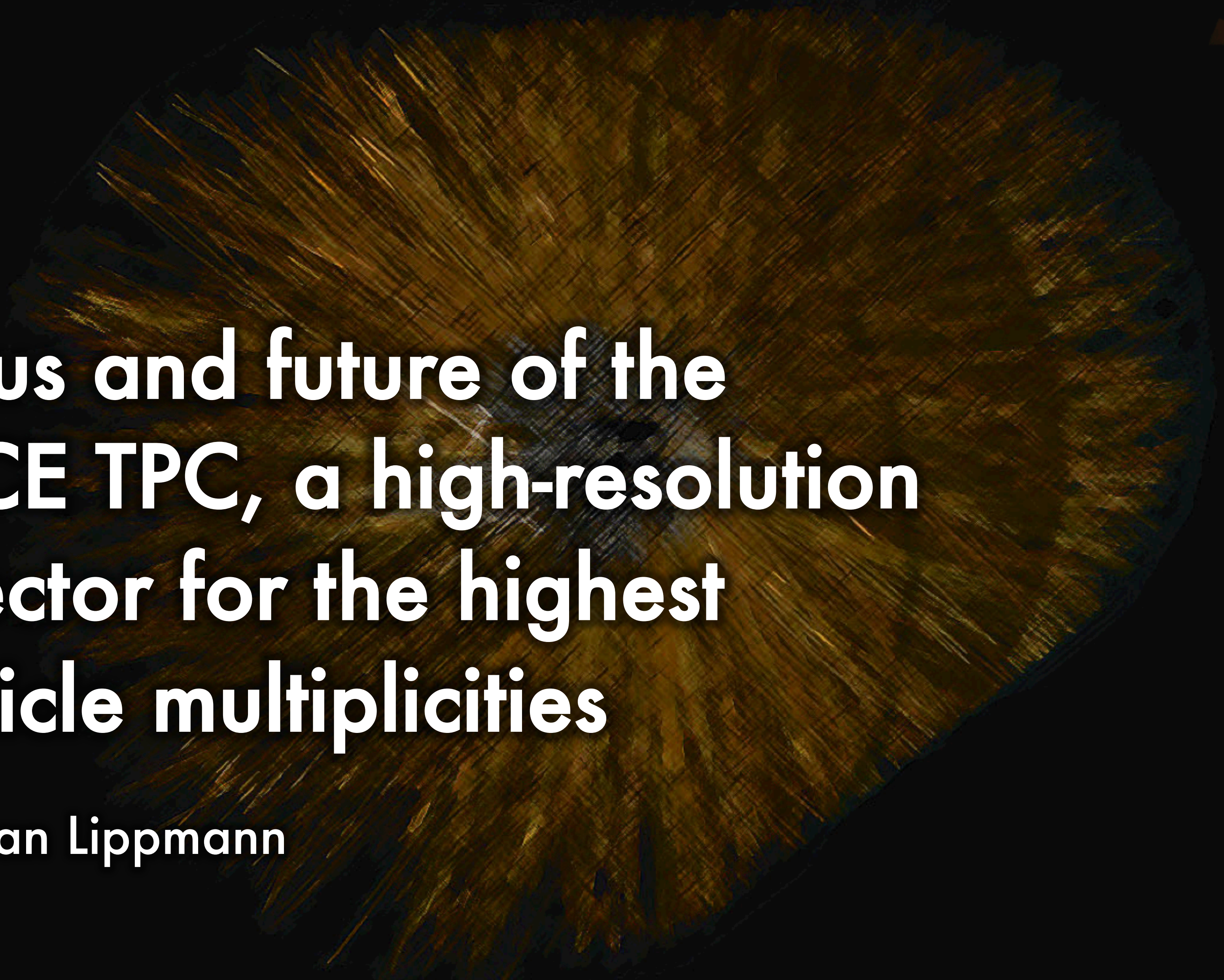
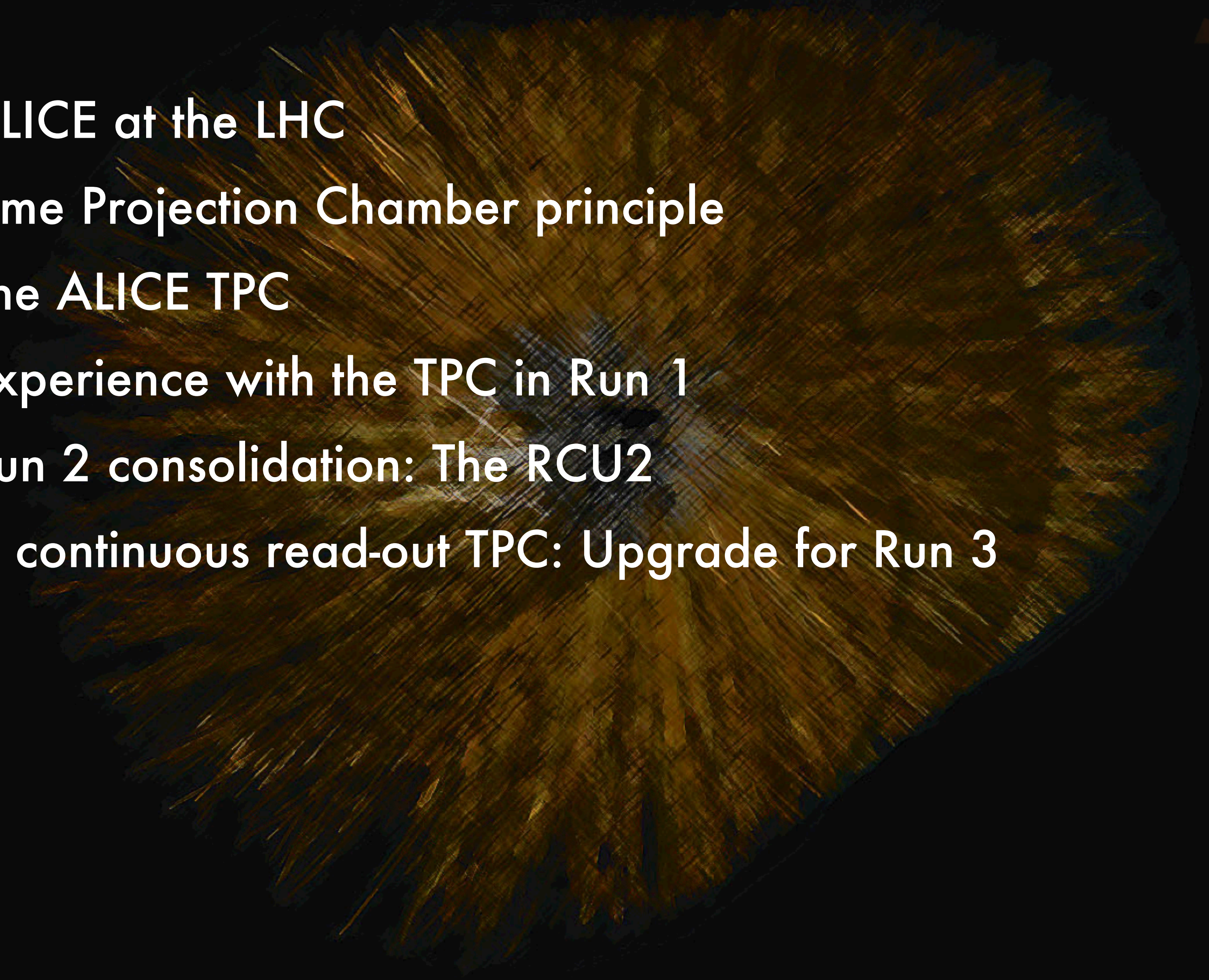


Status and future of the ALICE TPC, a high-resolution detector for the highest particle multiplicities

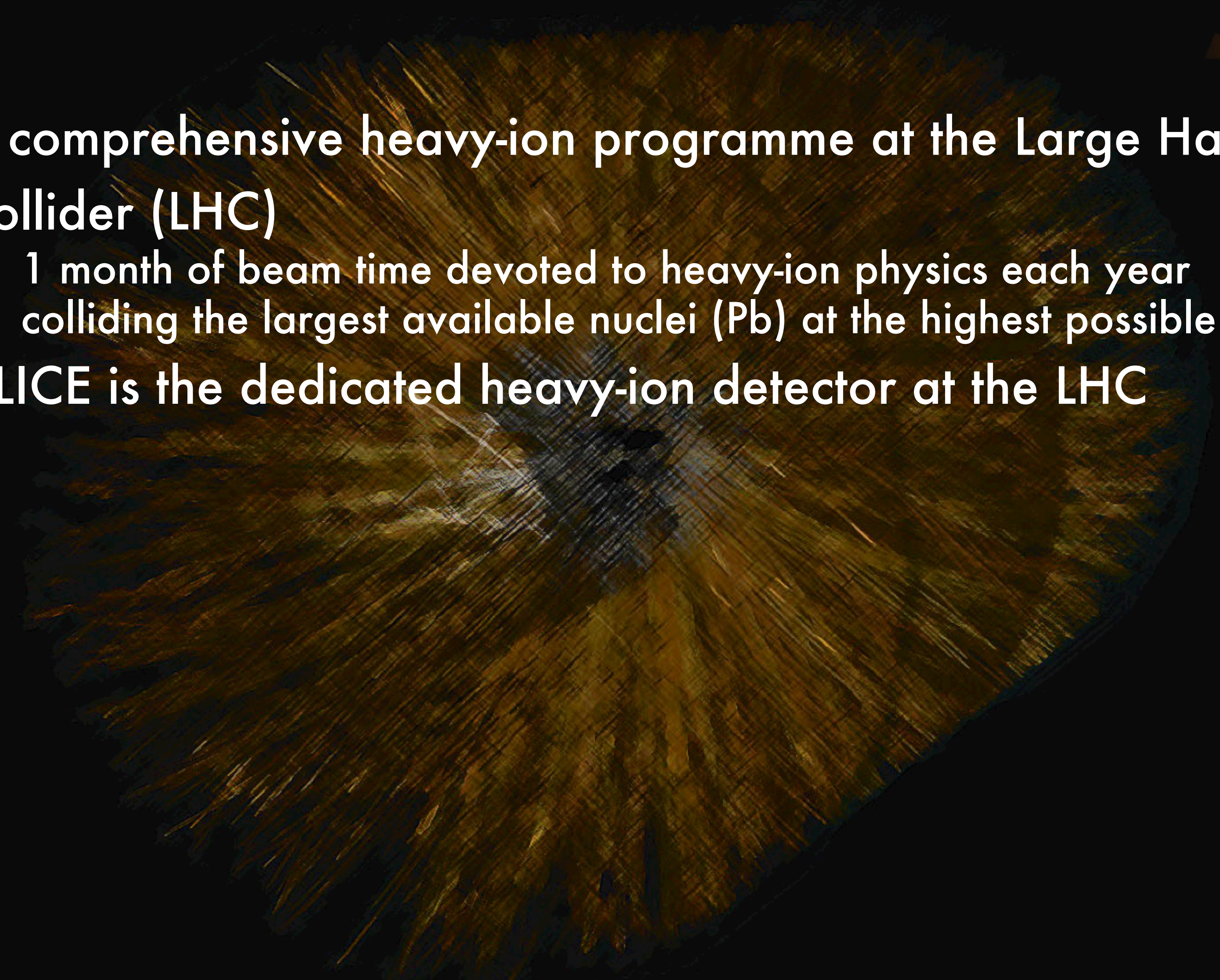
Christian Lippmann

Content



- ALICE at the LHC
- Time Projection Chamber principle
- The ALICE TPC
- Experience with the TPC in Run 1
- Run 2 consolidation: The RCU2
- A continuous read-out TPC: Upgrade for Run 3

Heavy-ion collisions at the LHC (1)



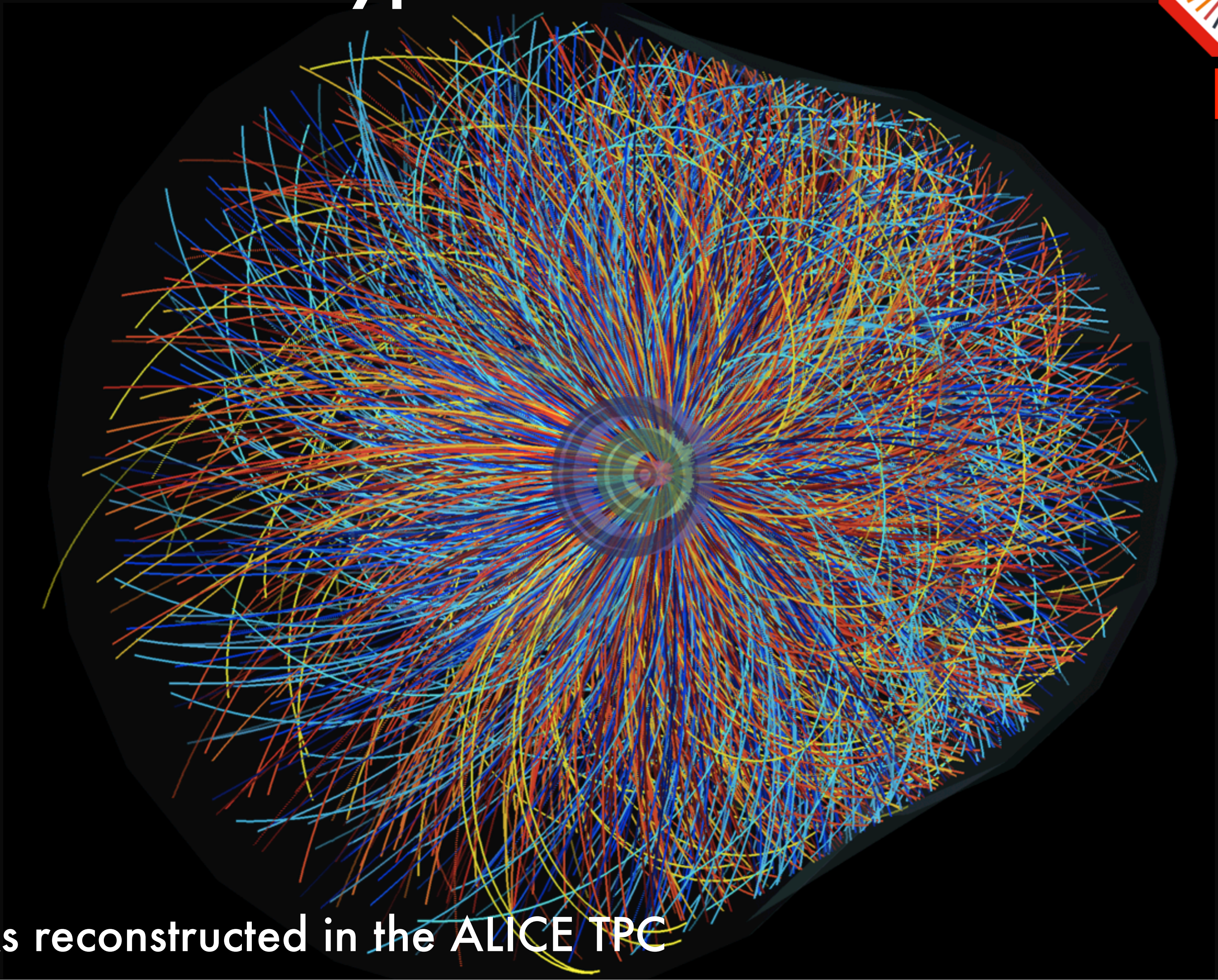
- A comprehensive heavy-ion programme at the Large Hadron Collider (LHC)
  - 1 month of beam time devoted to heavy-ion physics each year
  - colliding the largest available nuclei (Pb) at the highest possible energy
- ALICE is the dedicated heavy-ion detector at the LHC

Heavy-ion collisions at the LHC (2)

- A comprehensive heavy-ion programme at the Large Hadron Collider (LHC)
  - 1 month of beam time devoted to heavy-ion physics each year
  - colliding the largest available nuclei (Pb) at the highest possible energy
- ALICE is the dedicated heavy-ion detector at the LHC

	pp LHC design	pp ALICE 2012	Pb−Pb (design)	Pb−Pb (Nov 2011)
Centre of mass energy	14 TeV	8 TeV	5.5 ATeV x 208 = 1144 TeV total	2.76 ATeV x 208 = 574 TeV total
Luminosity	10^{34} Hz/cm^2	<10^{31} Hz/cm^2	10^{27} Hz/cm^2	4×10^{26} Hz/cm^2
Bunches per beam	2808	1374	592	358
Bunch spacing	25 ns	50 ns	100 ns	200 ns
β^*	0.5 m	3 m	0.5 m	1 m
Min. bias trigger frequency	10^9 Hz	<10^8 Hz	8000 Hz	3200 Hz
$dN_{ch}/d\eta$	unknown	6	~2300 (expected)	1600

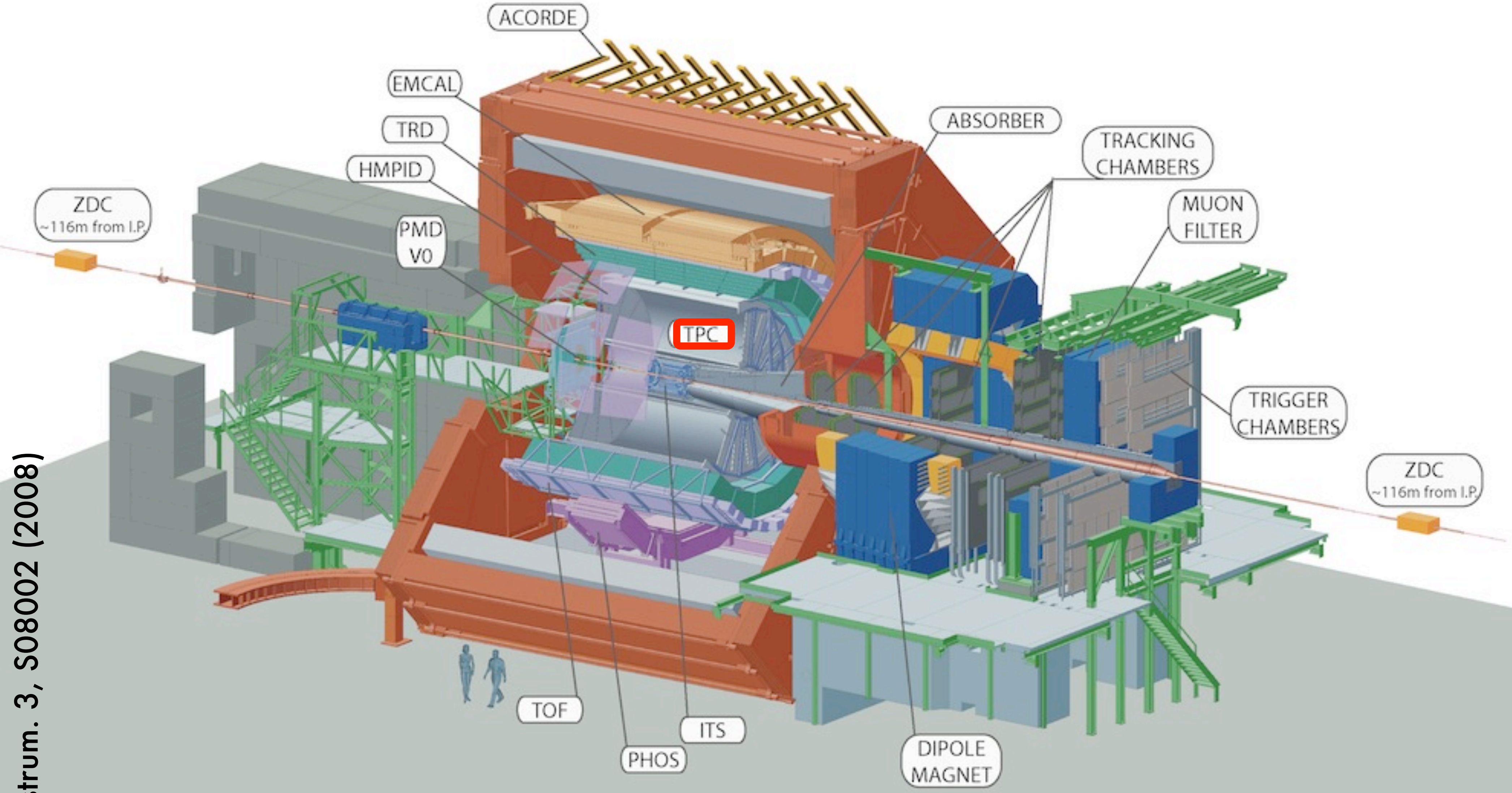
A typical Pb–Pb event



Tracks reconstructed in the ALICE TPC

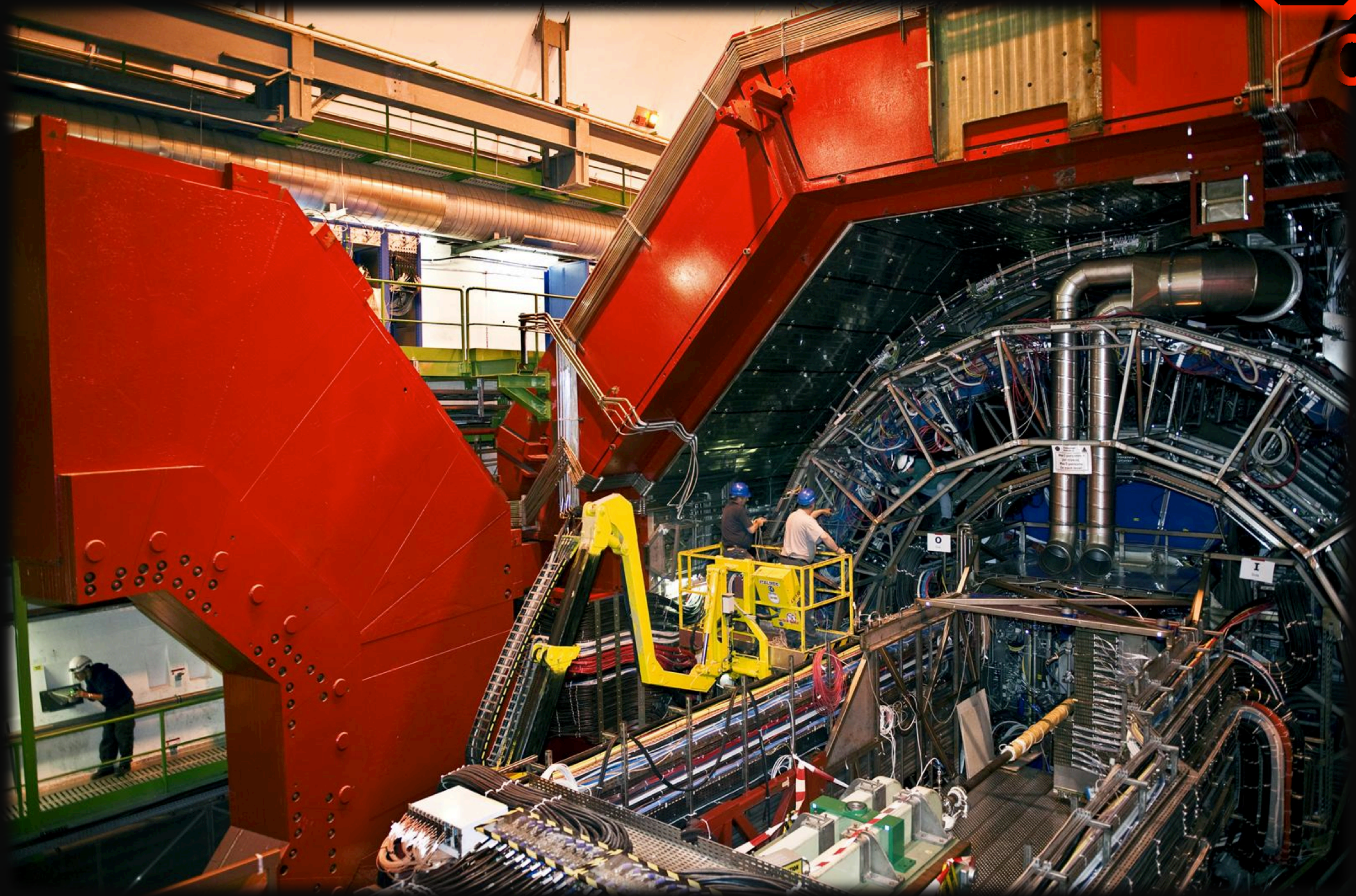
Size: 16 x 26 meters
Weight: 10,000 tons

