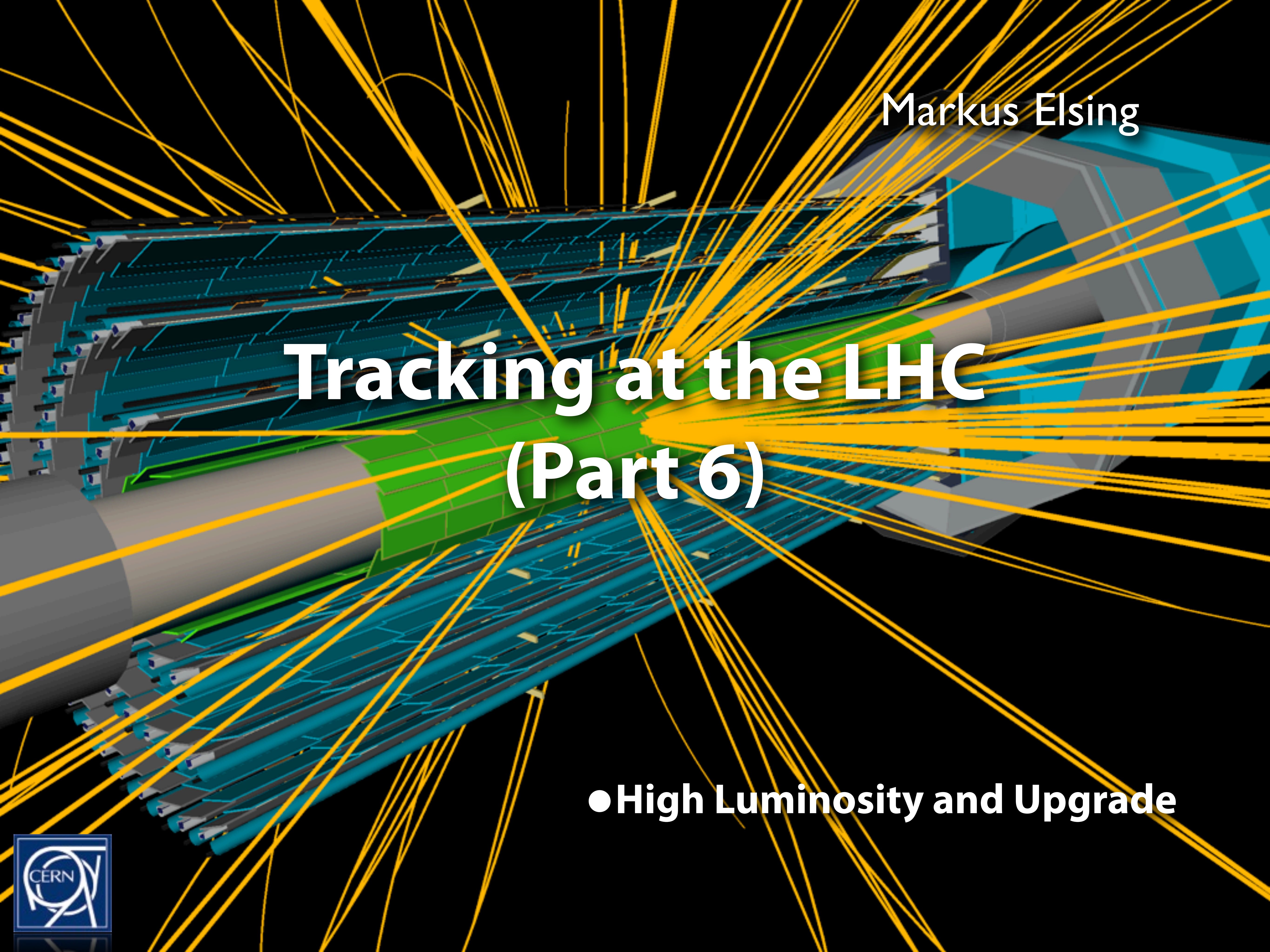


Tracking at the LHC
(Part 6)

Markus Elsing

- **High Luminosity and Upgrade**

Outline of Part 6

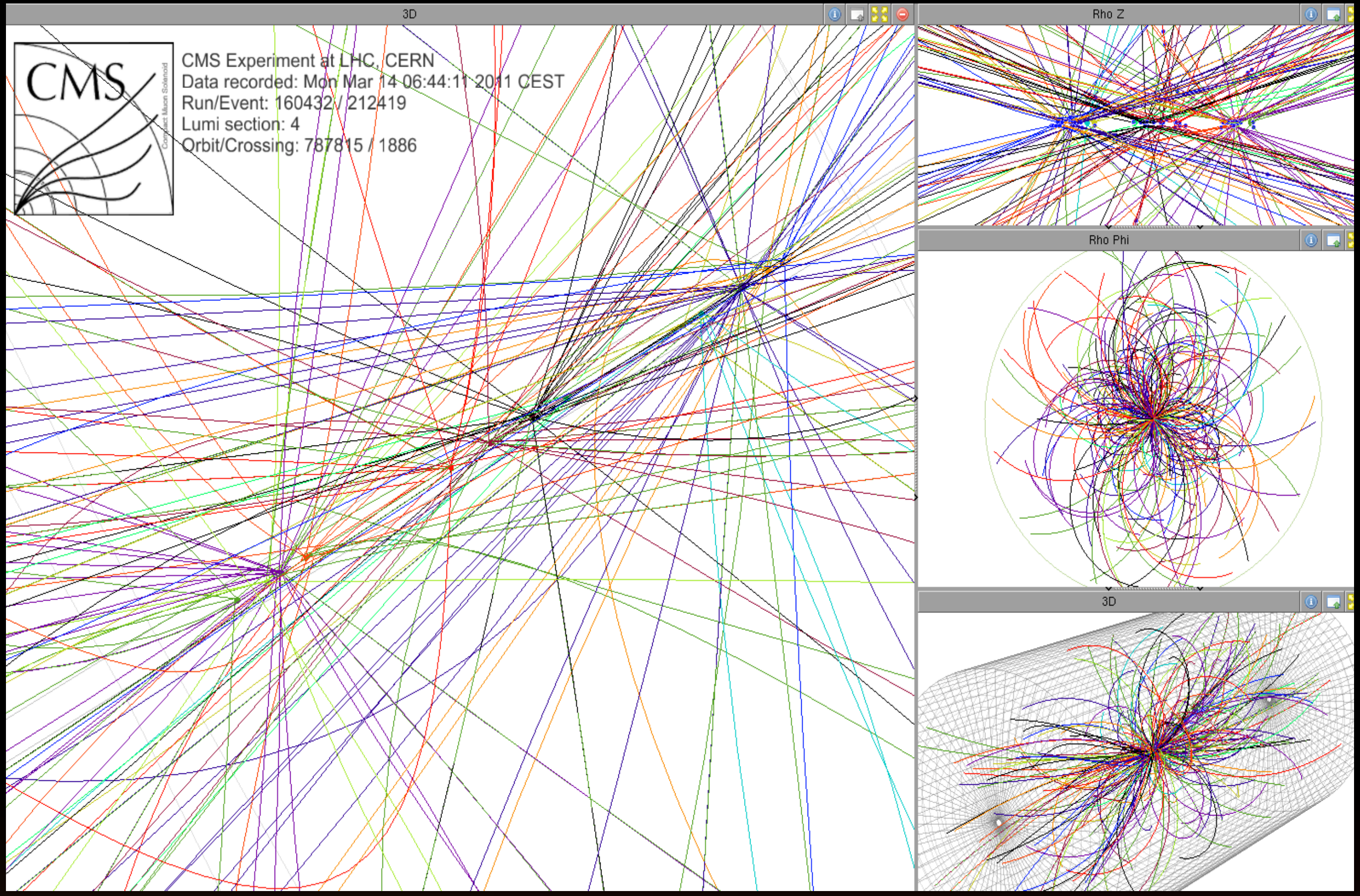
- expected tracking performance with high pileup

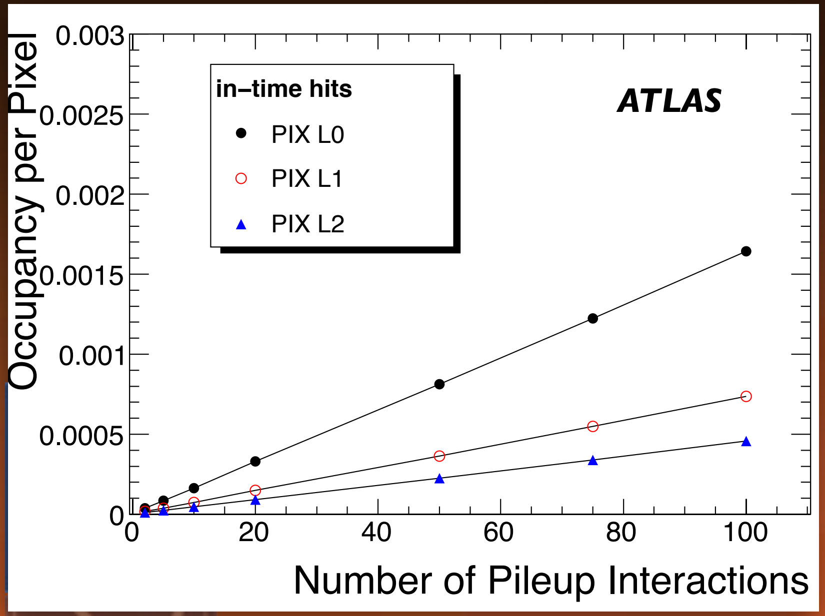
- evolution of tracking settings
  - ➡ including CPU and memory/size issues
  - ➡ brief look at heavy ion data to study those

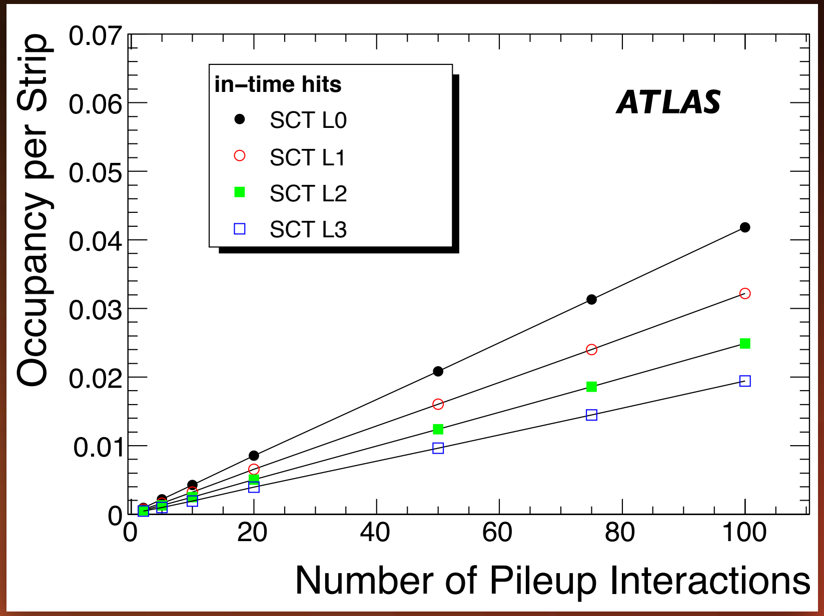
- discuss Phase-0 and Phase-1 upgrades for CMS+ATLAS
  - ➡ as well hardware track trigger concepts

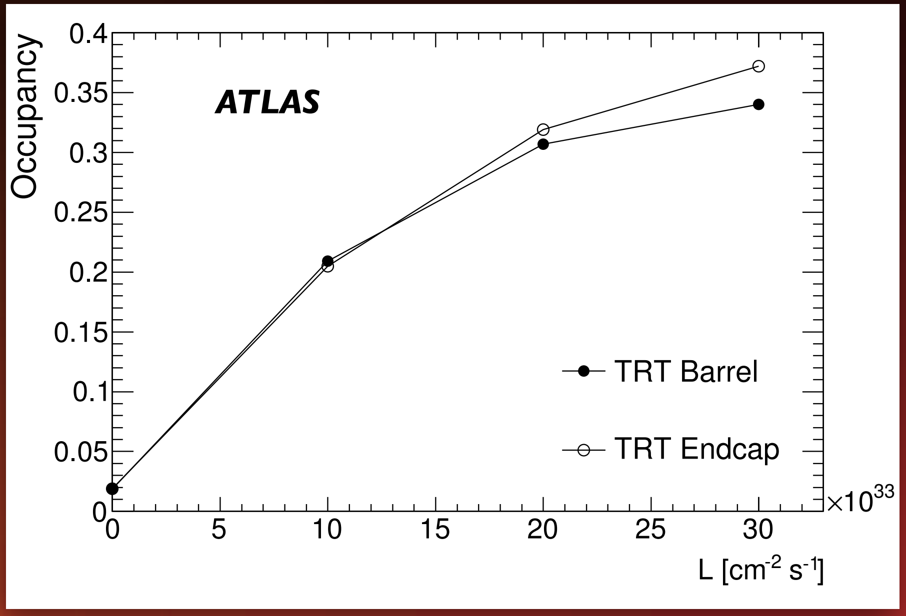
Tracking for High Occupancy - Pileup

- event pileup is a feature of the LHC
  - ➡ already sizable effects this year
  - ➡ ~23 events at design lumi
- detectors designed for $10^{34}\,cm^{-2}s^{-1}$
  - ➡ occupancies from pileup do not exceed hit density in jet cores !



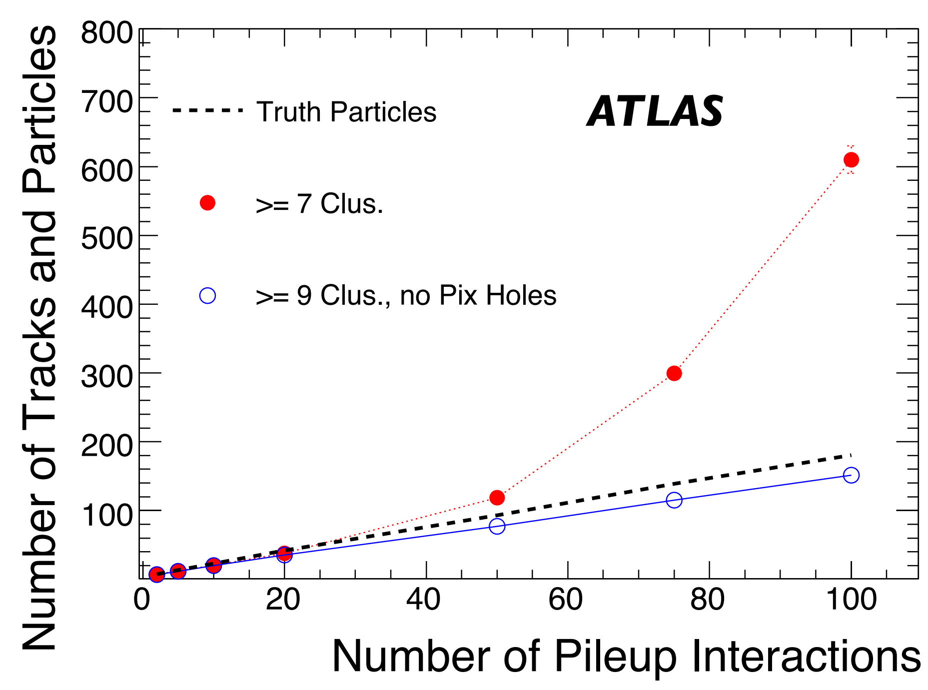


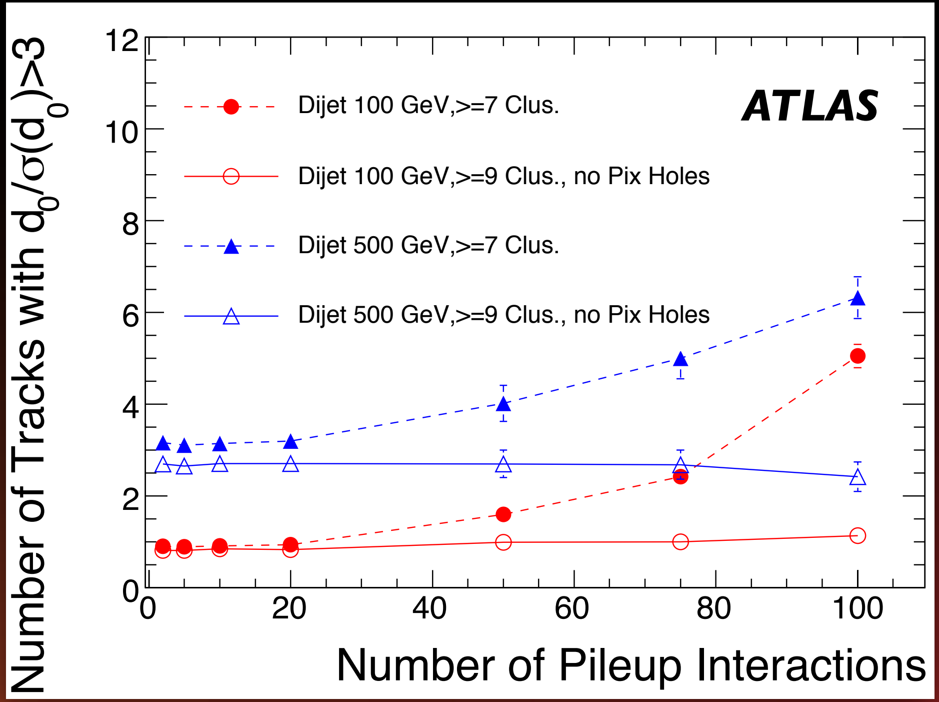


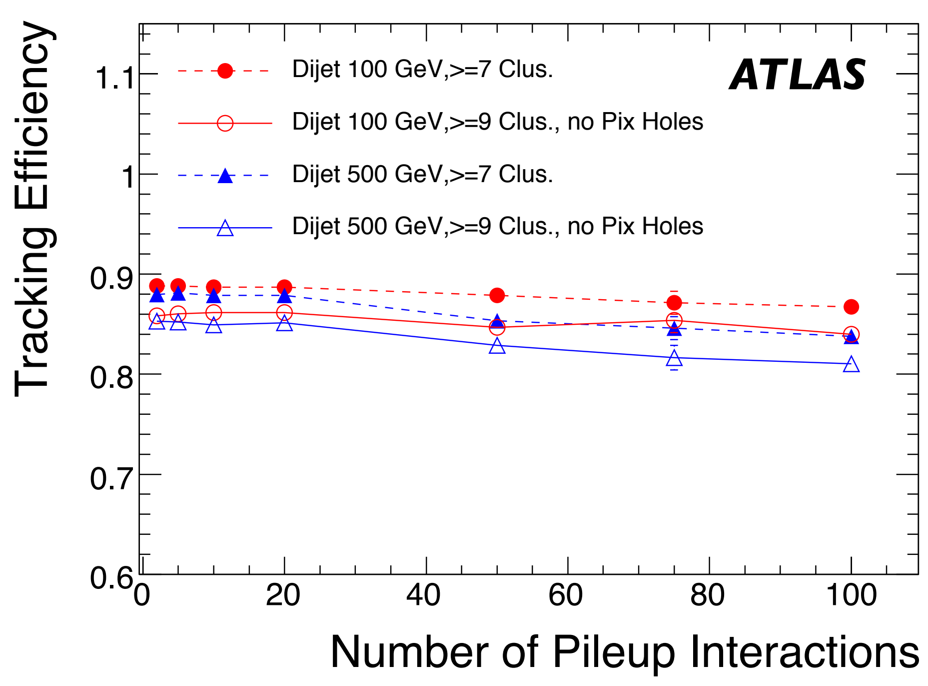


Tracking at High Luminosity (pp)

