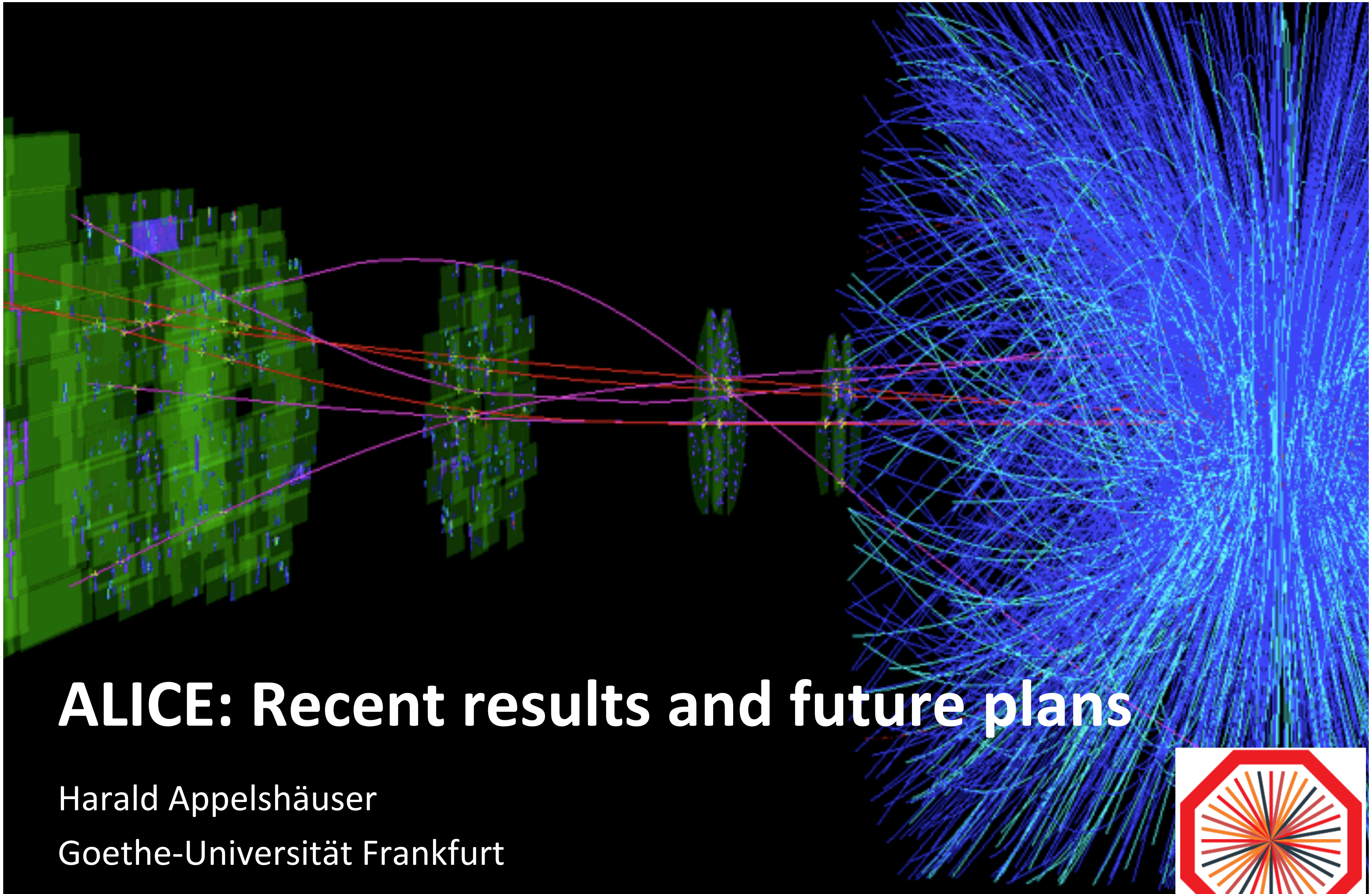


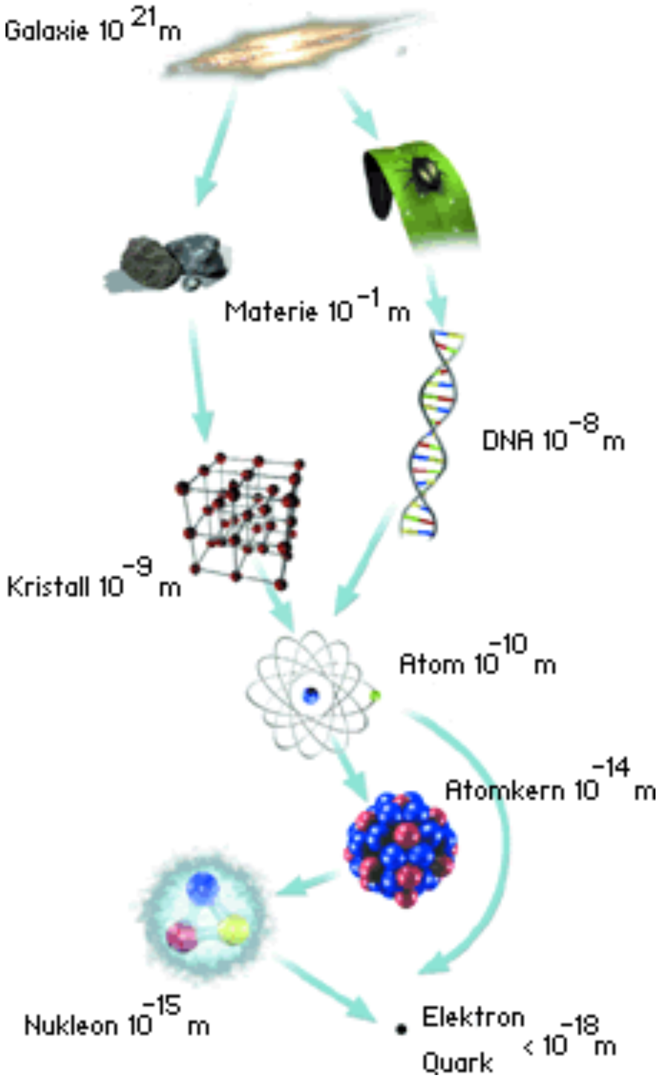
ALICE: Recent results and future plans

Harald Appelshäuser

Goethe-Universität Frankfurt

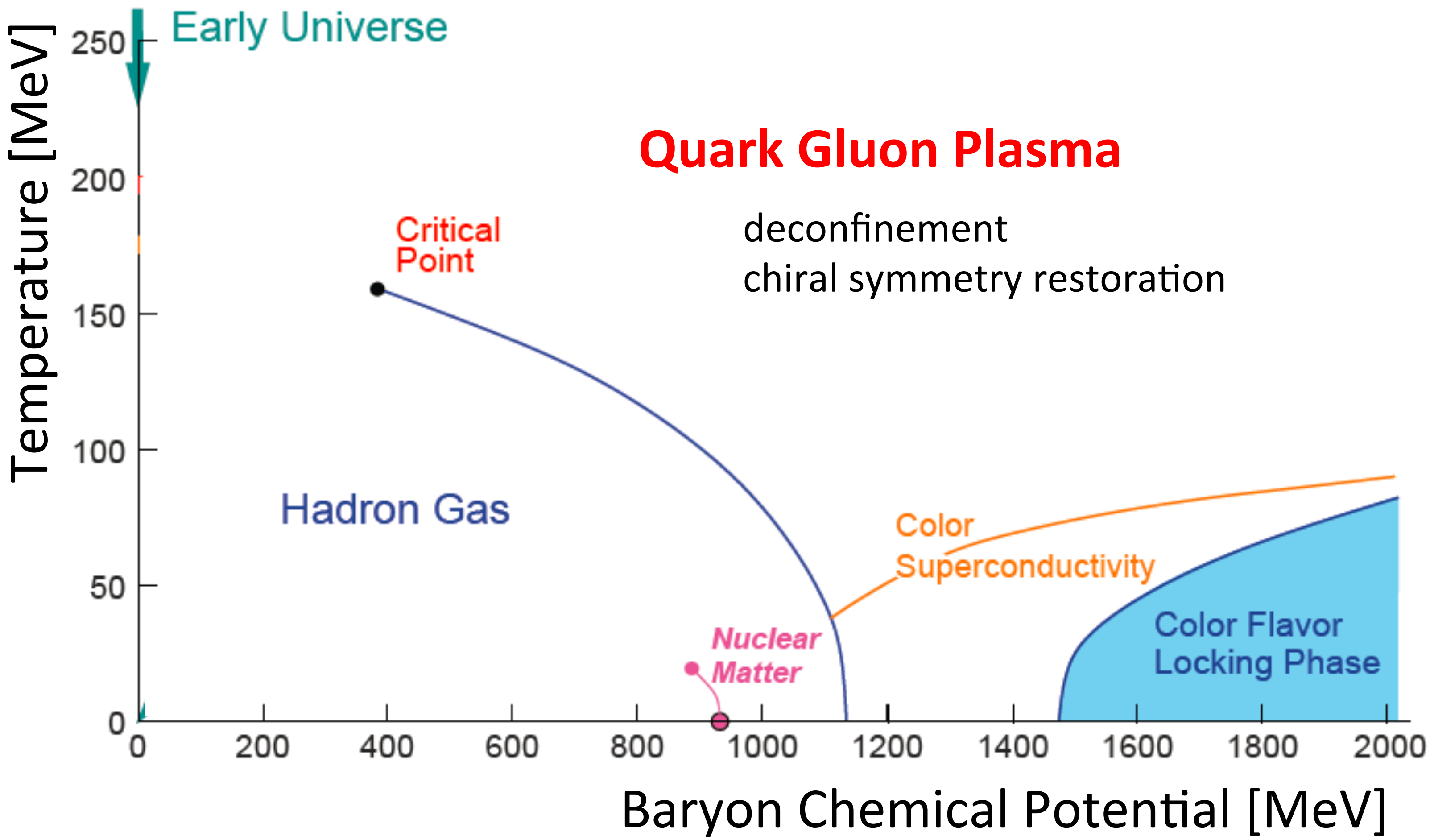
ALICE

Structure of Matter

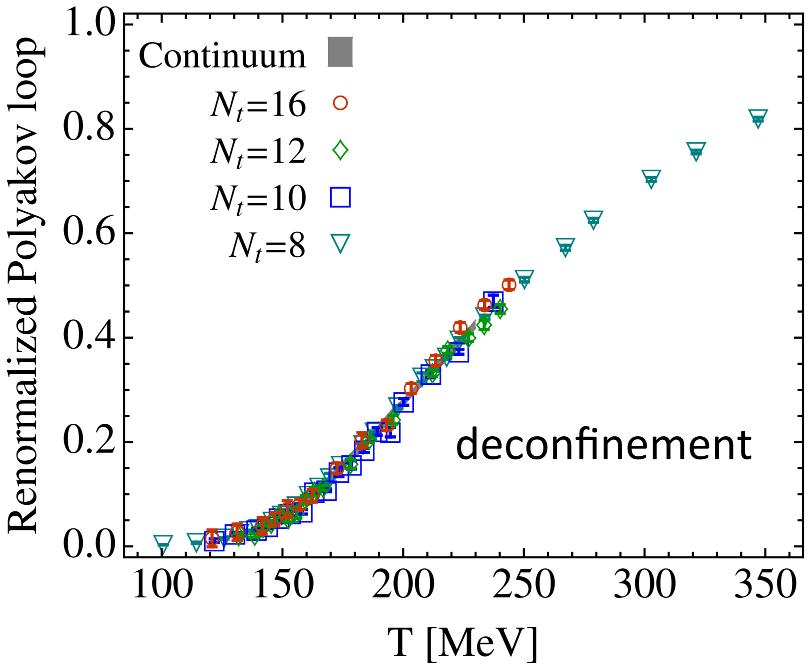


- the elementary building blocks of matter are quarks and gluons
- subsequent heating of matter releases new degrees of freedom
- what is the nature of *elementary* matter where the relevant degrees of freedom are quarks and gluons?

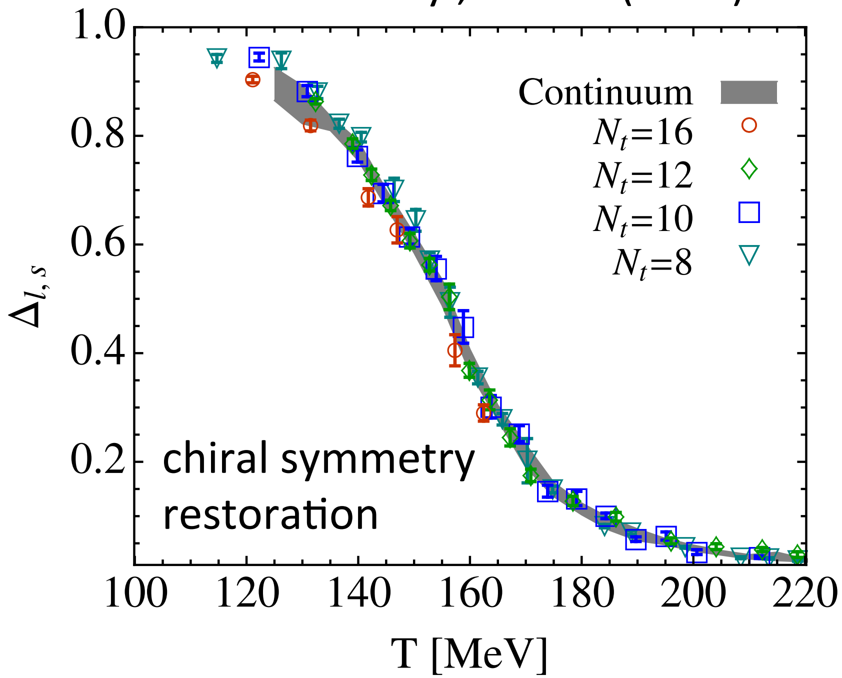
QCD phase diagram



QCD phase diagram



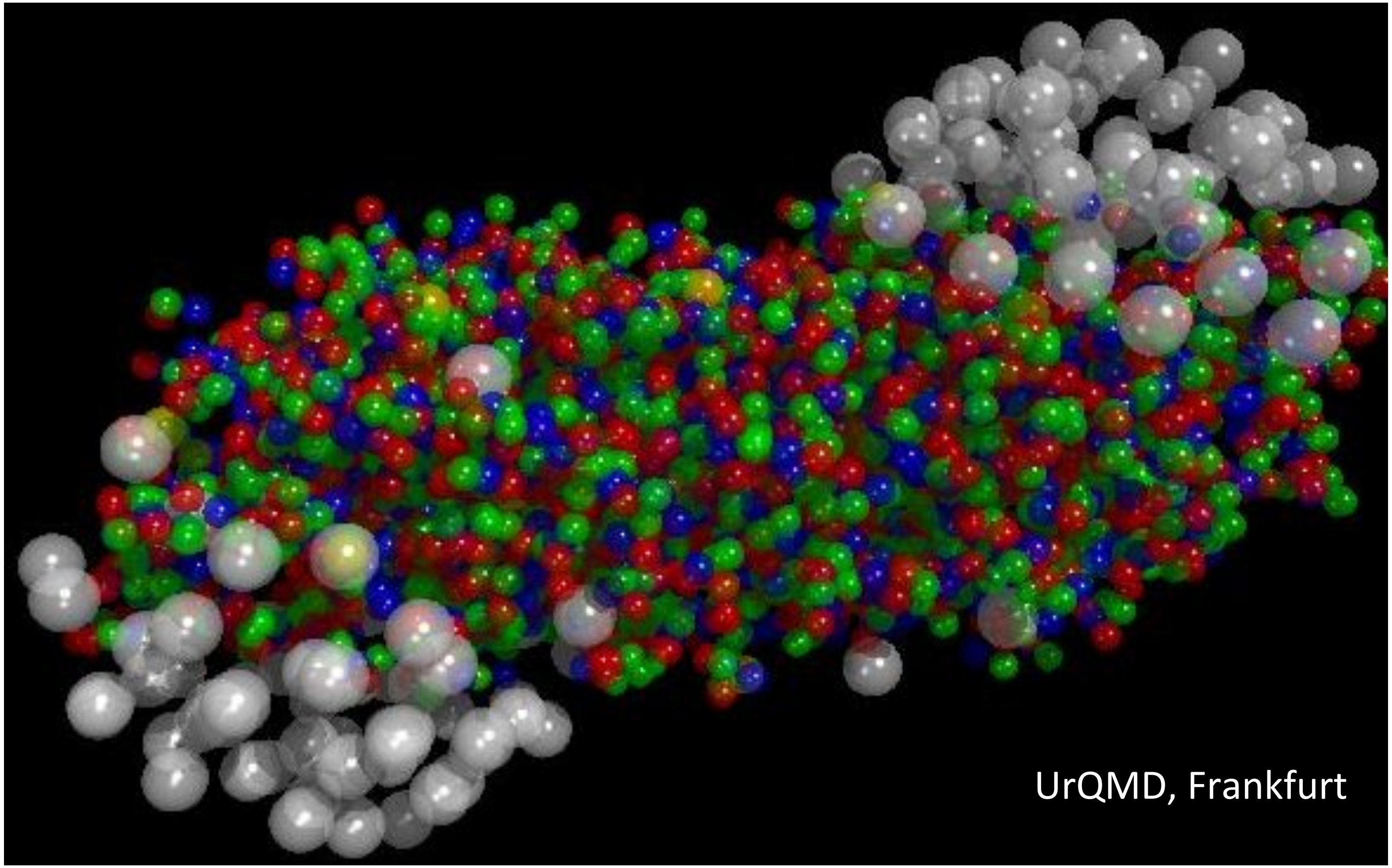
Sz. Borsanyi, JHEP 1 (2010)



Lattice QCD (μ_B = 0):

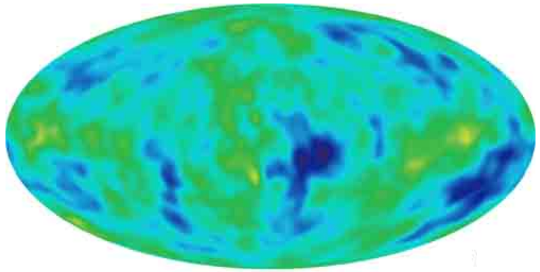
- deconfinement and chiral symmetry restoration at $T_c \approx$ 175 MeV

Quark-Gluon Plasma

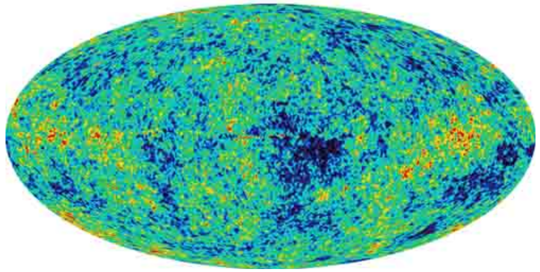


experimental program

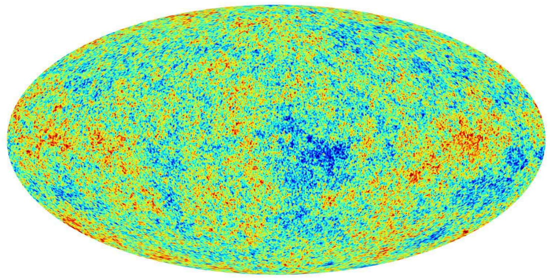
- CERN-SPS (since 1986):
  Heavy ions on *fixed targets*
  $\sqrt{s_{NN}} \approx 20$ GeV



