Upgrade project and plans for the ATLAS trigger

Francesca Pastore

(Royal Holloway Un. of London)

On behalf of the ATLAS Collaboration

Frontier Detectors for Frontier Physics

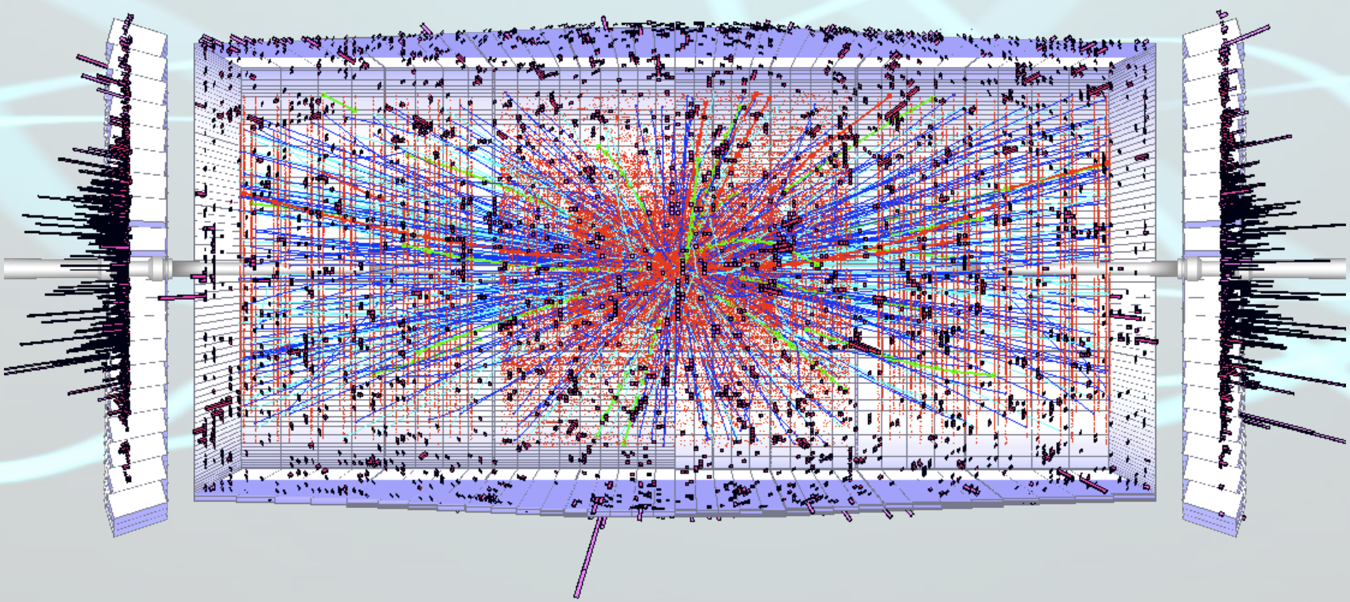
12th Pisa meeting on advanced detectors

La Biodola • Isola d'Elba • Italy

May 20 - 26, 2012

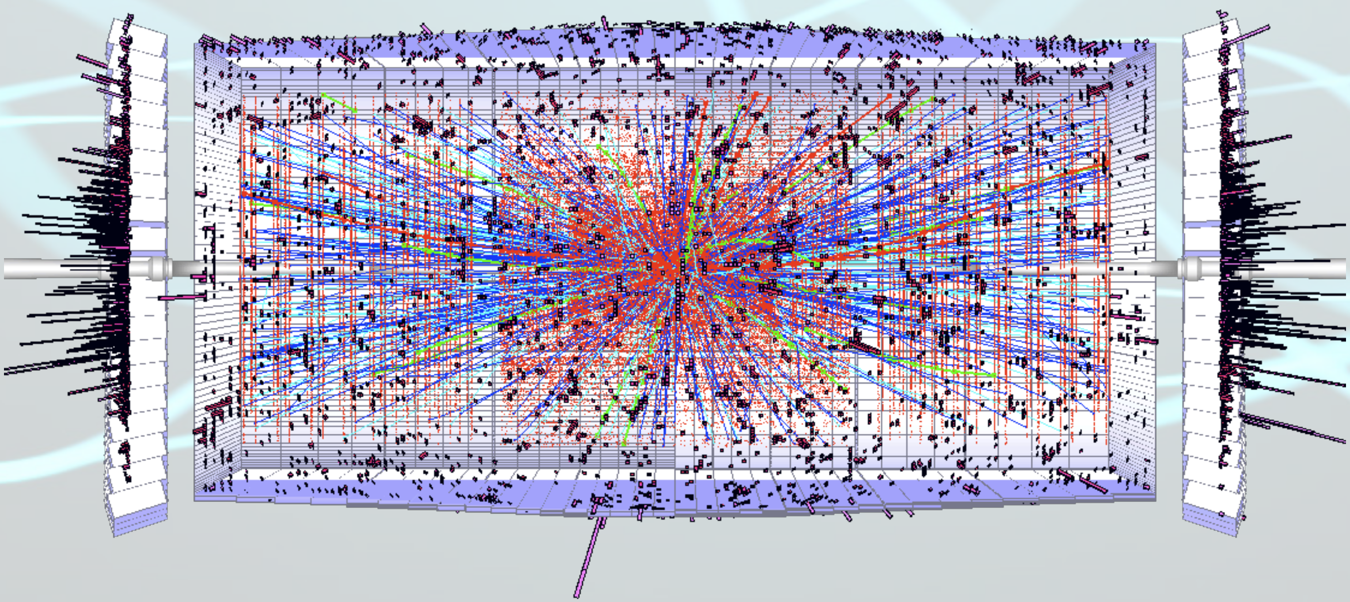
Outline

- LHC upgrade plans and physics motivations
- ATLAS experiment and its trigger system
- Current performance and extrapolations to High Luminosity (HL) scenarios
- Trigger upgrade plans (and investigations)



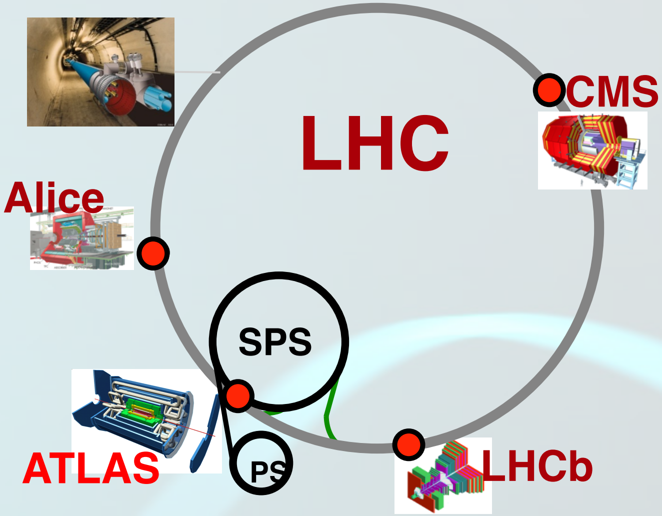
Outline

- LHC upgrade plans and physics motivations
- ATLAS experiment and its trigger system
- Current performance and extrapolations to High Luminosity (HL) scenarios
- Trigger upgrade plans (and investigations)



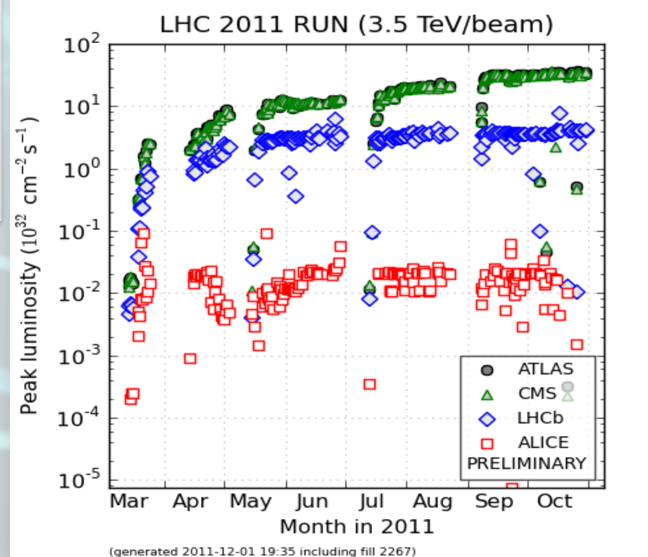
The Large Hadron Collider and HL-LHC

- A discovery machine with steady increase of luminosity
- Spectacular numbers in 2011:
  - Bunches of $O(10^{11})$ particles
  - Superconducting magnets cooled to 1.9 K with 140 tons of liquid He (magnetic field ~ 8.4 T)
  - Energy of one beam = 362 MJ (300 x Tevatron)



colliders		Energy (TeV)	BC time (ns)	L1 input rate (MHz)	Max peak luminosity ($cm^{-2}\ s^{-1}$)	Integrated luminosity per exp (/fb)
TeVatron	ppbar	2	396	2.5	4×10^{32}	11
2011 LHC	pp	7	50	40	3×10^{33}	5
2012 LHC	pp	8	50	40	7×10^{33}	20
Nominal LHC	pp	14	25	40	10^{34}	300

LHC peak luminosity increased almost linearly over the year – close to the limit



Every 3 years, a 1-year long (at least) shutdown with major component upgrades to increase luminosity for:

