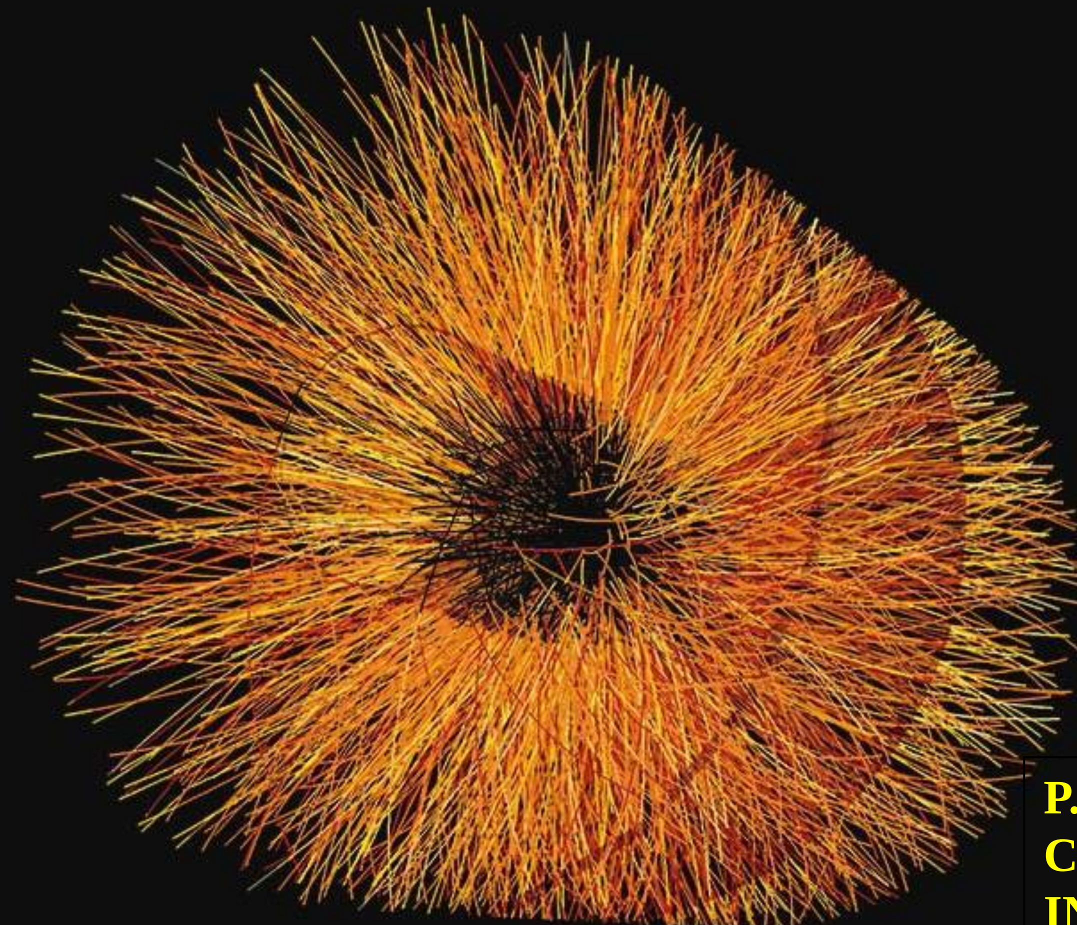
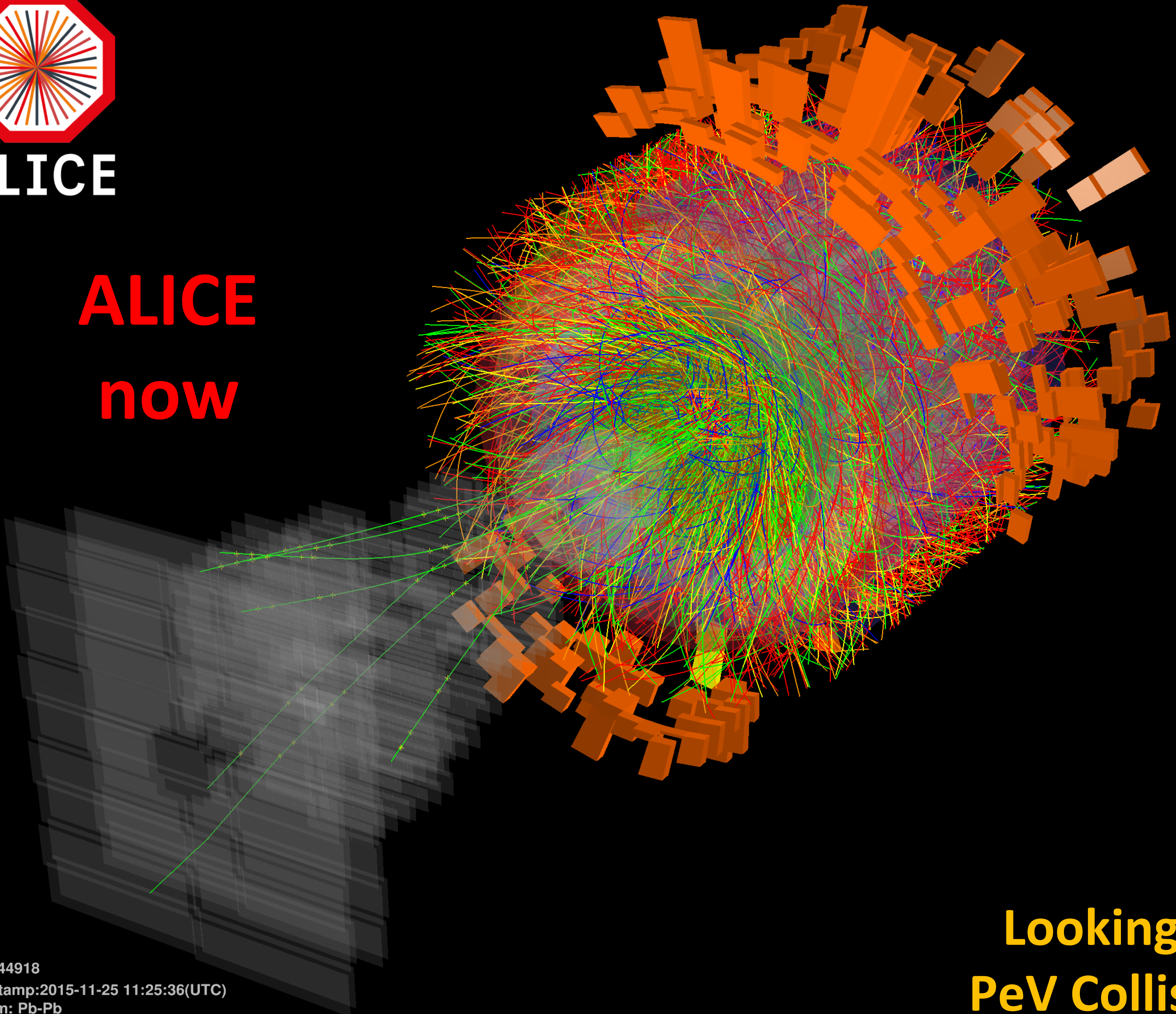
QCD thermodynamics
pressure and passion
August 25-26st 2016

ALICE
now and in future



P.Giubellino
CERN and
INFN Torino

ALICE now



Looking at
PeV Collisions

Over 25 years of work to get there

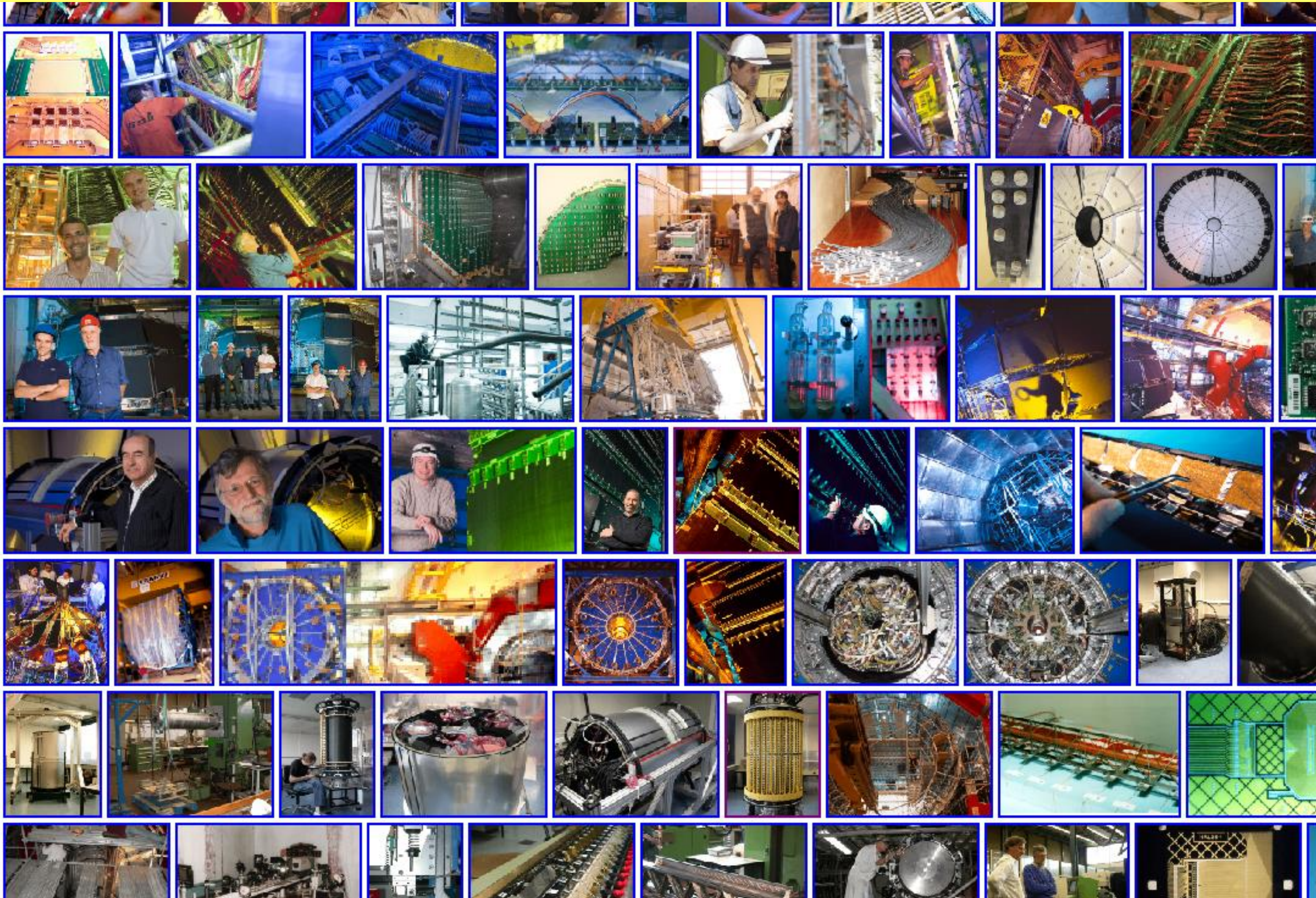
- The construction
  - 1990 - 1996 Design
  - 1992 - 2002 R&D
  - 2000 - 2010 Construction
  - 2002 - 2007 Installation
  - 2008 - 2010 Commissioning
- And since then, data taking!
  - 2010-2013 Run1
  - 2013-2014 Long Shutdown 1
  - 2015-> Run2

With along the way 4 major additions :

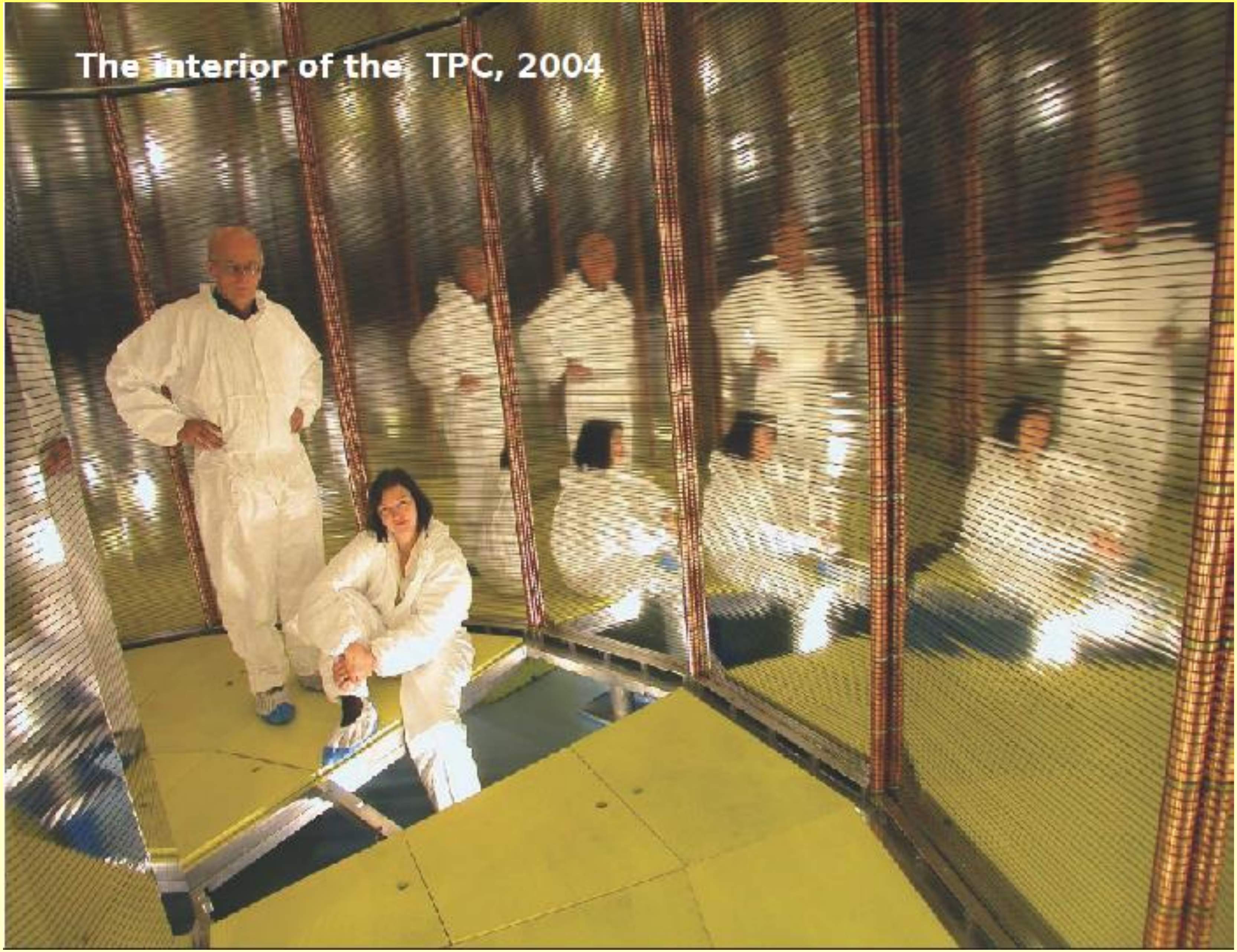
- 1996 Muon spectrometer
- 1999 TRD
- 2006 EMCAL
- 2010 DCAL
- And a number of minor ones
  - ACORDE cosmic trigger
  - V0 trigger/mult detector
  - ADD/ADA forward scintillators

ALICE in 2001

Through years of intense construction work



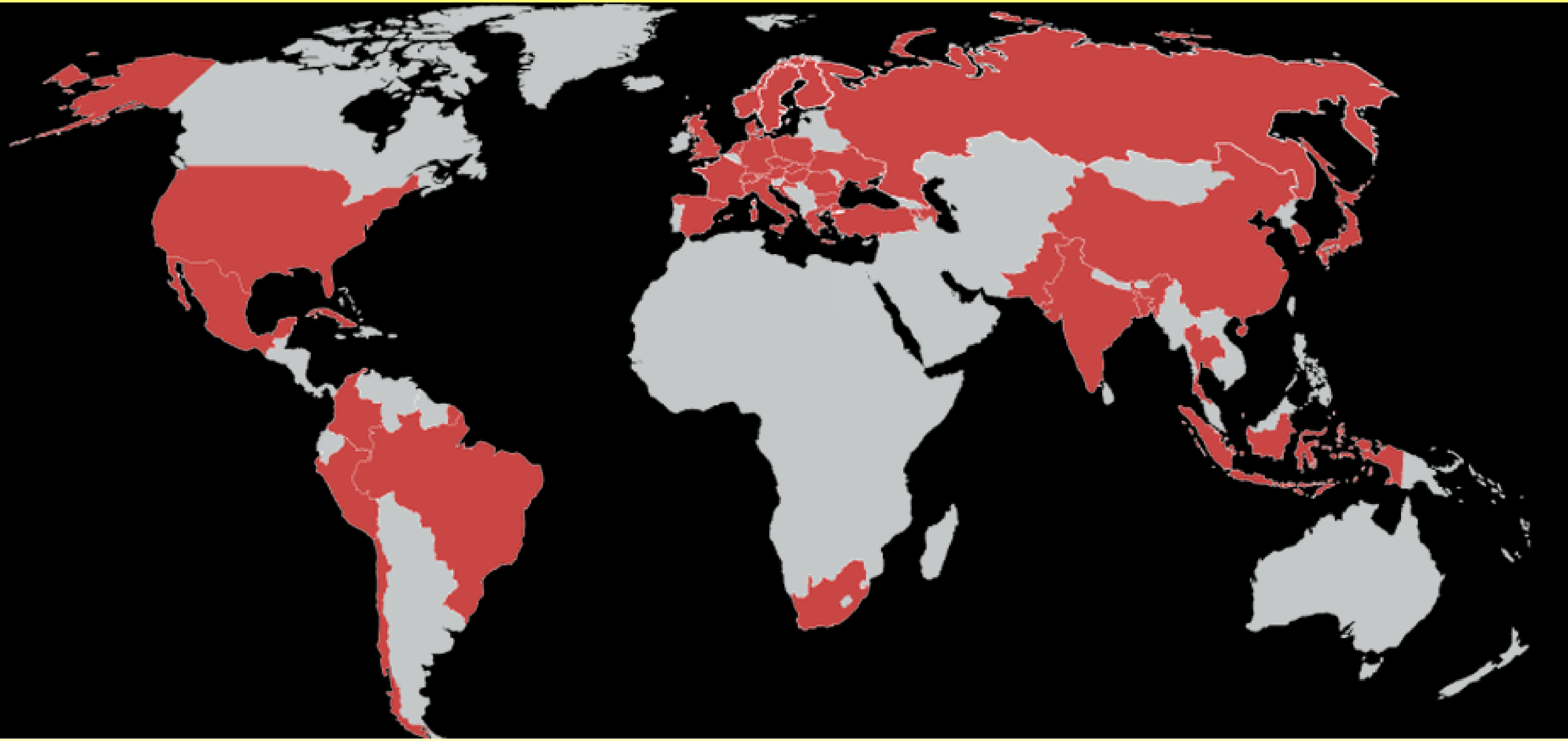
With Peter on the front line



ALICE in 2008

Formal end of ALICE installation July 2008

ALICE: a world-wide effort

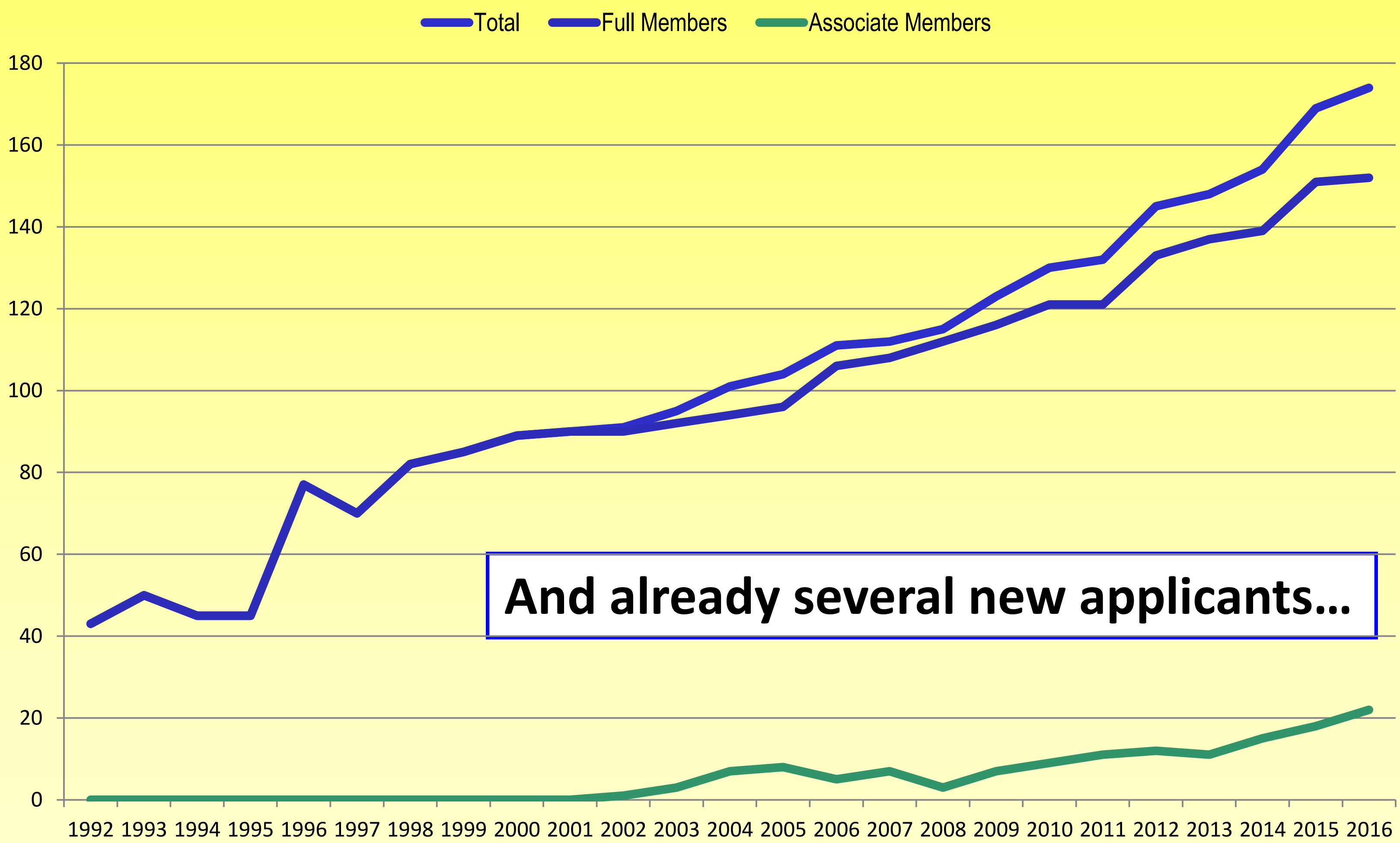


42 COUNTRIES – 174 INSTITUTES

Which keeps growing after 25 years!

