LHC upgrade
&
LHC-ATLAS upgrade

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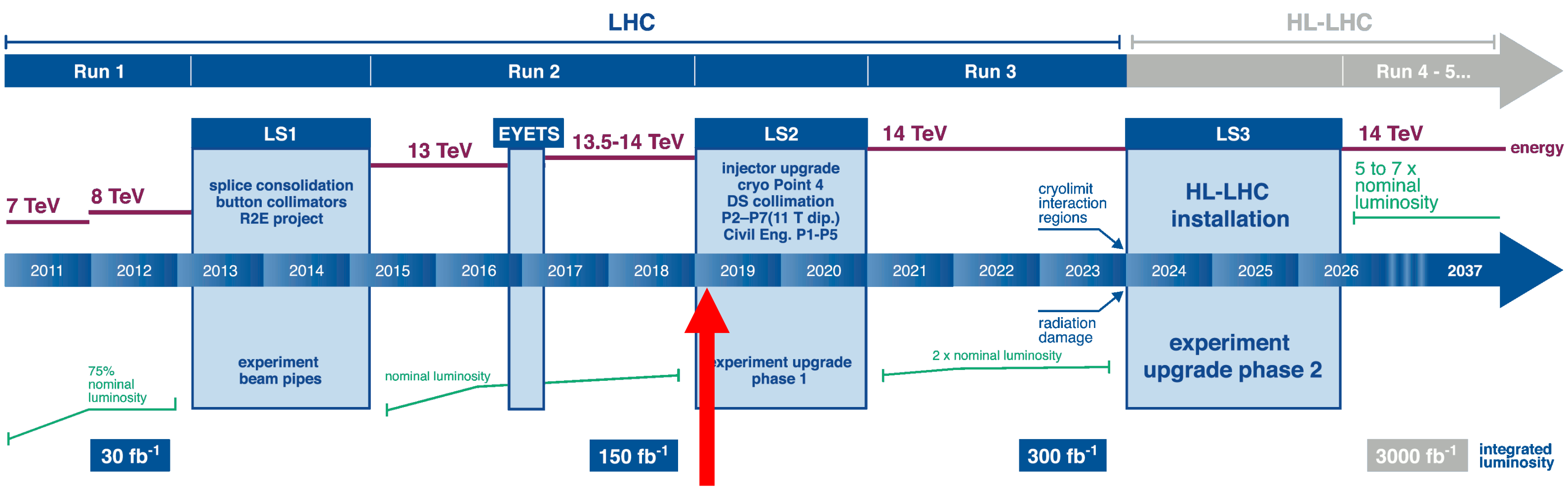
Strategy of energy frontier program

- How can we maximize chance to see a new physics?
  - Enhance the cross-section of new particle production
    - High energy of collisions
    - Resonance in e^+e^- collider (e.g. KEKB, LEP …)
  - Gain more opportunities
    - High luminosity

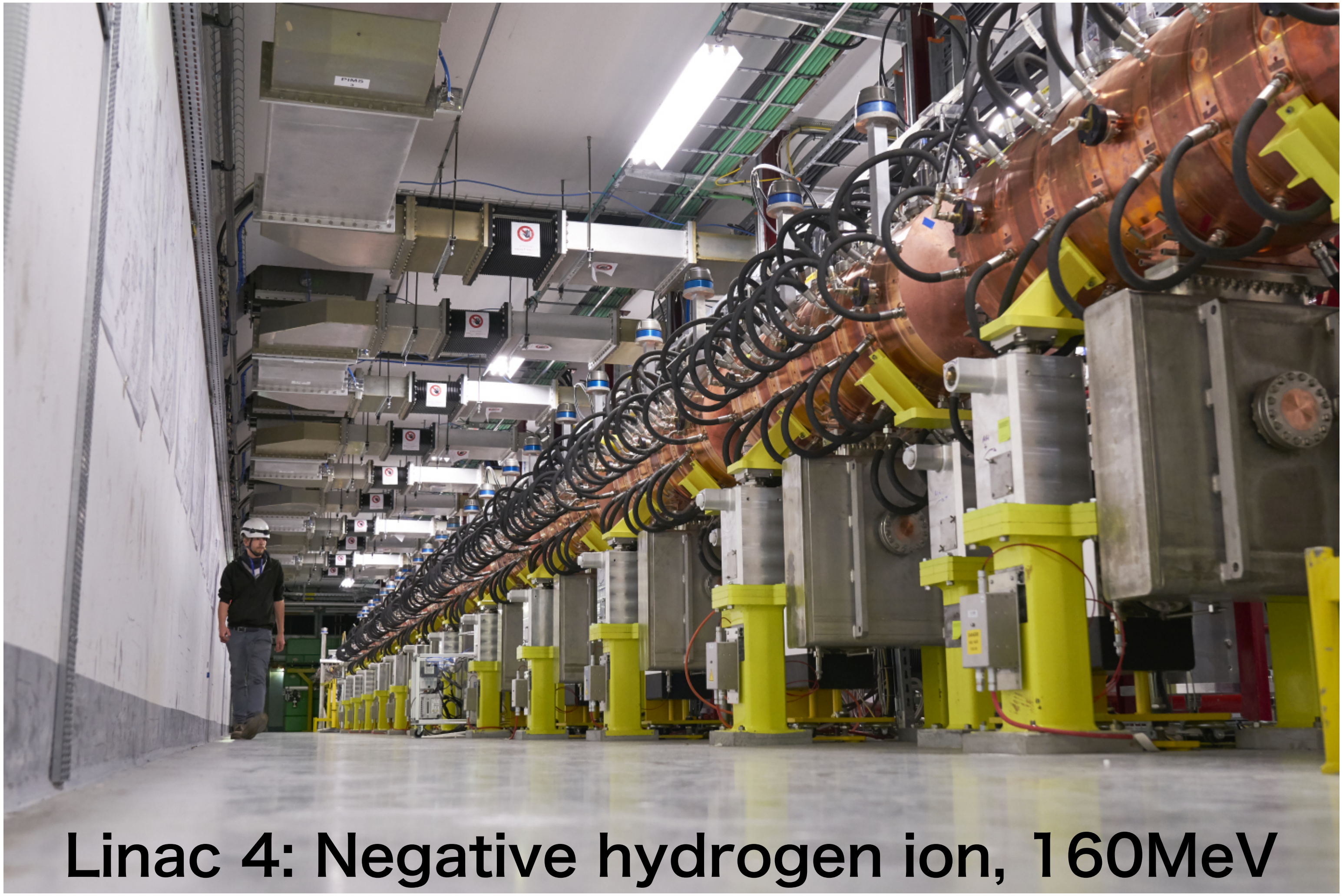
- LHC machine & LHC-ATLAS experiment:
  - Pushing energy frontier and luminosity frontier
  - Maximizing sqrt(s) up to 14 TeV
    - Hard limit with available SC magnets
  - Evolving luminosity with upgrade of systems

Time-line of the LHC project

- LHC evolving the luminosity
  - Successful physics runs with 7, 8, 13 TeV since 2010
  - Staging upgrades to increase the LHC luminosity
    - Long Shutdown 2 (2019 - 2020) for Run3
    - Long Shutdown 3 (2024 - 2026) for HL-LHC
  - High-Luminosity LHC (HL-LHC) operational after 2026
    - The luminosity will be 7.5 x design (~ 7.5 x $10^{34}/cm^2/s$)

