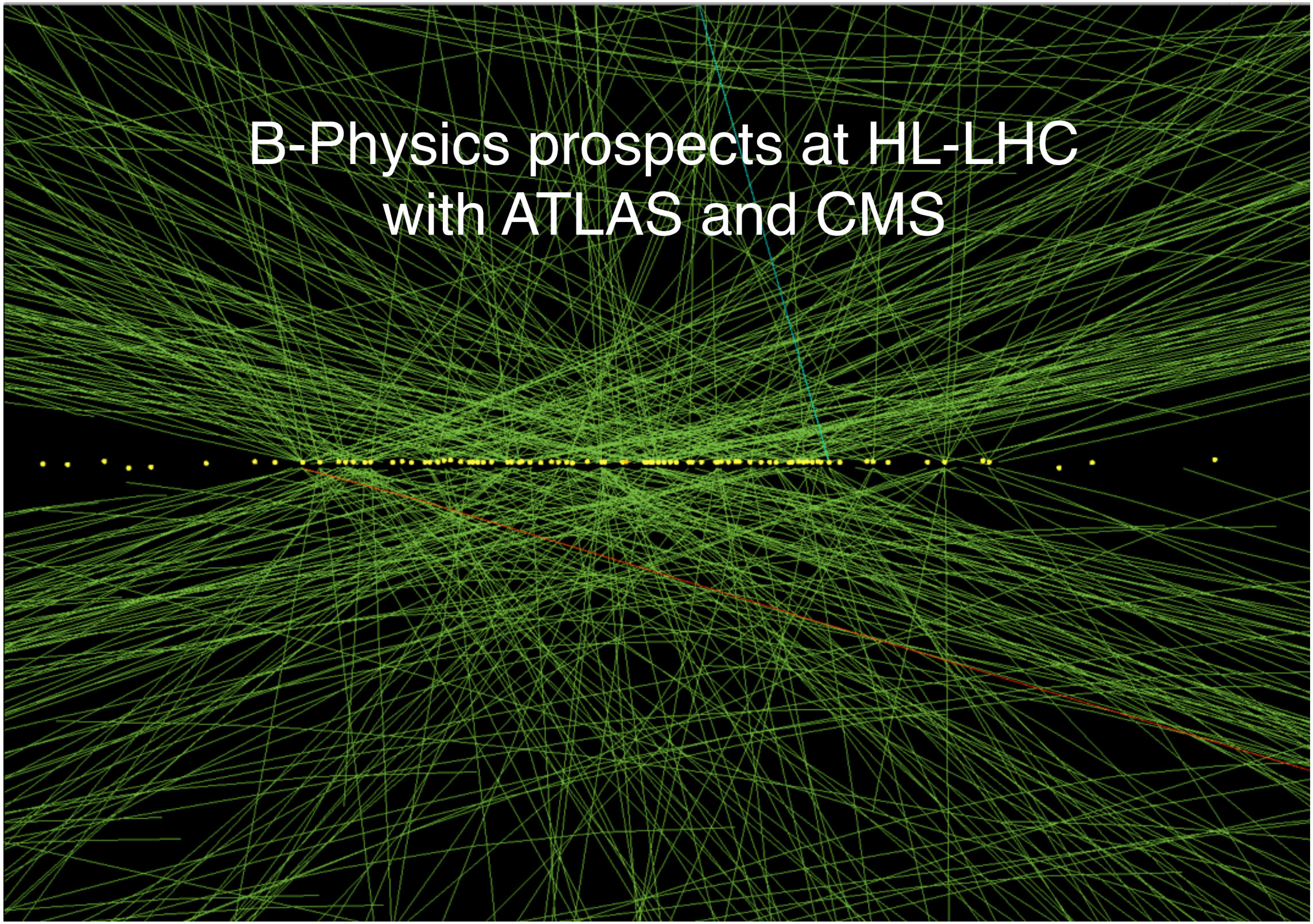
B-Physics prospects at HL-LHC with ATLAS and CMS

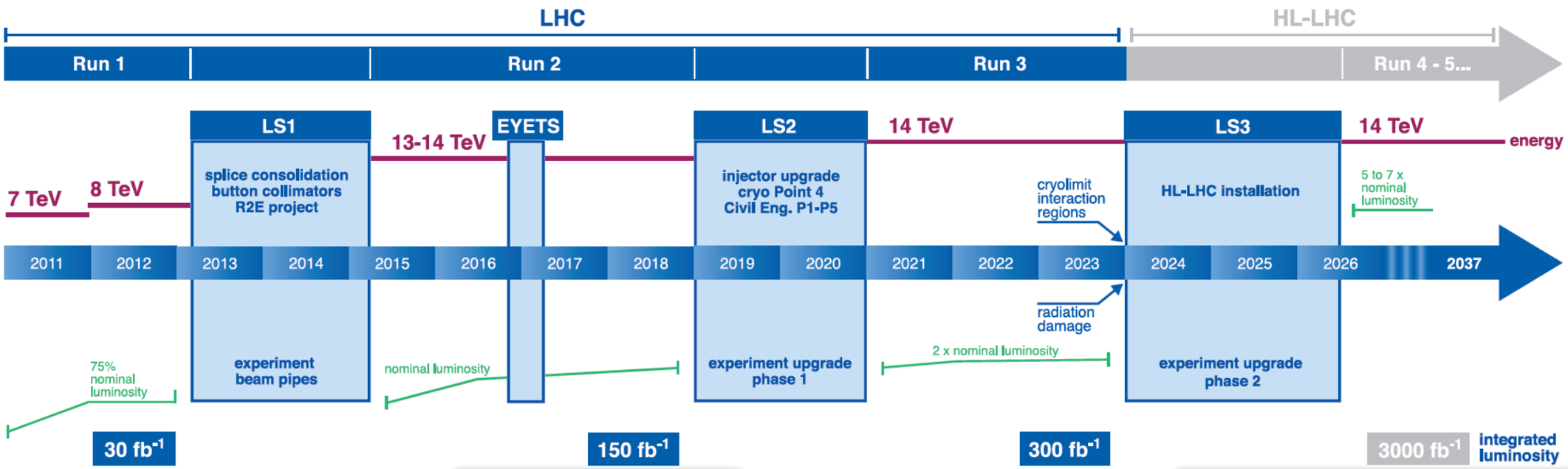


Fabrizio Palla
INFN Pisa
April 6th 2016, Manchester
"Theatre of the Dreams" LHCb meeting

Outline

- **ATLAS and CMS upgrades beyond LS3 (aka Phase2)**
  - **New Tracking detectors with improved functionalities**
    - **Real time tracking, less material budget, finer pixel pitches**
  - **Trigger strategies**
    - **Tracks will be available at Level-1**
  - **Timing detectors**
    - **Allow better primary vertex reconstruction as well as introduce some particle ID capabilities**
- **Some benchmarks to illustrate the physics potentials**
  - **Rare and less-rare B-Physics**
    - $B_{s/d} \rightarrow \mu\mu$ (CMS)
    - $B_s \rightarrow J/\psi\varphi$ (ATLAS)
    - Other channels are under study, but no results publicly available yet
      - *by no means the results shown are conclusive but they serve for guidance*

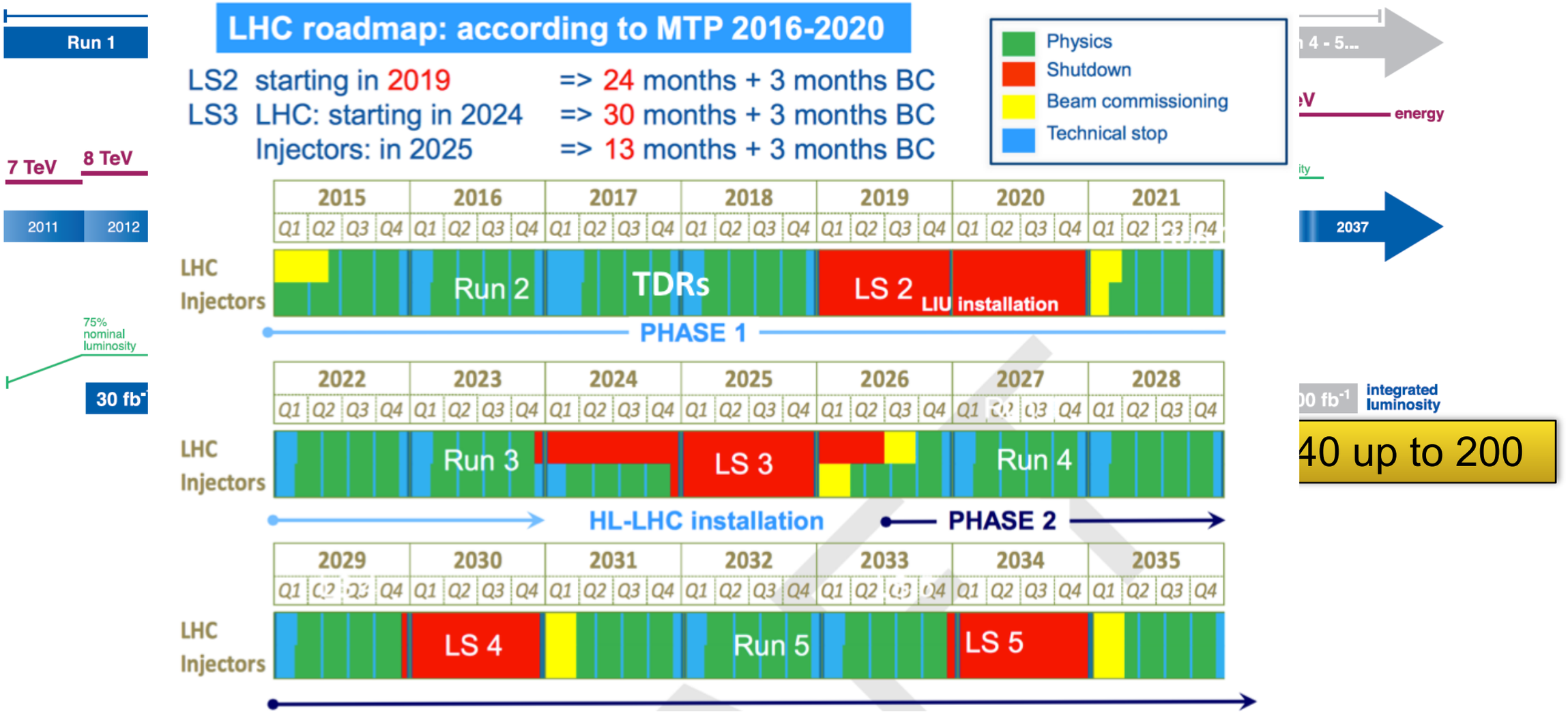
The HL-LHC scenario



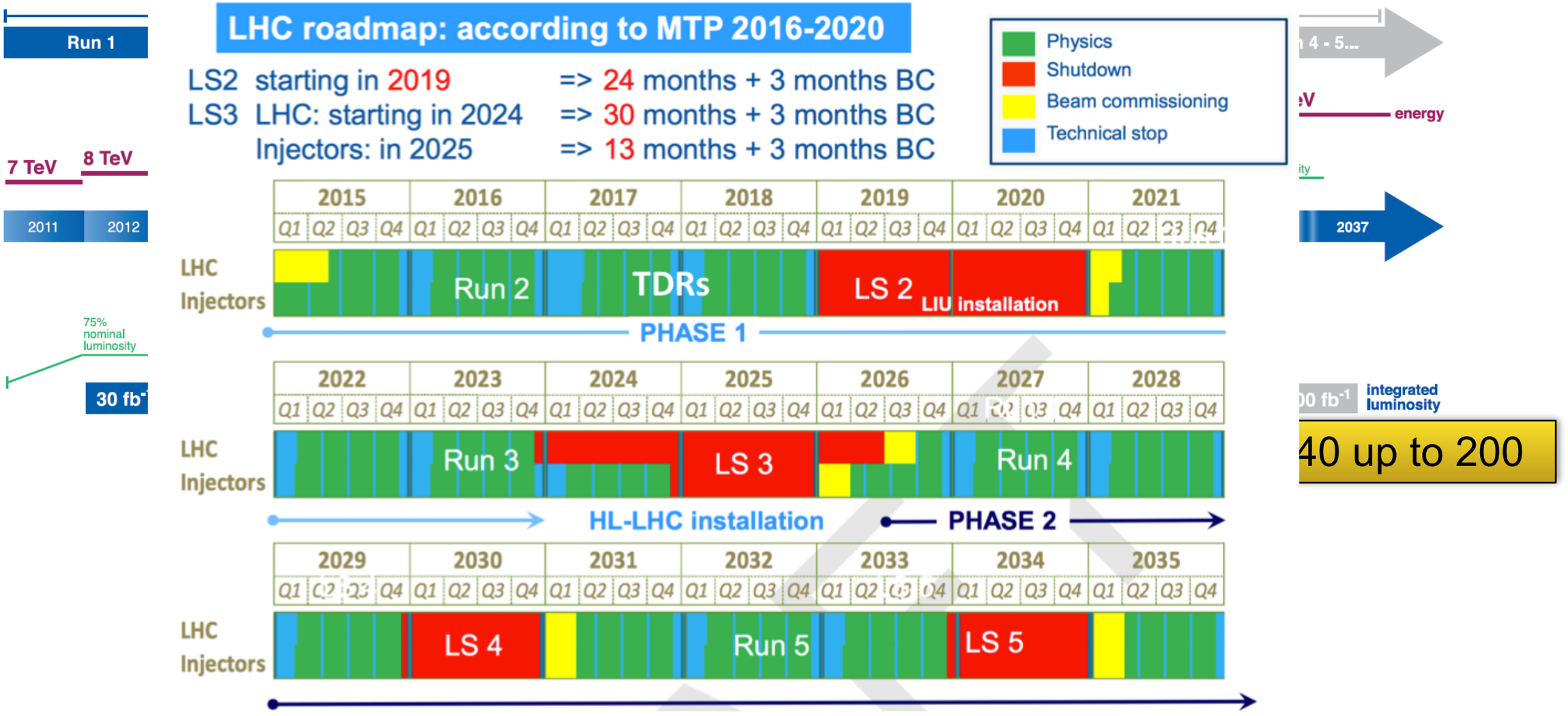
<pileup> ~30

<pileup> 140 up to 200

The HL-LHC scenario



The HL-LHC scenario



- At HL-LHC ~140 events/bx spread over ±15 cm (3 σ) - now up to 200

~3000 fb^{-1} expected in 10 years running

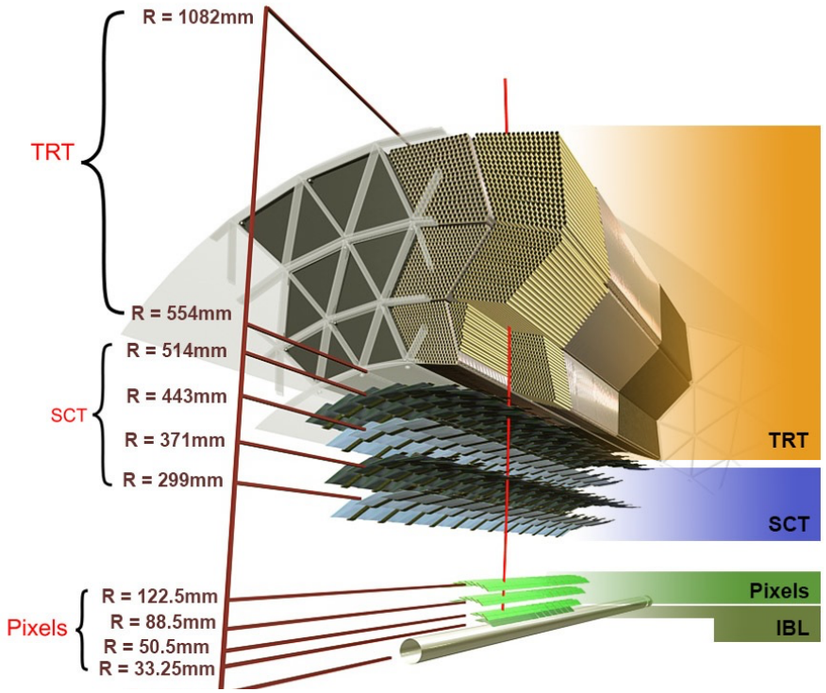
Excellent opportunity to search for (rare) and new phenomena

Need anyway still to trigger on "SM" objects (leptons, b, jets, MET)

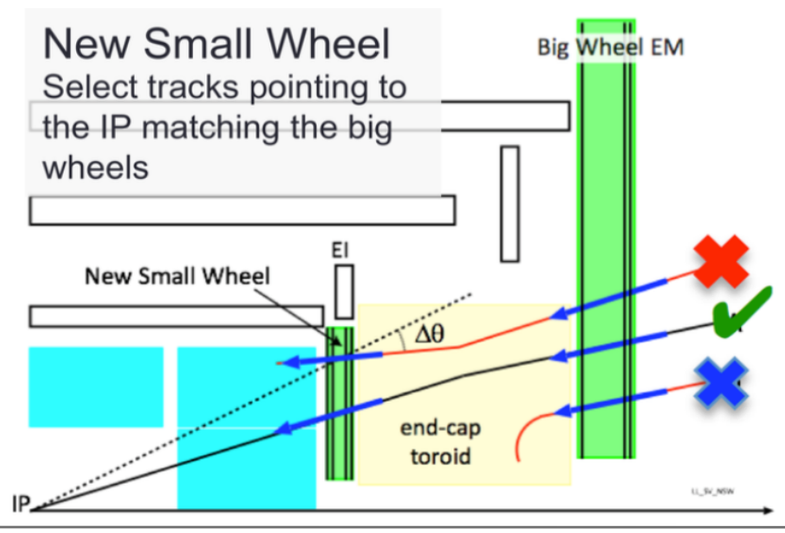
Relevant ATLAS Detector upgrades

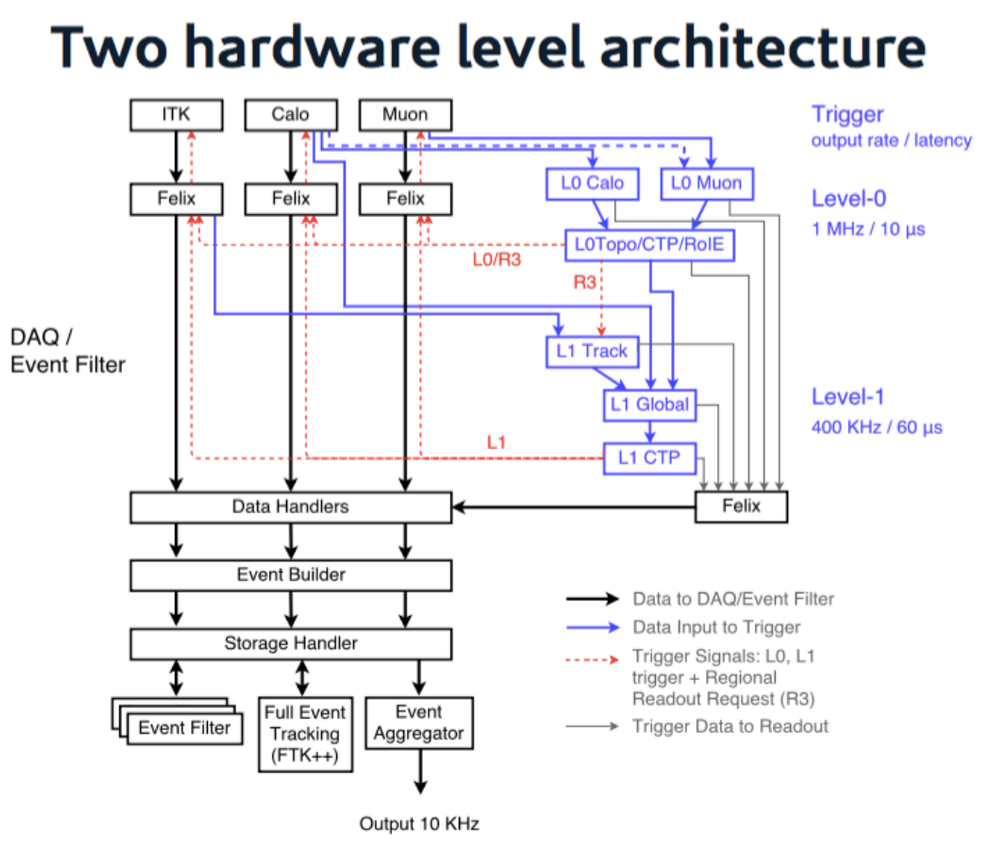
- **Inner Tracker:**
  - Inner B-Layer (2015)
  - Complete Si-Tracker for HL-LHC

- **Muon:**
  - Run3: Small Wheels
  - Upgrade of the Muon System

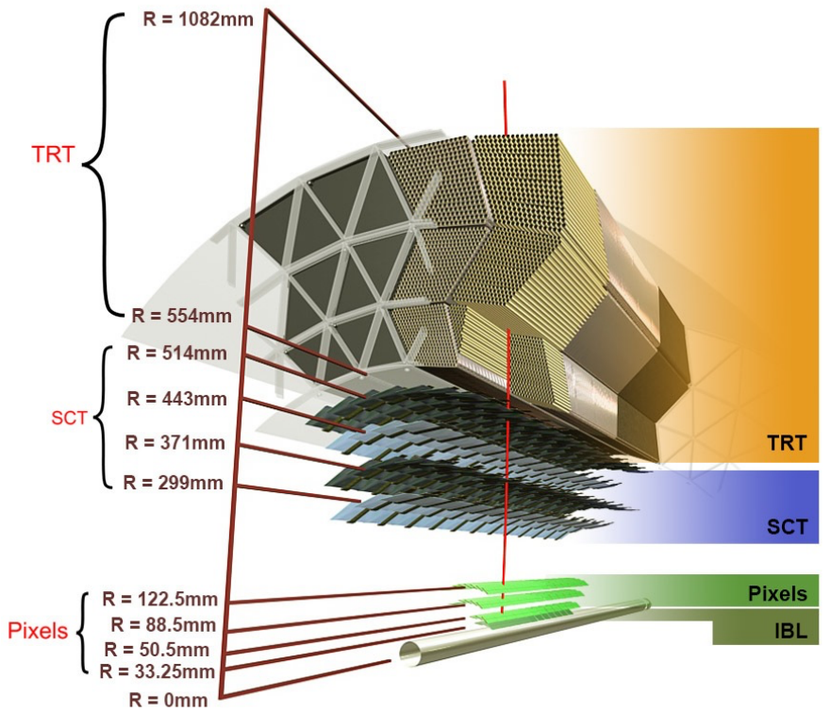


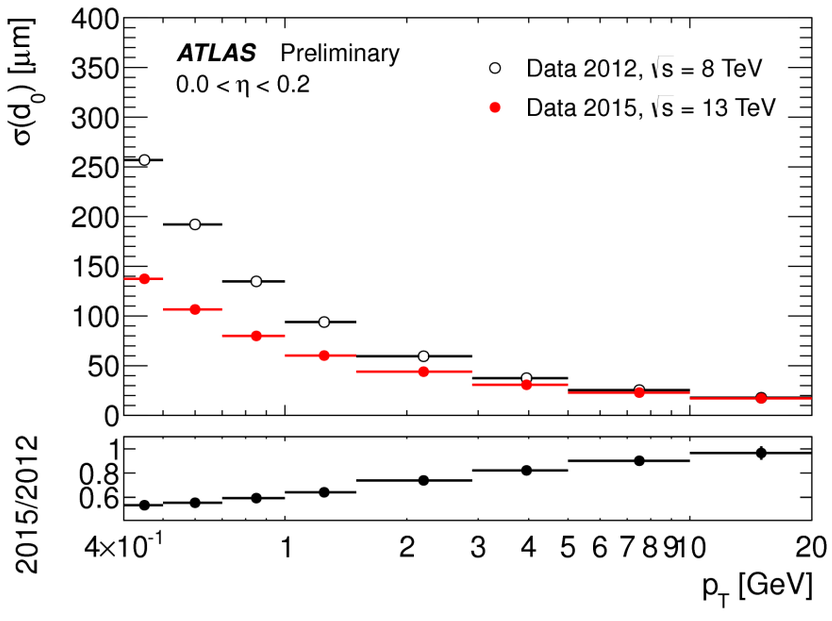
- **Trigger:**
  - Run2: topological L1
  - Run2/3: FTK (Online Tracking)

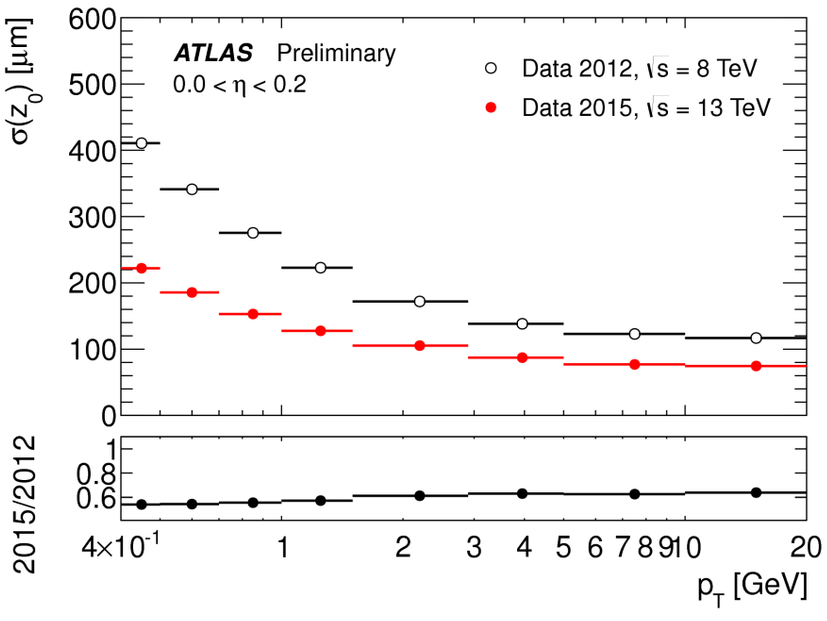




ATLAS IBL performance (2015)



