Study of hot QCD matter in ultra-relativistic heavy-ion collisions

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June 14, 2017

ALICE @ LHC:

D. Adamová, J. Bielčíková, F. Křížek, V. Kučera, S. Kushpil, M. Šumbera, T. Vaňát, M. Adam, A. Isakov, P. Príbeli, V. Raskina

J. Ferencei, M. Vajzer, J. Pospíšil, K. Vysoká

STAR @ RHIC:

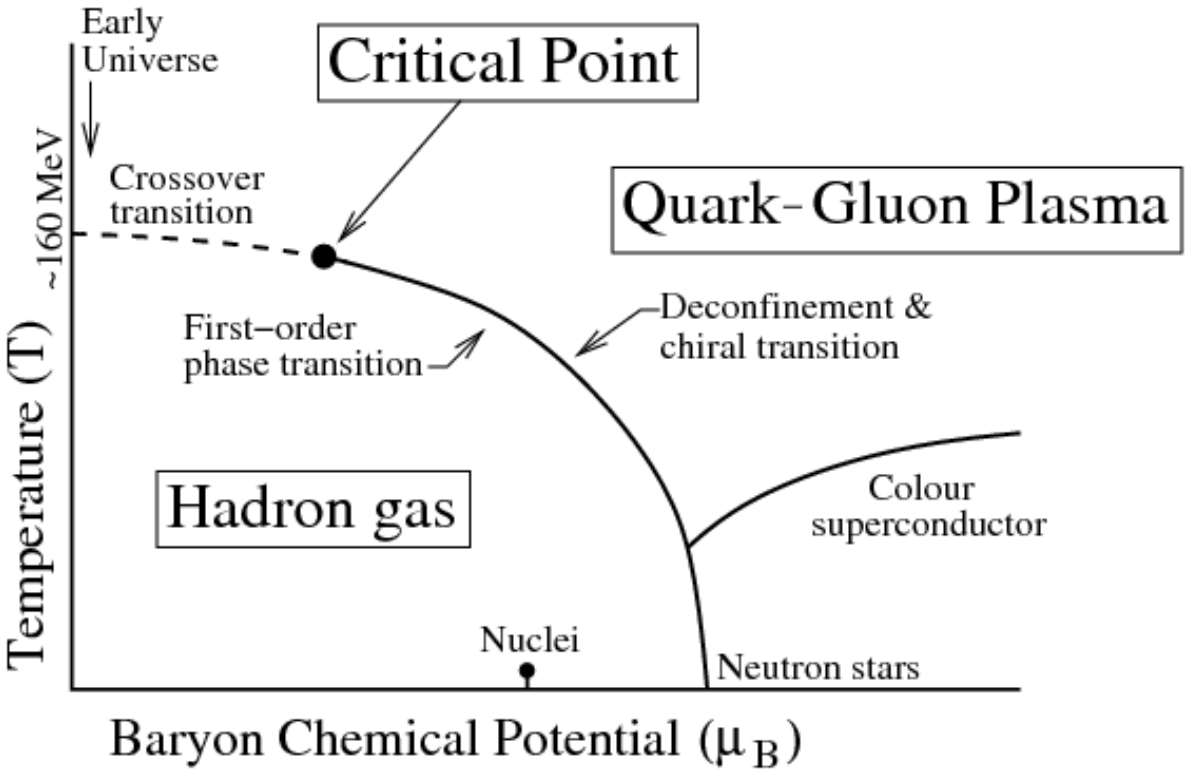
J. Bielčíková, P. Federič, M. Šumbera,

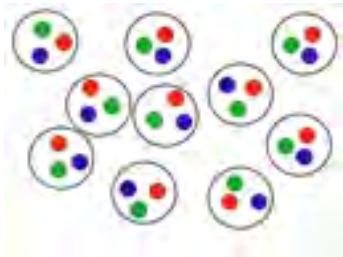
D. Makatun, J. Rusňák, M. Šimko, M. Kocmánek, M. Šaur, V. Agafonova

D. Tlustý, R. Vértesi

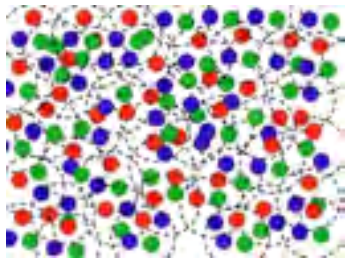
EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

Phase diagram of strongly interacting matter and QGP





Hadron Gas



Quark-Gluon Plasma

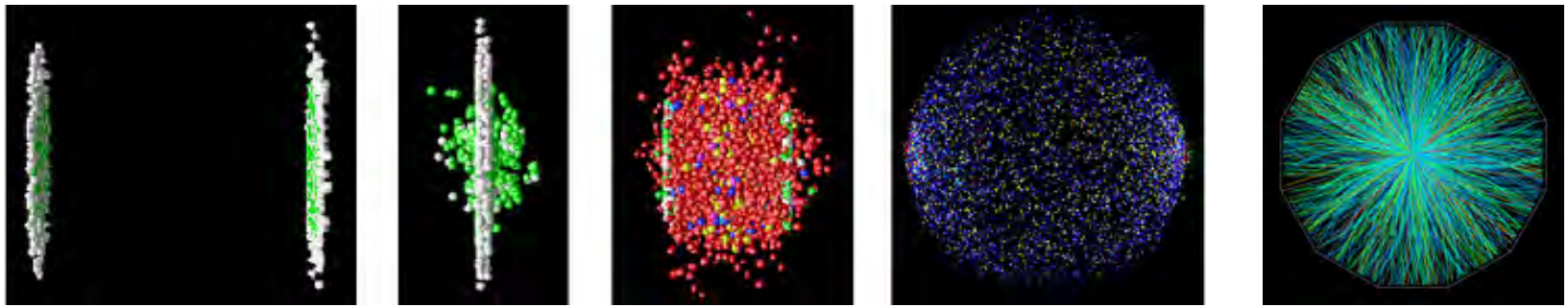
Hadron Gas $\rightarrow$ strongly coupled QGP from lattice QCD:

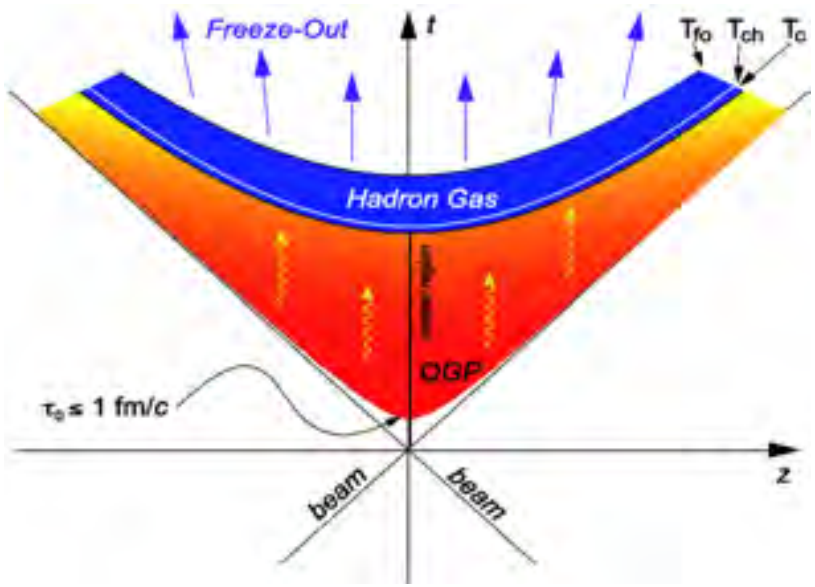
$$\varepsilon_c \approx 1\,\mathrm{GeV/fm^3} \approx 6 \times \varepsilon_{\mathrm{nucleus}}$$

$$T_c \approx 160\,\mathrm{MeV} = 2 \times 10^{12}\,\mathrm{K}$$

More about QGP in review **R. Pasechnik and M. Šumbera, Universe 3 (2017) 7**

Study of QGP using ultra-relavistic heavy ion collisions

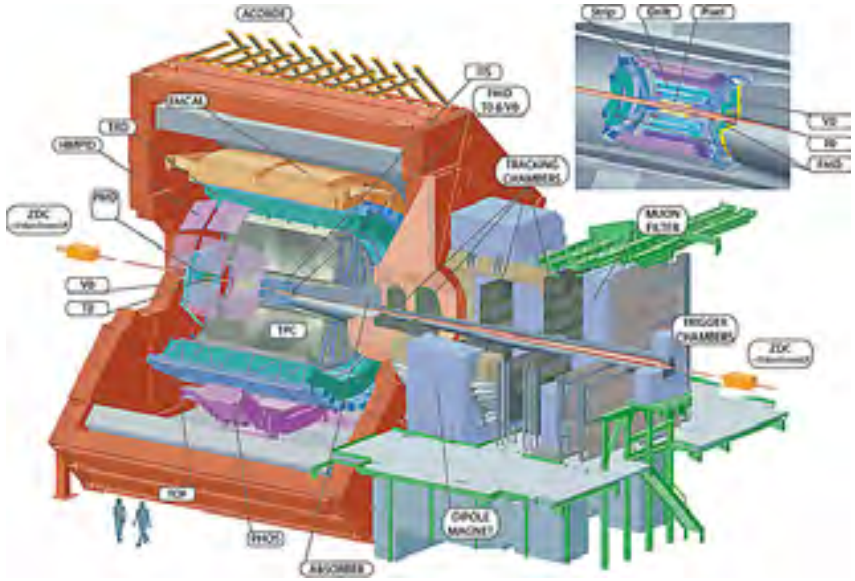




- Resolving QCD charges
  ($\tau \approx 0.3$ fm/c)
- Local thermal equilibrium
  ($\tau \approx 1$ fm/c)
- Formation of hadrons
  ($\tau \approx 10$ fm/c)
- Kinematic freeze-out
  ($\tau \approx 50$ fm/c)

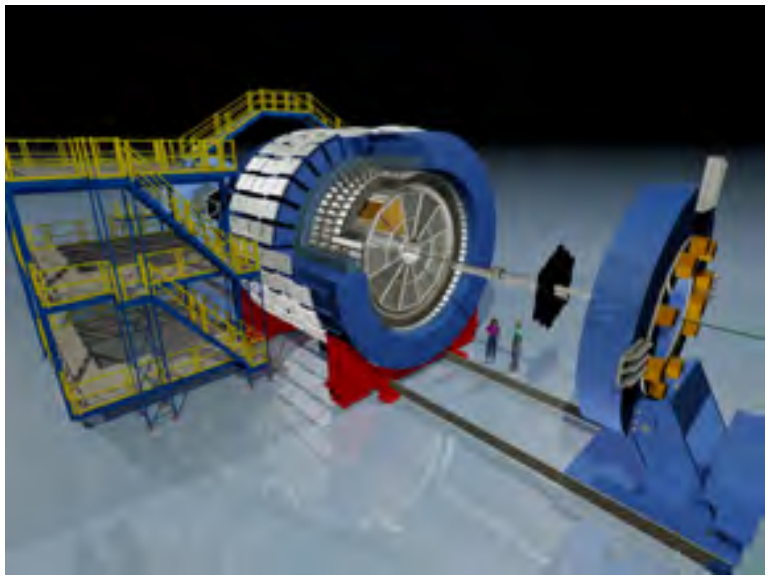
Detectors register products from all time phases.

A Large Ion Collider Experiment at the LHC



- p+p, p+Pb, Pb+Pb
- ions up to $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, p+p up to $\sqrt{s} = 13\,\mathrm{TeV}$
- NPI in ALICE (since 1995)
  - jet physics
  - Inner Tracking System (upgrade and maintenance)
  - computing

