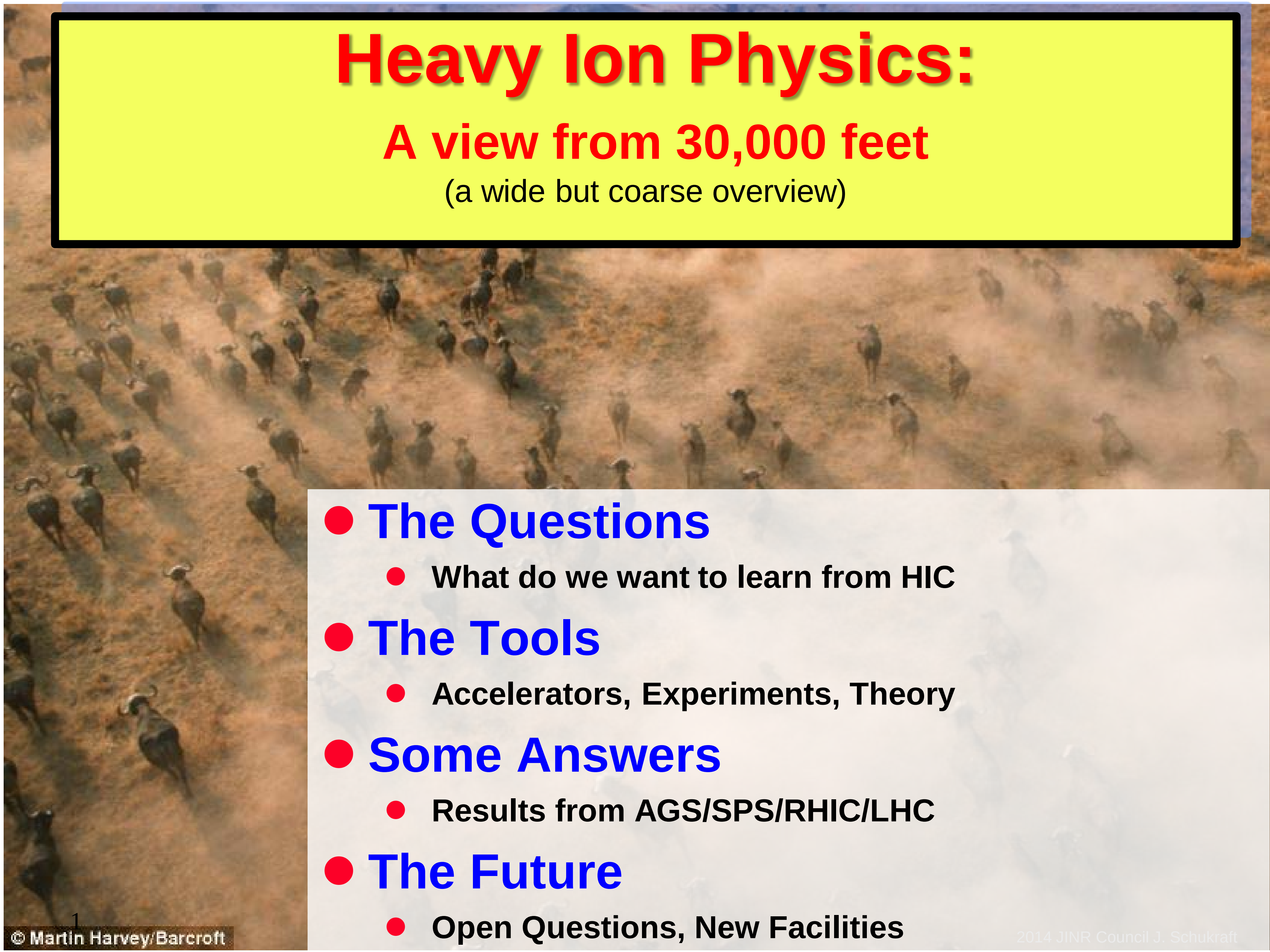
Heavy Ion Physics:

A view from 30,000 feet

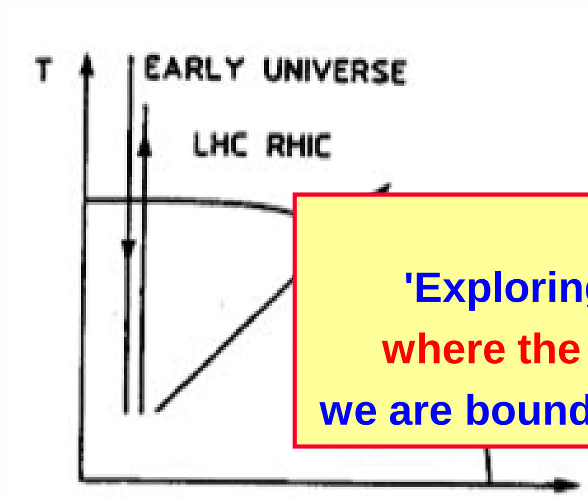
(a wide but coarse overview)



- **The Questions**
  - **What do we want to learn from HIC**
- **The Tools**
  - **Accelerators, Experiments, Theory**
- **Some Answers**
  - **Results from AGS/SPS/RHIC/LHC**
- **The Future**
  - **Open Questions, New Facilities**

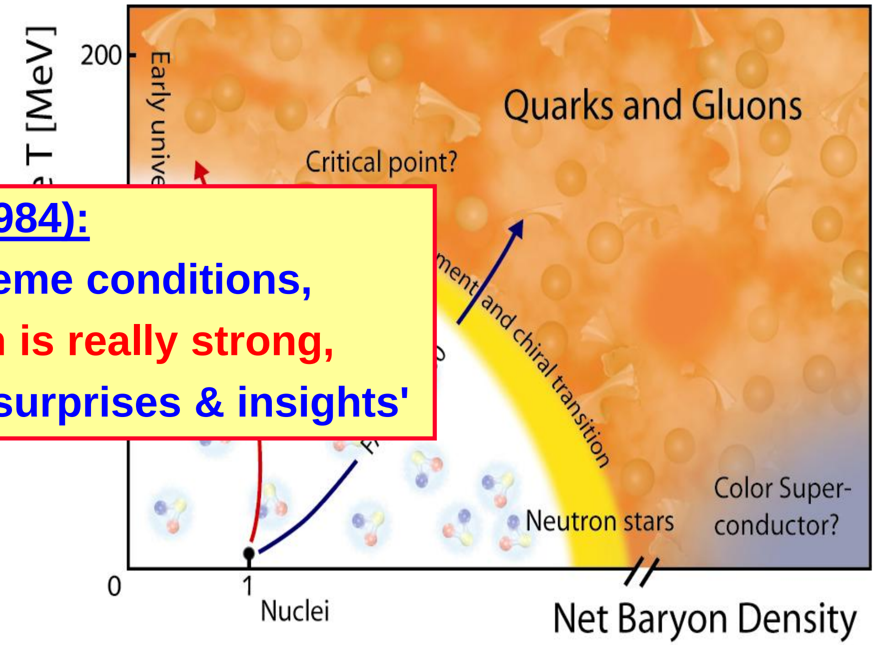
Matter under Extreme Conditions

- Phase diagram of strongly interacting matter



phase diagram, ca 1990

Bill Willis (ca 1984):
'Exploring QCD under extreme conditions,
where the strong interaction is really strong,
we are bound to find plenty of surprises & insights'



- ‘state of matter’ at high temperature & energy density: **‘The QGP’**
  - ⇨ theoretical expectations & predictions :
    - ✪ **weakly interacting plasma** / ideal gas of (quasi-free) quarks & gluons
    - ✪ partons are **deconfined** (not bound into composite color neutral hadrons)
    - ✪ **chiral symmetry** is restored (partons ≈ massless, vanishing gluon condensate)
  - ⇨ experimental definition

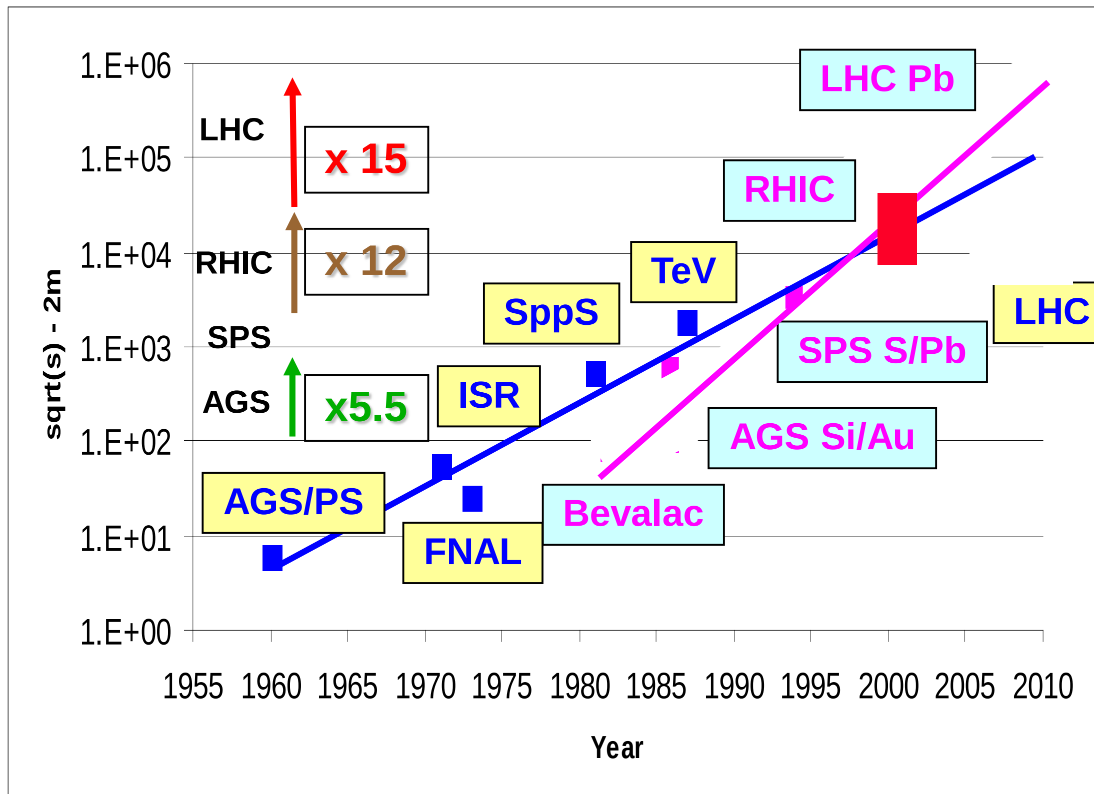
‘the stuff at high T where ordinary hadrons are no longer the relevant d.o.f’

Accelerators

- **Particle Physics: energy doubling time ~ 4 years**
- **Heavy Ion Physics: doubling time ~ 2 years**
  - ⇨ energy increase by factor 10^4 in ~ 30 years
  - ⇨ starting 70'- to early 80's at Bevalac/Berkely
    - ✪ field started by a few dozen physicists from a handful of countries
    - ✪ > 2500 physicists active worldwide today

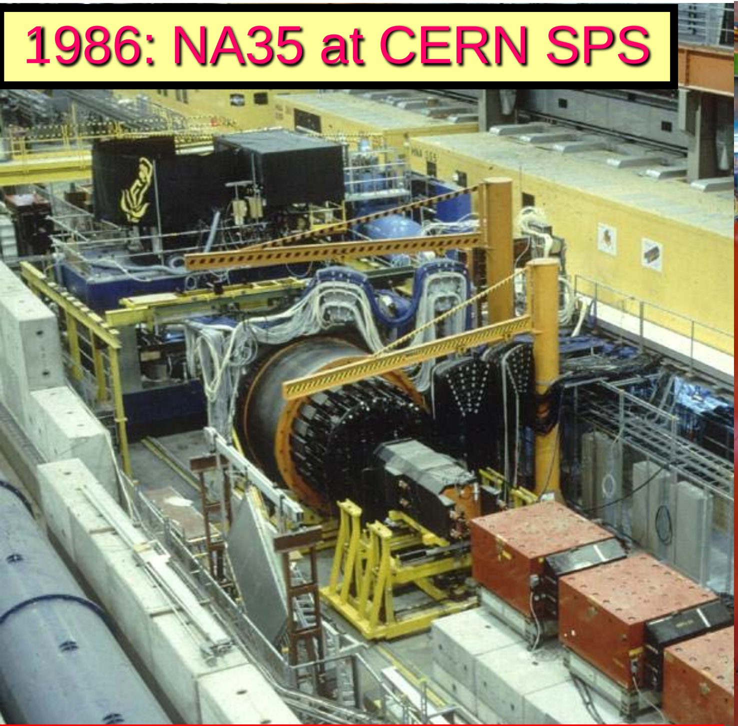
Field went from the periphery into a **central activity** of contemporary **Nuclear Physics**
(and now gets even some HEP guys excited !)

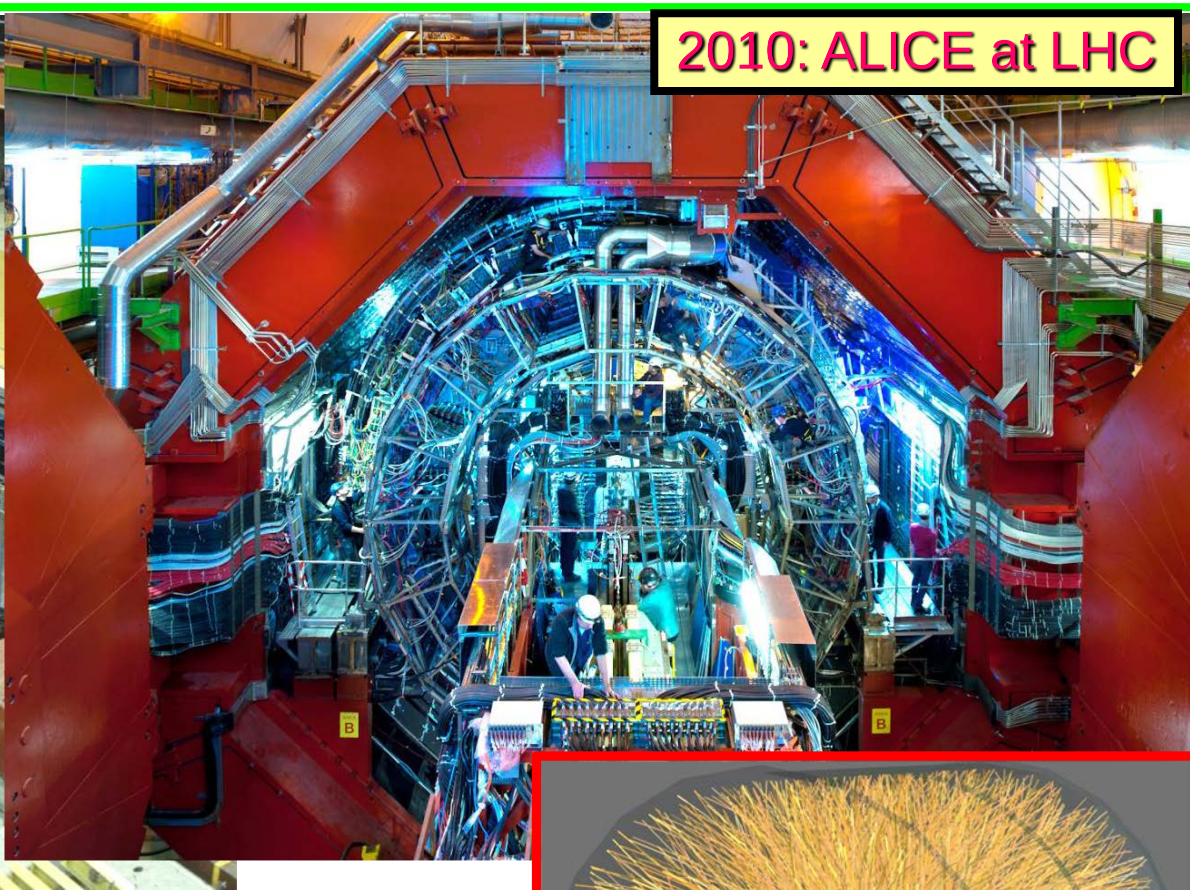
Total center-of-mass energy versus time

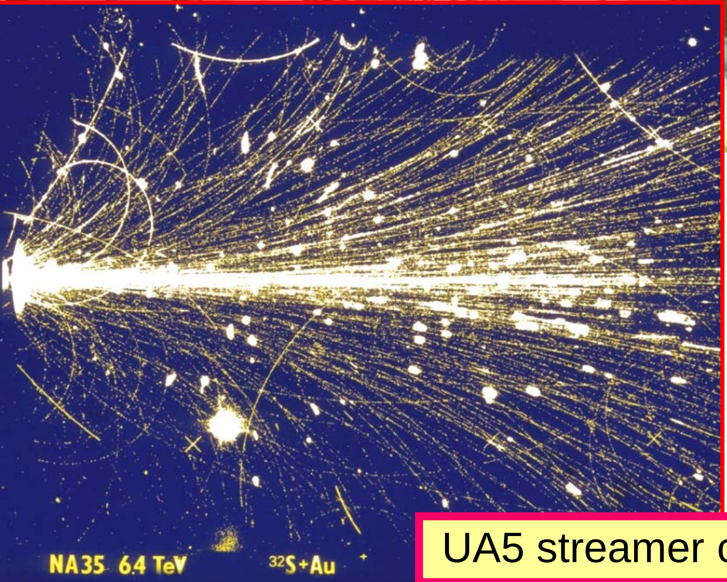


Livingston plot

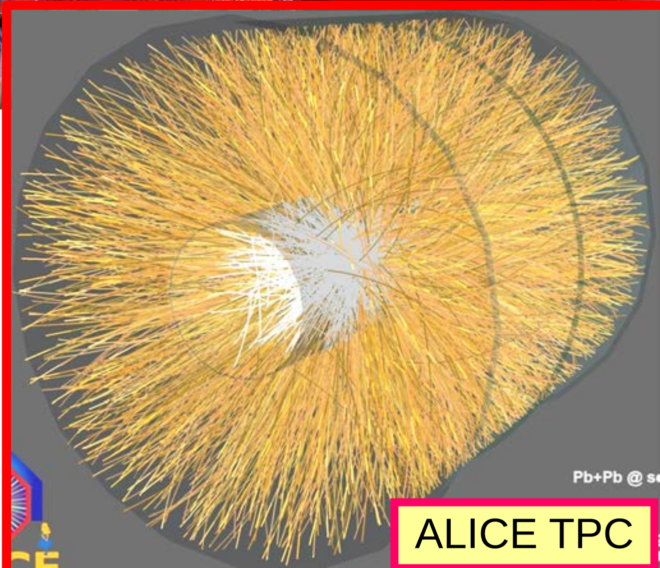
Experiments


1986: NA35 at CERN SPS


2010: ALICE at LHC

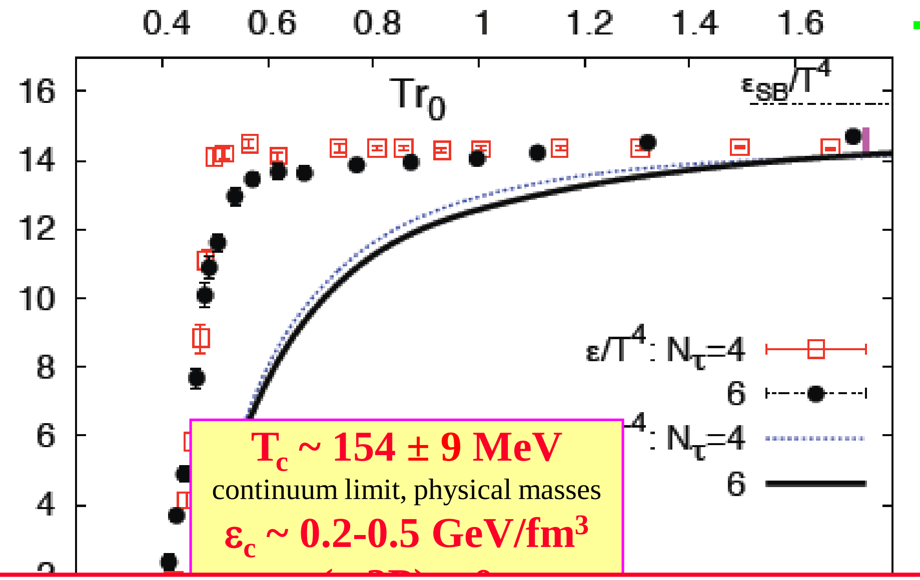


UA5 streamer chamber used in NA35

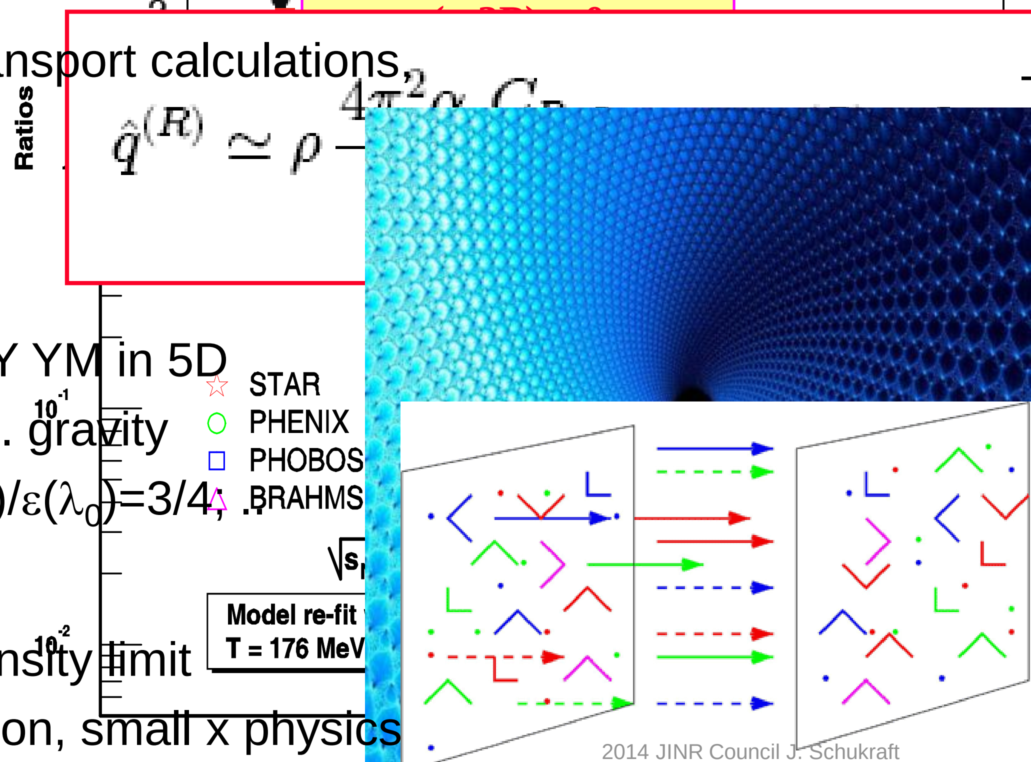

ALICE TPC

Theory

- **Lattice QCD**
  - ⇨ ideal for thermodynamics(static), EoS, T_c



- **Pert. QCD**
  - ⇨ cross sections, dynamical coefficients
- **Phenomenology**
  - ⇨ hydrodynamics, thermal models, transport calculations,
  - ⇨ event generators (Phytia, Hijing, ..)
- **Duality: AdS/CFT**
  - ⇨ 4D gauge theory equivalent to SuSY YM in 5D
  - ⇨ strong coupling => reduced to class. gravity
  - ⇨ remarkable results: $\eta/s = 1/4\pi$; $\varepsilon(\lambda_\infty)/\varepsilon(\lambda_0)=3/4$; ..
- **Color Glass Condensate**
  - ⇨ initial state: classsical FT in high density limit
  - ⇨ related to gluon shadowing, saturation, small x physics



SPS: 1986 - 2002(4); NA61: >2009

O, S, Pb

$\sqrt{s_{NN}}$ = 6.5 - 20 GeV/A, 3.9 - 17 GeV/A

Users: ~ 600

LHC: 2010 -

Pb, $\sqrt{s_{NN}}$ = 2.76, 5.5 TeV/A

Users: ~ 1000

AGS: 1986 - 1996(8)

Si, Au

$\sqrt{s_{NN}}$ = 2.5 - 5.5 GeV/A

Users: ~ 400

RHIC: 2000 -

d, Cu, Au,

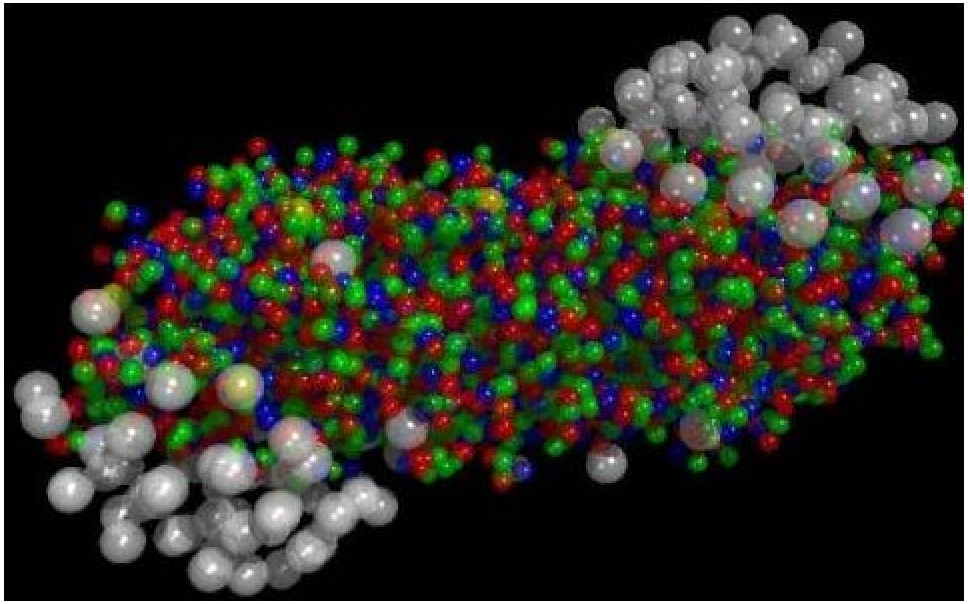
$\sqrt{s_{NN}}$ = 7.7-200 GeV/A

Users: ~ 1000

New State of Matter created at CERN

10 Feb 2000

http://press.web.cern.ch/press-releases/2000/02/new-state-matter-created-cern



Based on a (unpublished)

'common assessment' of

results from ~ half dozen experiments

collected & published over the course of the SPS Pb program (1994 - 2000)

http://arxiv.org/abs/nucl-th/0002042v1

The collected data from the experiments gives compelling evidence that a new state of matter has been created. This state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma..

'.. a QGP-like state ..'

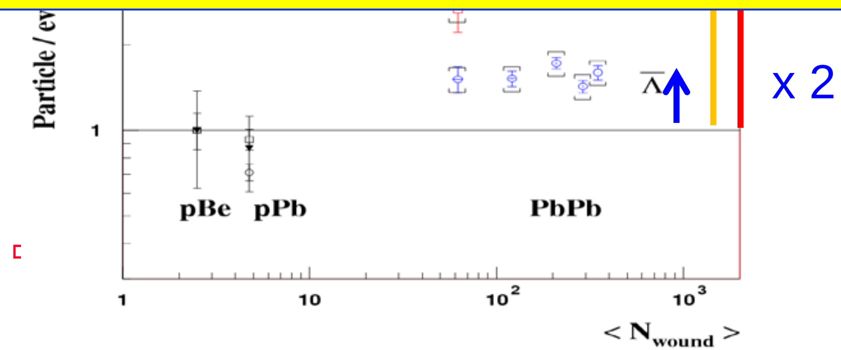
Main Results from SPS

- strangeness enhancement

- the experimental results have stood the test of time
- essence of the statements was & is correct

evidence for a new state of matter at the SPS energy range

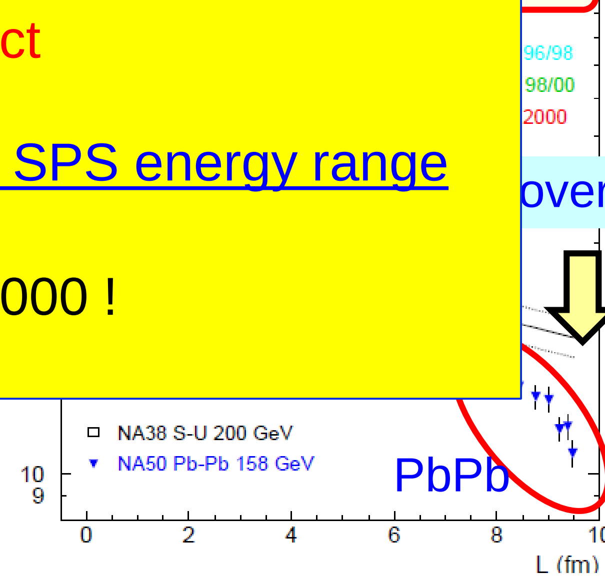
however, today more 'compelling' than in 2000 !
(later SPS results, RHIC energy scan, LHC)



- 'anomalous' J/Ψ suppression

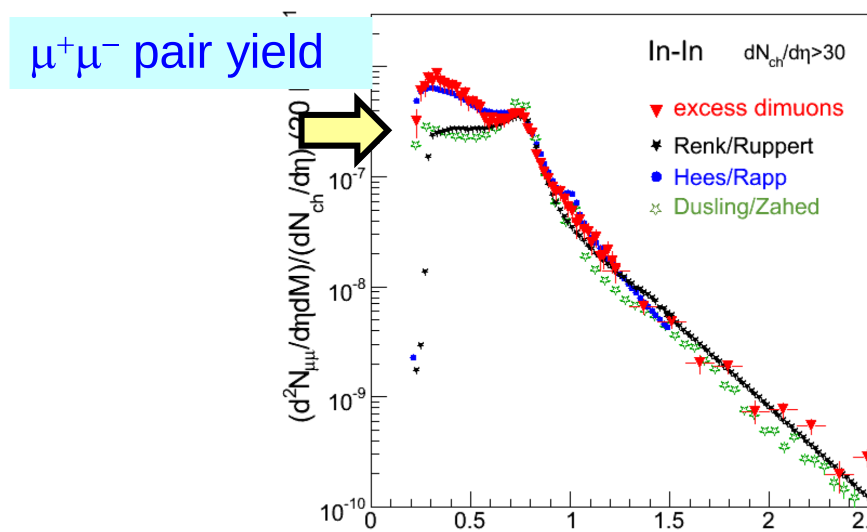
ent signal

over Drell-Yan



- low mass lepton pair enhancement

⇨'rho melting',
sign of chiral symmetry restoration ?