ALICE setup (1)

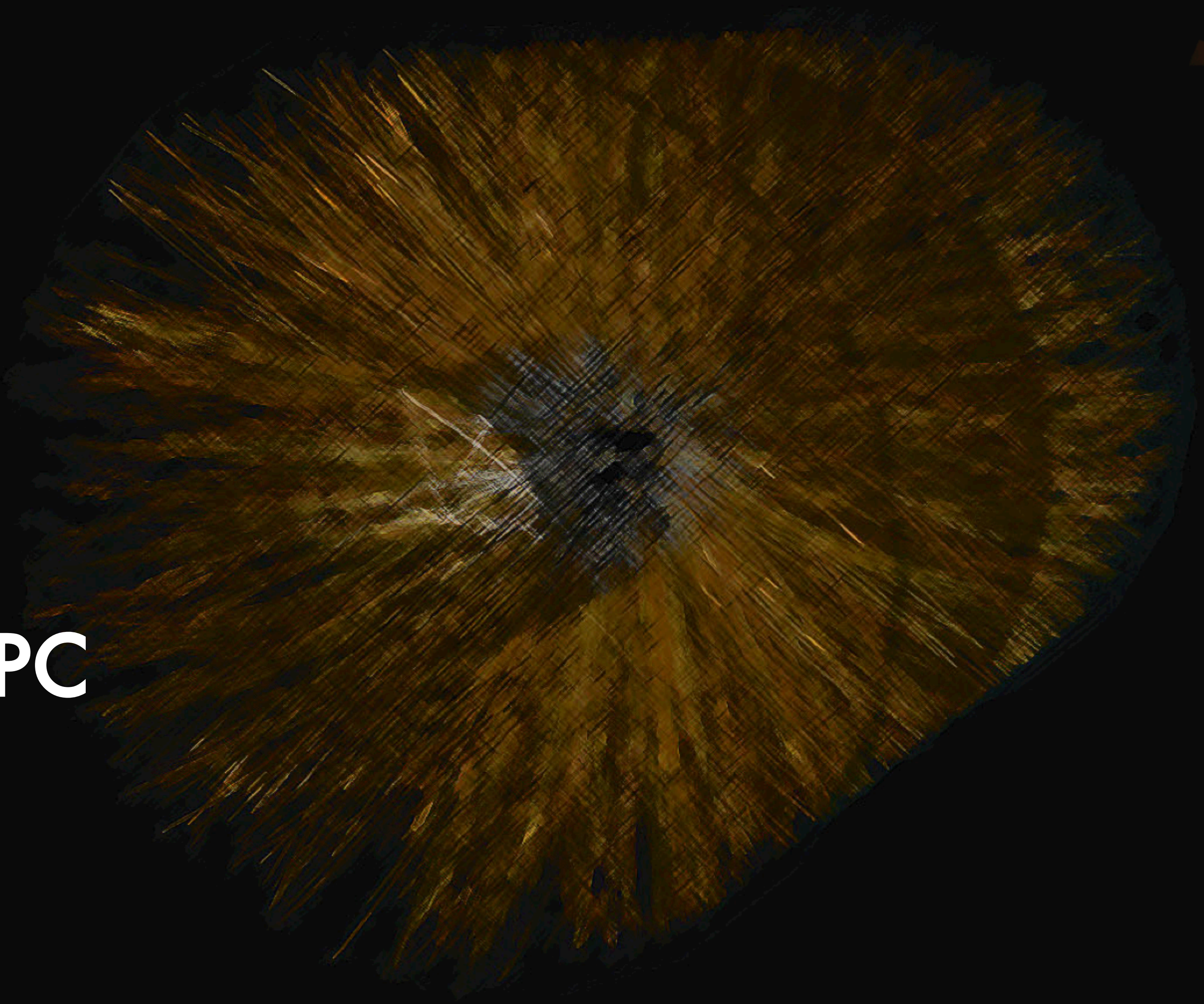


J. Instrum. 3, S08002 (2008)

ALICE setup (2)



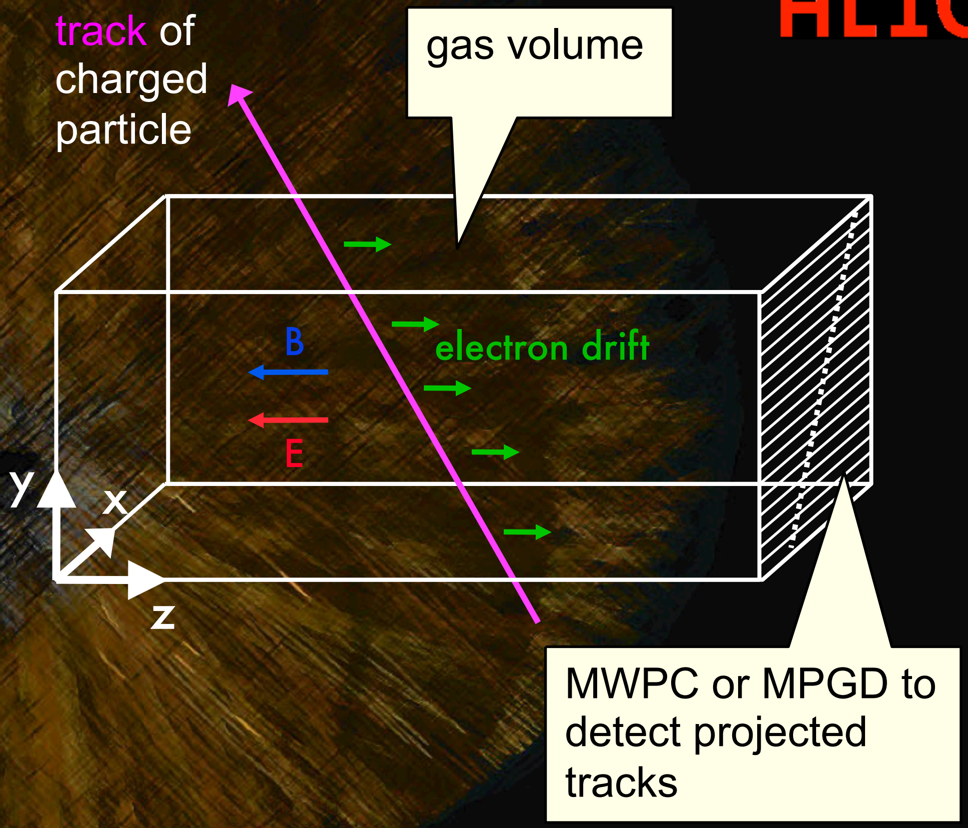
J. Instrum. 3, S08002 (2008)



TPC

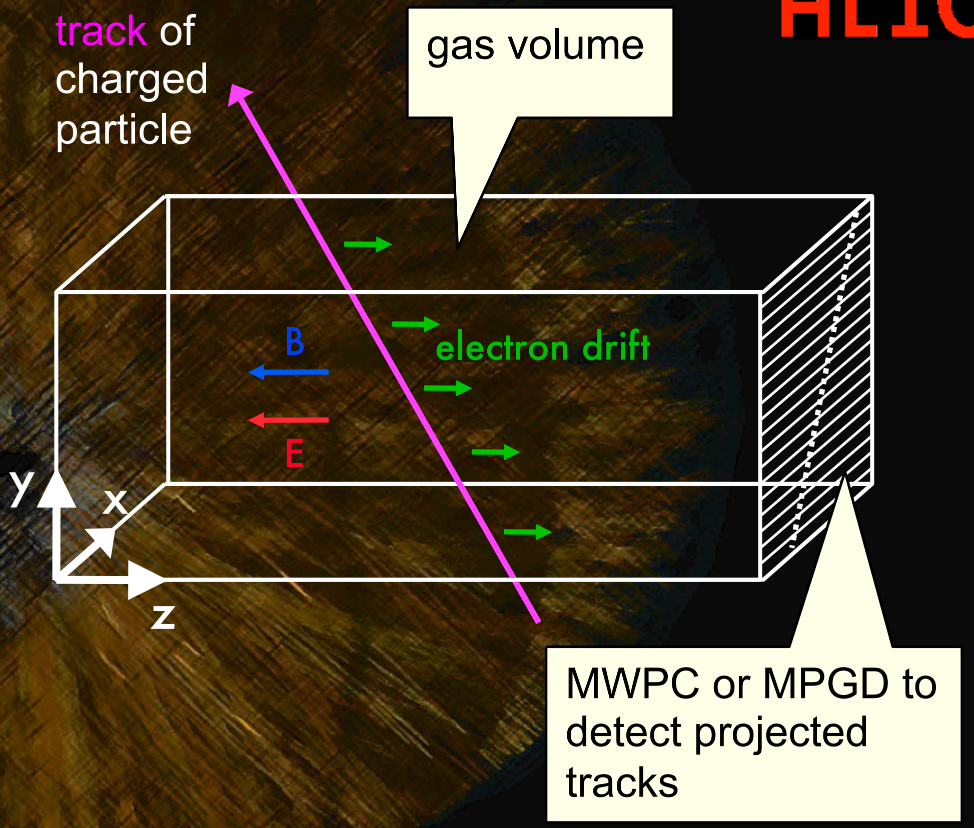
What is a TPC?

1) A charged particle ionises the gas inside a field cage with homogeneous E and B fields.
2) The electrons drift towards the readout elements (up to few m).
3) The projected track is registered on readout chambers (wire chambers, GEMs, ...).



What is a TPC?

1) A charged particle ionises the gas inside a field cage with homogeneous E and B fields
2) The electrons drift towards the readout elements (up to few m).
3) The projected track is registered on readout chambers (wire chambers, GEMs, ...).
4) The third coordinate is reconstructed from the drift time.



track of charged particle

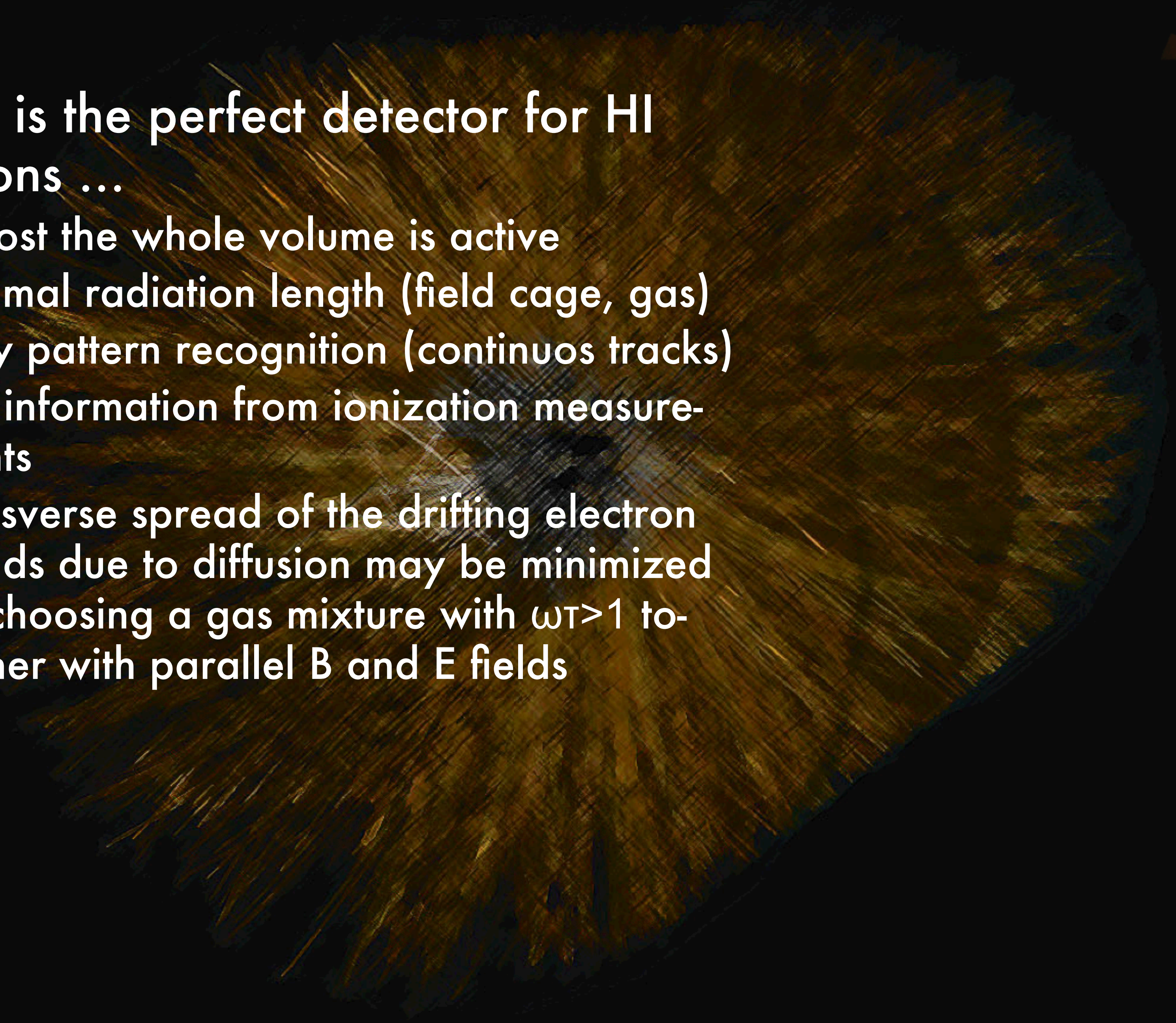
gas volume

MWPC or MPGD to detect projected tracks

$$\vec{u} = \frac{\mu|\vec{E}|}{(1+\omega^2\tau^2)} \left[\hat{E} + \omega\tau \left(\hat{E} \times \hat{B}\right) + \omega^2\tau^2 \left(\hat{E} \cdot \hat{B}\right) \hat{B} \right]$$

Langevin equation for the drift velocity vector with E and B fields

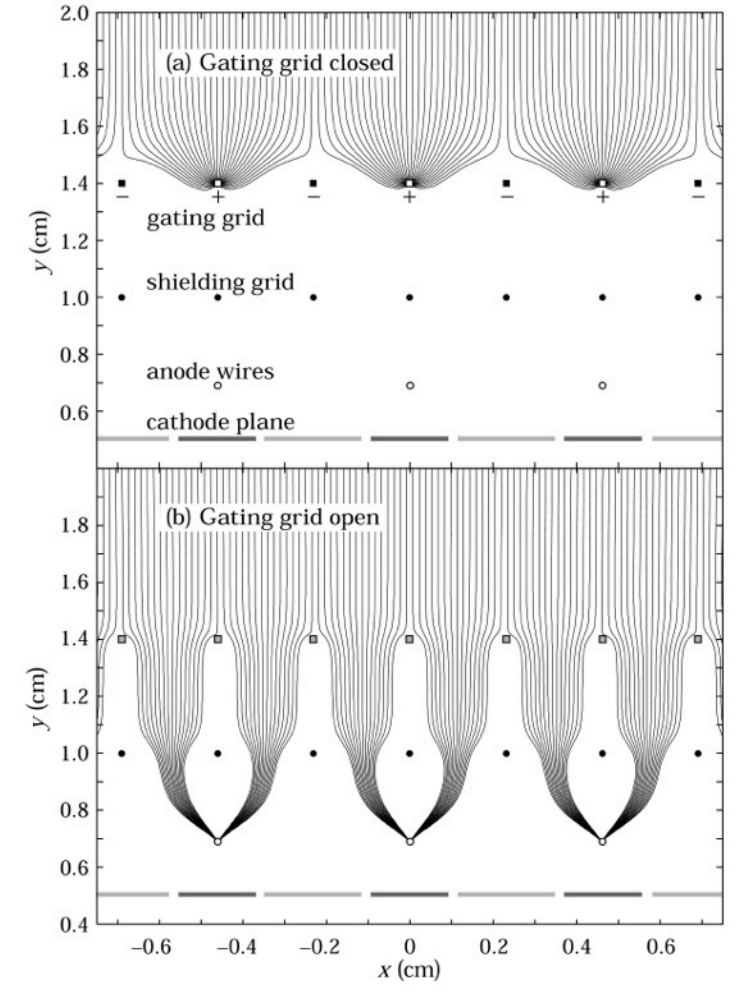
Why use a TPC?



- A TPC is the perfect detector for HI collisions ...
  - almost the whole volume is active
  - minimal radiation length (field cage, gas)
  - easy pattern recognition (continuos tracks)
  - PID information from ionization measurements
  - transverse spread of the drifting electron clouds due to diffusion may be minimized by choosing a gas mixture with $\omega\tau>1$ together with parallel B and E fields

Why use a TPC?

