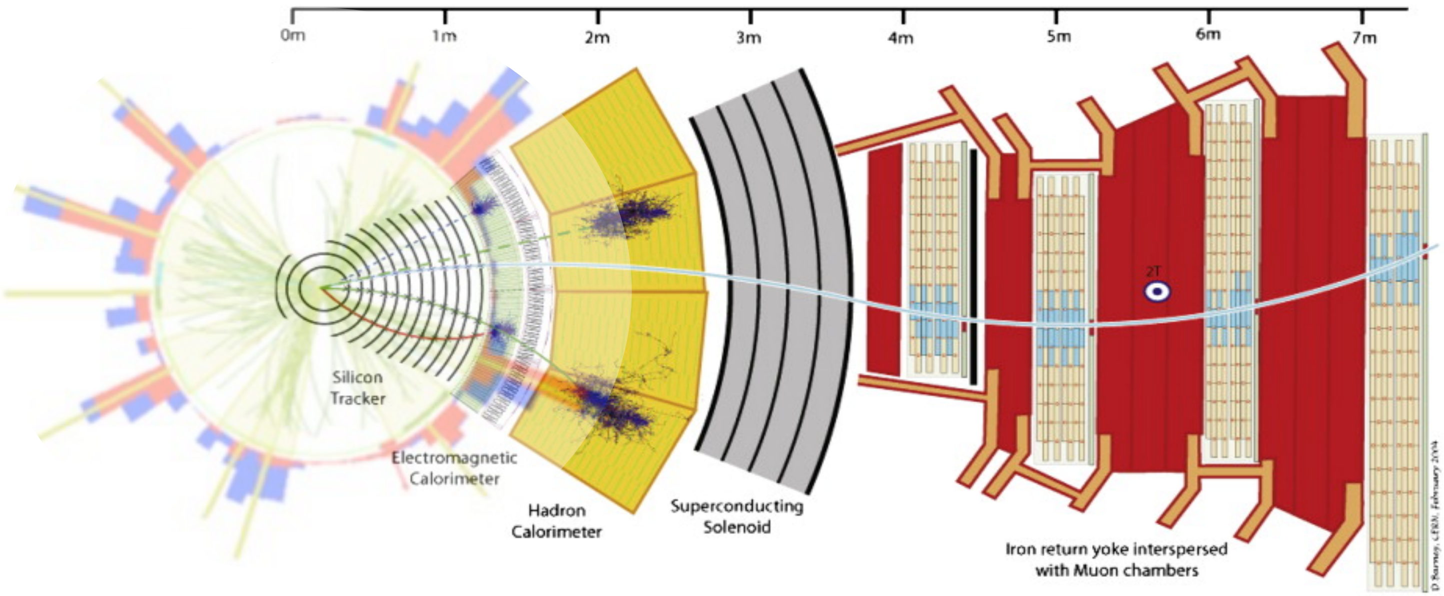
# CMS Upgrades Phase 1 & 2




CHIPP Meeting

Ben Kilminster
University of Zürich
on behalf of CMS Switzerland

Universität Zürich[UZH]

ETH Institute for Particle Physics

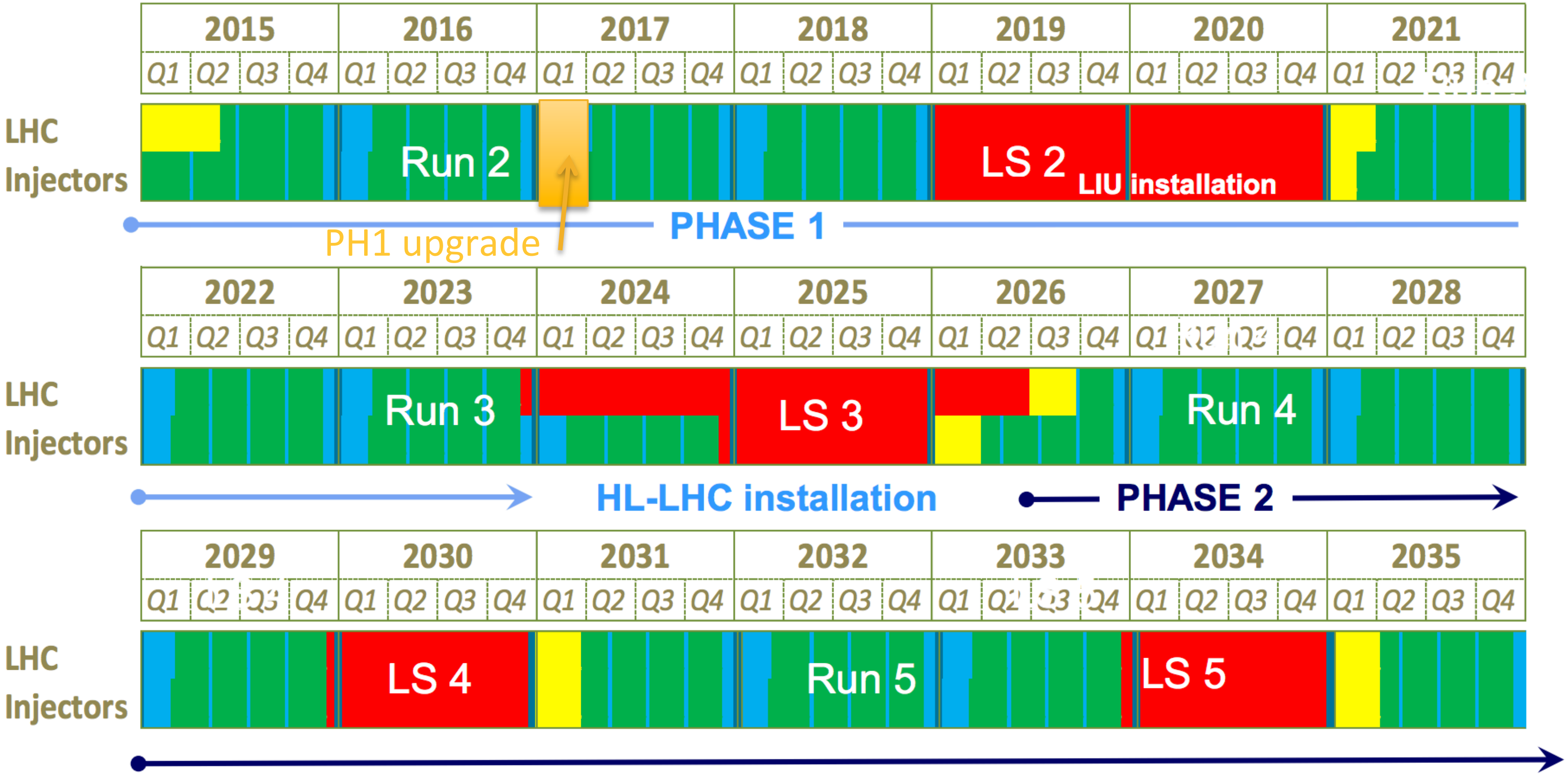
PAUL SCHERRER INSTITUT PSI

29 June 2015

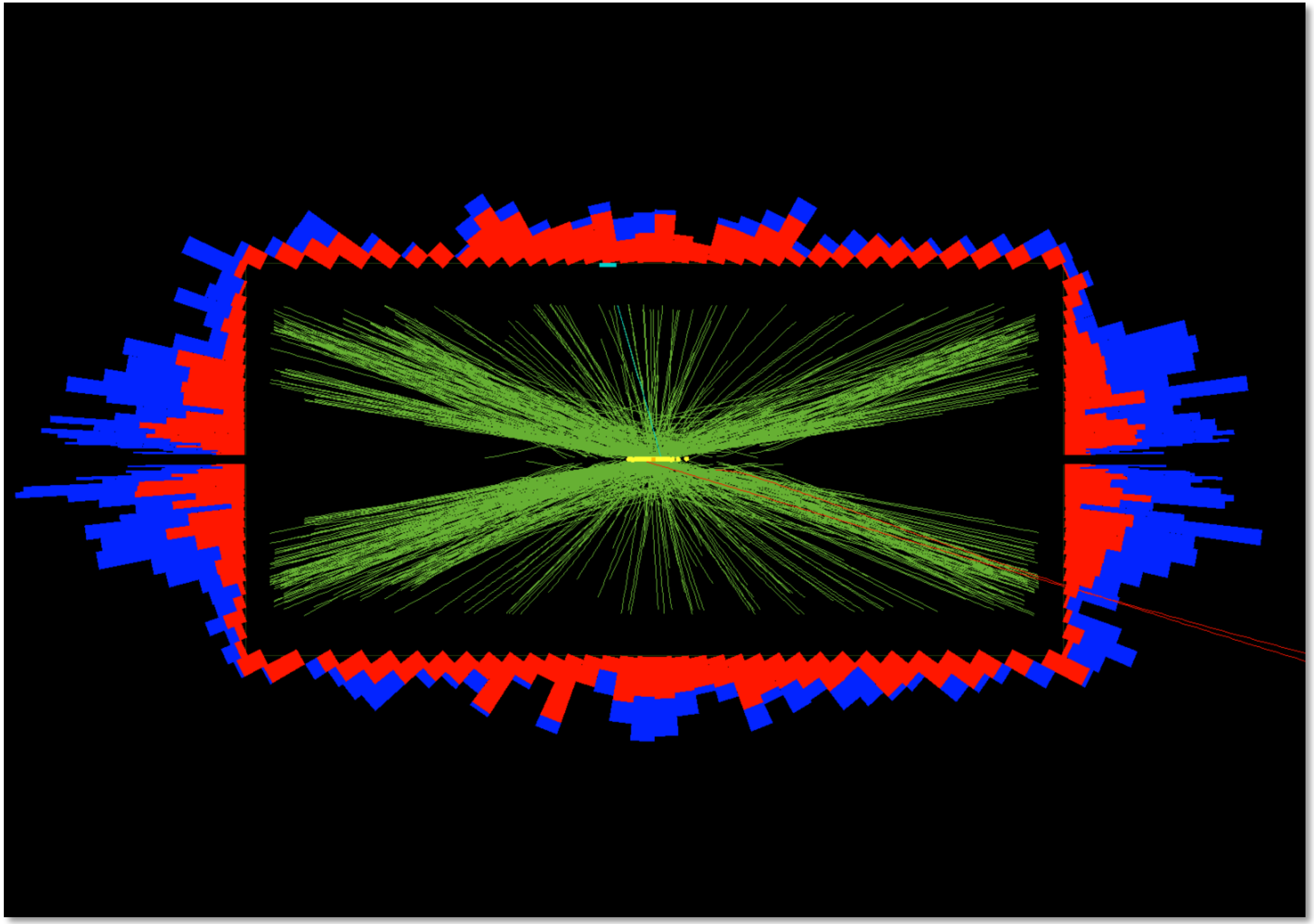
# LHC roadmap: according to MTP 2016-2020

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC

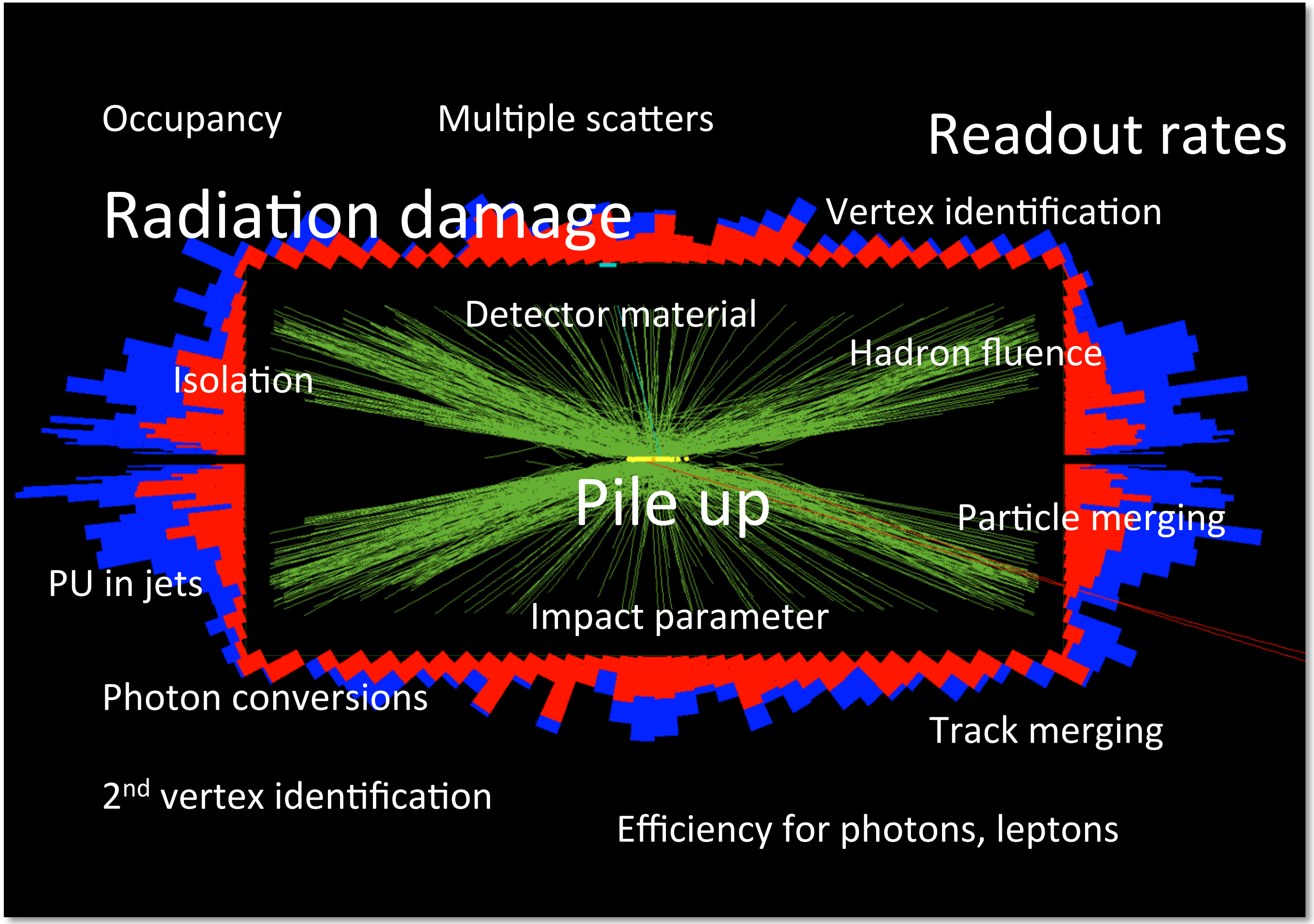
- Physics
- Shutdown
- Beam commissioning
- Technical stop



