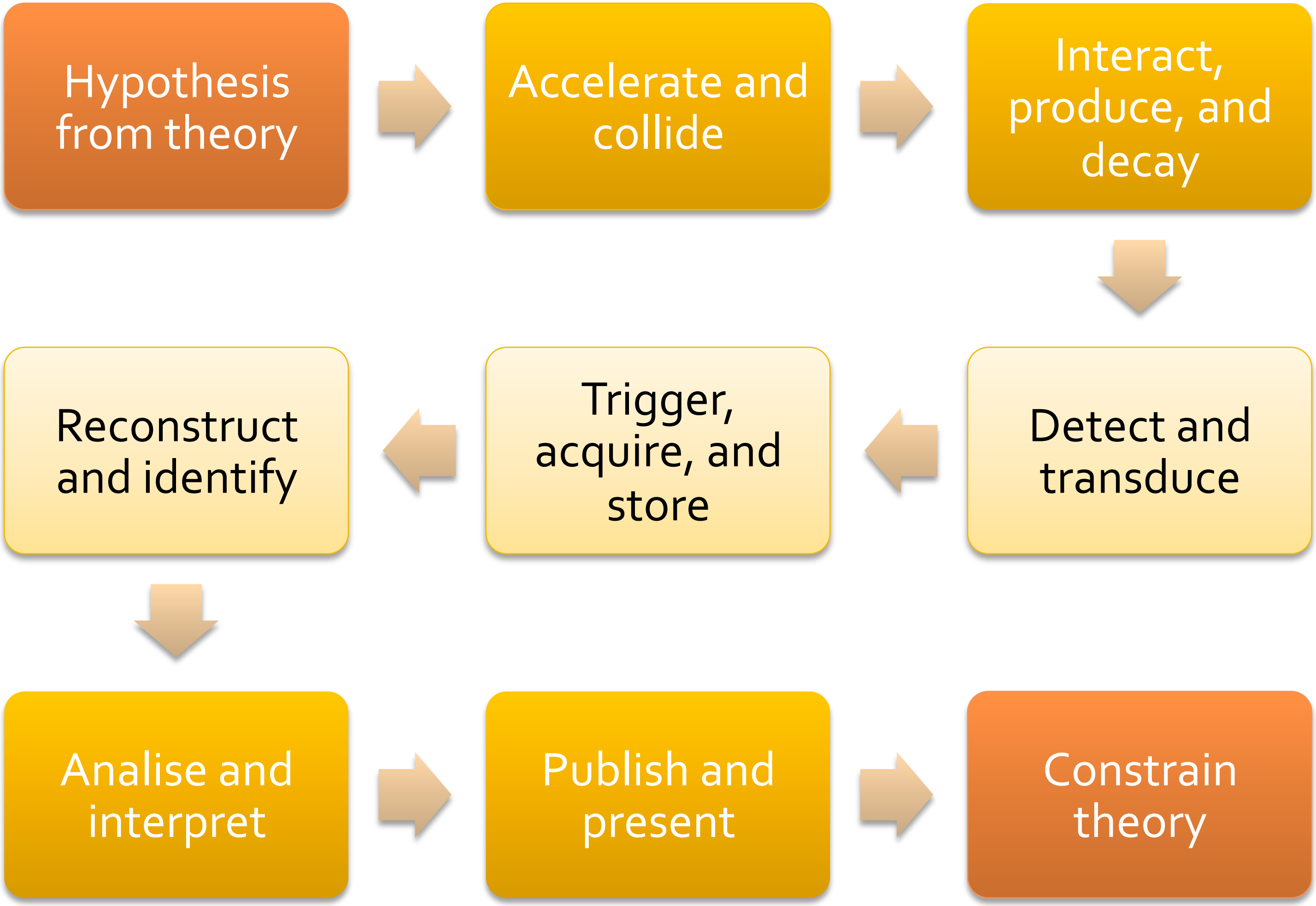
After the collisions, before the analysis.

Detectors, reconstruction, and trigger

andre@lip.pt

You are here



Hypothesis from theory

Accelerate and collide

Interact, produce, and decay

Detect and transduce

Trigger, acquire, and store

Reconstruct and identify

Analise and interpret

Publish and present

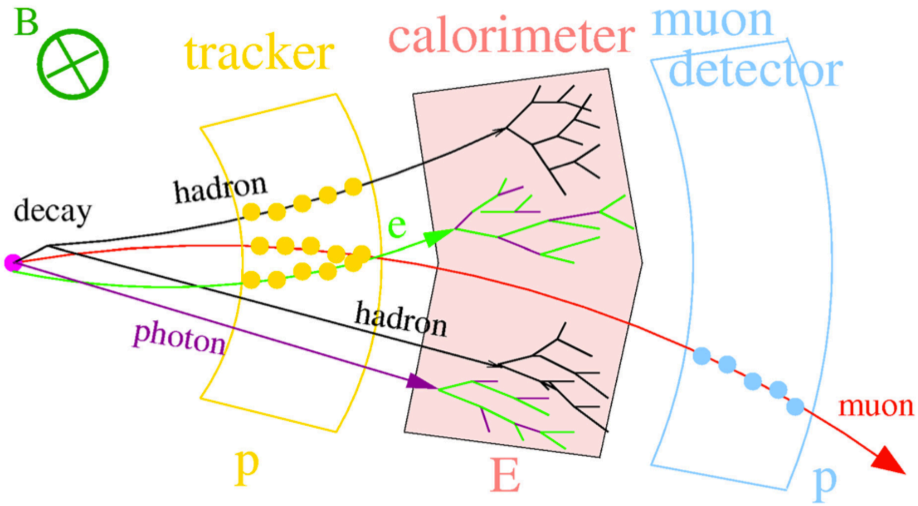
Constrain theory

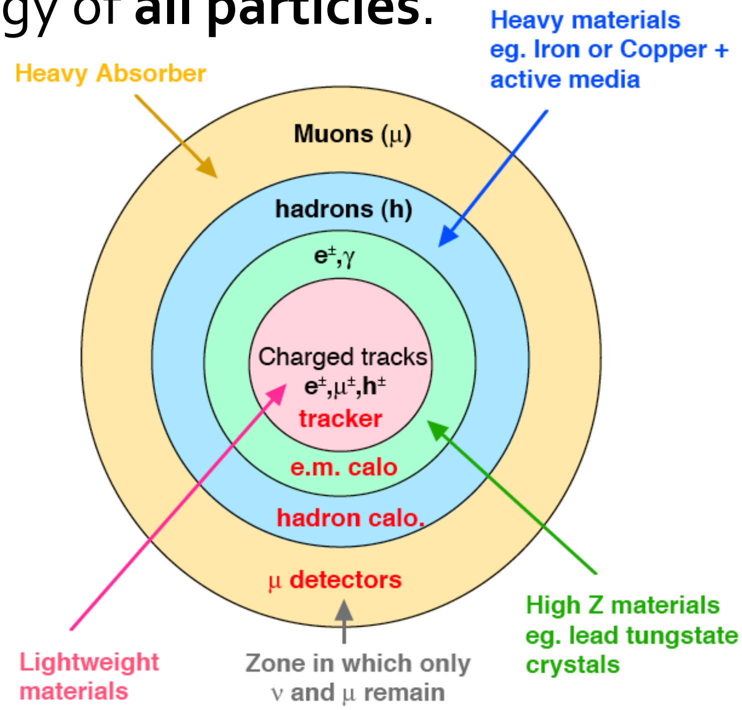
You are here

- Particles, interactions and detectors.
- Calorimetry and energy.
- Trackers and momentum.
- Trigger and acquisition.

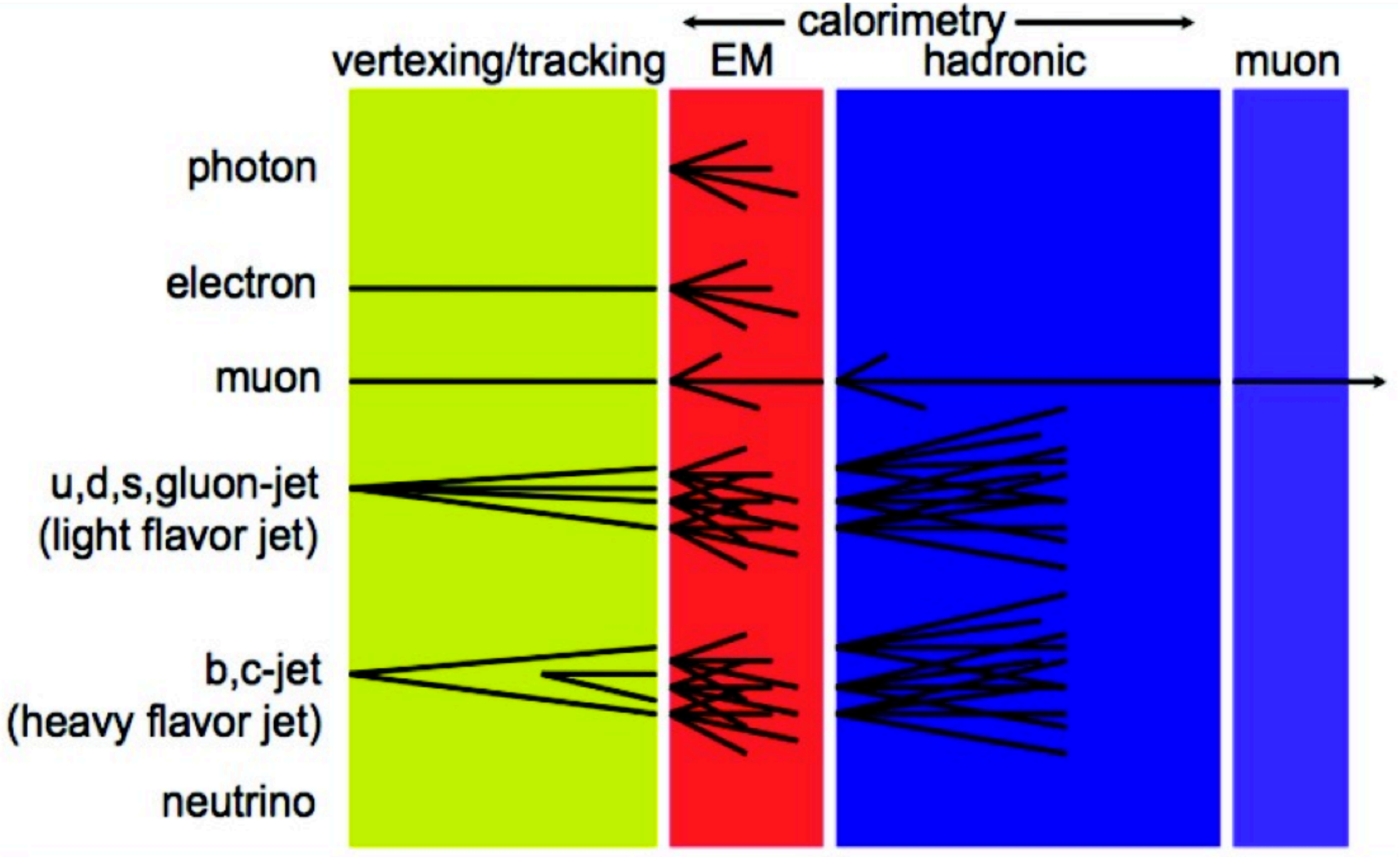
Peeling the hermetic onion

- Inner tracking
  - Measure charged particles **disturbing them the least possible**.
- Calorimetry
  - Measure as much as possible the energy of **all particles**.
- Outer tracking
  - Measure **muons**.



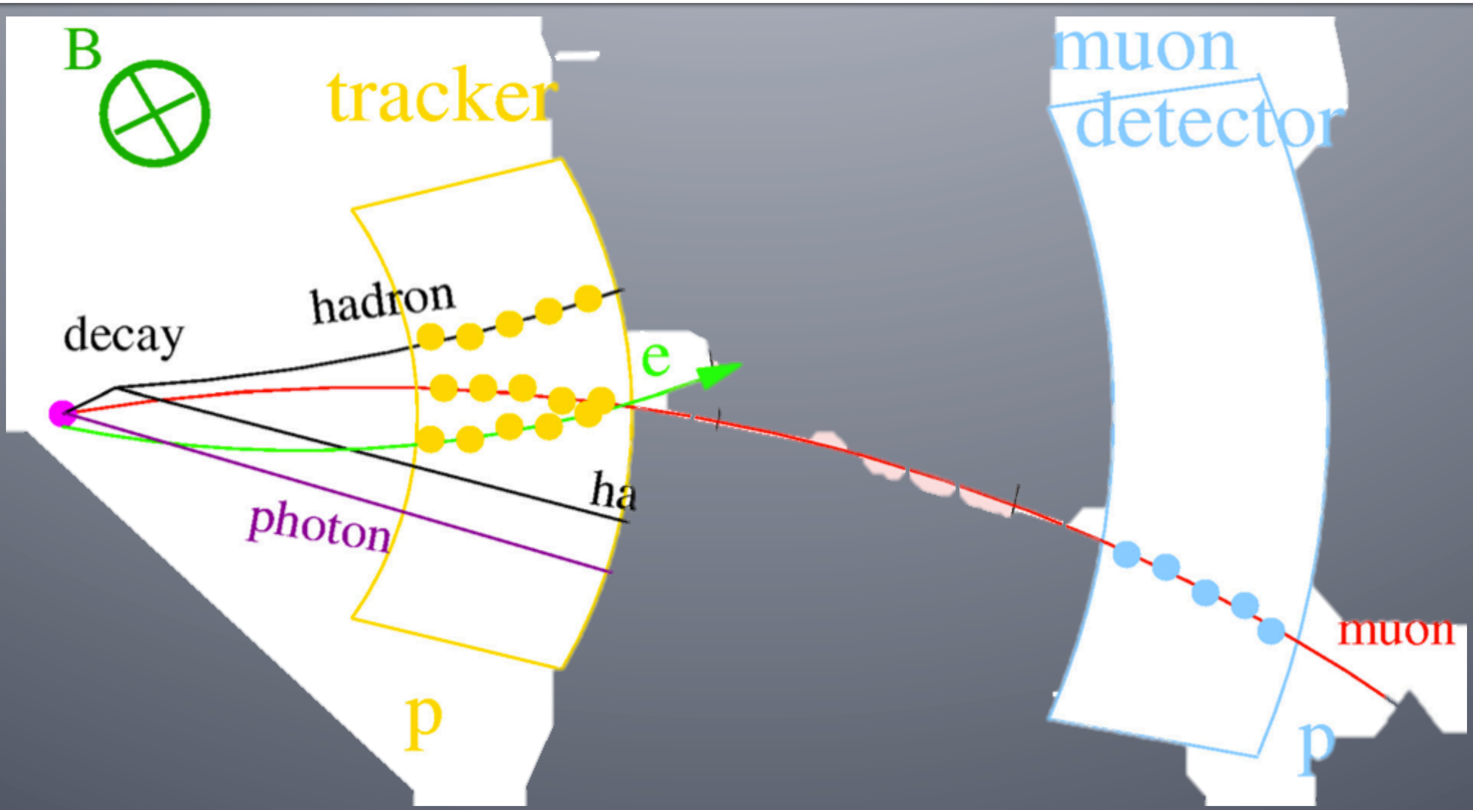


Particles and their decays



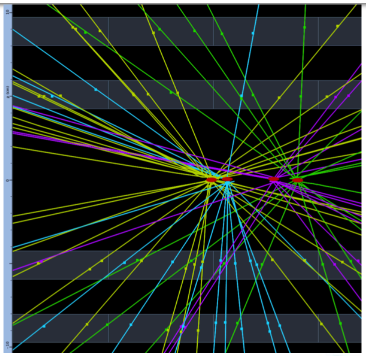
Tracking

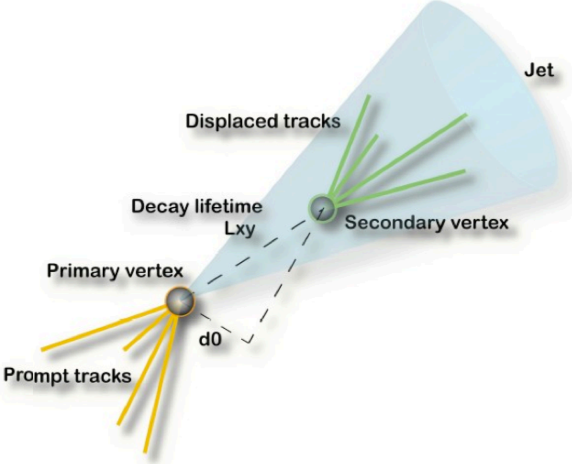
Trying to retrace the path of charged particles, including far-reaching muons.

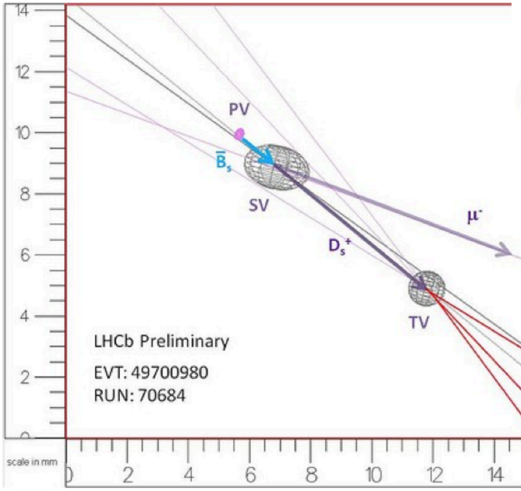


Tracking: why?

- To find the hard interaction vertex. ➔
- To identify secondary vertices. ➘
  - Longer-lived particles.
- To measure trajectory of particles.
  - Momentum and energy loss of charged particles.
  - Connection to showers in calorimeters (electrons, photons).
  - Provide inner leg for muon reconstruction.

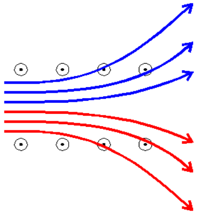






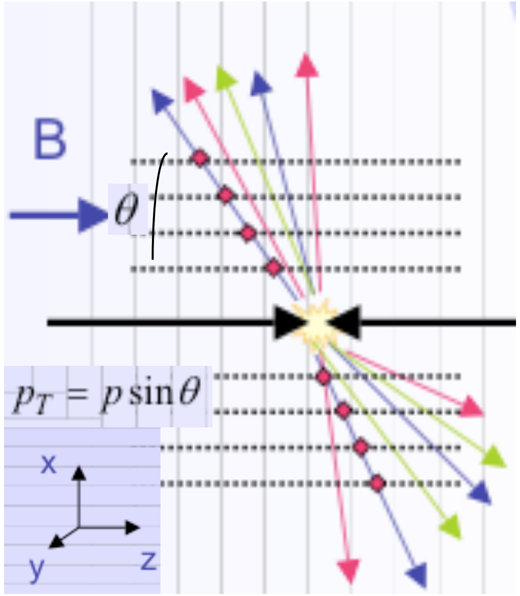
Tracking: what?

- Solid state detectors.
  - Pixels for vertexing.
  - Strips for tracking.
- Gaseous detectors.
  - Drift tubes, etc for outer tracking.



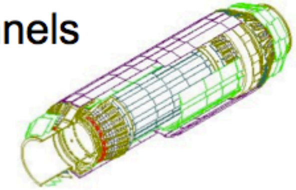
$$F = q\cdot v\cdot B = m\cdot\frac{v^2}{R}$$

$$\Rightarrow q\cdot B\cdot R = m\cdot v = \left|\vec{p}\right|$$

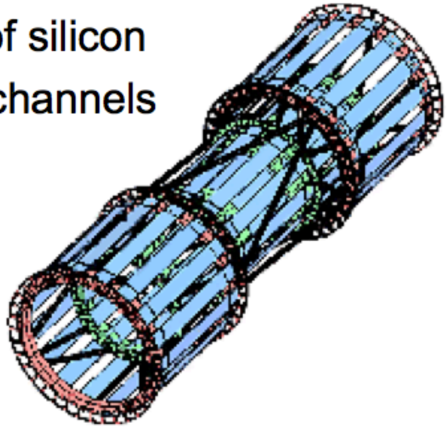


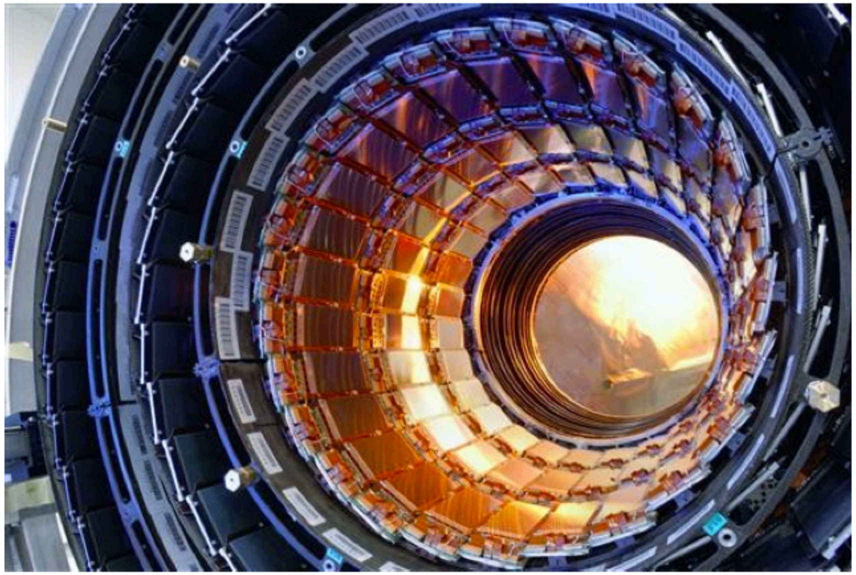
Tracking: how?

- LEP eg. DELPHI (1996)
  - 1.8 m^2 of silicon
  - 175k readout channels



- CDF SVX IIa (2001)
  - 6 m^2 of silicon
  - 175k channels

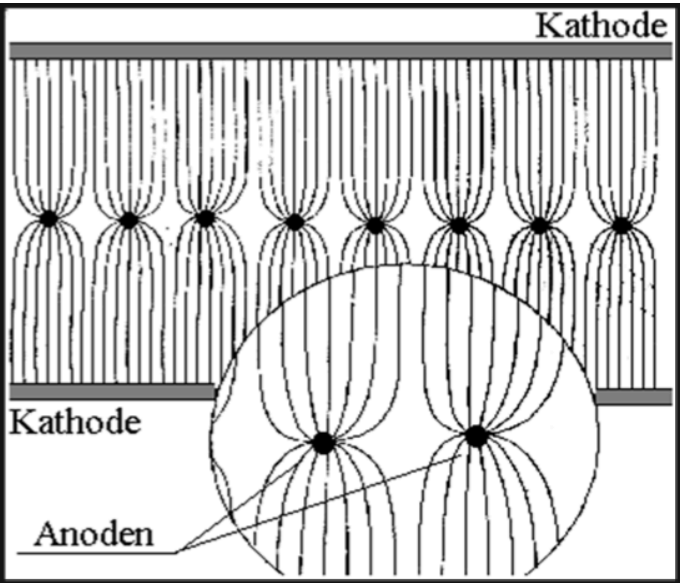


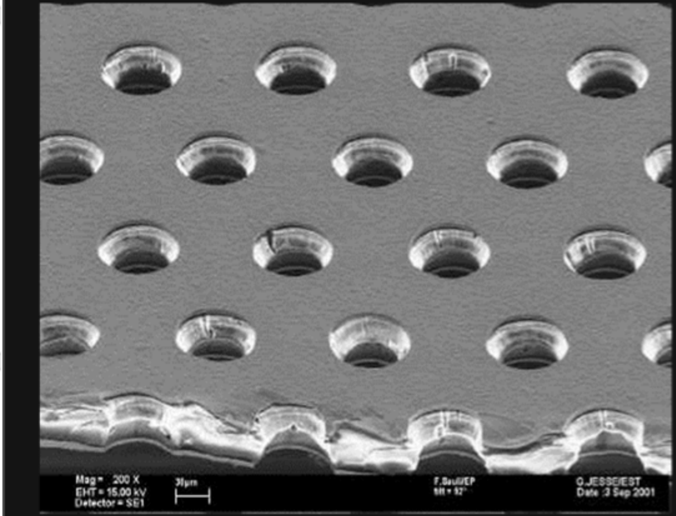


- CMS tracker
  - full silicon tracker
  - 210 m^2 of silicon
  - 10.7 M channels

Tracking: how?