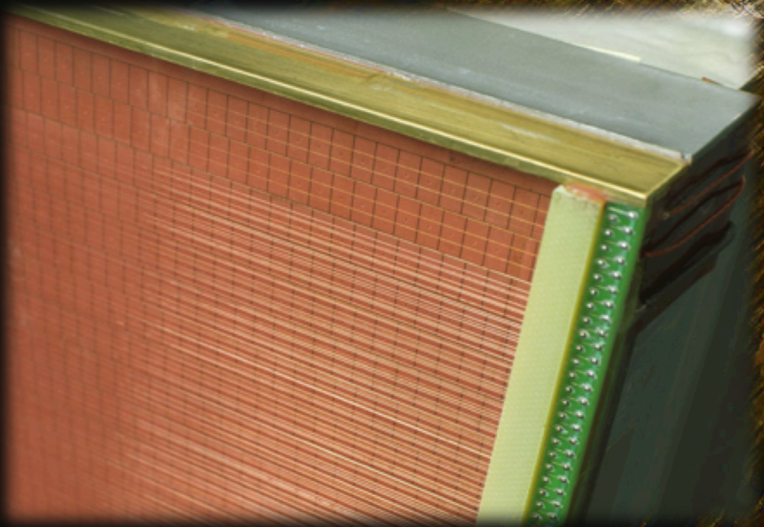
- A TPC is the perfect detector for HI collisions ...
  - almost the whole volume is active
  - minimal radiation length (field cage, gas)
  - easy pattern recognition (continuos tracks)
  - PID information from ionization measurements
  - transverse spread of the drifting electron clouds due to diffusion may be minimized by choosing a gas mixture with $\omega\tau>1$ together with parallel B and E fields
- ... but there are also limitations:
  - Gating needed to limit space charge in drift region ⇒ low trigger rates
  - Demanding calibration



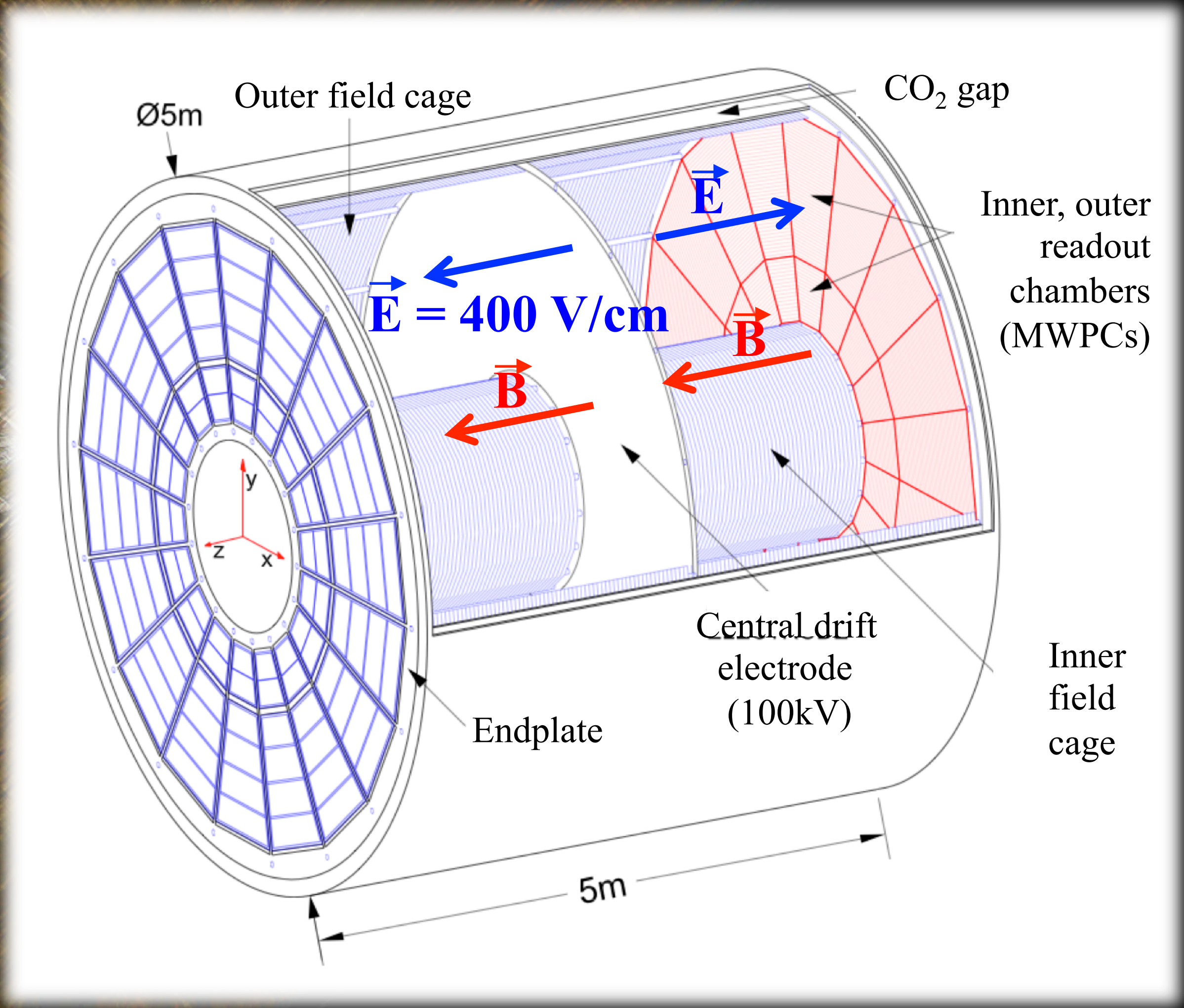
Principle of gating in TPCs

ALICE TPC field cage and MWPCs

- Gas volume ~92 m^3
- Material budget 3% X_0 around η=0
- 72 (=18×2×2) Readout chambers: MWPCs with cathode pad readout



Detail of one readout chamber

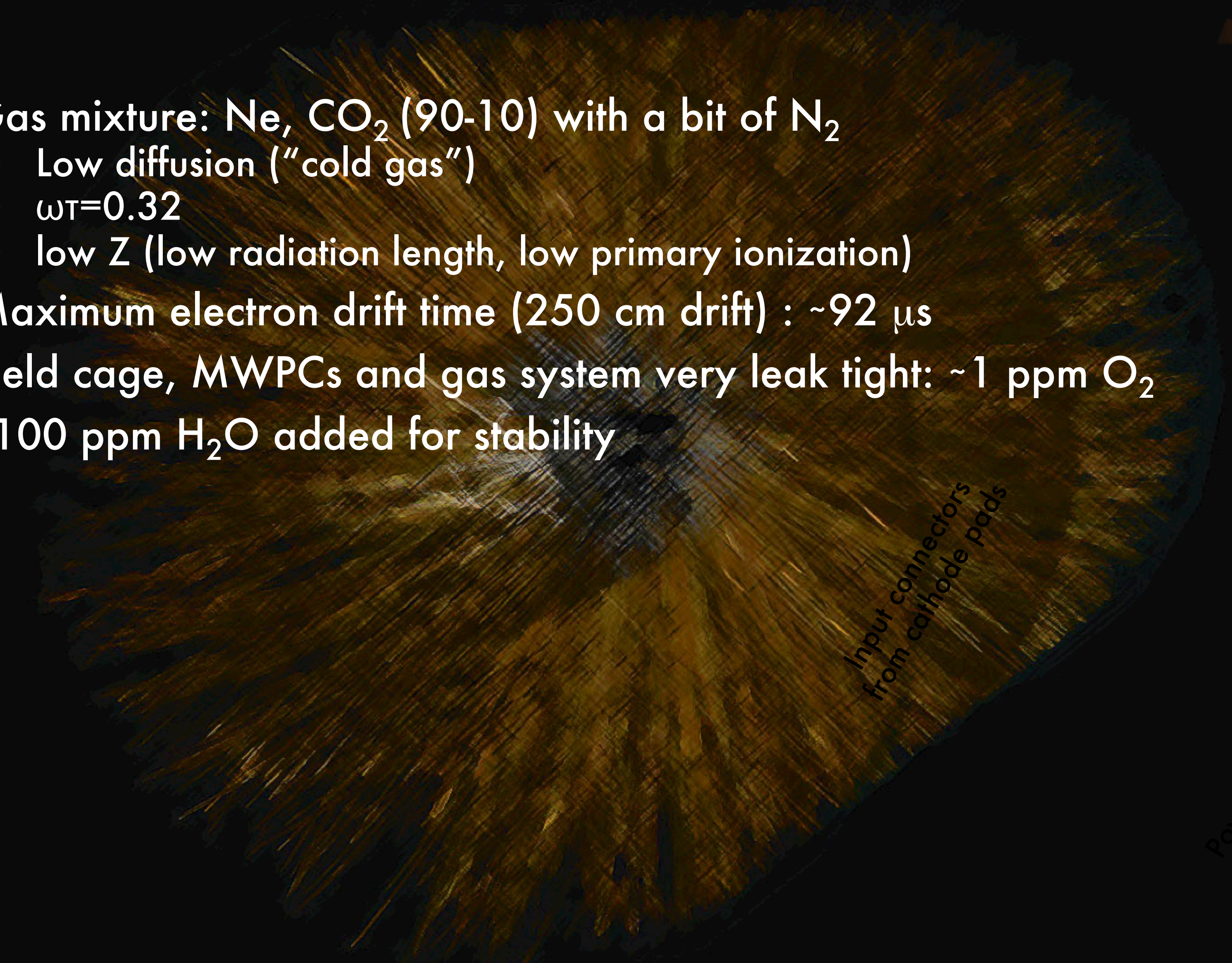


Low mass, high precision field cage

[Nucl.Instrum.Meth. A622 (2010) 316-367]

Gas and Front End Electronics (1)

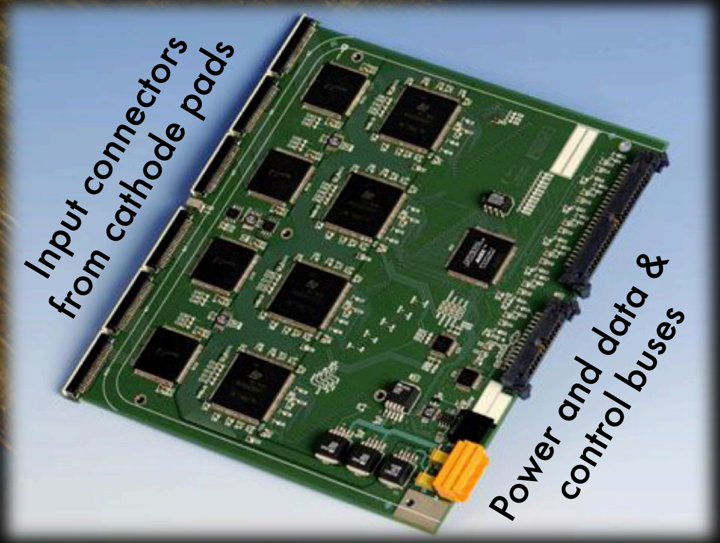
- Gas mixture: Ne, CO_2 (90-10) with a bit of N_2
  - Low diffusion ("cold gas")
  - $\omega\tau=0.32$
  - low Z (low radiation length, low primary ionization)
- Maximum electron drift time (250 cm drift) : ~92 μs
- Field cage, MWPCs and gas system very leak tight: ~1 ppm O_2
- ~100 ppm H_2O added for stability



[Nucl.Instrum.Meth. A622 (2010) 316-367]

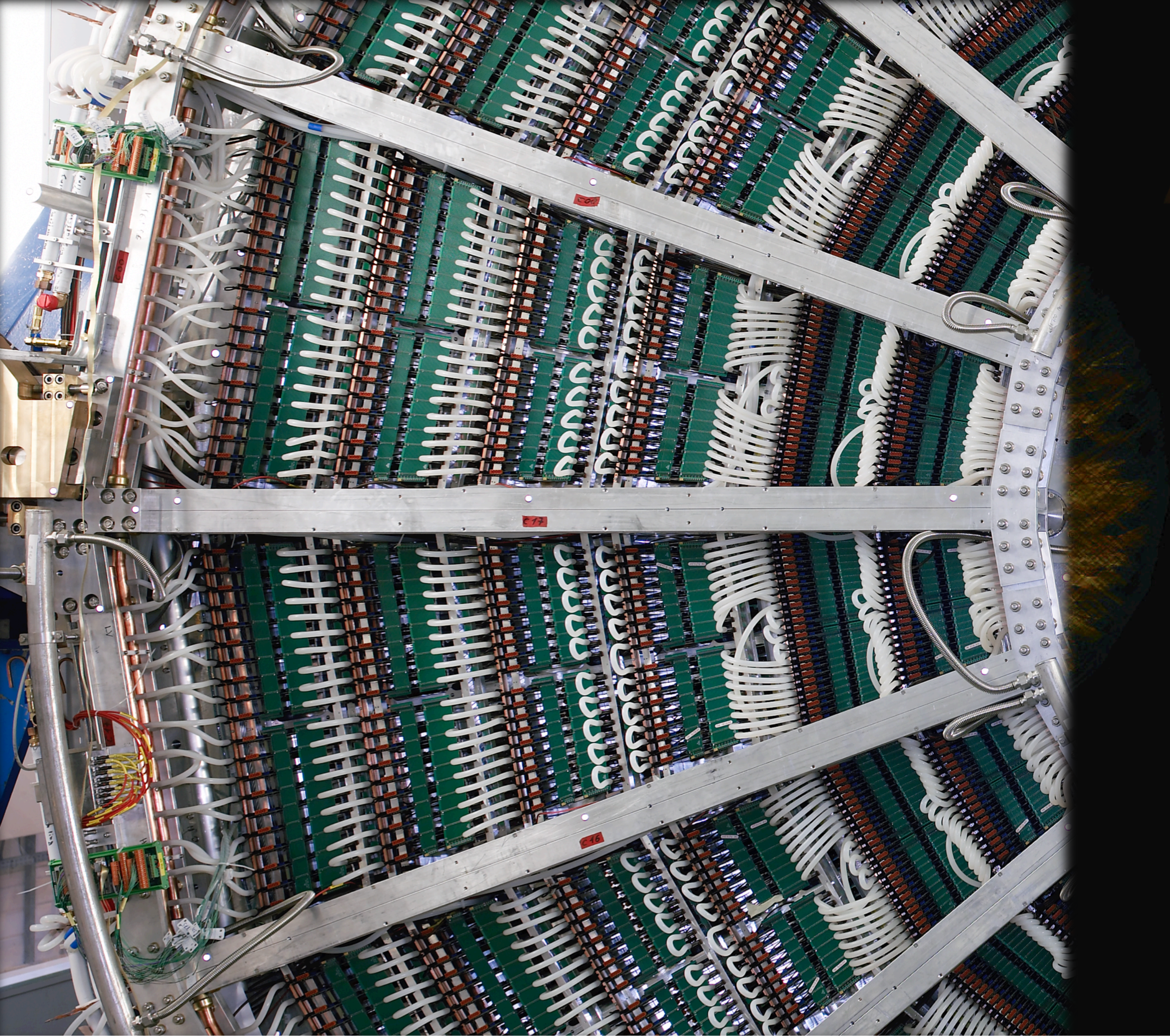
Gas and Front End Electronics (2)

- Gas mixture: Ne, CO_2 (90-10) with a bit of N_2
  - Low diffusion (“cold gas”)
  - $\omega\tau$=0.32
  - low Z (low radiation length, low primary ionization)
- Maximum electron drift time (250 cm drift) : ~92 μs
- Field cage, MWPCs and gas system very leak tight: ~1 ppm O_2
- ~100 ppm H_2O added for stability
- 557 568 read out pads and FEE channels
- 1000 time bins ⇒ 557 million voxels
- PreAmplifier ShAper (PASA)
  - 12 mV/fC, 190 ns FWHM
- ALTRO digital chip
- 0.7 ADC mean noise (700 e^-) on detector (Requirement: 1000 e^-)

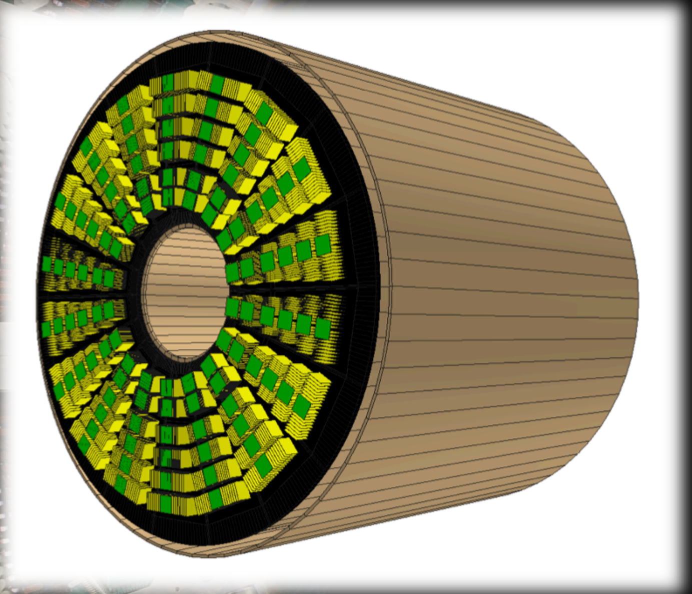


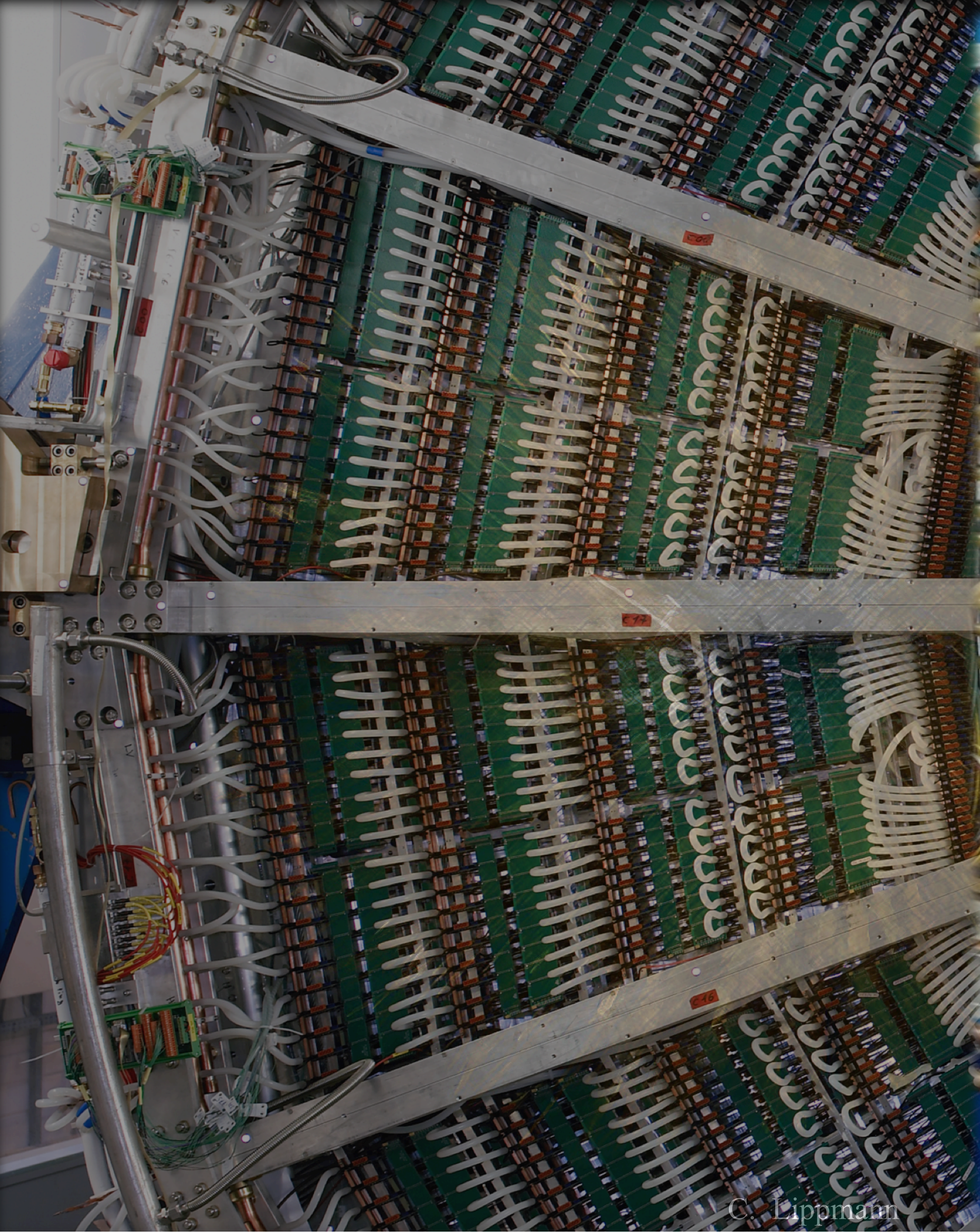
A TPC Front End Card holds 8 PASA and 8 ALTRO chips (4 each on each side)

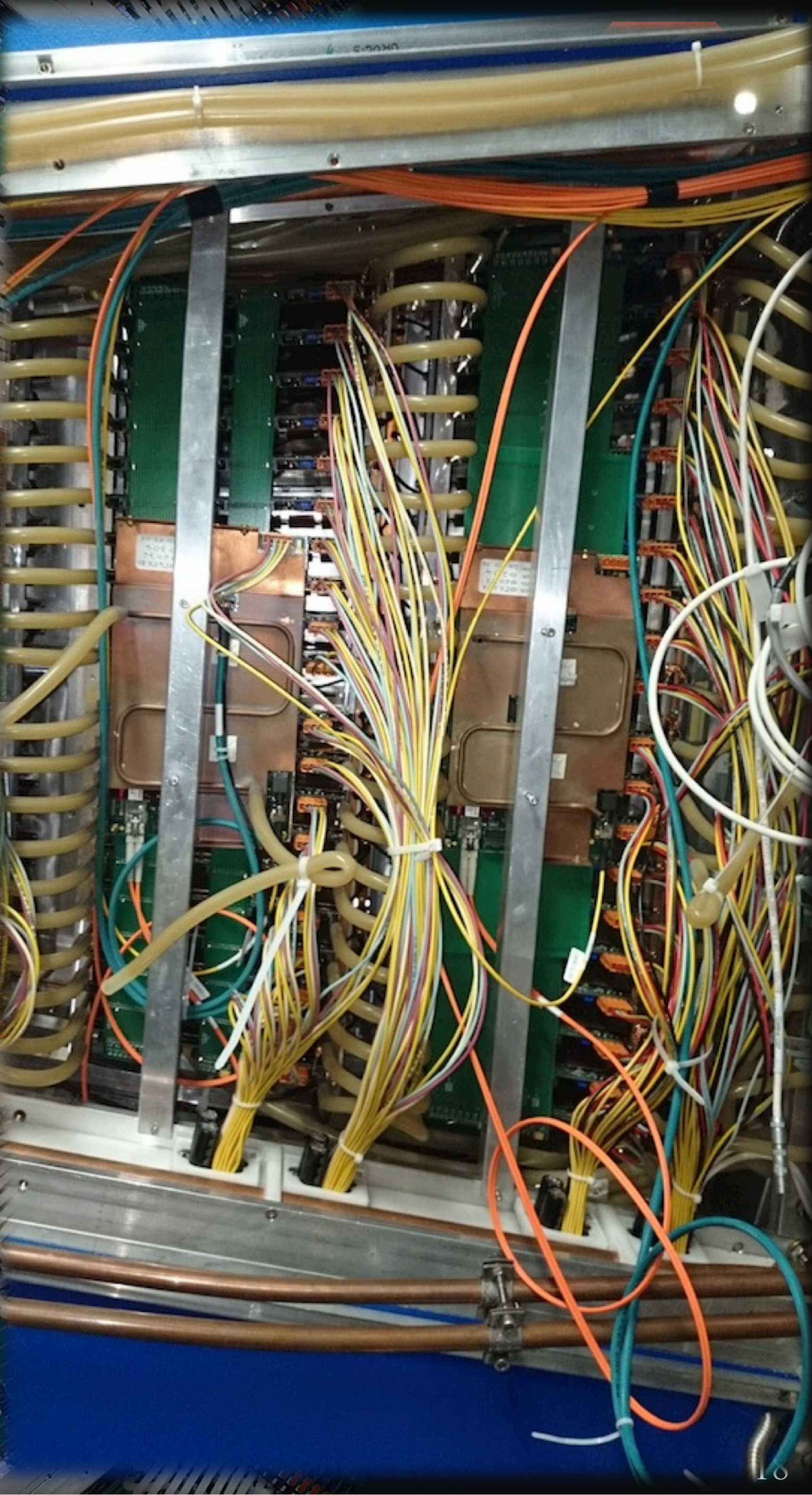
[Nucl.Instrum.Meth. A622 (2010) 316-367]



