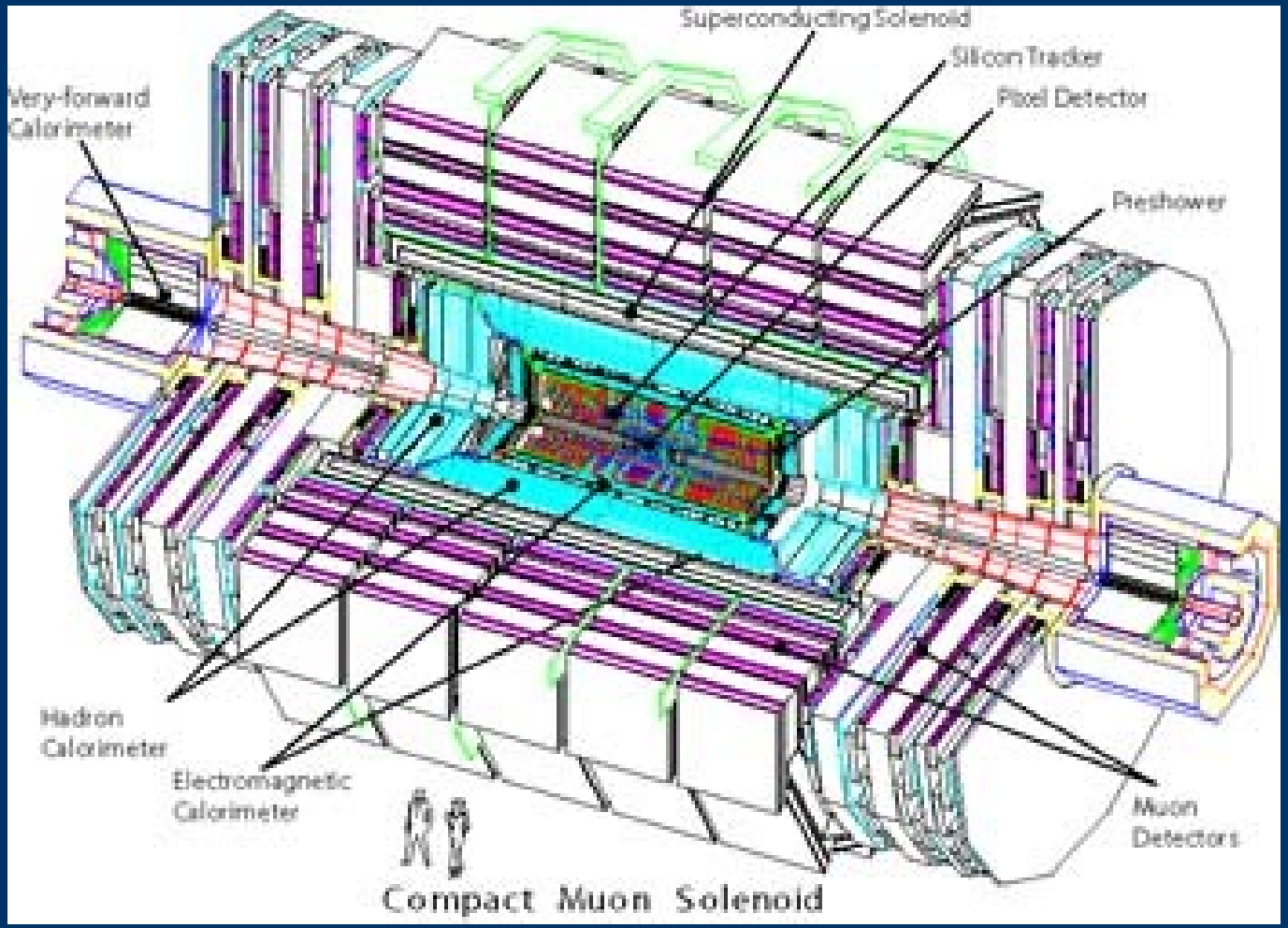
the CMS tracker

general overview / expected performance / use in the HLT

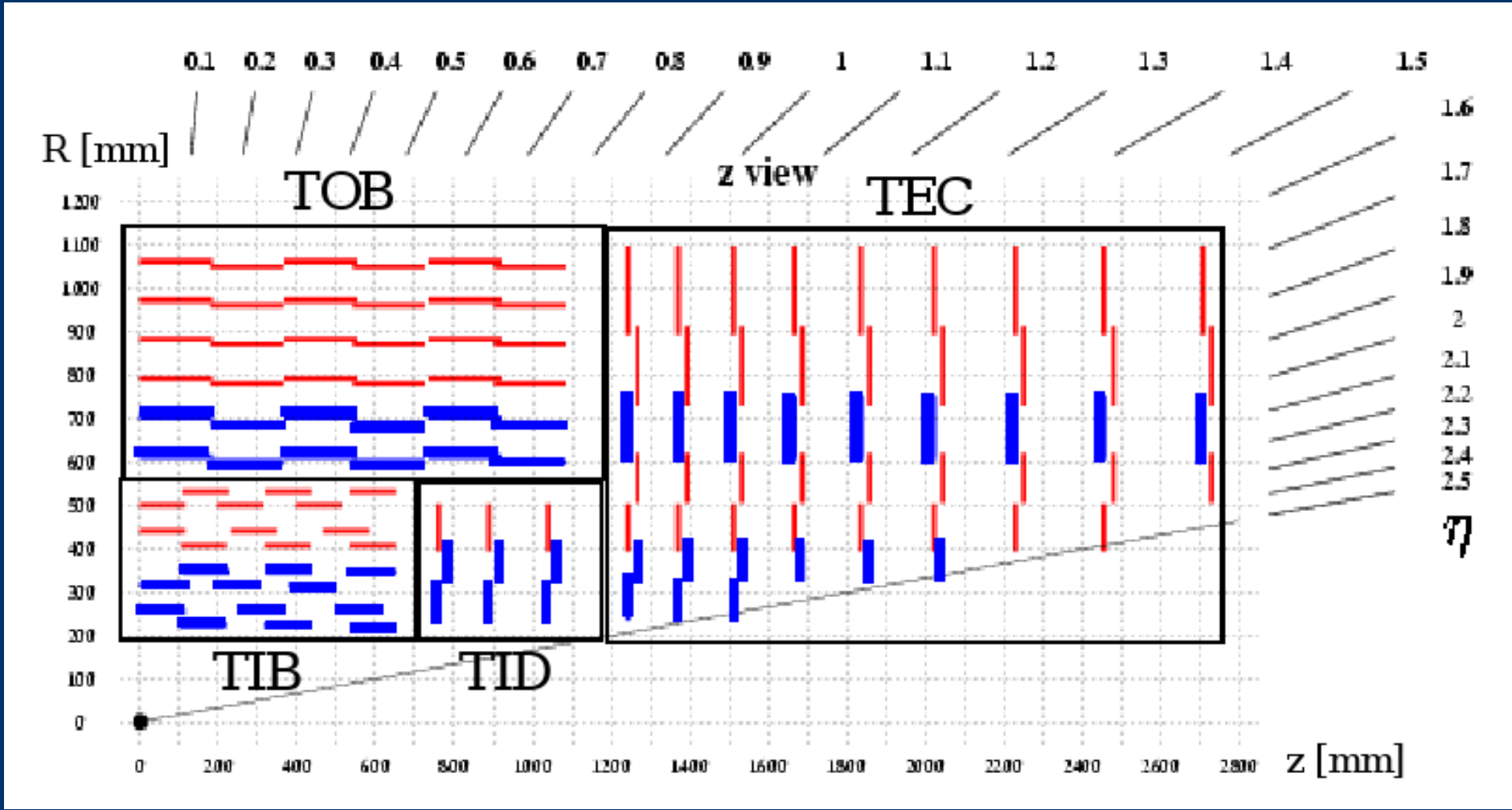
the CMS tracker

- Overview of the CMS tracker
  - overview
  - status of production / tests
- The CMS tracker: expected performance
  - offline track reconstruction
  - fast tracking
- The tracker in the High Level Trigger
  - introduction to CMS trigger
  - specific triggers

Overview of the CMS tracker : the CMS



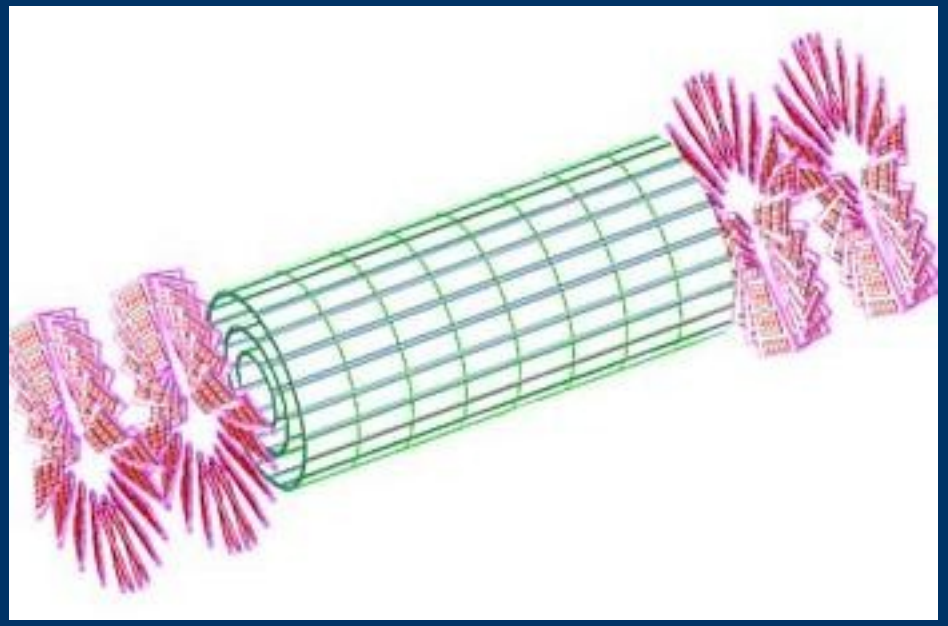
The CMS tracker: layout

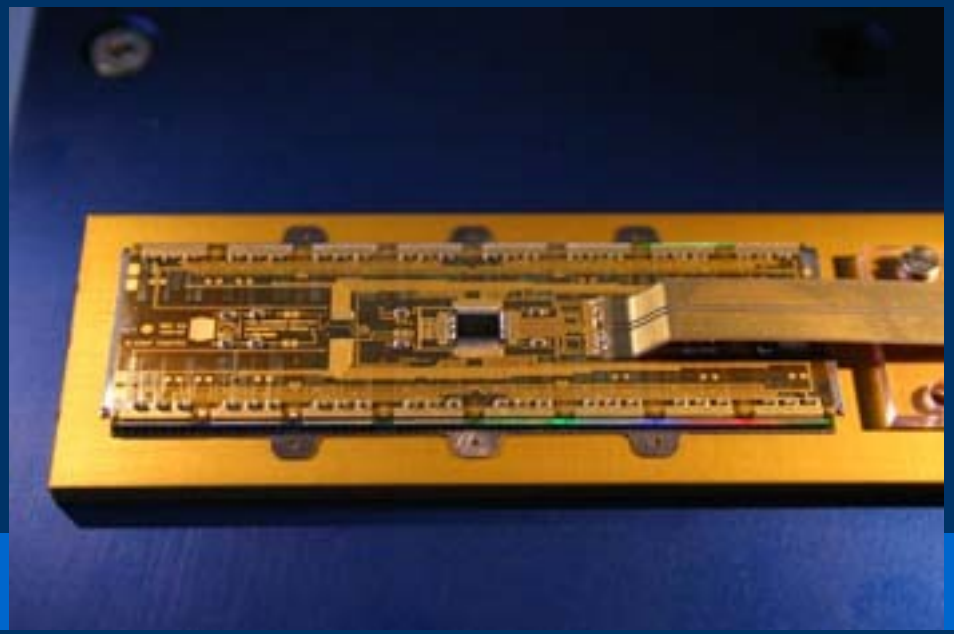


Double sided / single sided

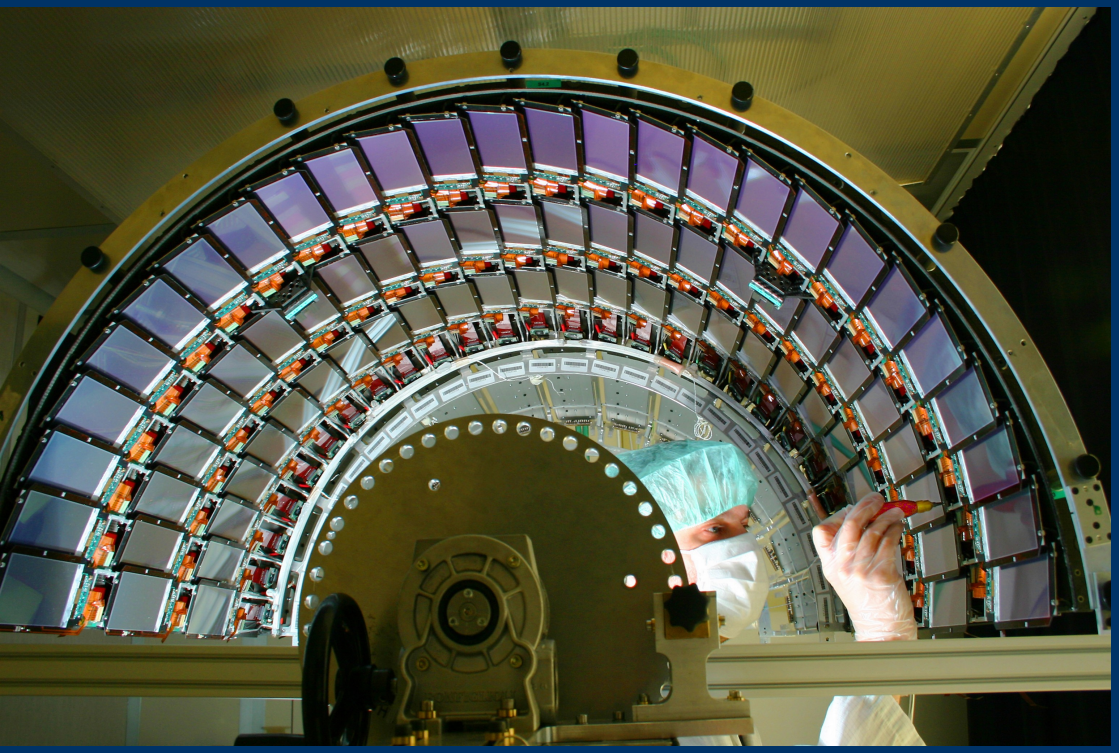
The CMS tracker : pixel detector

- Number of channels
  - 60 million
- Resolution
  - 3D space points
- Positions
  - 3 barrel layers (4, 7 and 11 cm)
  - 2 disks on each side
- Responsible institutes
  - Switzerland (barrel)
  - USA (end-caps)
- Current status
  - finalized module design





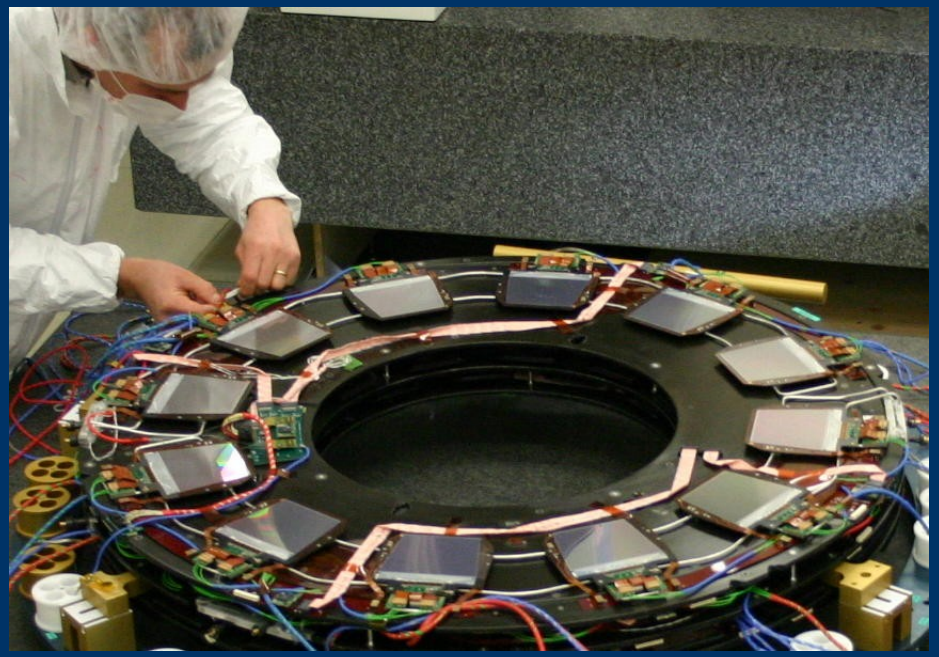
The CMS tracker : Inner Barrel

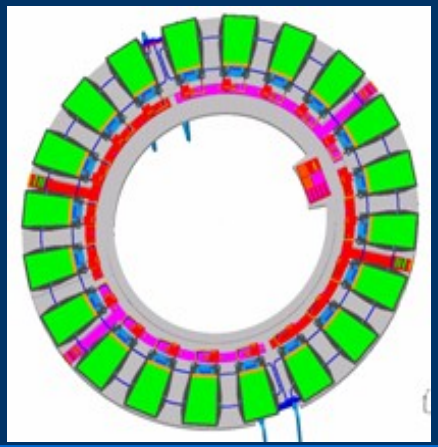


- Number of channels
  - ~2 million
- Resolution
  - double sided layers: 11/ 500 μm
  - single sided layers: Rϕ ~ 17 μm
- Positions
  - 4 barrel layers (R = 20-55 cm)
- Responsible institutes
  - INFN consortium
- Current status
  - first half arrived at CERN the 12th of June, second half expected by the end of August

