Nuclear Physics – Present and Future
a selection of (my own) highlights

- introductory remarks: physics in the strongly coupled limit
- news on the nucleon
- news on nuclear structure
- news on nuclear astrophysics and neutron stars
- news on hot and dense matter

pbm

INPC2010, Vancouver, July 5, 2010

FIAS Frankfurt Institute for Advanced Studies

a new paradigm: strongly coupled systems

strongly coupled systems arise when the scattering cross section becomes very large

the viscosity/entropy density ratio η/s of such matter is then 'universal', i.e. independent of its detailed structure

from purely dimensional considerations

$$\frac{F}{A} = \eta \frac{v}{d} \quad \rightarrow \quad \eta \quad \text{has dimensions of kg/(m s)}$$

the entropy density s has dimension $1/m^3$ ($k_B = 1$)

$\rightarrow$ η/s has dimension kg m^2 s^{-1}, i.e. the dimension of $\hbar$

a new paradigm: strongly coupled systems

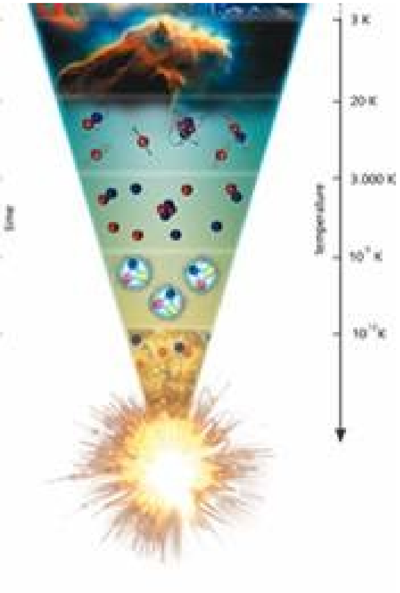
in strongly coupled systems, η/s is close to $\frac{\eta}{s} = \frac{\hbar}{4\pi}$
(Policastro, Son, Starinets, PRL 87 (2001) 081601)

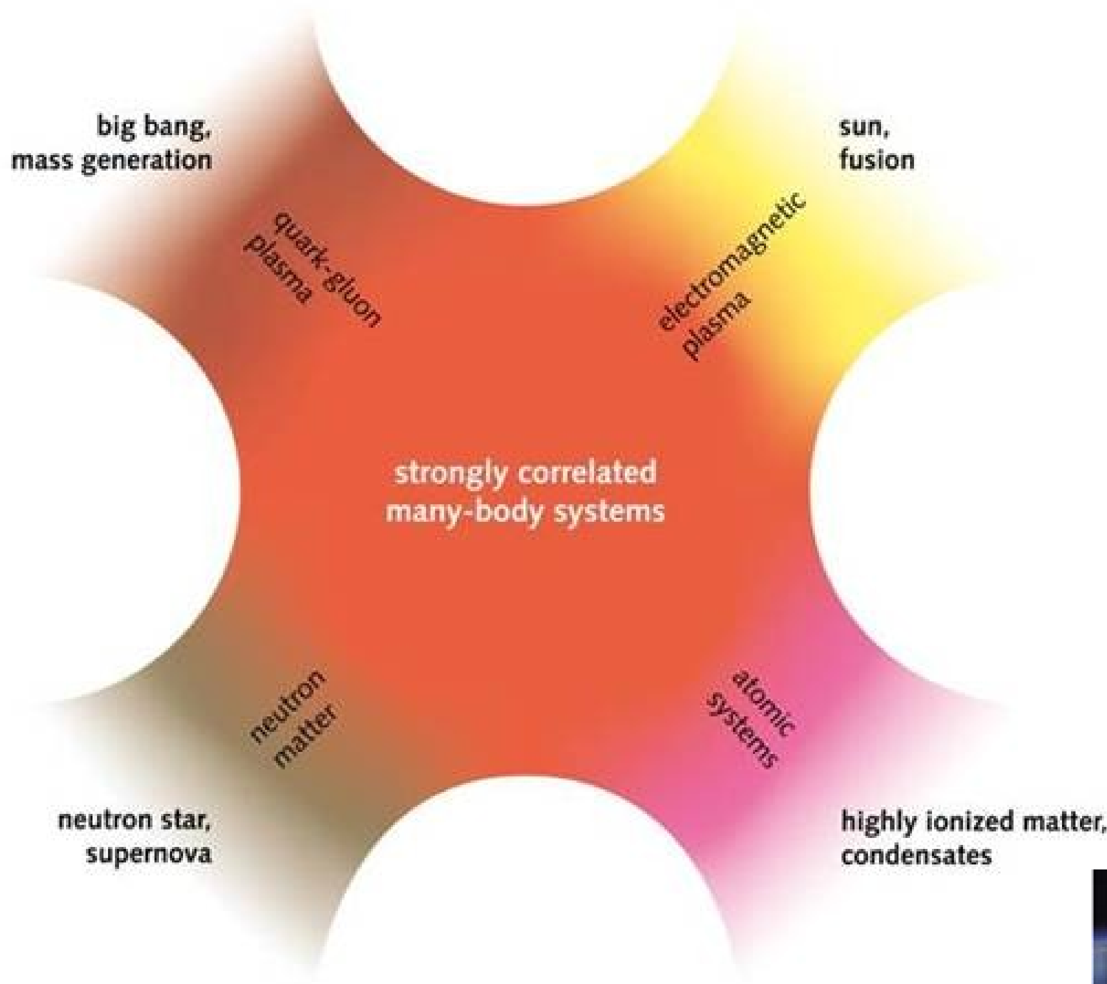
in weakly coupled systems, η/s is large and diverges for an ideal gas

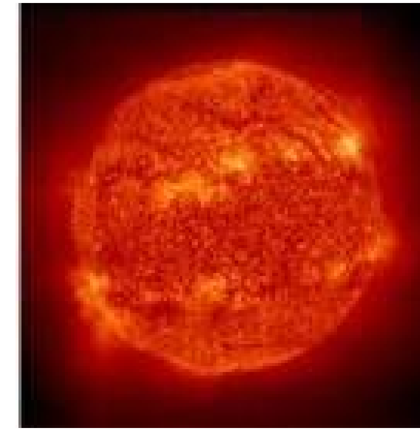
in the dilute limit, $\frac{\eta}{s} \sim \epsilon\tau >> 1$

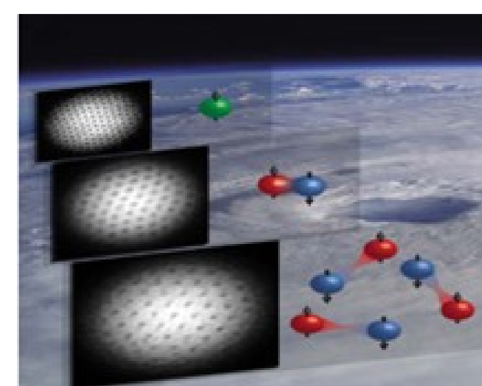
with ϵ : mean energy/particle
and τ : mean time between collisions

strongly coupled systems in nuclear physics and related areas





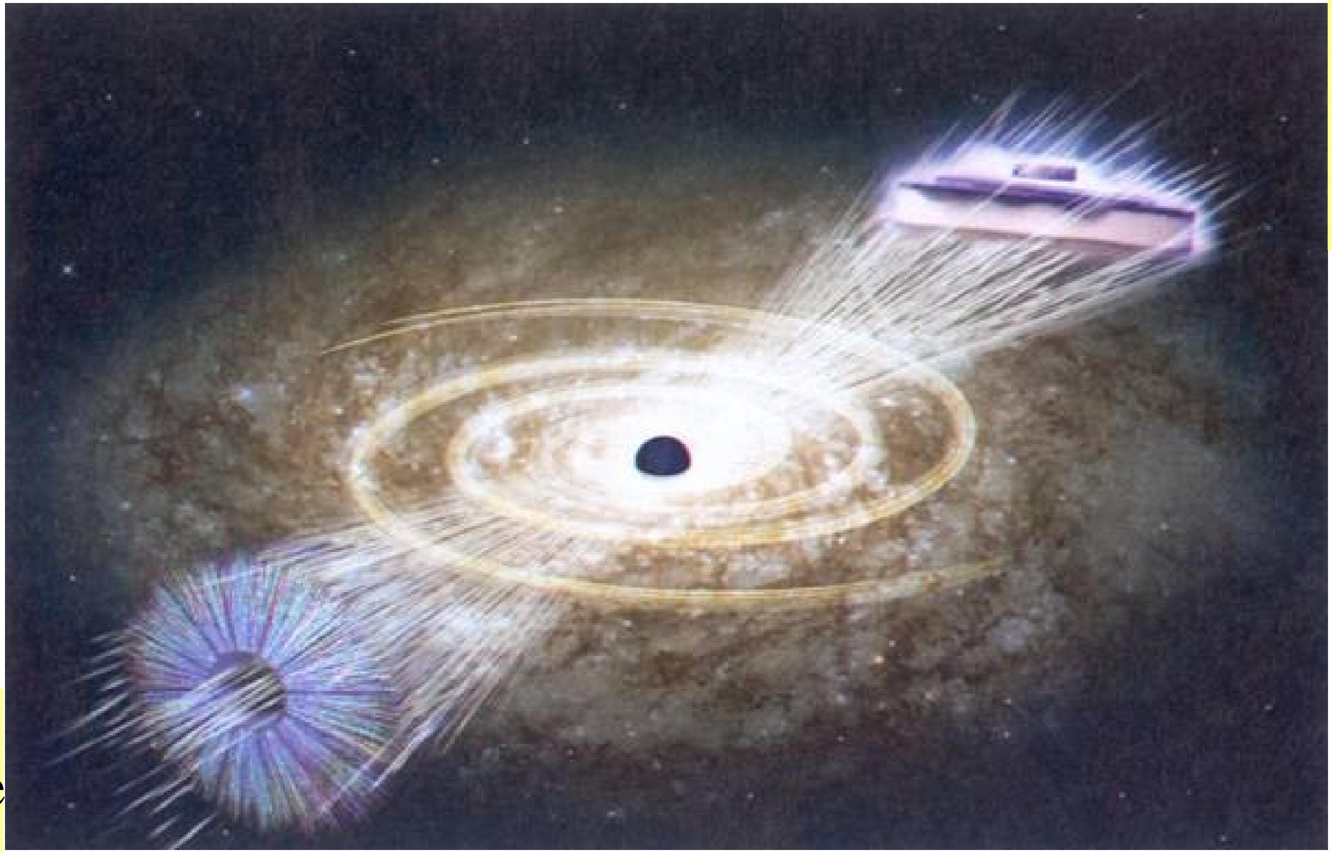




Black holes, strings, QGP and high-T_c superconductors

Nature 448 Aug. 29 (2007) 1001

Nernst effect in 2-d cuprates high T_c super-conductivity

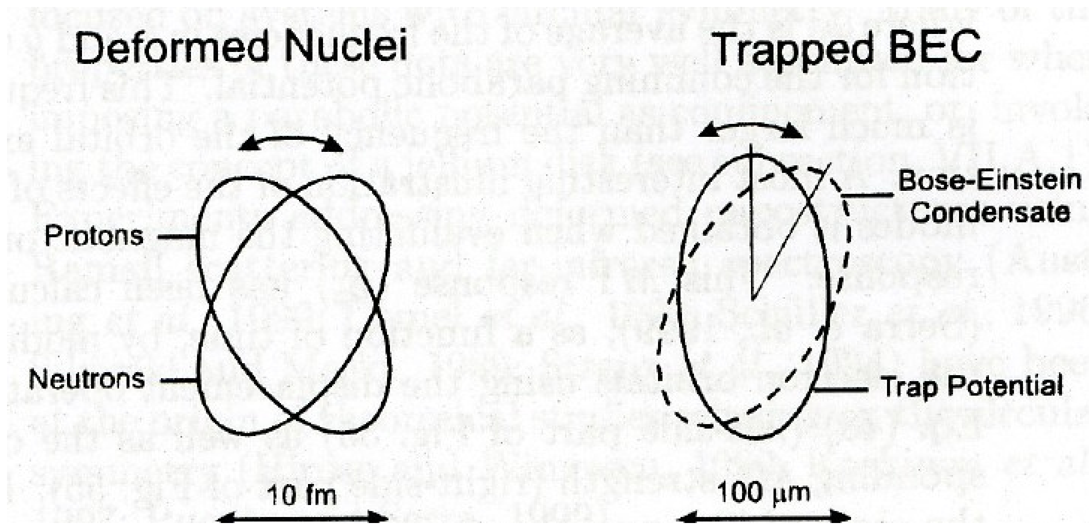


viscosity in the quark-gluon plasma (QGP)

AdS/CFT correspondence

collective vibrations in nuclei and trapped BEC's

the scissors mode

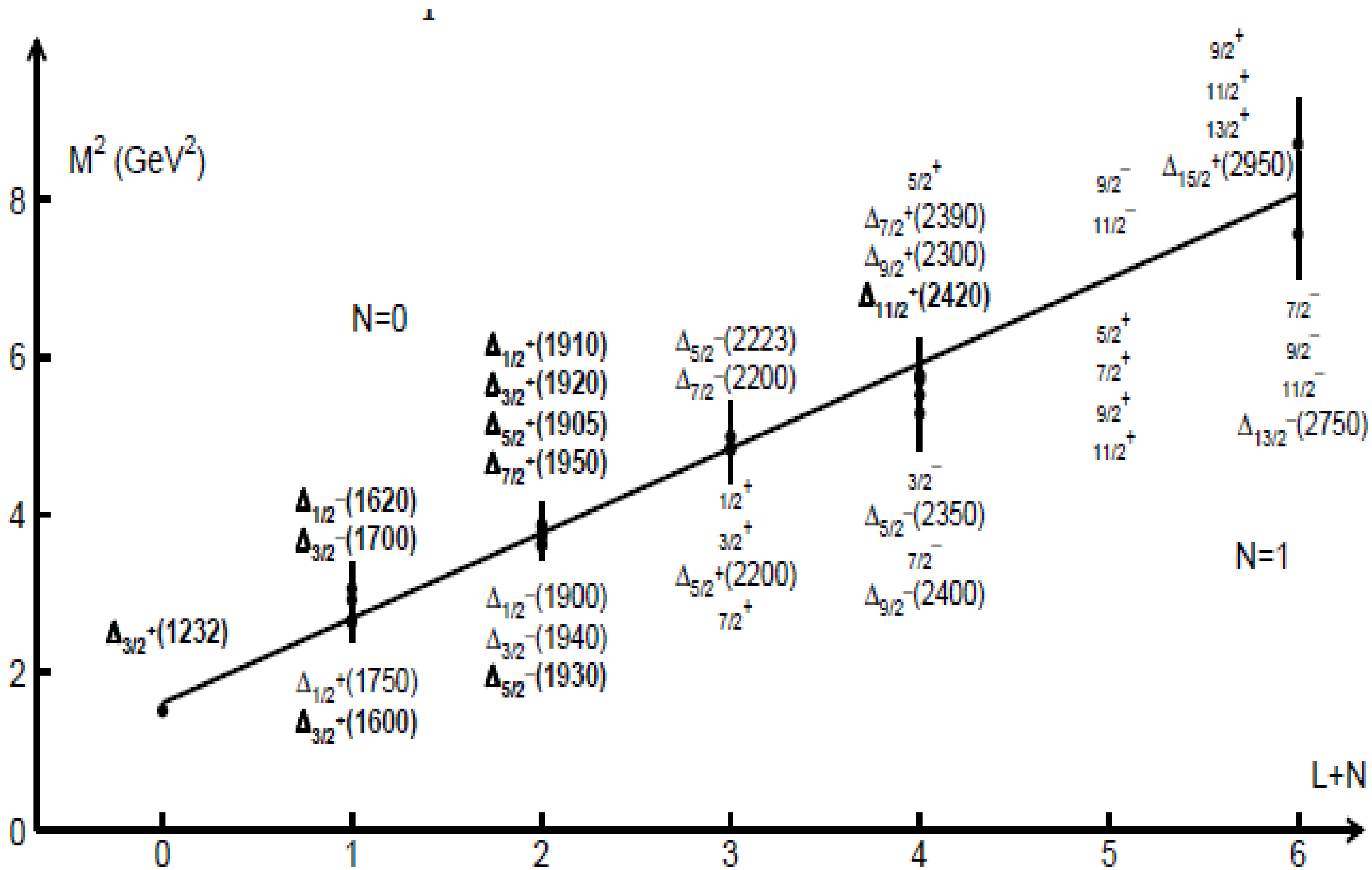


K. Heyde, P. Von Neumann-Cosel, A. Richter
Rev. Mod. Phys. (in print, 2010)

the AdS/CFT (QCD) correspondence on the baryon mass spectrum

Is the mass vs orbital angular mom. L relation suggested with AdS/QCD visible in the baryon spectrum?

E. Klempt, arXiv:1001.3290 [hep-ph]



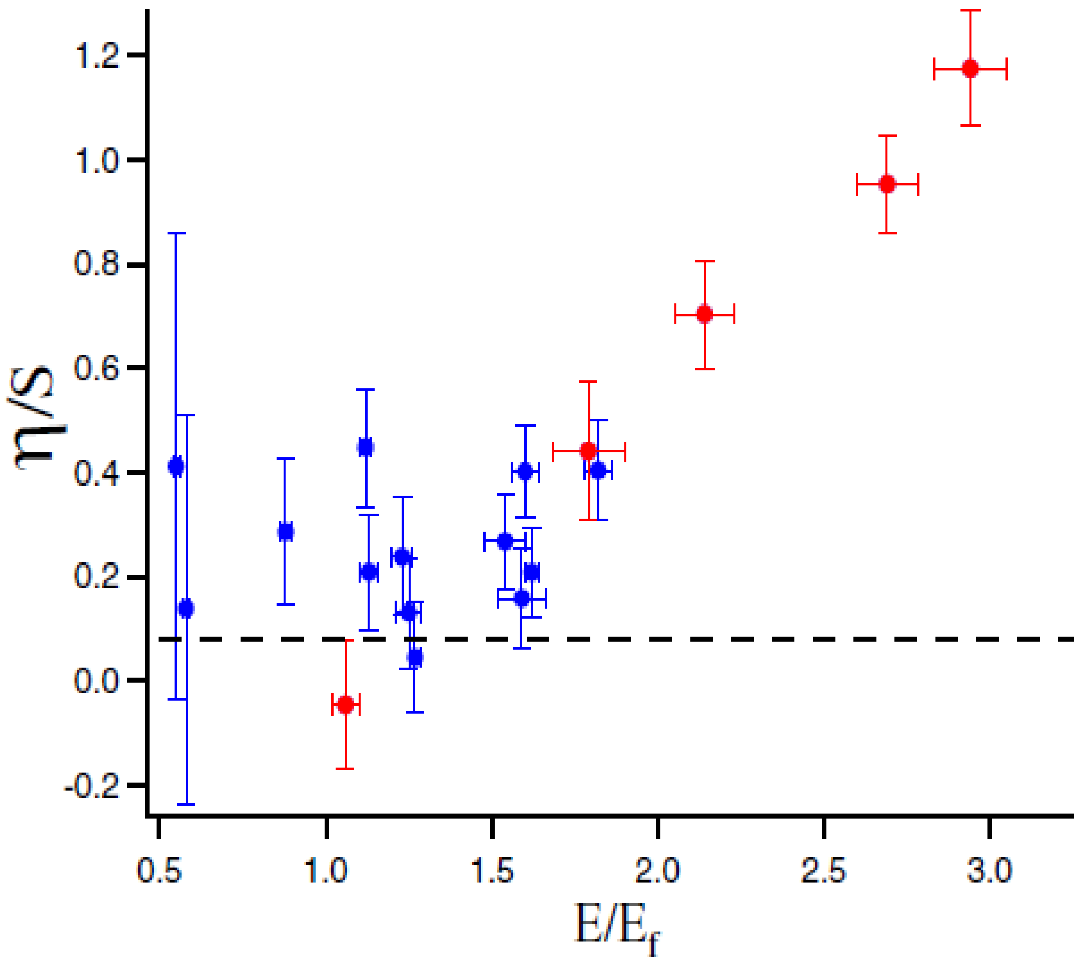
$$\mathbf{M^2 = a \cdot (L + N + 3/2) - b \cdot \alpha_D} \left[\mathrm{GeV^2}\right]$$

$a = 1.04\, GeV^2$ and $b = 1.46\, GeV^2$.

an ultracold interacting Fermi gas as a (nearly) perfect fluid

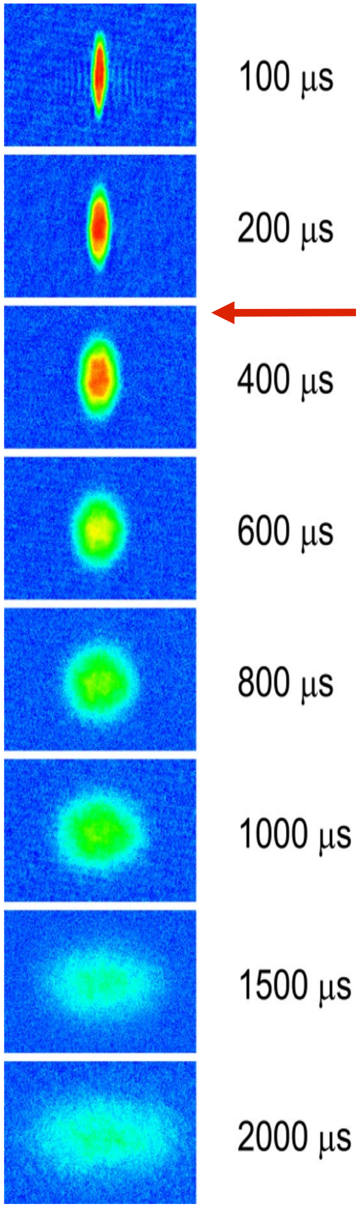
T(^{6}Li) = 200 nK

n.b.: it is not the superfluid phase which behaves as an ideal fluid!