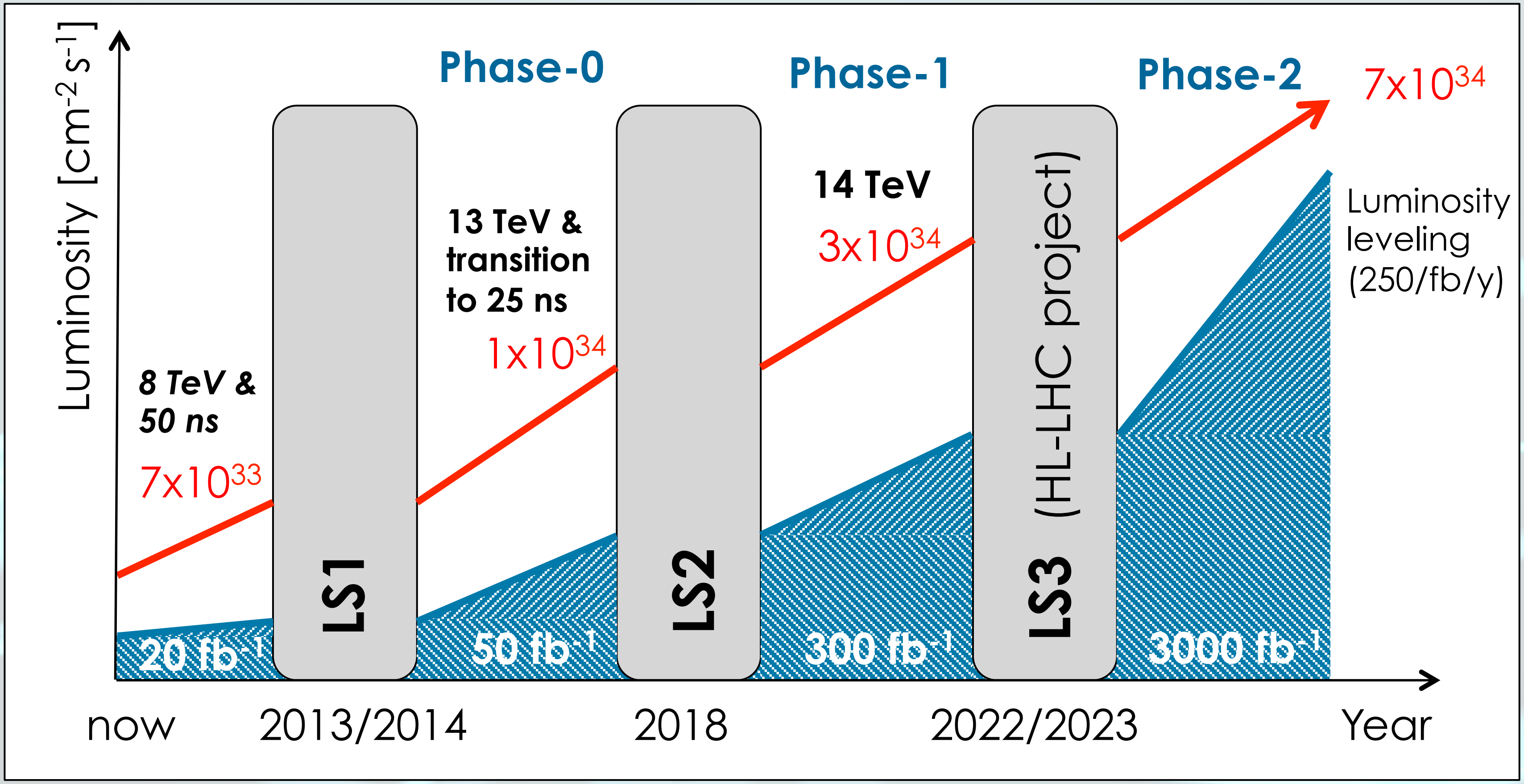
① Extending physics potential!

② After few years, statistical error hardly decreases

③ Radiation damage limits IR quadrupoles (~700 fb^{-1}), reached by ~2016

F.Pastore - PM2012, La Biodola

LHC luminosity forecast



F.Pastore - PM2012, La Biodola

LS1 (phase-0):
To design conditions: consolidation of the superconducting circuits

LS2 (phase-1):
Main upgrades of the injector chain (Linac4) and Collimation system

~2022: Beyond design
New magnet technology for the IR
New bigger quadrupoles → smaller β^*
New RF Crab cavities (?)

(HL)-LHC physics potential

- Increased statistics allows discover/exclude **SM Higgs**
- If Higgs exists:
  - 300 fb^{-1} : observe all H decay modes
  - 3000 fb^{-1} : precision measurements of Higgs properties
    - Mass 0.1%, width and rates < 10%
    - Couplings (WWH, ZZH, ttH) 10-20% → 5-10%

- **With 3000 fb^{-1}, we can increase the mass reach for:**
  - Boson-boson scattering
  - SUSY (exclude or extend the kinematic range)
  - New gauge bosons: Z', W'
  - Compositeness
  - Extra-dimensions
  - SM physics (TGC)

CERN-TH/2002-078
hep-ph/0204087
April 1, 2002

PHYSICS POTENTIAL AND EXPERIMENTAL CHALLENGES OF THE LHC LUMINOSITY UPGRADE

Conveners: F. Gianotti [1], M.L. Mangano [2], T. Virdee [1,3]
Contributors: S. Abdullin [4], G. Azuelos [5], A. Ball [1], ... [7], P. Bloch [1], M. Bosman [8], L. Casagrande [1], D. Cavalli [9], ... De Roeck [1], N. Ellis [1], P. Farthouat [1], D. Fournier [11], ... M. Huhtinen [1], K. Jakobs [13], C. Joram [1], ... M. Moretti[17], S. Moretti [2,18], T. Niinikoski [1], ... Palestini [1], C.G. Papadopoulos[21], F. Piccinini[2,‡], R. Pittau[22], ... P. Sharp [1], S.R. Slabospitsky[16], W.H. Smith [10], S. Stapnes [25], ... Z. Usubov[27,28], L. Vacavant [12], J. van der Bij[29], A. Watson [30], M. Wielers [31]

Studies started in 2002

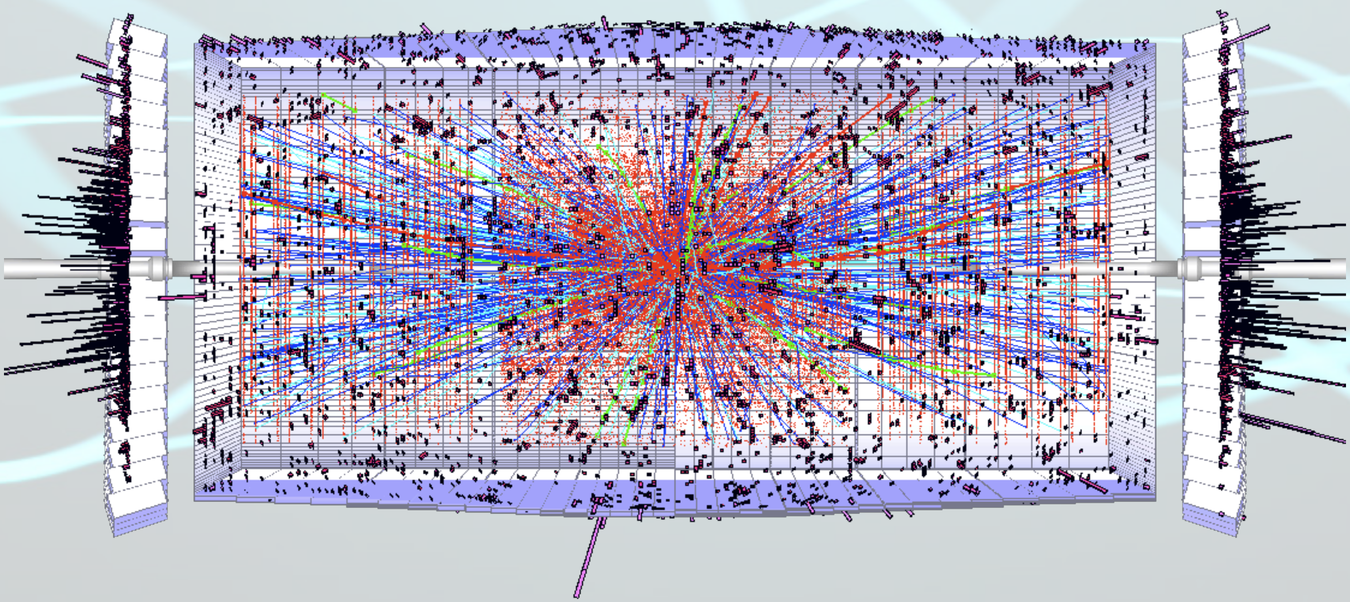
- **A lot of results are at the limit of what the HL-LHC can offer**
  - E.g. need both ATLAS and CMS 3000 fb^{-1} to achieve 5σ
- **Physics selection must be flexible and robust!**

Picture is not clear today, but many of the scenarios involve objects at (near) the electroweak scale (leptons ~20 GeV, b/tau tagging and Missing Et)