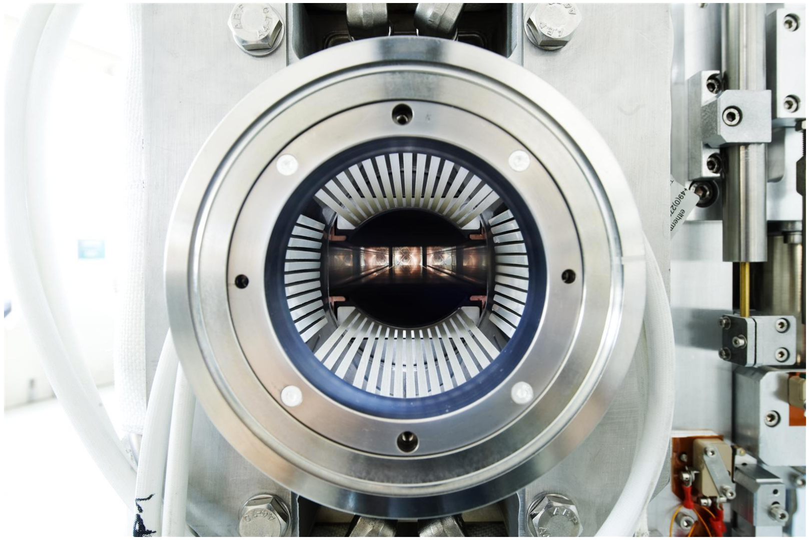


New LINAC for injection



Linac 4: Negative hydrogen ion, 160MeV

Control the high density beams



New collimation system

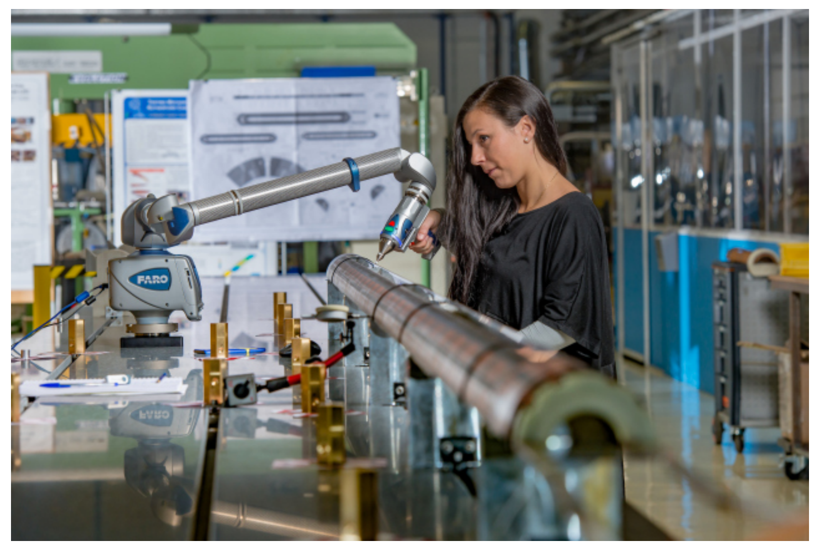
60 out of existing 188 collimators
will be replaced with new materials

15 - 20 new ones will be added
in dispersion suppressor regions

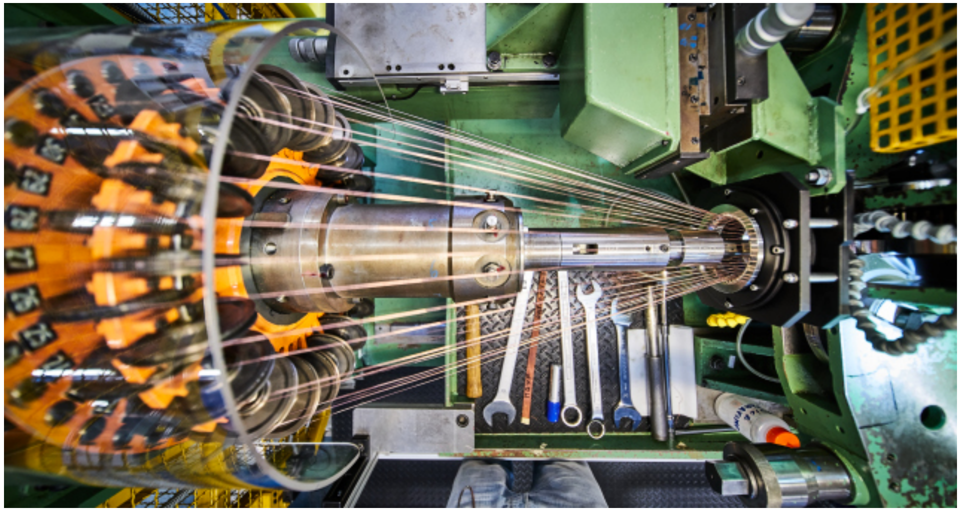
More powerful dipole

Pair of 11 Tesla bending magnets with
5.5m will replace 15m main dipoles
(a few out of 1223 dipoles)

Niobium and Tin Superconducting magnet



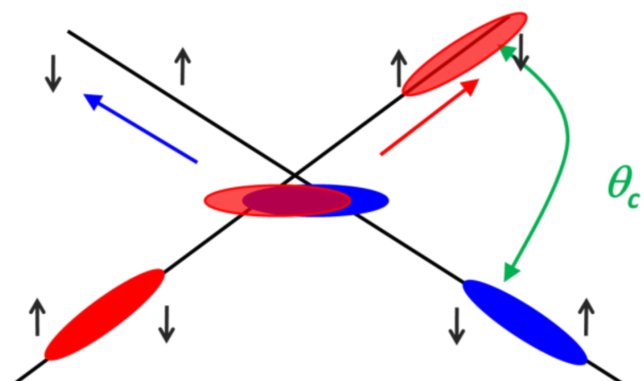
For focusing at collision points



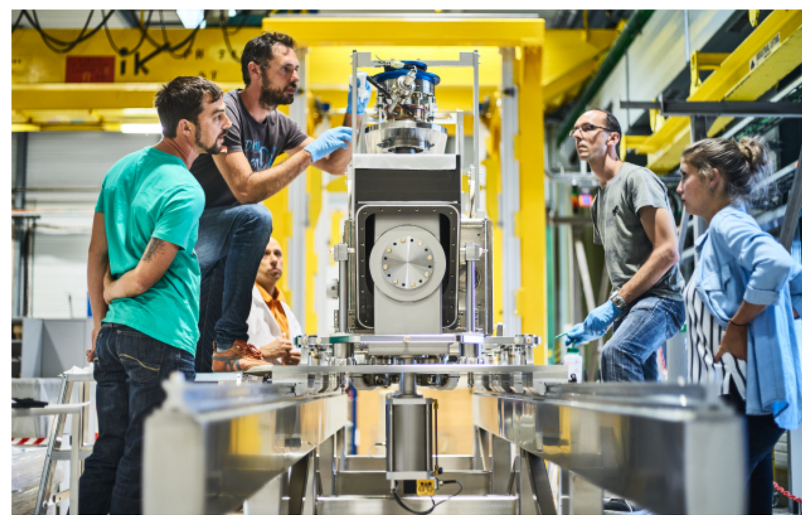
More powerful focusing magnets

12 Tesla quadrupole
(8 Tesla currently)
with niobium and tin SC

SC RF Crab Cavities



3.4 MV kick voltage
ultra-precise phase adjustment (0.001 degree)



HL-LHC parameters

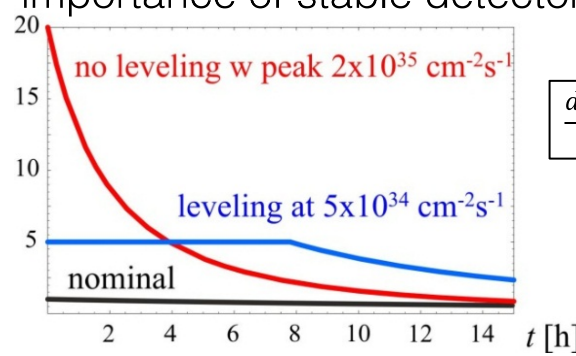
Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)
Beam energy in collision [TeV]	7	7
N_b	1.15E+11	2.2E+11
n_b	2808	2748
Number of collisions in IP1 and IP5	2808	2736 [1]
N_{tot}	3.2E+14	6.0E+14
beam current [A]	0.58	1.09
x-ing angle [μrad]	285	590
beam separation [σ]	9.4	12.5
β^* [m]	0.55	0.15
ε_n [μm]	3.75	2.50
ε_L [eVs]	2.50	2.50
r.m.s. energy spread	1.13E-04	1.13E-04
r.m.s. bunch length [m]	7.55E-02	7.55E-02
IBS horizontal [h]	80 -> 106	18.5
IBS longitudinal [h]	61 -> 60	20.4
Piwinski parameter	0.65	3.14
Geometric loss factor R0 without crab-cavity	0.836	0.305
Geometric loss factor R1 with crab-cavity	(0.981)	0.829
beam-beam / IP without Crab Cavity	3.1E-03	3.3E-03
beam-beam / IP with Crab cavity	3.8E-03	1.1E-02
Peak Luminosity without crab-cavity [cm^{-2} s^{-1}]	1.00E+34	7.18E+34
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [cm^{-2} s^{-1}]	(1.18E+34)	19.54E+34
Events / crossing without levelling and without crab-cavity	27	198
Levelled Luminosity [cm^{-2} s^{-1}]	-	5.00E+34 [5]
Events / crossing (with leveling and crab-cavities for HL-LHC)	27	138
Peak line density of pile up event [event/mm] (max over stable beams)	0.21	1.25
Leveling time [h] (assuming no emittance growth)	-	8.3
Number of collisions in IP2/IP8	2808	2452/2524 [7]
N_b at SPS extraction [2]	1.20E+11	2.30E+11
n_b / injection	288	288
N_{tot} / injection	3.46E+13	6.62E+13
ε_n at SPS extraction [μm] [3]	3.40	2.00

$$\boxed{L = \gamma \frac{n_b N^2 f_{\text{rev}}}{4\pi \beta^* \epsilon_n} R}$$

N = 2.2 x 10^{11} p/bunch
(1.2 x 10^{11} p/bunch at present)