Solenoidal Tracker At RHIC

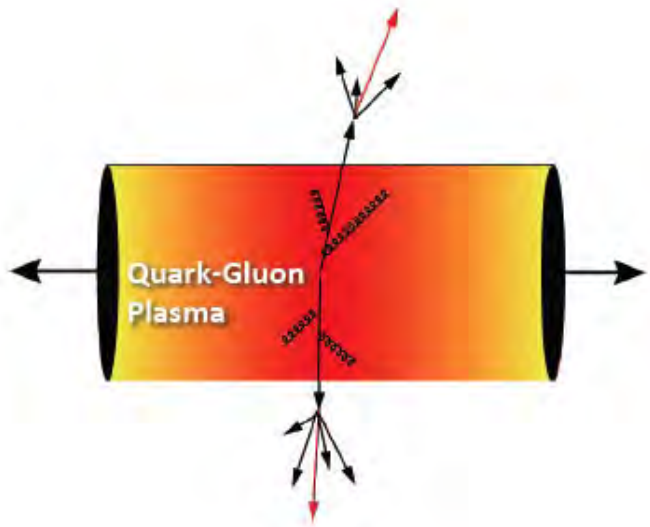


- Relativistic Heavy Ion Collider (RHIC) in BNL
- Discovery of QGP in 2005
- p+p, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, Au+Au, U+U
- ions $\sqrt{s_{\mathrm{NN}}} = 5-200\,\mathrm{GeV}$, p+p up to $\sqrt{s} = 510\,\mathrm{GeV}$ (polarized)
- NPI in STAR (since 2000)
  - jet physics, heavy-flavor quarks, femtoscopy
  - Heavy Flavour Tracker (simul.) and Zero Degree Calorimeter (support)
  - computing

Probes of strongly interacting matter

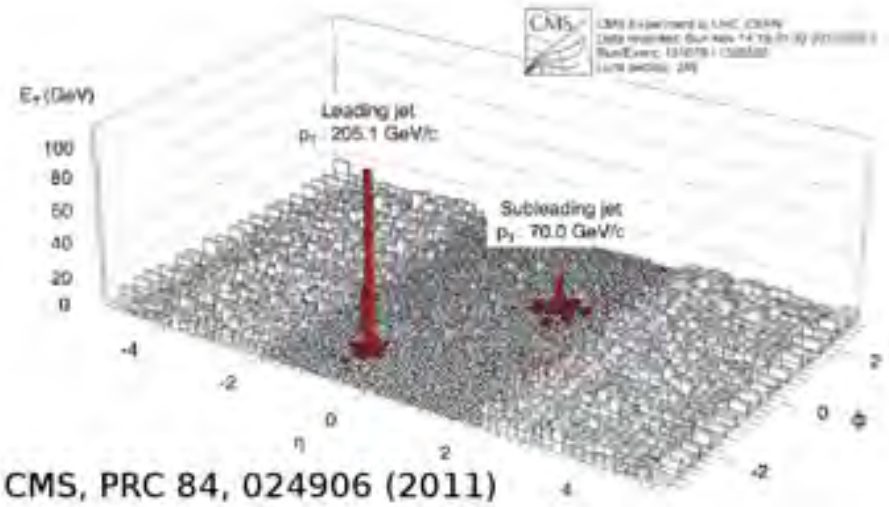
- Soft probes
  - Produced late ($\tau \approx 50$ fm/c)
  - Soft hadrons after freeze-out
  - Particle yields, spectra $\Rightarrow \varepsilon$
  - Hadron species abundance $\Rightarrow T$, μ
  - Femtoscopy $\Rightarrow$ emission source size
  - Collective flow $\Rightarrow \eta/s$, $\bar{\lambda}$

- Hard probes
  - Occur early ($\tau \leq 1$ fm/c)
  - pQCD jets, quarks c and b, Υ, ...
  - Tomography of unknown medium using known probes



High-p_T hadron suppression and jet quenching

Jet quenching:
Parton (q/g) in QGP medium loses energy.

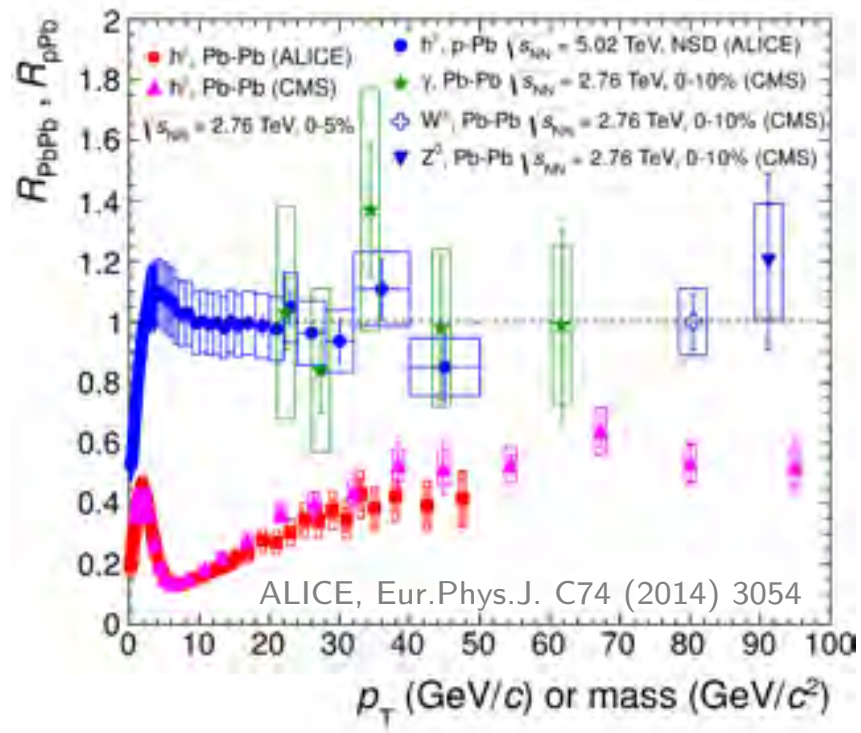


CMS, PRC 84, 024906 (2011)

