Heavy Ions in non-LHC experiments - an overview

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Workshop on

"Heavy Ions and Hidden Sectors "

4-5 December 2018, Louvain La Neuve, Belgium

photo: Ukraine

Outline

1. Introduction
2. Antihypernuclei
3. Dark photon search
4. Vorticity
5. Strangelets searches
6. Pentaquark searches
7. Dibaryon searches
8. Glueball
9. Summary and outlook

I Introduction

Relativistic Heavy Ion Collisions and Quark Gluon

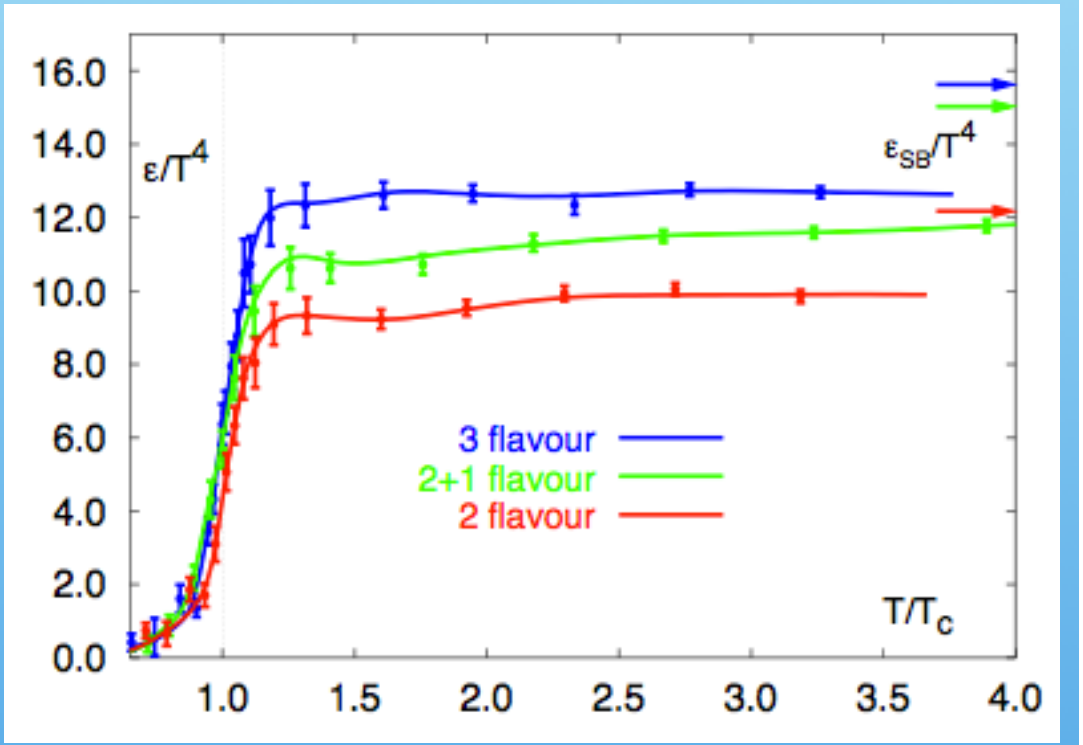
The QCD phase transition between hadronic and partonic phase

QCD on the lattice predicts a cross over at zero net baryon density with critical temperature Tc~154+-9 MeV (2014), critical energy density ~0.6 GeV/fm^3

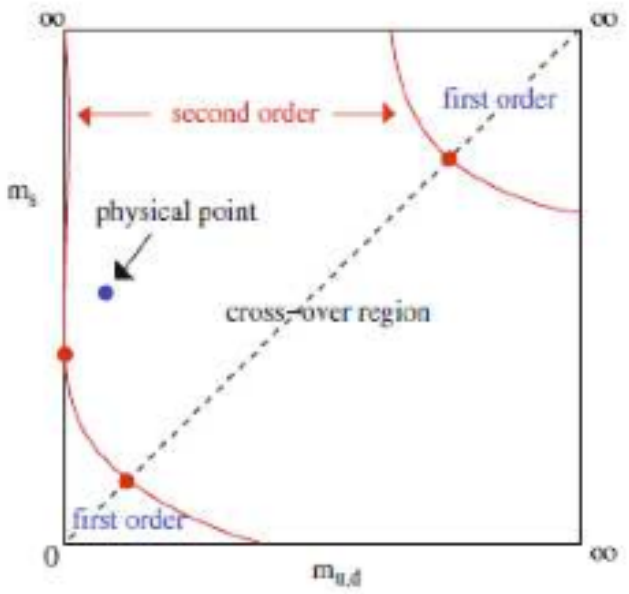
(Nuclear Density: rho=0.15 GeV/fm^3 Density inside Nucleon: rho=0.5 GeV/fm^3)

Zero net baryon density

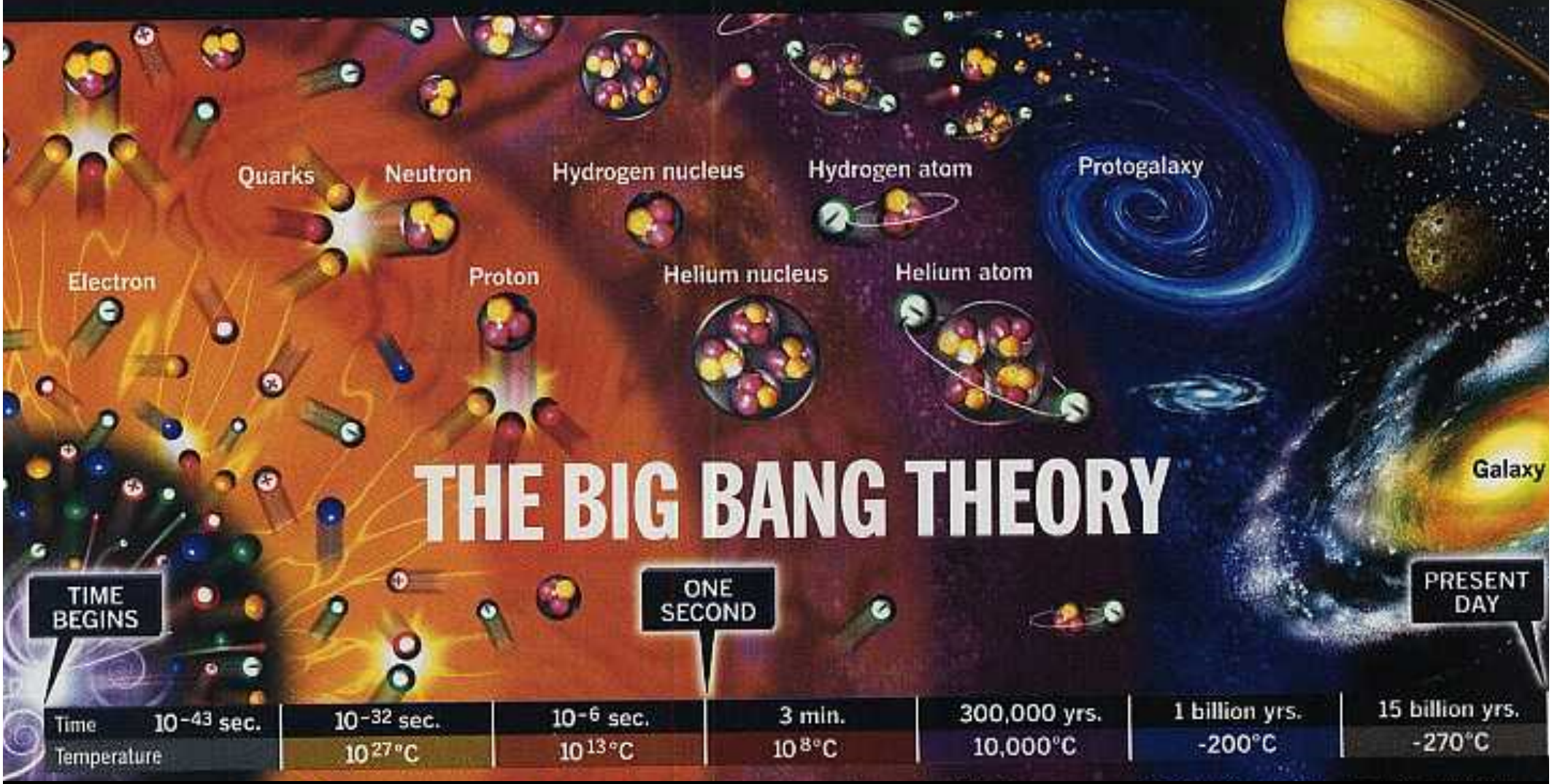
F. Karsch, Lect. Notes Phys. 583 (2002) 209, hep-lat/0106019



Zero net baryon density



The order of the transition depends on the parton masses. A cross over is expected by Lattice QCD for the physical point (for the physical u,d,s masses).

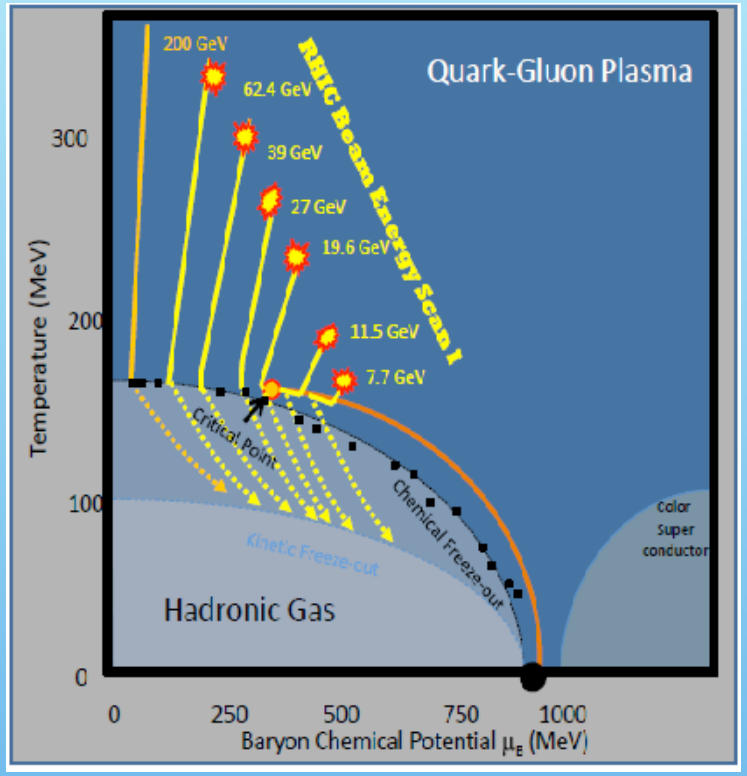


The transition from quarks and gluons to hadrons is believed that took place few 10-6 sec after the Big Bang.

The QCD phase transition is the only phase transition of the early universe that can be reproduced in the Lab today.

Why is this possible ? Because T(critical) is expected to be ˜200 MeV, and this is in principle reachable with todays accelerators

The expected QCD phase diagram



Phases of QCD Matter

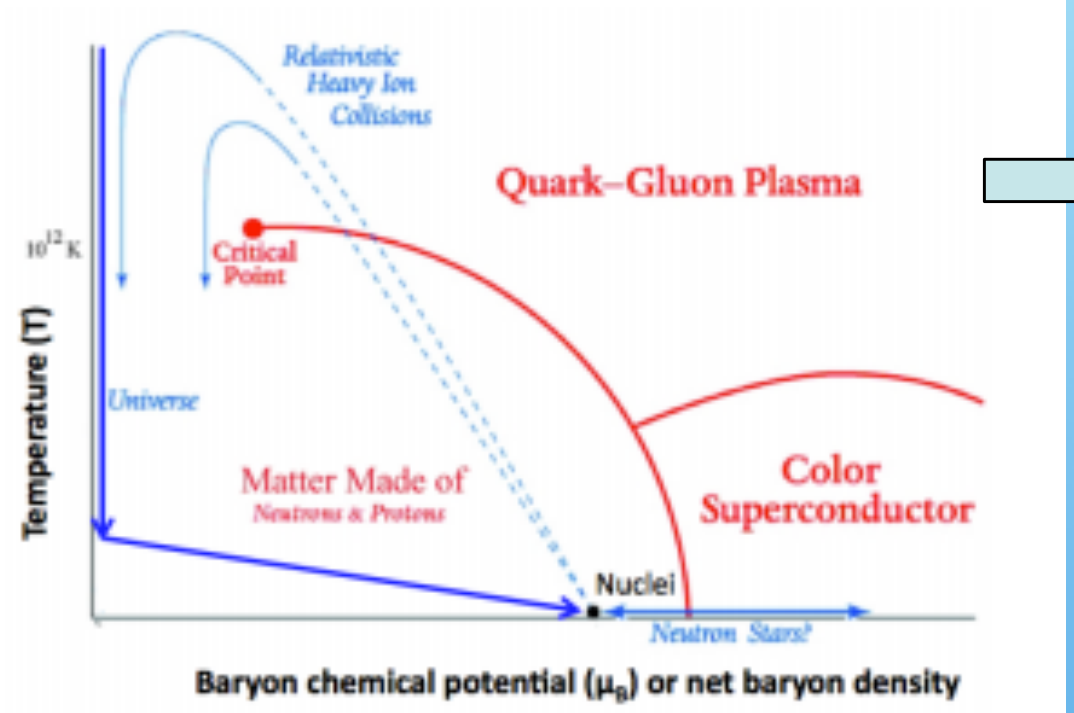
Areas of different net baryon densities and temperatures can be probed using different collision energies and nuclei.

The order of the transition is expected to change with the net baryon density.

Goal: explore experimentally the QCD phase diagram (order of transition, critical point, properties of the QGP).

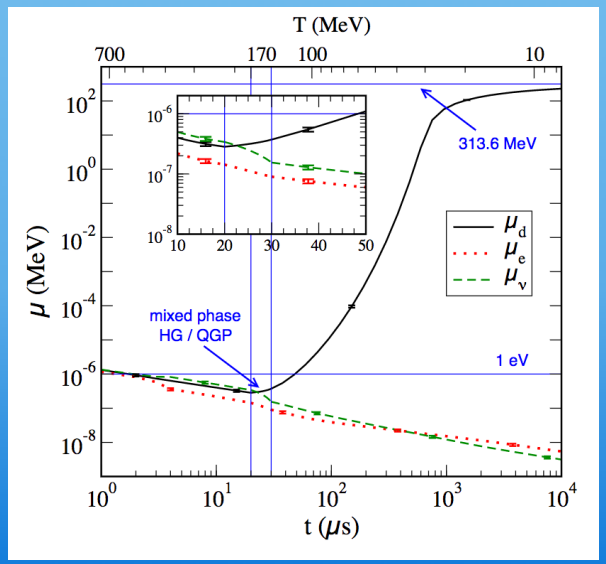
The QCD Phase Diagram and the Path of Early Universe through this diagram

Plot from review by Ph. Rosnet,1510.04200



Calculation and plot of the Path of Early Universe in (T, mu-B) plane was done by Uli Heinz and later from
S.K., P. Minkowski, J Phys G 28 (2002) 2063-2067, hep-ph/0204103 (fig.1).
S.K. P. Minkowski, Space Sci.Rev. 100 (2002) 175-192

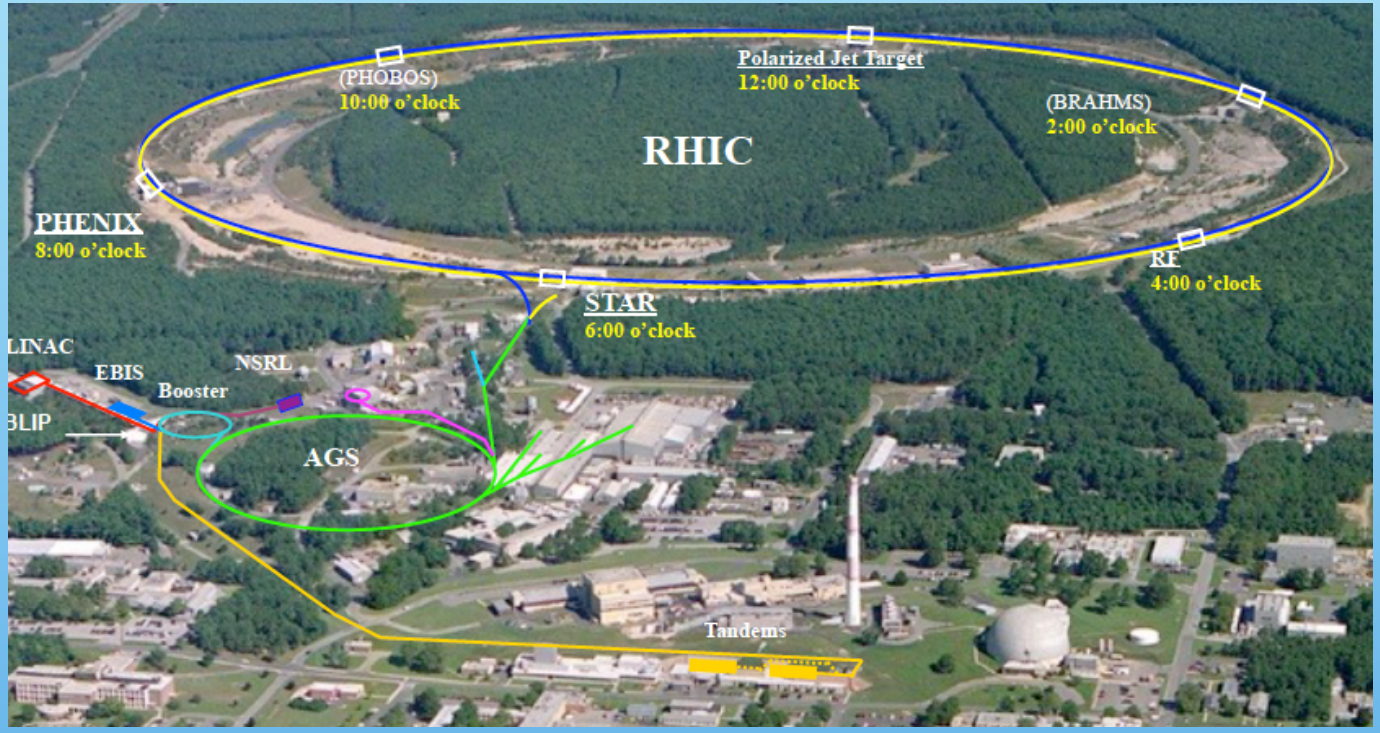
Later calculation: M Fromerth, J. Rafelski, astro-ph/0211346



Accelerators

Relativistic Heavy Ion Collider

at the Brookhaven Lab, Long Island, New York, USA



RHIC has been exploring nuclear matter at extreme conditions over the last 15 years 2000-2015

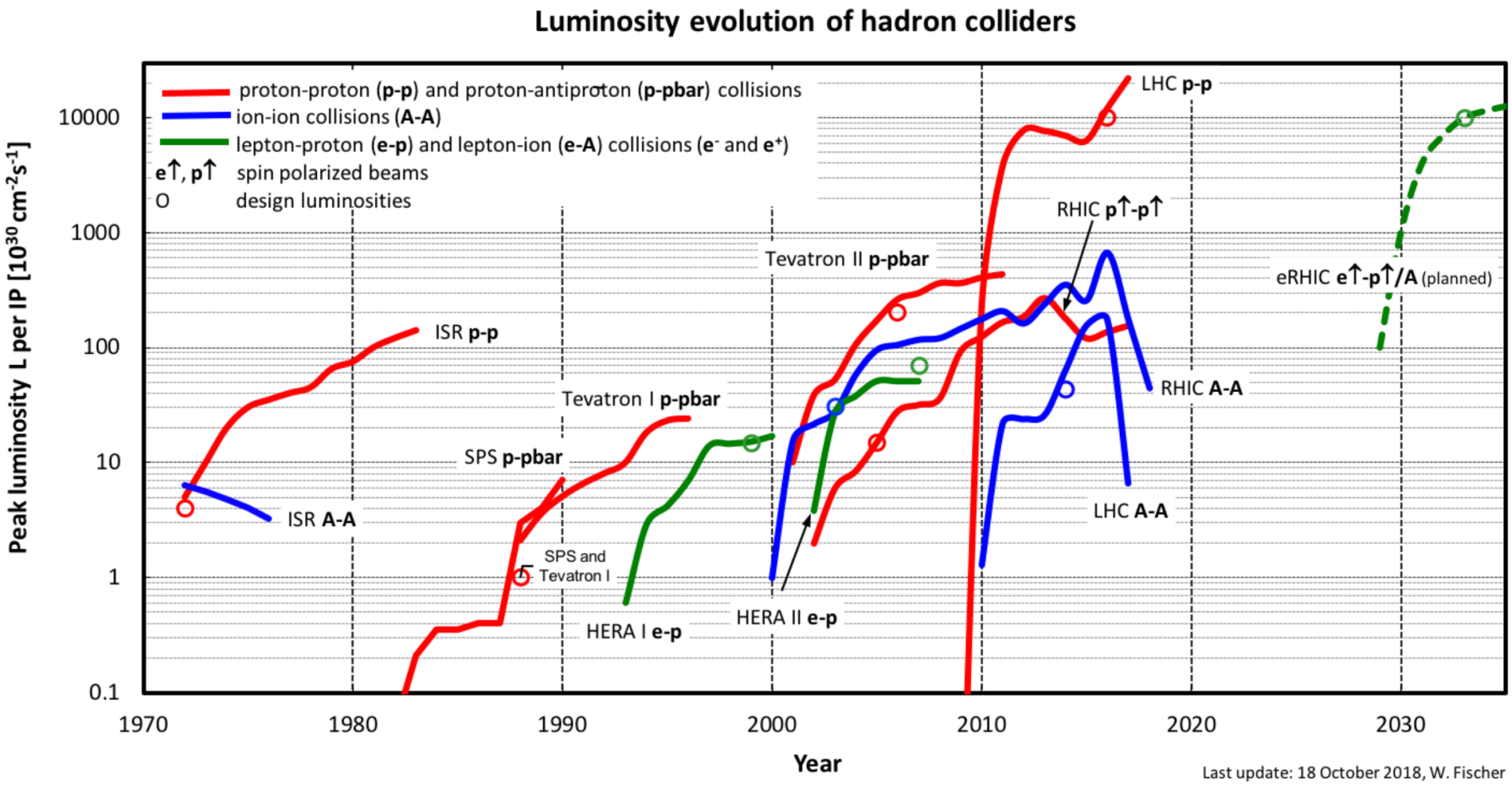
4 experiments initially:
STAR PHENIX
BRAHMS PHOBOS

Still runing: STAR and PHENIX

Colliding systems:
p+p, d+Au, Cu+Cu, Au+Au
Cu+Au, U+U

Energies A+A :
$\sqrt{s_{NN}}$ = 62, 130, 200 GeV
and low energy scan
7.7, 11.5, 19.6, 22.4, 27, 39 GeV
+ Fixed target

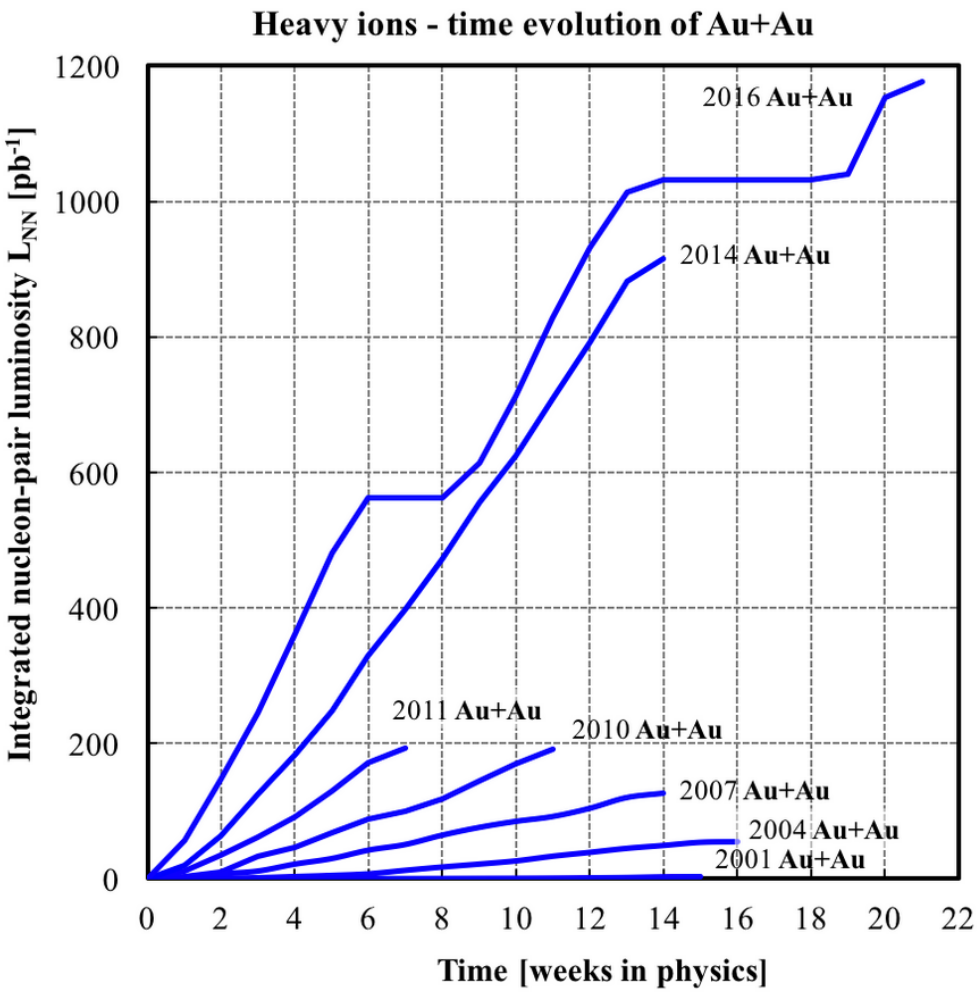
RHIC

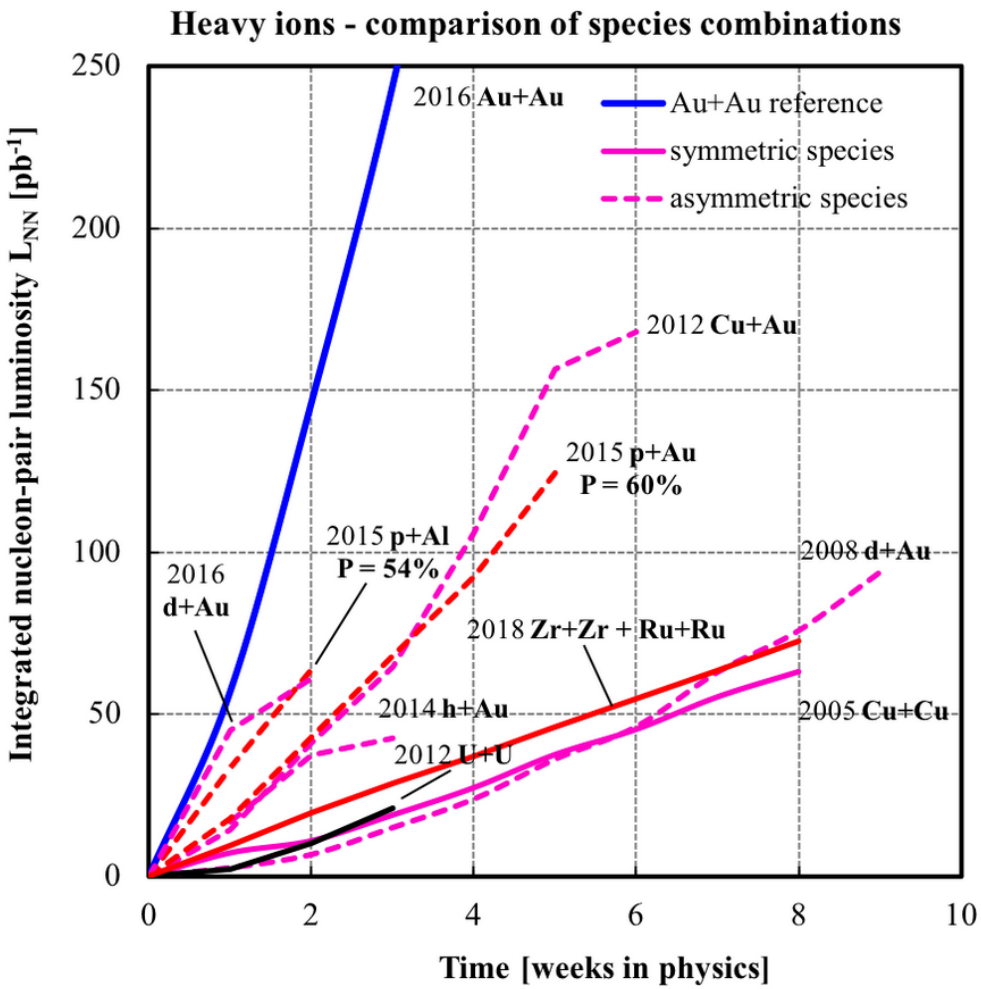


Luminosity per nucleon pair $L_{NN} = A_1 A_2 L$

Peak Luminosity AuAu 200 GeV 2016 : 1.55x10ˆ28 cm-2 s-1

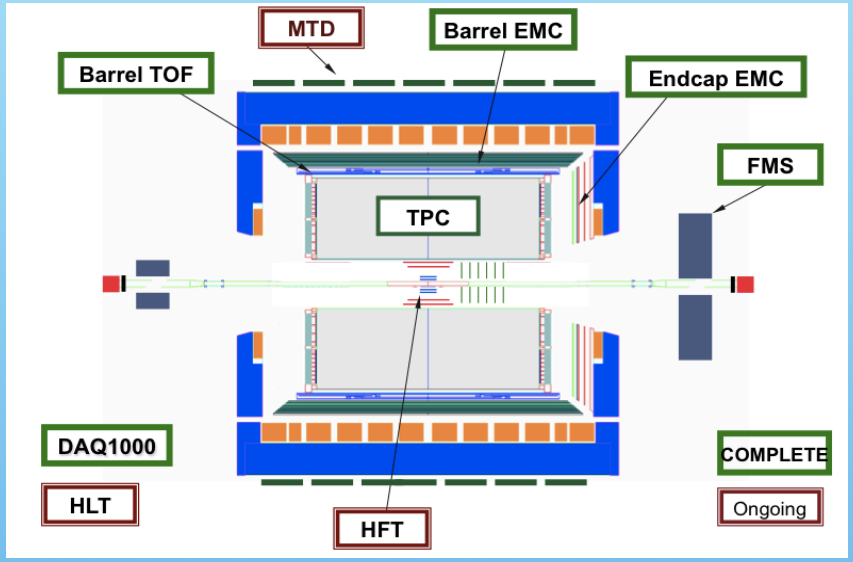
RHIC integrated Luminosity



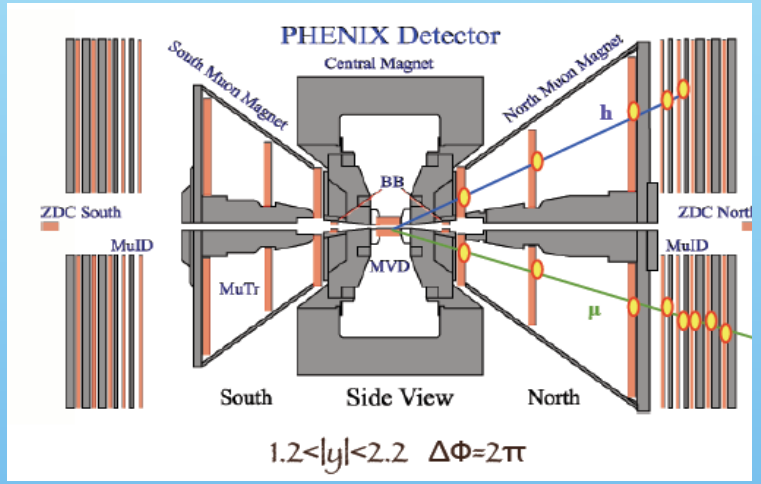


Current non-LHC Experiments with Heavy Ion program

STAR at RHIC

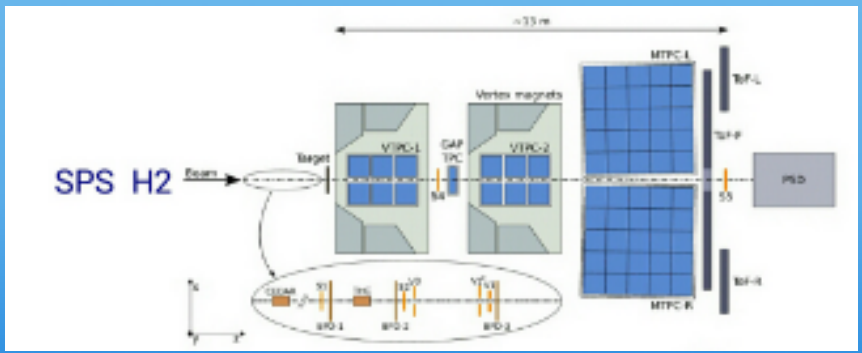


PHENIX at RHIC (data analysis only)