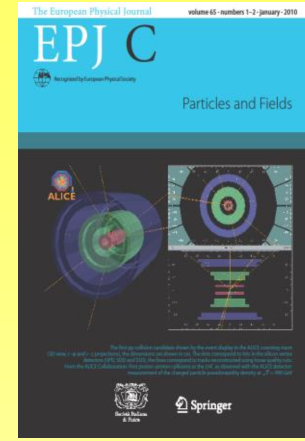
ALICE

Number of participating institutes in ALICE

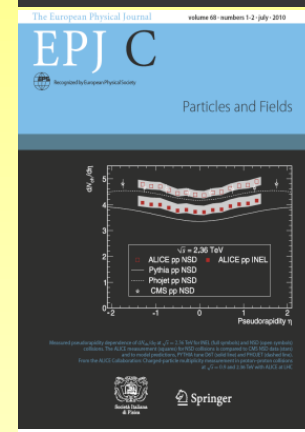


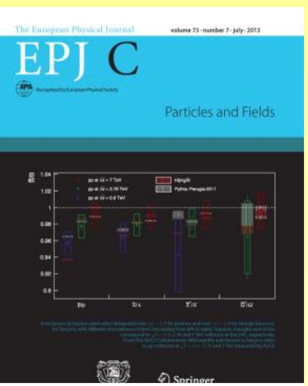
Keeps growing because it does not only have a great present… it is a scientific and technological program with great prospects!

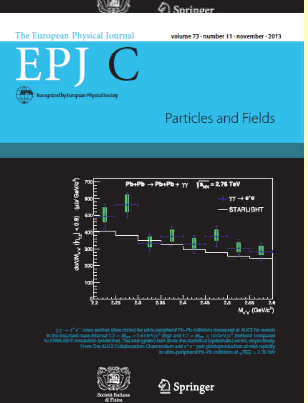
A program of major impact

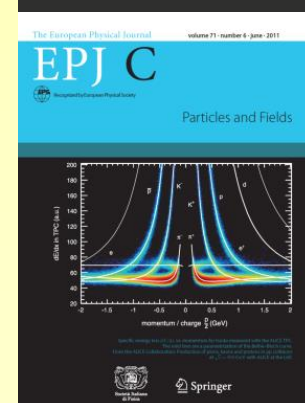


- A huge scientific output
  - **161 ALICE papers on arXiv**
  - **High impact papers (***average of ~80 citations per paper***) :** the top cited papers at the LHC after the Higgs discovery ones are HI physics papers (source: ISI).
  - **Several hundred** presentations at international conferences *each year*

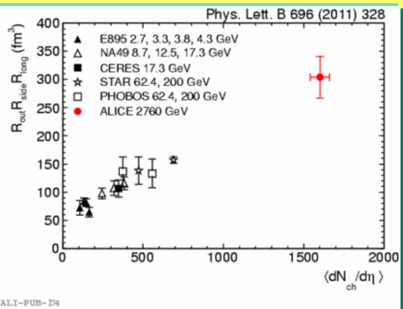


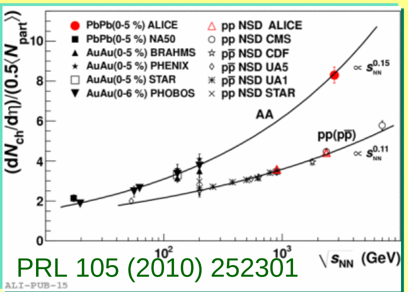


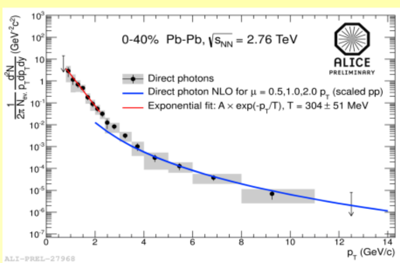




A lot of results already from RUN1





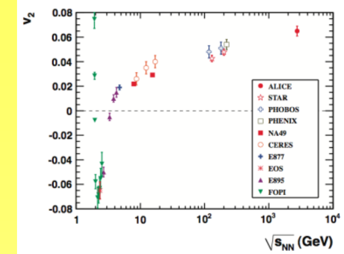


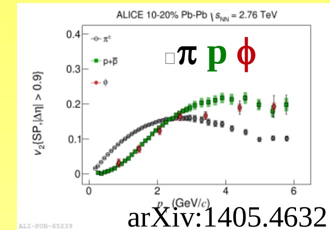
A continuous flow of new results

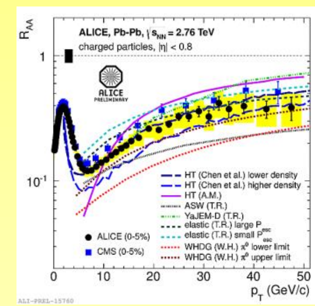
- global features defined
- QGP strongly interacting liquid even at higher T, access to transport coefficients
- energy loss of partons in QGP: wealth of data from leading particles and reconstructed jets, including heavy quarks
- Heavy quarks also appear to thermalize!
- rich results on charmonium, well on the way towards proof of deconfinement
- Access to low-x PDF from UPC

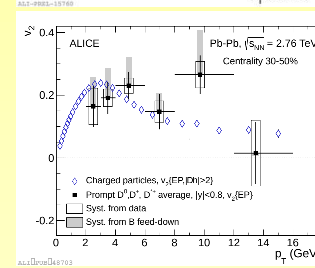
Intriguing, unexpected results from the pA run

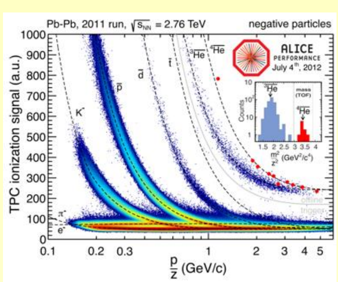
- How small a system to observe collective behaviour?

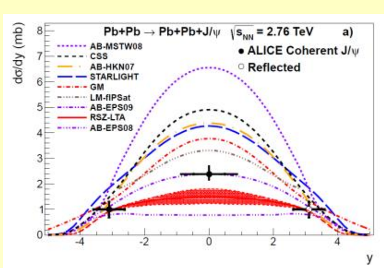


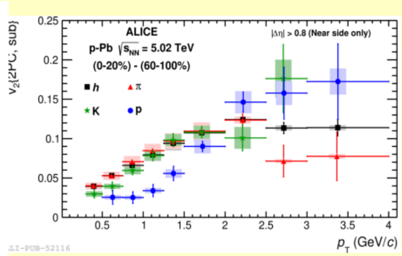


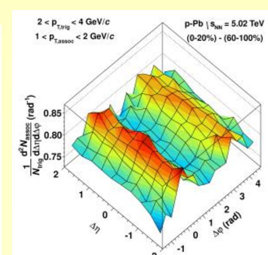


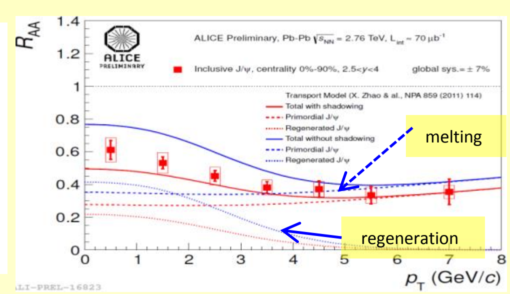












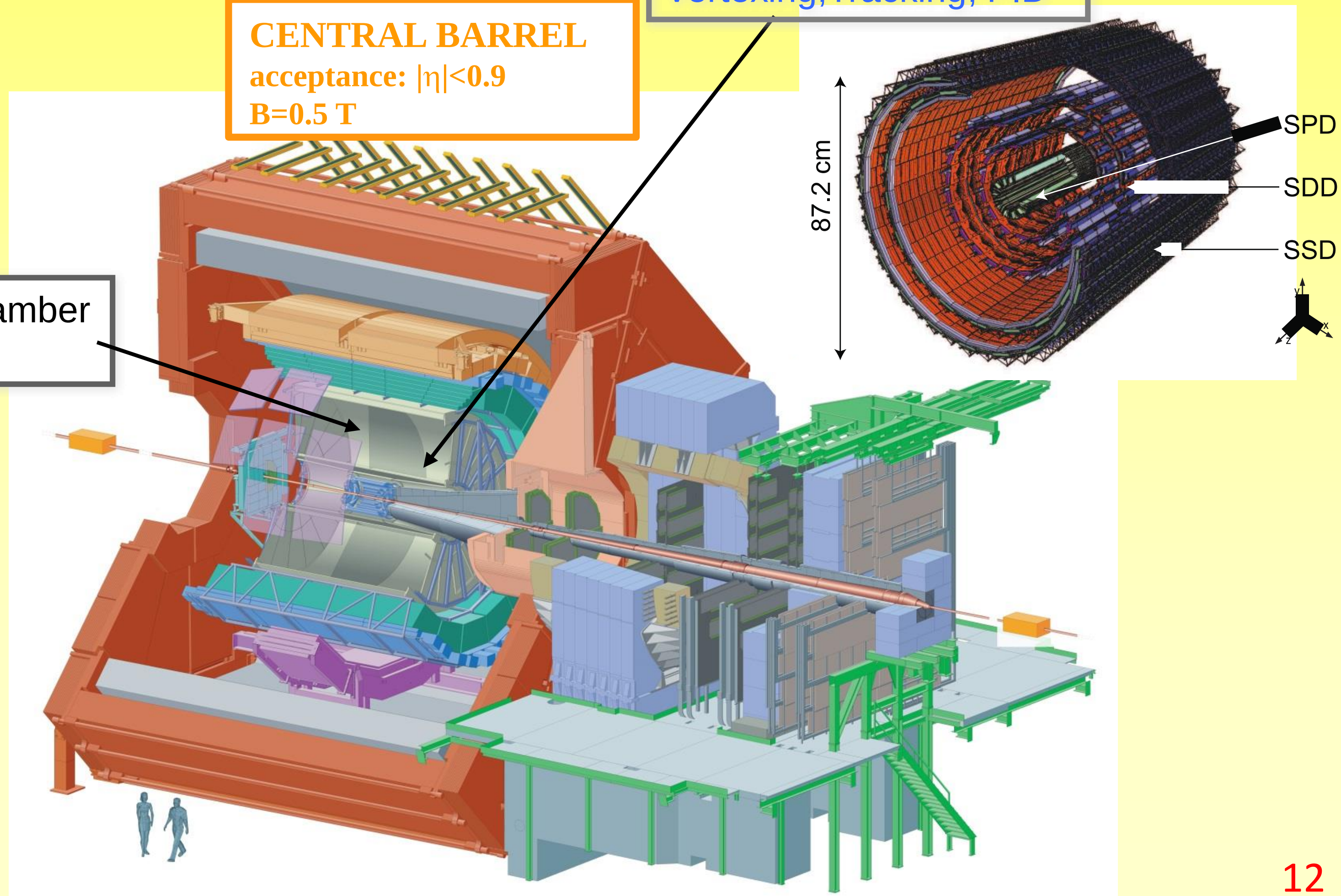
ALICE today: specificities

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

CENTRAL BARREL
acceptance: |η|<0.9
B=0.5 T

Inner **T**racking **S**ystem
Vertexing,Tracking, PID

Time **P**rojection **C**hamber
Tracking, PID



ALICE today: specificities

Particle identification over a wide momentum range

CENTRAL BARREL
acceptance: |η|<0.9
B=0.5 T

Inner **T**racking **S**ystem
Vertexing,Tracking, PID

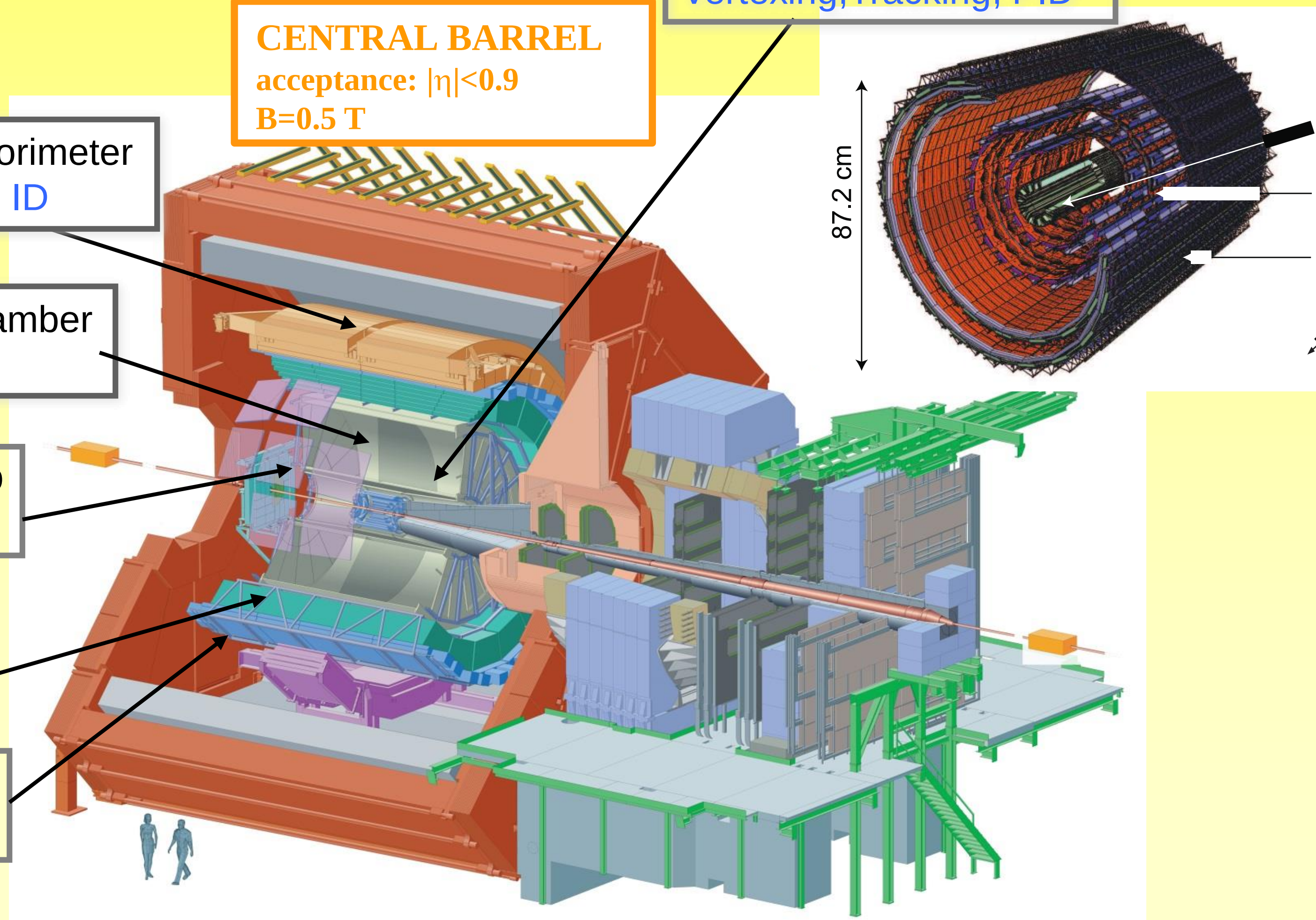
Eletro**M**agnetic **CAL**orimeter
Calorimeter, electron ID

Time **P**rojection **C**hamber
Tracking, PID

High **M**omentum **PID**
PID

Transition **R**adiation **D**etector
PID

Time **O**f **F**light
PID



The ALICE program

- **Core Business: PbPb**
  - **Study the properties of strongly interacting matter under extreme conditions of temperature and density.**
    - Understand confinement, producing and studying in the lab a deconfined plasma of quark and gluons (QGP)
    - Understand evolution of matter from the hot and dense deconfined phase towards ordinary hadrons (analogous to the early Universe evolution)
- **pp**
  - collect ‘comparison data’ for heavy ion program
    - many observables measured ‘relative’ to pp
  - comprehensive study of MB@LHC
    - tuning of Monte Carlo (background to BSM)
  - soft & semi-hard QCD
    - very complementary to other LHC experiments
    - address specific issues of QCD
  - very high multiplicity pp events
    - dN_{ch}/dh comparable to the one in HI => mini-plasma ?
- **pA**
  - Control experiment for PbPb
    - pp and pPb measurement are used as reference for the Pb-Pb ones.
  - Important measurements in their own right
    - Probe nucleus structure in a QCD regime of very small-x (gluon saturation, shadowing,…)

The ALICE runs

- The past:

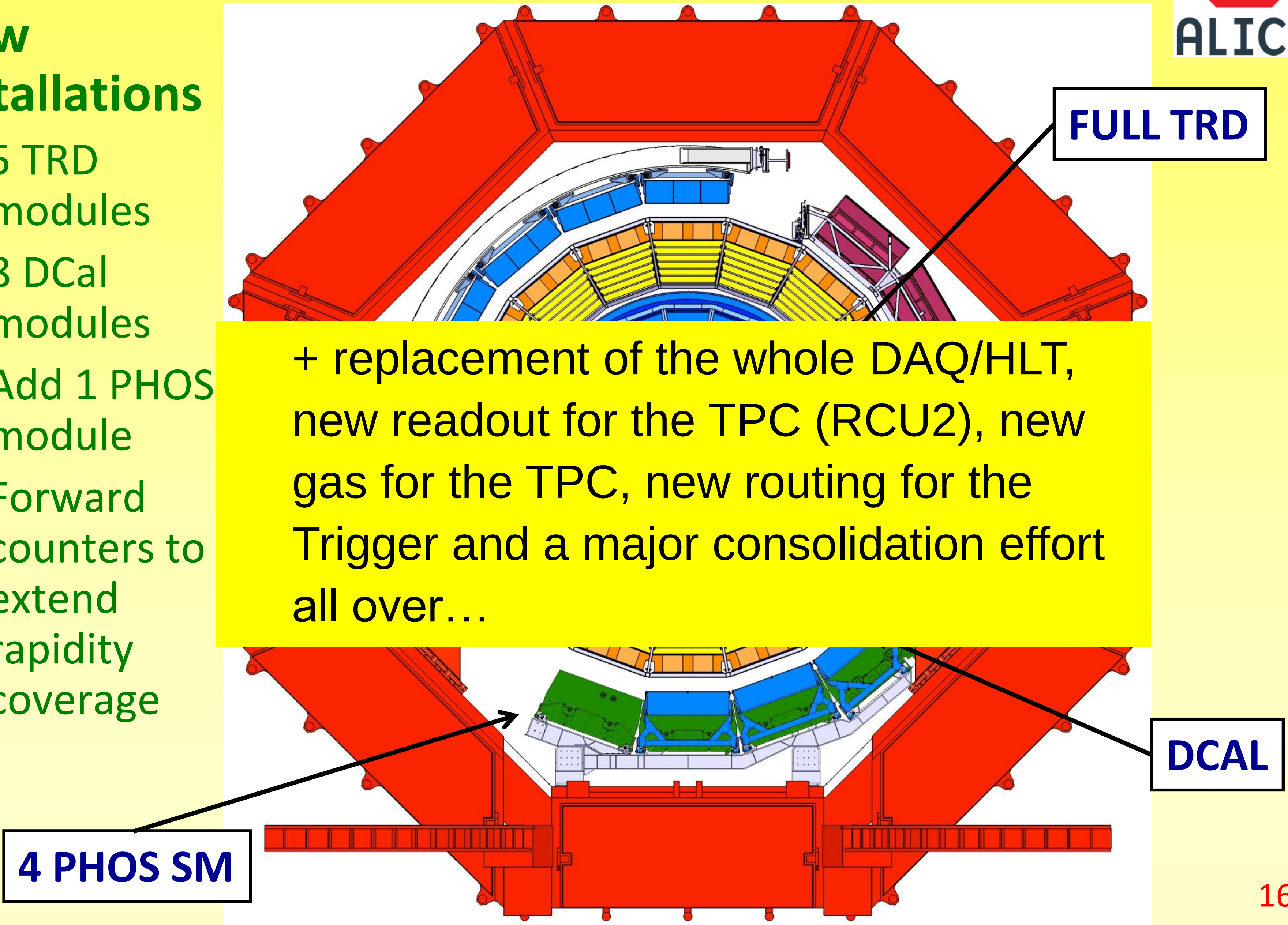
year	system	energy $\sqrt{s_{NN}}$ TeV	integrated luminosity
2010	Pb – Pb	2.76	~ 0.01 nb^{-1}
2011	Pb – Pb	2.76	~ 0.1 nb^{-1}
2013	p – Pb	5.02	~ 30 nb^{-1}

- The present:
  - **RUN2 (HI in 2015, 2016, 2018)** : will allow to approach the **1 nb^{-1}** for Pb-Pb collisions, with improved detectors and double energy (2015 and 2018), a p-Pb run with 10* statistics (this year), and high-statistics pp running (including High Multiplicity triggers).

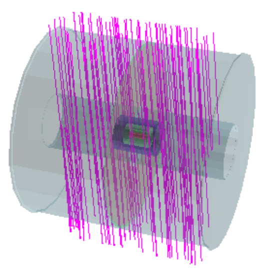
RUN2 vs RUN1

New installations

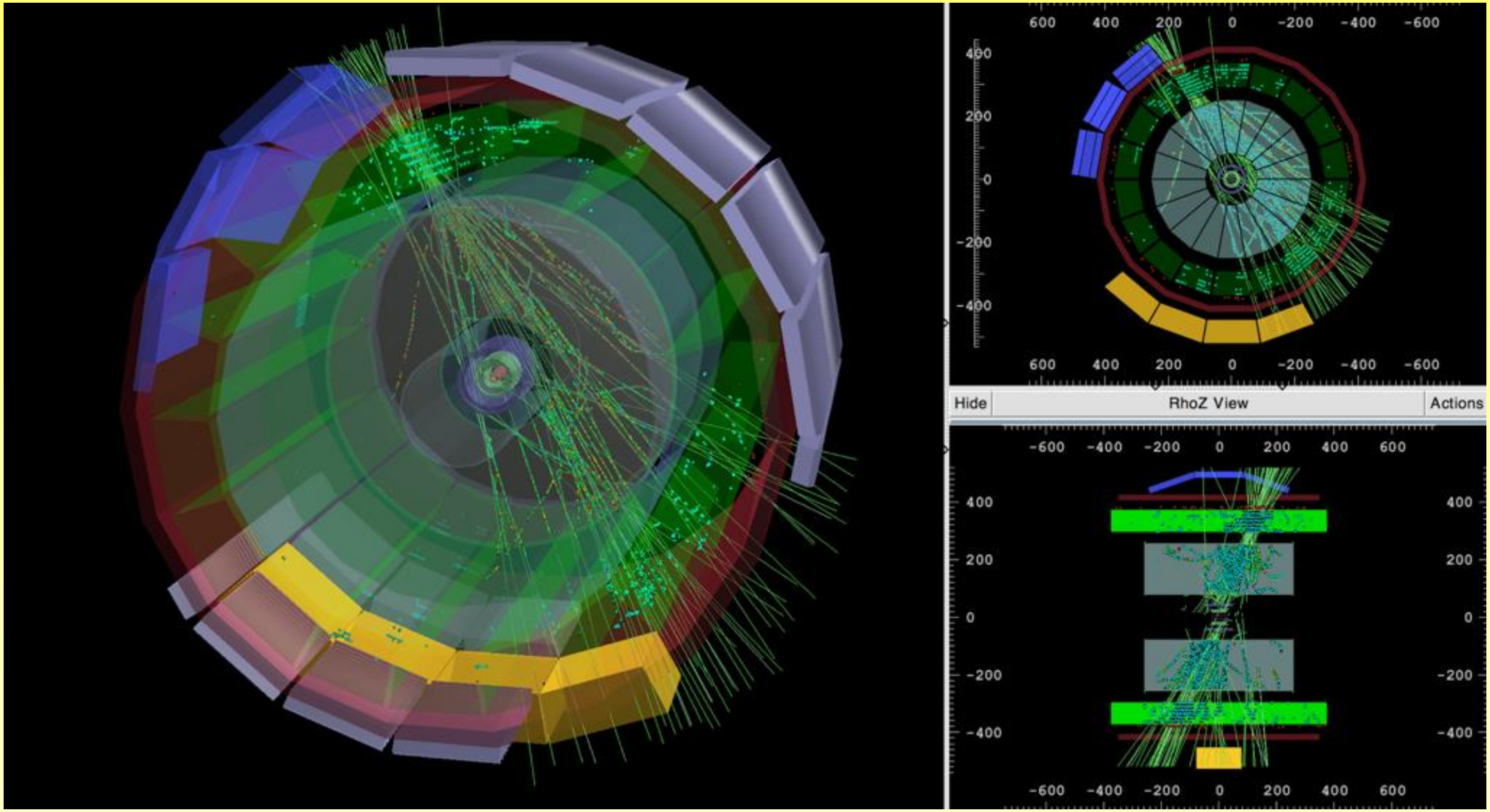
- 5 TRD modules
- 8 DCal modules
- Add 1 PHOS module
- Forward counters to extend rapidity coverage



+ replacement of the whole DAQ/HLT, new readout for the TPC (RCU2), new gas for the TPC, new routing for the Trigger and a major consolidation effort all over…

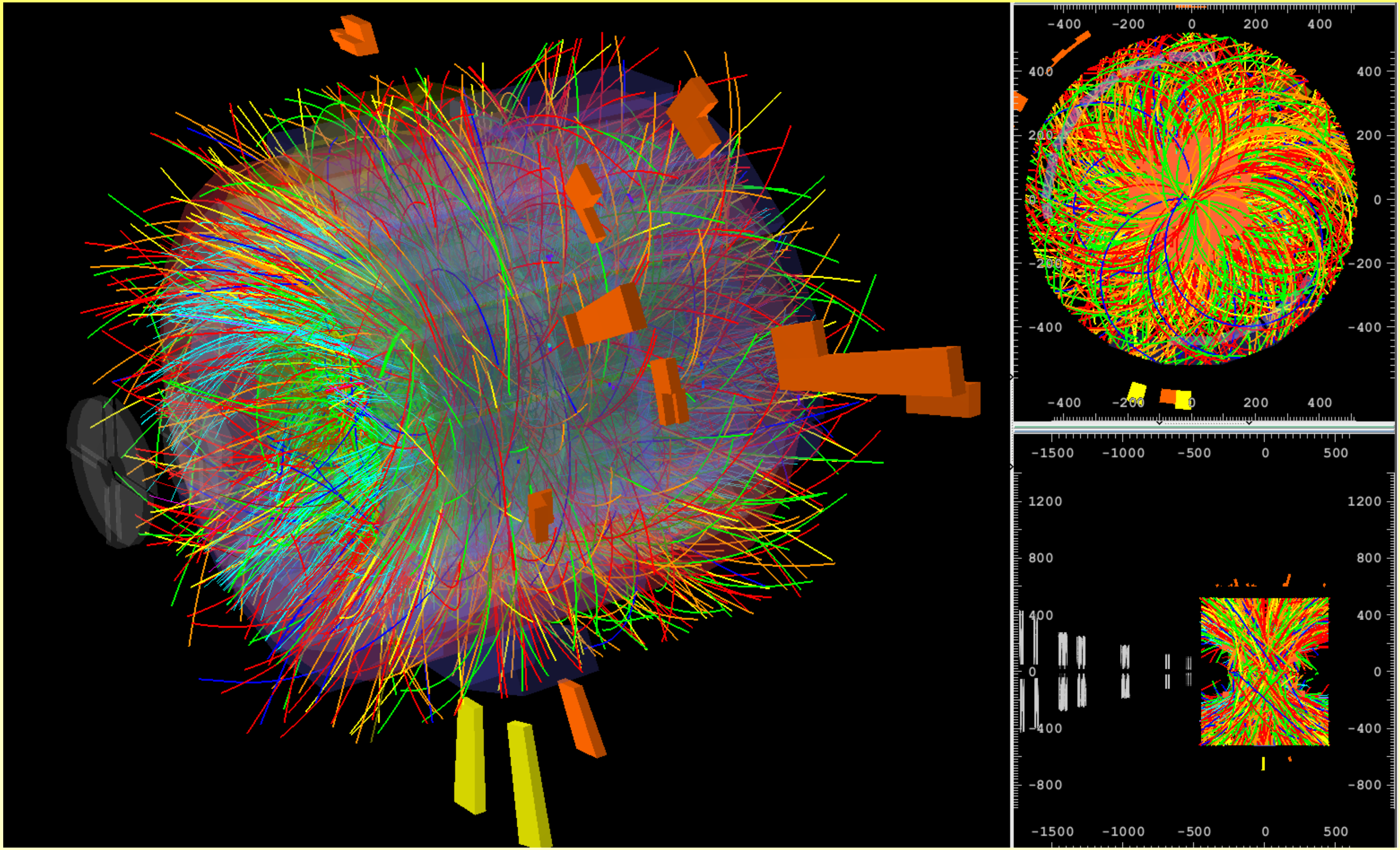


ALICE RUN2 restart: Cosmics...

