PIXEL 2016

Highlights

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UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique nucléaire et corpusculaire

Workshop format

- I liked very much the format of PIXEL2016, which allowed discussion of
  - present/past/future pixel detectors
  - ample time for physics motivations and achievements
  - detector layouts
  - sensors R&D
  - X-ray science
  - …

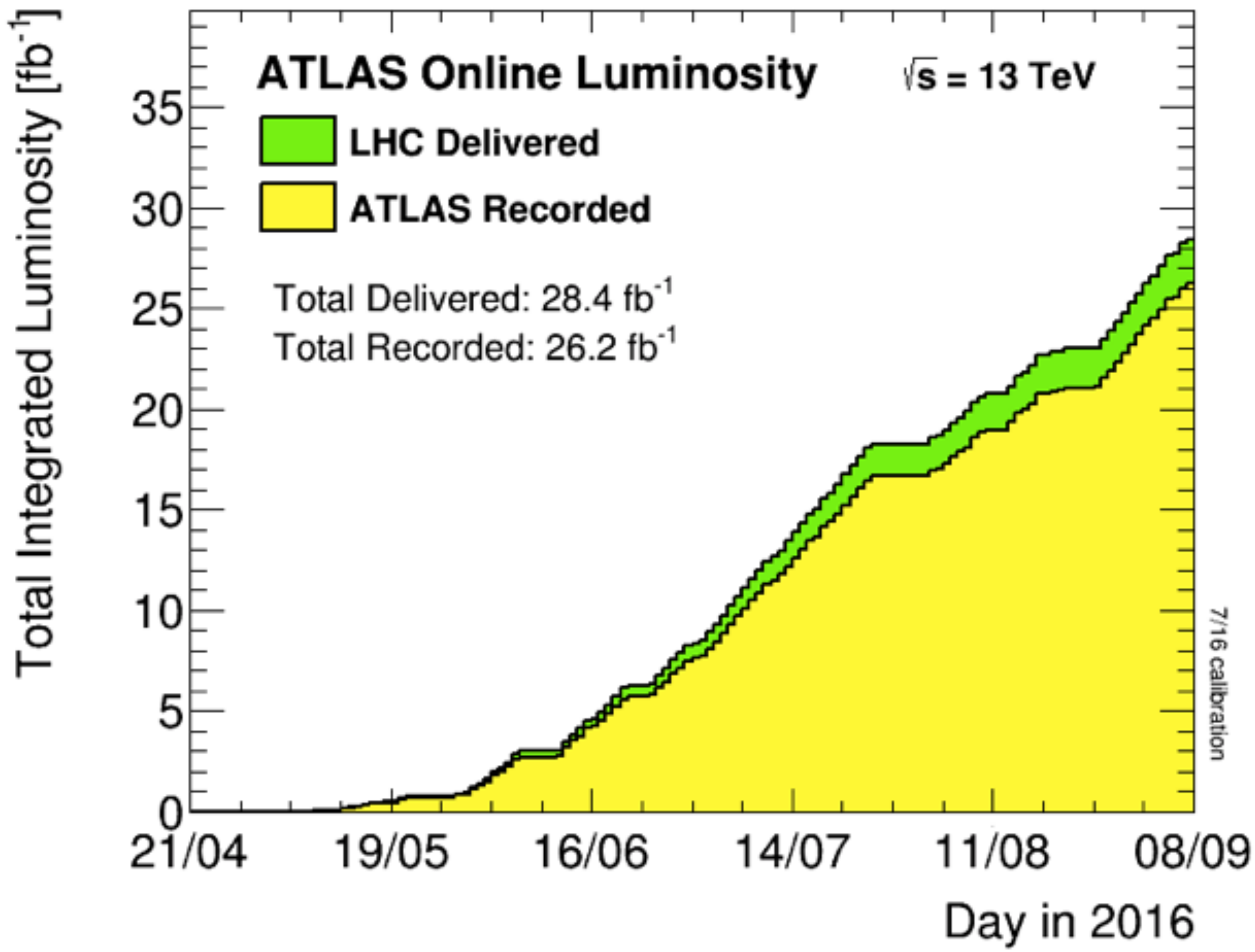
Ideal for (young) people working on the hardware.

Congratulations to the organisers

for the ideal format and the successful workshop

ATLAS and CMS running

The context



LHC is delivering **~0.4 fb^{-1}/day** !!

very clever people in the LHC control room

need of very clever people in the experiment's control rooms

Operation of pixel detectors

- … **fun ?** Life in LHC control rooms is **VERY hard**.

  ➡ We all should be EXTREMELY grateful to all the colleagues operating these fancy and delicate detectors. Annalisa, Kerstin, János and Giacomo showed us how many problems need to be solved for an efficient operation.

  ➡ I take the example of the ATLAS IBL, my experiment:

  - stave distortion vs. temperature (→ K. Lantzsch)
  - front-end LV current drift with exceeding TID (→ K. Dette)
  - prevention: mitigation of bandwidth limitation in B-layer (→A. La Rosa)

life is hard but

But life is also rewarding

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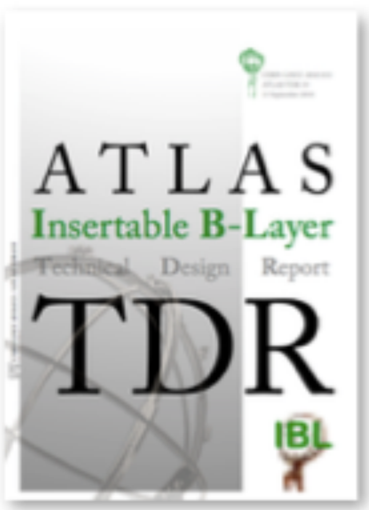
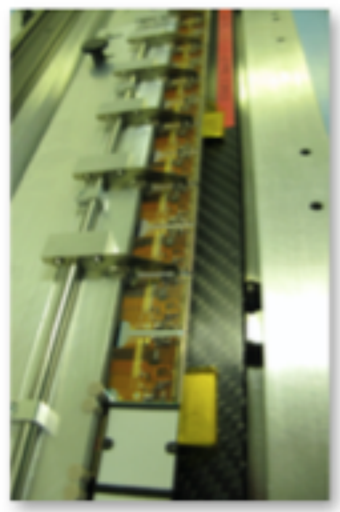
Summary (from A. La Rosa talk)

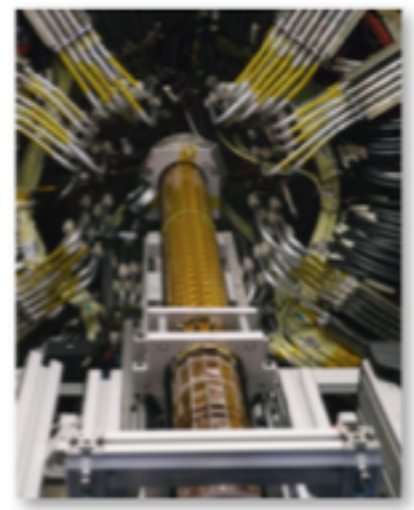
September 2010



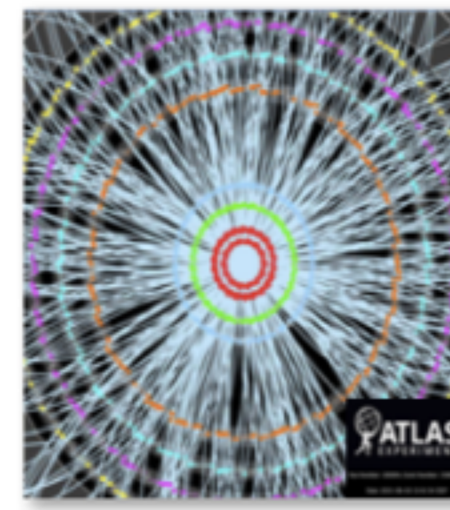
Mid 2012



May 2014



Since May 2015



The Long-Shutdown-1 was realized as an opportunity and finally a great success for the Pixel Detector upgrade:

- **4th Layer Pixel (IBL) successfully installed and in operation with good performance**
- **First** and **successful use-case** of **3D-Si** sensors in HEP experiment !

Now 3D also in: CMS-TOTEM PPS from next shutdown → Fabio Ravera
& ATLAS-AFP→ Sebastian Grinstein

But life is also rewarding

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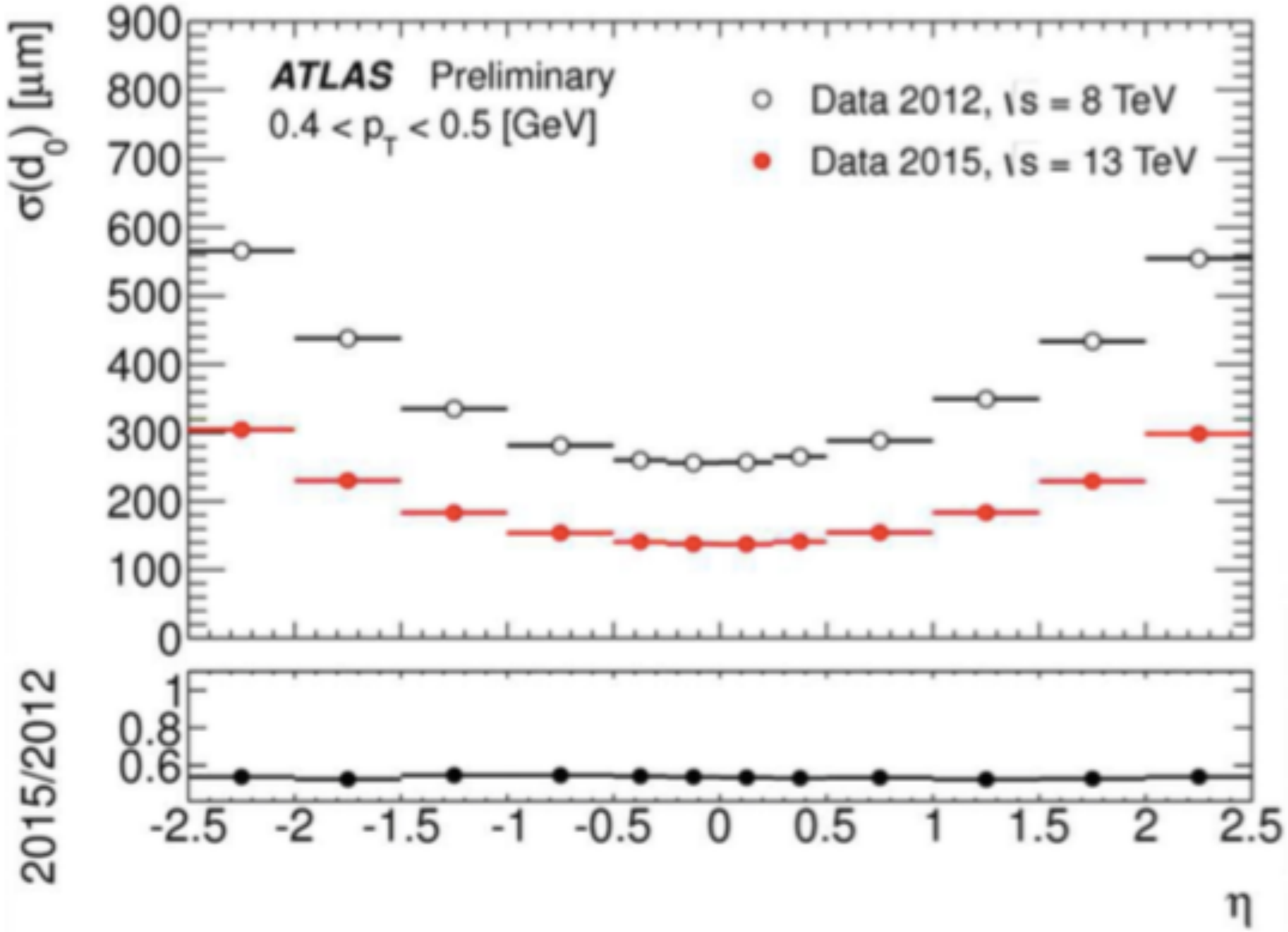
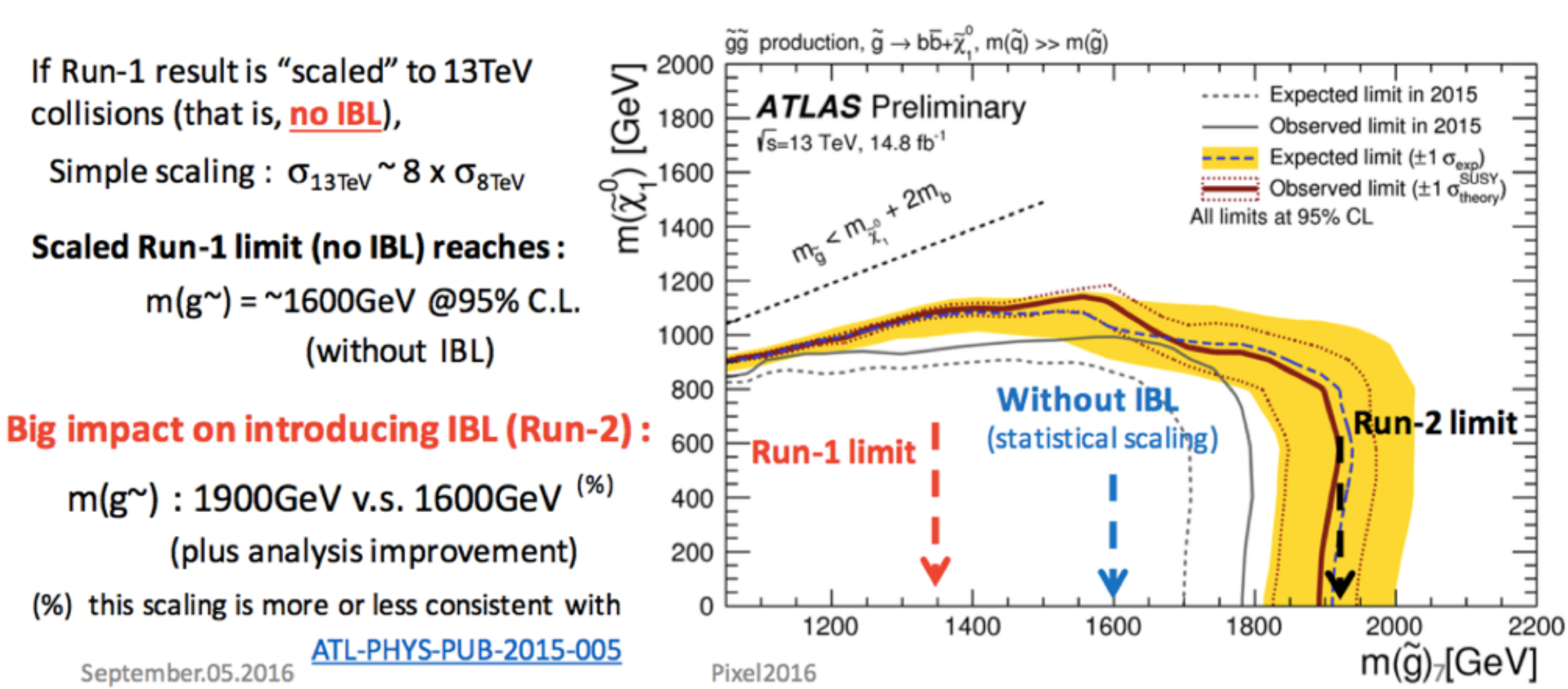