low thresholds are needed to avoid reduced acceptance and poor efficiencies

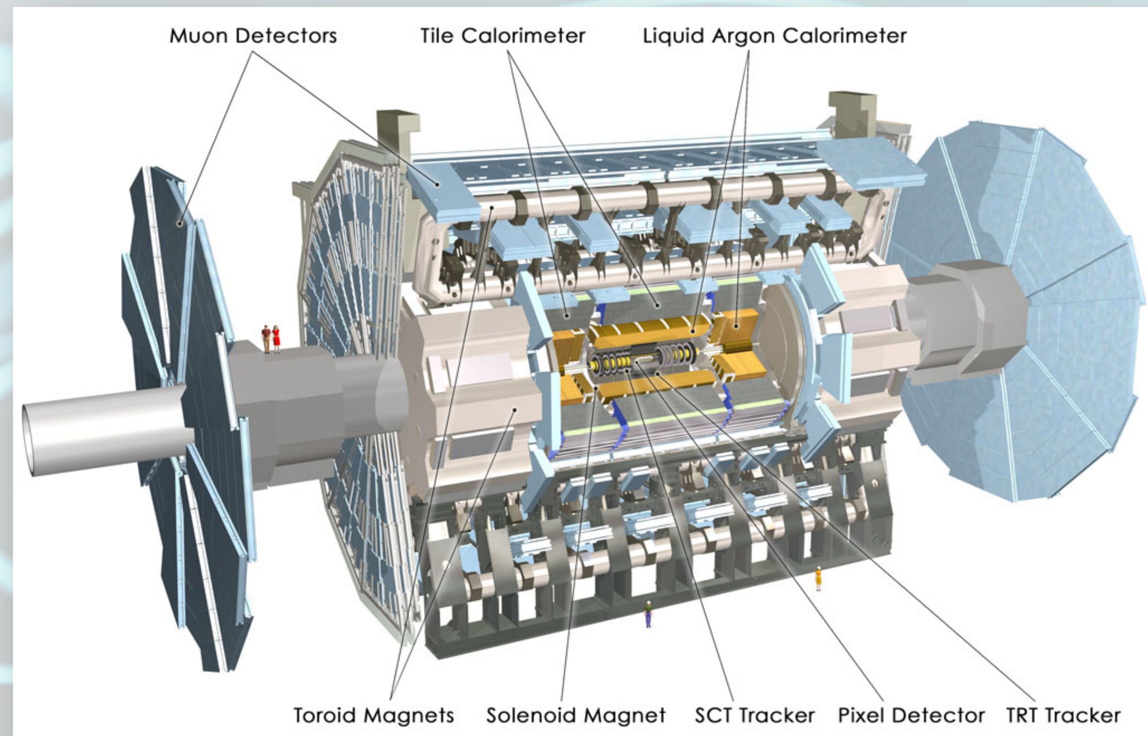
Outline

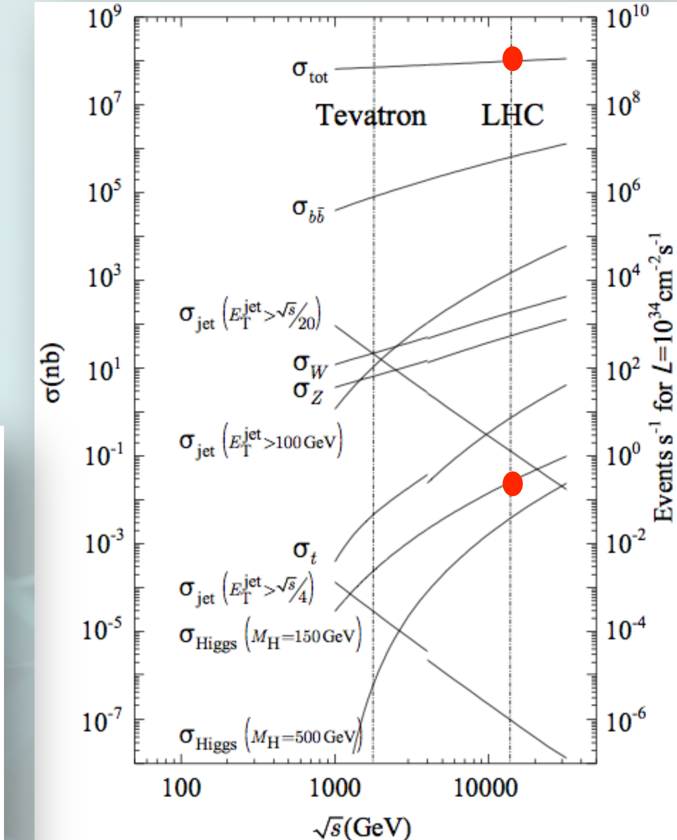
- LHC upgrade plans and physics motivations
- ATLAS experiment and its trigger system
- Current performance and extrapolations to High Luminosity (HL) scenarios
- Trigger upgrade plans (and investigations)



The ATLAS detector and its selection

- Designed to cope the LHC environment
  - σ_{pp} inelastic ~ 100 mb
  - Collision Rate = ~10^9 Hz
  - ~ 22 interactions / Bunch Crossing
- Stringent requirements for ATLAS sub-detectors
  - Fast electronics to resolve individual bunch crossings
  - High granularity (many channels) to resolve pile-up
  - Radiation resistant





$$\frac{\sigma_{tot}}{\sigma_{H(120\ \mathrm{GeV})}} \approx \frac{100\ mb}{1\ pb} \approx 10^{11}$$

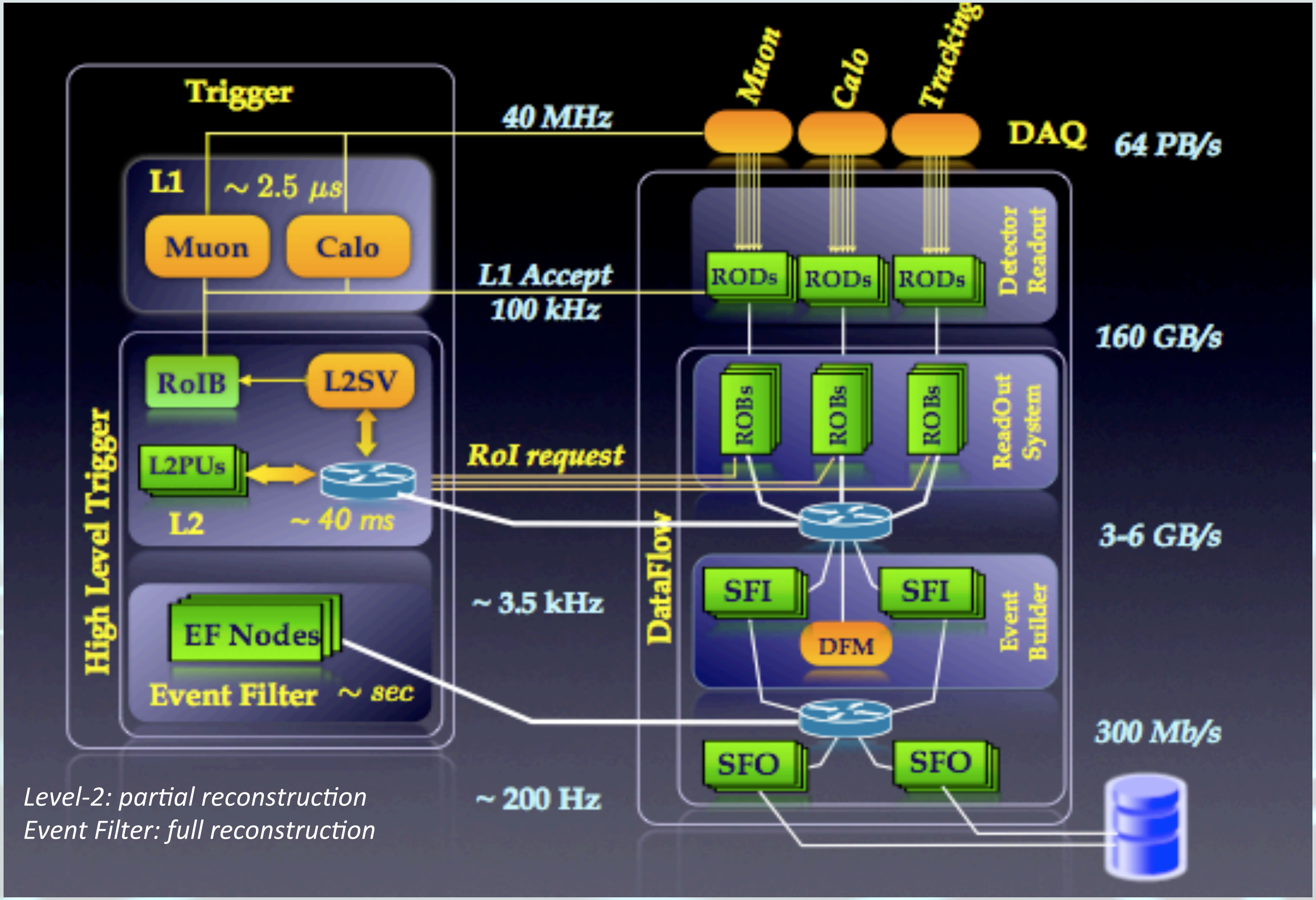
F.Pastore - PM2012, La Biodola

The ATLAS trigger/DAQ system

L1: Reduced-granularity information from Muon detectors and calorimeters

L2: selection based on regional readout pointed by the L1 (Region-of-Interest mechanism)

Menu: more than 600 chains with muon, electron, photon, tau, jet, and B-meson candidates, as well as global event signatures (MET)



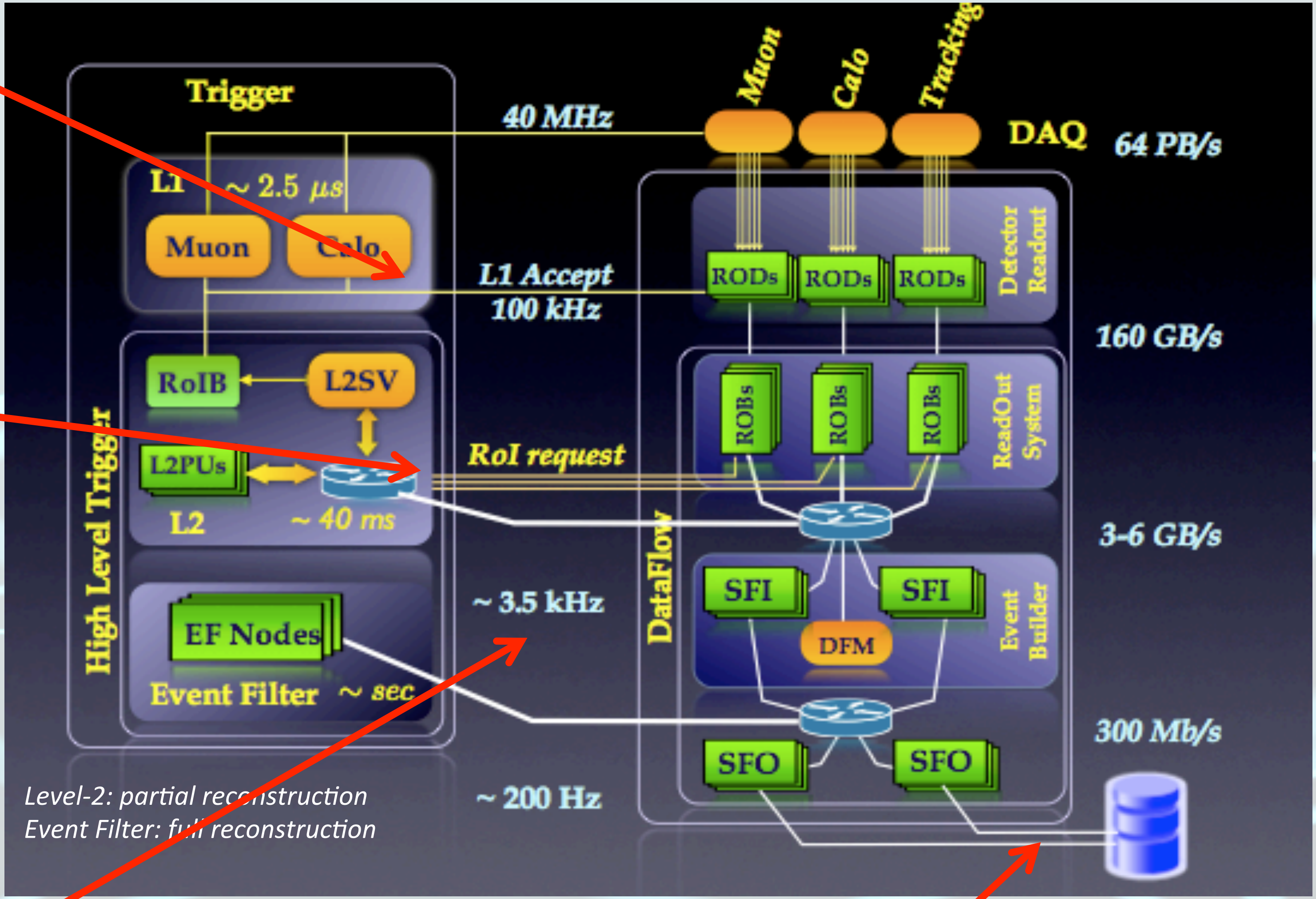
Design values

F.Pastore - PM2012, La Biodola

Today ATLAS trigger/DAQ operating values

L1 rate < 65-70 kHz
limited by detector readout

L2 input rate < 10-30 kHz
limited by the Read-Out System (ROS)



