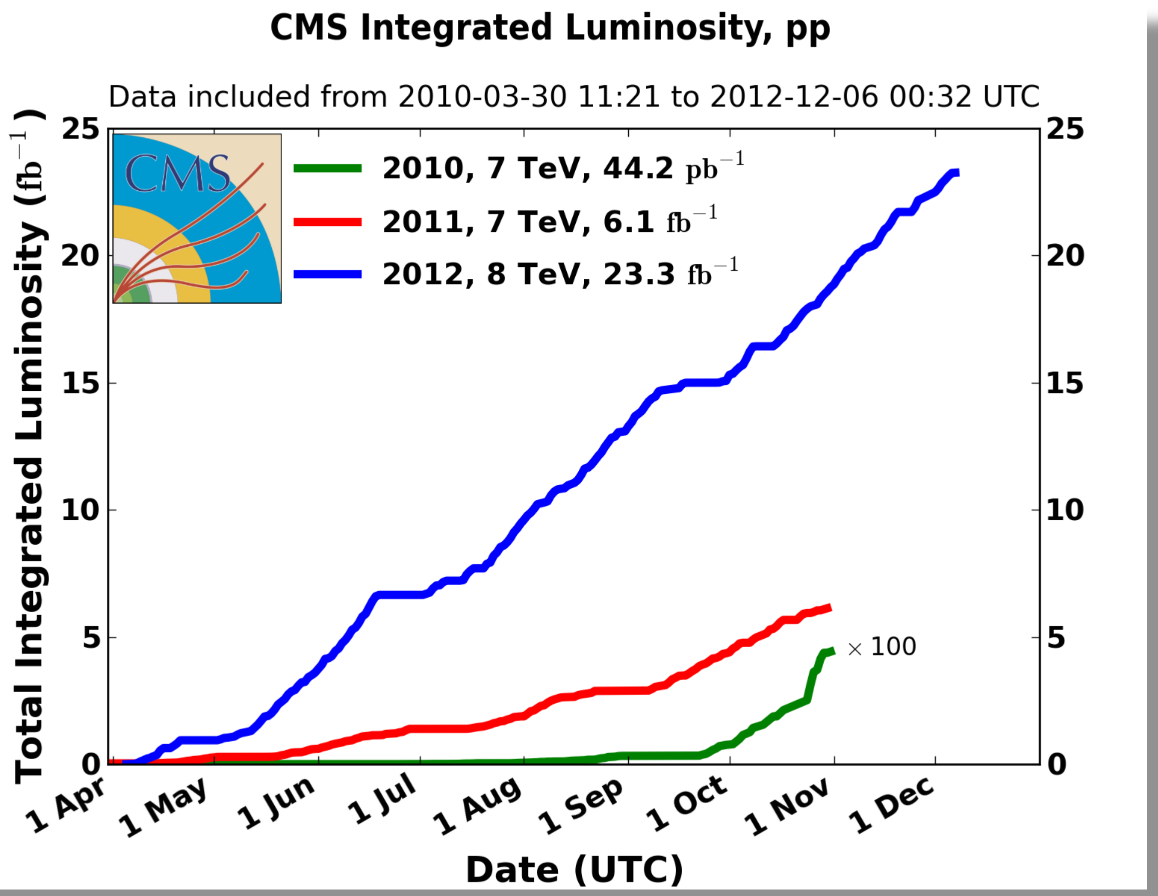
The LHC future: the CMS perspective

T.Camporesi, CERN

LHC prediction trustfulness



- 2010: **0.04 fb^{-1}**
  - 7 TeV
  - **Commissioning**
- 2011: **6.1 fb^{-1} (exp 5)**
  - 7 TeV
  - **… exploring the limits**
- 2012: **23.3 fb^{-1} (exp 20)**
  - 8 TeV
  - **… production**

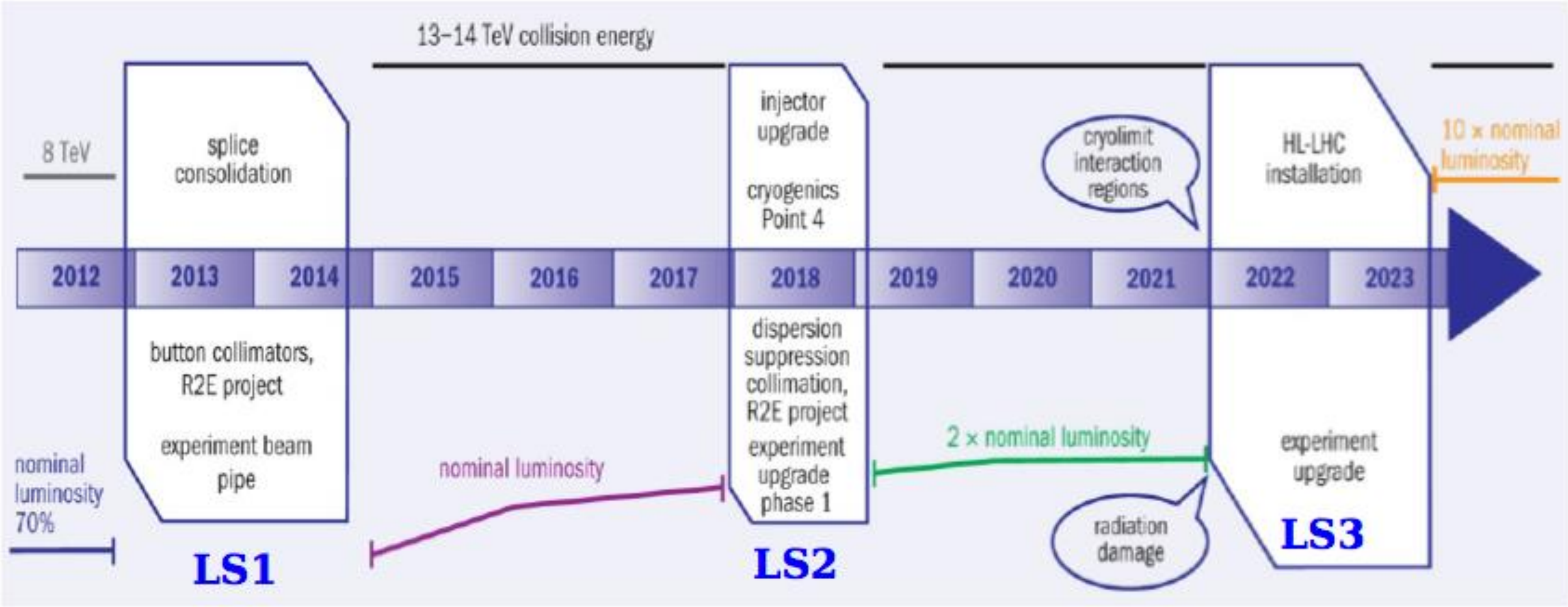
…. We better take seriously the LHC predictions….

LHC plans

Lucio Rossi and Oliver Brüning (CERN): HL-LHC

Krakow symposium, Sep 2012

`https://indico.cern.ch/contributionDisplay.py?contribId=153&confId=175067`



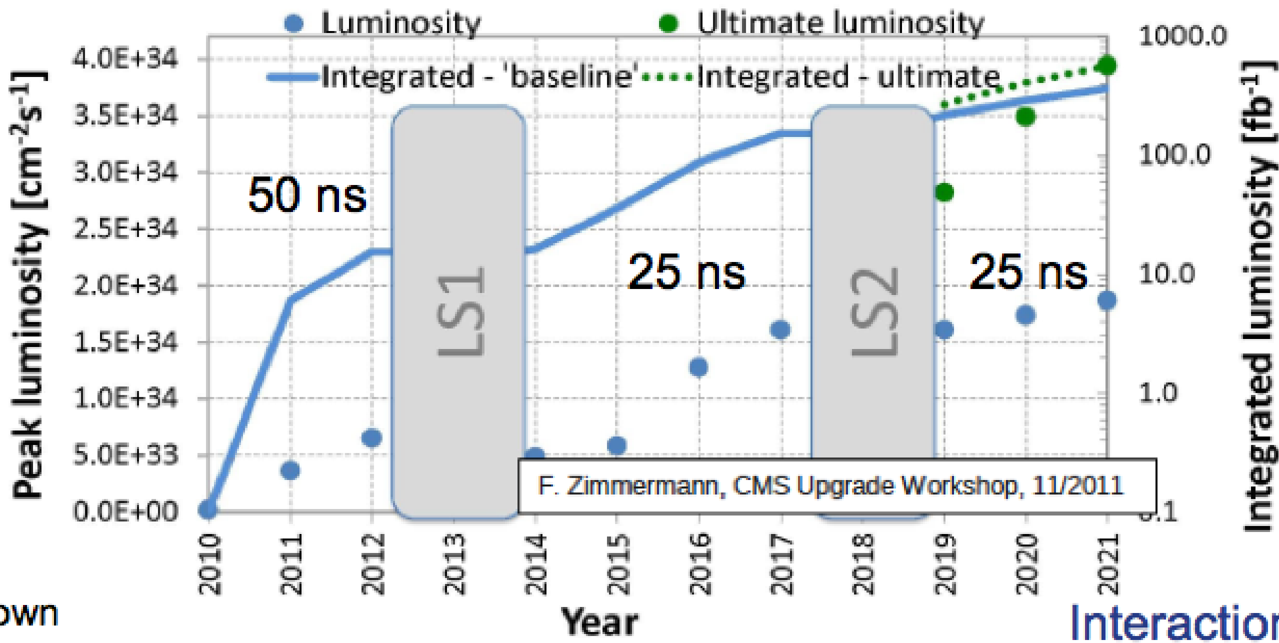
Map into CMS space

LHC | Energy increase 8 TeV to 13/14 TeV | Injection upgrade | **HL-LHC**

$PU = \begin{cases} 100@25ns \\ 200@50ns \end{cases}$

$PU = \begin{cases} 50@25ns \\ 100@50ns \end{cases}$

$PU = \begin{cases} 25@25ns \\ 50@50ns \end{cases}$



Luminosity-leveled at 5×10^{34} $cm^{-2}s^{-1}$ in HL-LHC

LS- Long Shutdown

Interaction region upgrade

8×10^{33} Hz/cm^2
30 fb^{-1}

LS1

2×10^{34} Hz/cm^2
300 fb^{-1}

LS3

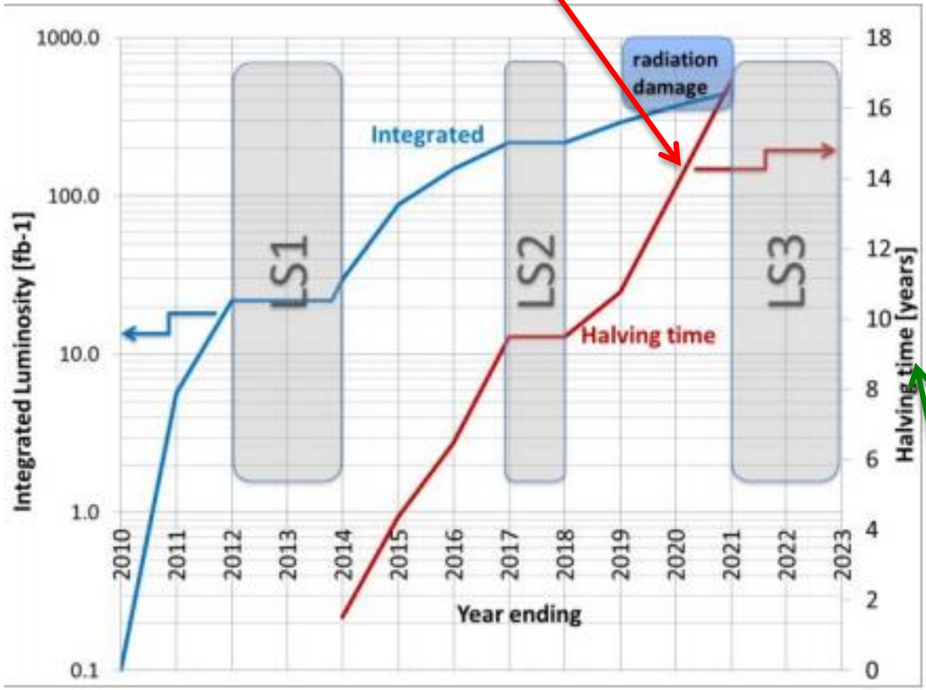
10^{35} Hz/cm^2
3000 fb^{-1}

Phase 1 Upgrade

Phase 2 Upgrade

A comment about statistics

Stat. halving time Assuming flat lumi accumulation



Flat lumi accumulation is probably not the right assumption: trigger selection can influence stats for specific searches/measurements

The accelerator complex

What we know

What to expect

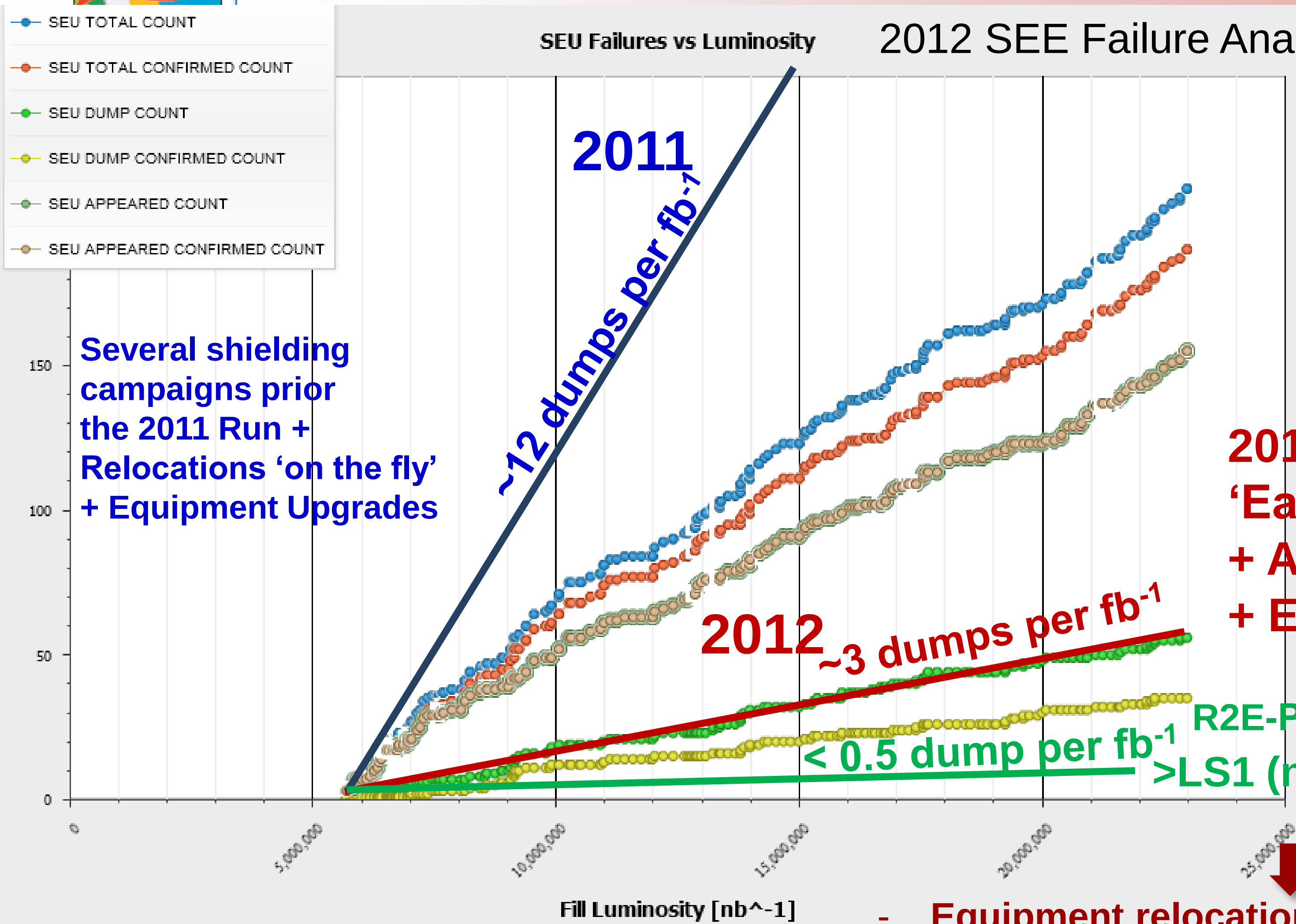
Performance from injectors 2012

Design report with 25 ns:
- **1.15×10^{11} ppb**
- **Normalized emittance 3.75 microns**

Bunch spacing [ns]	Protons per bunch [ppb]	Norm. emittance H&V [microns] Exit SPS
50	1.7×10^{11}	1.8
25	1.2×10^{11}	2.7

Radiation effects (SEU ++)

2012 SEE Failure Analysis

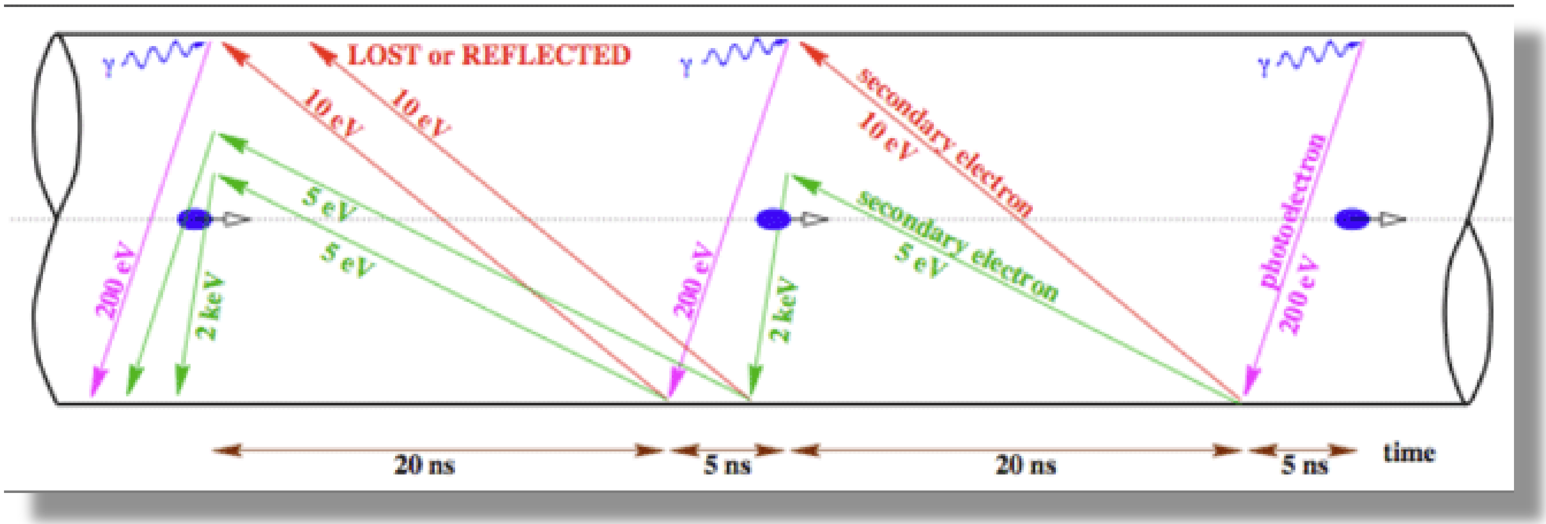


2011/12 xMasBreak
'Early' Relocation
+ Additional Shieldin
+ Equipment Upgrad

R2E-Project aiming for …
>LS1 (nominal -> ultimate)