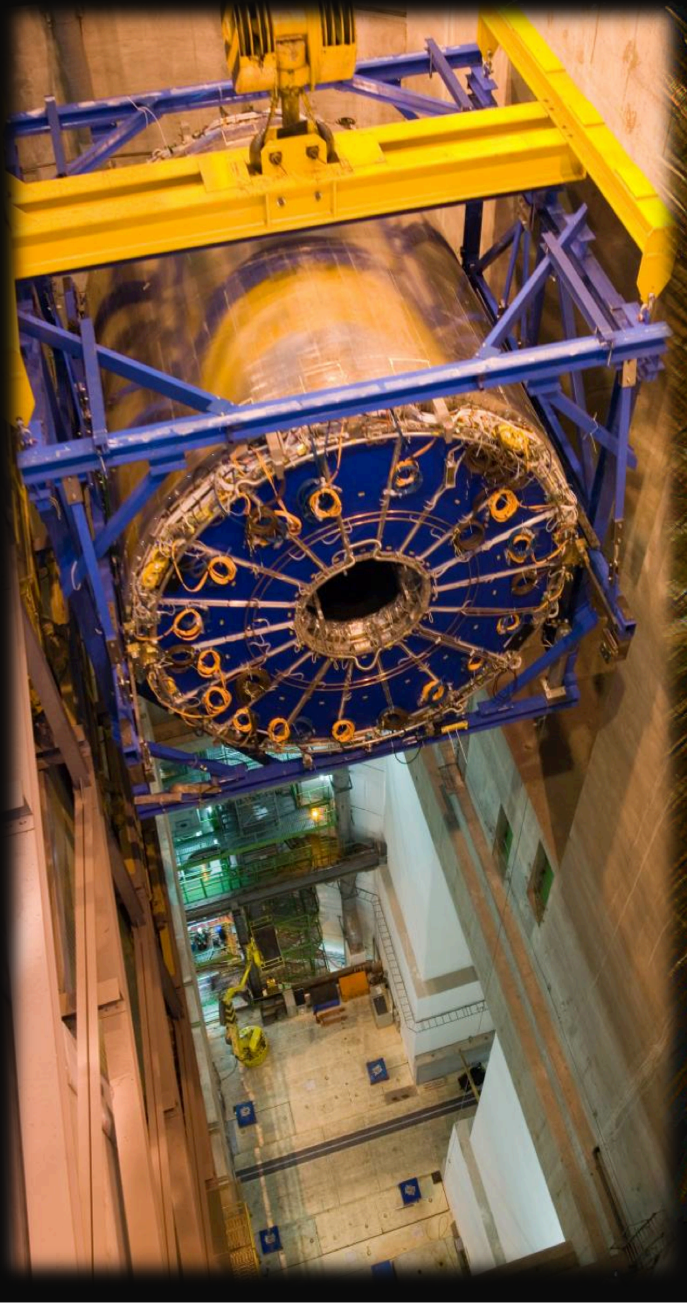
ALICE

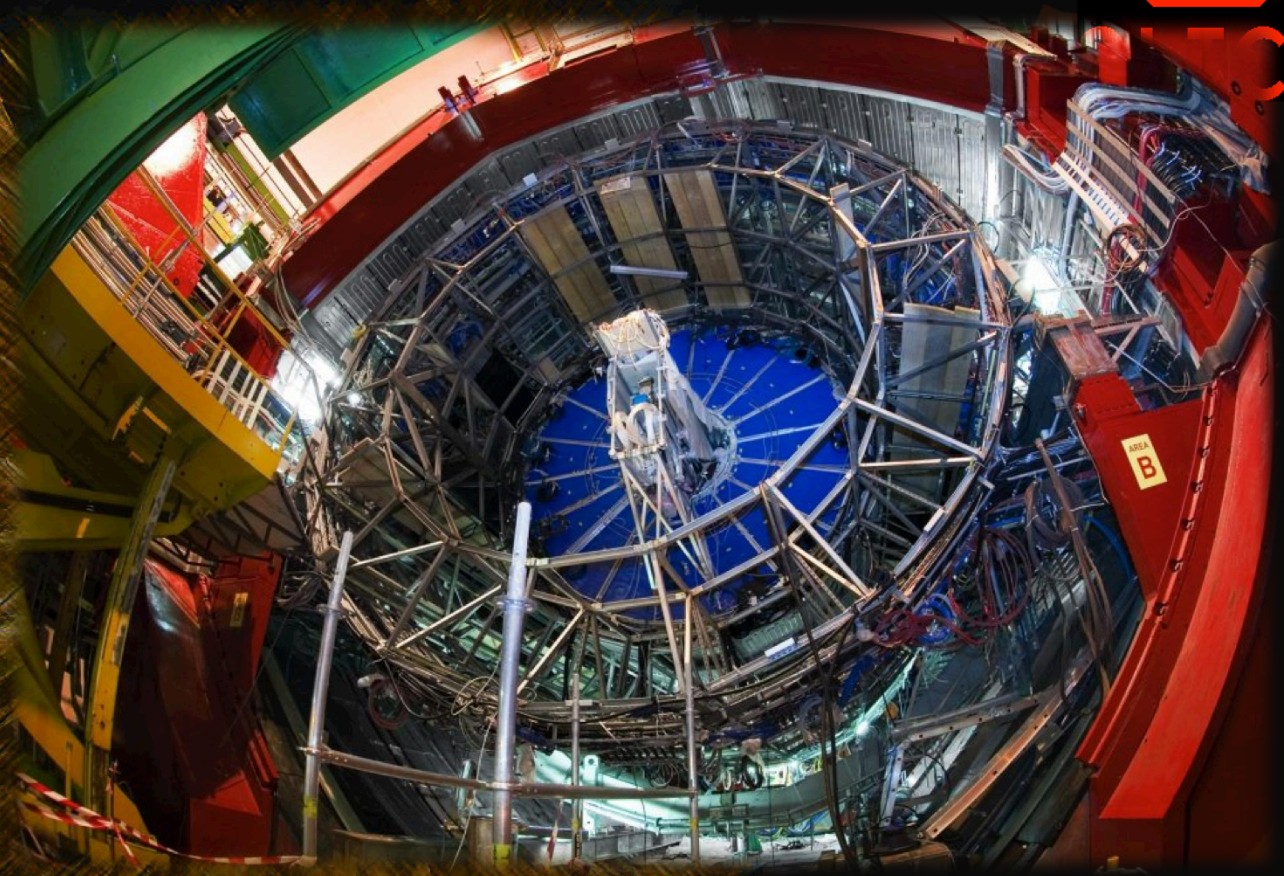



C00
C17
C16

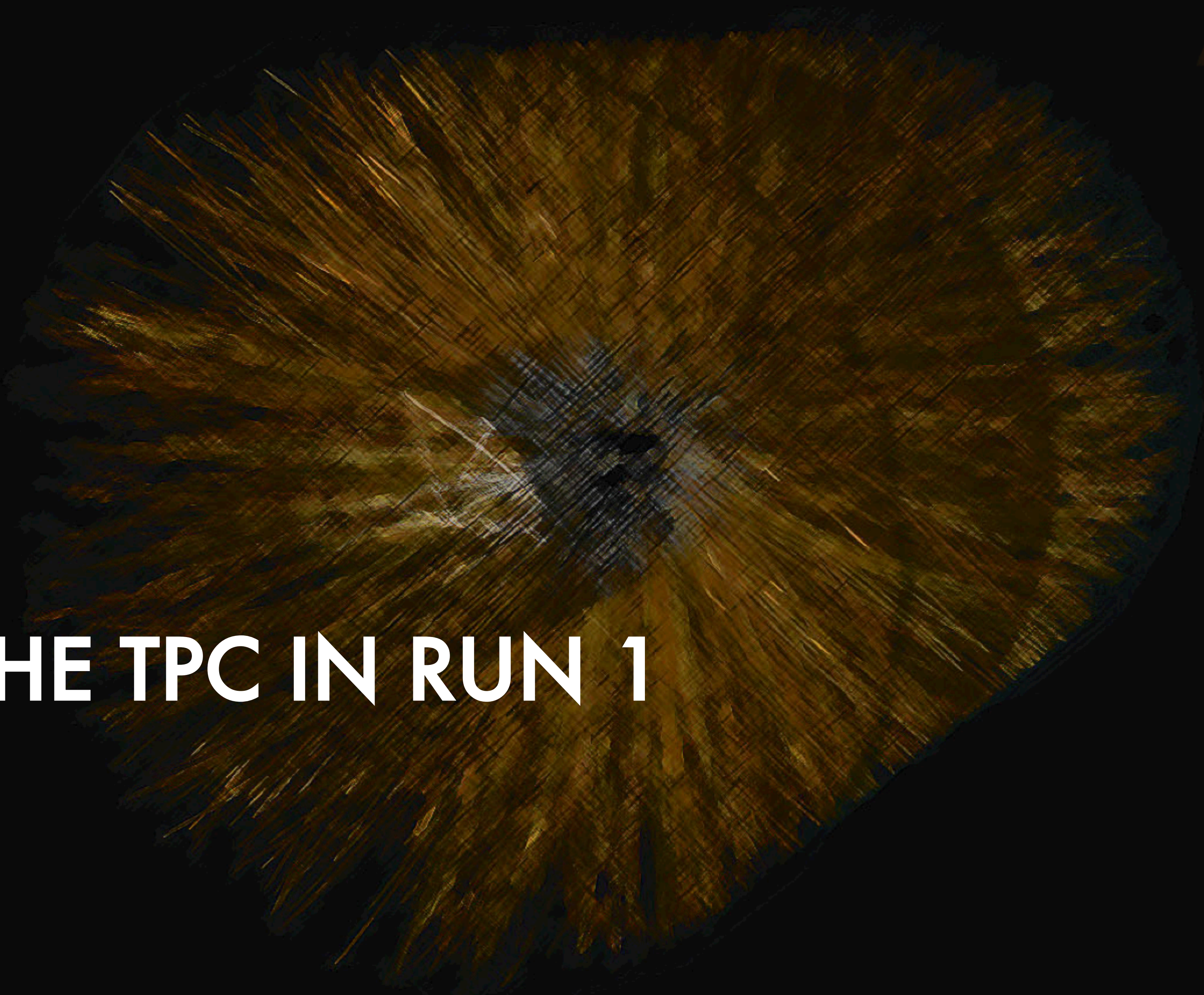


The past and the present





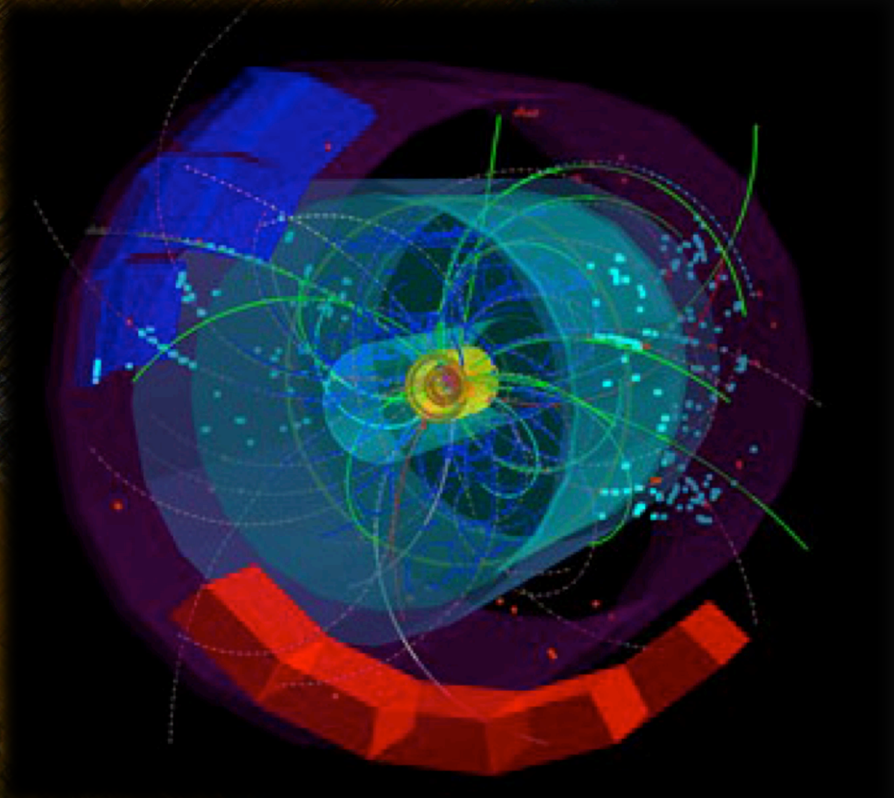
- Field Cage assembly: 2002 – 2004
- MWPC installation: 2005
- Electronics installation: 2006
- Installation into ALICE L3 magnet: 2007
- Commissioning & calibration: 2007 – 2009
- Data taking (Run 1): 2009 – 2013
- Consolidation during LHC Long Shutdown 1 (LS1)



THE TPC IN RUN 1

Luminosities and readout rates (1)

- pp interaction rates in ALICE:
  - ~10 kHz for large cross section observables, almost no event pile up in TPC
  - ≤200 kHz for rare processes, acceptable event pile up
  - ≤400 kHz with high beam background in 2012

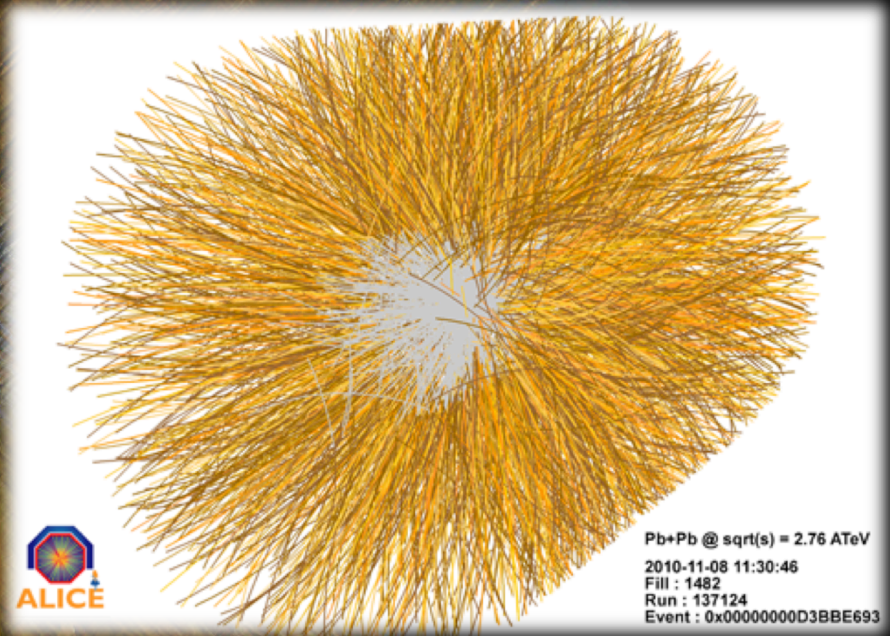


A pp collision at 7 TeV: reconstructed tracks in TPC, ITS and other subdetectors

- Maximum TPC readout rates:
  - 1 kHz for pp

Luminosities and readout rates (2)

- pp interaction rates in ALICE:
  - ~10 kHz for large cross section observables, almost no event pile up in TPC
  - ≤200 kHz for rare processes, acceptable event pile up
  - ≤400 kHz with high beam background in 2012 pp running
- Pb–Pb interaction rates:
  - ≤10 kHz Pb–Pb collisions
- Maximum TPC readout rates:
  - ~1 kHz for pp
  - 200 Hz for Pb–Pb (central)

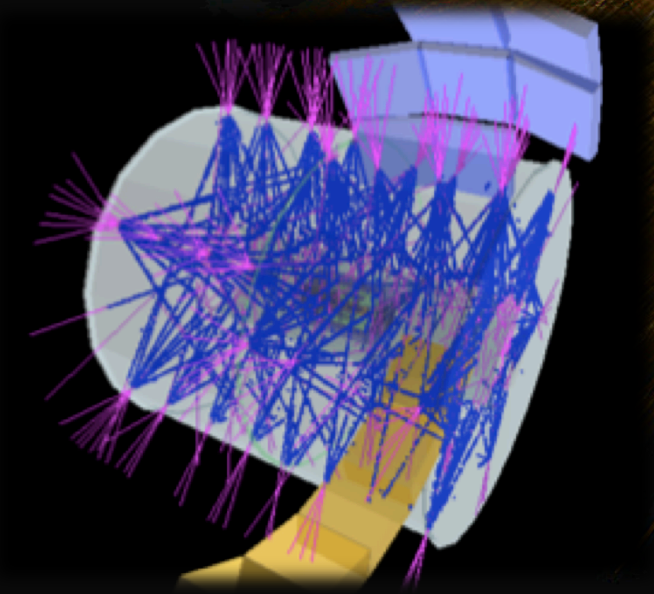


A central Pb–Pb collision at 2.76 ATeV: reconstructed tracks in the TPC

Calibration overview (1)

- The main TPC calibration procedures are
  1. laser data: drift velocity calibration and alignment

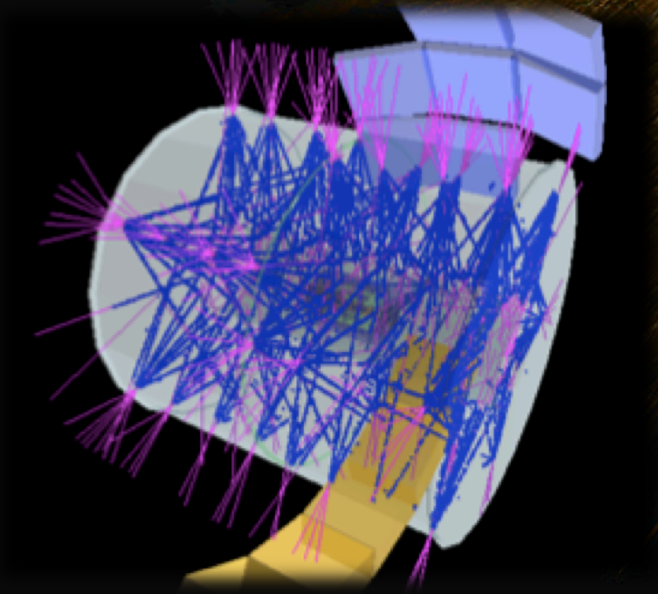
A reconstructed laser event in the TPC



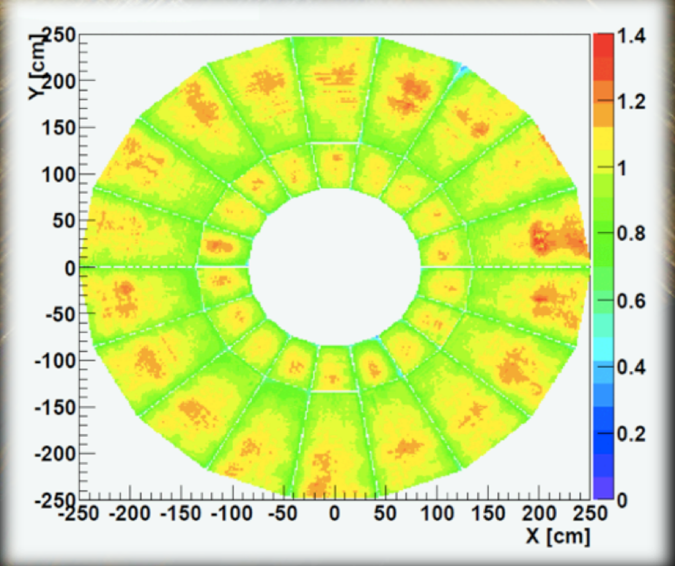
Calibration overview (2)

- The main TPC calibration procedures are
  1. laser data: drift velocity calibration and alignment
  2. gain calibration using short-lived radioactive gas (^{83}Kr)
     - produces characteristic electron spectrum in the right energy range
     - result: gain determination to within 1%

A reconstructed laser event in the TPC



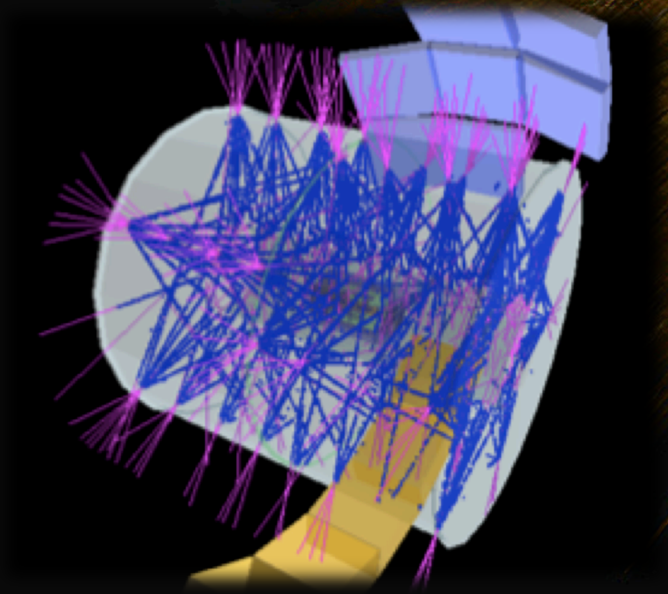
Pad-wise gain correction map from Kr calibration (C side shown)



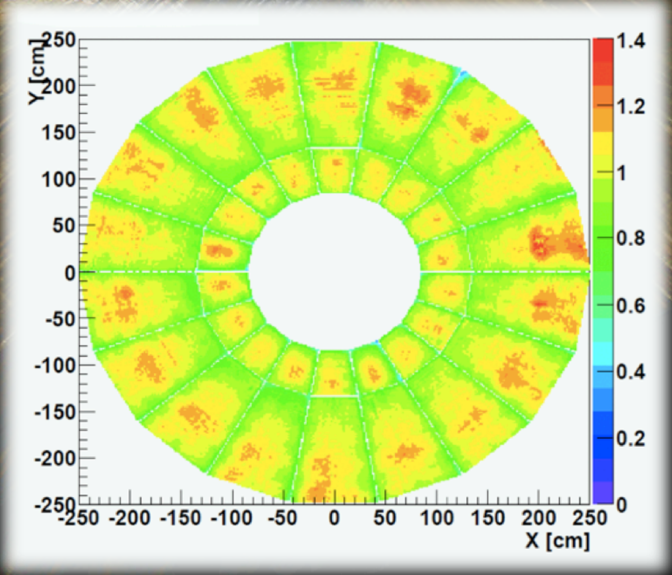
C. Lippmann

Calibration overview (3)

