B=3.8 T

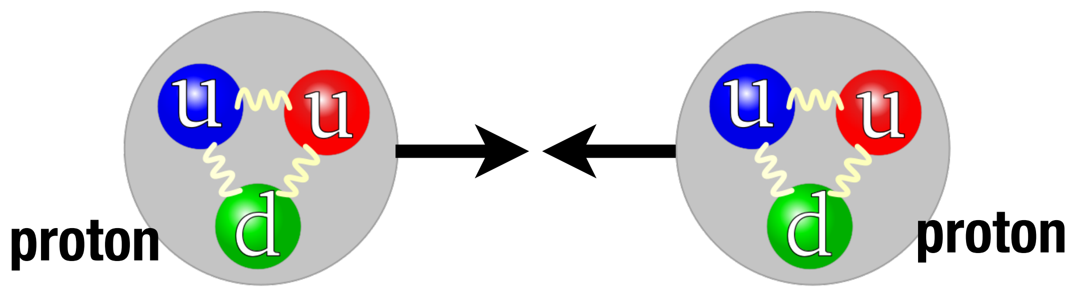


Particle detection at CMS

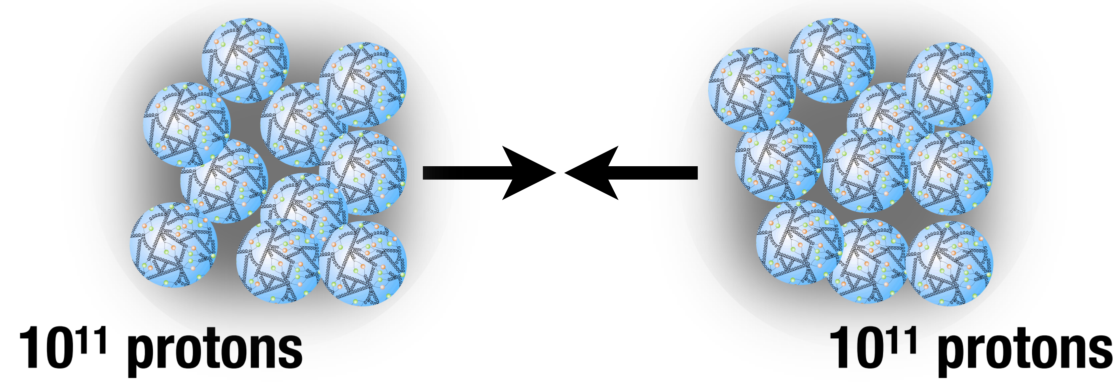


Proton-proton collisions

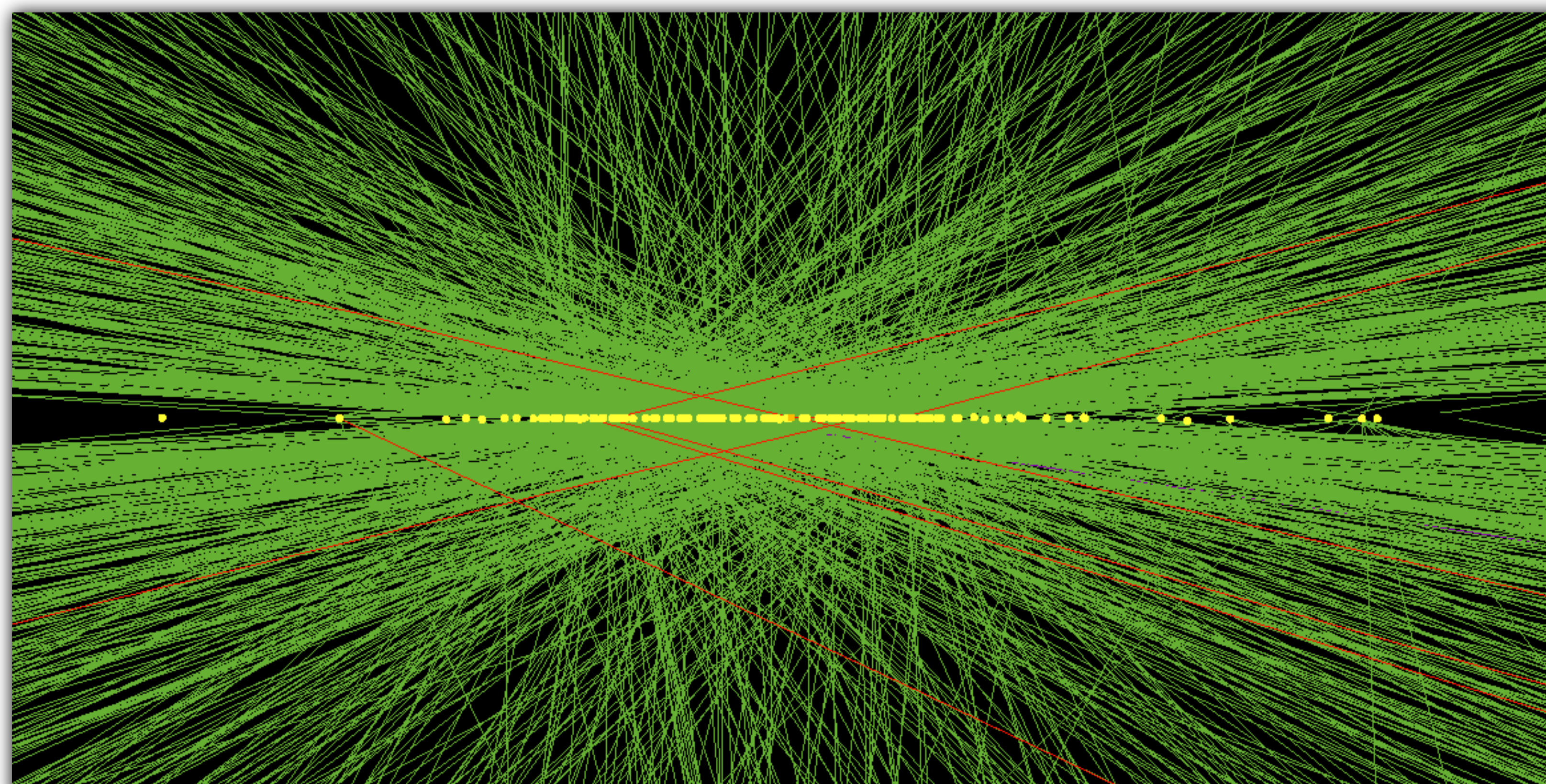
Parton distribution functions
describe momentum distribution of proton's constituents, measured from experiments



VS



<u>PILEUP:</u>
multiple overlapping pp interactions in the same bunch crossing



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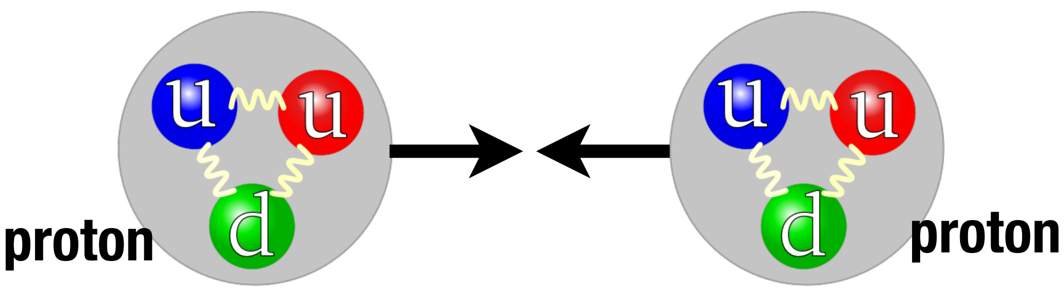
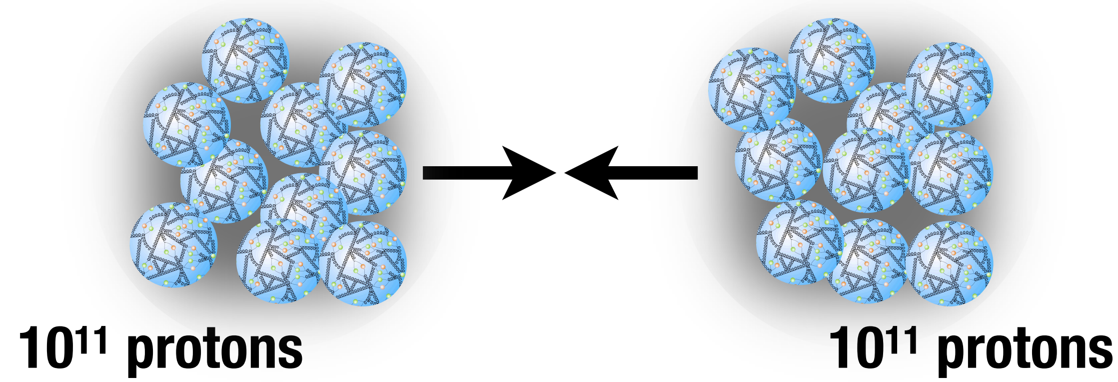


VS



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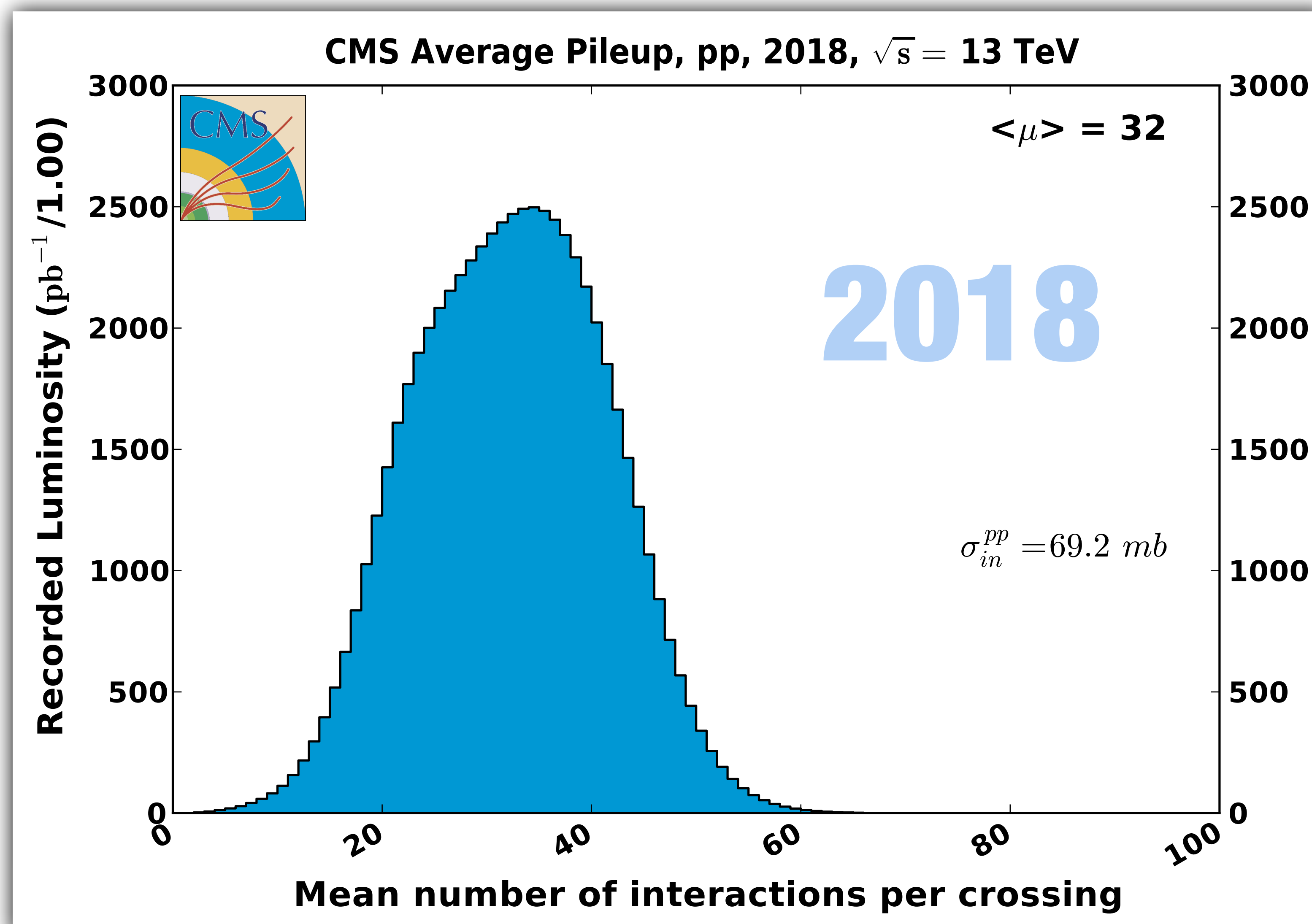
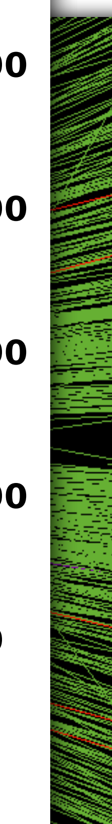
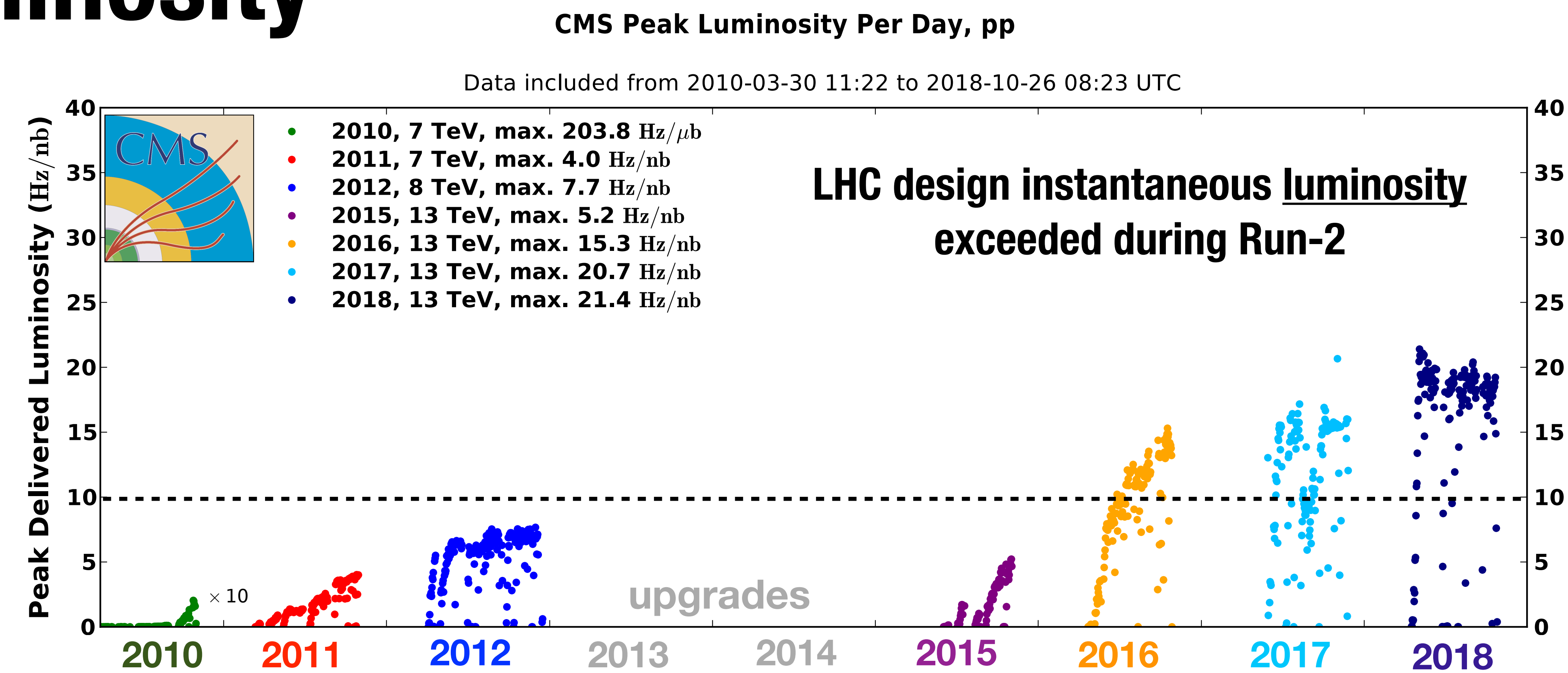




Luminosity



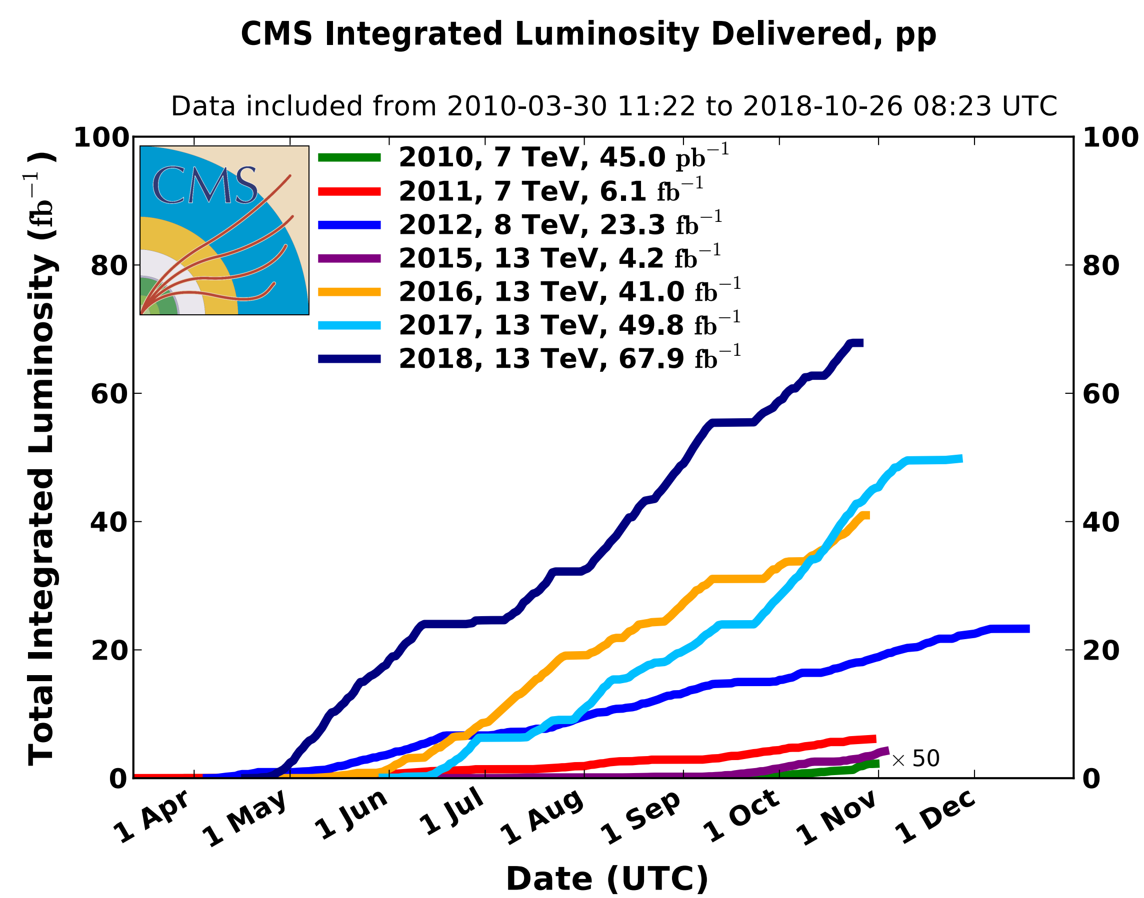
instantaneous luminosity

$$N = \sigma \times \underbrace{\int L\,dt}_{\text{integrated luminosity}}$$

number of events

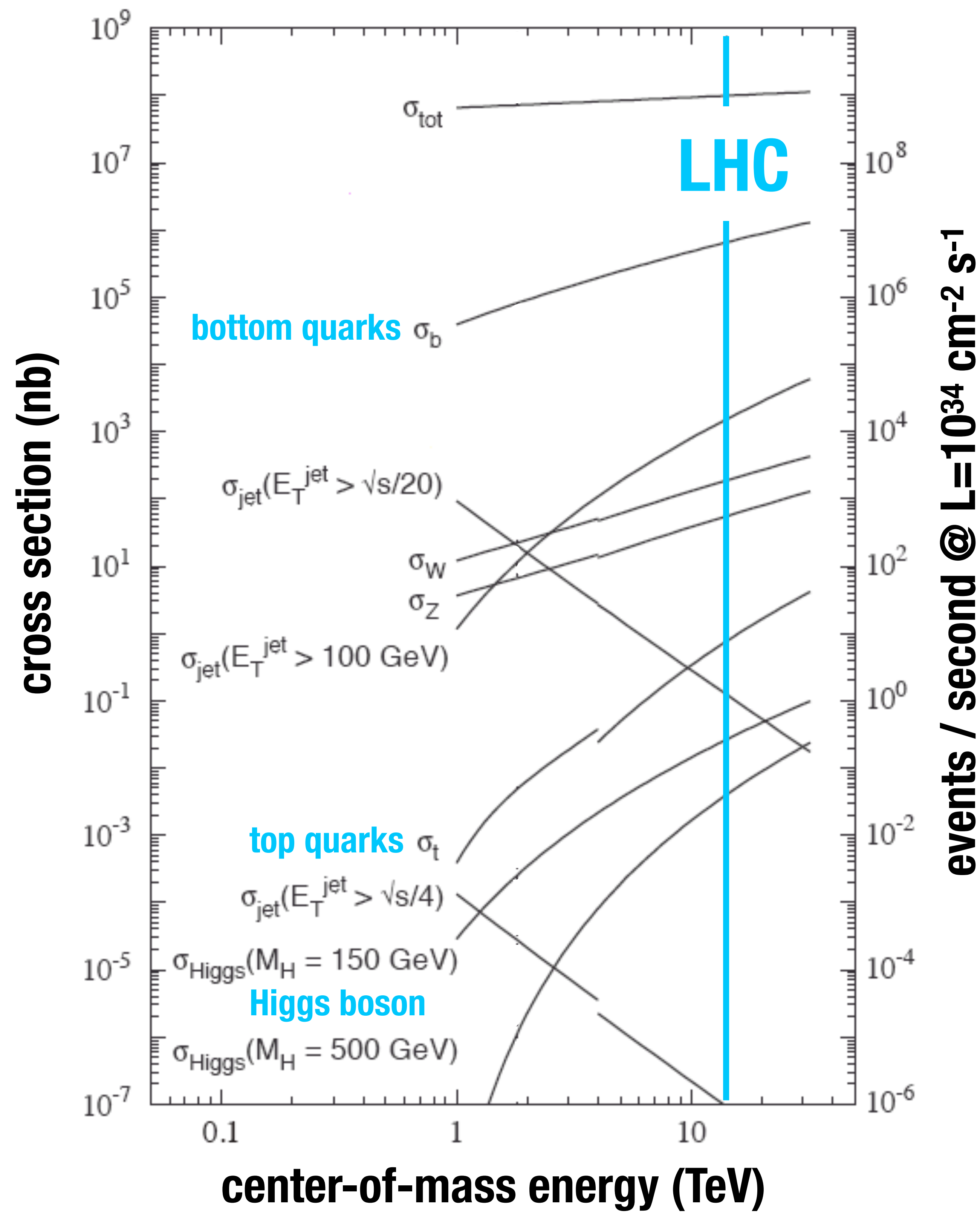
cross section

integrated luminosity



The LHC challenge

- Processes w. H/W/Z bosons, top quarks, etc. are comparably rare!
  - ~10 top quarks, <1 Higgs / sec
- Huge amount of info produced
  - A collision event ≈ 1MB
    ... 40 million times per second
    (=> 40 TB/s !!!)
- Trigger system reduces 40MHz collision rate to data rate that can be read out & written to disk (~1kHz)