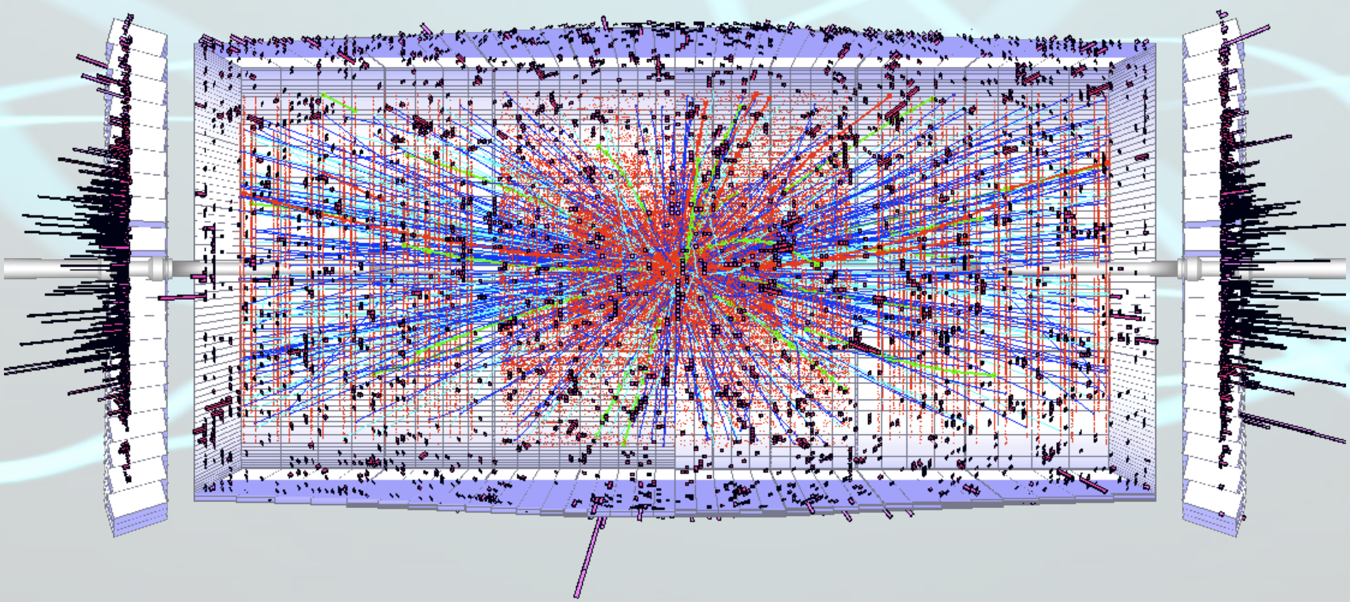
L2 output rate < 5-6 kHz
mainly limited by EF CPU and ROS readout limit
→HLT farm expanded to 75% of design capacity to handle higher pileup in 2011

Average output is 400 Hz
Limited by offline storage and computing resources at Tier-0

F.Pastore - PM2012, La Biodola

Outline

- LHC upgrade plans and physics motivations
- ATLAS experiment and its trigger system
- Current performance and extrapolations to High Luminosity (HL) scenarios
- Trigger upgrade plans (and investigations)



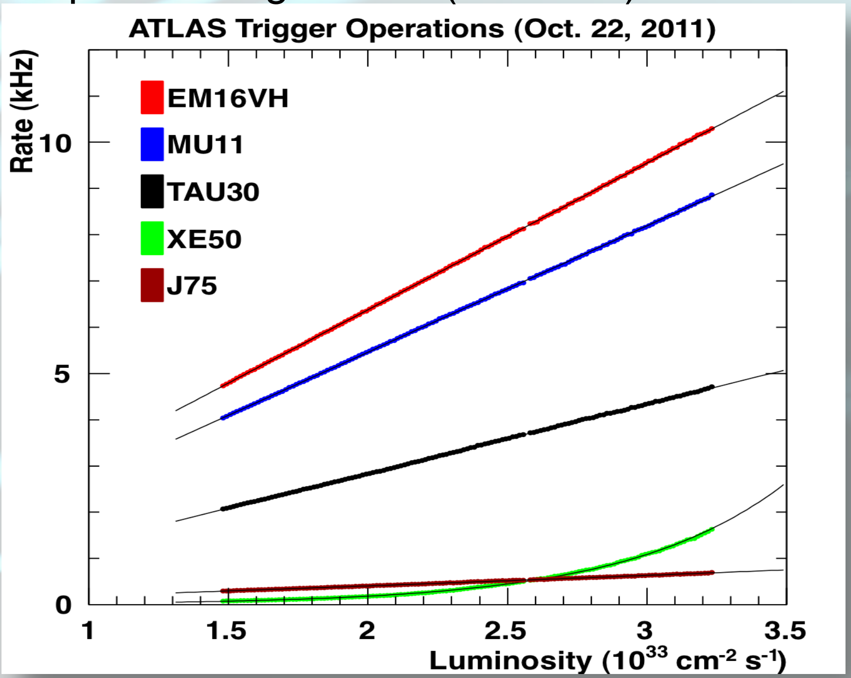
Trigger/DAQ predictions

Work has been done during the first years of data taking to:

1. Gain experience as guidance for upgrade decisions
2. Quantify expected performance for HL-LHC
   - Simulations, cross-check with data, limitations
3. Assess feasibility of increasing rejection power
   - With/without modest changes in the current TDAQ

2011 Level-1 trigger rates

Little predicting power for pile-up dependent signatures (like MET)



Example of extrapolation to high L

2011: Lmax = 3.3/nb/s (13 PU)

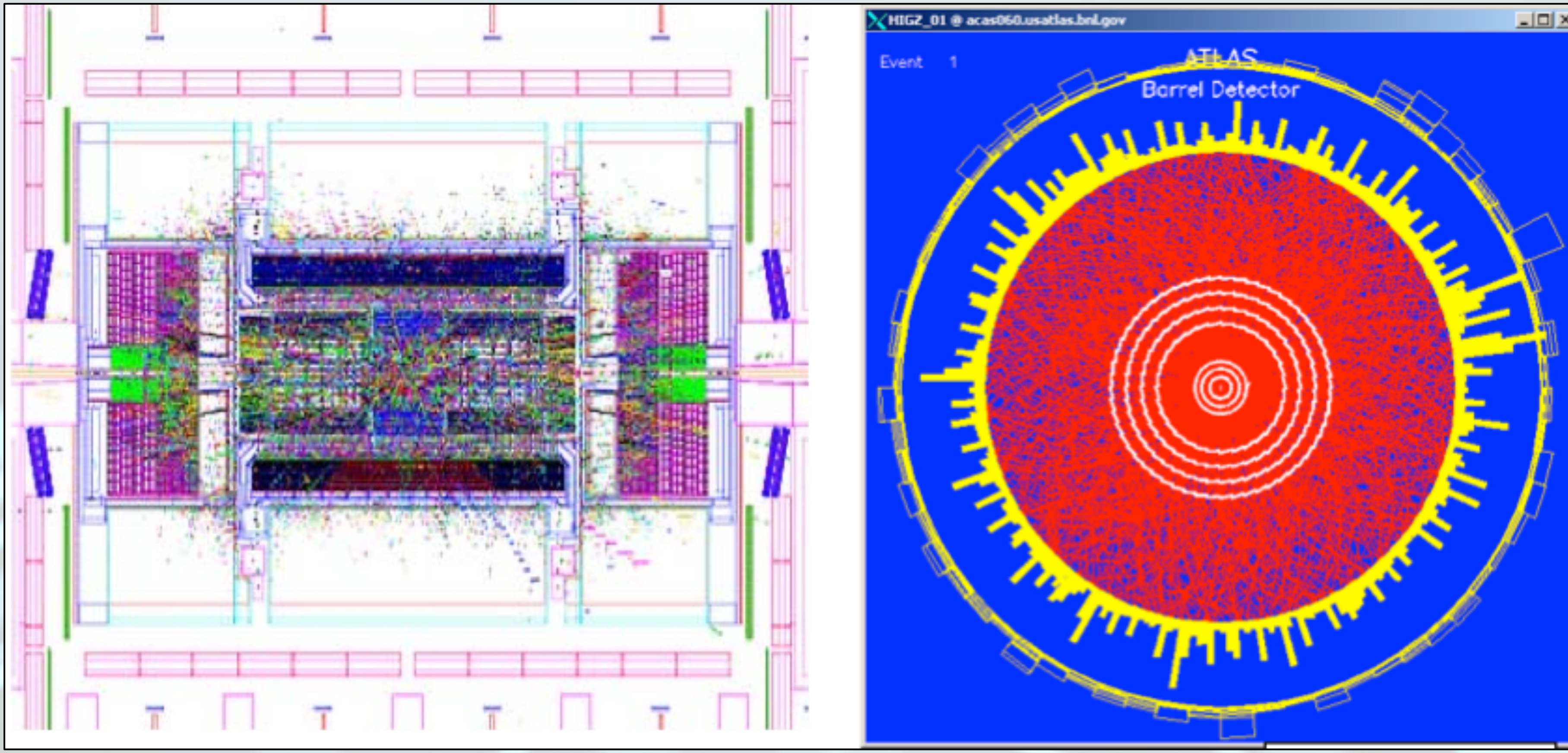
2012: Lmax = ~7/nb/s (30 PU) expected

Changes in the **2012 menu** to face expected increased trigger rates (with 20% safety margin)

