Relativistic Heavy-Ion Collisions

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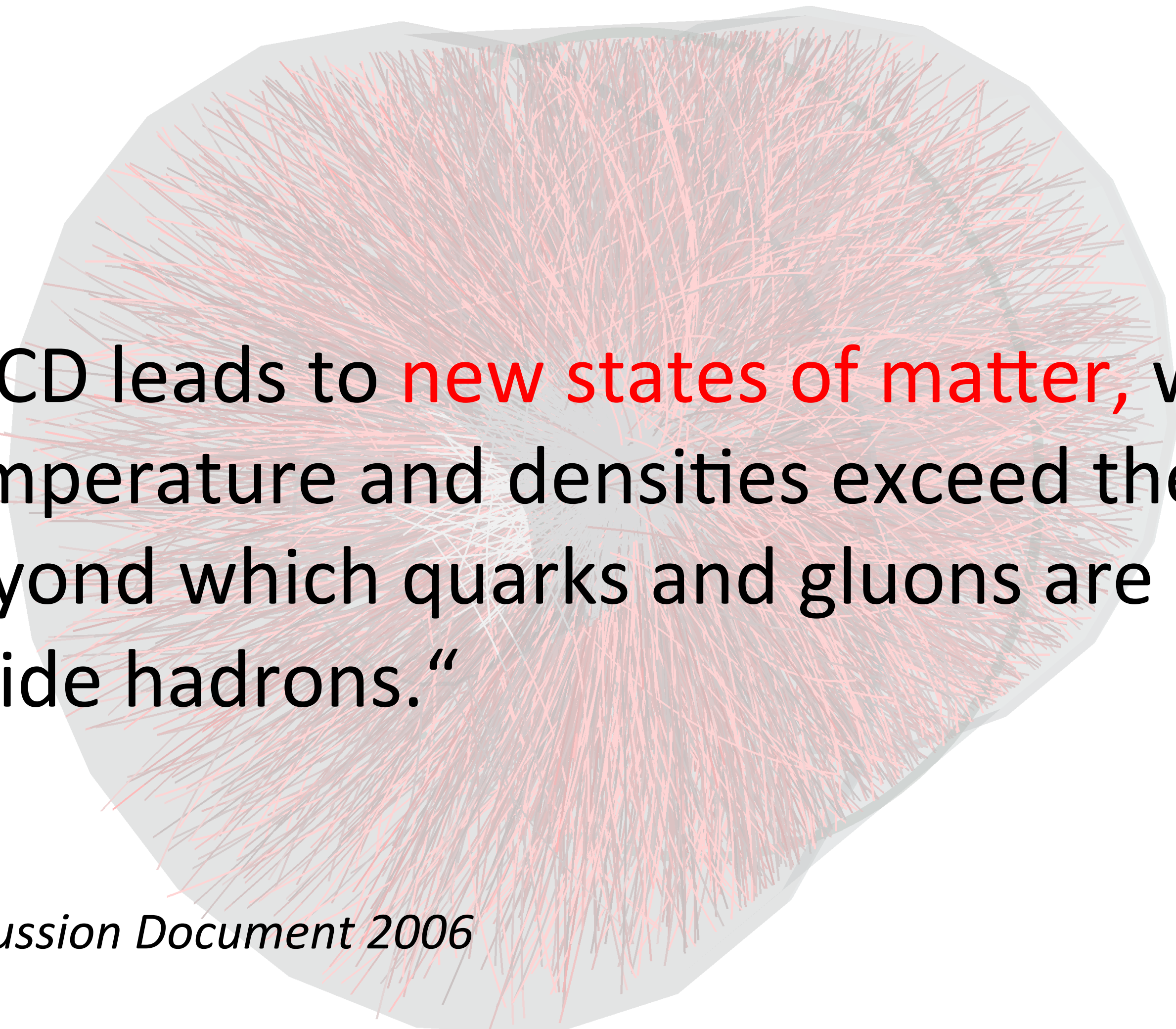
Cracow Open Symposium of the European Strategy Preparatory Group

Relativistic Heavy-Ion Collisions

- The Energy Frontier:
  Heavy-Ion Collisions at the LHC
- Challenges and Opportunities:
  New Facilities and Future Fixed-Target Running
- Synergies and complementarities:
  The Future RHIC Programme

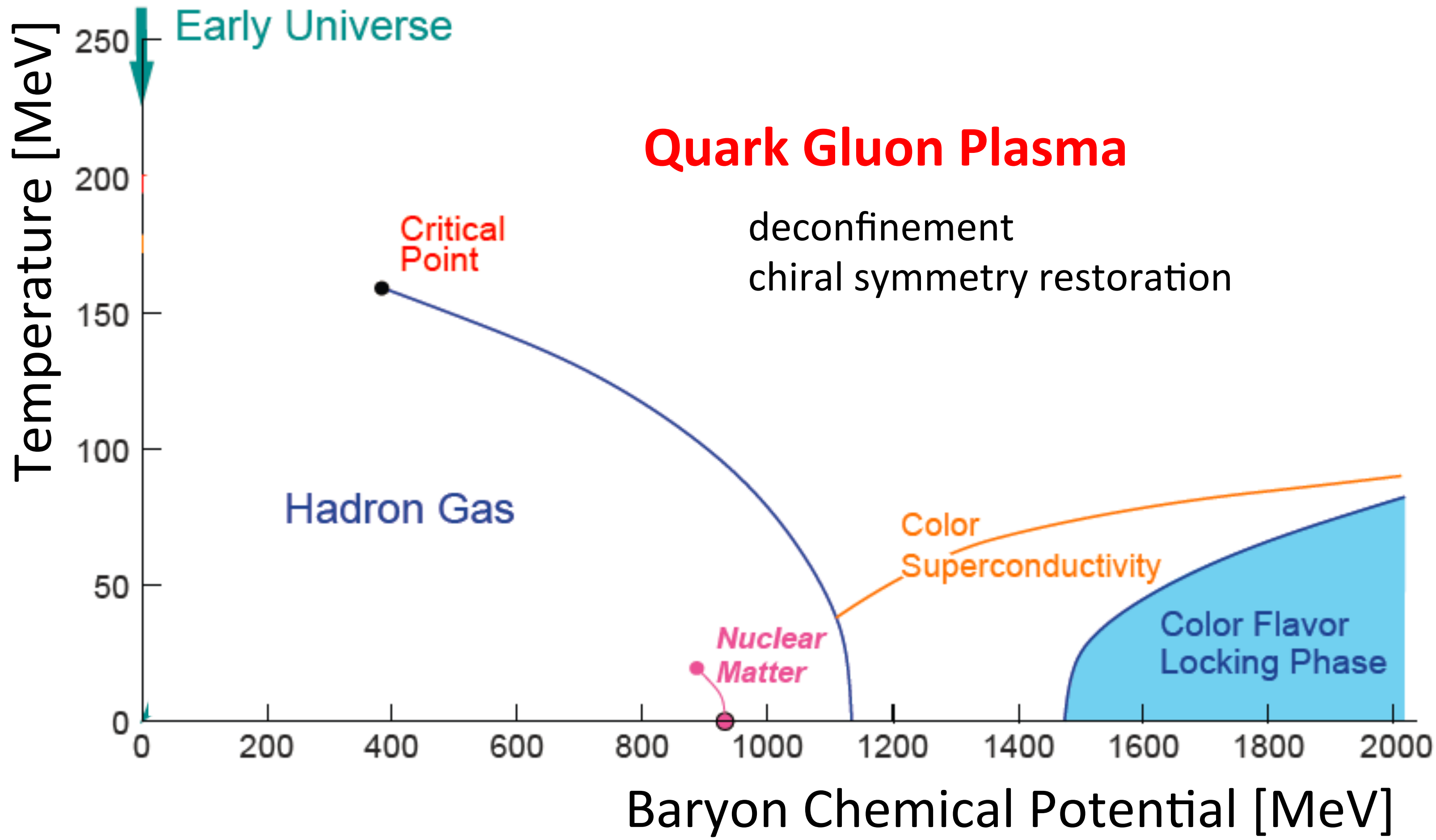
New states of matter



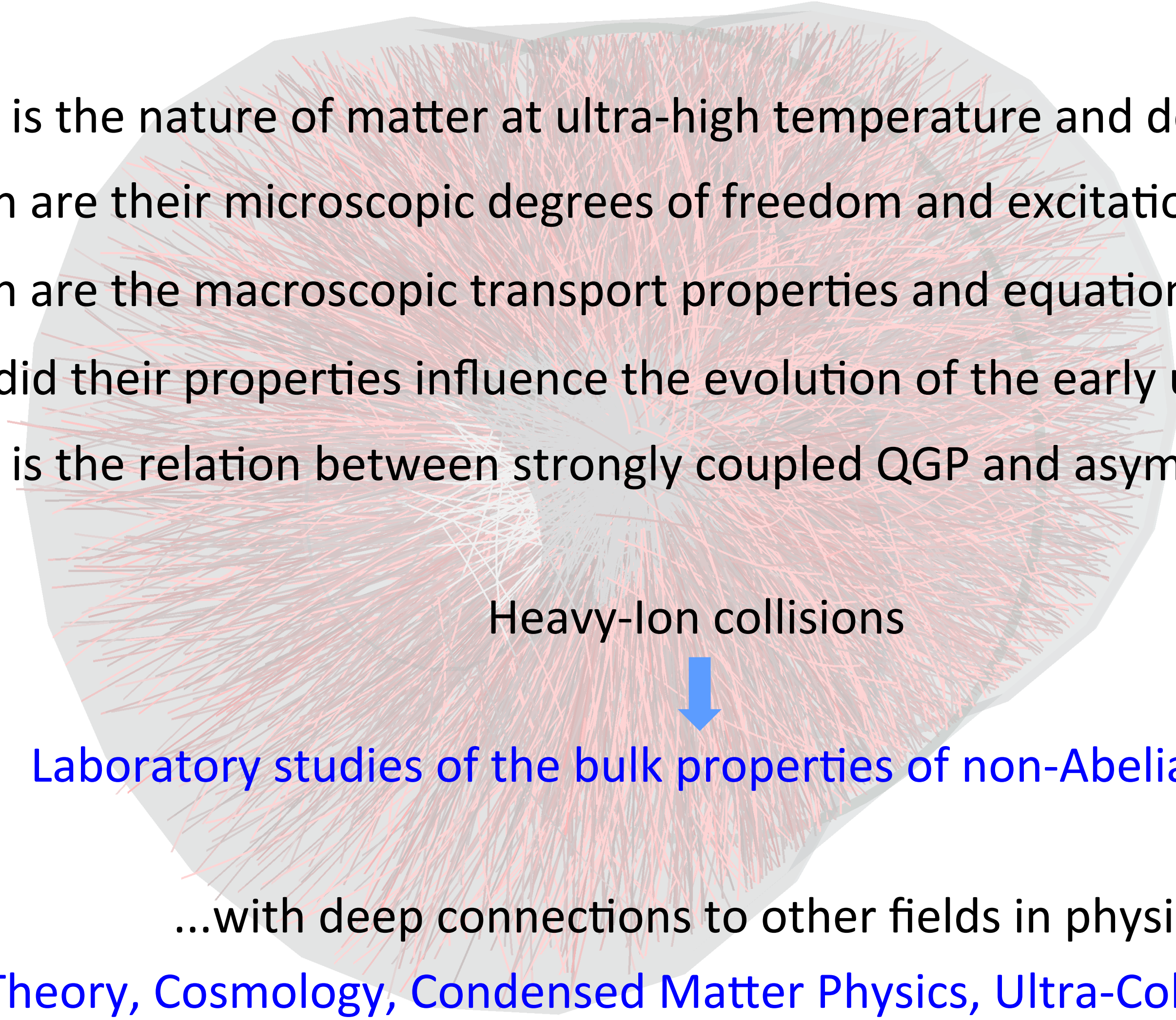
„QCD leads to new states of matter, when temperature and densities exceed the values beyond which quarks and gluons are confined inside hadrons.“

Discussion Document 2006

QCD phase diagram



Condensed QCD matter physics



- What is the nature of matter at ultra-high temperature and density?
- Which are their microscopic degrees of freedom and excitations?
- Which are the macroscopic transport properties and equation of state?
- How did their properties influence the evolution of the early universe?
- What is the relation between strongly coupled QGP and asymptotically free QCD?