# Upgrades summed up in one picture

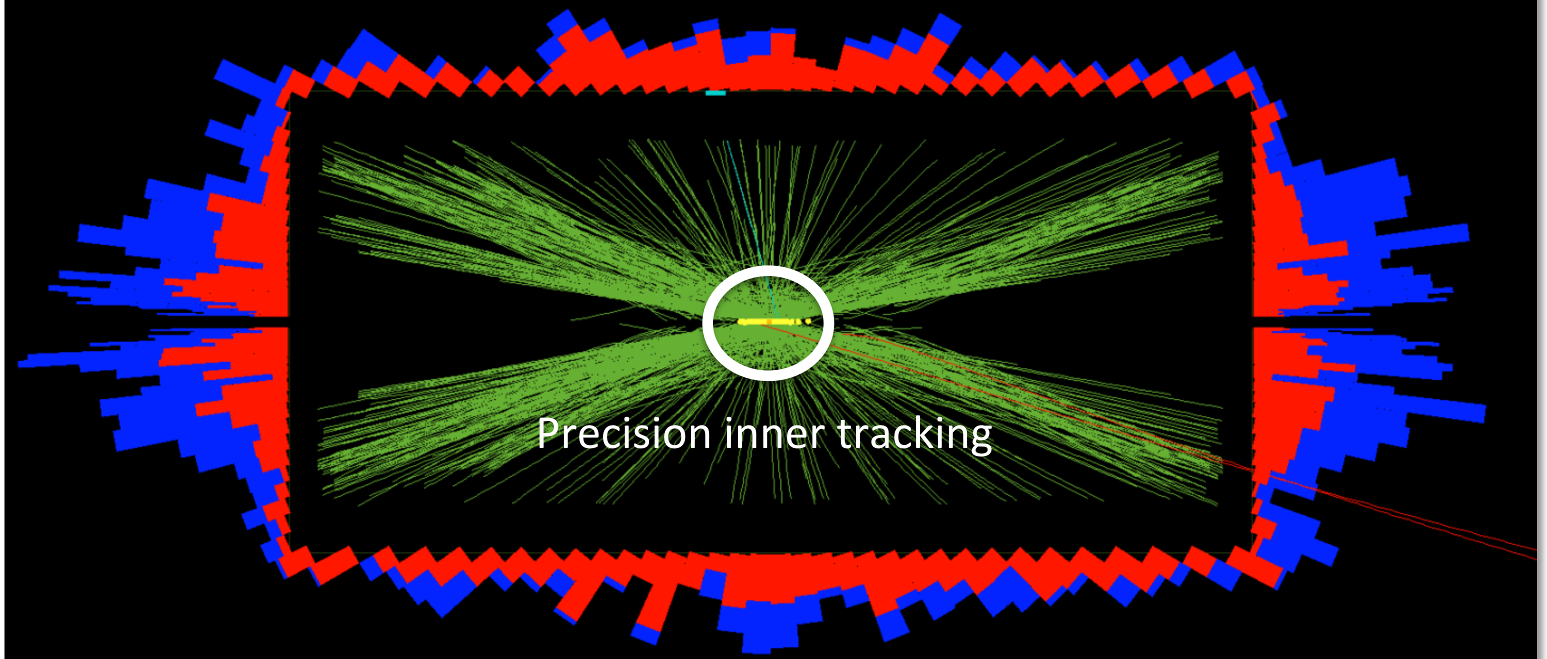


# Challenges


Occupancy
Multiple scatters
Readout rates
Radiation damage
Vertex identification
Detector material
Hadron fluence
Isolation
Pile up
Particle merging
PU in jets
Impact parameter
Photon conversions
Track merging
2nd vertex identification
Efficiency for photons, leptons

# Swiss focus phase 1

Upgrade efforts focused on high-occupancy interior of detector

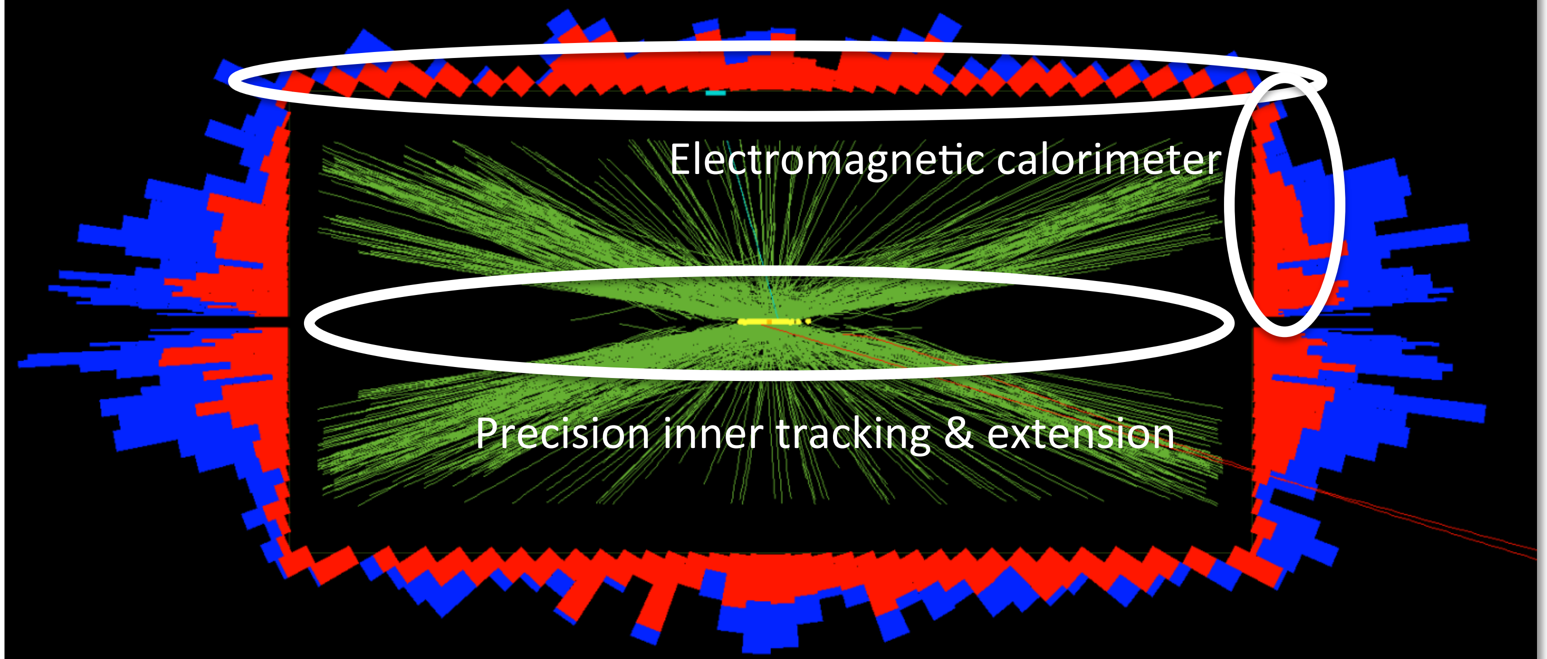



Especially important for vertex finding, H➞bb,
Pile-Up track removal

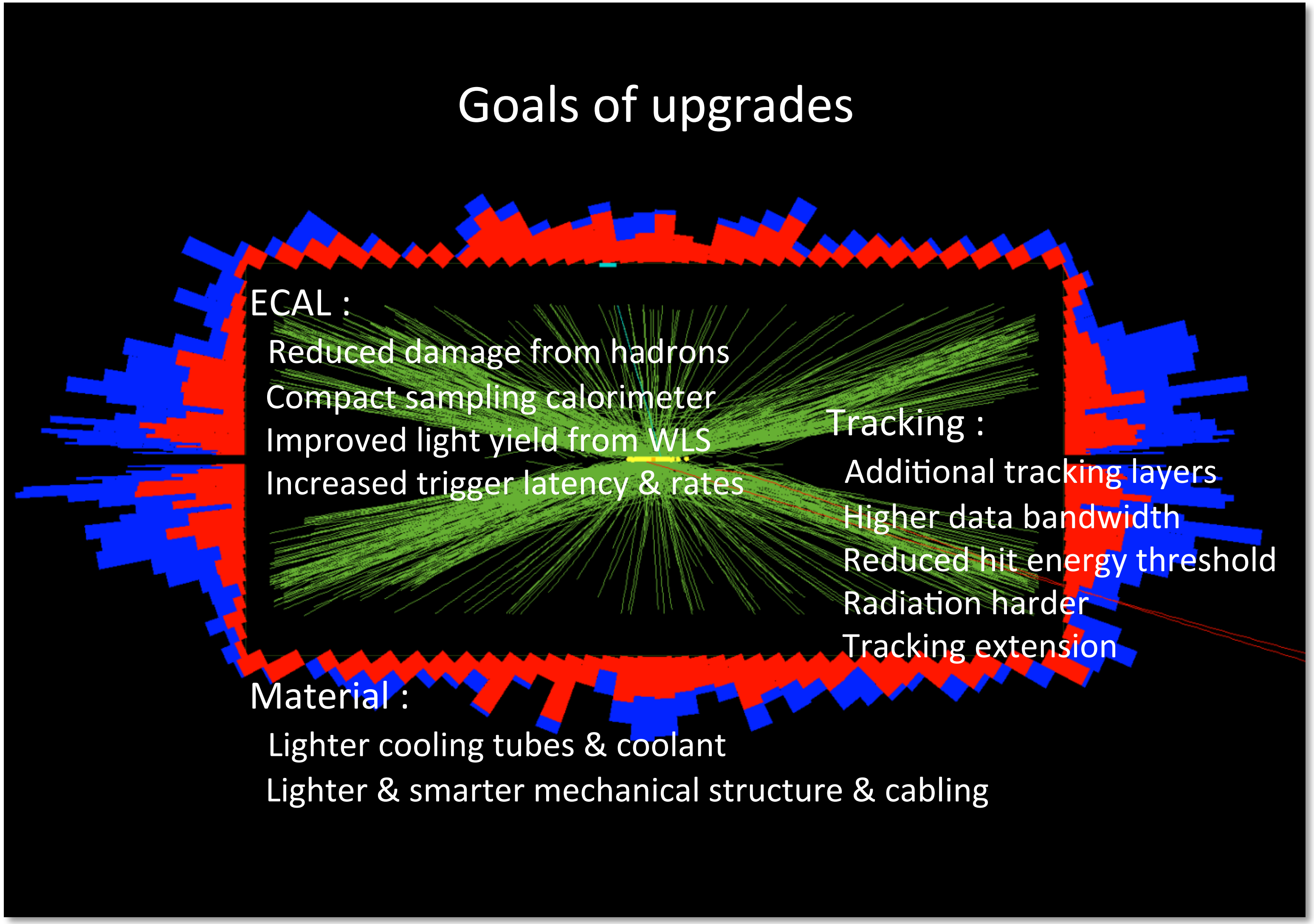
# Swiss focus phase 2

Upgrade efforts focused on high-occupancy interior of detector

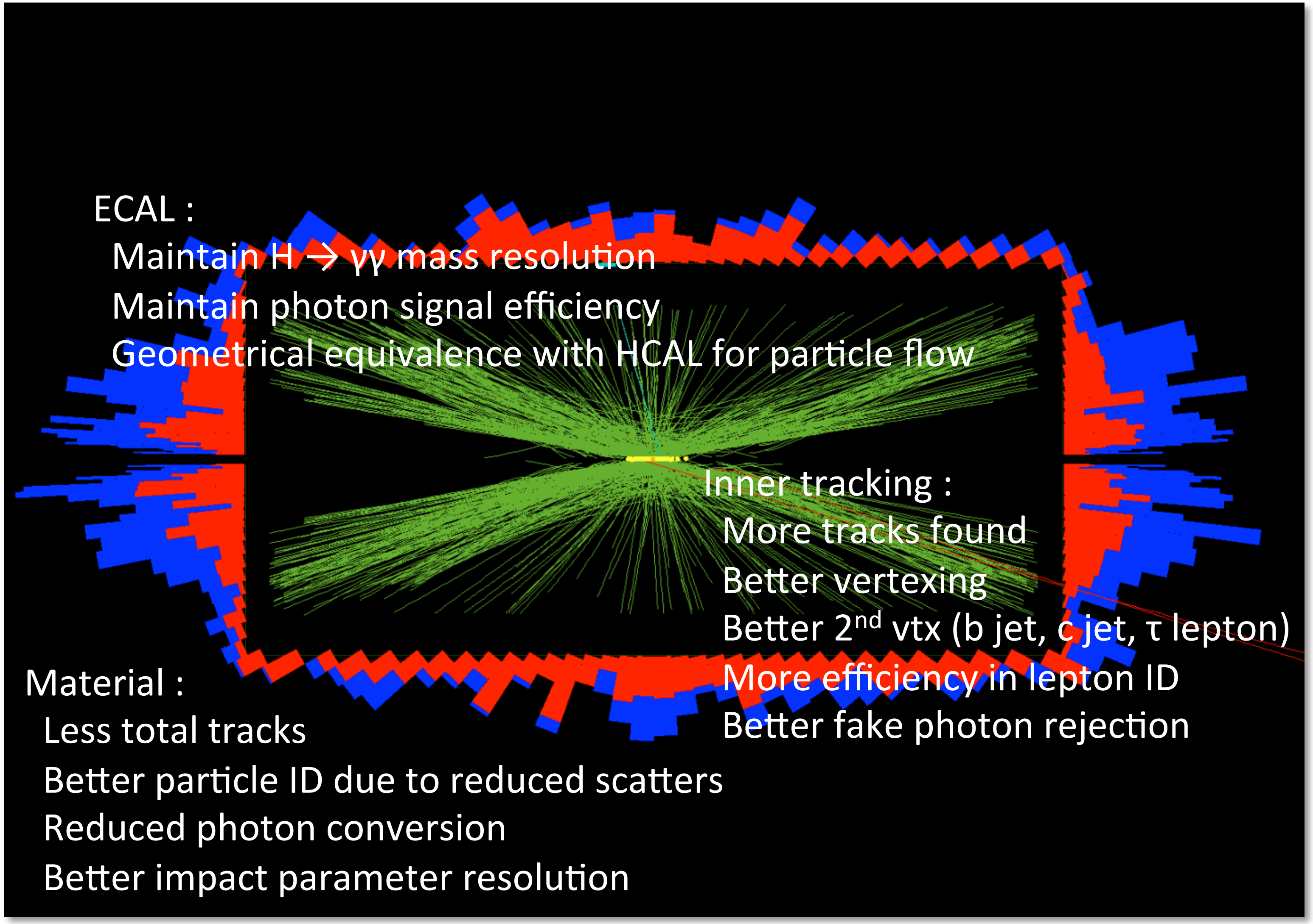
Physics especially important for H→γγ, H→bb, VecBosFus H