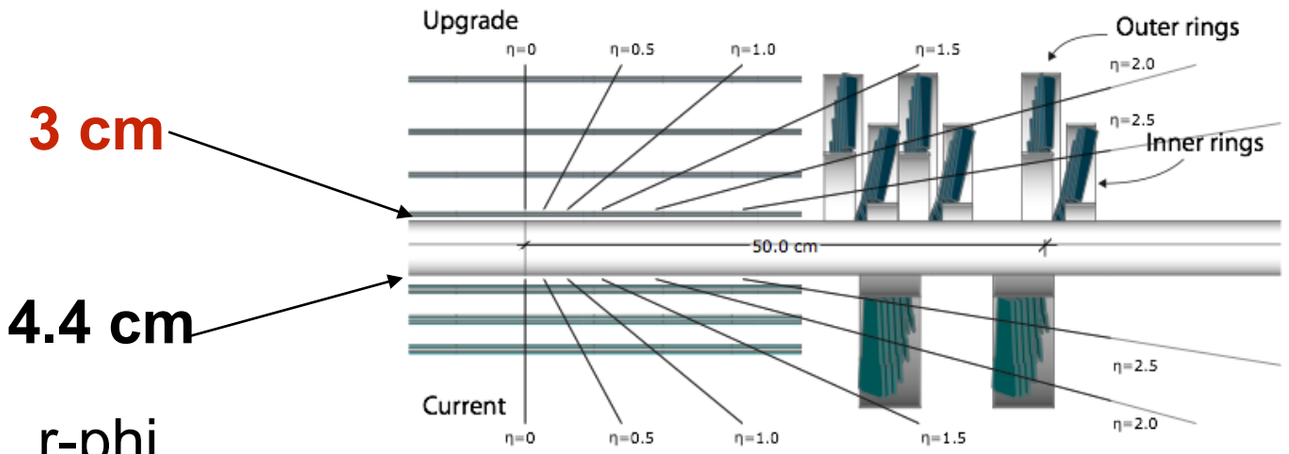


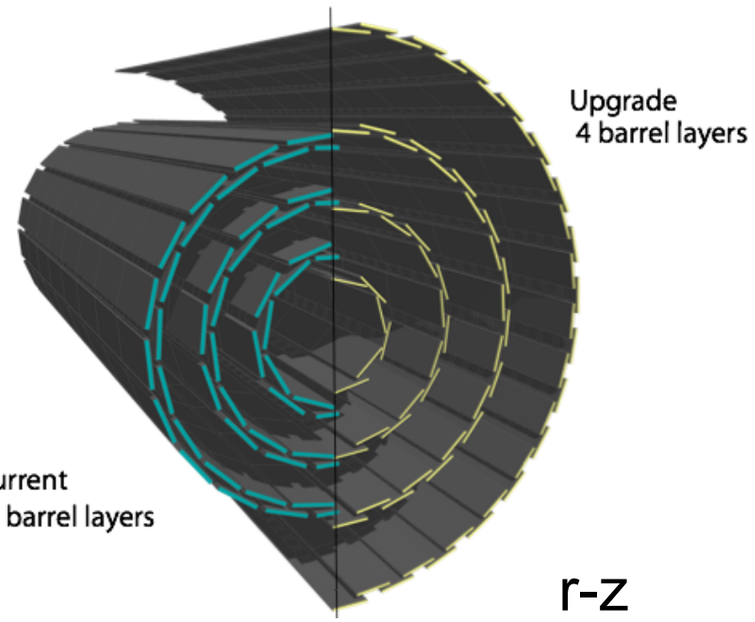


CMS New Pixel detector (2017)

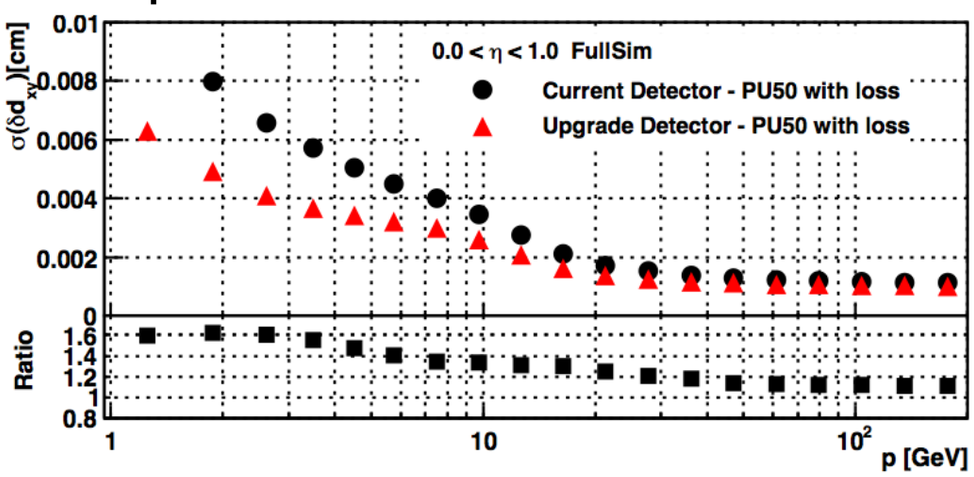
- **At the end of 2016 the pixel silicon detector will be replaced**
  - **One more layer, closer to the beam pipe -> better precision**
  - **Lower material budget -> lower multiple scattering**
- **Overall better performance for B-Physics**

CERN-LHCC-2012-016
http://cds.cern.ch/record/1481838?ln=en

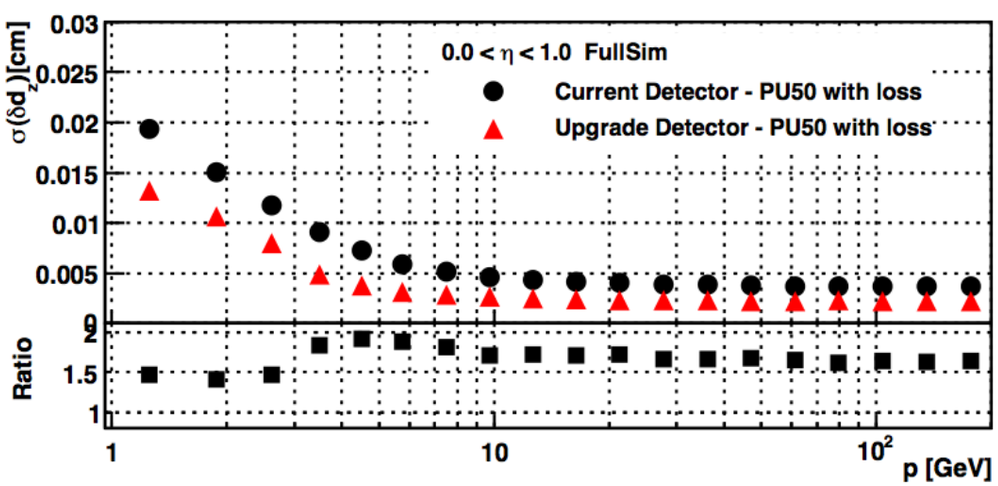




r-phi



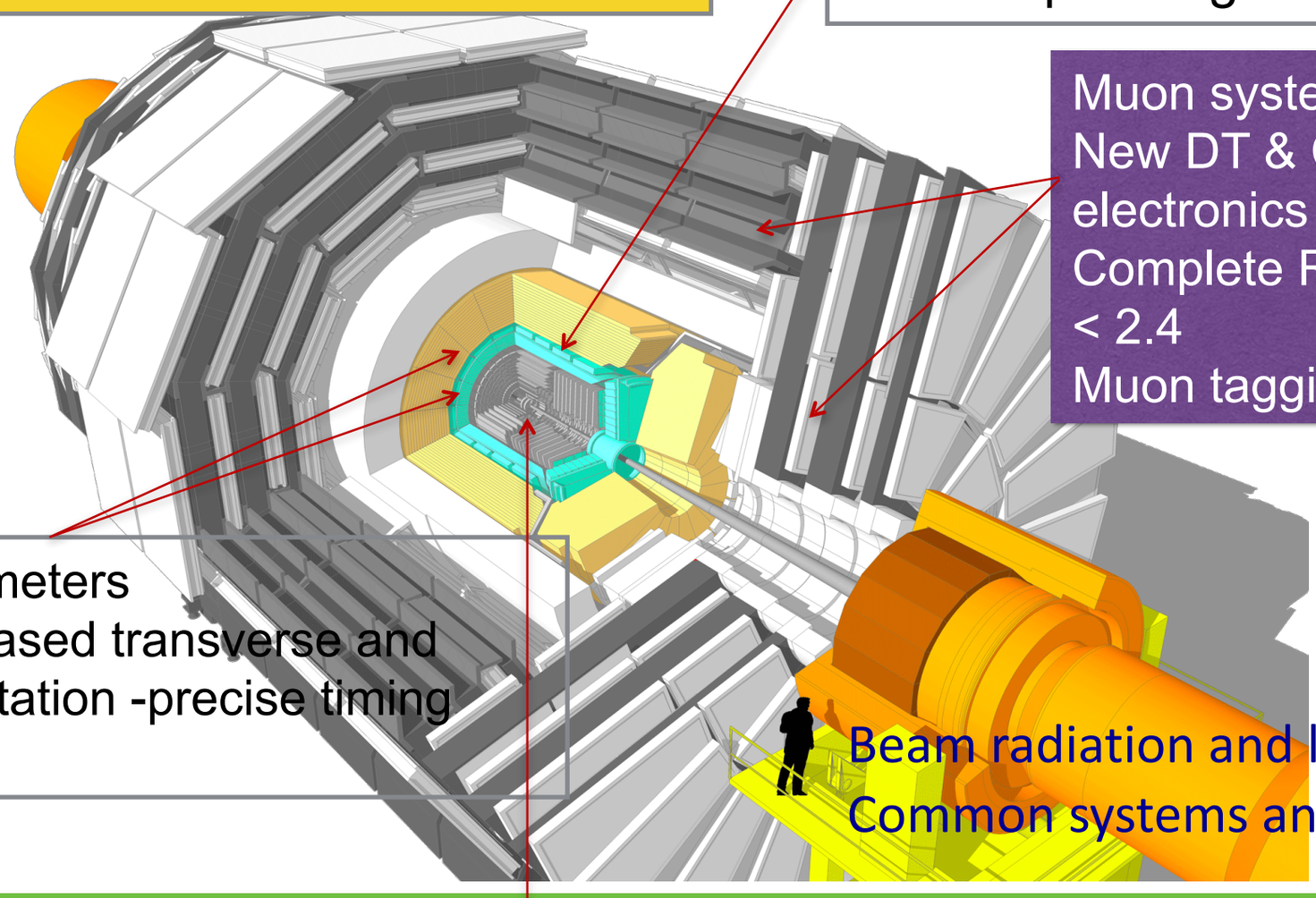
r-z



CMS Upgrades

Trigger/HLT/DAQ
Track information in Trigger (hardware)
Trigger latency 12.5 μs - output rate 750 kHz
HLT output 7.5 kHz

Barrel EM calorimeter
New FE/BE electronics with improved time resolution
Lower operating temperature (8◦)



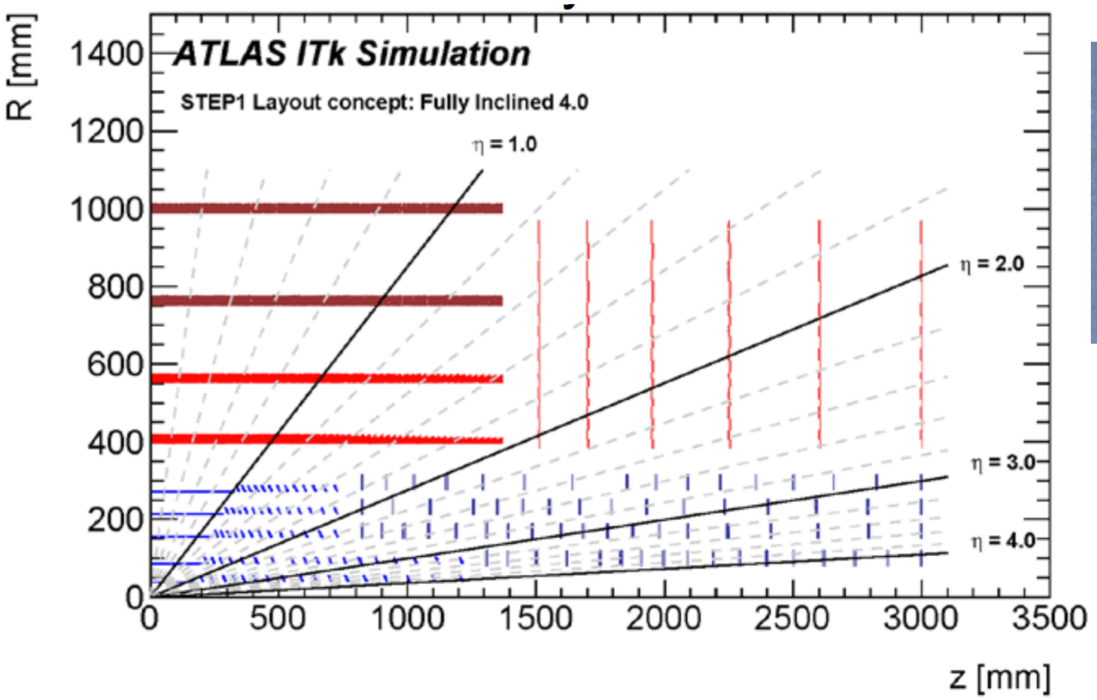
Muon systems
New DT & CSC FE/BE electronics
Complete RPC coverage $1.6 < \eta < 2.4$
Muon tagging $2.4 < \eta < 3$

New Endcap Calorimeters
Rad. tolerant - increased transverse and longitudinal segmentation -precise timing capability

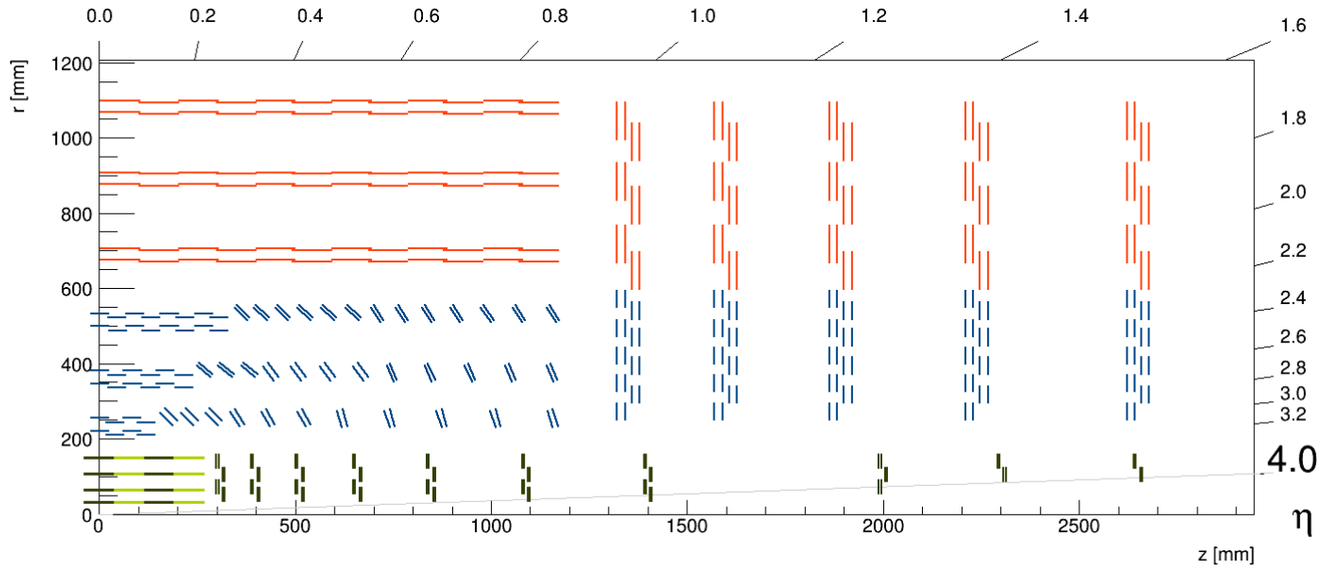
Beam radiation and luminosity
Common systems and infrastructure

New Tracker
Rad. tolerant - increased granularity - lighter
40 MHz selective readout in Outer Tracker for Trigger
Extended coverage to $\eta \simeq 3.8$

ATLAS and CMS Trackers @ HL-LHC

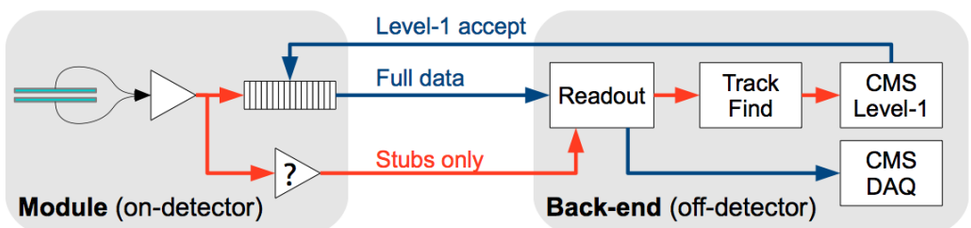


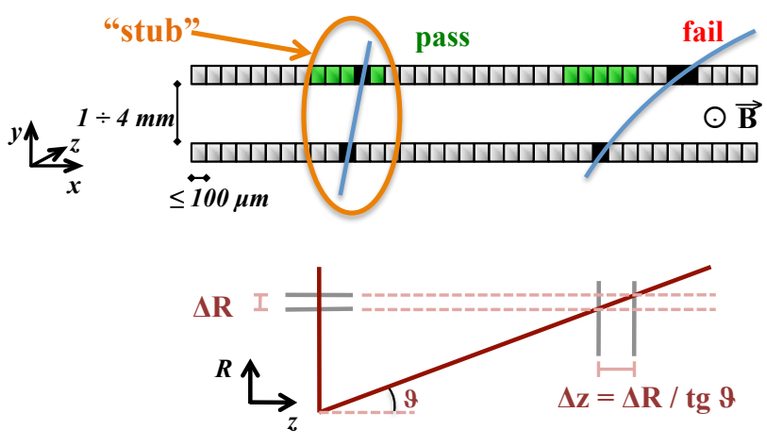
ATLAS studies undergoing wrt LOI layout:
coverage extended to η~4
5 pixel barrel layers, the innermost @ 3.9 cm (so far)
tilted geometry

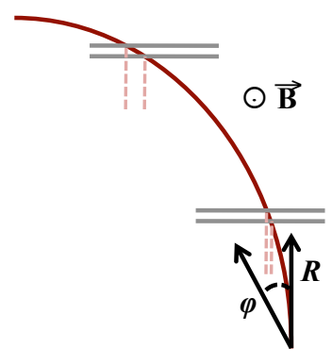


CMS also revisiting layout wrt TP:
coverage extended to η~3.8
4 pixel barrel layers, innermost @ 3 cm
50x50 μm² to 25 x100 μm² optimisation
<150 μm thickness

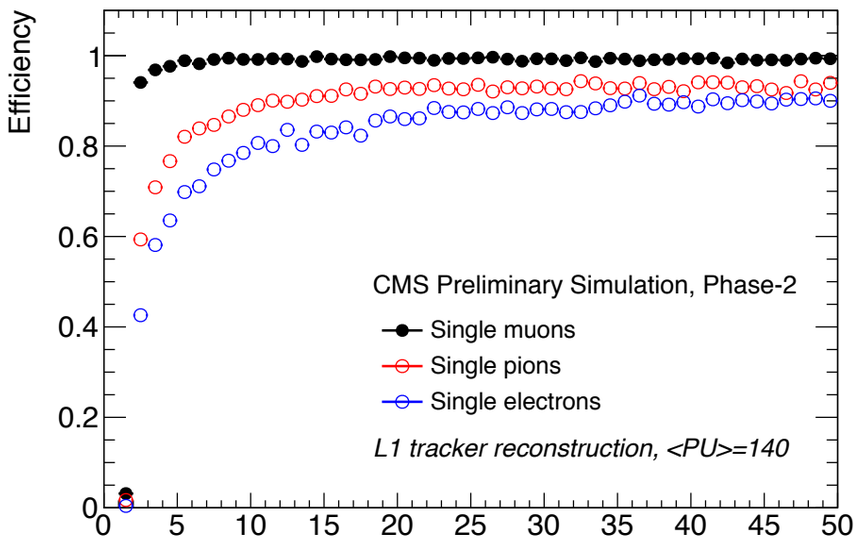
L1 Trigger functionality down to ~ 2 GeV p_T tracks

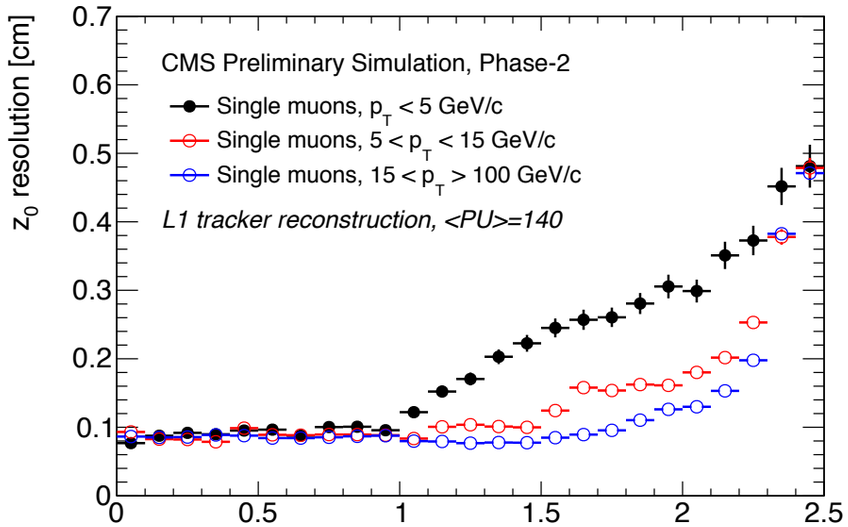


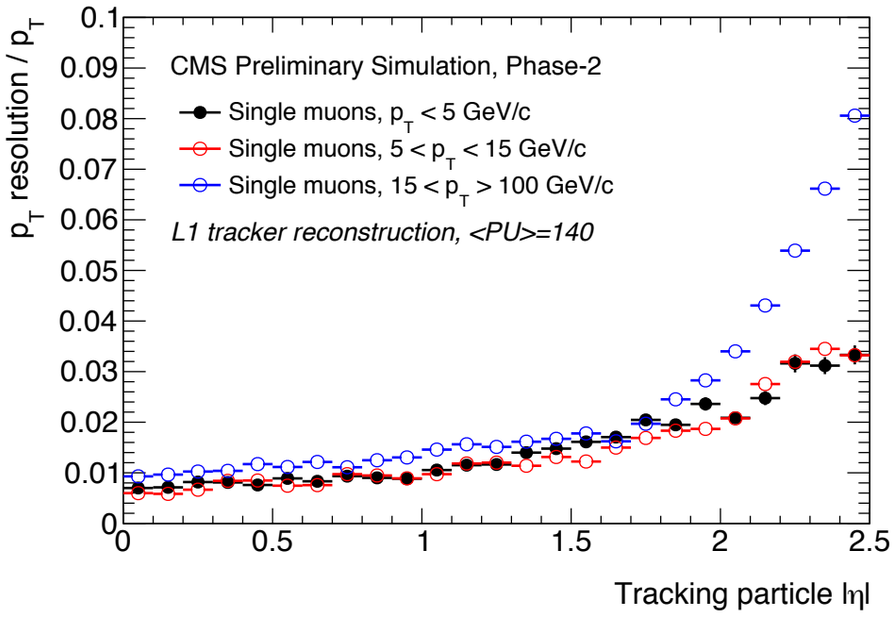


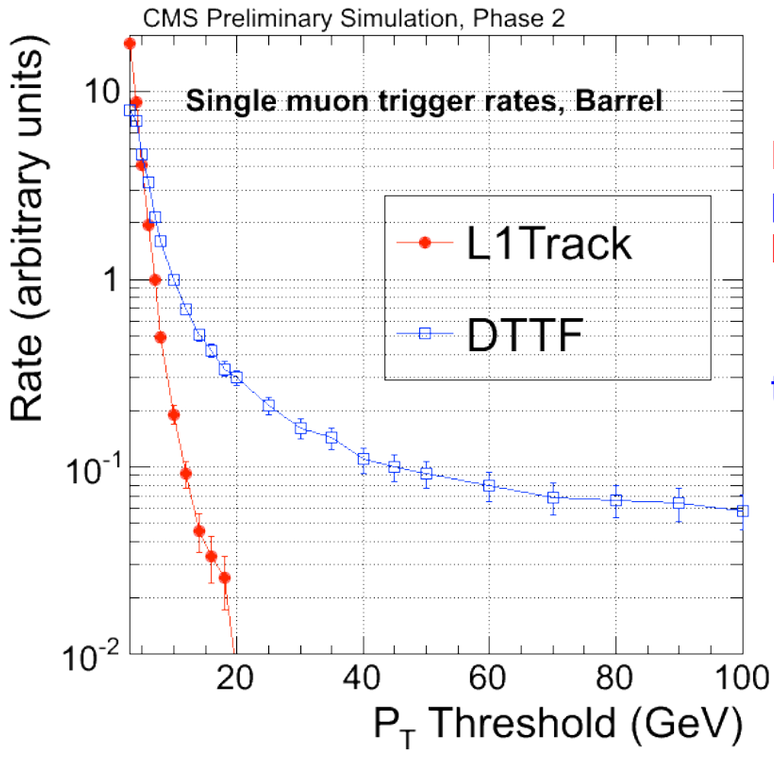


CMS L1 Track reconstruction







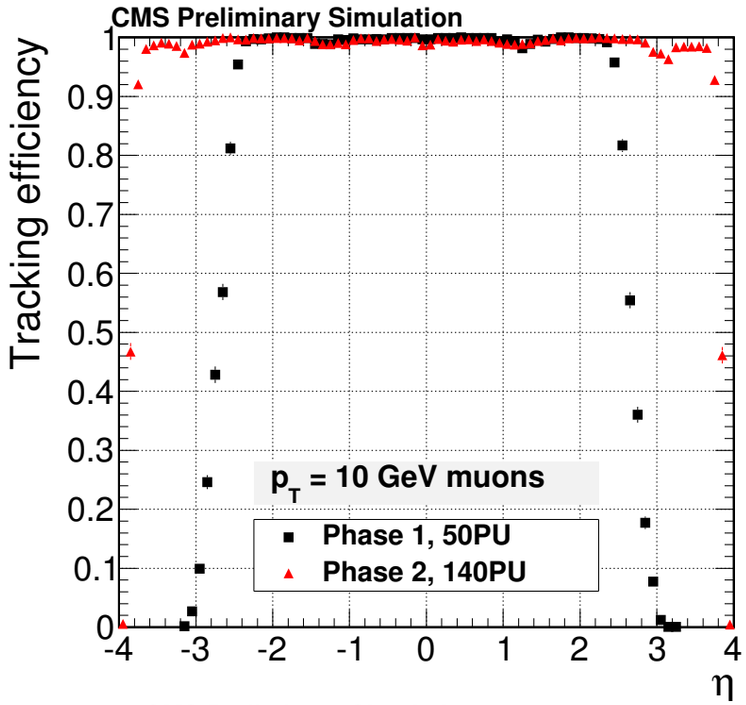


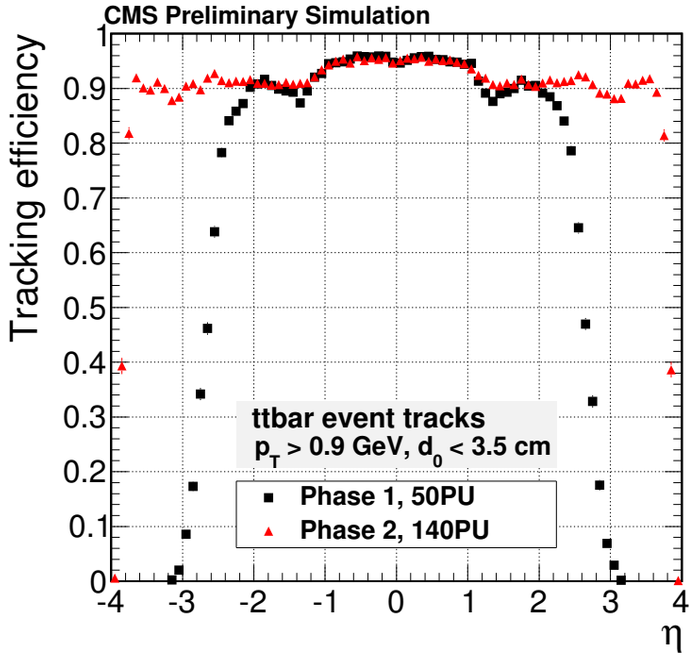
Matching Drift Tube trigger primitives with L1Tracks: large rate reduction

Normalized to present trigger at 10 GeV.

