LHC and CMS Upgrades

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47th Annual Fermilab Users Meeting
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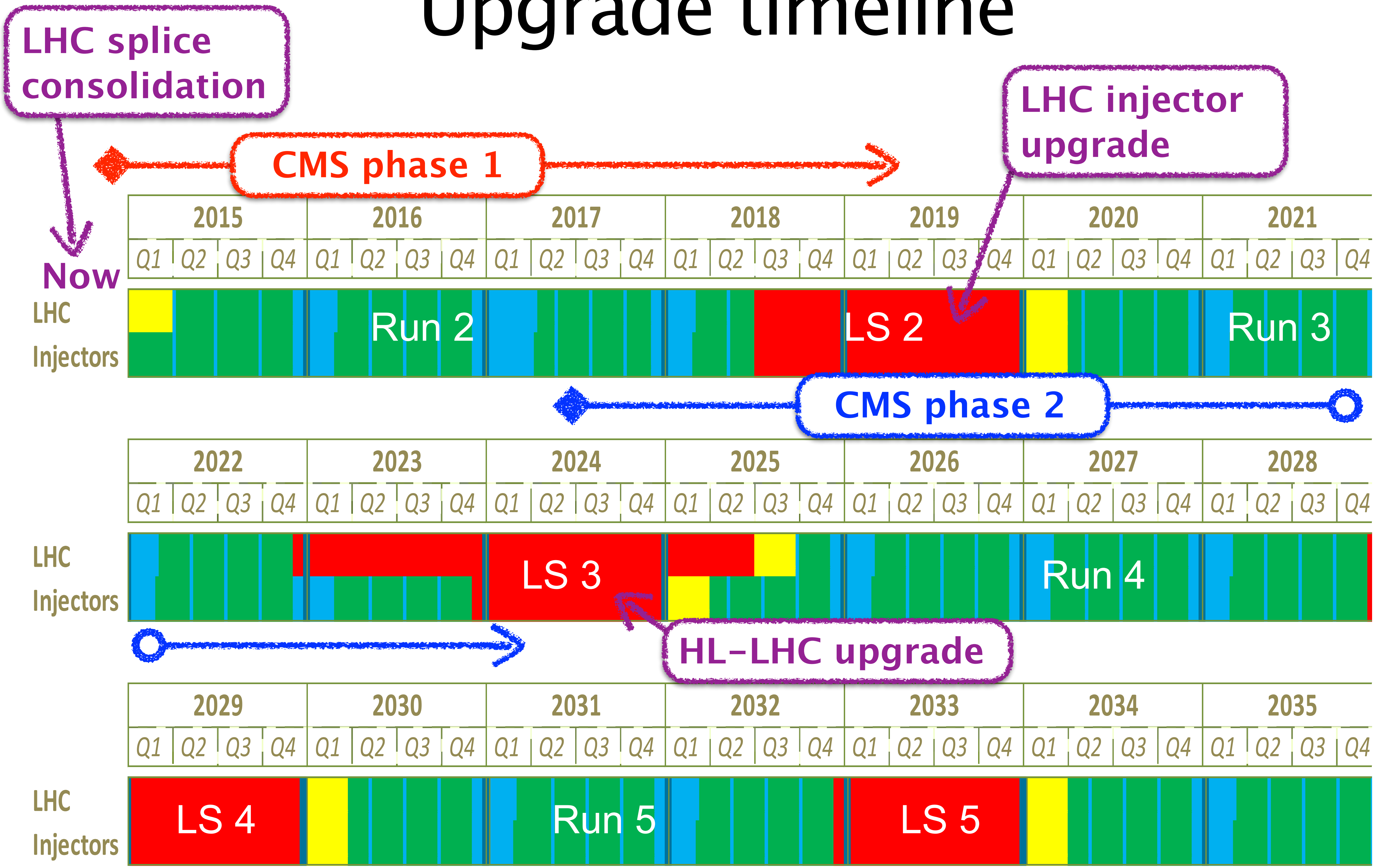
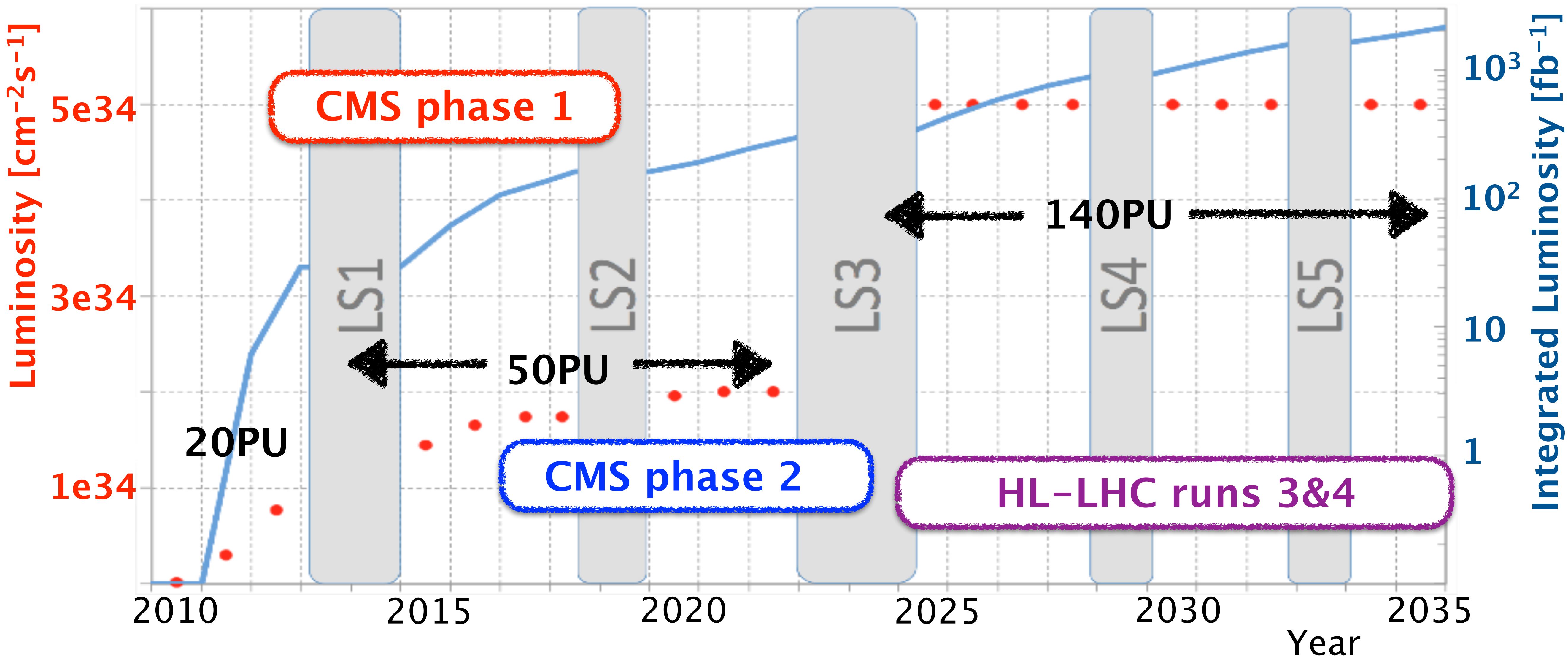
Upgrade timeline



Expected luminosity evolution



	Upgrade	Improves
LS1	Repair superconducting splices	L
LS2	Injector and collimation upgrades	$L \propto N/\varepsilon$,
LS3	Collision region apertures and crab cavities	$L \propto$ geometric factor$/\beta^*$

The main 2013-14 LHC consolidations

Opening:100%
1695 Openings and final reclosures of the interconnections
Closure: 95%

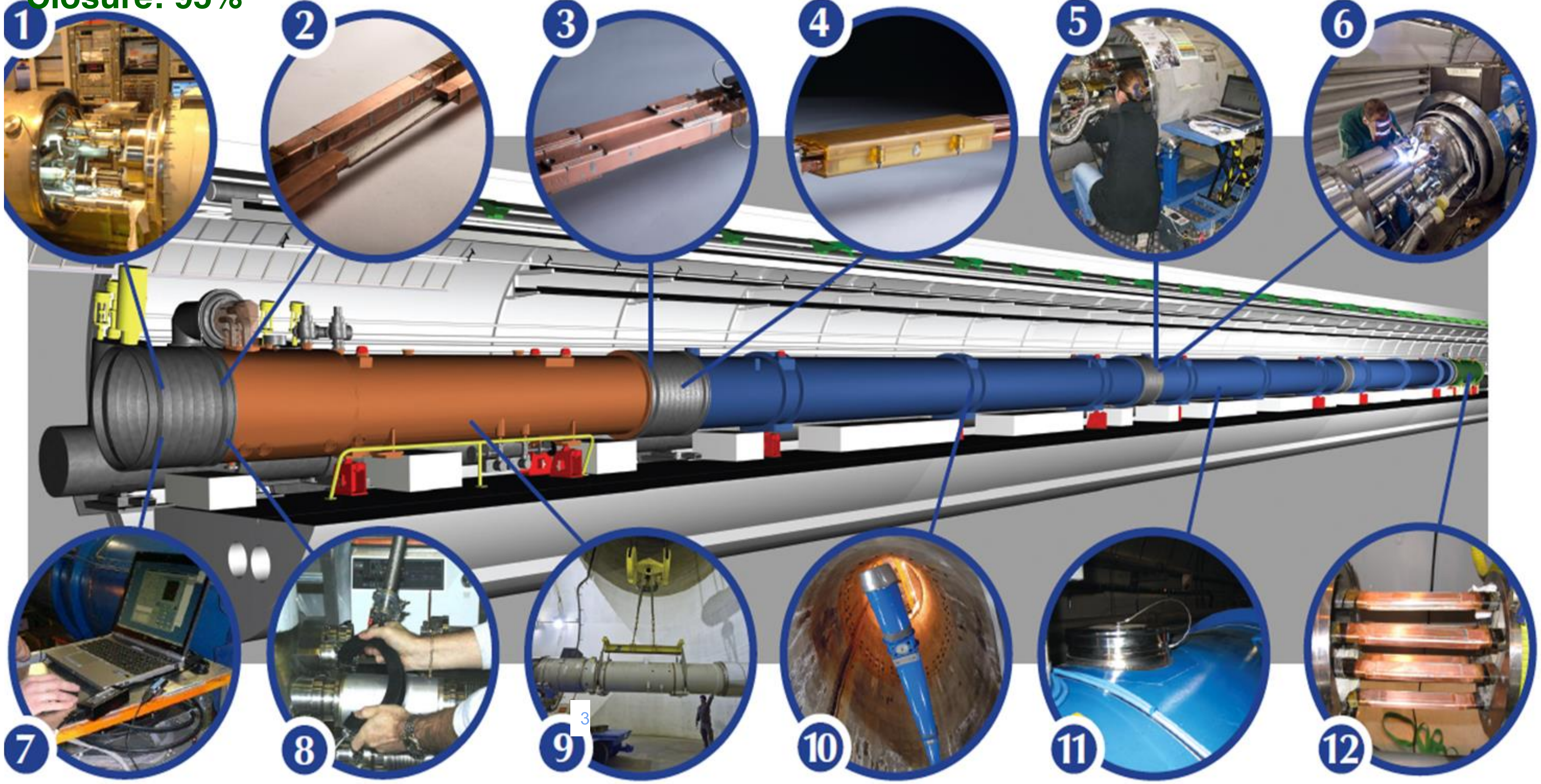
100 % done
Complete reconstruction of 3000 of these splices

100 % done
Consolidation of the 10170 13kA splices, installing 27 000 shunts

100 % done
Installation of 5000 consolidated electrical insulation systems

100 % done
300 000 electrical resistance measurements

100 % done
10170 orbital welding of stainless steel lines



80 % done
18 000 electrical Quality Assurance tests

80 % done
10170 leak tightness tests

3 quadrupole magnets to be replaced
Done

15 dipole magnets to be replaced
Done

100 % done
Installation of 612 pressure relief devices to bring the total to 1344

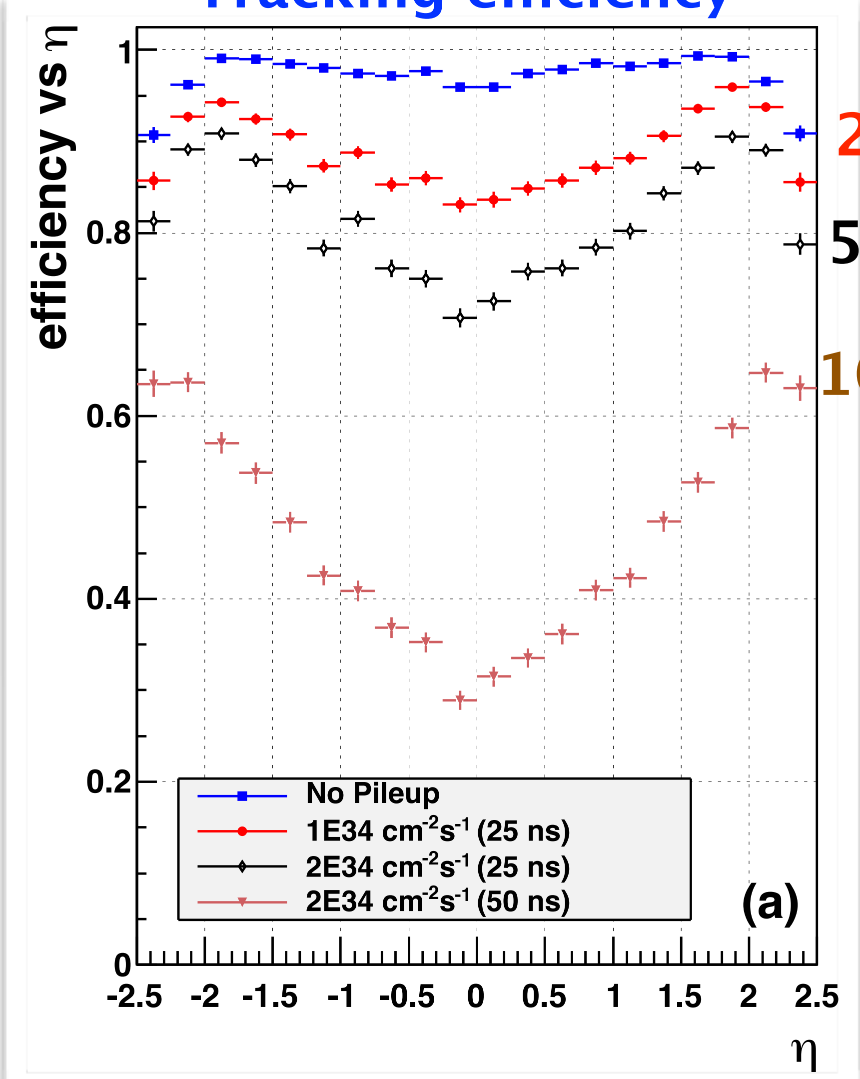
90 % done
Consolidation of the 13 kA circuits in the 16 main electrical feed-boxes