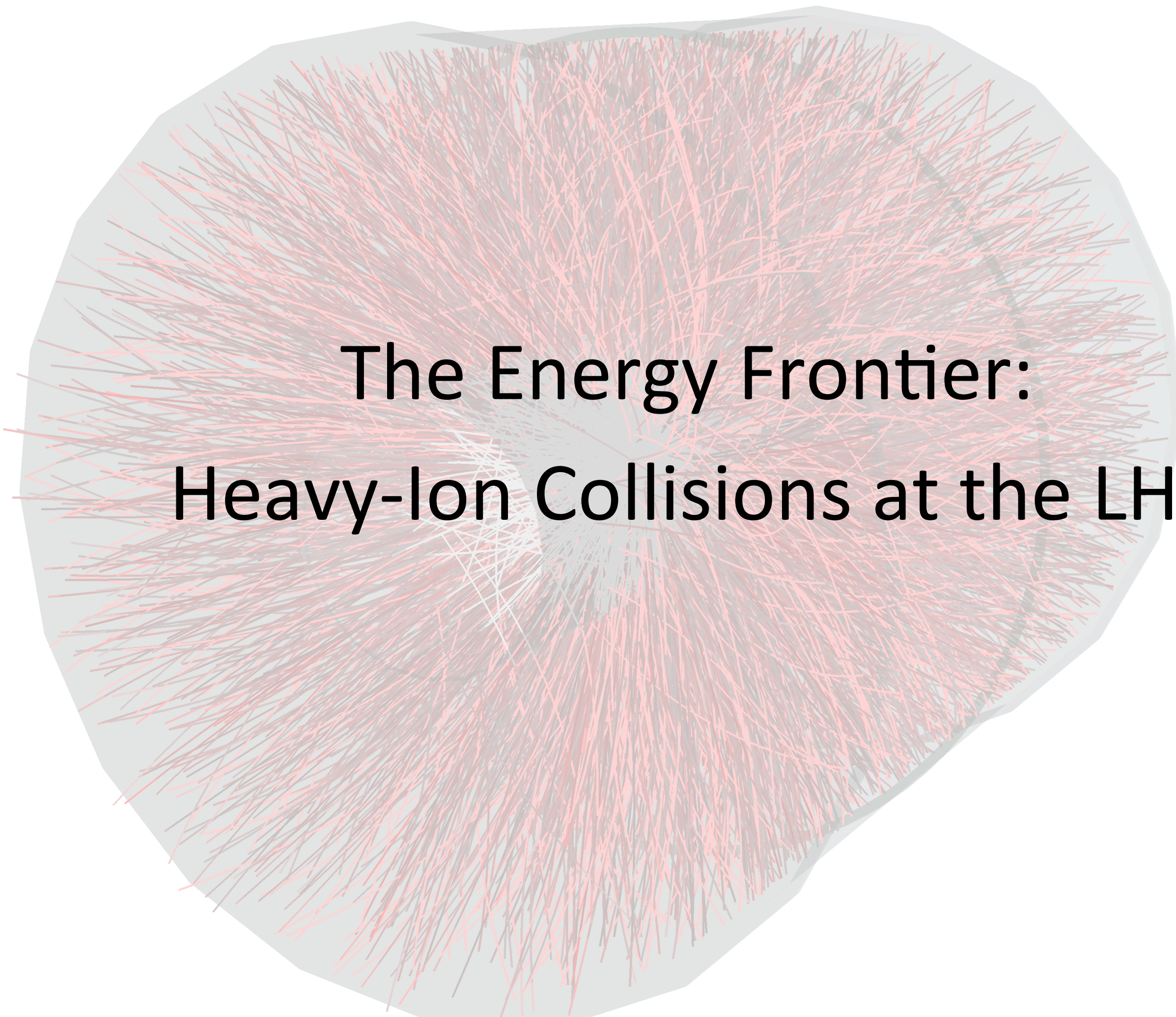
Heavy-Ion collisions

⬇

Laboratory studies of the bulk properties of non-Abelian matter

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

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

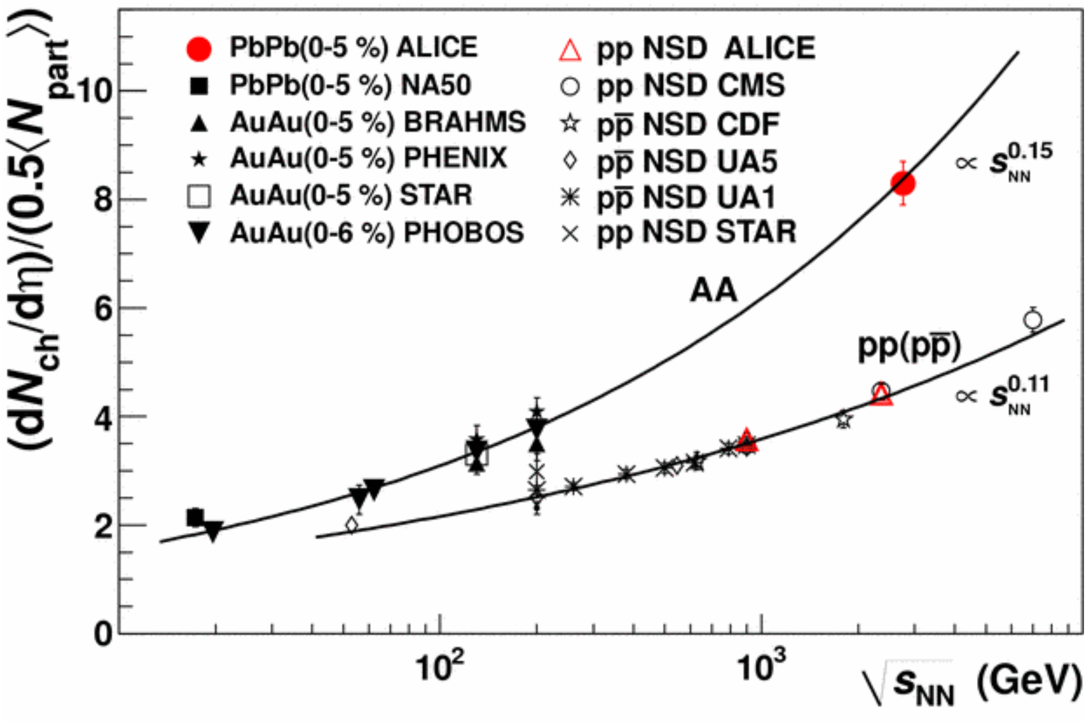


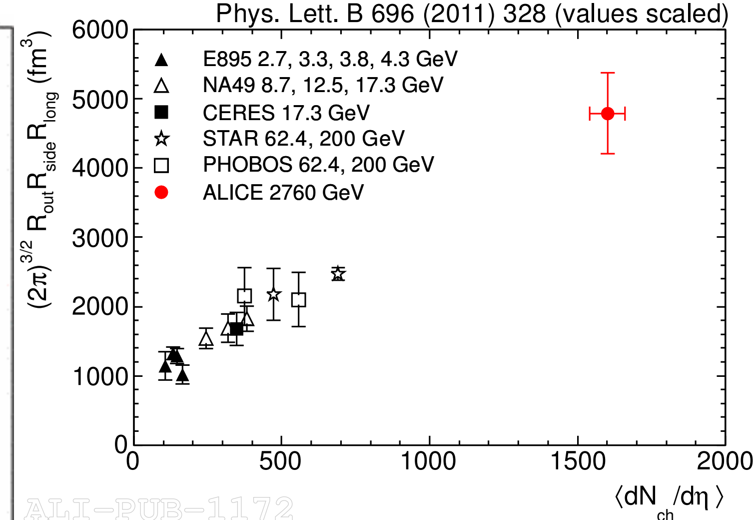
The Energy Frontier: Heavy-Ion Collisions at the LHC

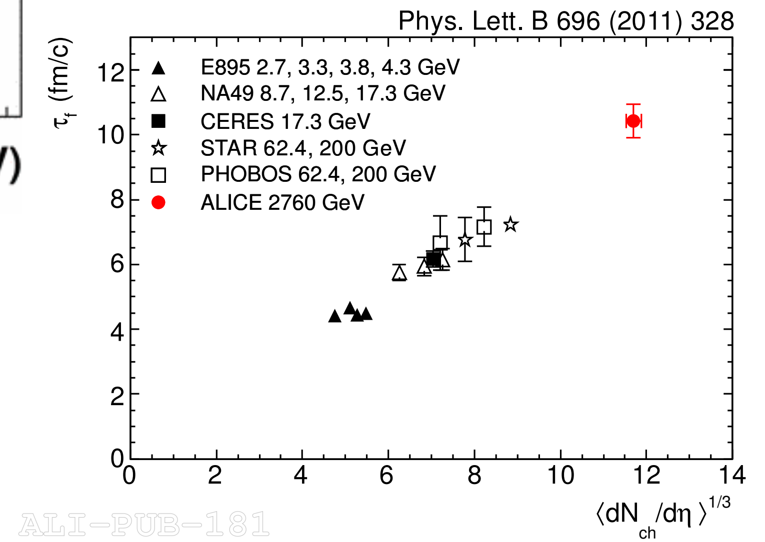
Heavy-ion collisions at the LHC are unique

- The net-baryon density at mid-rapidity is small ($\mu_B \approx 0$), corresponding to the conditions in the early universe
- The initial temperature and energy density are the highest achievable in the laboratory
- The large collision energy provides abundant production of hard probes
- First principle methods (pQCD, Lattice Gauge Theory) most applicable

Heavy-ion collisions at the LHC







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

LHC heavy-ion running

Phase 0: 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

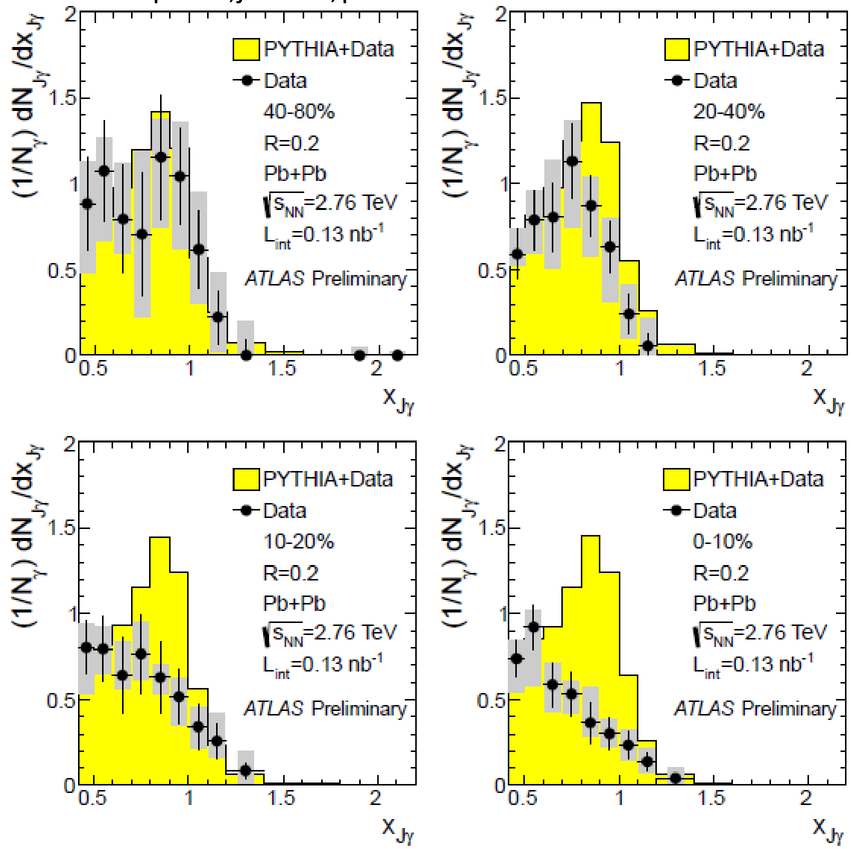
Major results by ALICE, ATLAS, CMS:

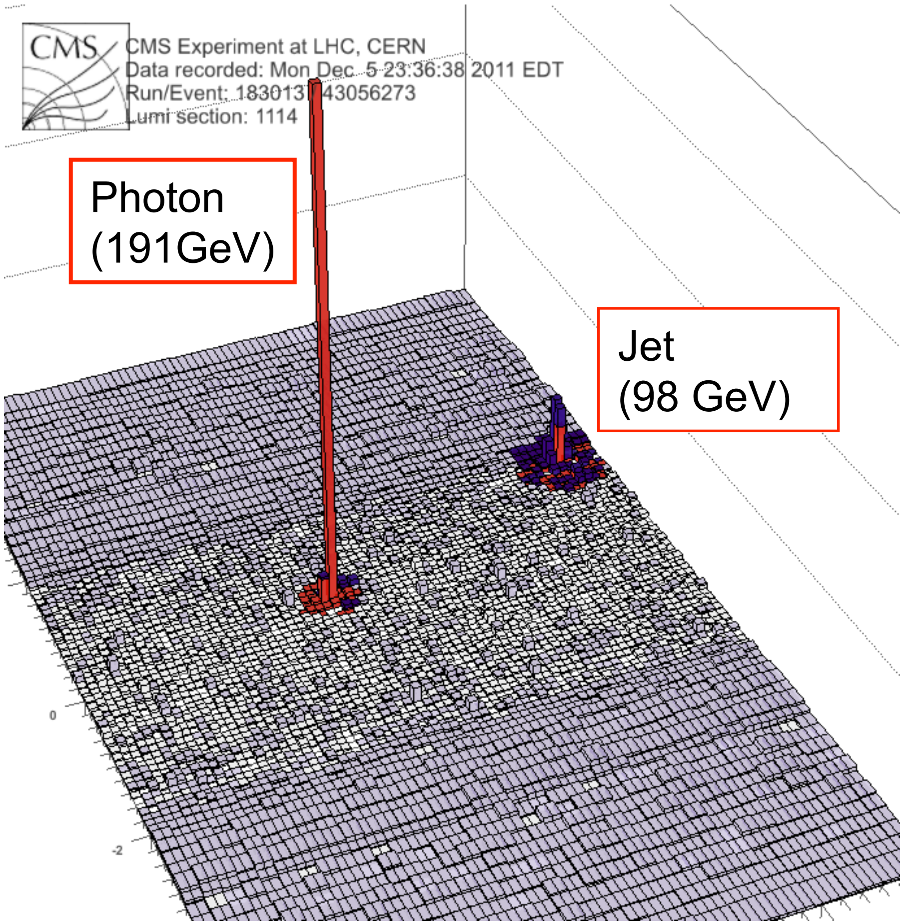
- Jets and jet quenching
- Electroweak probes
- Upsilon spectroscopy
- Charmonium suppression
- Heavy flavor R_{AA}, v_2
- Bulk properties