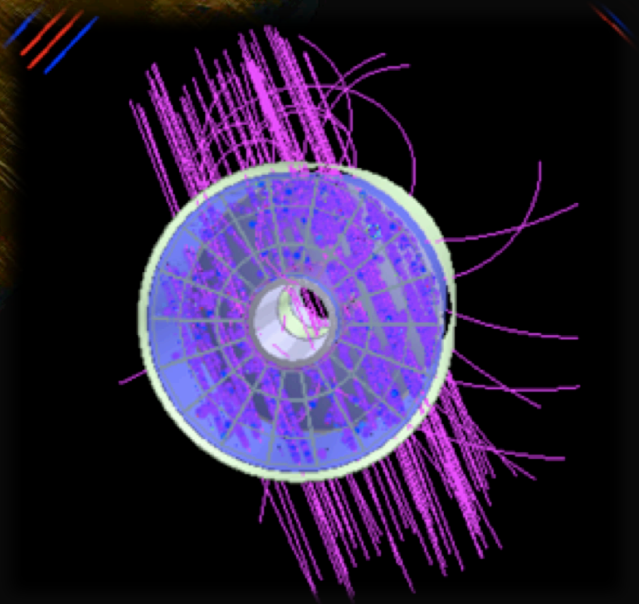
- The main TPC calibration procedures are
  1. laser data: drift velocity calibration and alignment
  2. gain calibration using short-lived radioactive gas (^{83}Kr)
     - produces characteristic electron spectrum in the right energy range
     - result: gain determination to within 1%
  3. cosmics and Physics (collisions) tracks: alignment and gain calibration



A reconstructed laser event in the TPC



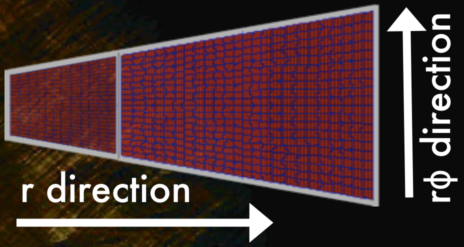
Pad-wise gain correction map from Kr calibration (C side shown)

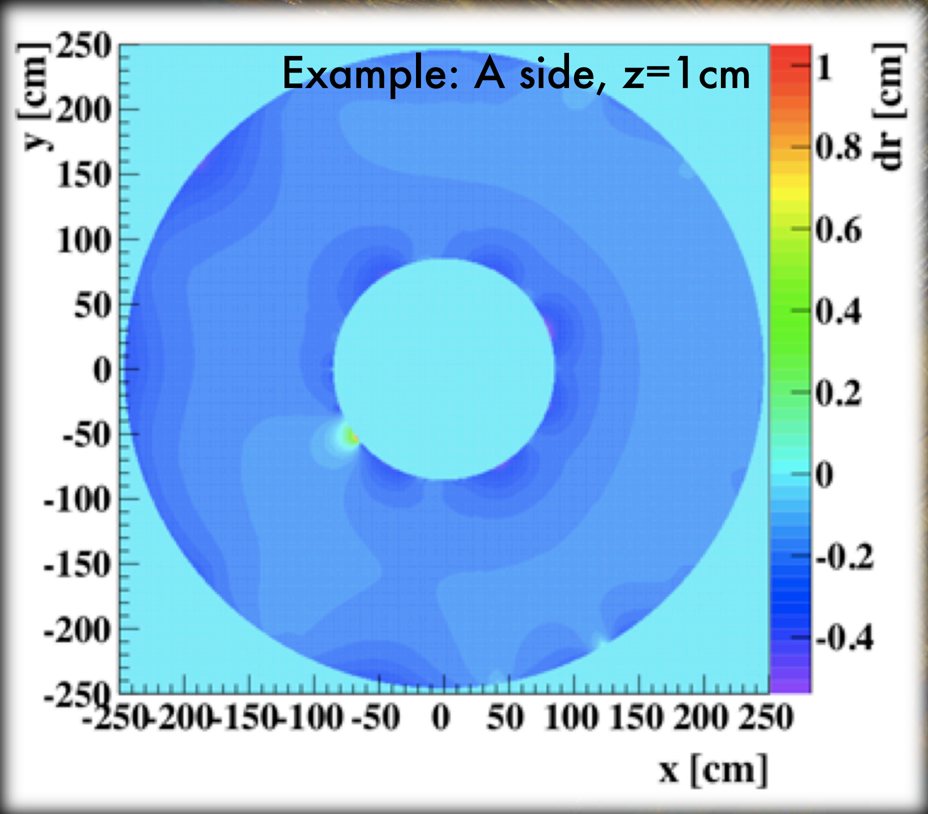


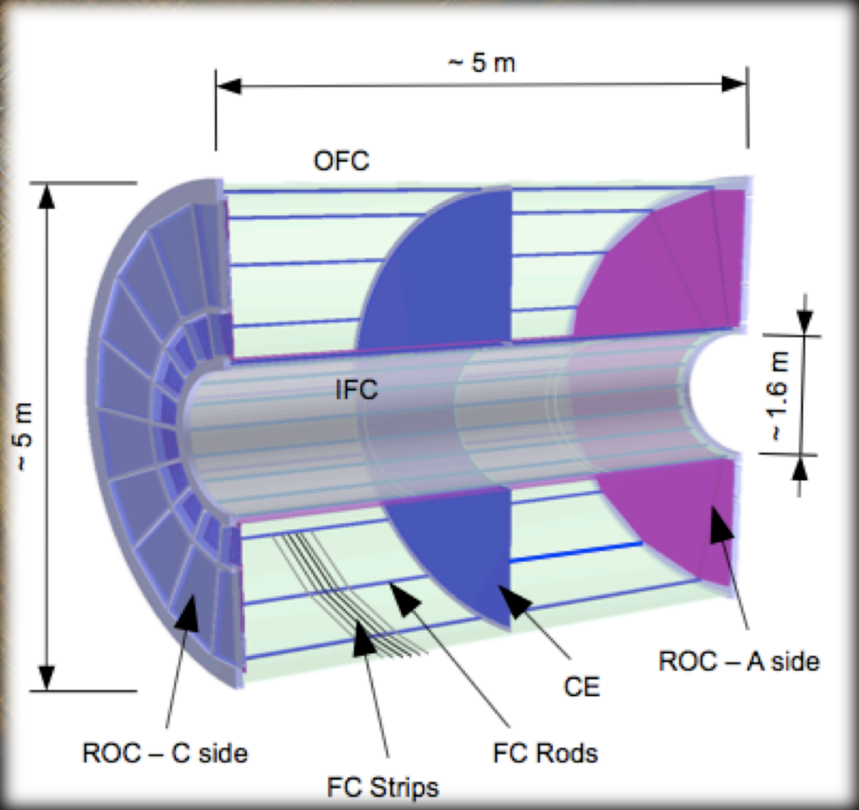
A cosmic muon shower, triggered by ACORDE

Example 1: Field cage imperfections

- Drifting electrons are deflected from ideal drift path
- Imperfections in the field cage
- Maximum (very local): δr = 10 mm (shown here); δrϕ = 0.8 mm

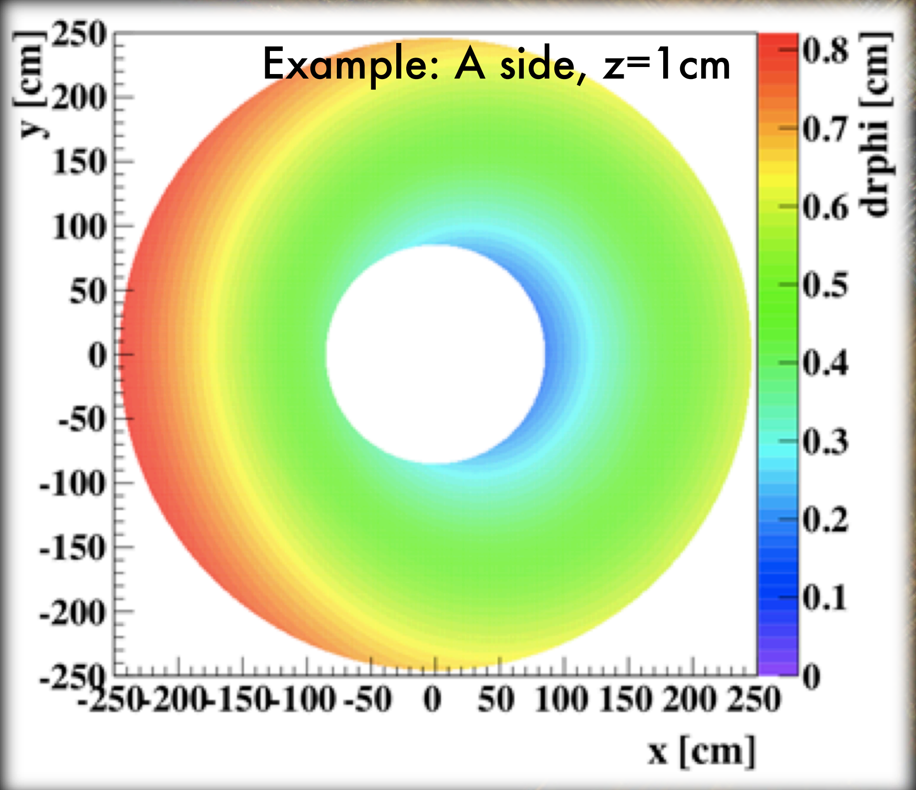


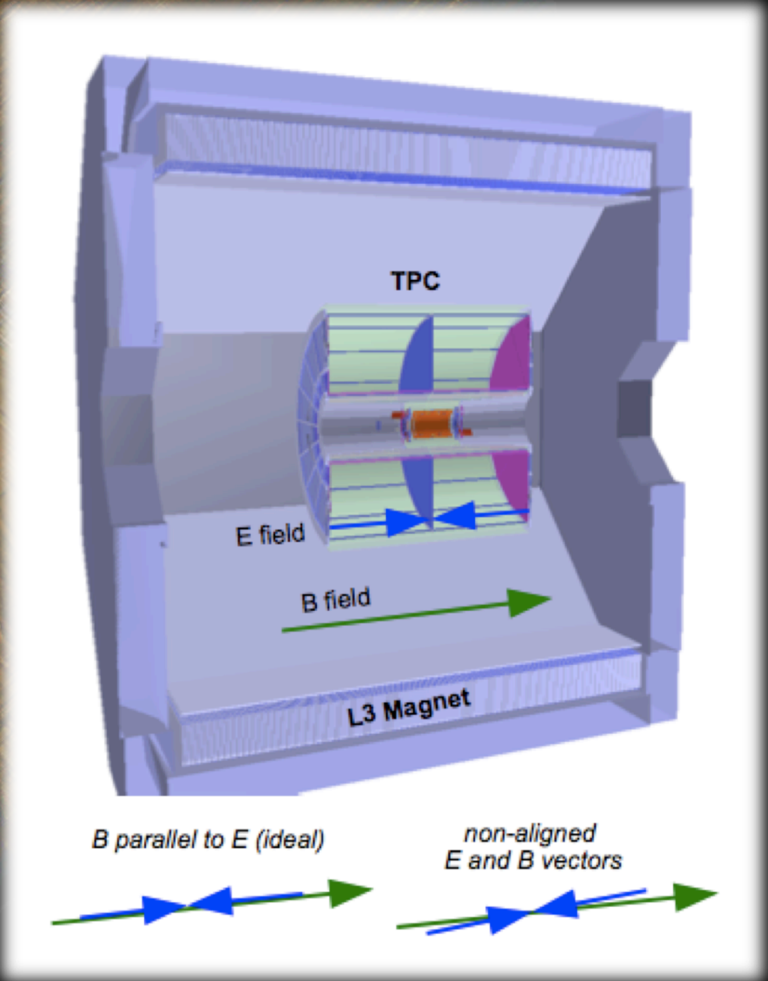

Example: A side, z=1cm



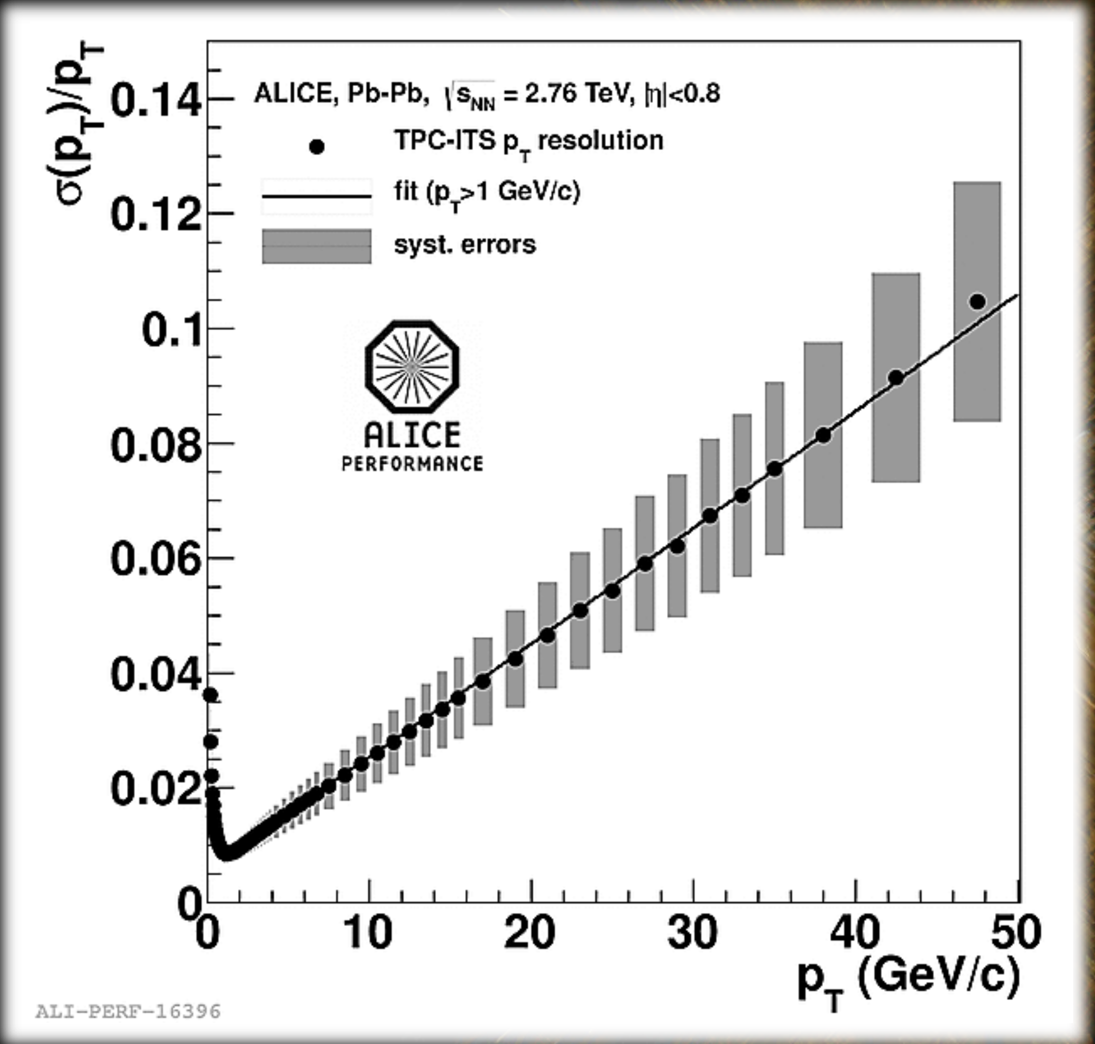
Example 2: Non–ideal B field

- Drifting electrons are deflected from ideal drift path
- B field shape (homogeneity) and alignment with E field
- Maximum: δr = 4 mm;
  δrϕ = 8 mm (shown here)





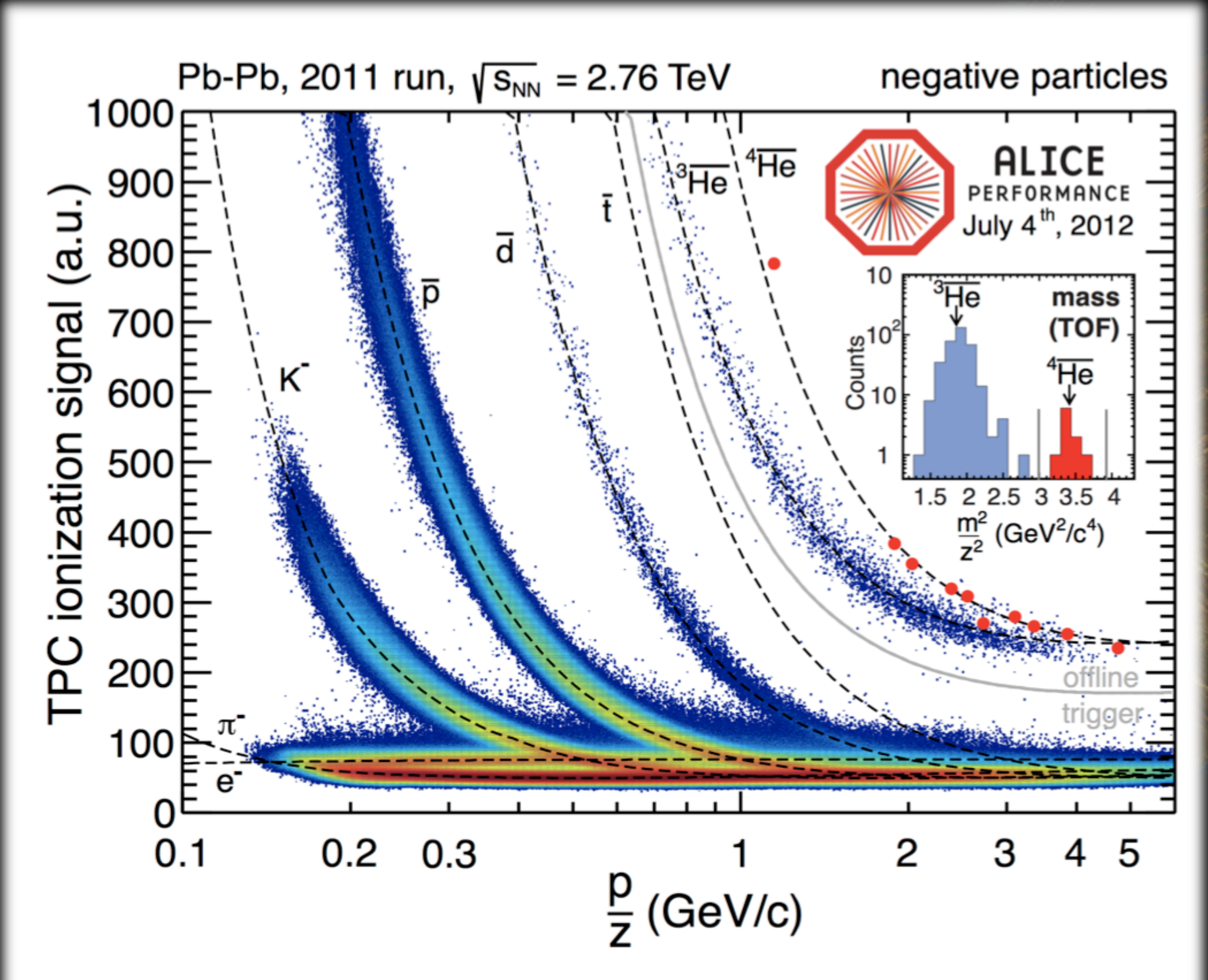
Transverse momentum resolution



Transverse momentum resolution with TPC and silicon Inner Tracking System (ITS). Status of the calibration which corresponds to the recent physics results.