- **Equipment relocations @ 4 LHC Points (>100 Racks, >60 weeks of work)**
- **Additional shielding**
- **Critical system upgrades (QPS, FGC)**

25 ns & electron cloud

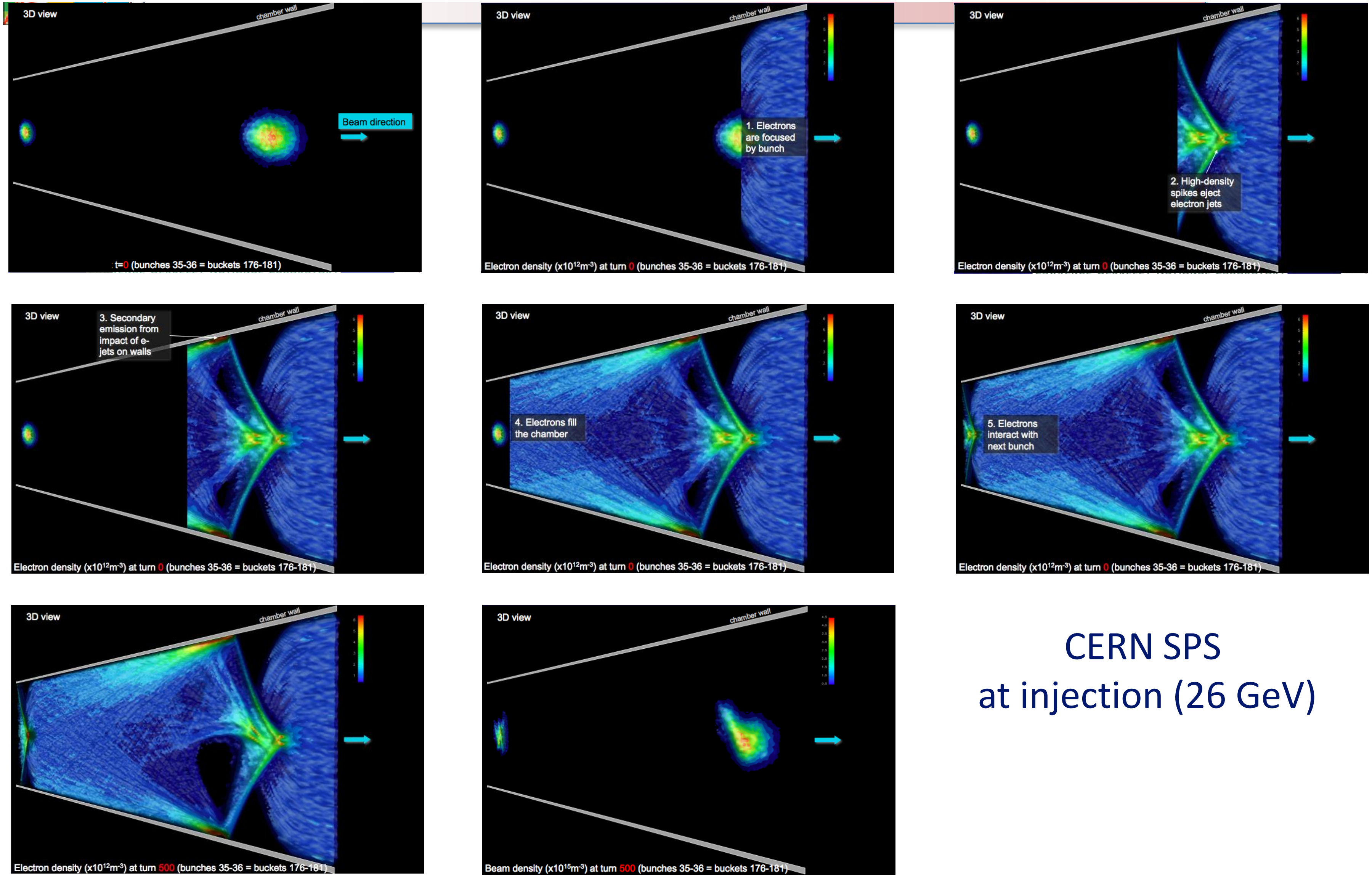


- Typical e⁻ densities: $n_e = 10^{10}$–10^{12} m^{-3} (~a few nC/m)
- Typical e⁻ energies: <~ 200 eV (with significant fluctuations)

Warp and Posinst have been further integrated, enabling fully self-consistent simulation of e-cloud effects: build-up & beam dynamics

Turn 1

Turn 500



CERN SPS
at injection (26 GeV)

Electron cloud: consequences

- Possible consequences:
  - single-bunch instability
  - multi-bunch instability
  - emittance growth
  - gas desorption from chamber walls
  - excessive energy deposition on the chamber walls (important for the LHC in the cold sectors)
  - particle losses, interference with diagnostics,…
- In summary: the EC is a consequence of the interplay between the beam and the vacuum chamber ⟹ "rich physics"
  - many possible ingredients: bunch intensity, bunch shape, beam loss rate, fill pattern, photoelectric yield, photon reflectivity, SEY, vacuum pressure, vacuum chamber size and geometry, …

Defense: design (saw-tooth pattern on the beam screen inside the cold arcs, NEG coatings, solenoids, etc.)

Electron bombardment of a surface has been proven to reduce drastically the secondary electron yield of a material.
This technique, known as **scrubbing**, provides a mean to suppress electron cloud build-up and its undesired effects

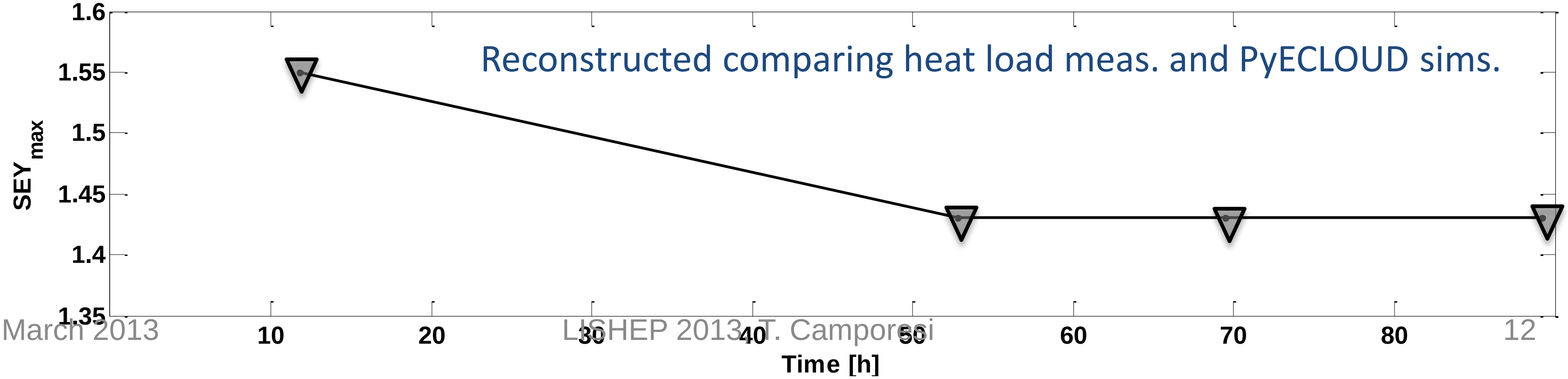
The 2012 25 ns scrubbing

3.5 days of scrubbing with 25ns beams at 450GeV (6 - 9 Dec. 2012):

- Regularly filling the ring with up to **2748b.** per beam (up to **2.7×10^{14} p**)

Scrubbing effects in the arcs:

- Quite **rapid conditioning observed in the first stages**
- The **SEY evolution significantly slows down** during the last scrubbing fills (more than expected by estimates from lab. measurements and simulations)



25 ns & electron cloud

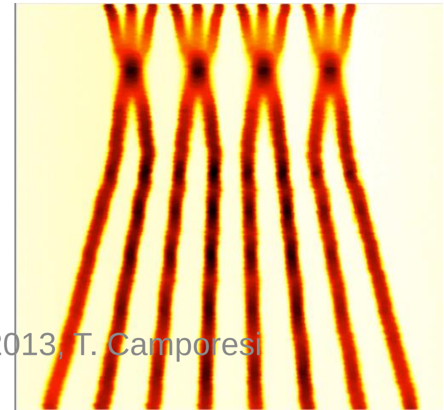
- There is a change of mode of operation with 25 ns. Electron cloud free environment after scrubbing at 450 GeV seem not be reachable in acceptable time.
- Personal convinction: Need to ramp and scrub
- Operation with high heat load and electron cloud density (with blow-up) seems to be unavoidable with a corresponding slow intensity ramp-up.
- 2015: SEY etc. will be reset - initial conditioning will be required
  - FROM LHC OPS: Will need to start with 50 ns and only later to move to 25 ns to recover vacuum, cryogenics, UFOs conditions we were used in 2012.

Beam from injectors LS1 to LS2

		Bunch intensity [10^{11} p/b]	Emittance,[mm.mrad]	Into collisions
25 ns ~nominal	2760	1.15	2.8	3.75
25 ns BCMS	2520	1.15	1.4	1.9
50 ns	1380	1.65	1.7	2.3
50 ns BCMS	1260	1.6	1.2	1.6

BCMS = Batch Compression and (bunch) Merging and (bunch) Splittings

Rende Steerenberg, Gianluigi Arduini, Theodoros Argyropoulos, Hannes Bartosik, Thomas Bohl, Karel Cornelis, Heiko Damerau, Alan Findlay, Roland Garoby, Brennan Goddard, Simone Gilardoni, Steve Hancock, Klaus Hanke, Wolfgang Höfle, Giovanni Iadarola, Elias Metral, Bettina Mikulec, Yannis Papaphilippou, Giovanni Rumolo, Elena Shaposhnikova,…



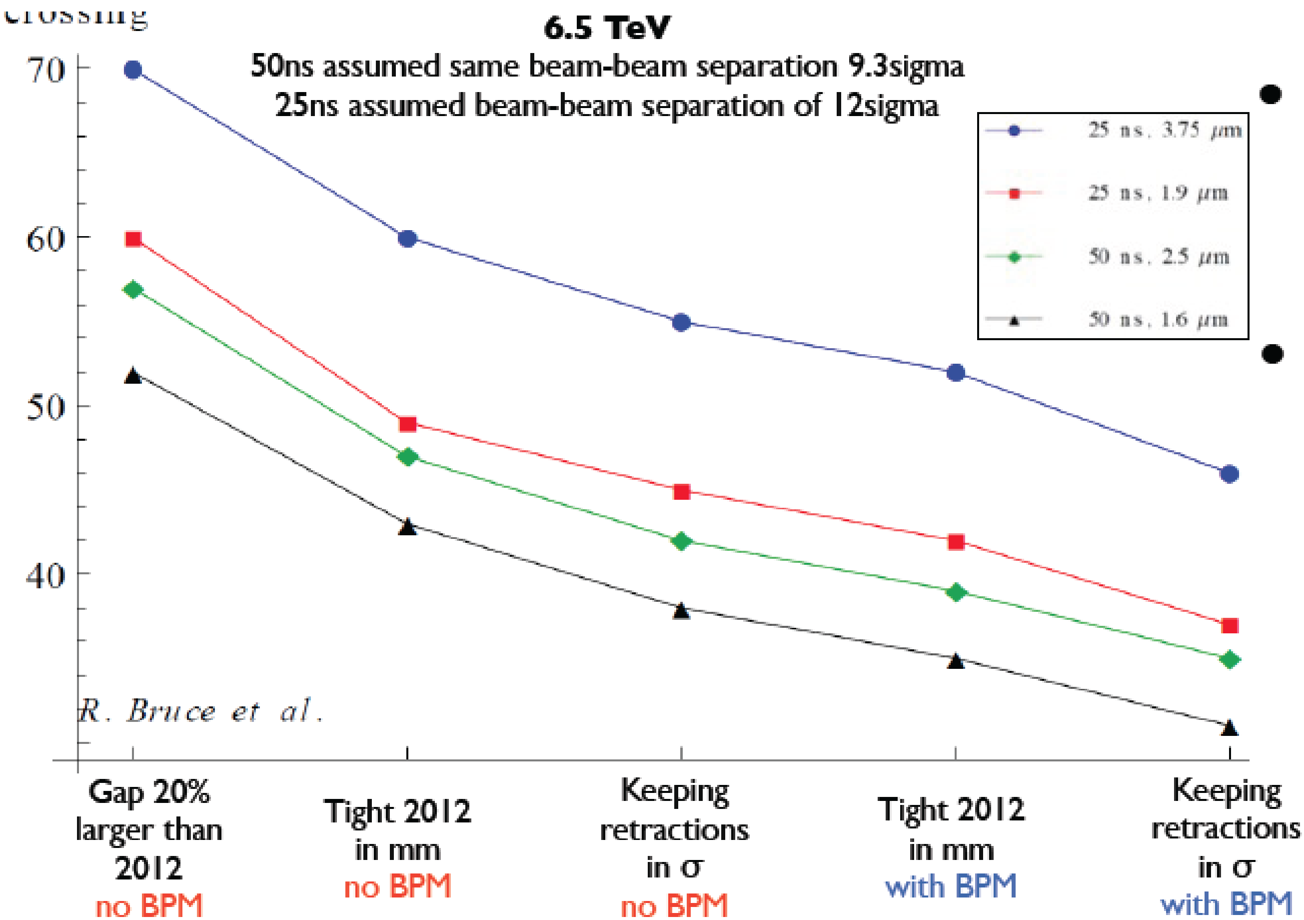
Batch compression & triple splitting in PS

50 versus 25 ns

	50 ns	25 ns
GOOD	• Lower total beam current • Higher bunch intensity • Lower emittance	• **Lower pile-up**
BAD	• **High pile-up** • Need to level • Pile-up stays high • High bunch intensity – instabilities…	• More long range collisions: larger crossing angle; higher beta* • Higher emittance • Electron cloud: need for scrubbing; emittance blow-up; • Higher UFO rate • Higher injected bunch train intensity • Higher total beam current

Expect to move to 25 ns because of pile up…

β* reach at 6.5 TeV



- Pessimistic scenario:
  - ➡ β* = 70cm at 25ns
  - ➡ β* = 57cm at 50ns
- Optimistic scenario:
  - ➡ β* = 37cm at 25ns
  - ➡ β* = 30cm at 50ns

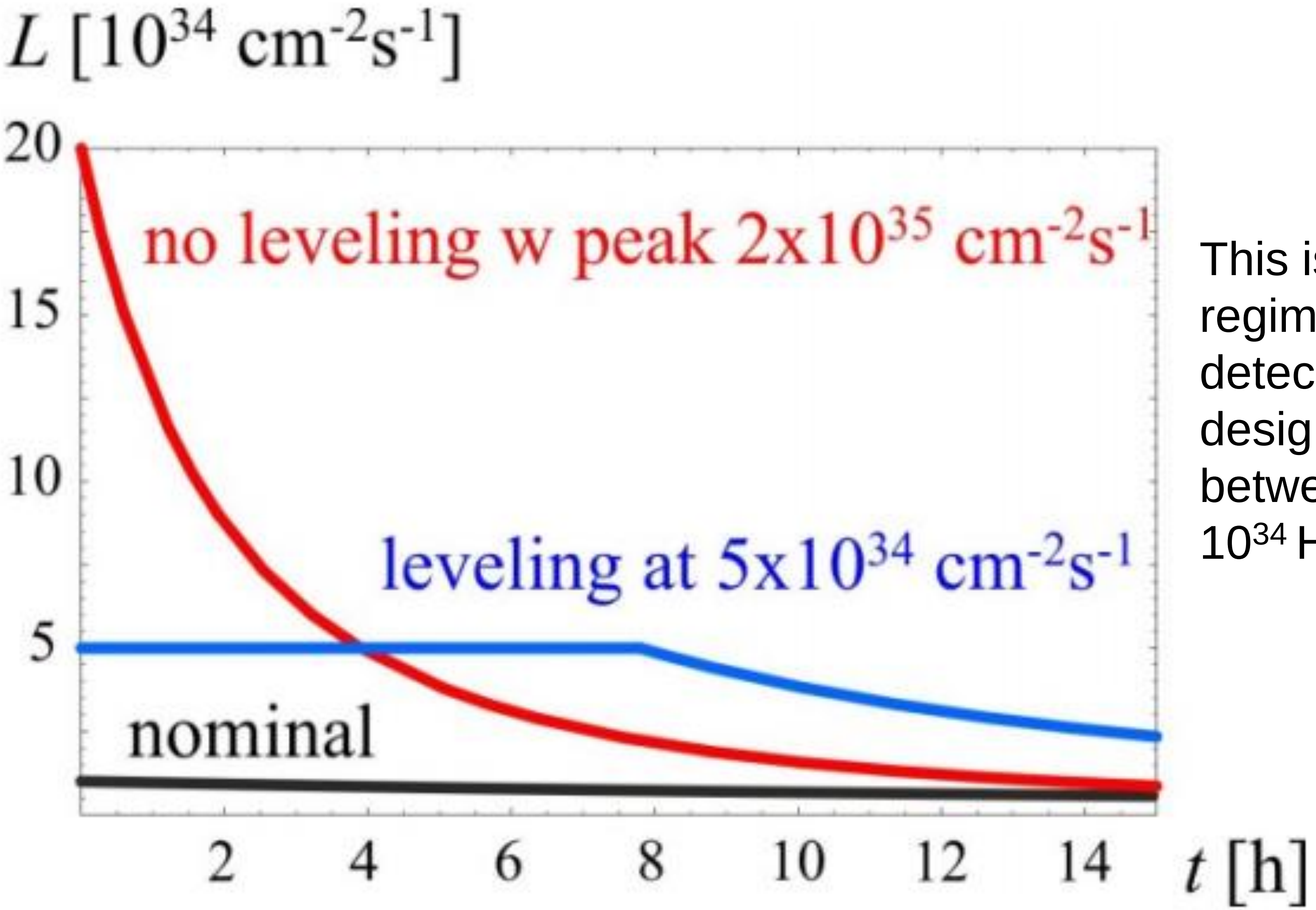
Potential performance

	Number of bunches	Ib LHC FT[1e11]	beta*X beta*sep Xangle	Emit LHC [um]	Peak Lumi [cm-^{2}s^{-1}]	~Pile-up	Int. Lumi per year [fb^{-1}]
25 ns	2760	1.15	55/43/189	3.75	9.2e33	21	~24
25 ns low emit	2320	1.15	45/43/149	1.9	1.5e34	42	~40
50 ns	1380	1.65	42/43/136	2.5	1.6e34 level to 0.9e34	74 level to 40	~45*
50 ns low emit	1260	1.6	38/43/115	1.6	2.2e34 level to 0.9e34	109 level to 40	~45*