August 2012, Washington DC
http://qm2012.bnl.gov

LHC HI-highlights – jet quenching

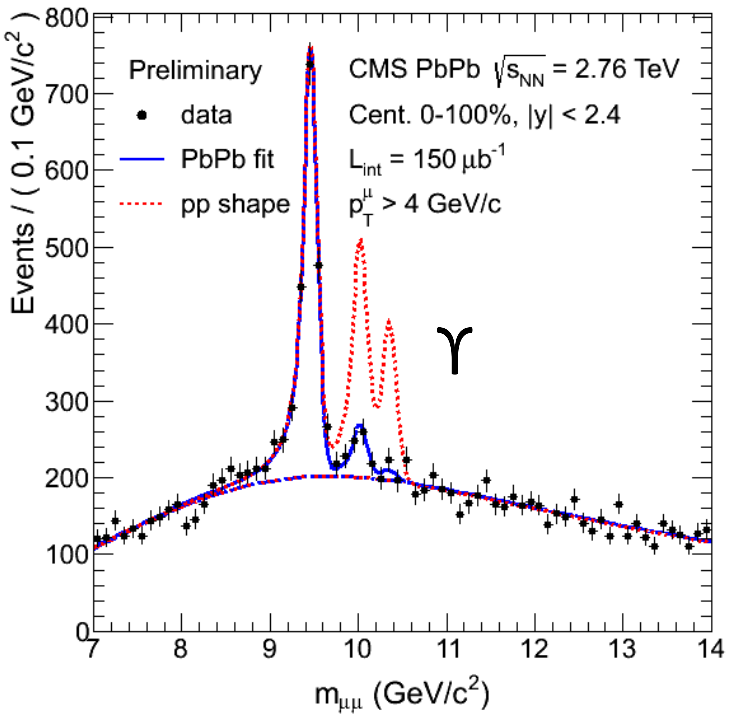
$x_{J\gamma}=p_{T,jet}/p_{T,\gamma}$

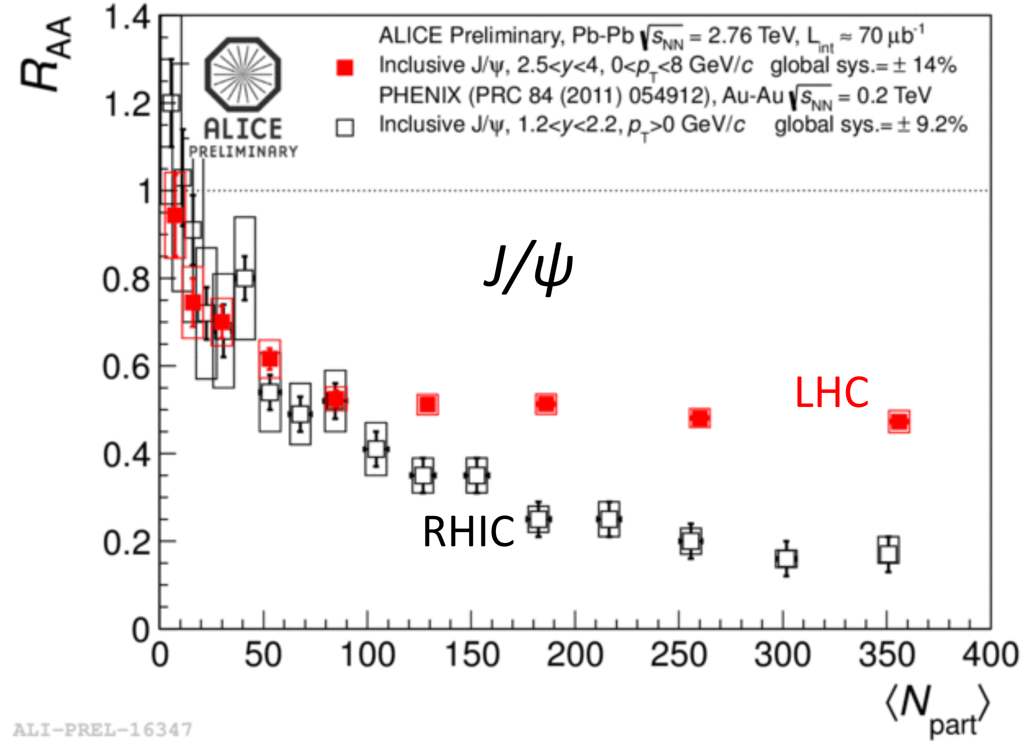




Direct observation of large partonic energy loss in the QGP via γ-jet imbalance

LHC HI-highlights – quarkonia suppression

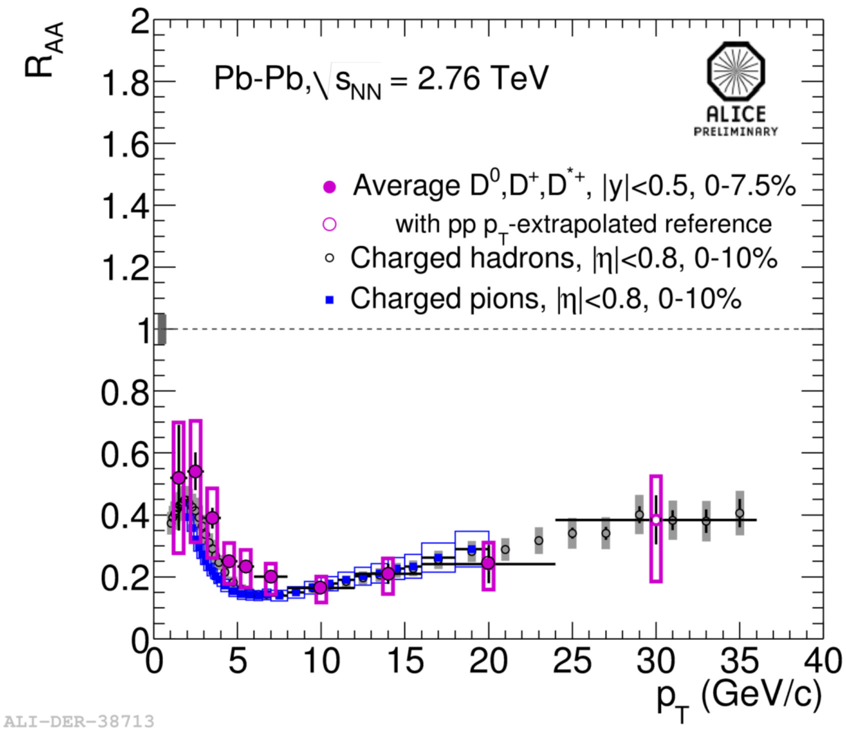


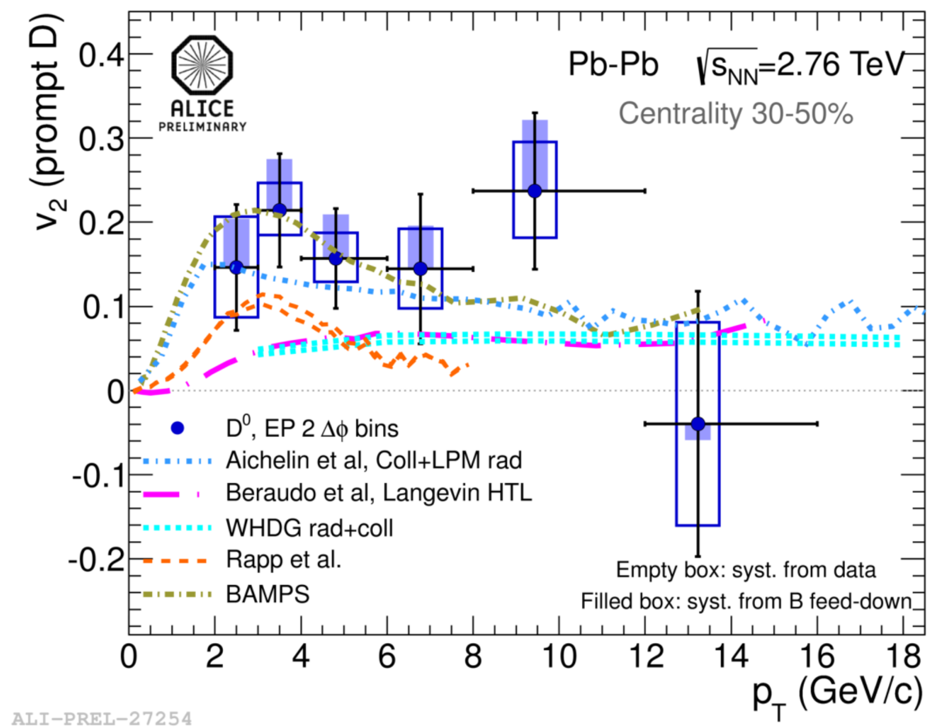


Melting of weakly bound bottonium states indicating strong color screening in the QGP

J/ψ suppression pattern at LHC qualitatively different from RHIC: enhancement via regeneration predicted as consequence of deconfinement and large charm cross section

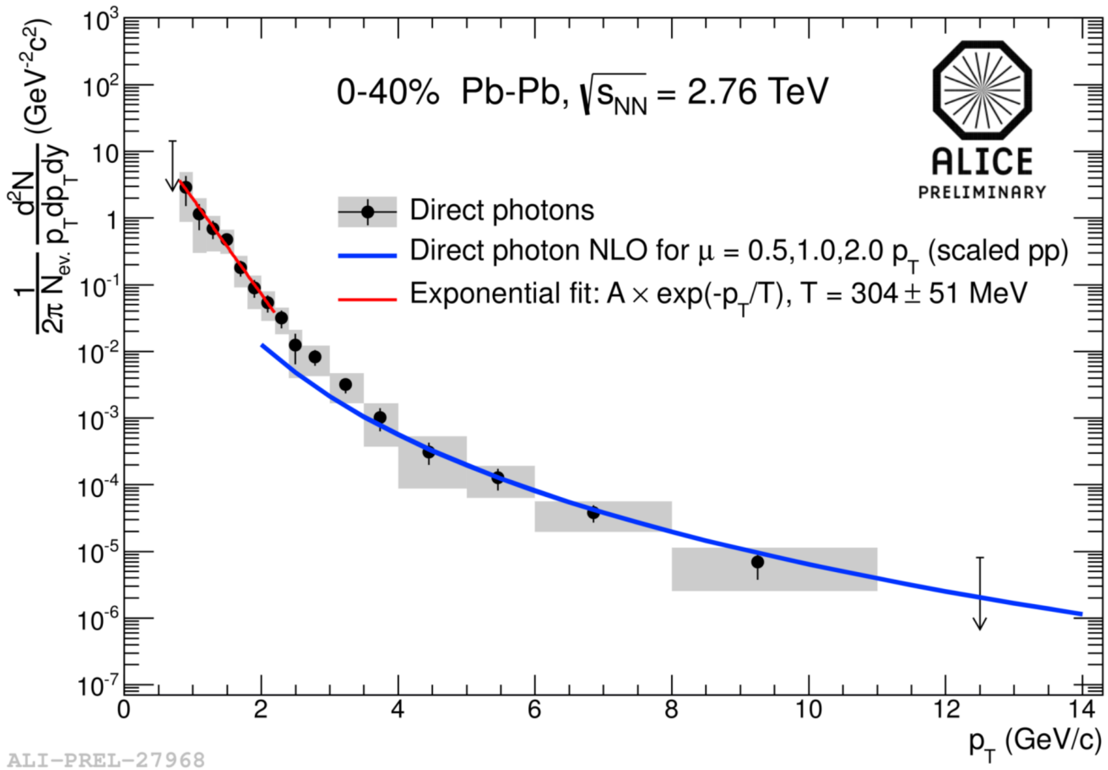
LHC HI-highlights – heavy flavor transport





Large quenching at high p_T and pronounced collectivity of heavy-flavor hadrons indicating very strongly coupled system

LHC HI-highlights – thermal radiation



Large excess of direct photons pointing to effective temperatures far above T_c:

Hottest system ever produced in a human laboratory

LHC near future - phase 1

Phase 0: 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

2013-2014: LS1

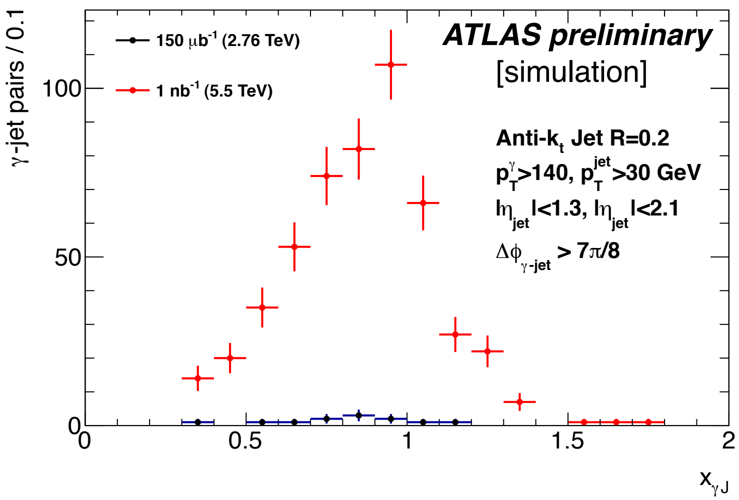
- detector completion and upgrades (ALICE-TRD, - CAL, ATLAS-IBL,...)

Phase 1: 2015-2017

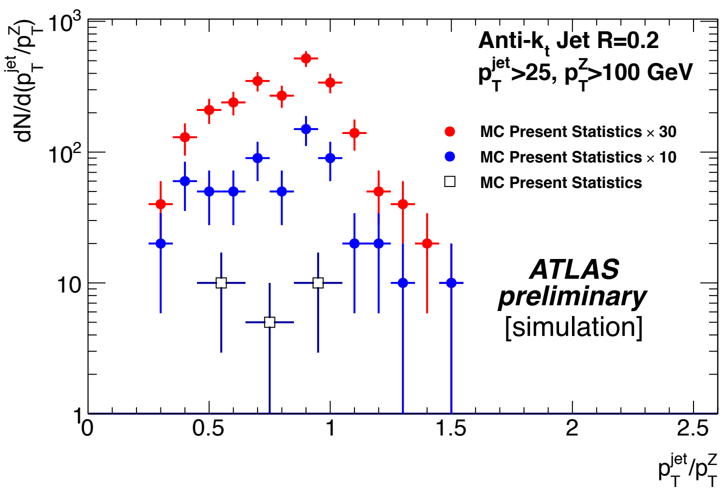
- 1 nb^{-1} Pb-Pb at $\sqrt{s_{NN}}$=5.5 TeV
- reference data pp, p-Pb