The CMS tracker : Inner Disks

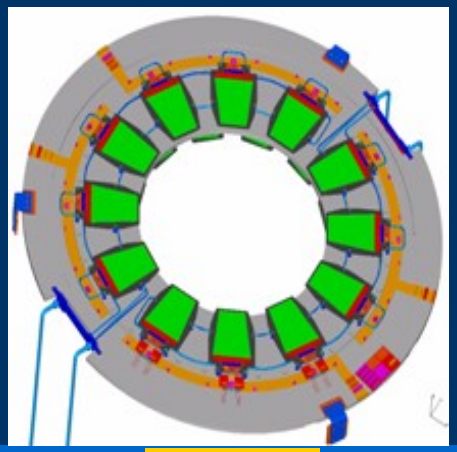
- Positions
  - 4 disks (R = 20 - 55 cm, z= 55 – 120 cm)
- Responsible institutes
  - INFN consortium
- Current status
  - first half integrated at Pisa





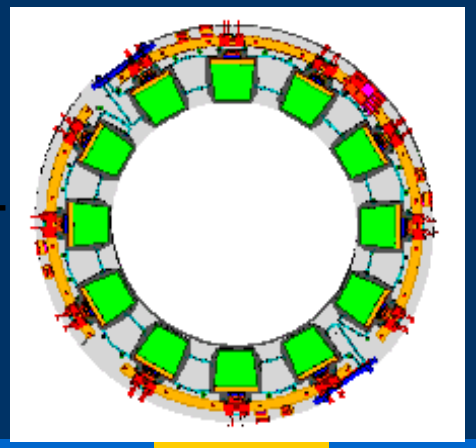
RING3

+



RING1

+



RING2

The CMS tracker: End Cap

- Positions
  - 9 disks on each side
  - 55 < R < 115 cm
  - 120 < z < 180 cm
- Responsible institutes
  - French/German/Belgium
- Current status
  - TEC+ assembly at Aachen
  - TEC- assembly at CERN

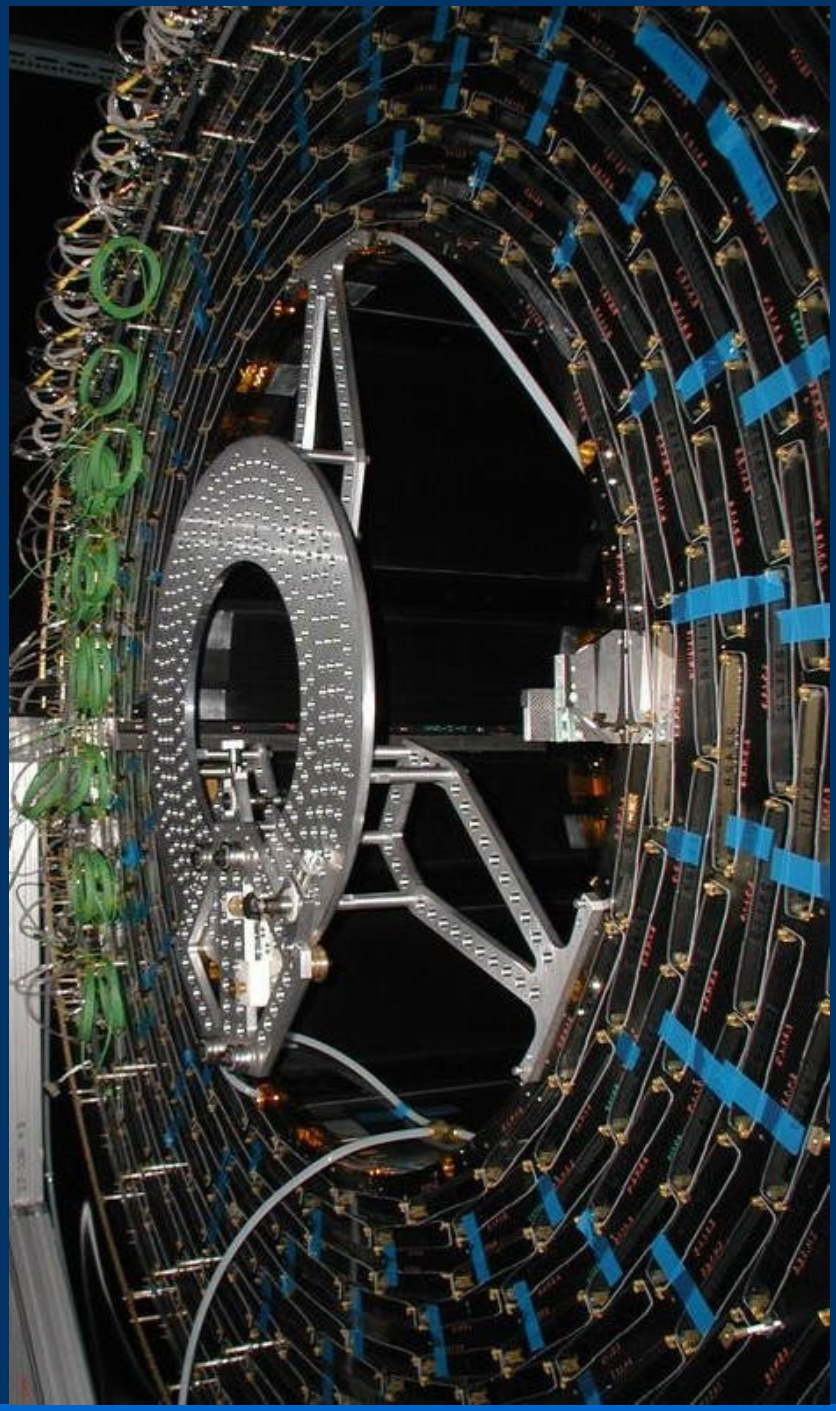






The CMS tracker: Outer Barrel

- Thick (500 micron) sensors with large pitch (120 μm, 200 μm)
- Resolution
  - tends to p/sqrt(12)
- Positions
  - 5 barrel layers
  - 55 < R < 115 cm, z < 120 cm
- Responsible institutes
  - USA (Santa Barbara, FNAL)
- Current status
  - ROD assembly at CERN



The CMS tracker : some numbers

CMS

B = 4 Tesla

all-silicon (15.000 modules, 200 m^2)

- ~ 12 R ϕ measurements over 1.2 m
- ~ 7 3D points
  - 3 pixel
  - 2 TIB/TID
  - 2 TOB/TEC

innermost pixel layer @ R = 4 cm

fully analog readout: pixel read-out relies heavily on charge sharing

deep sub-micron electronics throughout

tracker sensors:

320/500 μm

6” wafers

ATLAS

B = 2 Tesla

silicon/Transition Radiation Tracker

- 7 precision 3D points
- 36 TRT measurements

innermost pixel layer @ R = 5.5 cm

silicon readout (nearly) fully binary (except for pixel TOT)

DMILL

tracker sensors:

285 μm

4” wafers

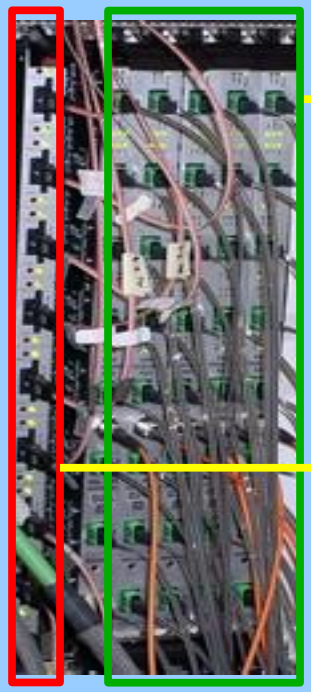
Overview of the CMS tracker : integration

analog data line: header + analog signal from 256 strips

OFF-detector electronics

On-detector electronics

hybrid (PLL, MUX, APV) + AOH



Digital Opto Hybrid

Clock & Control Unit

I^2C



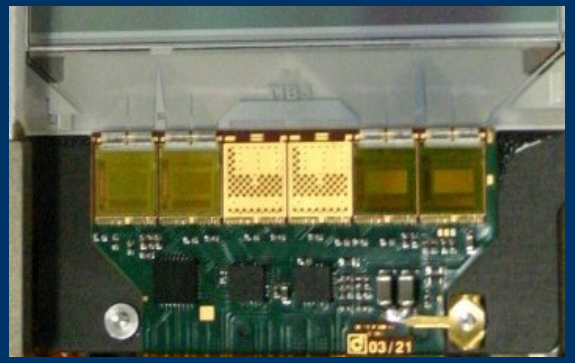
FEC

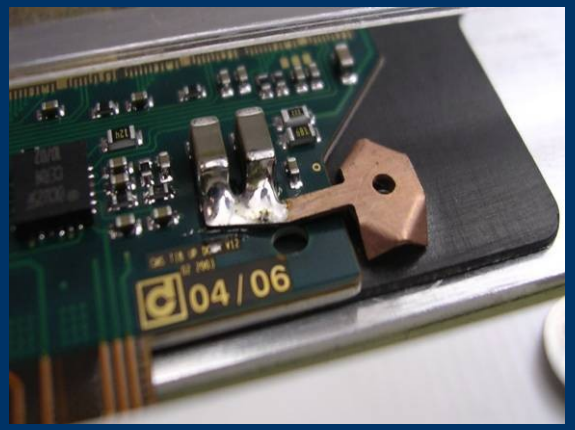
FED

optical clock and commands

The CMS tracker: on-detector electronics

- AOH: analog opto hybrid for transmission of analog frame from module to FED
- PLL: programmable delay
- MUX: multiplexer
- APV: front-end amplifier + analog pipeline
- DCU: digital control unit (temperature, humidity)
- CCU: clock and control unit (transforms to I^2C)





Overview of the CMS tracker : integration



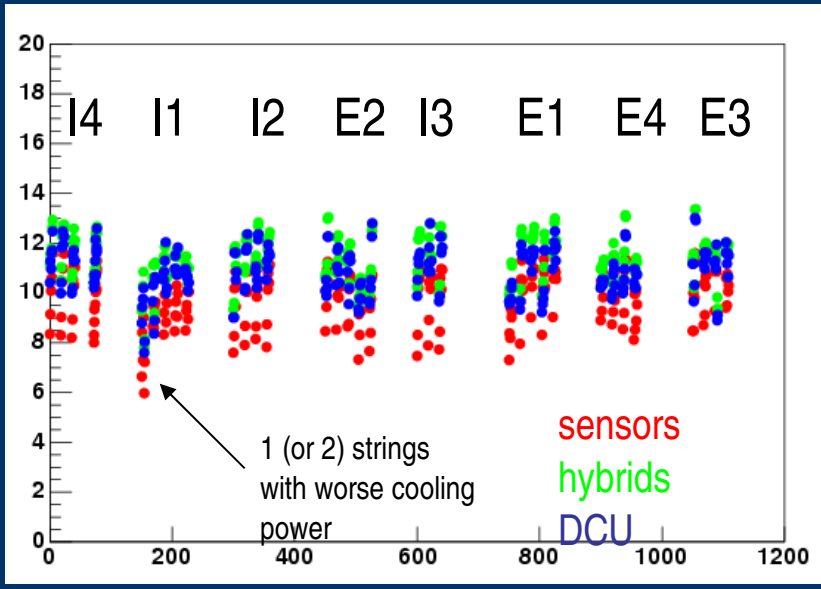
The CMS tracker: tests before shipment

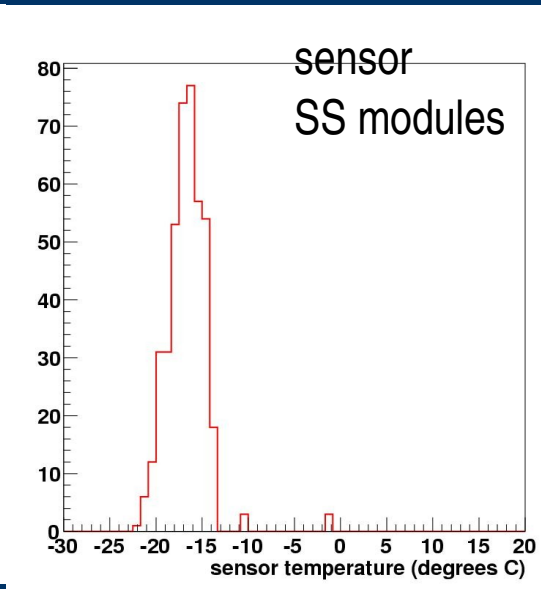
Cooling test in CMS-like conditions:

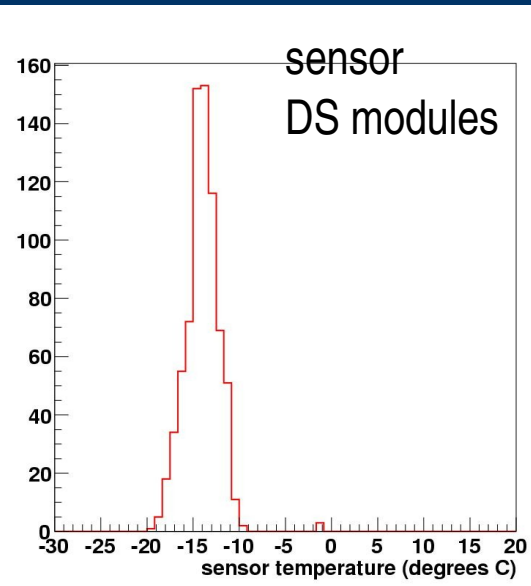
- nominal freon flow, environment temperature = -10 degrees, liquid temperature = -25 degrees
- temperatures monitored through on-detector thermistors

Overall performance is excellent (one reject on TID due to obstructed cooling loop).