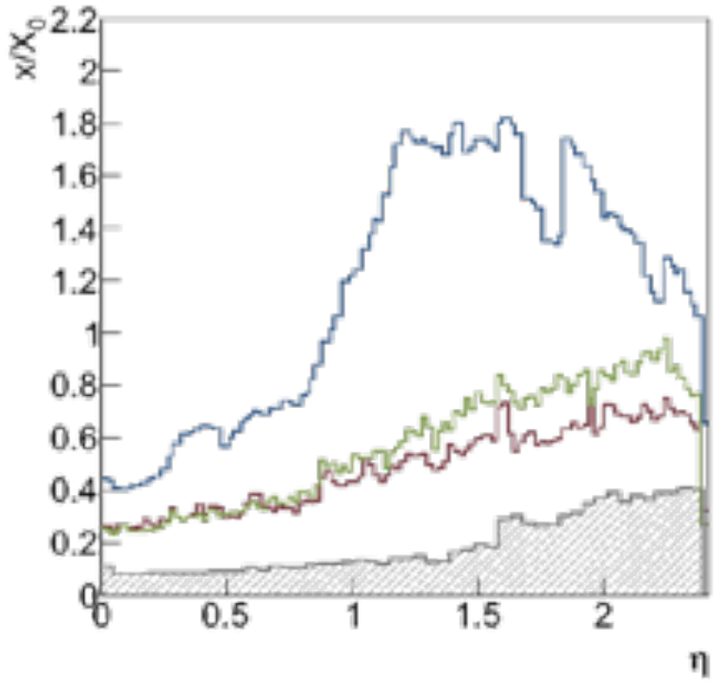
Performance: CMS

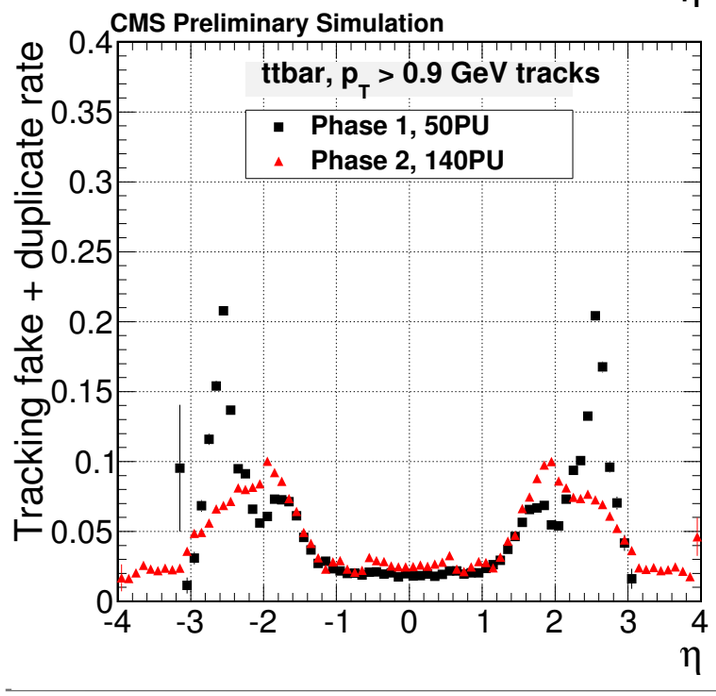
- Compare Phase-1 @ 50 PU with Phase-2 @ 140 PU

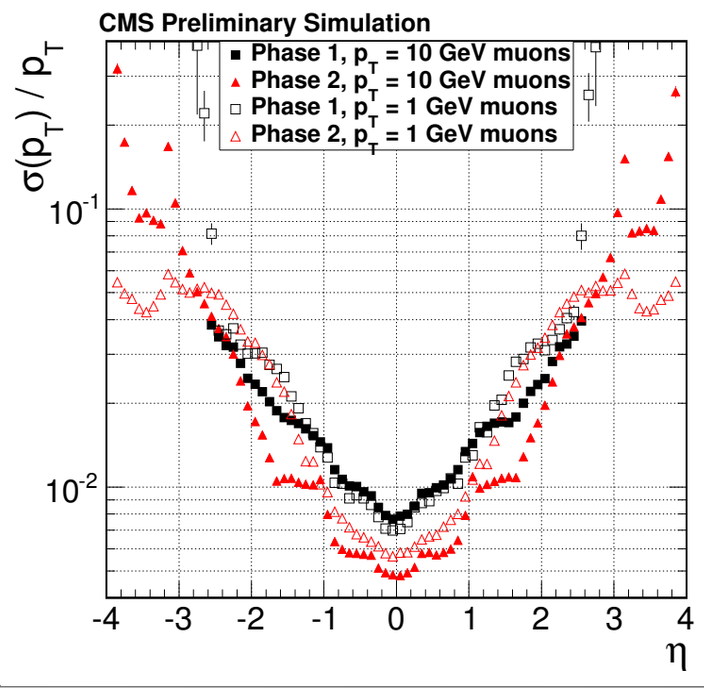




Phase-1 tracking software adapted to phase-2 geometry



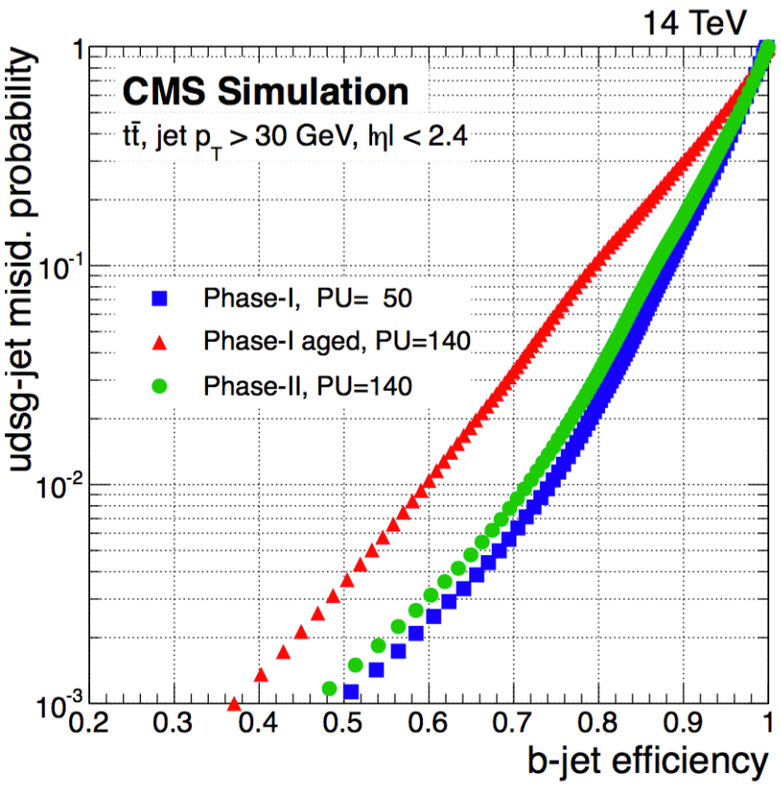


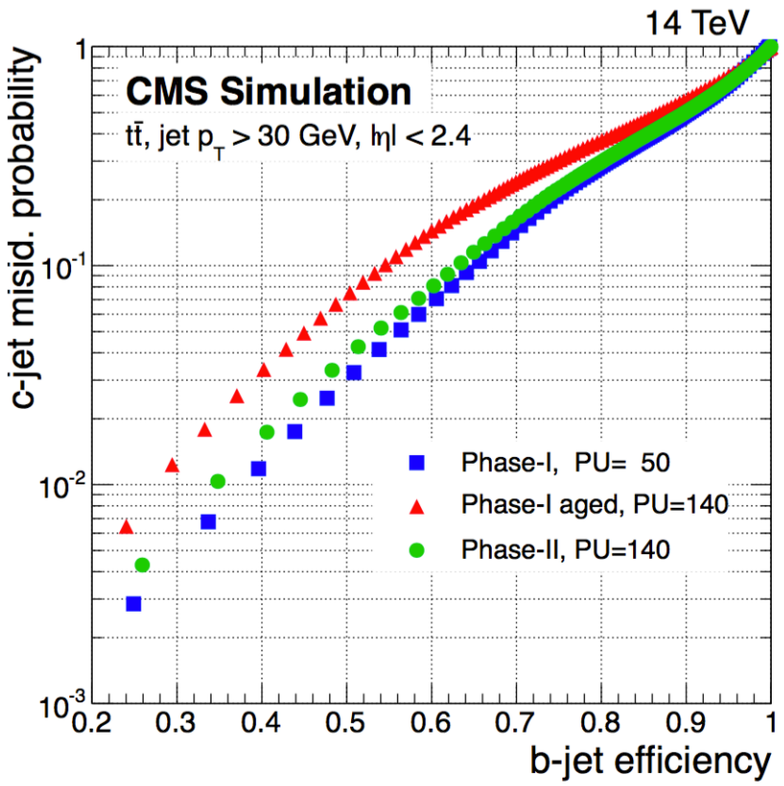


Expect substantial improvement also in z_0 resolution and b-tagging

Too early to give quantitative estimates

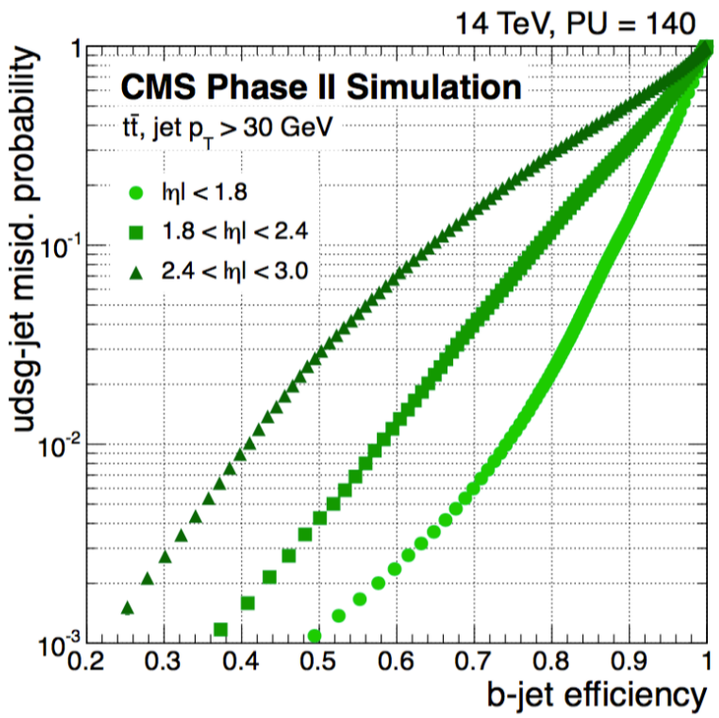
CMS b-tag capabilities

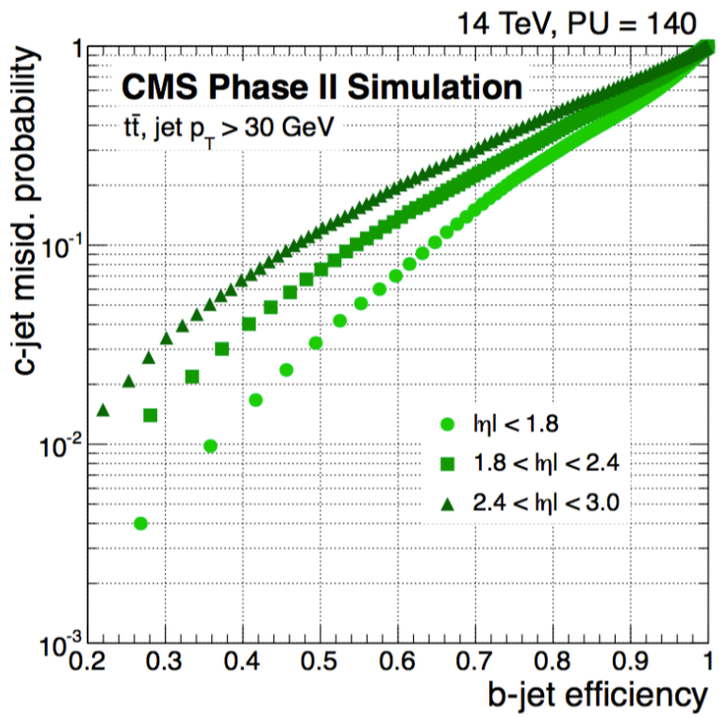




~same efficiency as Run1

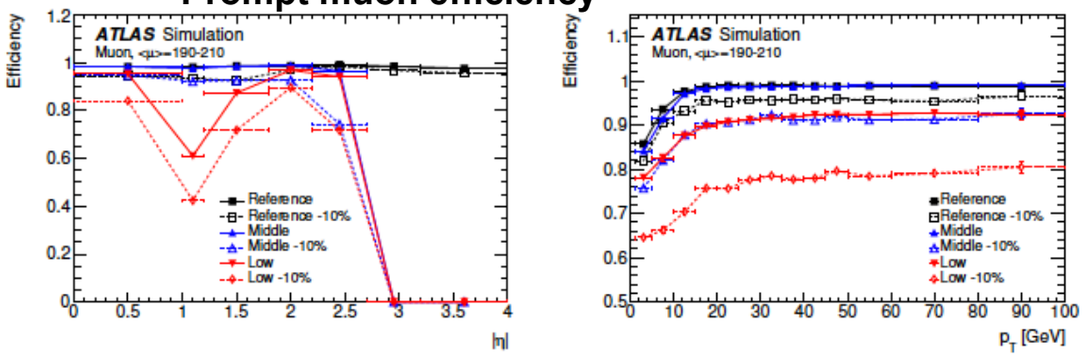
Extended b-tag coverage in the forward region



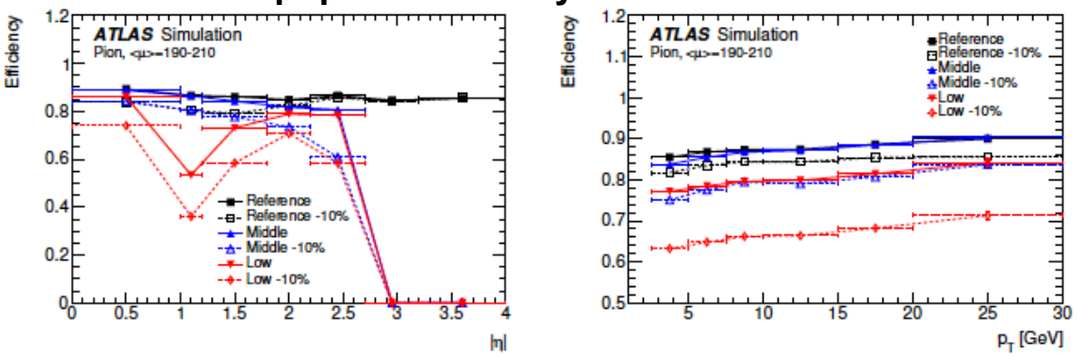


Performance: ATLAS

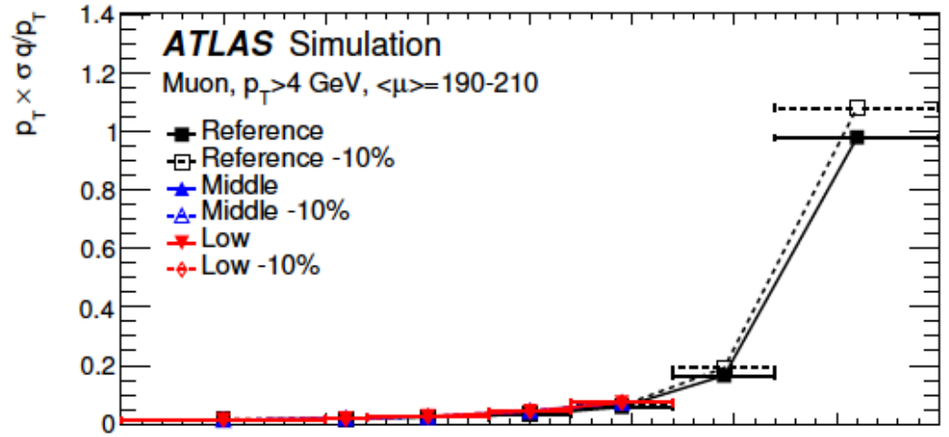
Prompt muon efficiency



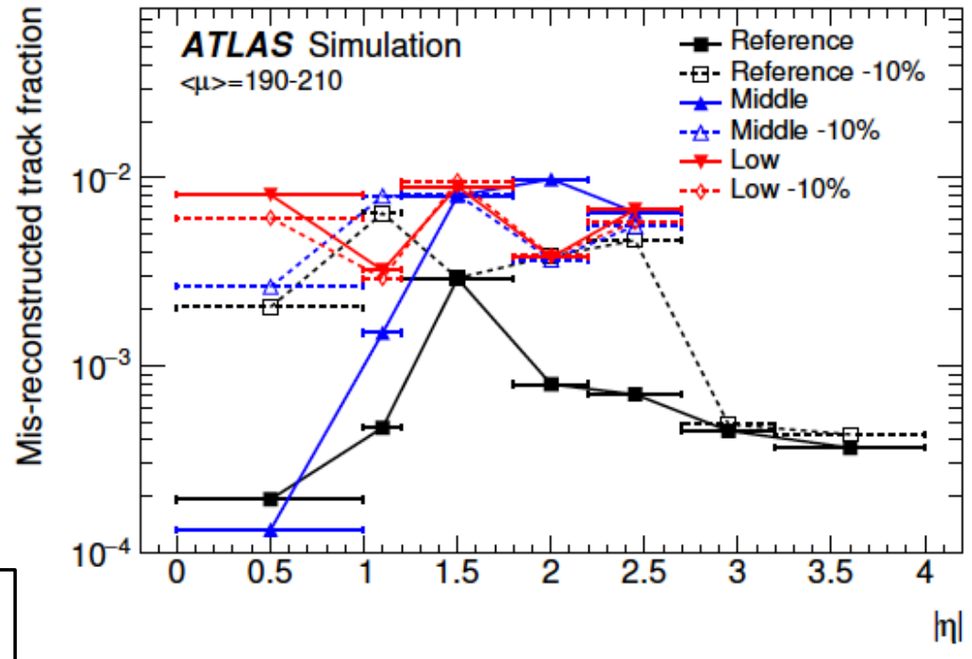
Prompt pion efficiency



Muon p_T resolution



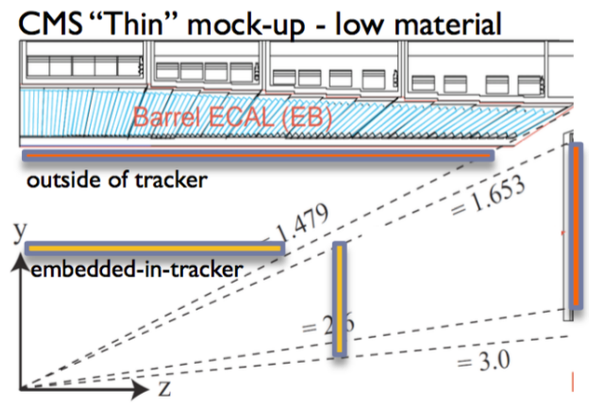
Fake rate

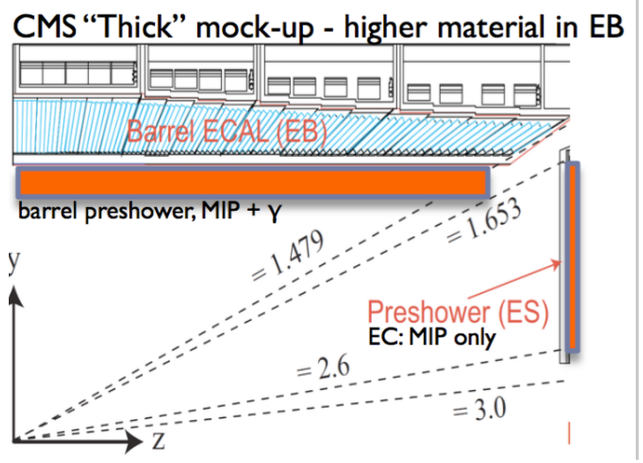


Black markers are for full coverage
Blue and red markers are cost-saving options with reduced coverage

Precise timing detectors

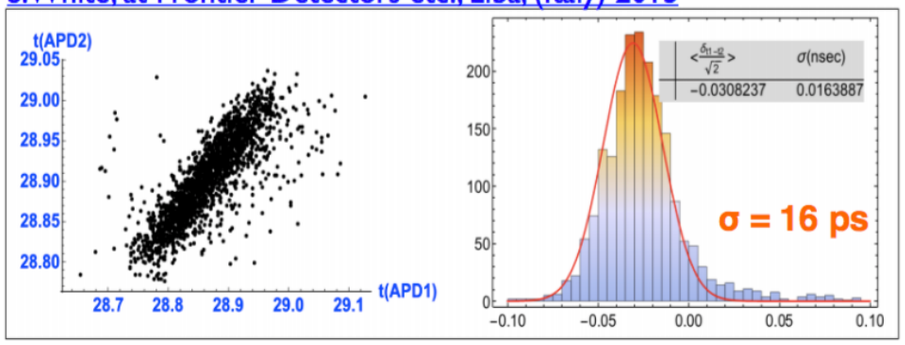
- **Both ATLAS and CMS exploring the usage of timing devices (no proposals yet!)**
  - **Those of interest for B-physics are for MIP timing**
    - **Assign a time stamp to each track**
      - ➨ **Reduced ambiguity to assign tracks to PV**
      - ➨ **Some particle ID possible**
  - **Few tens of ps time resolution**
    - **some π/K separation up to 2-3 GeV p_T in the barrel**





- Silicon sensors with internal gain
  - Use gain to extract clean MIP signature and sharpen rise time for precise timing measurement
- R&D on high gain APDs with field shaping and capacitative readout in 1 cm^2 pads
  - "Hyperfast Silicon": Tested to 0.9e14 1 GeV n. eq.

S.White, at Frontier Detectors etc., Elba, (Italy) 2015

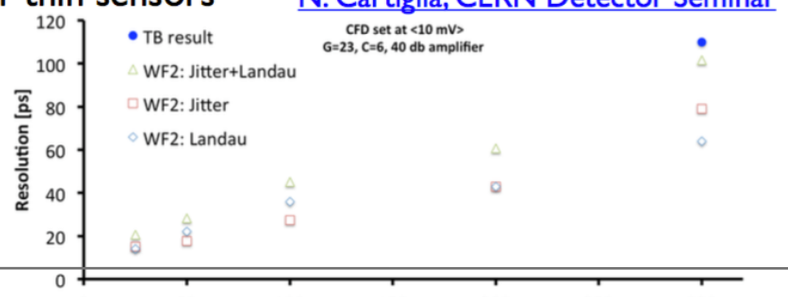


Looking at transimpedance amplifier from Newcomer, et. al. (Penn)

- Further R&D includes "Low-Gain Avalanche Device" (LGAD)
  - "Ultrafast" Silicon Device (UFSD) expect 30-50 ps for thin sensors
  - Measured 120 ps using thick sensor in test beam
    - New samples on the way, validate sim. expectations

Tested to ~1e14 1 GeV n. eq.
Some radiation issues known.
Looking at electronics from

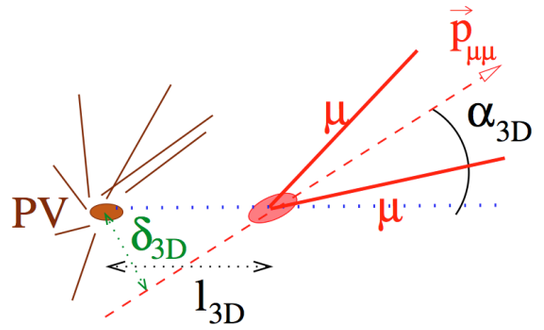
N. Cartiglia, CERN Detector Seminar

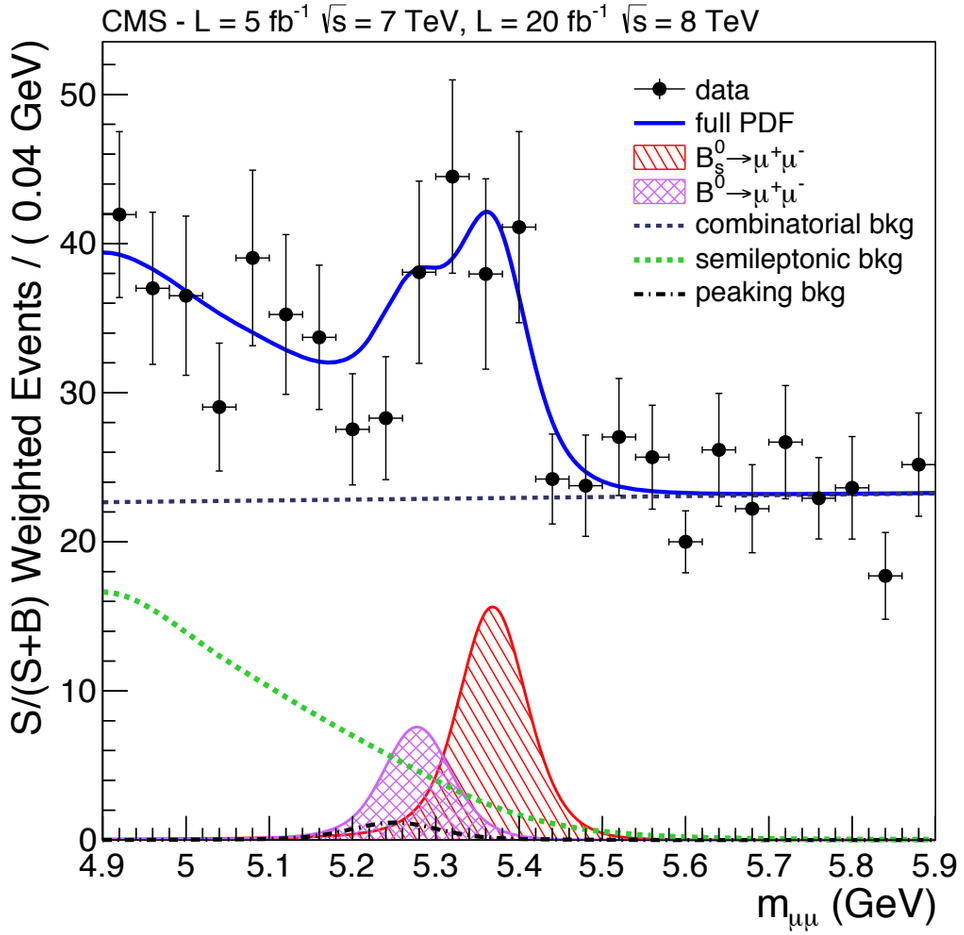


L. Gray talk at ACES2016

$B_{s/d} \rightarrow \mu\mu$

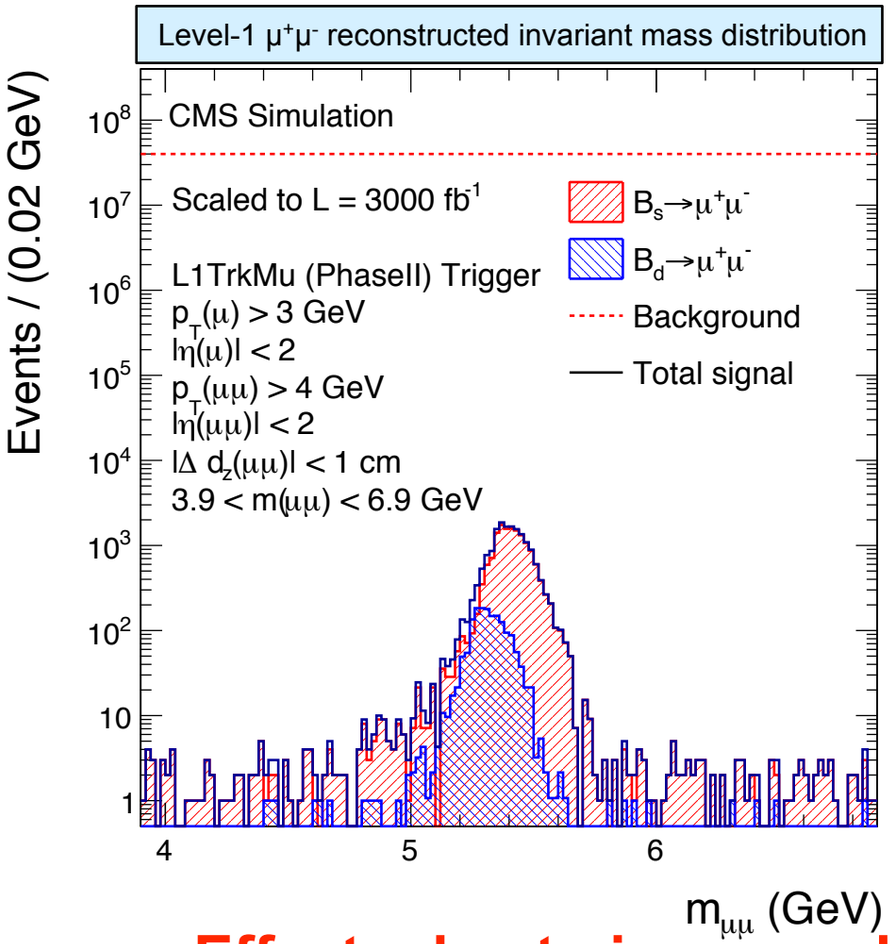
- **Monte Carlo studies based on CMS published analysis (Phys. Rev. Lett. 111 (2013) 101804)**
  - Average pileup in 2012 was 21
  - Basic analysis relies on
    - Low μ trigger p_T thresholds (3 GeV at L1)
    - Muon and di-muon vertex isolation
    - Displaced vertex
    - Di-Muon vertex aligned with flight path
    - Low μ fake rate (μ|π)<0.15% and (μ|K)<0.22%*
  - All above points will be possible with improved tracking detectors
  - Not yet studied the impact on timing detector effect