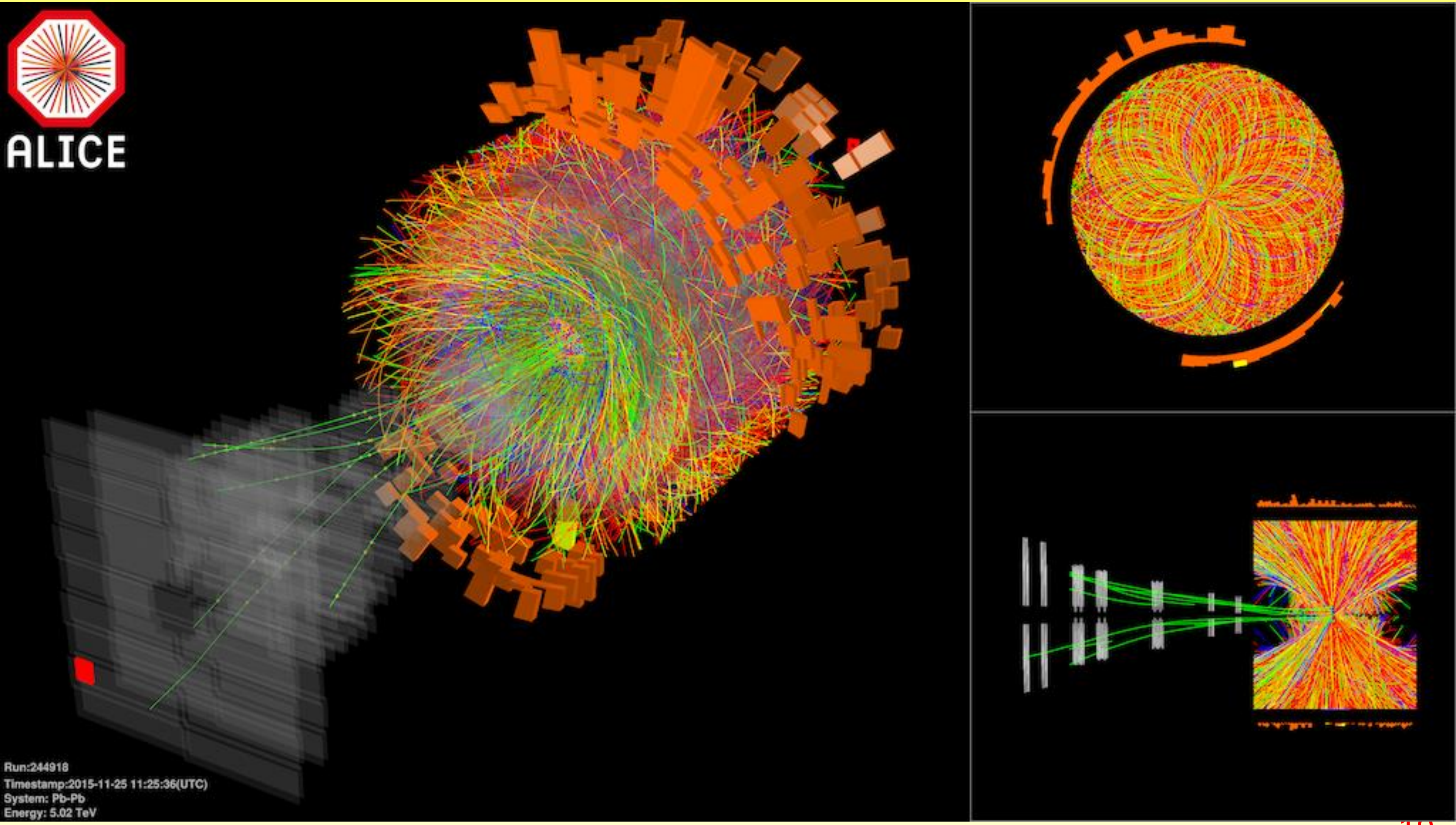


- Data for both calibration and Physics. Statistics >> RUN1

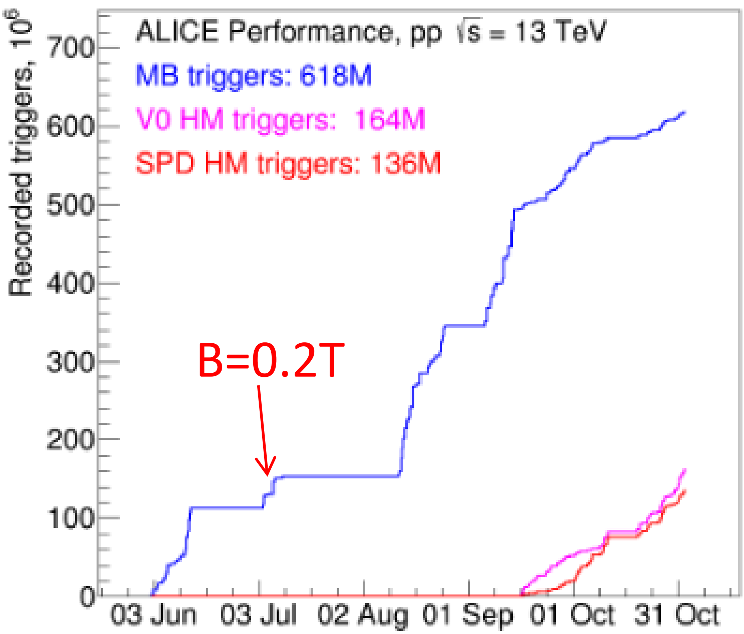
RUN2 2015: pp at 13 TeV

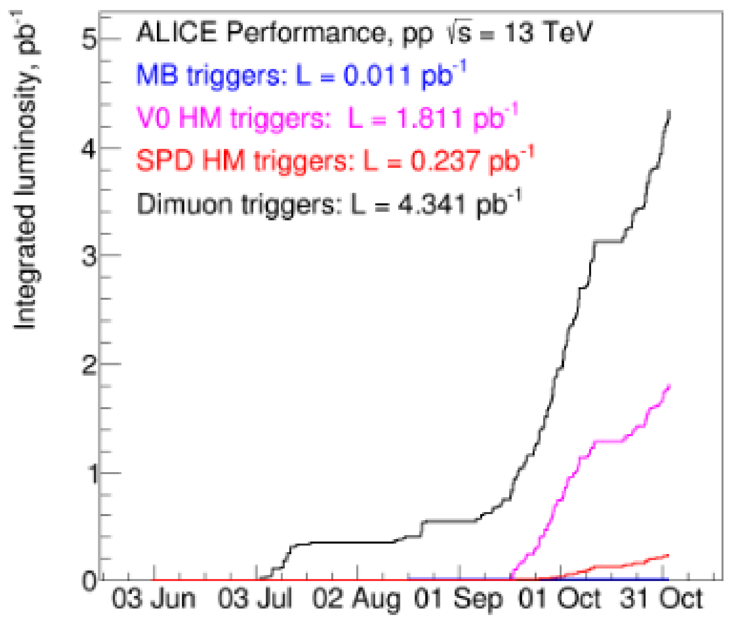


PbPb! PeV Collisions



2015 data taking overview: pp run at 13 TeV

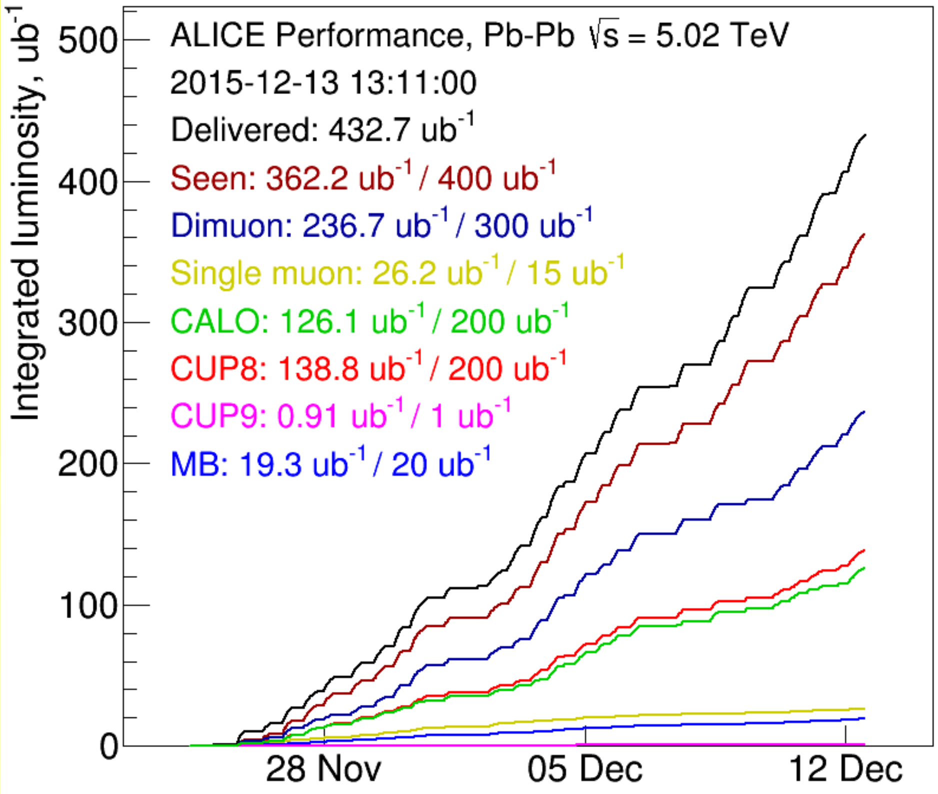


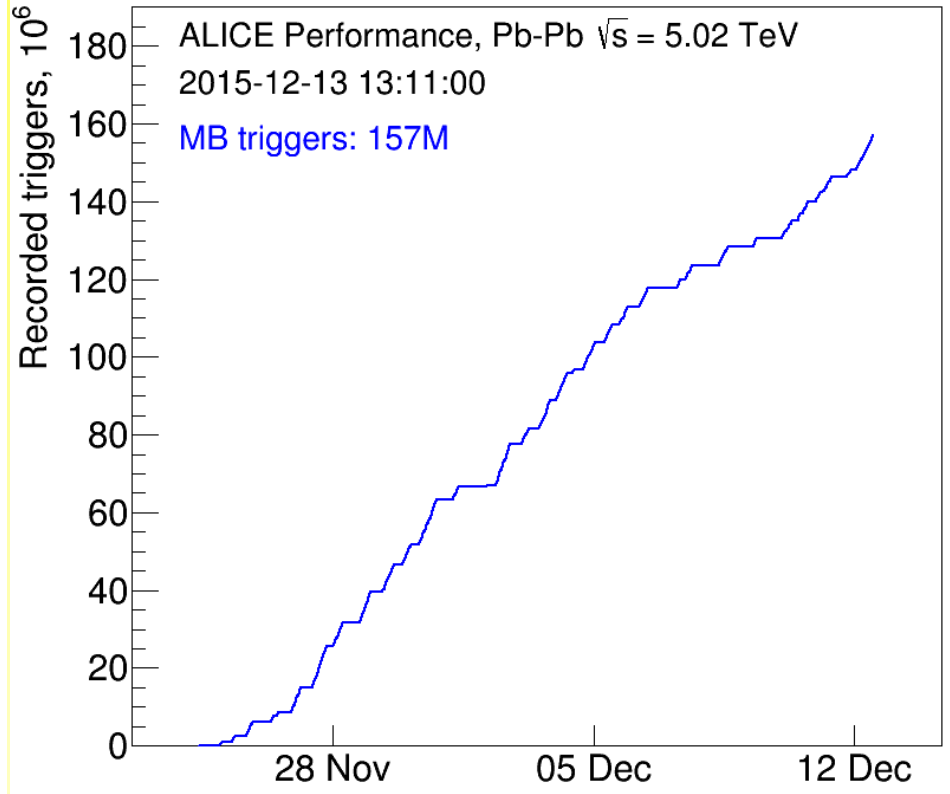


- **LHC restart (Isolated bunches): diffractive data taking with global OR triggers (V0 | AD | ZDC |SPD). Planned 100M, collected 165 M**
- **50ns: muon data taking**
- **90m run: diffractive data taking, collected ~250 nb^{-1}**
- **25ns: data taking at rates up to 5 Hz/μb with rare triggers and minimum bias data taking at low μ**

MB: planned 600M, collected 616M
muon triggers: planned 4pb^{-1} coll. 4.3 pb^{-1}
high mult triggers: planned 2pb^{-1} coll 1.8 pb^{-1}

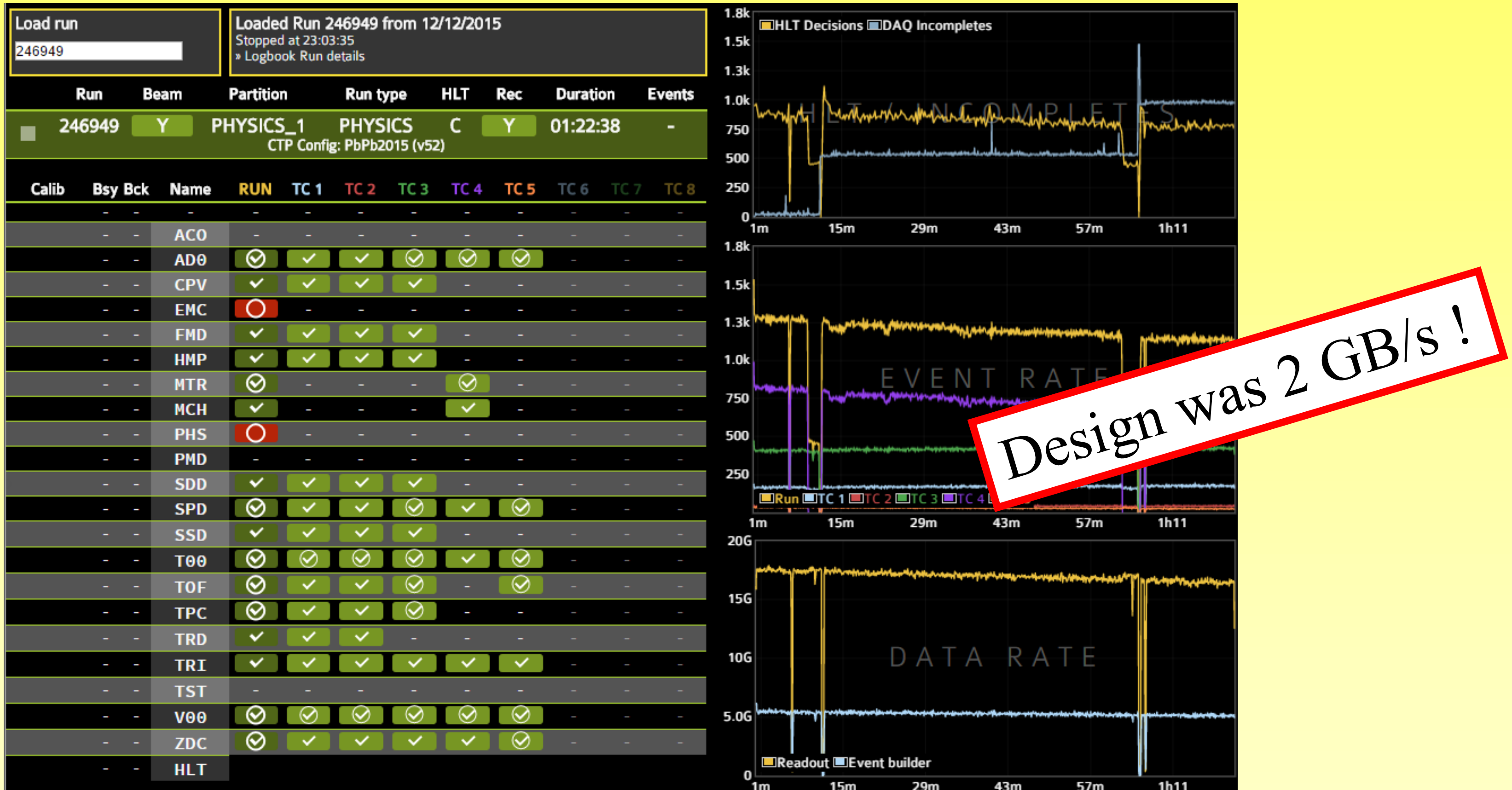
PbPb Run at 5.02 TeV





- Statistics close to our goals (especially for MB)

DAQ and HLT peak data rates during high intensity HI fills



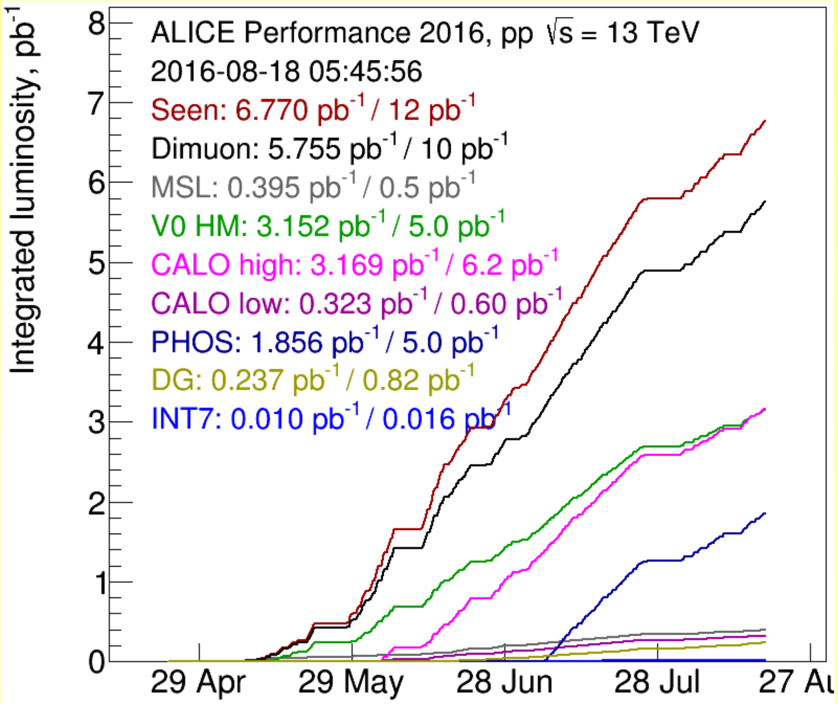
Peak data rates:
17 GB/s input from the detector
6 GB/s output to mass storage (after HLT compression)

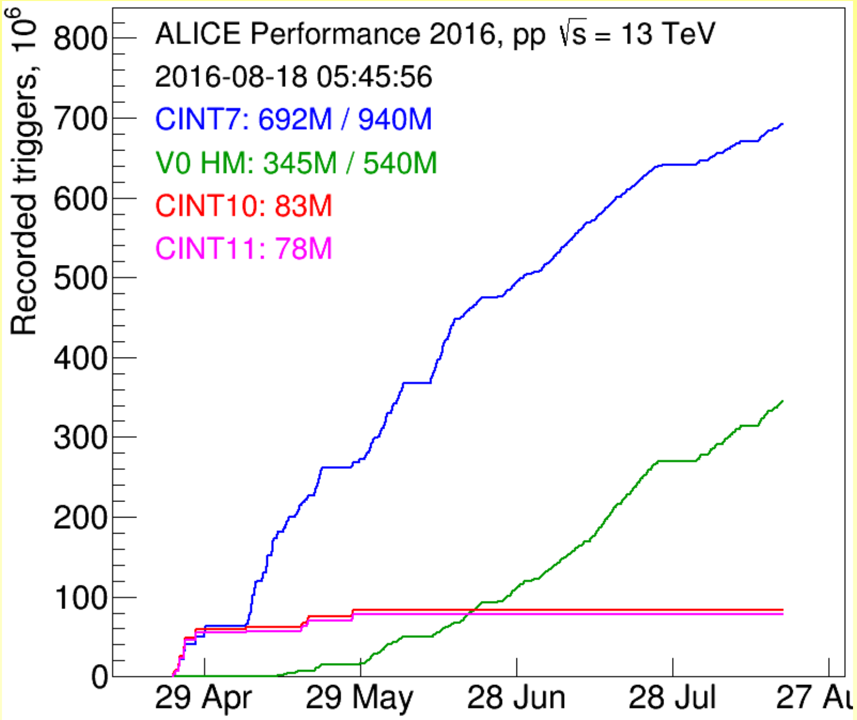
Over 7 Petabytes of data per year

ALICE – Performance 2016

Data Taking

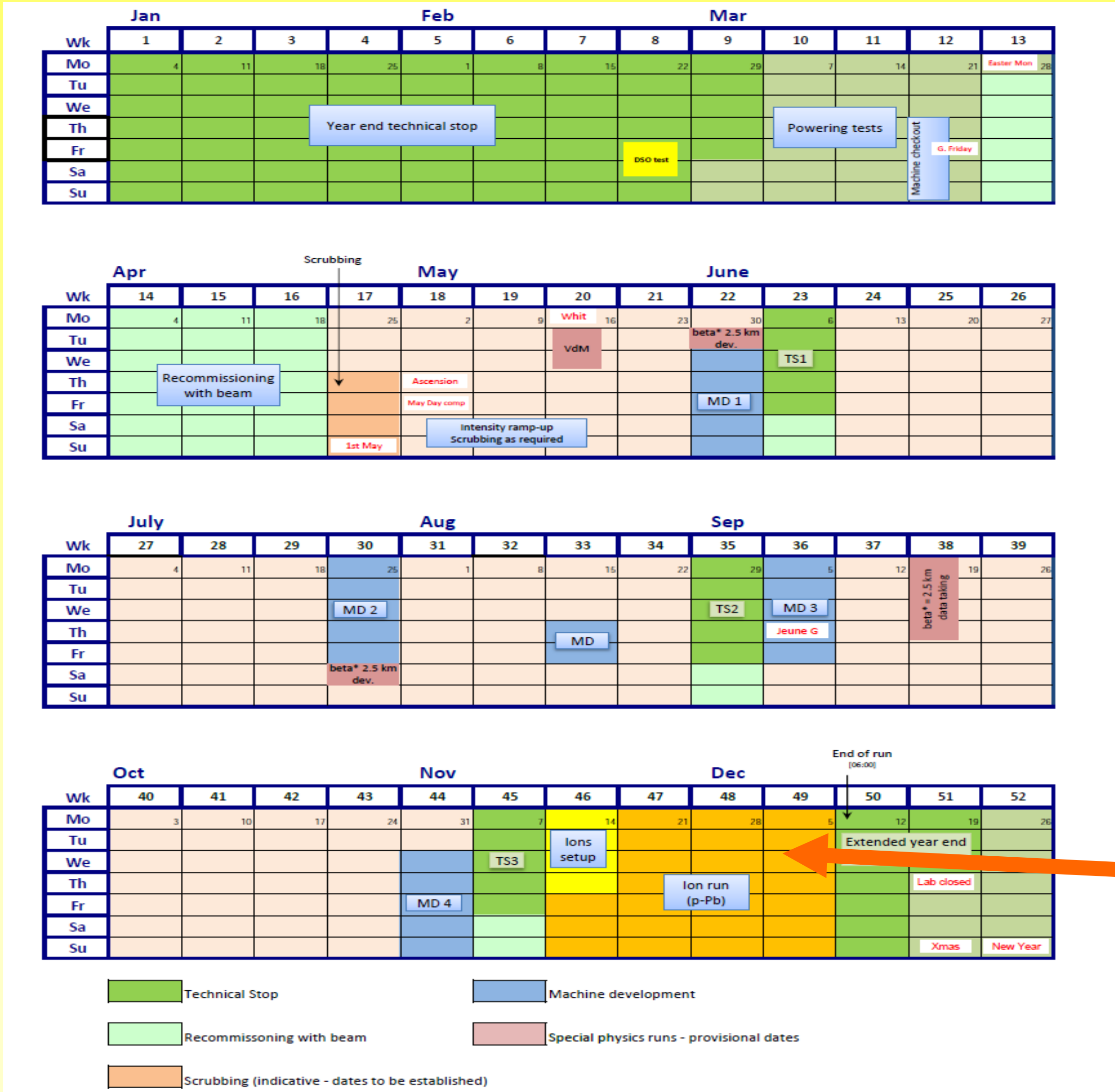
- ALICE is running with all 17 Detectors available
- Trigger selection include Minimum Bias and Rare Triggers
- ALICE is benefitting from long fills with 2000 bunches
- Overall Data Taking Efficiency is > 90%





pp data collection progressing very well;
expect to achieve goals for main pp data samples

Now taking more pp … eagerly waiting for pA at the end of the year



p-Pb run, ~ half at 8 and half at 5 TeV

Long term future of the LHC HI Program

- First discussions of the future beyond the originally approved LHC HI program (RUN1 and RUN2) around the development of the NUPECC Long Range Plan => first ideas of improving vertexing for heavy flavors and *10 times statistics
- Madrid NUPECC Town meeting May 2010 => TPC upgrade idea
- June 29th 2012 Town meeting of the whole HI community (at CERN)
  - Result: common document of the Community submitted to the Cracow European Strategy meeting, 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."***

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
- 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

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

The LS2 ALICE upgrades

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

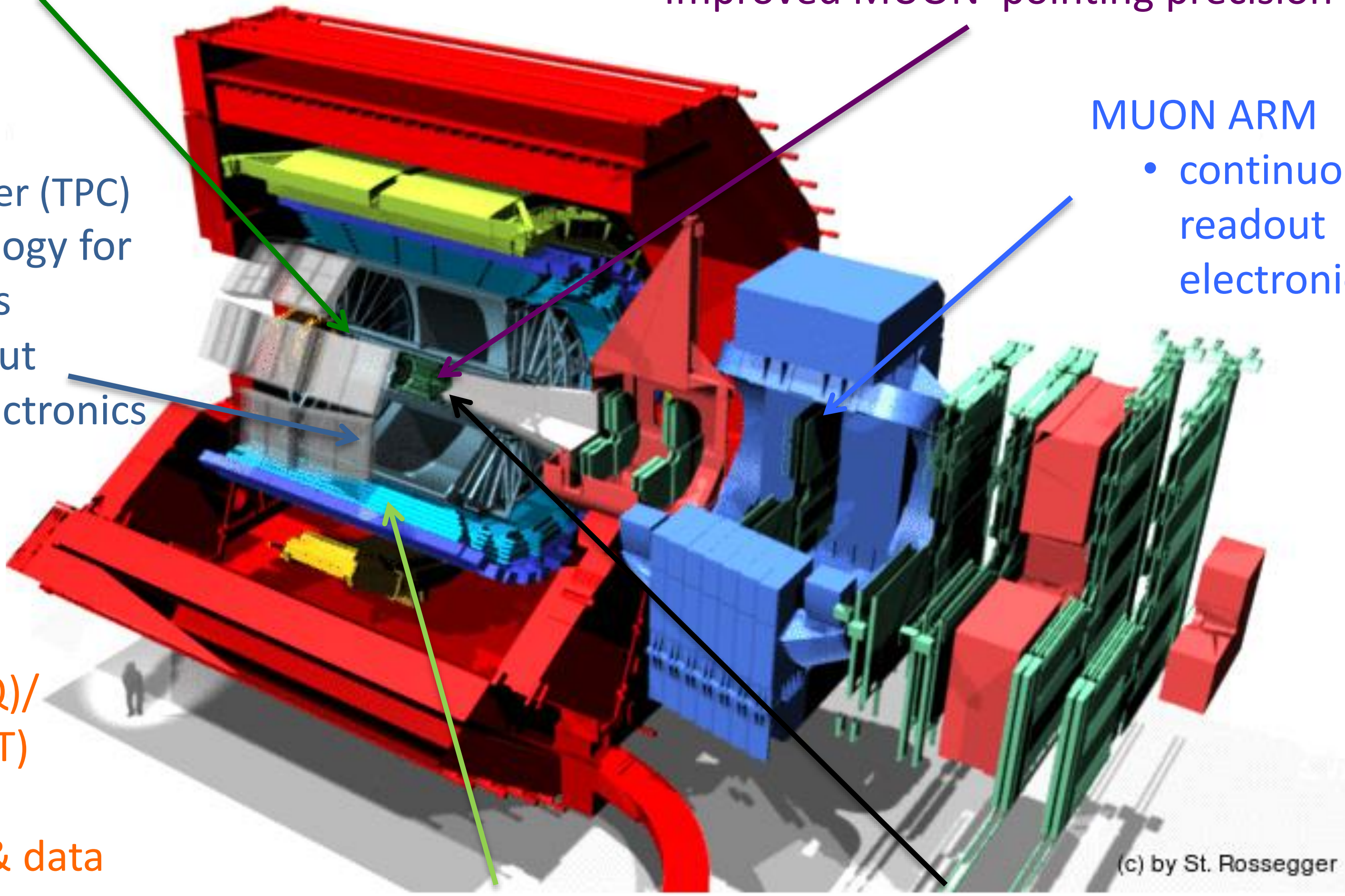
Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