13TeV collisions to start in April 2015

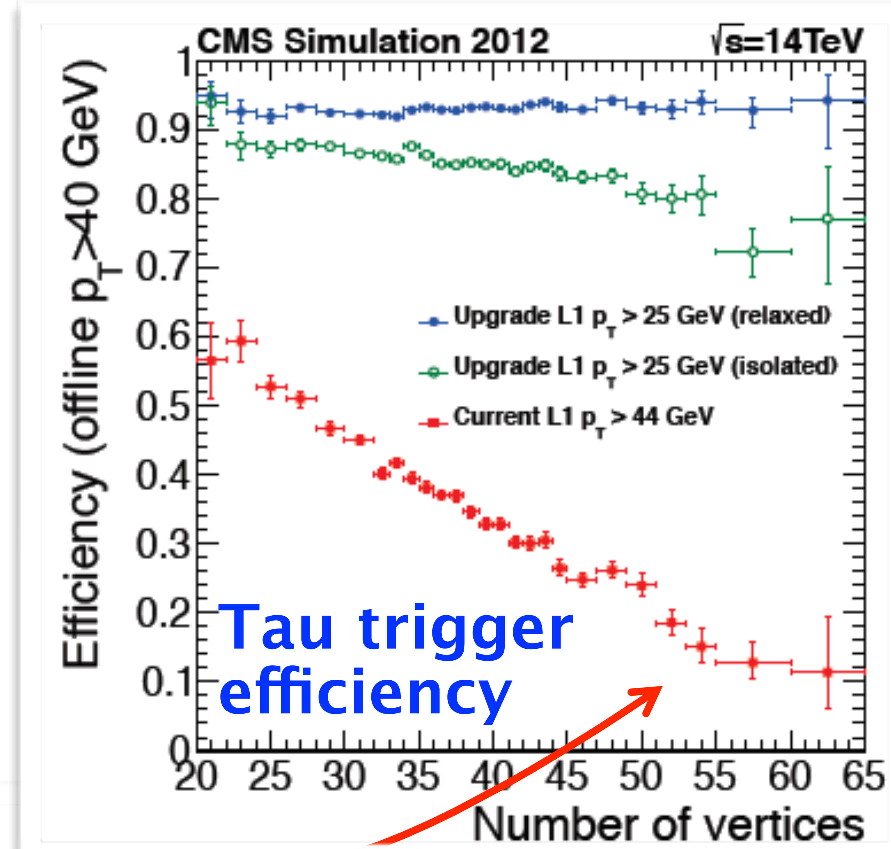
CMS phase 1 upgrade motivation

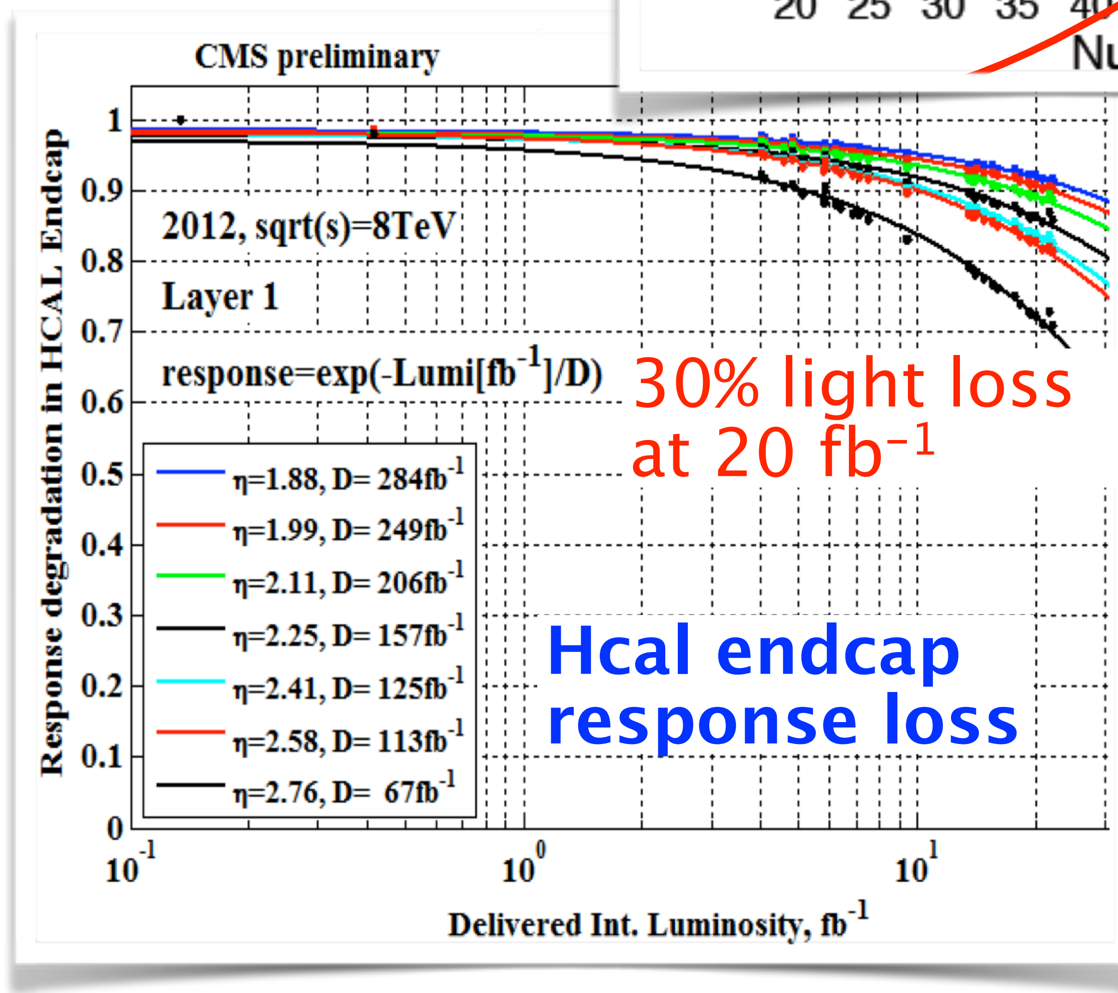
- **PU** will dramatically reduce **tracking efficiency**.
- **Increasing trigger thresholds** and **decreasing efficiency** from **PU** will affect SM objects.
- **Radiation damage** will cause light yield ➔ 0 in first layers of **endcap hadron calorimeter.**

Tracking efficiency



0PU
25PU
50PU
100PU





CMS phase 1 upgrade

Pixel detector

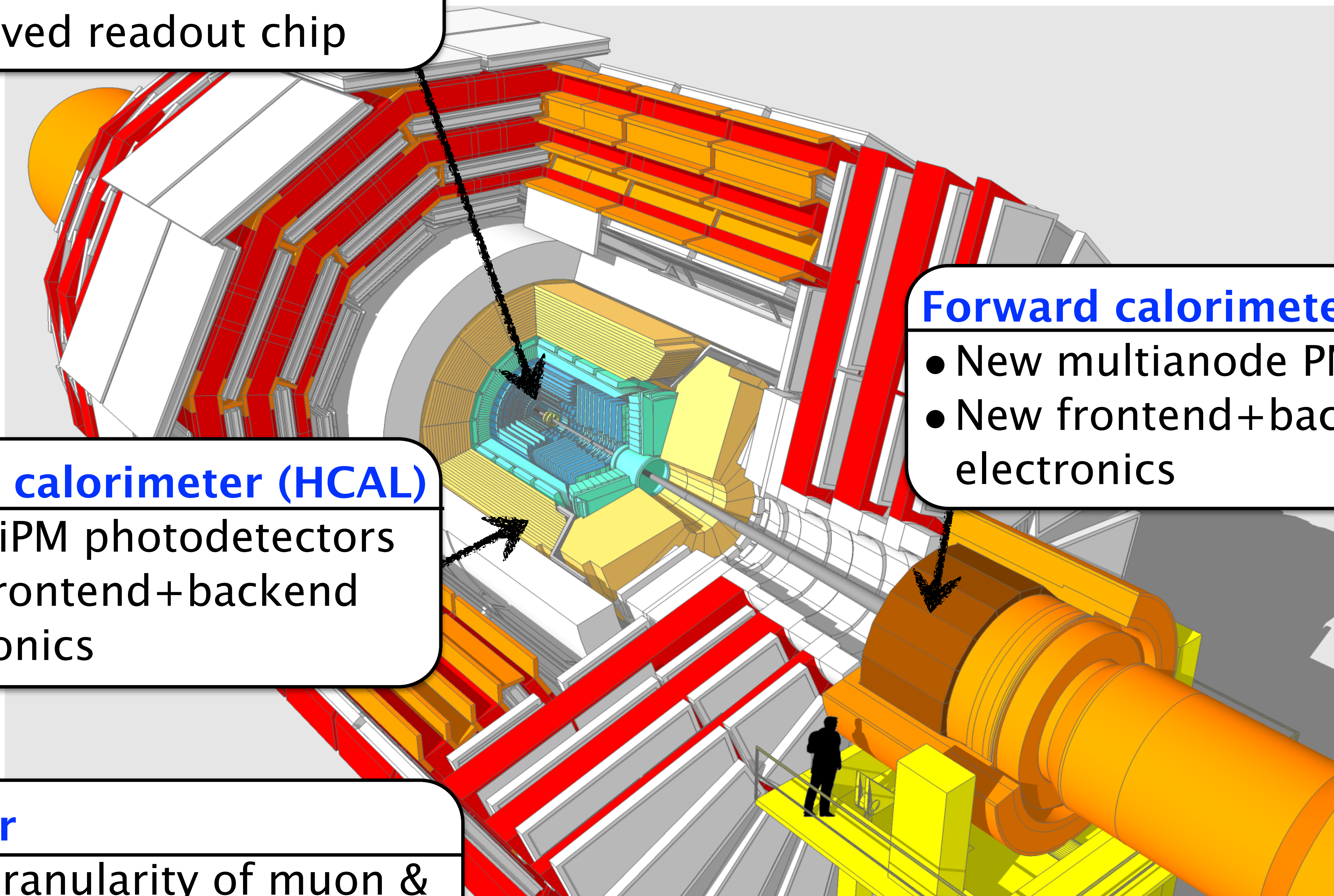
- additional layers
- less material
- improved readout chip

Forward calorimeter

- New multianode PMTs
- New frontend+backend electronics

Hadron calorimeter (HCAL)

- New SiPM photodetectors
- New frontend+backend electronics

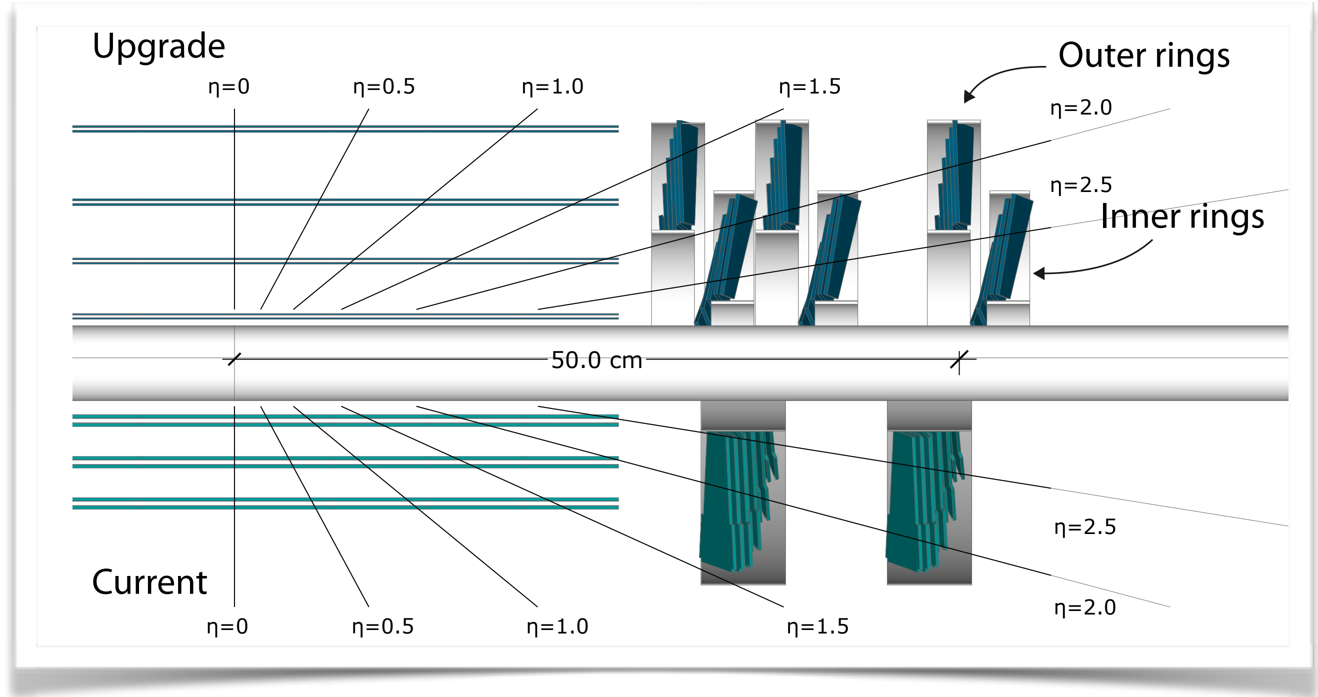


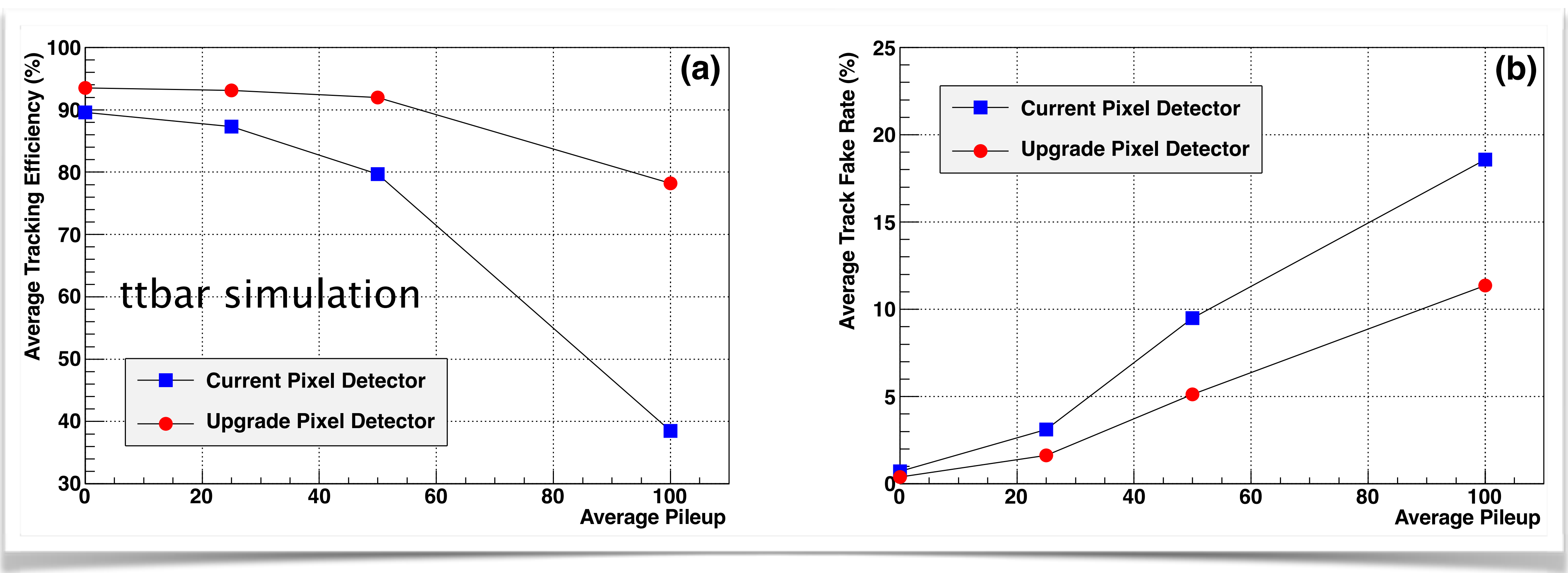
Trigger

- Full granularity of muon & calo systems in level-1 hardware trigger (L1)

Pixel detector upgrade

- Maintain **low data loss** in presence of **50 pileup** (PU) with new readout chip.
- **Additional layer** in barrel and forward systems.
- **Radiation tolerance** to 500 fb^{-1} [~1.5e15/cm^2 1MeV neutron equivalent].
- **Less material** in tracking volume.