$\beta^*\varepsilon_n$ = 0.15 m x 2.50 μm
(0.55 m x 3.75 μm at present)

Luminosity leveling with respect to importance of stable detector operation

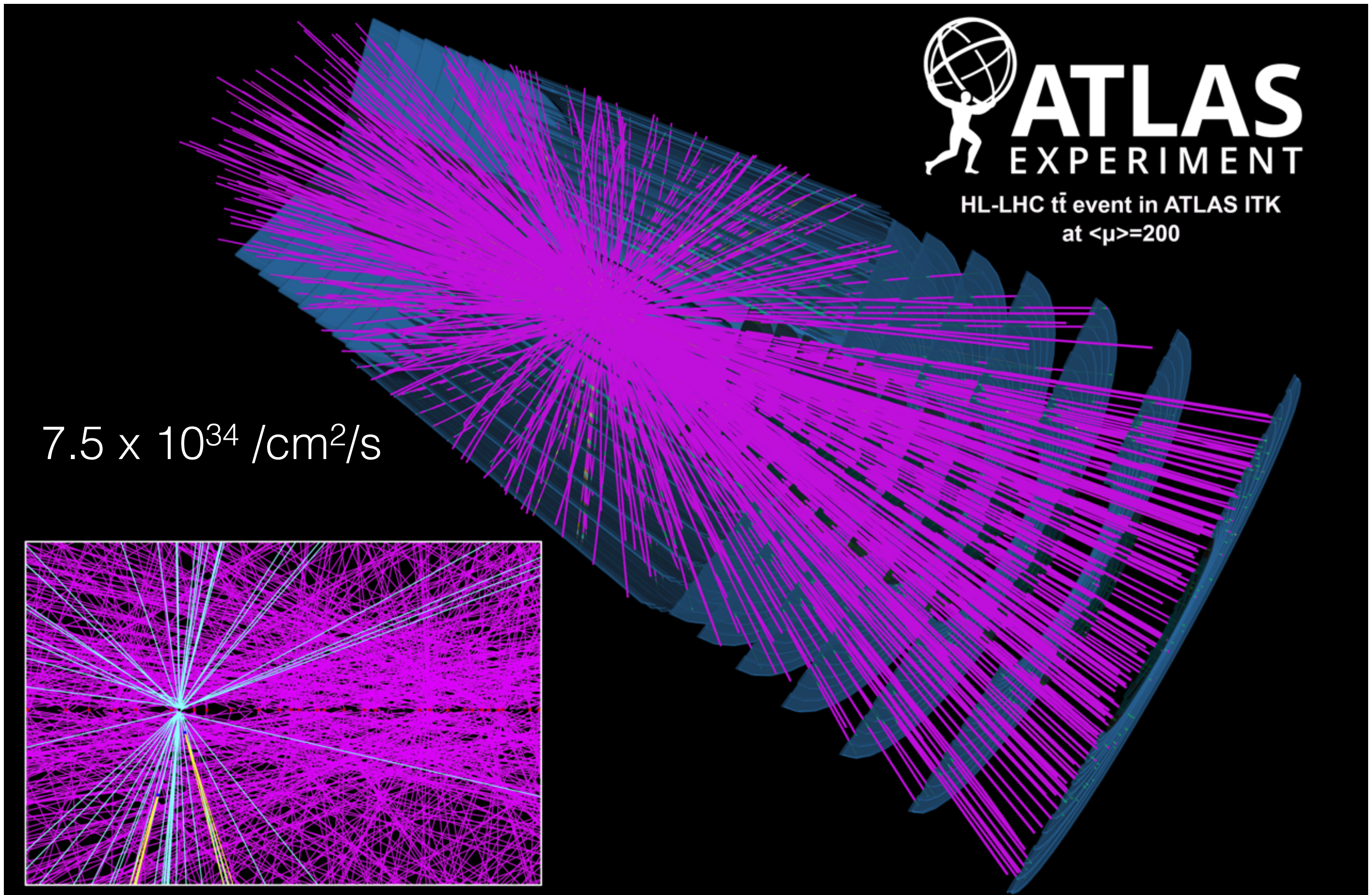


$$\boxed{\frac{dN_{\text{beam}}}{dt} = -n_{\text{IP}}\sigma_{\text{tot}}L_{\text{inst}}}$$

Expectation: 7.5 x 10^{34} /cm^2/s with leveling at maximum

200 simultaneous collisions!

Still big challenge even with leveling techniques



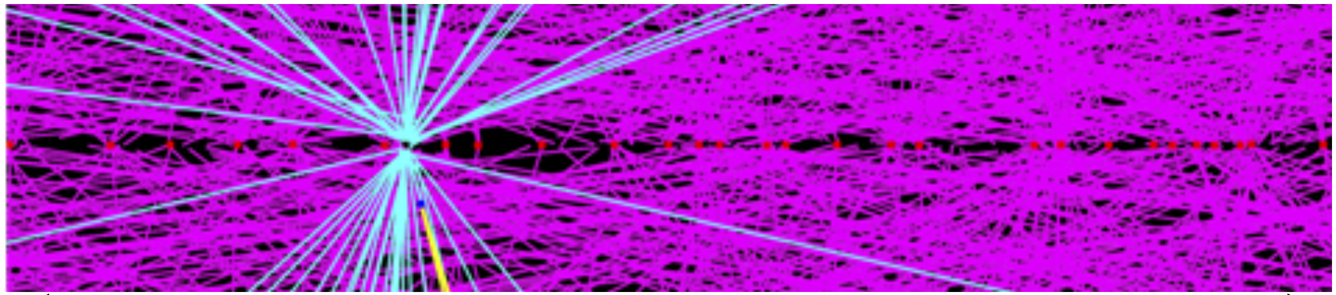
Challenges of the ATLAS

- **New pileup robust detector system**
  - Distinguish interesting events from the other collisions
    - New Inner Tracker (ITk)
    - High Granularity Timing Detector (HGTD)

- **New trigger DAQ system**
  - Taking advantage of recent commodity technologies (large FPGA, high-speed optic)
    - High bandwidth readout DAQ system
    - Sophisticated yet flexible trigger system

Inner Tracker upgrade

- Requirements of Inner Tracker @ HL-LHC



200 pileup collisions in 10 cm of beam luminous region

  - Keep performance of physics analysis by distinguishing interesting interactions from others
    - High granularity with large coverage
    - High tracking efficiency in the high pileup environment without problems of detector occupancy
  - Radiation hardness, martial reduction in layout, cost, ..
- Full silicon inner tracker system (ITk) for HL-LHC