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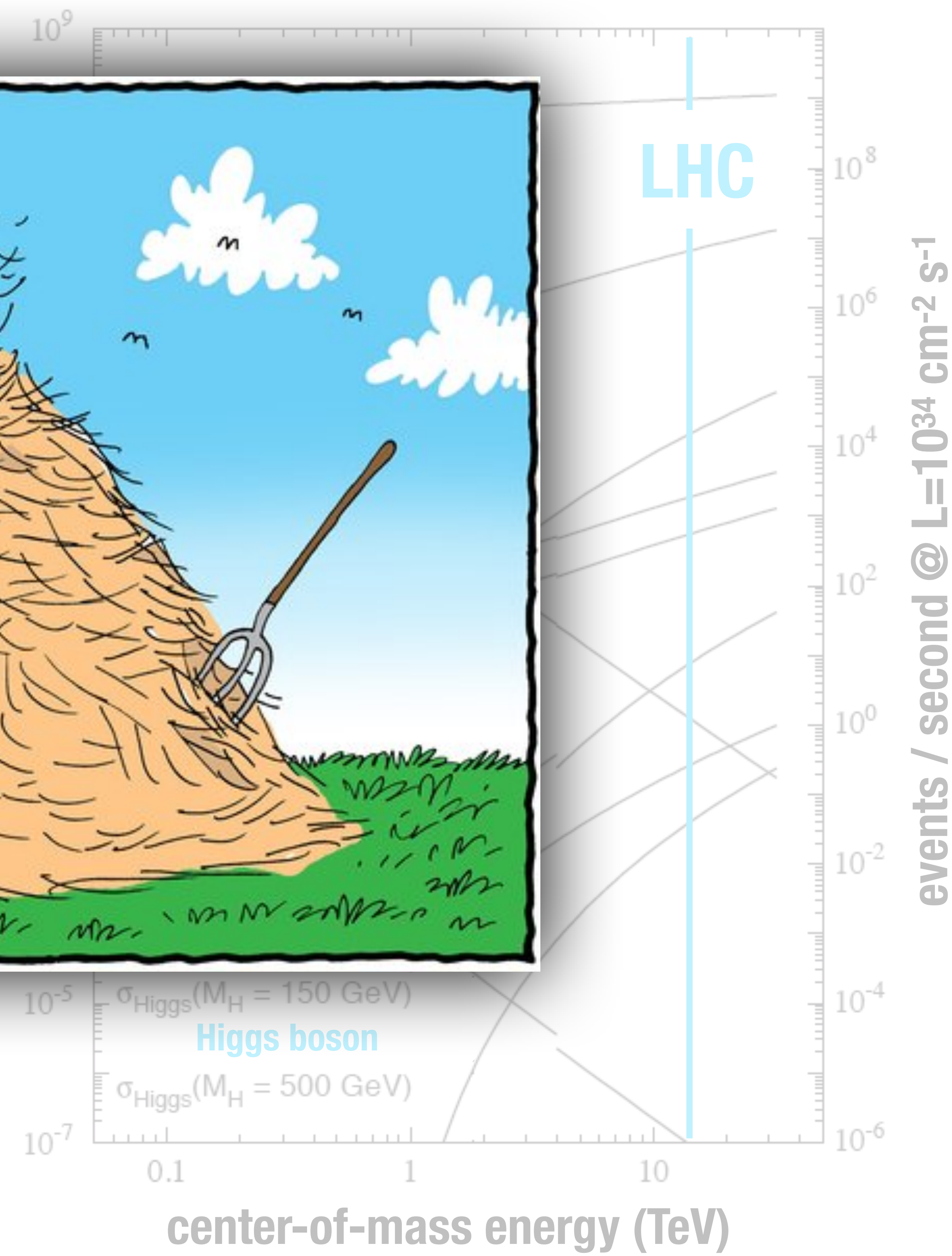
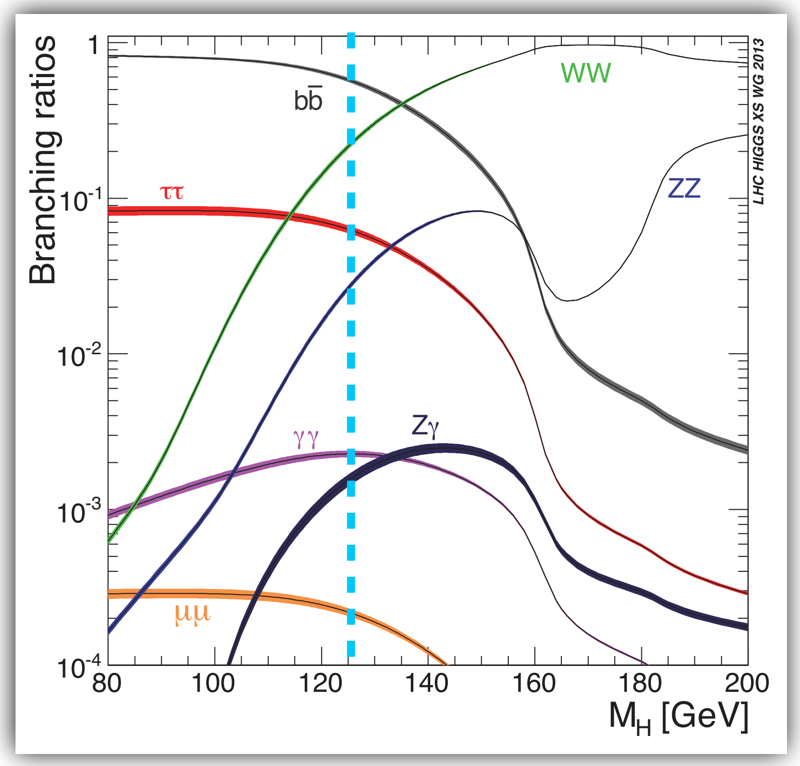
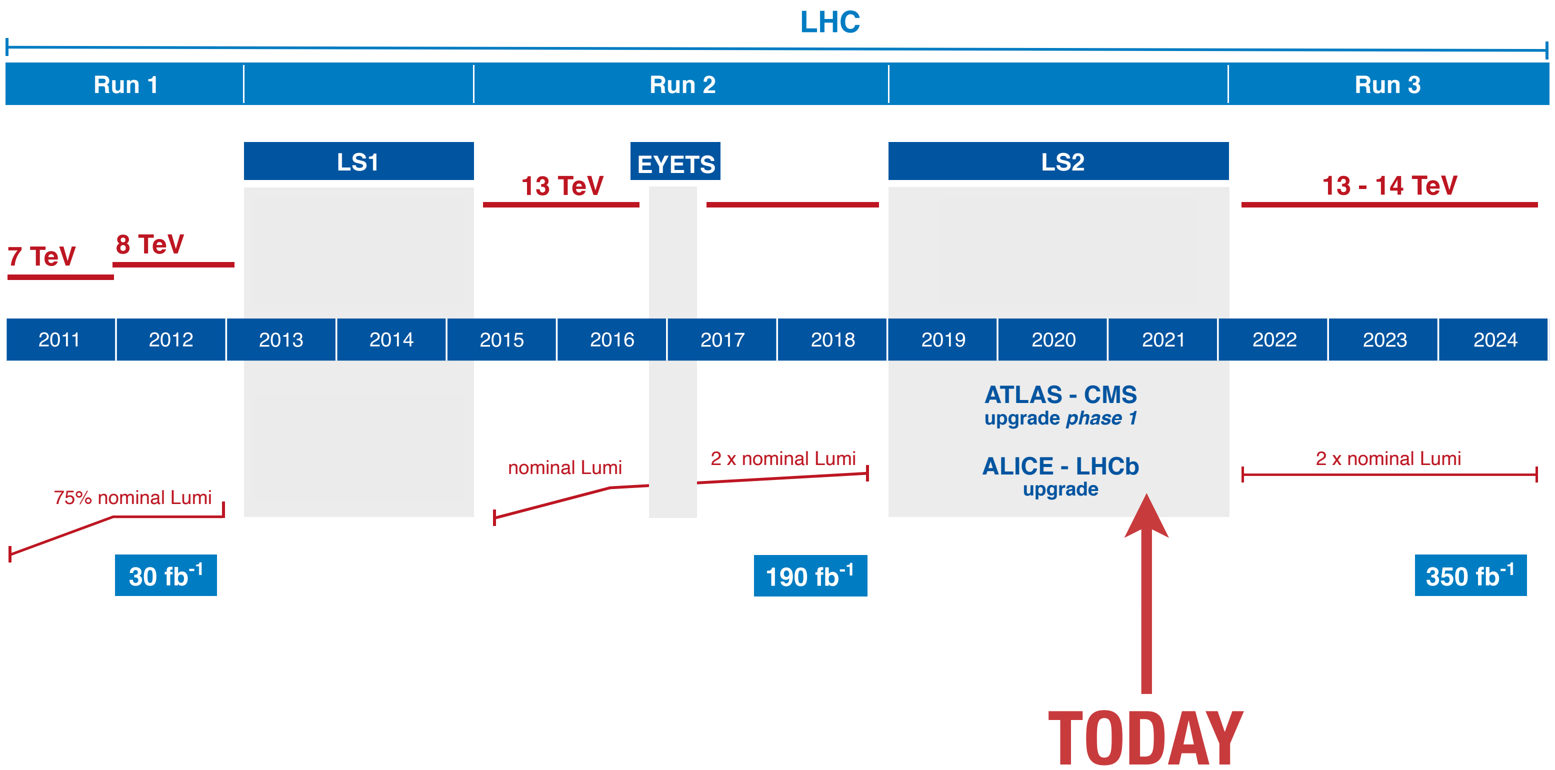


Where we are …

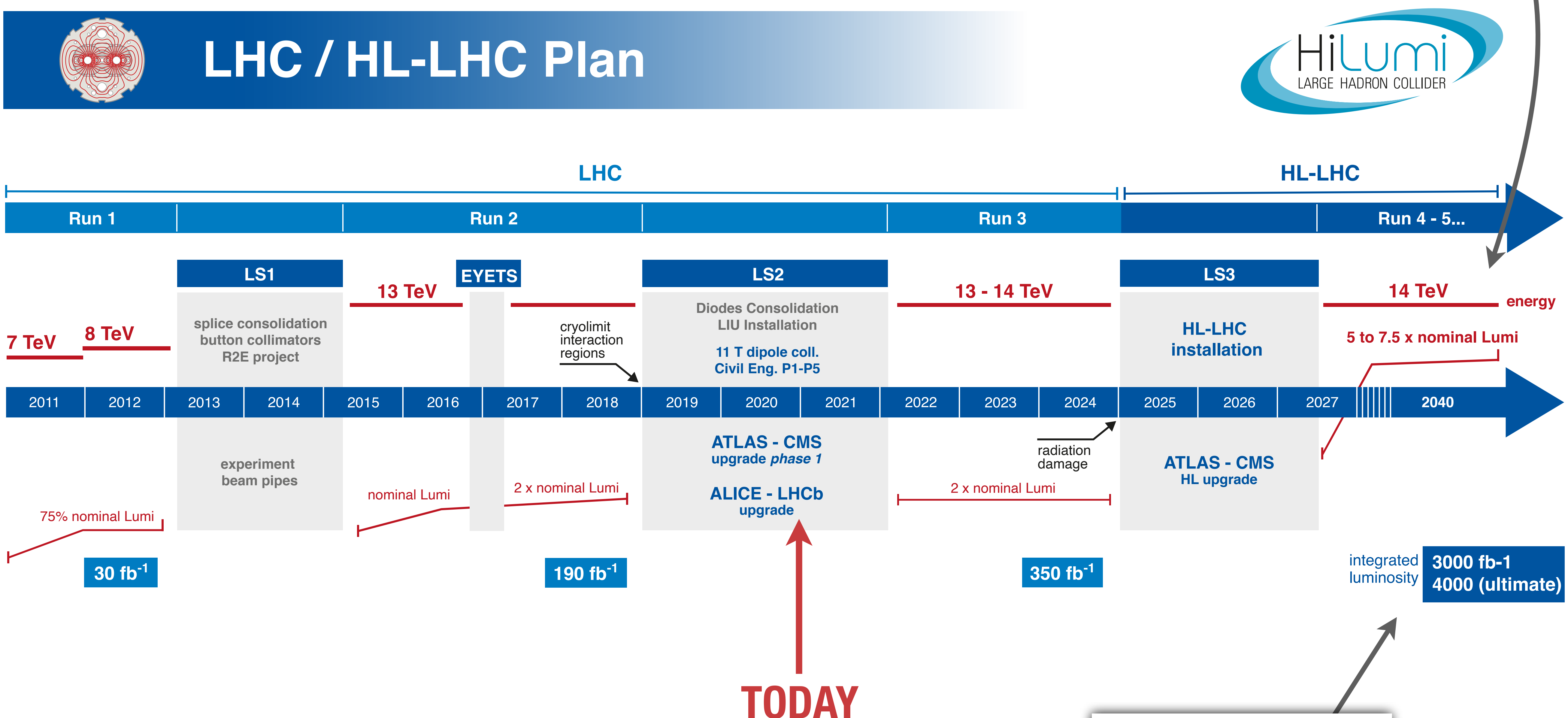
- SM Higgs triumph
- Precision tests of EW / top quark sectors
- New physics searches
  - *Directly* produce new massive particles
  - *Indirectly* study rare process & search for deviations





… where we are going

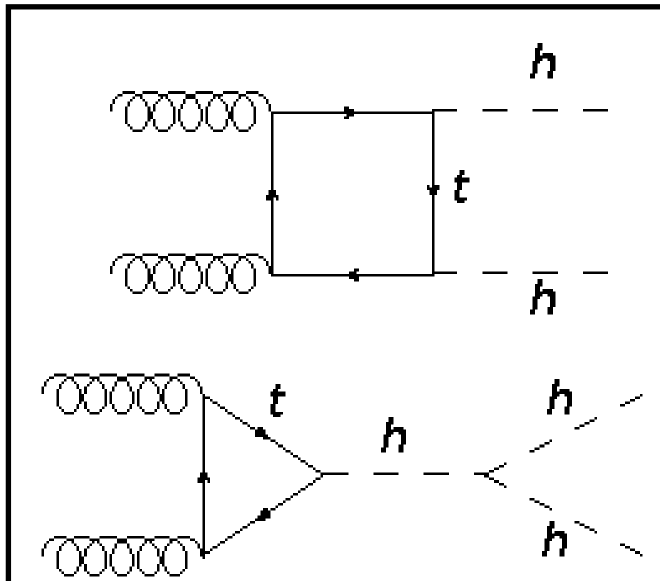
Peak instantaneous luminosity:
$\sim 7.5\times10^{34}$ cm^{-2}s^{-1}



Integrated luminosity:
3000-4000 fb^{-1}

Motivation

- **Higgs boson**
  - Precision measurements of properties & couplings
  - Rare decays
  - Measure Higgs self-coupling via di-Higgs production
    - *Probe shape of Higgs potential & nature of EWSB*



HH production

Table 57: Significance in standard deviations of the individual channels as well as their combination.

	Statistical-only		**Statistical + Systematic**	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

CERN-LPCC-2018-04

significance with $3000\ fb^{-1}$ / exp. !

Motivation

- **Higgs boson**
  - Precision measurements of properties & couplings
  - Rare decays
  - Measure Higgs self-coupling via di-Higgs production
    - *Probe shape of Higgs potential & nature of EWSB*

- **Extend discovery reach** in searches for beyond-SM scenarios

Motivation

- **Higgs boson**
  - Precision measurements of properties & couplings
  - Rare decays
  - Measure Higgs self-coupling via di-Higgs production
    - *Probe shape of Higgs potential & nature of EWSB*
- **Extend discovery reach** in searches for beyond-SM scenarios
- Search for **rare SM processes**, possibly enhanced by BSM physics
  - e.g. probe flavor-changing neutral currents, highly suppressed in SM

$\mathcal{B}$ limit at 95%C.L.	HL-LHC $3\ \mathrm{ab}^{-1}$, 14 TeV	Run-II (36/fb)
$t \to gu$	3.8×10^{-6}	2×10^{-5}
$t \to gc$	32.1×10^{-6}	4×10^{-4}
$t \to Zq$	$2.4 - 5.8 \times 10^{-5}$	$1.7\text{-}2.4 \times 10^{-4}$
$t \to \gamma u$	8.6×10^{-6}	$1.3\ 10^{-4}$
$t \to \gamma c$	7.4×10^{-5}	$2.0\ 10^{-3}$
$t \to Hq$	10^{-4}	$1.1\ 10^{-3}$

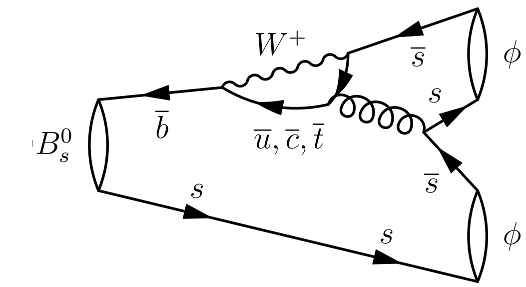
~order of magnitude improvement

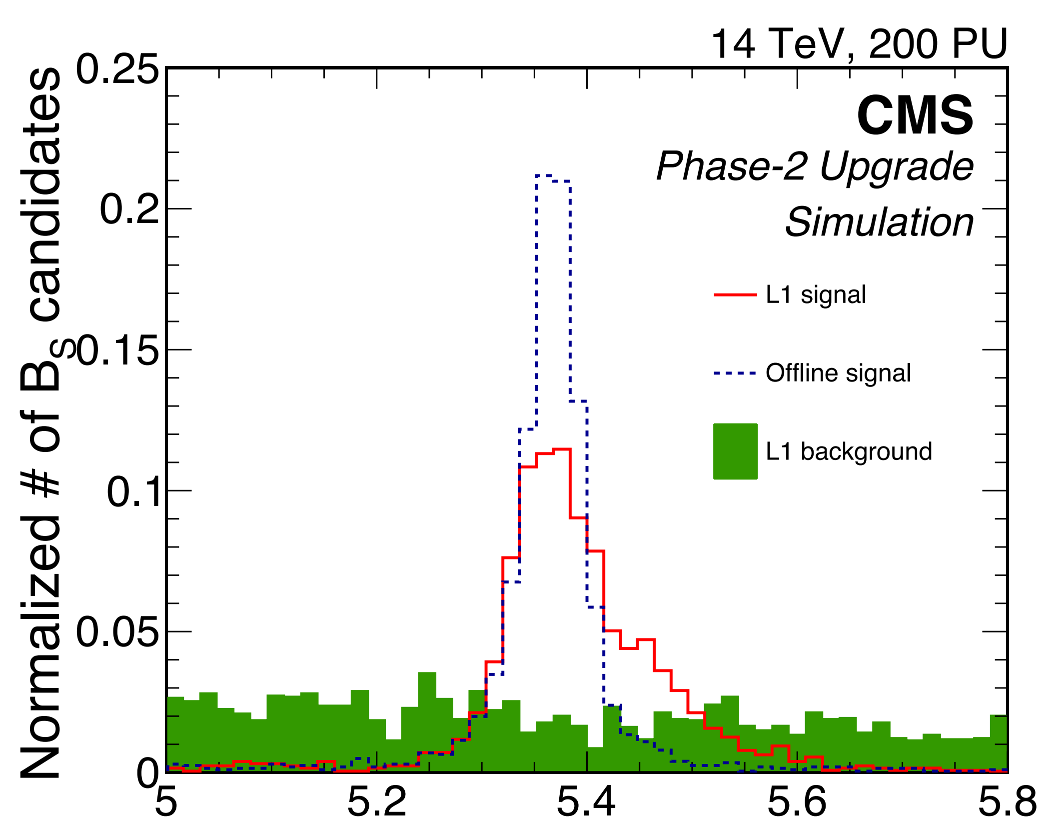
CERN-LPCC-2018-03

Motivation

- Probe processes with new sensitivity thanks to upgraded detector systems

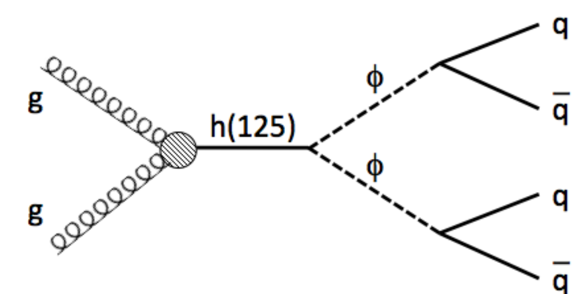
- $\underline{B^0_s \rightarrow \phi\phi \rightarrow 4K:}$ forbidden at tree-level in SM, probe new physics through loop contributions from new heavy particles **<= enabled by track trigger**