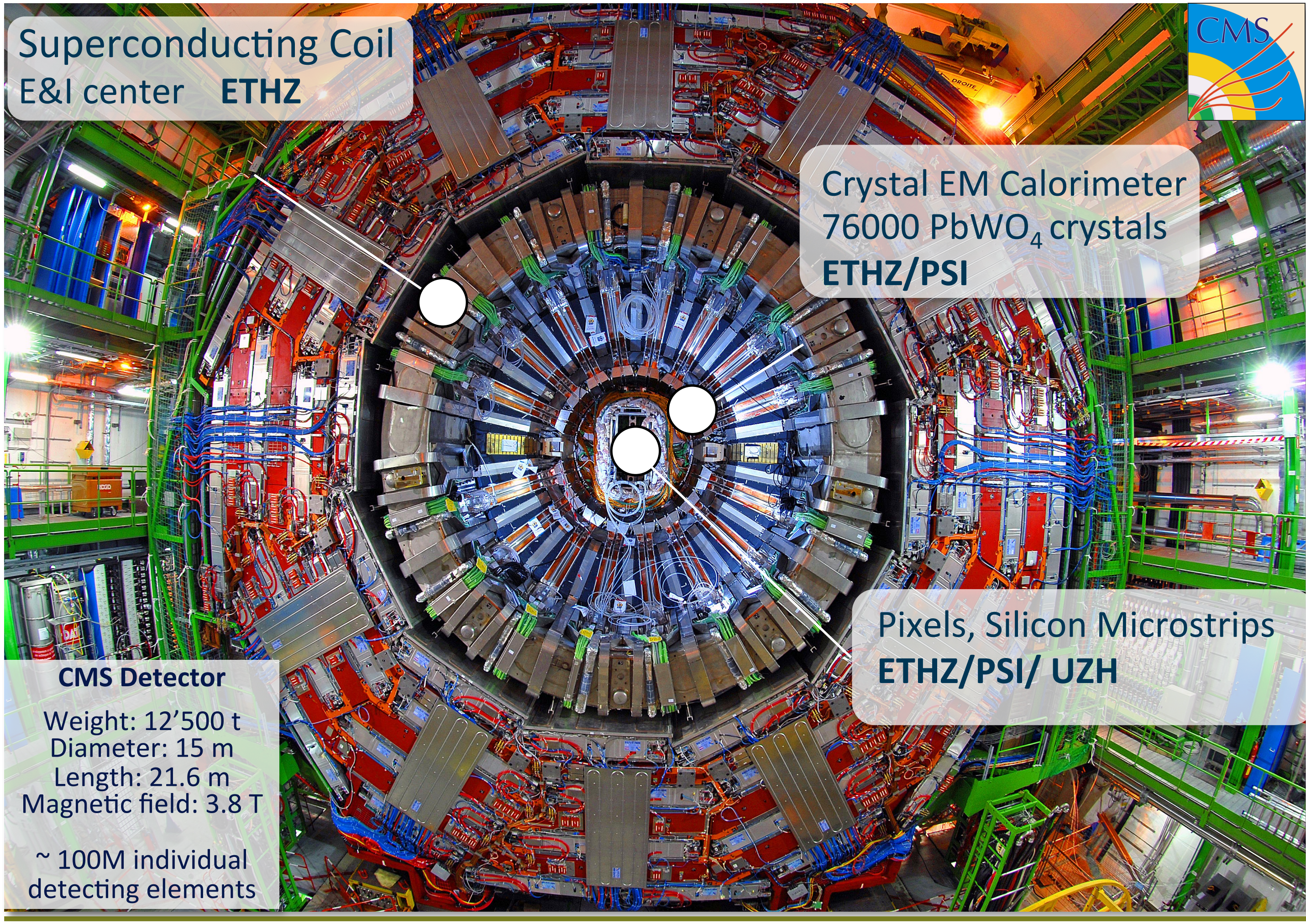
# Improvements sought



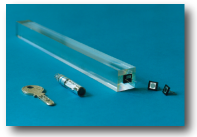
# Physics gain of improvements

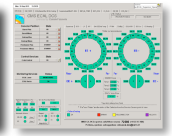


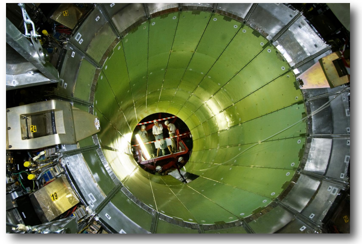
# CMS Construction: CH Contributions

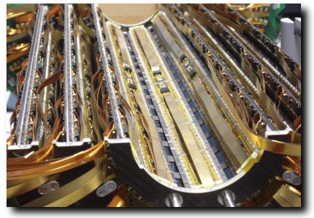


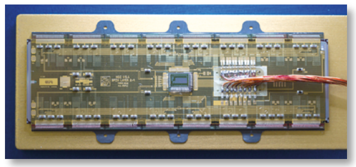

Important management roles since the 1990s







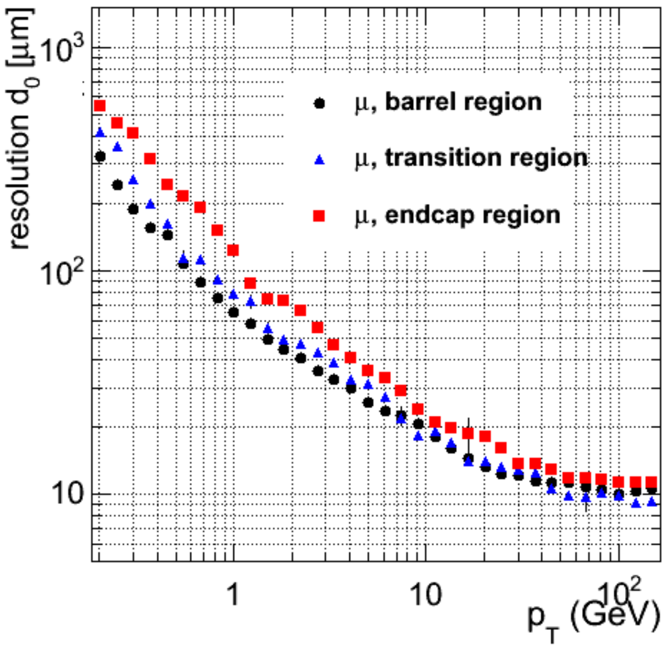




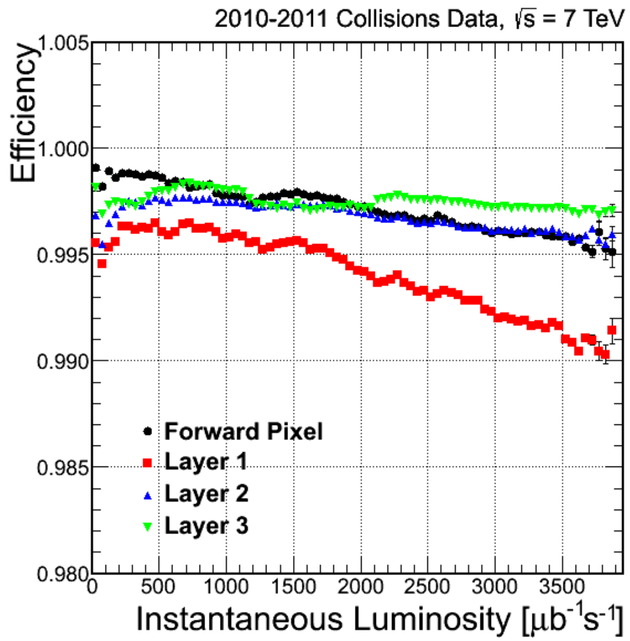
# Phase I Upgrades < 2018

## Silicon Pixel barrel (PSI, ETHZ, UZH)

# Limitations of Current Pixel System



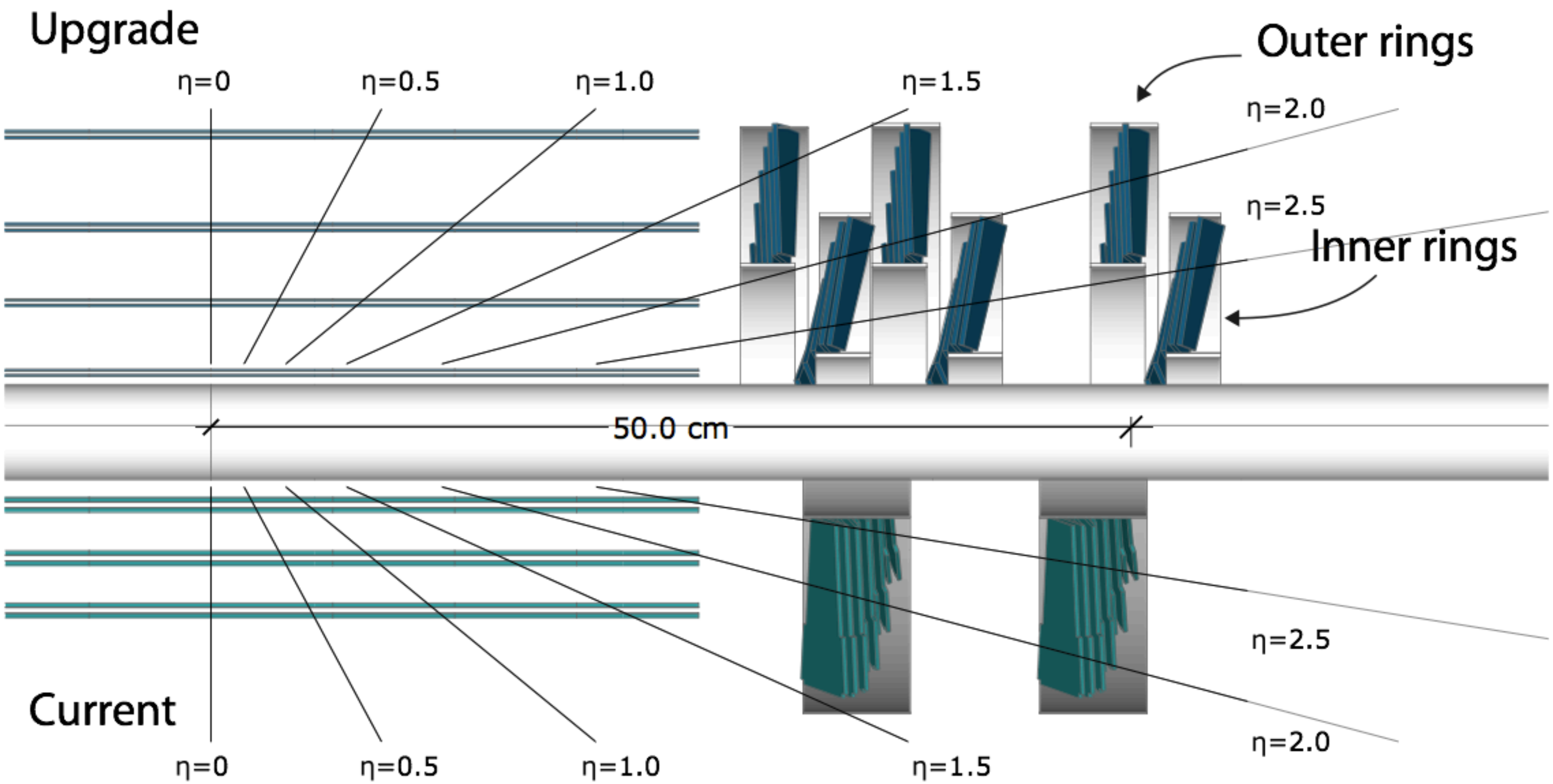

• Impact parameter resolution limited by material in forward region




•Track efficiency drops with Inst. Lumi

- Layer 1 hit **inefficiency**
  - LHC design $1\text{x}10^{34}$ @ 25 ns : 4%
  - LHC at $2\text{x}10^{34}$ @ 50ns : 50%
- Several bottlenecks
  - Buffer Space in ROC
  - Optical readout of modules
  - Front End data rate to event builder

# (To be) upgraded pixel detector



# Readout Modifications : ROC

## Readout Chip (ROC) function :

- Stores and outputs hit information for pixels exceeding set threshold within time window
  - Address, pulse height, time stamp stored

- ROC changes:

– **Increase** DC time-stamp- / data-**buffers** (12 / 32 → 24 / 80)
– ROC internal token passage & double buffered (64) readout
– 160 Mbit/sec **digital readout** for pixel addr. & pulse heights
– ROC level 8-bit ADC for pixel pulse height digitization
– **Reduced** pixel in-**time threshold** of **<1600e** (present 3400e)

| ROC version | Rate [MHz/cm2] |
|---|---|
| PSI46 (ana) | ~100 |
| PSI46dig | ~200 |
| PSI46dig+ (L1) | ~500 |

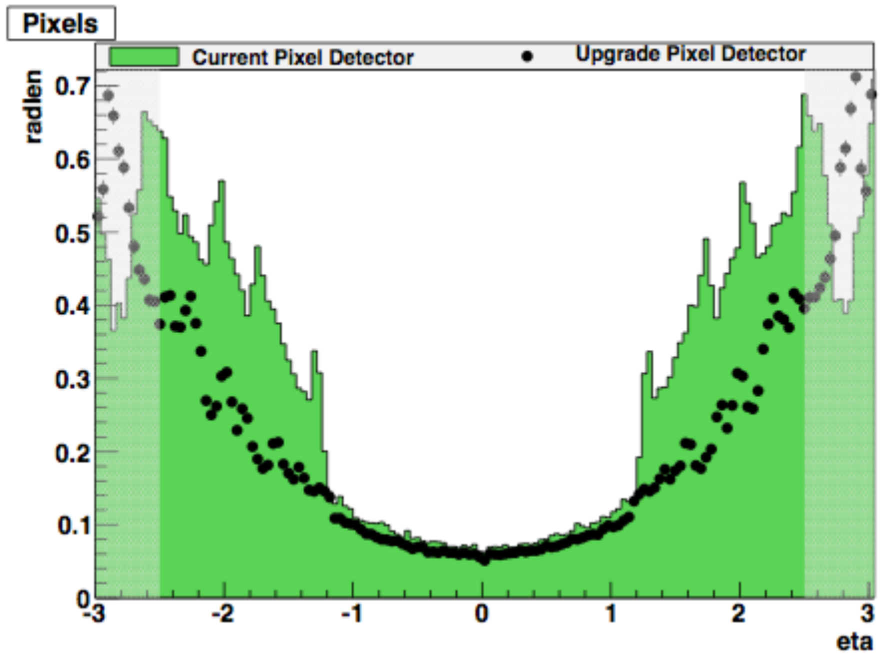
- Increase data transmission rate **(factor x 4)**

# System parameters : Current & 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) | $100\mu$ x $150\mu$ | $100\mu$ x $150\mu$ |
| In-time pixel threshold | 3400 e | 1800 e |
| Pixel resolution (r-phi x z) | $13\mu$ x $25\mu$ | $13\mu$ x $25\mu$ (or better) |
| Cooling | $C_6F_{14}$ (monophase) | $CO_2$ (biphase) |
| Material budget $X/X_0$ ($\eta$=0) | 6% | 5.5% |
| Material budget $X/X_0$ ($\eta$=1.6) | 40% | 20% |
| Pixel data readout speed | 40MHz (analog coded) | 400Mb/sec (digital) |
| 1st layer module link rate (100%) | 13 M pixel/sec | 52 M pixel/sec |
| Readout chip pixel rate cabability | ~120 MHz/cm$^2$ | ~580 MHz/cm$^2$ |
| control & ROC programming | TTC & 40MHz $I^2C$ | TTC & 40MHz $I^2C$ |

# Material budget

Current vs. Upgrade detector

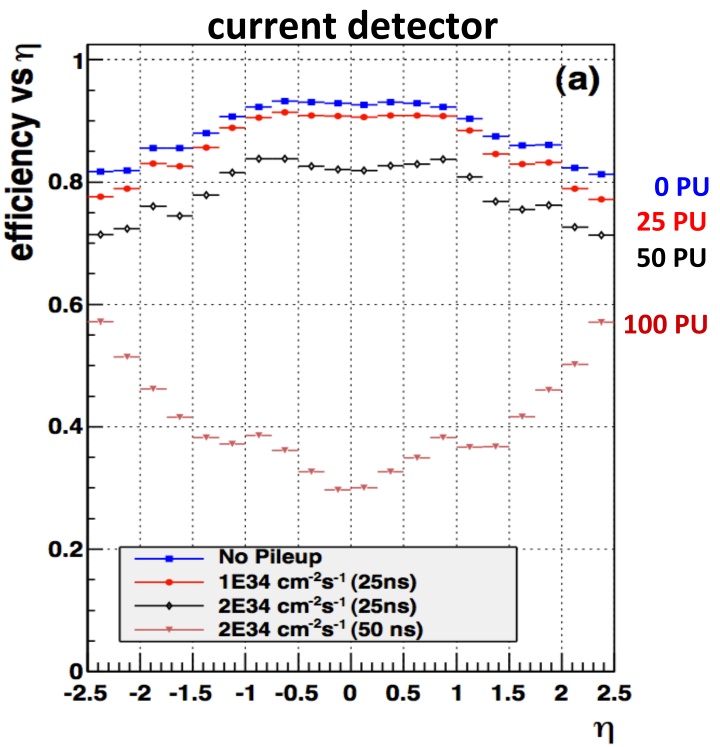



Green is current Pixel system
Data points show improvement

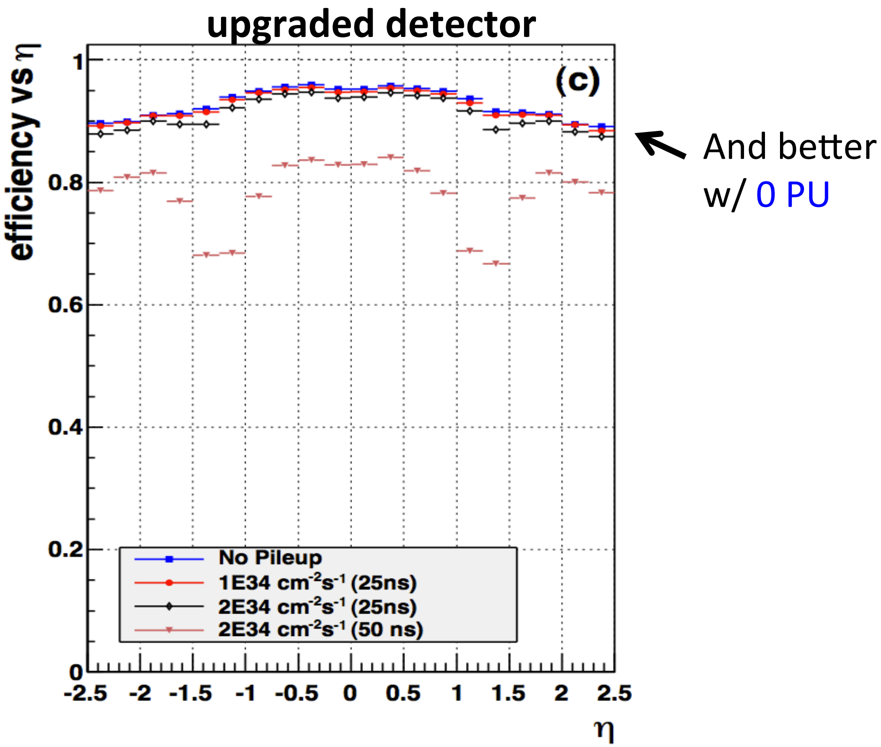
From simulation of radiation lengths

# Performance in Tracking Efficiency

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




Fake Rate= **6%** (η=0, 100PU)



