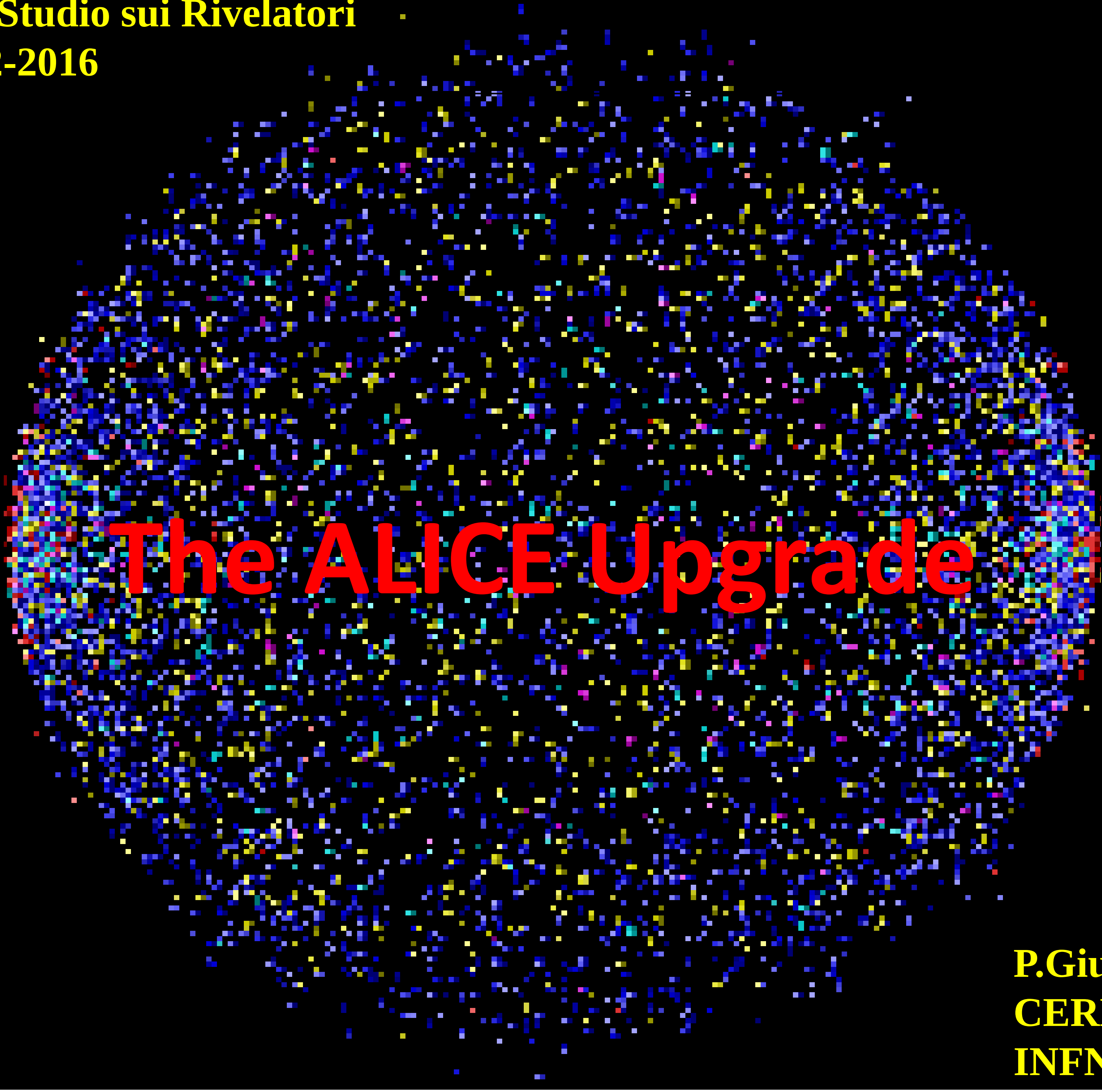
Giornate di Studio sui Rivelatori
Cogne 26-02-2016



The ALICE Upgrade

P.Giubellino
CERN and
INFN Torino

Experiments are alive… ALICE has already evolved a lot!

- **ALICE history:**
- 1990-1996: Design
- 1992-2002: R&D
- 2000-2010: Construction
- 2002-2007: Installation
- 2008 : Commissioning
- 2009-> Data Taking

- **4 TP addenda along the way:**
  - 1996 : muon spectrometer
  - 1999 : TRD
  - 2006 : EMCAL
  - 2010 : DCAL

Plus the V0 and the ADA/ADD counters added without TP

And it started like this: Early ALICE Designs

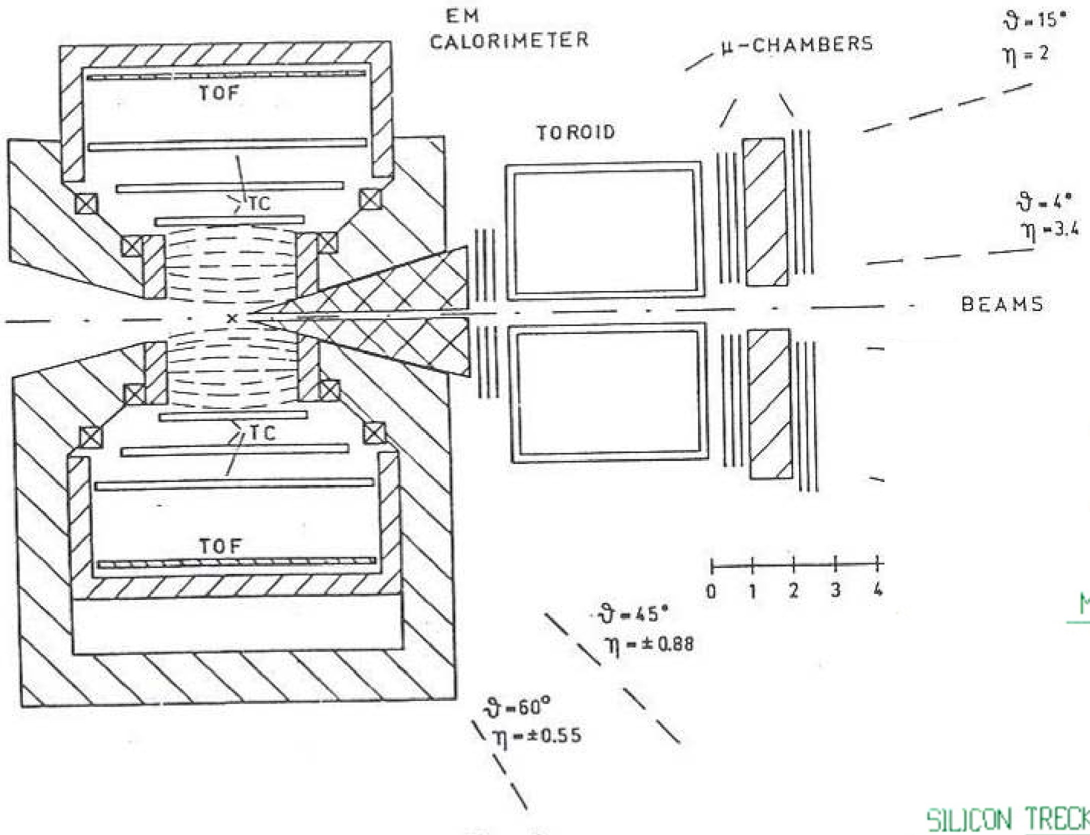
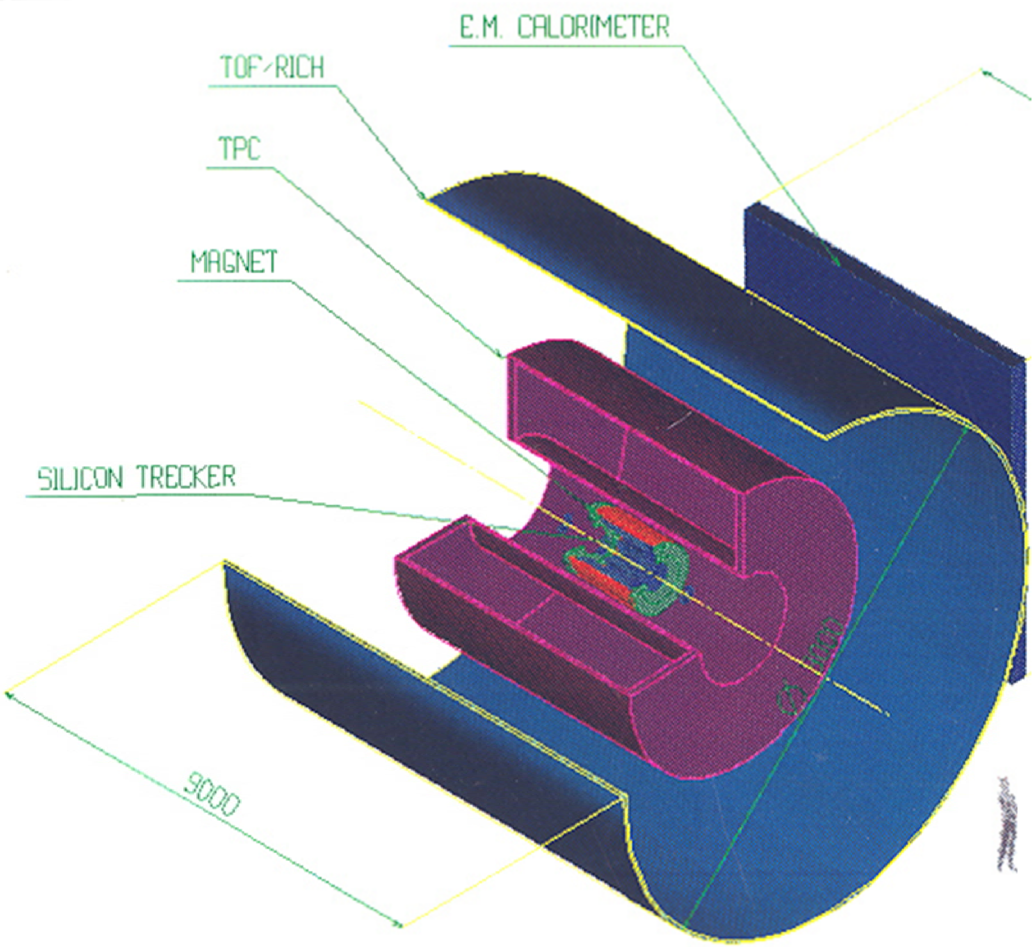


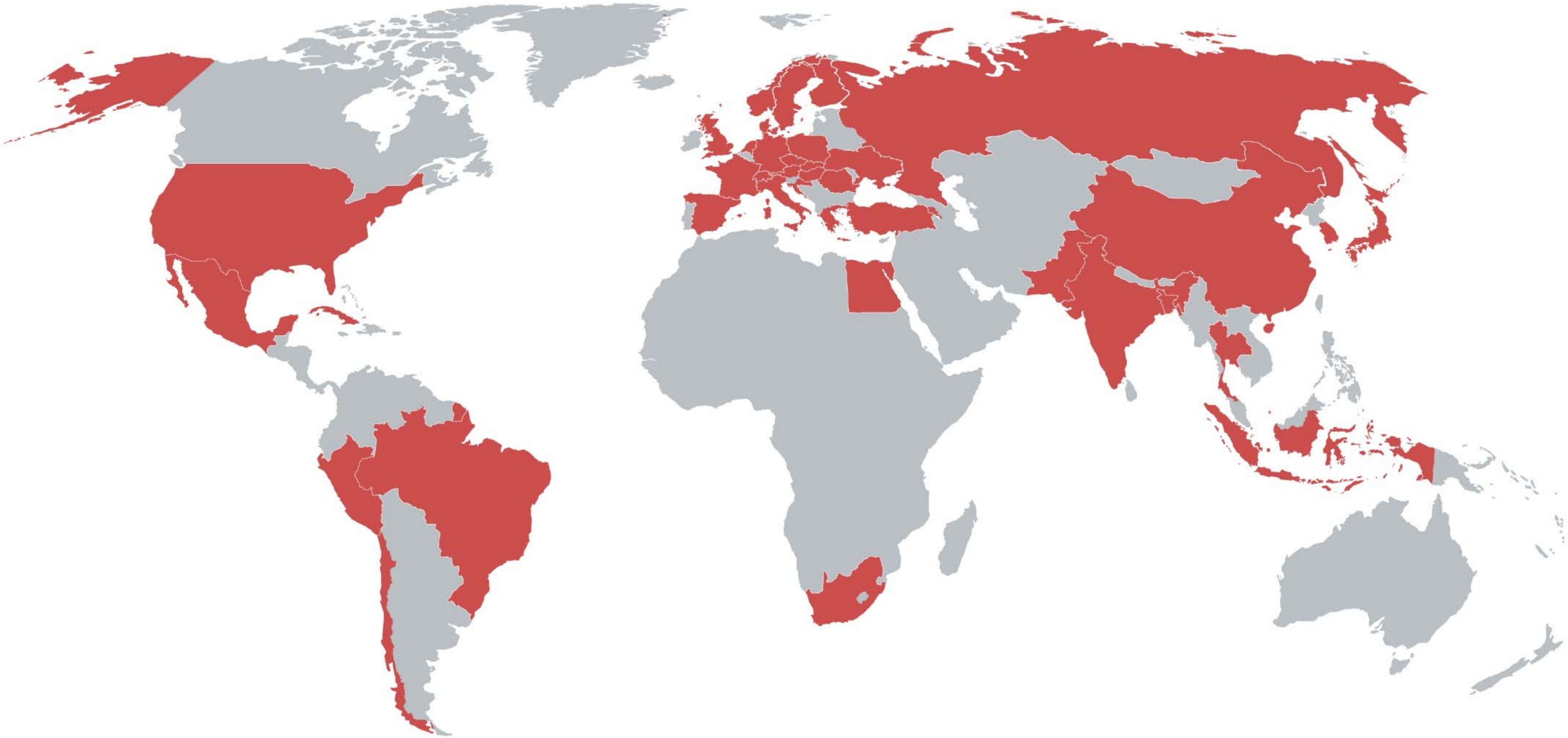
Fig. 3

1990 Design (Aachen)
open axial field magnet
(AFS/ISR, + NA38 muons)

1992 Design (Evian)
no muons
thin (<17%X_0) and small solenoid

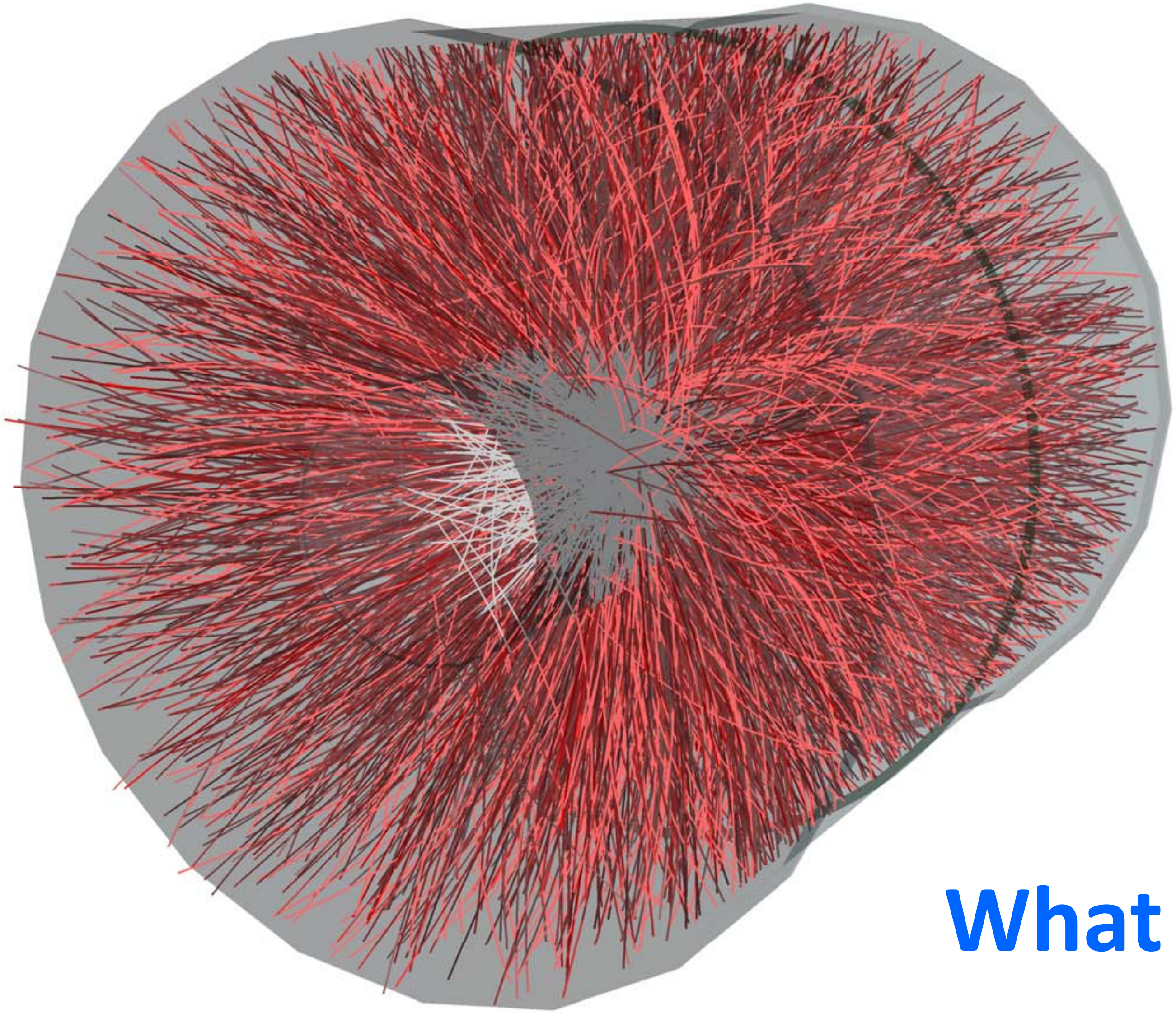


ALICE: a world-wide effort



1660 SCIENTISTS - 42 COUNTRIES – 169 INSTITUTES

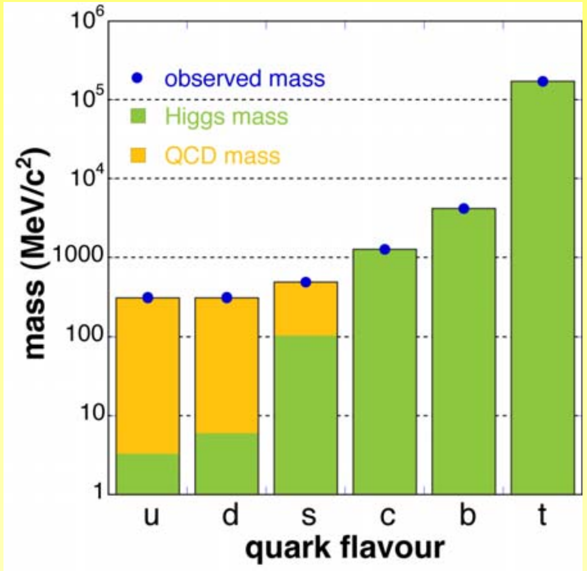
To study the world's most energetic and most complicated collisions



What for?

Why HI Collisions?

- What are the fundamental properties of strongly interacting matter as a function of temperature and density?
- What are the microscopic mechanisms responsible for them?
  - What are the microscopic degrees of freedom and excitations of matter at ultra--high temperature and density?
  - Which are its transport properties and equation of state?
- How did its properties influence the evolution of the early universe?
- How is mass modified by the medium it moves in?
- How do hadrons acquire mass?
- What is the structure of nuclei when observed at the smallest scales, i.e. with the highest resolution?



Most of the observed mass of light quarks is generated by the spontaneous breaking of chiral symmetry

- **Heavy-Ion collisions:**

Laboratory studies of the bulk properties of non-Abelian matter

- ...with deep connections to other fields in physics:

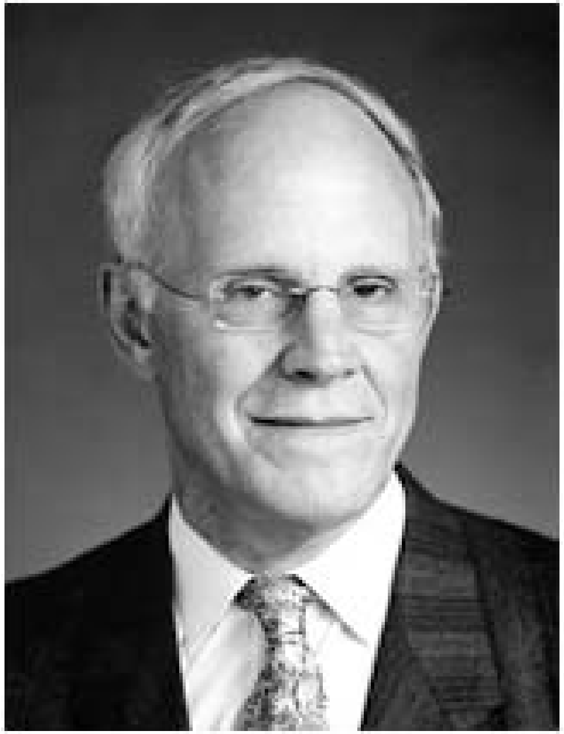
String Theory, Cosmology, Condensed Matter Physics, Ultra--Cold Quantum Gases

A long way...

- Hagedorn 1965: mass spectrum of hadronic states $\rho(m) \propto m^{\alpha} \exp(m/B)$
  - => Critical temperature T_c=B
- QCD 1973: asymptotic freedom
  - – D.J.Gross and F.Wilczek, H.D. Politzer
- 1975: asy[mptotic …] q[uarks] and gluons

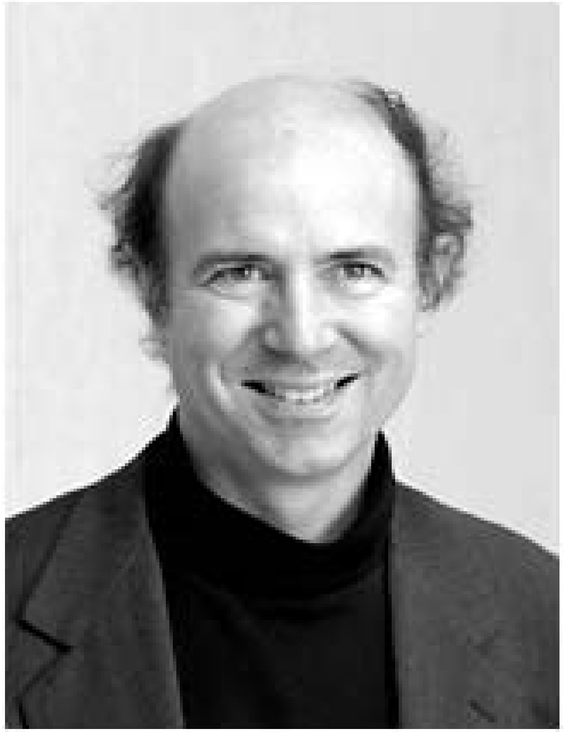
Prize motivation: "for the discovery of asymptotic freedom in the theory of the strong interaction"

Nobel Prize in Physics 2004



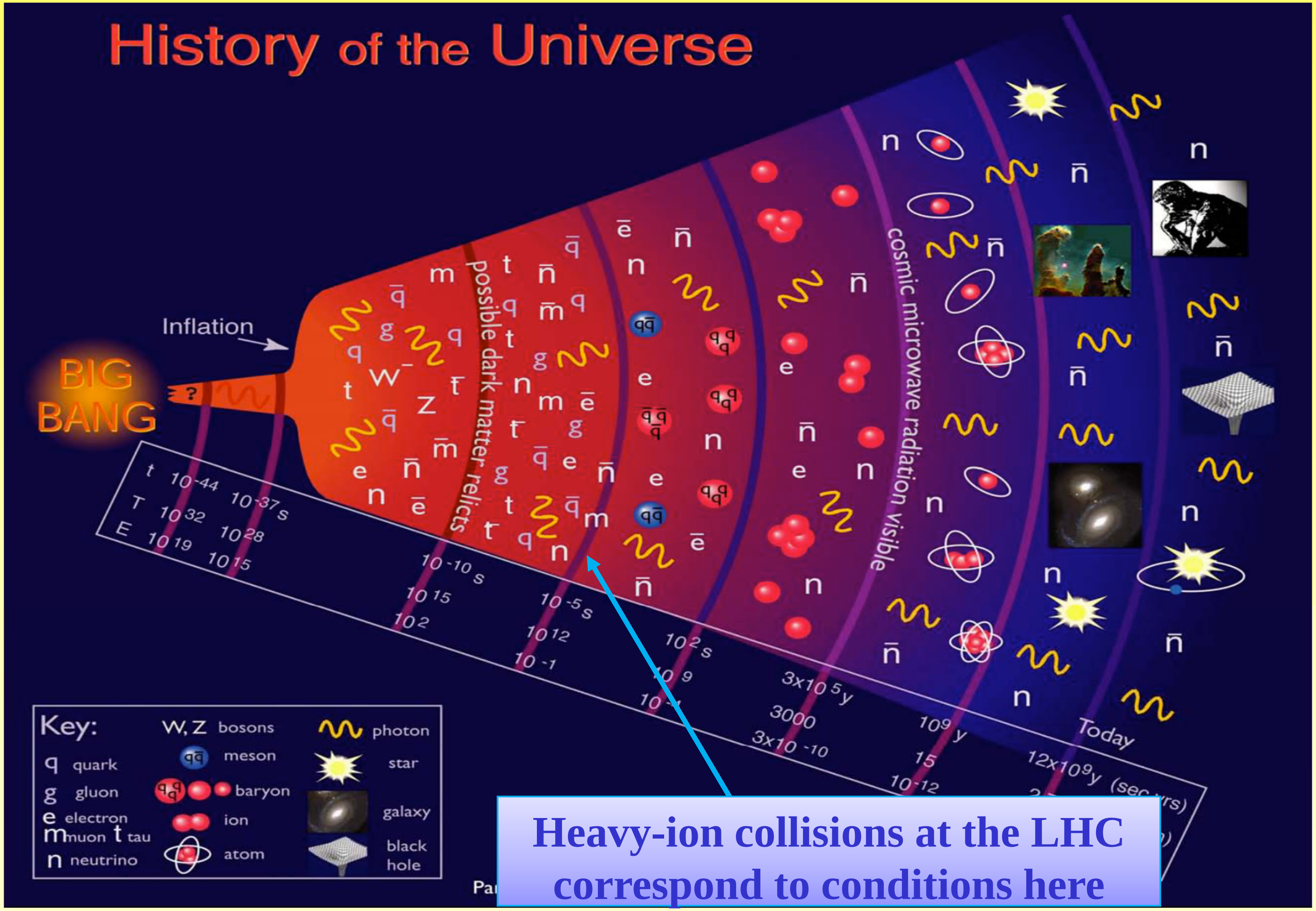
David J. Gross

H. David Politzer



Frank Wilczek

Brief History of Our Universe



Heavy-ion collisions at the LHC correspond to conditions here

Many critical features of our universe were established in these very early moments.

The exploration of the phase diagram of strongly interacting matter: a world wide enterprise

At CERN, involves about 1500 scientists in three large experiments ALICE, CMS and ATLAS (2010-2028…)

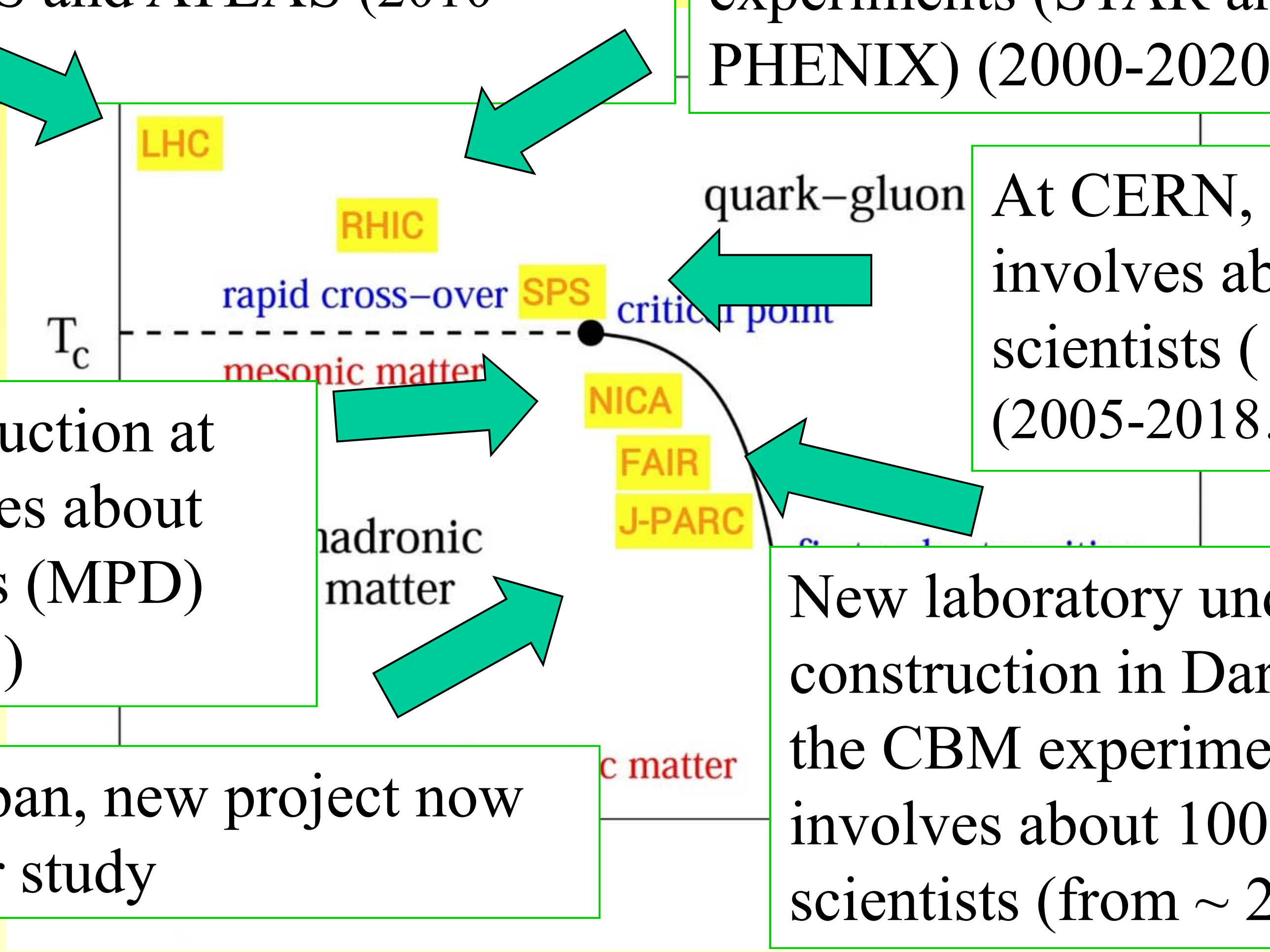
At BNL, involves about 1000 scientists in two large experiments (STAR and PHENIX) (2000-2020…)

At CERN, involves about 300 scientists (SHINE) (2005-2018…)

Under construction at JINR, involves about 500 scientists (MPD) (from ~ 2018)

In Japan, new project now under study

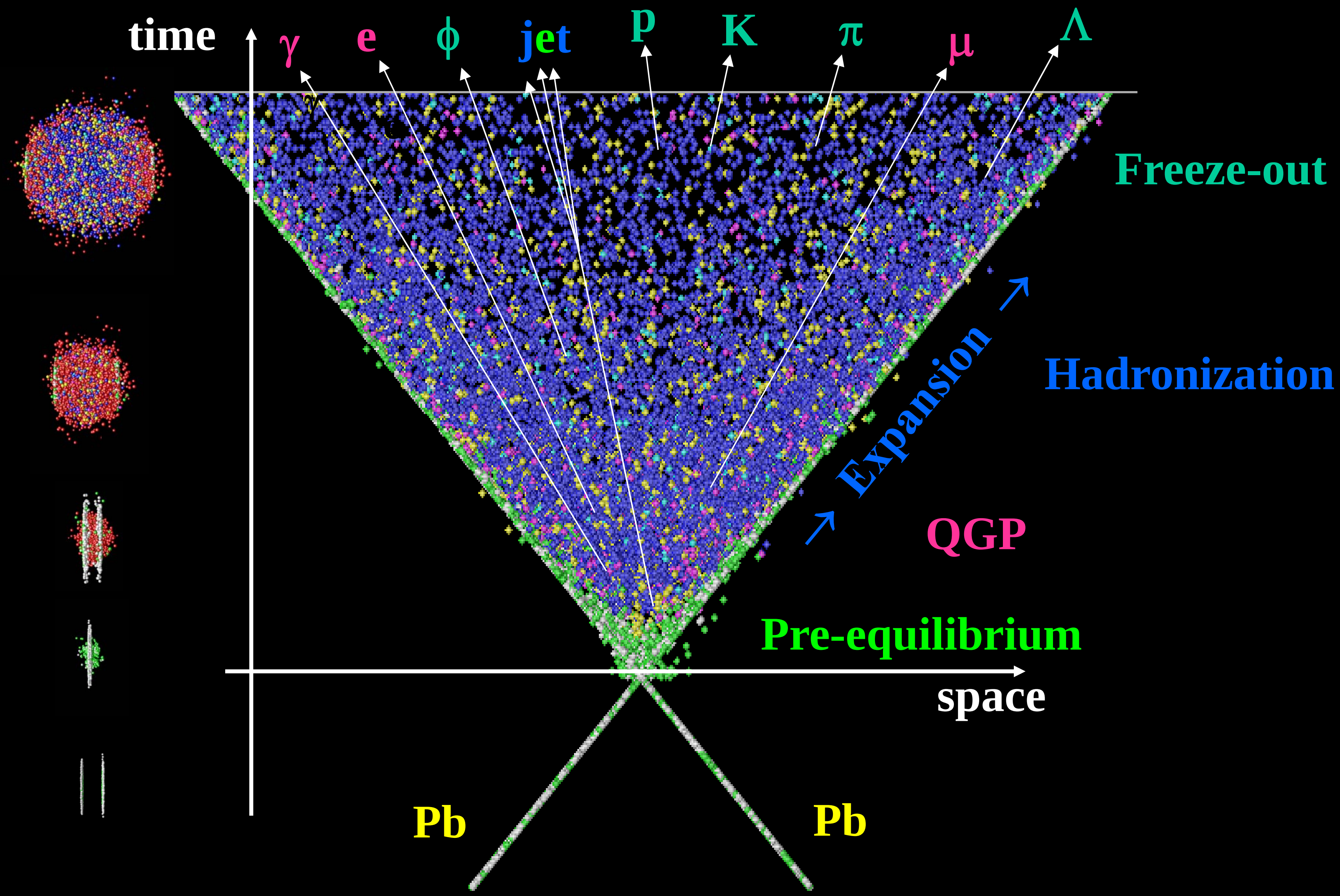
New laboratory under construction in Darmstadt. the CBM experiment involves about 1000 scientists (from ~ 2020)



Why Heavy Ions @ LHC?

- It is a ***different matter*** as compared to RHIC (and even more to SpS)
  - Larger temperature, volume, energy density and lifetime
    - Study QGP properties vs T …
  - small net-baryon density at mid-rapidity ($\mu_B \approx 0$), corresponding to the conditions in the early universe
  - large cross section for '**hard probes**' : high p_T, jets, heavy quarks,…
  - First principle methods (pQCD, Lattice Gauge Theory) more directly applicable
  - new generation, large acceptance state-of-the-art detectors
    - Atlas, CMS, ALICE, [LHCb, for pA]
- A comprehensive program, ***complementary*** to the one at RHIC (and later FAIR)

Space-time Evolution of the Collision



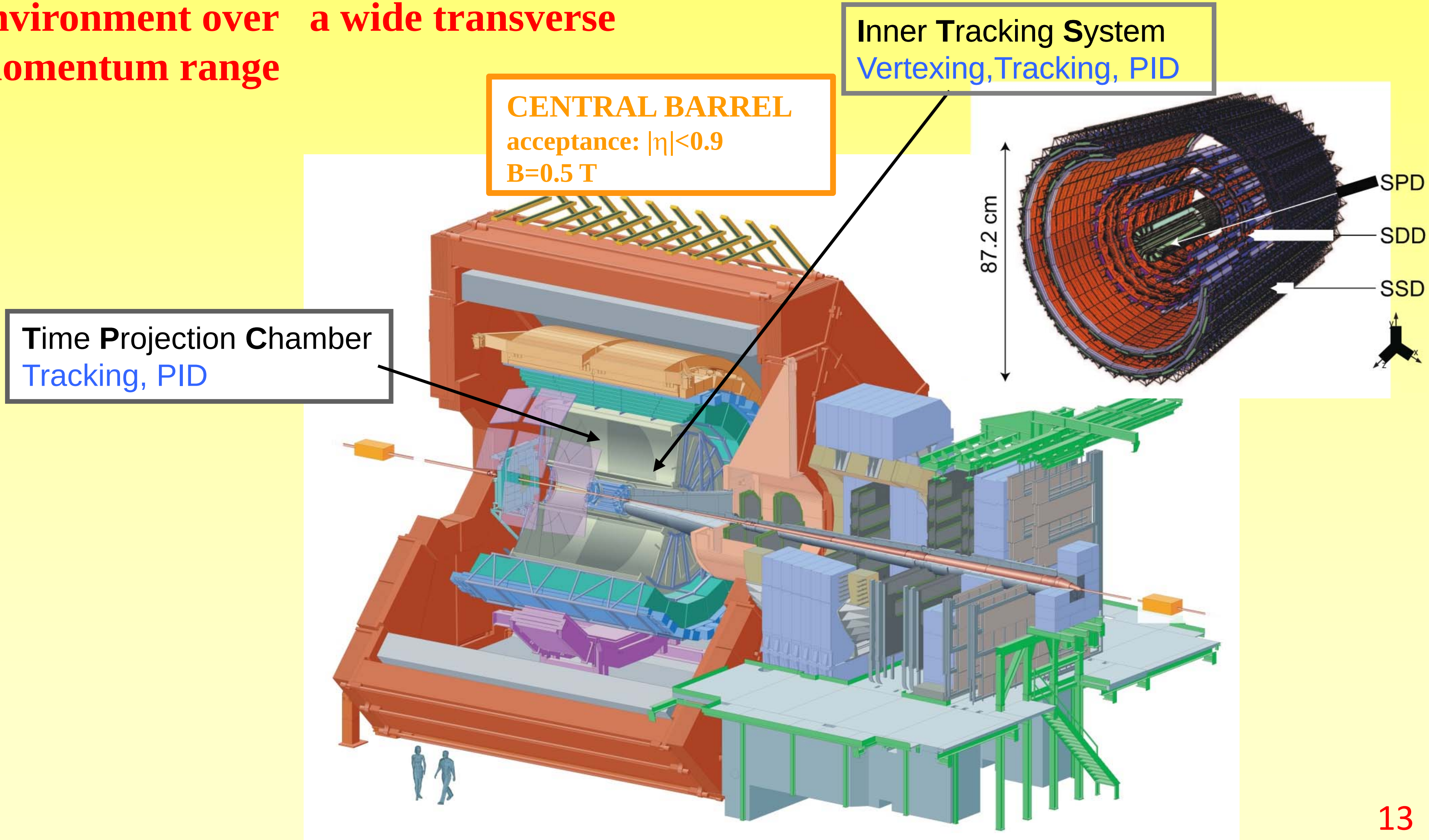
Experiments at the LHC...

- ALICE
  - Experiment designed for Heavy Ion collision
    - only dedicated experiment at LHC, must be comprehensive and able to cover all relevant observables
    - **VERY robust tracking** for p_T from **0.1 GeV/*c*** to **100 GeV/*c***
      - high-granularity 3D detectors with many space points per track (**560 million** pixels in the TPC alone, giving 180 space points/track)
      - **very low material budget** (**< 10%X_0** in r < 2.5 m) -> Low p_T hadrons, low-mass dileptons
    - **PID** over a very large p_T range
      - use of essentially all known technologies: TOF, dE/dx, RICH, TRD, Ecal, topology
    - Hadrons, leptons, photons, jets + Excellent vertexing
- ATLAS and CMS
  - General-purpose detectors, optimized for rare processes
    - Excellent Calorimetry = > Jets
    - Excellent dilepton measurements, especially at high p_T
    - Very large acceptance in rapidity
- Now Joined by LHCb for pPb

Each required 20 years of work by a worldwide collaboration...