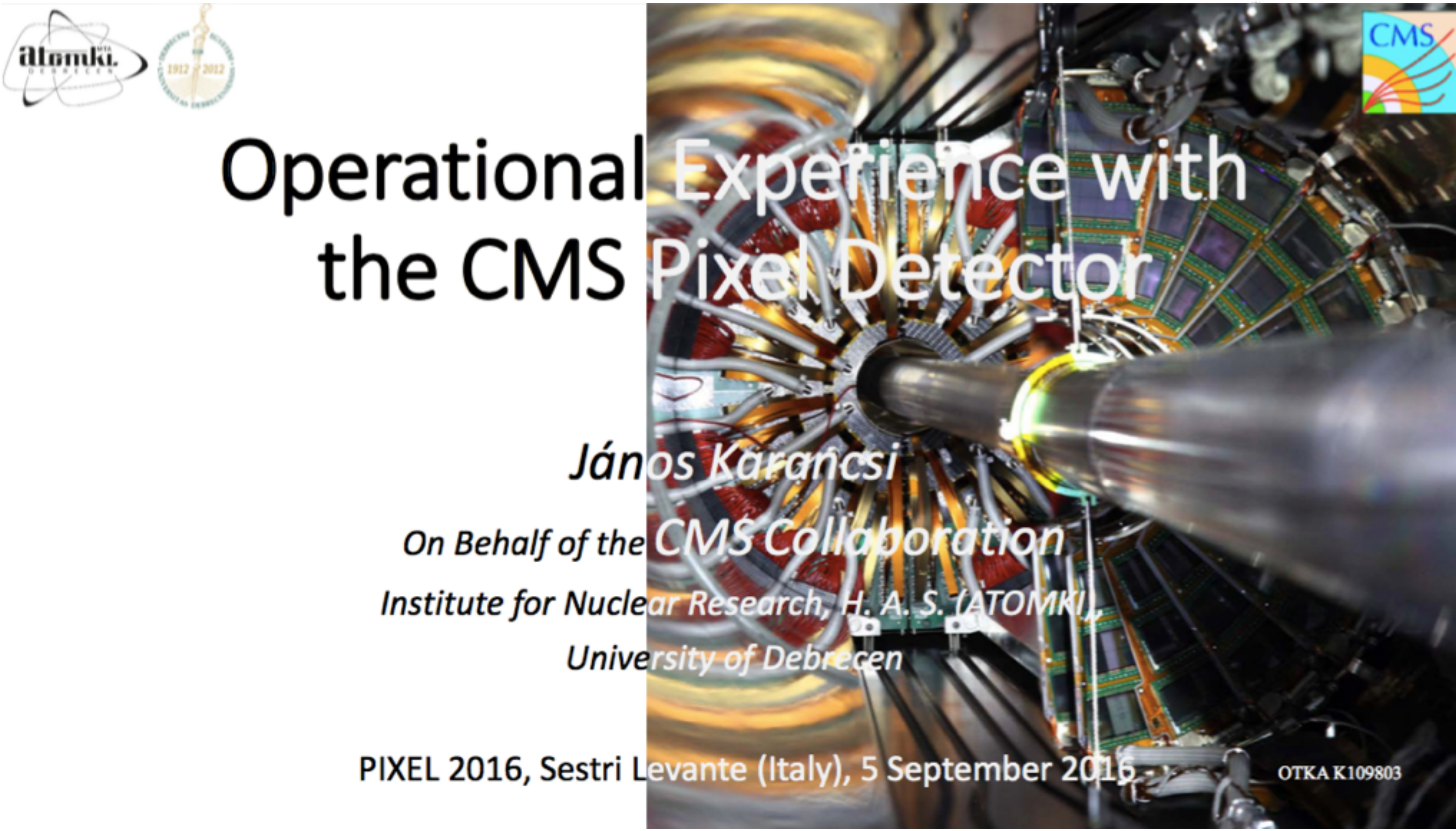
d_0 resolution vs. η
Red: with IBL
Black: without IBL

factor ~2 improvement in track d_0 impact parameter

But life is also rewarding

- talk by Soshi Tsuno:
  - ➡ 65% of analyses uses b-tagging, for which the PIXEL detector is essential, in particular for multi b-tagged processes:





Similarly for CMS Pixel:

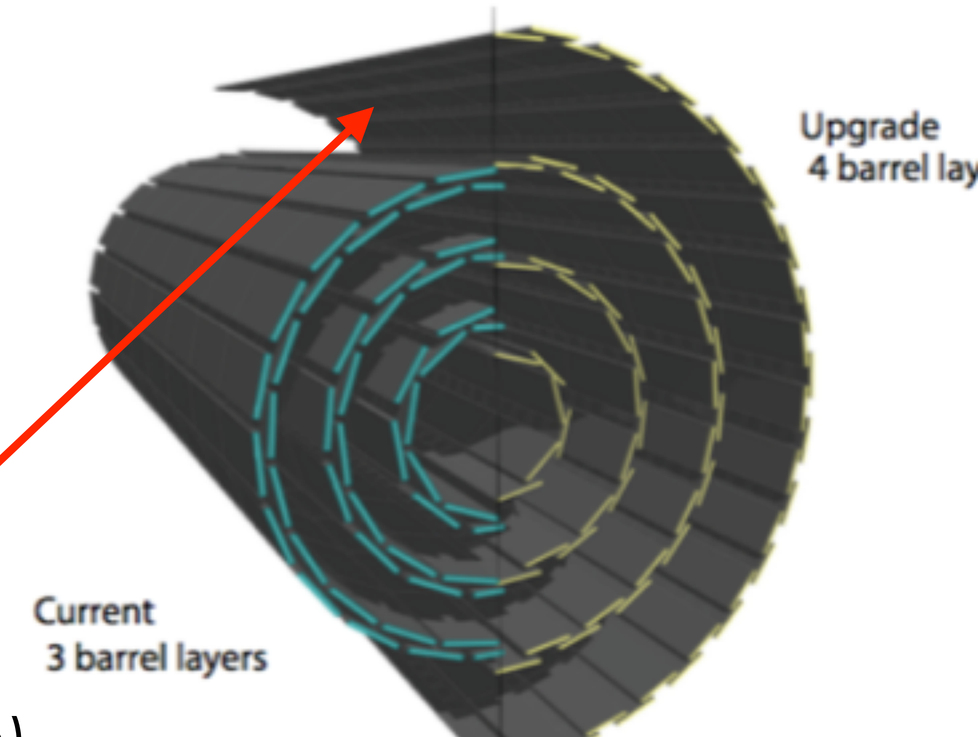
- successful commissioning in Run2
- working fraction is high: 98.7%
- very good overall performance

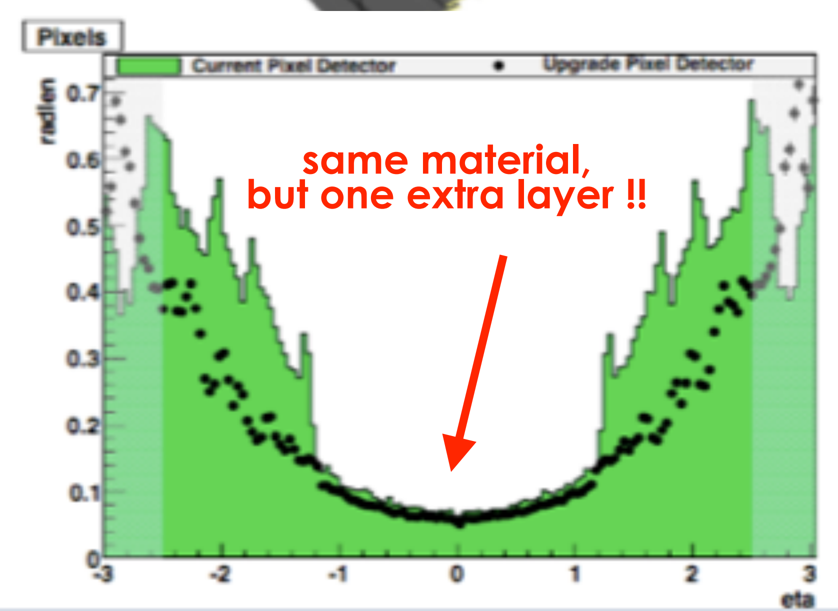
the near future

CMS new pixel for Phase 1

In LHC Phase1, we expect $2*10^{34} cm^{-2} s^{-1}$, which exceeds the capability of present CMS Chip (ROC) and data links

- New pixel for CMS to maintain or improve at higher lumi present performance (→ V.R. Tavolaro, A. Starodumov).
- Unchanged:
  - ➡ pixel size, sensor technology, module concept
- New features:
  - ➡ New readout chip for higher rate capability
  - ➡ Additional barrel layer and endcap disk
  - ➡ First layer closer to interact. point (30 → 22.5mm)
  - ➡ Reduced material budget; new CO_2 cooling
  - ➡ Lower operational threshold





Module production reaching completion.

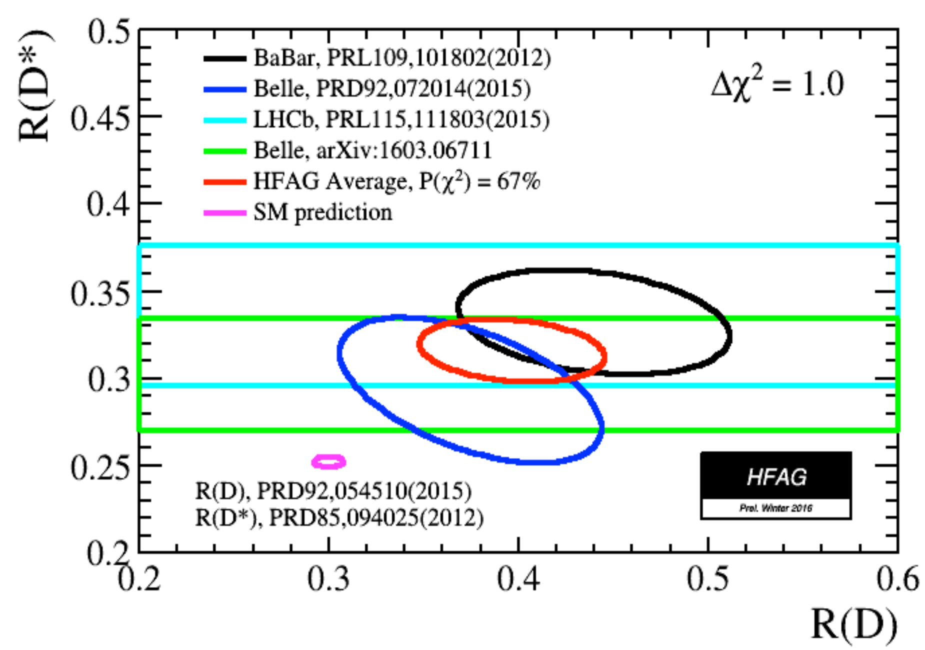
Installation during 2016-2017 EYETS

Other pixel detectors,

- CORE components of important experiments looking for BSM
  - ➡ **NA62,** with its GigaTracker with micro-channel cooling and 200ps time resol.: $K^+ \to \pi^+ \nu\nu$ decay, SM BR: ~10^{-10} , 40events x 2years (2016-2018)
  - ➡ **μ3e**, featuring 2 x 0.%1X_0 monolithic layers and 1.25Gb/s links (F. Aeschenbacher): $\mu^+ \to e^+ e^+ e^-$ charged-lepton flavour violation at 10^{-16} (from 2019)
- and also solve puzzles from presently running experiments:
  - ➡ **Belle-II PXD**, with its two-layers of 75μm thick DEPFET, to take 40xlumi of Belle to solve present anomalies in the flavour sector and look for new physics:

$$R(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)} \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^{(*)} \ell^- \overline{\nu}_\ell)}$$