- 6.5 TeV
- 1.1 ns bunch length
- 150 days proton physics, HF = 0.2
- 85 mb visible cross-section
- * different operational model – caveat - unproven

All numbers approximate

HL -LHC

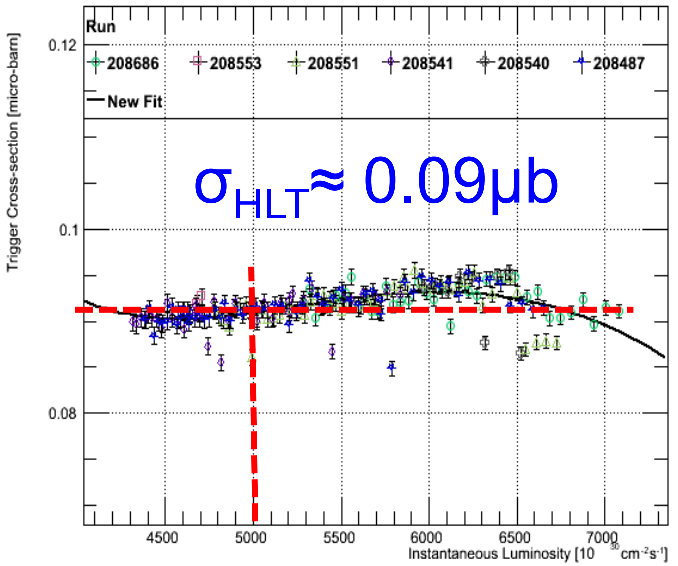


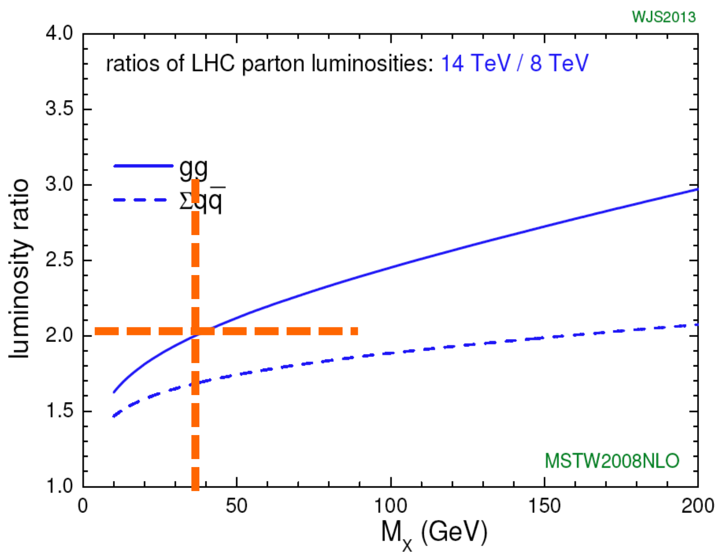
This is a new regime: Phase 1 detectors were designed to handle between 1 and 2 10^{34} Hz/cm^2

The CMS view point

The short term challenges
The upgrade program:
Phase 1
Phase 2 (HL LHC)

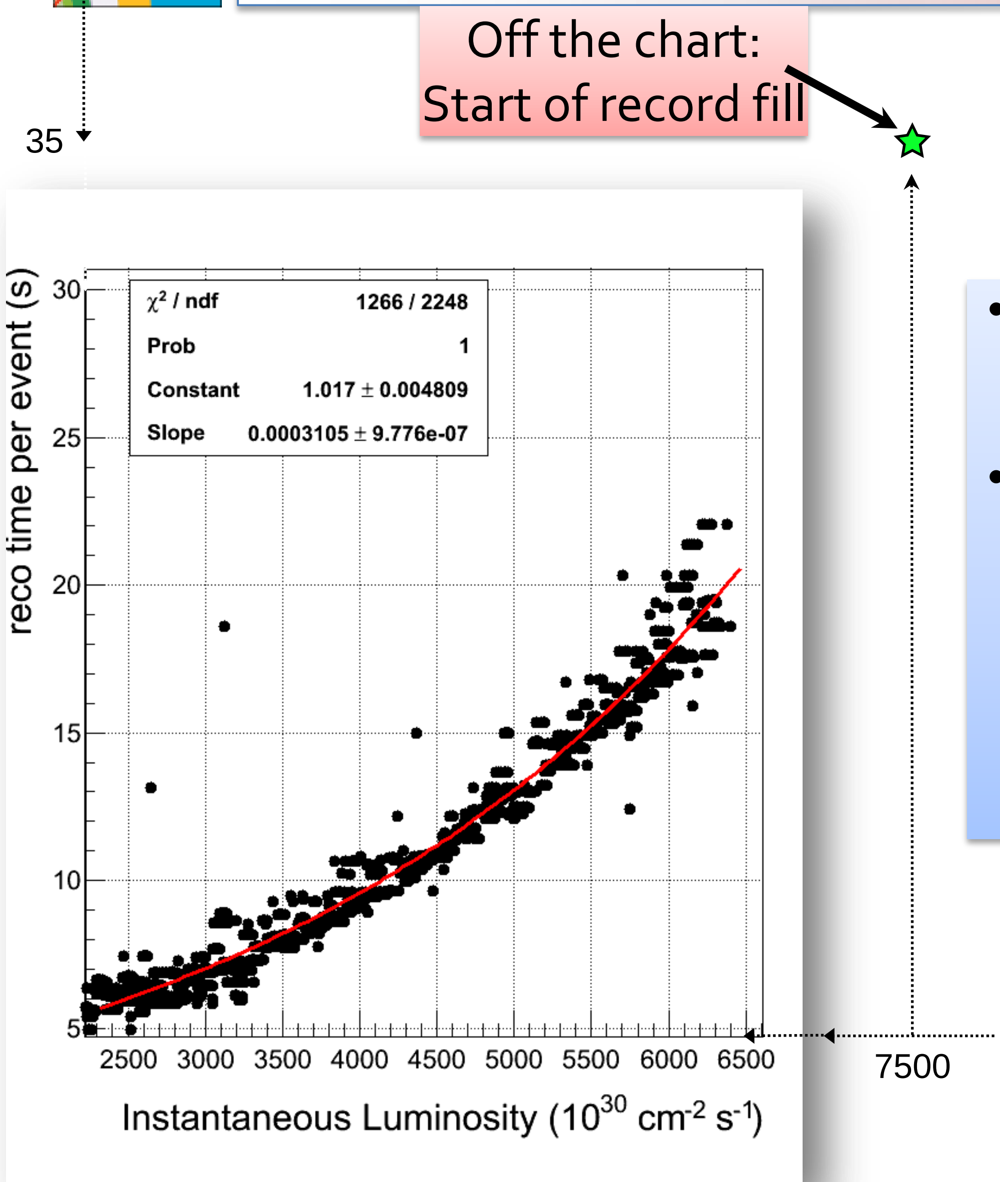
HLT : challenges for 2015





- 2012: 8 TeV HLT σ ~0.09 µb
  - PU=25, small dependence on PU
- 8 TeV→ 14TeV ⇒ rates double
  - Average output rate of ~ 1.2kHz at $10^{34}cm^{-2}s^{-1}$ if menu untouched.
- To keep the present acceptance:
  - Improve HLT object reconstruction
    - Allowing tighter cuts
  - Reconsider strategies
    - More cross triggers
  - Will need more CPU
    - e.g. to extend PF usage
    - Particularly if PU <> grows above 25

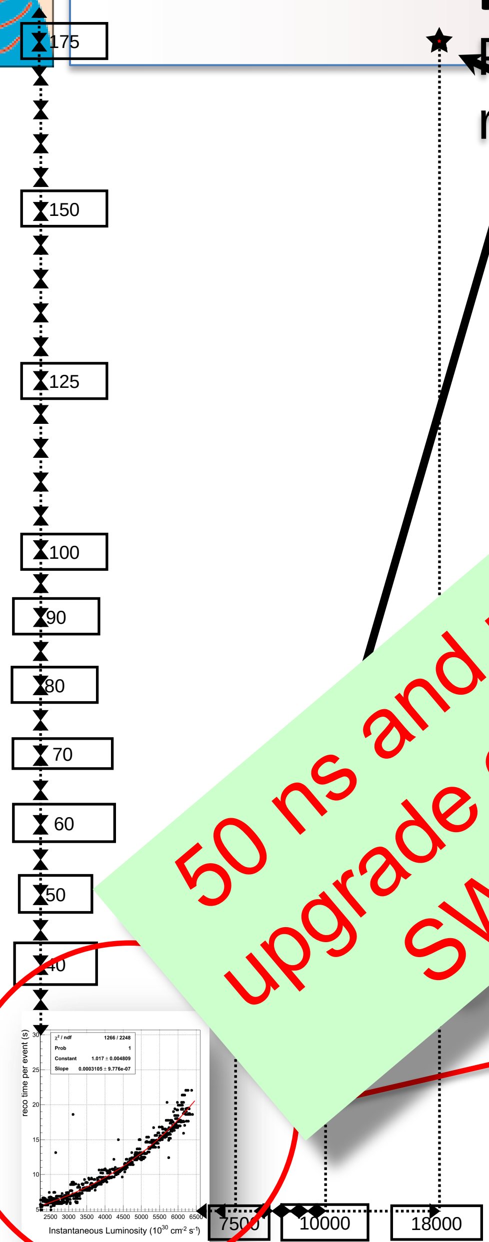
The Tier-0 Today



- Many improvements
  - But reco time is still non-linear with instantaneous luminosity
- Preparing for both extremes of 25 and 50 ns bunch spacing
  - Goal is to keep the physics performance the same as run1.
    - Our physics projections are made with that assumption.

50 ns spacing is too hard…

Points measured from cur… release as run on high…



50 ns and ultimate lumi need major upgrade of computing resources and SW improvements/sacrifices

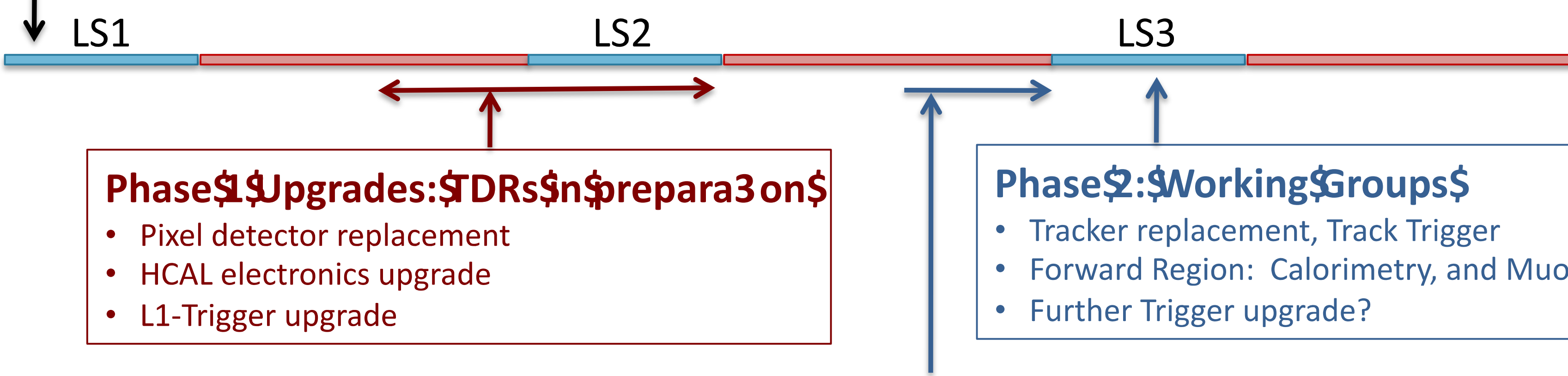
- Proj…
  - …tor of 10 reduction in …vent to maintain our …formance at highest …luminosities
  - …tically?
    - Could conceivably foresee factor of 2 reduction in cpu time per event
      - We already gained factor of 3 in early 2012

Previous slide

Peak lumi X 10^{33} Hz/cm^2

CMS upgrade program

LS1$Projects:$n$produc3on$
- Completion of muon coverage (ME4)
- Improve muon operation (ME1), DT electronics
- Replace HCAL photo-detectors in HF (new PMTs) and HO (HPD→SiPM)



Phase1Upgrades:$TDRs$n$prepara3on$
- Pixel detector replacement
- HCAL electronics upgrade
- L1-Trigger upgrade

Phase$2:$Working$Groups$
- Tracker replacement, Track Trigger
- Forward Region: Calorimetry, and Muons?
- Further Trigger upgrade?

- Longevity → Phase 2
- Phase 2 Scope
- Targeted R&D program

} 2013

- Technical Proposal 2014

Detector upgraded in LS1

Short term (LS1)

- Completion of staged projects:
  - Completion of muon coverage
  - Implement Cold tracker operation
- Fix problems detected in first LHC run
  - See Gilvan → HF, Cerenkov light from PMT windows: replace PMTs with new thinner window and multianode PMTs
  - See Gilvan → Replace HPD for HO with Si-PM (unforeseen instability of HPDs at fields lower than 3 T)
  - Consolidation of DT front-end fiber readout (sector collector)off-cavern: allows intervention and easy reconfiguration for trigger upgrade +new front-end theta trigger board (FPGA based)
- Prepare for future upgrades :
  - New smaller diameter beam-pipe (necessary if wanting to install new pixel in extended end of year shutdown)
  - Optical splitting of calorimeter trigger lines+ new optical output for muon trigger (to allow parallel commissioning of trigger upgrade –μTCA based- during LHC operation in 2014-2015)
  - See Gilvan → Install new HF backend electronics (μTCA to replace VME) : first step of full HCAL upgrade

LS1 Muon Upgrades

Trigger performance: significantly lower threshold for same rate

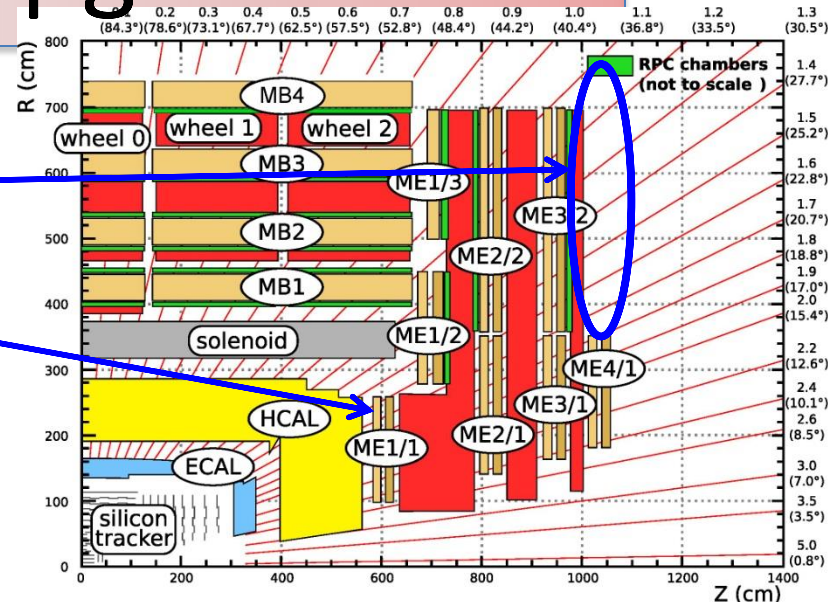
CSC and RPC: ME4/2 (1.25<|η|<1.8)