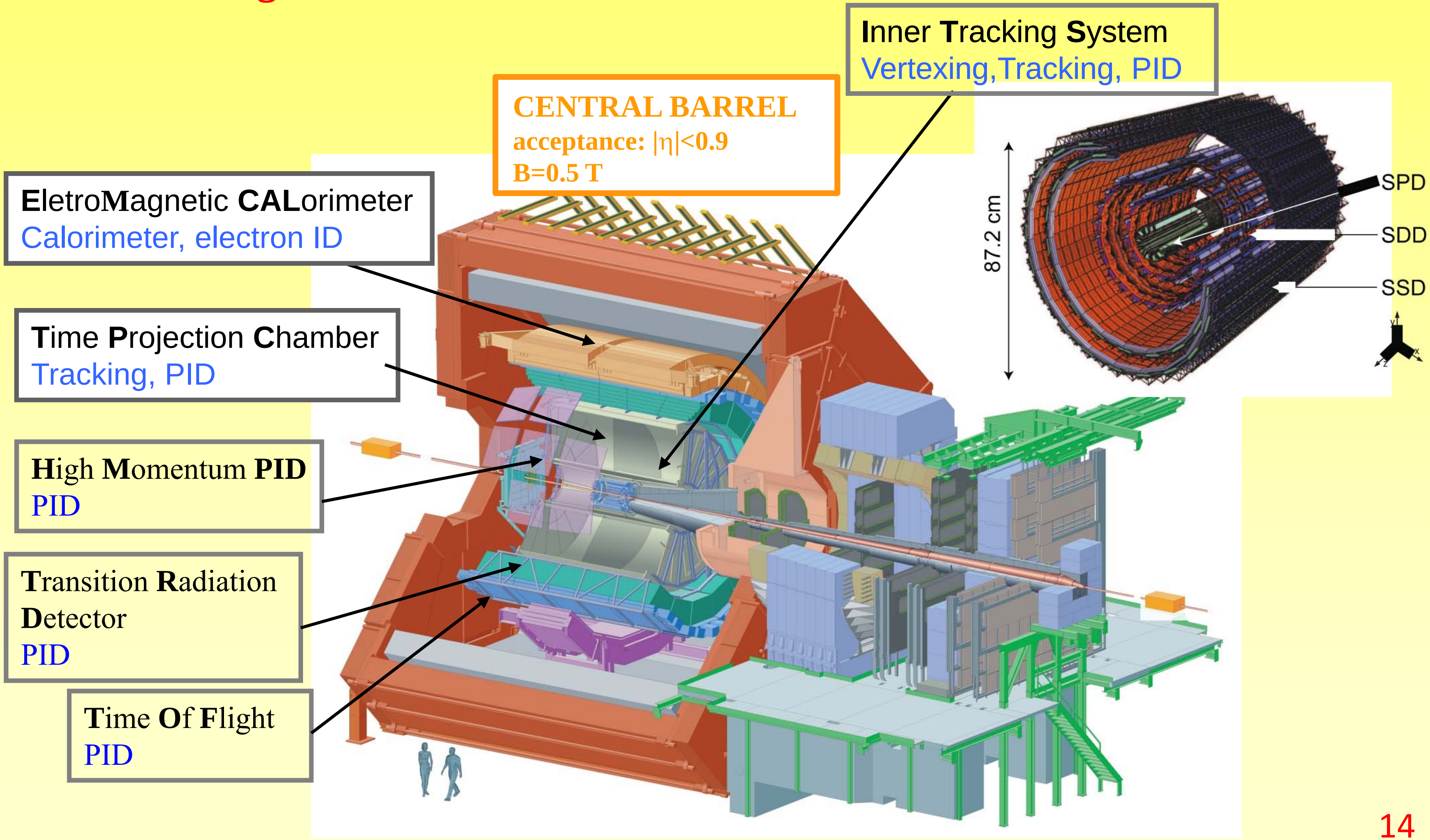
ALICE Detector Specifics

Excellent track and vertex reconstruction capabilities (TPC, ITS) in a high multiplicity environment over a wide transverse momentum range

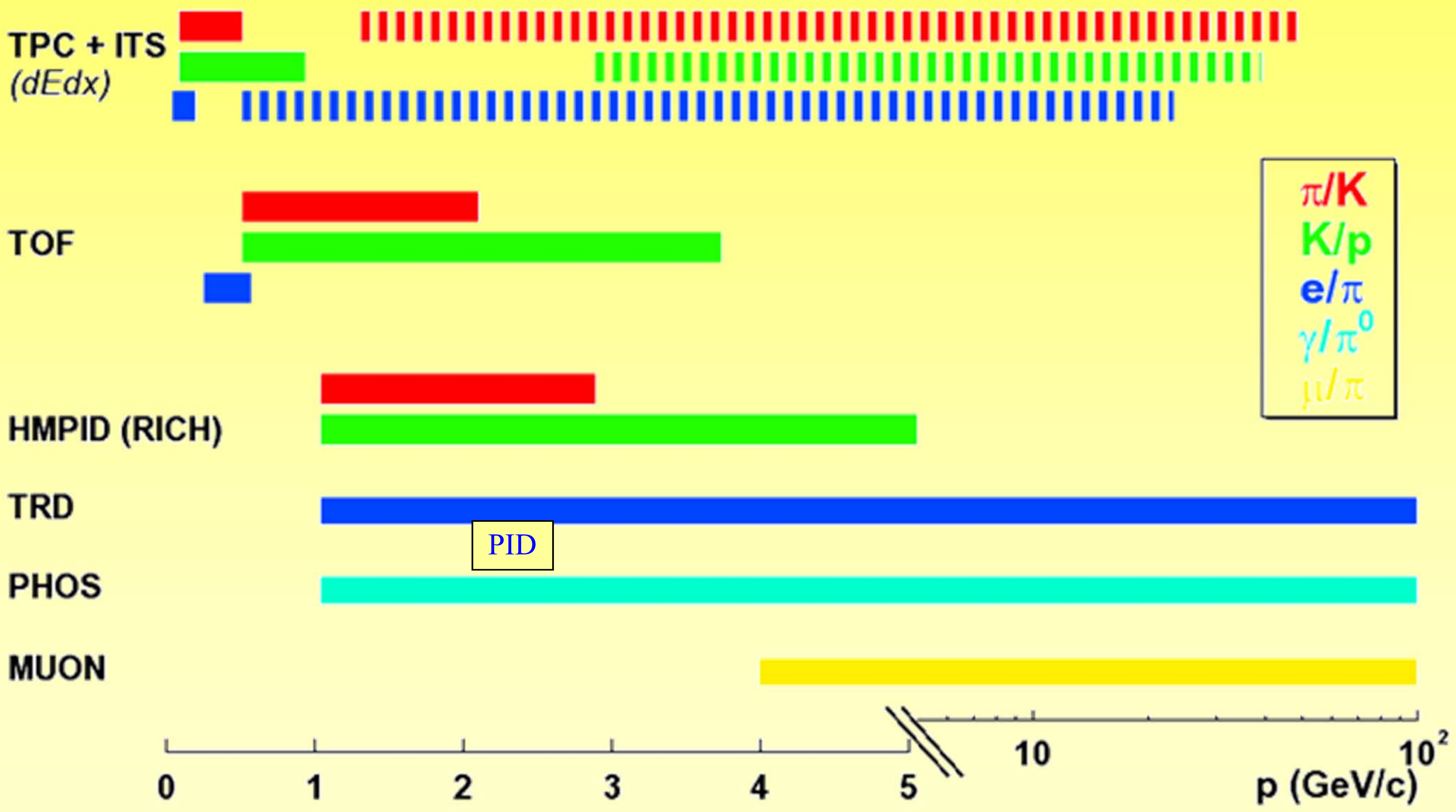


ALICE Detector Specifics

Particle identification over a wide momentum range



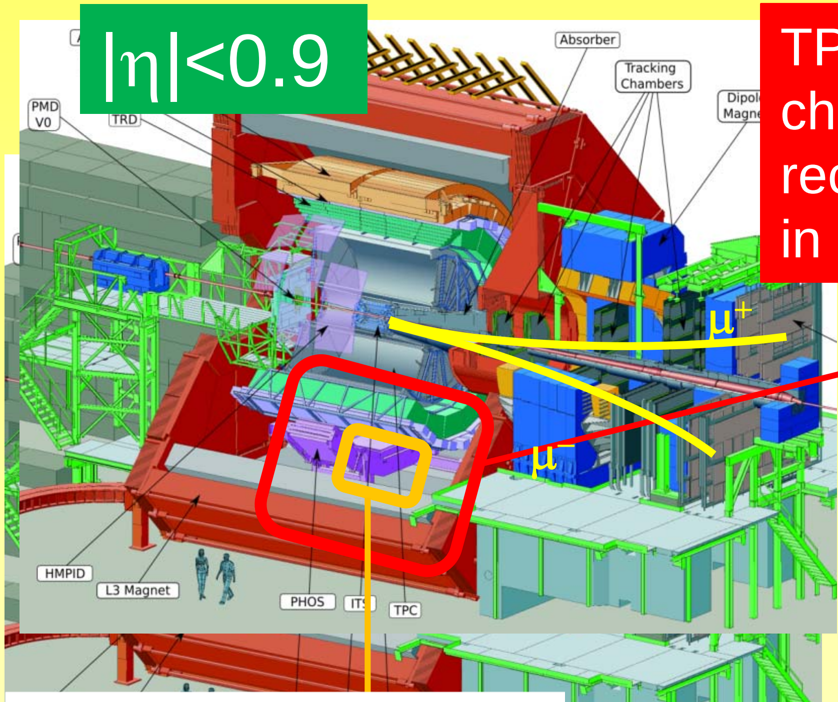
ALICE PID



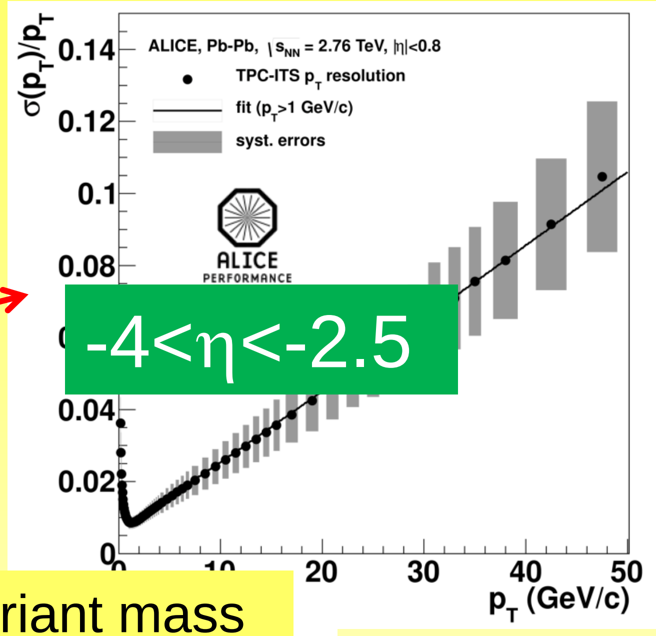
+ decay topologies ((K^0, K^+, K^-, Λ, φ, D) K and Λ beyond 10 GeV/c

ALICE performance: tracking/vertexing

|η|<0.9

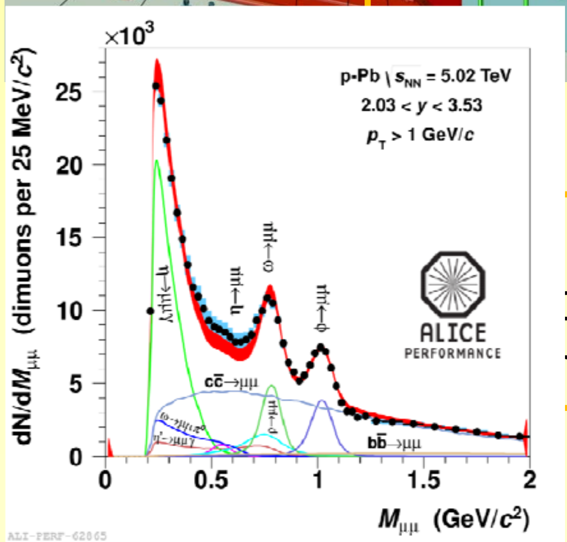


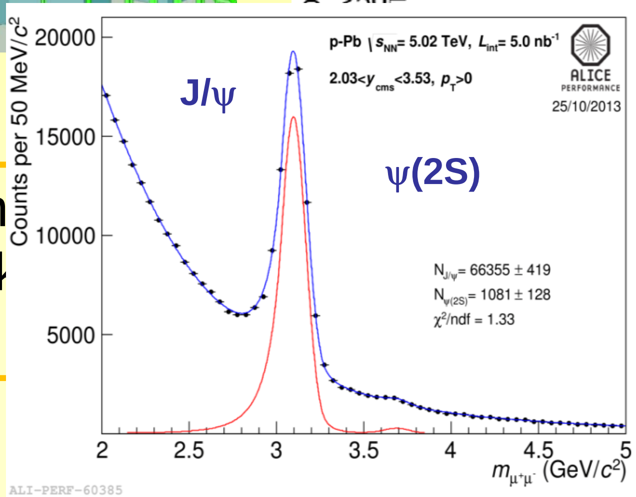
TPC+ITS: charged track reconstruction in |η| < 0.9

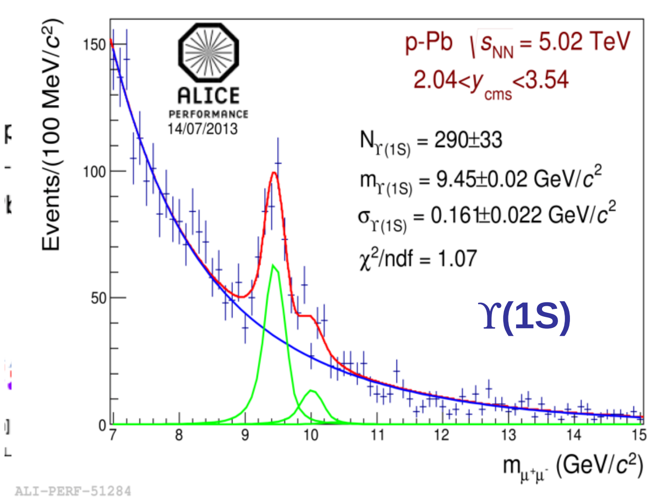


-4<η<-2.5

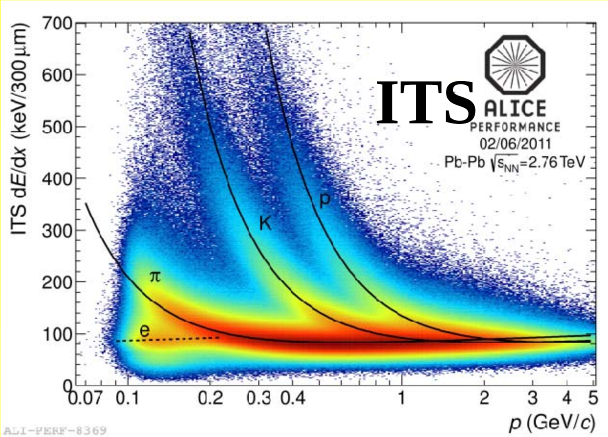
Di-muon invariant mass

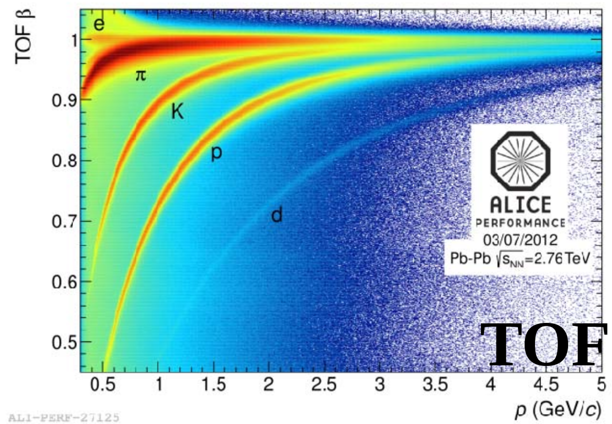


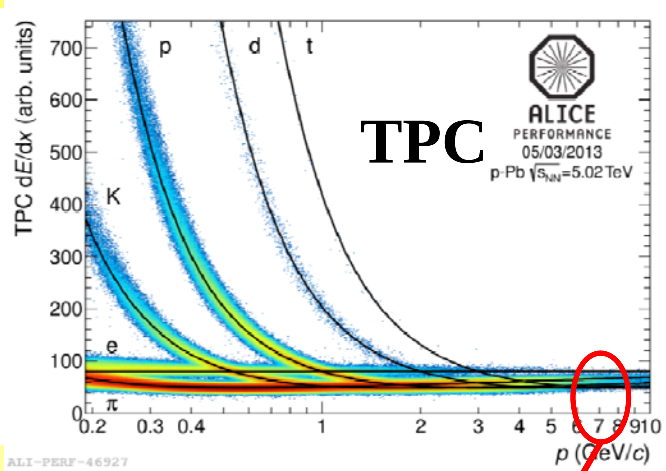


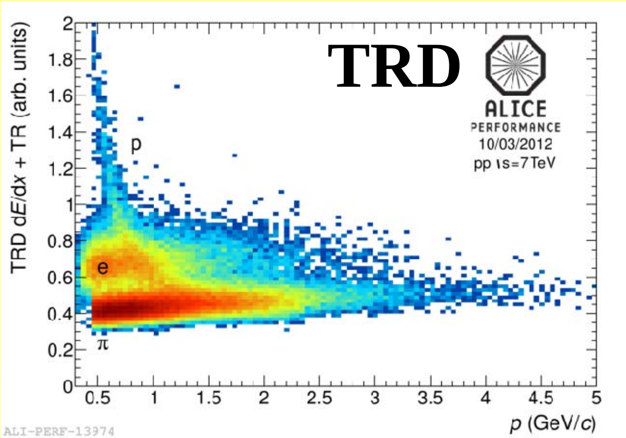


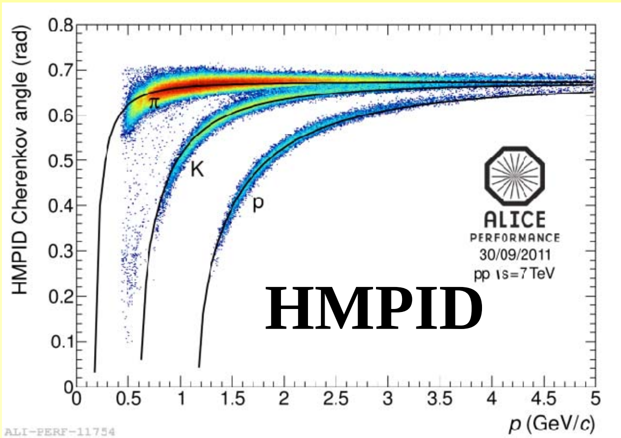
ALICE performance: PID

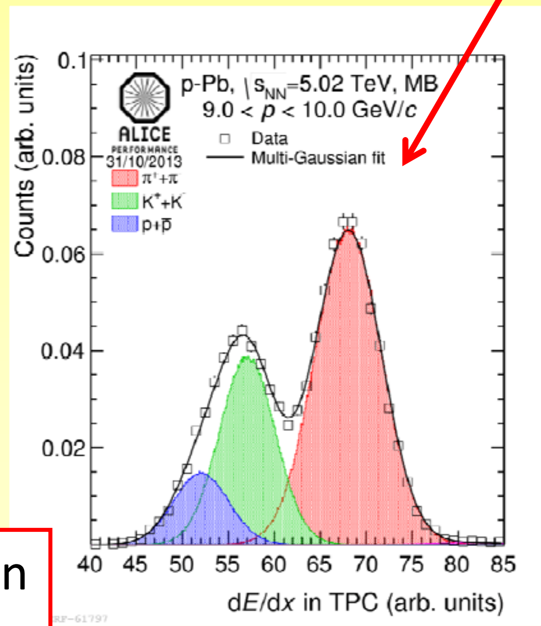












- ALICE uses practically all known techniques

Statistical separation in relativistic rise region

The ALICE program

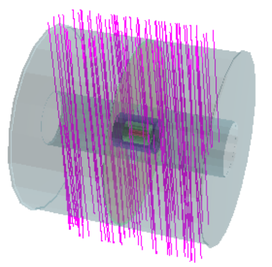
- The past:

year	system	energy $\sqrt{s_{NN}}$ TeV	integrated luminosity
2010	Pb – Pb	2.76	~ 0.01 nb^{-1}
2011	Pb – Pb	2.76	~ 0.1 nb^{-1}
2013	p – Pb	5.02	~ 30 nb^{-1}

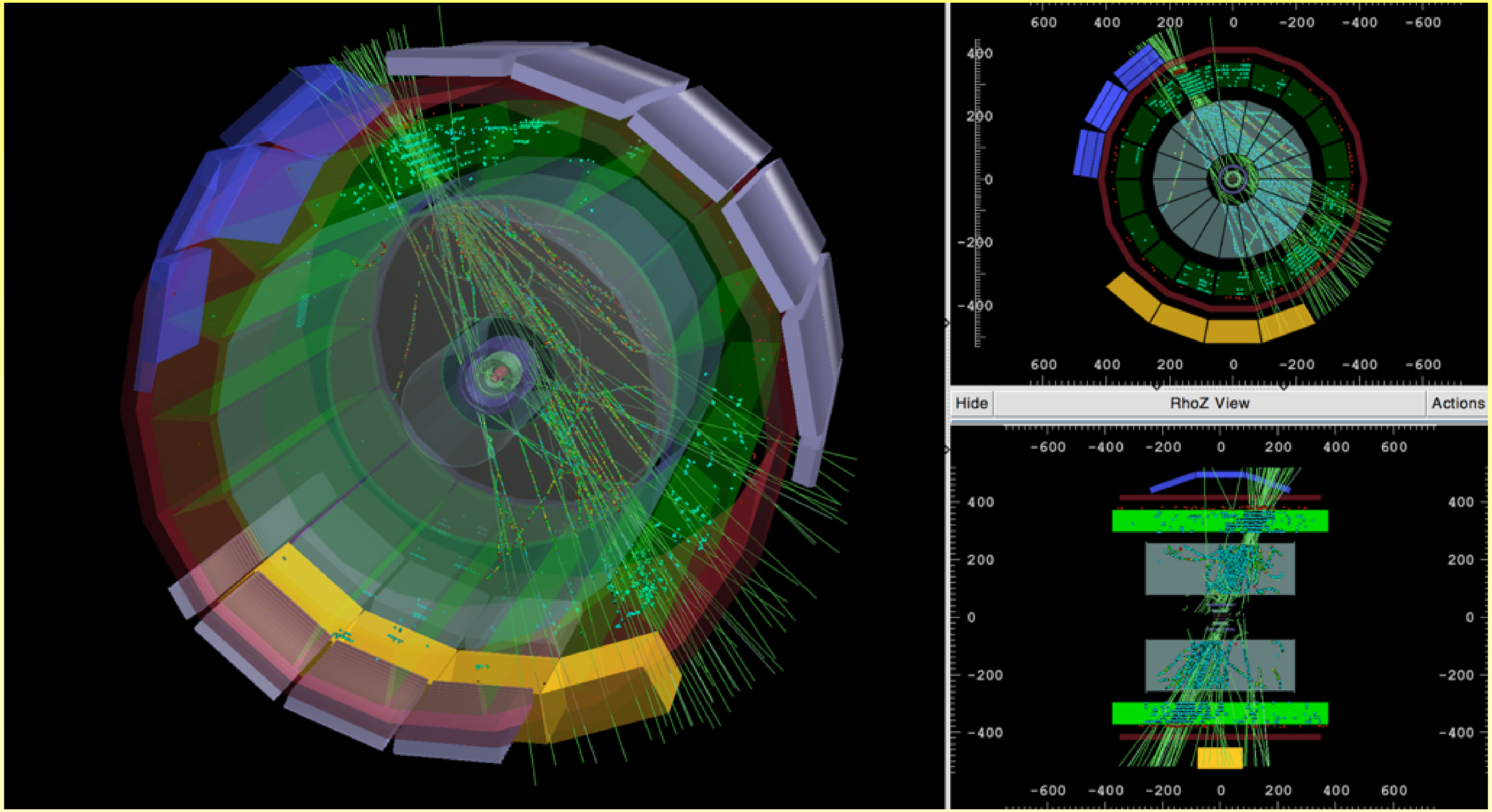
- The present:
  - **RUN2 (2015, 2016, 2018)** : will allow to approach the **1 nb^{-1}** for Pb-Pb collisions, with improved detectors and double energy (2015 and 2018), and a p-Pb run with 10* statistics (this year)

- The Future:
  - **RUN3 + RUN4 (2021, 22, 23 and 27, 28, 29): 10 nb^{-1}** with major detector improvements (plus a dedicated low-field run and pPb)

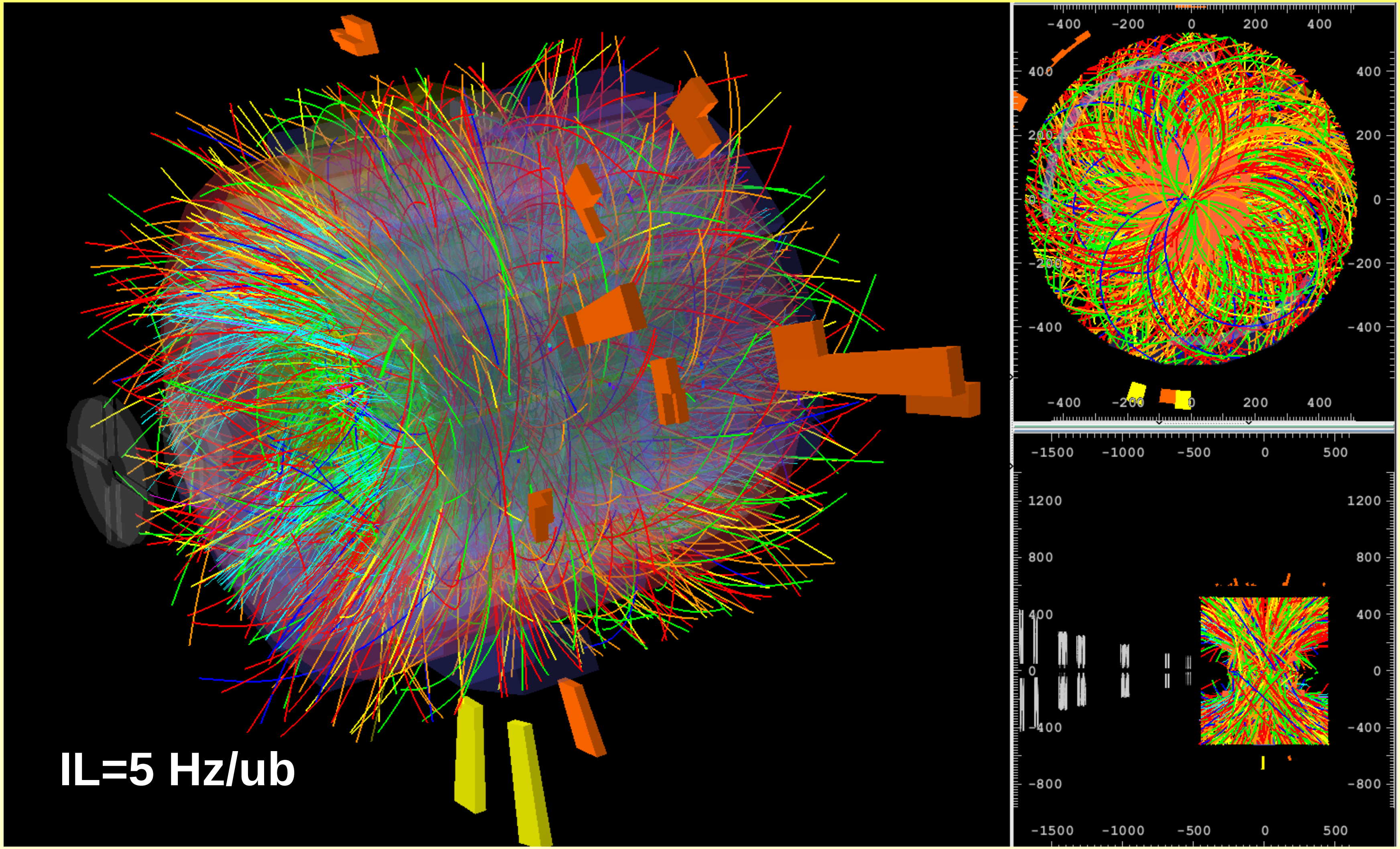
- So: three phases, each jumping one order of magnitude in statistics and progressively improving the detectors



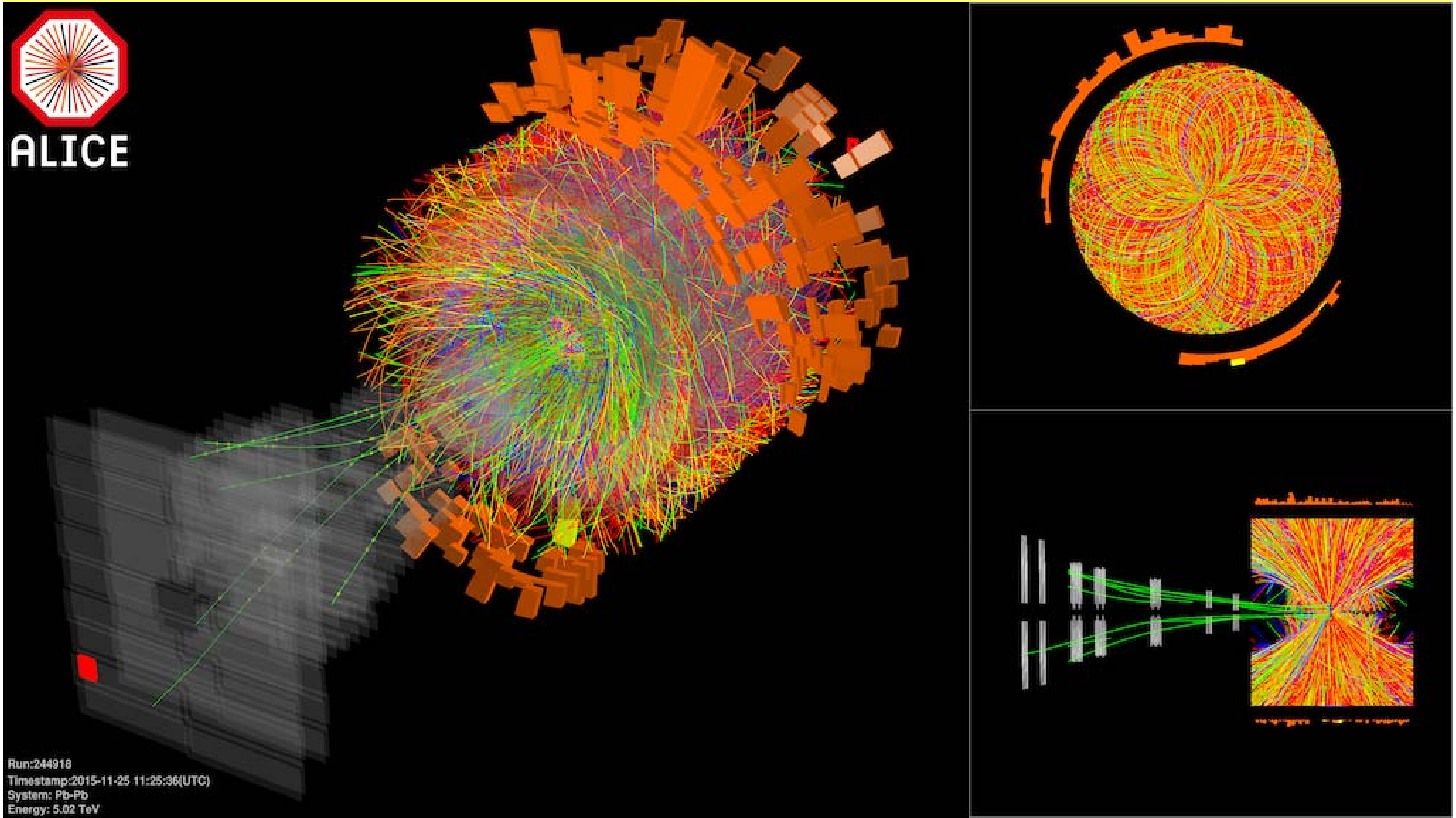
ALICE RUN2: Cosmics...



RUN2 2015: pp at 13 TeV



RUN2 PbPb: PeV Collisions!



The LS2 Upgrade

ALICE Upgrade for RUN3 and RUN4 (after LS2)

- Focus on rare probes, study their coupling with QGP medium and their (medium-modified) hadronization process
- **low-transverse momentum observables** (complementary to the general-purpose detectors)
  - not triggerable => need to examine full statistics.
  - Target:
    - Pb-Pb recorded luminosity $\geq 10\ nb^{-1}$ ➡ 8×10^{10} events
    - pp (@5.5 Tev) recorded luminosity $\geq 6\ pb^{-1}$ ➡ 1.4×10^{11} events

o Gain a factor **100** over the statistics of the approved programme

- **Operate ALICE *at high rate* while preserving its uniqueness, superb tracking and PID, and enhance its vertexing capability and tracking at low-p_T**

Physics goals of the ALICE upgrade

Precise measurement of heavy-flavour hadron production (spectrum, elliptic flow) in a wide momentum range, down to very low p_T

Jet quenching and fragmentation: PID of jet particle content, heavy flavour tagging, correlations

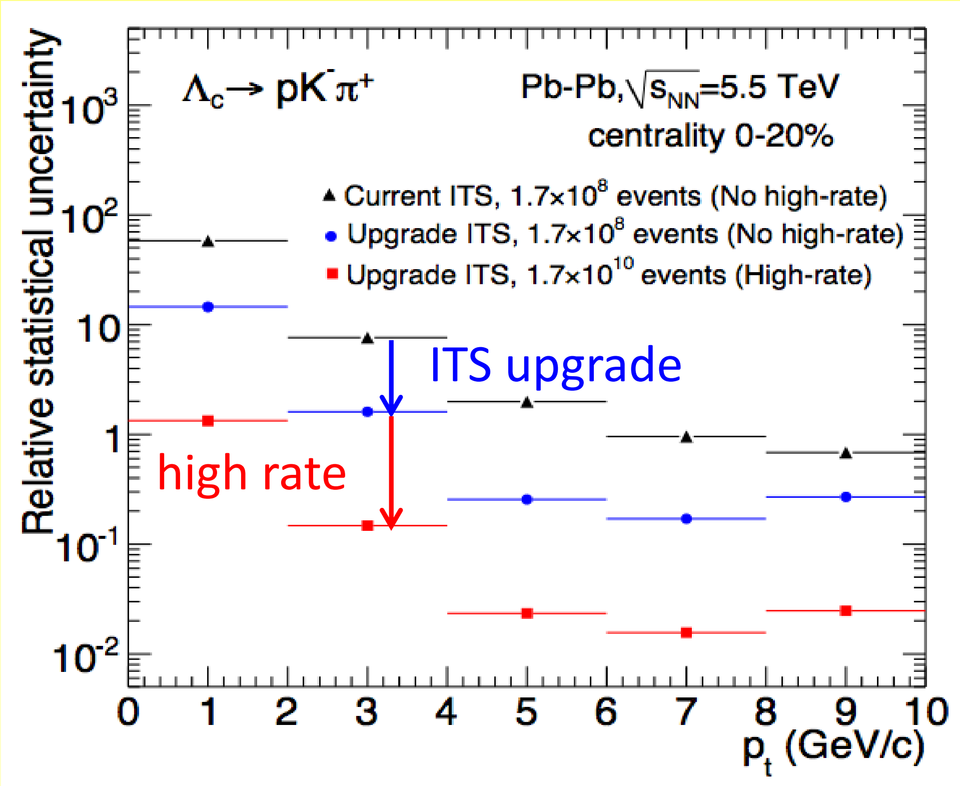
Measurement of low-mass and low-p_T di-leptons (from ρ,ω,.. decay, in-medium $q\bar{q} \rightarrow l^+l^-$, direct photons) ➞ **electromagnetic radiation from QGP**

J/ψ, ψ' states down to zero p_T in wide rapidity range

Heavy nuclear states

Example of performance studies: $\Lambda_c \rightarrow pK\pi$

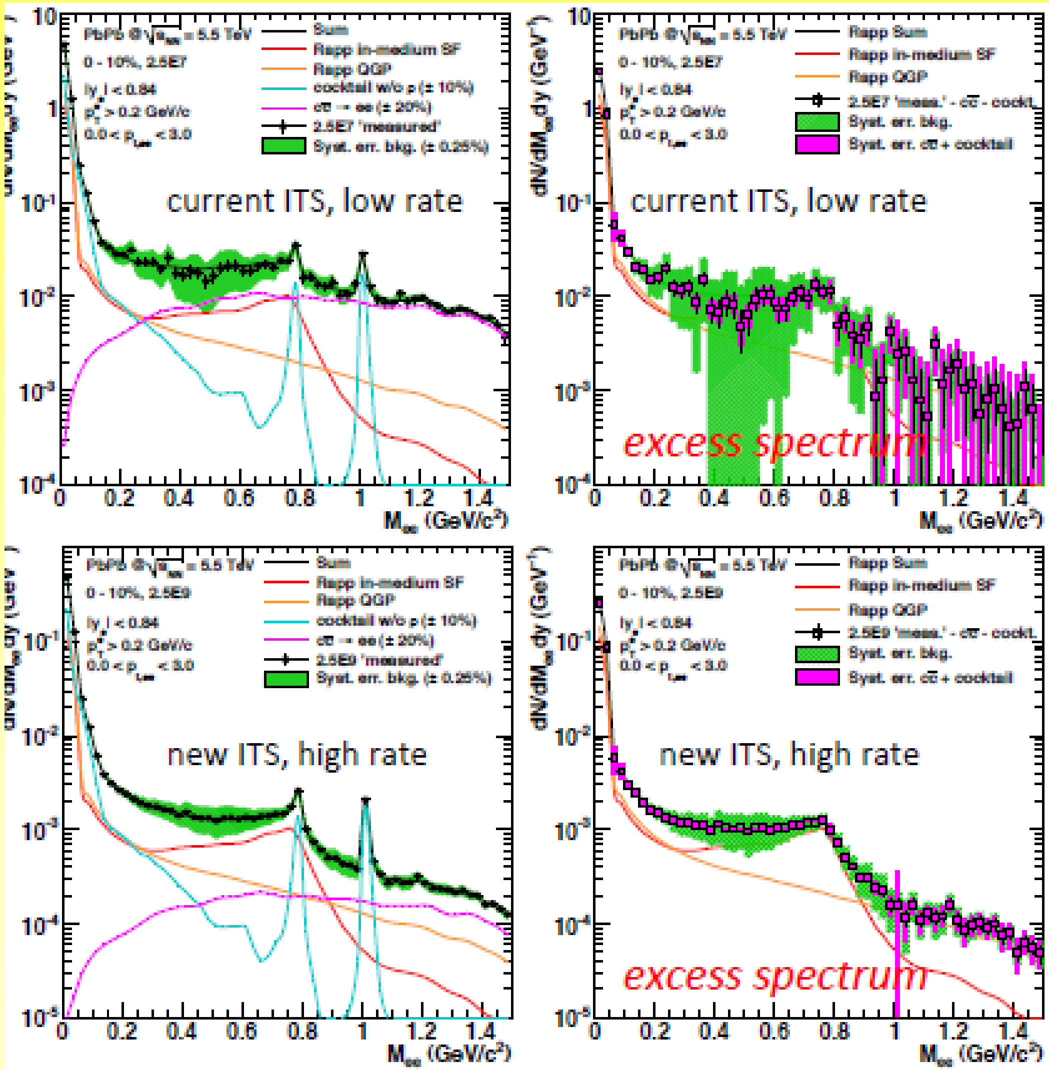
- Λ_c $c\tau$=60 μm, to be compared with D^+ $c\tau$=300 μm
  → practically impossible in Pb-Pb with current ITS



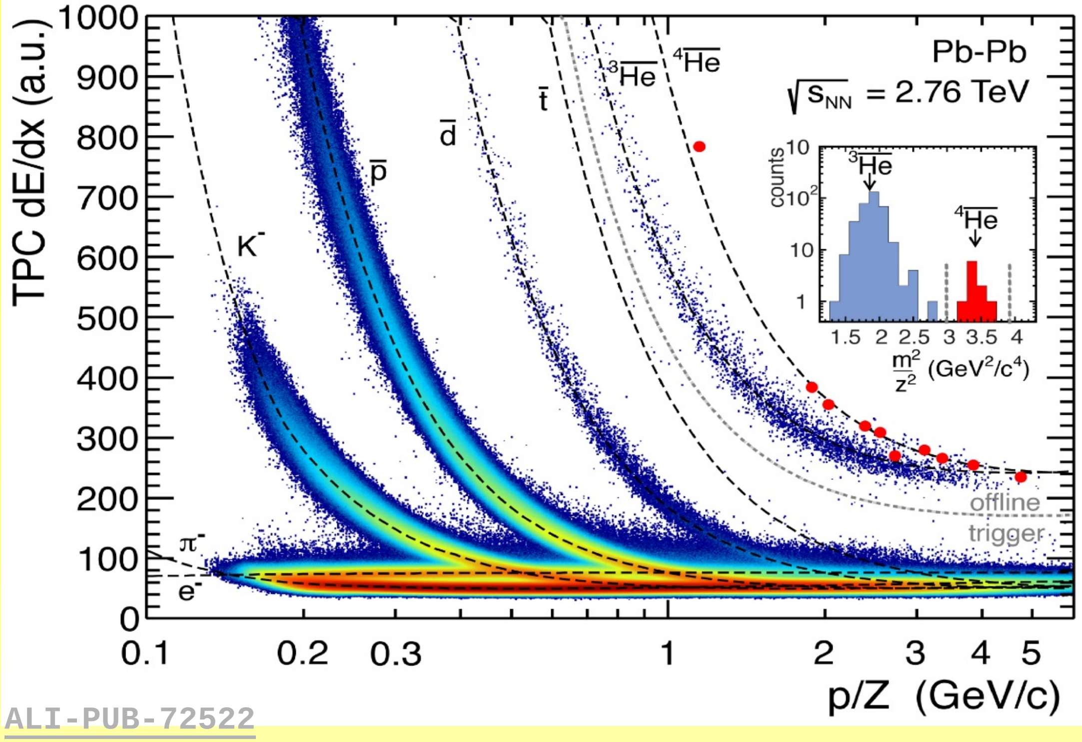
With new ITS and high-rate, measurement down to 2 GeV/*c*

Example of performance studies: low-mass e^+e^-

- e-PID in TPC and TOF
  - Needs high-rate readout
- Dalitz rejection, conversion and charm suppression
  - New ITS improves major sources of systematic uncertainties



Expected yields of heavy nuclear states per 10^{10} central collisions



- Anti-alpha 5×10^4
- Anti-hypertriton (Λ p n) 2×10^5
- Anti-(Λ p n n) 7×10^2
- Anti-(Λ p n n n) 3
- H (Λ Λ) $> 10^5$
- Λ n $> 10^5$

ALICE Upgrade Physics Reach: summary

p_T coverage (p_T^{min}) and statistical error for current ALICE with approved programme and upgraded ALICE with extended programme. Error in both cases at p_T^{min} of "approved".