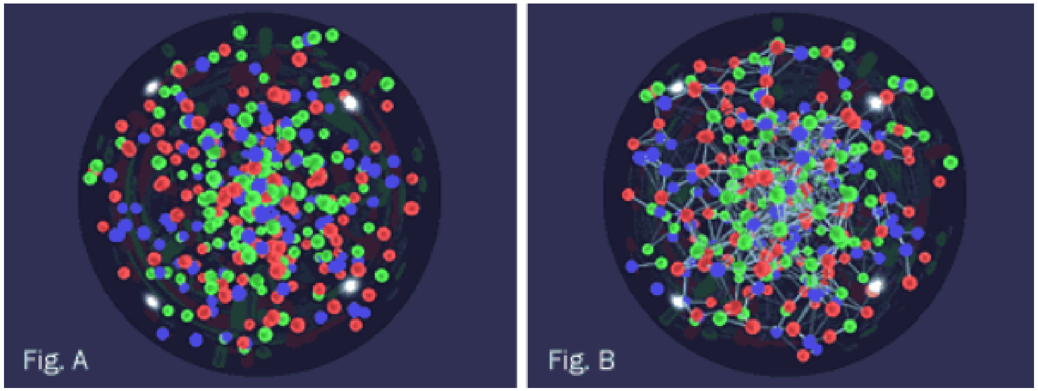


http://www.bnl.gov/newsroom/news.php?a=1303

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005



These images contrast the degree of interaction and collective motion, or "flow," among quarks in the predicted gaseous quark-gluon plasma state (Figure A, see mpeg animation) vs. the liquid state that has been observed in gold-gold collisions at RHIC (Figure B, see mpeg animation). The green "force lines" and collective

+ENLARGE

Based on a (published) **comprehensive (re)analysis** of the first years of RHIC (2000 - 2004)

Nucl.Phys.A757:1-284,2005

.. created a new state of hot, dense matter out of the quarks and gluons .., but it is a state quite different and even more remarkable than had been predicted.

i' **..the QGP ..'**

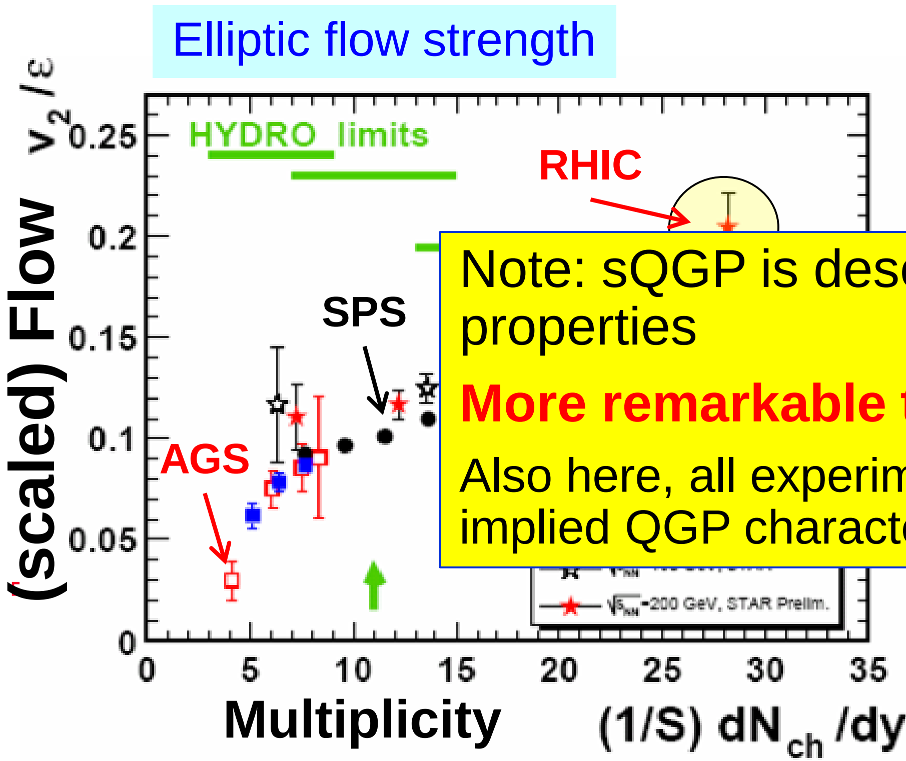
but

'.. a QGP ..': sQGP

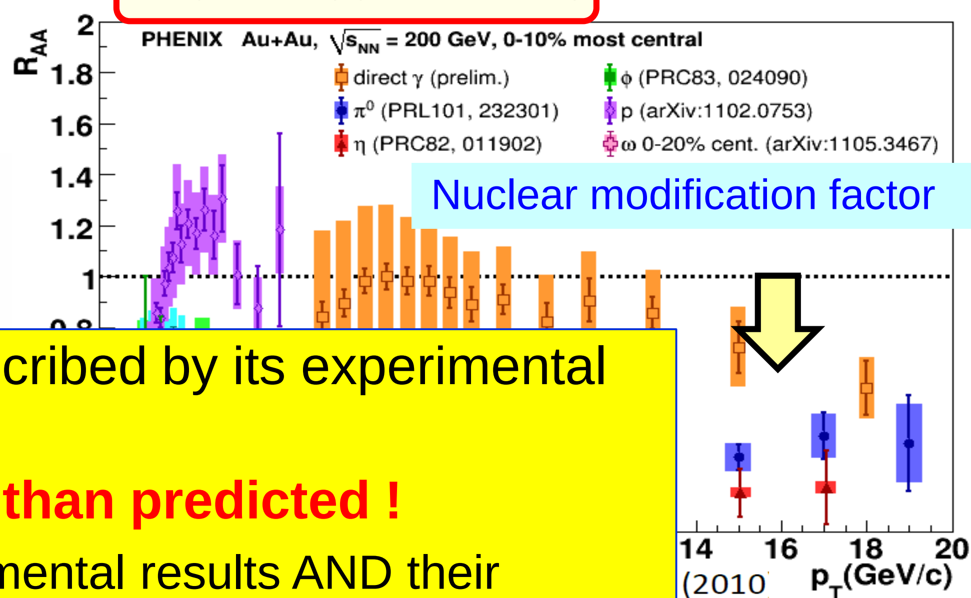
sQGP: strongly interacting QGP

Main Results from RHIC

- strong elliptic flow
  - ⇨ ~ maximum possible i.e 'ideal liquid' ($\eta/s \approx 0$)
  - ⇨ mostly produced in the early phase (partonic?)



- high p_T suppression 'jet-quenching'
  - ⇨ very strongly interacting (large energy loss)

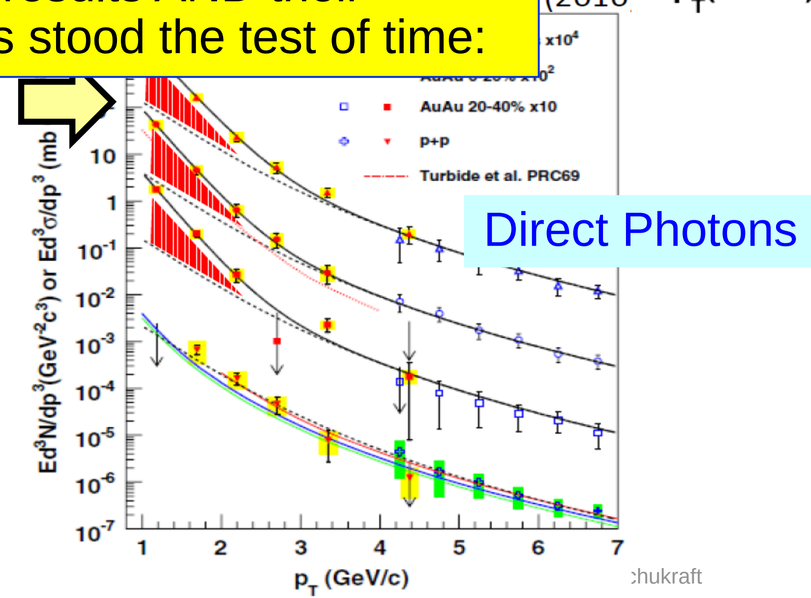


Note: sQGP is described by its experimental properties

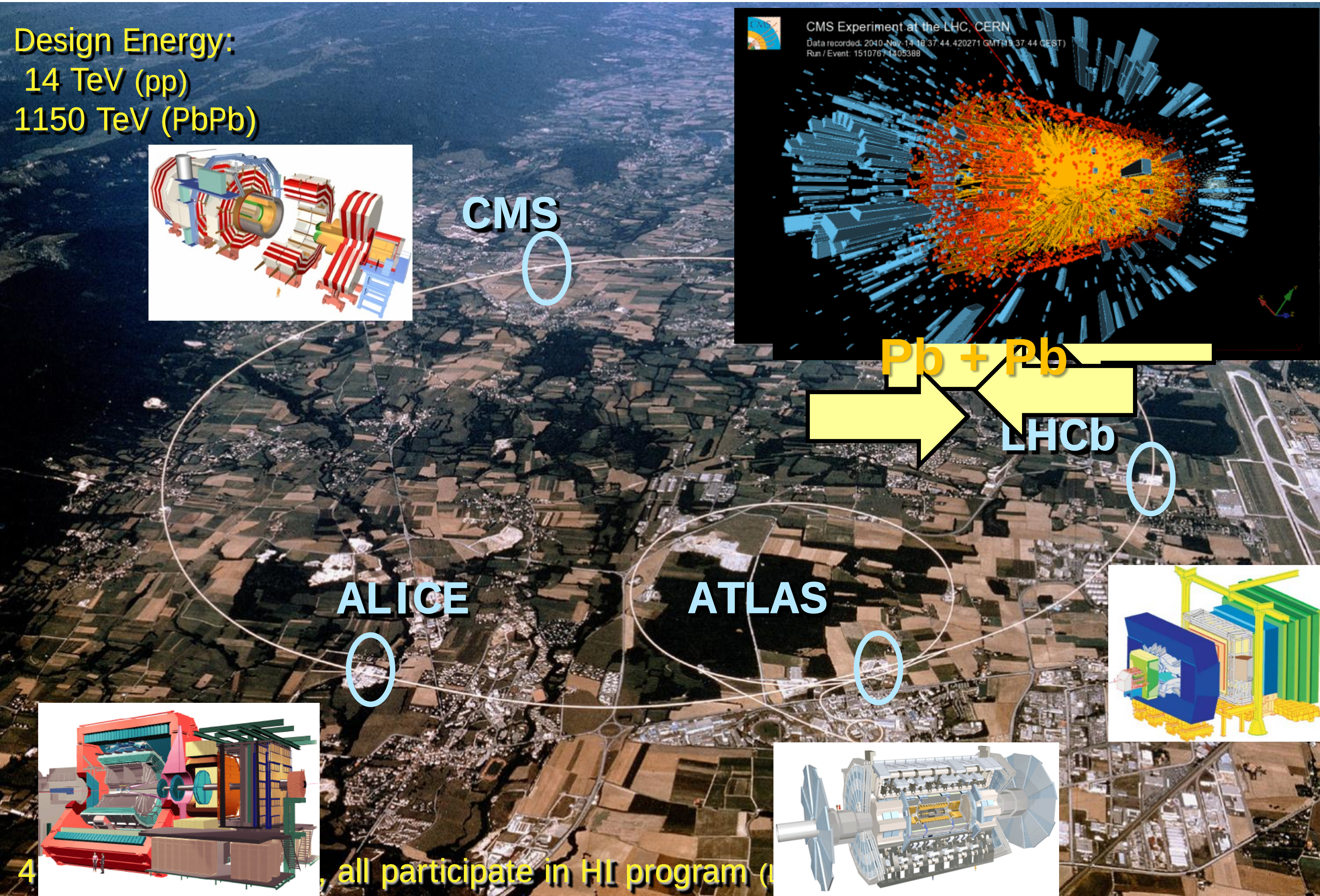
More remarkable than predicted !

Also here, all experimental results AND their implied QGP characteristics stood the test of time:

- direct 'thermal' photons => 'hot matter'
  - ⇨ data: inverse slope T ~ 220 ± 20 MeV
    model dependent T_0: 300 - 600 MeV



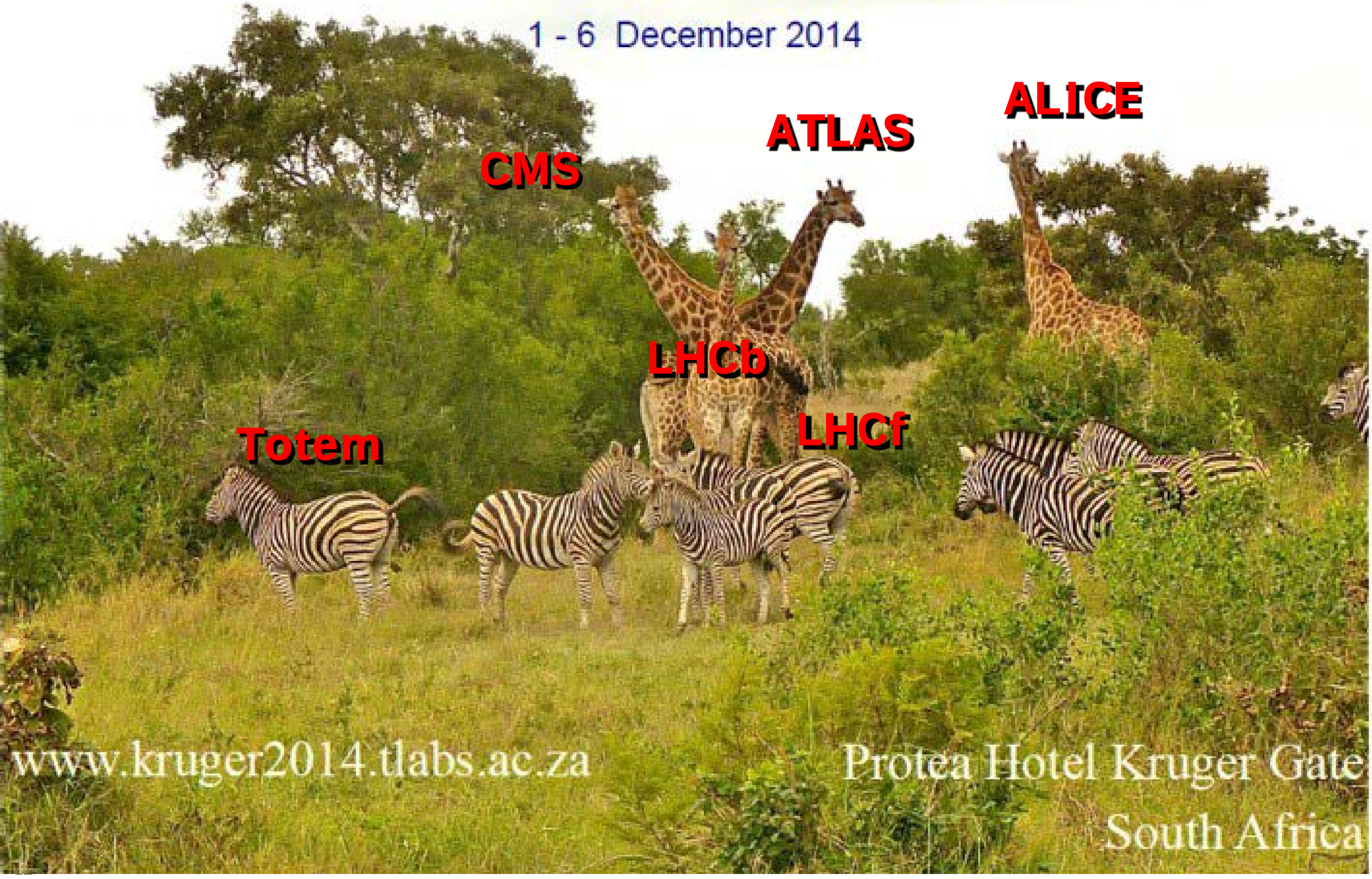
Collider of 'Large Hadrons'
Large Hadron Collider



KRUGER 2014

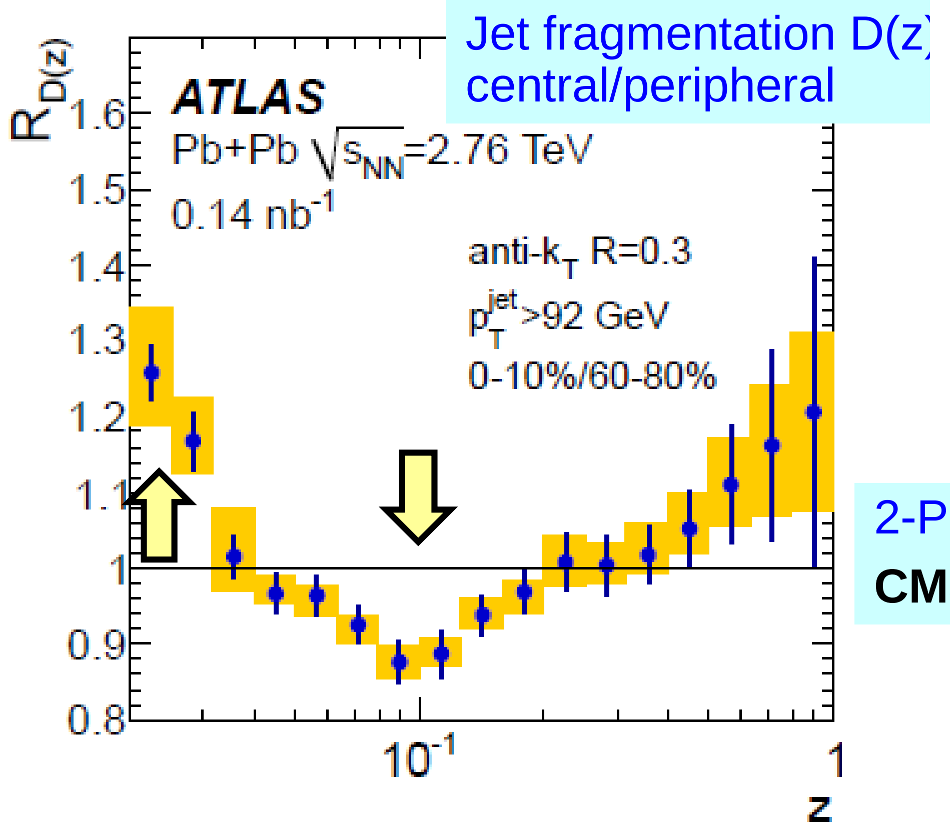
DISCOVERY PHYSICS AT THE LHC

1 - 6 December 2014

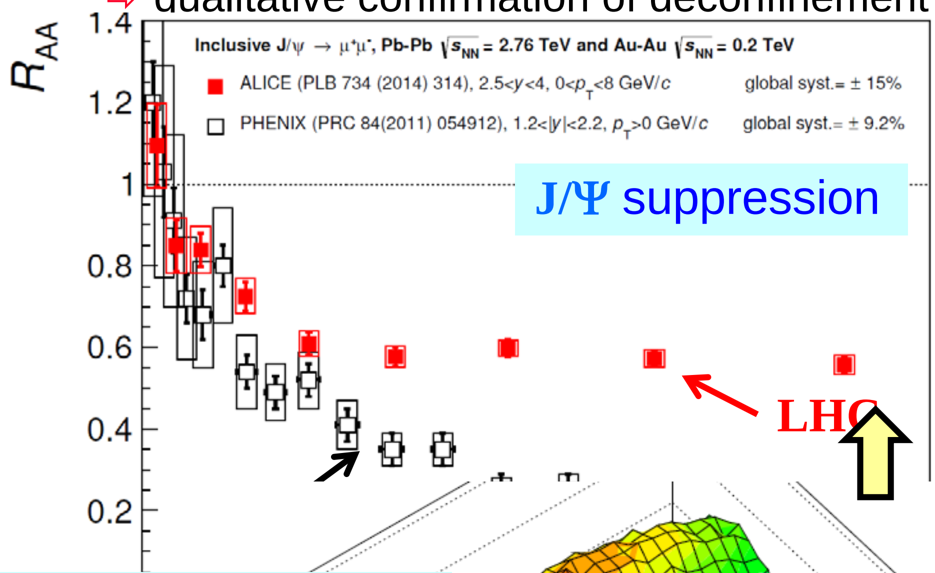


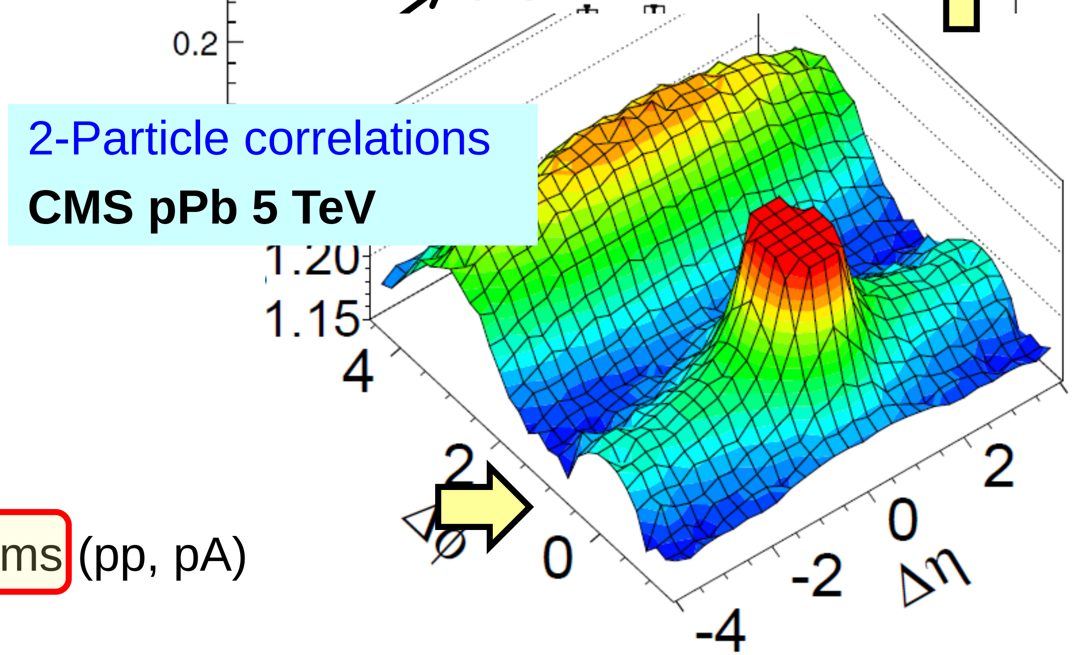
Main Results from LHC

- in-medium jet fragmentation
  - ⇨ insight into dynamics of jet quenching
    - ✪ multiple soft gluon radiation at large angles (inverted angular and time ordering !!)



- J/Ψ coalescence & seq. Υ melting
  - ⇨ SPS/RHIC J/Ψ puzzle solved
  - ⇨ qualitative confirmation of deconfinement

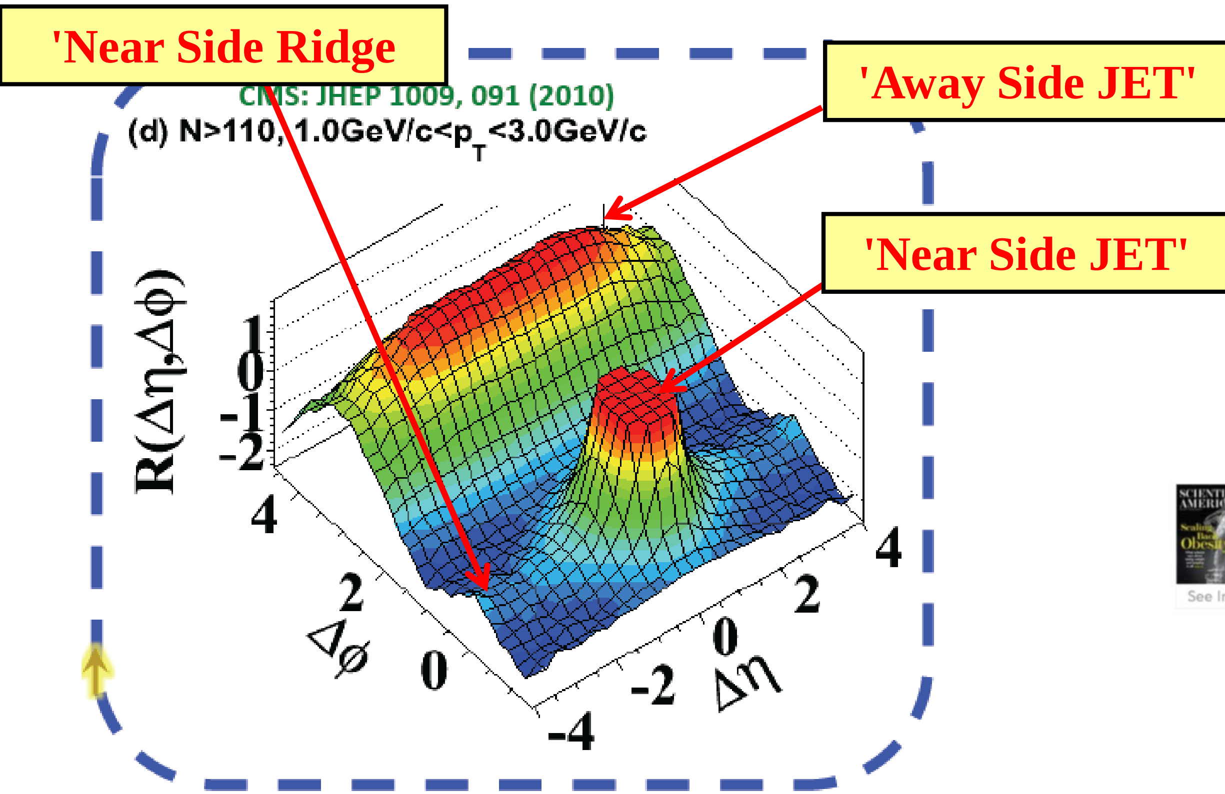




- the ever surprising ideal liquid
  - ⇨ collective hydro flow in small systems (pp, pA)

Discovery

- The first LHC Discovery (pp, Sept 2010)
  - ⇨ long range rapidity 'ridge' in 2-particle correlations
    - ✪ visible in the highest multiplicity pp collisions
    - ✪ arguably still the most unexpected LHC discovery



If we are here today it is because we didn't succeed to kill it.

We have therefore submitted the paper to expose our findings to the scrutiny of the scientific community at large.

G. Tonelli, CERN/INFN/UNIPI CERN LPCC/EP/PP SEMINAR September, 21 2010

Particles That Flock: Strange Synchronization Behavior at the Large Hadron Collider

Scientific American, February (2011)

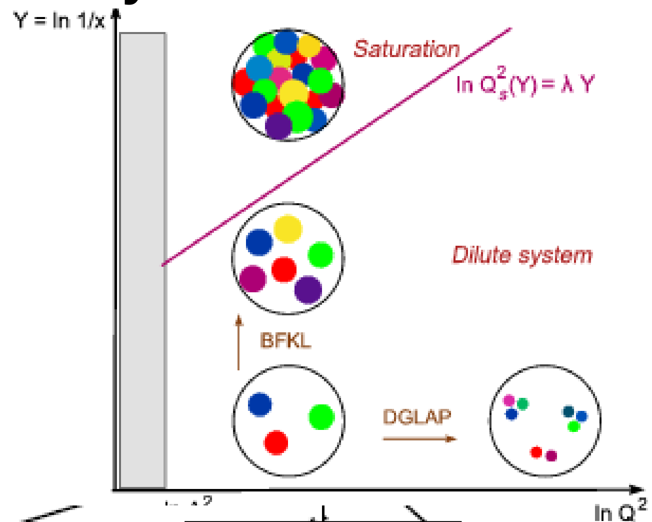
Scientists at the Large Hadron Collider are trying to solve a puzzle of their own making: why particles sometimes fly in sync

The 'Opera' defense !

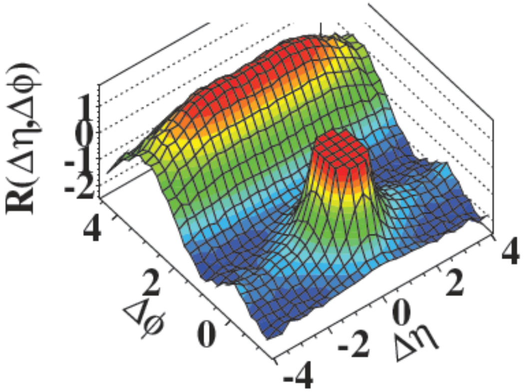
Origin of the pp 'Ridge'

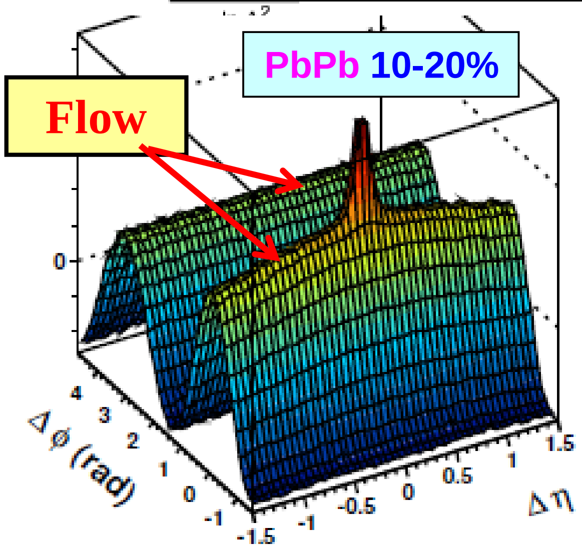
- Spawned a large number of different explanations
  - ⇨ mostly rather ad hoc, very speculative, or outright weird

- Color Glass Condensate CGC: **'first principles' theory**
  - ⇨ classsical FT in high density limit (small x, small Q^2)
  - ⇨ 'new state of cold & dense parton matter'
  - ⇨ some success describing aspects of ep, pp, eA:
    geometric scaling, low-x, particle production, ..
    - ✪ however, no 'smoking gun' so far…

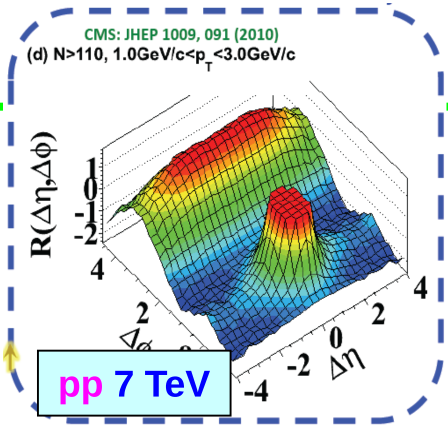


- Collective flow (Hydro) ?
  - ⇨ vaguely similar correlations in nucleus-nucleus





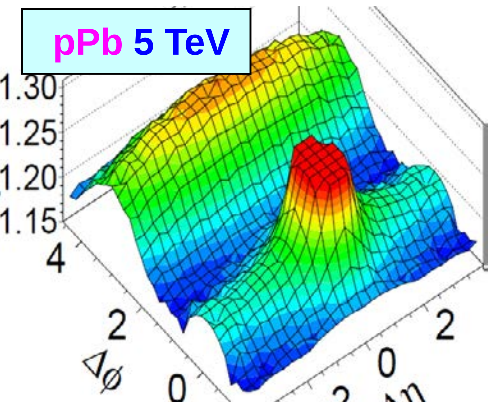
it looks like a rose, it smells like a rose