- tracking with very high pileup
  - ➡ rate of fake tracks (fakes) increases
  - ➡ more tracks with large IP significant (tracking mistakes)
- pileup track selection
  - ➡ adapt tracking settings to pileup conditions
    - e.g. ATLAS: requiring 9 out of 11 hits, cut on “no Pixel holes”
  - ➡ suppresses fakes at expense of some efficiency



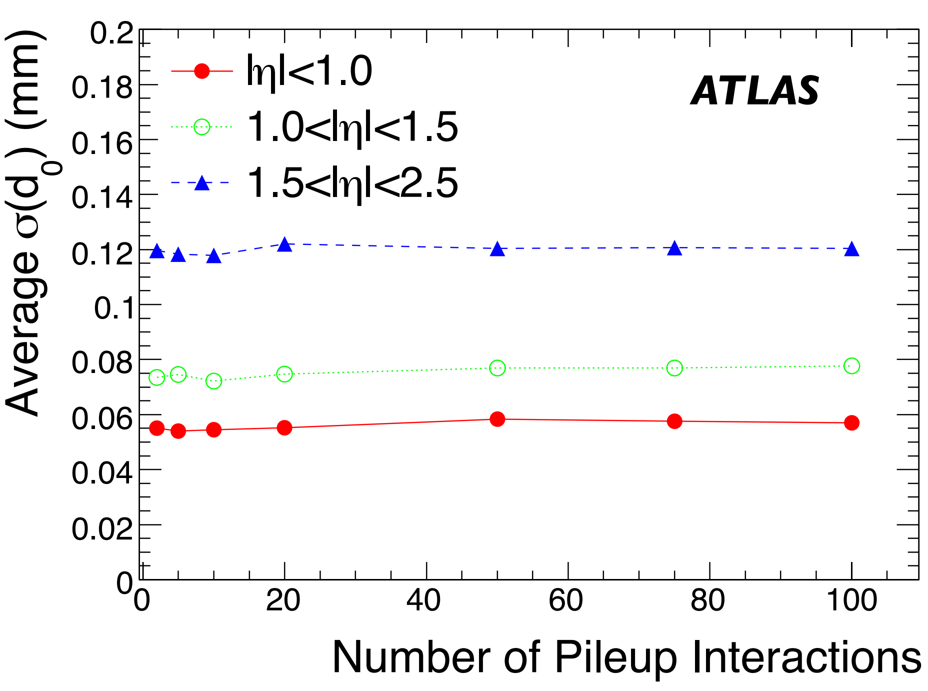


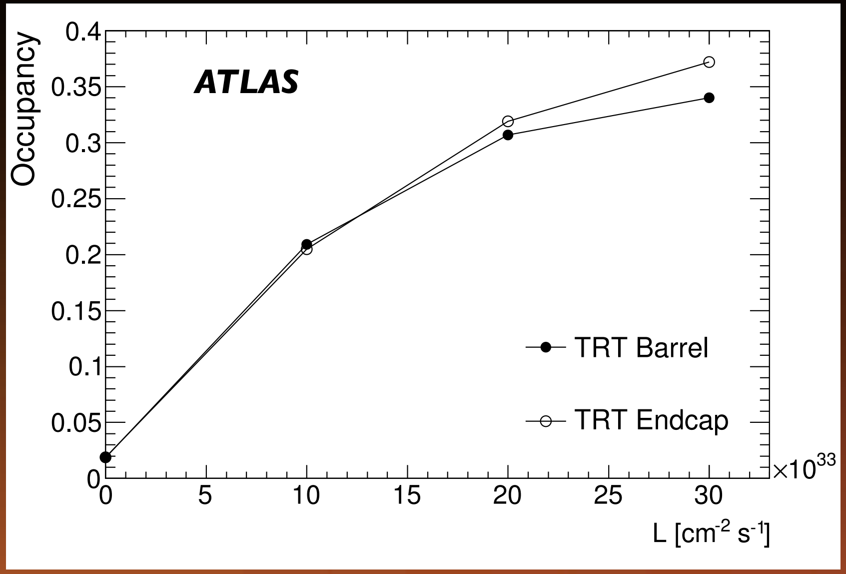


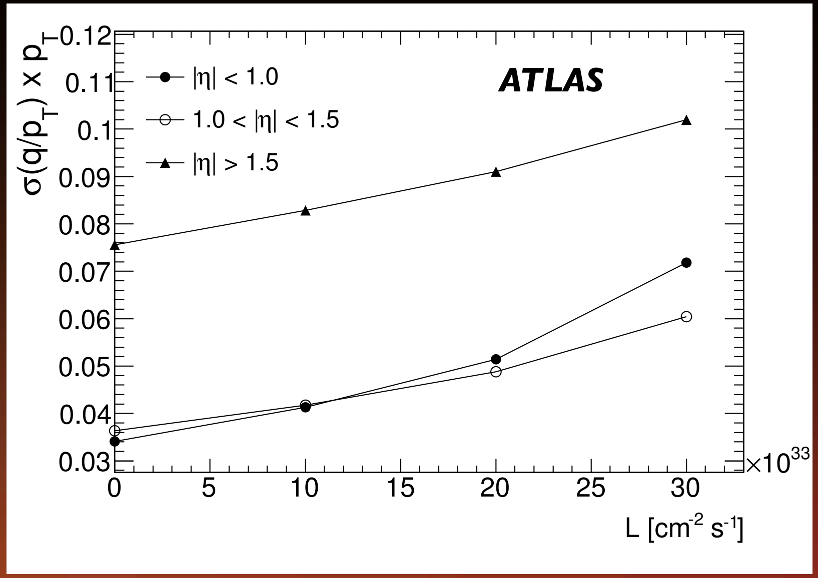
Tracking at High Luminosity (pp)

- small effects expected on tracking resolution
  - ➡ occupancy in pixels and strips still small

- exception is ATLAS TRT
  - ➡ rate of good hit (leading edge seen) drops
  - ➡ momentum resolution slowly deteriorates



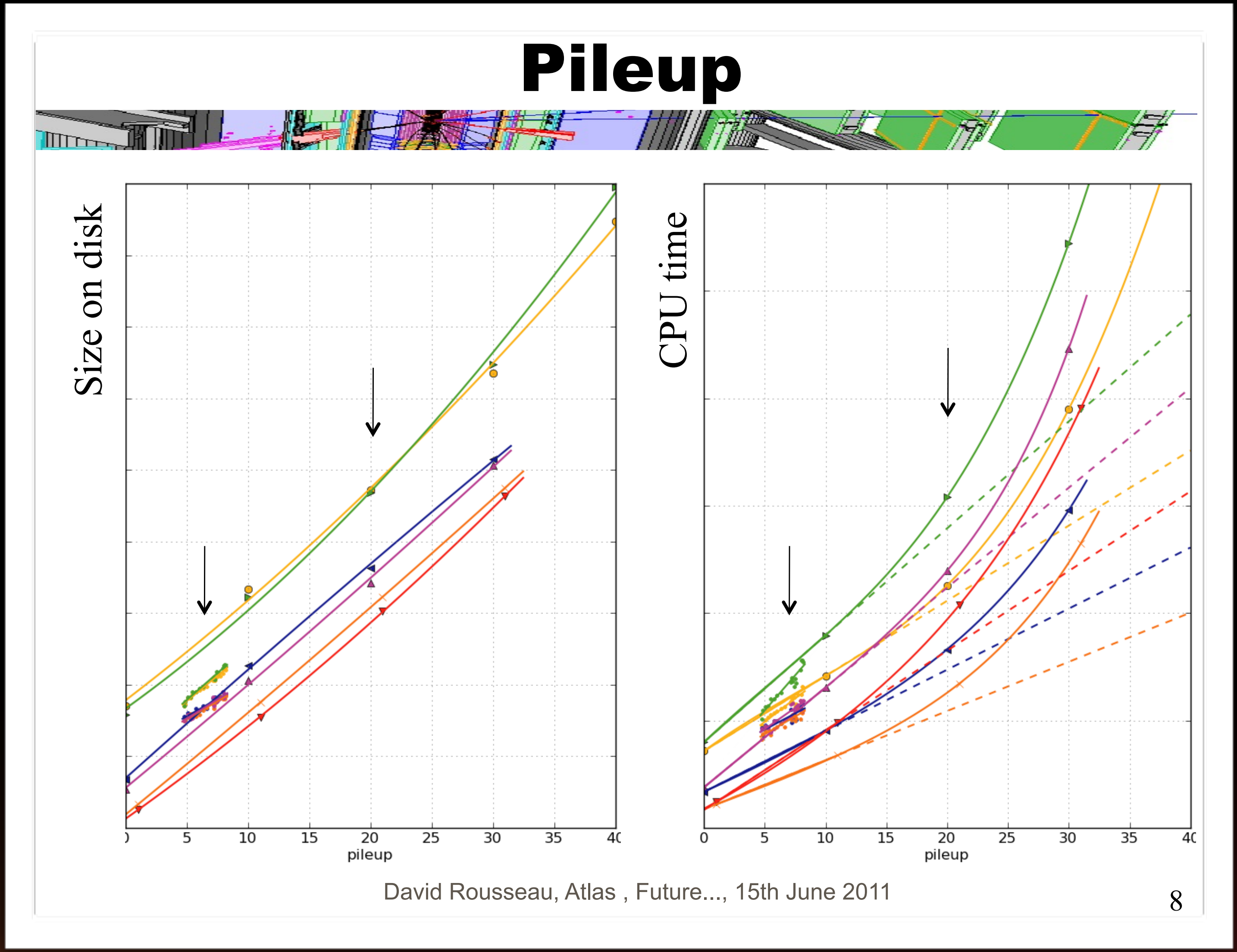




Pileup and Computing Resources

- resource needs scale fast
  - ➡ tracking is a resource driver

- tracking principles:
  - ➡ combinatorial problem
  - ➡ naive scaling
    - like ~n!
  - ➡ clever tracking strategies
    - dampen it to $\sim n^2$ or $\sim n^3$



Pileup

David Rousseau, Atlas , Future..., 15th June 2011

8

- natural tension between
  - ➡ desire to maximize physics
  - ➡ requirement to stay within available resources

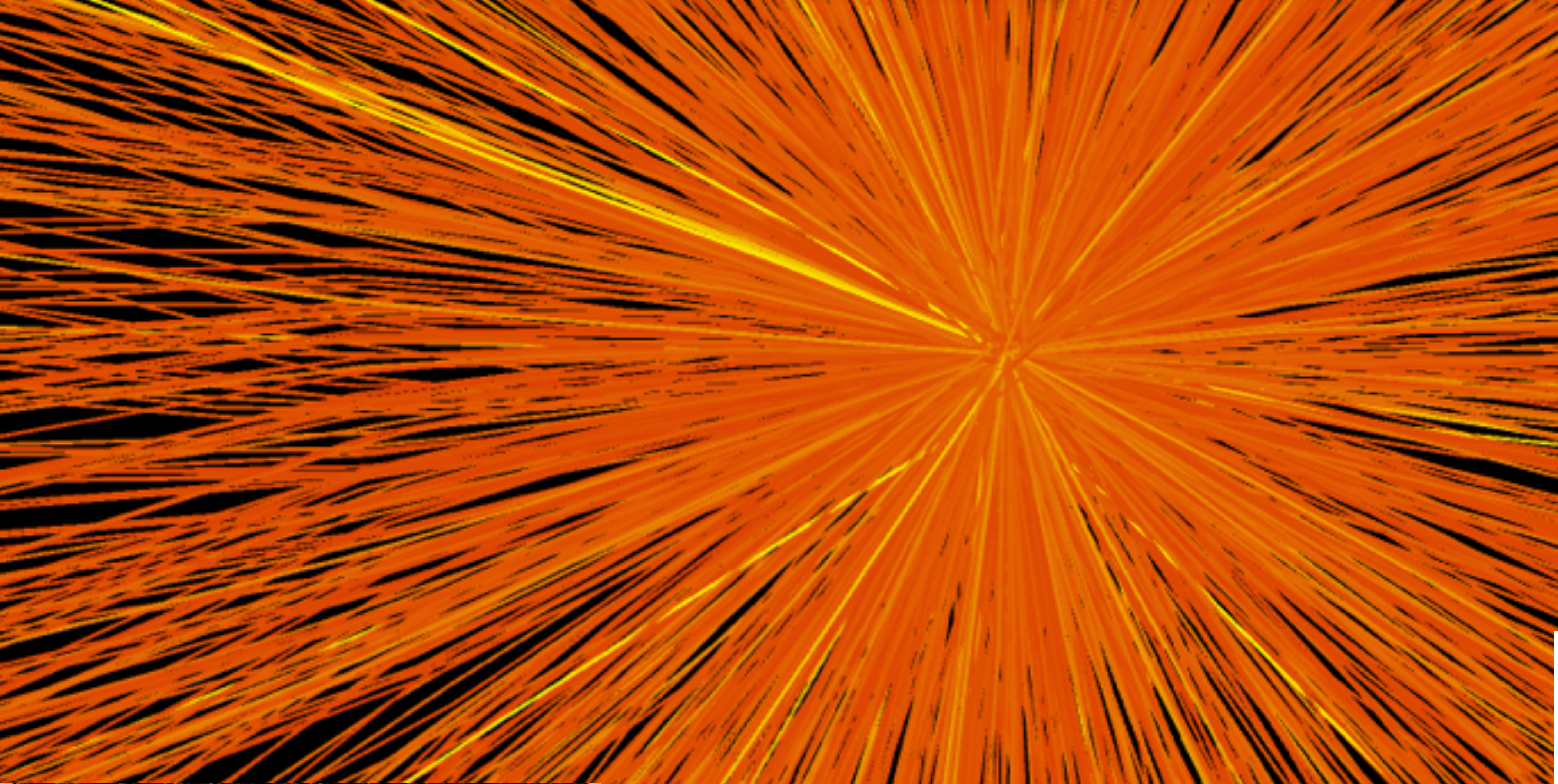
Reconstruction Strategy vs Pileup (ATLAS)