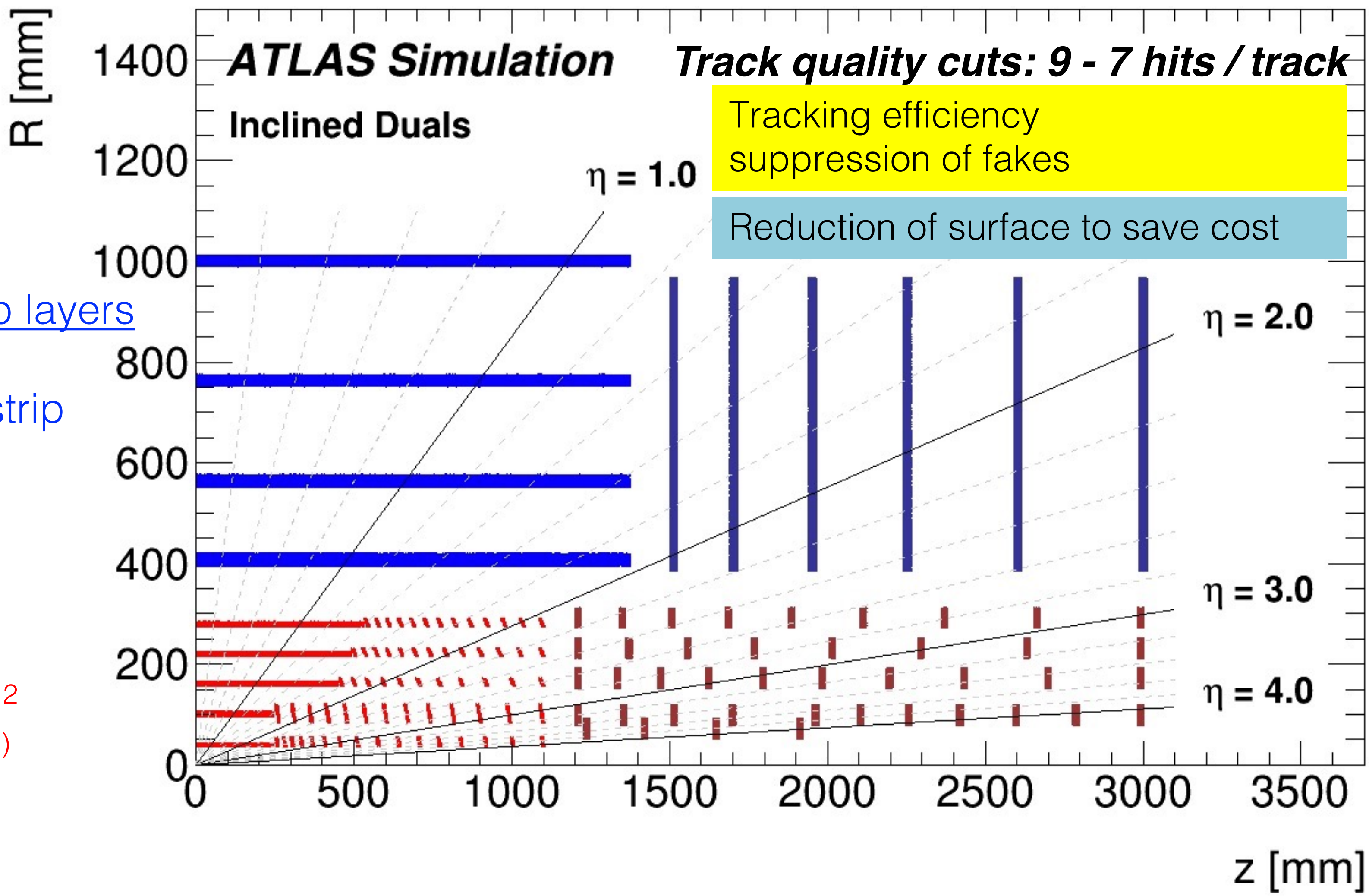
Inner Tracker layout

<u>4 doublet strip layers</u>

- 50M ch
- 70-80 um strip
- 160 m^2

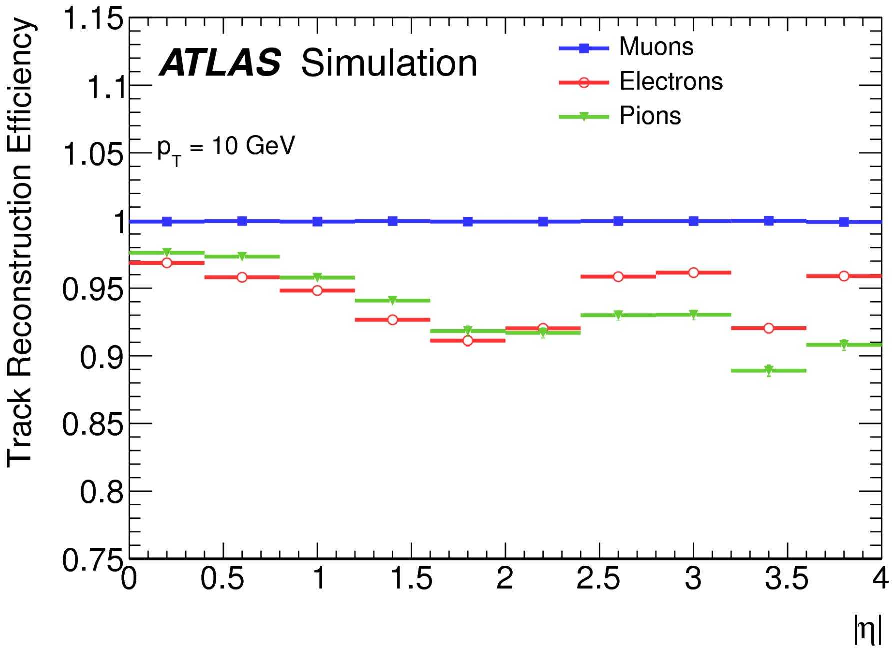
<u>5 pixel layers</u>

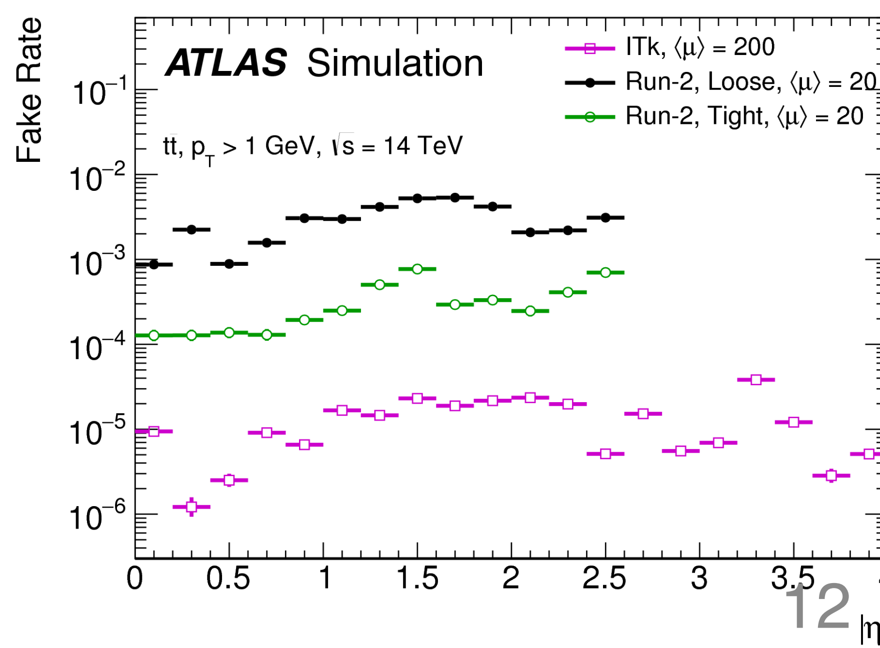
- 5B ch
- 50 x 50 um^2 (or 25 x 100 um^2)
- 13 m^2



Tracking performance

- Efficiency (p_T=10 GeV mono chromatic samples)
  - For muons ~ 100%
  - For pions/electrons ~ 90 - 98%
- Control a fake rate
  - A minimum 9 - 7 hits requirement
  - Longer arms of silicon detectors and higher granularity

