Heavy Ion Experiments

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Challenges of heavy-ion physics

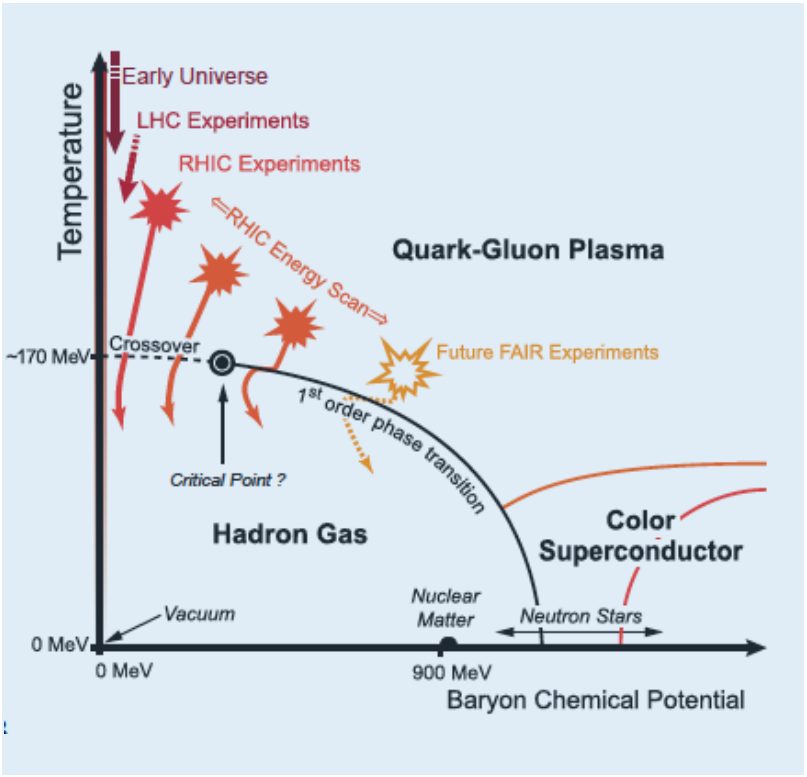
Exploration of the QCD phase diagram:

- nature of the phase transition and search for critical point
- properties of the quark-gluon plasma at high temperature (RHIC/LHC) and large density (GSI FAIR)
- exotic phases of QCD matter

Complementarity of RHIC, LHC and FAIR heavy-ion programs

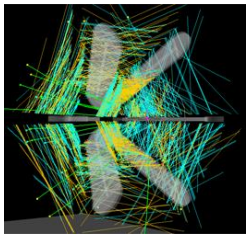
Center of mass energies for different accelerators:

GSI: $\sqrt{s_{NN}}$ ~ 1-2 GeV
RHIC: $\sqrt{s_{NN}}$ ~ 200 GeV
LHC: $\sqrt{s_{NN}}$ ~ 5500 GeV

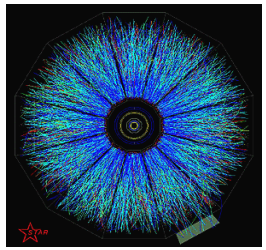


Heavy-ion physics in the Czech Republic

Ongoing experiments:

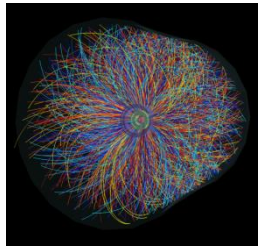


HADES @ GSI: NPI ASCR

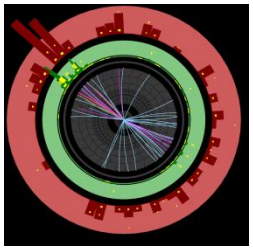


STAR @ RHIC: FNSPE CTU in Prague, NPI ASCR

PHENIX @ RHIC: Charles University, FNSPE CTU in Prague



ALICE @ LHC: FNSPE CTU in Prague, NPI ASCR, IoP ASCR



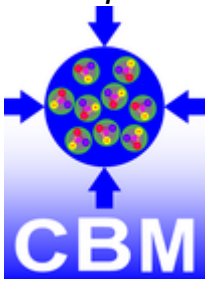
ATLAS (HI) @ LHC: Charles University

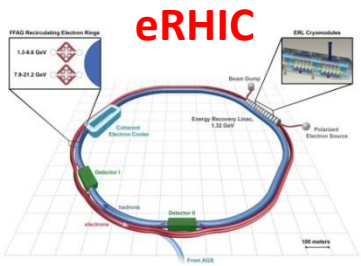
→ *see talk by A. Kupco*

Future experiments:

CBM @ FAIR, GSI

eSTAR/sPHENIX @ eRHIC

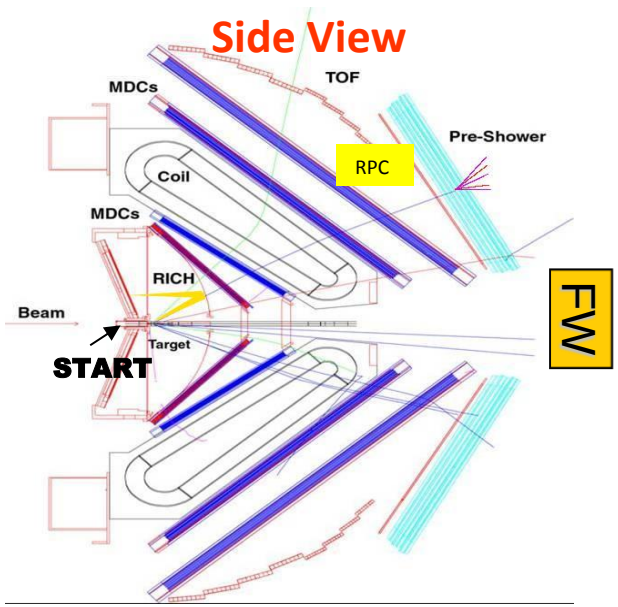


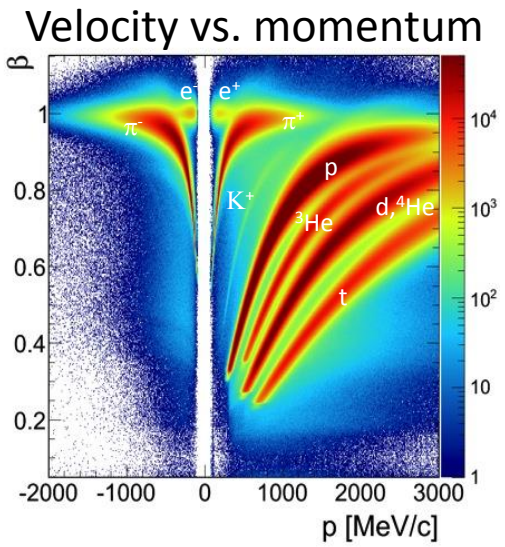


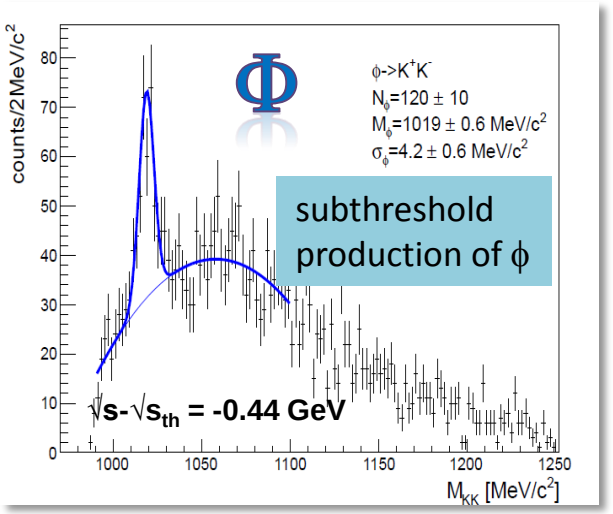
HI theory and phenomenology: FNSPE CTU, NPI → *see talk by M. Malinsky*

Main source of funding: MEYS (INGO, ESF: ECOP) and GACR

HADES:High Acceptance Di-Electron Spectrometer







Czech team (NPI):

5 scientists, 2 Ph.D. and 1 MSc. students
Since 2007 defended: 1 MSc. and 1 Ph.D. theses

Key roles in the collaboration (105 members):

Deputy spokesperson, Collaboration board chair
Technical board: TOF coordinator, ECAL coordinator

Active participation in preparation for transition to HADES@FAIR (ECAL) and CBM@ FAIR (PSD detector)

see e.g. JINST 9 (2014) C05002

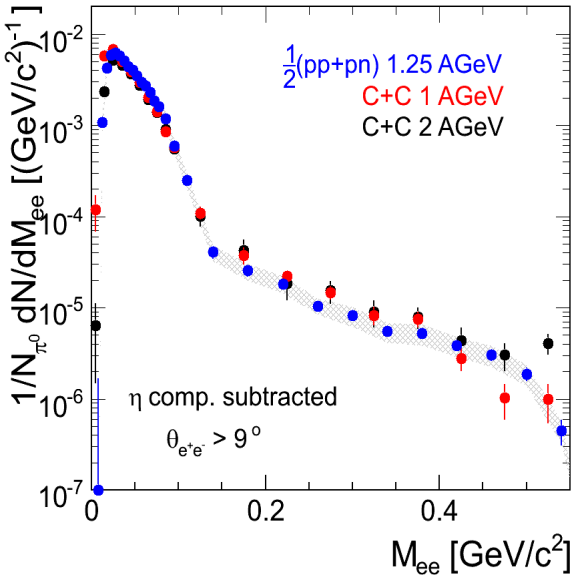
Matter at SIS energy:

- moderate density (1-3x ρ_0) and temperature (T < 80MeV)
- long lifetime: τ~15 fm/*c*
- baryon dominated

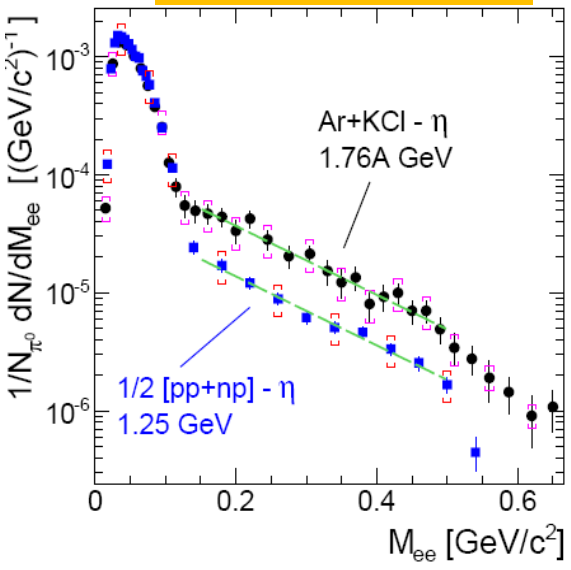
Czech team focuses on rare and penetrating probes + helps with particle identification studies.