Topic	Observable	Approved (1/nb delivered, 0.1/nb m.b.)	Upgrade (10/nb delivered, 10/nb m.b.)
Heavy flavour	D meson R_{AA}	p_T>1, 10%	p_T>0, 0.3%
	D from B R_{AA}	p_T>3, 30%	p_T>2, 1%
	D meson elliptic flow (for v_2=0.2)	p_T>1, 50%	p_T>0, 2.5%
	D from B elliptic flow (for v_2=0.1)	not accessible	p_T>2, 20%
	Charm baryon/meson ratio (Λ_c/D)	not accessible	p_T>2, 15%
	D_s R_{AA}	p_T>4, 15%	p_T>1, 1%
Charmonia	J/ψ R_{AA} (forward y)	p_T>0, 1%	p_T>0, 0.3%
	J/ψ R_{AA} (central y)	p_T>0, 5%	p_T>0, 0.5%
	J/ψ elliptic flow (forward y, for v_2 =0.1)	p_T>0, 15%	p_T>0, 5%
	ψ'	p_T>0, 30%	p_T>0, 10%
Dielectrons	Temperature IMR	not accessible	10% on T
	Elliptic flow IMR (for v_2=0.1)	not accessible	10%
	Low-mass vector spectral function	not accessible	p_T>0.3, 20%
Heavy nuclei	hyper(anti)nuclei, H-dibaryon	35% ($^4_\Lambda$H)	3.5% ($^4_\Lambda$H)

ALICE Upgrade Physics Reach: MFT

p_T coverage (p_T^{min}) and statistical error for current ALICE with approved programme and upgraded ALICE with extended programme. Error in both cases at p_T^{min} of "approved".

Topic	Observable	MUON Upgrade (10/nb delivered, 10/nb m.b.)	MUON + MFT Upgrade (10/nb delivered, 10/nb m.b.)
Heavy flavour	J/ψ from B R_{AA}	-	p_T>0, 10% @ 1 GeV (to be improved "a la LHCb")
	J/ψ from B v_2	-	Not evaluated yet
	μ decays from charmed hadrons	-	p_T>1, 7% @ 1 GeV
	μ decays from beauty hadrons	-	p_T>2, 10% @ 2 GeV
Charmonia	Prompt J/ψ R_{AA}	-	p_T>0, 10% @ 1 GeV
	Prompt J/ψ v_2	-	Not evaluated yet
	ψ'	p_T>0, 30%	p_T>0, 10% @ 1 GeV
Dielectrons	Low mass spectral func. and QGP radiation	-	p_T>1, 20% at 1 GeV

Running scenario after the upgrade

- Pb–Pb
  - int. luminosity per year 2.85 nb^{-1} (peak L = 7×10^{27} $cm^{-2}s^{-1}$)
  - needed int. luminosity 10 nb^{-1}, statistics 8×10^{10} events
  - 3.5 month of running
  - +1 month of special run at low field for dielectrons
- p–Pb
  - max event rate 200 kHz, flat (L = 10^{29} $cm^{-2}s^{-1}$)
  - needed int. luminosity 50 nb^{-1}, statistics 10^{11} events
  - 0.5 month of dedicated p–Pb run
- pp
  - max event rate 200 kHz, flat (L = 3×10^{30} $cm^{-2}s^{-1}$)
  - needed int. luminosity 6 pb^{-1}, statistics 4×10^{11} events
  - ~ 2 months of dedicated pp run

The list above fulfills the ALICE physics program as presented in the LoI.

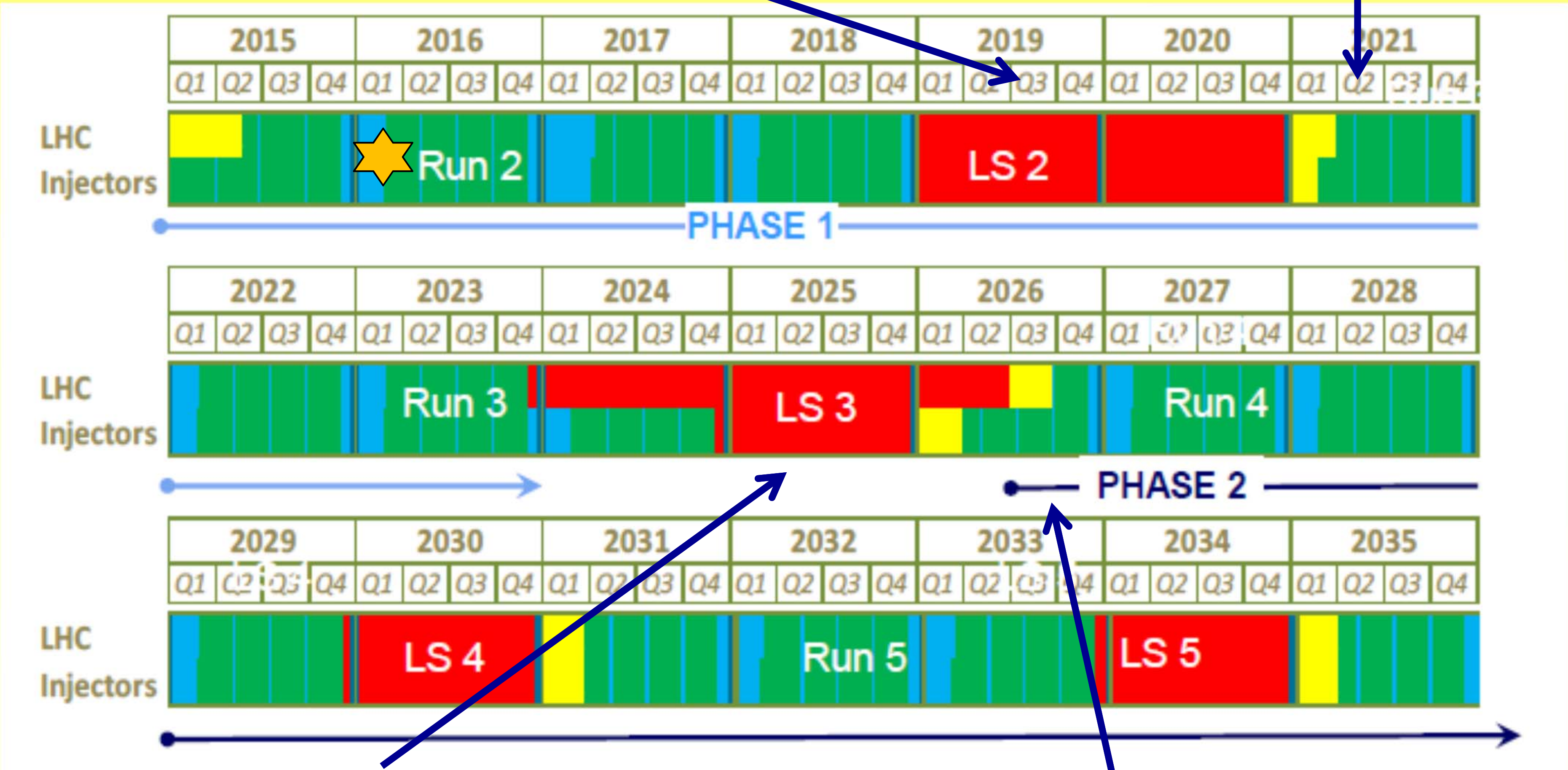
A run with lower mass nuclei (e.g. Ar) could be considered in addition, if a physics case for it would emerge.

LHC Schedule

ALICE

PHASE I Upgrade
ALICE, LHCb major upgrade
ATLAS, CMS ‚minor' upgrade

Heavy Ion Luminosity from 10^{27} to 7 x10^{27}



PHASE II Upgrade
ATLAS, CMS major upgrade

HL-LHC, pp luminosity from 10^{34} (peak) to 5 x10^{34} (levelled)

The ALICE Upgrade In a nutshell:

Goal:

- High precision measurements of rare probes at low $p_{T,}$ which cannot be selected with a trigger. Target a recorded Pb-Pb luminosity $\geq 10\ nb^{-1}$ ➡ 8×10^{10} events to gain a factor 100 in statistics over the Run1+Run2 programme
- Significant improvement of vertexing and tracking capabilities

Detector:

- Read out all Pb-Pb interactions at a maximum rate of 50kHz (i.e. $L = 6x10^{27}\ cm^{-1}s^{-1}$) upon a minimum bias trigger
- Perform online data reduction based on reconstruction of clusters and tracks
- Improve vertexing and tracking at low p_T ➔ New Inner Tracking System (ITS)

The ALICE upgrades

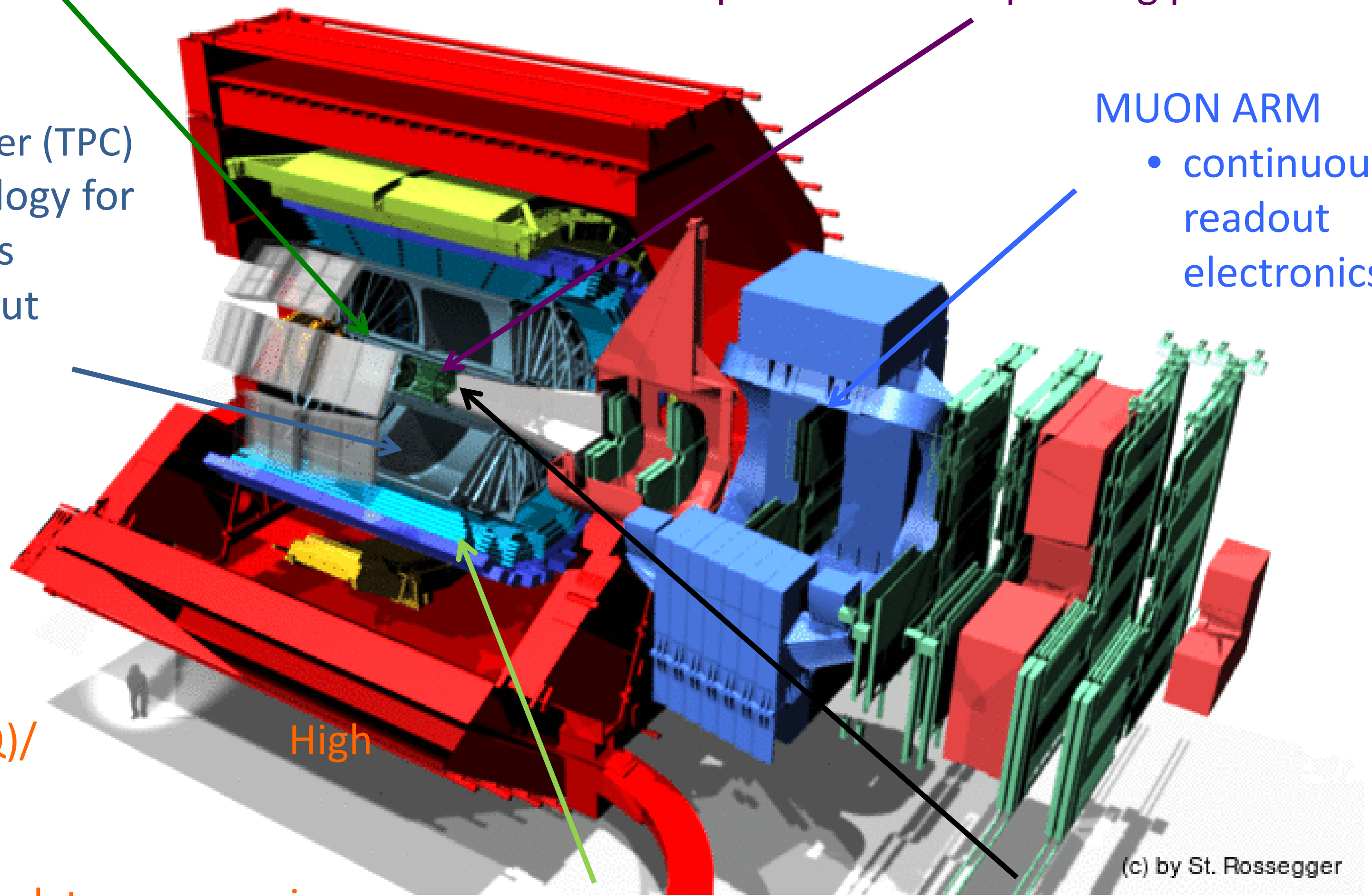
ALICE

New Inner Tracking System (ITS)
- improved pointing precision
- less material -> thinnest tracker at the LHC

Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

Time Projection Chamber (TPC)
- new GEM technology for readout chambers
- continuous readout
- faster readout electronics

MUON ARM
- continuous readout electronics



New Central Trigger Processor

Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

TOF, TRD, ZDC
- Faster readout

New Trigger Detectors (FIT)

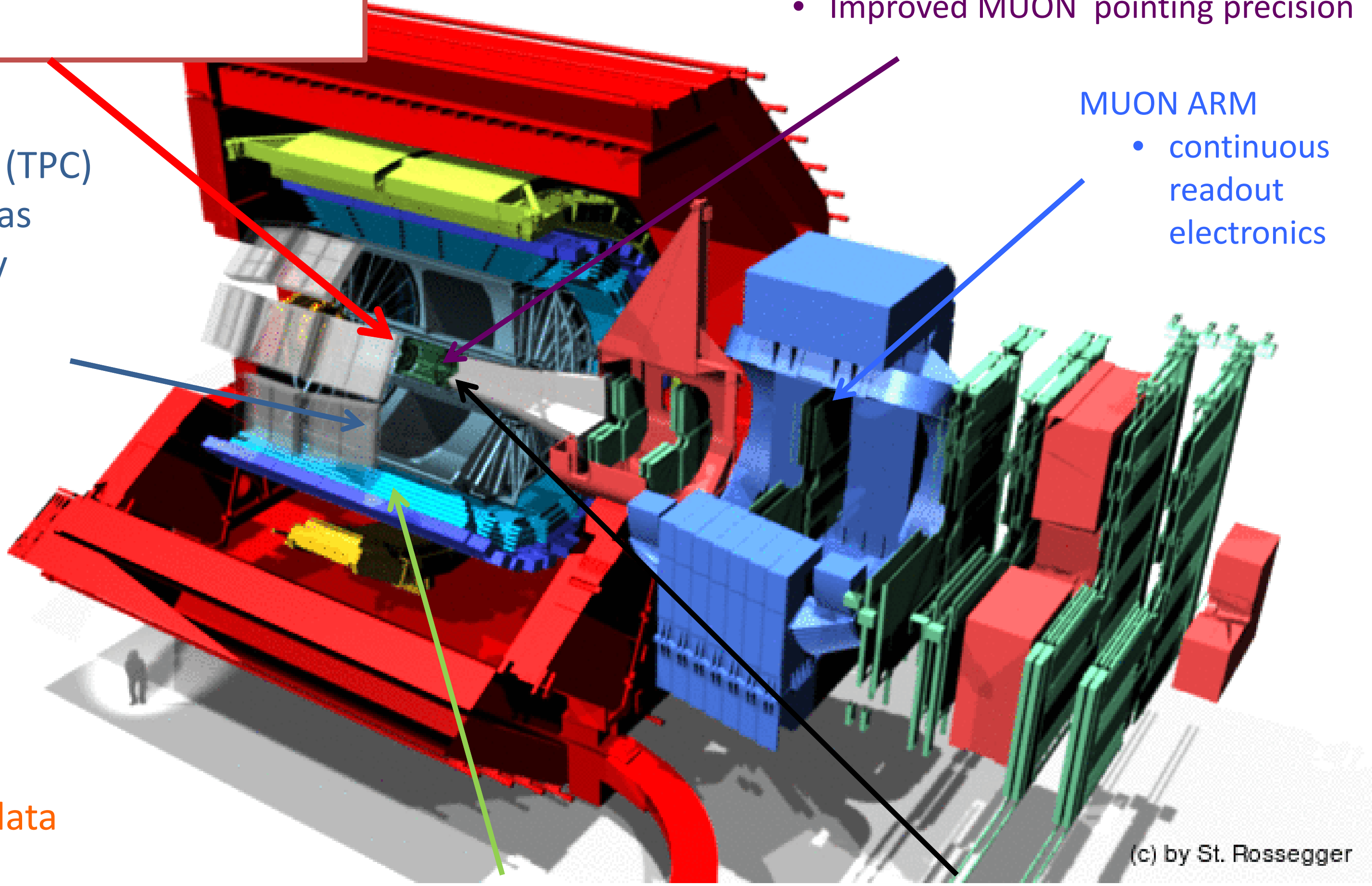
ALICE Upgrade

New Inner Tracking System (ITS)
- **improved pointing precision**
- **less material**

Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

MUON ARM
- continuous readout electronics

Time Projection Chamber (TPC)
- New Micropattern gas detector technology
- continuous readout



New Central Trigger Processor (CTP)

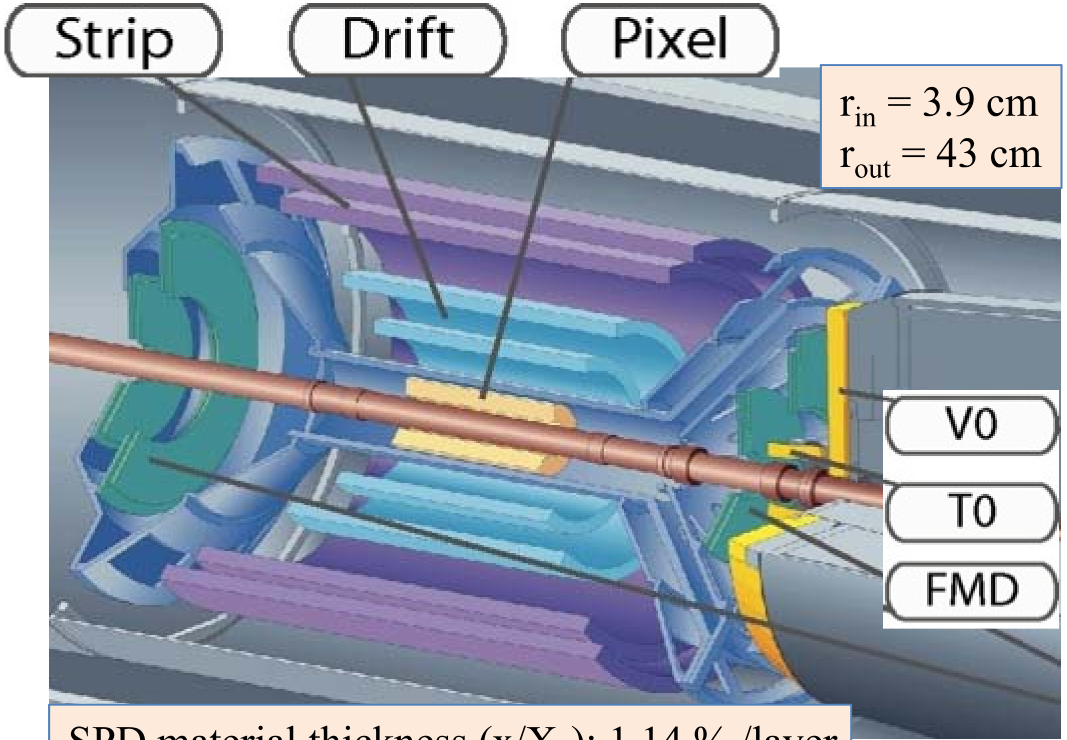
Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

TOF, TRD
- Faster readout

New Trigger Detectors (FIT)

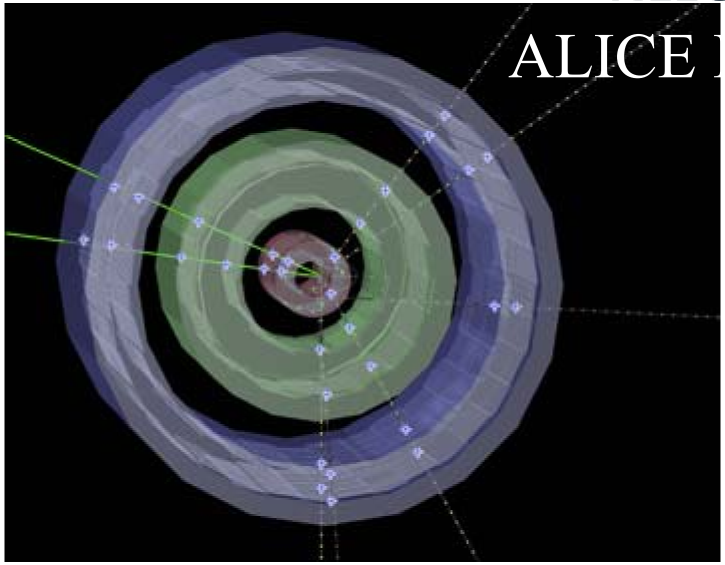
The Current Inner Tracking System

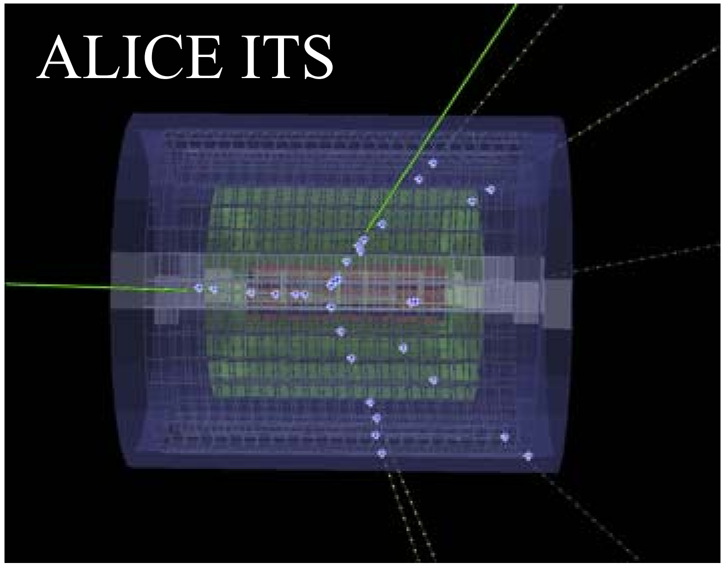
A Large Ion Collider Experiment



r_{in} = 3.9 cm
r_{out} = 43 cm

SPD material thickness (x/X_0): 1.14 % /layer





Current ITS

6 concentric barrels, 3 different technologies

- 2 layers of silicon pixel (SPD)
- 2 layers of silicon drift (SDD)
- 2 layers of silicon strips (SSD)

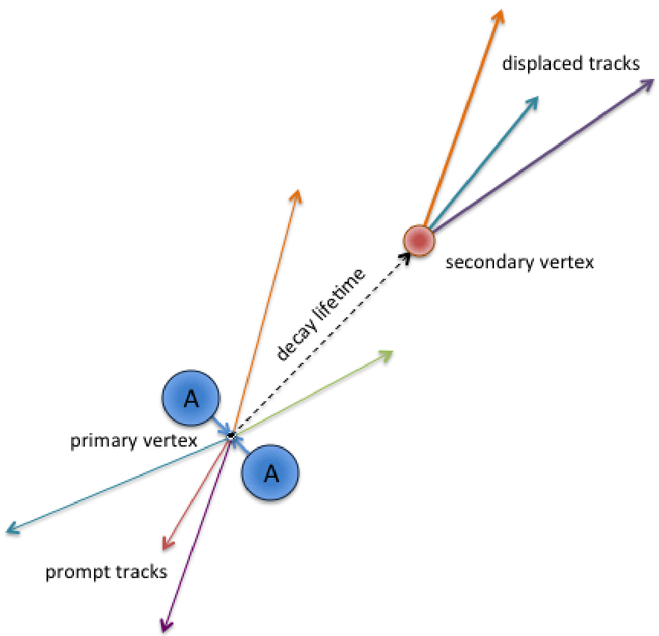
Secondary vertex determination

A Large Ion Collider Experiment

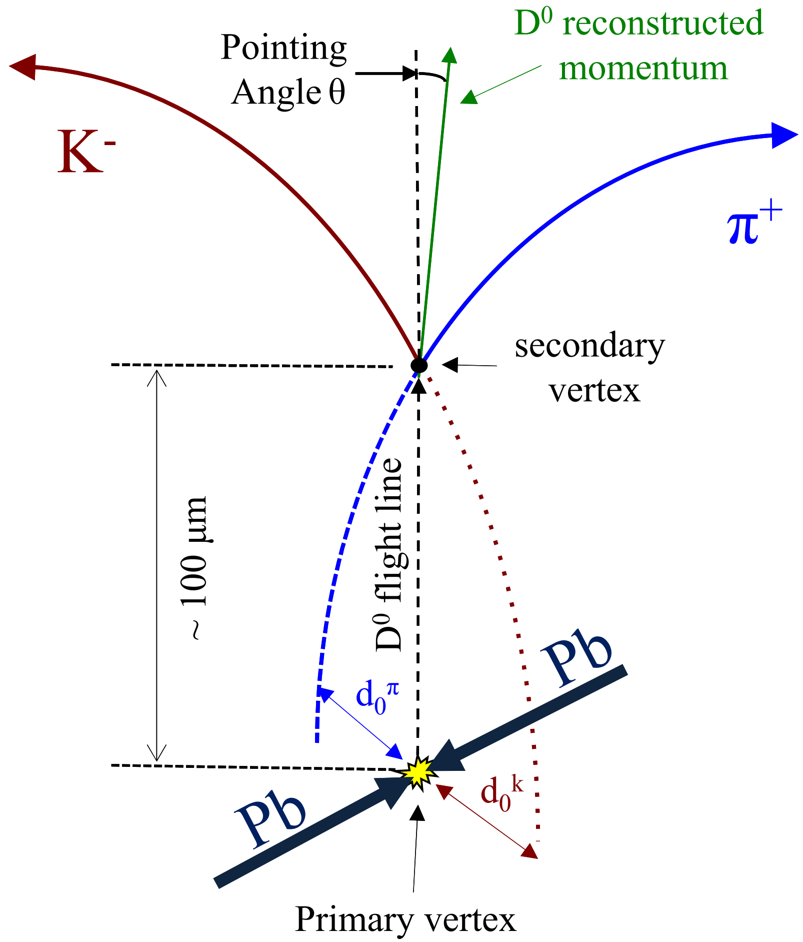
ALICE

Open charm (➔ QGP hard probe)

Particle	Decay Channel	cτ (μm)
D^0	$K^- \pi^+$ (3.8%)	123
D^+	$K^- \pi^+ \pi^+$ (9.5%)	312
D_s^+	$K^+ K^- \pi^+$ (5.2%)	150
Λ_c^+	$p K^- \pi^+$ (5.0%)	60



Example: D^0 meson

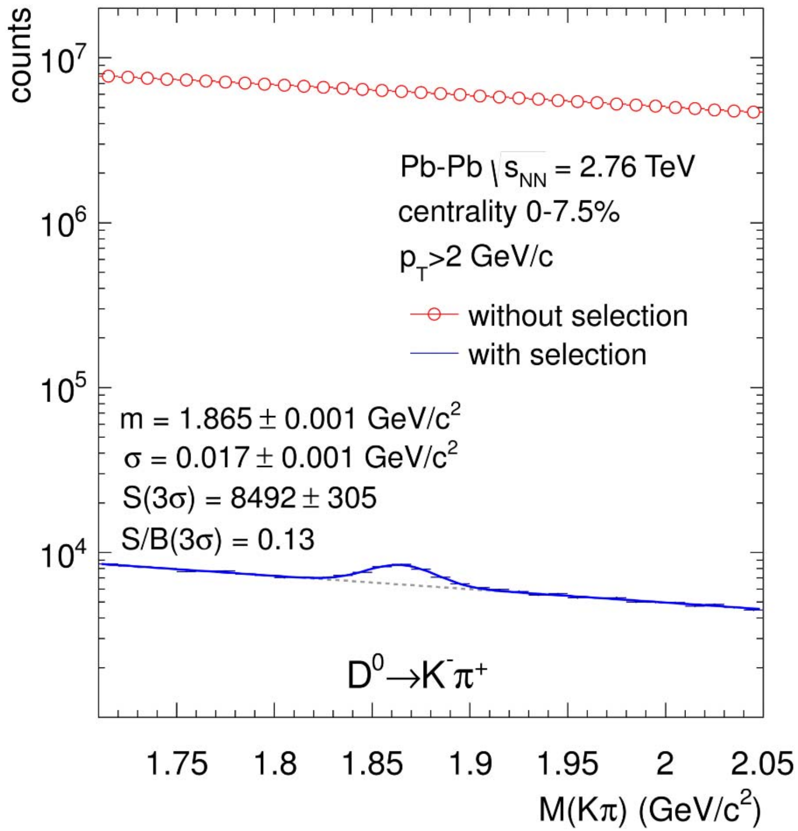


Analysis based on invariant mass, PID and decay topology

Secondary vertex determination

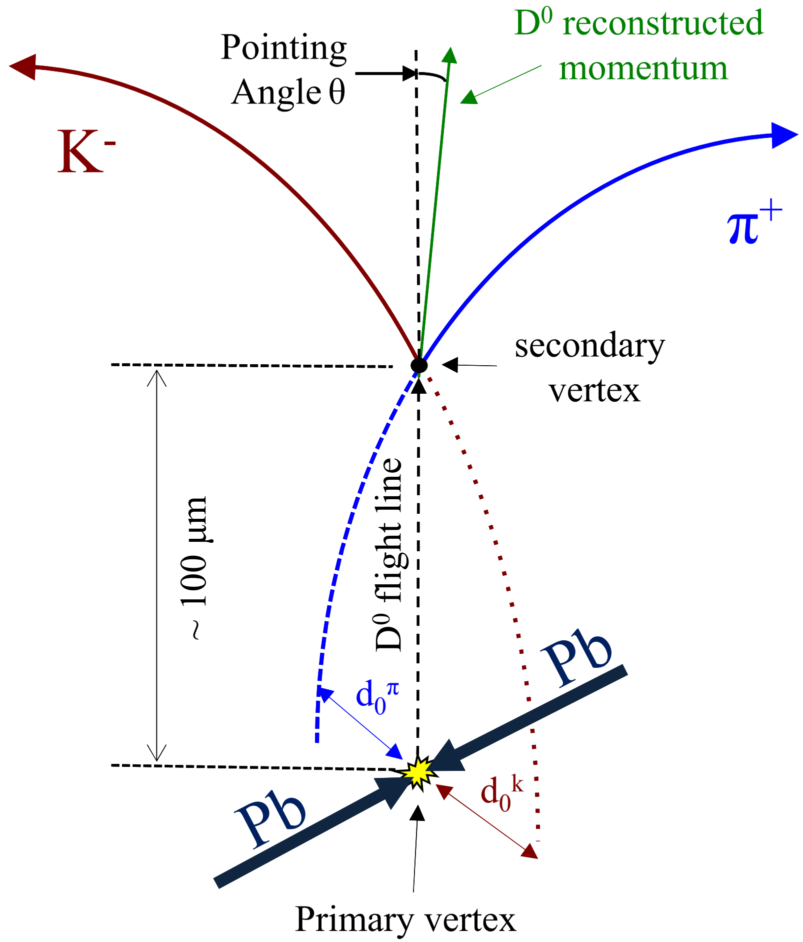
A Large Ion Collider Experiment

ALICE, Int. J. Mod. Phys. A 29 (2014) 1430044



Invariant mass distribution of $K^-\pi^+$ pairs before and after applying selection criteria on the relation between the secondary (D^0 decay) and primary vertices

Example: D^0 meson



Analysis based on invariant mass, PID and decay topology

ITS upgrade design objectives

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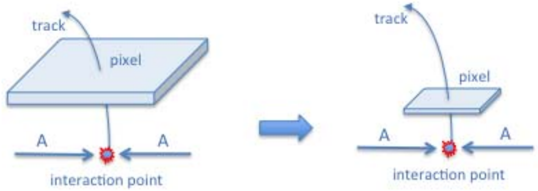
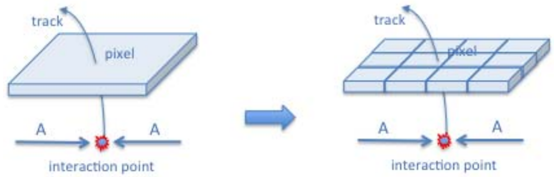
1. Improve impact parameter resolution by a factor of ~3



- Get closer to IP (position of first layer): 39mm ➡ 23mm
- Reduce x/X_0 /layer: ~1.14% ➡ ~ 0.3% (for iner layers)
- Reduce pixel size: currently 50μm x 425μm ➡ O(30μm x 30μm)

2. Improve tracking efficiency and p_T resolution at low p_T

- Increase granularity:
    - 6 layers ➡ 7 layers
    - silicon drift and strips ➡ pixels



3. Fast readout

- readout Pb-Pb interactions at > 100 kHz
  (currently limited at 1kHz with full ITS)

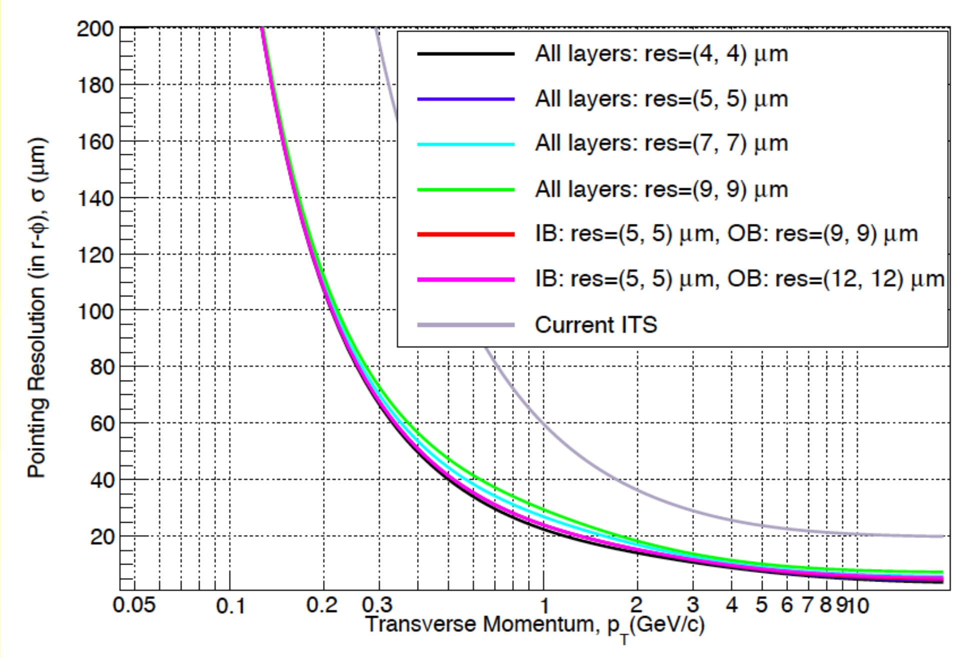
4. Fast insertion/removal for yearly maintenance

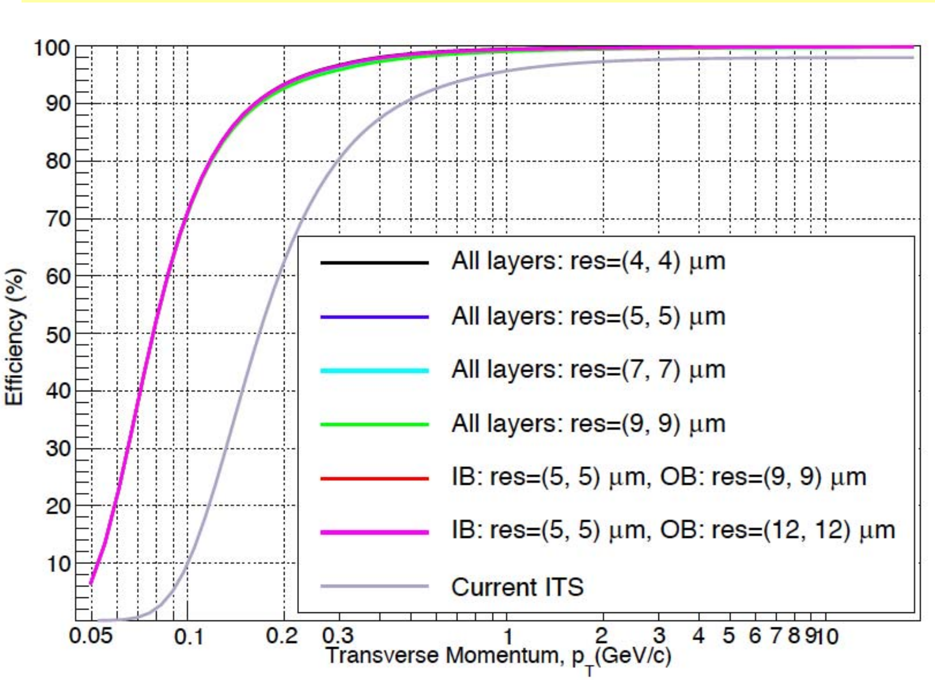
- possibility to replace non functioning detector modules during yearly shutdown

Radiation levels (layer 0)

TID: 2.7 Mrad, NIEL: 1.7×10^{13} 1 MeV n_{eq} cm^{-2} (safety factor 10)