- Increased thresholds on single leptons
- Added isolation criteria
- Tightened criteria to keep thresholds below 25 GeV
- Optimized selections on jets and MET
- Added more combined selections

For details on specific trigger performance, see related posters at this conference

ATLAS picture at ~$10^{35}cm^{-2}s^{-1}$



- 230 minimum bias collisions per 25 ns bunch crossing
- ~ 10 000 particles in $| \eta | \leq 3.2$
- Mostly low p_T tracks

Expected trigger rates at HL-LHC

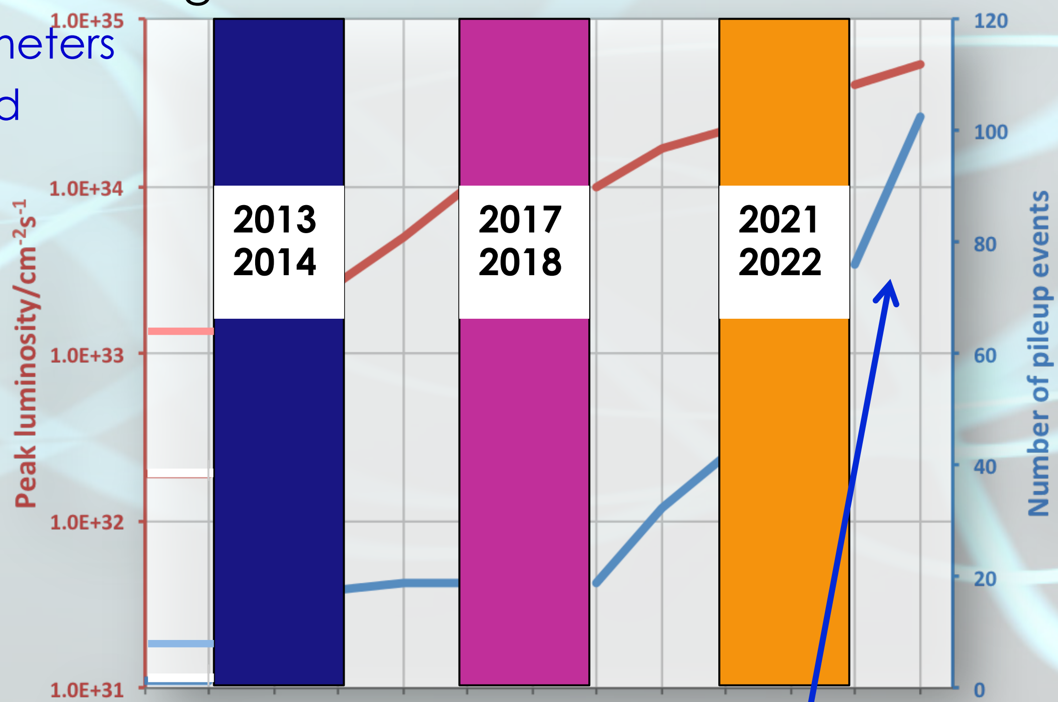
- Trivial increase due to the corresponding increase in luminosity
- Main source of background
  - Jets mimicking electrons
  - High radiation in the forward regions

Including safety factors
- 30% for extrapolations to $3x10^{34}/cm^2/s$
- Additional factor 2 for irradiation tolerance

- Higher occupancies in the detectors bring:
  1: Reduced rejection power of the algorithms
  - Worse resolution in calorimeters
  - Less effective isolation and pattern recognition

  2: Larger event size
  - Reduced max L1 rate for fixed bandwidth

  3: Increased fake rate
  - Increased double-object trigger rates

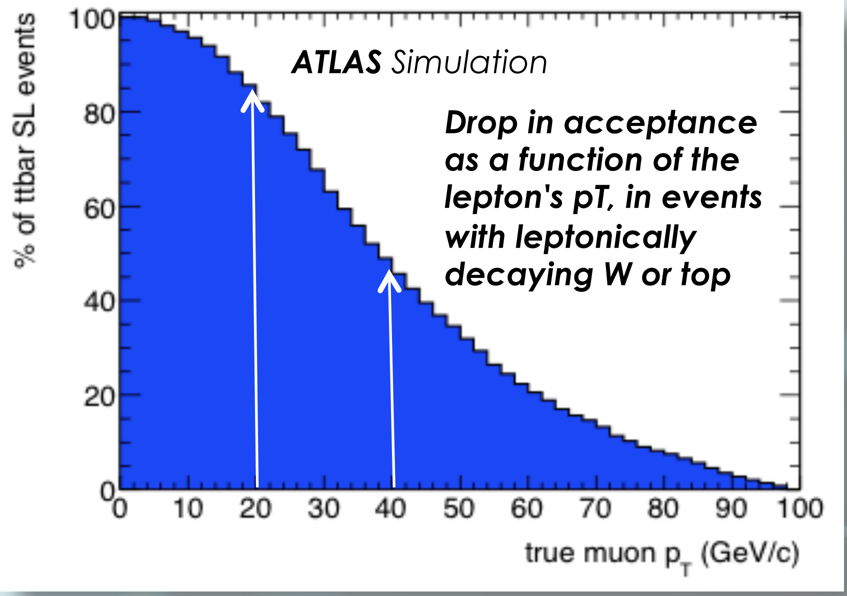


Number of pile-up events

F.Pastore - PM2012, La Biodola

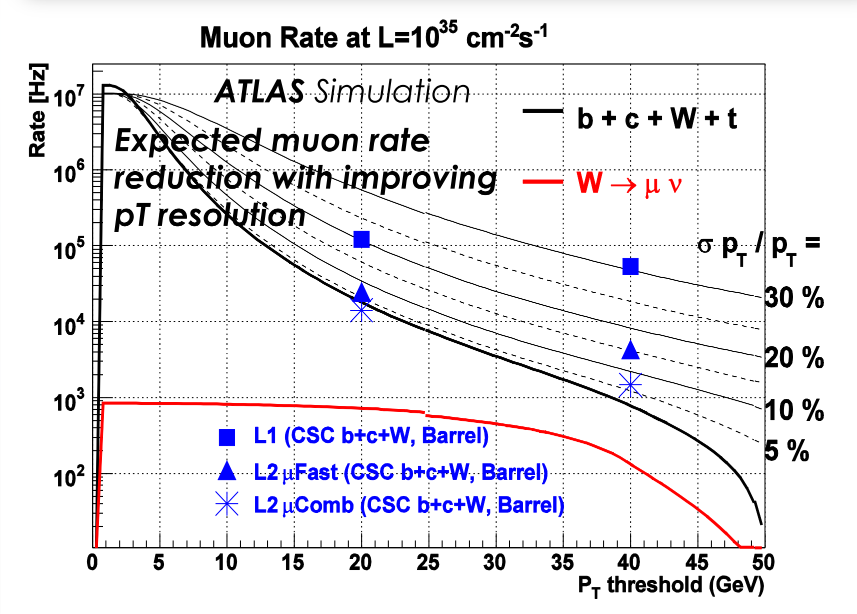
Requirements for a trigger at HL-LHC

- Maintain adequate trigger selections with:
  - **Inclusive single leptons** with thresholds similar to LHC
  - (very) high-pt objects
  - Di-lepton, exclusive / multi-object triggers
- → maintain current sharing of bandwidth
  - 60% taken by high p_T leptons
  - **20 kHz each for L1 muons and electrons**
- A simple increase of thresholds can reduce signal efficiency drastically



Need for more sophisticated trigger criteria

- Level-1 trigger
  - Move software algorithms into electronics
  - Require better resolution →
  - Add inner tracker information
- High level trigger
  - More complex reconstruction



F.Pastore - PM2012, La Biodola

But reconstruction complexity/timing naively scale with the number of tracks....

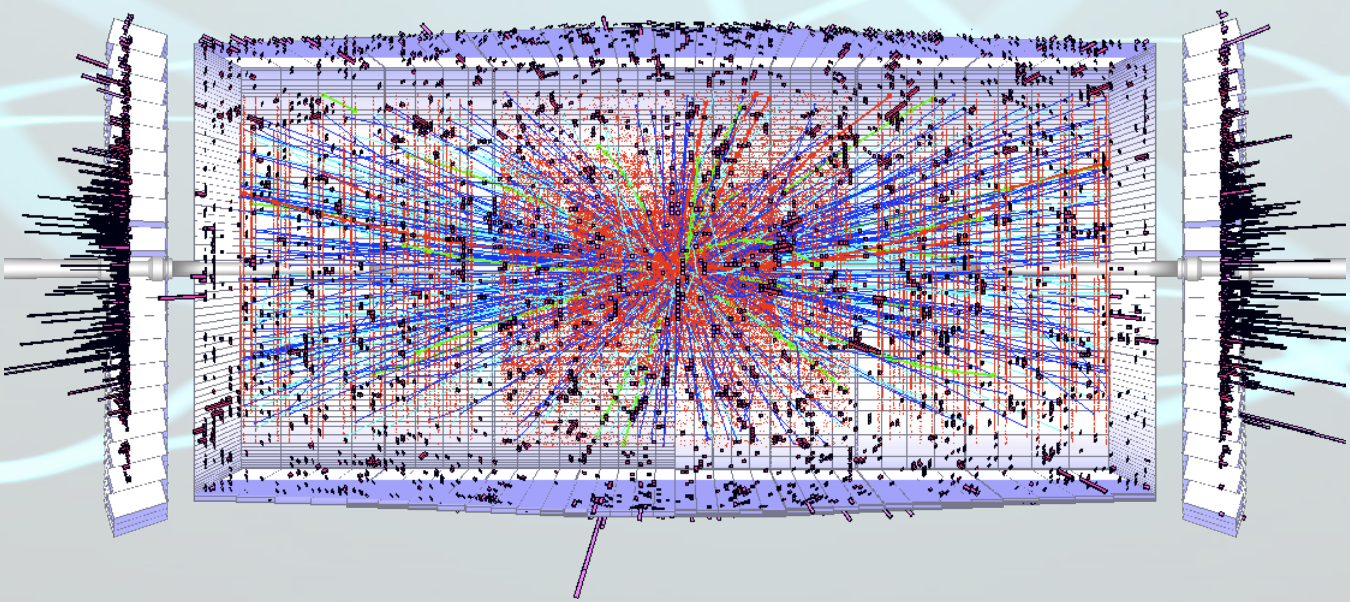
At any level, it may require

- longer timings (latencies)
  - At L1 means change the Front End Electronics
- And higher data throughputs
  - Increased network and offline/trigger CPU needs