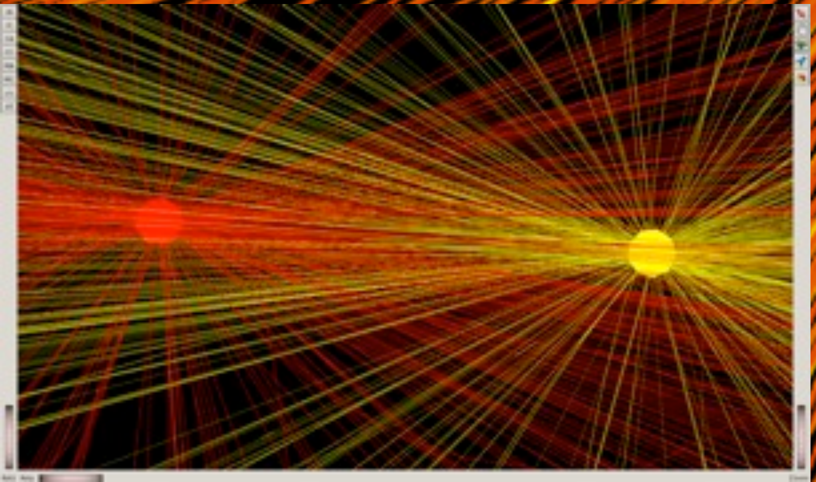
2009 / early 2010	commissioning Min.Bias	pt > 50 MeV open cuts, robust settings min. 5 clusters
2010 stable running < ~4 events pileup	low lumi physics program (soft QCD, b-physics, ...), b-tagging...	pt > 100 MeV min. 7 clusters
2011 pp running ~8 events pileup	focus more on high-pt physics (top, W/Z, Higgs), b-tagging...	pt > 400 MeV, harder cuts in seeding min. 7 clusters
Phase I upgrade including IBL 24-50 events pileup	high-pt physics, study new physics (I hope), b-tagging....	pt > 900 MeV, harder tracking cuts, min. 9 clusters
SLHC up to 100-200 events pileup	replace Inner Detector to cover very high luminosity physics program	further evolve strategy... R-o-I or z-vertex seeding, reco. per trigger type, GPUs

- ➡ requirements on tracking evolves with physics program
- ➡ different luminosity regimes require different working points

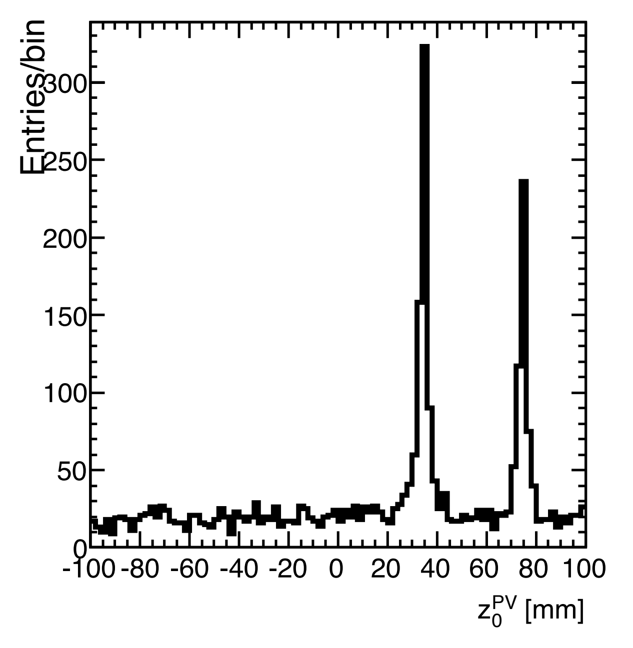
Tracking in Heavy Ions

- What if the tracker suddenly looks like this ?

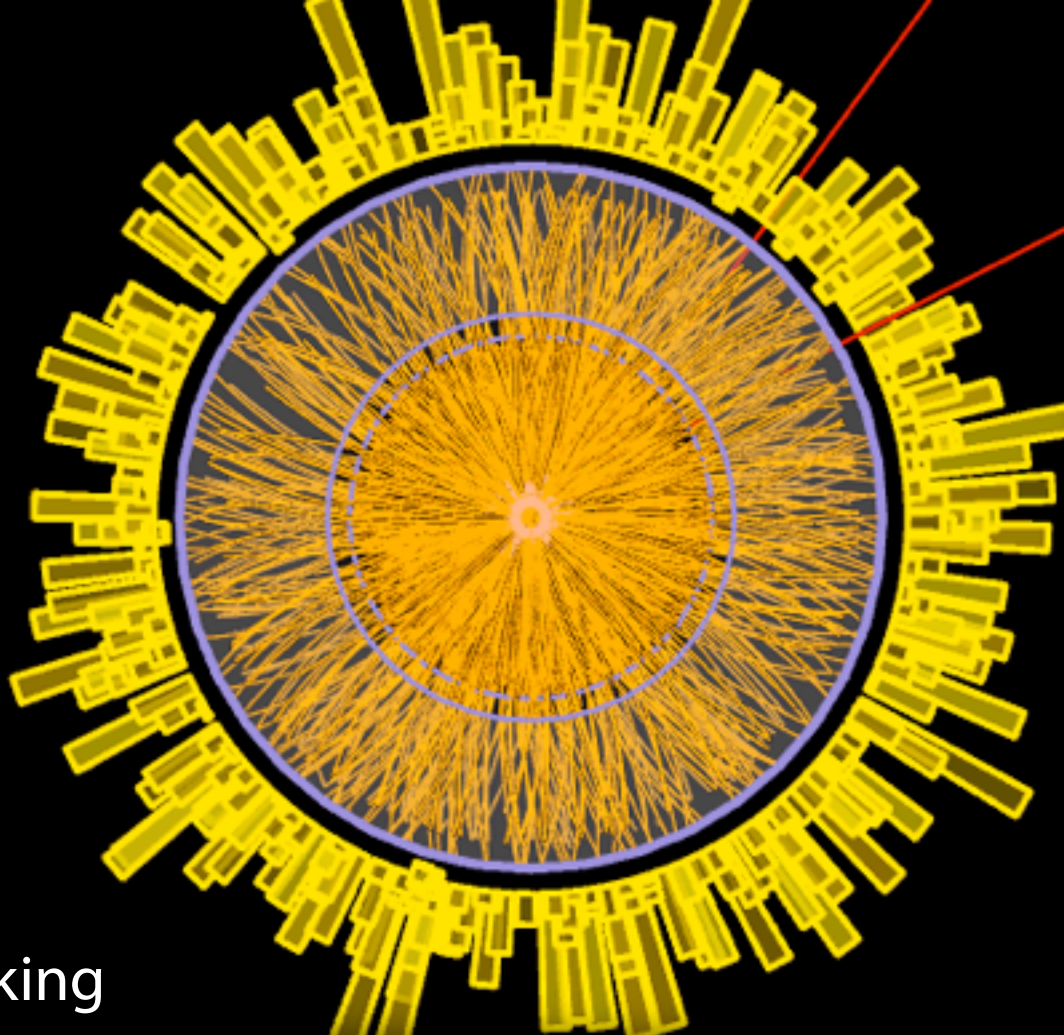




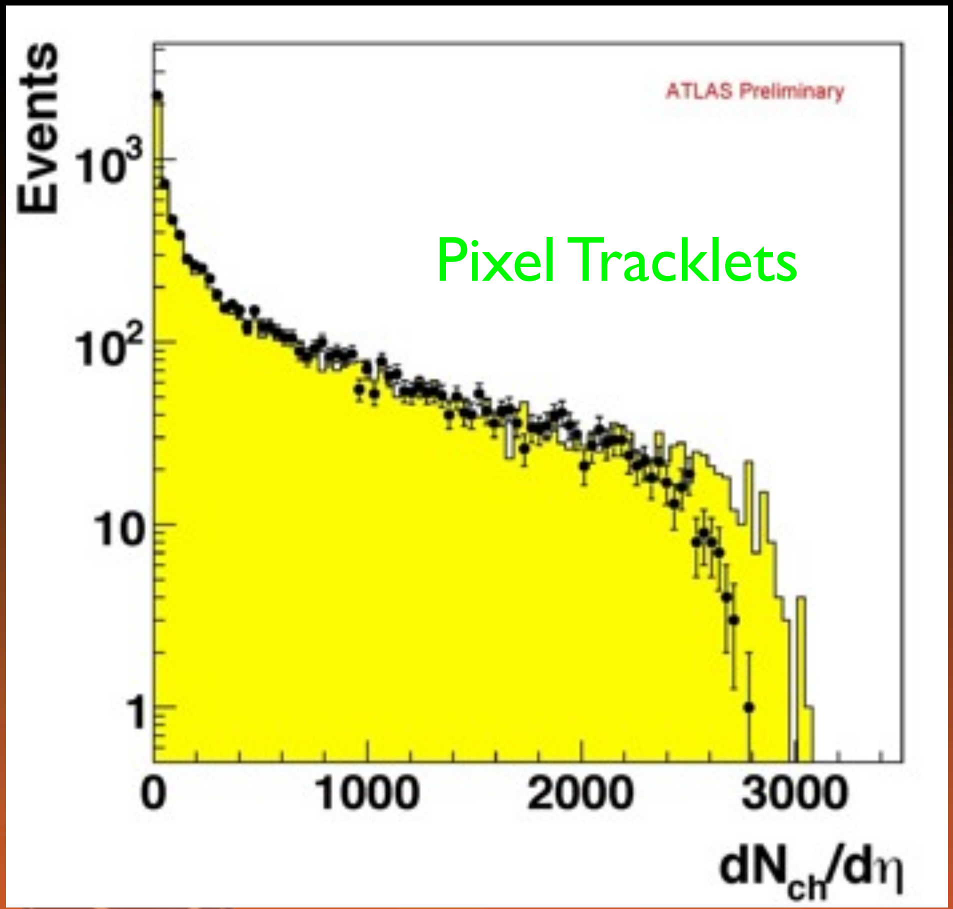
2 central Pb-Pb events pileup,
result was a timeout crash in Tier-0

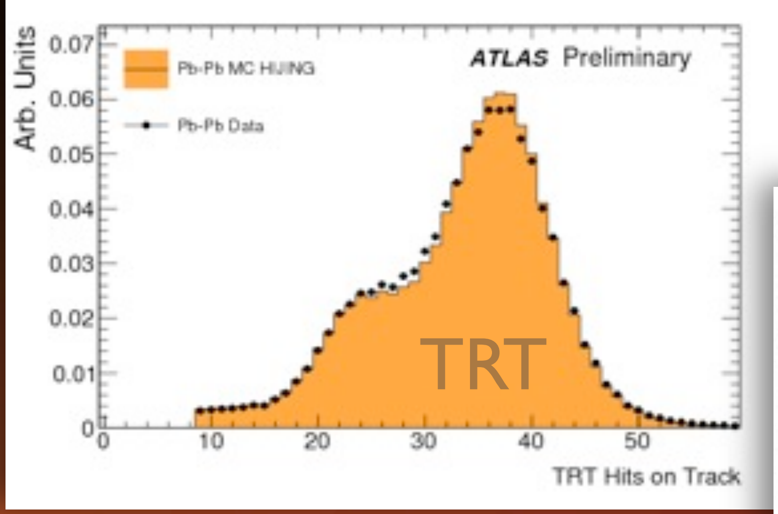


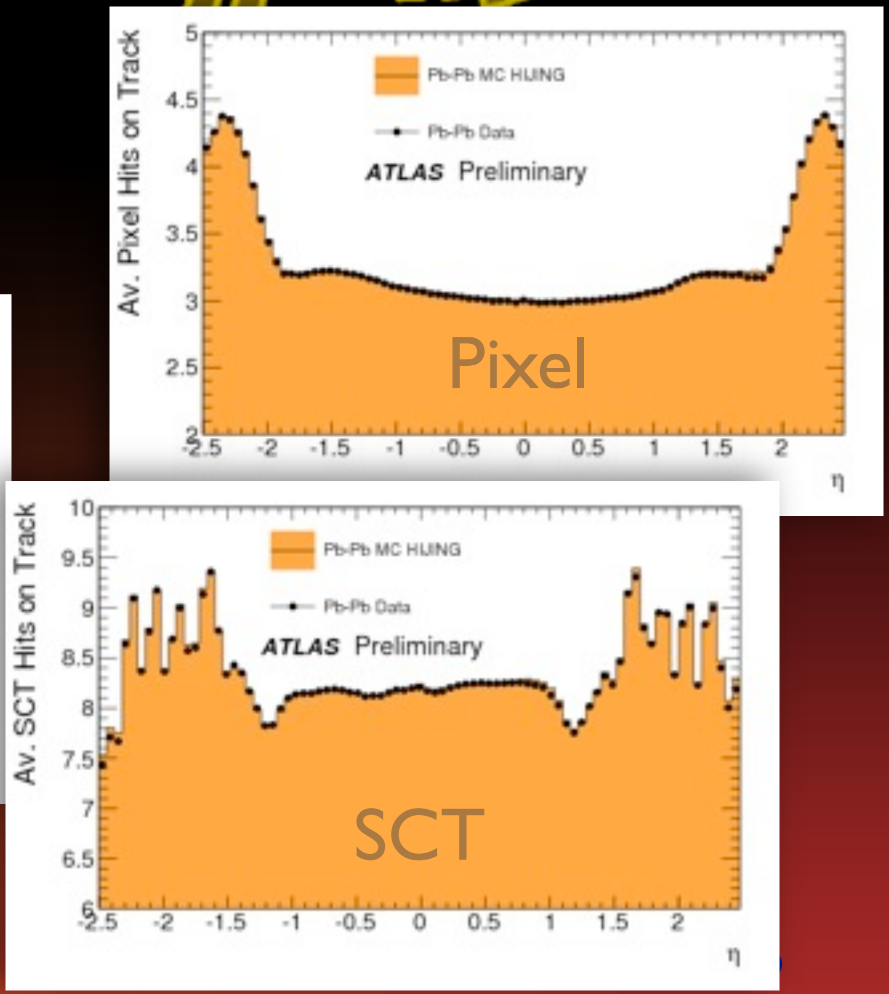
Heavy Ion Tracking

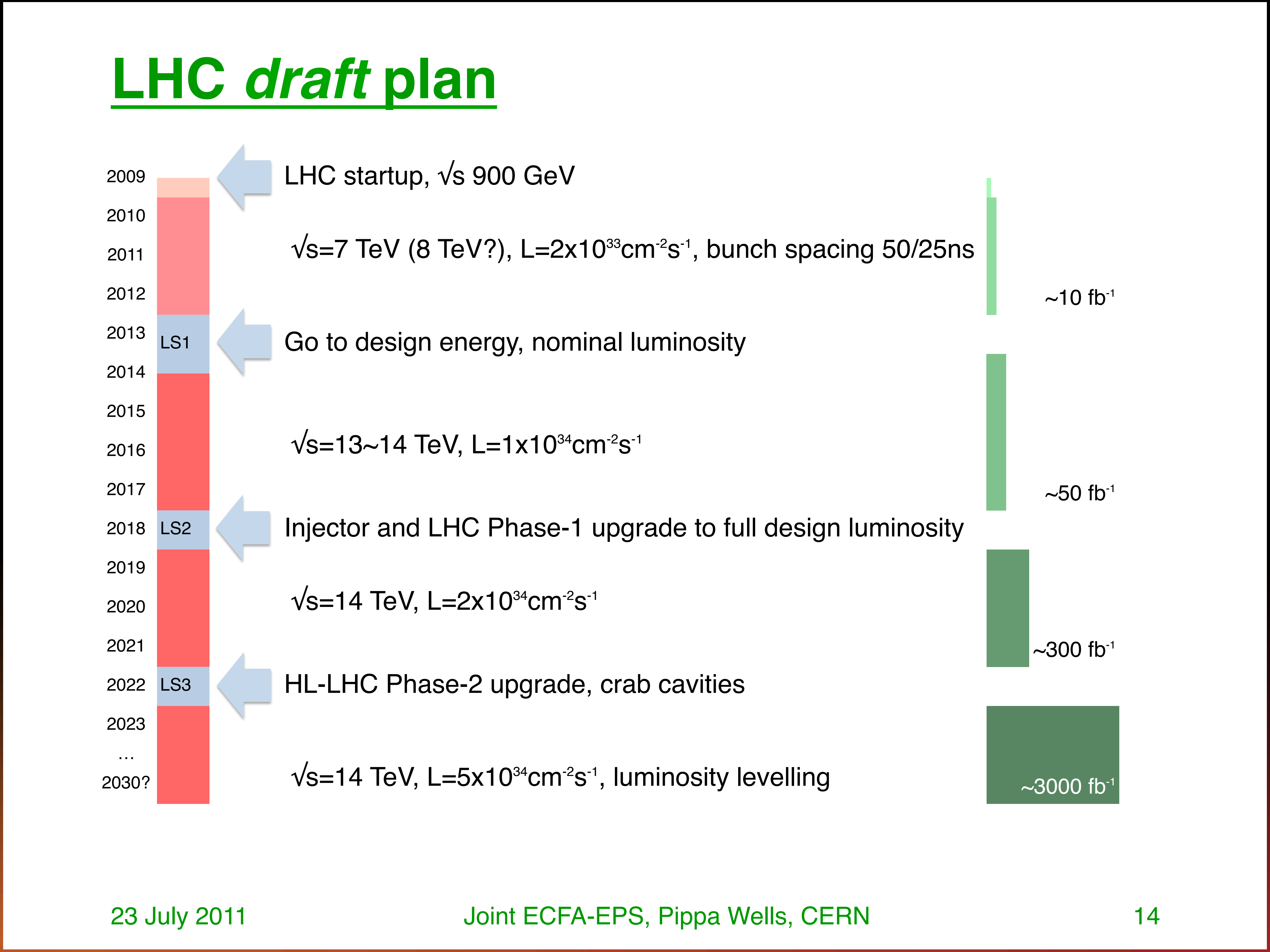


- high multiplicity tracking
  - ➡ adapt seed finding
    (z vertex constraint to save CPU)
  - ➡ tighten hit requirement to control fakes in central events (similar to sLHC setup)
- excellent tracking performance
  - ➡ good testing ground for high occupancy tracking
  - ➡ can study performance vs “centrality” (occupancy)