LHC phase 1 – Jets

1 nb^{-1} Pb-Pb at $\sqrt{s_{NN}}$=5.5 TeV

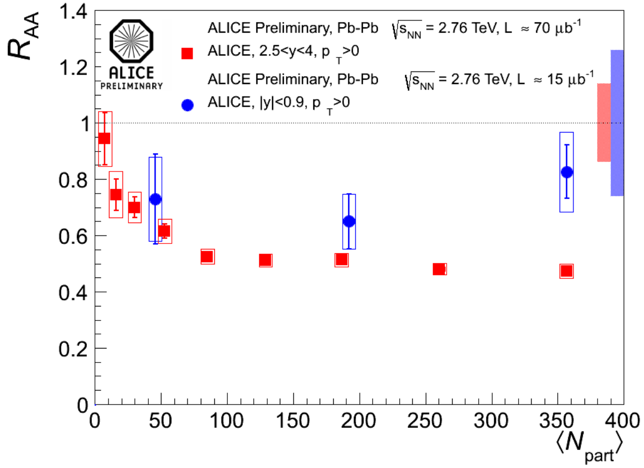


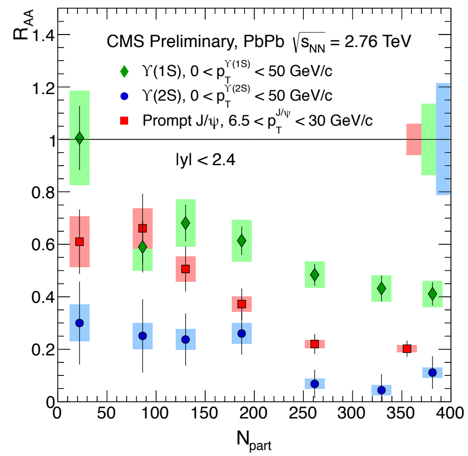
→ detailed studies of γ-jet imbalance



→ first measurements of Z-jet studies

LHC phase 1 – Quarkonia and HF



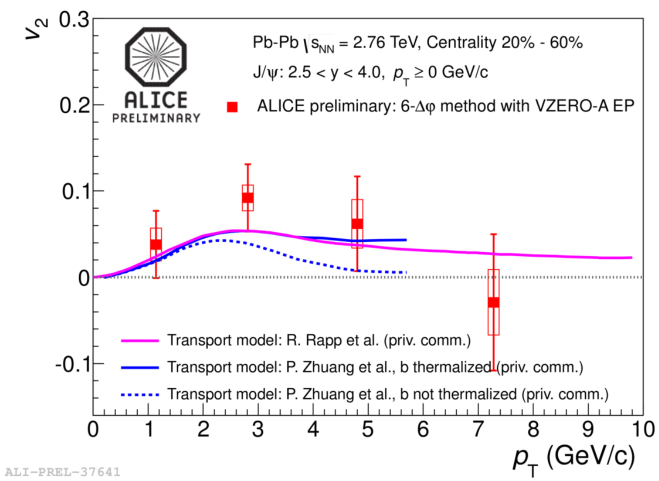


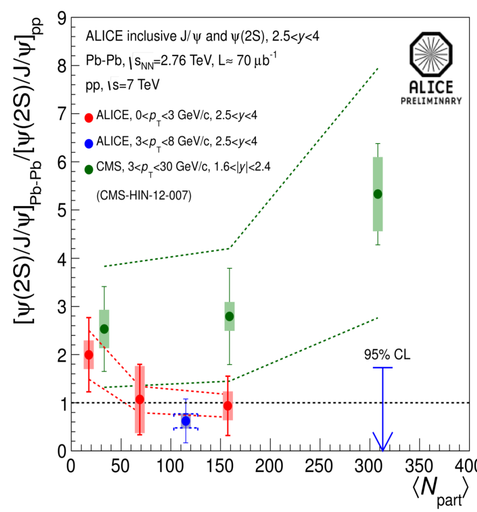
Quarkonia:

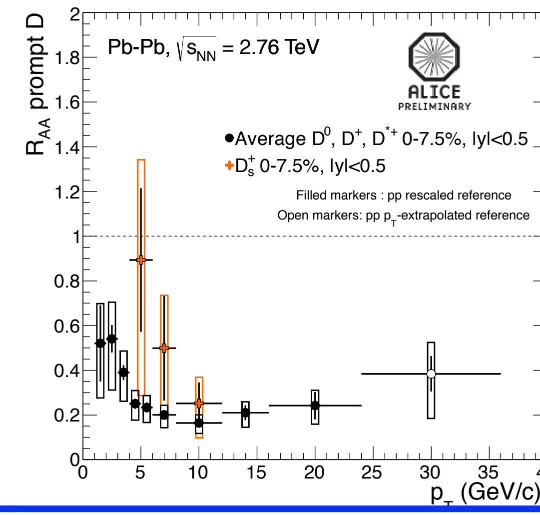
- ϒ(2s,3s) melting: onset behaviour
- low p_T J/ψ regeneration
- J/ψ collectivity
- ψ' puzzle

Heavy Flavors:

- D_s R_{AA}
- …







LHC phase 1

after completion of Phase 1 (1 nb^{-1} Pb-Pb at $\sqrt{s_{NN}}$=5.5 TeV) there will be high-precision data available on some of the key observables

BUT

there are major opportunities at the LHC to be explored with increased Pb-Pb luminosity!

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

LHC upgrade – Phase 2

2017-2018: LS2

- significant detector upgrades
- LHC collimator upgrades

Phase 2: 2019-LS3 and beyond:

- aiming for luminosity increase to 6×10^{27} $cm^{-1}s^{-1}$
  → peak collision rate 50 kHz, average 20 kHz
  → *O* (10) nb^{-1} Pb-Pb at $\sqrt{s_{NN}}$=5.5 TeV
- pp and p-Pb reference data
- more nuclei

ALICE – upgrade strategy

Dedicated heavy-ion experiment

→ upgrades focus on heavy-ion physics

Strengthen the uniqueness of ALICE

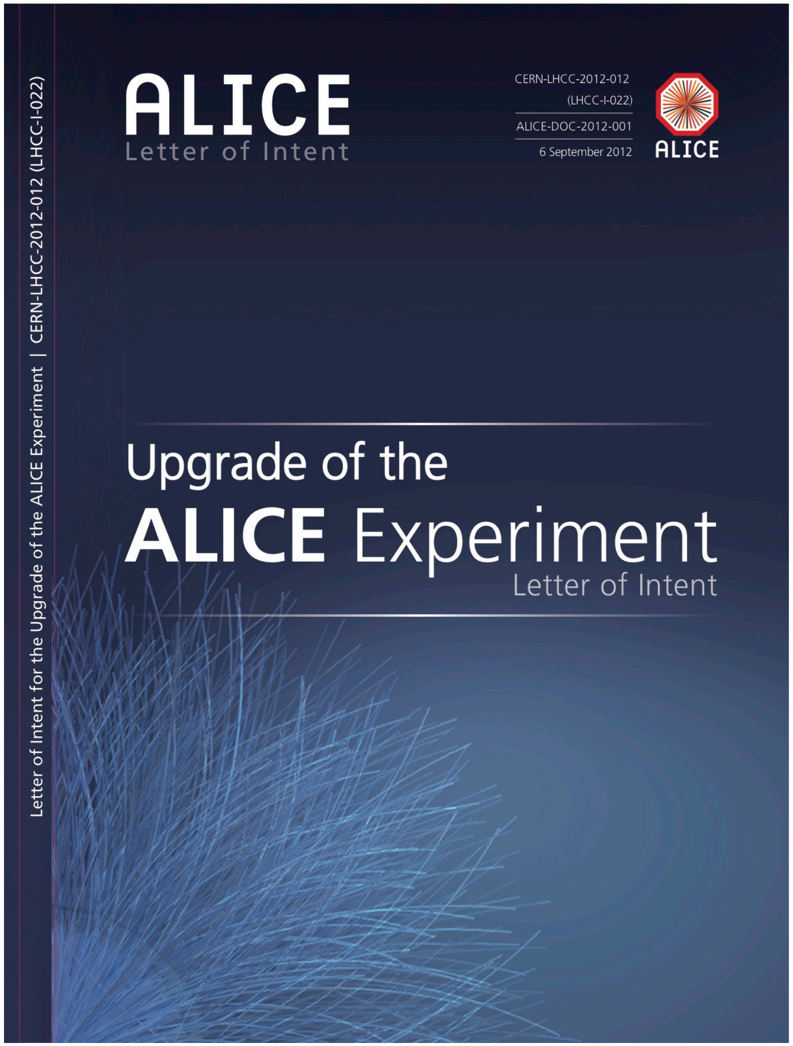
→ improve low p_T tracking, vertexing, and PID capabilities, reduce material budget

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

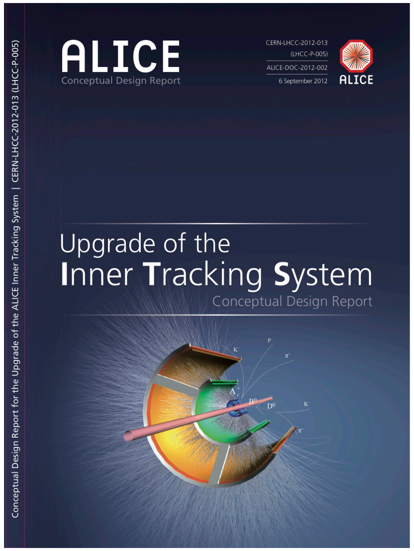
→ comprehensive *Letter of Intent* submitted to LHCC

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

ALICE – core upgrades

LS2 (2017-18): - 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

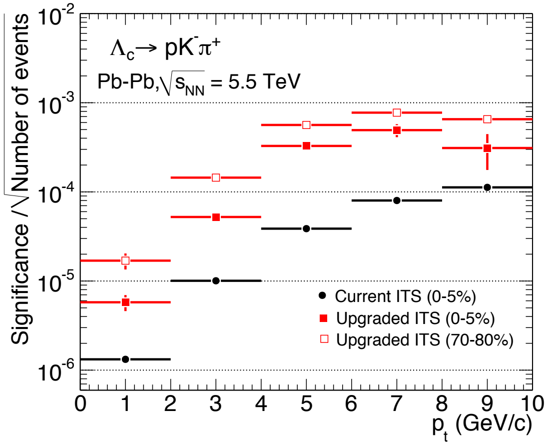
→ continuous readout at 50 kHz

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

→ 1 TB/s into online systems
→ partial event reconstruction (20 GB/s to tape)

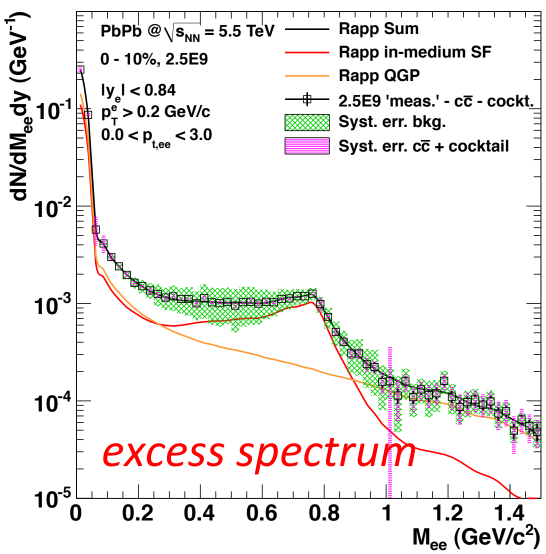
ALICE upgrade – physics performance (examples)

Study of charm and beauty thermalization in QGP:
heavy-flavour elliptic flow, high p_T suppression and spectra/ratios at low p_T



Low momentum quarkonium dissociation and, possibly, regeneration as signature for deconfinement and charm equilibration

Low mass dileptons to assess initial temperature and partonic equation of state, and the chiral nature of the phase transition



Heavy-Ion collisions at the LHC - conclusions

LHC offers unique opportunities to study QCD matter at μ_B=0 in heavy-ion collisions via hard and electroweak probes.

The currently approved HI program (1 nb^{-1}) provides an essential step towards an era of precision measurements.

Full exploitation of the physics potential of the LHC and of the complementarity of the experiments requires extension to 10 nb^{-1}, which implies a heavy-ion programme at the LHC beyond LS3.

Related upgrades need to be prepared for LS2, necessary R&D has started.

Heavy-Ion collisions at the LHC - conclusions

Conclusions of the Heavy-Ion Town Meeting June 29 2012 at CERN:

http://indico.cern.ch/event/HItownmeeting

Contribution ID 55:

„1. 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"

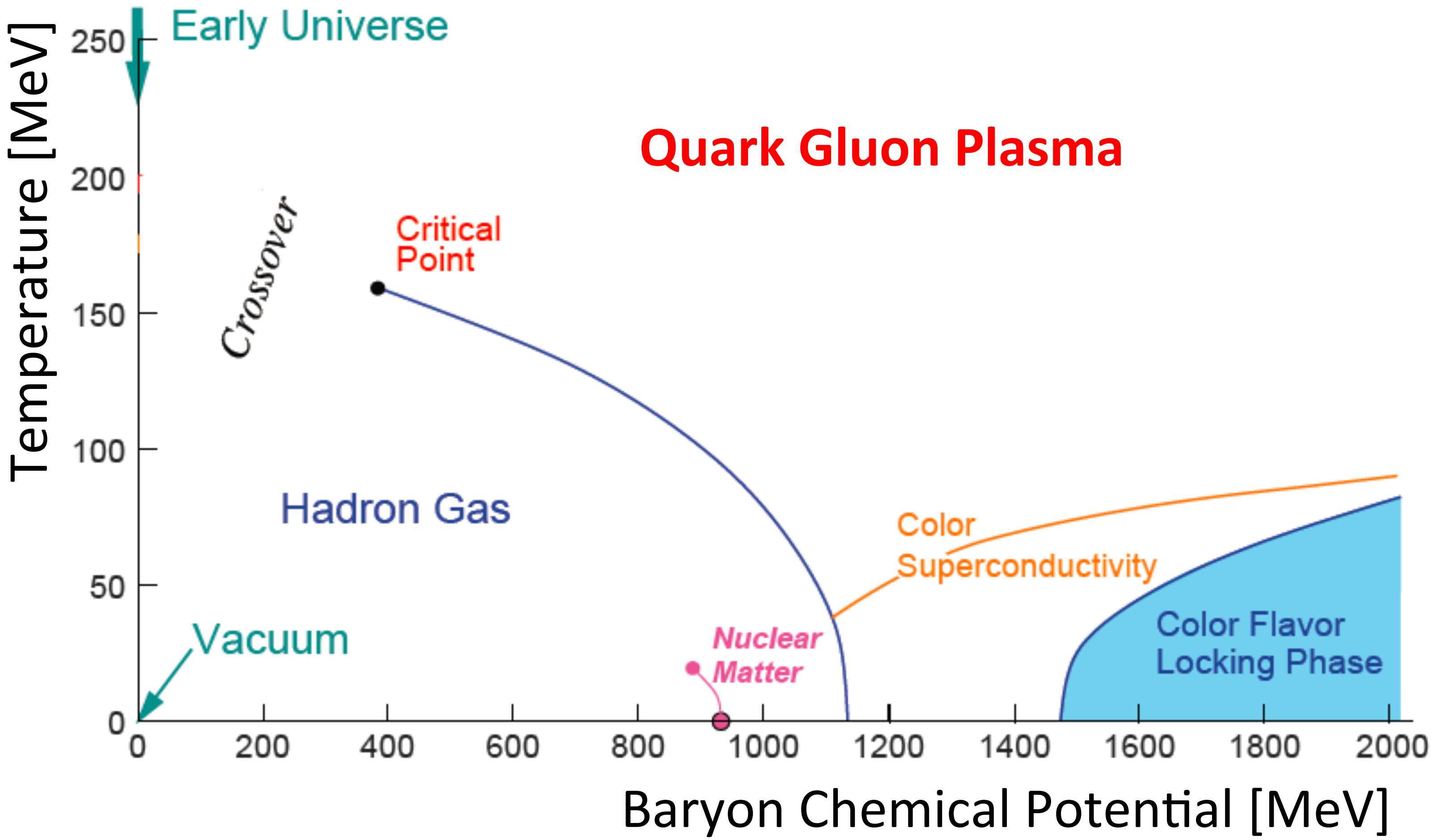
Priority endorsed by NUPECC:

Contribution ID 32:

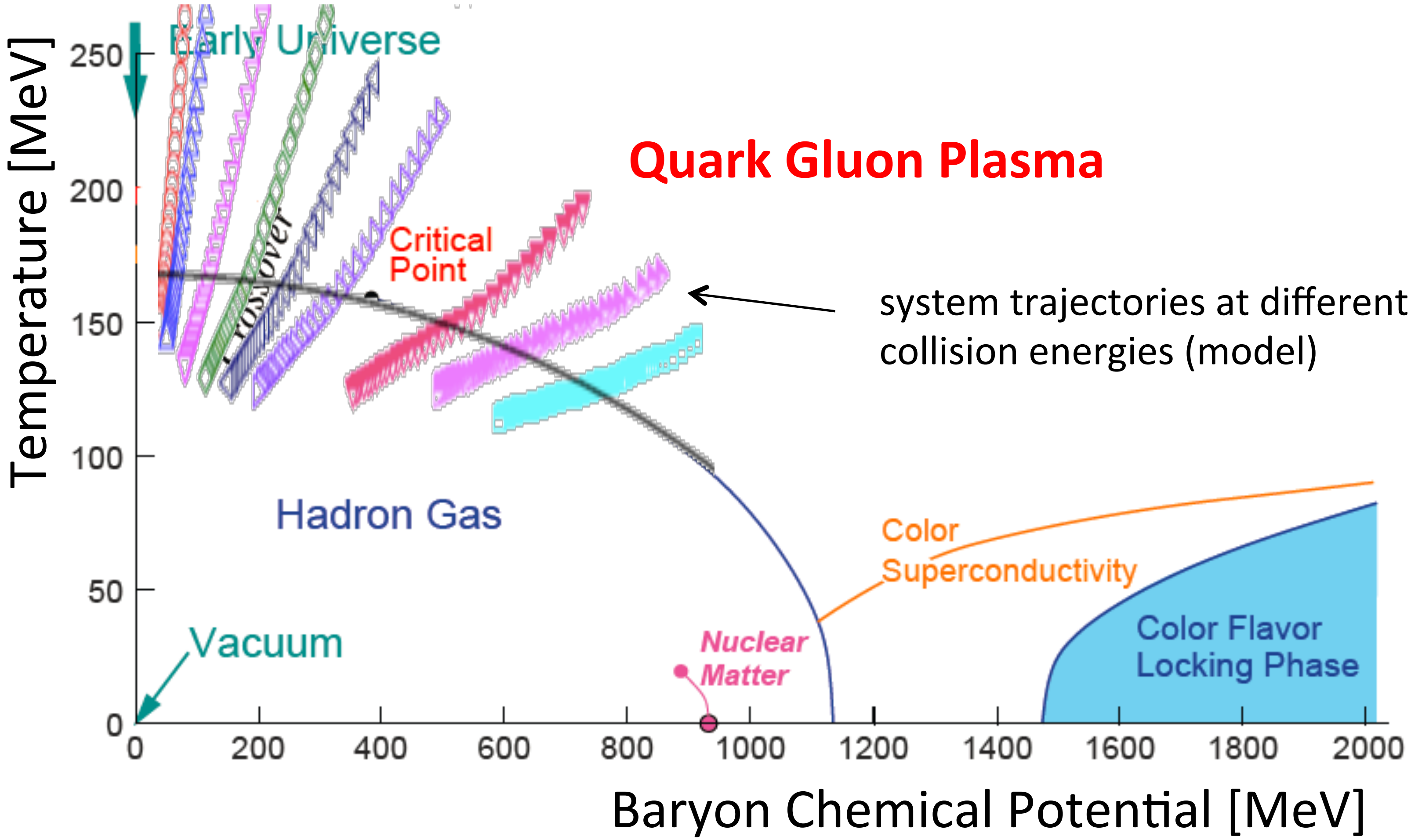
„Support for R & D to complete a technical design report for the LHeC was also included among the recommendations in the Long Range plan, but with lower priority. From the point of view of the Heavy Ion community, the LHec could thus be seen as an interesting option in the future, if the necessary critical mass of people could be assembled. The recent proposal to use Point 2 (where the ALICE experiment is located) as the interaction region for the LHeC is not supported, if installation were to start before 2025, because it is incompatible with the top priority of the Long Range plan."

Challenges and Opportunities:
New facilities and future fixed-target running

High baryon densities



High baryon densities

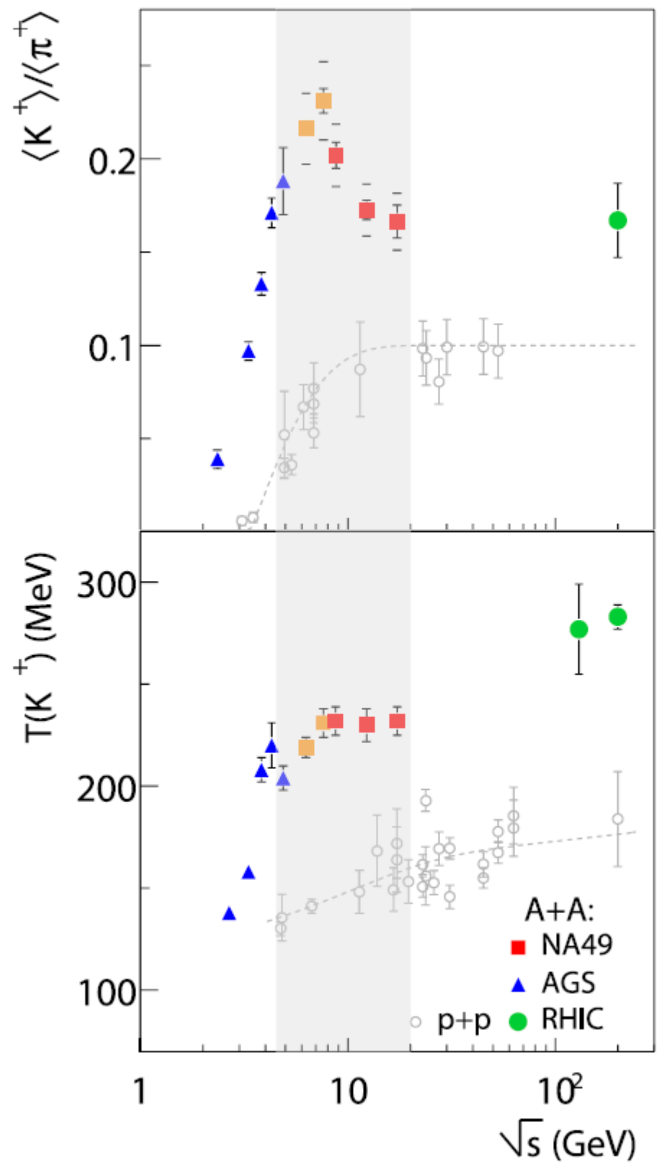


system trajectories at different collision energies (model)

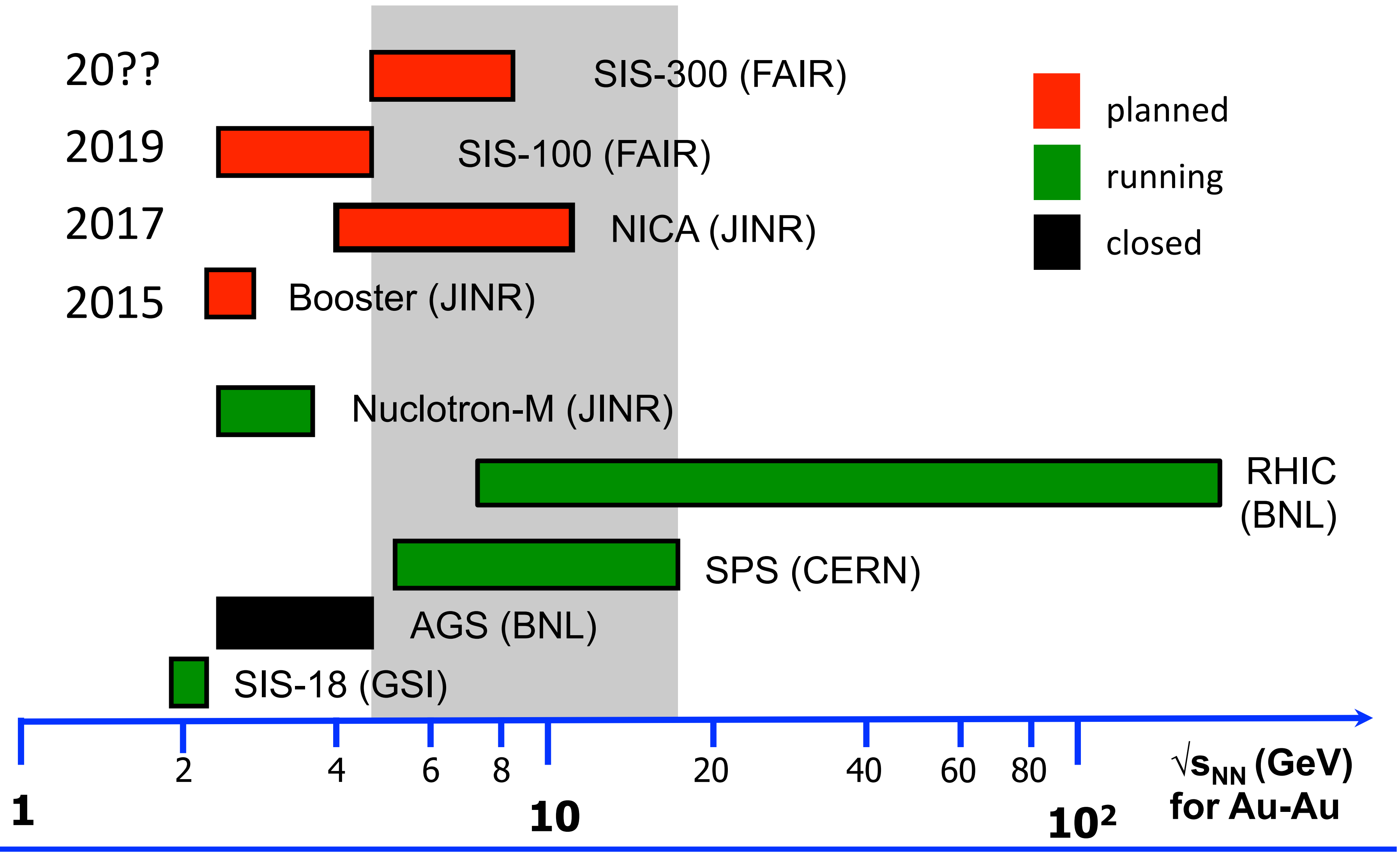
Onset of deconfinement

Tantalizing results from pioneering beam energy scans by NA49 at SPS:

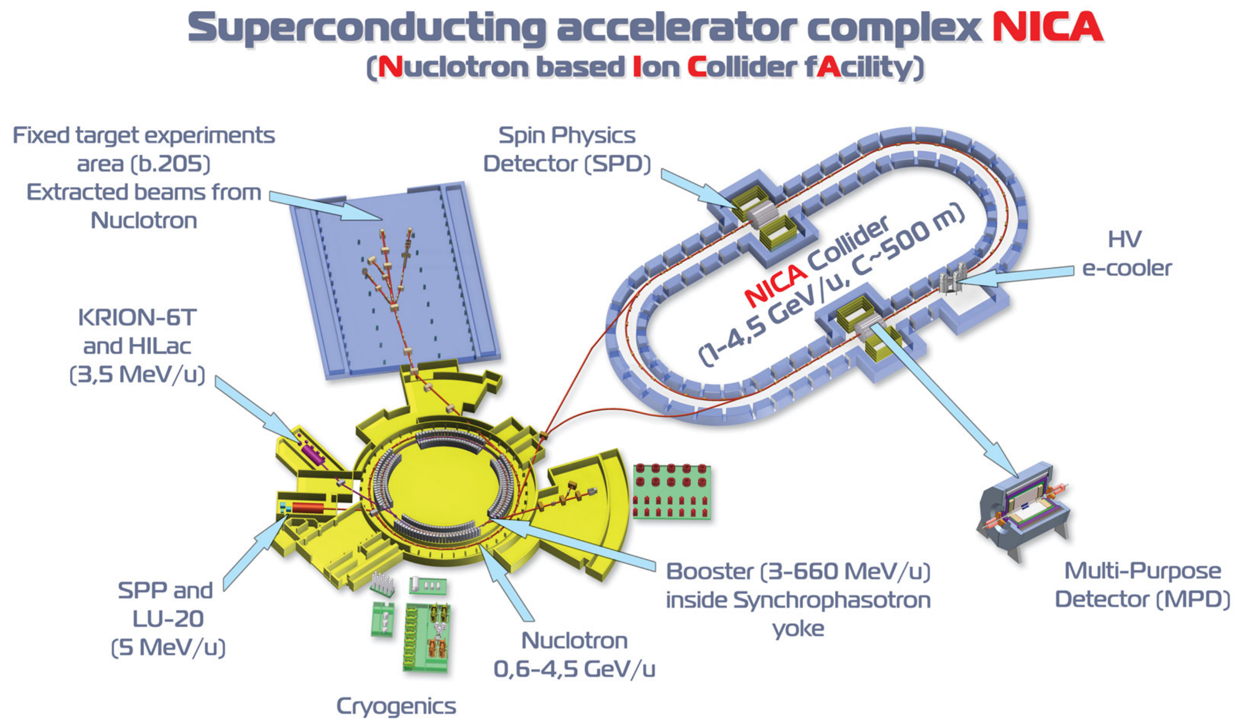
- Onset of deconfinement around $\sqrt{s_{NN}}$=10 AGeV?
- Is there a critical point in the QCD phase diagram?