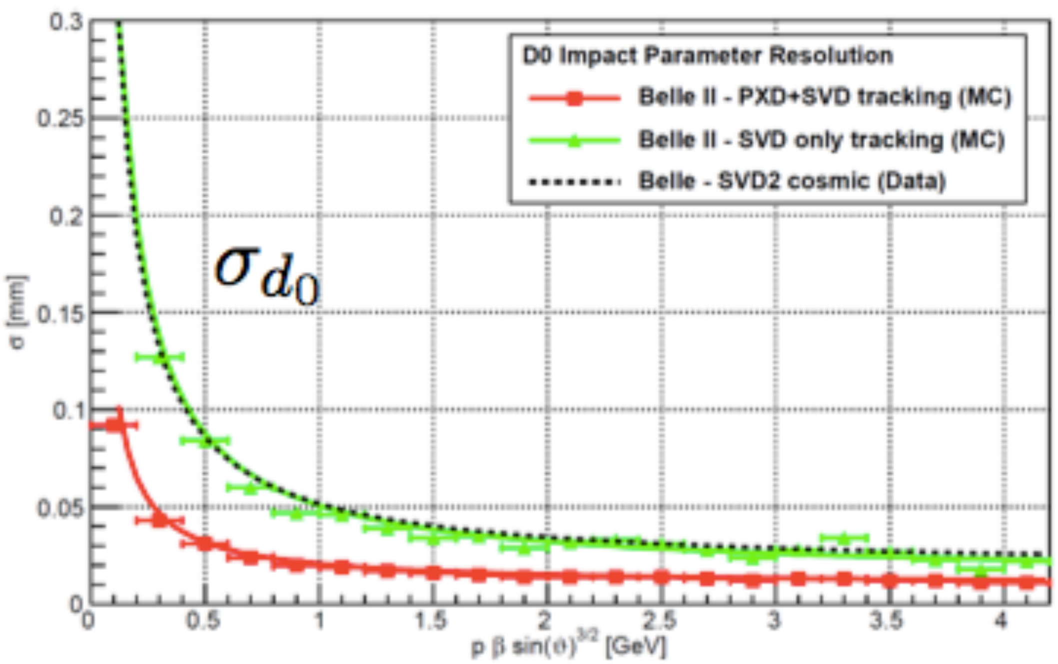
~4sigma discrepancy

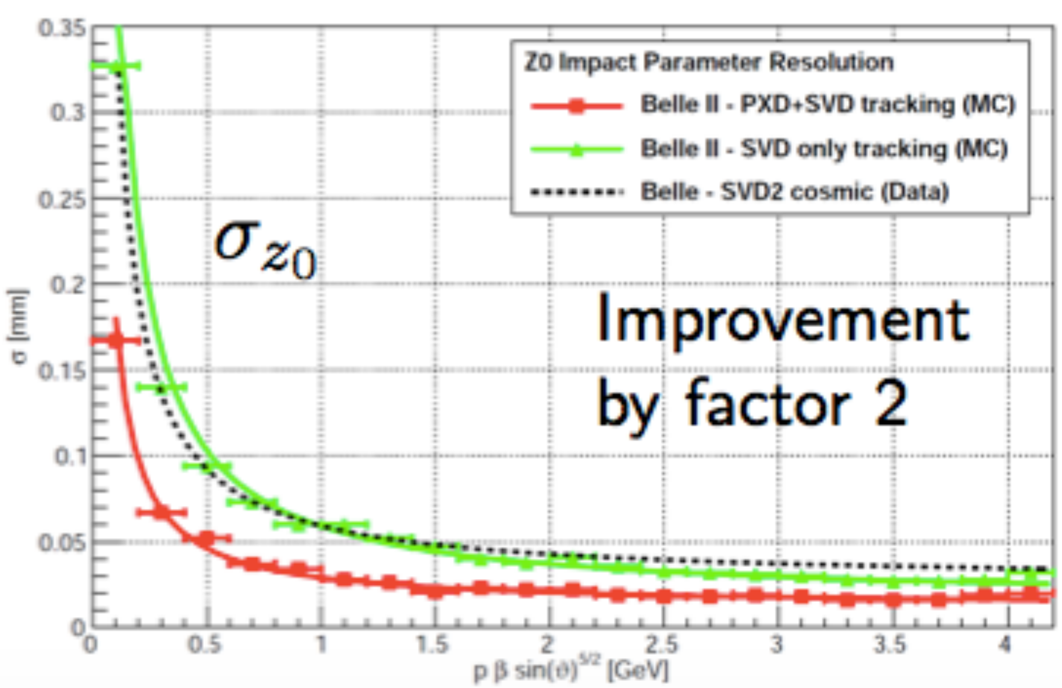


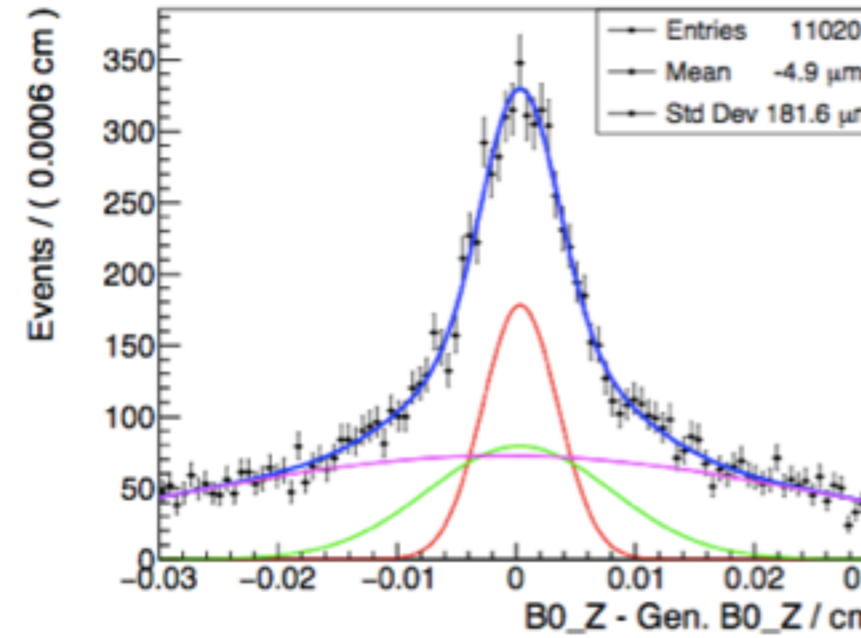
Belle-II PxD:

Fernando Abudinen

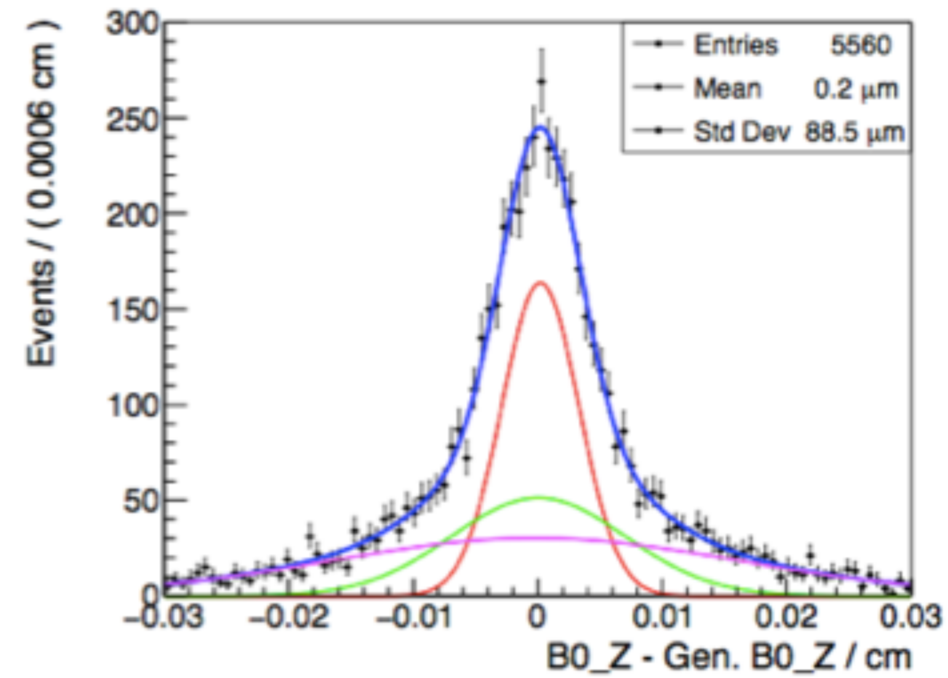
$$B^0 \to \pi^0 \, \pi^0$$
$$\hookrightarrow \gamma \, \gamma$$
$$\hookrightarrow e^+ e^-$$





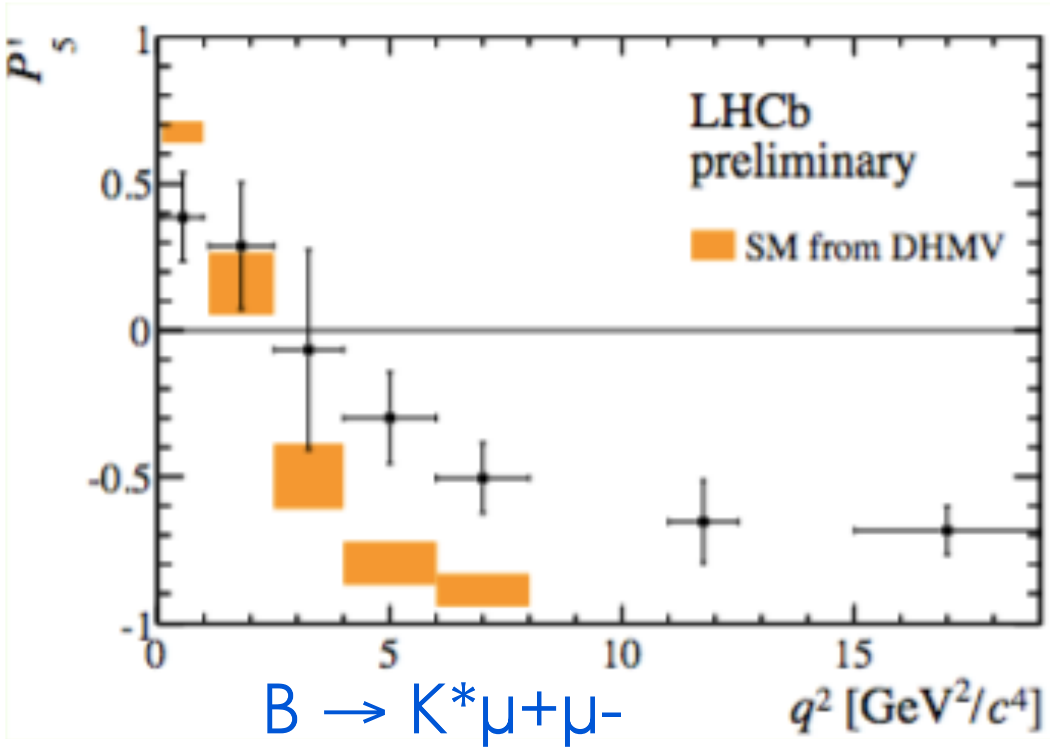


No PXD Hit required

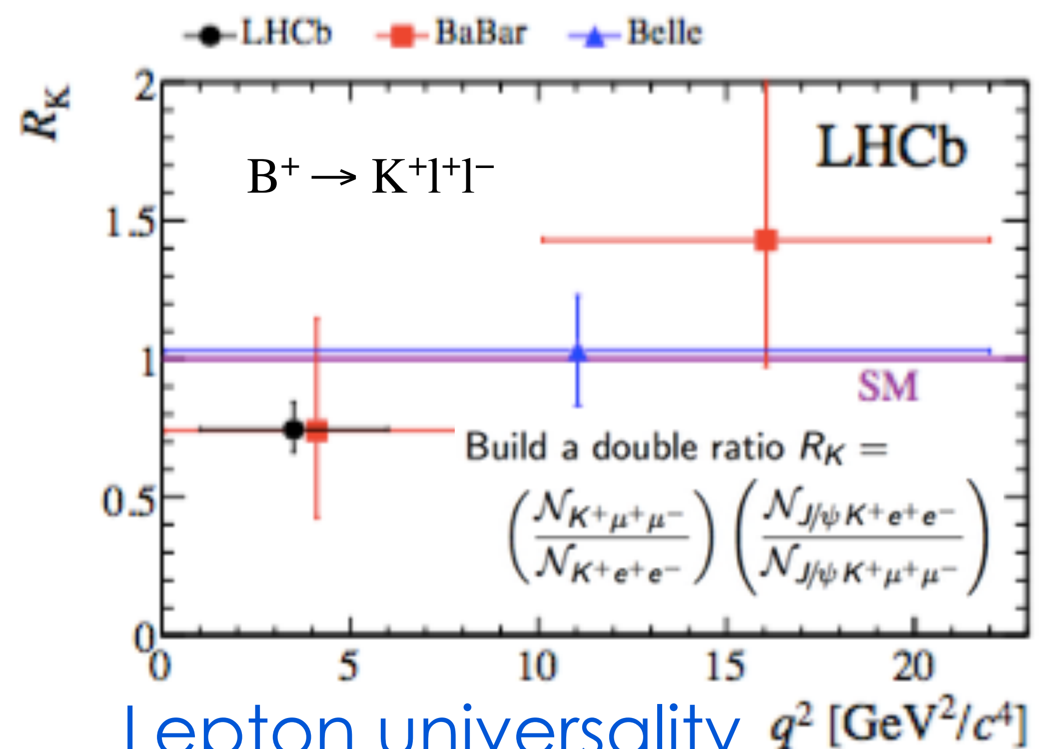


At least one track (e^+ or e^-) has one PXD Hit

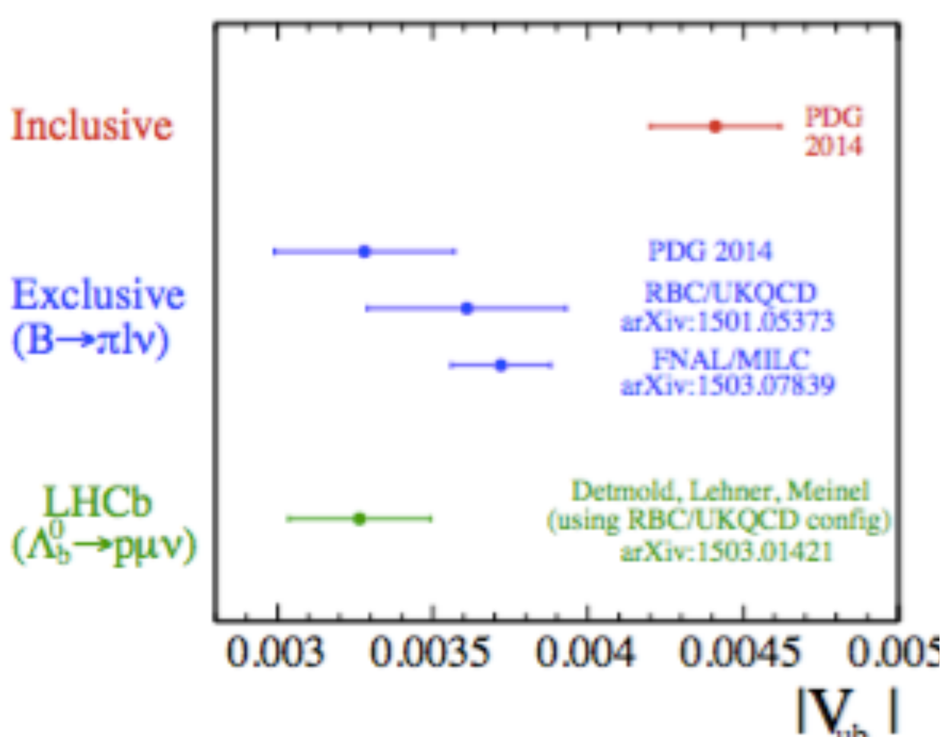
a handful of intriguing 3-4 σ anomalies from LHCb



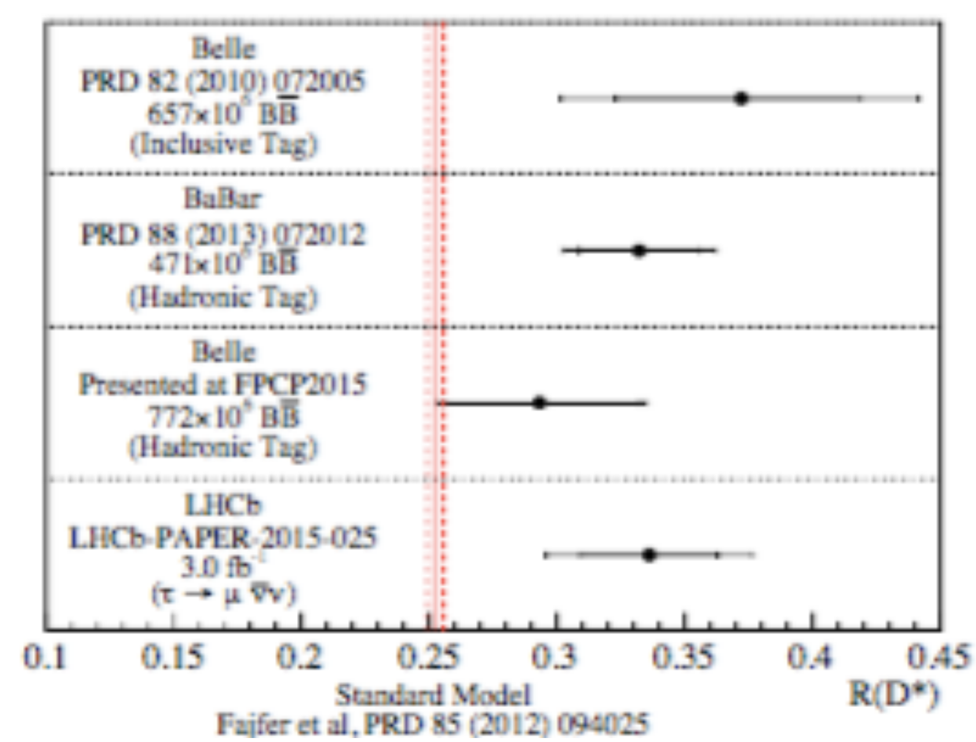
B → K*μ+μ-



Lepton universality



V_{ub} puzzle



B → D*τυ


The VELO Pixel
Detector Upgrade
Emma Buchanan
University of Bristol
On behalf of the LHCb VELO Upgrade Group
Pixel 2016, 5th September 2016, Sestri Levante

LHCb Phase 1 upgrade

- Increased statistics for improved sensitivities to very rare decays
- Limited from present 1MHz readout ⇒ get rid of trigger and readout all data at 40 MHz;
  - needs upgrade of FE electronics and of tracking
  - **Pixel VErtex LOcator**: from silicon strip to hybrid pixels
    - ➡ thinner sensors (300 -> 200 μm)
    - ➡ **VELOPix chip**: readout rate 40 MHz with 20Gb/s output bandwidth (130nm CMOS technology); doable since fixed-target geometry ⇒ material outside of acceptance volume
    - ➡ closer to the beam (8 -> 5.1 mm), in the secondary vacuum