Nuclear modification factor

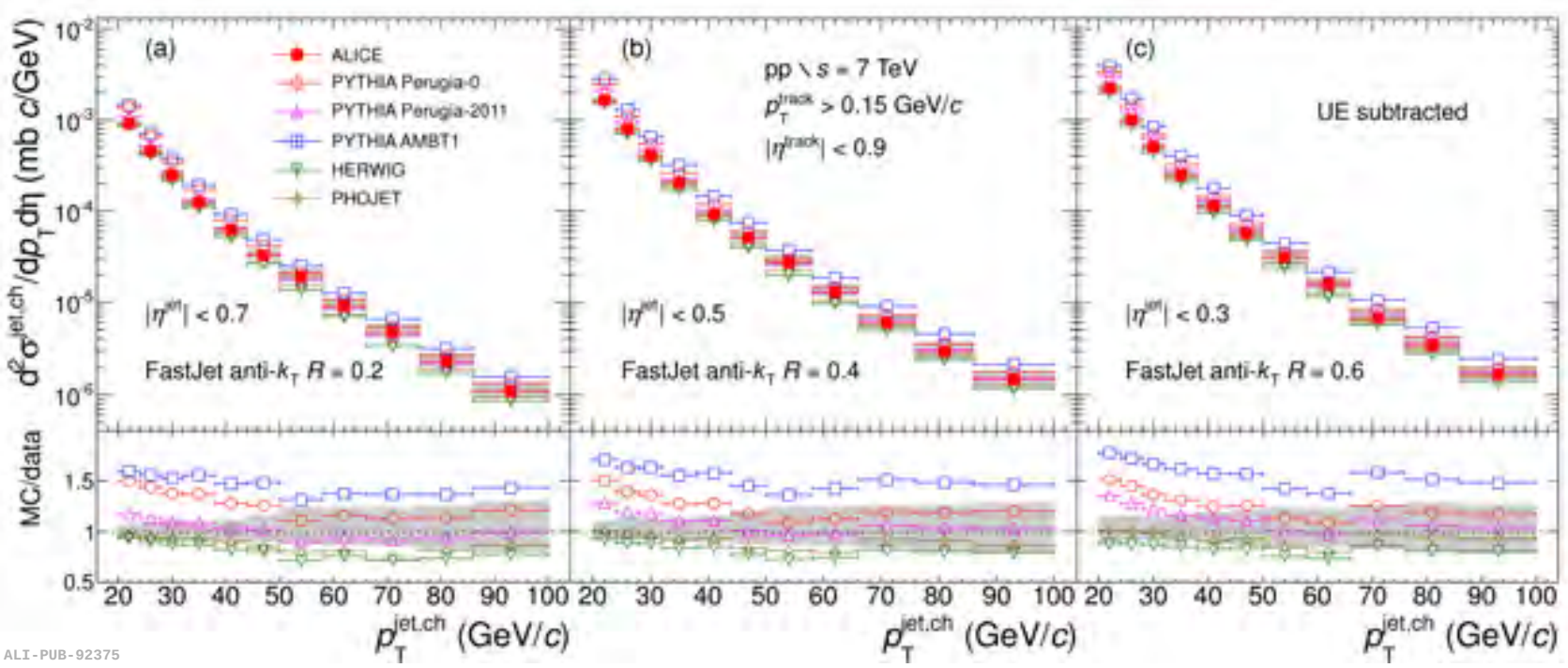
$$R_{AA} = \frac{\mathrm{d}^2N/\mathrm{d}p_T\mathrm{d}\eta|_{A+A}}{\langle N_{\mathrm{coll}}\rangle \cdot \mathrm{d}^2N/\mathrm{d}p_T\mathrm{d}\eta|_{p+p}}$$

$\langle N_{\mathrm{coll}}\rangle$ mean number of NN collisions
$R_{AA} < 1$ medium-induced suppression
$R_{AA} = 1$ pp-like production
$R_{AA} > 1$ medium-induced enhancement



Inclusive charged-jet measurements in p+p at the LHC

- Cross-section measurements of inclusive charged jets
- Baseline for $A + A$
- Data for tuning MC event generators (PYTHIA, HERWIG,. . .)

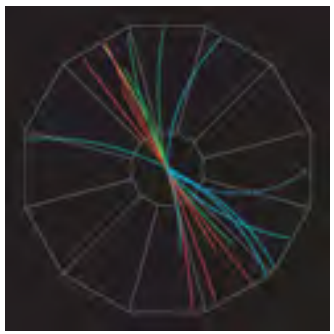


ALICE, Phys.Rev. D91 (2015) 11, 112012; Ph.D. thesis of M. Vajzer

Jet quenching at RHIC

- Jet reconstruction is challenging due to large, fluctuating background and small cross-section at RHIC
- $p_{\mathrm{T,leading\ hadron}} > 5\,\mathrm{GeV}/c$ bias
- Large suppression of charged-jet production in central Au+Au observed at top RHIC energy

