Heavy Ion Physics from molecular resonances to deconfinement (brief review)

Mihai Petrovici, Summer Student Program, Bucharest, July 22, 2019

A few remarks !

***“If you want to live a happy life,
tie it to a goal, not to people or things”
(Albert Einstein)***

***"I want to know God's thoughts; the rest are details.”
(Albert Einstein)***

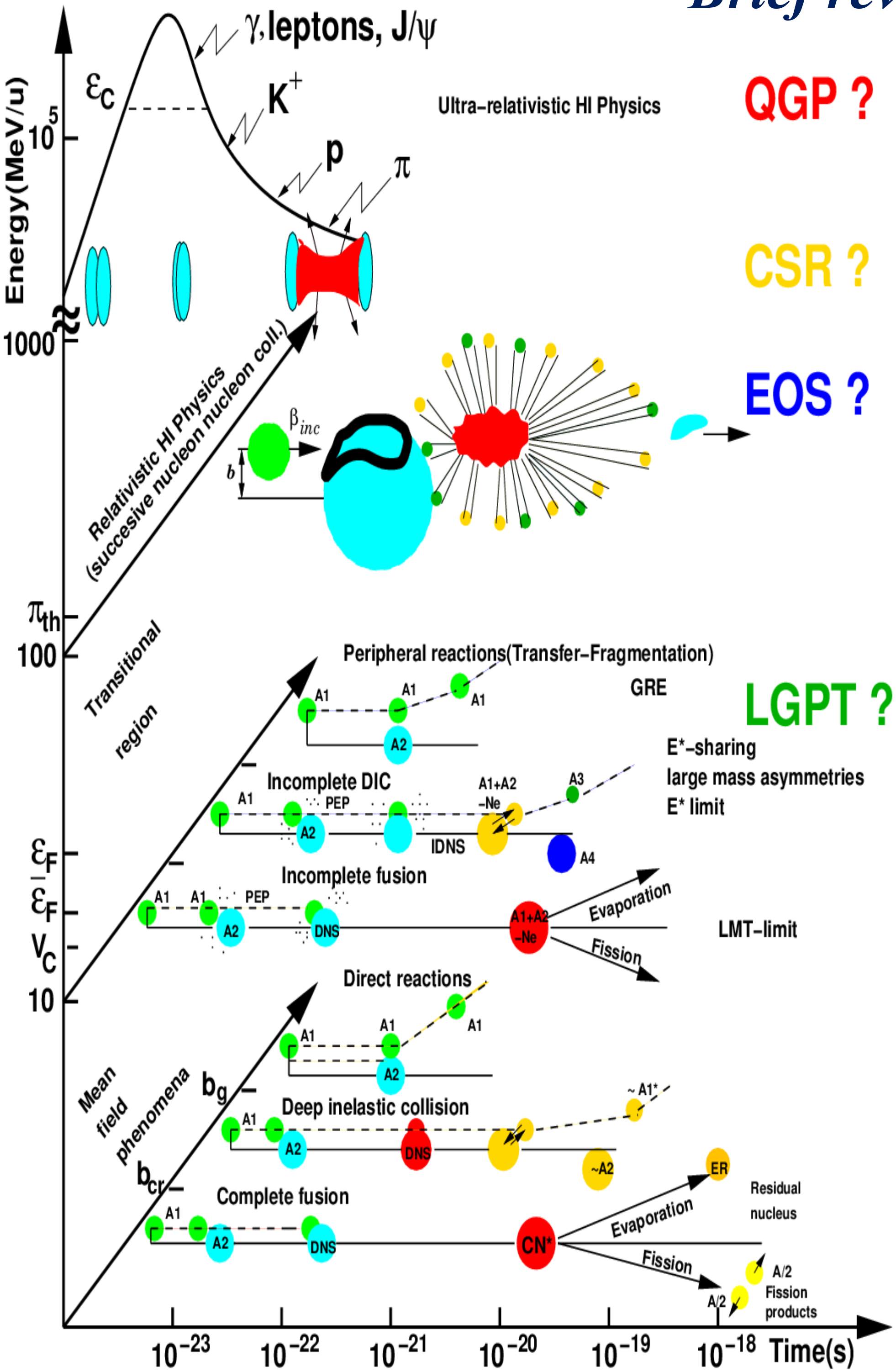
***“We are not to tell nature what she’s gotta be …
She’s always got better imagination than we have.”
(Richard Feynman)***

***“The only way to make progress
is to defy one of those prohibitions that are
uncritically accepted without good reasons”
(M. Gell-Mann)***

***“If you thought that science was certain,
well that is just an error on your part.”
(Richard Feynman)***

***“Attempts to calculate the electron mass from the first principles
might be as futile as attempts to calculate the shape of the Solar System,
or the anatomy of frogs.
Still, we must try.”
(Frank Wilczek)***