Installation in 2019/2020

ALICE new ITS

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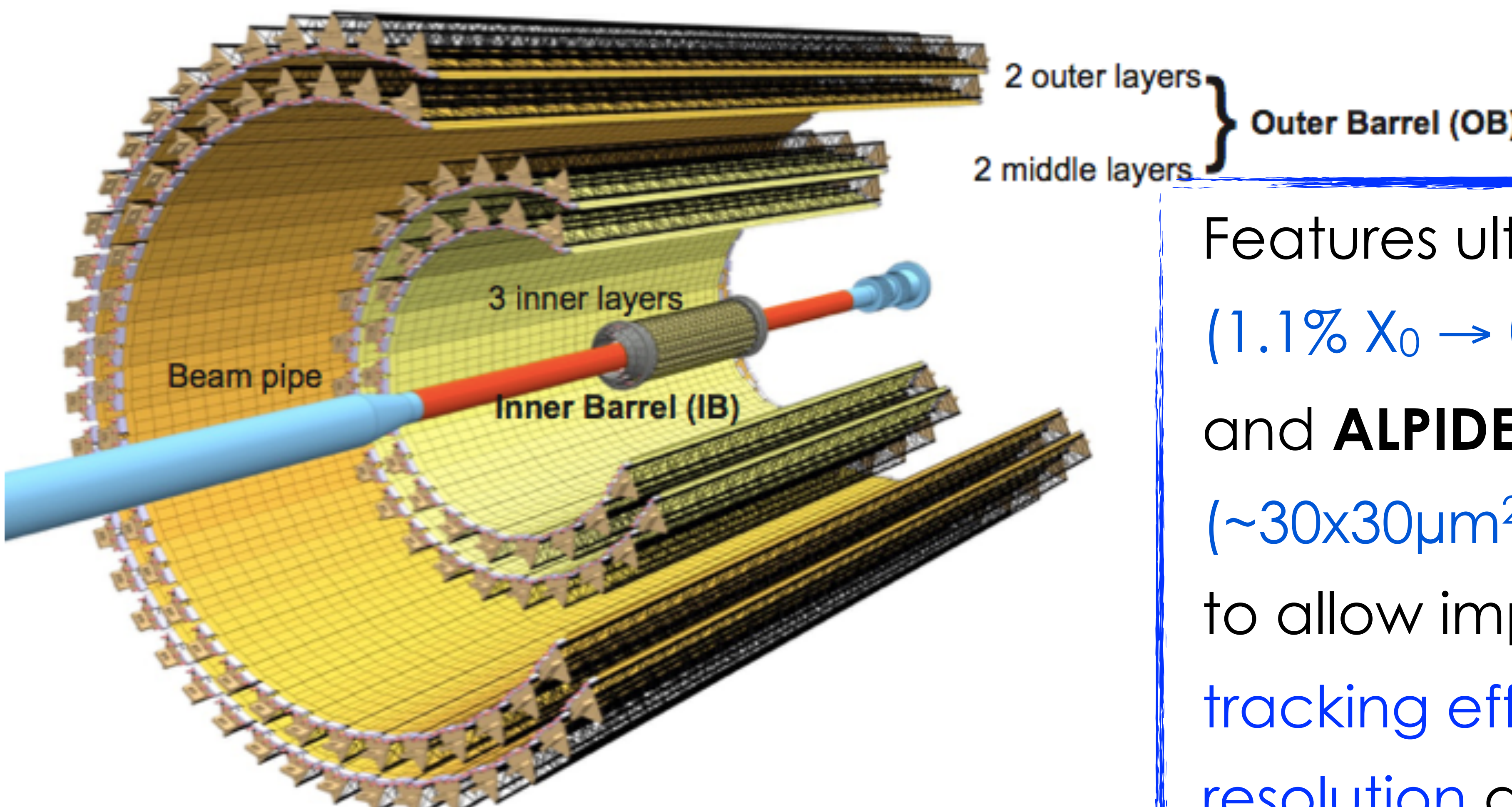
A Large Ion Collider Experiment

The Upgraded ITS

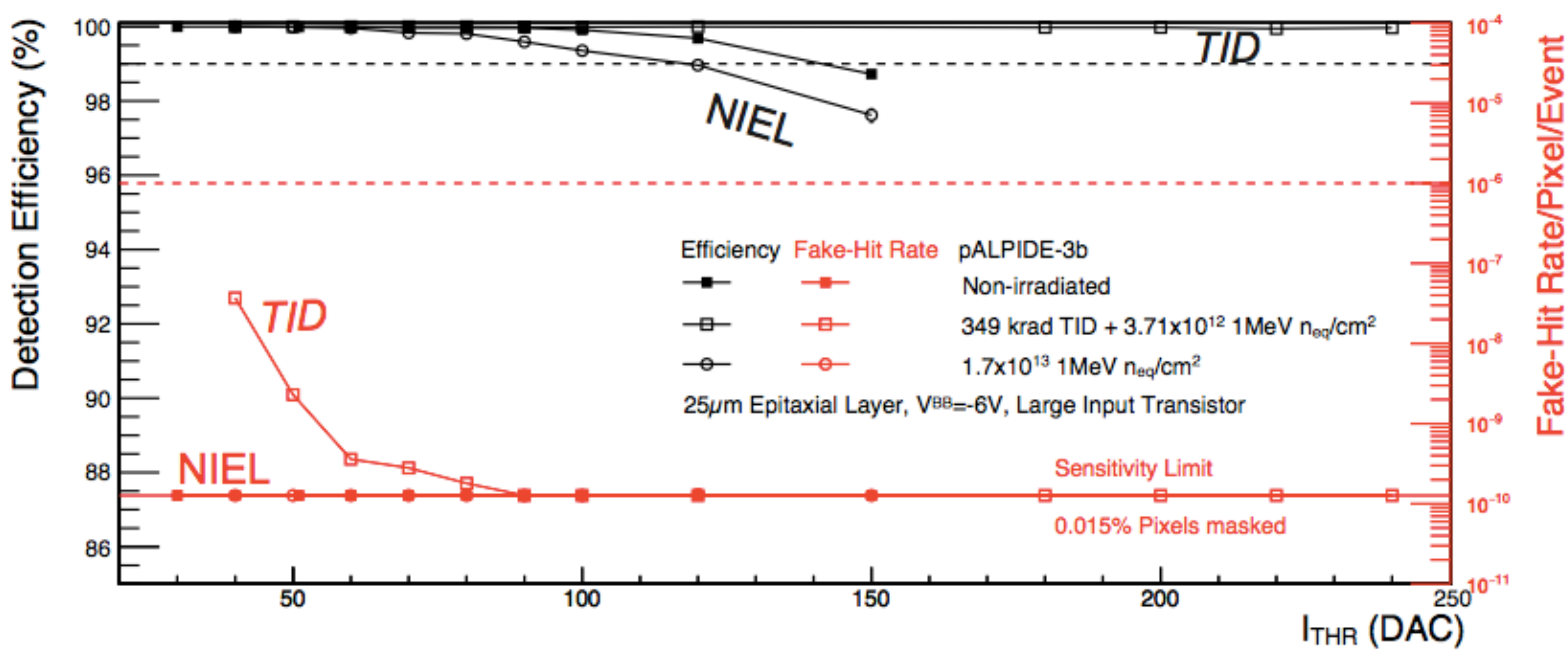


- 7 layers
- 12.5 Gigapixels
- Binary readout
- ~ 10 m^2 active surface

50µm thick MAPS

Features ultralight mechanics ($1.1\%\ X_0 \rightarrow 0.3\%\ X_0$) and **ALPIDE** monolithic chip (~30x30µm^2, 50µm thick) to allow improvement of tracking efficiency, low-p_T resolution and impact parameter resolution of a factor ~3 in r-φ and ~5 in z at p_T=0.5GeV, as well as

Test Beam Result of a Full-Scale ALPIDE Prototype



- Final pixel layout and front-end circuit selected
- Radiation effects visible
- Large operational margin maintained after NIEL and TID irradiation

Further details in **Miljenko Šuljić's talk** on Thursday

Wafers of final ALPIDE chip delivered and being tested

- In parallel to these upgrades, the experiments are seeing important steps forward in the software tools
    - for present trackers
    - and for HL-LHC trackers
- Pick one of the several works submitted to this workshop:

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Tracking In Dense Environment

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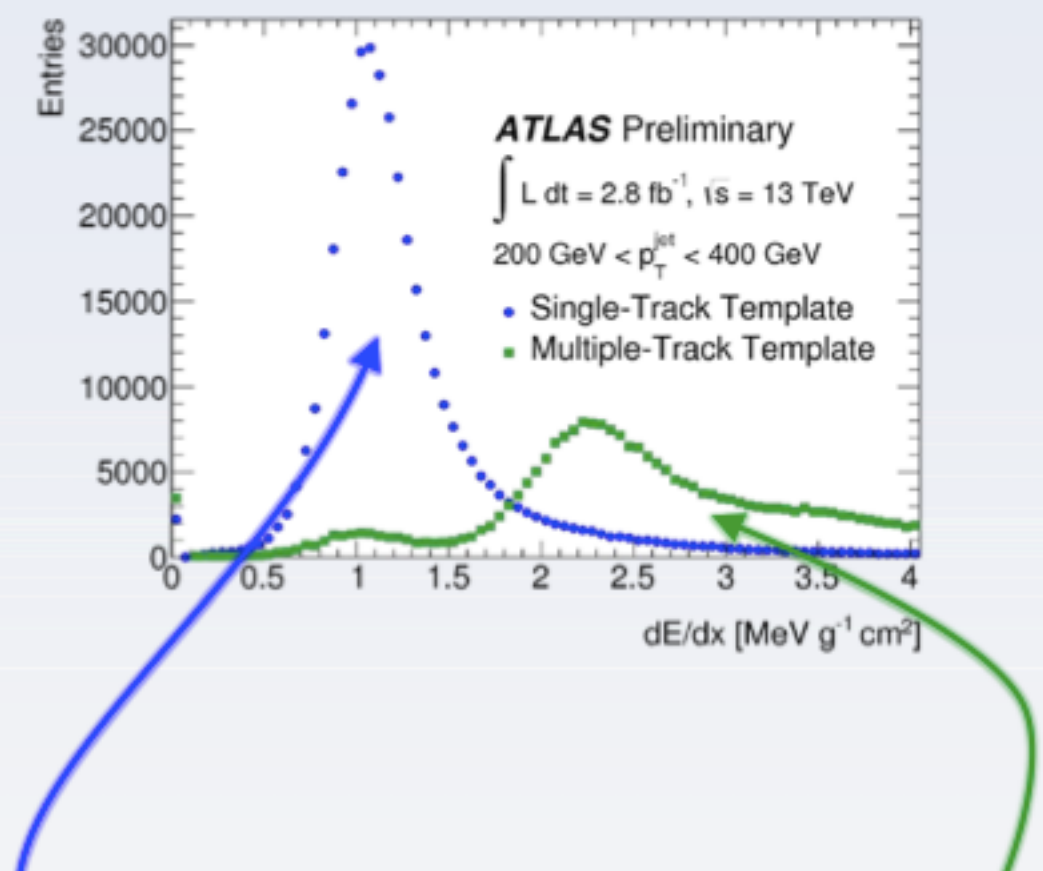
- Jason Mansur showed how T.I.D.E. for high-p_T jets is important for **b-tagging** and **τ reconstruction** as well as **boosted systems** (for which we need more and more the help of trackers)

  - ➡ Artificial Neural Networks used to detect merged pixel clusters and retain tracking efficiency in jet cores.
  - ➡ Data-driven method to determine fraction of lost hits in jets, that uses the pixel dE/dx measurement.
  - ➡ Result: "tracking inefficiency found to be 1-3.5%, significantly improved since Run1, and in good agreement with simulation"

Again: this is one of many examples I could have taken of what can be done with present detectors by a bunch of good young scientists



- Single particle: peak at MIP energy, two particles: peak at 2x MIP energy
- Ratio of events beneath two peaks gives probability to loose track due to merging

Pixels for X-Ray science

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very interesting session

09:00 - 12:35 Pixel for x-ray science

Convener: Prof. Norbert Wermes (University of Bonn)

09:00 **Development of Pixel Detectors for X-ray Space Science and use in terrestrial applications** *35'*
Speaker: Dr. Andrew Holland (Open University UK)
Material: Slides

09:45 **JUNGFRAU: a pixel detector for Photon Science at free electron laser facilities** *12'*
Speaker: Dr. Aldo Mozzanica (Paul Scherrer Institut)
Material: Slides

10:00 **Low energy and high resolution performance of the MOENCH hybrid pixel detector** *12'*
Speaker: Dr. Roberto Dinapoli (Paul Scherrer Institut)

10:15 **The EIGER detector systems** *12'*
Speaker: Dr. Gemma Tinti (Paul Scherrer Institute)

10:30 **COFFEE BREAK** *30'*

11:00 **Poster Session** *50'*

11:50 **Design and Development of an Event-driven SOI Pixel Detector for X-ray Astronomy and Light Dark Matter Search** *12'*
Speaker: Dr. Ayaki Takeda (Kyoto University)
Material: Slides

12:05 **Evaluation of a pulse counting type SOI pixel using synchrotron radiation X-ray** *12'*
Speaker: Dr. Ryo Hashimoto (High Energy Accelerator Research Organization)
Material: Slides

12:20 **Development of CdTe Pixel Detectors Combined with an Aluminum Schottky Diode Sensor and Photon-Counting ASICs** *12'*
Speaker: Dr. Hidenori Toyokawa (Japan Synchrotron Radiation Research Institute)
Material: Slides