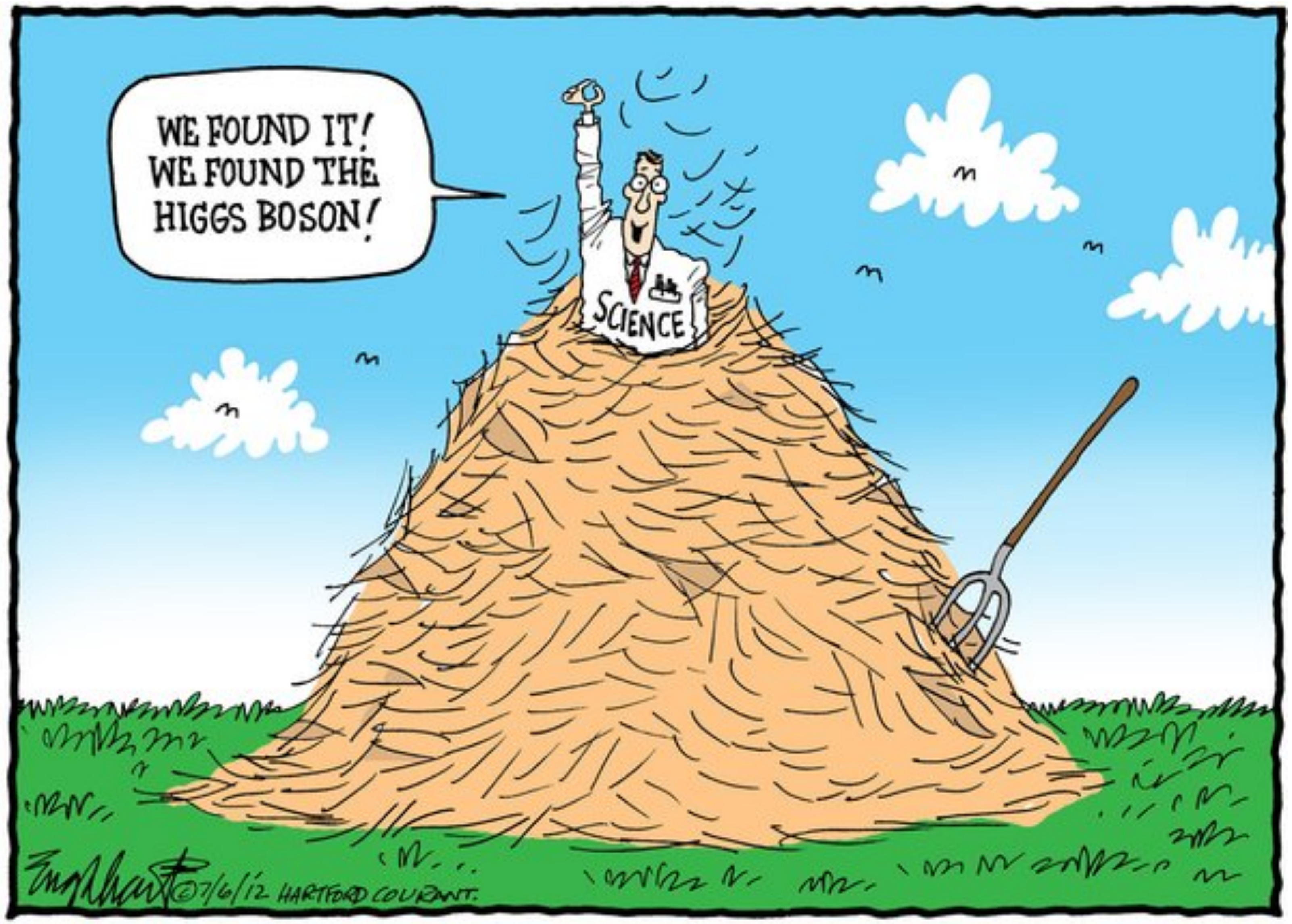
CMS-TDR-014

- Exotic Higgs decays involving new light scalars decaying to jets
  - prompt decays overwhelmed by background processes
  - long-lived => unexplored territory possibly **enabled by track trigger**



CERN-LPCC-2018-04

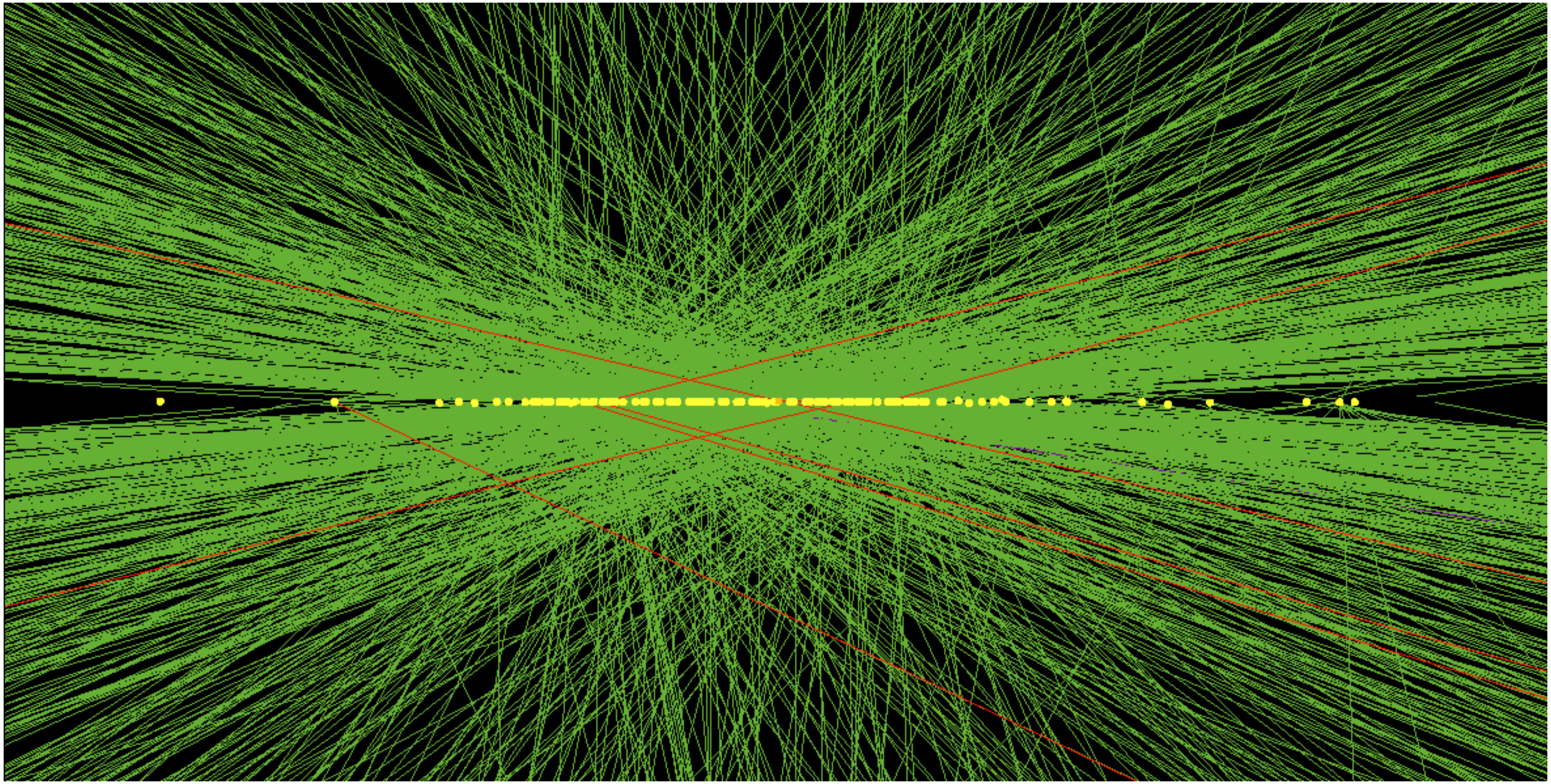
To study the physics processes of interest, we have to efficiently identify the collisions where they occur (trigger!) …



… which is an even greater challenge at the HL-LHC!

The price for high luminosity

Simulated event display with average pileup of 140

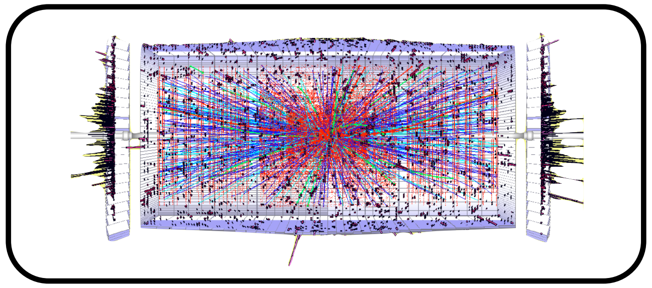


PILEUP: number of overlapping interactions (expected average ~200)

<u>Particularly challenging for trigger system!</u>

Trigger system: **CURRENT**

Which collision events to read out & store for offline analysis?



L1 hardware-based trigger

muons **calorimeters**

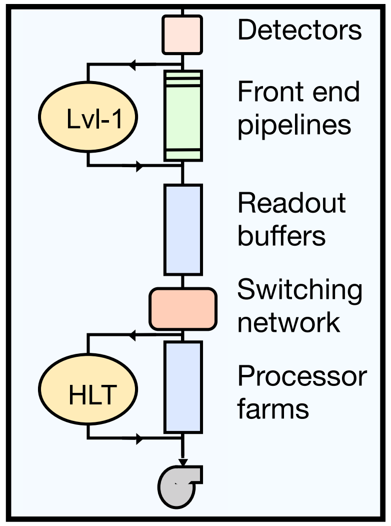
High-level software-based trigger ("HLT")
full detector granularity

40 MHz

"latency"
~4 μs

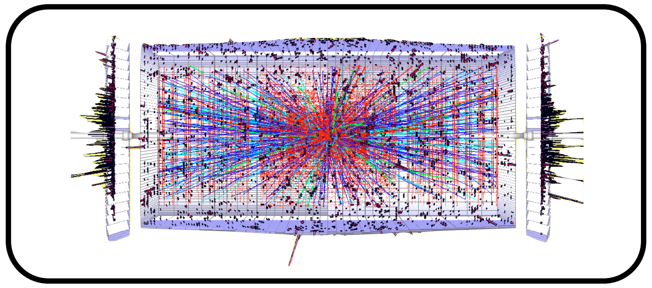
L1 output: 100 kHz

HLT output: ~1 kHz



Trigger system: **HL-LHC**

Which collision events to read out & store for offline analysis?



L1 hardware-based trigger

TRACKS | muons | calorimeters

High-level software-based trigger ("HLT")
full detector granularity

40 MHz

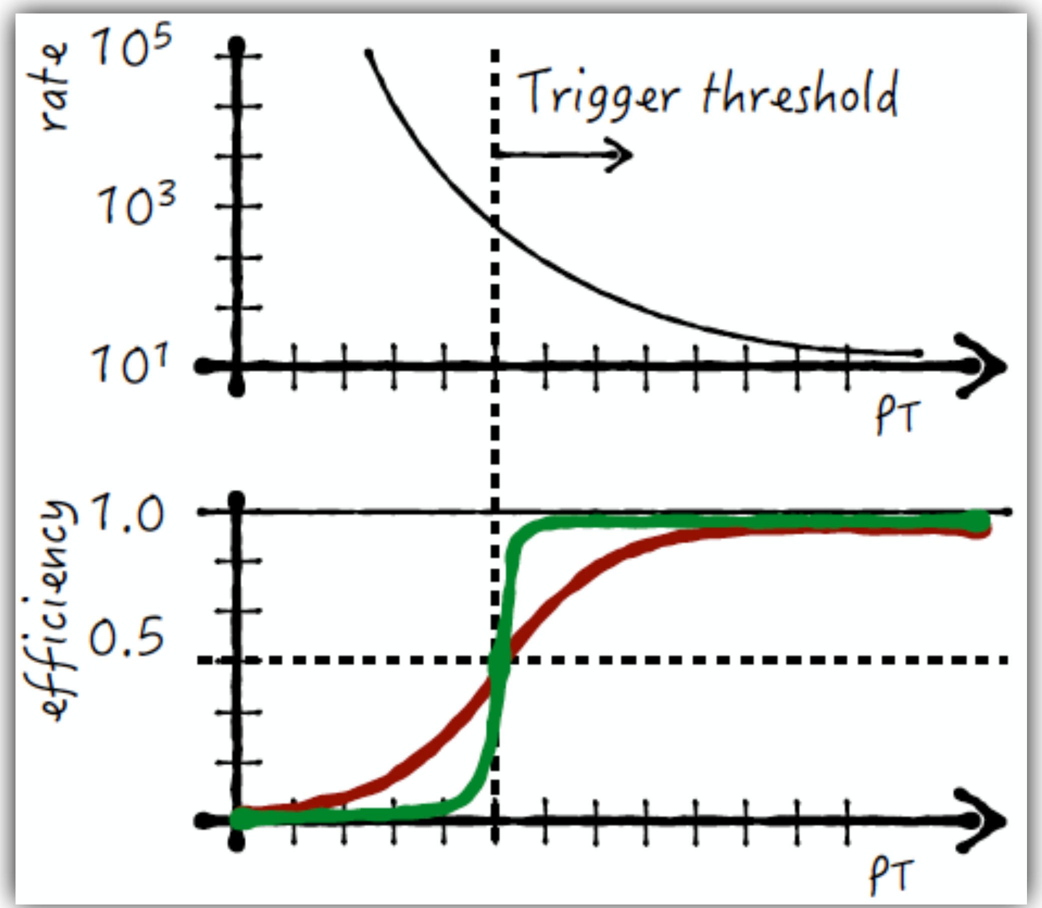
~~~4 μs~~ → 12.5 μs

L1 output: ~~100 kHz~~ → 750 kHz

HLT output: ~~~1 kHz~~ → 7.5 kHz
~~~

Why tracking @ L1?

- At HL-LHC, event rates would exceed what can be read out at L1
- *Physics goals* rely on excellent detector performance & trigger capabilities
- Typical handle to control event rates at trigger level -- momentum thresholds



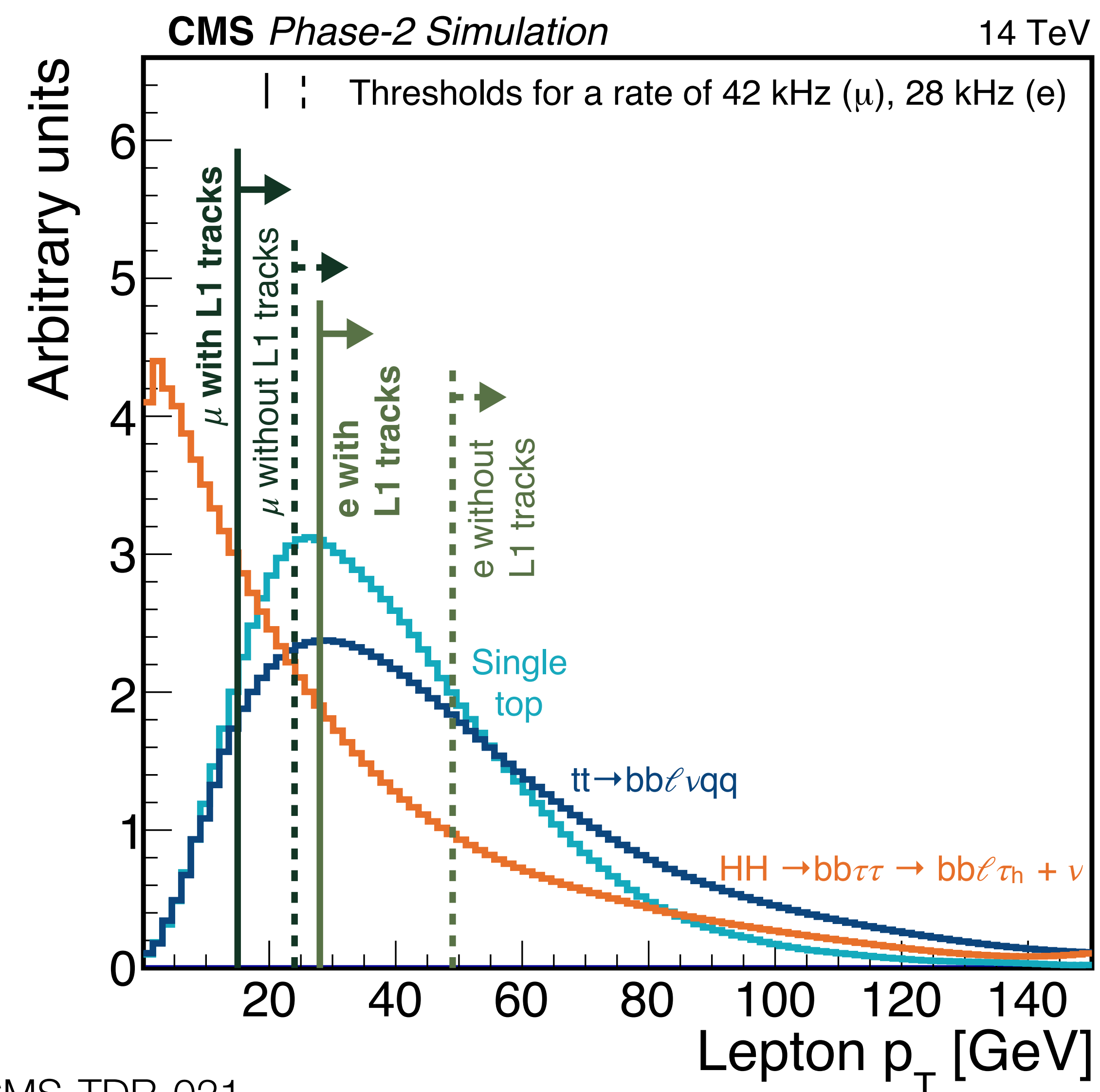
Increasing thresholds limits physics potential + alone insufficient!