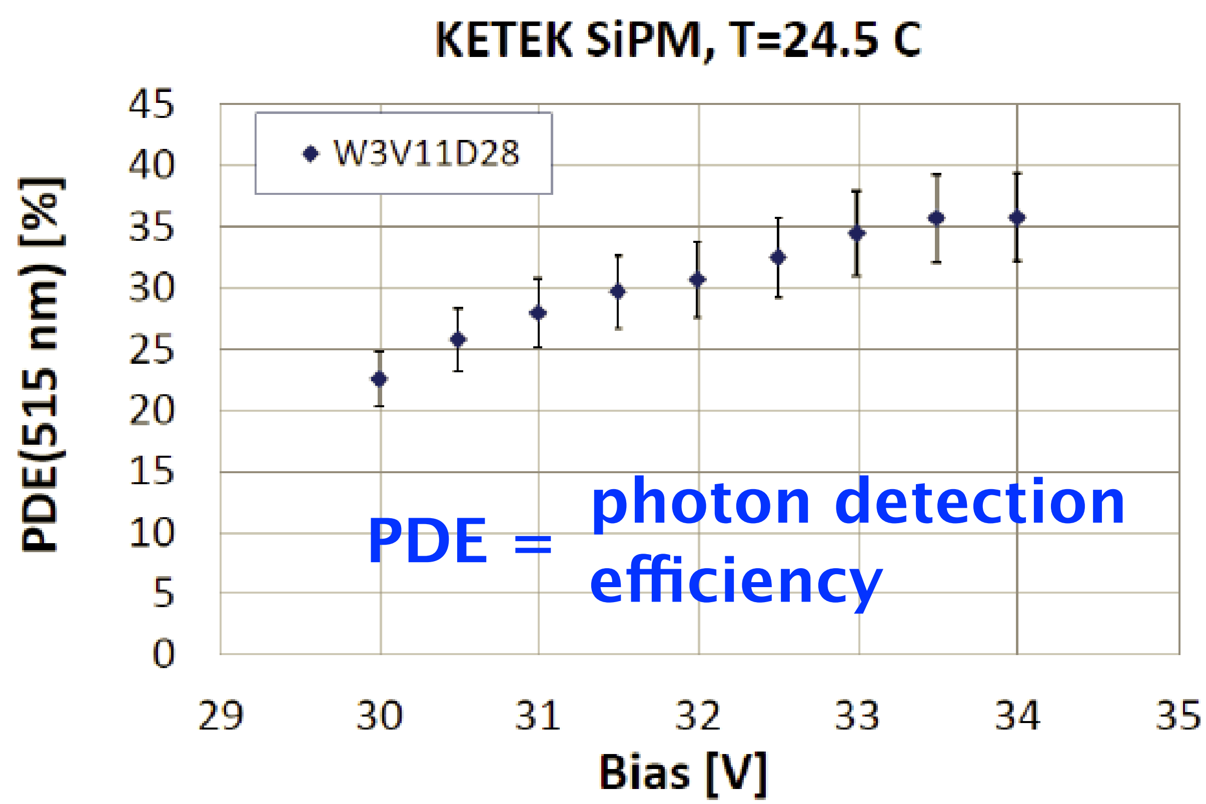




Hadron calorimeter upgrade

Barrel and endcap calorimeters

- Replace HPD photodetectors (anomalous noise + drifting response) with **SiPMs**.
  - Small, low voltage, 100-400x higher gain, 3x higher PDE than HPD.
- Allows **longitudinal segmentation** and **radiation damage calibration** (depth dependent).

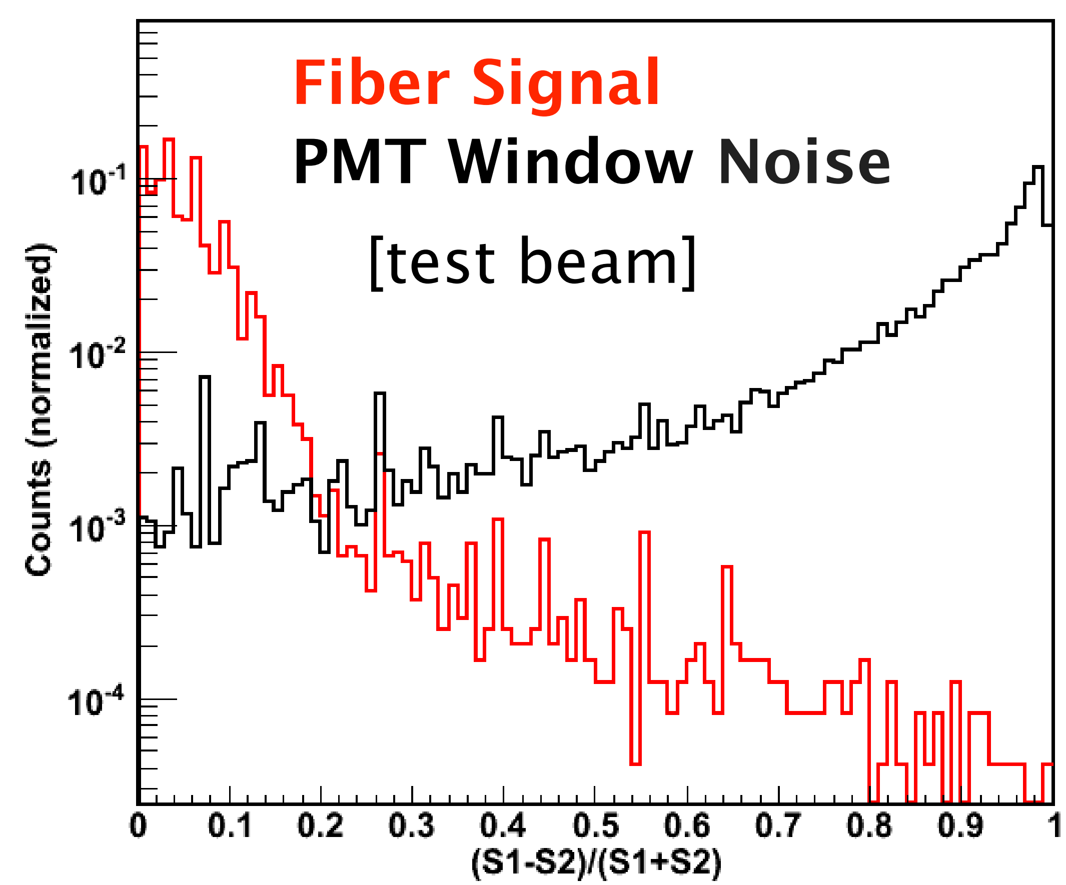


Forward calorimeter

- **Multi-anode PMTs** and **timing information** in readout allows rejection of beam backgrounds.

Backend electronics

- Higher speed **μTCA** to handle **increased data volume.**
- **redundancy** to improve robustness of system



L1 trigger upgrade

- **Level-1 trigger rate** limited to **1kHz**, 4μs latency by detector readout.
- Mitigate through improved:
  - **muon triggers**: μ p_T resolution w/ full information from 3 systems in track-finding.
  - **calorimeter triggers**: e/γ/μ isolation & jet/τ resolution w/ PU subtraction
- Increased system flexibility and algorithm sophistication require **high bandwith optical links, larger FPGAs, μTCA telecom standard electronics.**
- Build/commission in parallel with current system.

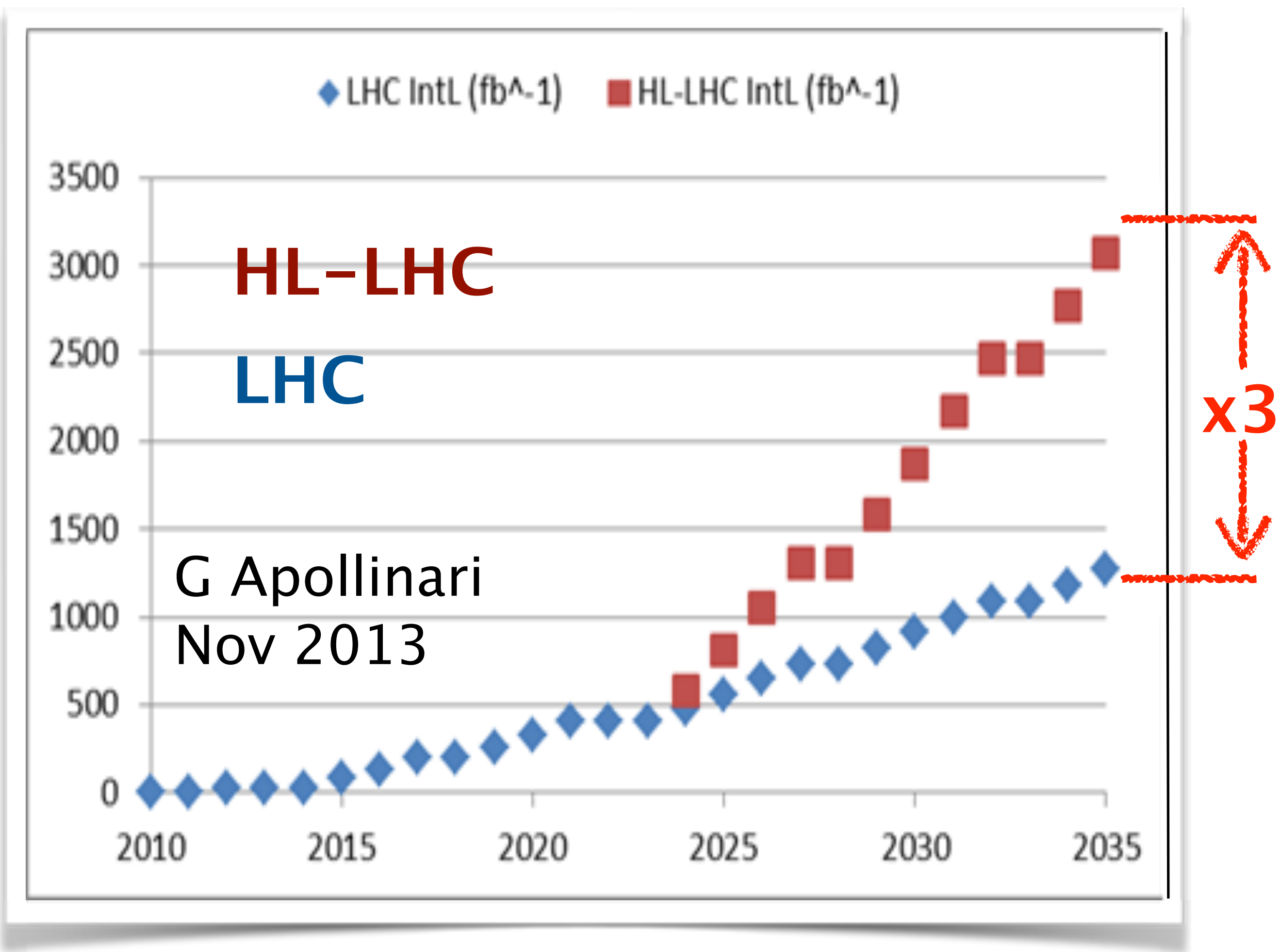
Trigger efficiency @ 2e34 $cm^{-2}s^{-1}$

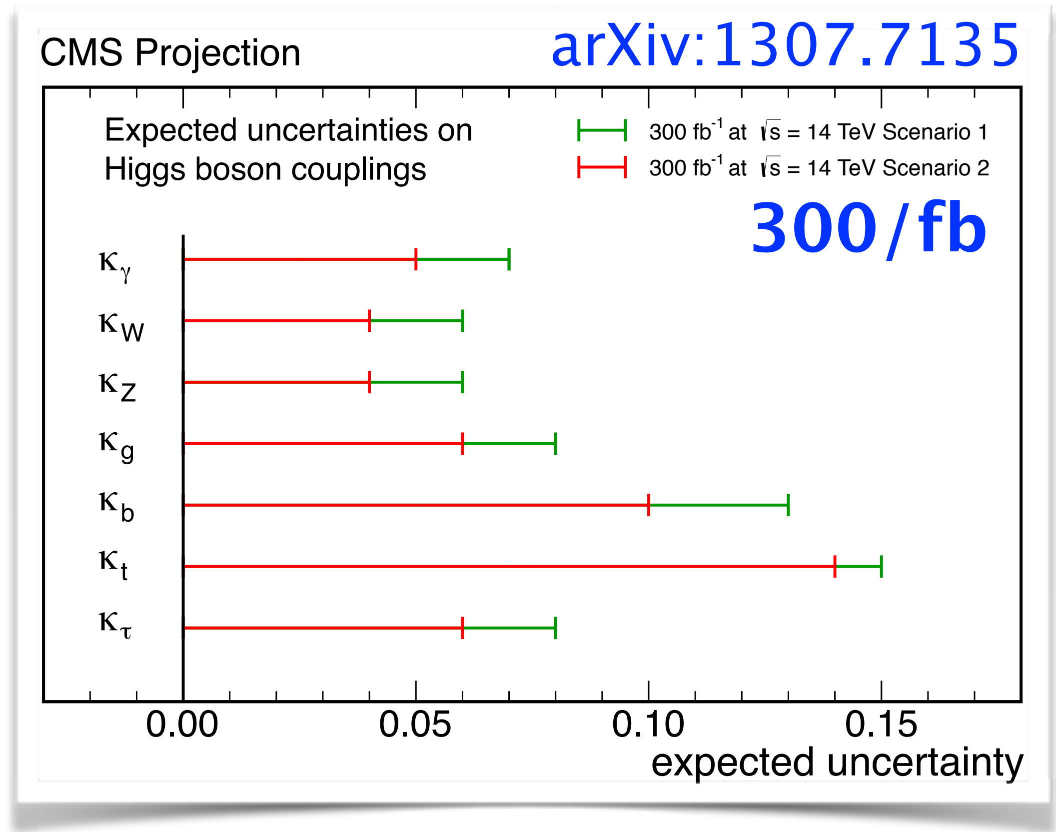
Channel	Current	Upgrade
W(eν),H(bb)	37.5%	71.5%
W(μν),H(bb)	69.6%	97.9%
VBF H(ττ(μτ))	19.4%	48.4%
VBF H(ττ(ετ))	14.0%	39.0%
VBF H(ττ(ττ))	14.9%	50.1%
H(WW(eeνν))	74.2%	95.3%
H(WW(μμνν))	89.3%	99.9%
H(WW(eμνν))	86.9%	99.3%
H(WW(μeνν))	90.7%	99.7%