- Drift Tubes.
- Microstrip Gas Counters.
- Gas Electron Multipliers.

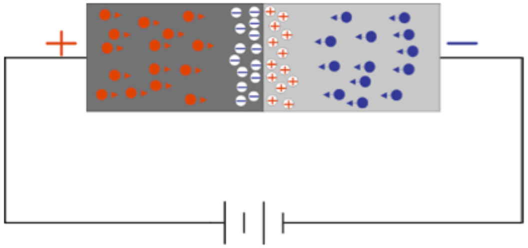


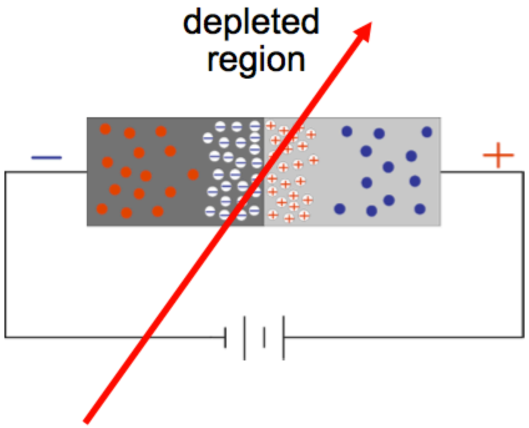


Inner trackers

Silicon detectors

- Silicon detector is a p-n diode
  - p-type (more holes)
  - n-type (more electrons)
  - Current can flow if forward biased

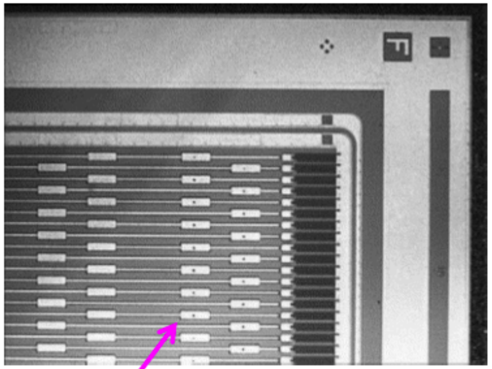




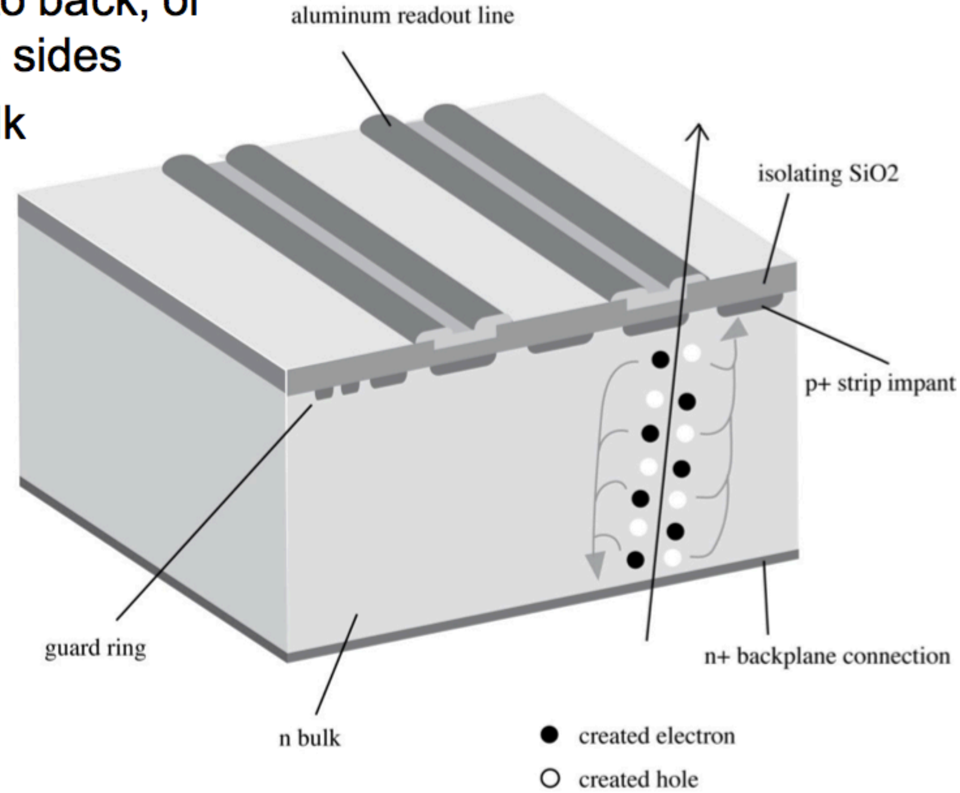
- Reverse bias to create a depletion layer with no mobile charge carriers
  - Passage of a charged particle releases electron-hole pairs by ionisation
  - 20 000 to 30 000 pairs in 300 μm
  - Signal >10 times more than background noise
  - High enough resistivity to allow full depletion (i.e. full depth of sensor) with a few 100V

Microstrips sensors

- Make many diodes on one wafer
  - ~50 μm strip pitch (possible with planar fabrication process)
  - Glue wafers back-to back, or make strips on two sides
  - eg. p strips in n bulk

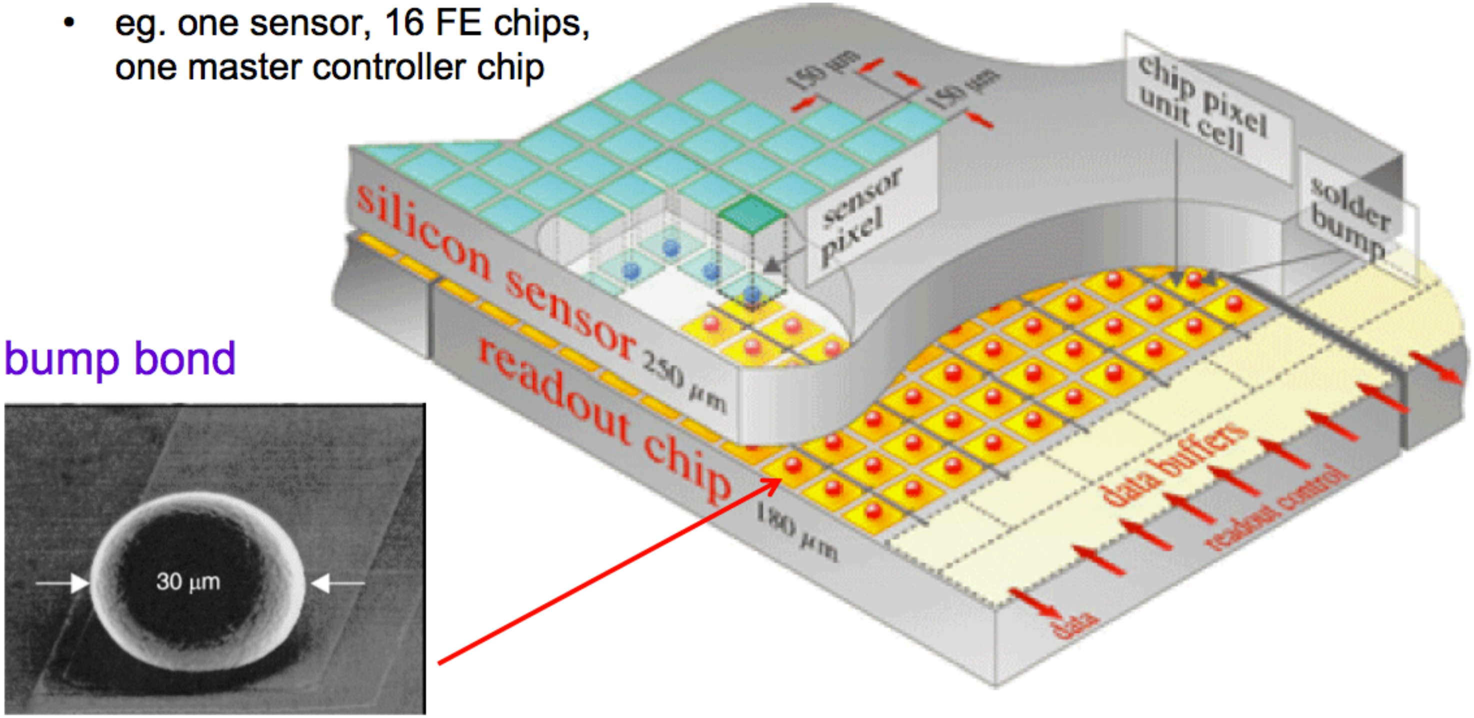


Metalisation above strips, with bond pads



Pixel sensors

- 2-d position information with high track density.
  - Back-to-back strips give “ghost” hits. Pixels give unambiguous point
- Hybrid pixel detectors with sensors and readout chips bump-bonded together in a module
  - eg. one sensor, 16 FE chips, one master controller chip



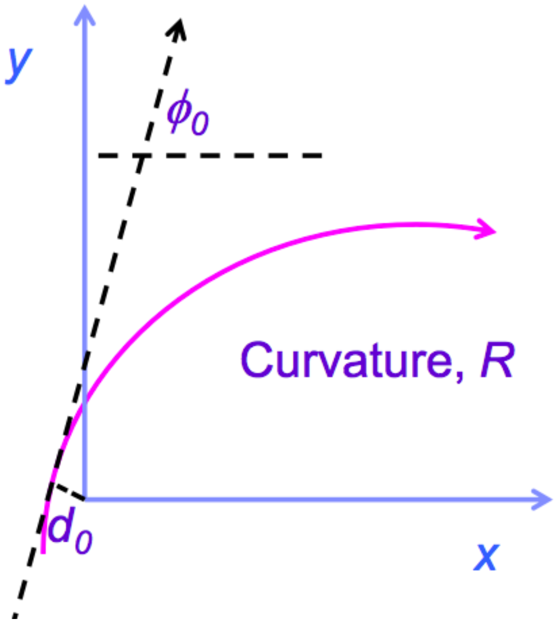
Tracks

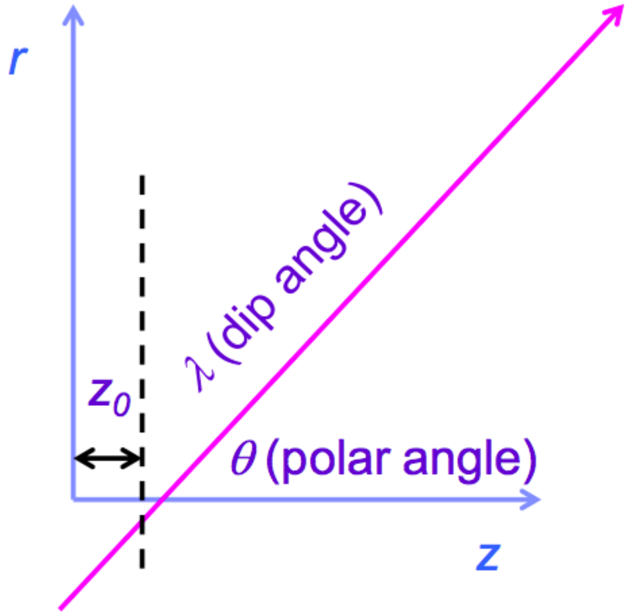
Track coordinates

With a uniform B field along the z-axis (= beam line), track path is a helix (i.e. for ALICE, ATLAS or CMS central trackers)

Pseudorapidity, $\eta = -\ln \tan(\theta/2)$. Transverse momentum, $p_T = p \sin\theta$

Transverse (*xy*) and Longitudinal (*rz*) projections. Define impact parameter w.r.t. point of closest approach to origin or PV

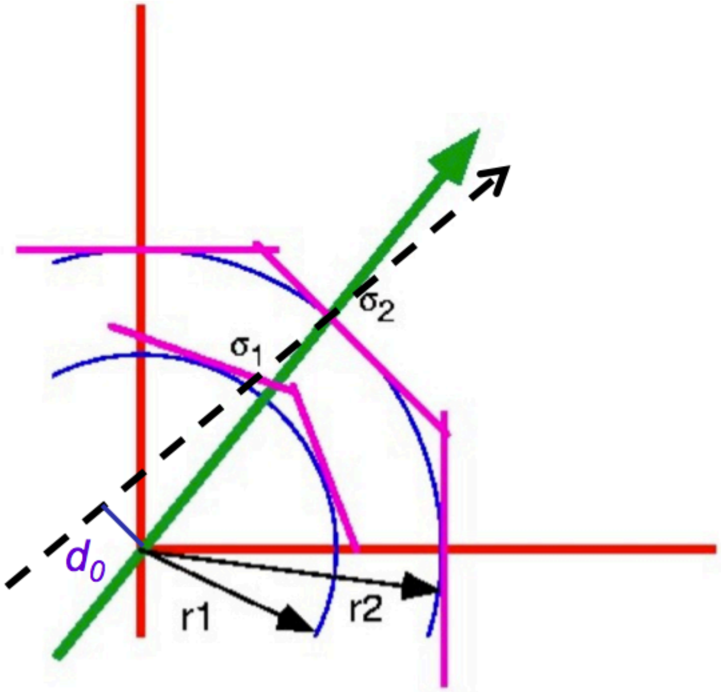




Impact parameter resolution

Uncertainty on the transverse impact parameter, d_0, depends on the radii and space point precision.

Simplified formula for just two layers:



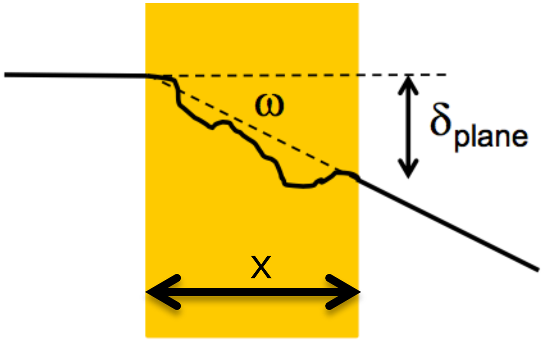
$$\sigma_{d_0}^2 = \frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}$$

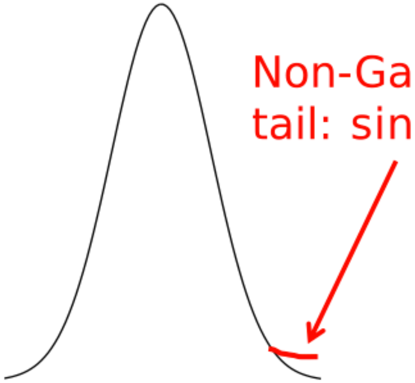
Suggests small r_1, large r_2, small σ_1, σ_2

But precision is degraded by multiple scattering…

Multiple scattering

- Particle incident on a thin layer, fraction x/X_0 of a radiation length thick, is bent by angle ω





Non-Gaussian tail: $\sin^{-4}(\omega/2)$

- Distribution of ω is nearly Gaussian (central 98%)
- $d_0 = r\tan\omega \approx r\omega$

K. Nakamura et al. (PDG), J. Phys. G 37, 075021 (2010)

$$\sigma_{d_0} = \frac{r}{\beta c p} 13.6\text{MeV}\sqrt{\frac{x}{X_0}}\left[1 + 0.038\log\left(\frac{x}{X_0}\right)\right]$$

- Higher momentum, *p* → less scattering
- Best precision with small radius, *r*, and minimum thickness *x*

Transverse IP resolution

For a track with $\theta \neq 90°$ $\quad r \rightarrow \frac{r}{sin\theta}, \; x \rightarrow \frac{x}{sin\theta}$

Resulting in:

$$\sigma_{d_0} \approx \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}} \oplus \frac{r}{p\sin^{3/2}\theta} 13.6\mathrm{MeV}\sqrt{\frac{x}{X_0}}$$

$$\sigma_{d_0} \approx a \oplus \frac{b}{p_T \sin^{1/2}\theta}$$

Constant term depending only on geometry

and term depending on material, decreasing with p_T

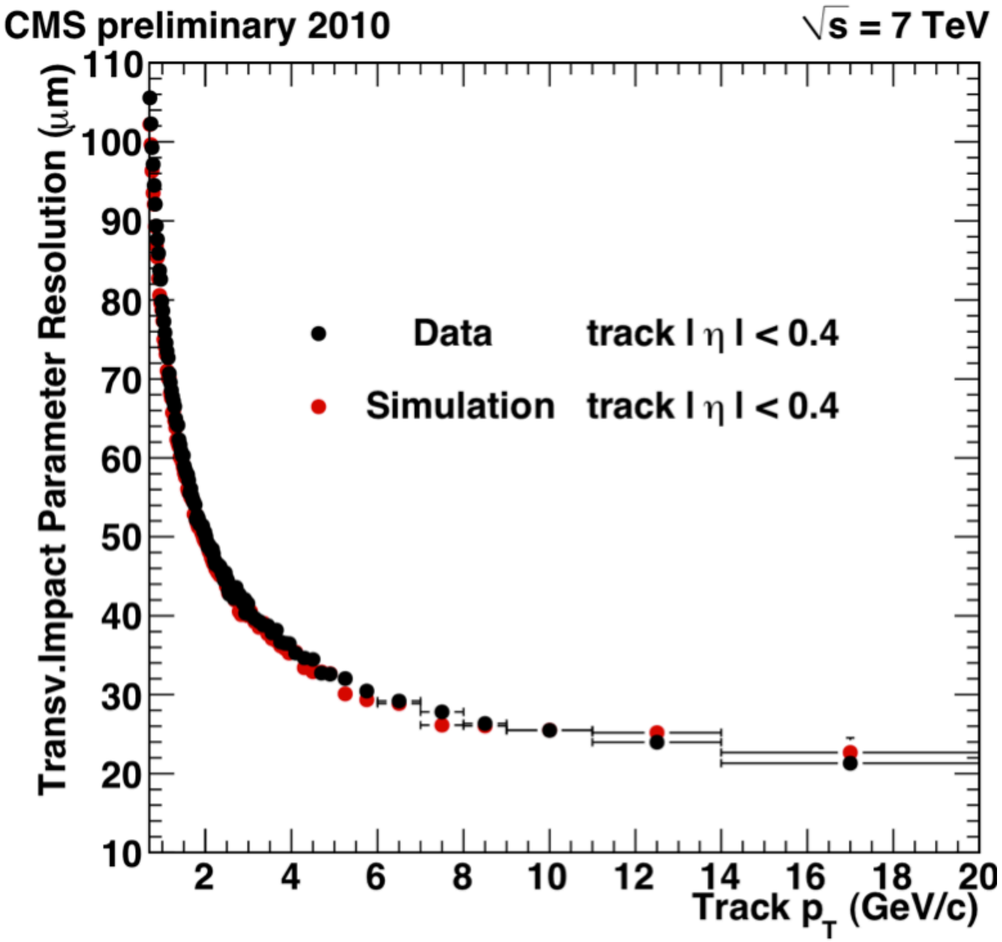
CMS transverse IP resolution

$$\sigma_{d_0} \approx a \oplus \frac{b}{p_T \sin^{1/2}\theta}$$

Observed:

100 μm @ 1 GeV,

20 μm @ 20 GeV



Momentum measurement

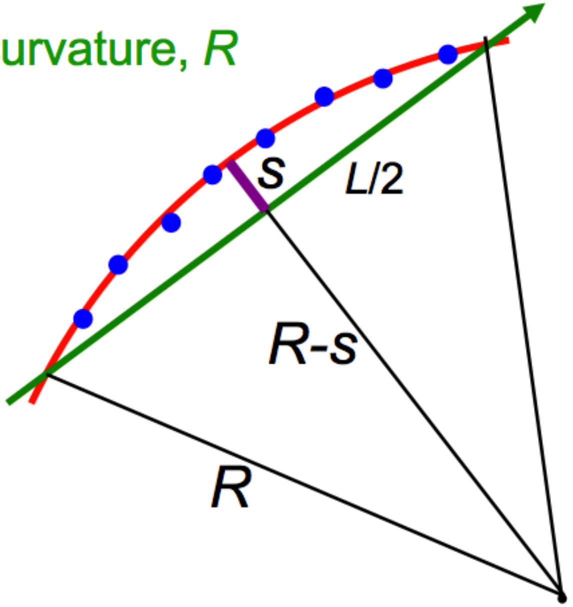
- Circular motion transverse to uniform B field:

$$p_T[\mathrm{GeV/c}] = 0.3 \cdot B[\mathrm{T}] \cdot R[\mathrm{m}]$$

- Measure sagitta, *s*, from track arc → curvature, *R*

$$R = \frac{L^2}{2s} + \frac{s}{2} \approx \frac{L^2}{2s}$$

- $$\frac{\sigma_{p_T}}{p_T} = \frac{8p_T}{0.3BL^2}\sigma_s$$



- Relative momentum uncertainty is proportional to p_T times sagitta uncertainty, σ_s. Also want strong B field and long path length, *L*

Measuring momentum

Sagitta uncertainty, σ_s, from N points, each with resolution $\sigma_{r\phi}$ is:

$$\sigma_s = \sqrt{\frac{A_N}{N+4}}\,\frac{\sigma_{r\phi}}{8}$$

Statistical factor $A_N = 720$:
(Gluckstern)

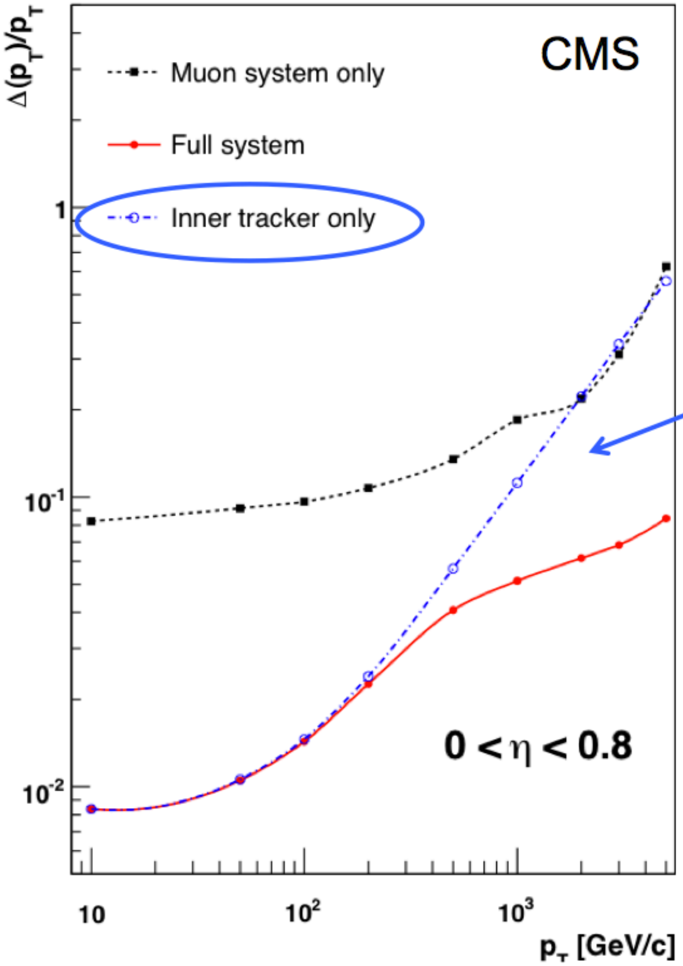
The point error, $\sigma_{r\phi}$ has a constant part from intrinsic precision, and a multiple scattering part.

