ATLAS, CMS and LHCb Trigger/DAQ systems for flavour physics

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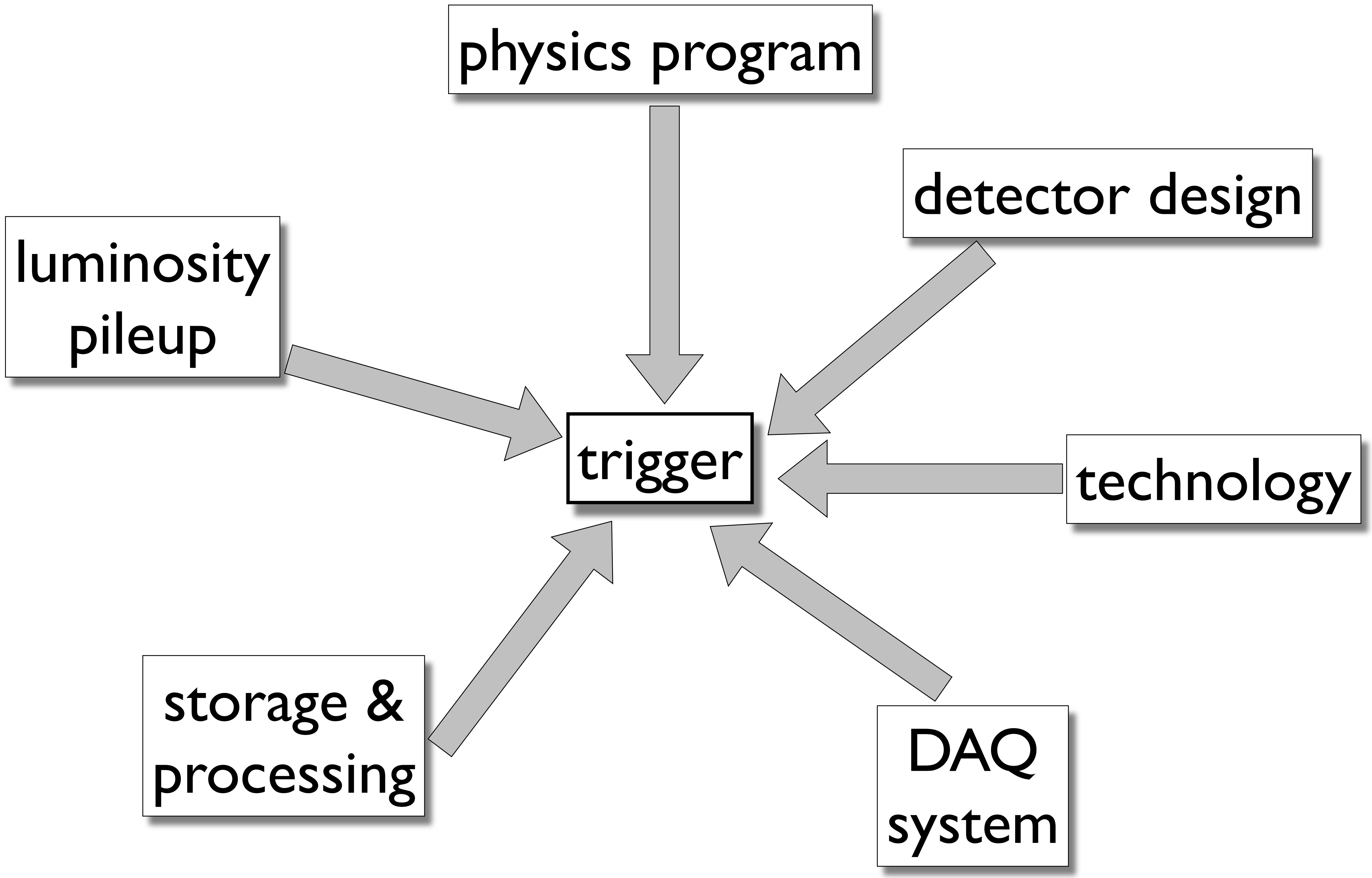
Beauty 2013

Requirements for the trigger system



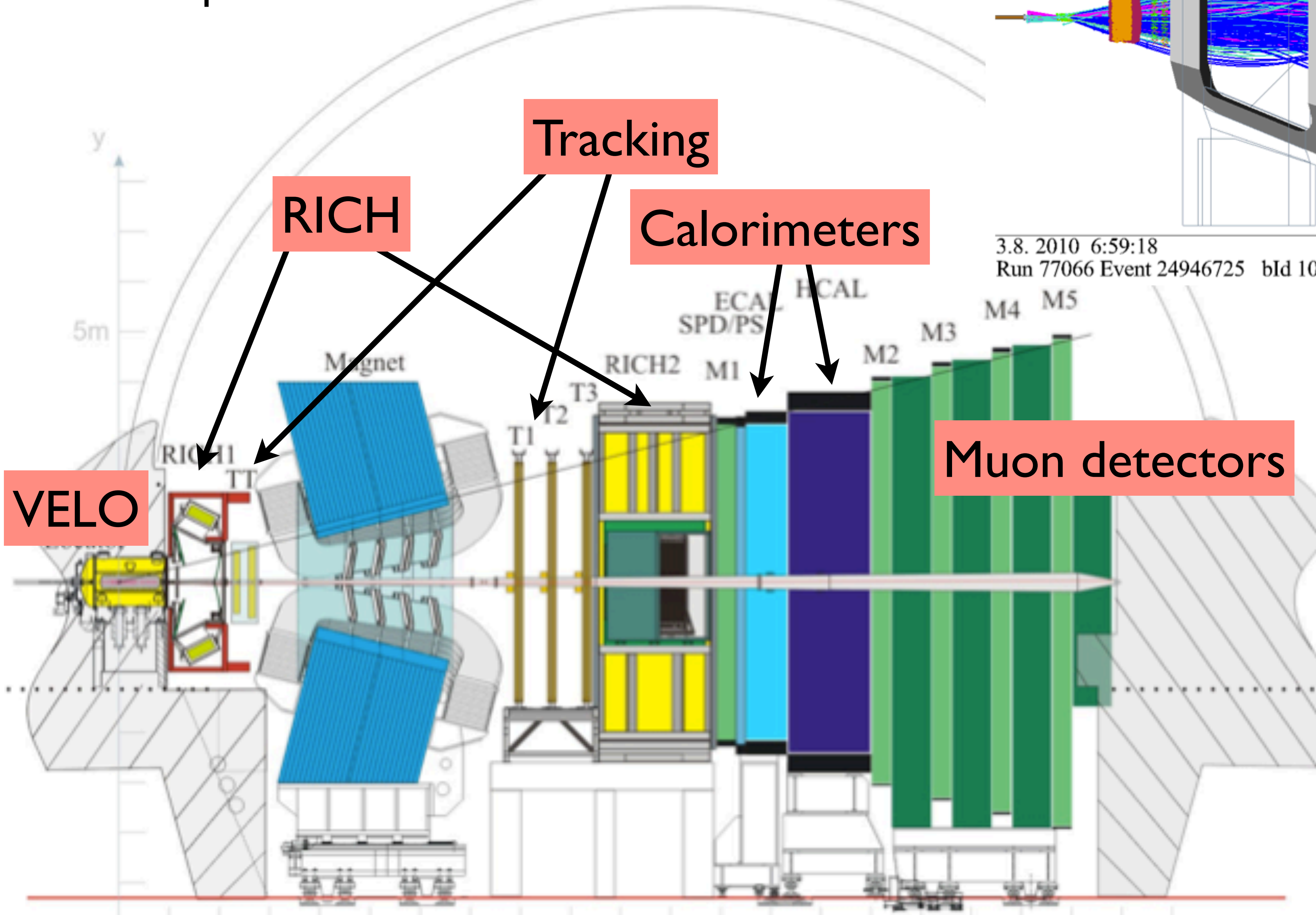
ATLAS, CMS and LHCb Trigger/DAQ systems for flavour physics

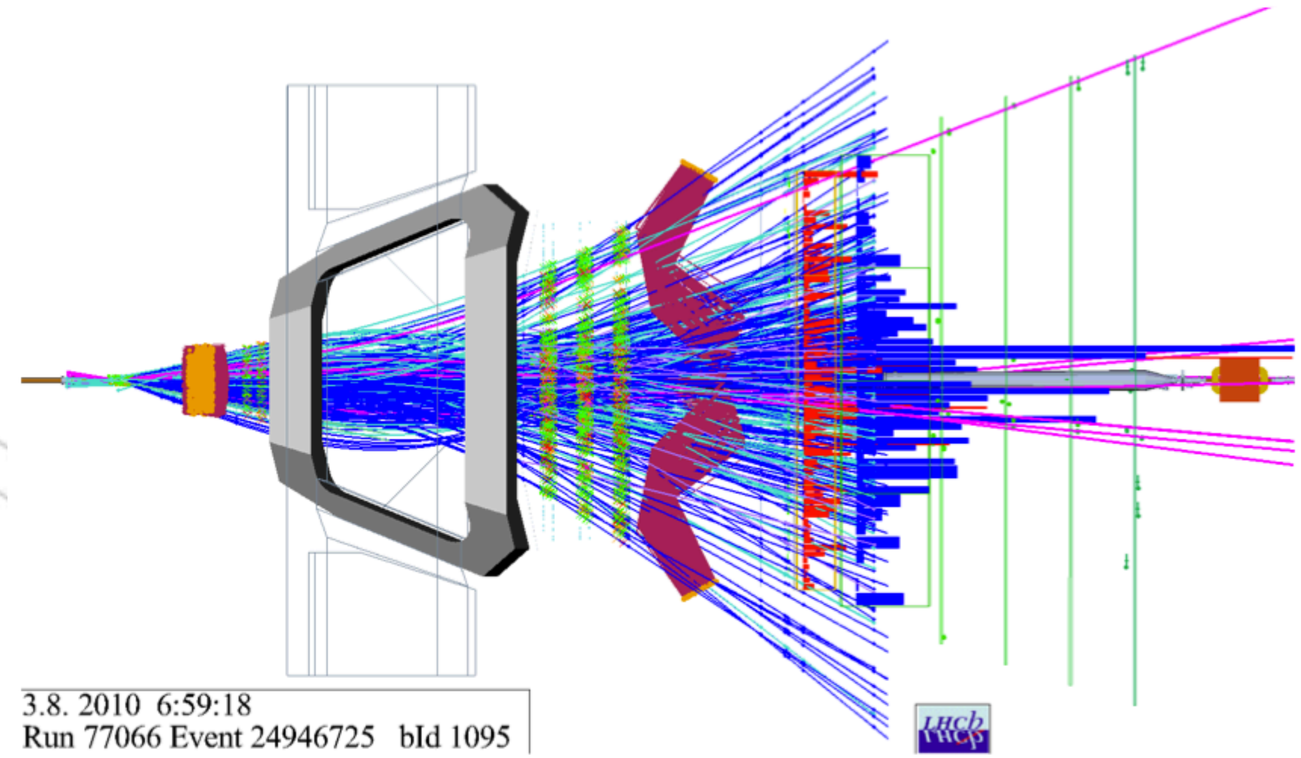
GP detectors
~4pi acceptance
~10^8 channels
highest possible lumi >7E33

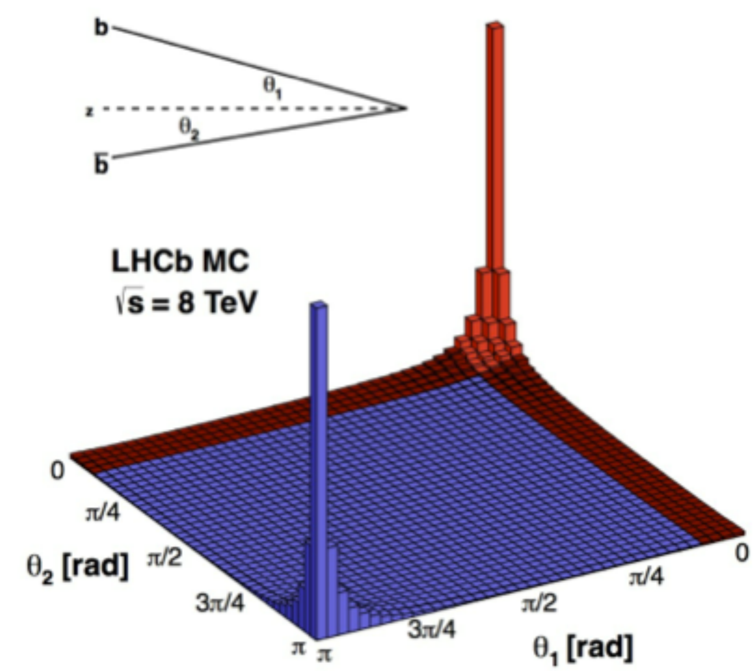
specialized detector
forward spectrometer
~10^6 channels
lumi leveling ~4E32

LHCb detector

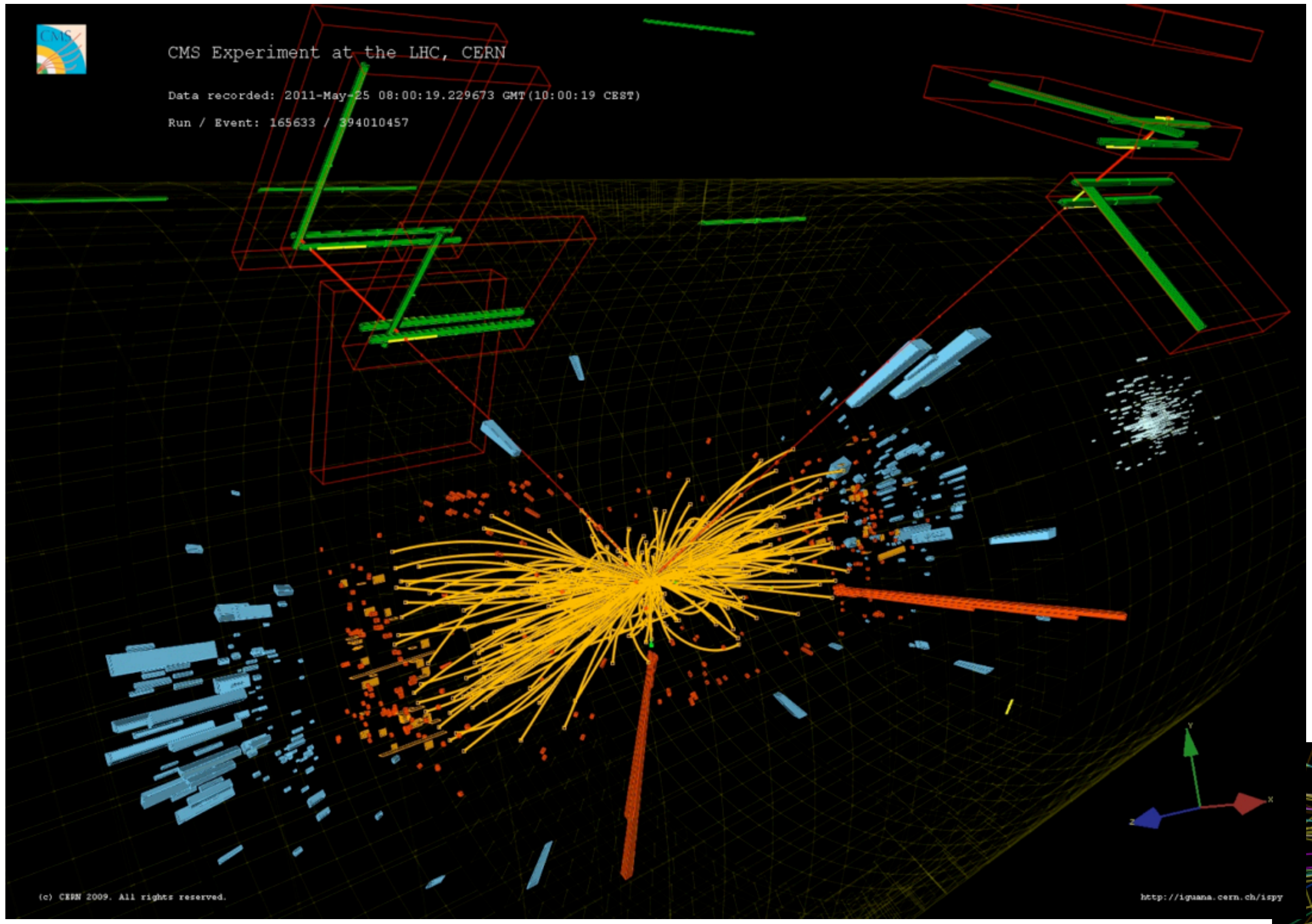
- ~6mb pp->ccX, ~0.3mb pp->bbX
- LHC is a Flavor Factory!
- LHCb: forward single arm spectrometer
- Acceptance 2<eta<5





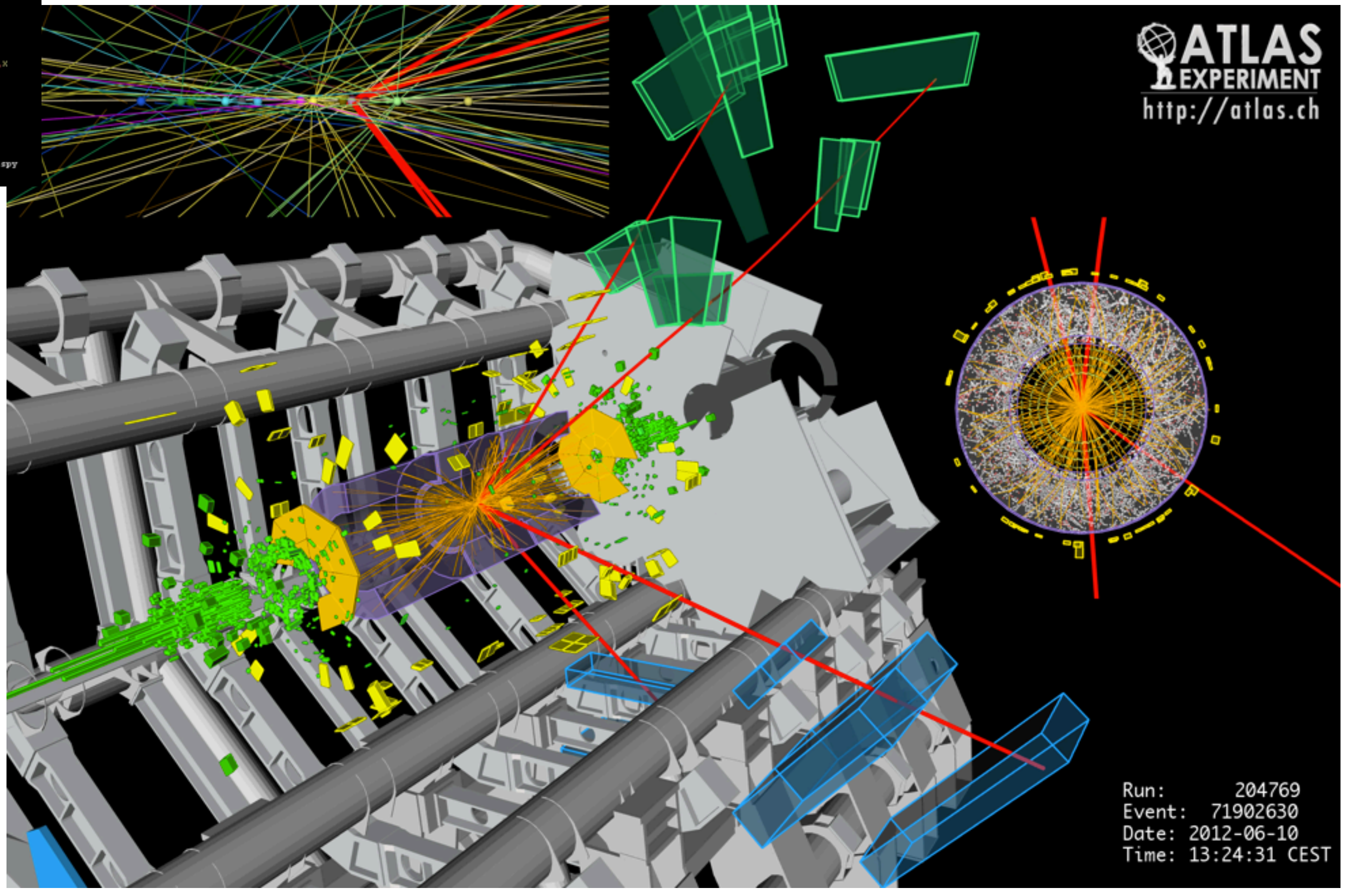


CMS and Atlas event displays



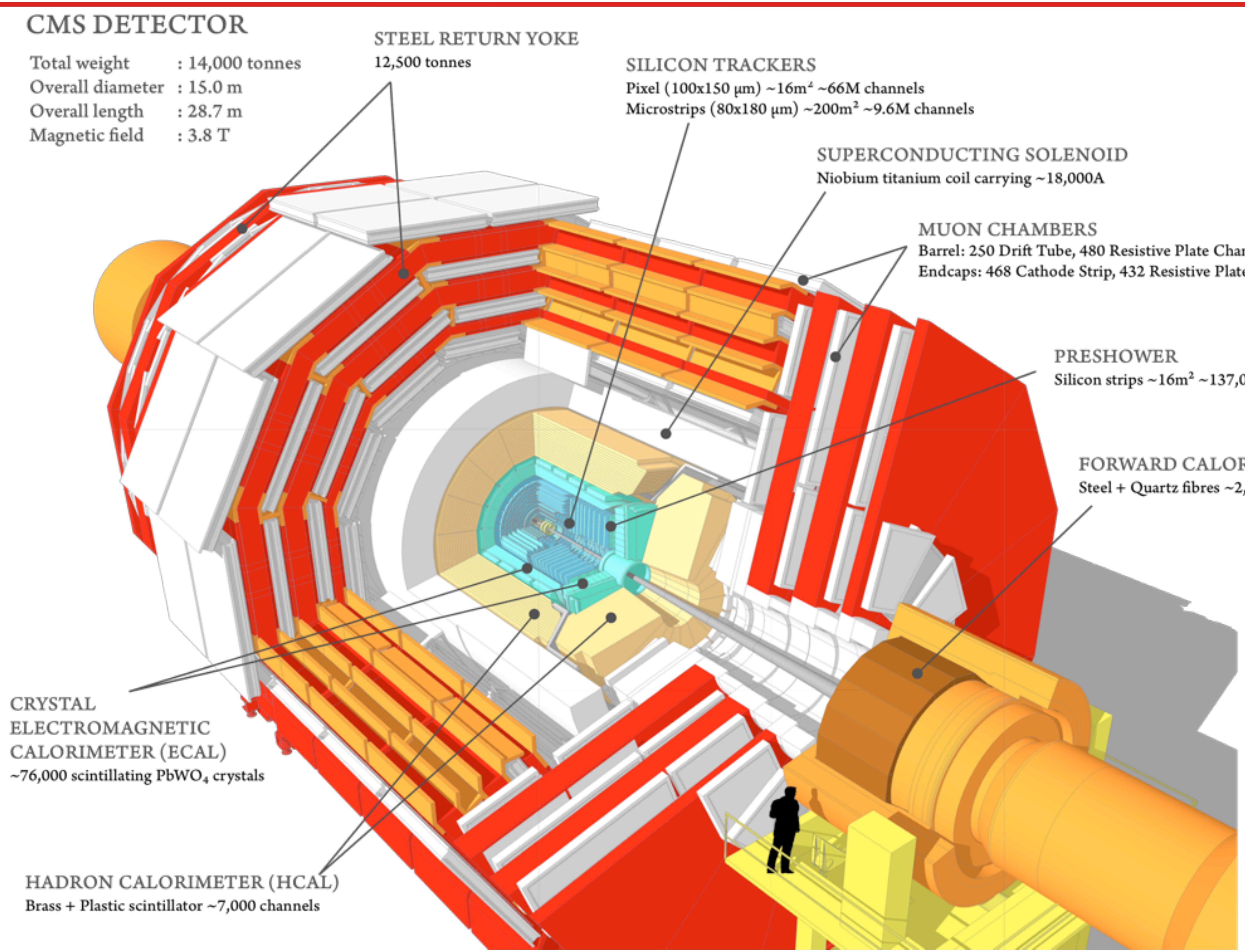
- Detectors optimized for high Pt leptons and jets
  - Higgs search, direct new physics searches
- Central/mid rapidity
- Calorimeter hermeticity (missing E)