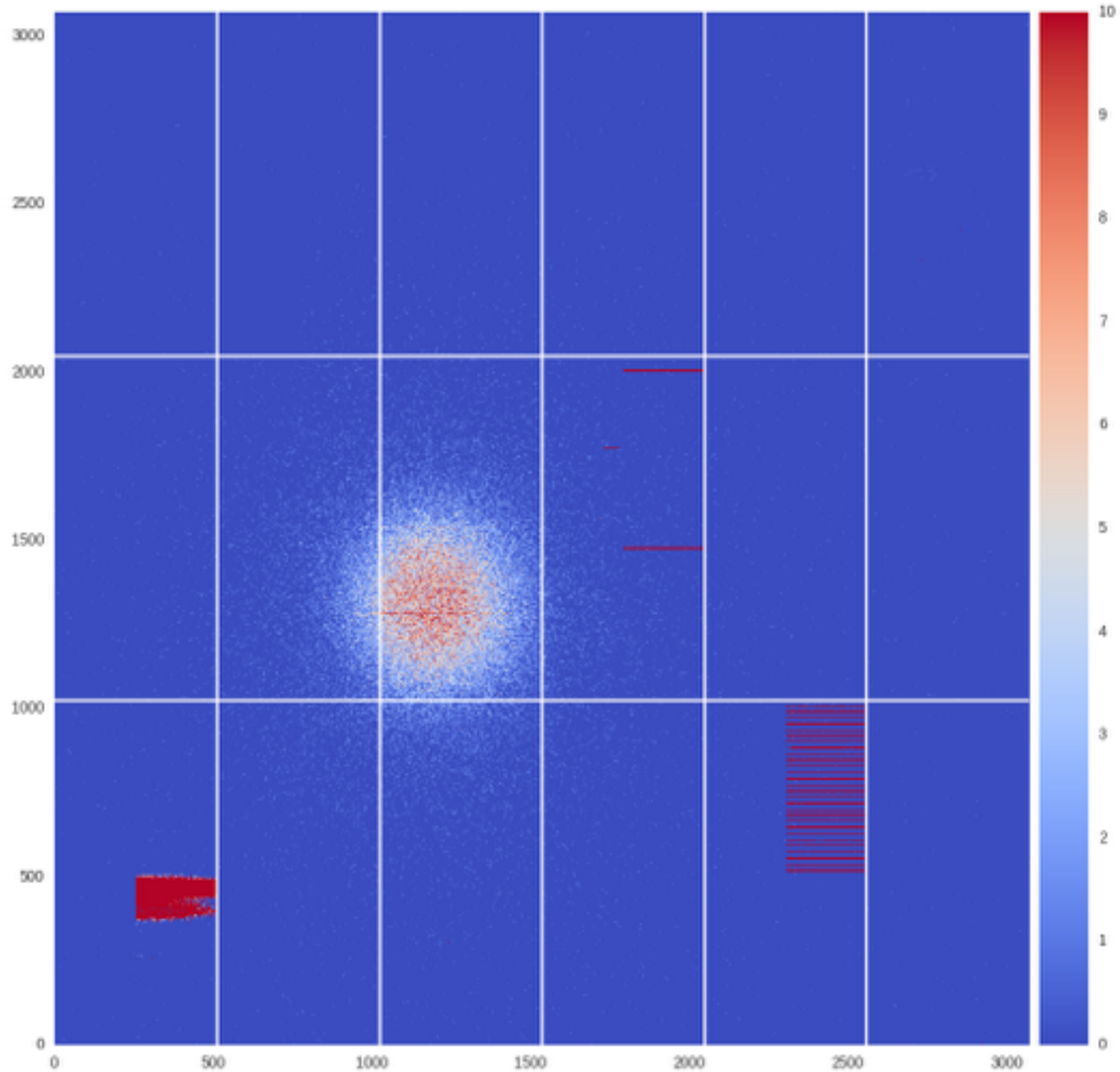
Hybrid Detectors of the SLS Detector group

DETECTOR	Mode of operation	Pixel pitch [µm]	Min. Noise [e-rms]	Maximum frame rate [kHz]	Max. Dynamic range
EIGER	SPI (Synchrotrons)	75	100	22	Up to 32 bits with summation
JUNGFRAU	CI (Synchrotrons +FELs)	75	50	2	~10^4 12keV photons
MOENCH	CI (Synchrotron +FELs(?))	25	35	2	~150 12keV photons

R. Dinapoli

EIGER: 9Mpixel detector (almost) ready

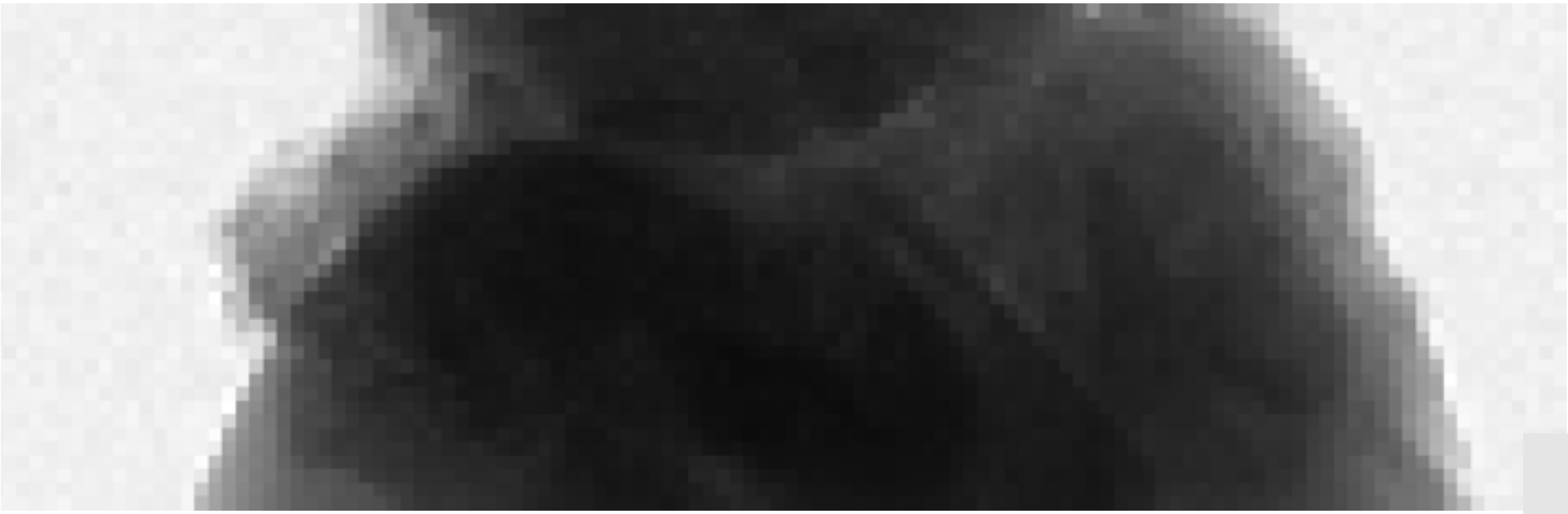
Sr 90 source



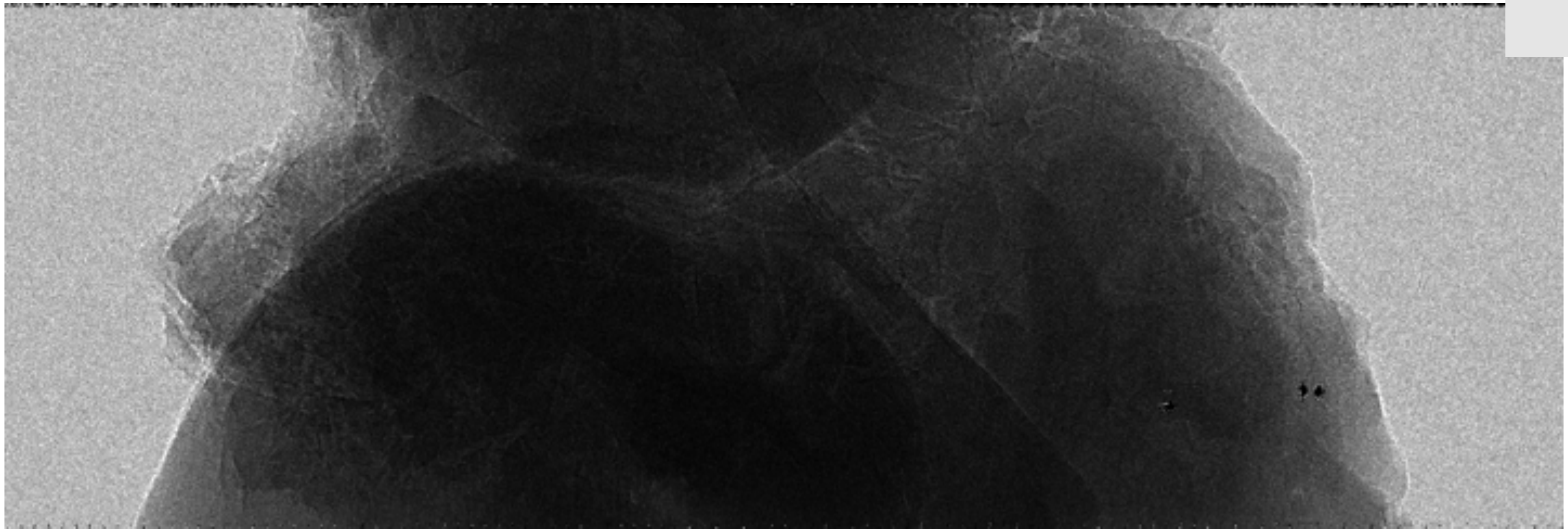
R. Dinapoli

Moench: micron resolution with interpolation

25 µm pixels



Interpolated



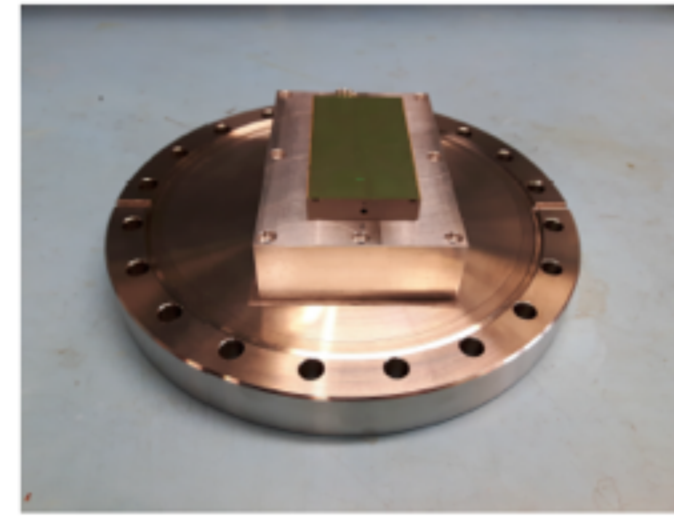
MÖNCH02
TOMCAT 16.7 keV
Kidney stone
2 µm bins

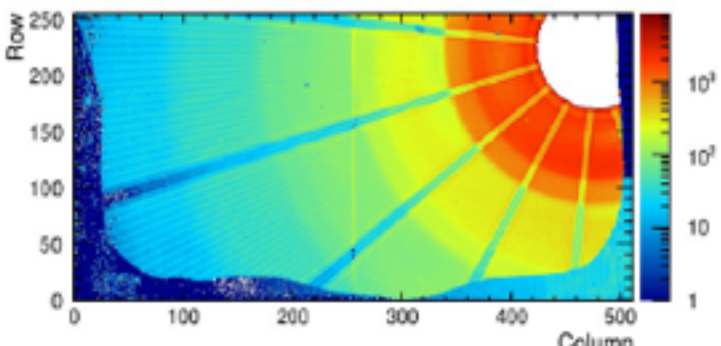
PAUL SCHERRER INSTITUT PSI

Jungfrau: dynamic range up to 10^4 12keV photons

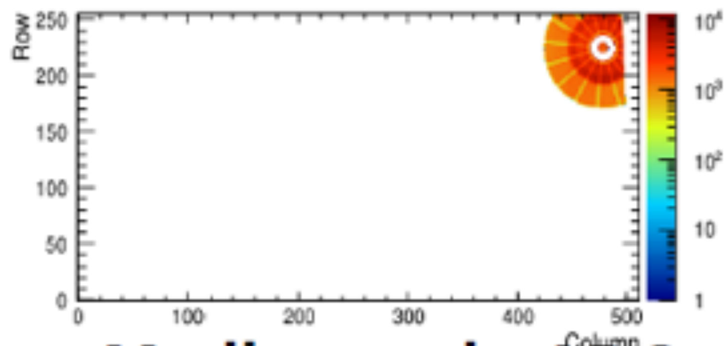
Image of Fresnel Zone Plate diffraction orders at XIL beamline, SLS:

- extreme ultraviolet 92 eV photons
- vacuum 10^{-7} mbar
- etched sensor (no Al), module mounted to flange