ITS performance improvement

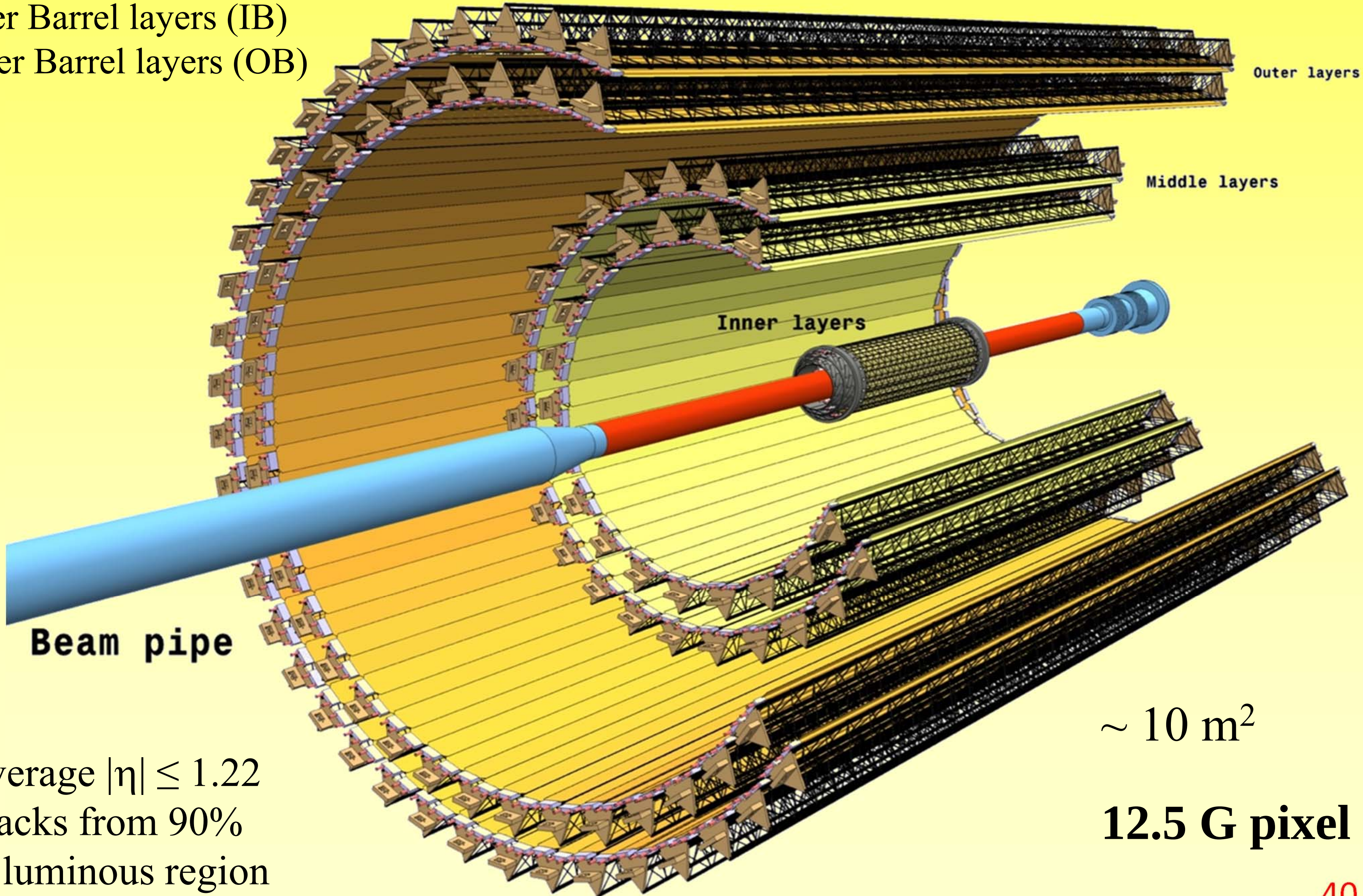




New ALICE ITS

7 layers based on Monolithic Active Pixel Sensors (MAPS)

3 Inner Barrel layers (IB)
4 Outer Barrel layers (OB)



$\sim 10\ m^2$

12.5 G pixel

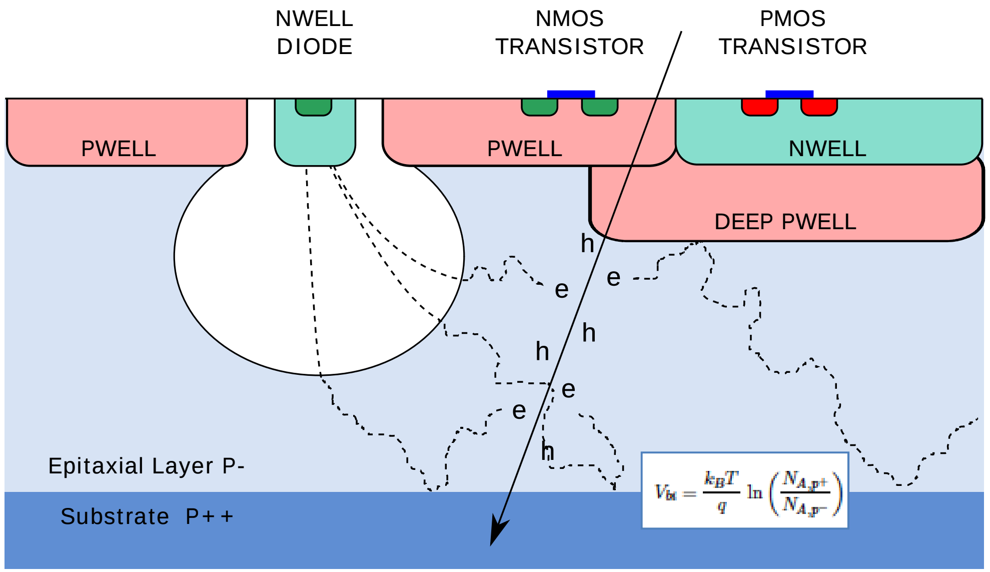
η coverage $|\eta| \leq 1.22$
for tracks from 90%
most luminous region

ITS Pixel Chip – technology choice

A Large Ion Collider Experiment

ALICE

CMOS Pixel Sensor using TowerJazz 0.18μm CMOS Imaging Process



Tower Jazz 0.18 μm CMOS

- feature size 180 nm
- metal layers 6
- gate oxide 3nm

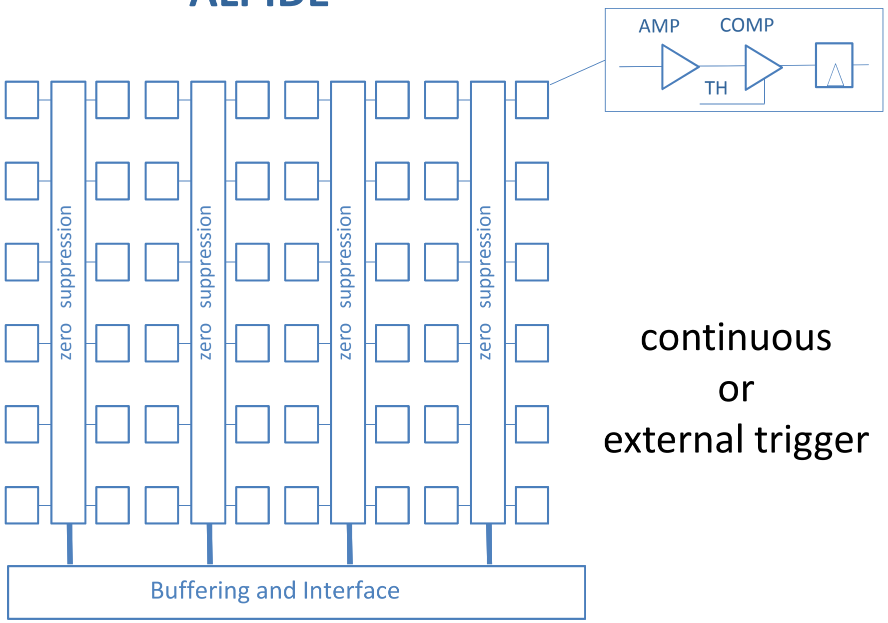
substrate: $N_A \sim 10^{18}$
epitaxial layer: $N_A \sim 10^{13}$
deep p-well: $N_A \sim 10^{16}$

- High-resistivity (> 1kΩ cm) p-type epitaxial layer (18μm - 40μm thick) on p-type substrate
- Small n-well diode (2-3 μm diameter), ~100 times smaller than pixel => low capacitance
- Application of (moderate) reverse bias voltage to substrate (contact from the top) can be used to increase depletion zone around NWELL collection diode
- Quadruple well process: deep PWELL shields NWELL of PMOS transistors, allowing for full CMOS circuitry within active area

ITS Pixel Chip – two architectures

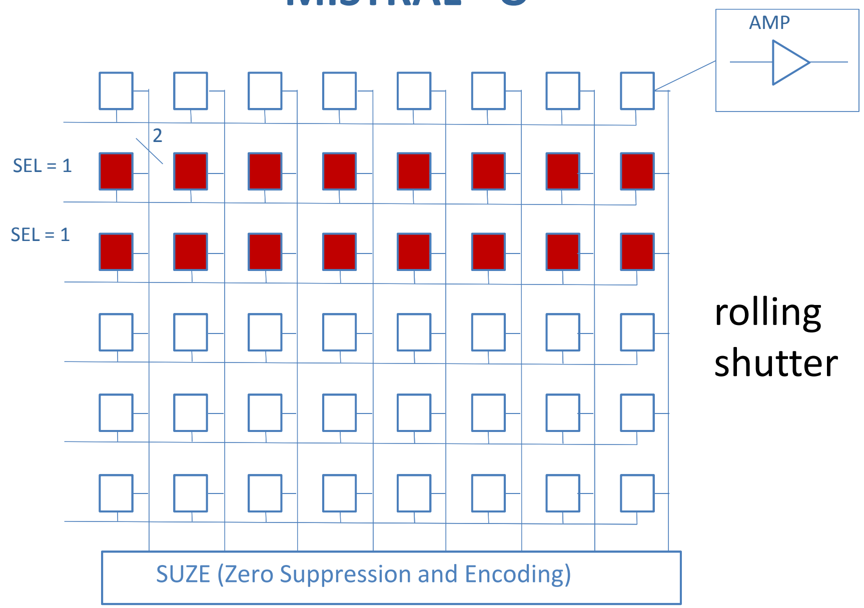
ALICE

ALPIDE



continuous
or
external trigger

MISTRAL - O



rolling
shutter

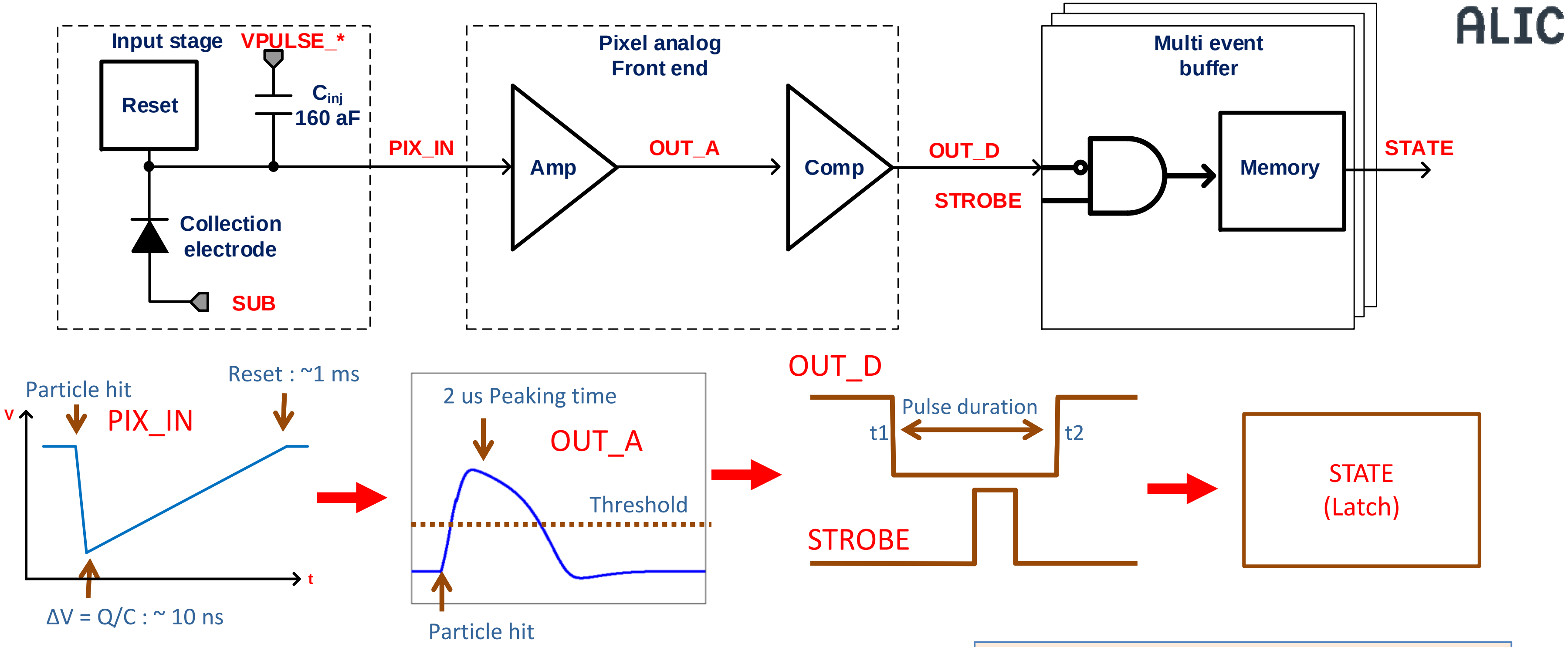
	ALPIDE		MISTRAL-O
Pixel pitch	28μm x 28μm	Pixel pitch	36μm x 64μm
Event time resolution	<2μs	Event time resolution	~20μs
Power consumption	~35mW/cm^2	Power consumption(*)	97mW/cm^2
Dead area	1.1 mm x 30mm	Dead area	1.7 mm x 30mm

ALPIDE and MISTRAL-O have same dimensions (15mm x 30mm), identical physical and electrical interfaces: position of interface pads, electrical signaling, protocol

(*) might further reduce to 73mW/cm^2

ALPIDE Principle of Operation

ALICE



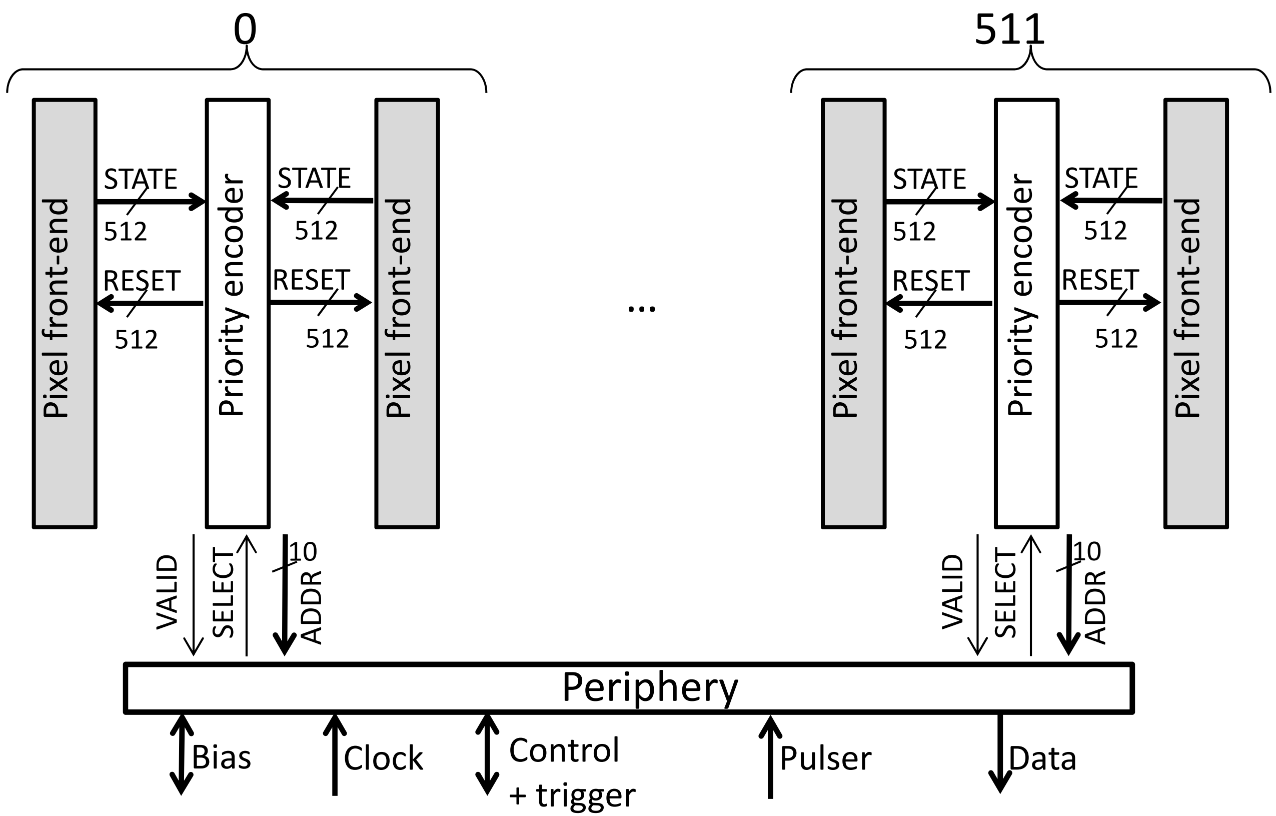
ultra low-power front-end circuit
40nW / pixel

Front-end acts as delay line

- Sensor and front-end continuously active
- Upon particle hit front-end forms a pulse with ~1-2μs peaking time
- Threshold is applied to form binary pulse
- Hit is latched into memory if strobe is applied during binary pulse

ALPIDE Principle of Operation

A Large Ion Collider Experiment



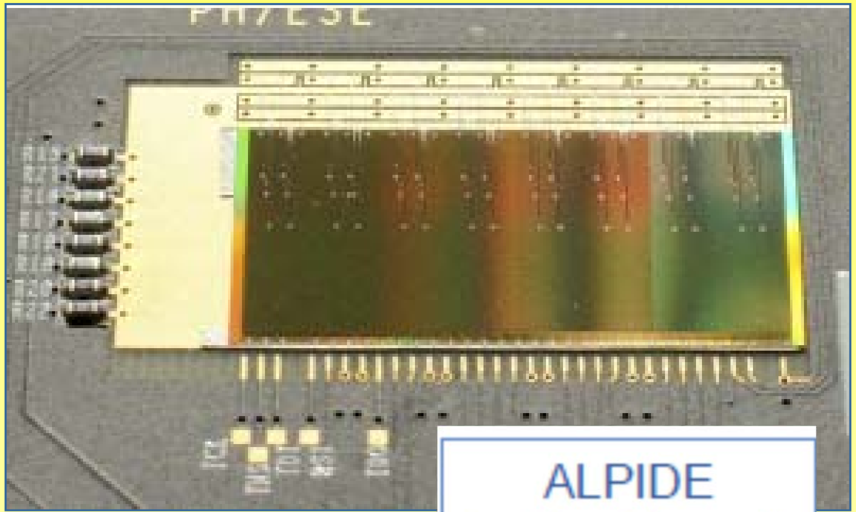
Pixel Matrix - Hit driven architecture

low-power matrix readout ~ 2mW

- Priority encoder sequentially provides addresses of all hit pixels present in double column
- No activity if no hit (**no free running clock**) ➔ low power

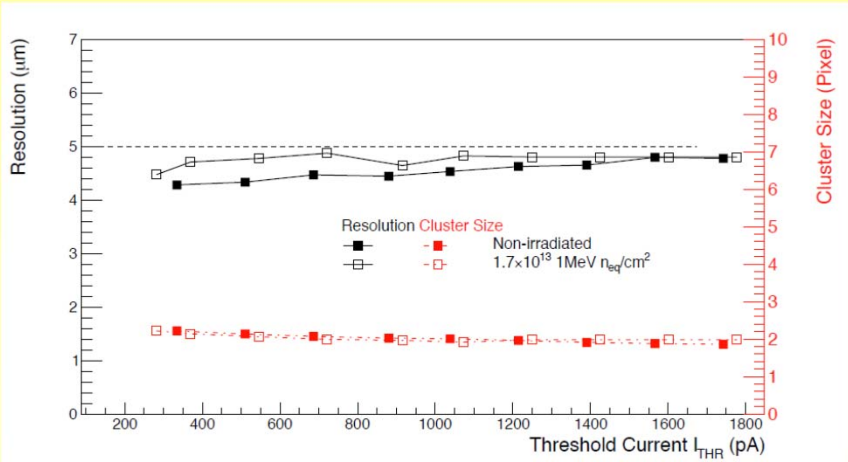
PIXEL Chip (ALPIDE): experimental results

pALPIDE-2 - 2nd full-scale prototype (2015)



ALPIDE
(~15 x 30 mm^2)

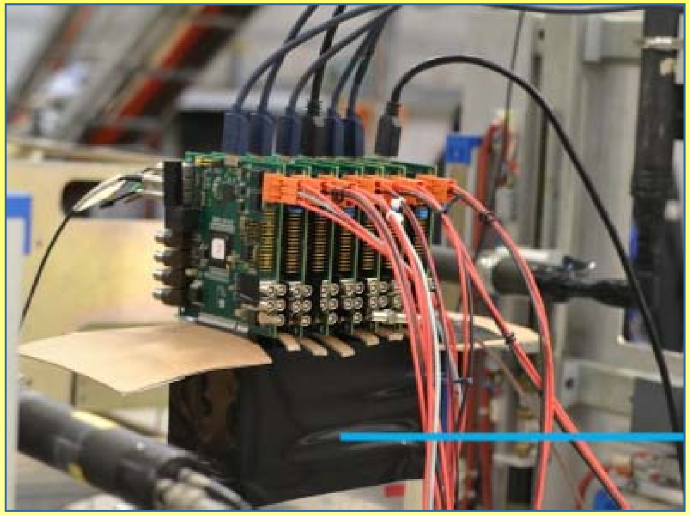
$\sigma_{det} \approx 5\ \mu m$



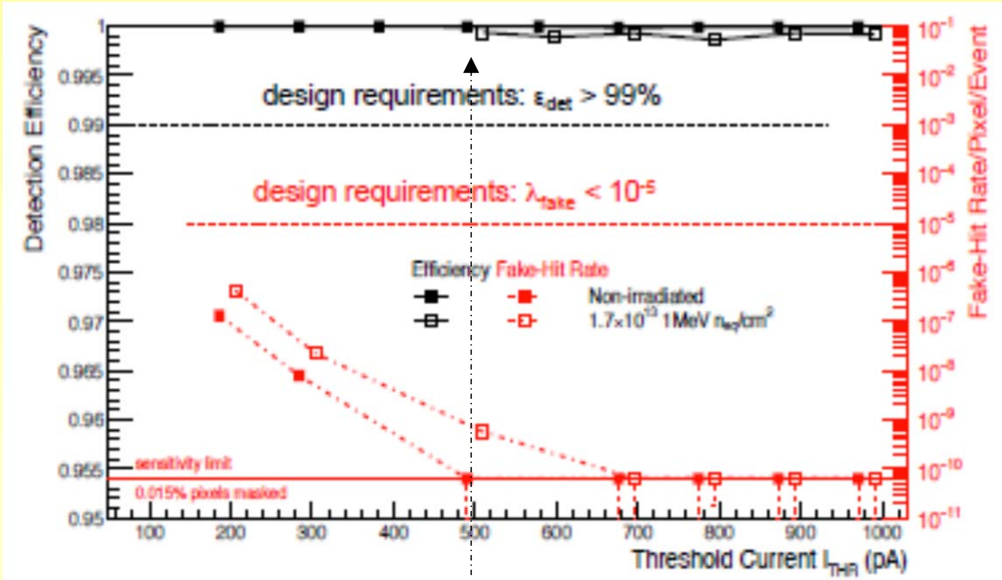
Measurements at PS: 5 – 7 GeV π^-

Results refer to chips with 25μm high-res epi layer, thinned to 50 μm:
1 non irradiated and 1 irradiated with 10^{13} 1MeV n_{eq} / cm^2

Test beam (7-plane telescope)

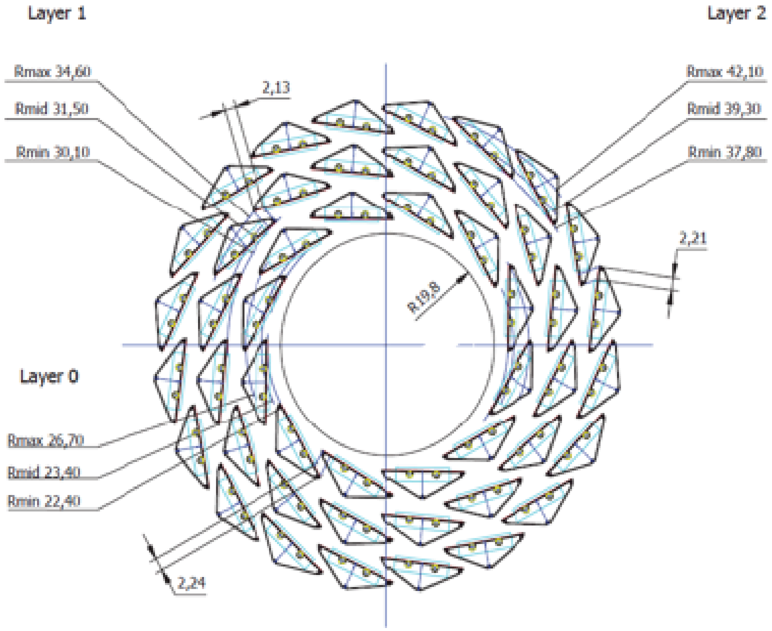


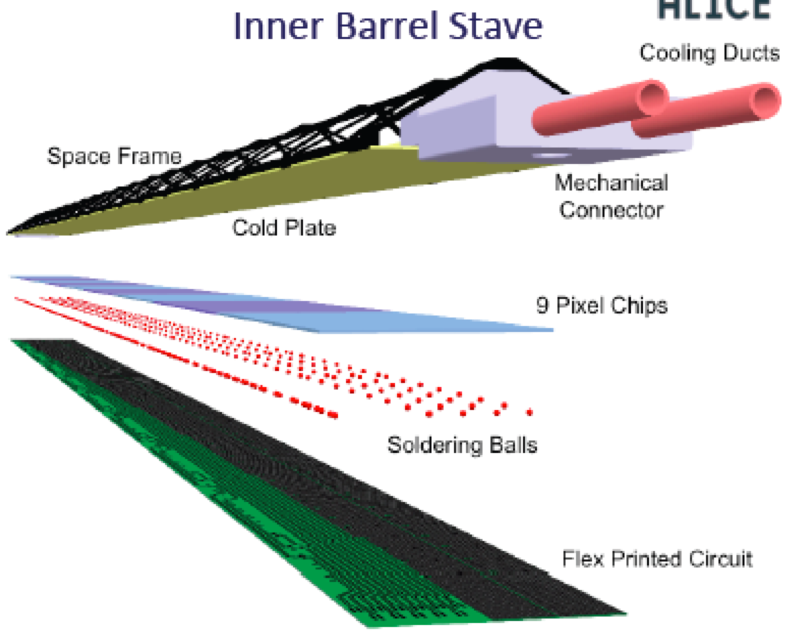
$\lambda_{fake} << 10^{-5}$/event/pixel @ $\varepsilon_{det} > 99\%$



Nominal threshold setting I_{THR} = 500 pA

Inner Barrel





Inner Barrel (IB): 3 Inner Layers

Radial position (mm): 23, 31, 39

Length in z (mm): 271

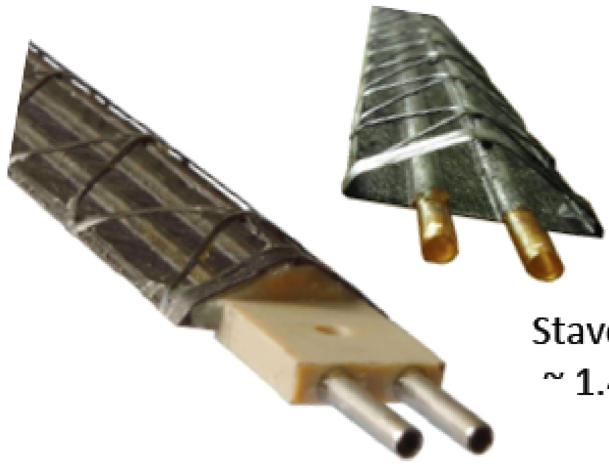
Nr. of staves: 12, 16, 20

Nr. of modules/stave: 1

Nr. of chips/module: 9

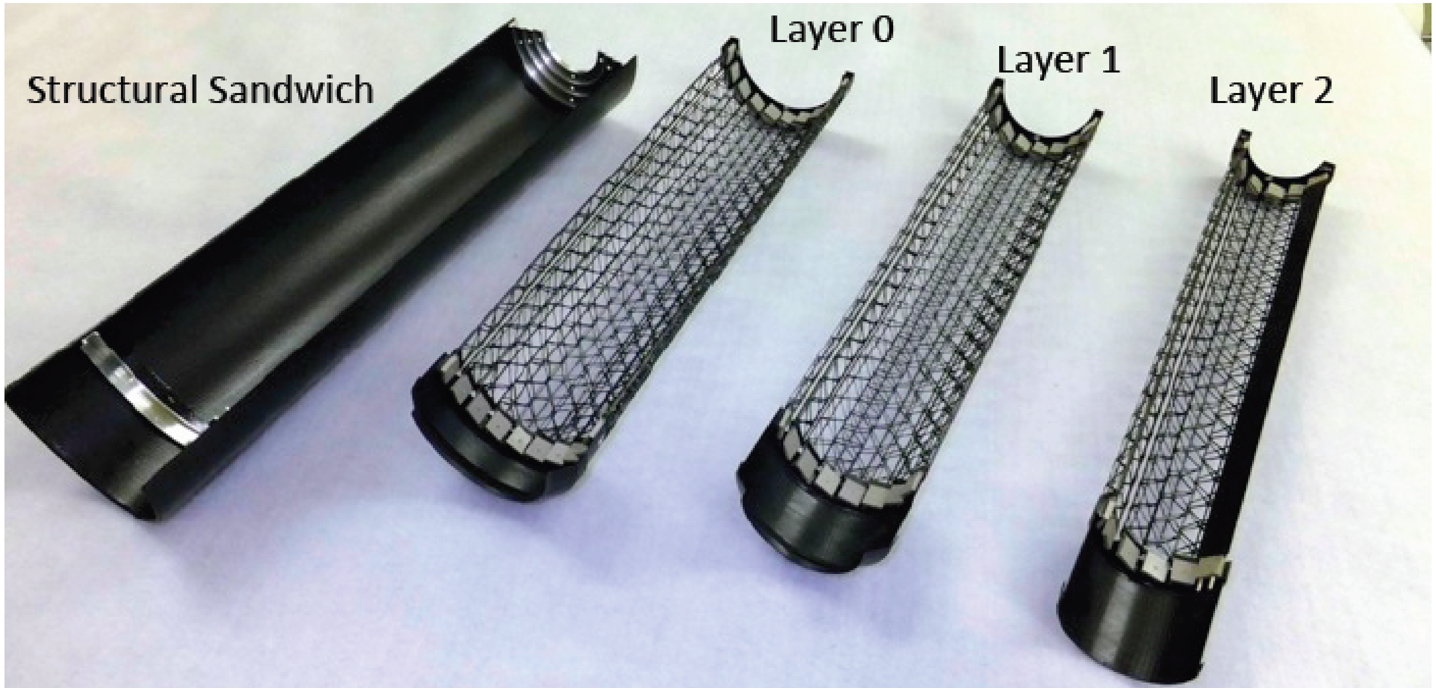
Nr. of chips/layer: 108, 144, 180

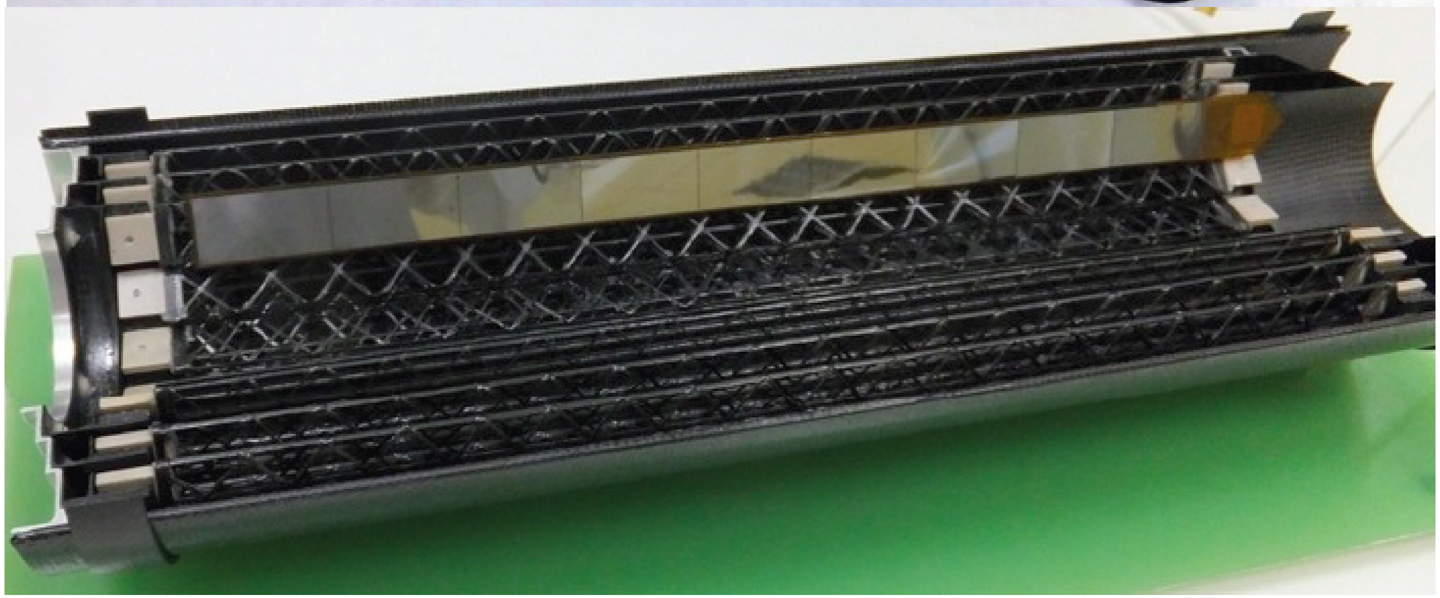
Material thickness: $\leq 0.3\% X_0$ per layer



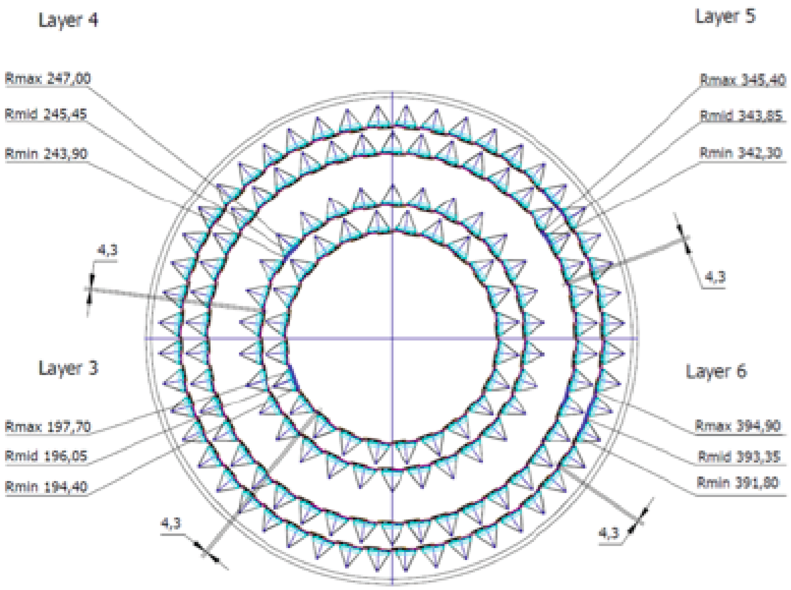
Stave weight
~ 1.4 grams

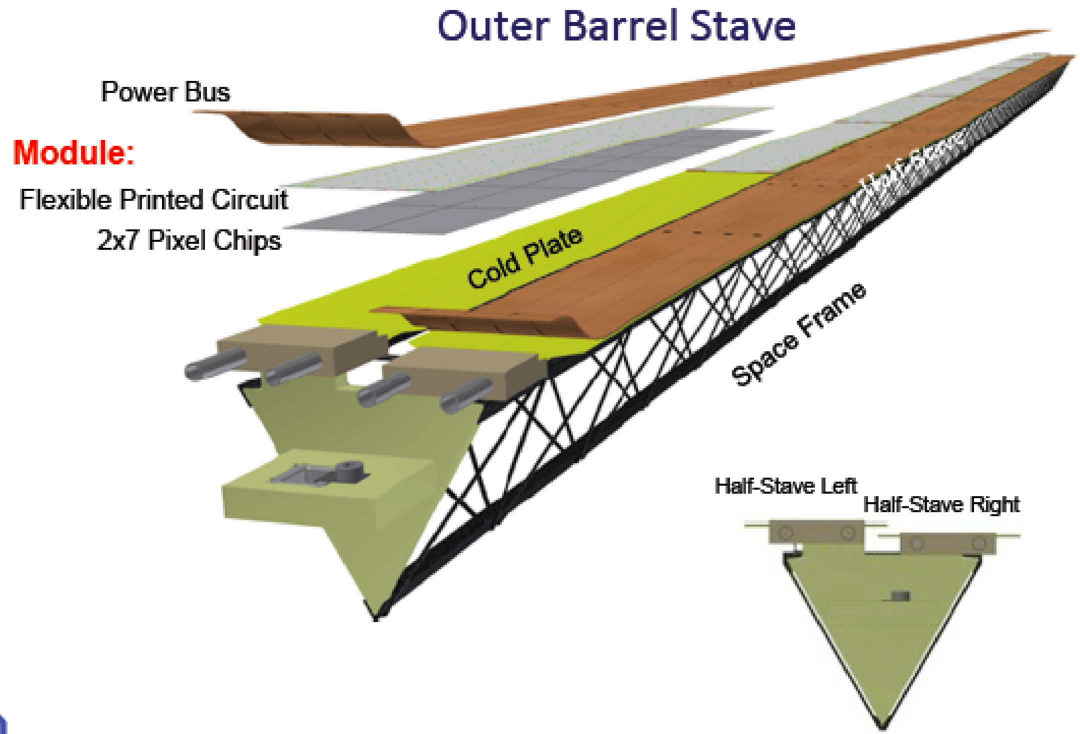
Inner Barrel: full-scale prototypes of the mechanical structures





Outer Barrel





Outer Barrel (OB): 2 ML + 2 OL

Radial position (mm): 196, 245, 344, 393

Length in z (mm): 843, 1475

Nr. of staves: 24, 30, 42, 48

Nr. of half-staves/stave: 2

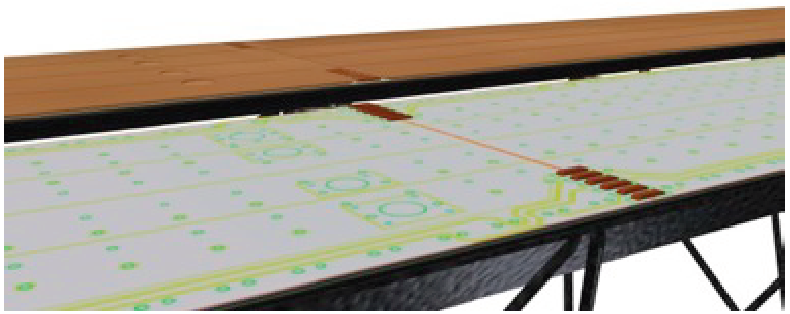
Nr. of modules/half-stave: 4 (ML), 7 (OL)

Nr. of chips/module: 14

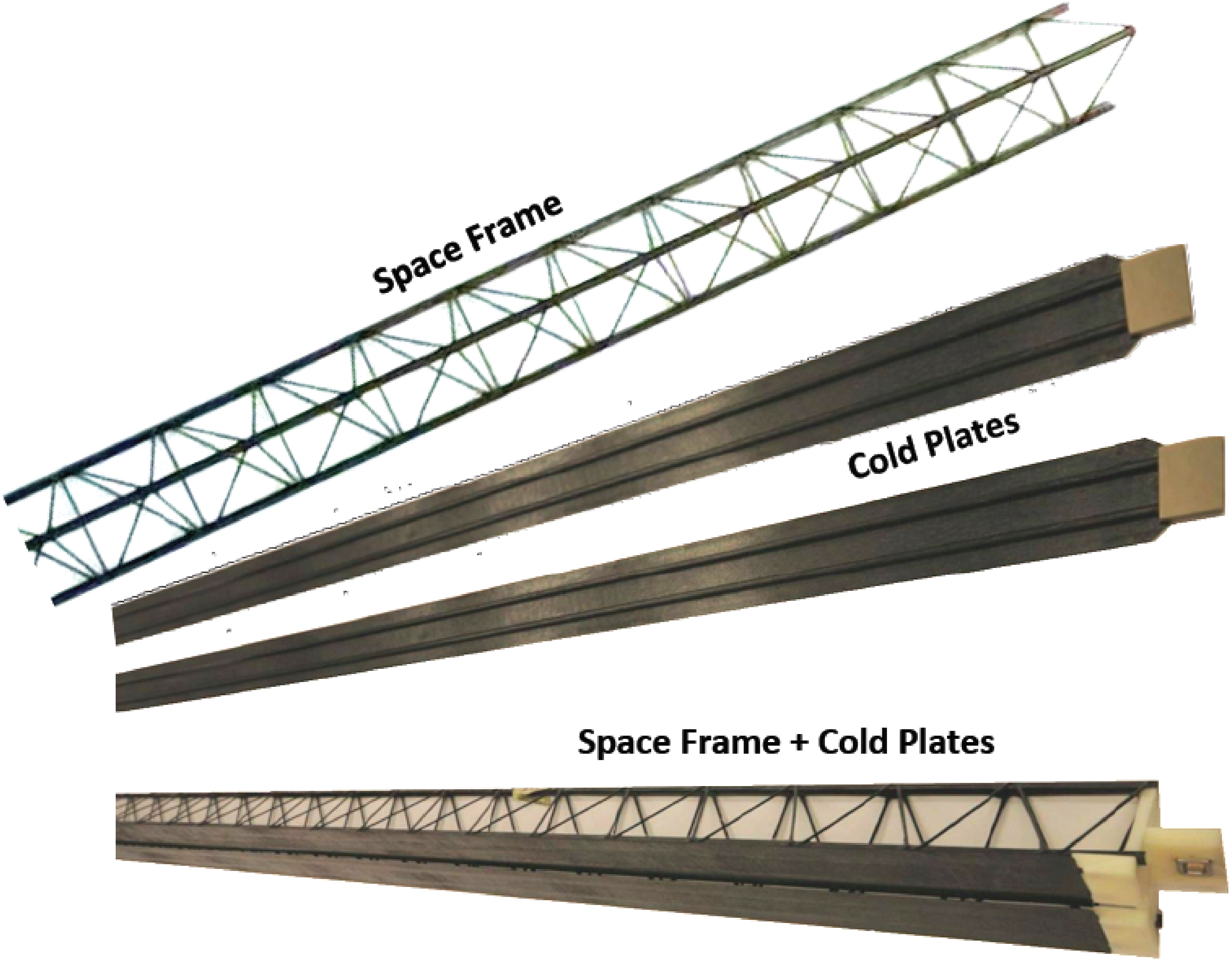
Nr. of chips/layer: 2688, 3360, 8232, 9408