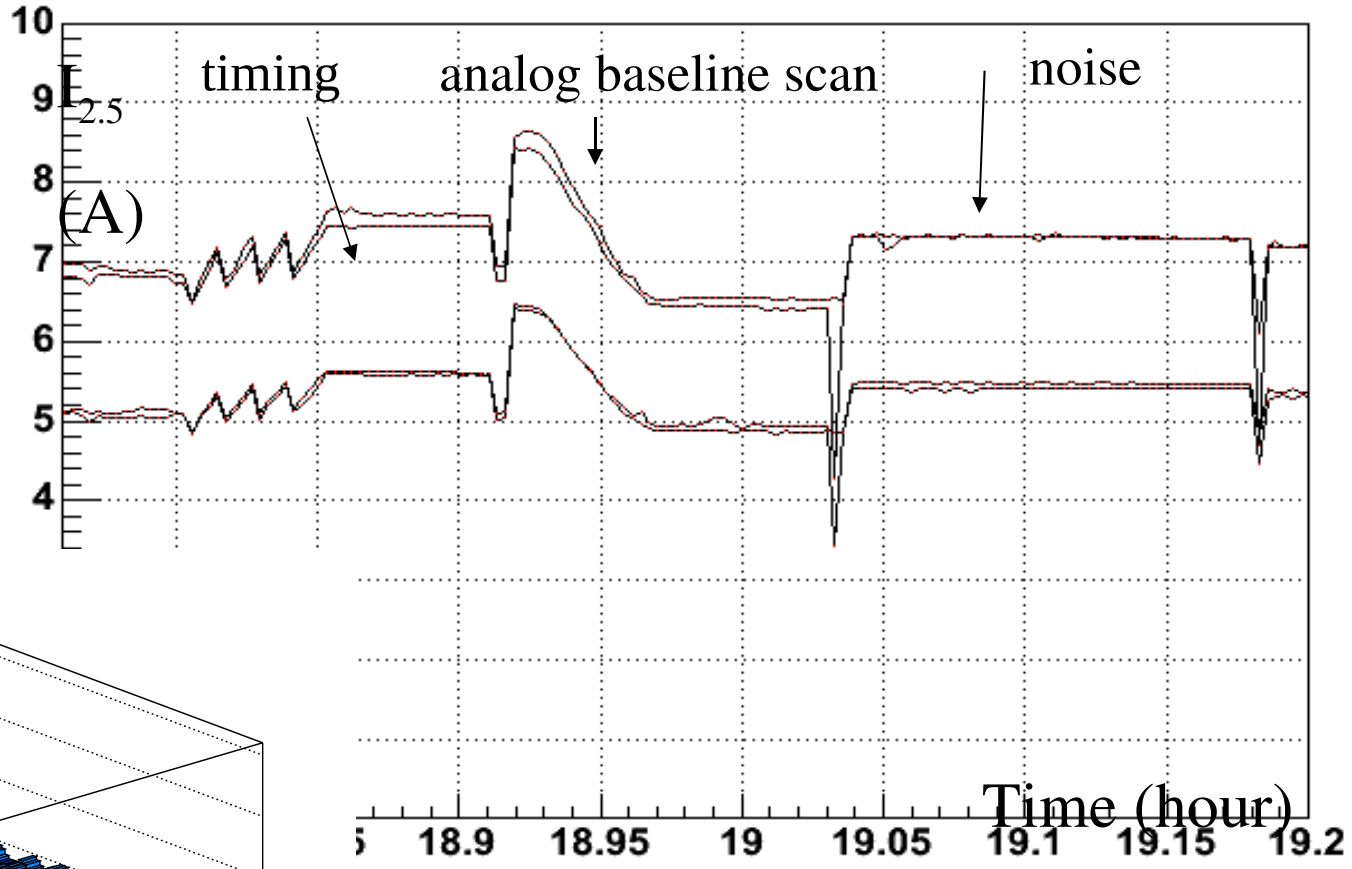
Careful look into Δ T varying the liquid temperature in some cases reveals slightly reduced thermal coupling liquid-module: re-mounting the module cures the problem

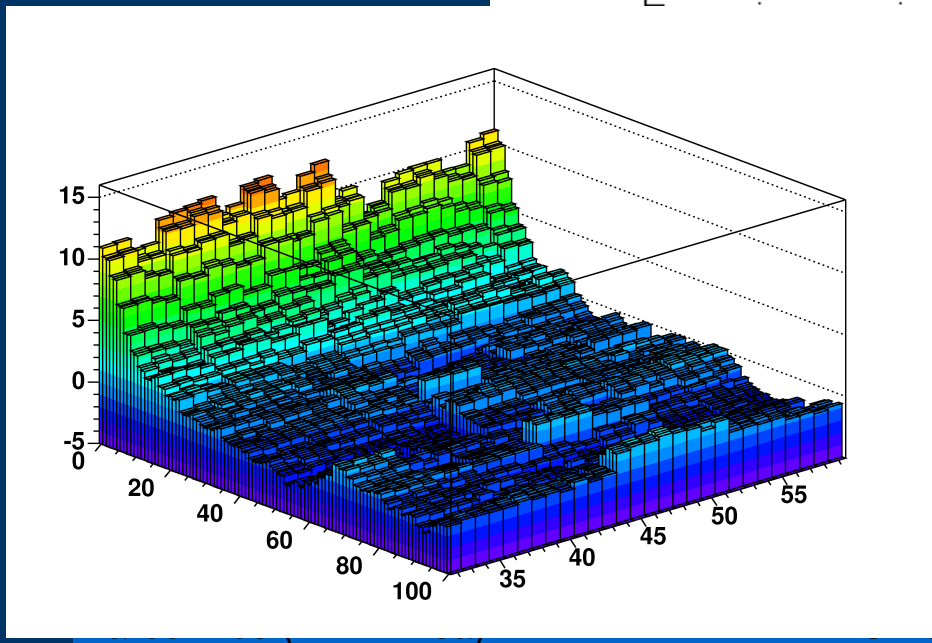






Overview of the CMS tracker : tests before shipment





Stability of power consumption, baseline, temperature, noise during long-term test

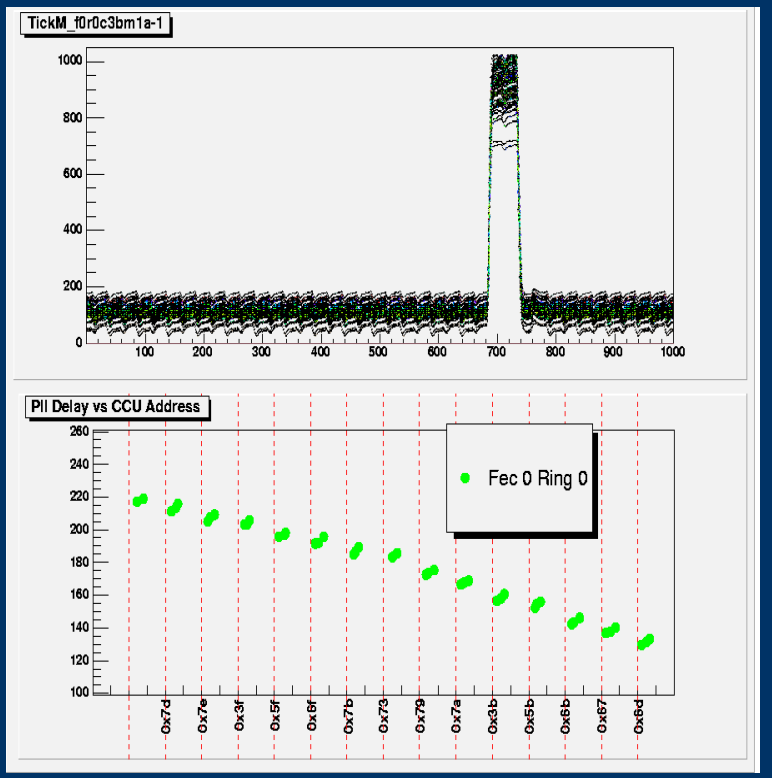
The CMS tracker: tests before shipment

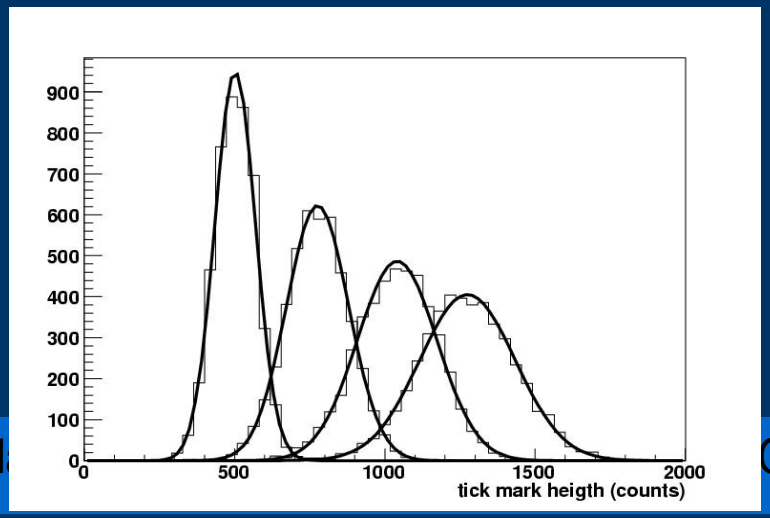
Full configuration of the tracker exercised.

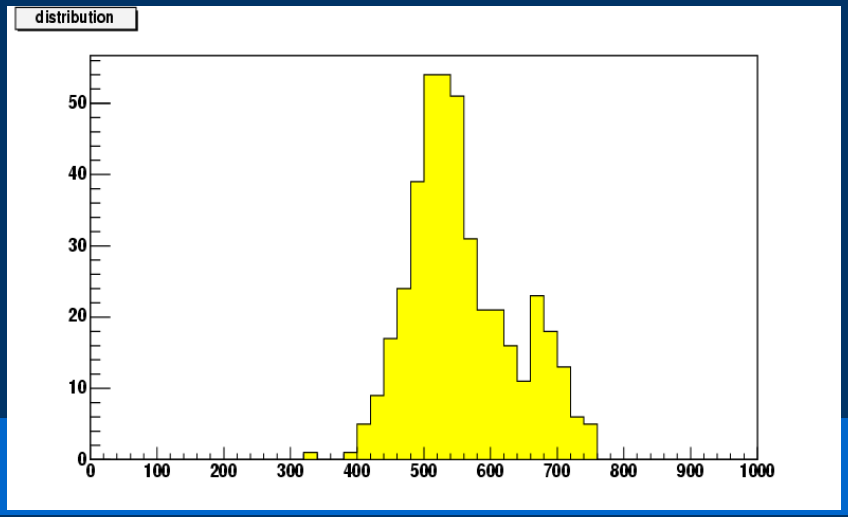
Relies heavily on the “tick mark”, a digital one sent out by the APV at regular intervals:

time alignment -->

optical link response (in ADC counts: 640 counts = 800 mV, i.e. a gain of 0.8 counts/mV) for 4 gain settings and for the chosen one



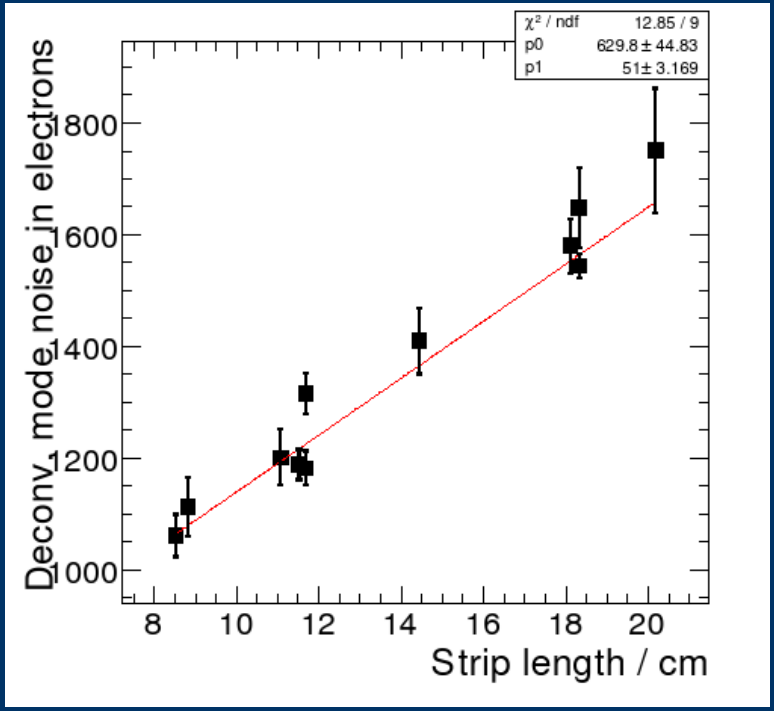




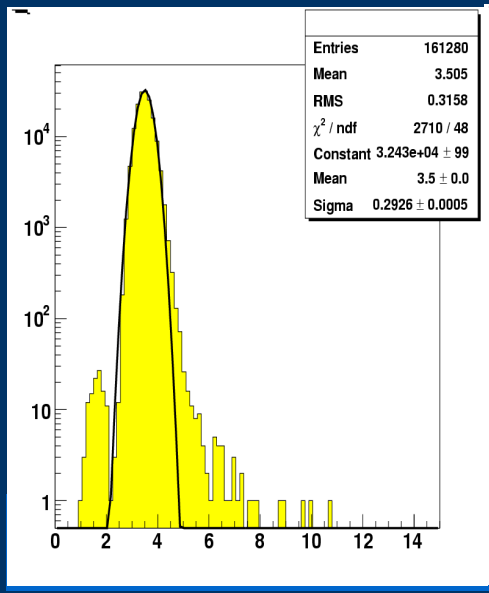
The CMS tracker: noise performance

Noise performance in CMS-like conditions

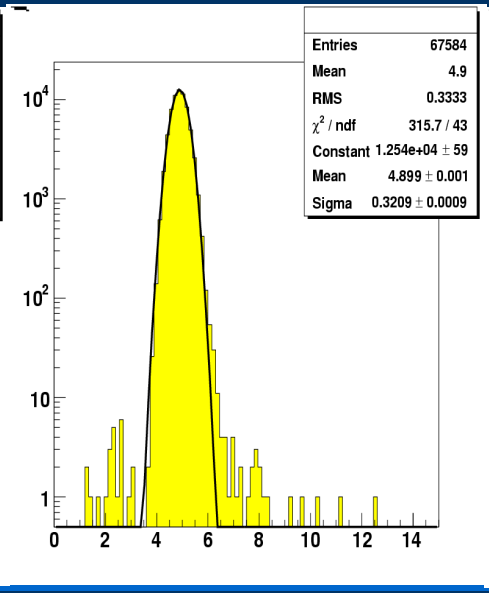
– operating the chip in deconvolution mode - of large-scale structures very satisfactory



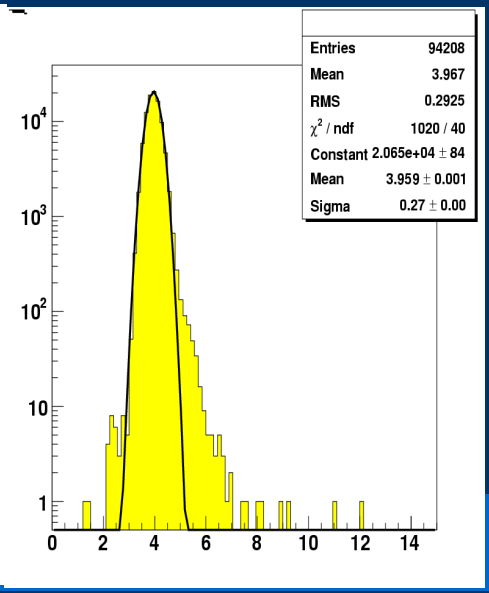
L2 (double sided)



L3 single sided)