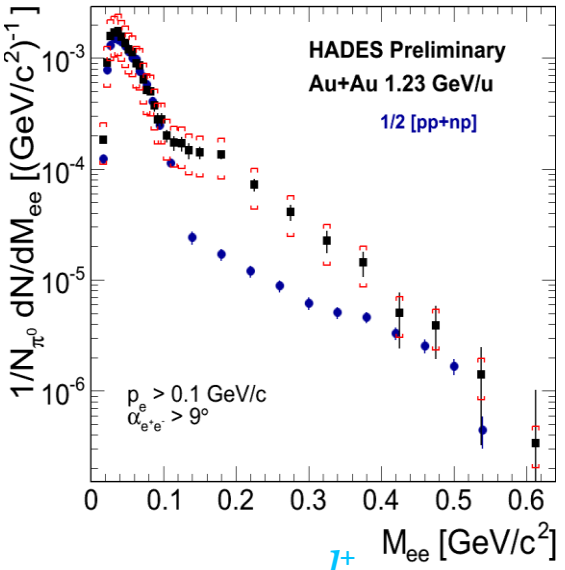
Dileptons: excess above η contribution

PLB 690 (2010) 118



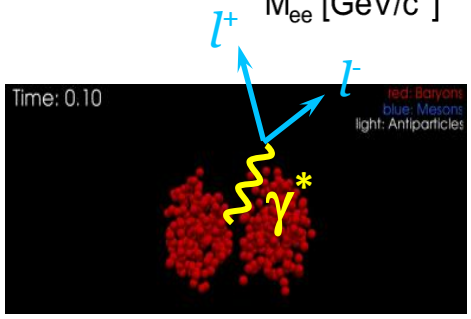
PRC84 (2011) 014902





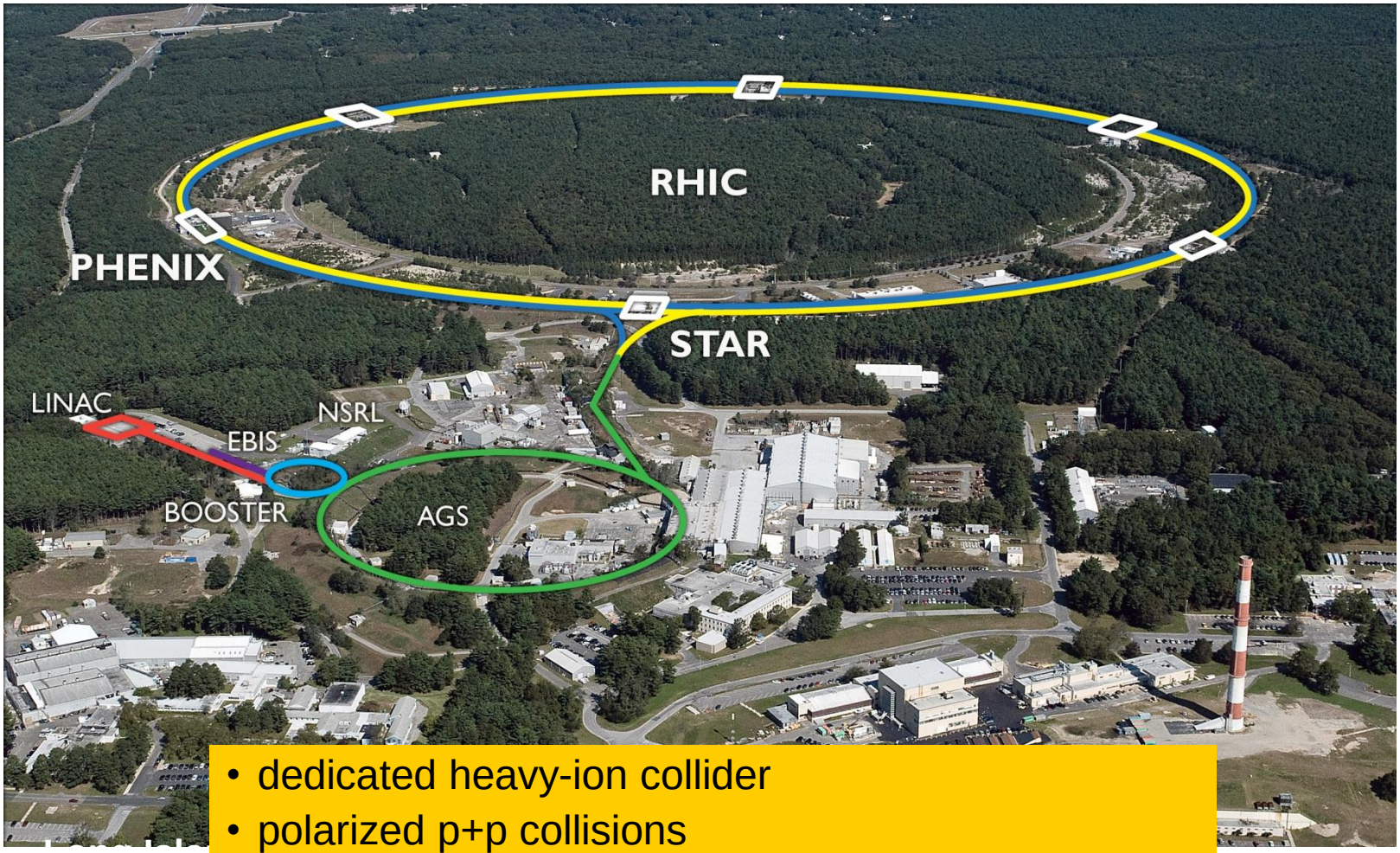
CNM effects: PLB 715 (2012) 304

e^+e^- excess @ 1-2 AGeV



- excess above NN reference at M_{ee} > 150 MeV/c^2 increases from ~0 (light systems) to ~3 (Ar+KCl) and ~8-10 in Au+Au
- precise measurement of NN (np and pp) reference was an essential input
- excess yield scales with system size ~ $A_{part}^{1.4}$ → multistep processes?
- rapid increase of relative yield reflects the number of Δ/ N* regenerated in fireball with lifetime ~10 fm/c

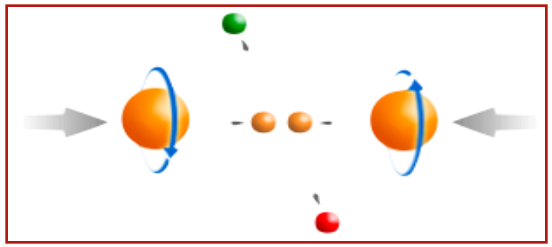
Relativistic Heavy Ion Collider



- dedicated heavy-ion collider
- polarized p+p collisions
- species p, d, ^{3}He, Cu, Au, U
- large flexibility in collision energy

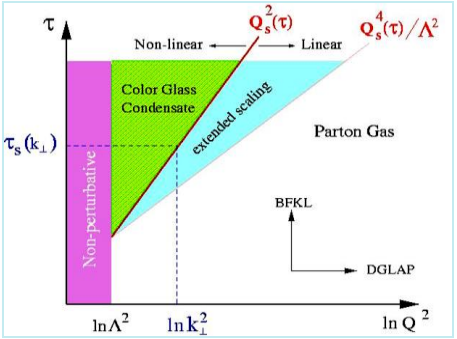
  ions: $\sqrt{s_{NN}}$=5-200 GeV, p+p: up to 510 GeV

RHIC Physics Focus



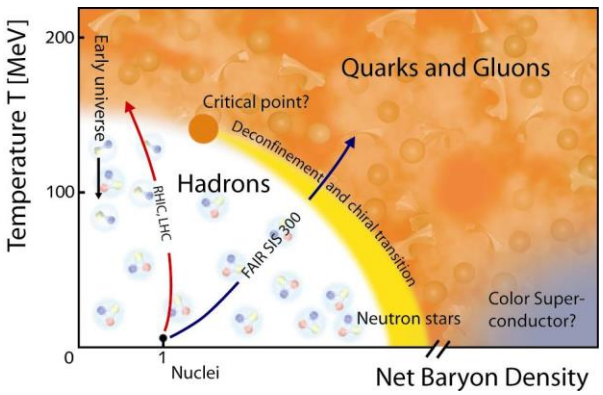
Polarized *p+p* program

- Study ***proton intrinsic properties***



Forward program

- Study low-x properties, search for ***CGC***
- Study elastic (inelastic) processes (pp2pp)
- Investigate ***gluonic exchanges***



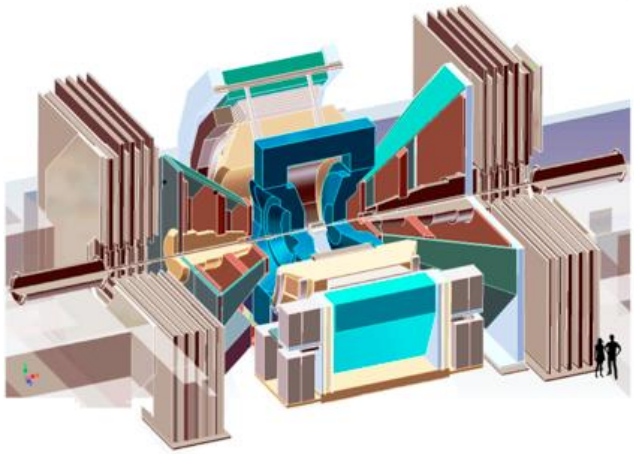
1) At 200 GeV top energy

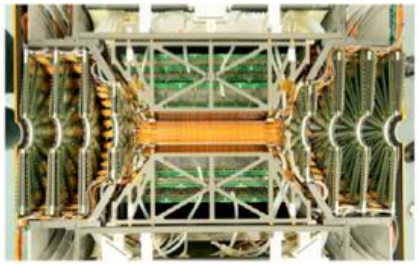
- Study ***medium properties, EoS***
- pQCD in hot and dense medium

2) RHIC beam energy scan

- Search for the ***QCD critical point***
- Chiral symmetry restoration

Proton spin studies at PHENIX





PHENIX:
- high resolution and rate capabilities
- central arms key strengths for π^0 and η
- forward muon arms $1.2<|\eta|<2.4$
- vigorous upgrade program

Czech participation:
FVTX, development of Si-strip detectors for polarimetry target, Si-W calorimeter

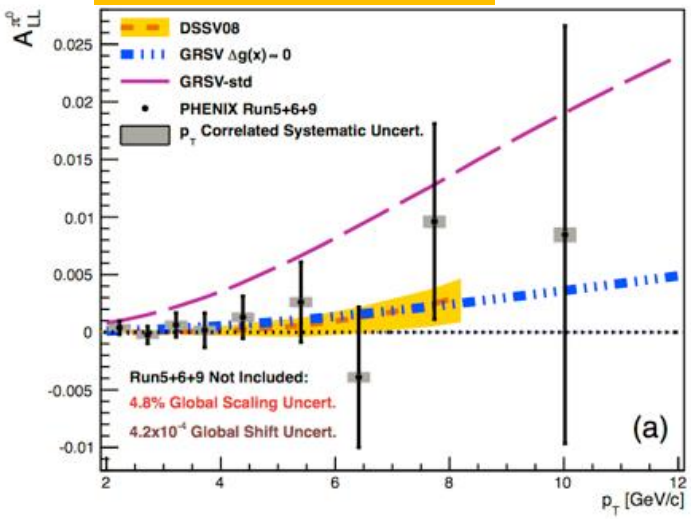
Origin of spin proton – open questions:
Gluon polarization in the polarized proton?
Light quarks and anti-quarks polarization?
Siver's function change of sign in pp vs DIS?
Quark transversity distributions?
Origin of large forward A_N?