Stopped data taking but data analysis is in progress

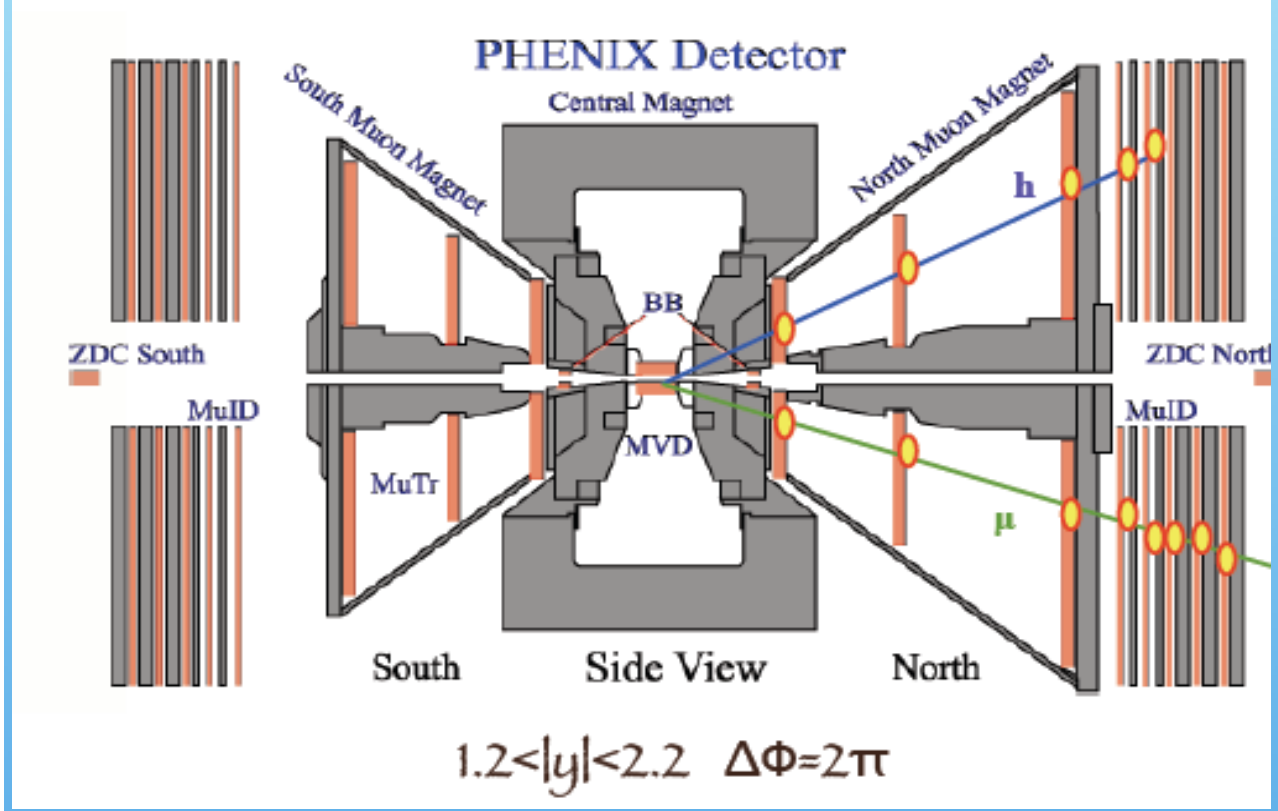
NA61/SHINE at SPS



HADES at GSI

Current non-LHC Experiments with Heavy Ion program

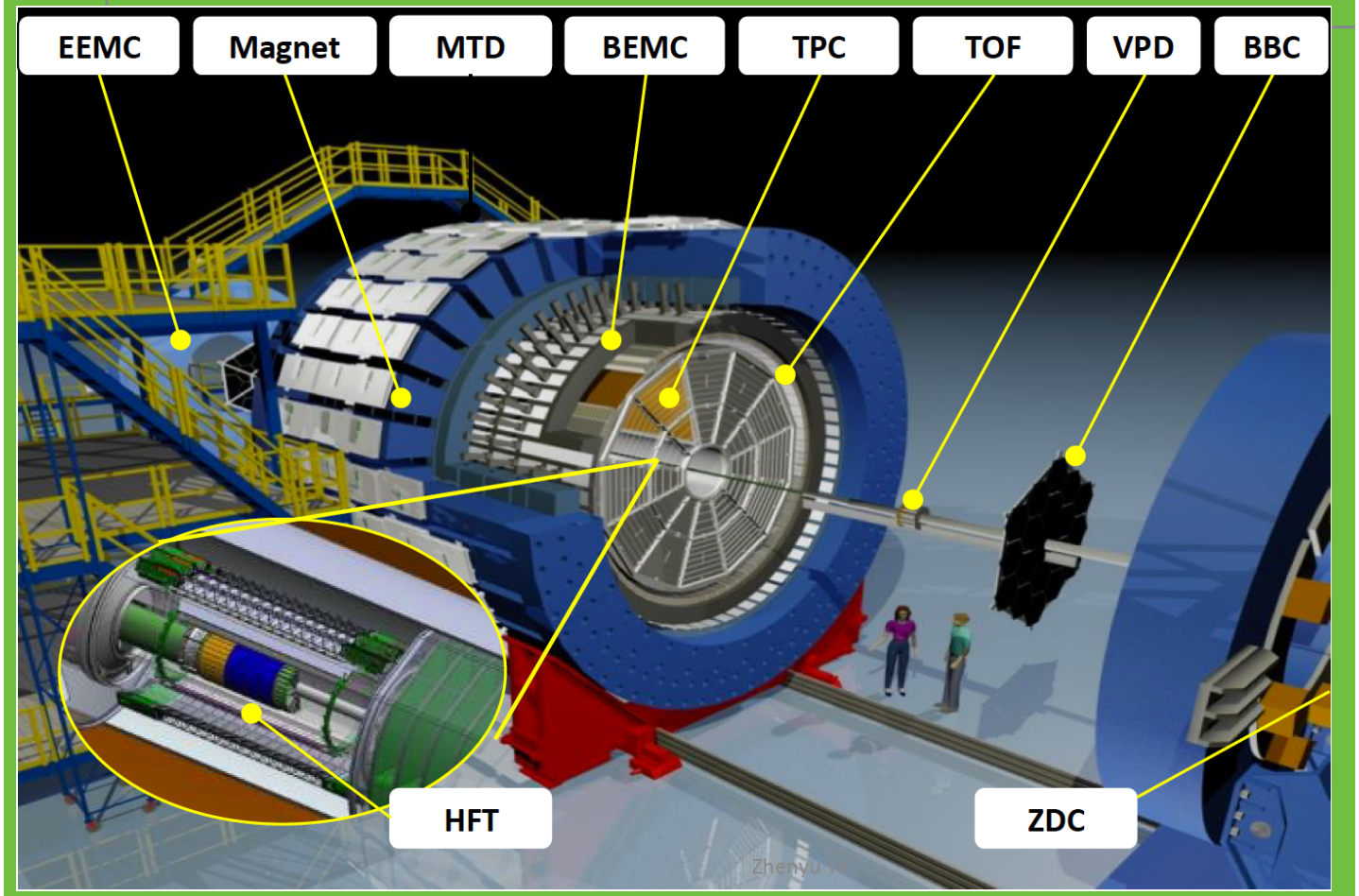
PHENIX at RHIC
(data analysis only)



Hadron, electron, photon identification
Muon identification

Stopped data taking but data analysis is in progress

The STAR detector



- **Tracking and PID (full 2π)**
  TPC: $|\eta| < 1$
  TOF: $|\eta| < 1$
  BEMC: $|\eta| < 1$
  EEMC: $1 < \eta < 2$
  HFT (2014-2016): $|\eta| < 1$
  MTD (2014+): $|\eta| < 0.5$
- **MB trigger and event plane reconstruction**
  BBC: $3.3 < |\eta| < 5$
  EPD (2018+): $2.1 < |\eta| < 5.1$
  FMS: $2.5 < \eta < 4$
  VPD: $4.2 < |\eta| < 5$
  ZDC: $6.5 < |\eta| < 7.5$
- **On-going/future upgrades**
  iTPC (2019+): $|\eta| < 1.5$
  eTOF (2019+): $-1.6 < \eta < -1$
  FCS (2021+): $2.5 < \eta < 4$
  FTS (2021+): $2.5 < \eta < 4$

Previous and present experiments

BNL AGS (E866, E917 …)

CERN SPS (NA35, NA36, NA49, NA44,
WA80, WA93, WA98
WA85, WA94, WA97, NA57,
NA50, NA52. NA61/SHINE…)

BNL RHIC (STAR PHENIX PHOBOS BRAHMS)

CERN LHC (ALICE, CMS. ATLAS,, LHCb)

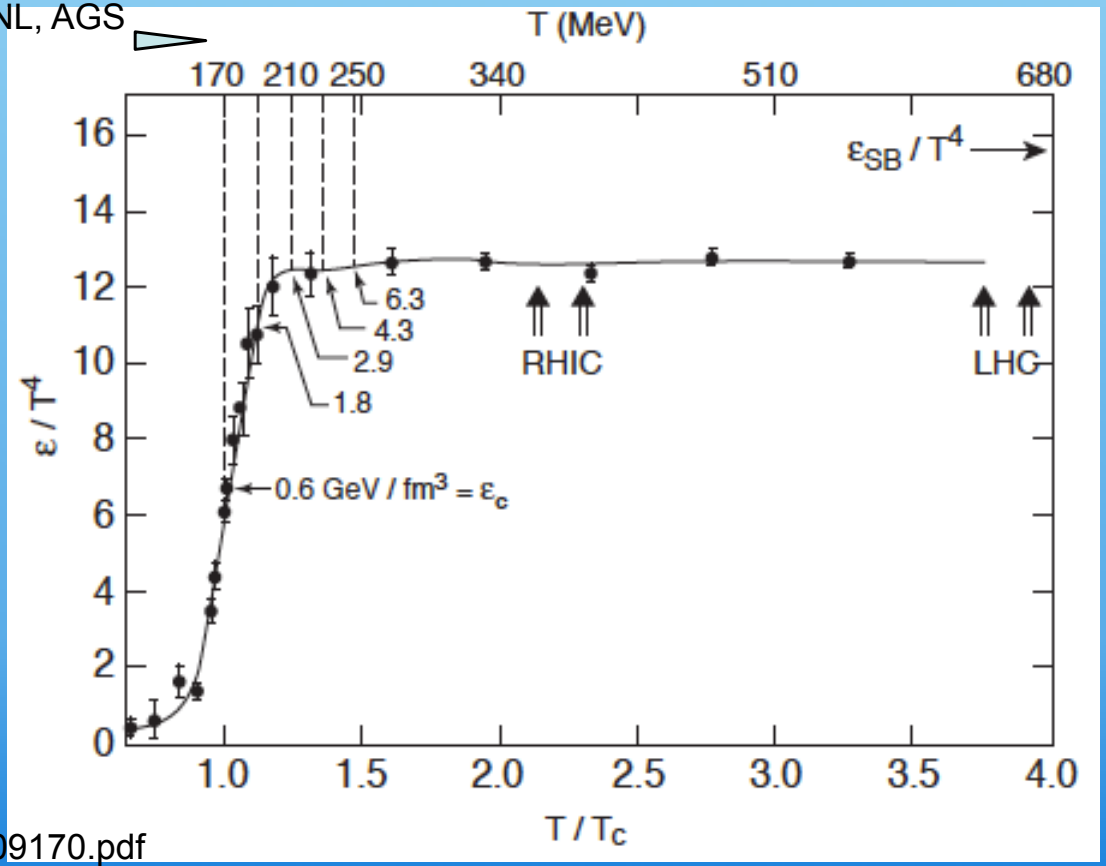
Reach of accelerators in terms of initial Temperature

CERN, LHC

BNL, RHIC

CERN, SPS

BNL, AGS



U. Heinz, 0009170.pdf

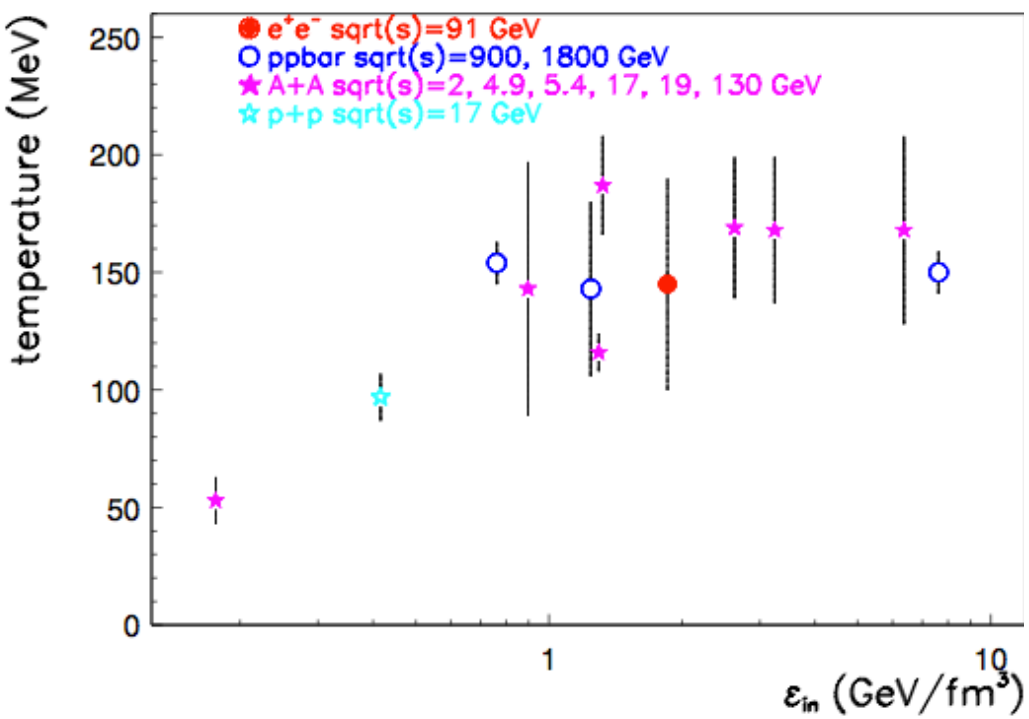
Signatures of the Quark Gluon Plasma

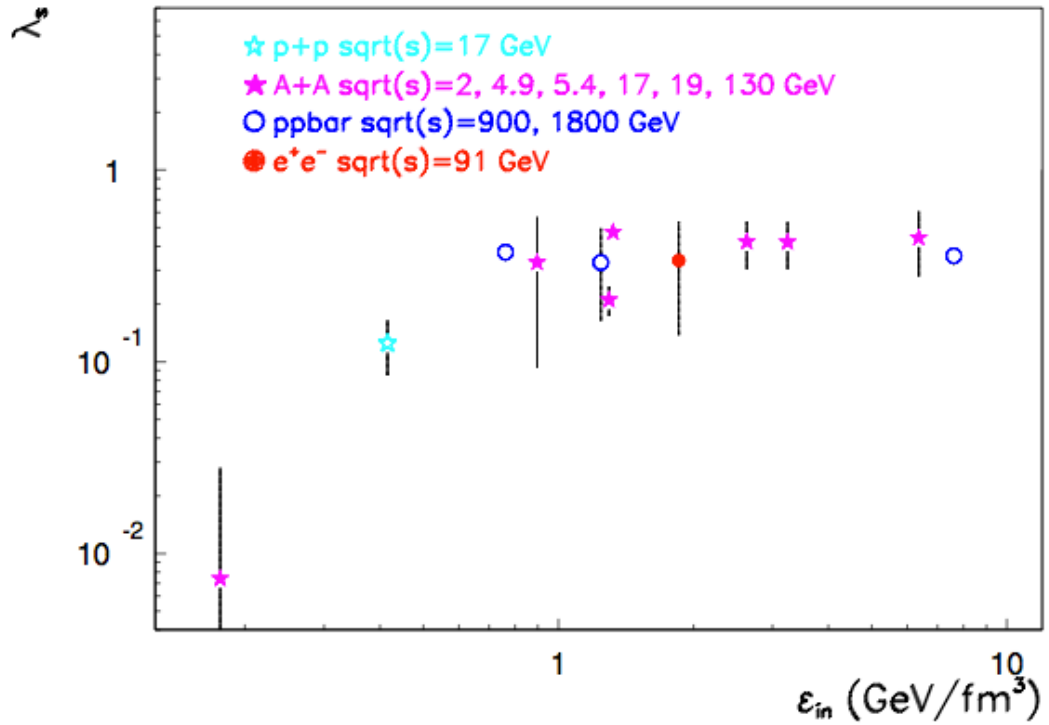
Direct photons from QGP → T(QGP)
Strangeness enhancement (Mueller, Rafelski 1981) → K/pi
U,d,s yields for T(freeze out) or pT slopes (Van Hove, H Stoecker et al) → plateau vs energy at Tc → e_init(crit), sqrt(s)("crit")
Multiquark states from QGP (Greiner et al) → 'small QGP-lumps'
Critical fluctuations near the critical point, Tc → K/pi, <pT>, etc
Hadronic mass/width changes (Pisarski 1982) → rho etc
Charmonia suppression (Satz, Matsui 1987) → T(dissociation) of ccbar, bbbar
Jet quenching (J D Bjorken 1982) → medium density

--> Goal is to achieve a combination of many signatures

Onset of QCD phase transition at mu_B=0 around ~ 0.8 GeV/fmˆ3

S.K., Peter Minkowski, 2001 New J. Phys. 3 4

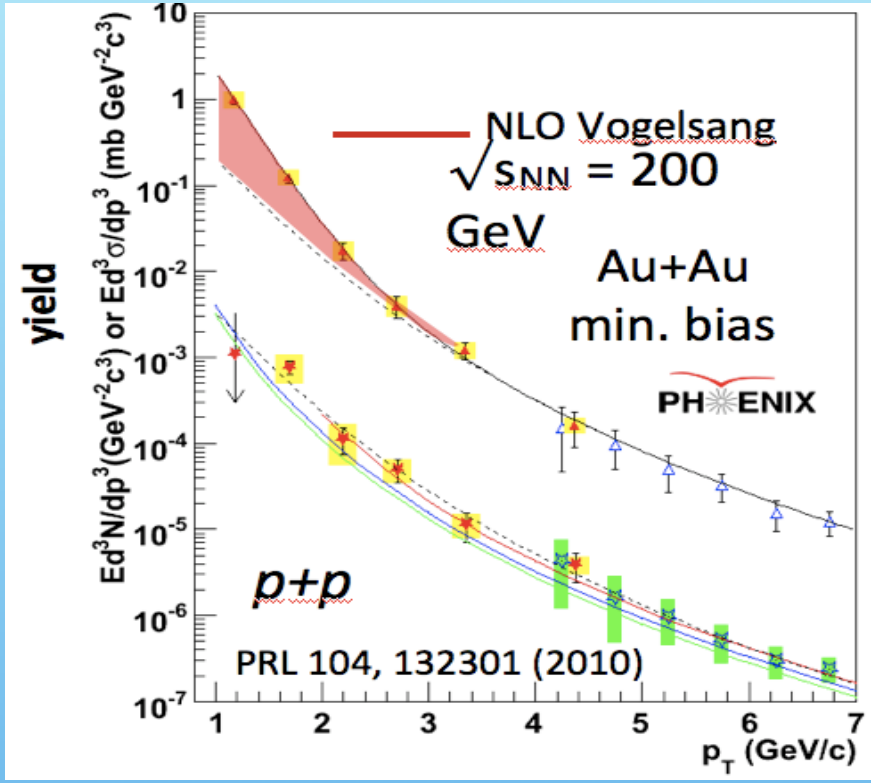


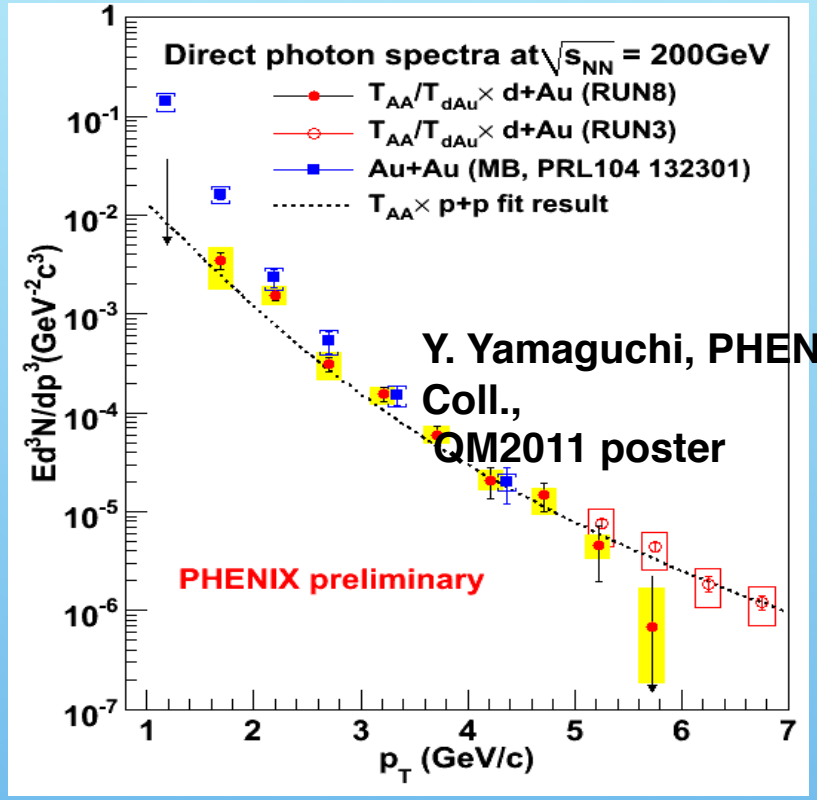


After extrapolating all data to muB=0, small and large systems exhibit universality, versus the Bjorken energy density.

The onset of saturation, approx 0.8 GeV/fmˆ3 reveals the onset of the QCD phase transition (vgl Van Hove's signature)

RHIC PHENIX: Direct photon excess in min bias Au+Au at 200 GeV





Confirmed also with other measurement method : PHENIX 1405.3940, published in PRC 91 (2015) 064904

Direct photons in p+p described by NLO

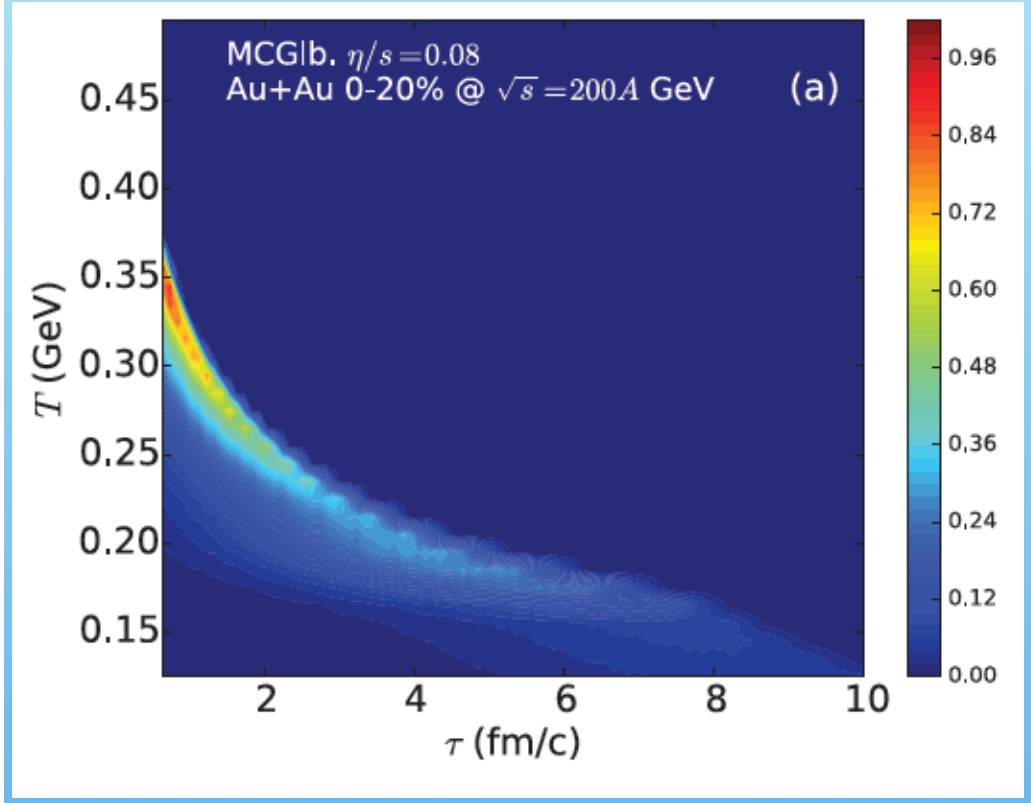
Direct photon excess in min. bias Au+Au at 200 GeV over p+p at 200 GeV below pT ~2.5 GeV

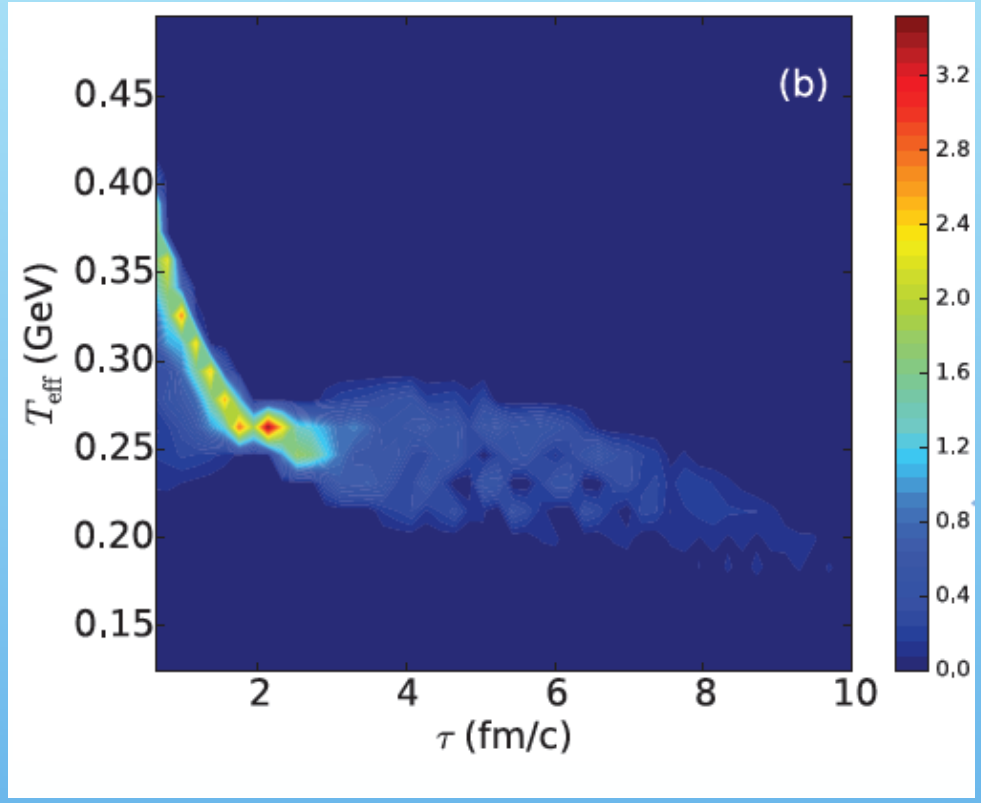
Exponential spectrum in Au+Au - consistent with thermal below pT ~2.5 GeV with inverse slope 220 ± 20 MeV --> T(init) from hydrodynamic models : 300-600 MeV, depending on thermalization time

Critical d+Au check : No exponential excess in d+Au

RHIC
Theory on direct photons

C. Gale et al, 1308.2440





The 3rd dimension in these plots is cross section of photons

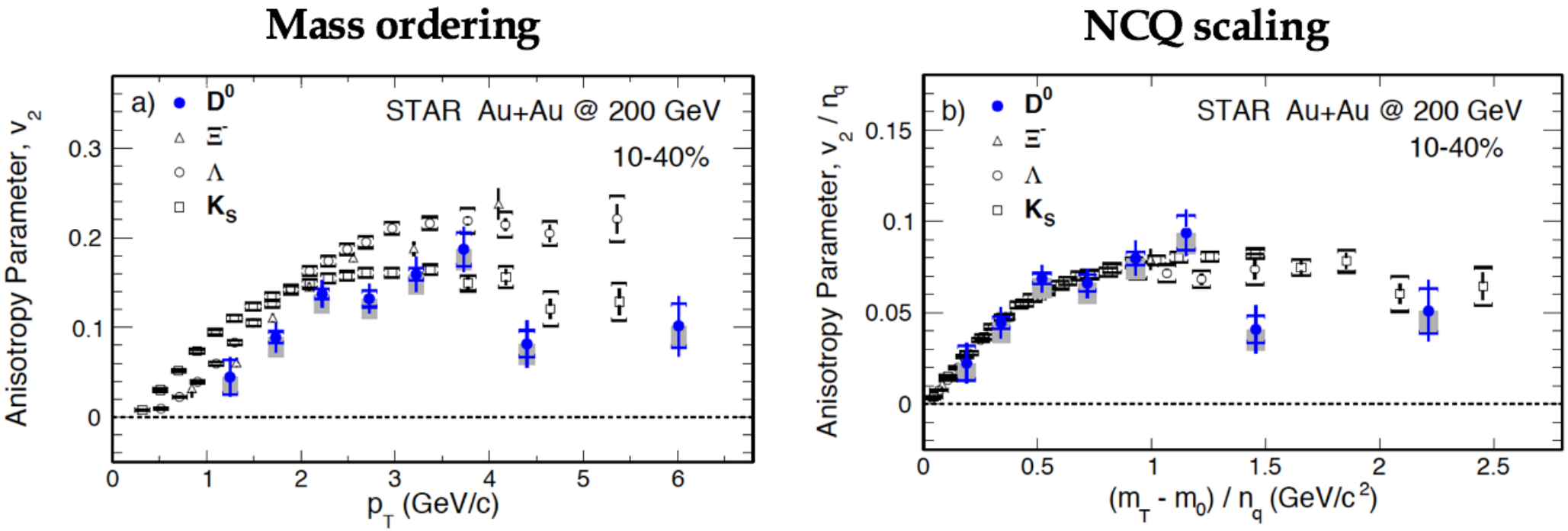
$$\frac{dN^{\gamma}/dydTd\tau}{dN^{\gamma}/dy}$$

T(init) ~350 MeV ->
T(observed)=260 MeV

Number of Constituent Quark scaling

Number-of-Constituent-Quarks scaling

Au+Au at sqrt(s)=200 GeV 1701.06060, STAR



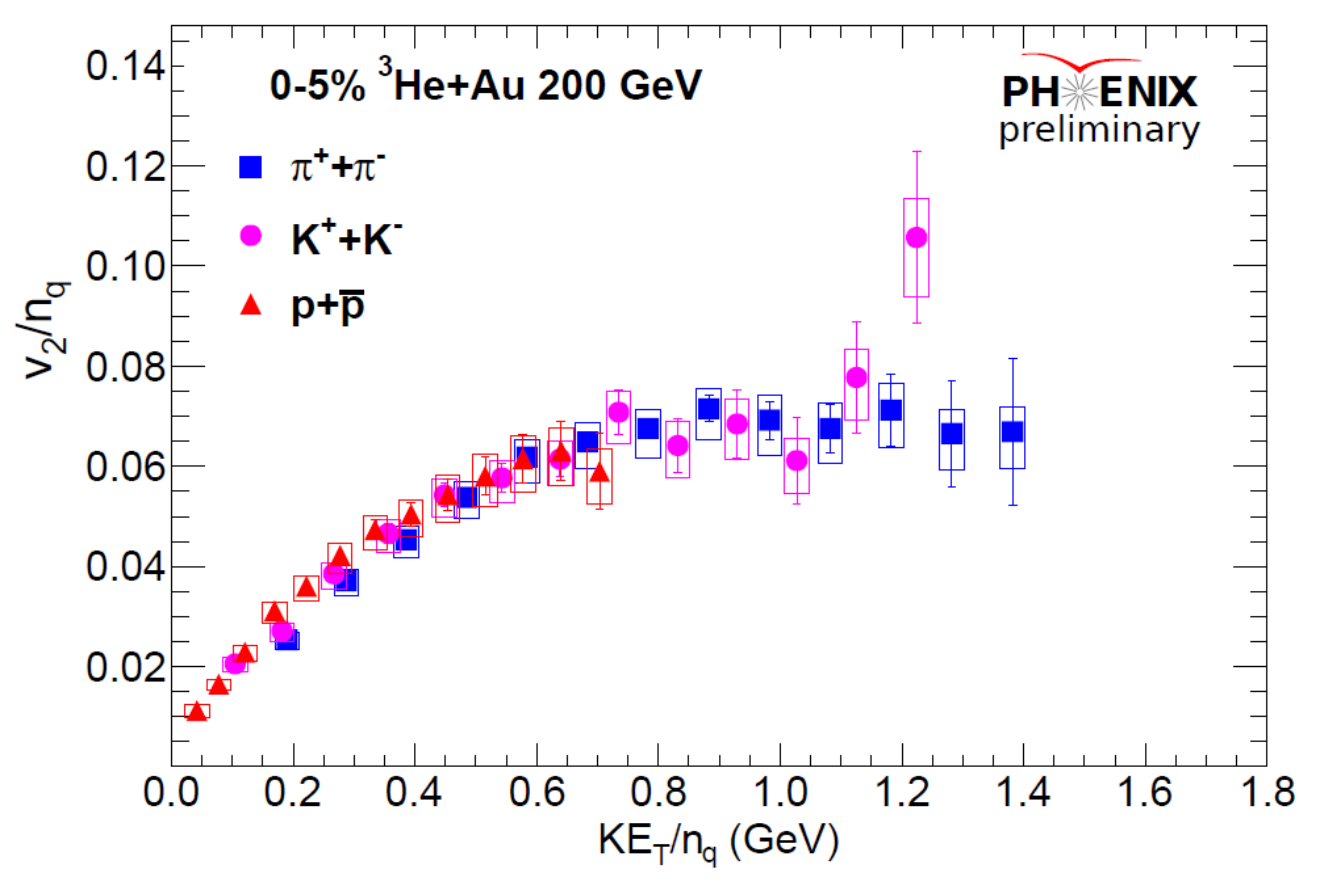
Strange hadrons as well as D0 follow the Number-of-Constituent-Quarks scaling

-> suggest hadronization out of partonic matter

-> Thermalization of charmed mesons?