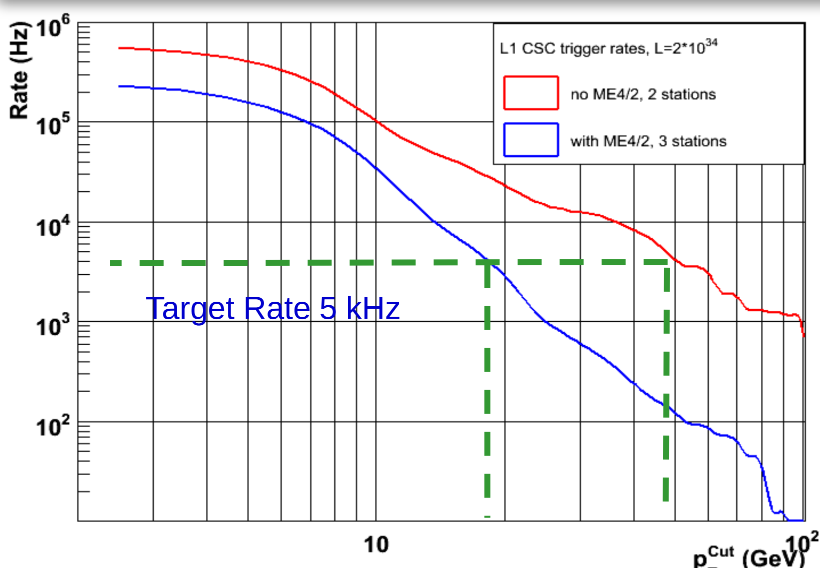
More hits, lower rates

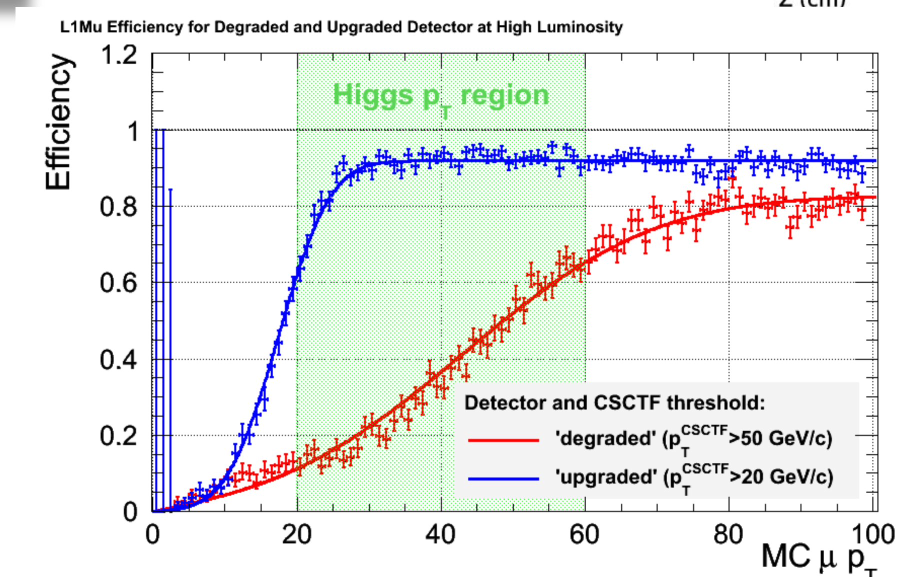
CSC: ME1/1 (2.1<|η|<2.4) new digital boards and trigger cards : higher strip granularity

Electronics reliability

DT: new trigger readout board and relocation of sector collector from UXC55 to USC55 (new optical links)



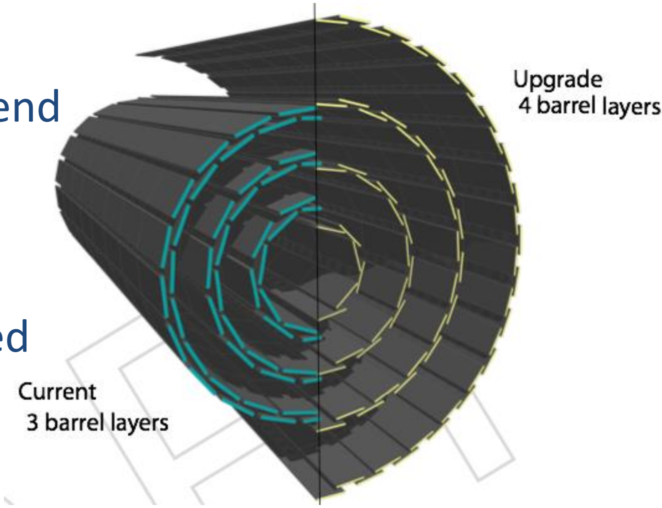


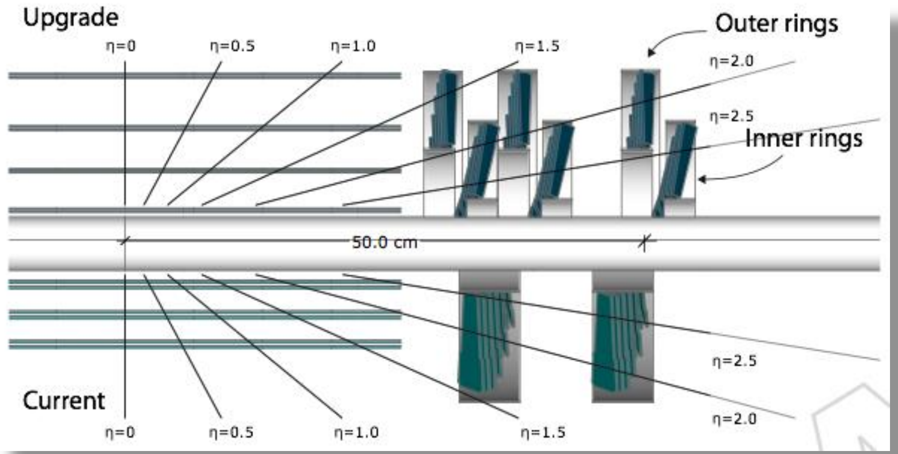


Medium term (LS1 to LS2): pixel

Features of New Design

- Robust design: 4 barrel layers and 3 endcap disks at each end
- Smaller inner radius (new beampipe), large outer
- New readout chip with expanded buffers, embedded digitization and high speed data link
- Reduced mass with 2-phase CO_2 cooling, electronics moved to high eta, DC-DC converters



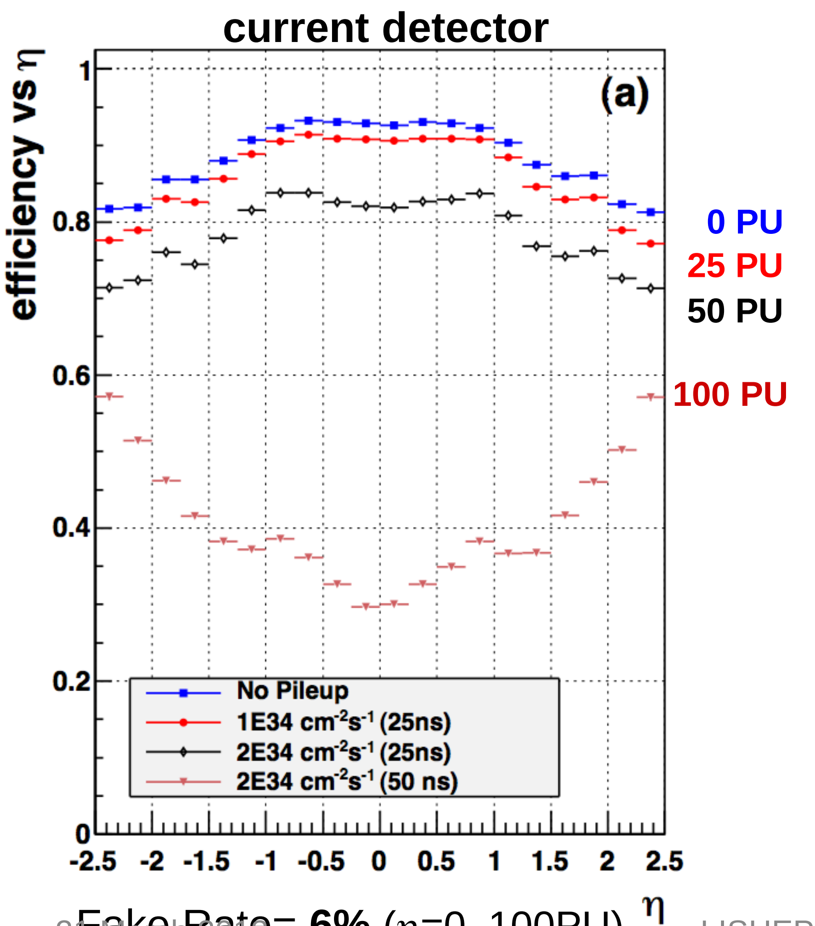


Ready to install by end of 2016

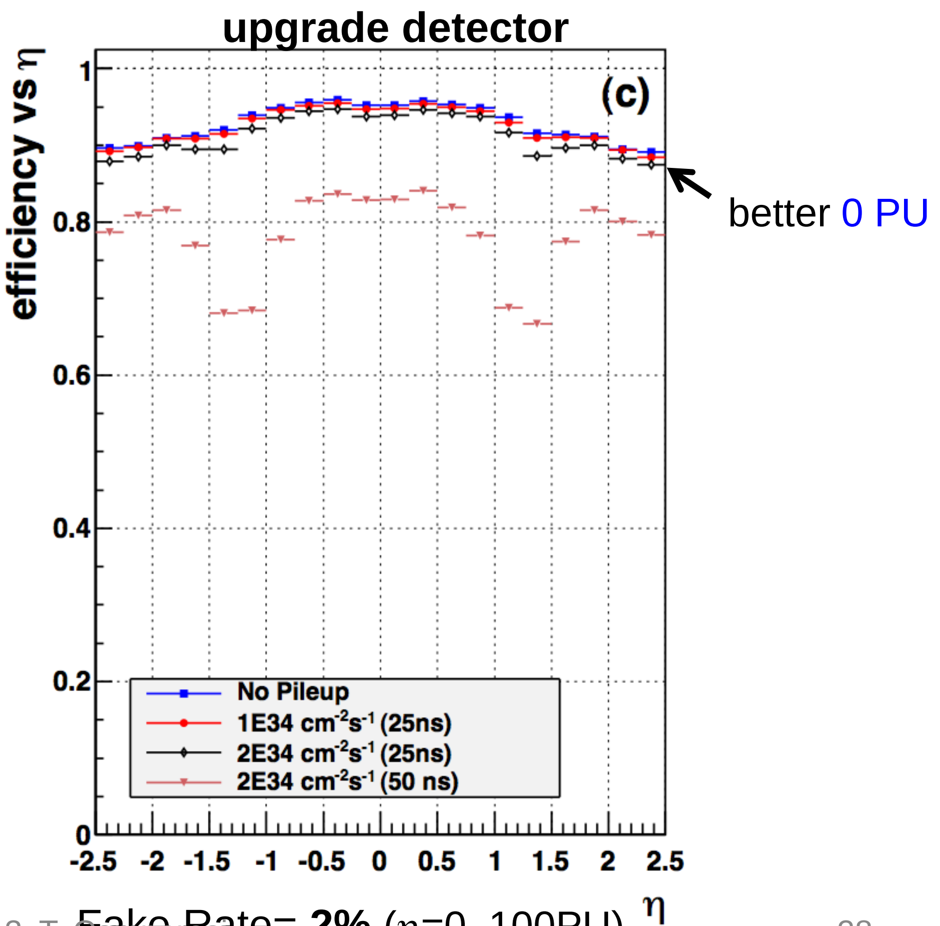
Upgraded Pixel tracking

Current Pixel front end designed to handle 10^{34}...
Beyond the FE buffer structure does not keep up

Tracking efficiency for $t\bar{t}$ sample with ROC data losses. → pions etc. (hadronic interactions)

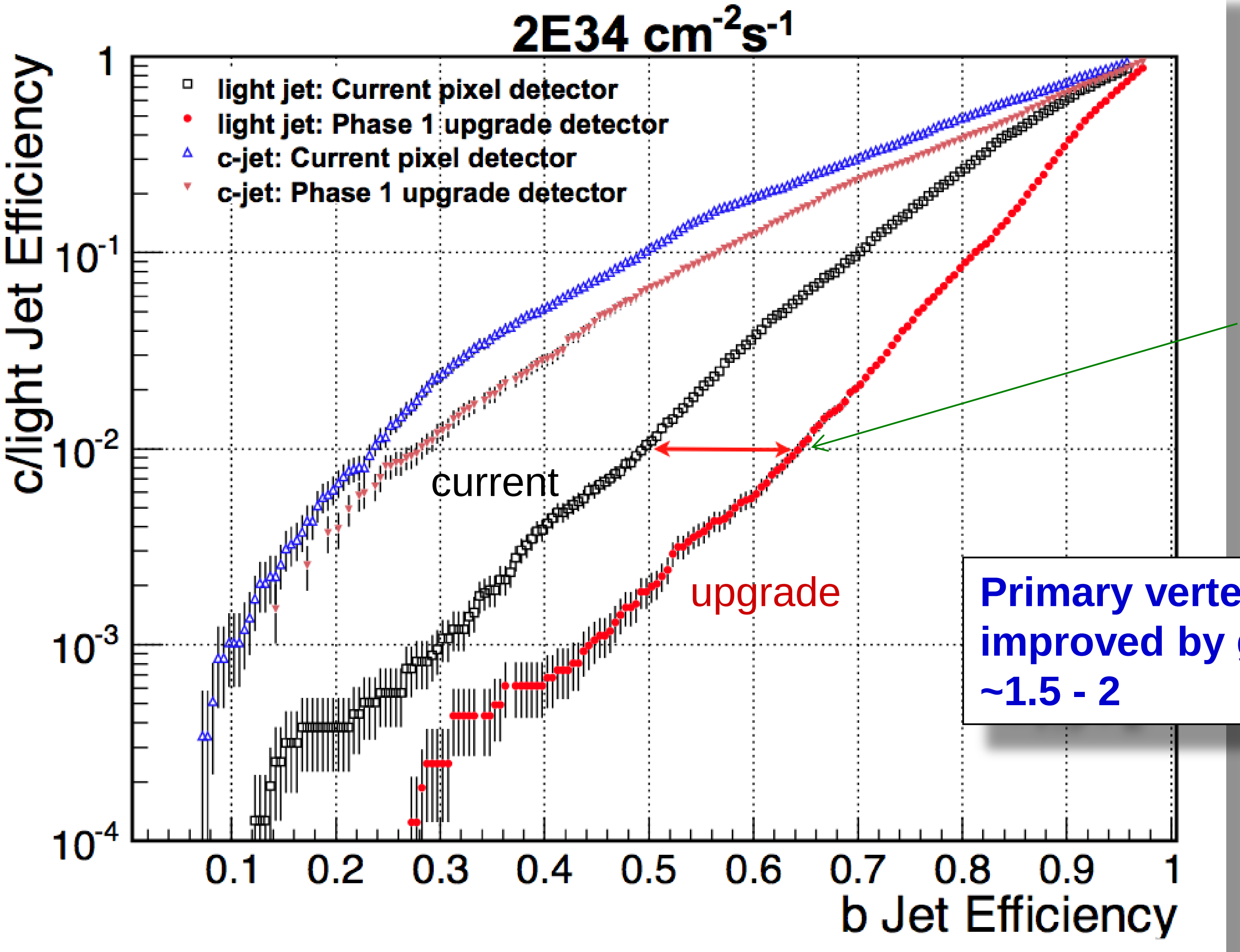


Fake Rate= **6%** (η=0, 100PU)



Fake Rate= **2%** (η=0, 100PU)

Upgrade: Pixel b-tagging



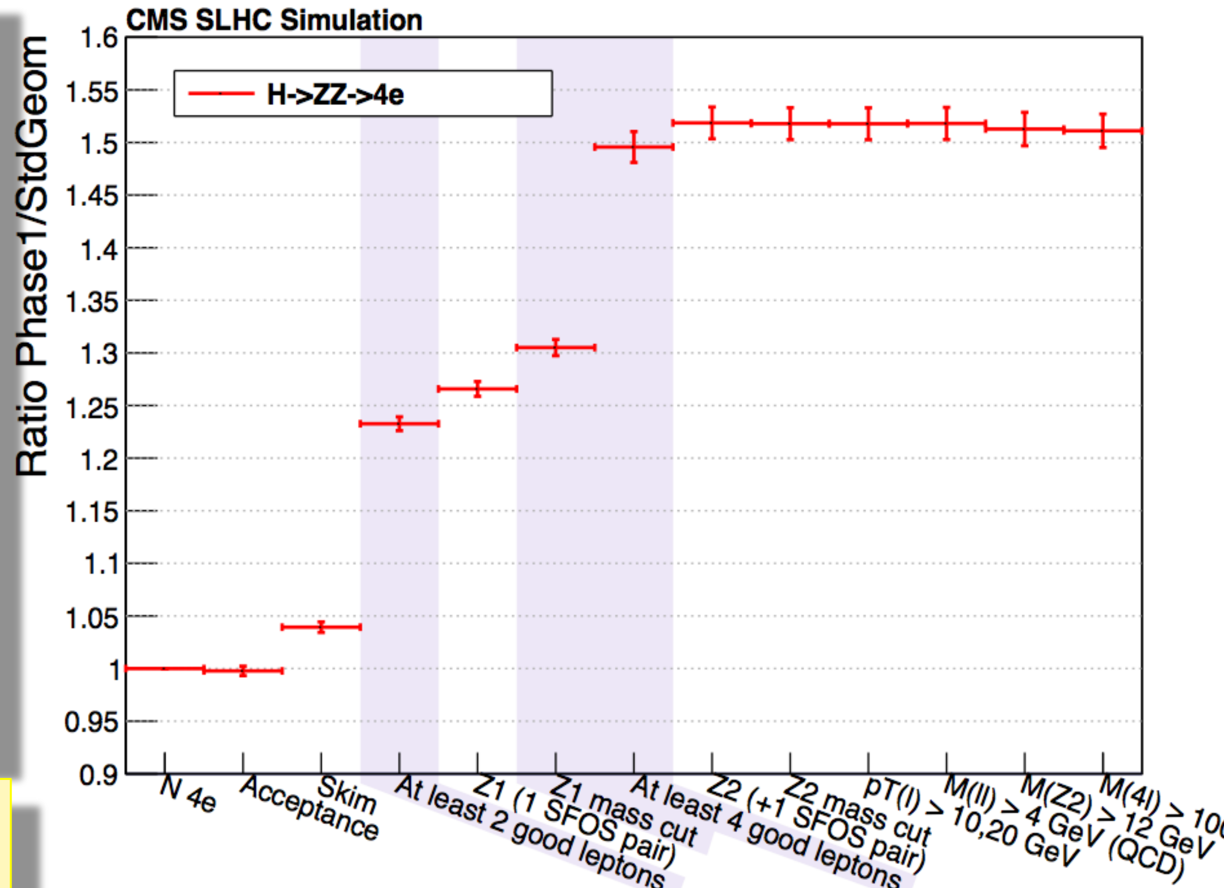
b-jet efficiency ~ 1.3x better @ 10^{-2} udg-rej.