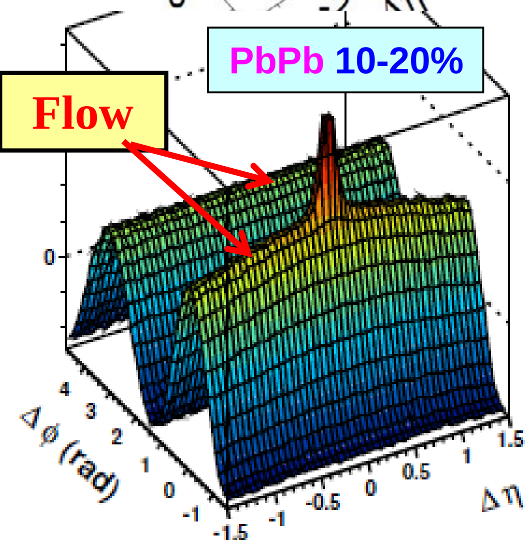
pp 7 TeV

.. With ALL the bells & whistles of hydro flow…

measured to be fully collective

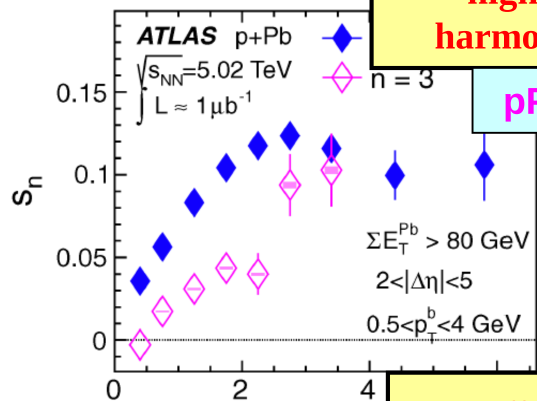


pPb 5 TeV



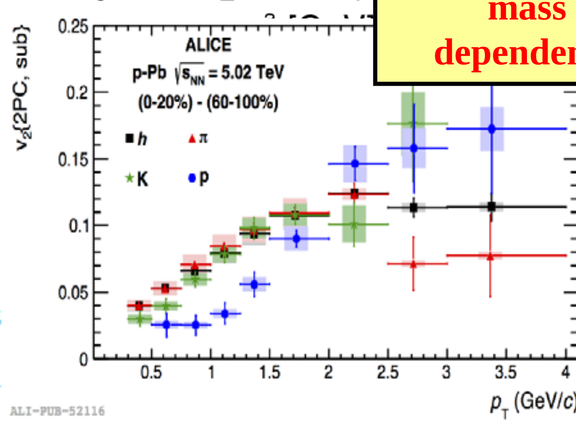
Flow

PbPb 10-20%



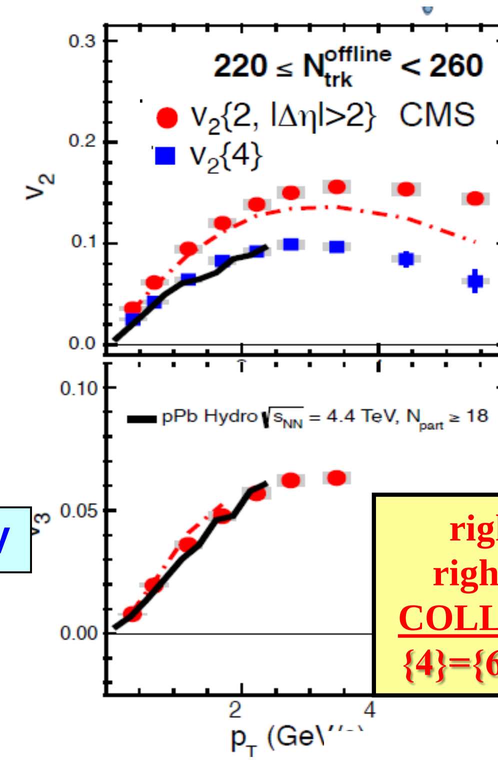
higher harmonics

pPb 5 TeV



mass dependence

pPb 5 TeV



pPb 5 TeV

right size
right shape
COLLECTIVE
{4}={6}={8}= ∞

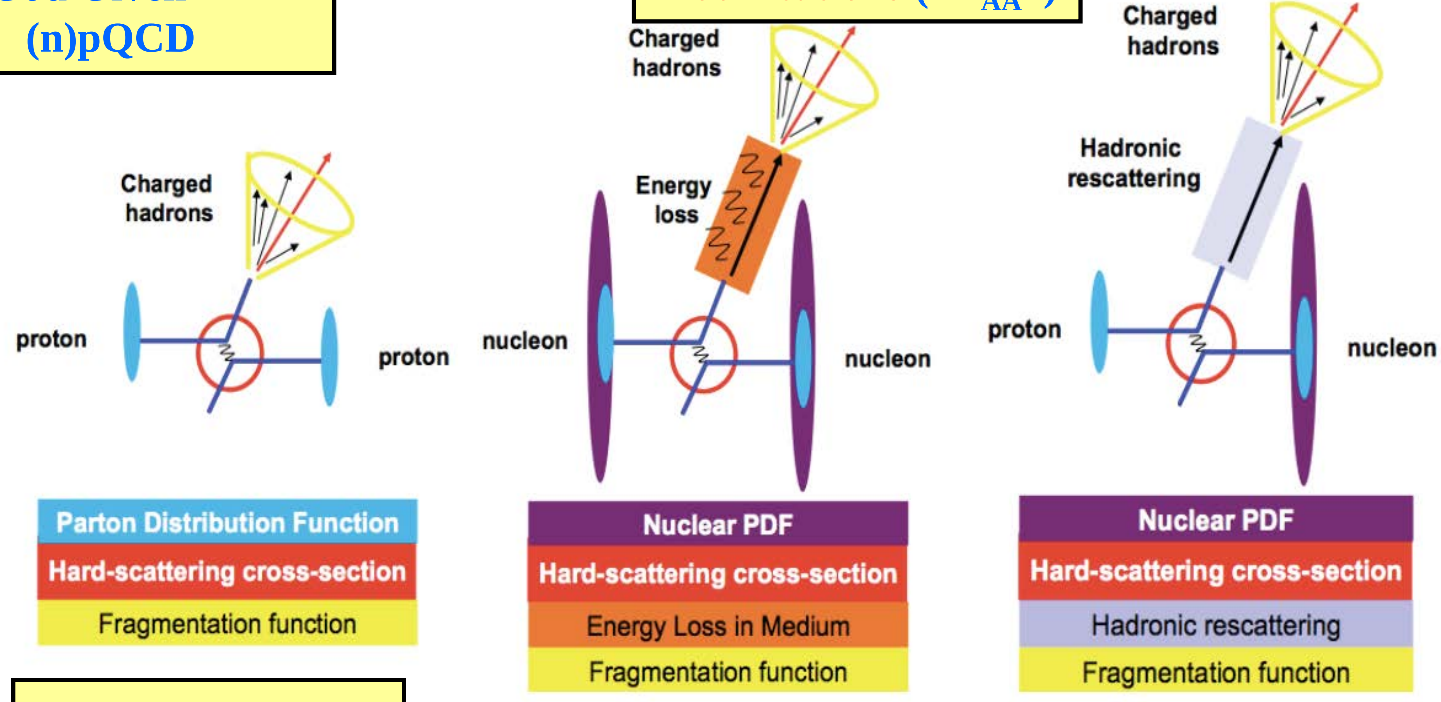
URHI Paradigm (Modus Operandi)

- large & dense systems = our physics
- small & dilute systems = comparison data

pp:
God Given = (n)pQCD

AA:
'Hot Matter' modifications ("R_{AA}")

pA:
CNM modifications



MB pp/e^+e^-
The modifications start here !

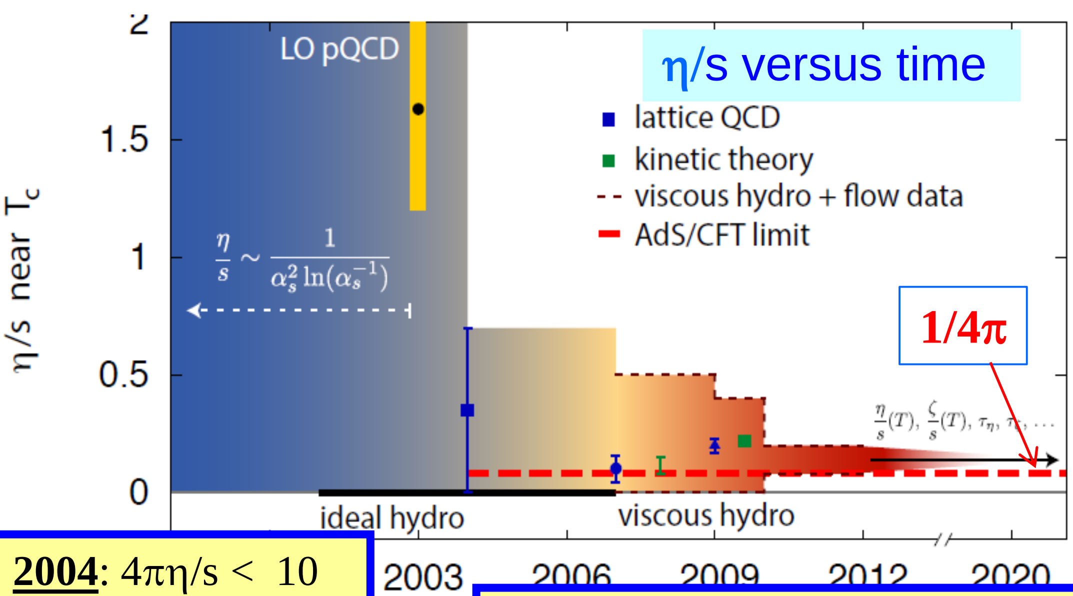
'central' pp/pA:
Hot Matter ?

Eric Appelt 2 Quark Matter 2014, Darmstadt

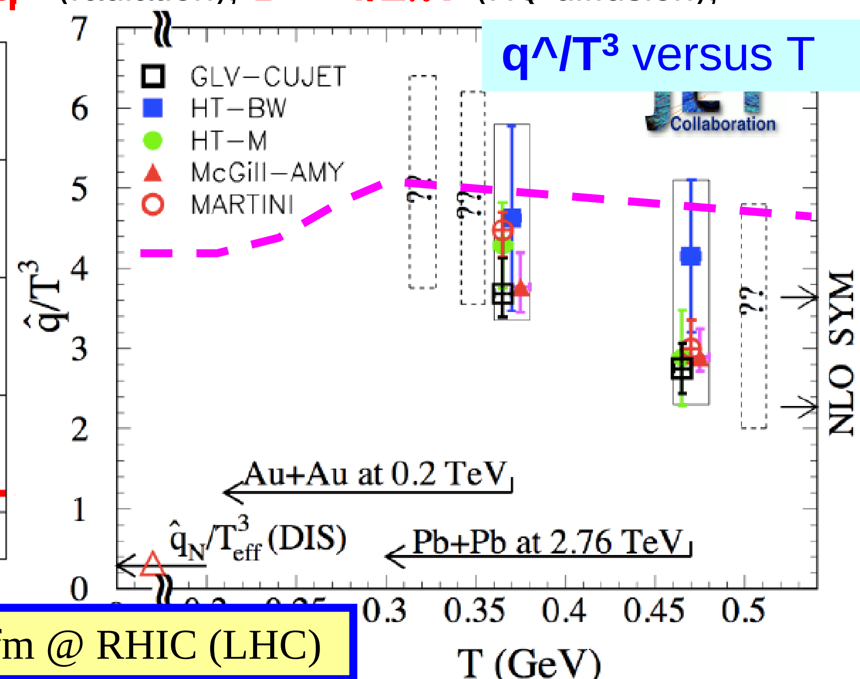
sQGP: The stuff at high T..

We set out to find a weakly interacting gas of quarks & gluons

- **'Very strongly interacting, almost perfect liquid' :** sQGP
  - ⇨ **'Macroscopic' piece of matter with amazing properties**
    - reaches thermo/hydro equilibrium incredibly fast & in small volumes (< 1 fm)
    - tiny viscosity reveals density fluctuations in the initial state, event-by-event !
    - dynamically evolves, expands and cools
    - transforms into a hadron resonance gas which stays at or close to equilibrium
  - ⇨ **we can experimentally measure its properties and follow its evolution !**
    - transport coefficients: **η/s** (viscosity/Entropy), **q^** (radiation), **D ≈ 4/2πT** (HQ diffusion),



2004: 4πη/s < 10
2014: 4πη/s ≈ 1 - 2



q^ ≈ 1.2 ± 0.3 (1.9 ± 0.7) GeV²/fm @ RHIC (LHC)

Answers … and new Questions

- What we know:
  - ⇨ increasingly precise measurements of **macroscopic properti**
    - η/S, ξ, q^, e^, D, EoS, c_s, …
  - ⇨ good evidence for **deconfinement** (J/Ψ, Υ)
    - J/Ψ coalescence = **color conductivity**, Υ suppression = **resonance melting**
  - ⇨ some evidence for **chiral symmetry restoration,** but indirect
    - strangeness ???, low mass l^+l^- (connection between rho melting and chiral sym ?)
  - ⇨ the relevant dof (particles, excitations, ..) are **NOT free quarks & gluons**
    - the interaction is much too strong !

How is it!

- What we don't know
  - ⇨ **what ARE the relevant dof** in the QGP ?
    - pseudoparticles, collective excitations (plasmons, ..), 'glueballs', ..
  - ⇨ **What is the dynamics ?** 'looking under the hood' of the sQGP
    - how can it happen so fast, and in very small systems (incl. pp ?)
  - ⇨ **Where is the onset ?**
    - how does collectivity & statistical behavior emerge with size & energy density ?

Why is it so?

Future directions I

- High Energy Frontier: 2015 - 2022

How ?

⇨ **increased precision** Heavy Quarks, Quarkonia, Jets, γ, W/Z, …

- transport coefficients, screening length, EoS, T dependence RHIC/LHC, …

⇨ unravel **dynamics & sQGP structure**: looking for non-equilibrium effects

Why ?

- jet-quenching (parton-plasma scattering 'Rutherford experiment')
- sQGP **onset in small systems** (pp, pA): finite size/lifetime effects

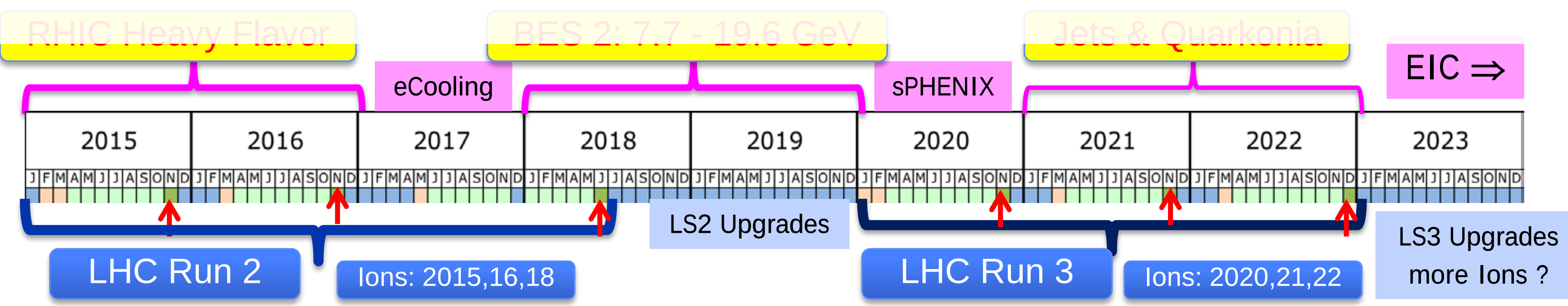
- Upgrades

⇨ **LHC**: **Energy**(x2)/**Luminosity**(x2-5) : Run2: $\mathcal{L} \approx$ 2x10^{27} , R3: 5x10^{27}, R2+3: 10nb^{-1}

- **LS2: Alice/Atlas/CMS**: faster DAQ, better Trigger, improved Si-vertex

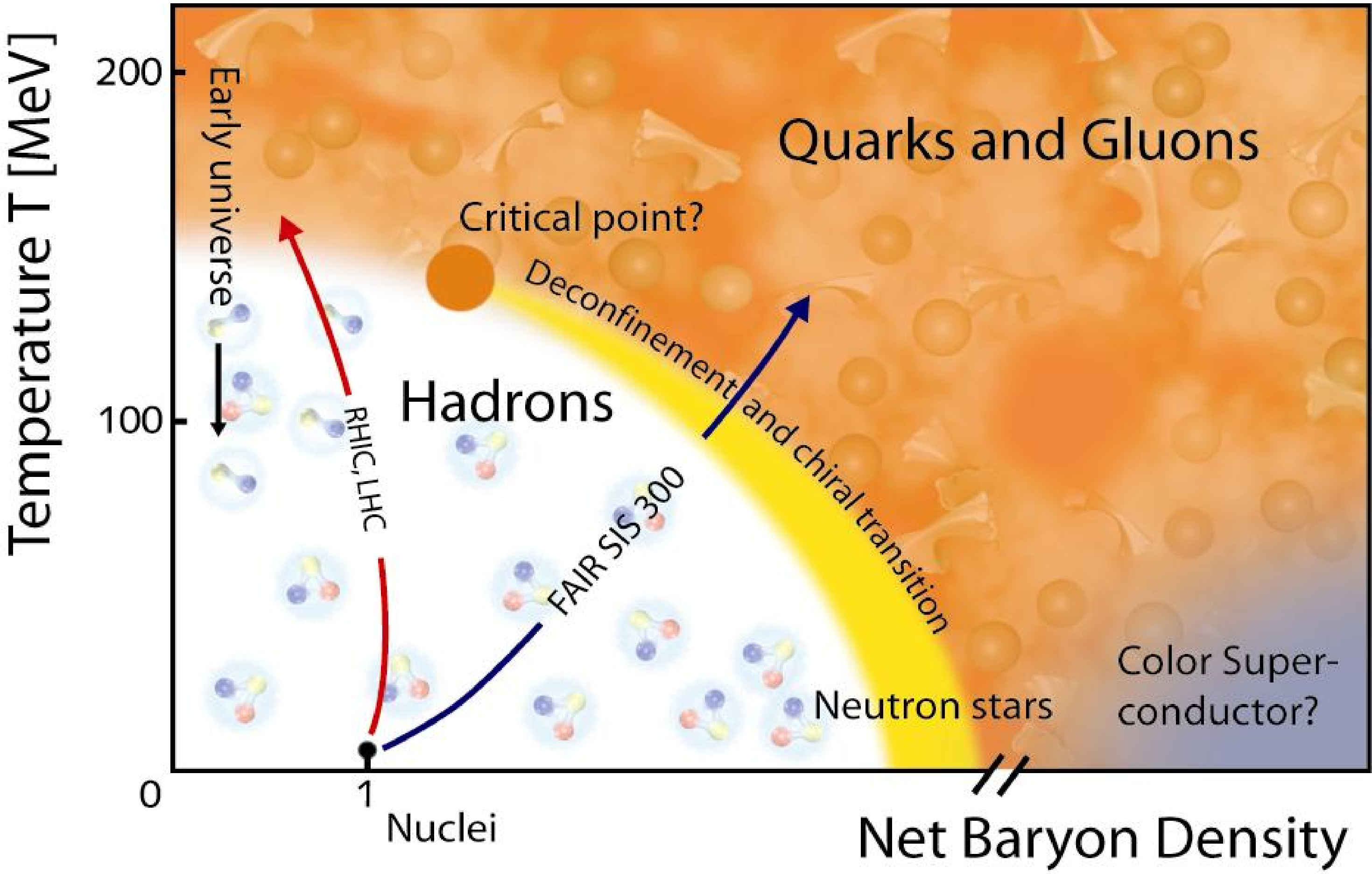
⇨ **RHIC**: **e-cooling** for BES 2 $\mathcal{L}$ x 3-10, $\sqrt{s_{NN}}$ = 7.7 - 19.6 GeV/A

- **Star**: improved TOF & tracking, **sPhenix**: new large acceptance detector



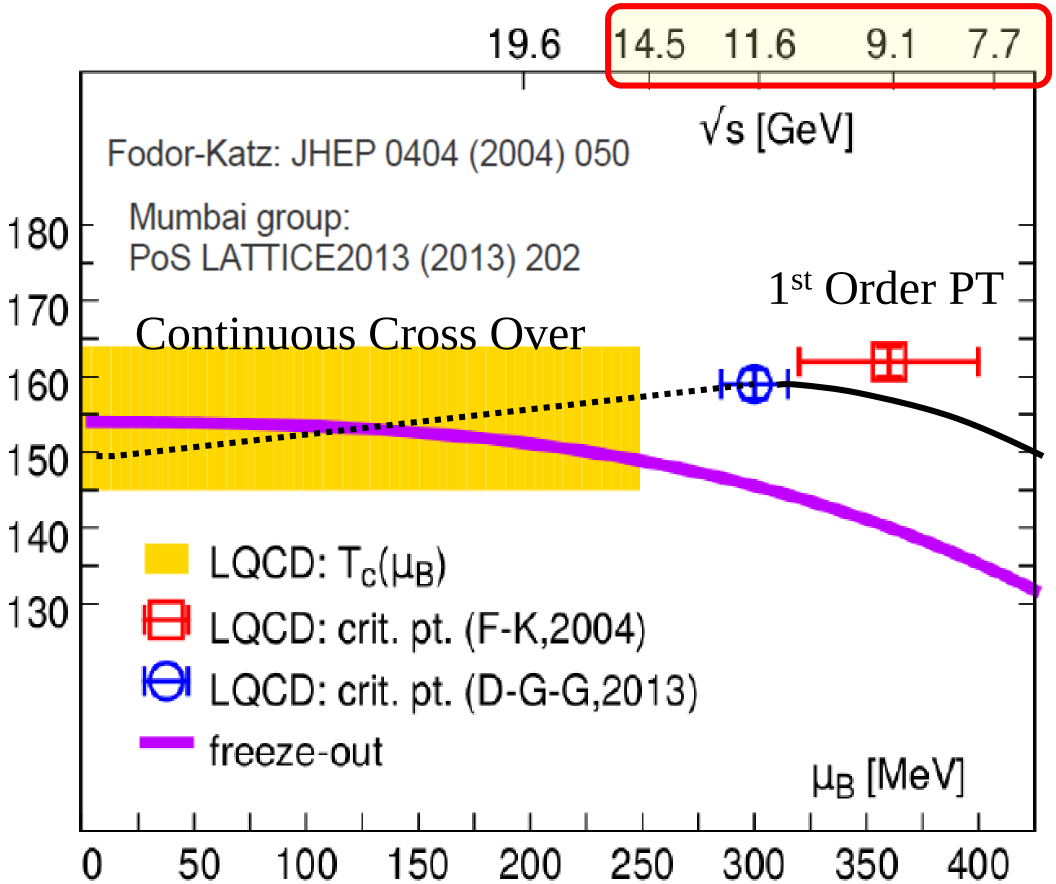
Future Directions II

- High Baryon Density Frontier
  - ⇨ search for the **QCD Critical Point**
  - ⇨ **QGP onset** at low energy
  - ⇨ QGP properties at **high baryon density** (eg Chiral symmetry, in medium masses)



QCD Critical Endpoint

- An important landmark in the phase diagram of matter (1st order ⇔ cross over)
  - ⇨ LQCD hints, but no consensus **where** it is located
    - ✪ nor, in fact, **if** it does exist..
  - ⇨ will CP(T, μ_B) be **reachable** with heavy ions ?
  - ⇨ will fluctuation **signals** survive ?



Searching for the CP is very important:

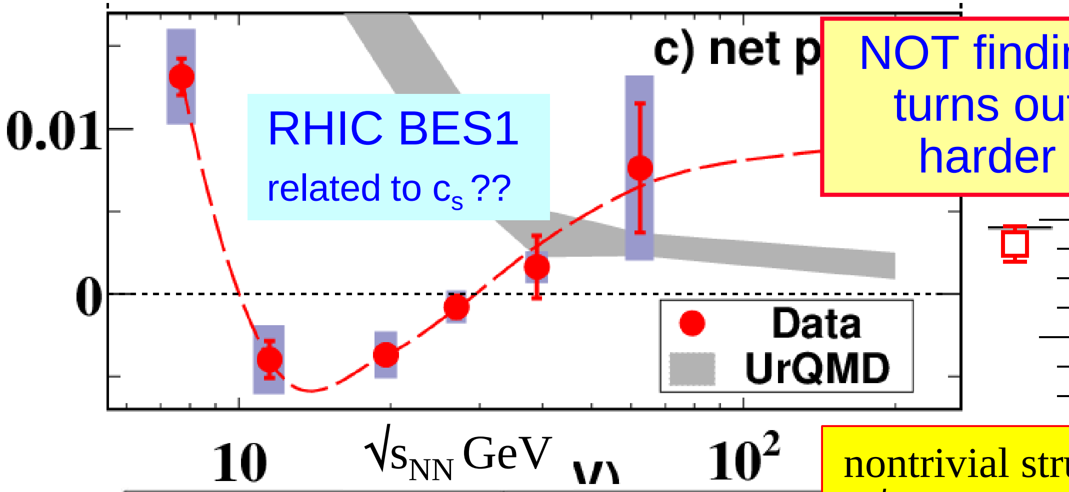
High Risk,

but potentially also

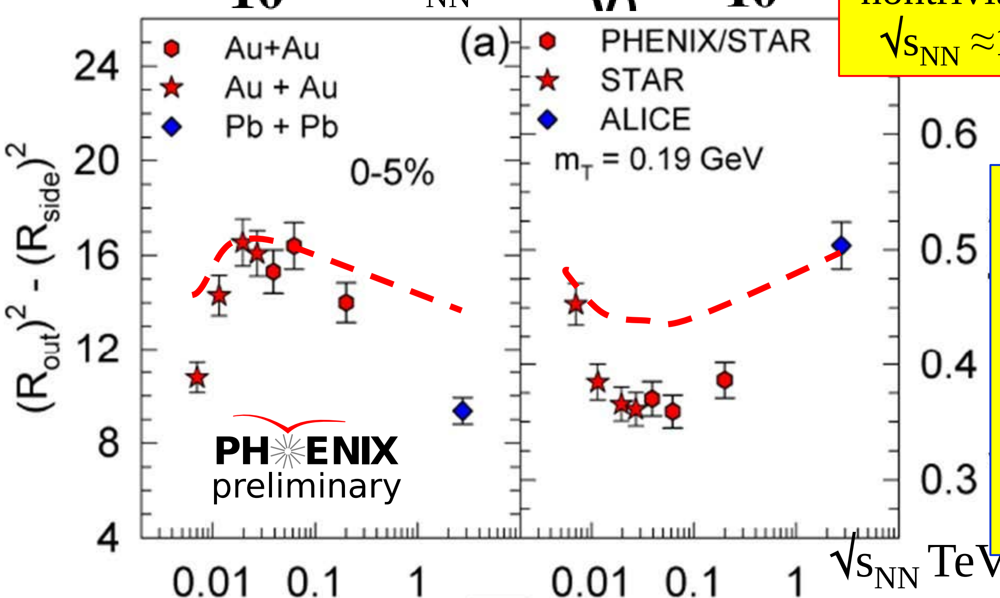
High Return !

The Low Energy Frontier

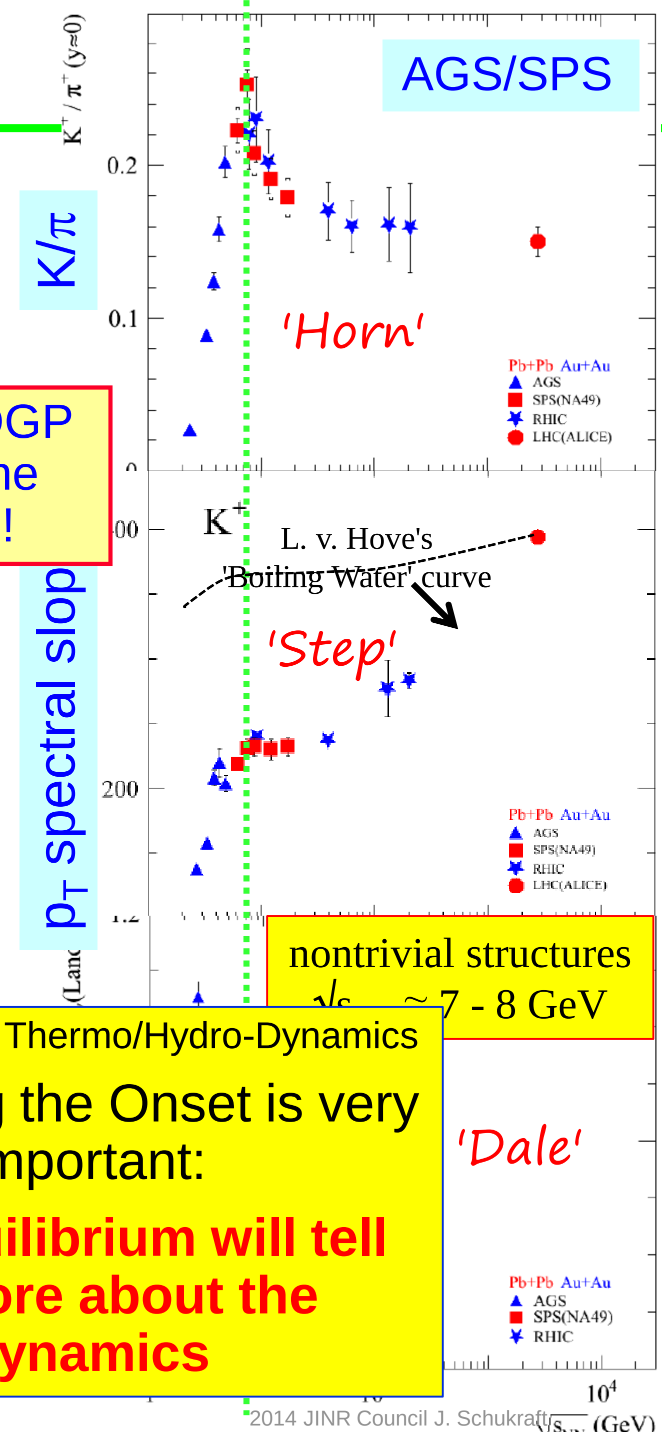
- The 'Onset' of the QGP f(T, ρ_B, r) = f($\sqrt{s}$, A+B, b)
  - ⇨ many hints, no coherent picture
    - onset may be very gradual, even signal specific



NOT finding the QGP turns out to be the harder problem!



nontrivial structures $\sqrt{s_{NN}} \approx$10-20 GeV



nontrivial structures $\sqrt{s_{NN}} \approx$ 7 - 8 GeV

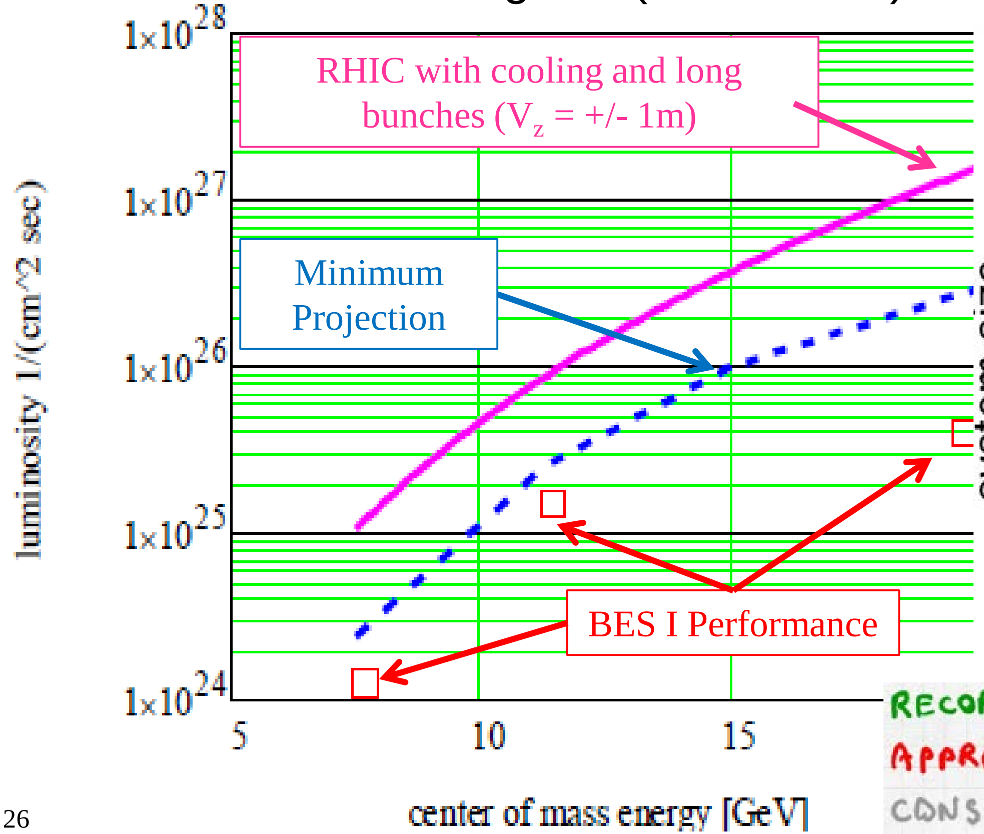
Equilibrium => Thermo/Hydro-Dynamics

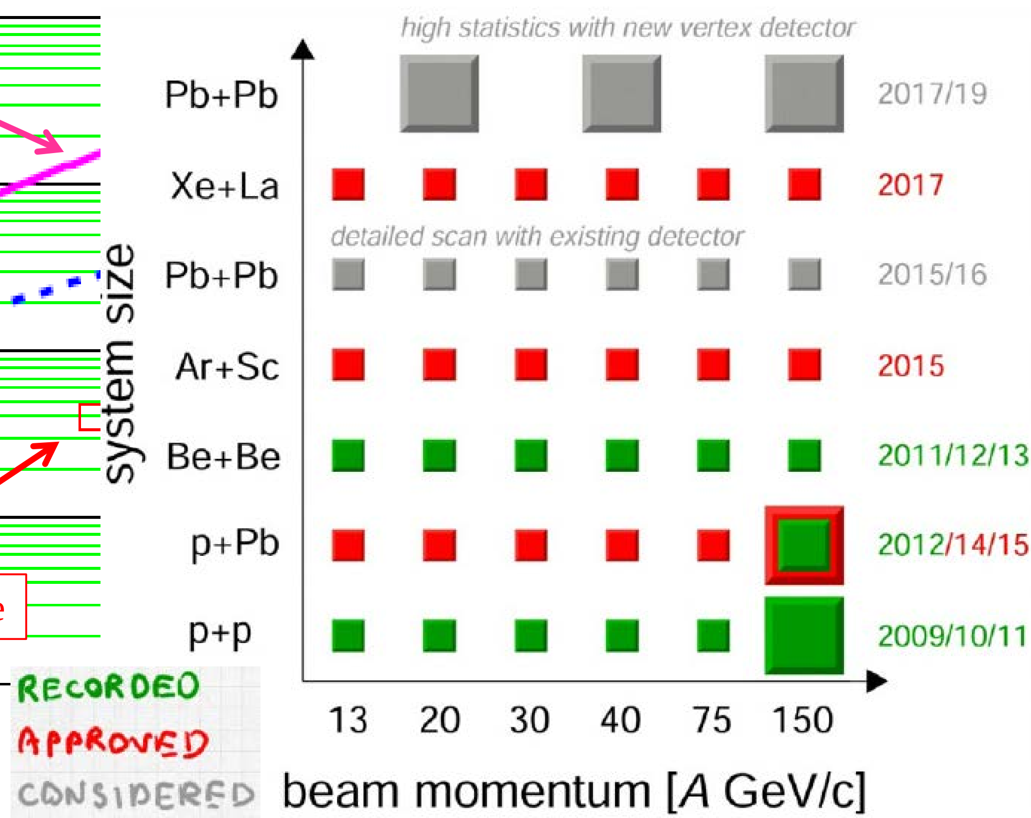
Measuring the Onset is very important:

Non-equilibrium will tell us more about the dynamics

Existing Facilities & Experiments

- RHIC BES 2: 2018-2019
  - ⇨ **e-cooling** for BES 2 $\mathcal{L}$ x 3-10, $\sqrt{s_{NN}}$ = 7.7 - 19.6 GeV/A
    - ✪ Fixed Target option (Target wire inside BP): Tested, but not analysed. E_{lab} > 4 GeV/A
  - ⇨ **Star** (improved TOF & tracking): Hadronic probes, incl. Φ, Hyperons; e^+e^- LMR ?
- SPS FT: **NA61**: 2009-2017(19?)
  - ⇨ systematic energy and volume scan (fragmented beams) $\sqrt{s_{NN}}$ = 5 - 17 GeV/A
  - ⇨ **NA61:** Hadronic signals (fluctuations). **NA60'** (HF, $\mu^+\mu^-$ LMR): Resources ??