- Expected: $\sigma(p_T)/p_T = 5\%$ [ALICE PPR II, 2006 J. Phys. G: Nucl. Part. Phys. 32 1295]
- Current official number: $\sigma(p_T)/p_T = 20\%$ at 100GeV/c
- For next round of pyhsics results: $\sigma(p_T)/p_T < 10\%$ at 100 GeV/c
- Ultimately, including also the TRD, the resolution can reach even 3% at 100 GeV/c
- Note: Performance epends not only on TPC

PID with the TPC

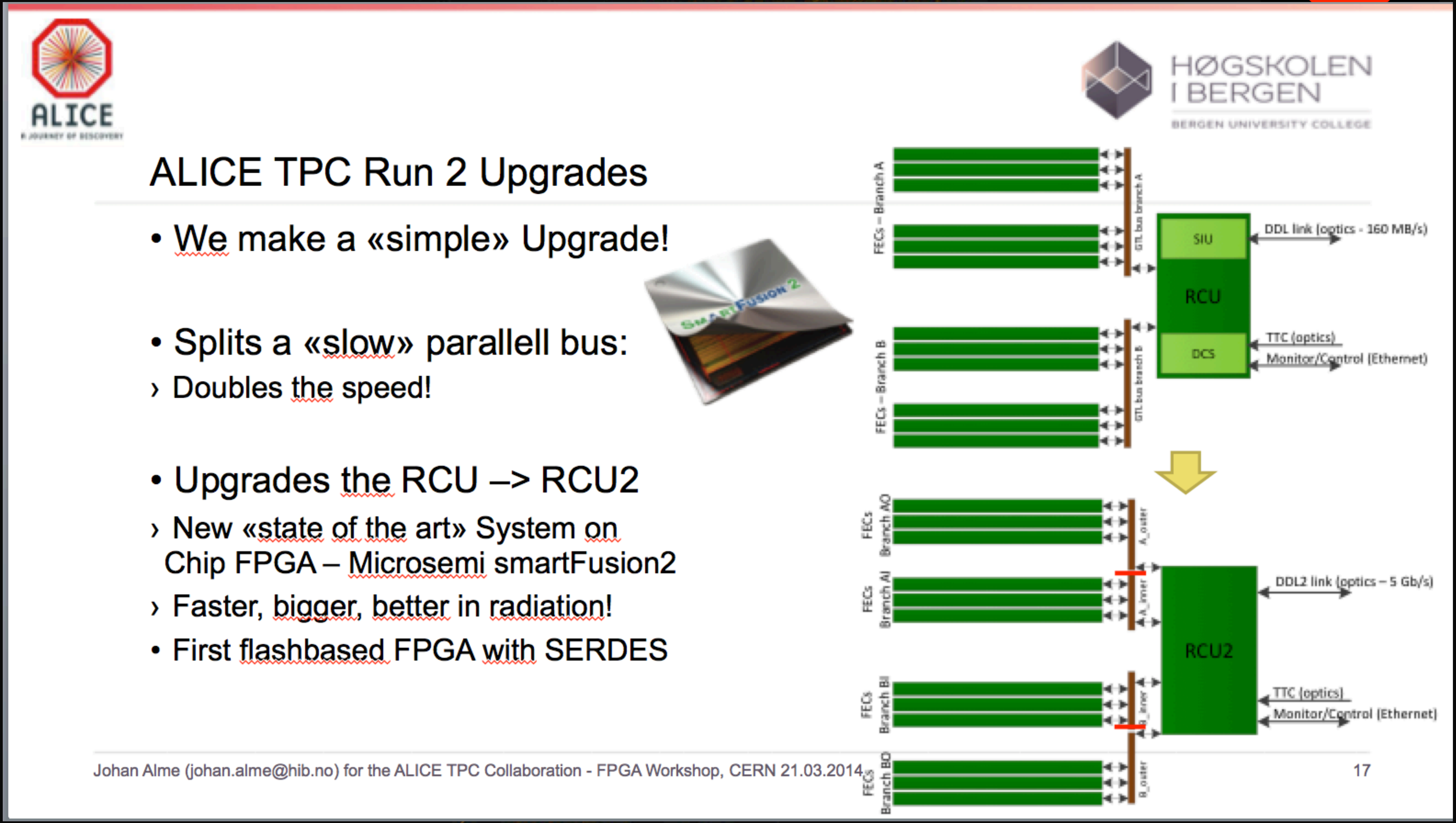


10 anti-alpha candidates from Pb-Pb collisions (PID using TPC and TOF)

- Measured Resolution with maximum number of samples: $\sigma_{dE/dx} \approx 5\%$
- Expected: 5.5% [ALICE PPR II, 2006 J. Phys. G: Nucl. Part. Phys. 32 1295]
- Resolution for the highest multiplicity HI events: $\sigma_{dE/dx} \approx 6\%$
- Expected: 7%

TPC UPGRADE FOR RUN 2

ALICE TPC Run 2 Upgrades



ALICE
A JOURNEY OF DISCOVERY

HØGSKOLEN
I BERGEN
BERGEN UNIVERSITY COLLEGE

ALICE TPC Run 2 Upgrades

- We make a «simple» Upgrade!
- Splits a «slow» parallell bus:
  - › Doubles the speed!
- Upgrades the RCU –> RCU2
  - › New «state of the art» System on Chip FPGA – Microsemi smartFusion2
  - › Faster, bigger, better in radiation!
- First flashbased FPGA with SERDES

Johan Alme (johan.alme@hib.no) for the ALICE TPC Collaboration - FPGA Workshop, CERN 21.03.2014

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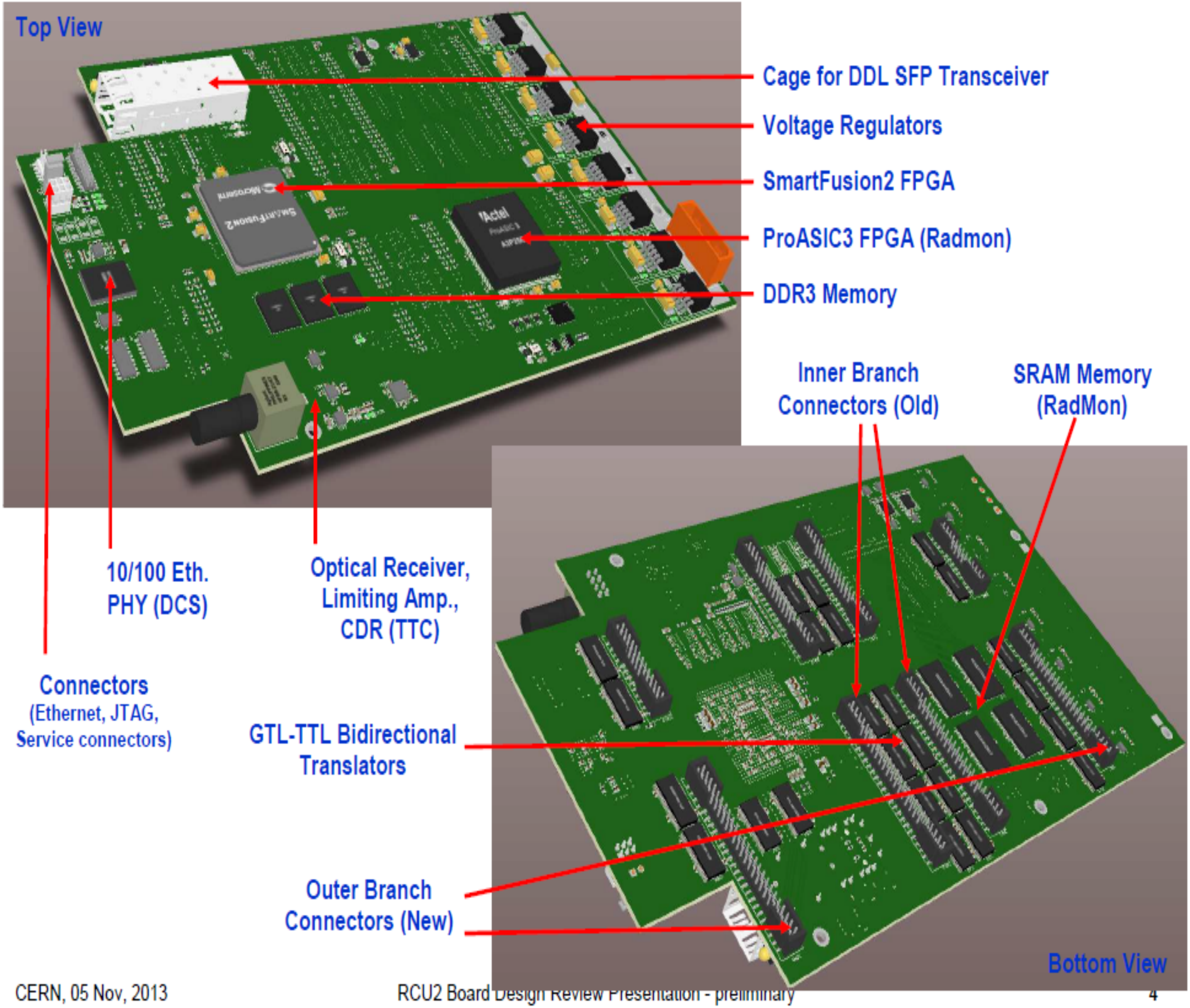


Top View

Cage for DDL SFP Transceiver

Voltage Regulators

SmartFusion2 FPGA

ProASIC3 FPGA (Radmon)

DDR3 Memory

Inner Branch Connectors (Old)

SRAM Memory (RadMon)

10/100 Eth. PHY (DCS)

Optical Receiver, Limiting Amp., CDR (TTC)

Connectors (Ethernet, JTAG, Service connectors)

GTL-TTL Bidirectional Translators

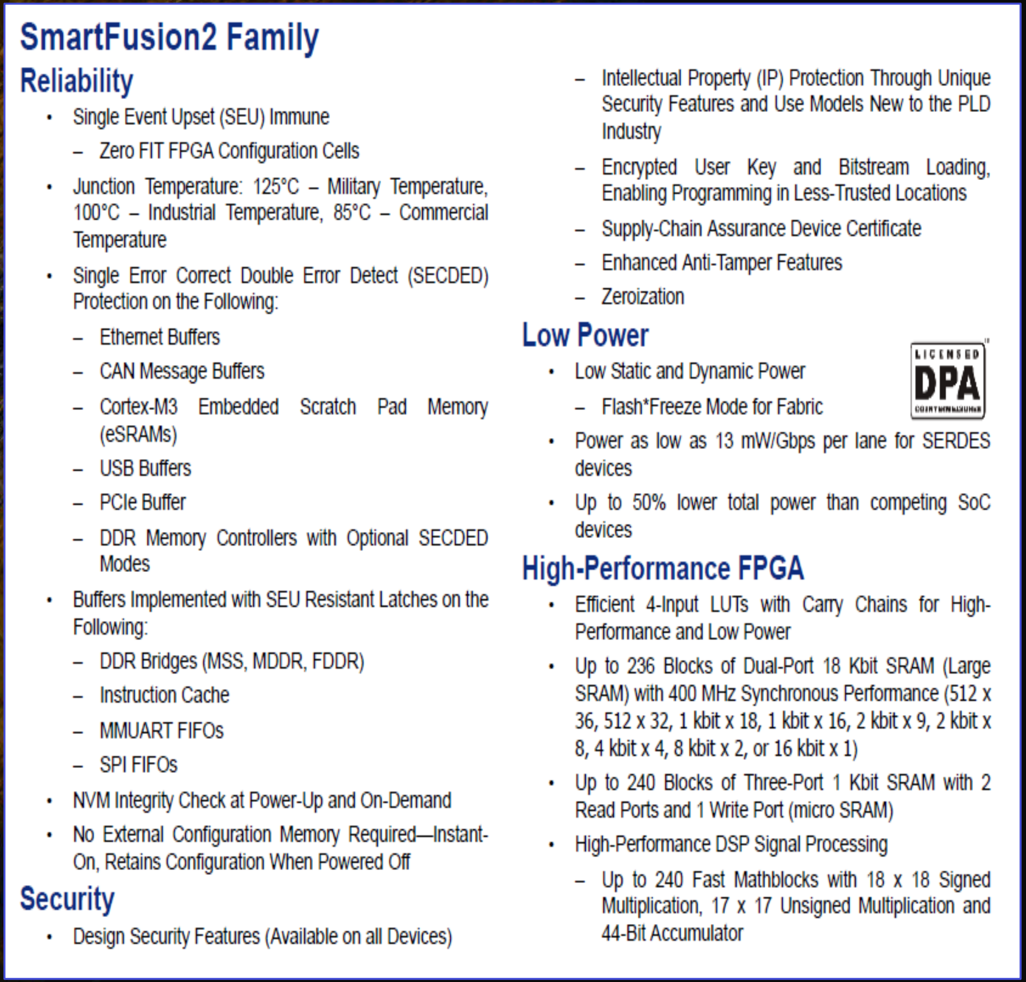
Outer Branch Connectors (New)

Bottom View

Microsemi smartFusion2 – The Perfect Choice?

- The Microsemi smartFusion2 is a brand new device.
  - › Only enginering sampled released when we started to use it.

- A few surprises were encountered with this new device.
  - › Especially given our positive experience with Actel/Microsemi devices



SmartFusion2 Family

Reliability

- Single Event Upset (SEU) Immune
  - Zero FIT FPGA Configuration Cells
- Junction Temperature: 125°C – Military Temperature, 100°C – Industrial Temperature, 85°C – Commercial Temperature
- Single Error Correct Double Error Detect (SECDED) Protection on the Following:
  - Ethernet Buffers
  - CAN Message Buffers
  - Cortex-M3 Embedded Scratch Pad Memory (eSRAMs)
  - USB Buffers
  - PCIe Buffer
  - DDR Memory Controllers with Optional SECDED Modes
- Buffers Implemented with SEU Resistant Latches on the Following:
  - DDR Bridges (MSS, MDDR, FDDR)
  - Instruction Cache
  - MMUART FIFOs
  - SPI FIFOs
- NVM Integrity Check at Power-Up and On-Demand
- No External Configuration Memory Required—Instant-On, Retains Configuration When Powered Off

Security

- Design Security Features (Available on all Devices)
  - Intellectual Property (IP) Protection Through Unique Security Features and Use Models New to the PLD Industry
  - Encrypted User Key and Bitstream Loading, Enabling Programming in Less-Trusted Locations
  - Supply-Chain Assurance Device Certificate
  - Enhanced Anti-Tamper Features
  - Zeroization

Low Power

LICENSED DPA

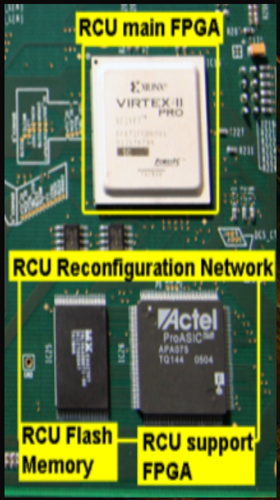
- Low Static and Dynamic Power
  - Flash*Freeze Mode for Fabric
- Power as low as 13 mW/Gbps per lane for SERDES devices
- Up to 50% lower total power than competing SoC devices

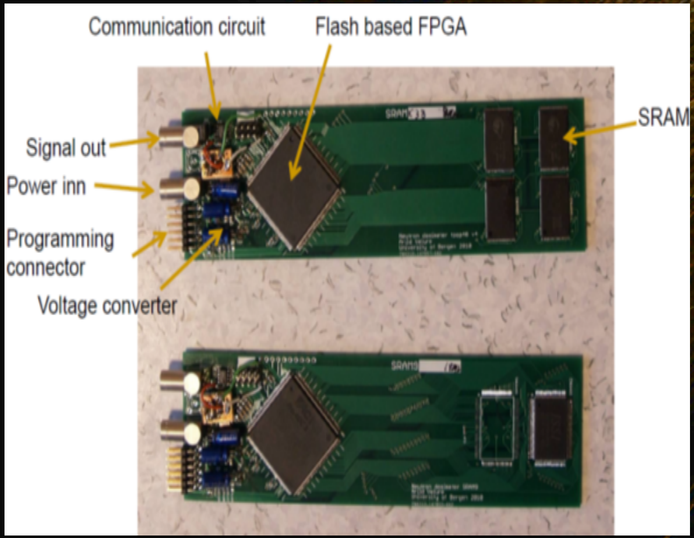
High-Performance FPGA

- Efficient 4-Input LUTs with Carry Chains for High-Performance and Low Power
- Up to 236 Blocks of Dual-Port 18 Kbit SRAM (Large SRAM) with 400 MHz Synchronous Performance (512 x 36, 512 x 32, 1 kbit x 18, 1 kbit x 16, 2 kbit x 9, 2 kbit x 8, 4 kbit x 4, 8 kbit x 2, or 16 kbit x 1)
- Up to 240 Blocks of Three-Port 1 Kbit SRAM with 2 Read Ports and 1 Write Port (micro SRAM)
- High-Performance DSP Signal Processing
  - Up to 240 Fast Mathblocks with 18 x 18 Signed Multiplication, 17 x 17 Unsigned Multiplication and 44-Bit Accumulator

Monitoring of Radiation Levels

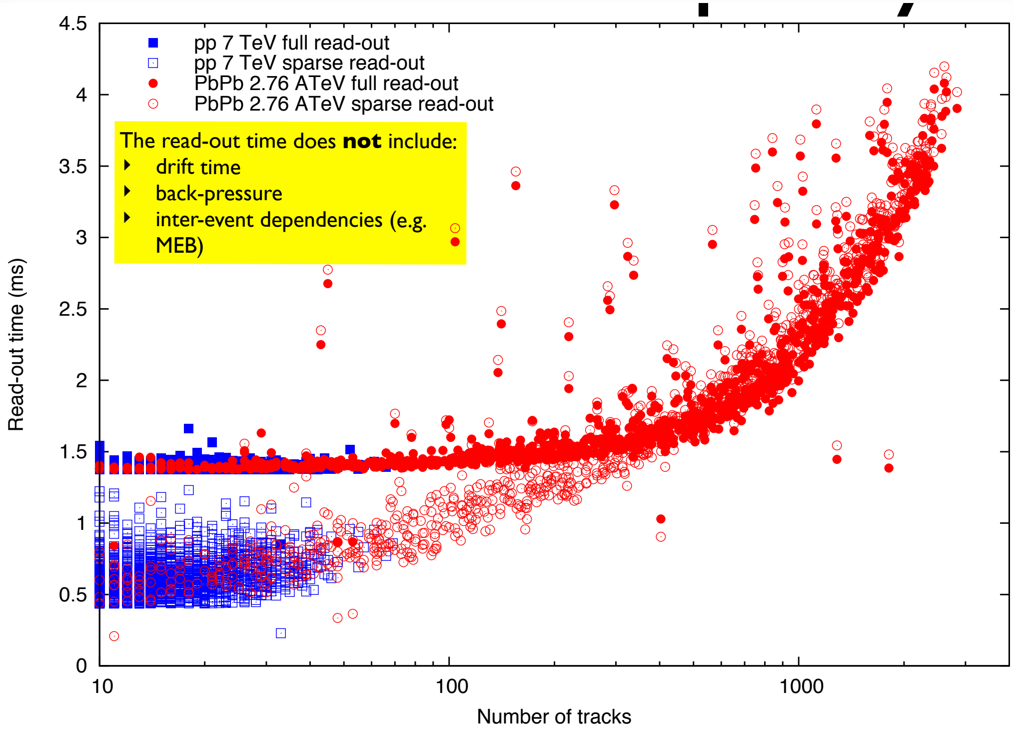
- On the present RCU we have the Reconfiguration Network acting as a radiation monitor
- This is an interesting feature to keep for the RCU2:
  - Additional SRAM memory and Microsemi proASIC3 250 added to the RCU2
    - Not enough user-IOs on the smartFusion2 for this feature
  - Low risk – design already done and proven*
  - Cypress SRAM – same as used for the latest LHC RadMon devices
    - Extensively characterized in various beams (n,p,mixed) and compared/benchmarked to FLUKA MC simulations by the CERN EN/STI group





Arild Velure "Design, implementation and testing of SRAM based neutron detectors", Master Thesis 2011

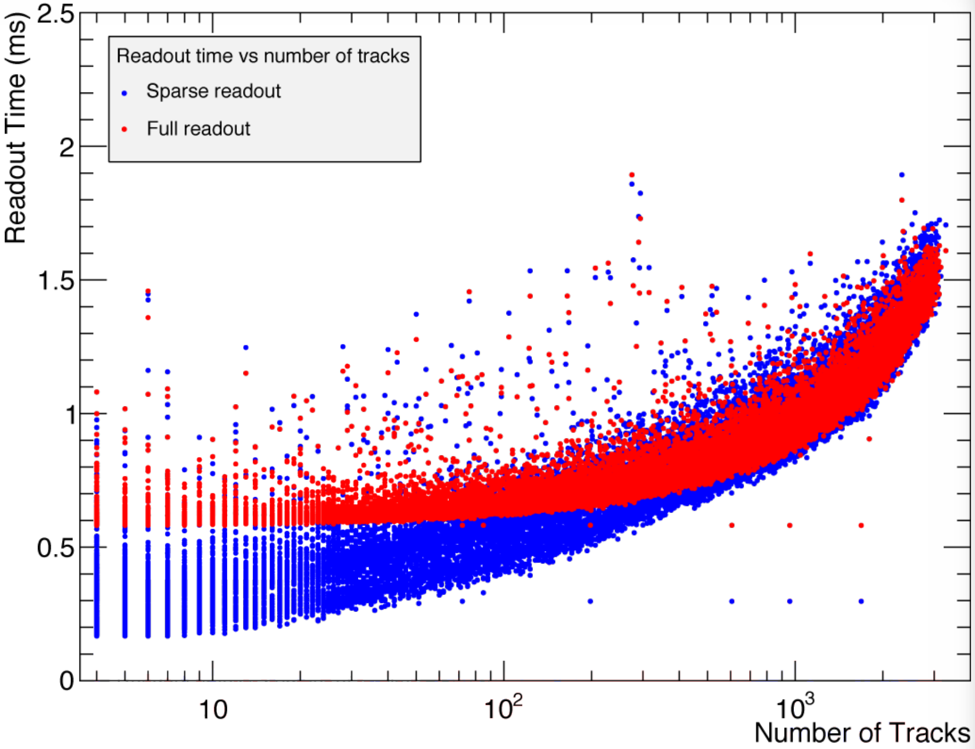
Performance simulation



The read-out time does **not** include:

- drift time
- back-pressure
- inter-event dependencies (e.g. MEB)

Measurement (2010)