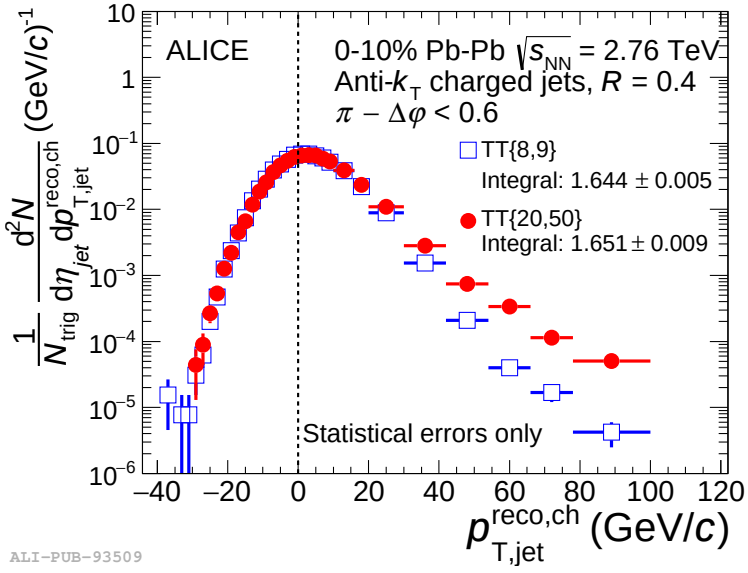
Ph.D. thesis of J. Rusňák

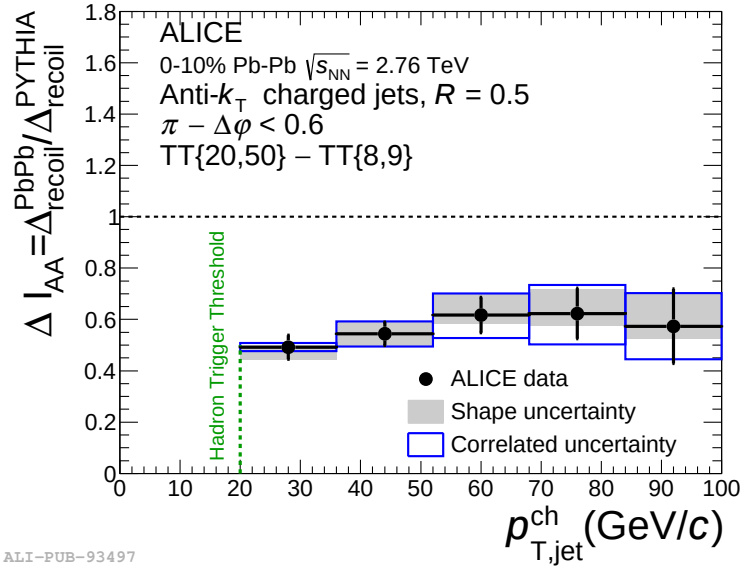


di-jet in p+p

Au+Au

Jet quenching with hadron+jet observables at the LHC





ALICE,

JHEP 09 (2015) 170

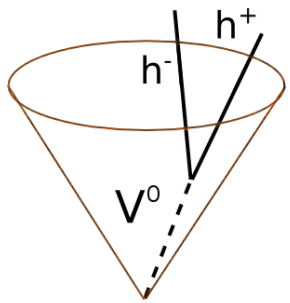
- ◇ TT = trigger track; TT$\{X, Y\}$ means $X < p_{T,trigger} < Y$ GeV/c
- ◇ Bckg. jets removed using coincidence of a high-p_T hadron and a jet in recoil
- ◇ Data driven approach without jet fragmentation bias

$$\Delta_{recoil} = \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp_{T,jet}^{ch} d\eta}\bigg|_{p_{T,trig} \in TT\{20,50\}} - \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp_{T,jet}^{ch} d\eta}\bigg|_{p_{T,trig} \in TT\{8,9\}}$$

Yield of jets is suppressed. Mean energy loss is about 8 ± 2 GeV.

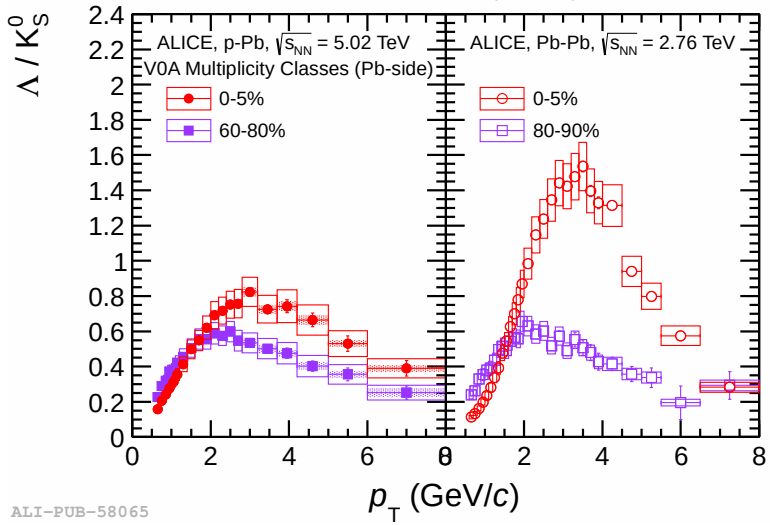
Strangeness production in jets and bulk at the LHC

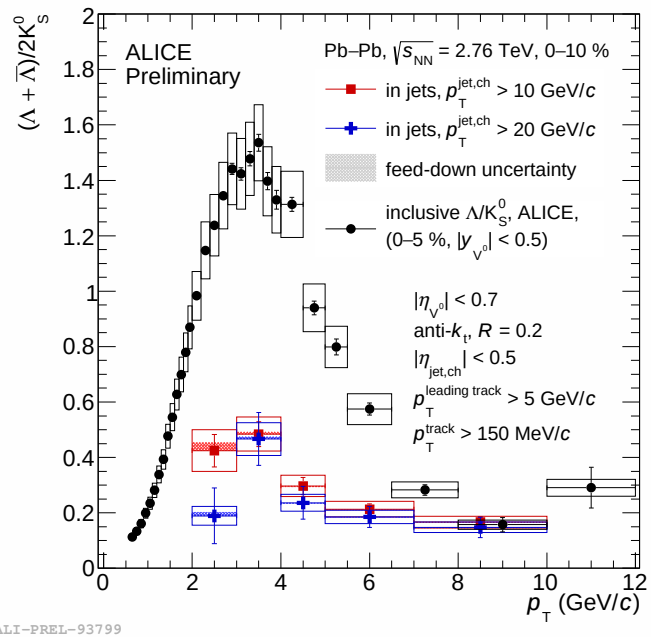
- Final state of HI collision exhibits enhanced production of 2–7 GeV/c baryons to mesons relative to pp
- Does Baryon anomaly arise from jet fragmentation or bulk?
- Angular matching of V^0 and jet



- In central Pb–Pb collisions $(\Lambda + \bar{\Lambda})/2K^0_S$ is lager for inclusive particles than for particles in jets
  $\Rightarrow$ baryon anomaly arises from bulk