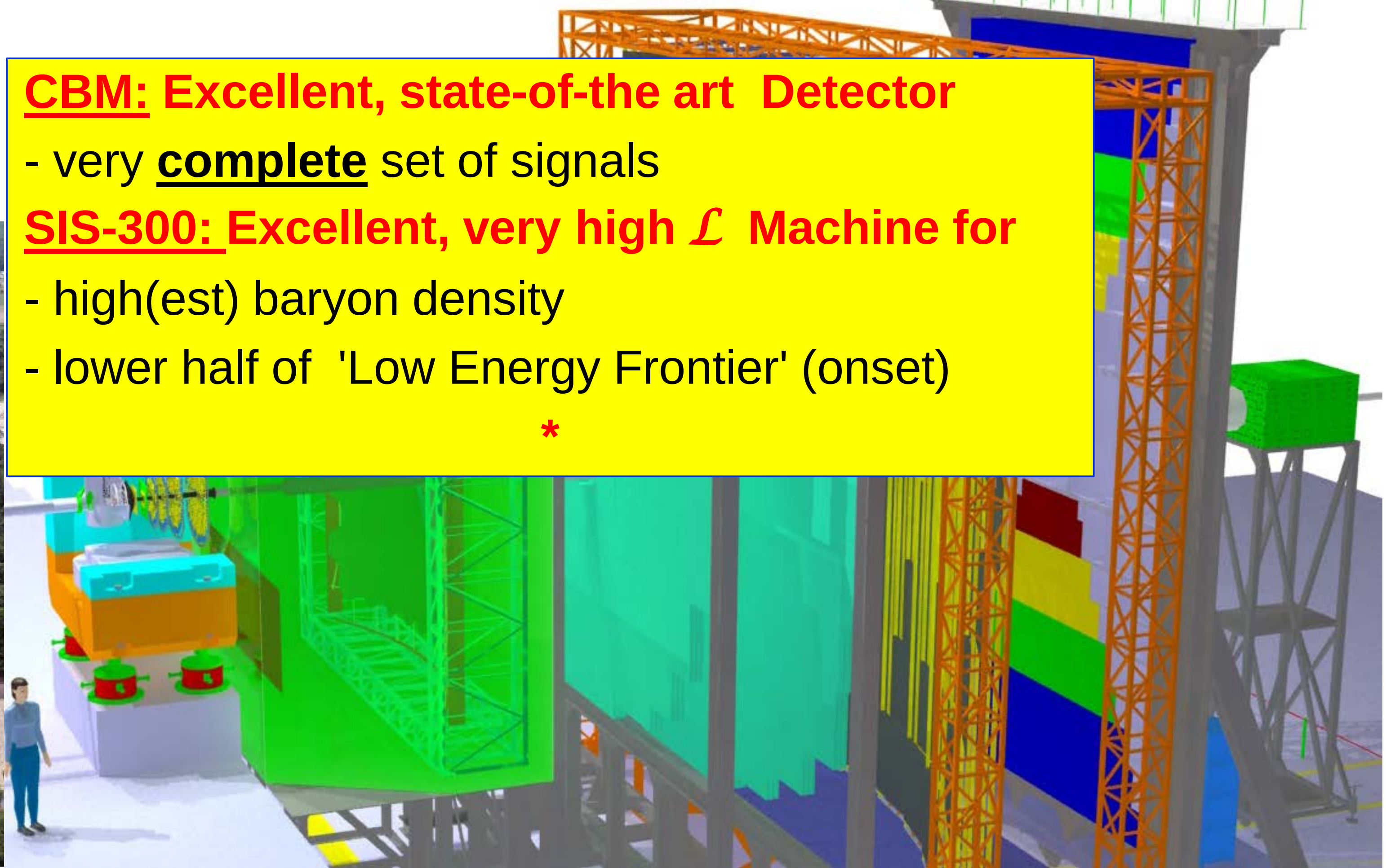




New Facilities & Experiments

- GSI/FAIR: SIS-100 ≥ 2019 (SIS-300 tbc)
  - ⇨ **E_{lab} = 10** (35) GeV/A ($\sqrt{s_{NN}}$ < 4.5 (8.4) GeV for Au/U), very high $\mathcal{L}$/event rates
  - ⇨ **Hades** upgrade (Ag+Ag), **CBM** experiment
    - Hadrons, Heavy Flavors, J/Ψ, continuum lepton pairs

* **Hopefully the two will meet sooner rather than later..**



CBM: Excellent, state-of-the art Detector

- very **complete** set of signals

SIS-300: Excellent, very high $\mathcal{L}$ Machine for

- high(est) baryon density

- lower half of 'Low Energy Frontier' (onset)

*

New Facilities & Experiments

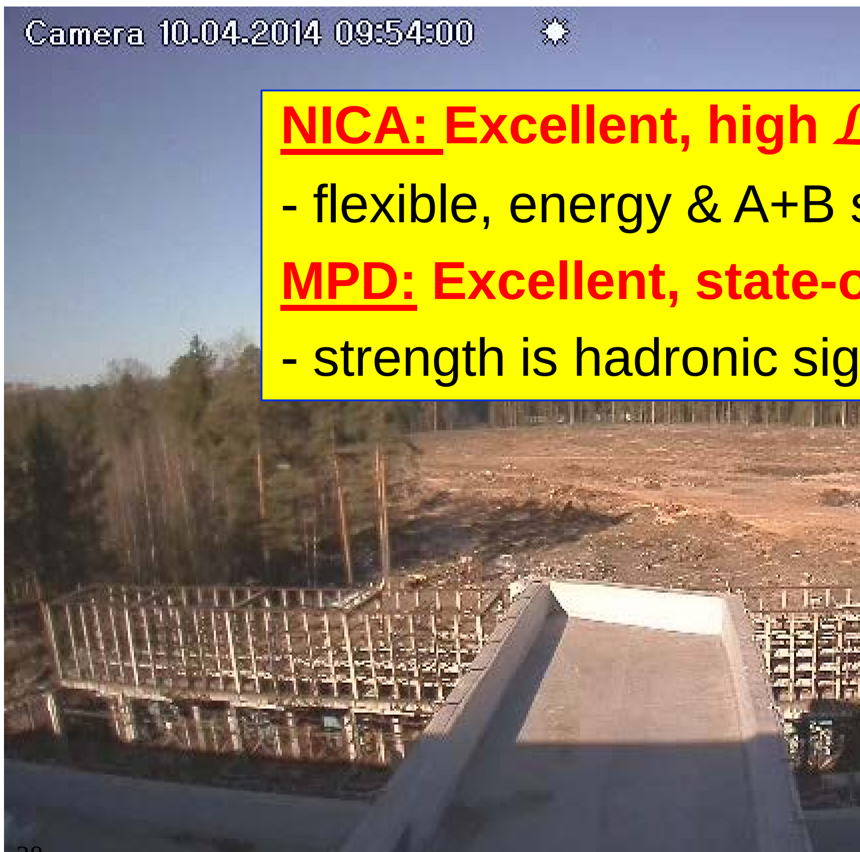
- JINR/NICA: ≥ 2019 $\sqrt{s_{NN}}$ = **4 - 11 GeV** (Au beams),
  - ⇨ fairly high $\mathcal{L}$ (Au ~10^{27}), flexible collider (A+B, pA), extracted beams (BM@N)
  - ⇨ **MPD** experiment
    - ✪ large acceptance (stage 3); Hadrons + calorimeter

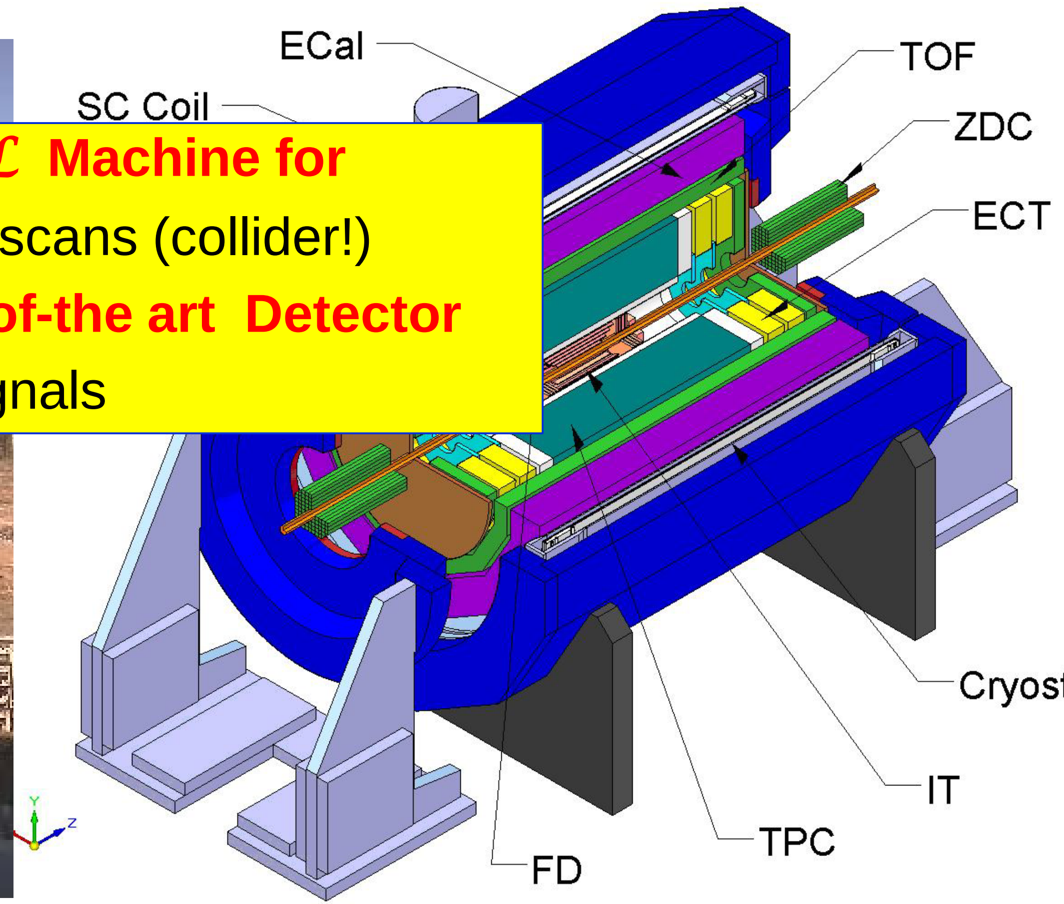
NICA: Excellent, high $\mathcal{L}$ Machine for

- flexible, energy & A+B scans (collider!)

MPD: Excellent, state-of-the art Detector

- strength is hadronic signals

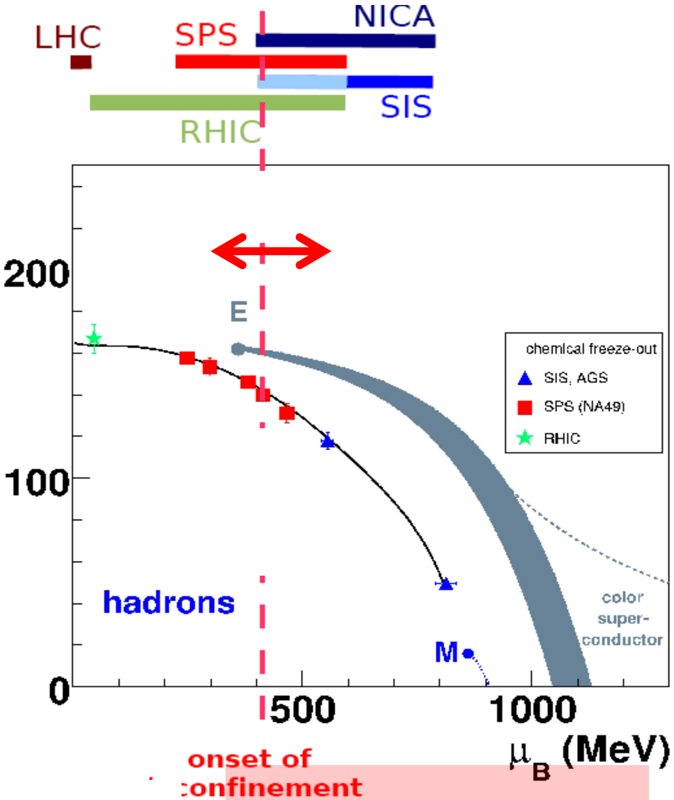


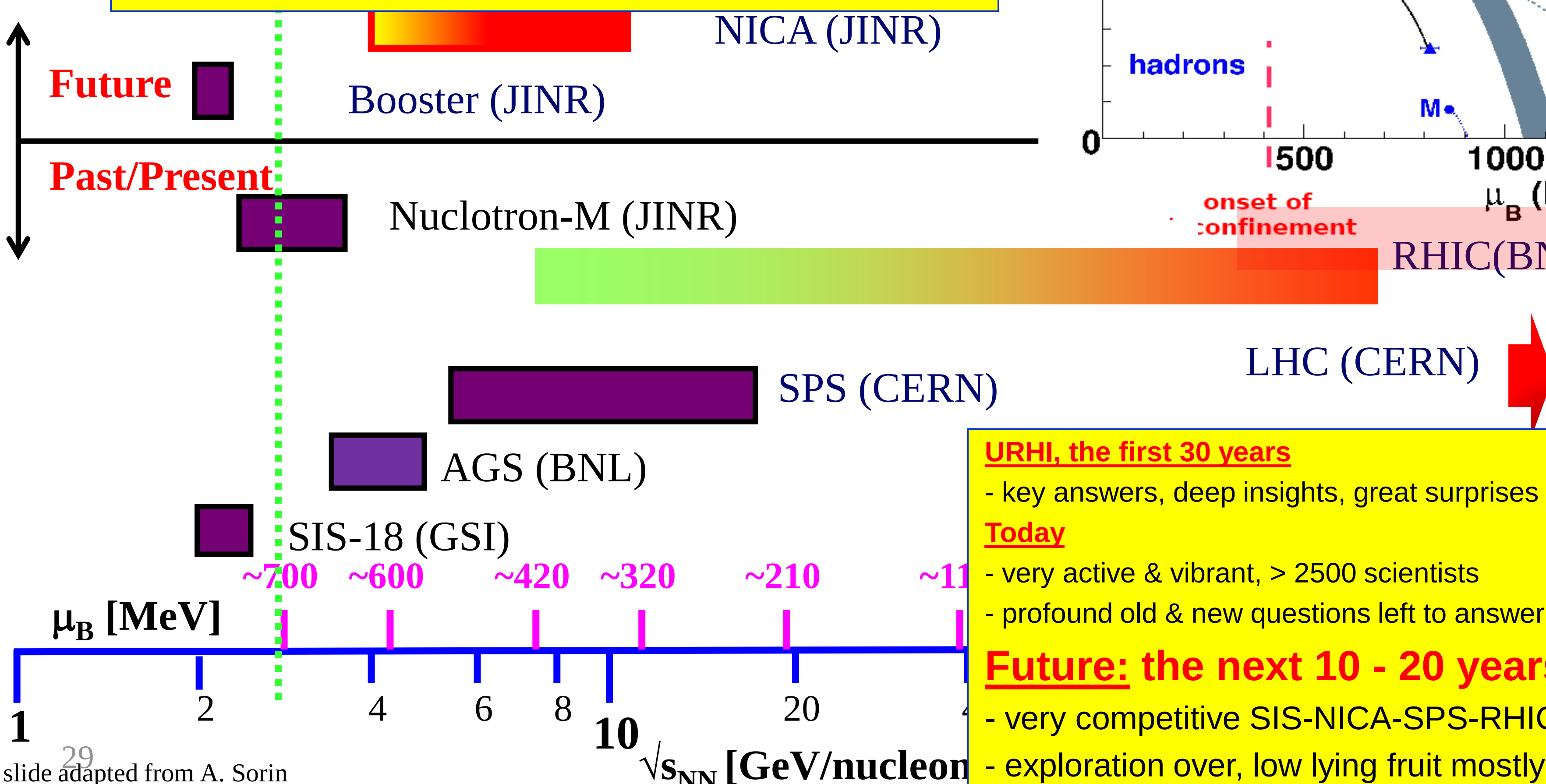


Past-Present-Future

URHI, the first 30 years
- key answers, deep insights, great surprises

Today
- very active & vibrant, > 2500 scientists
- profound old & new questions left to answer





URHI, the first 30 years
- key answers, deep insights, great surprises

Today
- very active & vibrant, > 2500 scientists
- profound old & new questions left to answer

Future: the next 10 - 20 years
- very competitive SIS-NICA-SPS-RHIC-LHC
- exploration over, low lying fruit mostly taken?

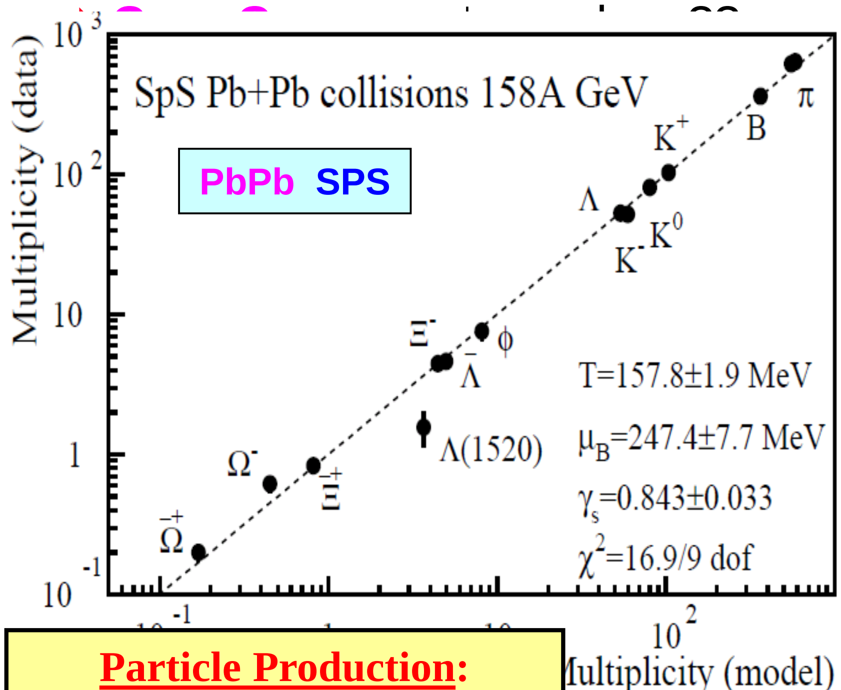
slide adapted from A. Sorin

Spares/Backup

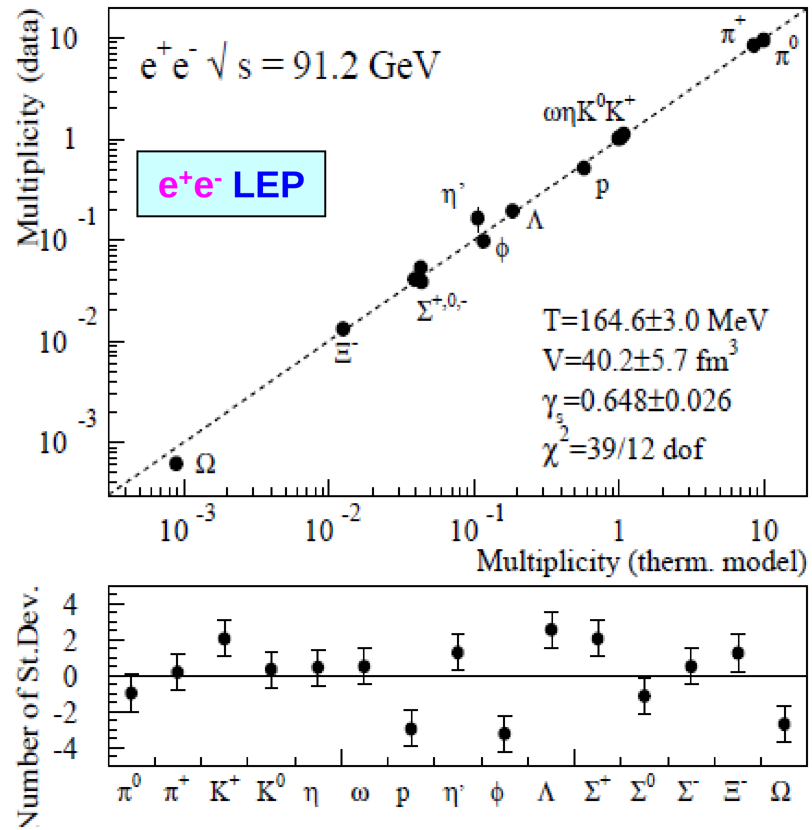
pp-pA-AA: Similarities & Differences

- **Similar Particle Production**
  - ⇨ Striking & very non-trivial similarities between pp(e+e-) and AA
  - ⇨ Striking & very non-trivial difference ('strangeness enhancement):

- **Different Explanations (in general)**
  - ⇨ **Born** (pp) <-> **Evolving** (AA) into equilibrium
  - ⇨ γ_s(GC) or r_c (SC) are fudge factors (fttb), i.e. not predicted/calculable as f(√(s),dn/dy, ..)



Particle Production:
Data versus Thermal Model



Known, but often ignored

- **No quantitative interpretation which smoothly describes small & large**
  - ⇨ despite evident relevance for understanding H

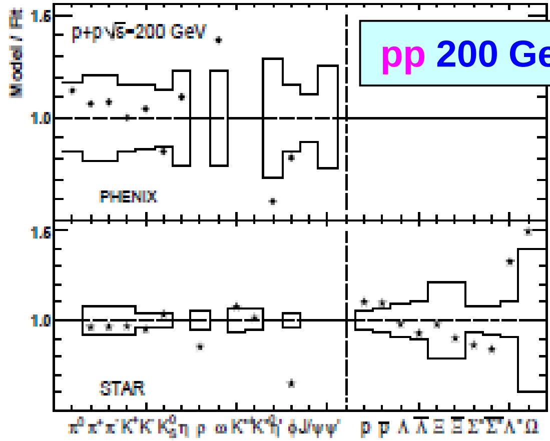


FIG. 18: Ratio of integrated yields predicted by the statistical model [40] to those of the constrained Tsallis fits for various particles. Results for fits to PHENIX data are shown in the upper panel and STAR data in the lower panel. The band reflects the uncertainty of the Tsallis fit results and includes the trigger uncertainty of 9.7% for PHENIX. The lower panel ... prediction was ... IX. There are ... l dashed line

Particle production:
Data /Thermal Model

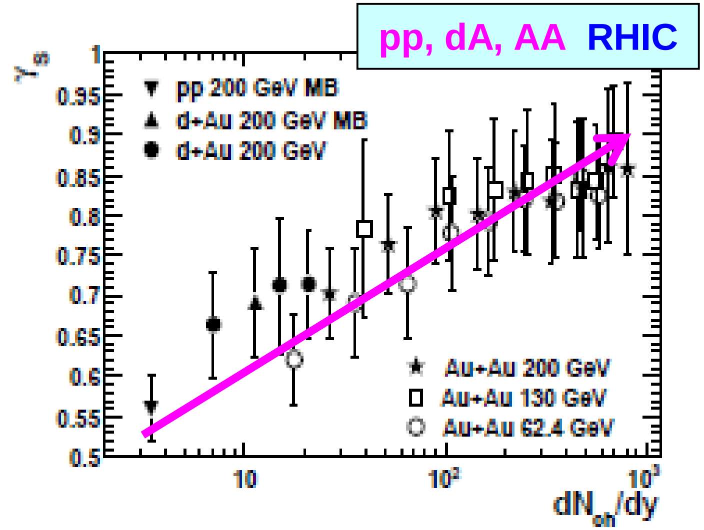


FIG. 35: Strangeness suppression factor extracted from chemical equilibrium model fit to pp and d+Au data at 200 GeV, and Au+Au data at 62.4 GeV, 130 GeV, and 200 GeV. Errors shown are the total statistic... ties. The 200 GeV pp and Au+... Ref. [17].

Particle production:
γ_s vs dN_{ch}/dy

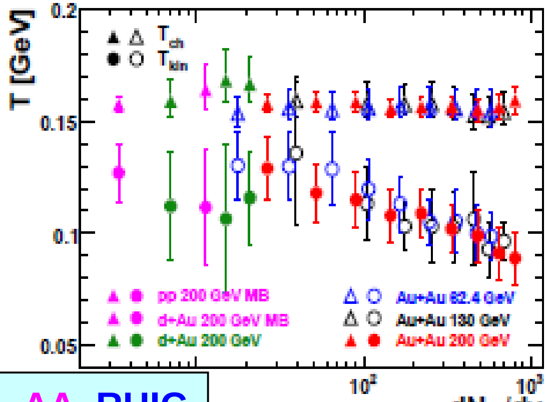
Although statistical models are not commonly used to describe $p + p$ data the agreement of the statistical model calculation with the STAR results was found to be accurate for most particles except for the ρ, ϕ, and Λ^* [40]. Leaving aside baryons, for which the calcula-

nificantly suppressed in these collisions. The strangeness suppression factor in medium-central to central Au+Au collisions is not much below unity; the strangeness and light flavor are nearly equilibrated, which may suggest a fundamental change from peripheral to central collisions.

Star http://arxiv.org/abs/0808.2041 Phenix http://arxiv.org/abs/1005.3674 STAR http://arxiv.org/abs/nucl-ex/0607033

Momentum Spectra

- Weil, so schließt er messerscharf, *nicht sein kann*, *was nicht sein darf*



pp, dA, AA RHIC

Radial Flow fit (BW):
T & <β> vs dN_{ch}/dy

FIG. 36: (color online) Chem[...] peratures as a function of [...] Errors shown are the total statistical and systematic uncertainties. The 200 GeV pp and Au+Au data are taken from Ref. [17].

The interpretation of the fit parameters is difficult in the context of a $p+p$ collision where the system is not expected to thermalize and the volume is small. It is important to note that in a pure thermal model, all emitted particles would be expected to reflect the same temperature. Non-thermal effects such as flow would modify this result. In $p+p$ collisions, the particle spectra clearly show different slopes and those slopes are not in agreement with the T parameter that results from the statistical model fit to the particle ratios. As no flow is thought to be present in the $p+p$ system and the results of Section IV B support that conclusion, this result is a further indication of contributions to the particle spectra from non-thermal processes like mini-jets.

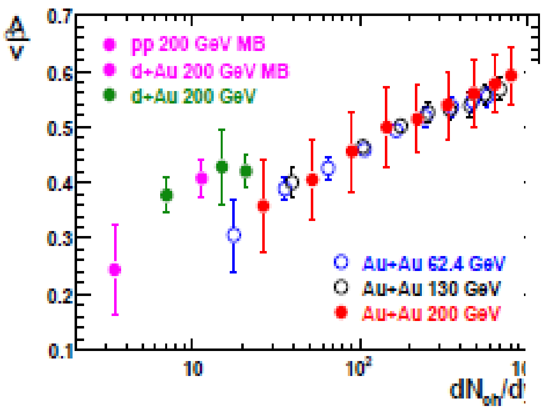


FIG. 37: (color online) Average transverse radial flow v[...] ity extracted from blast-wave model fit to pp and d+A[...] 200 GeV, and to Au+Au collisions at 62.4 GeV, 130 [...] and 200 GeV as a function of the charged hadron multipl[...] Errors shown are the total statistical and systematic u[...] tainties. The 200 GeV pp and Au+Au data are taken [...] Ref. [17].

pp 200 GeV

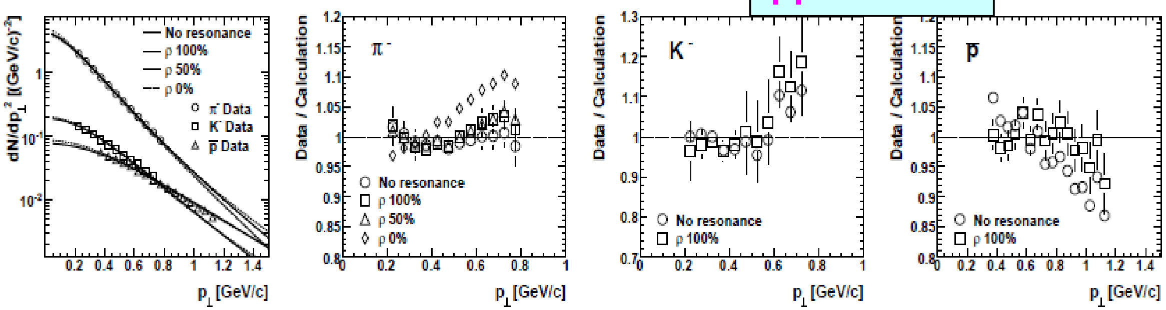


FIG. 45: Left panel: Fit of the calculated spectra (curves) to the measured ones (data points) in pp collisions at 200 GeV [17]. Four calculated spectra are shown for π^- (upper curves): including resonances with three different ρ contributions and excluding [...] wn for K^- (middle curves) and $\bar{p}$ (lower curves): including resonances with [...] s: Ratios of data spectrum to calculations. Two calculations are shown for [...] r π^-. Error bars are the quadratic sum of the statistical and point-to-point [...] two sets of the data points for π^- and only one set for K^- and $\bar{p}$.