-> Production of hadrons mainly via recombination of partons

Number of constituent quark scaling seen also in small systems: 3He+Au



S Huang, STAR, QM15

The familiar behavior of number of quark scaling observed in Au+Au collisions is also seen in the small ^{3}He+Au system

Heavy Ion Collisions: dominant hadron production mechanism via quark coalescence

- The "Number of Constituent Quark Scaling" suggests dominan hadron production via quark coalescence out of a hadronizing QGP.
- Other data like particle yields and ratios agree also with production via coalescence

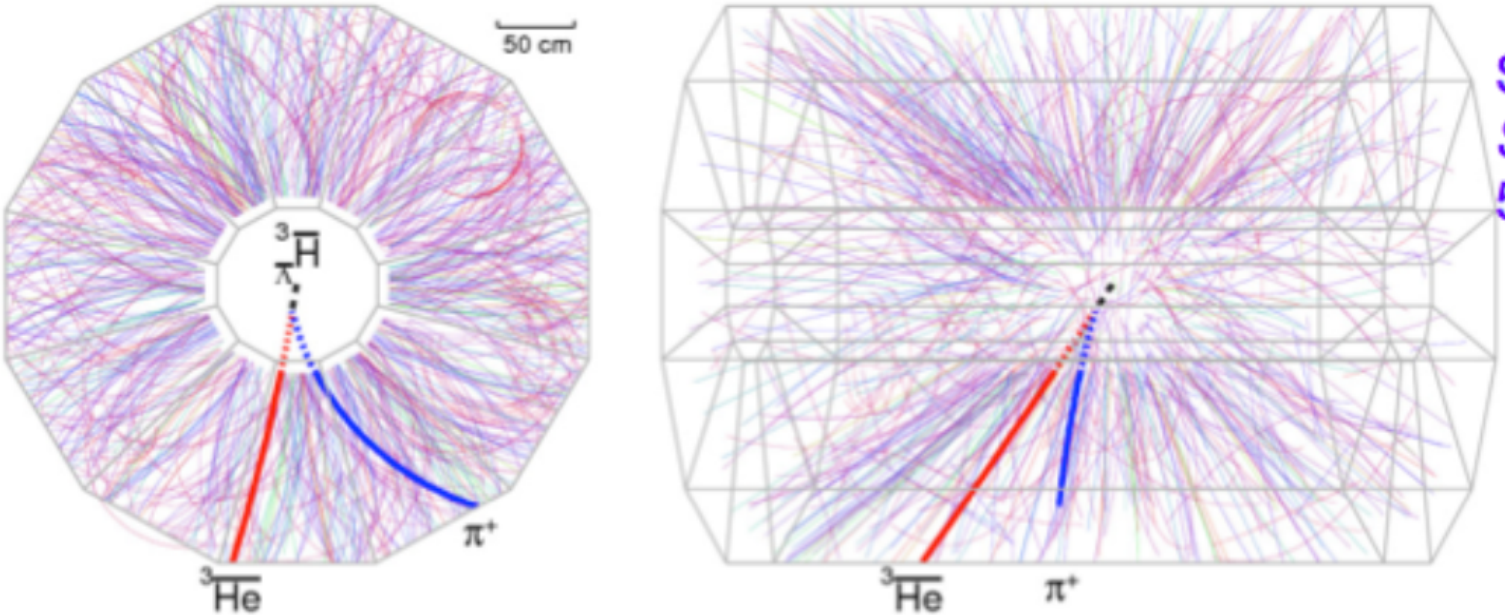
- As a consequence the hot and dense partonic matter produced in heavy ion collisions is expected to be a good source of multipartonic states like :
pentaquarks, tetraquarks, dibaryons, strangelets, glueballs and hybrids

since the coalescence production mechanism is expected to be enhanced in the QGP and can dominate the overall cross section

Antihypernuclei

RHIC antihypertriton

Hypertriton: consists of a Lambda, a proton and a neutron, was discovered in 1952. However no antihypernuclei were observed, until STAR.

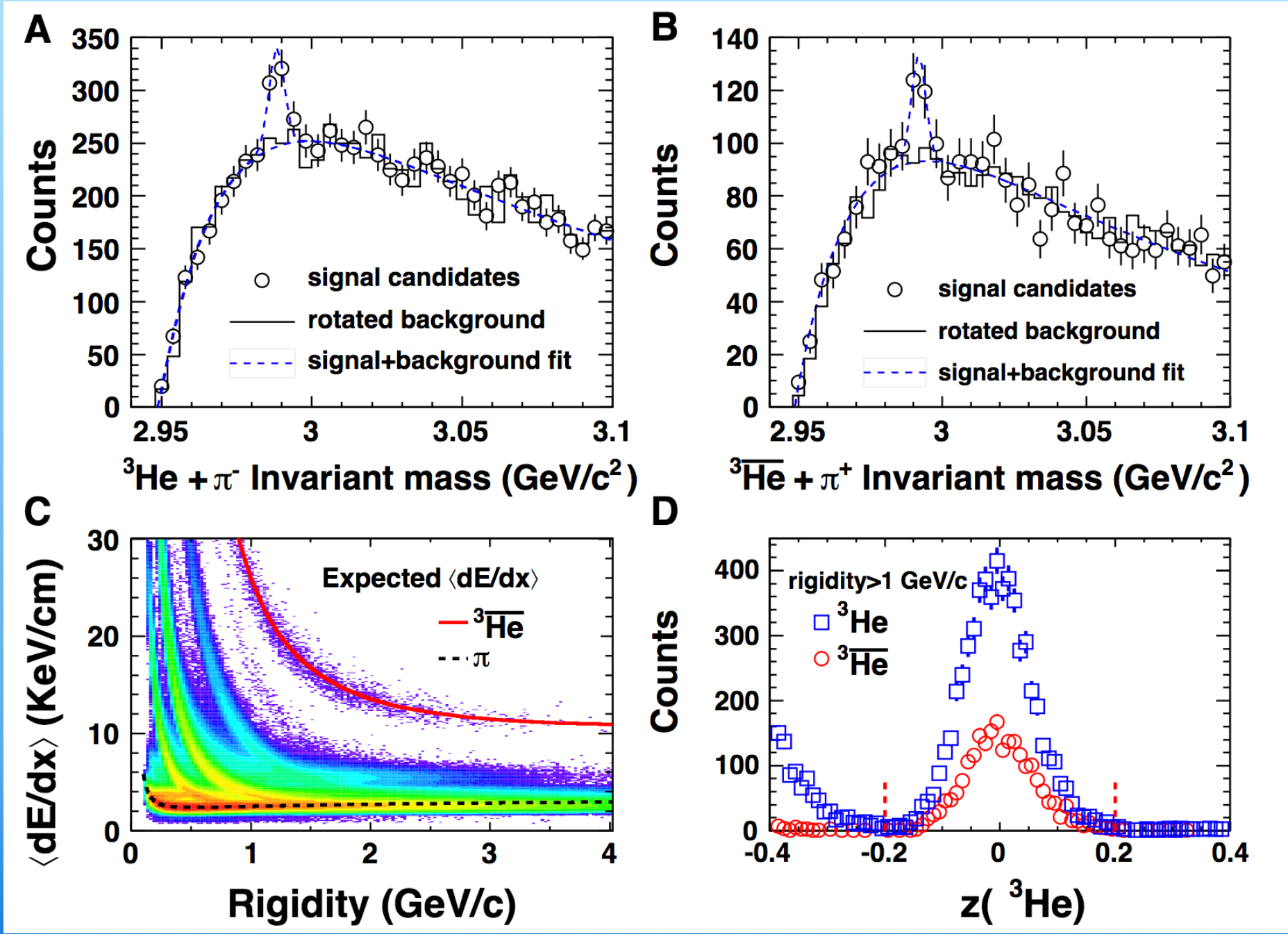


STAR Collab., *Science* **328**, 58 (2010)

$$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^-$$

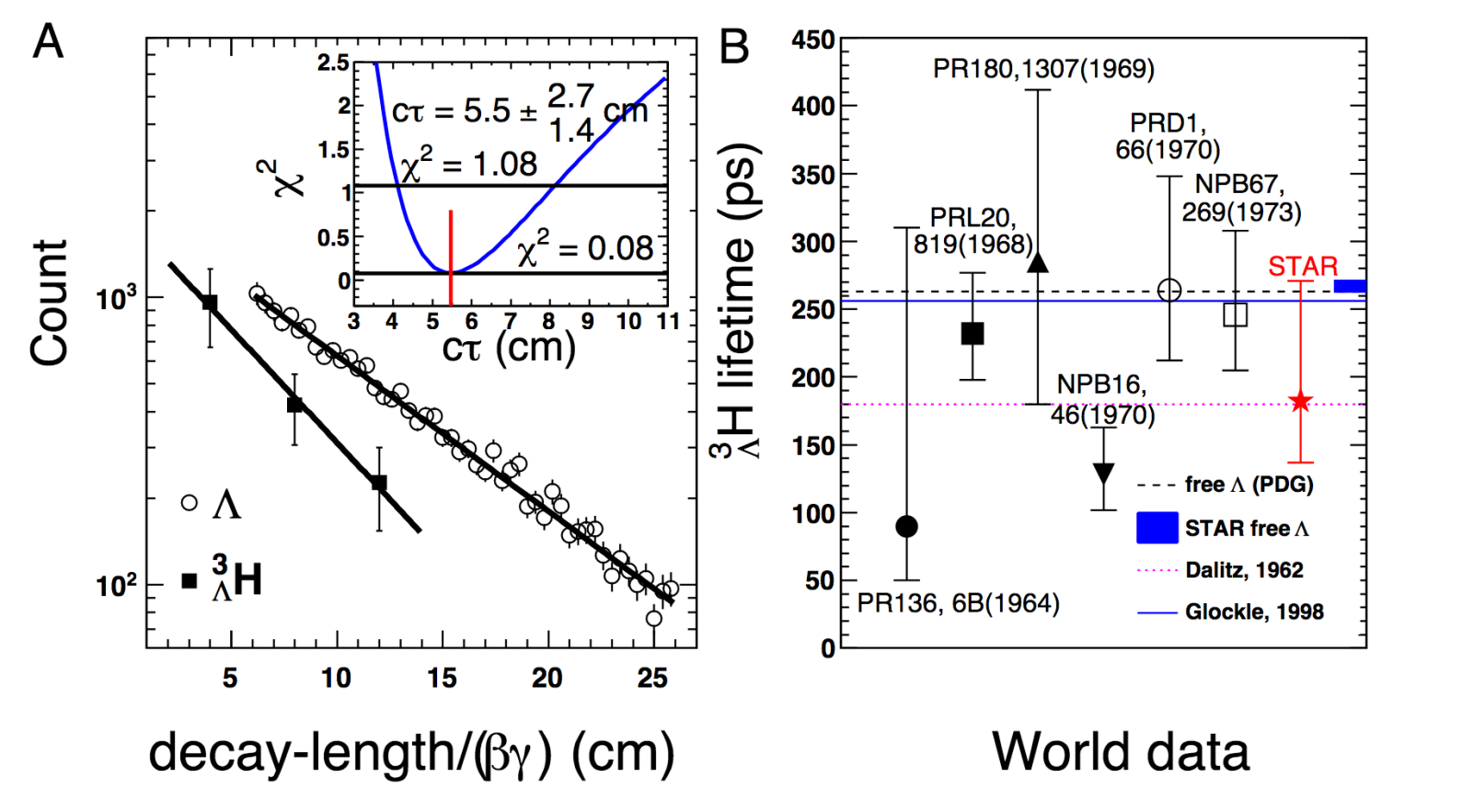
- ★ Anti-hypertriton: anti-proton, anti-neutron & anti-Λ – the first antinucleus with strangeness, and the heaviest antinucleus so far.
- ★ After searching >100 million AuAu collisions, found 70 anti-hypertritons.
- ★ Published in *Science* in March 2010; News stories in *Nature*, *Scientific American*, *National Geographic*, many news outlets worldwide.

STAR antihyernucleus



Hypertriton and Lambda lifetime

STAR, 2010 paper



STAR Hypertriton lifetime=

$$182 \pm^{89}_{45} \pm 27 \text{ ps}$$

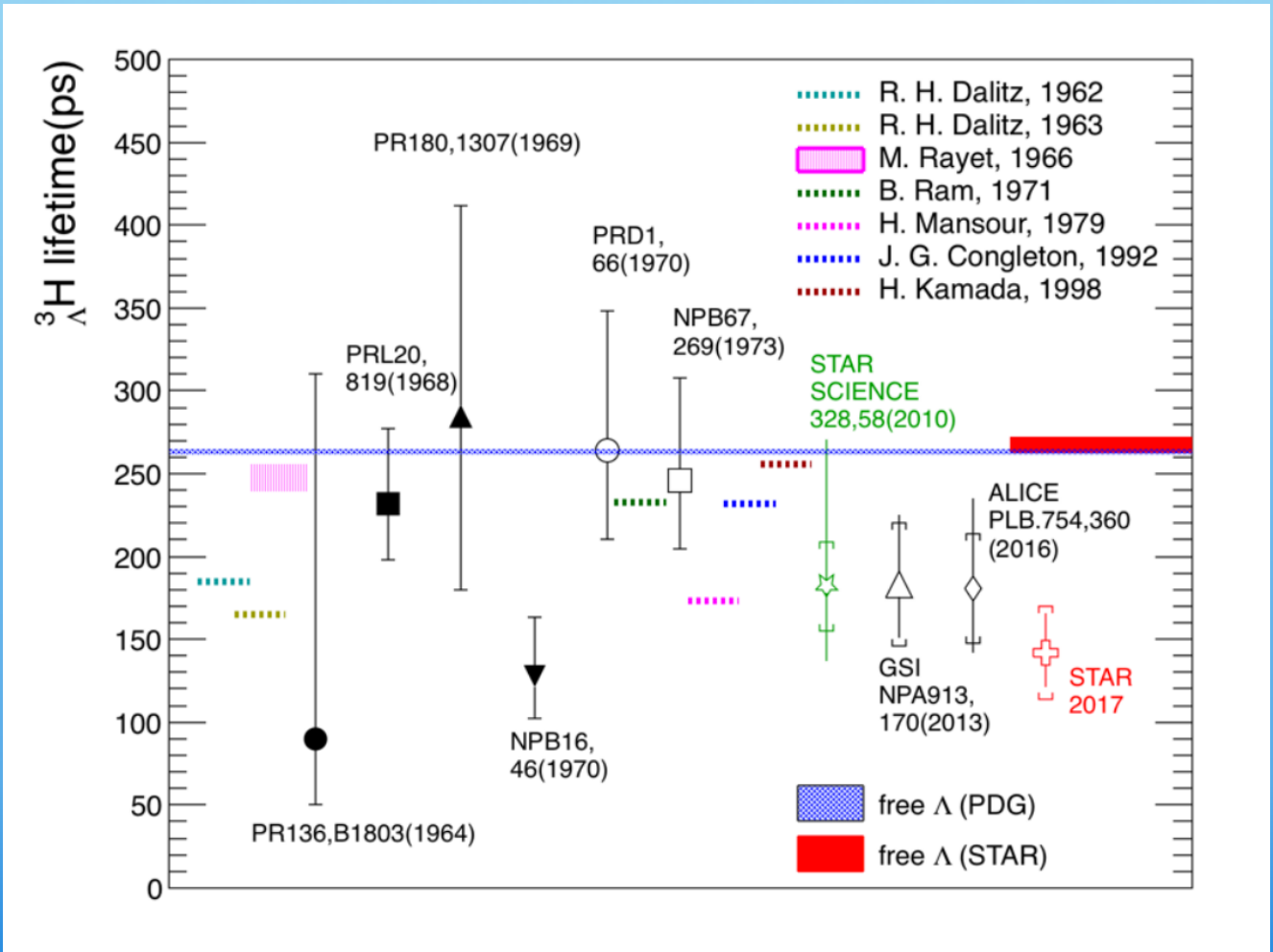
Lambda->proton lifetime PDG=

$$\tau = 263 \pm 2 \text{ ps}$$

2010: lifetime within uncertainties consistent with Lambda to proton + pi- lifetime

Hypertriton and Lambda lifetime

Phys.Rev. C97 (2018) no.5, 054909

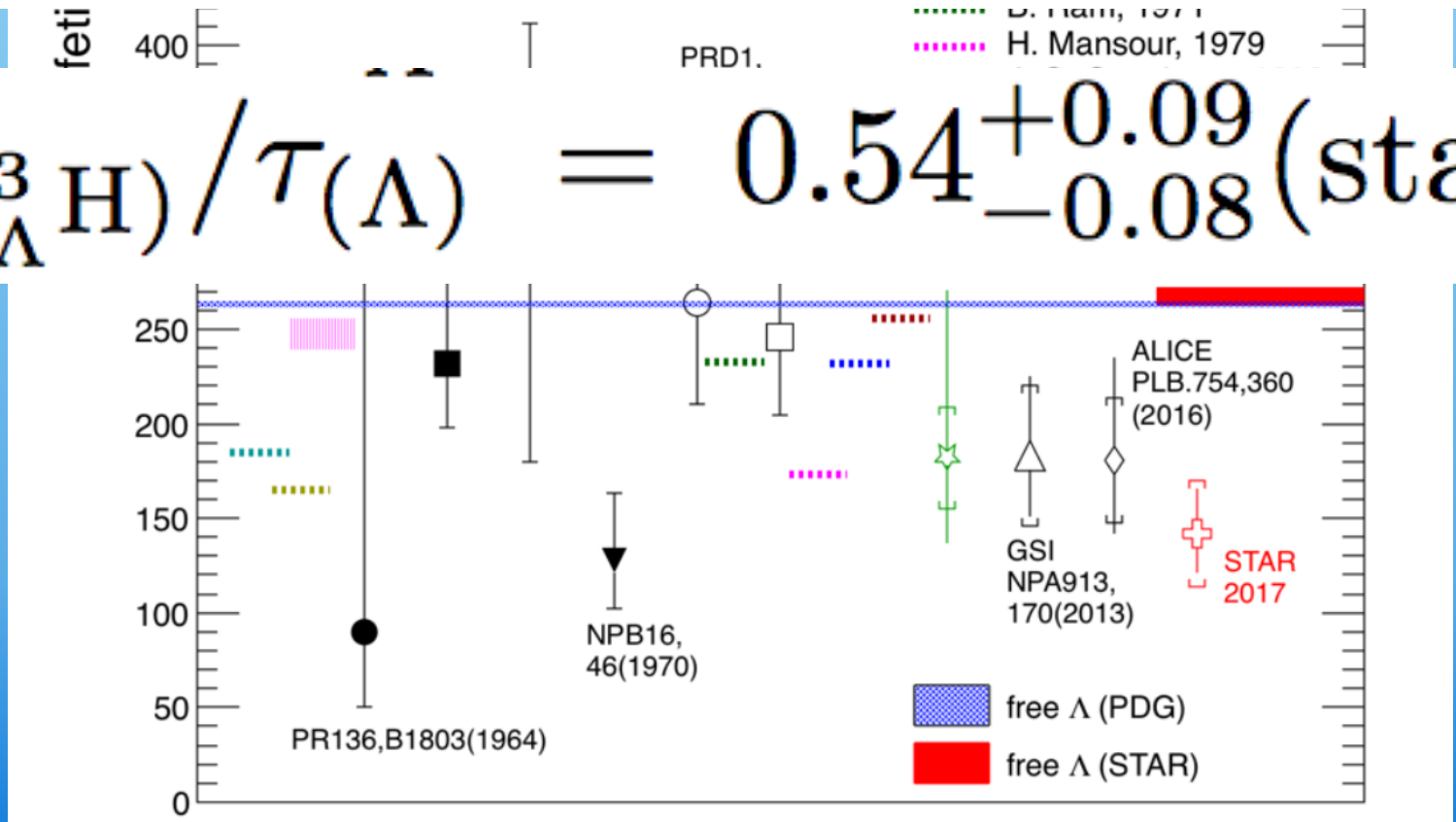


STAR Hypertriton and Lambda lifetime

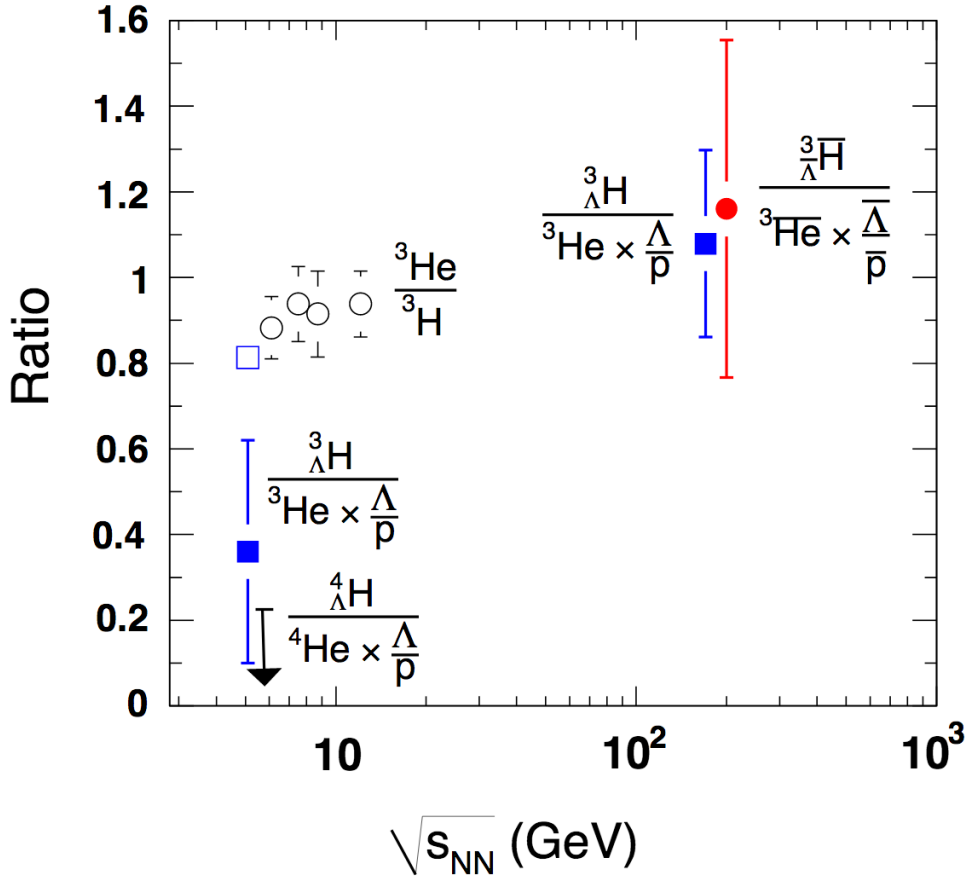
Phys.Rev. C97 (2018) no.5, 054909

$$\tau = 142^{+24}_{-21}\,(\text{stat.}) \pm 31\,(\text{syst.})$$

$$\left(\tau_{({}^{3}_{\Lambda}\text{H})}/\tau_{(\Lambda)} = 0.54^{+0.09}_{-0.08}(\text{stat.})\right)$$



STAR Antihypernucleus

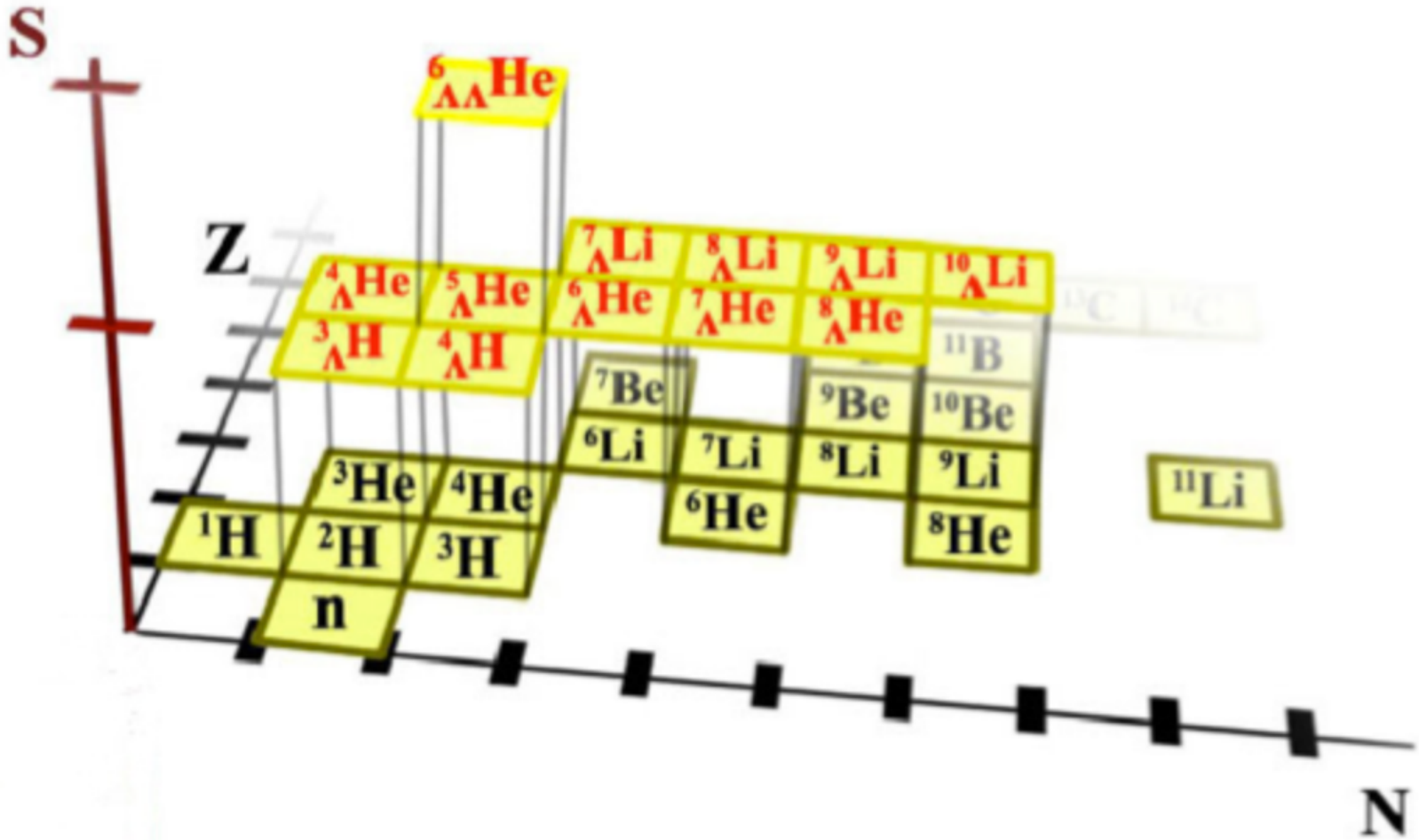


$$\frac{^3_\Lambda H}{^3He \times \frac{\Lambda}{p}}$$

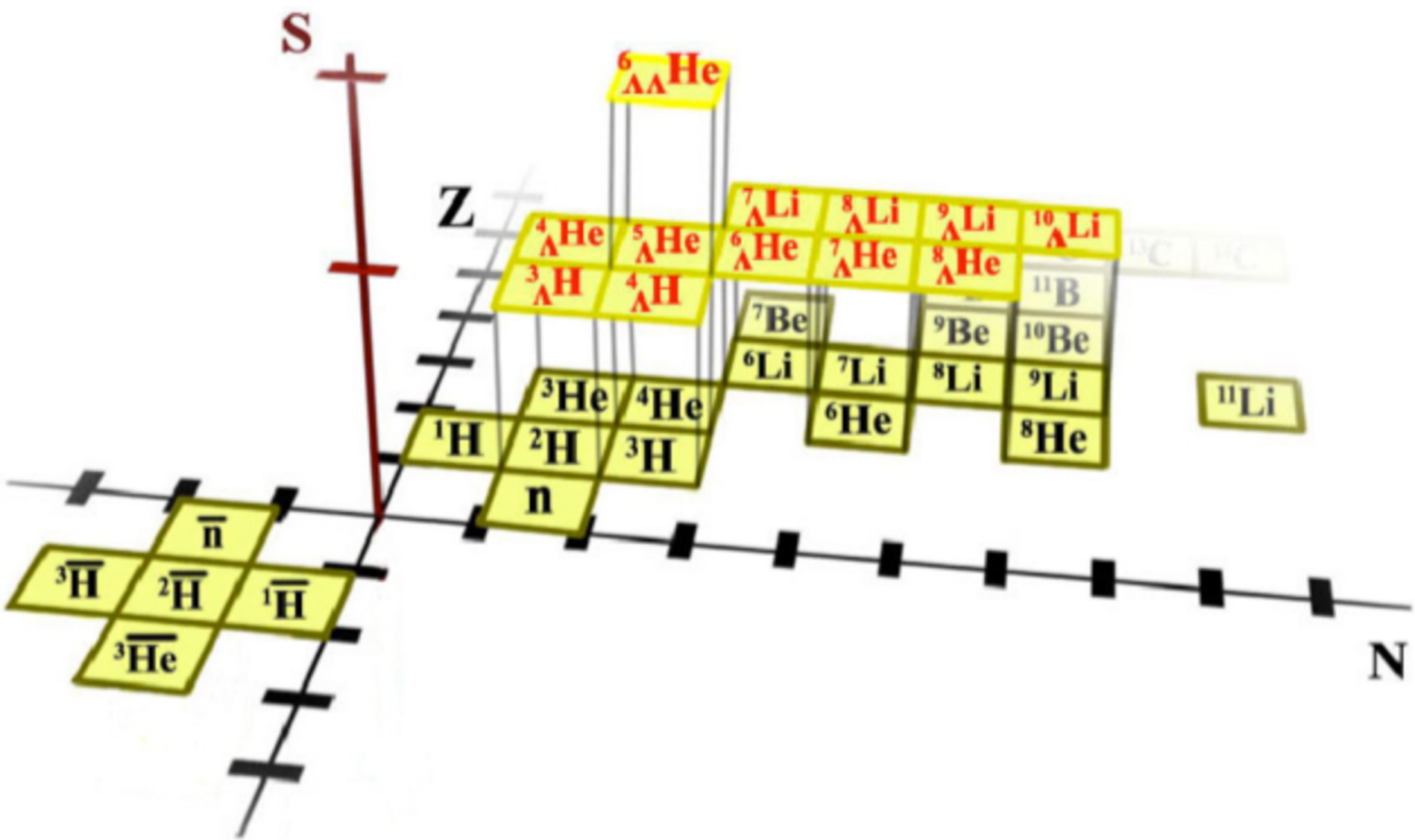
$$\frac{^3_{\bar\Lambda}\bar{H}}{^3\overline{He} \times \frac{\bar\Lambda}{\bar p}}$$