John E. Thomas, Nucl. Phys. A380 (2009) 665c
Physics Today, May 2010

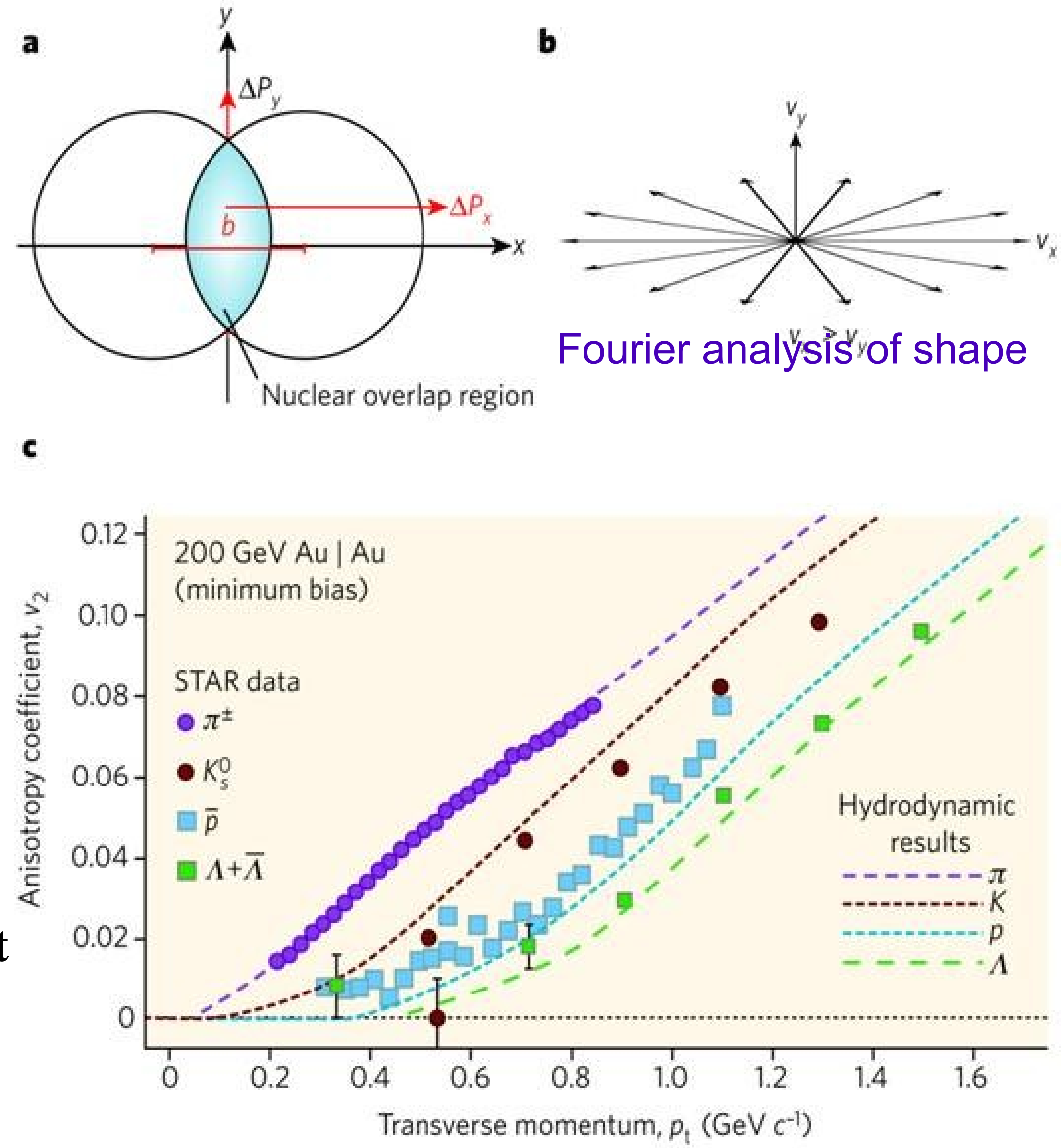
QGP and ultra-cold quantum gases



ultra-cold ^{6}Li
< 100 nK
~10^{-12} eV

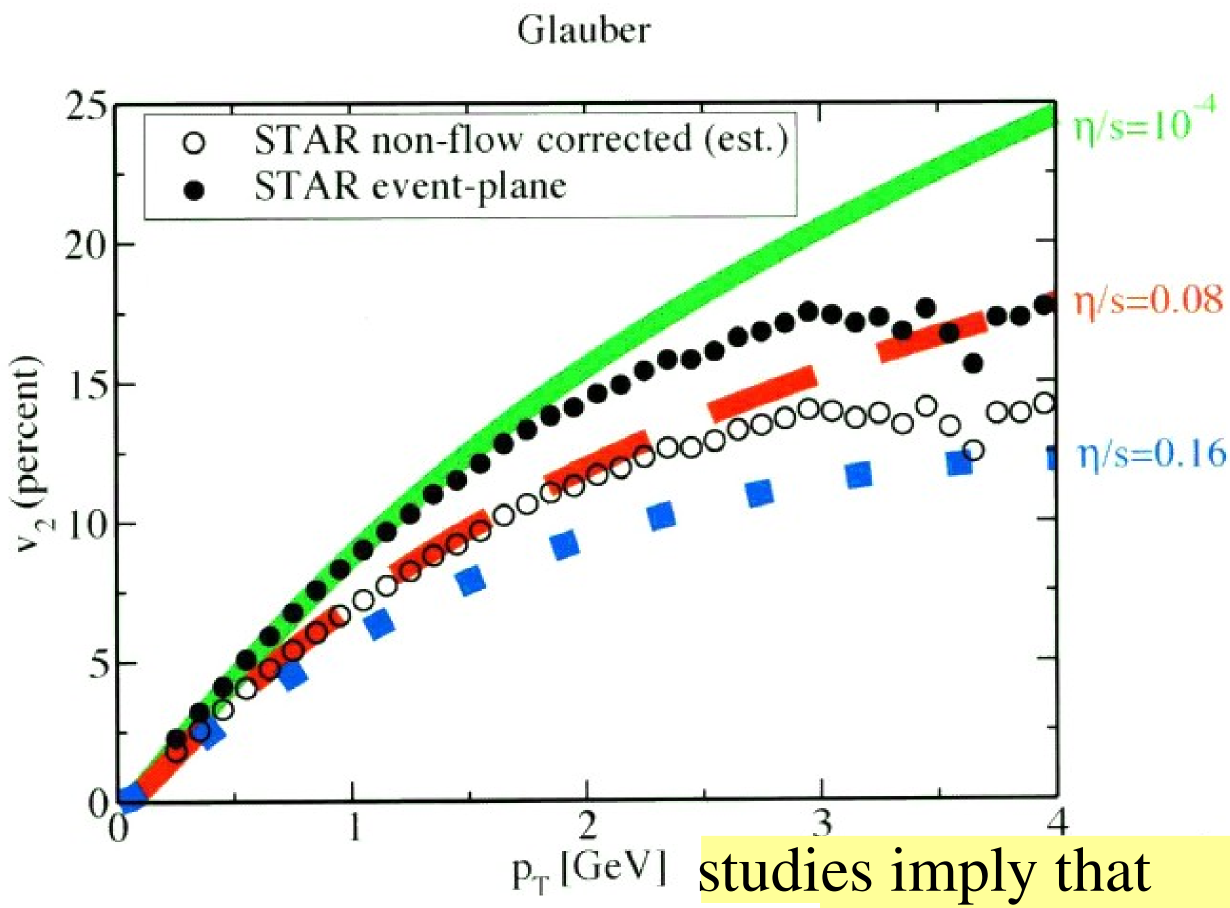
QGP
2.1 TK
~10^{8} eV

collective expansion at strong coupling



Fourier analysis of shape

the QGP as a nearly perfect fluid



studies imply that
η/s > (3×AdS/CFT limit)
not compatible with data

Luzum & Romatschke, PRC 78 (2008) 034915

Note: viscosity of QGP is 25 orders of magnitude larger than that of ultra-cold Li it is η/s that counts!

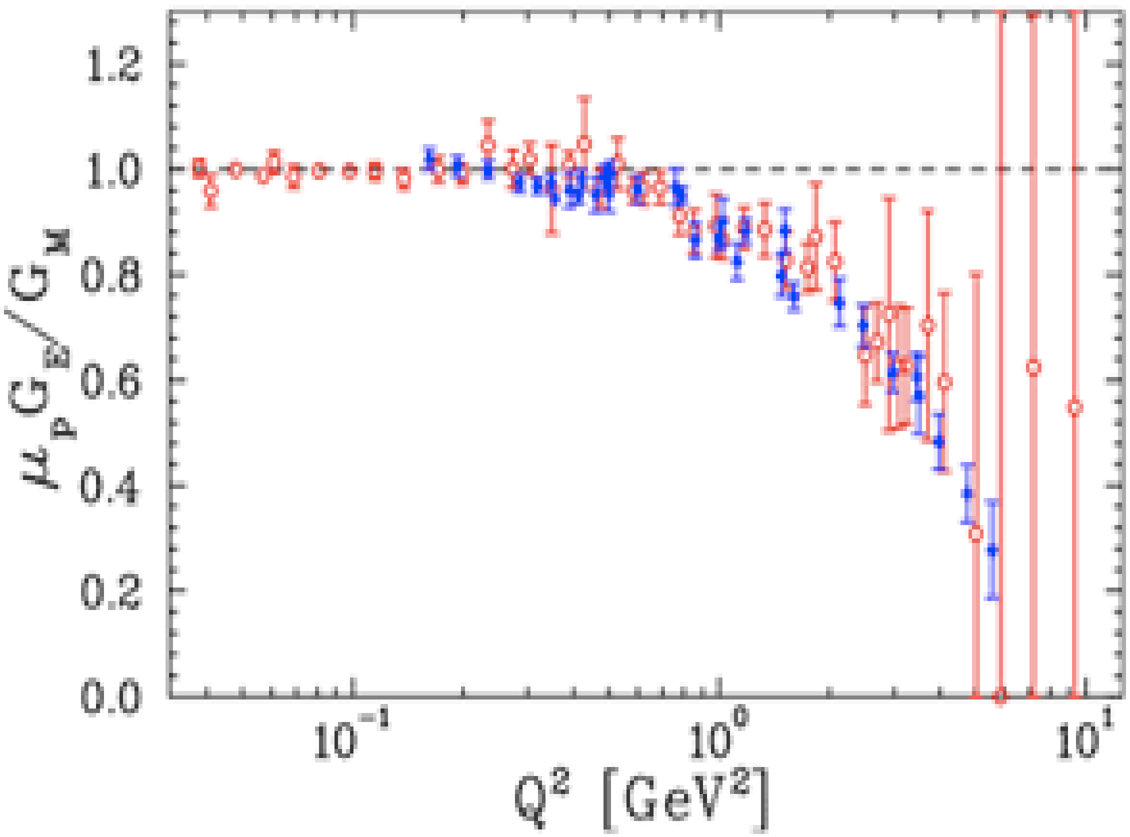
nucleon structure

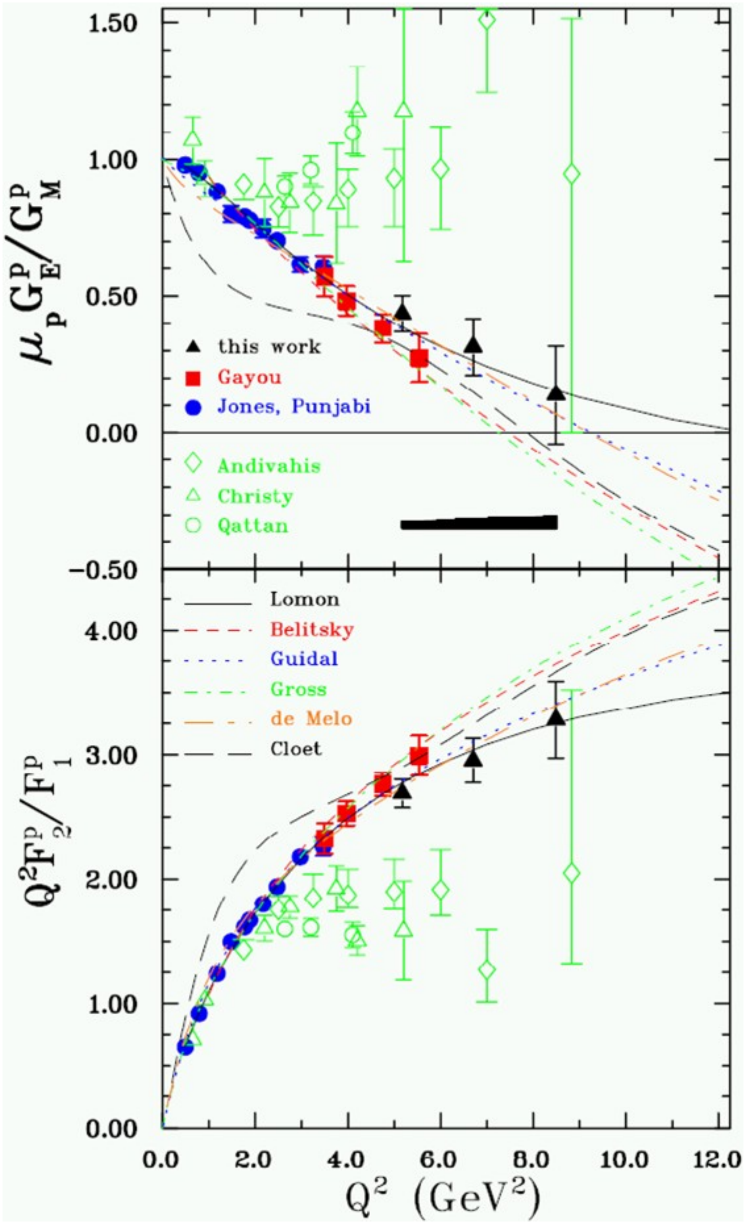
recent progress from Bates, MAMI, and JLab
also Hermes and Compass experiments (spin structure)

focus here on the distribution of charge and magnetization within the nucleon

recent review: Perdrisat, Punjabi, Vanderhaeghen, hep-ph/0612014

electric/magnetic formfactor of the proton

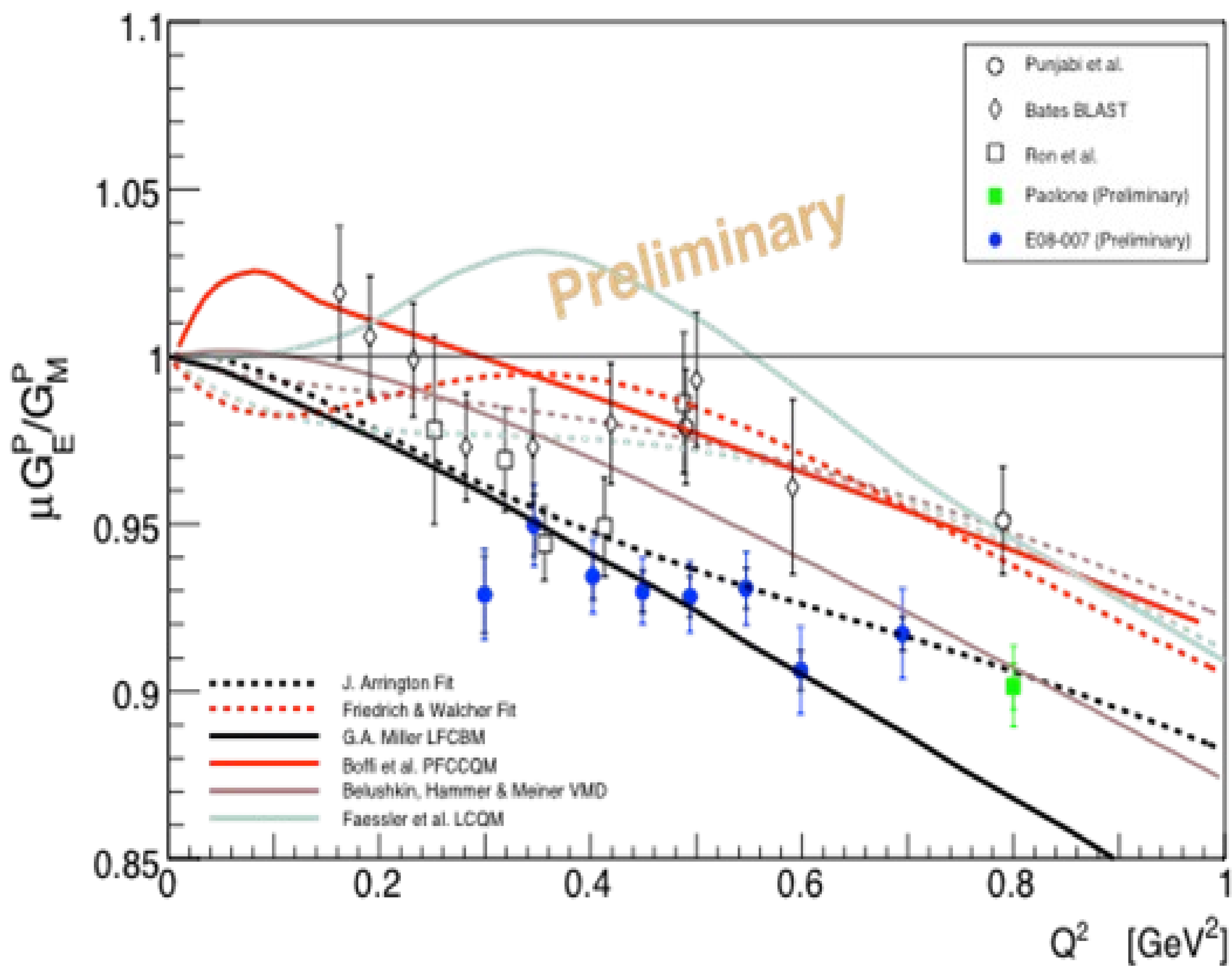




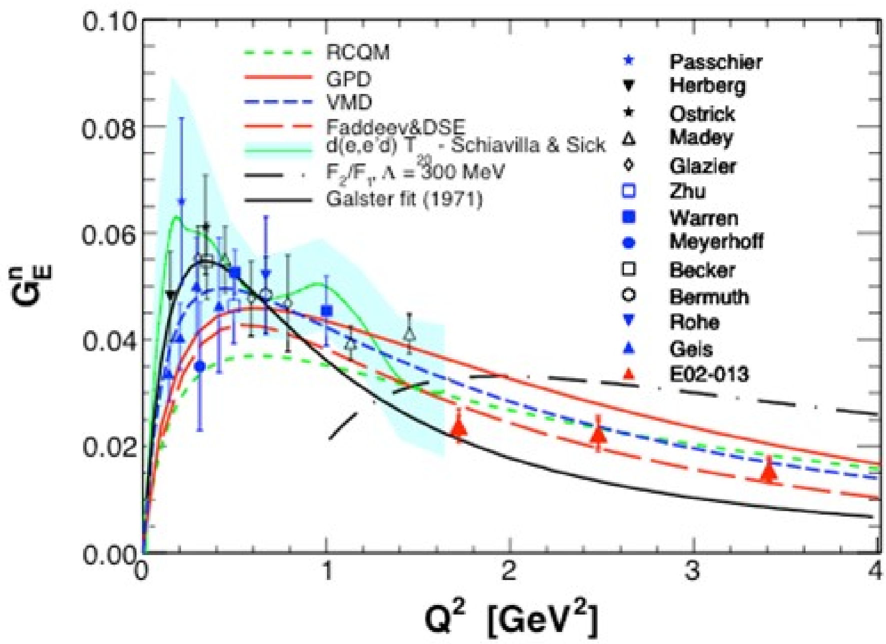
measurements from JLab reconcile Rosenbluth and recoil polarization measurement

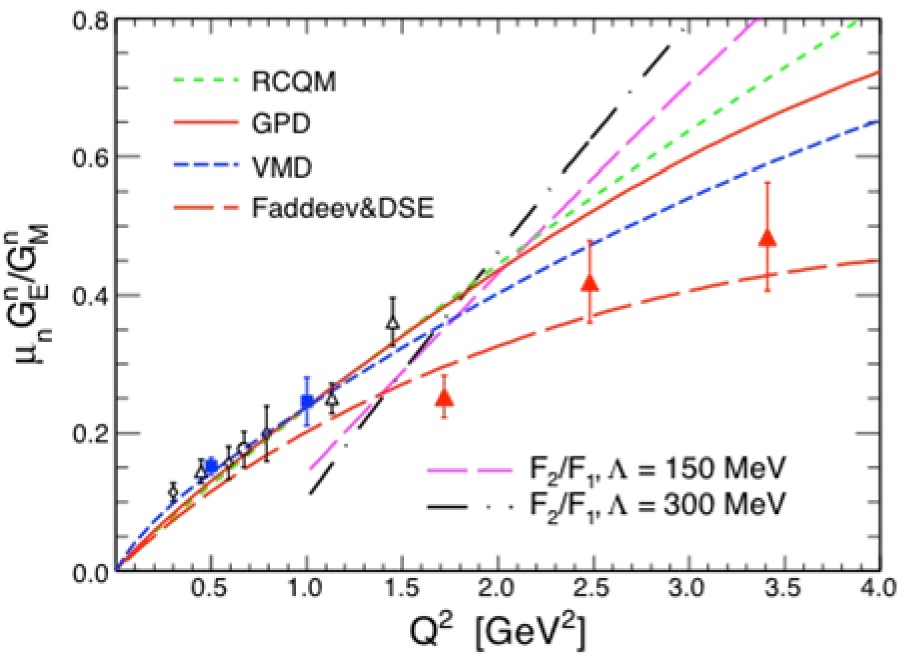
electric charge and magnetization are distributed very differently in the proton

the form factor ratio at low Q^2



structure of the neutron





electric formfactor of the neutron now well measured up to $Q^2 = 4$ GeV^2

nucleon form factors

nucleon form factors are now experimentally well established

– main advances through the recoil polarization technique first suggested by Akhiezer and Regalo

A. I. Akhiezer and M. P. Rekalo, Sov. Phys. Dokl. **13**, 572 (1968) [Dokl. Akad. Nauk Ser. Fiz. **180**, 1081 (1968)].

A. I. Akhiezer and M. P. Rekalo, Sov. J. Part. Nucl. **4**, 277 (1974) [Fiz. Elem. Chast. Atom. Yadra **4**, 662 (1973)].