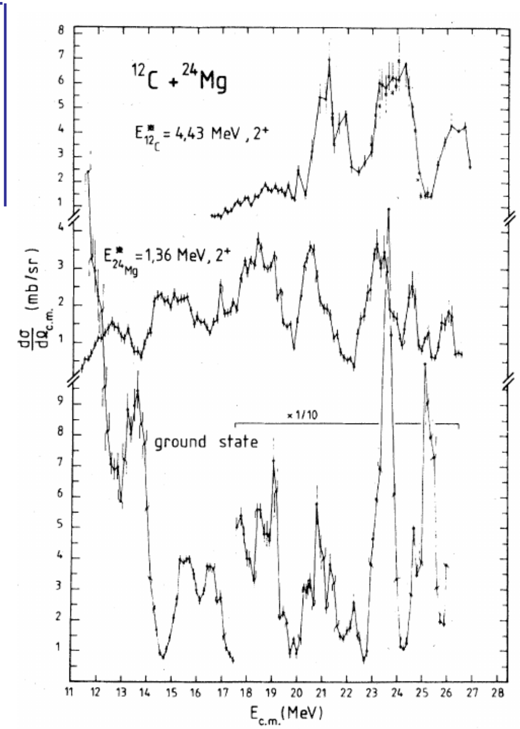
Brief review

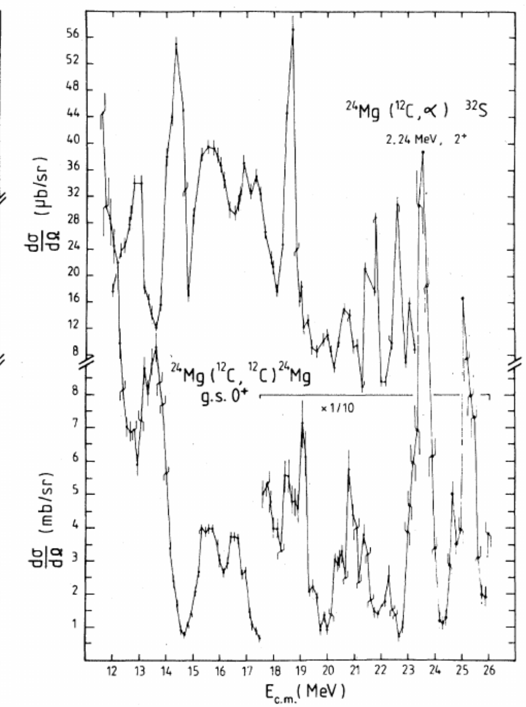


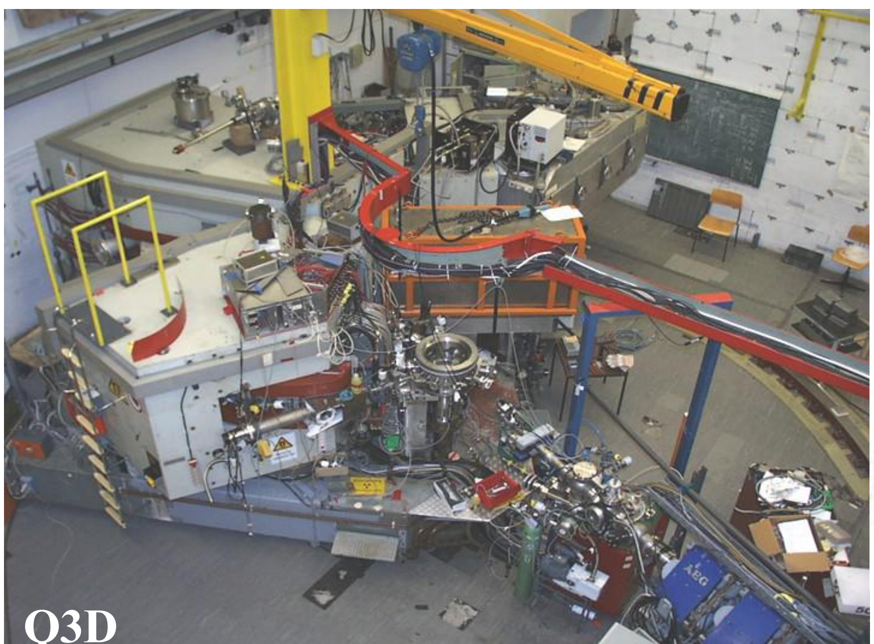
The very first tandem accelerator experiments with heavy ions.
D.A.Bromley et al., Phys.Rev.Lett. 4(1960)365

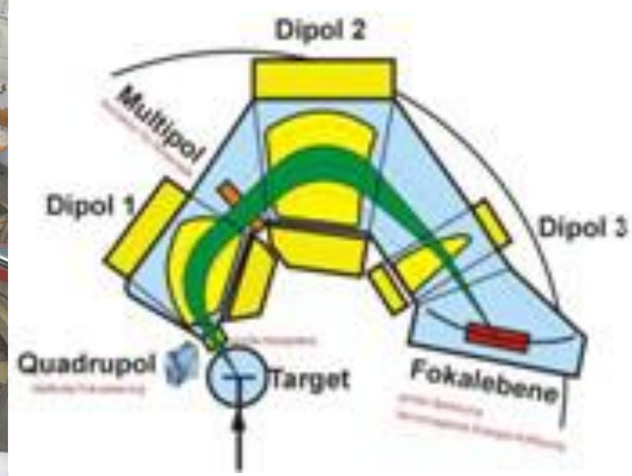
Example of Molecular Resonances - experiment

1978









M.C.Mermaz, A.Greiner, B.T.Kim, M.J.LeVine, E.Müller, M.Ruscev, M.Petrascu, M.Petrovici, and V.Simion, Phys.Rev. C24(1981)1512

Molecular Resonances - theory

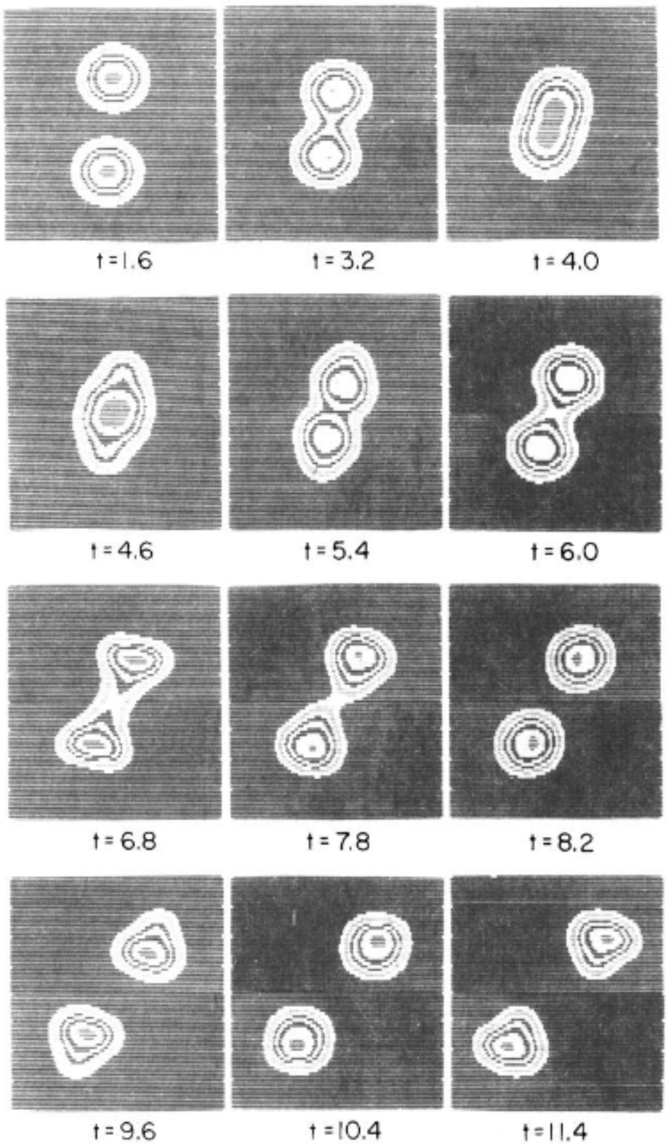
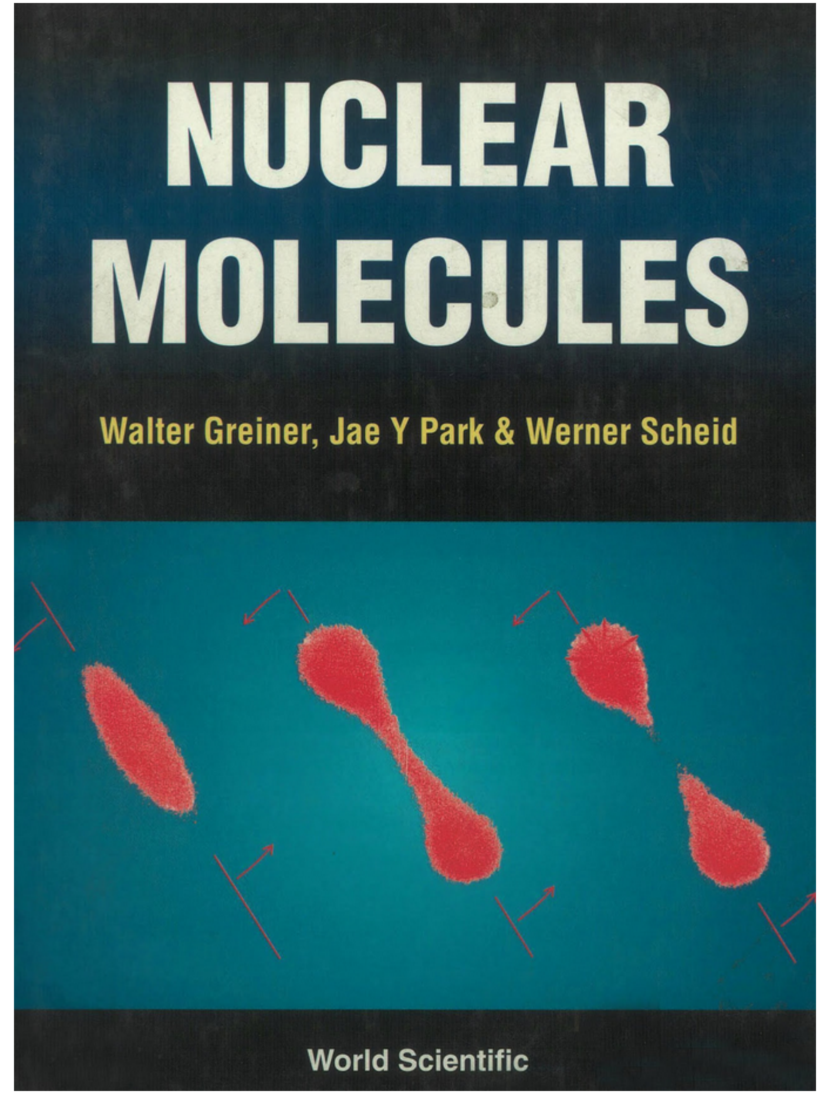


FIG. 3. Contour lines of the density integrated over the coordinate normal to the scattering plane for an $^{16}O + ^{16}O$ collision at E_{lab} = 105 MeV and incident angular momentum $L = 5\hbar$. The times t are given in units of 10^{-22} sec.