ALICE, Phys.Lett. B728 (2014) 25–38

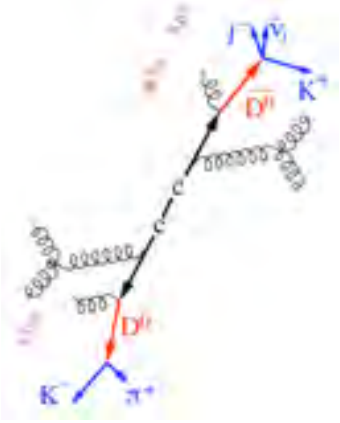


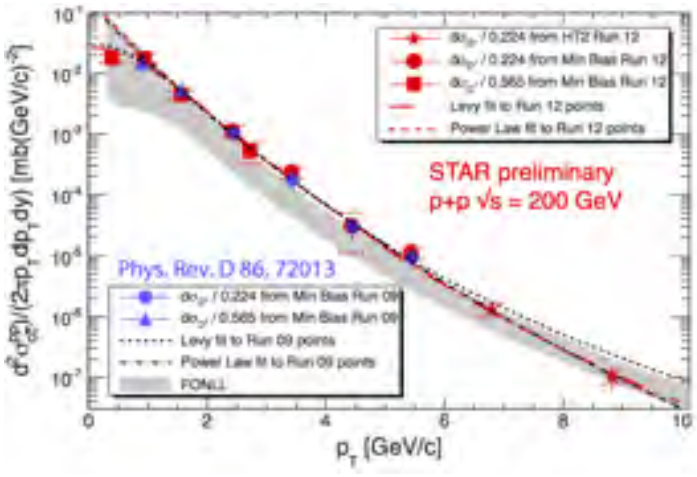


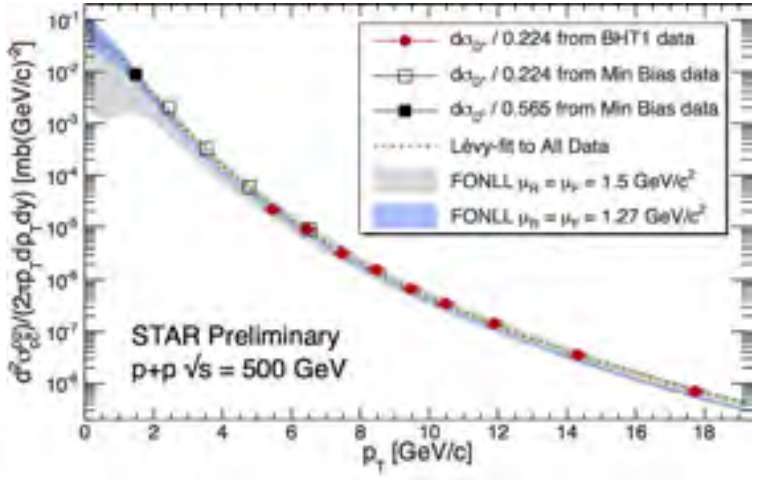
Ph.D. thesis of V. Kučera (ALICE Thesis Award 2016)

Nucl.Part.Phys.Proc. 276–278 (2016) 181–184

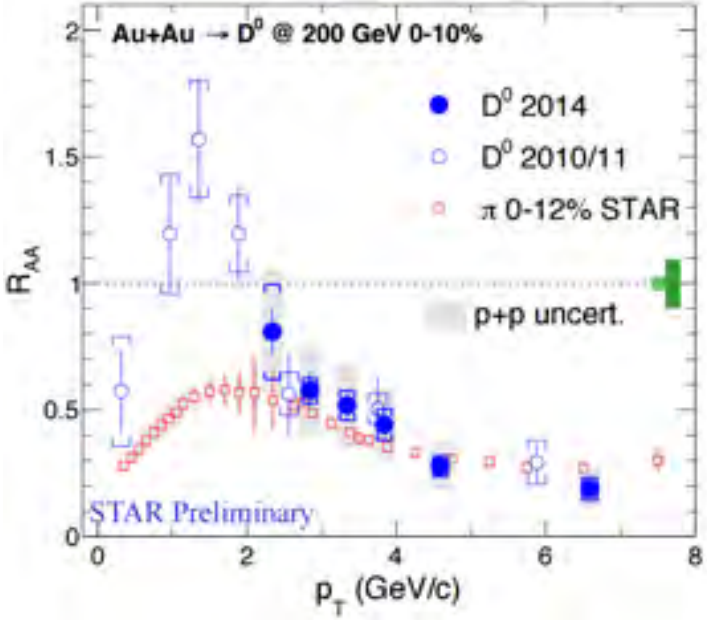
Open charm production at RHIC





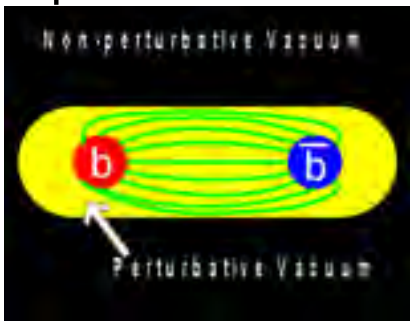


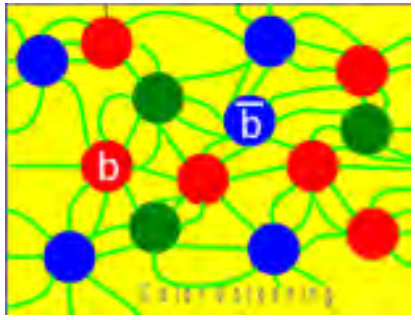
- D^0 and D^* cross-section in p+p at $\sqrt{s} = 200$ and 500 GeV
  - constraints on pQCD calculations (data on upper FONLL limit)
  - reference for Au+Au collisions →
- Suppression of charm in Au+Au consistent with light hadrons at high-p_T