– up to $Q^2 = 6$ GeV^2
not in pQCD regime

– dipole scaling $G_{Ep} \sim G_{Mp}/\mu_p \sim G_D$ valid only in low Q^2 regime

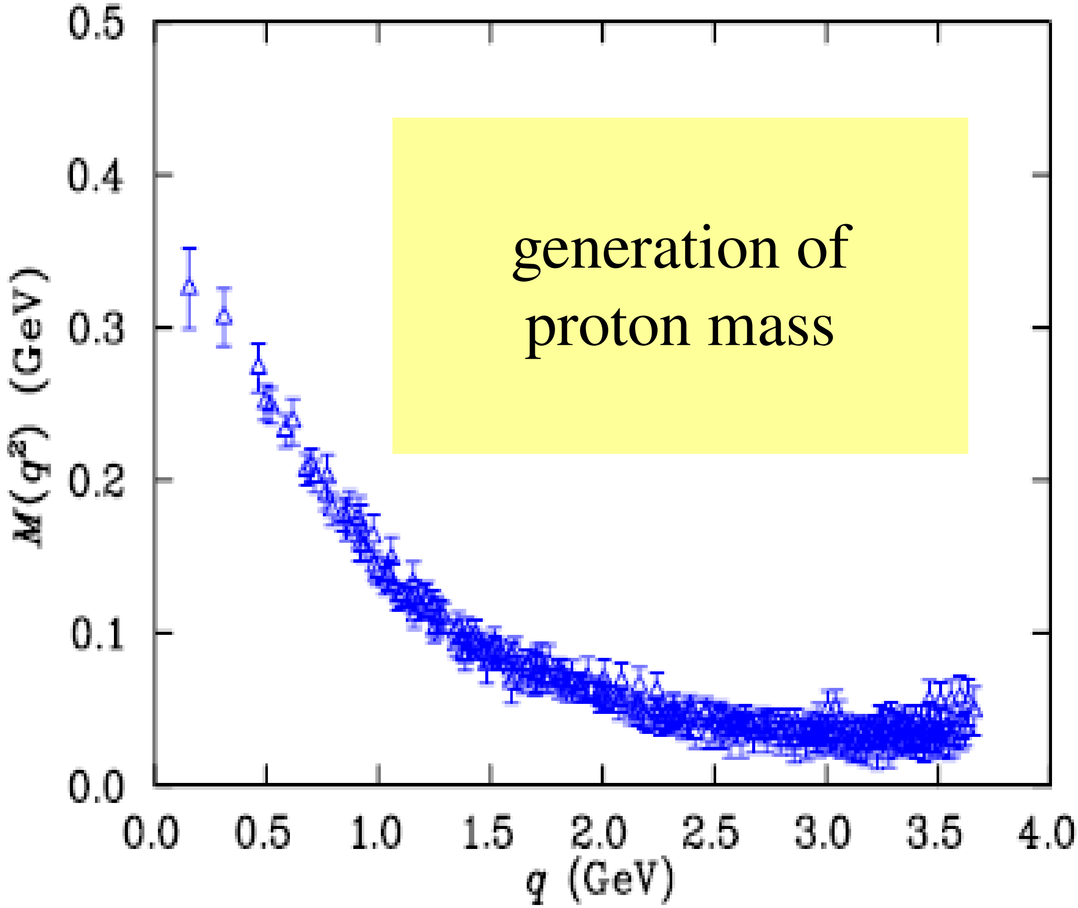
– phenomenological models (mainly based on vector dominance) are quite successful in describing the data but:

a detailed understanding based on QCD is still outstanding (LQCD, data at large Q^2)

constituent vs current quarks

the dressing of the current quarks is now well understood

will it depend on the surrounding baryon structure?



generation of proton mass

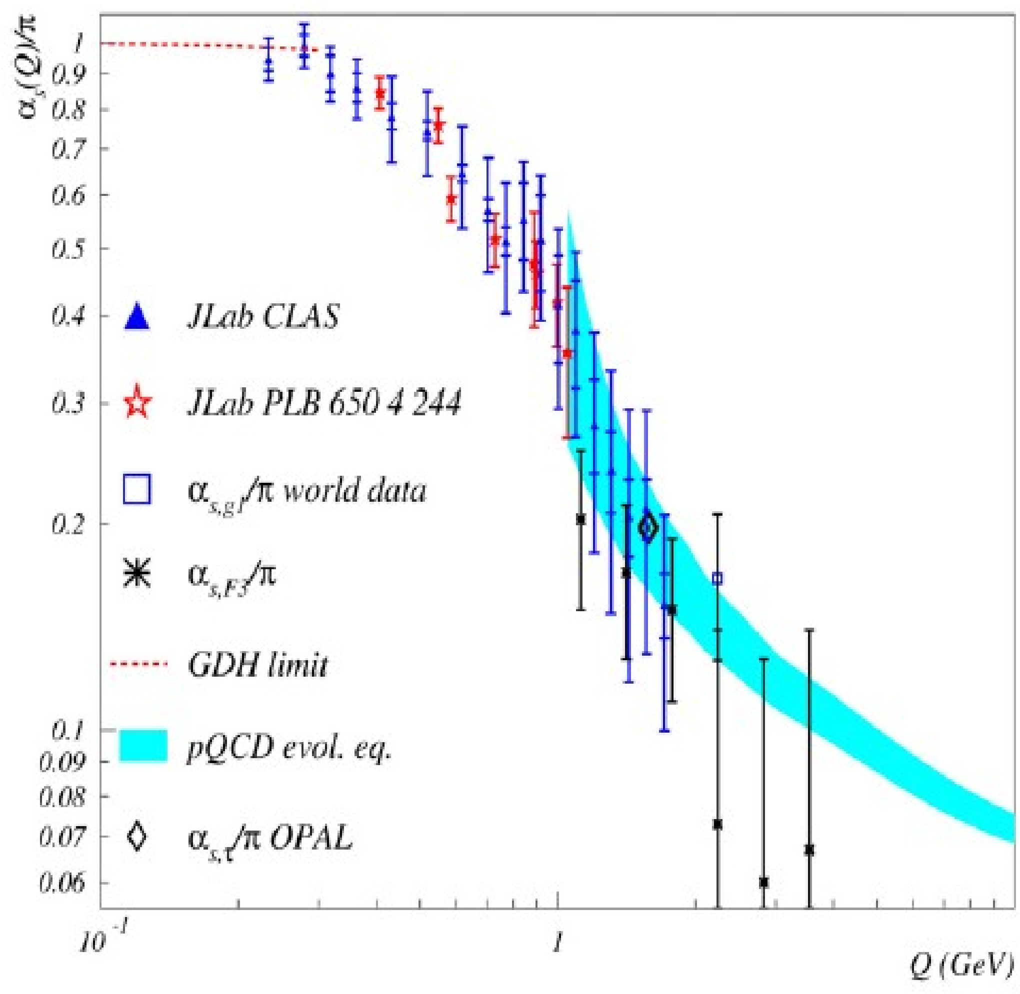
the quark mass from unquenched lattice QCD

P.O. Bowman et al., Phys. Rev. D71 (2005) 054507

the QCD strong coupling constant from sum rules and spin structure function data

new data from CLAS@JLab give first evidence for leveling off at low Q^2

Deur et al., Phys. Lett. B665 (2008) 349



is QCD in the non-perturbative region a conformal field theory?

exotic mesons?

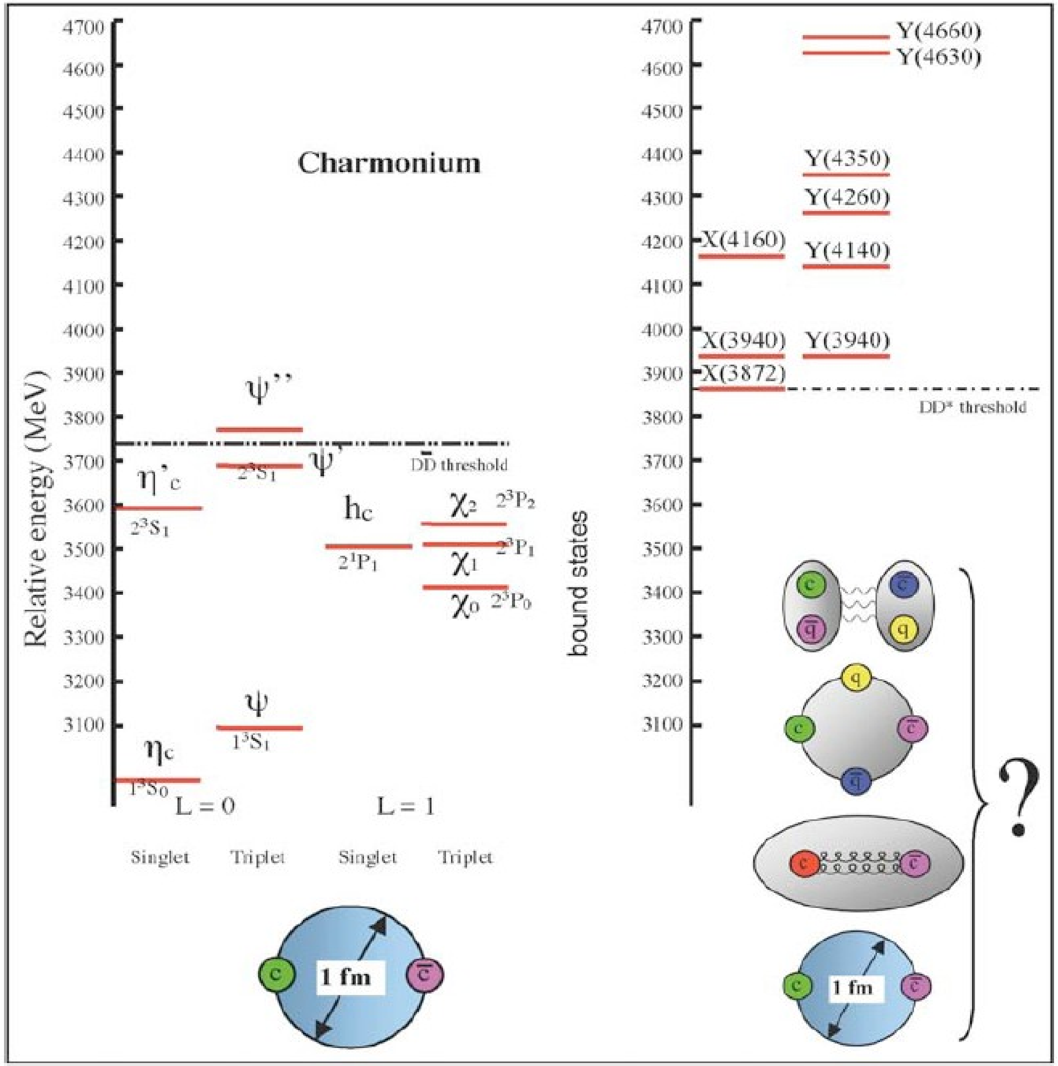


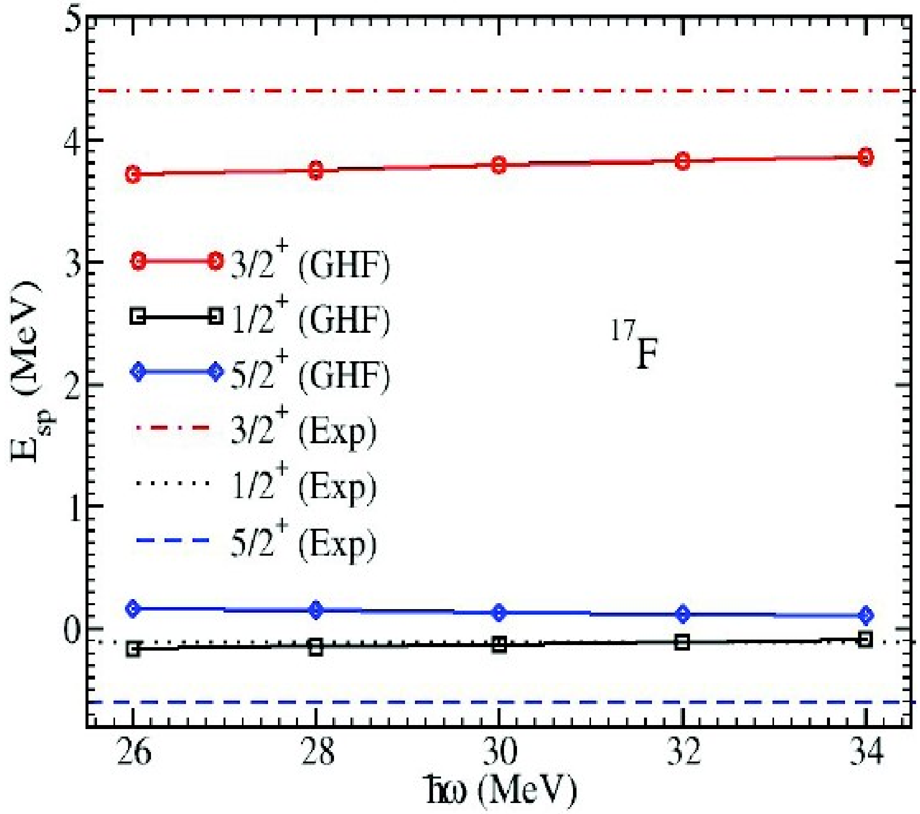
Fig. NUPECC LRP2010

are the X Y Z states discovered by BABAR, BELLE, and CESR multi-quark states, or meson molecules, or …   PANDA territory

nuclear structure
progress in theory

ab initio calculation in the coupled cluster approach of the low-lying levels and the proton halo state in ^{17}F

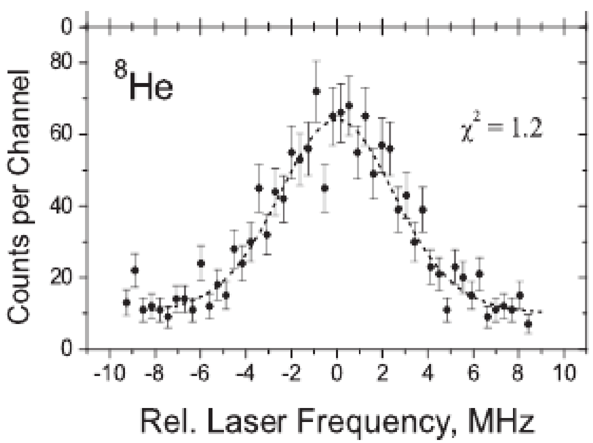
the separation energy of 105 keV is well reproduced



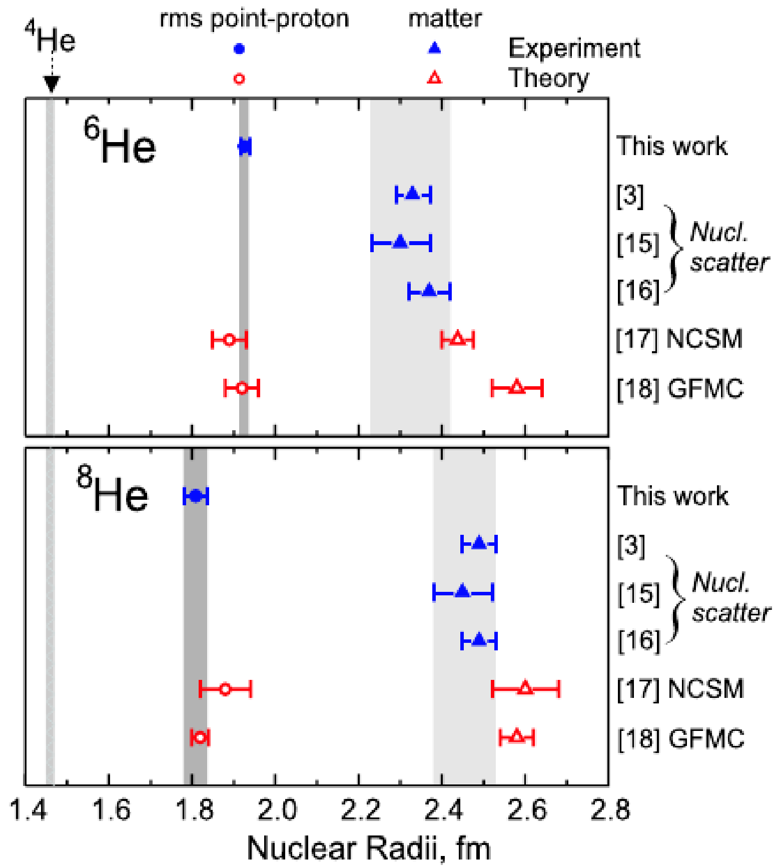
UNEDF SciDAC Collaboration
Universal Nuclear Energy Density Functional

nuclear charge radius of ^{8}He – the most neutron-rich of all particle-stable nuclei

Peter Mueller et al., PRL 99 (2007) 252501
laser spectroscopy of individual atoms laser cooled and stored in a magneto-optical trap (method developed at ATLAS/Argonne, measurements: GANIL)



precise measurement of the isotope shift of 2^3S_1 -> 3 $^3P_2$ transition -> root-mean-square nuclear charge radii



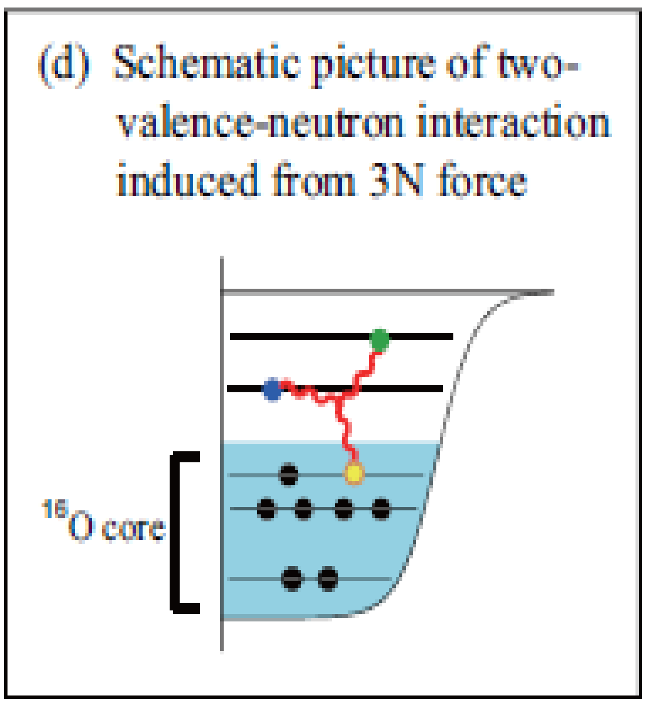
significant **shrinking** of **charge radius** between ^{8}He and ^{6}He while **matter radius** is **growing**
cm motion of s-state protons rel to neutrons ->
sensitivity to neutron correlations
- more spherical as reproduced by *ab initio* calculations*

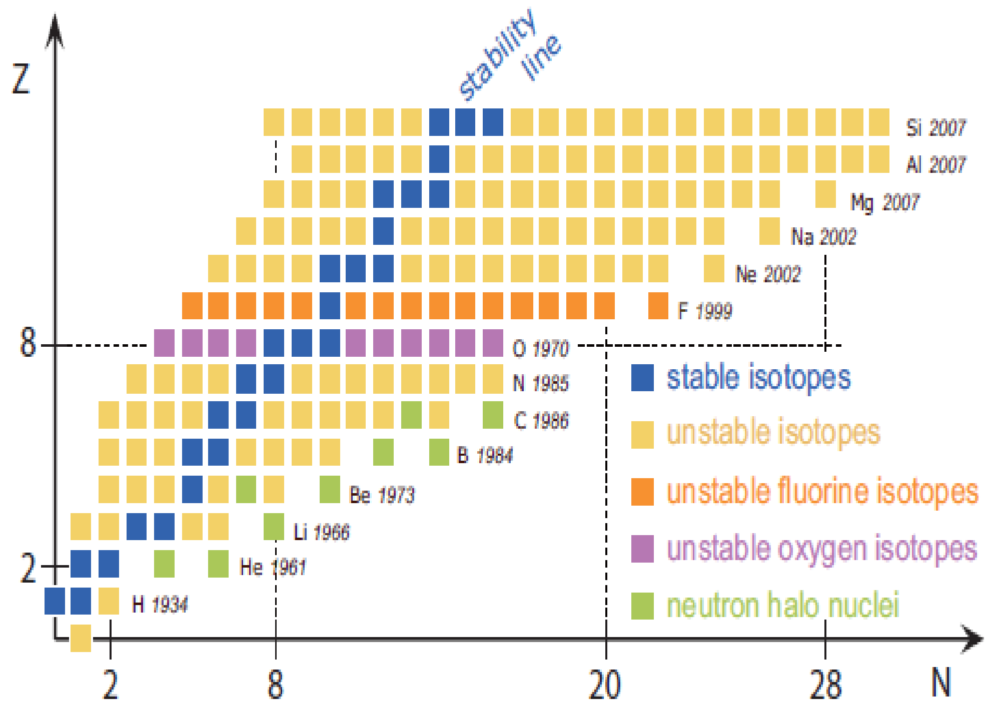
*: S. Pieper et al and Caurier/Navratil

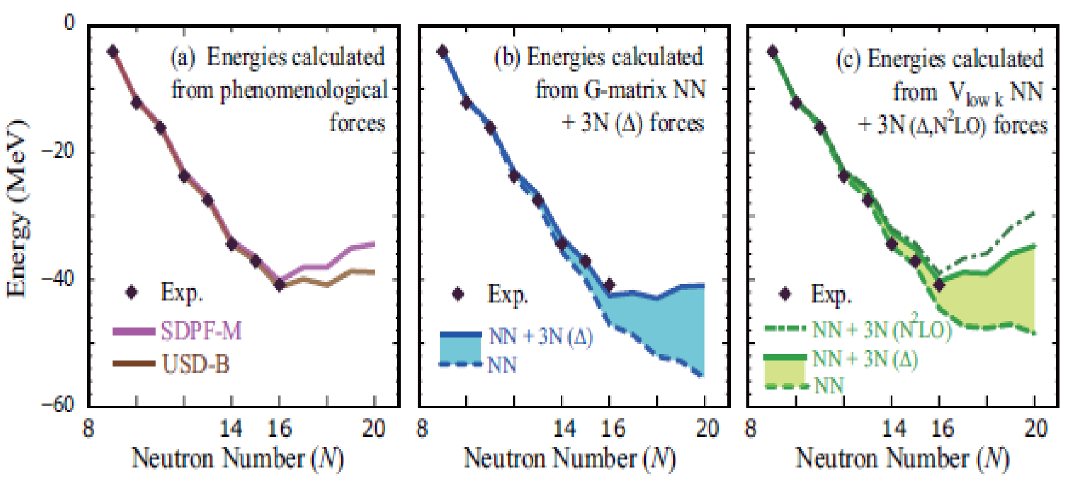
nuclear structure
3-body forces and the neutron drip line in O isotopes