- BNL-RHIC (since 2000):
  Heavy-ion collider
  $\sqrt{s_{NN}} = 200$ GeV

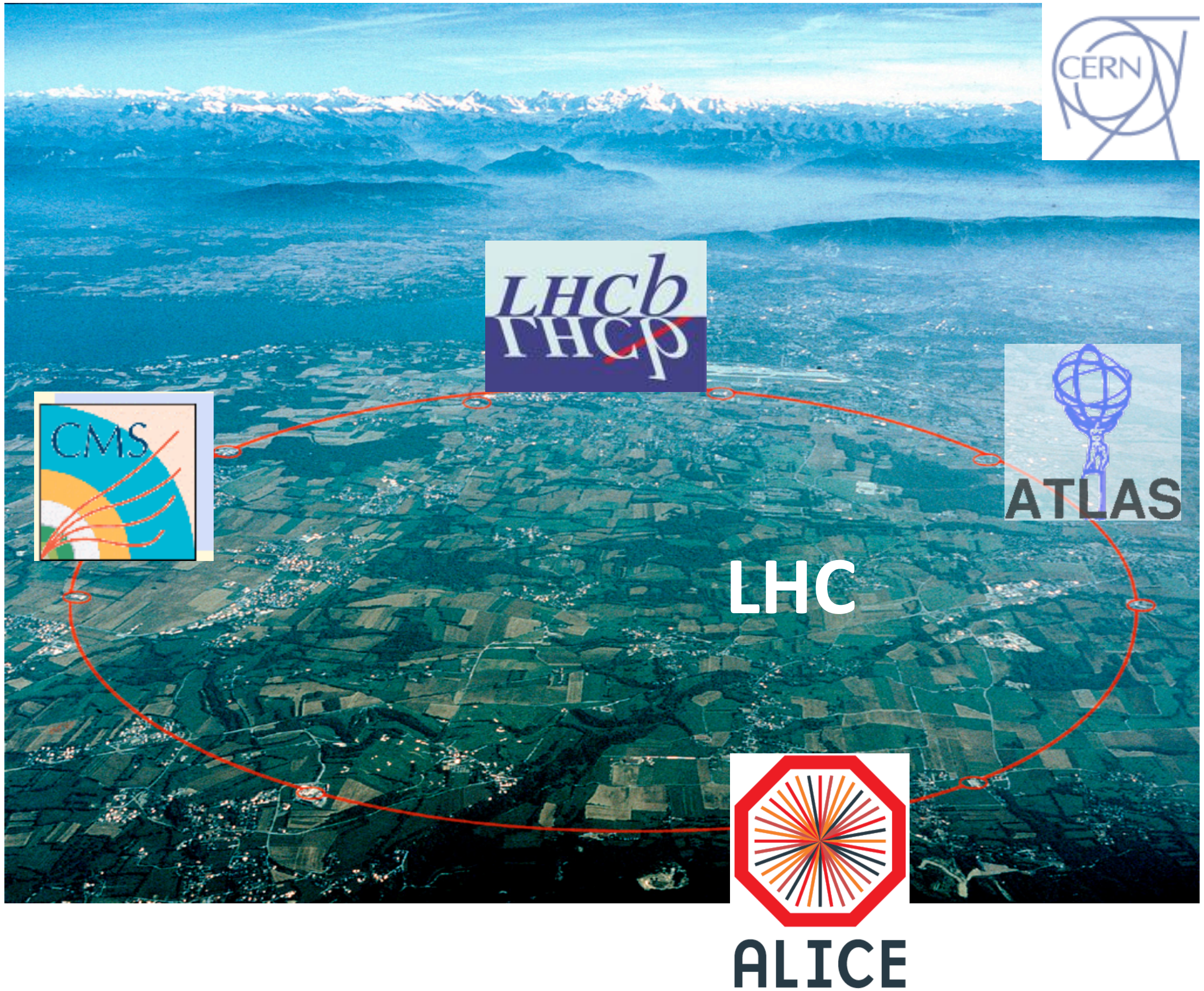


- CERN-LHC (since 2010)
  Heavy-ion collider
  $\sqrt{s_{NN}} = 2.76$ TeV (5.1 TeV in 2015)



→ detailed characterization of the QGP properties

LHC



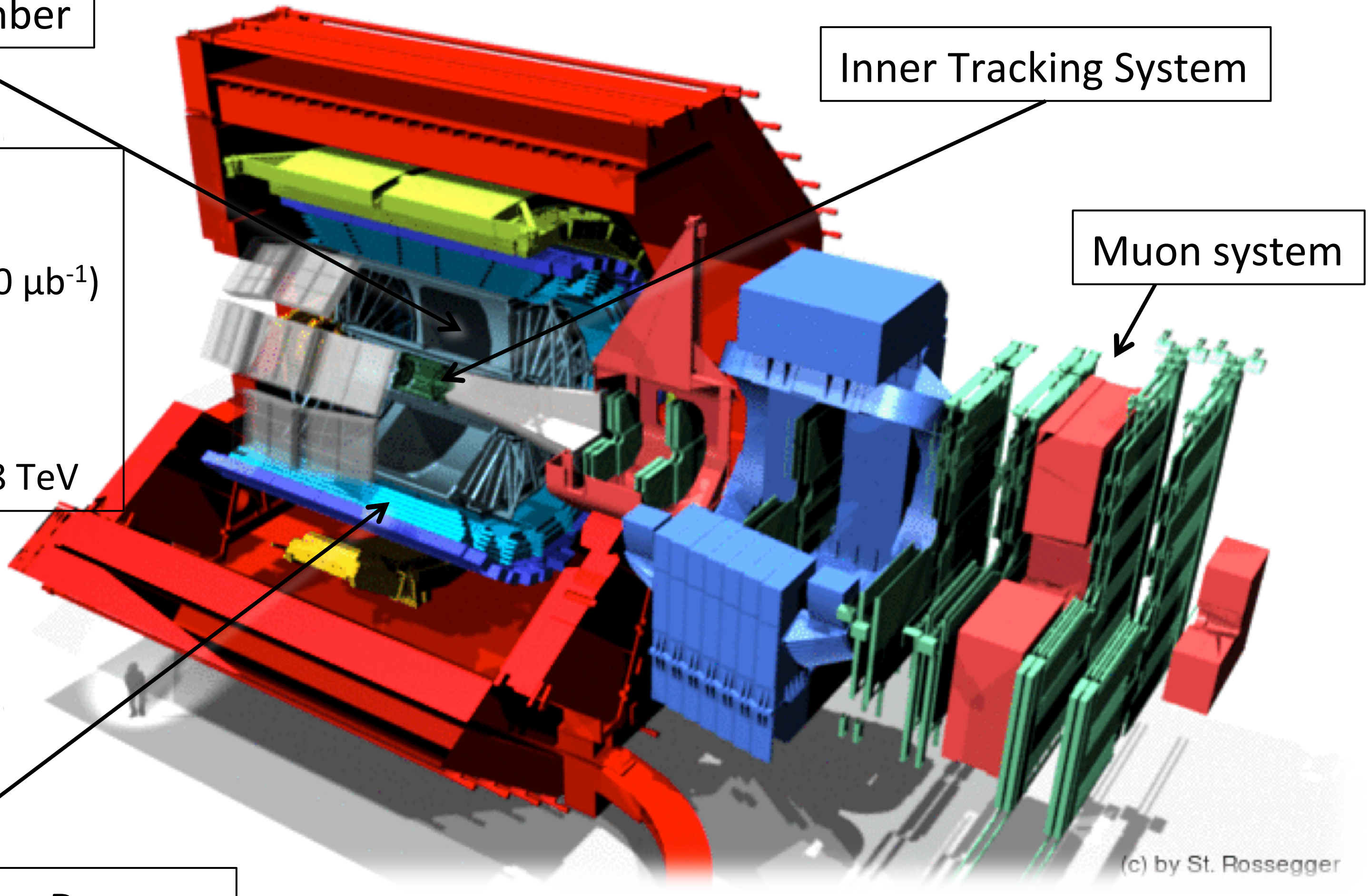
- pp ($\sqrt{s}$ = 8 TeV)
- pPb ($\sqrt{s_{NN}}$ = 5 TeV)
- Pb-Pb ($\sqrt{s_{NN}}$ = 2.76 TeV)
- 4 large experiments
- ALICE dedicated for heavy-ion collisions
- significant HI program conducted by ATLAS and CMS

ALICE detector at the LHC

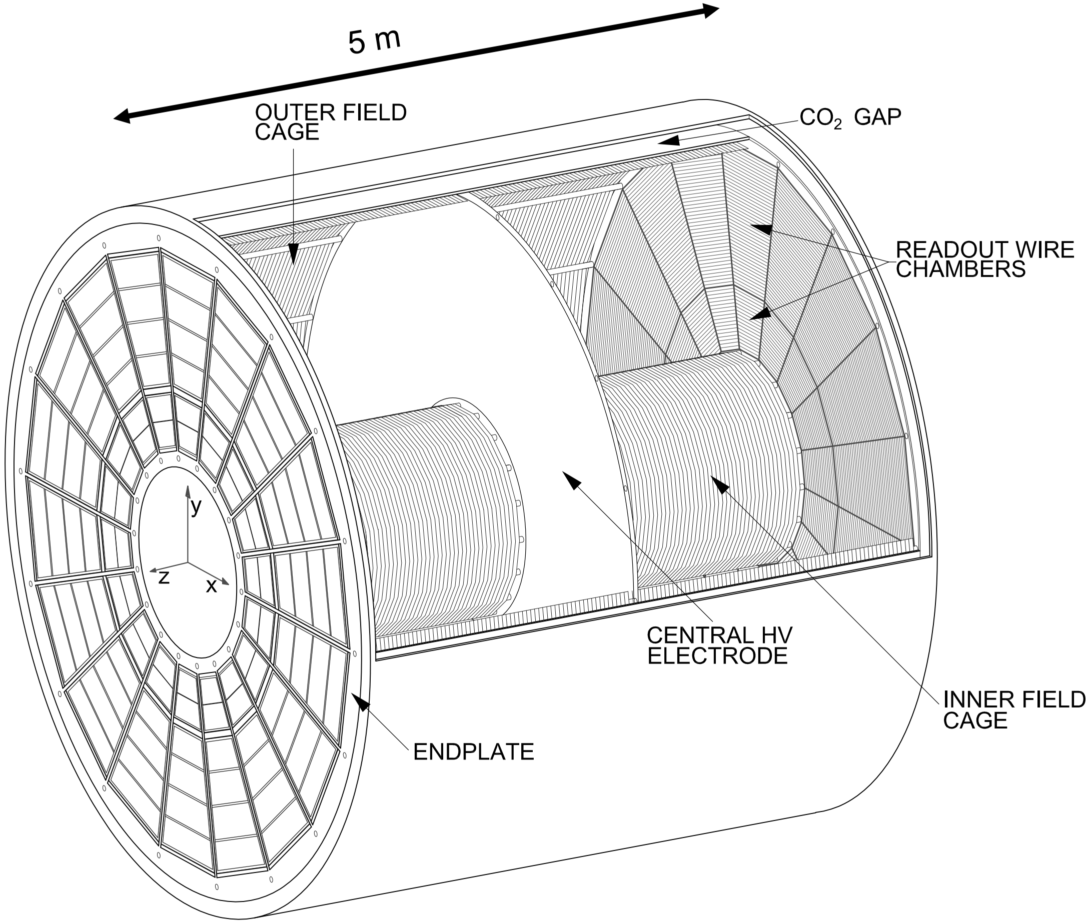
Run1:
Pb-Pb at 2.76 TeV
(2010: 10 μb^{-1}, 2011: 150 μb^{-1})

p-Pb at 5.02 TeV

pp at 0.9, 2.36, 2.76, 7, 8 TeV



ALICE TPC



Active volume ~92 m^3

Run1:

- $Ne\text{-}CO_2\text{-}N_2$ (90-10-5)
- $Ne\text{-}CO_2$ (90-10)

Run2:

- $Ar\text{-}CO_2$ (90-10)

72 MWPC-based readout chambers:

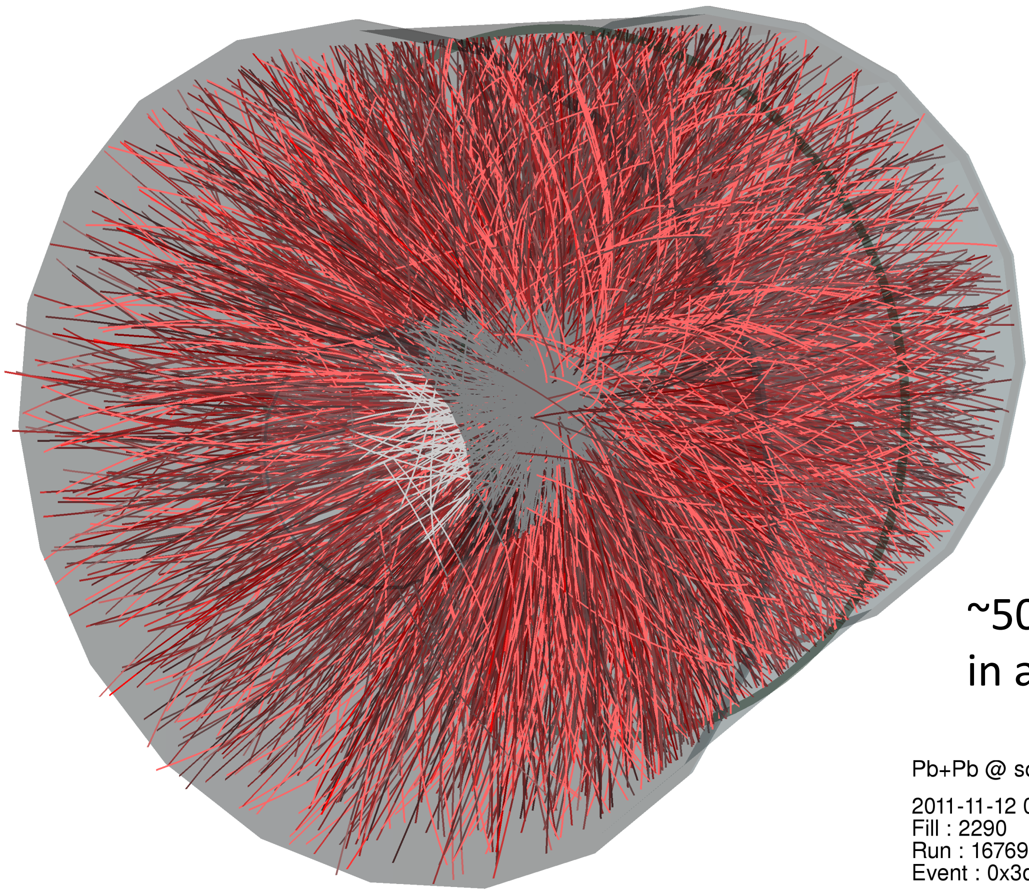
- 2x 18 IROC
- 2x 18 OROC

557,568 readout cathode pads

pad sizes:

- 4x7.5 mm^2 (IROC)
- 6x10, 6x15 mm^2 (OROC)

Pb-Pb event display

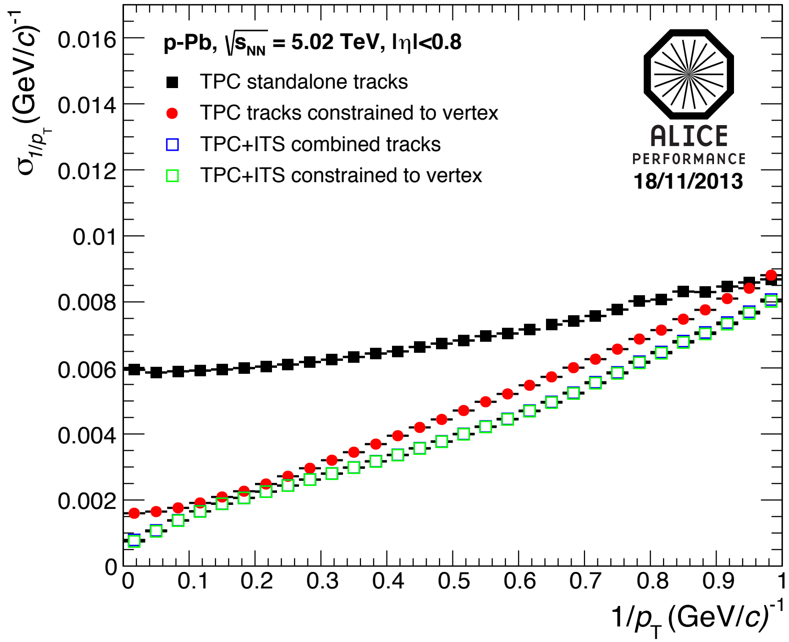


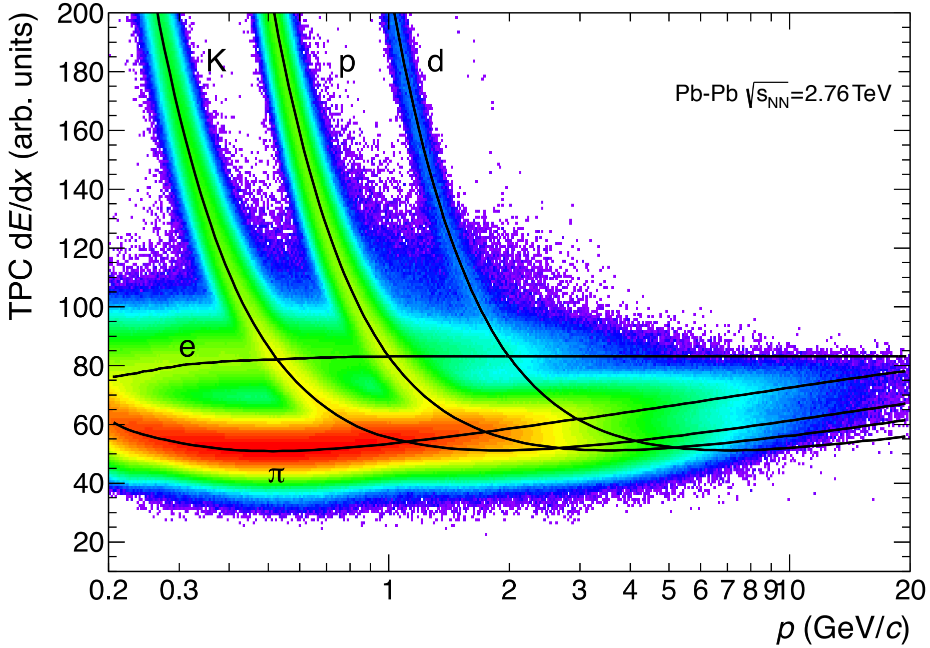
~5000 charged particles
in a central Pb-Pb collision