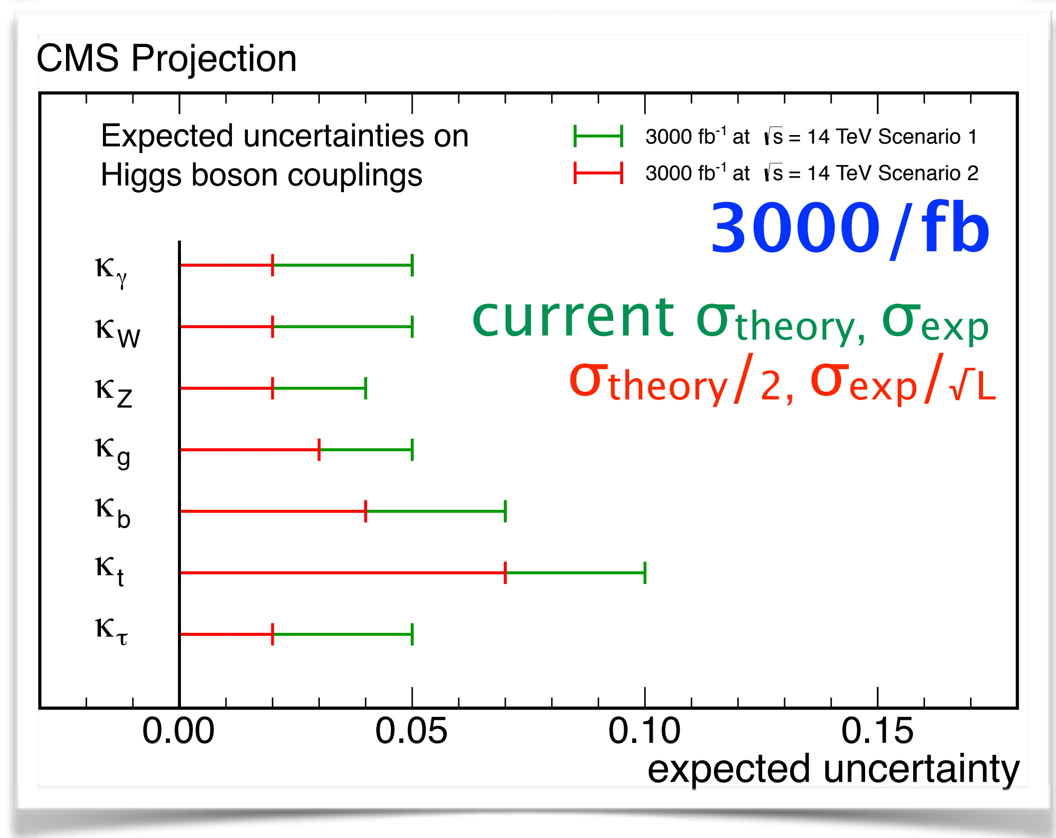
Maintain **lepton thresholds** below W peak, recover **tau trigger** at high PU.

High luminosity LHC

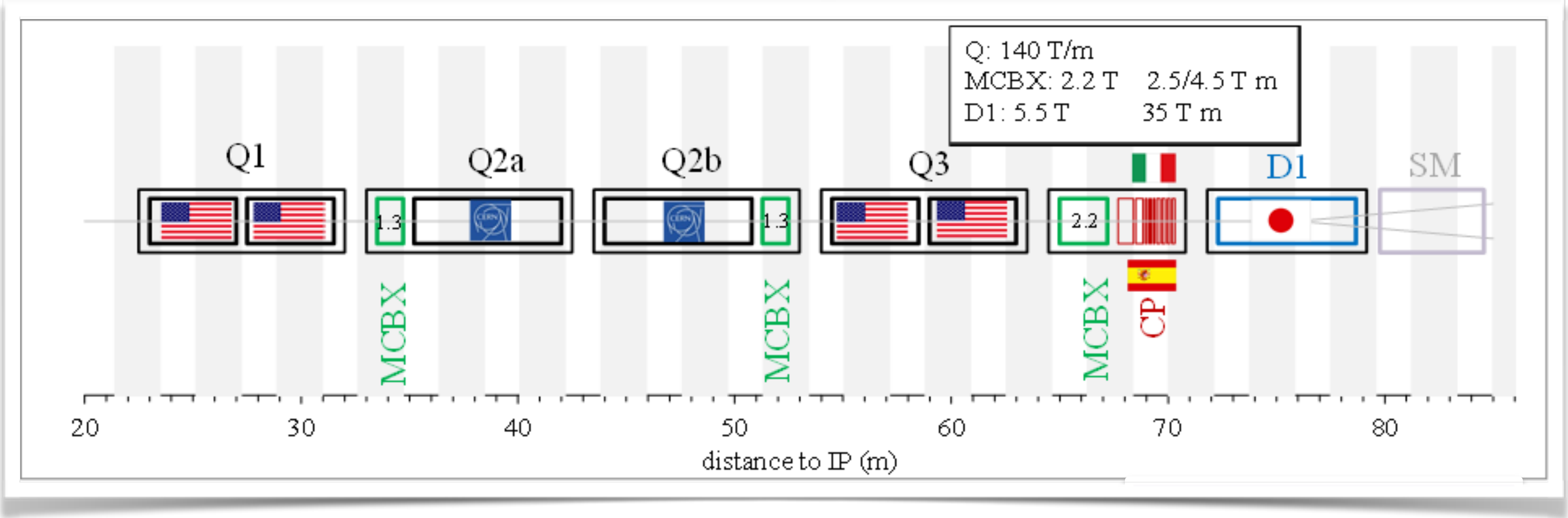
- Interaction region quadrupoles require **replacement at ~700 fb^{-1}** because design radiation limit.
- HL-LHC allows **factor ~3 increase** in luminosity w.r.t. LHC.
- **Factor 2-3 improvement** in Higgs coupling precision.

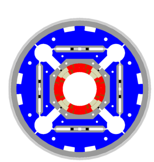






Interaction region quadrupoles



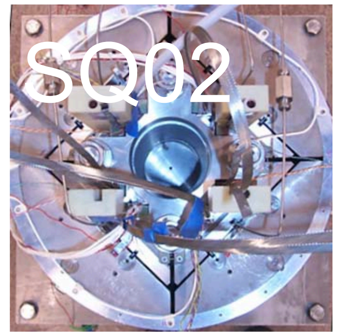
		Type	Material	Field/Gradient (T)/(T/m)	Aperture (mm)	Length (m)
	Q1,Q3 Q2	Single aperture	Nb_3Sn	(12.1) 140	150	8 6.7

- Radiation damage require magnet replacement.
- Increased aperture needed for β* 60 ➔ 15 cm.
- Primary **LARP** (BNL, FNAL, LBNL, and SLAC) **contribution.**
- Q1 and Q3 will probably each consist of 2 ~4.5m long magnets for a total of 20 quadrupoles.

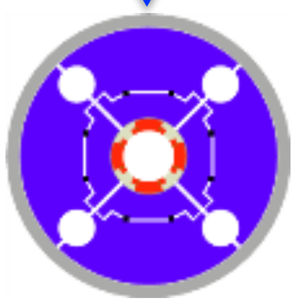
Ten years of R&D

LARP

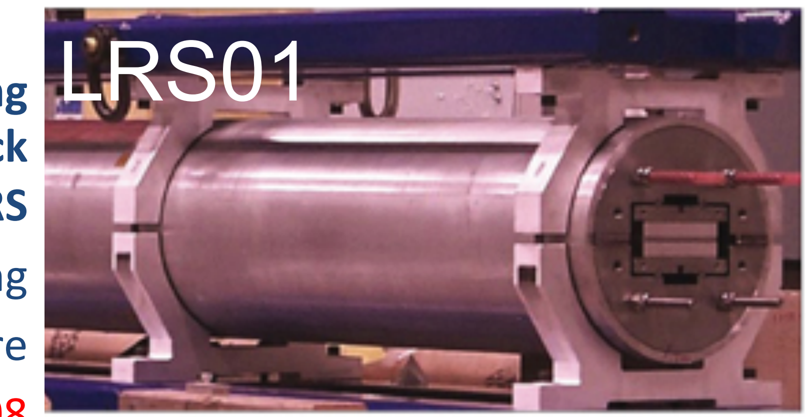
Subscale Quad. SQ
0.3 m long
110 mm bore
2004-2006



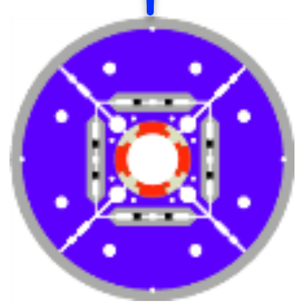
Technology Quadrupole TQS - TQC
1 m long
90 mm bore
2006-2010

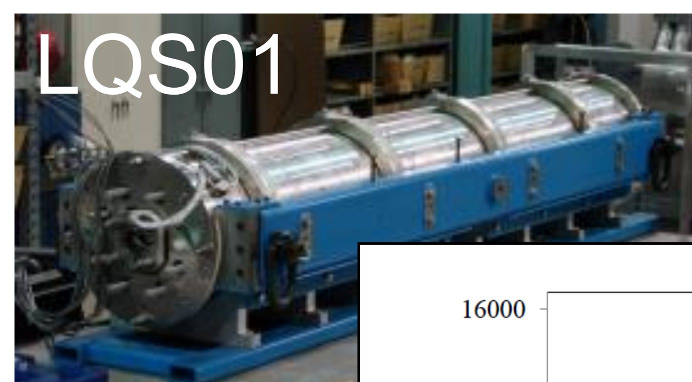


Long Racetrack LRS
3.6 m long
No bore
2006-2008

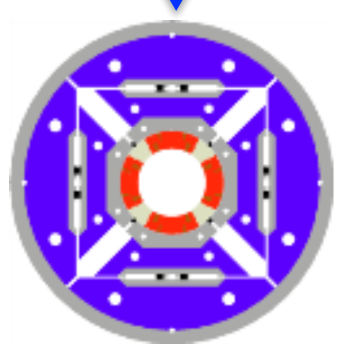


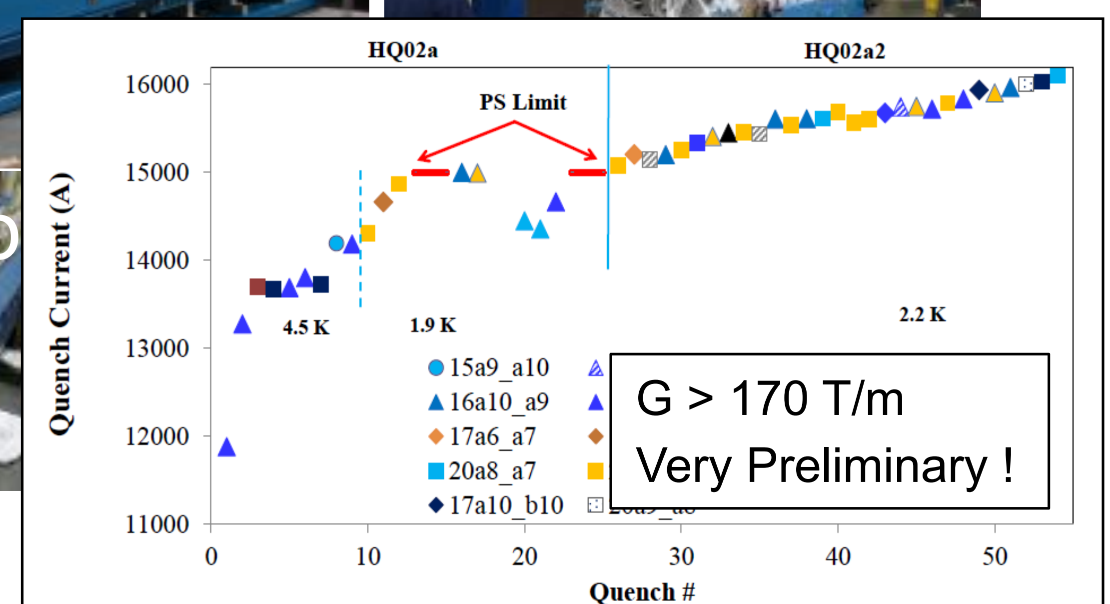
Long Quadrupole LQS
3.7 m long
90 mm bore
2007-2012