Primary vertex resolution improved by gain factor ~1.5 - 2

Pixel upgrade: use case H→4ℓ

Event selection: *(as 2012 analysis)*

- events with ≥ 4 isolated leptons
- 2 leptons with p_T>17 GeV and 8GeV
- same 2 leptons with N_{pixhit} >2
- e-reconst. PF and η<2.5, p_T>7GeV
- μ-reconst. PF and η<2.4, p_T>5GeV
- leptons from primary vertex SIP_{3D}< 4
- 40 GeV < M_{Z1} < 120 GeV
- 12 GeV < M_{Z2} < 120 GeV
- p_T(l) >10,20 GeV & M_{4l} >100 GeV



Significant gain in signal reconstruction efficiency:

H→ 4μ	+41%
H→ 2μ2e	+48%
H→ 4e	+51%

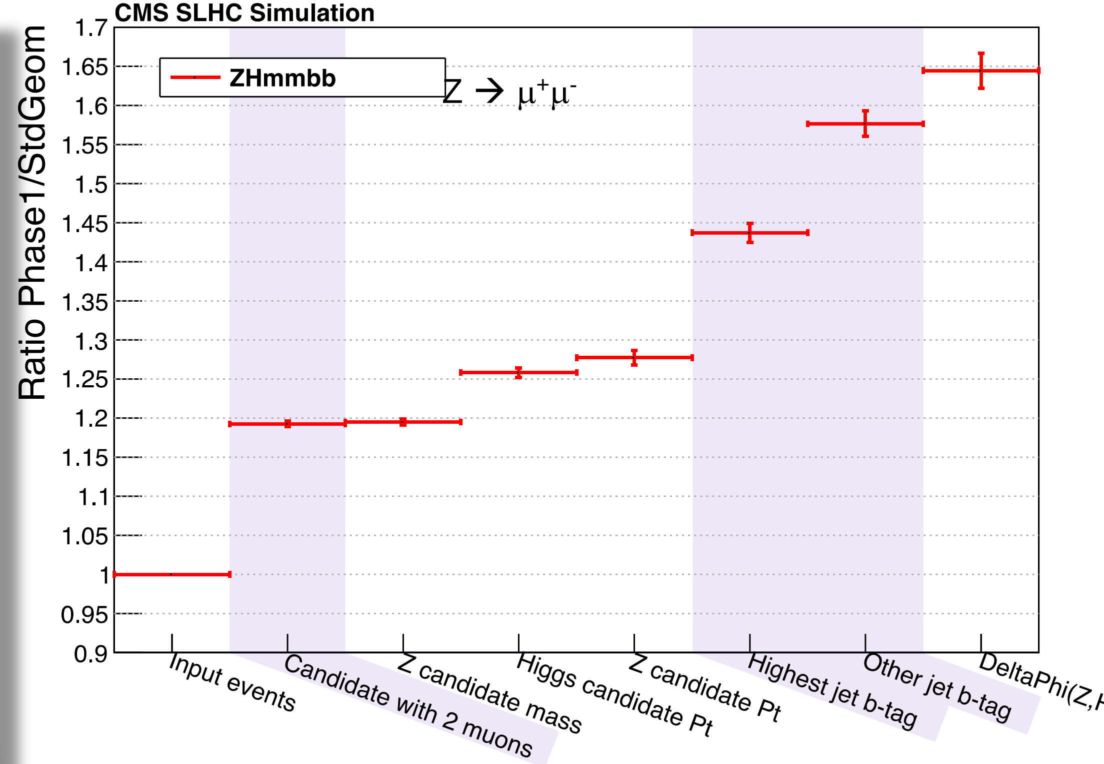
Conclusion:

Upgrade detector provides physics reach as current detector with 40-50% more efficiency.

Pixel upgrade:ZH → $\ell^+\ell^-$+2 b-jets

Event selection:

- events with ≥ 2 leptons + ≥ 2 jets
- p_T>20 GeV for leptons & jets
- H with highest p_T combination
- Z with hightest p_T combination
- 75 GeV < M_Z < 105 GeV
- p_T >100 GeV for both H & Z
- H & Z back to back: $\Delta\phi$ < 2.9
- CSV tag on both b-jets
- light jet rejection 0.1% (HE) & 1% (LE)

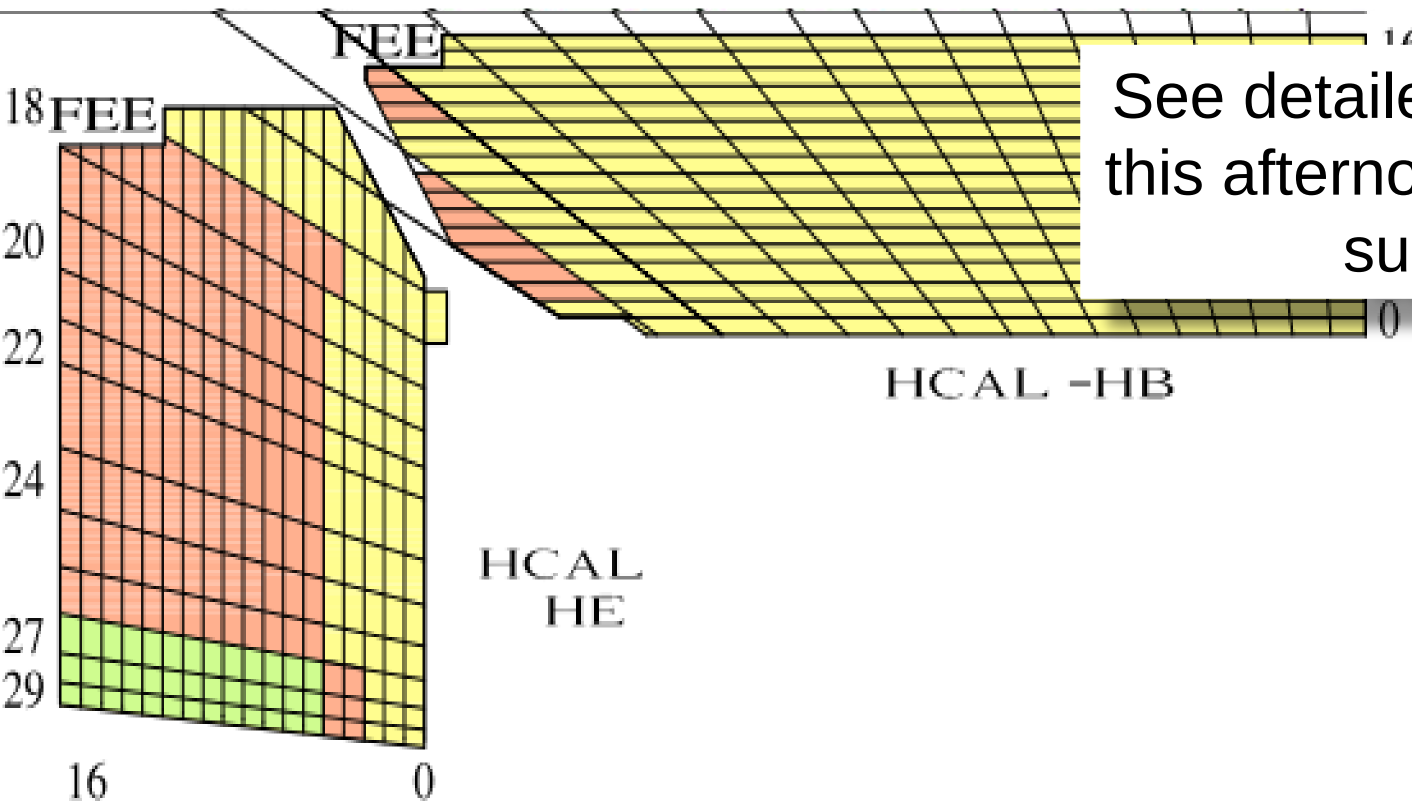


Both lepton channels ($\mu\mu$, ee) show gain of 65% in signal efficiency for upgraded system.

HLT Trigger with 3 out of 4 hits from upgraded pixel for muons may benefit significantly.

Upgrade pixel system will lead to considerable increased sensitivity in this channel.

LS1 to LS2: HCAl



See detailed presentation this afternoon: here only a summary

s
mentation
PU suppression,
igger)

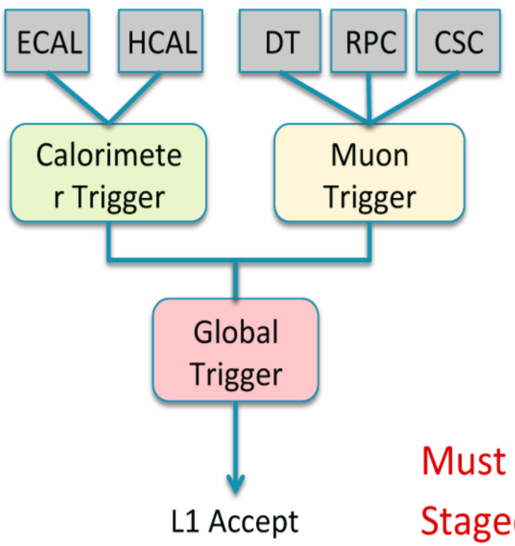
S2

Paramount to maintain efficient Particle flow approach in high pileup environment

L1 Trigger Upgrade

Goal of the L1 Trigger Upgrade

To maintain about the same physics acceptance (**Higgs** and Searches!) as we have today at higher luminosity, pile-up, and √s after LS1 and LS2?



Target improvements

- EG isolation with PU subtraction
- Jet finding with PU subtraction
- Tau finding with much narrower cone
- Muon p_T resolution in difficult regions
- Calo isolation of muons with PU subtraction
- Global trigger: bring the HLT functionality to L1

Must upgrade in parallel with current trigger system

Staged upgrade, each stage providing improvement

Implementation

- High bandwidth optical links for all I/O
- Large, modern FPGAs (Xilinx Virtex-7) and memory in standard boards
- Implement in industry standard μTCA architecture

Allows a more compact system with much more capability and flexibility

Longer term: LS3,HL-LHC

Si –trackers to be replaced: tracker in L1 trigger

Endcap calorimeters very likely to need replacement/upgrades (assessing longevity)

Muon chambers: the detectors themselves should still be ok. Issue will be trigger (and possibly readout)

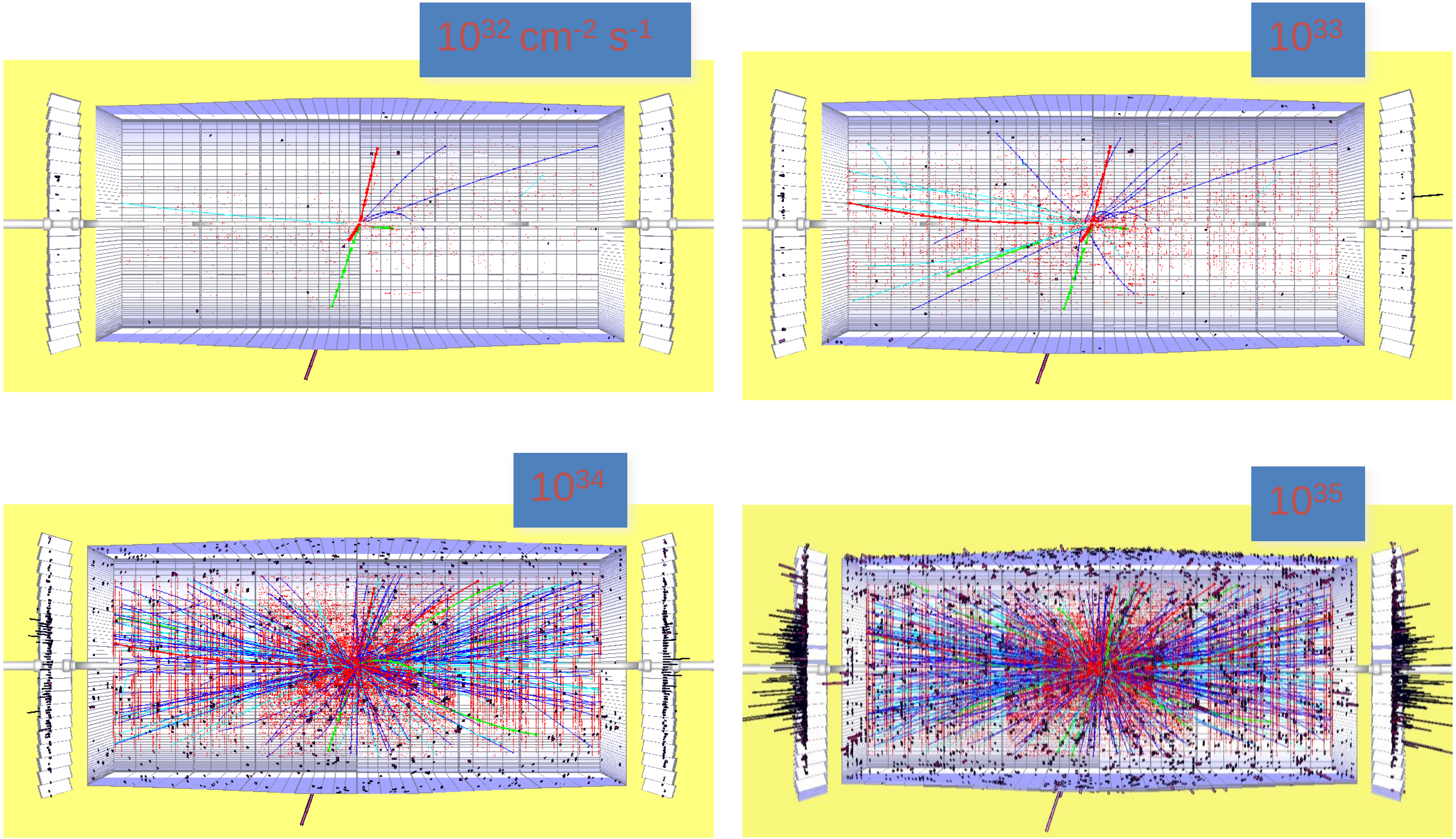
Physics needs & performance: being assessed

HL-LHC /LS3

- Need stepping up R&D and design effort in the next 2 years: if we want to be ready for installation in 2022 we need to have clear ideas (read TR-level) of what to build by end 2014.
- 0^{th} order: need a detector with the same performance as today: hence require replacement of components rad damaged
- But running at lumi of 5 10^{34} (pileup $\gtrsim$ 100) will require substantially improved detector

Challenges of HL HLC

- 5 10^{34} Hz/cm^2 luminosities challenges for CMS
  - Trigger: studying of having Tracker in L1 trigger to provide parameters of tracks with P_t >2 GeV (including estimate of vertex!) to correlate with other trigger info at first level
  - Exploring what would be needed to have 1 MHz L1 trigger (and longer L1 trigger decision latency)
  - Particle flow : will need high calorimetric granularity
  - In forward region will need to have ways to estimate vertex origin of physics objects (thinking about VBF like tagging) : looking into what VERY forward tracking and fast timing devices could do.



10^{32} cm^{-2} s^{-1}
10^{33}
10^{34}
10^{35}

Preview (special fill): what we learned

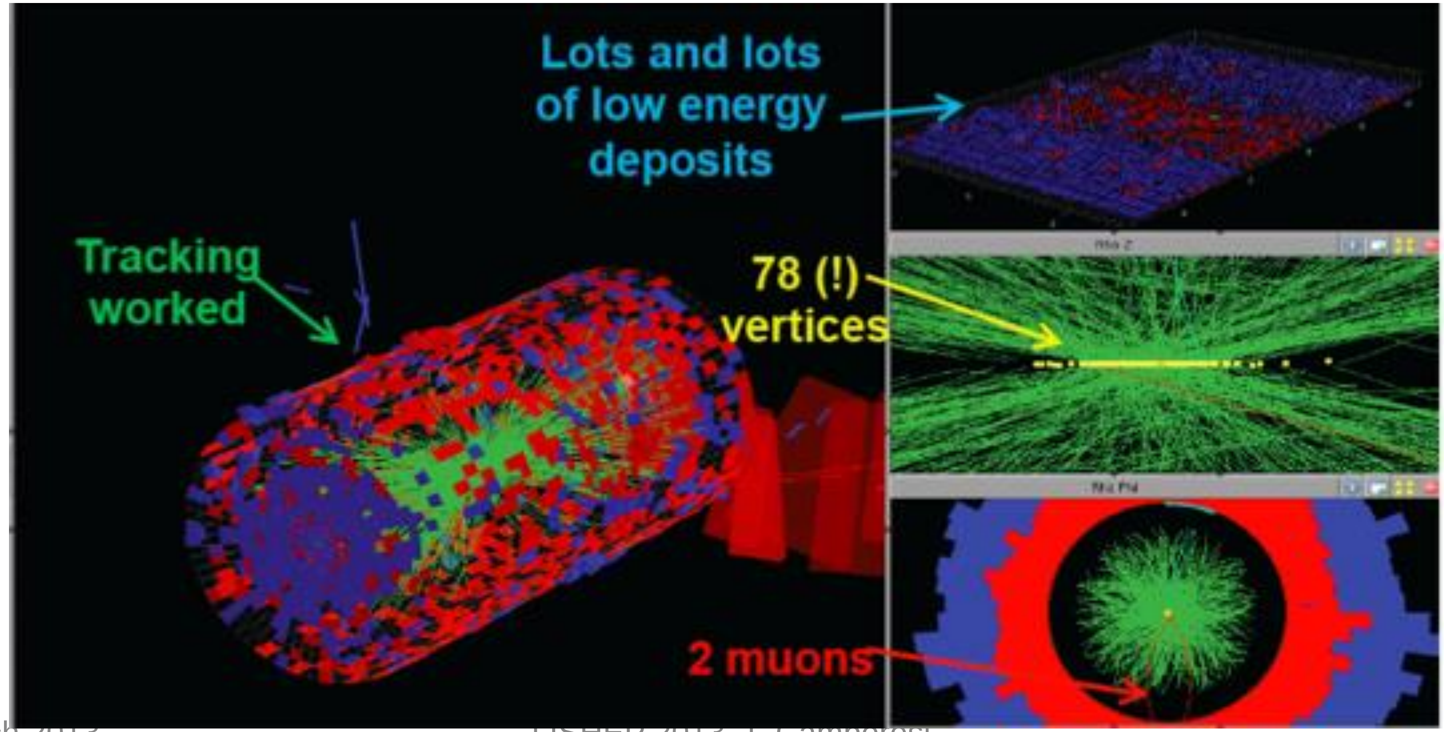
Reconstruction algorithms are such that one can assume that with

- a working detector (this implies major upgrades for LS3!)
- adequate granularity

one can cope with extreme conditions…

Heavy ion running an additional proof.