Heavy-Ion facilities for high-μ_B studies



Future facilities - NICA



NICA:

- Based on existing Nuclotron at JINR/Dubna
- Heavy-Ion collisions in fixed-target (2015) and collider (2017) mode ($\sqrt{s_{NN}}$= 4-11 AGeV)

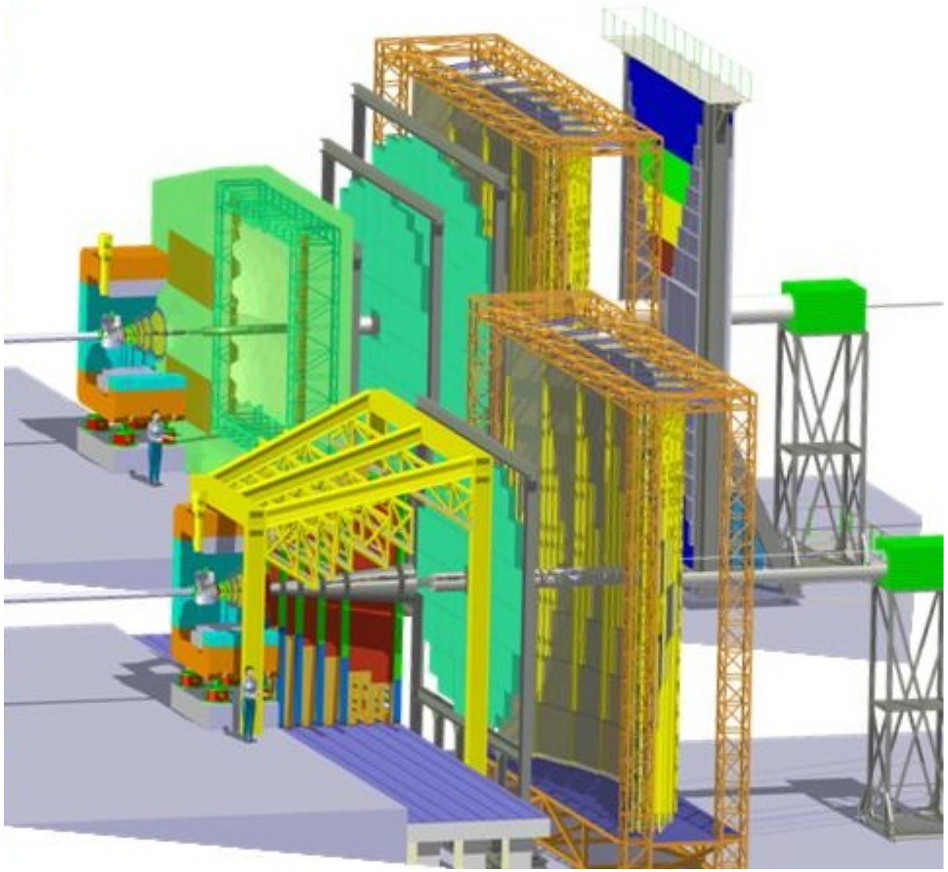
→ Competitive high luminosity collider at the low energy end

Future facilities - FAIR

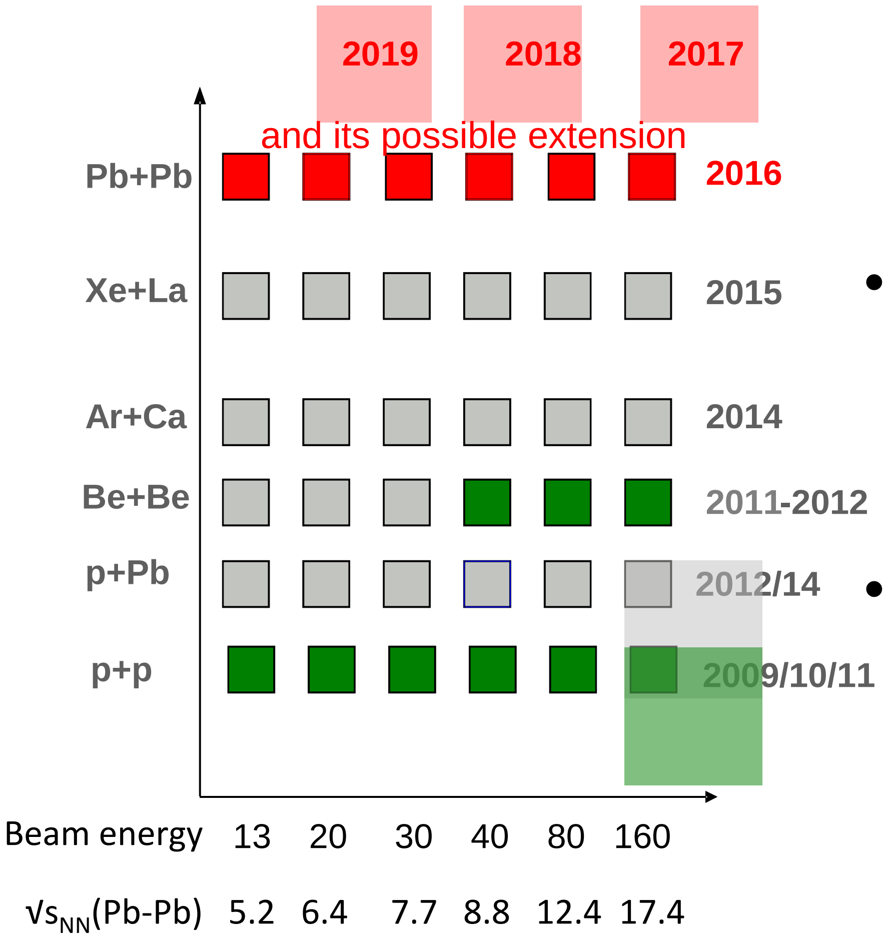
Compressed-Baryonic-Matter Experiment (CBM) at FAIR/GSI Darmstadt

2019: SIS100 ($\sqrt{s_{NN}}$ = 2-4.5 AGeV)
20??: SIS300 ($\sqrt{s_{NN}}$ = 4.2-9 AGeV)

- Fixed-target heavy-ion collisions at unprecedented rates (up to 10^9 ions/s)
- Study of rare probes (EM and charm) at highest baryon densities



SPS fixed-target: NA61/SHINE

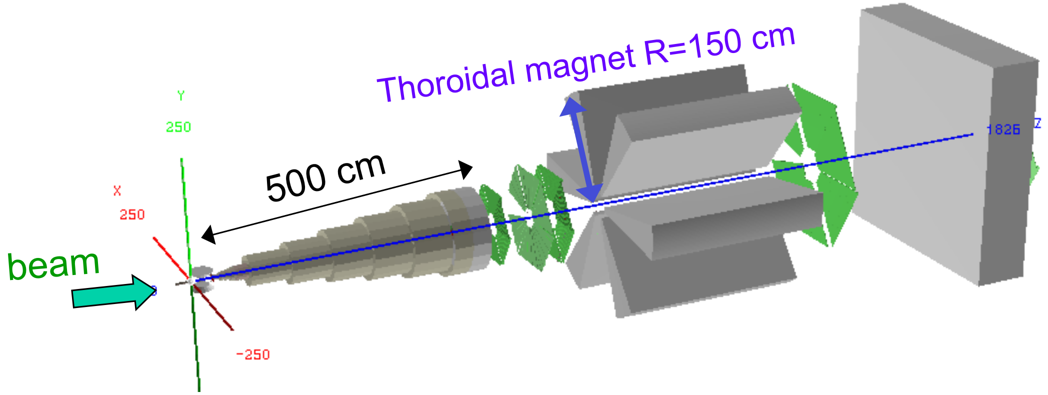


- systematic scan of system sizes and collision energies to locate the critical point
- possible extension beyond 2016 for high-statistics Pb-Pb running and charm measurement (upgrade required)

Future activities at the SPS

Proposal for NA60-like dimuon spectrometers to measure low-mass dileptons and charm at E_{beam}=20 – 160 AGeV ($\sqrt{s_{NN}}$= 6-17 AGeV):

- complementary to NA61: leptons vs hadrons
- high physics potential: onset of deconfinement and critical point
- competitive with RHIC: high luminosity

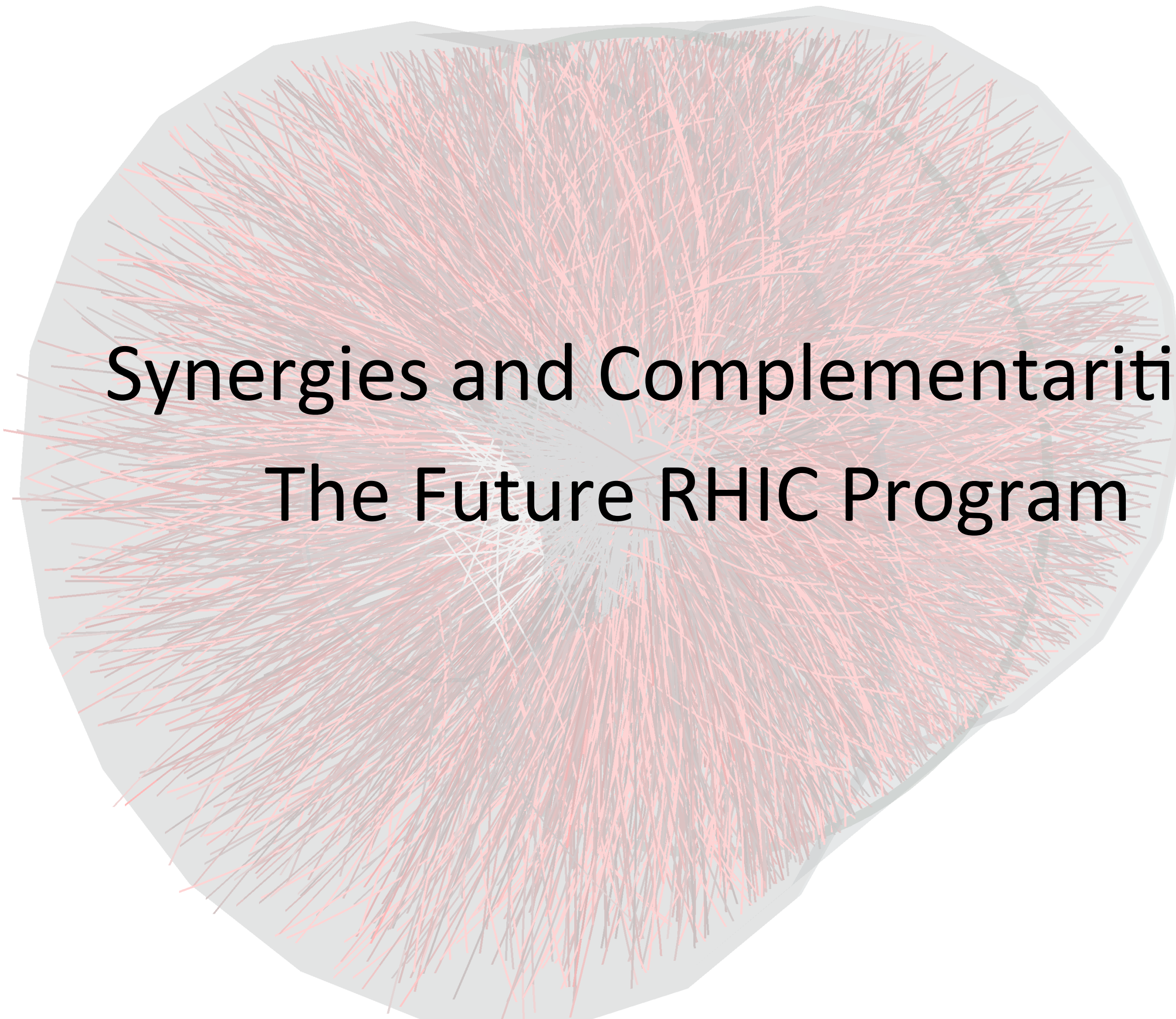


New facilities and fixed-target - conclusions

Conclusions of the Heavy-Ion Town Meeting:

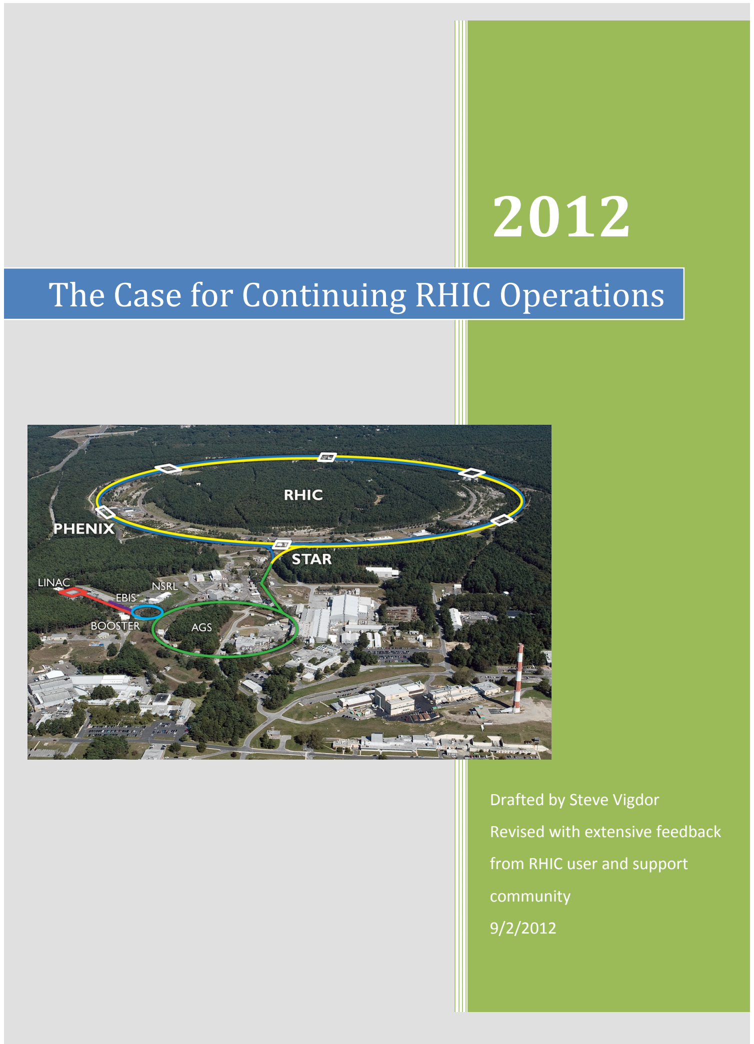
„2. At lower center of mass energies where the highest baryon densities are reached, advances in accelerator and detector technologies provide opportunities for a new generation of precision measurements that address central questions about the QCD phase diagram"

„The town meeting also observed that the CERN SPS would be well-positioned to contribute decisevely and at a competetive time scale to central open physics issues at large baryon density. In particular, the CERN SPS will remain also in the future the only machine capable of delivering heavy-ion beams with energies exceeding 30 AGeV, and the potential of investigating rare probes at this machine is very attractive."