Multiple scattering contribution:
(*L* is in the transverse plane)

$$\sigma_s \propto \frac{L}{p_T \sin^{1/2}\theta}\sqrt{\frac{L}{X_0}}$$

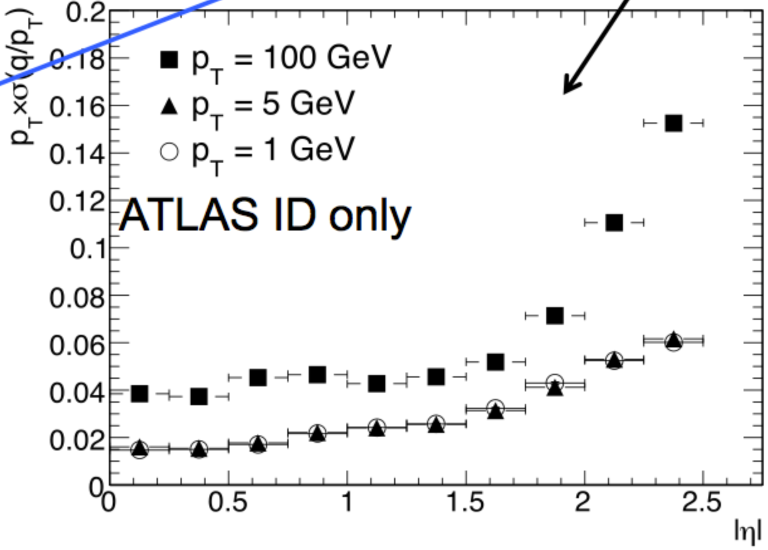
$$\frac{\sigma_{p_T}}{p_T} = \frac{8 p_T \cdot \sigma_s}{0.3 B L^2} \approx a \cdot p_T \oplus \frac{b}{\sin^{1/2}\theta}$$

Momentum resolution



Expected relative p_T resolution for muons vs |η| and p_T.

$$\frac{\sigma_{p_T}}{p_T} \approx a \cdot p_T \oplus \frac{b}{\sin^{1/2}\theta}$$

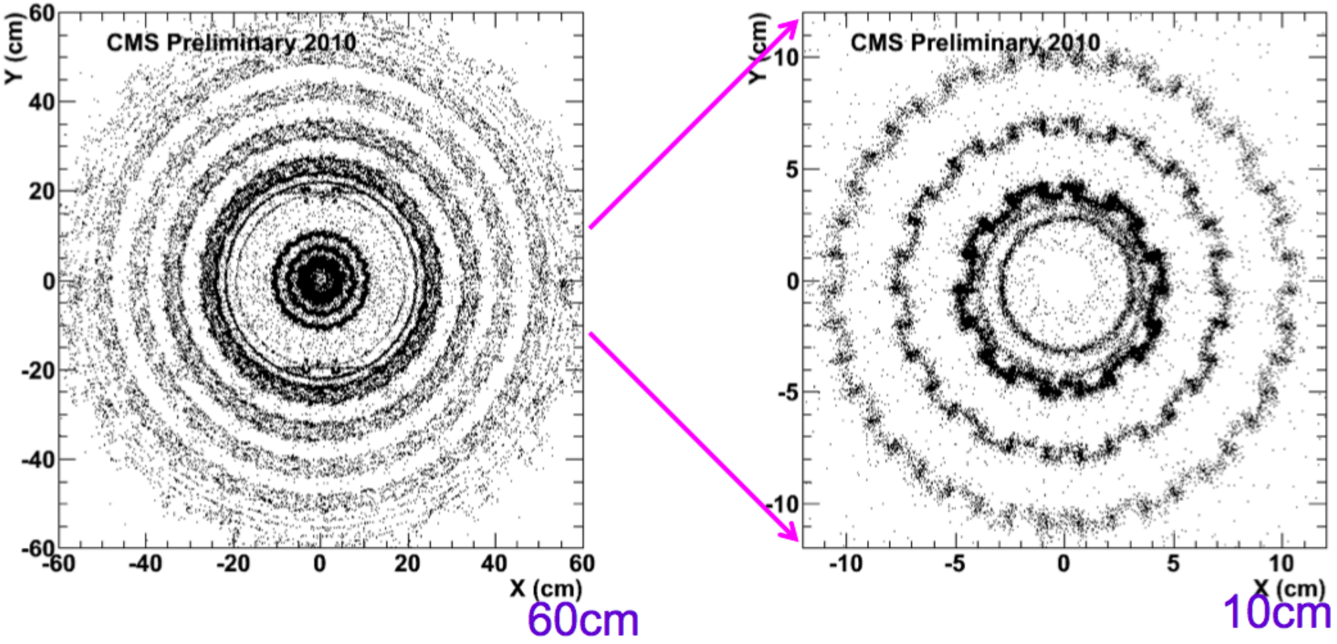


(More material) →

Calibration and alignment

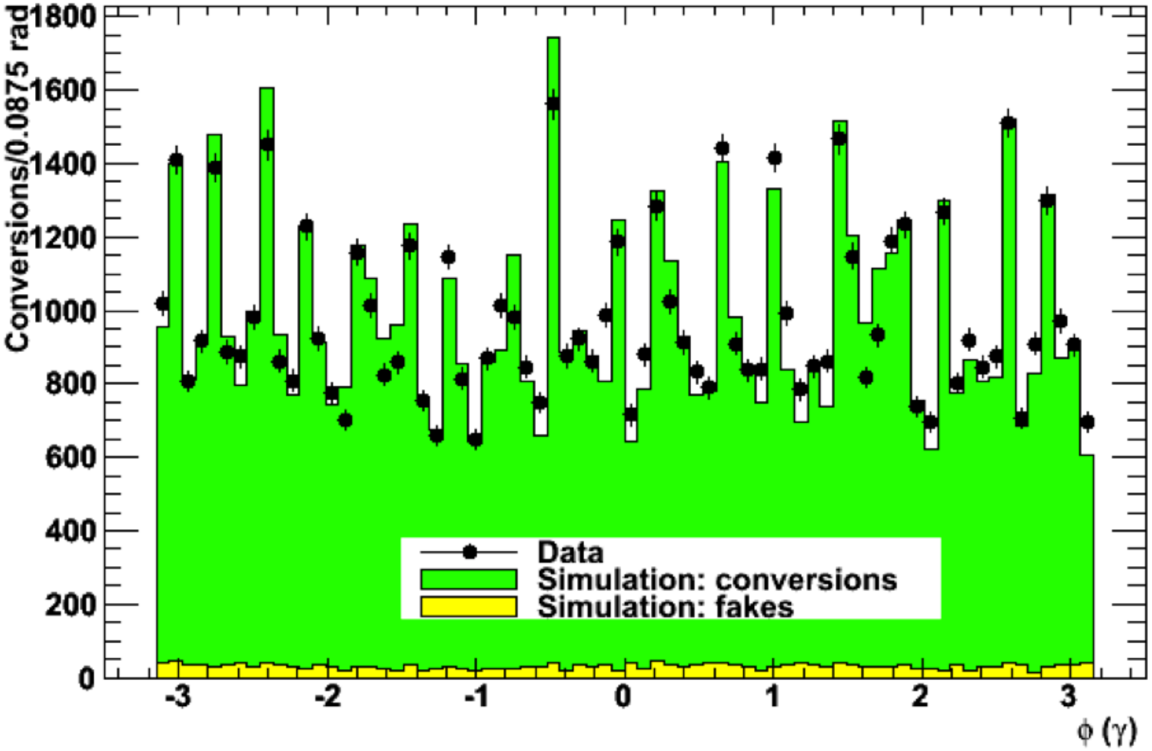
Checking material

- Conversions, $\gamma \rightarrow e^+e^-$, example from CMS
  - Two oppositely charged tracks
  - Consistent with coming from the same point
  - Consistent with fit to a common vertex, imposing zero mass



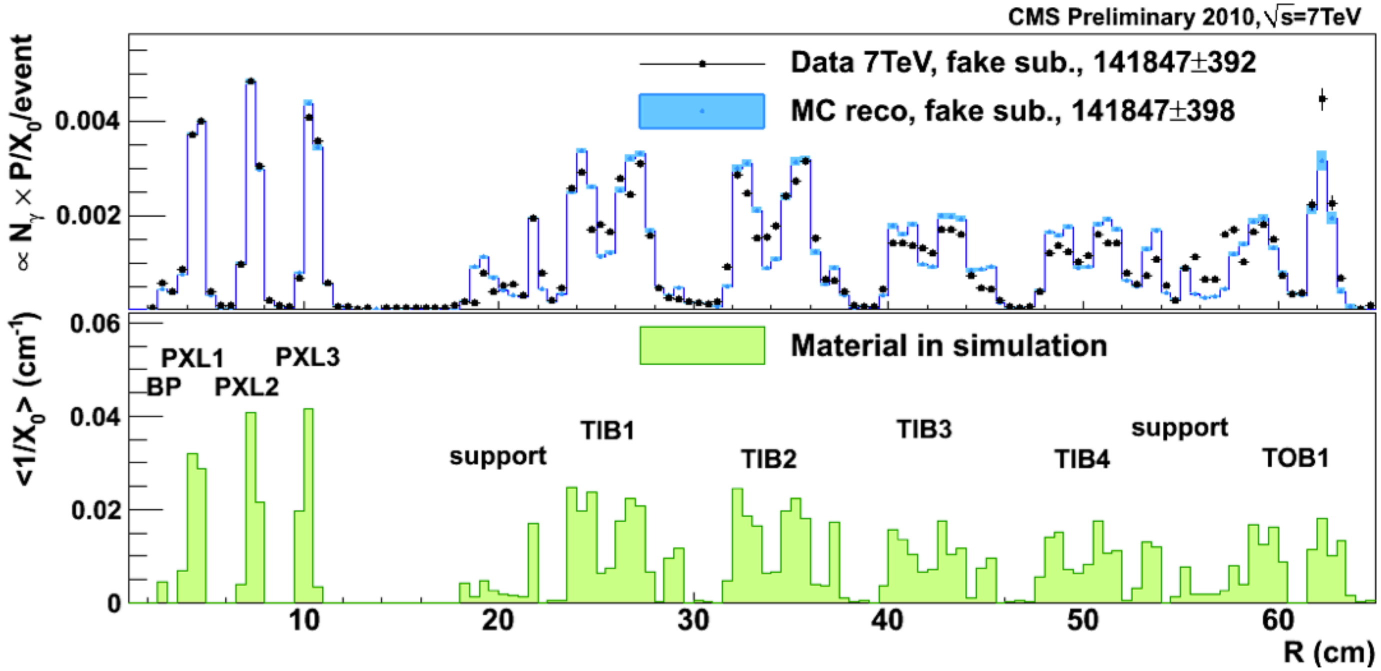
Checking material description

- ϕ distribution for conversions with $|z| < 26$cm, $R < 19$cm
- → Compare pixel barrel structure in data and simulation
- Spikes due to cooling pipes



Checking material description

- Correct for identification efficiency to make a quantitative measurement of pixel and inner tracker barrel material
- Relative agreement between data and simulation ~10%
- Local discrepancy for support between TIB and TOB



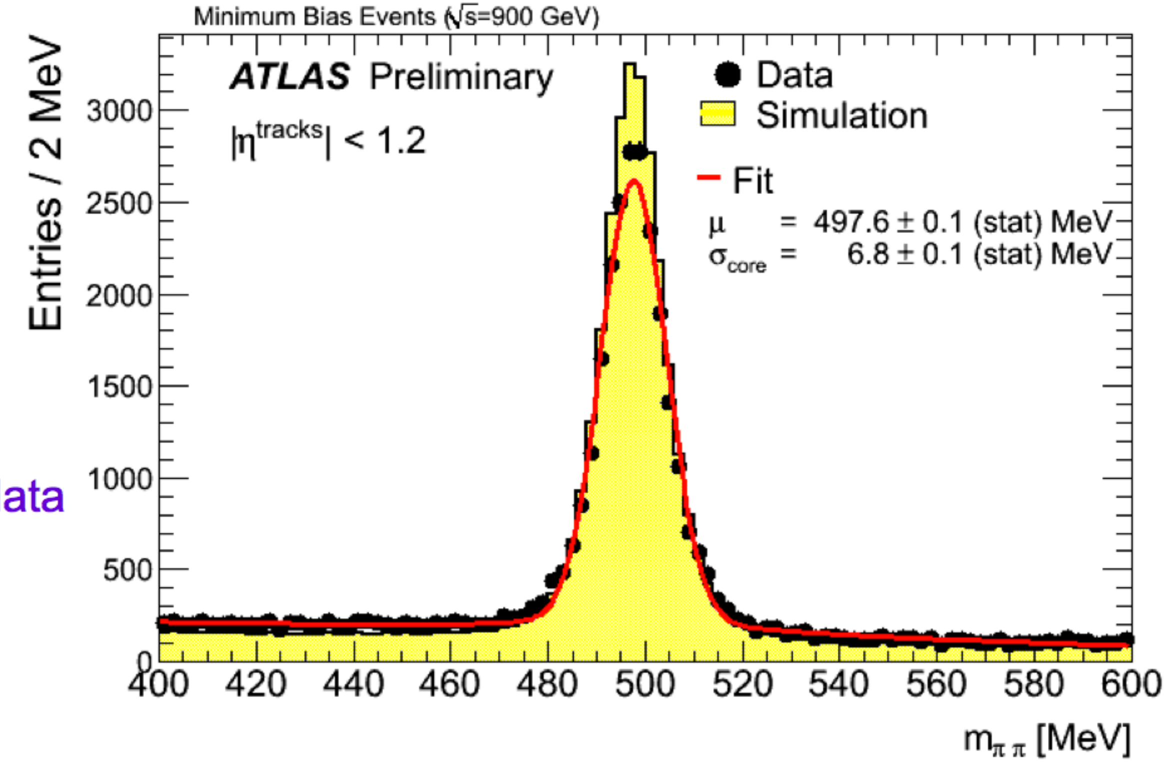
Checking alignment

$K^0 \rightarrow \pi^+\pi^-$

Two oppositely charged tracks, consistent with the same vertex.

Assume the tracks are pions. Reconstruct the pair invariant mass.

World Average PDG value 497.614 ± 0.024 MeV



ATLAS example:2009 data slightly broader than simulation

ATLAS-CONF-2010-019

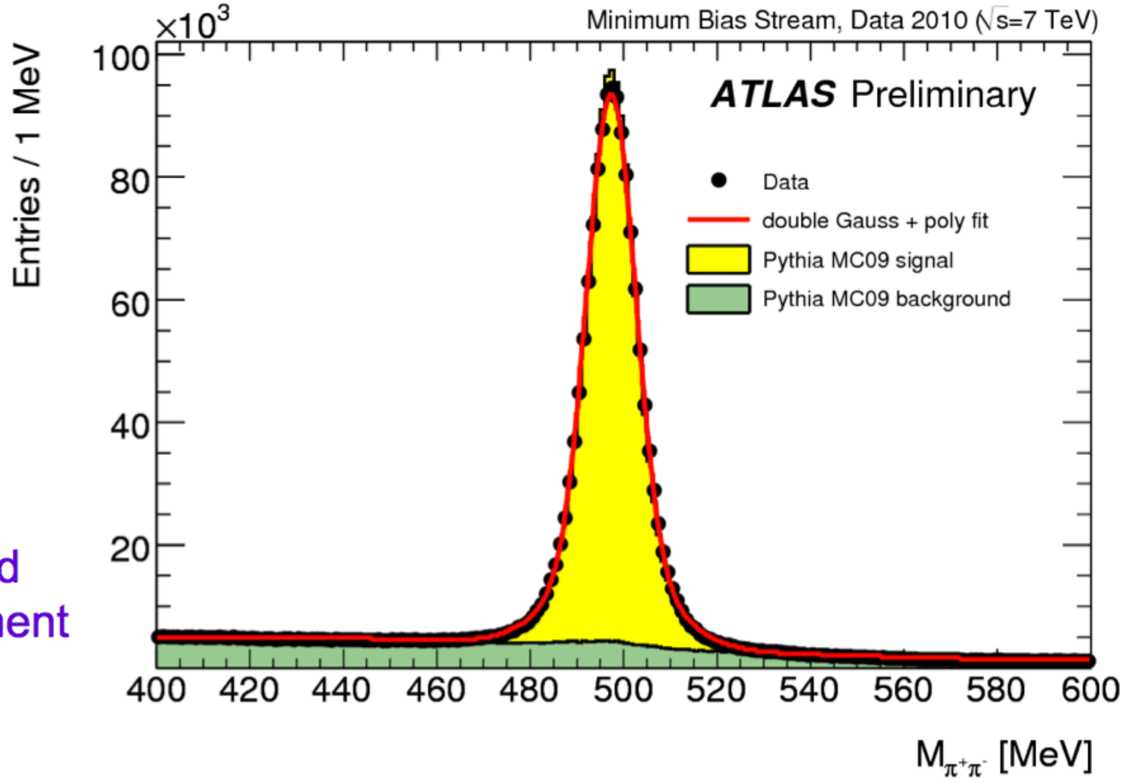
Checking alignment

$K^0 \rightarrow \pi^+\pi^-$

Two oppositely charged tracks, consistent with the same vertex.

Assume the tracks are pions. Reconstruct the pair invariant mass.

World Average PDG value 497.614 ± 0.024 MeV

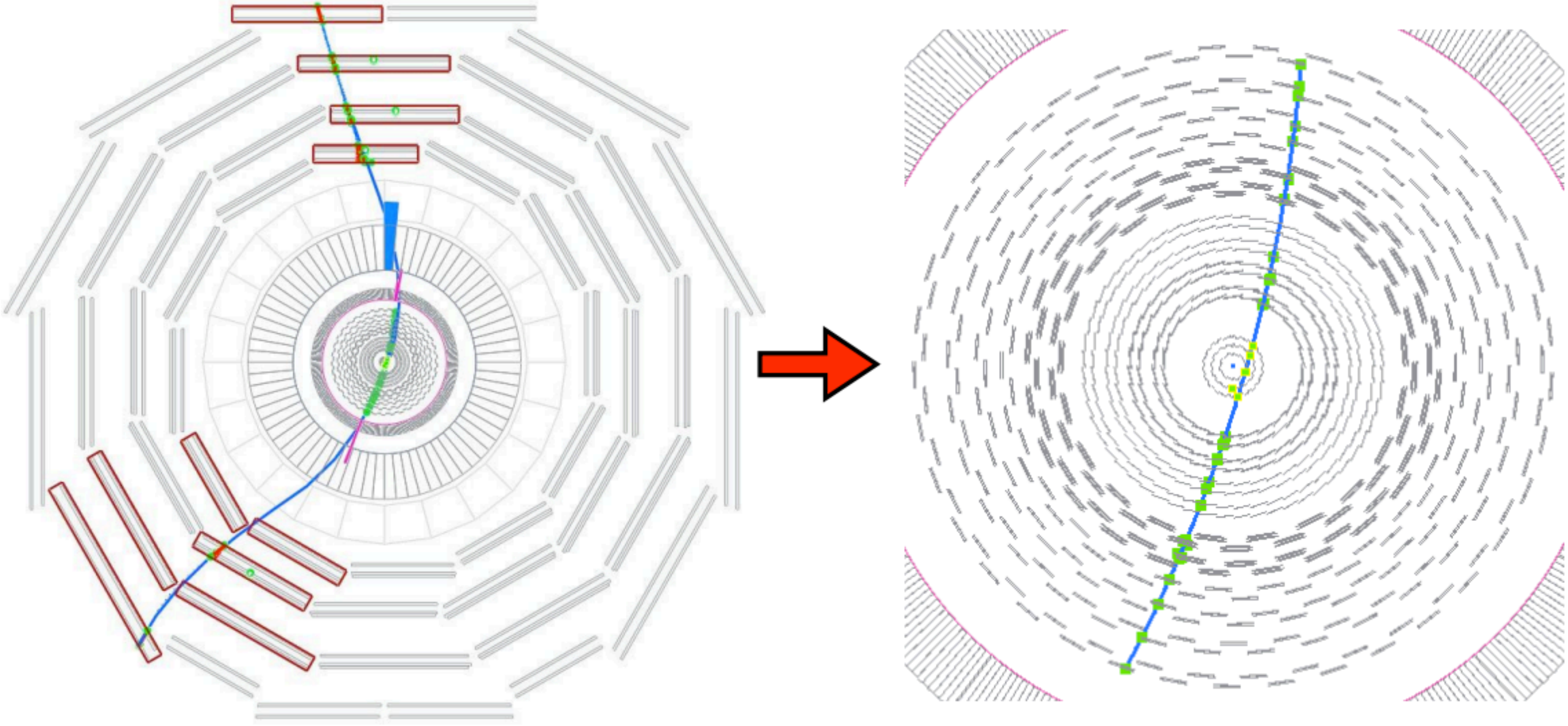


Much better agreement with 2010 sample and improved alignment

ATLAS-CONF-2010-033

Outer trackers

The cosmic muon that crossed all

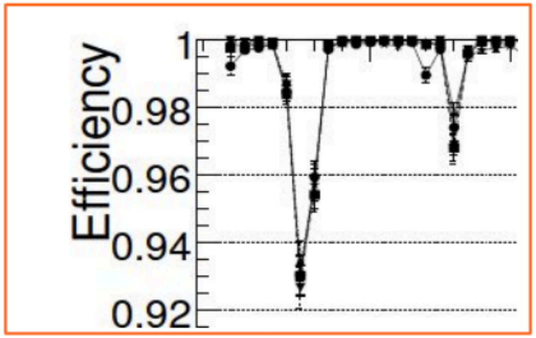


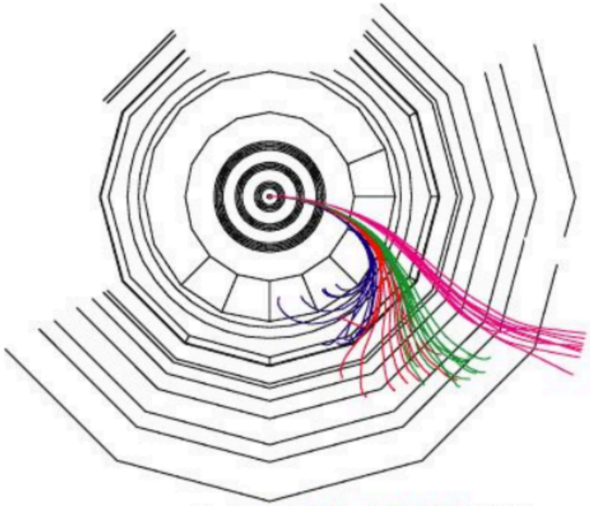
Finding muons: not just outside in

- Standard approach: Outside-in
  - Standalone Muon
  - Combine with tracker track to fit GlobalMuon
- “Muon-ID”: complementary Inside-out approach
  - Extrapolate every track outward
  - Find compatible deposits in ECAL, HCAL, HO, muon hits
  - Determine muon 'compatibility'