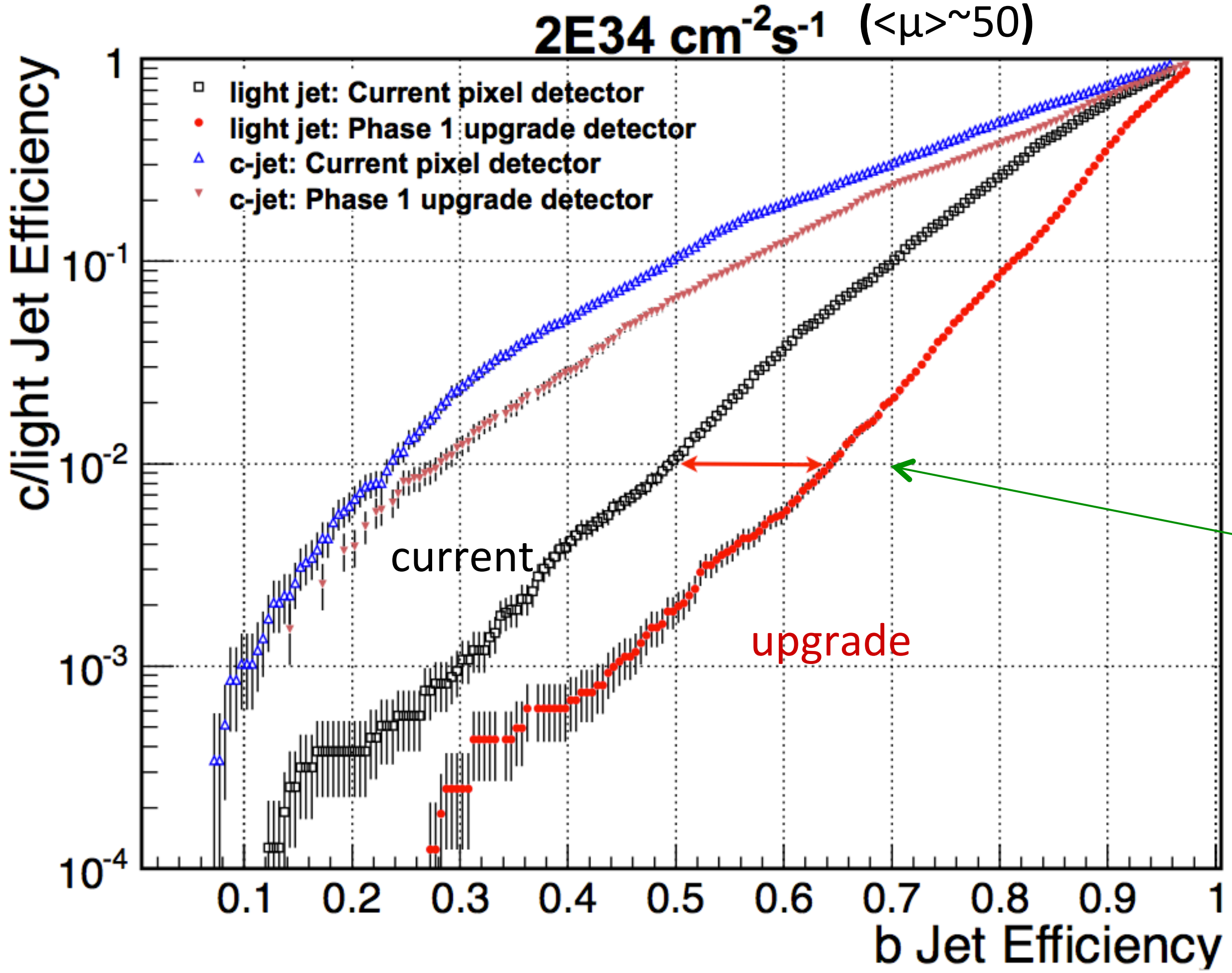

Fake Rate= **2%** (η=0, 100PU)

Results in significant gain in signal reconstruction efficiency for multi-lepton final states:

$H \rightarrow ZZ \rightarrow 4\mu$ + 41%

$H \rightarrow ZZ \rightarrow 4e$ + 51%

# Improved B-tagging and Vertexing




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

2 b-jets → $(1.3)^2$ ~1.69

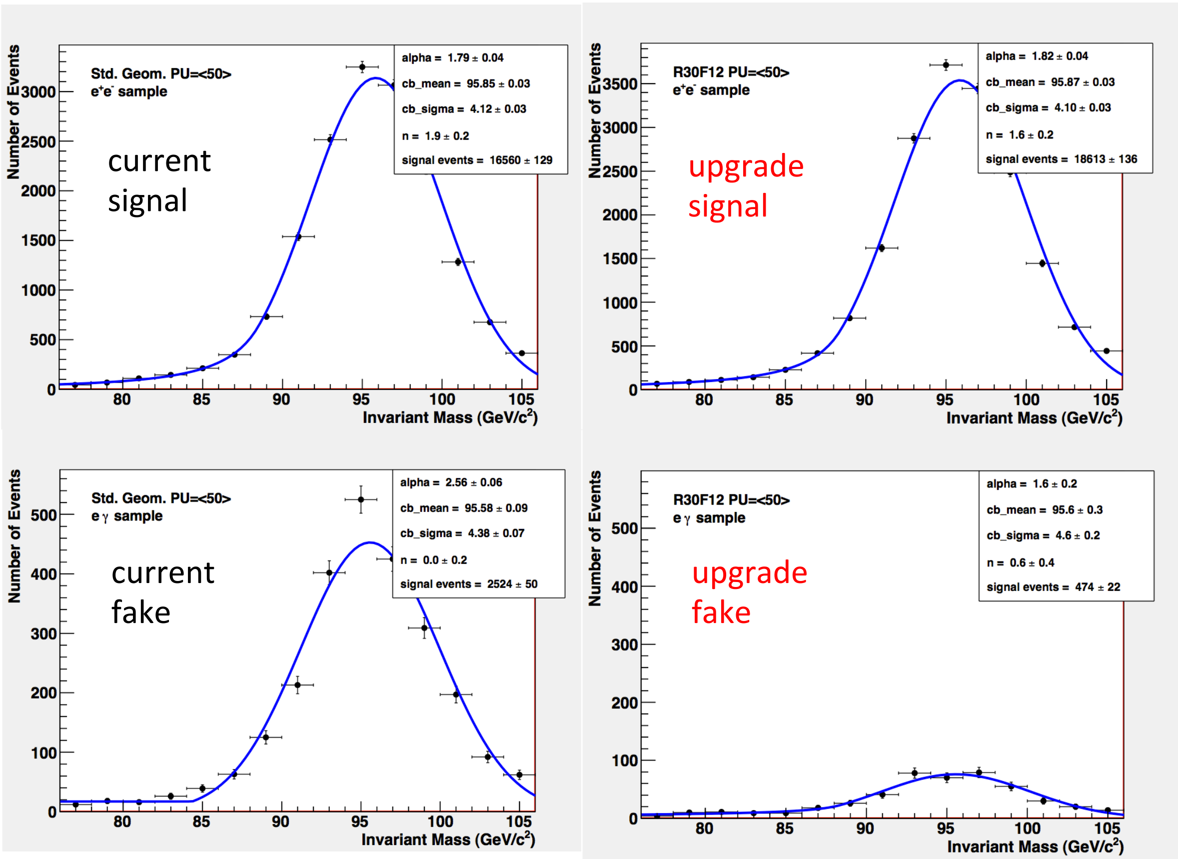
Upgrade detector much more robust w.r.t pile up than current one.

Upgrade Pixel @ <μ>=50 ⇔ Current Pixel @ <μ>=0

→ maintain physics capability or better at large PU

# SUSY particle searches with $\gamma\gamma+E_T^{miss}$

- SUSY searches with $\gamma\gamma + E_T^{miss}$ have little background from SM ($W\gamma\gamma$ & $Z\gamma\gamma$ small)
- Background dominated from mis-identification of electrons and photons.
- Fake rate of electrons being identified as photons depends crucial on pixel detector
- MC study of fake rate with $Z^0$ decays into $e^+e^-$




***Conclusion:***

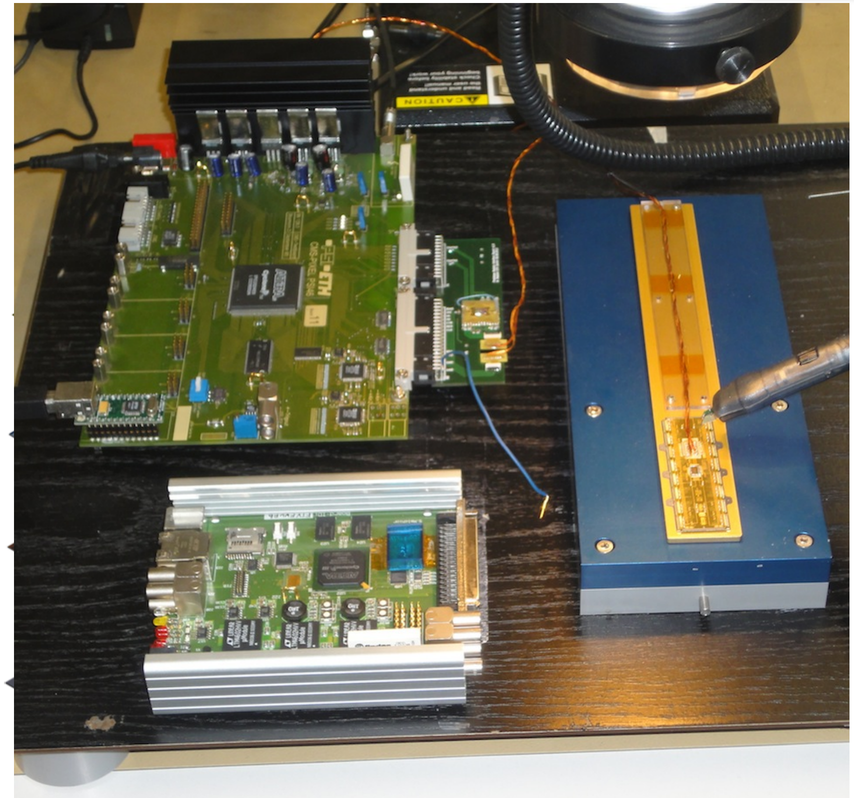
fake rate depends crucial on pixel performance.

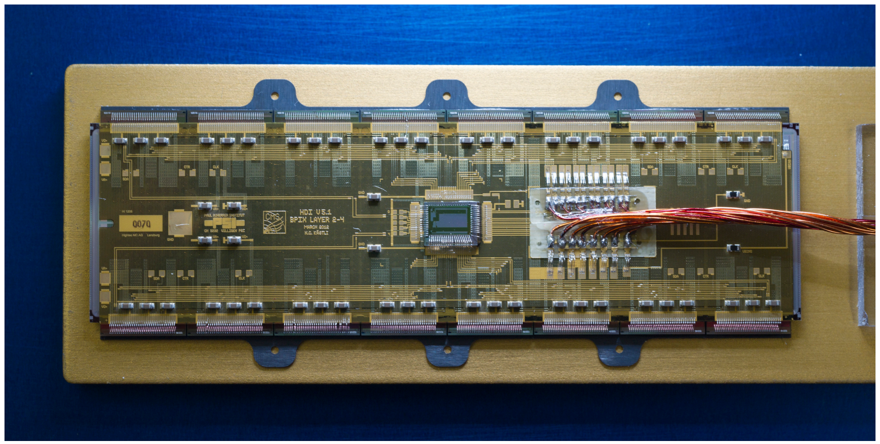
current detector 7.0 %
upgrade detector 1.25%

# Phase 1 upgrade status

# Module Testing and Construction

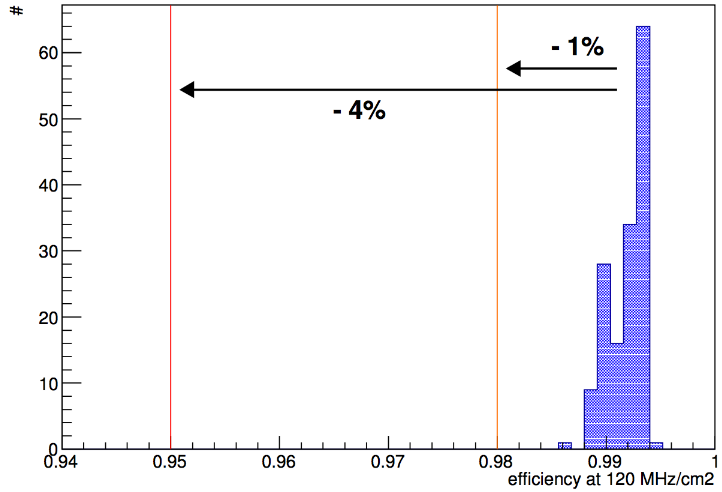
- CH-consortium builds L1 and L2 modules (33%)
  - Provide Test Board for whole collaboration
- Procedure now in place for production and testing



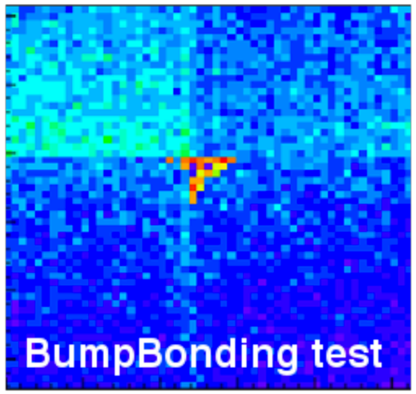


# Module qualification: X-ray testing

- Tests : VCAL calibration, hit efficiency vs. rate maps, uniformity ➞ determine module grade

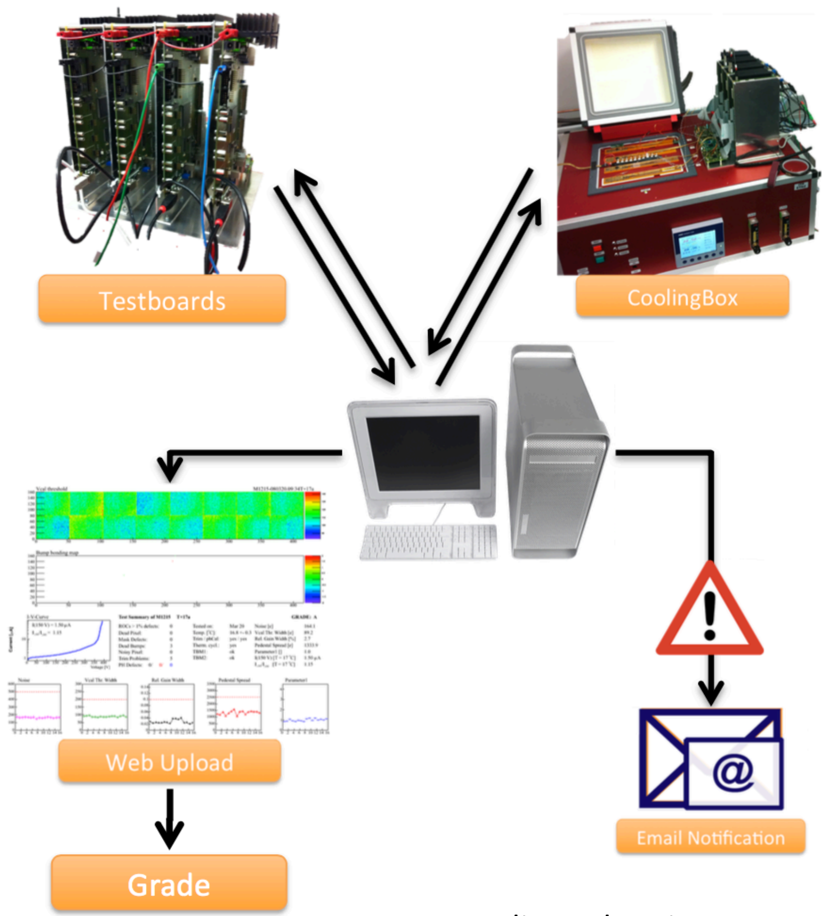



Pirmin Berger, ETHZ



# Module quality

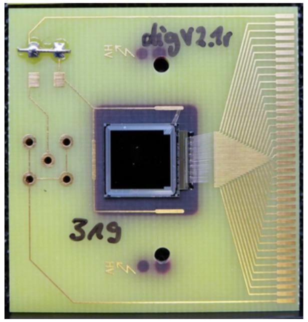
- “elComandante”
- Full qualification of modules and performance
- Analysis code
- Database management
- Run by groups testing pixel modules in CH, Germany, Italy, U.S.