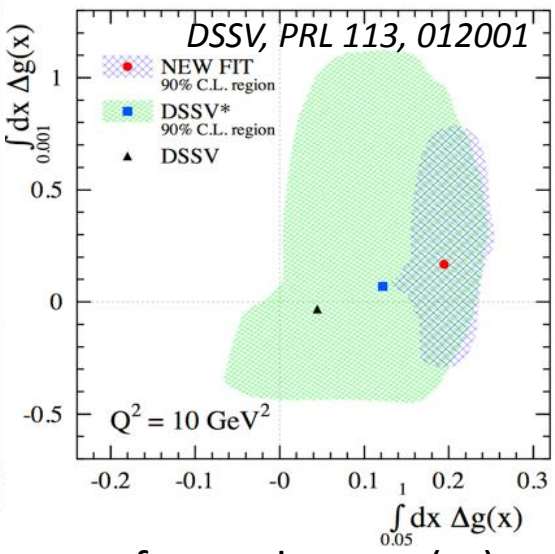
Czech team (Charles University, FNSPE CTU):
participate in PHENIX spin program since 2004
10 scientists, 8 Ph.D. students, 5 engineers

CZ contributions in red

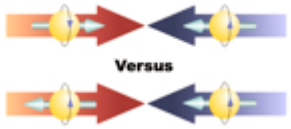
Recent spin results from PHENIX

*PRD **90**, 012007 (2014)*





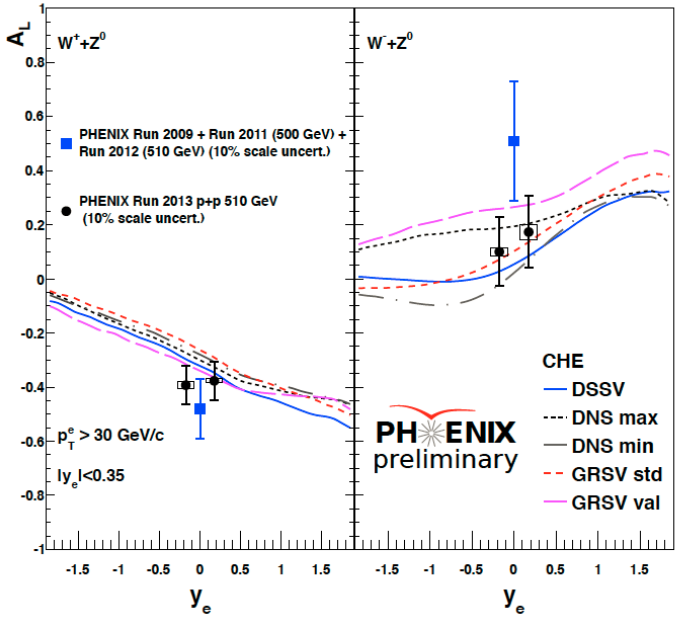
Gluon polarization:

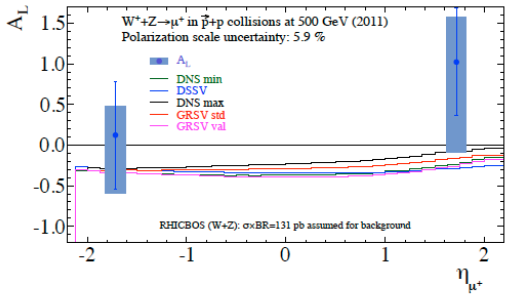


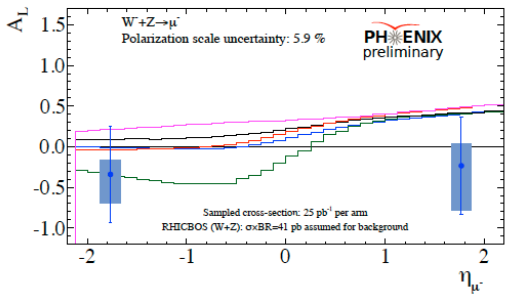
precision measurement of A_{LL} (incl. STAR jet data)

→ data indicate *positive gluon polarization at high p_T and constrain PDF fits*

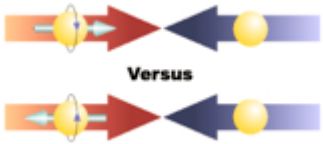
Next: extend sensitivity to *smaller* x_g: go forward $x_g \sim \exp(-\eta)$ and higher $\sqrt{s}$=500 GeV $x_g \sim 1/\sqrt{s}$





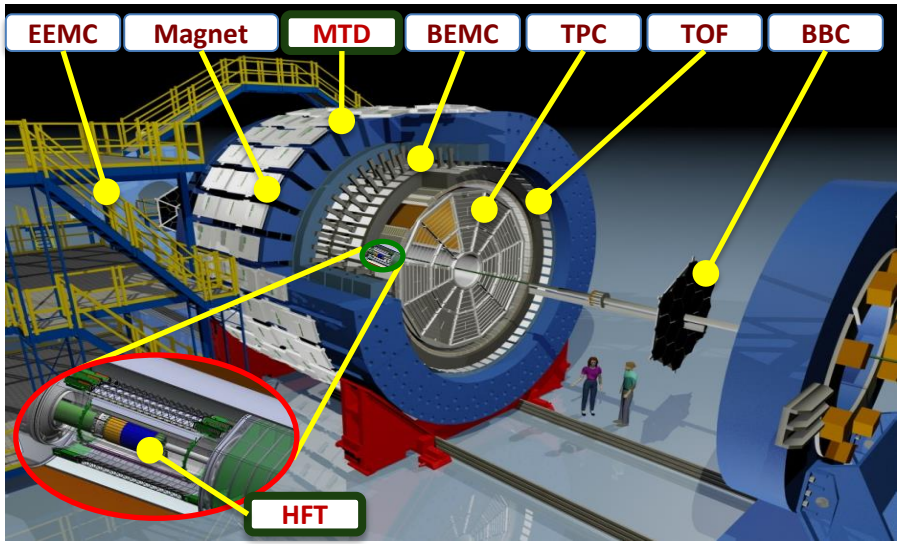


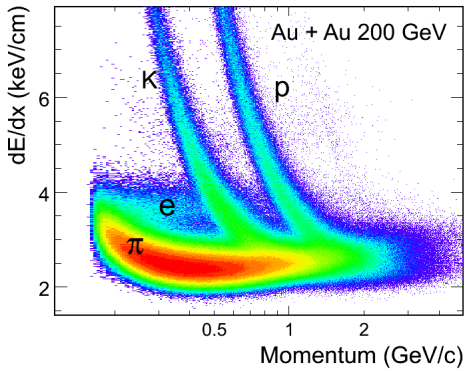
Quark polarization:

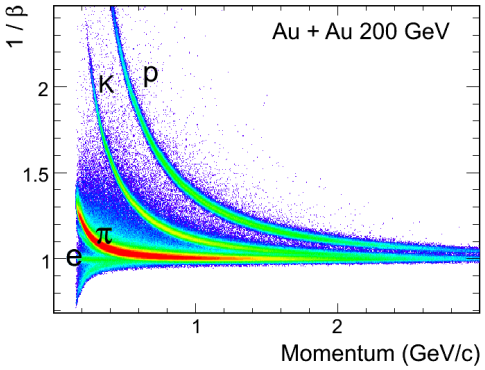


precision measurement of A_L in electron channel, high statistics forward muon 2013 data on the way

STAR experiment







Czech participation:
Heavy Flavor Tracker upgrade (simulations, tests)
Beam Energy Scan II – iTPC upgrade (2018-2019)
→ *see talk by Z. Dolezal*

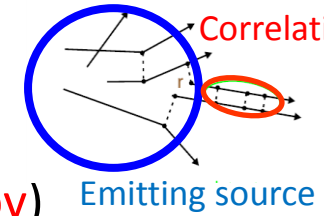
Czech team (NPI, FNSPE CTU):
Since 2007: team grew to current 4 scientists, 4 postdocs, 4 Ph.D., 4 MSc. and 3 Bc. students
Defended: 4 Ph.D., 10 MSc. and 11 Bc. theses → 4 MSc. went to study Ph.D. abroad

Key roles in the collaboration (568 members):
convenership of Physics Working Groups (PWG):
High-p_T/Jet-like correlations (2007-9)
Heavy-Flavor PWG (2009-12)

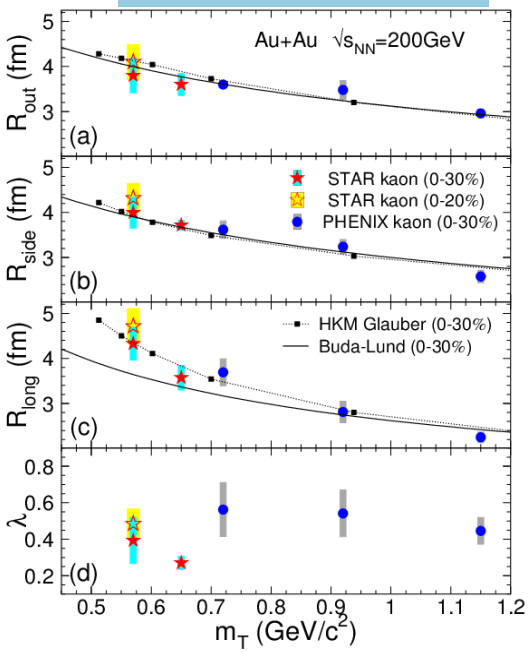
STAR Talks committee: 2007-8, 2010-11, 2012-now
Run 2015: ZDC on-call expert

Hot and dense matter and its tomography

Hot and dense QCD matter ('bulk'):
- collective behaviour (anisotropic flow, v_2)
- emission source size (correlation femtoscopy)

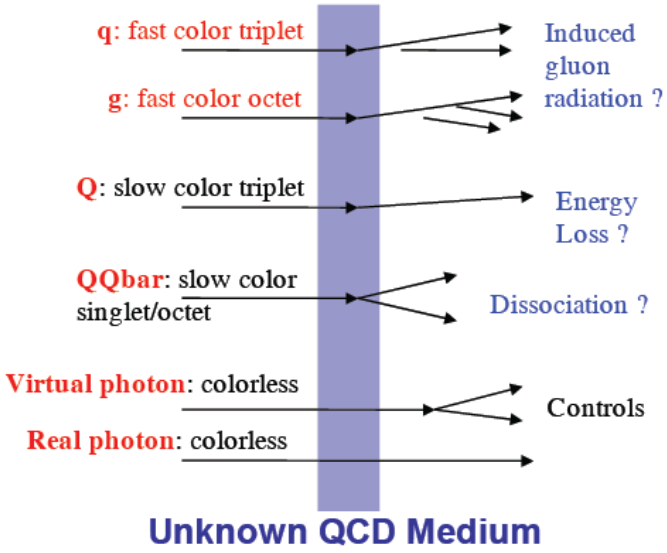


Unique 3D imaging of kaon source



PRC **88** (2013) 34906

How to measure its properties?