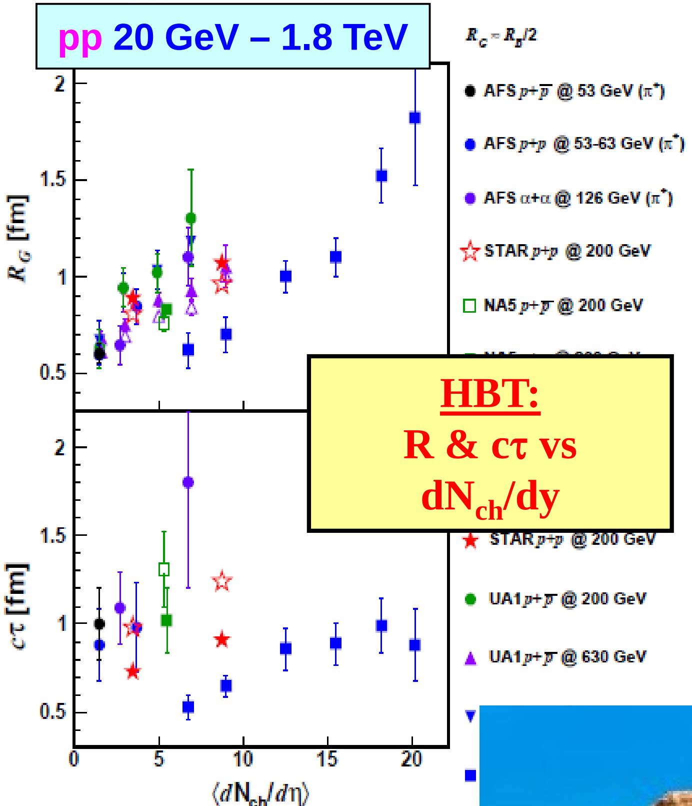
Radial Flow fit (BW):
Data/Fit (π,K,p)

Star http://arxiv.org/abs/0808.2041

HBT radii

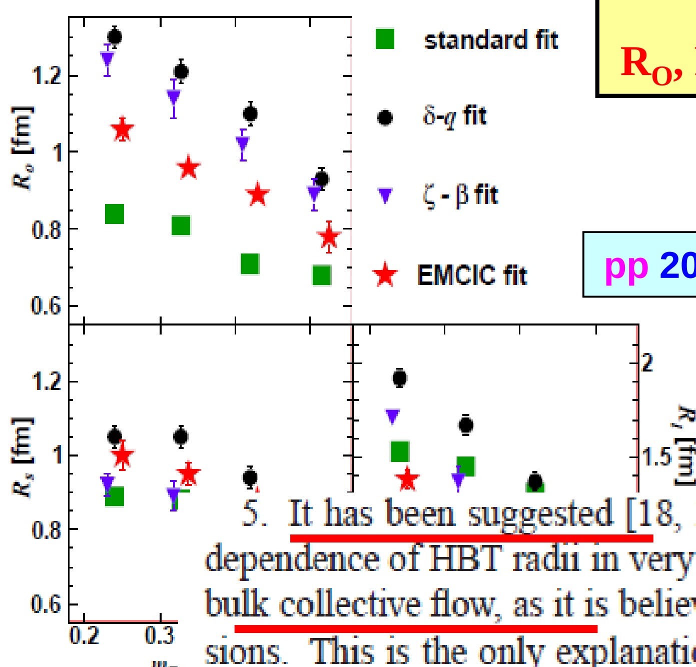
- N_{ch} & m_T dependence of radii in AA: hallmark of expansion

pp 20 GeV – 1.8 TeV



HBT:
R & cτ vs dN_{ch}/dy

FIG. 12: (Color online) The multiplicity deper
timescale parameters to 2-dimensional correla
sured by STAR, E735 [36], UA1 [63], AFS [64
legend on the right indicates that the first 7 sets
from fits to Eq. 7, in which case the parameter R
upper panel; the last 5 sets of datapoints come f
which R_G is plotted. As discussed in Section II
STAR and UA1, $R_G \approx R_B/2$. The UA1 Collal
their fits.



HBT:
R_O, R_S, R_L vs m_T

pp 200 GeV

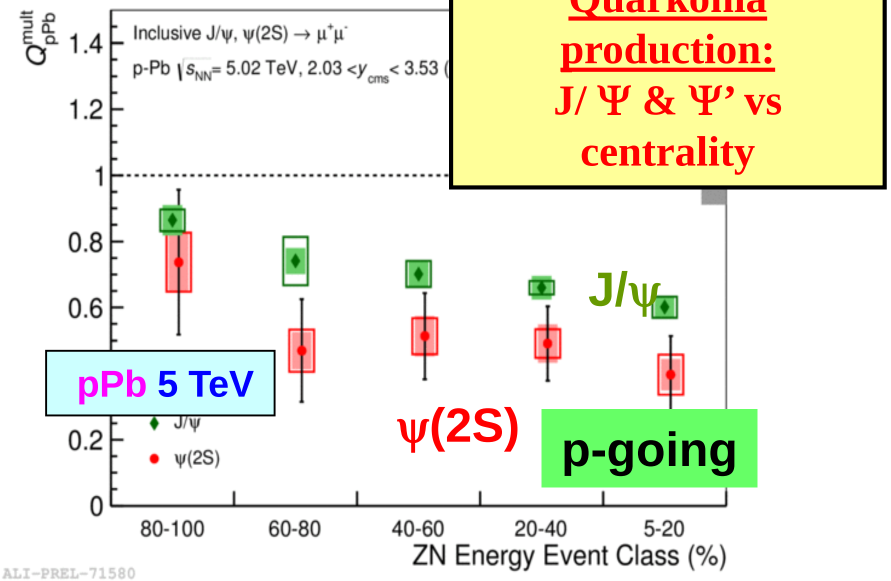
5. It has been suggested [18, 30, 31, 36, 78] that the p_T-dependence of HBT radii in very small systems might reflect bulk collective flow, as it is believed to do in heavy ion collisions. This is the only explanation that would automatically account for the nearly identical p_T-scaling discussed in Section V A. However, it is widely believed that the system created in $p+p$ collisions is too small to generate bulk flow.

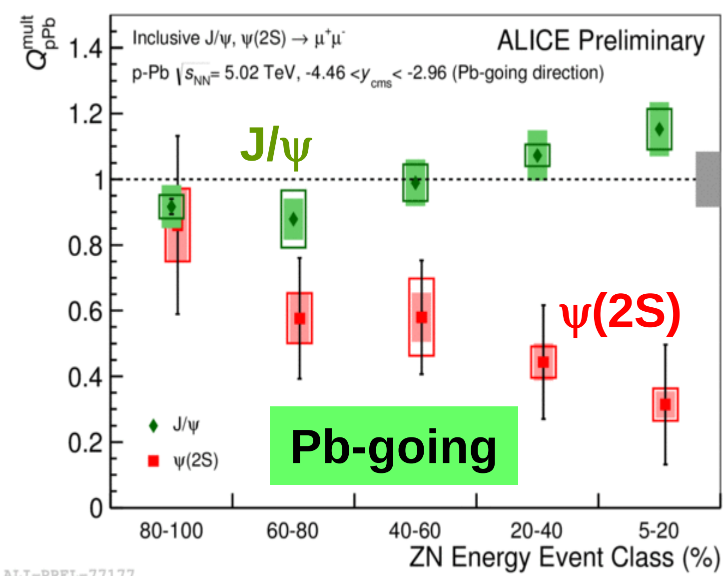
The remarkable similarity between the femtoscopic systematics in heavy ion and hadron collisions may well be coincidental. Given the importance of the m_T-dependence of HBT radii in heavy ion collisions, and the unclear origin of this dependence in hadron collisions, further theoretical investigation is clearly called for. Additional comparative studies of other soft-sector observables (e.g. spectra) may shed further light onto this coincidence.

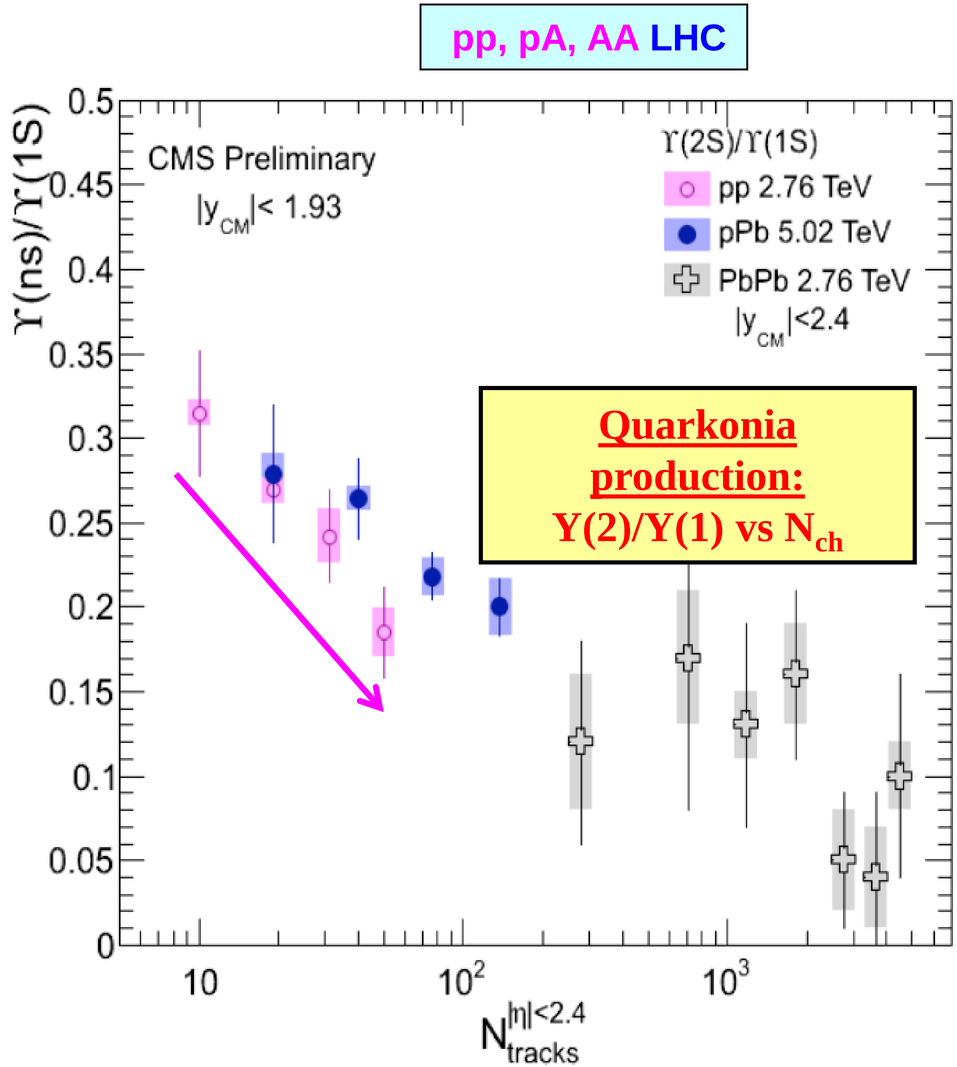
Star http://arxiv.org/abs/1

.. even quarkonia suppression ???

- that would be the straight-forward interpretation, at least..







Central pp/pA: What could it be ??

- (quasi) thermal particle ratios
- expanding HBT radii ?
- radial flow ?
- elliptic flow ?
- quarkonia suppression ???
- no (visible) jet quenching, however !

It looks like a rose …

It smells like a rose …

It feels like a rose …

It pricks like a rose …

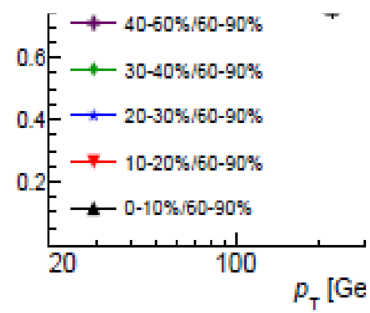
It sounds like a rose …

the dog that didn't bark at the rose ?

Evidence for hadronic deconfinement in $\bar{p}$-p collisions at 1.8 TeV

E735: Phys.Lett. B528 (2002) 43-48

T. Alexopoulos,[1*] E. W. Anderson,[2] A. T. Bujak,[3] D. D. Carmony[3] A. R. Erwin,[1] L. J. Gutay,[3] A. S. Hirsch,[3] K. S. Nelson,[1**] N. T. Porile,[4] S. H. Oh,[6] R. P. Scharenberg,[3] B. K. Srivastava,[4] B. C. Stringfellow,[3] F. Turkot,[7] J. Warchol,[5] W. D. Walker[6]



SCALING PROPERTIES OF THE TRANSVERSE MASS SPECTRA

J. SCHAFFNER-BIELICH[a], D. KHARZEEV[b], L. MCLERRAN[b] and R. VENUGOPALAN[b,c]

http://arxiv.org/abs/nucl-th/0202054

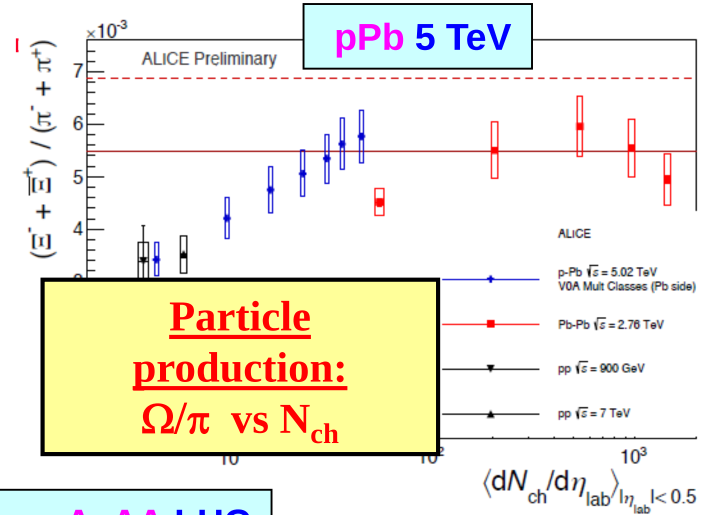
In summary, we showed that the transverse mass spectra of hadrons at RHIC follows one universal function of m_t. Radial flow is not necessary to describe the data. The same universal behavior seems to present in proton-antiproton collider data. The spectra at different centralities can be rescaled

Where is the 'onset' ? (how small is too small ?)

- Everything develops smoothly, from Min Bias pp to central AA

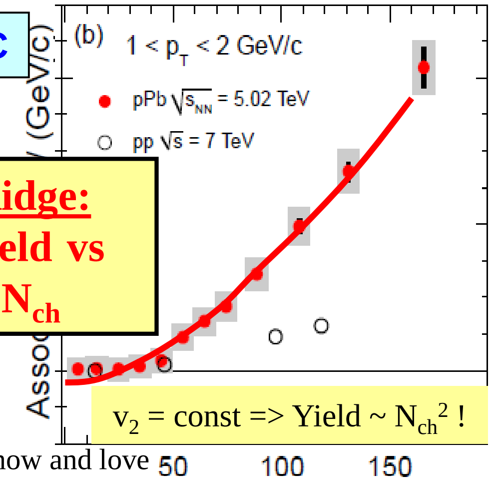
ve know how big

pPb 5 TeV



Particle production:
Ω/π vs N_{ch}

pp, pA LHC

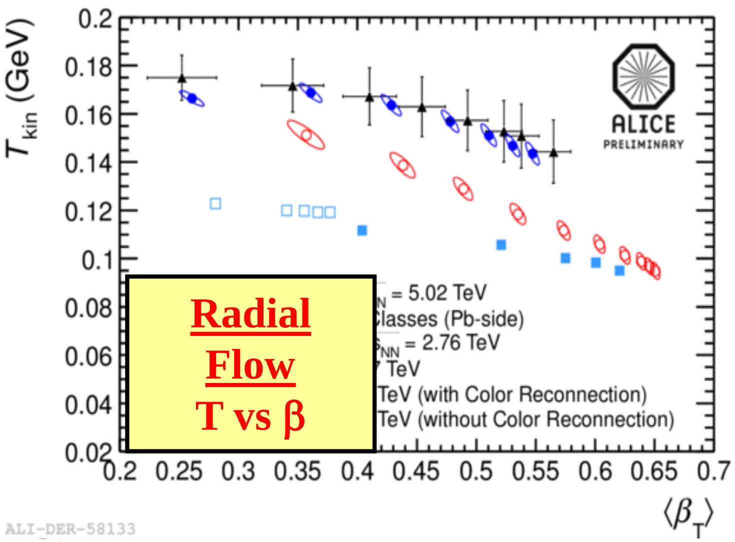


Ridge:
Yield vs N_{ch}

v_2 = const => Yield ~ N_{ch}^2 !

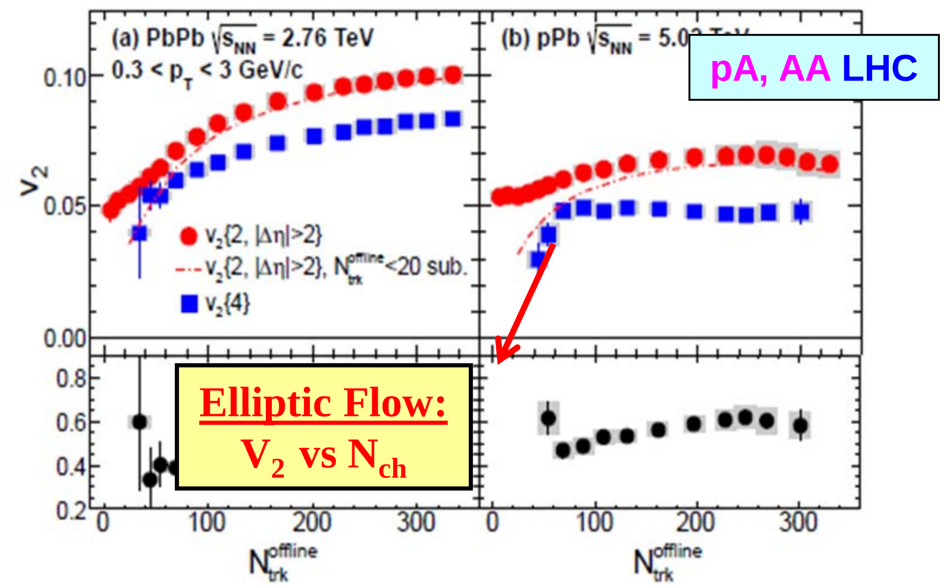
(*): Collectivity used as a shorthand for all we know and love about the 'perfect liquid'/QGP: Hydro, Thermo, dense matter, …

pp, pA, AA LHC



Radial Flow
T vs β

pA, AA LHC



Elliptic Flow:
V_2 vs N_{ch}

Hypothesis

- **We got used to live without a phase transition** **(for the most part)**
  - ⇨ the smooth but 'rapid cross-over' is, in practice, almost as good !
- **What about a smooth increase in 'collectivity*' ?**
  - ⇨ AA : very 'collective', an **almost infinite amount** of sQGP
  - ⇨ pA,'central' pp: quite collective, a **finite amount** of sQGP
  - ⇨ MinBias pp (e^+e^- ?): the 'soft' part is a bit collective, a mini-droplet of sQGP

(*): Collectivity used as a shorthand for all we know and love about the 'perfect liquid' sQGP': Hydro, Thermo, dense matter, …

- **Why bother ?**
  - ⇨ smaller systems => finite size/lifetime effects => **<u>lift the veil of thermodynamics</u>**
    - *see the dynamics at work*, rather then the end-results only
    - Hyperons in central pA: sequential strangeness saturation ???

<u>'Grand Unification'</u> : Challenge, opportunity
Common and coherent experimental & theoretical approach to soft QCD
from MB pp(e^+e^-) to central AA, with pA the bridge in between

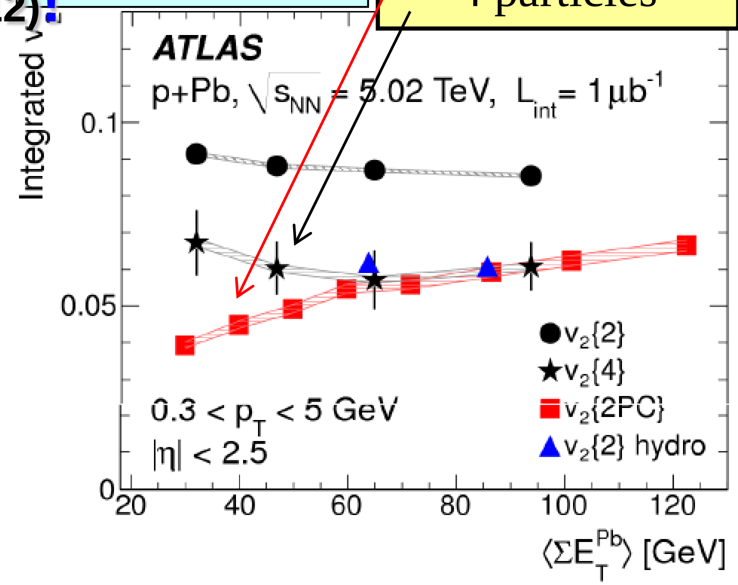
maybe solve a few longstanding mysteries along the way..

Ridges everywhere..

- **Ridge is much stronger in pPb** **(end 2012)!**
  - ⇨and is, in fact, a 'double ridge'
  - ⇨even and odd components (v_2, v_3)
  - ⇨collective multiparticle $v_2\{4\}$ (i.e., not 'jet' like)
  - ⇨mass dependent $v_2(m,p_t)$
  - ⇨now also seen in dAu at RHIC ! (tbc)
  - ⇨strength ≈ as **predicted** by some hydro model

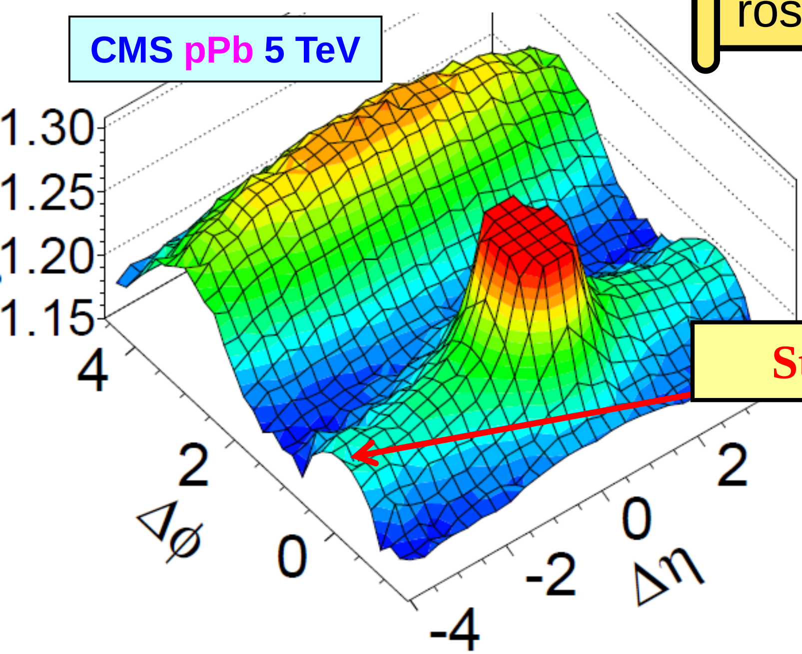
ATLAS pPb 5 TeV

2 particles
4 particles



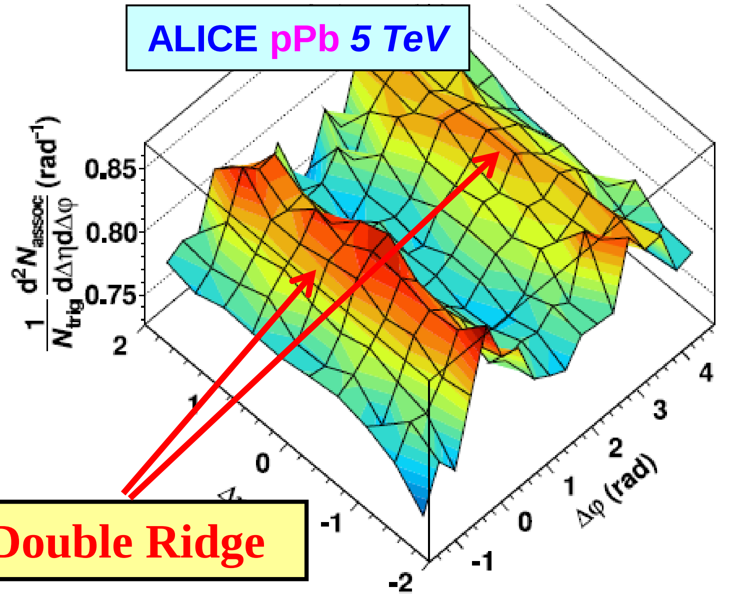
It looks like a rose …

CMS pPb 5 TeV



Stronger NSR

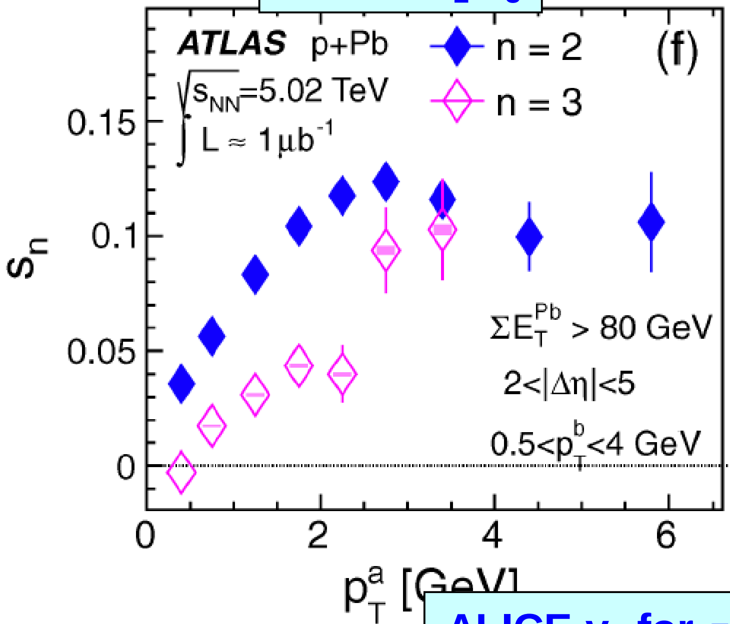
ALICE pPb 5 TeV



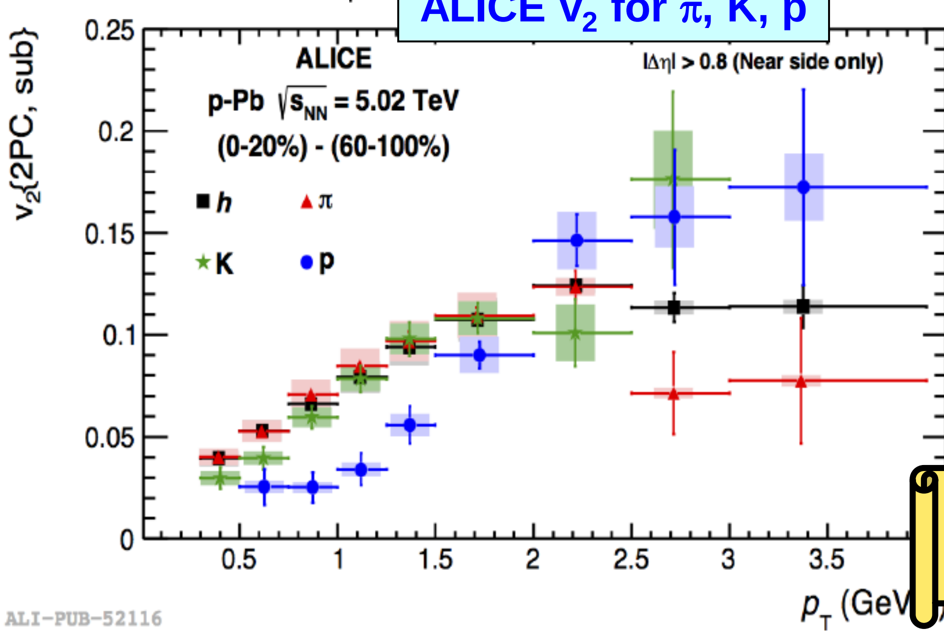
Double Ridge

More on the Ridge

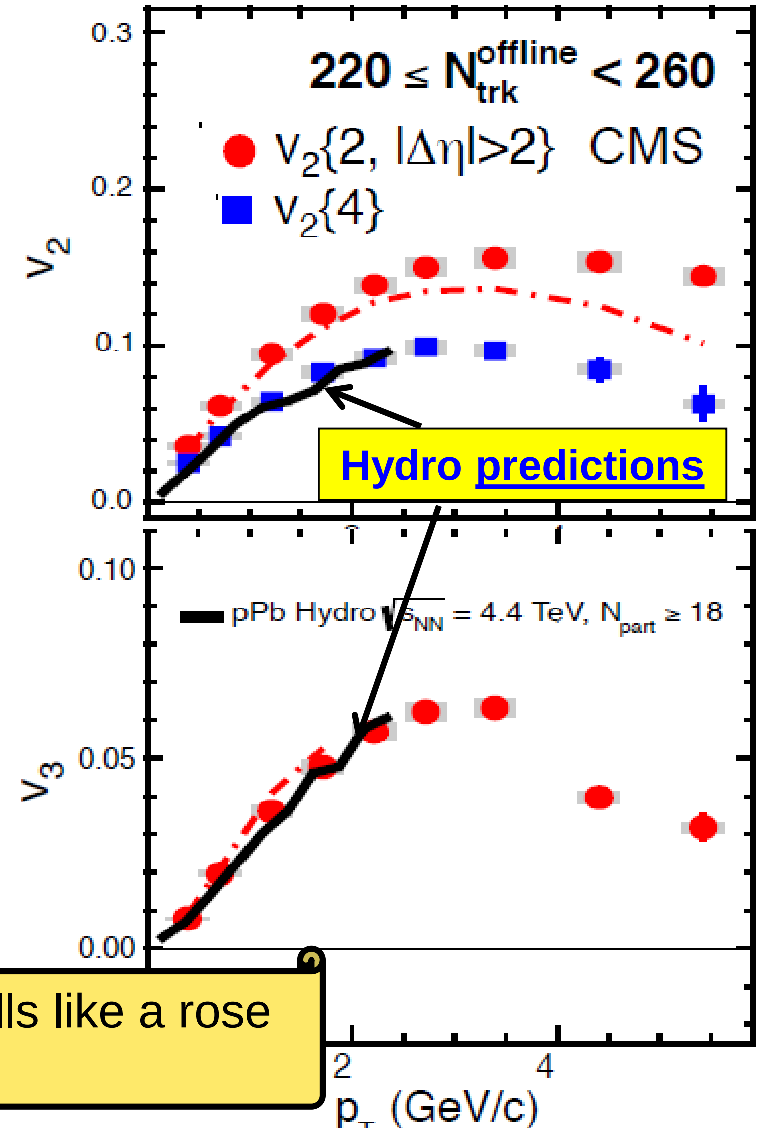
ATLAS v_2 v_3



ALICE v_2 for π, K, p



CMS $v_2\{2\}$, $v_2\{4\}$, v_3

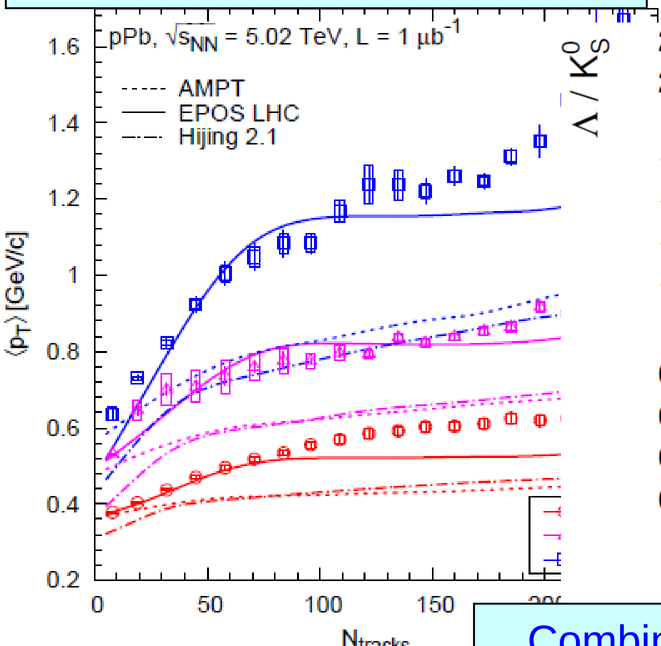


It smells like a rose …

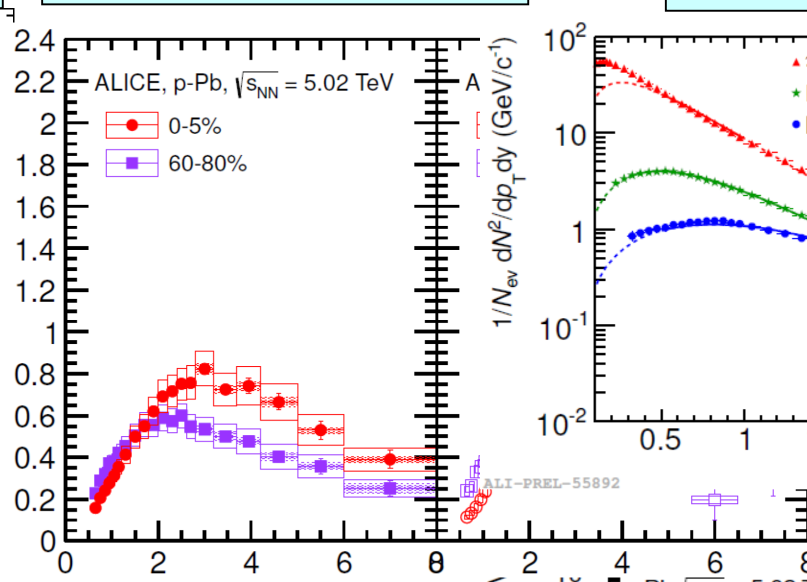
Where there is elliptic Flow..