Recover inefficiencies at muon chamber boundaries and low p_T (e.g. Muons which only reach the first muon station)

Inefficiency at eta cracks





p_t = 3.5, 4.0, 4.5, 6.0 GeV

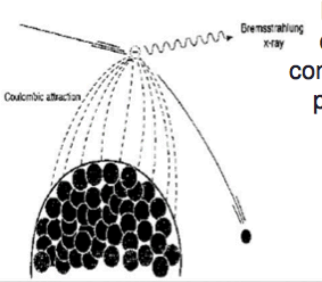
Muon bremsstrahlung

- Main energy loss due to ionization (Bethe-Bloch dE/dx)
- Additional energy loss through electromagnetic interaction in the coulomb field of the nucleus

$$-\left(\frac{dE}{dx}\right)_{brem} = \boxed{4\alpha\cdot N_A\left(\frac{e^2}{4\pi\varepsilon_0 c^2}\right)^2}\cdot\boxed{\frac{Z^2}{A}\cdot\ln\frac{183}{Z^{1/3}}}\cdot\frac{z^2}{m^2}E$$

Constant, independent on material and particle

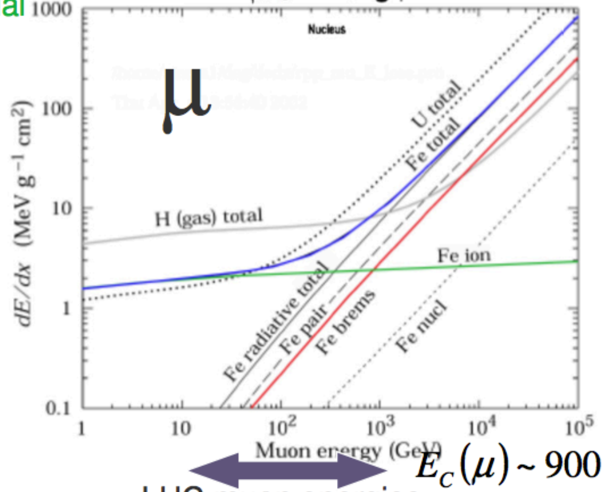
Properties of absorber material



Part of energy converted to photons

- Up to LHC energies, affected mainly electrons (Synch.radiation)

$$\left(\frac{dE}{dx}\right)_{\mu}\Big/\left(\frac{dE}{dx}\right)_{e} \sim \frac{1}{40.000}$$



$E_C(\mu) \sim 900\ GeV$

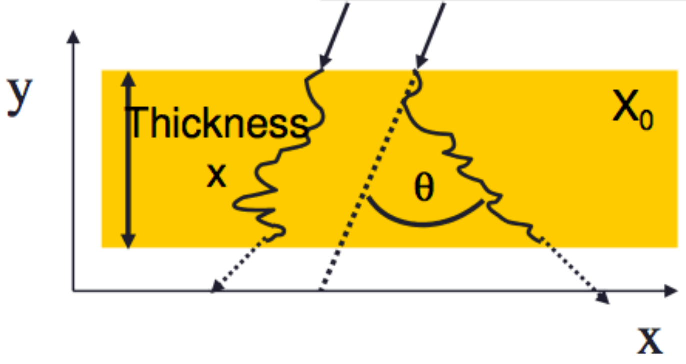
LHC muon energies

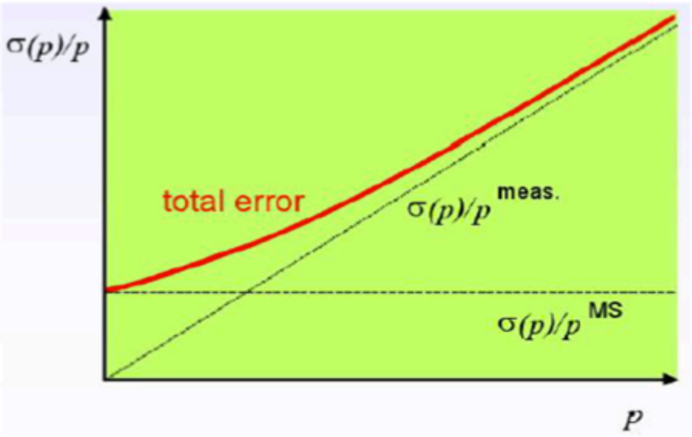
Muon multiple scattering

Multiple Rutherford scattering with the nuclei of the detector material

- Small changes per collisions
- Many collisions → in the sum measurable deviation from trajectory

$$\sqrt{<\alpha^2>} = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\left[1+0.038\ln(x/X_0)\right]$$





Multiple scattering limits resolution

Example 100 GeV Myon:

1 m Iron = 4 mrad ~ 4 mm

1 m Air = 0.02 mrad ~ 20 μm

Independent on particle's momentum
At large momenta detector resolution dominating

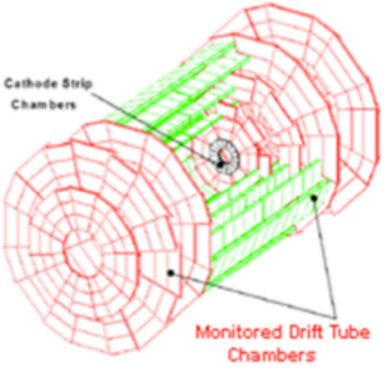
Momentum resolution

ATLAS

B = 0.7 T

L ~ 5 m

N = 3 Stations * 8 Points



s = 750 μm for 1 TeV Track

10% → σ = 75 μm

Δp/p ~ 6%

$$s = \frac{0.3 \cdot B[T] \cdot L[m]^2}{8 \cdot p[GeV]}$$

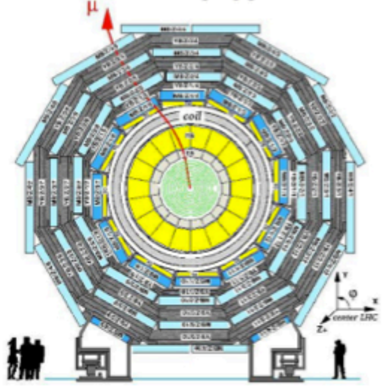
$$\frac{\Delta p_T}{p_T} \propto \frac{1}{s} \cdot \delta_{spatial} \cdot \sqrt{\frac{720}{N_{Stat}}}$$

CMS

B ~ 2 T (B-Field in Fe)

L ~ 3.5 m

N = 4 Stations * 8 Points in (rϕ)



s = 900 μm for 1 TeV Track

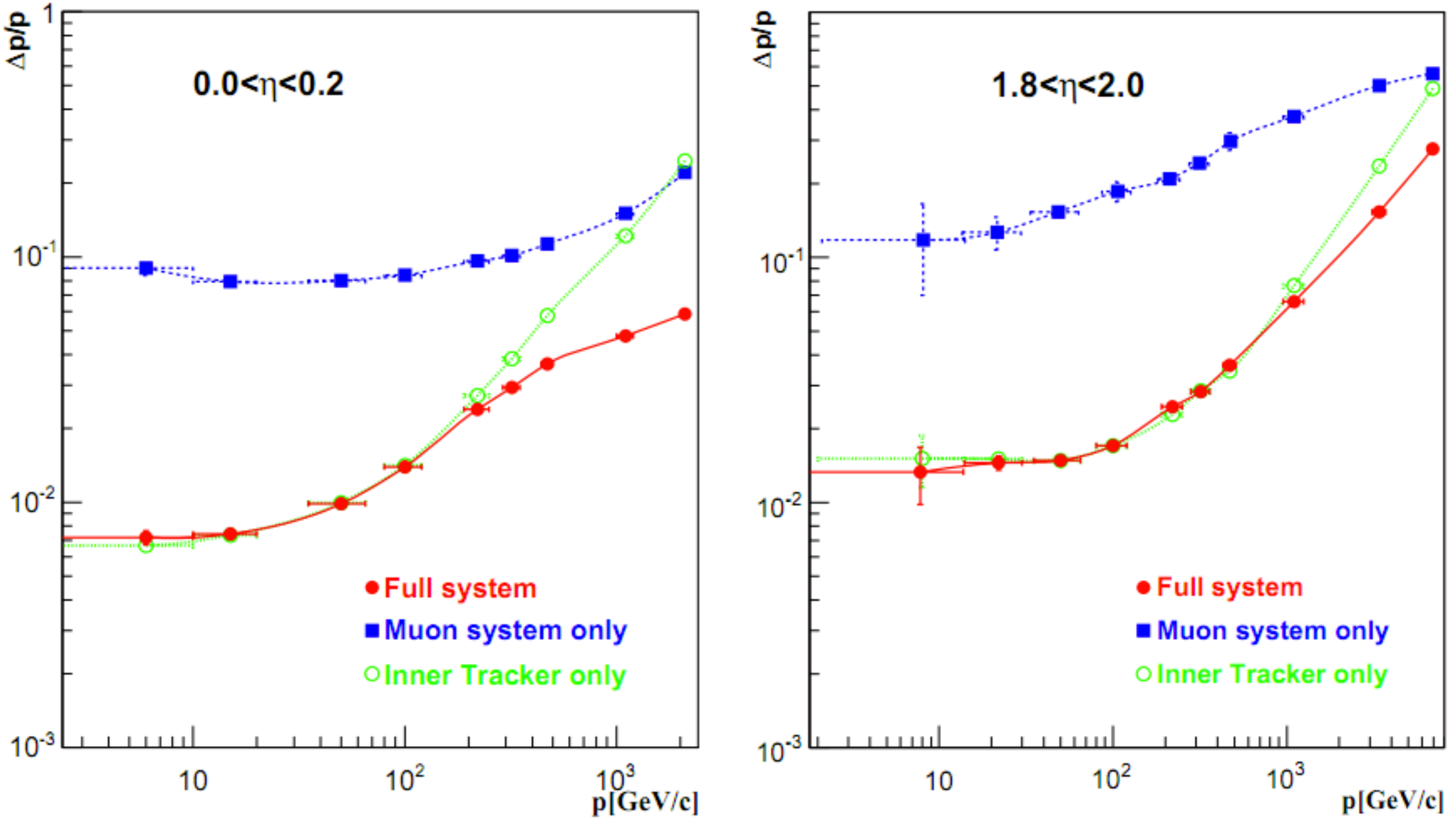
10% → σ = 90 μm

Δp/p ~ 12 %

(Multiple scattering in Fe ~100 μm)

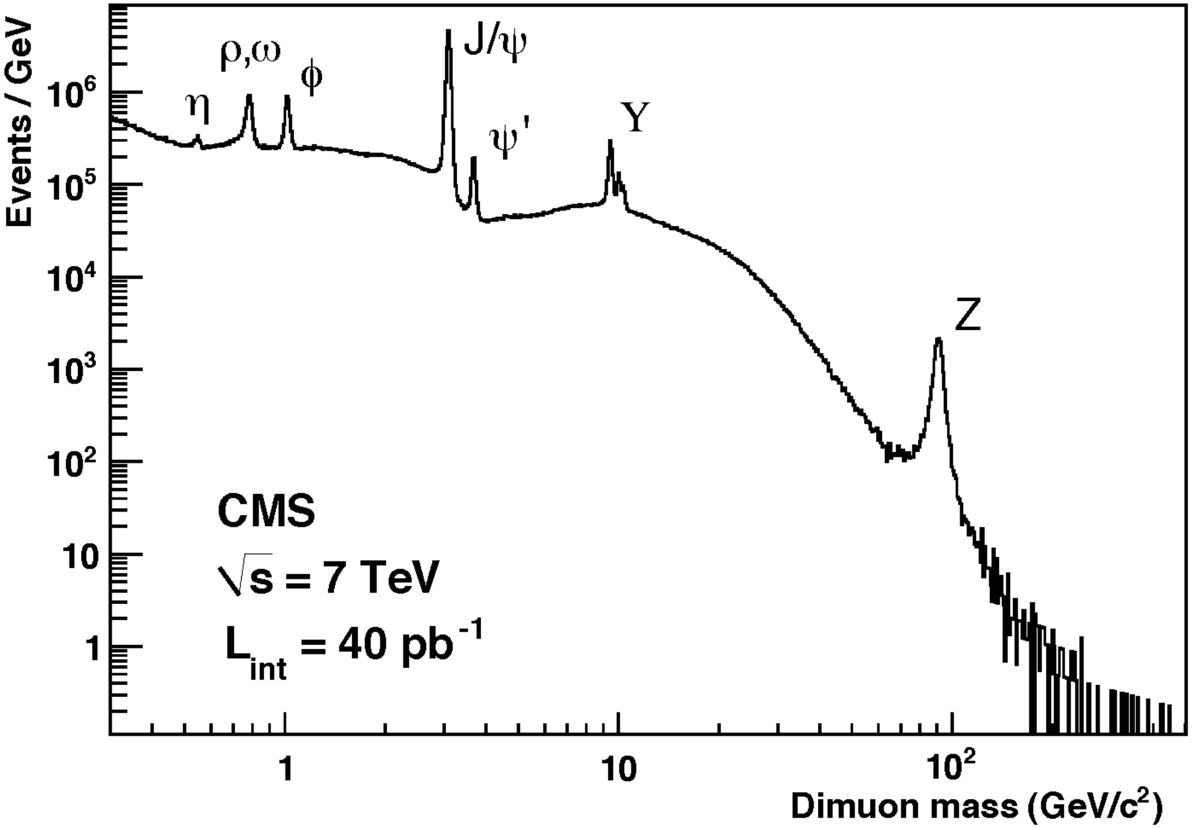
Combine with Tracker Δp/p ~ 2 %

Combined performance



CMS dimuon performance

- Dimuons from eta to Z



Trigger

Trying to keep one interesting collision, while rejecting 10^6 others.

Trigger: why?

10^8/sec

10^2/sec

10/sec

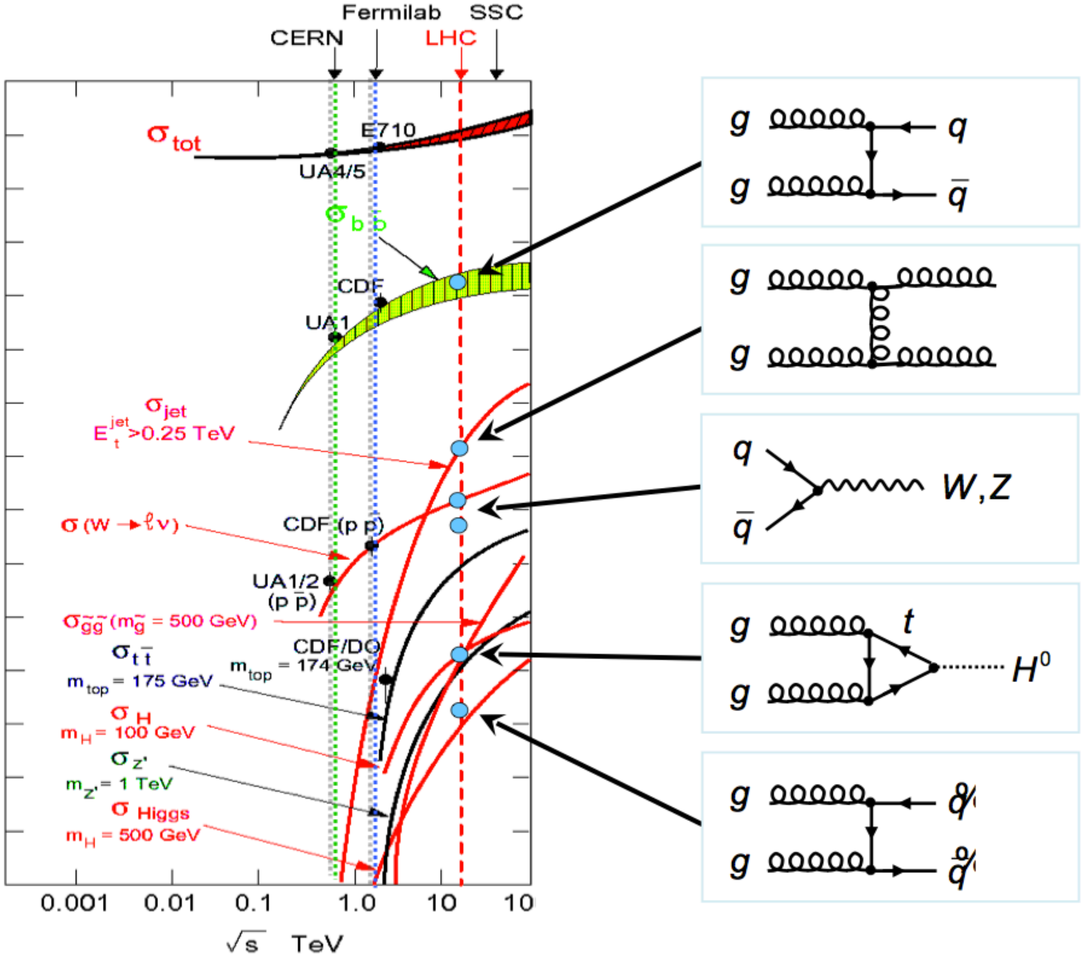
1/sec

1/(2 min)

1/(15 min)

1/(3 hr)

1/day



Quark-flavour production

High-p_T QCD jets

W, *Z* production

gluon-to-Higgs fusion

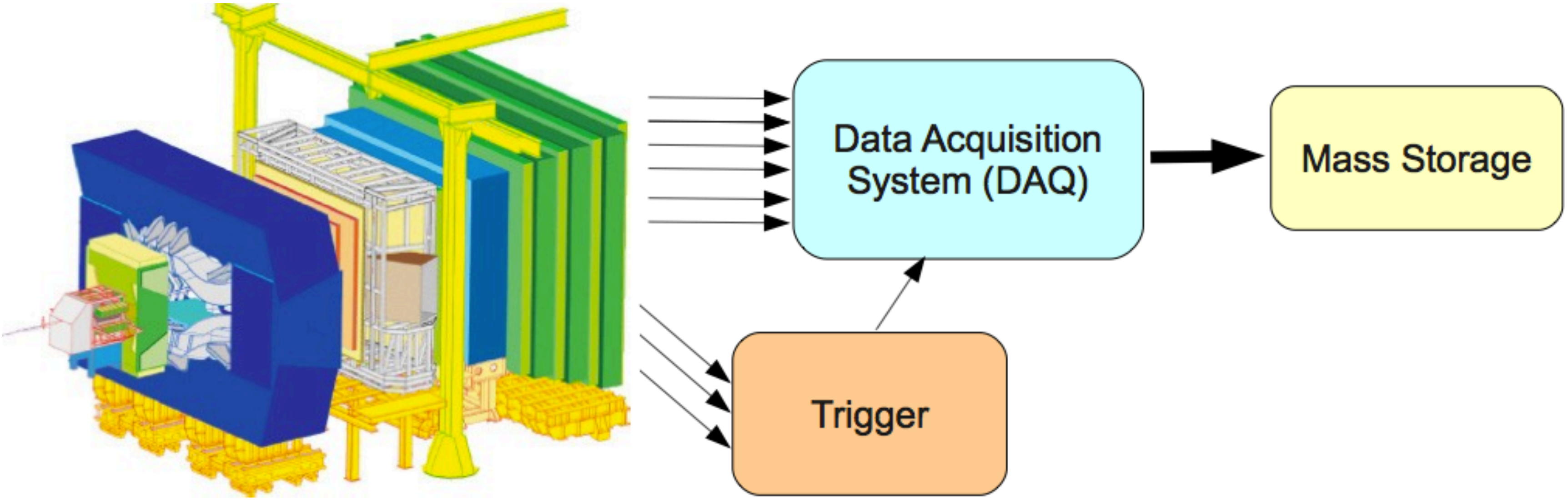
squarks, gluinos

($m \sim 1$ TeV)

$1\ \text{pb}^{-1} = 10^{36}\ \text{cm}^{-2}$

$15\ \text{nb} \cdot 10^{34}\ \text{cm}^{-2}\text{s}^{-1} = 150\ \text{Hz}$

Trigger: what?



Data Acquisition System (DAQ)

Mass Storage

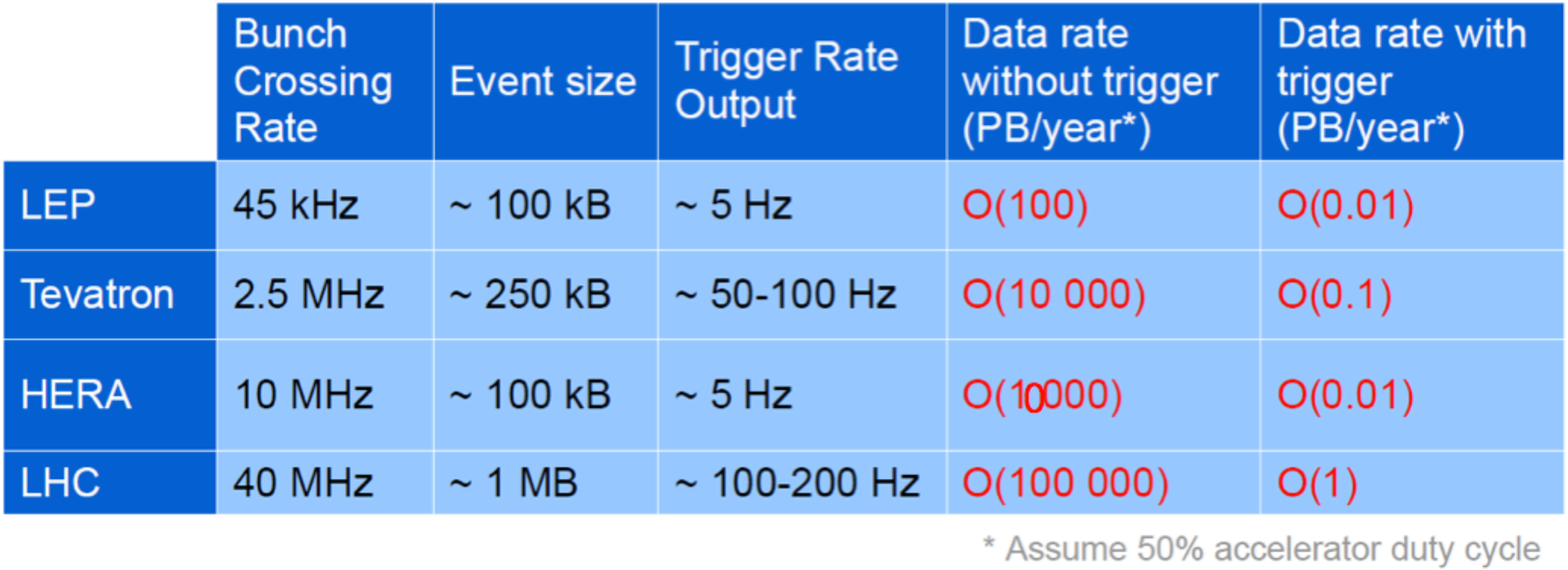
Trigger

DAQ is responsible for collecting data from detector systems and recording them to mass storage for offline analysis

Trigger is responsible for real-time selection of the subset of data to be recorded

Trigger: how?