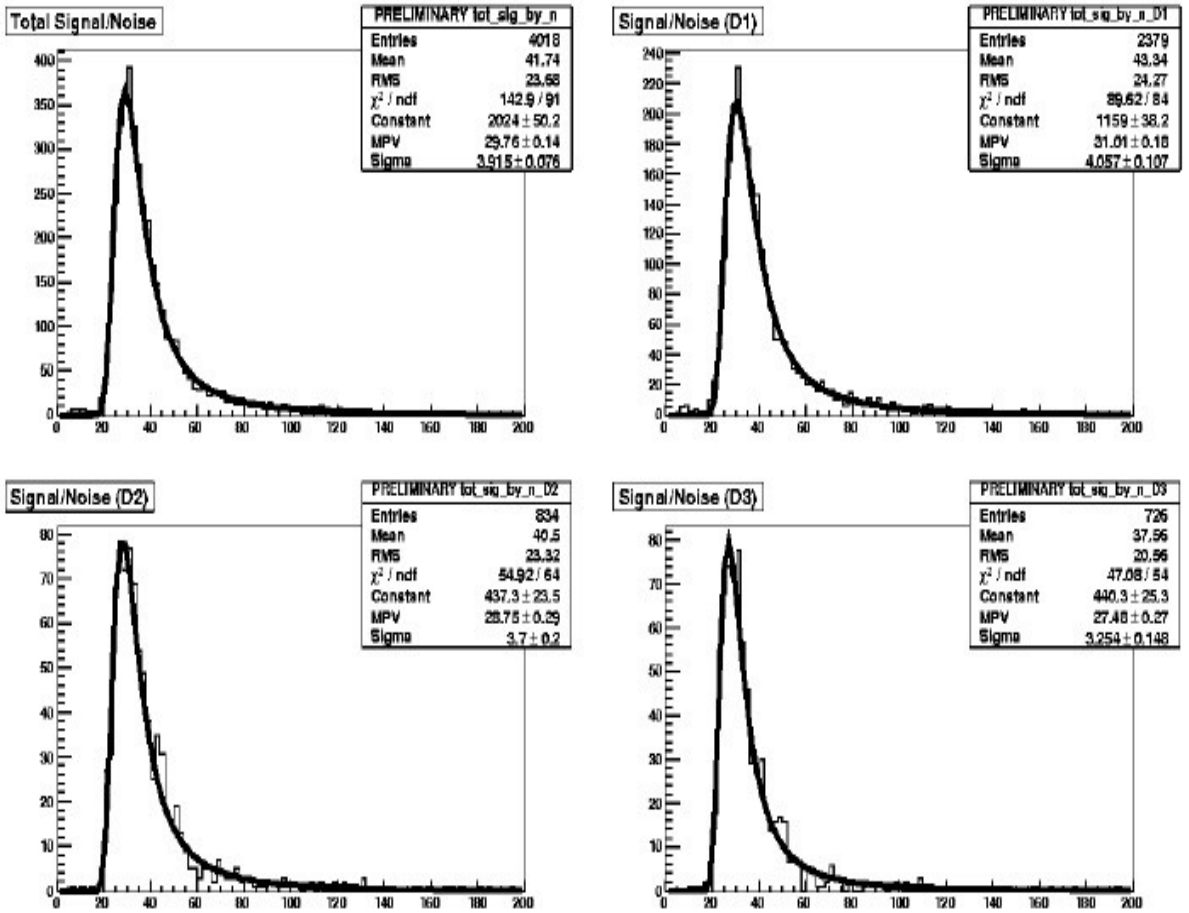


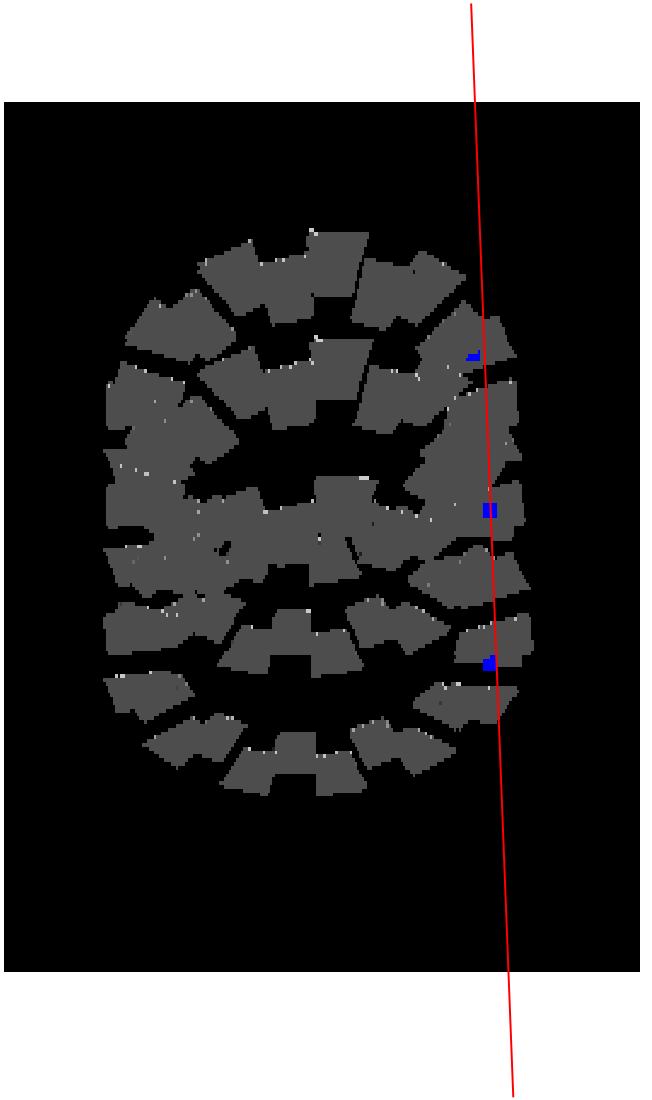
TID



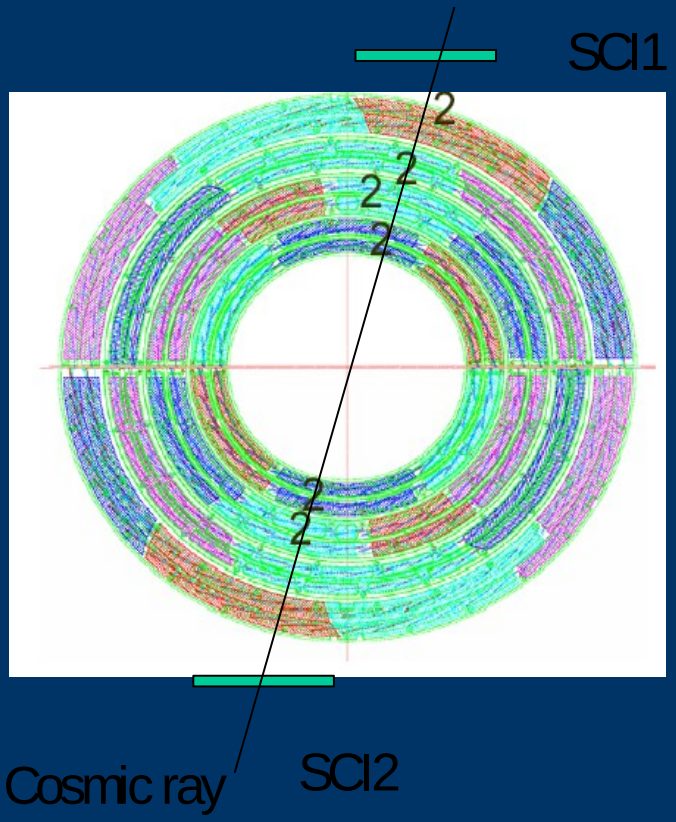
Very, very preliminary results of TID cosmic tests

runs taken in peak mode (3000 ev/run); ~8 Hz (~ 8 FED readout rate with SBS+VME and no zero suppression); **Signal to noise ratio >25 in peak mode.**



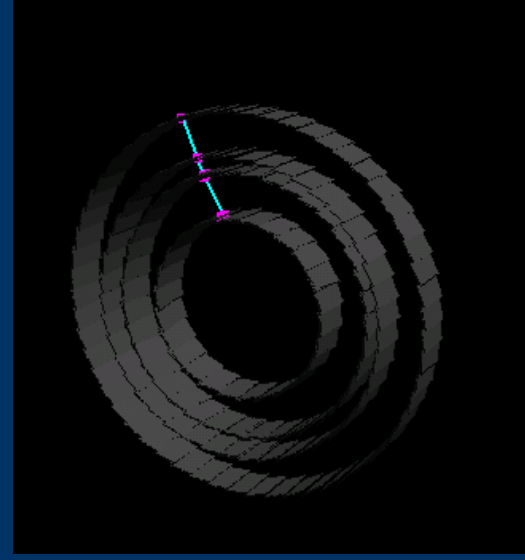


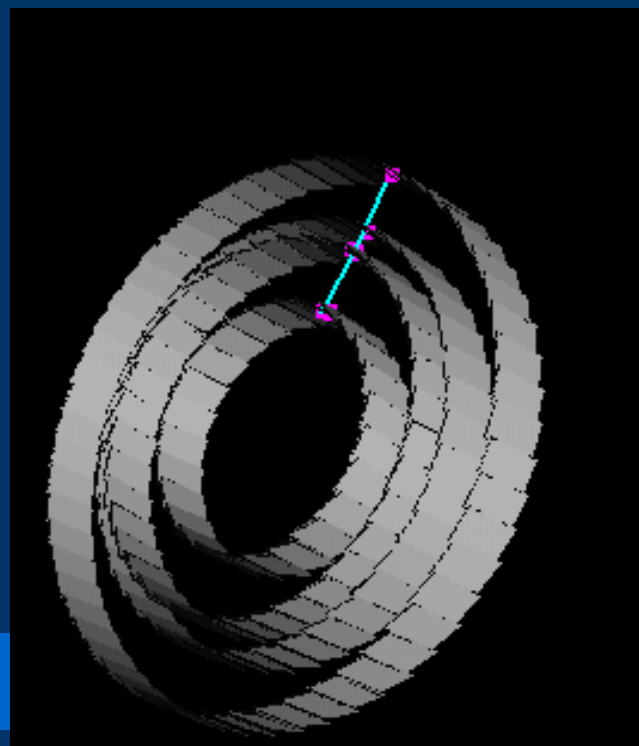
TIB cosmic tests before shipment to CERN



Data sent through full reconstruction in CMS software framework, debugging all steps

pedestal and noise determination
common mode subtraction
clusterization, hit creation
combination of stereo layers
track finding



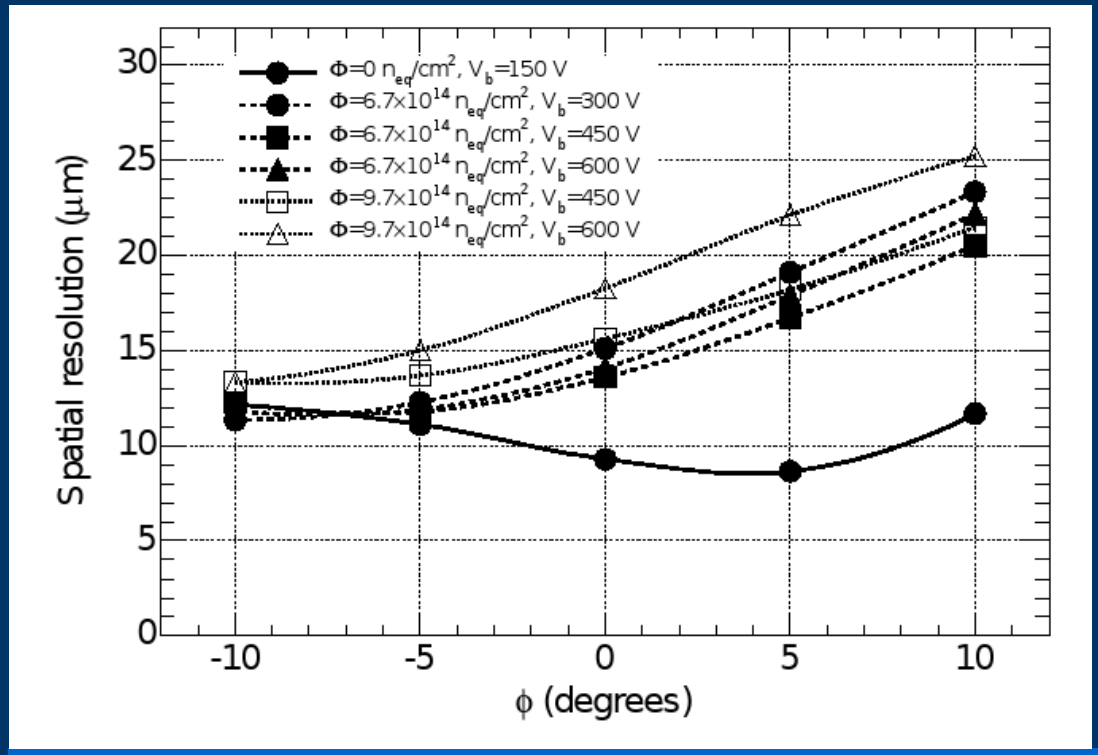


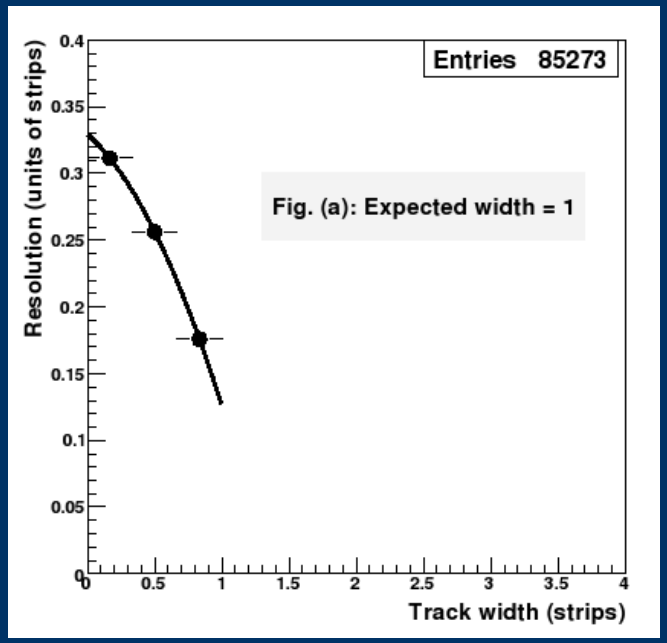
Cooling, powering and reading out a ϕ slice using the validation tests setup

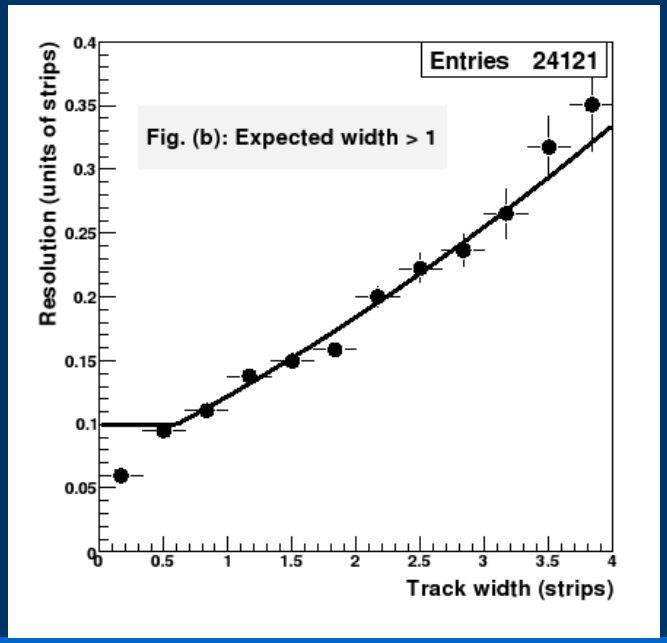
The CMS tracker: expected performance

The CMS tracker: performance

Hit resolution







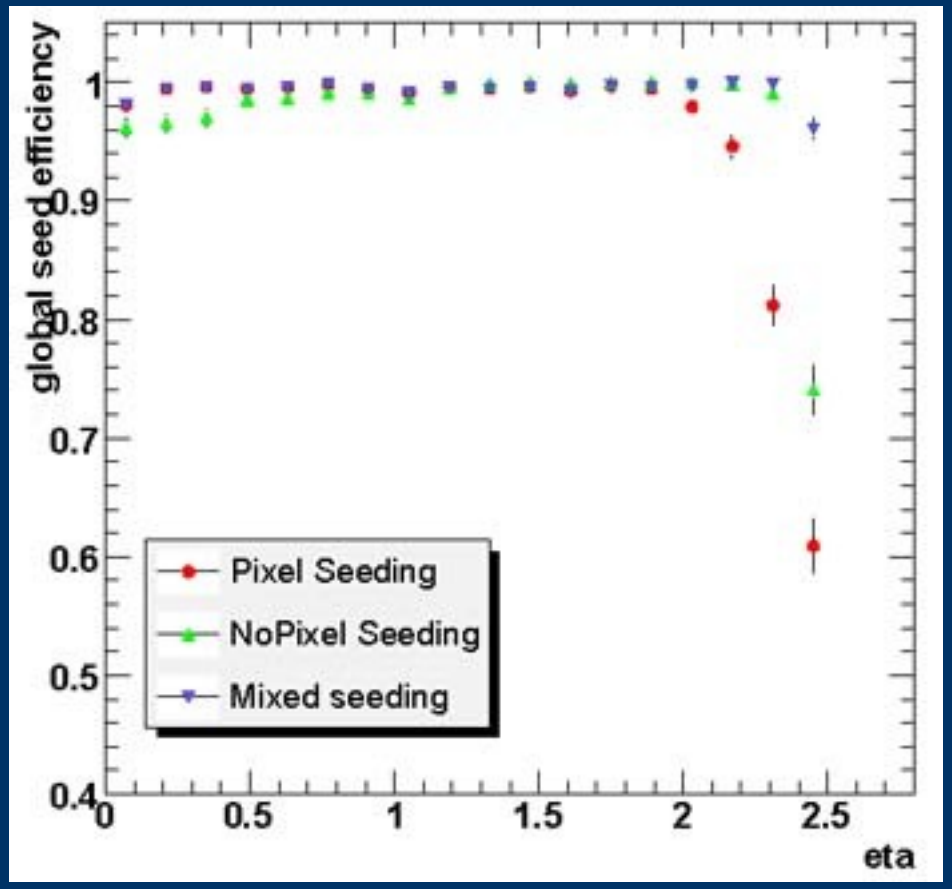
The CMS Tracker: expected tracking performance

- The baseline CMS tracking algorithm:
  - hit pairs + beam constraint used as seeds
    - typically hit pairs are collected on three pixel layers
    - hit pair creation on first TIB layers is possible as well
  - combinatorial Kalman filter trajectory building
    - track stubs are extrapolated to the next layer
    - if more than one compatible hit is found, the track is cloned
    - track stub and hit information are merged to create updated trajectory state
    - trajectory building for a stub is stopped if N (default N=2) consecutive layers fail to yield a compatible hit
    - stubs that have a at least N hits (default N=5) become track candidates
  - trajectory cleaning: if two or more track candidates have too many hits in common, the ones with the best x-squared are kept
  - track fitting: Kalman filter fit
- Alternative: road search or cloud algorithm (from CDF)
- Alternative: pixel-only

The CMS tracker: seed generation

seed generated from hit pairs + beam constraint

pixel-only (red)
innermost TIB layers (green)
combined (blue)