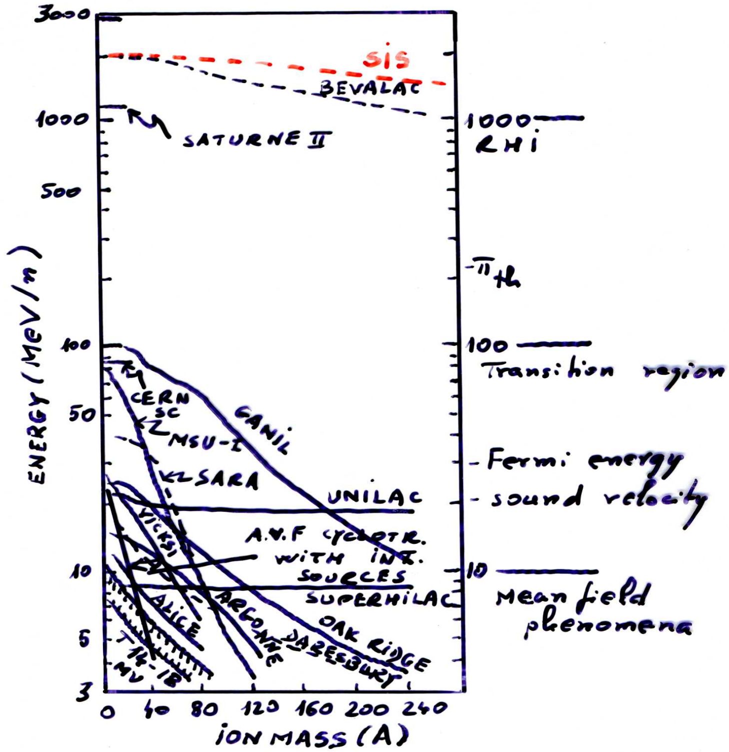
H.Flokard et al., Phys.Rev. C17(1978)1682

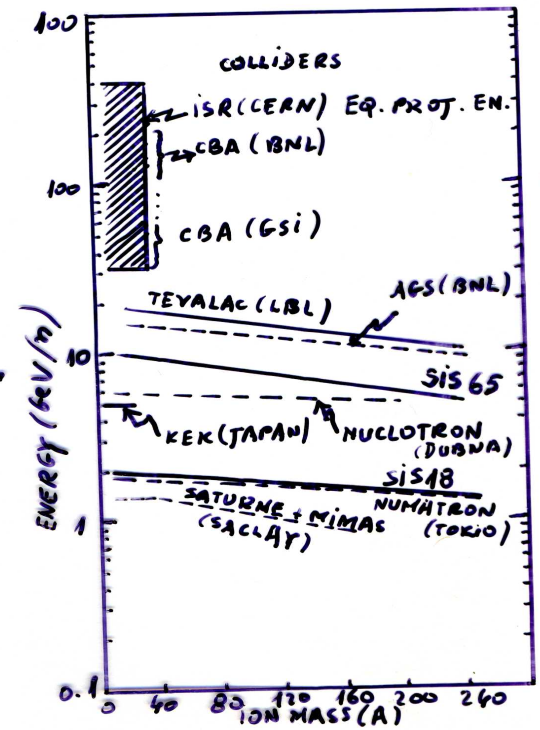
For details see:



1995; ISBN 981-02-1723-4 & references therein

Status of the main facilities - 1980





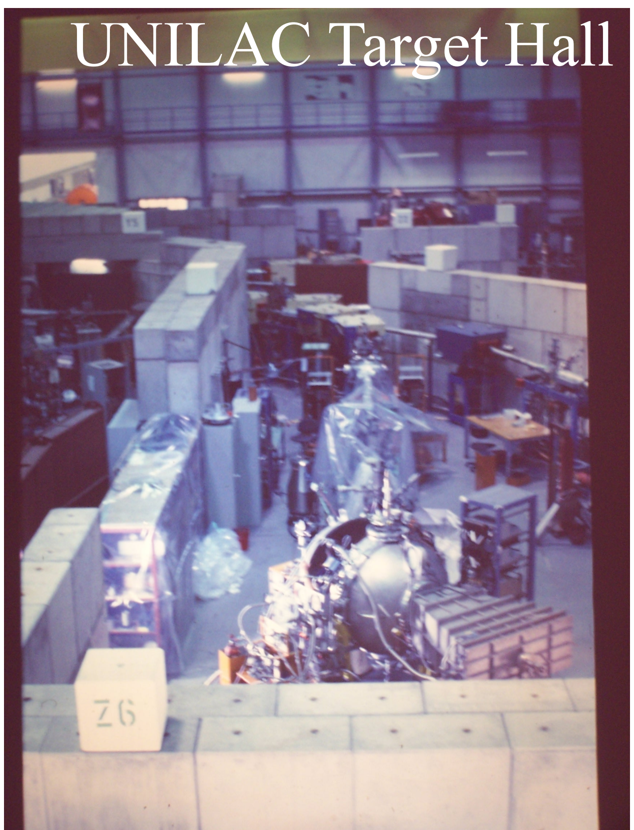
The SSC: A machine for the nineties
by Sheldon L. Glashow & Leon M. Lederman