We know that today trigger systems will be inadequate.

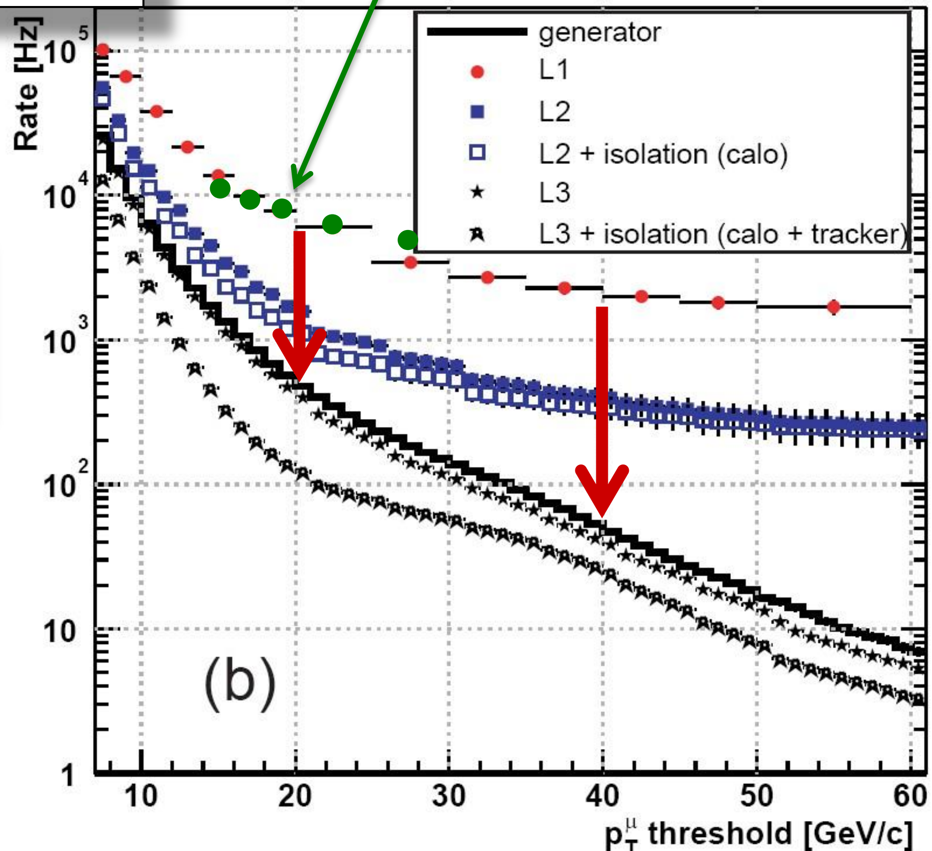


LS3: Tracker trigger

Tracker stubs to be correlated with Muon stubs: allows to reduce by factor muon trigger rate at the 'useful' P_t thresholds

Simulation confirmed by special fill at high lumi

Present trigger rates flattens out at $P_t \gtrsim 30$ GeV

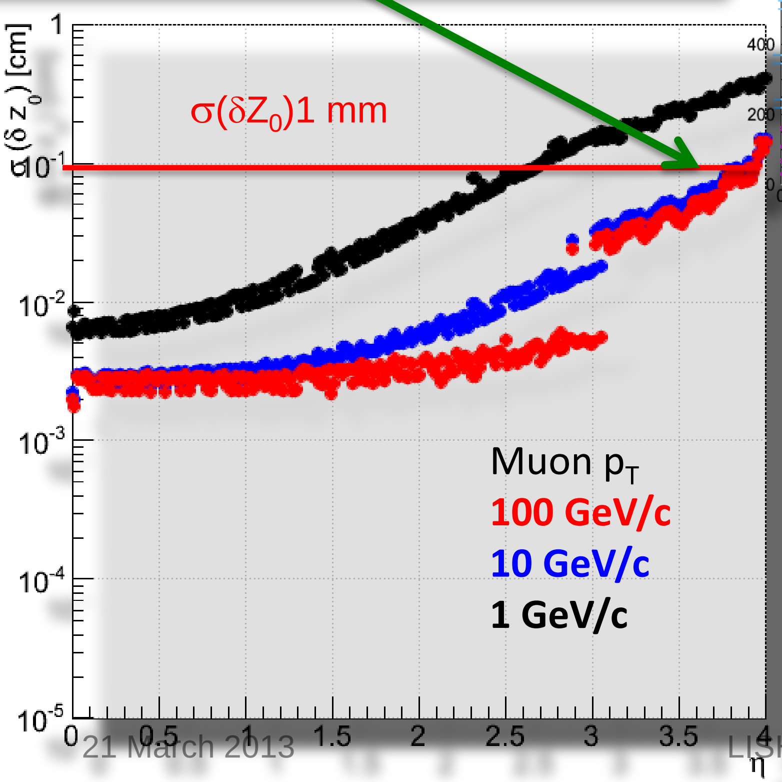


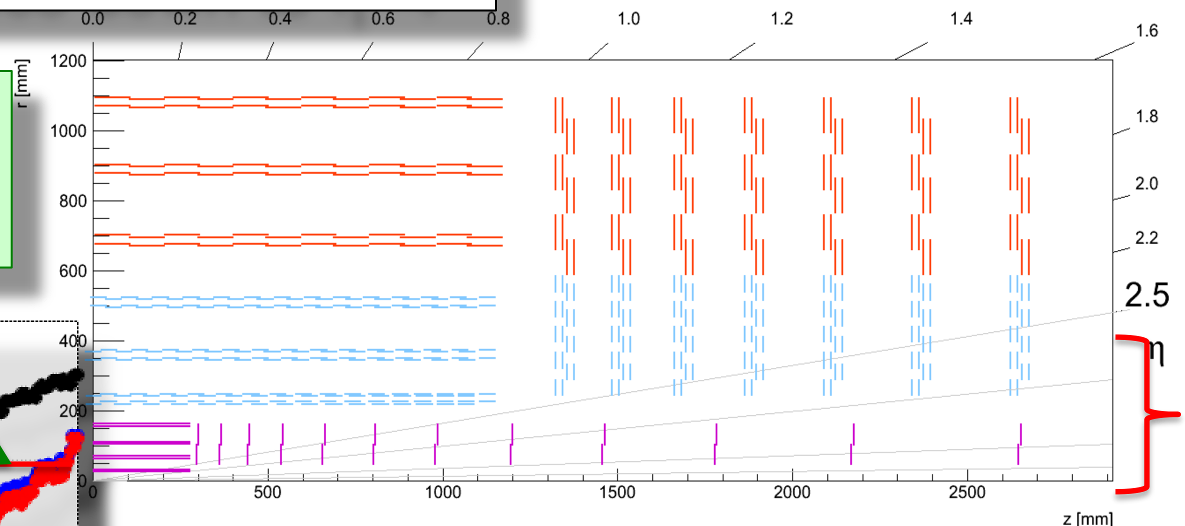
VERY forward tracking (CMS study)

Good resolution in Z_0 reco down to $\eta=4$

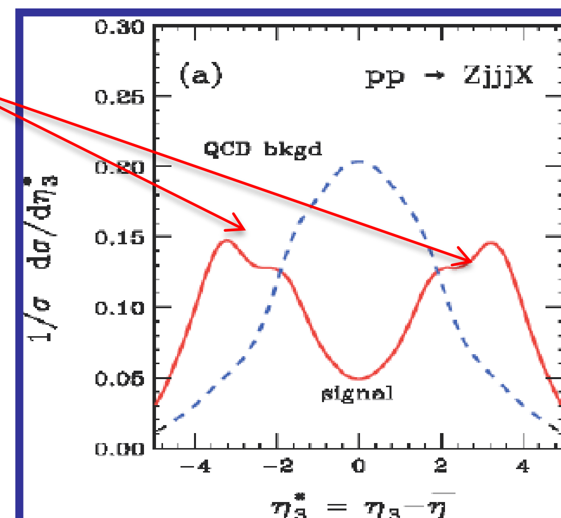
Courtesy of S. Mersi

- Resolution < 1mm
  for p_T>10 GeV/c down to η=4

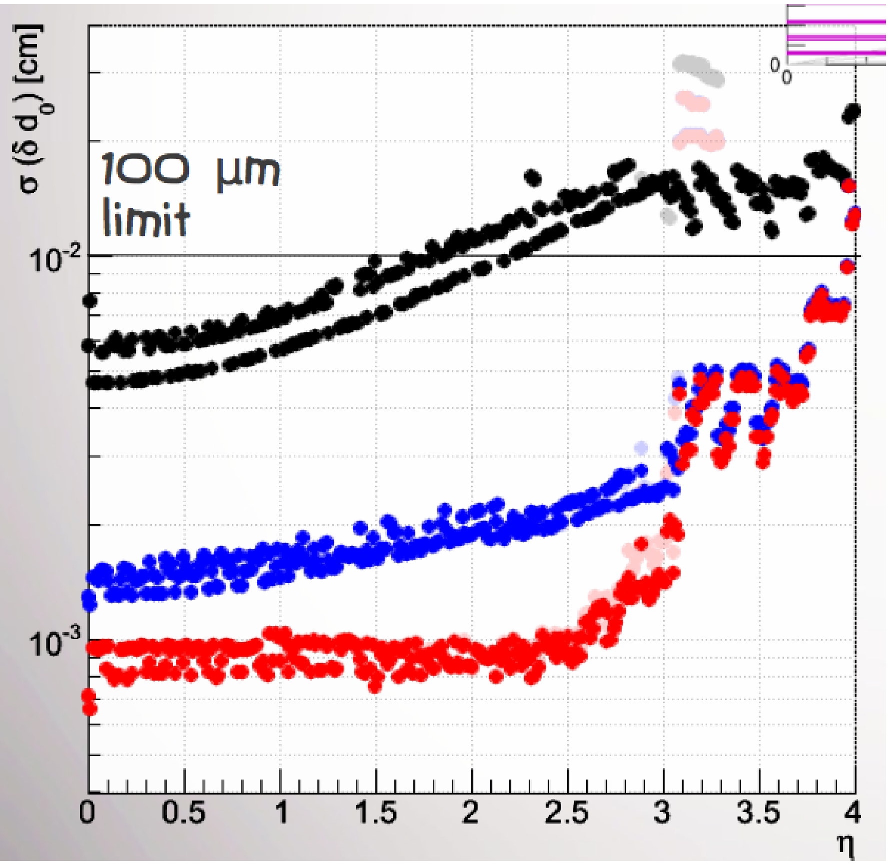


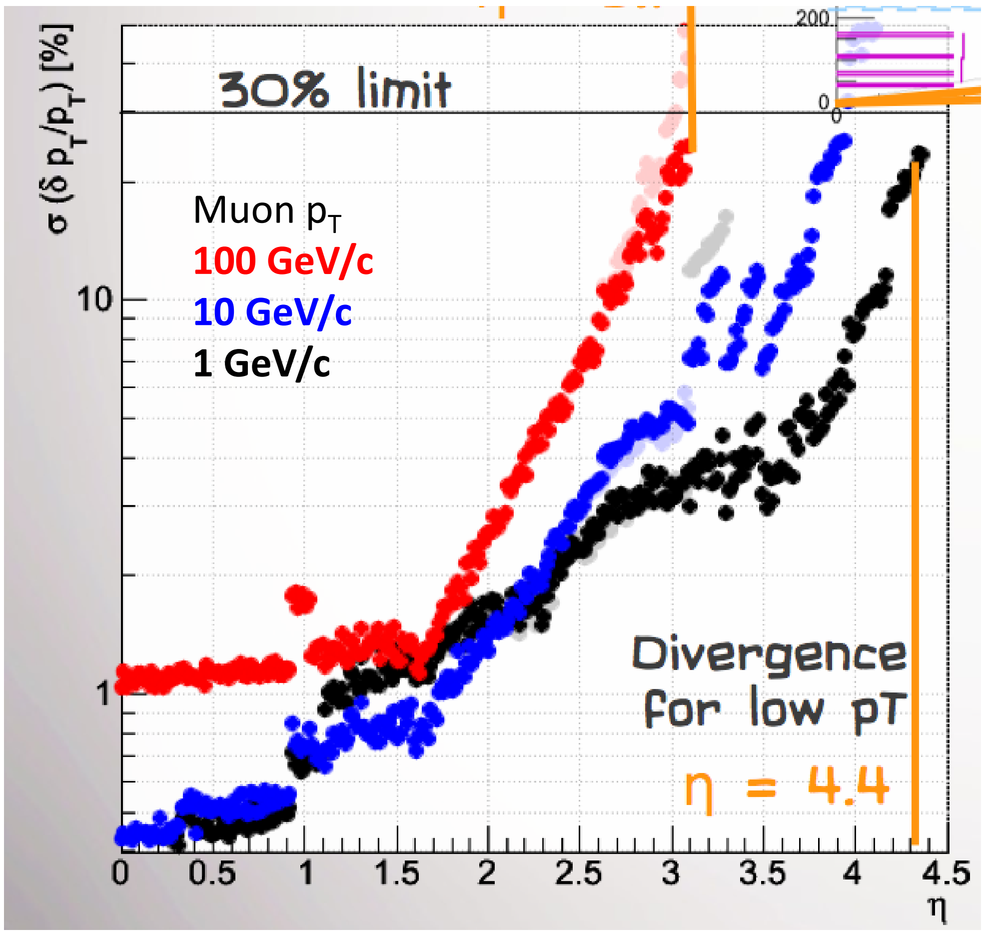


Beneficial to VBF tagging as it provides coverage for Barrel/Endcap service cracks



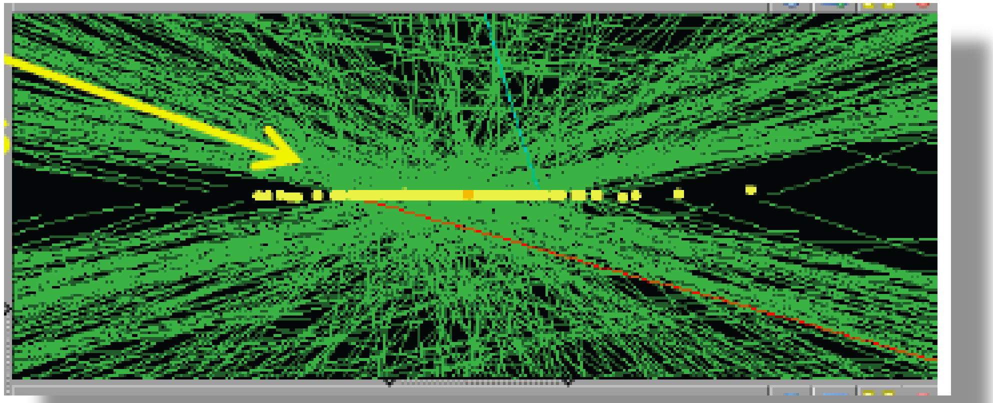
D0 and P_t resol VFPIXEL





Fast timing: needs

- For a luminous region distributed over ~ 10cm, collisions will be distributed over ~ 300ps



- The TOF at the Calorimeter at η ~ 0 depends on the time of the specific collision
- At Larger values of η the TOF depends both on the time and position of the specific collision

A dream for the moment

- Consider (for example) an EM pre-shower with 10~20ps (i.e few mm resolution in Z position) TOF resolution for MIP's and γ
  - Tracking identifies Z location of interesting collision (high Pt)
  - Preshower could deliver (TOF, η, ϕ) of cluster (can be a EM shower or cluster of jet particles) from that collision
  - Could imagine to correlate at trigger level Preshower(TOF, η, ϕ), Calorimeter(E,η, ϕ) and Tracking (P_t, Z vtx) info
  - At analysis level use Z location and time to select calorimeter clusters associated to interesting collision
- Could result in similar effective pile-up conditions comparable to what we are handling today
  - ! ! Neutral hadrons will need special attention ! !

An issue

- At the time of LS2 the detector will have components (e.g. forward calorimeters) whose manipulation might be rendered very difficult by the radiation problems.
- This and the space constraints in the experimental hall can become a significant constraint of what can be done…and extensive study need to be done and possibly non trivial tooling developed.
  E.g. HF calorimeter (300 tons object) on the + side of the experiment cannot be moved as a single piece (crane can handle 80 tons at most) … and its wedges will be radioactive to a level that dismantling into manageable units might be a real challenge

Summary

- CMS has been successful in exploiting the first LHC run and has a clear plan to maintain its excellent performance after LS1
- A new era where commissioning of new components will happen in parallel to LHC operation will start after LS1
- The experience from the past shows that we must have a clear idea of the CMS phase 2 detector within 2014, if we want to have it ready by LS3
- In some areas (e.g. calorimeters able to withstand a factor 10 of radiation compared to the first LHC phase, tracker/triggering, Very forward tracking…) vigorous R&D is necessary
- The potential of High Luminosity LHC will be exploited only if we start preparing for it NOW

Backup

Fast timing: state of the art

- Current state of the art for large scale systems is ~75ps: ALICE TOF
- Fast RPCs (small prototypes) : 60 ps
- Current State of the Art is 100~120ps for demonstrator TOF PET Calorimeter detectors
- The goal of 10~20ps Calorimeter TOF resolution is beyond the current state of the art, and clearly ambitious
- But so were many of today's features of LHC detectors 10 years before beams….
- Need to engage stakeholders : CERN, HEP laboratories, Universities into a focused R&D effort… and practical re-use of technology immediately obvious: PET scan.