Synergies and Complementarities: The Future RHIC Program

Future RHIC operation


2012

The Case for Continuing RHIC Operations

Drafted by Steve Vigdor
Revised with extensive feedback from RHIC user and support community
9/2/2012

RHIC community formulated their wish to continue operation for one more decade:

- Beam-energy scan (BES) II
- Luminosity increase x10, low cost
- Different ion species (U-U, Cu-Au)

RHIC future physics program (examples)

- Search for onset of deconfinement and critical point
  → study beam energy scan program
- Study of temperature dependence of QGP transport parameters
  → precision measurements of particle spectra and correlations
- Transition from strong coupling to asymptotic freedom
  → jet studies
- Study origin of initial density fluctuations
  → asymmetric ion collisions

→ implies machine and experiment upgrades

→ complementary to LHC programme

Future RHIC programme - conclusions

Conclusions of the Heavy-Ion Town Meeting:

„3. The complementarity of the LHC and RHIC is an essential resource in efforts to quantify properties of the Quark-Gluon Plasma"

My summary

The study of hot and dense QCD matter is a dynamically evolving subfield of nuclear physics with excellent scientific opportunities for the future:

- At the energy frontier, the LHC allows precision studies of quark-gluon matter at conditions similar to those of the early universe. Full exploitation of the physics potential requires upgrades and heavy-ion running at the LHC until at least 2025.

- New accelerator und detector technologies at future facilities NICA and FAIR will enable a comprehensive study of the QGP phase diagram at high baryon densities.

- The CERN-SPS will remain an important facility with high potential for specific studies on a competitive time scale.

- RHIC envisages a continuation of its heavy-ion programme which offers important complementarities present and future facilities in Europe.

backup

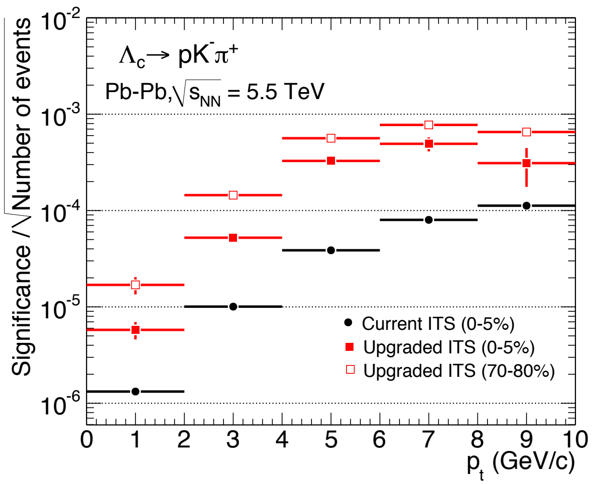
physics performance: heavy flavor

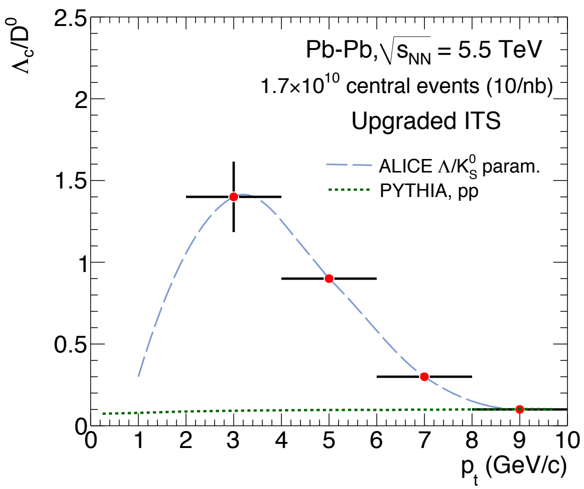
HF reconstruction:

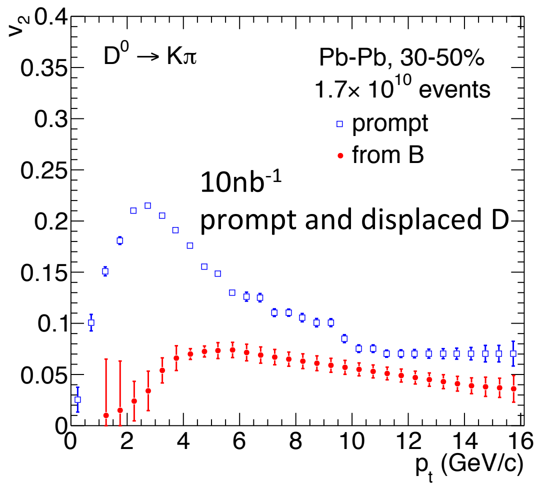
- secondary vertex reconstruction (ITS) + PID (ITS, TPC, TOF, TRD)

→ vertexing capability of new ITS improves significantly the sensitivity (S/B)

→ PID required: TPC upgrade mandatory for high statistics measurement







physics performance: low-mass e^+e^-

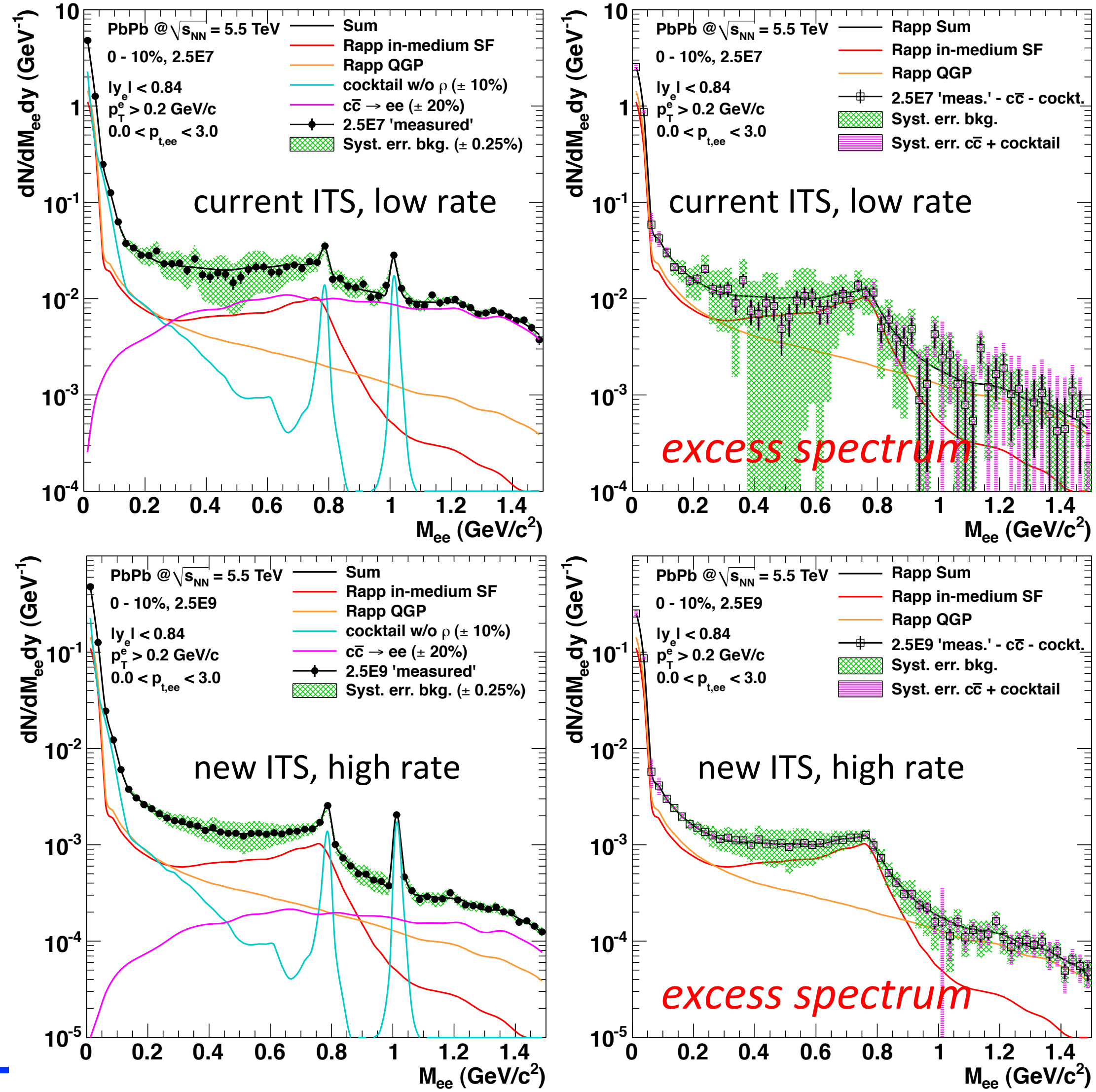
Low-mass e^+e^-:

- e-PID in TPC and TOF

→ high rate TPC required

- Dalitz rejection, conversion and charm suppression in ITS

→ new ITS improves major sources of systematic uncertainties



detector upgrades - ATLAS

LS1(2013-14): - additional pixel layer (Insertable B-layer, IBL)

→ improve b-tagging

LS2(2017-18): - fast tracking trigger (FTK)

→ improve high-multiplicity tracking

- calorimeter readout and trigger upgrade

→ improve selectivity of photon and electron trigger

- new forward muon detectors

→ improved muon triggers

LS3(2022): - replacement of inner detector (pixel and strips, reduced material budget)

→ improve tracking and resolution

detector upgrades - CMS

By end of LS2:
- new pixel vertex detector
- upgraded trigger
- extension of forward muon system
- refurbishment of hadron calo electronics
- DAQ upgrade

Important for Heavy-ion running at 50 kHz:

- HLT input limitation (3kHz) requires 0.95 rejection at Level 1 (0.5 achieved so far)

→ dedicated R&D effort started on Level 1 upgrade, largely driven by HI needs and HI community

LS3 (2022):
- new inner tracker
- trigger and DAQ
- ...

ALICE ITS upgrade

new ALICE Inner Tracking System:

→ 7 Si-layers (7 pixel or 3 pixel + 4 strip)
→ low material budget X/X_0= 0.3% per layer
(currently 1.14%)
→ improve vertex resolution by factor 3
→ improve low p_T tracking efficiency
→ allow for 50 kHz readout

CERN-LHCC-2012-05 / LHCC-G-159

Parallel 6C: R. Lemmon
Poster: G. Contin

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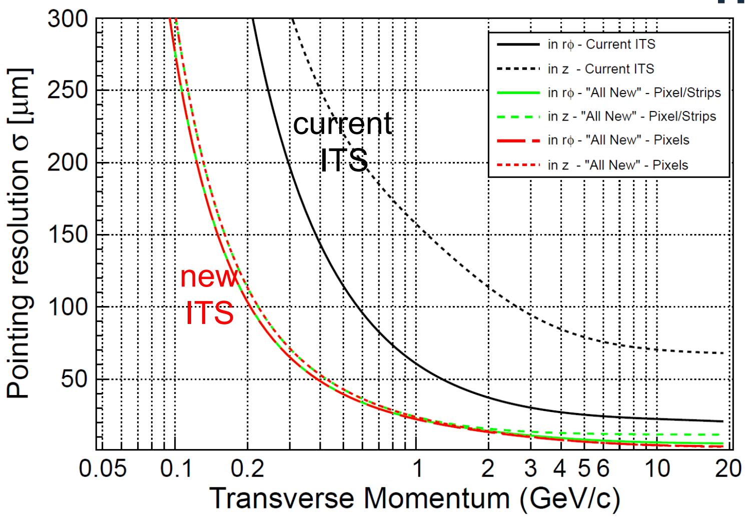
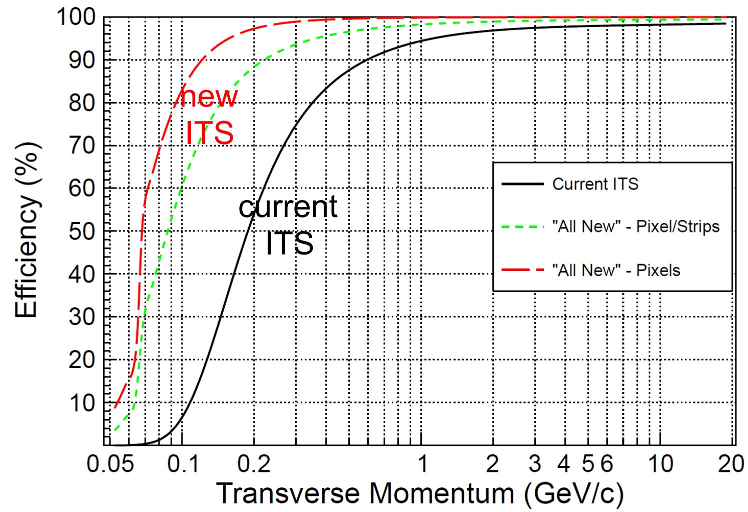
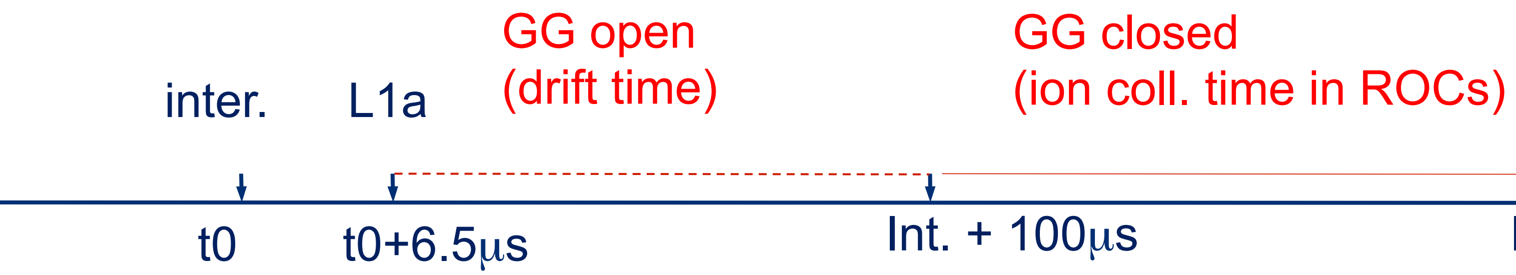