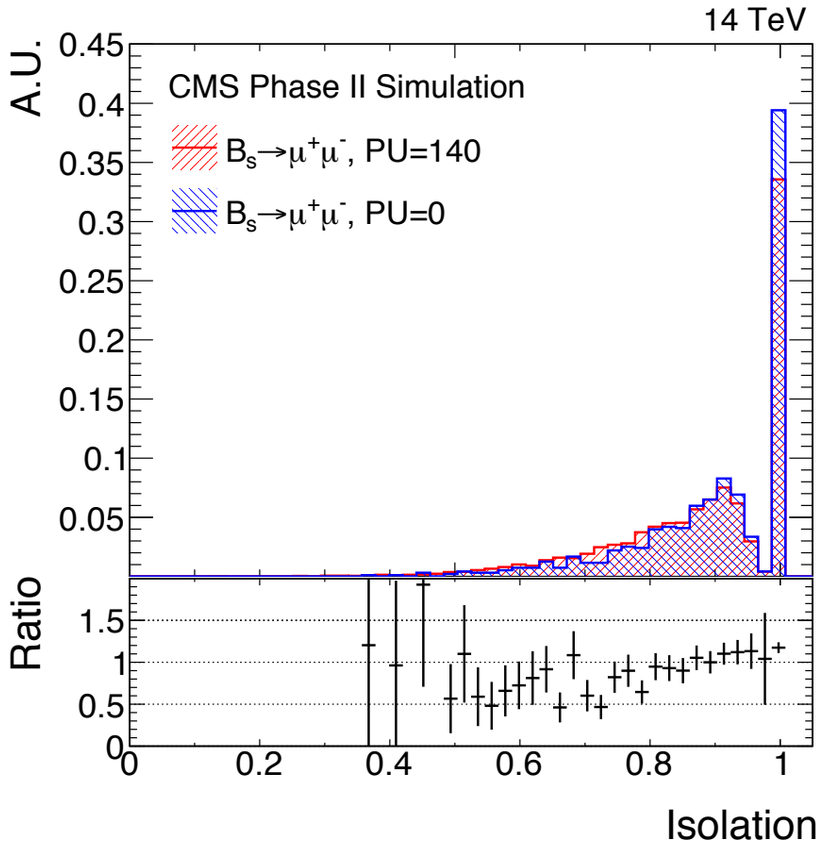
*ATLAS new result is 0.10% for K and 0.05% for π

Full GEANT simulation studies



Same trigger thresholds as the 2012 analysis
$p_T(\mu)>3$ GeV for $|\eta|<2$ at L1

Feasible only with the L1-Track Trigger: ~few hundred Hz @ L1
(using stand-alone Muon trigger with 4 GeV thresholds the rate is ~300 KHz)



Effects due to increased pileup

- Estimated loss of 2.5% in single μ tracking efficiency
- Assume conservative 30% loss in the isolation efficiency
  - checked with full simulation the effect on one isolation variable to be 16%

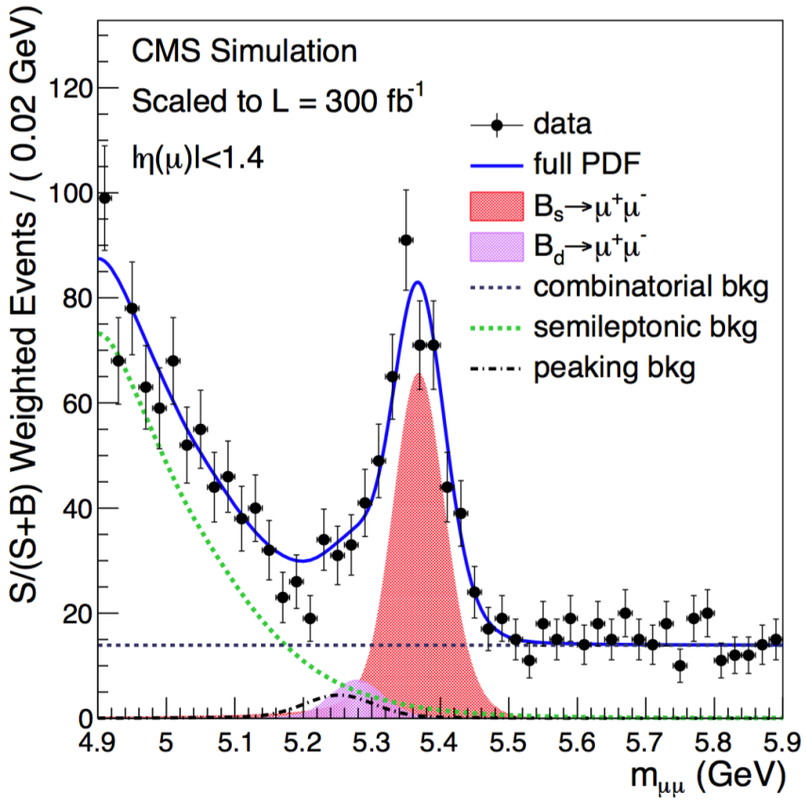
$$I = \frac{p_T(B)}{p_T(B) + \sum_{trk} p_T}$$

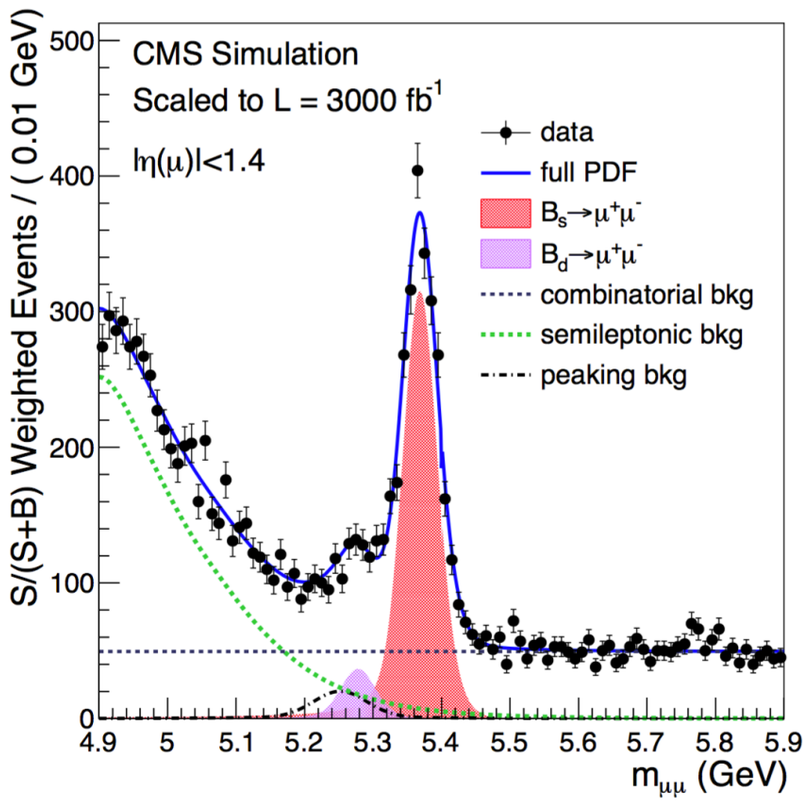
ΔR=0.7, p_T>0.9 GeV d_{ca} < 500 μm

Analysis assumptions

- The long. impact parameter resolution in the endcap (0.5 to 1 mm) is comparable to the average vertex separation
  - Reduced impact of this region in the analysis in discerning B_d from B_s peak.
- Systematics
  - f_s/f_u = 5% [now is 9%]
  - Normalization (still assume $B^{\pm} \rightarrow J/\psi K^{\pm}$) = 3% $\oplus$ 5%/$\sqrt{}$ (L/20 fb^{-1}) [now 5% from yields and 3% from BR]
  - Peaking background uncertainty = 10% $\oplus$ 50%/$\sqrt{}$(L/20 fb^{-1})
  - Semileptonic background uncertainty = 20% $\oplus$ 50%/$\sqrt{}$(L/20 fb^{-1})
- Detector resolutions
  - Tracker phase 2 detector has better momentum resolution
    - A factor of ~1.6 in the barrel and ~1.2 in the endcaps

Results





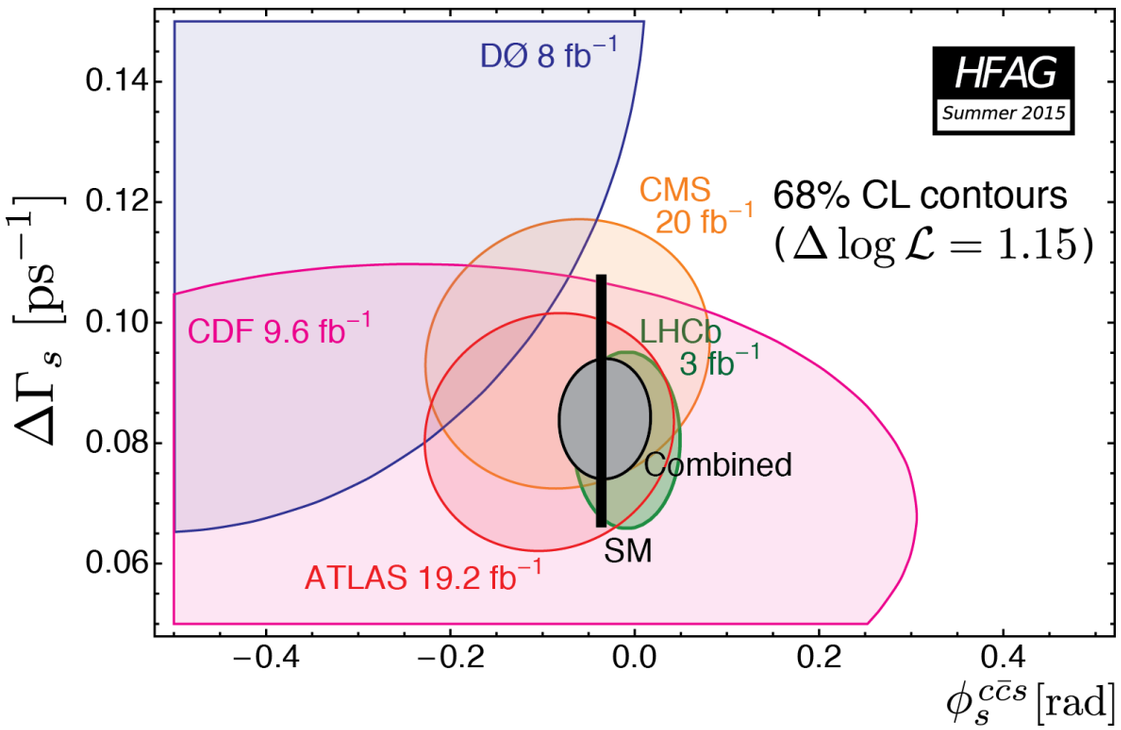
Improved Tracker

CMS PAS FTR-14-015

Estimate of analysis sensitivity

$\mathcal{L}$ (fb^{-1})	$N(B_s^0)$	$N(B^0)$	$\delta\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\delta\mathcal{B}(B^0 \to \mu^+\mu^-)$	B^0 sign.	$\delta\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B_s^0\to\mu^+\mu^-)}$
20	18.2	2.2	35%	> 100%	$0.0-1.5\,\sigma$	> 100%
100	159	19	14%	63%	$0.6-2.5\,\sigma$	66%
300	478	57	12%	41%	$1.5-3.5\,\sigma$	43%
300 (barrel)	346	42	13%	48%	$1.2-3.3\,\sigma$	50%
3000 (barrel)	2250	271	11%	18%	$5.6-8.0\,\sigma$	21%

$B_s \to J/\psi\phi$



FOM~ $\sqrt{(N_{signal}\ \varepsilon D^2)}\exp[-0.5(\sigma_t\ \Delta m_s)^2]$

Also untagged events contribute

Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})	Ref.
CDF	$J/\psi\phi$	9.6 fb^{-1}	$[-0.60, +0.12]$, 68% CL	$+0.068 \pm 0.026 \pm 0.009$	[2]
D0	$J/\psi\phi$	8.0 fb^{-1}	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	[3]
ATLAS	$J/\psi\phi$	4.9 fb^{-1}	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$	[4]
ATLAS	$J/\psi\phi$	14.3 fb^{-1}	$-0.119 \pm 0.088 \pm 0.036$	$+0.096 \pm 0.013 \pm 0.007$	[5]^p
ATLAS	above 2 combined		$-0.094 \pm 0.083 \pm 0.033$	$+0.082 \pm 0.011 \pm 0.007$	[5]^p
CMS	$J/\psi\phi$	20 fb^{-1}	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$	[6]
LHCb	$J/\psi K^+K^-$	3.0 fb^{-1}	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0033$	[7]
LHCb	$J/\psi\pi^+\pi^-$	3.0 fb^{-1}	$+0.070 \pm 0.068 \pm 0.008$	—	[8]
LHCb	above 2 combined		-0.010 ± 0.039(tot)	—	[7]
LHCb	$D_s^+D_s^-$	3.0 fb^{-1}	$+0.02 \pm 0.17 \pm 0.02$	—	[9]
All combined			-0.034 ± 0.033	$+0.084 \pm 0.007$	

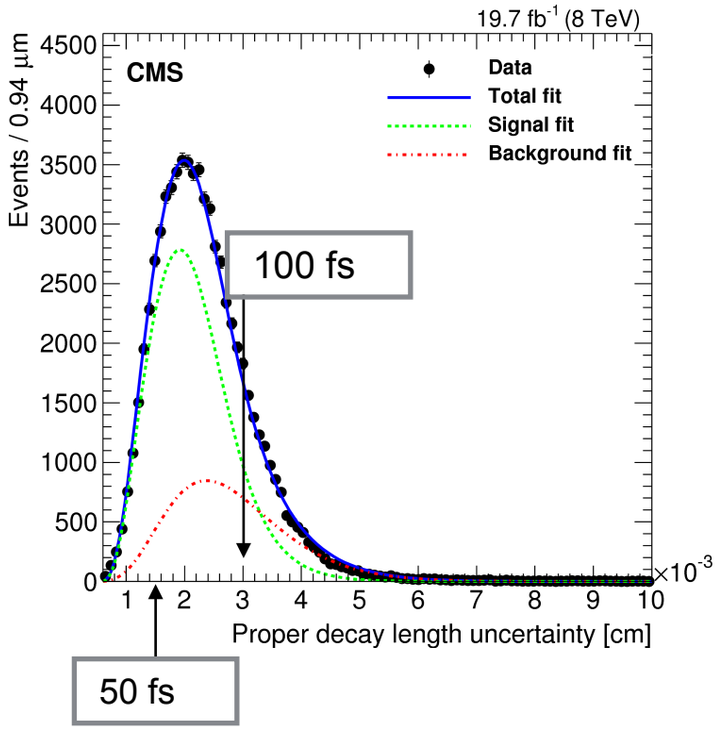
^{p} Preliminary.

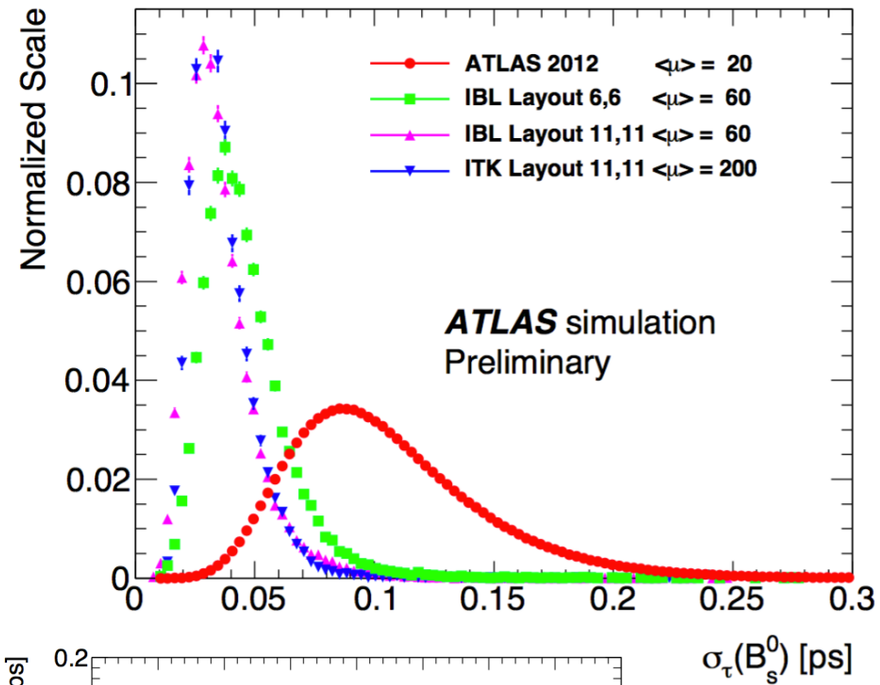
LHC Run 1 analyses

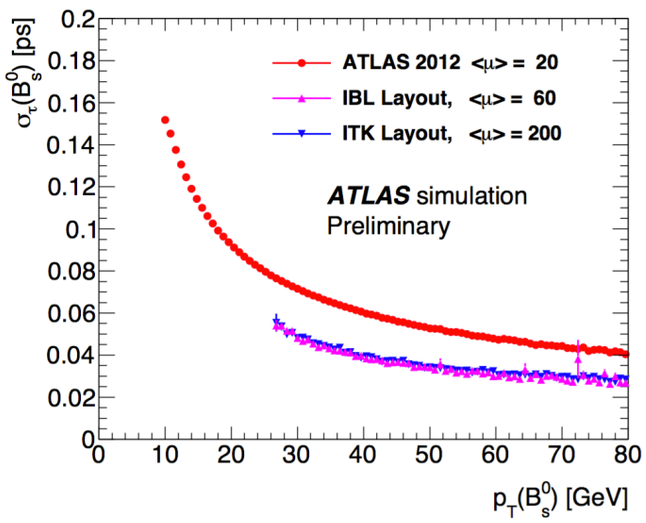
	εD^2 (%)	N_{signal}	σ_t (fs)
ATLAS	1.49	~75k	~60
CMS	1.31	~49k	~70
LHCb	3.73	~100k	~45

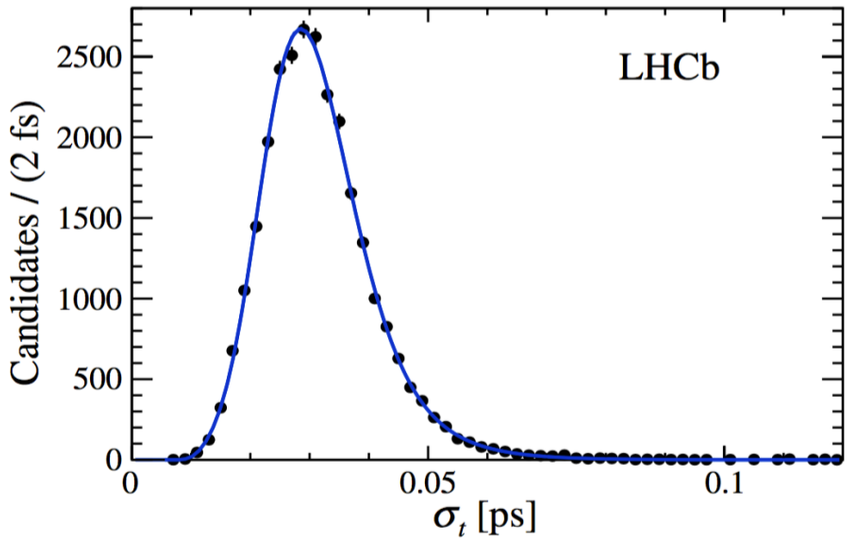
Proper time uncertainties

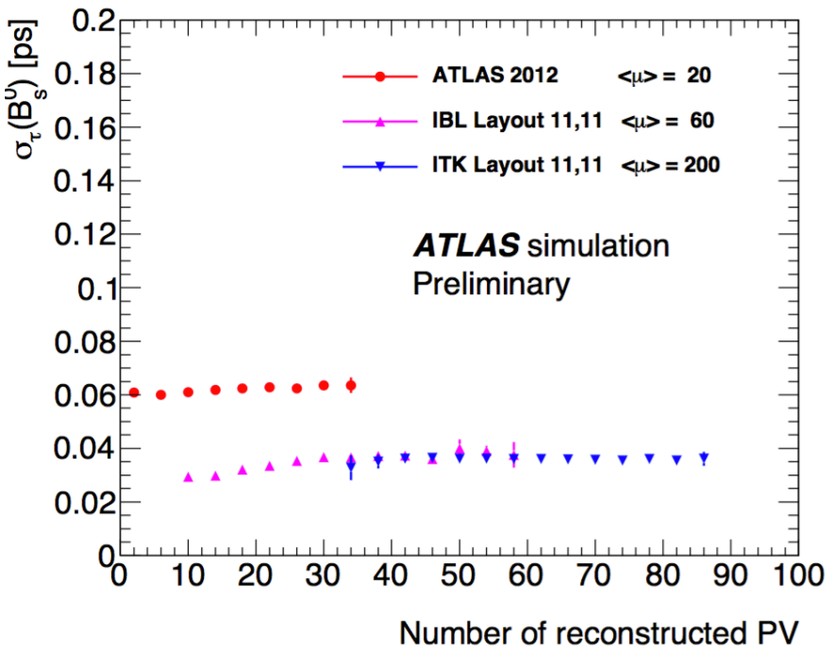
- **ATLAS and CMS currently limited by geometry and material budget**
  - **Next vertex detectors will impact extraordinarily**











$B_s \rightarrow J/\psi\phi$

- Increased proper time resolution beneficial
  - from ~60 fs (current analysis) to ~40 fs
- Level-1 Muon Trigger thresholds might severely impact the results
  - "aggressive" 6 - 6 GeV
    - may be doable with topological correlations at L1
  - conservative 11 - 11 GeV

ATL-PHYS-PUB-2013-010

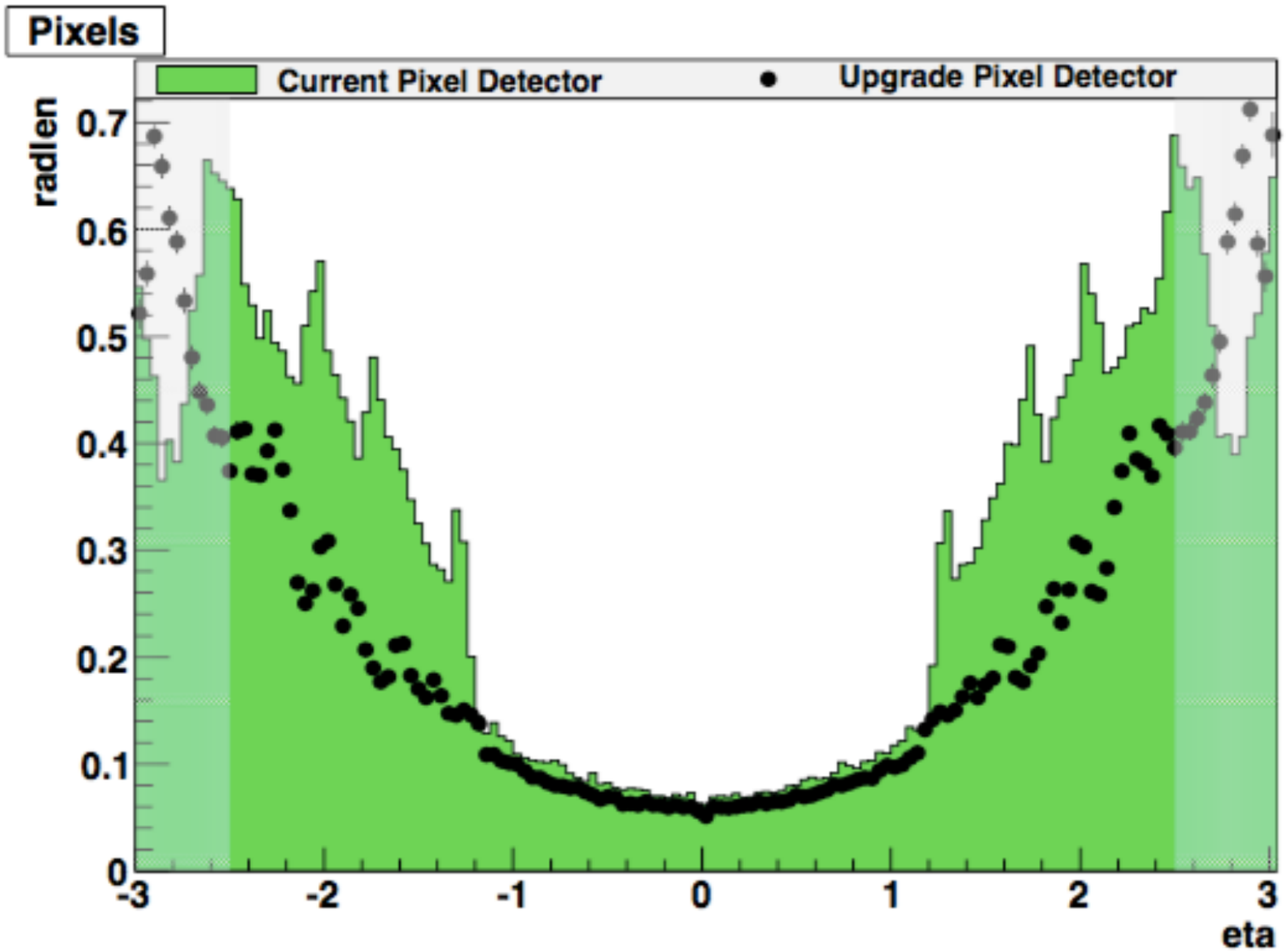
	2011	2012	2015-17		2019-21	2023-30+
Detector	current	current	IBL		IBL	ITK
Average interactions per BX $<\mu>$	6-12	21	60		60	200
Luminosity, fb^{-1}	4.9	20	100		250	3 000
Di-μ trigger p_T thresholds, GeV	4 - 4(6)	4 - 6	6 - 6	11 - 11	11 - 11	11 - 11
Signal events per fb^{-1}	4 400	4 320	3 280	460	460	330
Signal events	22 000	86 400	327 900	45 500	114 000	810 000
Total events in analysis	130 000	550 000	1 874 000	284 000	758 000	6 461 000
MC $\sigma(\phi_s)$ (stat.), rad	0.25	0.12	0.054	0.10	0.064	0.022

Conclusions and outlook

- **In the coming years, the LHC accelerator and the ATLAS and CMS detectors will undergo a series of upgrades in two major steps.**
  - **The first will result in a data sample corresponding to 300 fb^{-1} of integrated luminosity and the second to 3000 fb^{-1}.**
  - **New "all Silicon" Tracker detectors will be deployed with on-line tracking capabilities**
  - **New (lighter) vertex detectors will enhance the proper time resolutions of B hadrons**

- **With the increased data sample sizes it will be possible to reduce both systematic and statistical errors leading to high precision measurements of $B(B_{s/d} \rightarrow \mu\mu)$ and CP violating phase ϕ_s, which would allow stringent tests of the Standard Model**
  - **Other decay modes are expected to benefit**
  - **A new era for Heavy Flavour physics at ATLAS and CMS will be opened**

Backup



CMS Pixel Phase 1

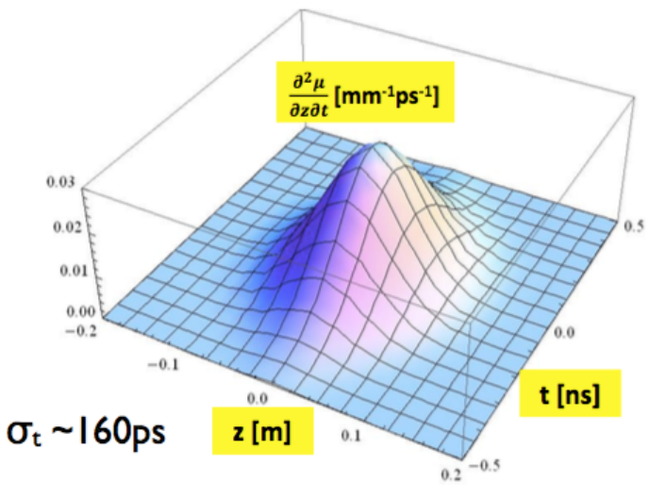
CMS Pixel Phase 1

Table 2.3: Average tracking efficiencies and track fake rates for muons with the additional cleanup cut and for a $t\bar{t}$ sample with default cuts for the current and upgrade pixel detector operating at zero pileup and at 2×10^{34} cm^{-2}s^{-1} (25 ns crossing time, *i.e.* 50 average pileup) without and with dynamic data loss (DL) simulated. The dynamic data loss simulated for the results below are fixed to the expected values for 2×10^{34} cm^{-2}s^{-1} (25 ns crossing time, *i.e.* 50 average pileup) . The statistical uncertainties on the efficiencies are about 0.1% and on the fake rates about 0.01%.