- .. there MUST be radial flow

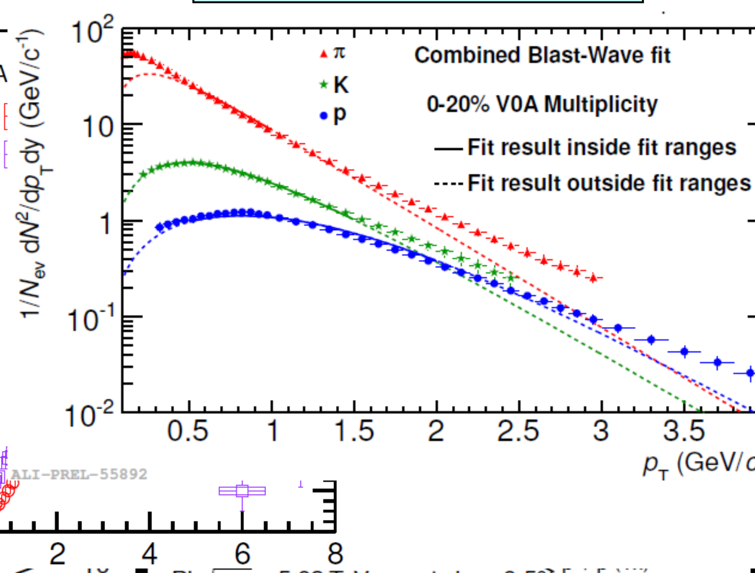
CMS $<p_t>$ versus N_{ch} for π, K, p



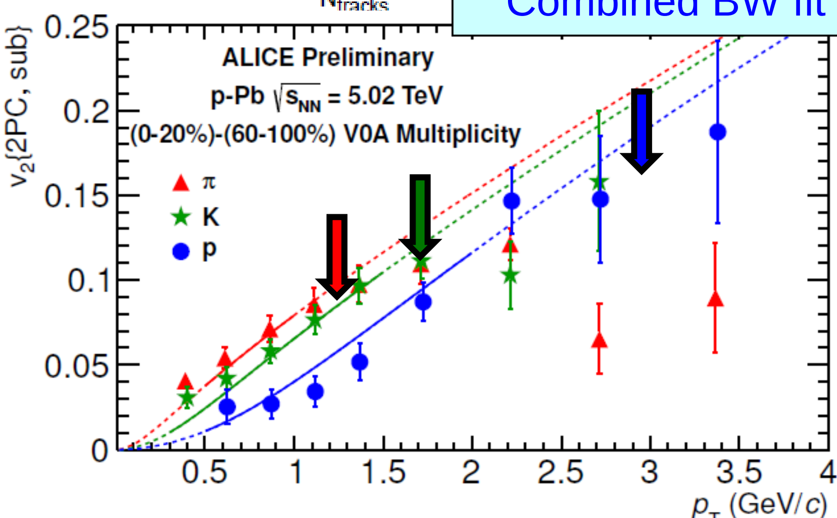
'Baryon Anomaly' Λ/K_0^S

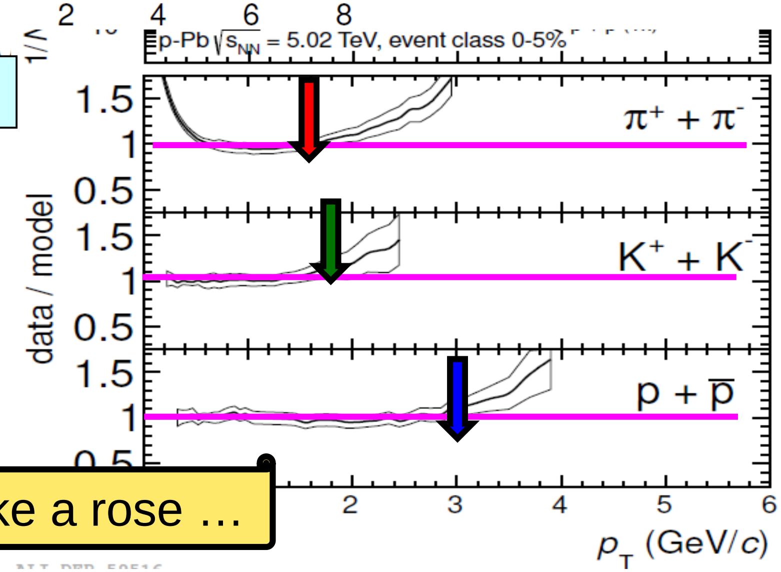


BlastWave Fit π, K, p



Combined BW fit to p_t and v_2



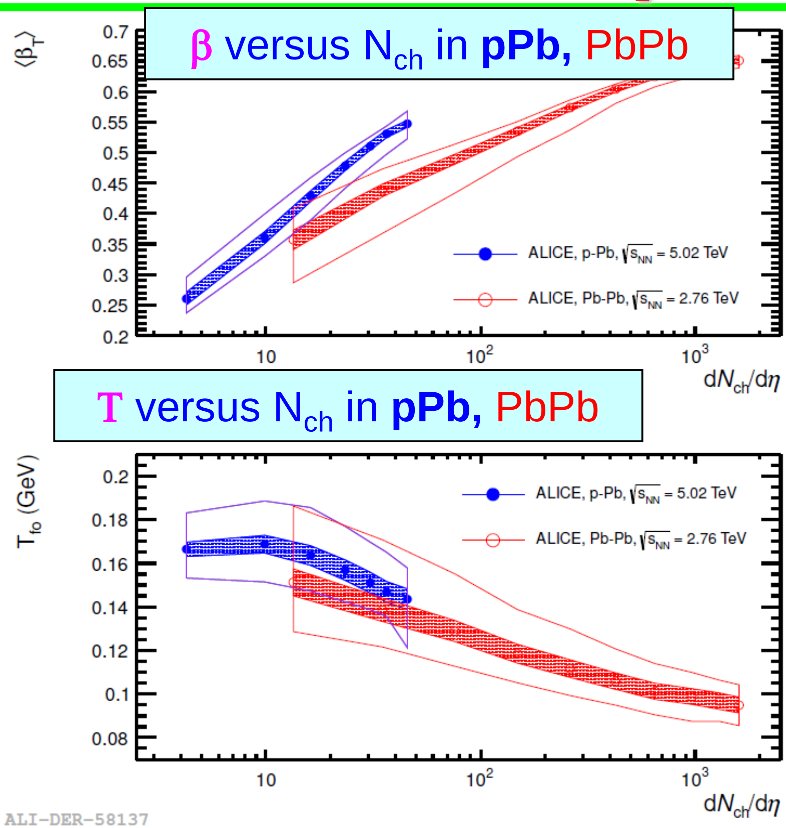


It pricks like a rose …

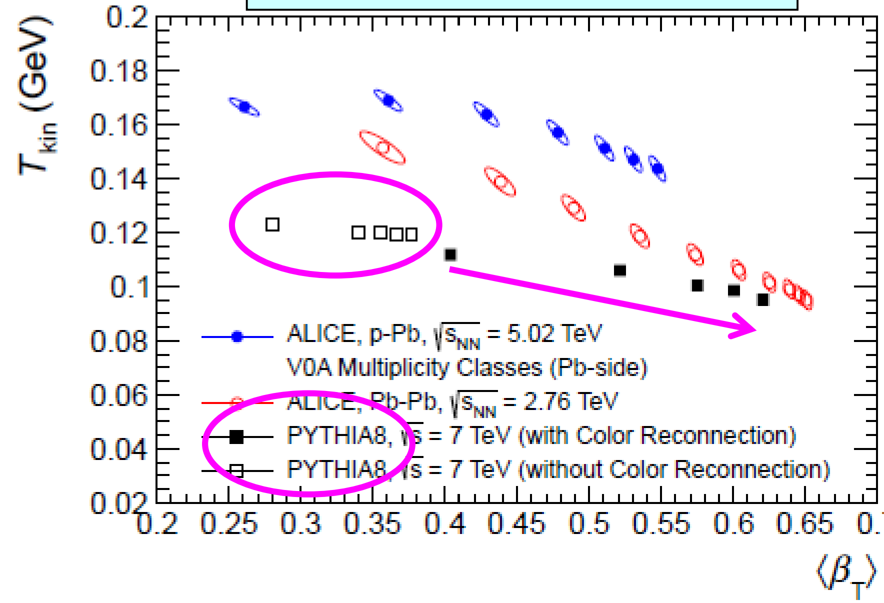
Another prediction come true ..

β versus N_{ch} in **pPb**, PbPb

T versus N_{ch} in **pPb**, PbPb



BW fit (β,T) **pPb** and PbPb



smaller fireball, larger gradient, more radial flow ?
as predicted (e.g.by Shuryak) ??

High Multiplicity pp and pA Collisions: The Hydrodynamics at its Edge

Edward Shuryak and Ismail Zahed

arXiv:1301.4470 [hep-ph]

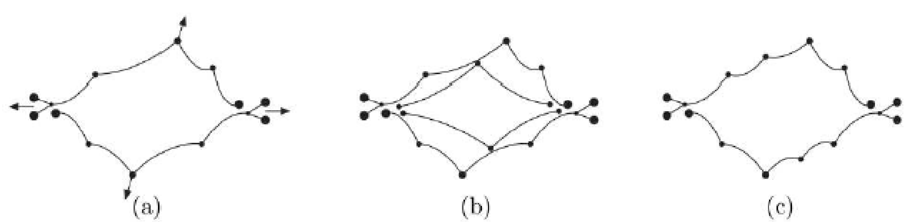
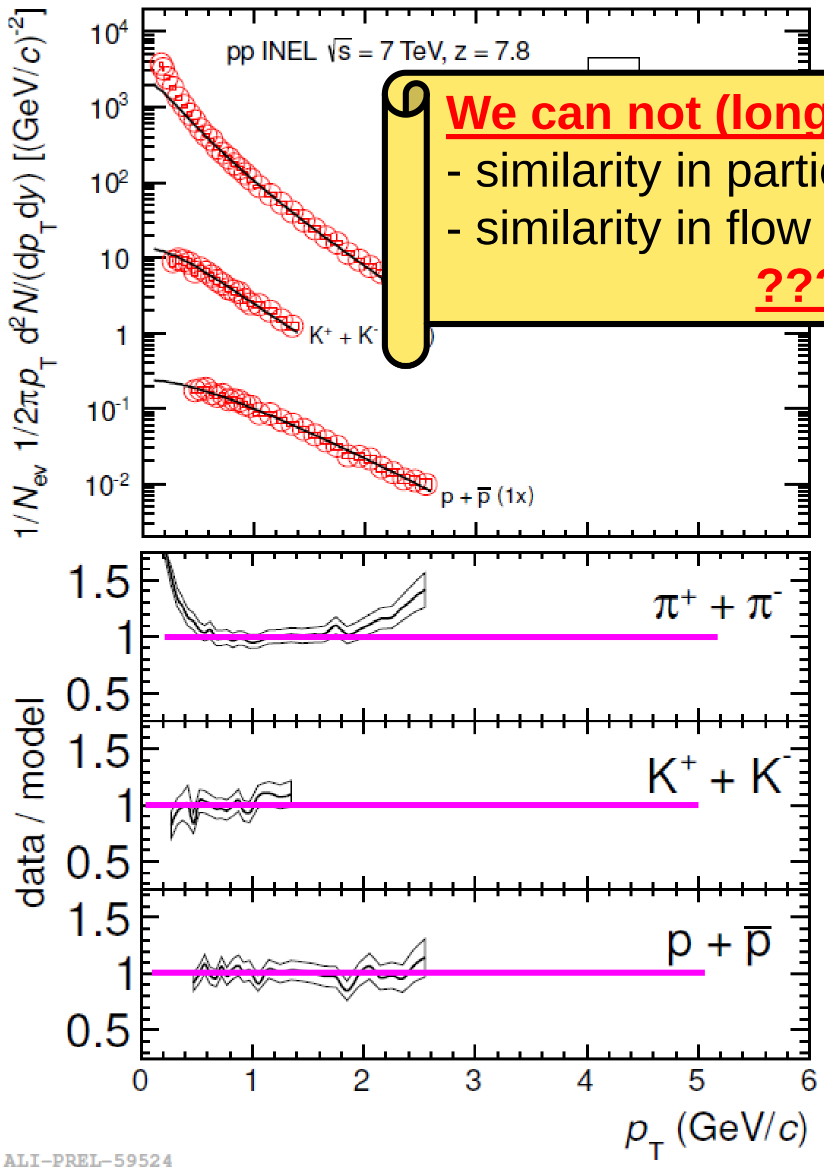


FIG. 2. Illustration of the color reconnection in the string fragmentation model (picture taken from [14]). The outgoing gluons color connected to the projectile and target remnants (a). The second hard scattering (b). Color reconnected string(c).

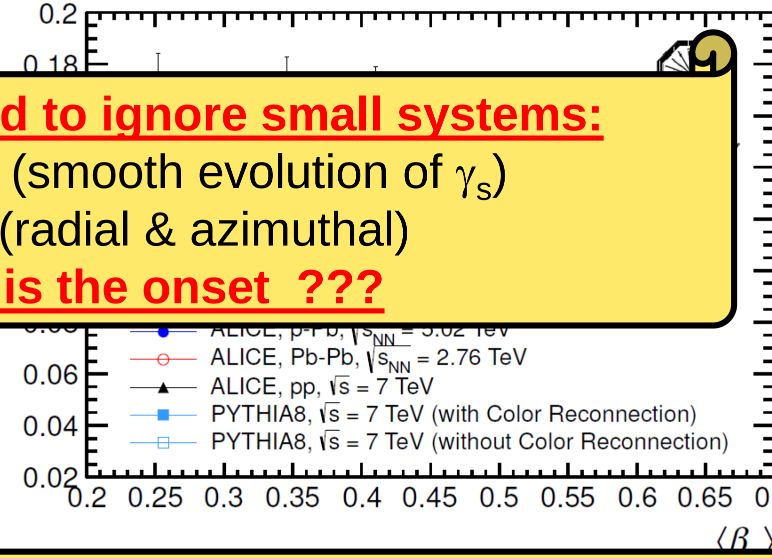
A. Ortez et al http://arxiv.org/abs/1303.6326v2

.. or too much of a good thing ?

BW fit to high multiplicity pp



BW fit (β,T) **pPb** and PbPb and **pp**



We can not (longer) afford to ignore small systems:

- similarity in particle ratios (smooth evolution of γ_s)
- similarity in flow patterns (radial & azimuthal)

??? Where is the onset ???

All Options look bad:

- Hydro everywhere (incl. low mult. pp)
- Hydro nowhere (incl. central PbPb)
- Looks like flow in pp but isn't (pPb ??)

Where are all the roses gone ...

pPb (pp): Panta Rhei ?

- **CGC ?**
  - ⇨ some results come natural, others need additional 'ad hoc' explanations
    - odd harmonics (v_3), cumulants $v_2\{4\}$, PID v_2,
- **Collective 'Hydro-like' flow in pA (& pp) ??**
  - ⇨ most results are 'natural' (at least within factor 2) if one assumes hydro..
  - ⇨ energy/particle density quiet comparable to AA (eg high N_{ch} pp@LHC ≈ Cu-Cu mid-central @RHIC)
  - ⇨ system size only few fm^3 ?? (presumably << 10 compared to >> 1000)
    - however, hydro has no intrinsic size, only ratio's: λ/r, and $\lambda \approx 0$! (from η/s)
    - a proton@LHC is more like a small nuc
  - ⇨ what other measurements are needed ?
- **In either case, more than a cu**
  - ⇨ <u>CGC</u>
    - discovered a 'new state of matter'
    - smoking gun for new 'first principle' limit of QCD
  - ⇨ <u>Hydro</u> stunning: a system the size of a single hadron behaves like 'macroscopic matter'
    - 'extra dimension' for QGP study: size !
    - finite size effects => correlation & coheren

<u>New State of Matter created at CERN</u> which features many of the characteristics of the theoretically predicted Colour Glass Condensate.

<u>RHIC Scientists found "Colorful Glass"</u> to serve the Perfect Liquid

<u>Rewrite the textbooks</u>
at least change the title from '**Heavy Ion** physics' to ..

Accelerators in Relativistic Heavy Ion Physics

Accelerator	Place	HI-Periods	Max. Energy	Projectiles	Experiments
Bevalac	LBNL, Berkeley	1984 - 1993	< 2 *A*GeV	C, Ca, Nb, Ni, Au, ...	Plastic Ball, Streamer Chamber, EOS, DLS
Synchro-Phasotron	JINR, Dubna	1974 - 1985	> 100 *A*MeV		
AGS	BNL, Brookhaven	1986 - 1994	14.5/11.5 *A*GeV	Si, Au	E802, ..., E917
SPS	CERN, Geneva	1986 - 2002	200/158 *A*GeV	O, S, In, Pb	NA34,... , WA80,...
SIS	GSI, Darmstadt	1992 - today	2 *A*GeV	Kr, Au	FOPI, KAOS, HADES
RHIC	BNL, Brookhaven	2000 - today	$\sqrt{s_{NN}} = 200$ GeV	Cu,Au	STAR, PHENIX, BRAHMS, PHOBOS
LHC	CERN, Geneva	2007(8) $\rightarrow$	$\sqrt{s_{NN}} = 5.5$ TeV	O, Ar, Pb	ALICE, CMS, ATLAS
SIS300	GSI, Darmstadt	2014? $\rightarrow$	30/45 *A*GeV	Ni, Au	CBM
Nuklotron	JINR, Dubna	?	~5 *A*GeV		

Fixed Target Experiments at Relativistic Energies

- Beam energies: 100*A* MeV → 2*A* GeV

- Pioneering experiments
  - BEVALAC: Plastic Ball and Streamer Chamber (1984 – 1986)
  - Syncho-Phasotron – Dubna (1975 – 1985)

- 2nd generation experiments
  - SIS-GSI: FOPI, KAOS, HADES (1990 – today)
  - BEVALAC: EOS-TPC, DLS (1990 – 1992)

- Physics:
  - Collective effects → Discovery and investigation of flow effects
  - Equation of state (EOS) → Study of compressibility of dense nuclear matter
  - In-medium modifications → Kaons, low mass di-leptons

- Basic result:
  - Nuclear matter can be compressed and high energy densities can be achieved

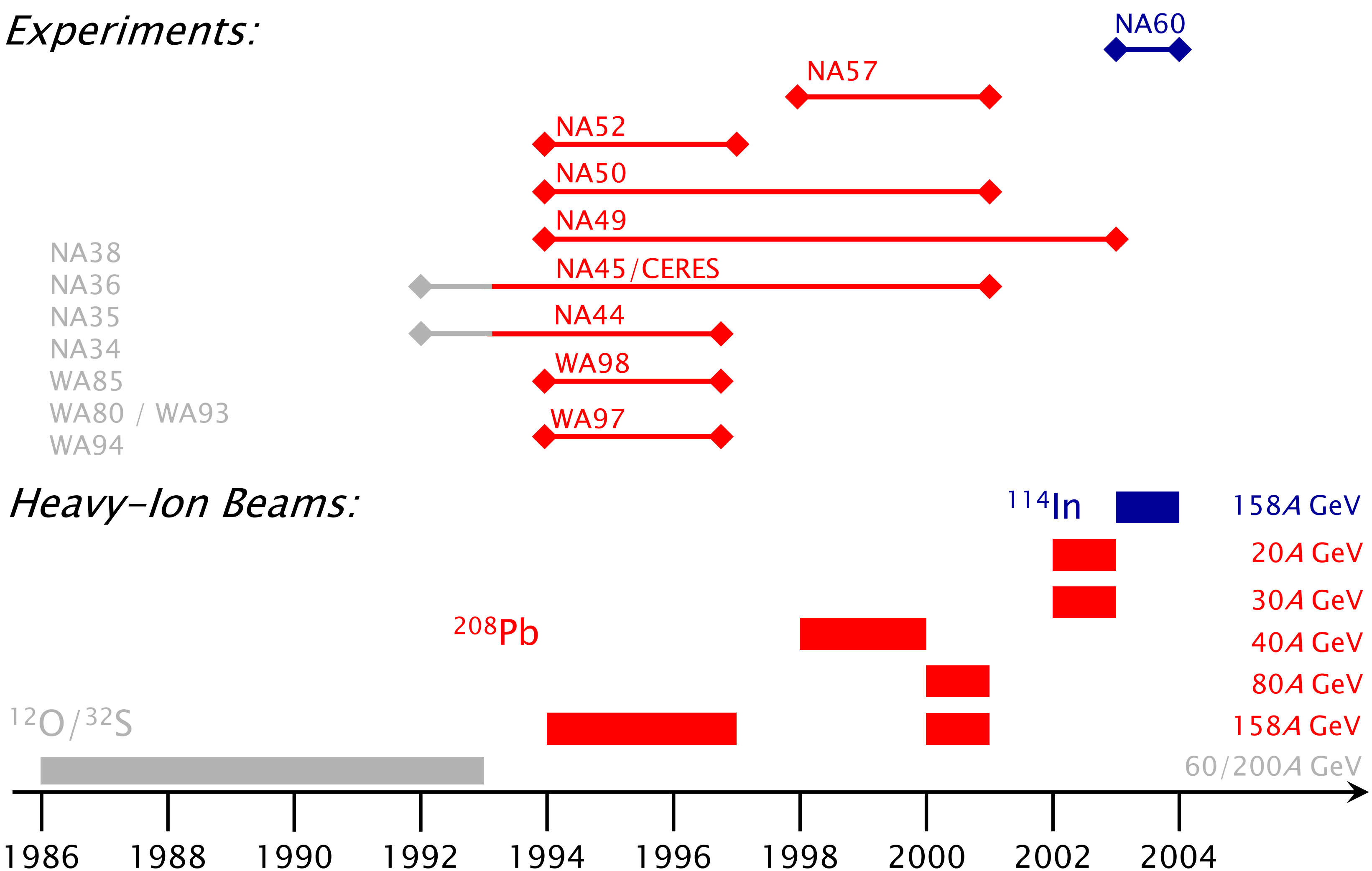
Fixed Target Experiments at Ultra-Relativistic Energies

- Beam energies: 2*A* GeV – 200*A* GeV
- Objective: Search for a Quark-Gluon Plasma (QGP) state
- 1st generation: "not-so-heavy" ion
  - SPS-CERN, projectiles: ^{16}O and ^{32}S, $E_{lab}^{max} = 200A$ GeV (1986 – 1993)
  - AGS-BNL, projectiles: ^{28}Si, $E_{lab}^{max} = 14.5A$ GeV (1986 – 1991)
- 2nd generation: heavy ions
  - SPS-CERN, projectiles: ^{208}Pb, $E_{lab}^{max} = 158A$ GeV (1994 – 2002)
  - AGS-BNL, projectiles: ^{197}Au, $E_{lab}^{max} = 11.5A$ GeV (1992 – 1994)
- Physics:
  - Signatures of a QGP (e.g. strangeness enhancement, J/ψ suppression, etc.)
  - Systematic studies (energy dependence) → look for onset phenomena
- Basic result:
  - Observations consisten with QGP hypothesis, but no unambigous evidence

Heavy Ion Experiments at the AGS

Experiment	Beam	Technology	Observables
E802	Si	Single arm magnetic spectrometer	Spectra (π, p, $K^{\pm}$), HBT
E810		TPCs in magnetic field	Strangeness (K^0_s, Λ)
E814		Magnetic spectrometer + calorimeters	Spectra (p) + E_t
E859		E802 + 2nd level PID trigger	Strangeness (Λ)
E866	Au	2 magnetic spectrometers (TPC, TOF)	Strangeness (Kaons)
E877		Upgrade of E814	
E891		Upgrade of E810	
E895		EOS TPC	Spectra (π, p, $K^{\pm}$), HBT
E896		Drift chamber + neutron detector	H^0 Di-baryon, Λ
E910		EOS TPC + TOF	p+A Collisions
E917		Upgrade of E866	

Heavy Ion Physics at the SPS



Heavy Ion Experiments at the SPS

Experiment	Beam	Technology	Observables
NA34	^{16}O, ^{32}S	Muon spectrometer + calorimeter	Di-leptons, p, π, K, γ
NA35		Streamer chamber	π^-, $K^0{}_s$, Λ, HBT
NA36		TPC	$K^0{}_s$, Λ
NA38		Di-muon spectrometer (NA10)	Di-leptons, J/ψ
WA80/WA93		Calorimeter + Plastic Ball	γ, π^0, η
WA85		Mag. spectrometer with MWPCs	$K^0{}_s$, Λ, Ξ
WA94		WA85 + Si strip detectors	$K^0{}_s$, Λ, Ξ
NA44	^{16}O, ^{32}S, ^{208}Pb	Single arm magnetic spectrometer	π, $K^\pm$, p
NA45		Cherenkov + TPC	Di-leptons (low mass)
NA49	^{208}Pb	Large volume TPCs	π, $K^\pm$, p, $K^0{}_s$, Λ, Ξ, Ω, ...
NA50		NA38 upgrade	Di-leptons, J/ψ
NA52		Beamline spectrometer	Strangelets
WA97		Mag. spectrometer with Si tracker	h^-, $K^0{}_s$, Λ, Ξ, Ω
WA98		Pb-glass calorimeter + mag. spectrom.	γ, π^0, η
NA57		WA97 upgrade	h^-, $K^0{}_s$, Λ, Ξ, Ω
NA60	^{114}In	NA50 + Si vertex tracker	Di-leptons, J/ψ
NA61		NA49 + xxx	

Heavy Ion Experiments at RHIC

Experiment	Technology	Observables
STAR	TPC and Si vertex tracker (+ EMCAL, TOF)	π, $K^{\pm}$, p, $K^0{}_s$, Λ, Ξ, Ω, ...
PHENIX	Drift chambers, calorimeter, RICH, TOF, muon spectrometer	γ, π^0, η, J/ψ, $K^{\pm}$, p, ...
BRAHMS	2 arm magnetic spectrometer	π, $K^{\pm}$, p (large acceptance)
PHOBOS	Magnetic spectrometer with Si tracker	charged particles (large acceptance)

Future LHC Program

upgrade to full energy
10 x more data

increase in luminosity
10x

high luminosity LHC
100 x more data

LS1
2014

LS2
7/2018-2019

LS3
2023-2025

2015-2018
runs:
5.5 TeV
PbPb (2015), PbPb (2016), pPb (2017)

goals:
jet, dijets, γ-jet, Z-jet
differentially versus centrality, flow plane, pid
multi-particle correlations, v_n correlations
parton transport and energy loss
color screening quarkonia
low-mass di-leptons, ρ-spectral function, thermal photons
saturation, low-x
collectivity in pA

2020-2022
runs:
5.5 TeV
pA, PbPb

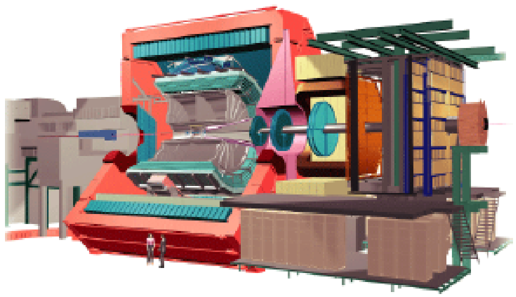
2025-2027
runs:
5.5 TeV
pA, PbPb, ArAr

goals:
jet, dijets, γ-jet, Z-jet, W-jet
differentially versus centrality, flow plane, pid
parton transport and energy loss
color screening quarkonia
low-mass di-leptons, ρ-spectral function, thermal photons
saturation, low-x
t-tbar in heavy-ions

Key future measurements to improve the heavy-ion standard model and understand the perfect liquid from QCD

Major upgrades to all LHC experiments

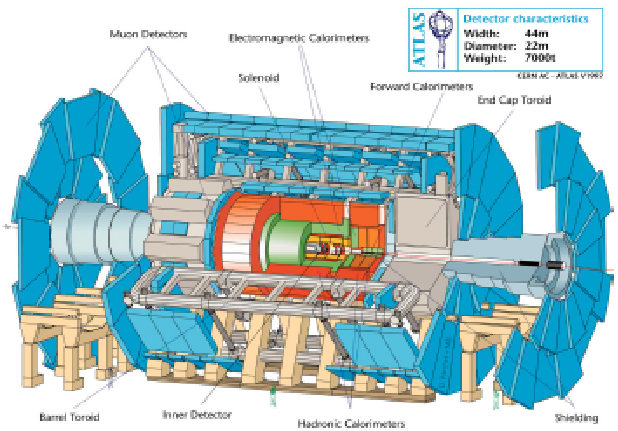
ALICE



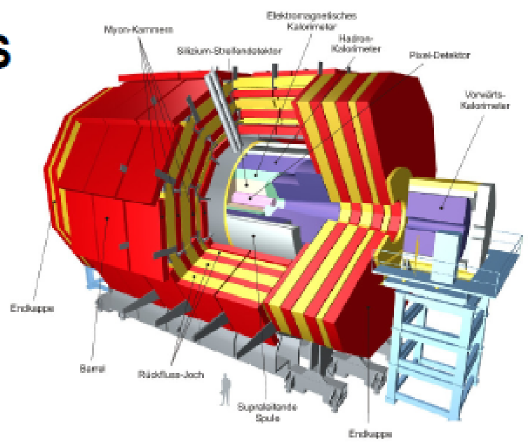
Expanded calorimetry
New inner tracker
Faster TPC readout
Improved data acquisition rate

ATLAS

Improved trigger system
New/extended inner tracker



CMS



Improved trigger system
New/extended inner tracker

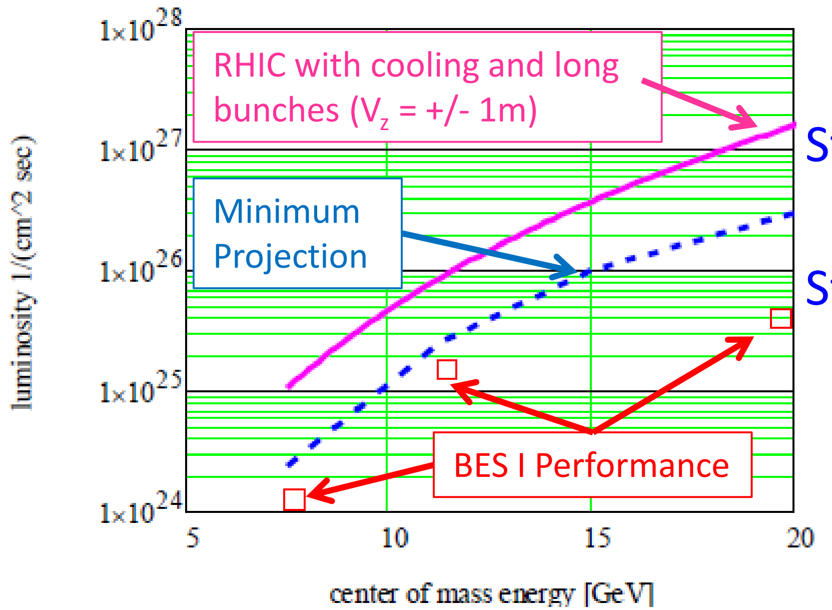
Brookhaven Lab Proposed 10 Year Plan

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2014	15 GeV Au+Au 200 GeV Au+Au	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p+p at 200 GeV p+Au, d+Au, ^{3}He+Au at 200 GeV High statistics Au+Au	Extract η/s(T) + constrain initial quantum fluctuations More heavy flavor studies Sphaleron tests Transverse spin physics	PHENIX MPC-EX Coherent e-cooling test
2017	No Run		Low energy e-cooling upgrade
2018-19	5-20 GeV Au+Au (BES-2)	Search for QCD critical point and onset of deconfinement	STAR ITPC upgrade Partial commissioning of sPHENIX (in 2019)
2020	No Run		Complete sPHENIX installation STAR forward upgrades
2021-22	Long 200 GeV Au+Au with upgraded detectors p+p, p/d+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia	
2023-24	No Runs		Transition to eRHIC