CERN-LHCC-2012-05 / LHCC-G-159

Parallel 6C: R. Lemmon
Poster: G. Contin

ALICE TPC upgrade



Parallel 6C: T. Peitzmann

Poster: T. Gunji

Limitation of the present system:

Readout rate limited to 3.5 kHz due to Gating Grid closing time

- Needed to prevent ions from drifting back into the drift volume

→ drift distortions from space charge

Solution:

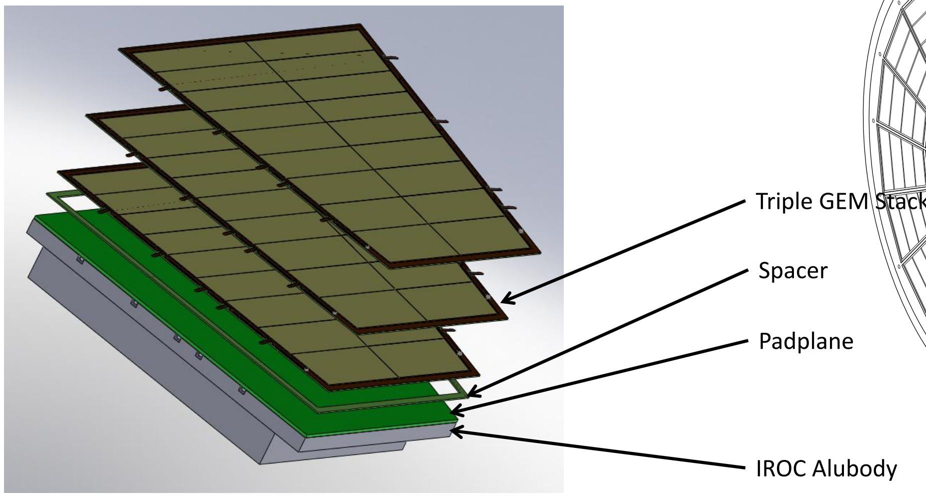
Replace present MWPC-based readout chambers by GEMs

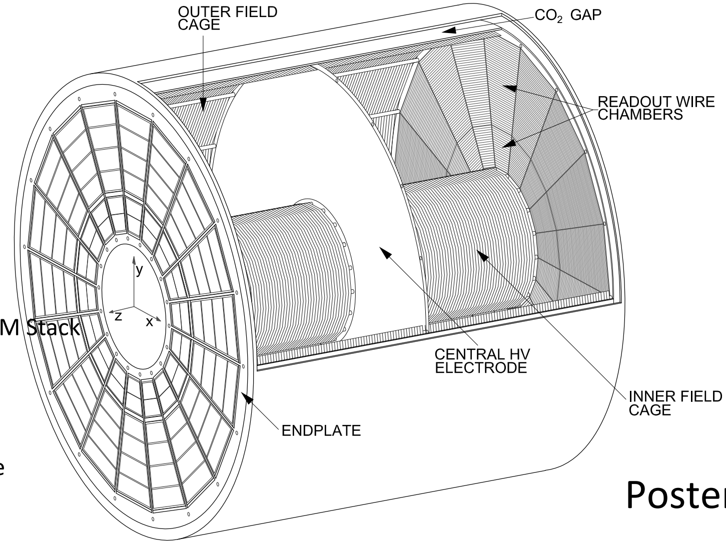
- GEMs have intrinsic property to block back-drifting ions

→ allows continuous operation at 50 kHz

→ preserves the present momentum and d*E*/d*x* resolution

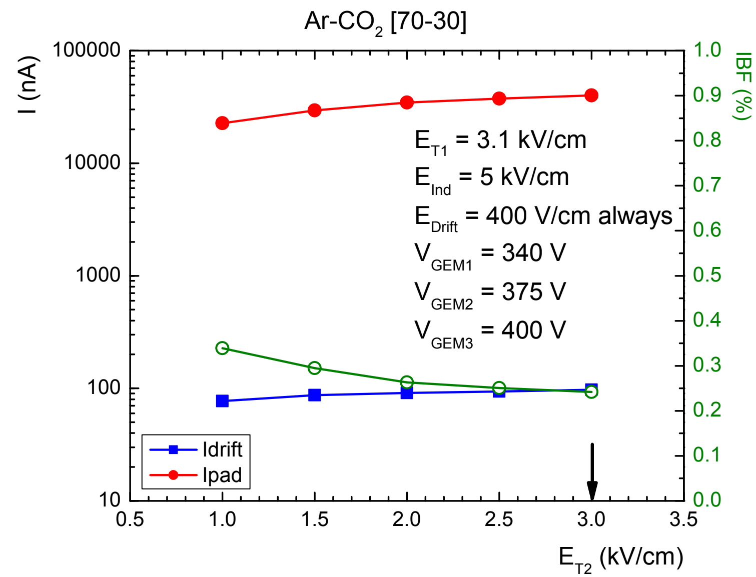
ALICE TPC upgrade





Poster: T. Gunji

- new TPC readout chambers with triple GEMs
- required *Ion Back Flow* (IBF) limit of 0.25% in reach
- prototype tests at PS and in ALICE cavern under preparation (2012/2013)
- new electronics for continuous readout needed

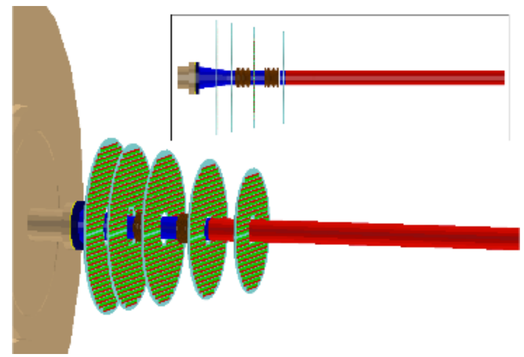


→ major R&D effort started

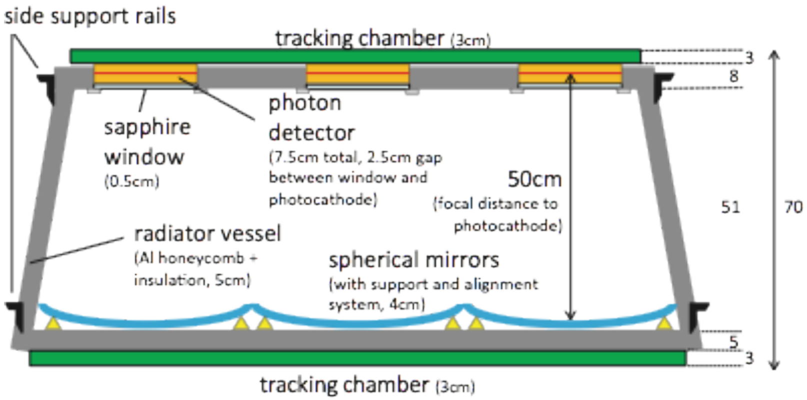
ALICE further upgrade options

Muon Forward Tracker

- 5 circular Si-pixel planes covering muon arm acceptance
- Improves secondary vertex, background rejection, mass resolution



Poster: A. Uras



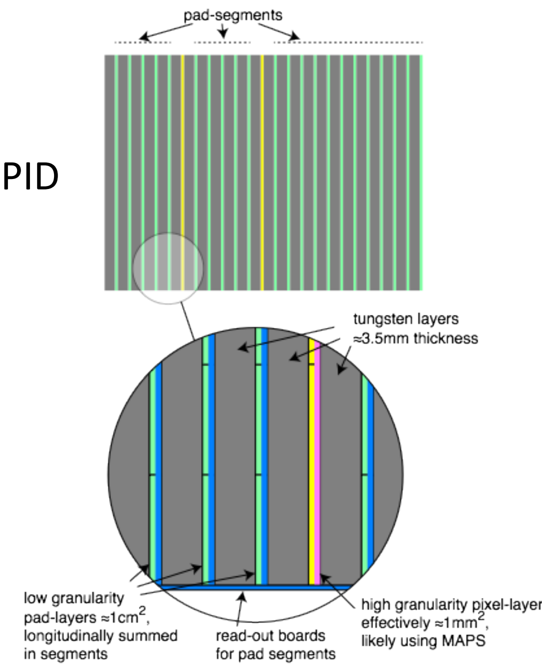
VHMPID

- focussing RICH for high momentum hadron PID in central barrel

Poster: T. Gunji

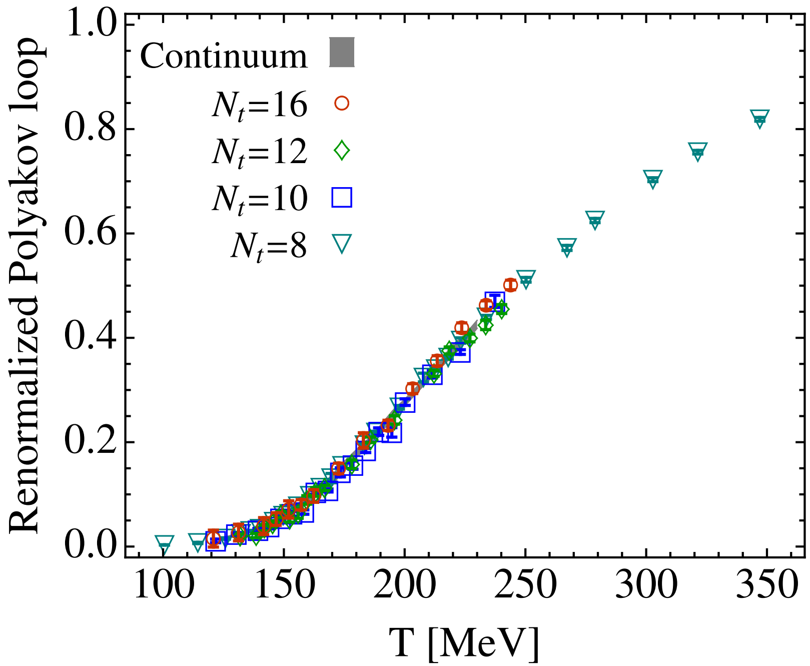
FoCal

- forward SiW calorimeter for low-x physics

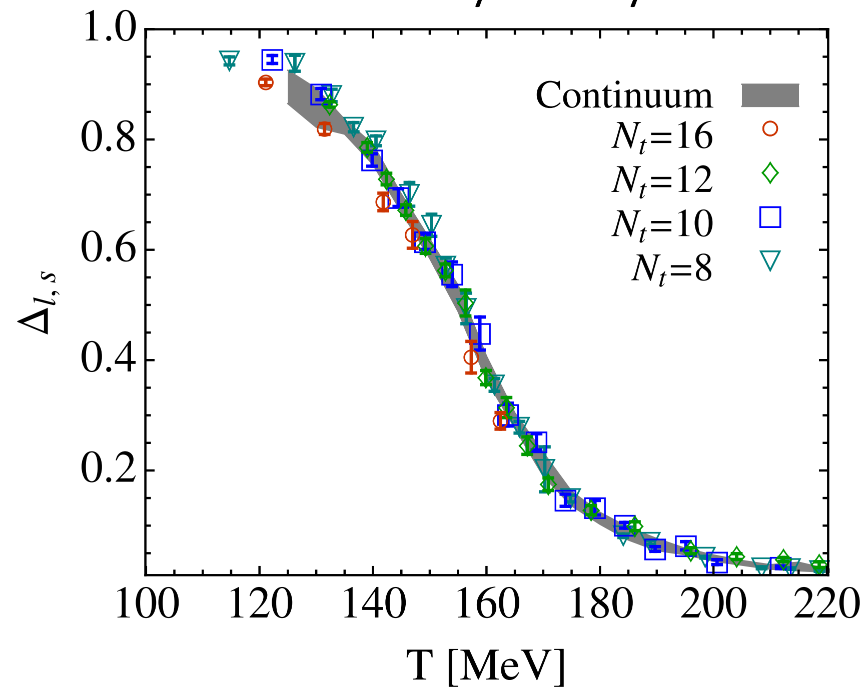


QCD phase transitions

Deconfinement



Chiral Symmetry



Lattice QCD predicts:

- transition of hadronic matter to deconfined quarks and gluons

  → Quark-Gluon Plasma, most elementary matter in SM
- restoration of chiral symmetry

Heavy-Ion collisions at the LHC - conclusions

Conclusions of the Heavy-Ion Town Meeting June 29 2012 at CERN:

http://indico.cern.ch/event/HItownmeeting

Contribution ID 55:

„1. 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"

Priority endorsed by NUPECC:

Contribution ID 32:

„Support for R & D to complete a technical design report for the LHeC was also included among the recommendations in the Long Range plan, but with lower priority. From the point of view of the Heavy Ion community, the LHec could thus be seen as an interesting option in the future, if the necessary critical mass of people could be assembled. The recent proposal to use Point 2 (where the ALICE experiment is located) as the interaction region for the LHeC is not supported, if installation were to start before 2025, because it is incompatible with the top priority of the Long Range plan."