Simulation for RCU2 and DDL2

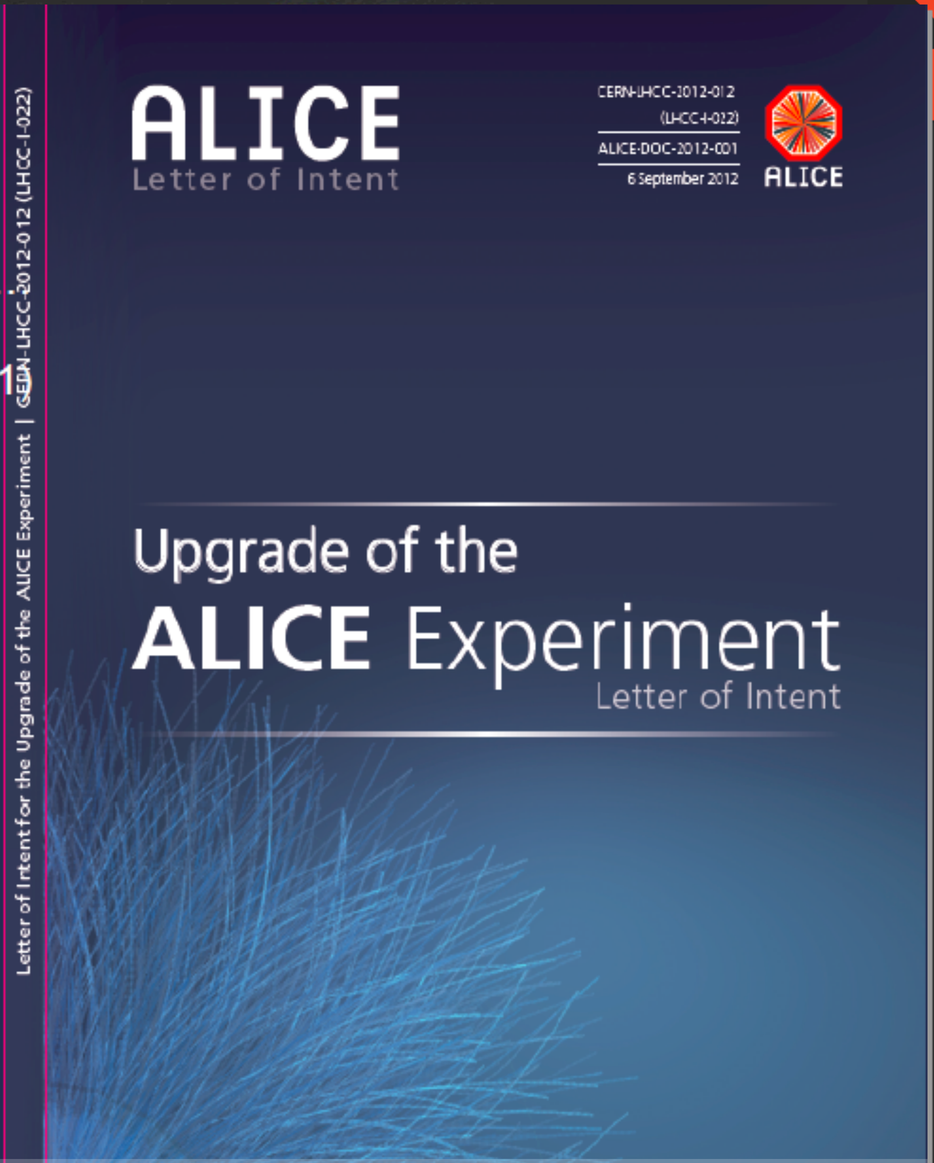
TPC UPGRADE FOR RUN 3

The future

- 2013: **pPb and Pbp**
  initial state effects, shadowing…
- 2013-14: LHC Long Shutdown 1 (LS1)
- 2015-17: **FULL ENERGY !!**
  pp @ 7 TeV,
  PbPb @ √sNN = 5.5 TeV
- 2018: LHC Long Shutdown 2
- ≥ 2019: **HIGH LUMINOSITY**
  50 kHz PbPb collisions

ALICE UPGRADES

- New vertex detectors
- Faster readout, high level triggers…
- TPC with continuous readout …



Letter of Intent for the Upgrade of the ALICE Experiment | CERN-LHCC-2012-012 (LHCC-I-022)

ALICE
Letter of Intent

CERN-LHCC-2012-012
(LHCC-I-022)
ALICE-DOC-2012-001
6 September 2012

ALICE

Upgrade of the
ALICE Experiment
Letter of Intent

ALICE upgrade Letter of Intent: Endorsed by LHCC

ALICE Upgrade Strategy for Runs 3 + 4

2013 **Long Shutdown I:**
Detector completion (ALICE)
and upgrades (ATLAS)

2018 **Long Shutdown II:**
Significant detector upgrades
ALICE, ATLAS, CMS, LHCb

LHC Schedule

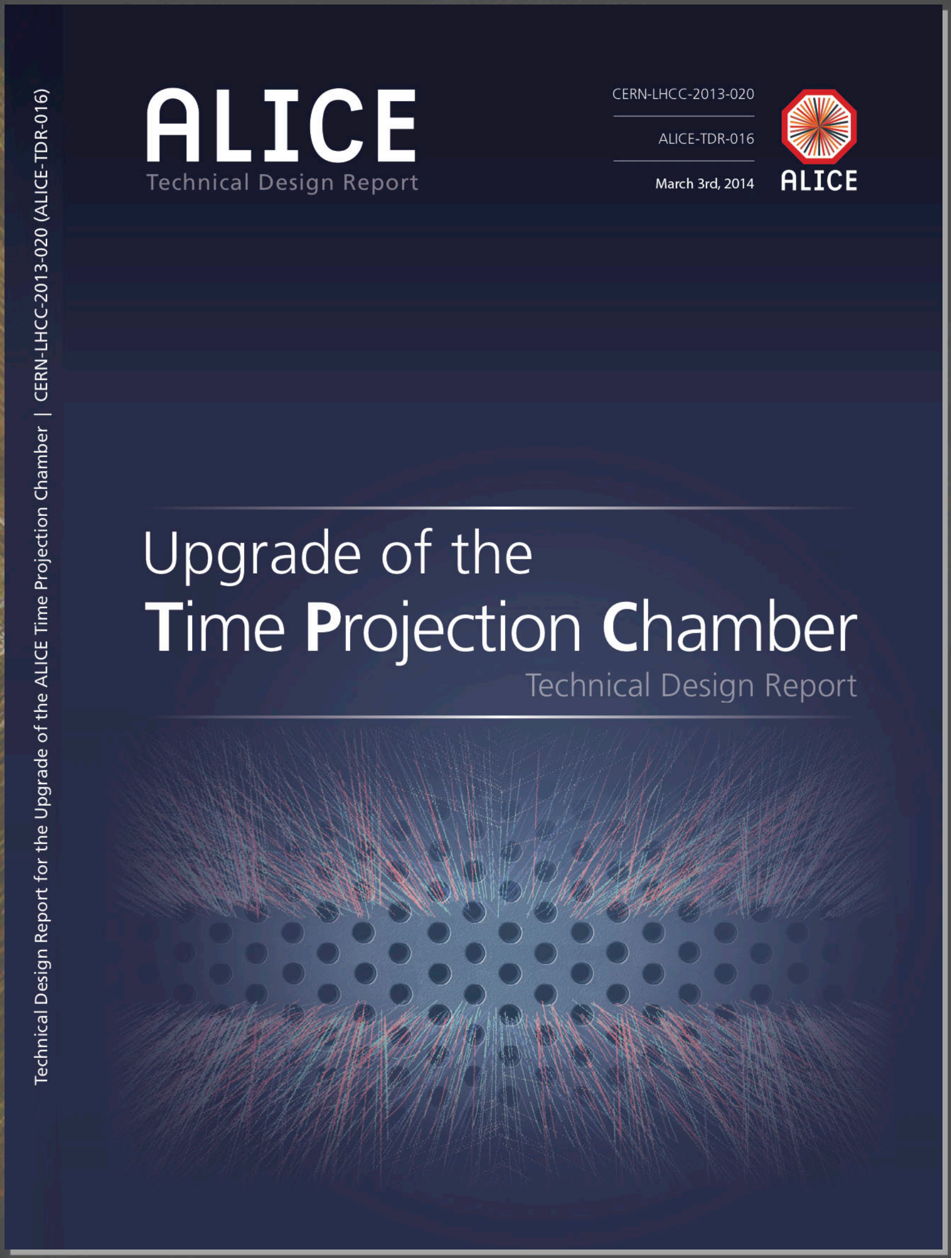
ALICE Upgrade →

2015 **Run 2:**
1 nb^{-1} Pb-Pb at $\sqrt{s_{NN}}=5.5$ TeV
reference data pp and p-Pb

2020 **Runs 3 + 4:**
ALICE target luminosity:
- ○ $L^{mb} \geq 10\ \mathrm{nb}^{-1}$
- ○ $6 \times 10^{27}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- ○ Maximum rate (high-rate upgrade):
  50 kHz (Pb-Pb)
  400 kHz (pp)

1. **Improved vertexing and tracking**
   - **New Inner Tracking System (ITS)**
   - Muon Forward Tracker (MFT)
   - TPC Upgrade with GEMs
2. **Fast data readout**
   - Upgrade of readout and online systems
   - Continuous data readout of the TPC
   - Online data compression based on clusters and tracks

The future



Technical Design Report for the Upgrade of the ALICE Time Projection Chamber | CERN-LHCC-2013-020 (ALICE-TDR-016)

ALICE
Technical Design Report

CERN-LHCC-2013-020
ALICE-TDR-016
March 3rd, 2014

ALICE

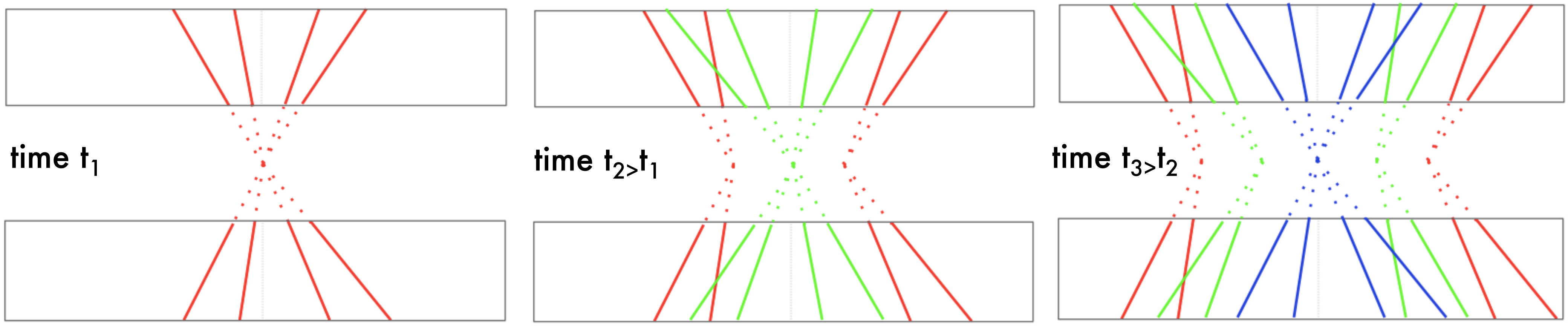
Upgrade of the
Time **P**rojection **C**hamber
Technical Design Report

ALICE TPC upgrade Technical Design Report

Continuous TPC readout

- Goal: Operate TPC at high luminosity
  - Luminosity for lead collisions: 6×10^{27} Hz/cm^2
  - Up to 50- kHz interaction rate
  - Up to 5 events overlapping (shown below)
  - Inspect all minimum bias events

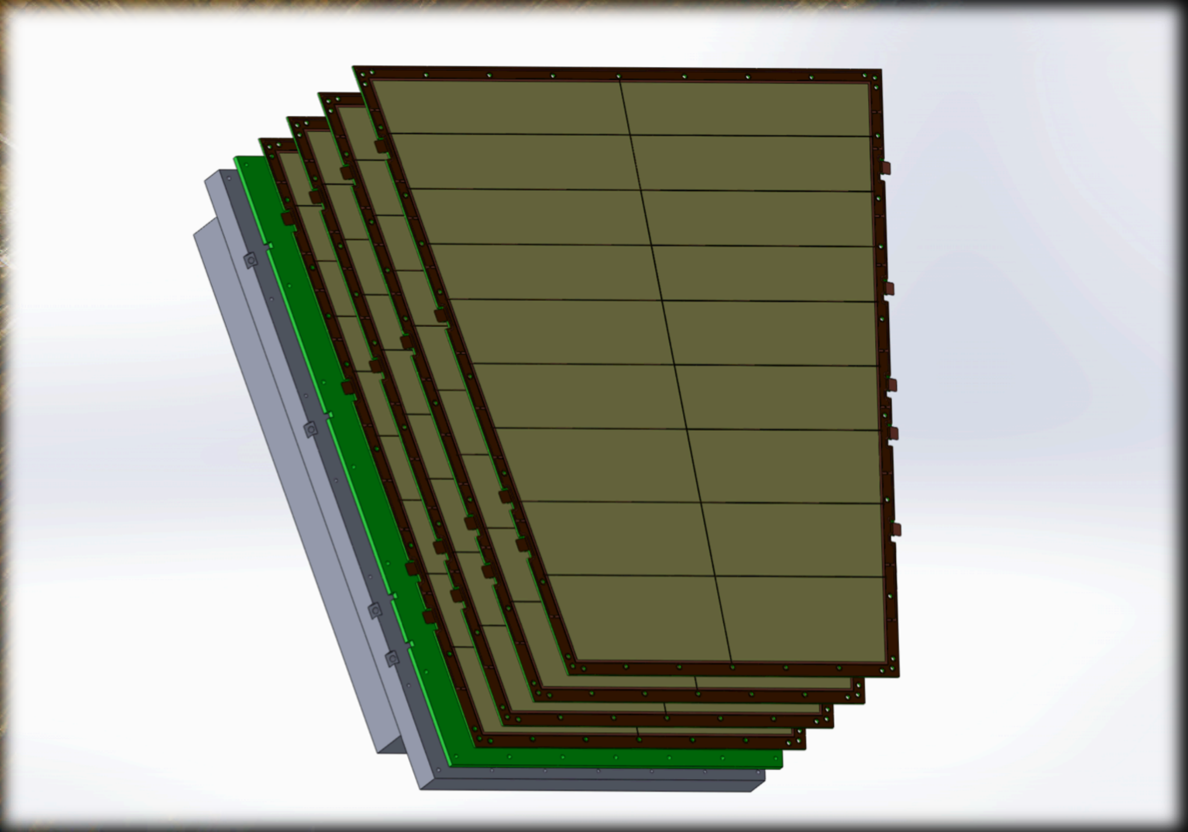
⇒ No gating
⇒ Continuous readout (no triggers)



Example of a time sequence with 3 events overlapping in the drift volume of the TPC

Upgrade plan

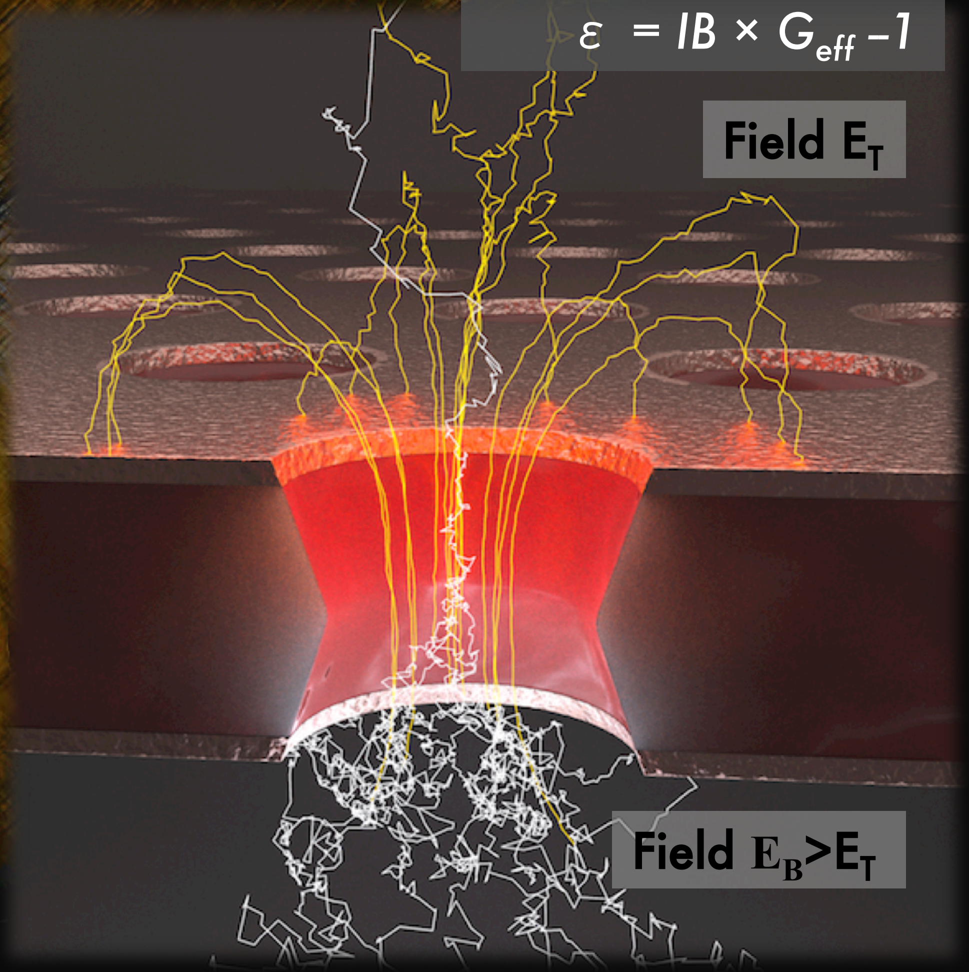
1. Keep existing field cage, gas mixture, laser and services
2. Replace wire planes by GEMs
3. New readout electronics, data acquisition (DAQ) and high-level trigger (HLT)
    - Continuous readout
    - online event reconstruction and calibration



Ion backflow suppression (1)

- Challenge: Minimize space charge in drift region!
- Low ion density in drift region requires
  - low primary ionization n_{ion}
  - low gain G_{eff}
  - low ion backflow IB

$$n_{tot} = n_{ion} \times IB \times G_{eff}$$
$$\varepsilon = IB \times G_{eff} - 1$$



Ion backflow suppression (2)

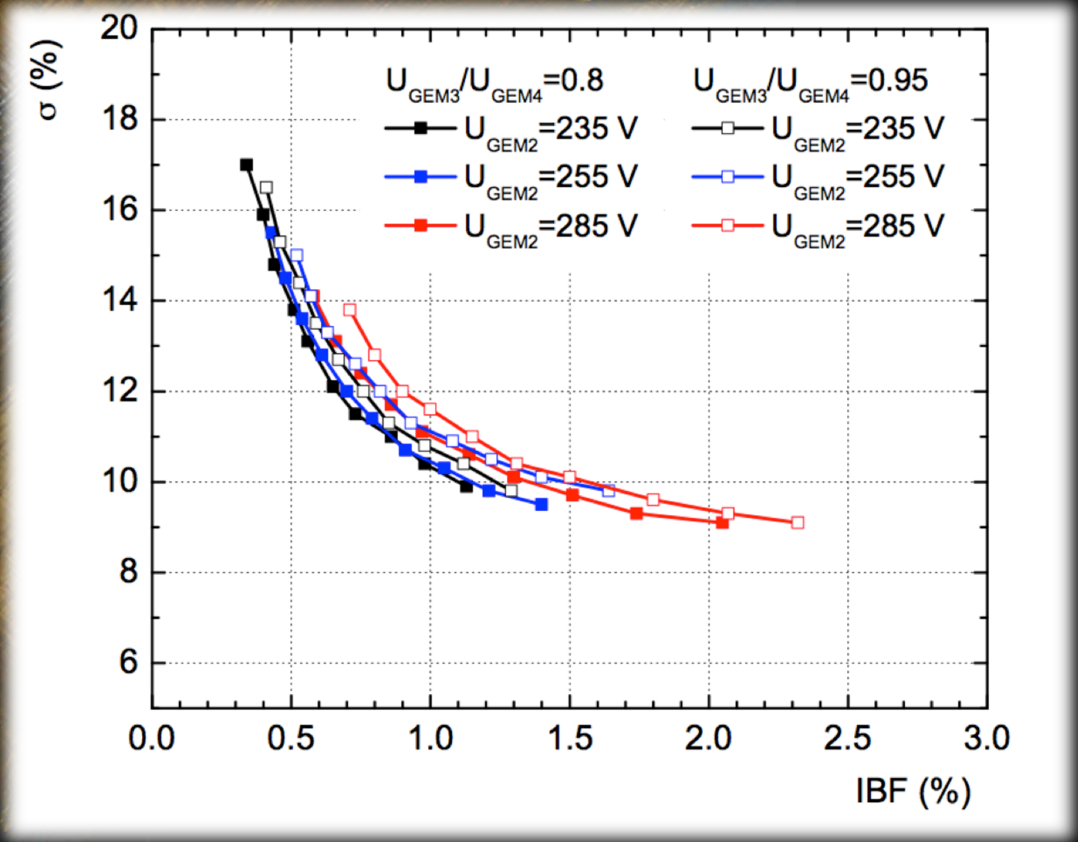
- Challenge: Minimize space charge in drift region!
- Goal: $IB = 1\%$, $\varepsilon = 20$ at $G_{\mathrm{eff}} = 2000$