The drip line at ^{24}O is shifted from ^{28}O due to 3-body forces

T. Otsuka et al., arXiv:0908.2607 [nucl-ex]



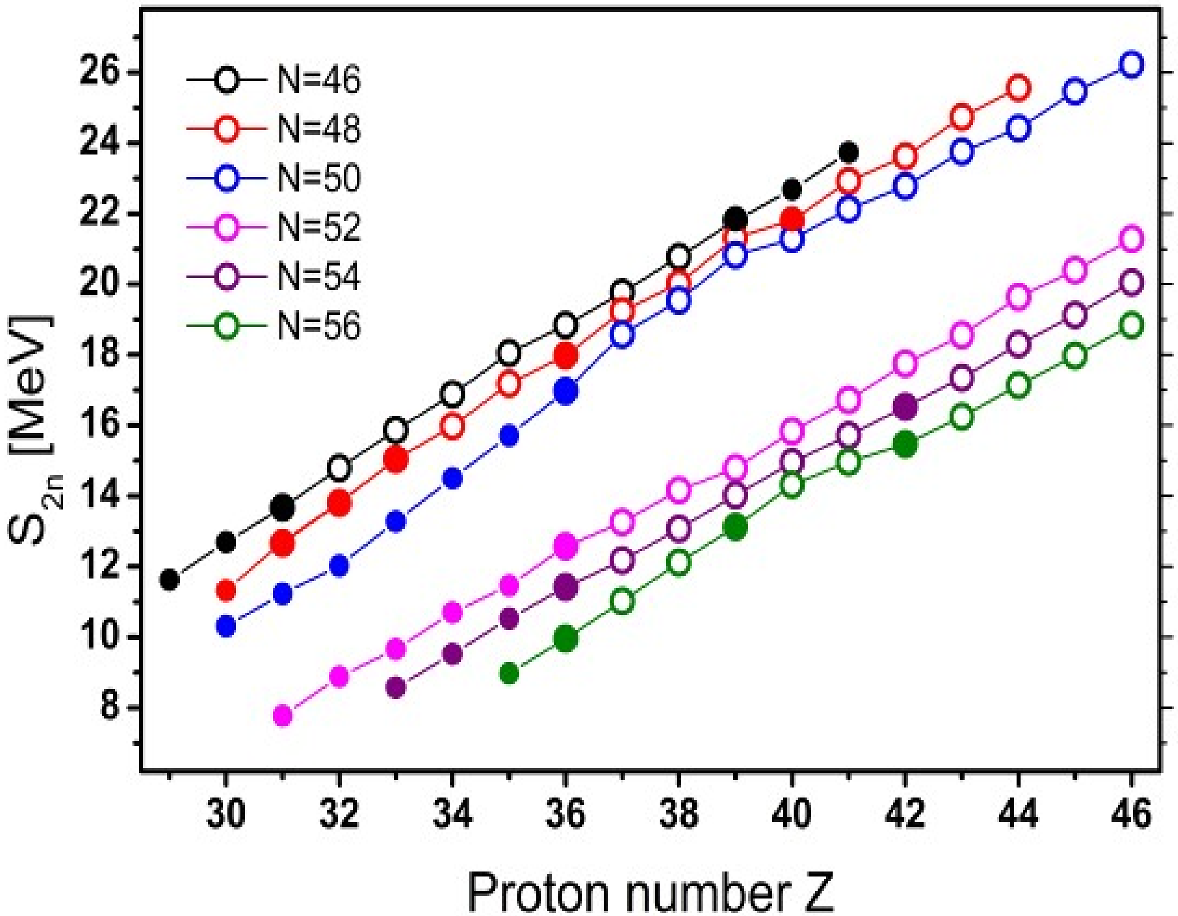




stability of N=50 shell gap

arXiv:0806.4489 [nucl-ex] Hakala et al., Jyvaskyla

precise mass measurements for a large number of nuclei show clearly that the N = 50 shell gap survives away from the valley of stability

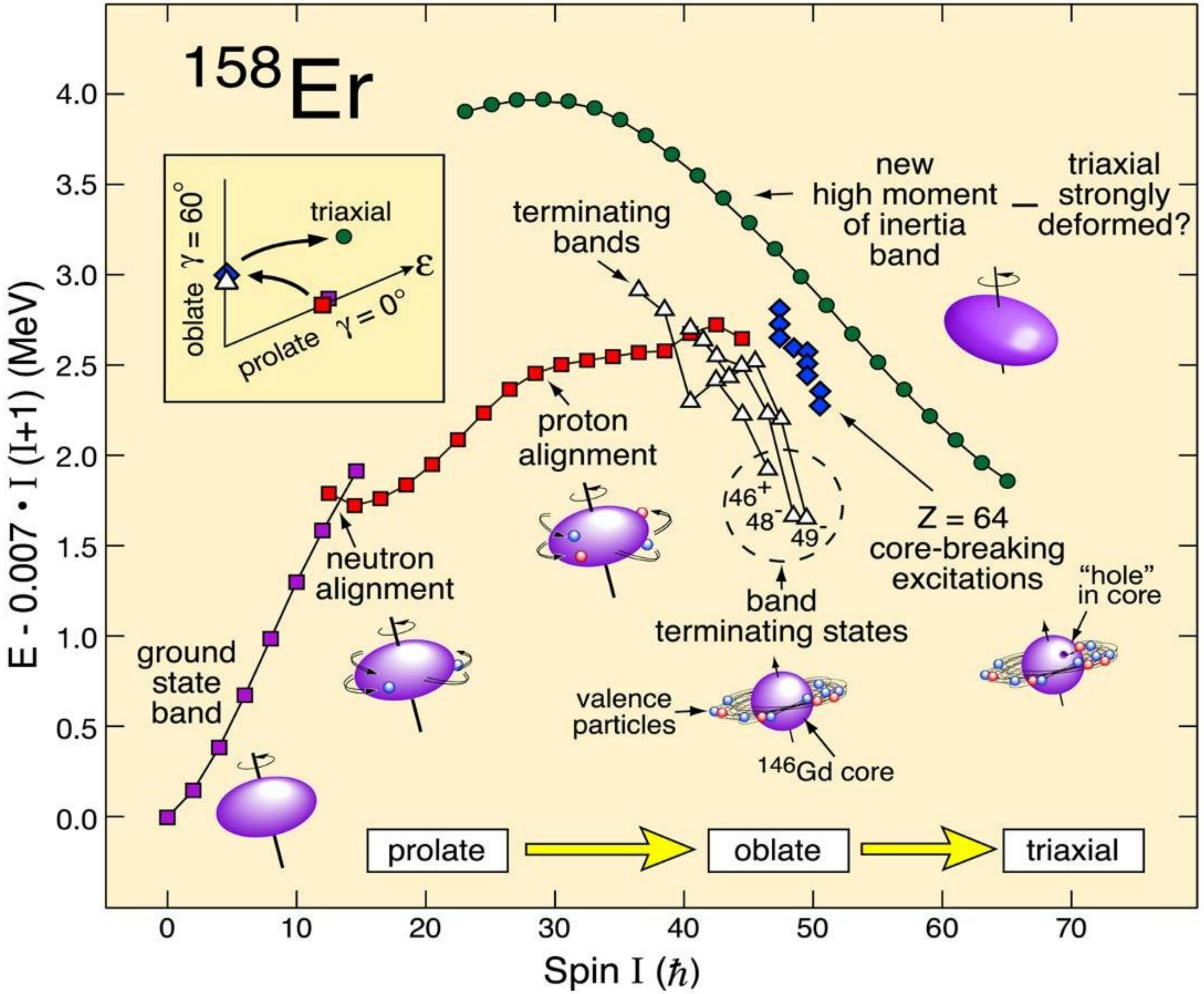


data from JYFLTRAP@IGISOL

nuclear structure at high spin

fig. courtesy Rauno Julin

impressive results from the various high-sensitivity gamma-ray spectrometers

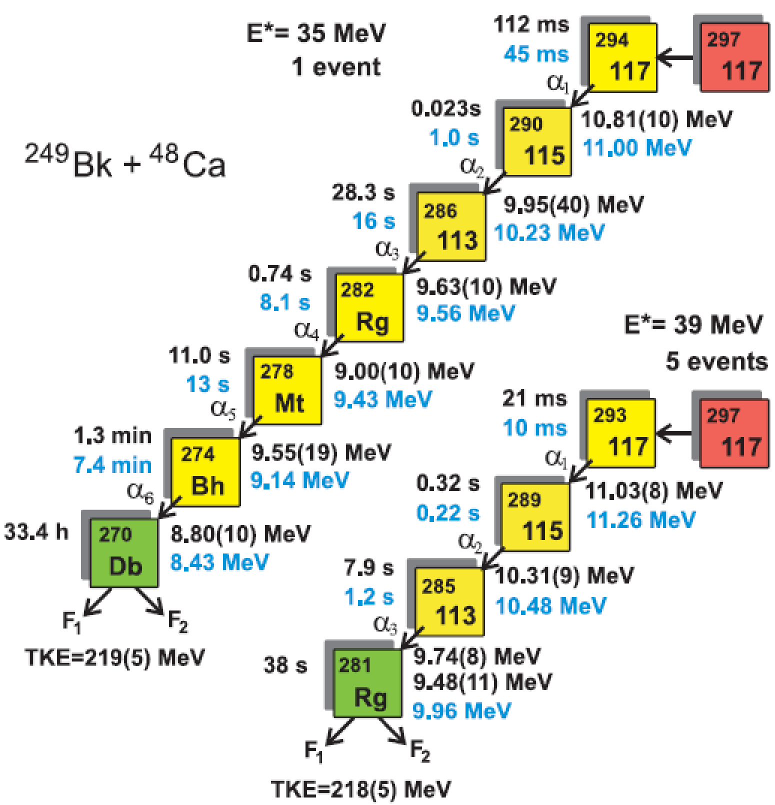


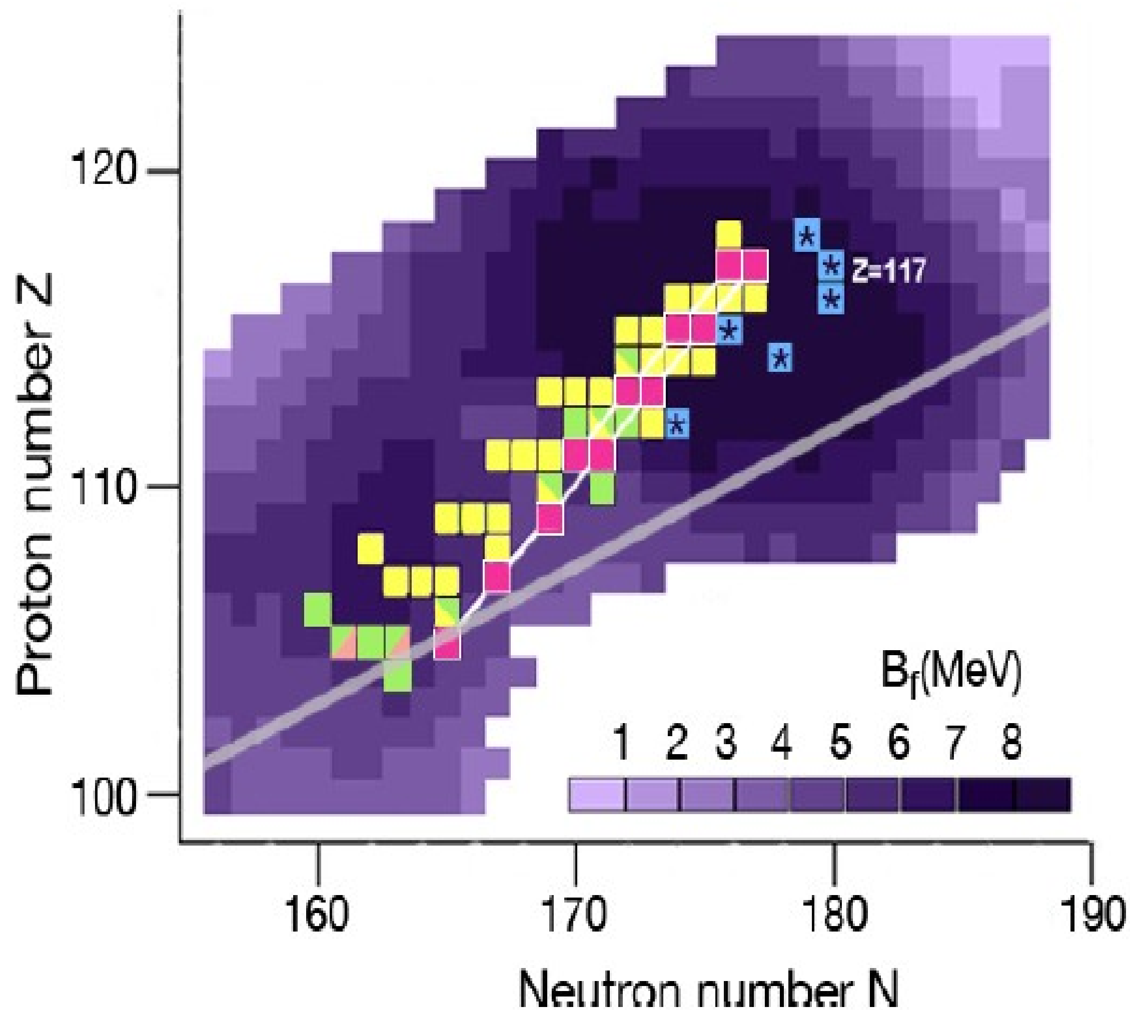
how to spin a nucleus and its microscopic mechanisms is now well understood – collective rotation returns at very high spin

superheavy nuclei

Y. T. Oganessian *et al.*, *Phys. Rev. Lett.* **104**, 142502 (2010)

2 isotopes of element 117 have been found at Dubna in ^{48}Ca + ^{249}Bk collisions

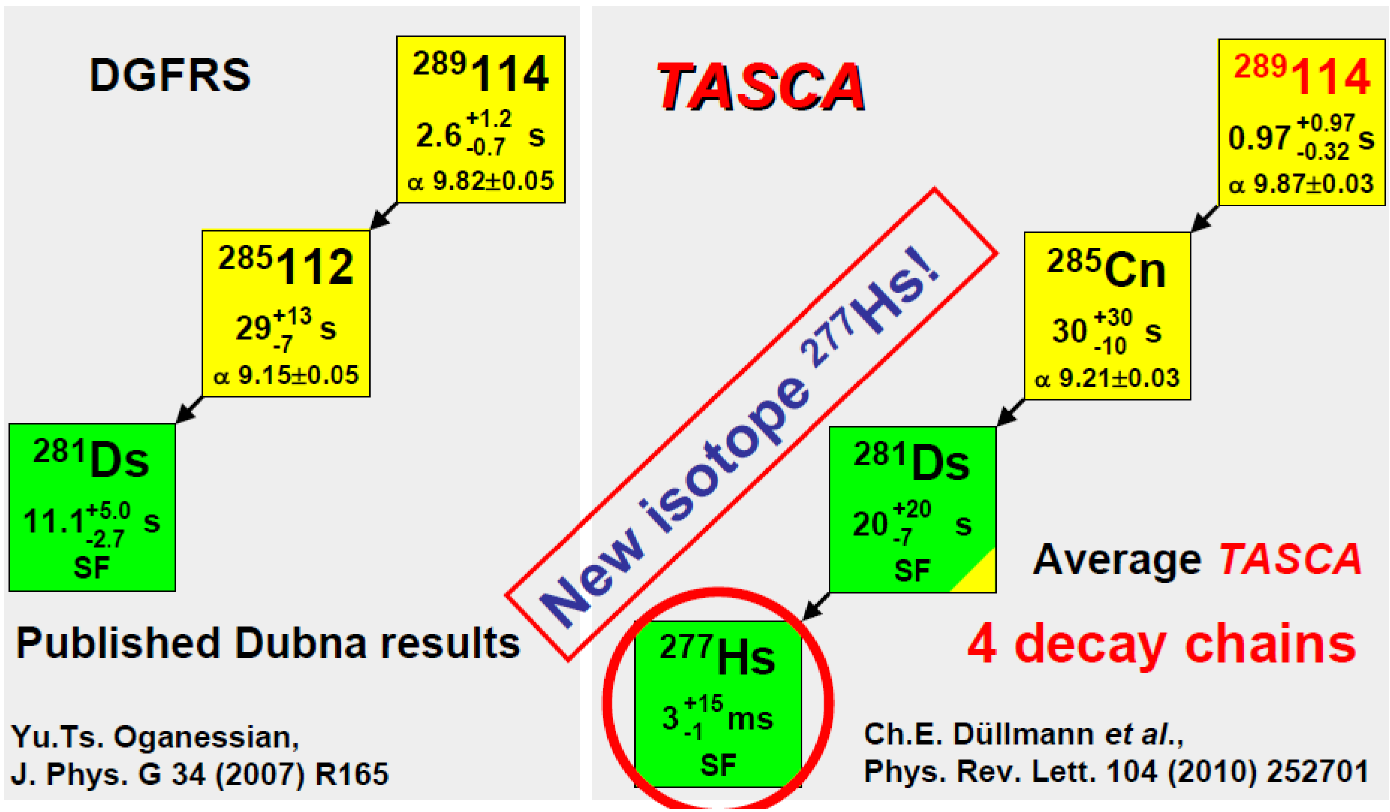




Dubna, ORNL, LLNL, Vanderbilt, Nevada-LasVegas coll.

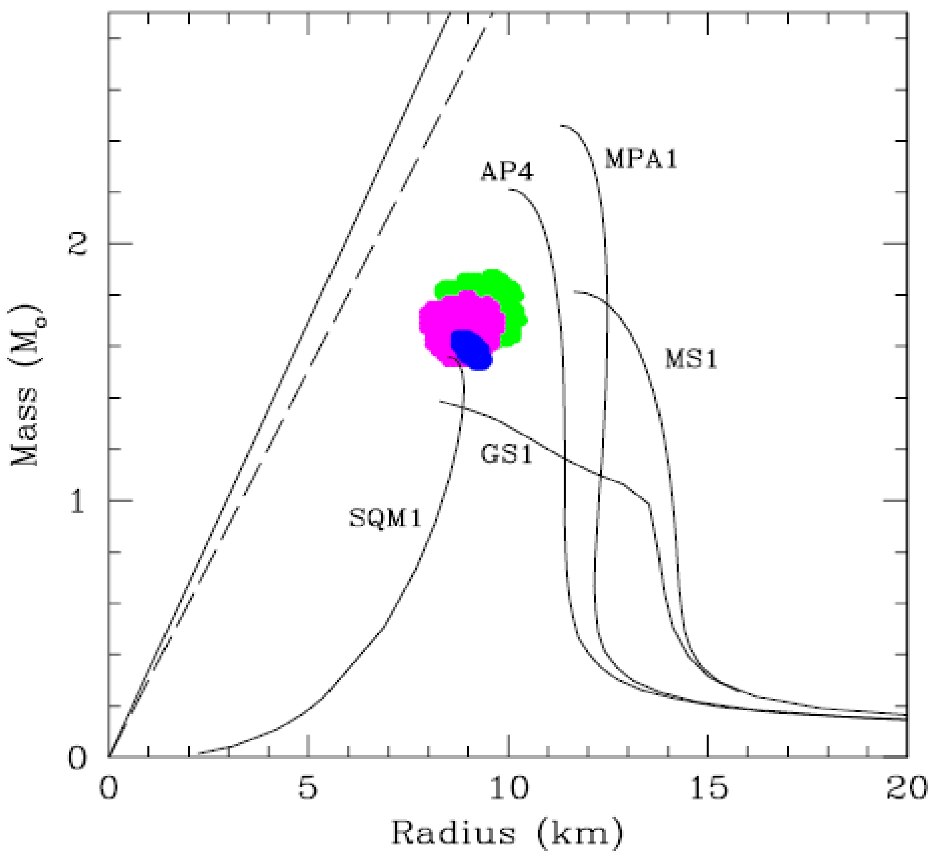
Element 114 – a first at GSI: $^{289}114$ decay

$^{48}Ca + ^{244}Pu \rightarrow ^{292}114^*$ → $^{289}114 + 3n$ **4 decay chains** / $^{288}114 + 4n$ **9 decay chains**



neutron stars and equation of state

determine cold matter equation of state by analysis of the mass-radius relation of three recently observed neutron stars