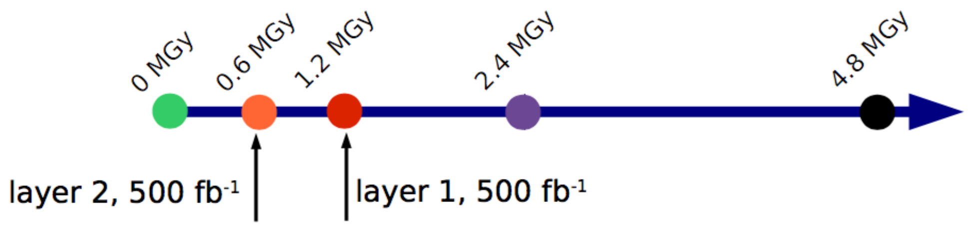

Felix Bachmair, ETH

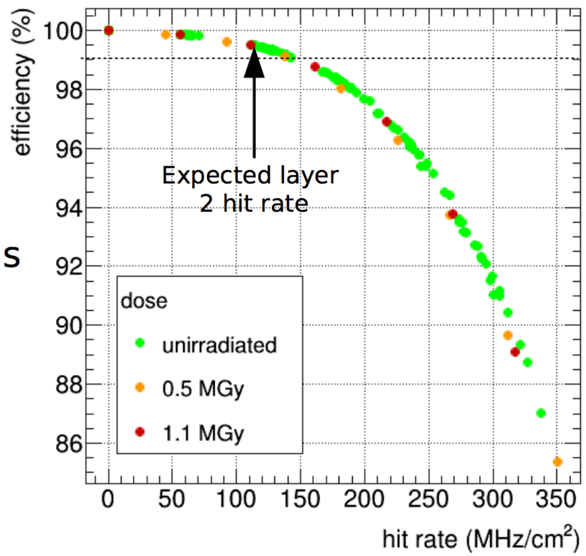
# Irradiation tests

- Verification of pixel ROC at high irradiation of phase 1 and beyond



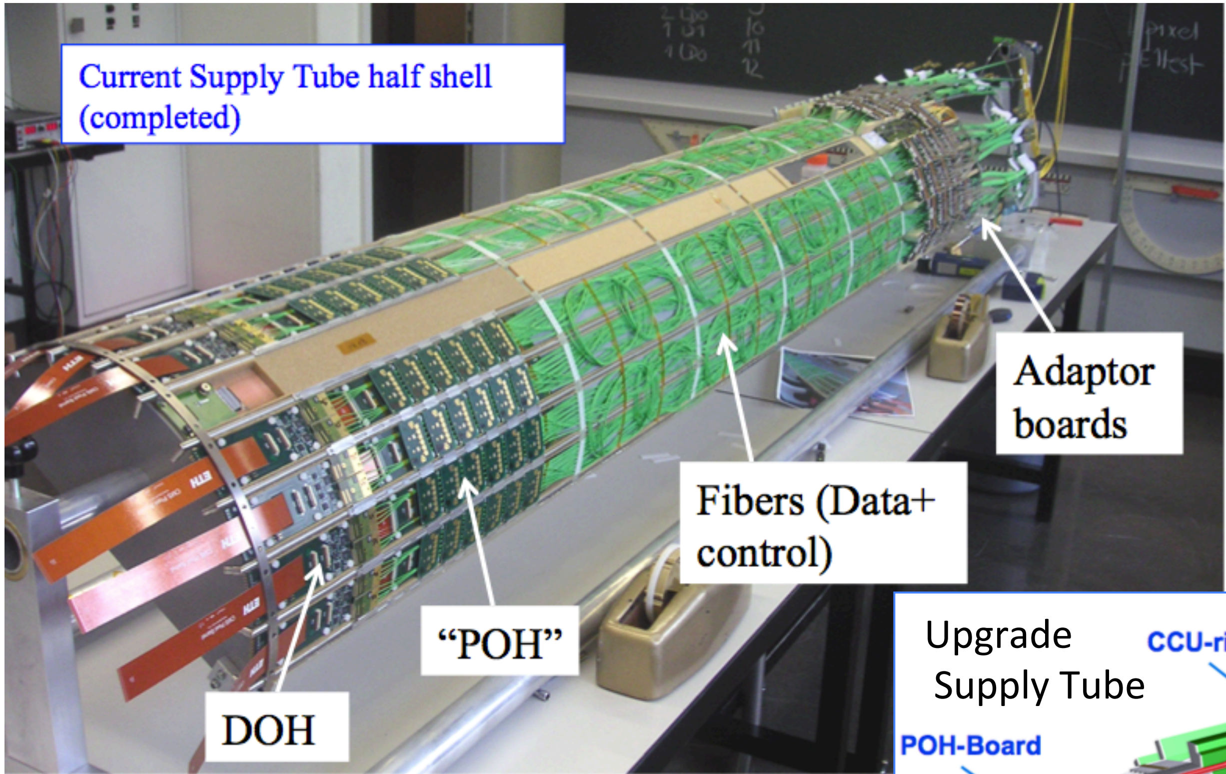
Jan Hoss, ETHZ




| dose (MGy) | observation |
|---|---|
| doses the ROC will actually face in CMS | - excellent performance |
| 1.1 | - need increased digital voltage 2.5 (better 2.6 V) for maximum pulse height coverage |
| 2.2 | - operate ROC at elevated analog voltage 1.7 V to reach 24 mA<br>- shaper feedback gets too weak |
| 4.2 | - further increase of analog voltage to 1.8 V |

# Supply Tube

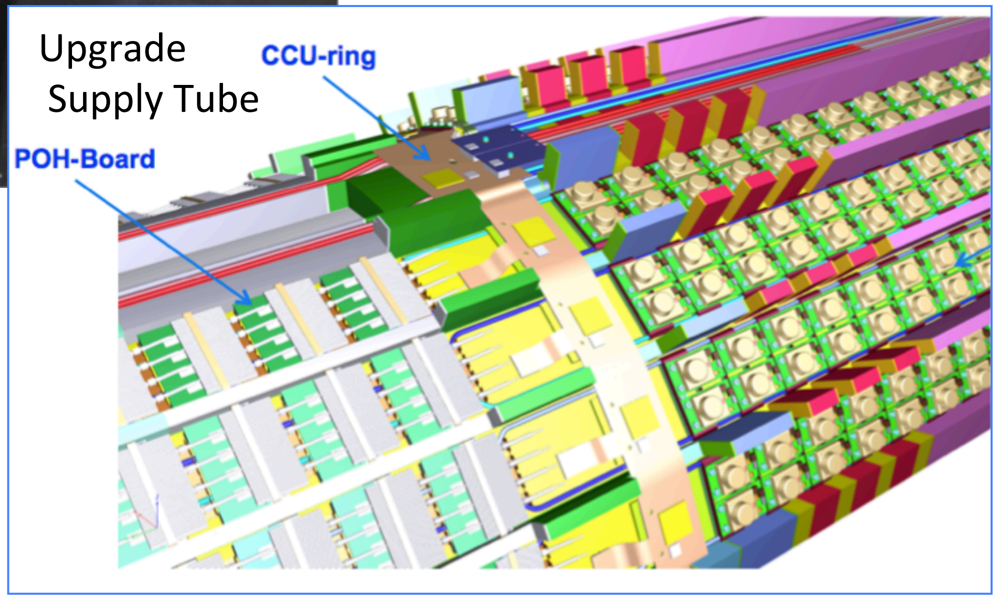



Challenge of new BPIX supply tube:

In very limited space (~1cm radial) have to fit many components :

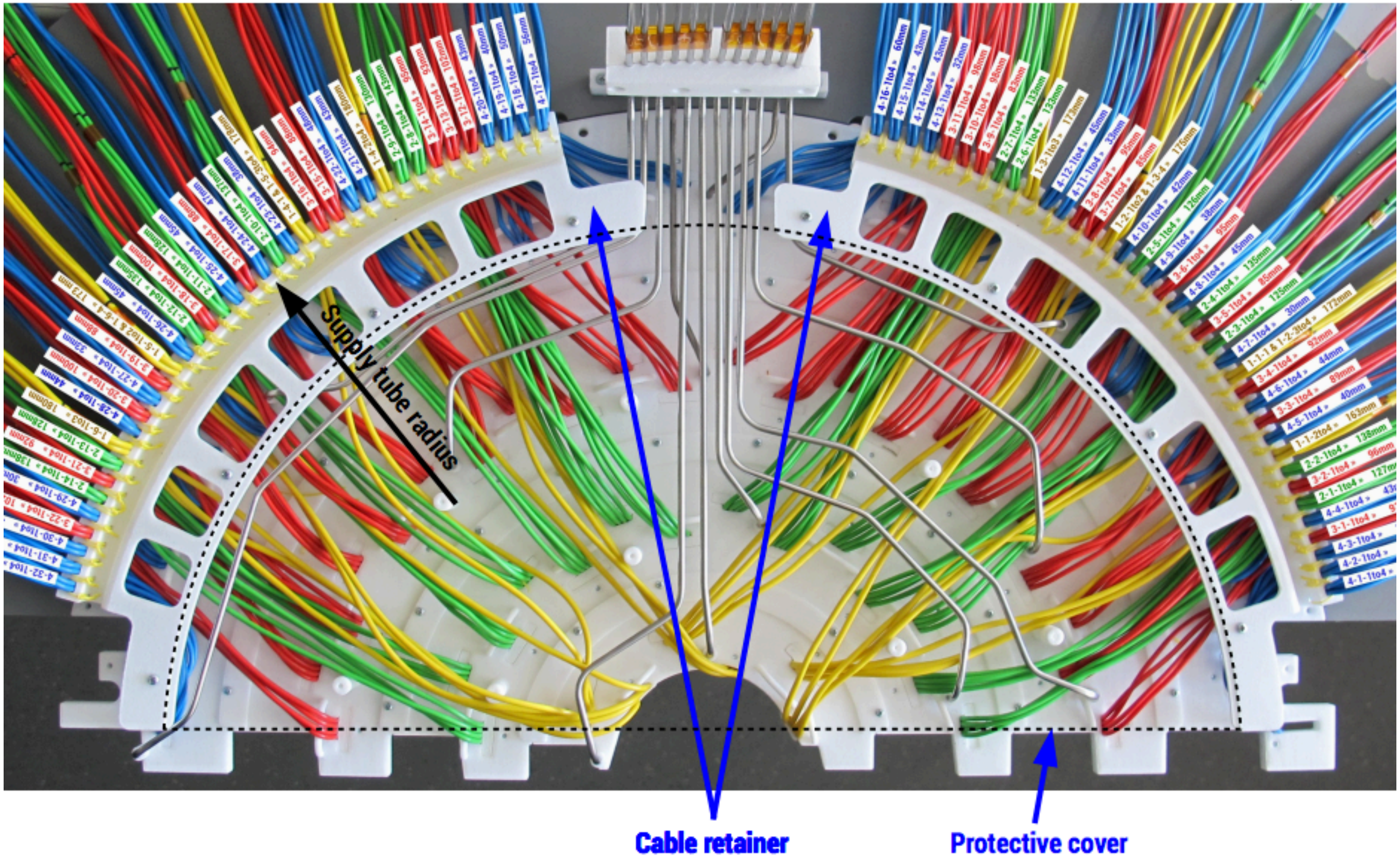
- DC-DC converters
- Pixel OptoHybrid (POH) & fibers
- Digital OptoHybrid (DOH) & fibers
- Comm. Control Unit (CCU) for DC-DC/POH/DOH/PLL/delay25
- $CO_2$ preheating & ST cooling

Concerted design effort by UZH, ETHZ, PSI & others
Construction & integration at UZH
Many different PCBs to be designed and functional interplay to be tested.