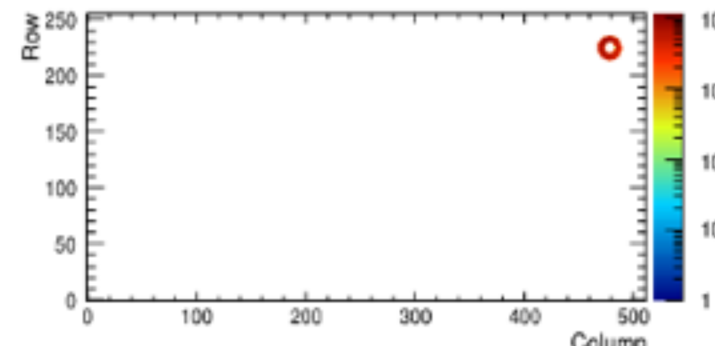




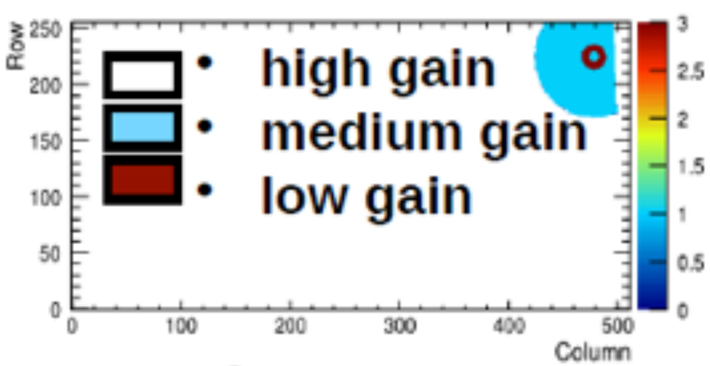
- High gain ADC



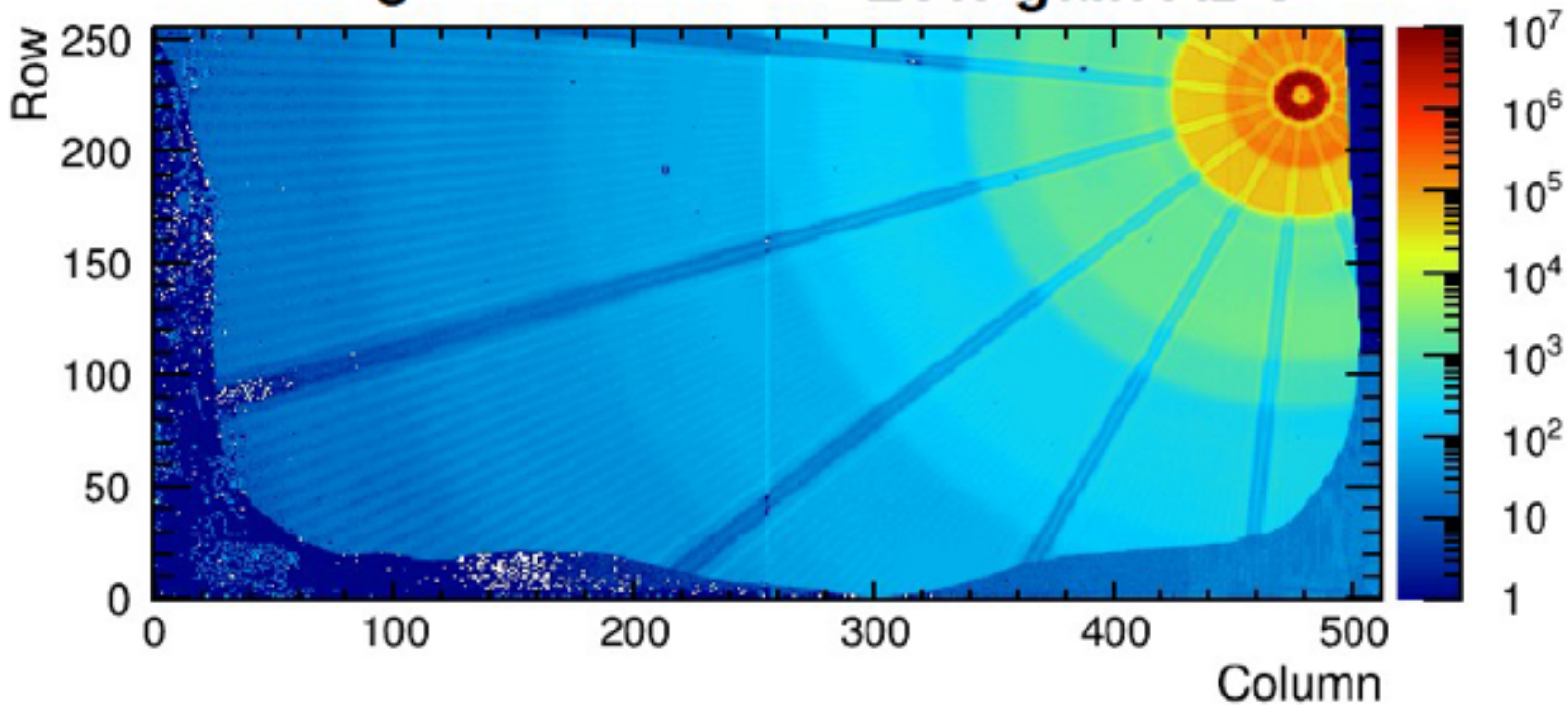
- Medium gain ADC



- Low gain ADC



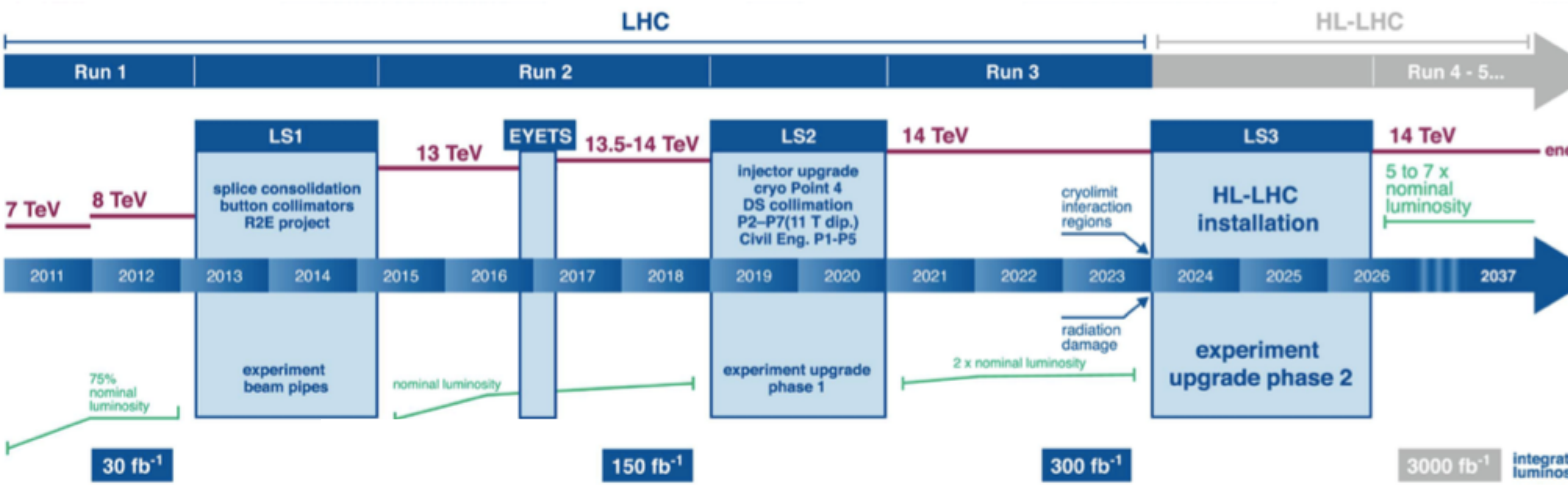
- Gain



R. Dinapoli

Do you by chance know these guys? ;)

PIXELS for the HL- LHC



High-Luminosity LHC:

approved CERN project to collect 3000 fb-1 (2026-2035)

PIXELS for the HL- LHC

- Very nice and thorough presentations on the HL-LHC conditions, challenges and progress towards the TDR's for the CMS and ATLAS pixels given by M. Garcia-Sciveres (with ref. to talks therein) and P. Morettini.

Performance

- Don't just want to do the same job with larger scale and higher intensity, want to do better!
  - Separation of boosted objects → Higher granularity yes, but can go further using clusters (Mansour, 9:15)
  - Suppression of pileup activity → Z-vertex separation (Smart, Migliore), timing (Seiden, Cartiglia; Mon., Neri, 12:10, Mulargua [P])
  - Higher rapidity coverage → Innovative layouts (Smart, Migliore) Which need lighter services!
  - Much higher trigger rate (all events look the same at high p/u) → Readout, track triggers Morettini, Kornmayer, Neri, 11:05)
  - Lower mass (also services) → Better cooling, new materials (Anderssen, Verlaat, Fri. 9, 10)
  - Faster pattern recognition → Dedicated hardware, Use more information (clusters shapes, timing)

Sept. 6, 2016 From LHC to HL-LHC – M. Garcia-Sciveres 23

PIXELS for the HL- LHC

<u>Enormous</u> challenges. Not exhaustive list of challenges:

- **Data extraction**: 40MHz readout (like Cal and Muon) impossible for innermost pixel layers since at R=39mm ~1Gb/s per cm^2 and per triggered MHz
  - ➡ at 40 MHz, would need to transfer ~160Gb/s per chip !
  - ➡ Since optical conversion stages not radhard enough we should fill the detectors with cables ! That we certainly do not want to do.
  - ➡ put optical links outside detector volume
  - ➡ use flex, twisted-pairs or micro-coaxial cables
  - ➡ **~5Gb/s/chip possible** over a length of ~5m ⇒ trigger rate of ~1MHz
  - ➡ readout chip: need small feature (65nm) technology
- **Trigger**: two approaches
  - ➡ self seeded tracklets (CMS) (→ E. Migliore)
  - ➡ two-stage (L0/L1) trigger (CAL+MUON at 40MHz, tracker at ~1MHz, ATLAS) (→ P.Morettini)

PIXELS for the HL- LHC

<u>Enormous</u> challenges. Not exhaustive list of challenges:

- **Mechanics, cooling:**

  Two main enabling technologies for HL-LHC:
  - CO_2 Evaporative Cooling → B. Verlaat
  - High thermal conductivity materials and adhesives → E. Anderssen

- **Powering:** serial power distribution (under development) seems the only possible solution

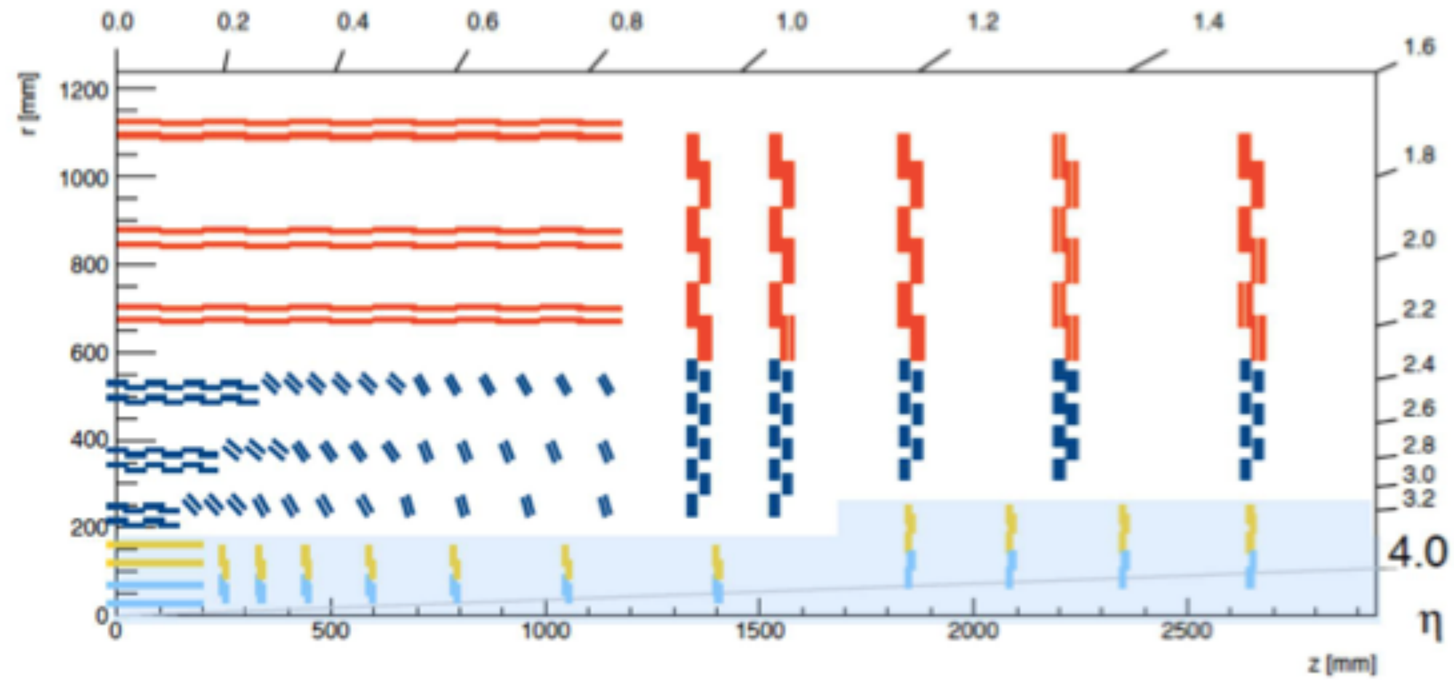
- **Radiation doses**: **1 Grad** and **$1.4 \times 10^{16} n_{eq}\,cm^{-2}$** in innermost layer (R=39mm)
  - ➡ **3D sensors**: 97.8% efficient and 15mW/cm^2 at $10^{16} n_{eq}\,cm^{-2}$ for IBL/AFP sensors; HL-LHC (50x50μm2) submitted (→ J. Lange). Question on production capability ??
  - ➡ **planar**: 100μm thin n-in-p ~97% and 25mW/cm^2 at $10^{16} n_{eq}\,cm^{-2}$ (→ A. Macchiolo). See very interesting talks by Nobu, Andrea and Richard on their recent work.
  - ➡ **CMOS**: very active community, many solutions being studied. I'll comment later.

CMS Pixel Detector design for HL-LHC

E.Migliore
Università di Torino/INFN

on behalf of the CMS Collaboration

The CMS Tracker in the HL-LHC scenario

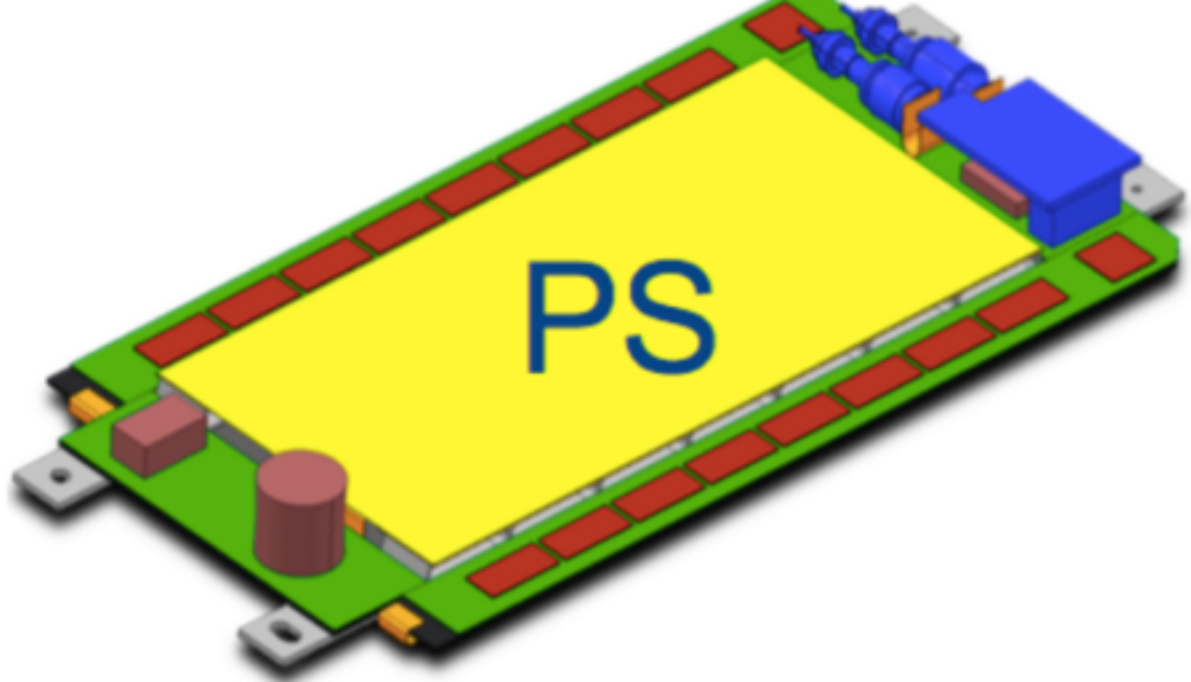


- Additional functional requirements for the overall Tracker:

REQUIREMENT	MOTIVATION
extended coverage	contribute to pileup mitigation (PF) up to $\|\eta\|\sim 4$
high granularity	robust two track separation in high energy jet
low material budget	improve tracking performance/momentum resolution measurement
measure pT>2 GeV tracks at 40 MHz	contribute to L1 trigger
deep front end buffers and higher readout bandwidth	compatible with 12.5 μs L1A latency and 750 kHz L1A trigger rate

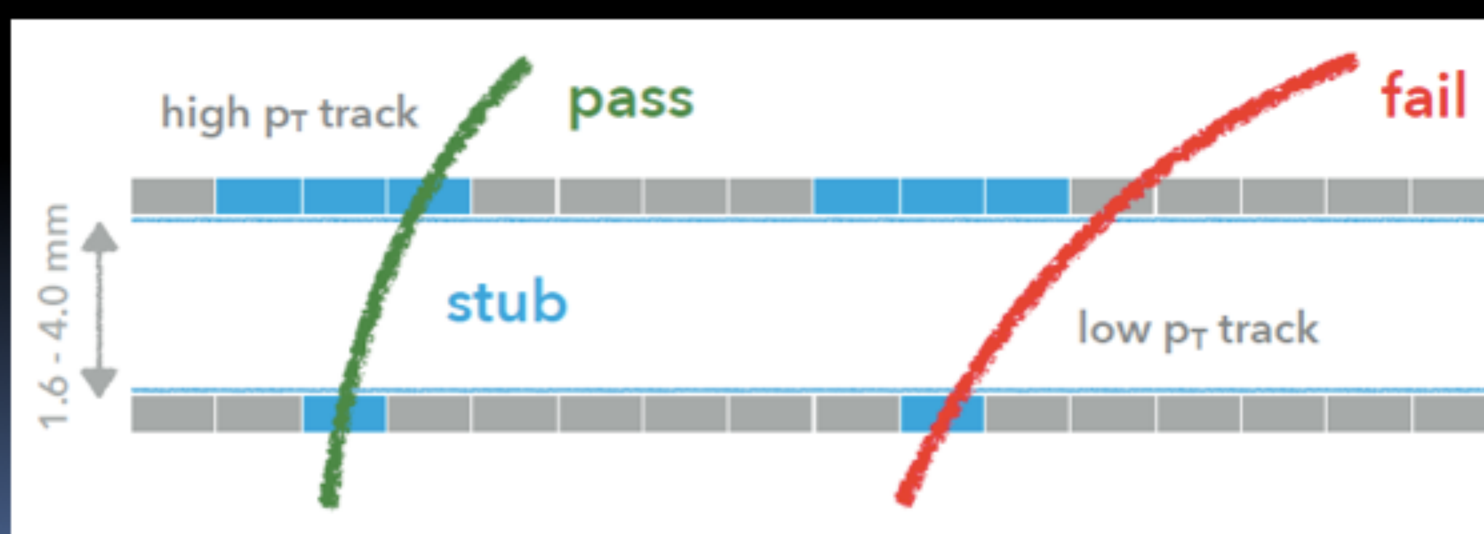
They all have implications on the design of the Inner Pixel!