MUON ARM
- continuous readout electronics

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

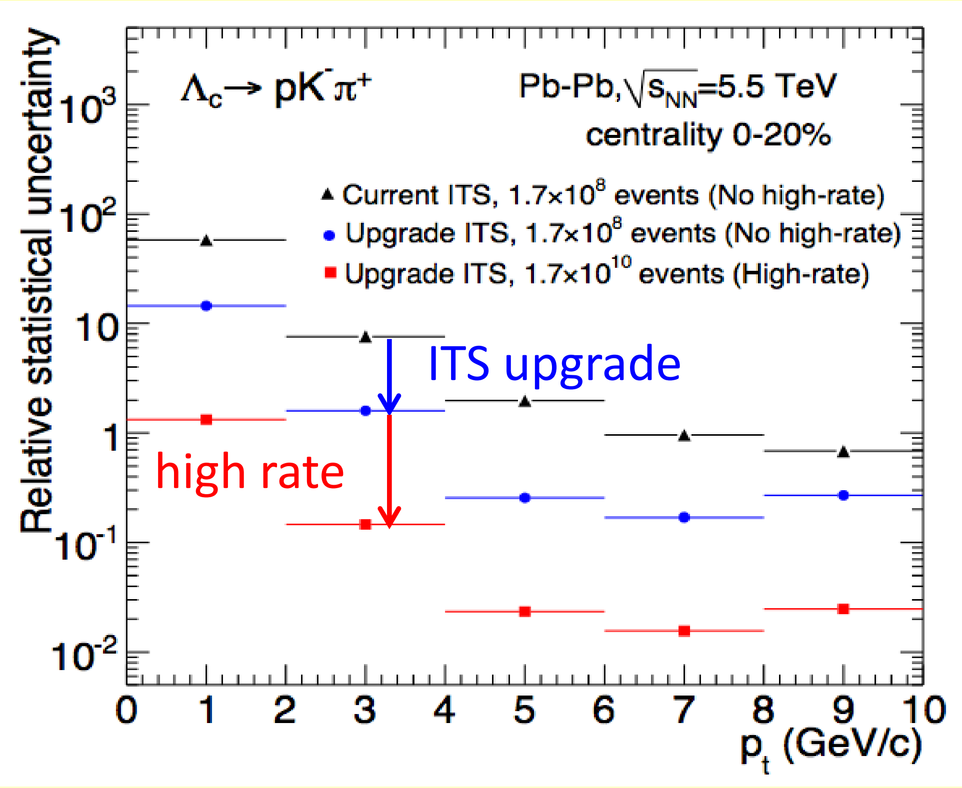
ALICE

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

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

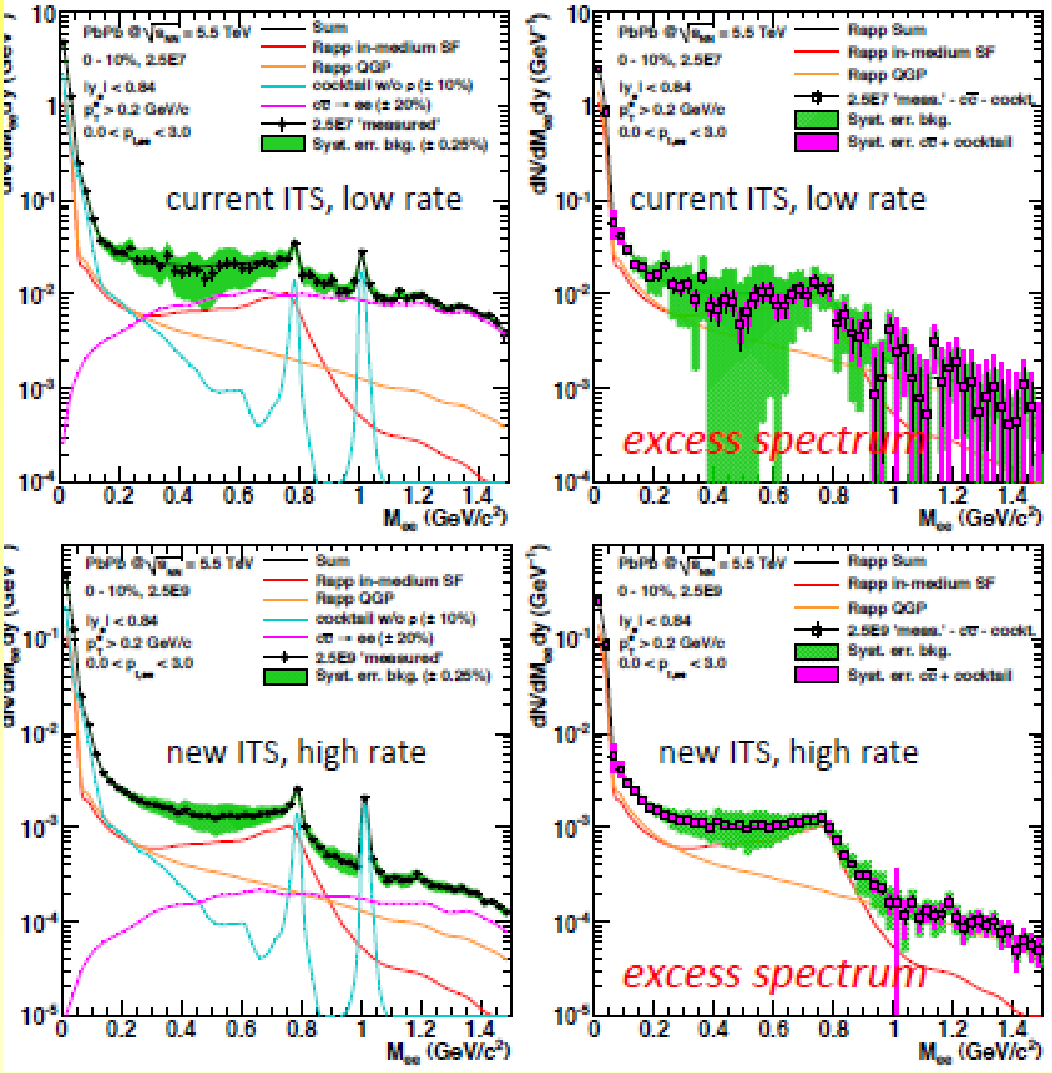
- Λ_c $c\tau$=60 μm, to be compared with D^+ $c\tau$=300 μm
  → practically impossible in Pb-Pb with current ITS



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



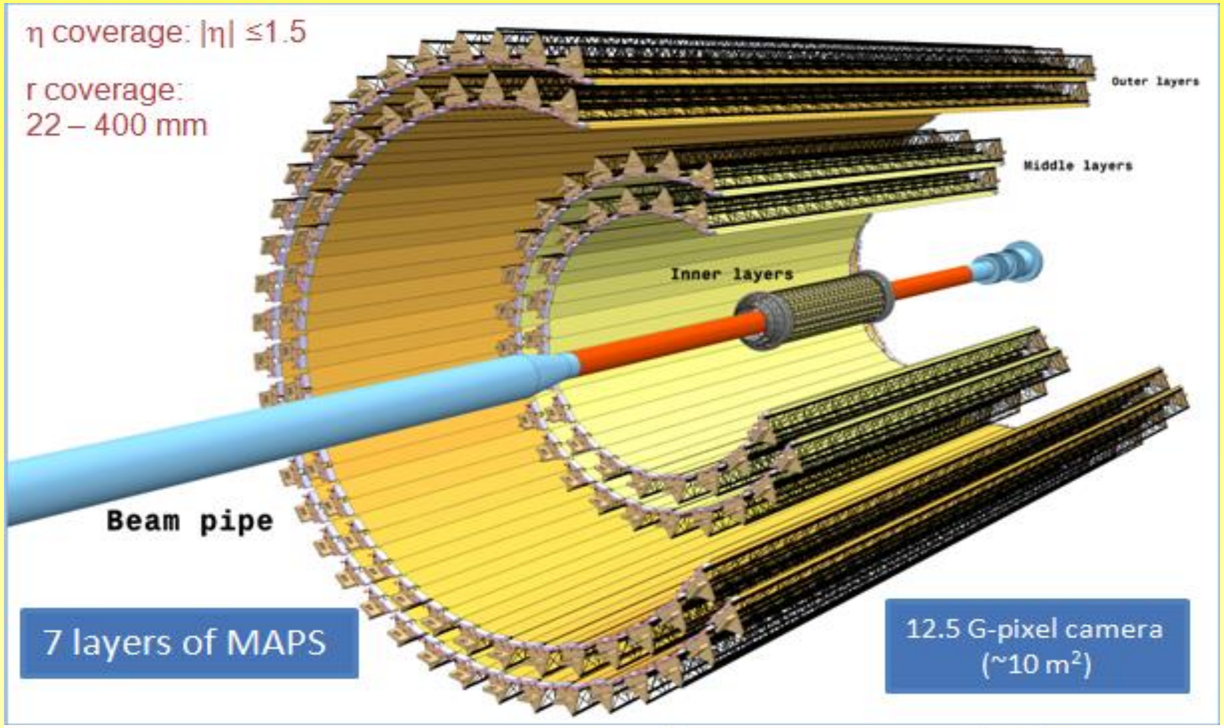
LoI and ITS CDR for the Upgrades, Submitted to the LHCC sept 6th 2012

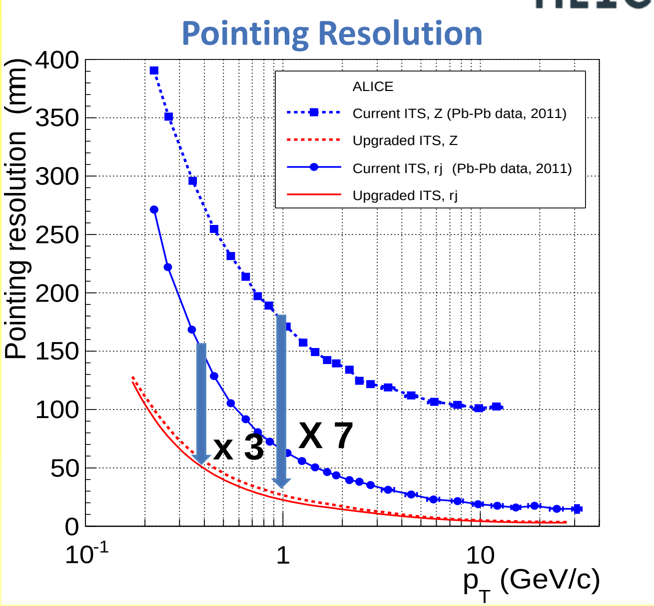
- **Endorsed by the LHCC** Sept 27^{th} , 2012:
  "The LHCC commends this joint approach to heavy ion physics and endorses the upgrade plans of the ALICE collaboration. The committee is looking forward to the seeing the detailed technical solutions presented in the respective TDRs. "
- **Approved by Research Board** Nov 28^{th} 2012
  "The Research Board approved the upgrade of ALICE for the physics case that has been made in the LoI, *based on up to 10 nb-1 of data taken with lead ions, implying that* ***the experiment will continue to run beyond 2018****. The CERN accelerator departments should assess the feasibility of delivering the requested integrated luminosity."*

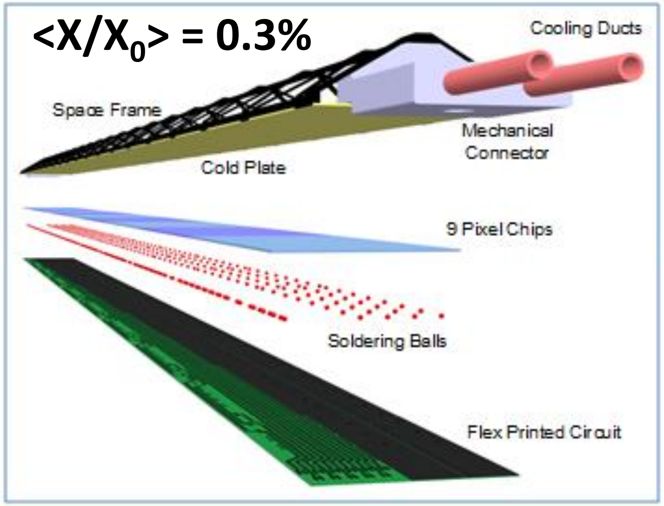
The ALICE Upgrade: status

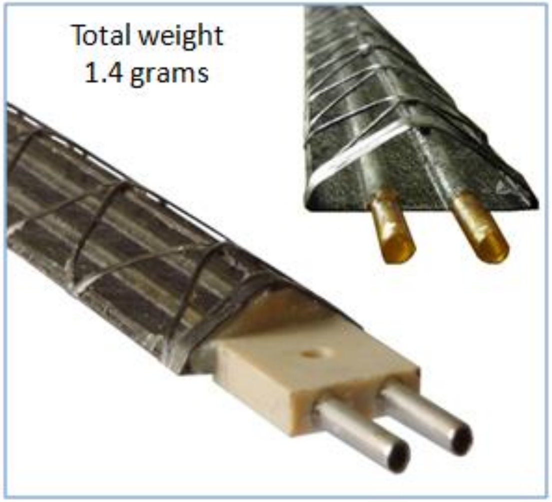
- **Five Pillars (each in a Technical Design Report), all approved by LHCC, UCG and RB in 2015**
  - Completely new Silicon Inner Tracking System
  - New or upgraded readout for all detectors to cope with the higher rate, new CTP and Trigger Detectors
  - New readout chambers for the Time Projection Chamber
  - New Silicon Tracker in front of Muon Absorber
  - New Data Acquisition System and High Level Trigger to handle the continuous readout, new Offline

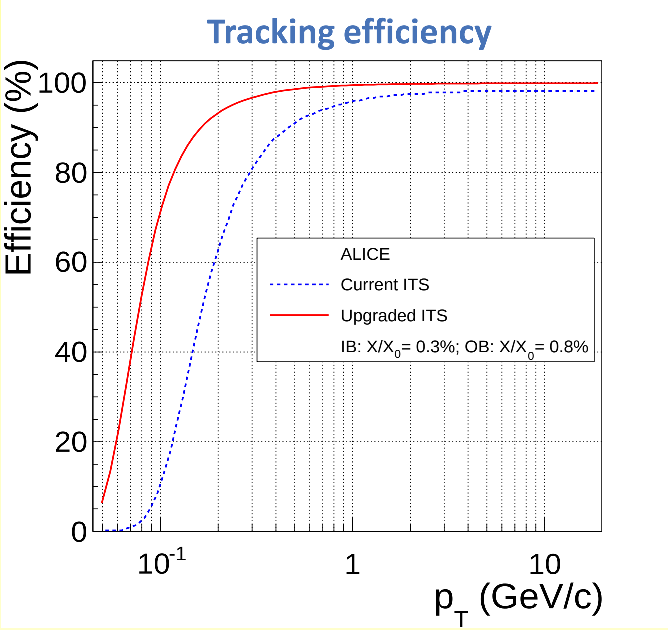
LS2 upgrade: new Inner Tracking System



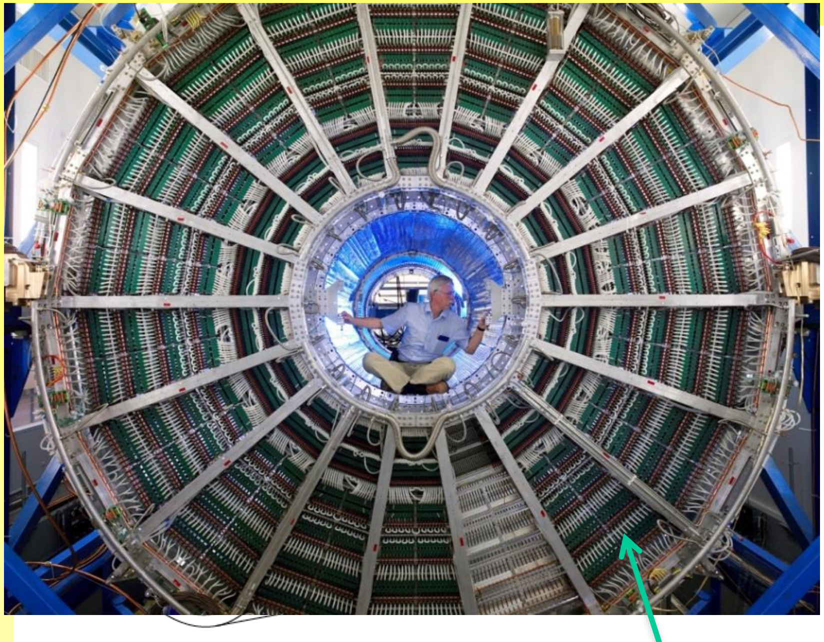








TPC Upgrade with GEMs



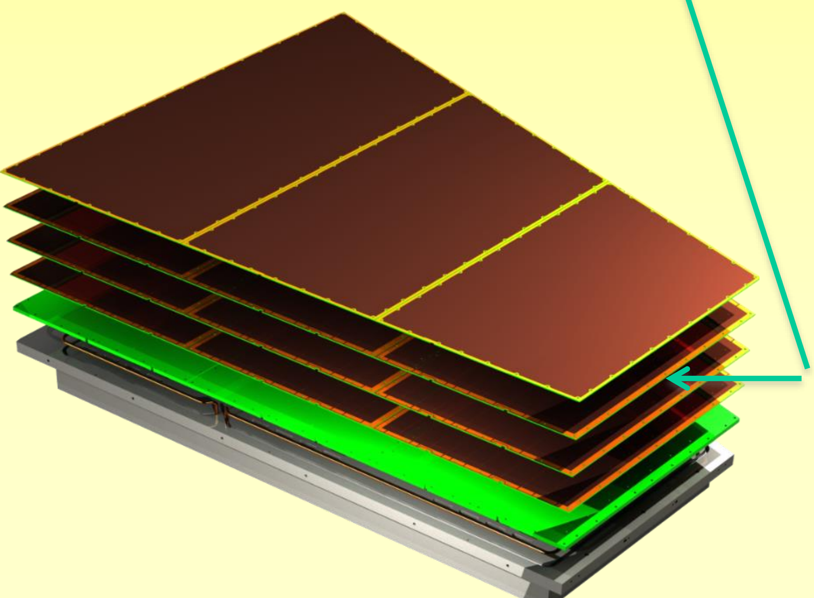
World Largest TPC
ALICE key tracking and PID instrument
500 million pixels

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



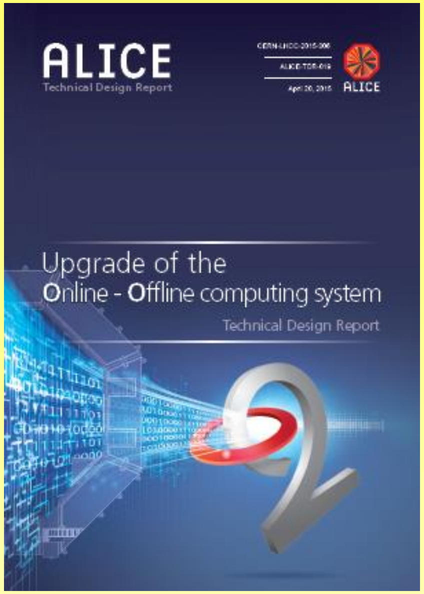
Replace wire chambers with quadruple-GEM

GEM and ROC EDR in November 2015

MoU sent to FA

Final decision on readout scheme taken

Online - Offline Computing Upgrade (O^2)



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

⇩ ⇧

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

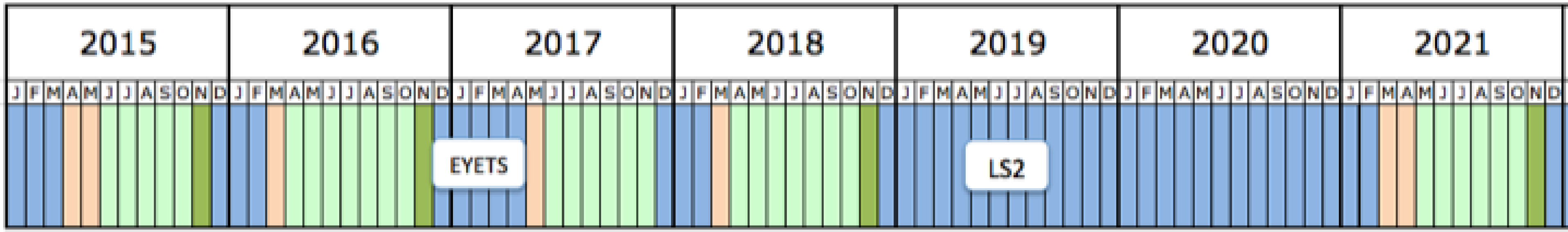
Tier 0

Tiers 1 and Analysis Facilities

20 GByte/s ⇔

Upgrade key milestones

ALICE



EYETS: O^2 EL and CV infrastructure in place

Nov-2017: ITS IB assembled

Dec-2015: SAMPA final prototype submission

Aug-2018: ITS OB assembled

Q3-2018: O^2 installed

19 Oct 2015: ITS pixel chip EDR

4 Nov 2015: TPC GEM and chamber EDR

→ start of production

Nov 2015: ITS stave EDR

Aug-Dec 2020: ALICE re-commissioning

Nov 2019-Jul 2020: install TPC/new ITS/MFT/FIT beampipe + close experiment

Mar-Oct 2019: TPC upgrade in cleanroom

Jan-Feb 2019: open experiment + remove TPC/ITS/beampipe

Dec-2018: TPC chamber production finished

Running scenario after the upgrade

- Pb–Pb
  - int. luminosity per year 2.85 nb^{-1} (peak $L = 7 \times 10^{27}$ $cm^{-2}s^{-1}$)
  - 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 dileptons
- 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 ($L = 3 \times 10^{30}$ $cm^{-2}s^{-1}$)
  - 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.