Ratio is close to unity, and is larger than at lower beam energy,suggesting an equilibrium in coordinate and momentum space populations of up down and strange quarks and antiquarks

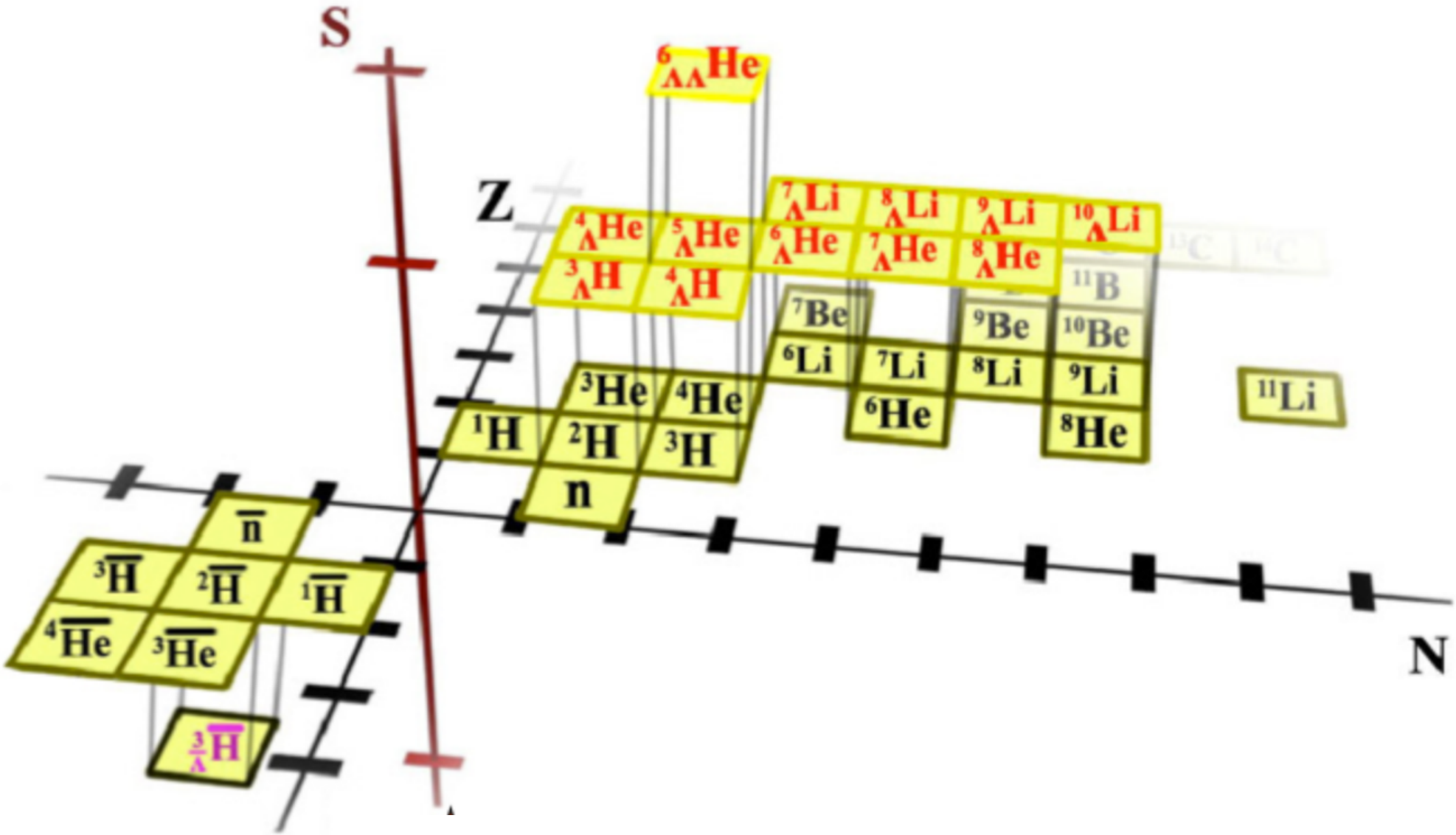
3-D chart of the Nuclides



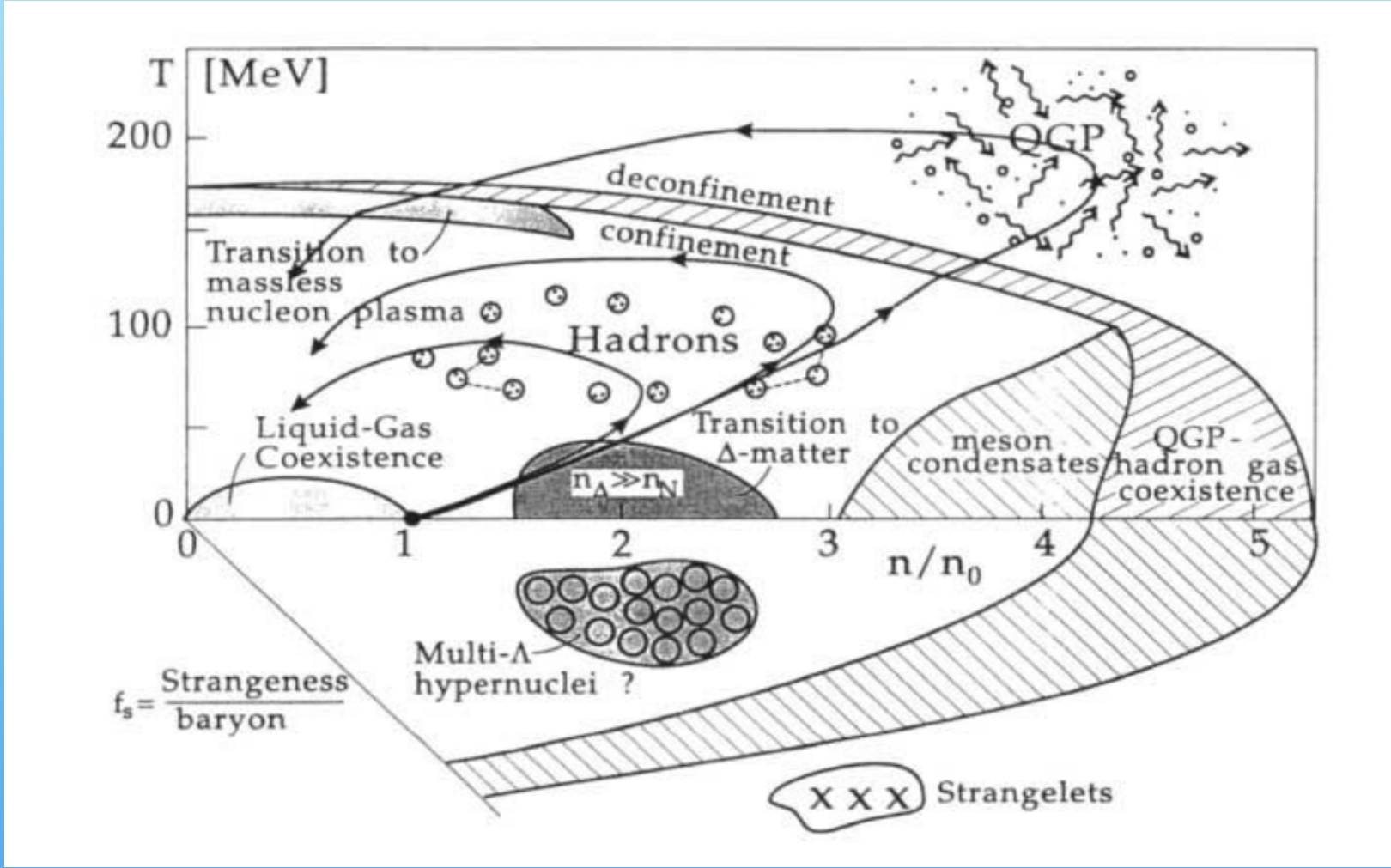
3-D chart of the Nuclides



3-D chart of the Nuclides



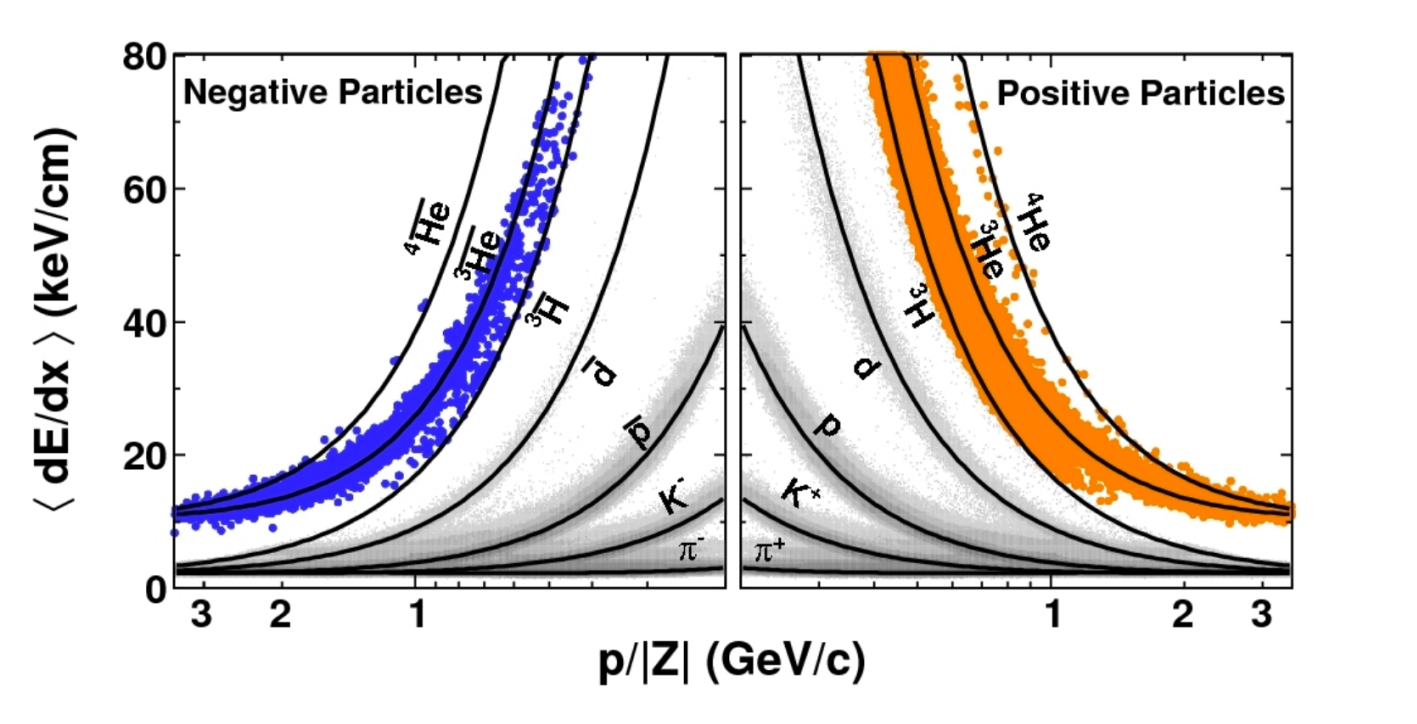
Phase diagram with Strangelets and hypernuclei



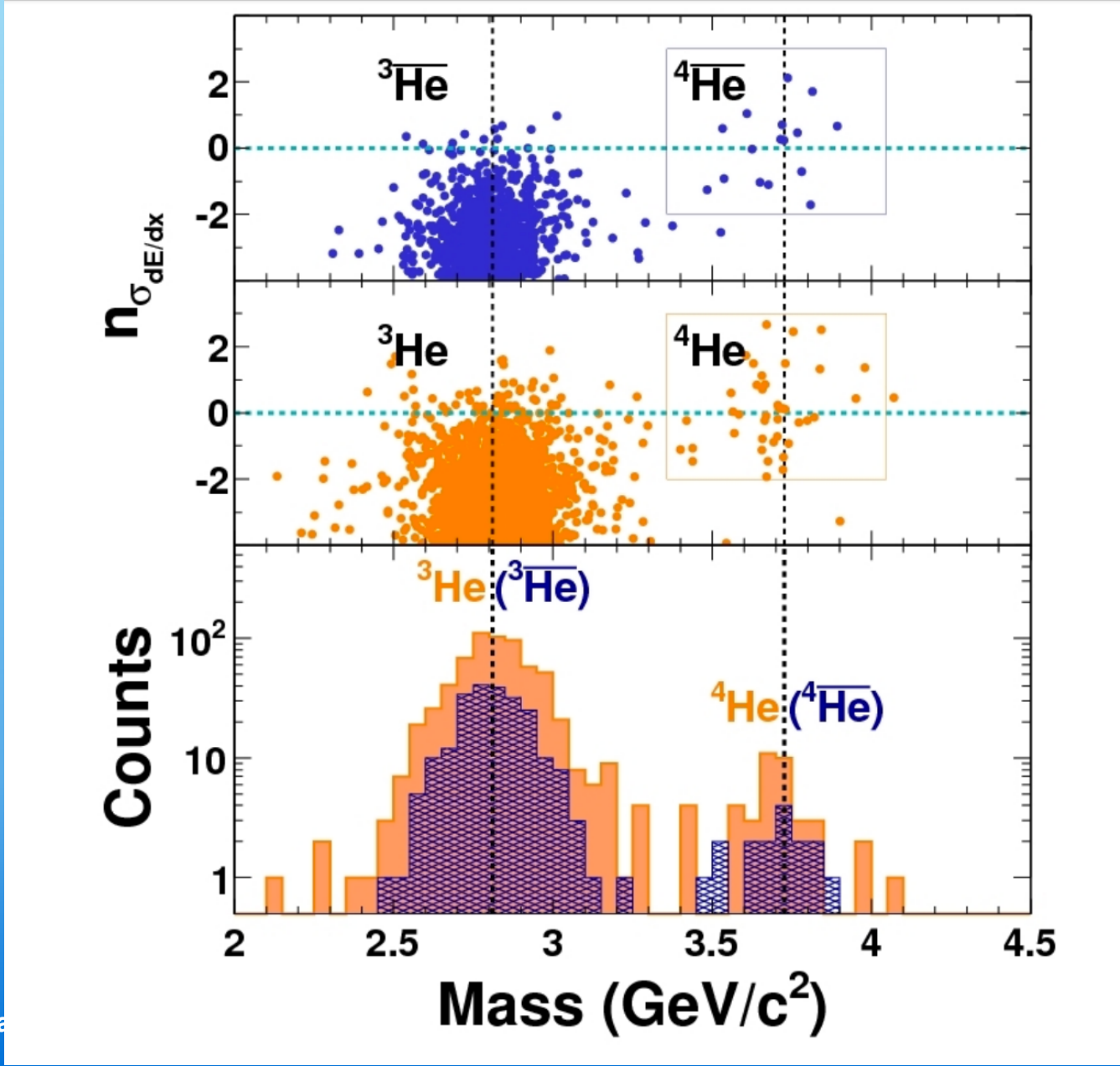
Int J of Mod Phys 1996,W. Greiner

STAR: Observation of the antimatter helium-4 nucleus

Nature 473 (2011) 353

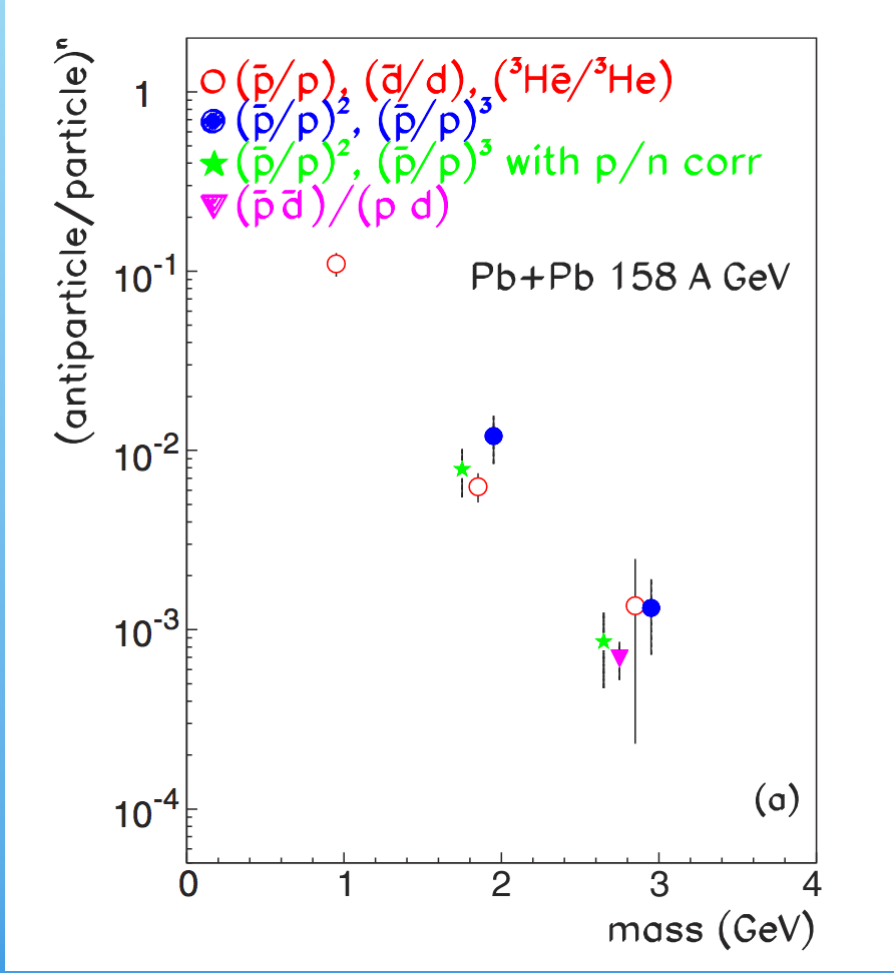


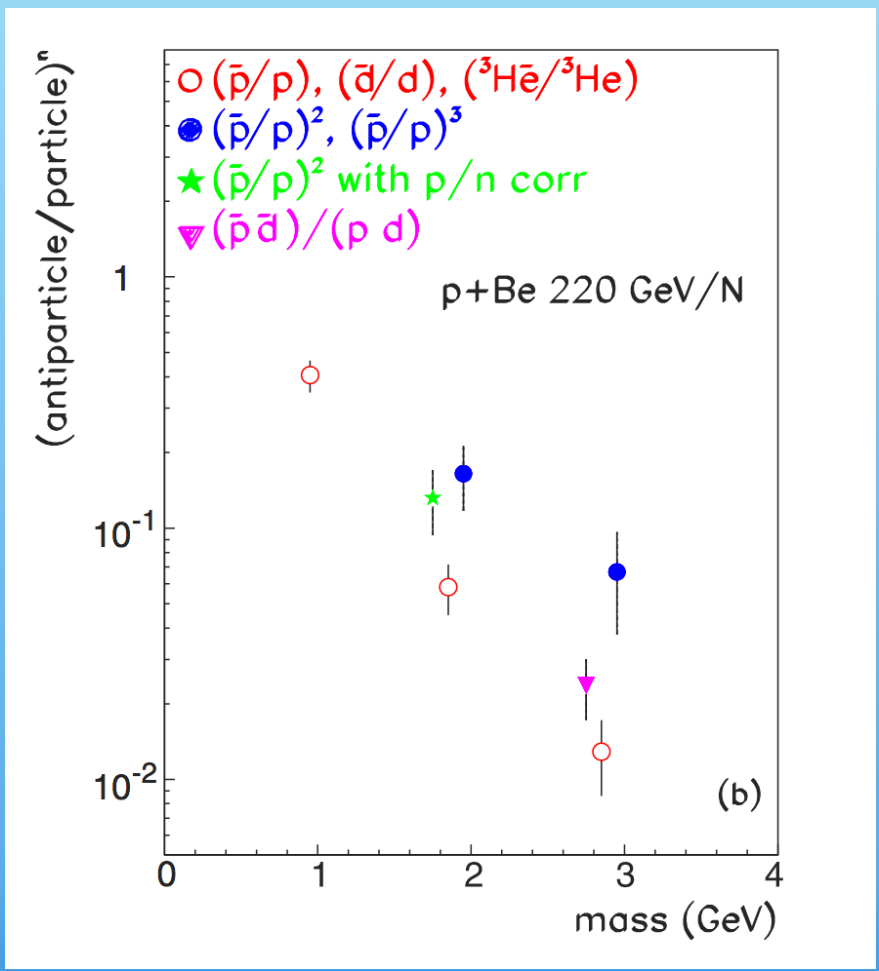
STAR: Observation of the antimatter helium-4 nucleus



NA52 Nuclei and antinuclei PbPb at sqrt(s)=17 GeV

NA52, New J.Phys. 5 (2003) 150





Data consistent with nuclei and antinuclei coalescence in A+A, unlike p+Be

Dark Photon Searches

PHENIX dark photon

PHENIX Dark Photon Search

PHENIX 1409.0851

A number of deviations between experimental data and the Standard Model like

*** the 3.6 sigma deviation of (g-2) of the muon**

*** the positron excess in cosmic rays observed in ATIC, PAMELA, and AMS-2**

can be attributed to the existence of a "dark photon", which is weakly coupled to the QED photon.

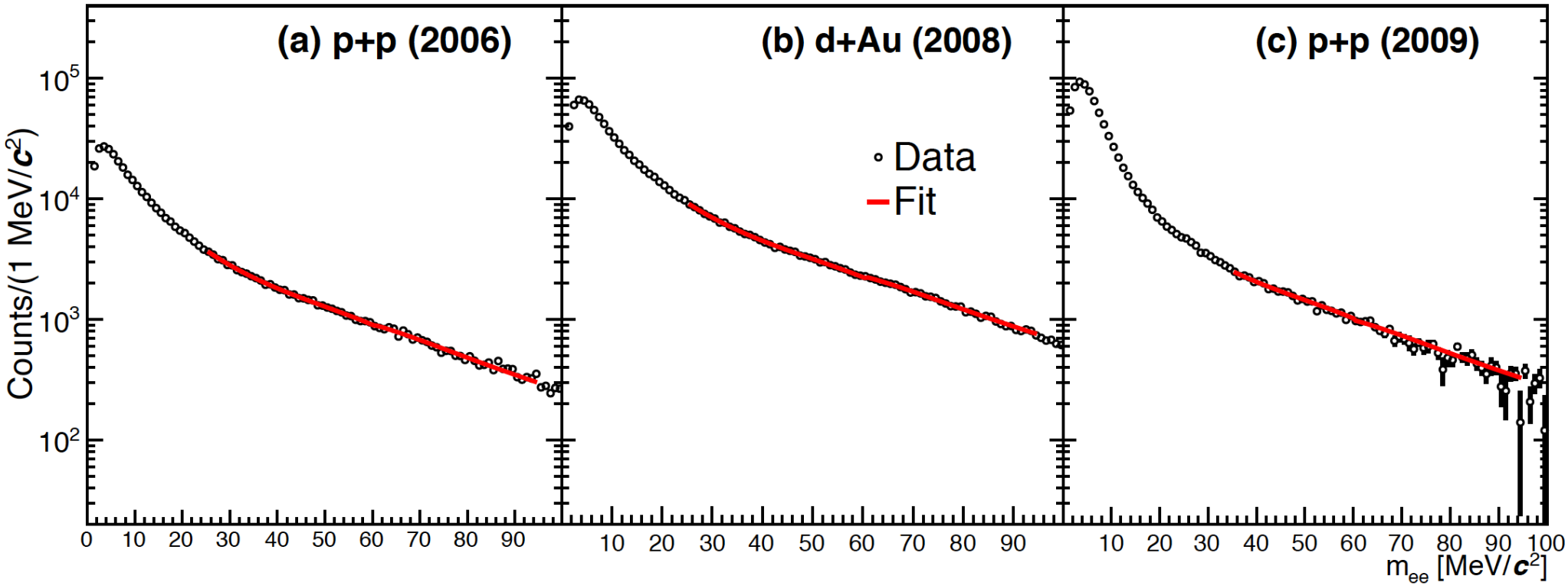
For m(DP)=m(DarkPhoton)>2m(electron) and < 2m(muon) decay into e+e- can be considered

PHENIX experiment at RHIC searhed for the Dark Photon in the channel

$$\pi^0, \eta \rightarrow \gamma U, U \rightarrow e^+e^-$$

PHENIX 1409.0851

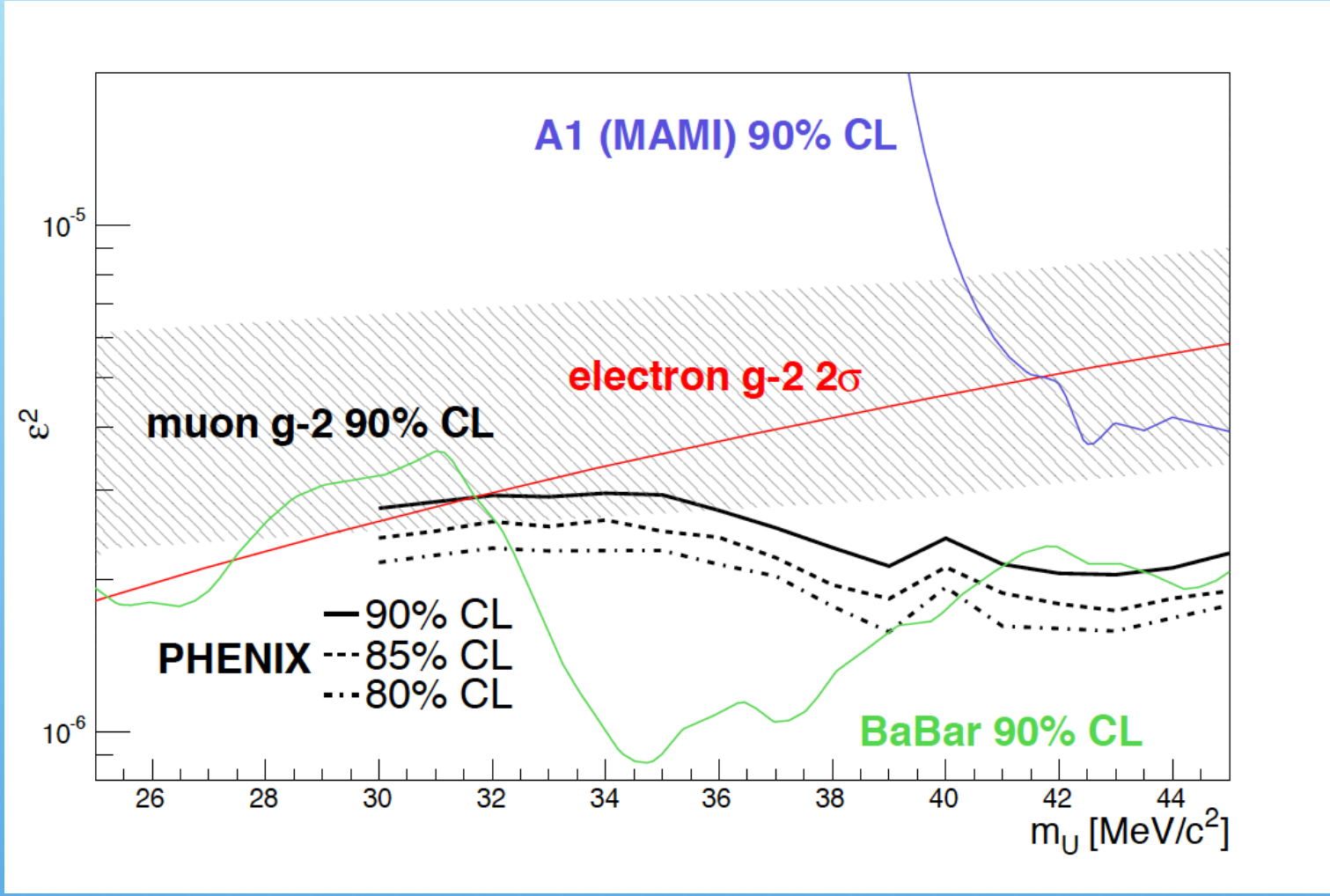
PHENIX Dark Photon Search



PHENIX e+e- invariant mass of data with fit describing known sources of e+e-

PHENIX 1409.0851

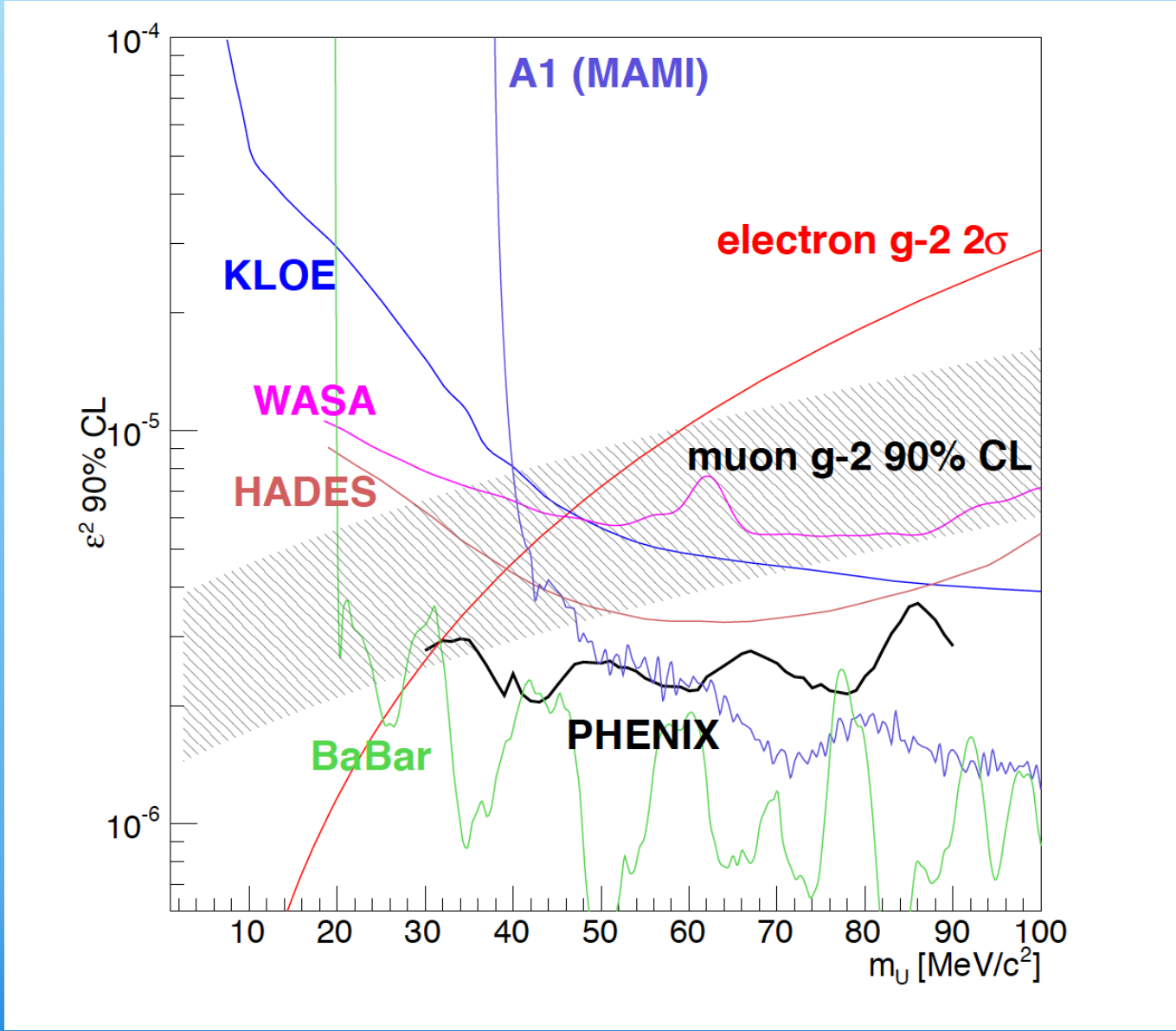
PHENIX Dark Photon Search



2-3 10ˆ-6 Upper limit derived on the square of the coupling of dark photon to Standard Model photon epsilonˆ2