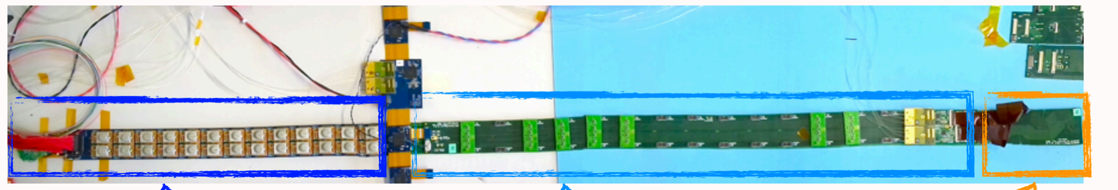
# Cabling mockup

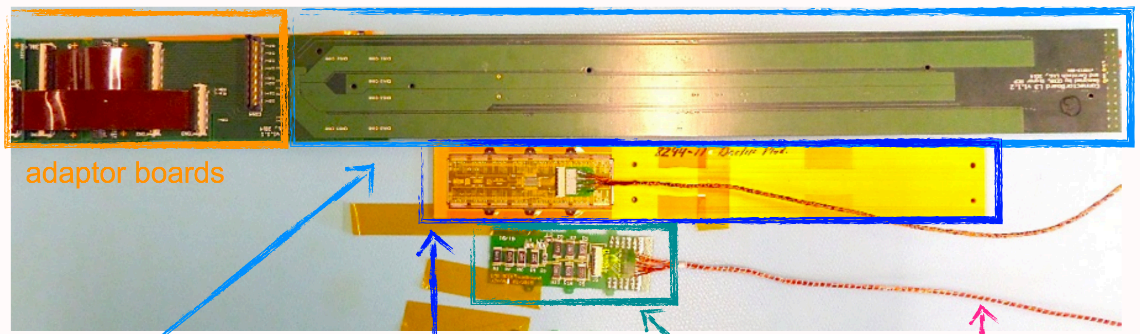
Silvan Streuli, PSI

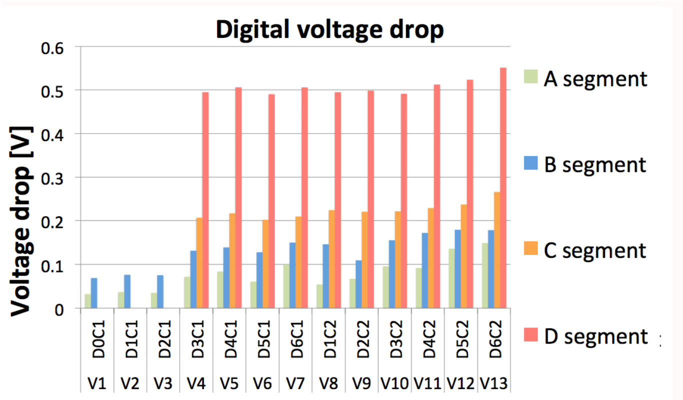


# Power tests of pixel supply tube

- Supply Tube electronics has 4 segments



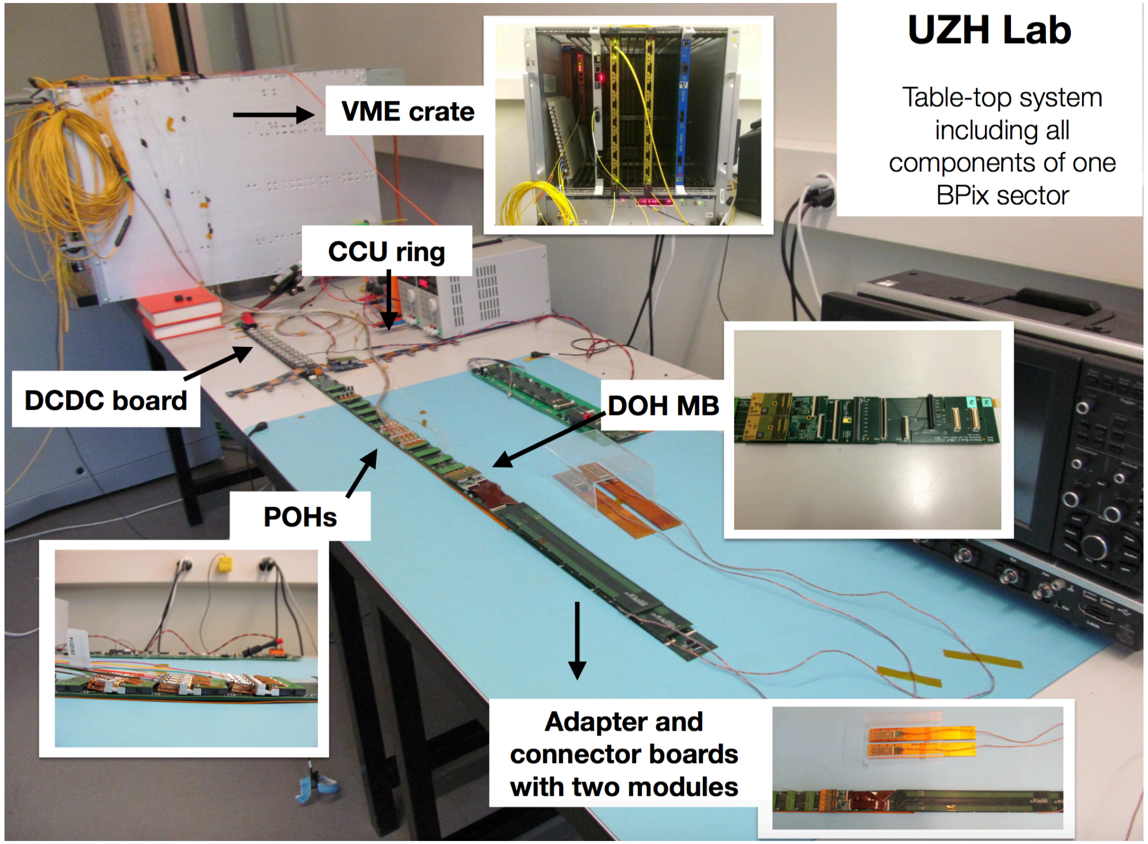



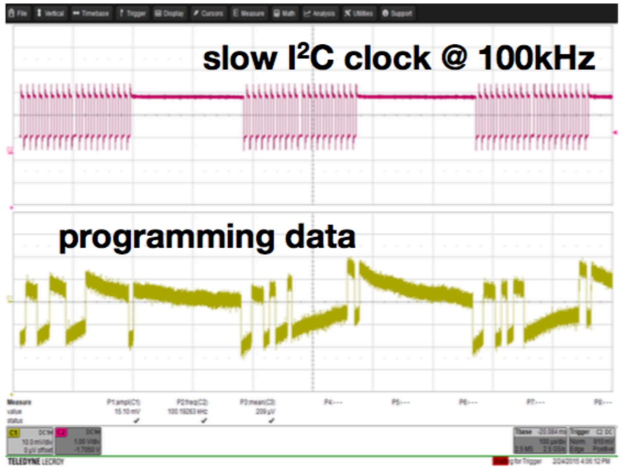

Deborah Pinna, UZH

- Voltages and currents measured across various boards
- Sufficient margin for modules verified

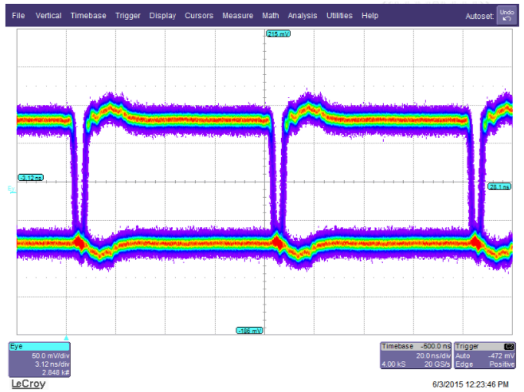
# Module readout and control

- Full vertical slice electronics test from module to VME DAQ



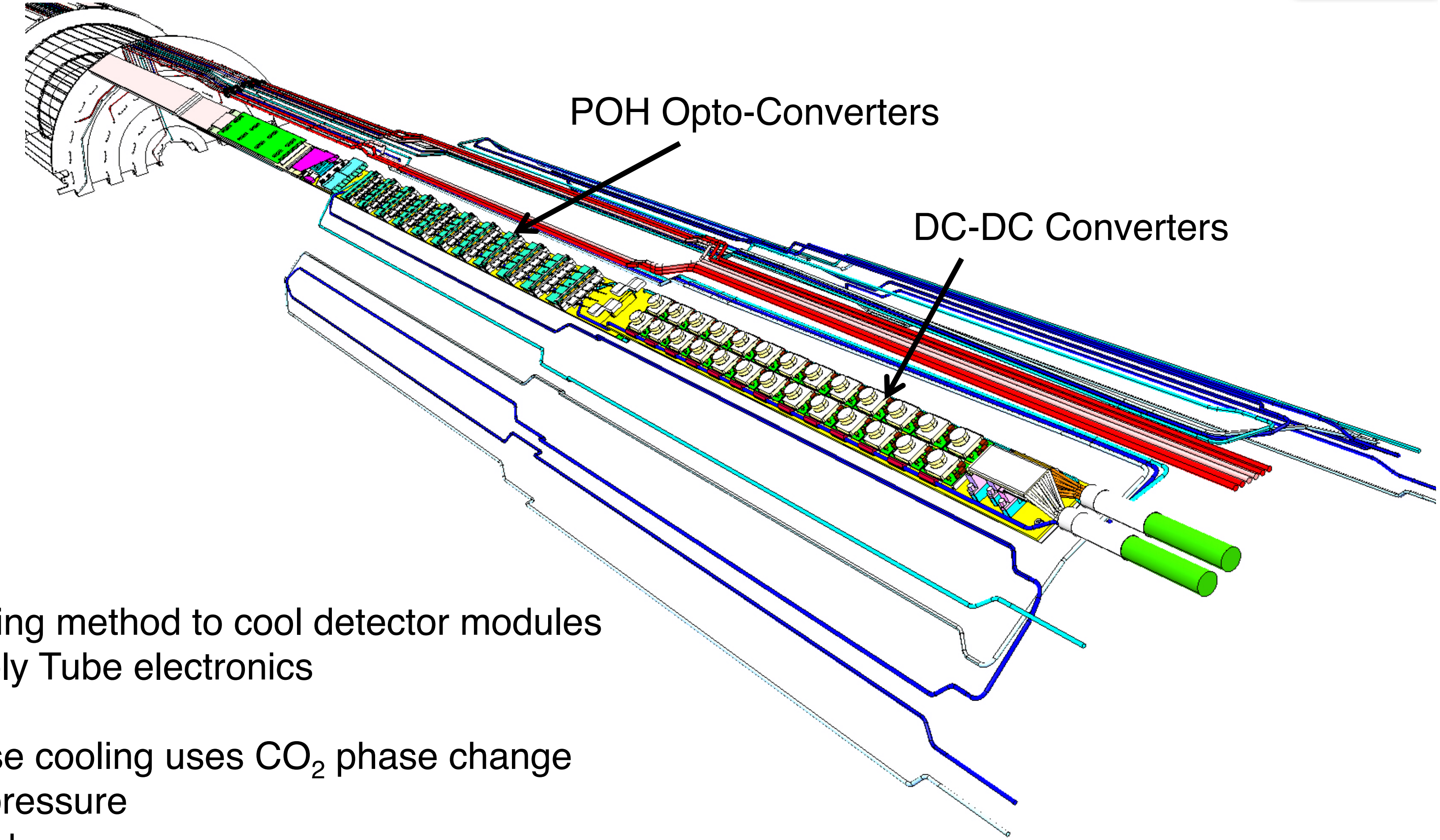




Jennifer Ngadiuba, UZH



Total jitter ~1.79 ns

# $CO_2$ Cooling Loop Engineering Model

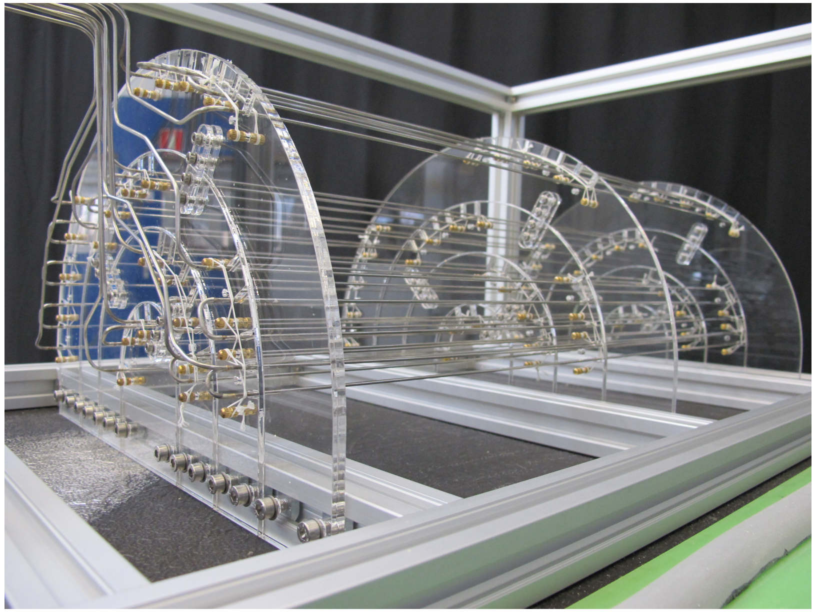



New cooling method to cool detector modules and Supply Tube electronics

Two-phase cooling uses $CO_2$ phase change

- High pressure
- Thin tubes
- Complicated bendings

# $CO_2$ Cooling Loop Engineering Model



Pressure tested to 200 bar – stressed with extreme heat, cold, and corrosion

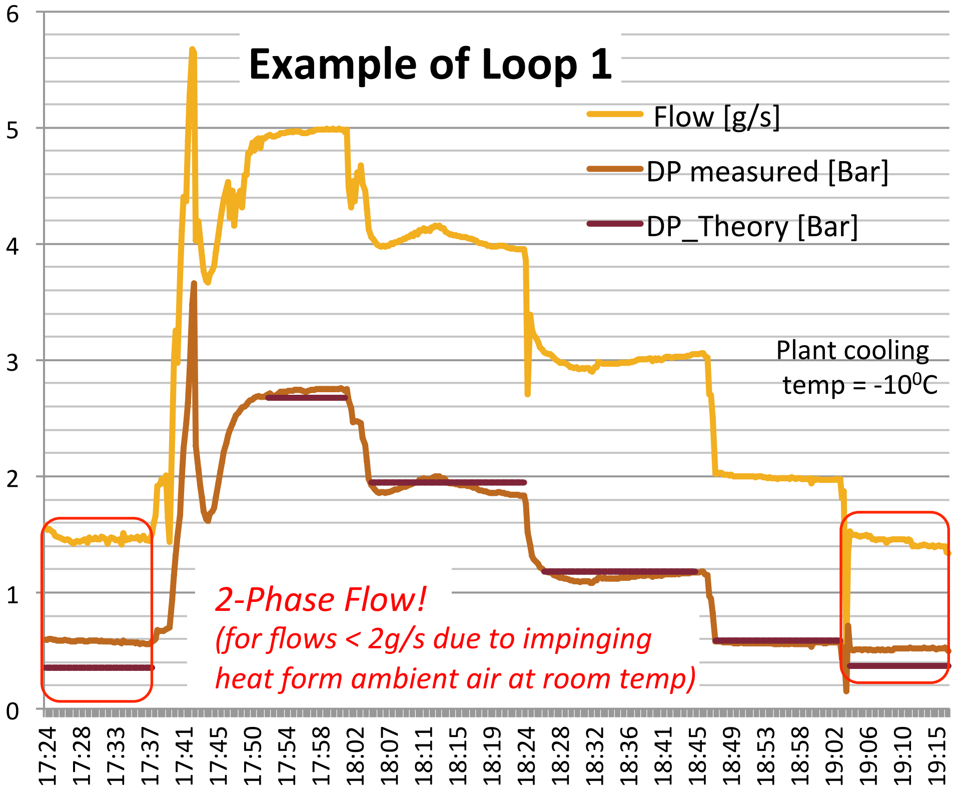
Complete replica of detector cooling built

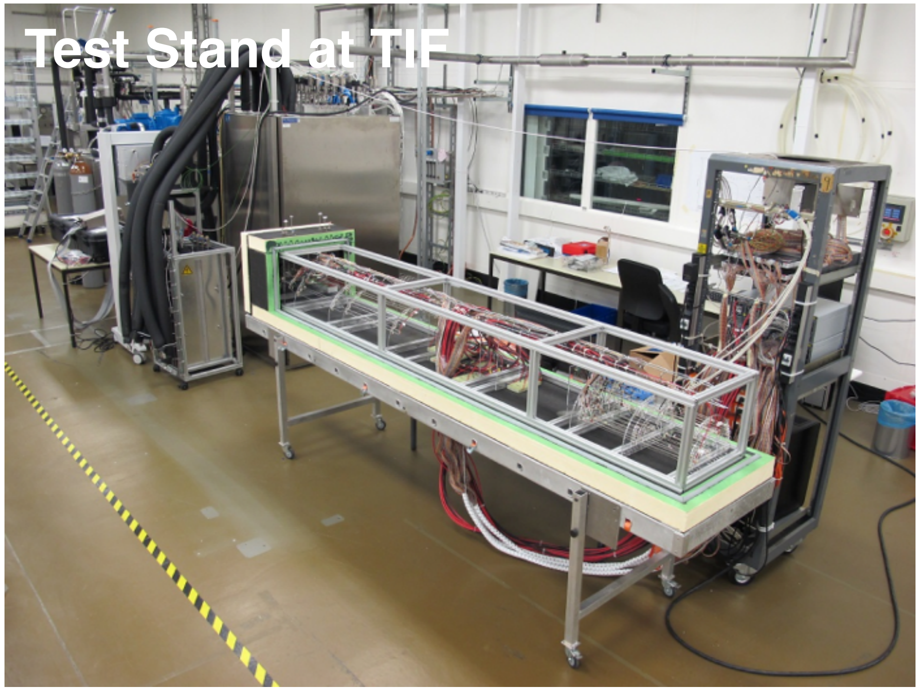
P. Robmann, UZH

# *BPIX thermal duplicate test*

- Test cooling with real BPIX tubing geometry to verify pressure drop over each loop and cooling behavior
- Measured pressure drops of liquid $CO_2$ through each of the 6 loops corresponds closely with theory
- Next: test pressure drop at -20$^0$C and nominal flow