The Upgrades are mainly devoted to increase robustness of L1 systems (HLTs are software based → more flexible)

Outline

- LHC upgrade plans and physics motivations
- ATLAS experiment and its trigger system
- Current performance and extrapolations to High Luminosity (HL) scenarios
- Trigger upgrade plans (and investigations)

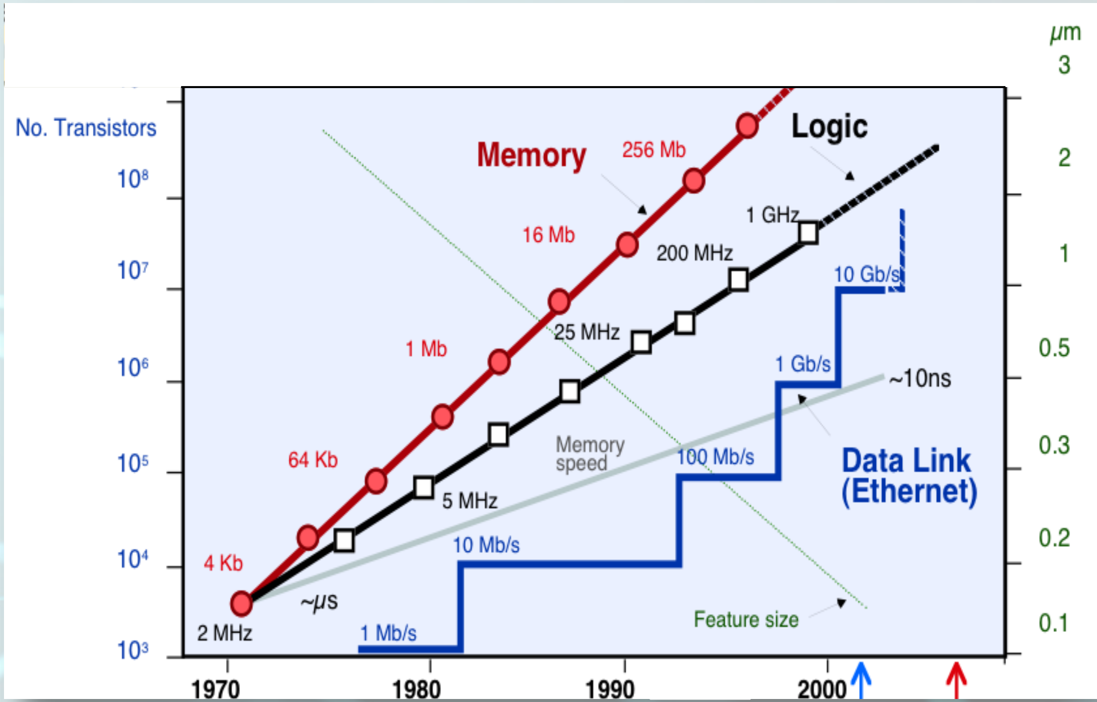


Readout/trigger electronics at HL-LHC

Help from technology to reach increased bandwidth, timing, maintenance and flexibility

We need:

- Parallelism (processing, multi-cores, GPUs)
- Dramatic increase in computing power & I/O
- Chips with increasing densities and reduced size
- Radiation resistant electronics



F.Pastore - PM2012, La Biodola

We can buy:

- Fast FPGAs
  - Modern FPGAs with huge processing & I/O capabilities
- Fast connections
  - Optical links up to 10 GBit
  - New network switches technologies
- New high precision clock @CERN
- Larger (and cheap) buffers
  - Track finding with CAM/LUT
  - Extend L1 Latency on detector FEE
- Fast Bus infrastructure - μTCA
  - Under study

Main ATLAS sub-detector upgrades

Due to aging and high occupancy…

2013

- **Phase-0**
  - Change in the Interaction Point region: New Aluminum beam pipes
    - To prevent activation problems and reduce muon background
  - New insertable pixel b-layer (IBL) (see related talk at this conference)

2018

- **Phase-1**
  - Replacement of the muon chambers in the inner Forward region
    - To face expected cavern background and reinforce **L1 trigger rejection**
  - Calorimeter readout upgrade (see related talks at this conference)
    - Higher granularity **to increase L1 rejection**

2022

- **Phase-2 (still to be defined)**
  - Inner trackers replacement
    - Current silicons damaged by radiation dose, TRT limit due to occupancy
  - Calorimeter upgrade (see related talks at this conference)
    - Radiation damage of electronics **and L1 trigger requirements**
    - Loss of efficiency due to space charge effects in the Forward regions
  - Muon spectrometer upgrade (detector/**trigger**)
    - To increase rate capability in highly radiated regions

The Trigger Upgrades need to take all of this into account and sometimes they drive the changes

Phases of the L1 trigger evolution

2013

2018

2022

- **Phase-0 upgrade:** be prepared for $L = 10^{34}/cm^2/s$
  - Allow **L1 topological** criteria / more exclusive selections
- **Phase-1 upgrade**: be prepared for $L = 3 \times 10^{34}/cm^2/s$
  - No major architectural changes to the detector read-out and DAQ planned up to Phase-1. We stay with current design limits:
    - L1 decision latency 2.5 μs + spare ~0.5 μs
    - Average Level-1 Accept rate < 100 kHz: 20 kHz for single leptons
  - Example of expected rates:
    - L1_EM23 isolated ~ 120 kHz
    - L1_MU20 isolated ~ 60 kHz

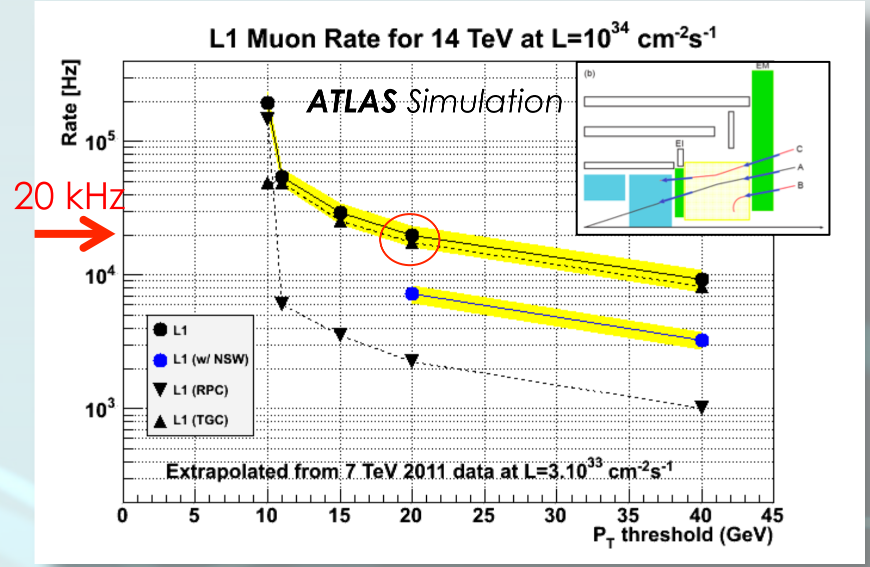
  → **Add more flexibility**
- **Phase-2 upgrade**: be prepared for $L = 7 \times 10^{34}/cm^2/s$
  - Expected rates are over the limit allowed by detector FEE
    - L1_EM30 ~ 500 KHz
    - L1_MU20 ~ 140 kHz

  → **Refine algorithms …allowing changes in the infrastructure**

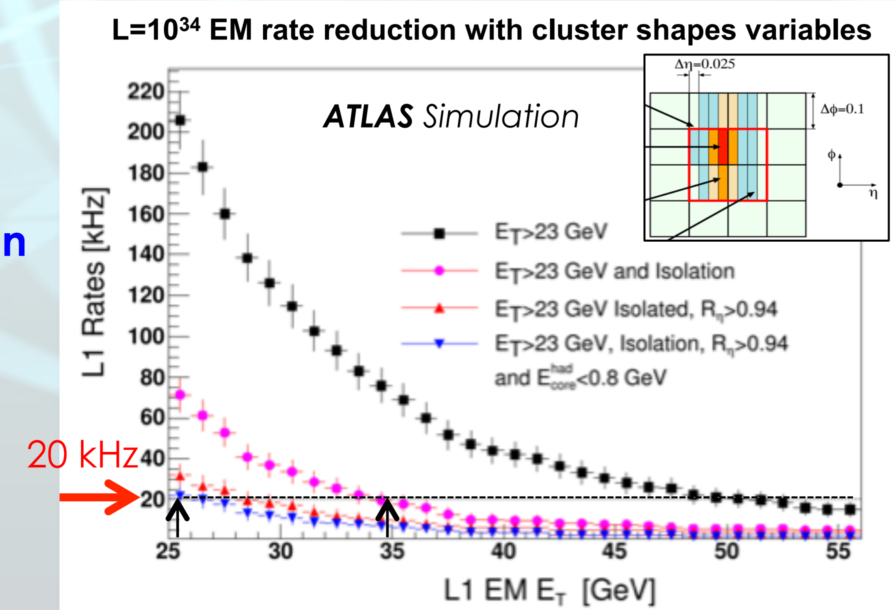
Any component installed in Phase-I must be fully operational also through Phase-II

First-level trigger evolution: Phase-1

- **L1 Muon trigger**: additional coincidence layer in the Forward spectrometer (New Small Wheel)
  - Improve angular (and p_T) resolution: up to **factor 3-10 rate reduction**
  - New detector technology (Micromega + small Thin Gap Chambers) replacing current Cathode Strip Chambers



- **L1 Calorimeter trigger**: increased trigger granularity
  - EM shower shape: **factor 3-5 rejection on low pt jets**
  - EM+H depth information: improve resolution on τ, jets and MET
  - New trigger electronics