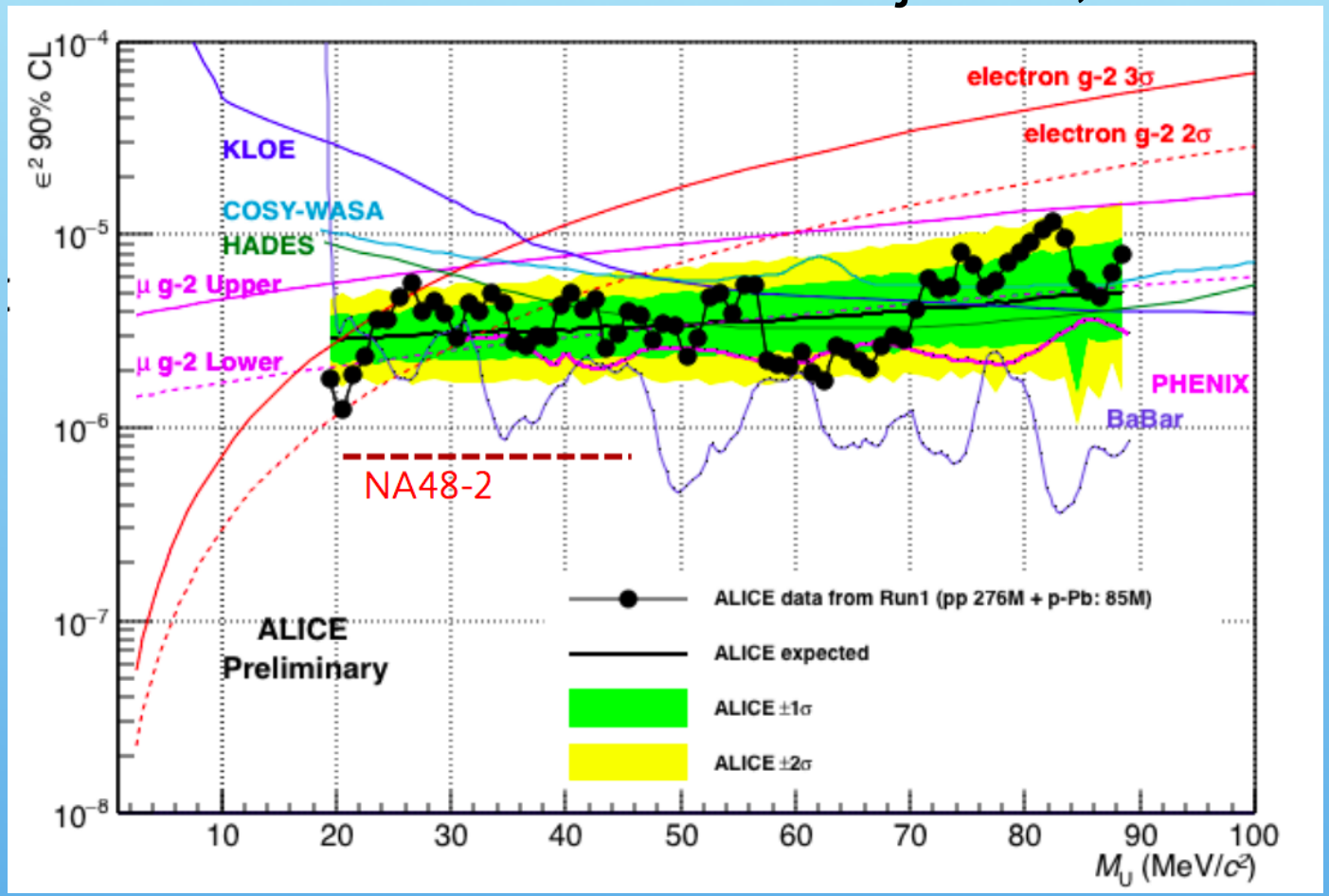
PHENIX Dark Photon Search

PHENIX 1409.0851



Comparison to ALICE and other data

Taku Gunji et al, ALICE collaboration



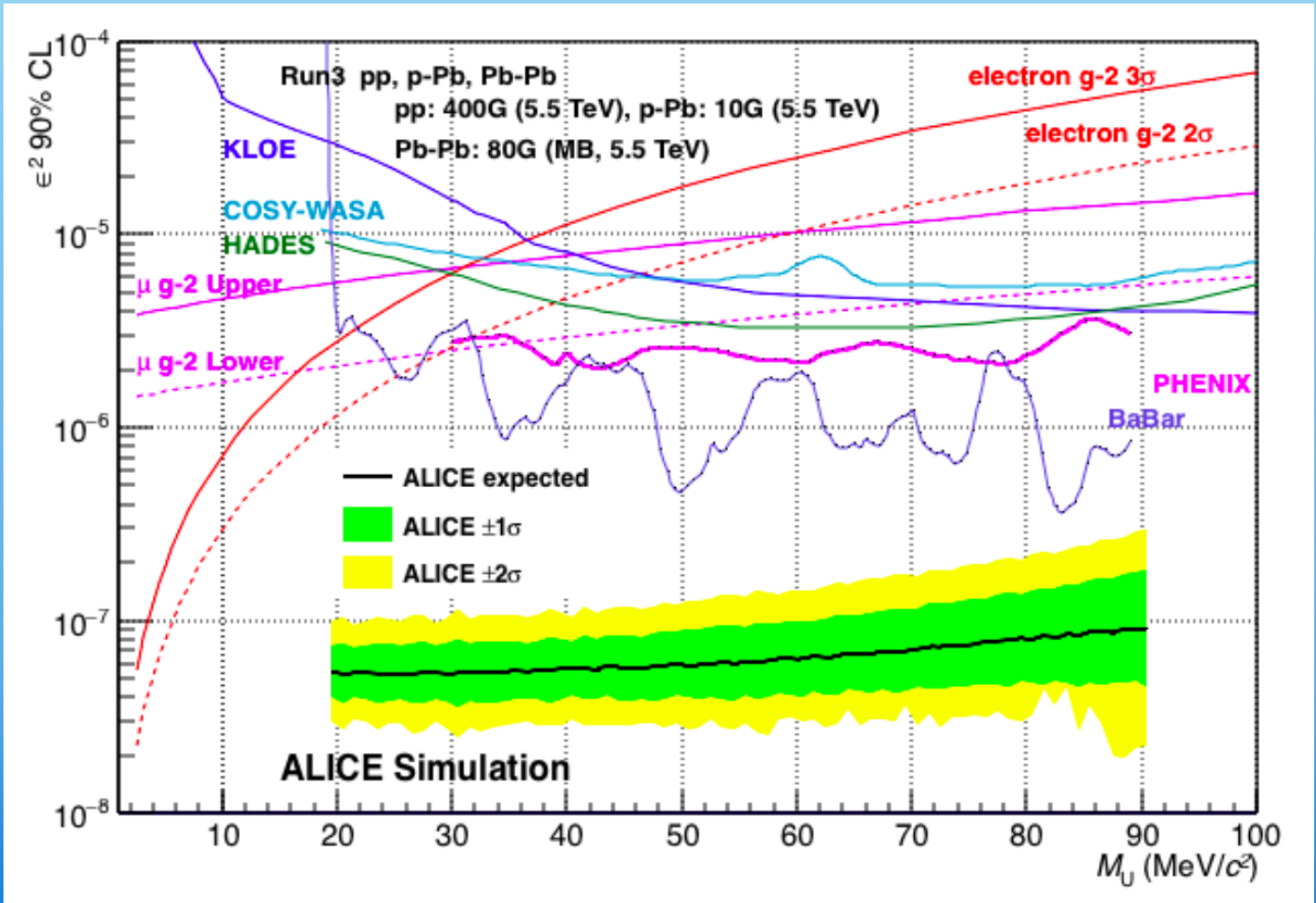
ALICE:
Similar ε^2 at 90% CL compared to other experiments

Worse than NA48-2 and BaBar

Comparison. HI data: ALICE, PHENIX, HADES
Dark photon to e+e- , is excluded as source of the muon g-2 anomaly but it may be source of positron excess in space or not have e+e- as final state

ALICE simulated future feasibility for dark photon

Expected improvement by an order of magnitude



Better statistics and resolution due to ALICE upgrades

Mass range 20-90 MeV

Taku Gunji et al, ALICE

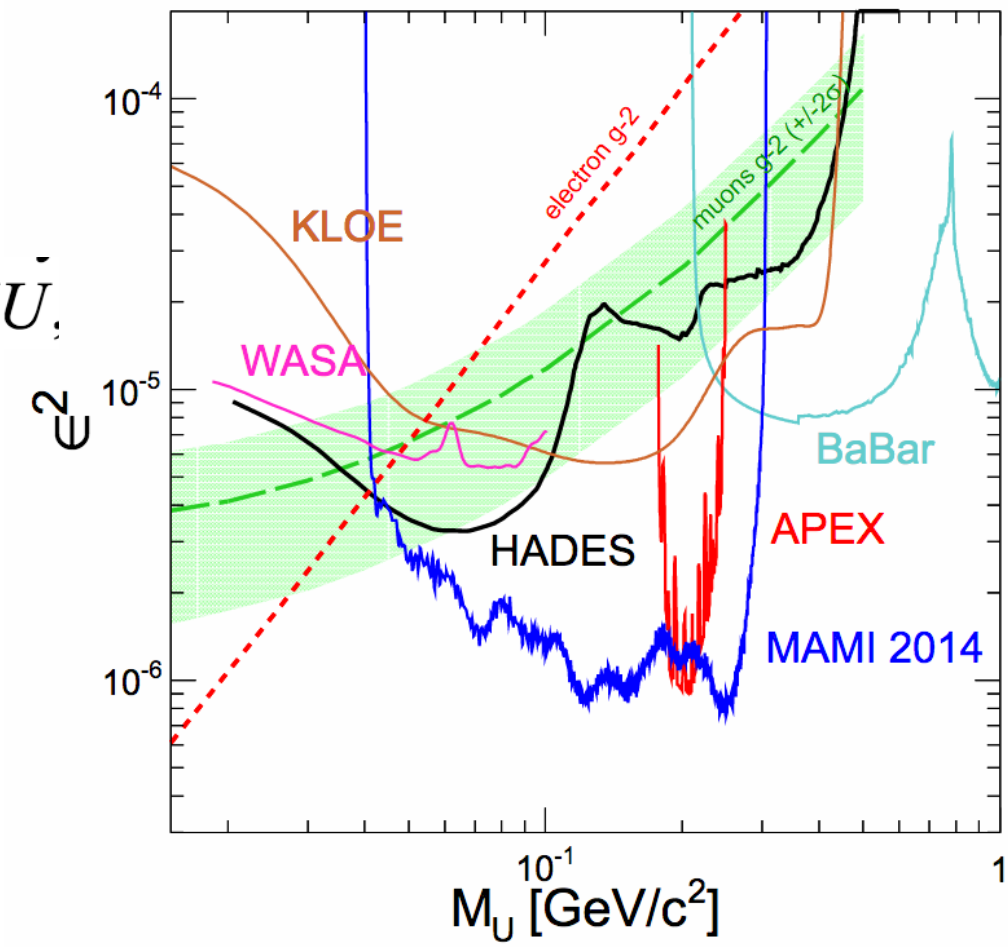
HADES (GSI) dark photon

Search for dark photon in p (3.5 GeV) +p, Nb and in Ar (1.756 GeV)+KCl collisions in e+e- final state

$$\pi^0 \rightarrow \gamma U,\ \eta \rightarrow \gamma U,\ \text{and}\ \Delta \rightarrow NU,$$

$$U \rightarrow e^+e^-.$$

They set upper limit at 90% CL in the kinetic mixing parameter squared, for the mass range for dark photon M(U) =0.02 - 0.55 GeV

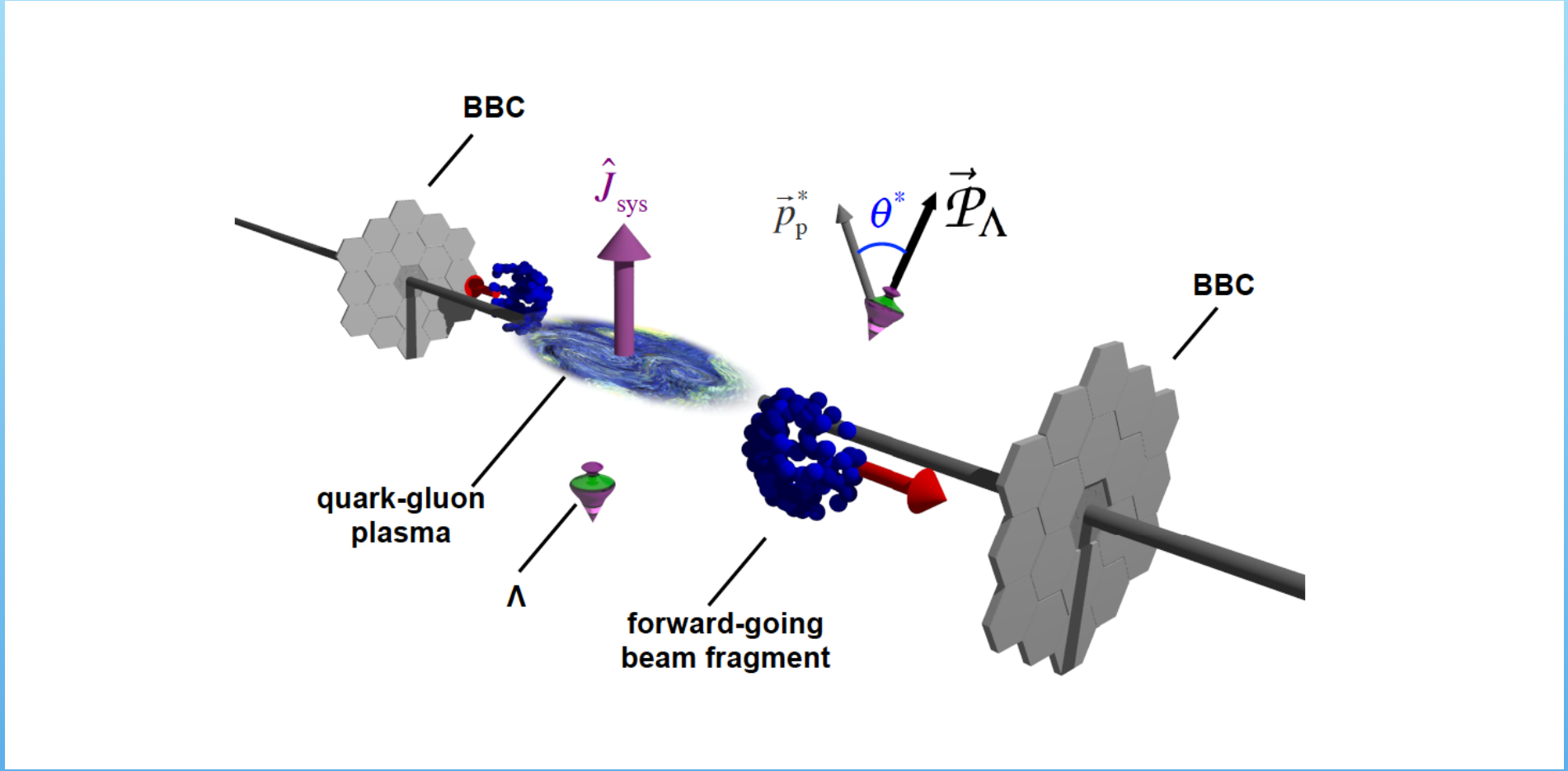


http://inspirehep.net/record/1333078/files/epjconf_meson2014_03006.pdf

First measurement of the Vorticity of QGP

First Vorticity measurement in AuAu 200 GeV 20-50% centrality

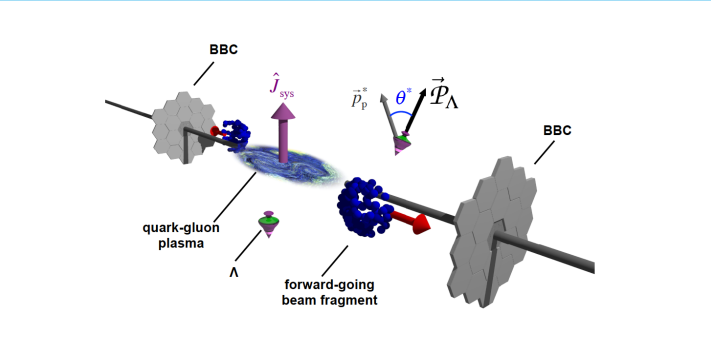
STAR, Nature, 2017, 1701.06657



Average vorticity points towards the direction of the angular momentum J(sys) of the collision.

First Vorticity measurement in AuAu 200 GeV 20-50% centrality

STAR, Nature, 2017, 1701.06657



$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right).$$

H: Lambda/Anti-Lambda

P_H : Lambda/AntiL polarizatin vector in the hyperon rest frame

decay parameter $\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$

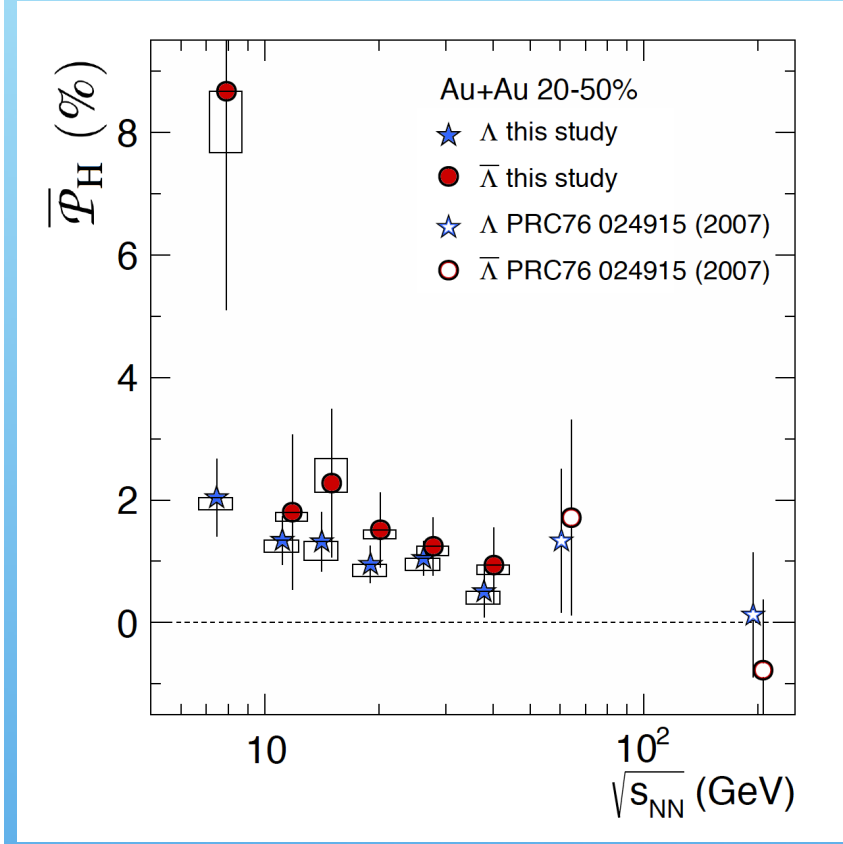
Average projection of the Polarization on J(sys) is extracted:

$$\overline{\mathcal{P}}_H \equiv \langle \vec{\mathcal{P}}_H \cdot \hat{J}_{sys} \rangle = \frac{8}{\pi\alpha_H} \frac{\left\langle \cos\left(\phi_p^* - \phi_{\hat{J}_{sys}}\right)\right\rangle}{R_{EP}^{(1)}},$$

noted as "global polarization"

sQGP vorticity measured

P_H: average polarization with
H: Lambda or Antilambda



STAR, Nature, 2017, 1701.06657

Measurement of vorticity in Au+Au collisions with 20-50% centrality via the average polarization of Lambda and Antilambda.

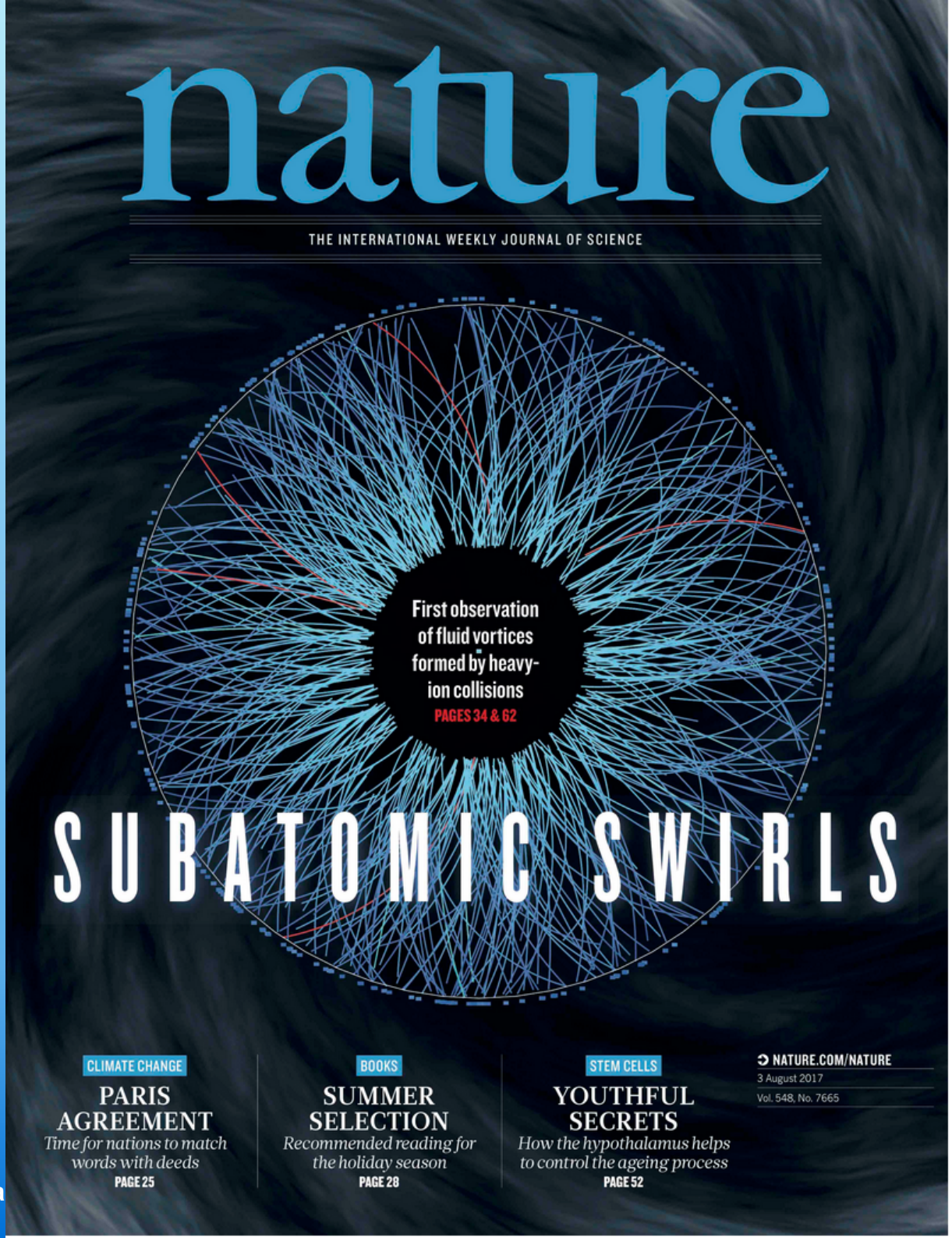
Fluid vorticity can be calculated using the hydrodynamic relation (Becatini et al 1610.02506.)

$$\omega = k_B T \left(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\overline{\Lambda}'}\right)/\hbar,$$

With T the temperature. The vorticity found is
omega = (9+-1) 10ˆ21 s-1
with an additional systematic error of a factor of 2 which by far surpasses the vorticity of all known fluids

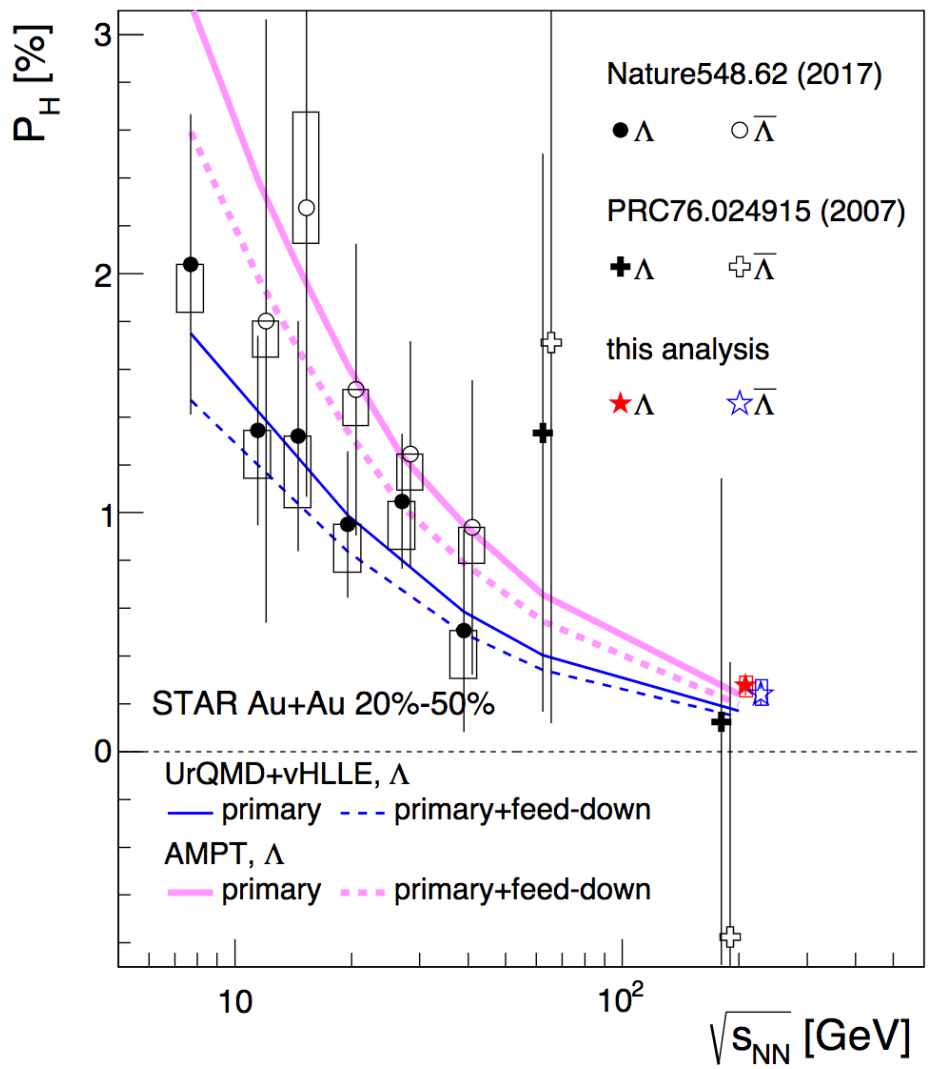
For example solar subsurface flow has omega= 10-7 s-1, and superfluid nanodroplets omega=10ˆ7 s-1

* The Quark Gluon Plasma produced in heavy ion collisions is
- hotter
- least viscous
- and has larger vorticity,
  from all fluids ever produced in the laboratory !


nature
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
First observation of fluid vortices formed by heavy-ion collisions
PAGES 34 & 62
SUBATOMIC SWIRLS
CLIMATE CHANGE
PARIS AGREEMENT
Time for nations to match words with deeds
PAGE 25
BOOKS
SUMMER SELECTION
Recommended reading for the holiday season
PAGE 28
STEM CELLS
YOUTHFUL SECRETS
How the hypothalamus helps to control the ageing process
PAGE 52
NATURE.COM/NATURE
3 August 2017
Vol. 548, No. 7665

New STAR results on global polarization of Lambda,Antilambda in Au+Au at 200 GeV

1805.04400



High precision measurement of a finite Lambda and Antilambda global polarization of the level of 0.1-0.5% (depending on centrality) in Au+Au at 200 GeV

Global polarization increases with decreasing collision energy

Exotic states

Strange Quark Matter

Strange Quark Matter (SQM) is a hypothetical state of matter consisting of roughly equal numbers of u , d and s quarks.

.