⇒ **Resulting distortions $(\mathcal{O}(\mathrm{cm}))$ can be corrected**

- Current issue under study: Optimisation of IB and energy resolution

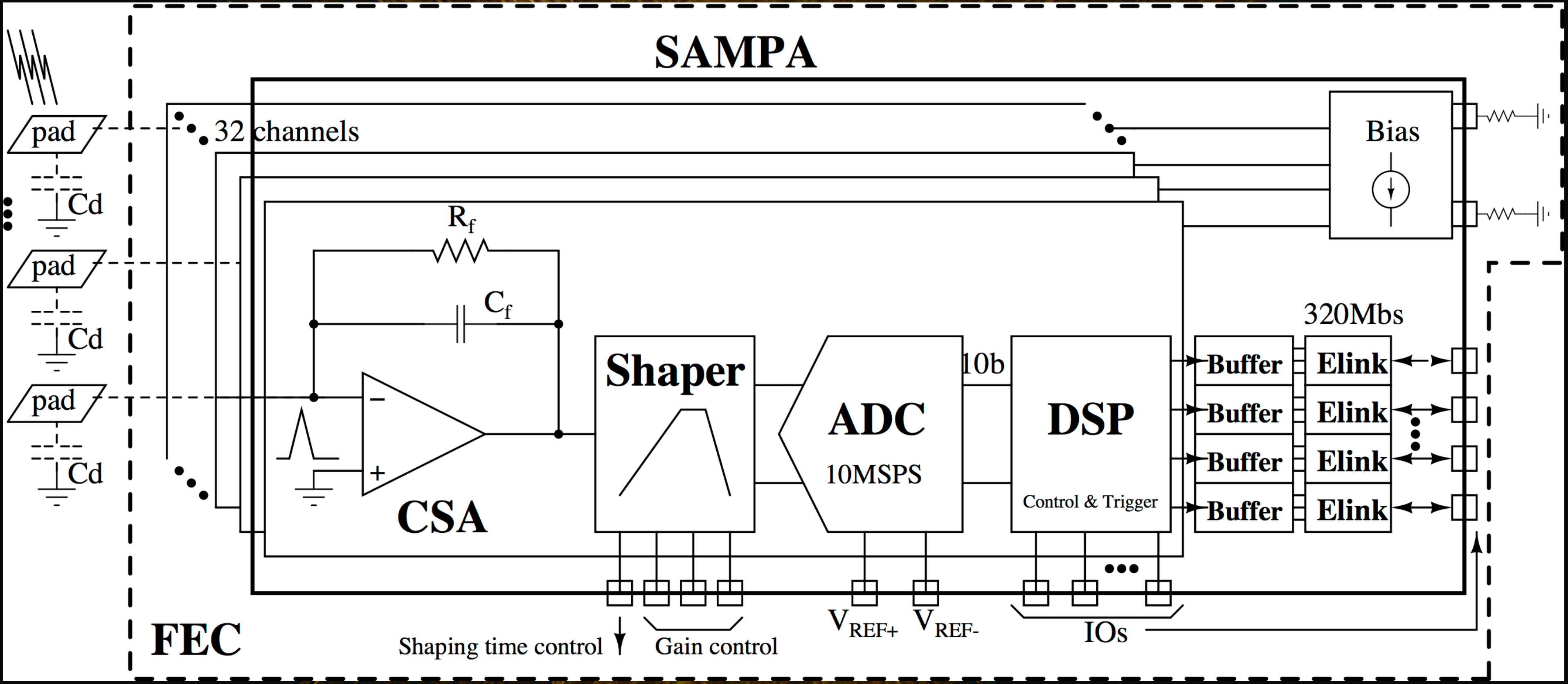
$$n_{tot} = n_{ion} \times IB \times G_{\mathrm{eff}}$$

$$\varepsilon = IB \times G_{\mathrm{eff}} - 1$$



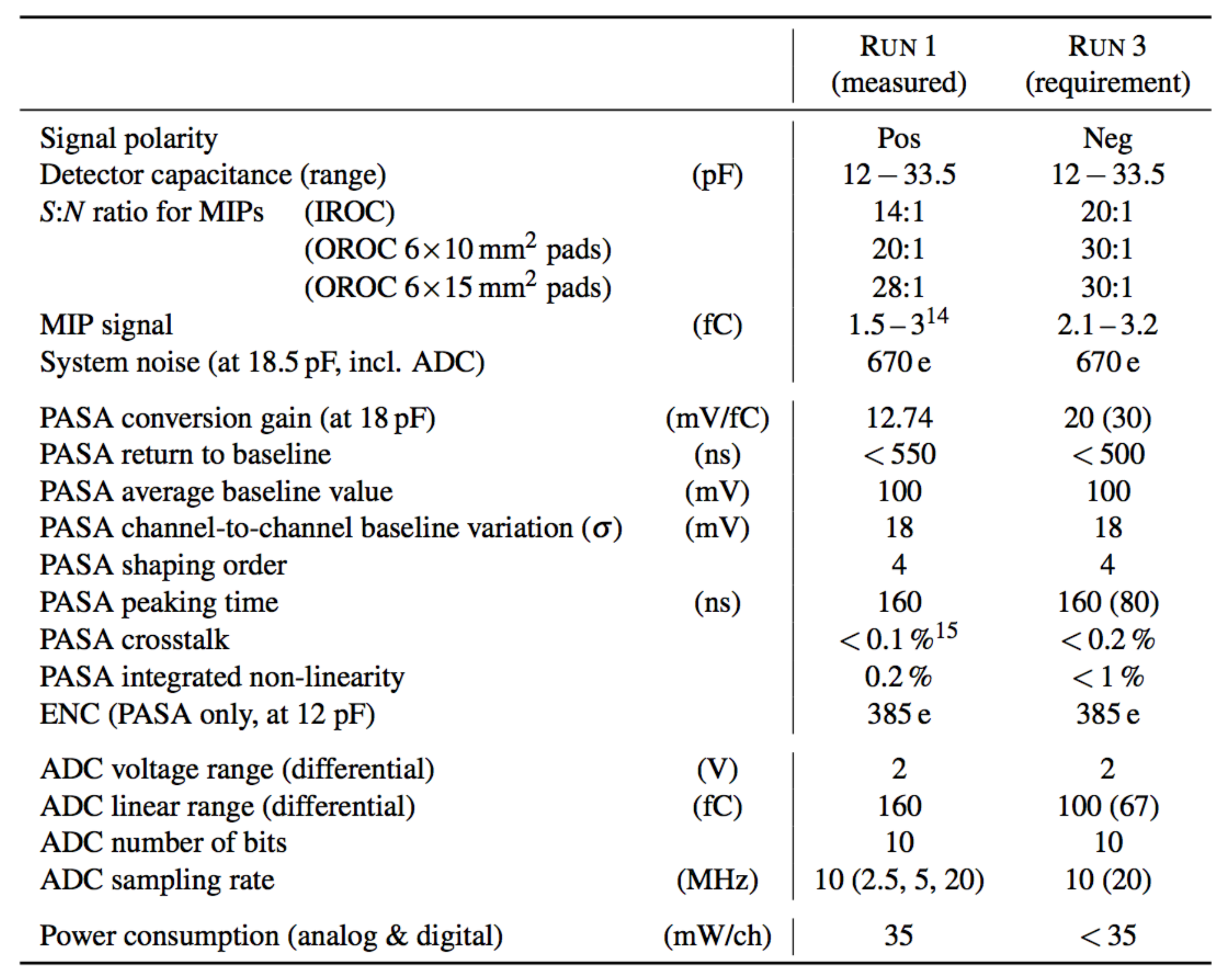
Read-out (1)

- SAMPA schematic



Read-out (2)

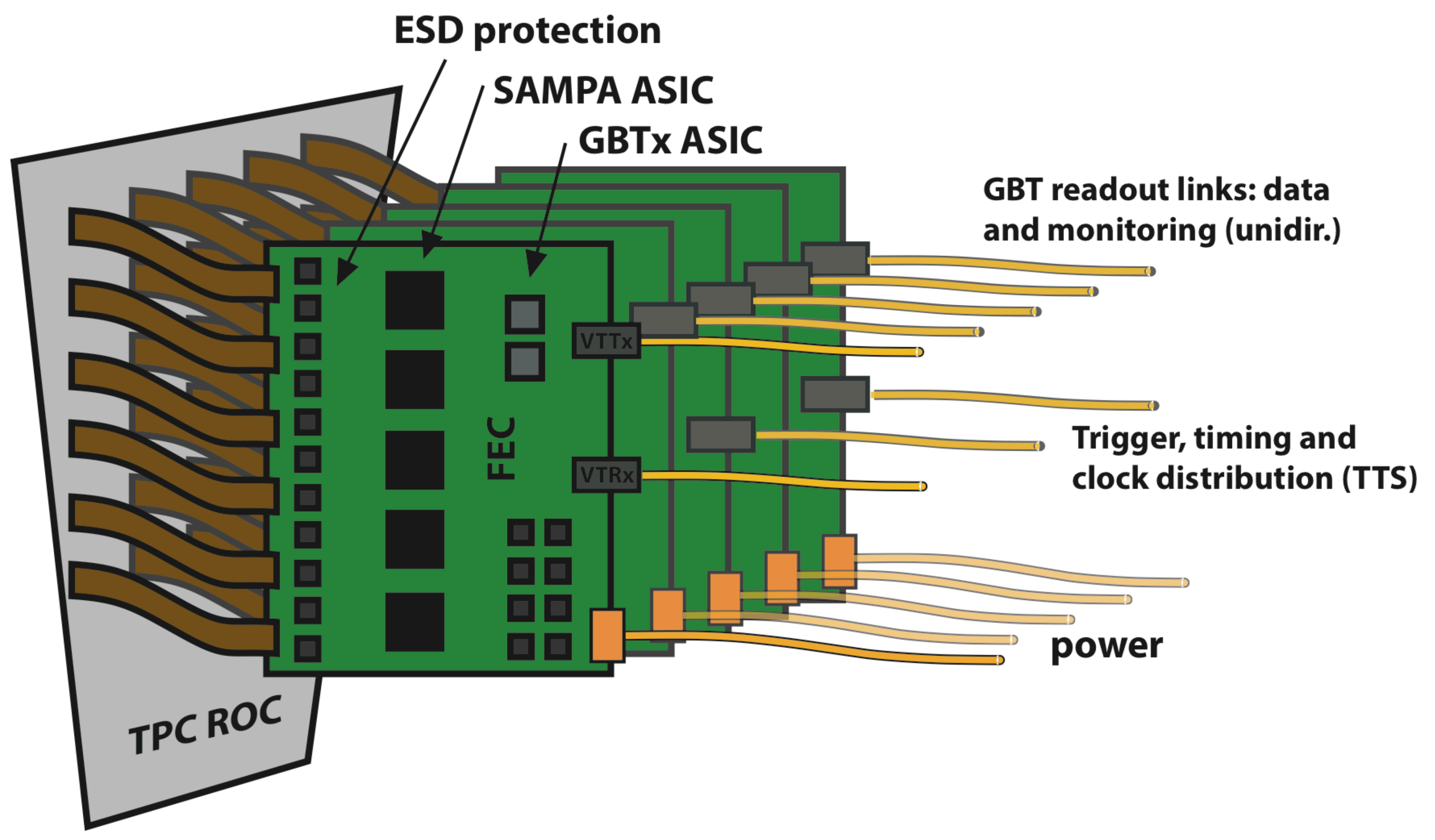
- PASA/ALTRO and SAMPA parameters



			RUN 1 (measured)	RUN 3 (requirement)
Signal polarity			Pos	Neg
Detector capacitance (range)		(pF)	12 – 33.5	12 – 33.5
S:N ratio for MIPs	(IROC)		14:1	20:1
	(OROC $6\times10\,\mathrm{mm}^2$ pads)		20:1	30:1
	(OROC $6\times15\,\mathrm{mm}^2$ pads)		28:1	30:1
MIP signal		(fC)	1.5 – 3[14]	2.1 – 3.2
System noise (at 18.5 pF, incl. ADC)			670 e	670 e
PASA conversion gain (at 18 pF)		(mV/fC)	12.74	20 (30)
PASA return to baseline		(ns)	< 550	< 500
PASA average baseline value		(mV)	100	100
PASA channel-to-channel baseline variation (σ)		(mV)	18	18
PASA shaping order			4	4
PASA peaking time		(ns)	160	160 (80)
PASA crosstalk			$< 0.1\,\%$[15]	$< 0.2\,\%$
PASA integrated non-linearity			0.2 %	$< 1\,\%$
ENC (PASA only, at 12 pF)			385 e	385 e
ADC voltage range (differential)		(V)	2	2
ADC linear range (differential)		(fC)	160	100 (67)
ADC number of bits			10	10
ADC sampling rate		(MHz)	10 (2.5, 5, 20)	10 (20)
Power consumption (analog & digital)		(mW/ch)	35	< 35

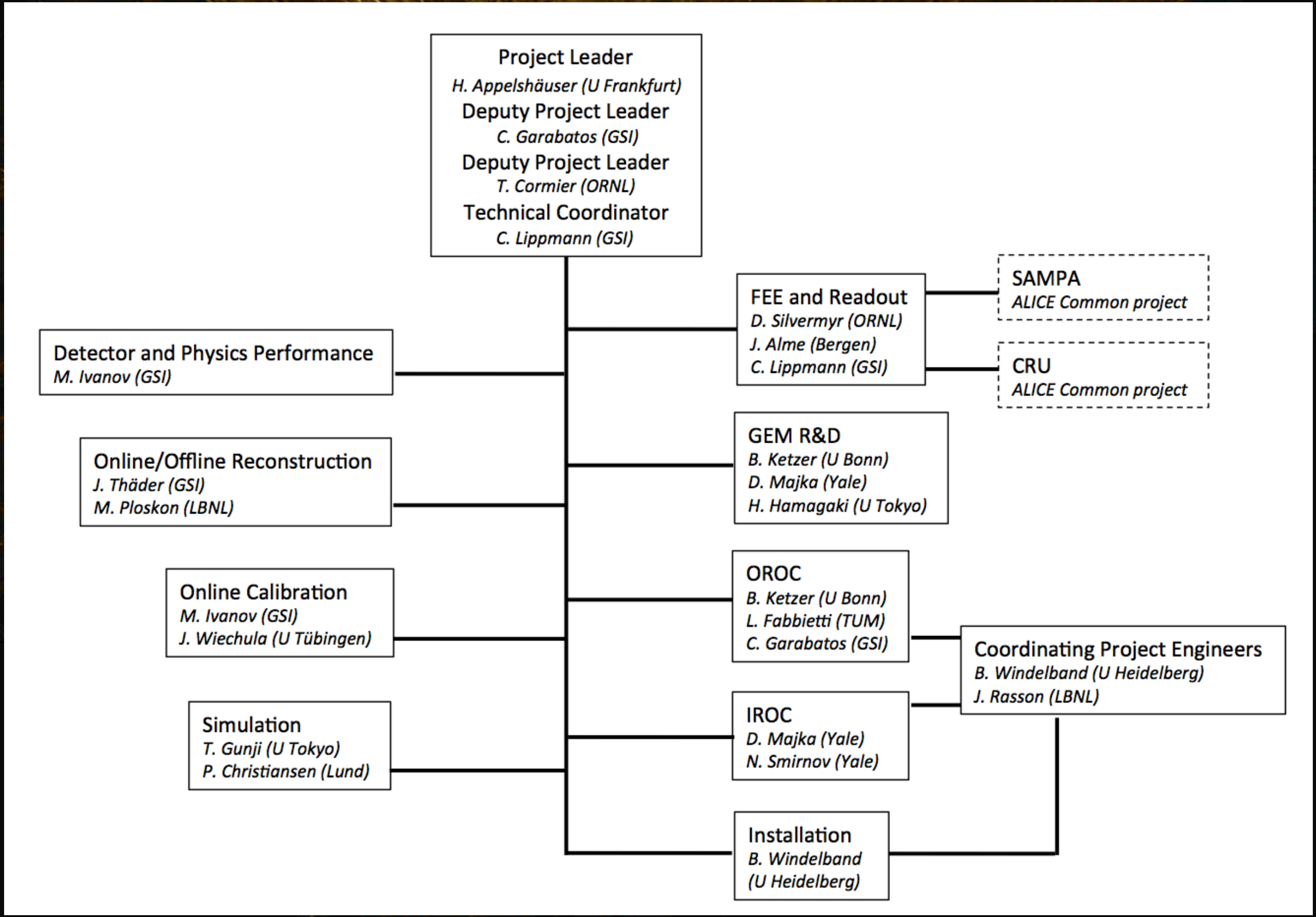
Read-out (3)

- SAMPA schematic



Read-out (1)

- TPC upgrade organisation



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Deputy Project Leader
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Deputy Project Leader
T. Cormier (ORNL)
Technical Coordinator
C. Lippmann (GSI)

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M. Ivanov (GSI)

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SAMPA
ALICE Common project

CRU
ALICE Common project

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B. Windelband (U Heidelberg)
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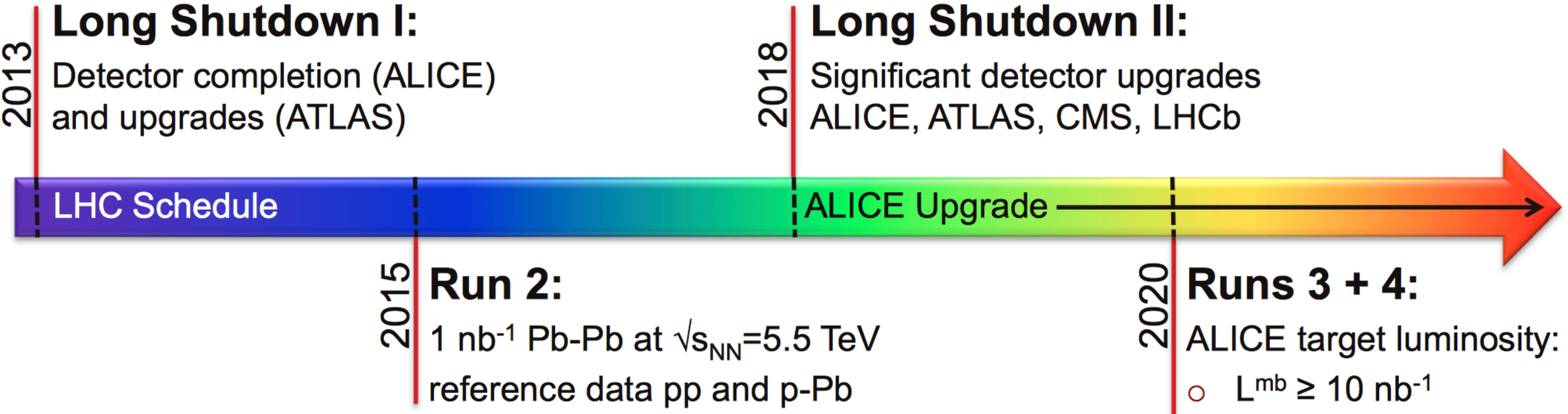
Installation
B. Windelband
(U Heidelberg)

ALICE Upgrade Strategy for Runs 3 + 4



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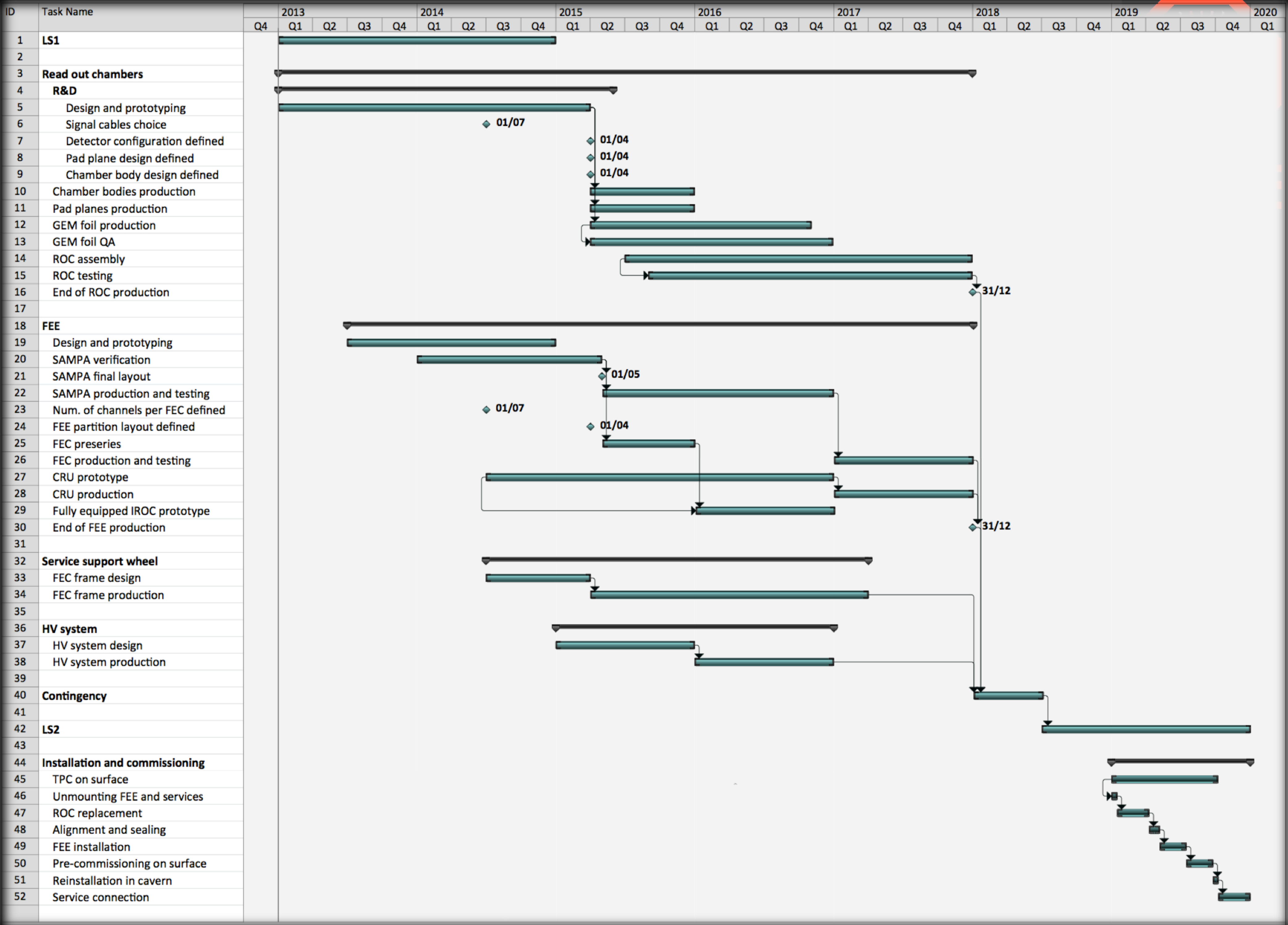

ID	Task Name
1	**LS1**
2	
3	**Read out chambers**
4	**R&D**
5	Design and prototyping
6	Signal cables choice
7	Detector configuration defined
8	Pad plane design defined
9	Chamber body design defined
10	Chamber bodies production
11	Pad planes production
12	GEM foil production
13	GEM foil QA
14	ROC assembly
15	ROC testing
16	End of ROC production
17	
18	**FEE**
19	Design and prototyping
20	SAMPA verification
21	SAMPA final layout
22	SAMPA production and testing
23	Num. of channels per FEC defined
24	FEE partition layout defined
25	FEC preseries
26	FEC production and testing
27	CRU prototype
28	CRU production
29	Fully equipped IROC prototype
30	End of FEE production
31	
32	**Service support wheel**
33	FEC frame design
34	FEC frame production
35	
36	**HV system**
37	HV system design
38	HV system production
39	
40	**Contingency**
41	
42	**LS2**
43	
44	**Installation and commissioning**
45	TPC on surface
46	Unmounting FEE and services
47	ROC replacement
48	Alignment and sealing
49	FEE installation
50	Pre-commissioning on surface
51	Reinstallation in cavern
52	Service connection

Summary

- The ALICE TPC is a large 3-dimensional tracking device for ultra-high multiplicity events
- It has been operated successfully with pp, Pb−Pb and p-Pb collisions at the LHC
- The TPC offers powerful particle identification and tracking in high multiplicity events
- For Run 2 we are working on a readout upgrade (RCU2)
- The LHCC has endorsed the Letter Of Intent for the upgrade of the ALICE central barrel
- A technical design report for the upgrade of the was submitted
- The TPC will be operated in a continuous mode with GEMs as readout detectors