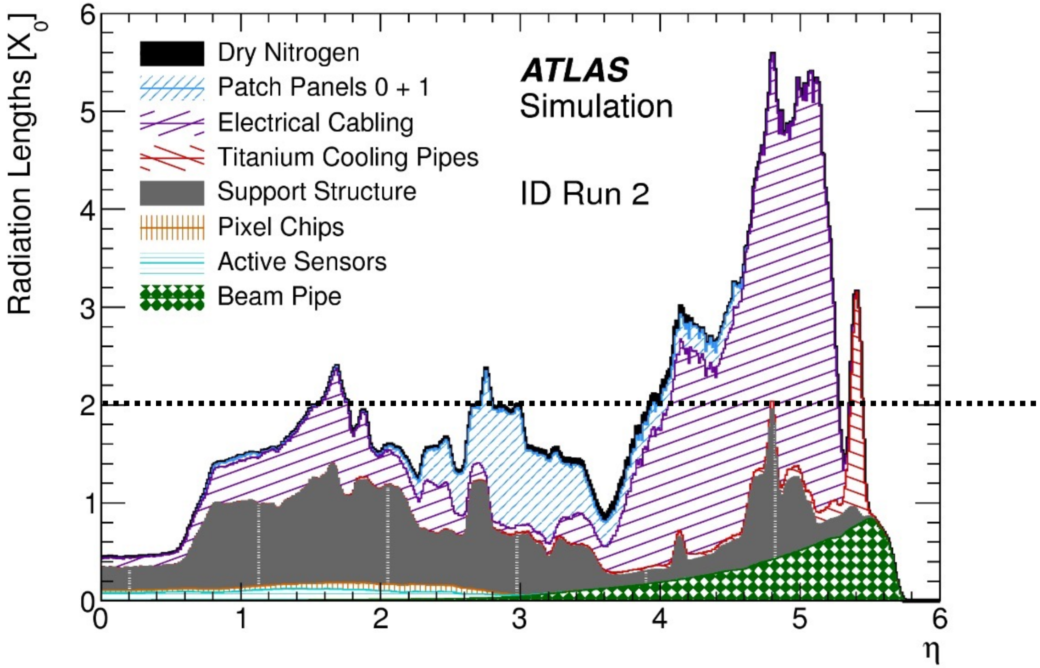




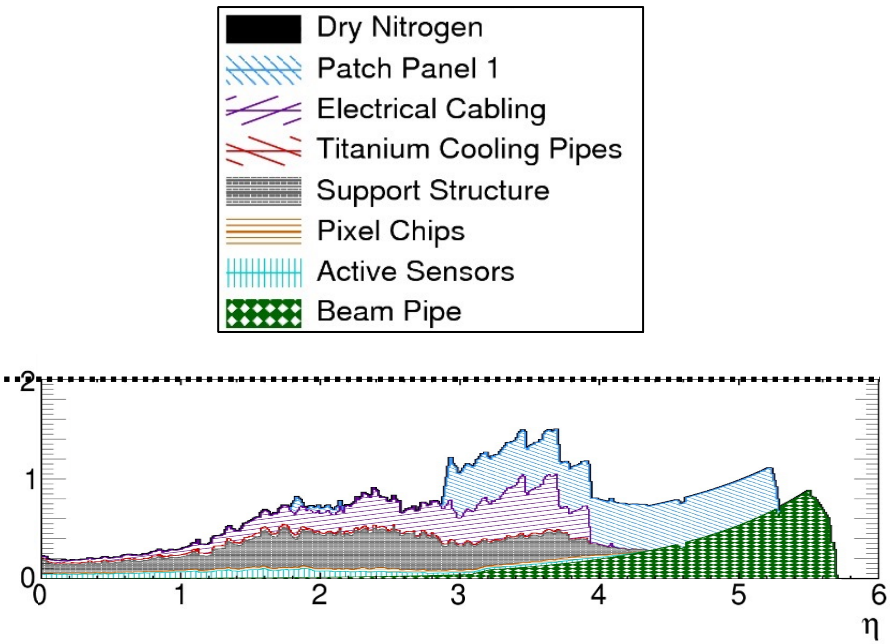
Significant reduction of material budget

- Successful material budget reduction
  - Factor 5 reduction in the radiation lengths with wider acceptance of detectors
  - Benefit in performance of tracking and calorimetry for precise e/γ reconstruction, as well as total ionization doses

Current ATLAS Inner Detector



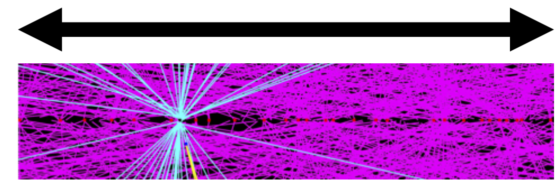
HL-LHC ATLAS ITk Detector

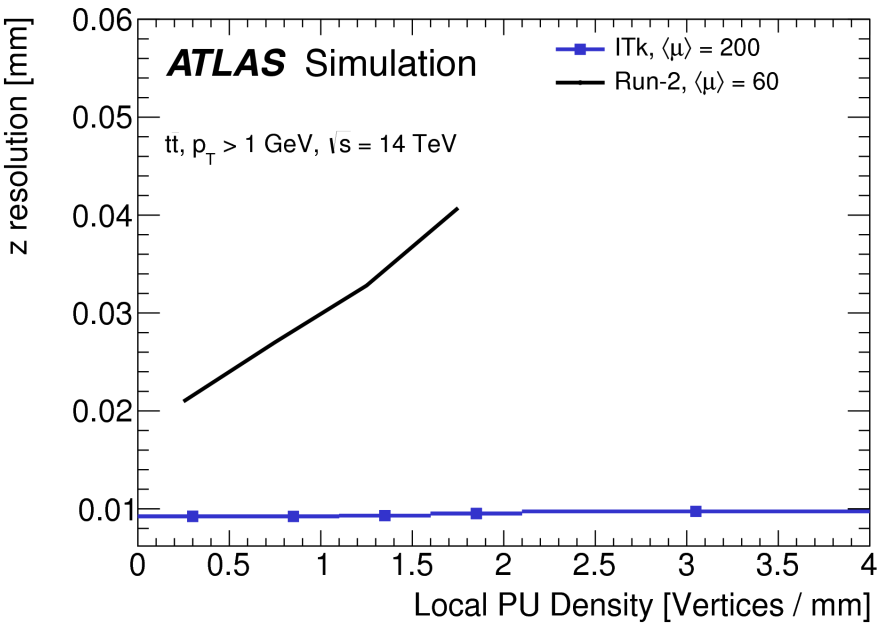


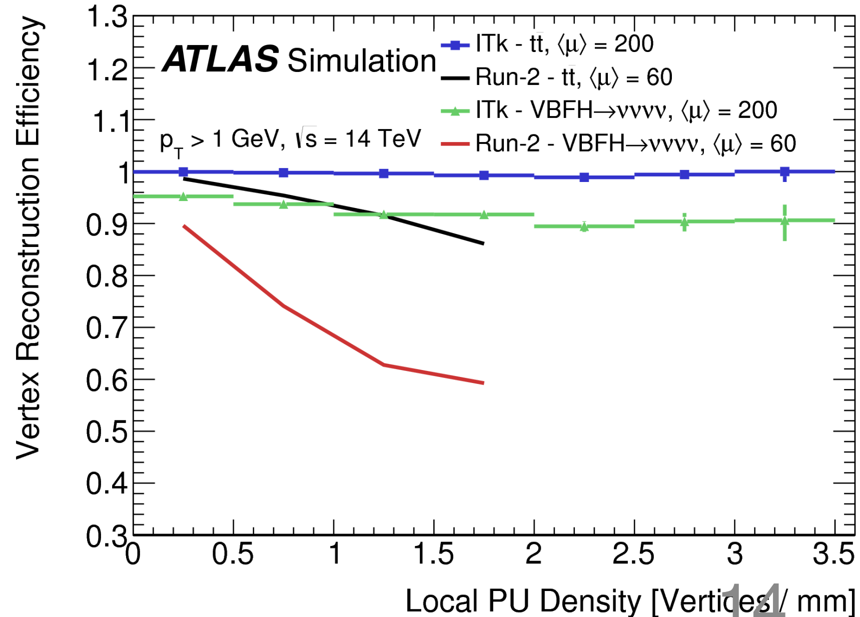
Vertexing performance

- Stable performance up to 200 pileup
  - 10um resolution in z
- Finding of interesting vertex
  - Good performance in reconstruction