Pb+Pb @ sqrt(s) = 2.76 ATeV

2011-11-12 06:51:12
Fill : 2290
Run : 167693
Event : 0x3d94315a

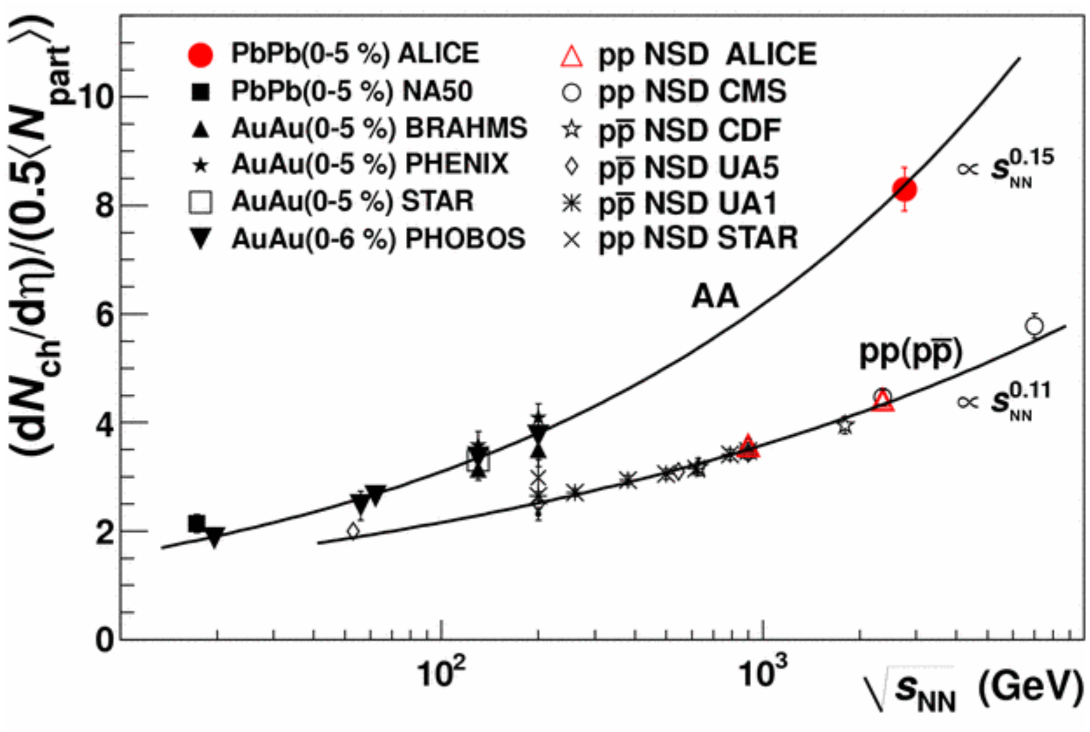
ALICE TPC performance in Run 1

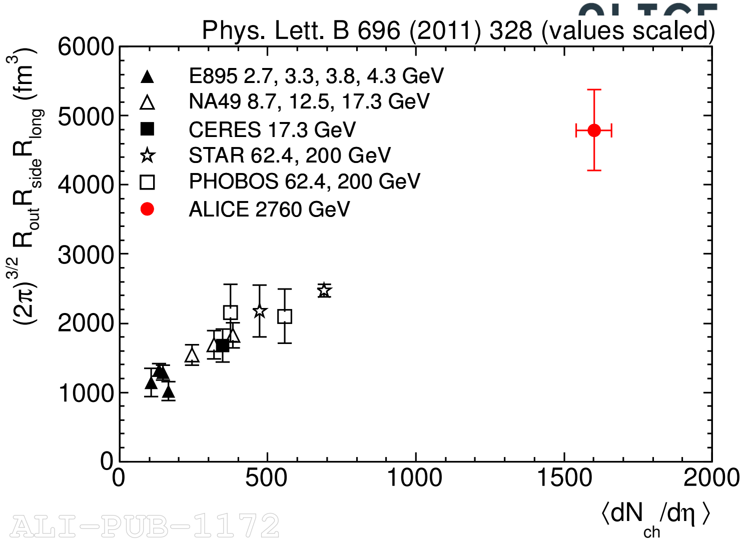


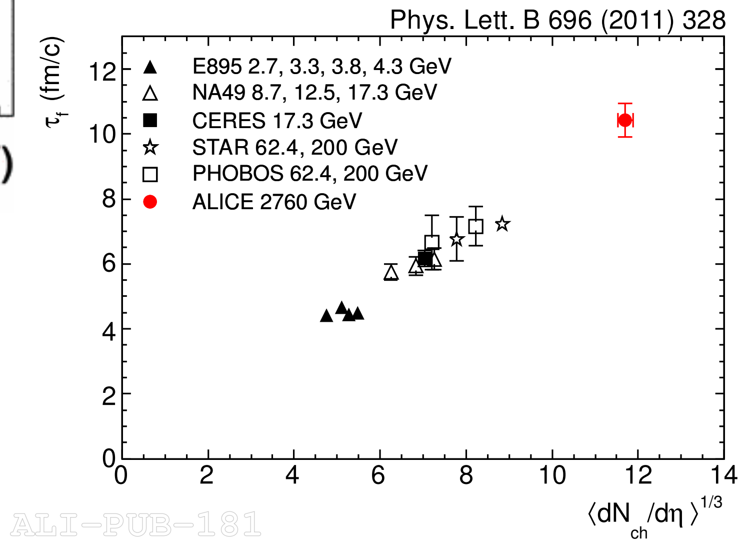


- momentum resolution: $\sigma(p_T)/p_T \leq 3.5\%$ at 50 GeV/c
- dE/dx resolution 7.6% in central Pb-Pb
- 65 of 77 ALICE papers based on TPC data
- readout rate ~300 Hz in central Pb-Pb, limited by electronics band width
  → will be increased by factor 2 in Run2

Heavy-ion collisions at the LHC



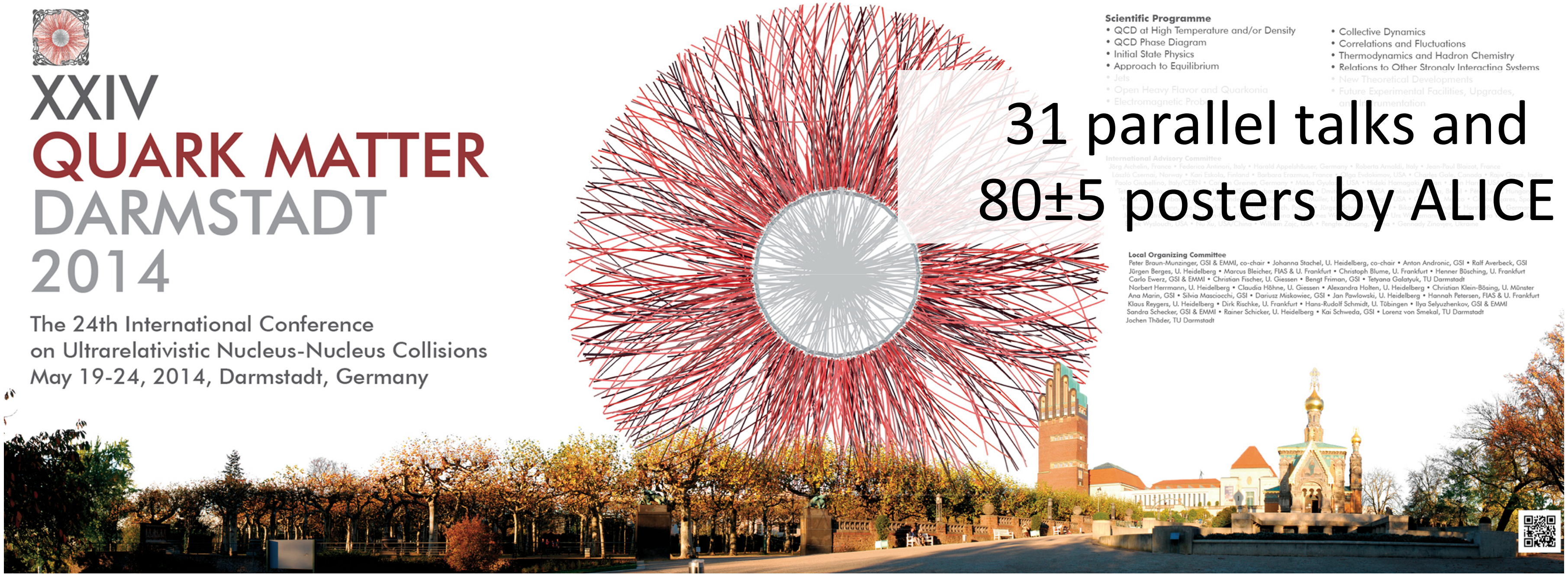




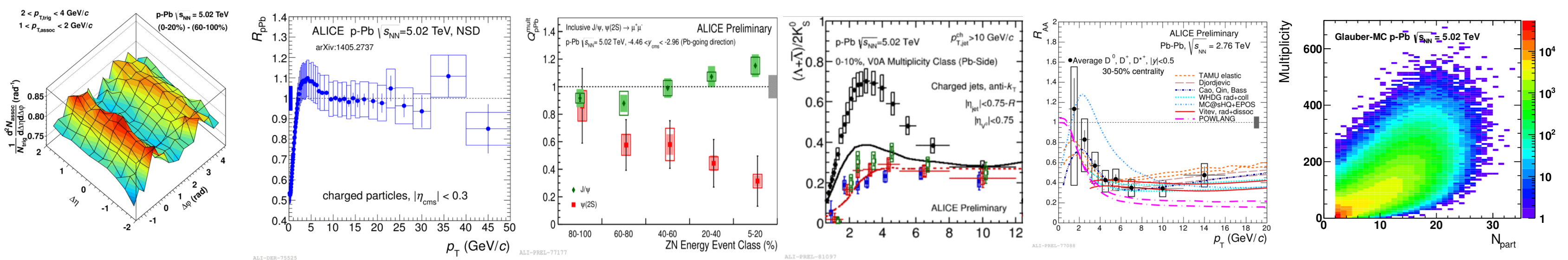
- Day 1: The fireball produced at the LHC is the largest, densest, and longest lived

- Perfect laboratory for detailed QGP studies

Heavy-ion collisions at the LHC



31 parallel talks and
80±5 posters by ALICE



1974

1974

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \rightarrow e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

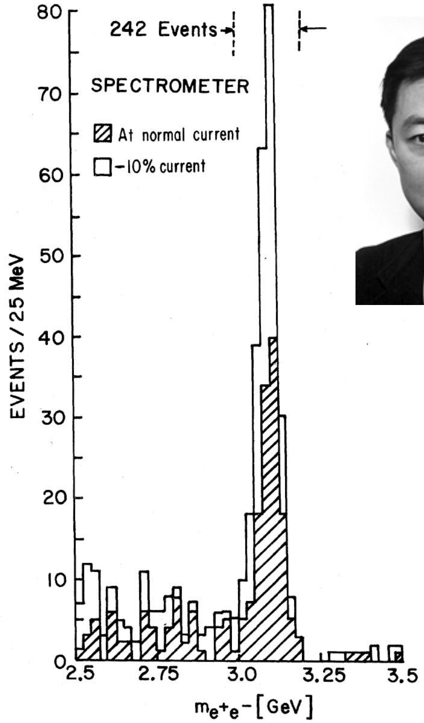
Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

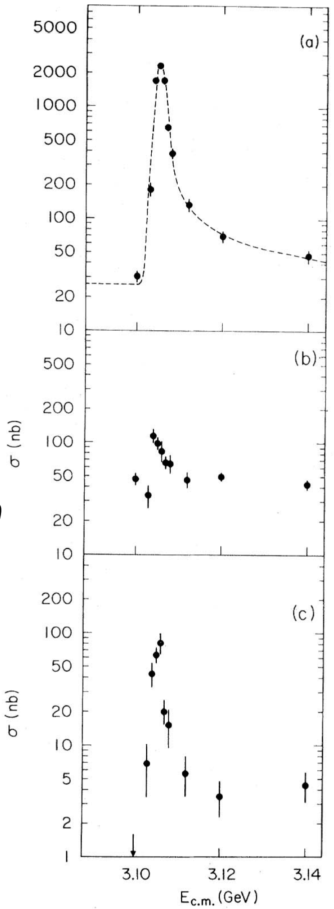
and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

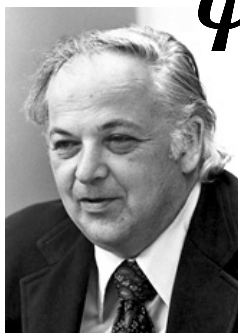
We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.



J



ψ



J/ψ as a probe for deconfinement

ALICE

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

1940 citations

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

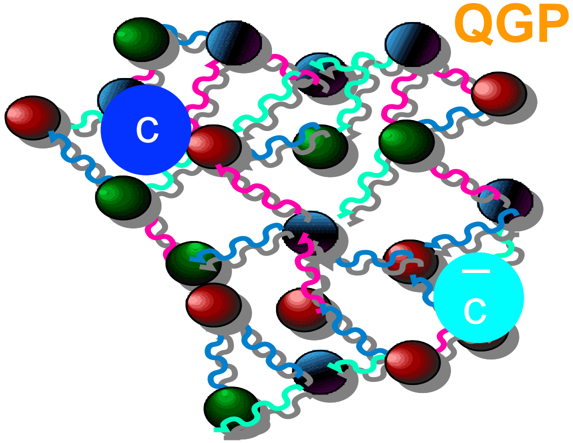
Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

Statistical QCD predicts that strongly interacting matter should at sufficiently high density undergo a

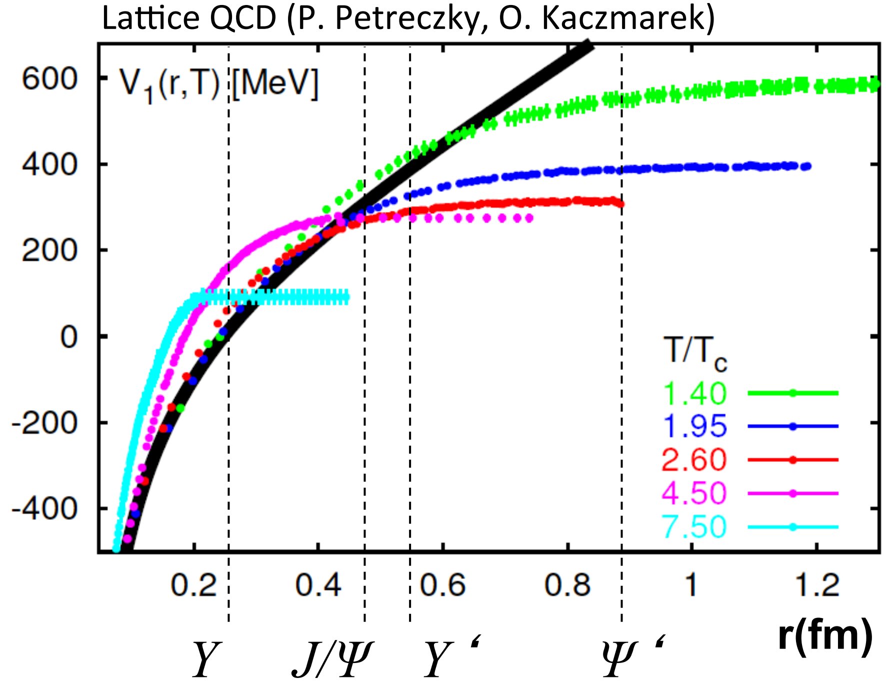
The basic mechanism for deconfinement in dense matter is the Debye screening of the quark colour

quarkonium-suppression



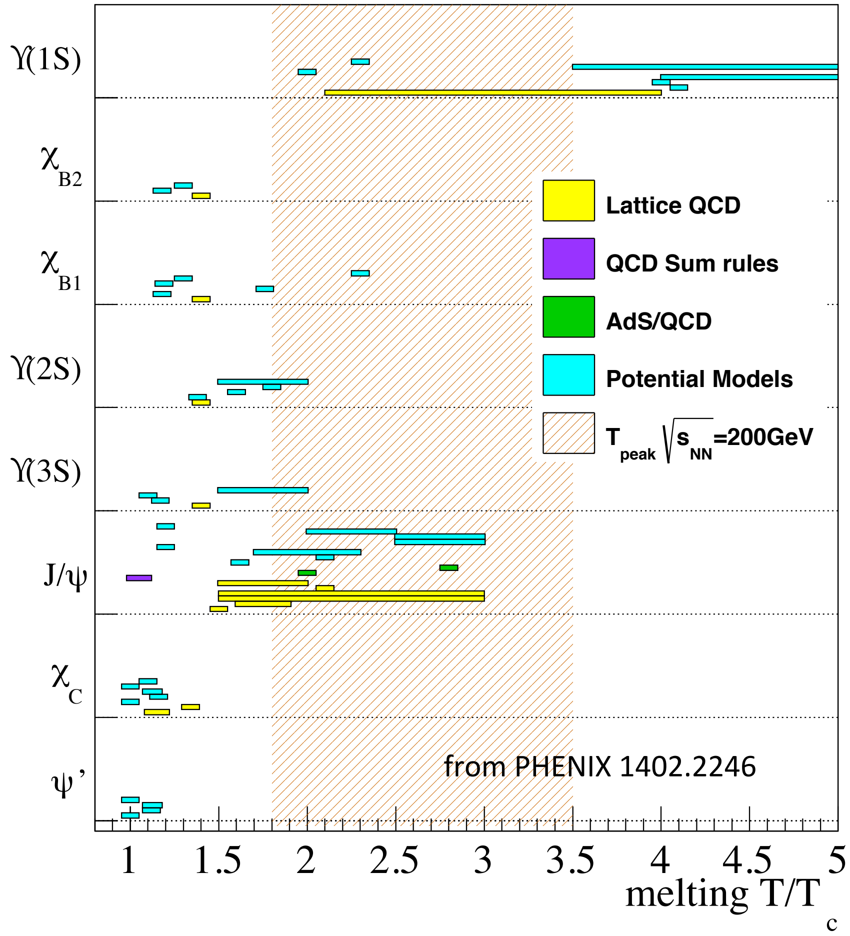
similar to Debye screening
in EM plasmas

$$T = 0: \qquad V_{Q\bar{Q}}(r) = -\frac{4}{3}\frac{\alpha_s \hbar c}{r} + kr$$

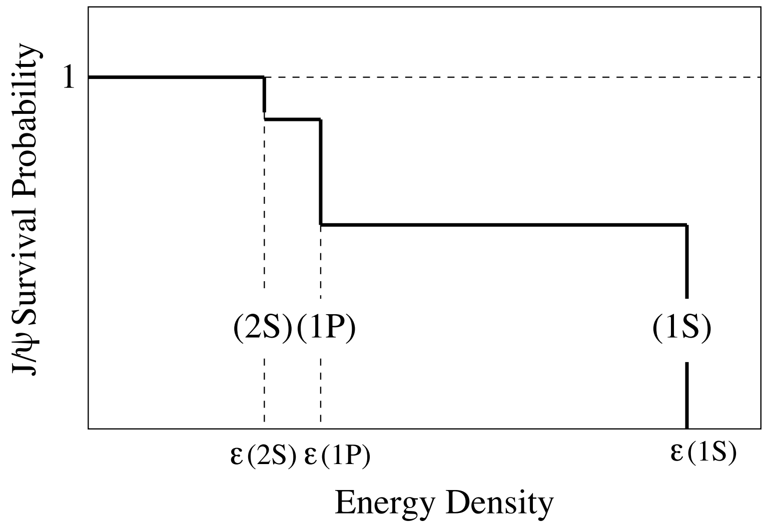


sequential melting → QGP-"Thermometer"

sequential melting

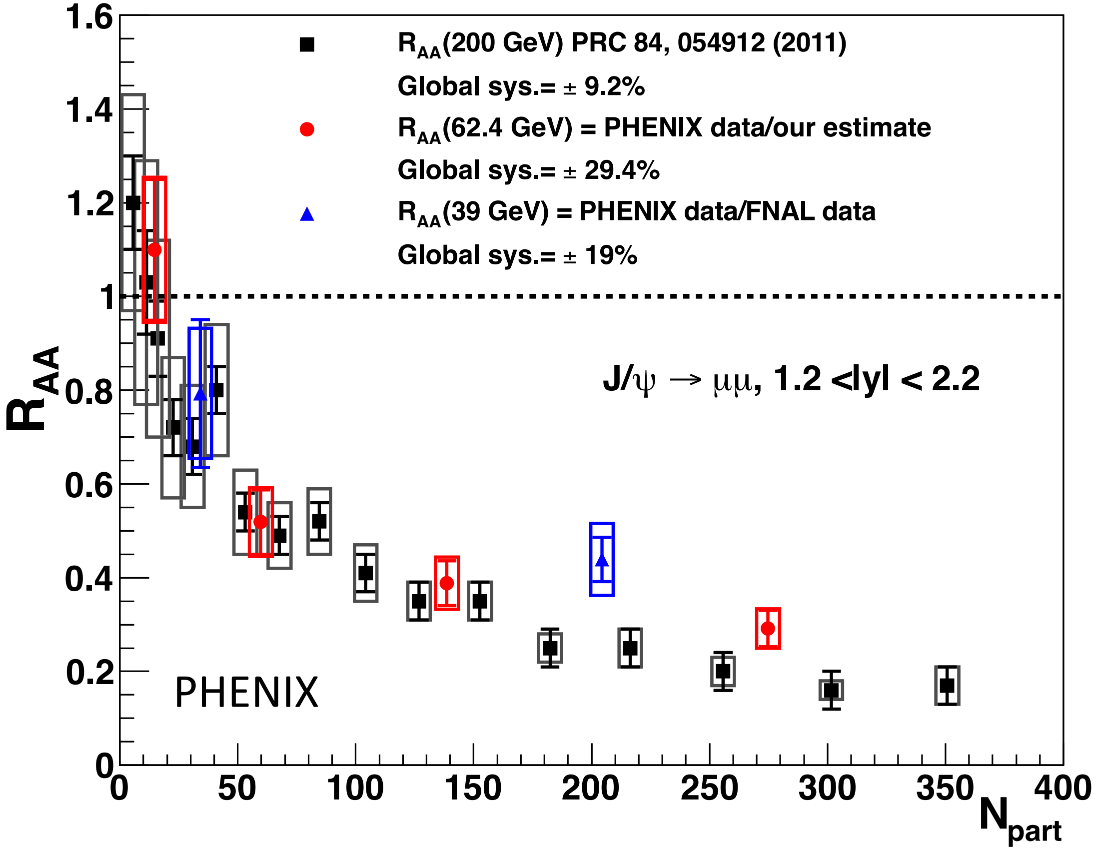


- Sequential melting expected in a wide range of models
- Feed-down affects ground-state yields