Material thickness: ~ 0.9% X_0 per layer

Module to Module and Power Bus connections

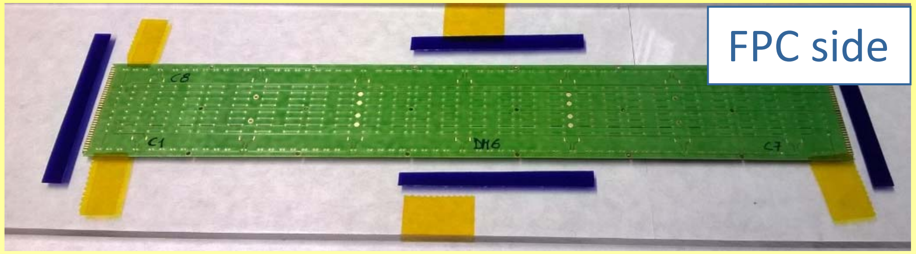


Outer Barrel: full-scale prototypes of the mechanical structures

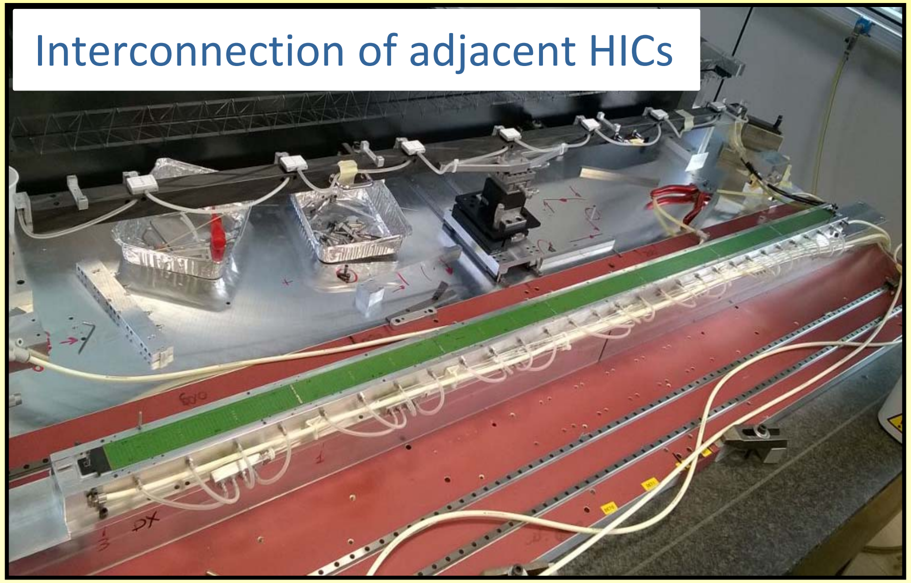


ITS Module & Stave prototypes

pixel chip side



FPC side

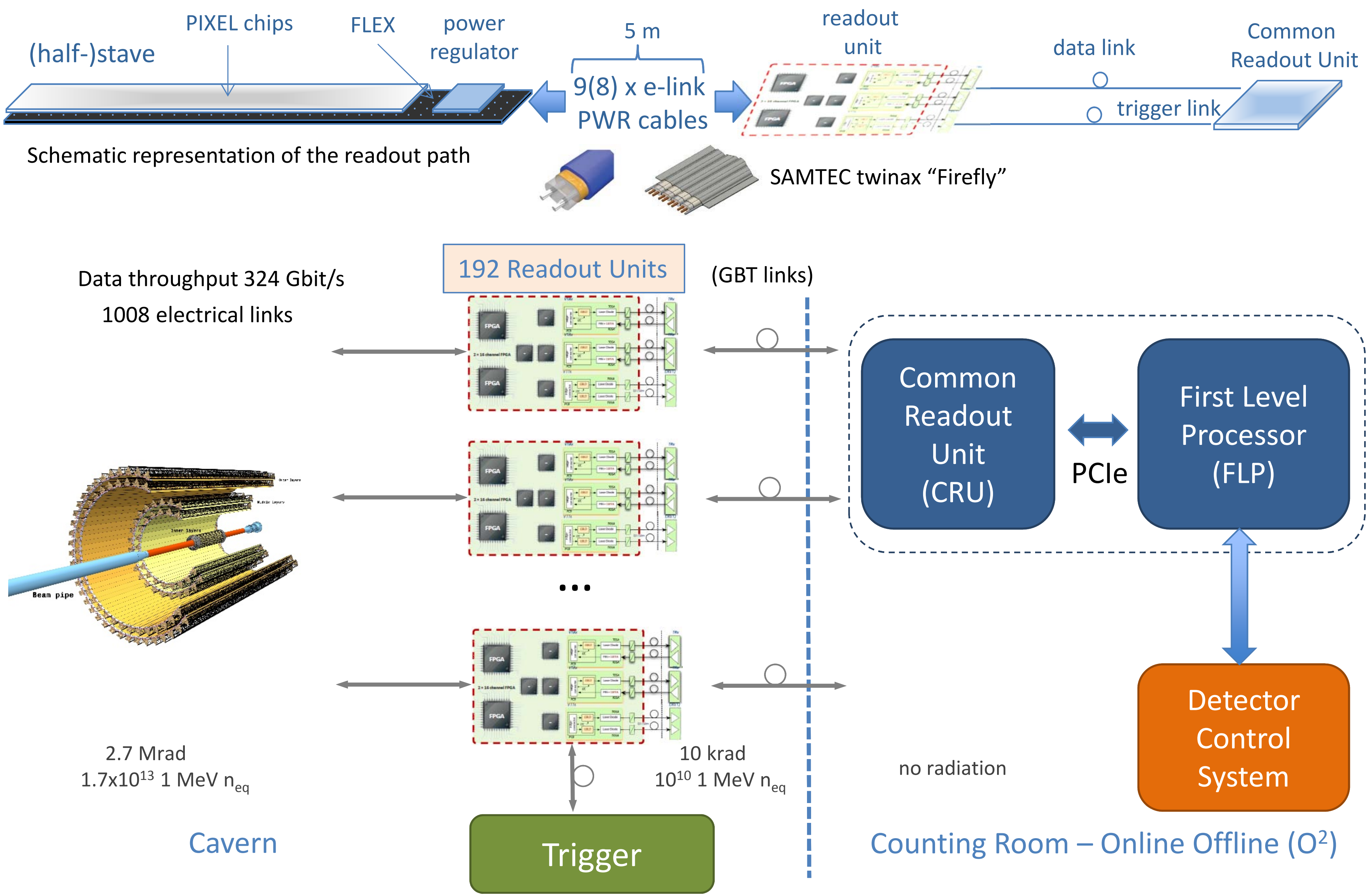


Interconnection of adjacent HICs

Semi-automatic Module Assembly Machine

Readout – general scheme

A Large Ion Collider Experiment



ALICE Upgrade

New Inner Tracking System (ITS)
- improved pointing precision
- less material -> thinnest tracker at the LHC

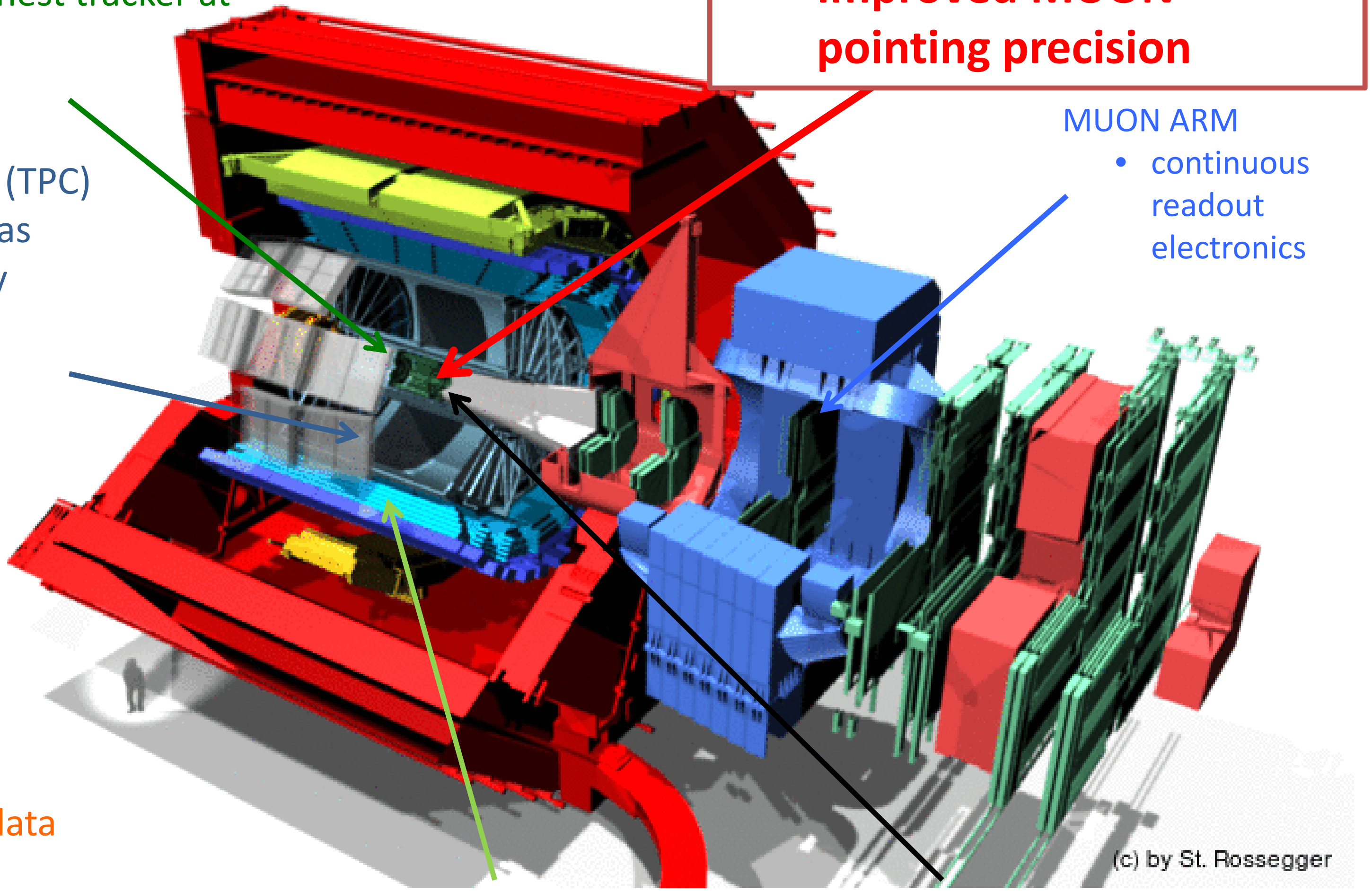
Muon Forward Tracker (MFT)
- **new Si tracker**
- **Improved MUON pointing precision**

Time Projection Chamber (TPC)
- New Micropattern gas detector technology
- continuous readout

MUON ARM
- continuous readout electronics

New Central Trigger Processor (CTP)

Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate



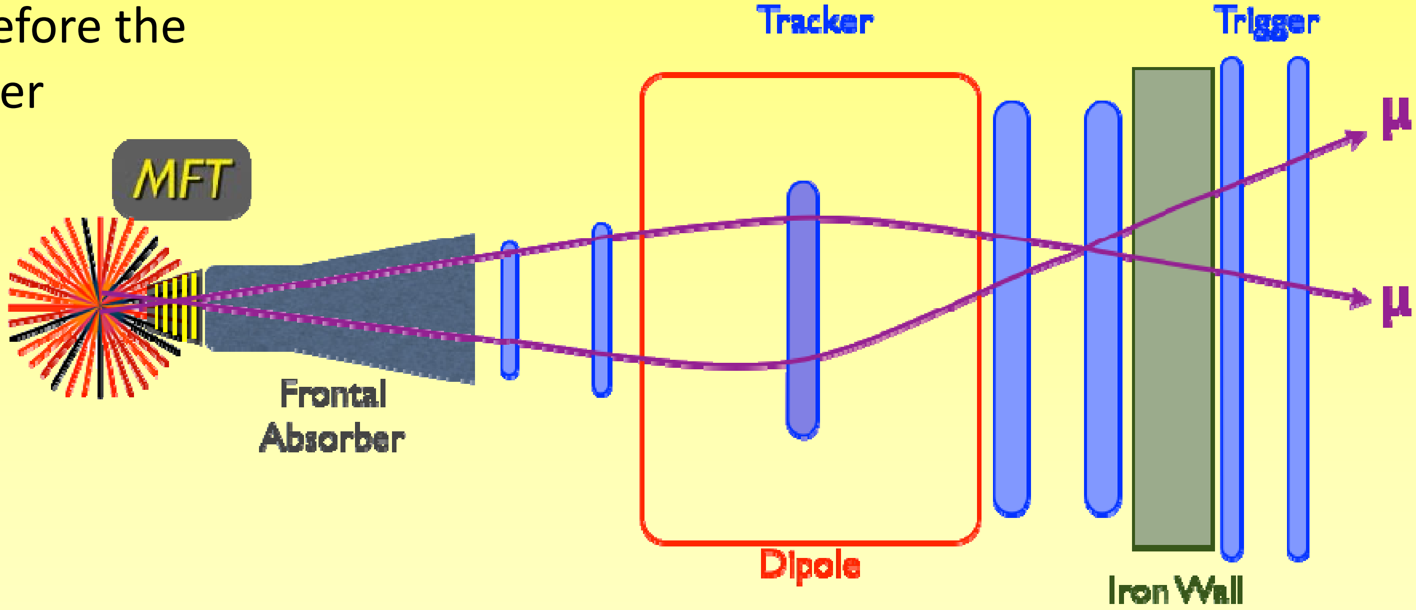
TOF, TRD
- Faster readout

New Trigger Detectors (FIT)

The Muon Forward Tracker (MFT)

Muon tracks are extrapolated and "**matched" to the MFT tracks** before the absorber

High pointing accuracy gained by the muon tracks after matching with the MFT tracks



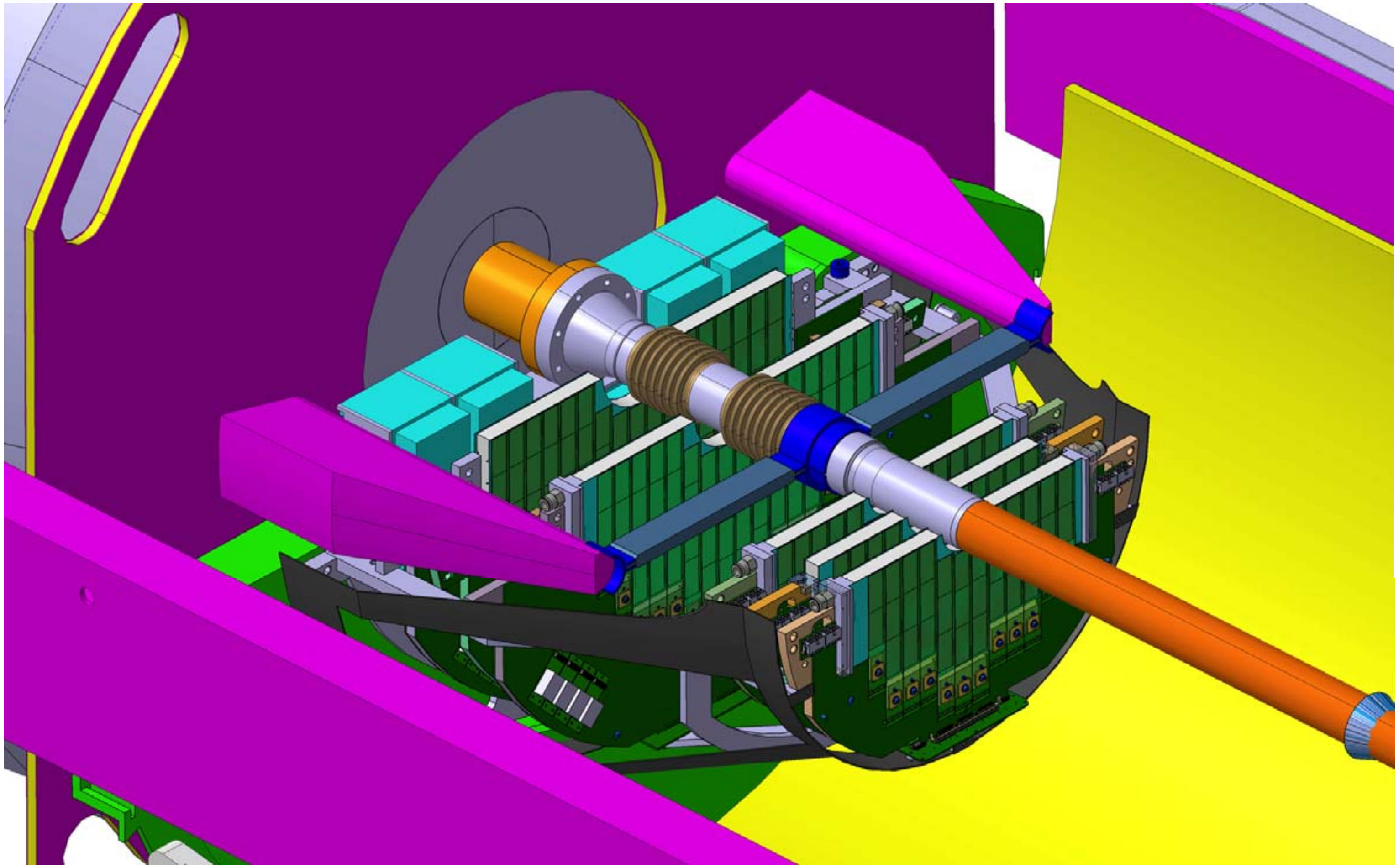
- Measurement of displaced vertex due to heavy flavour semi-muonic decays. Strong Lorentz boost effect at forward rapidity, even for p_T=0
- Measurement of single muons from charm and beauty, p_T>1 GeV/c
- Measurement of beauty down to p_T=0 from displaced J/ψ vertices.

Muon Forward Tracker: the detector

The MFT is a silicon pixel tracker complementing the acceptance of the ALICE upgraded Internal tracking system (ITS) and covering most of the acceptance of the muon spectrometer $2.5<\eta<3.6$.

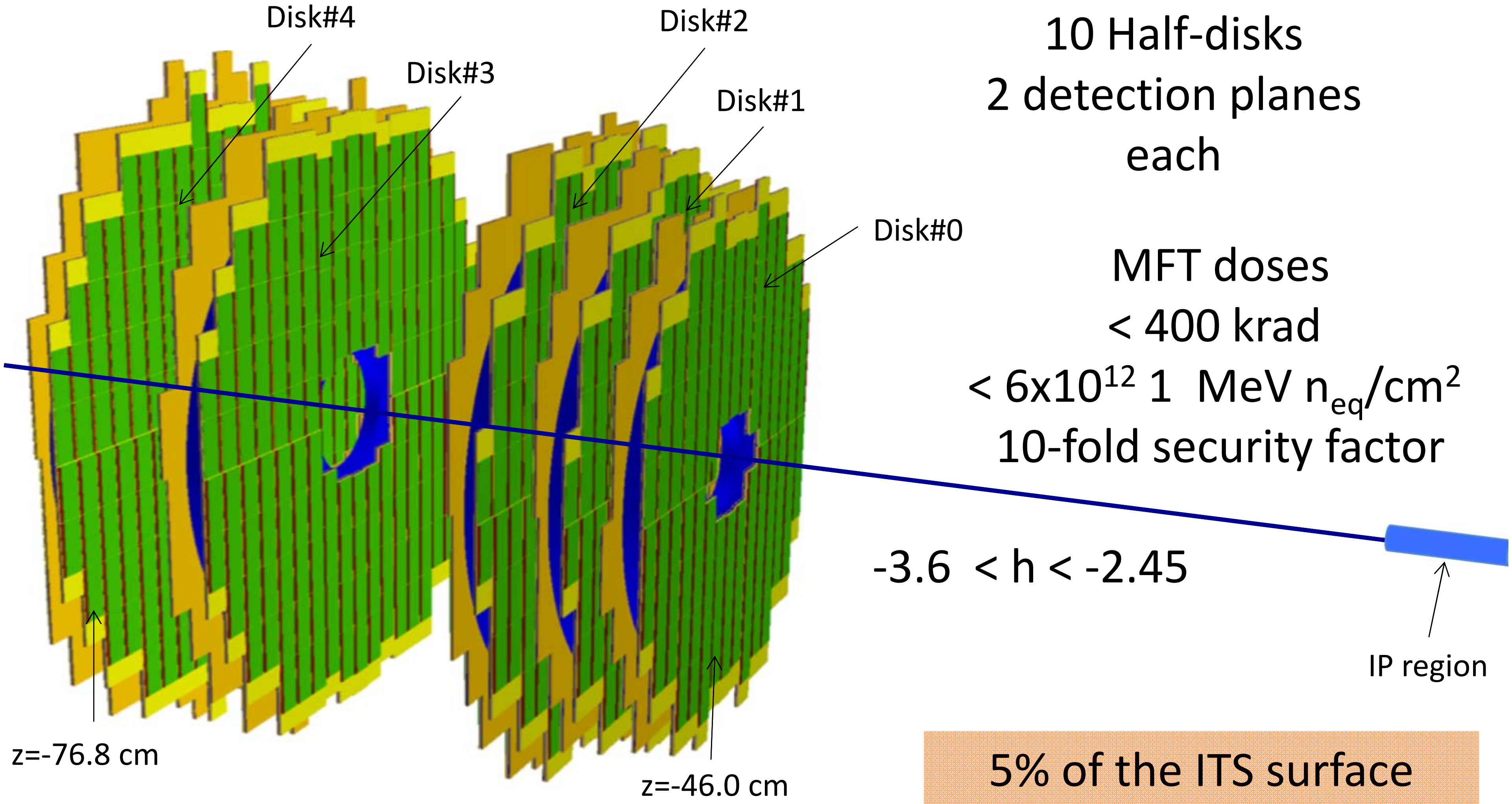
The MFT detector is placed inside the ITS outer barrel, between the ITS inner barrel and the absorber and surrounding the ALICE vacuum beam-pipe.

Common Silicon Sensor with ITS (15 mm x 30 mm)



MFT layout

920 silicon pixel sensors (0.4 m^2) in 280 ladders of 2 to 5 sensors each.



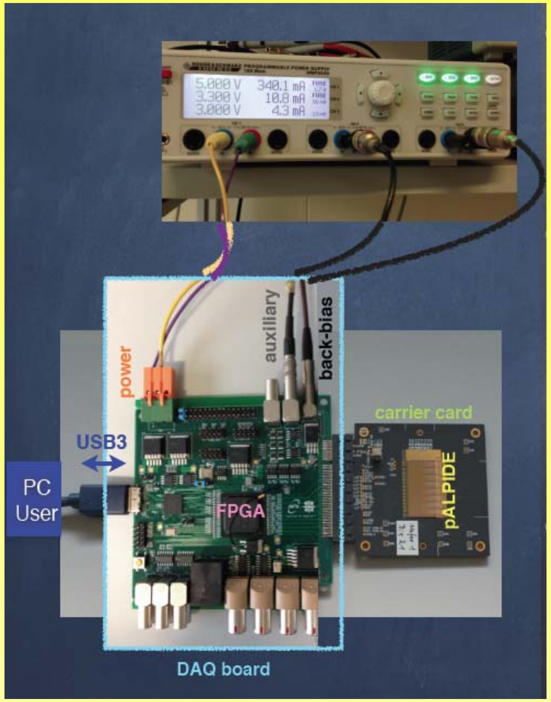
10 Half-disks
2 detection planes
each

MFT doses
< 400 krad
< 6×10^{12} 1 MeV n_{eq}/cm^2
10-fold security factor

$-3.6 < h < -2.45$

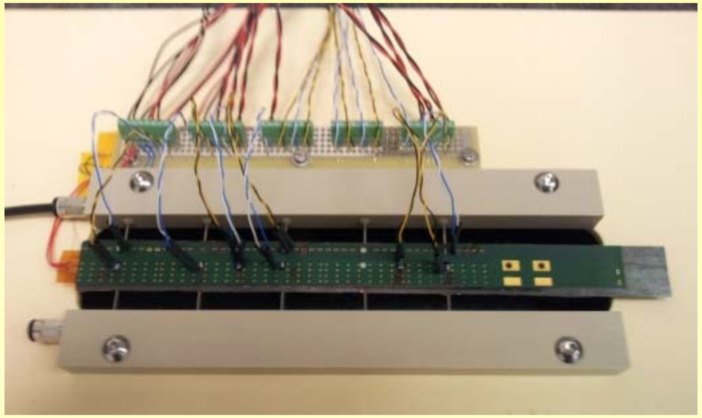
5% of the ITS surface
Twice the ITS inner barrel

MFT progress



pAlpide: In-lab test
& participation to development
and beam tests

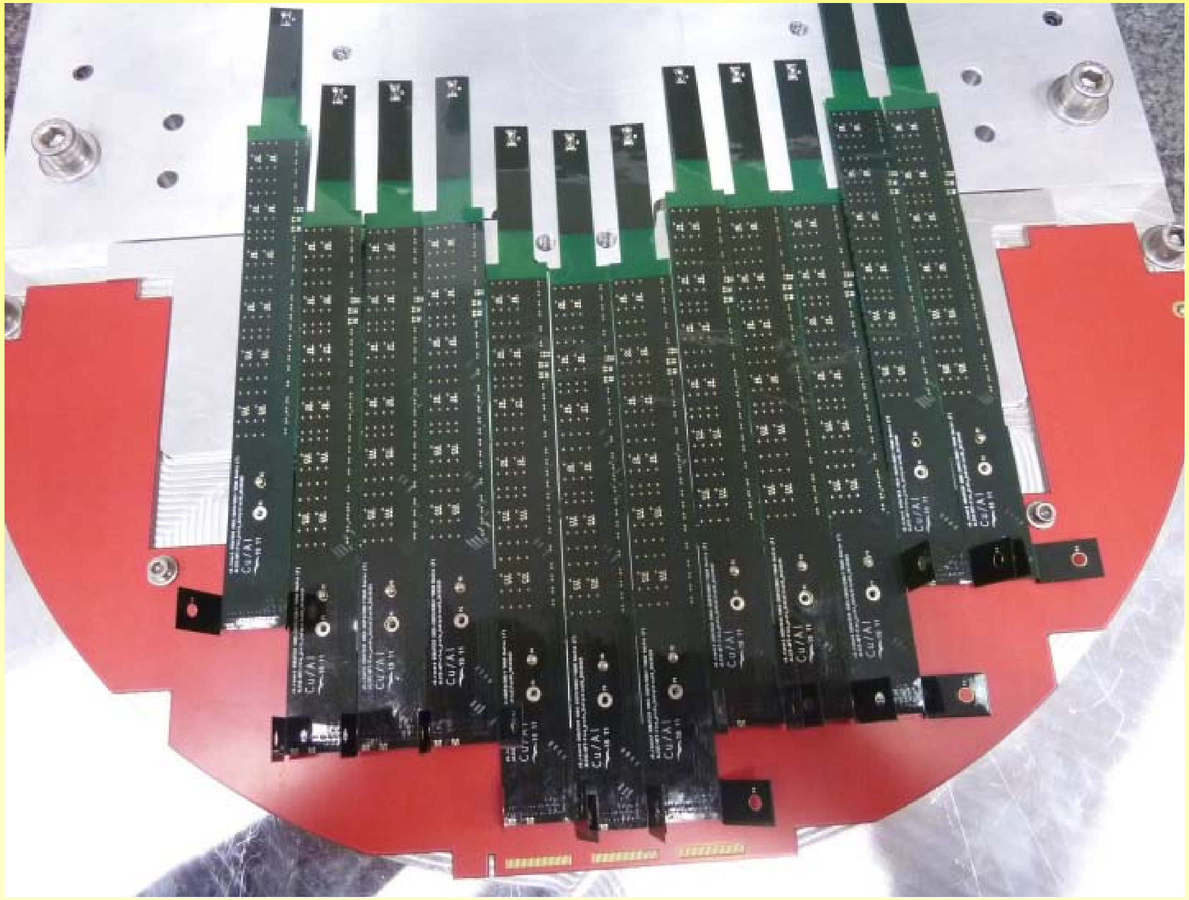
First HIC prototypes



Ladder Cooling Tests

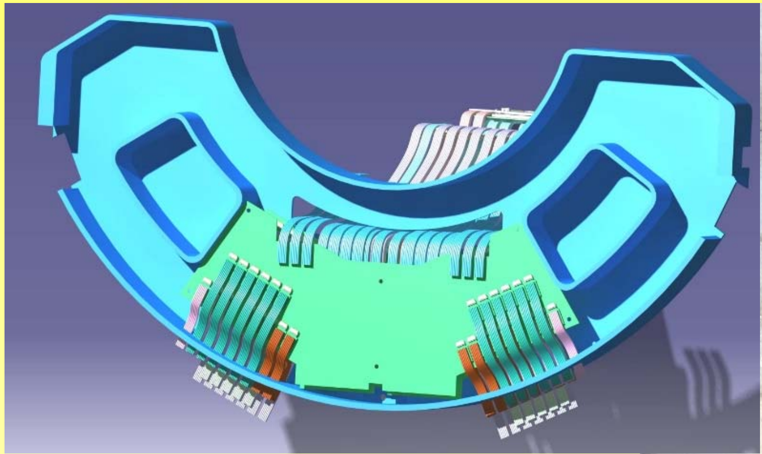
Half-Disk PCB Prototype

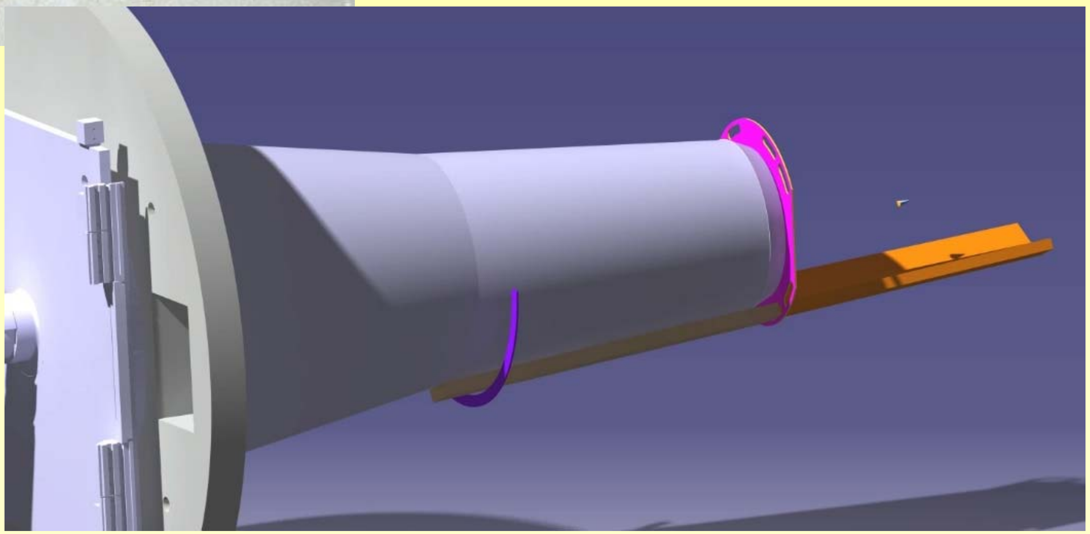
First MFT half-disk assembly test



MFT integration studies

Cabling along the absorber being studied : Simulation and mock-up





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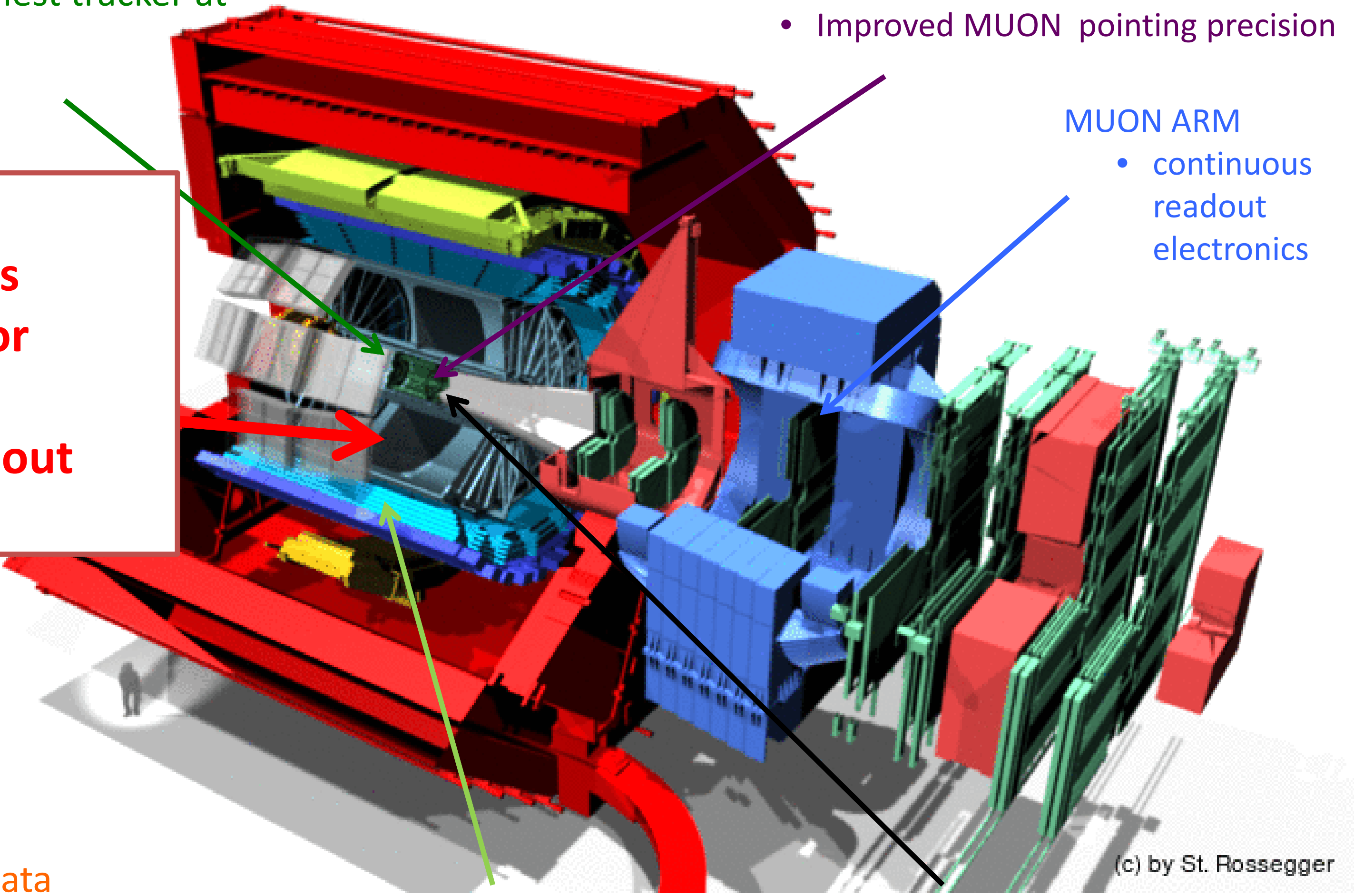
MUON ARM

- continuous readout electronics

TPC

- **Micropattern gas detector detector technology**
- **continuous readout**



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Data Acquisition (DAQ)/ High Level Trigger (HLT)

- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

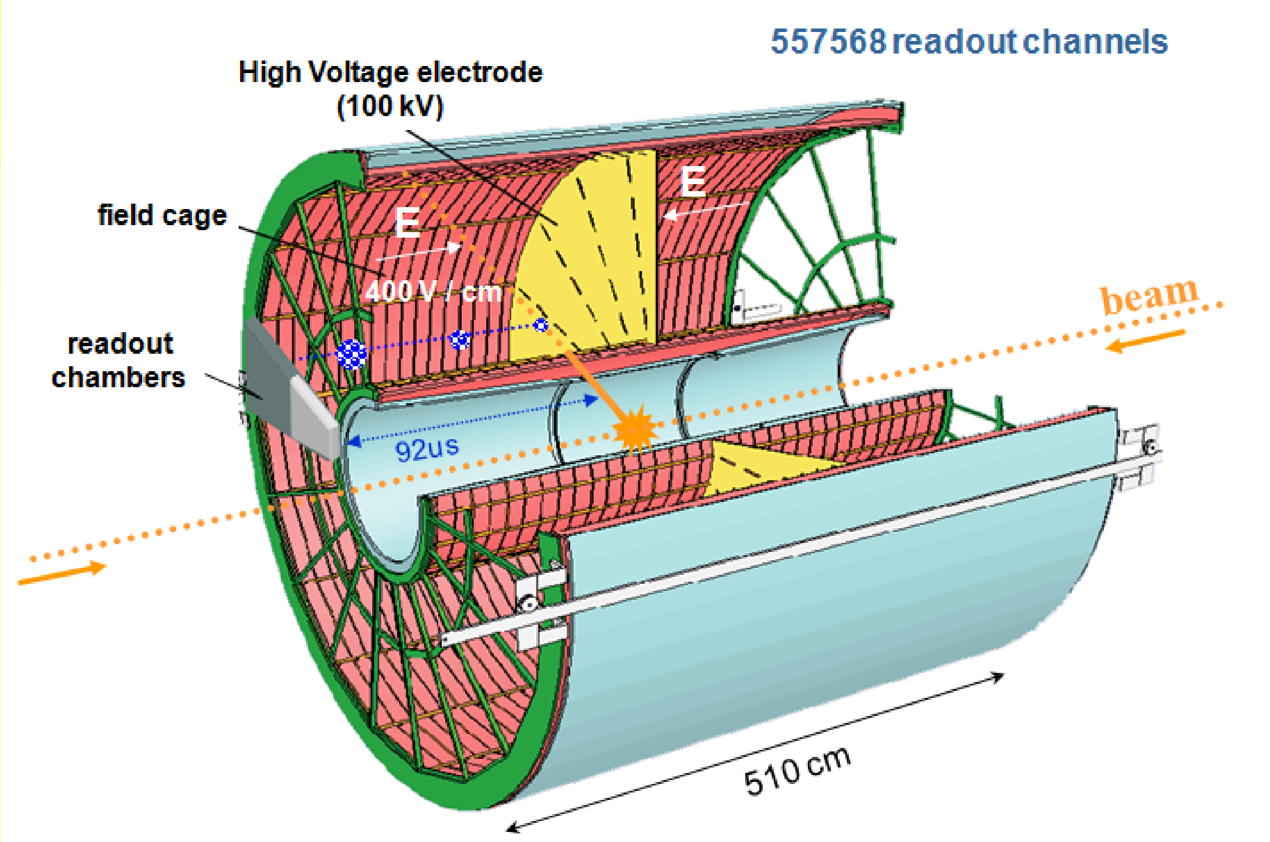
TOF, TRD

- Faster readout

New Trigger Detectors (FIT)

The ALICE TPC

- The largest TPC
- Probably the last accelerator TPC with wire chambers
- 90 m^3 of $Ne\text{-}CO_2(\text{-}N_2)$ or $Ar\text{-}CO_2$
- 36 Inner and Outer Readout Chambers
- 100 kV at Central Electrode
- Over half a million readout pads
- Operates at interaction rates of a few 100 kHz in pp and few kHz in Pb-Pb