Hard probes:

Jets, heavy quarks, quarkonia:
originate from initial hard parton scattering, carry a color charge
interact with nuclear matter

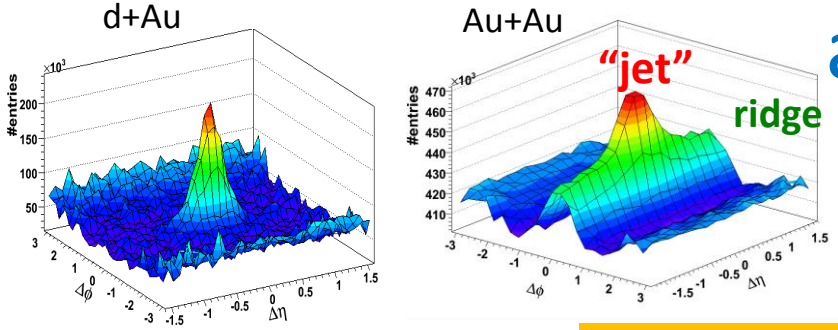
Photons, W and Z bosons:
do not carry color charge
provide information about initial state
nuclear parton distribution functions

Experimental observables: inclusive spectra, particle correlations, jets and jet shapes, γ-jets, jet-hadron, hadron-jet correlations …

Note: different observables have different sensitivity

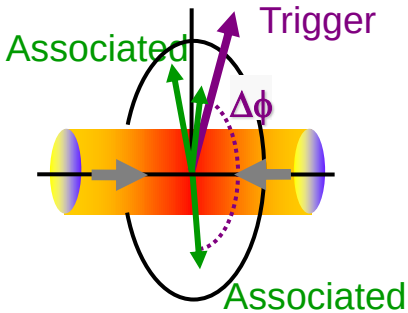
Czech contributions in red

Jet-like correlations: near-side ridge, away-side suppression

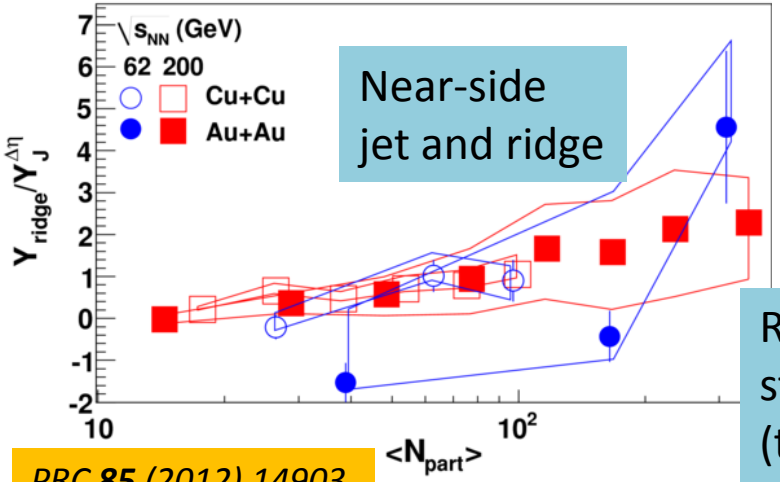


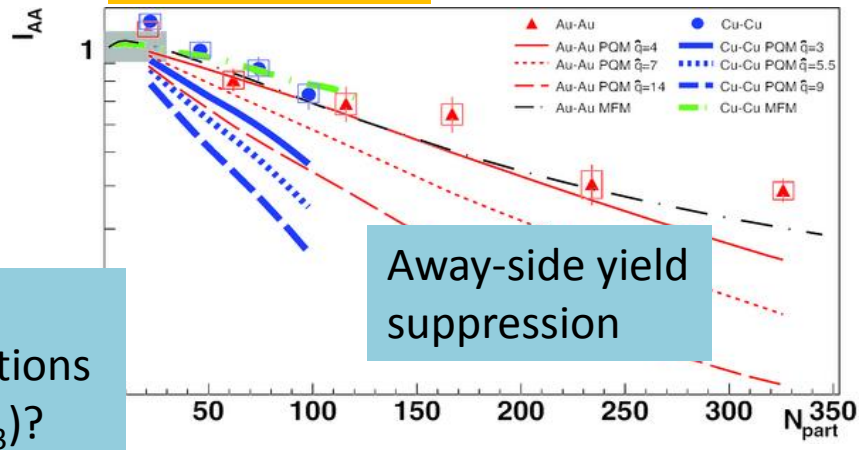
p_T^{trig}=3-4 GeV/c, 2 GeV/c <p_T^{assoc}< p_T^{trig}

*PRC **80** (2009) 64912*



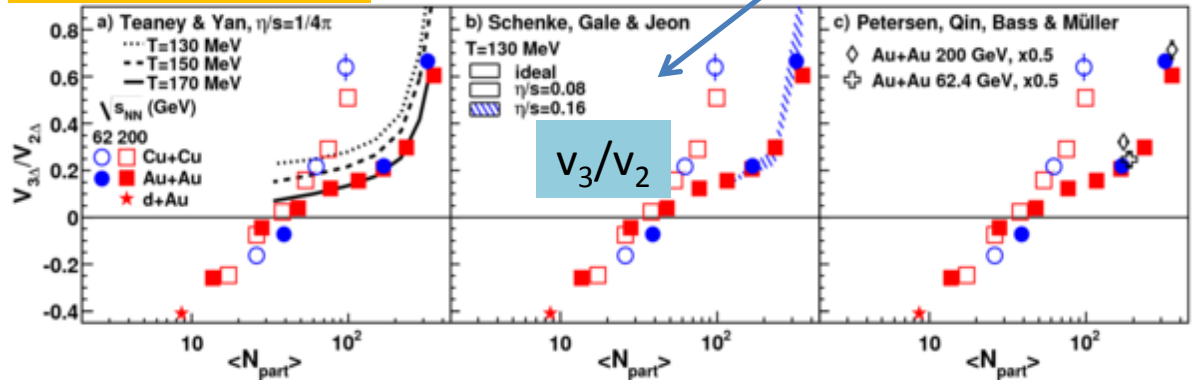
*PLB **683** (2010) 123*





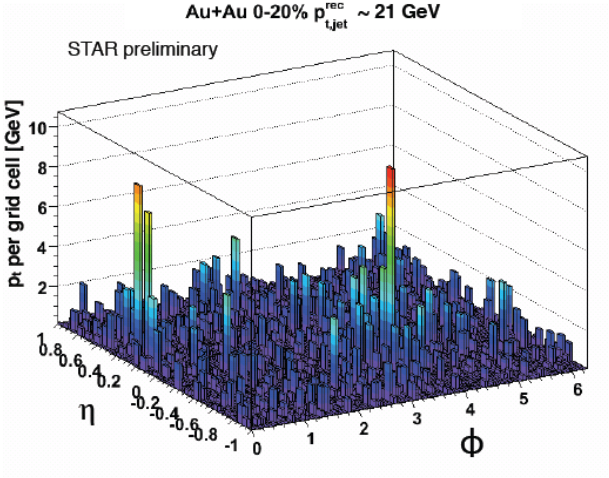
Ridge: initial state fluctuations (triangular v_3)?

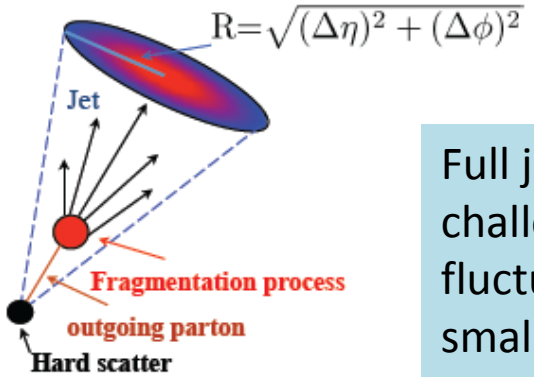
*PRC **85** (2012) 14903*



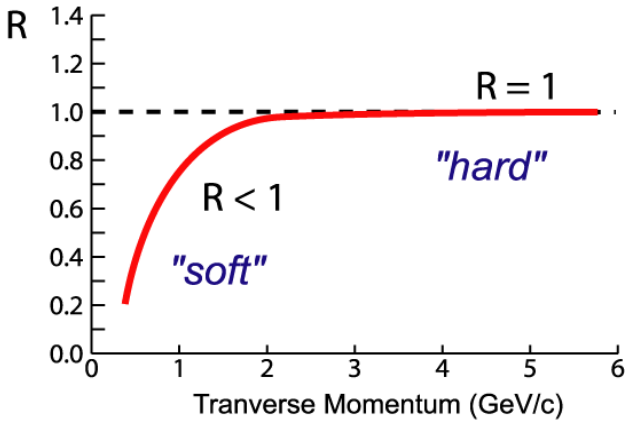
Detailed studies of dihadron correlations as a function of p_T, centrality and system size performed and published.

Jet suppression at RHIC





Full jet reconstruction challenging due to large and fluctuating background and small cross section at RHIC!