LHC *draft* plan

2009

LHC startup, $\sqrt{s}$ 900 GeV

2010

2011

$\sqrt{s}$=7 TeV (8 TeV?), L=2x10^{33}cm^{-2}s^{-1}, bunch spacing 50/25ns

2012

~10 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}

2017

~50 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}

2021

~300 fb^{-1}

2022 LS3

HL-LHC Phase-2 upgrade, crab cavities

2023

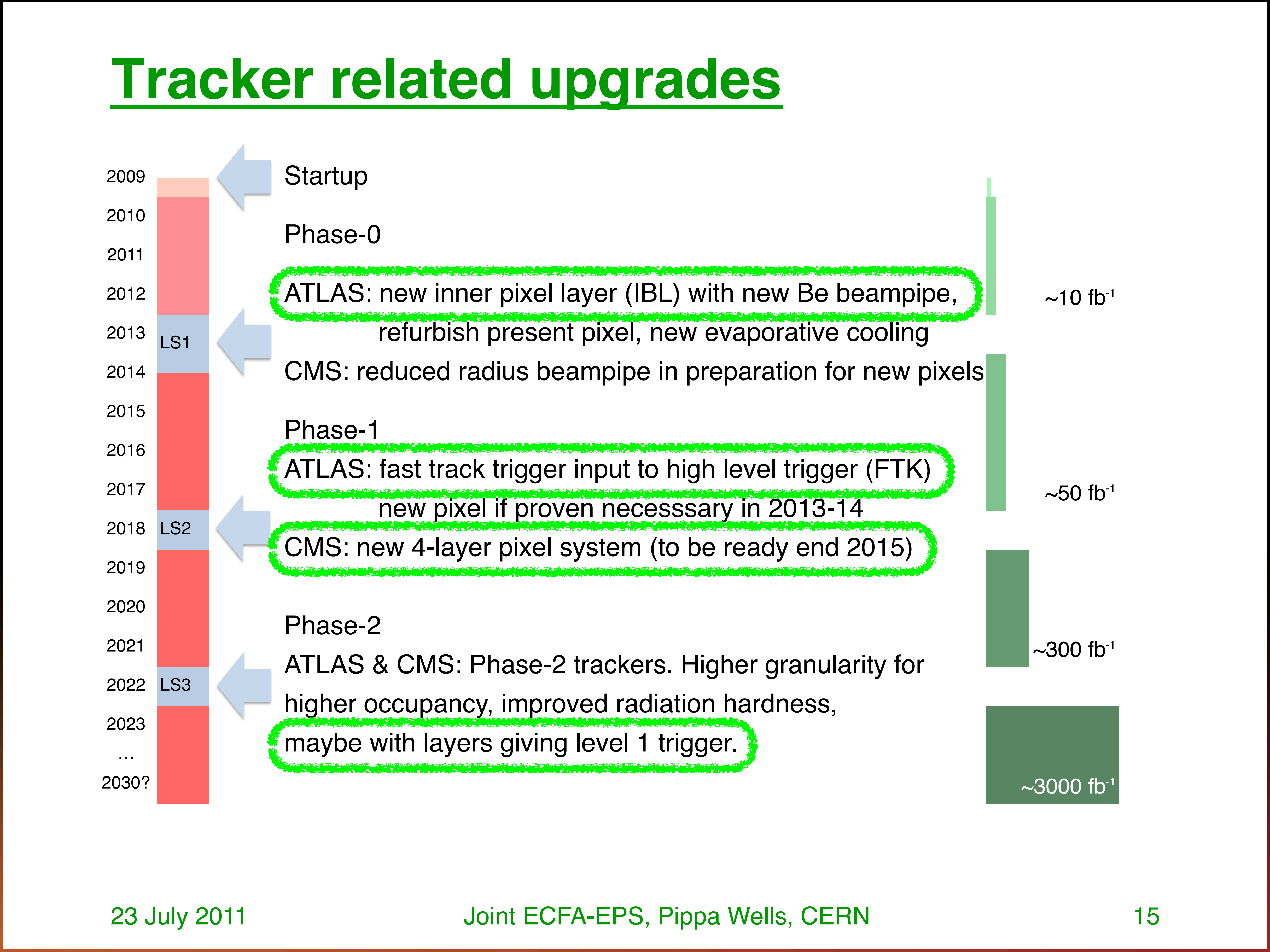
…

2030?

$\sqrt{s}$=14 TeV, L=5x10^{34}cm^{-2}s^{-1}, luminosity levelling

~3000 fb^{-1}

23 July 2011 Joint ECFA-EPS, Pippa Wells, CERN 14



Tracker related upgrades

Startup

Phase-0

ATLAS: new inner pixel layer (IBL) with new Be beampipe,
refurbish present pixel, new evaporative cooling

CMS: reduced radius beampipe in preparation for new pixels

Phase-1

ATLAS: fast track trigger input to high level trigger (FTK)
new pixel if proven necesssary in 2013-14

CMS: new 4-layer pixel system (to be ready end 2015)

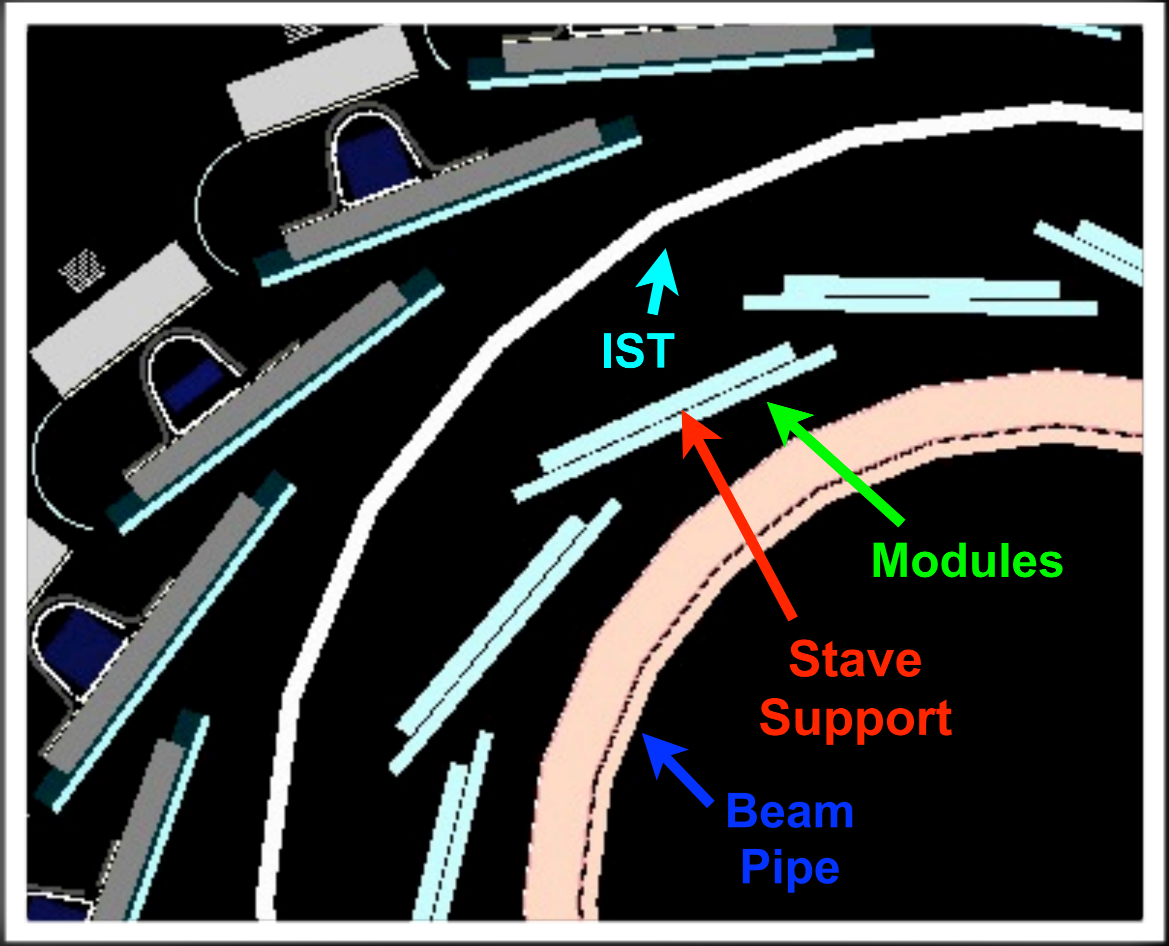
Phase-2

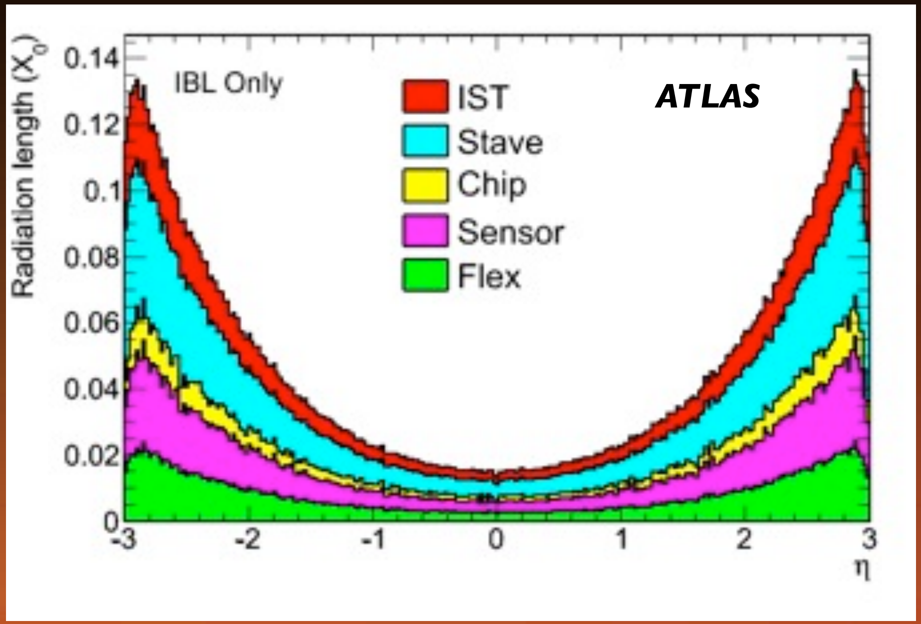
ATLAS & CMS: Phase-2 trackers. Higher granularity for higher occupancy, improved radiation hardness, maybe with layers giving level 1 trigger.

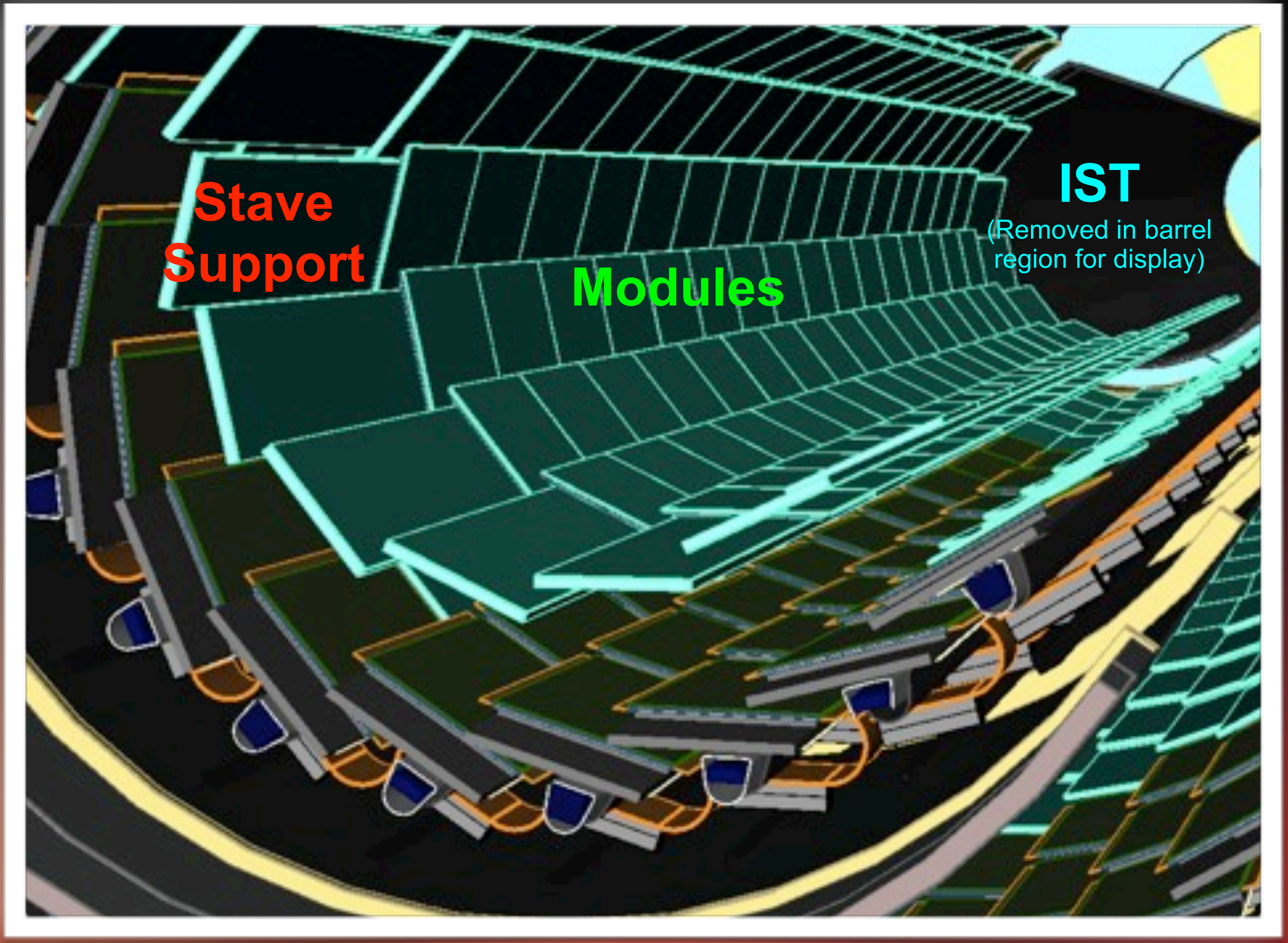
23 July 2011 Joint ECFA-EPS, Pippa Wells, CERN 15

ATLAS Upgrade: IBL

- **I**nsertable **B**-**L**ayer
  - ➡ 4th Pixel layer
  - ➡ smaller beam pipe (R_{min} = 25 mm)
  - ➡ IBL material adjusted to 1.5% X0
  - ➡ smaller z pitch (250 um)
- installation next shutdown
  - ➡ 2013/2014
  - ➡ ready for 14 TeV running
  - ➡ peak luminosities of $2*10^{34}$ $cm^{-2}s^{-1}$
  - ➡ 25-50 pileup events





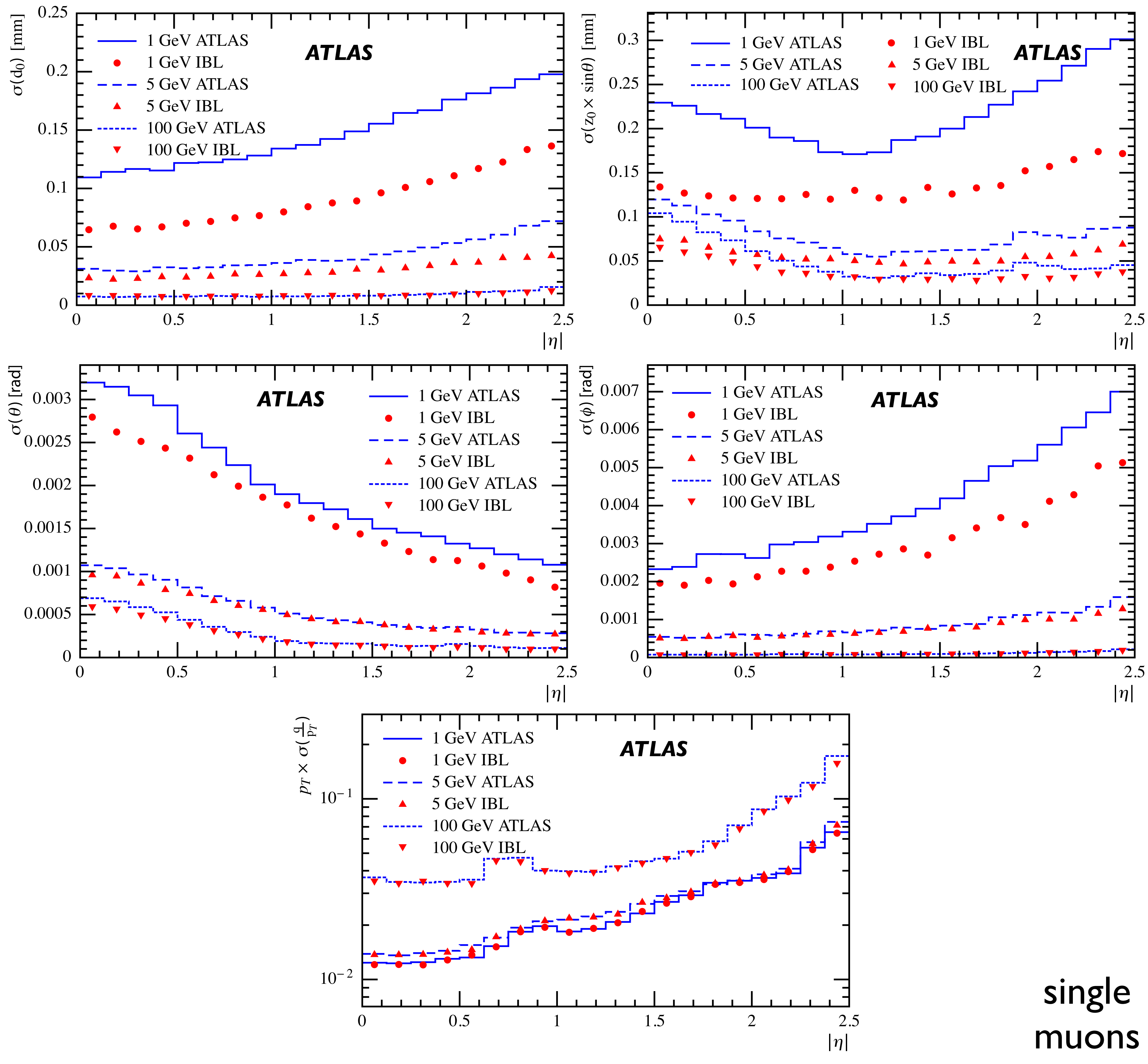


Tracking Performance with no Pileup

- expected results
  - ➡ smaller radius
  - ➡ small z pitch
  - ➡ less material between first and 2nd layer
  - ➡ track length ~ same

- improvements
  - ➡ better d_0 resolution
  - ➡ better z_0 resolution
  - ➡ θ and ϕ improved at low-pT
  - ➡ momentum resolution ~ unchanged

- as expected !