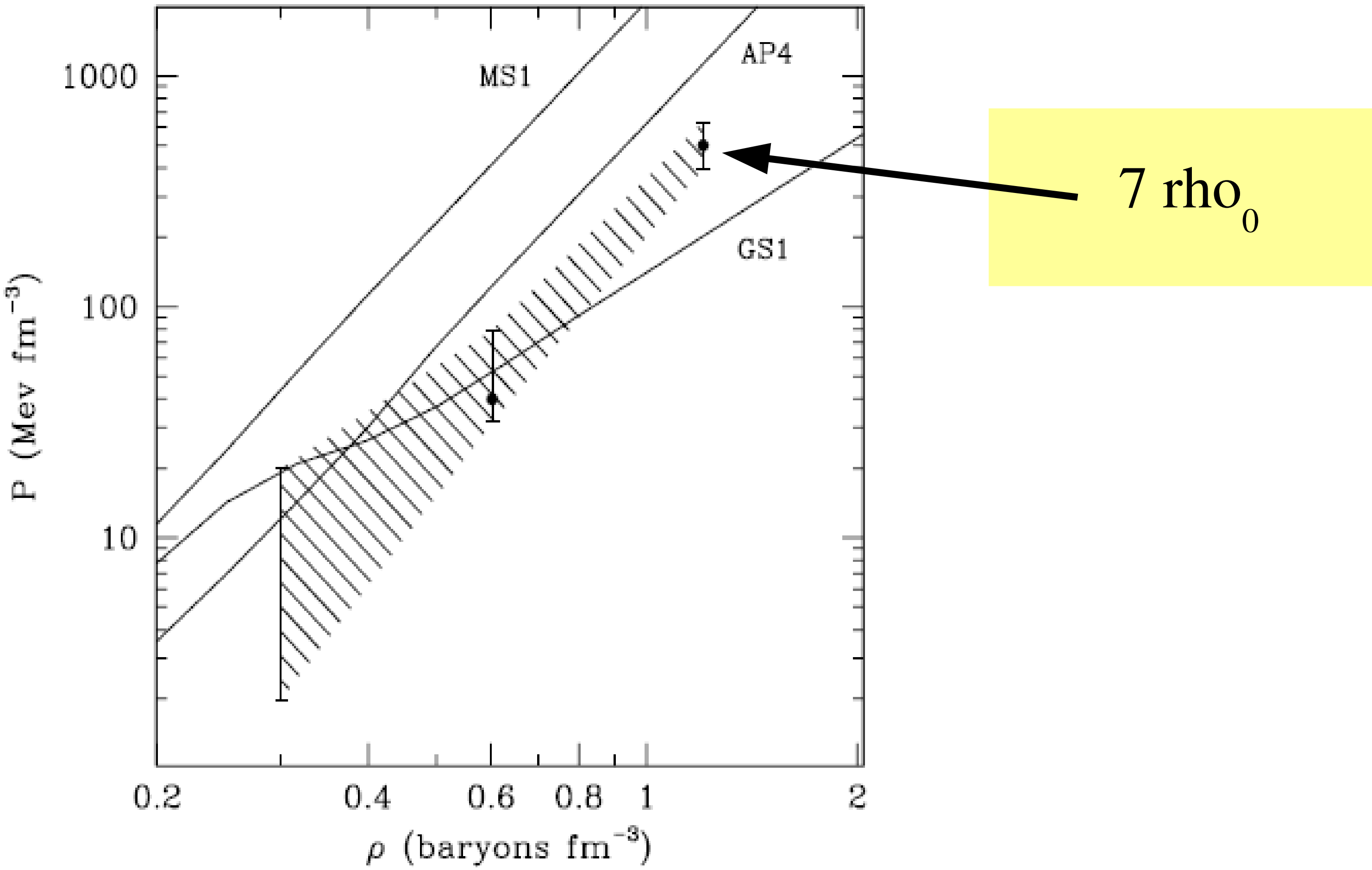
Rossi X-ray Timing Explorer
Chandra X-ray Observatory
XMM Newton

Oezel, Baym, and Guever, arXiv:1002.3153 [astro-ph.HE]

neutron stars and equation of state

equation of state is softer than that obtained using nucleonic degrees only

quark matter in the core of neutron stars?



Oezel, Baym, and Guever, arXiv:1002.3153 [astro-ph.HE]

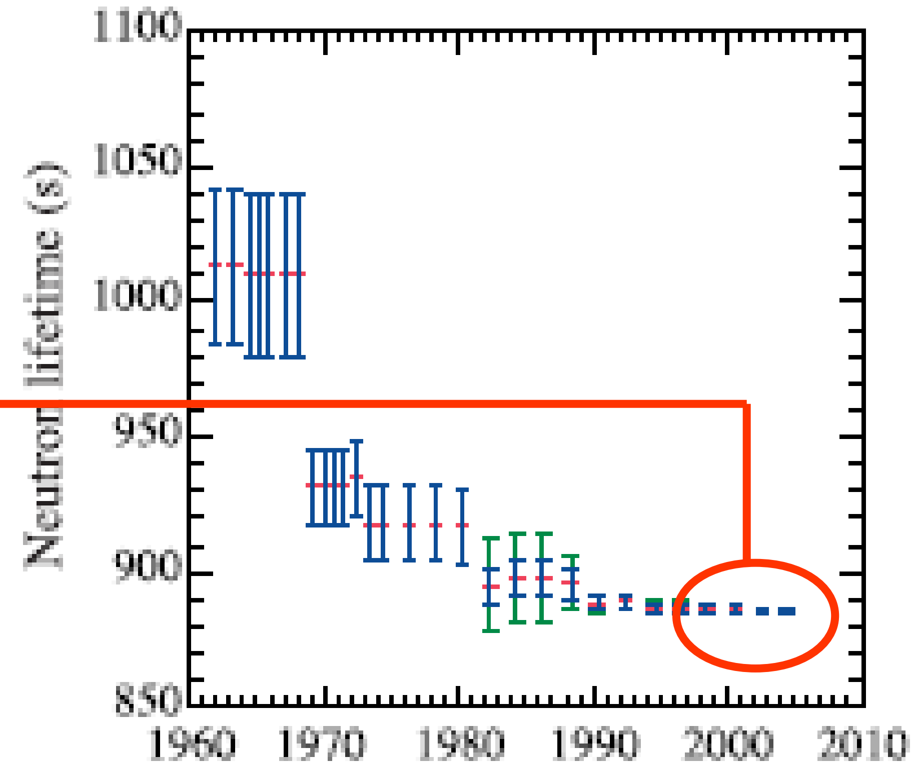
see, however, Steiner, Lattimer, and Brown, arXiv:1005.0811 [astro-ph.HE]

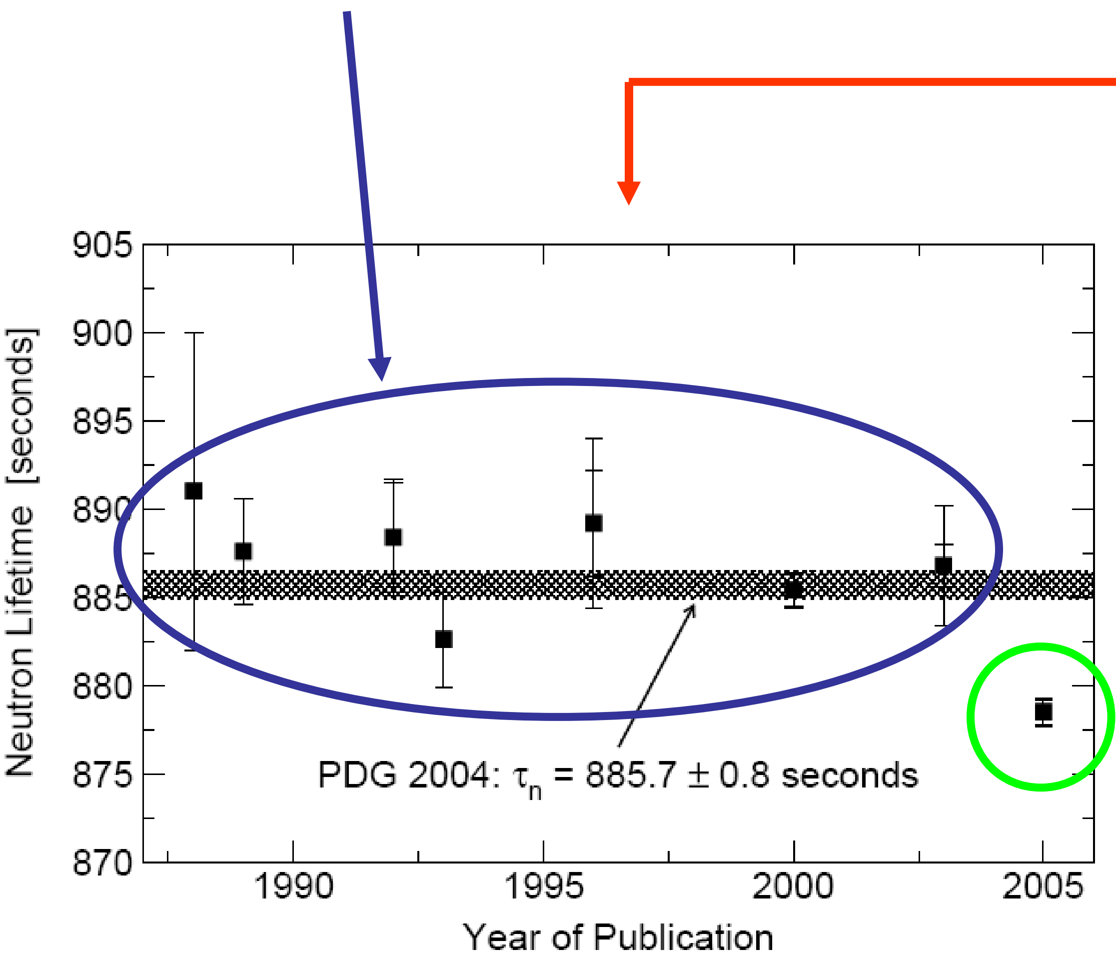
outstanding issues

The lifetime of the neutron

is, e.g. needed to understand element production in the early univrse

pre-2005 data seemed consistent





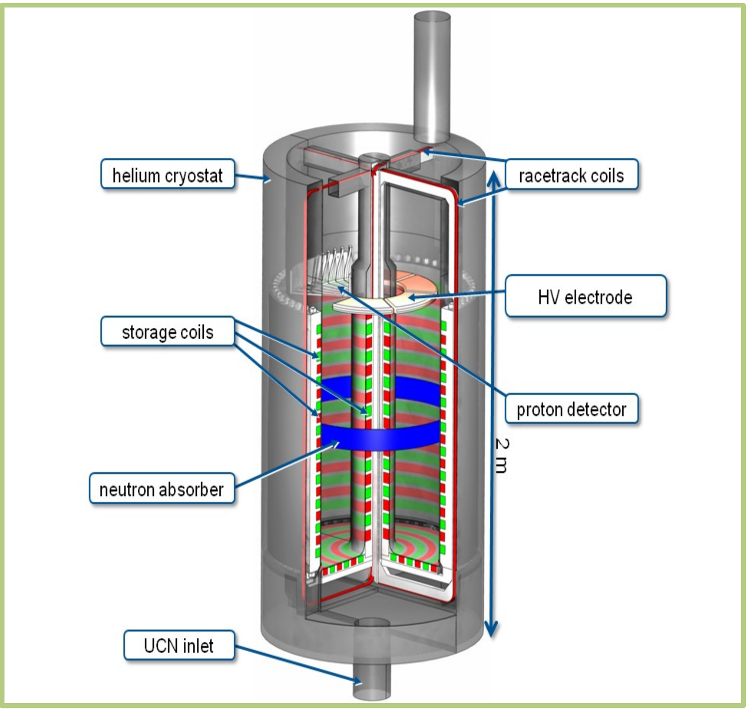
Serebrov *et al.*,

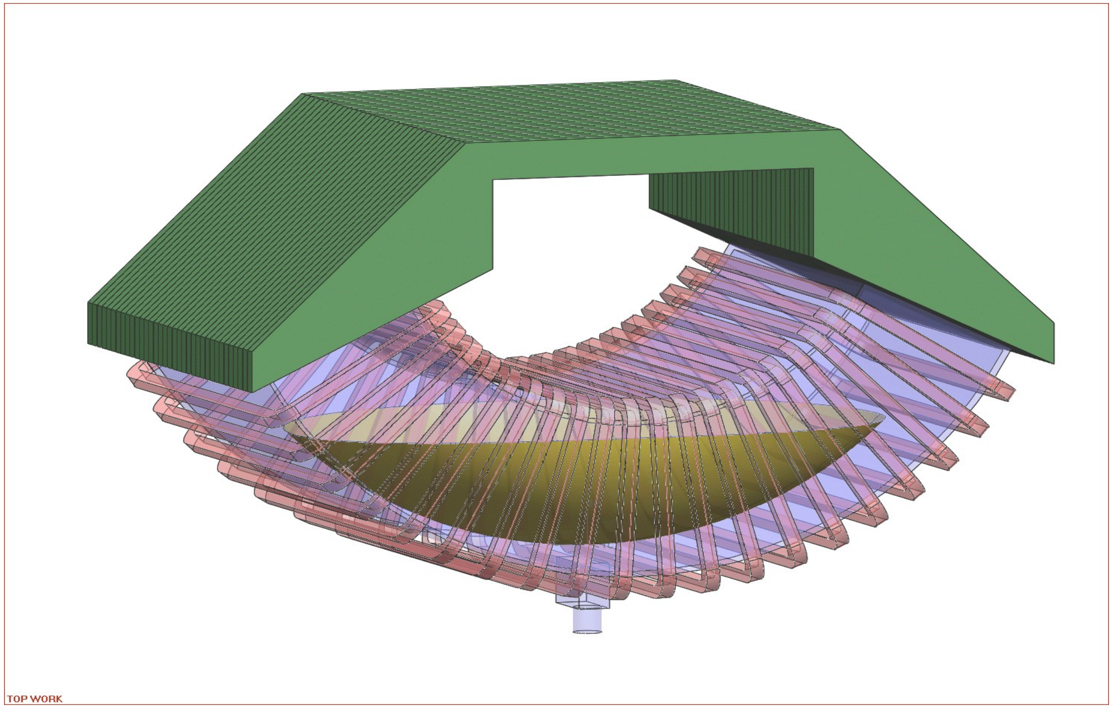
Phys. Lett. B 605, 72 (2005)

(878.5 ± 0.7 ± 0.3) seconds

new measurements very urgently needed

method of choice;
lossless storage of ultracold neutrons (100 neV) in a magnetic and gravitationally enclosed bottle
expected precision: 0.1 s





Penelope project
TU Munich

project at LANSCE, LANL

oscillatory structure in in-ring electron capture decays

observation of non-exponential orbital electron capture decays of hydrogen-like ^{140}Pr and ^{142}Pm Ions

Litvinov et al., GSI-ESR, Phys.Lett.B664:162-168,2008

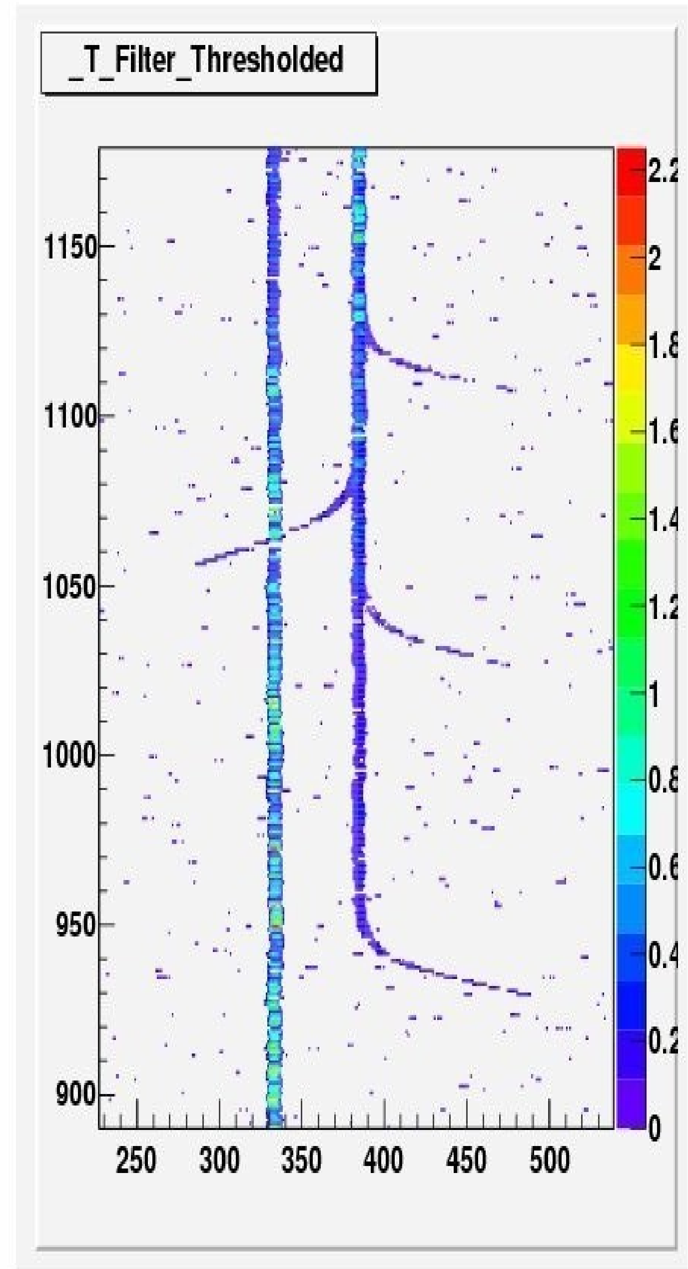
GSI oscillations in EC decays?

new 245 MHz oscillator

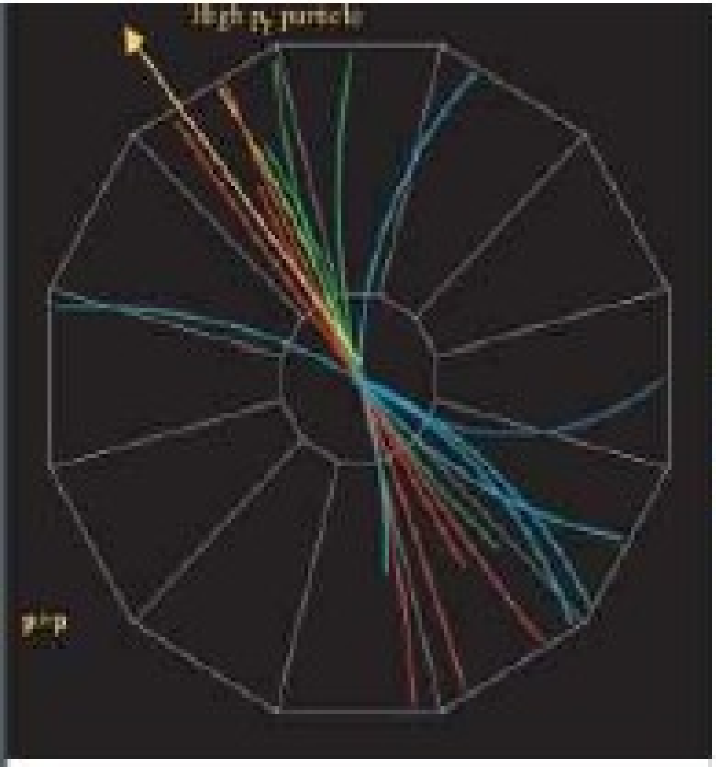
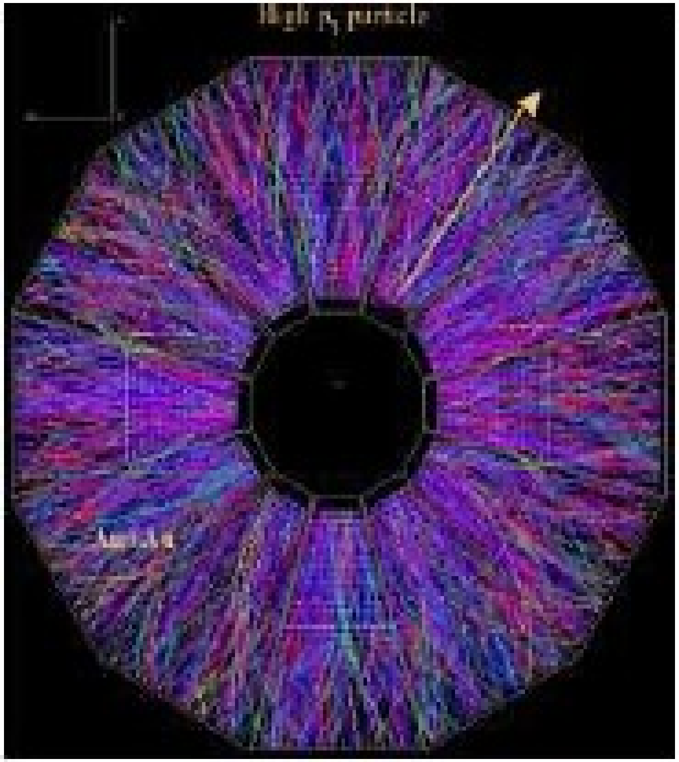
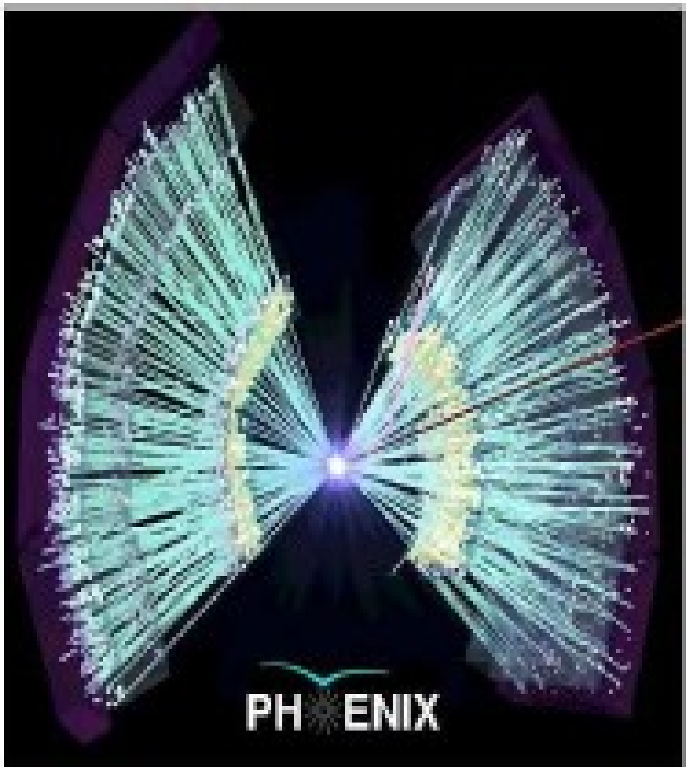
Operating at the 124th harmonic. $\Delta f = 1$ MHz