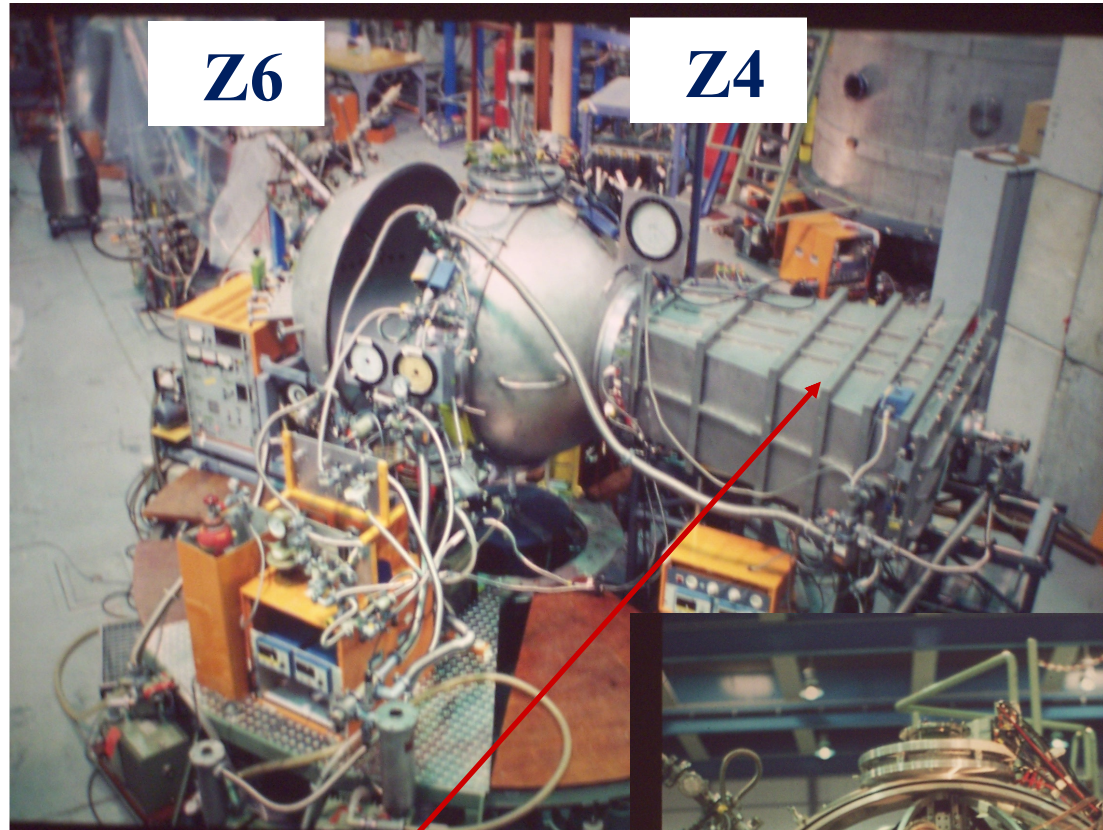
The high-energy hadron accelerators

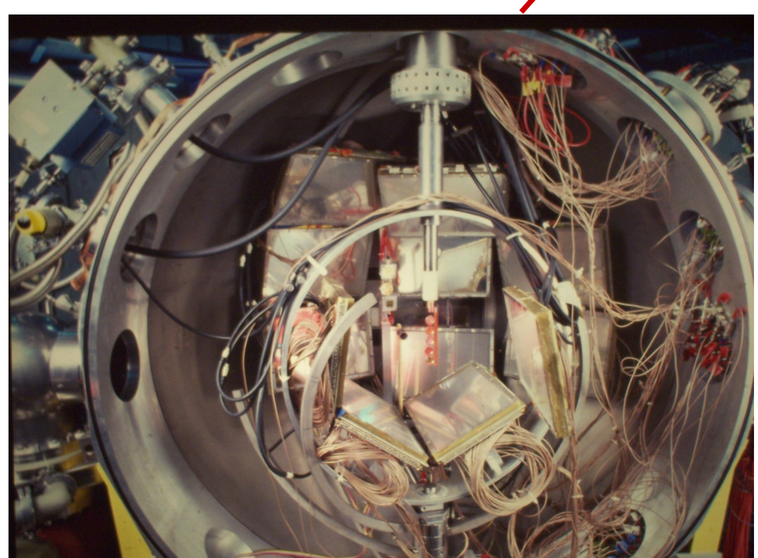
Machine	Location	Type	Beam energy (TeV)	CM energy (TeV)	Status
SPS	CERN	Fixed target	0.4	0.03	Operating
Tevatron II	Fermilab	-"-	0.8	0.04	-"-
ISR	CERN	pp collider	0.03	0.06	-"-
CBA (isabelle)	BNL	pp -"-	0.4	0.8	Cancelled
SppS	CERN	$p\bar{p}$ -"-	0.32	0.64	Operating (84/85)
Tevatron I	Fermilab	$p\bar{p}$ -"-	≥0.9	≥1.8	1986
Dedicated Coll.	Fermilab	$p\bar{p}$ -"-	2.0	4.0	Not recomended
UNK	USSR	pp -"-	3.0	6.0	1993 ?
SSC	?	pp collider	20	40	Our dream