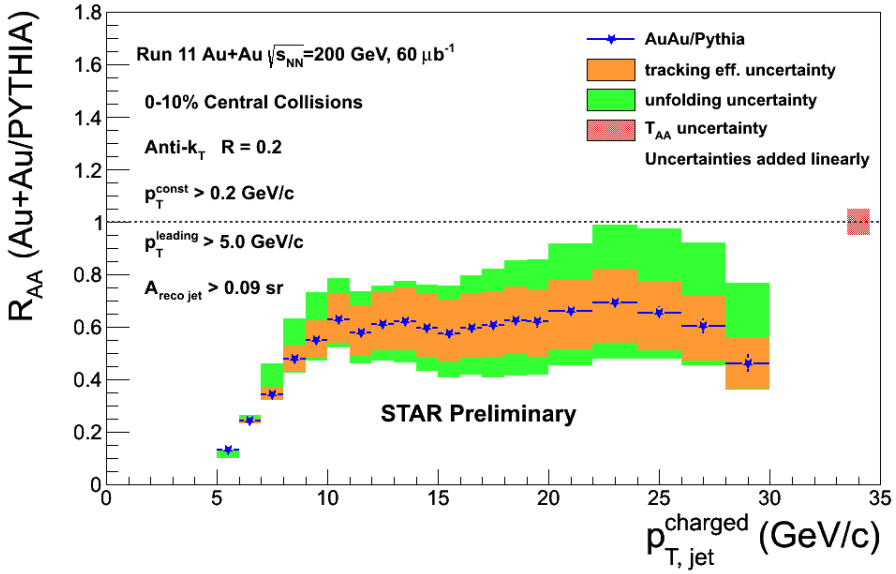


$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

… the way to compare A+A collisions with the reference (p+p) collisions

Charged jets

to be published 2015

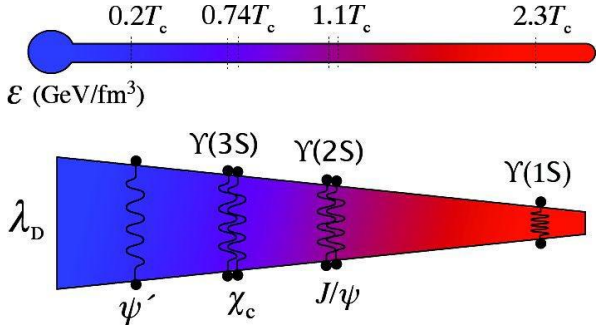


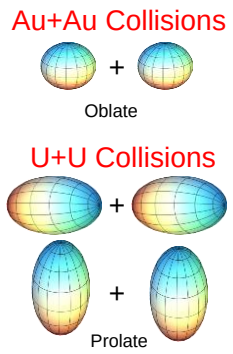
Large suppression of jet production in central Au+Au collisions observed

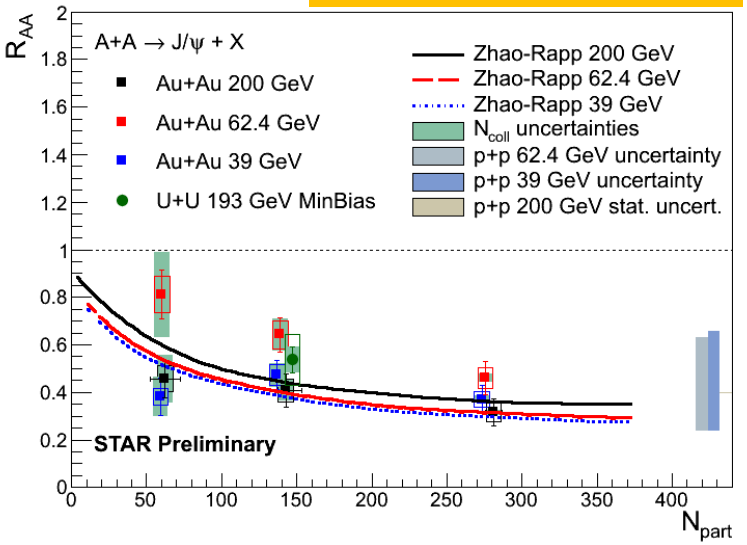
Quarkonia as QGP thermometer

Debye screening of heavy quark potential → quarkonia dissociation

U+U to be published 2015



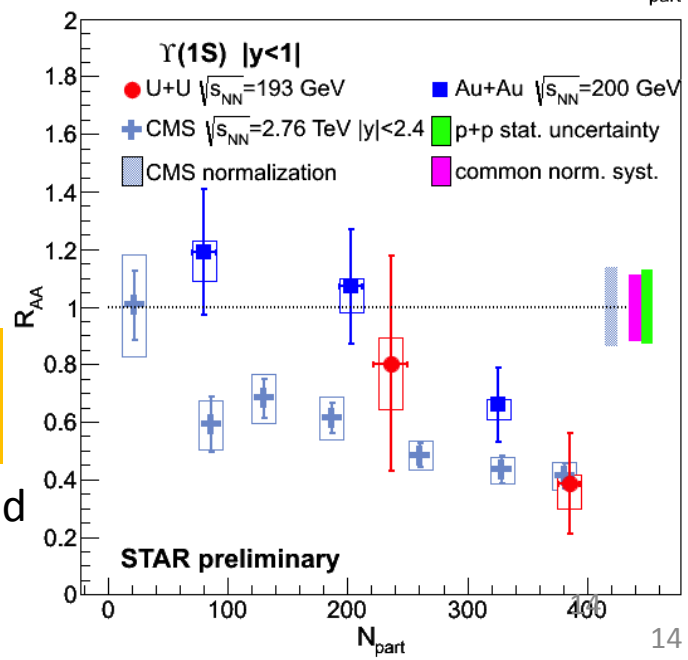




Sequential melting: temperature dependent dissociation of states

- J/ψ suppression observed in Au+Au collisions from 39-200 GeV and also in U+U collisions at 193 GeV similar to light hadrons
- ϒ(1S) suppression in central Au+Au collisions observed, new U+U data confirm and extend the Au+Au trend

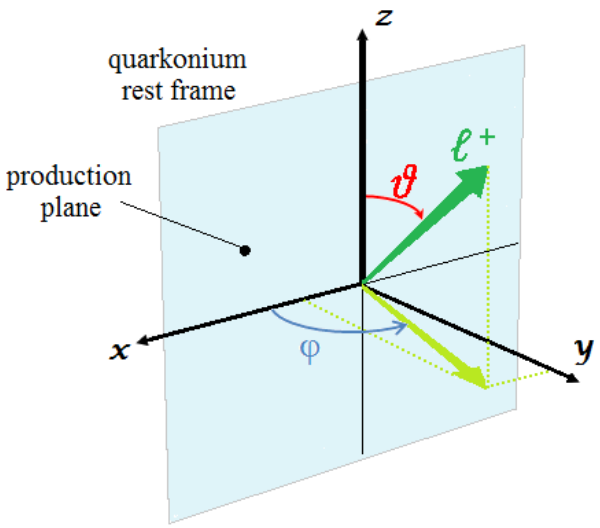
→ ϒ melting in hot and dense medium
Suppression at RHIC and LHC comparable at high N_{part}



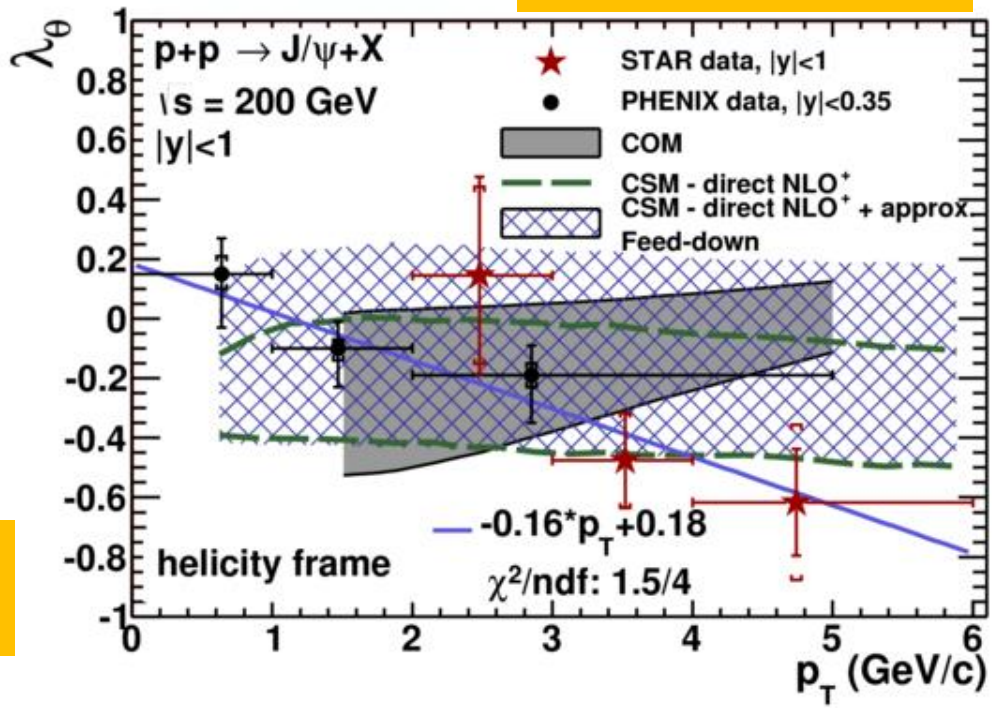
Note: rapidity range, CNM effects have to be still understood

→ RHIC 2015 p+Au run ongoing

J/ψ polarization in p+p collisions



Phys.Lett. B739 (2014) 180



J/ψ polarization measurement crucial to understand J/ψ production mechanism

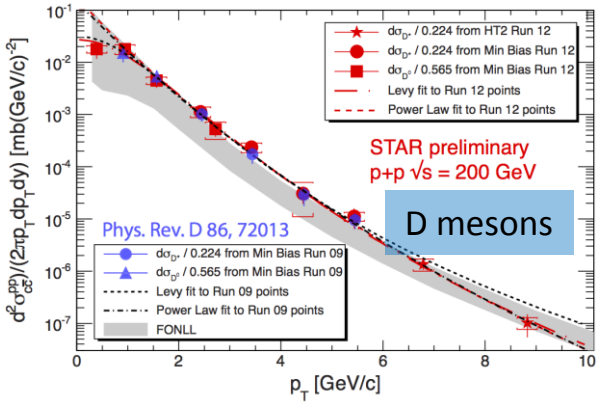
J/ψ polarization:

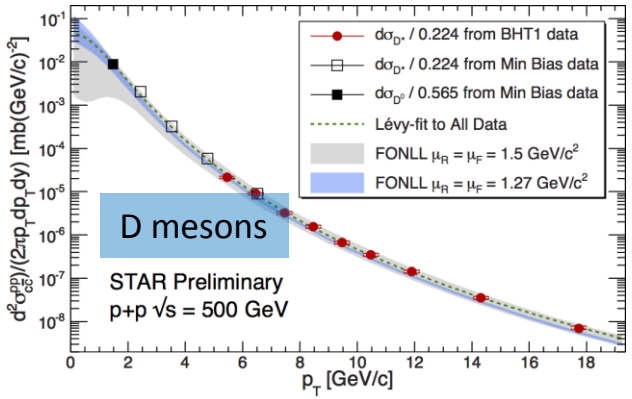
- analyzed in helicity frame from angular distribution of a lepton pair
- data at RHIC indicate trend towards longitudinal polarization with increasing p_T
- consistent with QCD NLO + Color Singlet Model
- new measurement in 500 GeV p+p ongoing
  (improved precision: 1.8 pb^{-1} vs ~22 pb^{-1}, will allow analysis of the full angular distribution)

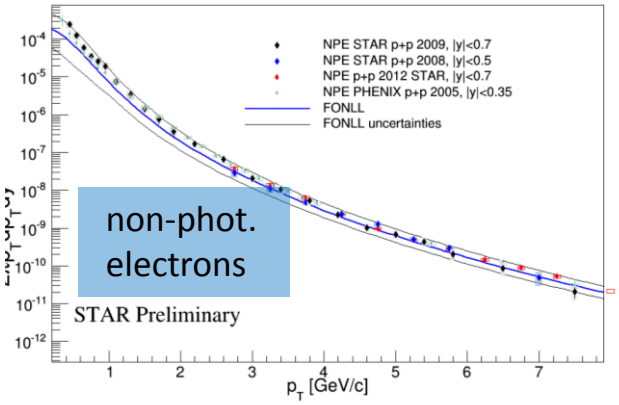
Open charm production at RHIC

*Phys. Rev. D **86** (2012) 72013*

to be published in 2015

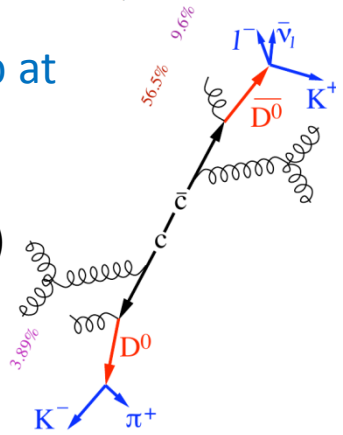






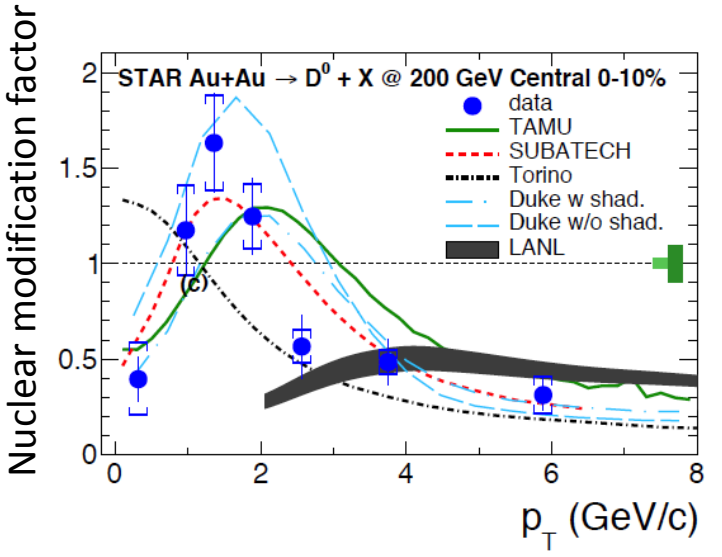
Measured D^0 and D^* cross section in p+p at 200 and 500 GeV:

- constraints of pQCD calculations (consistent with the FONLL upper limit)



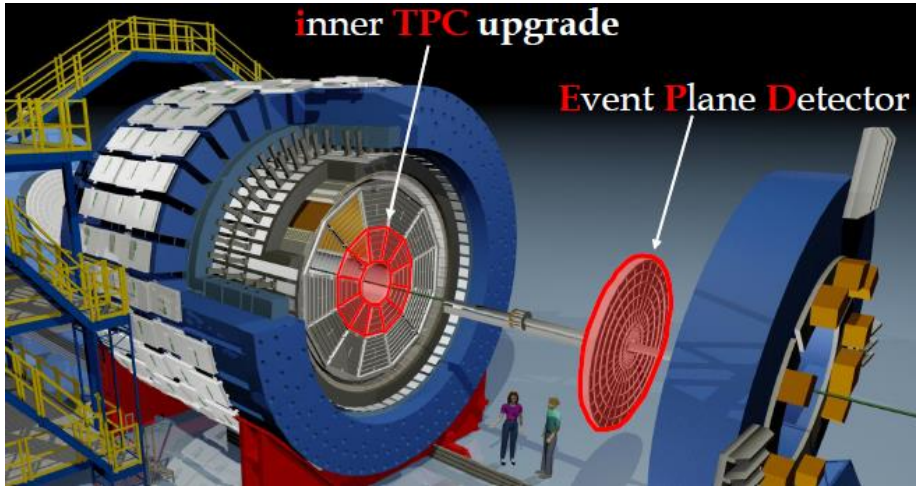
Measured non-photonic electrons from charm and beauty decays in p+p at 200 GeV:

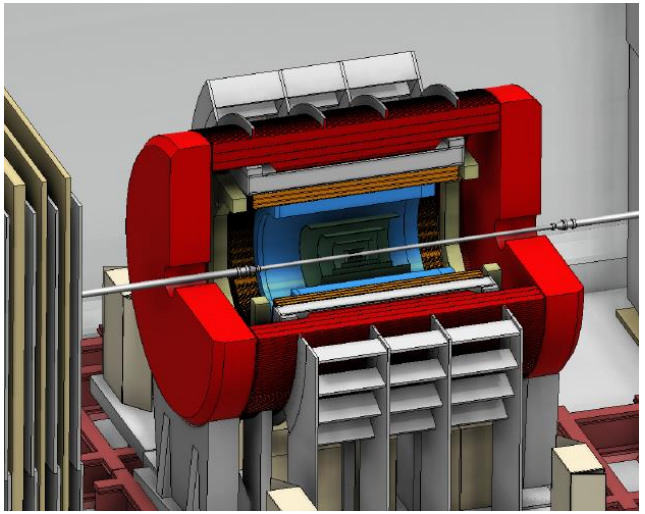
Crucial reference data for A+A collisions.



Suppression of charm production in central Au+Au collisions at high-p_T consistent with light hadrons.

Upgrades: STAR and sPHENIX → eRHIC





STAR major improvements for Beam Energy Scan II (2018-19) :

- iTPC upgrade (TPC inner sectors)
- EndCap TOF
- Event Plane Detector (crucial improvement of reaction plane measurement)

and further upgrades toward eSTAR at eRHIC

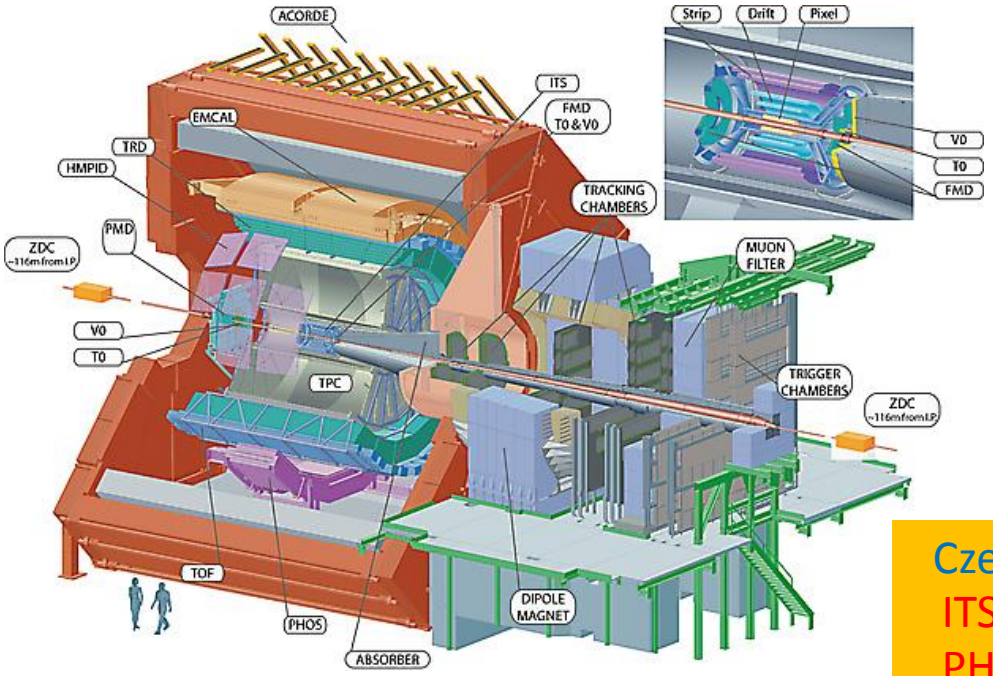
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0592

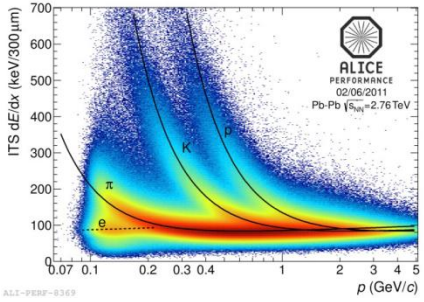
Proposed sPHENIX:

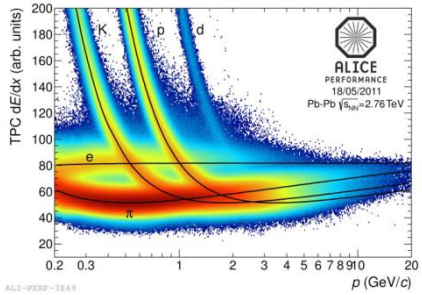
- EM + hadronic calorimetry in $|\eta| < 1.1$ (re-use existing BaBar 1.5 T solenoid)
- silicon tracking
- DAQ rate ~10 kHz
- full suite of jet and quarkonia data
- maximal overlap with LHC measurements

e.g. *arXiv:1207.6378*

ALICE experiment







- dedicated HI experiment at the LHC
- low momentum tracking + excellent PID

Czech participation:
ITS and its upgrade
PHOS calorimeter → *see talk by Z. Dolezal*