J/ψ suppression at RHIC - I

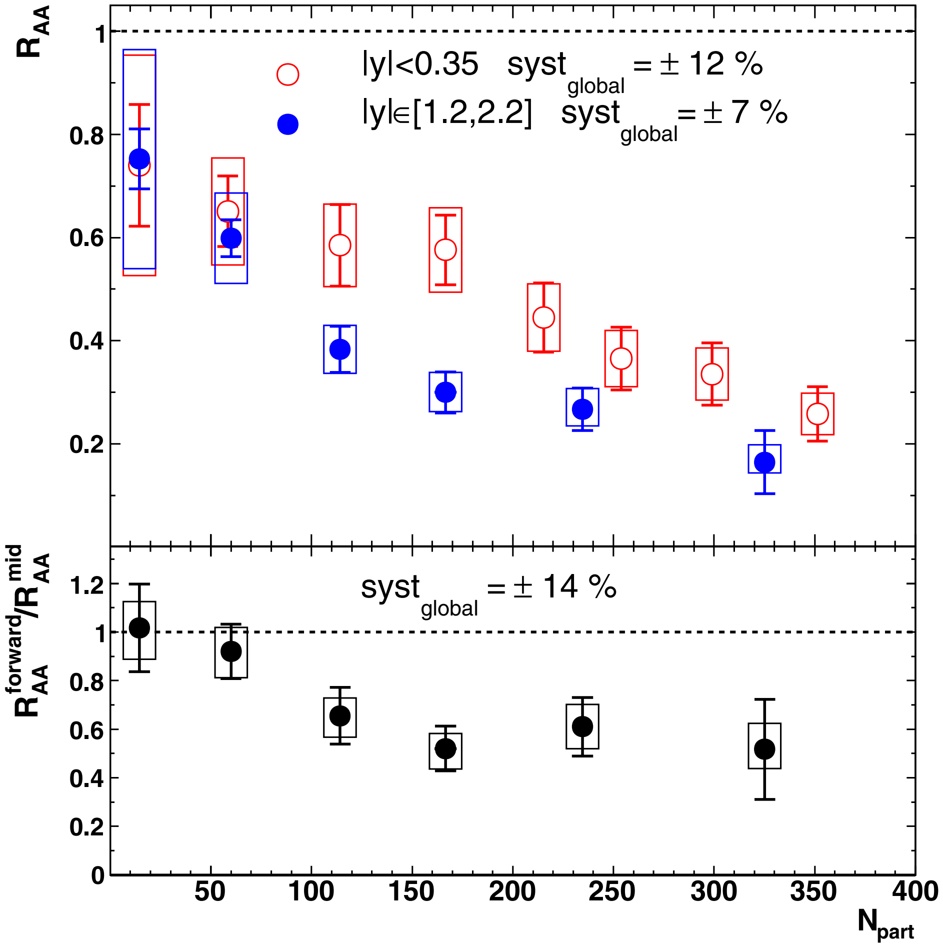
$R_{AA:}$ Yield in AA collisions, normalized to pp



- significant J/ψ suppression observed at RHIC
- but weak energy dependence

J/ψ suppression at RHIC - II

$R_{AA:}$ Yield in AA collisions, normalized to pp



J/ψ are less suppressed at mid-rapidity, despite larger energy density

What happens to c-quarks after QGP lifetime? Must show up in final-state hadrons

→ J/ψ regeneration?

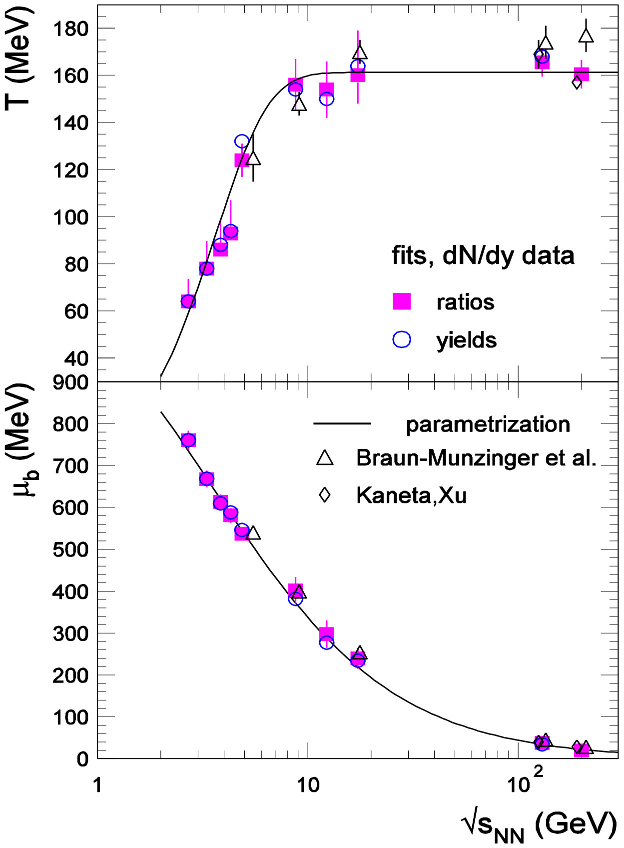
Several regeneration scenarios on the market.

Most drastic approach:
Statistical hadronization

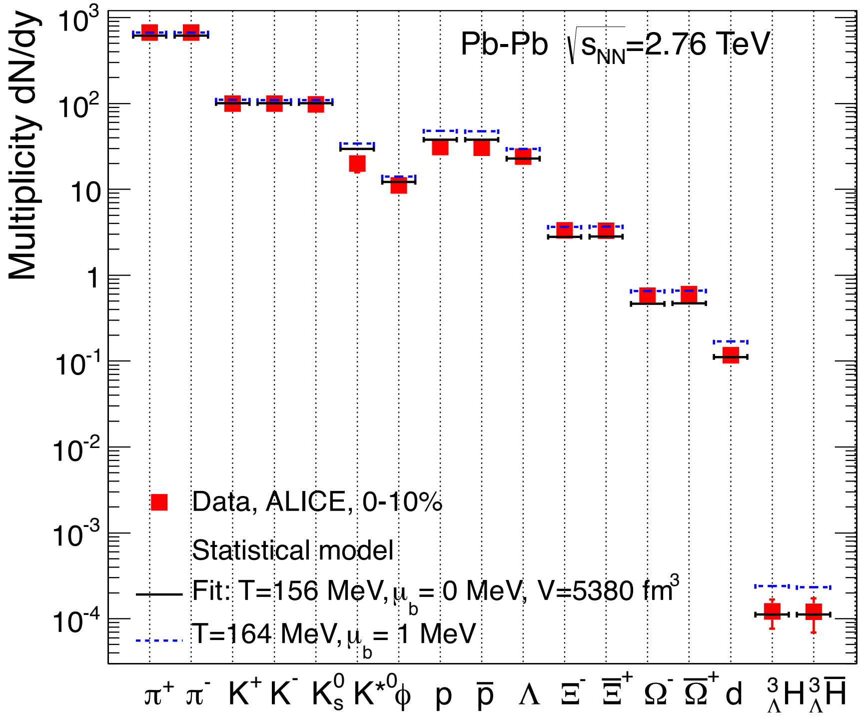
statistical hadronization

Final state hadron yields (u,d,s) are consistent with thermal production at the phase boundary, characterized by *T* and μ_B

Andronic, Braun-Munzinger, Stachel NPA772 (2006)

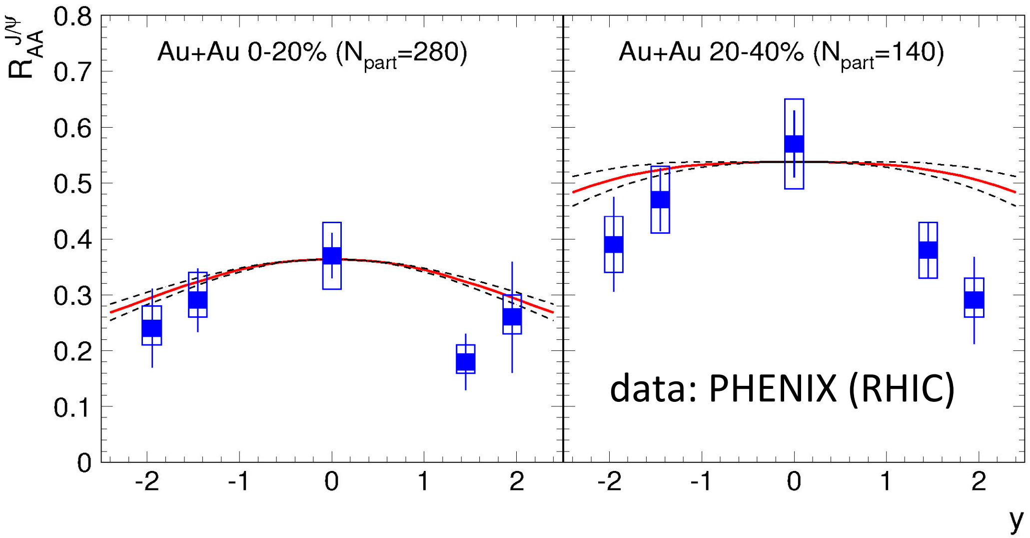


Stachel, Andronic, Braun-Munzinger, Redlich 1311.4662



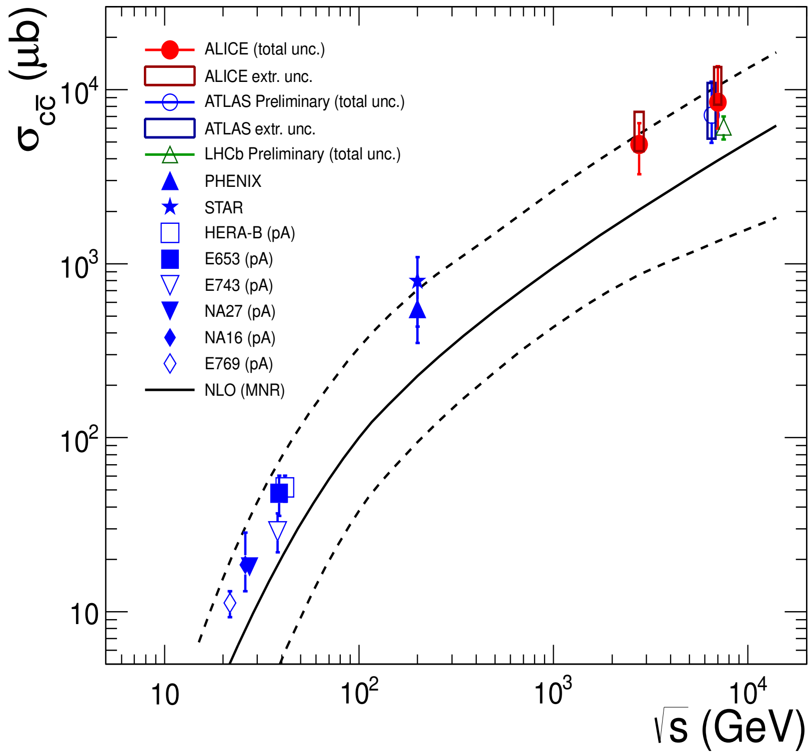
J/ψ regeneration

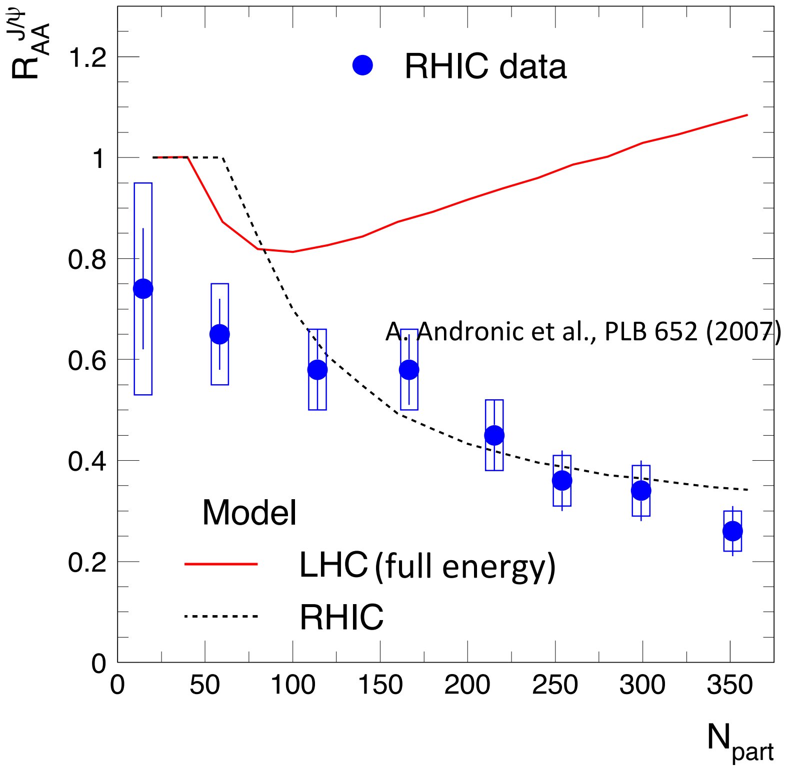
- all ccbar pairs are created in initial hard collisions
- *all* J/ψ are dissolved in the QGP
- hadrons with charm are formed at the phase boundary
- population follows statistical laws
- explains weak energy dependence in SPS-RHIC regime and rapidity dependence at RHIC



A. Andronic et al., PLB 652 (2007)

J/ψ regeneration



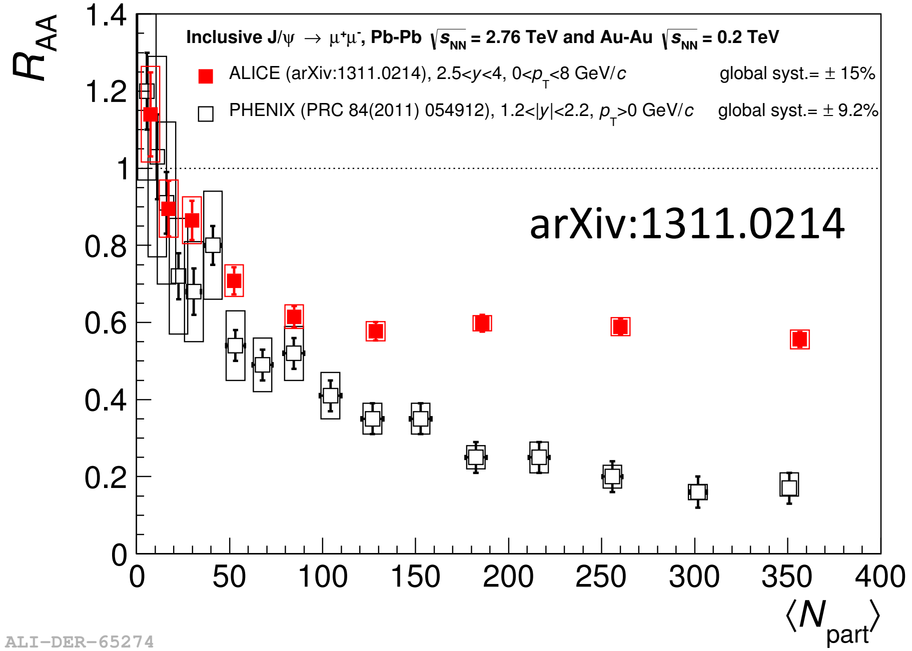


- strong dependence of J/ψ regeneration on total charm cross section

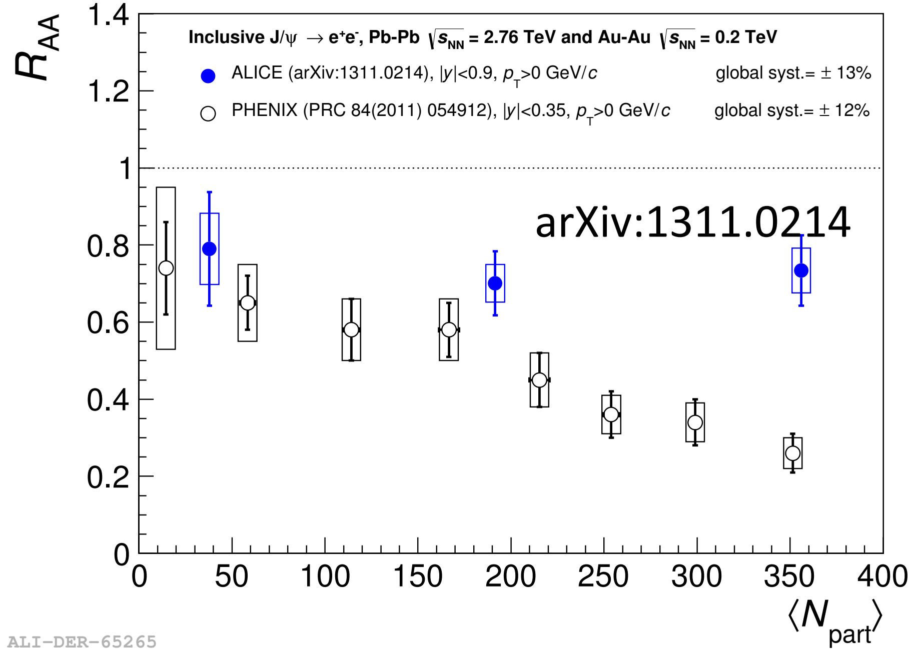
- drastic enhancement predicted at the LHC (full energy)

J/ψ from RHIC to the LHC

forward rapidity: J/ψ → μμ



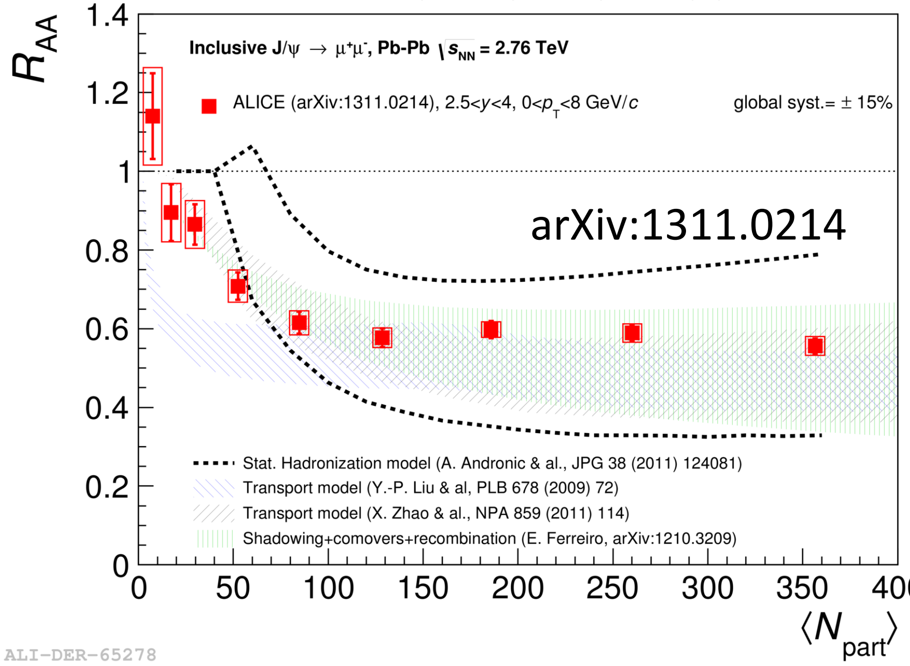
mid-rapidity: J/ψ → ee



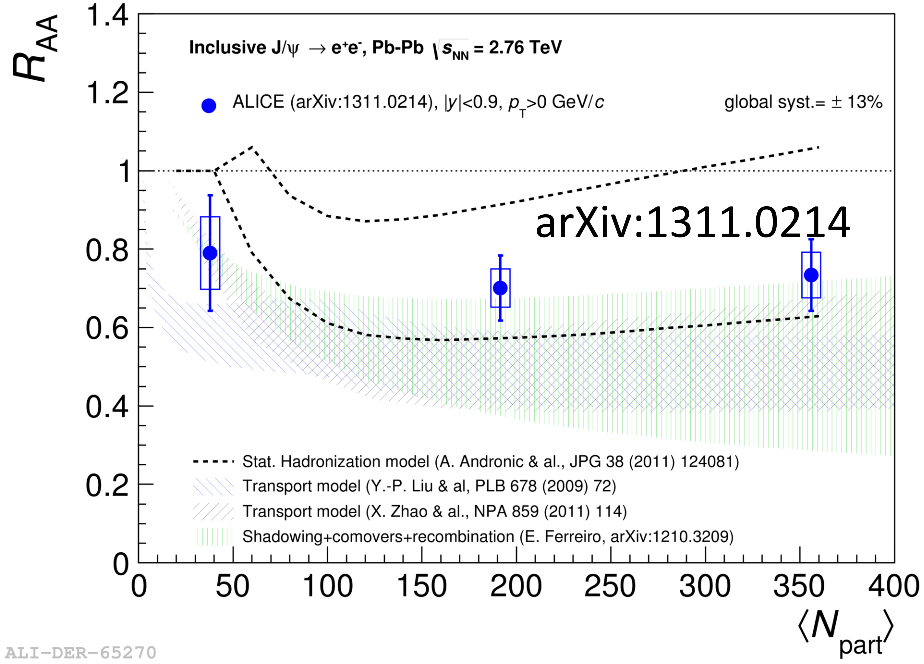
→ qualitatively new picture of J/ψ – suppression at the LHC