CMS ZZ(2mu2e) candidate

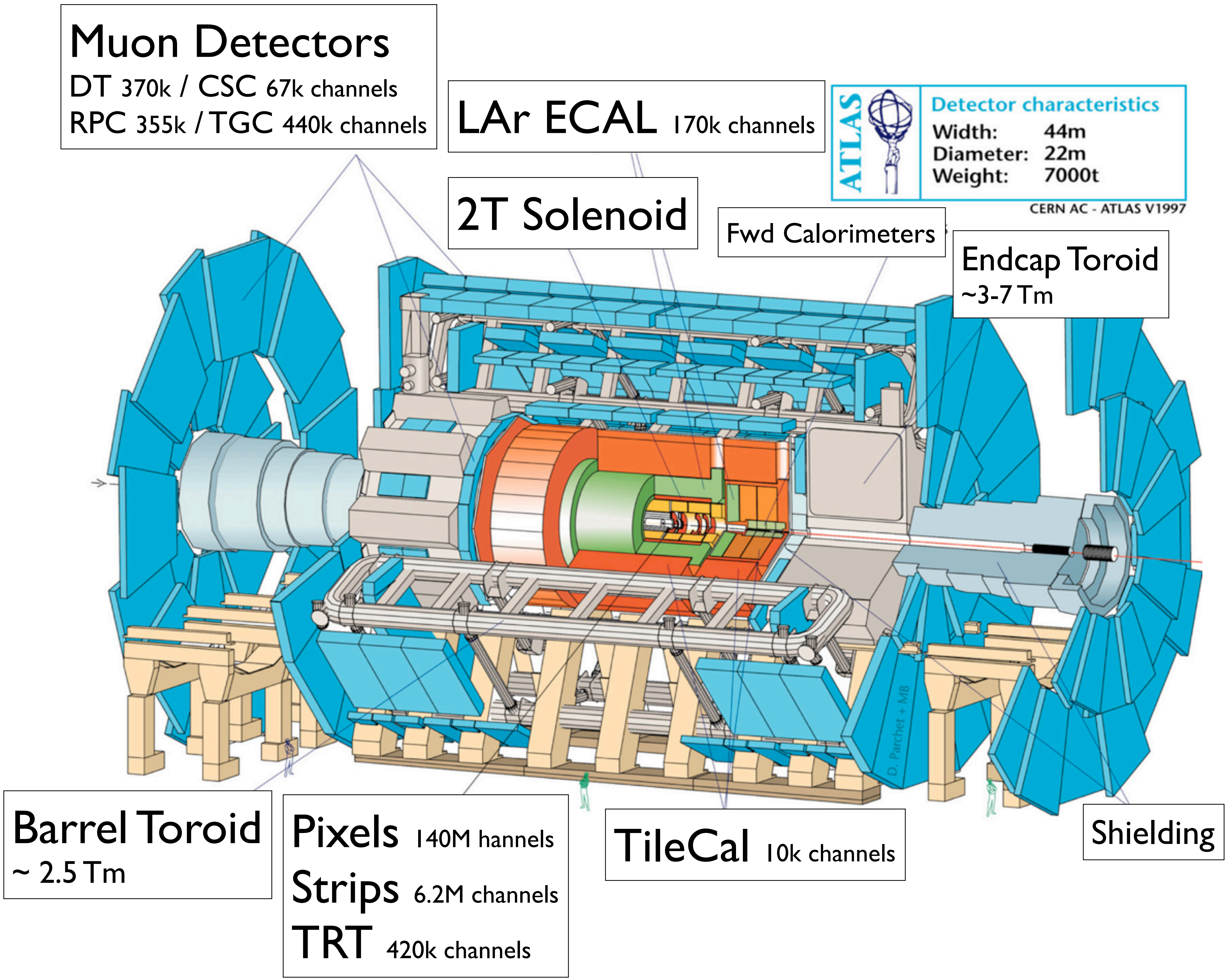


Atlas ZZ(4mu) candidate

CMS detector

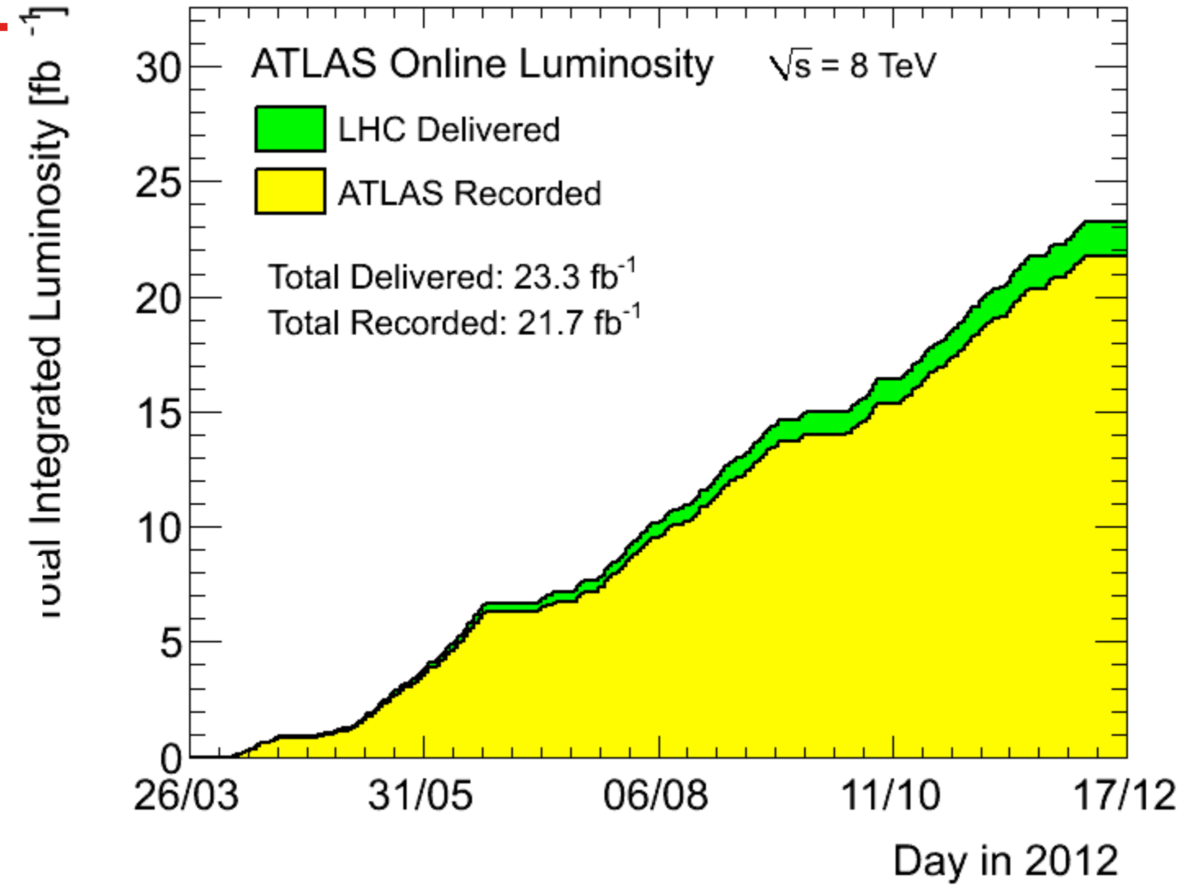


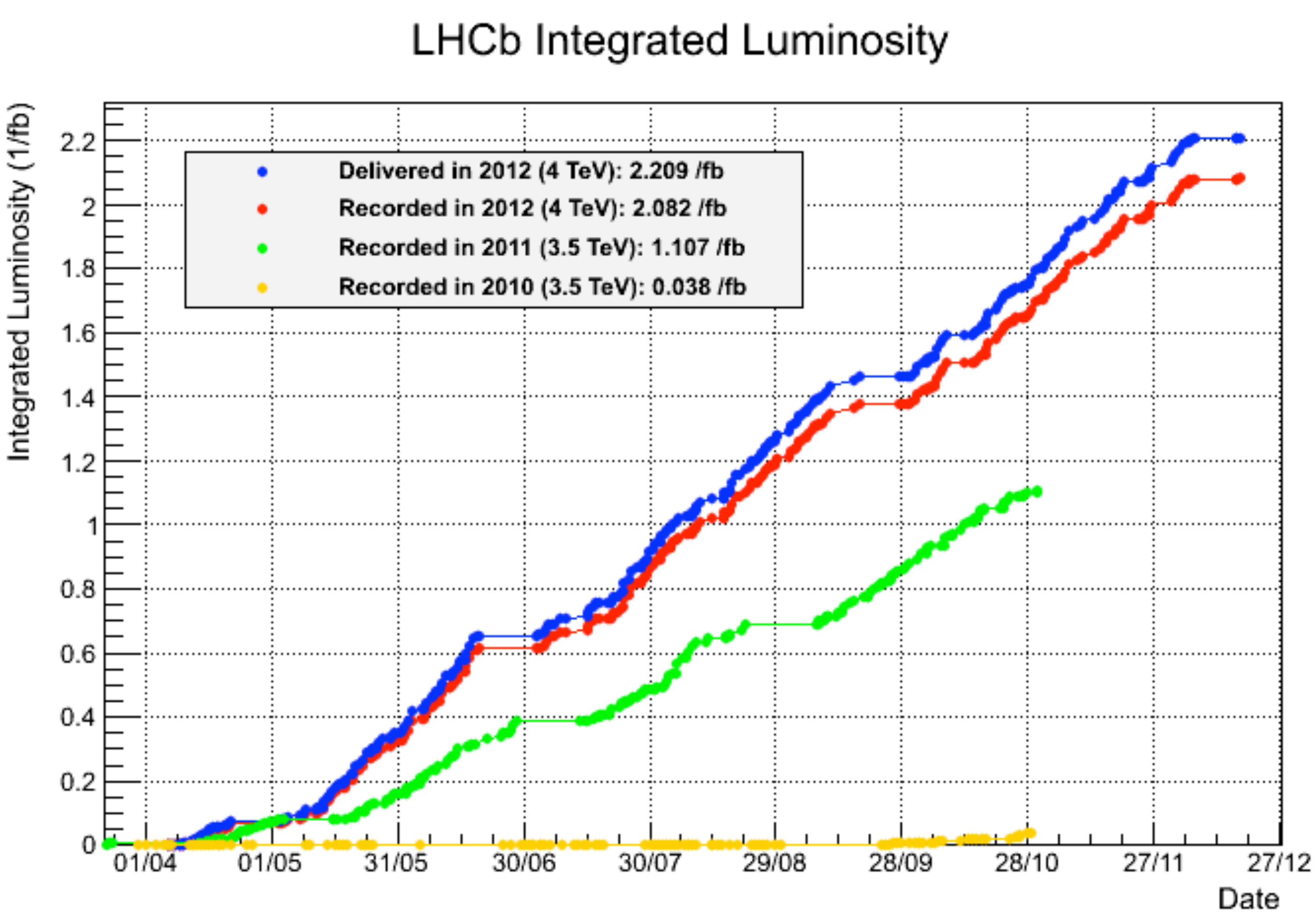
Atlas detector

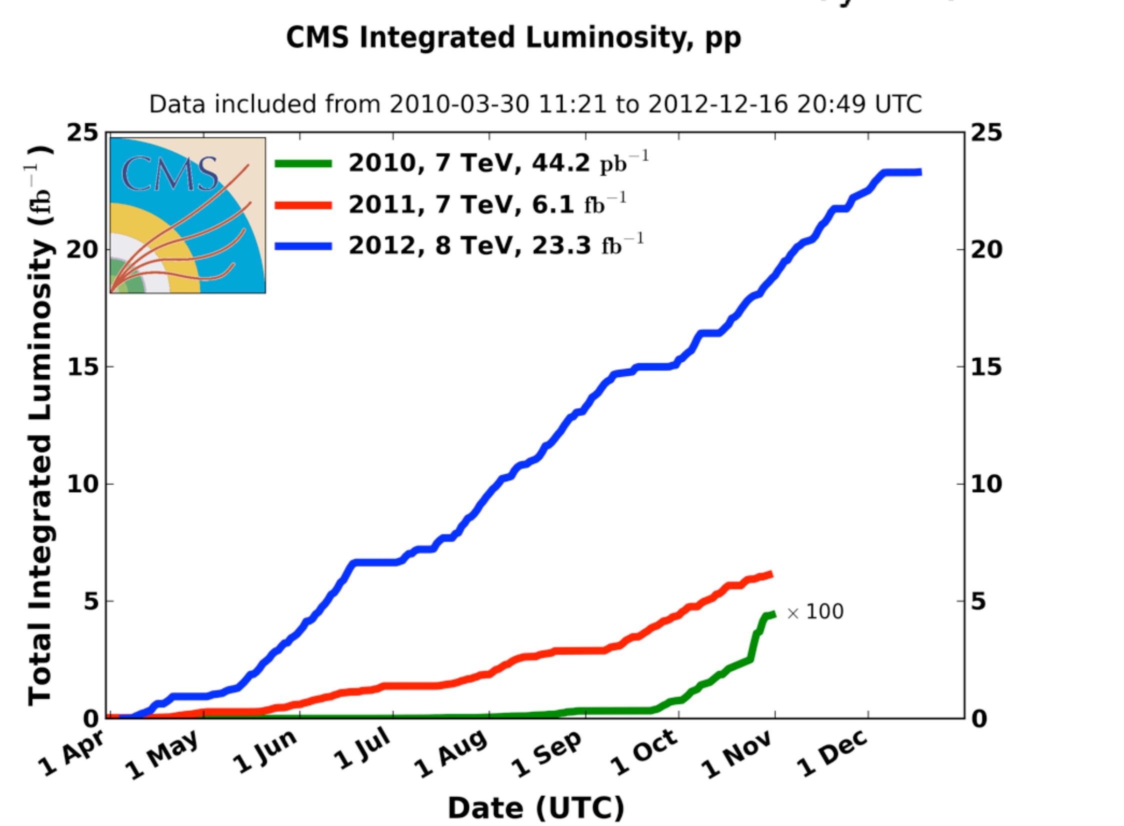


Luminosity and data taking

- Excellent performance of the LHC!
- More than 23 /fb delivered to Atlas/CMS experiments in 2012
- 2.2 /fb to LHCb
- Excellent data taking efficiency

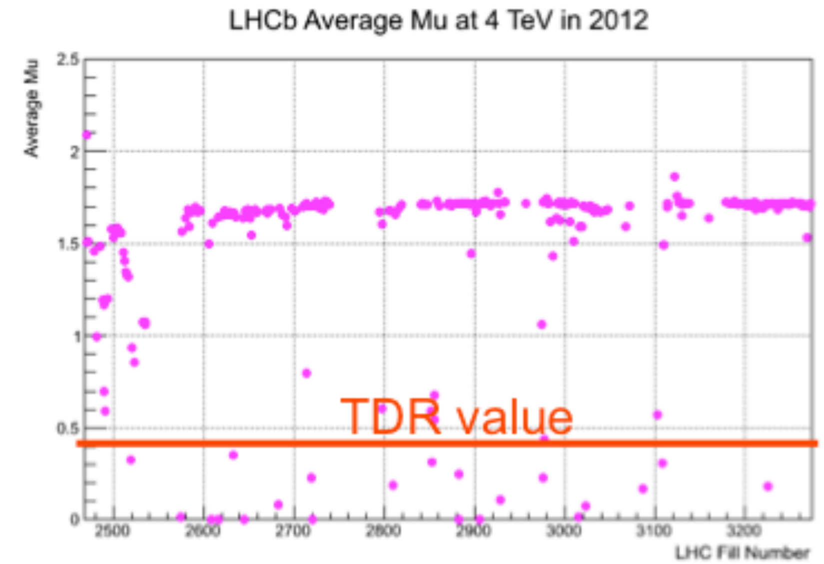


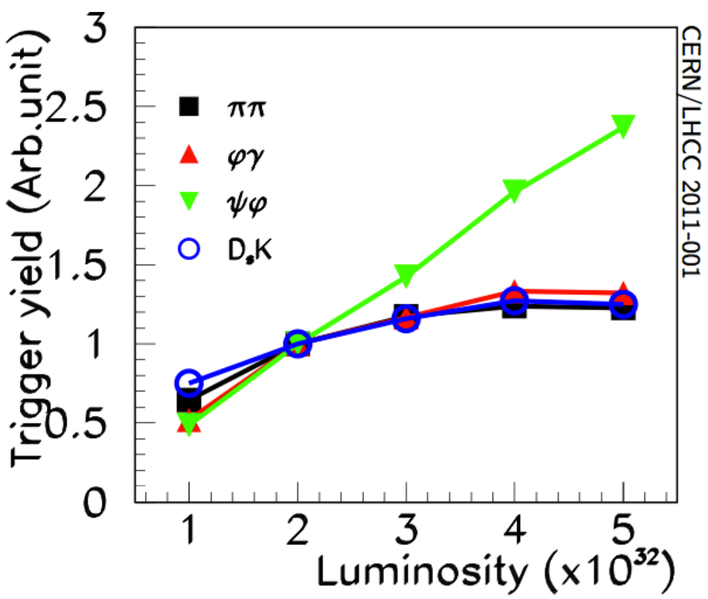


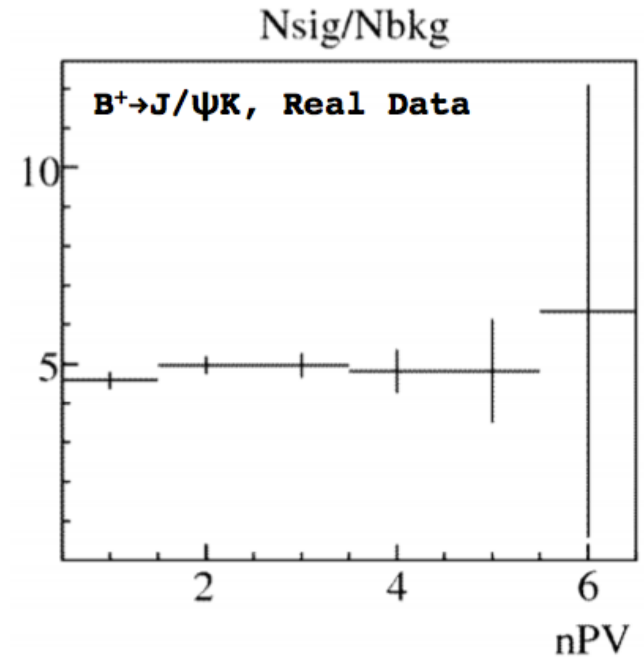


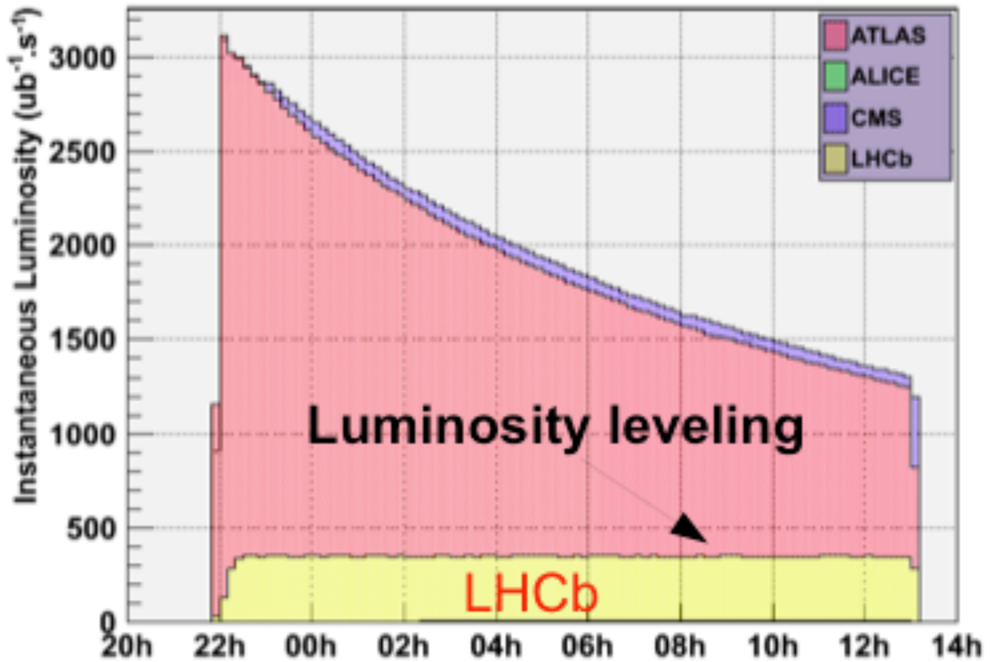
Luminosity at LHCb

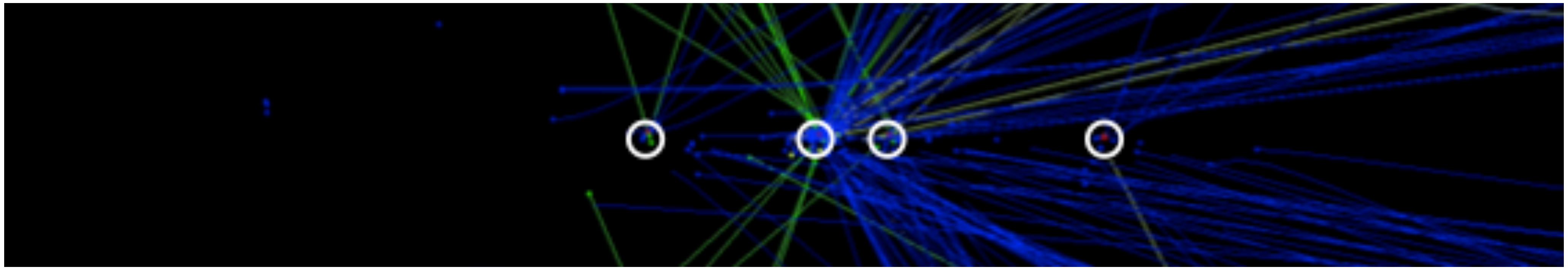
- Luminosity leveled at 4E32 by beam offset adjustment
- Larger than design, and running at 50 ns
  - 2012: <mu> ~ 1.7 (~ 10% of events mu≥4)
  - 2011: <mu> ranging from 0.4 to 2.5
- Performance for B decays shown to be unaffected











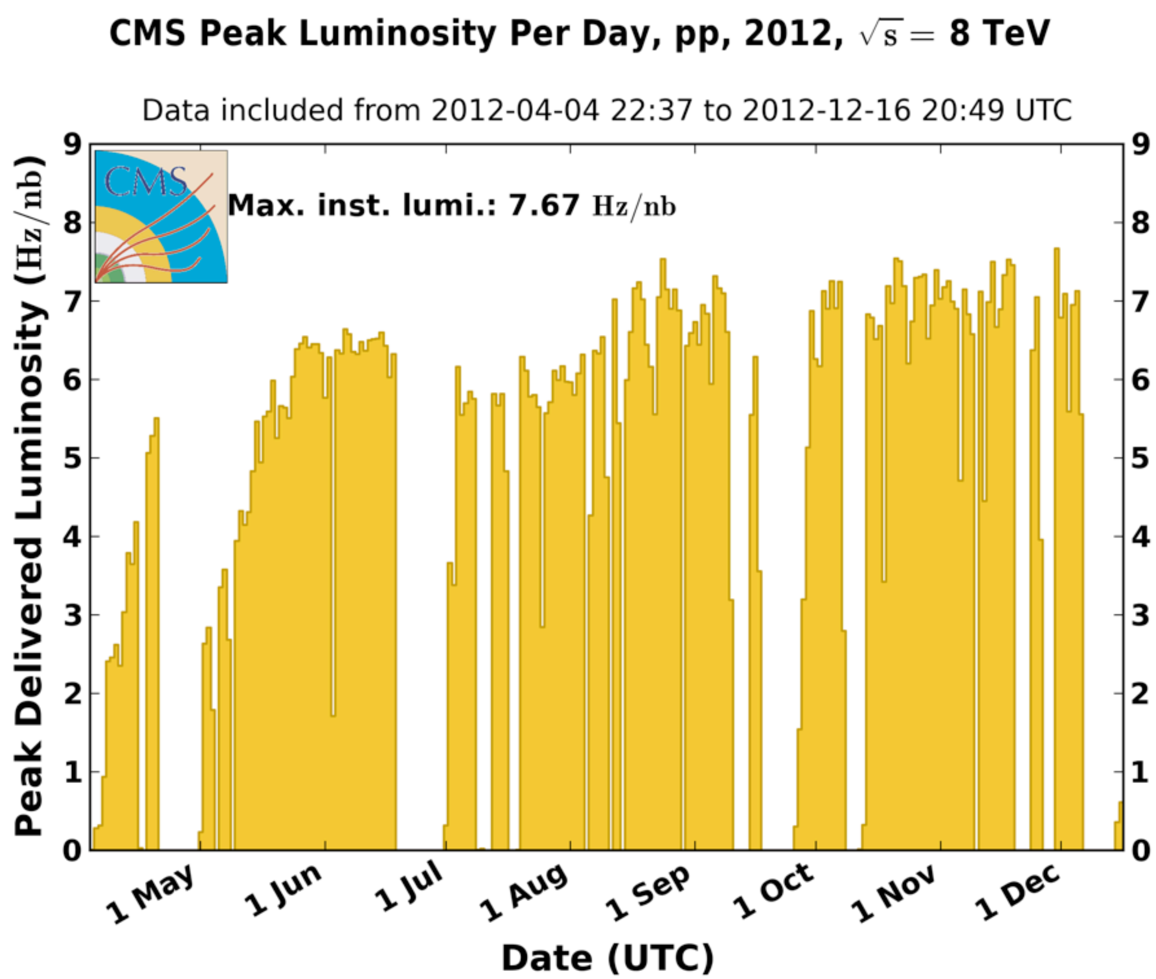
Impressive LHC performance

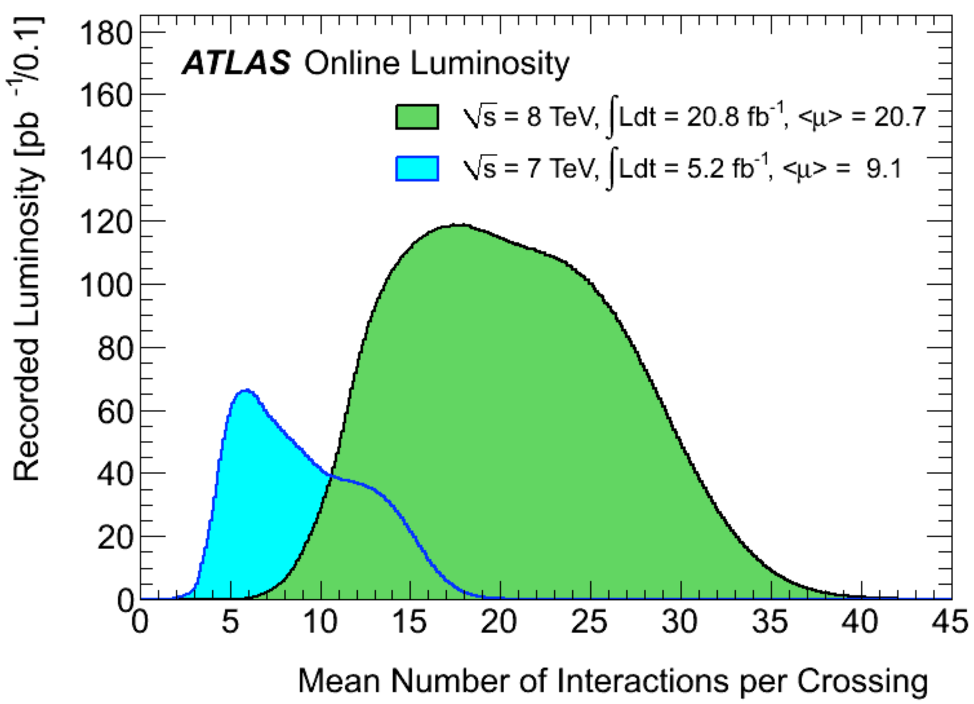
LHC and CMS Records Online in 2012 – Protons

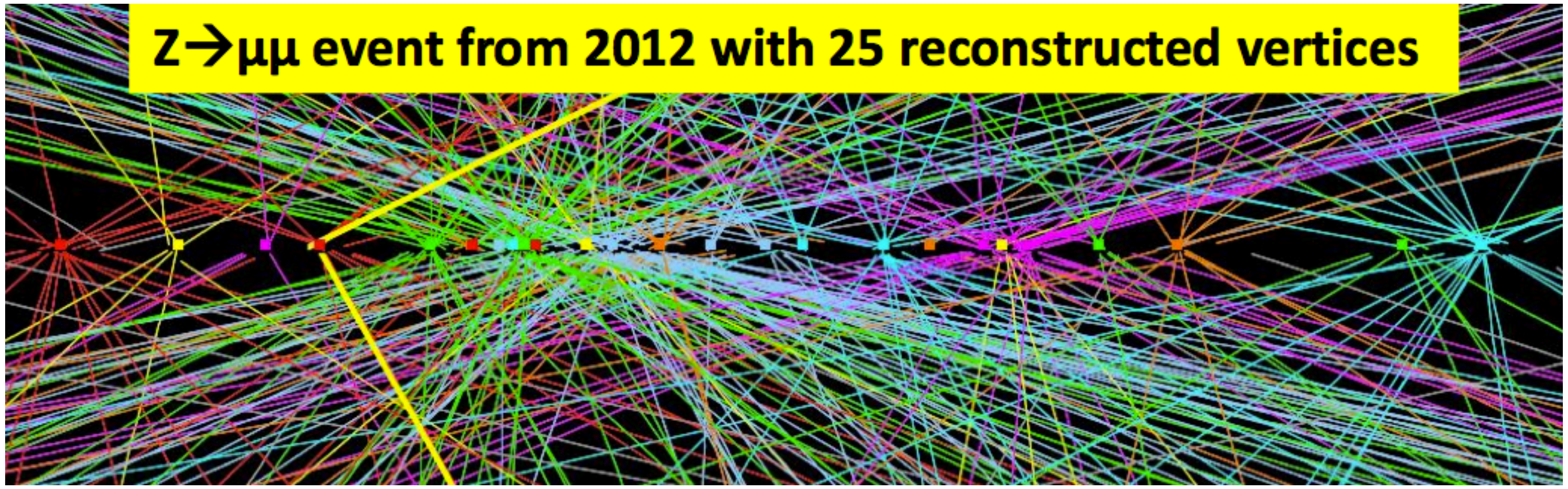
Peak Instantaneous Stable Luminosity	$7670.19 \times 10^{30} cm^{-2} s^{-1}$	Fill 3347	2012.11.30 01:16:49
Maximum Interactions per Crossing (pileup)	34.55	Fill 3347	2012.11.30 01:16:49
Maximum Luminosity Delivered in one Fill	246.28 pb^{-1}	Fill 2692	2012.06.02 05:10:16
Maximum Luminosity Delivered in one Day	286.08 pb^{-1}	Day 280	2012.10.06
Maximum Luminosity Delivered in one Week	1300.54 pb^{-1}	Week 24	2012.06.10
Maximum Luminosity Delivered in one Month	3693.06 pb^{-1}	Month 10	2012.10.01
Maximum Colliding Bunches	1380	Fill 2660	2012.05.24 15:34:46

LHC peak luminosity in 2012

- Reached > 7.5E33
- Almost at the design lumi, but at 50 ns running!
- Pileup already larger than LHC design at 25ns (~20)
- Last fills started at pileup ~35

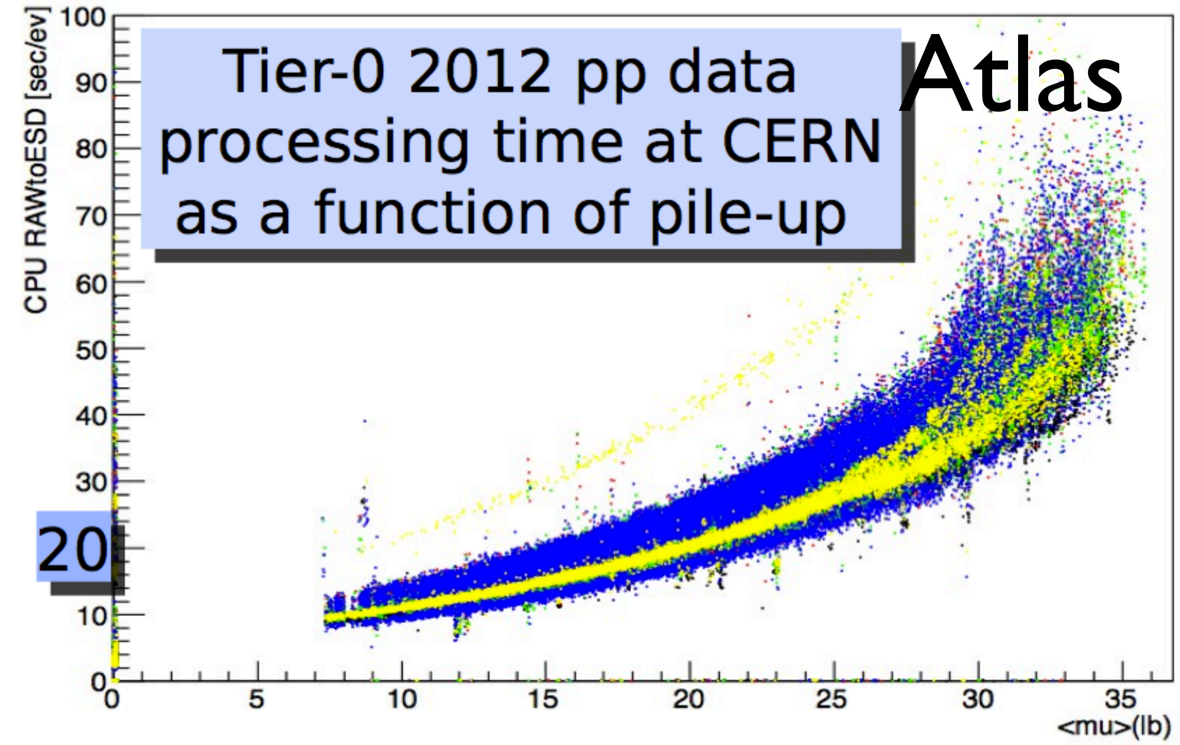


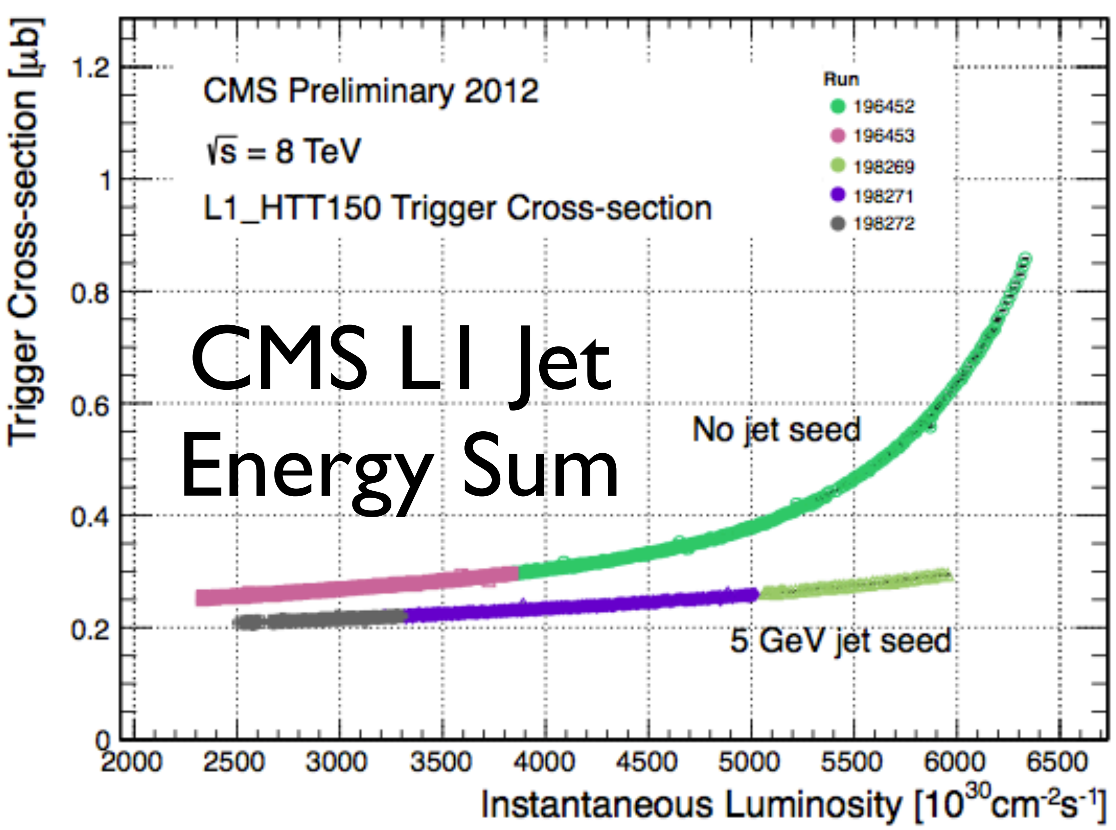


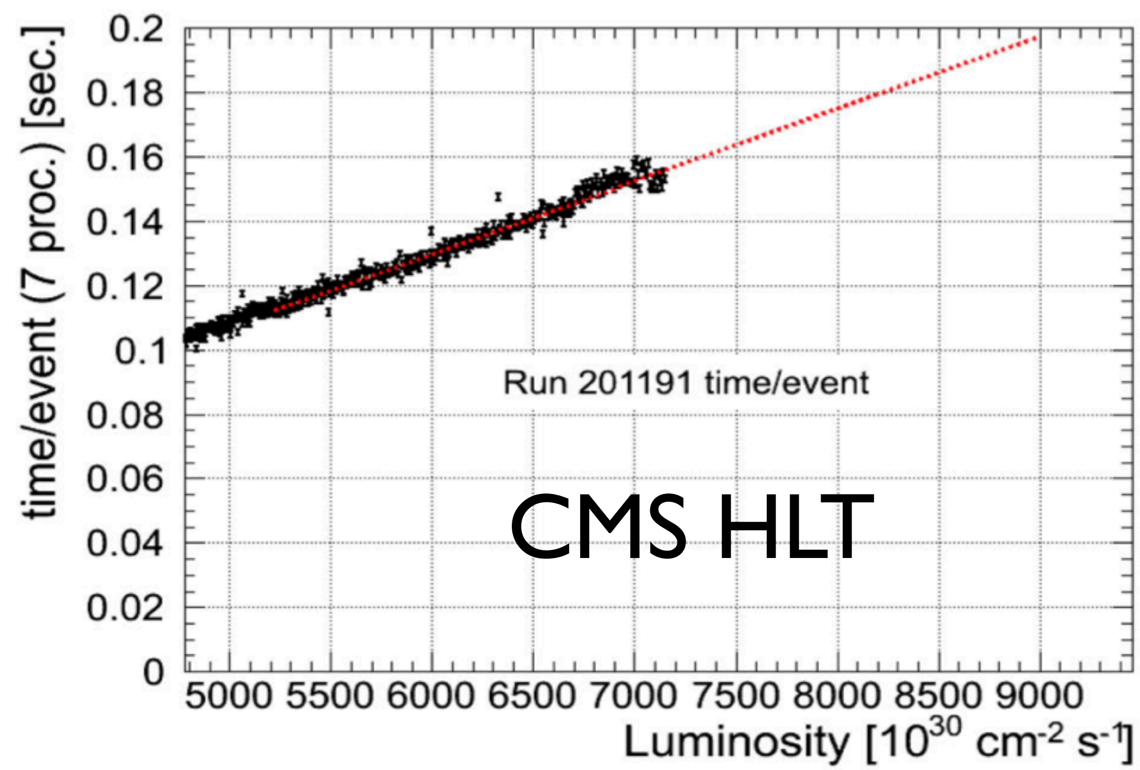


The pileup challenge

- Almost double pileup conditions than LHC design
  - Rates controlled with improved cuts on L1 and HLT objects + pileup subtraction
  - Reconstruction time: implementation of online tracking with respect to full (iterative) offline tracking