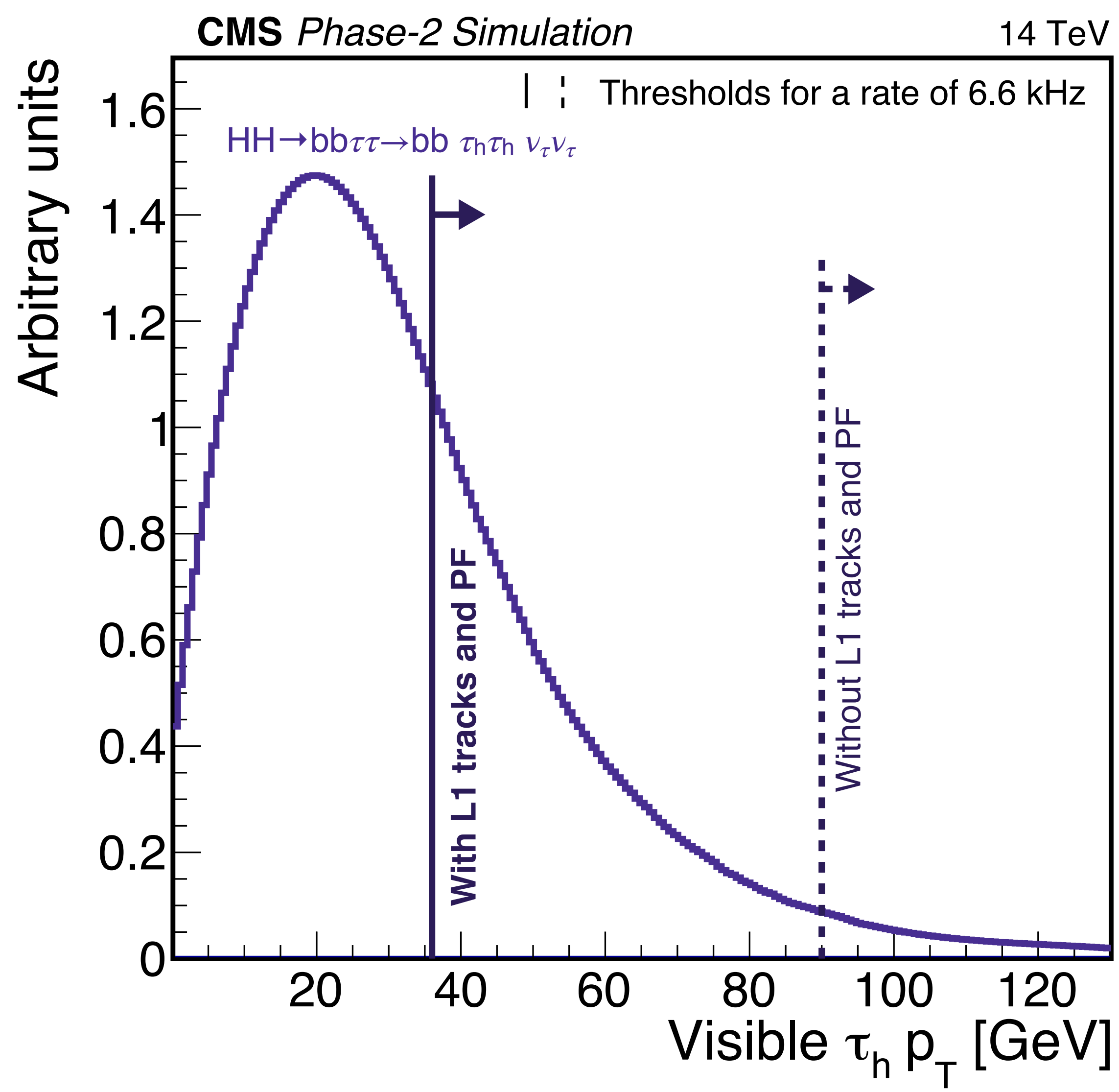
⇒ Tracking @ L1

Using tracking @ L1

Example: Charged leptons

Improve p_T measurement & identification => significant rate reductions



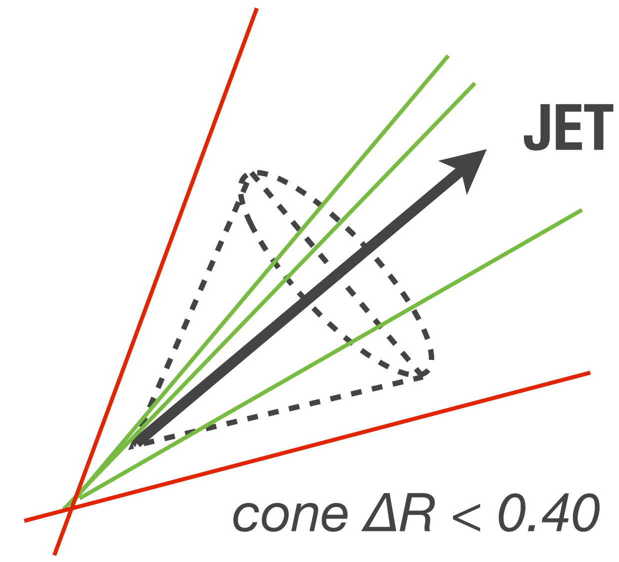


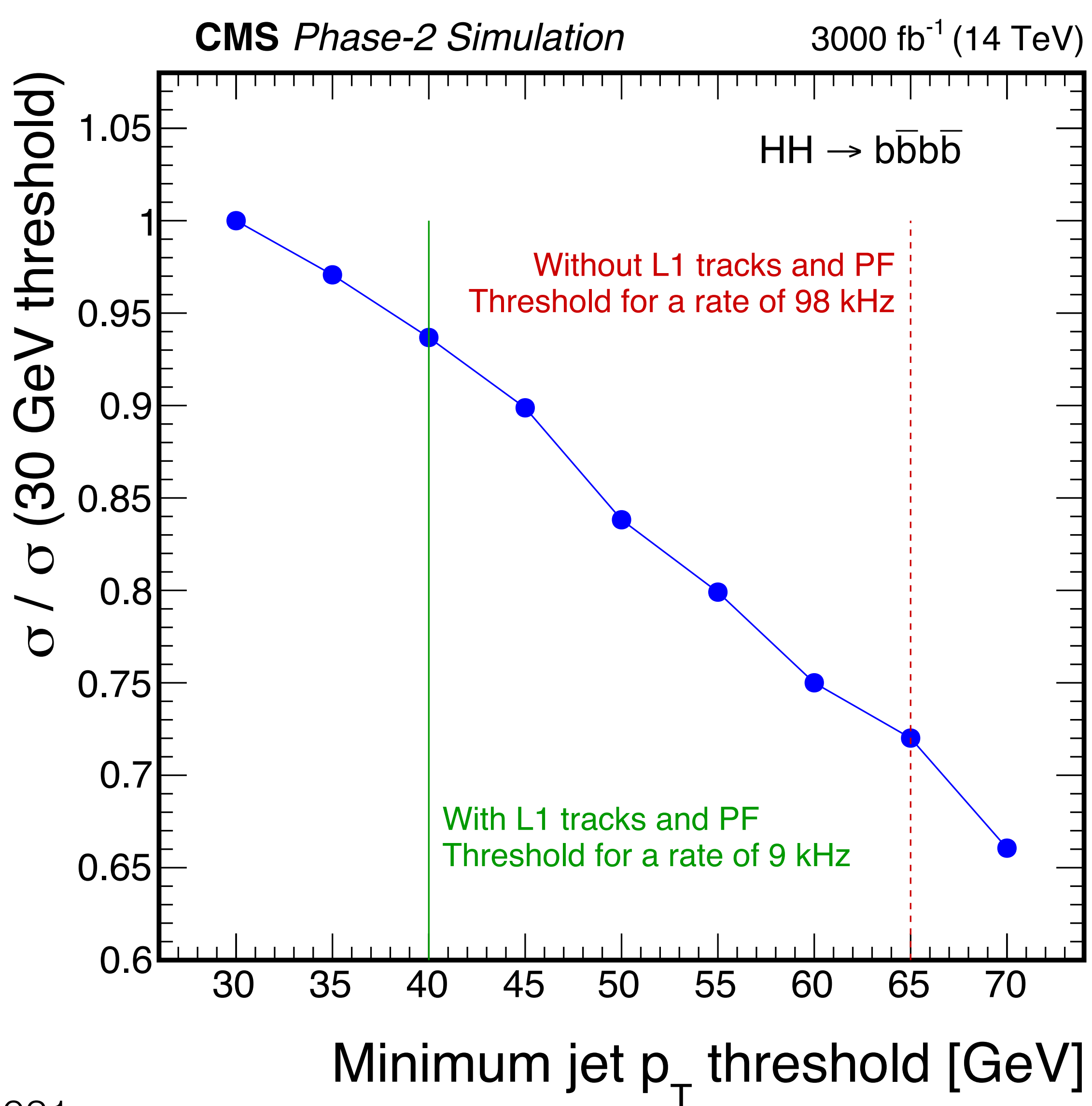
CMS-TDR-021

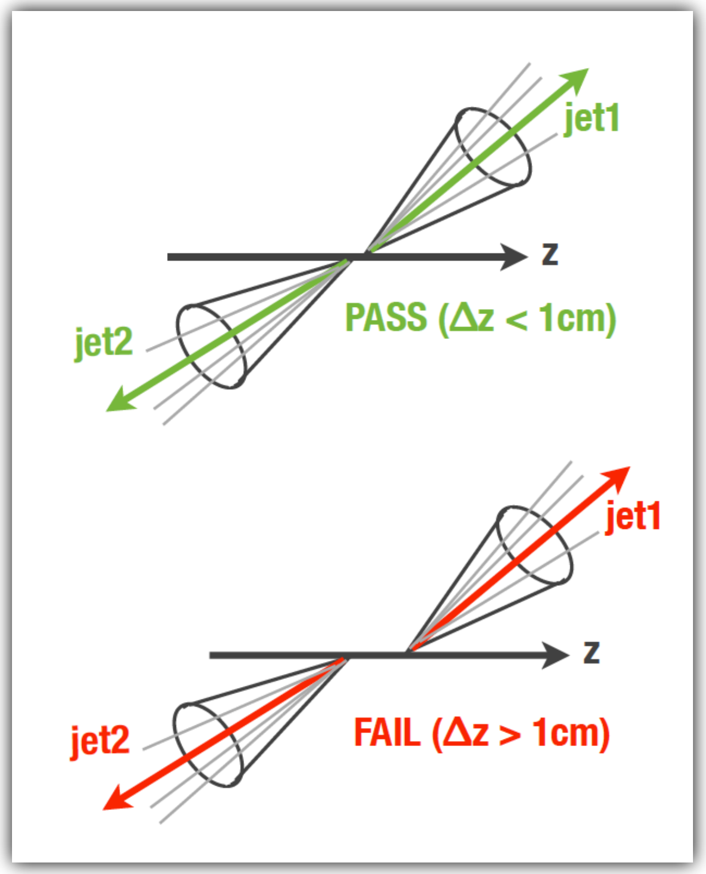
Using tracking @ L1

Example: *Jets*

Using tracks allows associating jets to common vertex to reject pileup, run lightweight PF @ L1



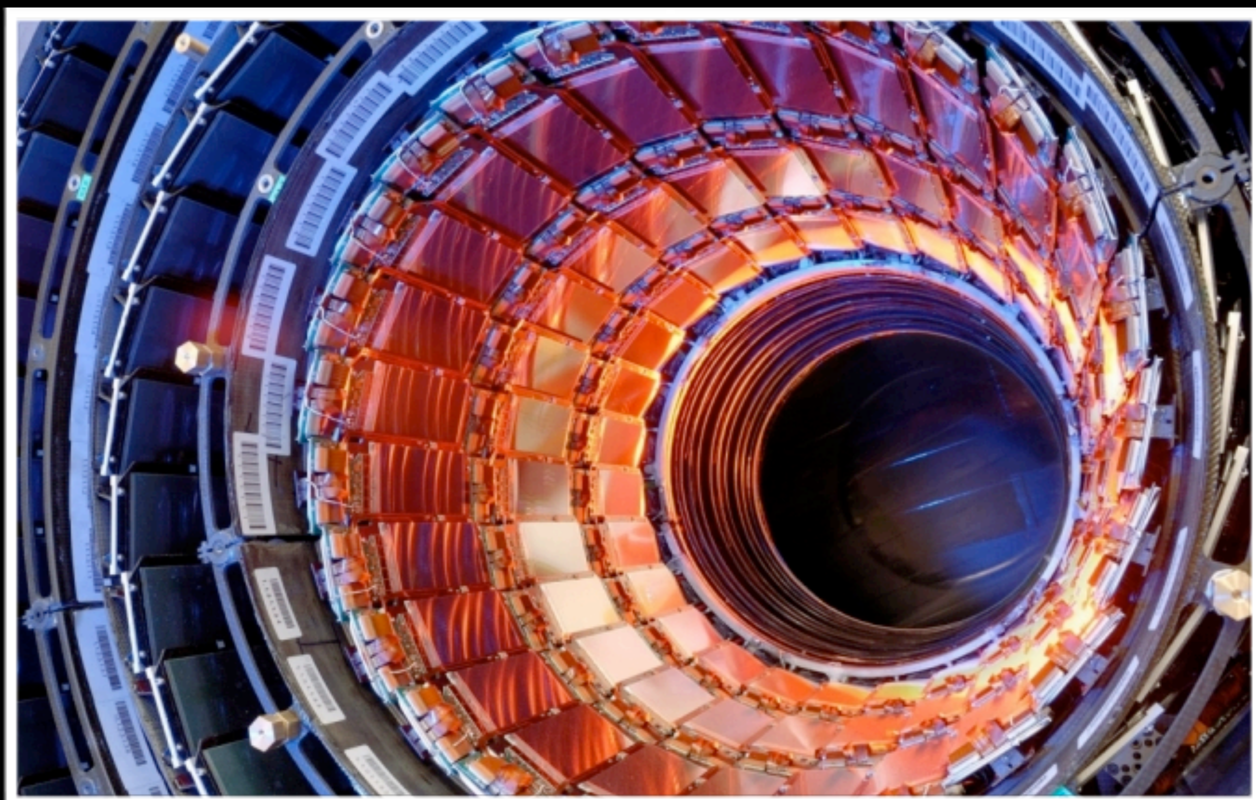


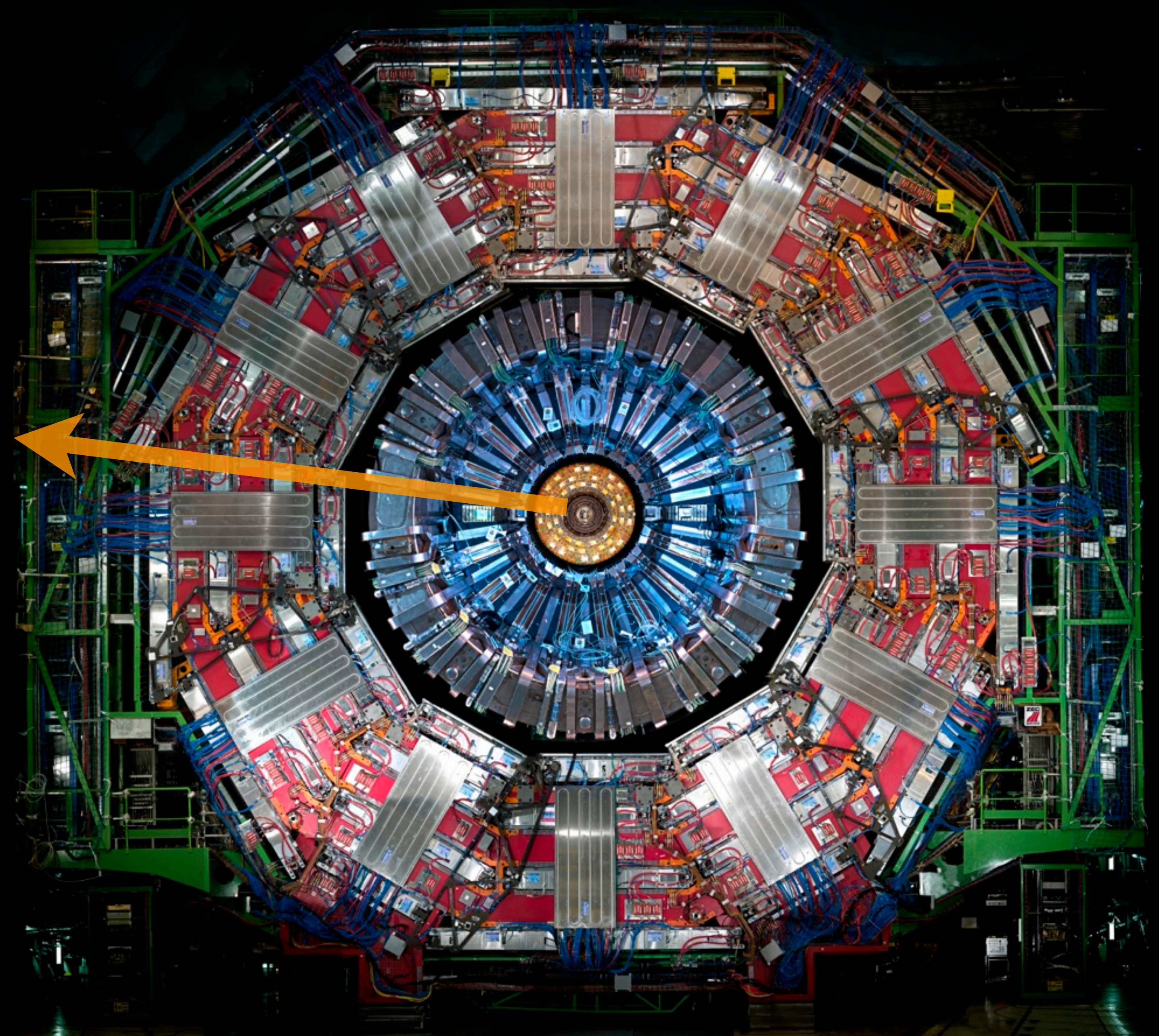


CMS-TDR-021

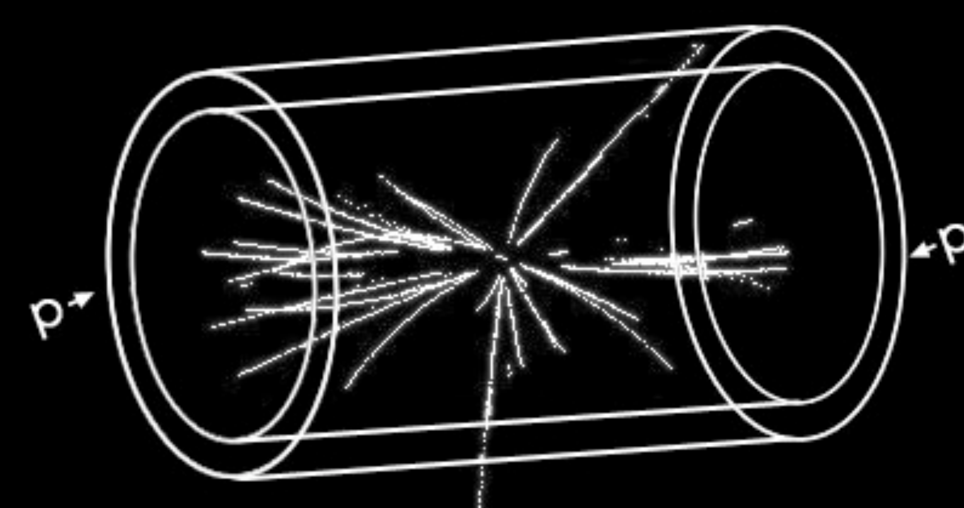
... how?

CMS tracker



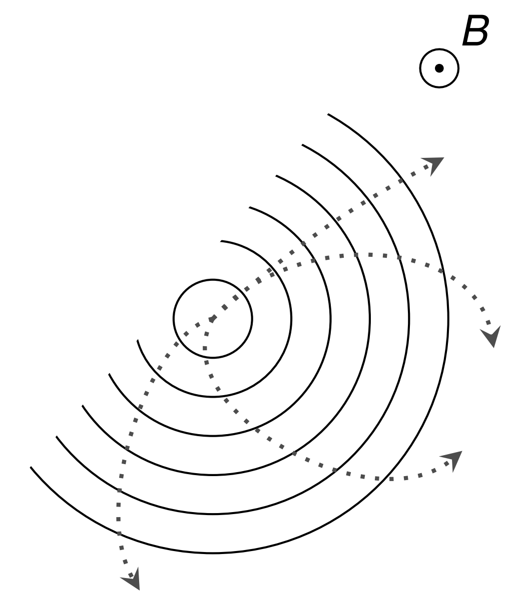


Finely segmented silicon sensors enable charged particles to be traced and, thanks to the magnetic field, for their momenta to be measured.
They also reveal the positions at which long-lived unstable particles decay.



CMS tracker for HL-LHC

- New all silicon outer tracker + inner pixel detector
  - Increased granularity for HL-LHC occupancies
  - Tracking in hardware trigger, identify particles with $p_T > 2$ GeV



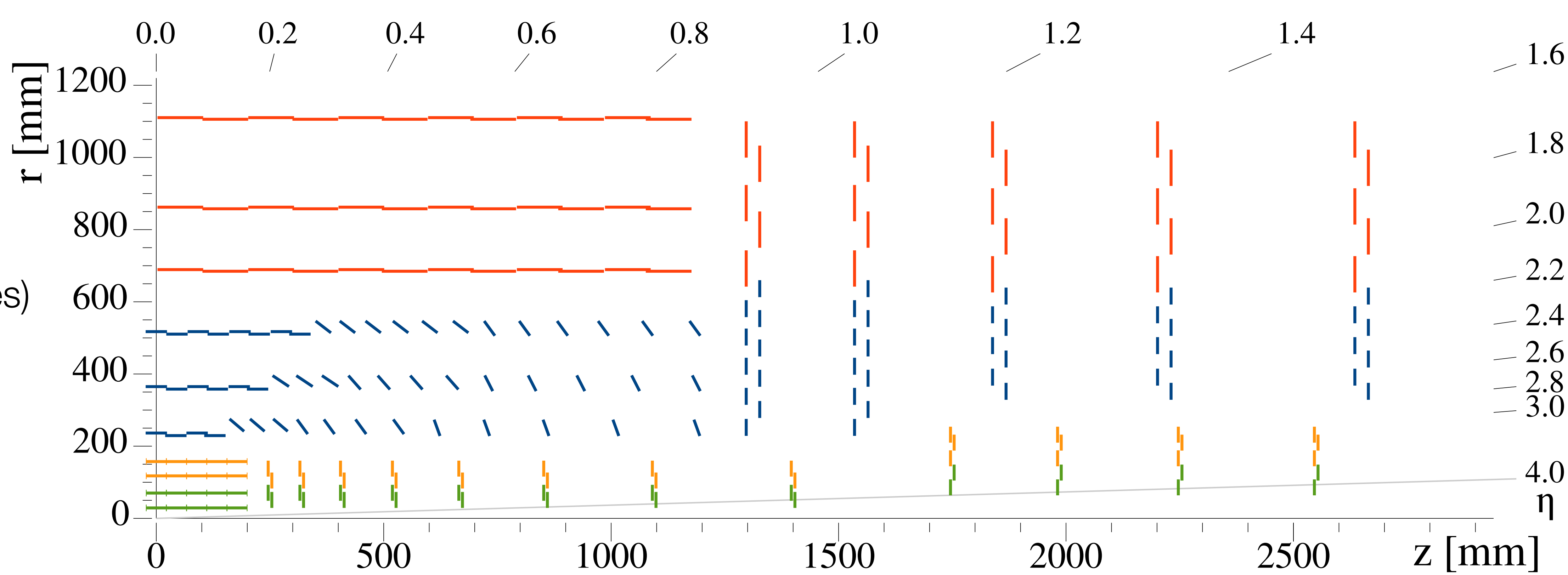
Outer Tracker

(**PS** vs **2S** modules)

Inner Pixel

(**1x2** vs **2x2** chip modules)

=> not used in L1



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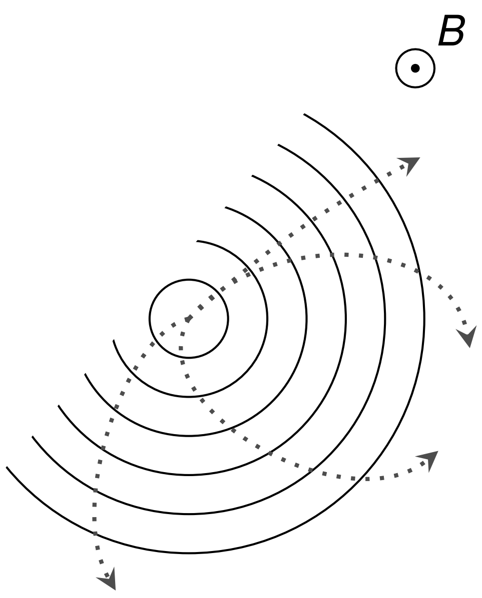