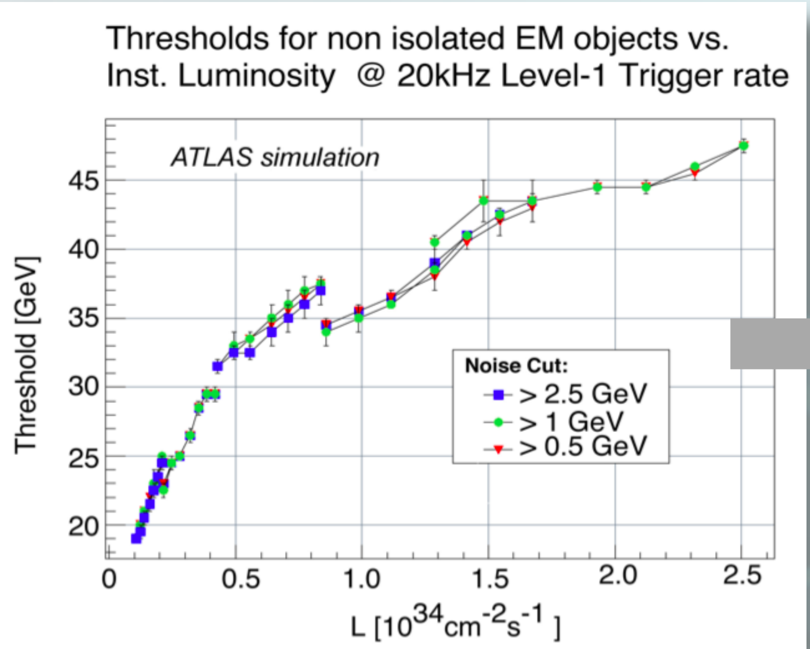


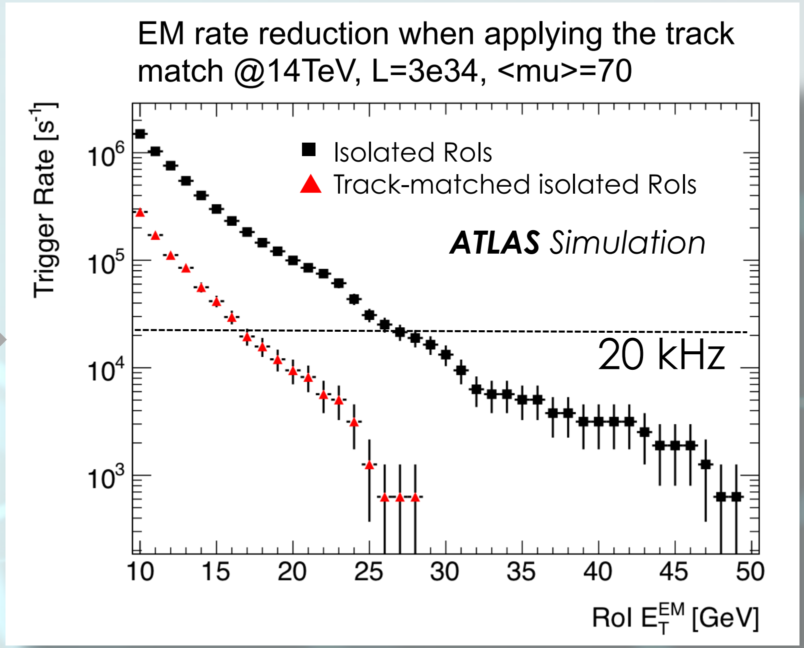
F.Pastore - PM2012, La Biodola

First-level trigger evolution: Phase-2

Expected rates at $7\times10^{34}/cm^2/s$:

- **L1_EM30**: ~500 KHz, reduced by x5 in Phase-1 → **100 kHz**
- **L1_MU20**: ~140 kHz, reduced by x3 in Phase-1 → **50 kHz**





- Two approaches are under investigation (not exclusive)
  1. Higher resolution for muon/calorimeters triggers
  2. More flexibility by adding **tracking information at L1**, which
     - Combines calorimeter/muon with tracks, to improve selection (**EM x10, MU x5**)
     - Provides track isolation and multiplicity for τ , impact parameter for b-tagging

Both approaches require extended L1 latency and high bandwidth...

F.Pastore - PM2012, La Biodola

TDAQ L1 upgrade parameter space

Lots of parameters we can play with. Still many decisions to be made

Increase the L1 decision latency
Increase from 2.5 up to 20 μs seems feasible, but could not be enough (if tracking is included)

More buffers, higher density chips

Increase the maximum L1A rate
Increase to more than 200 kHz could have severe implications: rebuild L1 processors and some FEE electronics

More links, more copper, more cooling

Split into two levels
Level-0: with short latency and high accept rate (up to 500kHz)
Level-1: with longer latency (10-30 μs) to accommodate the inclusion of tracking information

Save buffers

Hardware requirements
Most FEE will be replaced anyway (damaged by radiation)

Dataflow handling
Total event size
Segmentation of events

Physics requirements
Consider all benchmark channels

Design
consequences for the new trackers

Probable major upgrade for Phase-2

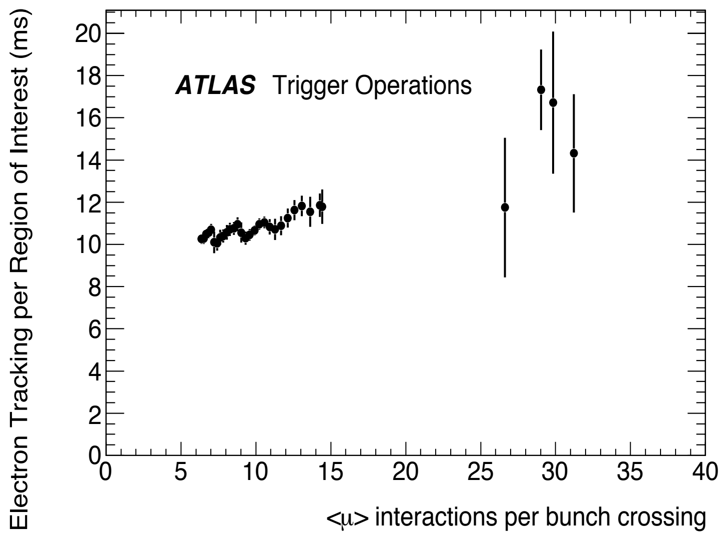
Higher levels trigger evolution

2013

- Mostly based on commodity components (except the ROS system)
- **Technology improvements should allow to handle increased demands**
  1. Hardware preprocessors (like FTK) integrated in the TDAQ
  2. More resources and ensured scalability
  3. Increased complexity: issues for configuration, control and monitoring

2018

Average time to run L2 algorithm for electron tracking versus number of int/BC



Gradual upgrade program

2022

- **Phase-0**:
  - Eliminate bottlenecks (mainly on network traffic) when possible
    - High-speed DAQ ROS card with increased density of readout links
  - Consider to use GPUs for L2 tracking algorithms
  - L2 and EF running on single-node (e.g. dynamic Event Building)
    - Automatic system balance and merge of networks
- **Phase-1**:
  - HW-based Fast Tracking Trigger at L2, **FTK project** (see poster by G.Volpi)
- **Phase-2**:
  - Change of number of physical trigger levels?
    - Intermediate trigger levels / reduction in number, …

Conclusions and timelines

- With HL-LHC and with upgraded detectors we would fully benefit from luminosity increase to have **more convincing conclusions for signals at the limit of the sensitivity**

- The ATLAS trigger upgrade program has many interesting technical challenges to cope with the High Luminosity scenario
  - We are investigating potential benefits of alternative technologies and schemas

- ATLAS **Phase-0 and Phase-1** upgrade already approved with a Letter of Intent (LoI):
  - https://cdsweb.cern.ch/record/1402470/files/LHCC-I-020.pdf
  - Technical Design Reports, within the end of **2013,** start the engineering design

- ATLAS **Phase-2** upgrade: many decisions to be taken in **2012**, before Phase-1 TDRs
  - ATLAS Phase-2 LoI by end of **2012**

Posters on ATLAS trigger at this Conference

- The ATLAS trigger system: performance and evolution
  - Poster by A.Sidoti
- Performance of the ATLAS jet trigger
  - Poster by M. Tamsett
- The ATLAS hadronic tau trigger
  - Poster by A. Tanasijczuk
- A Fast Hardware Tracker for the ATLAS Trigger System
  - Poster by G.Volpi

ATLAS talks and posters at this Conference

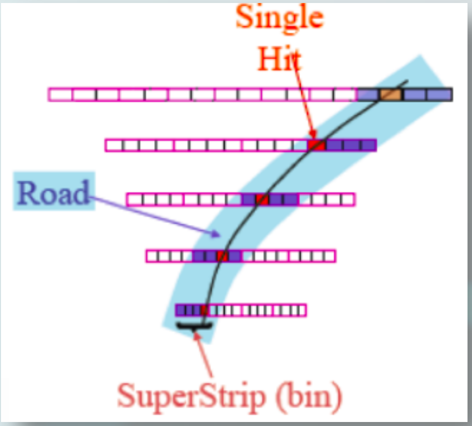
A Christoph Rembser ATLAS detector overview
P Sofia Maria Consonni Tracking and Calorimeter Performance for Tau Reconstruction at ATLAS
P Lucy Anne Kogan Determination of the jet energy scale uncertainty
P Federico Meloni Track and vertex reconstruction in the ATLAS Experiment
P Karoline Elfriede Selbach Neural network based cluster creation in the ATLAS silicon pixel detector
P Mario Sousa Single hadron response measurements in ATLAS
P Mark Cooke Monitoring radiation damage in the ATLAS Pixel Detector
P Andrea Favareto Status of the ATLAS Pixel Detector at the LHC
A Didier Ferrere Overview of the ATLAS Insertable B-Layer (IBL) Project
P Peter Lundgaard Rosendahl ATLAS Silicon Microstrip Tracker Operation and Performance
P Jonathan Stahlman Advanced Alignment of the ATLAS Inner Detector
A Ludovica Aperio Bella Status of the Atlas Liquid Argon Calorimeter and its Performance after two years of LHC operation
A Margret Fincke-Keeler Upgrade plans for ATLAS Forward Calorimetry for the HL-LHC
A Frank Seifert Upgrade plans for the ATLAS Calorimeters
A Steffen Staerz Upgraded readout electronics for the ATLAS LAr Calorimeter at the High Luminosity LHC
P Fernando Carrio Argos Upgrade for the ATLAS Tile Calorimeter readout electronics at the High Luminosity LHC
P Yesenia Hernandez Jimenez The ATLAS Tile Calorimeter performance at LHC
P Evelin Meoni Performances of the signal reconstruction in the ATLAS Hadronic Tile Calorimeter
P Djamal Boumediene Calibration and Monitoring systems for the ATLAS Tile Hadron Calorimeter
P Antonio Sidoti The ATLAS trigger system: performance and evolution
P Matthew Tamsett Performance of the ATLAS jet trigger
P Andres Jorge Tanasijczuk The ATLAS hadronic tau trigger
P Guido Volpi A Fast Hardware Tracker for the ATLAS Trigger System