~200 collision /~100 mm

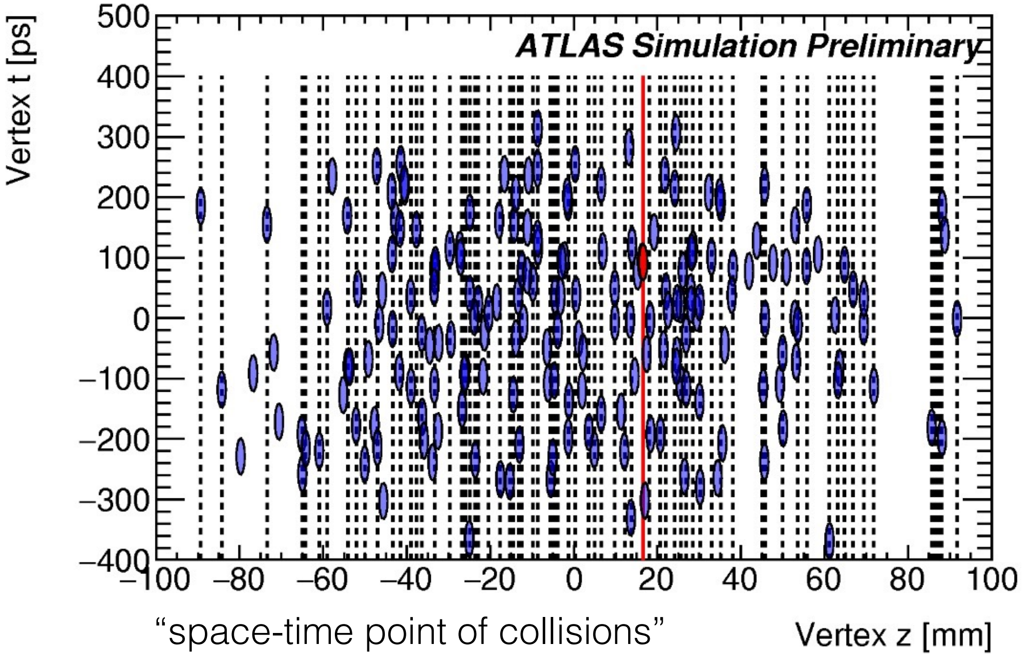




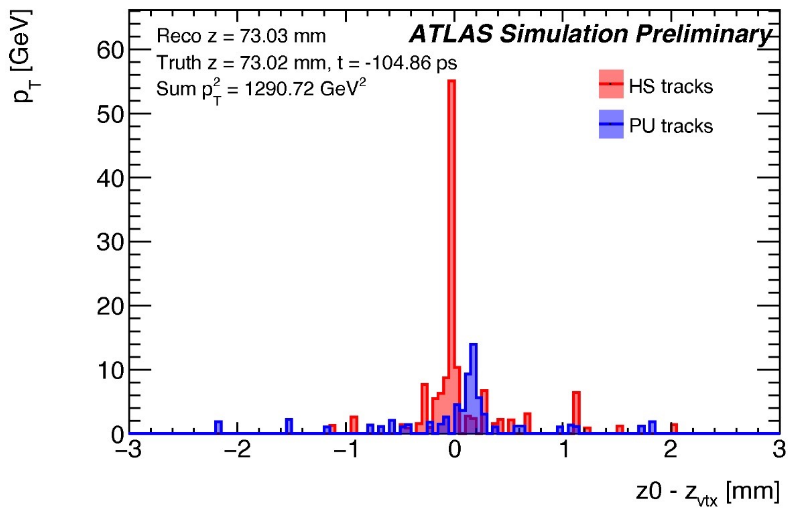


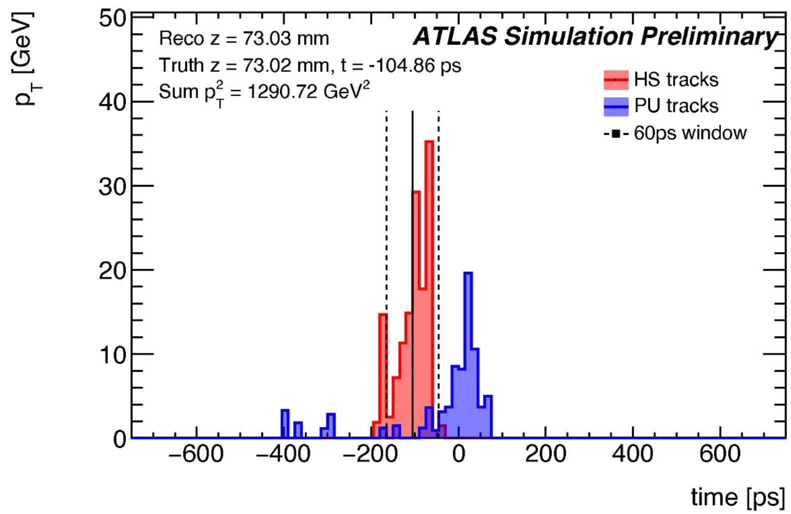
Another dimension for vertexing

- Beam luminous region has a finite space-time spread
  - ~ 4 cm in space & ~ 180 ps in time with 1 sigma of standard deviation
- Additional pileup separation power with timing information for tracks



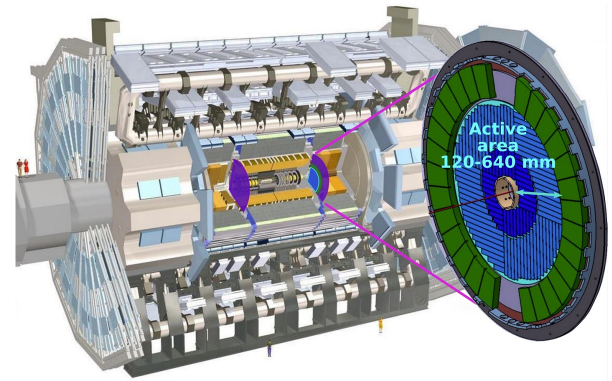
"space-time point of collisions"



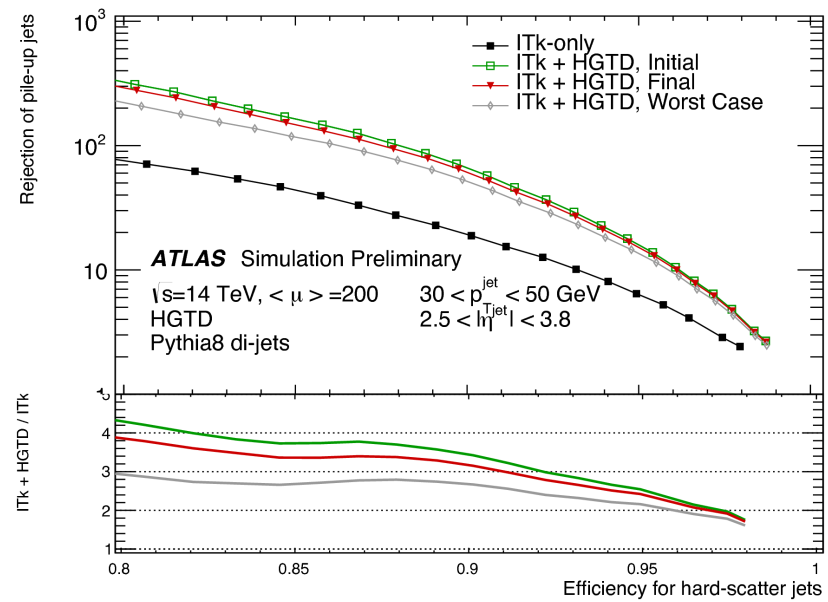


Timing detector HGTD

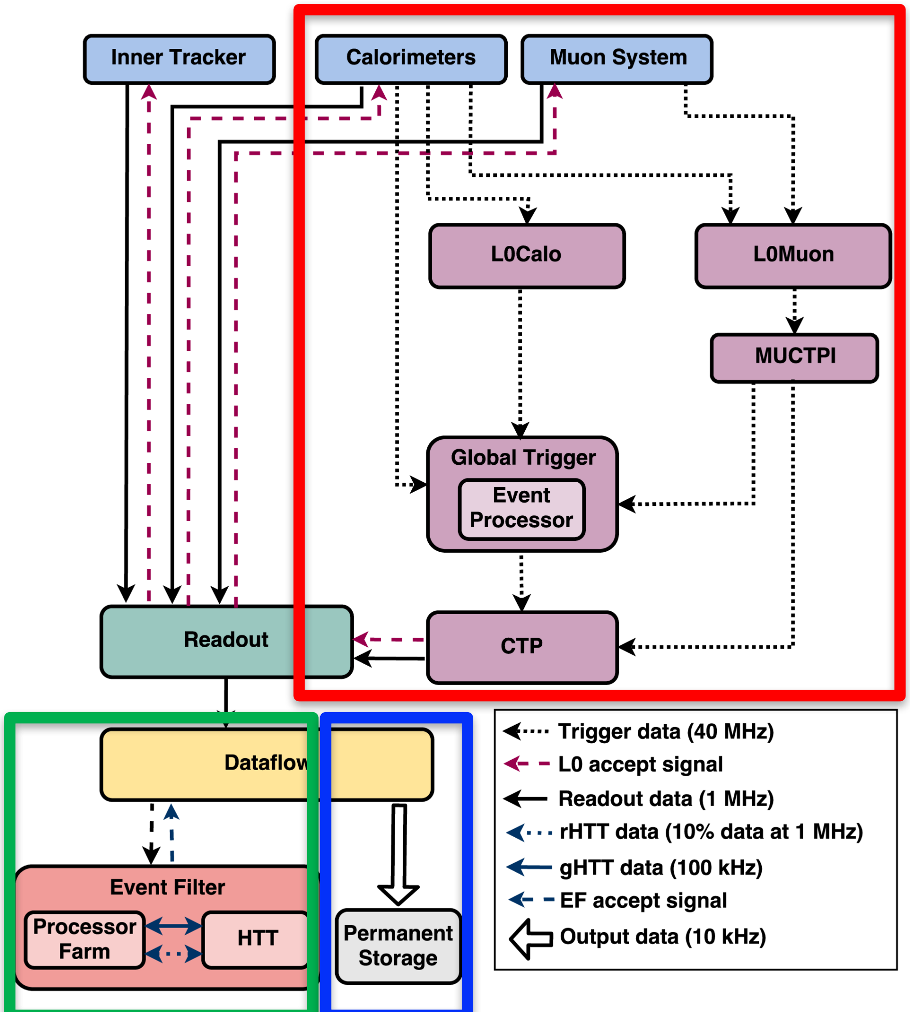
- High-Granularity Timing-Detector (HGTD)
  - 2 double planer layers
    - Pixel size: 1.3x1.3 mm^2
    - Thickness 50um
  - Coverage $2.4<|\eta|<4.0$
  - σ_t ~ 30 - 50 ps per track
    - Sensor ~ 25ps
      - Intrinsic landau fluctuation
    - Electronics ~ 25ps
    - Clock ~ 10ps
- Better performance to identify jets from interesting collisions by a factor of 2-4.