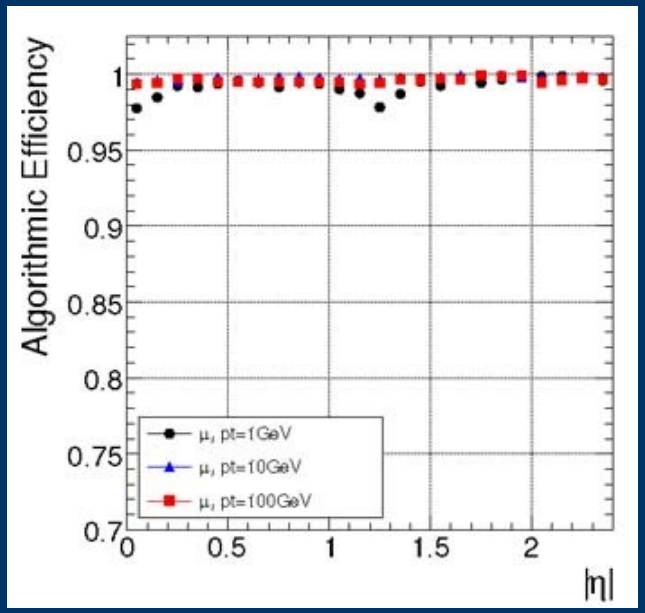


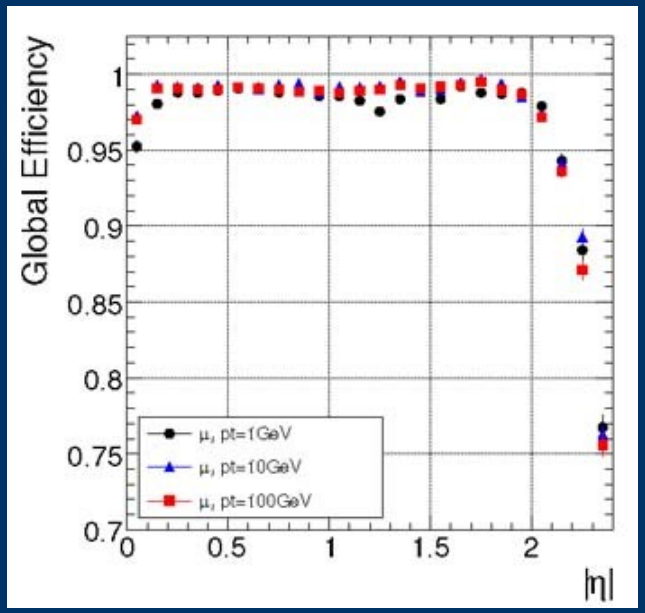
The CMS tracker: expected performance

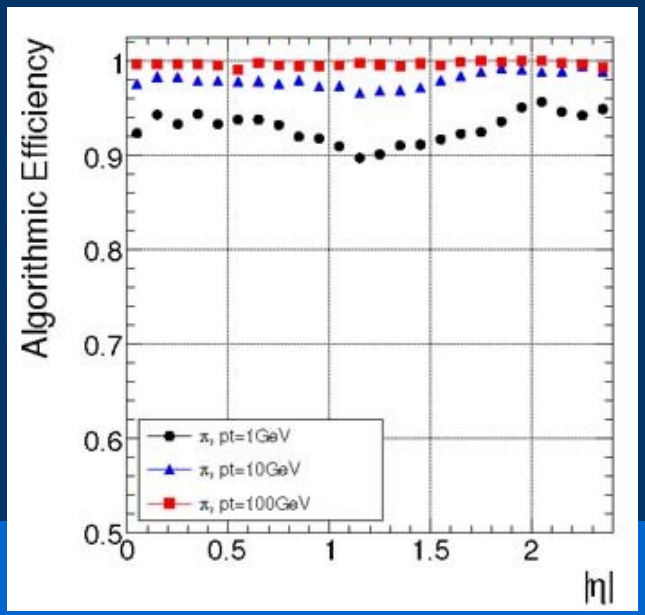
Track finding efficiency:

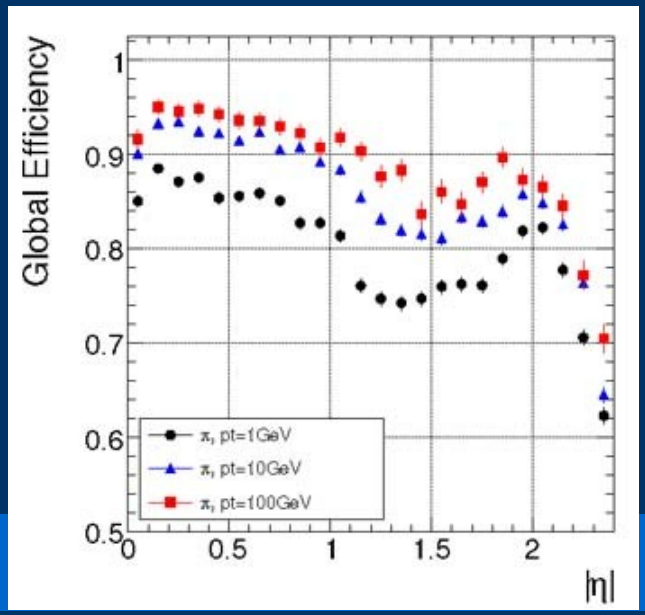
- global efficiency: all tracks
- algorithmic efficiency: tracks producing a sufficient number of hits

Nuclear interactions lead to a significant (global) efficiency loss for pions wrt muons

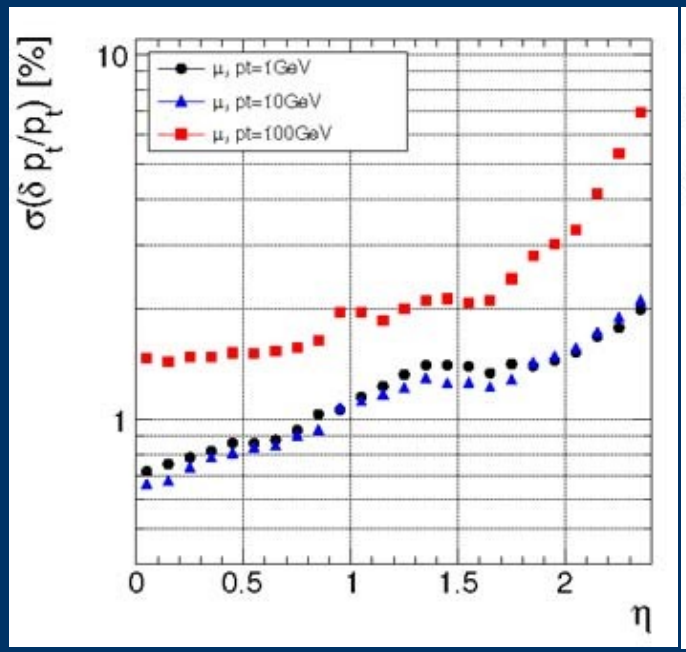


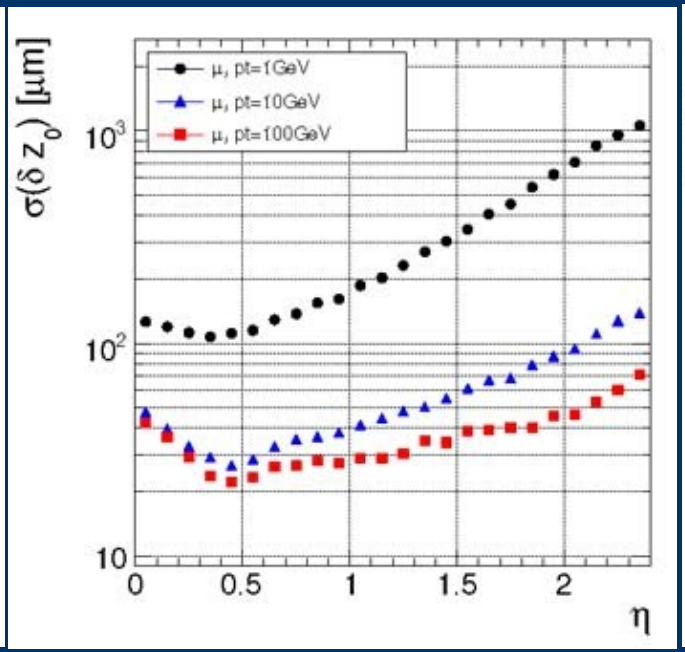


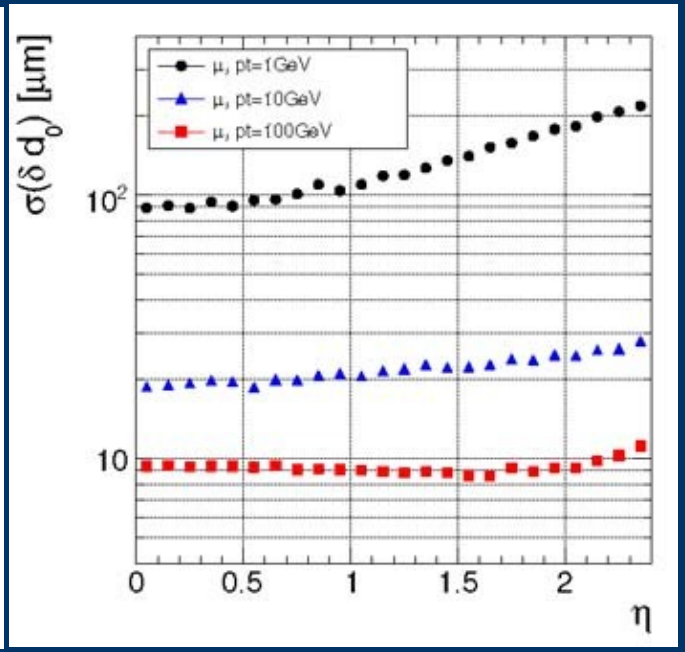




The CMS tracker: expected performance

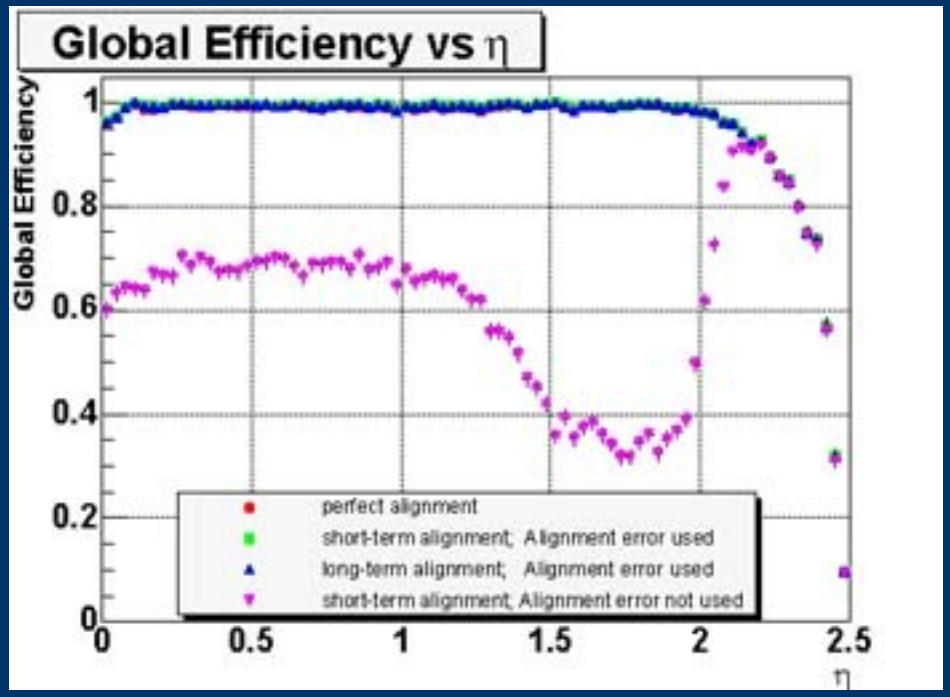


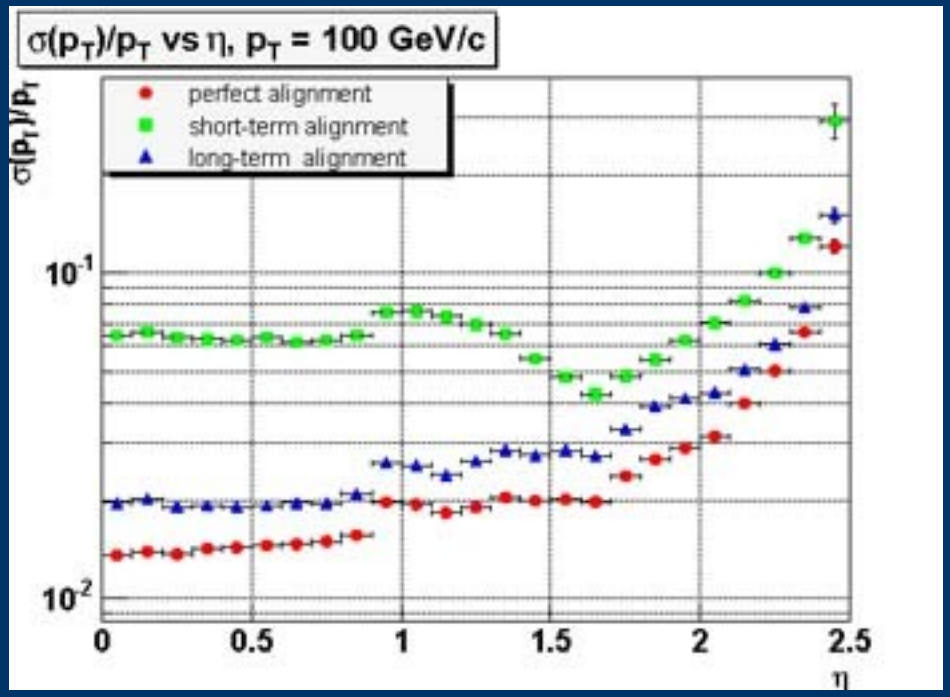




Selected track parameter resolutions

The CMS tracker: expected performance



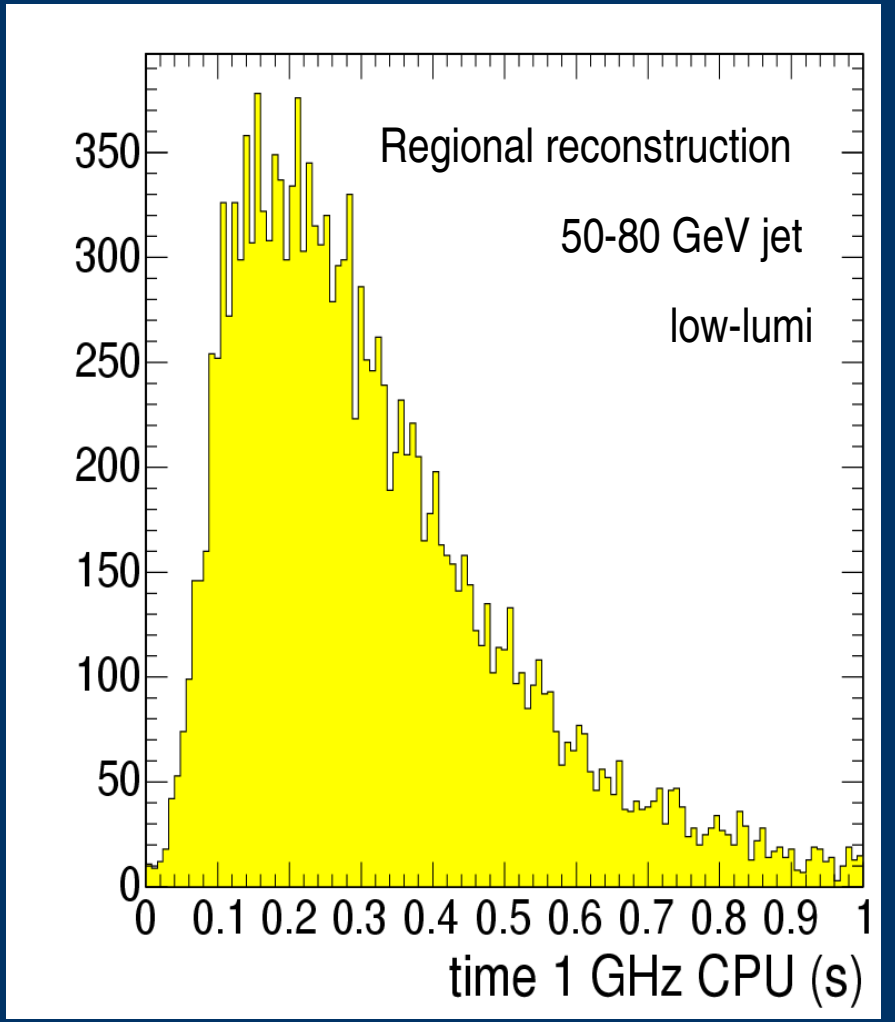


Effect of tracker misalignment on tracking efficiency and track parameter performance
short term scenario: engineering + survey (pixel aligned to 10 microns)
long term scenario: roughly 10 microns throughout

Tracking performance

Timing drives HLT algorithm design

- Track reconstruction with offline algorithm is very time-consuming: global reconstruction of a typical low-luminosity event takes several seconds on a modern-day CPU
- Regional reconstruction allows a considerable speed-up ---->
- Pixel-only reconstruction is an order of magnitude faster than full reconstruction