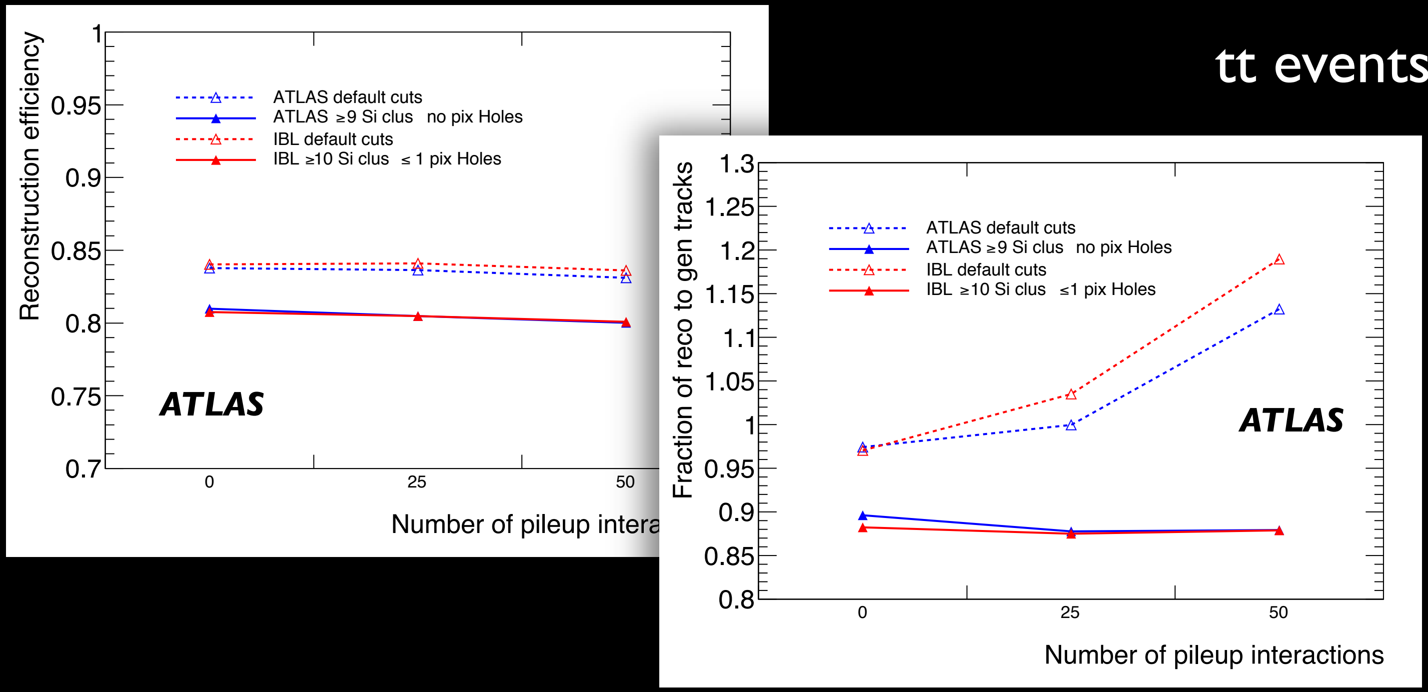


single muons

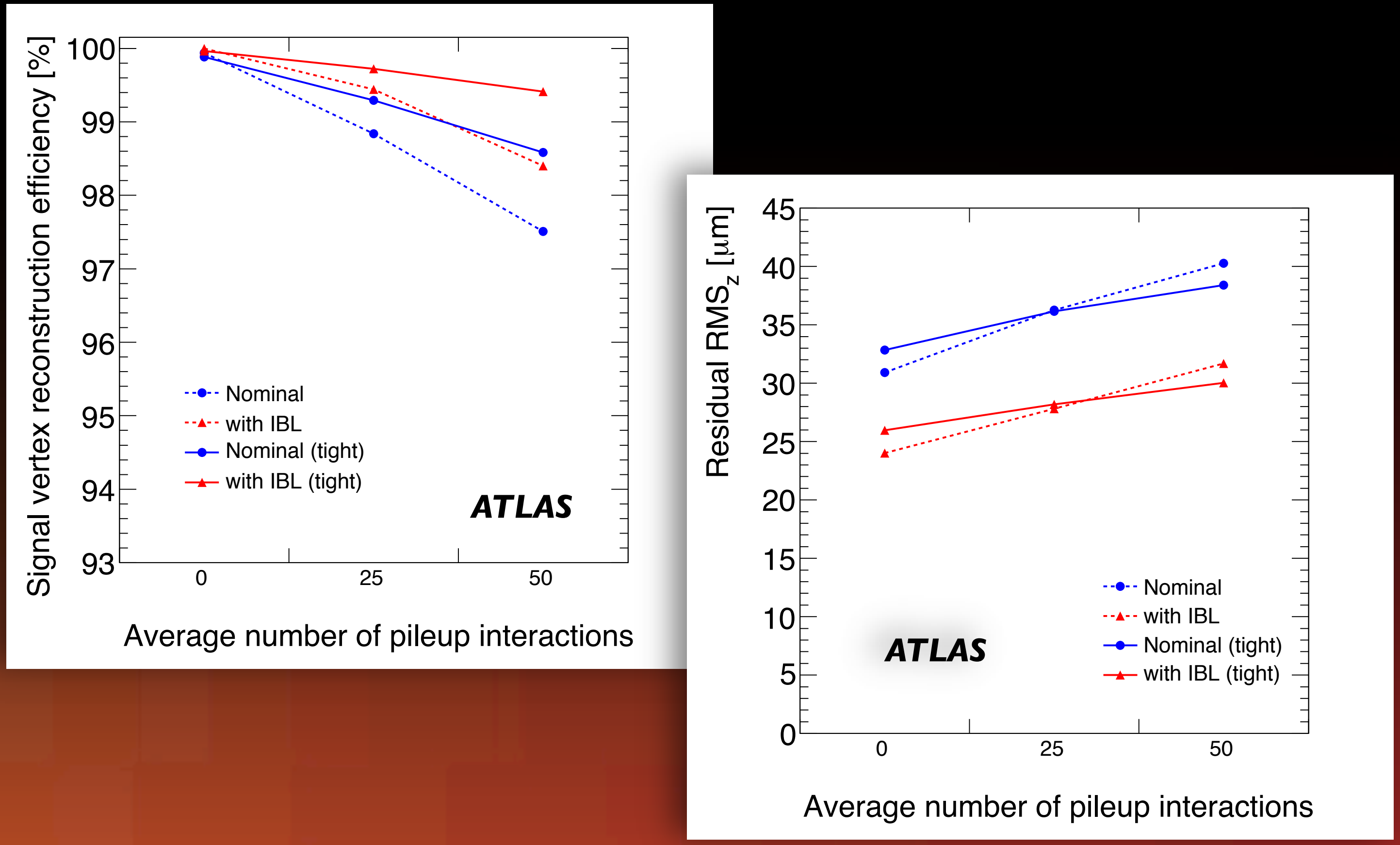
Tracking and Vertexing with High Pileup

- pileup selection with IBL
  - ➡ similar to current ATLAS
  - ➡ ≥10 IBL+Pixel+SCT hits, ≤1 pixel hole
  - ➡ benefit from additional layer
  - ➡ leaves room for eventual inefficiencies in b-layer (tracking robustness)

tt events

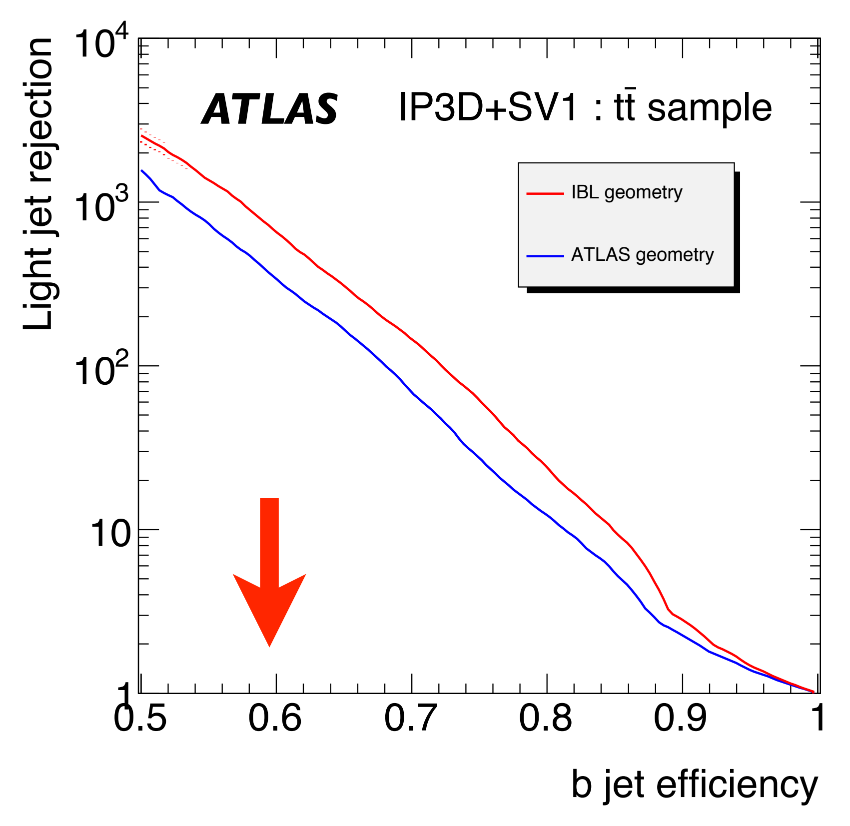


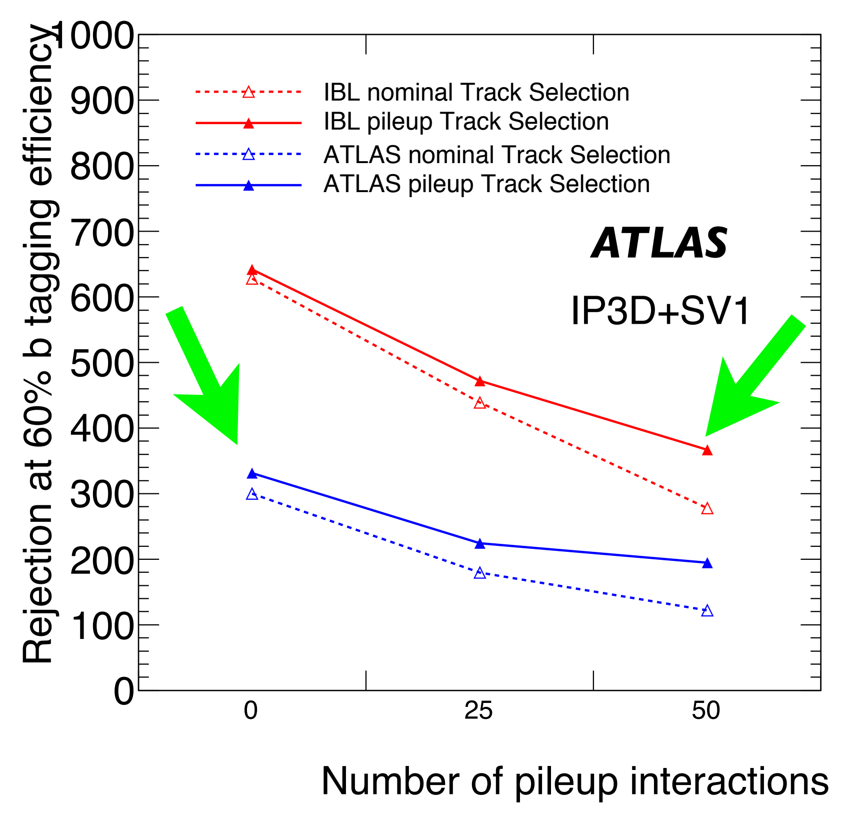
- vertexing with pileup
  - ➡ pileup effects visible
  - ➡ with IBL gains in resolution and vertex tail fraction as well with pileup
  - ➡ signal vertex efficiency affected
  - ➡ pileup selection better overall



b-Tagging with IBL and Pileup

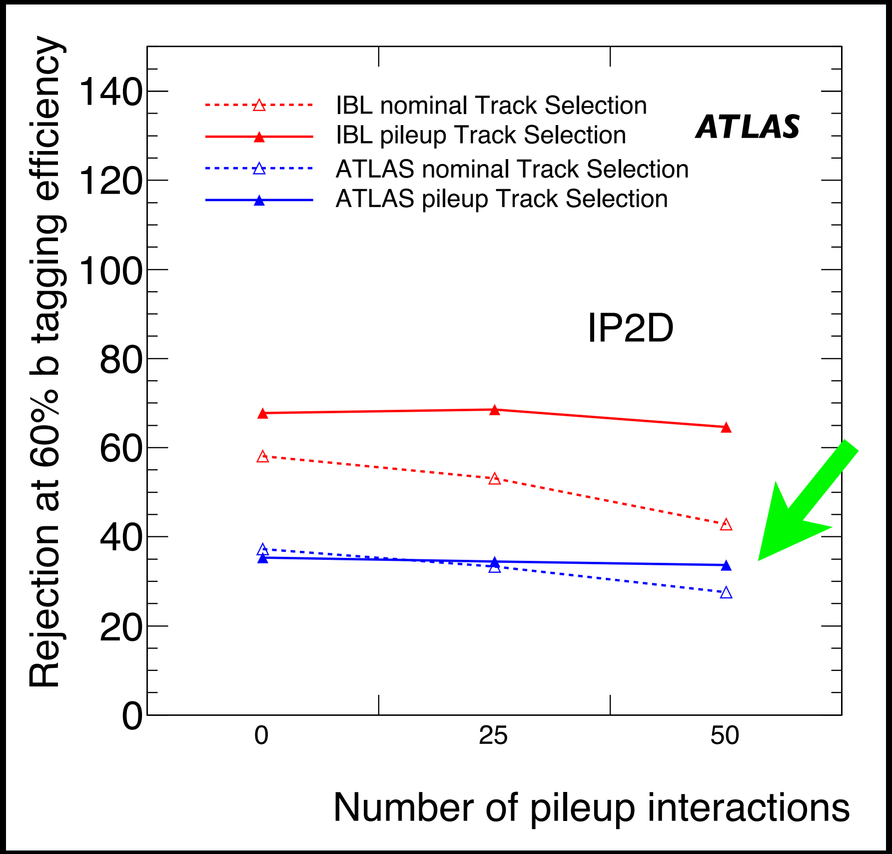
- example state of the art b-tagging
  - ➡ "IP3D" ~ $d_0 \oplus z_0$ impact significance likelihood
  - ➡ "IP3D+SV1" ~ adding secondary vertex information
- pileup affects b-tagging in many ways
  - ➡ additional jets and fake jets from in/out of time pileup
    - restrict to truth jets to get comparable results
    - real data: can use e.g. Jet-Vertex-Fraction
  - ➡ close-by pileup vertices
    - additional b-tag tracks
    - lead to significant z_0 offsets affecting IP3D
- good performance with IBL and pileup
  - ➡ as good or better as for current ATLAS without pileup