R. Becker, ETHZ



# Pixel upgrade management

- Roland Horisberger (PSI)
  - manager of phase 1 upgrade
- Andrei Starodumov (ETHZ), Wolfram Erdmann (PSI)
  - Module qualification & organization managers
- Lea Caminada (UZH)
  - System electronics/power/control tests manager

# Phase 2 upgrades

<= 2017 : Phase 1 highest priority

>= 2017 : Phase 2 begins in earnest

# CMS Phase 2 Technical Proposal

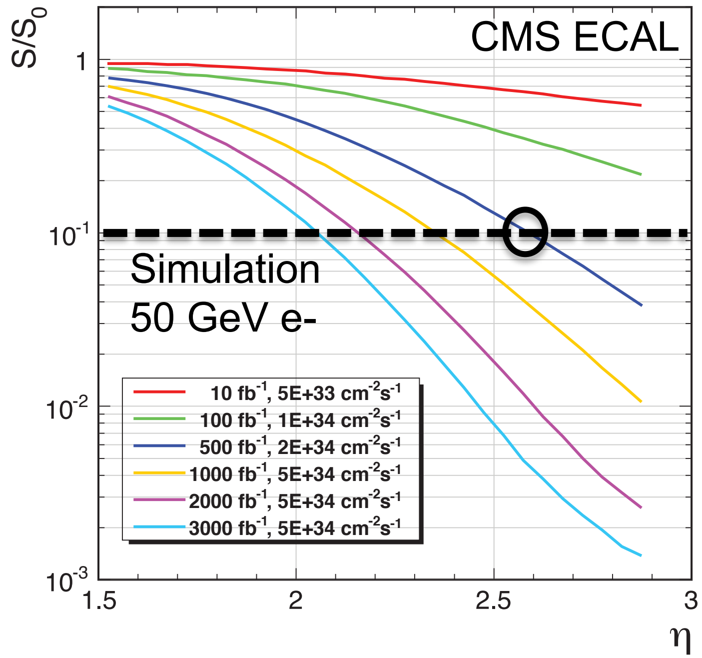
- Technical Proposal for phase 2 presented in 2015
- Upgrades :
  - Replace inner (pixel) and outer tracker
  - Replace endcap calorimeter & barrel calorimeter electronics
  - Add new level 1 track trigger
  - Added muon detectors for trigger enhancements
  - Improved electronics & triggering
- Ensures physics program up to 2035 (3000 $fb^{-1}$)
  - Precision Higgs
  - Search for H→HH self-coupling
  - Rare BSM process searches

# Phase II Upgrades

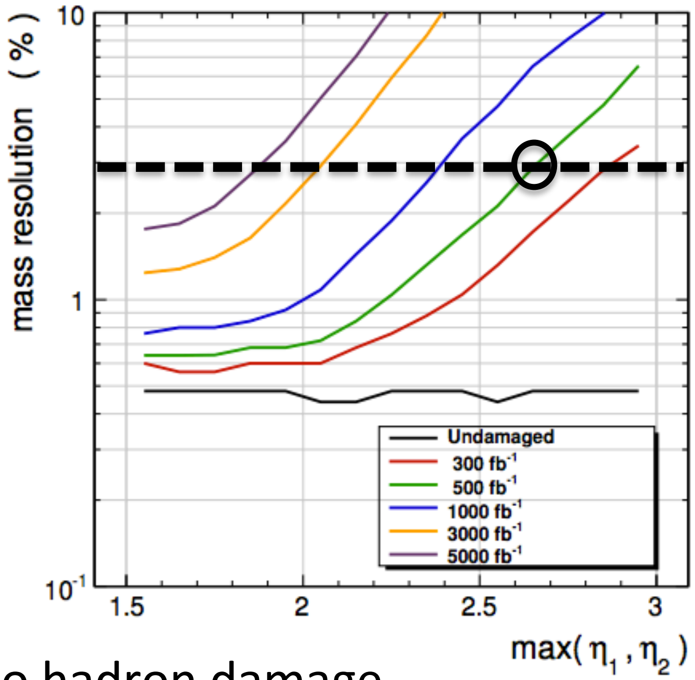
# ECAL (ETHZ)

# ECAL Longevity

Crystal Light transmission




H→γγ mass resolution (generator level)




- Cumulative loss of signal expected, due to hadron damage to crystals and aging of photo sensors
  - *Studies pioneered by ETHZ NIM A 545 (2005) 67, NIM A 564 (2006) 164, NIM A 622 (2008) 266, NIM A 684 (2012) 57*
  - *Radiation longevity of present electronics is currently being studied*
- A data validated aging model is implemented in CMS full simulation
  - tuning of reconstruction and study of physics performance degradation (including pile-up effects)

=> replace end caps after 500 $fb^{-1}$ to keep ECAL coverage to $\eta<2.6$

# ECAL EE Phase II Upgrade Technology

## Two EE choices have been studied and reviewed

- A "Shashlik" sampling calorimeter using scintillating LYSO or $CeF_3$ crystals
- A silicon-based sampling calorimeter ("HGC")
- An extensive review process has taken place during 2014 and 2015
- Similar performance and costs for the two options assessed on paper
- The management's proposal of choosing the HGC option was accepted in a vote of the CMS collaboration board (CB). This is the baseline for the Technical Proposal (TP).
- CB: wish expressed for a discussion on Backup plans.

### HGC calorimeter issues

- engineering challenges for electronics development and cooling

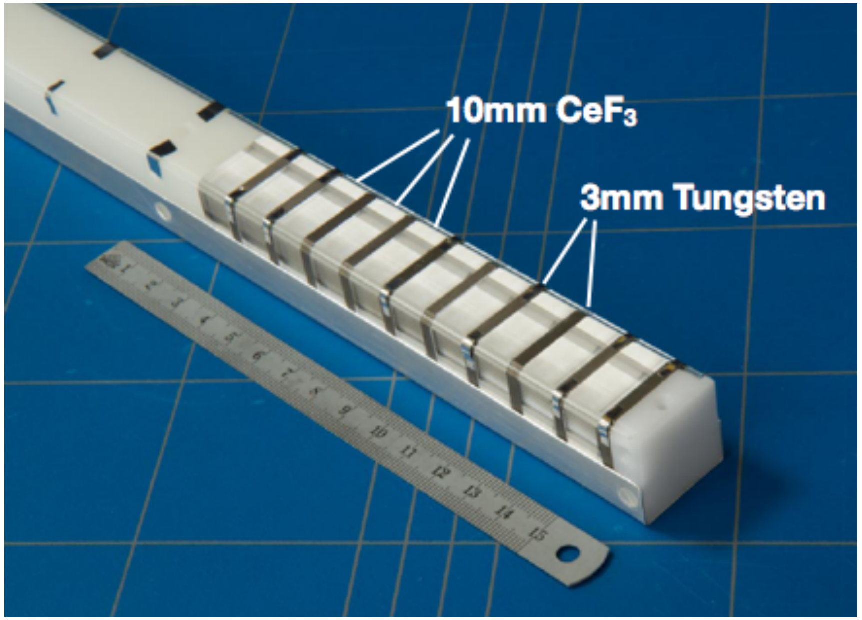
### Shashlik calorimeter issues

- radiation hardness of wavelength shifters, quality control of components during construction

# ETH contributions for Phase II

## “Strawman” layout:

- sampling calorimeter
- Absorber: W or Pb
- Scintillator: LYSO or $CeF_3$
- Readout: via wavelength-shifting fibers or capillaries
- Challenges: radiation hardness of all components



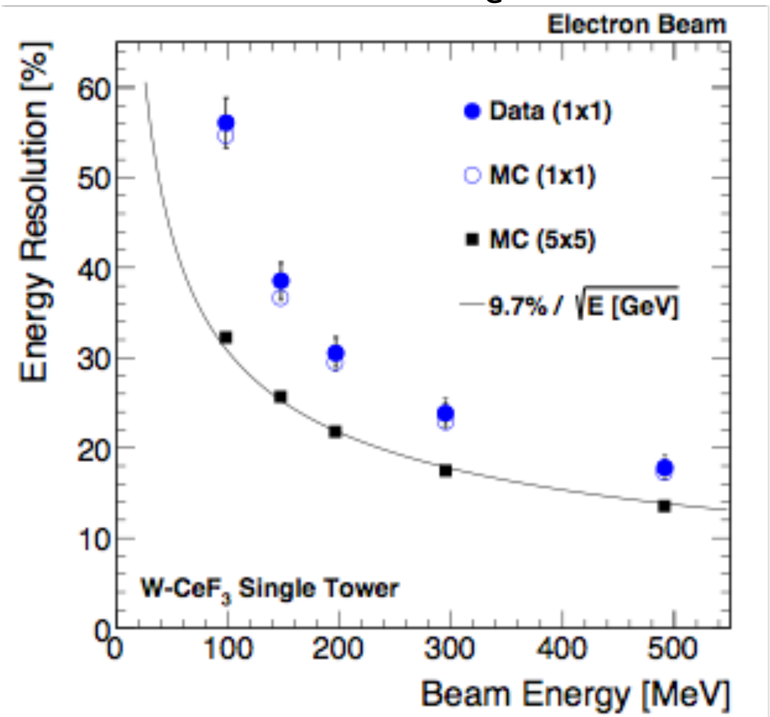

## R&D at ETHZ:

- $CeF_3$ , Ce-doped quartz fibers for wavelength-shifting
- Prototype calorimeter cell tests in high-energy electron beams

# ETH prototype beam tests

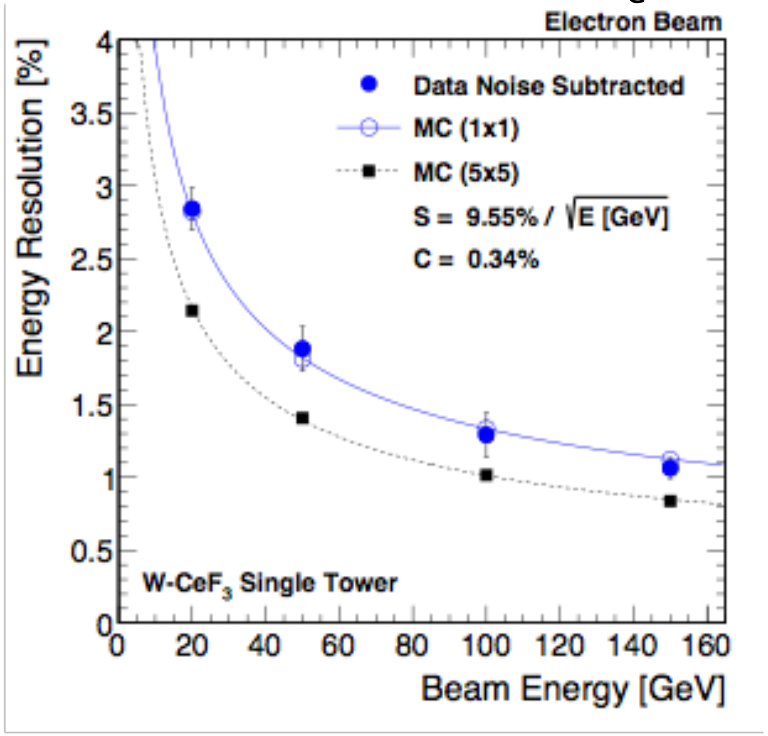
## Frascati BTF:

- May 2014
- Low energy: 98 < $E_e$ < 491 MeV




## CERN SPS H4 beam:

- October 2014
- High energy: 20 < $E_e$ < 150 GeV




- Energy resolution: good agreement with Geant4 simulation!
- Full-scale calorimeter would allow stochastic term < 10%

# ECAL Barrel Electronics also to be replaced

| ECAL Trigger | EB status | Phase 2 requirements |
|---|---|---|
| L1A rate | abs. max. (120-150) kHz | (500 to 1000) kHz |
| L1A latency | 6.4 µs (fixed) | (10 to 20) µs |
| ECAL ‘spikes’ | False triggers | mitigate |

ECAL ‘spikes’: signals from direct interactions in the APDs, causing false triggers)

Additional question: longevity of the electronics – this is presently studied

**Envisaged ETH contributions (in line with our past contributions)**

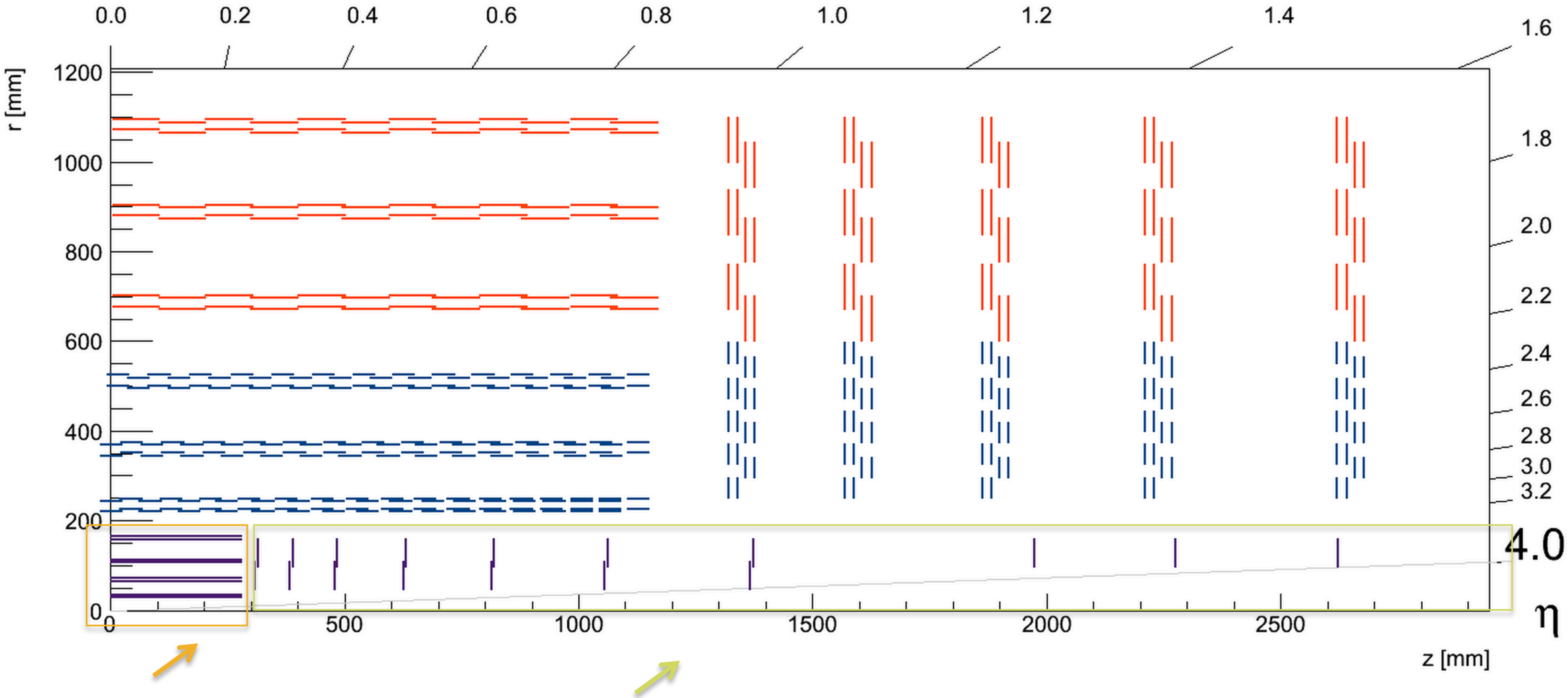
- Participation in the system design
- Leading contributions to the prototyping, fabrication and testing of Front-End electronics
- Adaptation and remake of the DCS components (as necessary)
- Complete integration and testing