→ Improving the signal-to noise ratio by 18 db
→ Providing the true decay time
→ Enabling a reliable computer analysis
→ Providing the frequency shift of the recoiling daughter ion at the decay point
→ Rendering the projection of the recoil (ν_e) momentum on the beam axis: $\Delta p \cos\theta$
→ **Allowing to observe individual decay times of many (...100) stored parent ions and to get some 50 000 EC decays within a few days**

this should provide a solid basis to settle the issue within a few months



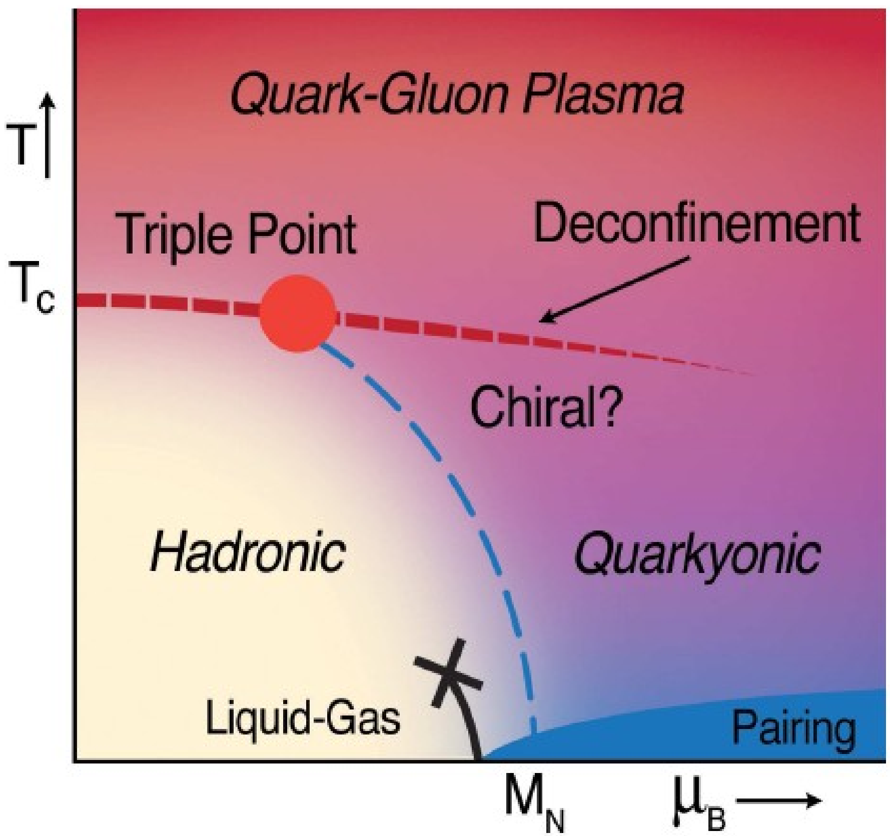
hot and dense matter

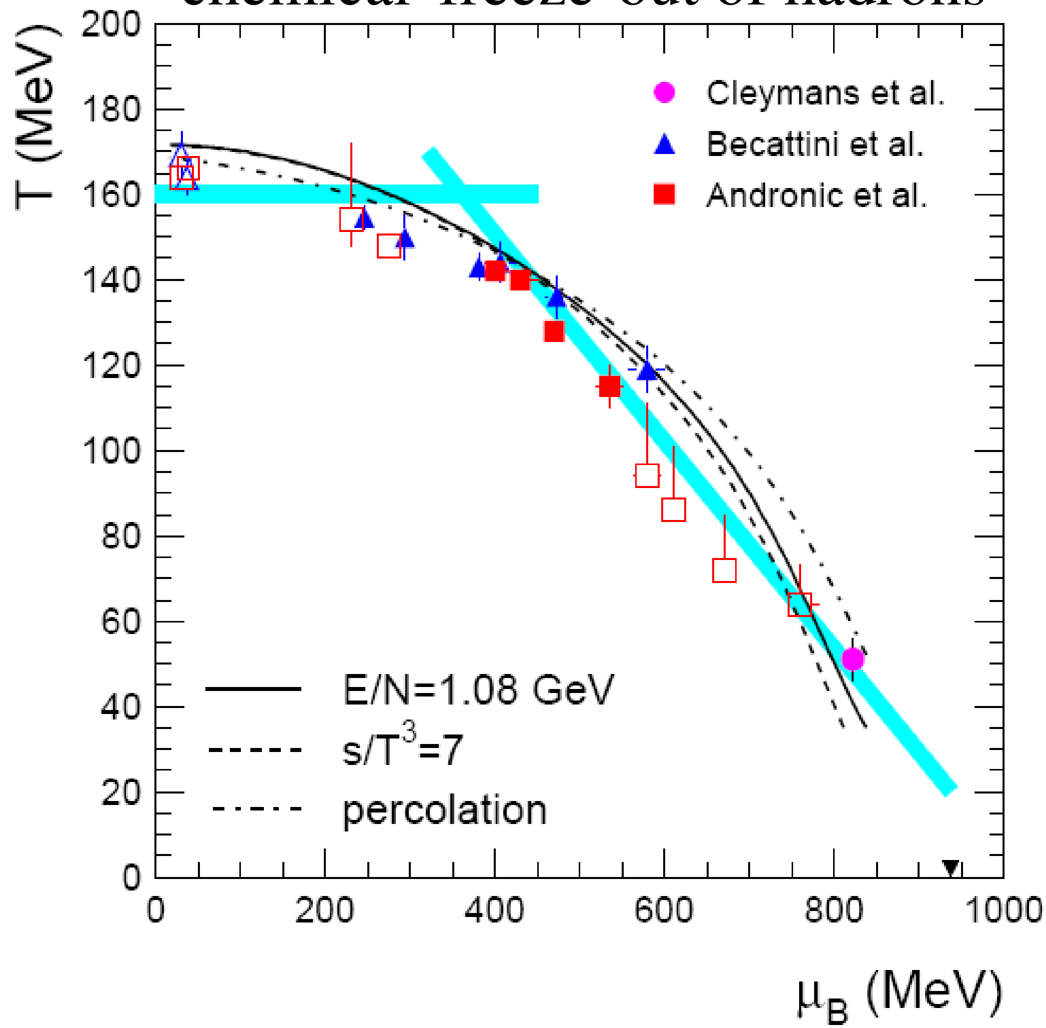
STAR pp STAR AuAu PHENIX AuAu

the QCD phase diagram

Andronic et al.,, arXiv:0911.4806
Nucl. Phys. A837 (2010) 65



data points:
'chemical' freeze-out of hadrons



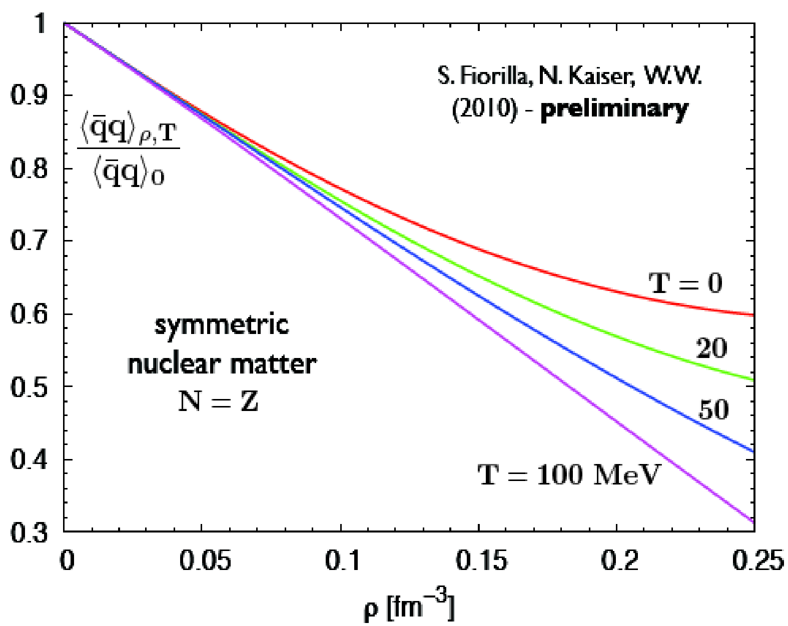
all lattice groups now agree: T_c(mu=0) is close to 170 MeV
Bazavov & Petreczky, arXiv:1005.1131 [hep-lat]
S. Borsanyi et al., arXiv:1005.3508 [hep-lat]

review: pbm, wambach
RMP 81 (2009) 1031

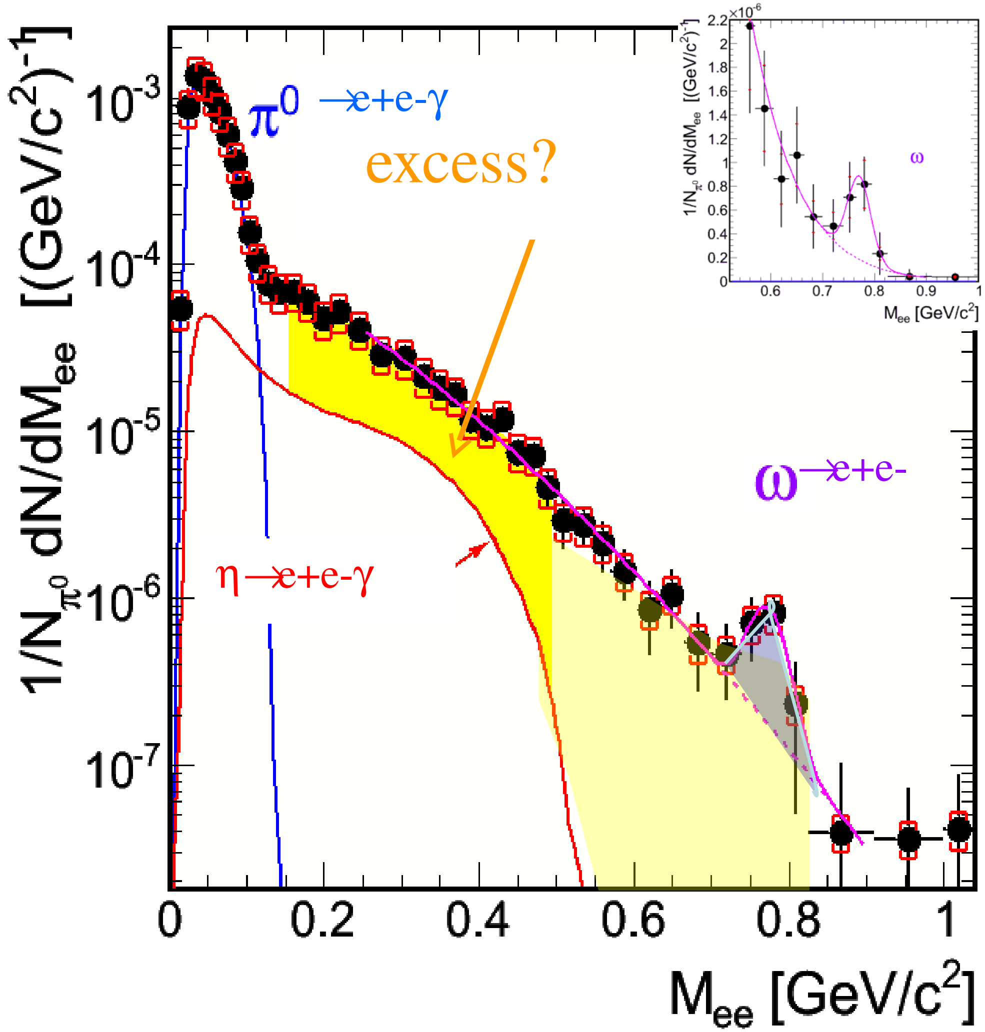
hadrons in dense matter and dilepton spectroscopy

HADES coll. @GSI
Ar+KCl, T = 1.75 A GeV

clear excess and direct omega observed



Fiorilla, Kaiser, Weise, 2010



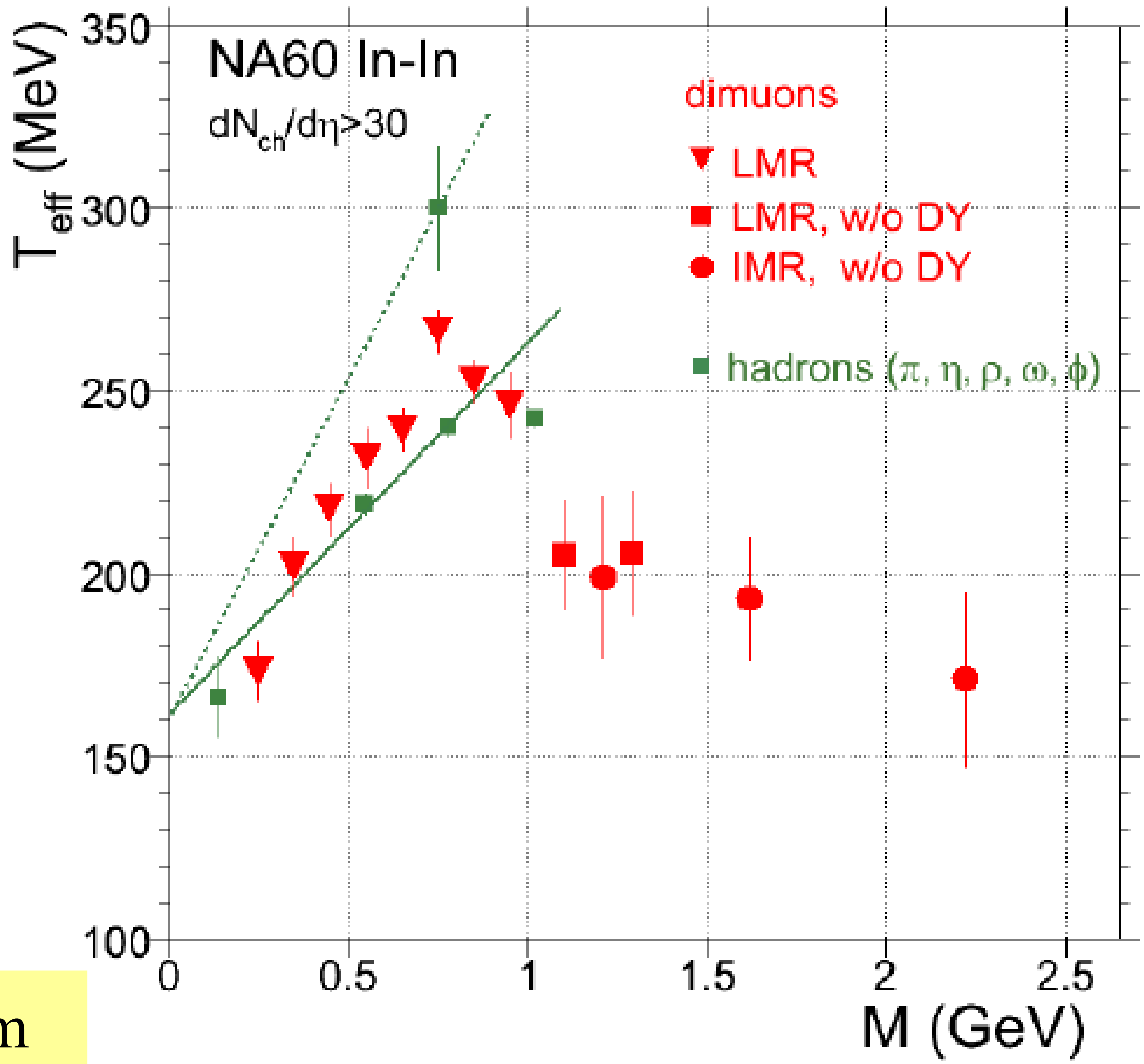
source of excess radiation: decay of baryonic resonances and reduced chiral condensate

hadrons in dense matter and dilepton spectroscopy
radial flow from thermal dimuon spectra

NA60 coll.
In+In, 158 A GeV
CERN SPS

initial rise in T_{eff} radial flow of hadronic origin

the drop for M > 1 GeV signals emission from weakly flowing partons thermal source with T = 200 MeV



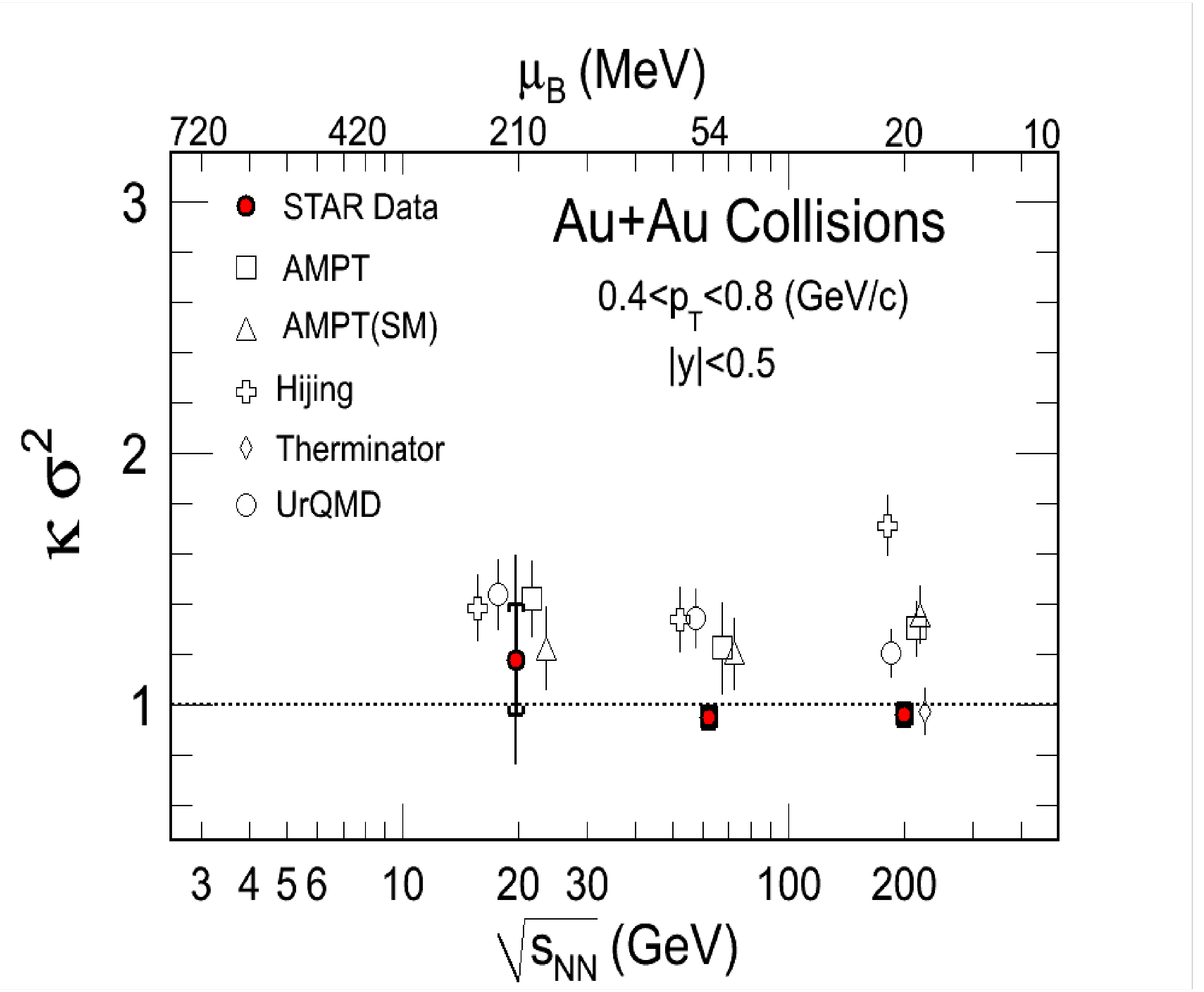
direct thermal radiation from the QGP

search for critical point with the energy scan at RHIC

measure higher moments of the mult. distribution of net protons as function of energy

no indication for anomalies yet

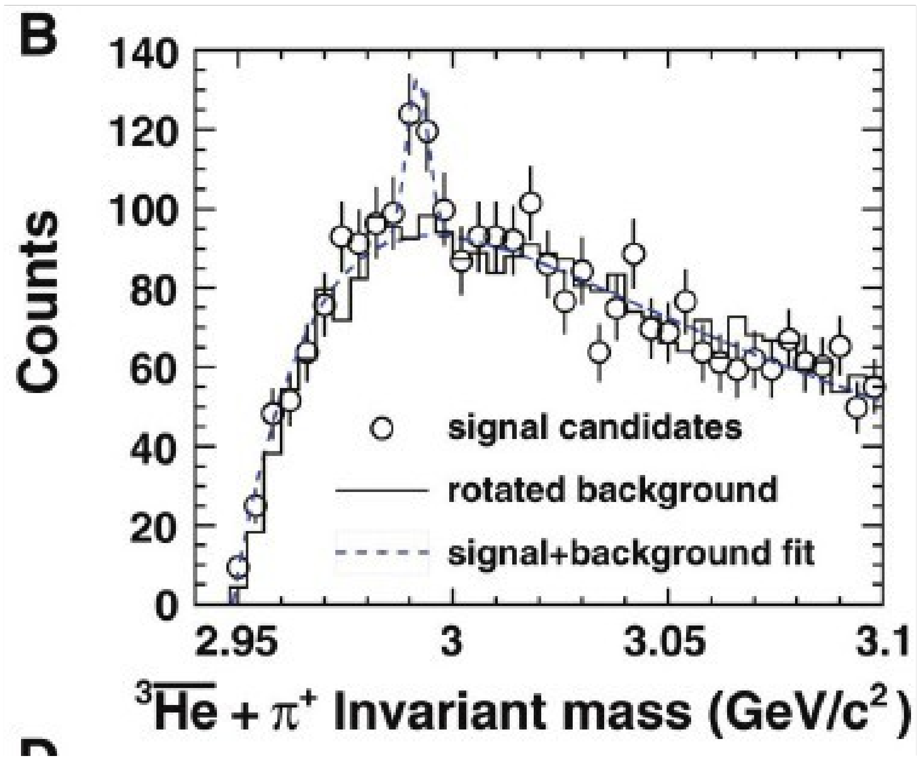
to come:
energy scan in 5 – 40 GeV cm energy range

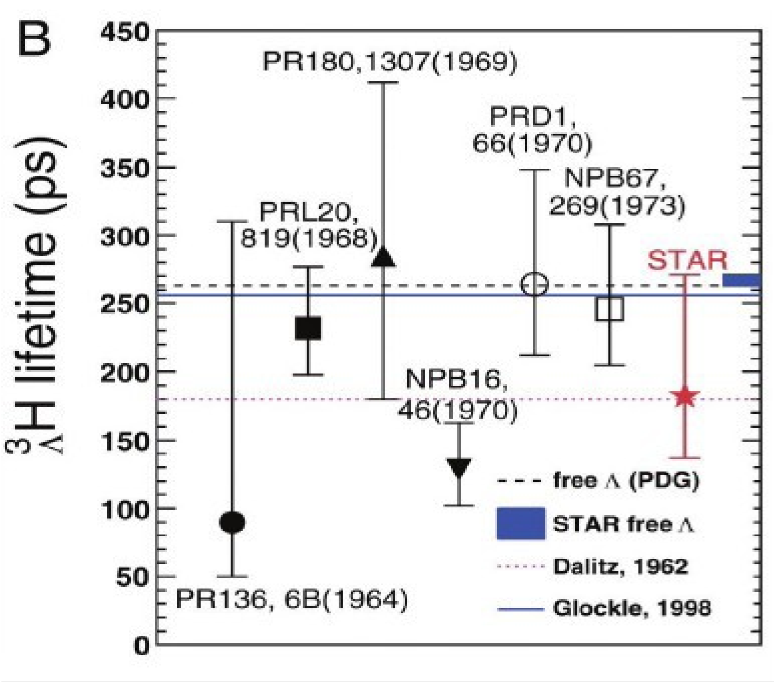


1st observation of an antimatter hypernucleus in Au-Au collisions

mass and life time of anti-hypertriton

are these exotic nuclei produced at the phase boundary?