Muon hit rates – simulated, endcap

- Curves w/wo neutron hits
  - Slow n capture
    → N*
      → de-excitation γ
        → electrons

- Highest rate/area in ME1/1
  - Up to 10 kHz/cm^2 at 1E35

- High total rates in ME4/2
  - Large area

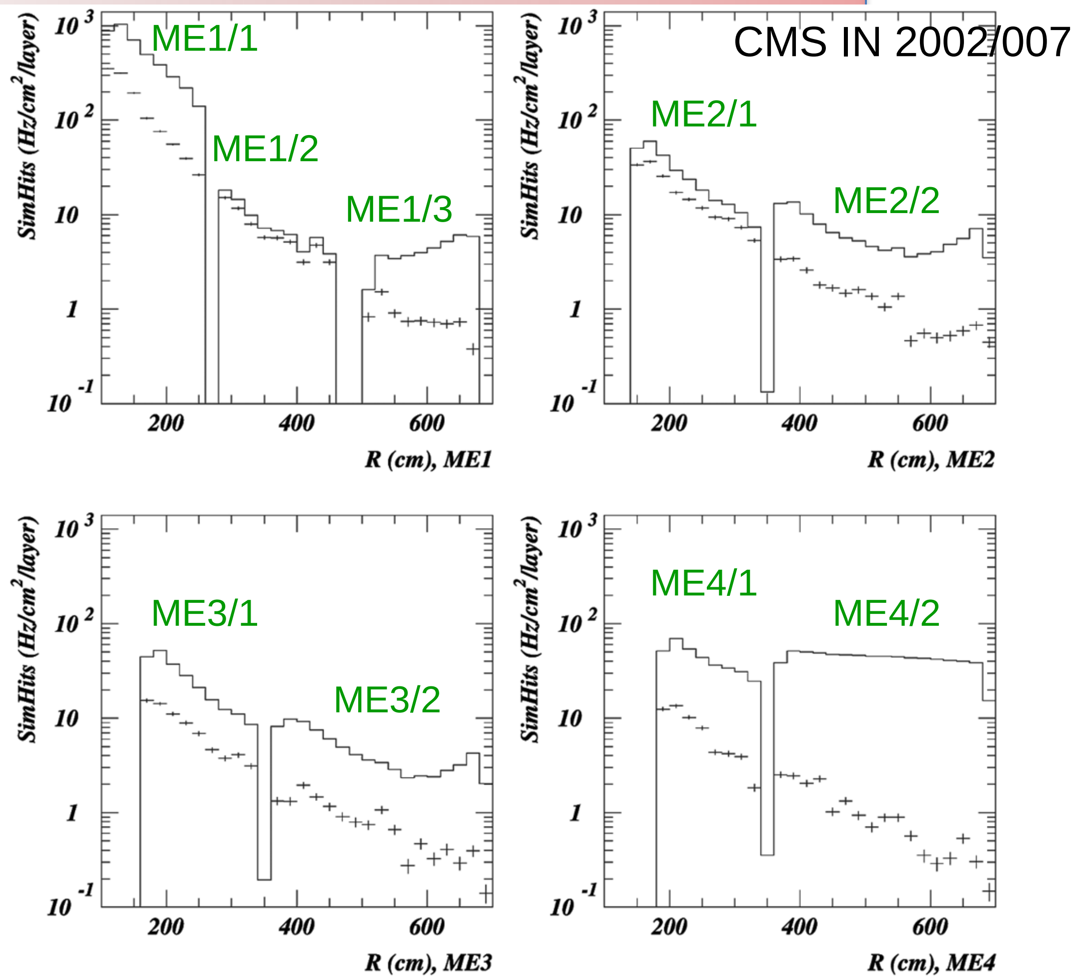


Figure 7: The simulated rates of SimHits (given in Hz/cm^2/layer) in each CSC station, as a function of the radial distance from the beam line. The solid histogram represents the cumulative rate of hits from cutoff pp interactions and low-energy neutrons; points with error bars show the rate of hits from minimum bias pp collisions without the low-energy neutrons (the errors are statistical).

HPD gain drifts

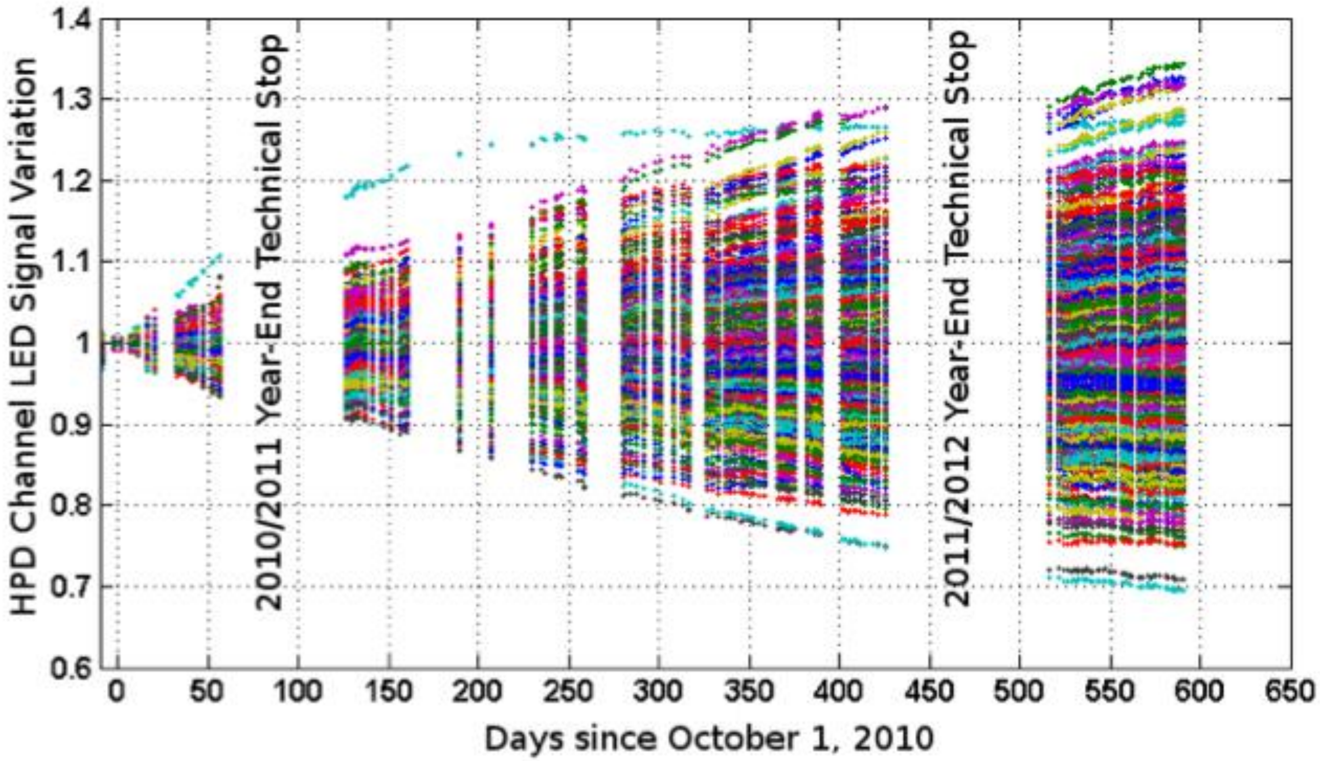


Figure 1.3: Divergence of the gains of individual HPD channels in the CMS HB and HE calorimeters (5184 channels) over a period of approximately two years as measured using the LED monitoring system. Detailed studies have indicated that these changes are consistent with photocathode migration in the HPD devices.

HCAL doses after 500 fb-1

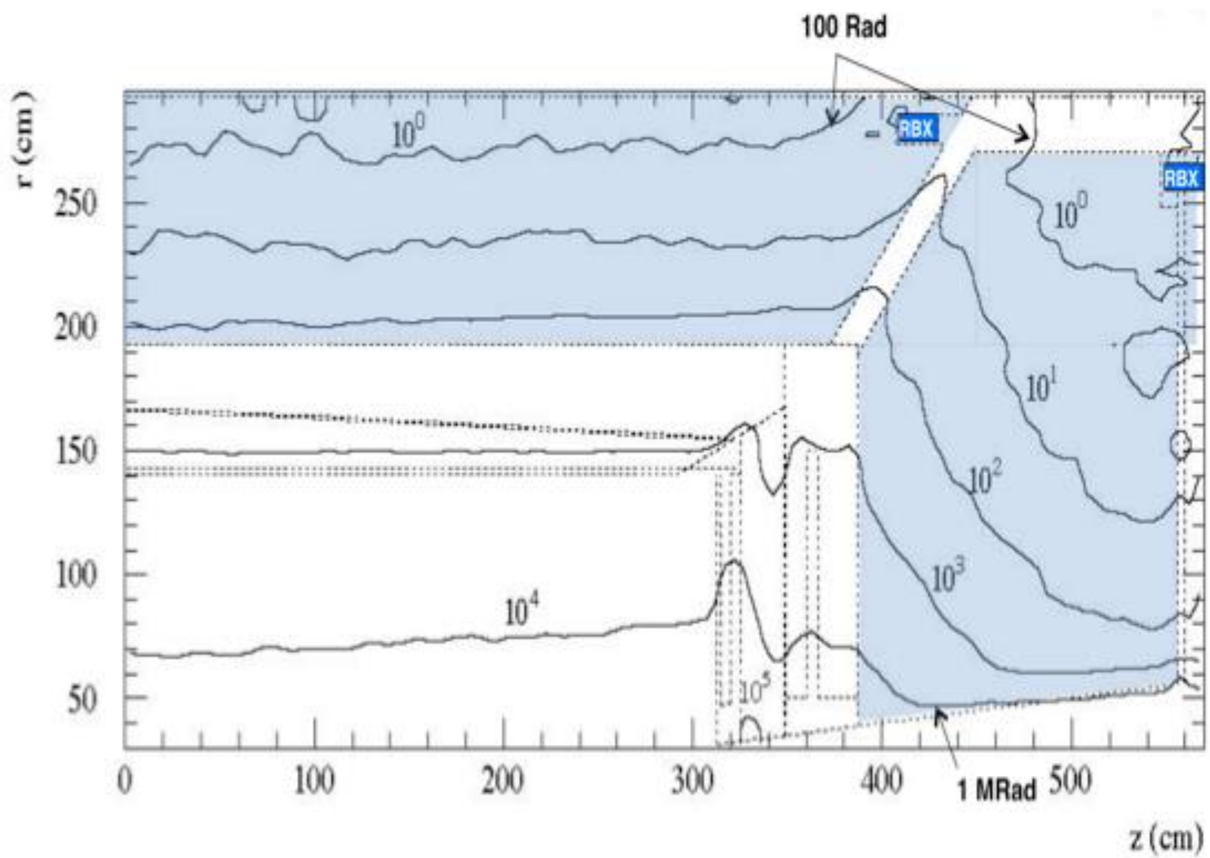


Figure 2.1: Radiation level contours in the HB/HE regions from FLUKA calculations after 500 fb^{-1} (in units of Gray).

Depth segmentation

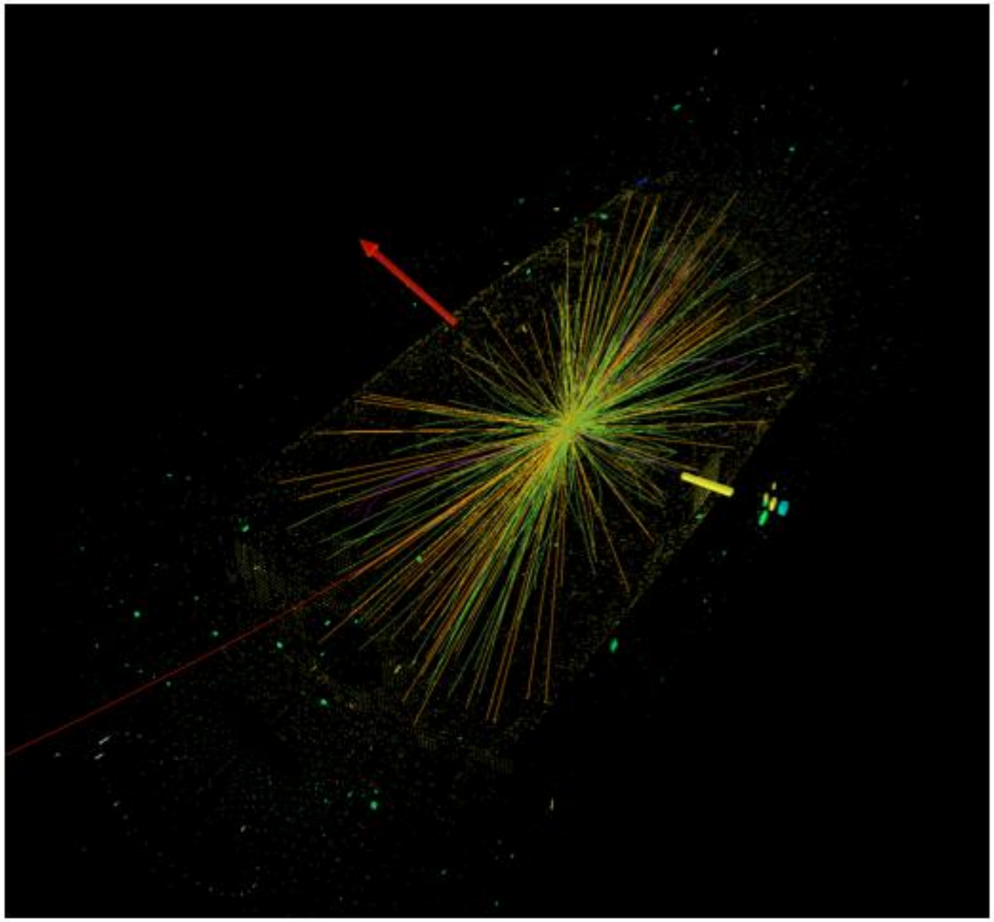


Figure 2.3: Event display of a single 100 GeV pion simulation in the environment of 50 pile-up events per 25ns bunch crossing showing the multi-depth energy deposition pattern in the barrel hadron calorimeter directly behind the energy cluster in the electromagnetic calorimeter.