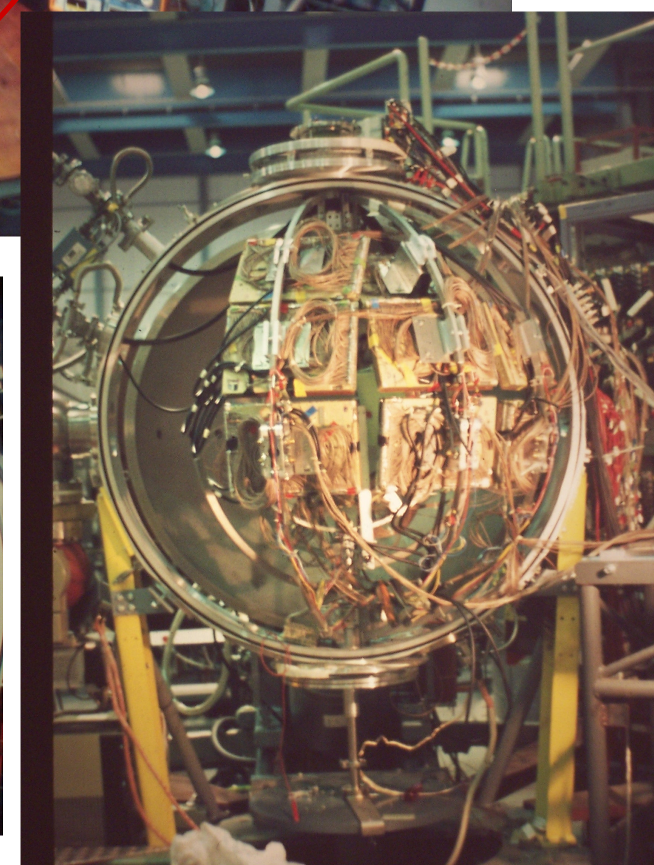
Heavy Ion Dissipative Collisions

1981





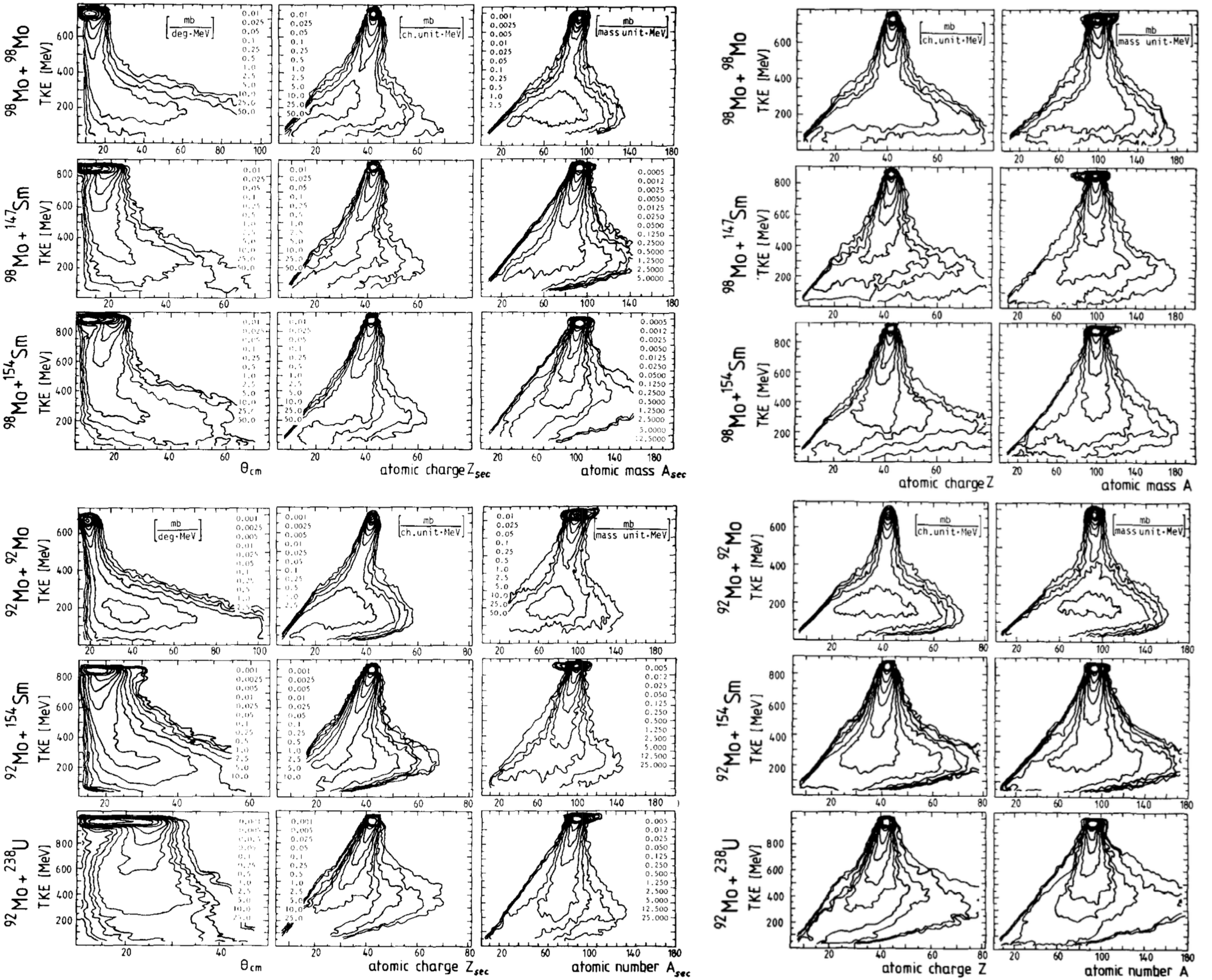




Heavy ion dissipative collisions

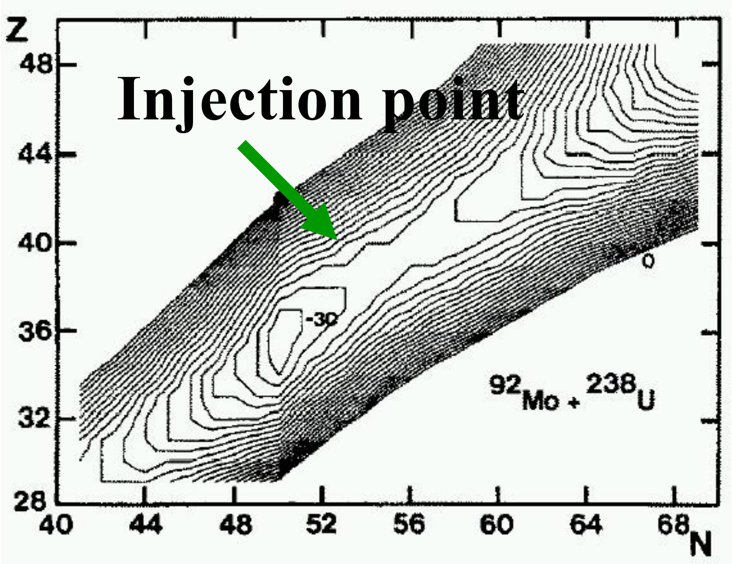
14.7 A•MeV

M. Petrovici et al., NP A477(1988)277



Heavy ion dissipative collisions

Dinuclear potential-energy

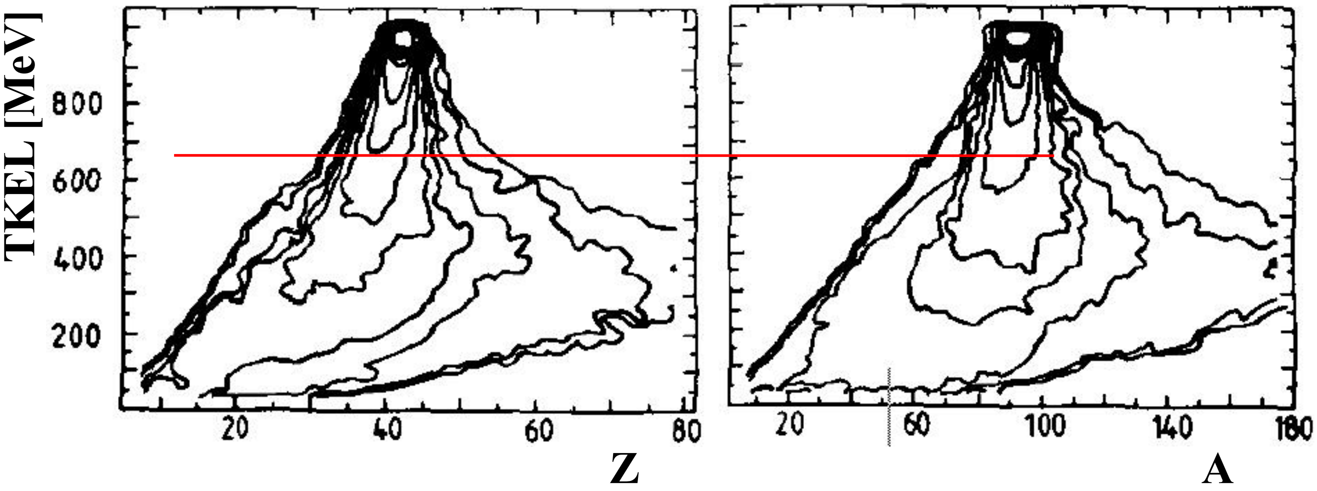


Strong gradient in the isospin dependent potential

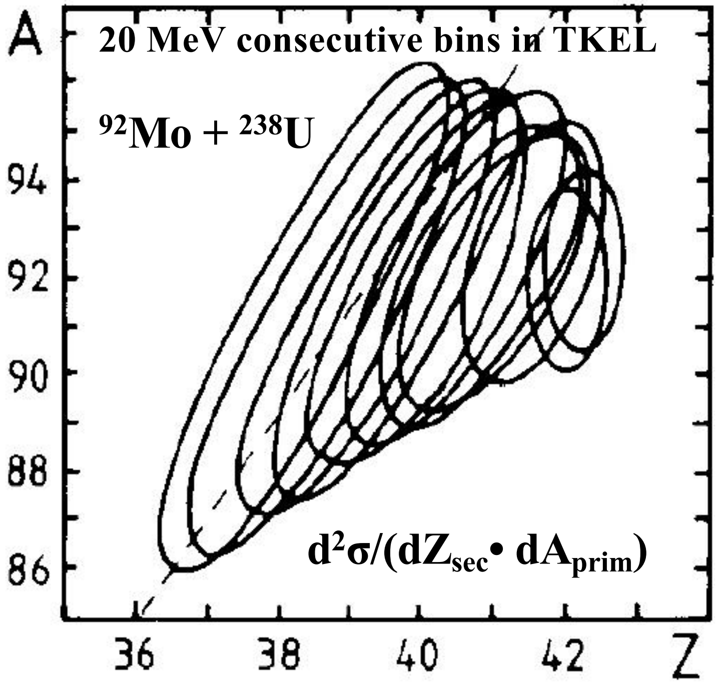
⇓

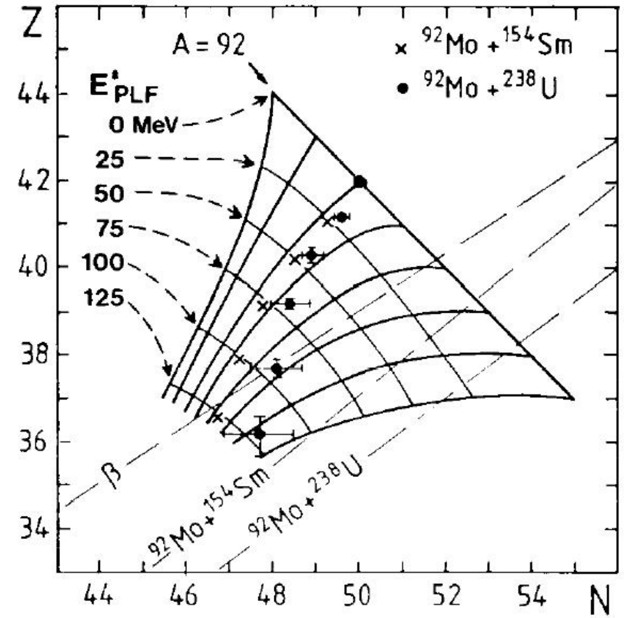
- *On a quantum treatment of charge equilibration in damped nuclear collisions*
  M. Petrovici
  J. Phys. G: Nucl. Phys. 7 (1981) 1515
- *Fast processes induced by heavy projectiles at incident energies of 10-20 MeV/u*