J/ψ at the LHC – centrality dependence

forward rapidity: J/ψ → μμ

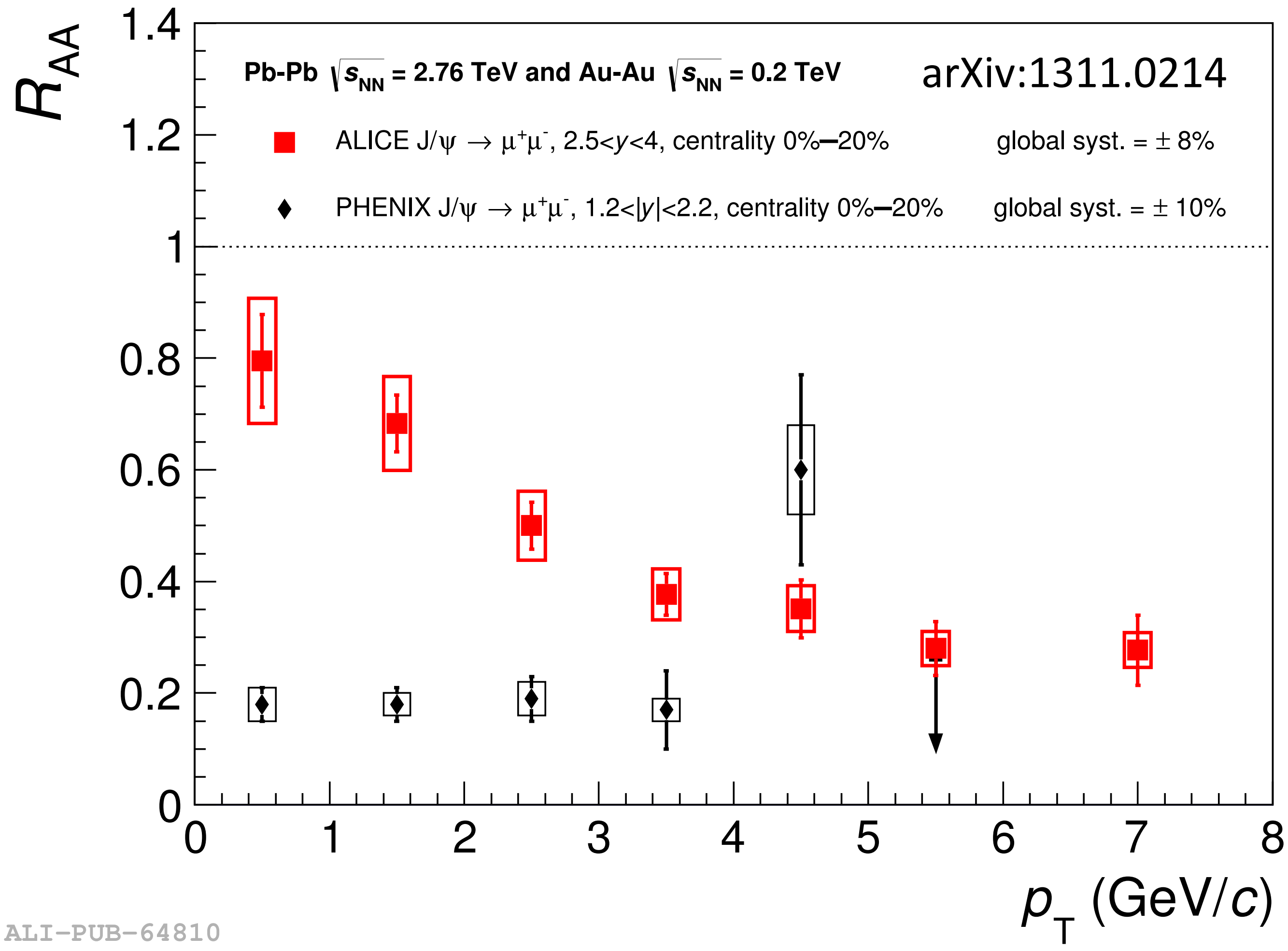


mid-rapidity: J/ψ → ee



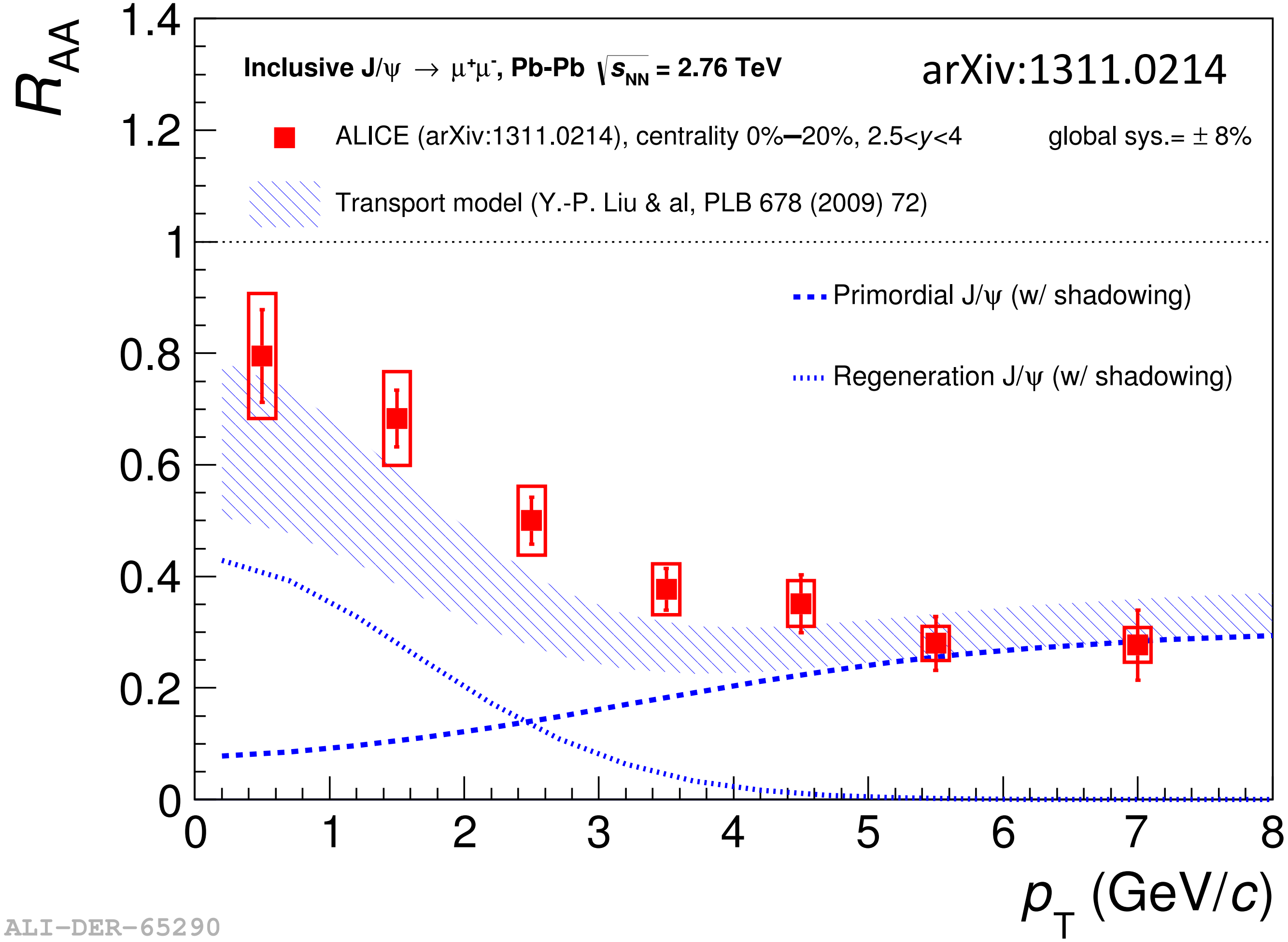
→ qualitatively new picture of J/ψ – suppression at the LHC
→ strong indication for significant regeneration

J/ψ transverse momentum dependence



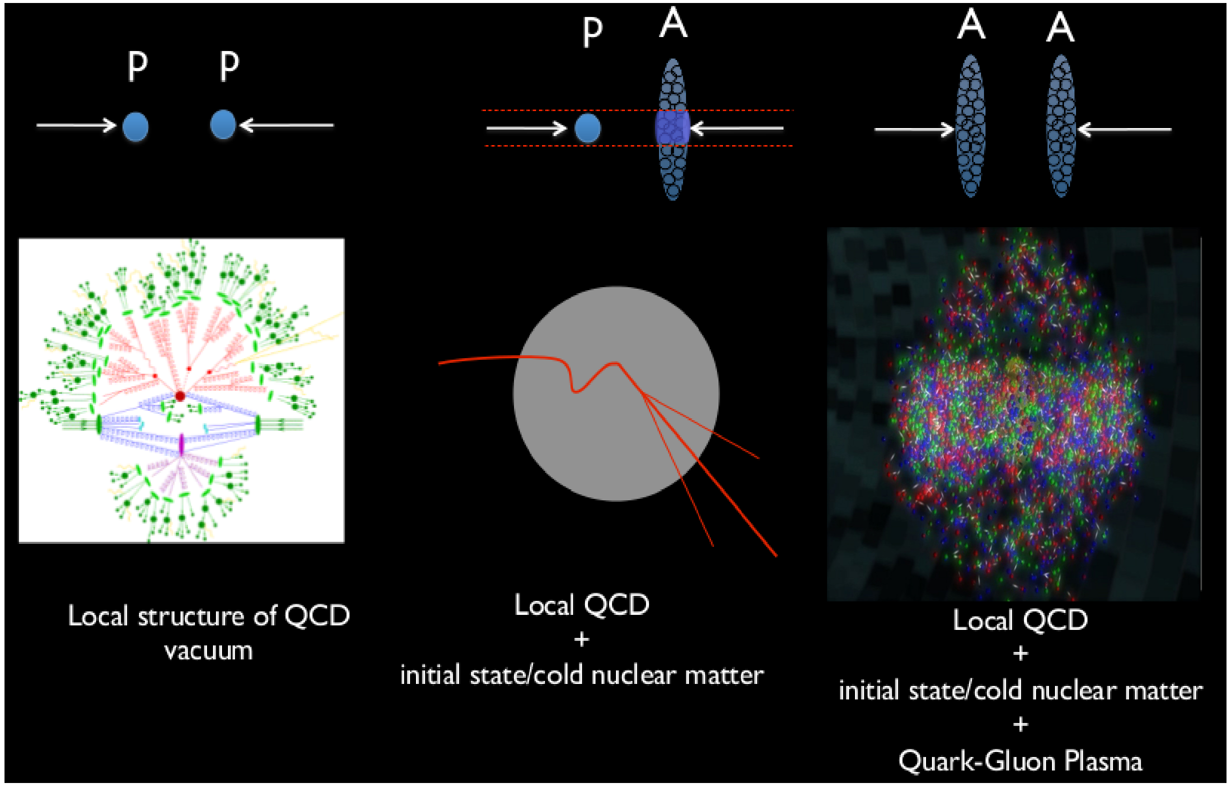
→ increase of J/ψ relative to RHIC at *low* p_T

J/ψ transverse momentum dependence



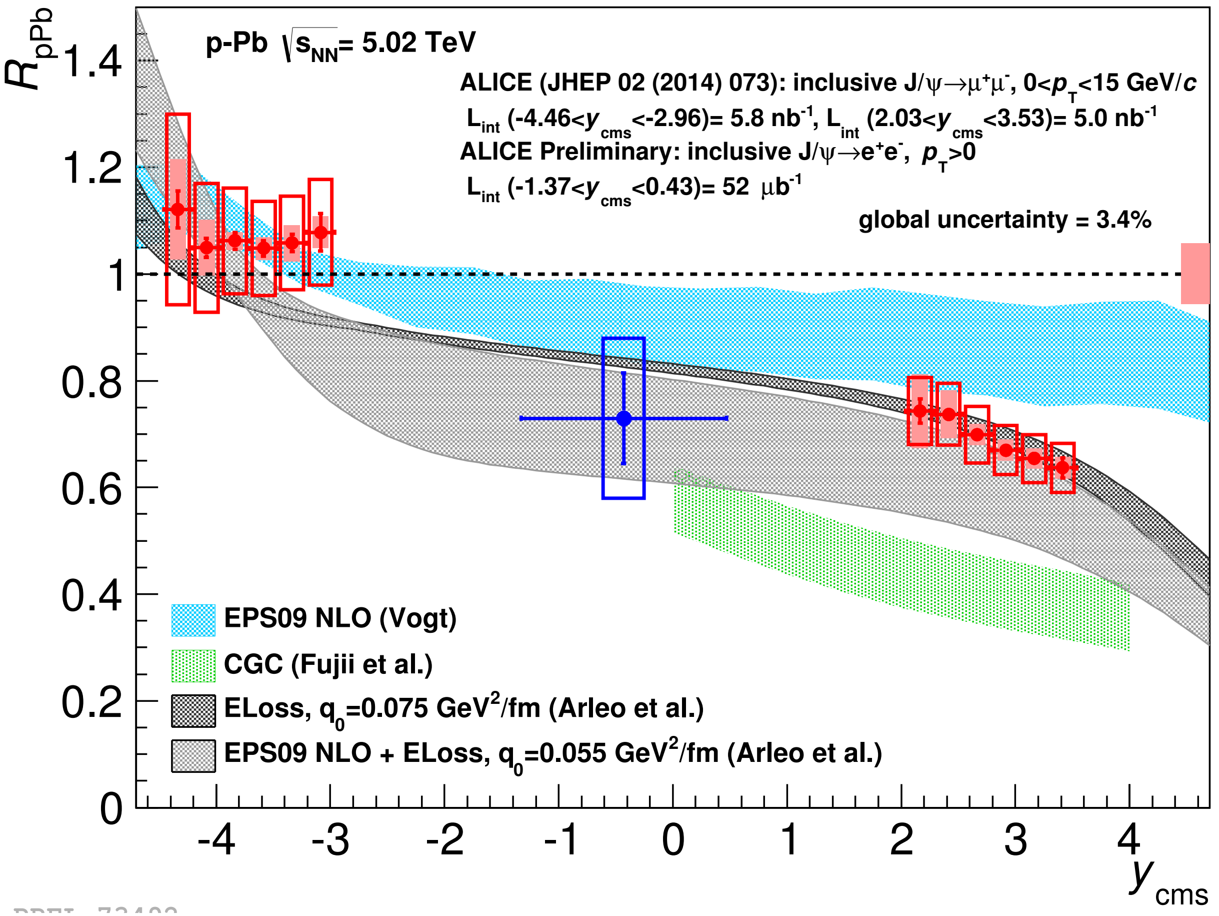
→ p_T – dependence consistent with J/ψ regeneration

p-Pb



R_{AA}: normalized particle production in Pb-Pb relative to pp (≠1?)
R_{pPb}: normalized particle production in p-Pb relative to pp (=1?)

J/ψ in p-Pb

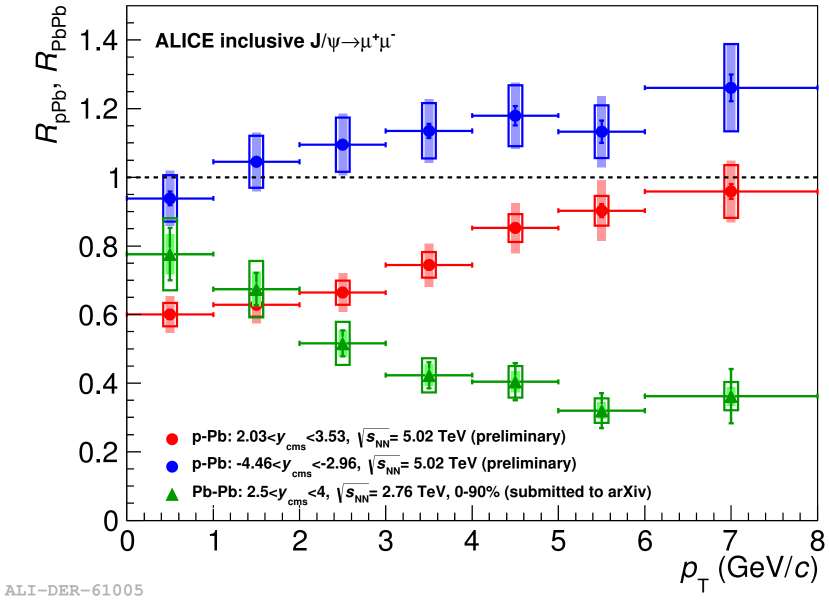


→ significant suppression also in p-Pb

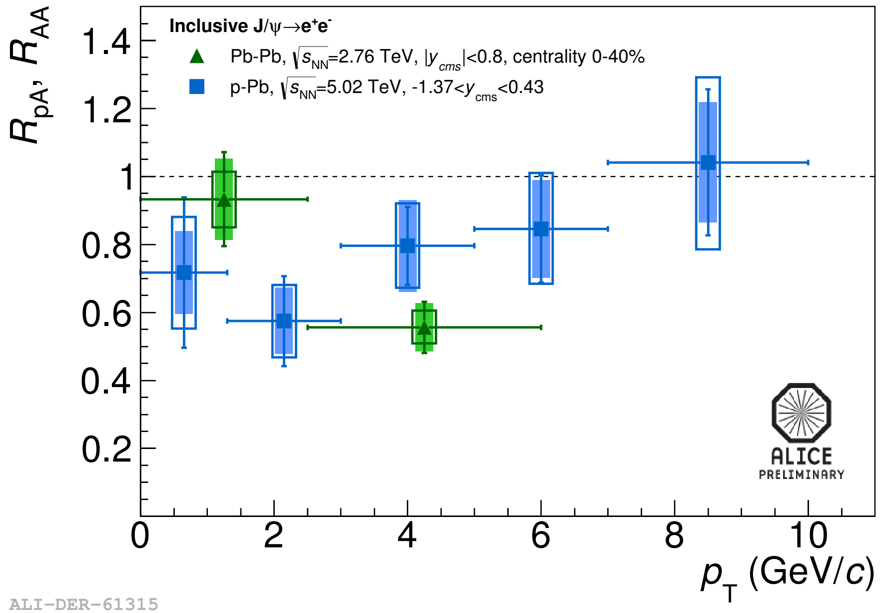
→ consistent with models including shadowing and/or energy loss