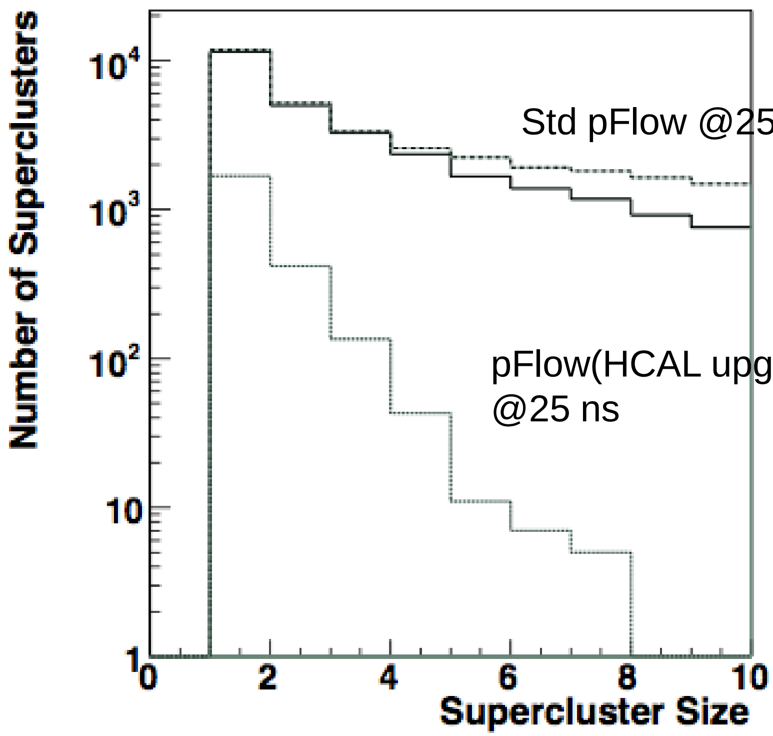
P flow with HCAl upgrade

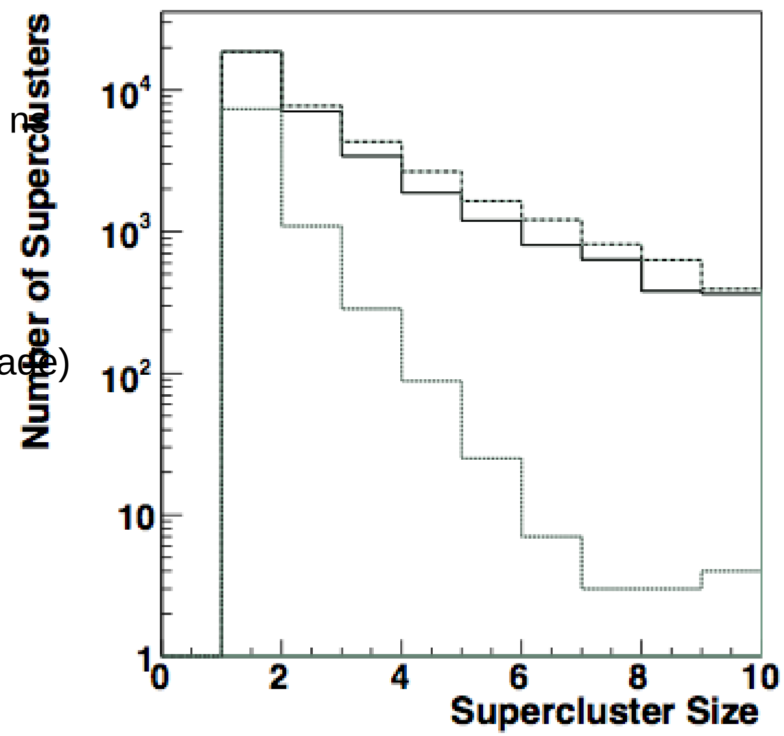
<Pileup>= 50

Barrel

Endcap

Std pFlow @50 ns

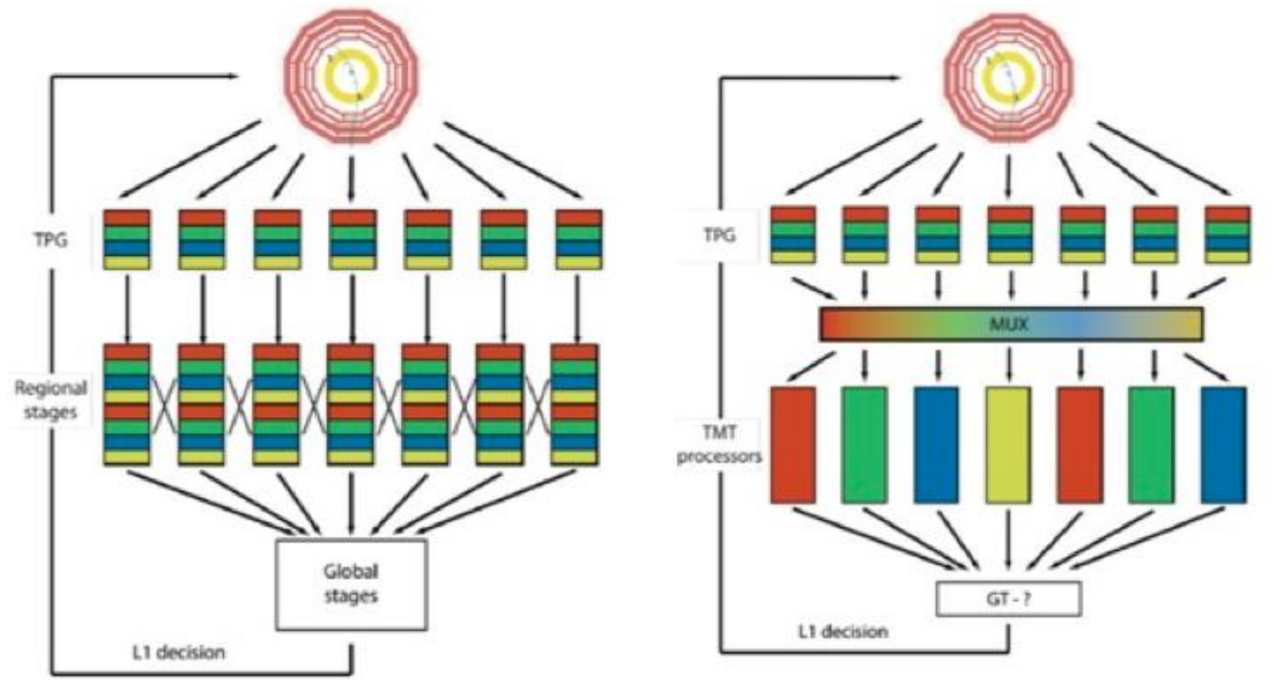




Pixel Parameters: Present & Upgrade

Parameter of Pixel System	***Present***	***Upgrade***
# layers (tracking points)	3	**4**
beam pipe radius (outer)	29.8 mm	22.5 mm (LS1)
innermost layer radius	44 mm	29.5 mm
outermost layer radius	102 mm	160 mm
pixel size (r-phi x z)	100μ x 150μ	100μ x 150μ
In-time pixel threshold	3400 e	1800 e
pixel resolution (r-phi x z)	13μ x 25μ	13μ x 25μ (or better)
cooling	C_6F_{14} (monophase)	CO_2 (biphase)
material budget X/X_0 (η=0)	6%	5.5%
material budget X/X_0 (η=1.6)	40%	20%
pixel data readout speed	40MHz (analog coded)	400Mb/sec (digital)
1^{st} layer module link rate (100%)	13 M pixel/sec	52 M pixel/sec
ROC pixel rate cabability	~120 MHz/cm^2	~580 MHz/cm^2
control & ROC programming	TTC & 40MHz I^2C	TTC & 40MHz I^2C

Calorimeter trigger upgrade



- two alternative architectures being proposed
- parallel triggering systems vs. time-multiplexed trigger
- similar hardware, different connections

Muon trigger upgrade

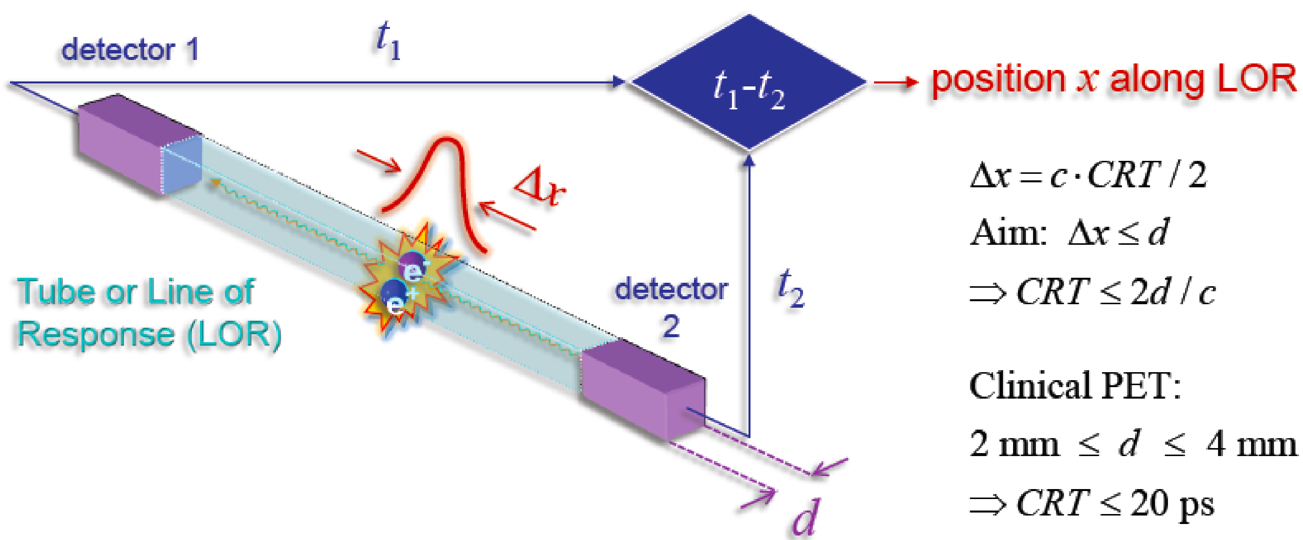
- Cathode Strip Chambers (CSC) trigger
  - outermost chambers to be added in 2013-2014
  - improve p_T resolution and thus reduce rate
  - increasing rate of trigger primitives
  - current design ($\Delta\varphi$ comparisons) does not scale well
  - switch to pattern matching system to accommodate higher occupancy
- Drift Tube (DT) trigger
  - move front-end electronics ("sector collectors") from experimental cavern to electronics cavern (2013)
  - all trigger electronics close to Global Trigger, always accessible in radiation-safe area
  - later: performance upgrade (higher resolution)

Fast timing practical interest

The holy grail: “10-picosecond PET”

With a CRT less than ~20 ps events an be localized directly:

- image reconstruction no longer necessary!
- only attenuation correction
- real-time image formation



$\Delta x = c \cdot CRT / 2$

Aim: $\Delta x \leq d$

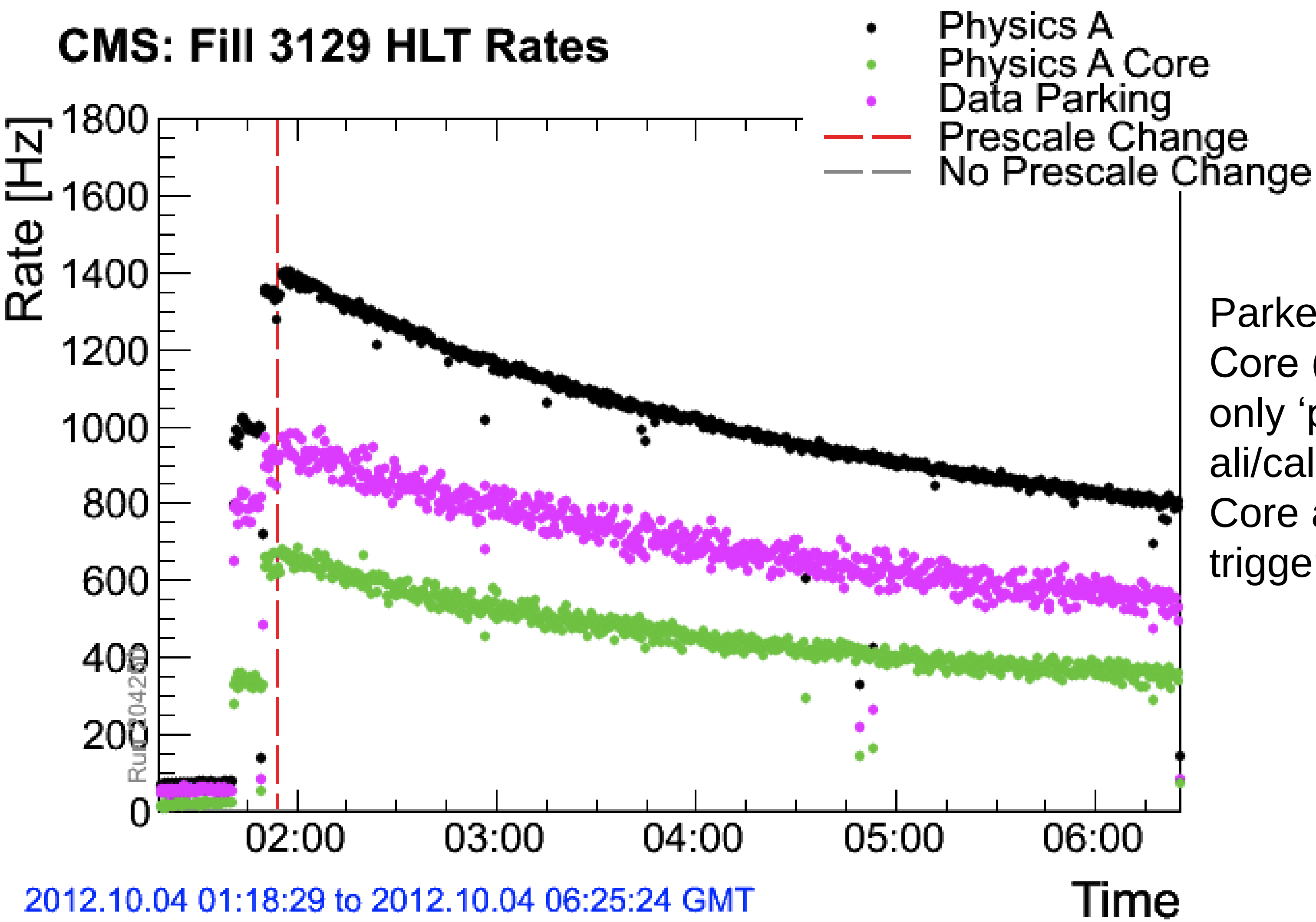
$\Rightarrow CRT \leq 2d / c$

Clinical PET:

2 mm $\leq d \leq$ 4 mm

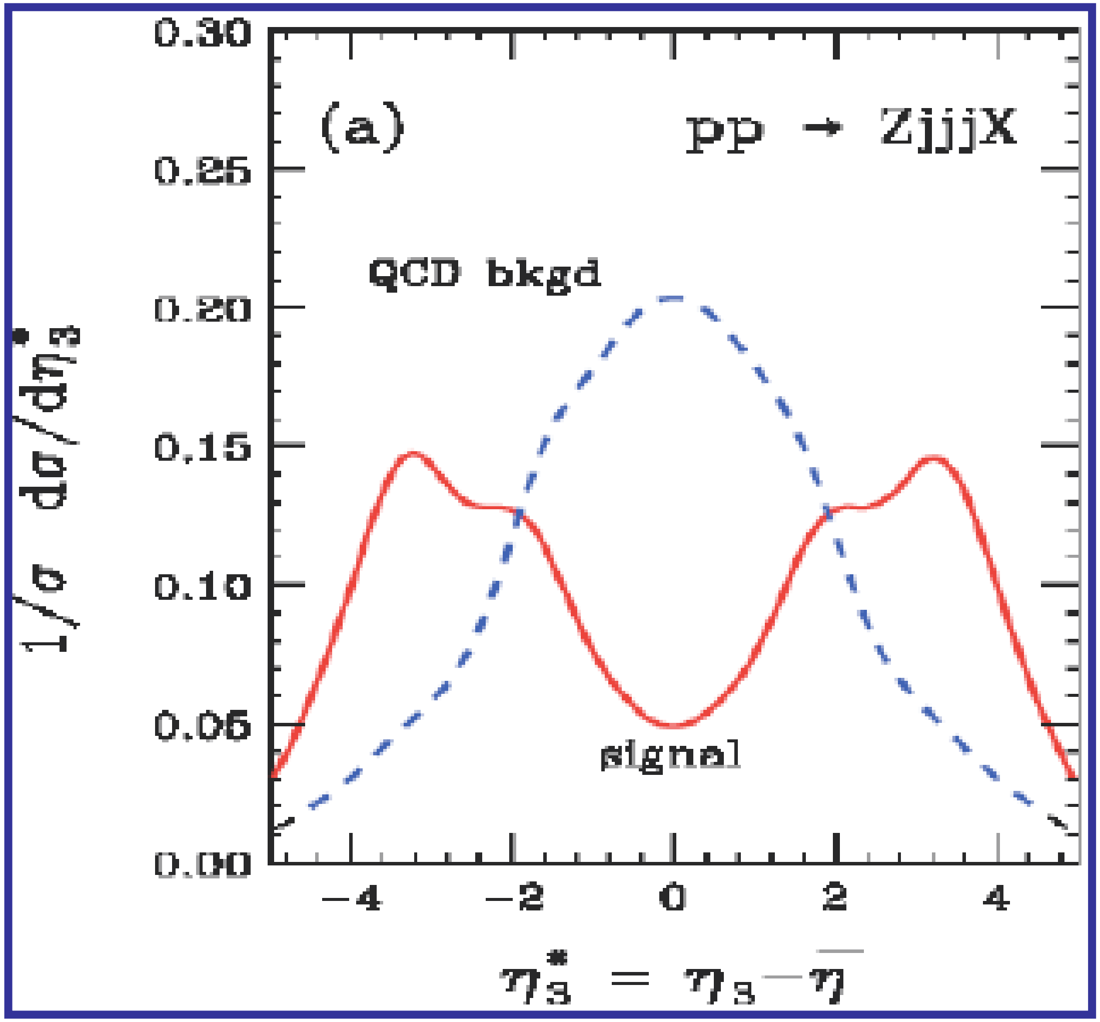
$\Rightarrow CRT \leq$ 20 ps

Data parking: a + for next year

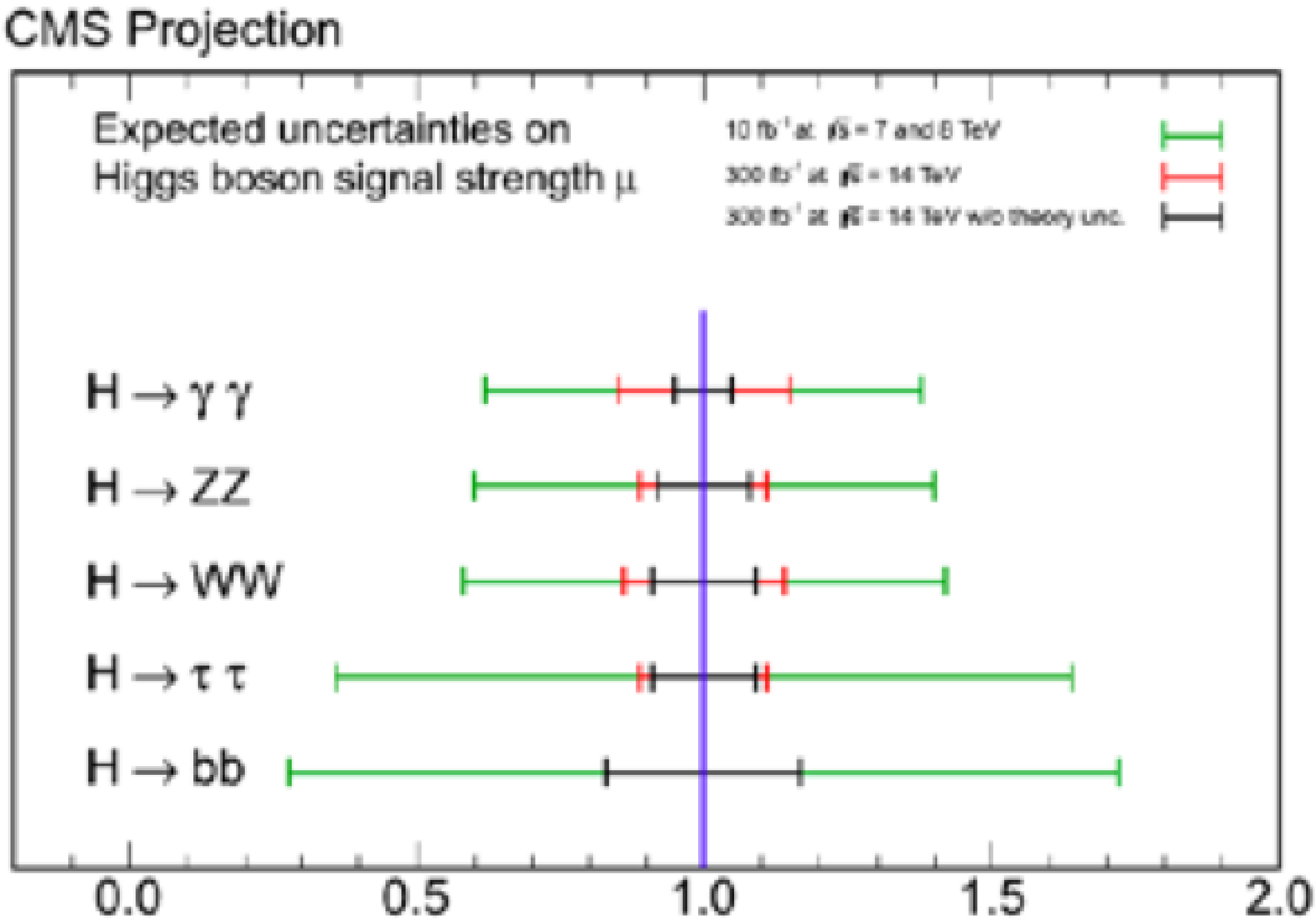


Parked data includes Core (will 'reprocess' only 'parked' with final ali/calib): i.e. 75% is Core and 25% new triggers

VBF tags


(a)
pp → ZjjjX
QCD bkgd
signal
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−4
−2
0
2
4
1/σ dσ/dη*₃
η*₃ = η₃ − η̄

Higgs couplings



Material budget VFWD pixel