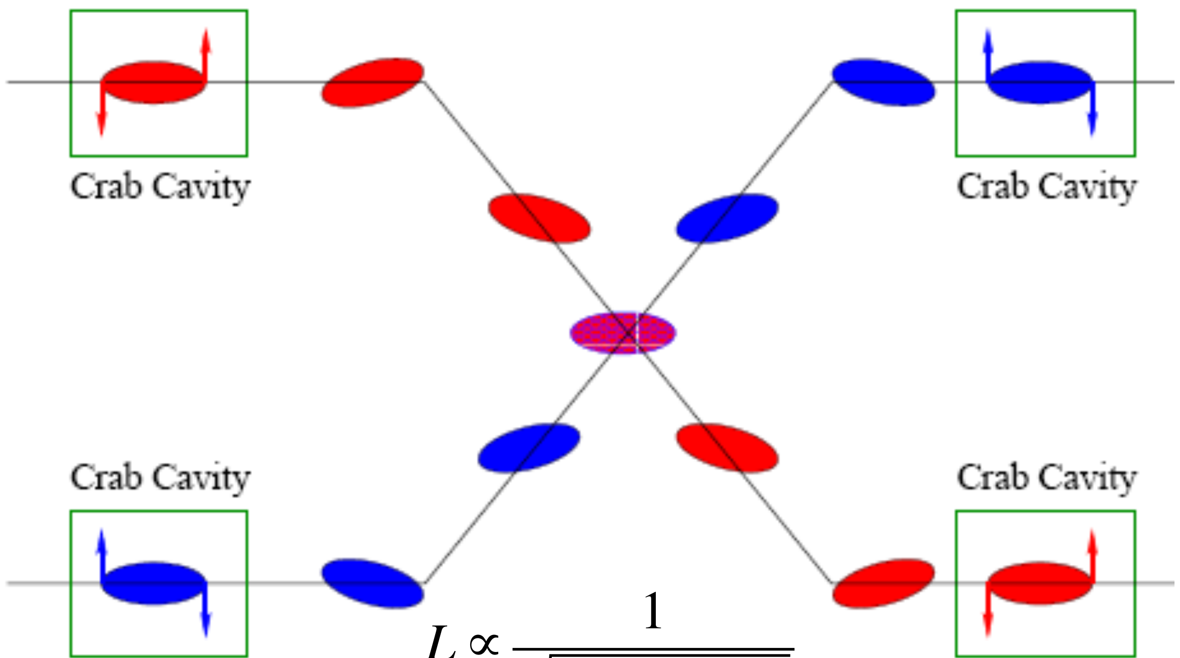


High Field Quadrupole HQ
1 m long
120 mm bore
2008-2014



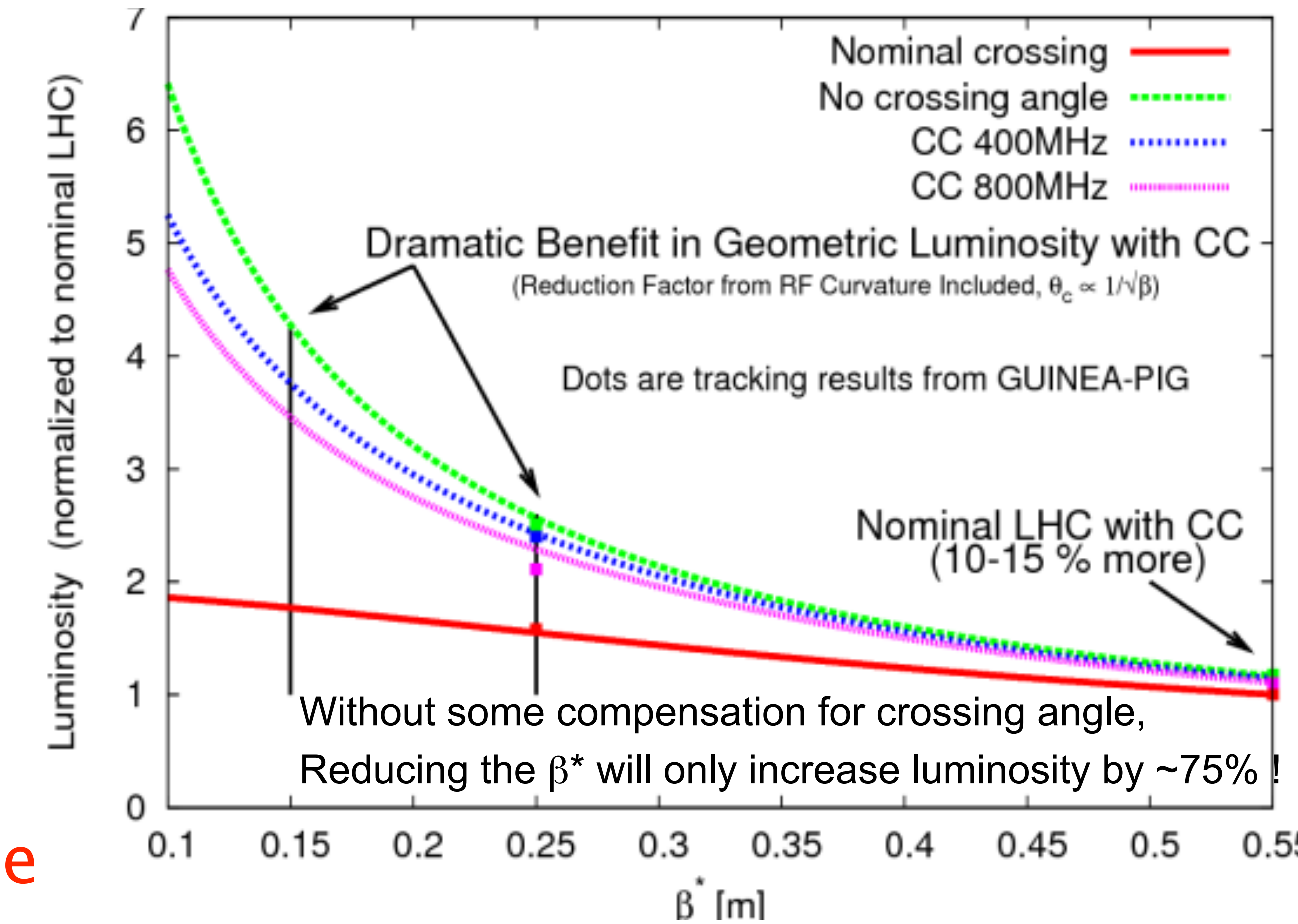


Crab cavities



$$L \propto \frac{1}{\sqrt{1+\left(\frac{\theta_c \sigma_z}{2\sigma_x}\right)^2}}$$

Piwinski angle



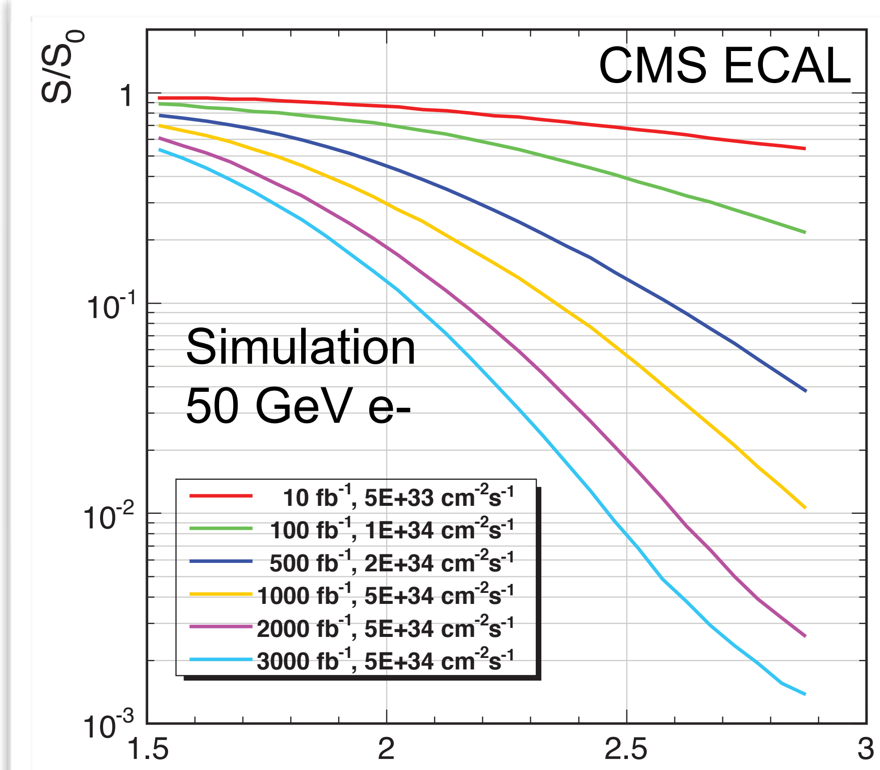
- **Technical challenges**:
  - Crab cavities have only barely been shown to work — and never in a hadron machine.
  - 19.4cm beam separation needs exotic “compact” design.
- **Additional benefit**: CCs allow easy detuning for luminosity leveling.

CMS phase 2 upgrade motivation

Facing **10 Mrad** and **$1x10^{15}$ neutrons/cm^2** 3000 fb^{-1}:

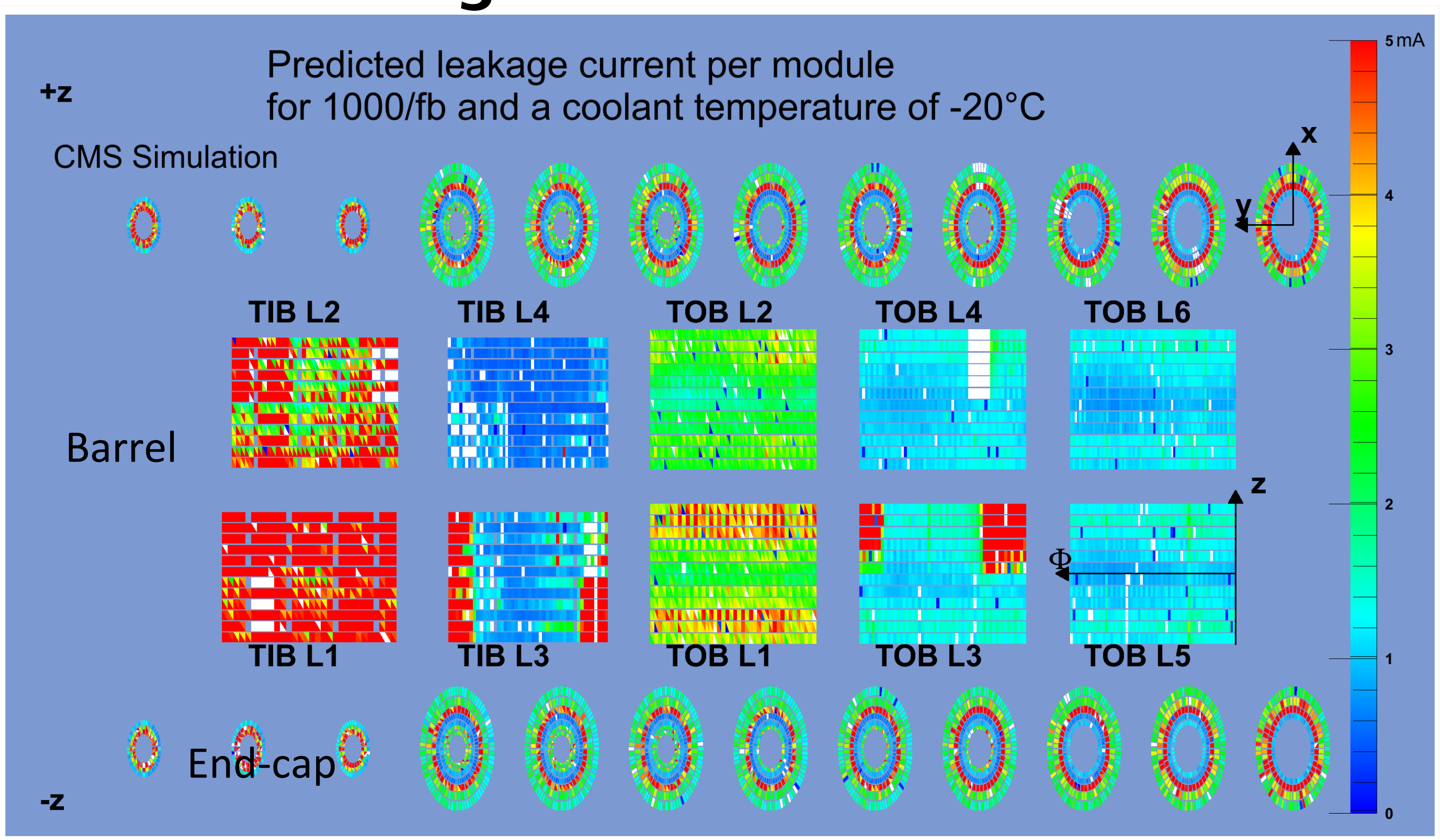
Things fall apart; the centre cannot hold;
Mere anarchy is loosed upon the world.
Yeats, 1919

Actually… with the right design
the center will hold!

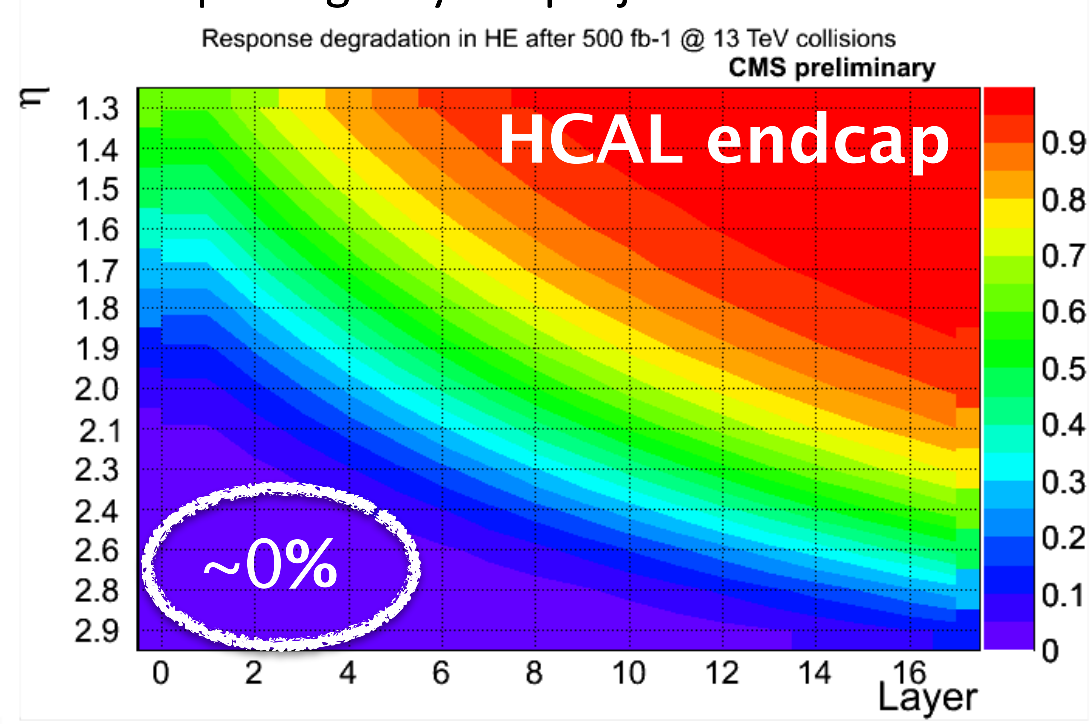


Crystal Light transmission

Tracker leakage current



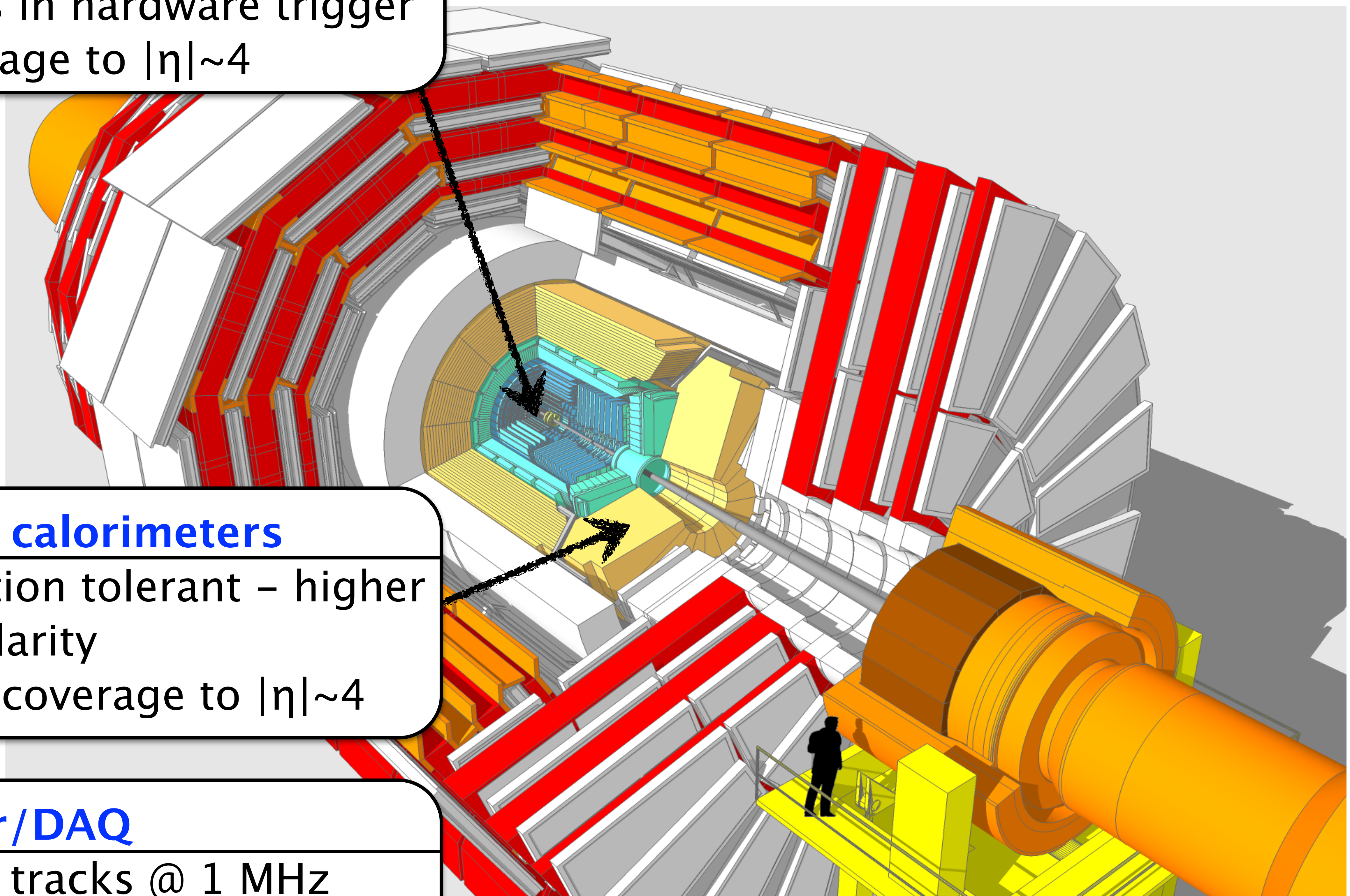
HE map of signal yield projection after 500 fb^{-1}