Outer Tracker

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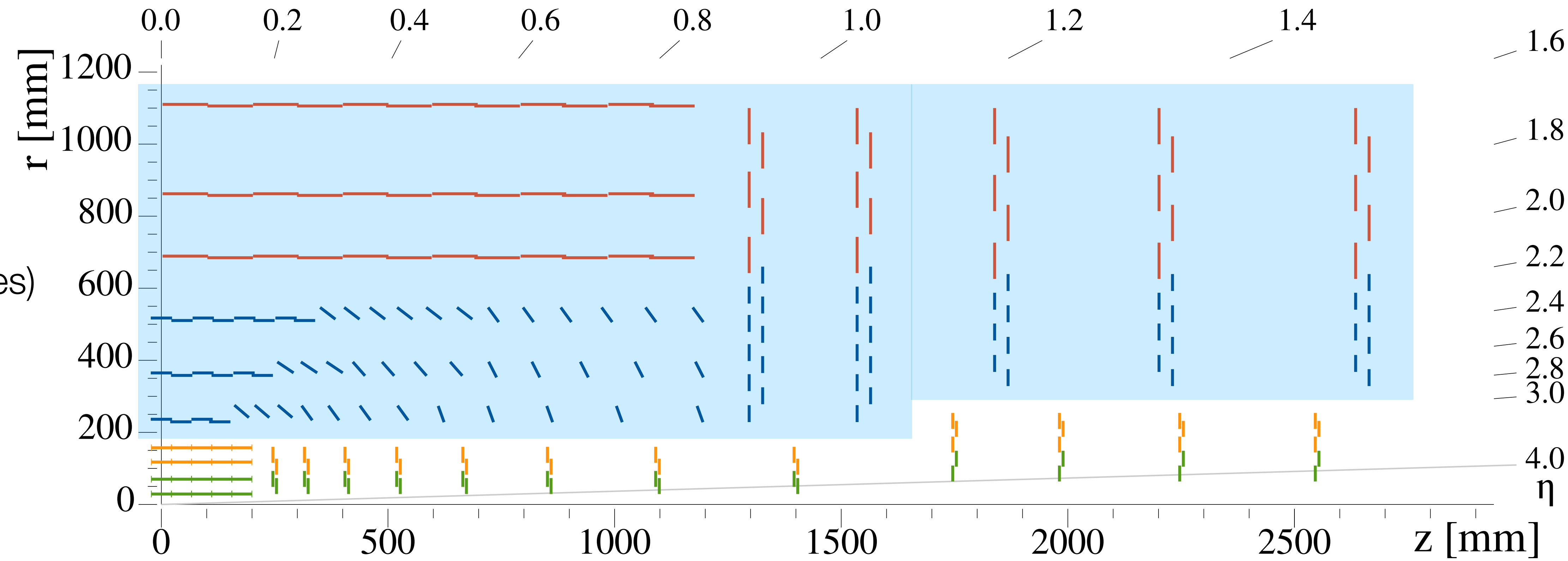
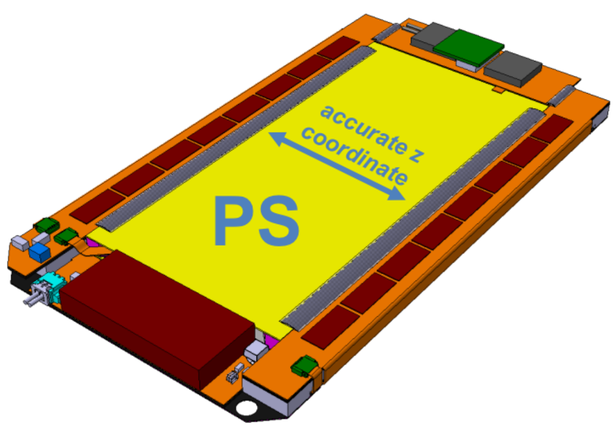


p_T module concept

- Modules provide p_T discrimination in front-end electronics through hit correlations between two closely spaced sensors

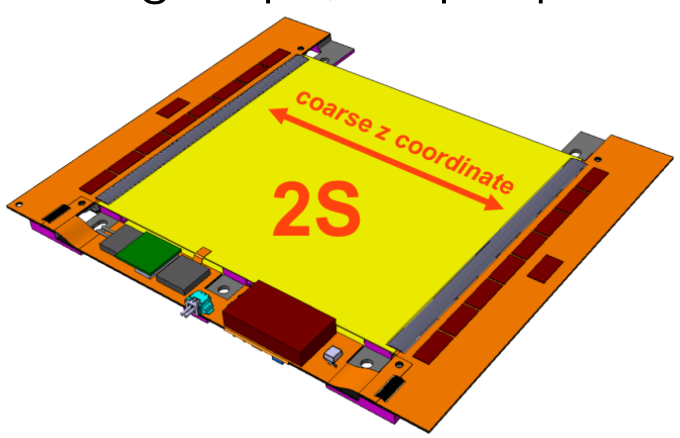
PS modules (pixel-strip)

- Top sensor: 2x2.5 cm strips, 100 μm pitch
- Bottom sensor: 1.5 mm x 100 μm pixels

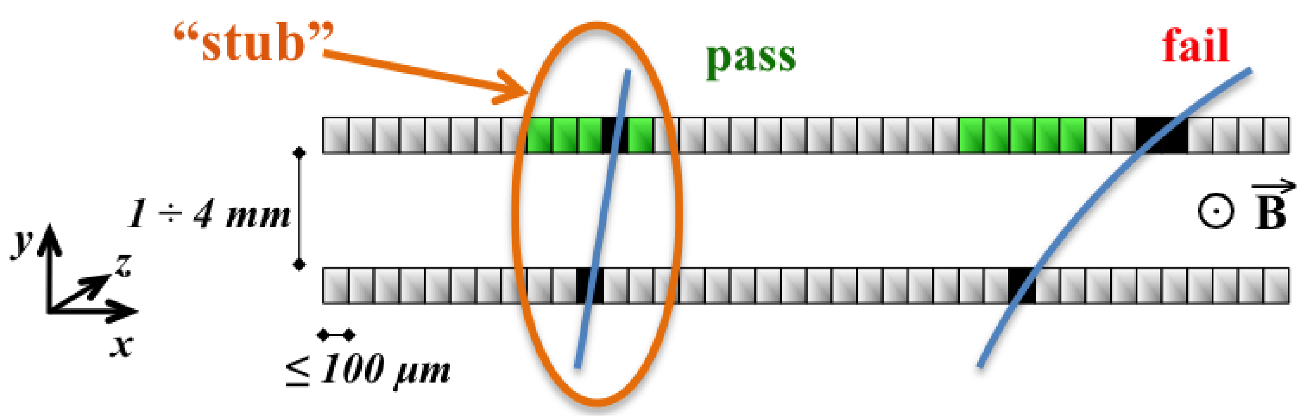


2S modules (strip-strip)

- Strip sensors 10x10 cm^2
- 2x5 cm long strips, 90 μm pitch



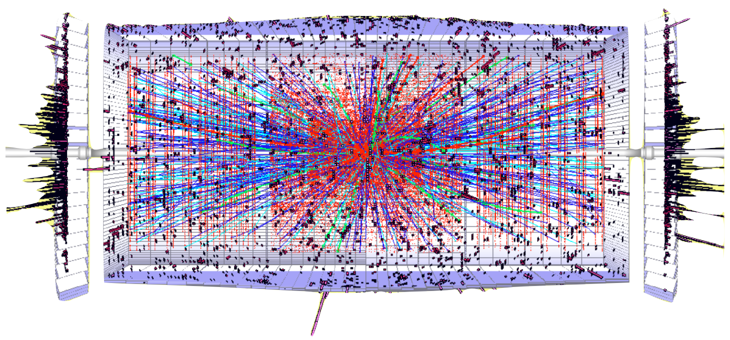
- **Stubs:** Correlated pairs of clusters, consistent with ≥2 GeV track
  - Data reduction at trigger readout (by factor 10-20)
  - *Stubs form input to track finding*



Tracking @ L1

- Reconstruct trajectories of charged particles with p_T > 2 GeV
  - At HL-LHC, expect ~7000 charged particles / BX, ~200 trajectories with p_T > 2 GeV

BX = bunch crossing

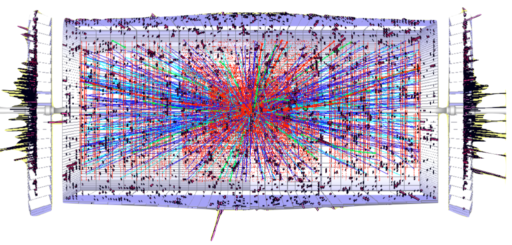


- Challenges
  - *Combinatorics* from ~15K input stubs / BX
  - *Data volumes* of up to ~30 Tbits/s
  - *L1 trigger decision within 12.5 μs, ~4 μs available for track finding*
    - ***A track trigger operating at 40 MHz with <10 μs latency has never been built***

- Utilize extensive parallel processing to tackle above challenges

Track trigger strategy

Data transfer (~50 Tbs)



Δt = 0 → **Data formatting** → **Pattern recognition** → **Track fitting + duplicate removal** → **Δt = 4 μs**

Output tracks to L1 trigger

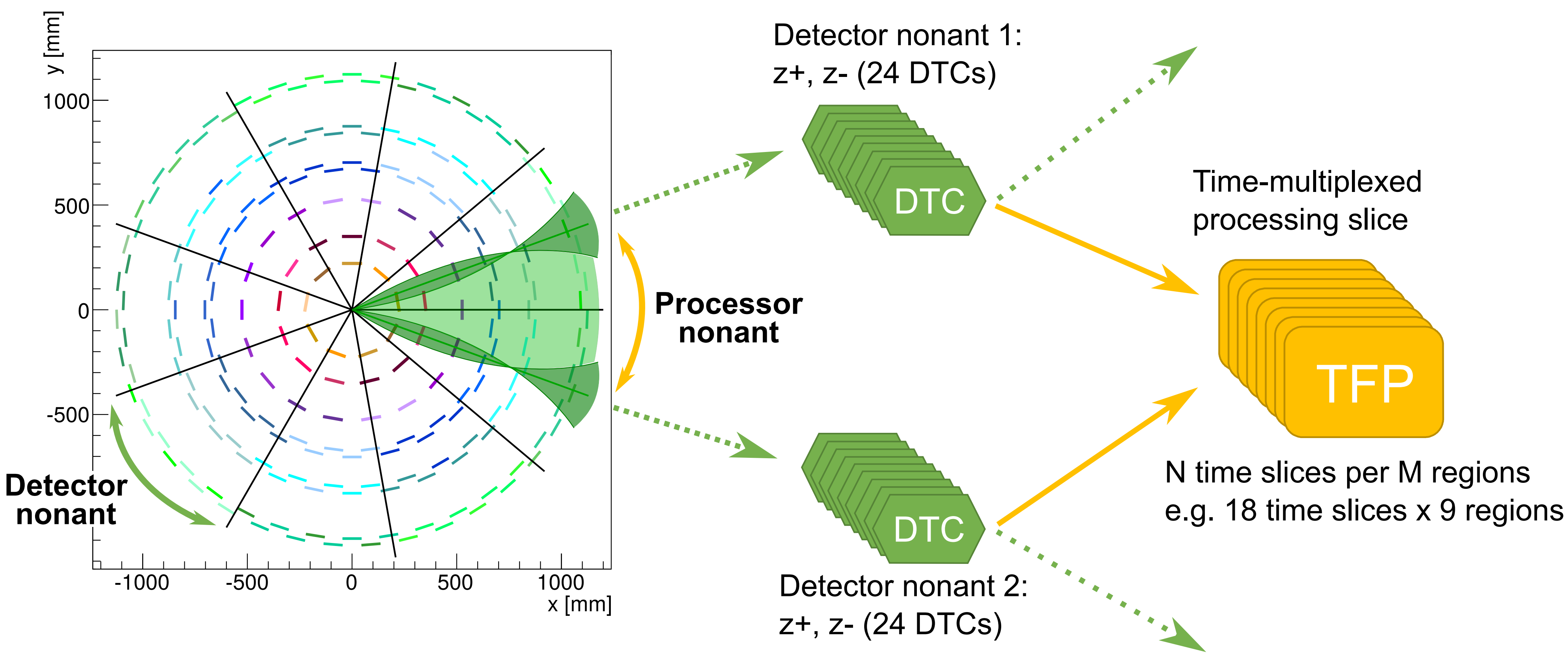
- Parallelization
  - Divide tracker in segments in ϕ
  - Time-multiplexed systems -- process several BX simultaneously

- Fully FPGA-based system
  - Off-the-shelf hardware
  - Programmable => flexibility

FPGA = Field Programmable Gate Array

System architecture

- Outer tracker divided in 9 ϕ sectors, time multiplexing factor of 18



Outer tracker

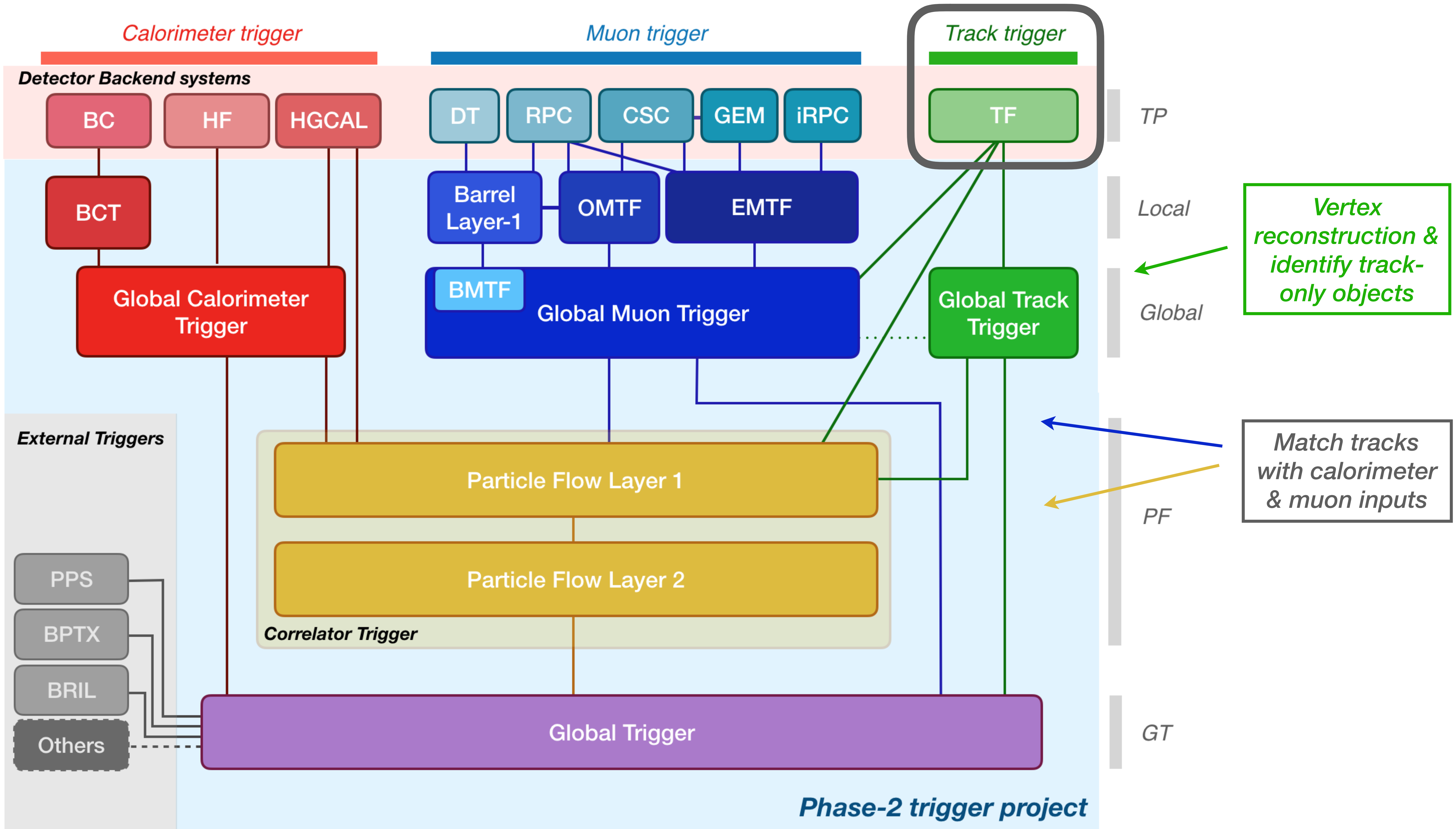
DTC = Data Trigger & Control boards

TFP = Track Finding Processor boards

DTCs perform stub pre-processing & distribute stubs to TFP boards (+ communicates with detector modules, forwards full event data upon L1 accept, etc.)

- new event received every 450 ns
- total system: 162 TFP boards

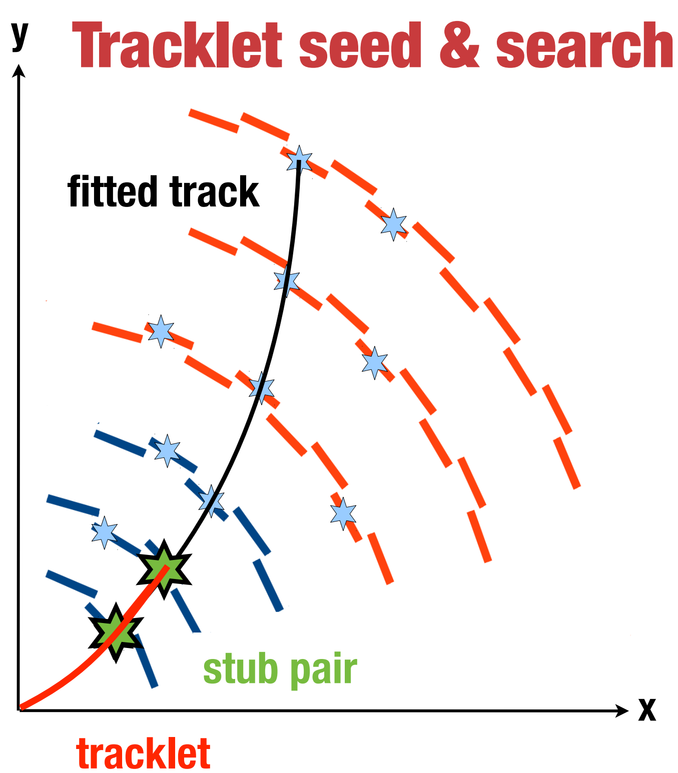
L1 trigger architecture



Algorithm overview

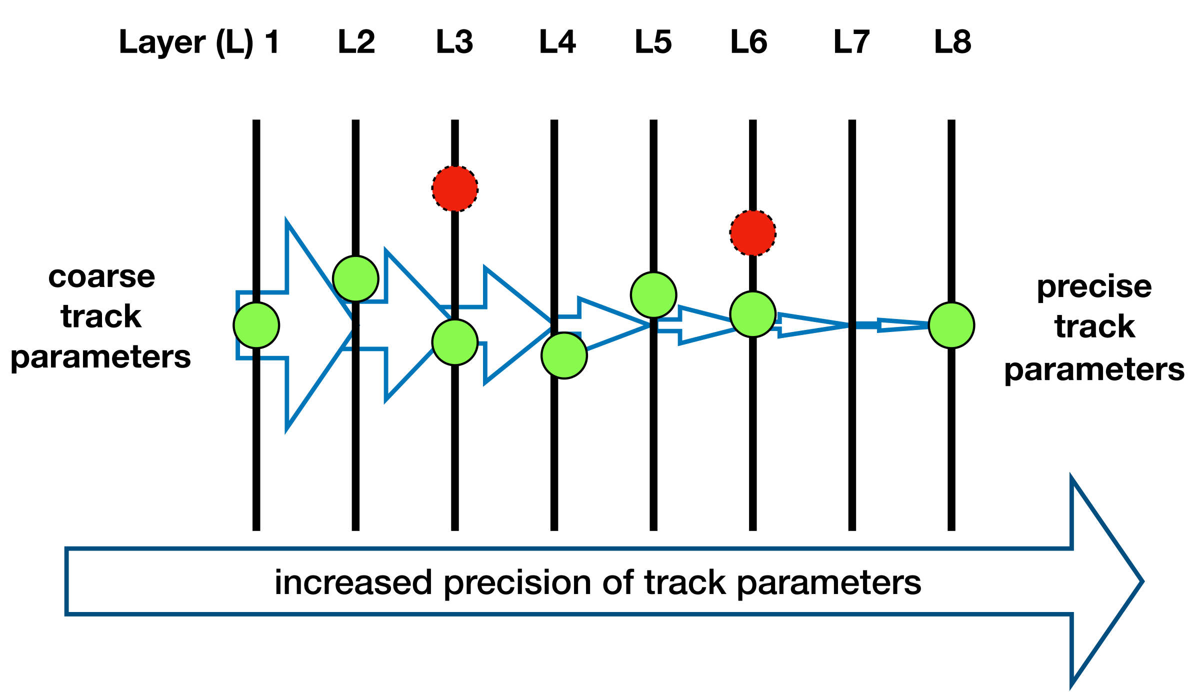
- Different algorithms have been explored at CMS for L1 track finding
  - Similar performance & demonstrated feasibility, detailed in Phase-2 Tracker TDR
- *Hybrid* algorithm combines ideas from legacy algorithms
  - Road-search algorithm based on “tracklet" seeds
  - Kalman Filter used to identify best stub candidates & provide track parameters