CMS track trigger
Pixel-Strip module



Self-seeded detectors

- The approach used in the CMS Pixel-Strip and Strip-Strip doublets, in the outer tracker. Here macro-pixels (100 μm x 1.5 mm) are used to get precise z measurement.
- The correlation between two layers can identify high momentum tracks and send them to the trigger processor.
- This approach benefits from the intense CMS magnetic field.



Pixel 2016 6/9/2016 21

Collection of arguments from E. Migliore talk

- Current baseline: planar sensors
  - n-on-p substrate — current detector n-on-n
  - thin sensors (100 μm ≤d≤200 μm) — current detector 285 μm
  - small pitch pixel cell (2500 μm² area) — current detector 15000 μm² area
- Usage of 3D sensors is an option for the layers more exposed to radiation damage.

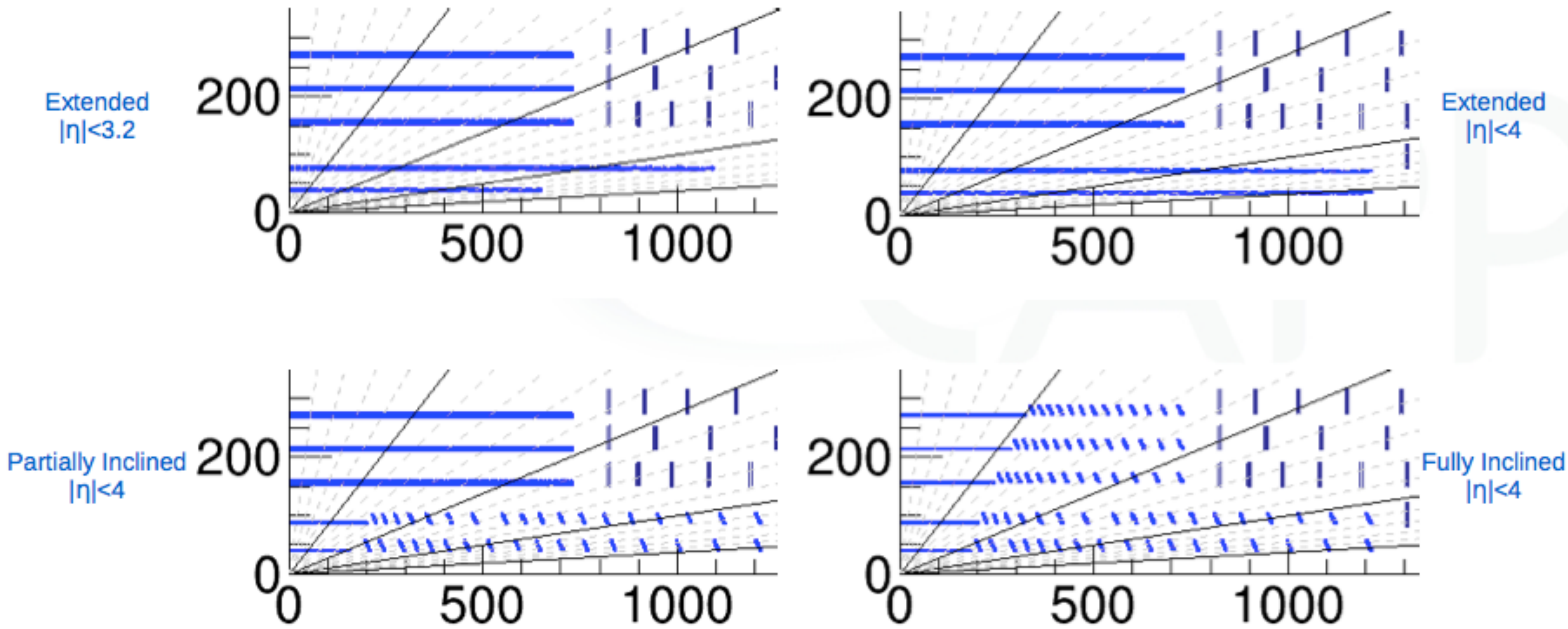
  Sensors with small pitch 3D pixels available (from CNM and FBK).

  Currently processed for bump-bonding of the readout chip.
- Preliminary indications from full-simulation studies on the aspect ratio: in BPIX better performance of rectangular pixels compared to square pixels:
- Last year has seen a focused but considerable effort to converge toward a realistic design of the CMS Inner Pixel for the TDR.
- Key points which will be clarified by R&D activities in the next months:
  - performance of small pitch pixels before/after irradiation
  - performance of 65 nm ROC
  - performance of serial powering

E. Migliore

Inner Detector Upgrades: Pixel Barrel

- Four layouts are under consideration for the ITk pixel barrel:
  Two 'extended' layouts (sensors parallel or perpendicular to beam line).
  Two 'inclined' layouts (with sensors also angled towards the beam-spot).



- All layouts consist of five pixel barrel layers.

decision to be taken soon

and now the holy grail:

NEW
SENSOR
TECHNOLOGIES

Everybody is discussing:

CMOS
CMOS
CMOS
CMOS
CMOS
CMOS
CMOS
CMOS
CMOS

CMOS for PIXELS

- How can ATLAS & CMS take advantage of CMOS sensors ?
  - ➡ passive CMOS sensors bonded to readout chip
  - ➡ CCPD: smart CMOS sensor glued to readout chip
  - ➡ fully monolithic: already a reality in HEP with STAR, mu3e, ALICE

→ production in ~weeks
→ very high yield
→ take advantage of RD53
→ pixel encoding possible

- Several (maybe too many ??) designs and foundries
  - "all of them will work"; testbeam measurements of few mm^2 hv-cmos chips shows: **99.7% effic. at 10^{15} neq/cm^2** with good timing;

    Recent ATLAS 2x2cm^2 submissions (CCPD & MAPS) to AMS and LFoundry
  - Showstoppers ? Can't see for the moment. Still lot of work to do to qualify but large margin to fit all HL-LHC requirements.
    Maybe more collaborative effort needed to qualify them in time (~2018)?

Great contribution from the **CLIC** community, although different requirements (→ see talk of Andreas Nürnberg)

Everybody is discussing:

Timing
Timing
Timing
Timing
Timing
Timing
Timing
Timing
Timing

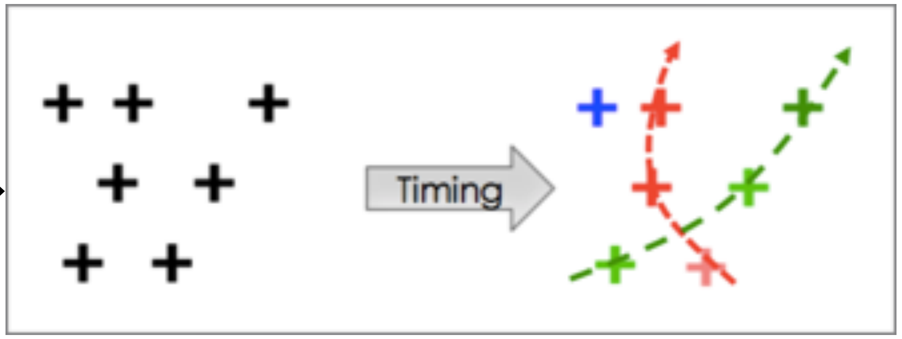
The 4D pixel challenge

Is it possible to build a tracker with concurrent excellent time and position resolution?

Can we provide from the same detector and readout chain:

Timing resolution ~ 10 ps
Space resolution ~ 10's of μm

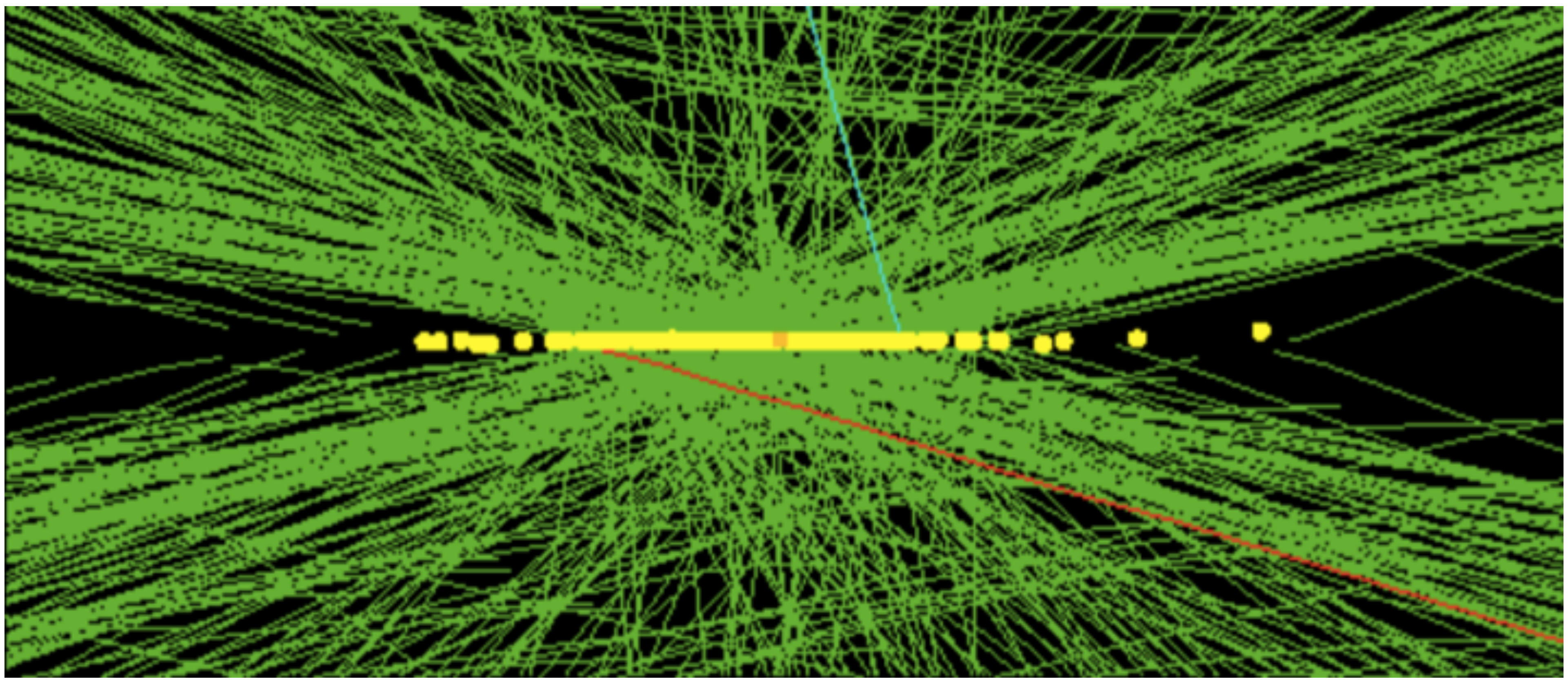
Tracking in 4 Dimensions



Is it important for the HL-LHC ??

At the HL-LHC
with 200 events pileup:

- **Time RMS between vertexes: 153 ps**
- **Average distance between two vertexes: 500 um**
- **Fraction of overlapping vertexes: 10-20%**
    - Of those events, a large fraction will have significant degradation of the quality of reconstruction



- fast and accurate pattern recognition
- pileup mitigation, by association of tracks to the hard vertex
    - ➡ need excellent Z_0 impact parameter resolution
    - ➡ but only ~10ps timing can resolve events overlapping in Z

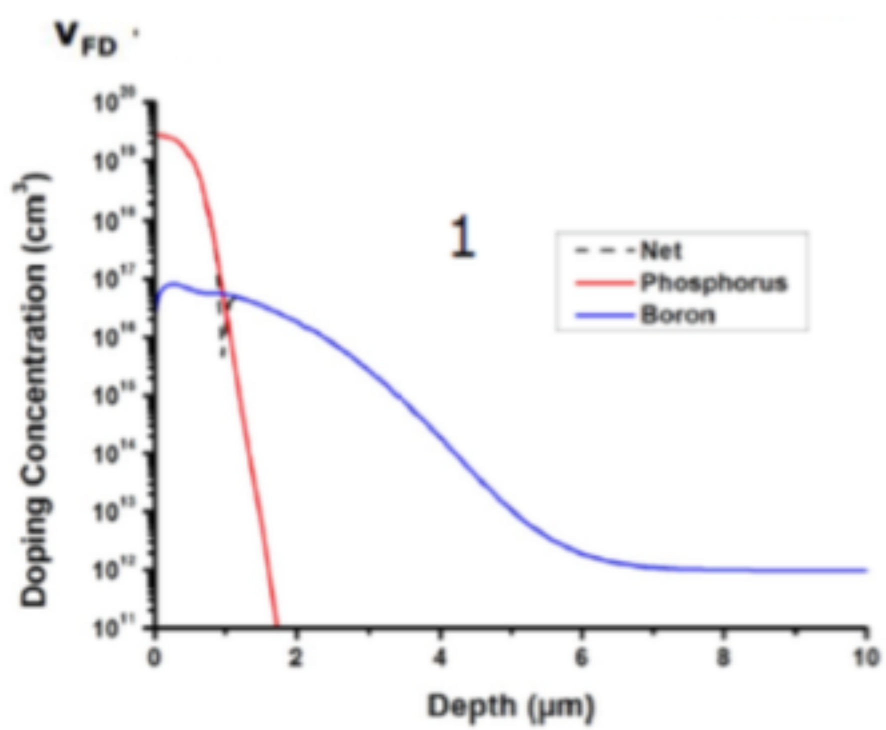
Low Gain Avalanche Detectors (LGADs)