CMS phase 2 upgrade

Tracker

- Radiation tolerant – high granularity – less material
- tracks in hardware trigger
- Coverage to |η|~4



Endcap calorimeters

- Radiation tolerant – higher granularity
- Study coverage to |η|~4

Trigger/DAQ

- L1 w/ tracks @ 1 MHz
- Latency >= 10 us
- HLT output 10 kHz

Tracker + track trigger

Strip tracker

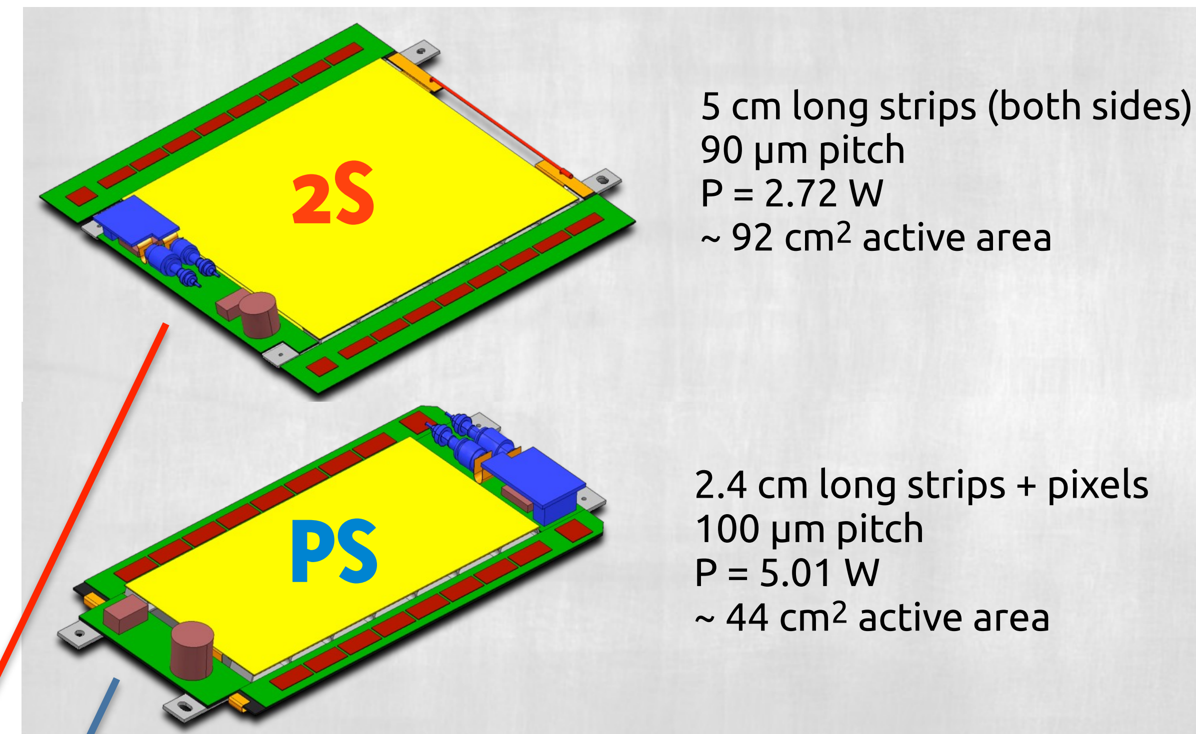
- Double sensor modules provide 40MHz trigger info for tracks w/ $p_T > 2$ GeV.

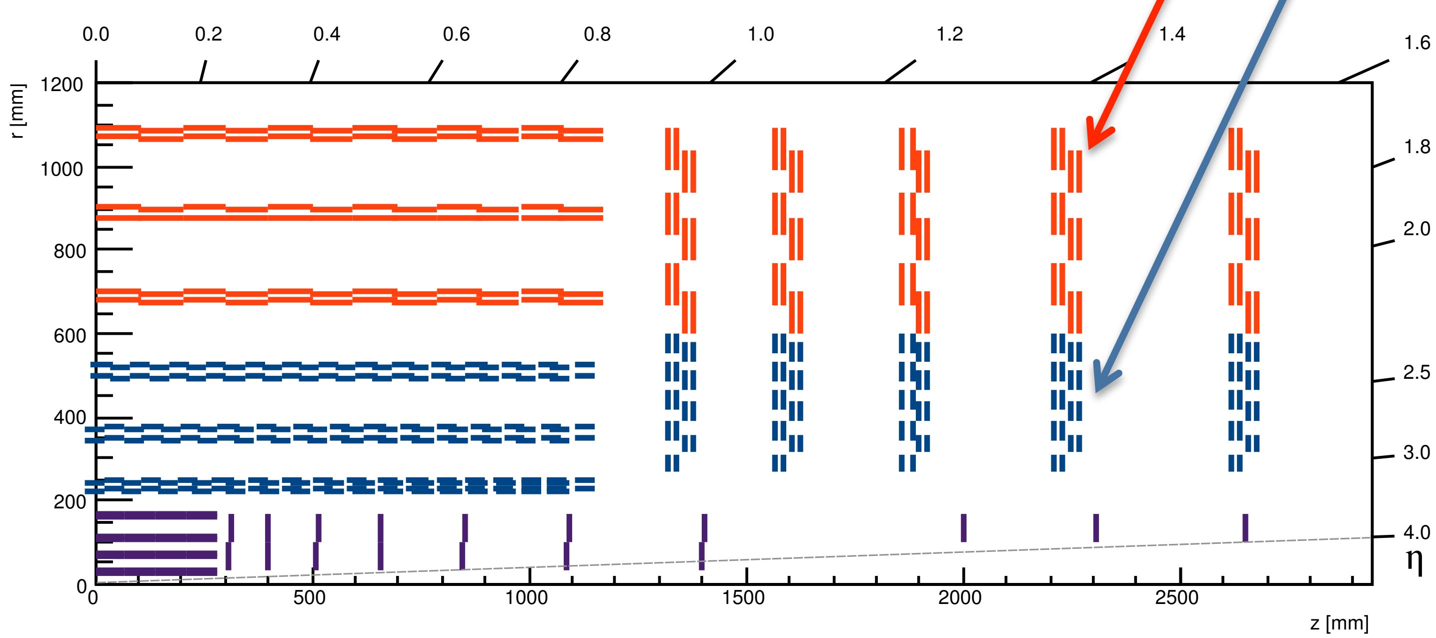
2 backend approaches based on input stubs

- Associative memory chips
- Pure FPGA

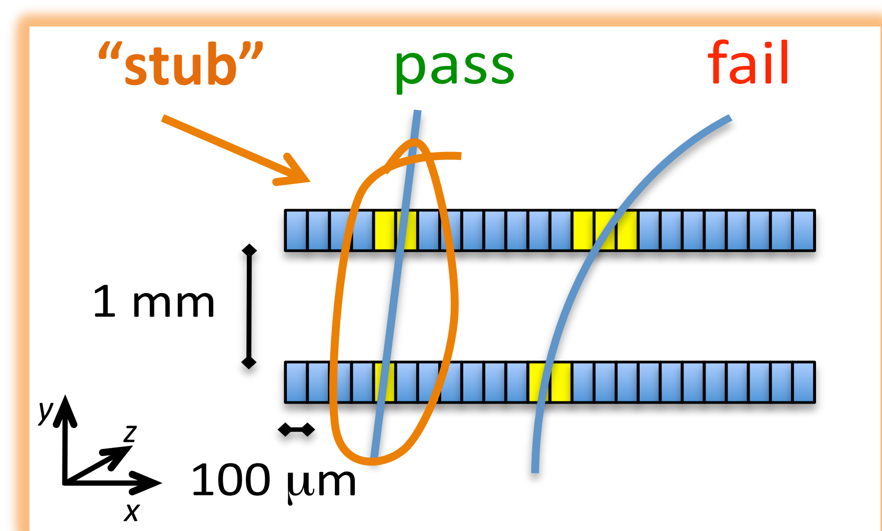
Pixel detector

- Same as phase1, but w/ 10 disks to $|\eta|$~4.
- Small pix 30x100μm; thin sensors 100μm





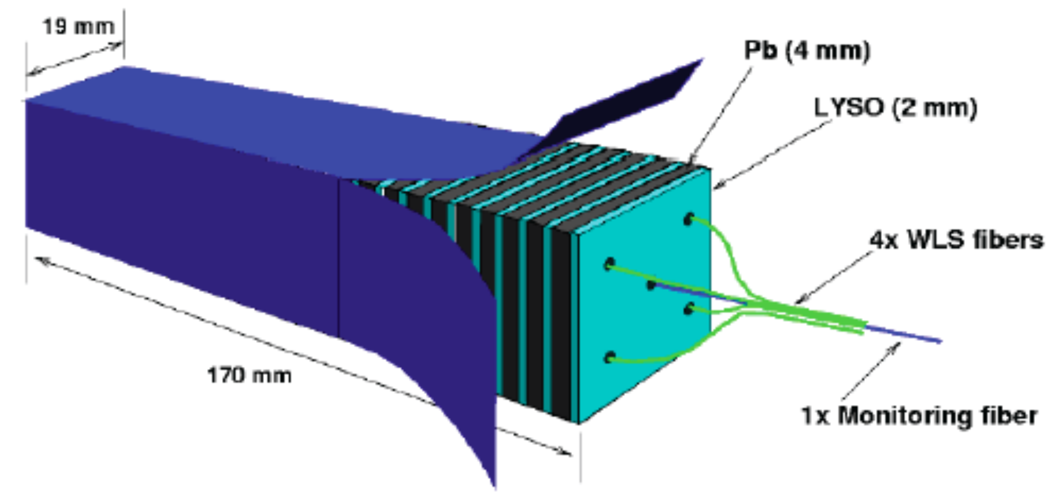
Trigger tracks selection in FE



Endcap calorimeters

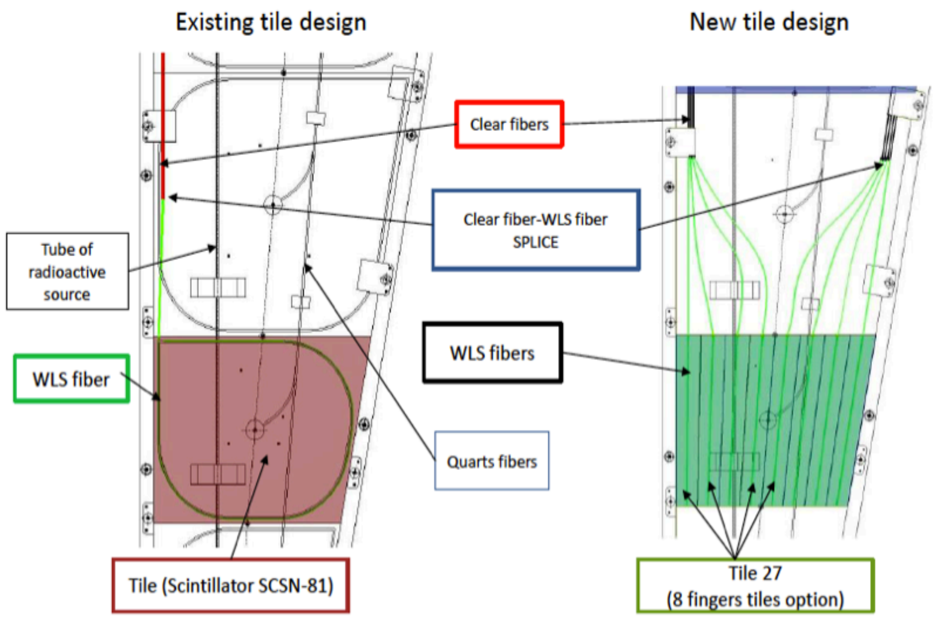
- Survive ~10 Mrad at $|\eta|$~4.
- Maintain/improve reco of **VBF jets, tau, boosted top/W/Z** at high PU.
- Take advantage of "**particle flow**" reconstruction.