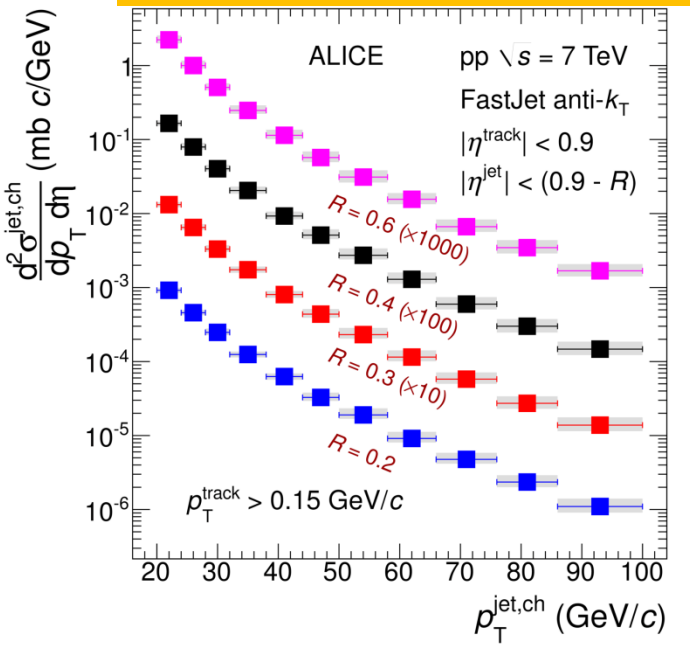
Czech team (NPI, FNSPE CTU, IoP):
Since 2007: team grew to current 10 scientists, 3 postdocs, 5 Ph.D. ,
6 MSc. and 10 Bc. students, 5 engineers, 2 technicians
Defended: 9 MSc. and 7 Bc. theses

Key roles in the collaboration (~1500 members):
2 convenerships of Physics Working Groups (PWG):
PWG Jets
PWG Ultraperipheral and Diffraction

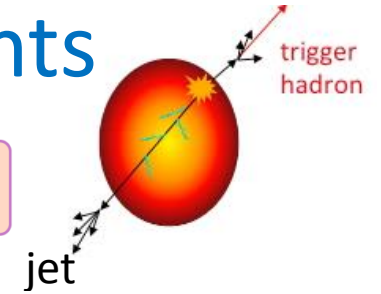
Run2: period coordinator, SSD on-call expert

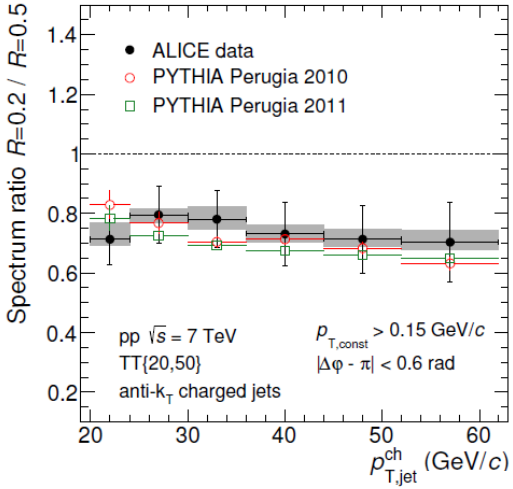
Inclusive jet and h+jet measurements

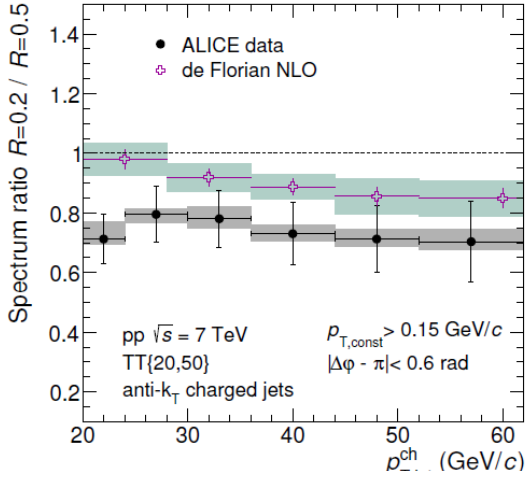
arXiv:1411.4969, to appear in PRD



$$\Delta_{recoil} = \frac{1}{N_{trig}}\frac{dN_{jet}}{dp_T}\Big|_{p_{T,trig}\in TT_{Sig}} - \frac{1}{N_{trig}}\frac{dN_{jet}}{dp_T}\Big|_{p_{T,trig}\in TT_{Ref}}$$





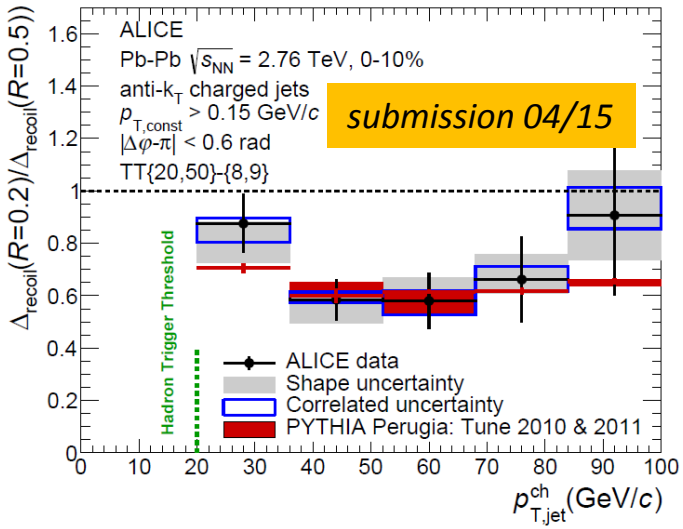


Inclusive charged jet production in pp at 7 TeV:

- cross-section, jet shapes
- reference for p-Pb measurements (scaling to 5 TeV)

Semi-inclusive recoil jet production:

- enables study of intra-jet and inter-jet angular broadening
- unique observable directly comparable to analytic pQCD calculations of quenching
- pp data at 7 TeV used to validate reference for Pb-Pb

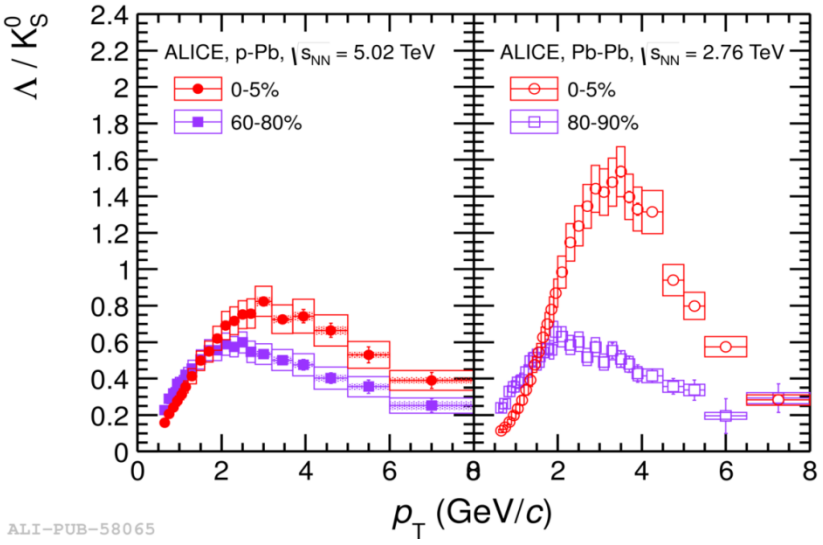


No evidence of intra-jet broadening: Δ_{recoil} for R=0.2/0.5 similar in pp and Pb-Pb collisions

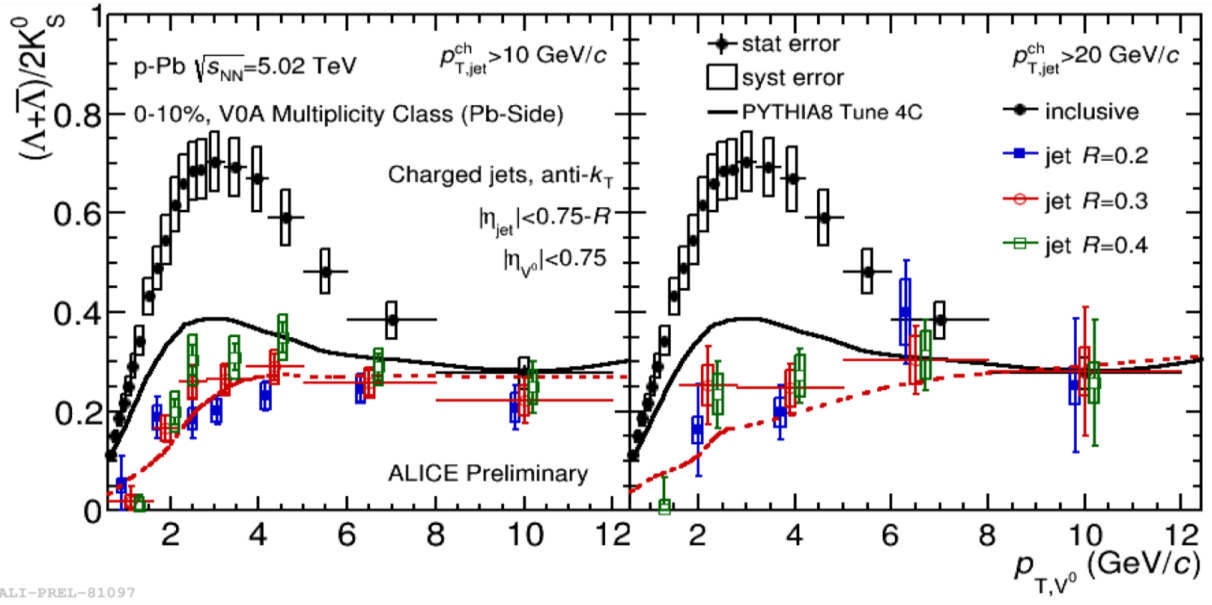
Strange particle production in jets and bulk

High multiplicity p-Pb and Pb-Pb collisions show many similarities:
double ridge structure, elliptic flow
and enhanced baryon/meson ratio

What is the physics origin of enhanced B/M?
radial flow? coalescence/recombination ?
→ measure B/M ratios in jets and compare to bulk