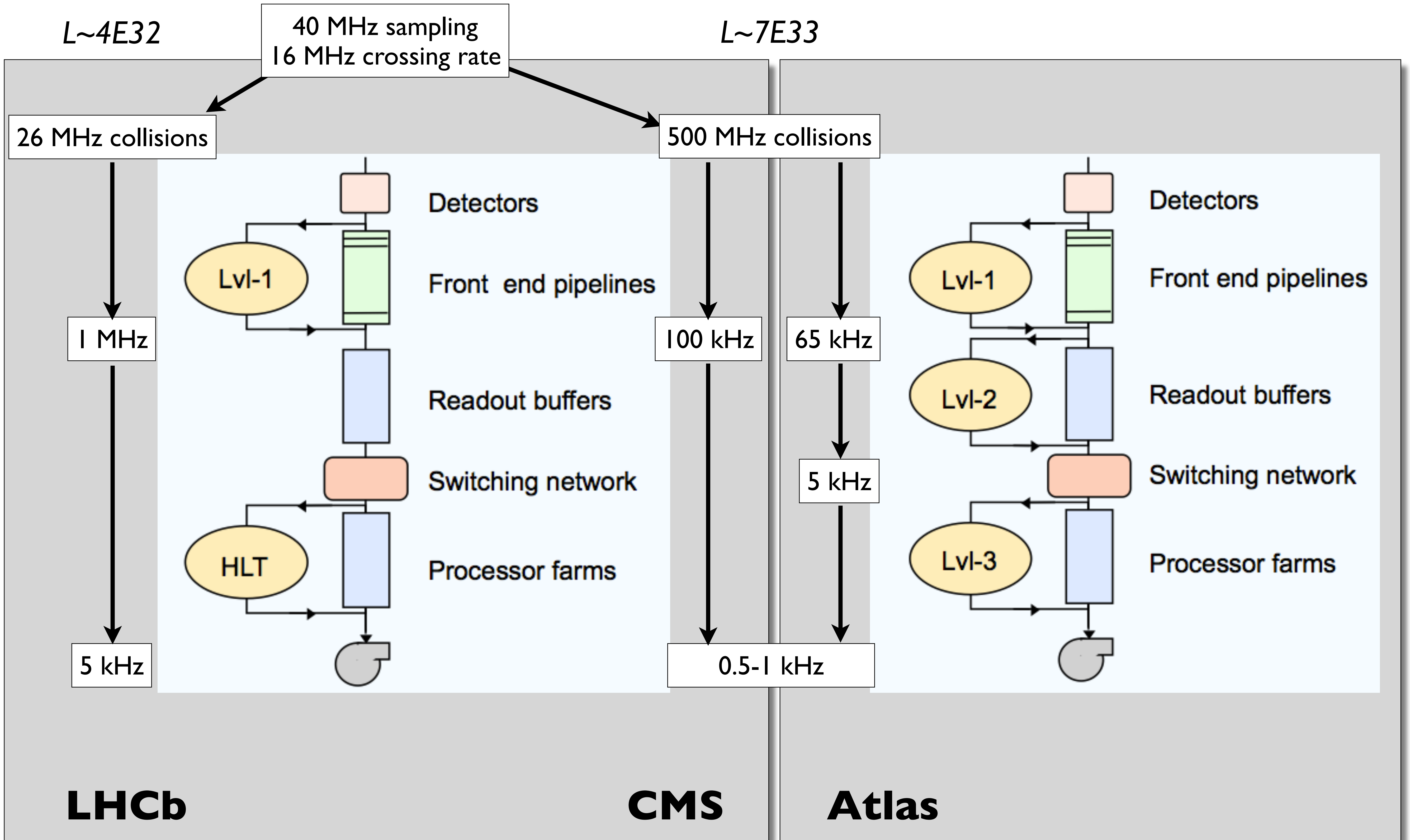






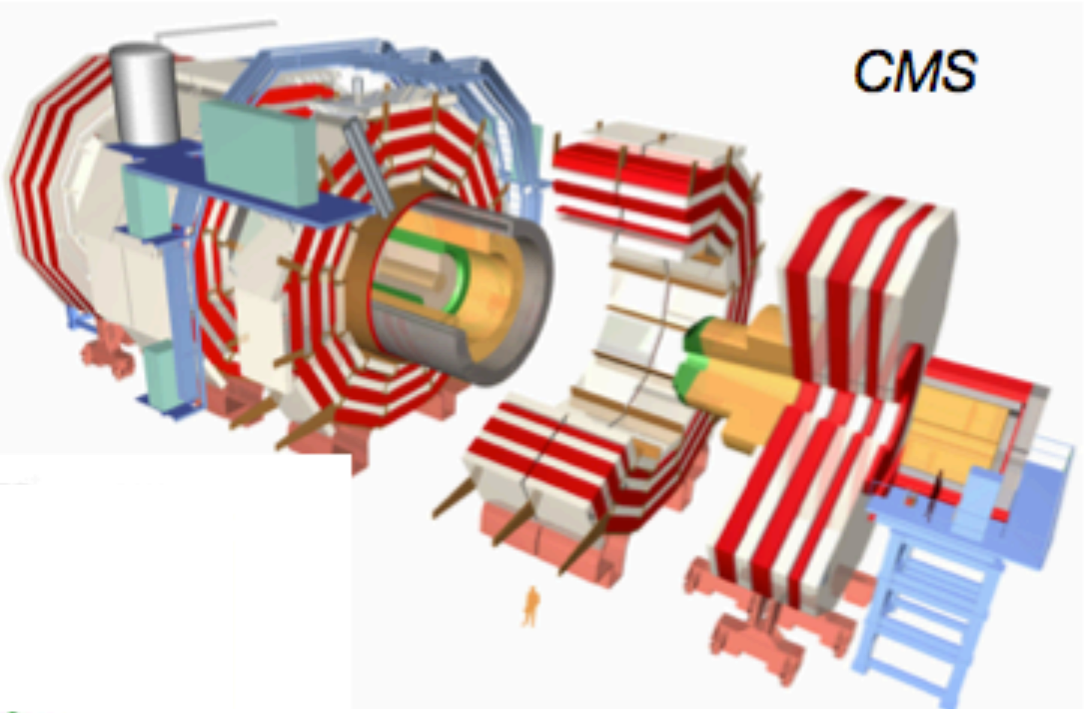
Trigger systems

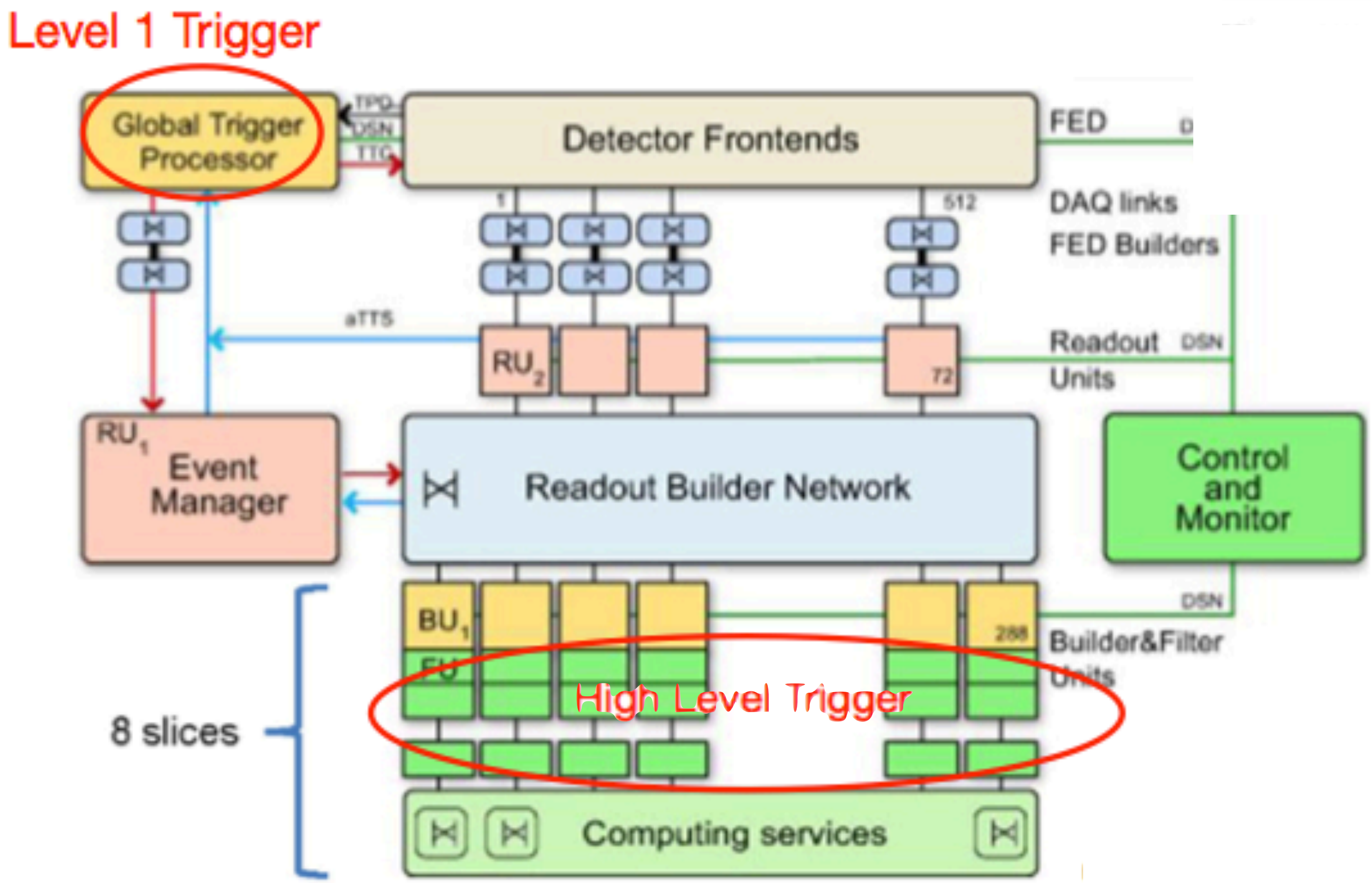
Trigger and readout structures



CMS trigger architecture

- Main goals: keep high trigger efficiency for EW physics while reducing QCD background
- Particle identification:
  high Pt e, mu, jets, missing Et

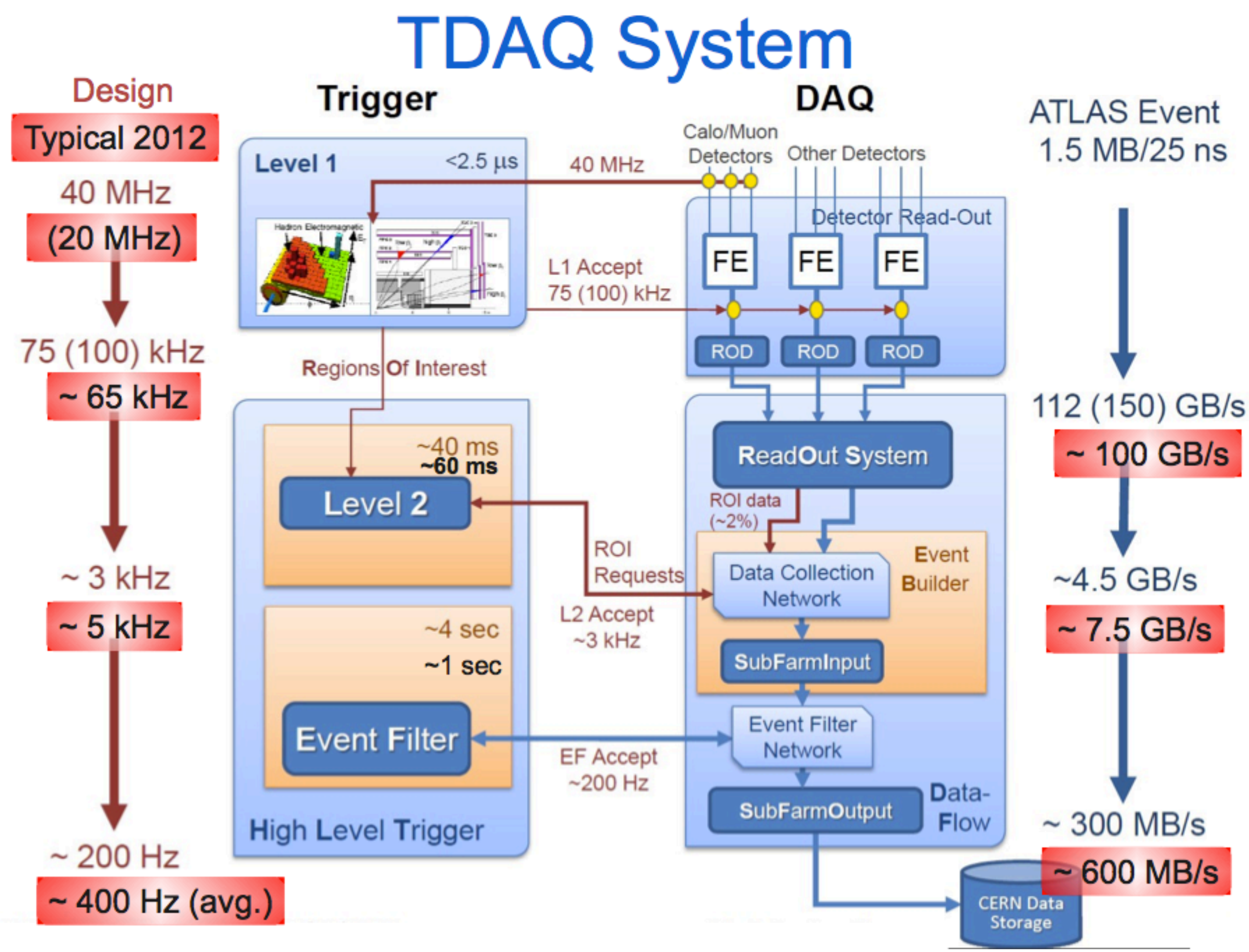




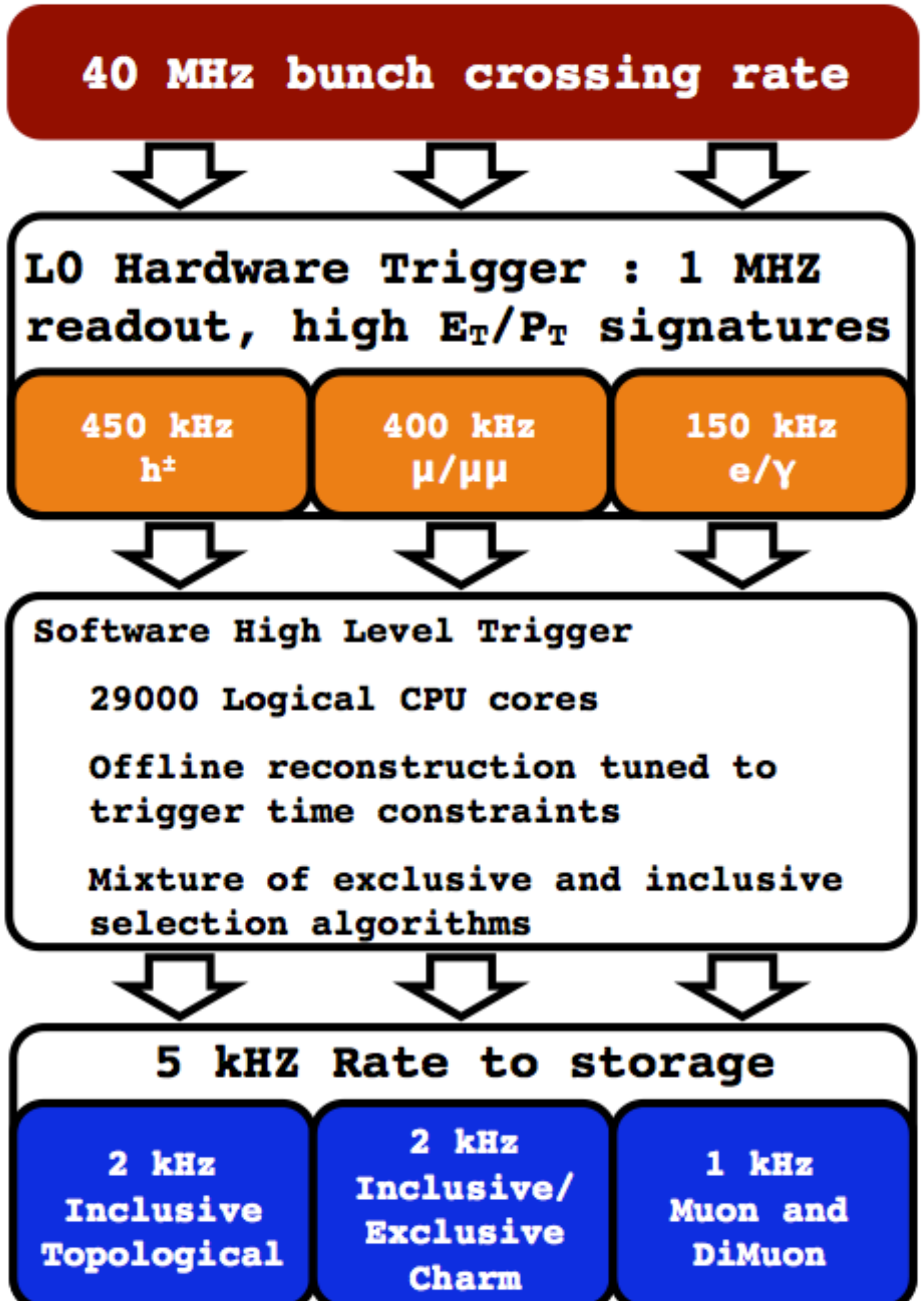
- Two levels trigger system
- L1 Trigger
  - 40 MHz input from calo and muon
  - dead-time free
  - 100 kHz selected events
- HLT
  - CPU farm for Event Building and filter algorithms.
  - Up to 1 kHz selected events (400 Hz "prompt-physics" + other). SW similar to offline reconstruction

Atlas trigger architecture

- 3-level trigger system
- L1 trigger input from calorimeter and muon RPC, 100(65) kHz output [design(2011-2012)]
- L2 trigger based on region-of interest, ~2% of event data read-out and reconstruction, 3(5) kHz output
- Event filter (L3) trigger, full event (but still some regional algorithm), 200(400) Hz output



LHCb trigger architecture

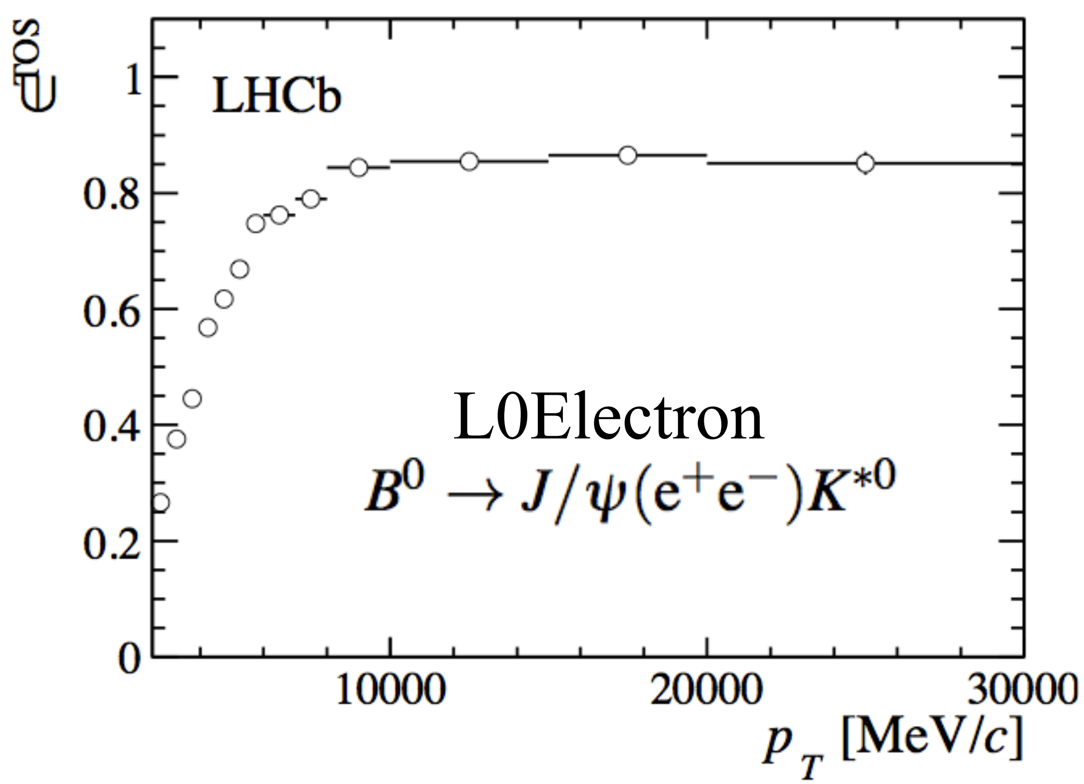


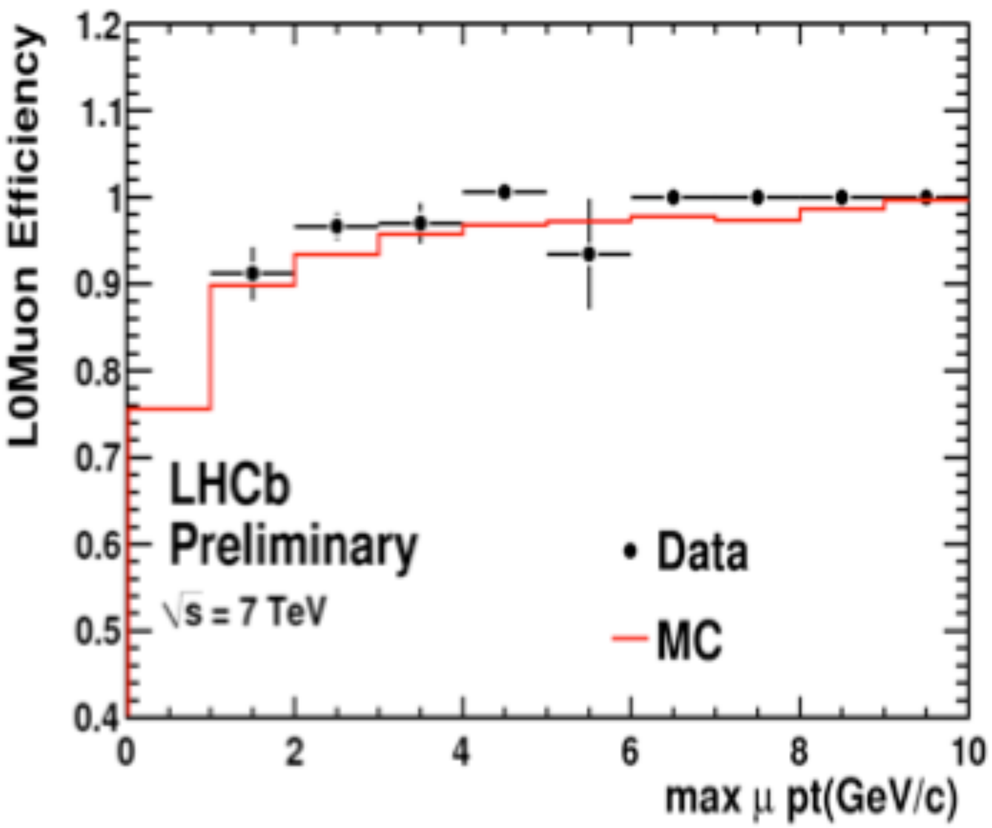
- Goals
  - Trigger on most interesting charmed meson
  - Trigger all B decays into charged tracks in inclusive way
  - Keep very high efficiency for rare B decays (muons, photons)
  - Keep large rate of dimuon events, prompt

- One synchronous hardware level, DAQ rate limited to 1 MHz
- Computing farm with software High Level Trigger
  - First rate reduction based on track reconstruction (HLT1 - selects 80 kHz)
  - Final inclusive/exclusive algorithms reconstructing B/D decay candidates (HLT2 - selects 5 kHz)

LHCb L0 trigger

- Calorimeter trigger: use (projective) cells from SPD, PS/ECAL, HCAL
  - Build hadron (sum of Et from HCAL, ECAL), photon (Et from ECAL when no SPD hits) and electron (Et from ECAL with SPD hits)
  - Compare Et of candidates to a fixed threshold
  - Veto based on number of SPD hits (limit HLT processing time)



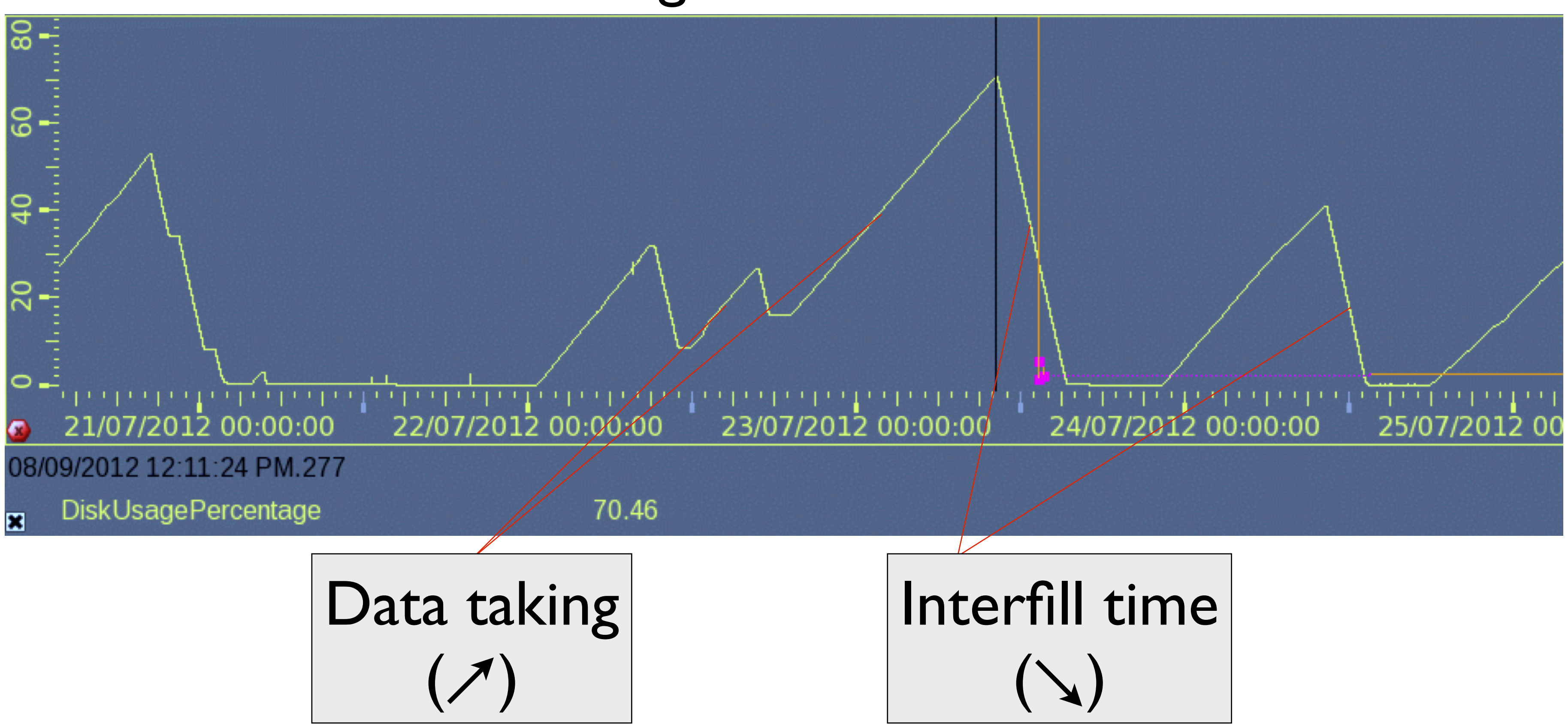


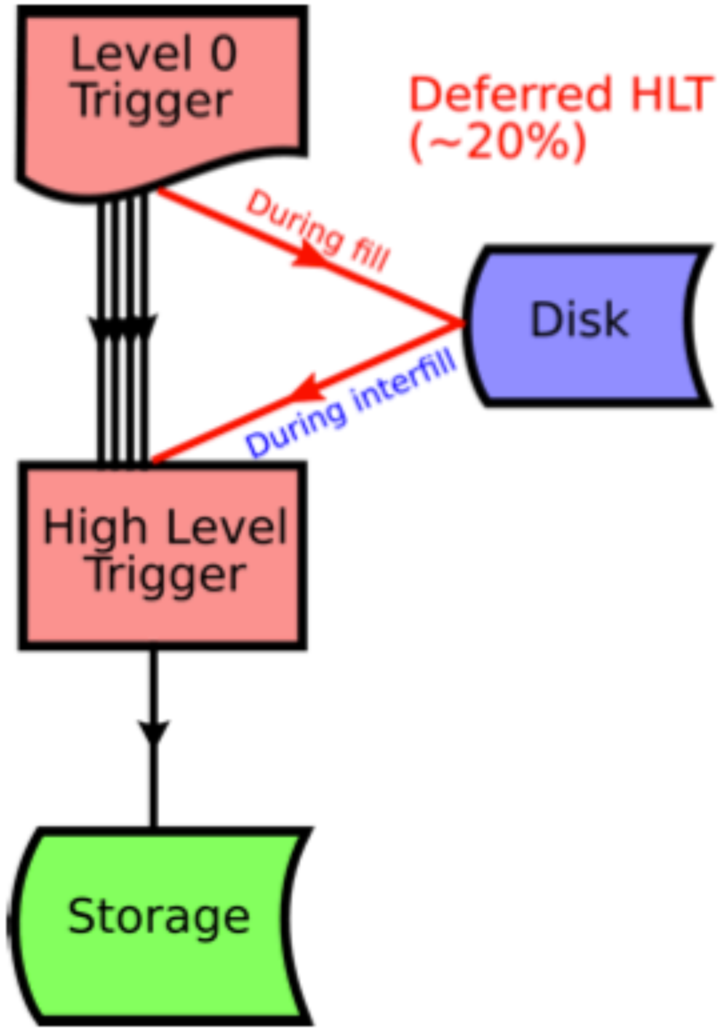
- Muon trigger: 5 muon stations (pad, strips) divided in 4 quadrants -> 4 processors
  - Each processor find two largest Pt muon candidates, with window in x projection corresponding to Pt>0.5 GeV
  - Position in the inner stations used to determine Pt with ~25% resolution wrt offline reconstruction
  - Threshold on largest Pt (and second largest Pt) for muon (dimuon) triggers