Identification of jets from interesting vertex

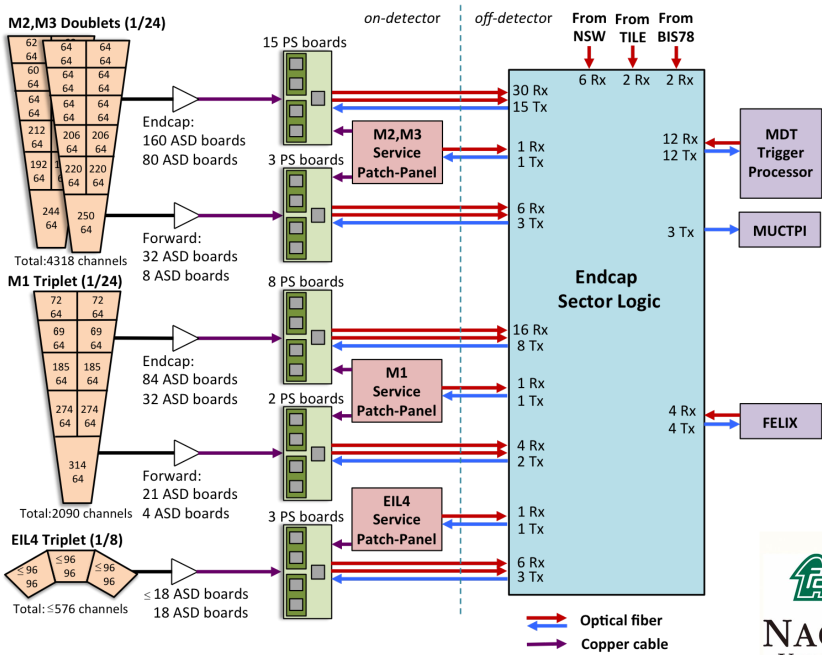


Trigger DAQ upgrade



- TDAQ system for HL-LHC ATLAS
  - L0 hardware-based trigger
  - EF software-based trigger
  - Permanent storage
- Upgrade highlights
  - With high-tech commodity
    - Modern FPGA
    - High speed fiber optics
  - Increased latency at L0
  - Hardware tracking system

Muon trigger upgrade



- Improvement with modern fiber optics and FPGAs
  - High speed link with large bandwidth between frontend and backend electronics
  - All binary hits of Thin Gap Cambers are sent to backend for every 40 MHz Bunch Crossings
  - Sophisticated algorithm of triggering in the backend

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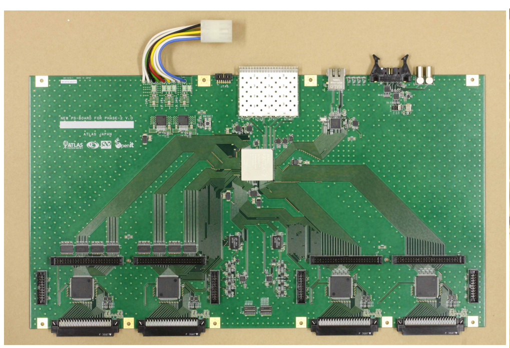
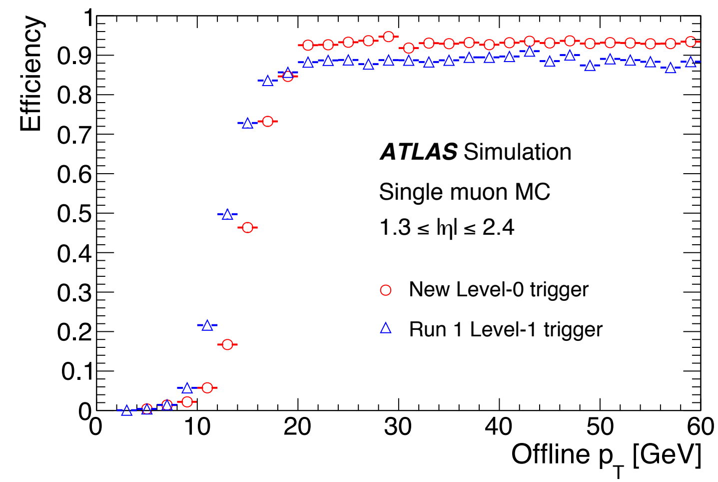
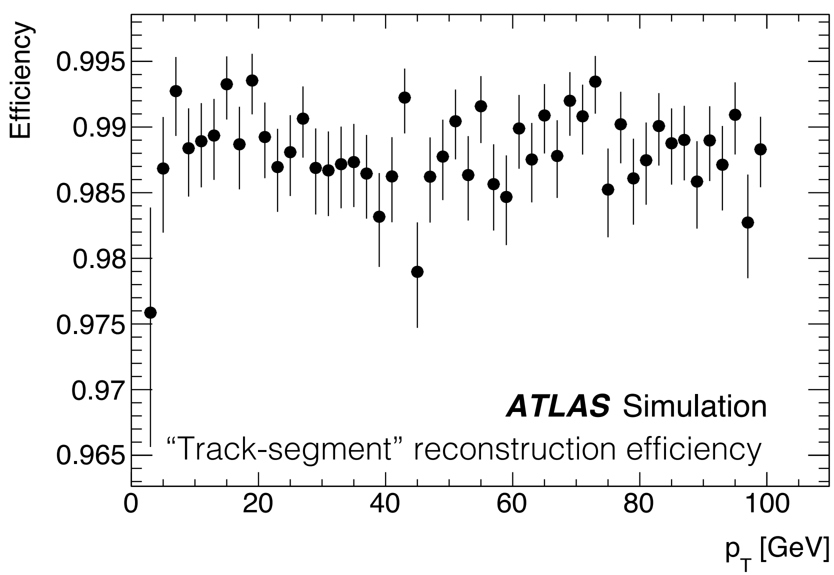
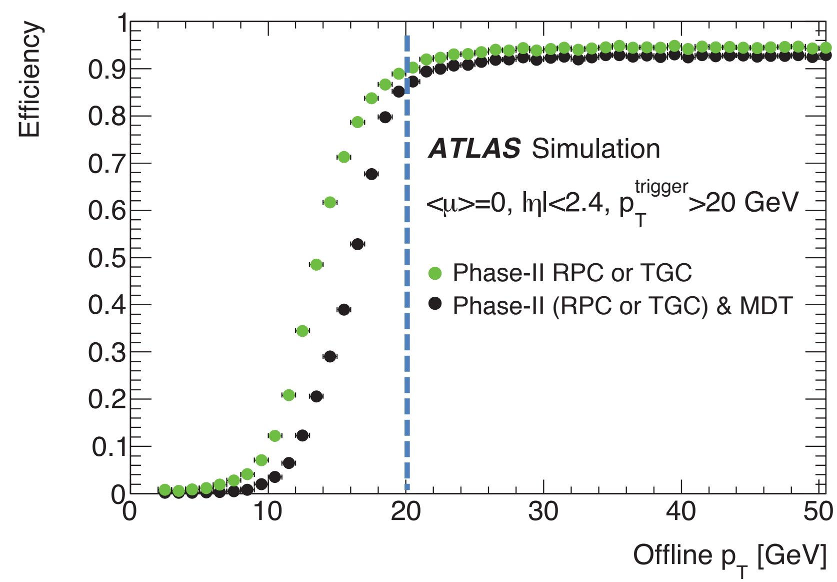




Muon trigger upgrade

- The longer latency at HW trigger allows to perform online full reconstruction of muons at L0 trigger
  - Addition of drift tubes (~ 700ns drift time) to hardware triggering logic to improve the precision
  - Further control of trigger rate with a sharper turn-on curve
  - Possibility of invariant mass reconstruction in trigger stage