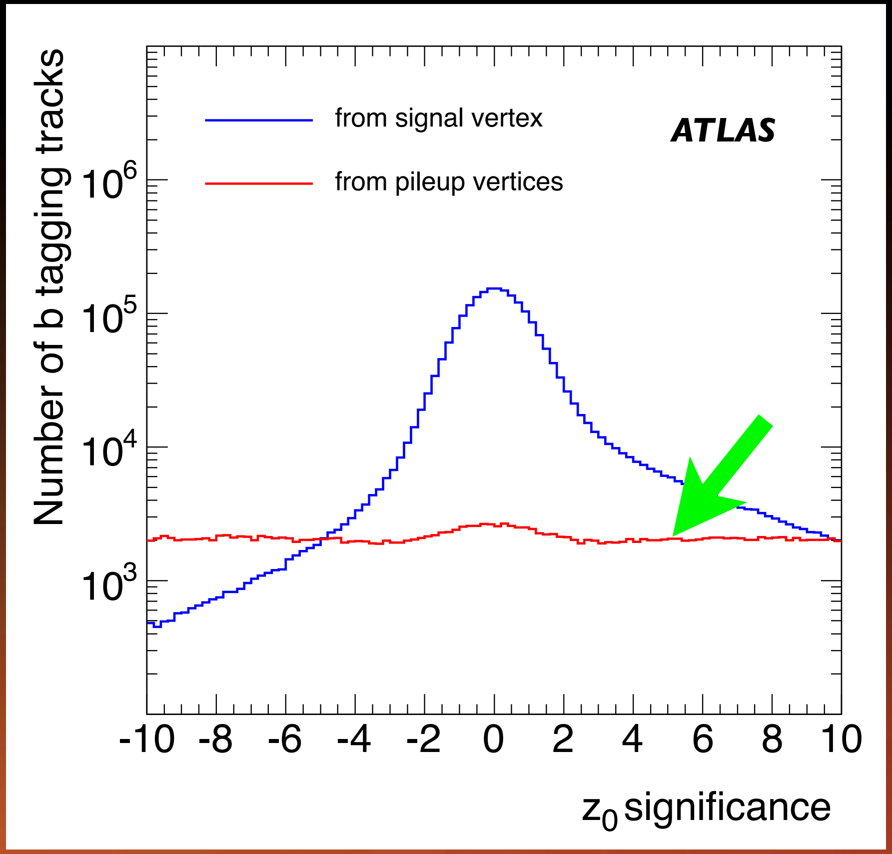


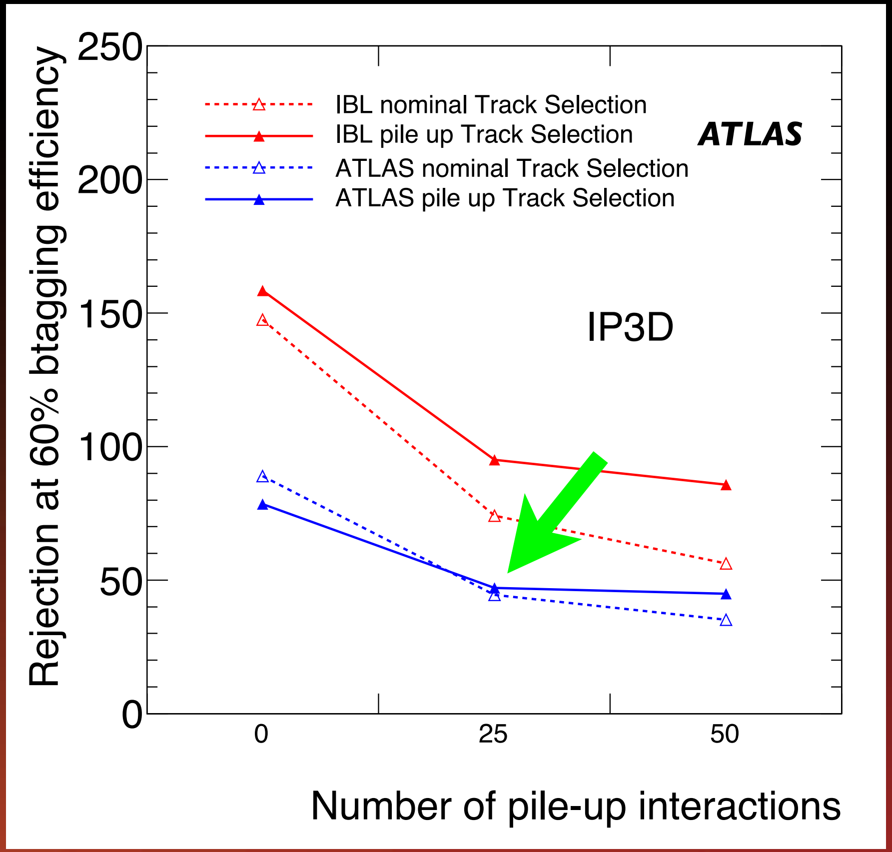


b-Tagging with Pileup

- performance could degrade fast
  - ➡ especially IP3D is very sensitive to tracks from nearby pileup vertices
  - ➡ significant z offsets due to nearby pileup vertices
    - needed to add cut to veto pileup tracks: **dz < 3.8σ if d0 < 2σ**
  - ➡ IP2D (Rϕ only)is much more "stable"

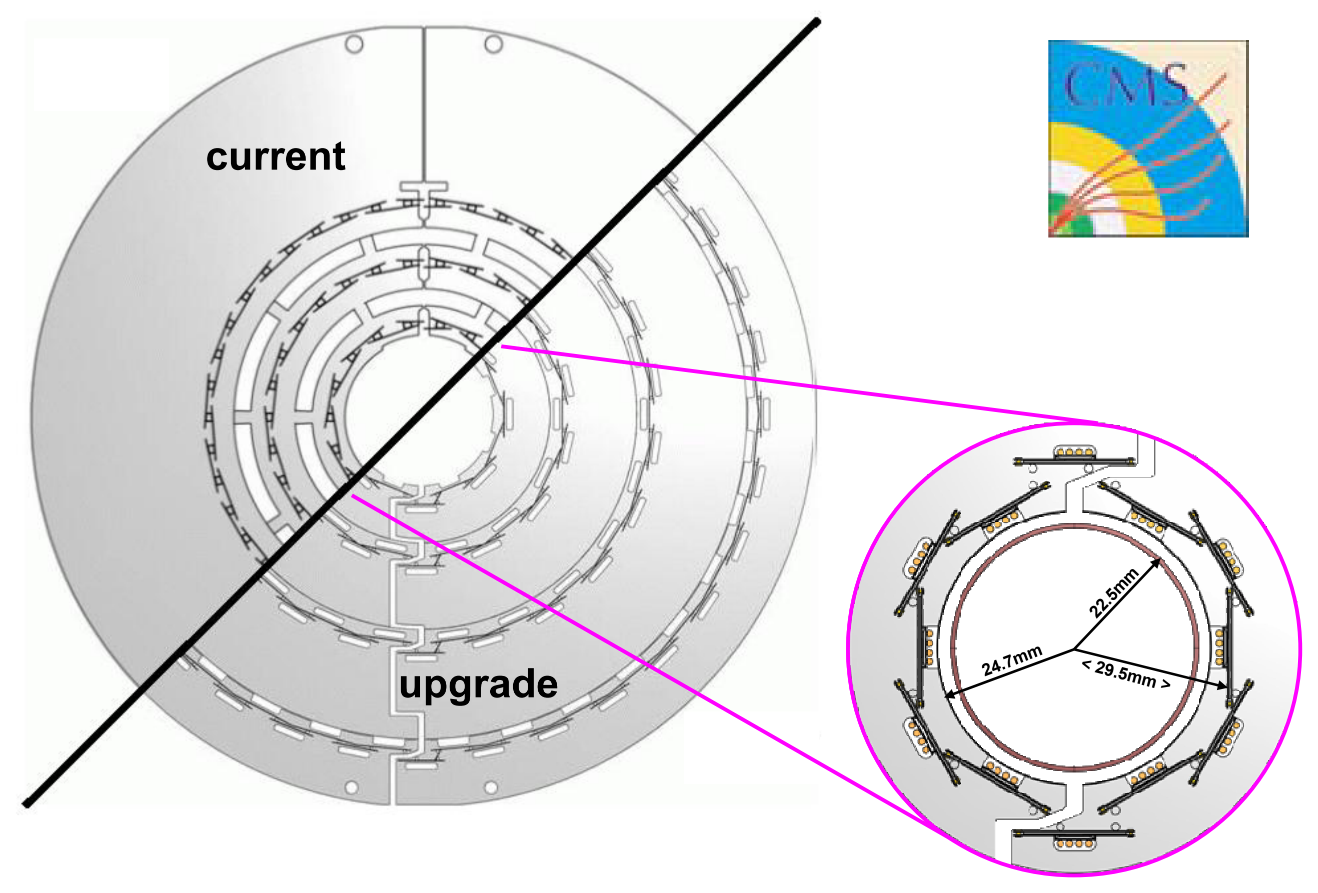


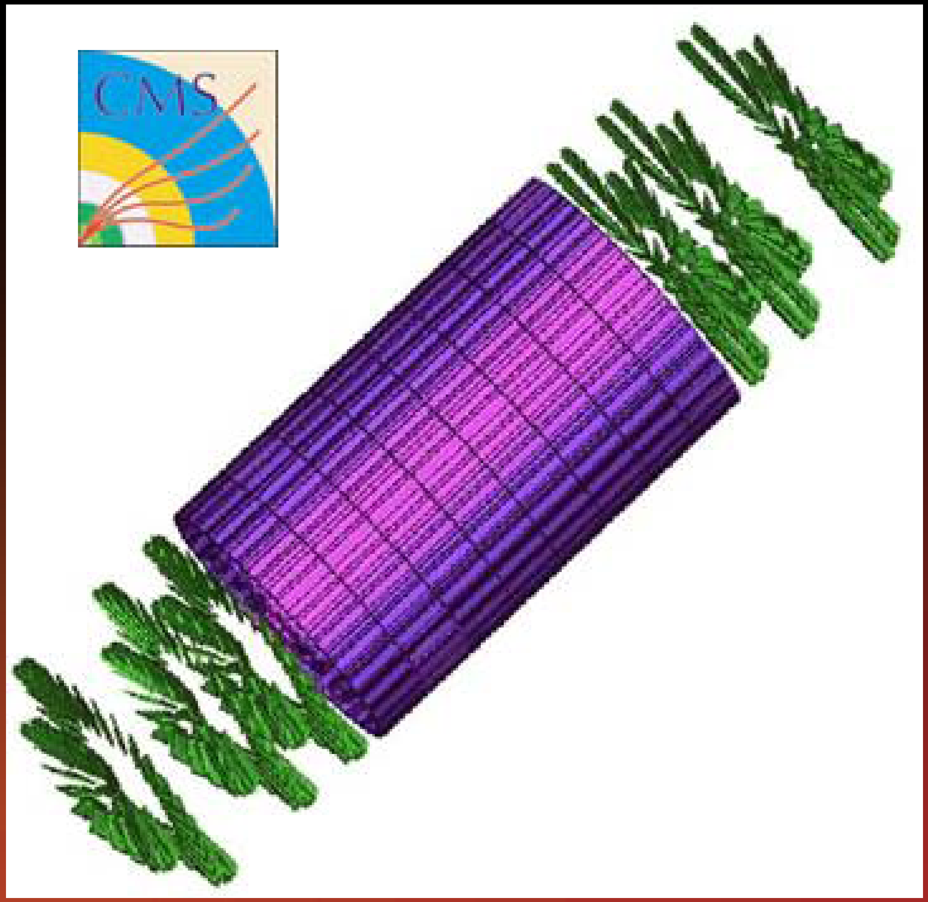




CMS Pixel Upgrade

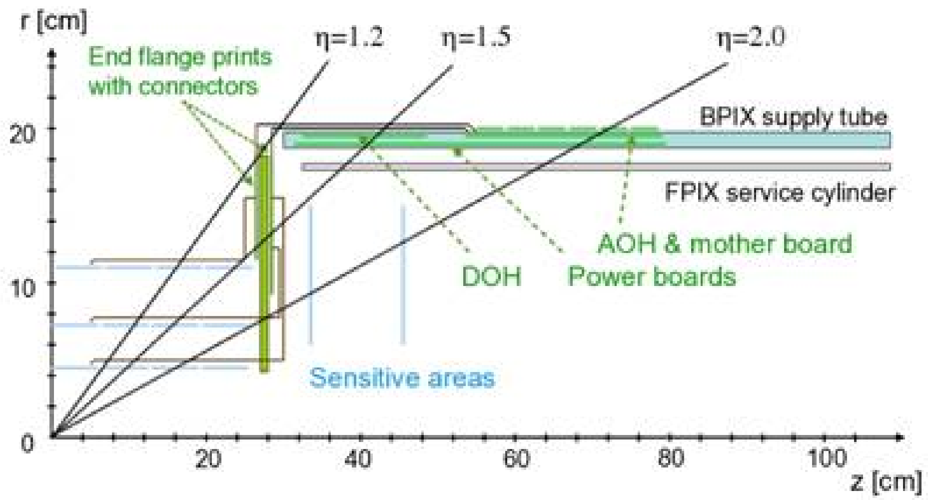
- goals of the upgrade
  - ➡ replace 3 layer, 2x2 disk system with a 4 layer, 2x3 disk system
    - hence 4 space points instead of 3
  - ➡ CO_2 cooling and move material to larger eta
    - significantly reduce X/X_0
  - ➡ reduce radius of innermost layer
    - better impact resolution
  - ➡ readout upgrade to be able to operate up to $2 \cdot 10^{34}$ occupancies





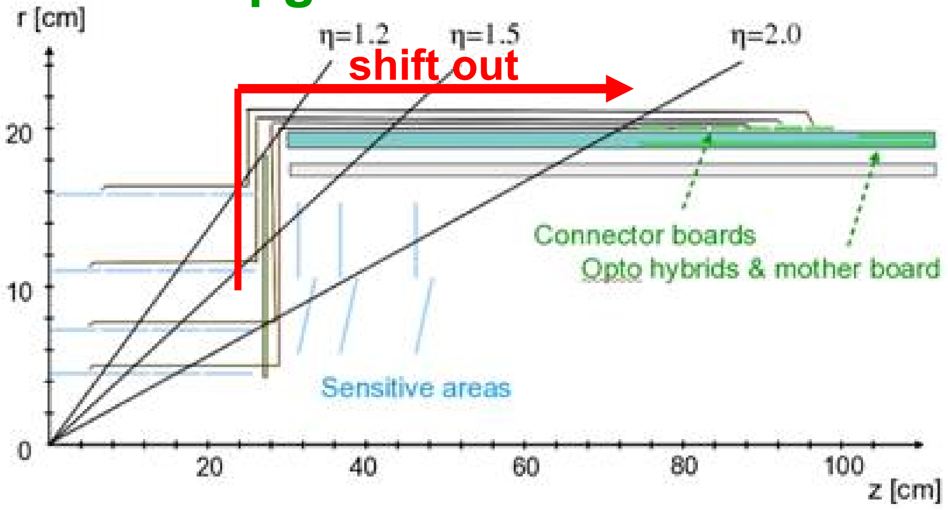
Shift Material out of Tracking Region

Current BPIX Services

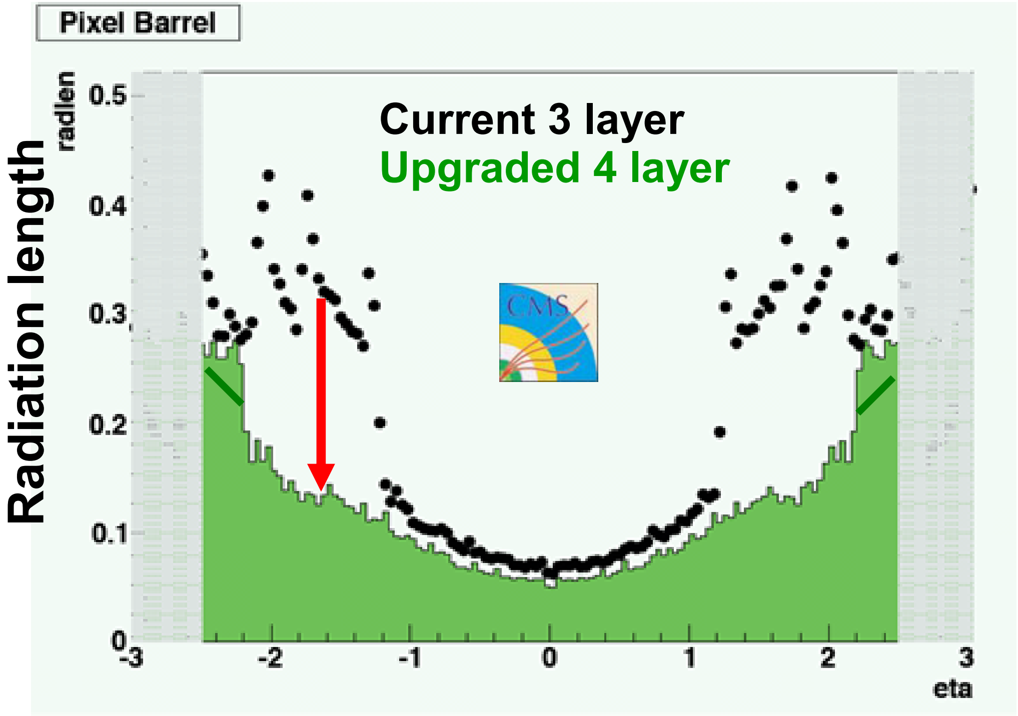


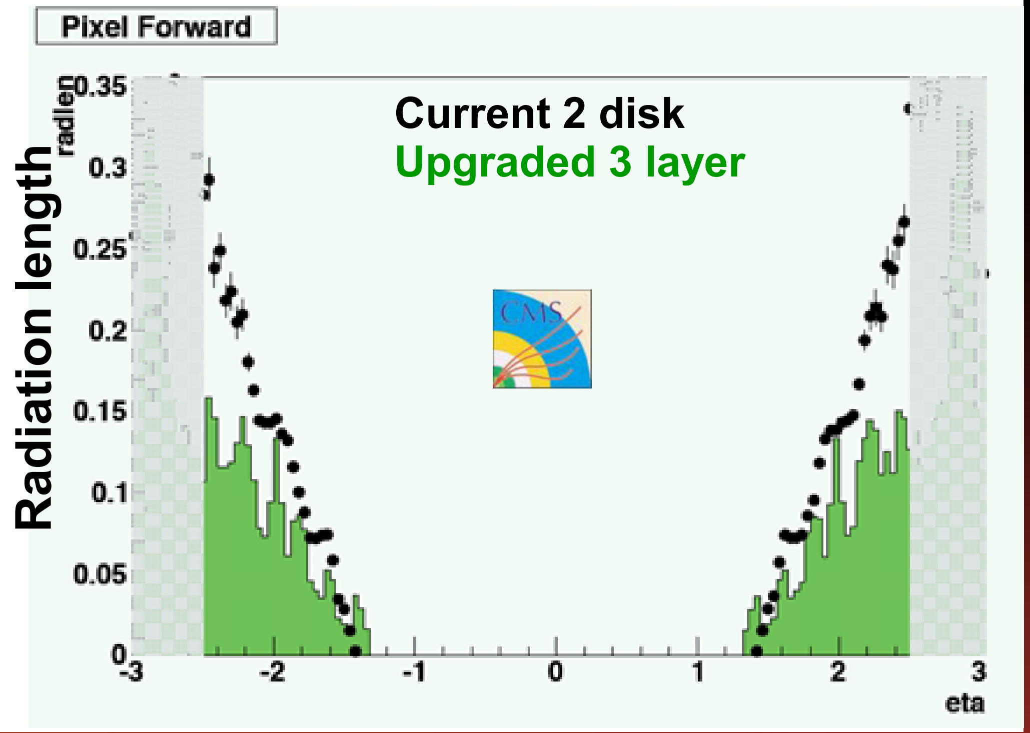
η<2.2 : weight = 16.9 Kg (3 layer)