Deferred HLT

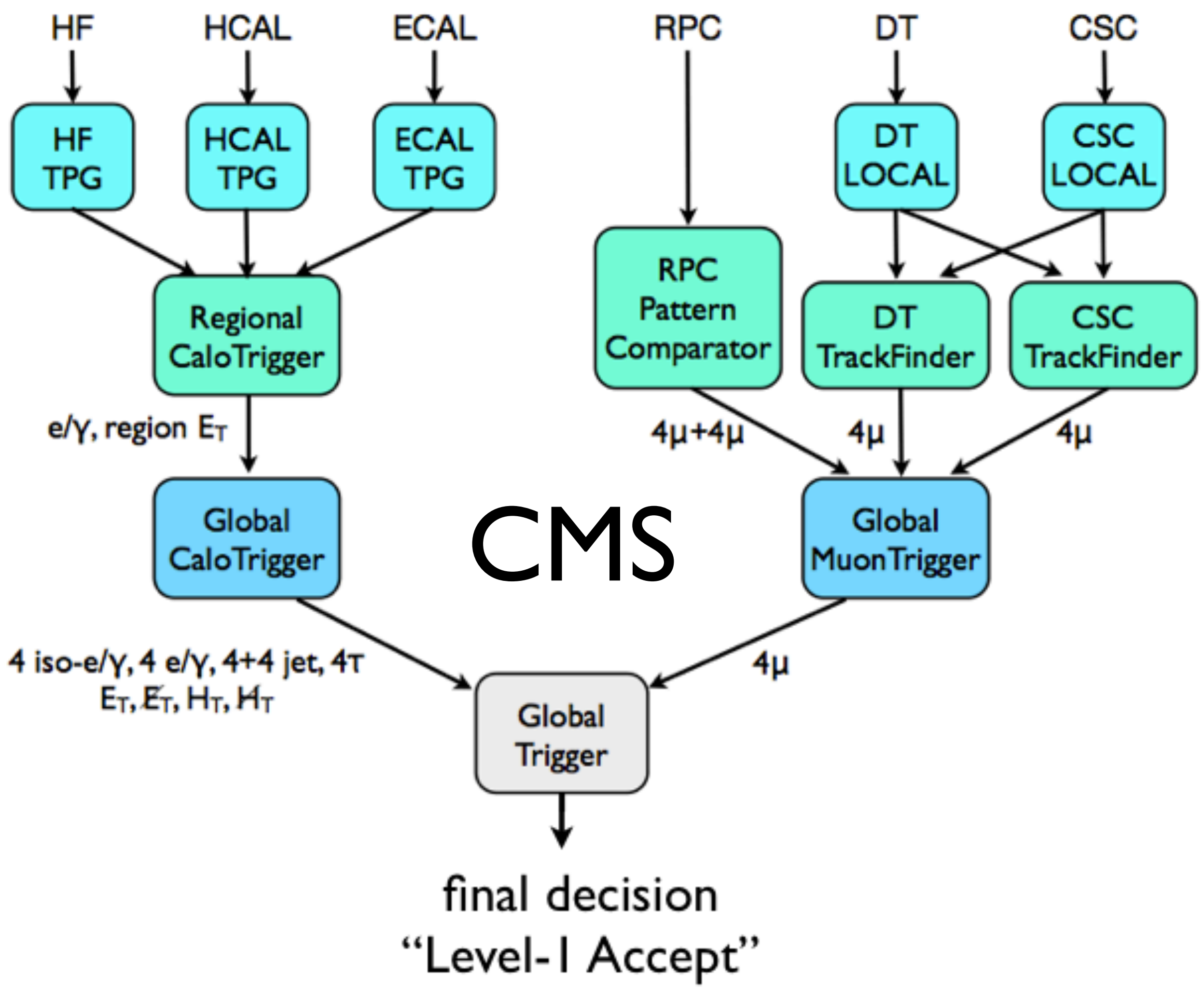
- Gain computing power in HLT farm allowing longer processing time per event
- L0 rate beyond HLT farm capacity overflowed to farm node disks (1 PByte total)
- ~20 % of events are deferred
- Processed during LHC interfill time

Farm disk usage vs time

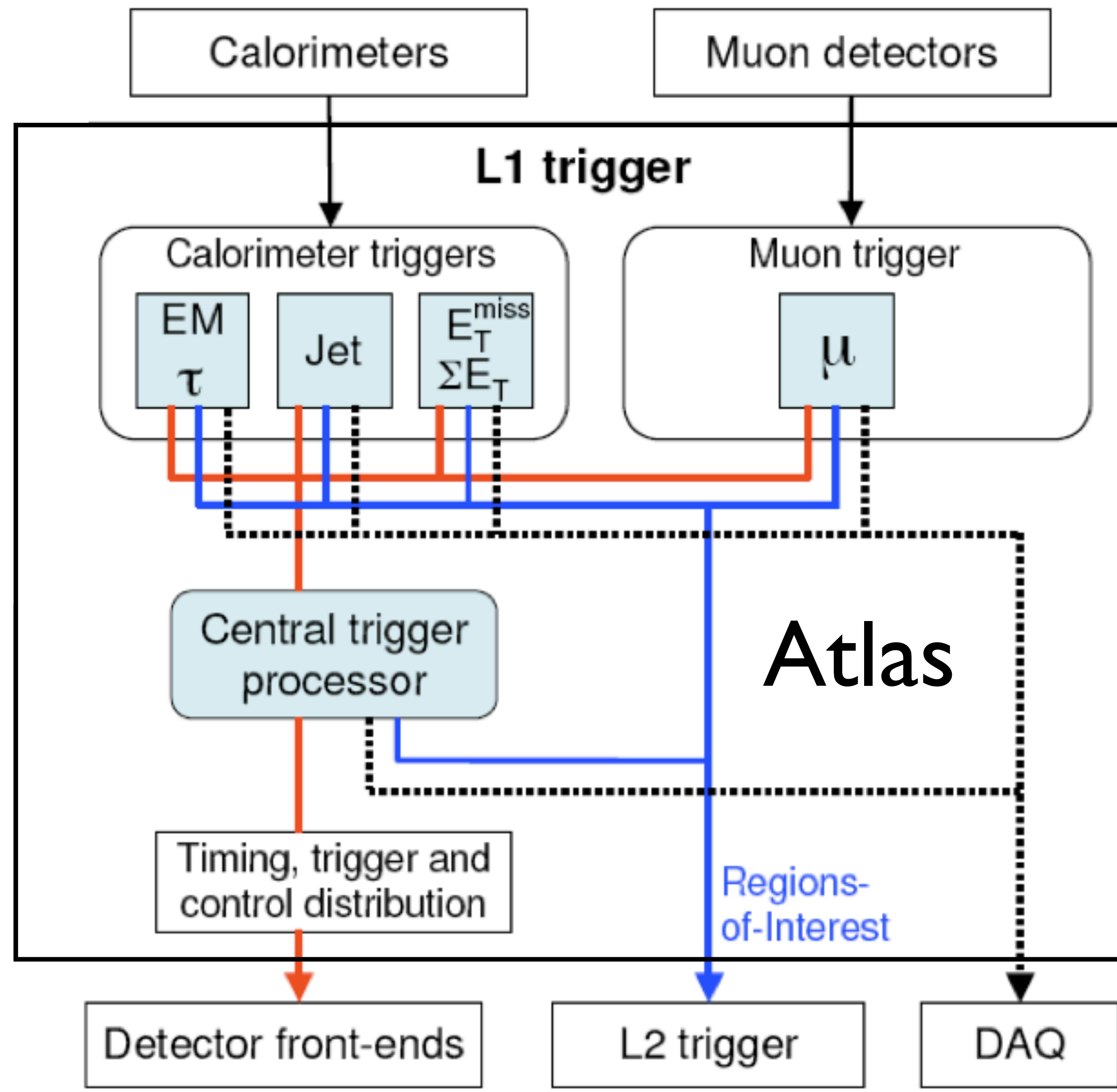




Level-1 Trigger in CMS/Atlas



- Custom-built hardware, ASICs (detector) and FPGAs (counting room)
- 40 MHz pipeline, dead-time free

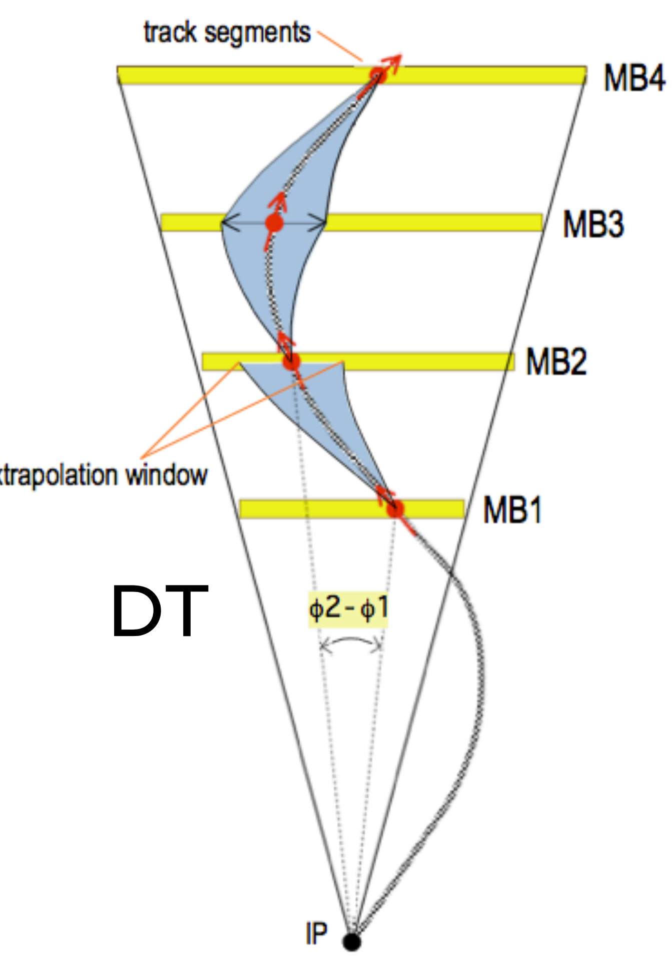


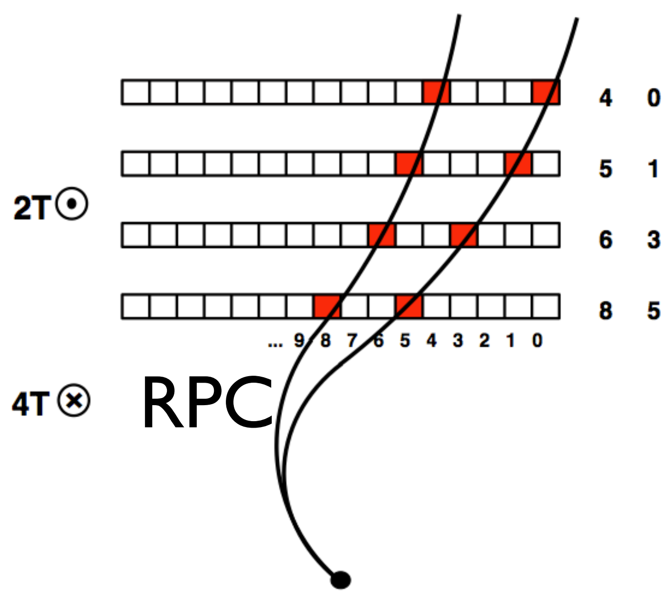
- More complex L1 trigger in CMS
  - Regional Trigger layer
  - Concurrent L1 objects built by RPC and DT/CSC
    - Plus exchange in barrel/endcap overlap region
  - Separated muon/calo global processors
- Atlas L1 providing ROI to L2

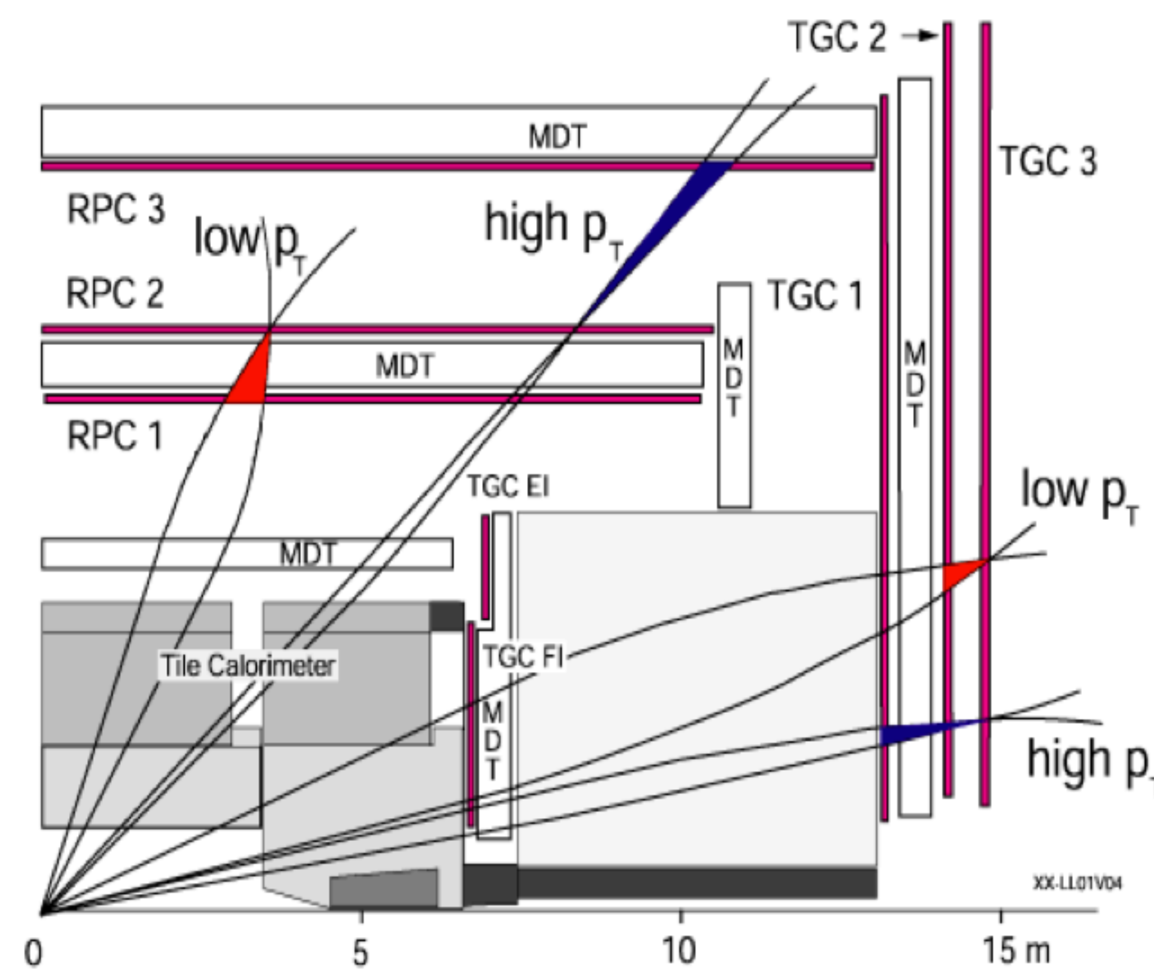
Example: L1 muon triggers algorithms

- CMS Drift Tubes barrel track finder
  - Oriented segments at muon chamber level
  - Extrapolation-and-matching, Pt assignment from difference in phi coordinate
- Similar algorithm for CSC in the endcaps
- RPC "pattern comparator trigger"
- Global Muon Trigger merging candidates and refining Pt assignment

- Atlas muon trigger
  - 3 layers of RPC(TGC) in the barrel(endcap)
  - Intermediate layer ("pivot") defining reference position
  - Measurement on inner(outer) layer defined the track bending for low(high) Pt
  - Width of the coincidence window defining the Pt cut

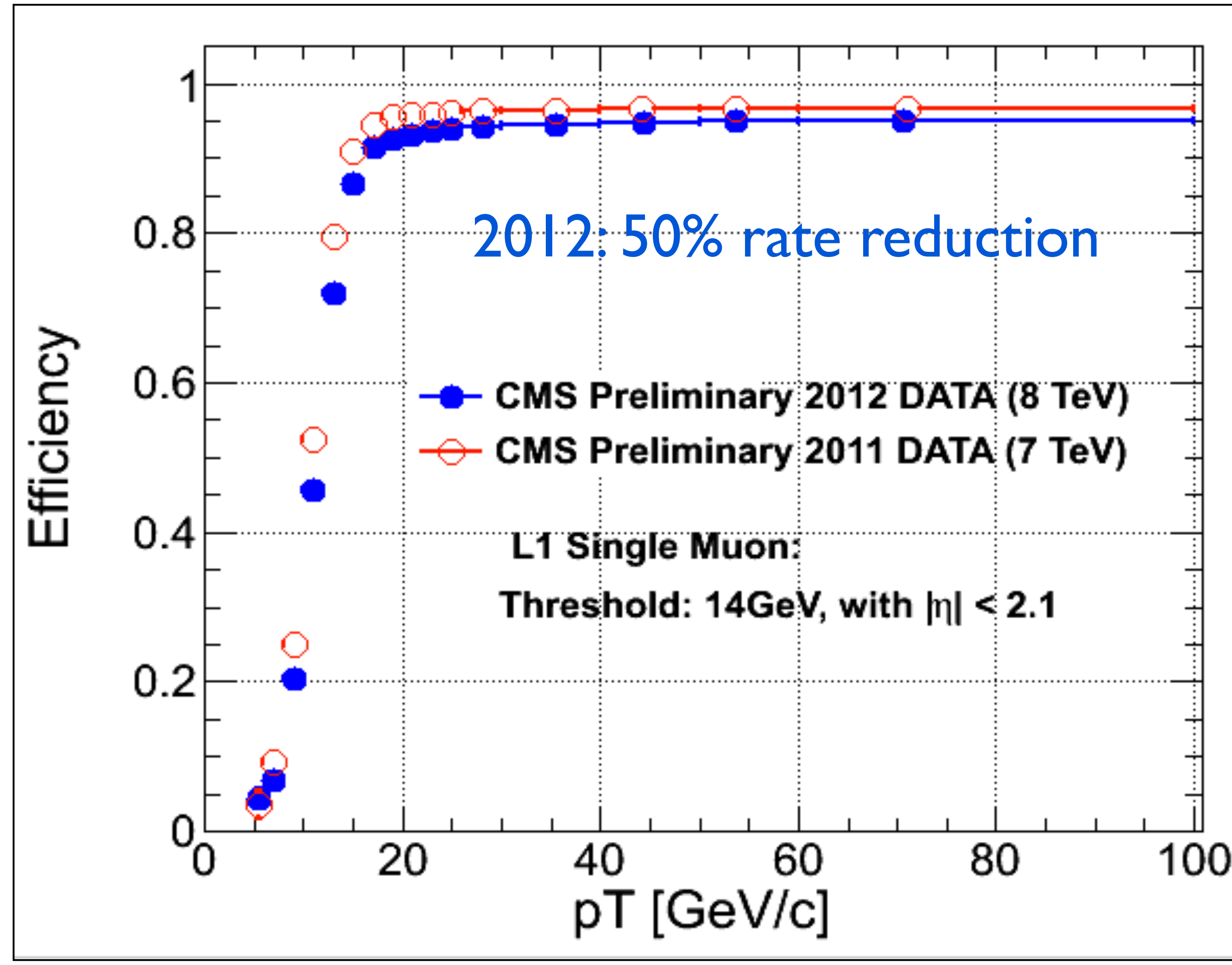


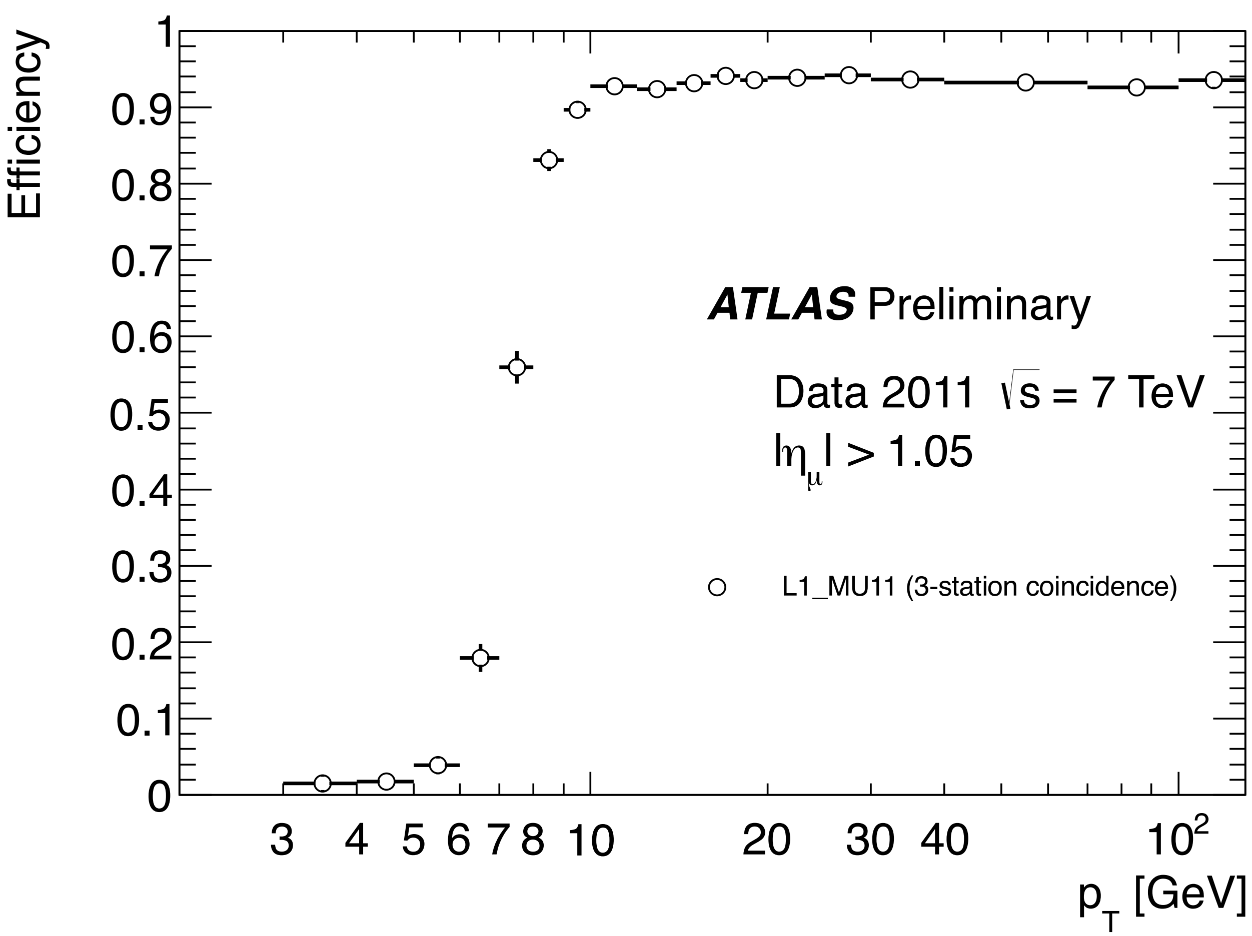




L1 Muon trigger performance

- CMS rate improvements in 2012
  - CSCTF tighter Pt assignment
  - Improvement in Global Muon Trigger pt merging
  - About 50% rate reduction, for few % efficiency cost
- Single muon L1 seed threshold at 14 GeV
  - Seeding HLT mu 40 GeV and iso mu 24 GeV

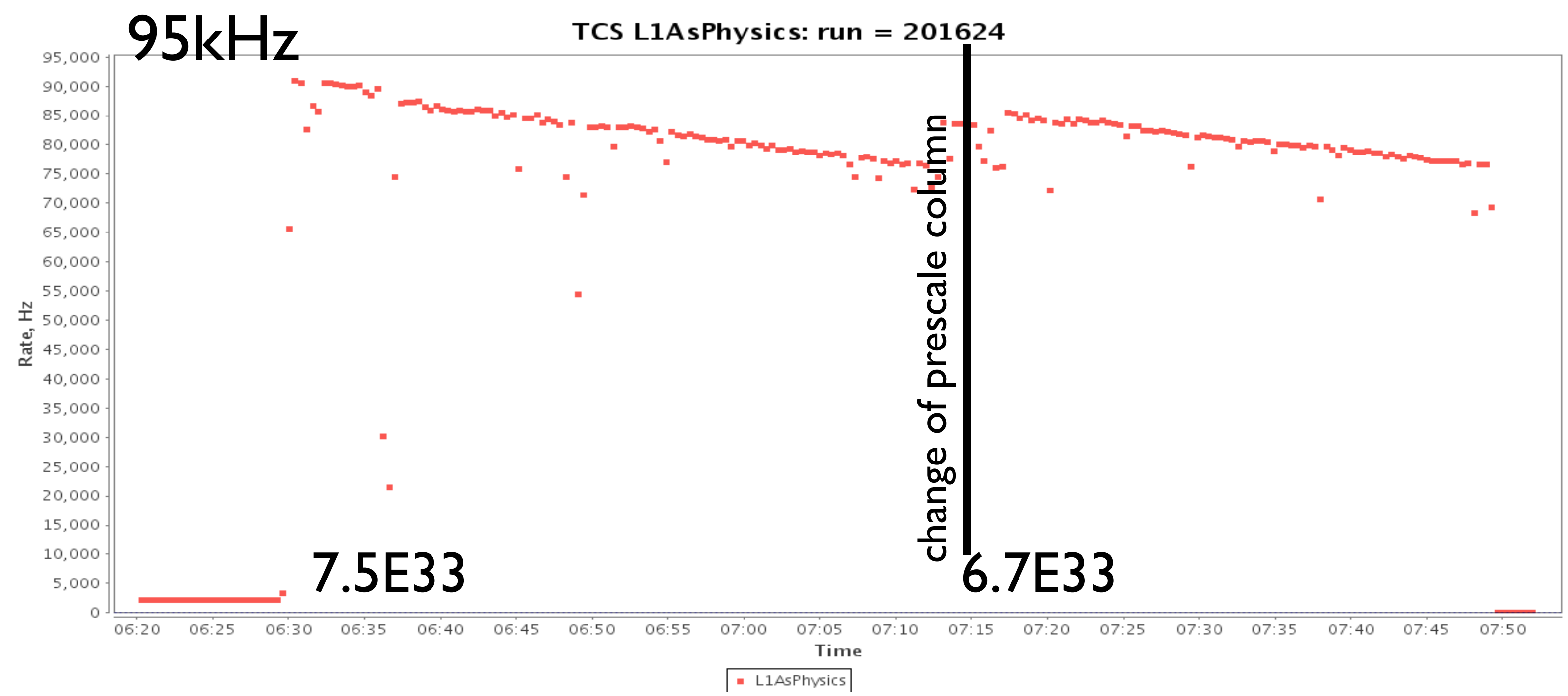




- Atlas single muon L1 seed at 15 GeV
  - (11 GeV for endcaps shown here)
- Seeding isolated muon trigger with threshold at 24 GeV

CMS L1 Trigger menu in 2012

- Record lumi fill with peak lumi ~ 7.5E33
- Start near to 100kHz
- ~5% initial deadtime, rapidly goes <3%



Trigger	Threshold (GeV)	Rate (kHz)	Physics
Single e/γ	20	13	Higgs, SM, EXO
Double e/γ	13,7	8	Higgs, SM, SUSY, EXO
Single μ	14 (|η|<2.1)	7	Higgs, SM, SUSY, EXO
Double μ	10, 0	6	Higgs, SM, EXO
e/γ + μ	12, 3.5	3	SM, SUSY, EXO
μ + e/γ	12, 7	1.5	SM, SUSY, EXO
Single Jet	128	1.5	SM, EXO
Quad Jet	36	3.5	SM, SUSY, EXO
H_T	150	5	SUSY, EXO
E_T^{miss}	36	8	SUSY, EXO

also (0,0) "high quality" for B-physics !!!

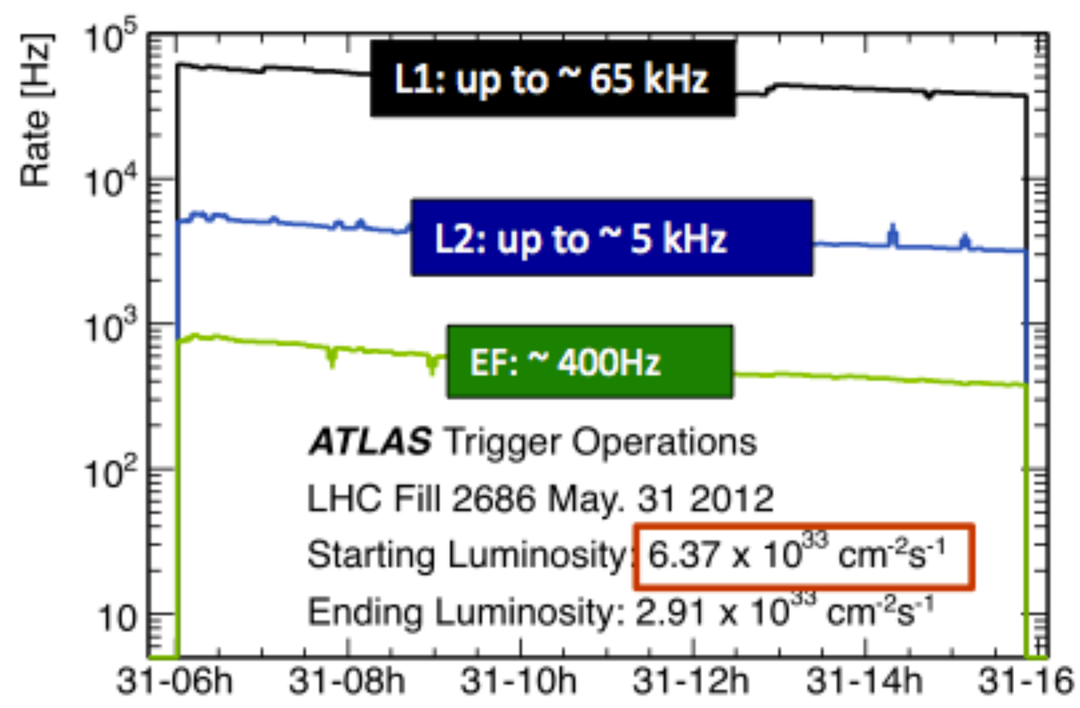
- Typical L1 trigger table for running in 2012
- Main single and multi-object triggers shown
- Rates reported for lumi ~6.6E33

Atlas EF trigger menu summary

- Goal: optimal sharing of available bandwidth
- Driven by physics priorities and discussions with physics sub-groups
- Most bandwidth given to most generic triggers
  - Single and double leptons, double photon, single jet and multijet, MET...
  - Specialized triggers (e.g. long lived) ~ 1 Hz each
  - ~20 % of the rate dedicated to supporting triggers (monitoring, efficiency determination, etc)
- Constraints at L1 and L2 bandwidths also critical
- Order of 500 triggers in the menu!
- Try to limit changes along the year to ease analysis
- The same considerations apply to CMS menu development