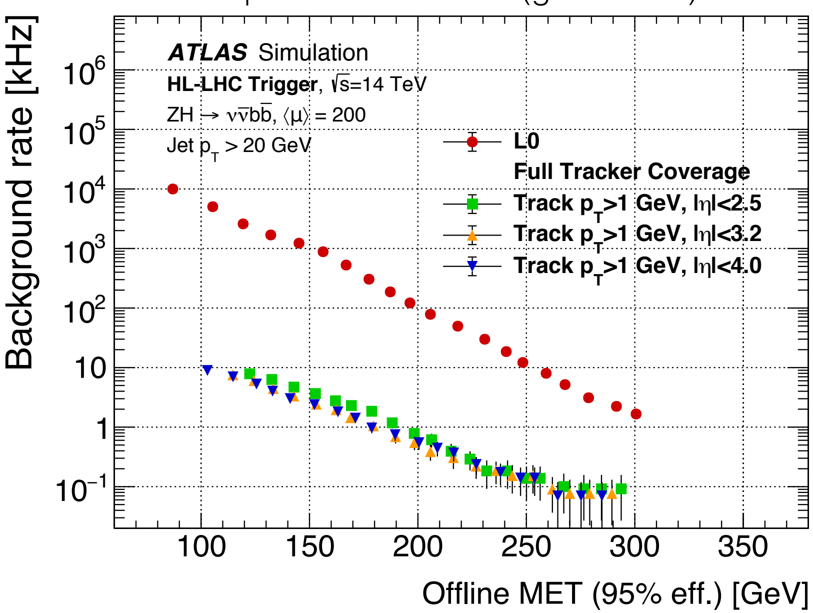




Online tracking capability

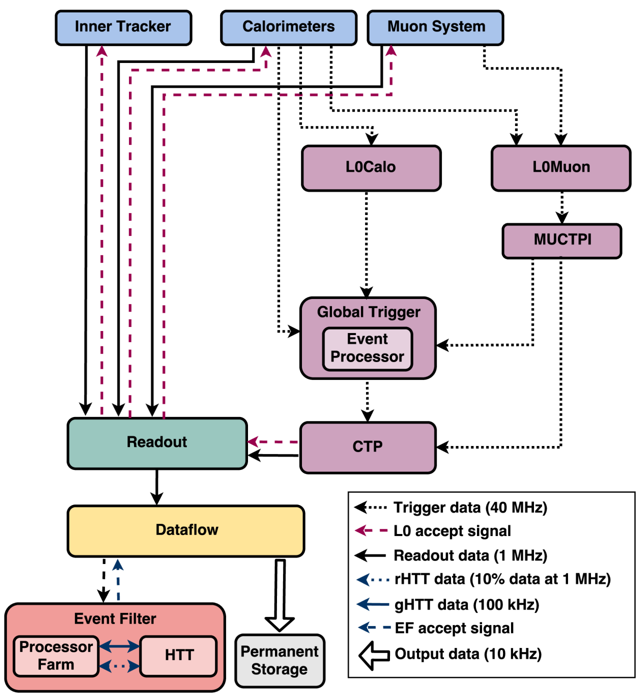
- Hardware Track Trigger (HTT) system
  - Provide tracks to software triggers as an input
  - Regional tracking runs at 1MHz, based on L0 objects
    - 2 GeV, $|\eta|<4.0$
    - Fast rejection for lepton trigger with feasibility of PV reconstruction
    - Factor 5 rejection of fake electrons at the beginning of EF
  - Global tracking at 100kHz
    - 1 GeV, $|\eta|<4.0$
    - Full event information
    - Chance to implement sophisticated algorithms in future

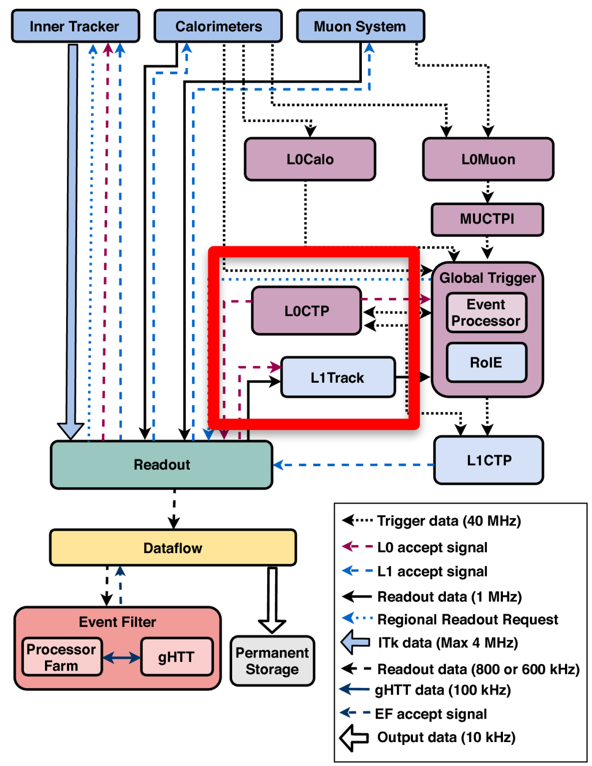
factor 10-500 rejection of backgrounds with improved online MET (global HTT)



Future system evolution

Capability of Hardware Tracking System in Hardware triggering stage is reserved for further flexibility in case a possible new physics requires it



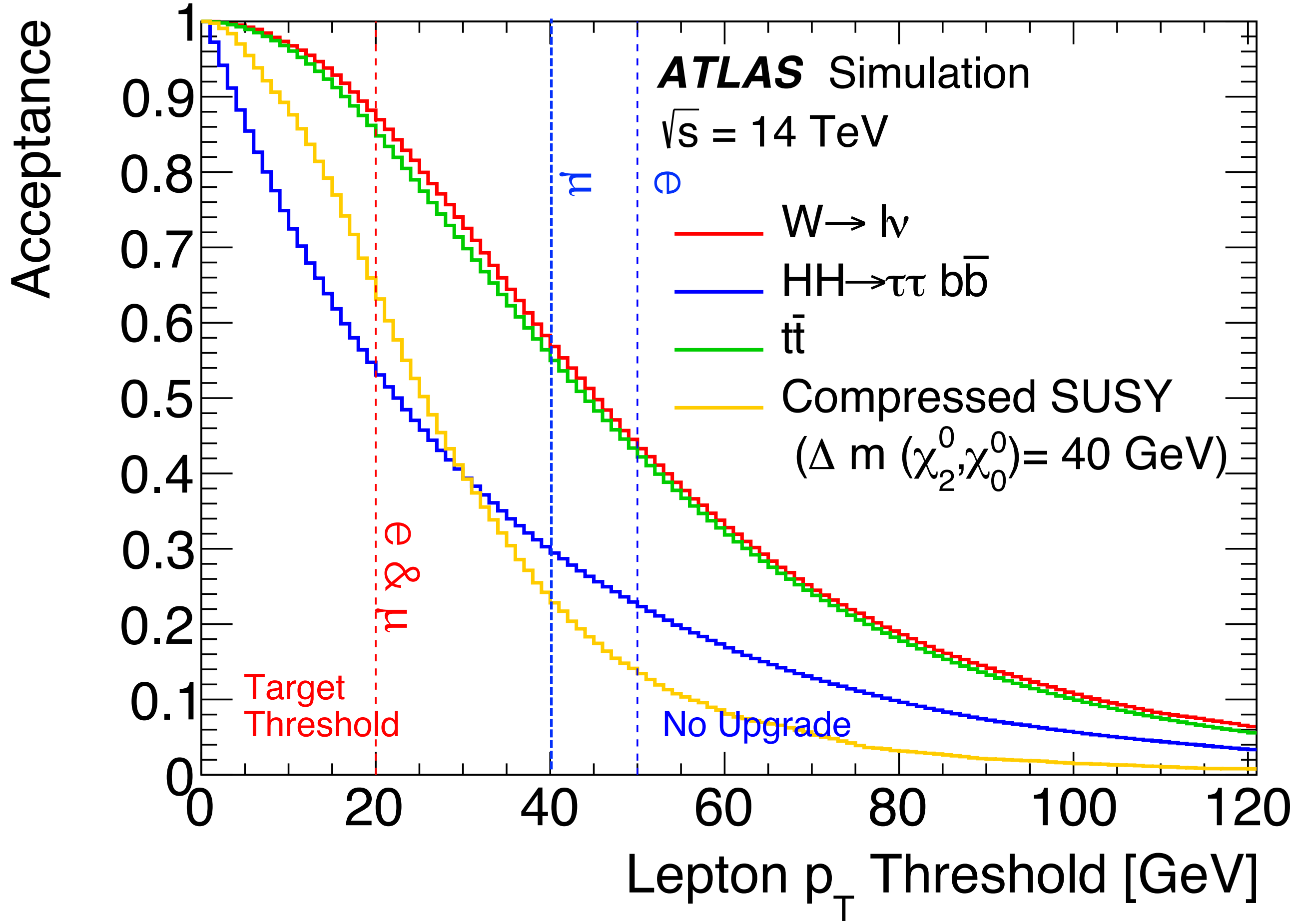


L1 tracking on hardware trigger stage

Conclusions

- LHC ATLAS experiment is in both high energy & high luminosity frontiers
- LHC upgrade
  - Machines compatible to luminosity 2 x 10^{35}/cm^2/s
  - 7.5 x 10^{34} /cm^2/s with luminosity leveling technique
- LHC-ATLAS upgrade
  - To keep physics capability with HL-LHC environment runs with 200 pileup collision events
    - Pileup robust detector systems (ITk and HGTD)
    - Flexible TDAQ system with latest technologies

Muon trigger update



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