Sample and Conditions		Tracking Efficiency (%)		Track Fake Rate (%)	
Sample	PU/DL/Cuts	Current	Upgrade	Current	Upgrade
Muon	0/No/Cleanup	97.4	98.1	0.0	0.0
Muon	0/Yes/Cleanup	93.9	97.9	0.0	0.0
Muon	50/No/Cleanup	90.1	94.9	0.22	0.17
Muon	50/Yes/Cleanup	81.5	94.4	0.23	0.17
$t\bar{t}$	0/No/Default	89.6	93.5	0.71	0.40
$t\bar{t}$	0/Yes/Default	85.6	93.2	0.68	0.41
$t\bar{t}$	50/No/Default	84.9	92.2	8.72	5.09
$t\bar{t}$	50/Yes/Default	79.7	92.0	9.49	5.13

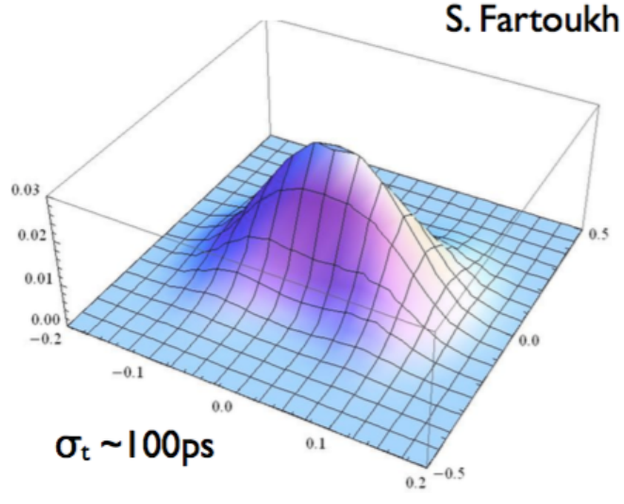
4D vertex reconstruction

S. Fartoukh



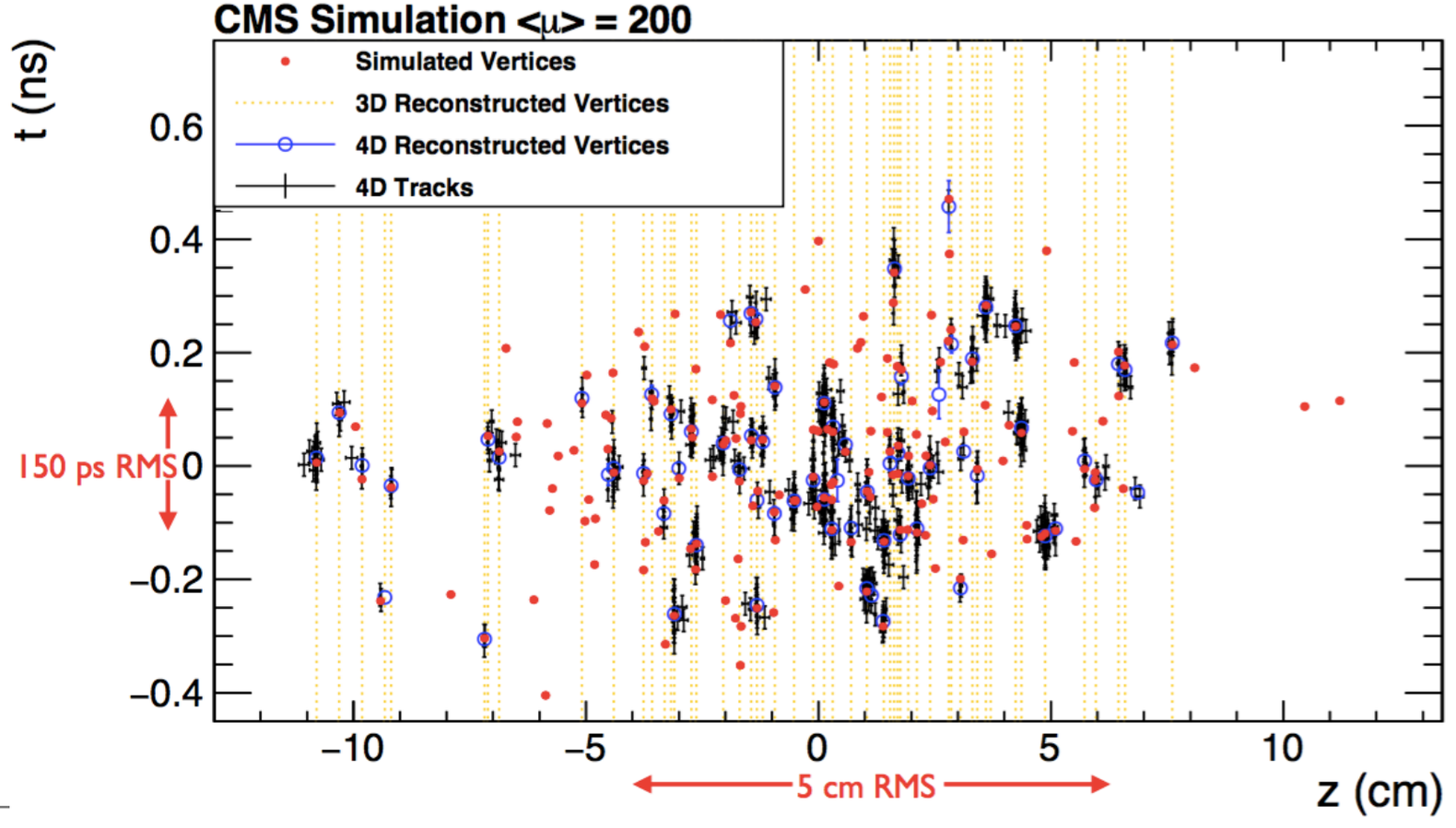
σ_t ~160ps

HL-LHC Baseline

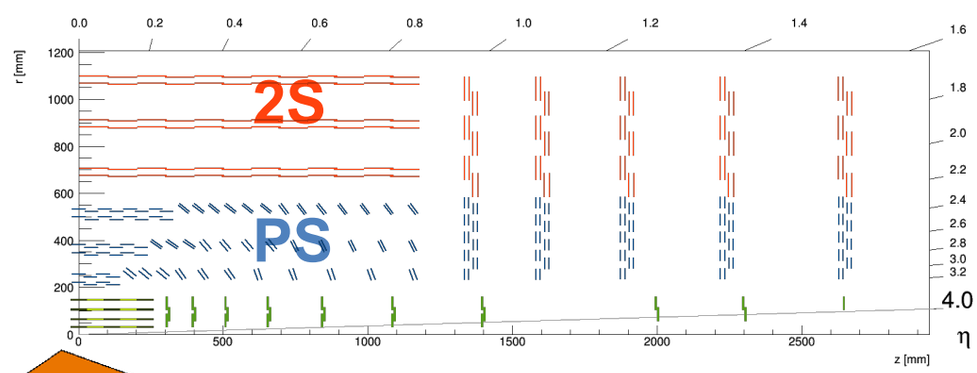


σ_t ~100ps

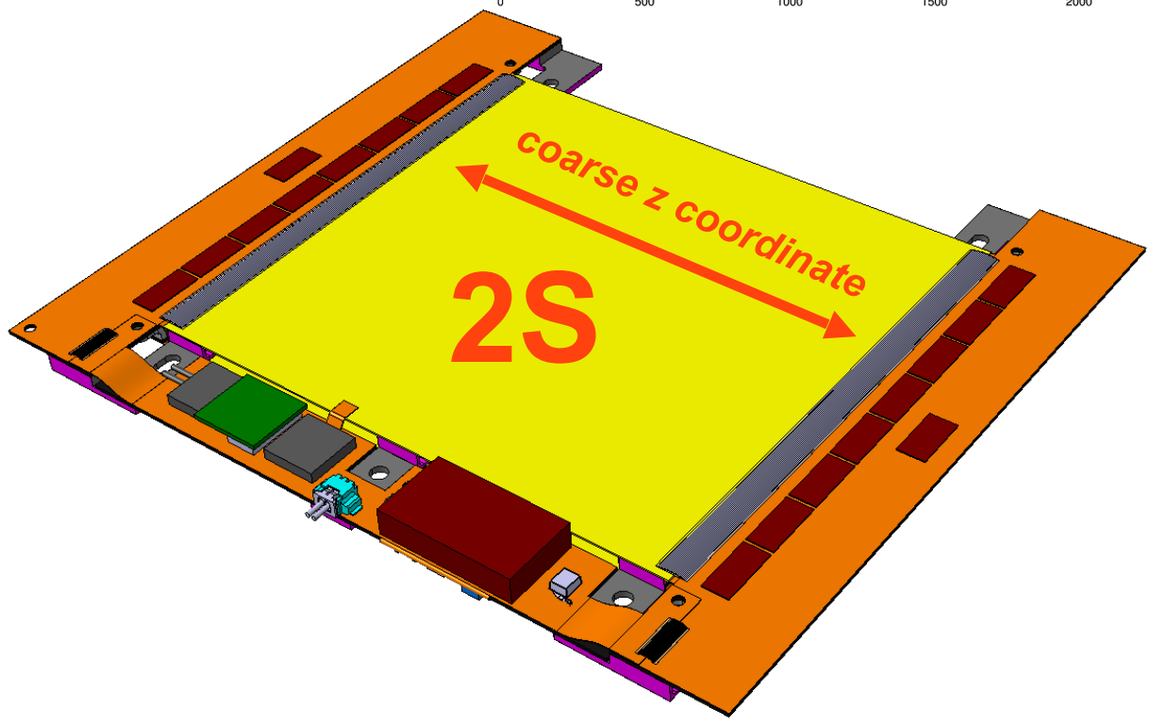
Crab-Kissing



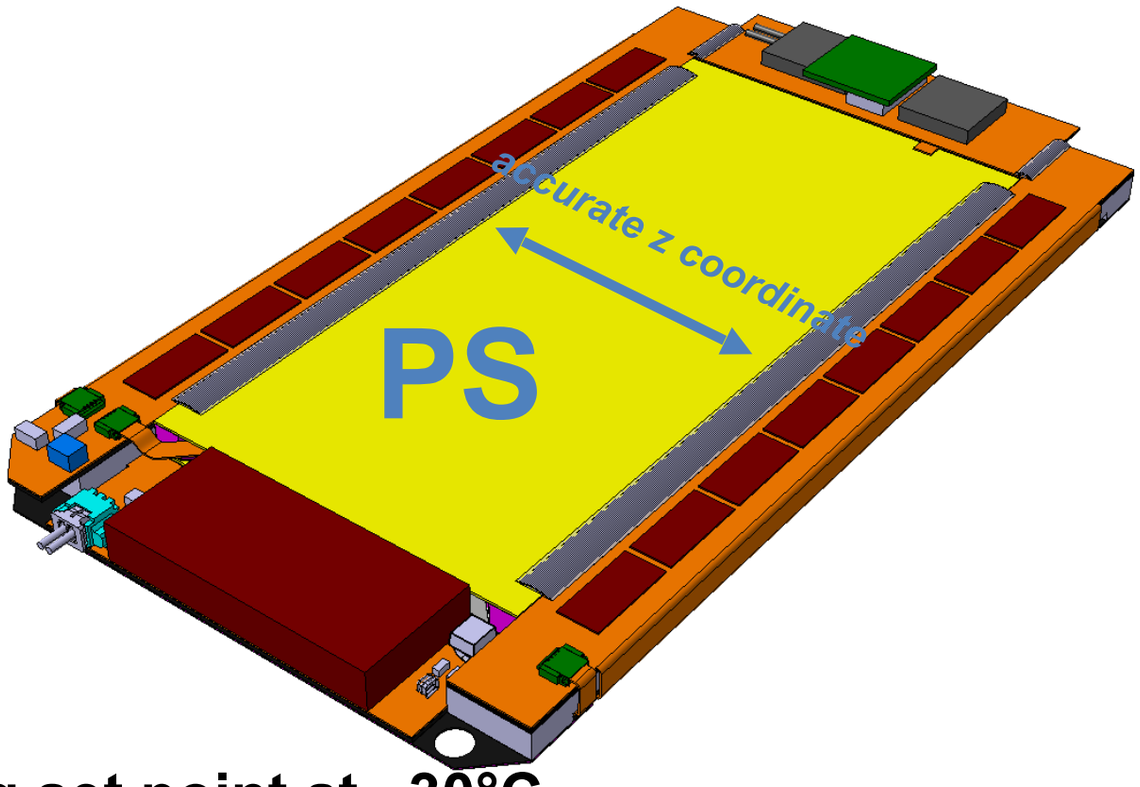
p_T modules



2 Strip sensors
2×1016 Strips: ~ 5 cm × 90 µm
2×1016 Strips: ~ 5 cm × 90 µm
P ~ 5 W
~ 2× 90 cm^2 active area
For R > 60 cm
Spacing 1.8 mm and 4.0 mm

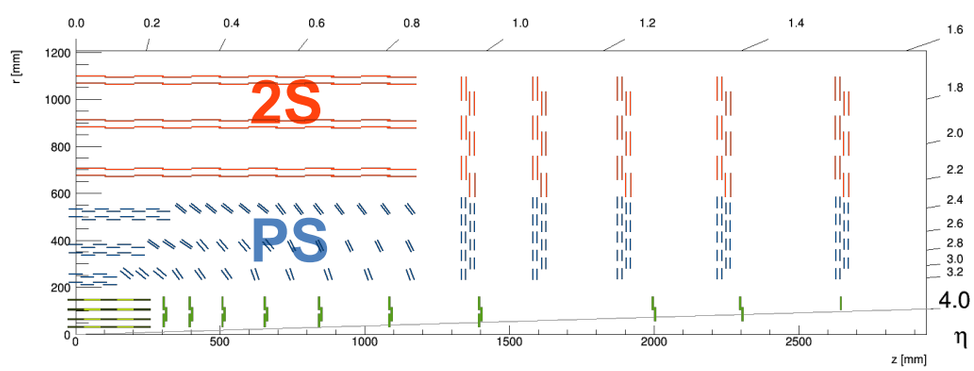


Pixel + **S**trip sensors
2×960 Strips: ~ 2.5 cm × 100 µm
32×960 Pixels: ~ 1.5 mm × 100 µm
P ~ 7 W
~ 2× 45 cm^2 active area
For r > 20 cm
Spacing 1.6 mm, 2.6 mm and 4.0 mm

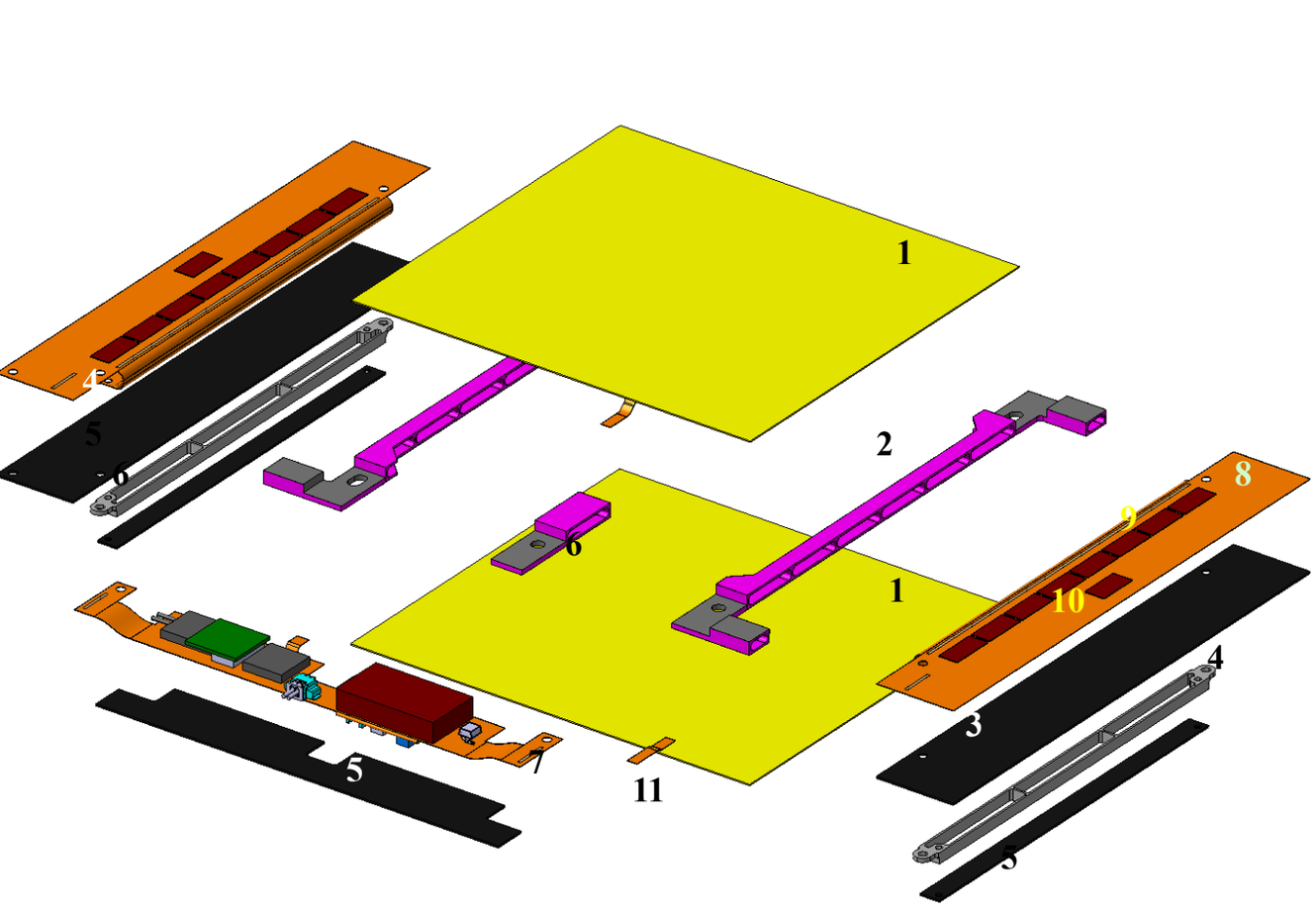


Operate sensors at about –20°C with cooling set point at –30°C

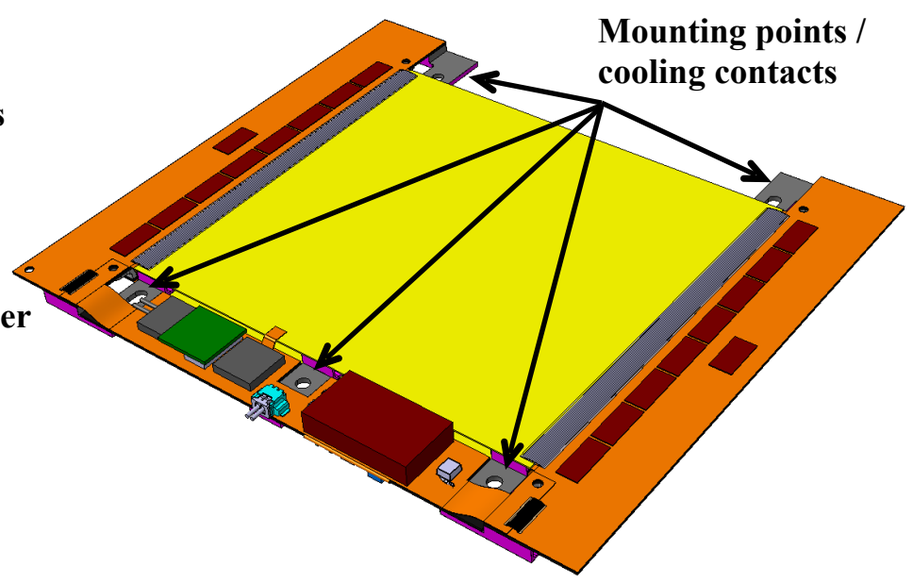
2S module

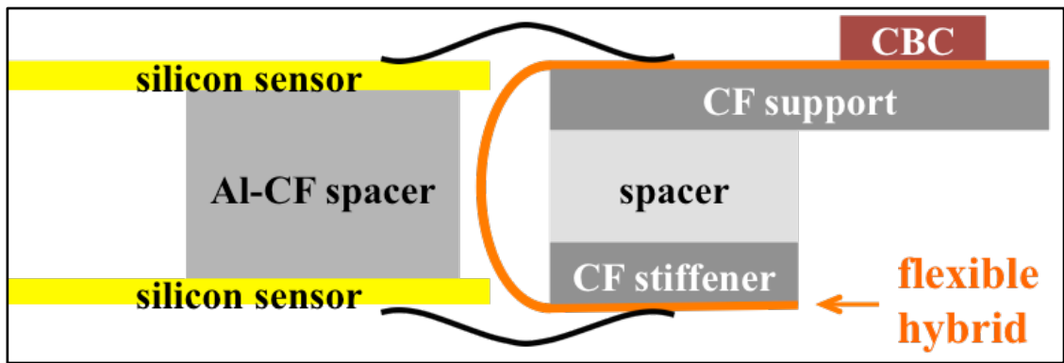


- Read out from the edges, to avoid difficult / expensive TSV technologies
- Flex hybrid circuit collects signals from both sensors
  - Supports wirebonding to sensors and bump-bonding of readout ASICs
  - Complex routing and high-density of lines
  - 8 CBC, 1016 channels per sensor per end
- The sensors has 90 μm pitch – at the limit of the hybrid technology!