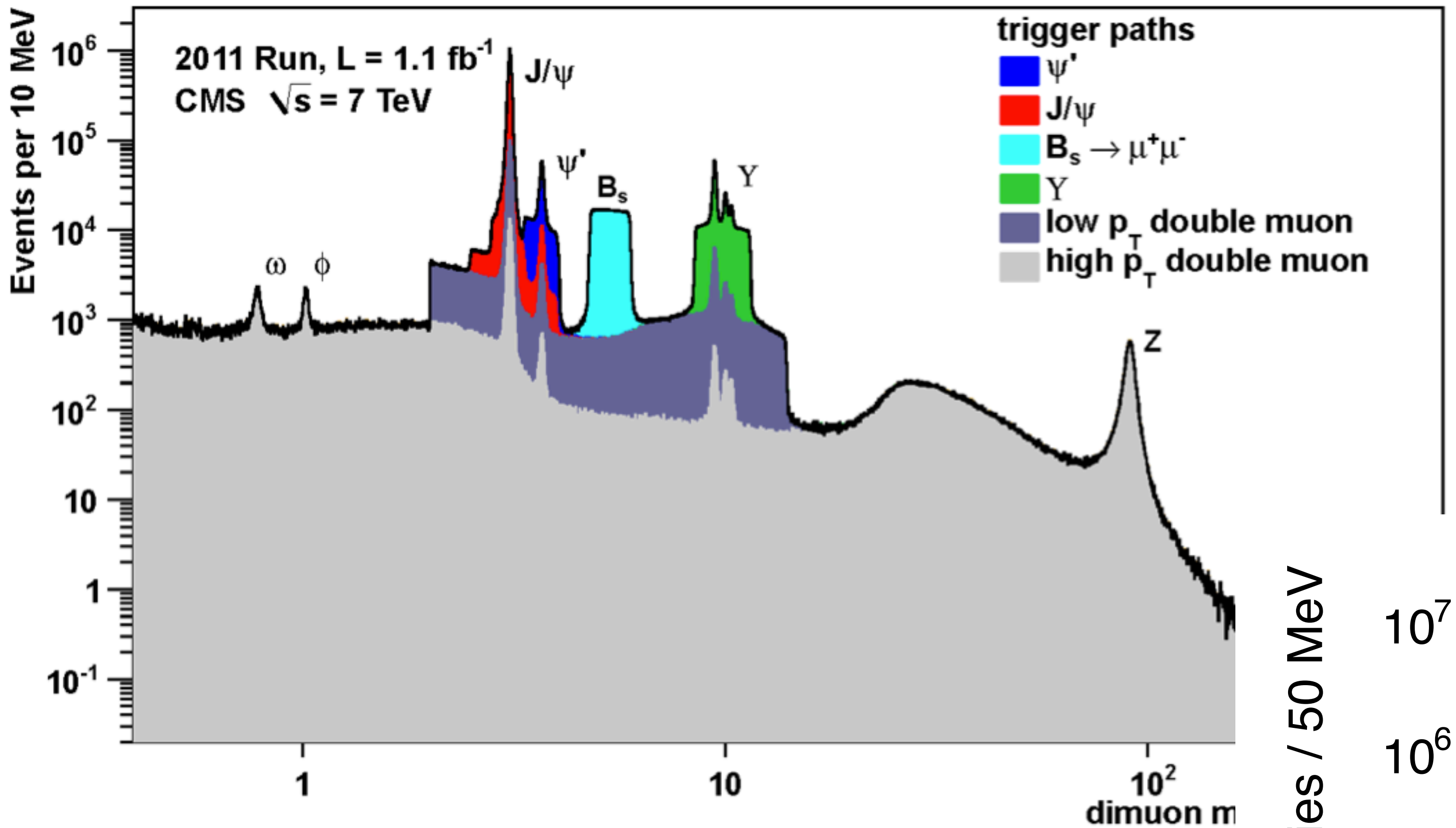
In addition (new in 2012): additional trigger
(B-physics, jet triggers)
recorded for later processing
(~200 Hz Atlas, ~400 Hz CMS)

Item	p_T threshold (GeV)	Rate (Hz) at 5×10^{33}
Incl. e	25	70
Incl. μ	24	45
ee	12	8
μμ	13	5
ττ	29,20	12
γγ	35,25	10
E_T^{miss}	80	17
5j	55	8

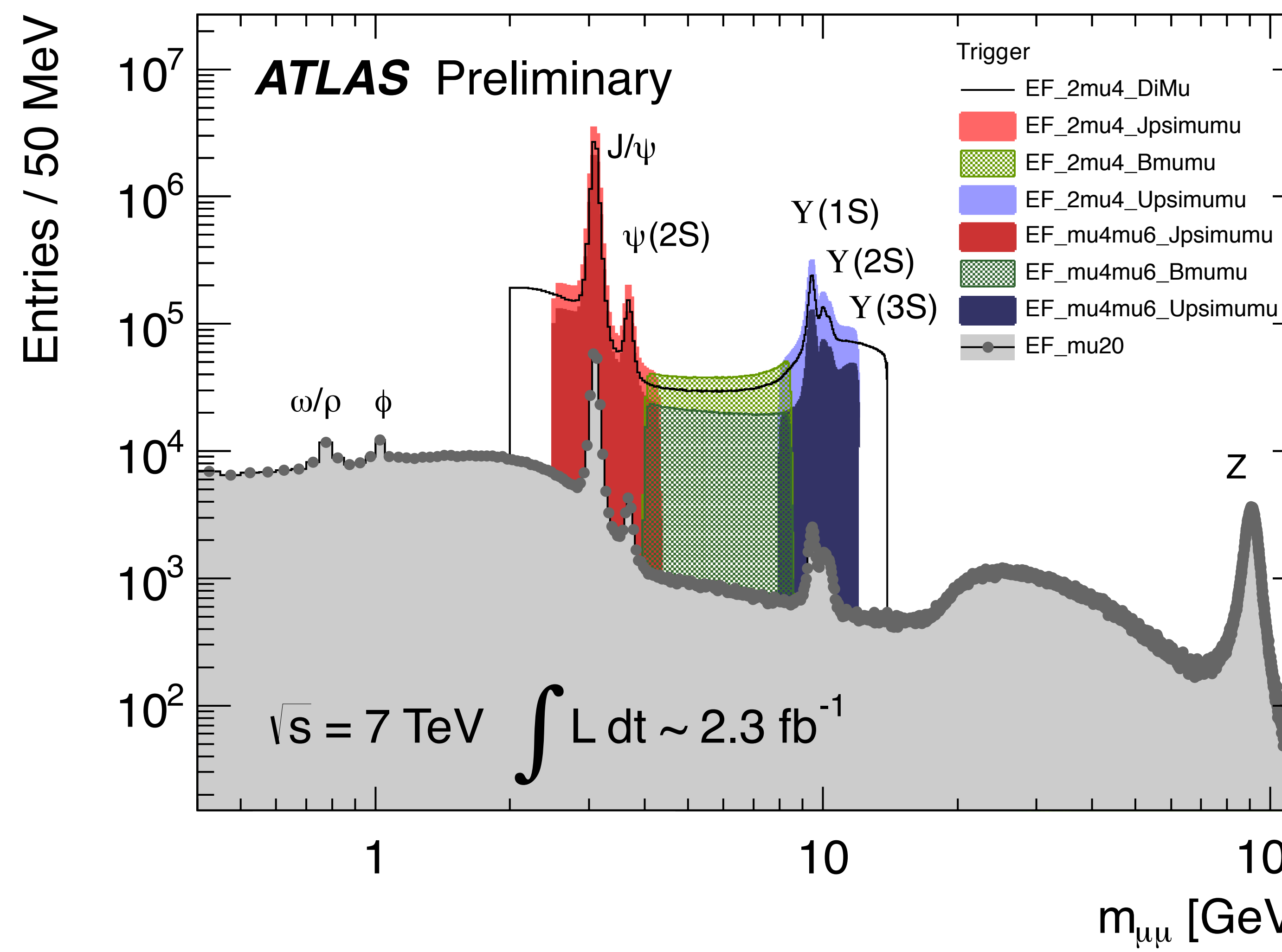


Muon triggers for heavy flavor

- CMS and Atlas dimuon mass spectra, divided into different HLT selections



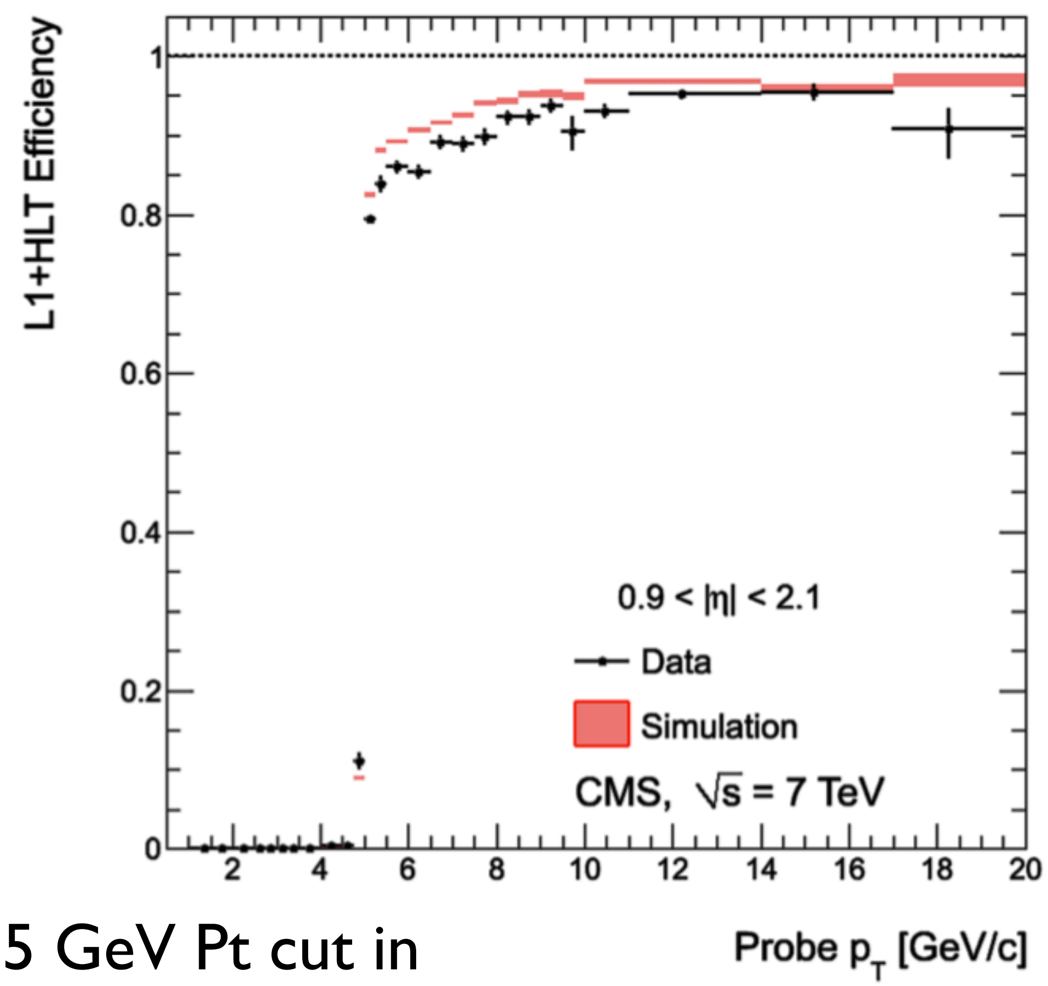
- Muon triggers for Heavy Flavor exploits vertex, mass and momentum constraints



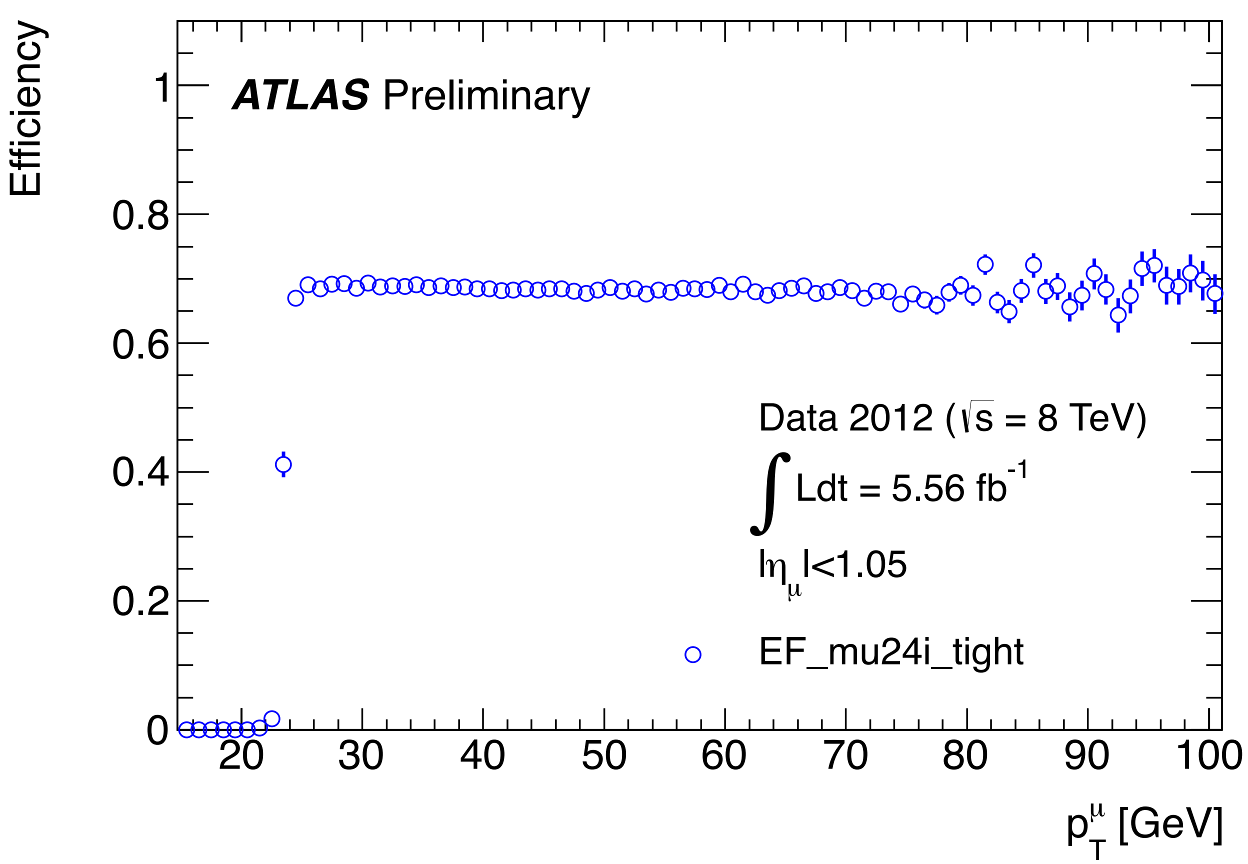
- Dimuon triggers with single muon Pt cut ~4-6 GeV depending on luminosity and trigger path
- Cut on track Pt/IP, dimuon Pt, dimuon vertex (displacement), dimuon mass

Muon high level trigger performance / 1

- Main single muon trigger: isolated muon Pt>24 GeV in both CMS and Atlas
- Main dimuon trigger: (13,13) in Atlas, (10,0) in CMS
  - Several low Pt dimuon triggers: lowest cut Pt(mu)> ~4-6 GeV in both experiments
- Efficiencies measured in J/psi and Z events to better than 1 %



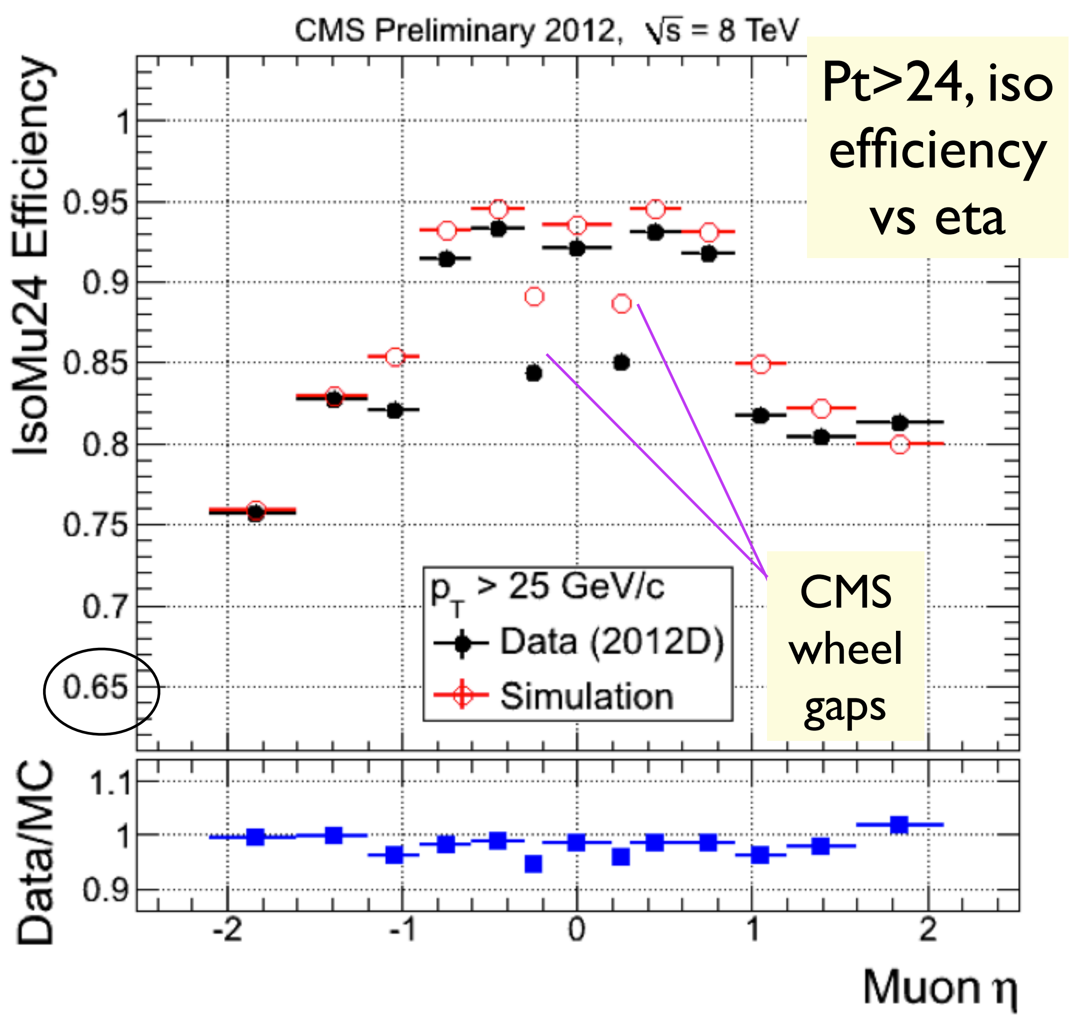
5 GeV Pt cut in CMS endcap (J/Psi T&P)

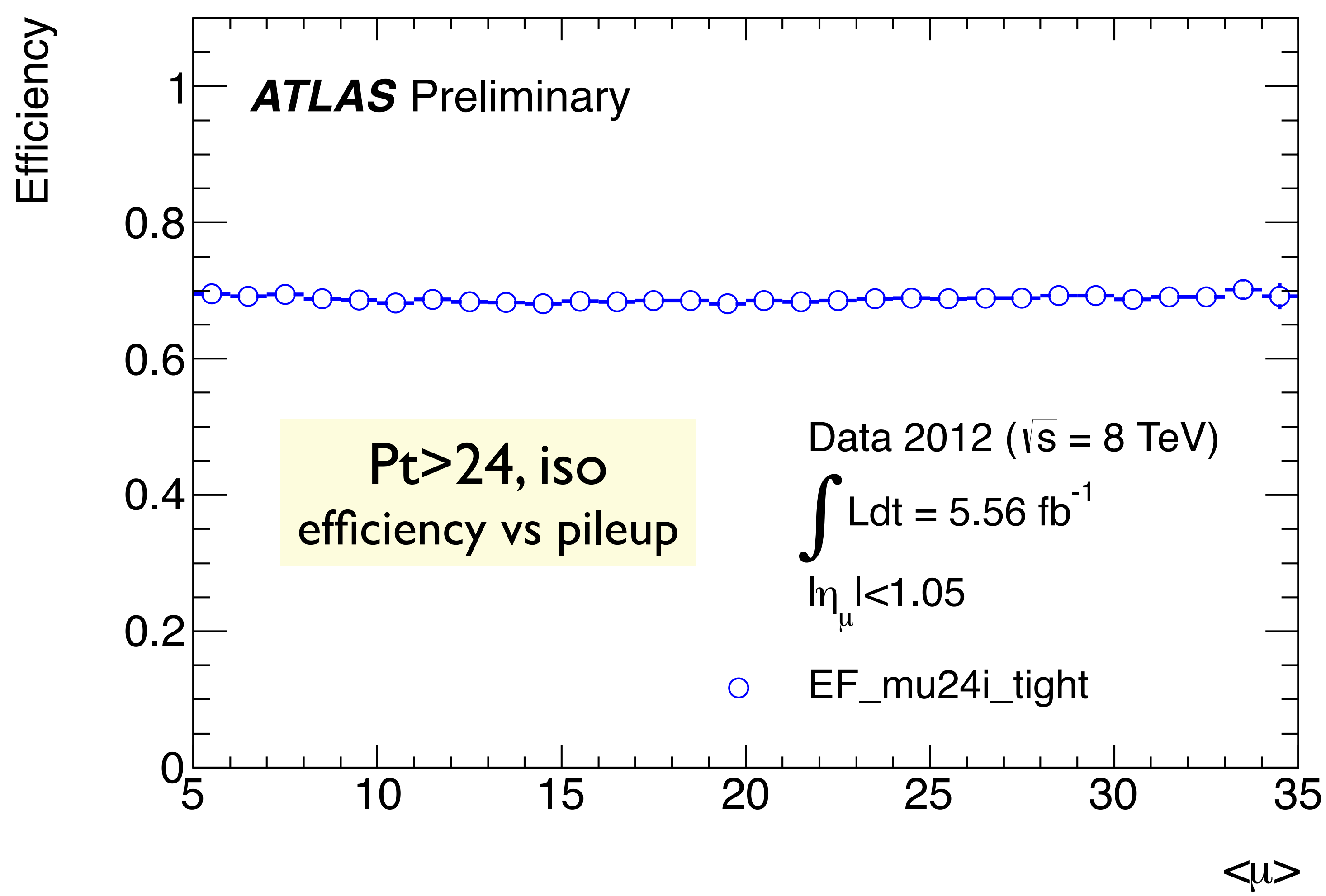


24 GeV isolated mu in Atlas barrel (Z T&P)

Muon high level trigger performance / 2

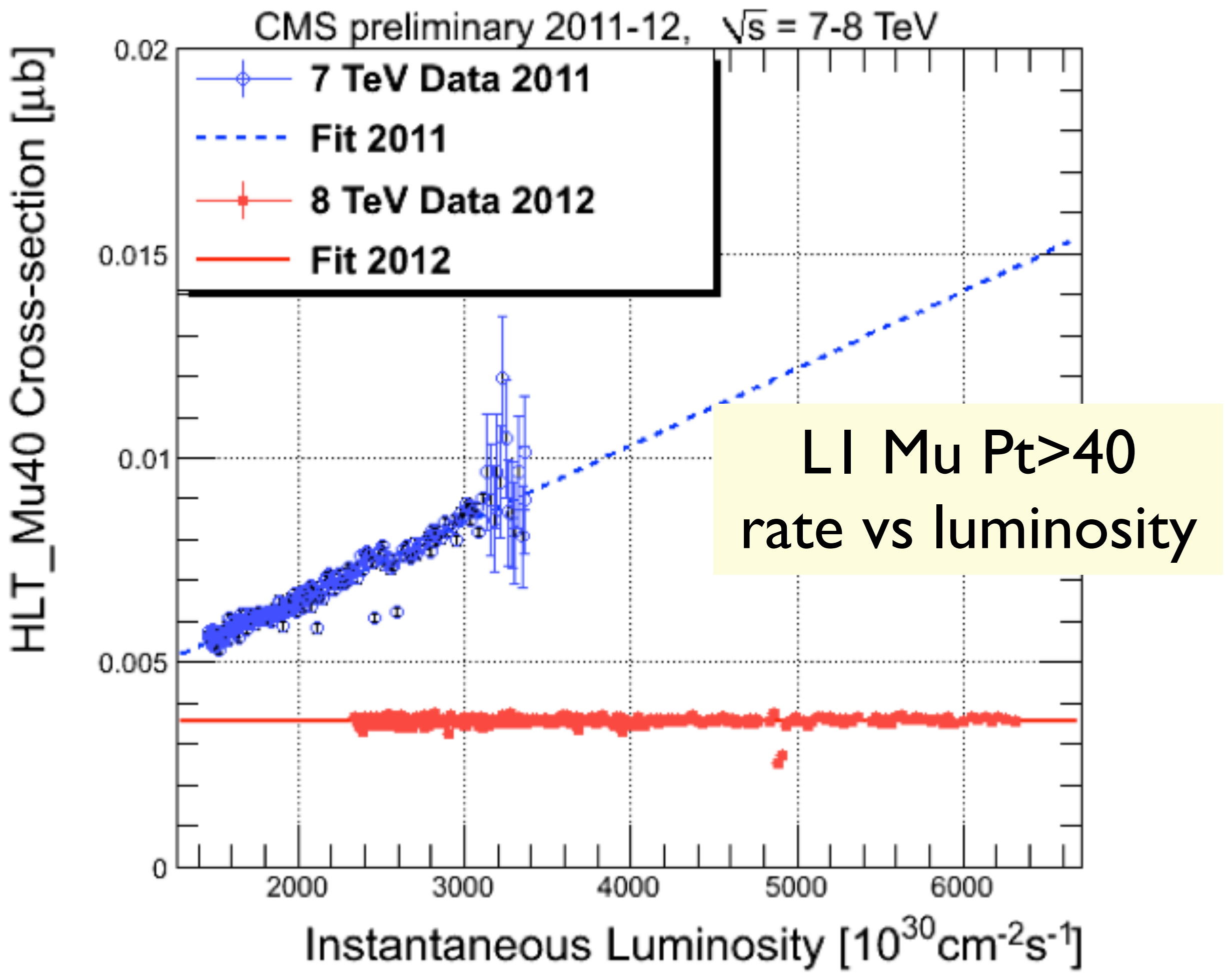
- T&P used to investigate all aspects of efficiency profiles and trigger purity
  - Efficiency vs pileup (flat over the full luminosity range)
  - Binning eta/phi, detector structure

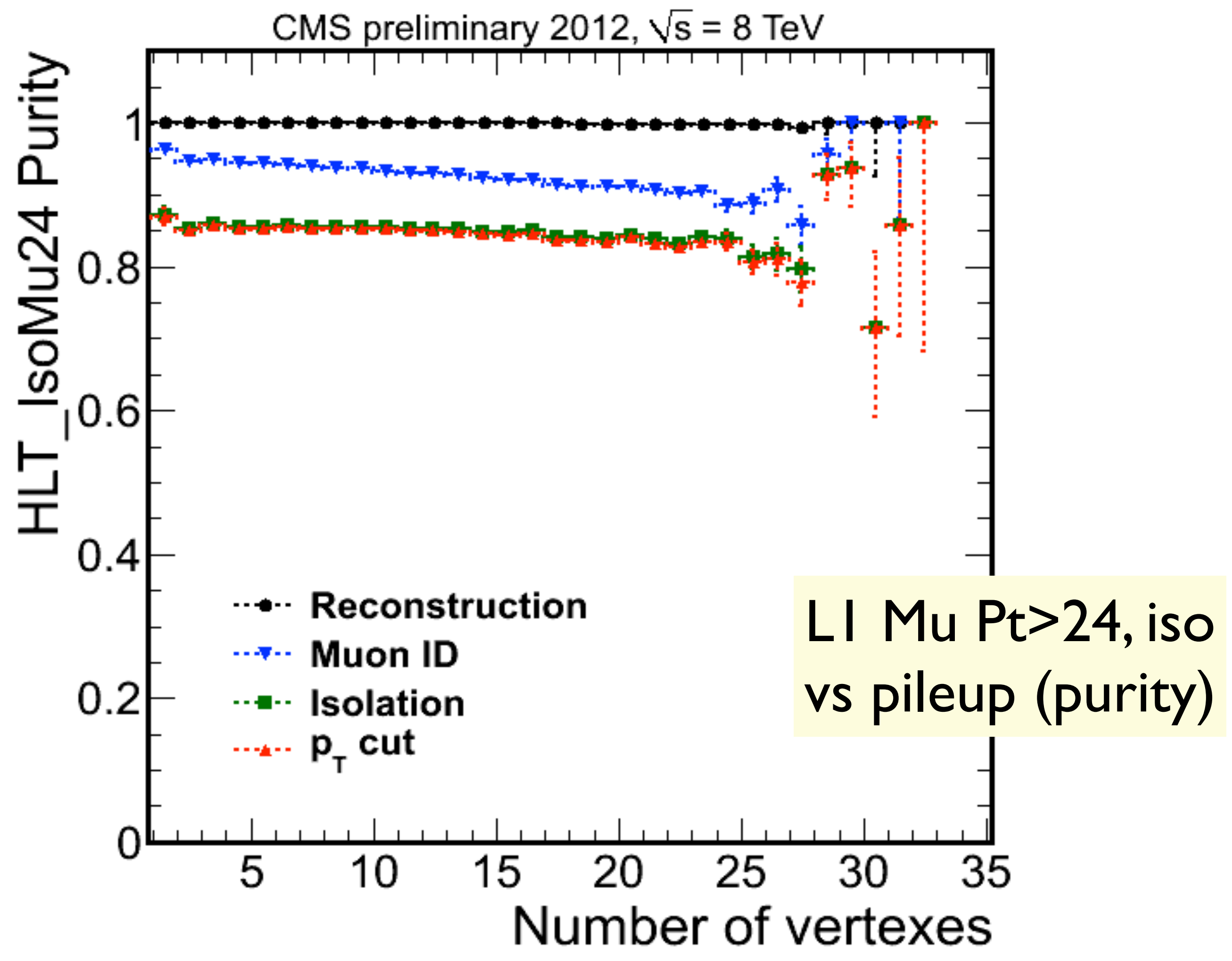




Muon high level trigger performance / 3

- Achieved excellent rate linearity in 2012 (improved HLT seeding and object quality cuts)
- Very good purity with respect to tight offline object





CMS trigger menu for B physics

Prompt reconstruction

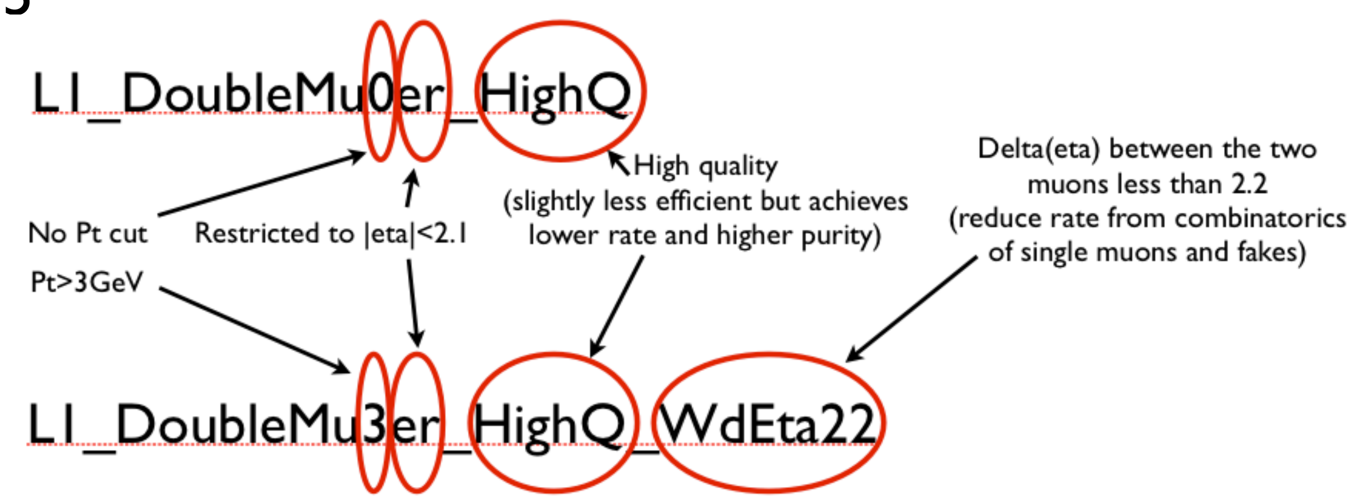
HLT, Hz	HLT path	L1 seed	L1, kHz
3.0	HLT_DoubleMu3_4_Dimuon5_Bs_Central	L1_DoubleMu0er_HighQ	9.2
2.5	HLT_DoubleMu3p5_4_Dimuon5_Bs_Central	L1_DoubleMu3er_HighQ_WdEta22	6.2
2.3	HLT_DoubleMu4_Dimuon7_Bs_Forward	L1_DoubleMu3er_HighQ_WdEta22	
10.5	HLT_DoubleMu4_Jpsi_Displaced	L1_DoubleMu3er_HighQ_WdEta22	
12.0	HLT_Dimuon7_Upsilon	L1_DoubleMu0er_HighQ	
20.0	HLT_Dimuon3p5_SameSign	L1_DoubleMu0er_HighQ	
5.0	HLT_Tau2Mu_ItTrack	L1_DoubleMu0er_HighQ	
2.5	HLT_Dimuon0_Jpsi_Muon	L1_TripleMu0_HighQ	0.5
1.7	HLT_Dimuon0_Upsilon_Muon	L1_TripleMu0_HighQ	