Low Energy Electron Cooling at RHIC

Electron Cooling can raise the luminosity by a factor of 3-10 in the range from 5 – 20 GeV

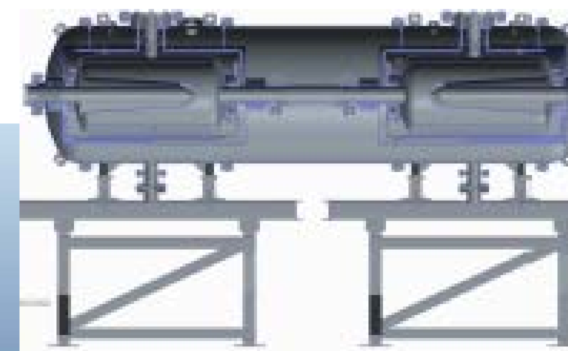
Long Bunches increase luminosity by factor of 2-5

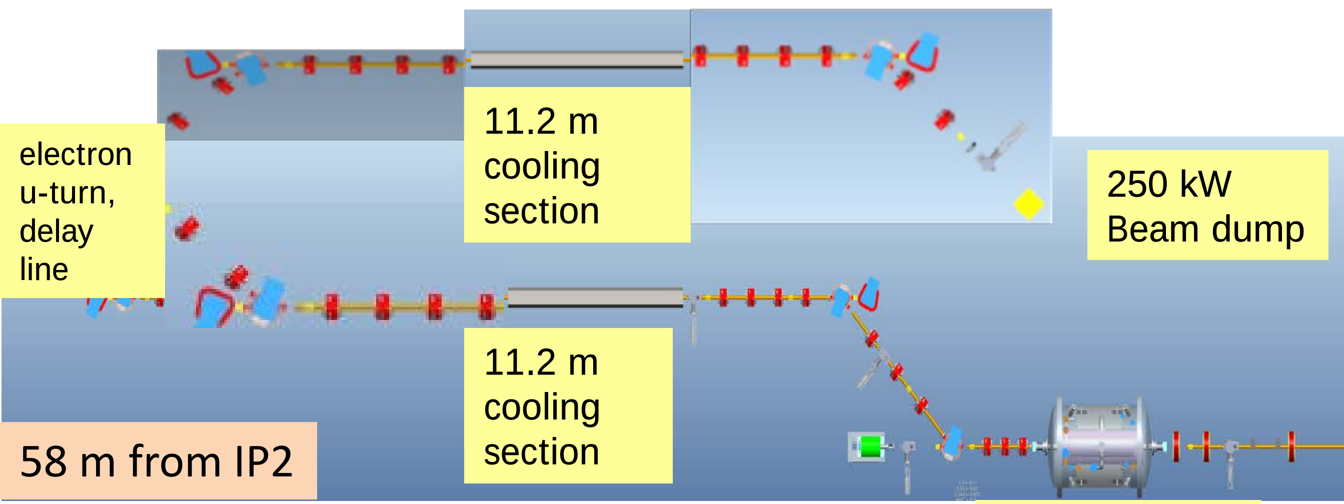


Stage I
$\sqrt{s_{NN}}$ = 5-9 GeV

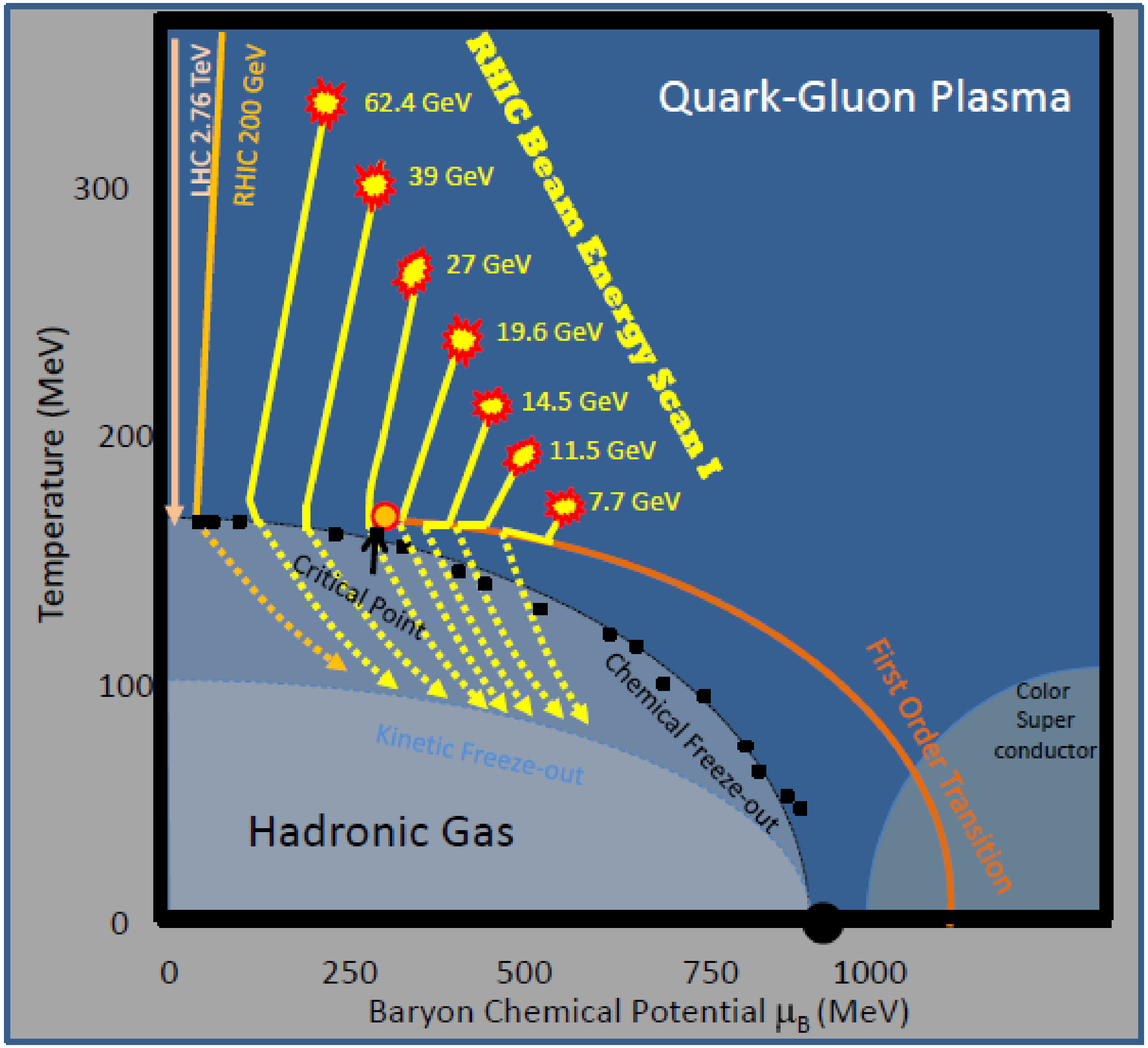
Stage II -- 3 MeV booster cavity
$\sqrt{s_{NN}}$ = 9-20 GeV

100 MHz SRF Gun





Phase Diagram of QCD Matter



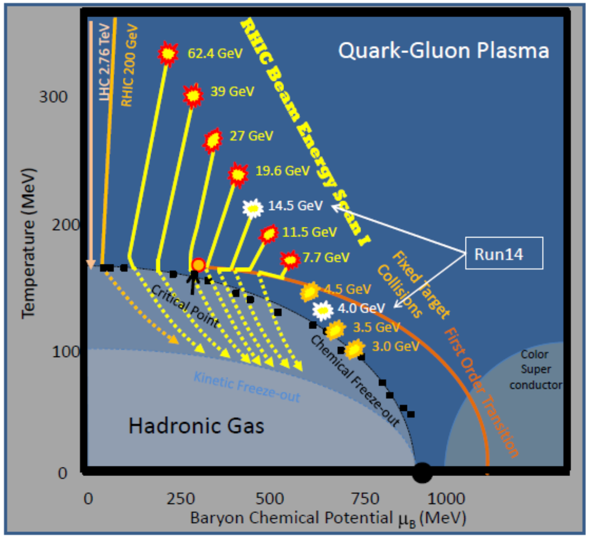
	Energy (GeV)	Chemical Potential μ_B	Pred. Temp. (MeV)
LHC	2760.0	2	166.0
RHIC	200.0	24	165.9
RHIC	130.0	36	165.8
RHIC	62.4	73	165.3
RHIC	39.0	112	164.2
RHIC	27.0	156	162.6
RHIC	19.6	206	160.0
SPS	17.3	229	158.6
RHIC	14.6	262	156.2
SPS	12.4	299	153.1
RHIC	11.5	316	151.6
SPS	8.8	383	144.4
RHIC	7.7	422	139.6
SPS	7.7	422	139.6
SPS	6.4	476	131.7
AGS	4.7	573	114.6
AGS	4.3	602	108.8
AGS	3.8	638	100.6
AGS	3.3	686	88.9
AGS	2.7	752	70.4
SIS	2.3	799	55.8

BES Phase II Proposal

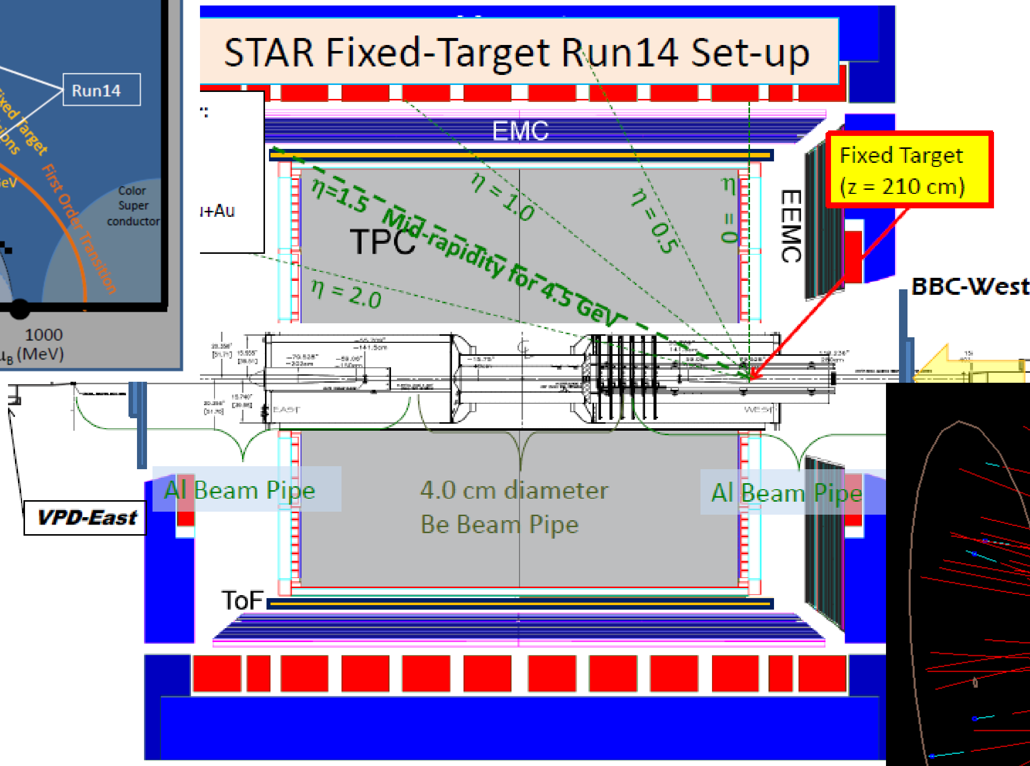
BES Phase II is planned for two 22 cryo-week runs in 2018 and 2019

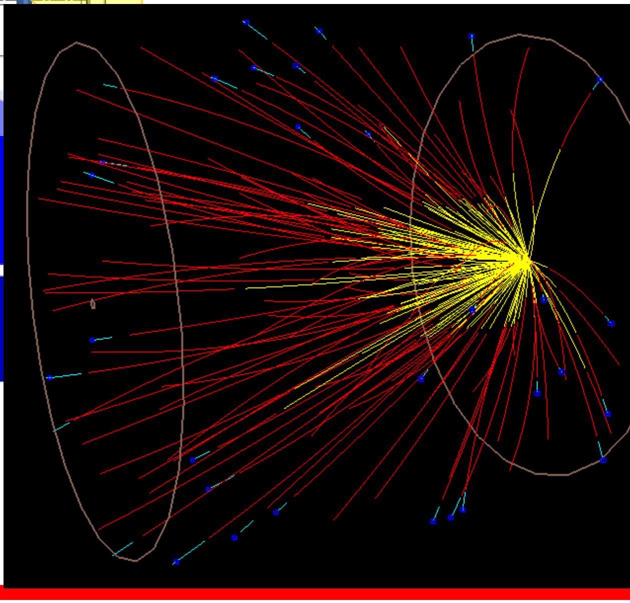
$\sqrt{S_{NN}}$ (GeV)	5.0	7.7	9.1	11.5	13.0	14.5	19.6
μ_B (MeV)	550	420	370	315	290	250	205
BES I (MEvts)	---	4.3	---	11.7	---	24	36
Rate(MEvts/day)		0.25		1.7		2.4	4.5
BES I $\mathcal{L}$ ($1\times10^{25}/cm^2sec$)		0.13		1.5		2.1	4.0
BES II (MEvts)		100	160	230	250	300	400
eCooling (Factor)	2	3	4	6	8	11	15
Beam Time (weeks)		**14**	**9.5**	**5.0**	**3.0**	**2.5**	**3.0**

RHIC Fixed-Target Program



Should measurements below 7 GeV prove essential, a fixed target program is being developed

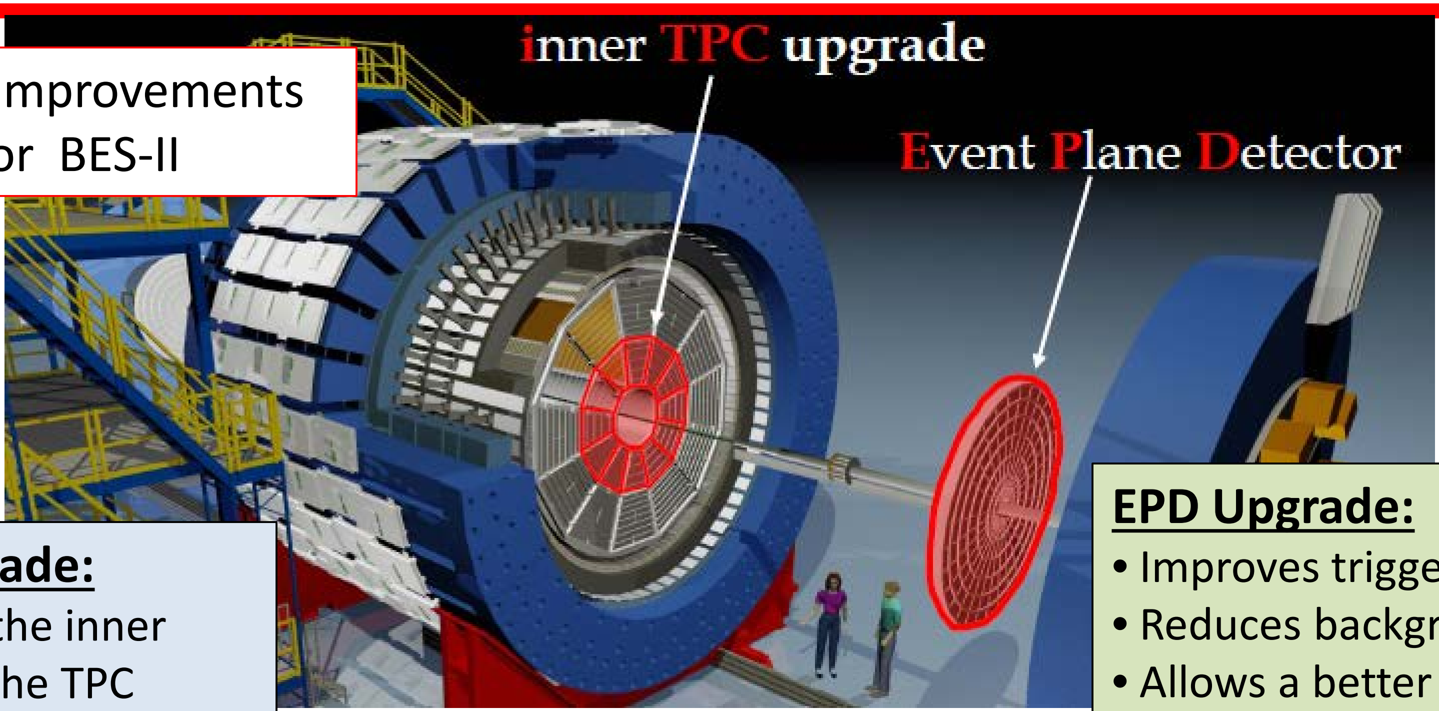




Au+Au event at 3.9 GeV from a test in Run 14

The STAR Upgrades and BES Phase II

Major improvements for BES-II



iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.7
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at forward rapidity

EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

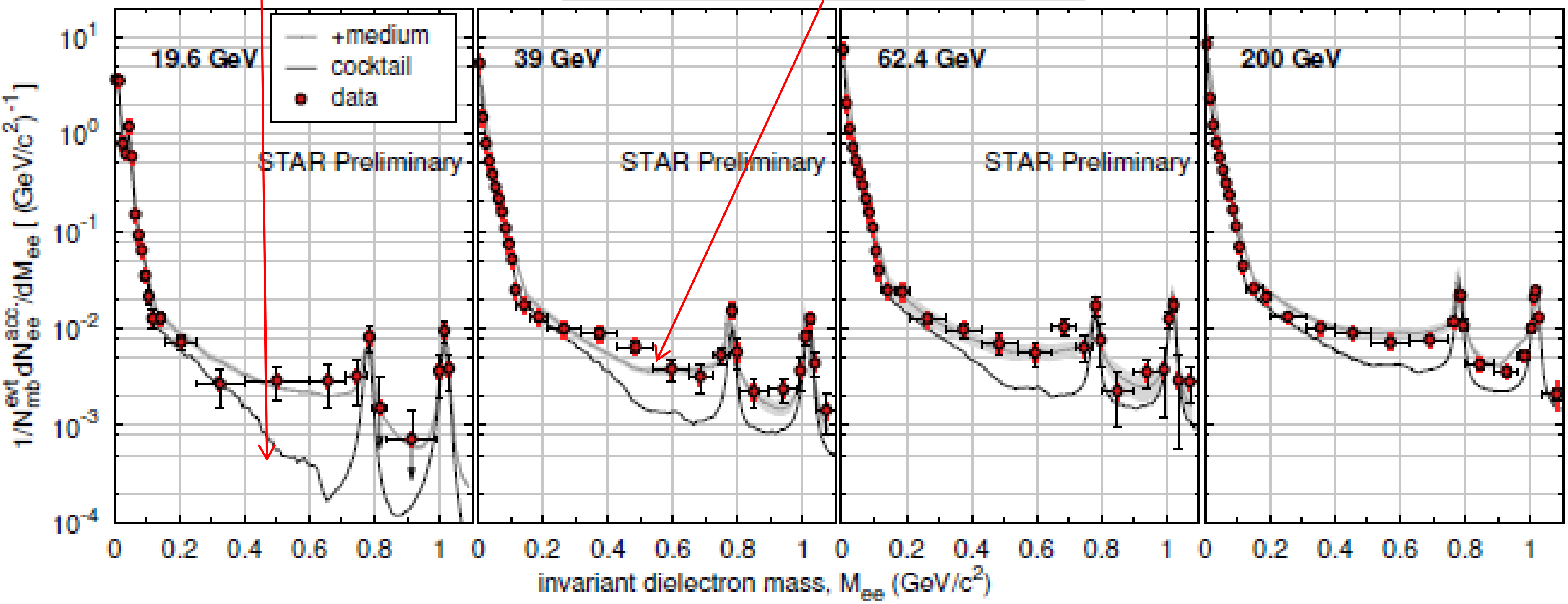
Bulk Penetrating EM Probes

R. Rapp, private communication,
R. Rapp Adv. Nucl. Phys. 25,1 (2000)

Low Mass Region:
Black lines are the Cocktail (excluding the ρ meson)

Grey lines are in medium calculations from R. Rapp which include both HG and QGP components (including medium broadened ρ meson). Model is able to match the data

Low Mass Region:
Emission depends on T, total baryon density, and lifetime



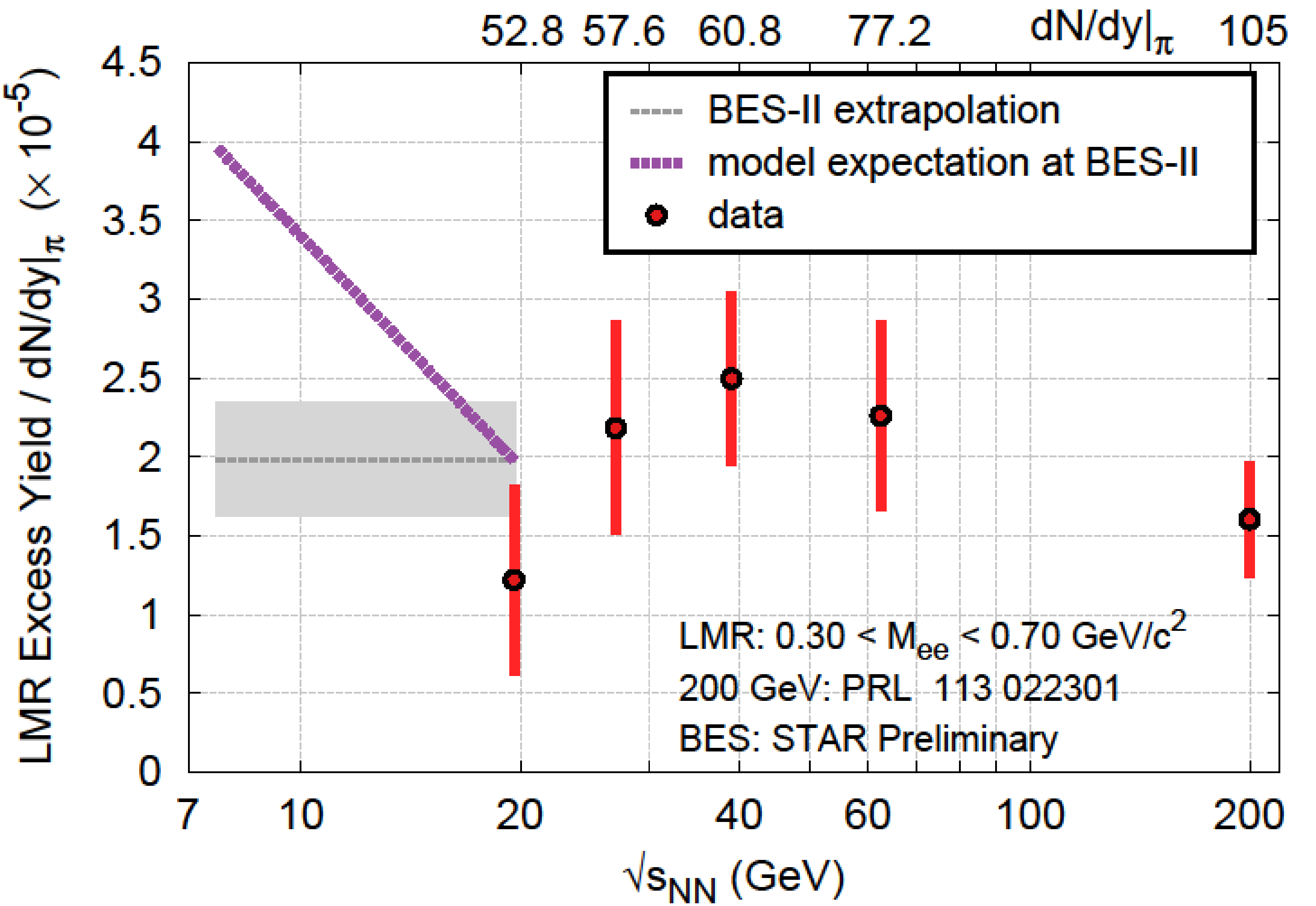
Bulk Penetrating EM Probes

BES-II:

- Measure LMR excess ➔ probes total baryon density (ρ) and lifetime dependence at lower √s

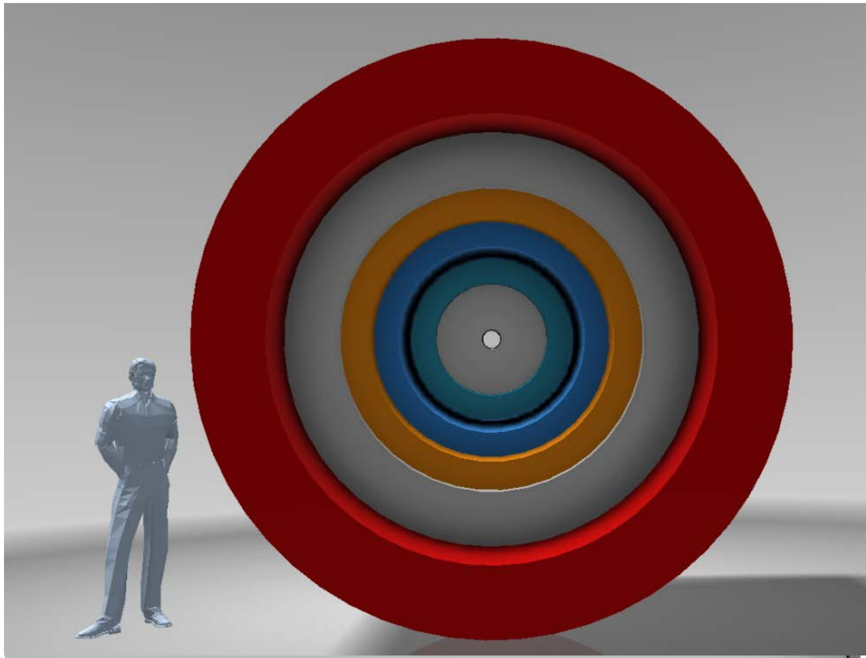
- Measure QGP thermal radiation (IMR) ➔ probes early temperature

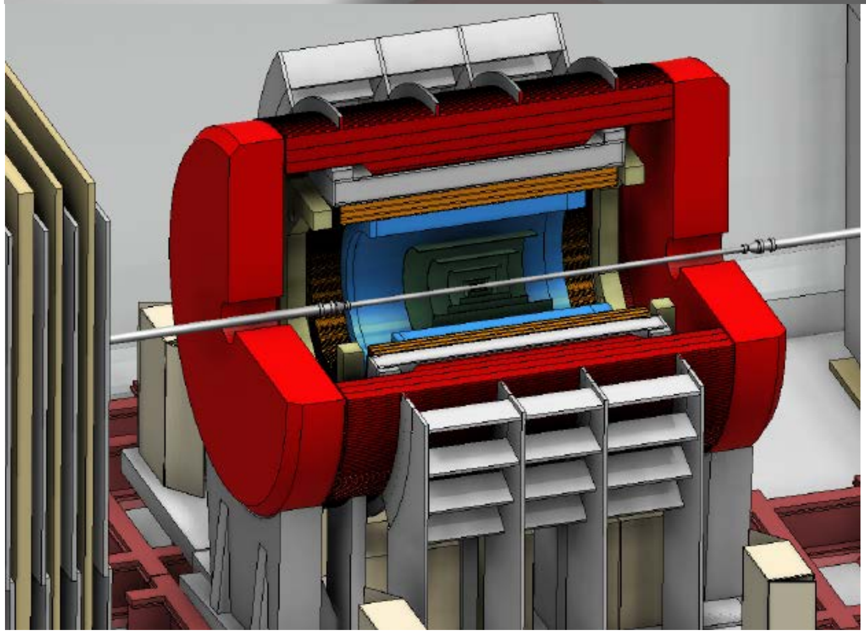
- Possible medium modifications of charm in the IMR



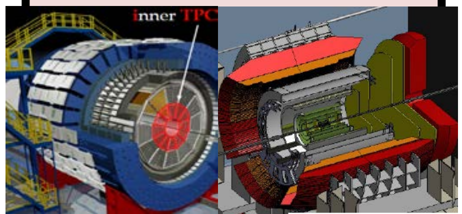
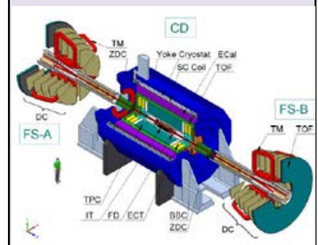
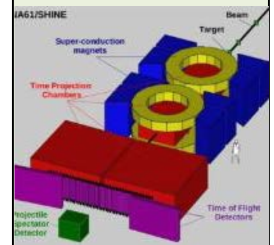
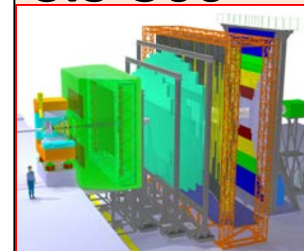
sPHENIX Upgrade

- Proposed sPHENIX:
  - EM+hadronic calorimetry over $|\eta| < 1.1$
  - Re-use existing BaBar 1.5T solenoid
  - Silicon tracking
  - DAQ rate ~ 10 kHz
- Will provide full suite of jet and quarkonia data
- Maximal overlap with LHC measurements





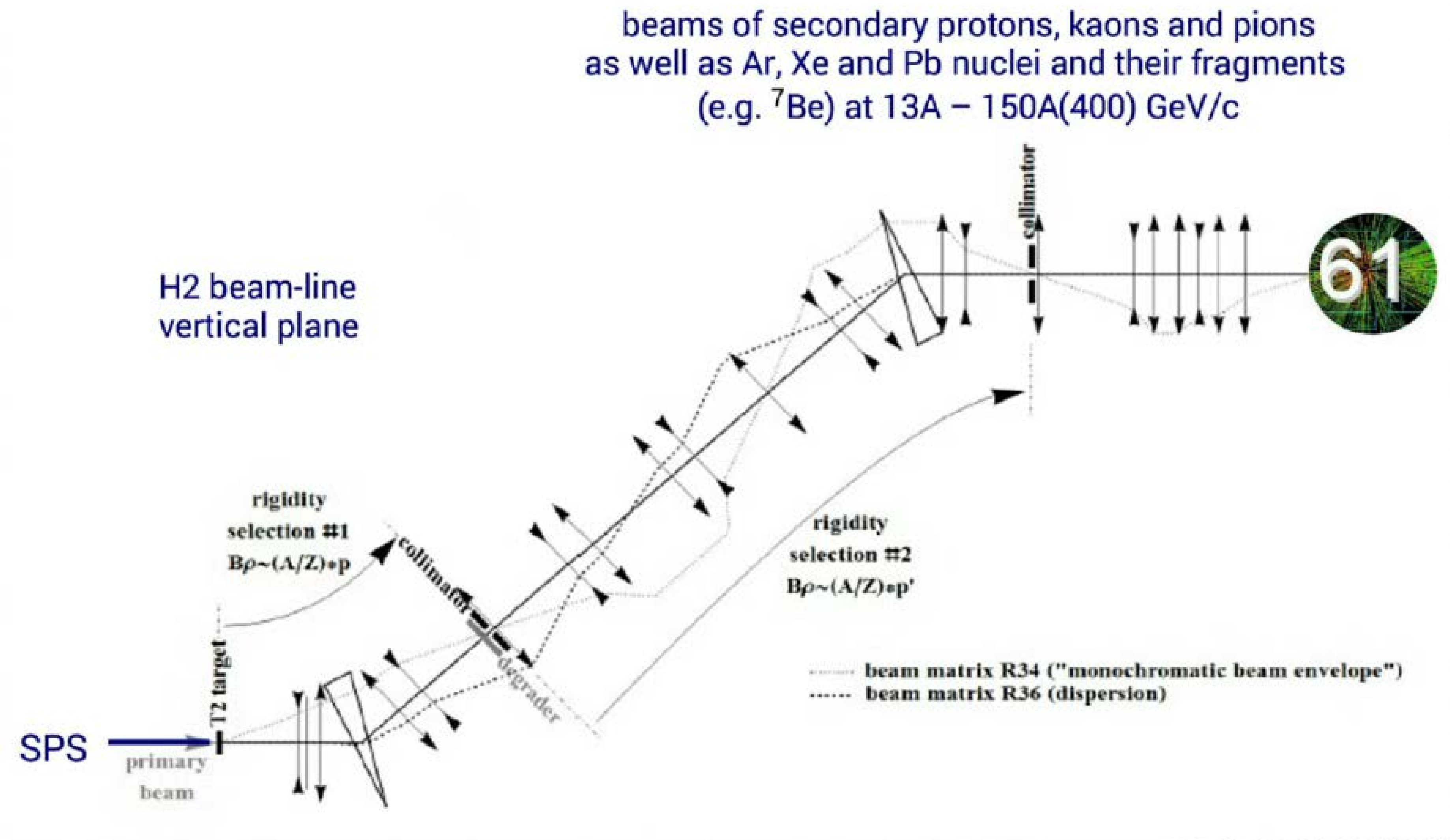
Comparison of Facilities

Facilty	RHIC BESII	NICA	SPS	SIS-300
Exp.:				
Start:	2018	>2018?	2009	?
Au+Au Energy: $\sqrt{s_{NN}}$ (GeV)	3.0 – 19.6+	2.7 - 11	4.9-17.3	2.7-8.2
Event Rate: At 8 GeV	10-100 HZ	<10 kHz	100 HZ	<10 MHZ
Physics:	CP,OD,DHM	OD&DHM	CP&OD	OD&DHM
			Fixed Target Lighter ion collisions	Fixed Target