Shashlik ECAL



Crystal scintillator (LYSO, CeF)
W/Pb absorber, 14_{mm}x14_{mm} cells

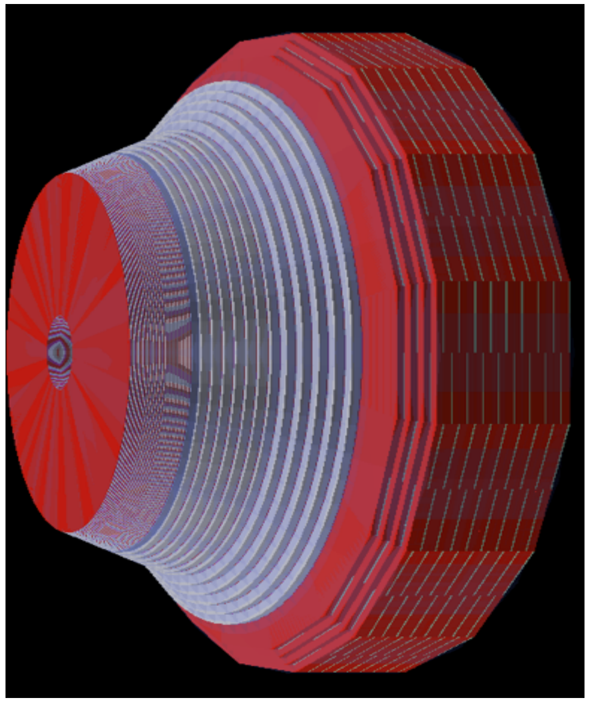
Refurbished HCAL



Radiation tolerant active material and configuration

High Granularity Calorimeter

- silicon based,
- 30 EM layers,
- 12 had layers,
- 3.7+1.4M channels
- 1_{cm}x1_{cm} cells



Trigger & DAQ

Level 1

- Upgrade of ECAL barrel electronics allows **10 μs latency**.
- **20 μs latency** achievable with changes to CSC readout.
- **1MHz L1 rate** to preserve menu for regions where track trigger is less efficient.
- Full crystal granularity at L1 for **track match**

High level trigger (HLT) & DAQ

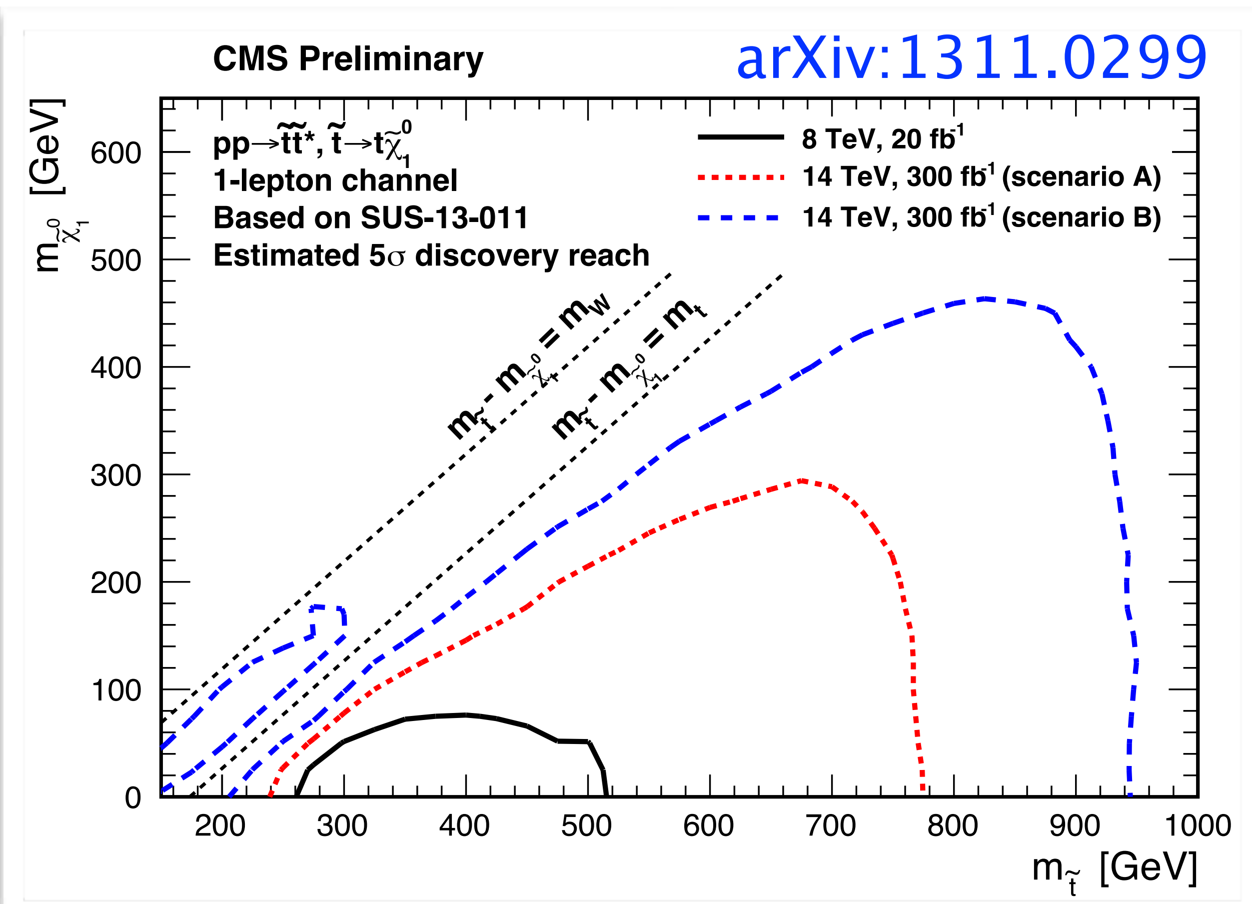
- 1 MHz into HLT
- 10 kHz into DAQ

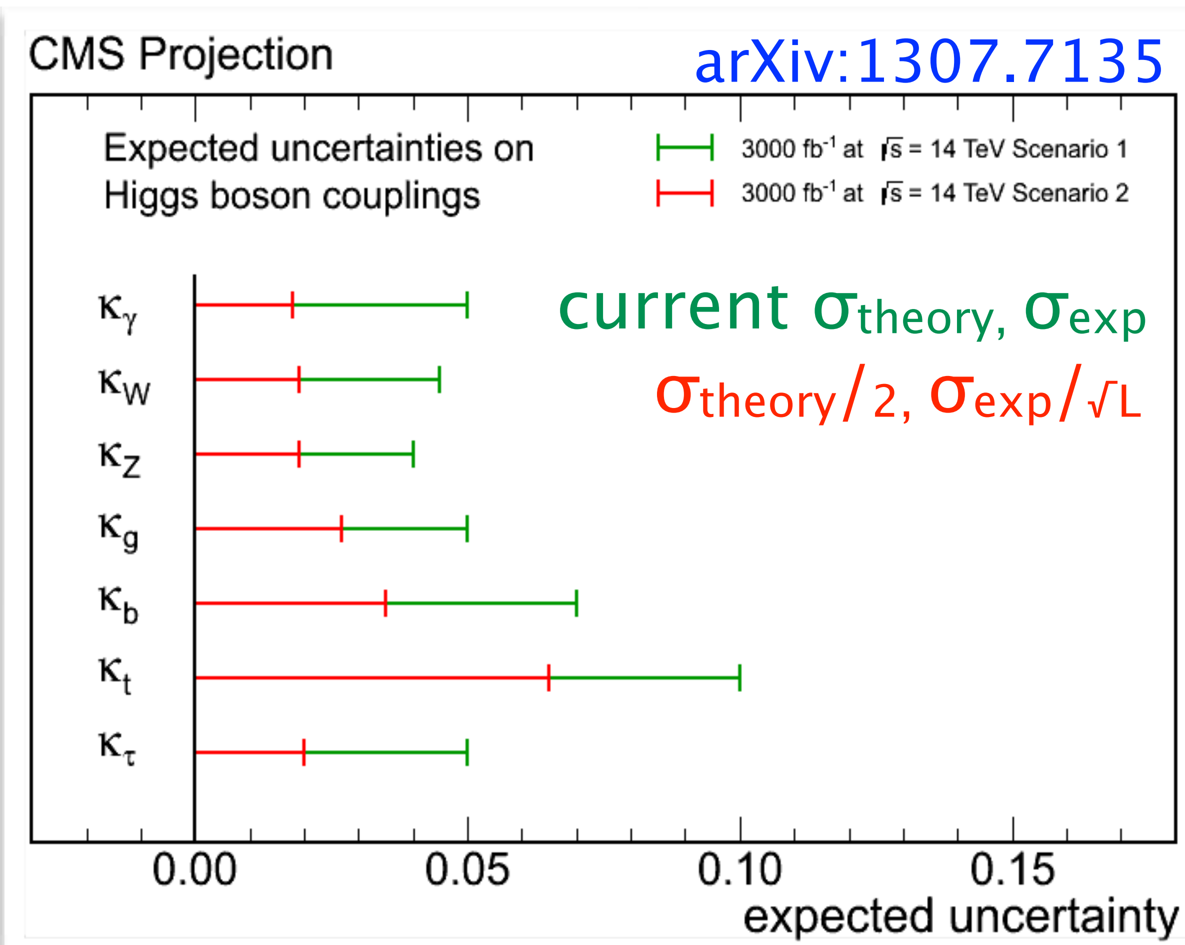
Moore's law over 10 years expected to allow these improvements.

Trigger, Threshold	Algorithm	Rate reduction
Single Muon, 20 GeV	Improved Pt, via track matching	~ 13 (central region)
Single Electron, 20 GeV	Match with cluster	> 6 (current granularity) >10 (crystal granularity) ($\mid\eta\mid < 1$)
Single Tau, 40 GeV	CaloTau – track matching + tracker isolation	O(5)
Single Photon, 20 GeV	Tracker isolation	40 %

Status & conclusion

- HL-LHC upgrades given **high priority by P5**.
- CMS phase 1 upgrades **CD23** review in August 2014.
- CMS phase 2 upgrade **technical proposal** coming in September 2014.
- LHC+experiments is a global effort, but the US, LARP, and Fermilab play **critical roles** in all phases and should strive to continue leading.





Additional Material

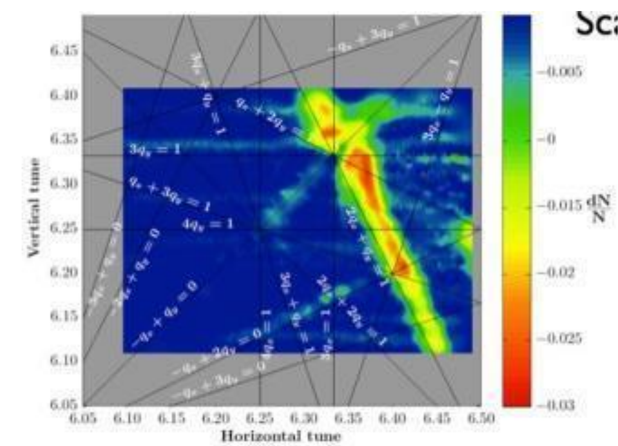
LS2 : LHC Injector Upgrades

LINAC4 – PS Booster:

- H^- injection and increase of PSB injection energy from 50 MeV to 160 MeV, to increase PSB space charge threshold
- New RF cavity system, new main power converters
- Increase of extraction energy from 1.4 GeV to 2 GeV

PS:

- Increase of injection energy from 1.4 GeV to 2 GeV to increase PS space charge threshold
- Transverse resonance compensation
- New RF Longitudinal feedback system
- New RF beam manipulation scheme to increase beam brightness



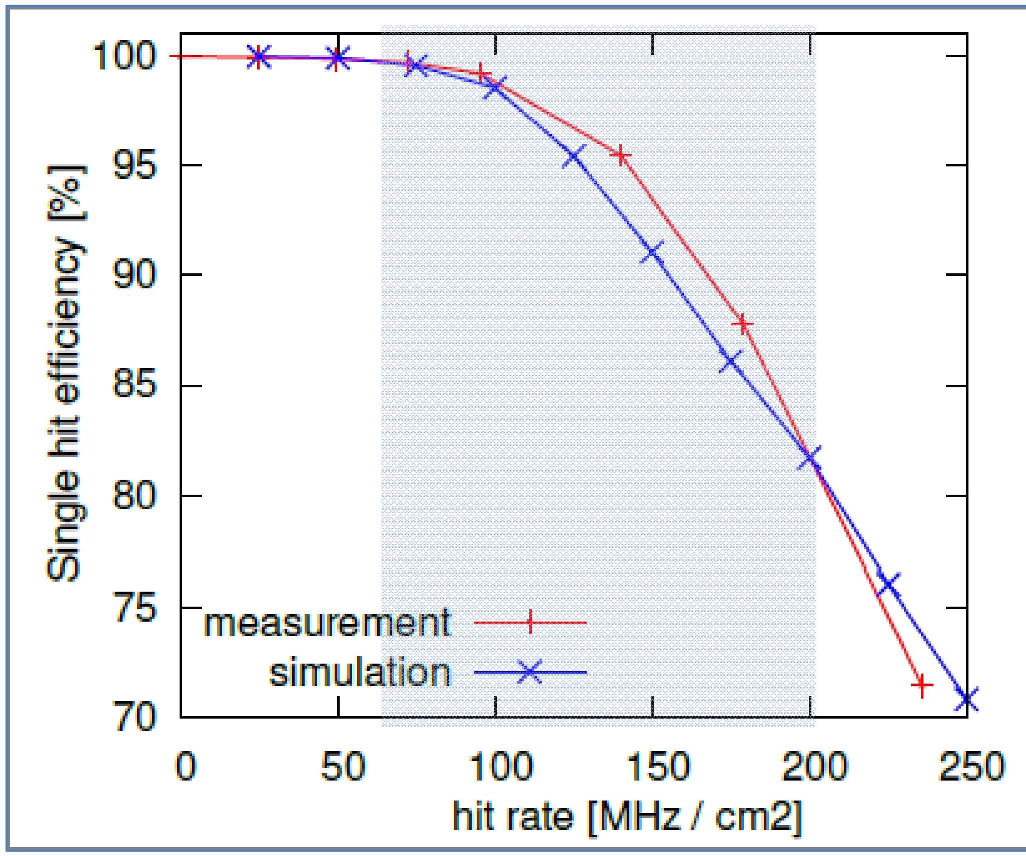
SPS

- Electron Cloud mitigation – strong feedback system, or coating of the vacuum system
- Impedance reduction, improved feedbacks
- Large-scale modification to the main RF system

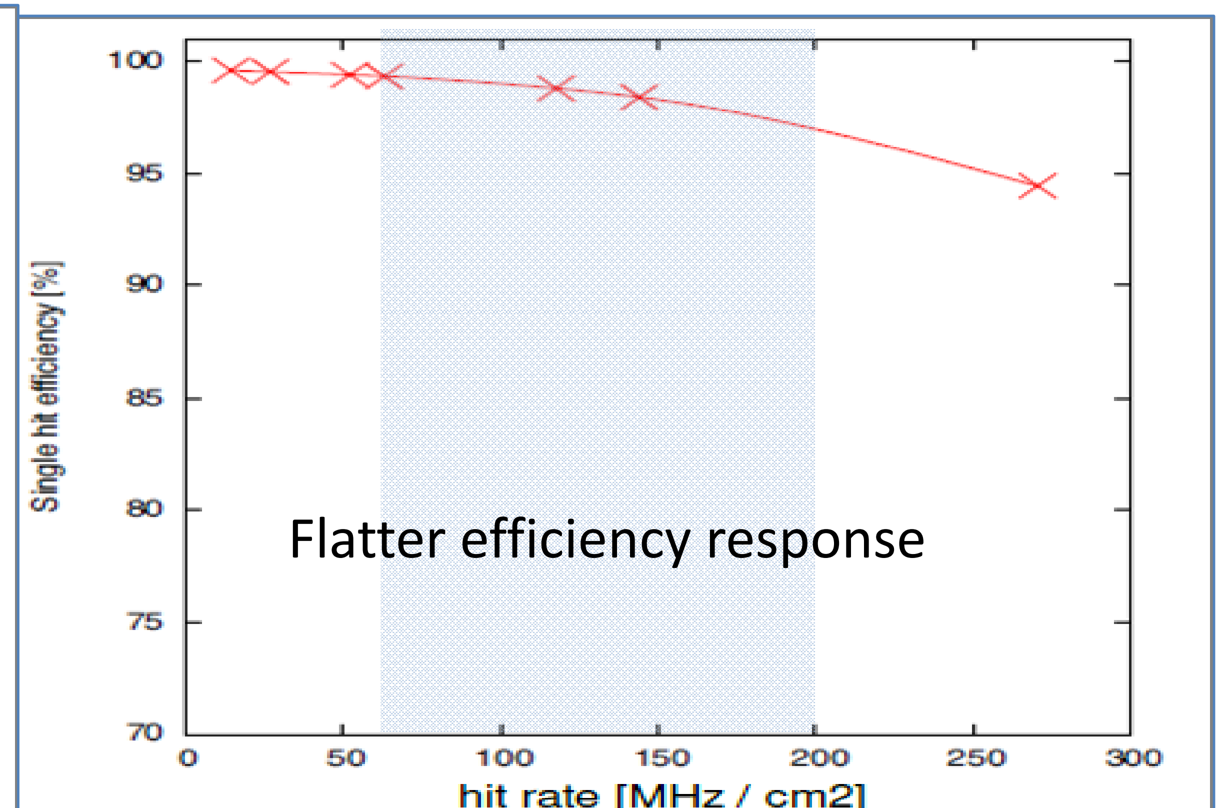
Pixel upgrade (1)

- Expected fluence in the Innermost disk
  - The old and the new ROC are contrasted for the same geometry using x-rays (Best case!)