Upgraded BPIX Services



η<2.2 : weight = 6.5 Kg (4 layer)

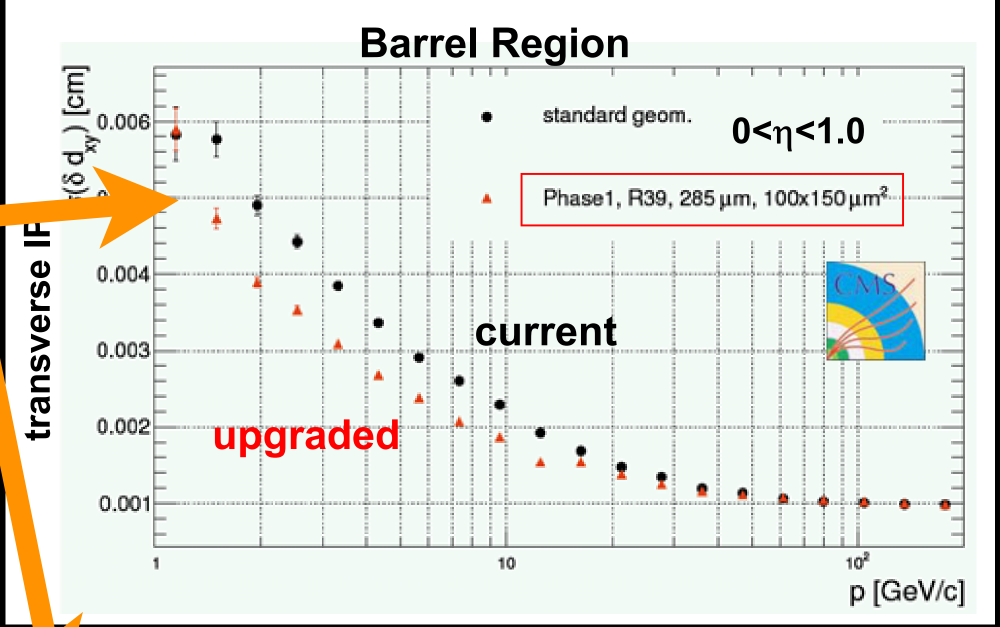


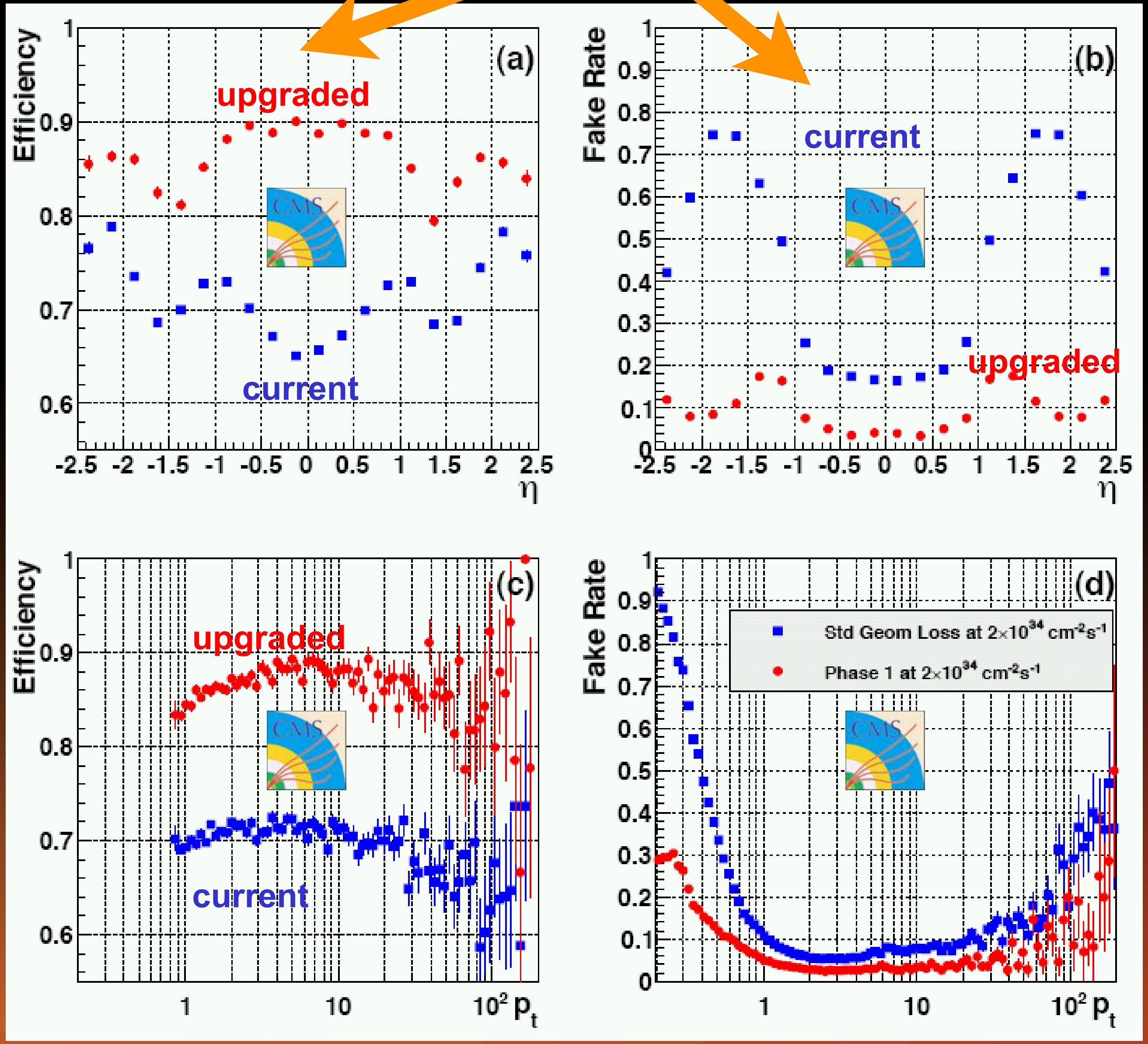


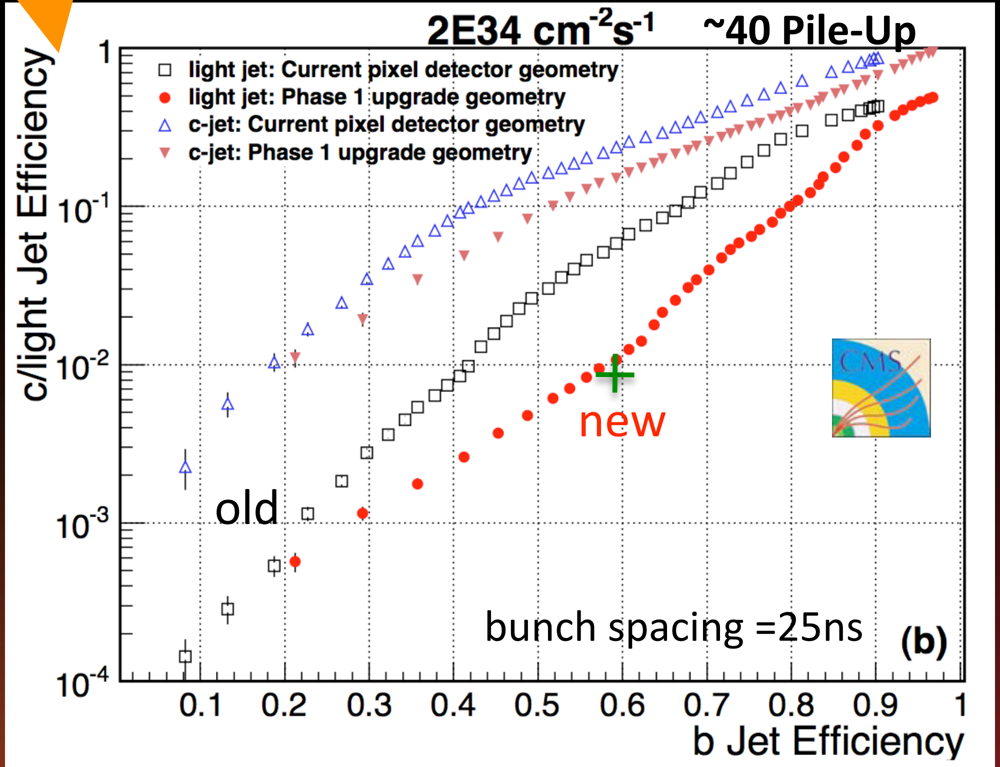
Markus Elsing

Effect on Physics Performance

- huge gains expected
  - ➡ especially for IP resolution and b-tagging
  - ➡ improved track seeding using 4 Pixel hits

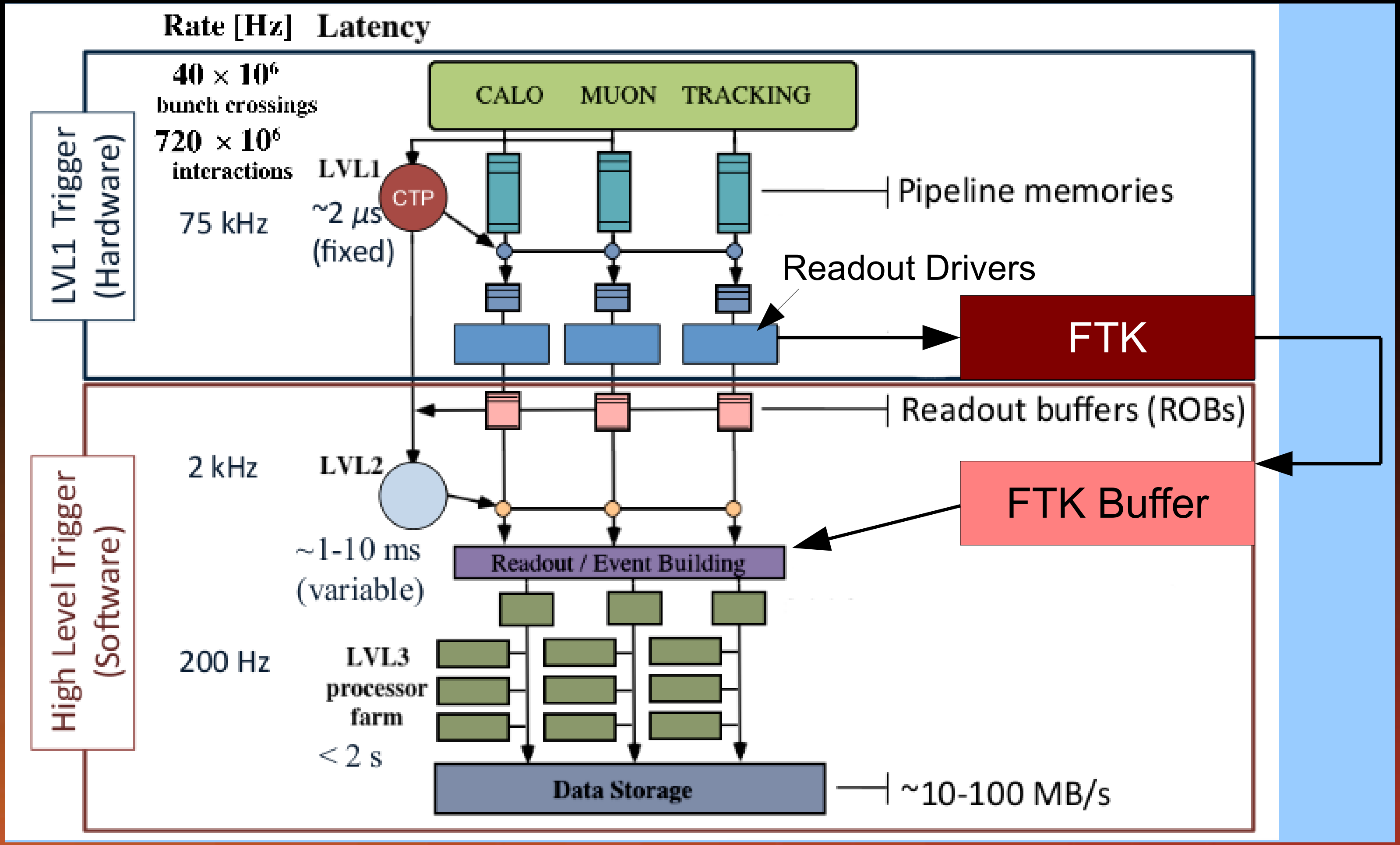






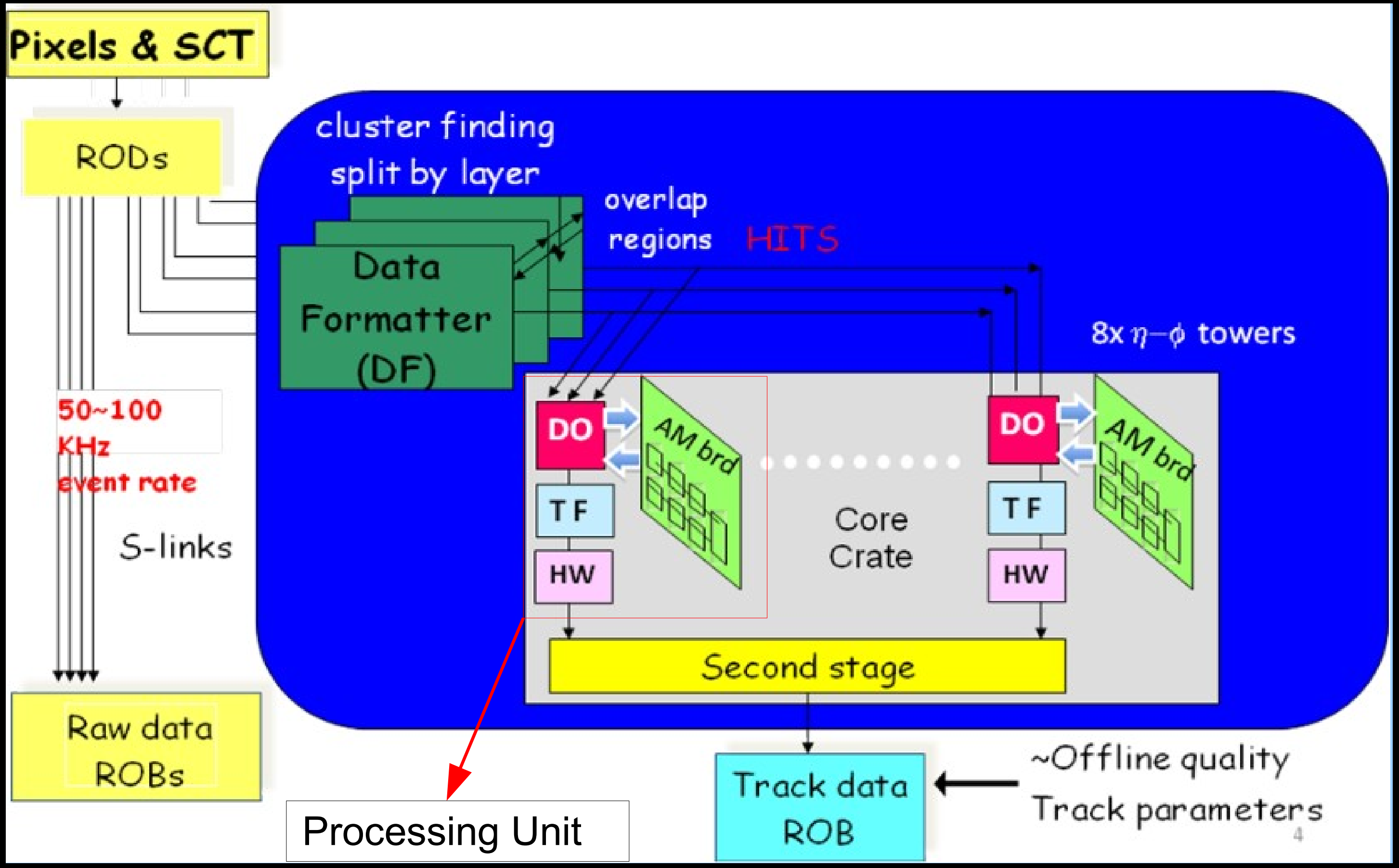
ATLAS Hardware Trigger Tracking (FTK)