Tracklet seed & search



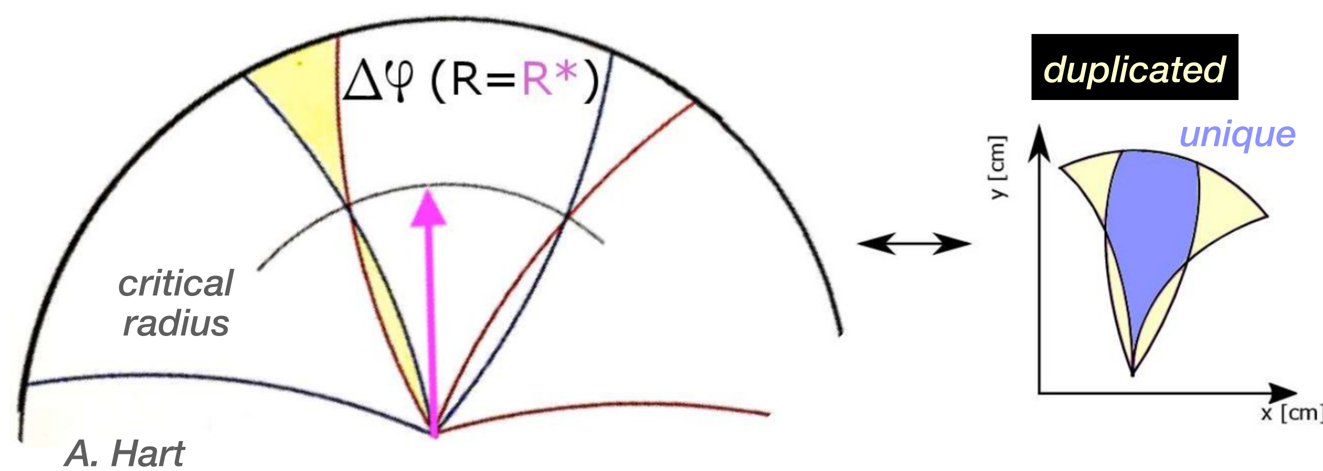
\+

Kalman Filter fitting

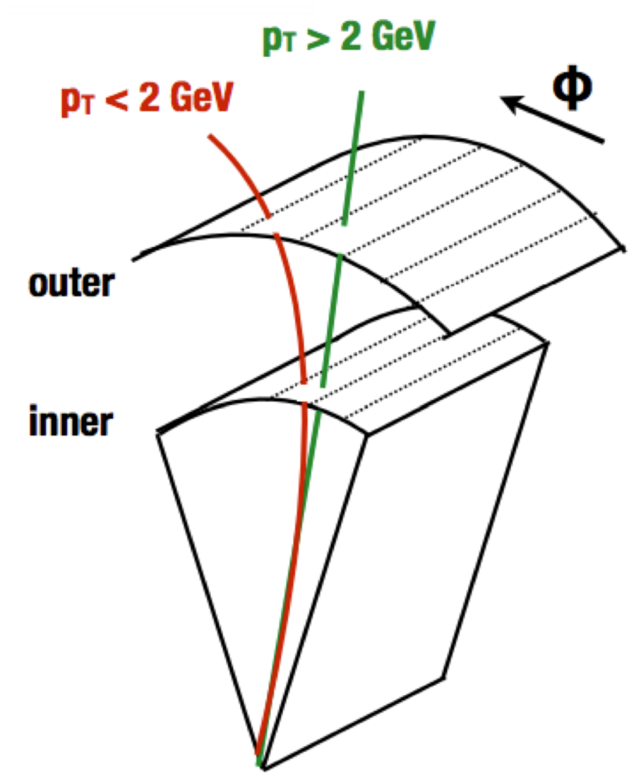


Parallelization

- Extensive parallelization in space & time (time multiplex of 18)
- Detector divided into 9 hourglass-shaped ϕ sectors
    - Hourglass shape prevents tracks above given p_T threshold from entering >1 sector => <u>no cross-sector communication required!</u>
    - Critical radius tuned to minimize overlap of stubs

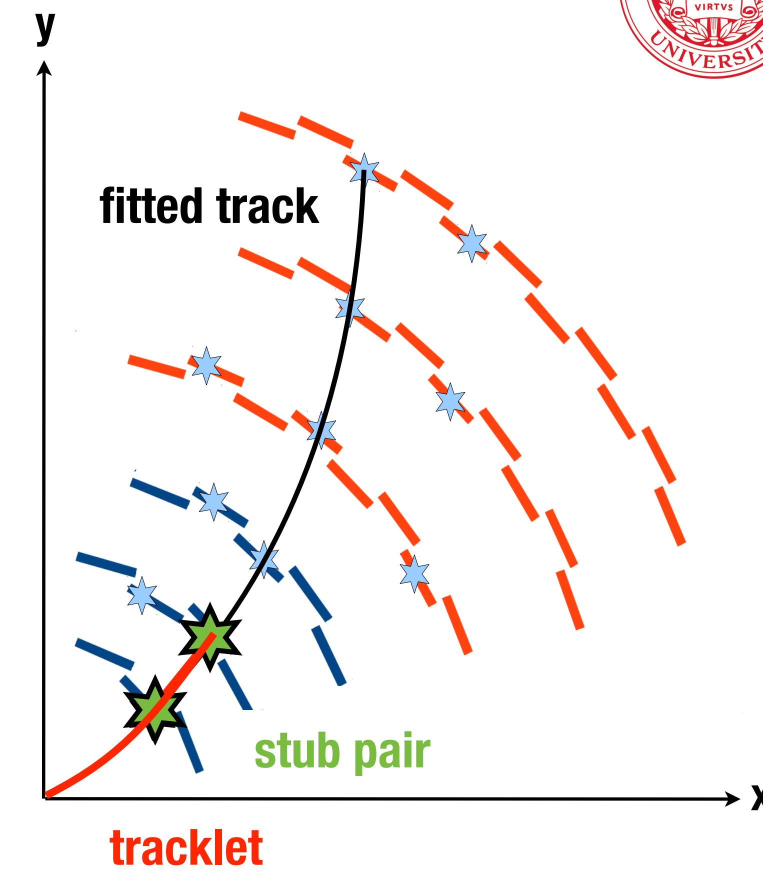


- Within-sector parallel data processing
    - Divide ϕ sector into “virtual modules”
    - Throughout algorithm, only consider combinations compatible with >2 GeV => <u>key to minimize combinatorics & simplify firmware</u>



Seeding & propagation

- **Seed** by forming tracklets
  - Pairs of stubs in adjacent layers/disks
  - Initial tracklet parameters from stubs + beam spot constraint
    - *Only combinations w. $p_T > 2$ GeV kept*

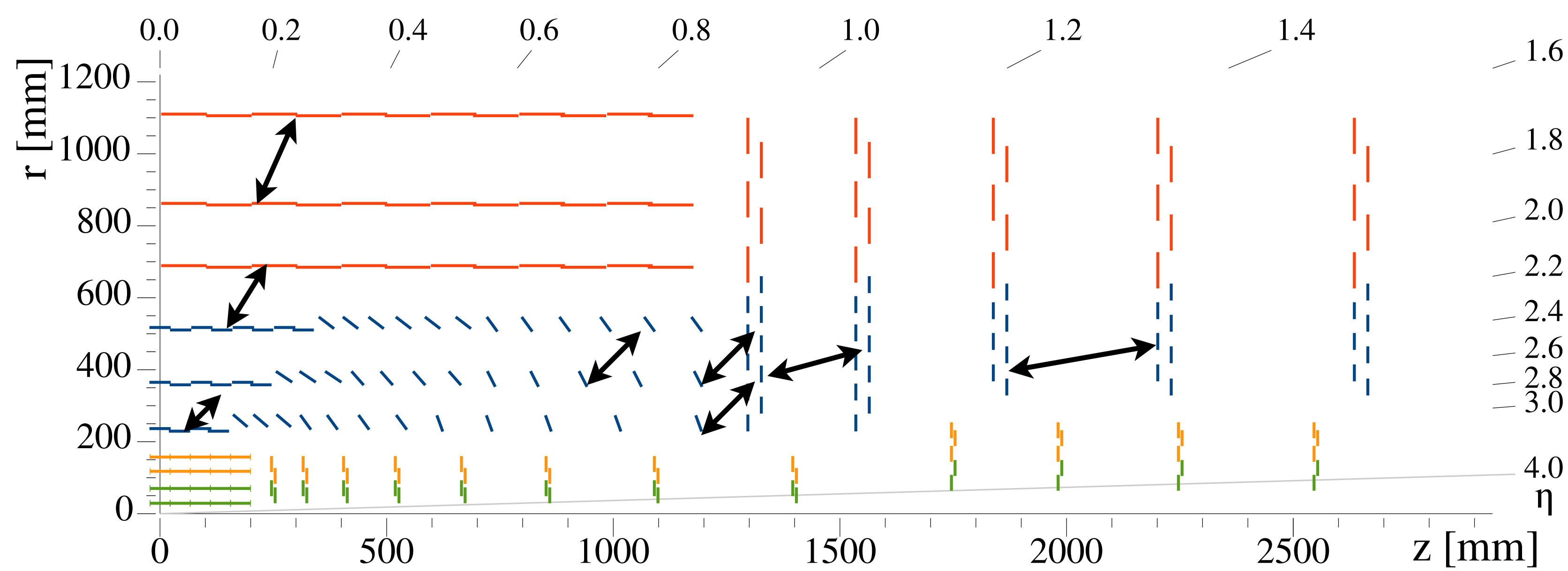


- **Project** to other layers/disks & match with compatible stubs within pre-defined windows
  - Inside-out & outside-in (more than 1 match allowed)
  - Calculate residuals used in fit

Central η:
L1+L2, L3+L4, L5+L6

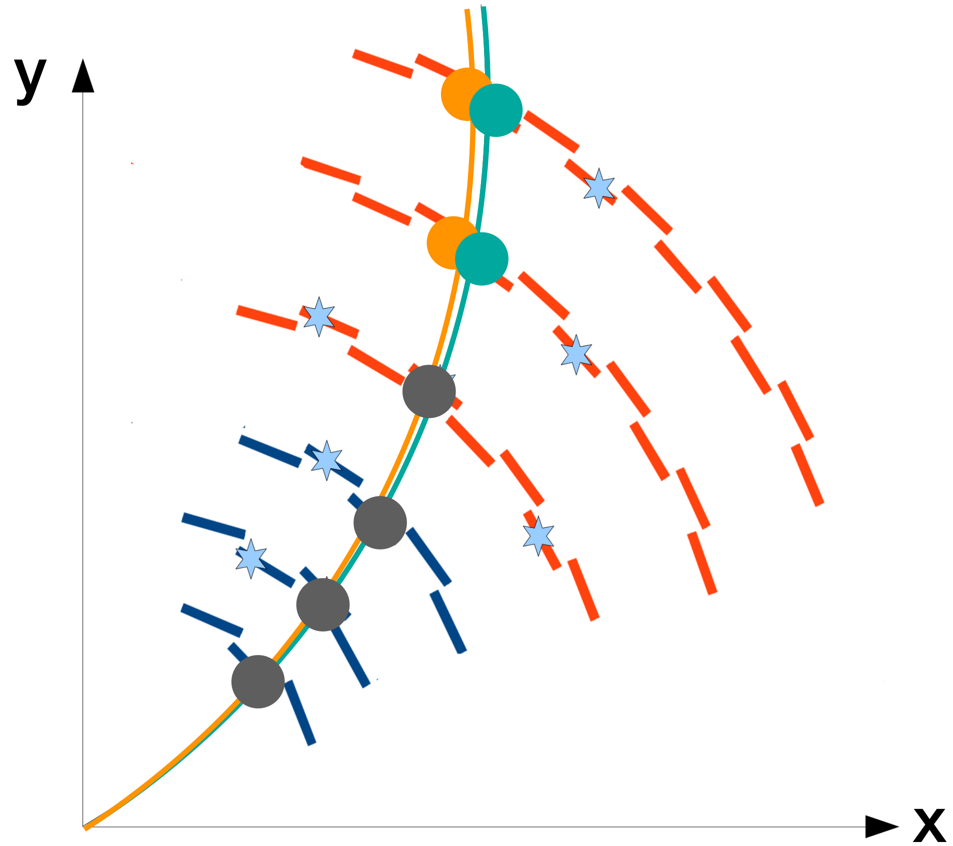
Barrel-disk overlap:
L1+D1, L2+D1, L1+L2

Disks:
D1+D2, D3+D4



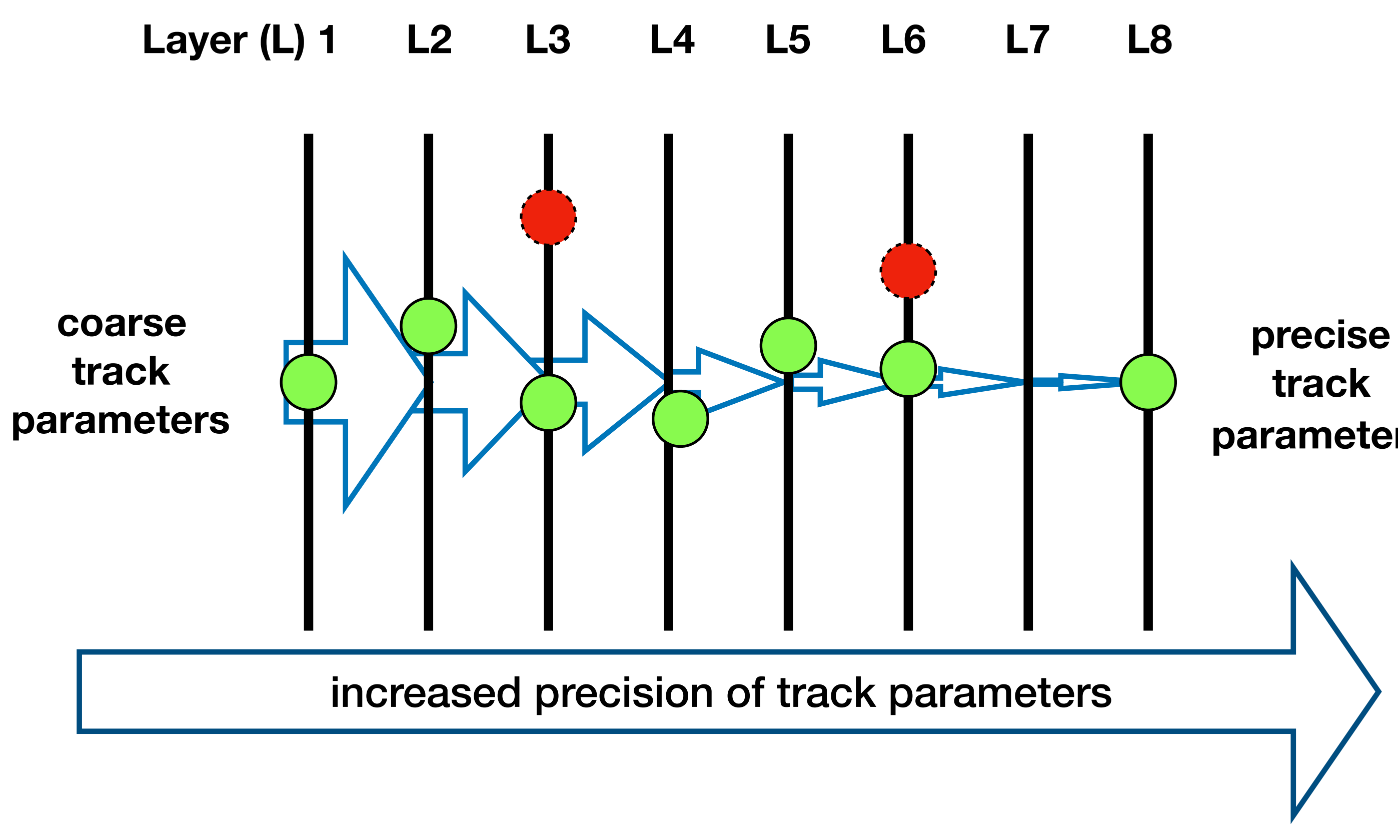
Duplicates & merging

- By construction, pattern recognition produces duplicate track candidates for a given charged particle
  - Redundancy in seeding (L1+L2 vs L3+L4, etc) ensures high efficiency, but leads to a given particle found >1 time
  - Additional duplicates may originate from tracks with combinatorial stubs
- Duplicates are removed by merging track candidates prior to fitting
- Currently, algorithm merges tracks sharing ≥ 3 stubs



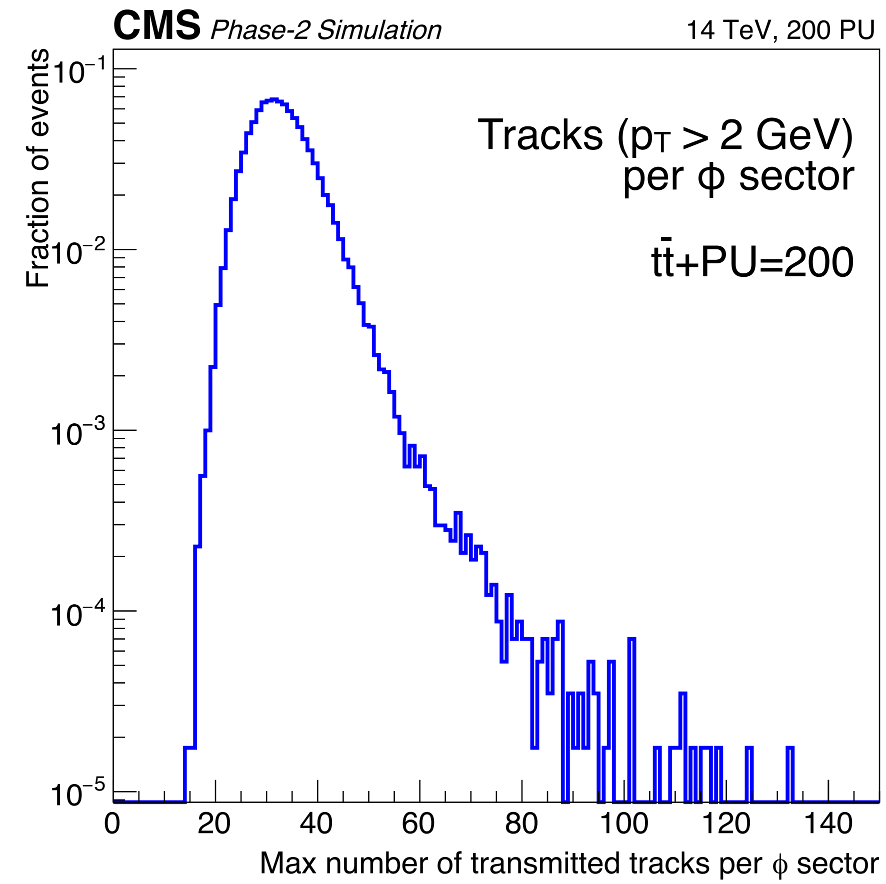
Track fitting

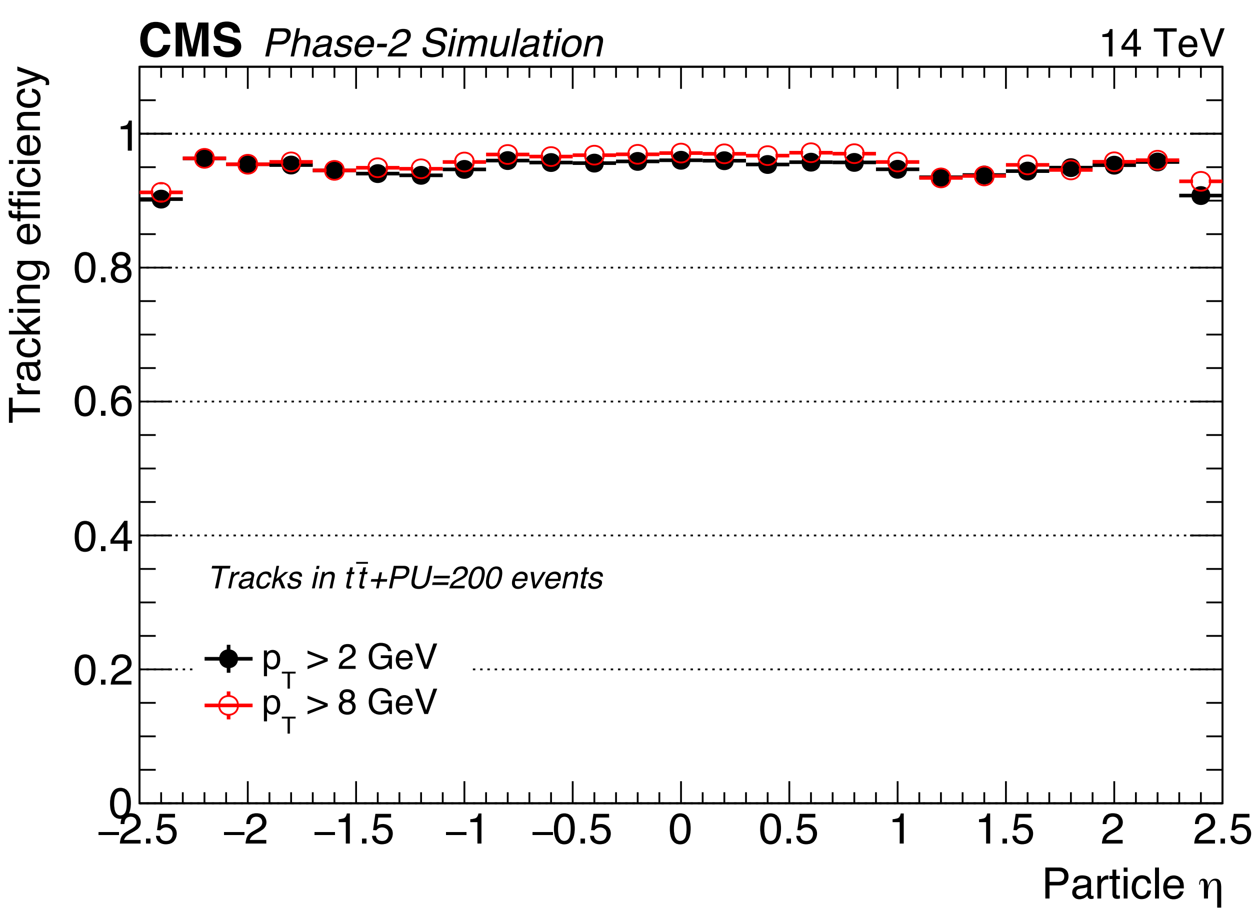
- Final track fitting uses Kalman Filter algorithm
- Iterative track fitting
  - Initial estimate of track parameters & their uncertainties from **tracklet seed**
  - Stub used to update helix parameters (weighted average)
  - χ^2 calculated, used to reject false candidates & incorrect stubs on genuine candidates
  - Repeat until all stubs are added
- Default is 4-parameter track fit — can be extended to additionally fit for d_0