  M. Petrovici, Invited talk
  Int. Conf. on Selected Aspects in Heavy Ion Reactions, Saclay, 1982
  Nucl. Phys. A387(1982)313c
- *The 92Mo+92Mo reaction at 14.7 MeV/u: approaching the limits of the classical deep inelastic process*
  S. Gralla, R. Bock, A. Gobbi, K. D. Hildenbrand, J. Kuzminski, U. Lynen, W. F. J. Muller, A. Olmi, M. Petrovici, H. Sann, H. Stelzer, J. Toke, H. J. Wollersheim
  Phys. Rev. Lett. 54(1985)1898

^{92}Mo + ^{238}U @ 14.7 A•MeV



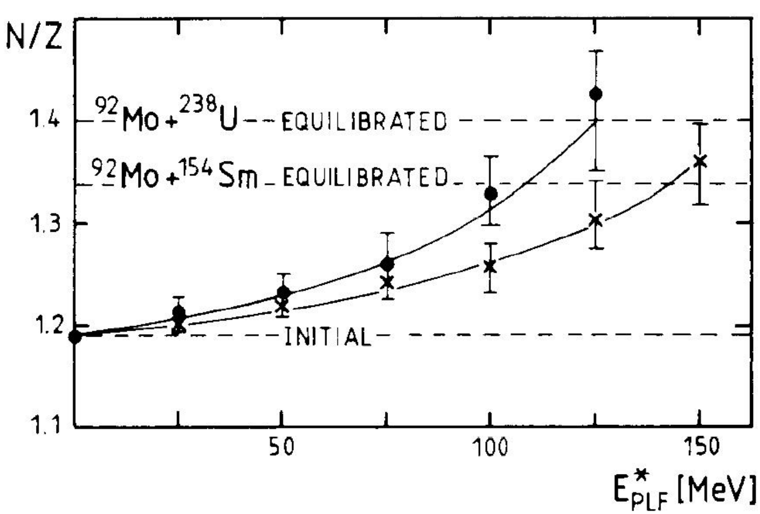
Heavy ion dissipative collisions



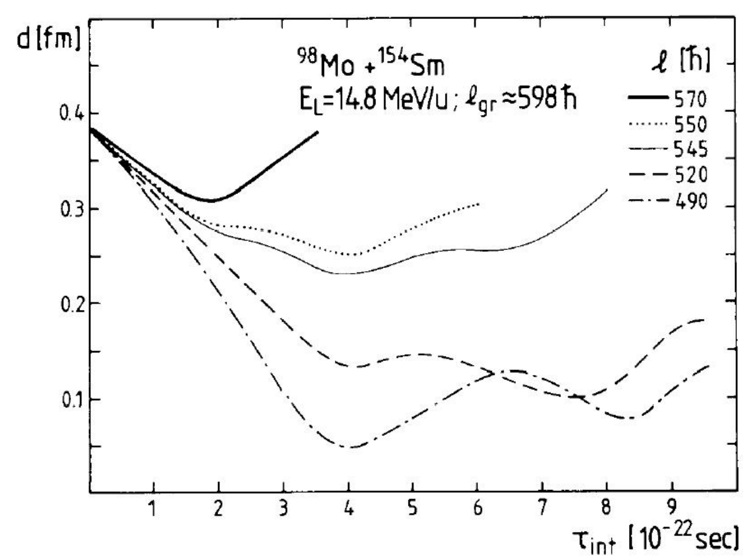


The grid - experimental centroids of the secondary charge and mass distributions for A=92 isobar in steps of 25 MeV excitation energy