STAR coll., Science 328 (2010) 51

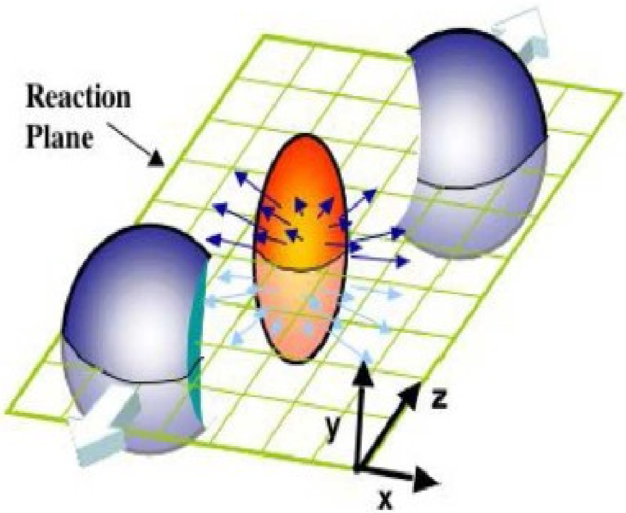
quark number scaling in hydrodynamic flow

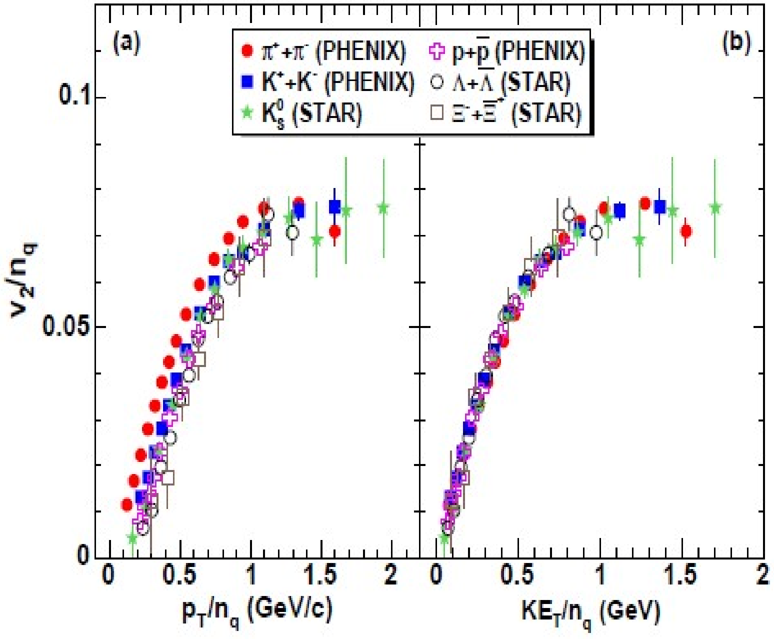
scaled flow coefficient for mesons and baryons coincide

is flow determined in the partonic phase?

***STAR*:**
*PRL**92**,* 052302(04)
*PRL**95**,* 122301(05)
*PRC**77**,* 54901(08)
*PRC**81**,* 44902(10)

PHENIX:
PRL 98, 162301 (07)



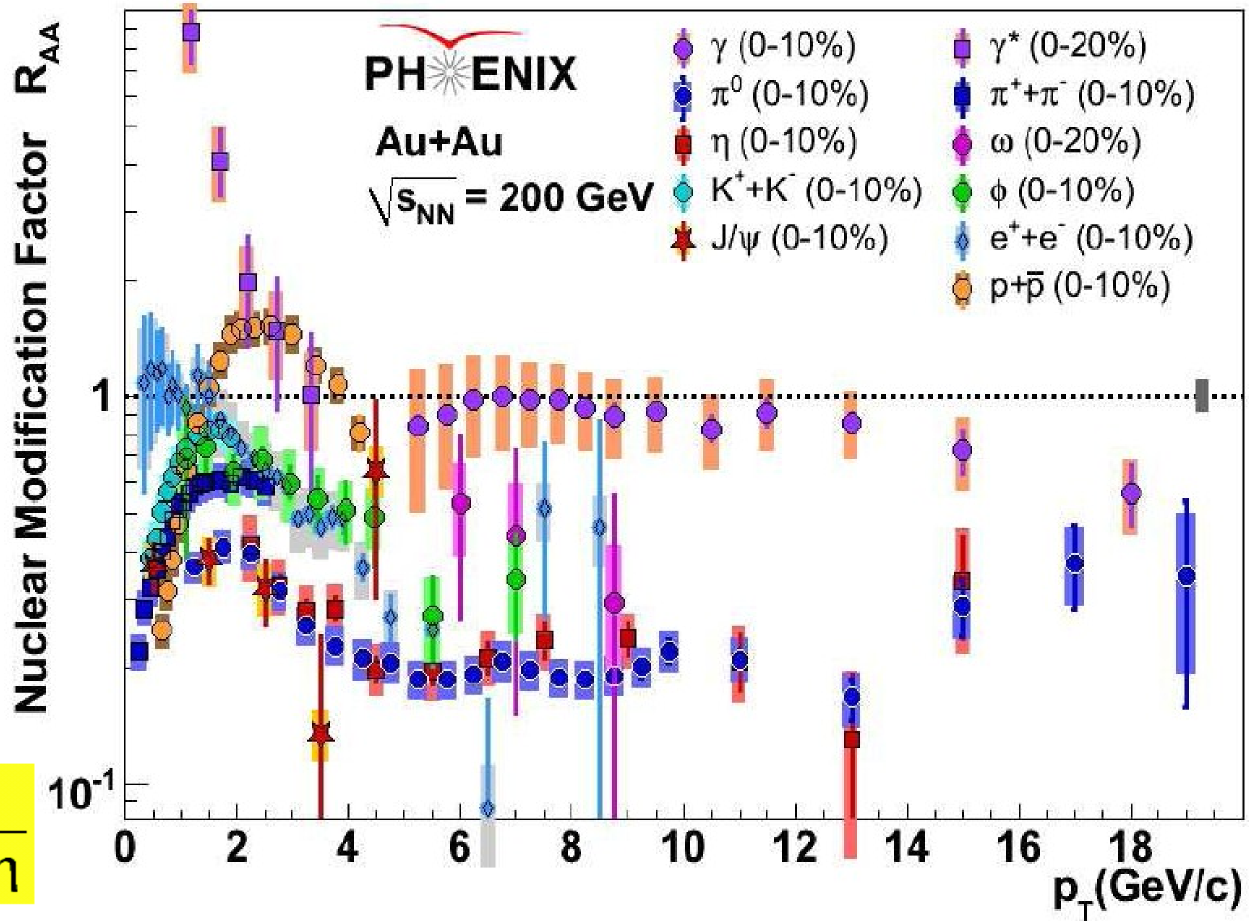


nuclear suppression factor R_{AA}

high momentum hadron suppression - quenched jets
low momentum photon enhancement – direct radiation from QGP
high momentum photons unmodified - control measurement

Fig. from M.J. Tannenbaum, arXiv:1006.5701 [nucl-ex]

pQCD region ever reached at LHC energy?



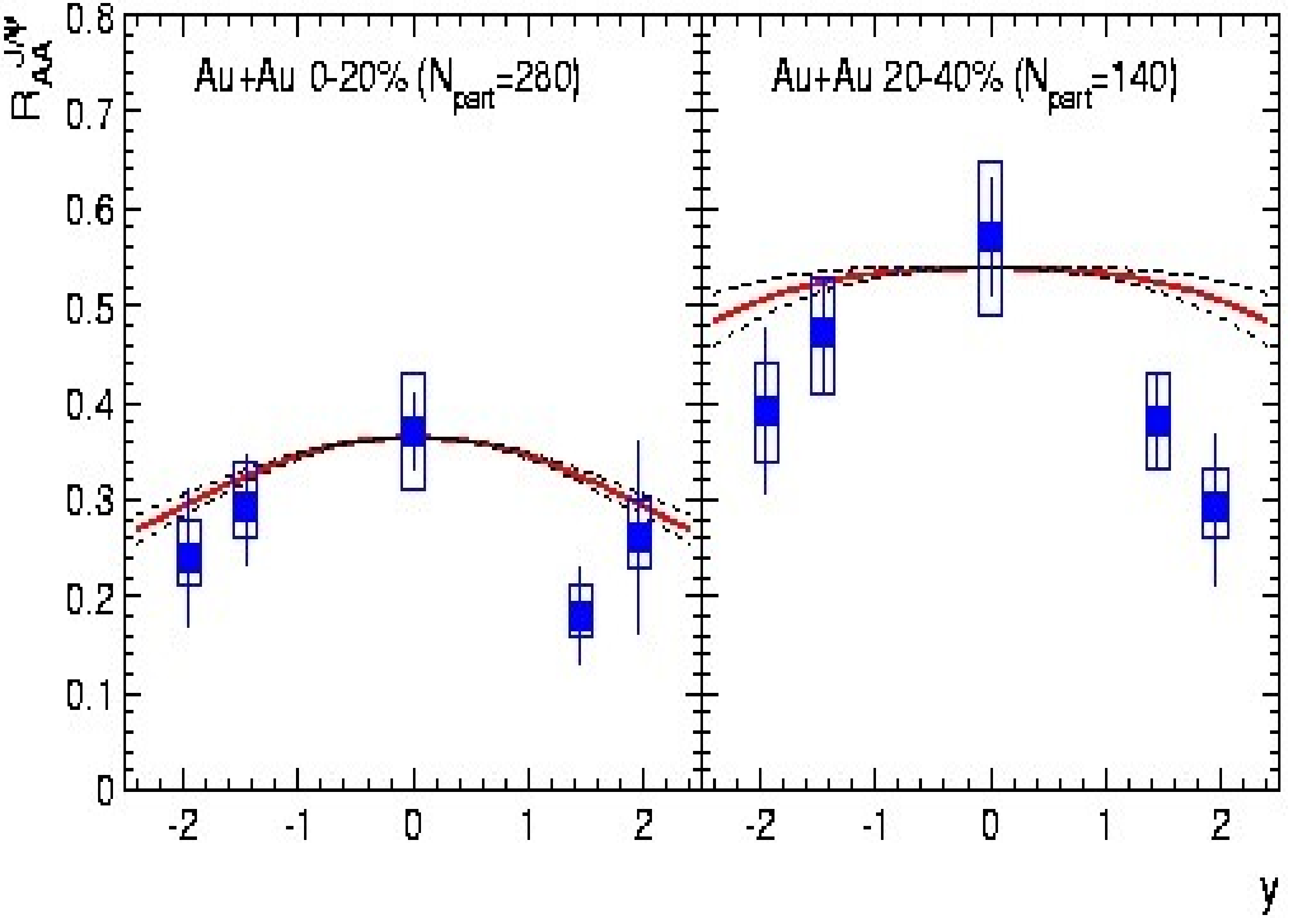
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

$\langle N_{binary} \rangle / \sigma_{inel}^{p+p}$

charmonium production from PHENIX at RHIC

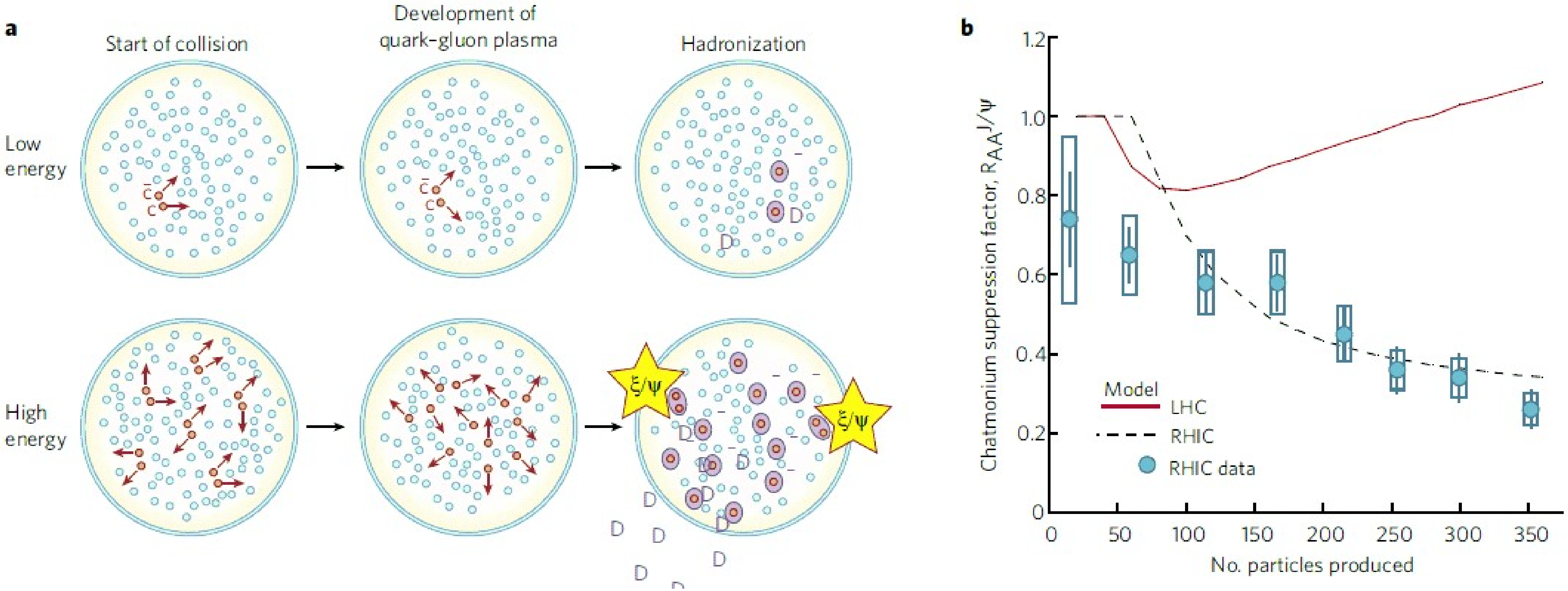
data: PHENIX coll.
Phys.Rev.Lett.98:232301, 2007.
nucl-ex/0611020

calc.: Andronic et al., Phys. Lett. B652 (2007) 659



suppression is smallest at mid-rapidity (90 deg. emission)
a clear indication for generation of J/psi at the phase boundary

quarkonium as a probe for deconfinement at the LHC

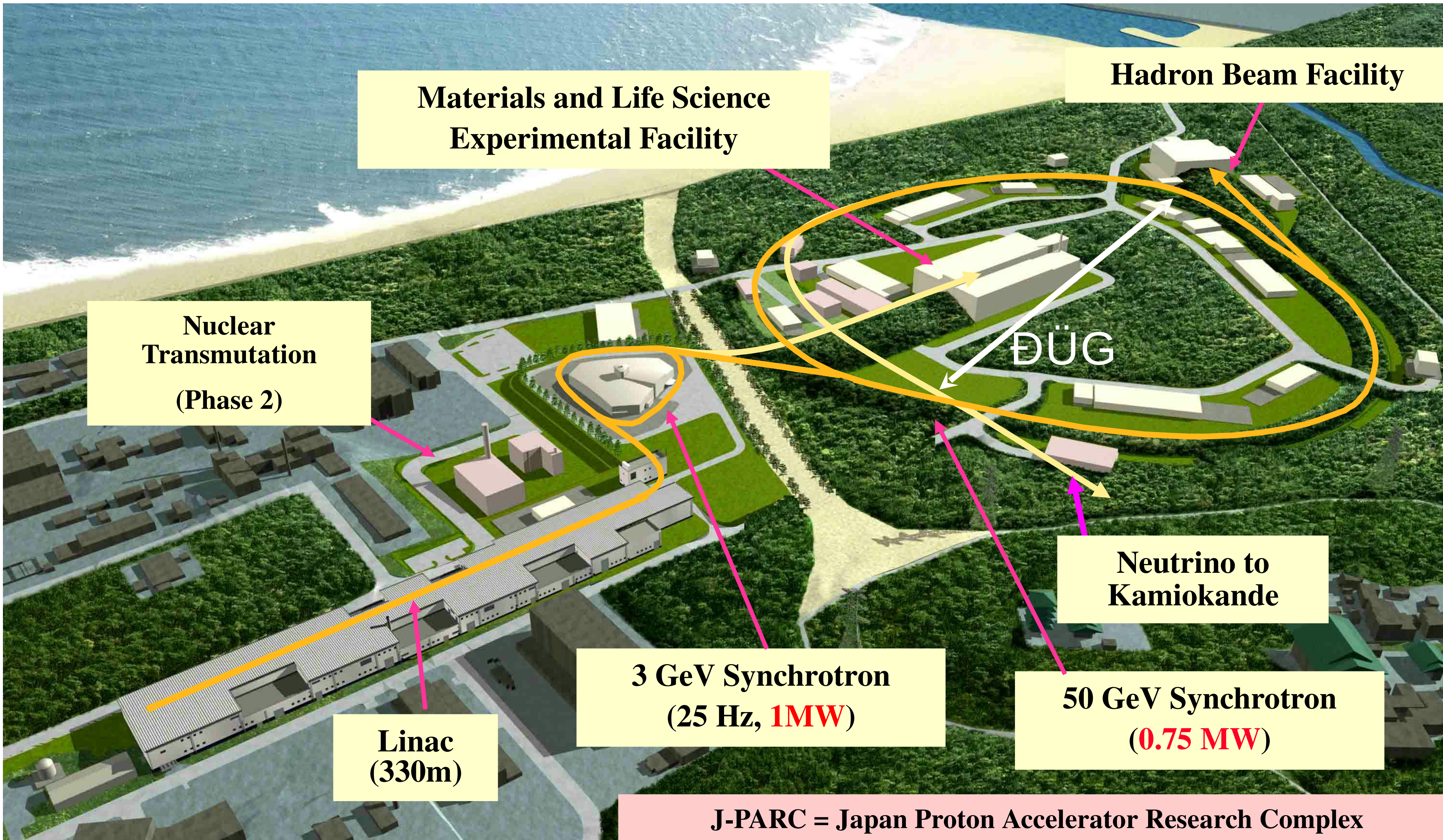


charmonium enhancement as fingerprint of deconfinement at LHC energy

Andronic, pbm, Redlich, Stachel, Phys. Lett. B652 (2007) 659

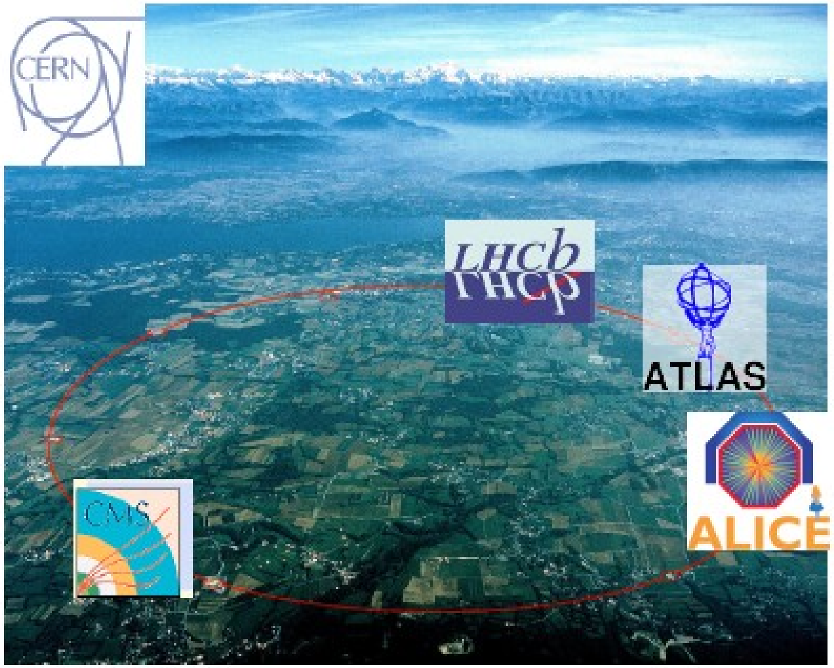
hot news: J-PARC facility running

1st neutrino event at SuperKamiokande on Feb. 24, 2010



joint project between KEK and JAEA

hot news: first data from LHC pp collisions



November 23, 2009

First proton-proton collisions at $\sqrt{s}$=900 GeV

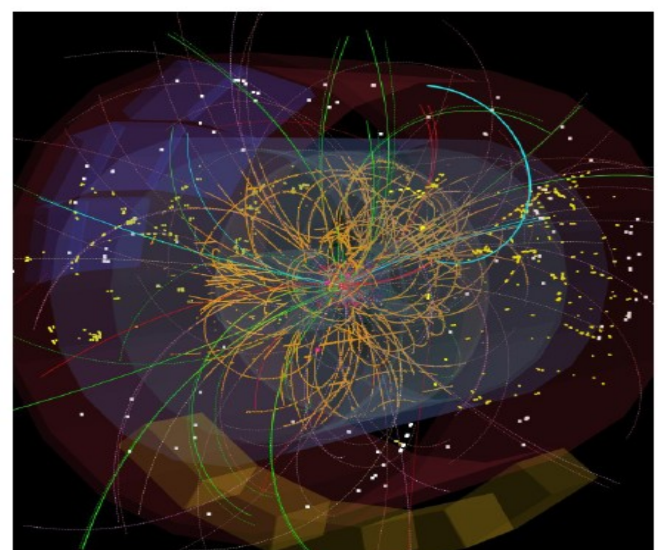
ALICE pseudo-rapidity density

(Nov 28)