LHC schedule assumptions

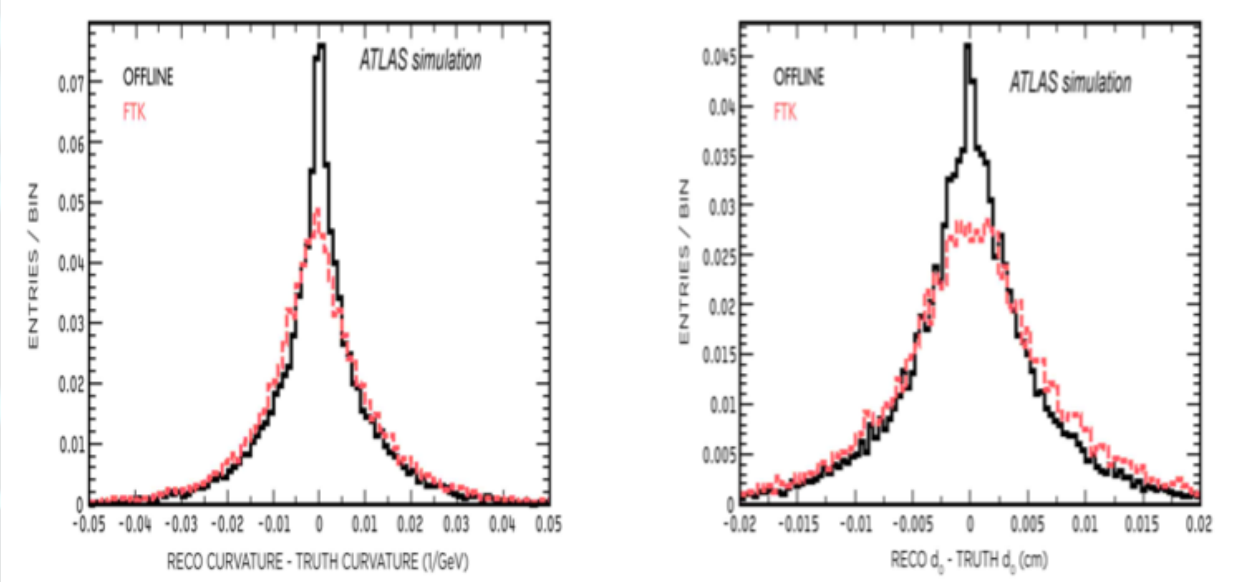
Year		
2009		✧ LHC startup, $\sqrt{s}$ = 900 GeV
2010		
2011		$\sqrt{s}$=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns
2012		~20-25 fb^{-1}
2013	LS1	Go to design energy, nominal luminosity
2014		
2015		
2016		$\sqrt{s}$=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns
2017		~75-100 fb^{-1}
2018	LS2	Injector and LHC Phase-1 upgrade to full design luminosity
2019		
2020		$\sqrt{s}$=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns
2021		~350 fb^{-1}
2022	LS3	HL-LHC Phase-2 upgrade, IR, crab cavities?
2023		
....		
2030?		$\sqrt{s}$=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity levelling
		~3000 fb^{-1}

Fast Tracker (FTK) for Level 2 trigger

- Provides tracking parameters at full L1 rate (100kHz) within O(100 μ s) L2 latency
  - Enhancing the capability for b / τ tagging and lepton isolation
  - Optimizing L2 selection
    - tracks available earlier
  - HW based
    - Track finder with AM chip + high resolution track fit



Pattern recognition



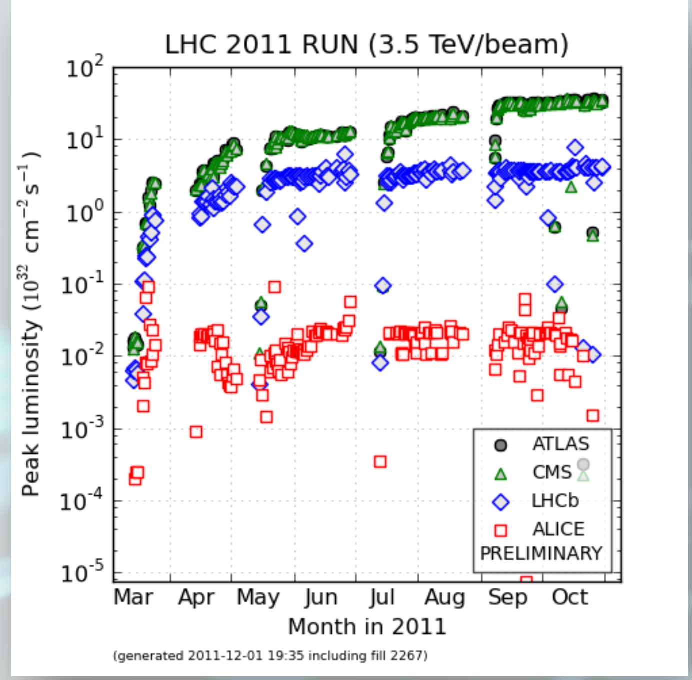
Curvature and impact parameter FTK resolution compared to offline

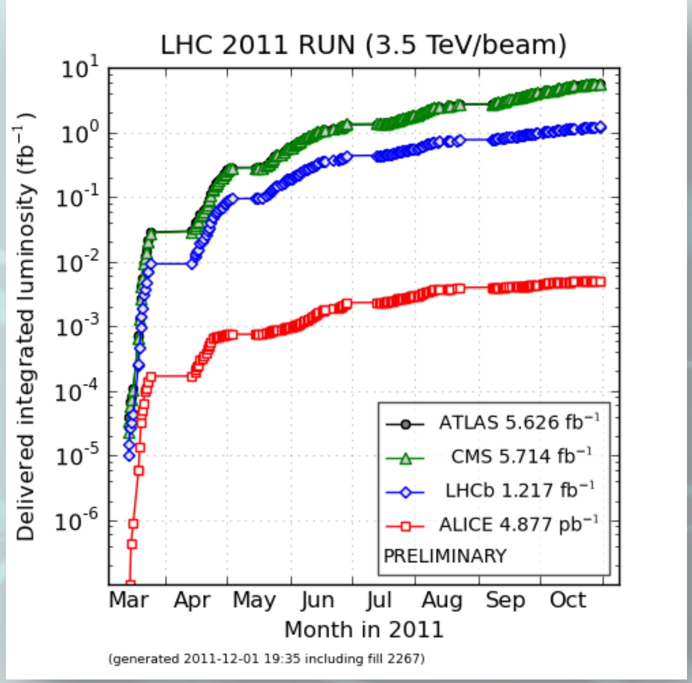
Poster by G.Volpi

2010: Technical Proposal
2012: slice with prototype boards
2013: full prototype and TDR
Phase-1: full installation

LHC 2011/2012 Luminosity and Limits

- **2011**: Peak luminosity increased almost linearly over the year – close to the limit
  - Doubling the expectations up to 3.3/nb/s
  - Pile-up reaches average peak 16 interaction/collision, much more than the experiments expected





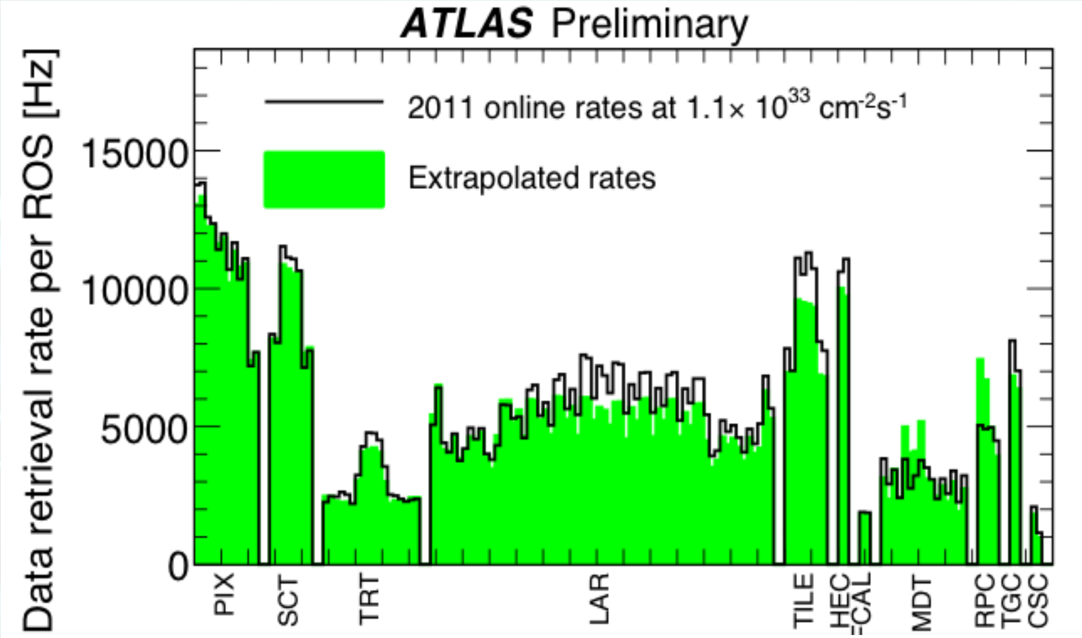
The important quantity this year is not the peak luminosity, but the integrated useful luminosity

F.Pastore - PM2012, La Biodola

- Minimal result for **2012**: either discovery of Higgs or exclusion at 95% CL down to 115 GeV
  - 5 σ discovery per experiment requires > 15 fb^{-1} (ideal target is ~20 fb^{-1} before long shutdown in 2013)
    - Difficult to tell precisely as we are at the edge of experimental sensitivity
  - Increase of Center of Mass Energy from 7 to 8 GeV, for less demanding requests on peak luminosity

LHC and the experiments had already been pushed very close to their limits and will require some major changes

ROS Limits



Data retrieval rates by L2 trigger algorithms at L=10e33

F.Pastore - PM2012, La Biodola