Bodmer A R 1971 Phys. Rev. D 4 1601
Witten E 1984 Phys. Rev. D 30 272
Terazawa H 1979 INS Report 338 University of Tokyo, Terazawa H 1989 J. Phys. Soc. Japan 58 3555, Terazawa H 1989 J. Phys. Soc. Japan 58 4388, Terazawa H 1990 J. Phys. Soc. Japan 59 1199

Absolutely stable Strange Quark Matter … is possible

E Witten, 1984

For more than few hundreds u,d,s quarks, the energy per baryon (E/A) of quark matter can be below the energy of the most stable atomic nucleus 56Fe, which has Energy per baryon number Mass(56Fe)cˆ2/56 = 930.4 MeV

With E/A(strange quark matter)= 4Bpiˆ2/muˆ3, the E/A of Strange Quark Matter can be

E/A = 829 MeV for bag constant B=57.5 MeV fm-3 (or Bˆ(1/4)=145 MeV) and

E/A = 915 MeV for bag constant B=85,3 MeV fm-3 (Bˆ(1/4)=160 MeV).

In this cases Strange Quark Matter from u,d,s quarks would be the ground state of matter.

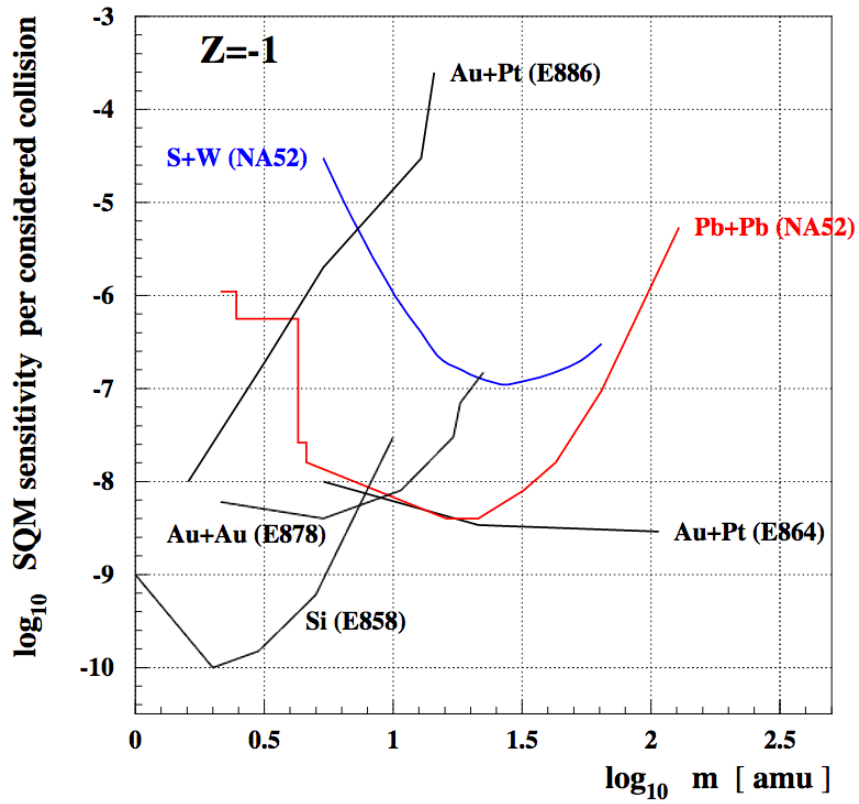
From Strangelets to Strange Stars

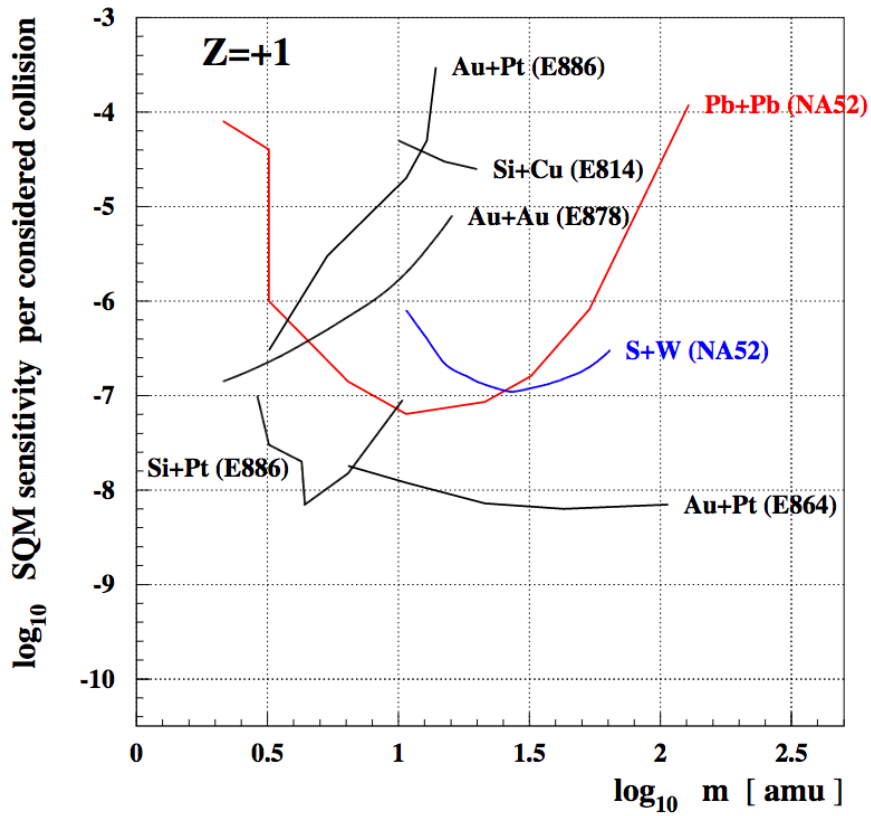
One may expect novel states to exist like strange nuggets or strangelets (for small A like A~10-100) to strange stars

Experimental searches for strangelets with small A

In accelerators (AGS BNL, NA52 at CERN SPS, etc)
In cosmic rays with detectors on earth (centauro events)
In Space (AMS)

Upper Limits at 90% CL on strangelet production from SPS NA52 and BNL heavy ion experiments E858, E878, E864

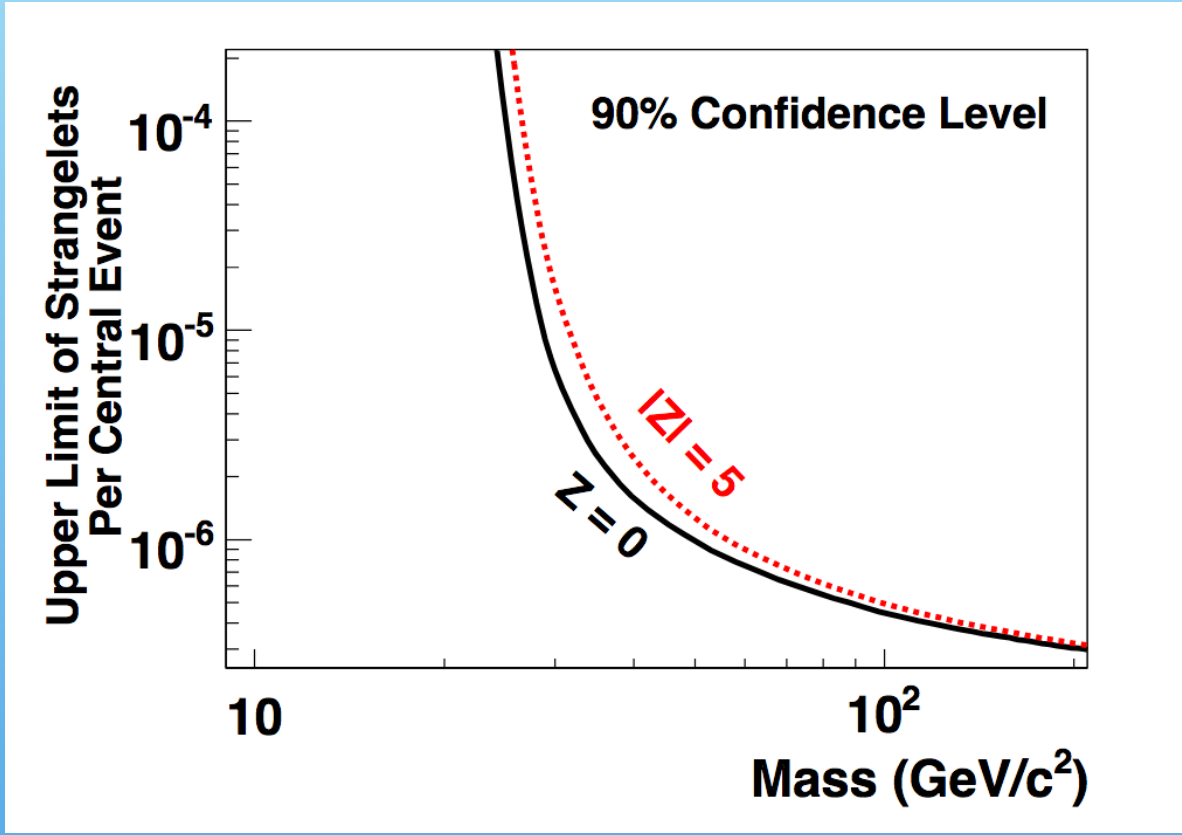




STAR Strangelet Search at the BNL Relativistic Heavy Ion

STAR Phys.Rev. C76 (2007) 011901

Strangelets in forward region are expected to have small charge to mass ratio and large rigidity (p/Z).
They are expected to deposit energy in the forward calorimeter STAR is sensible to strangelets with lifetime > 0.1 nsec



Upper limits of a few 10–6 to 10–7 per central Au +Au collision are set for strangelets with mass > 30 GeV.

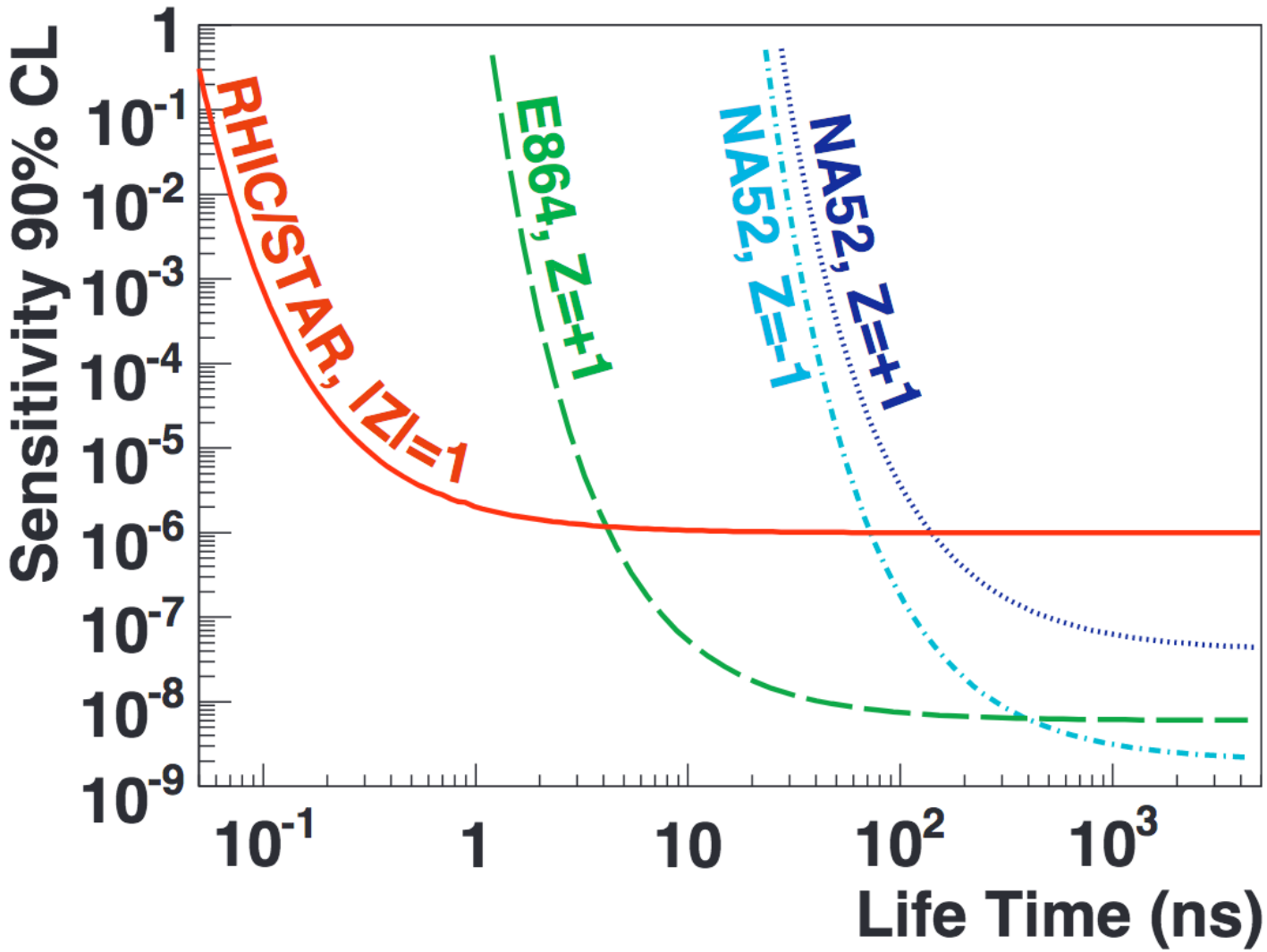
STAR Strangelet Search at the BNL Relativistic Heavy Ion

STAR Phys.Rev. C76 (2007) 011901

Search done in 61 million central Au+Au events

strangelet mass > 30 GeV.

lifetime > 0.1 nsec



Pentaquark searches

Search for the anti-Theta- ---> K- anti-n with PHENIX

J.Phys. G30 (2004) no.8, S1201-S1206

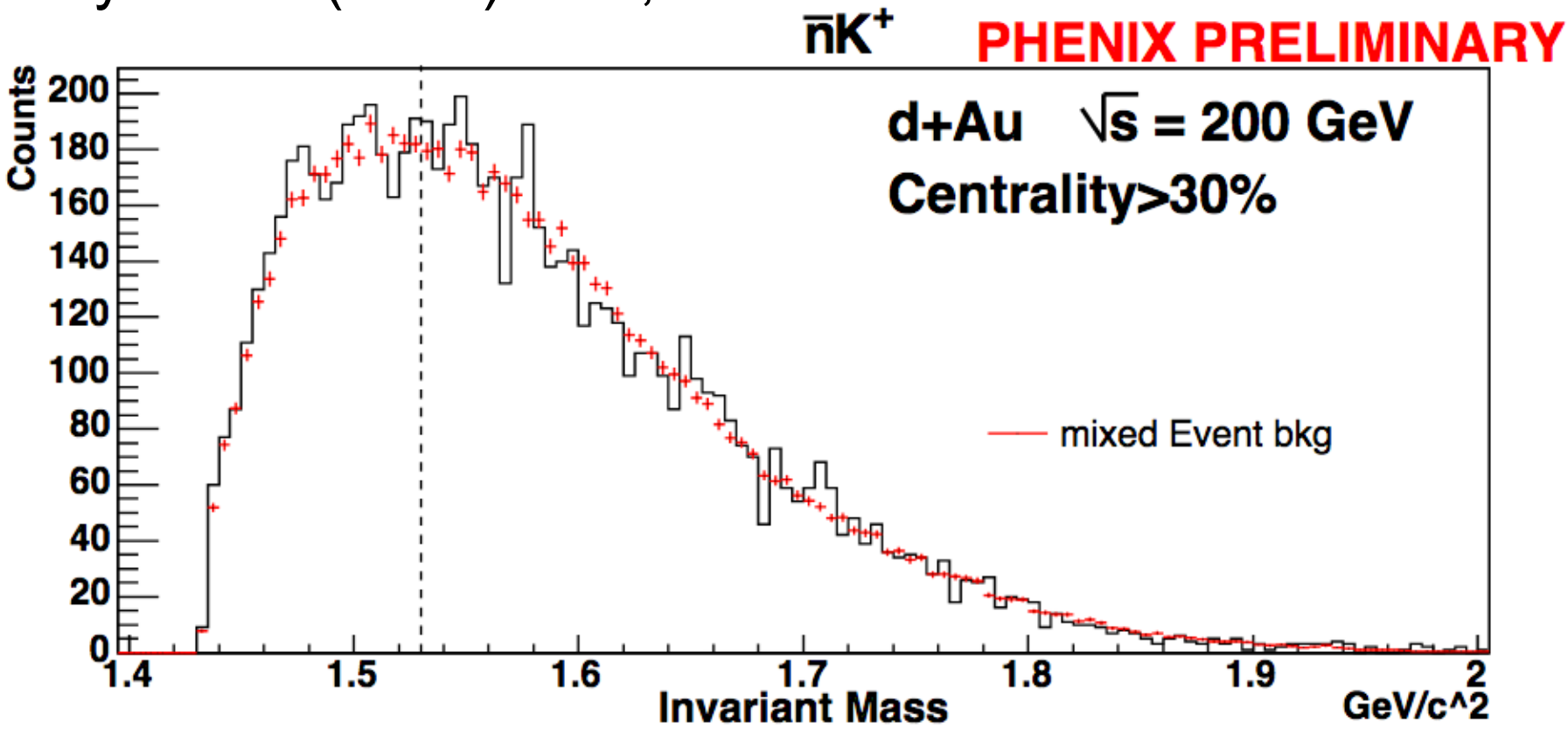
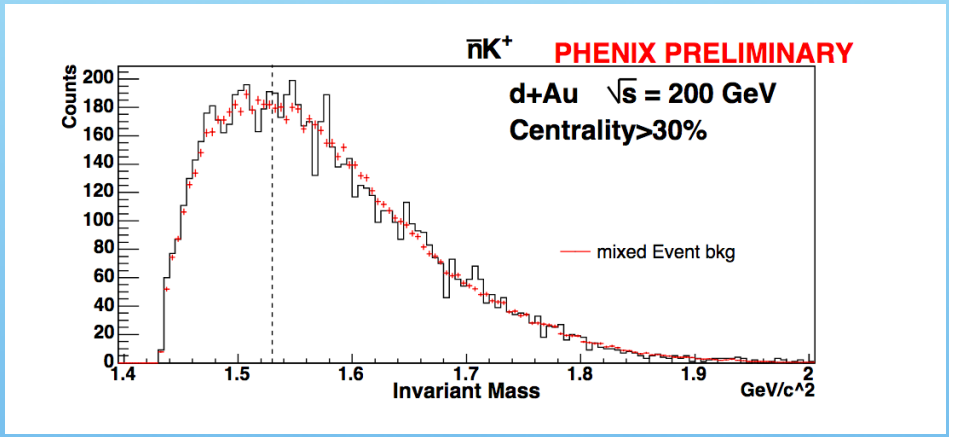


Figure 4. $K^+\,\overline{n}$ Invariant mass distribution. No peak is expected in the mass range between 1.5 GeV/c^2 and 1.6 GeV/c^2. It serves as a crosscheck for technical problems and particle misidentifications.

Search for the anti-Theta- ---> K- anti-n with PHENIX

J.Phys. G30 (2004) no.8, S1201-S1206

Conf proceeding



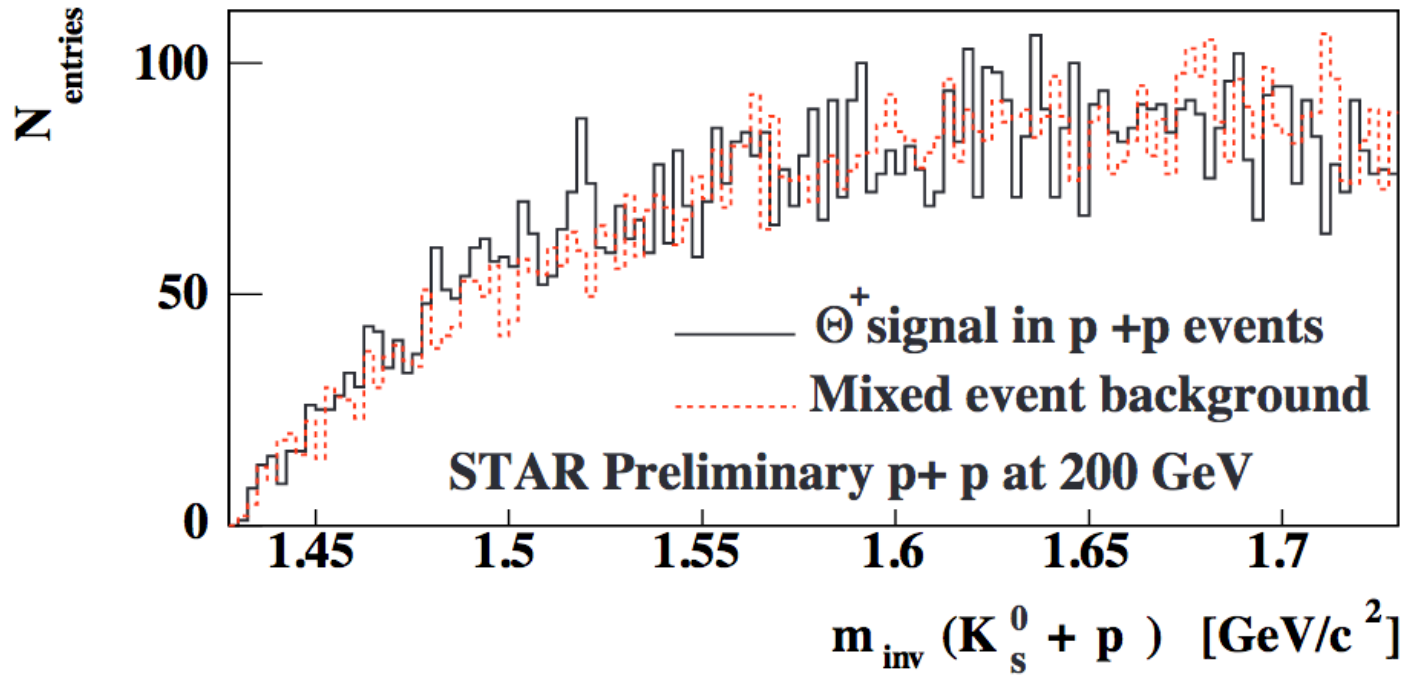
Charged kaons can be identified using the standard tracking and time of flight up to a momentum of 1.5 GeV/
Anti–neutron candidates are detected via their annihilation signal in the highly segmented electromagnetic calorimeter (EMCal).

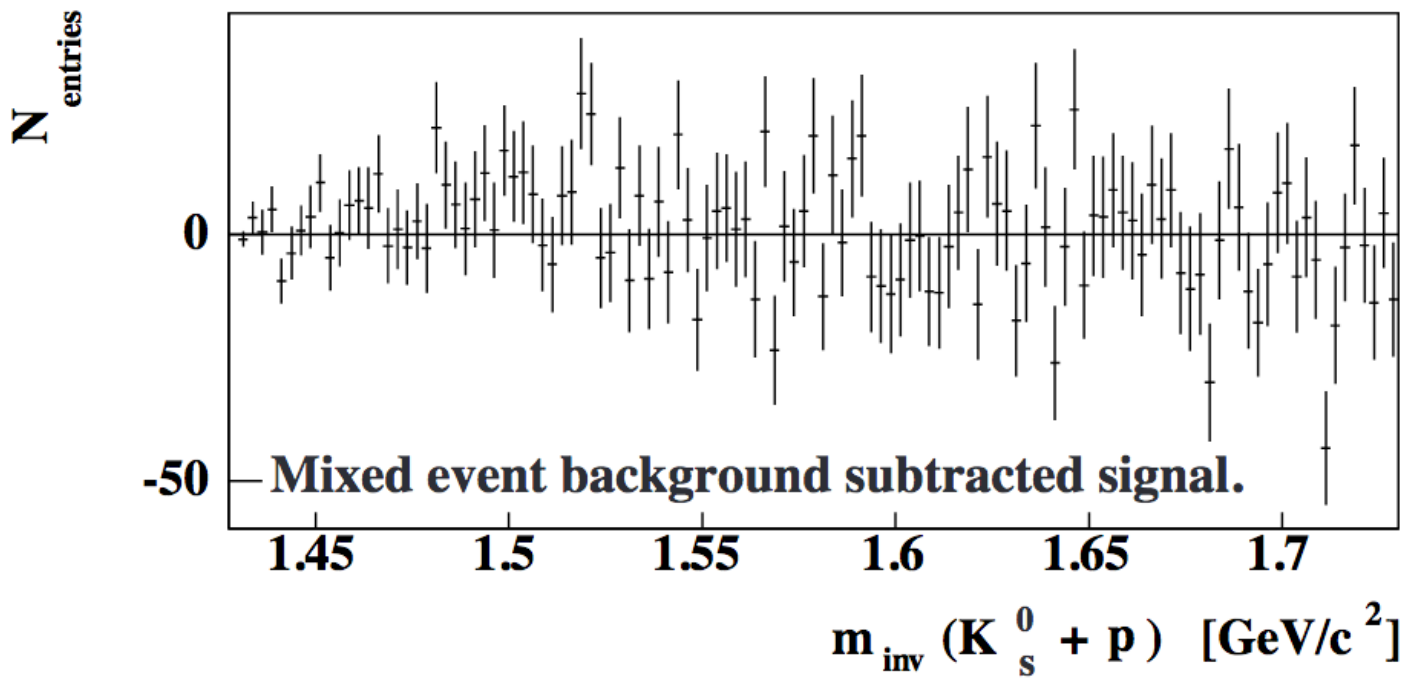
No anti-Theta-signal observed (no upper limits extracted).

STAR

Search for theta+ ->K0s p

S. Salur et al STAR coll., poster QM2004





Theta++ searches in STAR

d+Au 200 GeV

STAR,Huan Huang et al nucl-ex/0509037

$\theta^{++} \rightarrow p + K^{+}$

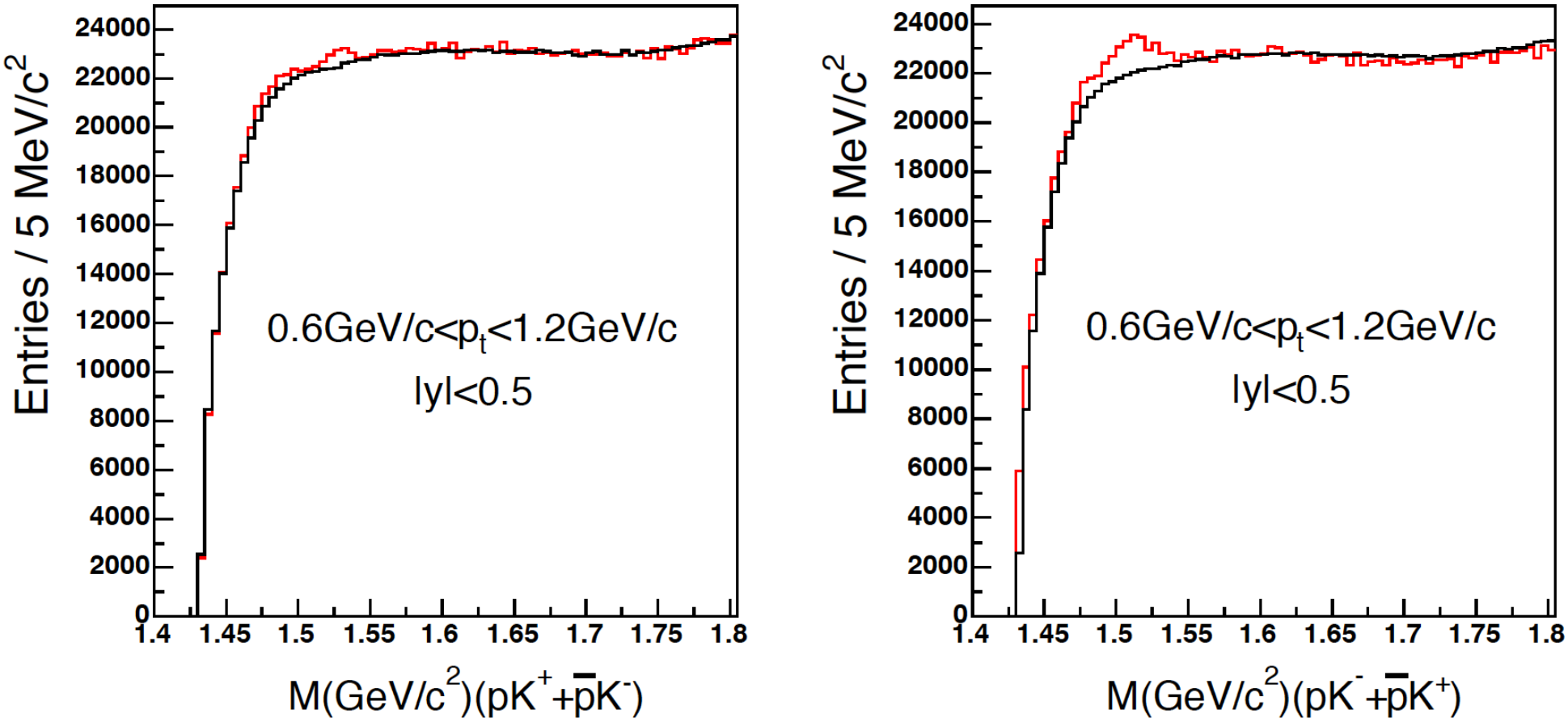


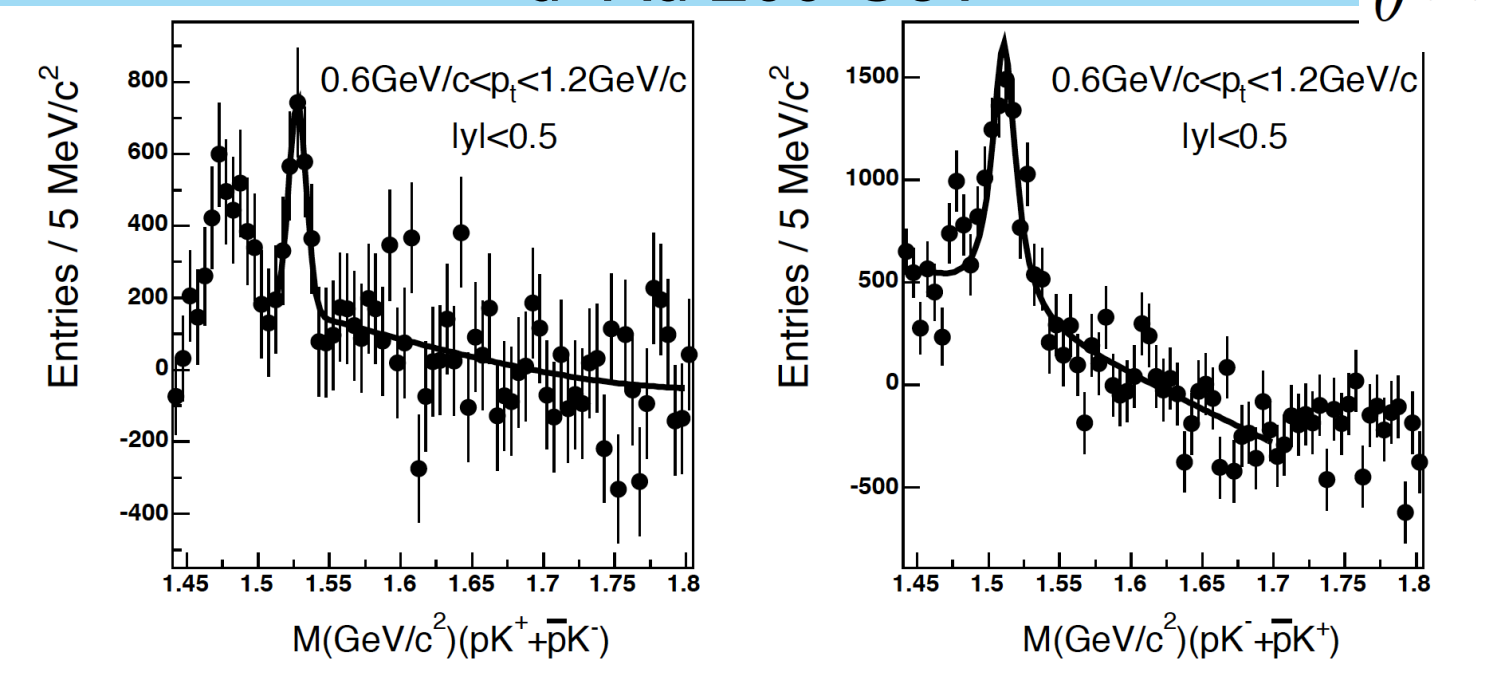
Fig. 1. Invariant mass distributions of $pK^+ + \overline{p}K^-$ (left) and $pK^- + \overline{p}K^+$ (right) from d+Au collisions at 200 GeV. The histograms are combinatorial backgrounds from event-mixing technique.