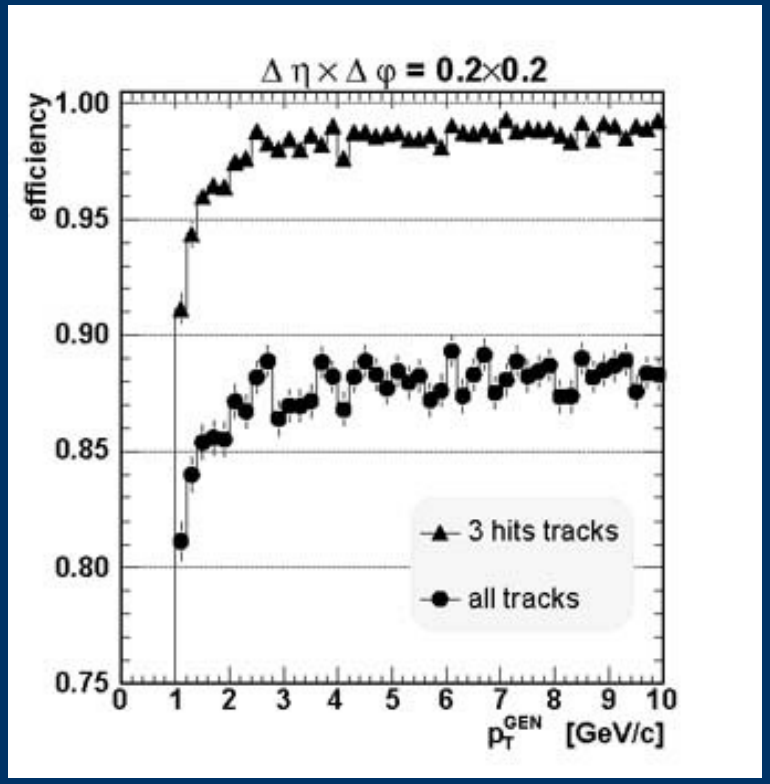
(*) Time measurements include only the pure algorithmic CPU requirement, Digi unpacking, hit creation are not accounted for

The CMS tracker: fast track reconstruction

Pixel-only track reconstruction:

Pixel hit pairs: (+ beam constraint) are used as seeds. Fully efficient, but very poor purity (10s of seeds per track)

Pixel hit triplets:
a fake rate of 10 %, even better when region constraints are applied.
efficiency limited by three-out-of-three requirement



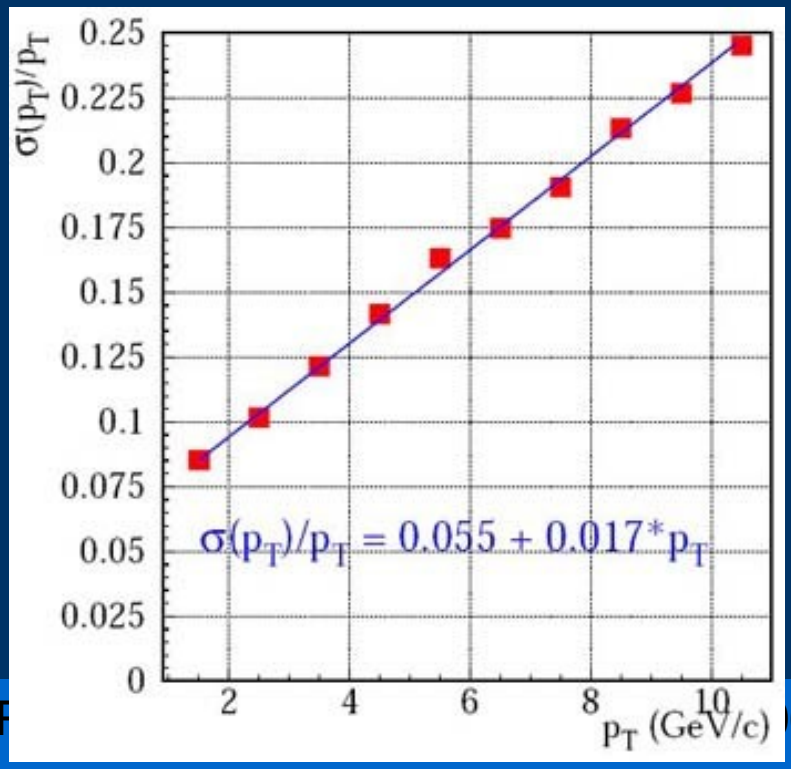
Tracking performance

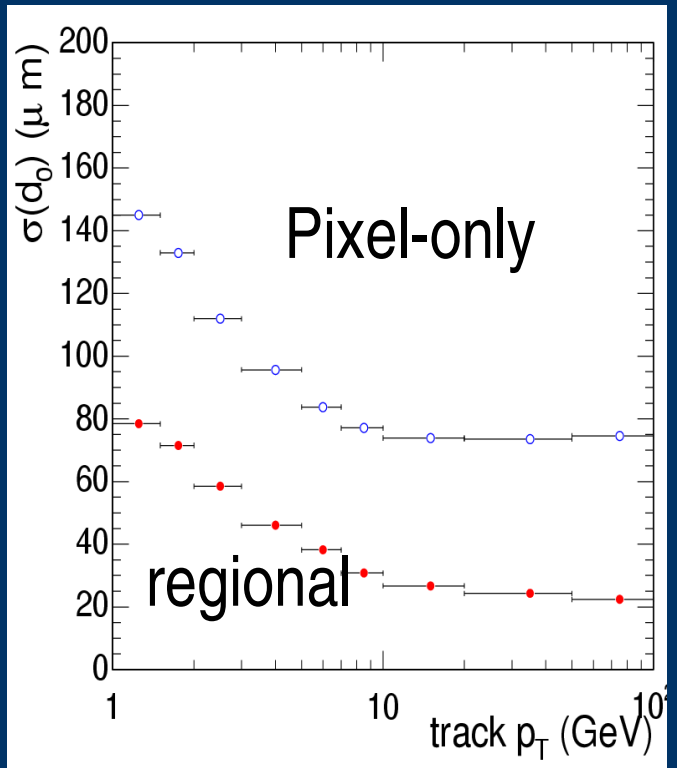
fast track reconstruction

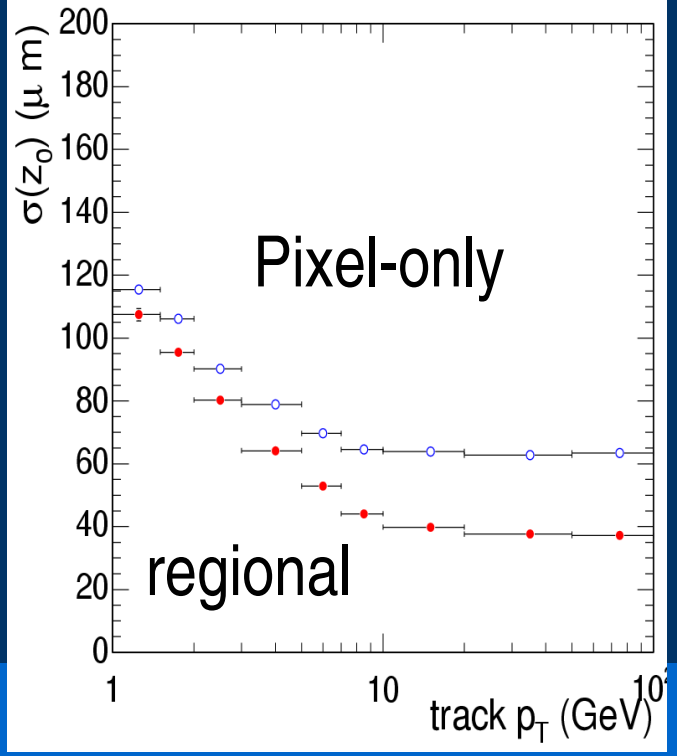
Three pixel measurement at radii of 4, 7 and 11 cm

Transverse impact parameter resolution suffers from small lever arm

Pixel-only impact parameter resolution affected strongly in transverse plane

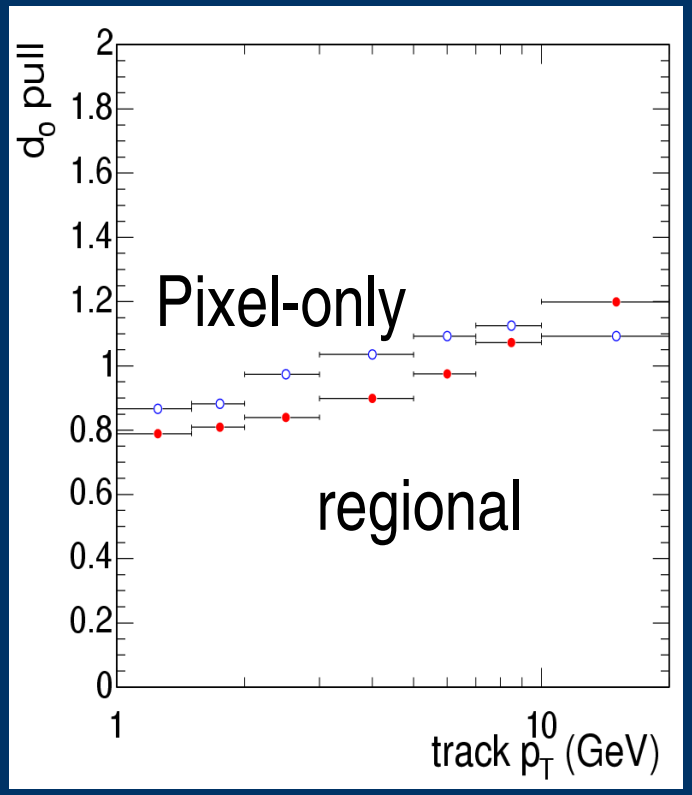


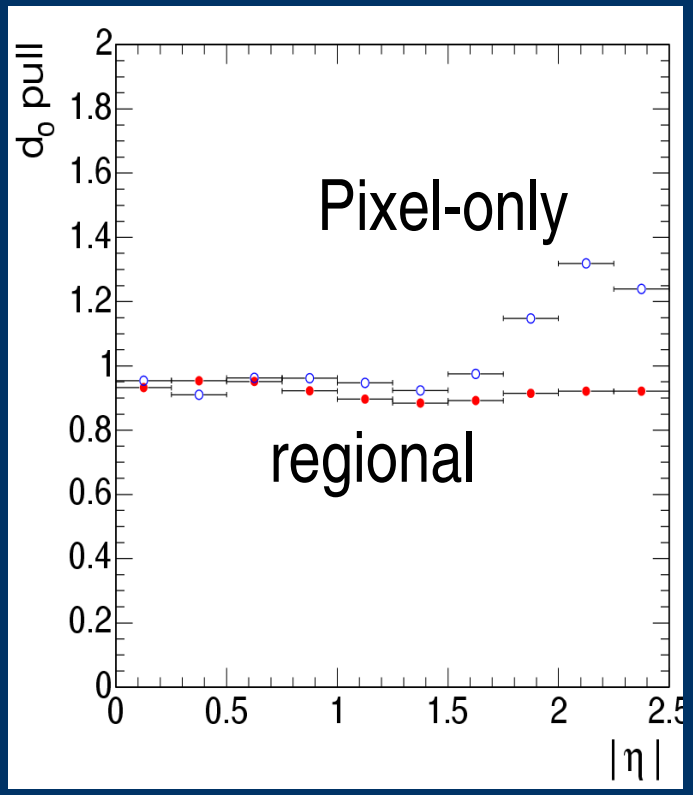




Tracking performance

error estimates





For lifetime b tagging errors are as important as measurement

Pixel-only reconstruction obtains errors precise to within 20% using:

- iterative hit clustering
- multiple scattering parameterisation
- numerical recipe to determine impact parameter errors

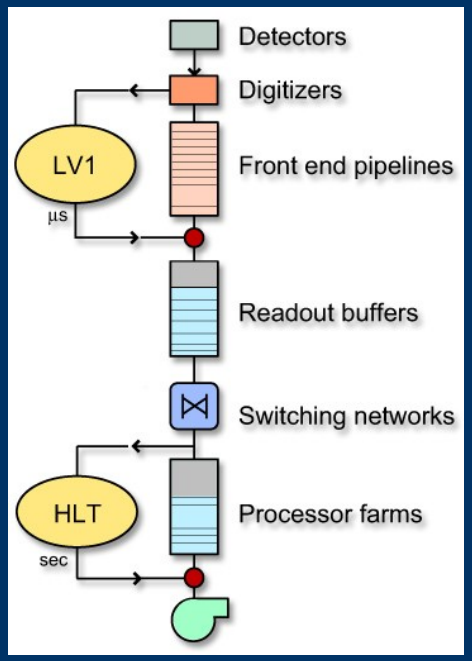
The CMS tracker: usage in the trigger

The CMS trigger

CMS

LVL1: 100 kHz

HLT: 150 Hz

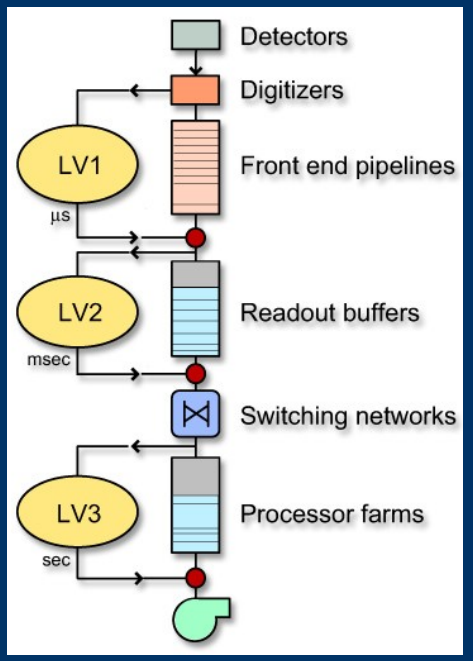


ATLAS

LVL1: 75 kHz

L2: 2 kHz

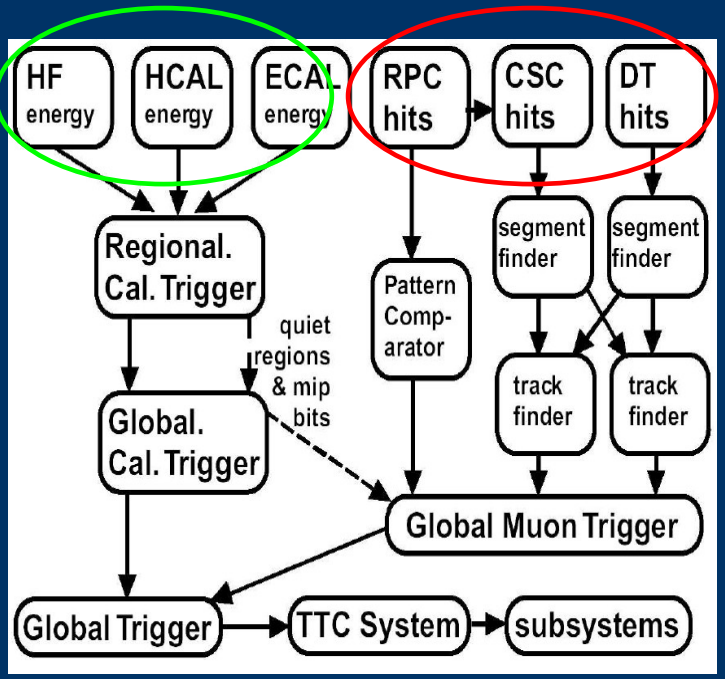
L3: 200 Hz



In the HLT:

- full-granularity information from the complete detector is available
- Flexible software environment on a filter farm; algorithms of arbitrary complexity can be used (similar to the offline)
- Most important constraint is the available CPU time

The CMS trigger: first-level



- Input: 40 MHz
- Output: 100 kHz
- information from calorimeters and (dedicated) muon stations
- processed in FPGAs
- Latency ~ 3μs

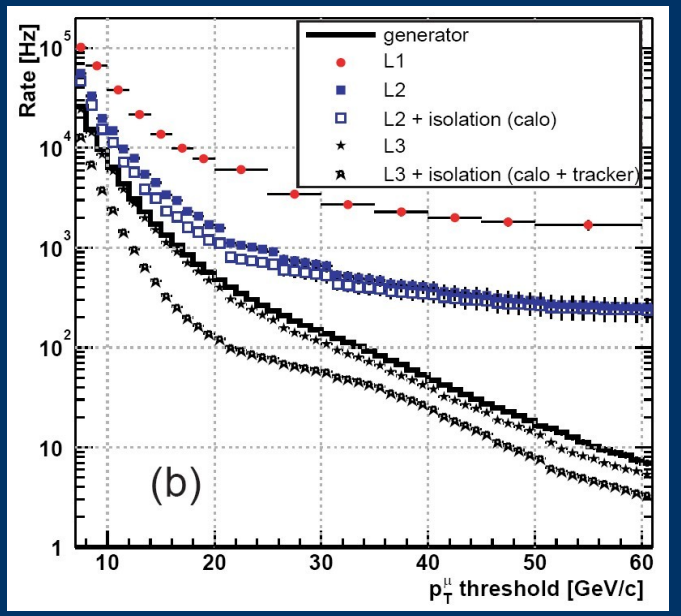
No tracker information in L1 foreseen for CMS(*)

(*) Some R&D scenarios for Super LHC foresee tracker L1 trigger capacity already before 2015

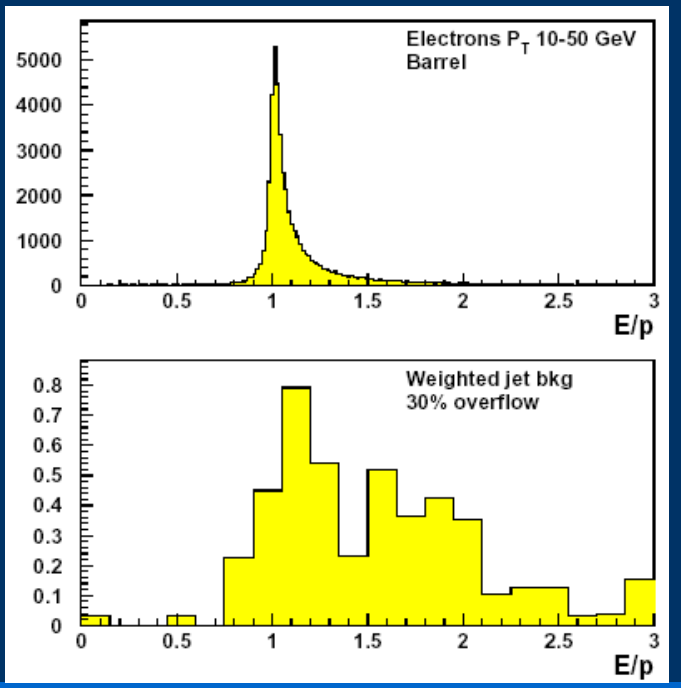
The CMS HLT: role of the tracker

Muons: tracker information is required to confirm muon chamber candidate, to ensure sufficient resolution of the muon trigger. Isolation may reduce the rates even further.