STAR, Phys.Rev. D86, 72013; Ph.D. thesis of D. Tlustý

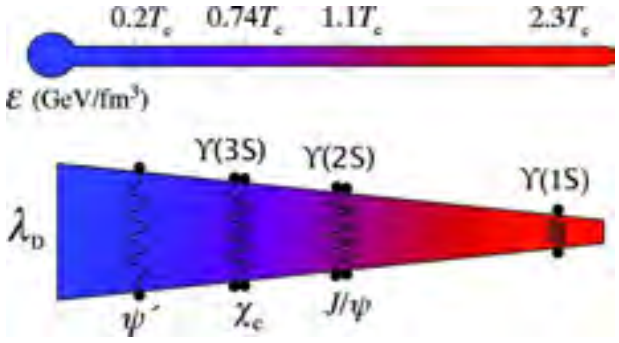
Quarkonia as QGP thermometer at RHIC

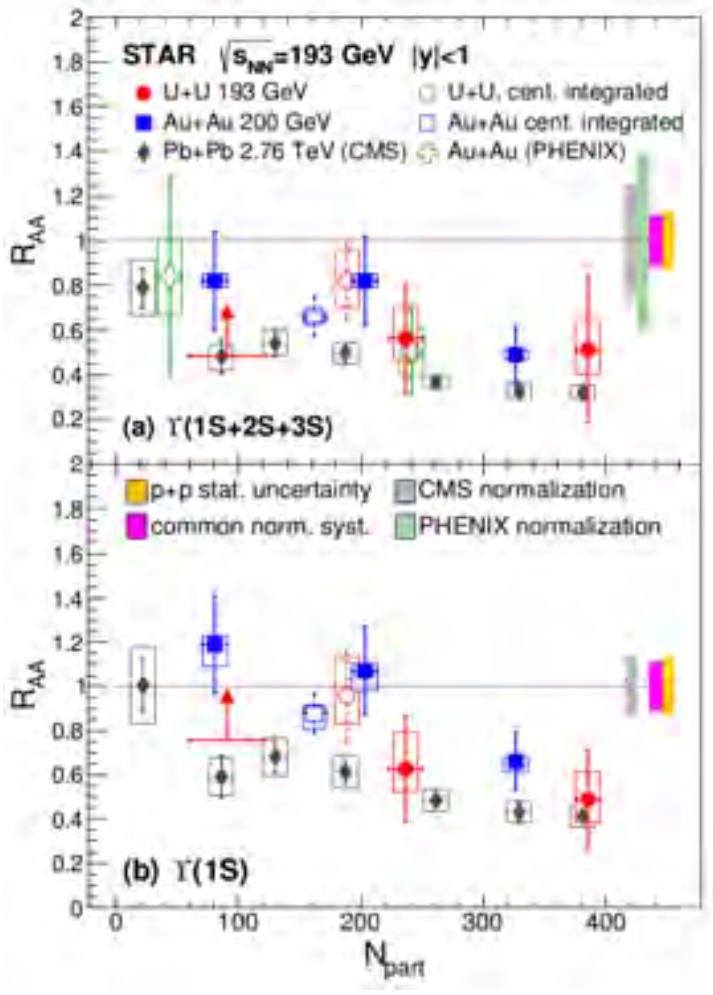




Debye screening of heavy-quark potential

$\Rightarrow$ sequential melting of quarkonia states



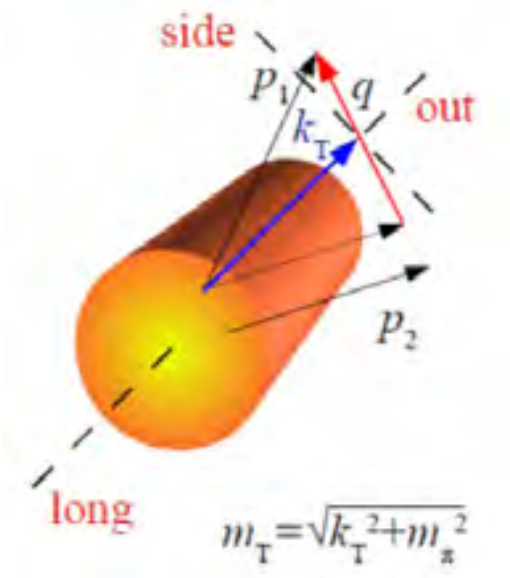


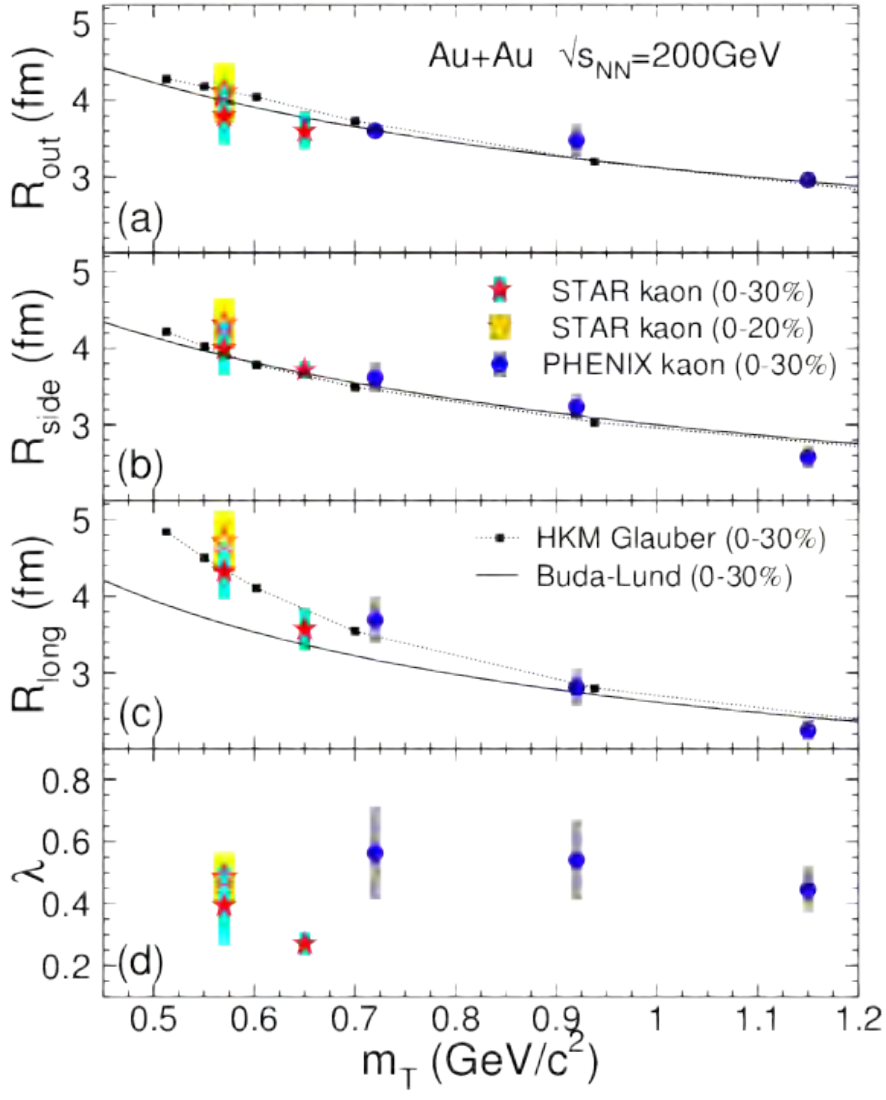
- Υ(1S) suppressed in central Au+Au
- U+U 20 % larger N_{part} than Au+Au
- suppression at RHIC and LHC comparable at high N_{part}