Current Pixel Detector



Upgrade Pixel Detector



FPiX Expected Fluence

Pixel upgrade (2)

Table 2.1: Values of dynamic data loss used in the simulations of the current and upgrade pixel detector operating at 1×10^{34} cm^{-2}s^{-1} (25 ns crossing time) and 2×10^{34} cm^{-2}s^{-1} (25 ns and 50 ns crossing time) for each barrel layer and forward disk and for particular bunch crossing intervals.

Detector	Radius (cm)	% Data loss for (cm^{-2}s^{-1} @ ns) 1×10^{34} @ 25	2×10^{34} @ 25	2×10^{34} @ 50
Current detector				
BPIX1	4.4	4.0	16.0	50.0
BPIX2	7.3	1.5	5.8	18.2
BPIX3	10.2	0.7	3.0	9.3
FPIX1 and 2		0.7	3.0	9.3
Upgrade detector				
BPIX1	3.0	1.19	2.38	4.76
BPIX2	6.8	0.23	0.46	0.93
BPIX3	10.2	0.09	0.18	0.36
BPIX4	16.0	0.04	0.08	0.17
FPIX1–3		0.09	0.18	0.36

Pixel upgrade (4)

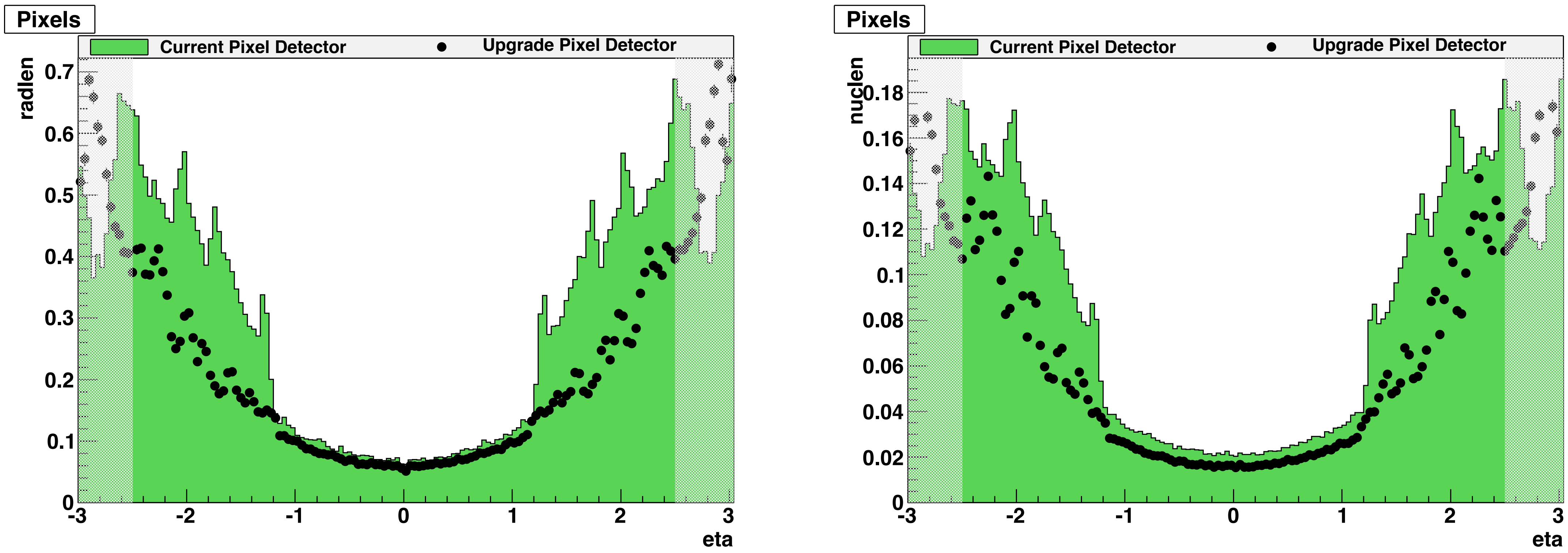
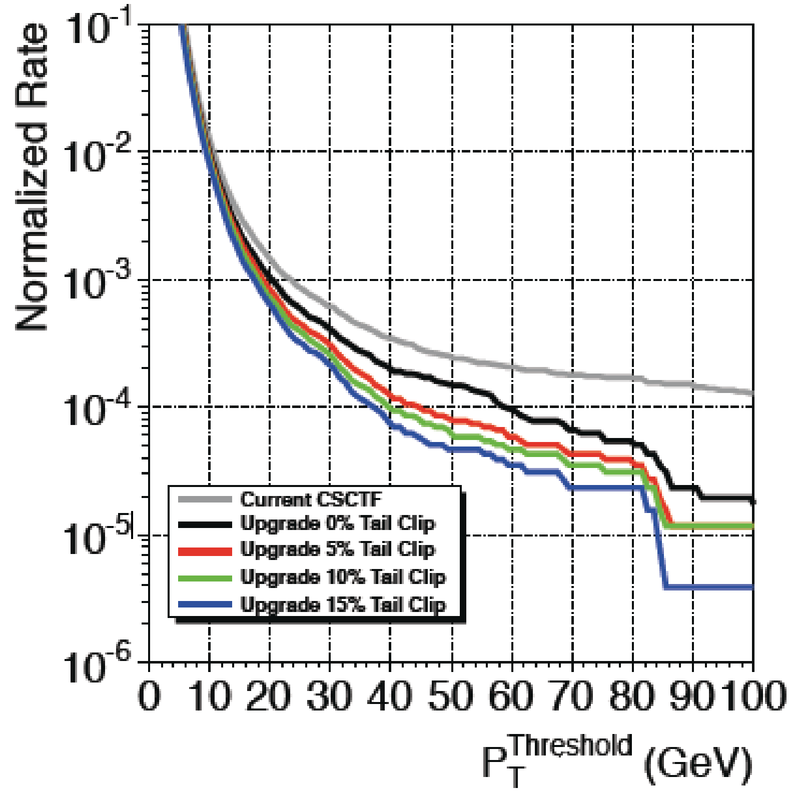


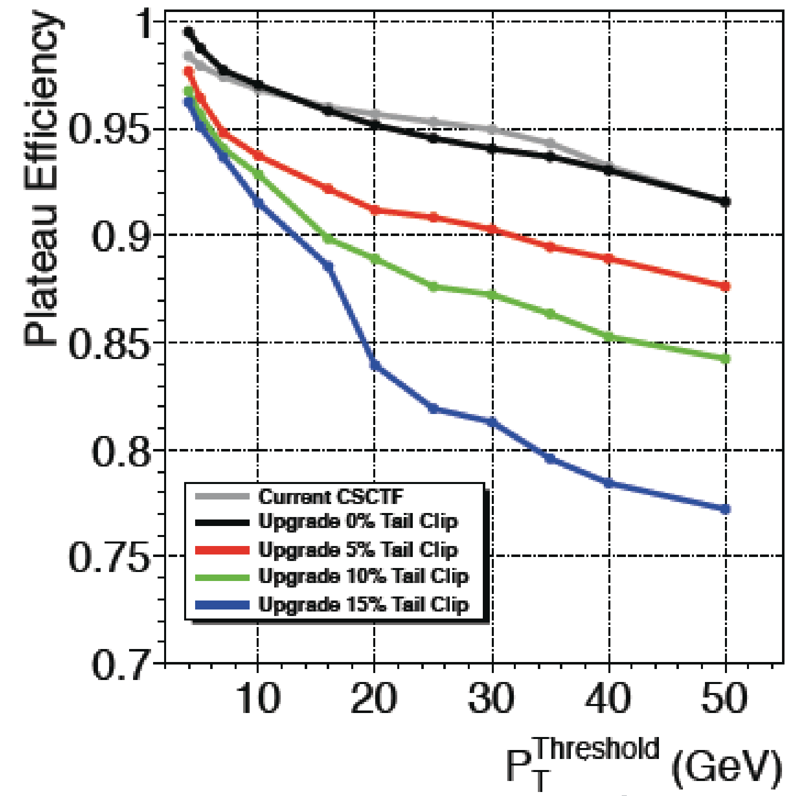
Figure 2.2: The amount of material in the pixel detector shown in units of radiation length (left), and in units of nuclear interaction length (right) as a function of η; this is given for the current pixel detector (green histogram), and the Phase 1 upgrade detector (black points). The shaded region at high $|\eta|$ is outside the region for track reconstruction.

Muon trigger upgrade (4)

LHC CMS Detector Upgrade Project

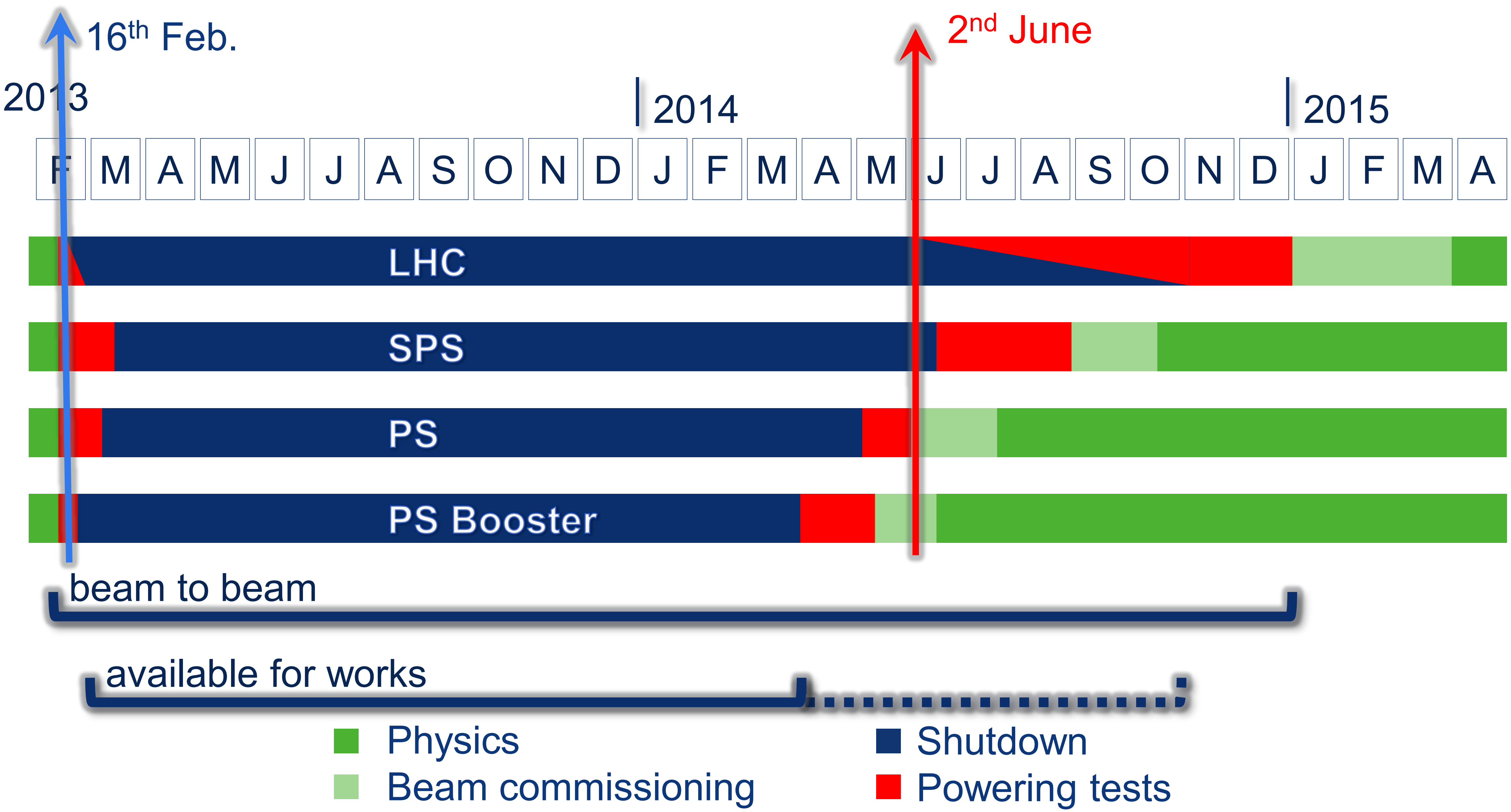
P_T Assignment Algorithm Studies





- Sophisticated p_T assignment (studied with BDTs) based on expanded list of information over current CSCTF
  - Tail Clipping: if a variable, e.g. $\Delta\varphi_{12}$,is in 5% (10%, 15%) tail, demote p_T to most probable value for given $\Delta\varphi_{12}$
  - Repeat over all 10 variables, report lowest demoted p_T
- Sharpens rate curve, factors of 2-3 rate reduction for modest efficiency loss (~5%, and programmable)

LS 1 from 16th Feb. 2013 to Dec. 2014



F Bordry – LHCP – June 2014

LHC upgrades: Maximize $\mathcal{L}$, minimize $\langle \mathrm{PU} \rangle$

$$\mathcal{L} = \frac{f \cdot k_b \cdot N_b^2}{4\pi\sigma^2} \quad \text{(head-on beams)}$$

$$\mathcal{L} = \frac{1}{4\pi}\left(\frac{E_{\mathrm{beam}}}{m_{\mathrm{p}}}\right)(f k_b N_b)\left(\frac{N_b}{\epsilon_{\mathrm{n}}}\right)\left(\frac{1}{\beta^*}\right) F(\theta_c, \sigma_z, \sigma)$$

$$\langle \mathrm{PU} \rangle = \frac{\mathcal{L} \cdot \sigma_{\mathrm{pp}}^{\mathrm{inelastic}}}{k_b \cdot f} \quad \text{(for given L)}$$

f = bunch frequency (11 kHz)
k_b = number of bunches (1380, 2808)
N_b = protons / bunch (1.6×10^{11})
ϵ_n = normalized emittance (2.5 μm)
β^* = optics parameter (60 cm)
F = geometric factor (40-80%)
θ_c = crossing angle (290 μrad)
σ_z = bunch length (7.55 cm)

Potential Improvement	Challenges	Solution	When
$\langle \mathrm{PU} \rangle \propto 1/k_b$ $\mathcal{L} \propto f k_b N_b$	e^- collimation, dump, long range collisions	Low emittance techniques with existing injectors	Now
$\mathcal{L} \propto E_{\mathrm{beam}}$	dipole splice resistance	splice consolidation	2013–14 (LS1)
$\mathcal{L} \propto N_b/\epsilon_n$	space charge in injectors, e^-	increase E of injectors, SPS coating	2018–19 (LS2)
$\mathcal{L} \propto 1/\beta^*$	aperture near IPs	new IP magnets	2023–25 (HL–LHC)
$\mathcal{L} \propto F$	crossing angle	crab cavities	