Delayed reconstruction (parking)

HLT, Hz	HLT path	L1 seed
48	HLT_Dimuon8_Jpsi	L1_DoubleMu0er_HighQ
6.5	HLT_Dimuon5_PsiPrime	L1_DoubleMu0er_HighQ
18	HLT_Dimuon5_Upsilon	L1_DoubleMu0er_HighQ
33	HLT_DoubleMu3p5_LowMass_Displaced	L1_DoubleMu3er_HighQ_WdEta22
15	HLT_BTagMu_Jet20_Mu4	L1_Mu3_JetC16_WdEtaPhi2
7	HLT_BTagMu_Jet60_Mu4	L1_Mu3_JetC52_WdEtaPhi2

Plus 8 triggers for the determination of tracking and muon efficiency and reference triggers

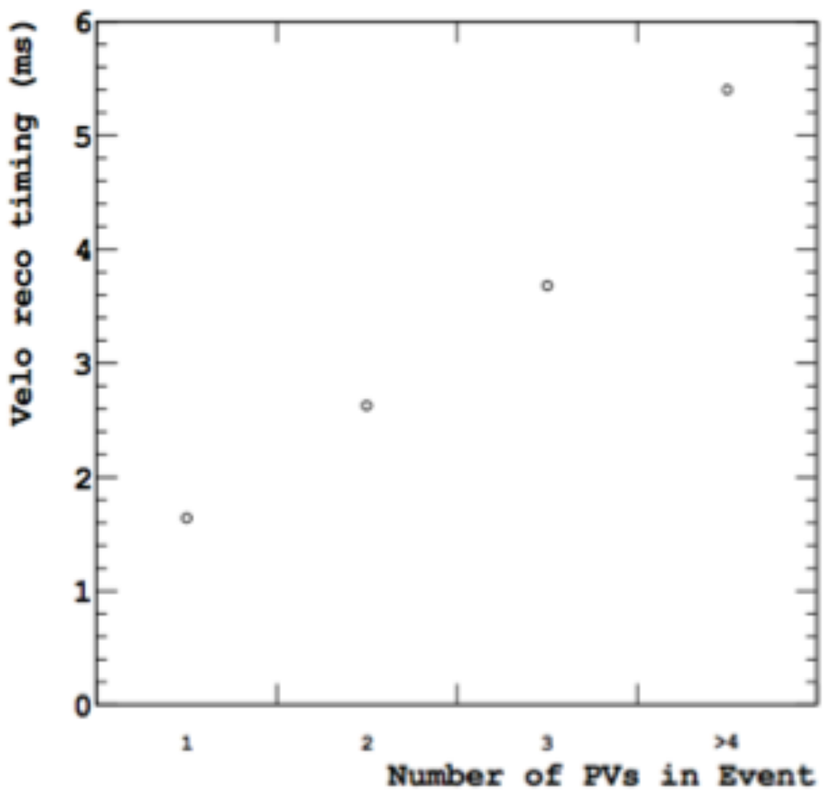
- Very low Pt cut or no pt cut at L1
- Good trigger purity and efficiency
- Topological conditions possible at L1
  - Separation between muons
  - Muon close to jet



- Exploits L3 muon reconstruction and vertexing for dimuon mass cuts and secondary vertex cuts

LHCb HLT1 displaced track trigger

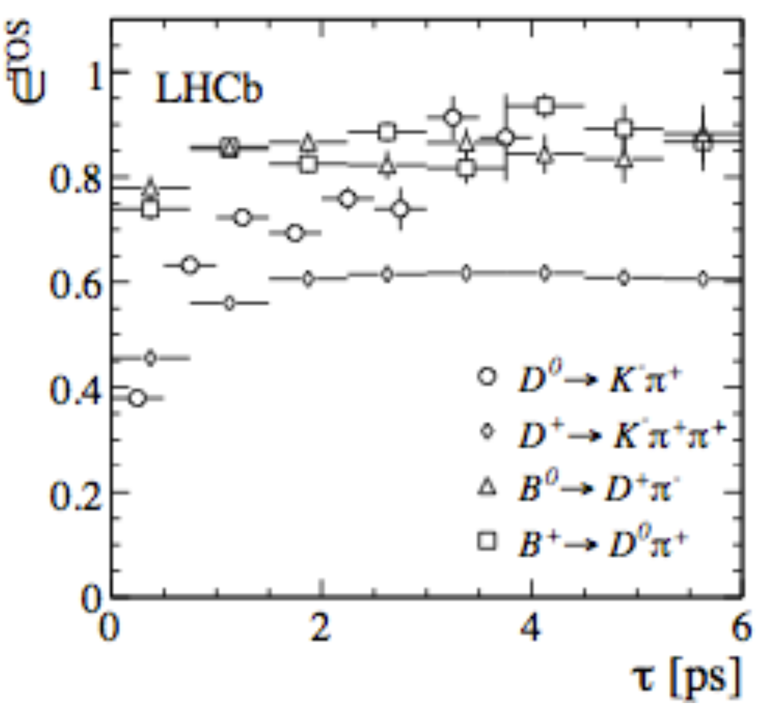
- HLT1: reconstruct track Pt, impact parameter or vertex displacement, dimuon (80 kHz)
  - Full VELO reconstruction (PV, track selection based on IP, quality)
  - Any L0: use good quality VELO track with large IP, cut on momentum
    - Reconstruct tracks with IT/OT in region of interest and cut on track quality; inclusive, xx kHz output



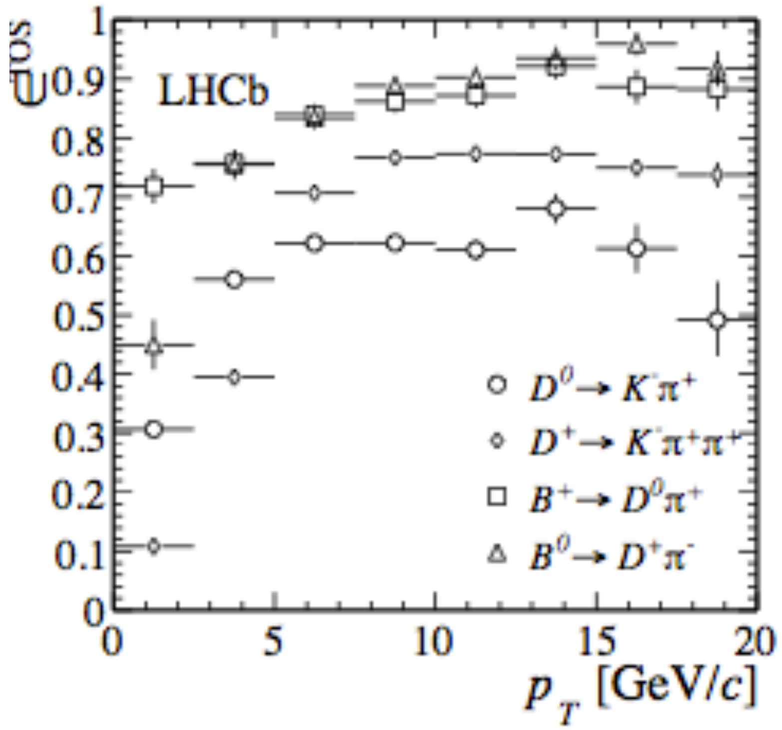
VELO reconstruction timing vs pileup

HLT1 track trigger effiency

B/D candidate decay-time

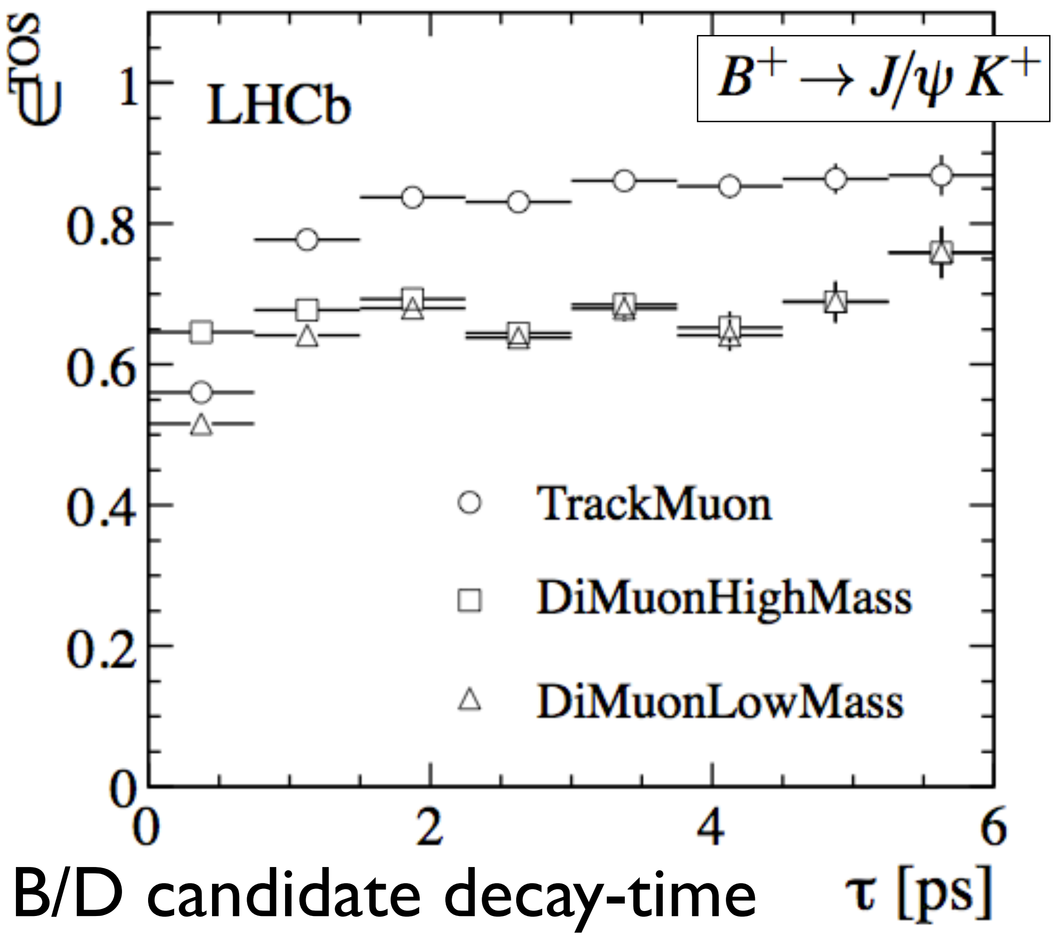


B/D candidate Pt

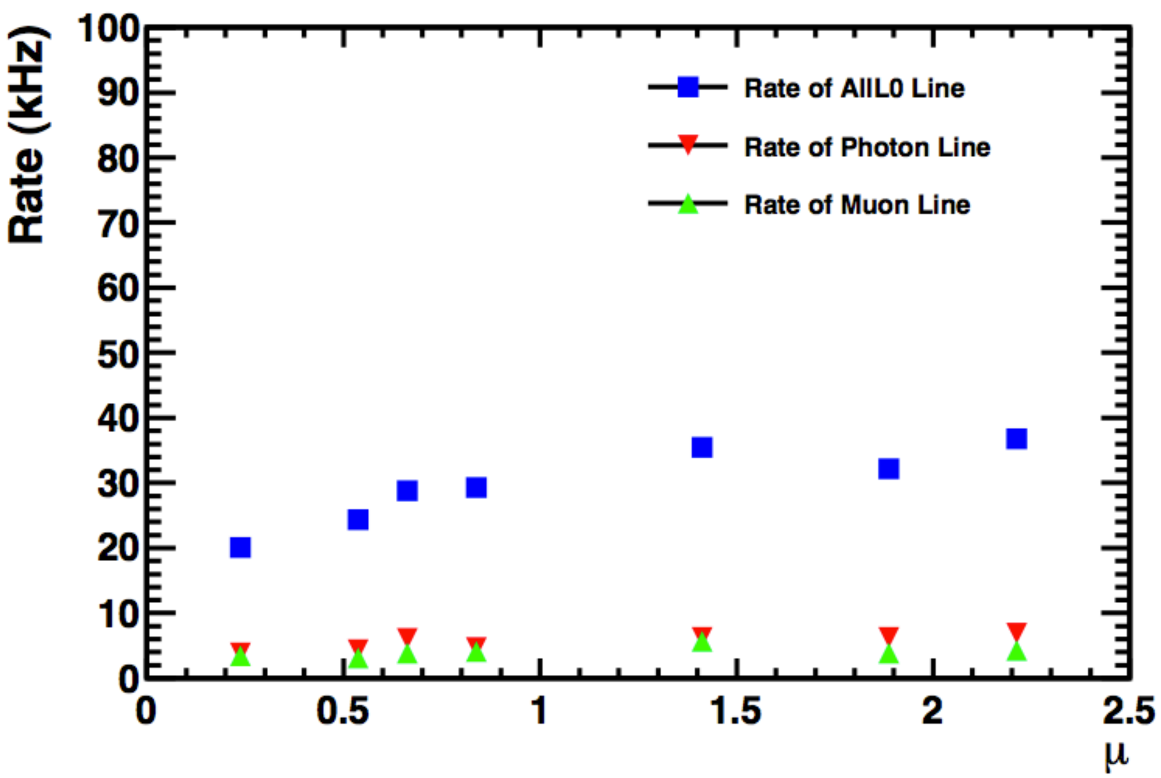


LHCb HLT1 muon trigger

- HLT1: reconstruct track Pt, impact parameter or vertex displacement, dimuon (80 kHz)
  - Full VELO reconstruction (PV, track selection based on IP, quality)
  - Any L0: use good quality VELO track with large IP, cut on momentum
    - Reconstruct tracks with IT/OT in region of interest and cut on track quality; inclusive, xx kHz output
  - If L0 (di)muon, match VELO tracks with muon hits in region of interest, reconstruct with IT/OT
    - Dimuon: build dimuons and cut on mass; allows relaxed momentum and IP cuts on tracks
    - Single muon also allows relaxed momentum and IP cuts on tracks

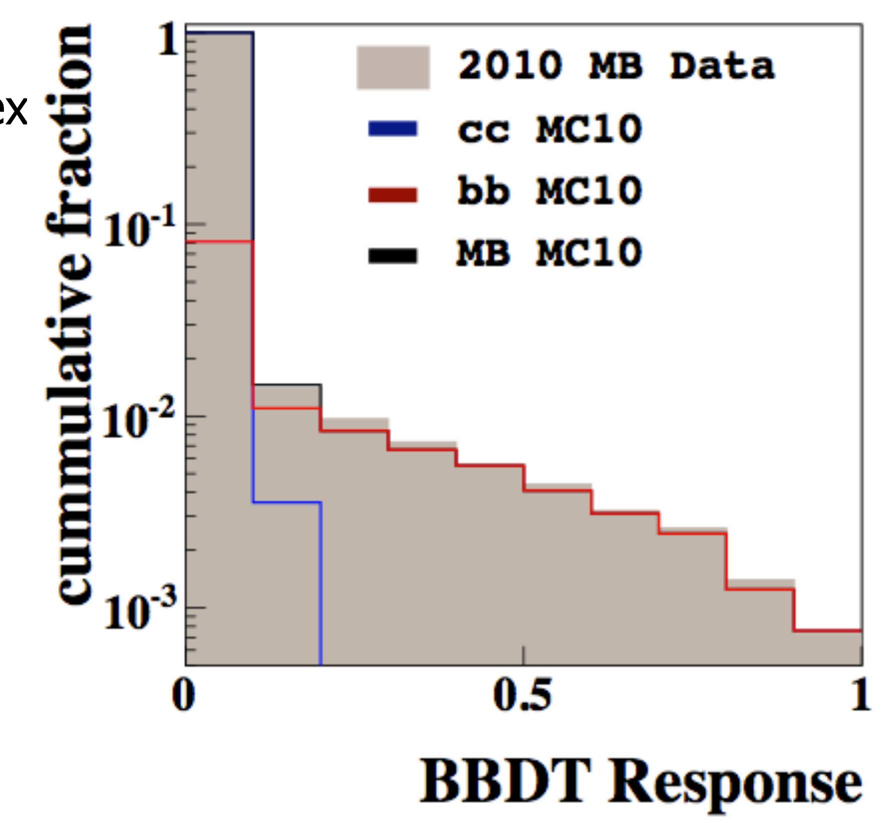


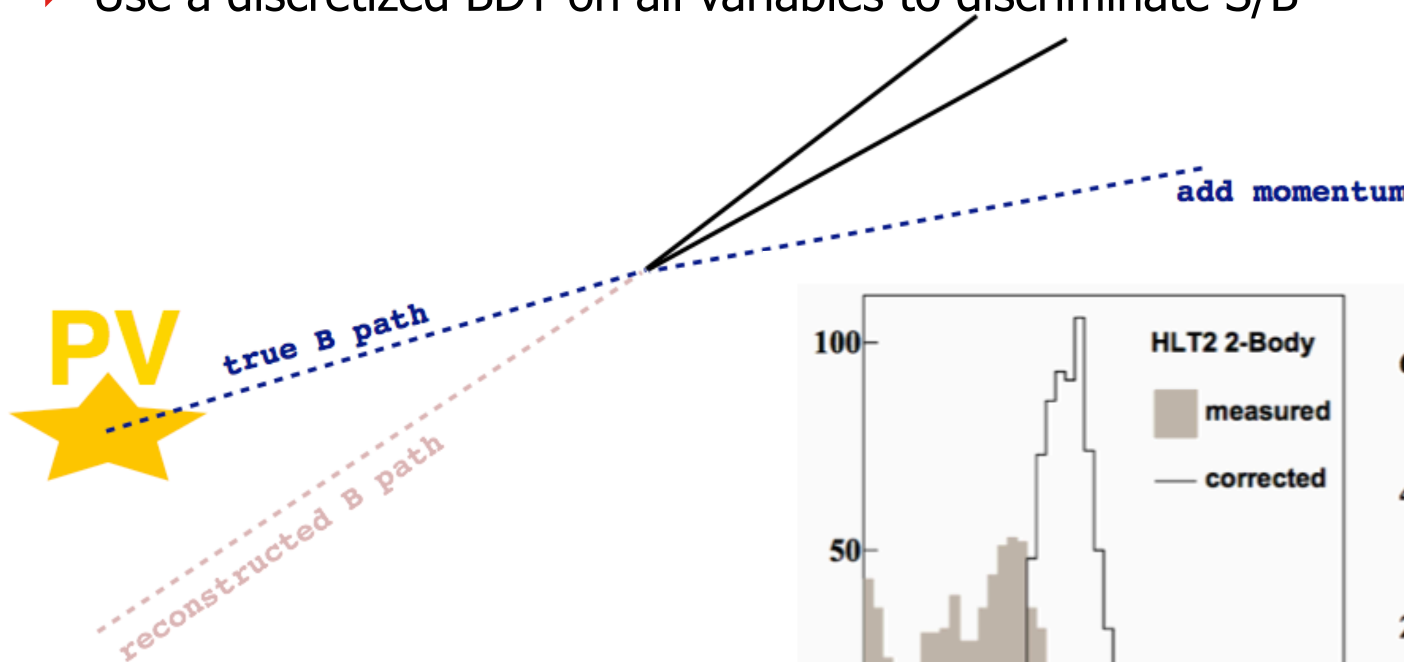
B/D candidate decay-time



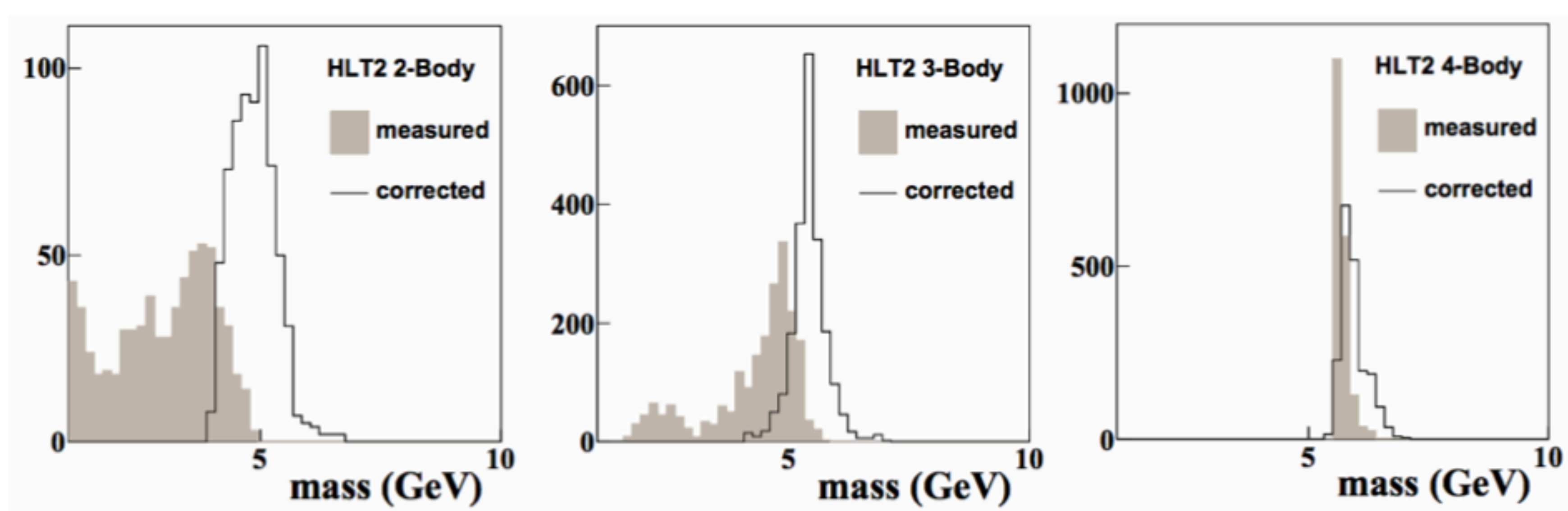
LHCb HLT2 - topological trigger

- Most inclusive and powerful trigger: topological trigger
  - Cover in principle all B decays with at least two tracks and displaced vertex
  - Build displaced vertex with two selected (chi2, IP, mu-e ID) tracks
  - DOCA cut to choose between keeping the 2-track candidate or seed for 3-track vertexing
  - Repeat up to 4 tracks
  - Corrected mass of the candidate adding the Pt missing wrt the direction of flight
  - Use a discretized BDT on all variables to discriminate S/B





$$m_{\mathrm{corrected}} = \sqrt{m^2 + |p'_{T\mathrm{missing}}|^2} + |p'_{T\mathrm{missing}}|$$

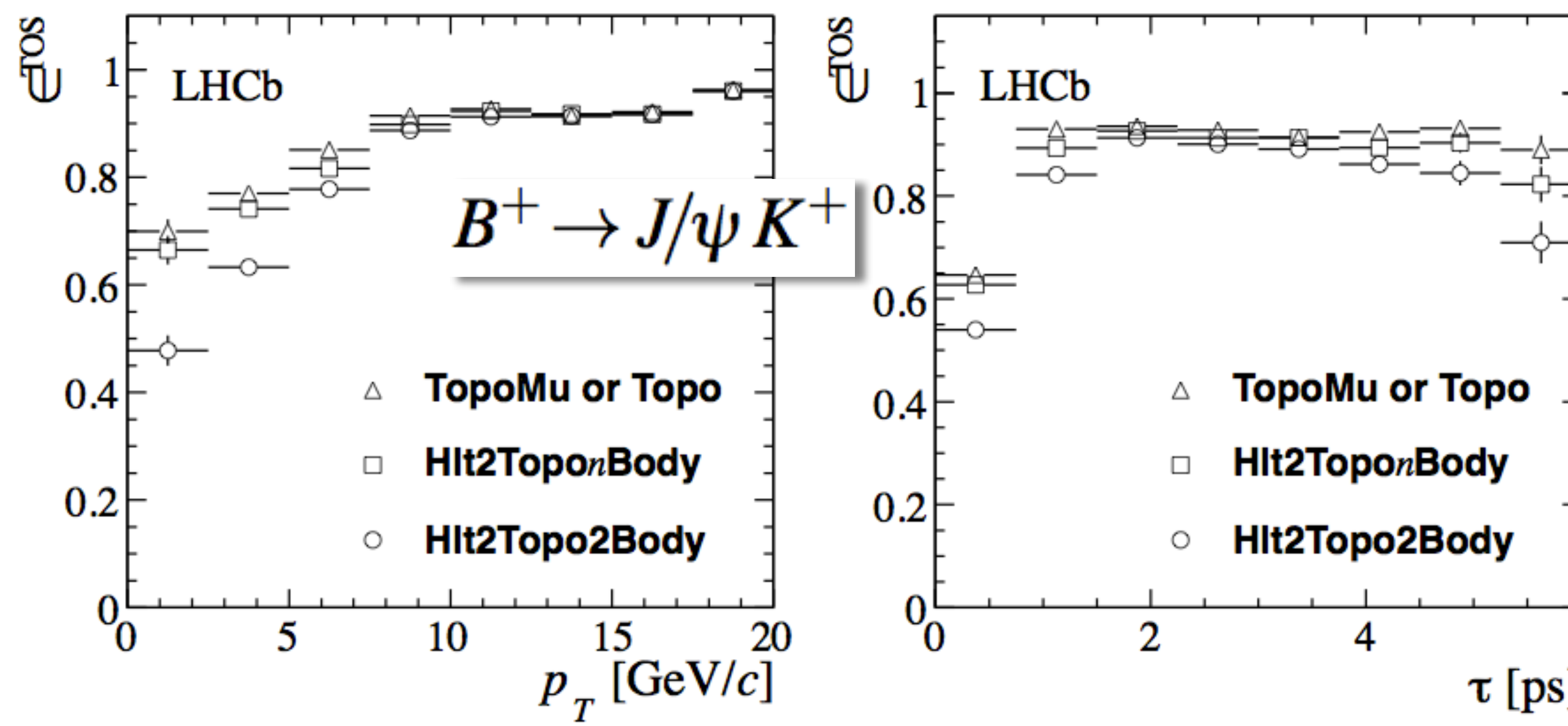


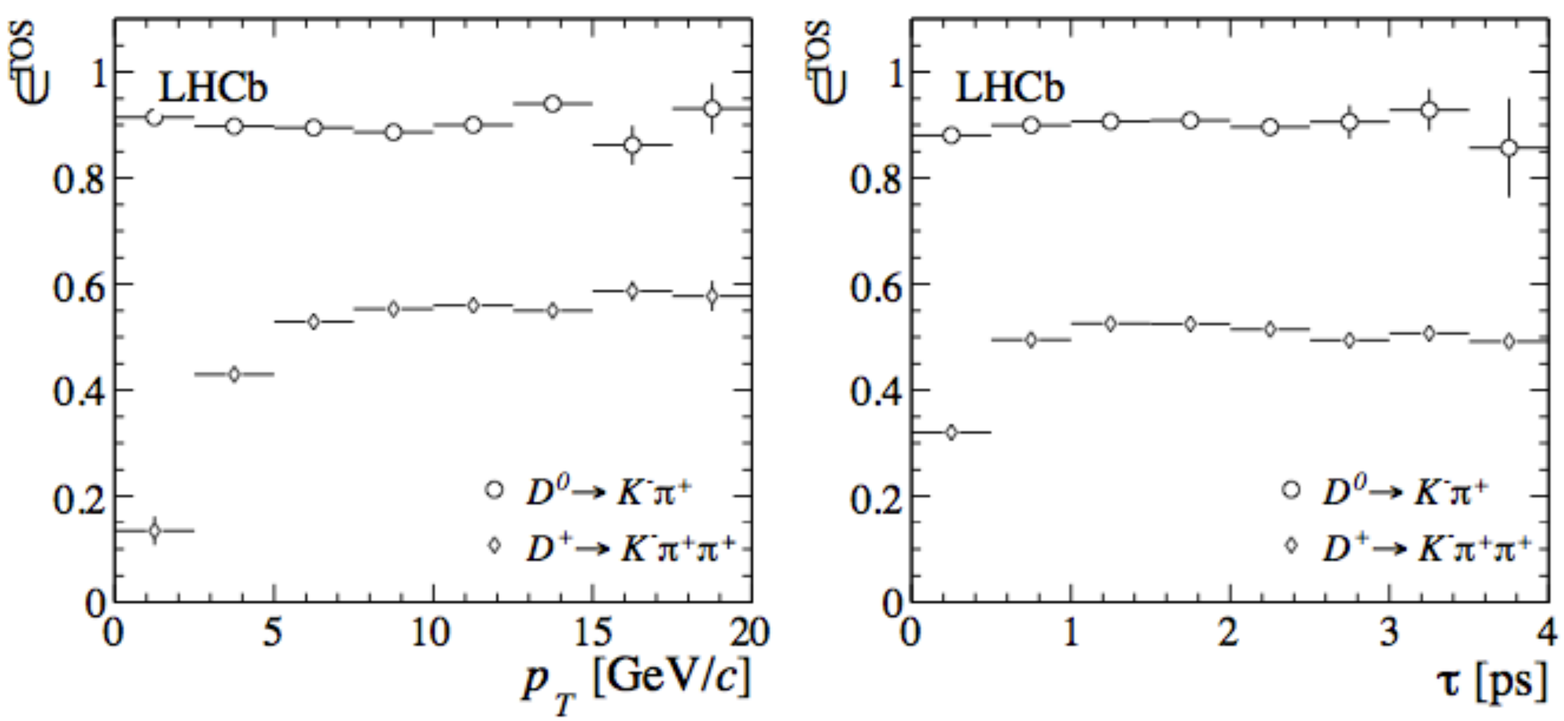
Corrected mass of B→K*μμ in 2,3,4 track topological triggers

LHCb HLT2 topological trigger performance

- Topological 2-body trigger alone: inclusive performance
  - nBody triggers increase performance al low Pt
- Also topological trigger with muon ID - efficiency gain is allowed (relaxed BBDT cuts)

D->Kpi, D->hhh





- Exclusive charm triggers
  - `D->Kpi, D->hhh`
  - nBody triggers increase performance al low Pt