STAR, Phys.Rev. C94 (2016) 064904

Imaging hot and dense fireball with STAR

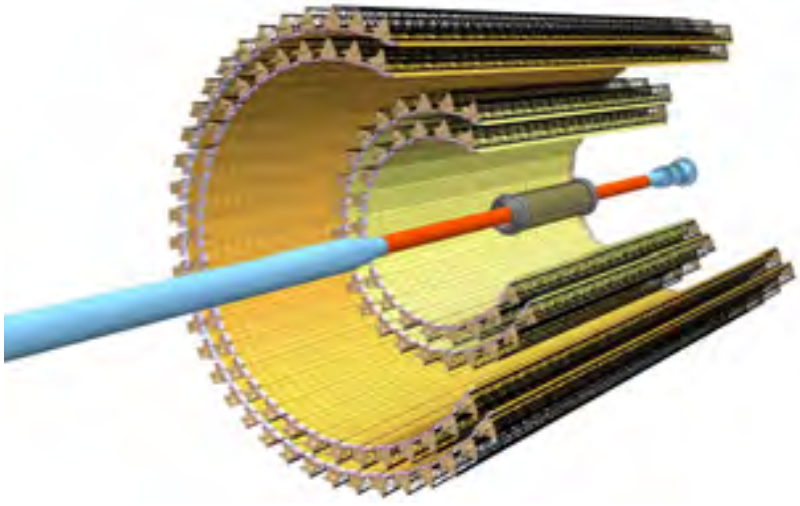
- Radii of a hot source emitting identical bosons using HBT
- K and π emission source properties compared to models





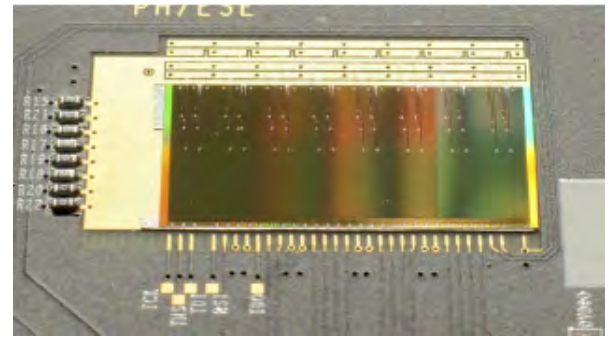
STAR, Phys.Rev. C88 (2013) 34906

ALICE Inner Tracking System upgrade



Pseudorapidity	$\lvert\eta\rvert < 1.2$
Innermost layer radius	22 mm
Si thickness per layer	50 and 100 µm
Pixel size	$30 \times 30\,\mu\text{m}^2$
Material budget per layer	0.3–0.8 % X_0
Max rate Pb–Pb	50 kHz
Number of pixels	12.5×10^9
Total area	$10\,\text{m}^2$

- Precision studies of QGP
- To be installed 2019–2020
- 7 layers of Monolithic Active Pixel Sensors
- Improve vertex reconstruction and tracking capability
- Increase data taking rate
- Fast removal and insertion



ALPIDE sensor
1024×512 pixels

Tests of radiation hardness for ALICE ITS upgrade project

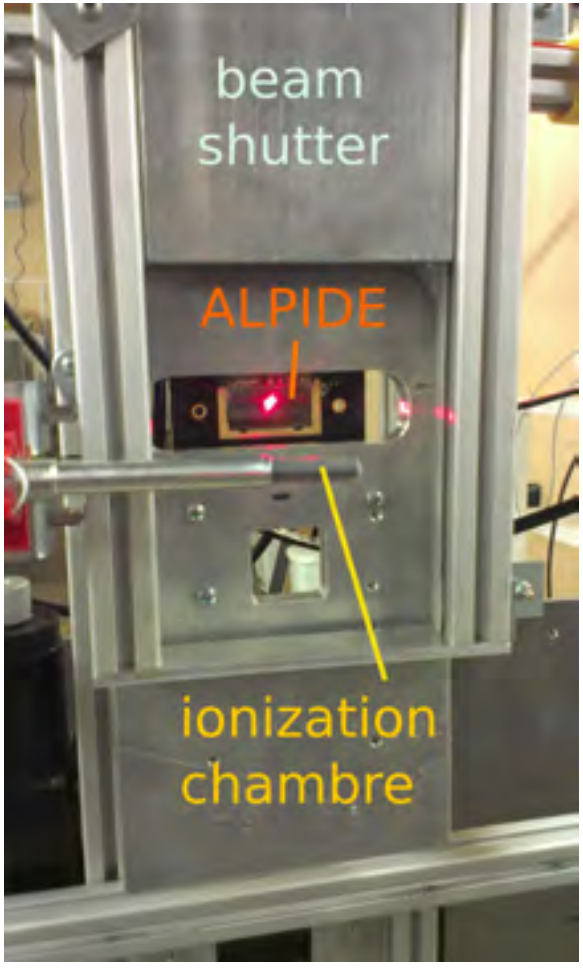
- Radiation hardness of electronics

  Total Ionization Dose up to 2.7 Mrad

  Non-ionizing energy loss up to 1.7×10^{13} $1\,\text{MeV}\ n_{eq}/\text{cm}^2$
- Cyclotron U-120M, $E_{\text{proton}} \approx 30\,\text{MeV}$
- On-line dosimetry 10^3–10^9 p $\text{cm}^{-2}\text{s}^{-1}$
- TID effects in silicon sensors,
  time response to protons,
  Single Event Upset cross-sections

  TDR: J.Phys. G41 (2014) 087002
- Measurement of SEU cross-sections in FPGA, fault mitigation techniques

  Ph.D. thesis of T. Vaňát



Setup for ALPIDE chip irradiation at NPI

Computing for ALICE and STAR

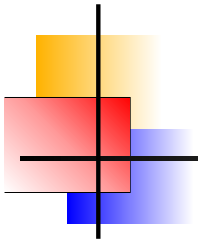
- Providing computing and storage resources for ALICE
  - $\approx$ 5M of jobs (in 2016)
  - $\approx$ 32 PB downloaded from Prague storage
  - $\approx$ 1.8 PB NPI site disc storage for ALICE
- Management of ALICE data processing at the WLCG Tier-2 center at Institute of Physics of the CAS
- Development of SW tools for
  - data analytics using Machine Learning

    MSc. thesis of M. Adam
  - jobs scheduling for distributed grid

    Ph.D. thesis of D. Makatun

Server xrootd5 (422 TB)

Servers xrootd1 (125 TB) and xrootd2 (89 TB)



Summary

- NPI ultra-relativistic heavy-ion group is involved in leading edge research exploring properties of hot and dense QCD matter
- Many opened questions: critical point, confinement, chiral symmetry restoration, . . .
- Outlook: Beam Energy Scan II at RHIC, Run 3 at the LHC, US Electron-Ion Collider program
- Challenges for development of detectors and computer resources