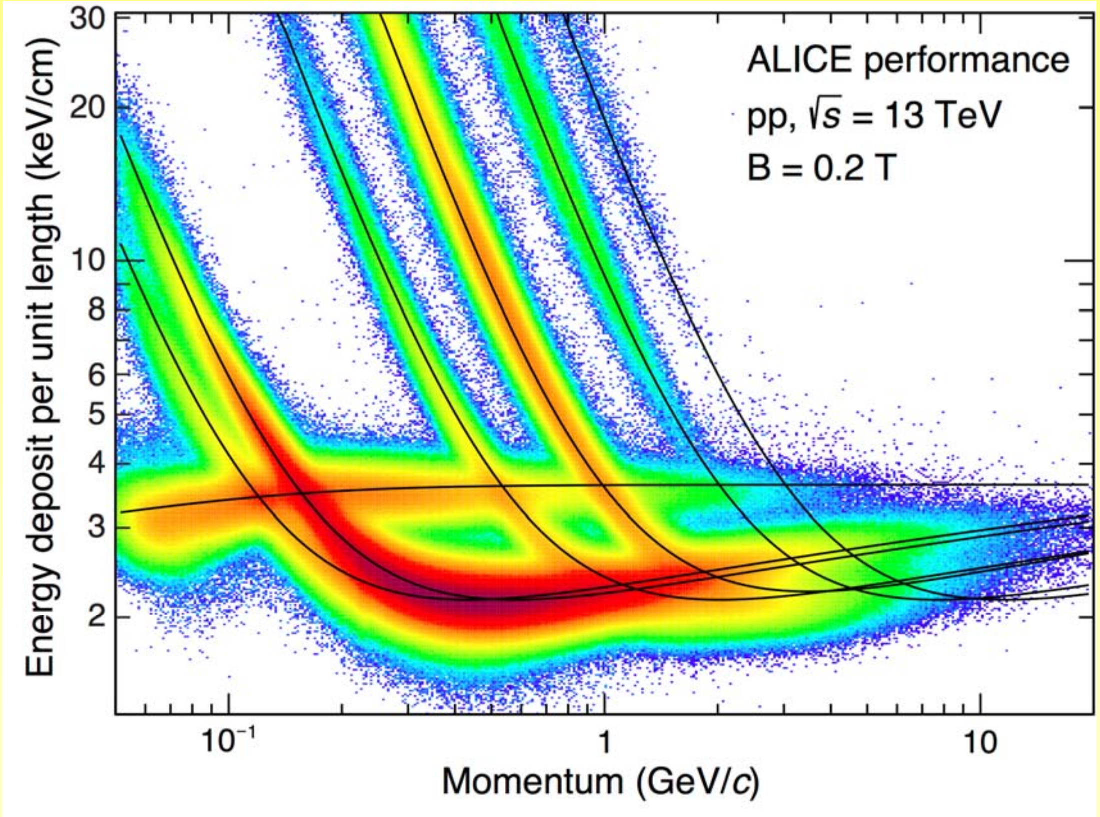


Performance: dE/dx

- With Ne-CO_2:
- $\sigma_{dE/dx} \approx$ 5.5 % in pp
- $\sigma_{dE/dx} \approx$ 7 % in central Pb-Pb
  - deterioration due to overlapping clusters

☞ Single-pad gain calibration with ^{83}Kr decays in the gas

2015 pp data at B = 0.2 T, Ar-CO_2 (88-12)

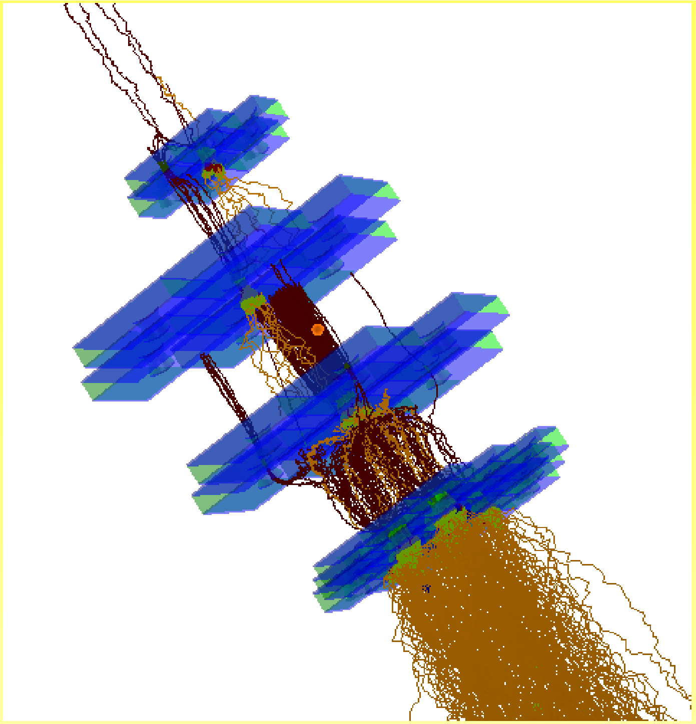


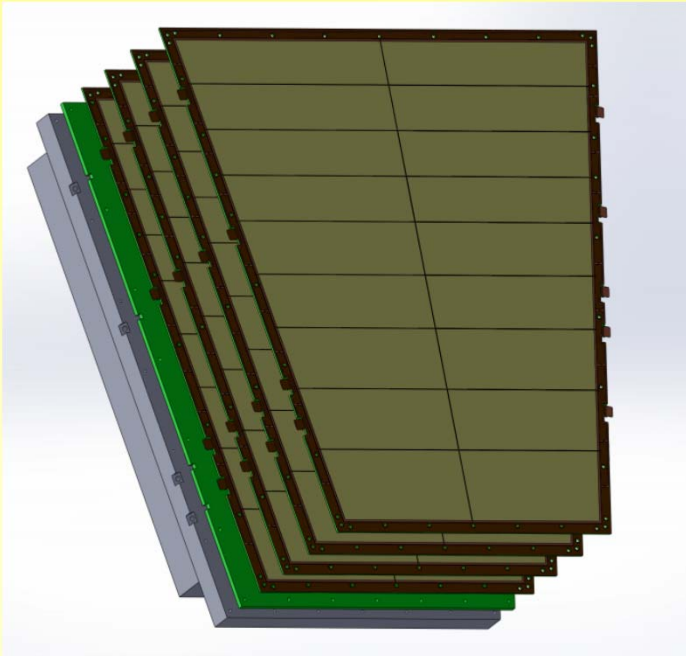
TPC Upgrade

With an average of 5 PbPb collisions inside the drift time of 100μs, the classic gating of TPC wire chambers does not work.

Replace wire chambers with 4-GEM or Micromega+2 GEM

Specified to have <20 Ions flowing back into the TPC volume for every primary electron being amplified, i.e. ion back flow (IBF) of <1% for a gas gain of 2000

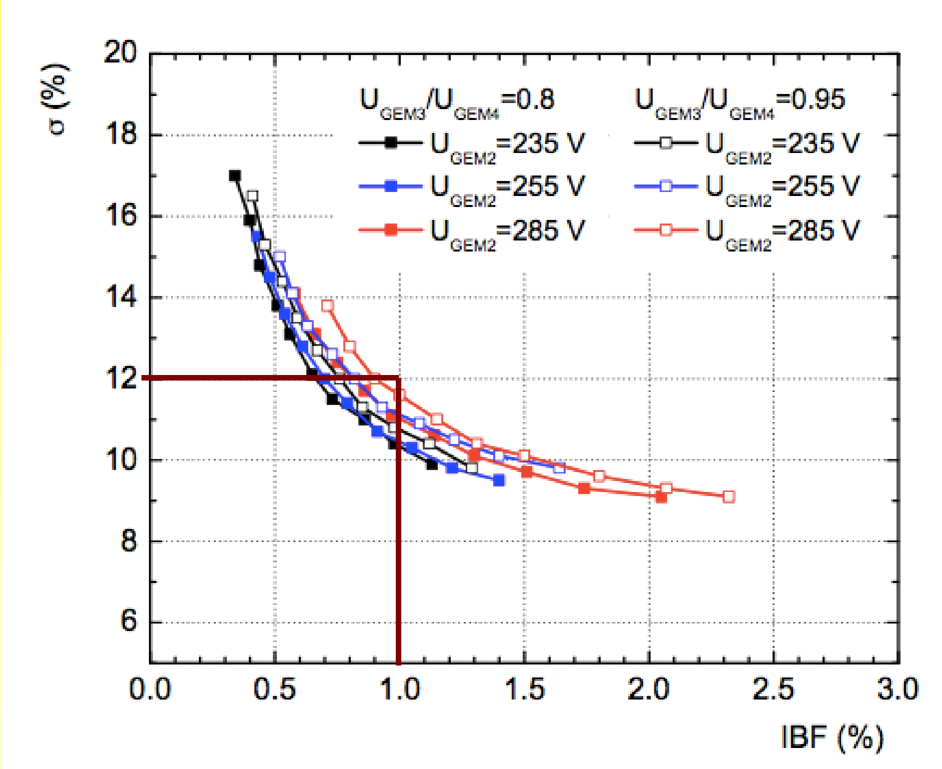


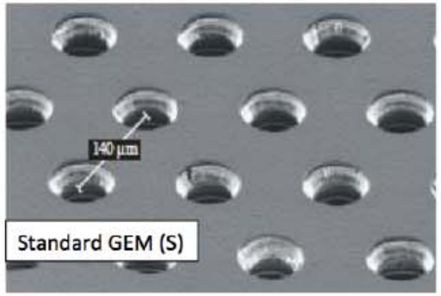


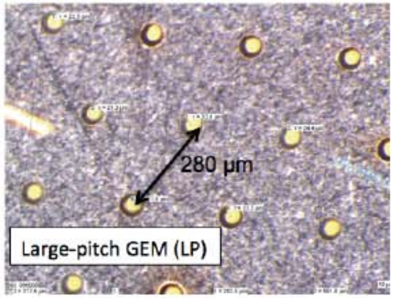
Exploded view of a GEM IROC

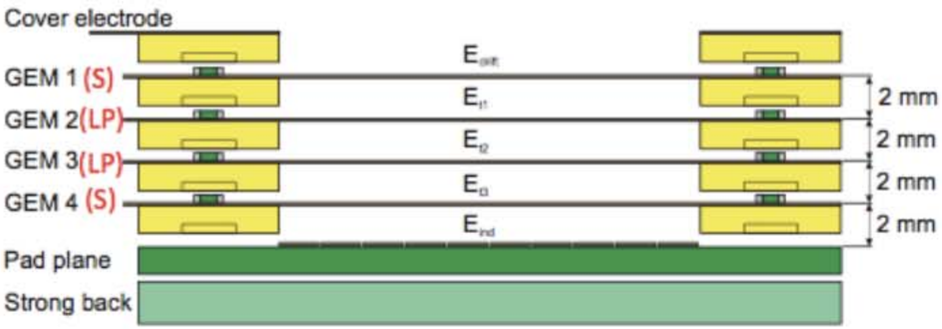
Replace MWPCs with GEMs

- Ion Back Flow in a GEM system was reduced from > 5 % (3 GEM) to < 1% (4 GEM)
  - discovered enhanced ion trapping at high rates
- Excellent dE/dx performance maintained, demonstrated also with test beams
- Robust against discharges, with alpha sources and test beams
  - Ne-CO_2-N_2 (90-10-5)



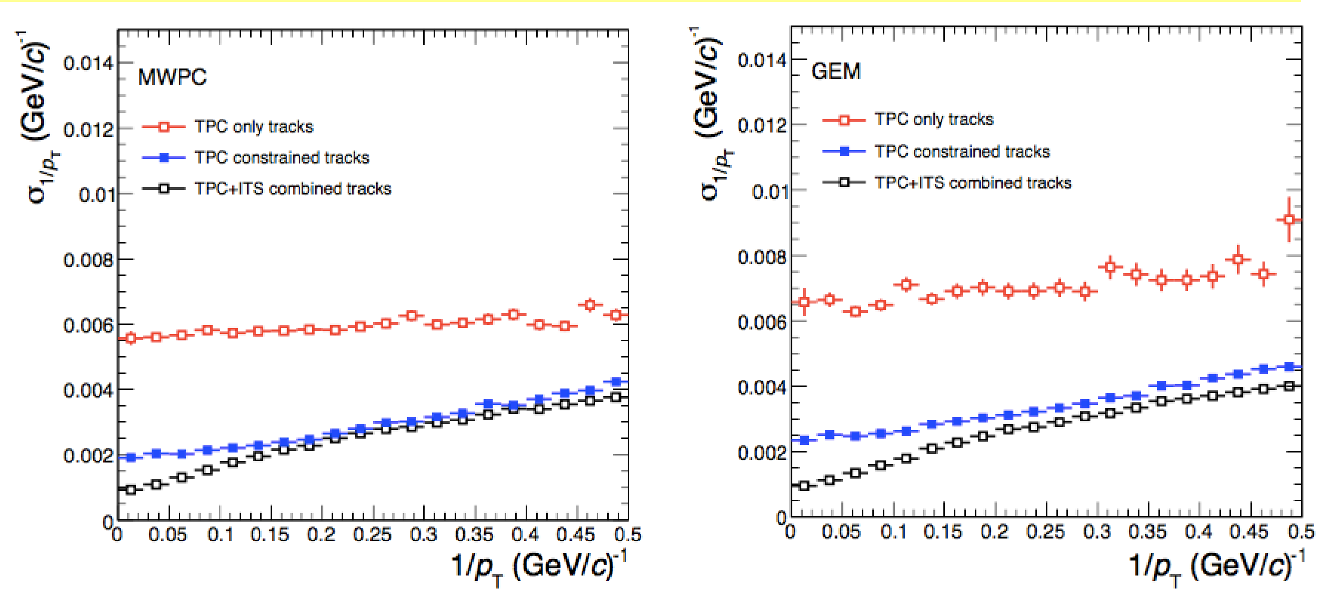




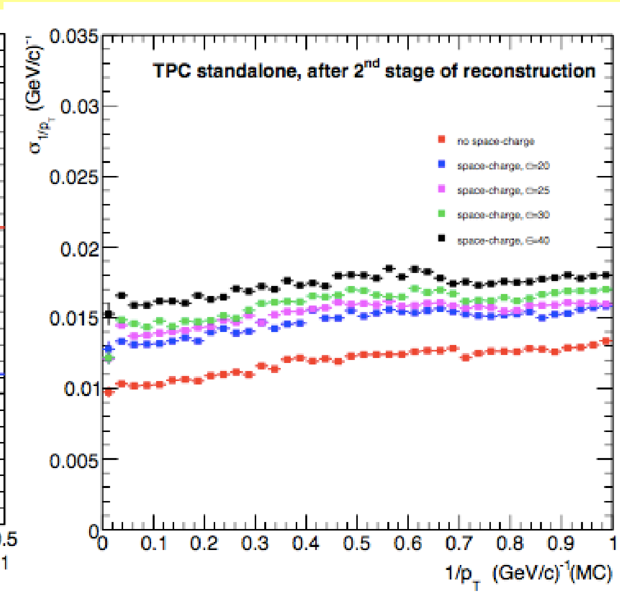


Reconstruction and corrections

- Main challenge are space-charge distortions of up to 20 cm
- Real-time map of distortions is used for online track reconstruction
- In a second stage, the required momentum resolution, with combined TPC-ITS tracking, is achieved



Comparison of $1/p_{\mathrm{T}}$ resolution for wires and GEMs



GEM performance at increasing multiplicities.
Expected: blue points

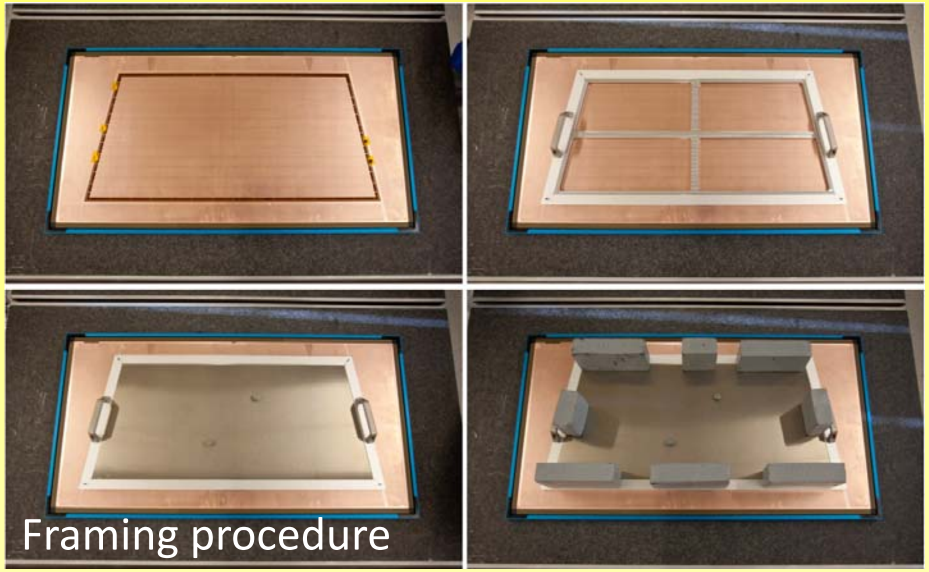
Preproduction

- Full sized prototypes of both chamber types have been produced and operated
  - reuse existing wire chambers

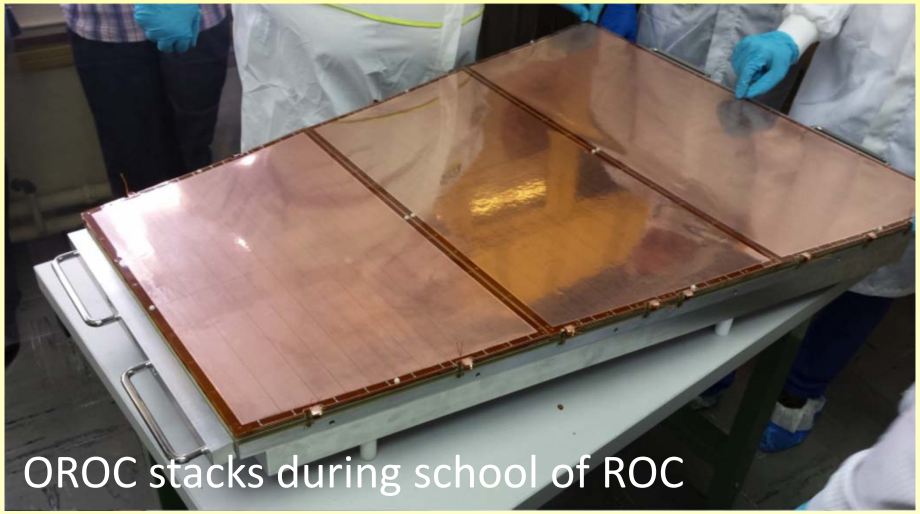
- Full chambers with new pad-planes etc and close-to-final GEM foil being produced now

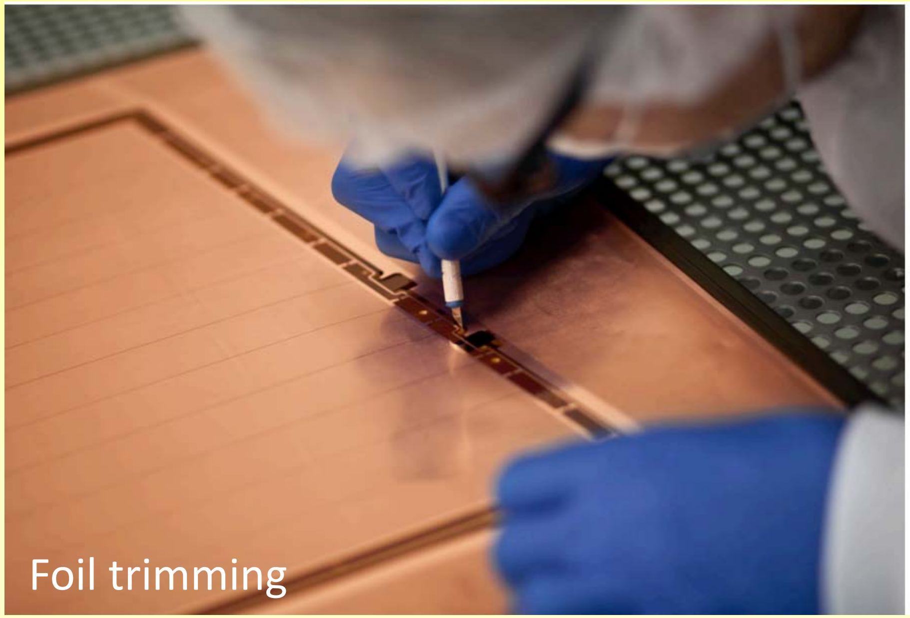
Single-mask GEM technology allows for production of ~1 m foils

Preparing for series production


Framing procedure

- EDR for ROC production in Nov 2015
- Pre-production run (2 IROC, 2 OROC) until February 2016
- ROC production launched after PRR in March 2016


OROC stacks during school of ROC


Foil trimming

ALICE Upgrade

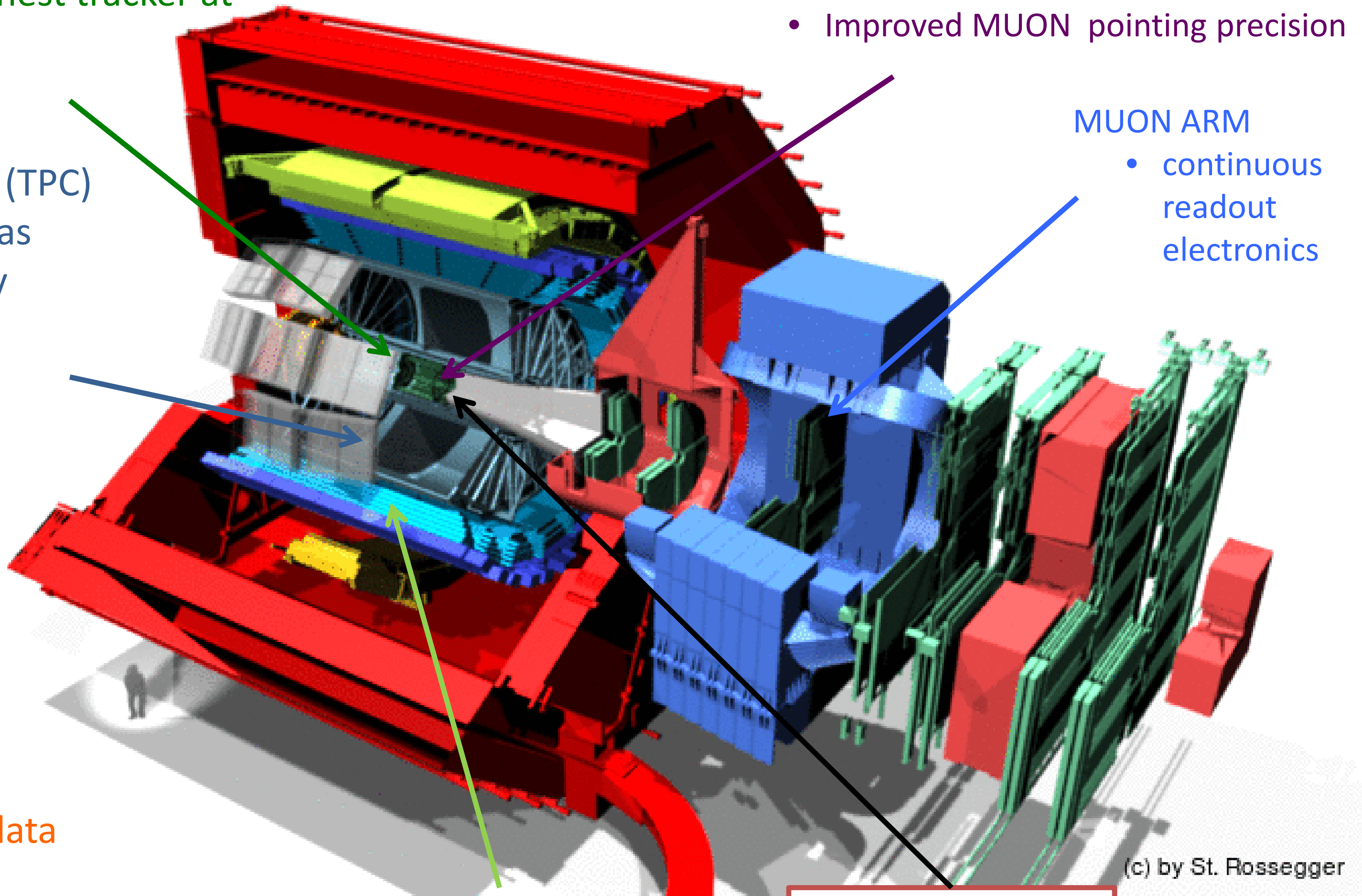
New Inner Tracking System (ITS)
- improved pointing precision
- less material -> thinnest tracker at the LHC

Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

MUON ARM
- continuous readout electronics

Time Projection Chamber (TPC)
- New Micropattern gas detector technology
- continuous readout

New Central Trigger Processor (CTP)



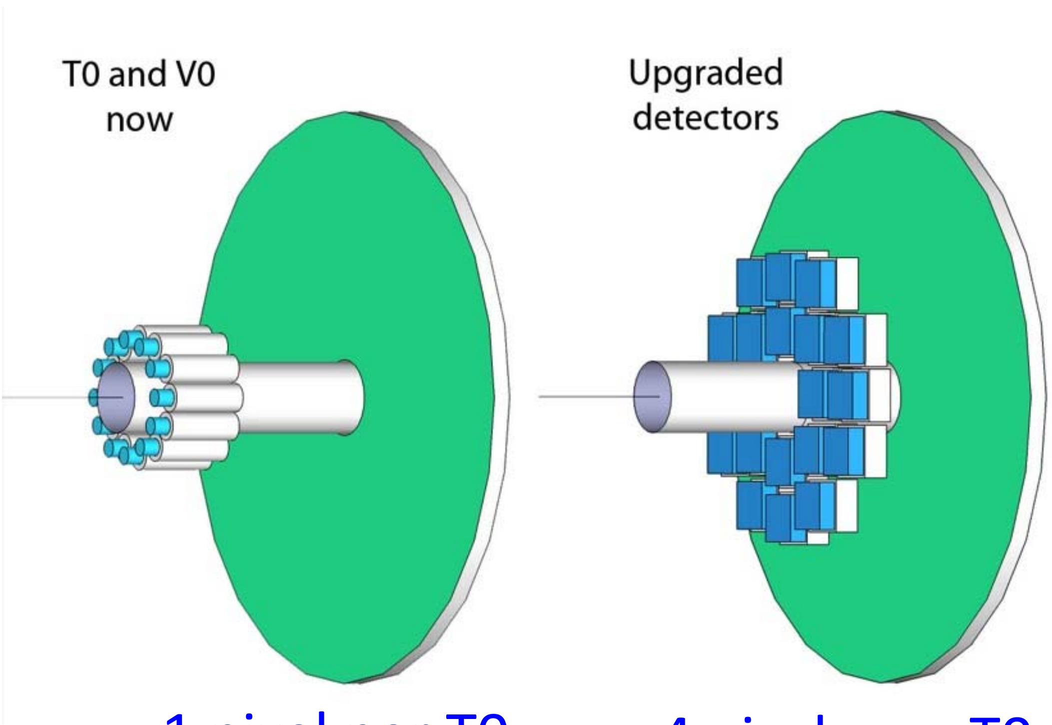
Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

TOF, TRD
- Faster readout

New Trigger Detectors (FIT)

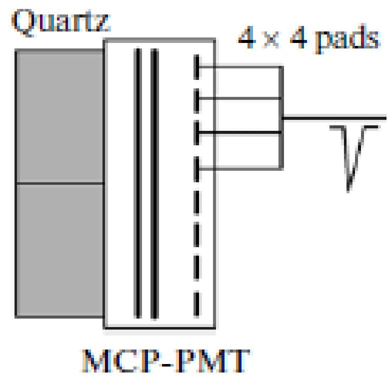
Fast Interaction Trigger (FIT)

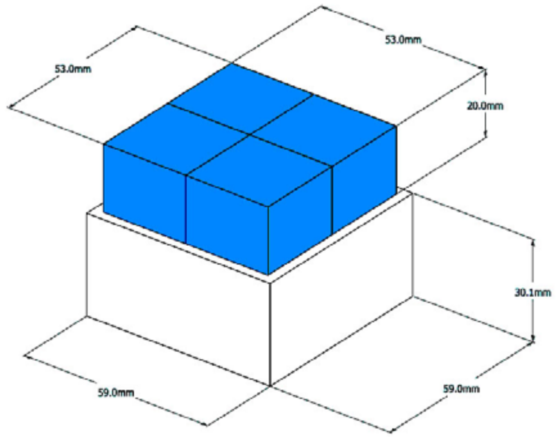
Upgraded Quartz Cherenkov (T0+) and Plastic Scintillator (V0+)



1 pixel per T0 module

4 pixels per T0+ module





FIT

- T0+ and V0+ Test beam campaigns 2014 & 2015

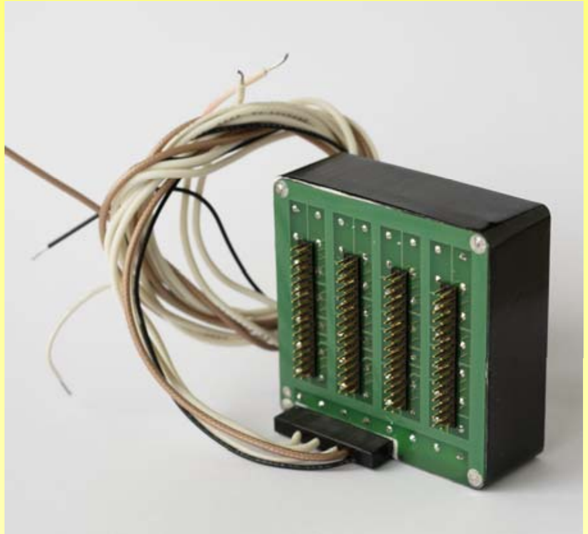
- T0+

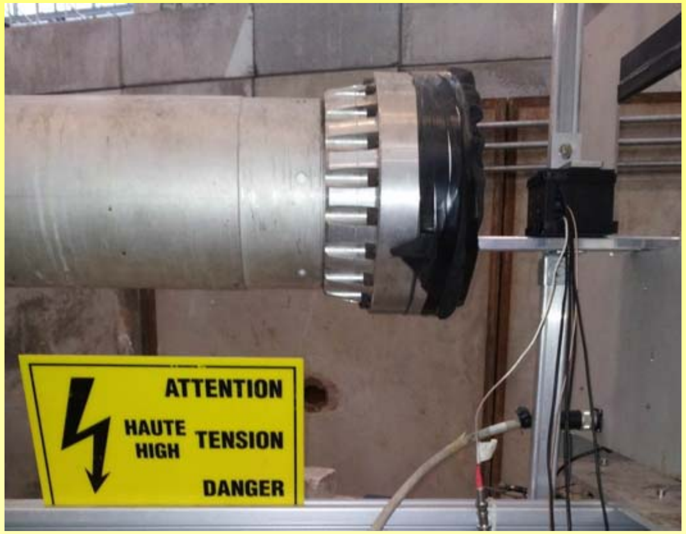
PS T10 Oct-2015

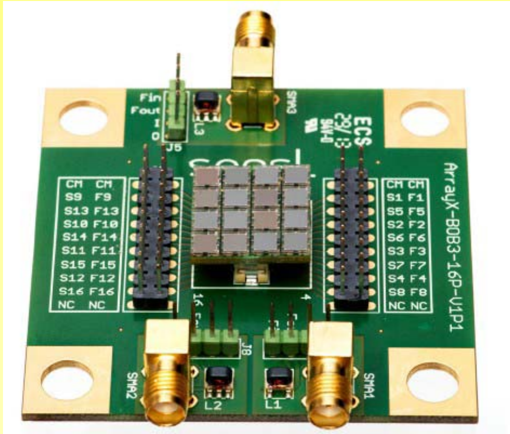
- V0+

Being tested now (Oct 2015) at T10:

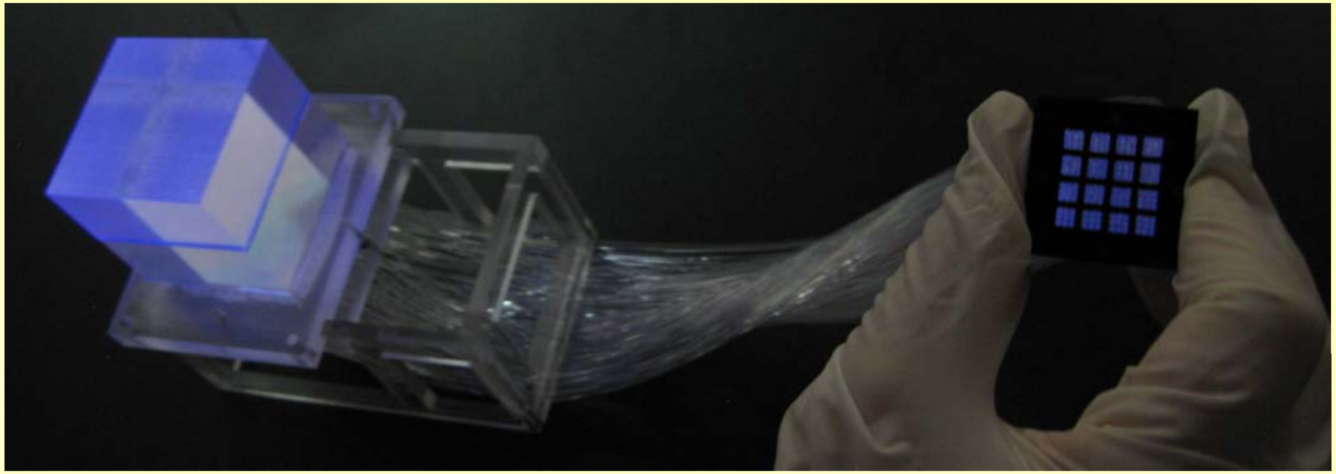
SiPM array Sensl 4x4



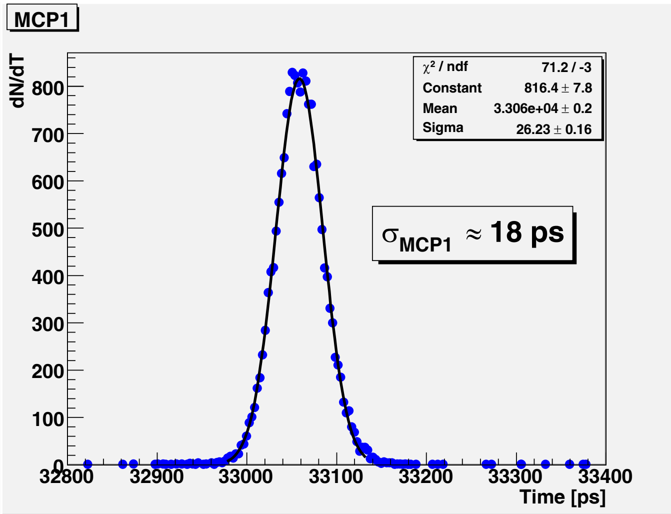


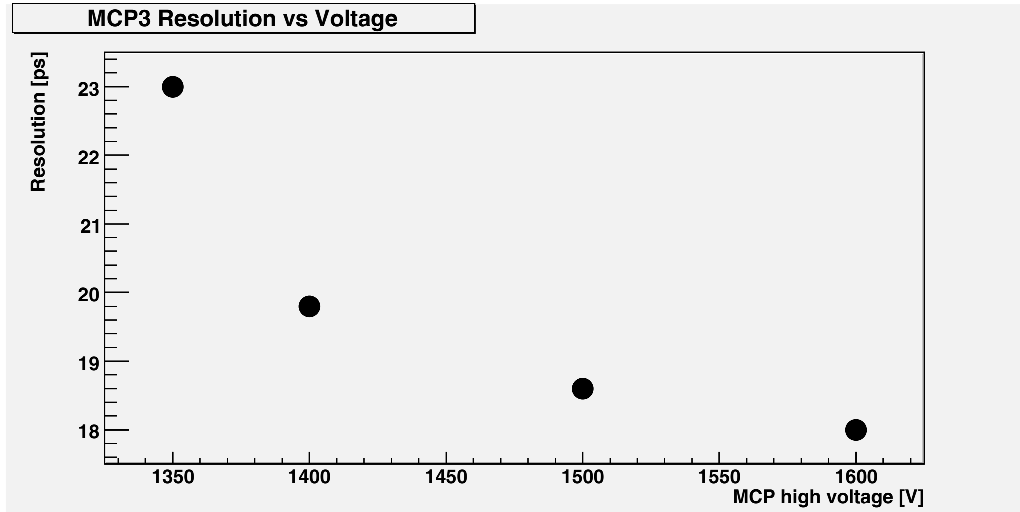


Tests at T10 using Time Readout Board (TRB2) and Time-Over-Threshold Add-On front-end electronics



FIT: T0+ Time Resolution





Excellent time resolution !

For Minimum Bias Trigger, TOF Time Zero and Vertex Selection.