Summary

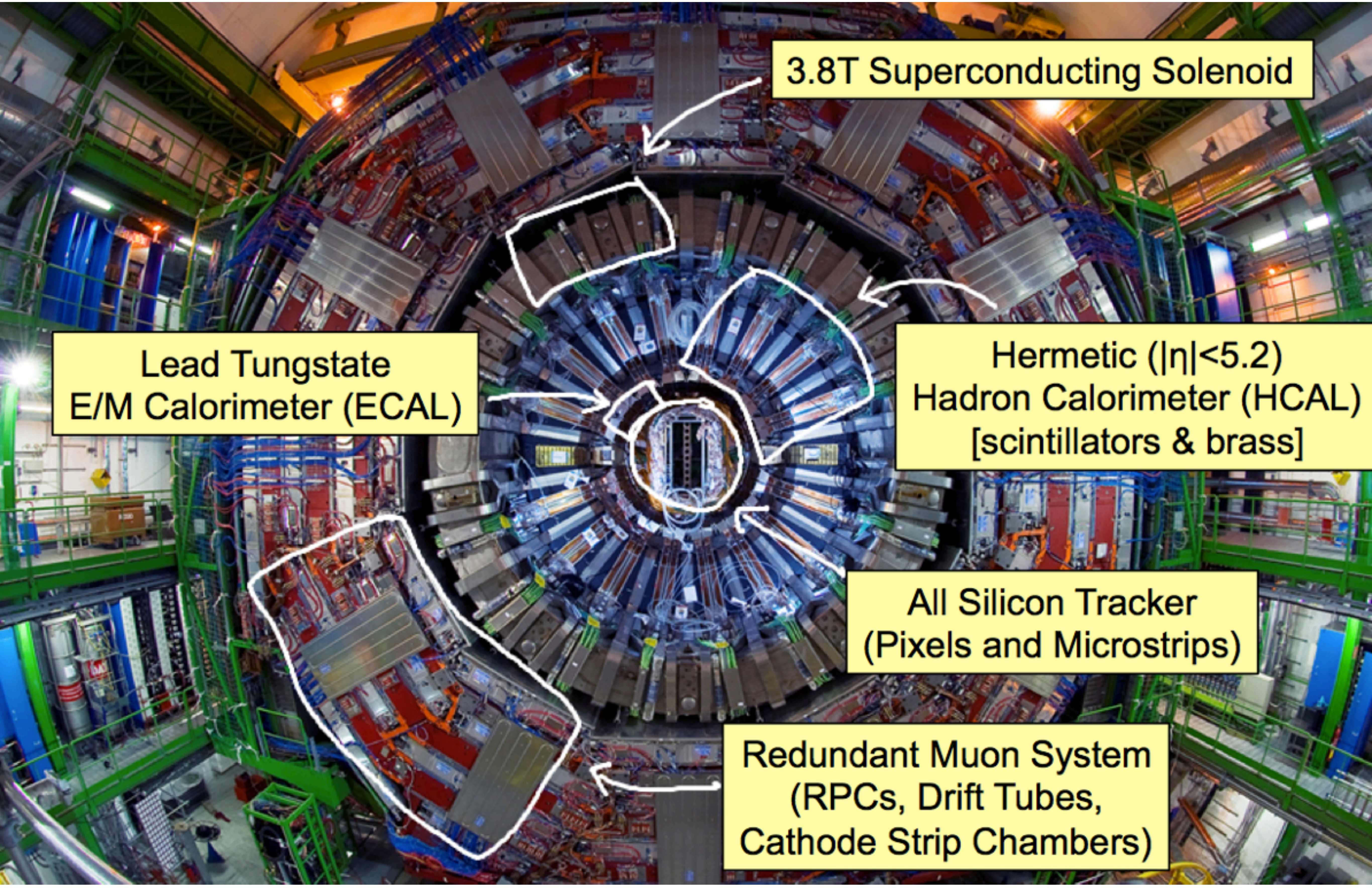
- Trigger in LHC environment is a hard job
- Constraints from many actors engaged in a complex interplay
  - Common goal is to maximize physics performance
  - Common constraints are DAQ rate, latency, storage rate, available CPU power
- Different detector designs but similar techniques (and technology) are employed

- The tough task of triggering at LHC accomplished with great success
  - Shown excellent performance for benchmark objects
  - Very good operation of the HW and SW infrastructures

- Looking forward to continued evolution of the trigger systems
  - Future LHC runs, lumi up to 10E35
  - Detector upgrades
  - DAQ system upgrades
  - Updated physics priorities

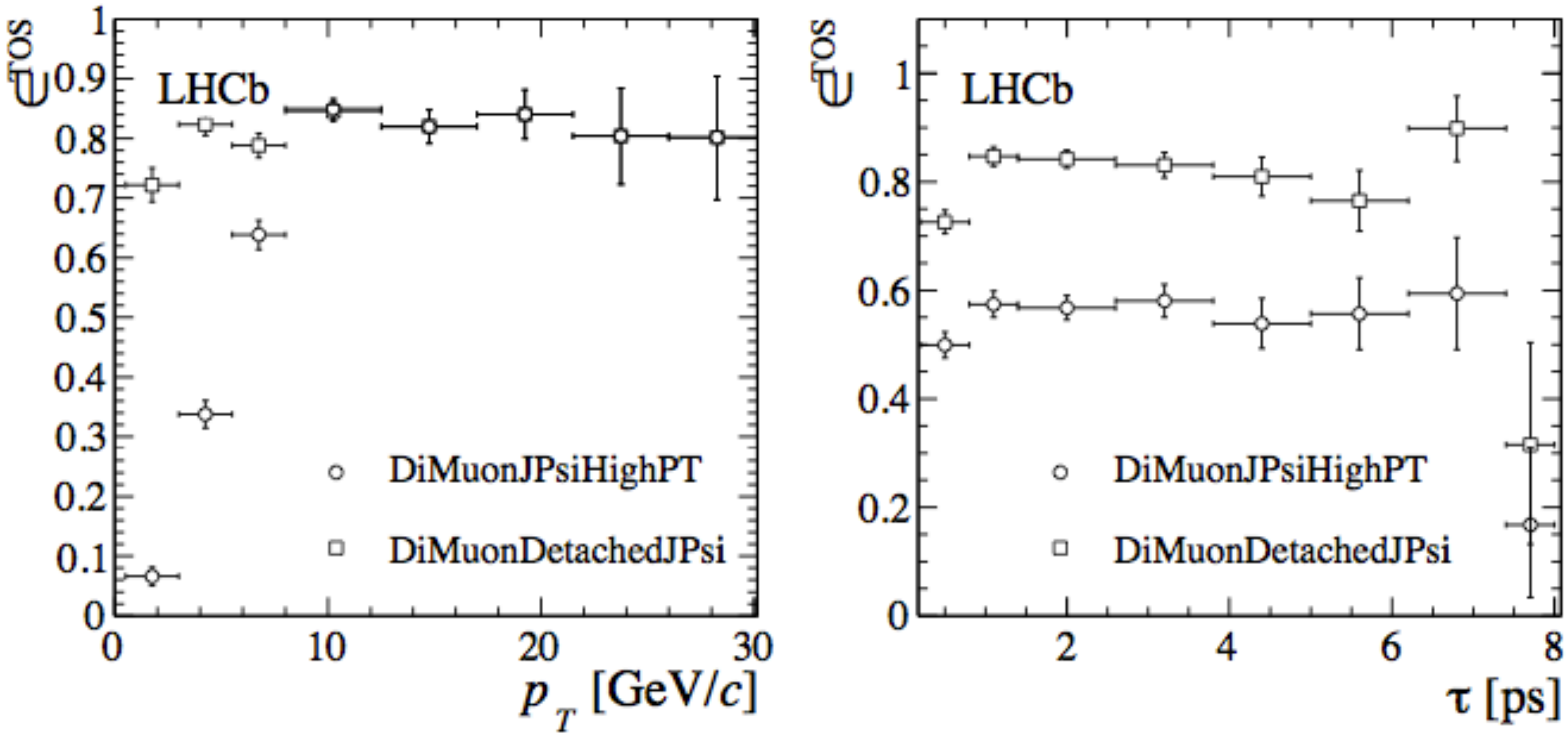
backup

CMS Detector: The real thing



LHCb HLT2 Muon triggers

- SingleMuon: IP cut, low Pt cut, prescaled by 2 (semileptonic B/D/tau, J/psi tag&probe)
- SingleMuonHighPt: Pt>10 GeV, no other track cuts (W, Z, Z tag&probe)
- DiMuon: JPsi(HighPt), Psi2S(HighPt), B using mass cuts
- Detached dimuon. "Heavy" and "JPsi" flavors with different mass cuts vs FD cuts



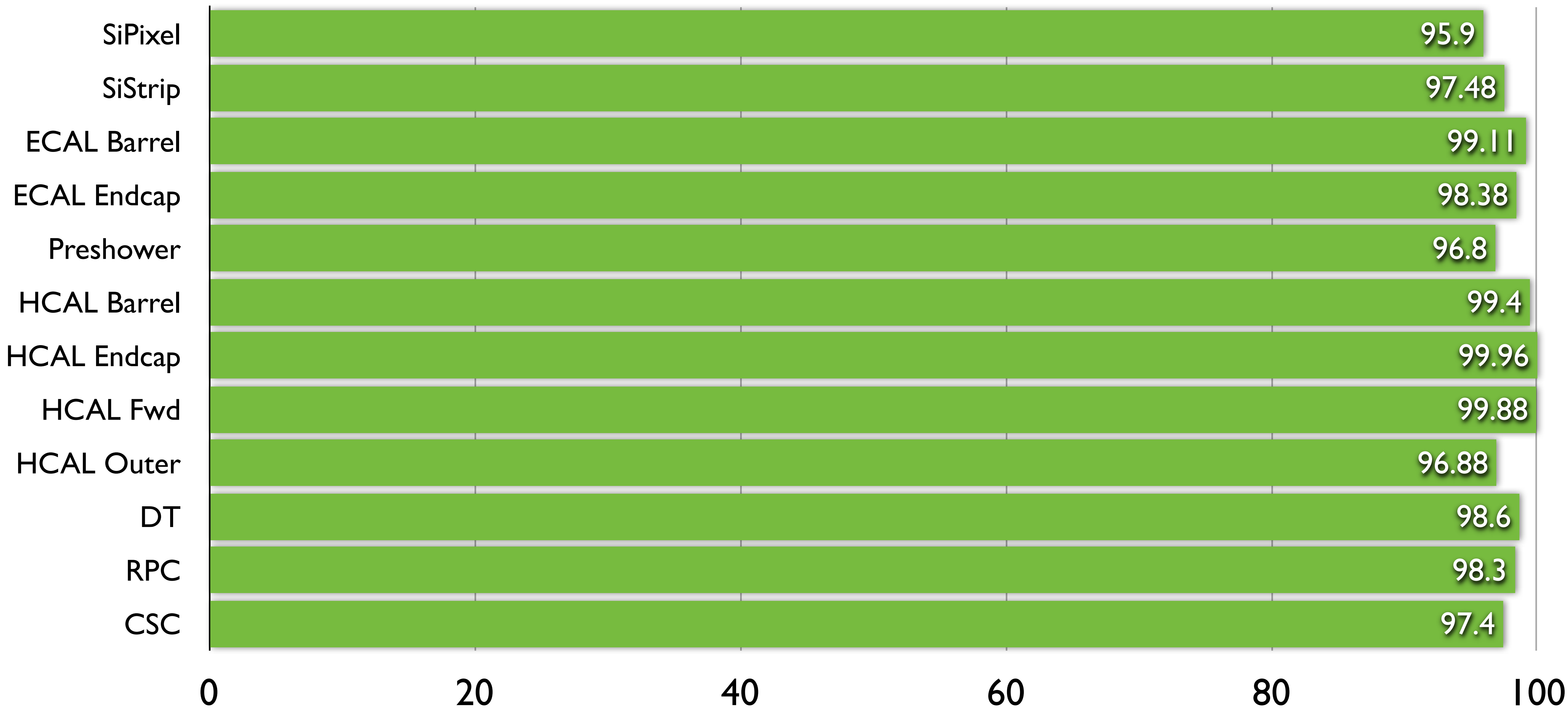
LHCb trigger in one slide

- Trigger on most interesting charmed meson
- Trigger all B decays into charged tracks in inclusive way
- Keep very high efficiency for rare B decays (muons, photons)
- Keep large rate of dimuon events, prompt

- 1 MHz L0: charged hadrons (450 kHz), muon/dimuon (400 kHz), e/gamma (150 kHz)

- HLT1: reconstruct track Pt, impact parameter or vertex displacement, dimuon (80 kHz)
  - Full VELO reconstruction (PV, track selection based on IP, quality)
  - Any L0: use good quality VELO track with large IP, cut on transverse momentum
    - Reconstruct tracks with IT/OT and cut on track quality; inclusive
  - If L0 (di)muon, build track with muon hits in window corresponding to extrapolation of track with P>6GeV
    - Build dimuons and cut on mass
    - Single muons allow relaxed momentum and IP cuts on tracks
- HLT2: track reconstruction, inclusive and exclusive selections (5 kHz)
  - Muon and dimuon trigger: uses offline muon id (1 kHz)
  - MVA-based, inclusive topological trigger (2 kHz)
  - Inclusive/exclusive charm (2 kHz)

CMS detector status: live channels



All subsystems close to 100% good channels.
CMS detector and FE electronics
not accessible since the beginning of 2009!

Atlas detector status: live channels

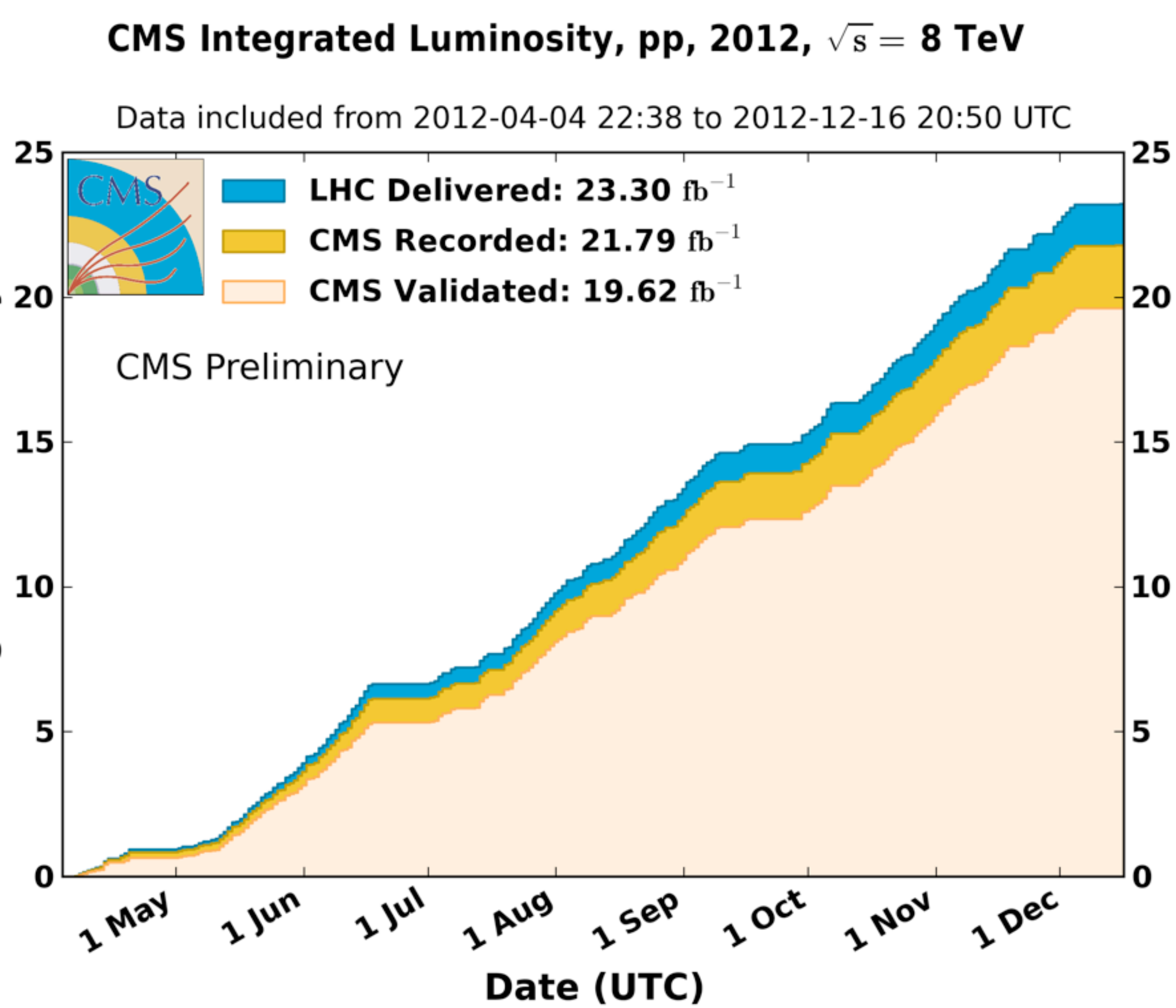
- Fraction of operational channels very close to 100% in most systems

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	95.0%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.9%
Tile calorimeter	9800	98.3%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	370 k	100%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	96.0%
RPC Barrel Muon Chambers	370 k	97.1%
TGC Endcap Muon Chambers	320 k	98.2%

CMS/Atlas Certification

ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.4	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.8%										

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.6 fb^{-1} of recorded data.

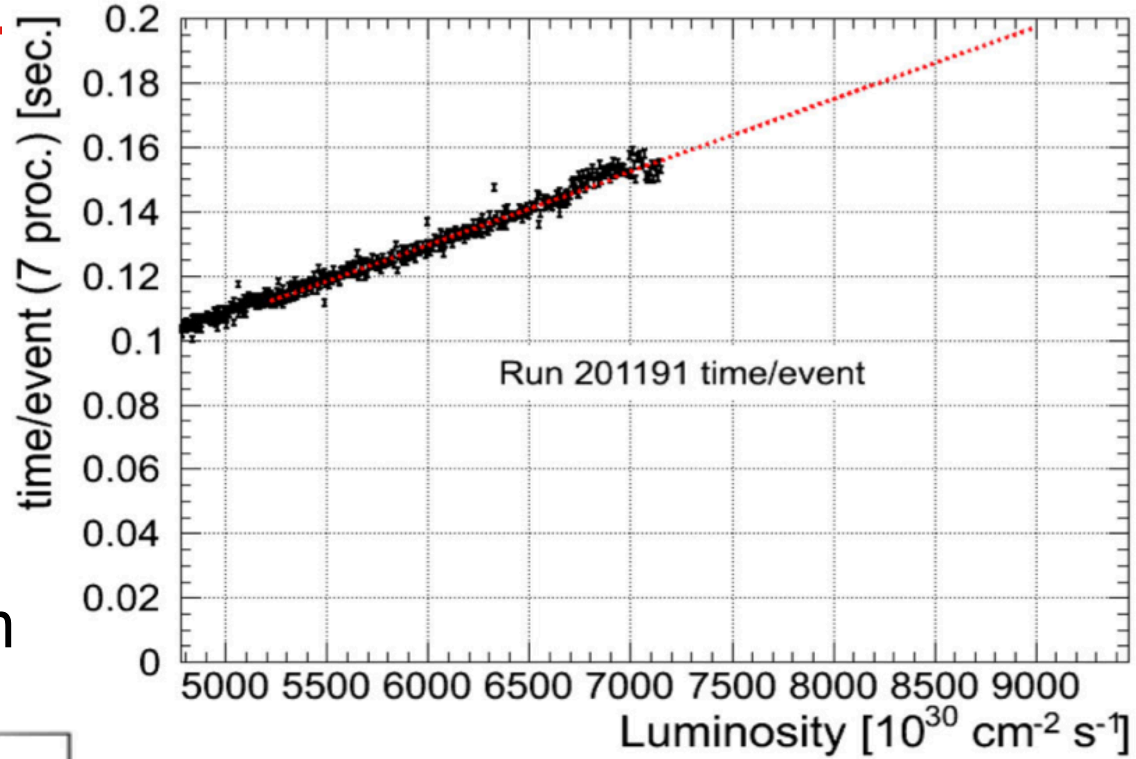


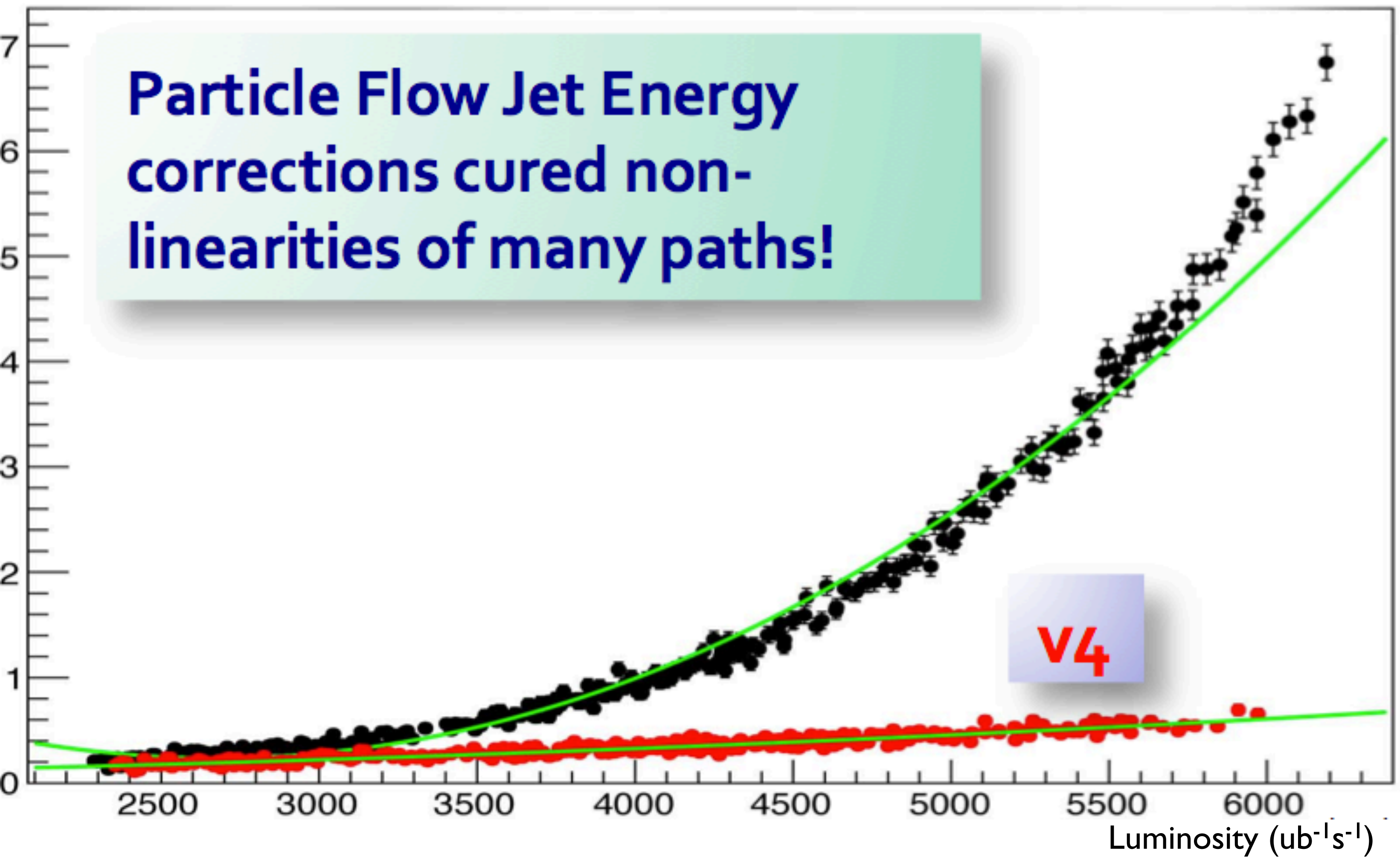
CMS Preliminary Results: Apr-Dec 2012 proton-proton collision runs									
Tracker		Calorimeters			Muon Spectrometer			Magnet	Operational
Pixel	SST	ECAL	ES	HCAL	CSC	DT	RPC		
98.9	99.6	98.6	99.3	96.6	99.3	99.8	99.4	98.6	99.2
All good for physics: 90%									

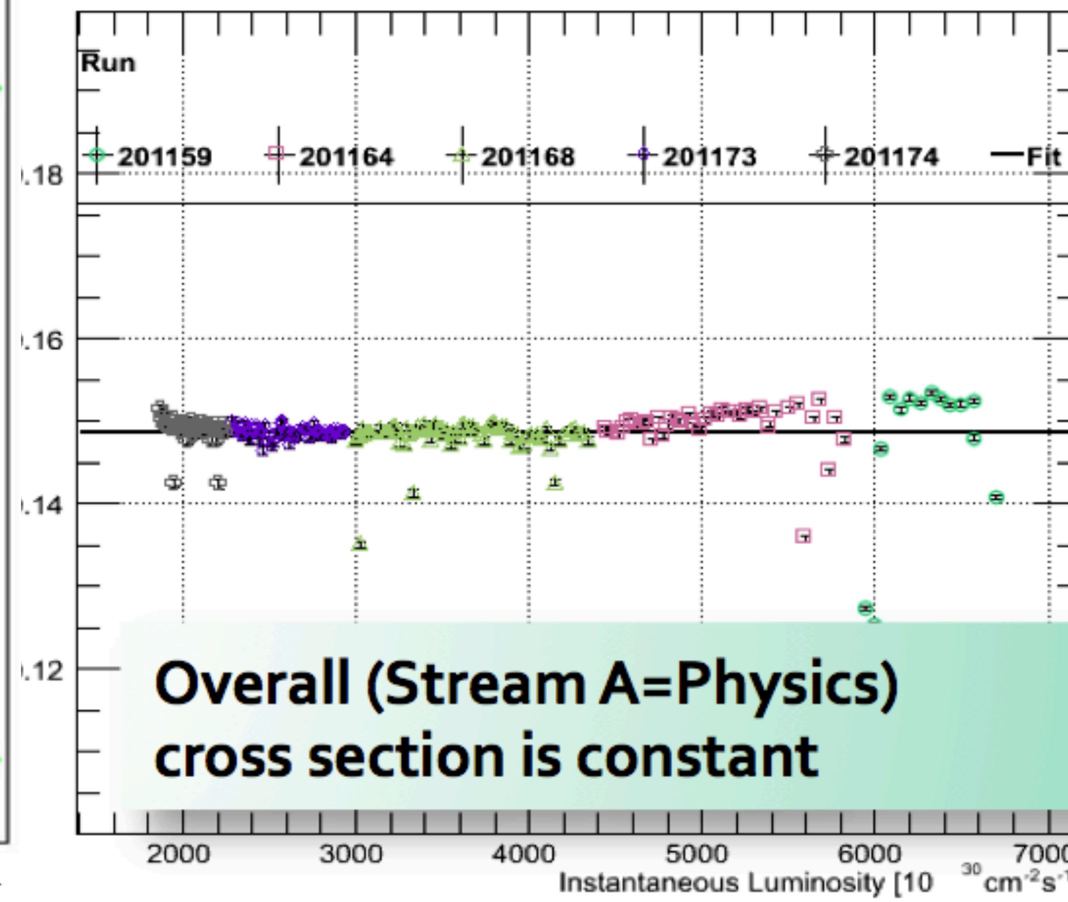
Luminosity weighted fractions (in %) of data certified as good for physics analysis relative to 21.79fb^{-1} of data recorded by the CMS experiment during 2012 proton-proton collisions at √s=8TeV between April 4th and December 17th.

CMS HLT performance

- CPU time scales linearly with luminosity
- Particle Flow Jet Energy corrections implemented in HLT: improved linearity
- Constant cross section of CMS physics data stream







Atlas muon triggers

Muon trigger at p_T>18 GeV in 2011

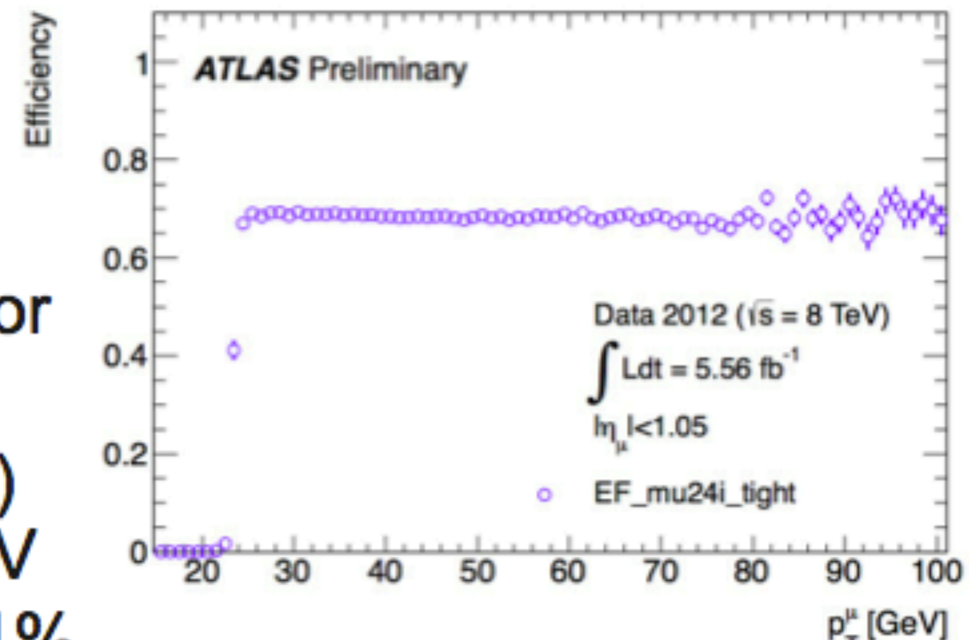
Tightened L1 trigger mid 2011 due to out-of-time hits with 50ns beam

Changes for 2012:

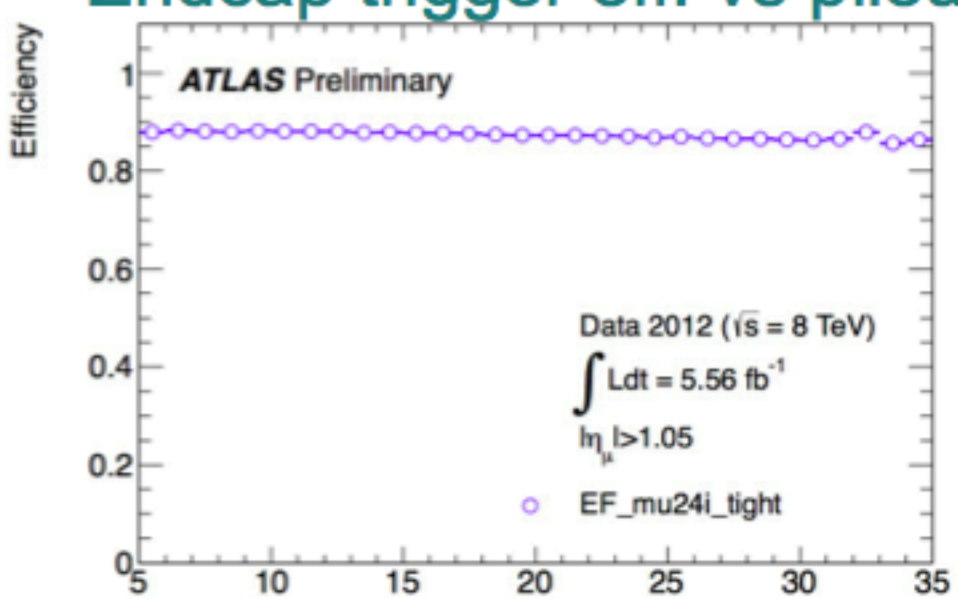
- Additional shielding installed in detector
- Raise to p_T>24 GeV
- Track isolation required (pileup robust)
- Di-muon raised from 2x10 to 2x13 GeV