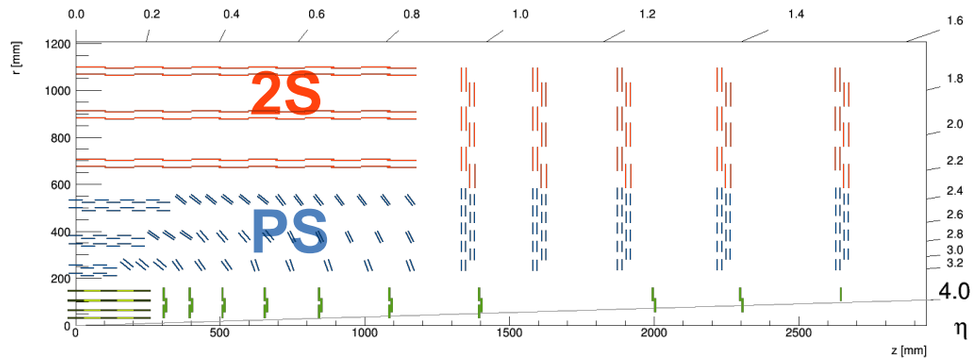


1. 2S silicon sensors
2. Al-CF spacer
3. CF support
4. Al-CF spacer
5. CF stiffener
6. Al-CF short spacer
7. Service Hybrid
8. FE Hybrid
9. CBC
10. CIC
11. HV tab

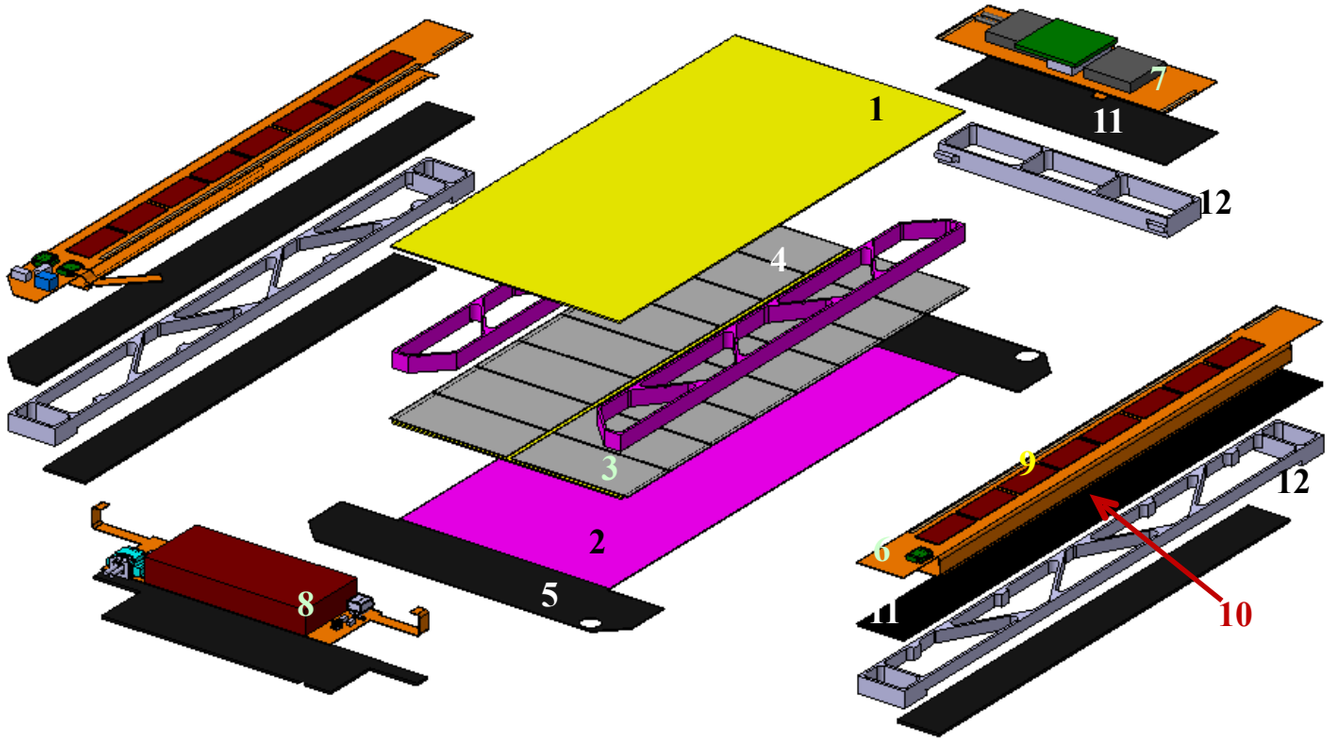




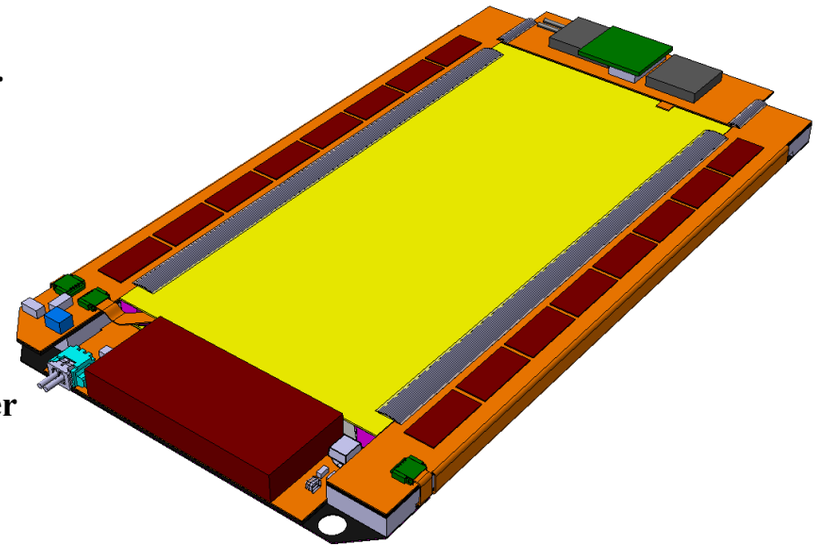
PS module

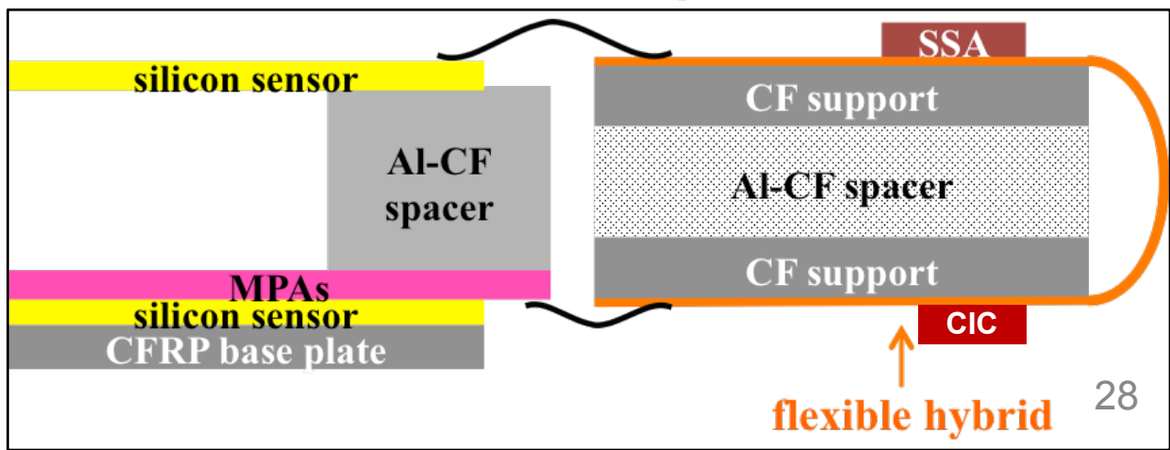


- Size limited to ½ 6” wafer
  - Cover the length with 2 chips – connect from the sides
  - 25 mm long strips required at low radii anyway
- Hard limit at 100 μm pitch in order to use (inexpensive) C4 bump-bonding
  - N.B. 30 m^2 of Macro-Pixel Sensors
- Segmentation in z is a compromise between z_0 resolution and power dissipation
- Deploy down to ~20 cm to achieve desired z_0 resolution in L1 tracking
  - Also much less expensive and power-hungry than pixel modules!!



1. **PS-s silicon sensor**
2. **PS-p silicon sensor**
3. **MPAs**
4. **Al-CF sensor spacer**
5. **CFRP base plate**
6. **FE Hybrid**
7. **Opto-Link Hybrid**
8. **Power Hybrid**
9. **SSA**
10. **CIC**
11. **Hybrid CF support**
12. **Al-CF Hybrid spacer**





Outer Trackers in Summary

ATLAS

CMS

High Granularity

25 mm × 75 μm
50 mm × 75 μm

25 mm × 100 μm
50 mm × 90 μm

Stereo strips
for z coordinate

Inner boundary 350 mm

Wedge modules in
the End Caps

Tracking @ Level-1

p_T modules

P.V. discrimination

Stub finding efficiency

Macro pixels
for z coordinate

Inner boundary 200 mm

half-size
PS modules

Rectangular modules in
the End Caps

Tilted Inner Barrel

Pixel Detectors

Enhanced radiation tolerance → thinner silicon sensors → less charge available
Possibly 3D sensors on in the inner regions

Improved two-track separation for high-energy jets

Readout chip with small cell-size and low detection threshold

→ **Common development in RD53, 2500 μm² cell size**

Are we heading towards very similar pixel detectors??
… maybe not… ☺️

- ➢ Boundaries
- ➢ Pixel cell aspect ratio
- ➢ Overall layout

Pixel Detectors Boundaries

Outer Boundary different (as discussed earlier)
ATLAS: 350 mm
CMS: 200 mm

Inner boundary also different
ATLAS: 39 mm (?)
CMS: 29 mm

Almost a factor of two difference in track density!
→ **Hit rates**
→ **Particle fluence**

ATLAS has detectors mounted onto the beam pipe
Requires insulation material for beam-pipe bakeout

CMS can extract/install the pixel detector with the beam pipe in place
Can go as close as mechanical tolerance allows

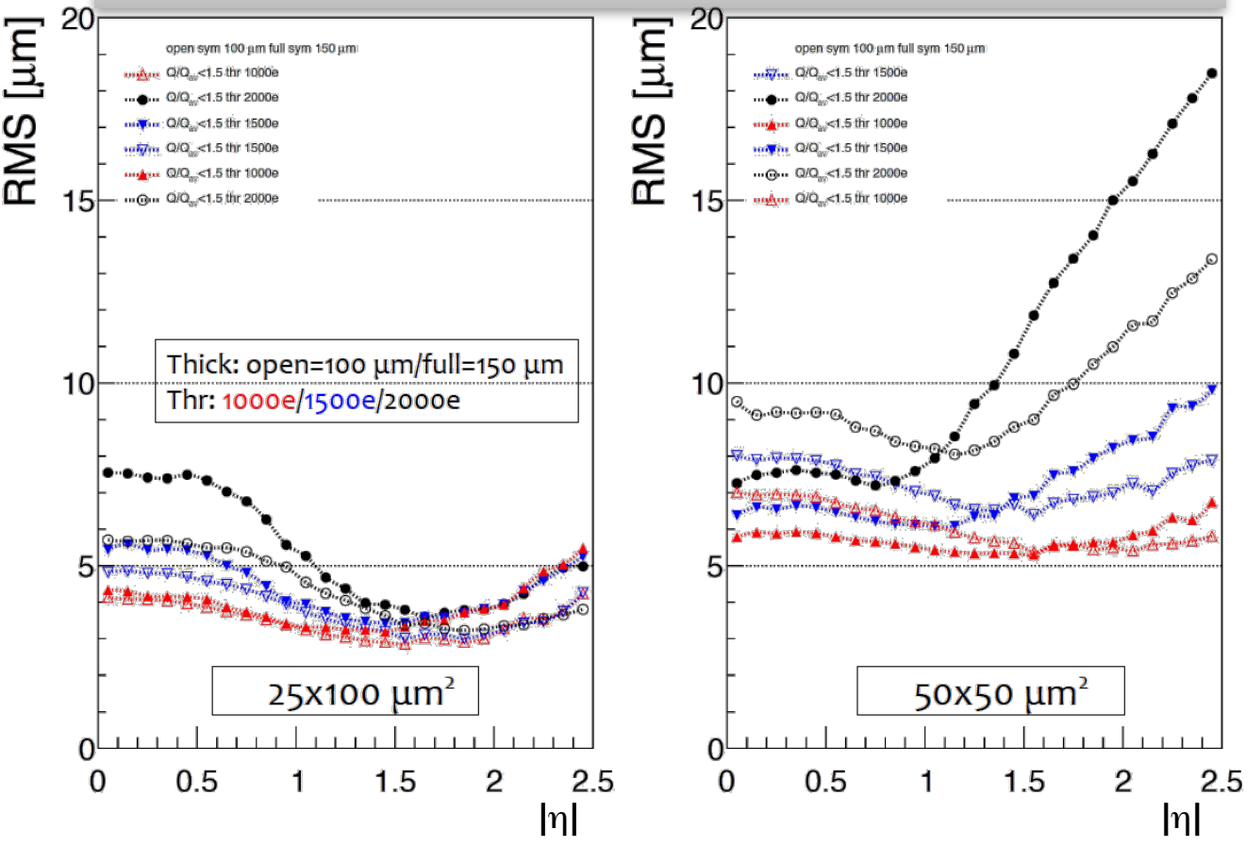
Will that remain the same? (… for CMS it will!)

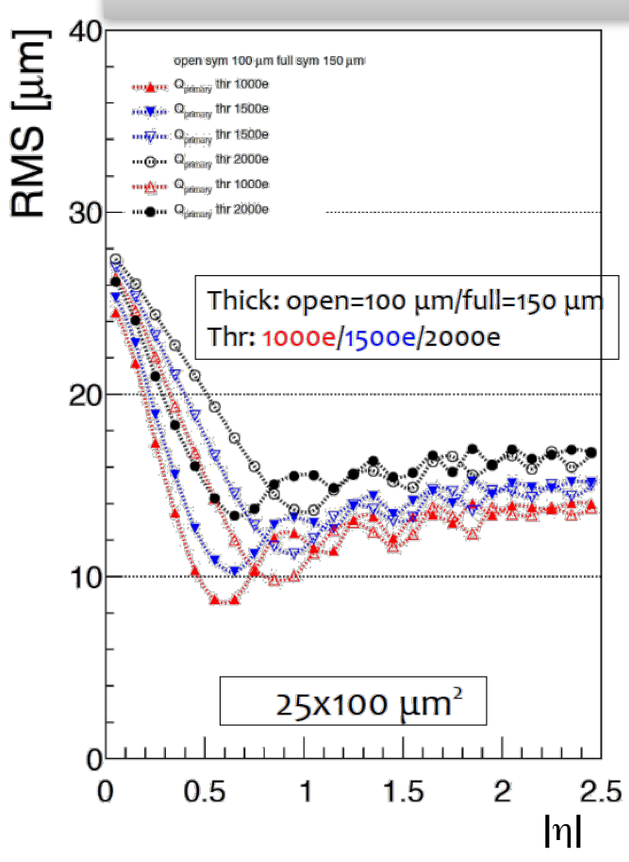
Pixel Aspect Ratio

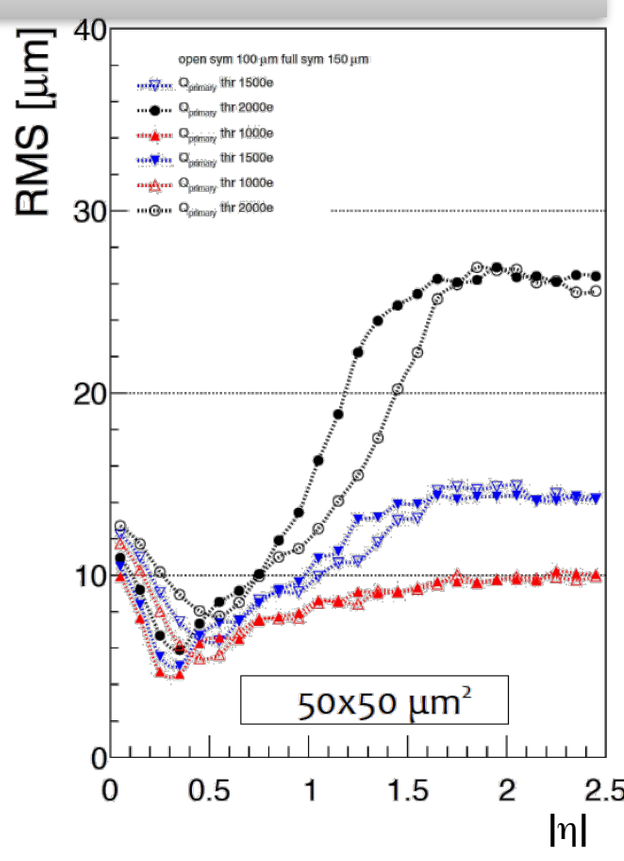
CMS: hit resolution studies in Barrel Layer 1

Full simulation, different sensor thickness and detection thresholds, no radiation damage

r-ϕ resolution | **z resolution**







CMS Conclusions:

Square pixels are better for z resolution in the central region, rectangular pixels are better in all other cases

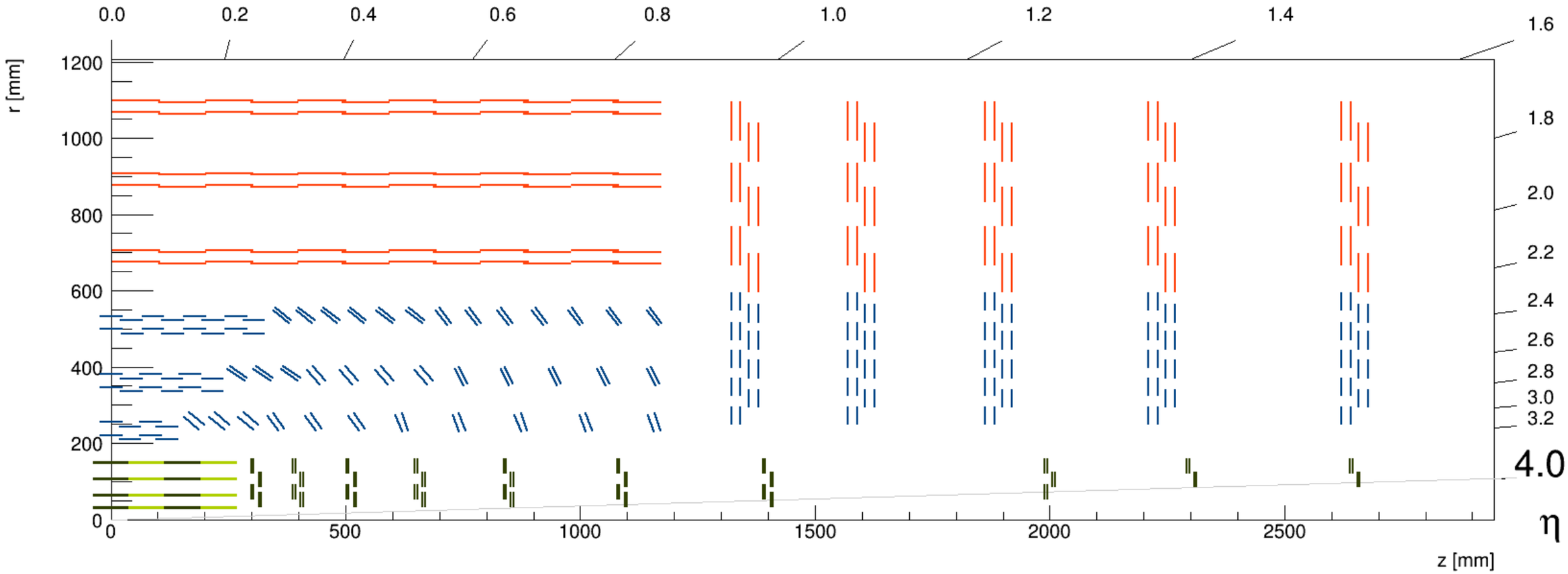
Square pixels require lower detection threshold (will get even worse with rad damage – ongoing)

Square pixels also aggravate substantially the bandwidth requirement (particularly relevant for CMS…)

Rectangular pixels are needed in a barrel flat geometry

ATLAS for the time being is focusing on using square pixels everywhere

Pixel Detector Layout: CMS

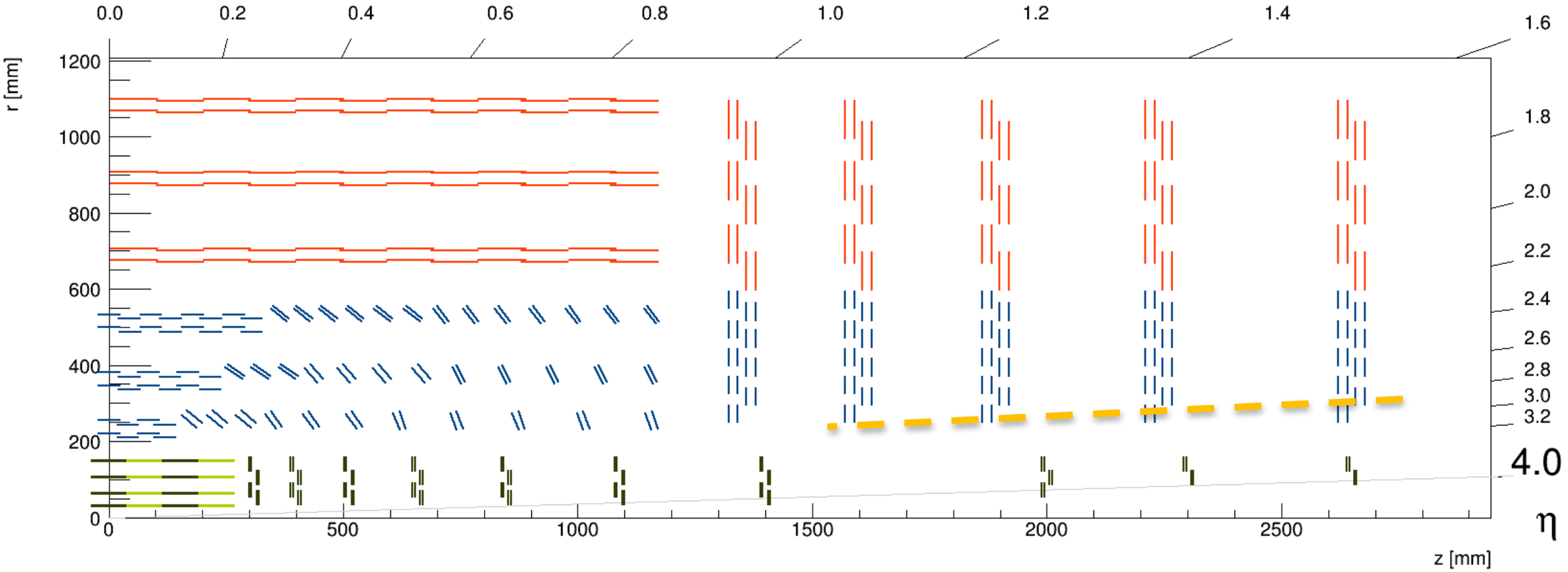


Started from a fairly “conventional” layout

- Barrel geometry inspired by “phase-1” detector
- End Cap geometry inspired by Outer Tracker Double-Disks
  - Different options for module size under consideration
  - Large pixels (×4 surface) could be used in the outermost layers/rings, to save power

<u>BUT</u>:

Pixel Detector Layout: CMS



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  - Large pixels (×4 surface) could be used in the outermost layers/rings, to save power

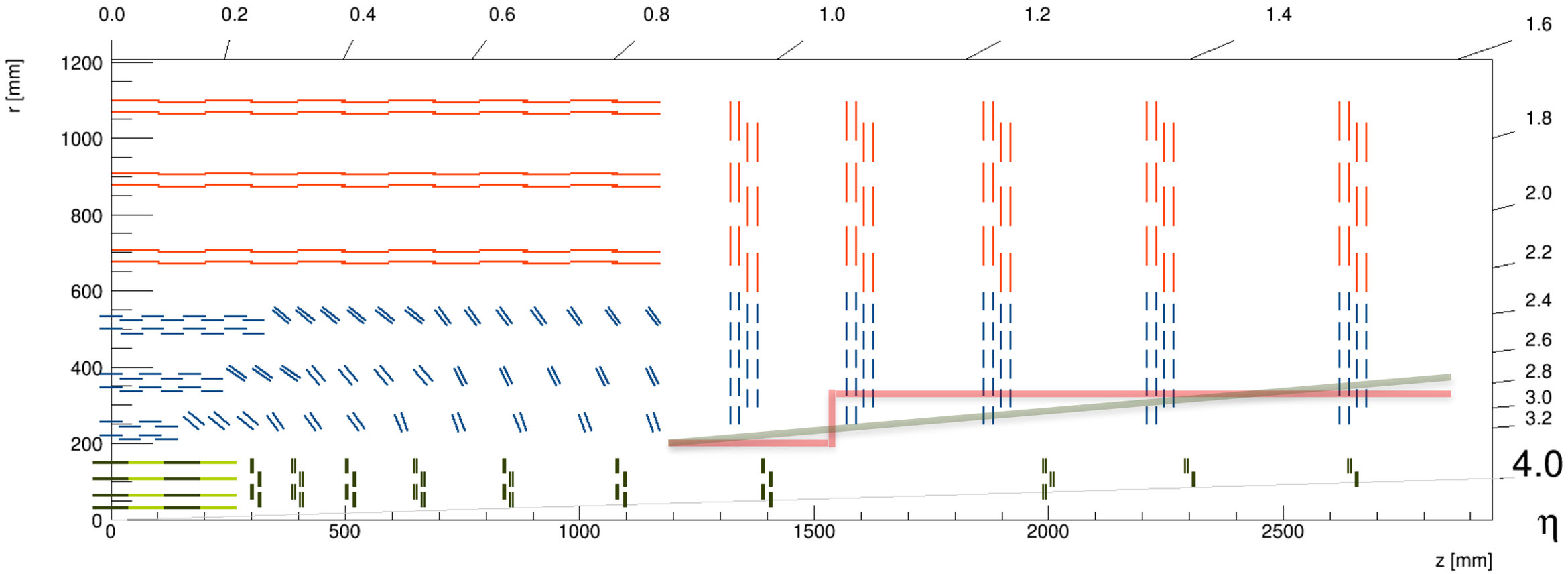
<u>BUT</u>:

Installation of the central section around the beam pipe requires a larger opening in the forward part

The detector slides in with an inclined angle!

The OT/Pixel boundary must be at larger radius in the forward part

Pixel Detector Layout: CMS



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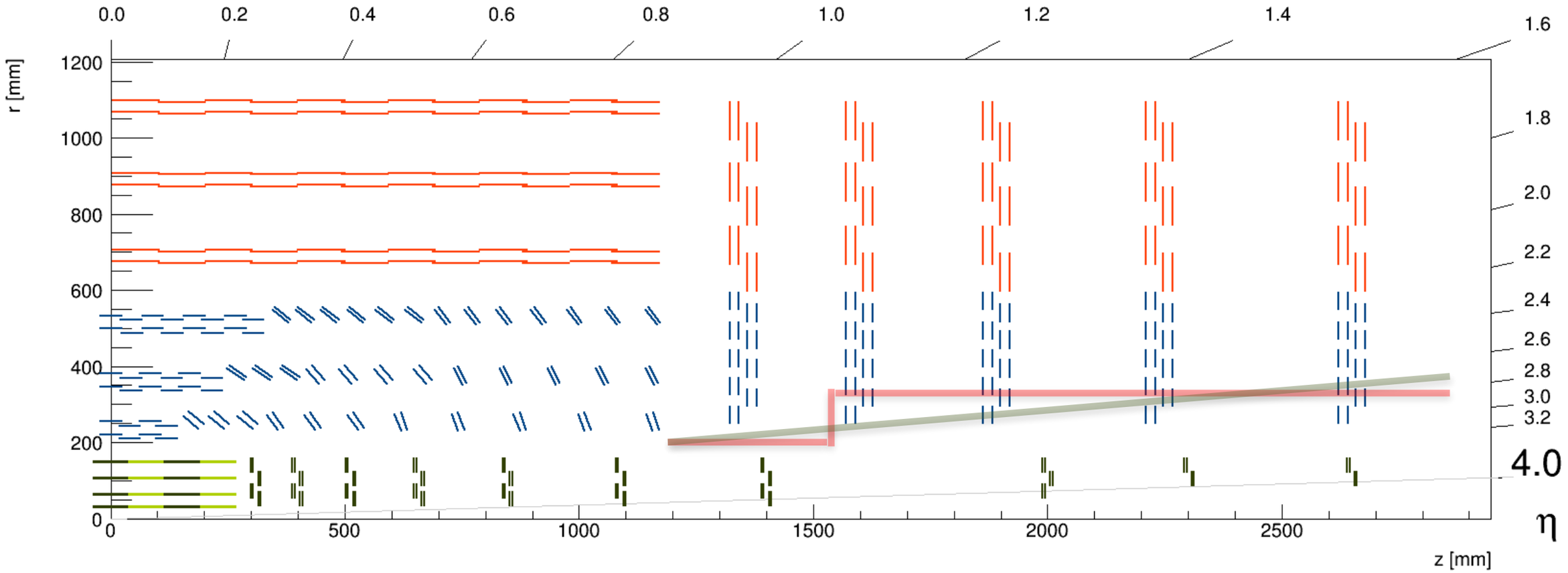
The OT/Pixel boundary must be at larger radius in the forward part

A step? Where? How large?

A conical boundary? (… watch complication...)

Pixel Detector Layout: CMS



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The detector slides in with an inclined angle!

The OT/Pixel boundary must be at larger radius in the forward part

A step? Where? How large?

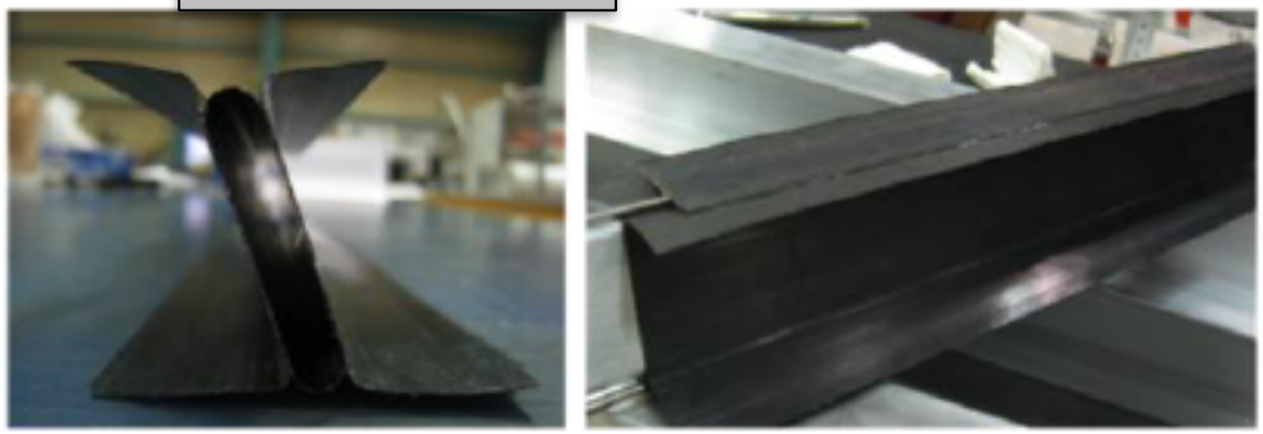
A conical boundary? (… watch complication...)