# Phase II Upgrades
## Inner tracker (PSI, ETHZ, UZH)

- <= 2017 : Phase 1 highest priority
- >= 2017 : Phase 2 begins in earnest

# New Inner tracking model envisioned

## Baseline Phase 2 pixel detector in Technical Proposal



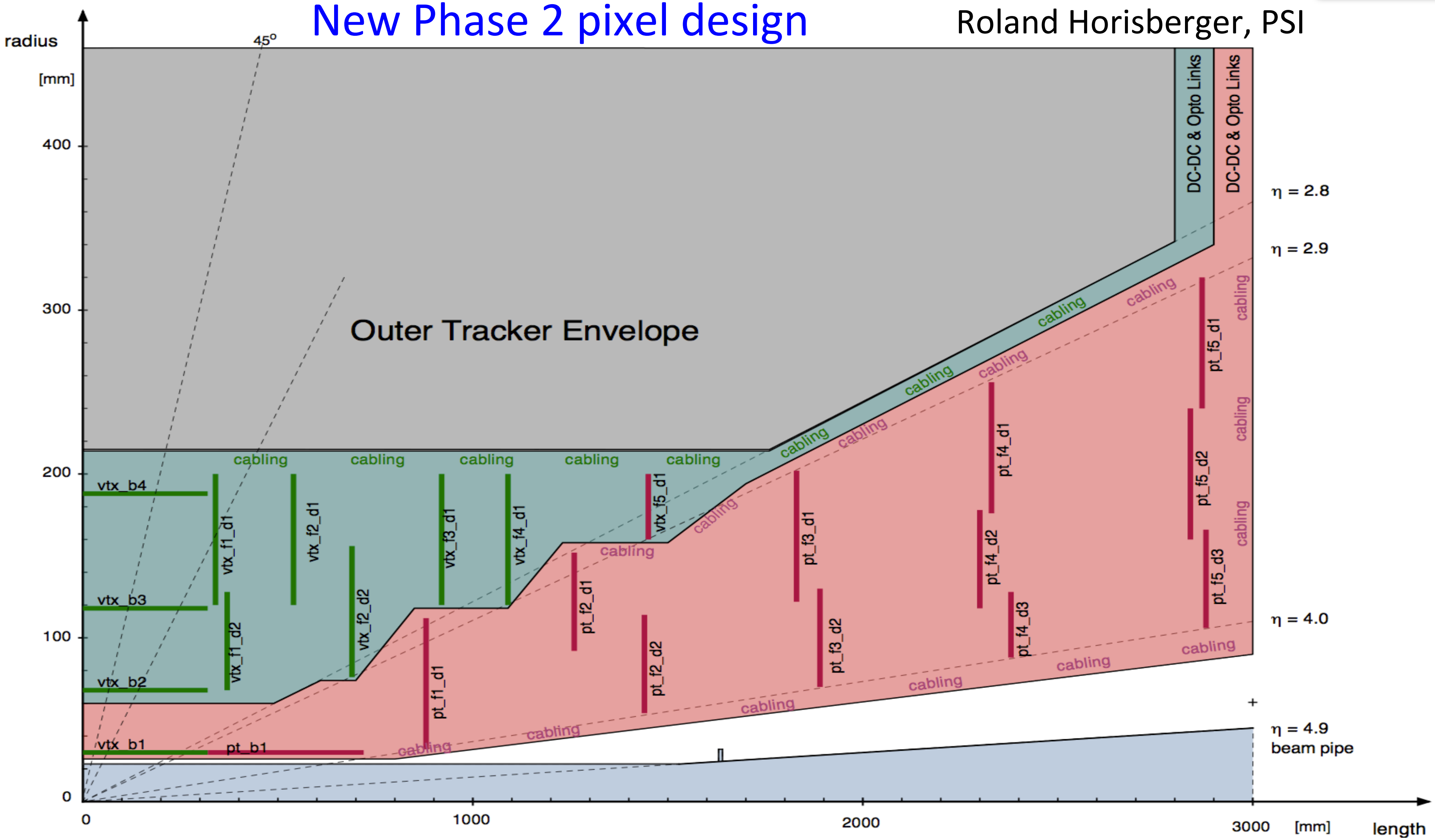

Barrel layers

Forward disks

# New Inner tracking model envisioned

New Phase 2 pixel design

Roland Horisberger, PSI




Note: services at fixed eta to reduce material, conical detector mechanics

# Pixel ROC for very precise coordinates

Forward jet measurements and pileup removal with precision dP/P tracking to $|\eta| < 4$

→ Enables new capabilities for vector boson fusion Higgs production

VFPIX pixel sensors

- 15um x 400um pixel size
- Requires 8-bit pulse height
- High radiation tolerance
- Achieve 1.5 um position resolution

PSI ROC (w/ 110 nm) may achieve this (whereas other options envisioned cannot)

# *Current BPIX detector (1994-2008)*

| | *PSI* | *UZH* | *ETHZ* | *others* |
|---|---|---|---|---|
| • system conception & performance simulation | x | | | |
| • ROC development *(DMILL & 250nm IBM)* | x | | | |
| • TBM development | x | | | x |
| • sensor development & production, testing | x | x | | |
| • module design & high rate beam testing | x | | | |
| • bump-bonding & module production | x | | | |
| • module testing & qualification | | | x | |
| • mechanics design & production & cooling | | x | | |
| • Supply Tube design & production & testing | | x | | |
| • electronic control & readout chain & PCB's | | x | x | x |
| • BPIX assembly & system integration | x | | | |
| • pixel installation & PP0 planning | x | | | |
| • DAQ (FED,FEC) & Power | x | | | x |
| • commissioning & operations *(→ ongoing)* | x | x | x | x |

# *Phase I Upgrade BPIX detector (2010-2017)*

| | PSI | UZH | ETHZ | others |
|---|---|---|---|---|
| • system conception & performance simulation | x | | | *simulation* |
| • ROC development *(PSI46dig, PSI46digL1 in 250nm IBM)* | x | | | |
| • TBM development | | | | x |
| • sensor qualification & testing | x | | | |
| • module design & x-ray high rate testing | x | | x | |
| • bump-bonding & module production *(Layer 1&2)* | x | | | *Layer 3&4* |
| • module testing & qualification | | | x | x |
| • mechanics design & production & cooling | x | | x | *($CO_2$)* |
| • Supply Tube design & production & PCB's | | x | | x |
| • electronic control & readout chain & POH, . .. | x | x | x | |
| • BPIX assembly & system integration | x | | | |
| • pixel installation & interaction with IR | x | | | |
| • DAQ (FED,FEC) & Power | | | | x |
| • commissioning & operations | x | x | x | x |

# Plans for Phase II Upgrade

- Swiss institutions historically committed to pixels → continue this in Phase II

***Capabilities & Strengths:***

- ROC design  with good analog pulse height resolution ( 8 bit)
- sensor design & testing
- system conception
- Supply Tube & service integration
- module production & testing
- pixel installation & interface to IR & beam pipe issues

***Plans :***

- build BPIX layers 1-4  ( 5?)
- evolve PSI46digL1 ROC with 8-bit pulse height for VFPIX use in 110nm CMOS

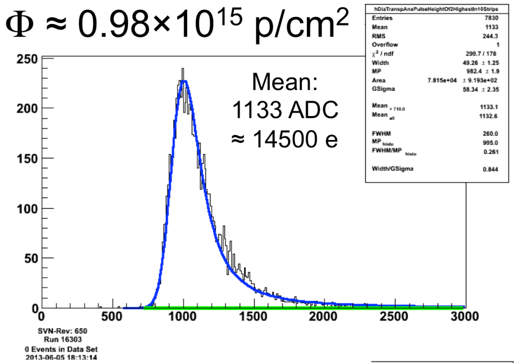
# Conclusions

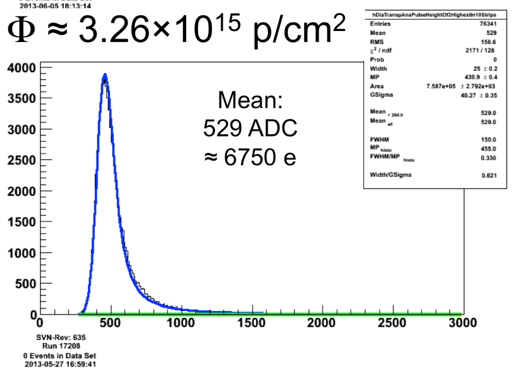
- Phase 1 barrel pixel upgrade on schedule for 2016/2017 Technical Stop installation
  - Phase 1 upgrade benefits from strong Swiss leadership & expertise :
    - PSI Readout chip will perform according to expectations
    - Pixel modules being assembled and tested
    - New cooling technique replica built and verified
    - Full vertical electronics & powering test chain developed
    - Mechanics under construction
- Phase II upgrades defined and being developed
  - Inner and outer tracker to be fully replaced (highest priority of CMS)
    - Swiss consortium (UZH, PSI, ETHZ) to build inner barrel detector (modules, detector, Supply Tube)
    - Expect a version of PSI ROC to work for outer layer as well as very forward pixel
  - Electromagnetic Calorimeter
    - ECAL endcap replacement
    - ECAL barrel electronics upgrade
- CMS-CH intends to continue its vital role in CMS ECAL and Pixel

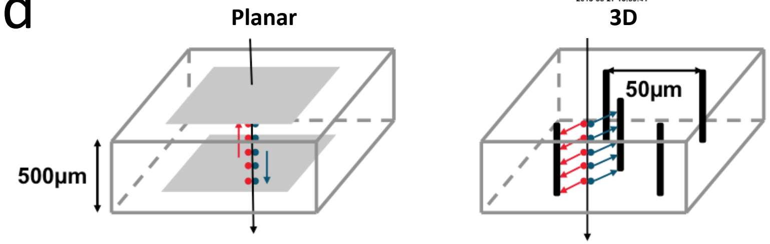
# Backup

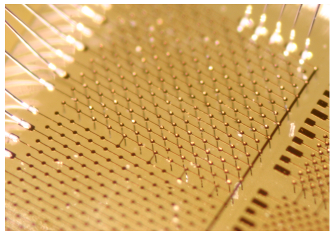
# Diamond R&D

- Diamond sensors can be operated @300 $^0$K
  - Excellent thermal conductor → heat removal
- Low leakage current
  - good signal/noise ratio even at high radiation dose ~$10^{15}$ p/cm$^2$
- Planar strip, pad, pixel and 3D structures tested
- Diamond projects:
  - ATLAS & CMS Beam Conditions Monitor
  - CMS Pixel Luminosity Telescope (?)
  - ATLAS Diamond Beam Monitor



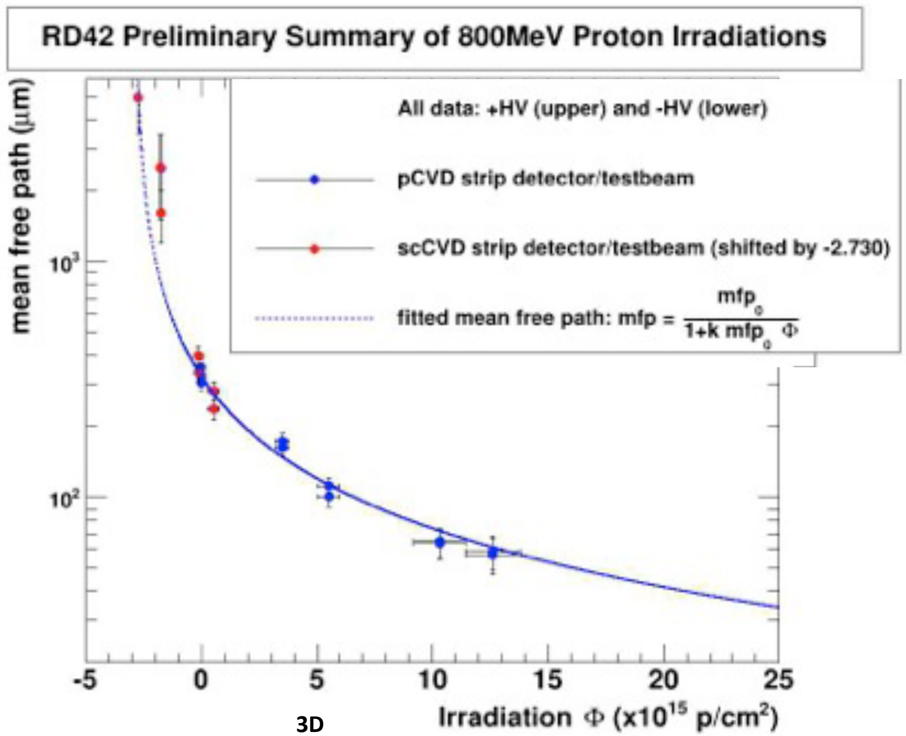



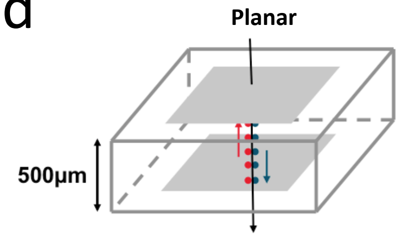



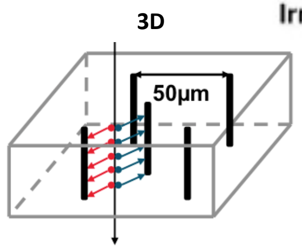



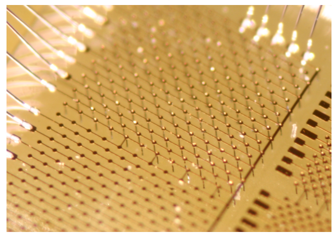
# Diamond R&D

- Diamond sensors can be operated @300 $^0$K
  - Excellent thermal conductor → heat removal
- Low leakage current
  - good signal/noise ratio even at high radiation dose ~$10^{15}$ p/cm$^2$
- Planar strip, pad, pixel and 3D structures tested
- Running construction projects:
  - ATLAS & CMS Beam Conditions Monitor
  - CMS Pixel Luminosity Telescope
  - ATLAS Diamond Beam Monitor



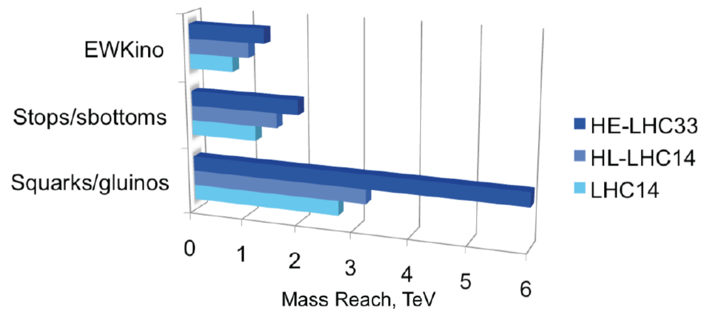
# Phase II Physics Program

- Precision survey of Higgs sector
  - Properties
  - Study rare decays (eg H→μμ @ 5σ )
  - Study (self-) couplings (ie. HH → bbɣɣ)
  - Study VV scattering ….
- Precision SM physics
  - Top Factory
  - EWK precision studies, …
- Search for new physics in very rare processes
  - Characterize any New Physics discovered during Phase 1 @ 14 TeV

"CMS at the High-Energy-Frontier", Input to the Update of the European Strategy for Particle Physics, CMS-Note 2012/006

| Coupling | Uncertainty (%) | | | |
|---|---|---|---|---|
| | 300 fb$^{-1}$ | | 3000 fb$^{-1}$ | |
| | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 |
| $\kappa_\gamma$ | 6.5 | 5.1 | 5.4 | 1.5 |
| $\kappa_V$ | 5.7 | 2.7 | 4.5 | 1.0 |
| $\kappa_g$ | 11 | 5.7 | 7.5 | 2.7 |
| $\kappa_b$ | 15 | 6.9 | 11 | 2.7 |
| $\kappa_t$ | 14 | 8.7 | 8.0 | 3.9 |
| $\kappa_\tau$ | 8.5 | 5.1 | 5.4 | 2.0 |

Scenario 1: systematics as in 2012
Scenario 2: theory syst. scaled by a factor ½, other systematics scaled by 1/√L




*"Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. (...) "*

Whitepaper "Update of the European Strategy for Particle Physics"