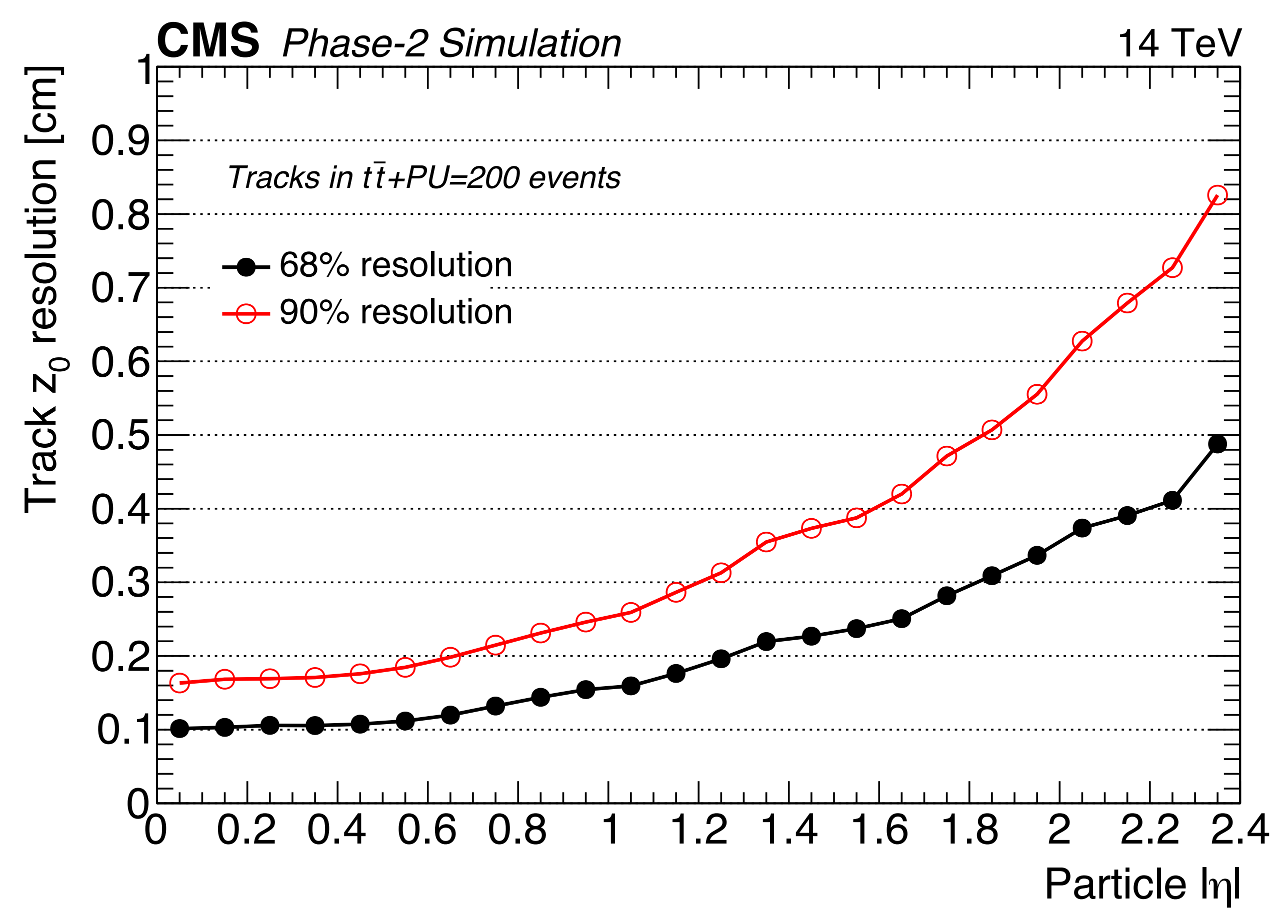


Performance

- Examples of expected L1 tracking performance based on simulation
  - High efficiency across p_T/η
  - Precise z_0 resolution for vertex association

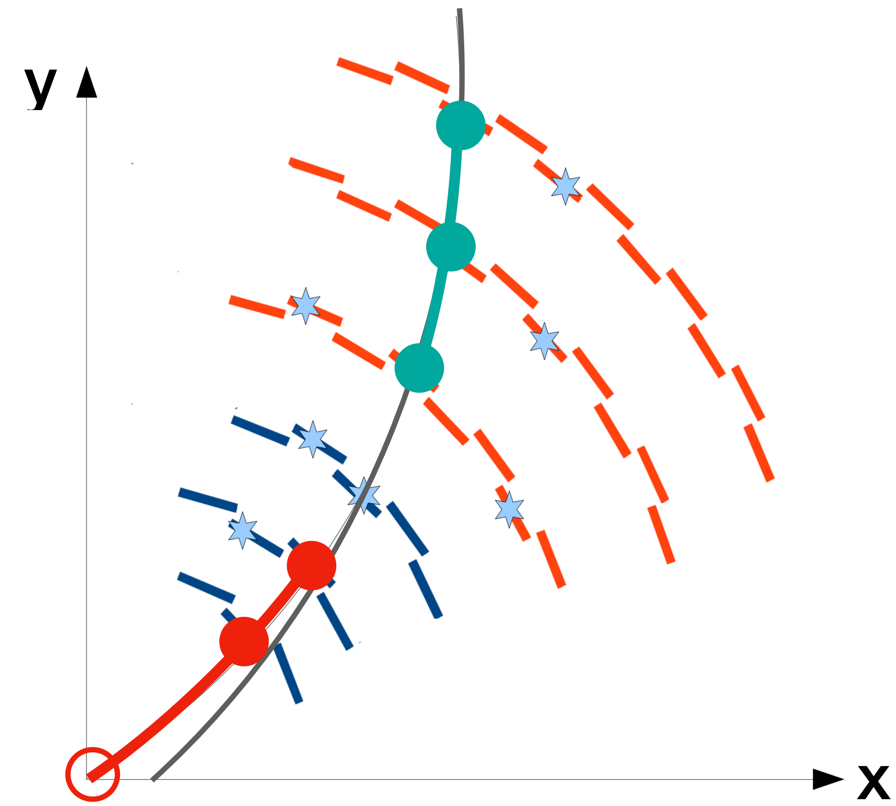






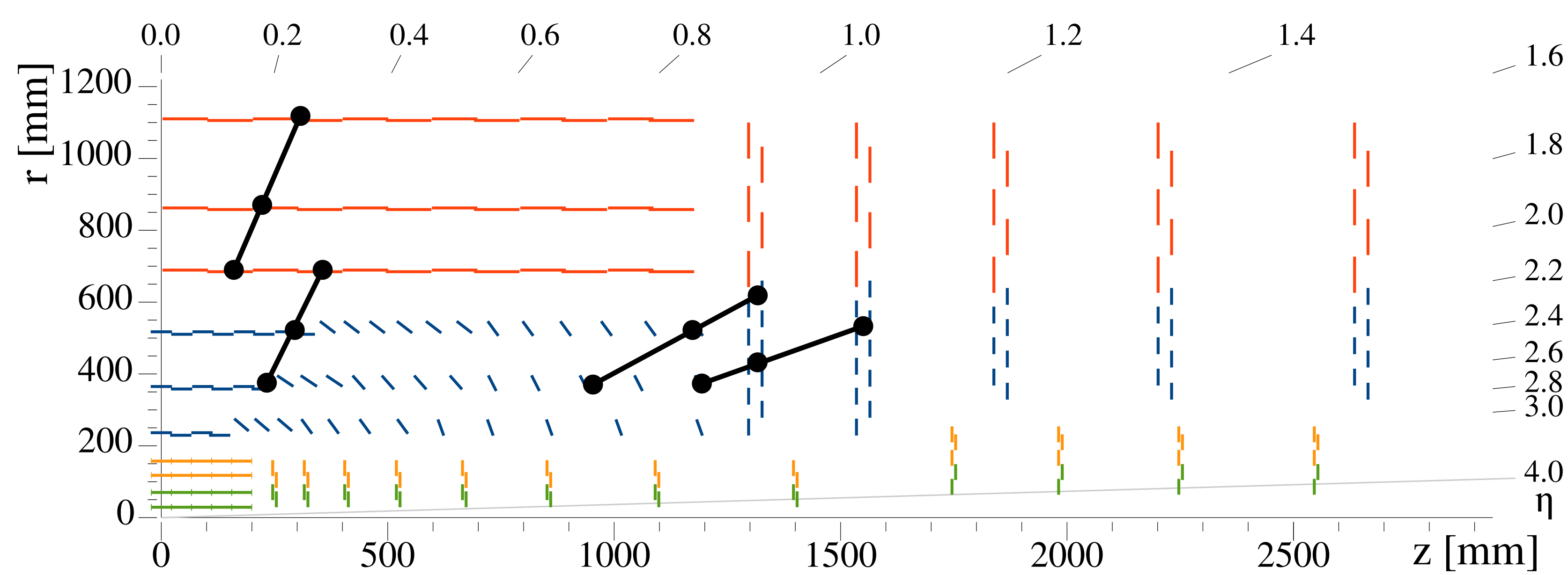
Displaced tracking

- Actively exploring an *extended tracking* setup to include capability of reconstructing long-lived particle trajectories



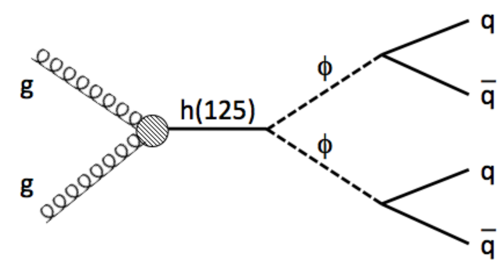
- How? Modified seeding
    - ***Prompt*** — tracklets (2 stubs + origin)
    - ***Displaced*** — triplets (3 stubs)
    - Displaced seeds propagated to other layers/disks similar as prompt to find matching stubs
- How? 5-parameter Kalman Filter fit

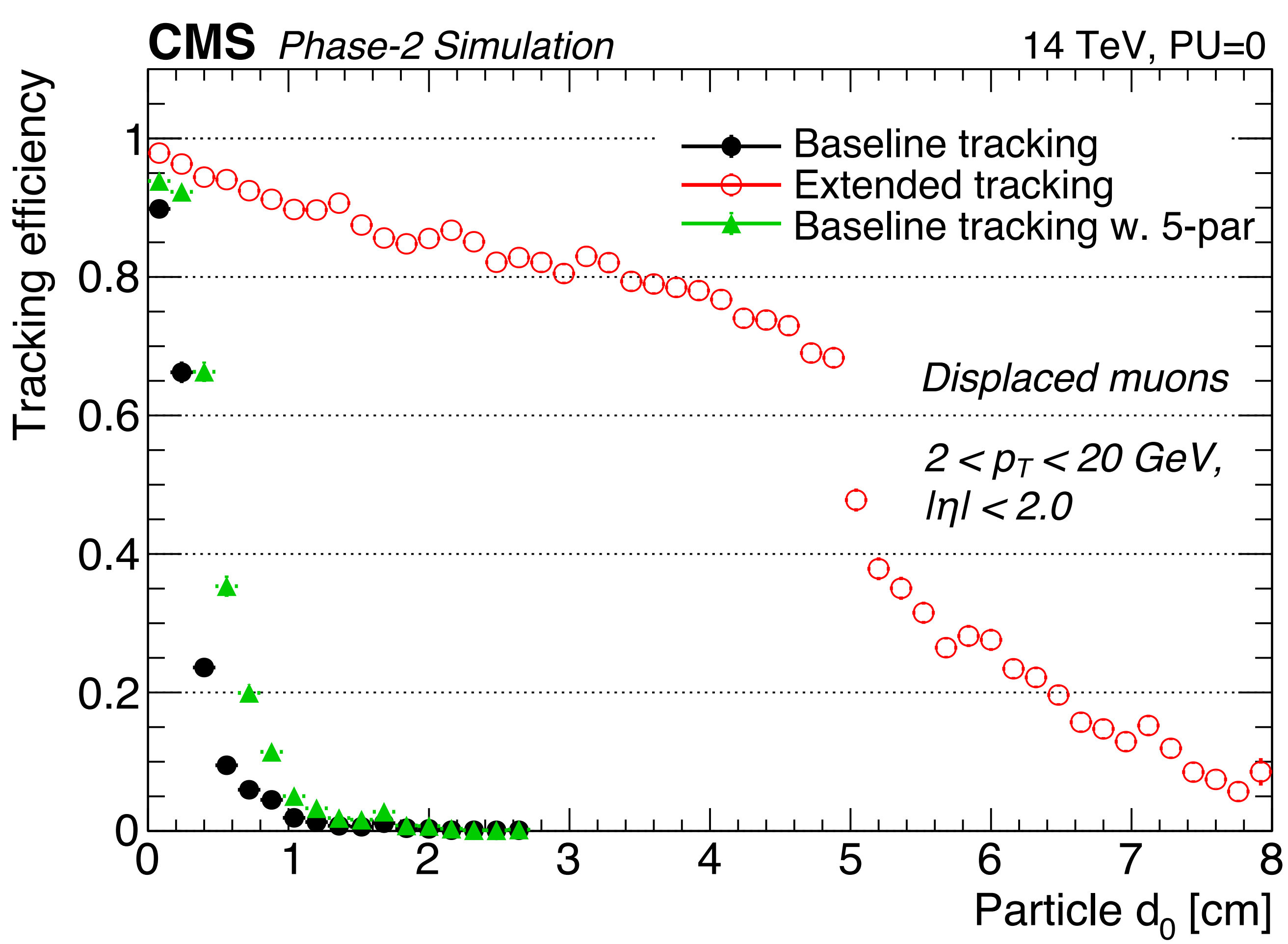
Triplet seeds:
L4L5L6, L2L3L4,
L2L3D1, L2D1D2

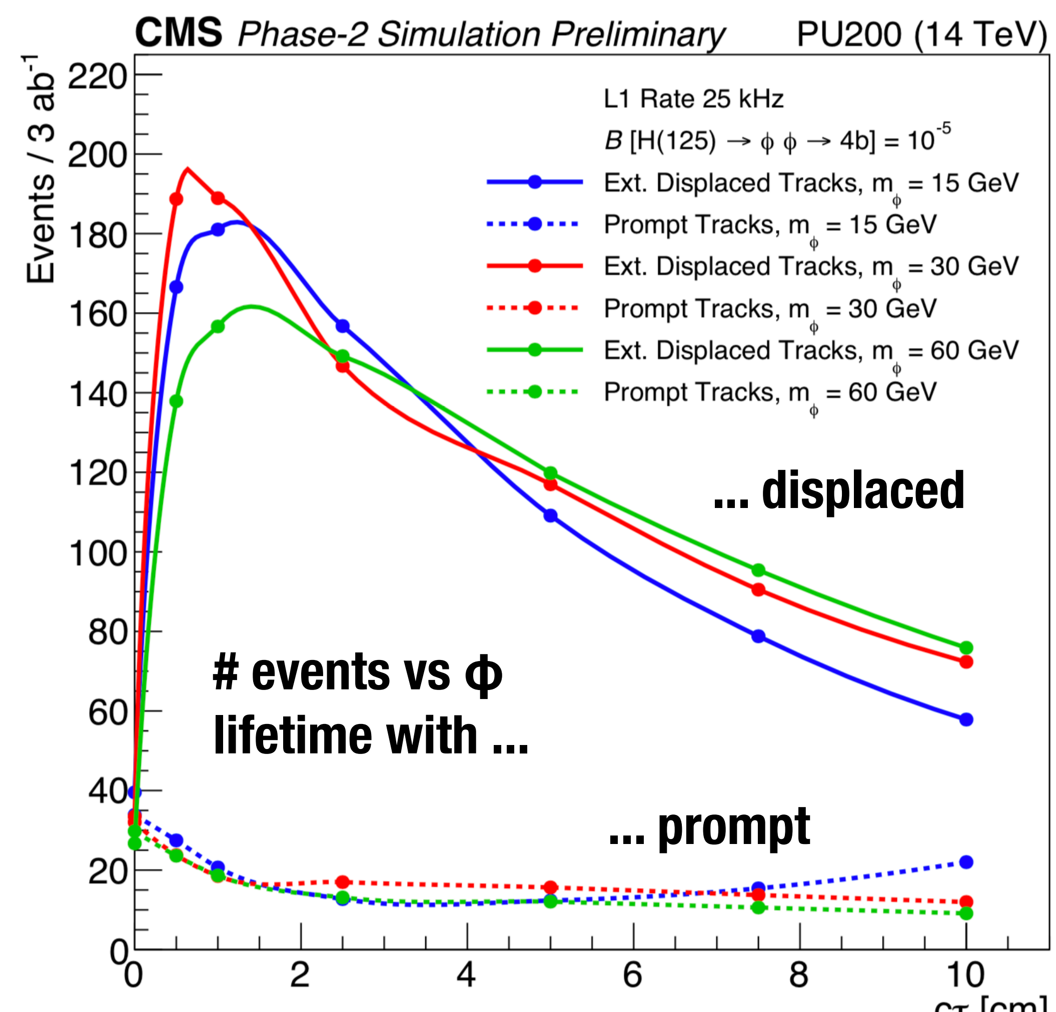


Displaced performance

- Extended tracking recovers efficiency for large d_0 particles
  - Increase in track rate ~40% (conservative estimate)
- As example studied in context of triggering on exotic Higgs boson decays
  - H => ϕϕ => 4 jets, where ϕ is long-lived



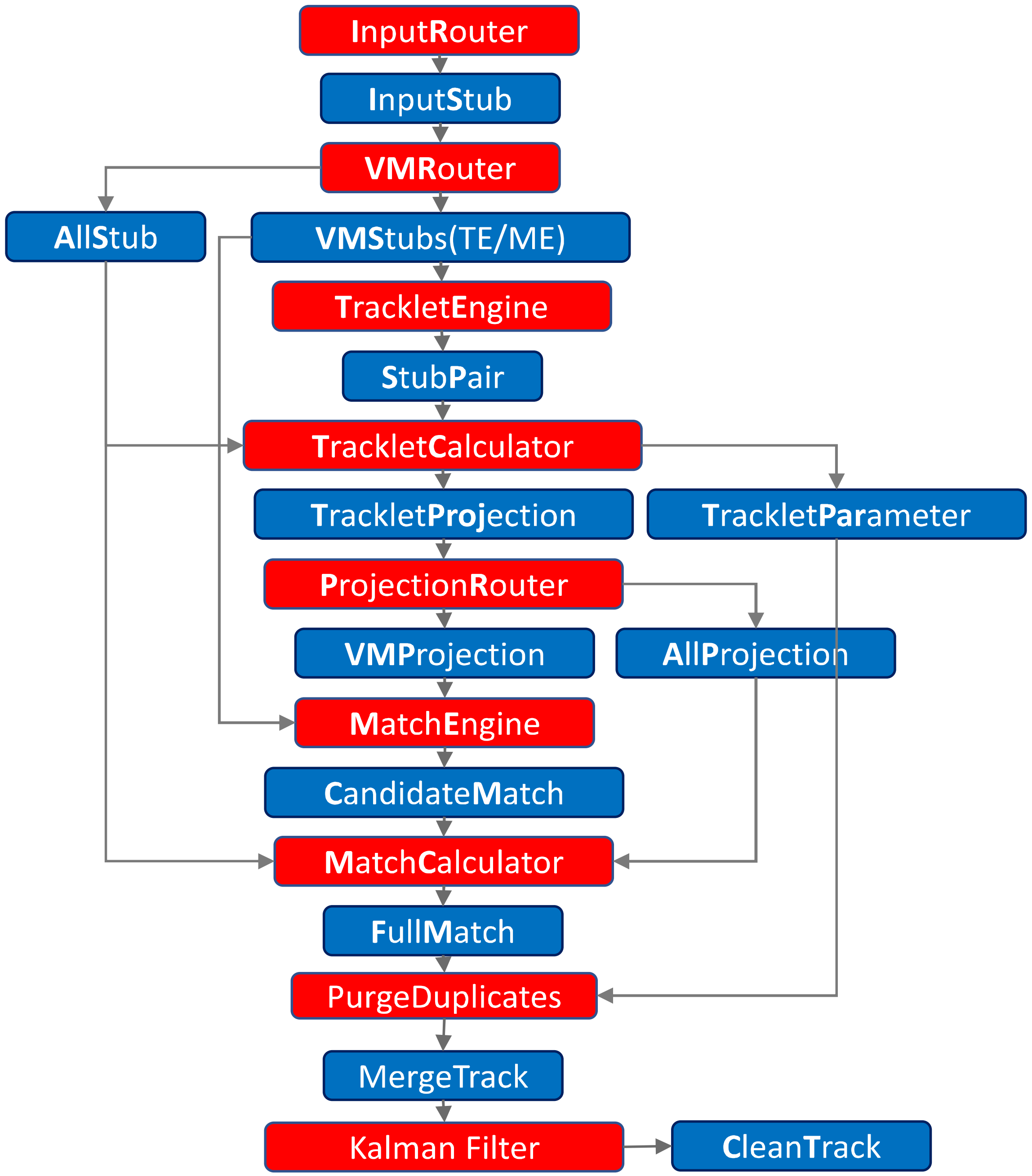




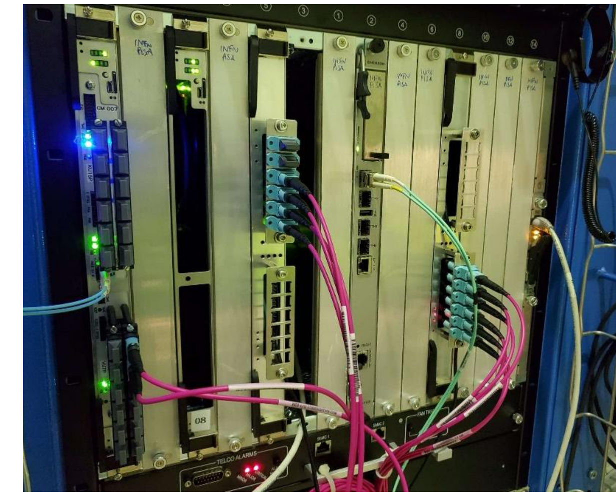
CERN-LPCC-2018-04

Implementation

- Track finding implemented as dedicated **processing modules** with **memory modules** storing data between steps
- Seeding & propagation steps implemented using Xilinx Vivado HLS
- Kalman filter largely implemented in VHDL
- Top-level modules connected in VHDL