J/ψ in p-Pb vs Pb-Pb

forward/backward rapidity: J/ψ → μμ



mid-rapidity: J/ψ → ee

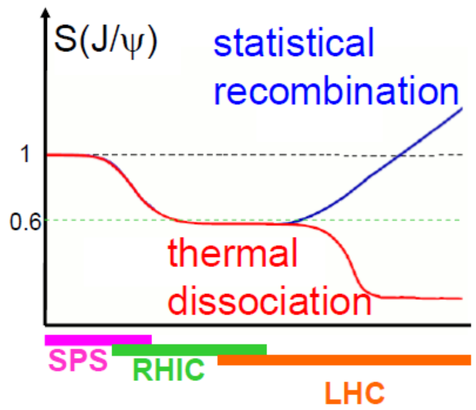


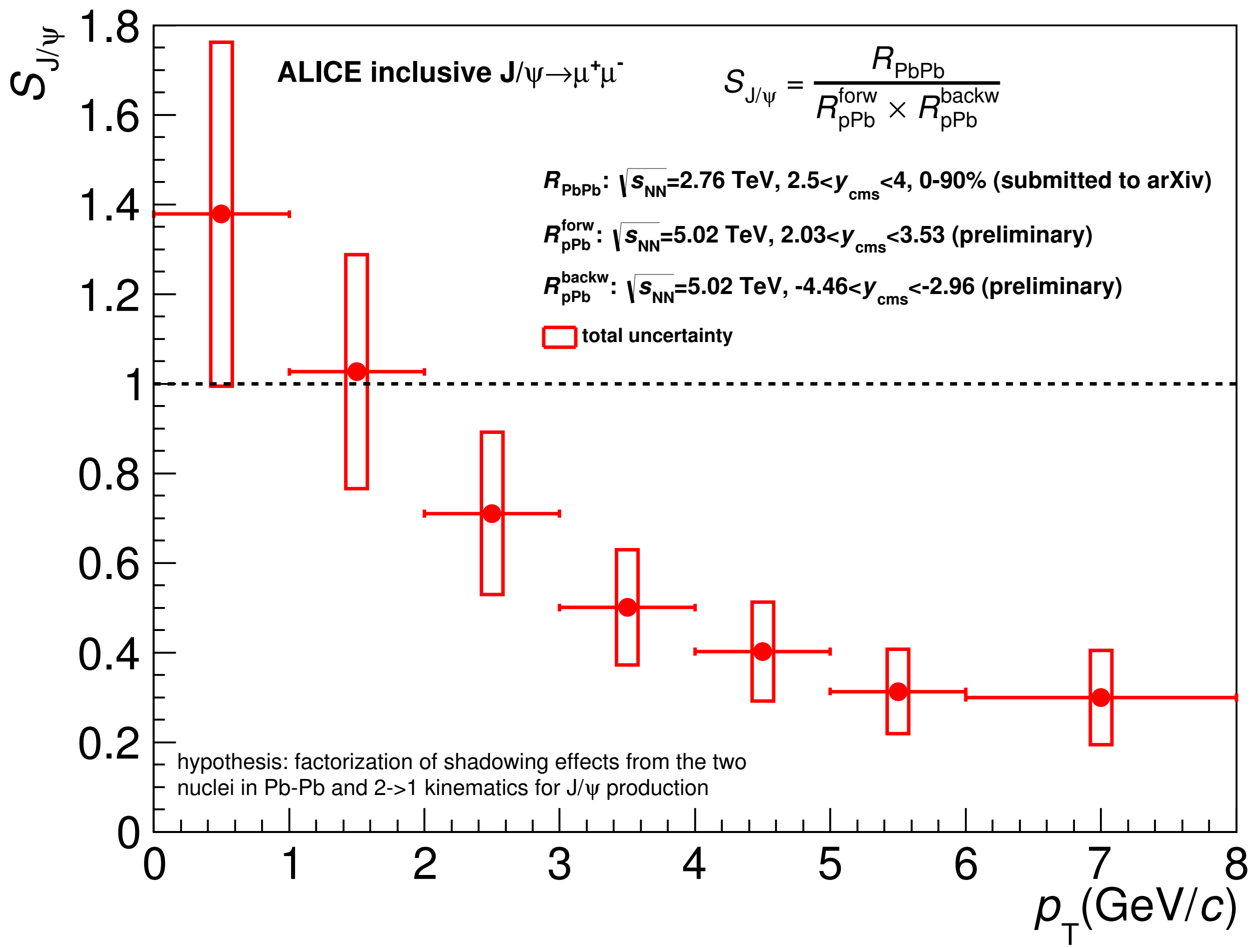
Characteristic difference of p_T dependencies:

- in p-Pb: suppression at low p_T → nuclear parton distributions
- in Pb-Pb: enhancement at low p_T → regeneration

→ hot-medium effects in Pb-Pb show up relative to p-Pb (and Pb-p)

J/ψ enhancement at the LHC





→ strong indication of J/ψ regeneration at the LHC

ALICE – past, present and near future

Run 1: 2010-2013

- 0.15 nb^{-1} Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV
  i.e. twice the design luminosity (at 50% design energy)!
- reference pp data at $\sqrt{s}$=2.76 TeV
- 30 nb^{-1} p-Pb at $\sqrt{s_{NN}}$=5 TeV

→ striking new phenomena observed

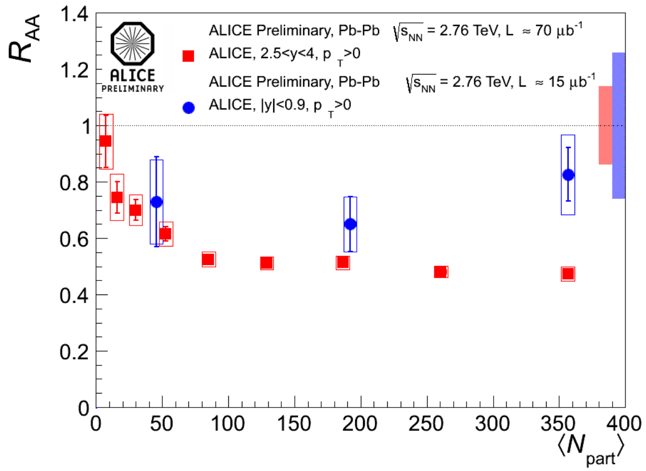
2013-2014: LS1

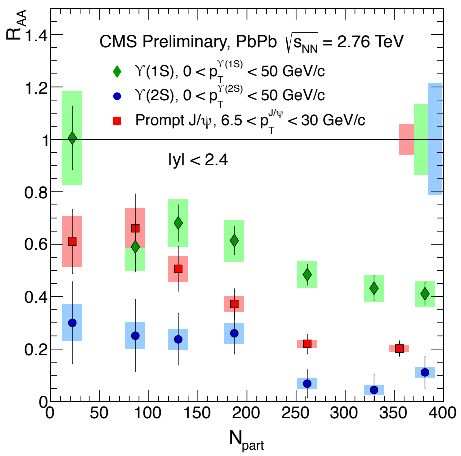
- detector completion and upgrades (TPC readout, TRD completion)

Run 2: 2015-2017

- 1 nb^{-1} Pb-Pb at $\sqrt{s_{NN}}$=5.1 TeV
- reference data pp, p-Pb

LHC Run 2– Quarkonia and HF



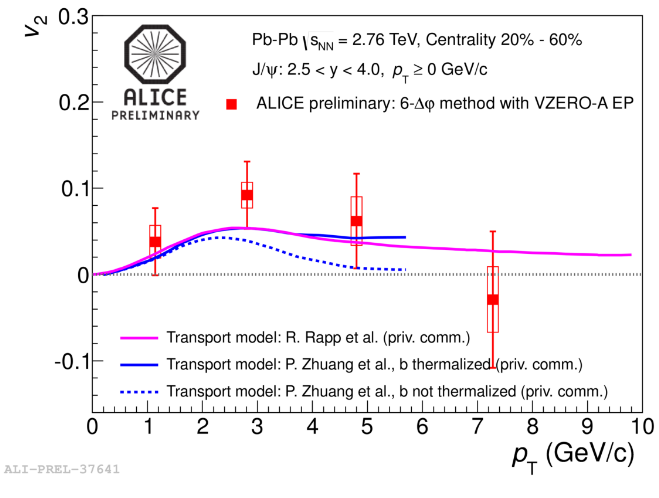


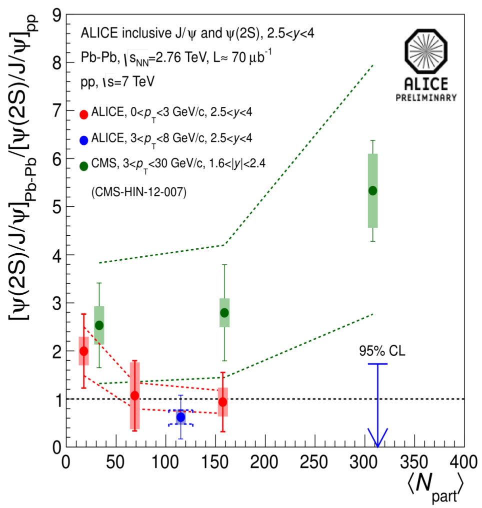
Quarkonia:

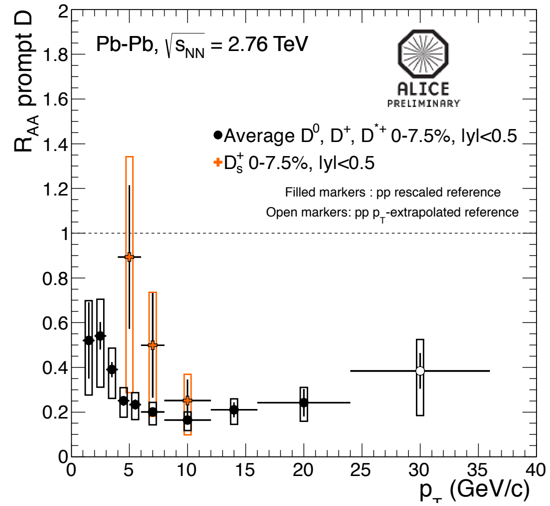
- ϒ(2s,3s) melting: onset behaviour
- low p_T J/ψ regeneration
- J/ψ collectivity
- ψ' puzzle

Heavy Flavors:

- D_s R_{AA}
- …







future opportunities at LHC

after completion of Run 2 (1 nb^{-1} Pb-Pb at $\sqrt{s_{NN}}$=5.1 TeV) there will be high-precision data available on some of the key observables

BUT there will be major opportunities at the LHC to be explored
with increased Pb-Pb luminosity in Run 3 (O(10/nb) Pb-Pb at $\sqrt{s_{NN}}$=5.5 TeV) and significant detector upgrades

future opportunities at LHC

Jets - precision measurements:
γ-Jet, b-Jet, Z-Jet, multi-Jet,
PID fragmentation functions,
TeV-scale jet quenching

ϒ spectroscopy - 1s, 2s, 3s states, onset-behaviour

Charmonia - low p_T J/ψ over wide rapidity range, ψ‘, X_c

Heavy Flavors - comprehensive measurement of D, D^*, D_s, Λ_c, B, Λ_b:
Baryon/Meson ratios down to low p_T, R_{AA}, v_2
accurate normalization for quarkonia

EM radiation - low mass dileptons

Exotica - anti- and hypernuclei

→ enter 10 nb^{-1} regime

ALICE – upgrade strategy

Dedicated heavy-ion experiment

→ upgrades focus on heavy-ion physics

Strengthen the uniqueness of ALICE

→ improve low p_T tracking, vertexing, and PID capabilities, reduce material budget

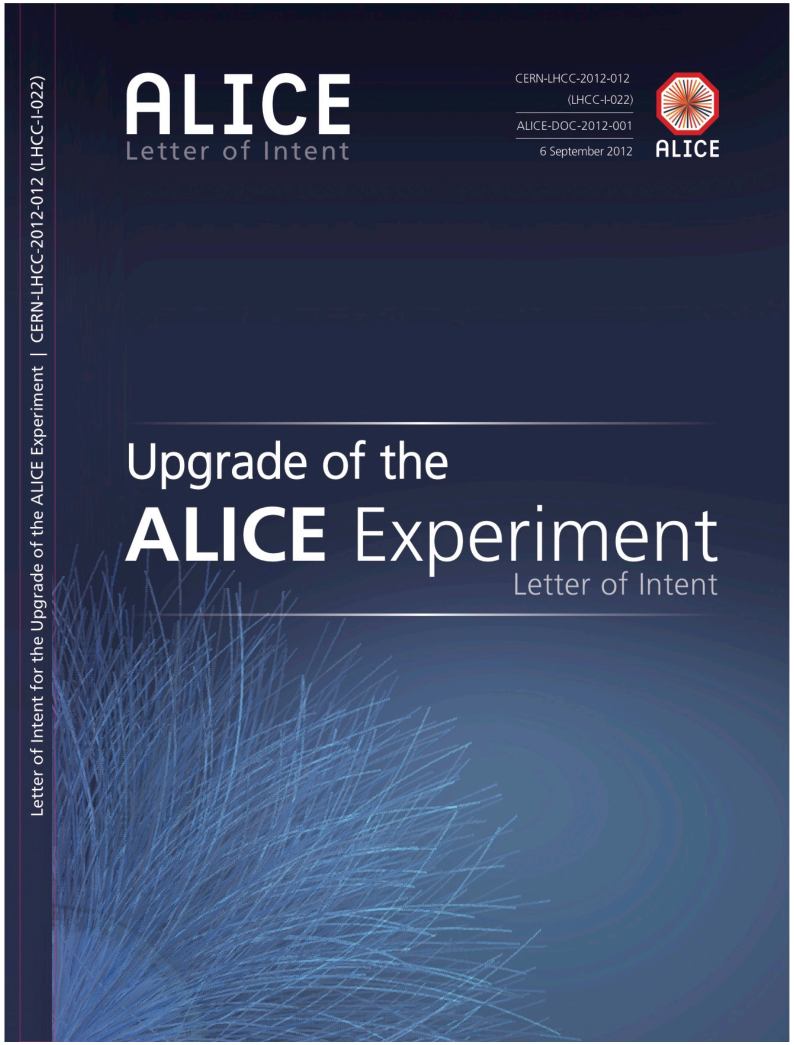
Many of the key observables, though „rare“, do not allow low-level triggering

→ high rate capability of detectors and readout systems

→ emphasizes complementarity to ATLAS and CMS

ALICE upgrade LOI

ALICE

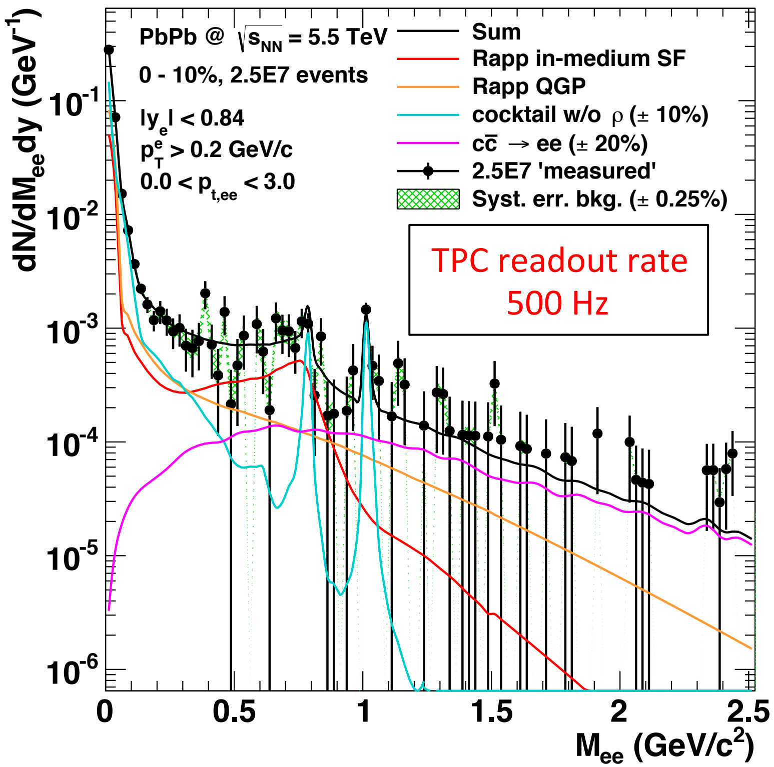


→ comprehensive *Letter of Intent* endorsed by LHCC

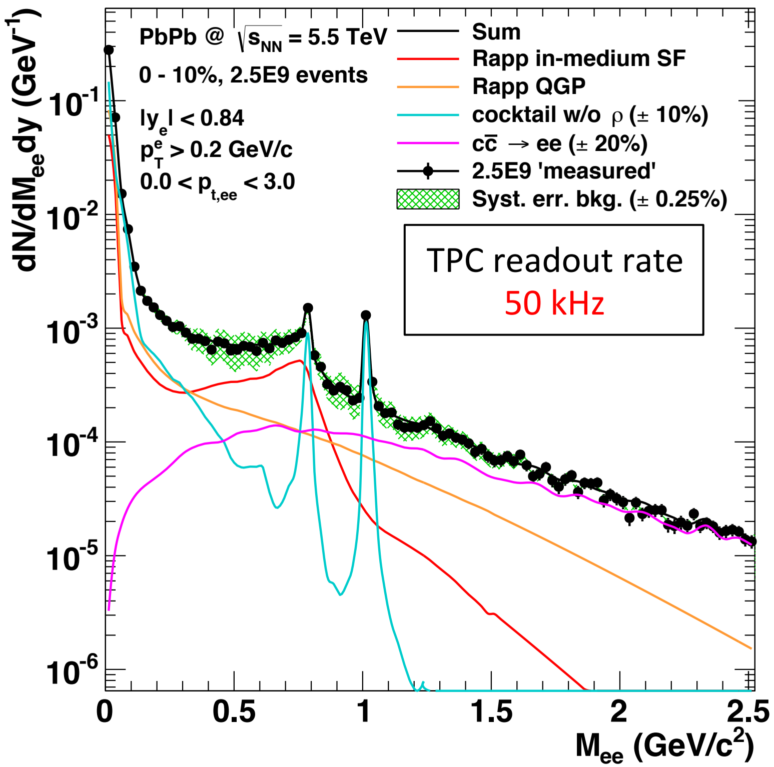
https://cdsweb.cern.ch/record/1475243/files/LHCC-I-022.pdf

example: low-mass di-electrons

2.5×10^7 Pb-Pb (0-10%)



2.5×10^9 Pb-Pb (0-10%)



- full exploitation of Run3 physics potential requires significant TPC upgrade

ALICE – core upgrades

LS2 (2018-19): - Upgrade Inner Tracking System (ITS)

→ improve vertex resolution
and low p_T tracking capability,
faster readout, reduced material budget

- Upgrade TPC with GEM-based readout chambers

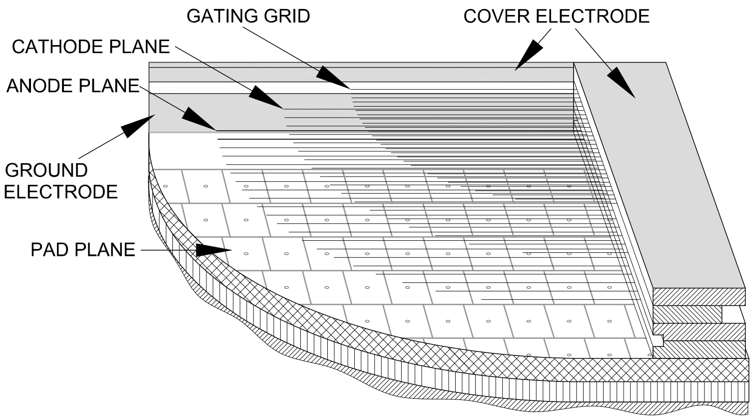
→ continuous readout at 50 kHz collision rate in Pb-Pb

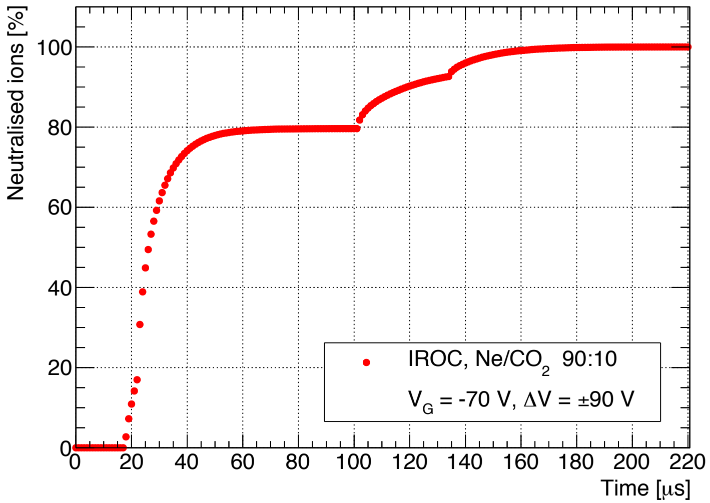
- Upgrade of readout electronics and online systems
HLT, DAQ, trigger

→ 1 TB/s into online systems

→ partial event reconstruction (20 GB/s to tape)

TPC upgrade - limitation of the present system





present MWPC-based readout chambers employ a gating grid:

after 100 μs of electron drift time, the gating grid needs to be kept close for ~200 μs to prevent back-drifting ions into the drift region

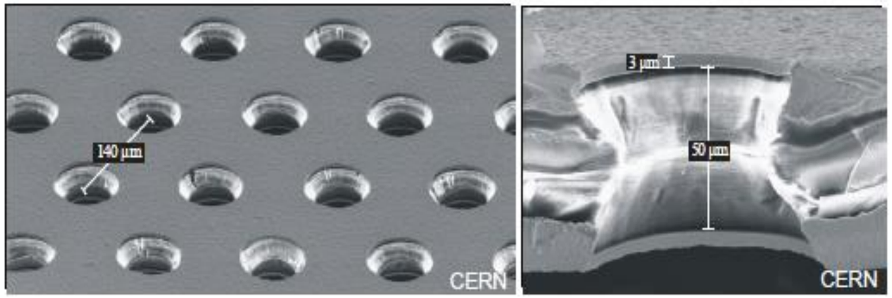
→ total time ~300 μs limits maximal readout rate to ~3 kHz

ignoring the GG closure time (i.e. keeping it open all the time) leads to excessive space point distortion due to space charge accumulation in drift volume.