- Data rates are too high record every full event.
  - Reduce rates, typically by factor 10^4-10^5.

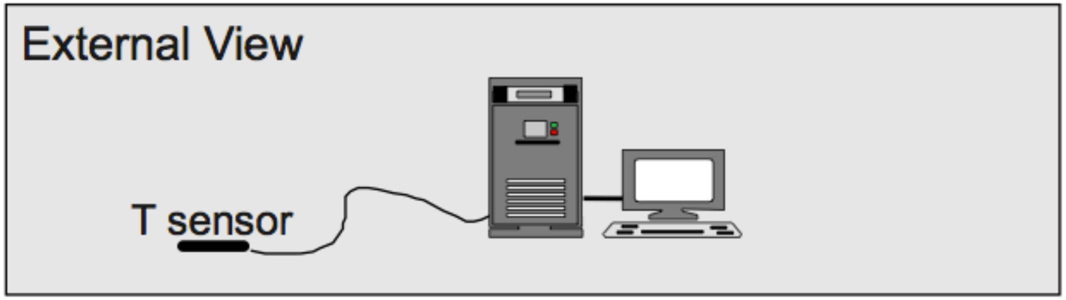


	Bunch Crossing Rate	Event size	Trigger Rate Output	Data rate without trigger (PB/year*)	Data rate with trigger (PB/year*)
LEP	45 kHz	~ 100 kB	~ 5 Hz	O(100)	O(0.01)
Tevatron	2.5 MHz	~ 250 kB	~ 50-100 Hz	O(10 000)	O(0.1)
HERA	10 MHz	~ 100 kB	~ 5 Hz	O(10000)	O(0.01)
LHC	40 MHz	~ 1 MB	~ 100-200 Hz	O(100 000)	O(1)

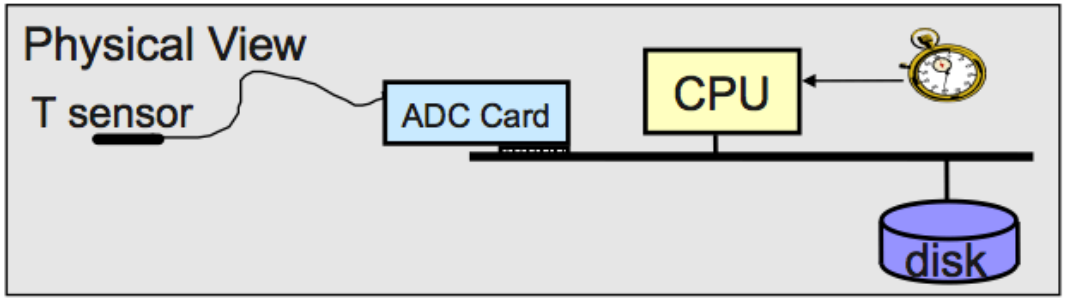
* Assume 50% accelerator duty cycle

Building an acquisition system

Simple DAQ system

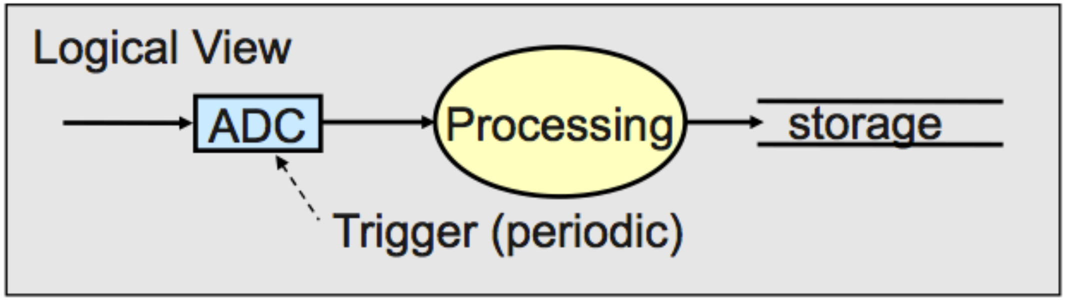


System to measure temperature at fixed rate



Analog-to-digital converter (ADC) digitizes signal

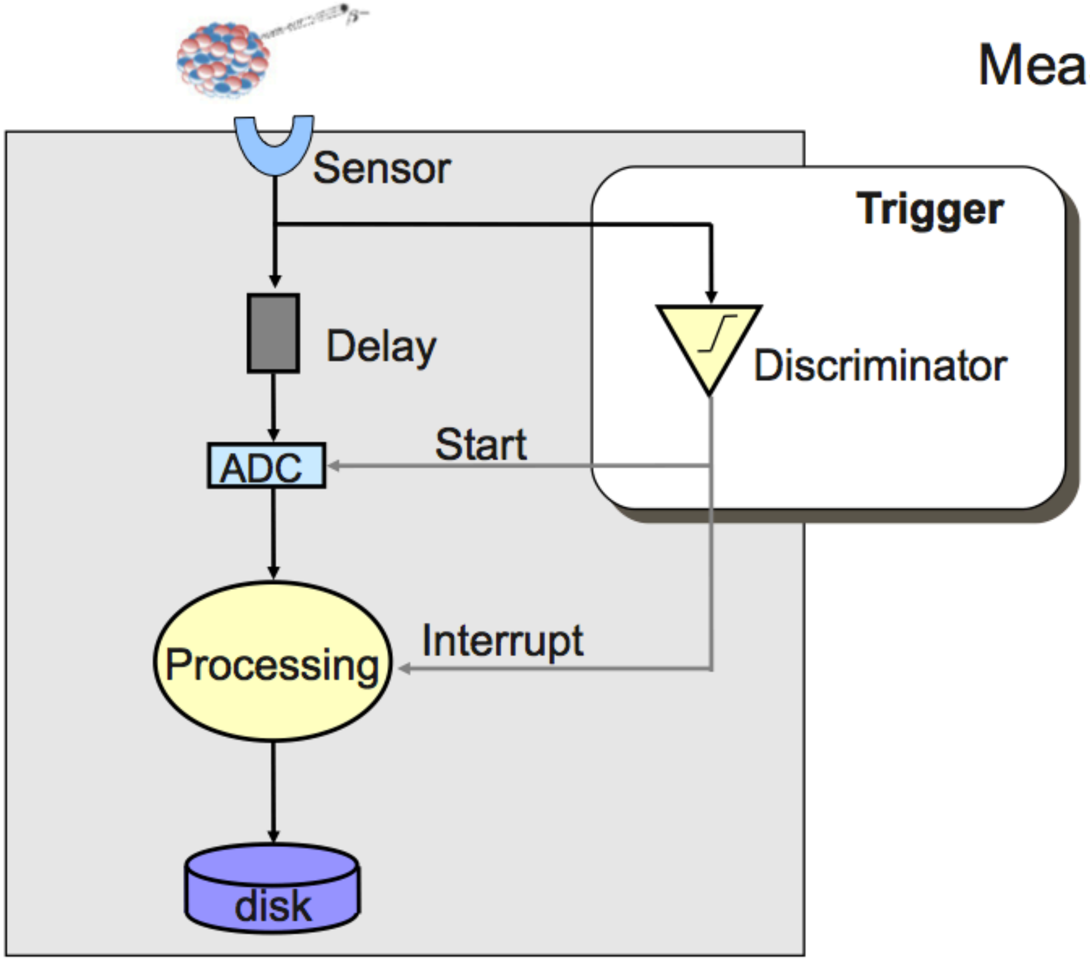
PC does readout and records data to disk



Rate limited by conversion, readout and data recording

If τ=1ms, max rate is 1 kHz

Adding a trigger



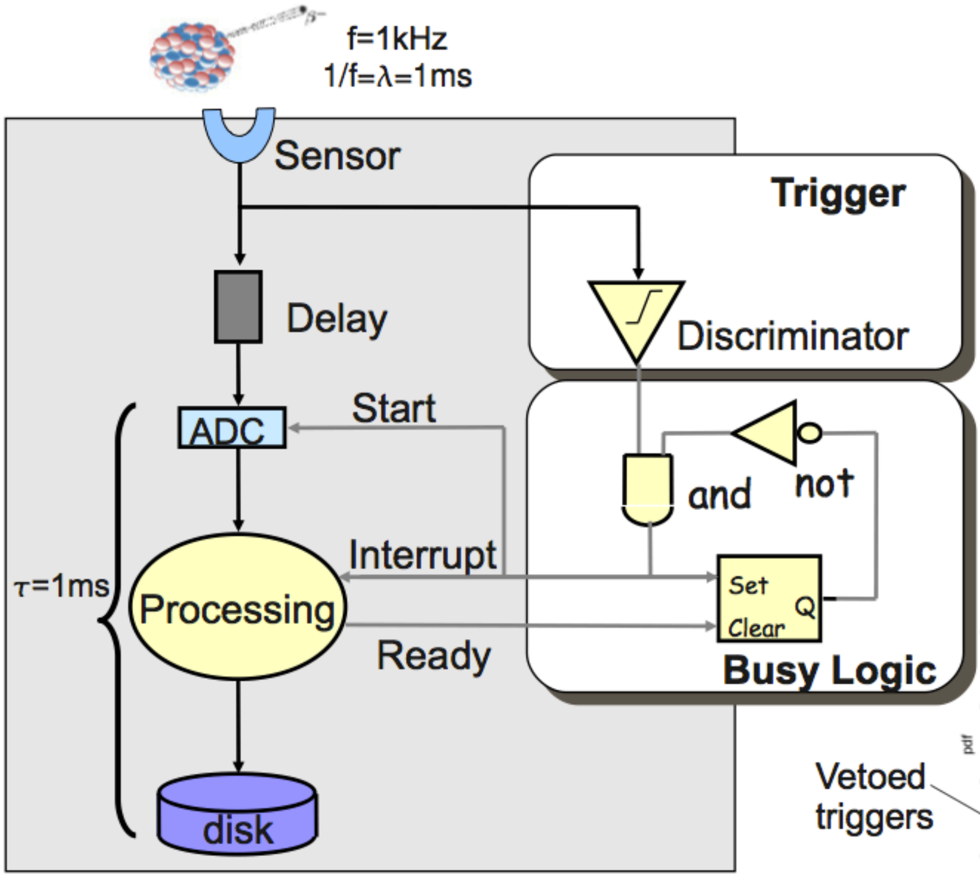
Measurement of β decays

With unpredictable signal, we need a physics based trigger

Delay of signal to ADC needed to synchronize with trigger signal (Trigger Latency)

Delay can be a long cable in simplest cases

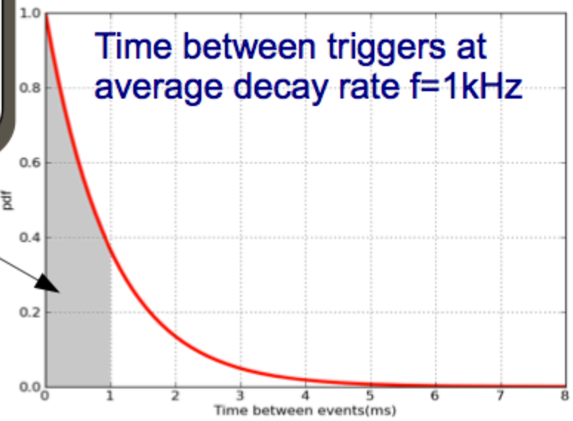
Adding busy logic



With stochastic process, new signals can arrive while system is still processing

Busy logic prevents this

No longer able to process 1 kHz of rate (deadtime)

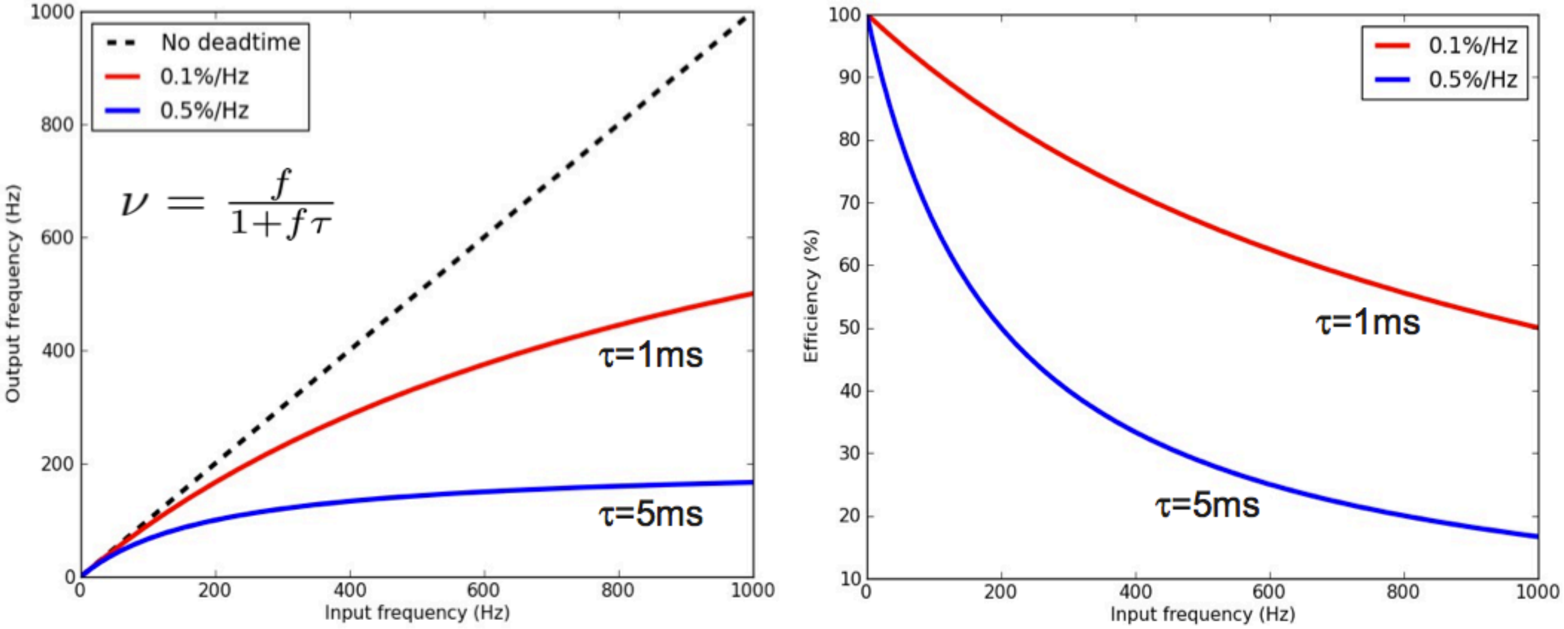


Dead time

At output rate ν, the system will only be accept (1-ντ) of triggers

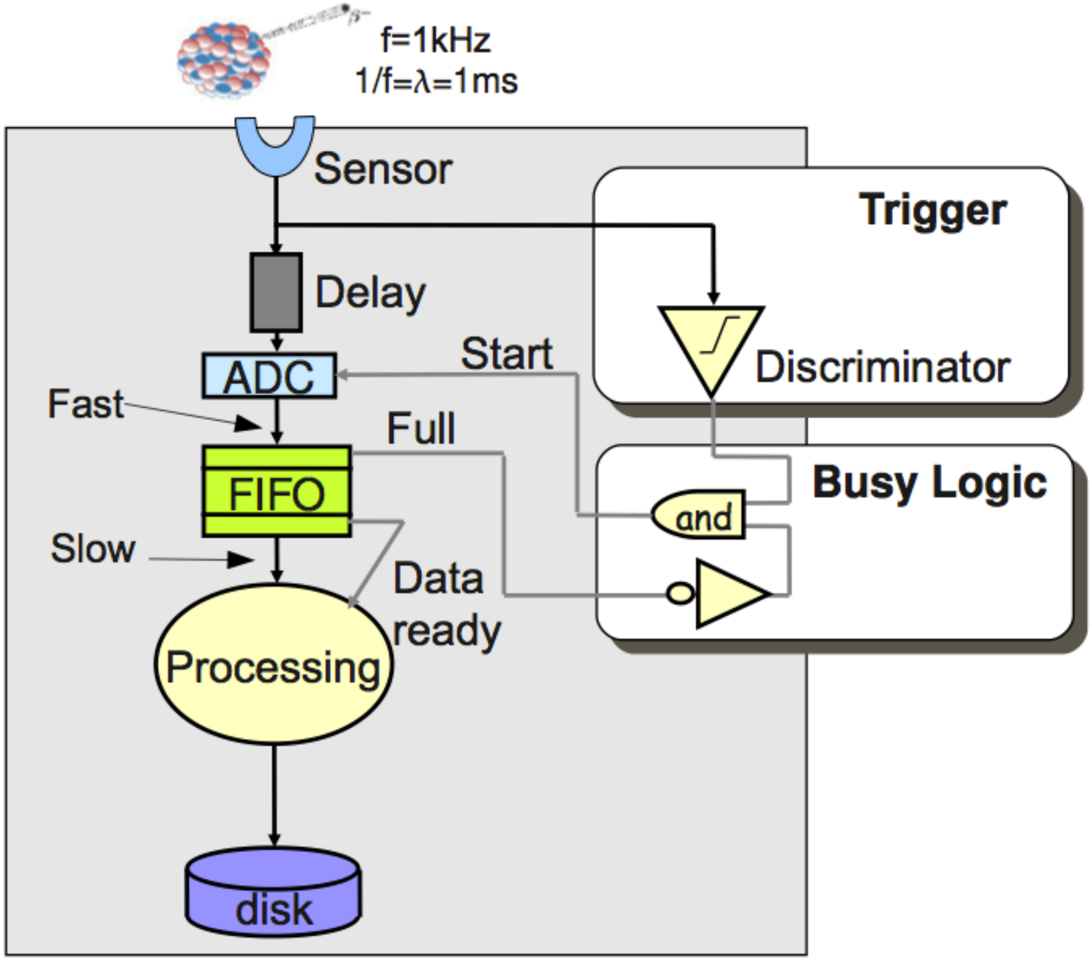
$$\nu = f(1 - \nu\tau) \Rightarrow \nu = \frac{f}{1 + f\tau} < f$$

f input rate
τ readout time



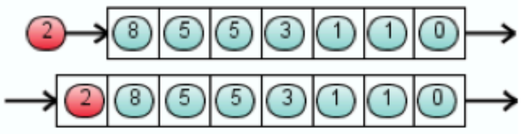
Unless readout time<<time between triggers,
we will have very inefficient system – normally highly undesirable

Derandomizing buffer



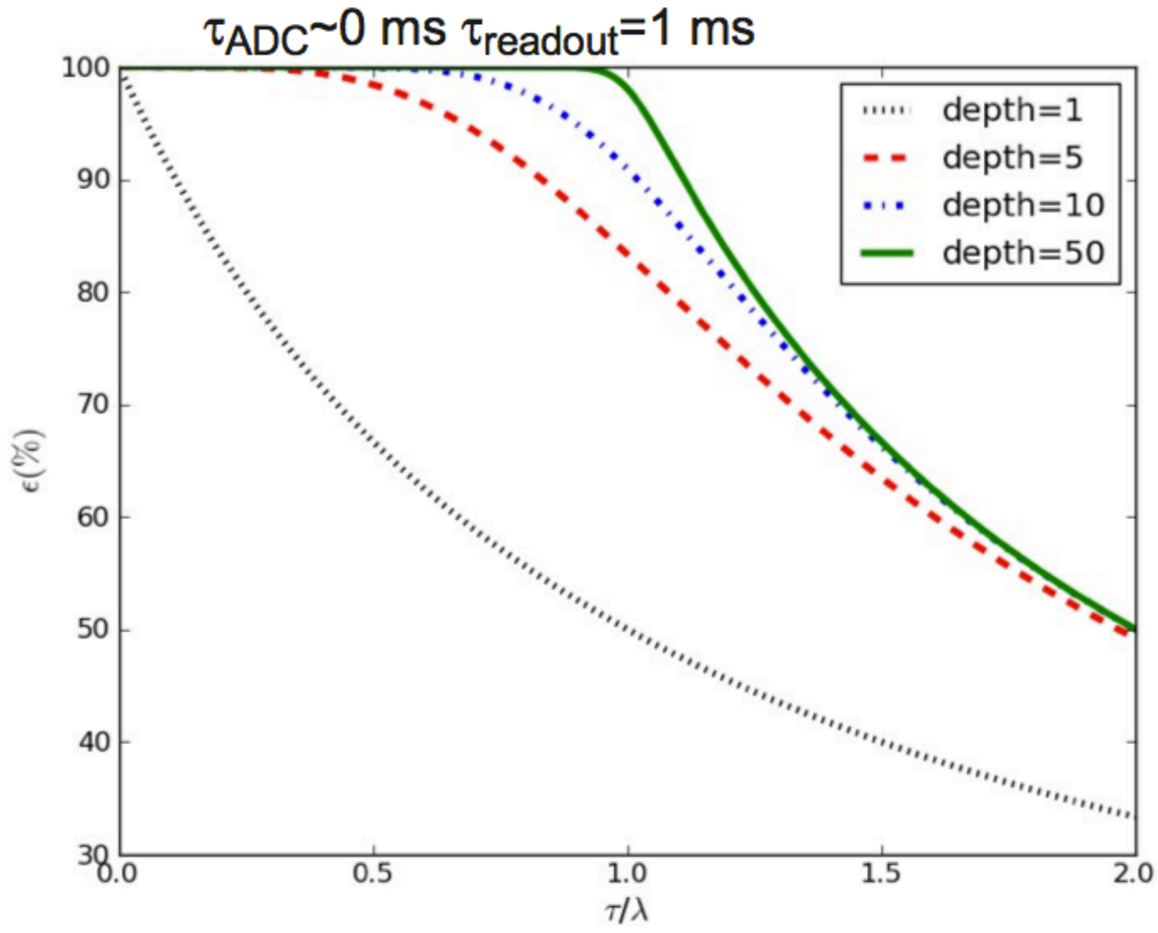
Smooth out fluctuations (derandomize) by introducing an fast, intermediate buffer

Organized as a queue First-In, First-Out (FIFO)