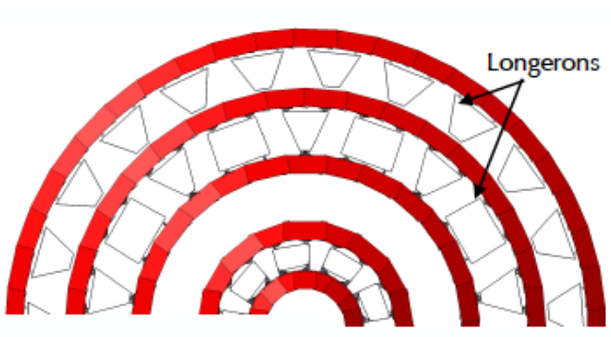
Work in progress

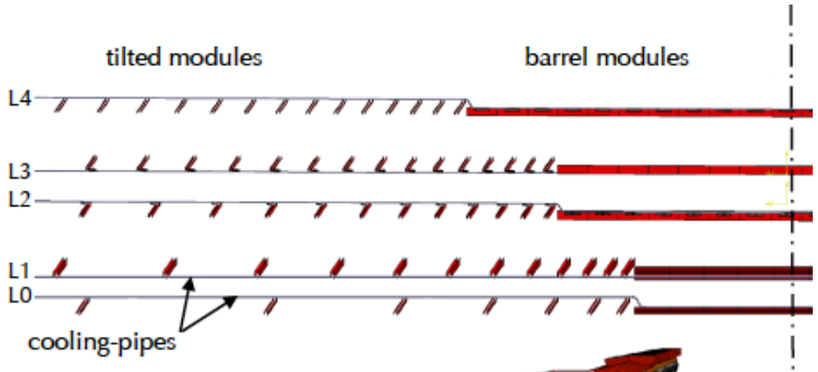
Pixel Detector Layout: ATLAS

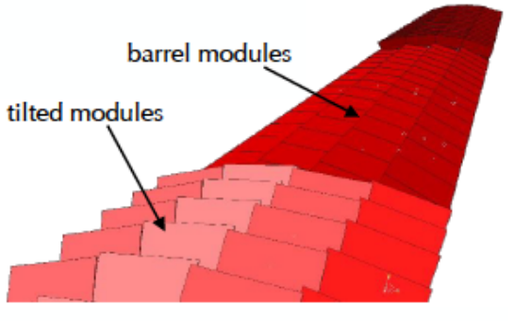
As alternative to the flat barrel, two options to implement progressively tilted modules under development…