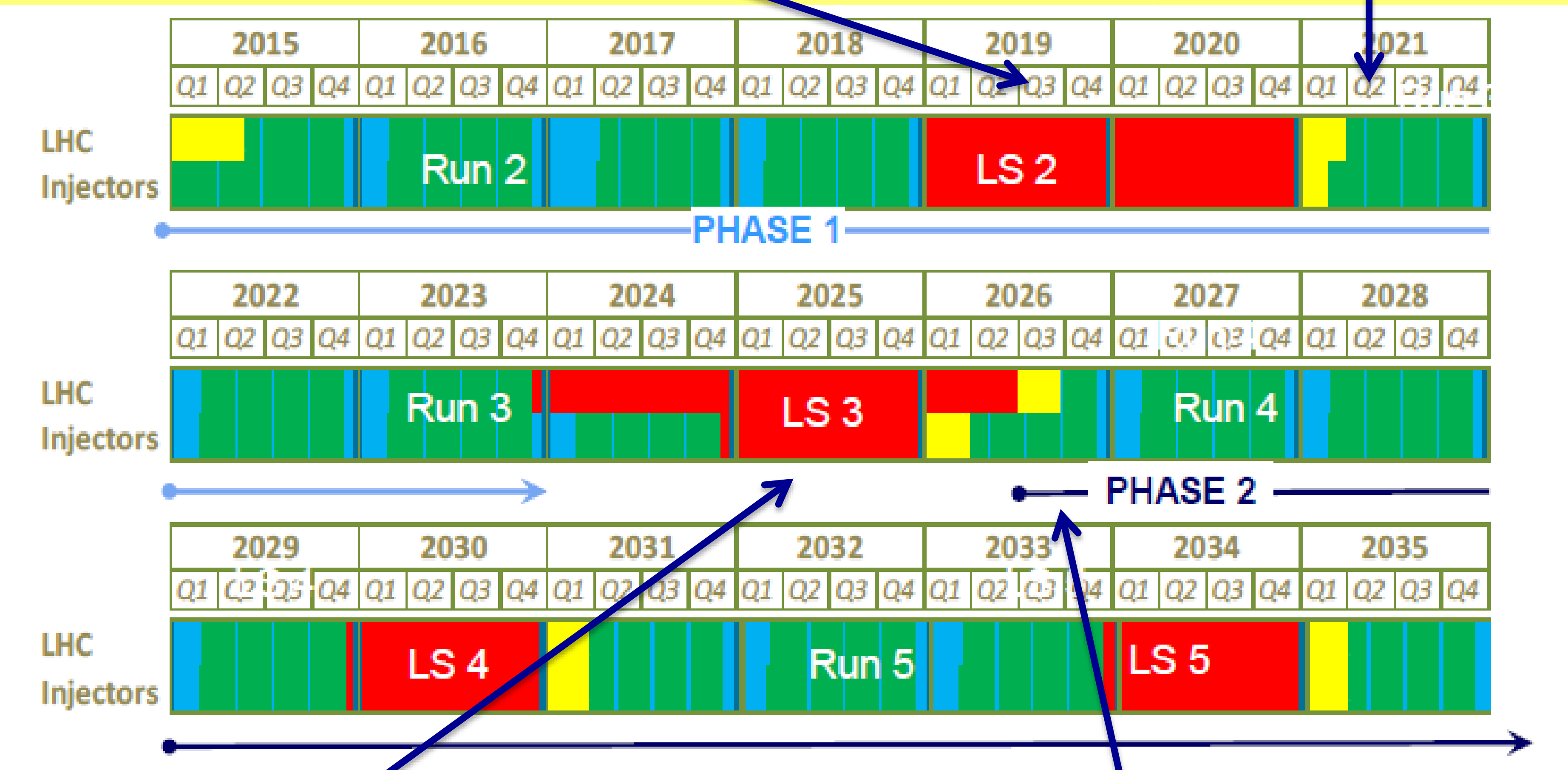
LHC Schedule

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)

Conclusions

- **Four phases of ALICE life**
  - A long preparation and construction
  - A very fruitful RUN1
  - The present RUN2 with 10 times the statistics and an improved detector
  - The future RUN3 and RUN4 with a further jump in statistics (10 times the luminosity, but 100 times the number of collected events) and a MUCH improved detector

- Peter has been a key player all along, in his many functions in the experiment: Project Ledaer of the TPC, Chair of the Collaboration Board, member of the Editorial Board, Member of the Physics Board, editor of the Upgrade LoI… and constant reference for new ideas and in-depth physics discussions. …. **And he will certainly play a major role also in the ALICE future he has shaped.**


-40
-20
0
20
40
30
20
10
-10
-30
Happy Birthday Peter!

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)

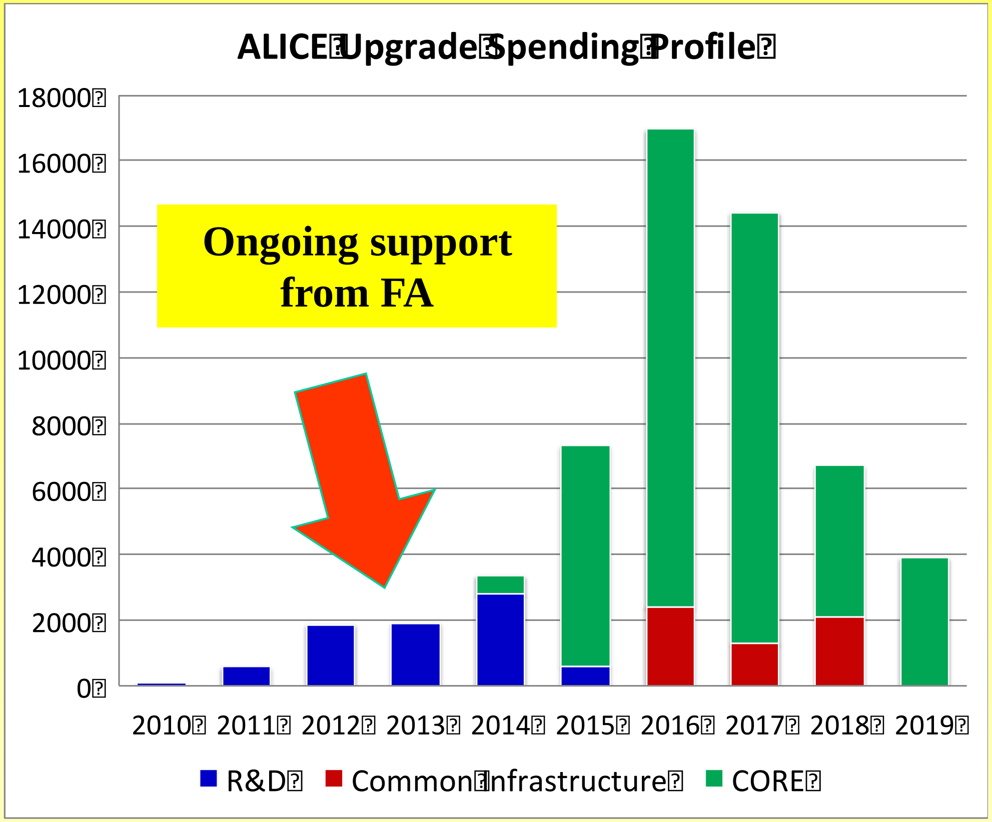
- The Future:
  - **RUN3 + RUN4 (2021, 22, 23 and 27, 28, 29): 10 nb^{-1}** with major detector improvements (plus a dedicated low-field run and pPb)

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

spares

Upgrades: CORE investment estimates & timelines

ALICE upgrade subsystem	CORE cost (MSF)
1. ITS	13.4
2. TPC	9.1
3. MFT	4.1
4. Other projects (Muon, TRD, TOF, etc..)	7.5
5. O2 (online/offline)	9.3
6. Common infrastructure	5.8
Total (MSF)	49.2
R&D costs MSF	7.85
GRAND TOTAL including R&D	57.0



- current best estimate (in 2014 values), final values appear progressively in the TDRs and UCG report.
- Sharing within the projects fixed on the basis of responsibilities, as detailed in the TDRs.
- Strong commitment from the collaboration: the know-how and human resources necessary to carry each of the upgrade projects exist. All projects backed by the commitment of large consortia of strong groups. The indications from the funding agencies in response to the group’s funding requests are encouraging, and give us confidence that the necessary funds will be available.

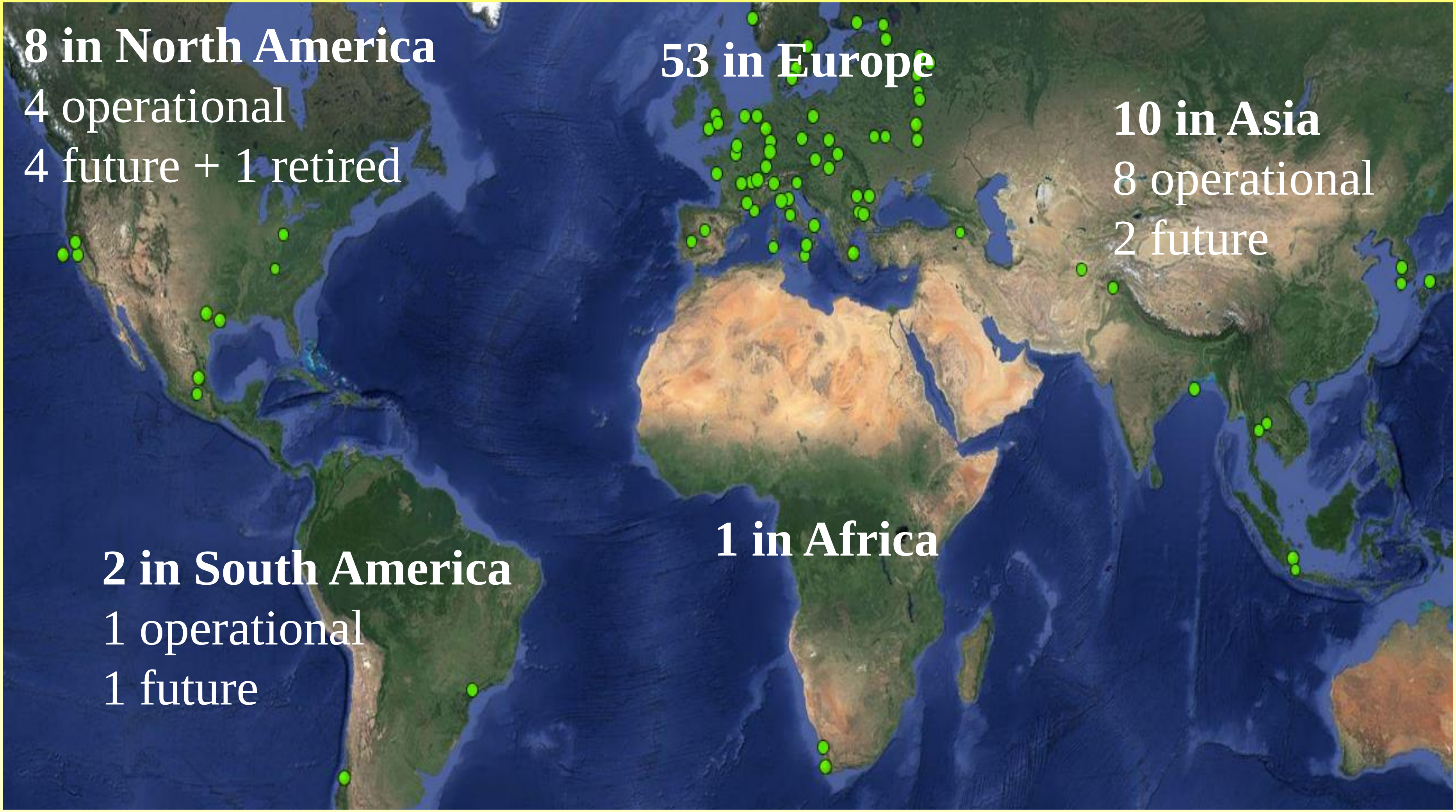
ALICE Upgrade Common Projects

Common Projects Item	Cost[MCHF]
Design and engineering	1.1
Installation Manpower	1.0
Services	1.6
Beam Pipe	1.5
Access and Support structures	0.6
Total	**5.8**

- Cost of common Projects to be shared by the whole collaboration, following the same rules as for M&O-A.
- Work progressing rapidly, beam pipe design has been finalized and is in the process of validation by the LHC.

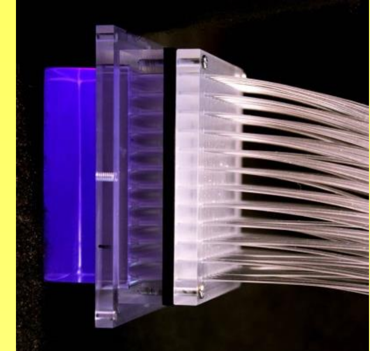
STORING, PROCESSING AND ANALYSIS OF THE DATA:

The ALICE GRID



- Currently over 60k jobs run in parallel….

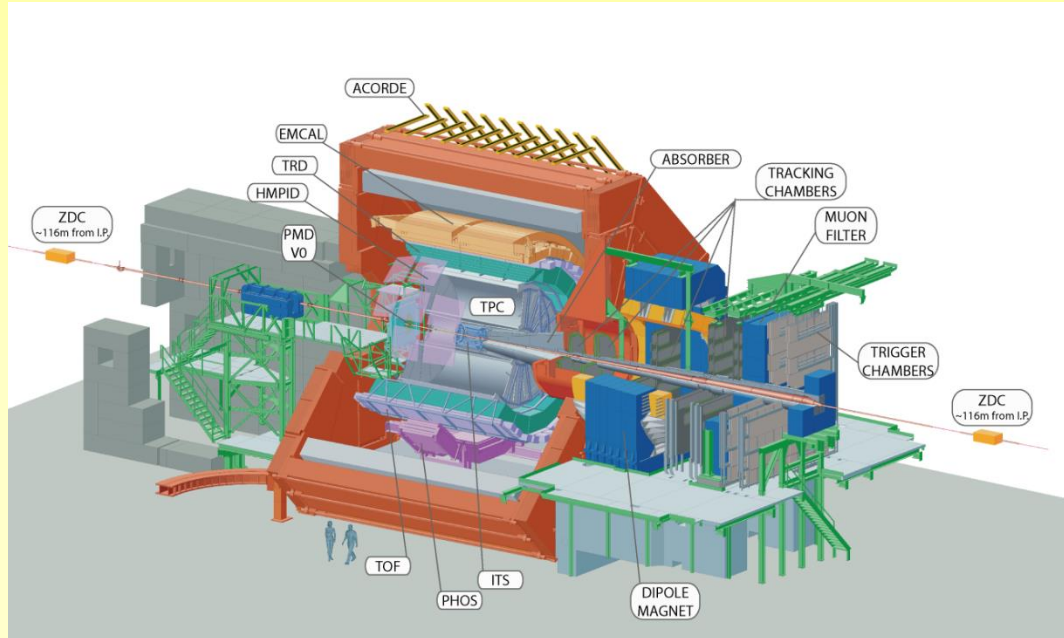
Upgrade of the ALICE Readout and Trigger System



FIT

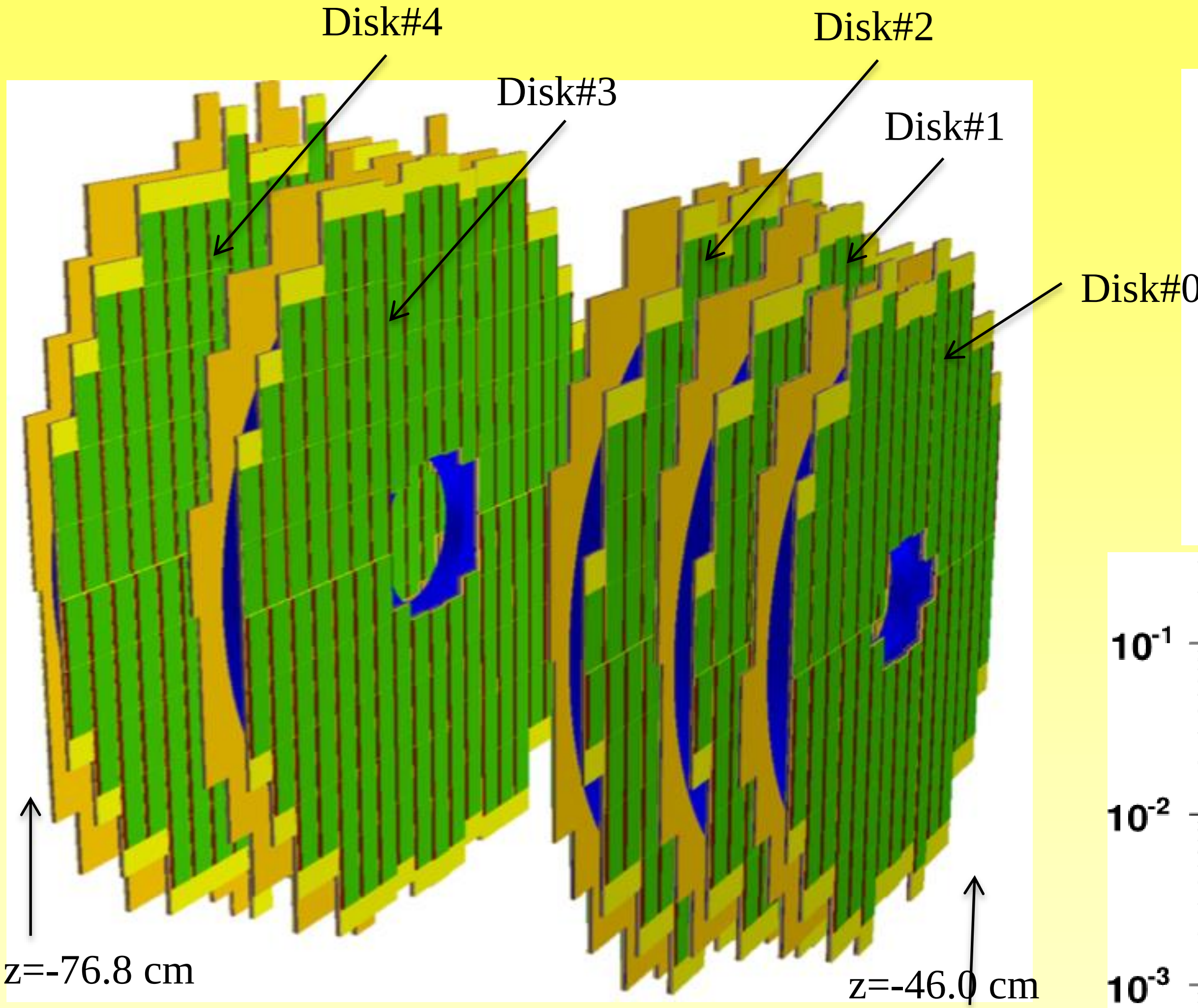
- New Forward Trigger Detector (FIT)
- New Central Trigger Processor (CTP)
- Electronics upgrade for 100 kHz Pb-Pb interaction rate of
  - Time Of Flight Detector (TOF)
  - Transition Radiation Detector (TRD)
  - Muon System
  - TOF
  - ZDC