(muon rate @ 10^{34} cm^{-2} s^{-1}, CMS DAQ TDR (LHCC 2002-26)) –>



Electrons: confirmation using pixel seed leads to a crucial reduction of the (π^0) background. Matching of track and ECAL cluster (E/P) allows further refinement



b/τ: Identification of b- and hadronic τ-decays only (efficiently) possible using the tracker

CMS "trigger table"

Trigger	L1		HLT	
	threshold (GeV)	Rate (kHz)	threshold (GeV)	Rate (kHz)
μ	14	2.7	19	25
e	29	3.3	29	33
γ			80	4
τ-*jet*	86	2.2	86	3
1,3,4-jet	177,86,70	3.0	657,247,113	9
1,3,4 b-jet			350,150,55	17

Low-luminosity (2×10^{33} cm^{-2} s^{-1}) indications for thresholds and rates for selected triggers from the DAQ-TDR LHCC 2002 / 026 table. Thresholds are given as 95% efficiency points. L1 rates contain a safety factor ~ 3, to take into account systematics uncertainties

Online τ-tagging

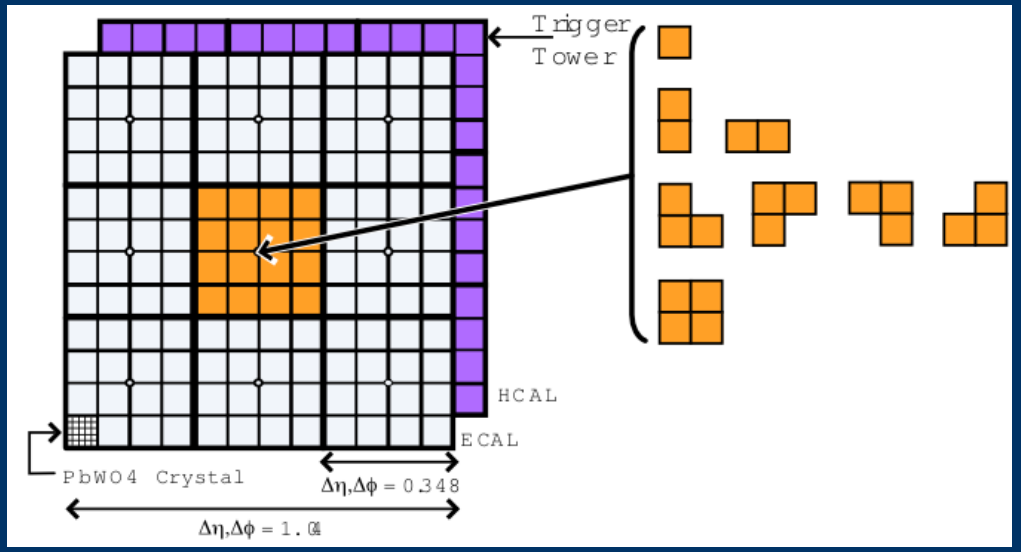
calorimeter selection

Primary interest comes from MSSM Higgs bosons

Most t leptons decay hadronically. Experimentally they can be distinguished from QCD jets as τ-jets are low multiplicity much more collimated than QCD jets at the same E_T.

L1r equires an energetic (95% efficient for $E_T > 86$) calorimeter cluster.

A j et veto is applied: the calorimeter cluster is accepted only if the active towers are distributed in narrow patterns



Calorimeter reconstruction of first two L1 candidates is refined in the HLT.

$$P_{isol} = \sum_{\Delta R<0.40} E_T - \sum_{\Delta R<0.13} E_T$$

Online τ-tagging

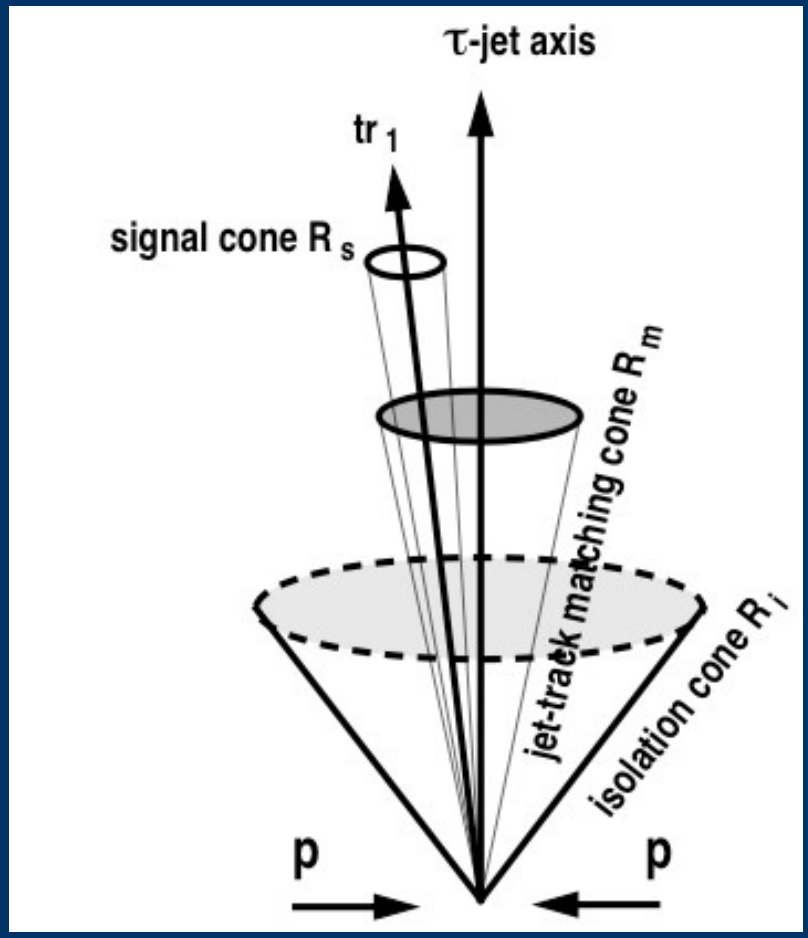
tracker isolation

Tracks are reconstructed in a region of interest (jet cone R_m). Selection:

- Associated to the Primary Vertex
- $p_T > 1$ GeV/c

P_T of the Leading Track (i.e. highest p_T track) must exceed a treshold of ~3-6 GeV/c

Isolation based on the number of tracks inside isolation cone (R_i) is applied.

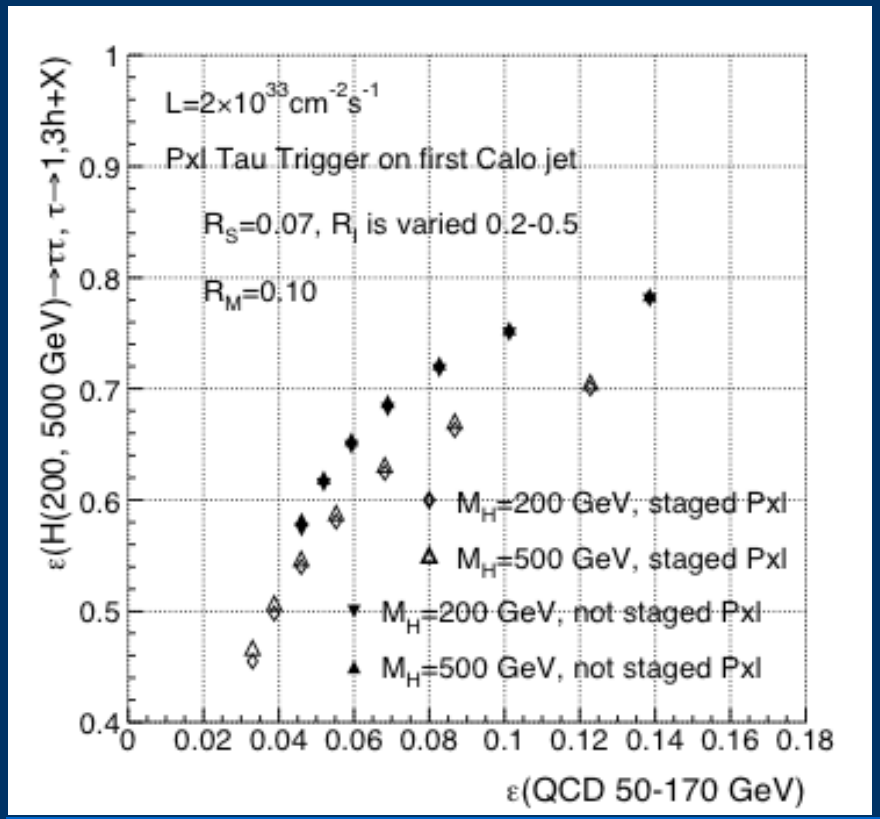


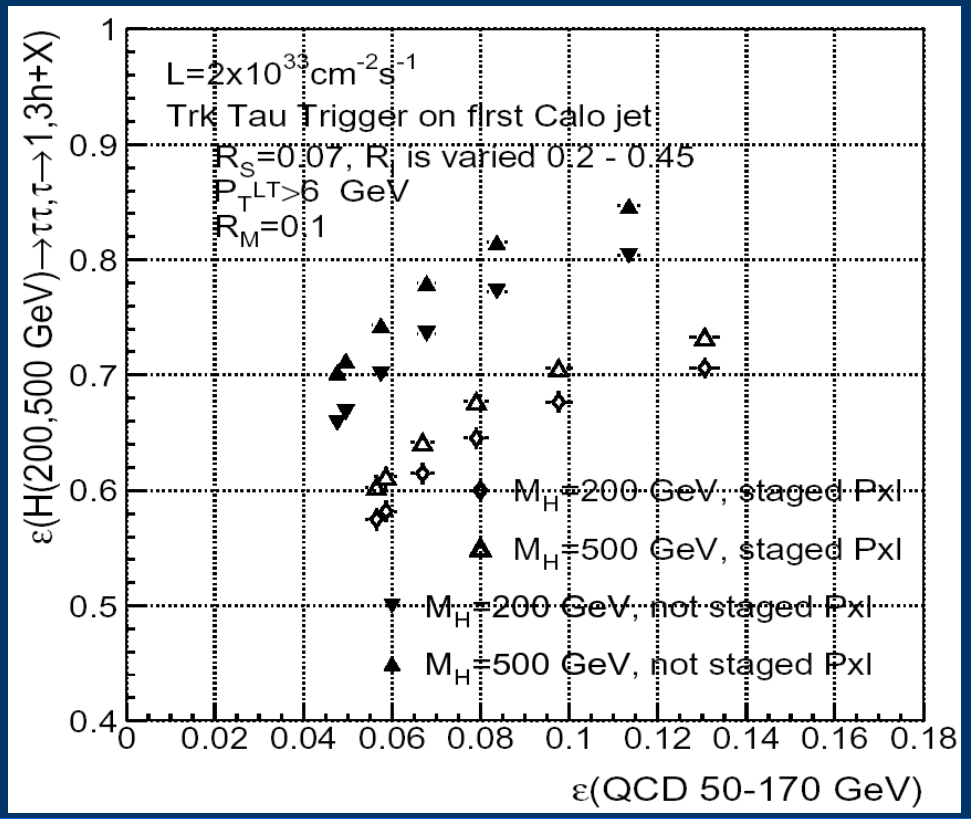
Online τ-tagging

tracker selection

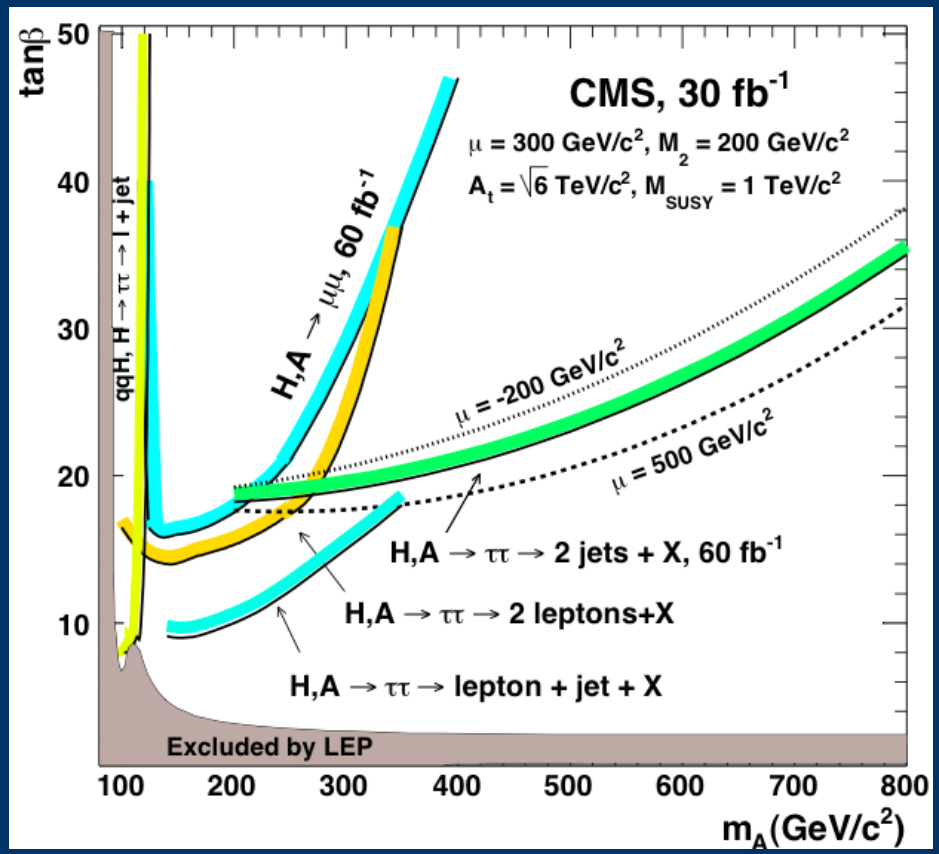
Pixel-only and full tracker τ-identification/isolation at low luminosity

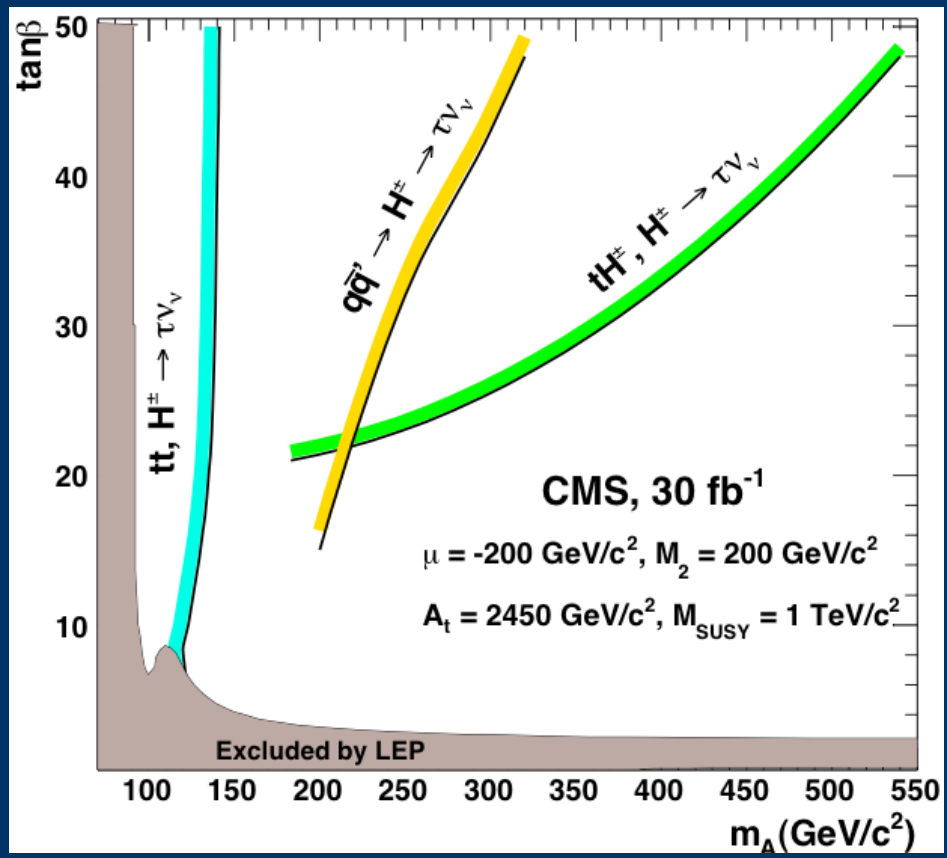
Complementary speed vs precision performance: pixel-only used for di-τ trigger, full-tracker for single τ





τ-jet trigger





Many important discovery channels involve τ leptons in the final state. For hadronic decays of τ leptons with sufficient transverse momentum (greater than 86 GeV/c), tracker-based identification/isolation allows efficient online event selection.