ALICE Upgrade

New Inner Tracking System (ITS)
- improved pointing precision
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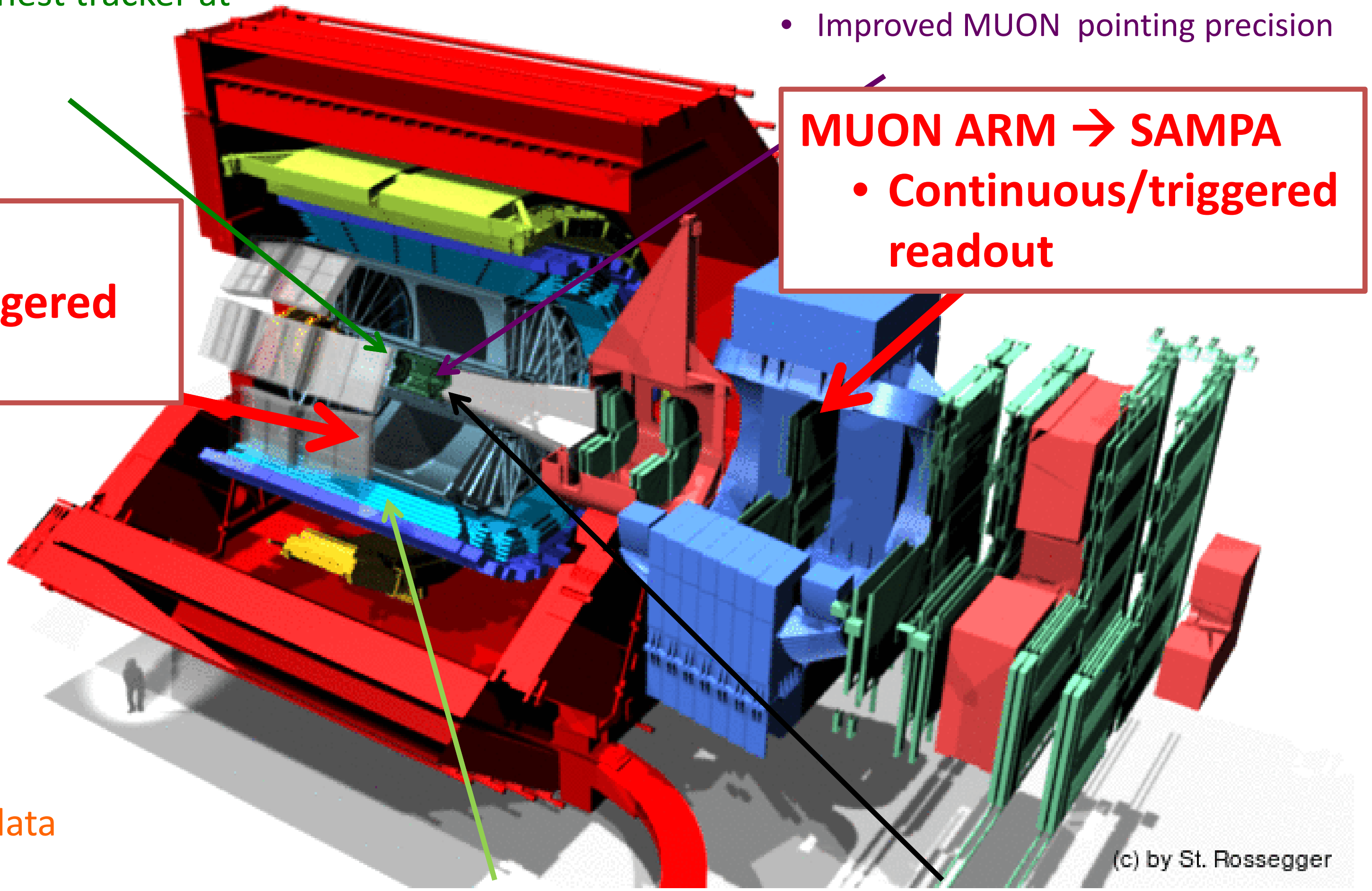
Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

TPC → SAMPA
- **Continuous/triggered readout**

MUON ARM → SAMPA
- **Continuous/triggered readout**

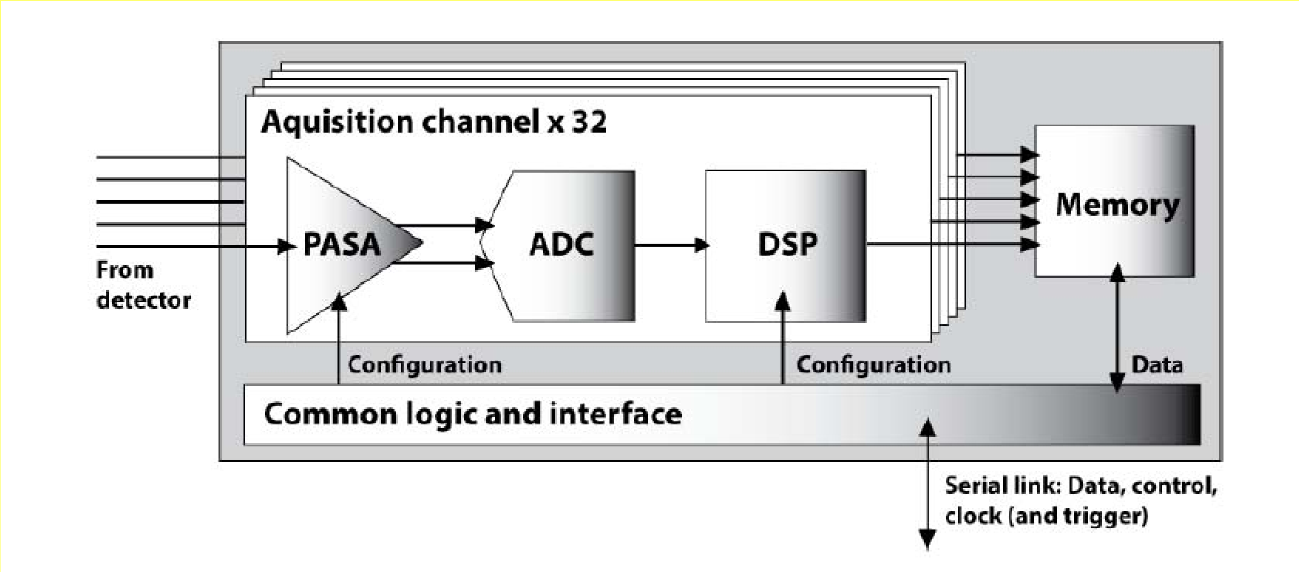


Data Acquisition (DAQ)/
High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

TOF, TRD
- Faster readout

New Trigger Detectors (FIT)

SAMPA Chip



PASA: Low Noise Shaping Amplifier

ADC: 10MHz, 10bit low power SAR ADC

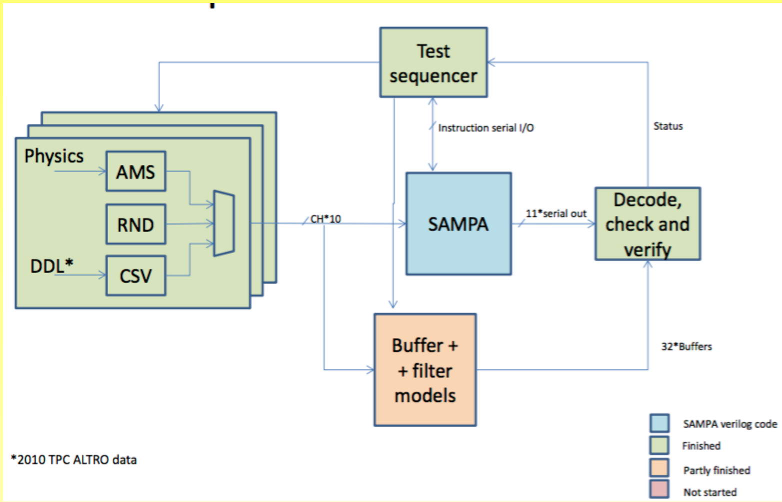
DSP: Digital Signal Processing i.e. signal shaping, zero suppression …

Memory, Serial link: High Speed links to Data Acquisition

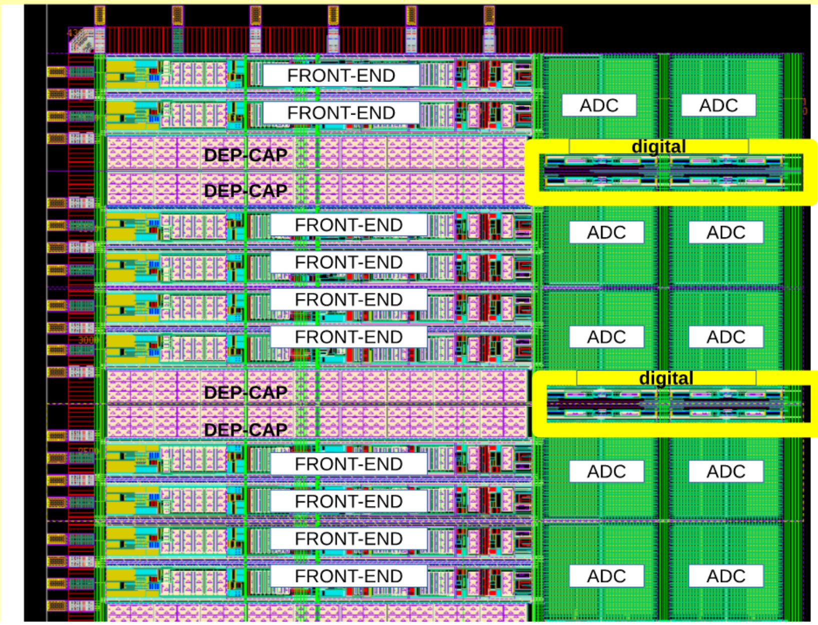
SAMPA

- MPW2: individual blocks qualified in simulations
- MPW2: full implementation ongoing
- SAMPA packaging: contract awarded to IMEC, design is already ongoing

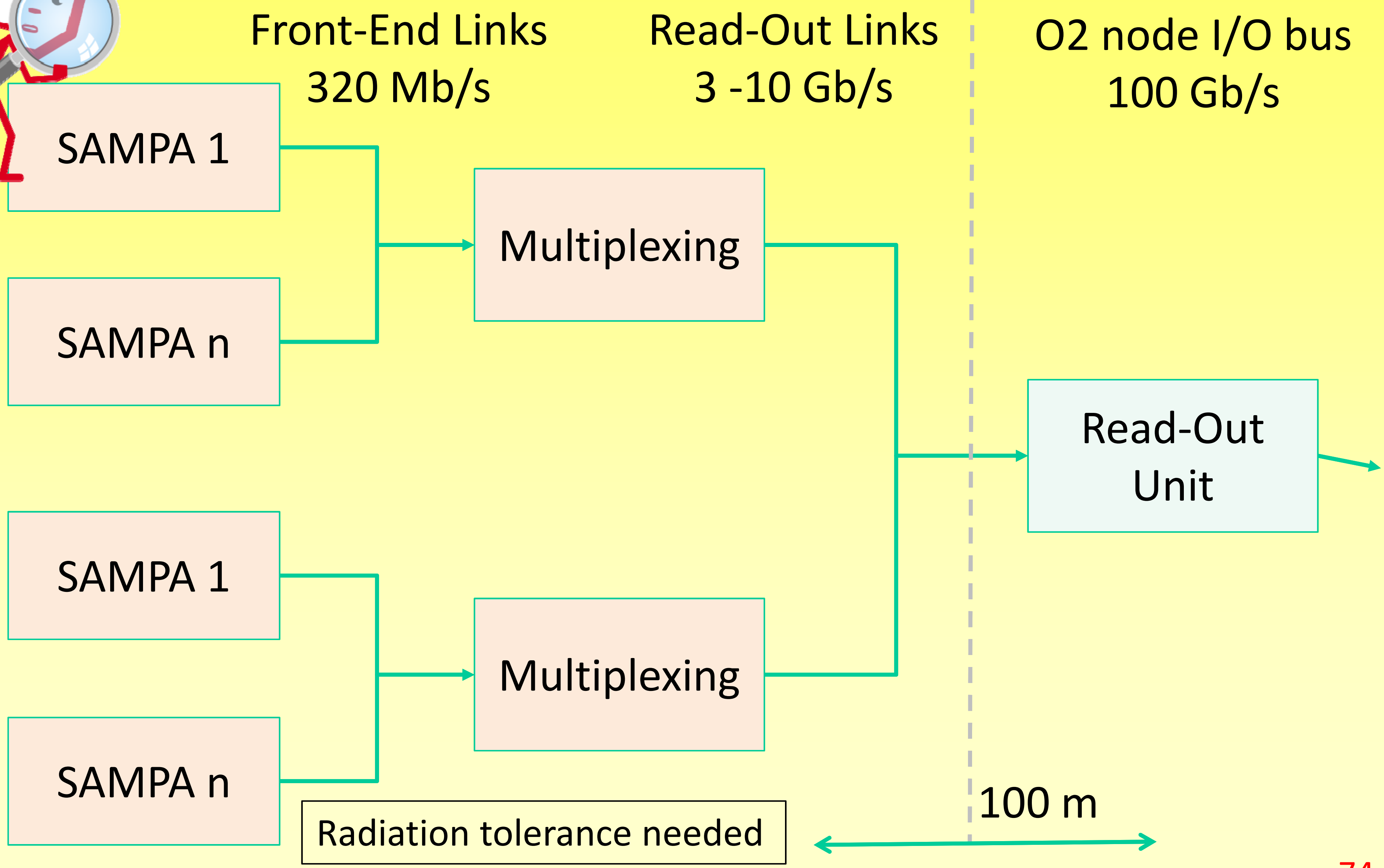
Full SAMPA simulation test bench



- **MPW2: full size/full functionality ASIC**
  - in production

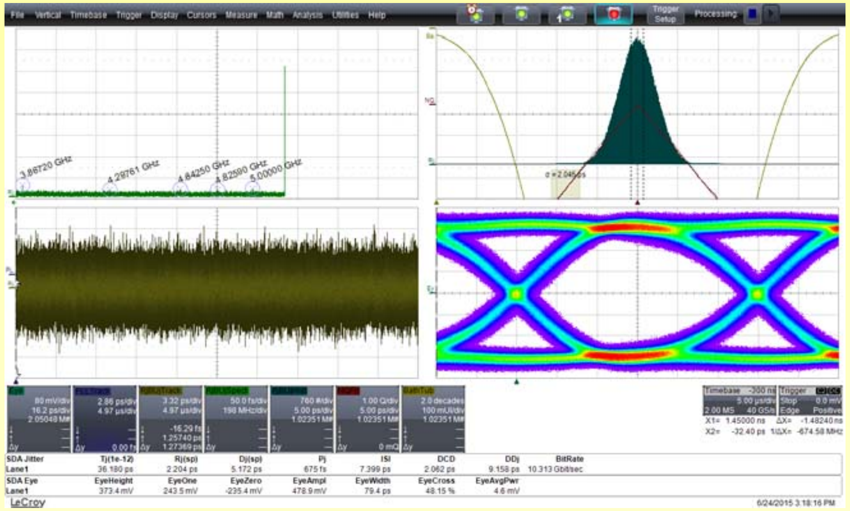


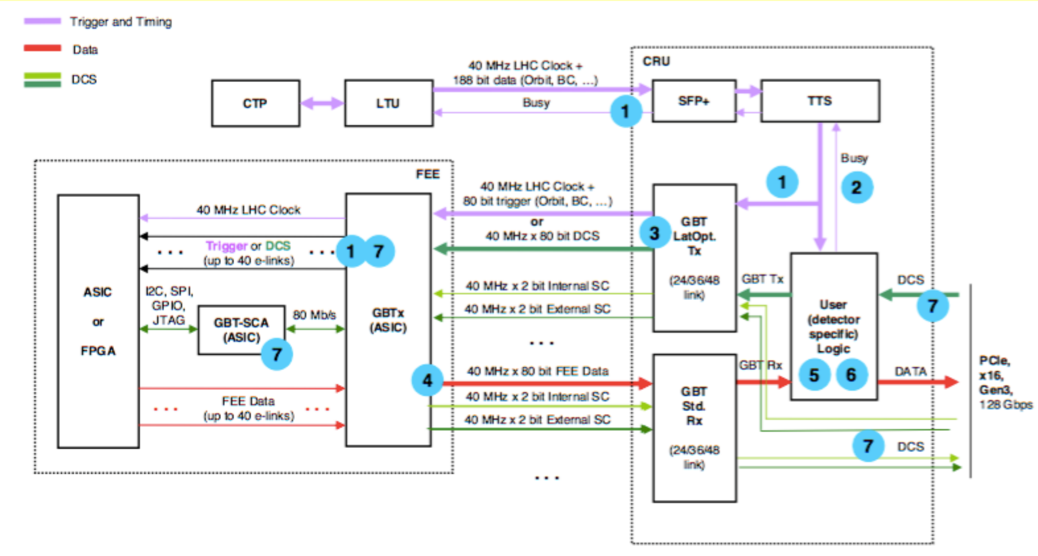
CRU: Common Read-Out Unit



CRU: common readout unit

- CRU (PCI based), prototype tested,
  pre-series production to be started
- Detector specific firmware specifications defined





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Time Projection Chamber (TPC)
- New Micropattern gas detector technology
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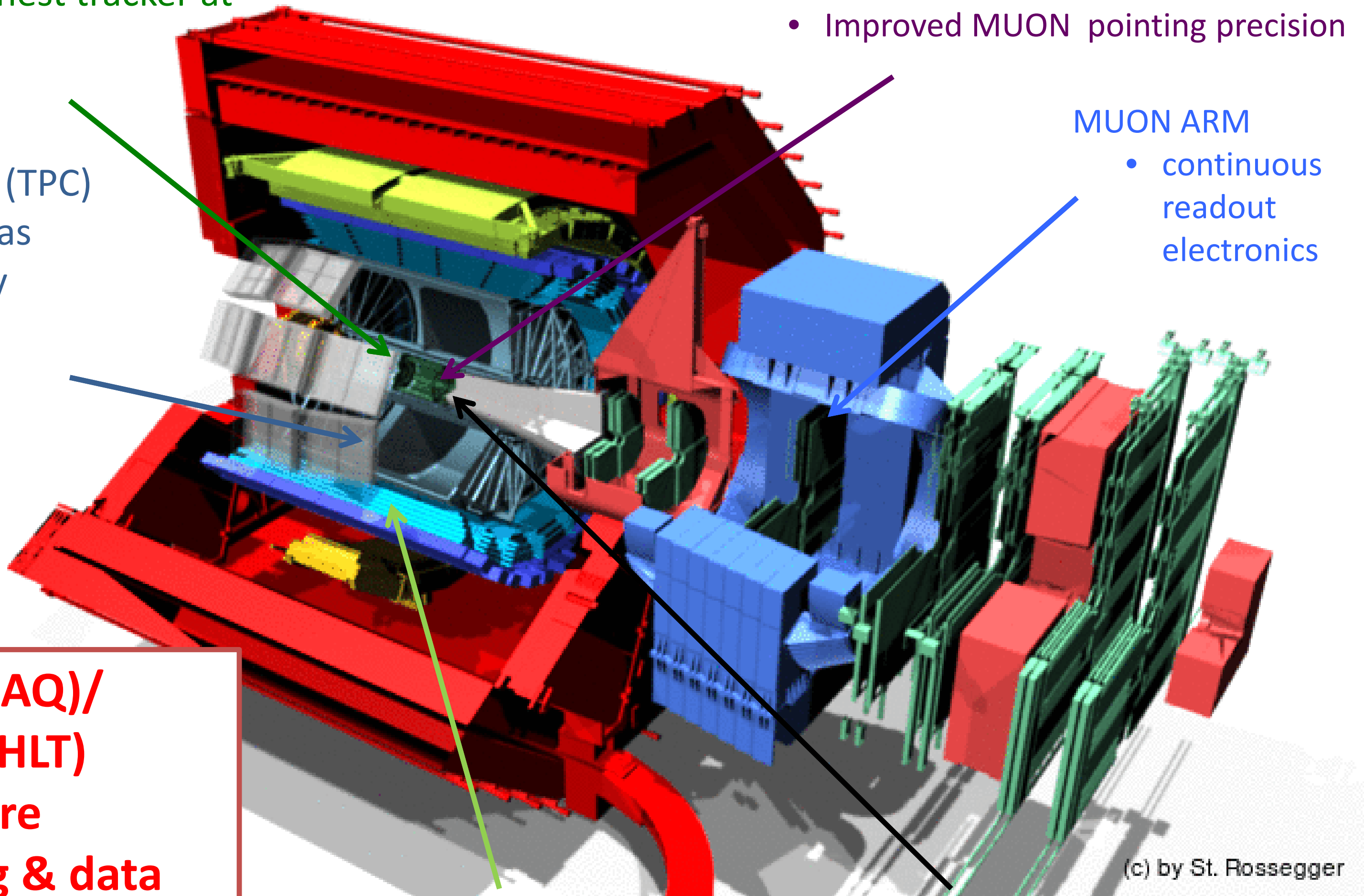
New Central Trigger Processor (CTP)

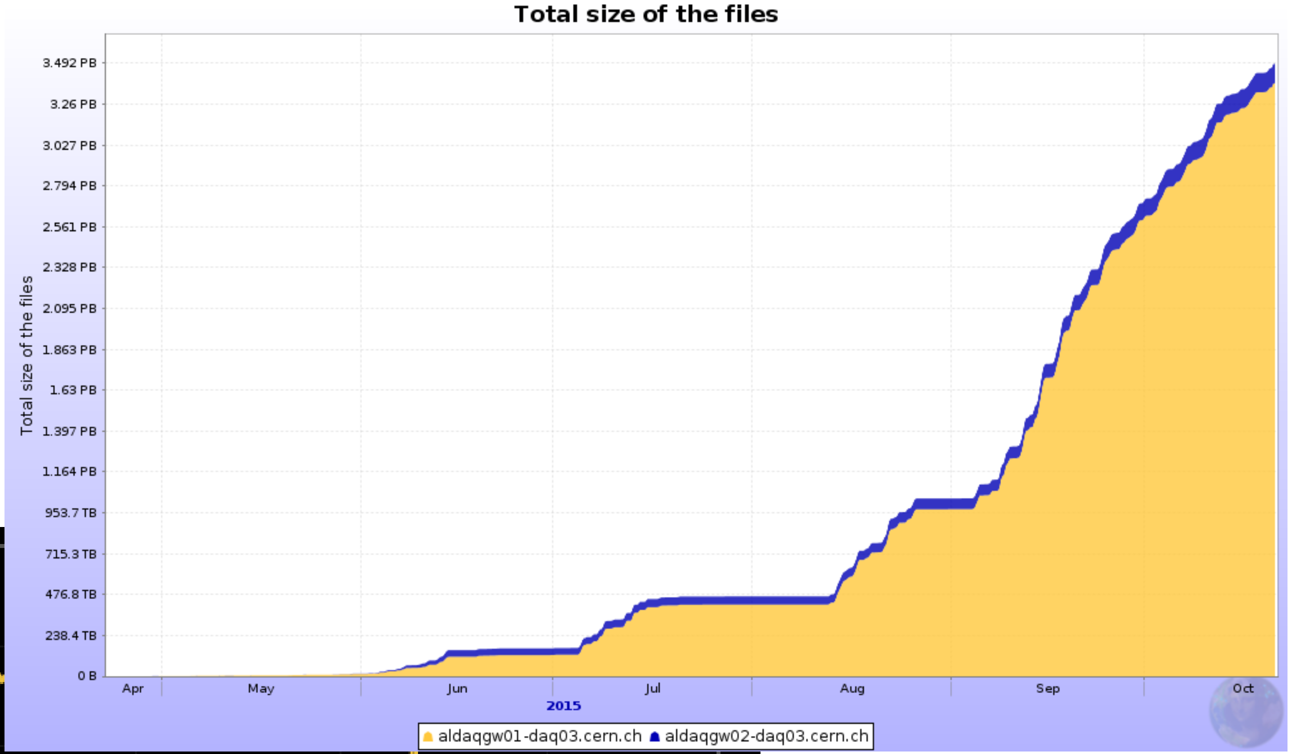


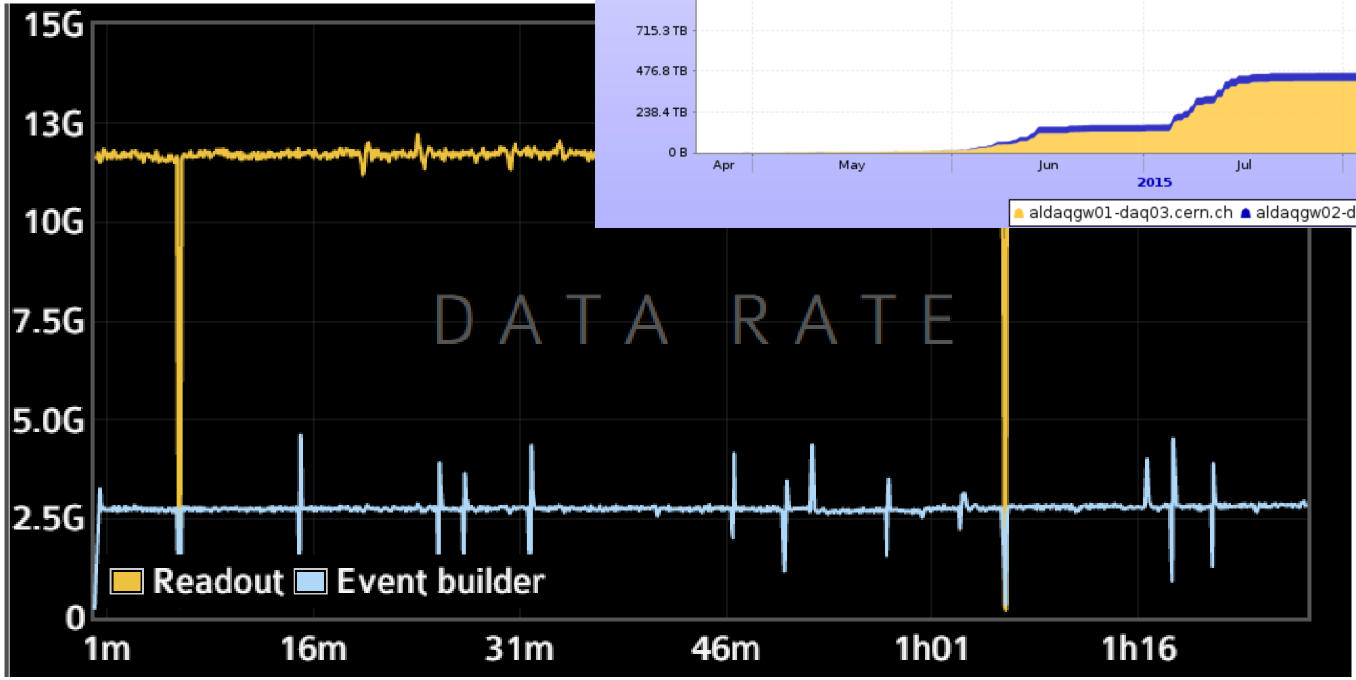
Data Acquisition (DAQ)/ High Level Trigger (HLT)
- **new architecture**
- **on line tracking & data compression**
- **50kHz PbPb event rate**

TOF, TRD
- Faster readout

New Trigger Detectors (FIT)

ALICE Run 2 Data taking Performance





Requirements for Runs 3 and 4

1. After LS2, LHC will deliver min bias Pb-Pb at 50 kHz
   - 100 x more data than today
2. Physics topics addressed by ALICE upgrade
   - Very small signal-to-noise ratio and large background
   - Triggering techniques very inefficient if not impossible
   - Needs large statistics
3. Support for continuous read-out (TPC)
   - Collision rate is faster than intrinsic rate of the slowest detector (TPC)
   - Detector read-out triggered or continuous by Time Frames of ~ 20ms

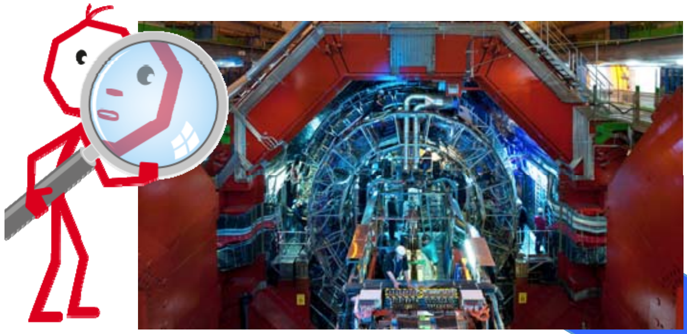
➔ Too much data to be stored

➔ Compress data intelligently by processing it online

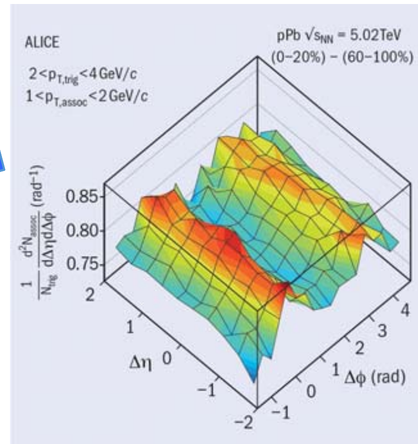
A Large Ion Collider Experiment

O² Project

Requirements for Run 3 (2020)



Detector	Input to Online System (GByte/s)	Peak Output to Local Data Storage (GByte/s)
TPC	1012	50
TRD	20	3
ITS	40	26
Others	23	9
Total	**1095**	**88**



- Handle >1 TByte/s detector input
- Online reconstruction to reduce data volume
- Common hw and sw system developed by the DAQ, HLT, Offline teams

Data Flow

Paradigm shift

Data of all interactions shipped from detector to online farm in triggerless continuous mode

HI run 1.1 TByte/s

Data volume reduction by cluster finder
No event discarded
Average factor 2.2(factor 2.5 for the TPC data)

500 GByte/s

Data volume reduction by tracking
All the events go to data storage
Average factor 5.5 (factor 8 for the TPC data)

90 GByte/s

Data Storage: 1 year of compressed data

- Bandwidth: Write 90 GB/s Read 90 GB/s
- Capacity: 60 PB

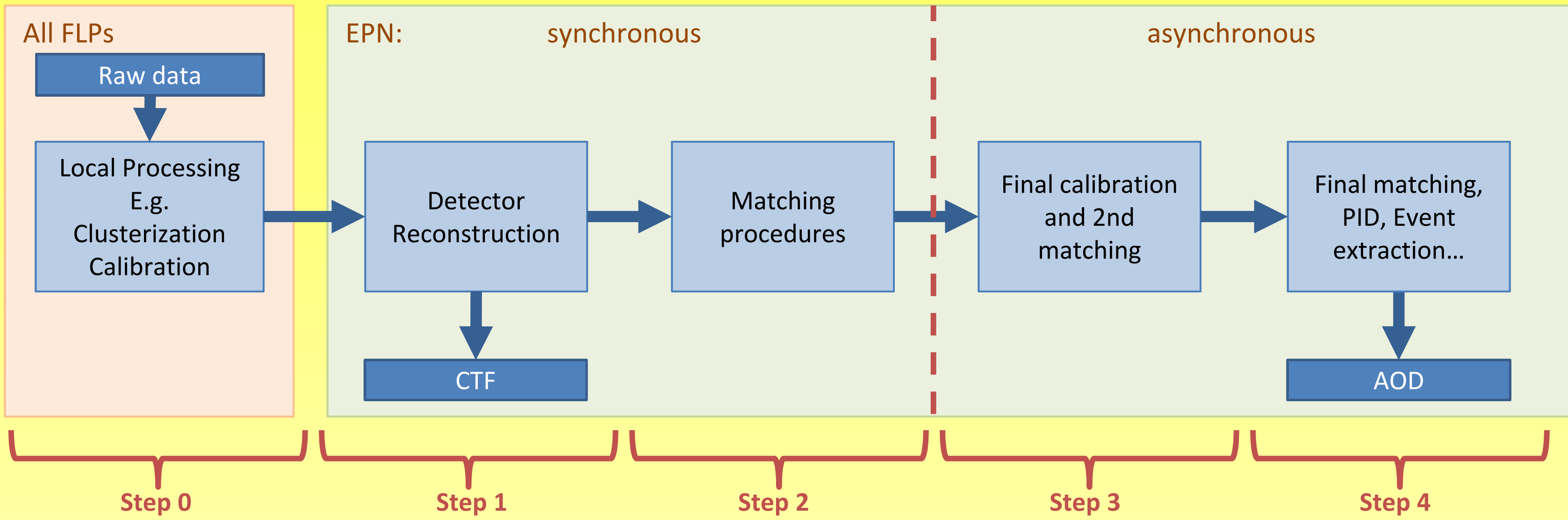
20 GByte/s

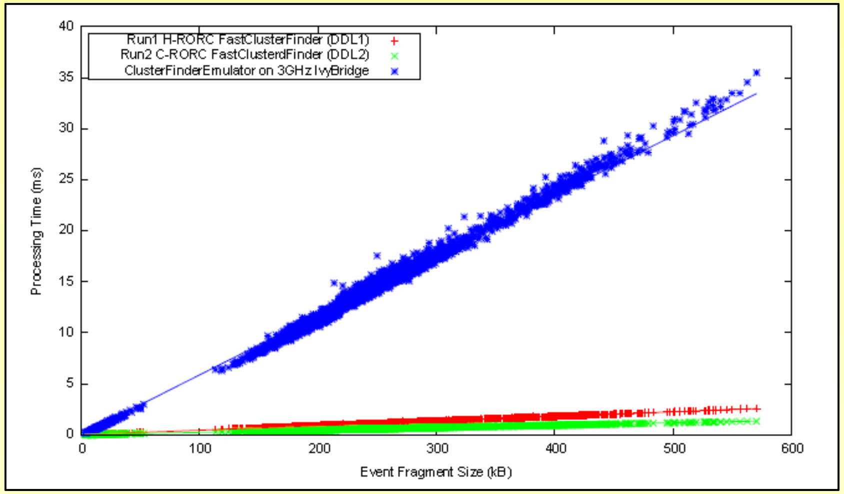
Tier 0

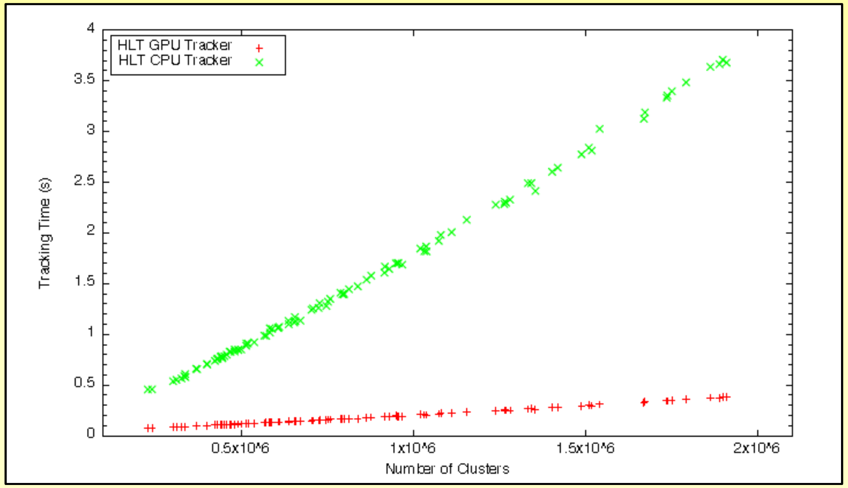
Tiers 1 and Analysis Facilities

Asynchronous event reconstruction with final Calibration with a delay of few hours.

Reconstruction with hardware acceleration



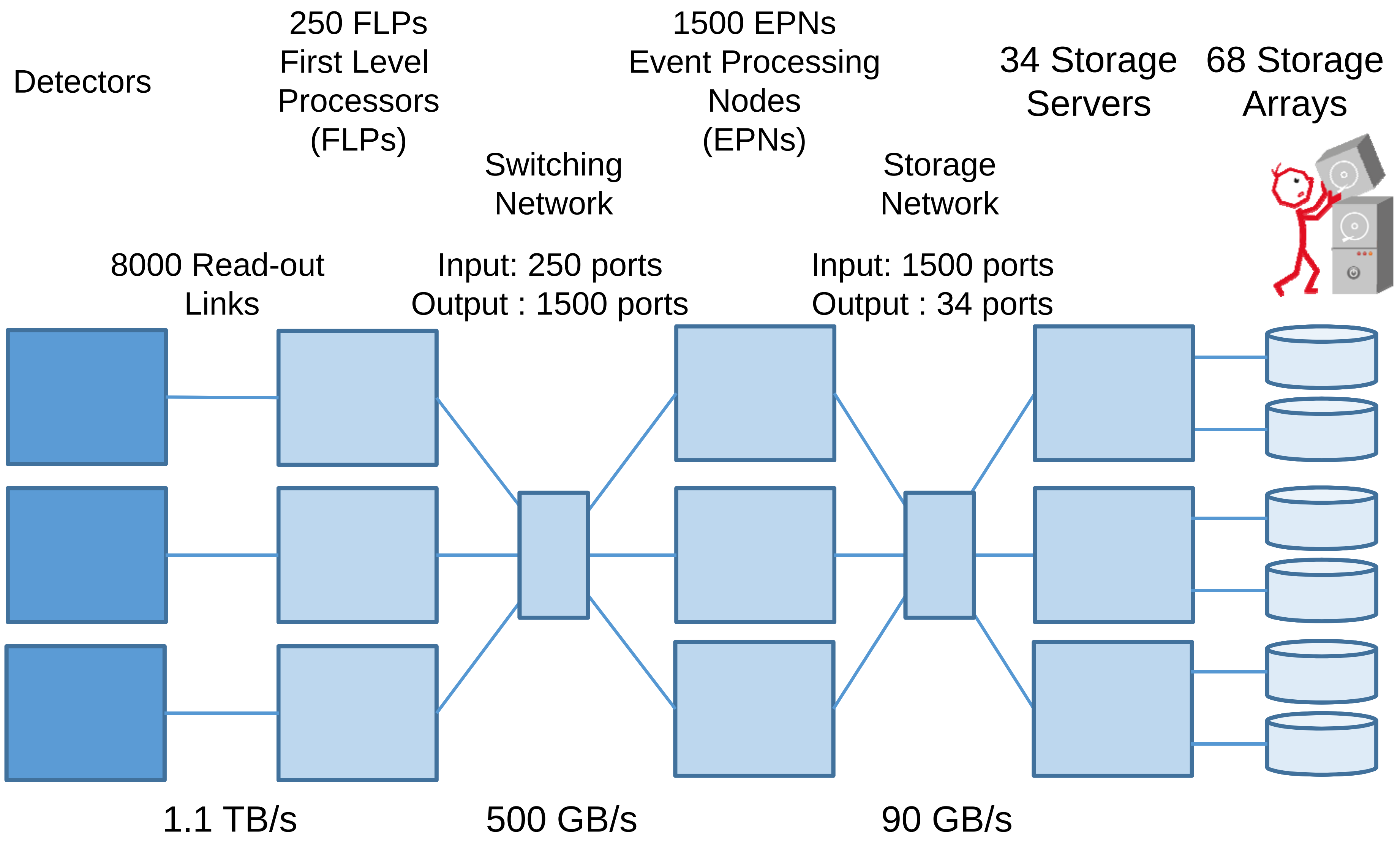




- Acceleration of TPC cluster finder using **FPGA**s
- 25 times faster than the software implementation

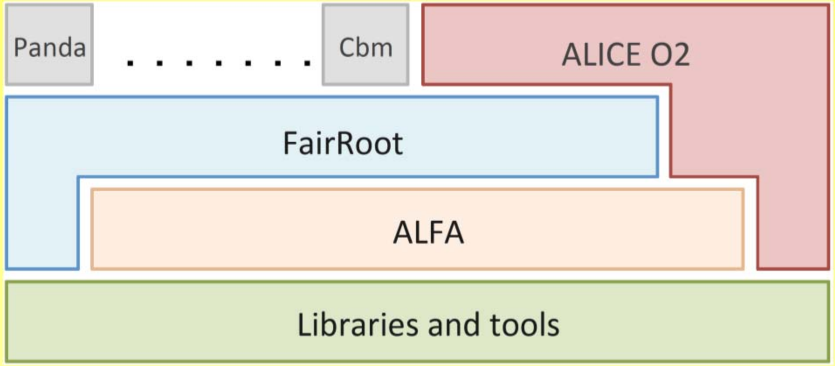
- Acceleration of TPC Track using **GPU**s
- 1 GPU replaces 30 CPU cores and uses 3 for I/O

Hardware Facility



Software framework and system simulation

- New software framework developed together with the Fair experiments
  - Message-based multi-processing
  - Ease of development
  - Ease to scale and extend with different hardware
- System simulation



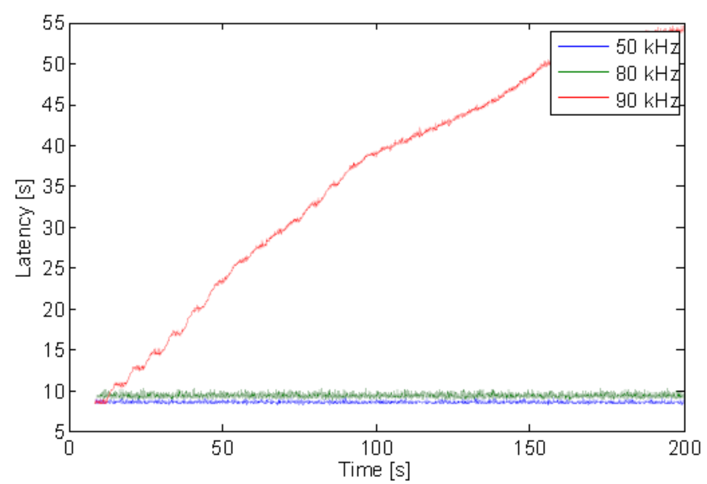


Figure 10.9: System scalability of the network layout 2 at up to 80kHz.

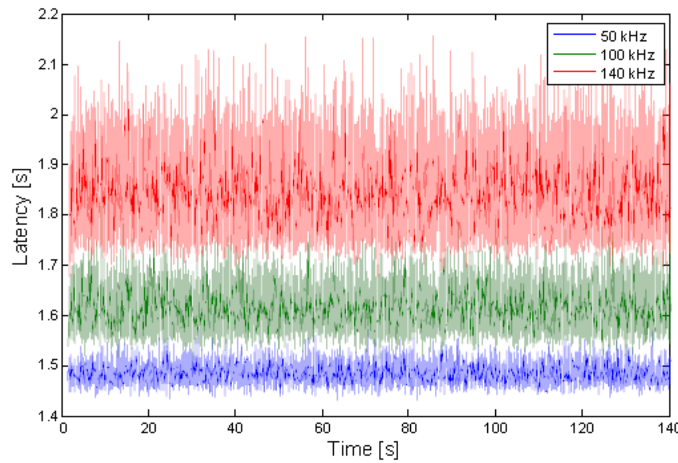
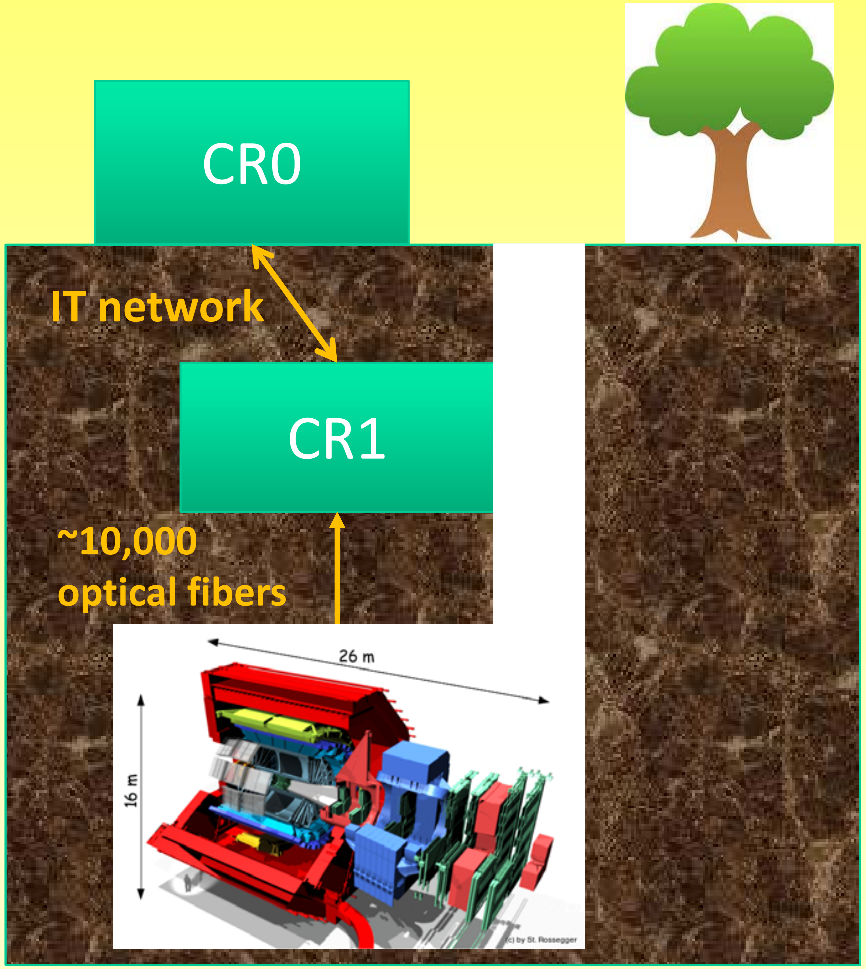


Figure 10.10: System scalability of the network layout 3 at up to 140kHz.