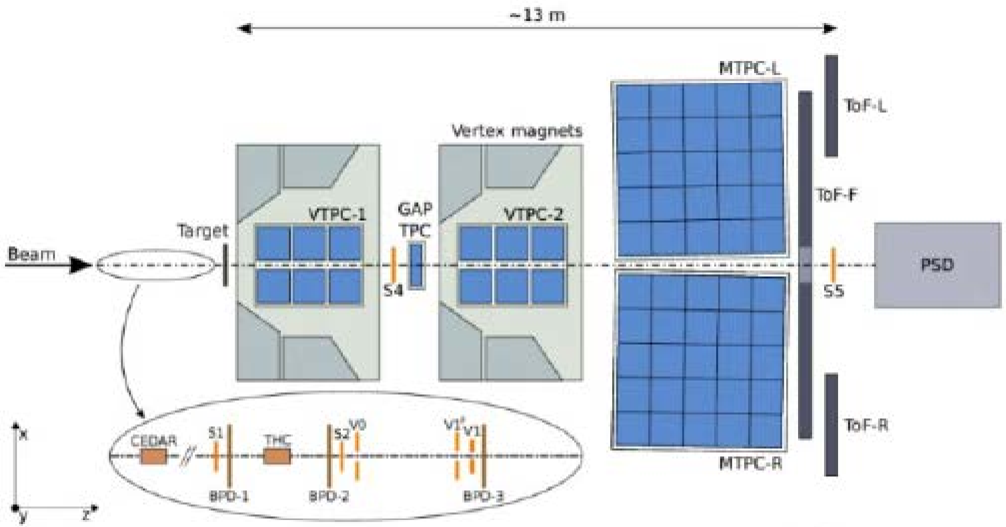
CP = Critical Point
OD = Onset of Deconfinement
DHM = Dense Hadronic Matter

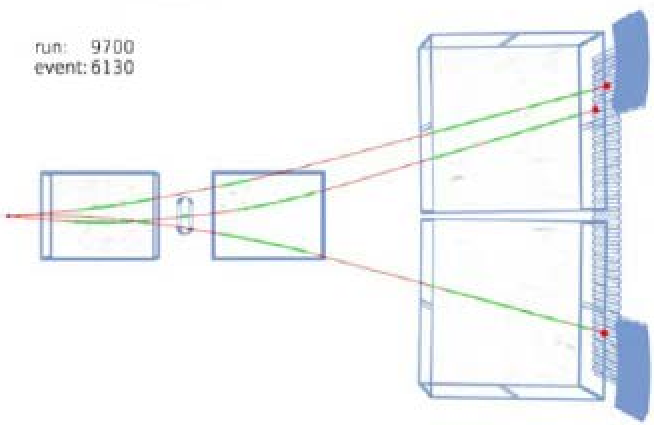
Conclusion:
RHIC is the best option

Acceleration chain → H2 beam-line → Detector



NA61/SHINE detector





(p+p interaction at 40 GeV/c measured in the NA61/SHINE detector)

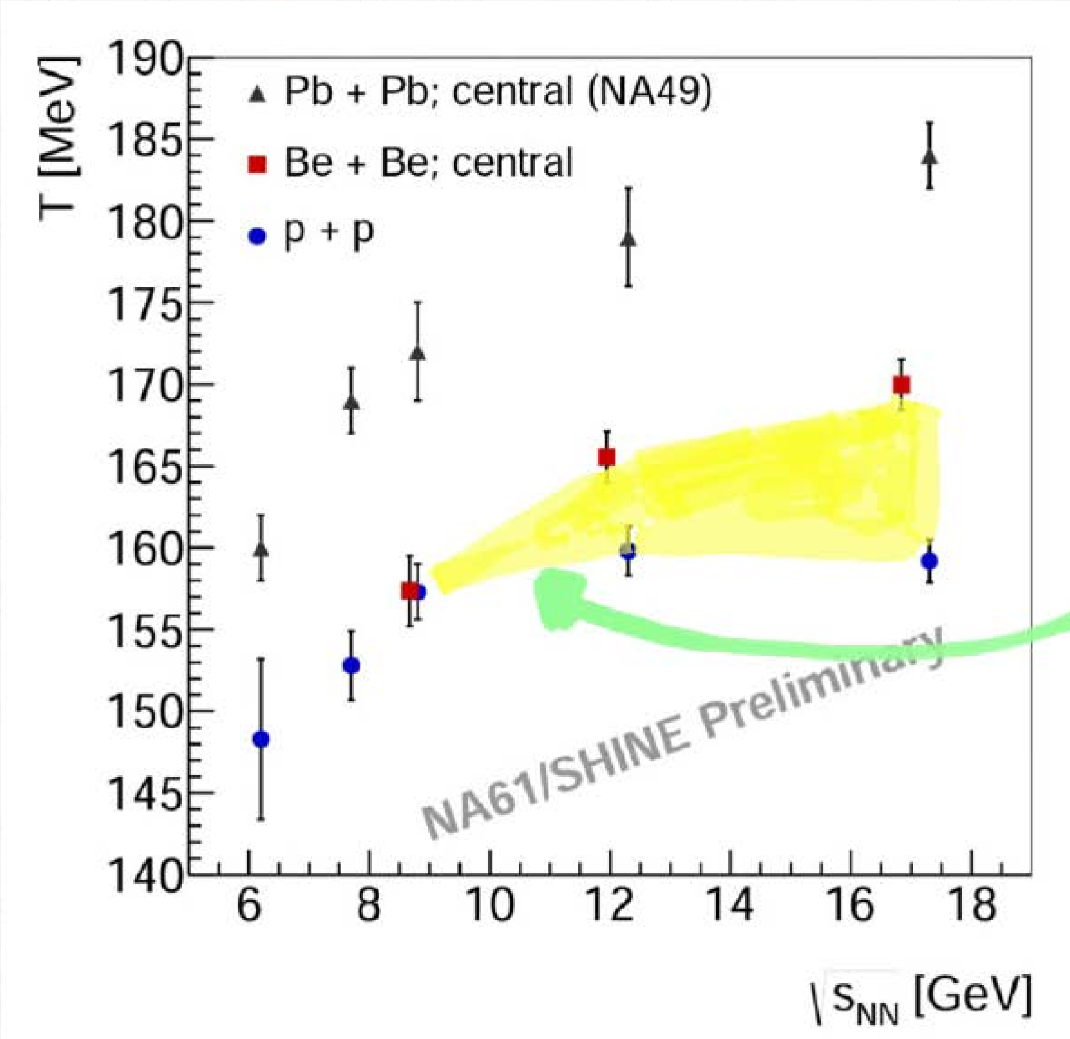
- A large acceptance hadron spectrometer
- Beam particles measured in set of counters and MWPC detectors
- Charged tracks measured in set of 5 **TPCs** → measurement of $\boldsymbol{q}$, $\boldsymbol{p}$ and identification via dE/dx
- 3 ToF walls: identification via time of flight measurement
- **Projectile Spectator Detector** counts the non-interacting nucleons of the beam particle

  NA61 → CBM
- VERTEX DETECTOR

  CBM → NA61

JINST **9** P06005

π^- m_T SPECTRA: (p+p vs Be+Be vs Pb+Pb) vs $\sqrt{s_{NN}}$

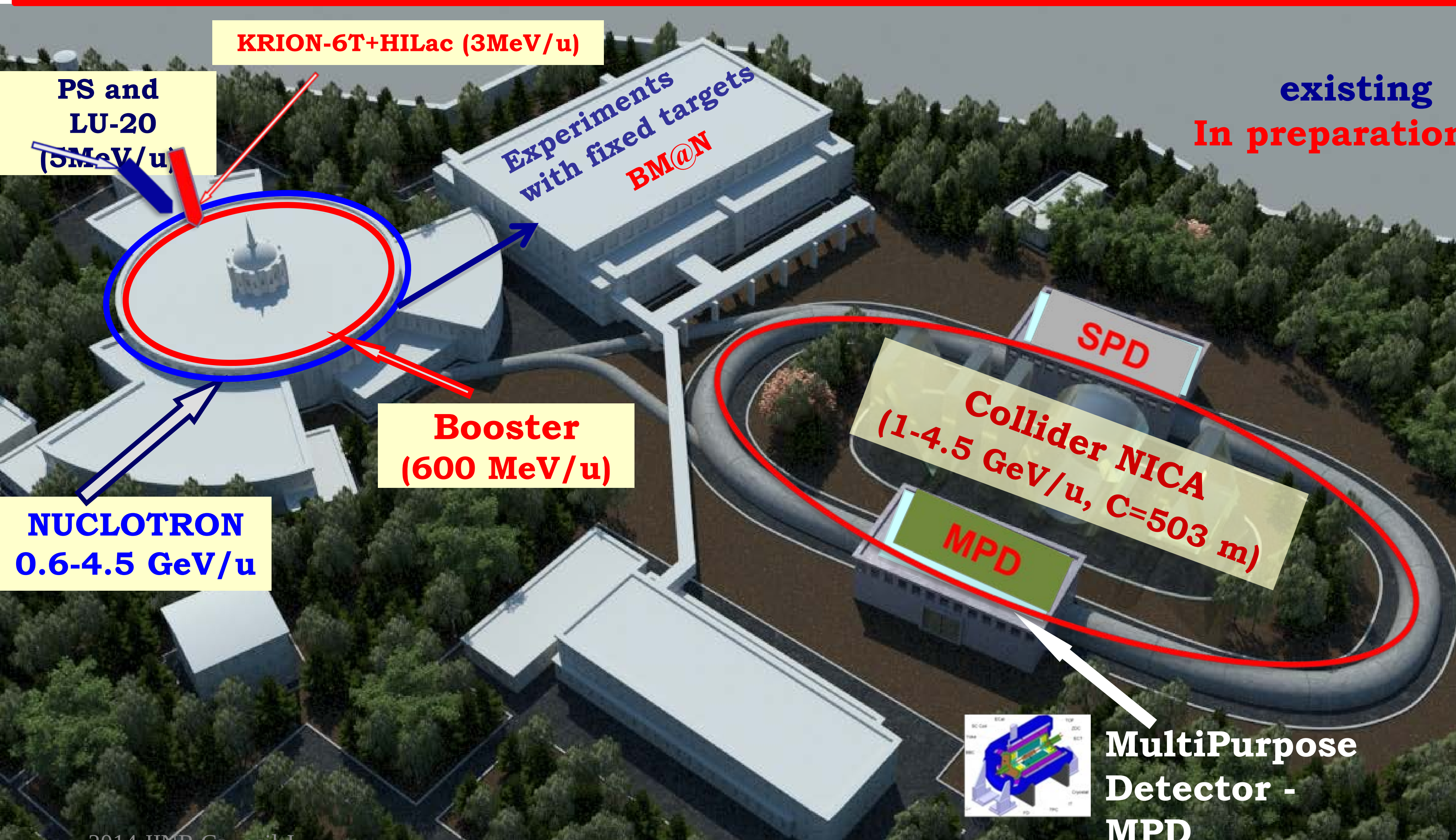


ONSET OF COLLECTIVITY IN Be+Be AT ≈ 75A GeV/c

NICA Complex

Collider basic parameters:

$\sqrt{s_{NN}}$ = **4-11** GeV; ***beams***: *from* **p** to **Au**; **L**~10^{27} cm^{-2} c^{-1} (Au), ~10^{32} cm^{-2} c^{-1} (p)



Summary: The NICA Beams

Heavy ion colliding beams up to $^{197}Au^{79+}$ + $^{197}Au^{79+}$

at $\sqrt{s_{NN}} = 4 \div 11$ GeV , $L_{average} = 1x10^{27}\ cm^{-2} \cdot s^{-1}$

Light-Heavy ion colliding beams of the same $\sqrt{s_{NN}}$ and the same or higher $L_{average}$

Polarized beams of protons and deuterons in collider mode:

p↑p↑ $\sqrt{s_{pp}} = 12 \div 26$ GeV $L_{max} \approx 1x10^{32}\ cm^{-2} \cdot s^{-1}$

d↑d↑ $\sqrt{s_{NN}} = 4 \div 13.8$ GeV

Extracted beams of light ions and polarized protons and deuterons for fixed target experiments:

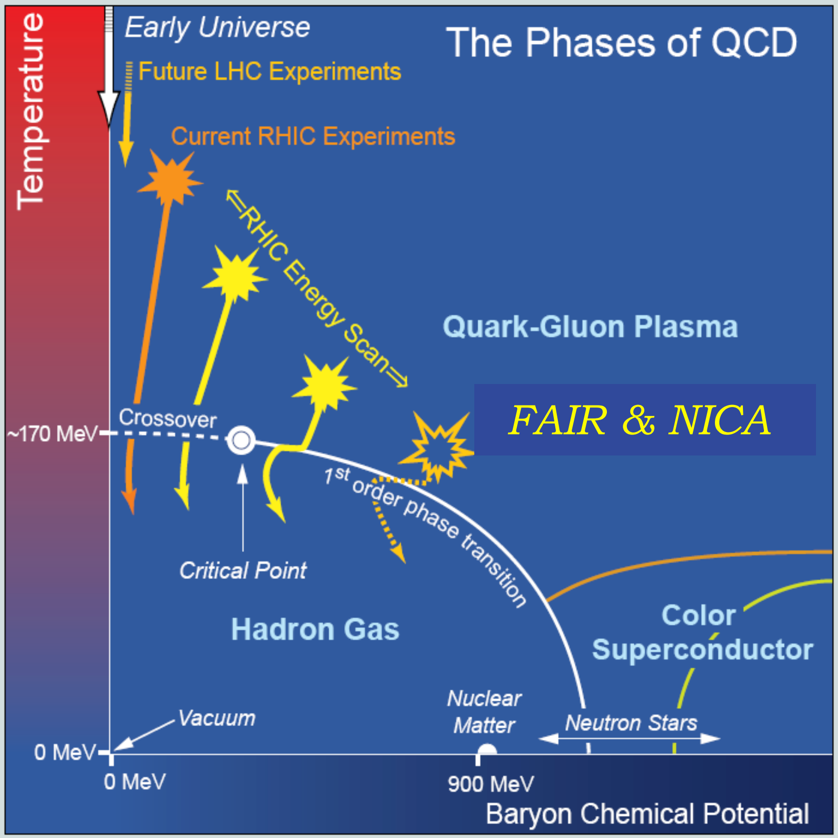
Li ÷ Au = 1 ÷ 4.5 GeV /u ion kinetic energy

p↑, p↑ = 5 ÷ 12.6 GeV kinetic energy

d↑, d↑ = 2 ÷ 5.9 GeV/u ion kinetic energy

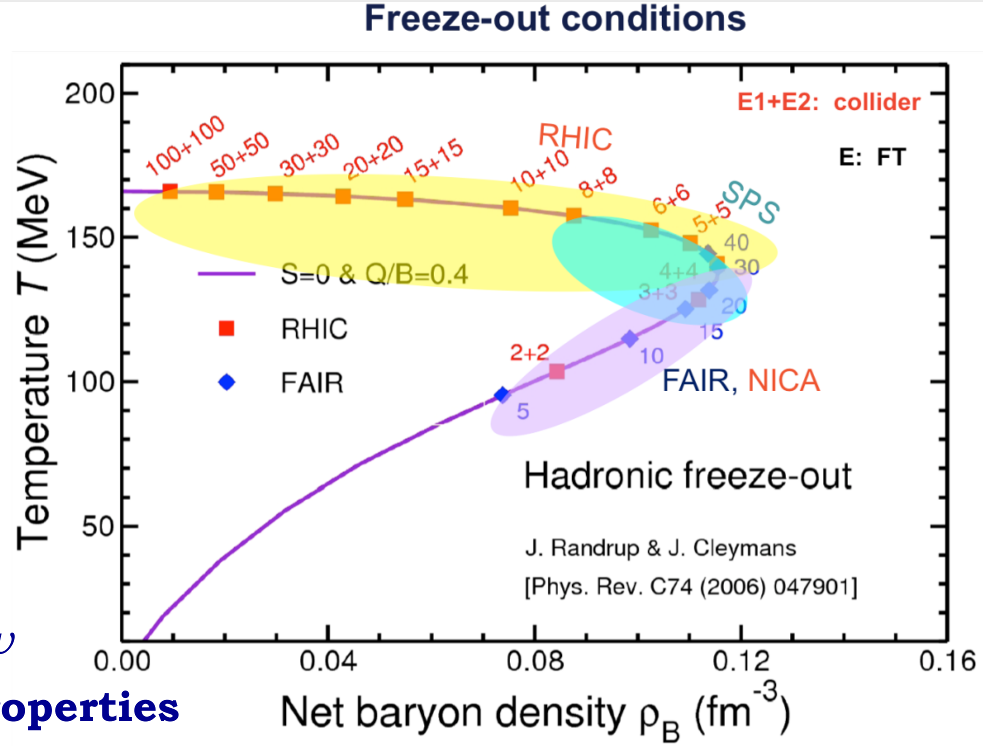
The set of NICA beams provides unique possibility both for basic and applied researches in the forthcoming decades

Physics



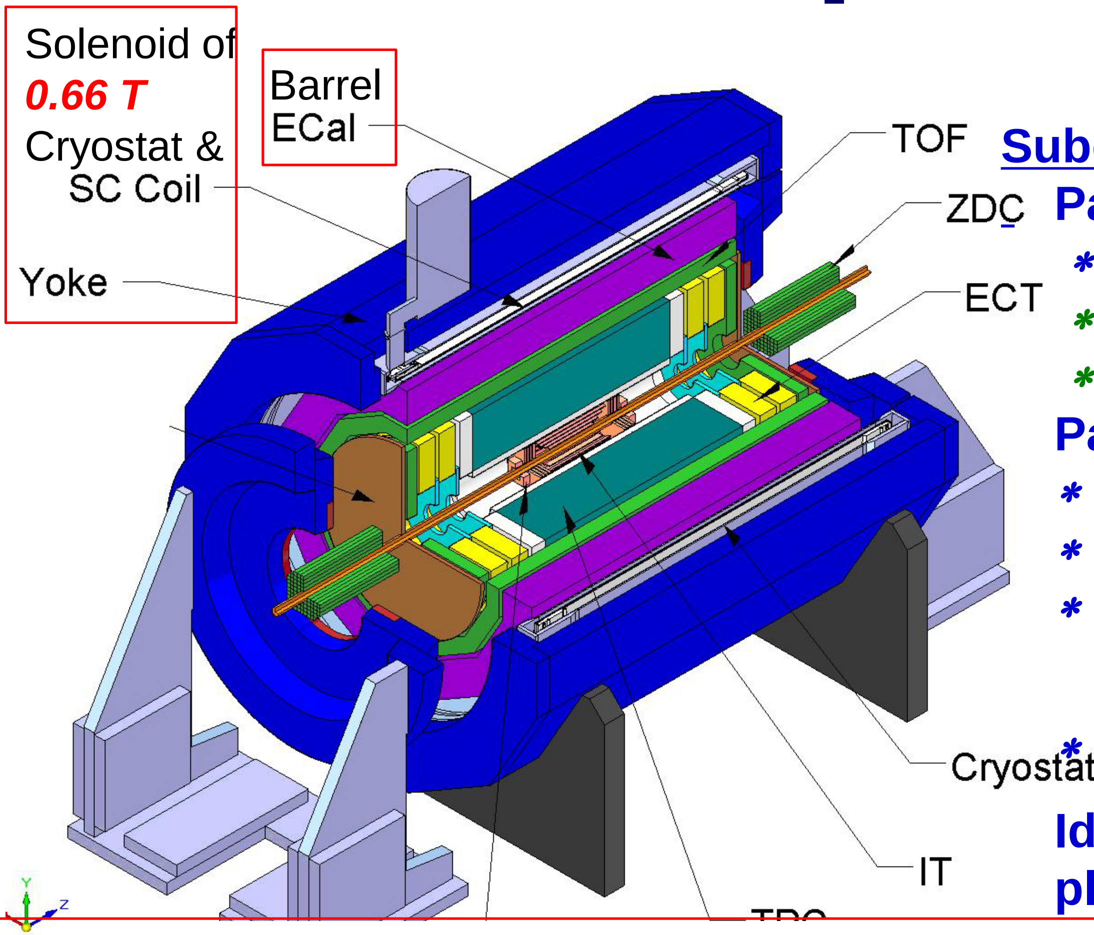
QCD matter at NICA :

- *Highest net baryon density*
- *Energy range covers onset of deconfinement*
- *Complementary to the RHIC/BES, FAIR and CERN experimental programs*



- **Bulk properties, EOS** - *particle yields & spectra, ratios, femtoscopy, flow*
- **In-Medium modification of hadron properties**
- **Deconfinement (chiral), phase transition at high ρ_B** - *enhanced strangeness production*
- **QCD Critical Point** - *event-by-event fluctuations & correlations*
- **Strangeness in nuclear matter** - *hypernuclei*

MultiPurpose Detector (MPD)



Subdetectors & probes' identification:

Particle Tracking:

- *Time projection chamber (TPC)*
- *Inner tracker (IT)*
- *End Cap Tracker (ECT)*

Particle identification:

- *Time-of-flight detector (TOF)*
- *Electromagnetic calorimeter (Ecal)*
- *Time projection chamber (TPC)*

Triggering (T0)

- *Fast Forward Detector (FFD)*

Identification of centrality and event plane:

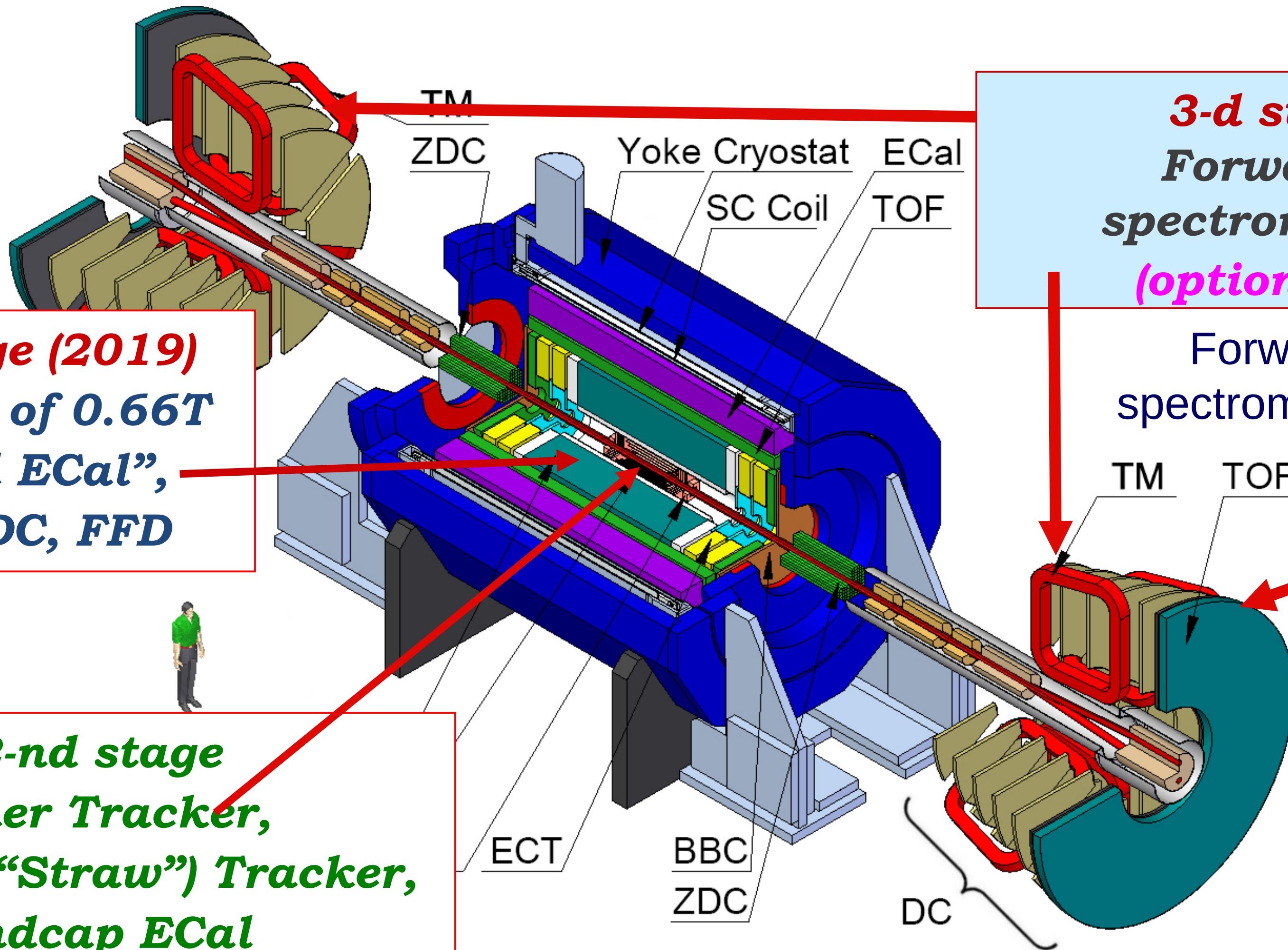
MPD advantages:

Disadvantage: weight ≈ 1200 tons

- ✓ *maximum and homogeneous detection efficiency (2π symmetry),*
- ✓ *high "transparency" for particles (small amount of matter;*
- ✓ *high quality of trajectories' reconstruction and particle identification*
- ✓ *high detection rate (~ 7 kHz)*

MultiPurpose Detector (MPD)

3 stages of MPD commissioning



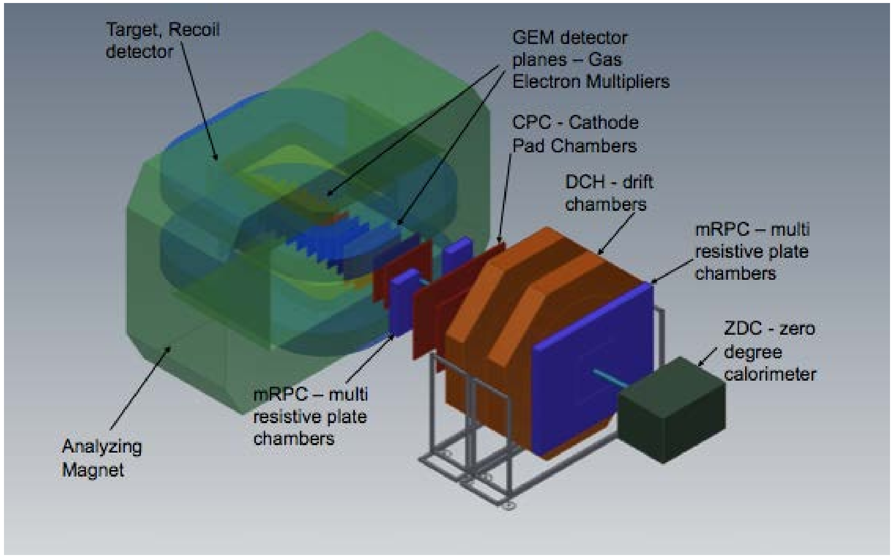
3-d stage
Forward-spectrometers
(optional ?)

Toroid

1-st stage (2019)
Solenoid of 0.66T
"Barrel ECal",
TPC, ZDC, FFD

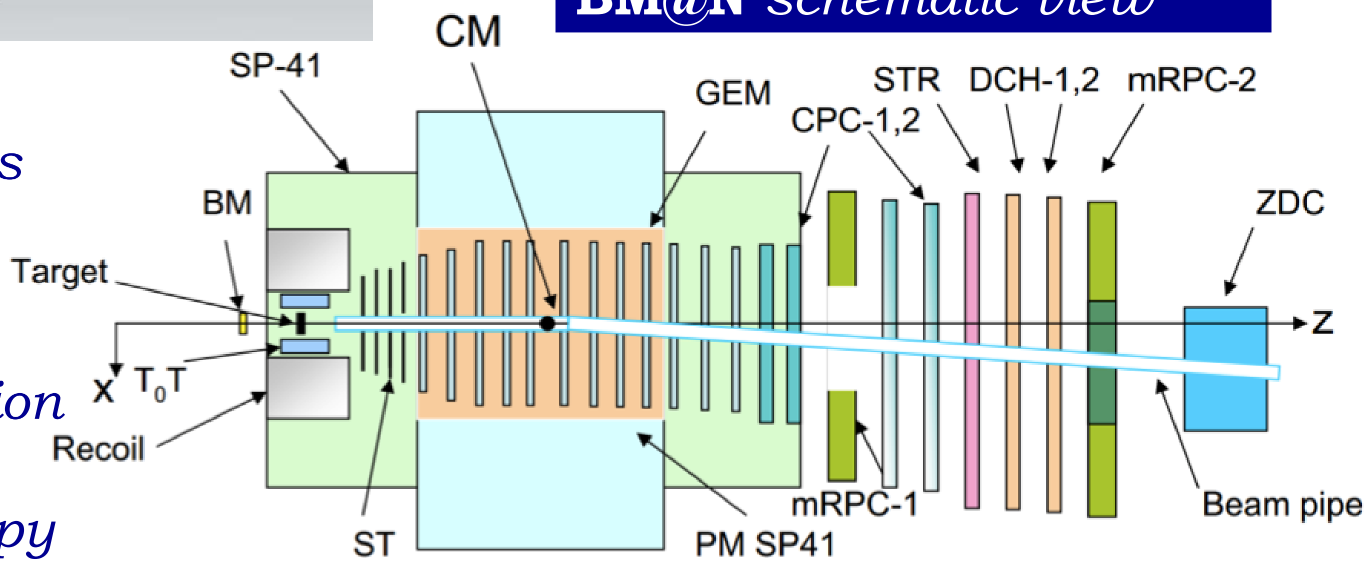
2-nd stage
Inner Tracker,
EndCap ("Straw") Tracker,
Endcap ECal

BM@N (Baryonic Matter at Nuclotron): *the 1st stage*



Collaboration of scientific centers:
INR, SINP MSU, IHEP + S-PSUniversity (Russia);
GSI, Frankfurt U., Gissen U. (Germany):
+ CBM-MPD IT-Consortium,

BM@N *schematic view*



Physics:

- ✓ *in-medium effects for strangeness & vector mesons*
- ✓ *hyperon production*
- ✓ *hadron femtoscopy*
- ✓ *electromagnetic probes (optional)*

SPD (Spin Physics Detector) at NICA

Collider provides both:
transversally & longitudinally
polarized ***p*** & ***d***
with energy up to $\sqrt{S}$ = ***27 GeV***

The issues to be studied:

- *MMT-DY processes*
- *J/Ψ production processes*
- *Spin effects in inclusive high-*p_T *reactions*
- *Spin effects in one and two hadron production processes*
- *Polarization effects in heavy ion collisions*

The Collaboration is forming

Project is under preparation