***x & • - centroids of the secondary N-Z distributions for ^{92}Mo + ^{154}Sm and ^{92}Mo + ^{238}U**, respectively*



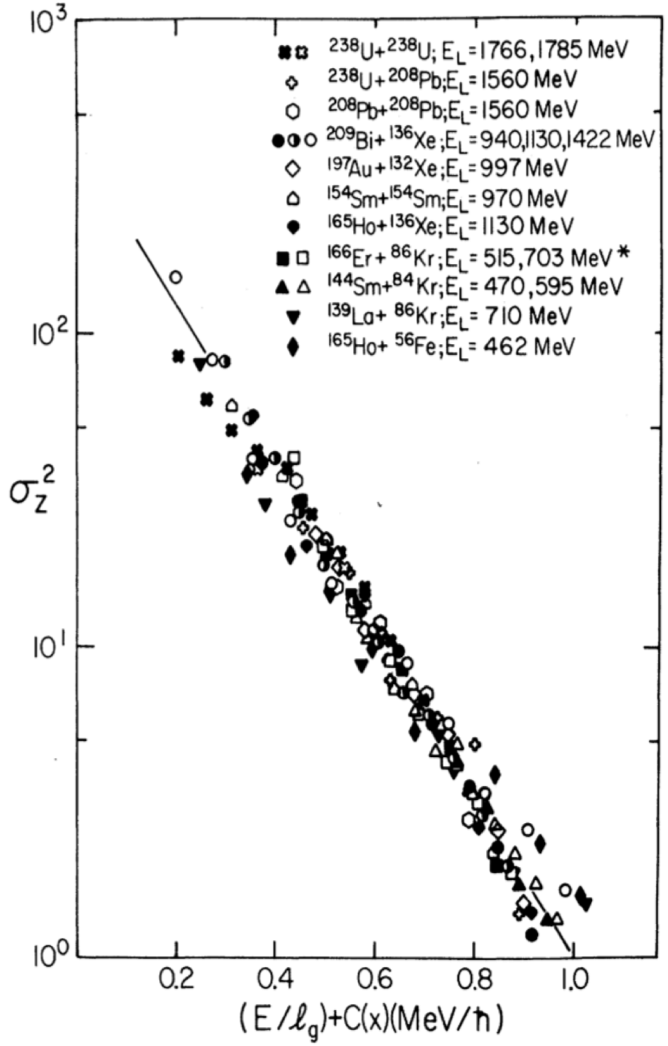
TDHF calculations



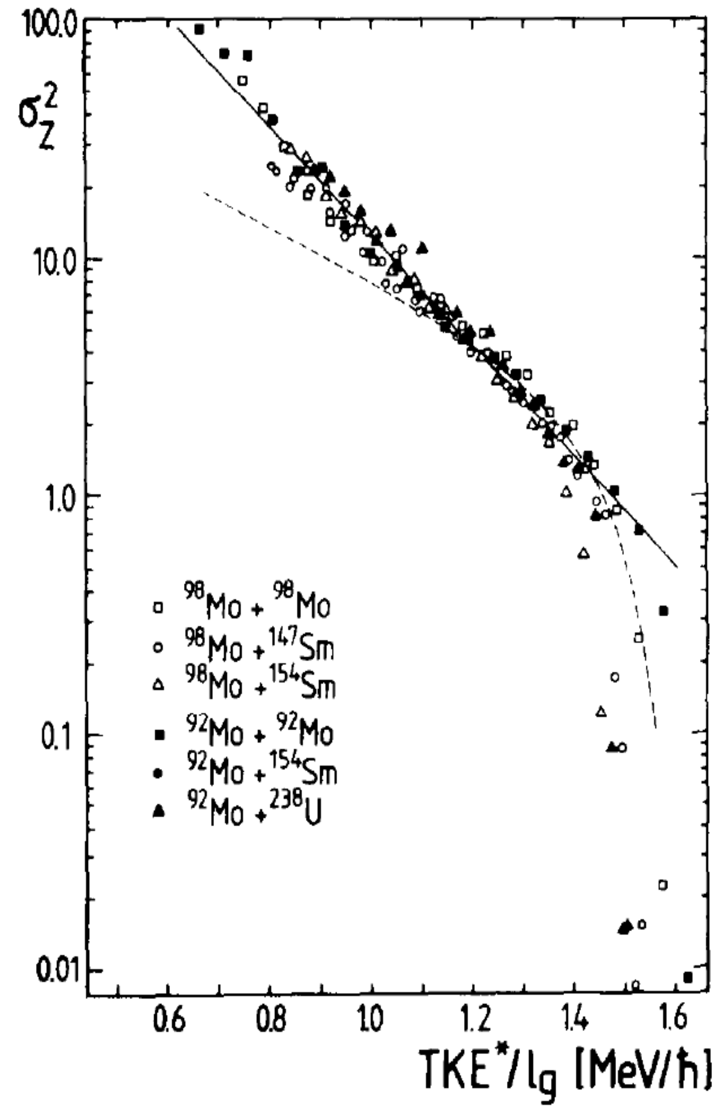
d – distance between the centre of mass of protons and neutrons

M. Petrovici et al., NP A477(1988)277

Heavy ion dissipative collisions (scaling)

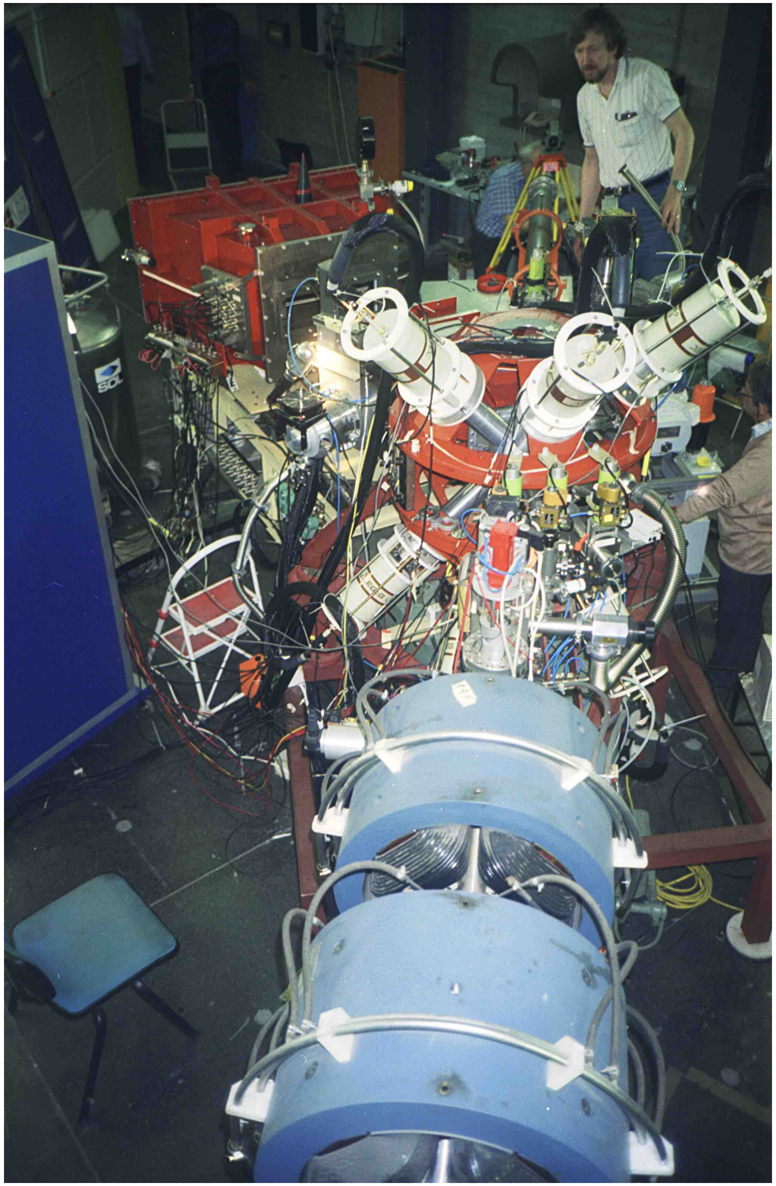


H.J.Wollersheim et al., Phys. Rev, C25(1982)338

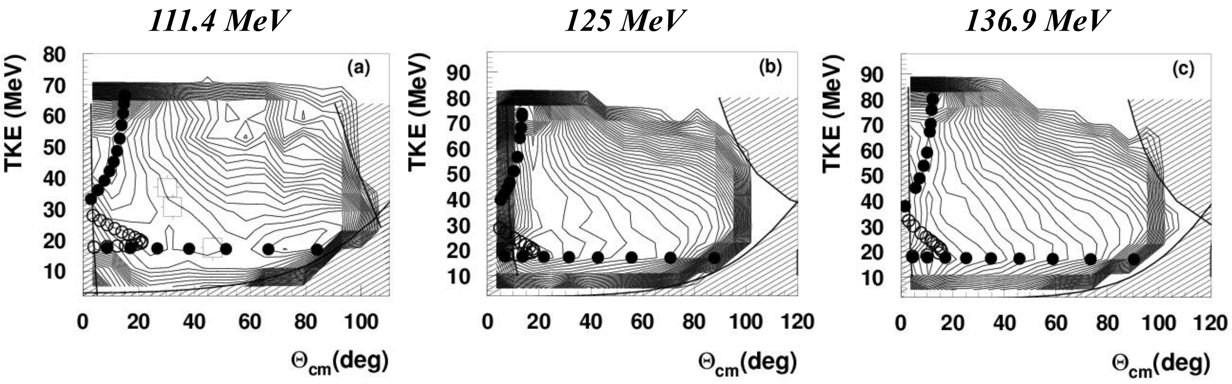


M. Petrovici et al., Nucl.Phys. A477(1988)277

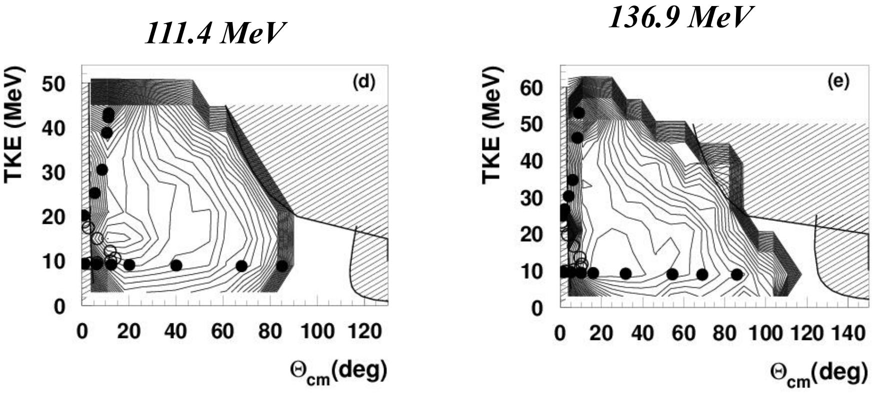
Dissipative collisions in light systems (scaling)