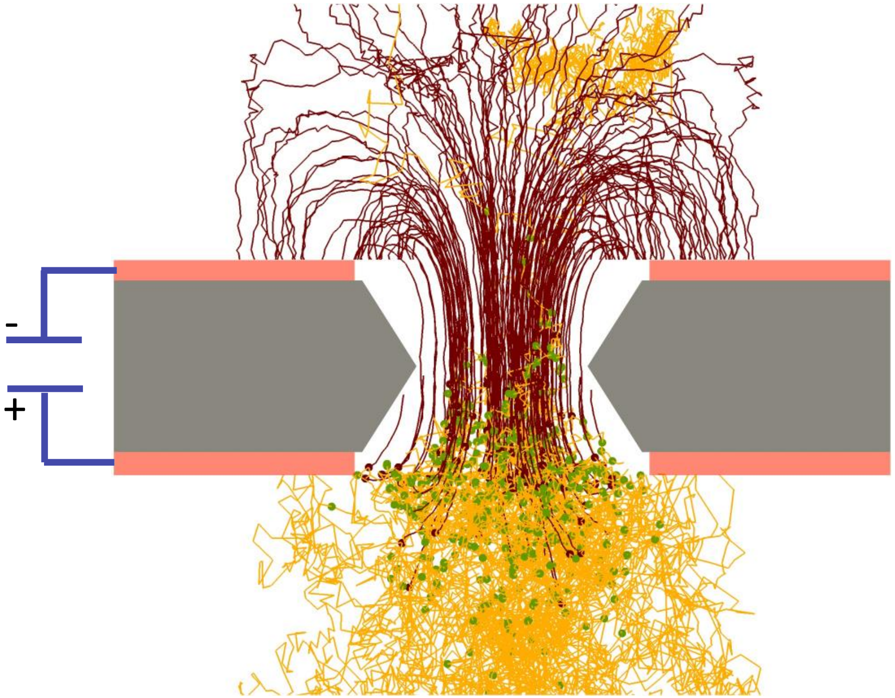
→ novel technologies required to block ions: MPGDs

→ allows for ungated („continuous“) readout
N.B.: on average 5 events pile up in the TPC at 50 kHz and $t_{d,max}$ = 100 μs

GEMs



Electron microscope photograph of a GEM foil



GEM:

- micro-patterned gas detector for electron multiplication
- proven to work reliably in high-rate applications
- in a TPC with continuous readout: back-drifting ions into drift space

→ IBF can be minimized by optimization of GEM geometry and field configuration

→ requires significant R&D effort

→ build on experience from R&D for PANDA and ILC TPCs

design specifications

Main TPC performance goals:

- enable continuous readout at 50 kHz collision rate in Pb-Pb

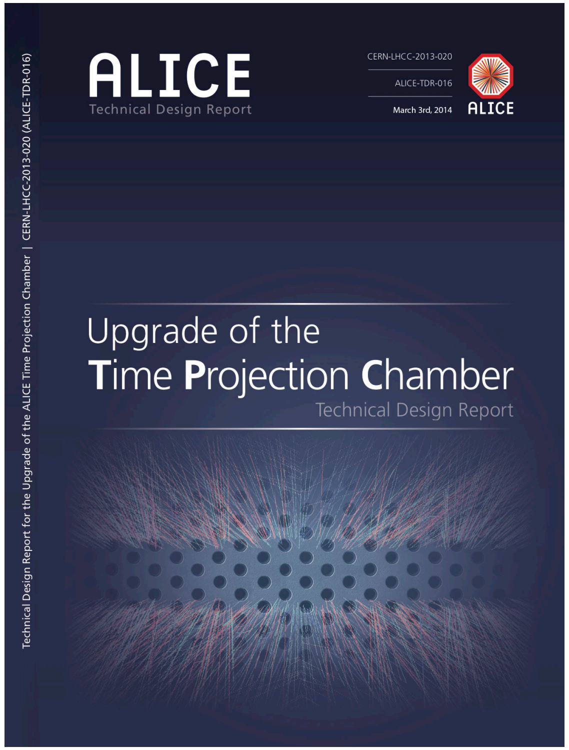
- efficient charged-particle tracking and dE/dx resolution <8.5%

→ new readout chambers (gain 2000 in Ne-CO_2-N_2 (90-10-5))
  - ion backflow (IBF) ≤ 1%, i.e. ε < 20
  - energy resolution σ(^{55}Fe) ≤ 12%

→ new readout electronics
  - continuous readout
  - negative signal polarity

→ novel calibration and online reconstruction schemes
  - online data compression by factor 20
  - space charge distortions

ALICE TPC Upgrade TDR

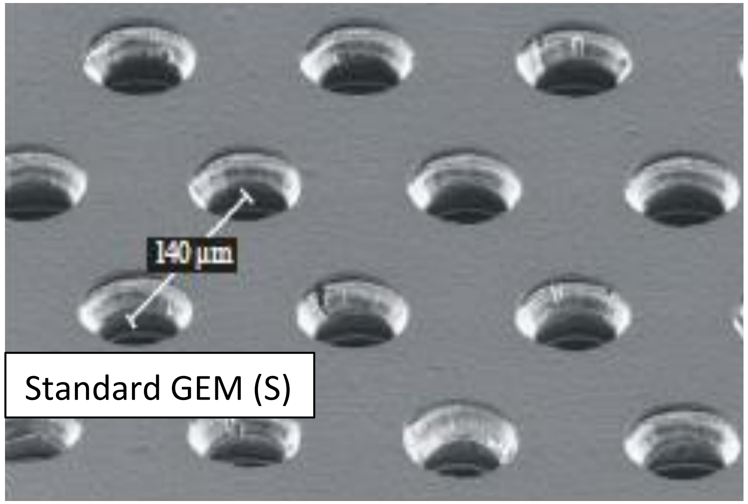


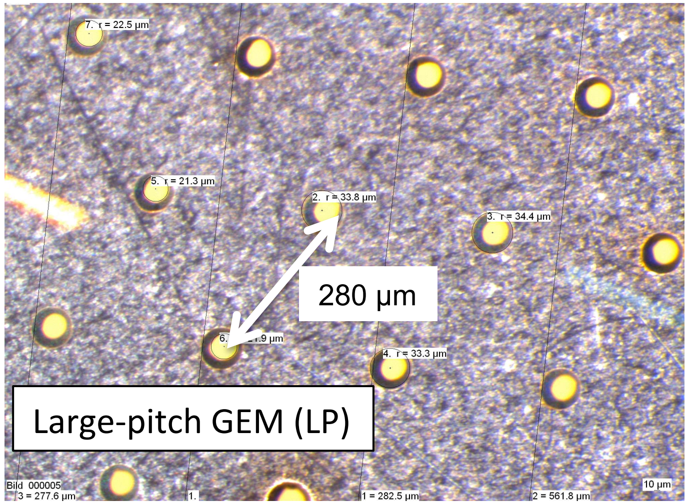
TPC Upgrade TDR submitted to LHCC in March 2014

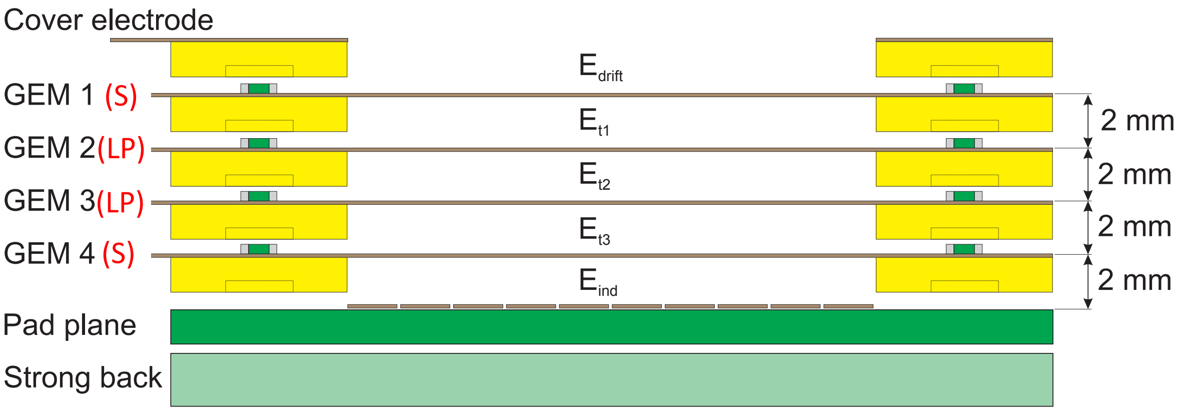
CERN-LHCC-2013-020

Croatia	Zagreb	Department of Physics, University of Zagreb
Denmark	Copenhagen	Niels Bohr Institute, University of Copenhagen
Finland	Helsinki	Helsinki Institute of Physics
Germany BMBF	Bonn	Helmholtz-Institut für Kern- und Strahlenphysik, Rheinische Friedrich-Wilhelms-Universität Bonn
Germany BMBF	Frankfurt	Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt
Germany BMBF	Heidelberg	Physikalisches Institut, Ruprecht-Karls Universität Heidelberg
Germany BMBF	Munich	Physik Department, Technische Universität München
Germany BMBF	Tübingen	Physikalisches Institut, Eberhard Karls Universität Tübingen
Germany BMBF	Worms	FH Worms, Worms
Germany GSI	Darmstadt	Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung
Hungary	Budapest	Wigner Research Center for Physics, Budapest
India	Kolkata	Bose Institute
India	Bhubaneswar	Institute of Physics
India	Bhubaneswar	National Institute of Science Education and Research
India	Indore	Indian Institute of Technology
India	Mumbai	Indian Institute of Technology
India	Kolkata	Variable Energy Cyclotron Centre
Japan	Tokyo	University of Tokyo
Mexico	Mexico City	Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México
Norway	Bergen / Tonsberg	Department of Physics, University of Bergen, Vestfold University College, Tonsberg
Norway	Bergen	Faculty of Engineering, Bergen University College
Pakistan	Islamabad	Department of Physics, COMSATS Institute of Information Technology Islamabad
Poland	Cracow	The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Science
Romania	Bucharest	National Institute for Physics and Nuclear Engineering
Slovakia	Bratislava	Faculty of Mathematics, Physics and Informatics, Comenius University
Sweden	Lund	Division of Experimental High Energy Physics, University of Lund
USA DOE	Omaha	Creighton University, Omaha, Nebraska
USA DOE	Houston	University of Houston, Houston, Texas
USA DOE	Berkeley	Lawrence Berkeley National Laboratory, Berkeley, California
USA DOE	Livermore	Lawrence Livermore National Laboratory, Livermore, California
USA DOE	Oak Ridge	Oak Ridge National Laboratory, Oak Ridge, Tennessee
USA DOE	West Lafayette	Purdue University, West Lafayette, Indiana
USA DOE	Knoxville	University of Tennessee, Knoxville, Tennessee
USA DOE	Austin	The University of Texas at Austin, Austin, Texas
USA DOE	Detroit	Wayne State University, Detroit, Michigan
USA DOE	New Haven	Yale University, New Haven, Connecticut
USA NSF	San Luis Obispo	California Polytechnic State University, San Luis Obispo, California
USA NSF	Chicago	Chicago State University, Chicago, Illinois

TDR baseline solution: 4-GEM stack



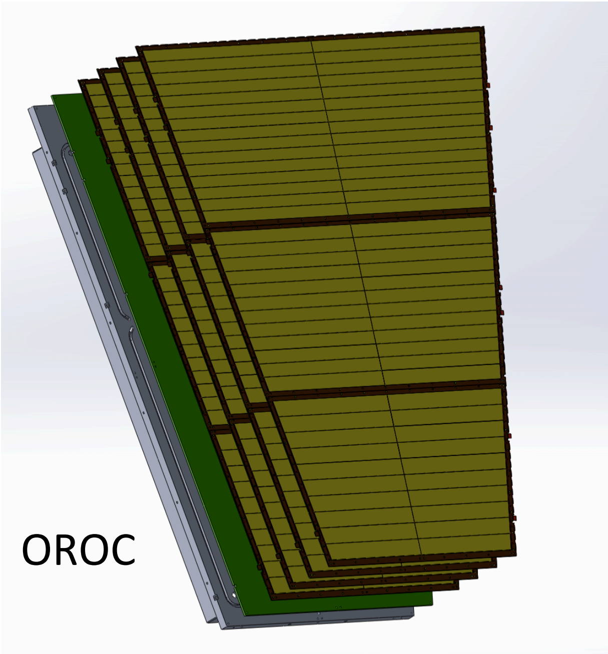


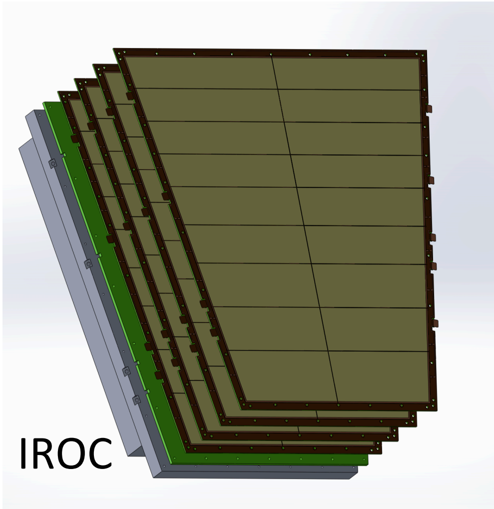


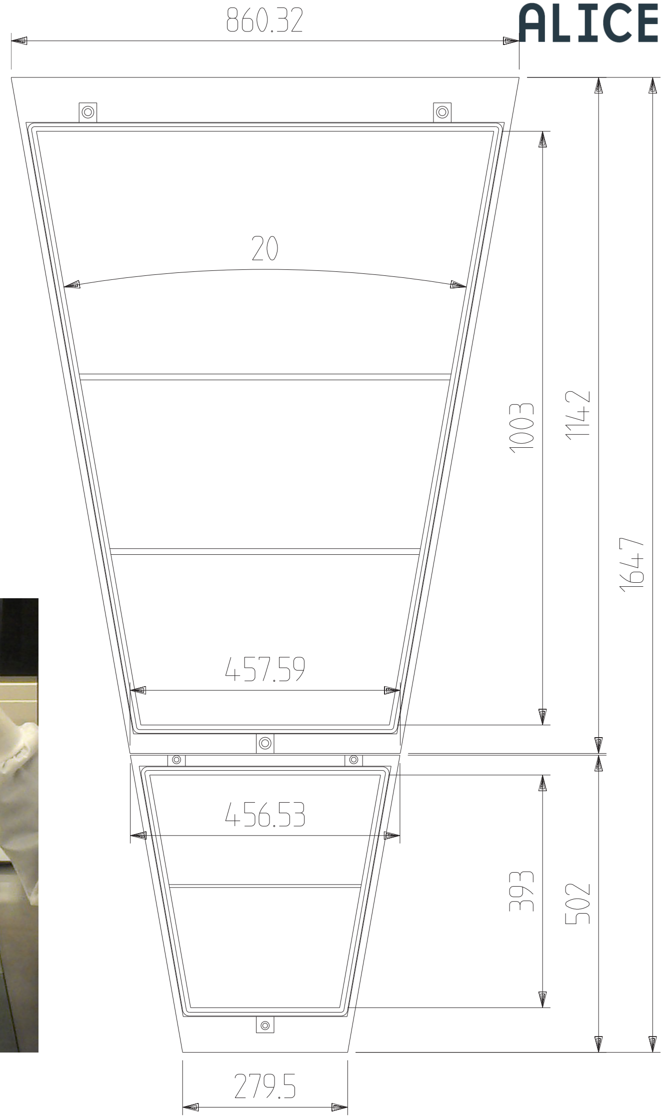
Baseline solution (S-LP-LP-S) employs standard (S) and large-pitch (LP) GEMs

$U_{GEM1}<U_{GEM2}<U_{GEM3}<U_{GEM4}$

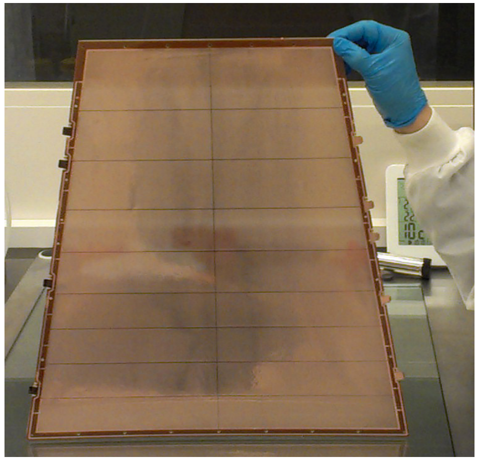
TDR baseline solution: 4-GEM stack





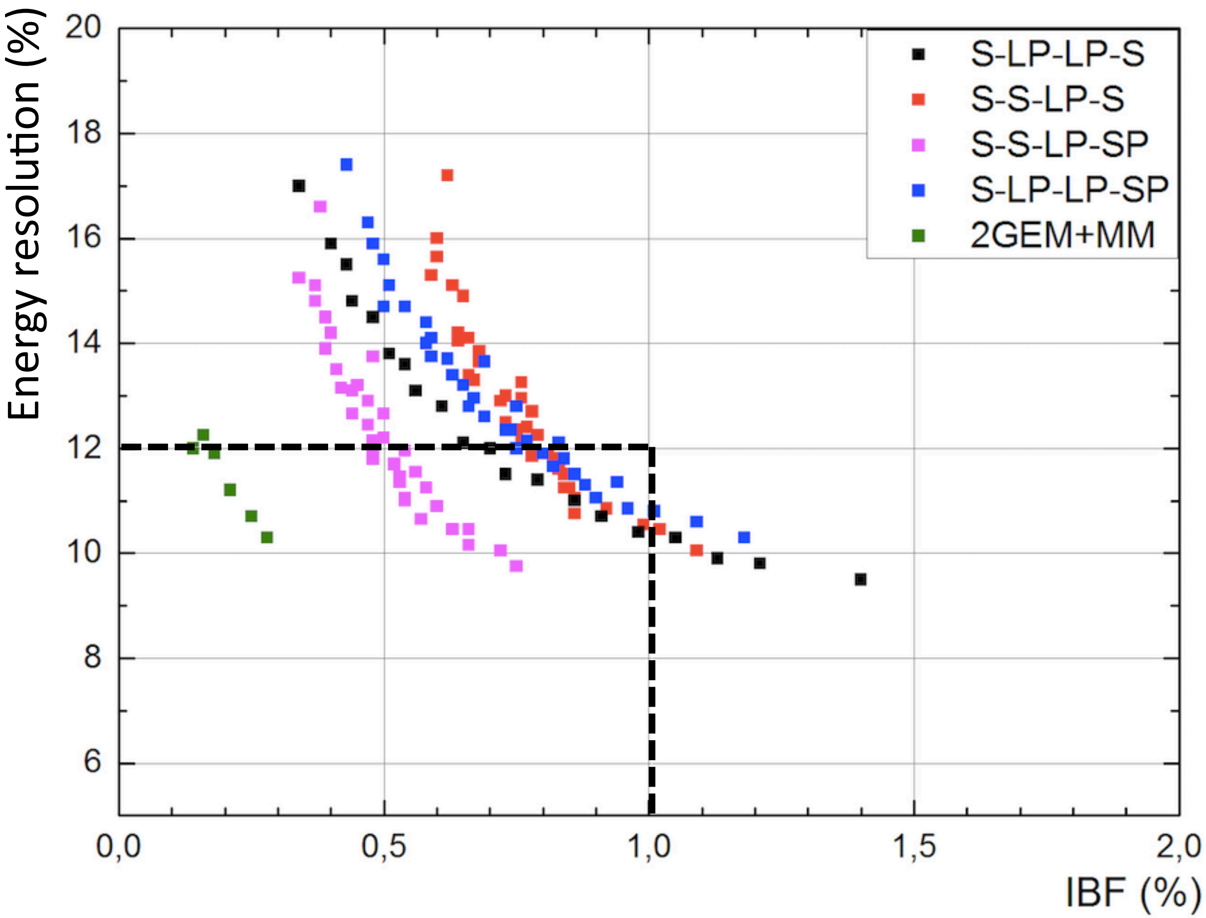


- large-size single-mask foils
- 1/layer in IROC, 3/layer in OROC



Full IROC prototype
B. Ketzer (U Bonn) L. Fabbietti (TU München)