- Left: 4x10 Gb/s network – Right: 56 Gb/s network
- Scalability simulated via the latency of a data blocks in the system

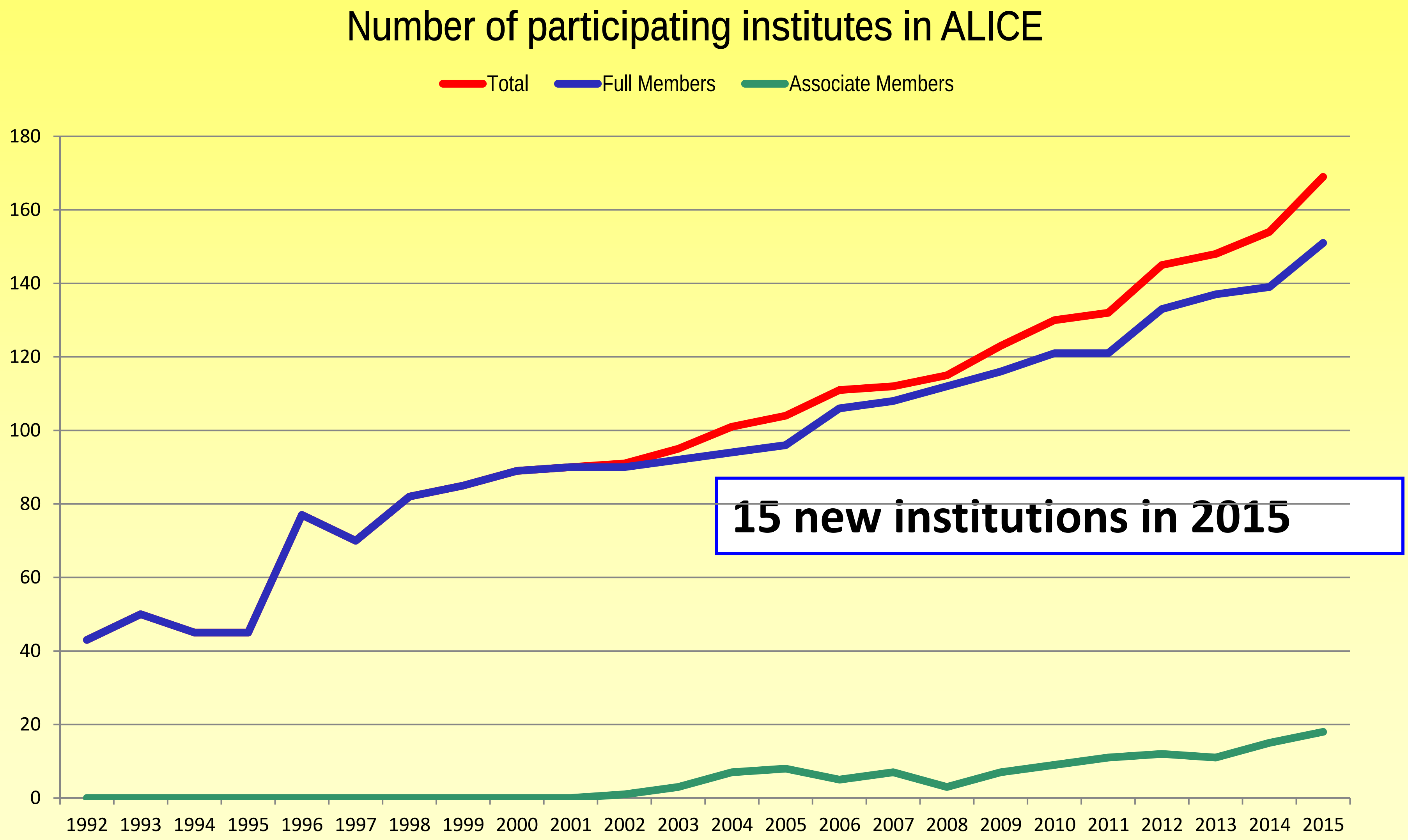
O^2 Computing Farm

- O^2 TDR and UCG documents recommended for approval by LHCC and UCG
- O^2 computing farm:
  - ~ 100 k CPU cores
  - ~ 5000 GPUs
  - ~ 60 PB of storage
- O^2 computing rooms
  - CR1: existing room adequate
  - CR0: new room and infrastructure needed
- Aim at a Power Usage Effectiveness (PUE) < 1.15



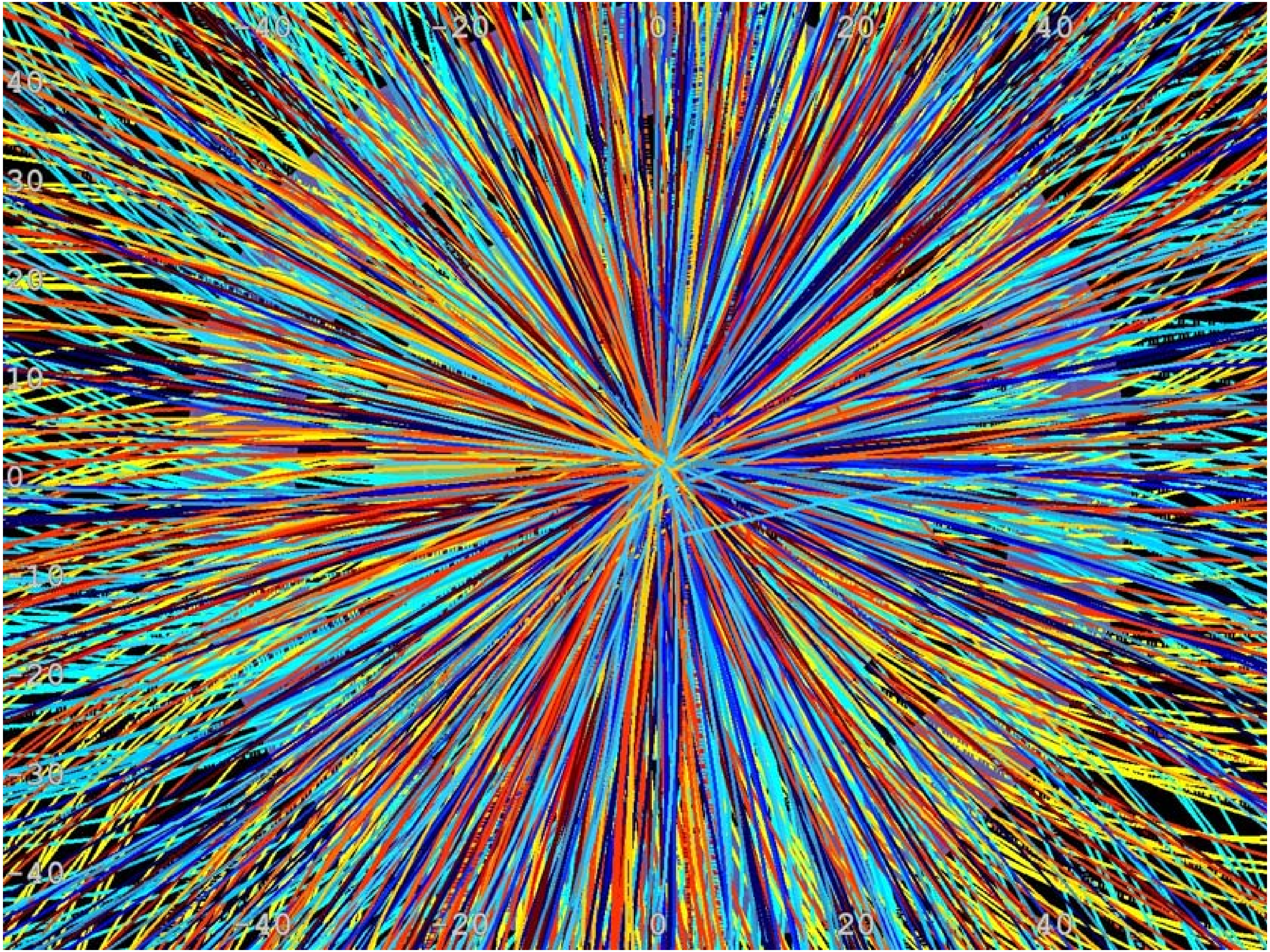
Is the ALICE Upgrade attractive?

A lot of people think so....



Conclusions

- ALICE is harvesting Physics results from RUN1 and now also RUN2, with a much improved detector
- RUN2 is progressing very well
- The Collaboration is preparing a major Upgrade for LS2, to operate in RUN3 and RUN4
  - The Upgrade involves major challenges in detectors, electronics and computing
  - Frontier developments of diffferent teachnolgies
  - An exciting plan for the years to come!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40

spares

Long term future of the LHC HI Program

- All experiments are building on the success of RUN1 and learning from the results
- June 29th 2012 Town meeting of the whole HI community
  - Very important meeting, resulting in a common document of the Community submitted to the Cracow one, and indicating clearly the extension of the LHC HI program, including the ALICE upgrade, as its first priority. Remarkable coherence of ALICE, ATLAS and CMS
    - "***The top priority for future quark matter research in Europe is the full exploitation of the physics potential of colliding heavy ions in the LHC.***"
- All 3 experiments would benefit from the PbPb luminosity upgrade, and in their upgrades would strengthen their complementarity
- NUPECC also submitted a document to the Cracow European Strategy Meeting
  - Stresses the commitment of the Nuclear Physics Community to the ALICE long term programs, "top priority for European Nuclear Physics"

The European Strategy

– 2012 Cracow European Strategy Meeting

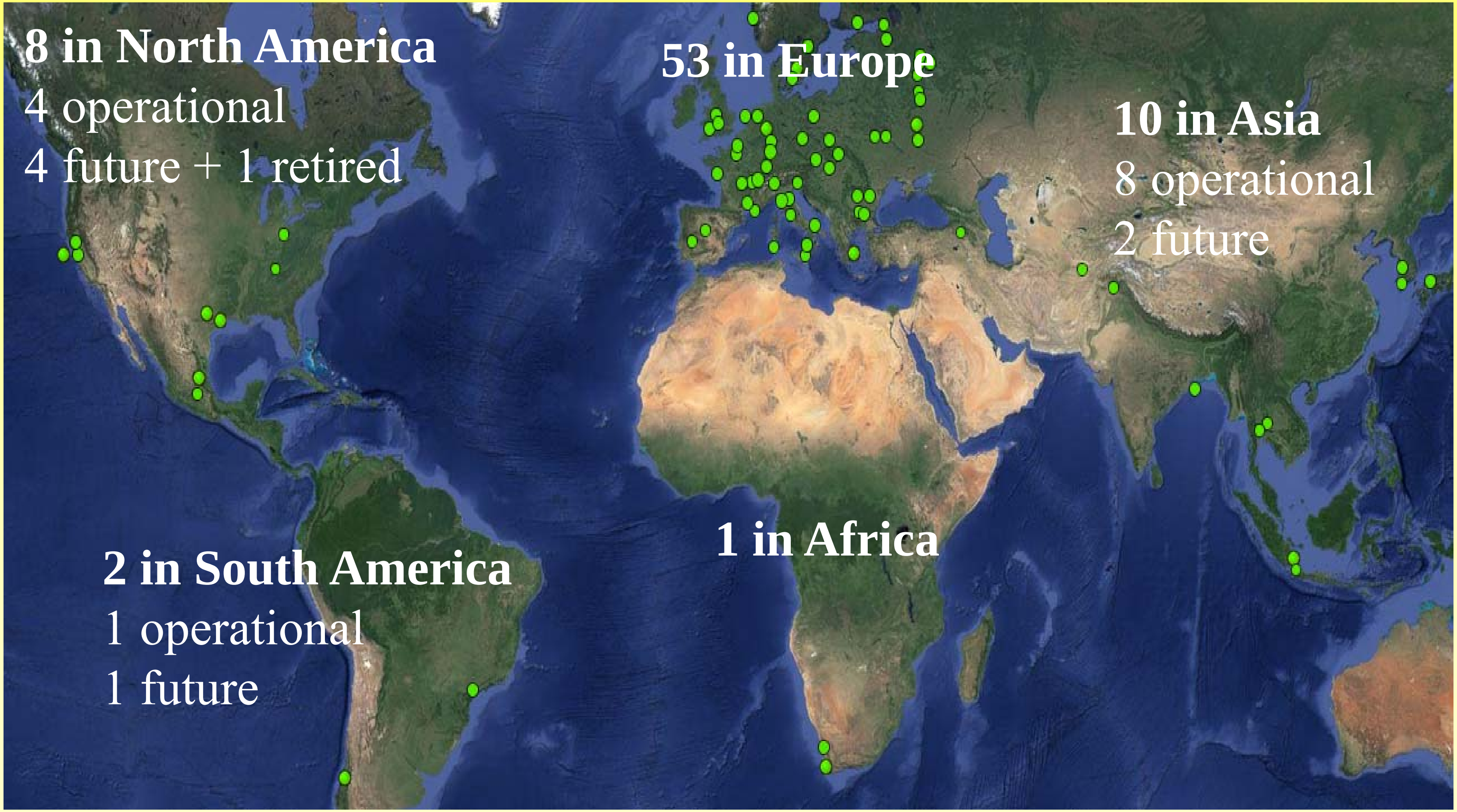
- Heavy Ion Physics an integral part of the future LHC program till at least the mid 2020s

– Erice final document on the European Strategy for Particle Physics

- Heavy Ions are an integral part of the top priority of the plan: "*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. This upgrade programme will also provide further exciting opportunities for the study of flavour physics* ***and the quark-gluon plasma."***

STORING, PROCESSING AND ANALYSIS OF THE DATA:

The ALICE GRID

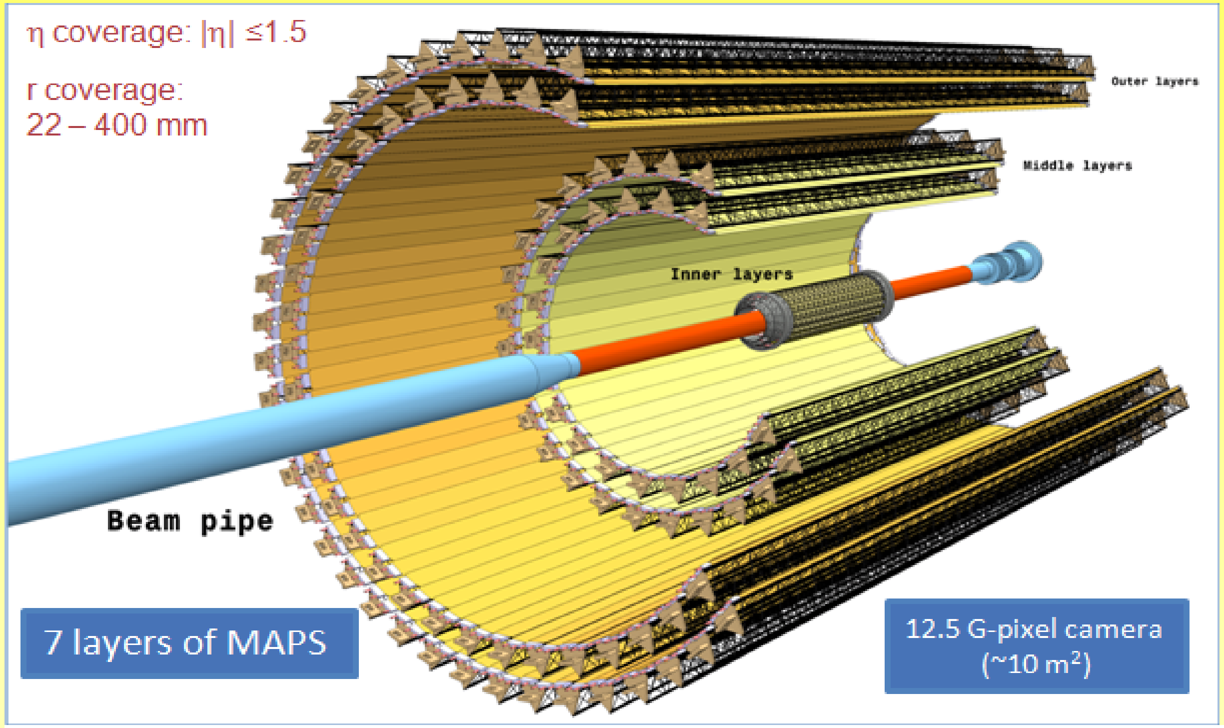


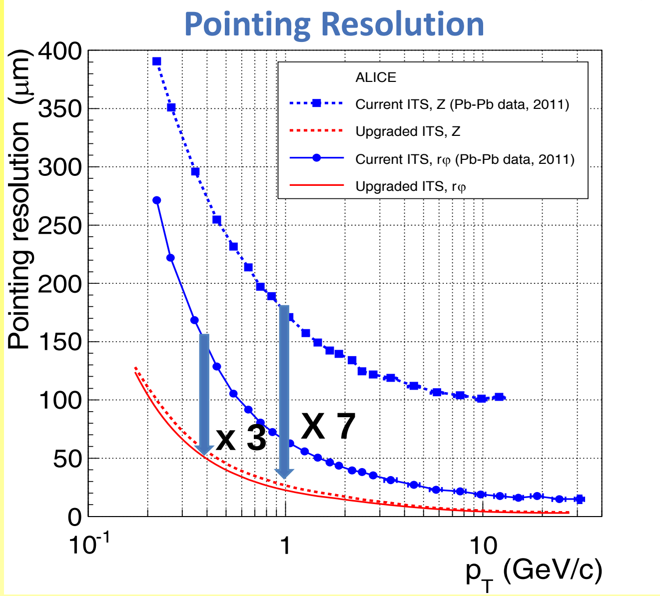
- Currently over 60k jobs run in parallel….

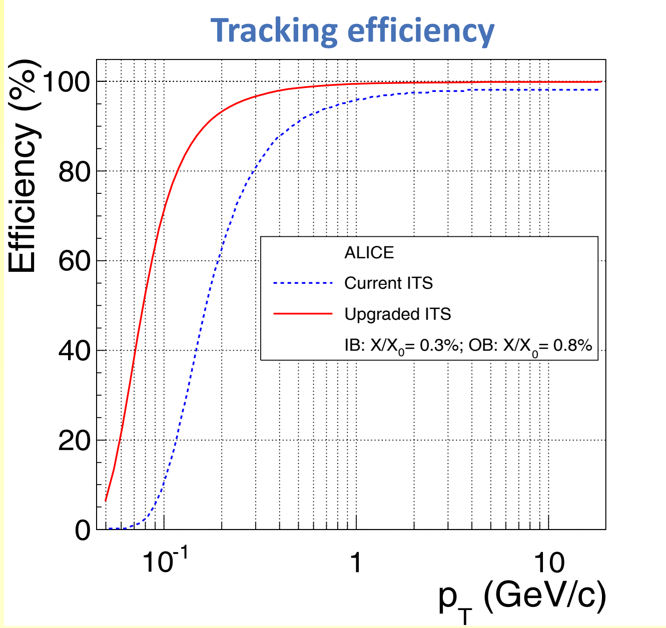
The ALICE Upgrade: status

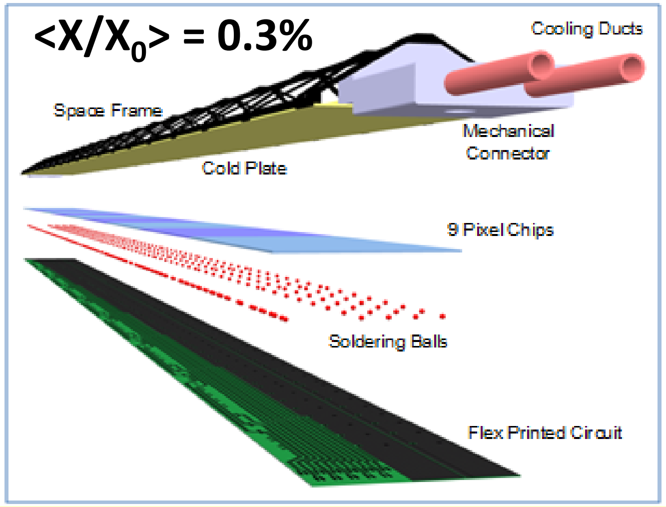
- **Five Pillars (each in a Technical Design Report), all approved by LHCC, UCG and RB, the latest this past September:**
  - Completely new Silicon Inner Tracking System
  - New or upgraded readout for all detectors to cope with the higher rate, new CTP and Trigger Detectors
  - New readout chambers for the Time Projection Chamber
  - New Silicon Tracker in front of Muon Absorber
  - New Data Acquisition System and High Level Trigger to handle the continuous readout, new Offline

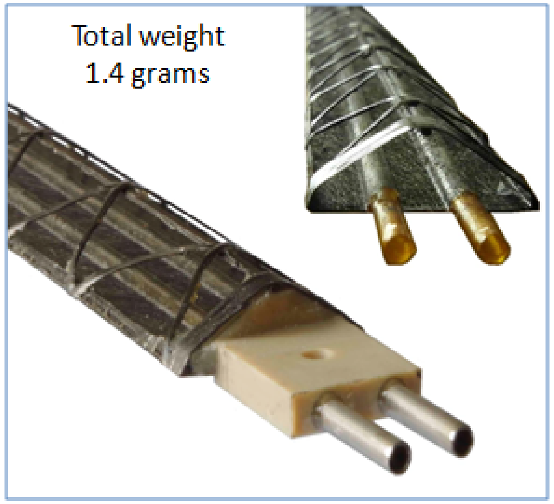
LS2 upgrade: new Inner Tracking System



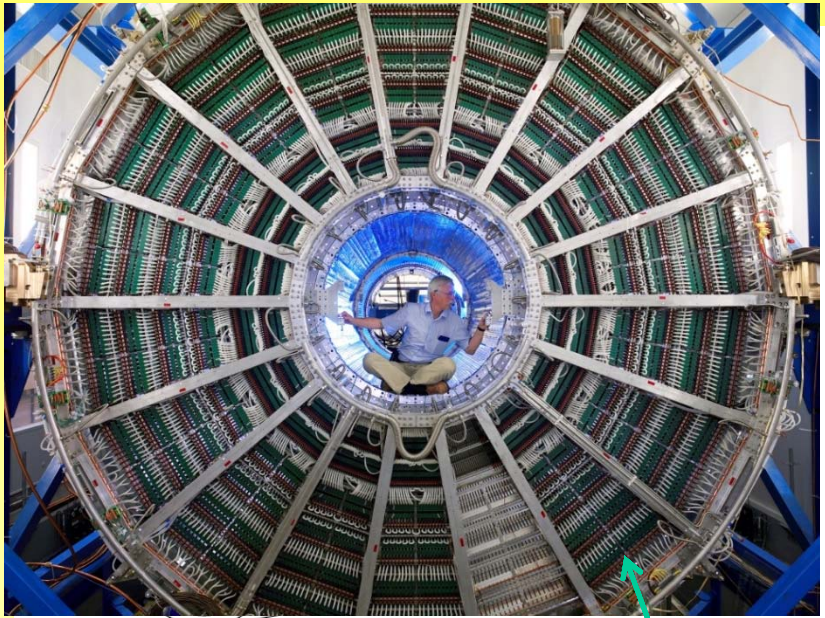








TPC Upgrade with GEMs



World Largest TPC
ALICE key tracking and PID instrument
500 million pixels

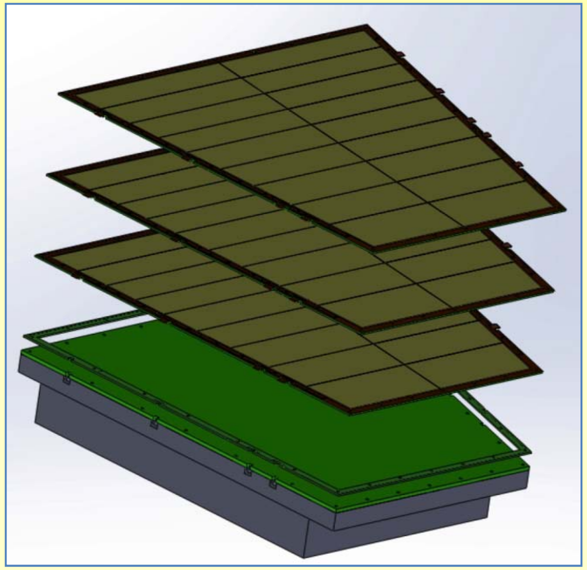
To operate at the 50 kHz rate => no gating grid => need to minimize Ion Back Flow to keep space charge distortions at a tolerable level

Replace wire-chambers with GEMs

- 100 m^2 single-mask foils
- Limit Ion-Back-Flow into drift volume
- Maintain excellent dE/dx resolution

New readout electronics

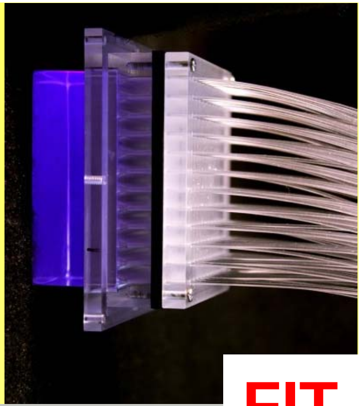
Keep all other subsystems



Replace wire chambers with quadruple-GEM (full scale prototypes tested in beam in late 2014)

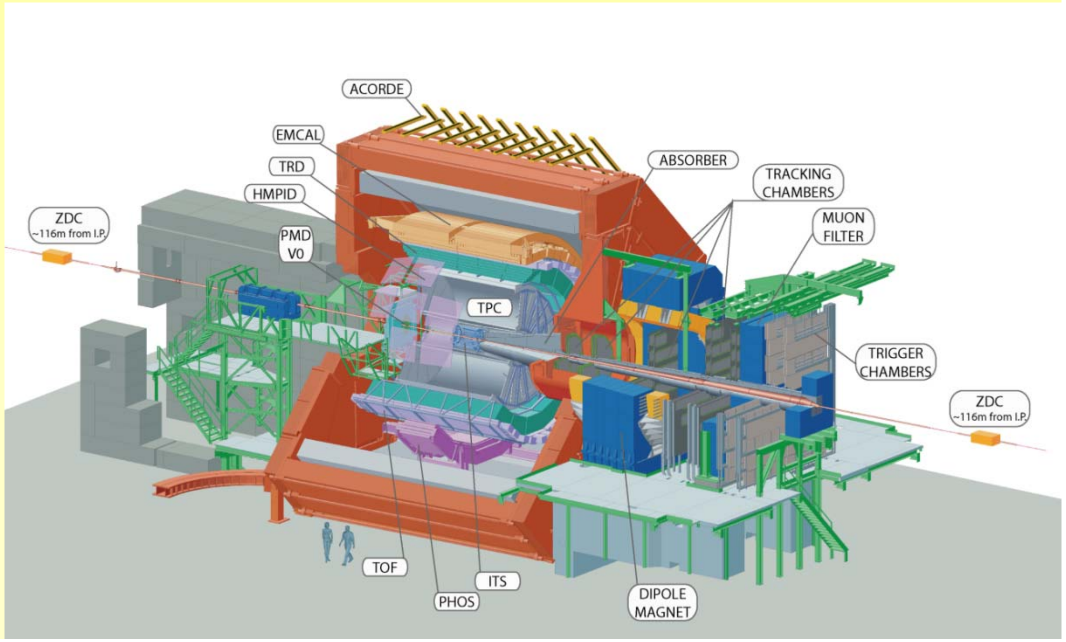
Upgrade of the ALICE Readout and Trigger System

- **New Forward Trigger Detector (FIT)**
- **New Central Trigger Processor (CTP)**
- **Electronics upgrade for 100 kHz Pb-Pb interaction rate of**
  - Time Of Flight Detector (TOF)
  - Transition Radiation Detector (TRD)
  - Muon System
  - TOF
  - ZDC

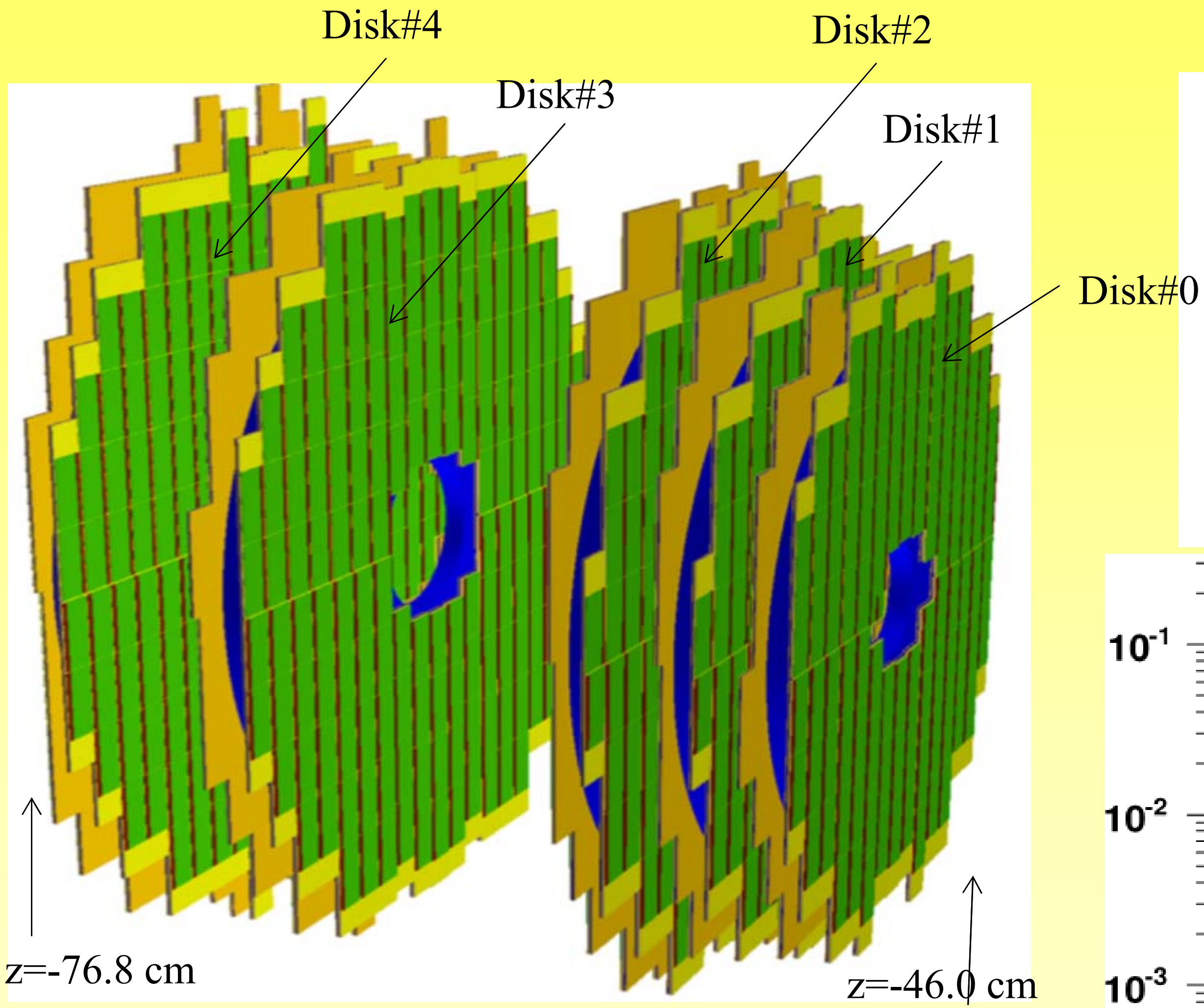


FIT

Common TDR,
Including also the
Common Readout Unit (CRU)
and the FRONTEND for TPC
and Muons (SAMPA chip)
Endorsed by LHCC
Approved by UCG



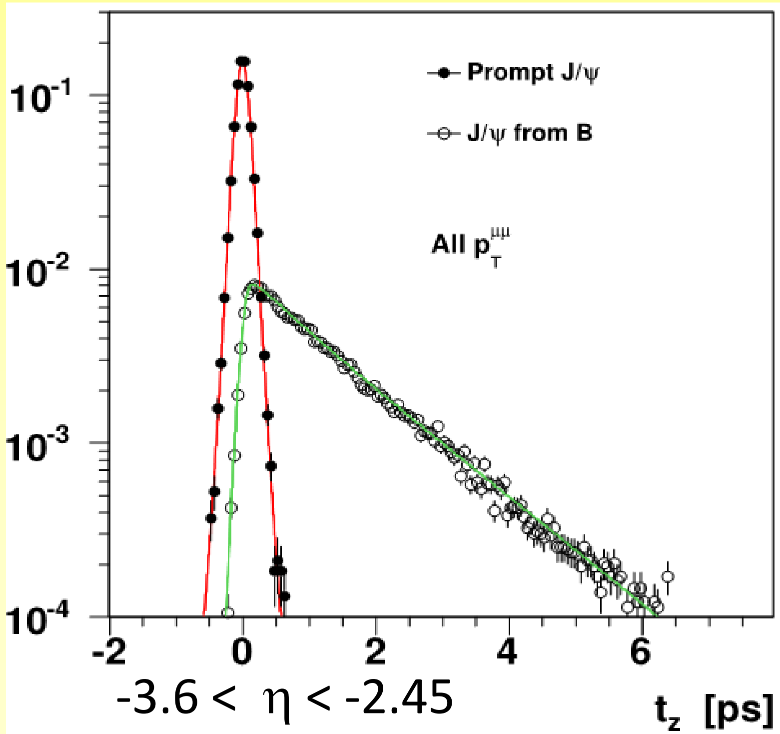
Muon Forward Tracker



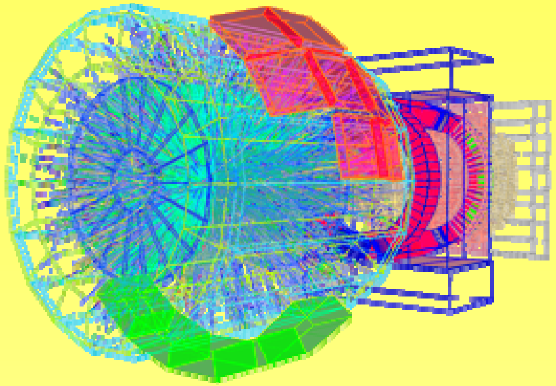
Secondary vertexing for the muon spectrometer

- **c → μ**
- **b -> J/ψ**
- **low mass di-muons**
- **ψ(2S)**
- **...**

- **10 Half-disks** of 2 detection planes each
- 896 **silicon pixel sensors** (0.4 m^2) in 280 ladders
- **Common pixel chip development with ITS**



A flood of data…



50 kHz

1 TByte/s into PC farm

Reconstruction
+
Compression

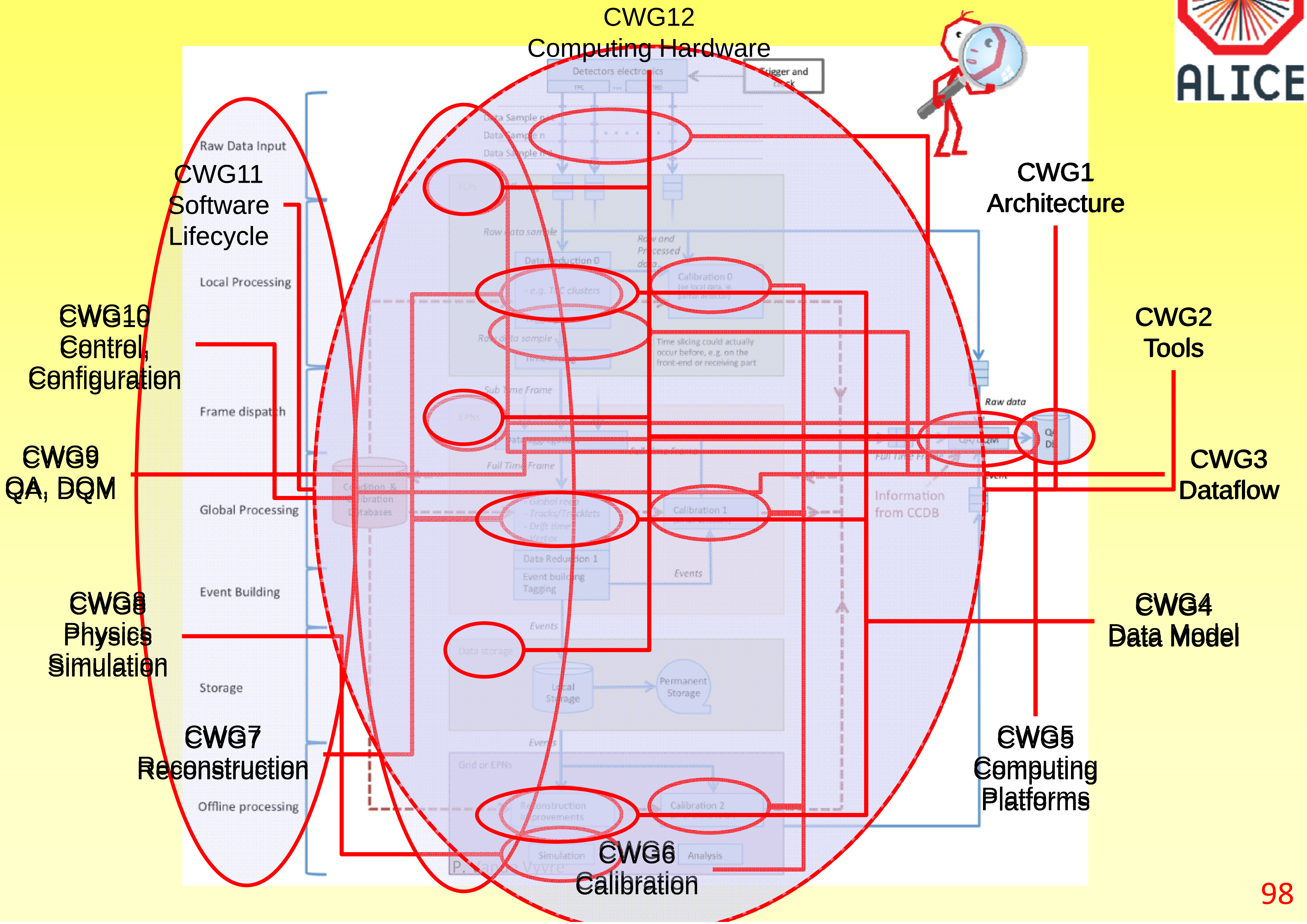
O^2 (Online Offline) System

Storage

75 GB/s

← PEAK OUTPUT
(20 GB/s average)

O^2 Computing Working Groups



ALICE goals for Run 2

- complete the originally approved heavy ion program, i.e. collection of **1/nb in Pb-Pb collisions at top energy (13 TeV p equivalent (5.5 TeV)) x10 current statistics**
- pp reference running @ 13 TeV
  - Two main goals
    - reference rare trigger sample for 1/nb Pb-Pb
    - increase reference unbiased sample
  - 48 weeks running with rare triggers :
    - 60/pb (1.5 equivalent int lumi of 1/nb Pb-Pb → not dominant in uncertainty)
  - 24 weeks running with min bias
    - 10 G events → better significance than Pb-Pb for D^0
- pp reference running @ 5 TeV (limited sample)
  - Min bias => direct reference at low p_T -> $O(10^9)$ events
    - Charm, identified particles, correlations, … Trigger correction for triggered sample
  - Triggered=> validate/constrain reference at high p_T -> O(1/pb)
    - R_{pPb} high p_T charged particles, jets, quarkonia,…
- another p-Pb run, given the exciting results of the first one :
  - p-Pb run in Run 2 requested by all experiments
    - Goal: 1 G events **(x10 current)**
      - would ~ match pp significance for D^0