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



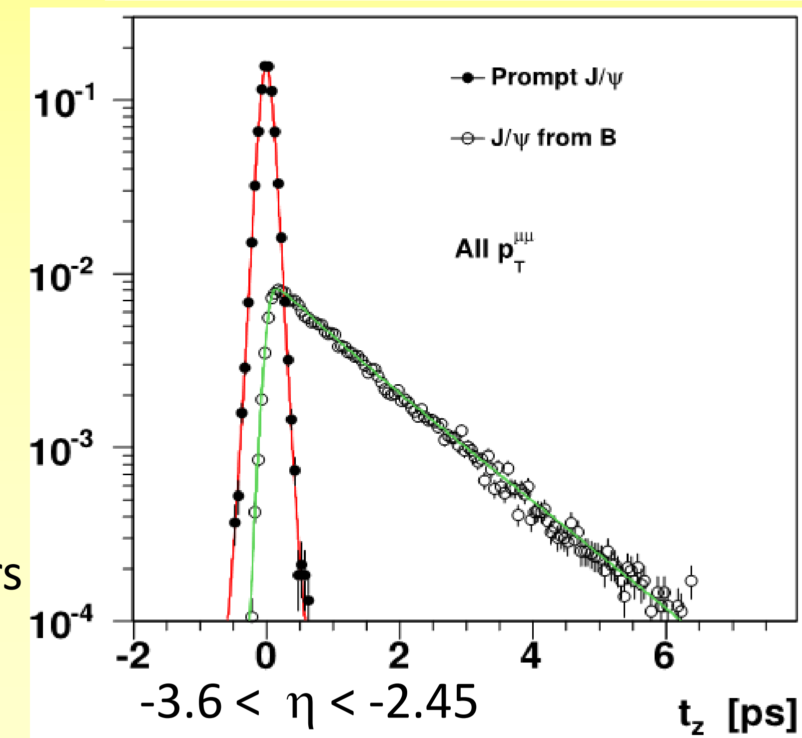
Muon Forward Tracker

ALICE



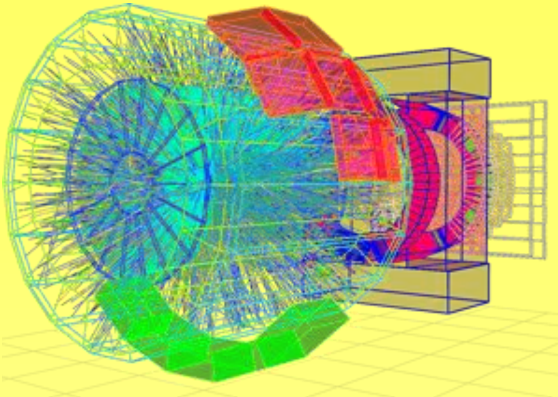
Secondary vertexing for the muon spectrometer

- **$c \rightarrow \mu$**
- **$b \rightarrow J/\psi$**
- **low mass di-muons**
- **$\psi(2S)$**
- **...**



- **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

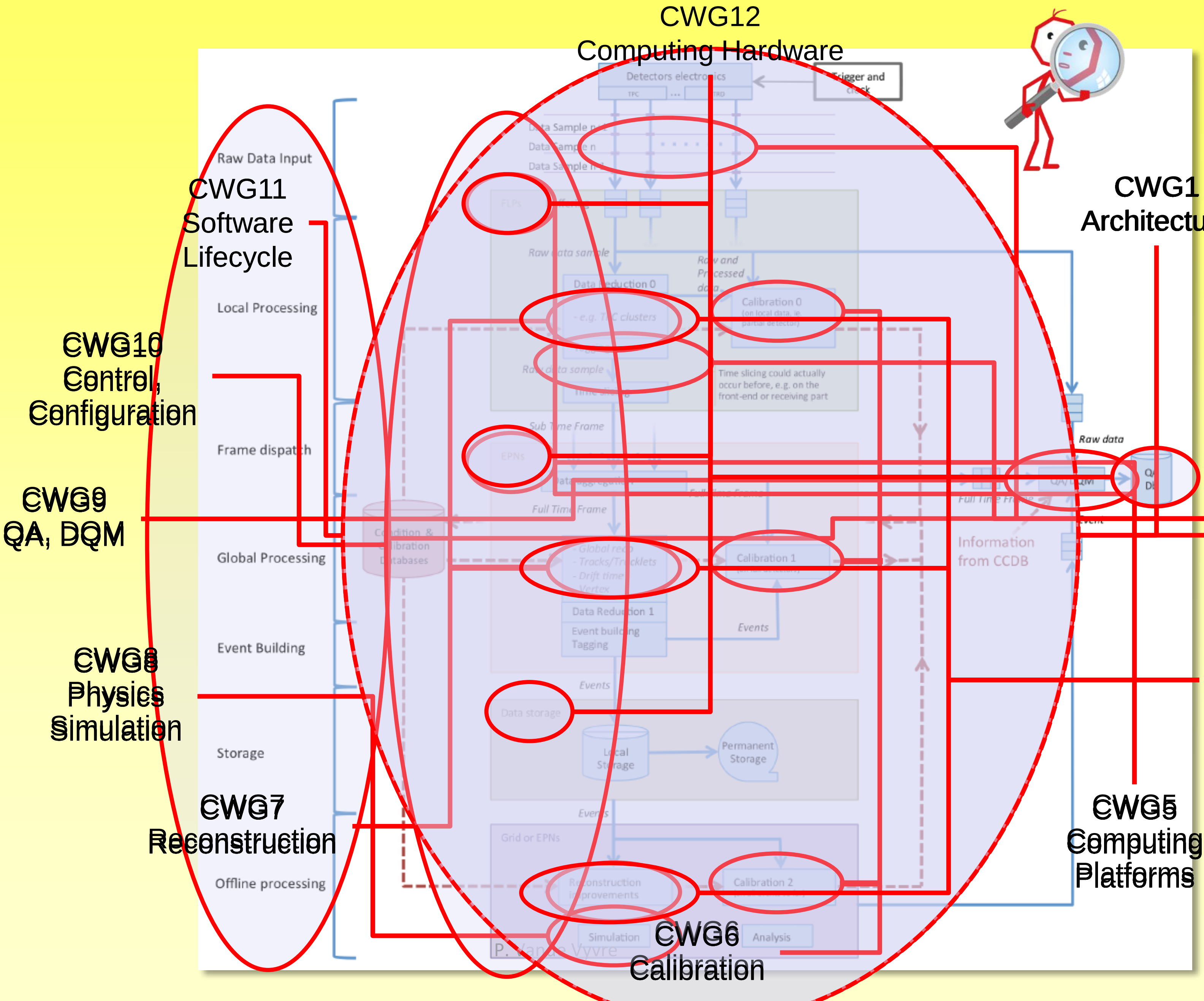
O^{2} (Online Offline) System

Storage

75 GB/s

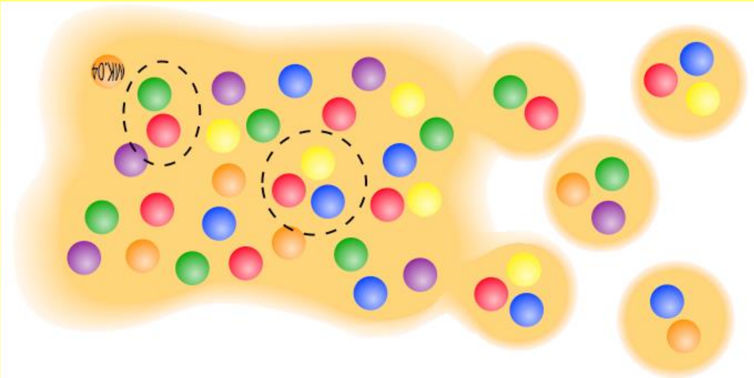
← PEAK OUTPUT
(20 GB/s average)

O^2 Computing Working Groups



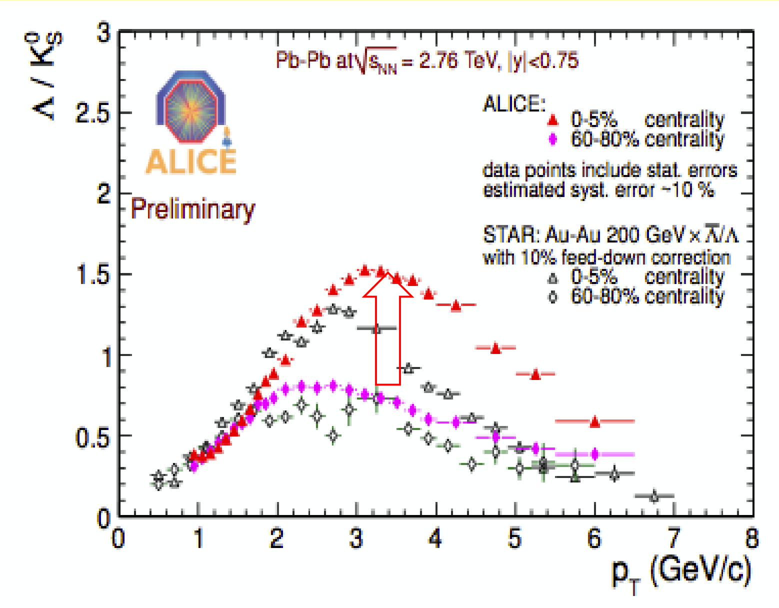
HF thermalization and in-medium hadronization: Λ_c and D_s as probes

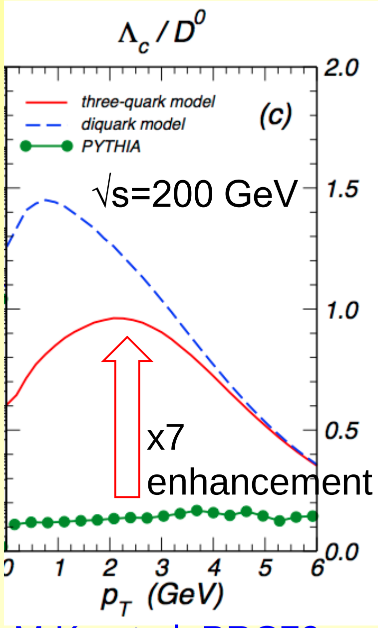
- Baryon/meson enhancement and strangeness enhancement → indication of light-quark hadronization from partonic system



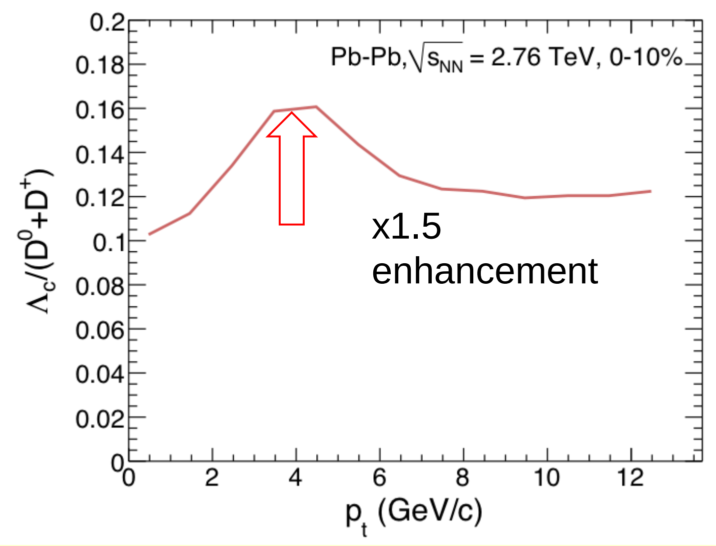
➡ Charm baryons (Λ_c)

- Λ_c/D enhancement predicted by coalescence models. Size of effect depends strongly on details of c quark thermalization





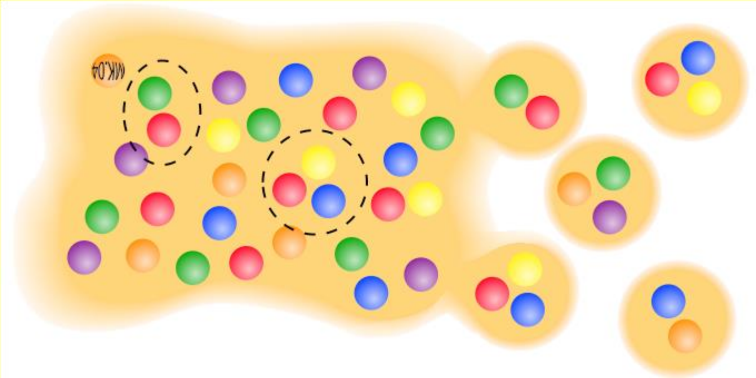
C.M.Ko et al. PRC79



R. Rapp et al. PRC86

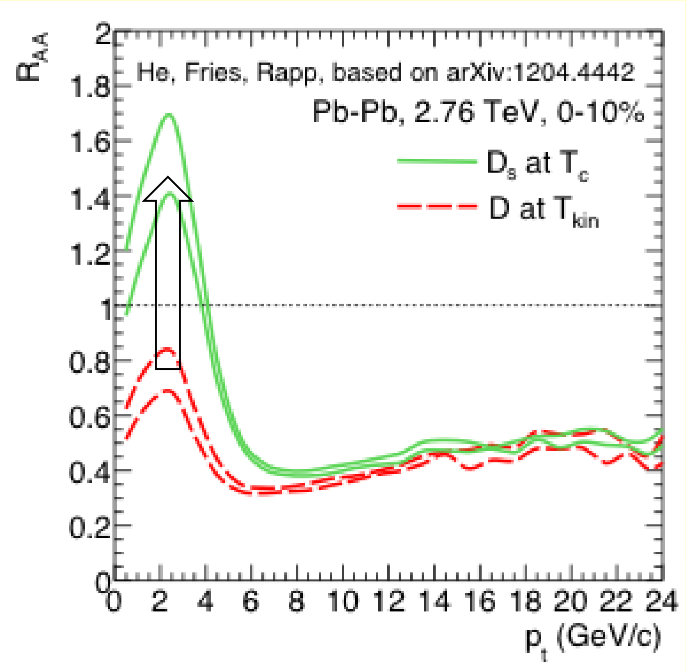
HF thermalization and in-medium hadronization: Λ_c and D_s as probes

- Baryon/meson enhancement and strangeness enhancement → indication of light-quark hadronization from partonic system

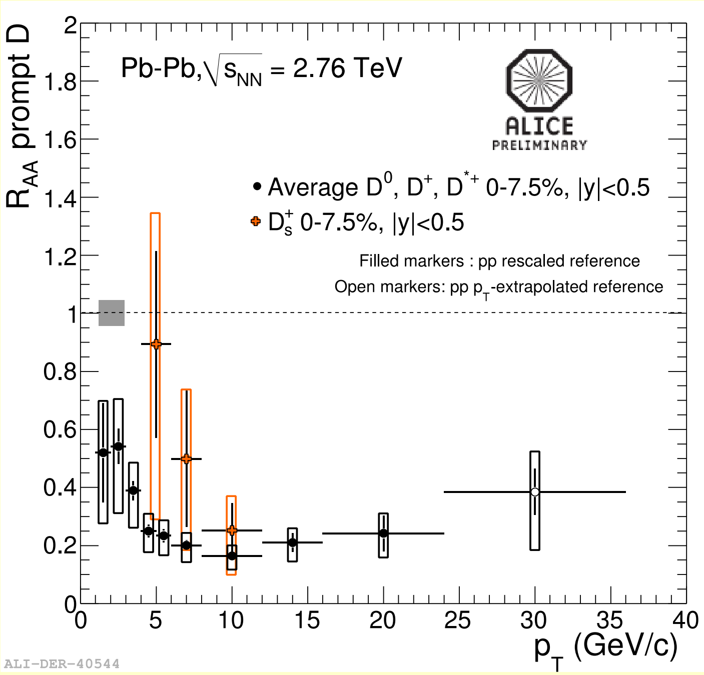


➡ Charm-strange mesons (D_s)

Factor 2 enhancement for D_s/D predicted by coalescence

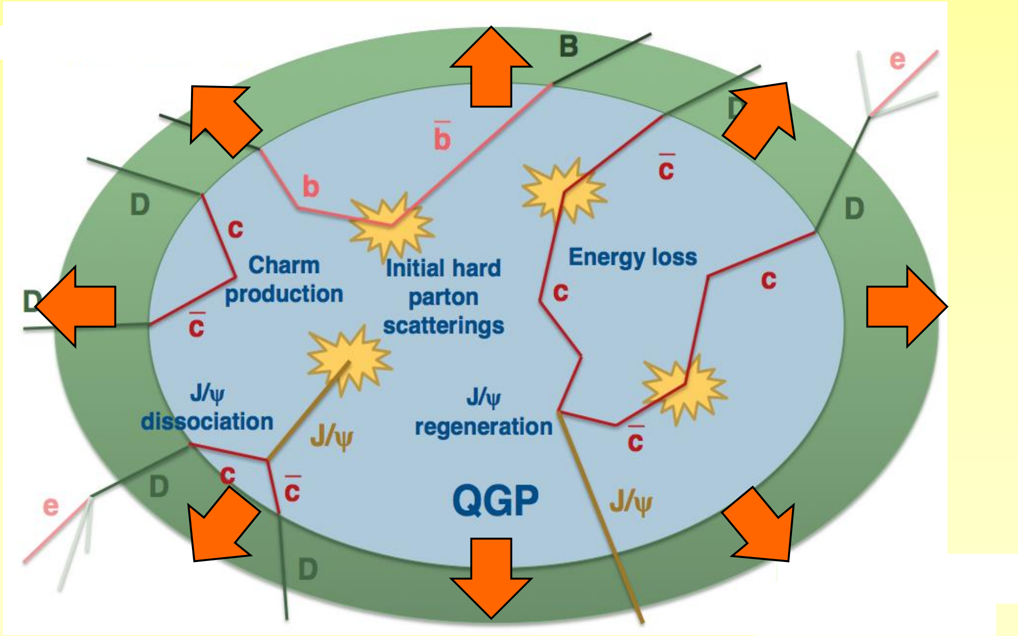


Our first measurement is intriguing, but not conclusive

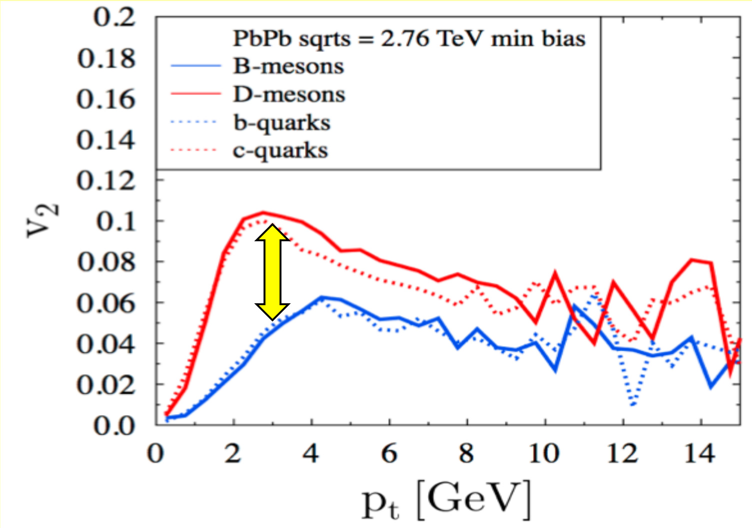


Heavy flavour v_2

- Uniqueness of heavy quarks: cannot be "destroyed/created" in the medium → transported through the full system evolution
- Due to their large mass, c and b quarks should "feel" less the collective expansion
  - → need frequent interactions with large coupling to build their v_2 → $v_2^b < v_2^c < v_2^q$
- HF v_2 sensitive to medium viscosity and equation of state

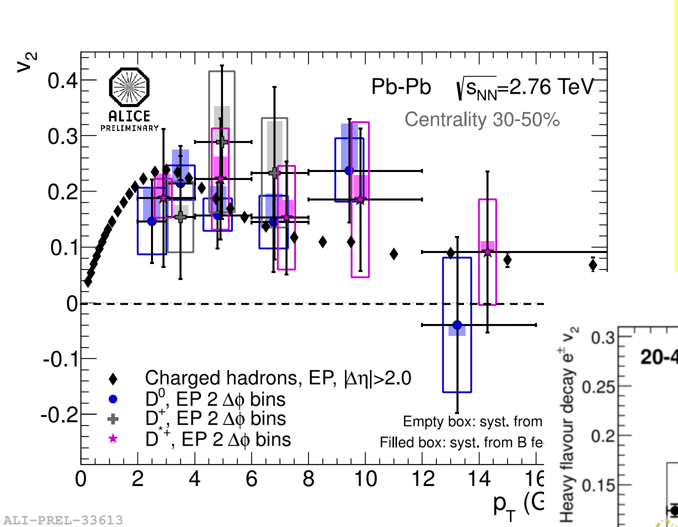


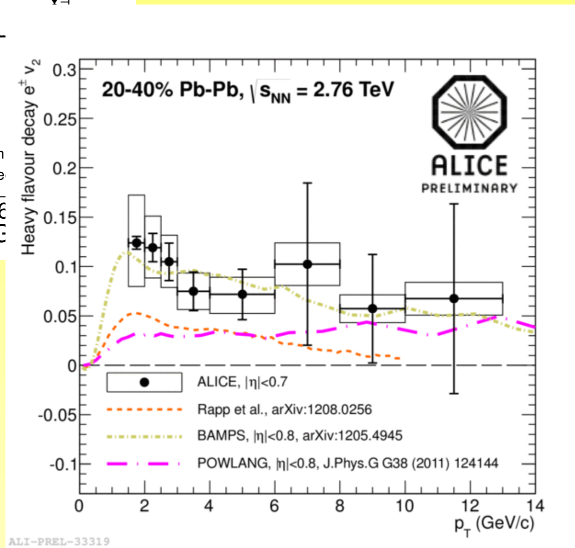
See also J. Uphoff et al., R. Rapp et al., A. Beraudo et al.