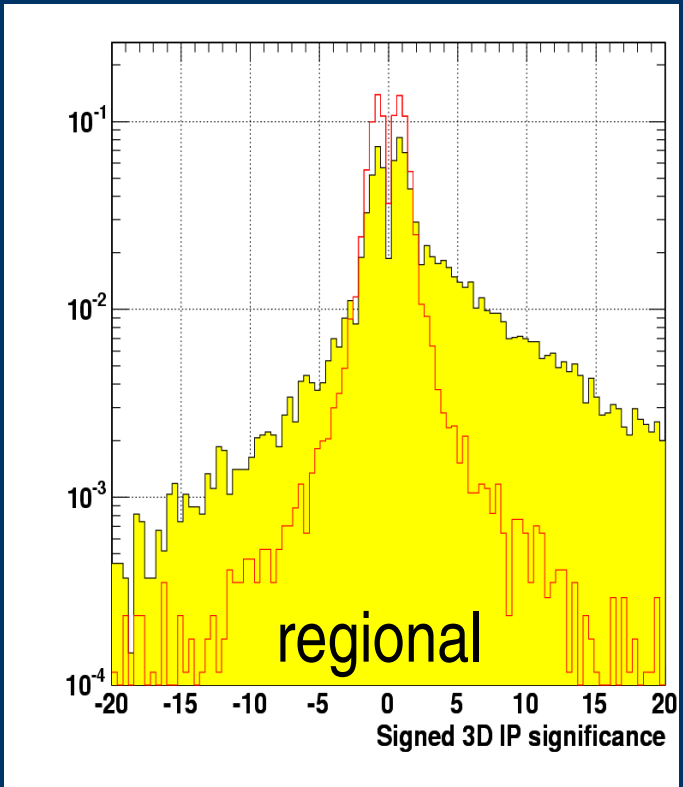
Online b-tagging

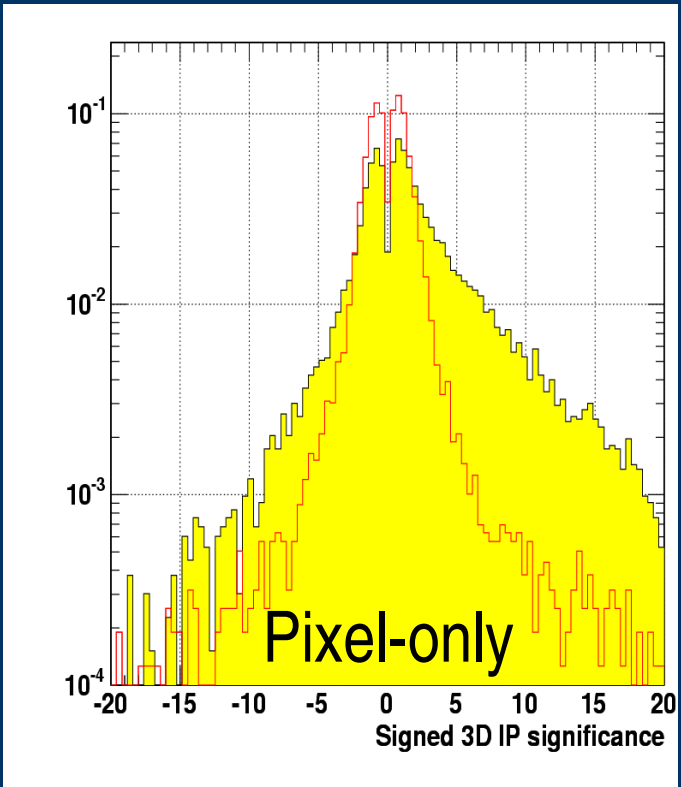
Hadronic final states (i.e. without isolated leptons or photons) are hard to trigger in LHC. Enormous QCD production drives the inclusive jet trigger thresholds for 1st, 3rd and 4th jet to 657,247,113 GeV. Compare CDF, where hadronic top mass and cross section measurements used the 4-jets trigger with a 10 GeV threshold.

The rejection that can be efficiently reached is limited by bb production to a factor ~20 (Roughly 5% of QCD events with a sufficiently hard scatter contains at least one b-quark).

Online b-tagging may help for fully hadronic final states with at least one hard b-jet in the tracker fiducial region. Our benchmark channel: hadronic decays of top pairs.

Online b-tagging

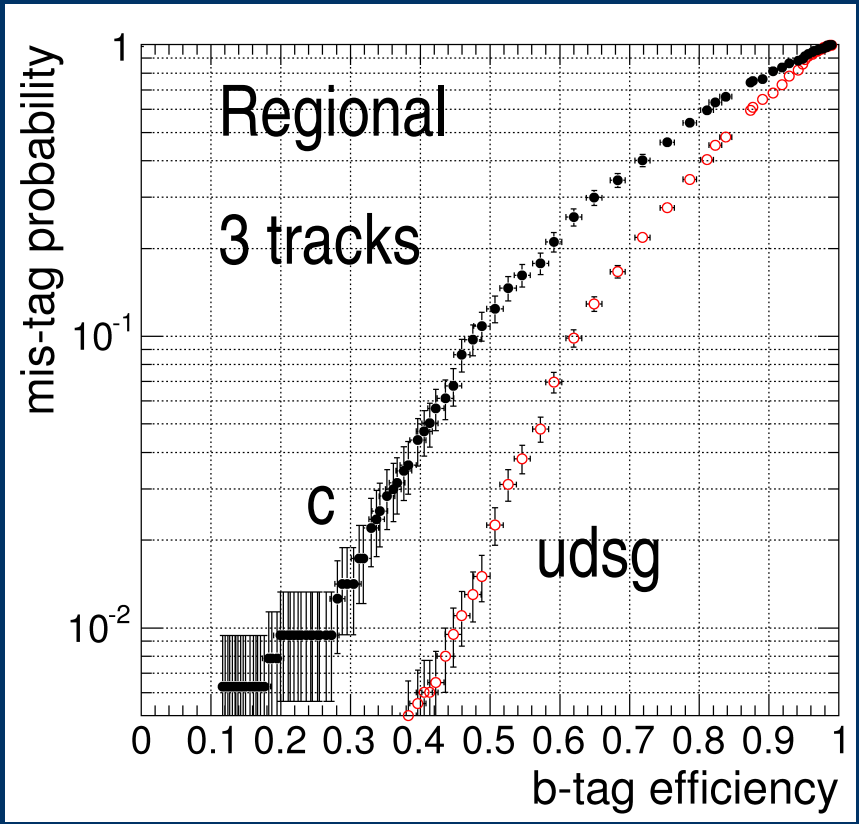


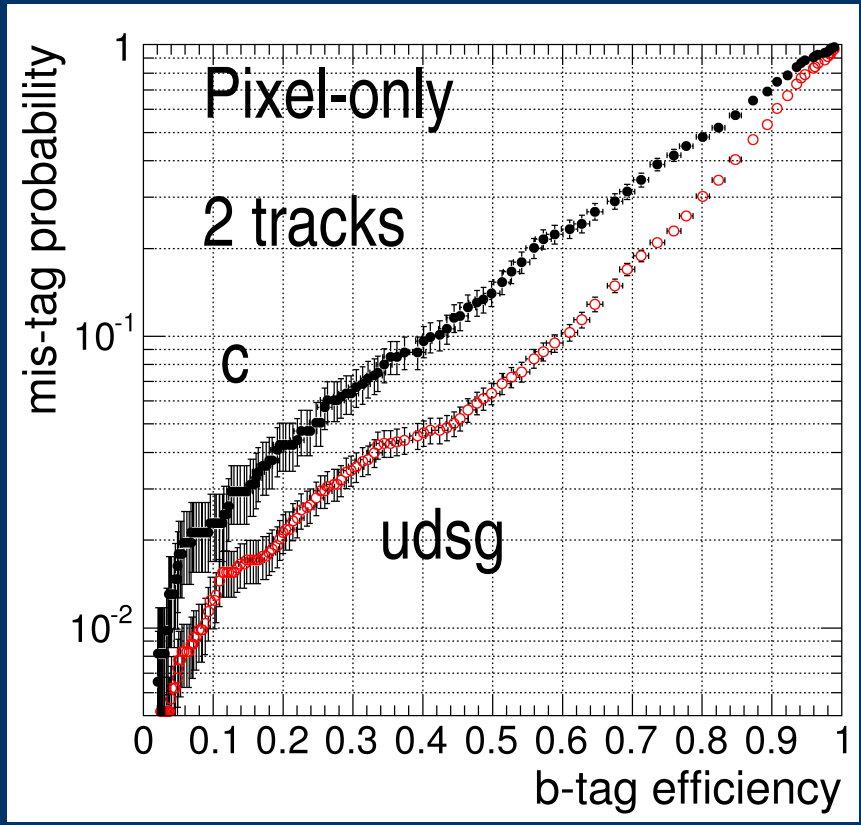


50-80 GeV jets in di-jet events with low-lumi pile-up, jets reconstructed using iterative cone algorithm on ECAL + HCAL towers, PV from divisive algorithm on pixel hit triplets

Positive tail in signed 3D impact parameter significance shows the tagging power of both approaches

Online b-tagging





Regional reco offers good rejection for ε_b = 50%

Pixel-only works very well at low rejection

Online b-tagging

inclusive b-jets trigger

Complementary performance vs time characteristics of pixel-only and regional algorithm on complete tracker

Results are extremely correlated: the pixel-based pre-selection does not significantly affect the efficiency

- L1 : hadronic streams, but also muon and e/ streams
- L2 : jet E_T thresholds, 350, 150, 55 GeV
- L2.5 : pixel-only b-tag, OR leading and Next-to-leading jet
- L3 : regional b-tag

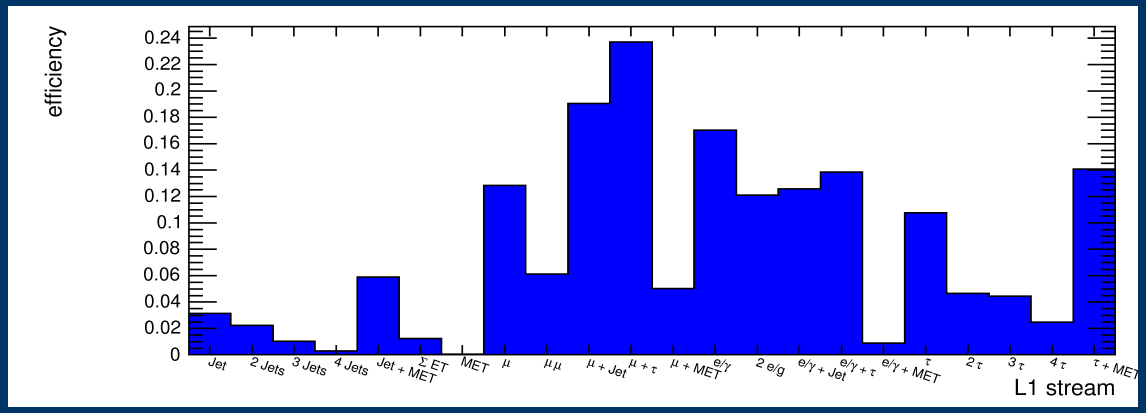
QCD di-jet rate: 16 Hz

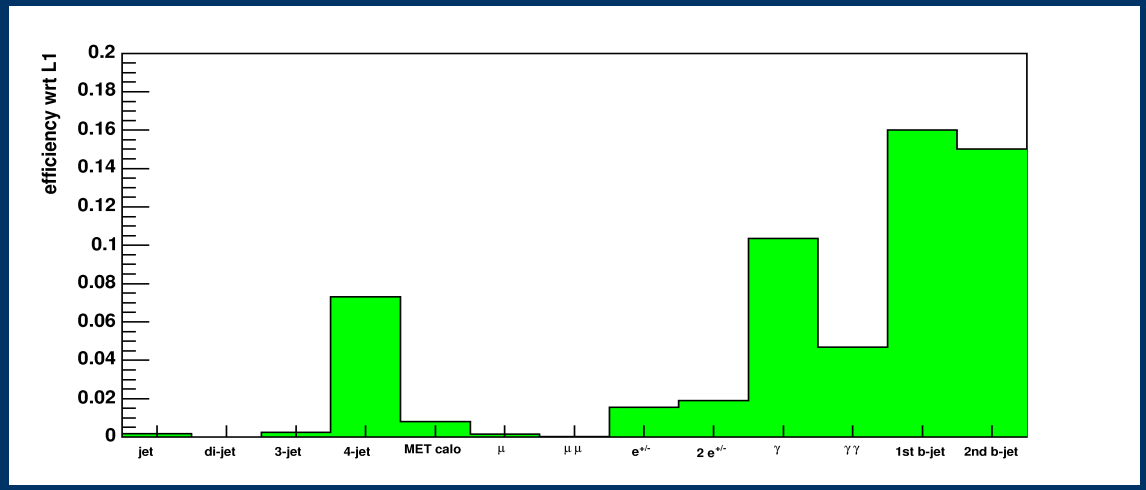
More than half of these events is triggered by at least one other trigger: only 7 Hz are added to existing budget.

Timing: $t = 50\ \text{kHz} \times t_{jet} + 1\ \text{kHz} \times t_{pixel} + 200\ \text{Hz} \times t_{tracker}$

Online b-tagging

signal efficiency





L1 efficiency

Muon+e/γ+jets: 57 %

HLT efficiency

b-jets: 26%

n-jets: 7.5 %

Total jets: 28 %

fully hadronic decays of top pairs.

Total signal efficiency at low luminosity: 16%

Online b-tagging

Fully hadronic final states are of interest at the LHC!

Something simply needs to be done about the high N-jet thresholds if we want to have a decent trigger efficiency for fully hadronic final states like top events. Online b-tagging certainly helps: extra rejection of factor 20 allows to reduce jet thresholds. Signal efficiency = 15%.

Signal inefficiency strongly correlated to offline. Calibration of online selection can be performed, in the same way as the offline b-tagging calibration

Offline isolation of fully hadronic top events and their use for mass and cross-section measurement are being studied (C. Ciocca, U. Bologna, M.V.)

Conclusions

CMS is building the largest-ever silicon-based tracker

Integration of pixel, TIB/TID, TOB and TEC structures well-advanced at various sites

Expected tracking performance – offline and online - is excellent

- regional application of combinatorial Kalman filter based algorithm –> “offline” quality tracks in later stages of the HLT
- pixel-only tracking -> pattern recognition successfull, resolution sufficient for early rejection.

Tracking plays a crucial role for muon and electron triggers AND:

- τ-jet decays of MSSM Higgs bosons efficiently triggered thanks to online - tag
- Inclusive b-jets trigger improves the trigger efficiency for fully hadronic final states.