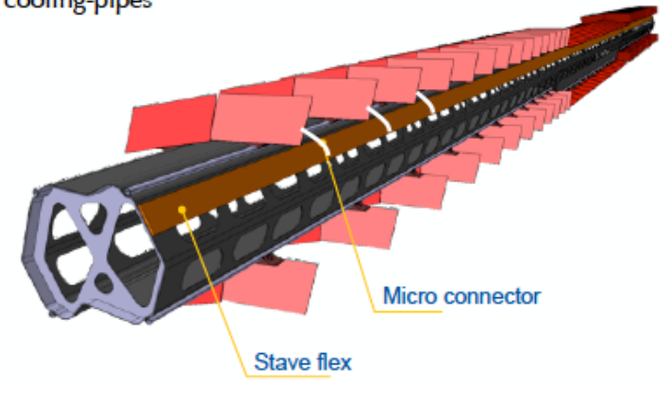
I-beam support



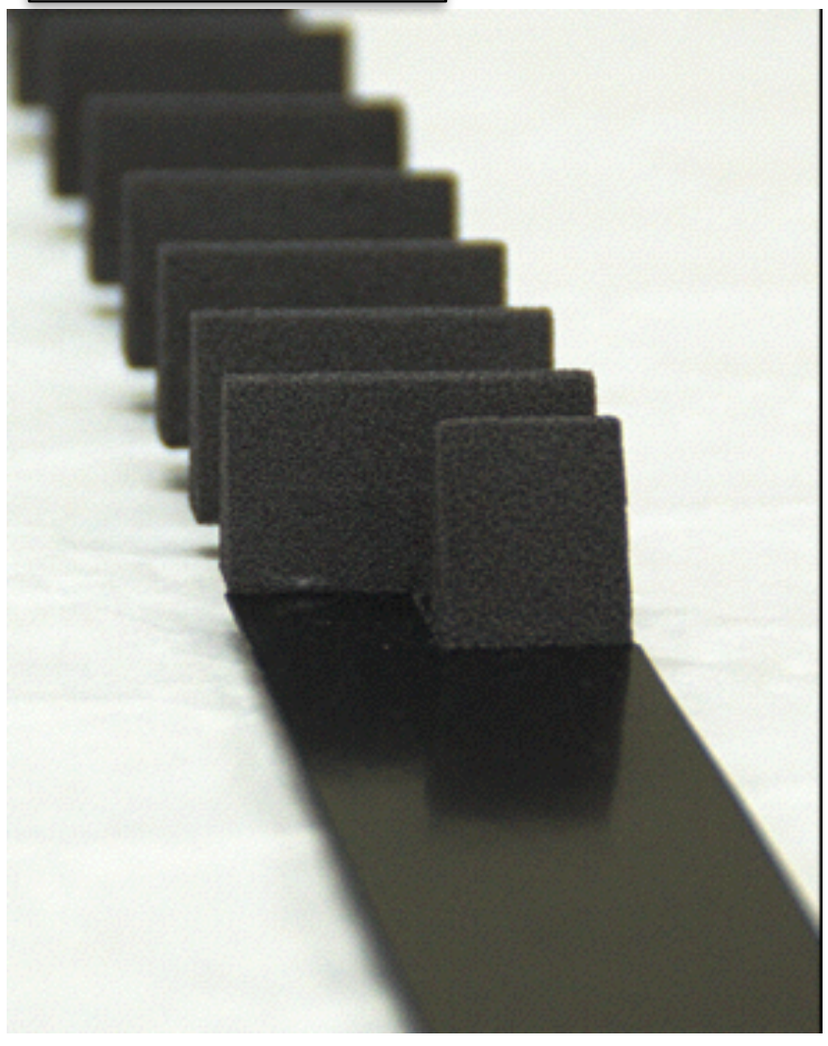






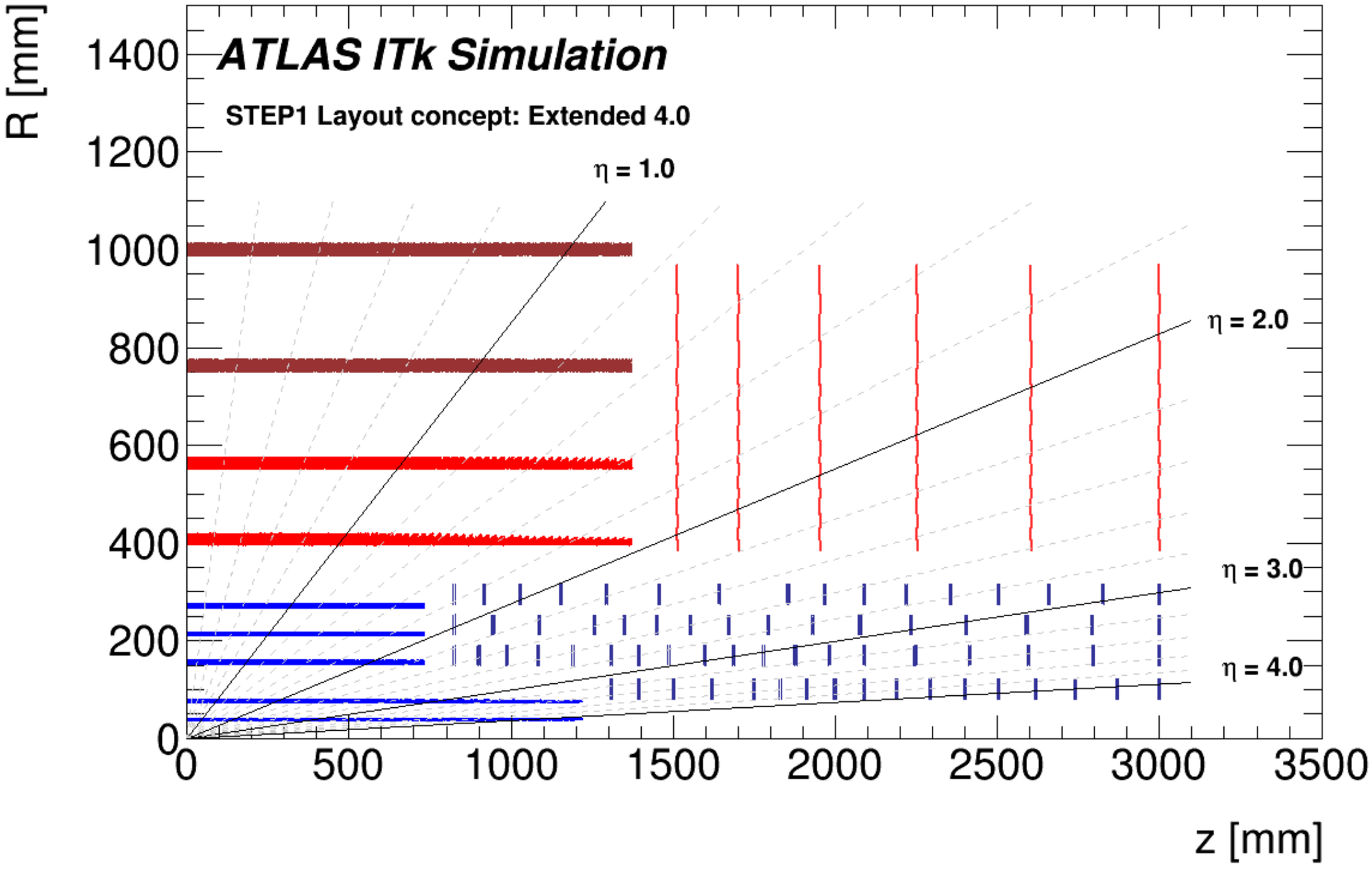


Alpine support



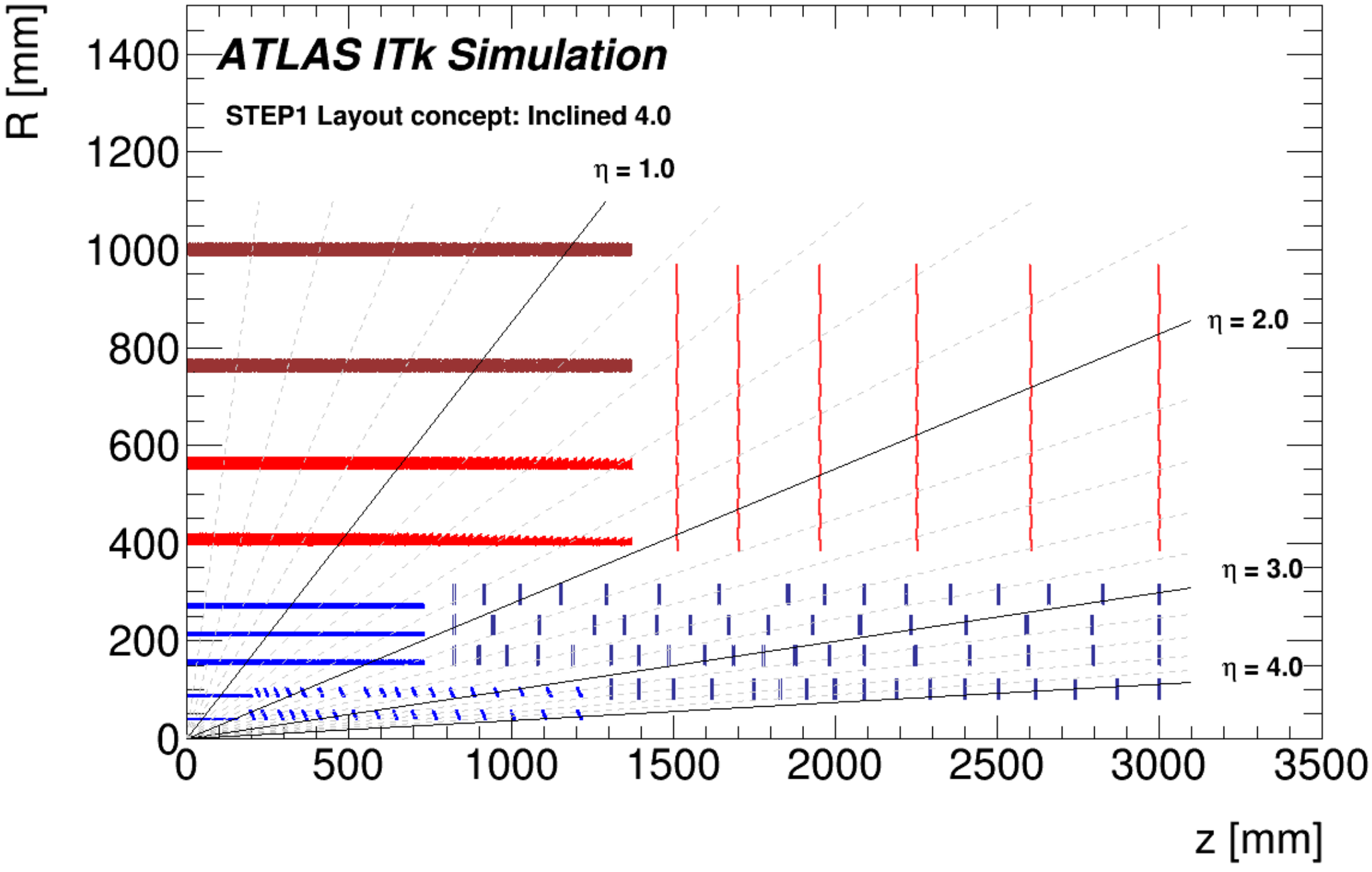
Pixel Detector Layout: ATLAS

…. to be combined with a creative end-cap layout…



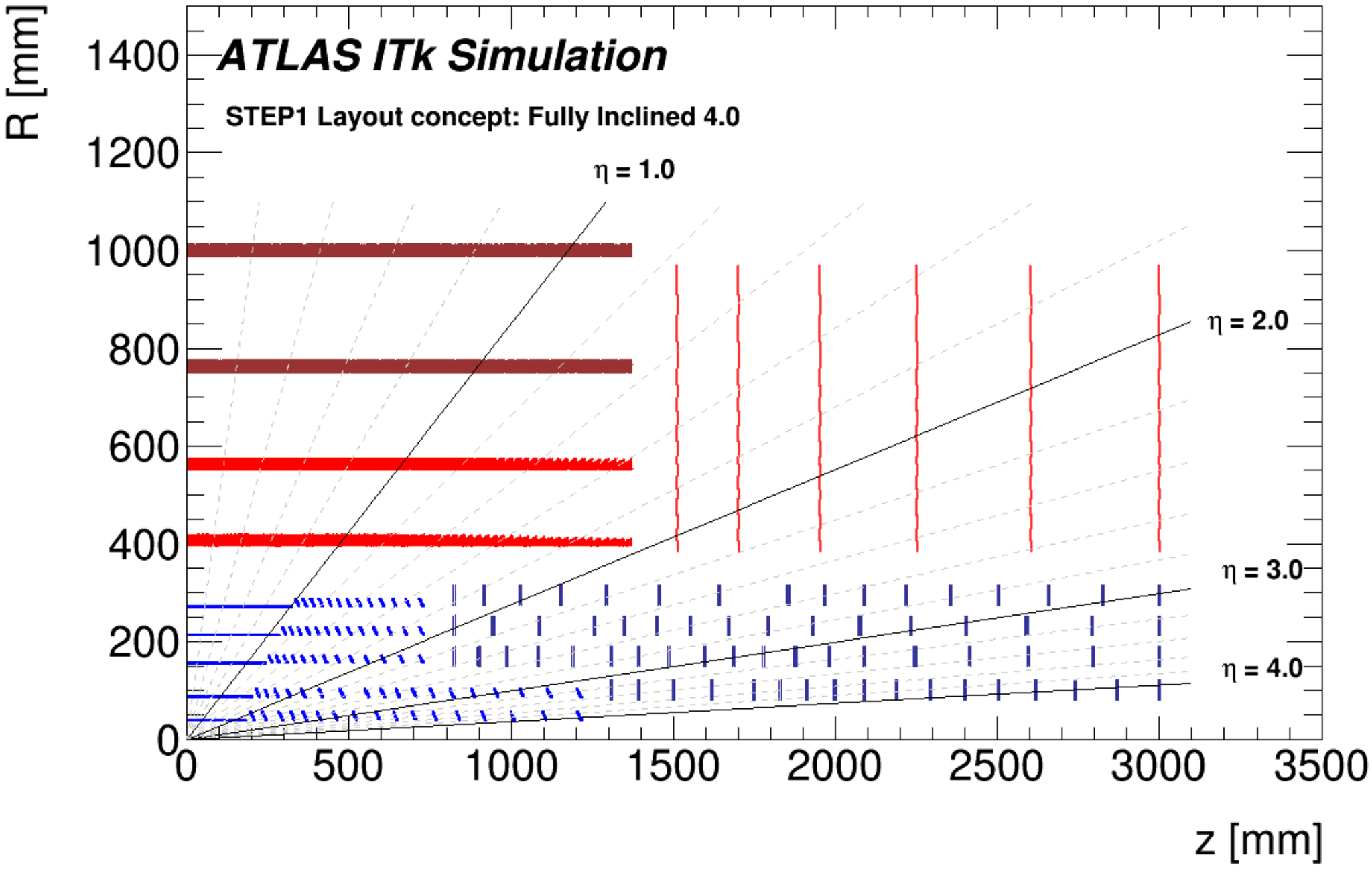
Pixel Detector Layout: ATLAS

…. to be combined with a creative end-cap layout…

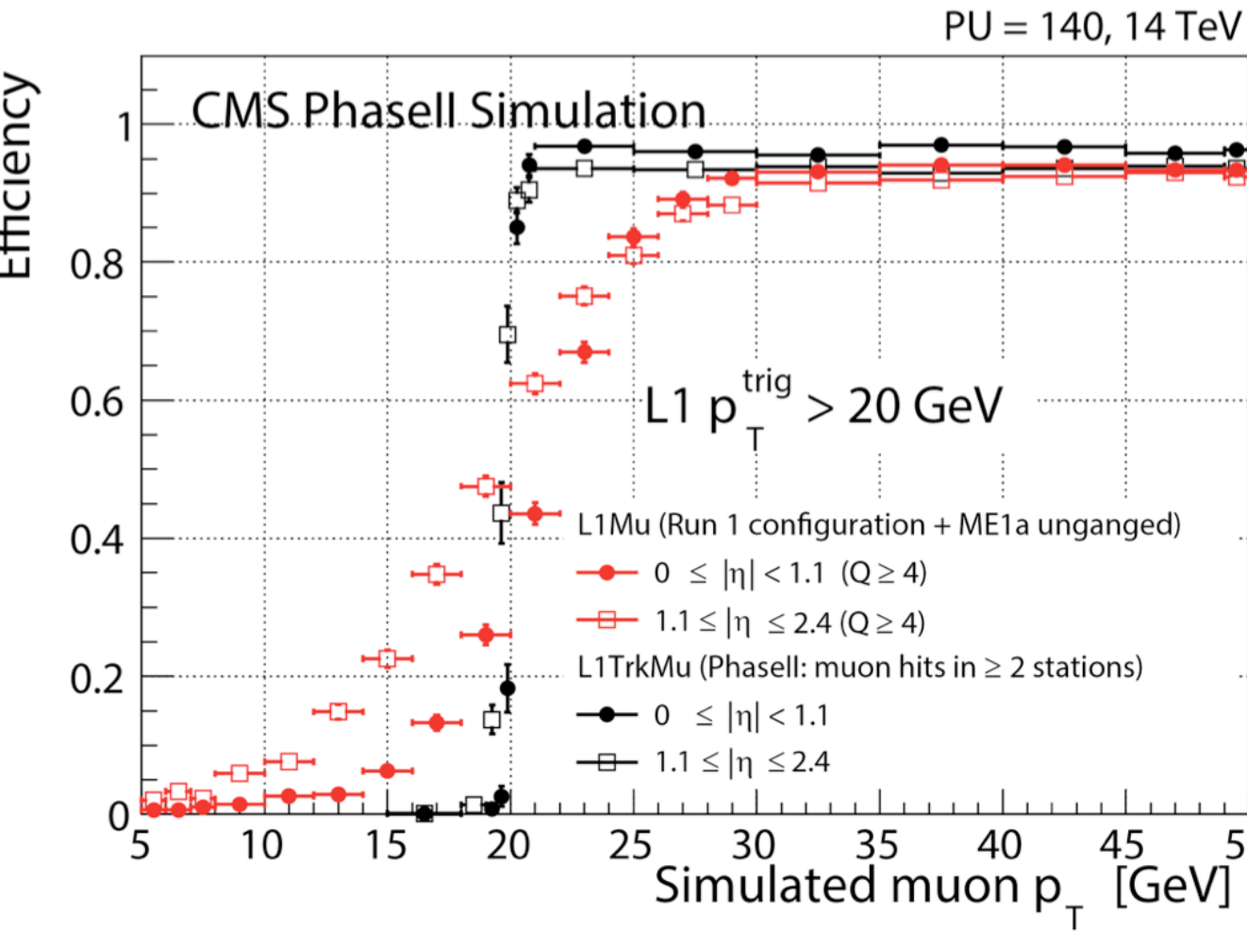


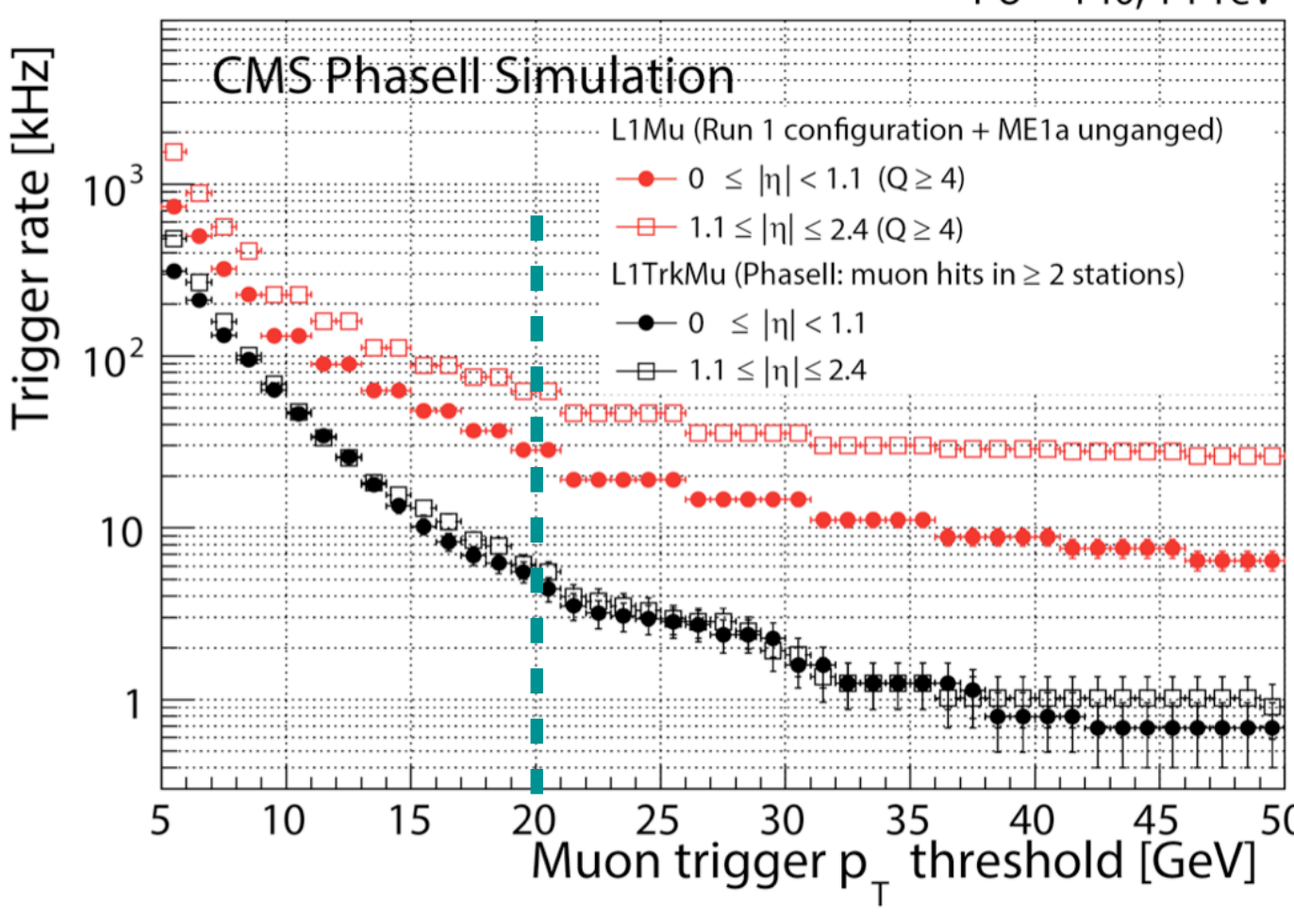
Pixel Detector Layout: ATLAS

…. to be combined with a creative end-cap layout…



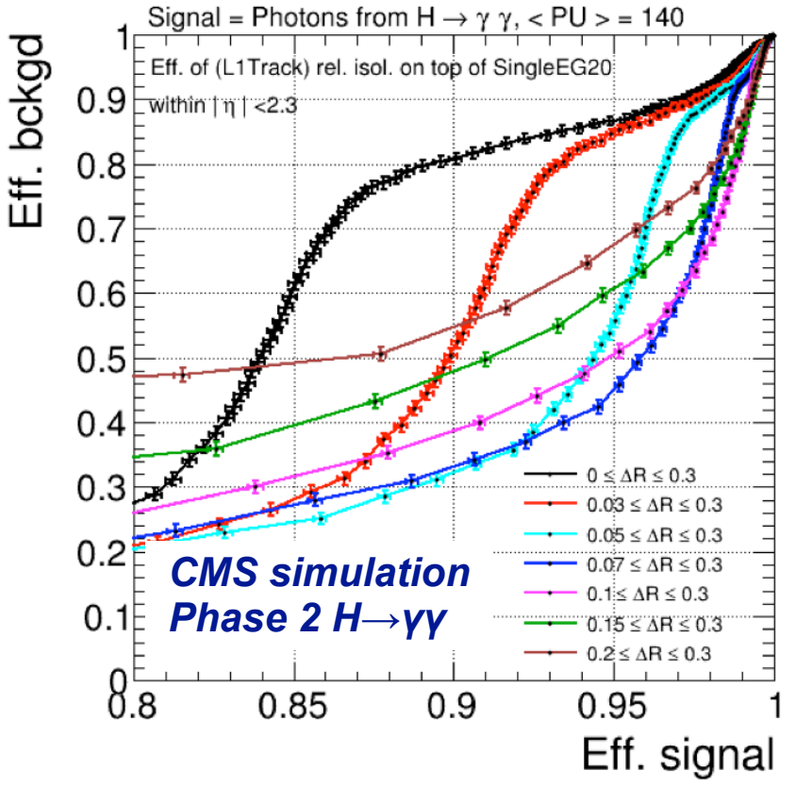
Track Trigger performance: Muons

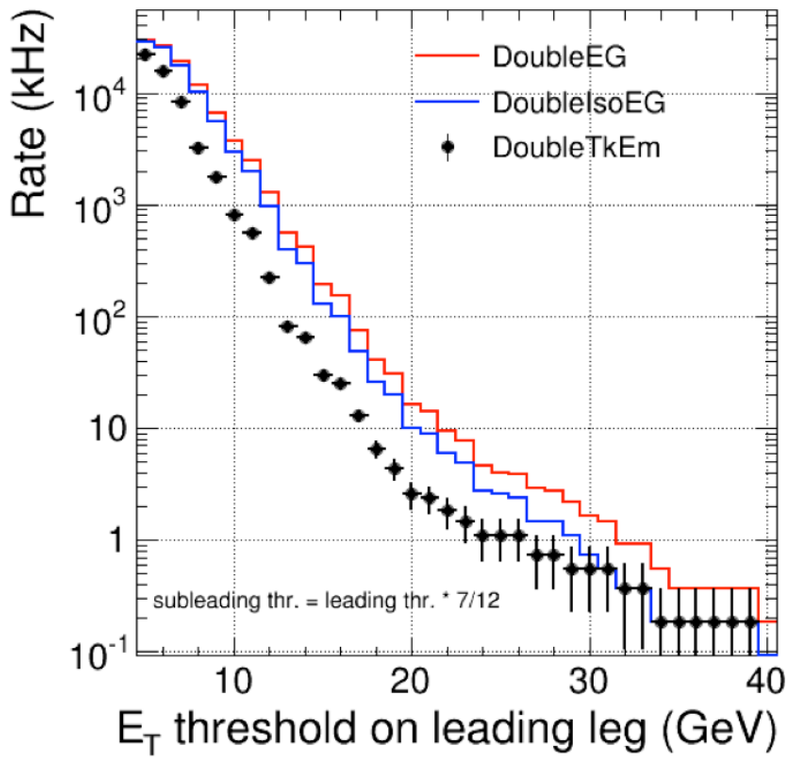


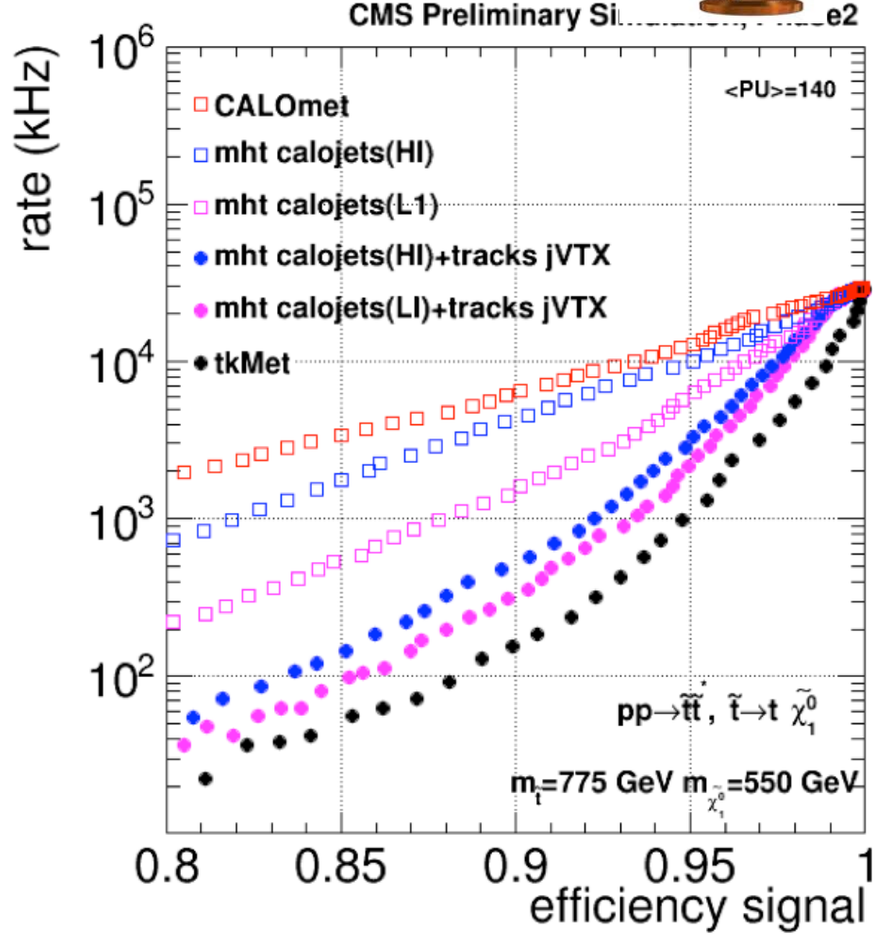


- Sharpens turn-on curve and improves efficiency
  - For a cut of 20 GeV the rate can be reduced by a factor of O(10)

Tracker Trigger performance: electrons, photons and jets

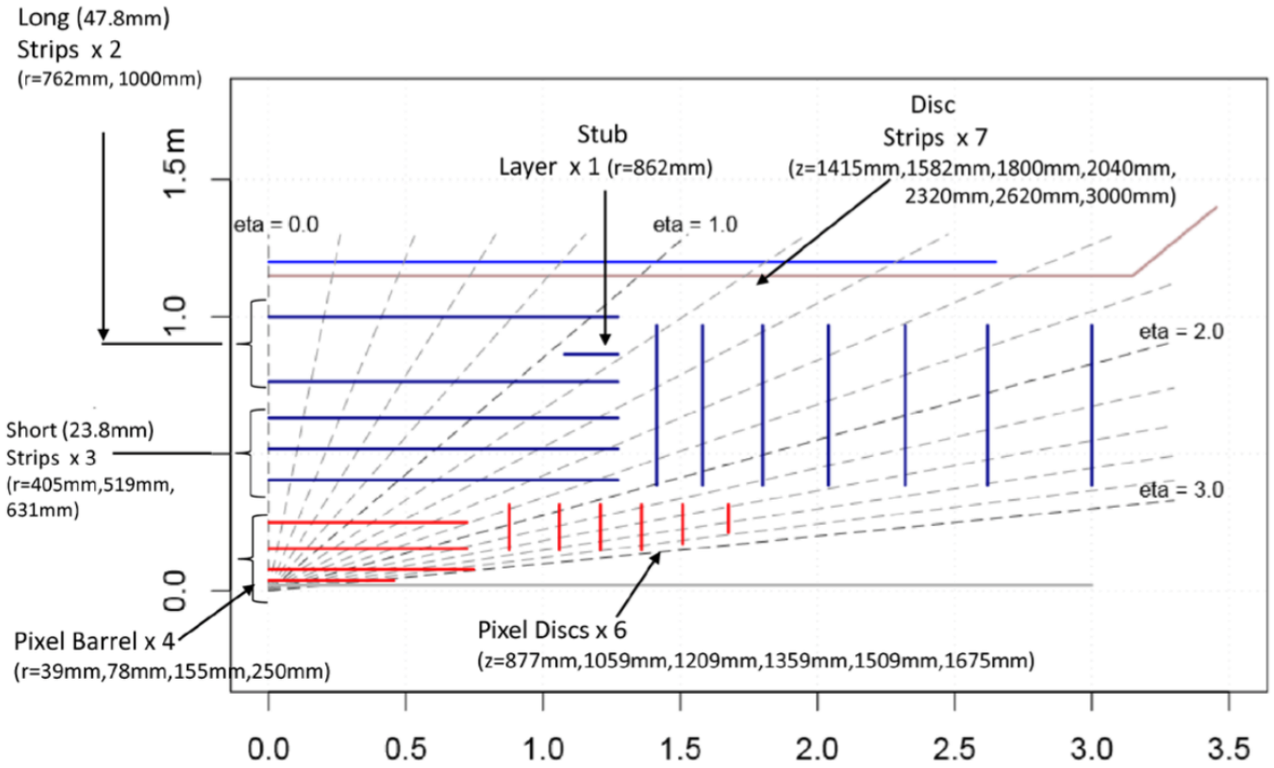




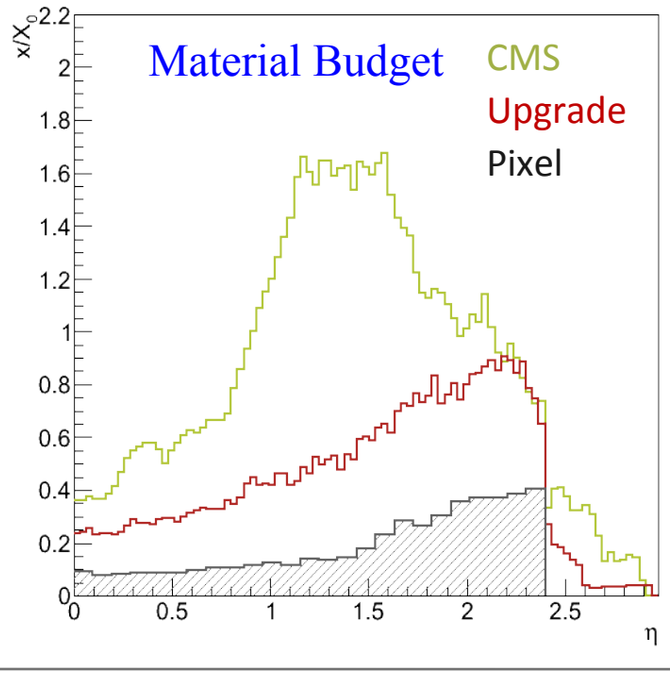


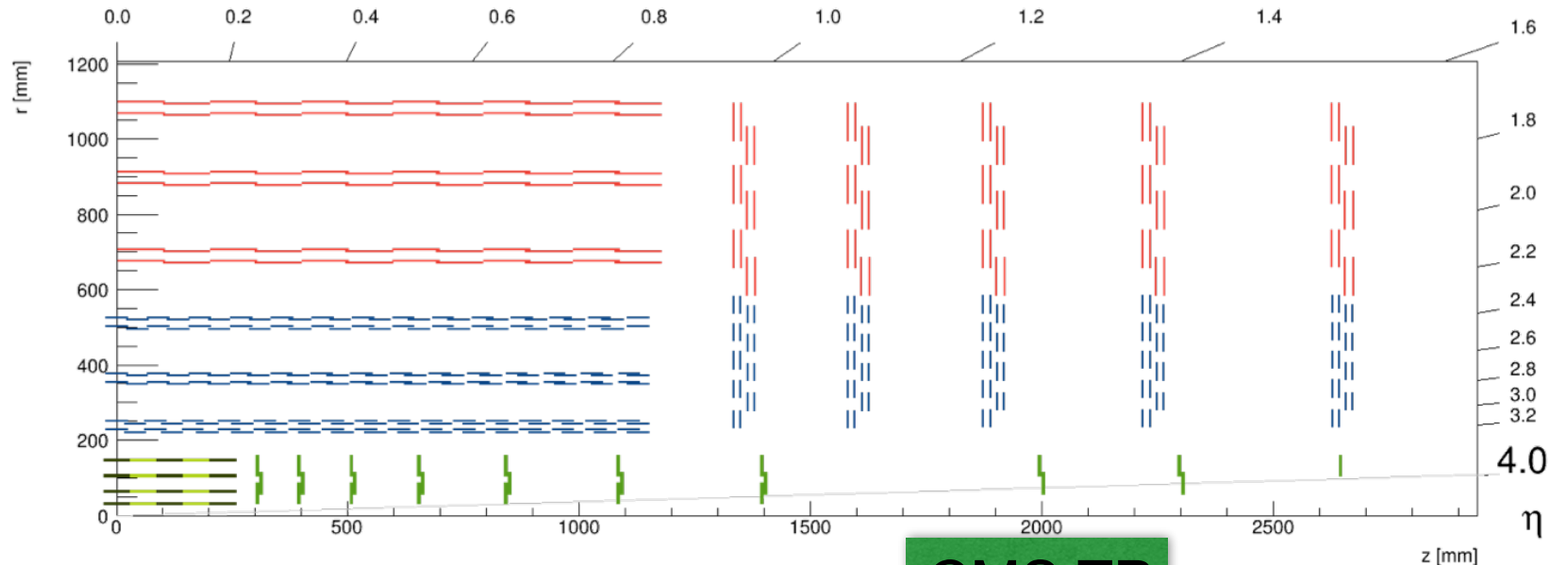
- Match Tracker track to ECAL deposit
  - Isolation for electrons and photons
    - Allows to keep H →γγ signal high
- Jets from the same z-primary vertex
  - Reduce the multi-jet rate
  - Could be used to measure the Missing ET

ATLAS and CMS Trackers @ HL-LHC

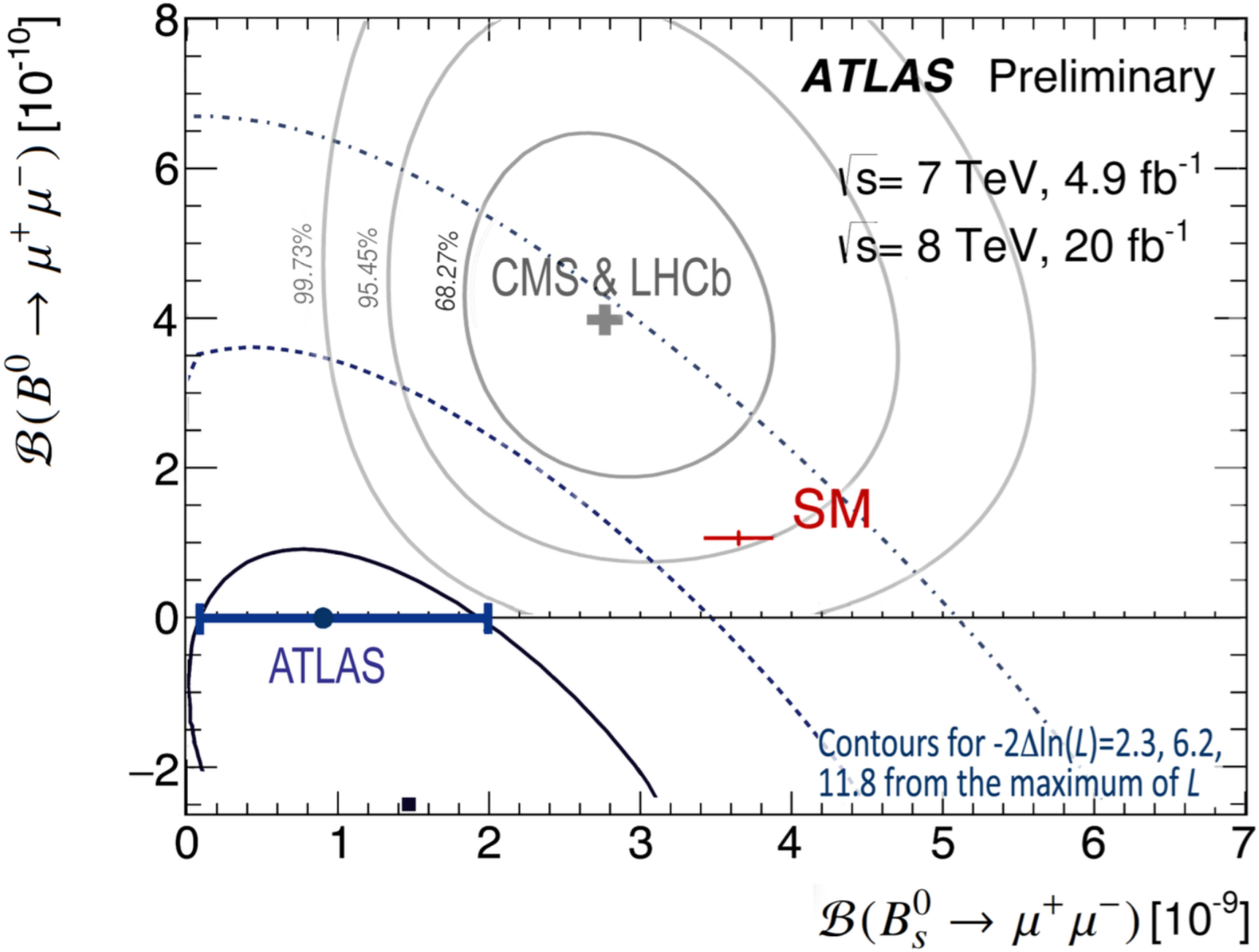


ATLAS LOI

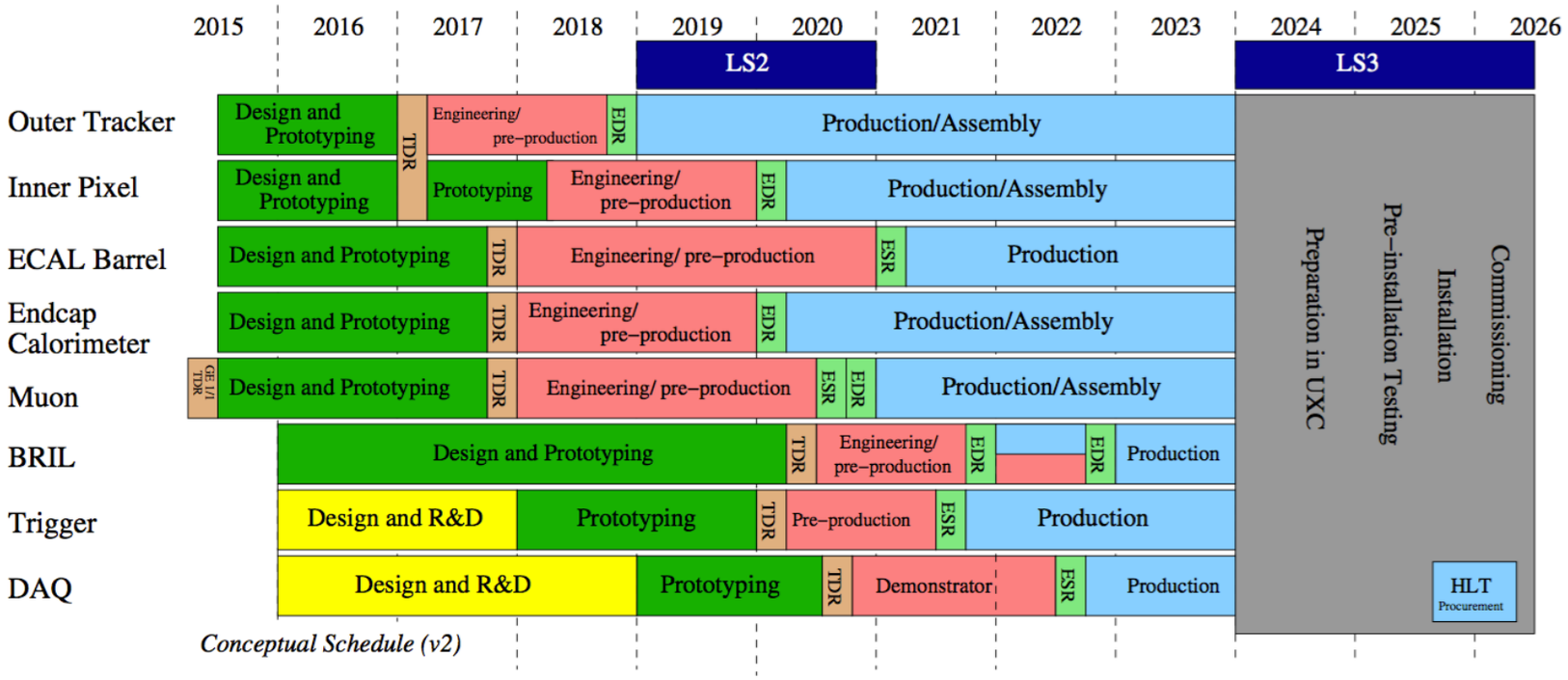




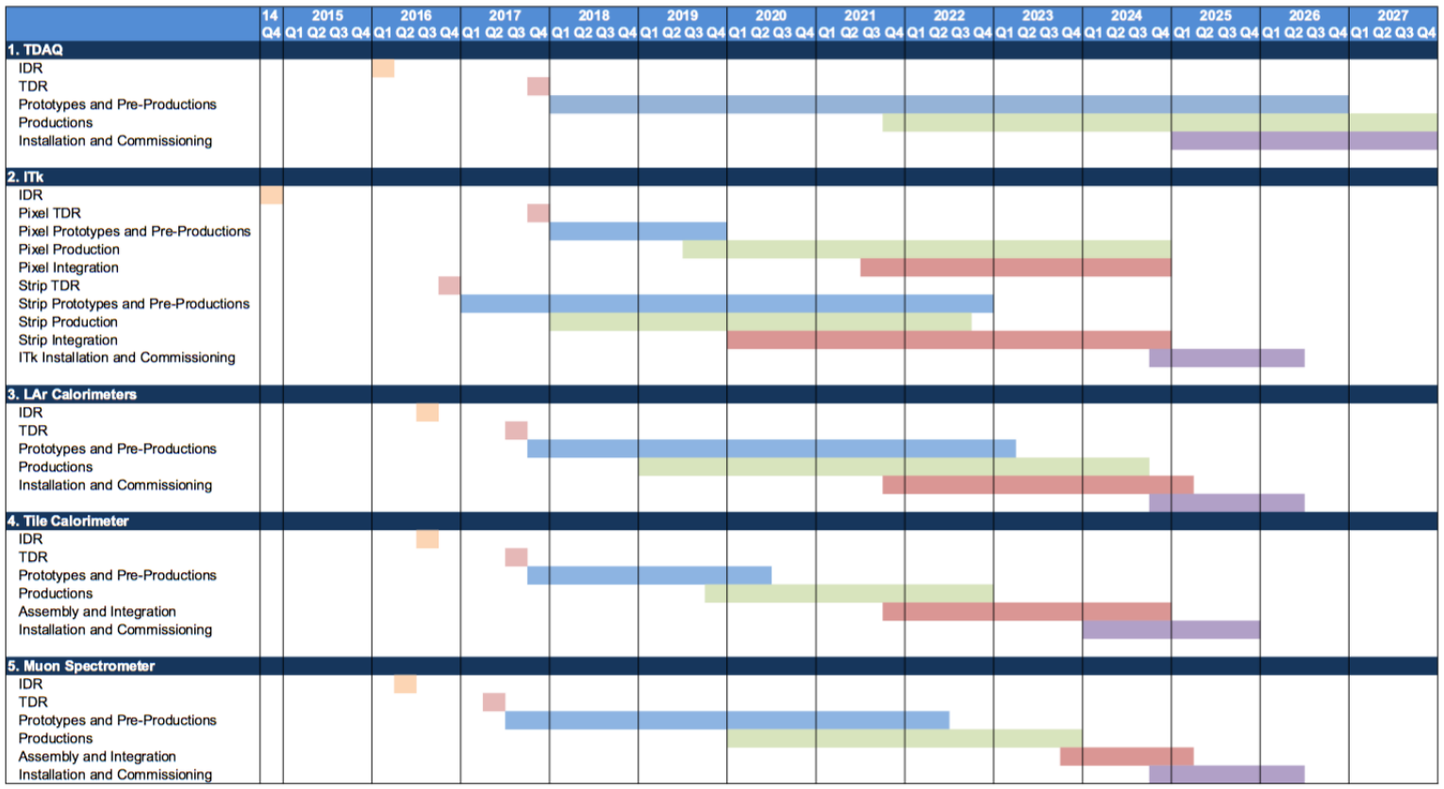
CMS TP


ATLAS Preliminary
√s= 7 TeV, 4.9 fb-1
√s= 8 TeV, 20 fb-1
99.73%
95.45%
68.27%
CMS & LHCb
SM
ATLAS
Contours for -2Δln(L)=2.3, 6.2, 11.8 from the maximum of L
$\mathcal{B}(B^0 \to \mu^+\mu^-)\,[10^{-10}]$
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)\,[10^{-9}]$
8
6
4
2
0
−2
0
1
2
3
4
5
6
7

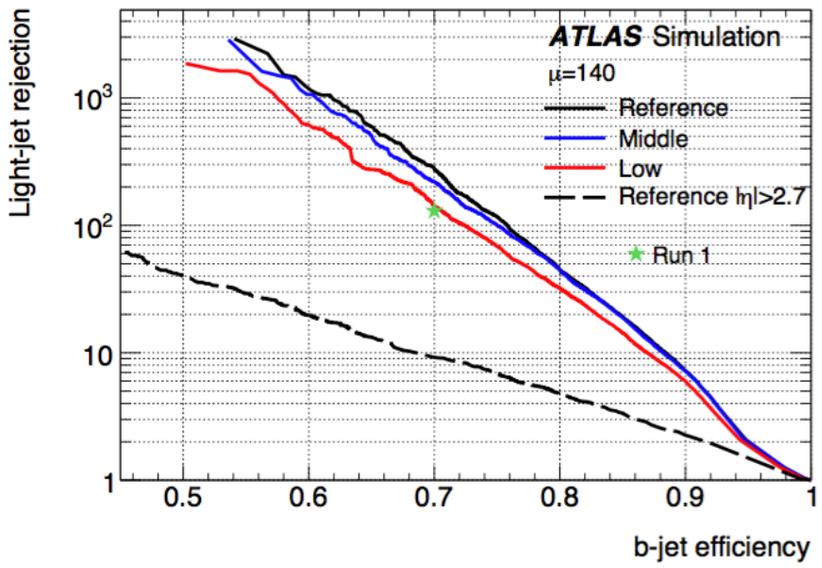
CMS timeline

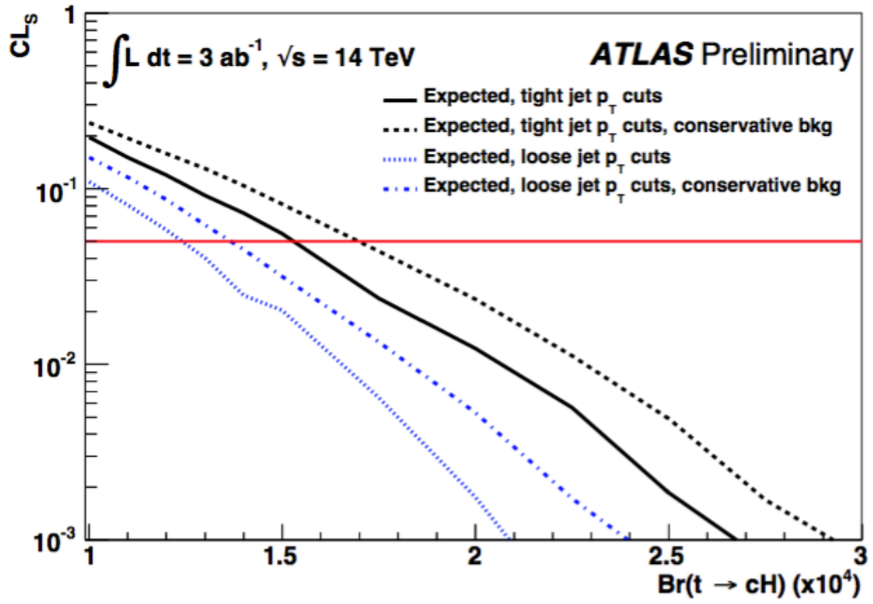


ATLAS timeline



FCNC Higgs couplings





Usage of b-tag is vital

- t→c H, H→$\gamma\gamma$
  - some models could be ruled out

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}