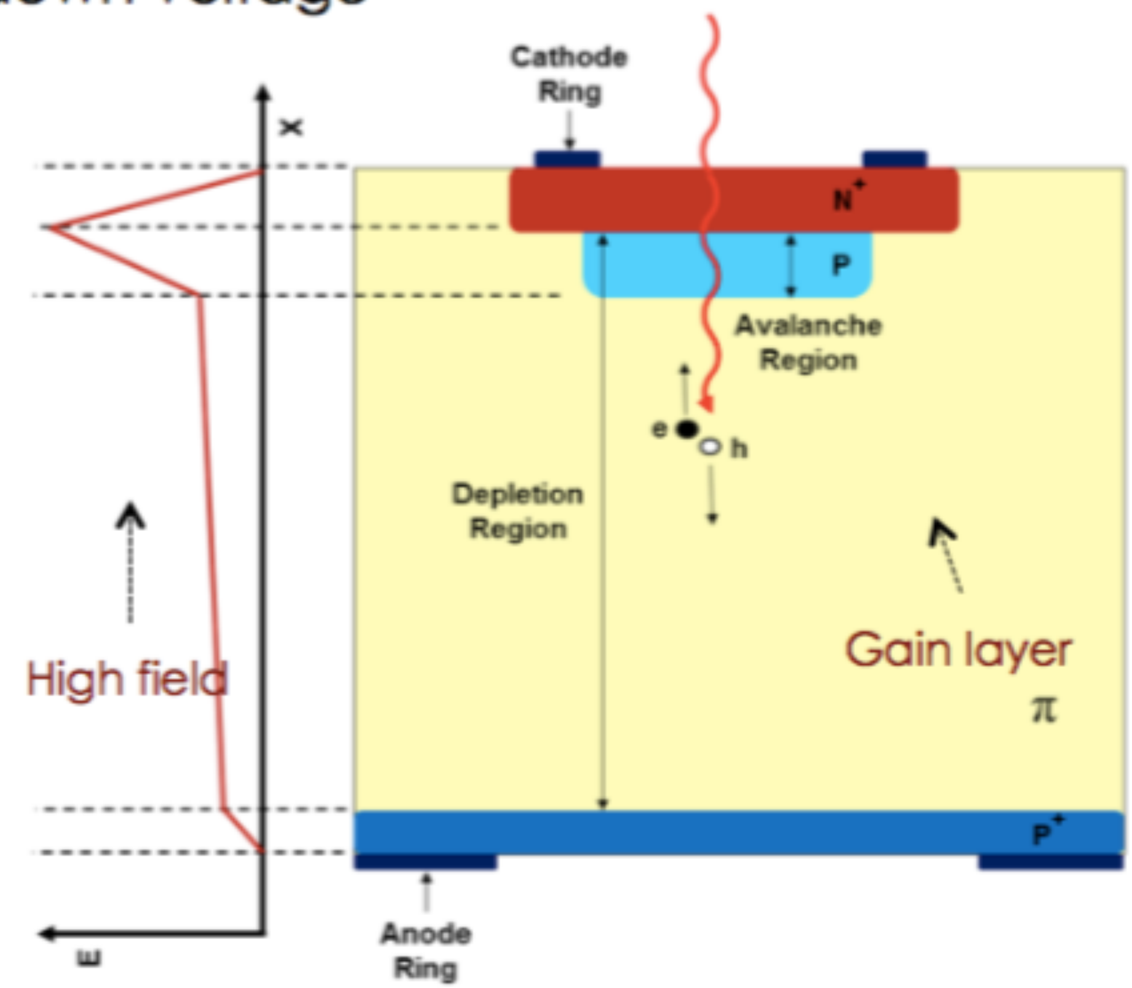
The LGAD sensors, as proposed and manufactured by CNM

(National Center for Micro-electronics, Barcelona):

High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage





Adding a highly doped, thin layer of of p-implant near the p-n junction creates a high electric field that accelerates the electrons enough to start multiplication. Same principle of APD, but with much lower gain.

Ultra Fast Silicon Detectors

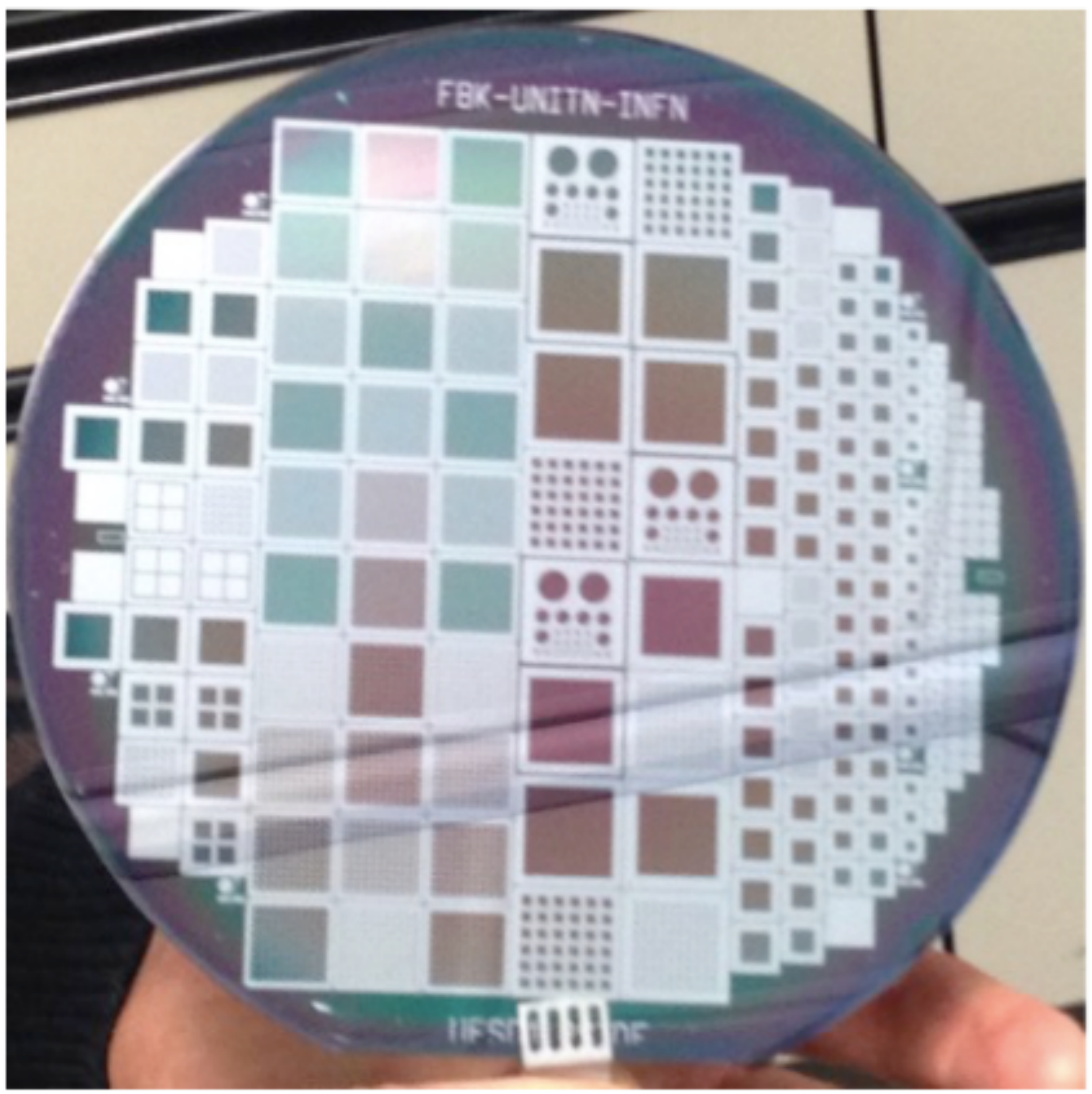
UFSD are LGAD detectors optimized to achieve the best possible time resolution

Specifically:

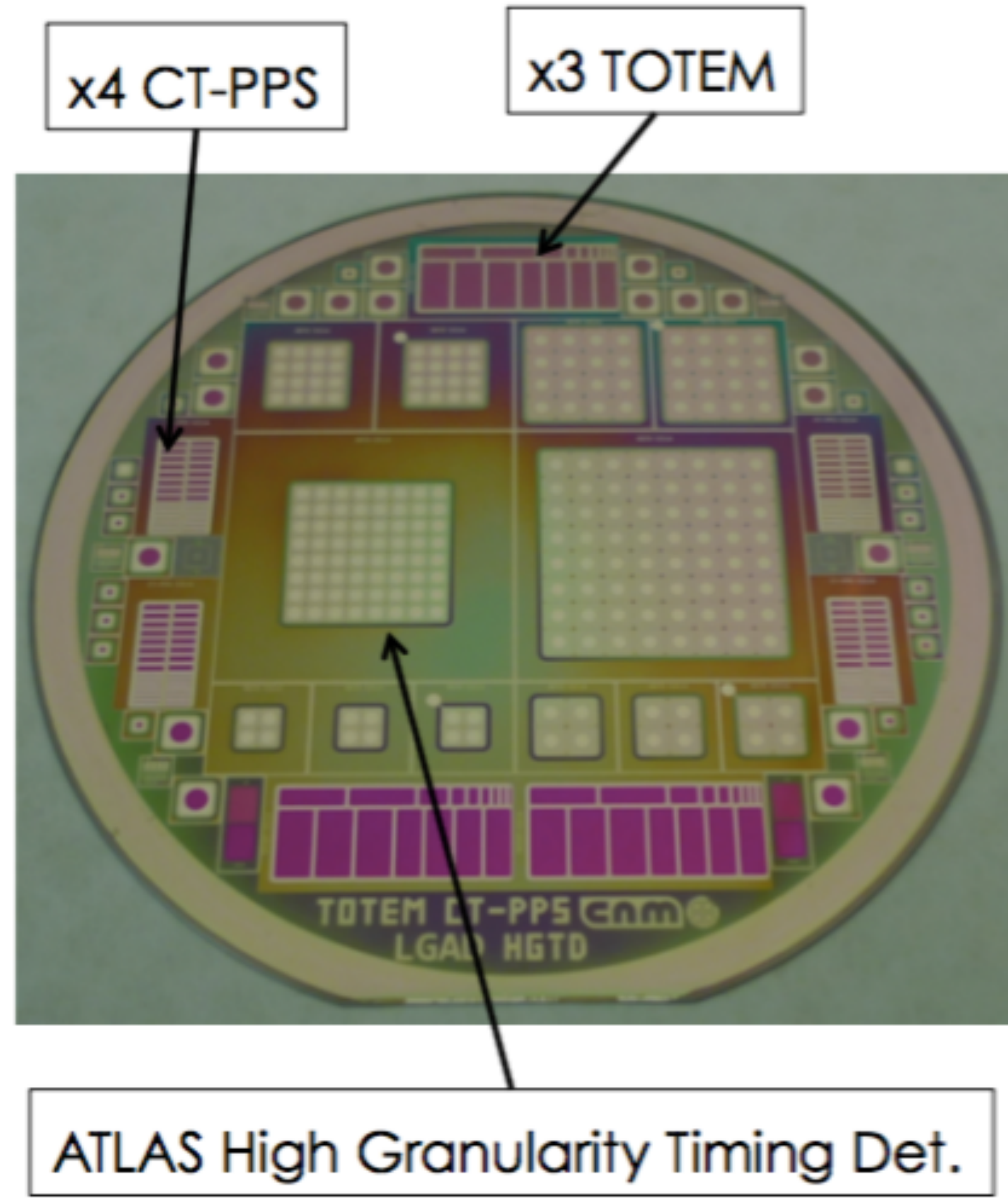
1. Thin to maximize the slew rate (dV/dt)
2. Parallel plate – like geometries (pixels..) for most uniform weighting field
3. High electric field to maximize the drift velocity
4. Highest possible resistivity to have uniform E field
5. Small size to keep the capacitance low
6. Small volumes to keep the leakage current low (shot noise)

Sensors: FBK & CNM

FBK 300-micron production
Very successful, good gain and overall behavior
➔ We have now a second producer



CNM 75-micron
CNM 50-micron production



N. Cartiglia, INFN, Torino - 4D pixel - Sestri 2016

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2016 CERN **testbeam** of

CNM-UFSD 1.2 x 1.2 mm^2, 50µm thick (C = 3pF, Gain = 15)

Time resolution as difference w.r.t. very accurate (~15ps) SiPM

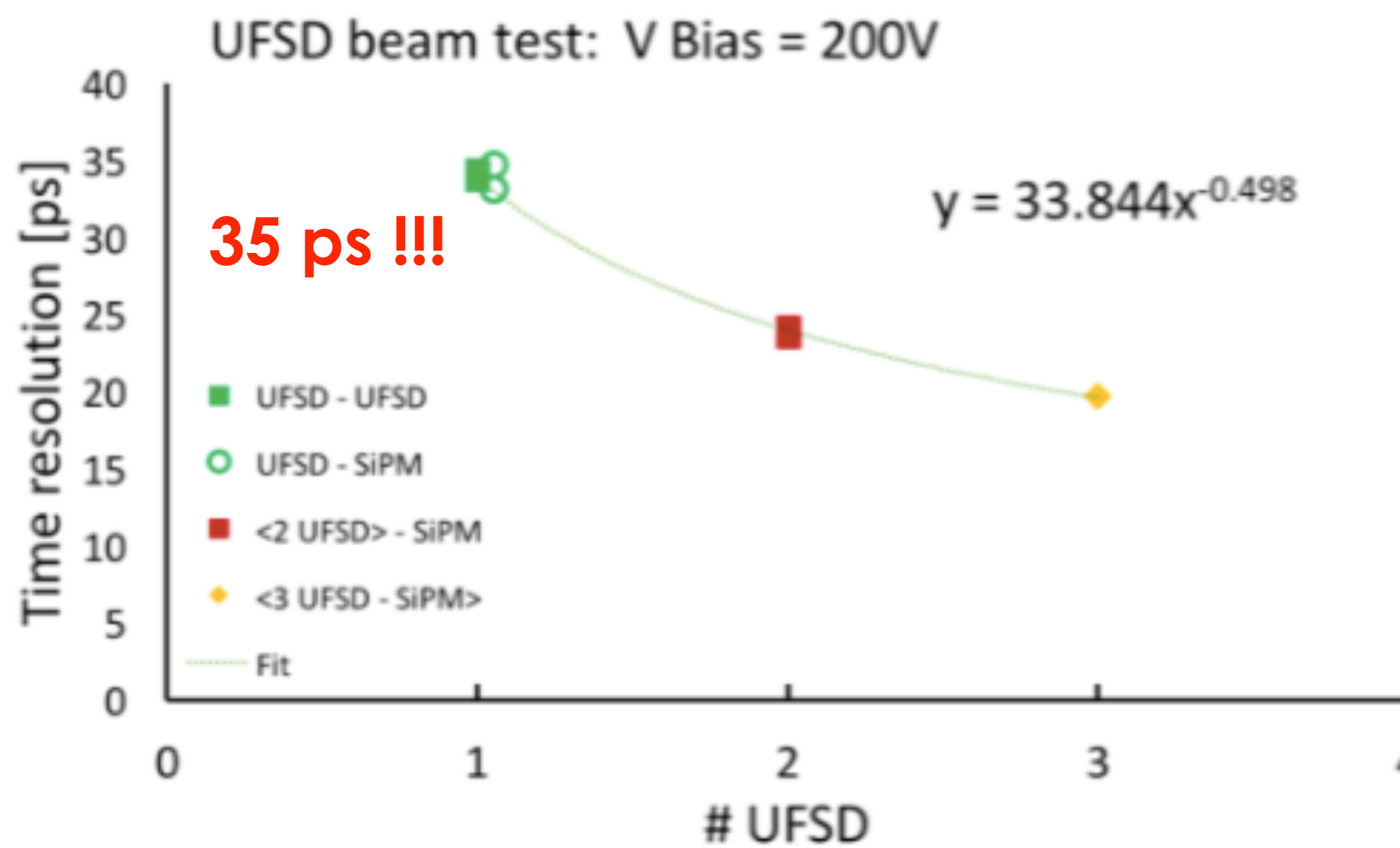
N. Cartiglia, INFN, Torino - 4D p

Multiple UFSD tracking system

Timing Resolution [ps]		
Vbias [V]	200V	240V
N=1 :	34.6	25.6
N=2 :	23.9	18.0
N=3 :	19.7	14.8

Submitted to NIMA

http://arxiv.org/abs/1608.08681v1



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Next steps:

- Radiation hard studies
- Electronics for larger sensors (20-30 pF)

Final Remarks

- Pixel detectors became more and more important for present and future experiments
  - large variety, following the physics requirements
  - software progress
  - hardware (mechanics/sensor/readout/services) progress

- The prohibitive HL-LHC requirements is a challenge also for the good-old hybrid pixels

- CMOS and ~10ps tim resolution are the new eldorado
  - Hard to say if we will manage to benefit from these new technologies at the HL-LHC