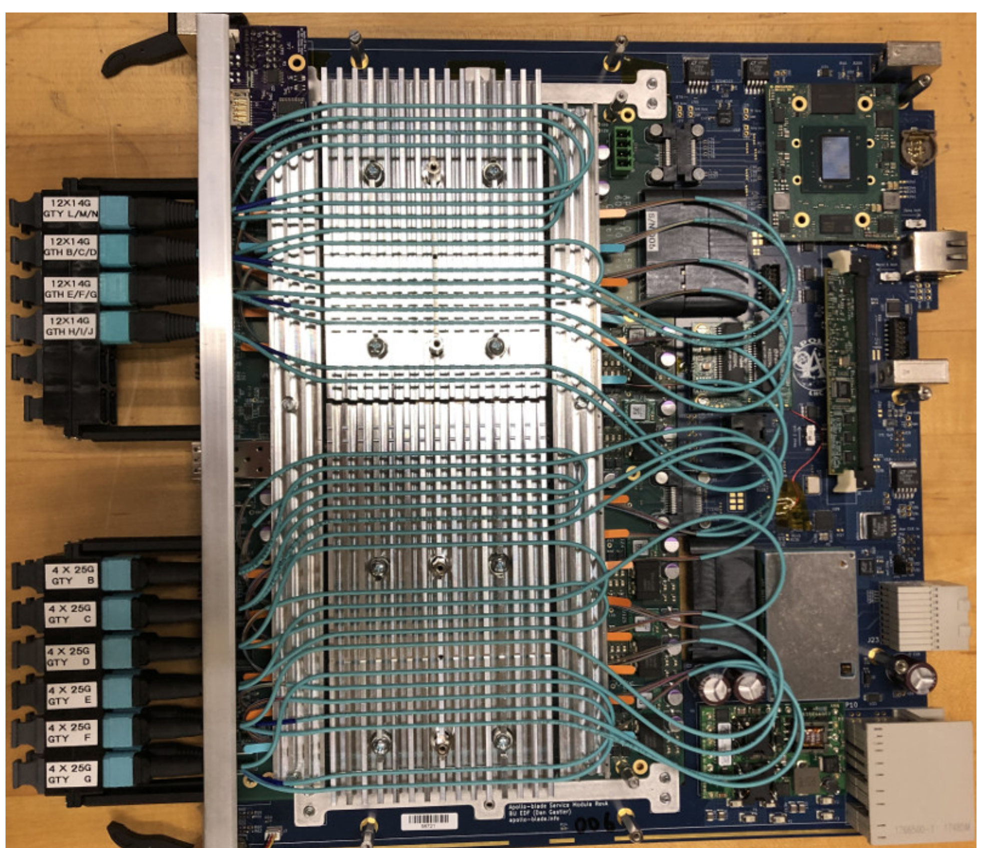
Hardware demonstration



Test stand @ CERN
with Apollo & Serenity blades

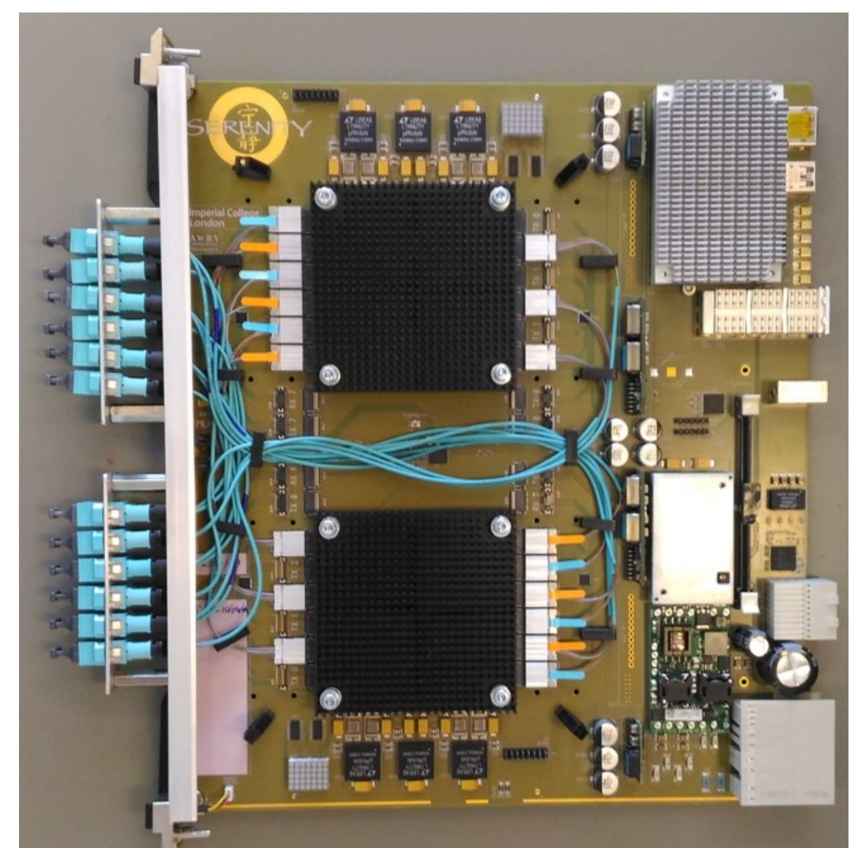
- Hardware for track-finding based on ATCA platform (CMS standard for HL-LHC upgrade)
- Demonstration of algorithm in progress

Apollo: track finding processing boards
- *Service Module* provides infrastructure components
- *Command Module* contains two large FPGAs, optical fiber interfaces & memories



arXiv:1911.06452

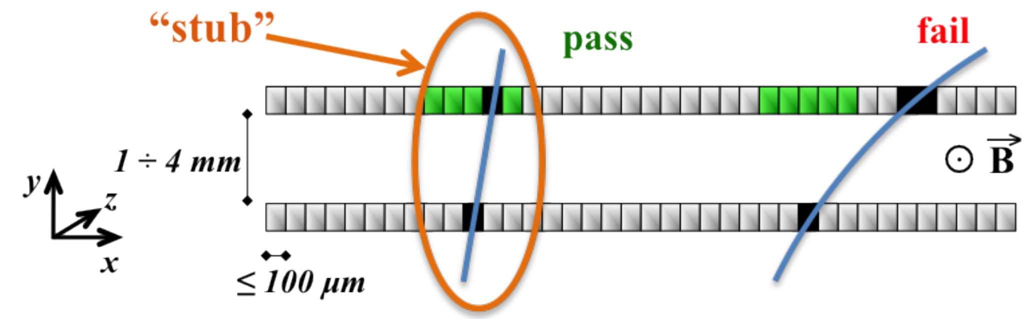
Serenity: DTC processing
- Carrier card provides services
- Daughter cards host FPGAs for data processing



cds:2646388

Summary

- Incorporating tracking in L1 trigger critical to achieve required event rate reductions for CMS at HL-LHC
  - Key to achieve physics goals



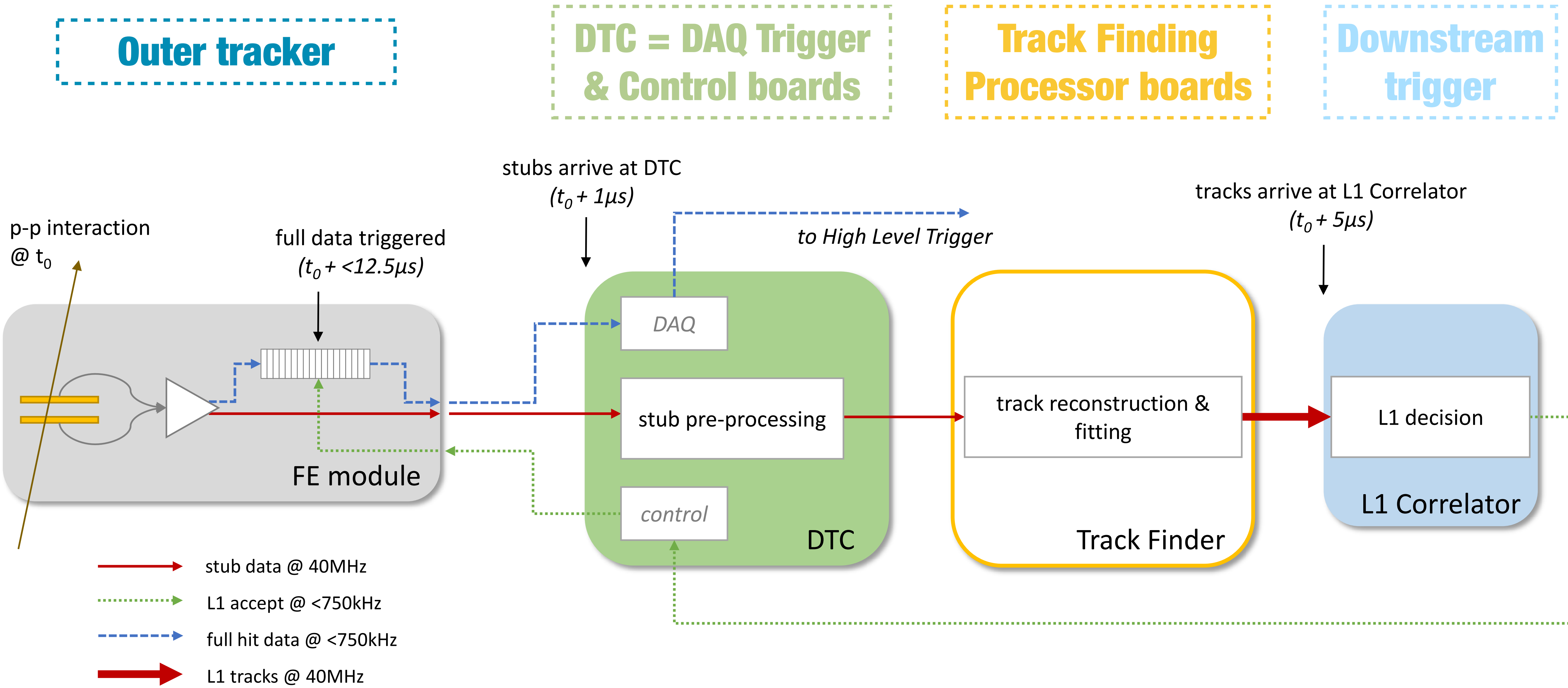
- Track triggering on this scale never implemented before
  - Relies on unique detector design with "p_T modules"
  - System design based on off-shelf electronics (FPGA)
  - Legacy demonstrators showed feasibility of systems w. required performance

- Extension to *displaced tracking* brings feasibility of probing physics scenarios involving long-lived particles

- *Working toward specifications of final system & next-level demonstrators !*

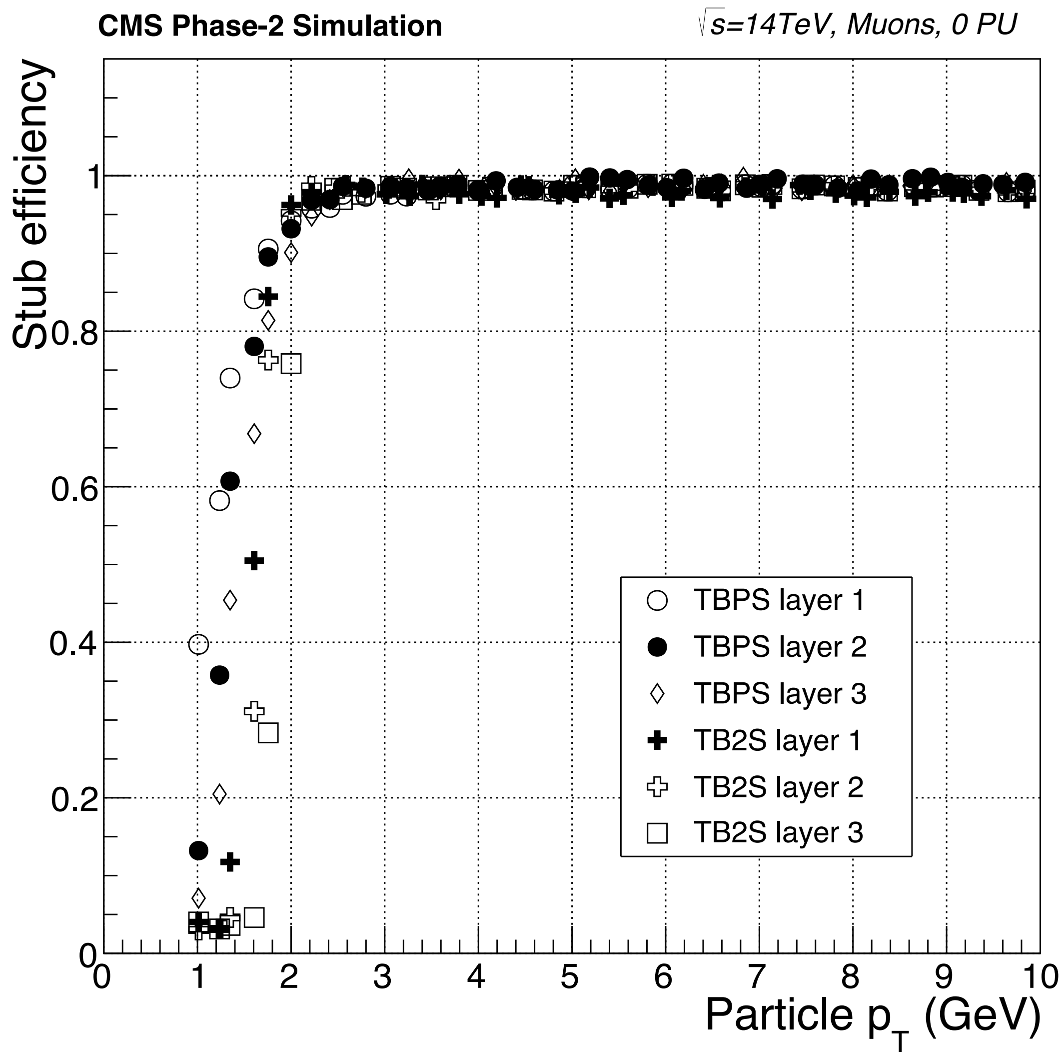
BACKUP

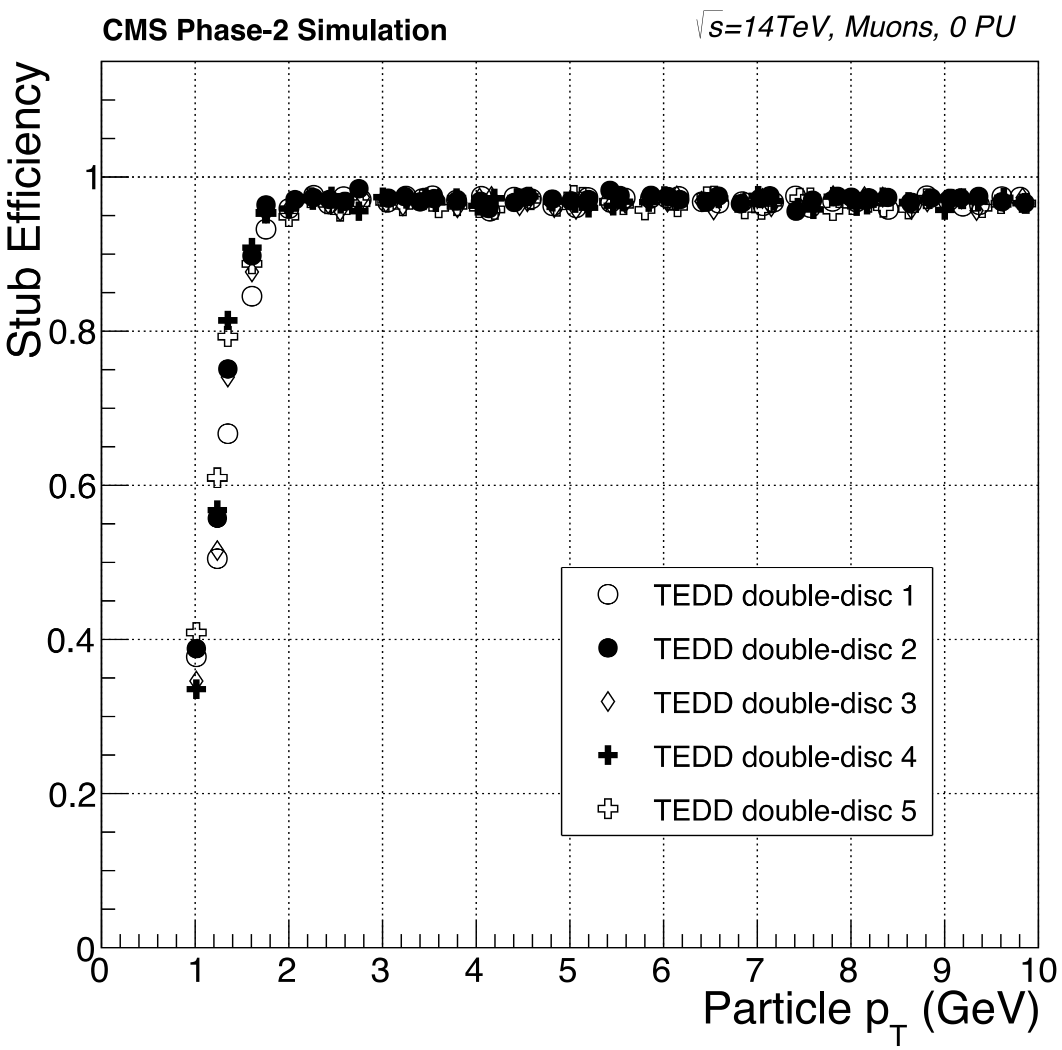
Data flow

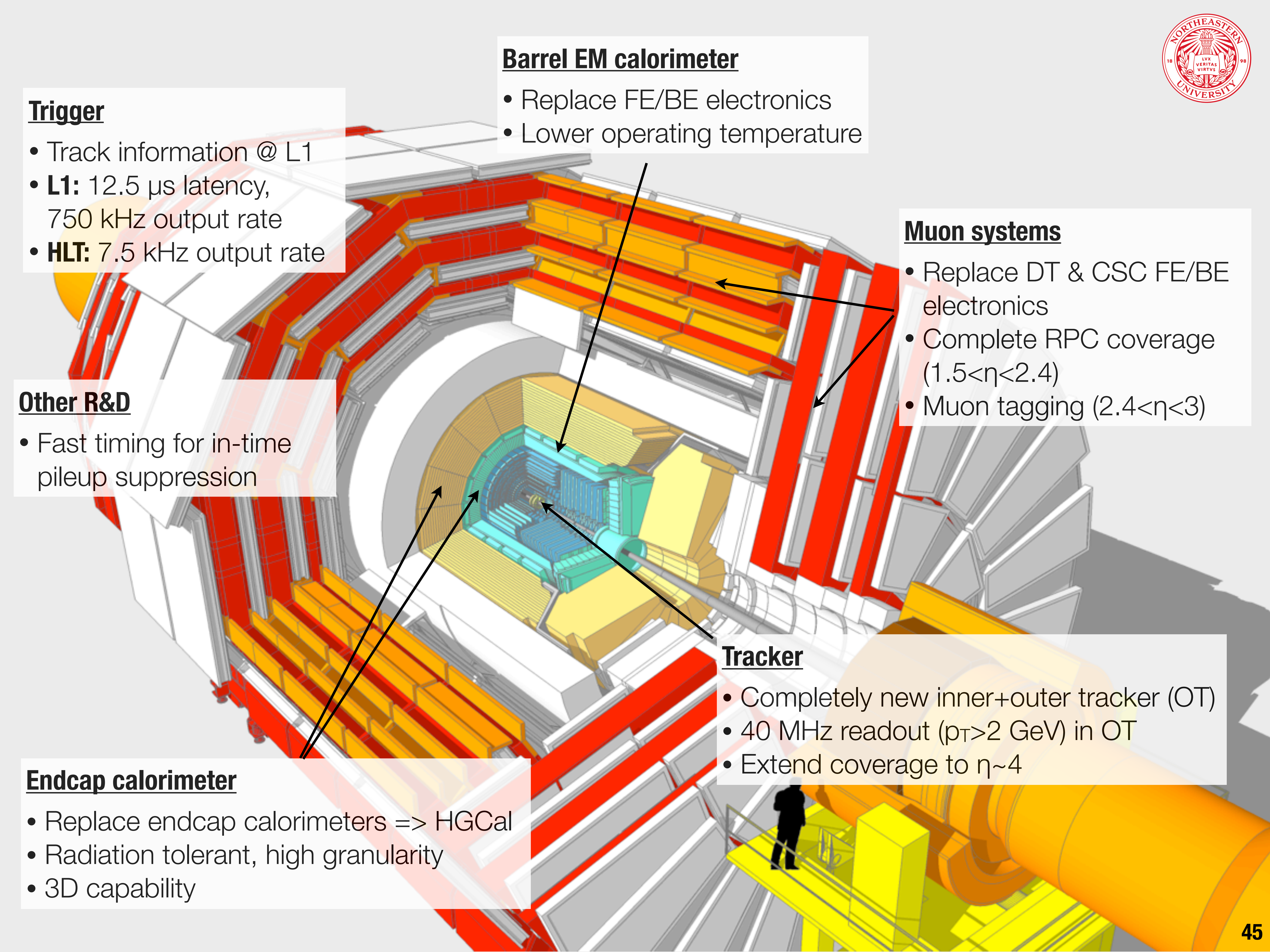


Outer tracker
DTC = DAQ Trigger & Control boards
Track Finding Processor boards
Downstream trigger
p-p interaction @ t_0
full data triggered (t_0 + <12.5μs)
stubs arrive at DTC (t_0 + 1μs)
to High Level Trigger
tracks arrive at L1 Correlator (t_0 + 5μs)
FE module
DAQ
stub pre-processing
control
DTC
track reconstruction & fitting
Track Finder
L1 decision
L1 Correlator
stub data @ 40MHz
L1 accept @ <750kHz
full hit data @ <750kHz
L1 tracks @ 40MHz

Stub finding efficiency






Trigger
• Track information @ L1
• L1: 12.5 μs latency, 750 kHz output rate
• HLT: 7.5 kHz output rate
Barrel EM calorimeter
• Replace FE/BE electronics
• Lower operating temperature
Muon systems
• Replace DT & CSC FE/BE electronics
• Complete RPC coverage (1.5<η<2.4)
• Muon tagging (2.4<η<3)
Other R&D
• Fast timing for in-time pileup suppression
Tracker
• Completely new inner+outer tracker (OT)
• 40 MHz readout (pT>2 GeV) in OT
• Extend coverage to η~4
Endcap calorimeter
• Replace endcap calorimeters => HGCal
• Radiation tolerant, high granularity
• 3D capability

2016 demonstrator systems

- Algorithms implemented in emulation software + firmware
- Hardware demonstrators used to validate feasibility & performance
  - µTCA boards with Virtex-7 FPGA
    - **Tracklet:** *3 boards for ϕ sectors + 1 board emulates input & receives output tracks, AMC13 card for clock & synchronization, 240 MHz clock*
    - **HT+KF:** *5 boards for processing + 3 boards for input / output*
- Excellent performance demonstrated in hardware + measured 3-4 µs latency