Decouples the fast front-end (ADC) from slow readout

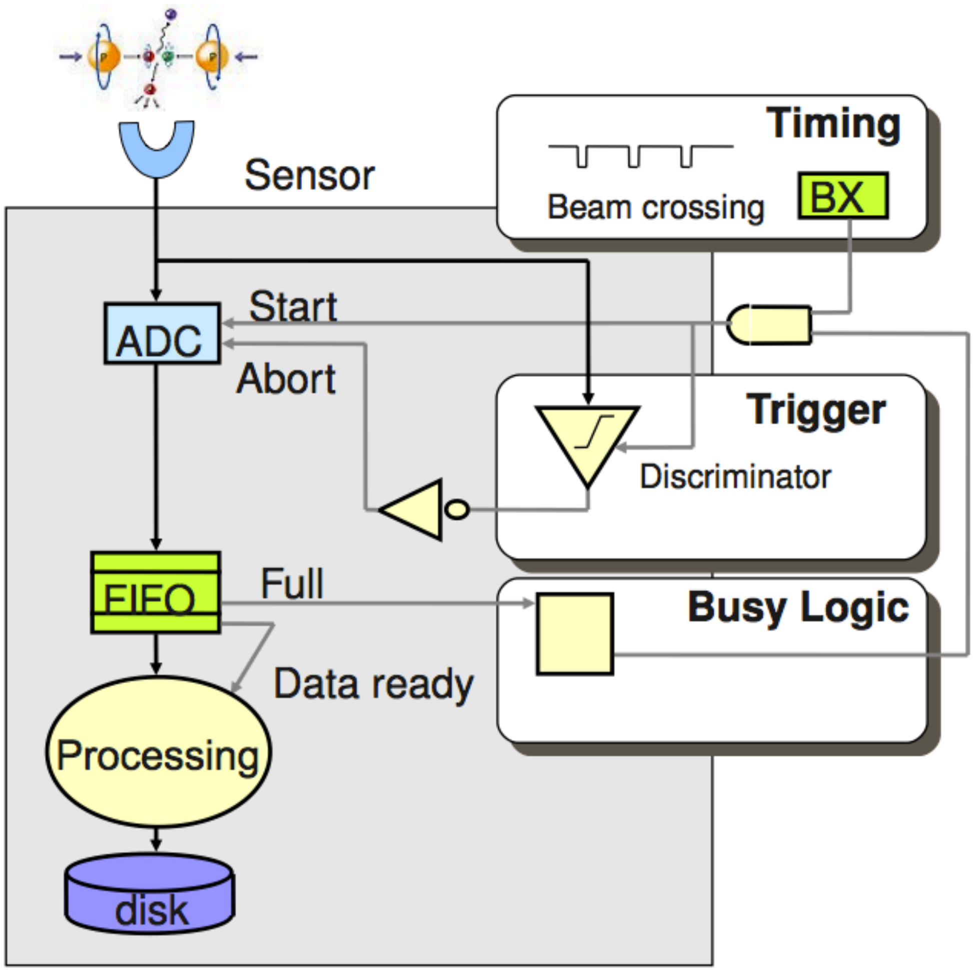
Deadtime with derandomizer



With moderate sized buffer we can retain good efficiency up to f~1/$\tau_{readout}$

Avoids having
to over-design
the full DAQ system

Working with bunched beams



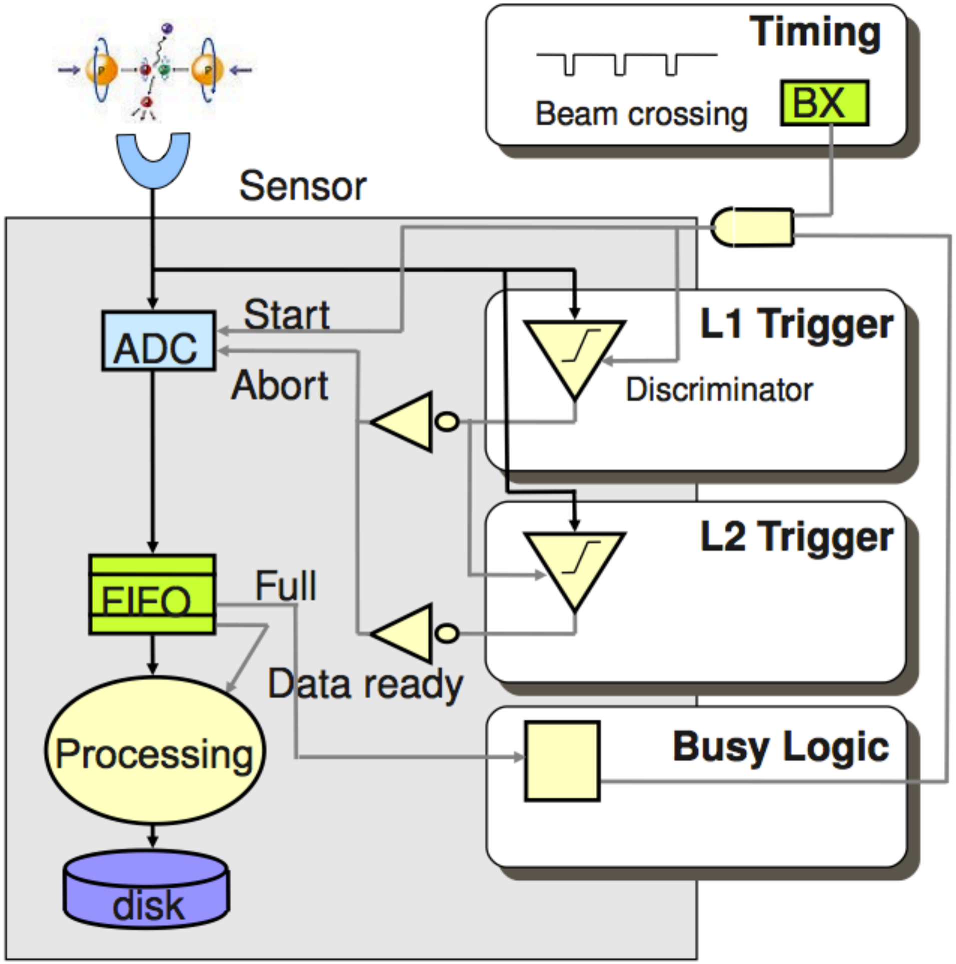
ADC now synchronous with beam crossing

Trigger rejects events

Still need FIFO as trigger output still stochastic

No trigger deadtime if trigger latency below beam crossing interval

Multi-level triggers



For complicated triggers latency can be long

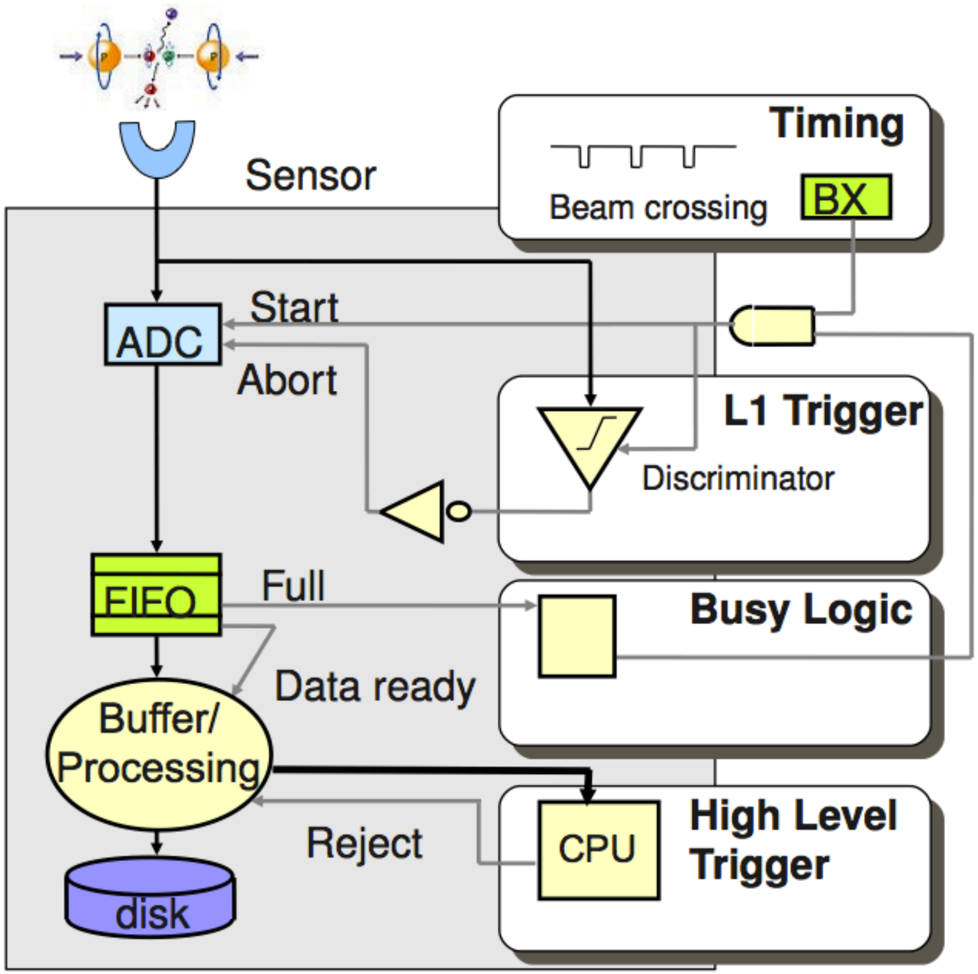
- if $\tau_{trig} > \tau_{BX}$, deadtime>50%

Split trigger in several levels with increasing complexity and latency

All levels can reject events

- with $\tau_{L1} < \tau_{BX}$, trigger deadtime only $\nu_{L1} \cdot \tau_{L2}$

Multi-level trigger



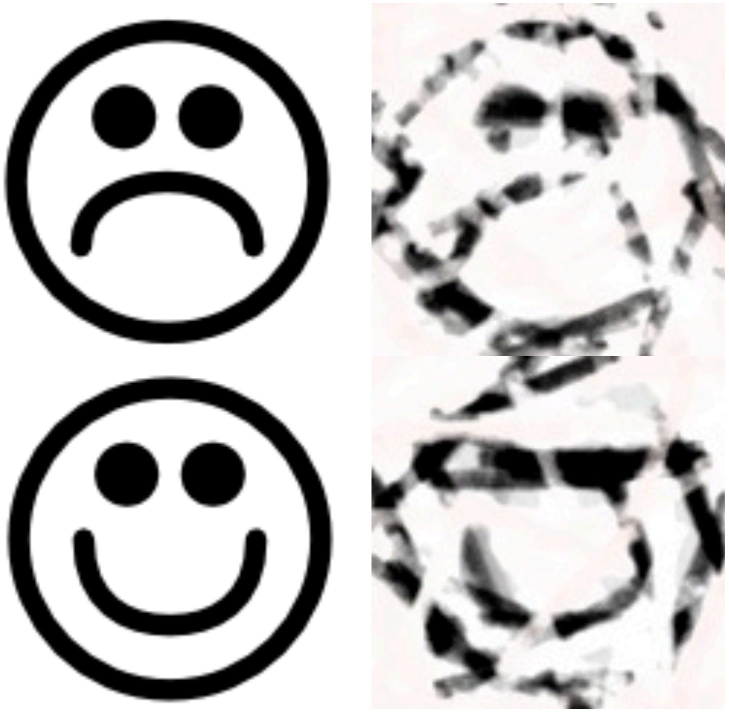
For optimal data reduction can add trigger level between readout and storage (High-level trigger)

Has accessed to some/all processed data

Level-1 trigger

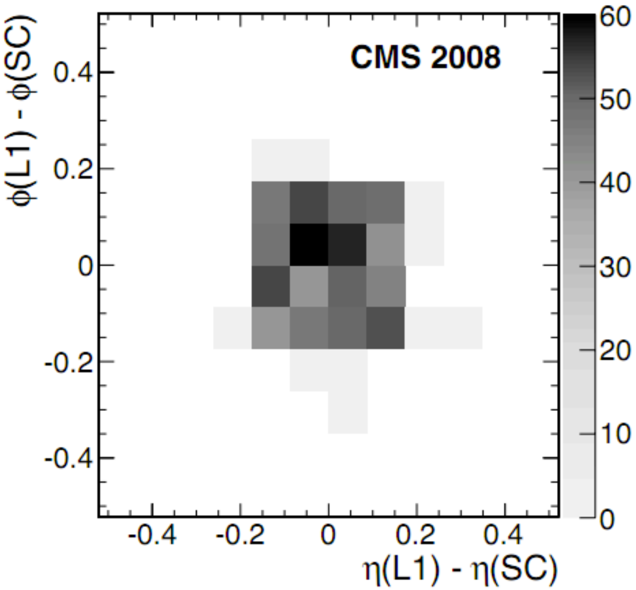
Level-1: a sufficient look

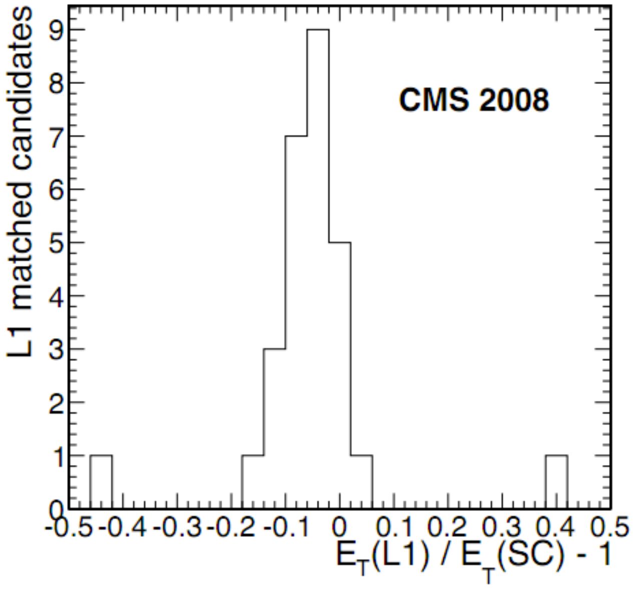
- Not all information is needed to decide to if an event should be kept.



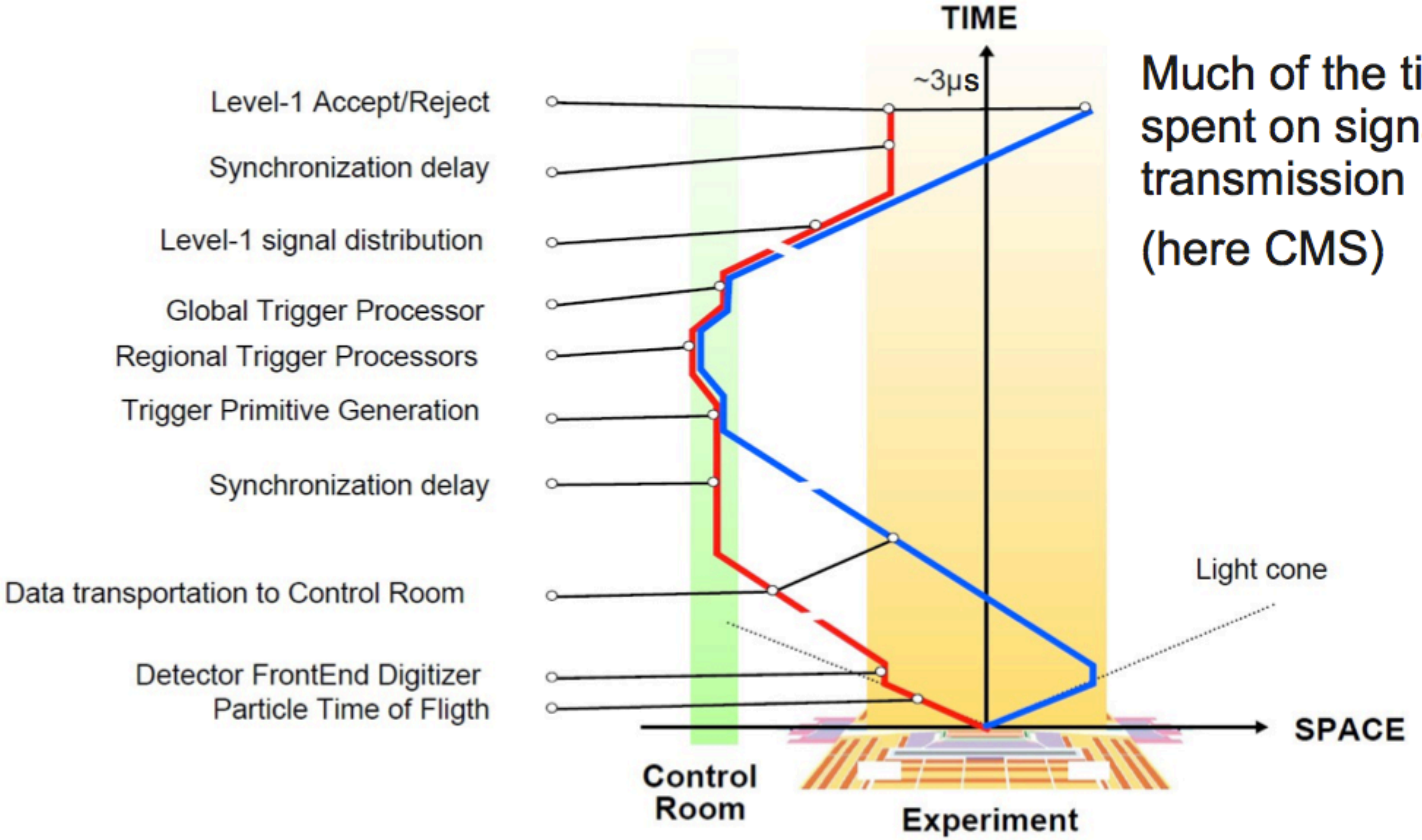
Level-1: a sufficient look

- Information for level-1 decision is kept at a minimum.
  - Spatial resolution and energy resolution are much coarser than offline.





Level-1 Latency

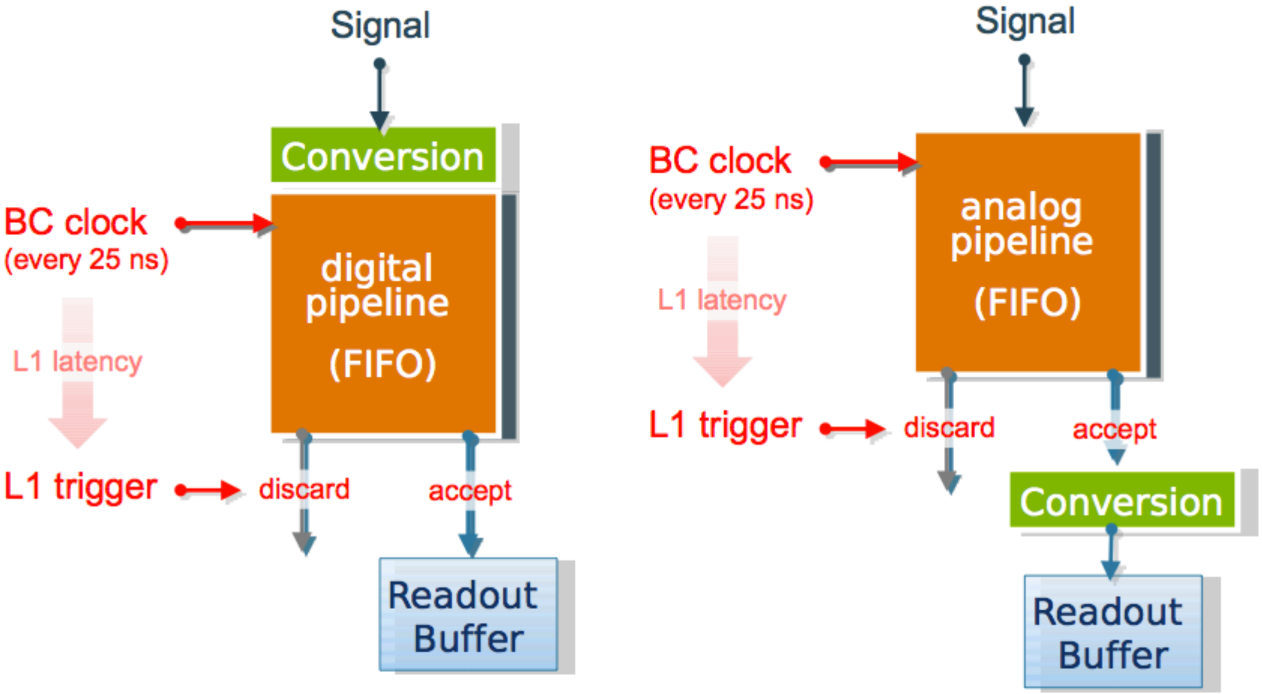


Much of the time spent on signal transmission

(here CMS)

Pipelined front-ends

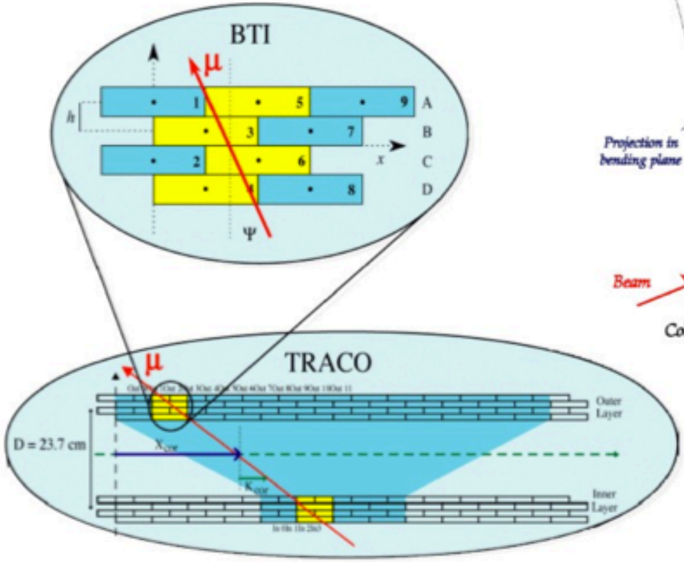
During L1 processing data for all bunch crossings buffered
Use pipeline in data path for holding data
- many variations (analog/digital, on/off detector)
Length of pipeline determines maximum L1 latency

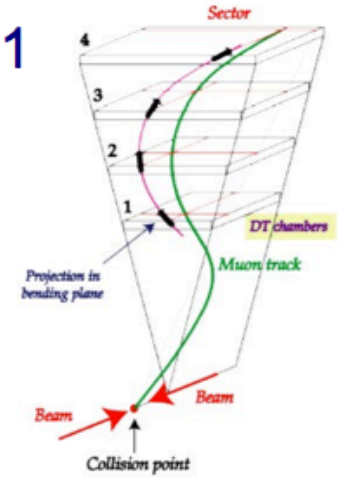


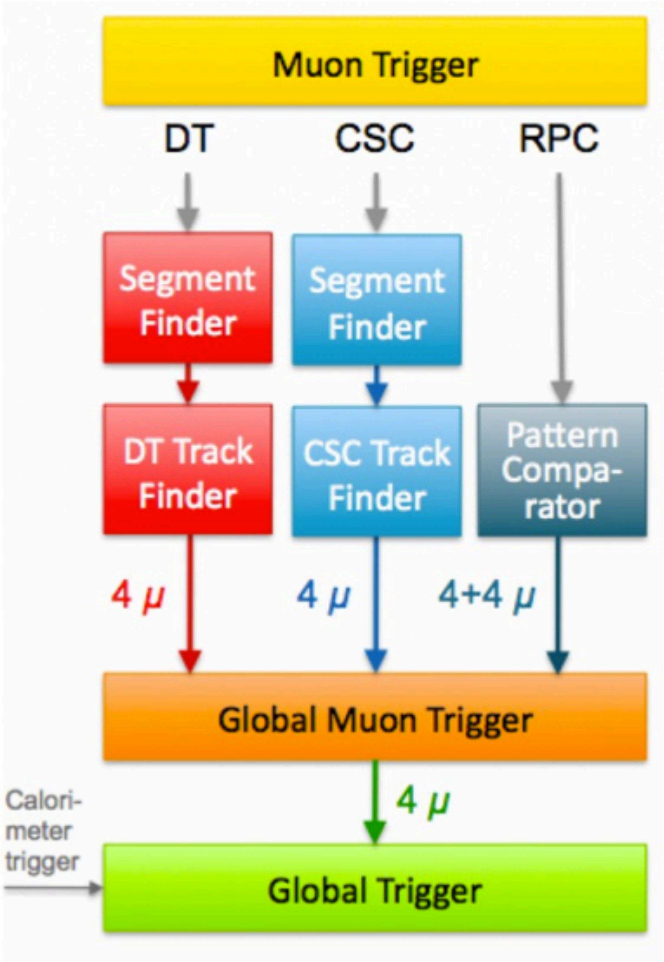
Level-1 Muon trigger

Reconstruct segments in each muon chamber
Combine segments to form track
and measure p_T (rough)