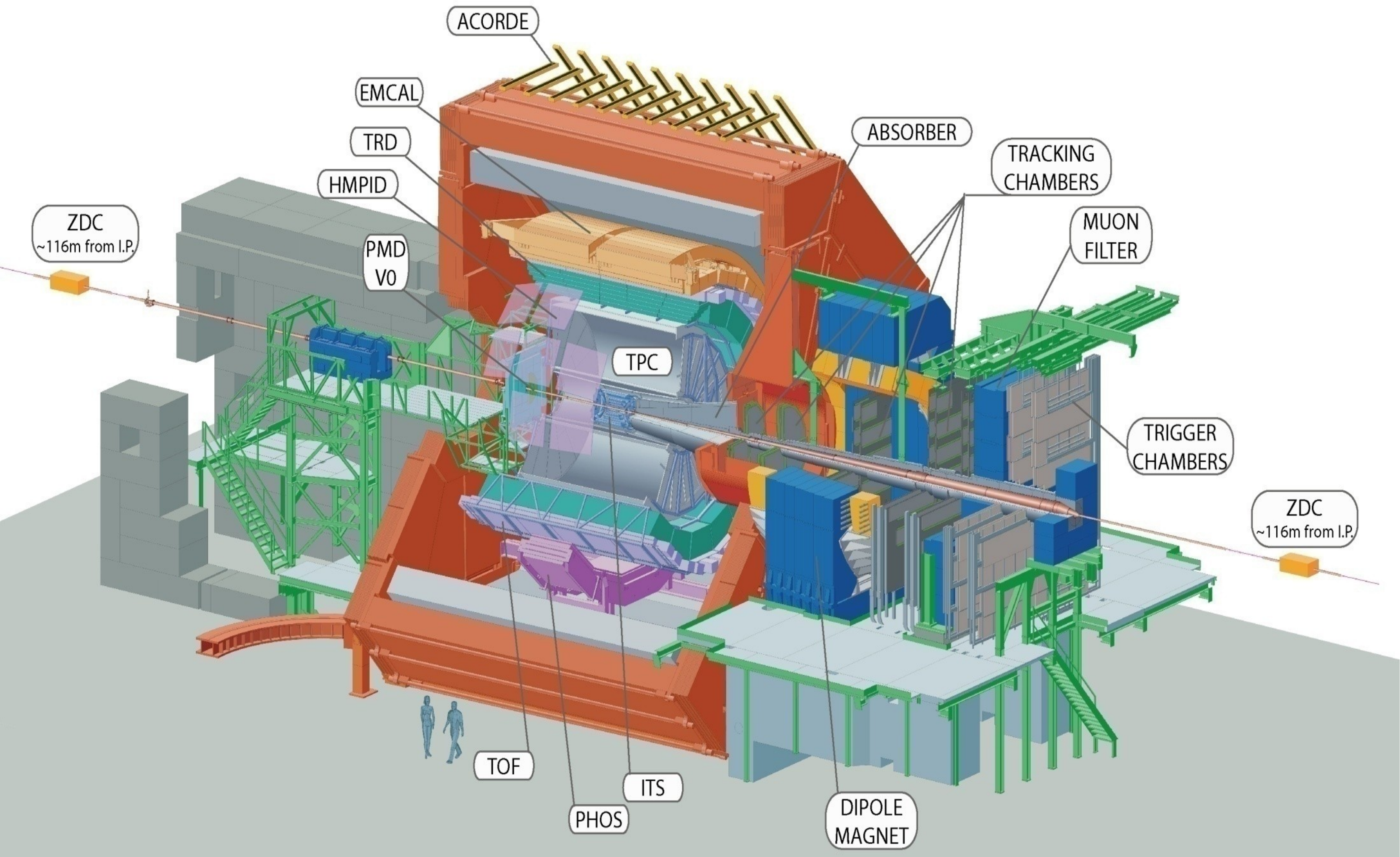
Eur. J. Phys. C65 (2010) 111

Dec 6, 2009 pp at $\sqrt{s}$=2.36 TeV

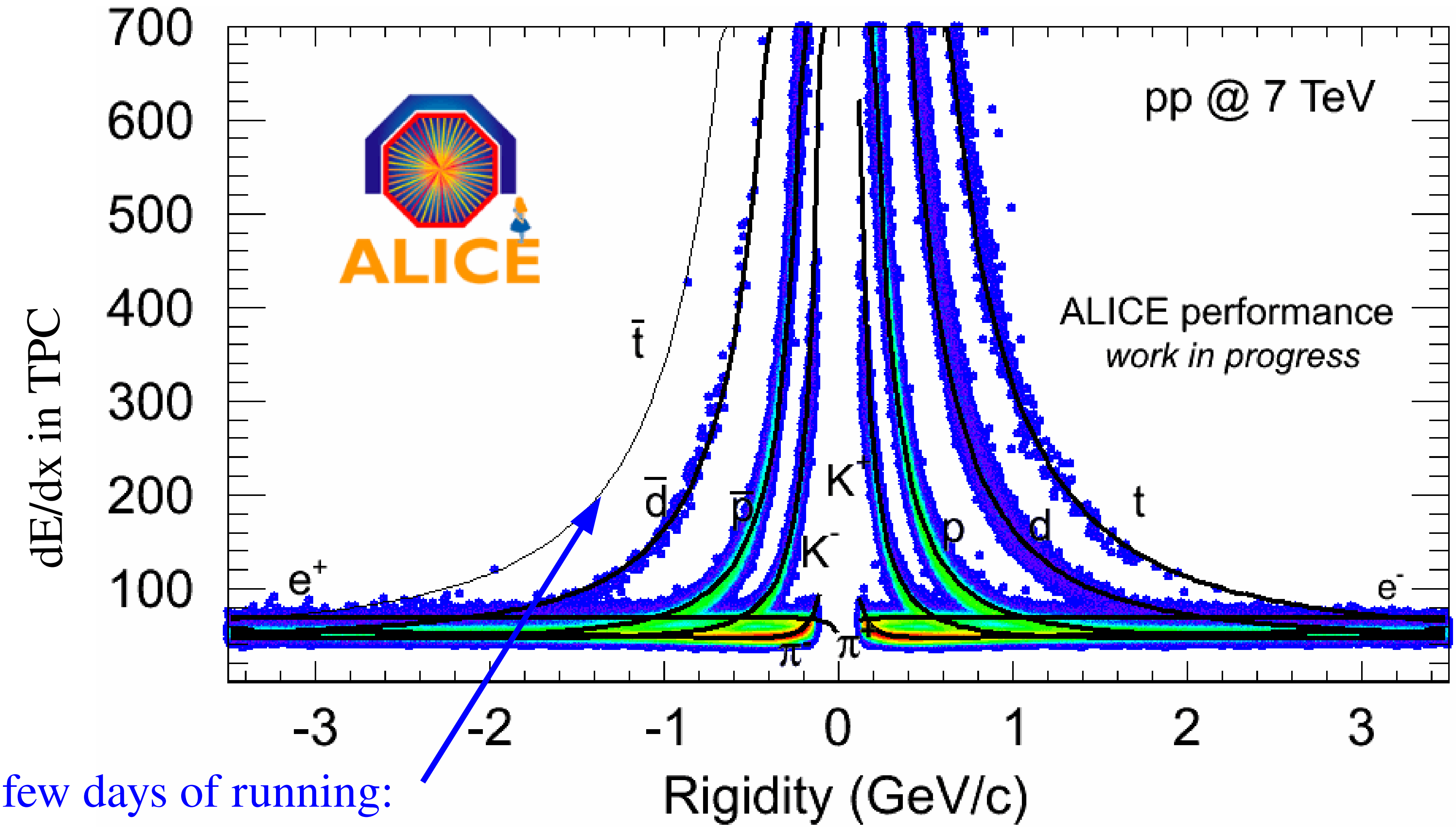
Mar 30, 2010 pp at $\sqrt{s}$=7 TeV



ALICE, the major nuclear physics experiment at LHC



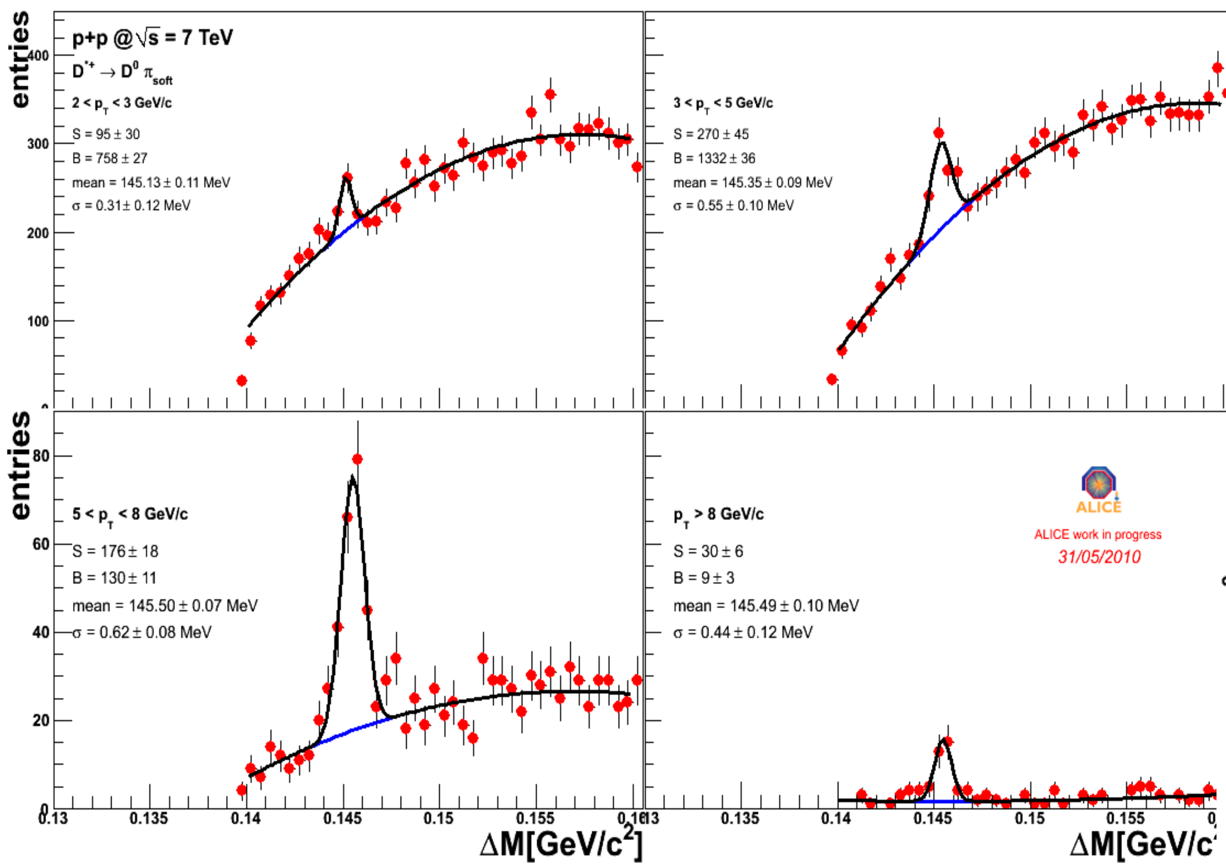
ALICE has very good particle identification

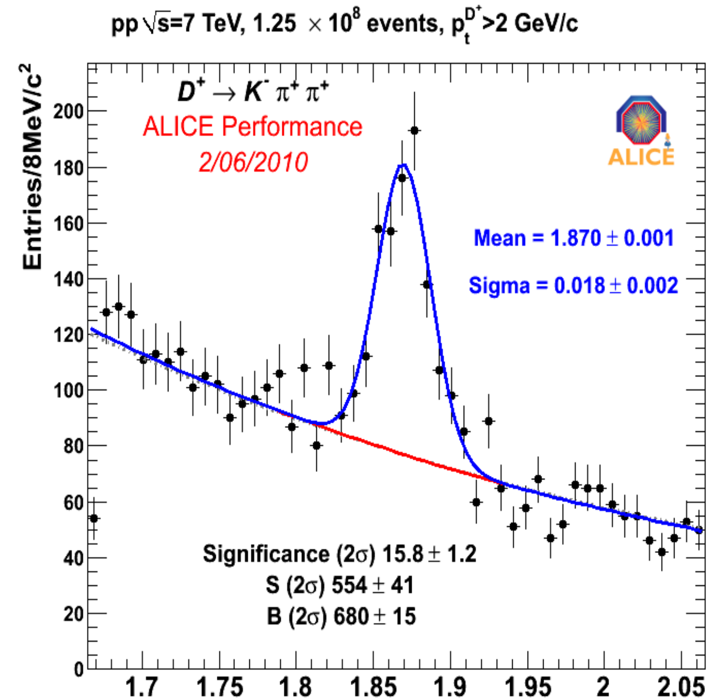


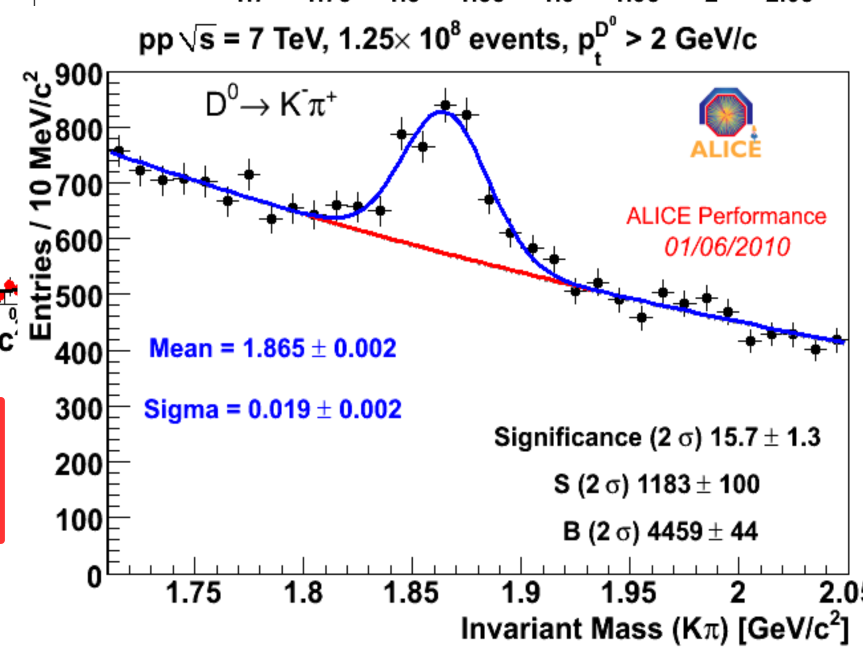
few days of running: already antitritons visible – very clean

first observation of D^0, D^+ and D^{0*} in 7 TeV pp data

1.25 10^8 events

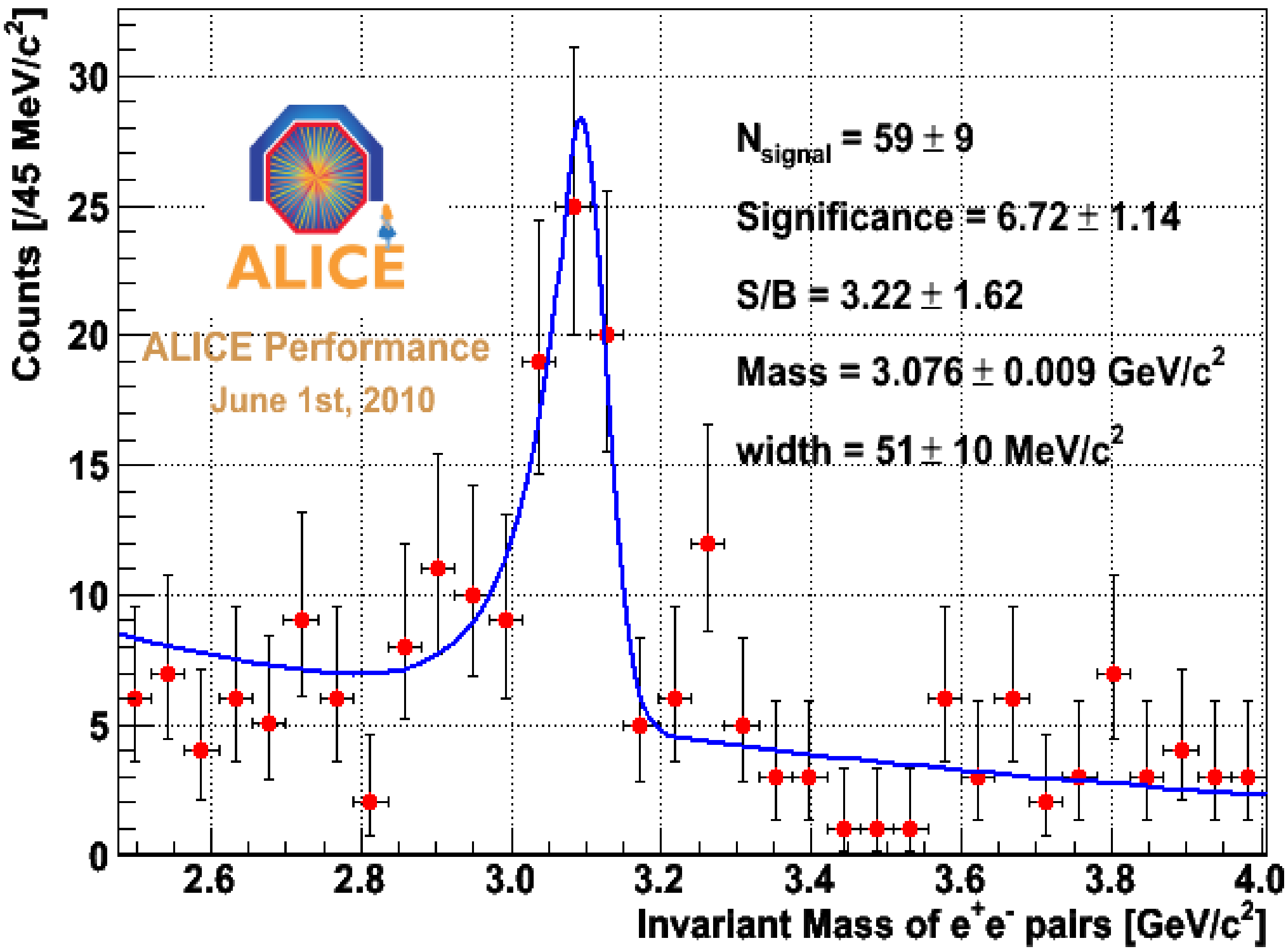


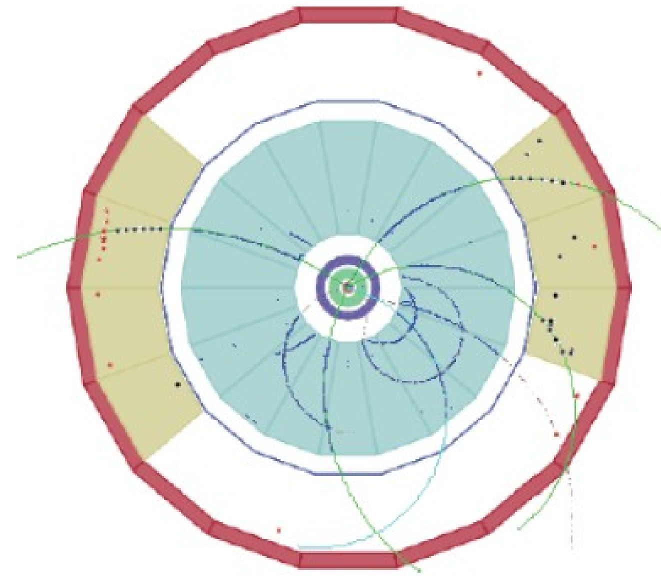




for 10^9 events, expect to measure open charm for $p_t = 0.5 – 15$ GeV/c

first J/psi in ALICE central barrel from 110 million pp collisions at 7 TeV





expect about
500 J/ψ mesons
by Sep. 2010 -->
p_t and y distributions
and production
cross section

outlook

new facilities

LHC - running (PbPb in Nov. 2010)
J-PARC - running
JLab 12 GeV upgrade - under construction
RHIC II – underway in stages
new ISOL facilities – SPIRAL2, SPES, HIE-Isolde
FRIB
FAIR
Eurisol
… eRHIC, eLIC, LeHC
a very rich menu - let's watch out for time lines

summary

- nuclear physics has diversified
- many truly exciting new results
- QCD in the non-perturbative regime and much more
- more interconnections among different subfields
  (strongly coupled systems, …)
- .. and to other disciplines

I look forward to an exciting conference