IBF performance in MPGD systems

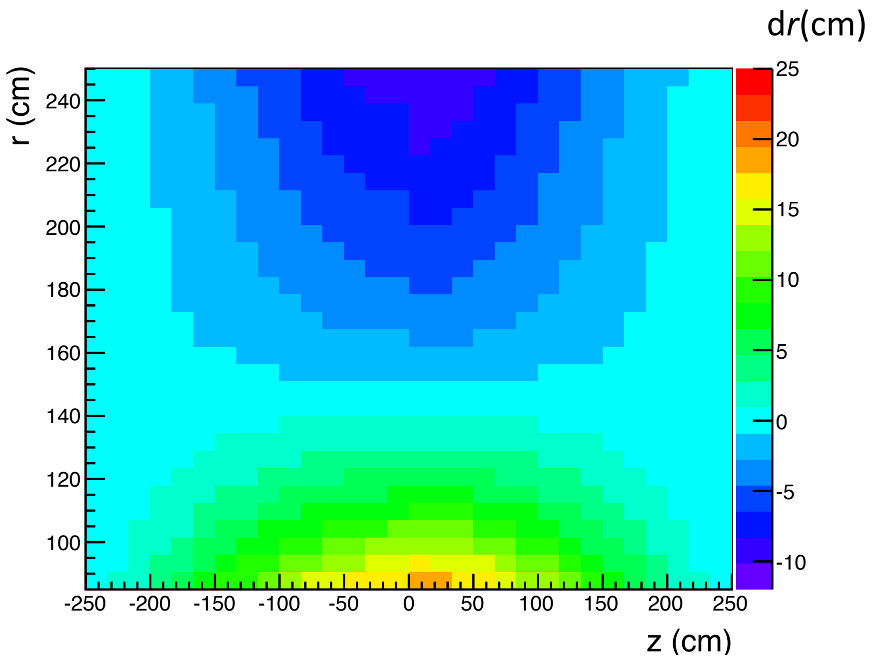


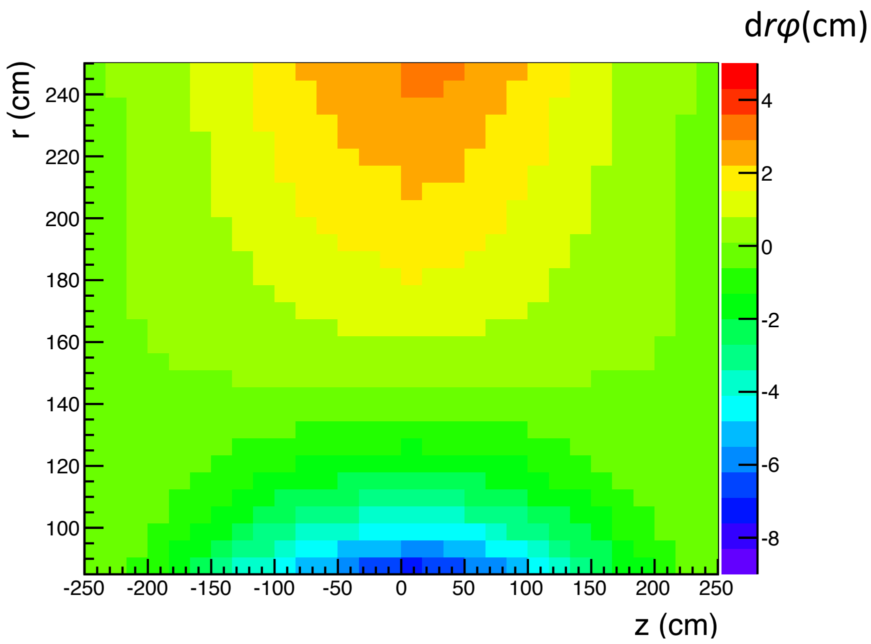
IBF=0.5% can be reached in 4GEM systems

Alternative technology: 2GEM+MM

space charge distortions

50 kHz Pb-Pb, Ne-CO_2-N_2 (90-10-5), gain =2000, IBF = 1% (ε = 20), t_d^{ion} = 0.16 s
→ ions from 8000 events pile up in the drift volume



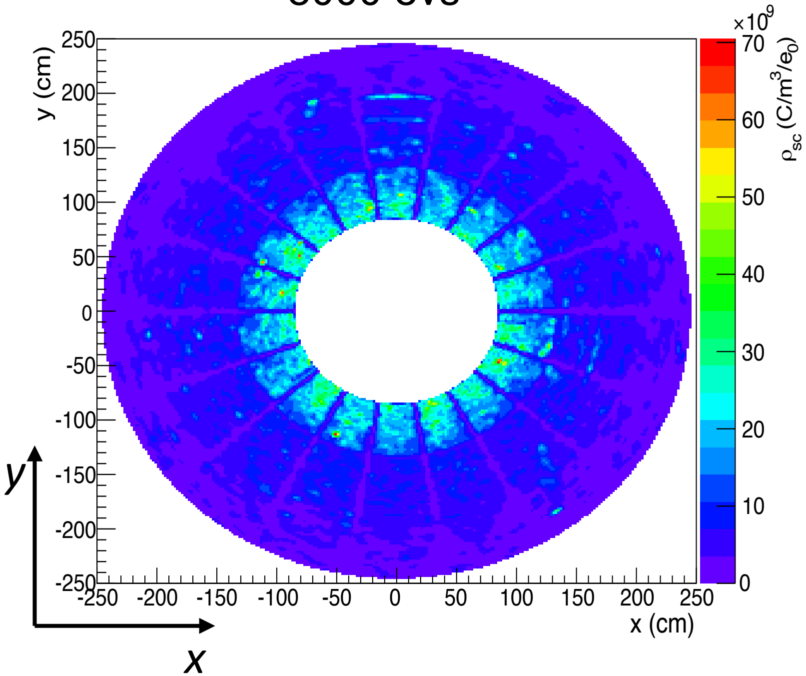


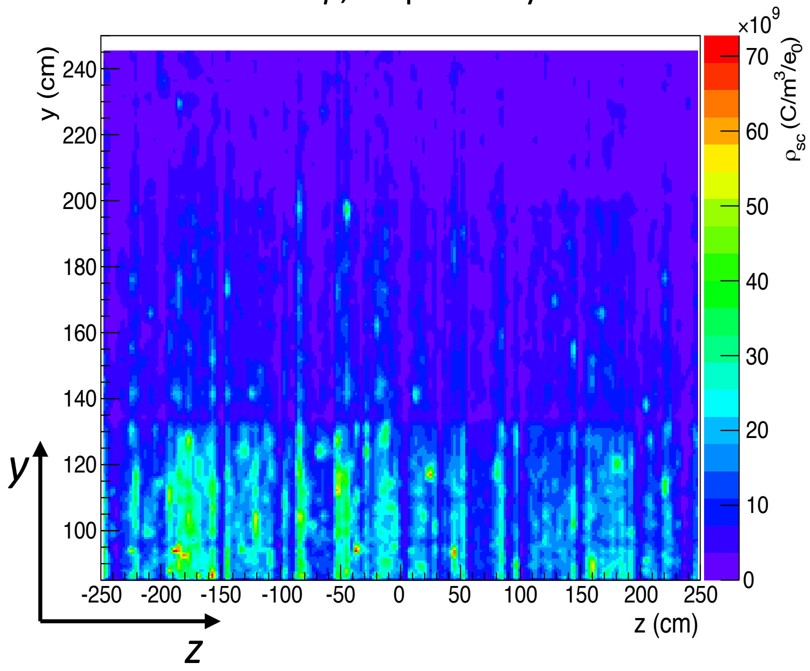
- at small *r* and *z* distortions reach *dr* = 20 cm and *drφ* = 8 cm
- corrections to a few 10^{-3} (500 μm) are required for final resolution

space charge distributions

projections are shown in small slices in *z* and *φ*, respectively

8000 evs





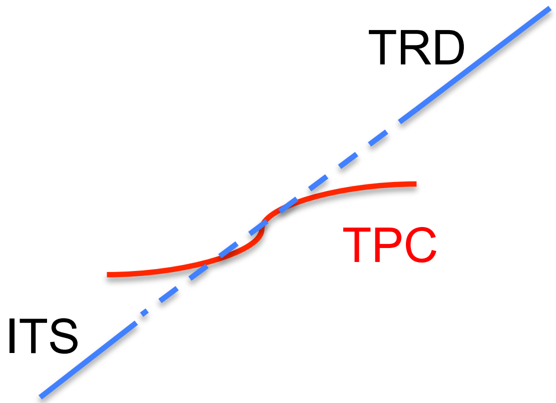
Study of space-charge distributions and variations in space and time based on real Pb-Pb raw data

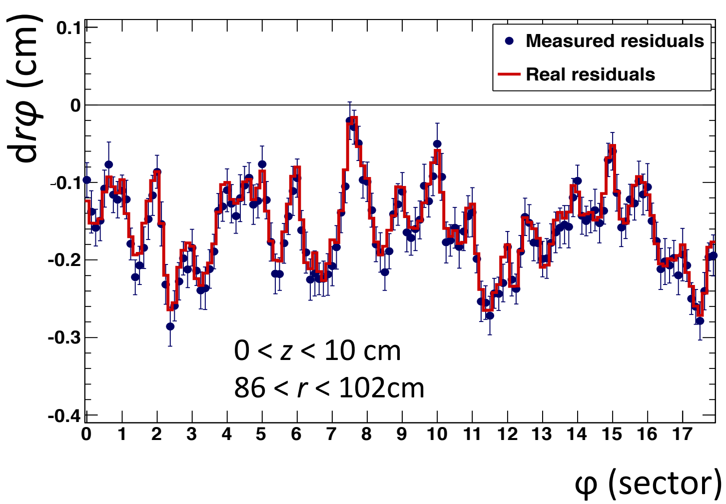
In Ne-CO_2-N_2 (90-10-5) at 50 kHz, 8000 „ion events" pile up within 160 ms

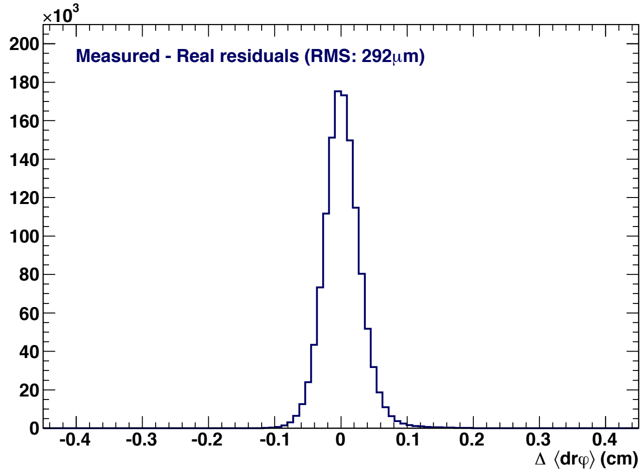
Significant fluctuations O(1%) of the space charge distributions need to be considered

online distortion correction

- use external track reference from ITS-TRD interpolation
- update interval: 5ms



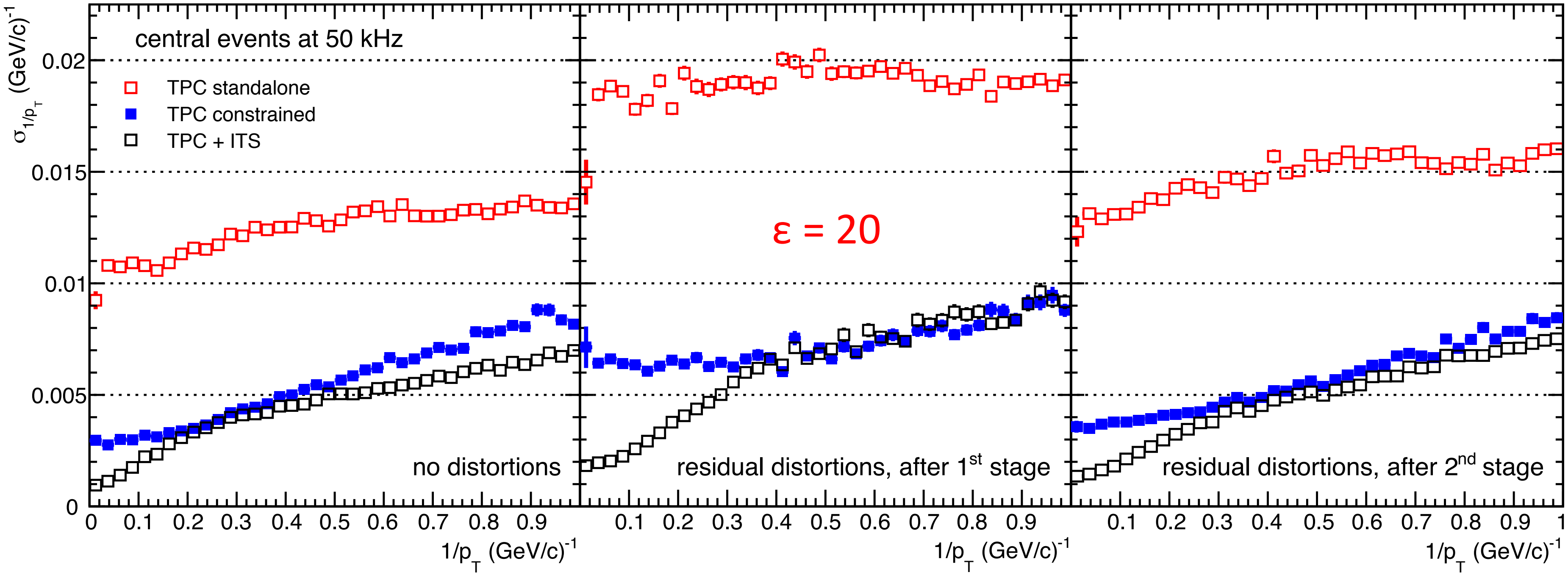




→ spatial fluctuation pattern well described

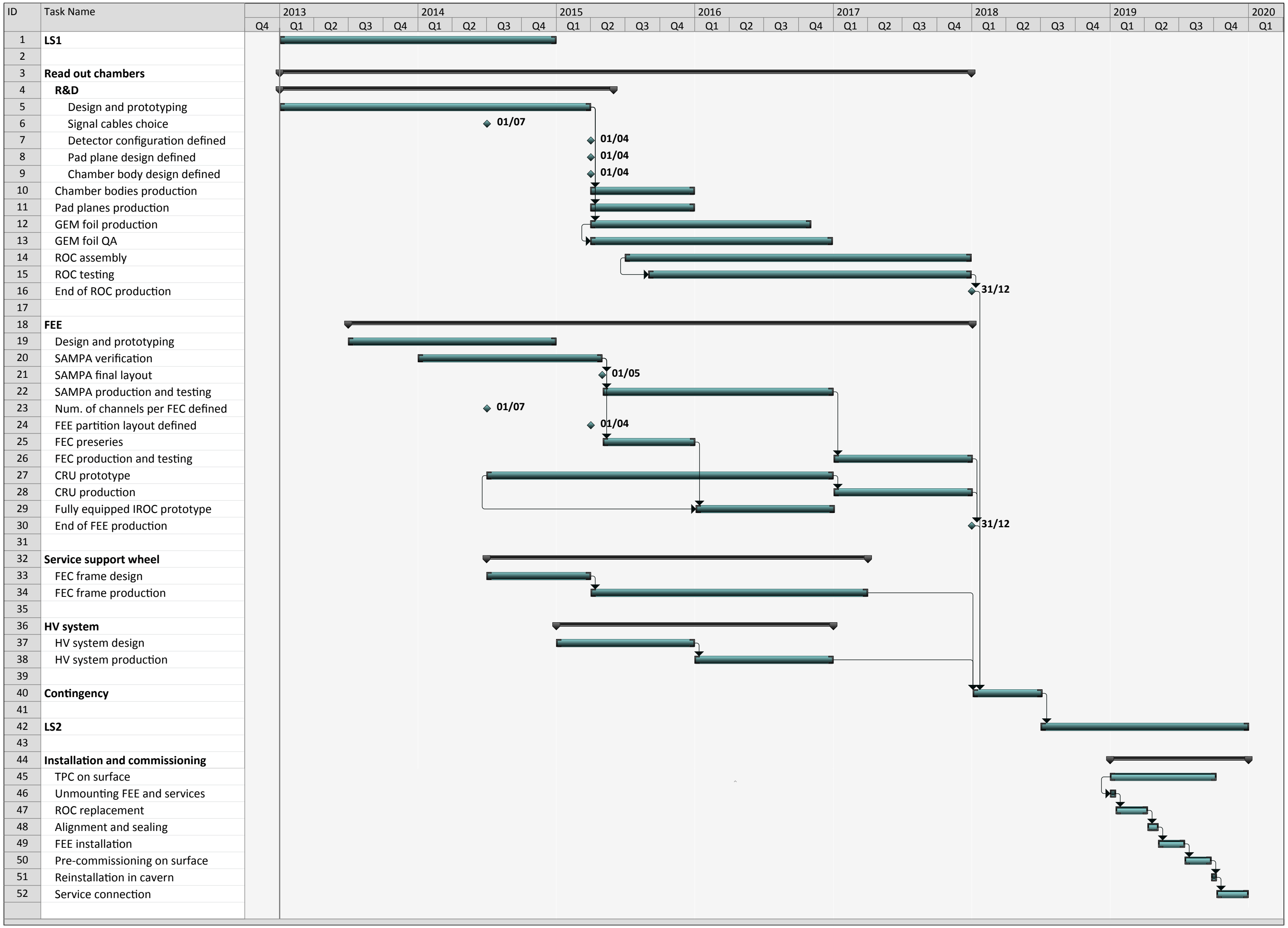
→ residual fluctuations significantly improved

online tracking: momentum resolution



- momentum resolution after first reconstruction stage factor 1.5 - 2 worse than ideal
- practically fully recovered after second reconstruction stage

TPC upgrade - time schedule



summary

Heavy-Ion program from LHC-Run1 concludes with major new results to characterize the nature of hot and dense elementary matter

Significant improvement of data quality expected in Run 2

ALICE plans a major upgrade of their detector systems to enable full exploitation of the LHC physics potential in Run 3

A technical solution for TPC readout chamber upgrade based on GEMs is demonstrated in a TDR to the LHCC

R&D is ongoing to assess all technological options and optimize the present solution