Example: CMS Muon L1







Muon Trigger

DT → Segment Finder → DT Track Finder → 4 μ

CSC → Segment Finder → CSC Track Finder → 4 μ

RPC → Pattern Comparator → 4+4 μ

Global Muon Trigger → 4 μ

Calorimeter trigger

Global Trigger

Level-1 Global trigger

Multiple sources of L1 triggers combined in one place
for final decision of “accept” or “reject” (global/central trigger)
 - also includes busy logic

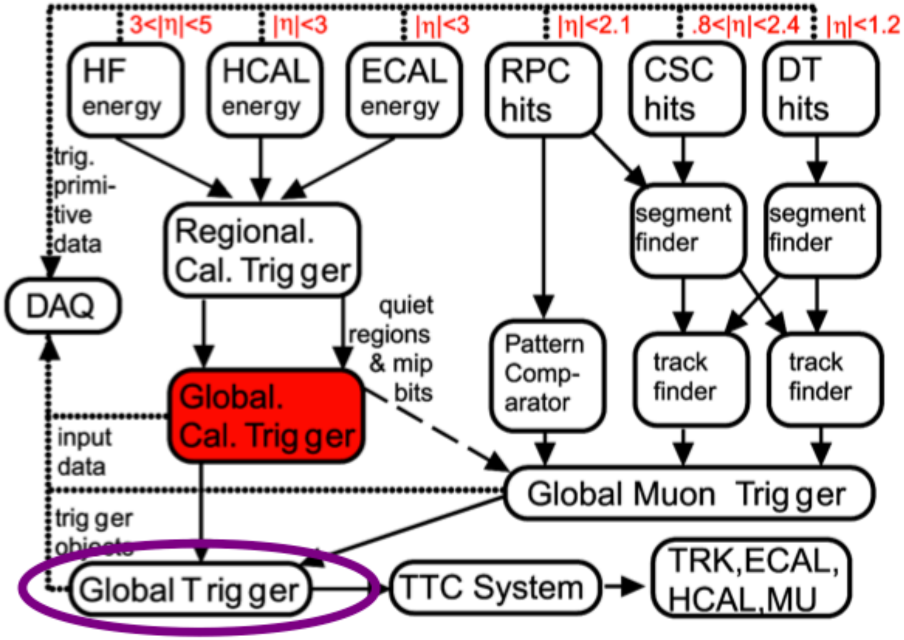
Can either be big OR of input triggers, require combinations of certain trigger objects or even some topological cuts

Example:

Pass event if:

- 1 muon with p_T>20 GeV, or
- 2 muons with p_T>5 GeV, or
- 1 electron with p_T>7 GeV and 1 muon with p_T>5 GeV, or
- 1 muon above 15 GeV and no jet within $\Delta\phi$ of 0.2 rad,

Example: CMS L1 Trigger

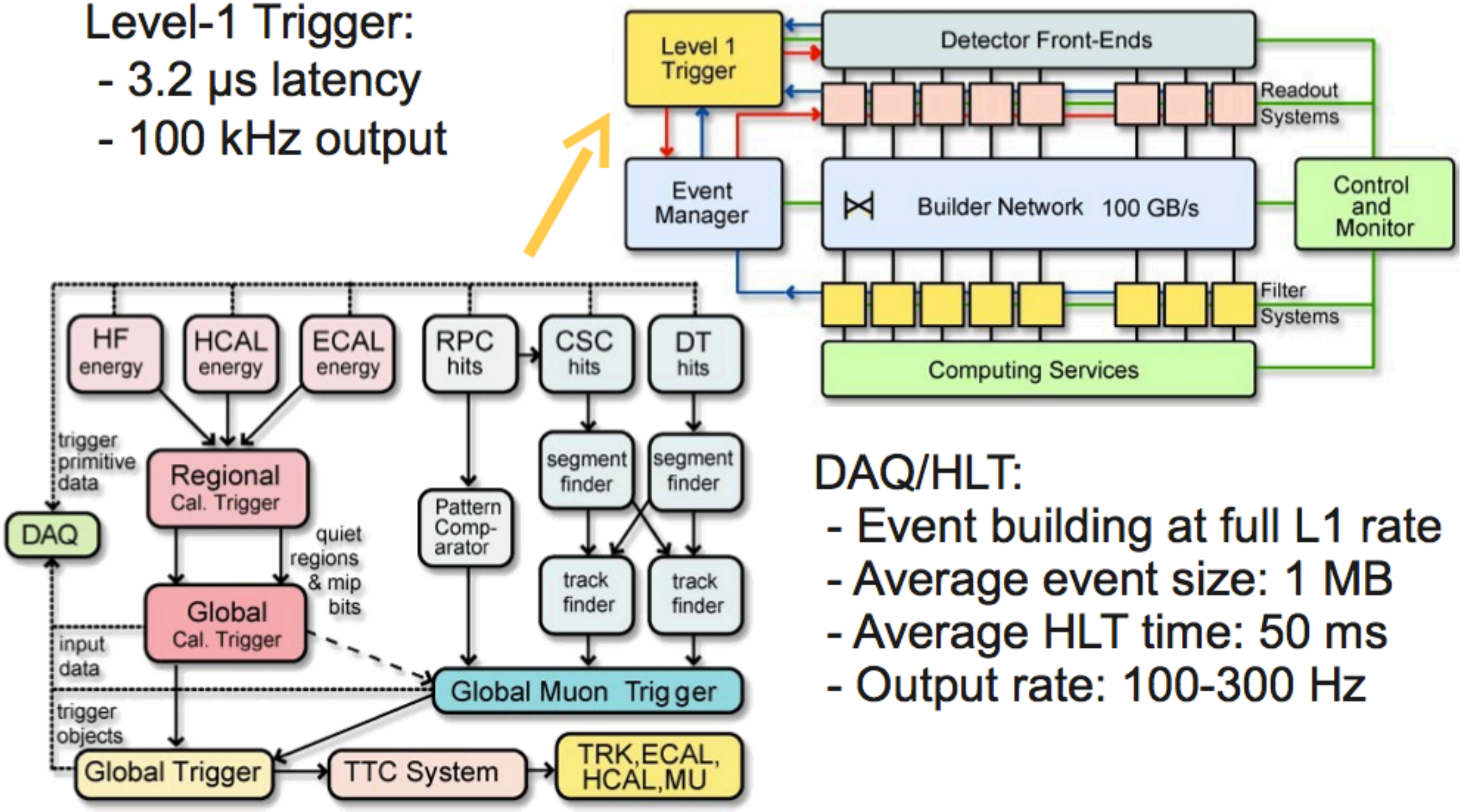


Event building

Event building

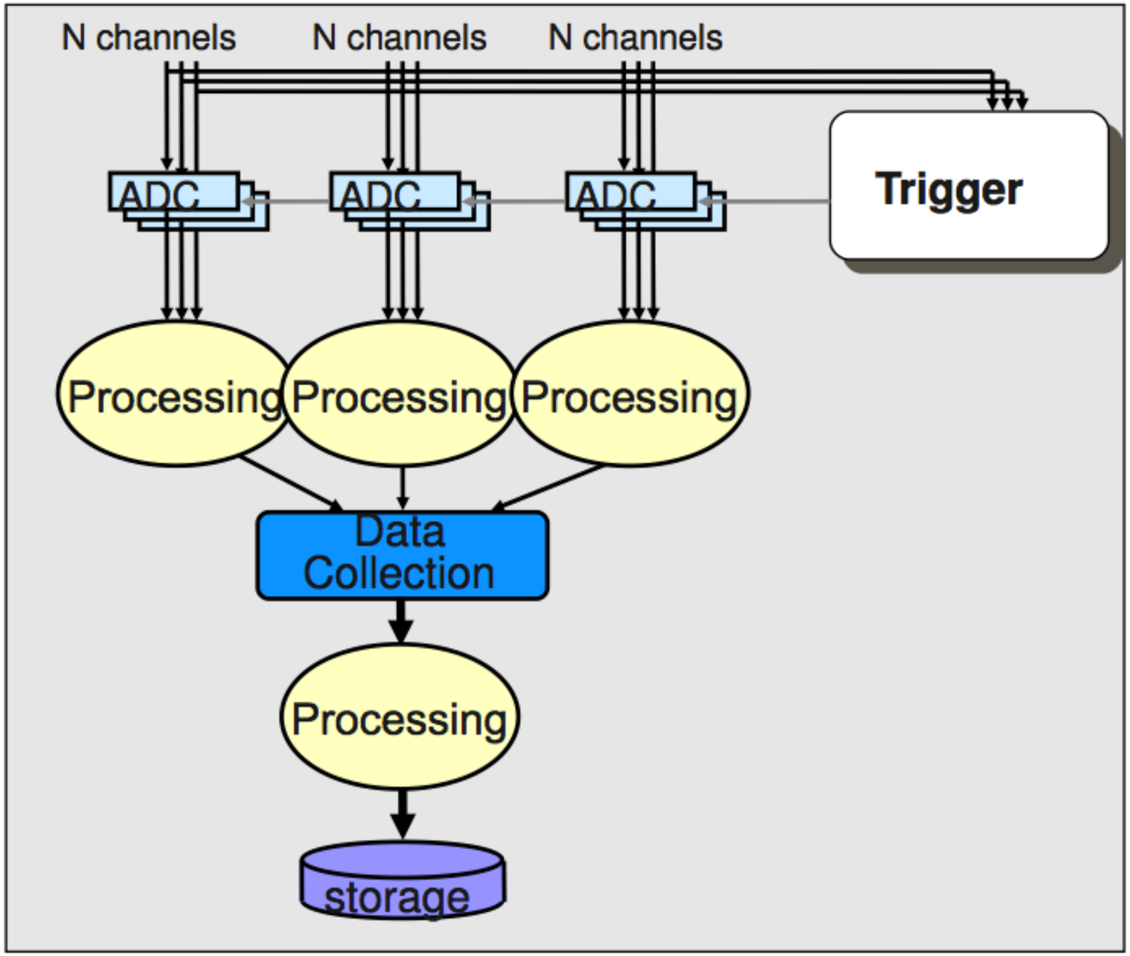
Overall Trigger & DAQ Architecture: 2 Levels

Level-1 Trigger:
- 3.2 μs latency
- 100 kHz output



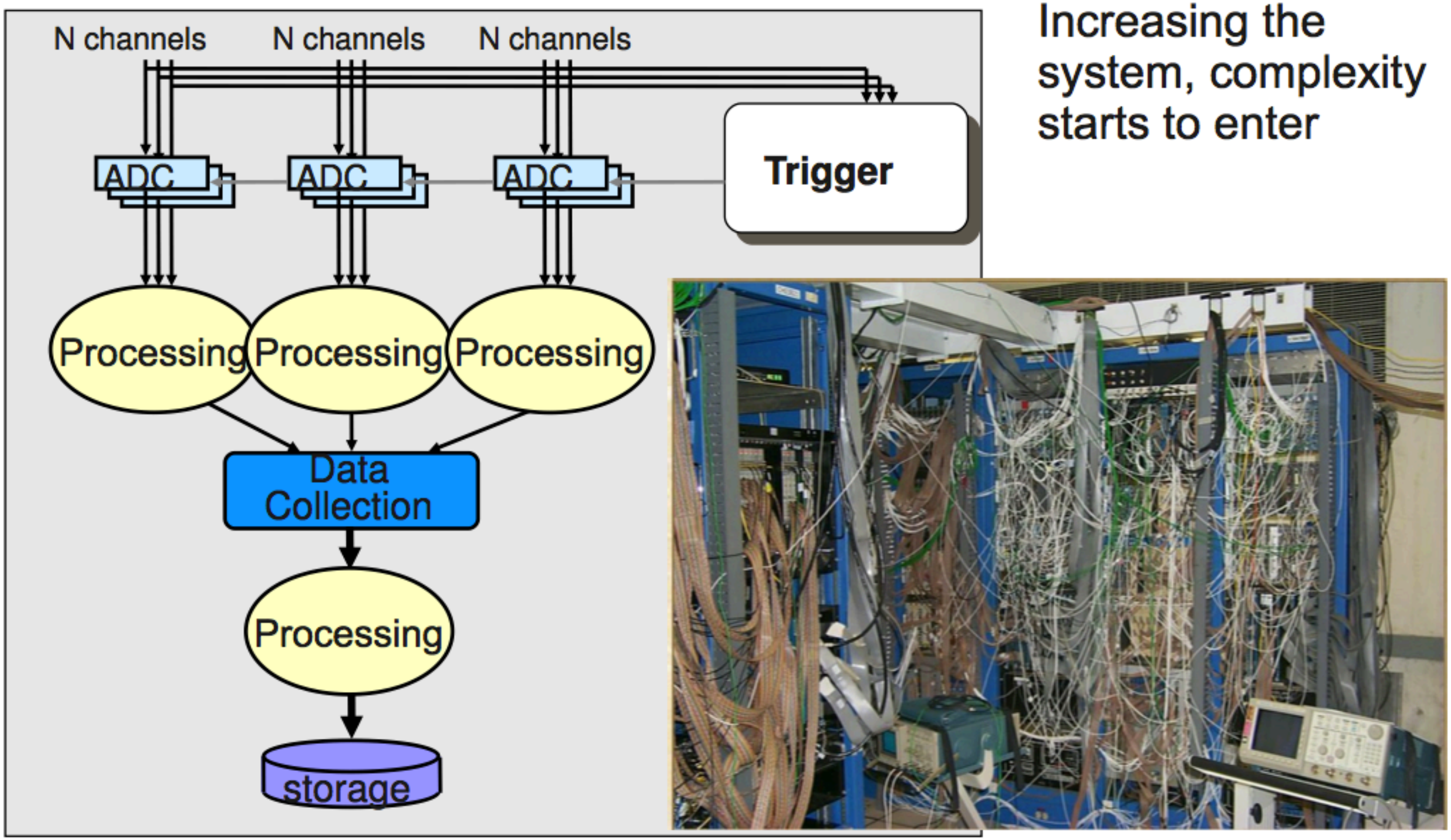
DAQ/HLT:
- Event building at full L1 rate
- Average event size: 1 MB
- Average HLT time: 50 ms
- Output rate: 100-300 Hz

Scaling up



Increasing the system, complexity starts to enter

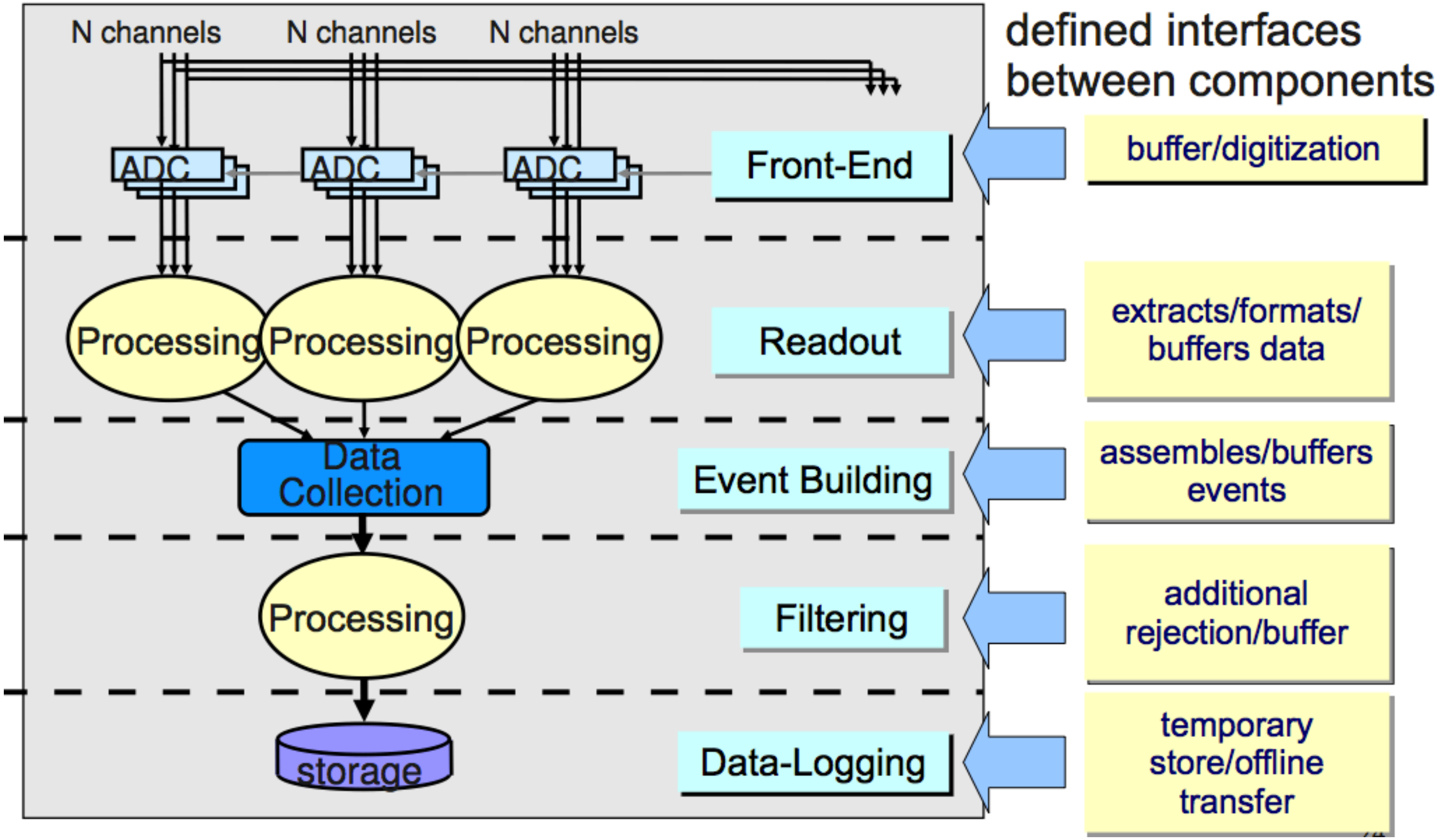
Scaling up



Increasing the system, complexity starts to enter

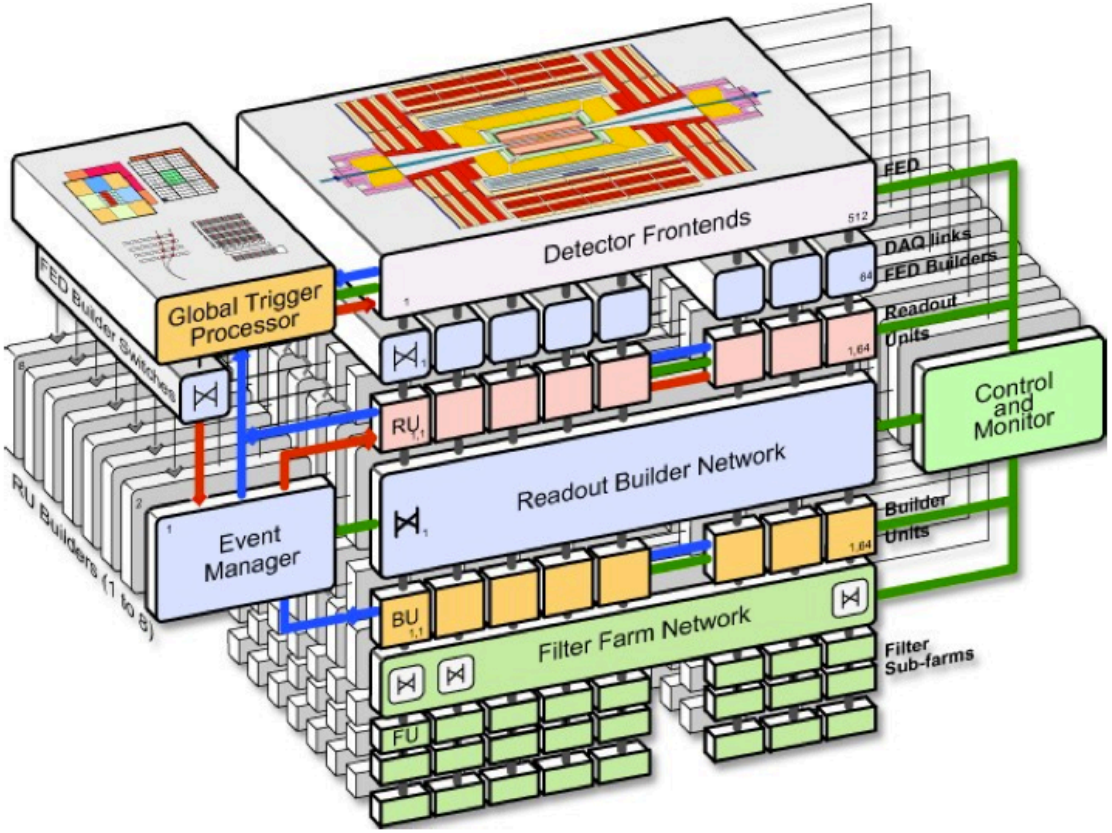
Scaling up

Need to impose structure with well-defined interfaces between components



CMS 3D event builder

Event building and filtering done in 8 independent "slices" to facilitate 100 kHz rate



High-level trigger

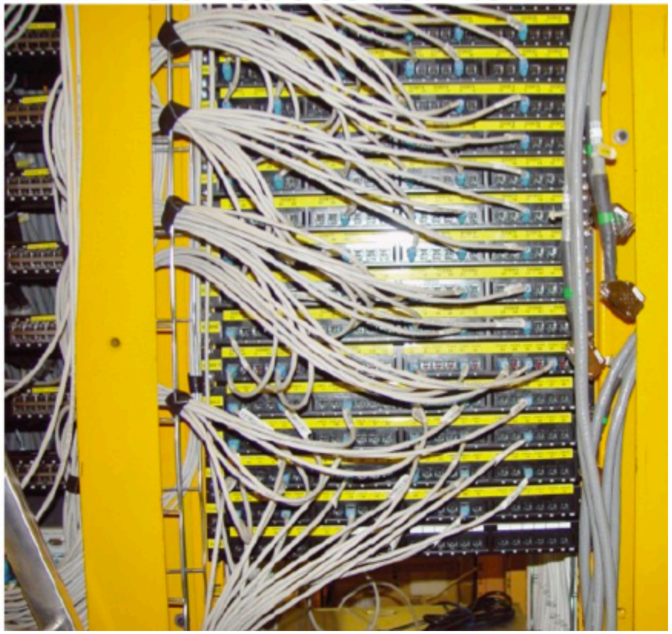
High-level trigger

Final selection in software triggers using large commercial PC farms
- acces to full granularity and offline reconstruction-like algorithms
- extremely flexible
- slow (1-100+ ms latency), so use many PCs at the same time

Events are independent, so trivially parallelizable on PC cluster

ATLAS HLT farm:

LHCb readout switch:



HLT processing

5-100 kHz input rate requires fast algorithms

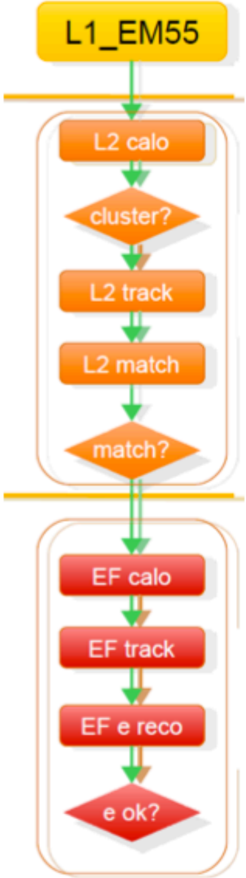
Processing is typically done multiple steps:

Start by confirming L1 results

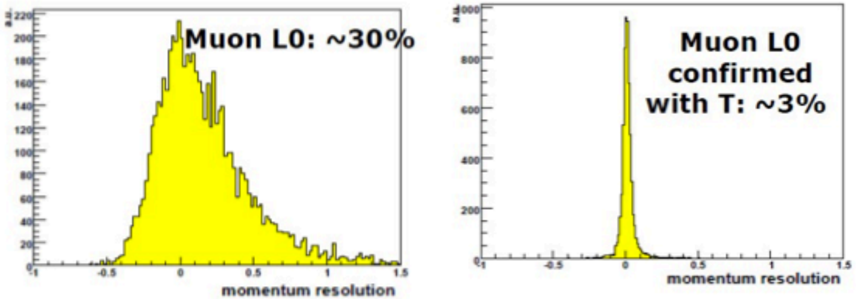
- Only process data in region where L1 found “object”
  - * ATLAS also only reads out detector in region of interest (RoI) at L2 (reduce data traffic)
- Use full granularity of detector readout
- Combine with info from other detectors (trackers)
- reject events as soon as algorithm step fails

Fullscale event reconstruction to find specific B-decay, all jets, etc. is done at lower rates

ATLAS electron trigger



LHCb muon trigger

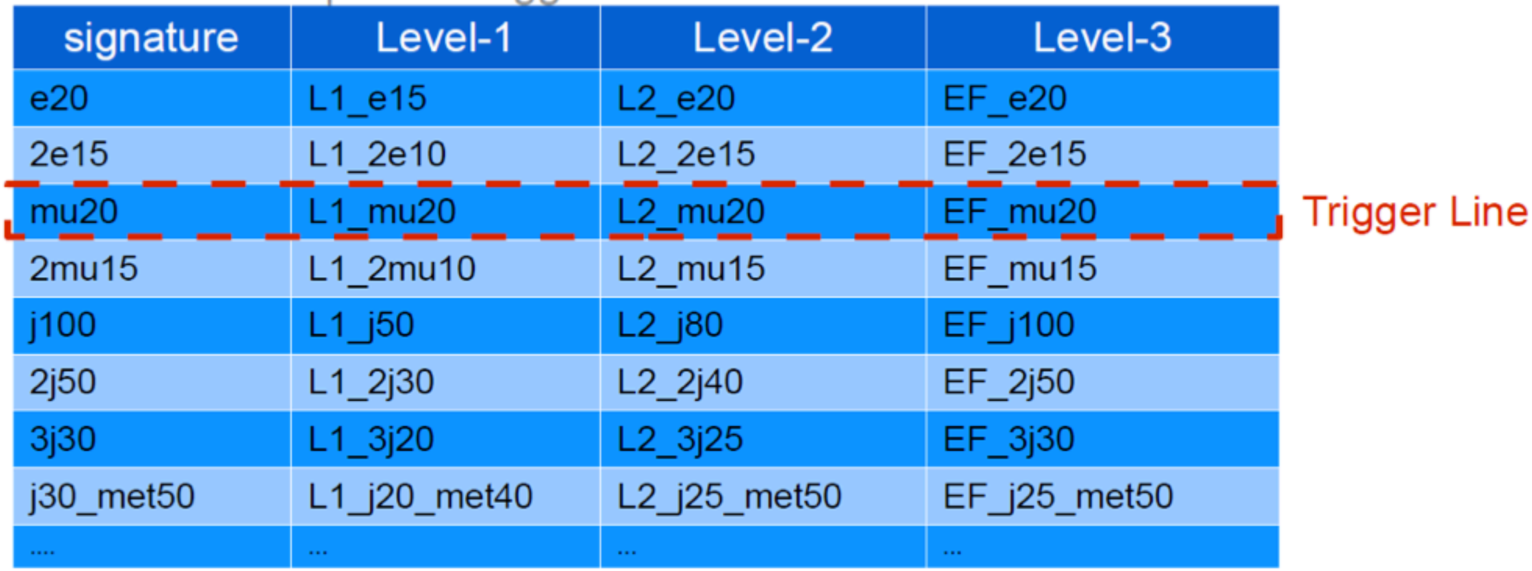


Trigger menus

Each physics signature will one or more “trigger lines” to select it

Collection of trigger lines is “trigger menu” which defines all of the physics the experiment wants to collect events for

Illustrative example of a trigger menu



signature	Level-1	Level-2	Level-3
e20	L1_e15	L2_e20	EF_e20
2e15	L1_2e10	L2_2e15	EF_2e15
mu20	L1_mu20	L2_mu20	EF_mu20
2mu15	L1_2mu10	L2_mu15	EF_mu15
j100	L1_j50	L2_j80	EF_j100
2j50	L1_2j30	L2_2j40	EF_2j50
3j30	L1_3j20	L2_3j25	EF_3j30
j30_met50	L1_j20_met40	L2_j25_met50	EF_j25_met50
....	...	...	...

Trigger Line

Typical to have several hundred trigger lines at hadron collider

Trigger menu varies with luminosity and time

Pre-scaling

Not all triggers need to be recorded at full rate

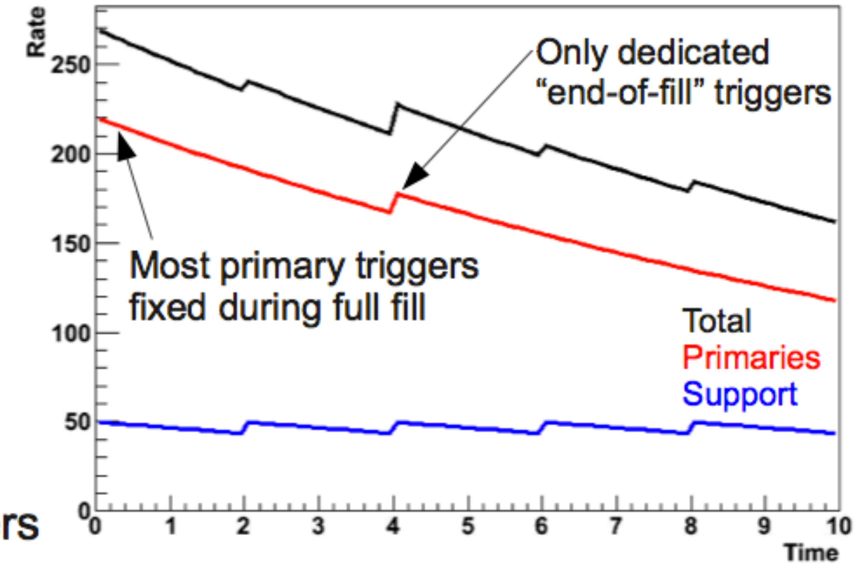
- often want to just sample low E_T events
- some triggers might just be too high rate

Use prescale for trigger lines

Example:

- prescale of 50 for "e10" line
  records 2% of 10 GeV electron triggers
- prescale of 1 for "e20" line
  Records all 20 GeV electron triggers

Simulated rate evolution in an LHC fill



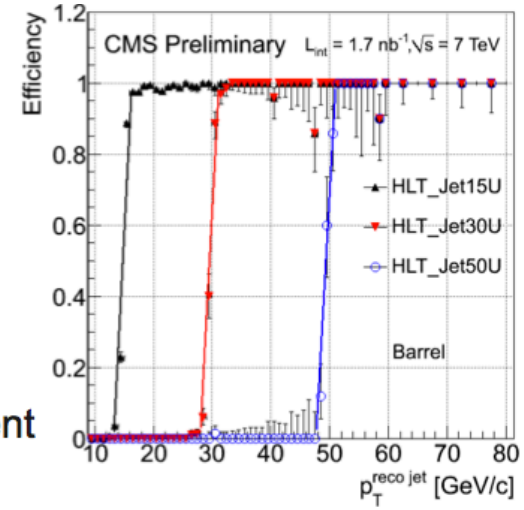
Prescales should be done early to avoid unnecessary rates
Normally implemented in global trigger logic

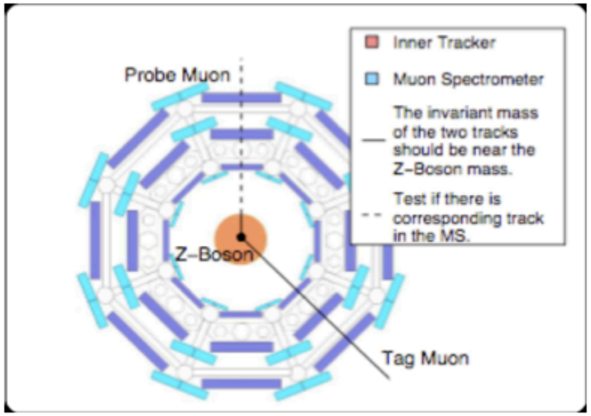
Trigger efficiencies

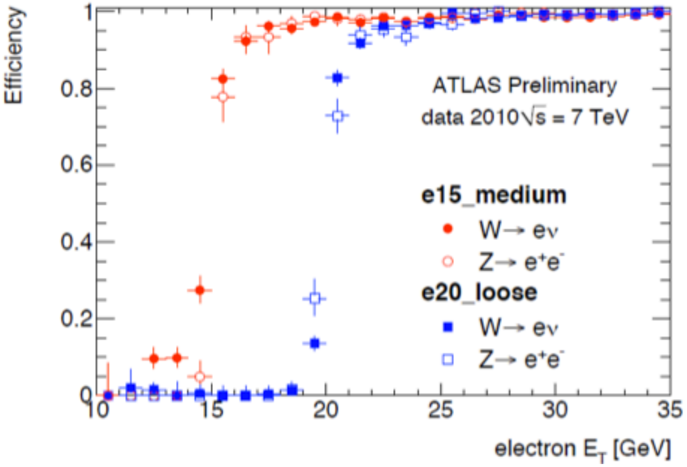
Does the trigger record all signal events?

Different ways to measure trigger efficiency

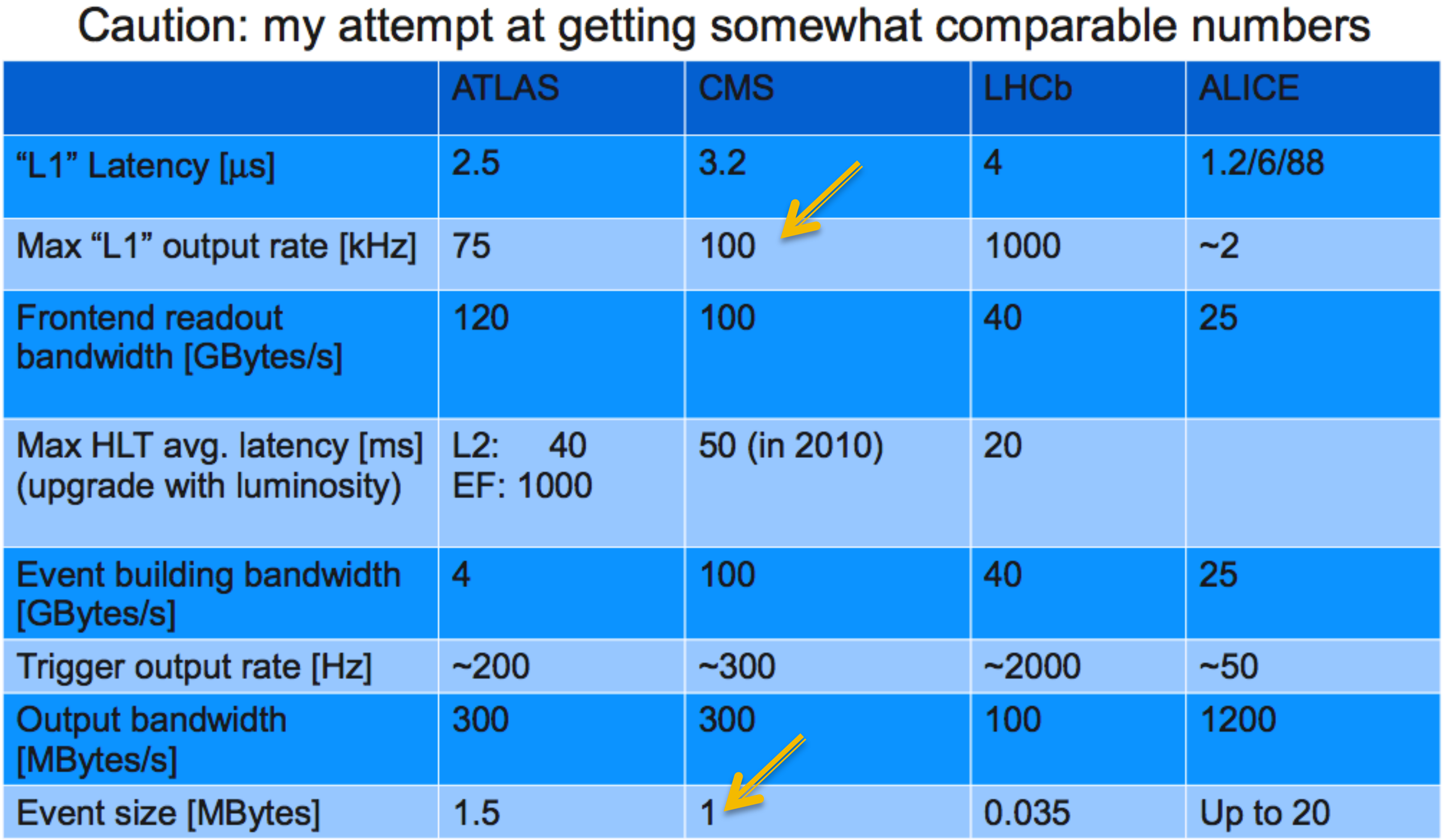
- "tag-and-probe"
  Trigger on 1 particle from resonance and measure how often 2nd particle is triggered
- "Boot-strap"
  Use looser (prescaled) trigger line
- "Orthogonal" trigger
  Trigger on one physics signature, measure a different
- Simulation







2011 LHC Trigger/DAQ comparison



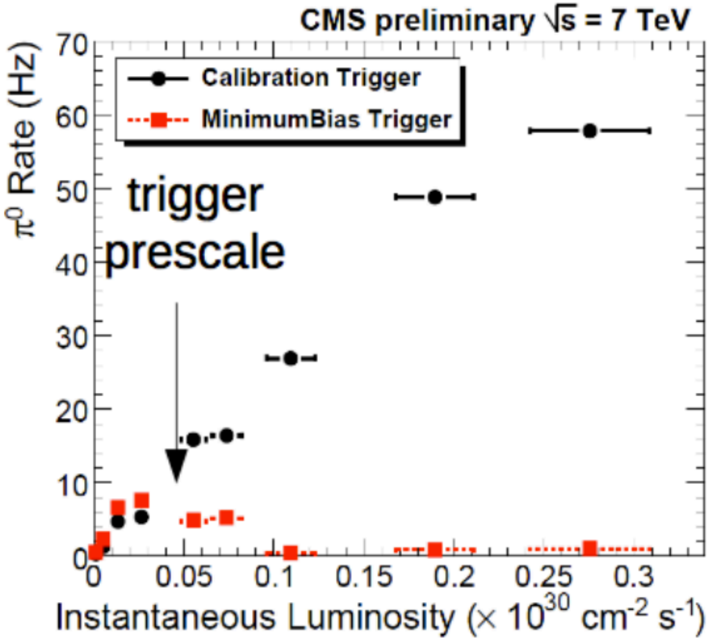
Caution: my attempt at getting somewhat comparable numbers

	ATLAS	CMS	LHCb	ALICE
"L1" Latency [µs]	2.5	3.2	4	1.2/6/88
Max "L1" output rate [kHz]	75	100	1000	~2
Frontend readout bandwidth [GBytes/s]	120	100	40	25
Max HLT avg. latency [ms] (upgrade with luminosity)	L2: 40 EF: 1000	50 (in 2010)	20	
Event building bandwidth [GBytes/s]	4	100	40	25
Trigger output rate [Hz]	~200	~300	~2000	~50
Output bandwidth [MBytes/s]	300	300	100	1200
Event size [MBytes]	1.5	1	0.035	Up to 20

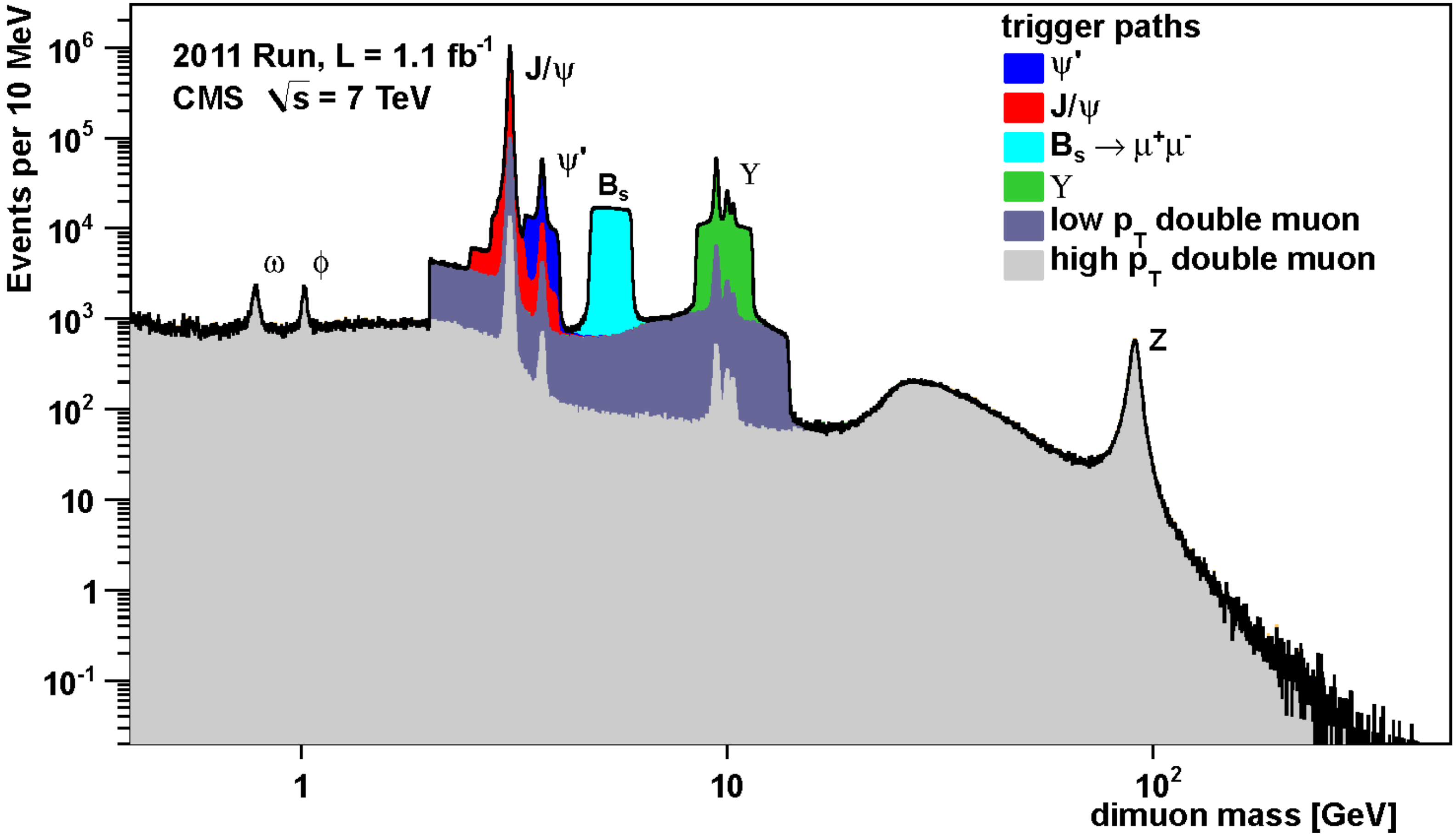
Rules are meant to be bent

- 300 Hz applies to the full event (A) stream.
- If you do not need the full event, **drop content, gain rate**.

- Used mostly in alignment and calibration:
  - Keep only tracks.
  - Keep only pion and eta diphotons clusters. ➔
  - Keep only MET and electron data (W).



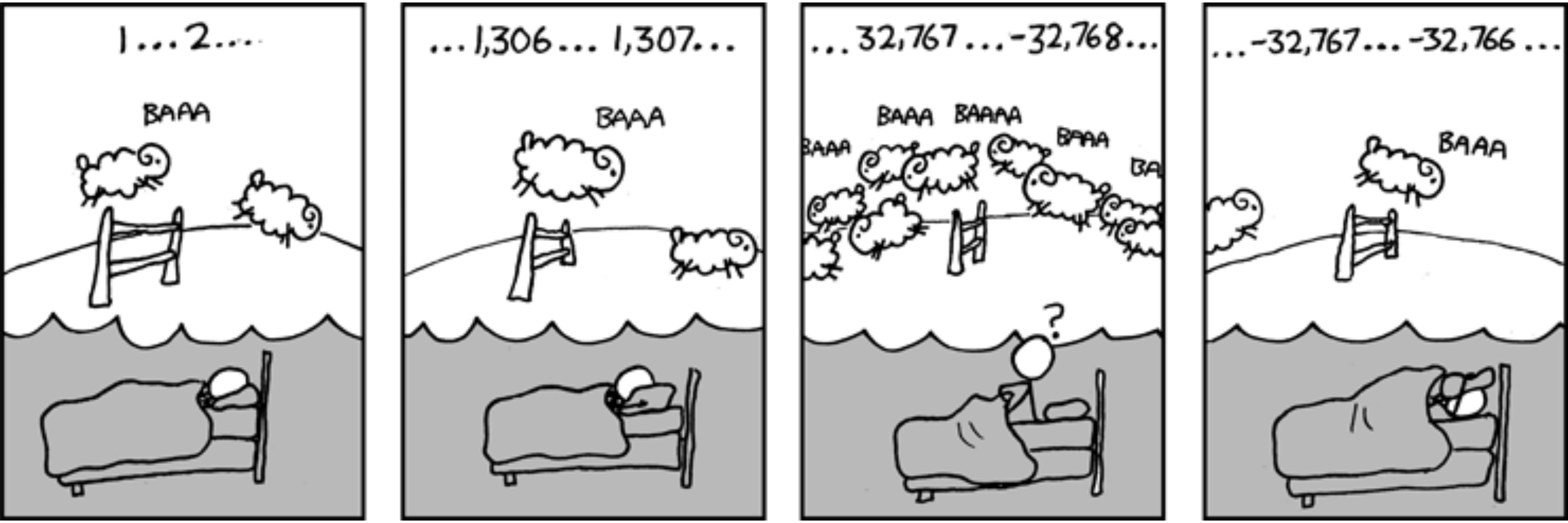
The power of flexibility



Tracking and trigger

- Tracking systems are crucial.
  - CMS is particularly good at it.
    - Particle flow makes extensive use of tracking to disentangle the calorimeter deposit.

- Trigger is where analysis cuts start.
  - CMS has a simple two-level system.
  - CMS has a flexible system that has shown its trumps in 2011.


1...2...
BAAA
...1,306... 1,307...
BAAA
...32,767...-32,768...
BAAA
BAAAA
BAAA
BAAA
BA
?
...-32,767...-32,766...
BAAA