Efficiencies measured in $Z \rightarrow \mu\mu$ to <1%

Barrel trigger eff. vs p_T

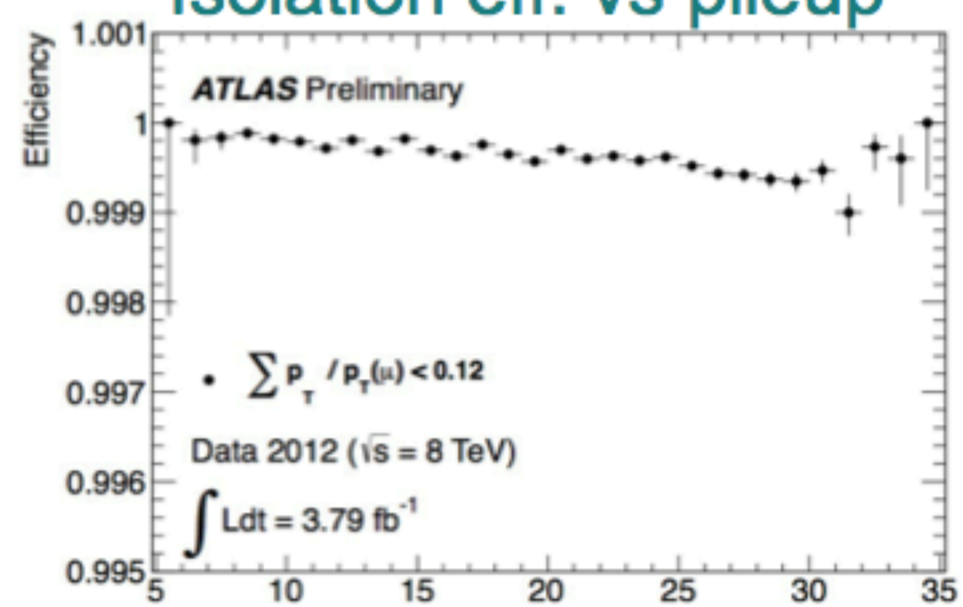


Endcap trigger eff. vs pileup



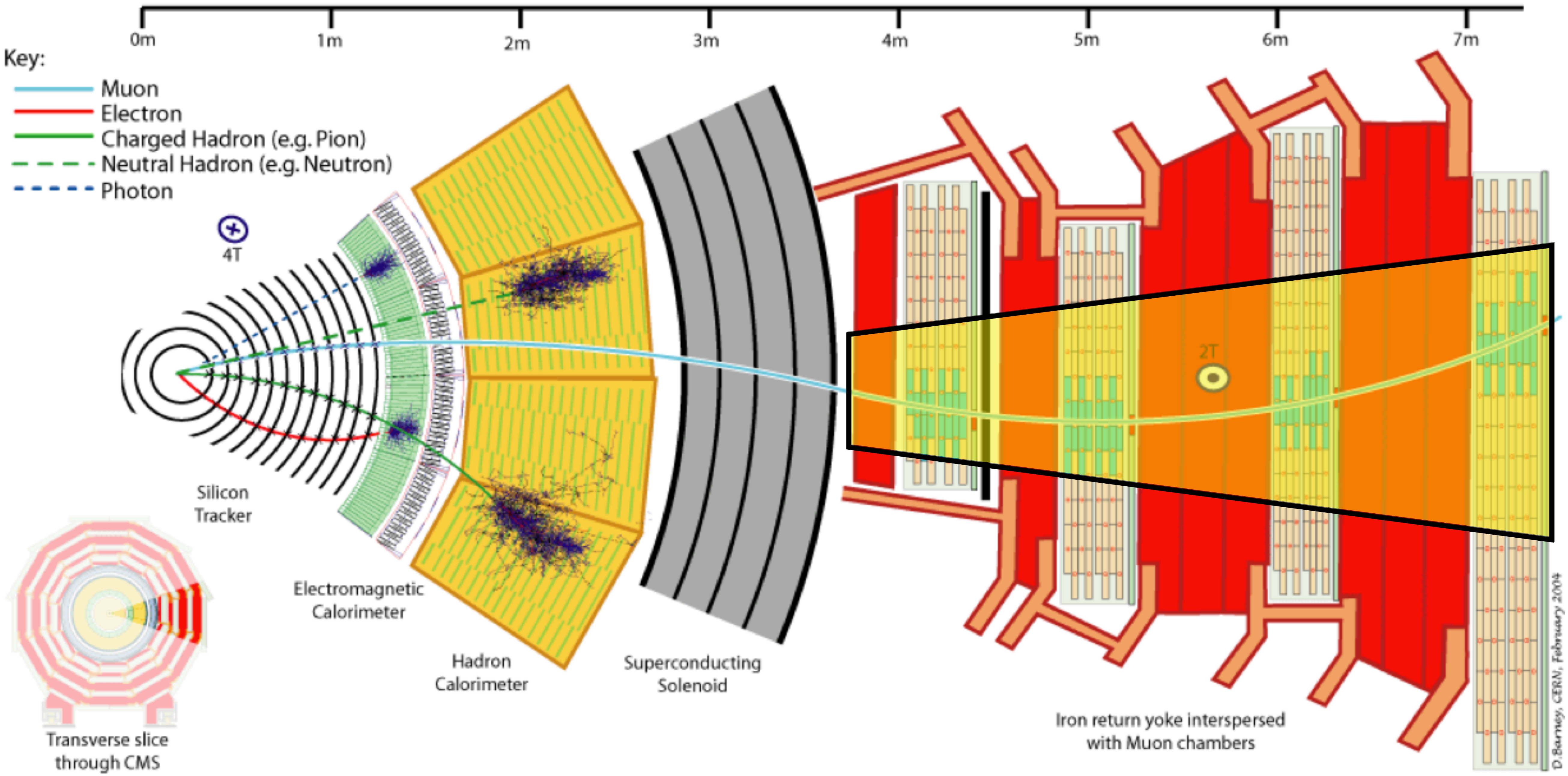
Average interactions per bunch crossing (pileup)

Isolation eff. vs pileup

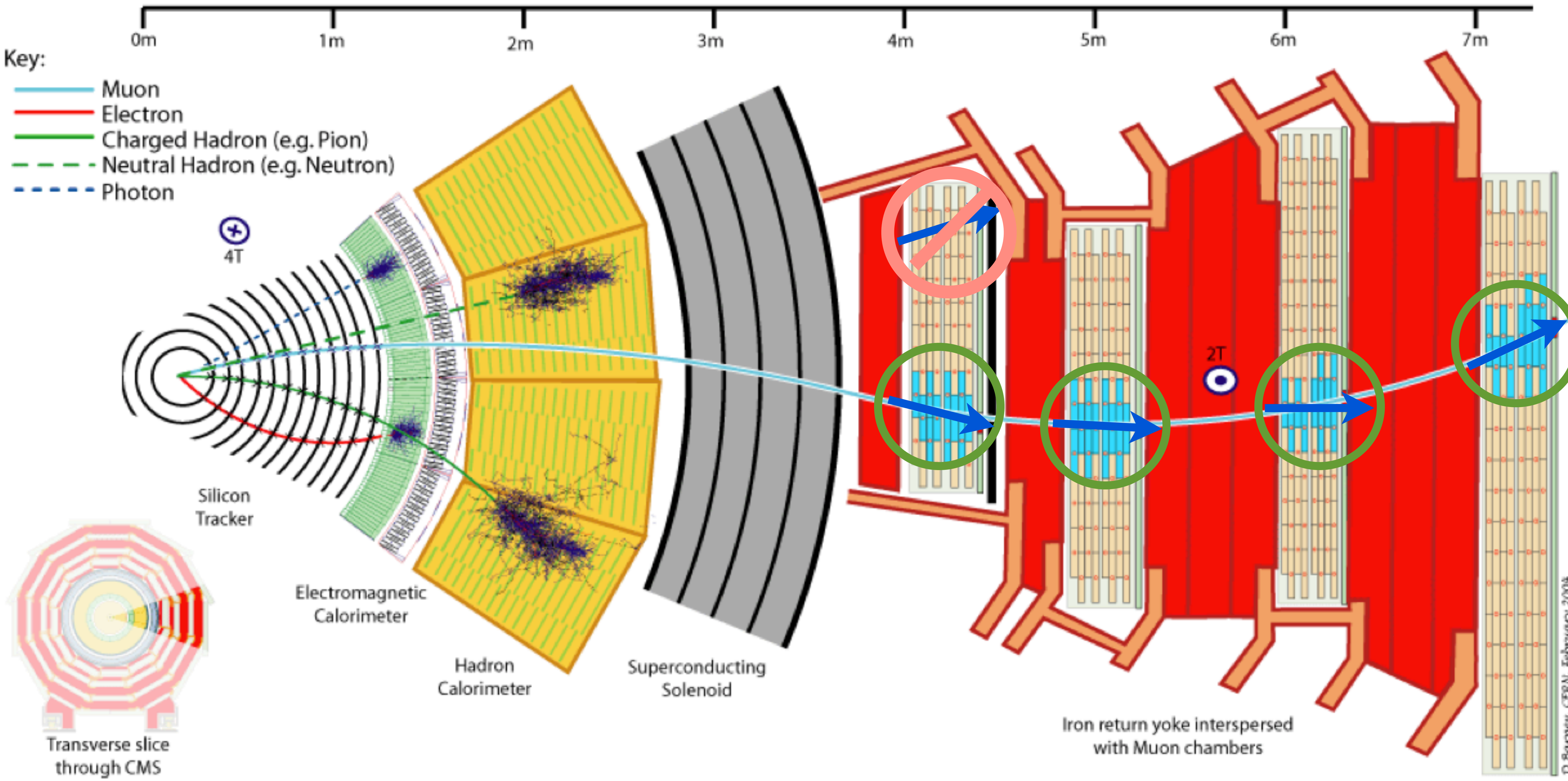


Average interactions per bunch crossing (pileup)

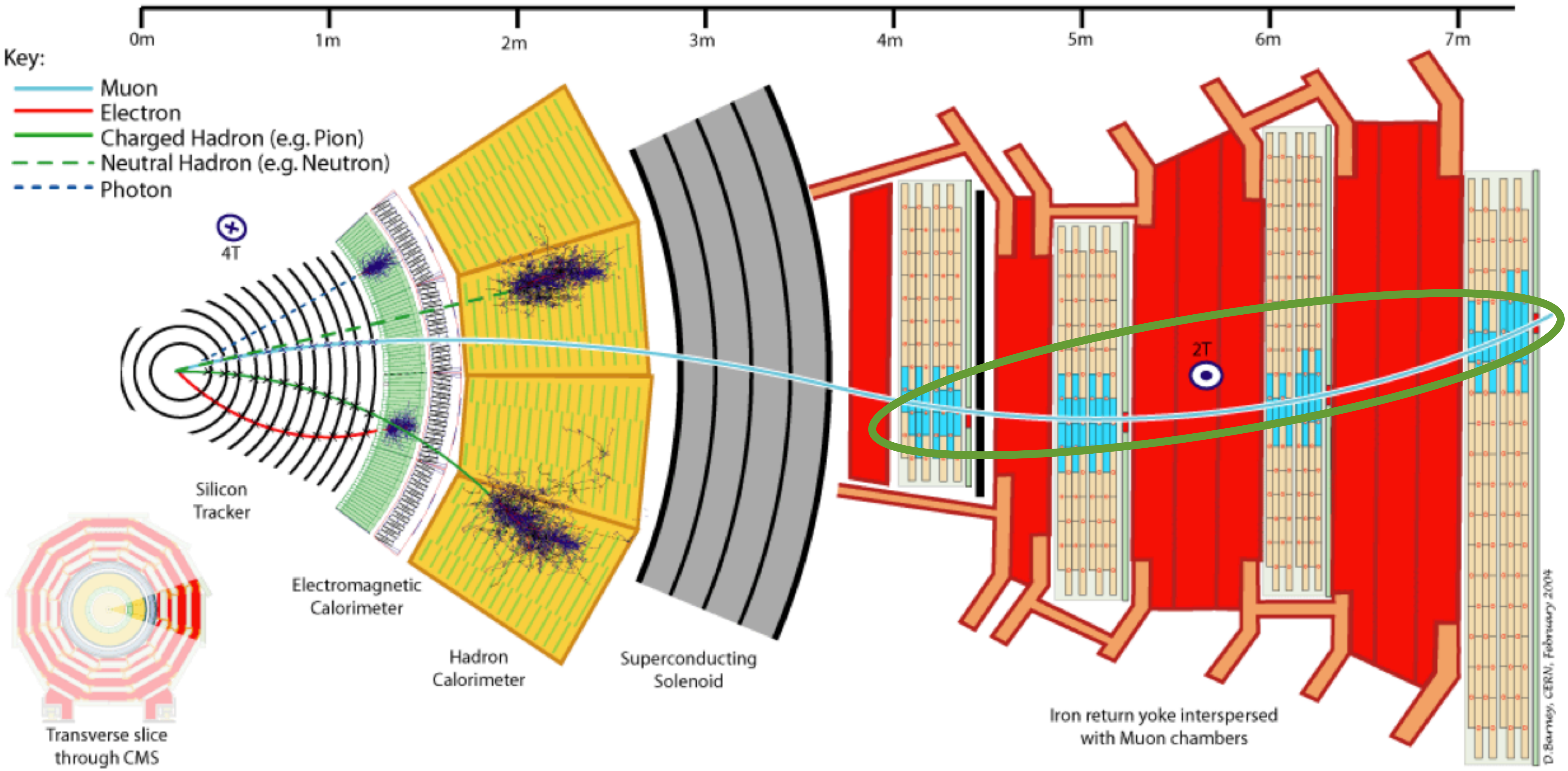
L1 defining (eta,phi) region



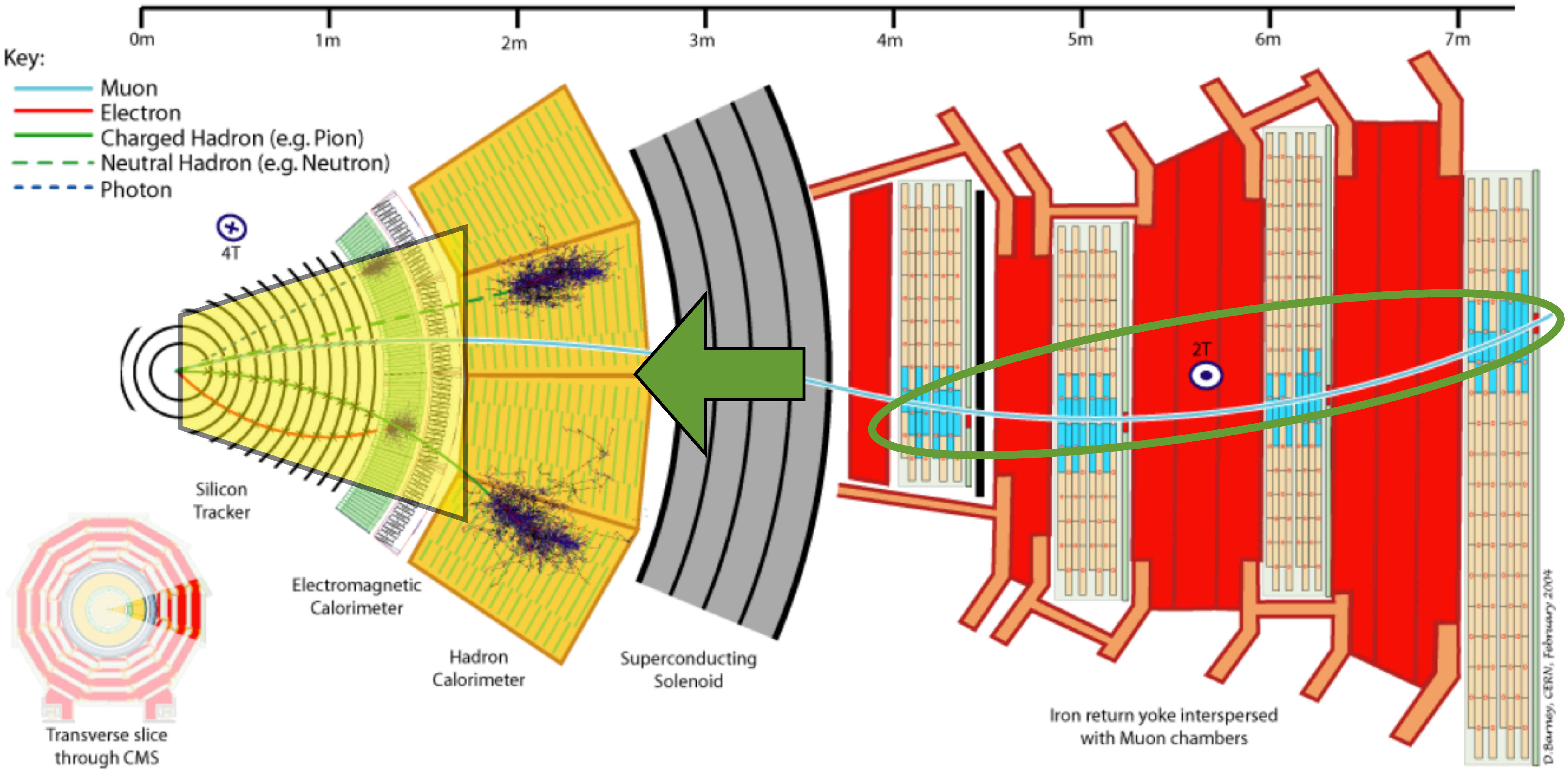
Reconstruct and select muon segments



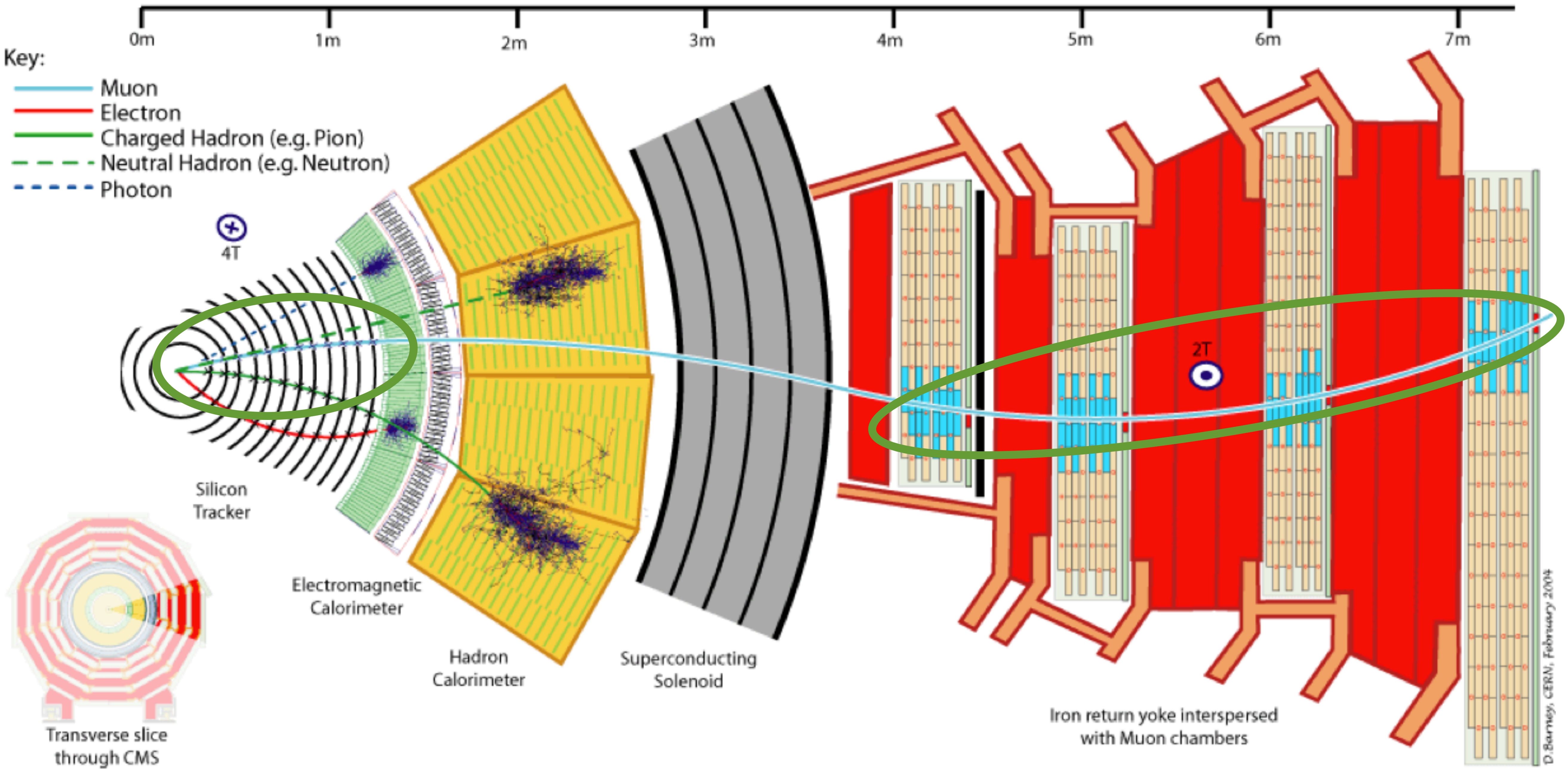
Fit a track in the muon system ("L2 muon")



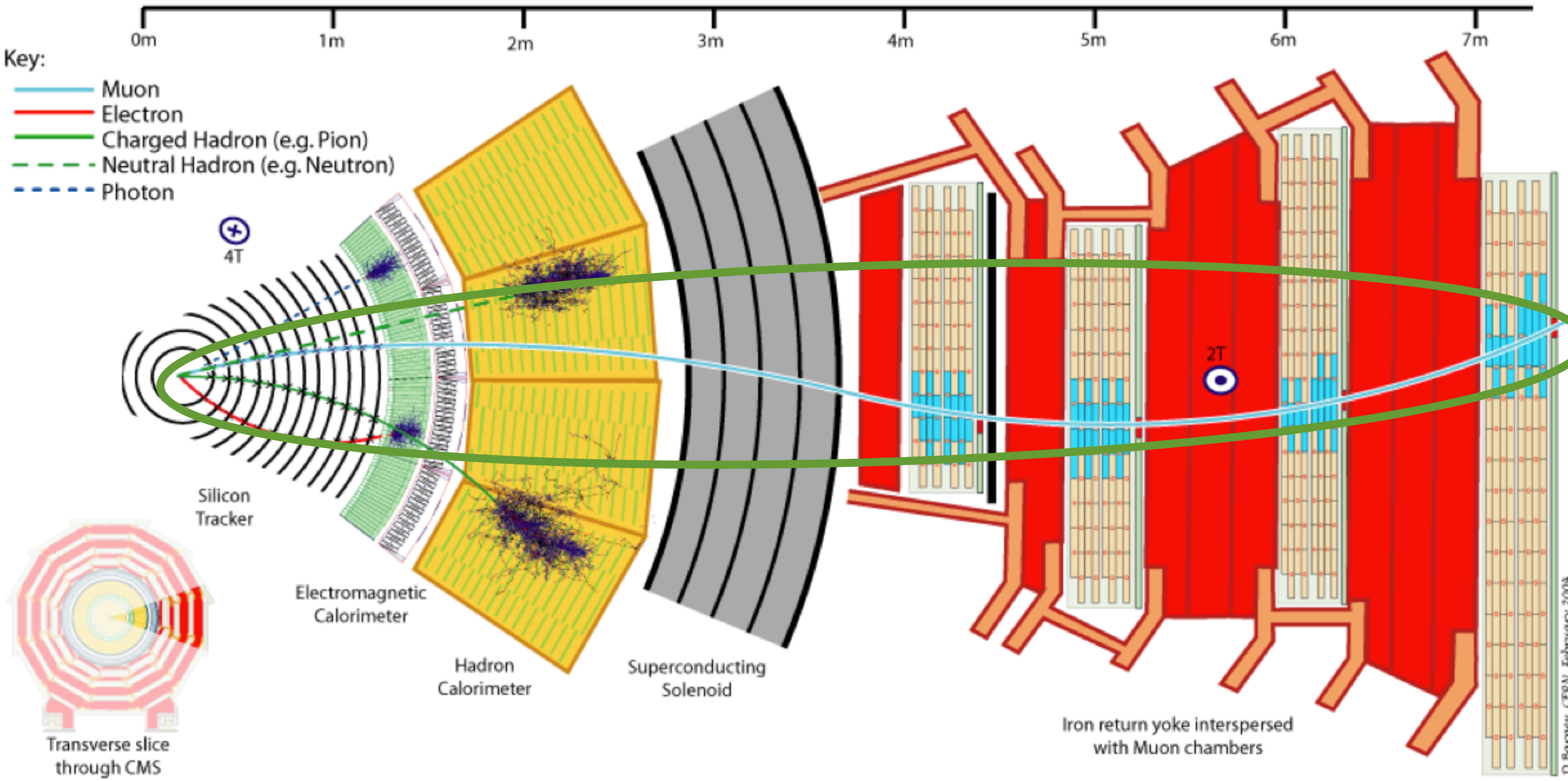
Extrapolate L2 back to the tracker



Reconstruct and select inner tracks



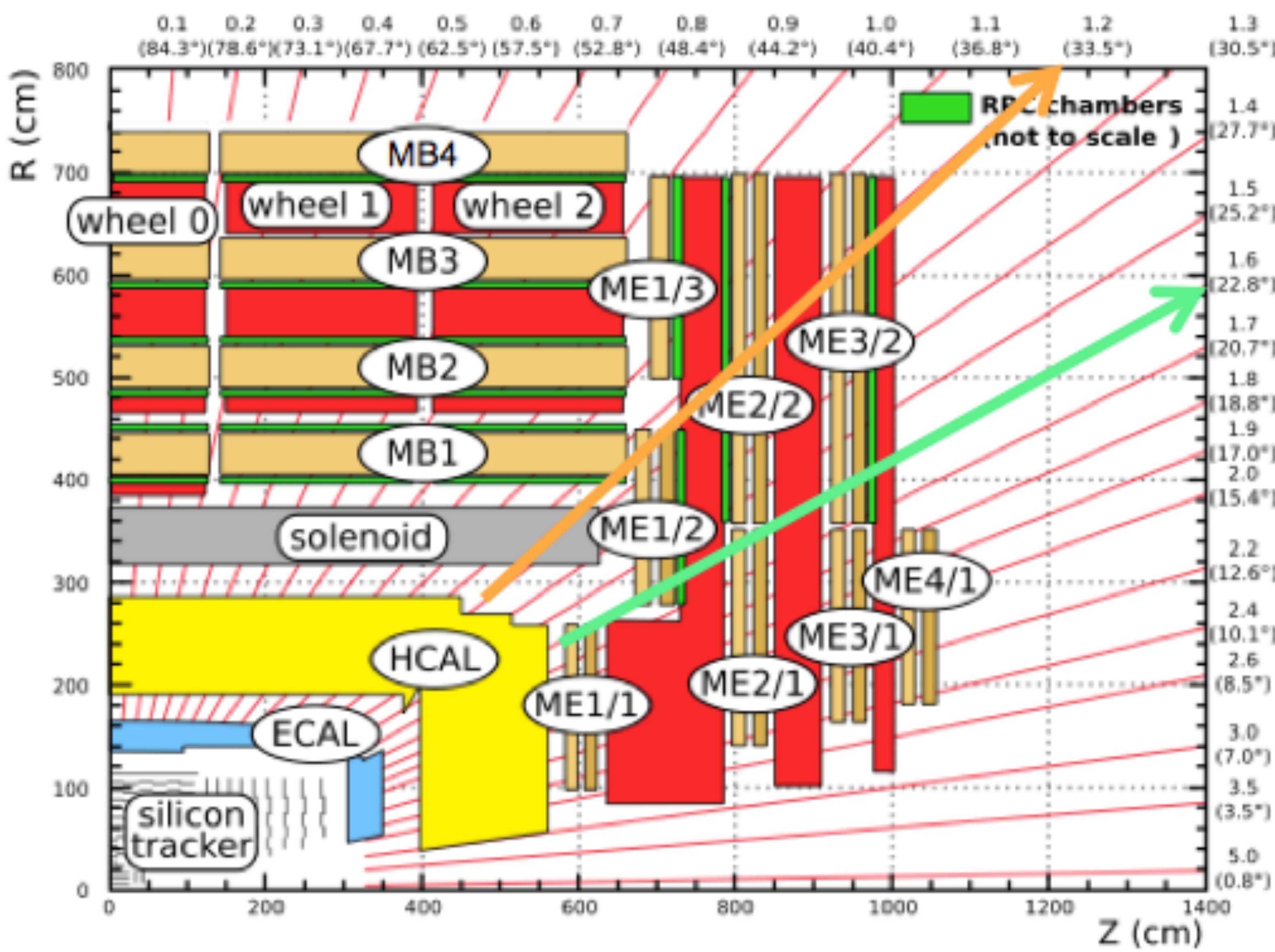
Refit and get a "L3 muon"



CMS Muon Detectors

- Robust, efficient and redundant muon system design
- 4 stations interleaved with iron return yoke

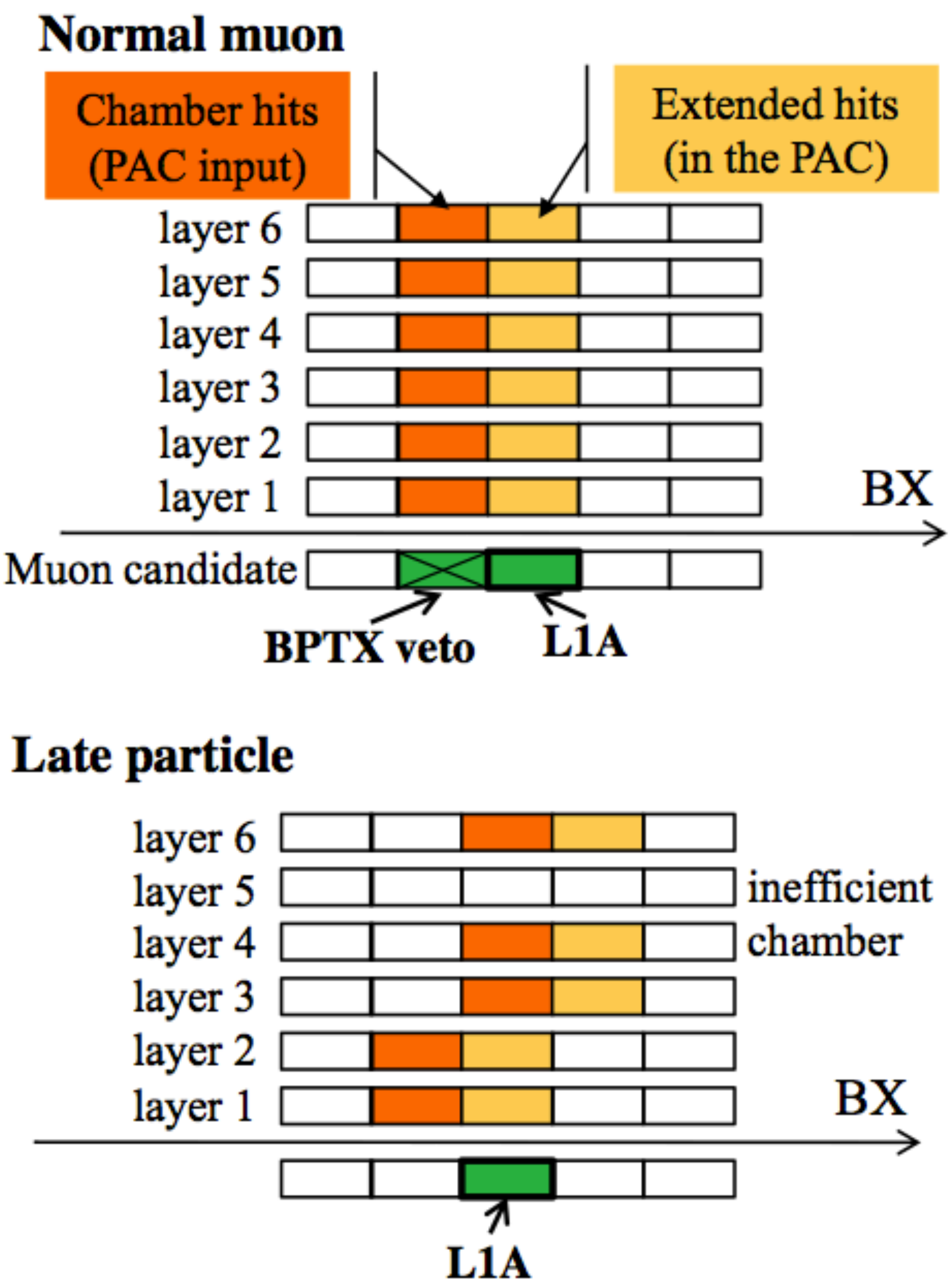
- Cylindrical barrel region:
  - 4 coaxial stations. Chambers are grouped into 5 wheels of 12 azimuthal sectors
  - Equipped with Drift Tube and Resistive Plate Chambers



- Planar endcap region:
  - 4 planar stations (4th station completion in 2013-2014)
  - Equipped with Cathode Strip Chambers and RPC

- Muon system tasks: muon identification and Pt measurement, BX identification (at L1 Trigger)

RPC trigger for slow particles



The PAC trigger allows us to provide a dedicated triggers for delayed muon-like particles (HSCP):

- In the PAC logic the detector signals are **extended in time to 2 BXs**
- On the GMT input the PAC candidates **delay is reduced by 1 BX** w.r.t. the DT and CSC candidates
- **Thus:**
  - ⇒ Hits of a "late particle" **generate trigger in the proper BX!**
  - ⇒ In-time muon candidates appear in 2 BXs: the first candidate is too early, the second one is in the proper BX. The first candidate is masked on the GT by the BPTX veto – signal synchronous to collision, but advanced by 1 BX (used for all triggers to eliminate pre-triggering).