J. Aichelin et al. in arXiv:1201:4192

Heavy flavour v_2: present and future





- ALICE preliminary results with full 2011 sample (10^7 events in 30-50%)
- Indication of non-zero v_2
- But uncertainties are substantial
  - Reduction by x0.6 expected with 2015-16 data

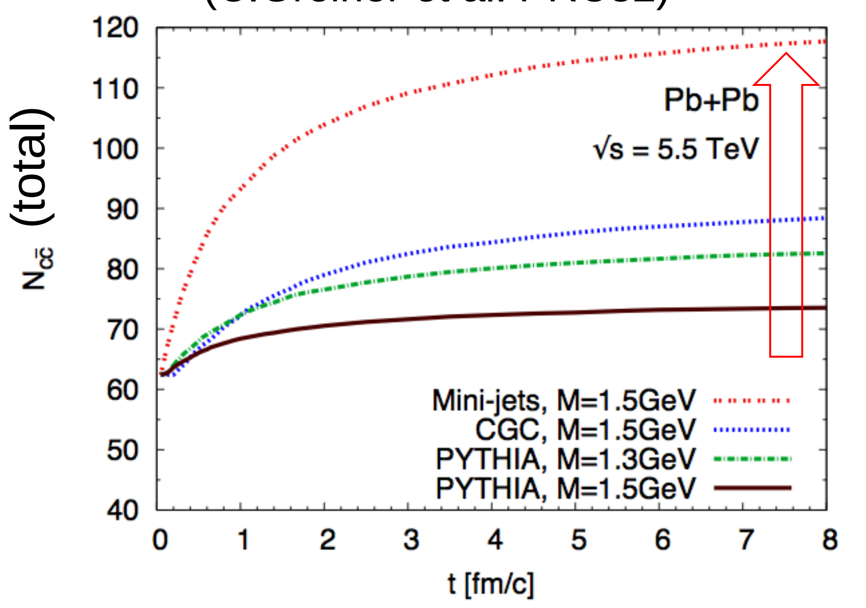
→ Need precise measurement of v_2 of D and B mesons to answer these questions:

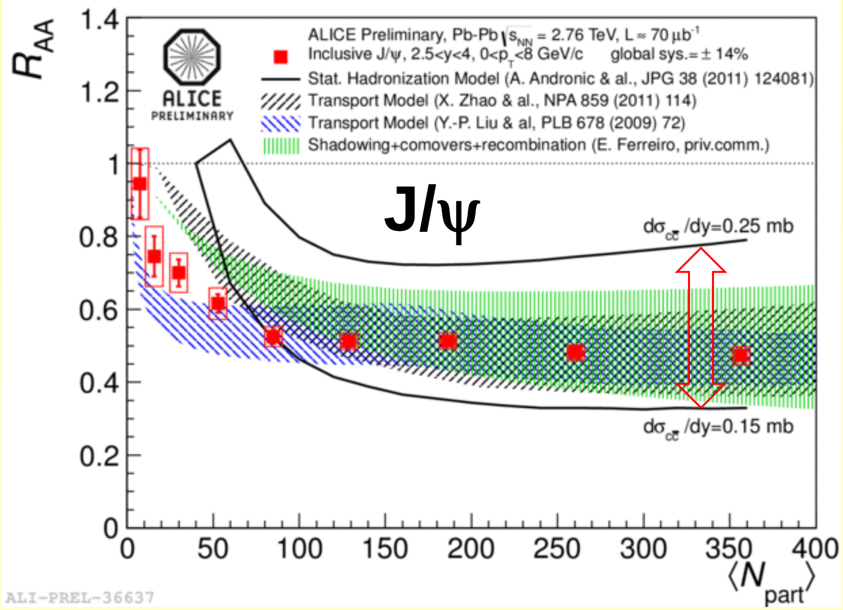
- is v_2 of charm the same as of pions?
- is v_2 of beauty smaller than of charm?
- comparison with models → HQ transport coefficient of QGP

Measuring the total charm production

- Reaching $p_T \rightarrow 0$ in central Pb-Pb provides:
  - Handle on the possibility to detect thermal charm production
    - May increase low-p_T yields by up to 50-100%
    - Sensitive to initial temperature of the QGP
  - Natural normalization for total charmonium production
    - Total charm yield: main uncertainty in J/ψ regeneration models

(C.Greiner et al. PRC82)



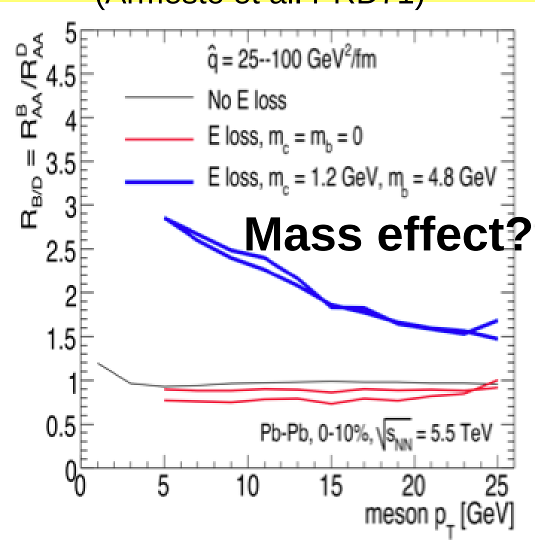


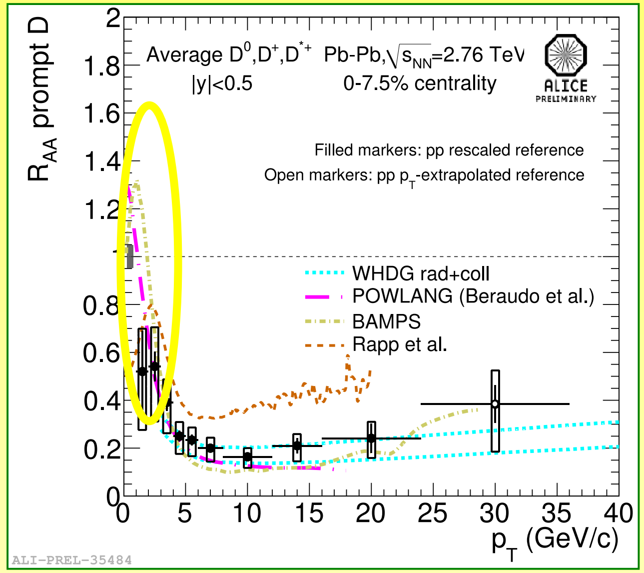
(see also C.M.Ko et al. PRC77)

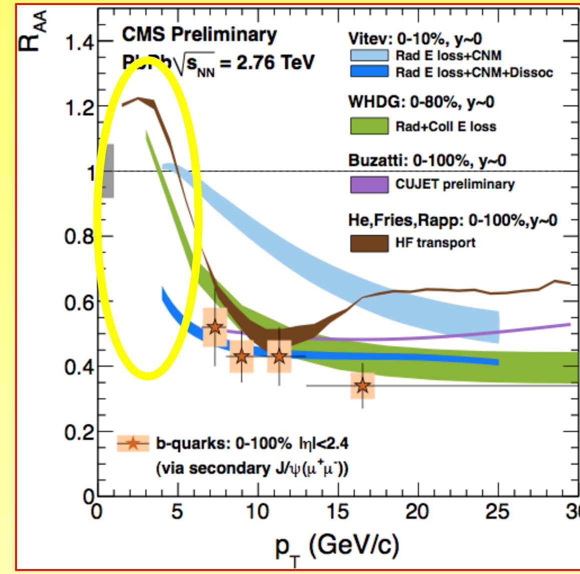
Heavy-flavour quenching

- Goal: measure D and B separately down to low p_T

B/D R_{AA}
(Armesto et al. PRD71)





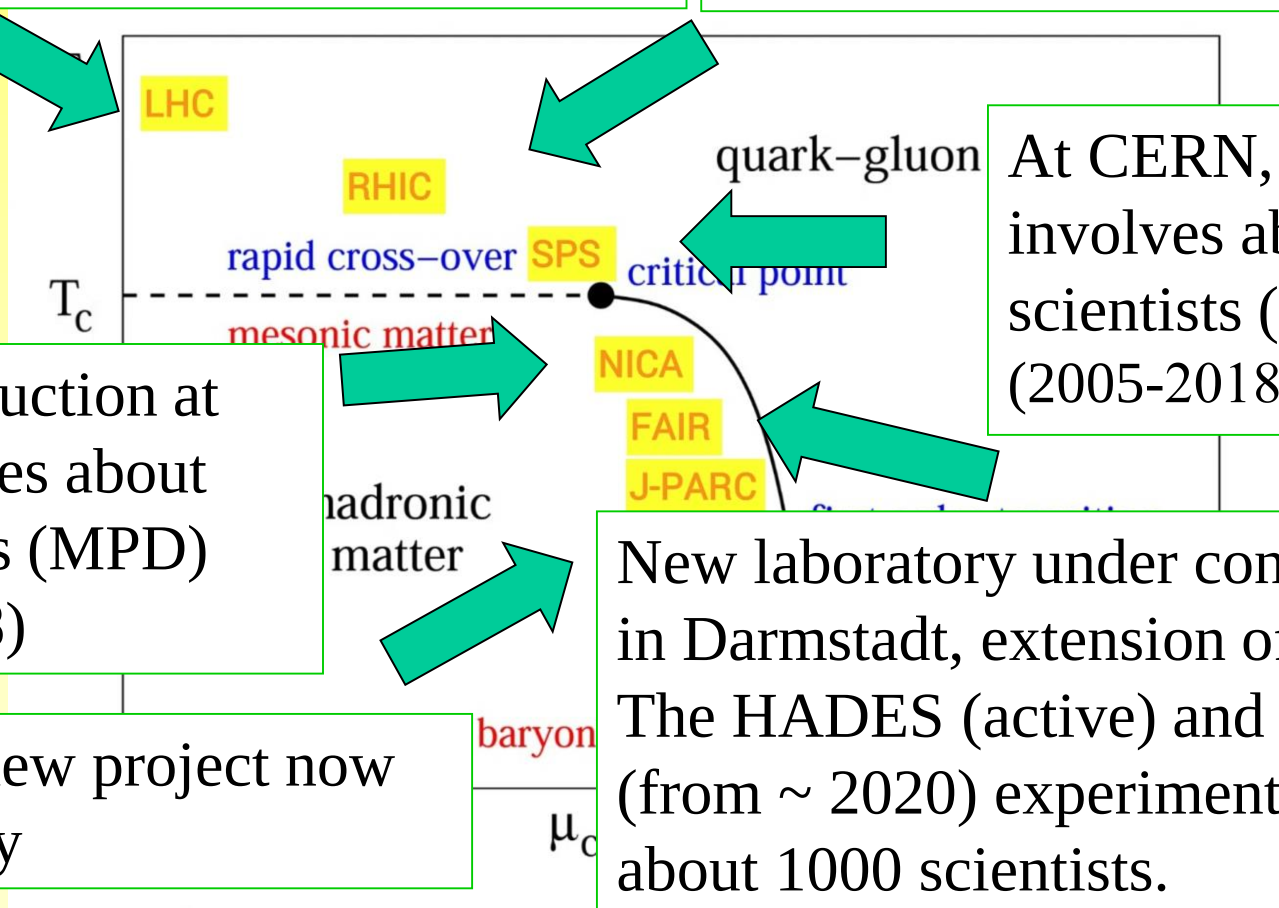


- Latest ALICE (charm) and CMS (beauty) data from QM2012: not conclusive in comparison with models at low p_T
- Overcome current ALICE limits:
  - charm difficult for $p_T \rightarrow 0$ (background is too large)
  - indirect B measurement via electrons (loose correlation p_T^B vs p_T^e)
- **Build on ALICE uniqueness at low p_T: PID, low material and B field**

Heavy-Ion Physics: a world wide enterprise

At CERN, involves about 1500 scientists in all four large experiments ALICE, CMS, ATLAS and now also LHCb (2010-2028…)… and even LHCf

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)

New laboratory under construction in Darmstadt, extension of GSI. The HADES (active) and CBM (from ~ 2020) experiments involve about 1000 scientists.

In Japan, new project now under study

Why Heavy Ions @ LHC?

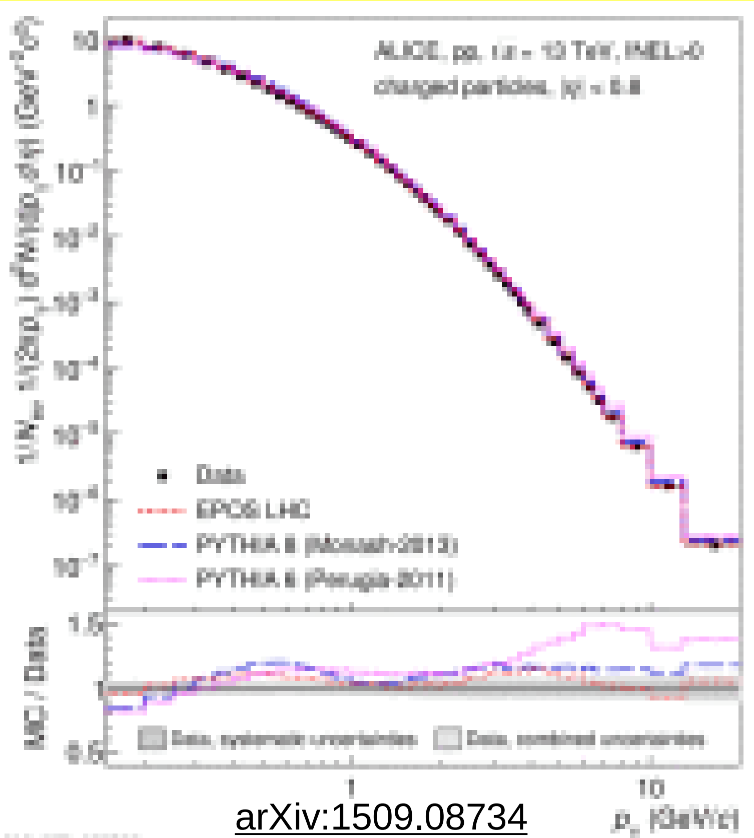
- It is a ***different matter*** as compared to RHIC (and even more to SpS)
  - Larger temperature, volume, energy density and lifetime
    - Study QGP properties vs T …
  - small net-baryon density at mid-rapidity ($\mu_B \approx 0$), corresponding to the conditions in the early universe
  - large cross 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 ones at RHIC and FAIR

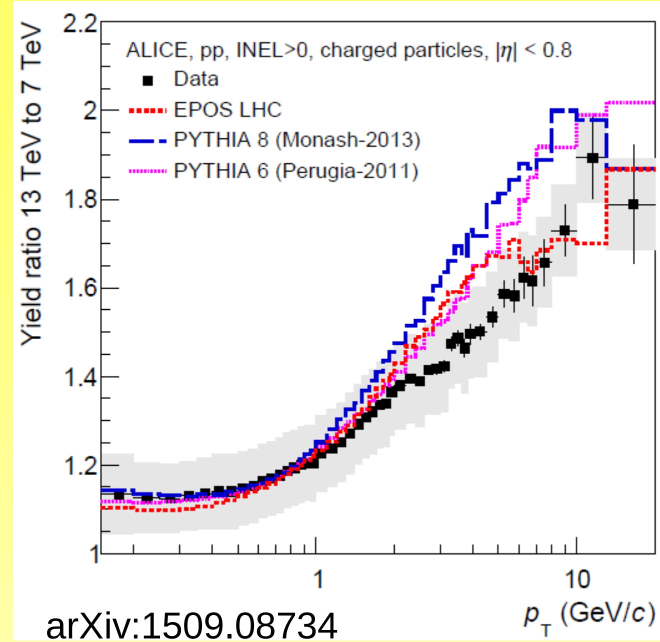
Experiments at the LHC…

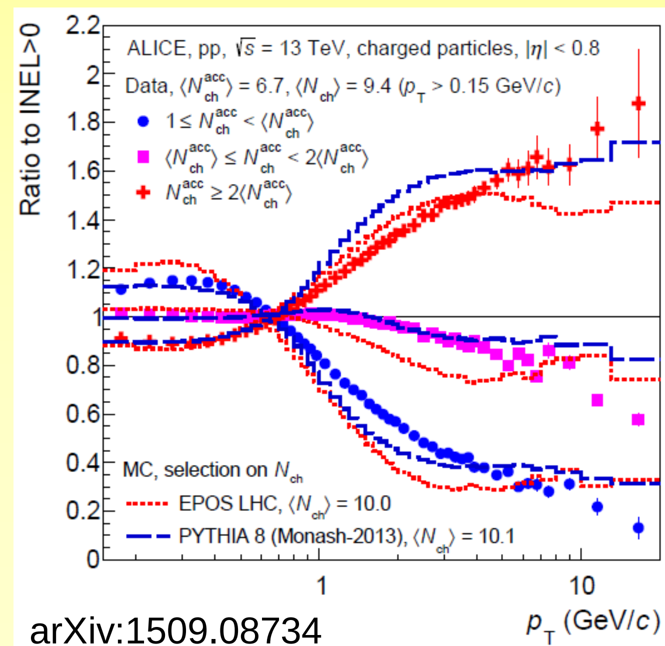
- ALICE
  - Experiment designed for Heavy Ion collision
    - only dedicated experiment at LHC, must be comprehensive and able to cover all relevant observables
    - **VERY robust tracking** for p_T from **0.1 GeV/*c*** to **100 GeV/*c***
      - high-granularity 3D detectors with many space points 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)
    - **PID** over a very large p_T range
      - use of essentially all known technologies: TOF, dE/dx, RICH, TRD, Ecal, topology
    - Hadrons, leptons and photons + Excellent vertexing
- ATLAS and CMS
  - General-purpose detectors, optimized for rare processes
    - Excellent Calorimetry = > Jets
    - Excellent dilepton measuremens, especially at high pT
    - Very large acceptance in rapidity
- Now Joined by LHCb for pPb

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

P_T distributions at 13 TeV







- Spectrum significantly harder than at 7 TeV
- shapes depend strongly on charged-particle multiplicity
- in fair agreement with event generators.