Theta++ searches in STAR

STAR,Huan Huang et al nucl-ex/0509037

d+Au 200 GeV

$\theta^{++} \rightarrow p + K^{+}$



Right plot: Lambda(1520) and antiparticle seen
Left plot theta++ candidate peak at mass=1528+-2 MeV and significance of 4.2 sigma
Width is corresonding to detector resilution
Peak at 1460 MeV is due to missidentified pion as Kaon from Delta decays.

Theta++ searches in STAR

STAR,Huan Huang et al nucl-ex/0509037

$$\theta^{++} \rightarrow p + K^{+}$$

dE/dx in the TPC: pi/kaon separation possible up to 0.6 GeV/c and pi/proton separation up to 1.0 GeV/c

Au+Au collisions 200 GeV

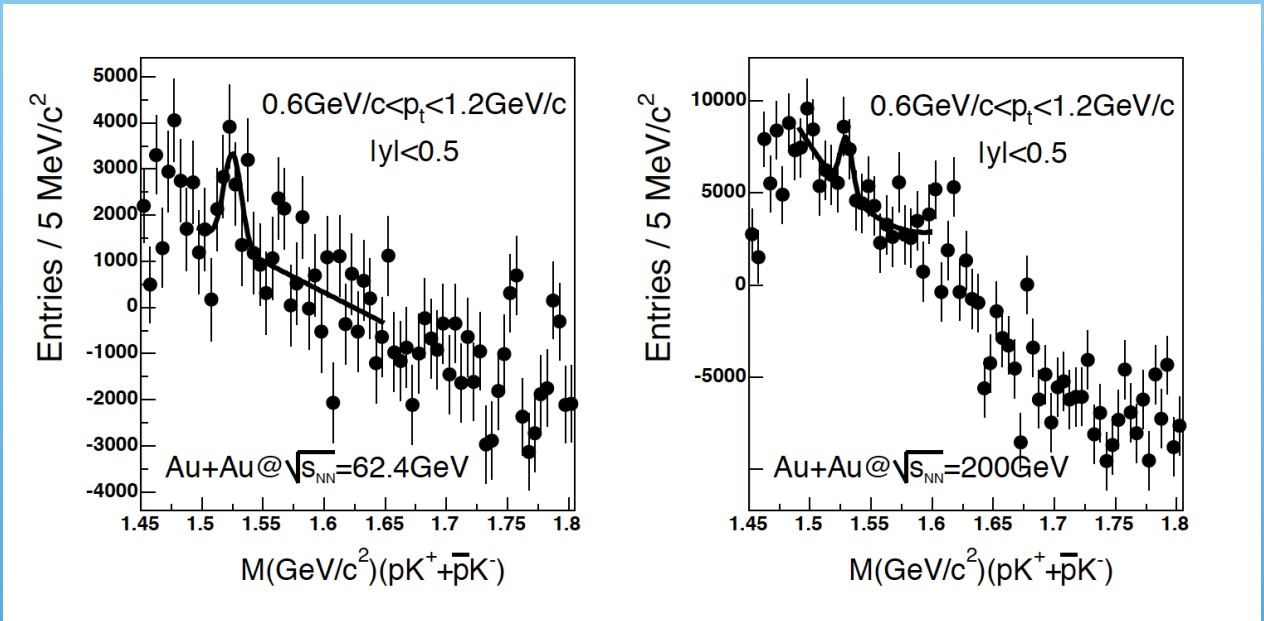


Fig. 3. Invariant mass distributions of $pK^{+} + \overline{p}K^{-}$ from Au+Au collisions at 62.4 GeV (left) and at 200 GeV (right) after subtraction of combinatorial background. The curves are a fit of Gaussian and polynomial function.

HADES search for a doubly charged dibaryon

1410.8004

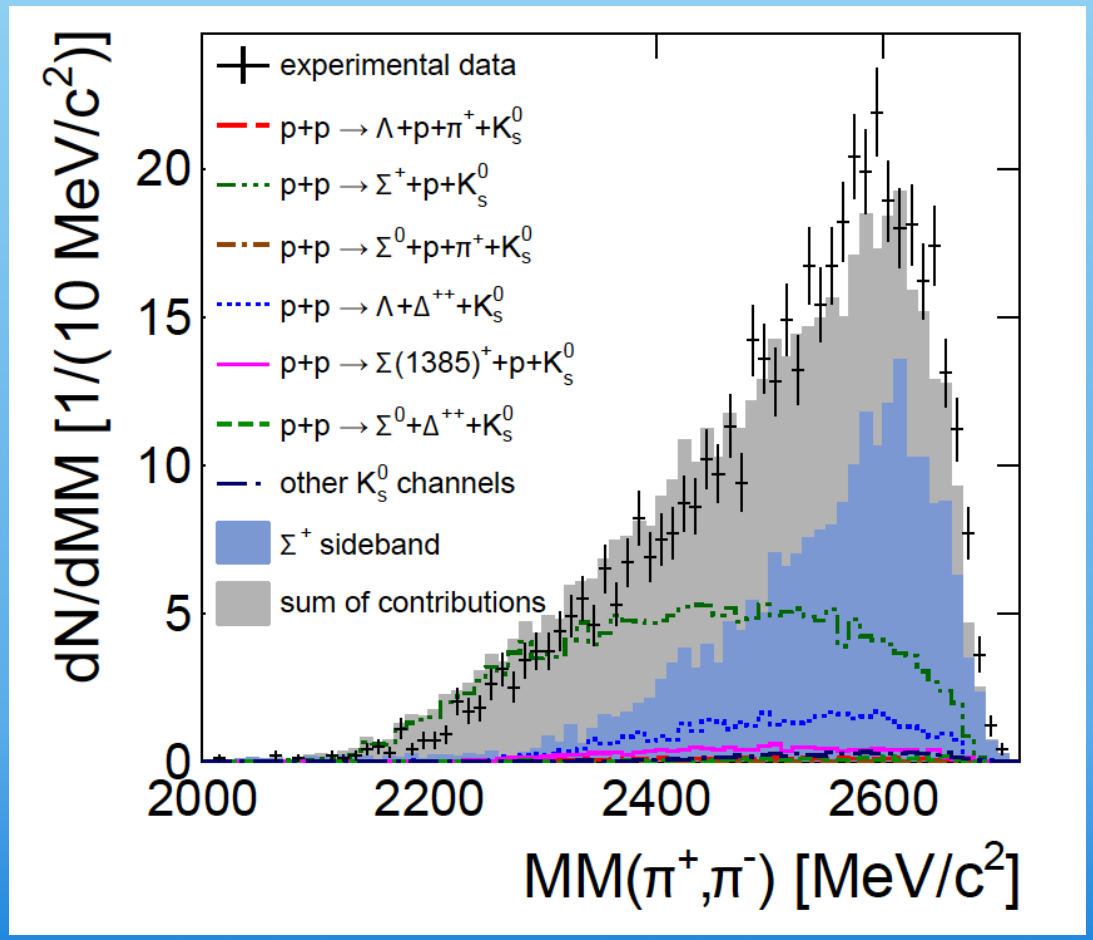
Sigma+=uus
y++ (uusuud)

$$pp \to \mathcal{Y}^{++}K^0 \to \Sigma^+ pK^0 \to n\pi^+ pK^0$$

Measurement: proton, pi +,pi-,pi+

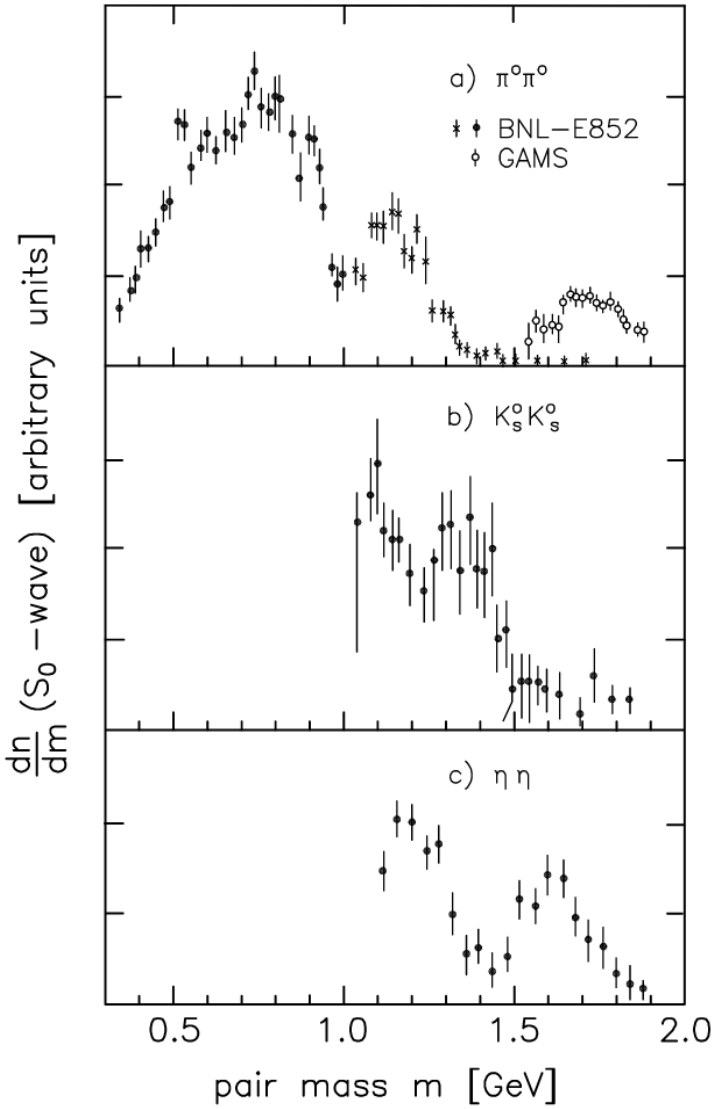
Namely pi+pi- from K0s pi+ from the Sigma+ decay into neutron + pi+ and proton associated with Sigma

No pi+enhancement seen in the missing mass spectrum



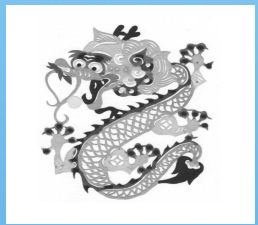
QGP: a Glueball production Fabrik?

Glueballs from QGP



Peter Minkowski, Wolfgang Ochs, Eur.Phys.J. C9 (1999) 283-312

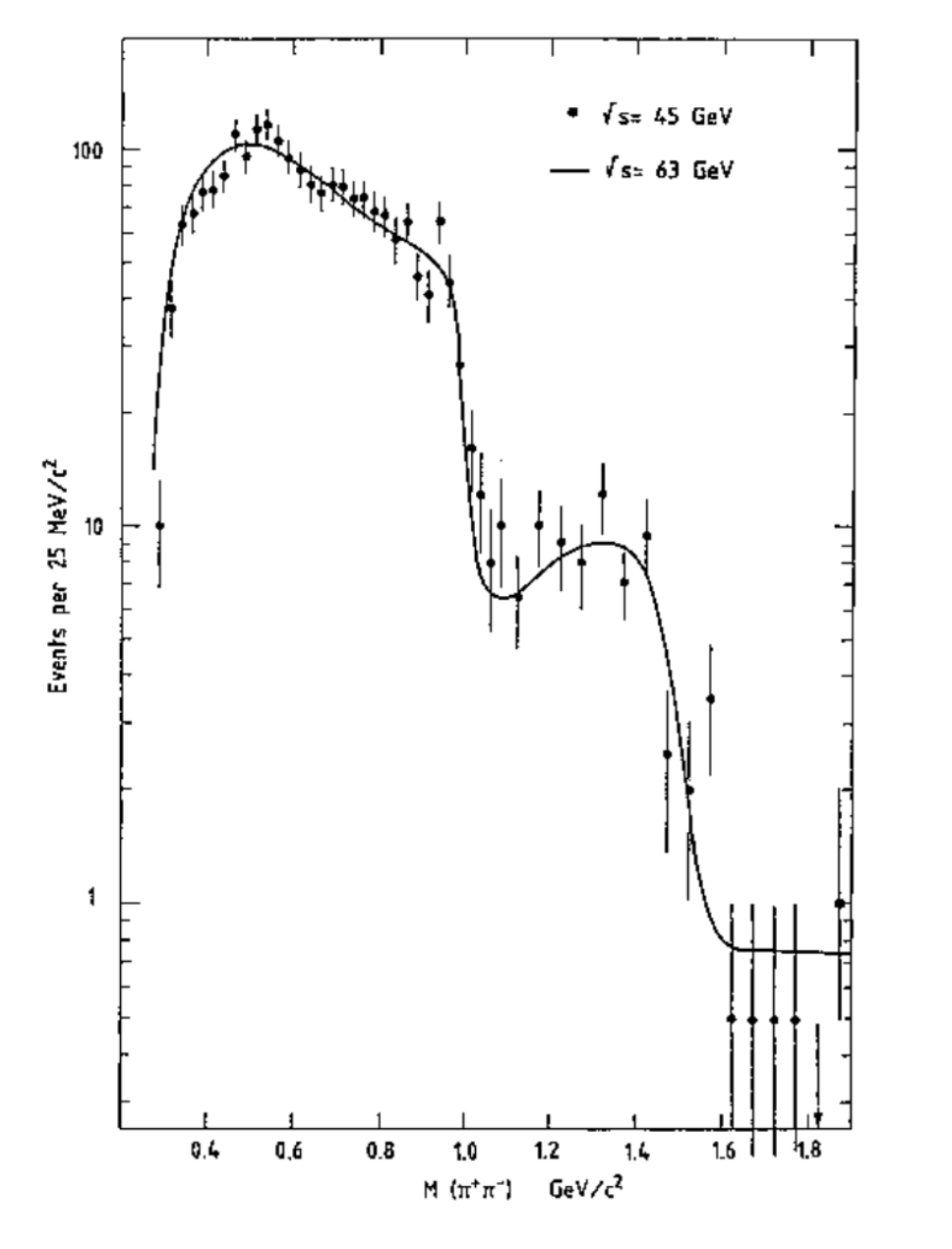
"Red Dragon"
decay into pipi, KK, eta eta



name	PDG	mass (MeV)	mass^2(GeV)^2	width (MeV)
gb (0^{++})	$f_0(400-1200)$	~ 1000	$\sim 1.$	$500-1000$
	$f_0(1300)$			
gb (0^{-+})	$\eta(1440)$	$1400 - 1470$	2.07	$50 - 80$
gb (2^{++})	$f_J(1710)$	1712 ± 5	2.93	133 ± 14

Table 15: Properties of the basic triplet of binary glueballs gb.

Glueballs from QGP

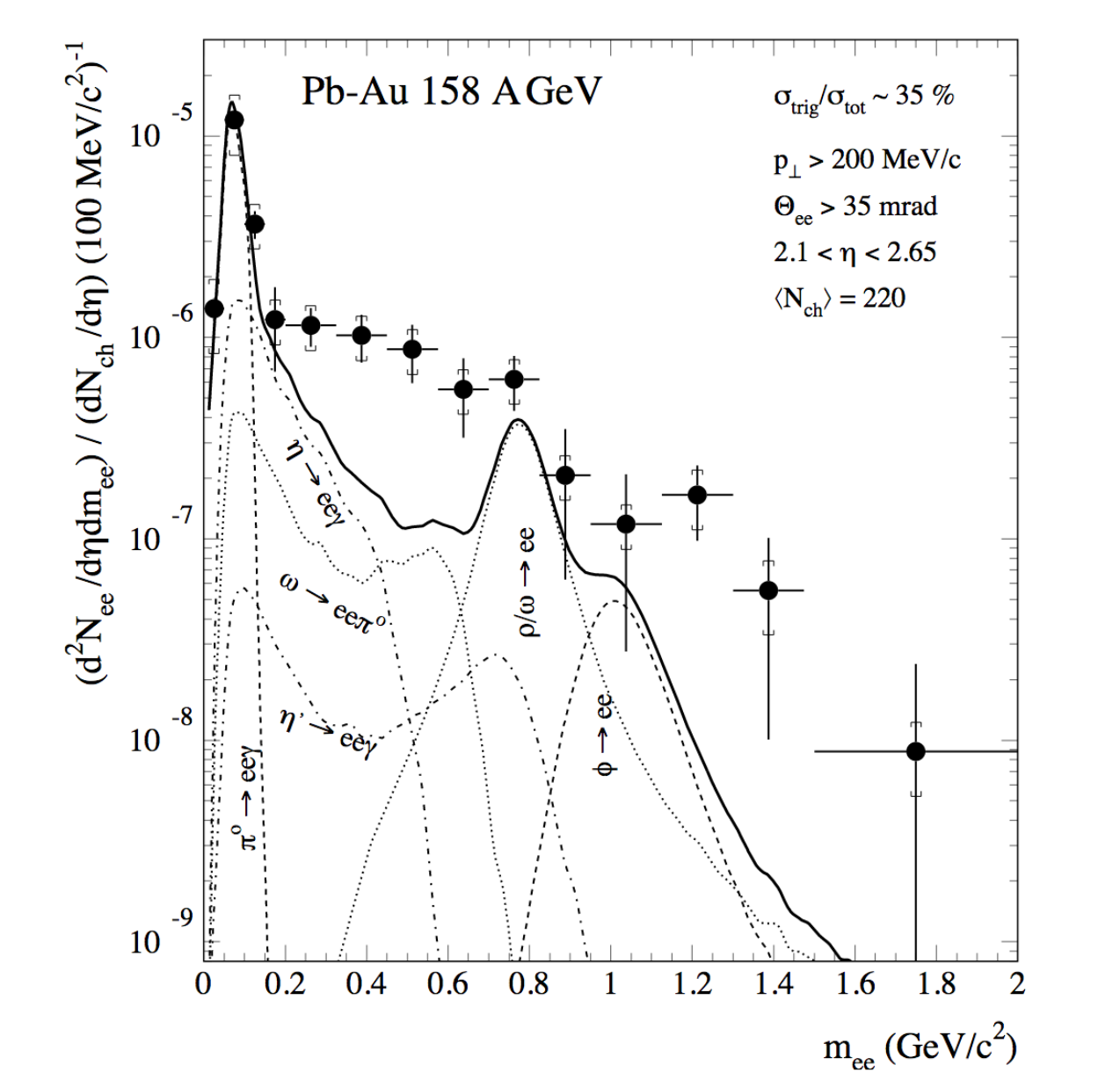


"Red Dragon"
decay into pi+pi-

Peter Minkowski, Wolfgang Ochs
Eur.Phys.J. C9 (1999) 283-312

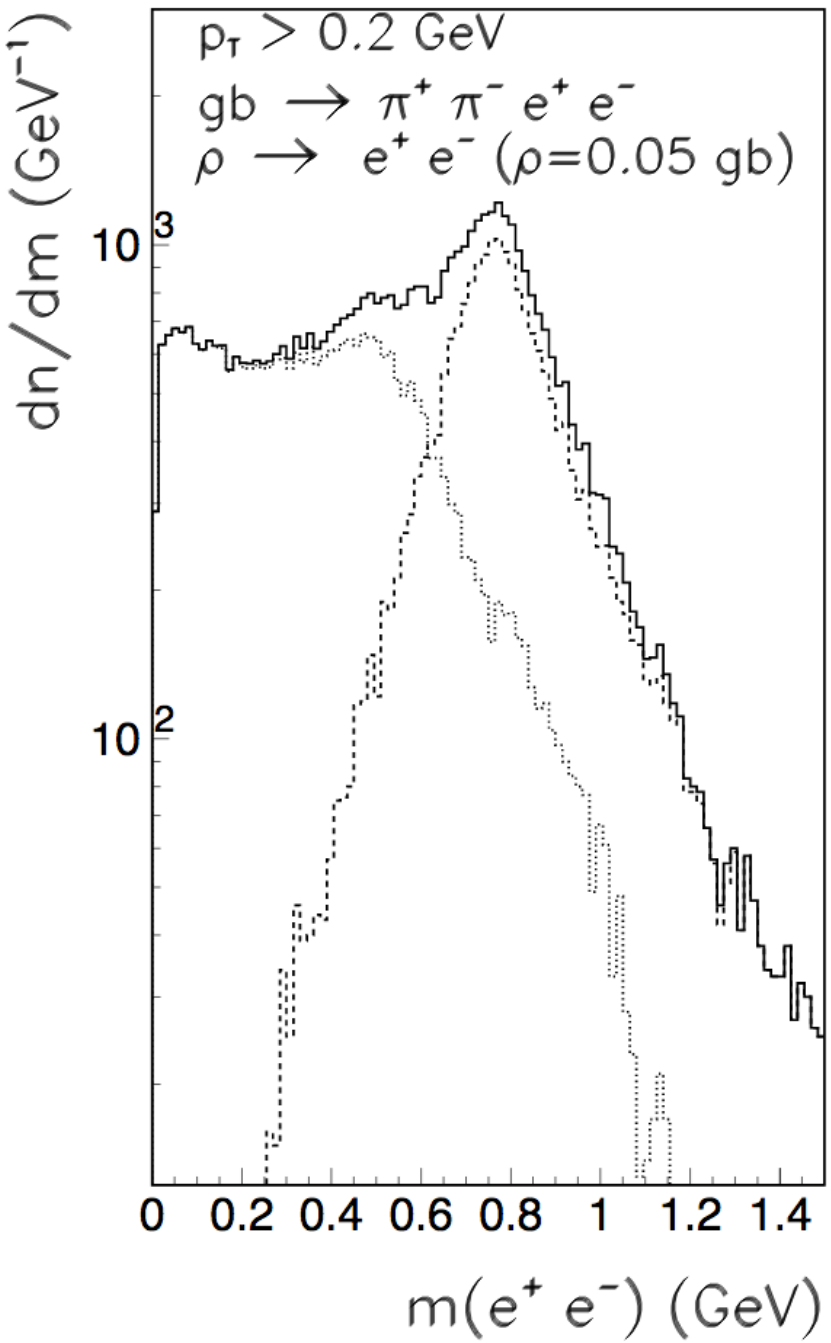
Glueballs from QGP

SK P. Minkowski, Phys.Lett. B472 (2000) 155-160



CERES data e+e-

Glueballs from QGP



SK P. Minkowski, Phys.Lett. B472 (2000) 155-160

This analysis could explain CERES excess data by a " sigma " -assumed as a 0++ glueball- enhancement

We proposed an enhancement of Glueball as a signature o QGP and we suggested search for glueballs in Heavy Ion collisions

Conclusions and perspectives

sQGP

* The Quark Gluon Plasma produced in heavy ion collisions is an extraordinary state of matter :

- 100,000 times hotter than the core of the sun (T ~ 200 MeV, 2.3x10^{12} K).

- least viscous than any observed fluid -> the Perfect Fluid

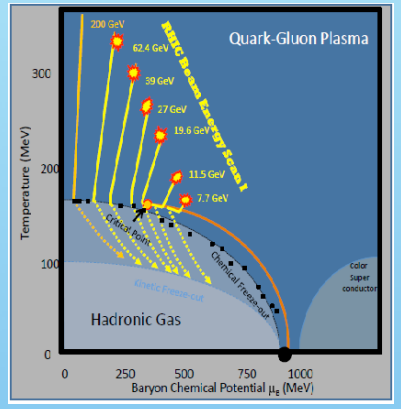
- with larger vorticity by many orders of magnitude than all fluids produced in the laboratory

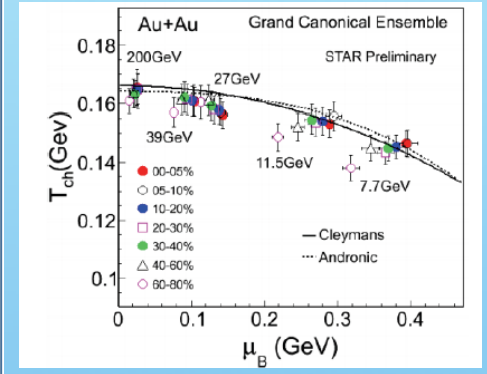
* Very high density of partons -> hadrons produced

* Very large magnetic field

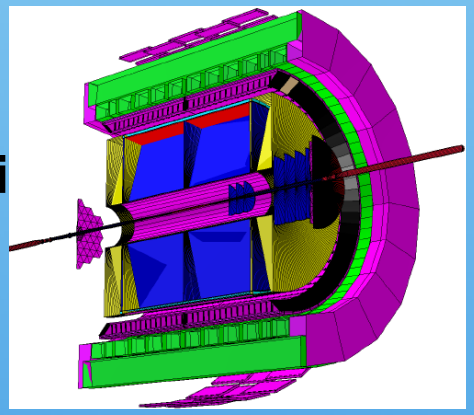
That may be relevant for new particle and new phenomena searches. in Heavy Ion Collisions

STAR future plans



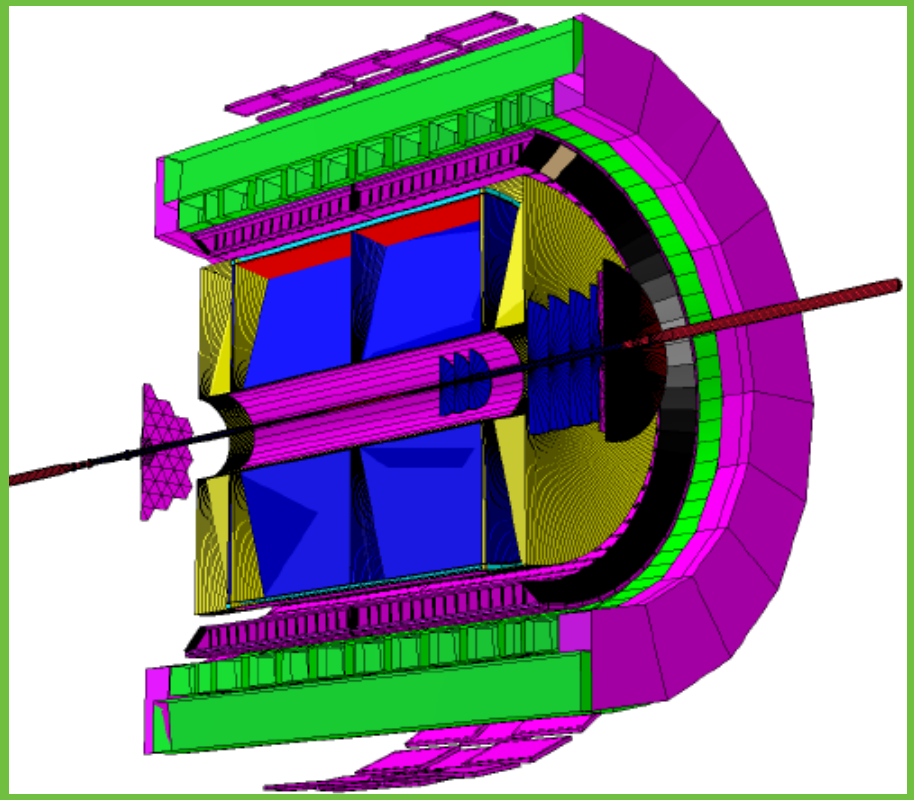


Beam Energy Scan (BES) II 2019-2020
Will continue the BES I program
"Hot" QCD, search for a possible critical point and discontinuities in the energy dependence of QGP signatures
-> FAIR and NICA



STAR forward rapidity program (2.5-eta-4): Hcal, Ecal, tracki
(Silicon and sTGCs)
"Cold" QCD, Proton TMDs, gluon saturation
Test Electron Ion Colider (EIC) detector technologies
Milestone: 2021 p+p run and sPHENIX data taking 2022+
-> EIC

STAR forward rapidity program



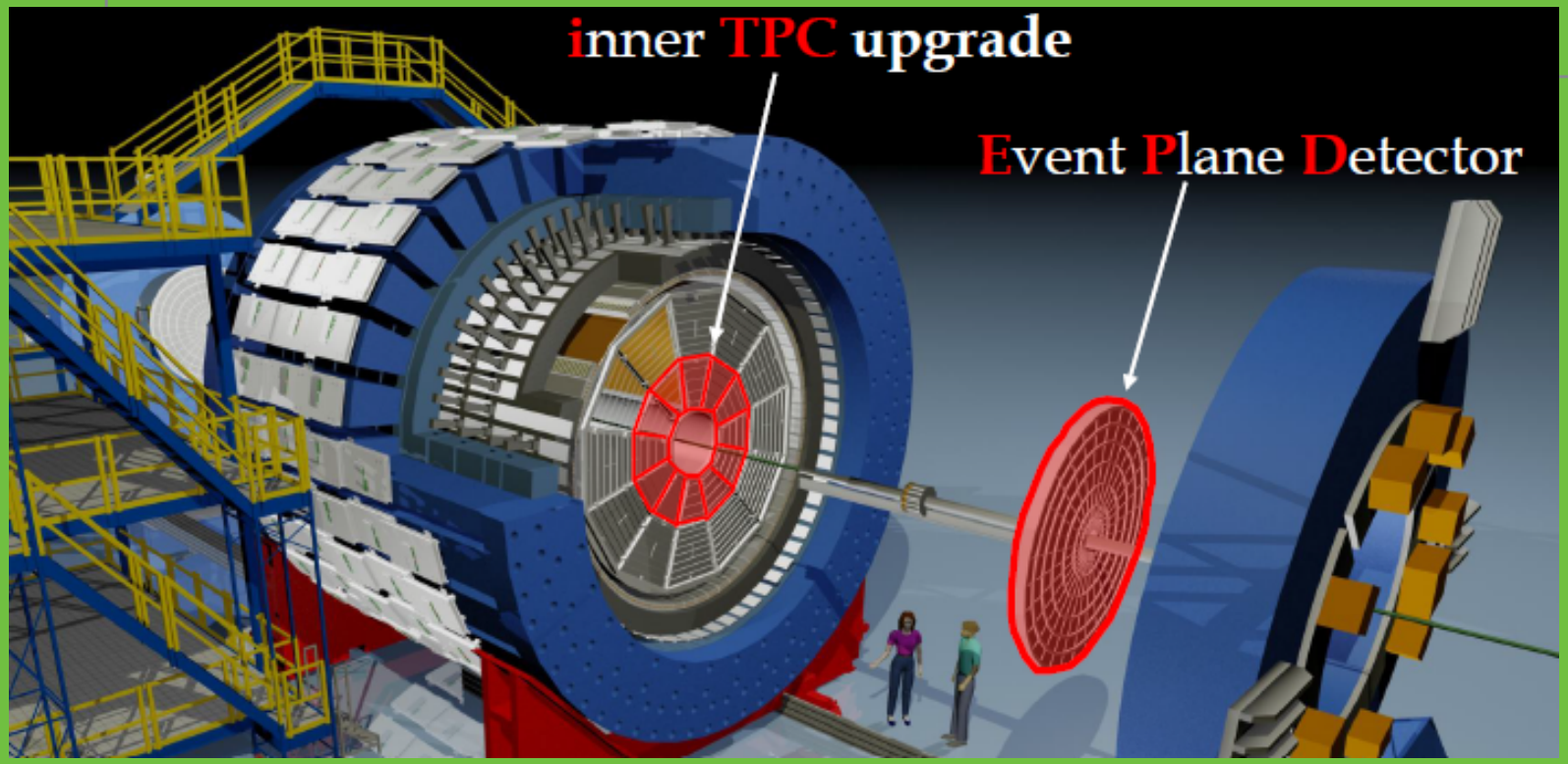
3 Silicon discs

4 Small-strip Thin Gap Chambers

ECal: use upgraded PHENIX PbSc calorimeter

HCal: Iron-scintillator

STAR upgrades



iTPC: inner sector of TPC. Extends peudorapidity acceptance from 1 to 1.5. Improves dE/dx

Endcap TOF: particle identification 0.9-eta-1.5

Event Plane Detector: will provide better and independent determination of centrality and event plane

STAR goals

BES-II

Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events
9.8	19.6	205	4.5 weeks	400M
7.3	14.5	260	5.5 weeks	300M
5.75	11.5	315	5 weeks	230M
4.55	9.1	370	9.5 weeks	160M
3.85	7.7	420	12 weeks	100M
31.2	7.7 (FXT)	420	2 days	100M
19.5	6.2 (FXT)	487	2 days	100M
13.5	5.2 (FXT)	541	2 days	100M
9.8	4.5 (FXT)	589	2 days	100M
7.3	3.9 (FXT)	633	2 days	100M
5.75	3.5 (FXT)	666	2 days	100M
4.55	3.2 (FXT)	699	2 days	100M
3.85	3.0 (FXT)	721	2 days	100M

SK for the STAR Collaboration, ICNFP2018

STAR BES-II goals

Table 8: Event statistics (in millions) needed in BES-II for various observables. This table update estimates originally documented in Ref. [45].

Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to $p_T = 5$ GeV/c	-		160	125	92
Elliptic Flow (ϕ mesons)	80	120	160	160	320
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	20	30	35	45	50
Azimuthal Femtoscopy (protons)	35	40	50	65	80
Net-Proton Kurtosis	70	85	100	170	340
Dileptons	100	160	230	300	400
$>5\sigma$ Magnetic Field Significance	50	80	110	150	200
Required Number of Events	100	160	230	300	400

+100M for each FXT energy

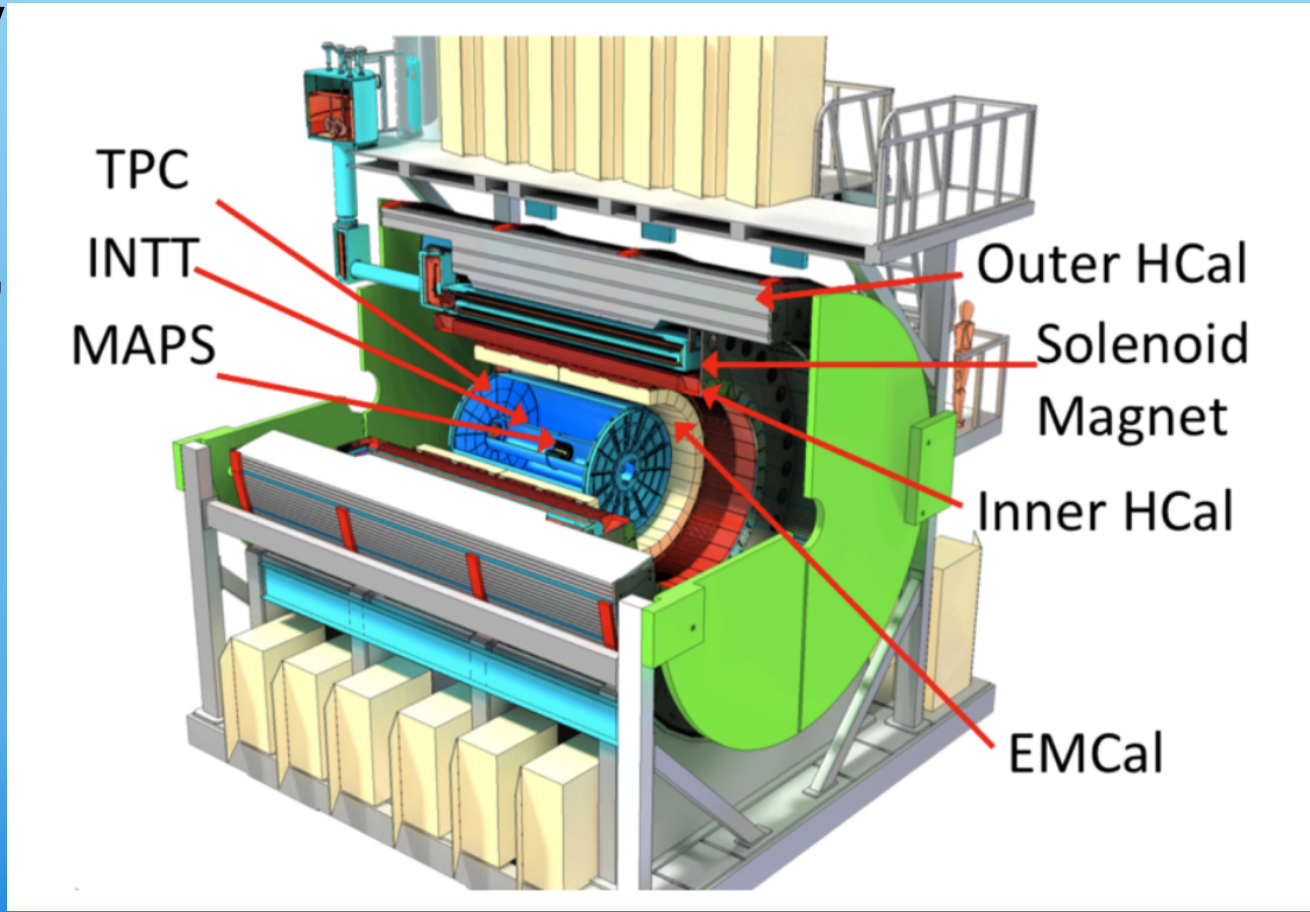
Typically factor 20 more than for BES-I

* detector project at RHIC: sPHENIX

sPHENIX: start data taking 2022

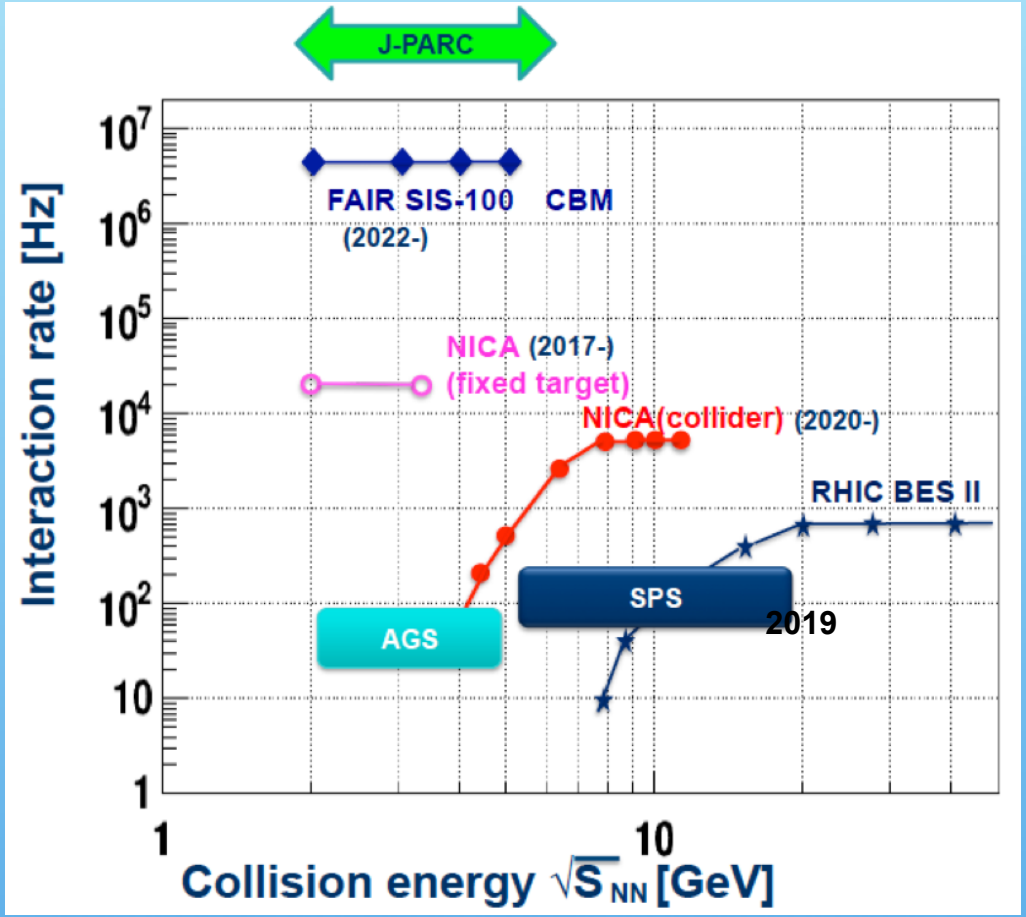
Extended Calorimetry precision vertexing and tracking for jet quenching, charm, beauty

Will be able to search for dark photon with higher mass than PHENIX



M. Connors,
Nucl.Phys. A967 (2017) 548-551

Energy scans with Heavy Ions
Future: BESII, NICA, FAIR, J-PARC



T. Sakaguchi, QM2017

Center of mass energy (sqrt(s)NN) of facilities for future heavy ion runs: FAIR: 2-6 (10) GeV, NICA: 4-11 GeV, RHIC: 7 (2.5) - 200 GeV LHC: 2.76, 5 TeV, J-PARC: 1-10 GeV
FCC (100 km circular ring, p+p at sqrt(s)=100 TeV, Pb+Pb at sqrt(s)=39 TeV)

Conclusions and perspectives

Heavy Ion collisions offer special conditions of hot and dense partonic matter with high multiplicity, high magnetic field and large vorticity

*** promising for discovering new states that can benefit from these conditions**

- **Heavy ion data exhibit the "Number of Constituent Quark Scaling" suggesting dominant hadron production via quark coalescence out of a hadronizing QGP.**

Major advantage of Heavy Ions for multipartonic states is the production via colaescence

Conclusions and perspectives

- Absolutely stable Strange Quark Matter may be possible (E Witten).
- Strange Quark Matter can exist in the core of neutron stars or quark stars

- Small droplets of Strange Quark Matter can be produced in particle collisions in accelerators and are searched by experiments as well as by space experiments like AMS.

- Exotic hadrons with strangeness like antihypernuclei and the anti-helium-4 have been observed in heavy ion collisions.

- Search for a Dark Photon in p+p,p+A and A+A collisions have set upper limits

T. Sakaguchi, QM2017

Perspectives non-LHC

STAR

- RHIC BESII (2019-2020) and fixed target

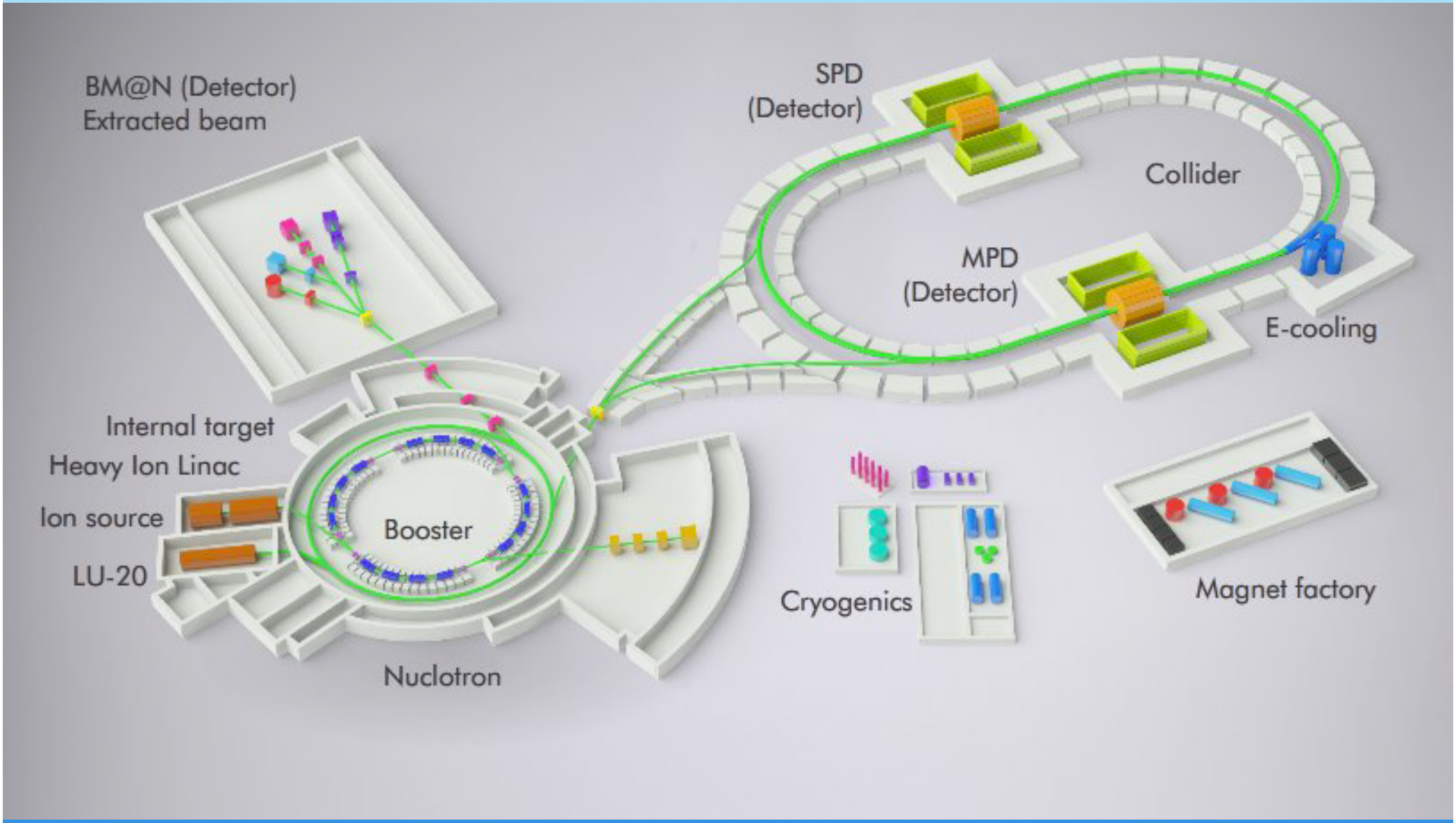
- sPHENIX (2020+)

- NA61 (SPS)

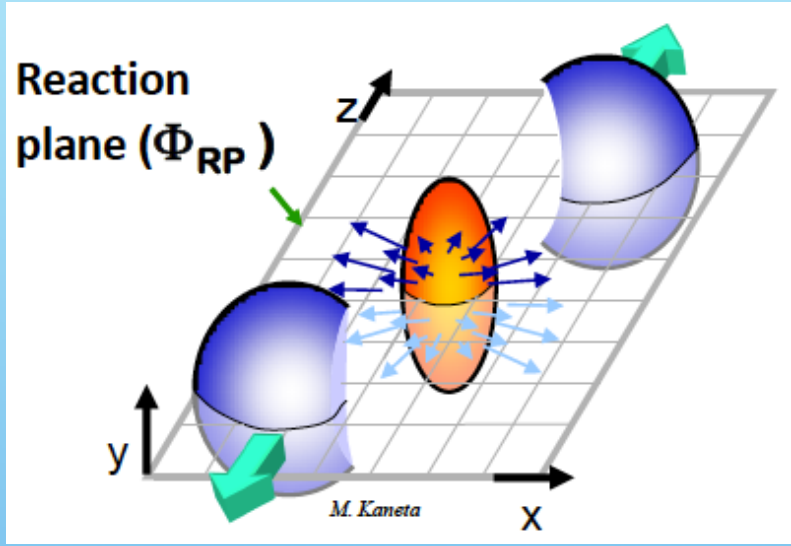
- New dedicated accelerator facilities and corresponding new experiments
- NICA in Dubna, Russia
- FAIR in GSI, Germany
- J-PARC in Japan,
- will allow to progress in significant way in the next decades.

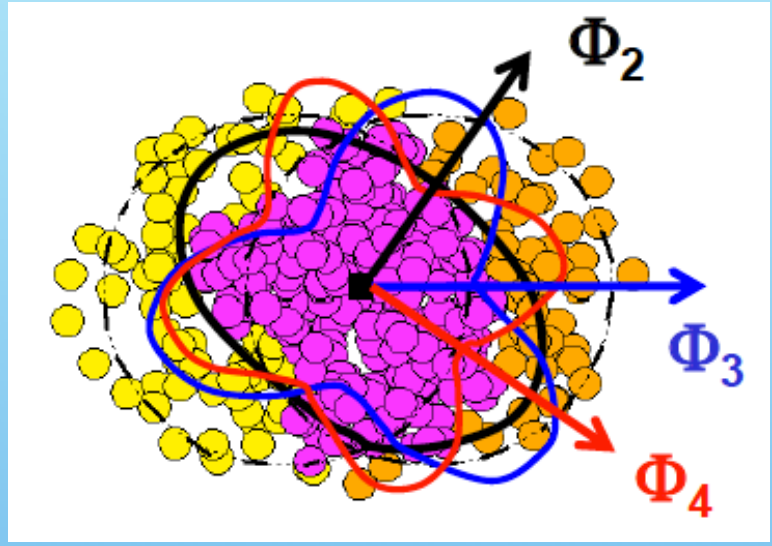
Thank you very much

NICA


BM@N (Detector)
Extracted beam
SPD
(Detector)
Collider
MPD
(Detector)
E-cooling
Internal target
Heavy Ion Linac
Ion source
LU-20
Booster
Nuclotron
Cryogenics
Magnet factory

Flow coefficients v_n, n=1,2,3..





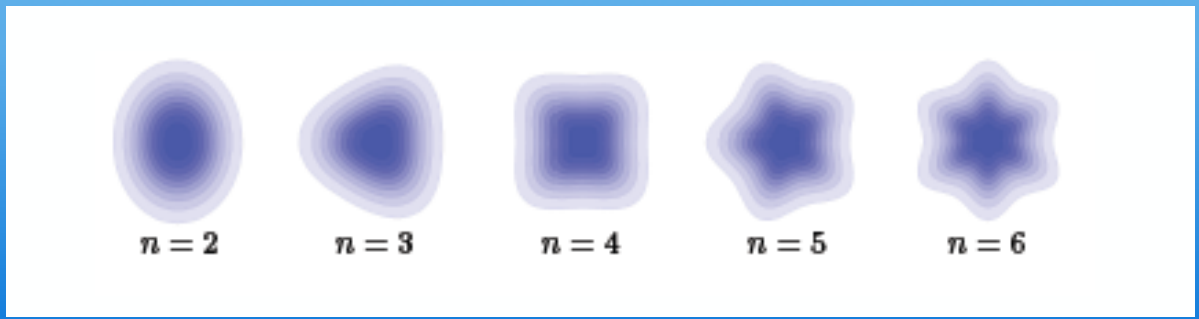
Matter in the overlapp area of two colliding nuclei gets compressed and heated

Initial anisotropy gets transfered into the momentum space via pressure gradients

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_n)]$$

$$v_n = \langle \cos[n(\phi - \Phi_n)] \rangle$$

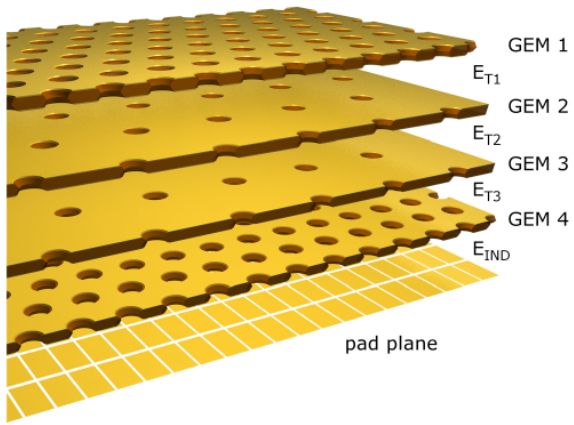
v : flow coefficients
(v1: directed flow,
v2: elliptic flow, ...)



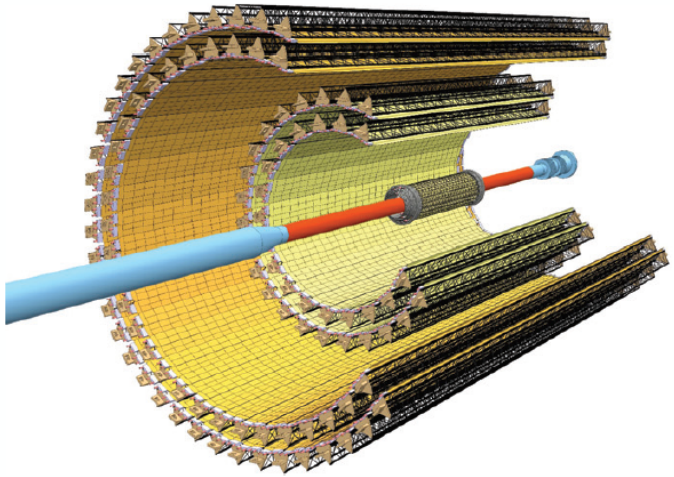
Higher harmonics

LHC experimental upgrades
ALICE upgrades for run-3

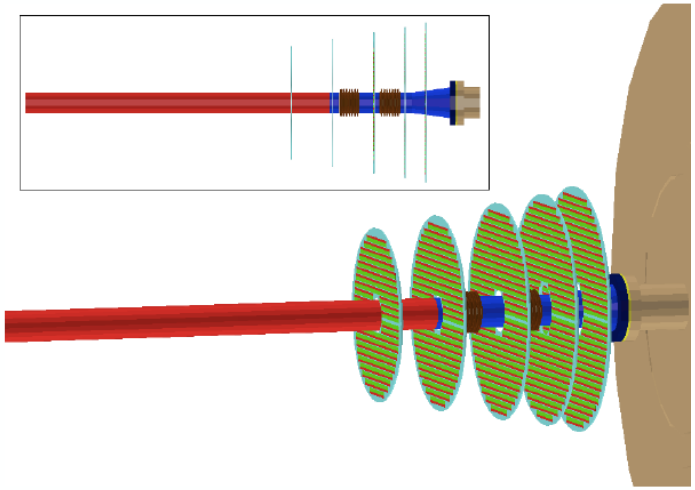
GEM-TPC



ITS

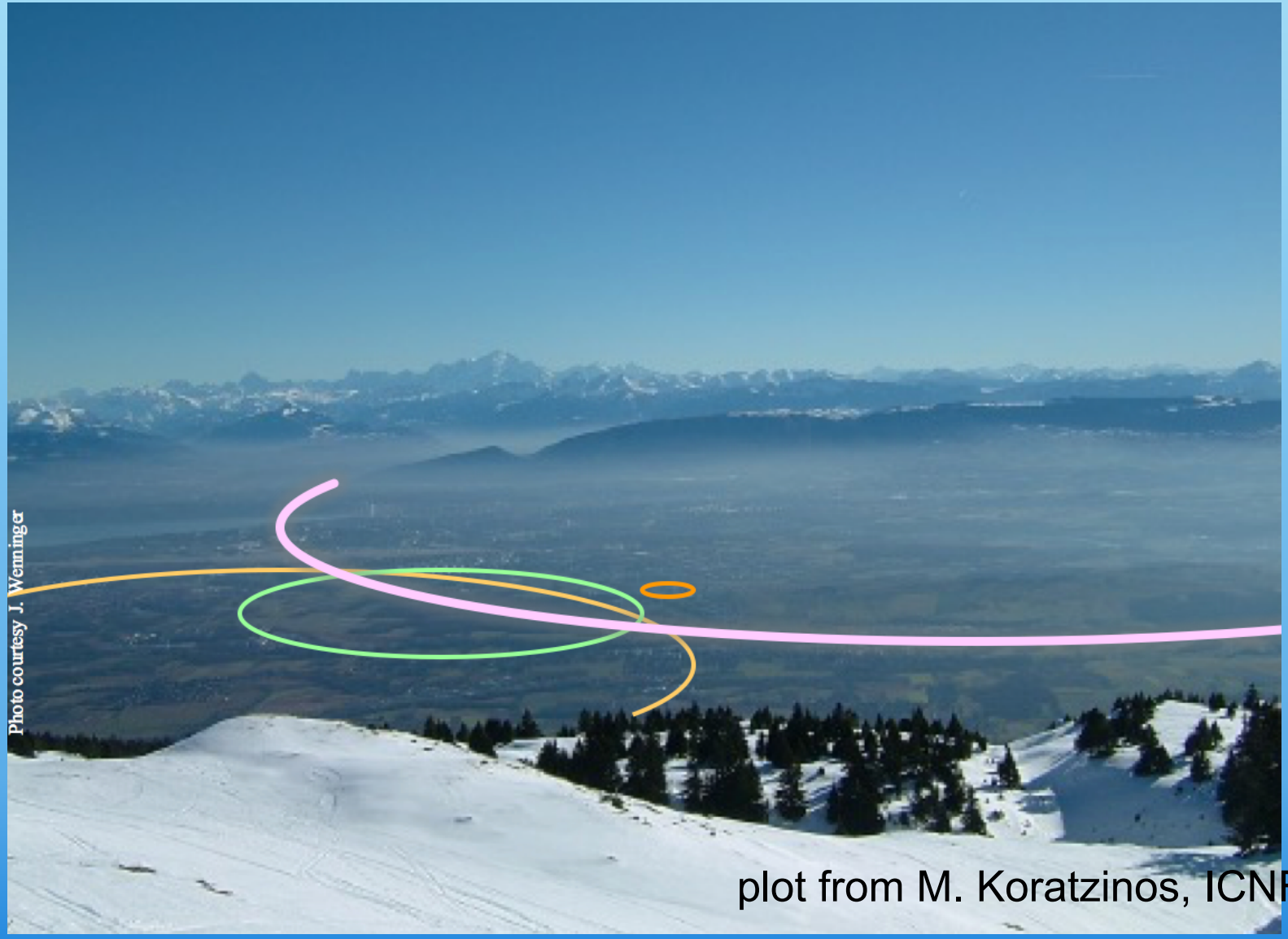


MFT



MFT: will provide secondary vertex reconstruction in forward rapidity
ITS : low pT reach and improved accuracy
High rate
The Upgrades will allow high statistics and high resolution strangeness measurements

A view into the far Future : FCC



plot from M. Koratzinos, ICNFP2017

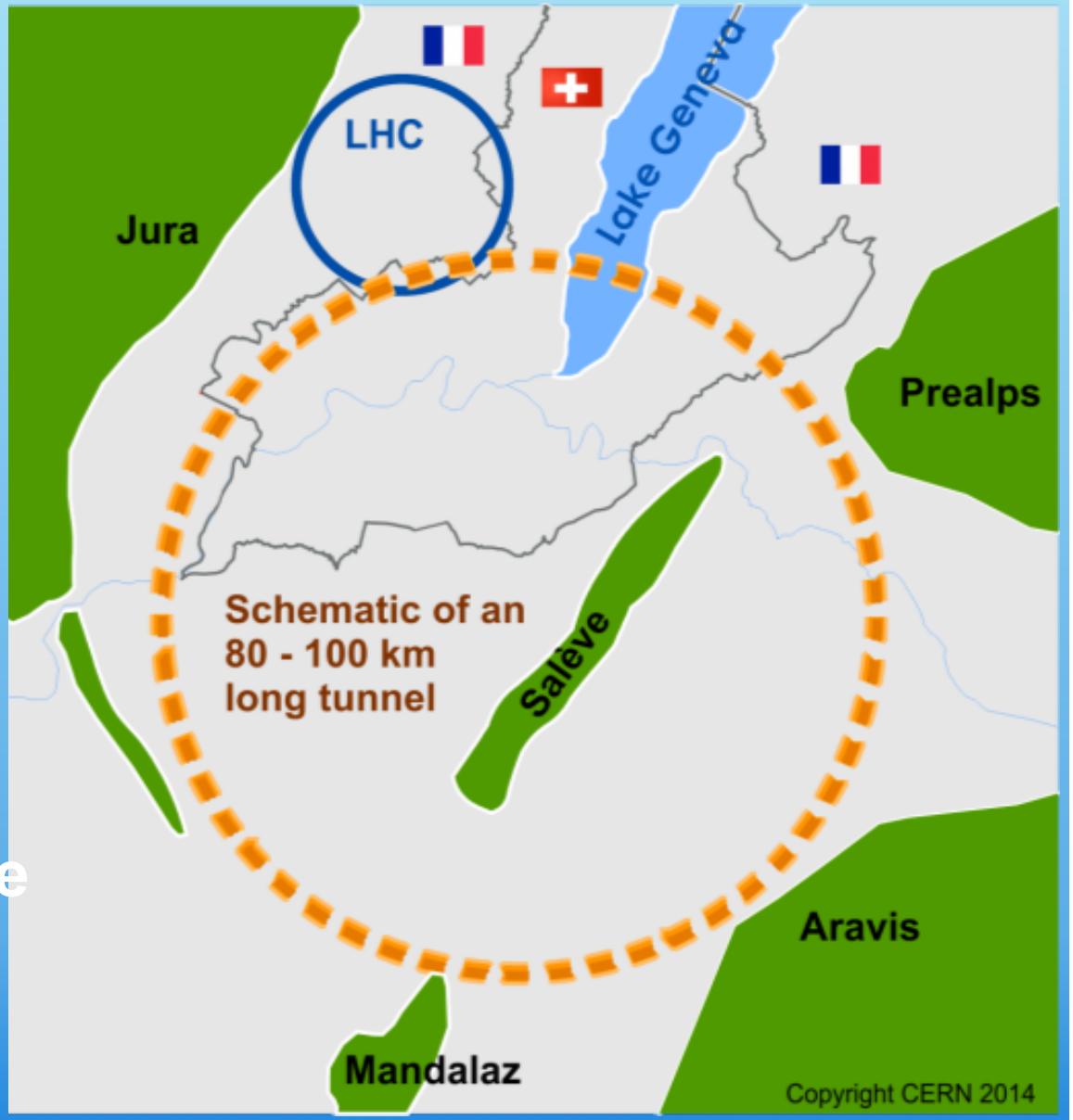
FCC: The Vision

~100 km tunnel, 16 T magnets
sqrt(s)= 100 TeV pp collisions

FCC-hh
FCC-ee
FCC-he

Possible first steps
***FCC-ee, E_CM=90-400 GeV**
******HE-LHC*** **16T 28 TeV**
in LEP/LHC tunnel

FCC-AA : sqrt(s)NN=40 TeV



Strangeness related possible Highlight of FCC ? :
Strangelet production may be possible in FCC !

range of photon emission	fraction of total photon yield	
	AuAu@RHIC 0-20% centr.	PbPb@LHC 0-40% centr.
$T = 120\text{-}165\,\mathrm{MeV}$	17%	15%
$T = 165\text{-}250\,\mathrm{MeV}$	62%	53%
$T > 250\,\mathrm{MeV}$	21%	32%
$\tau = 0.6 - 2.0\,\mathrm{fm/c}$	28.5%	26%
$\tau > 2.0\,\mathrm{fm/c}$	71.5%	74%

C. Gale et al, 1308.2440

*** Most photons at RHIC and LHC are emitted from time near Tc**
*** Their effective temperature is enhanced by strong radial flow (effective temperature of hadrons decaying into photons are above Tc due to mass dependence of radial flow).**
*** However a very high temperature early initial collision stage is required to generate this radial flow**

Conclusions:
*** Photons can be used as a thermometer**
*** T>Tc is reached**
*** More model calculations needed to fit the data and extract the T(init)**