Paper draft under preparation

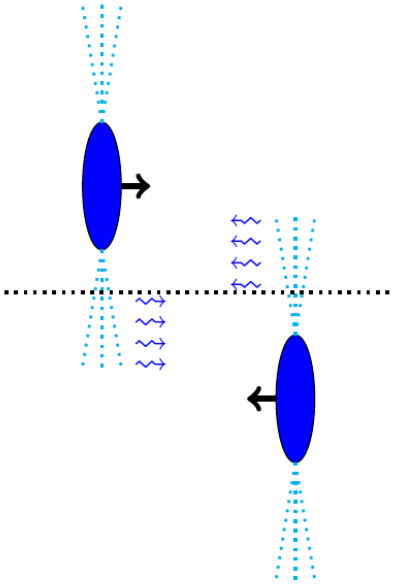


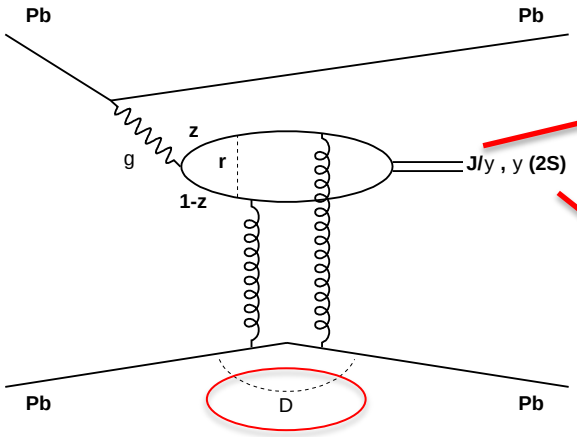
p-Pb collisions:
Λ/K^0_S in jets < inclusive
Λ/K^0_S in jets ~ pp/PYTHIA

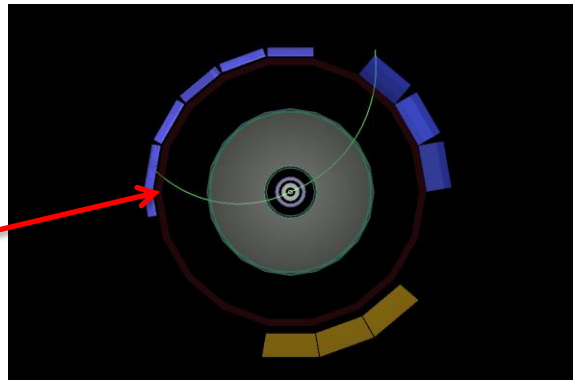
- targeted analysis in Pb-Pb ongoing

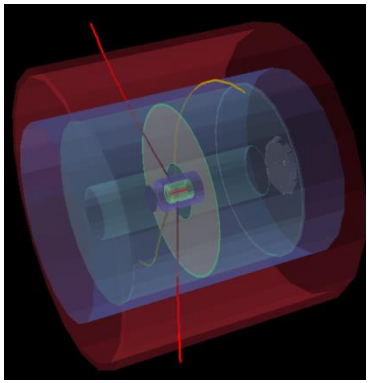
ALICE ultra-peripheral collisions: the LγHC

Accelerated lead-ions ➔ beam of quasi-real photons







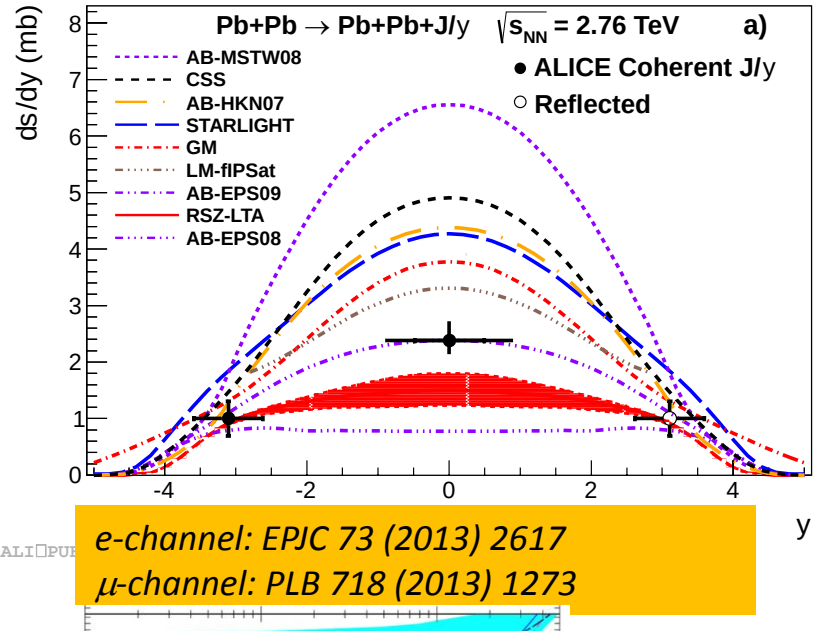


p/Pb-Pb data allow to study γPb, γp and γγ collisions at highest possible energies ever!

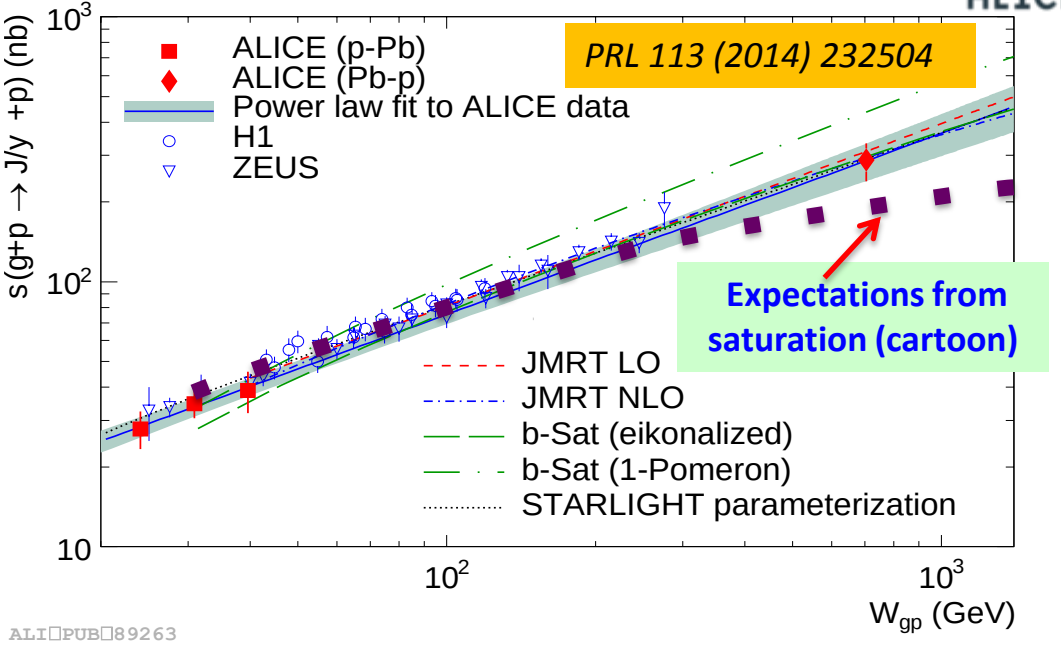
Exclusive vector meson photo-production off protons and off Pb-ions:

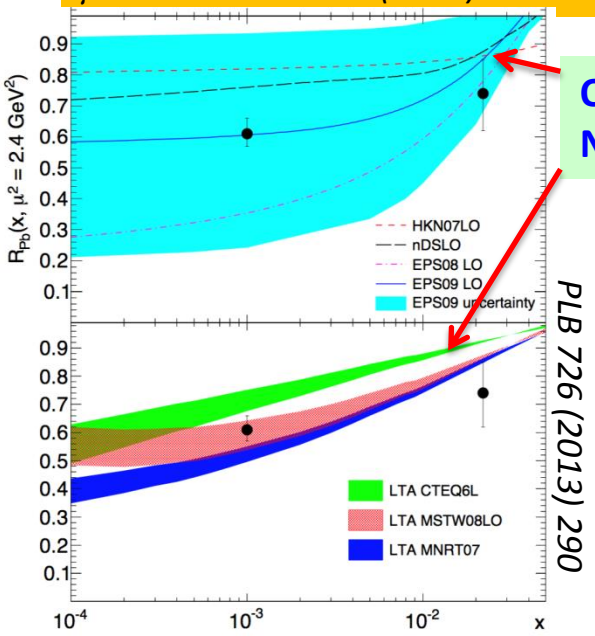
- vector meson used as a microscope
- kinematics completely determined
- detector contains only decay products of the vector meson
- crucial: a large coverage to veto the presence of another particles

Insights into shadowing and saturation



e-channel: EPJC 73 (2013) 2617
μ-channel: PLB 718 (2013) 1273





PLB 726 (2013) 290

Old
New

Shadowing:

- structure of nuclei is NOT a sum of nucleons
- origin and behavior with x and Q^2 at small x ?

ALICE UPC data: most precise measurement at small x, evidence of strong nuclear shadowing at $x \sim 10^{-3}$

Saturation:

- ALICE: a factor of 2 larger energy than HERA

Gluon distribution does not change behaviour from HERA to Run1 LHC energies

Organization of conferences, workshops, schools, collaboration meetings, outreach

Conferences: SPIN-Praha conference "Advanced Studies Institute on Symmetries and Spin" (yearly, Charles University)

Workshops: 4th International workshop on "High-p_T physics at LHC", 2009 (CTU, NPI)
"Jets in proton-proton and heavy-ion collisions", 2010 (CTU, NPI)

Schools: 25th Indian Summer School of Physics (NPI, Charles University, CTU)
"Understanding Hot and Dense QCD Matter"
2 weeks hands-on course "*Particle physics data analysis and simulations for ALICE and STAR experiments*"

Collaboration meetings organization:
ALICE: ALICE Physics week (March 2008)
STAR: STAR Collaboration meeting (May 2011)
new tradition: STAR Regional Collaboration meetings to strengthen collaboration within Europe together with WUT (Warsaw) and newly also FIAS (Frankfurt), 4 times
HADES: HADES Collaboration meeting (May 2013)

Outreach: CERN Master Classes, Excursions to CERN, Open Doors Days, talks for high-school students (driven by FNSPE CTU)

Very good and intense collaboration within experiments across participating Czech institutions.

Summary

Czech institutions contribute significantly and successfully to world leading heavy-ion experiments (ALICE, ATLAS-HI, STAR, PHENIX, HADES/CBM)

- since the RECFA visit in 2007 the involvement of Czech teams increased significantly (by a factor of ~3)
- leadership in collaboration structures (ALICE, STAR, HADES)
- large participation of young scientists and students
- active participation in data taking, data analyses and paper preparation
- presentations of physics results and invited talks at major international conferences

Clear path toward Czech participation in future heavy-ion experiments:

participation in the upgrades at BNL, CERN and GSI
eSTAR and sPHENIX at eRHIC at BNL
CBM at FAIR@GSI

Concerns:

- sustainability of current intensive involvement and growth of excellent research due to uncertain level and stability of future funding
- not enough attractive job positions and financial resources to keep students and young and talented physicists motivated to conduct research in the Czech Republic and to attract excellent foreign students and scientists from abroad