- goal is to provide high quality tracks at input to High Level Trigger
  - ➡ FTK runs at nominal 100 *kHz* Level-1 trigger rate
- physics motivation
  - ➡ *b* and *τ* tagging, lepton isolation, improve Level-2 rejection at high lumi.
- requires hardware system with special readout links

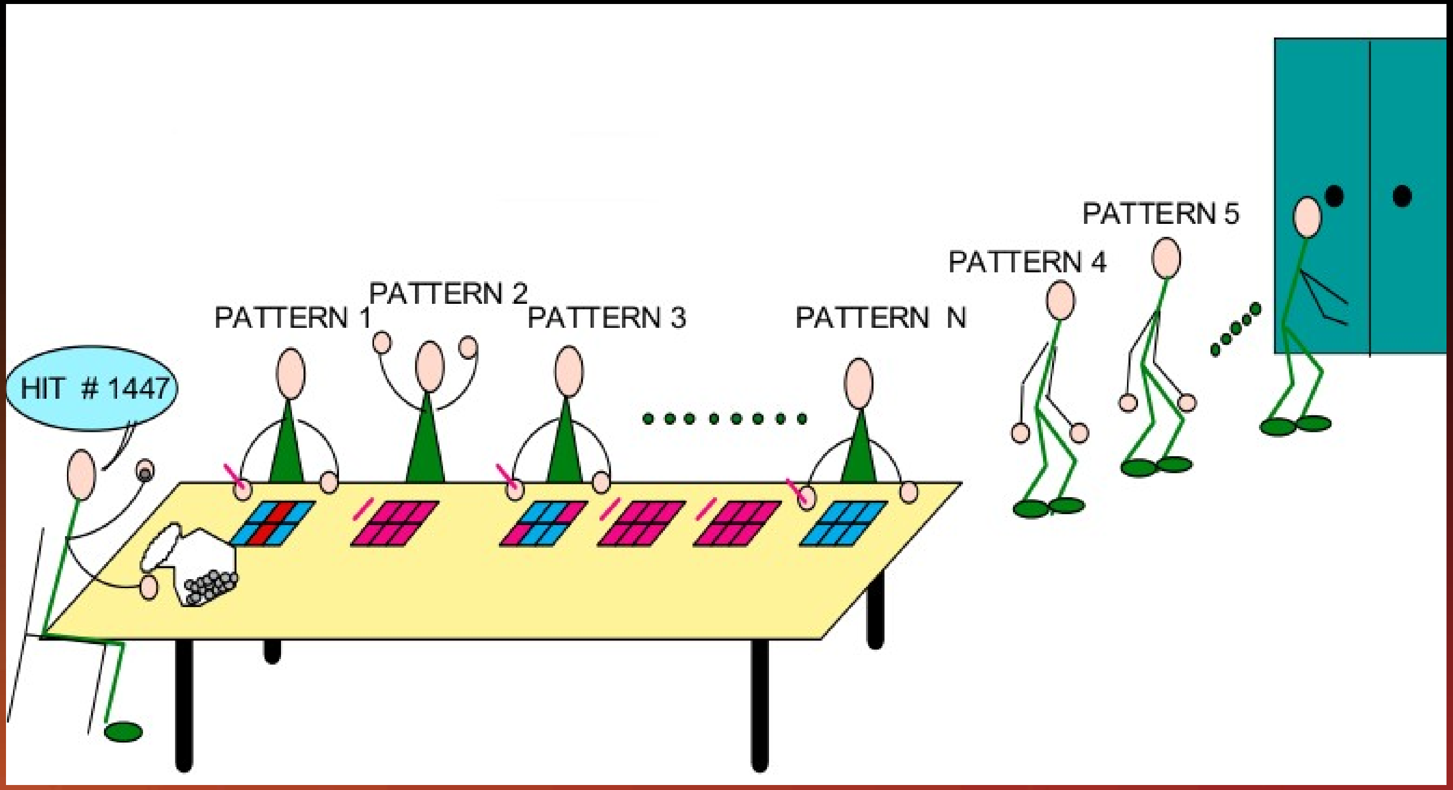


FTK - Overview

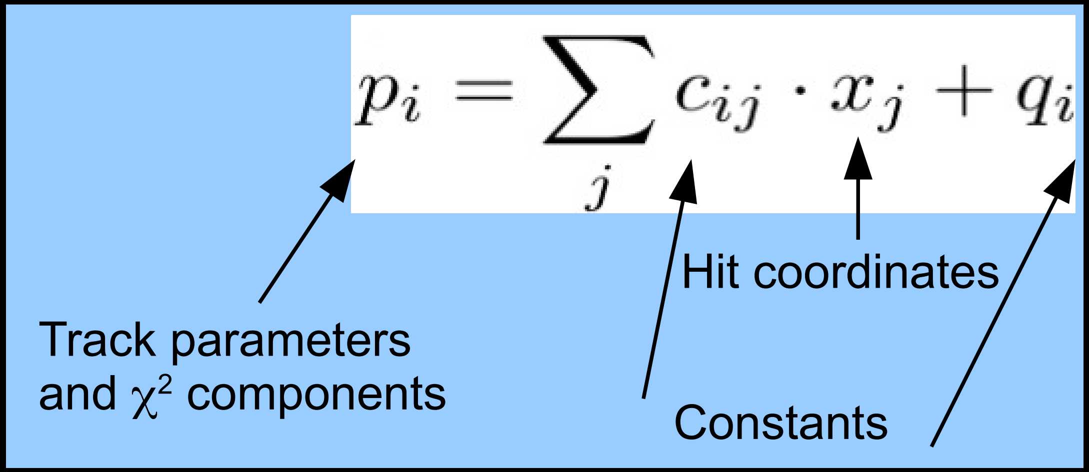
- architecture follows CDF
  - ➡ Data formatter
    - clustering, routing to η-ϕ towers
  - ➡ Data organizer (DO)
    - stores hits, communicates between pattern recognition and track fitting
  - ➡ Associative Memory (AM) board
    - Pattern recognition
  - ➡ track Fitter (TF)
    - FPGA-based track fitting



- associative memory
  - ➡ millions of predefined hit patterns
  - ➡ hits are evaluated against all patterns in parallel, leading to hugh timing gains !



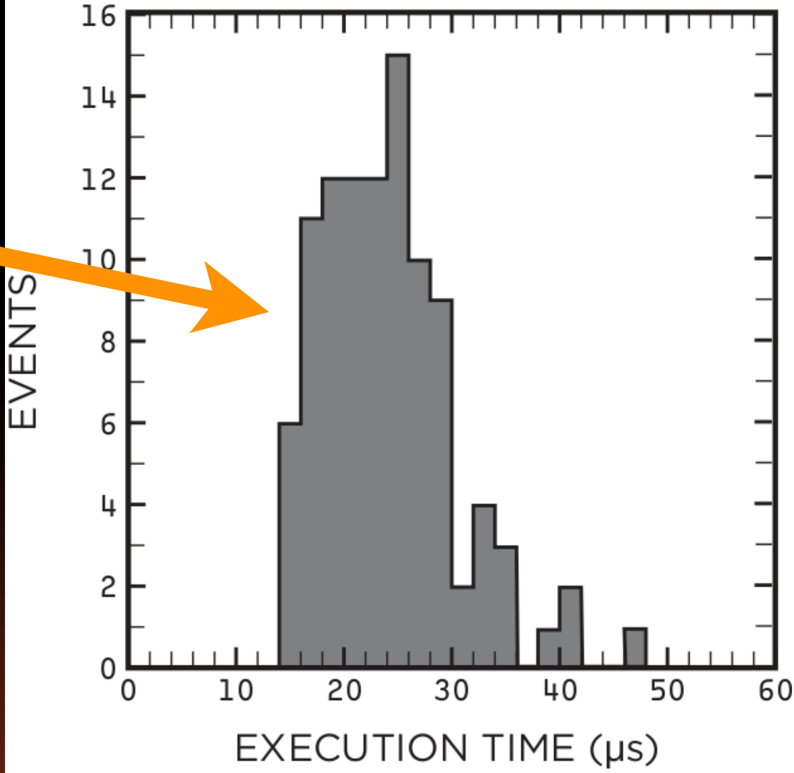
FTK - Overview

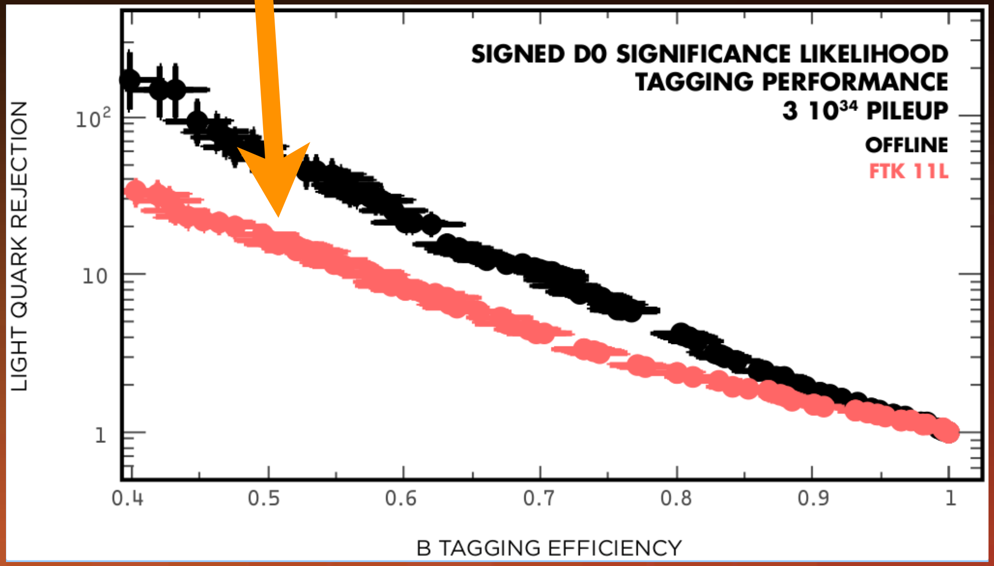


$$p_i = \sum_j c_{ij} \cdot x_j + q_i$$

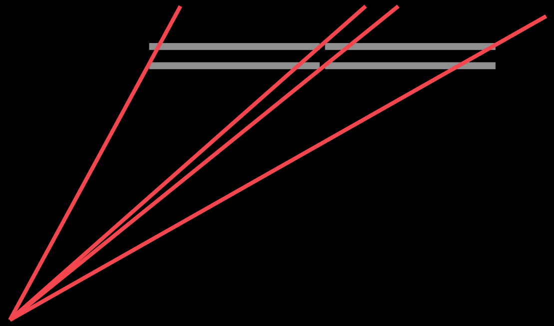
- fast track fitting
  - ➡ divide detector in regions
  - ➡ approximate track fit by a linear equation
  - ➡ determine constants using full resolution in those regions (from offline)
  - ➡ implement in FPGA chips, track fit ~ 1 *nsec* (full ~ 1 *msec*)

- performance
  - ➡ timing for H→bb with 75 pileup, full scan, p_T >1 GeV
  - ➡ tracking efficiency > 90% compared to offline
  - ➡ approximated track fit limits resolution of fit
  - ➡ example: b-tagging performance at 75 pileup

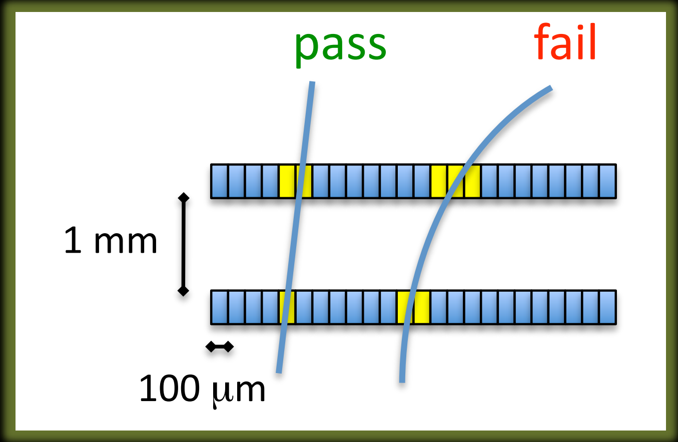




CMS Track Trigger for Phase-2

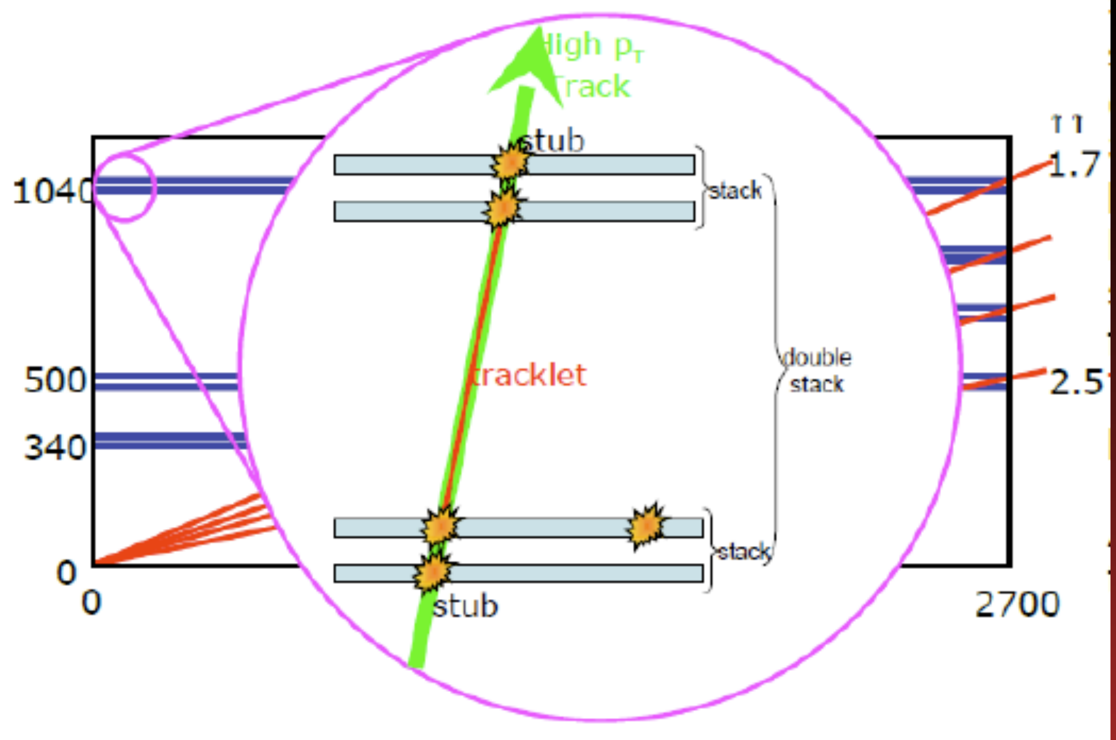


- R&D for a track trigger
  - ➡ pushes ideas similar to FTK to bring tracking to Level-1 (!)
  - ➡ motivation is to keep Level-1 rate at 100 *kHz*
    - confirm muons in tracker
    - electron/photon isolation with tracks
  - ➡ requires ~6 *μsec* latency (length of ECAL pipelines)



- seed finding in coincidences in 2 adjacent modules
  - ➡ double module layers would drive the layout of the upgrade tracker

- track finding/fitting
  - ➡ currently investigating FPGA solution
  - ➡ consider associative memory (like FTK)



Let’s Summarize...

- discussed expected pileup tracking performance
  - ➡ effects on resolutions and fake rates
  - ➡ vertexing and b-tagging
  - ➡ tracking settings to optimize performance and resource needs

- discussed Phase-0 and Phase-1 upgrades
  - ➡ ATLAS and CMS Pixel upgrades
  - ➡ hardware track trigger concepts for Level-1 and Level-2

THAT'S ALL !!!