$^{19}F + ^{27}Al$ @ 111.4; 125 & 136.9 MeV

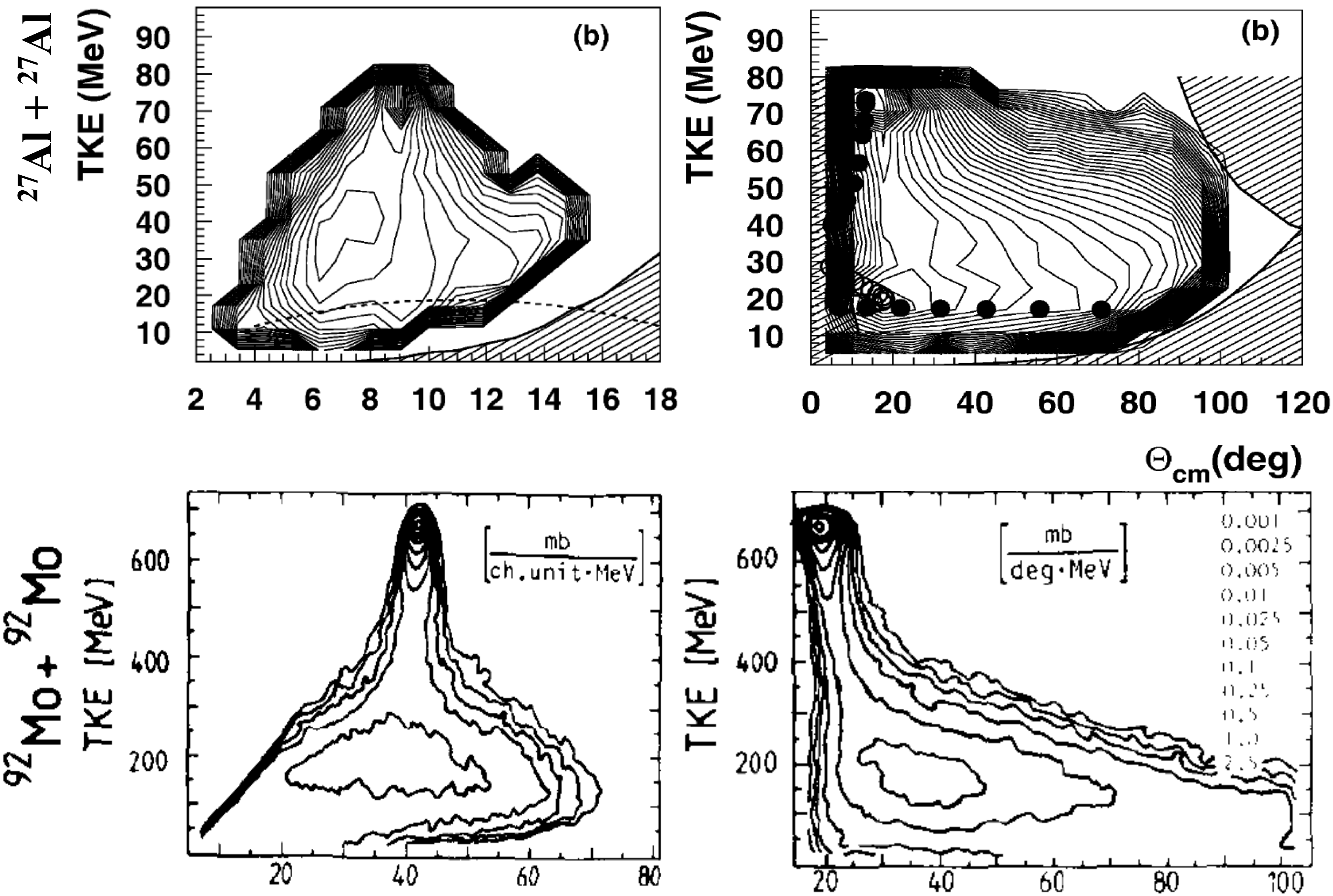


$^{19}F + ^{12}C$ @ 111.4 & 136.9 MeV



A. Pop and DRACULA Collaboration, Nucl.Phys A679(2001)793

Similarities in Dissipative Processes



Similarities in Dissipative Processes

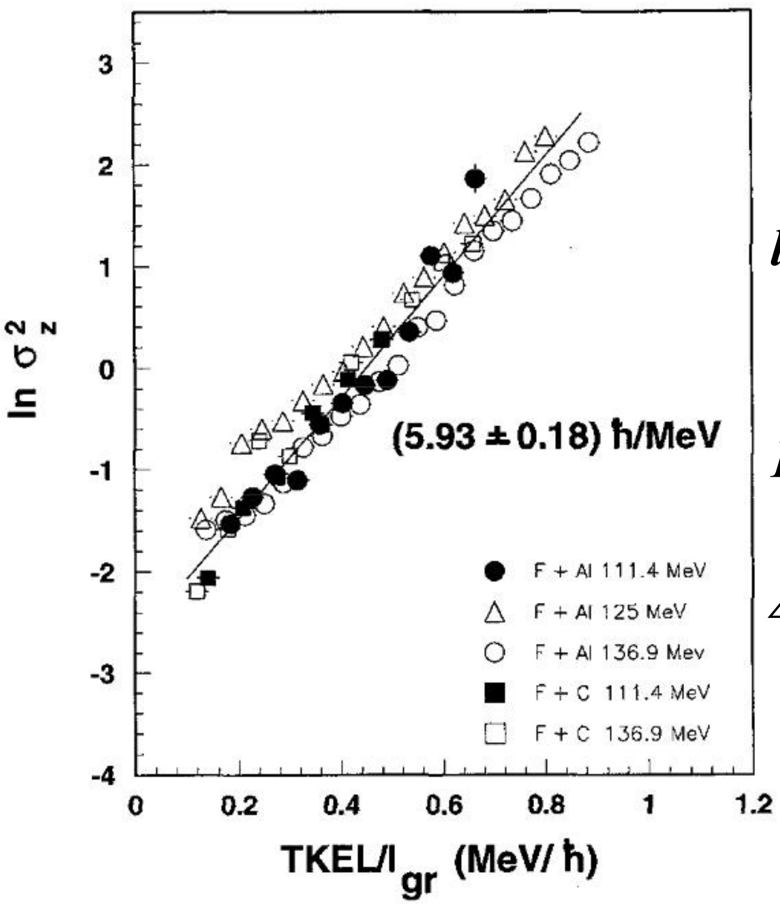
Charge variance systematic revisited

$^{19}F + ^{27}Al$ @ 111.5; 125 & 136.9 MeV

$^{19}F + ^{12}C$ @ 111.4 & 136.9 MeV

Phenomenological models predict a linear dependence of TKEL on the impact parameter

$$\Rightarrow t = t_0 \cdot \exp(s[TKEL/l_{gr} - \Delta/l_{gr}])$$

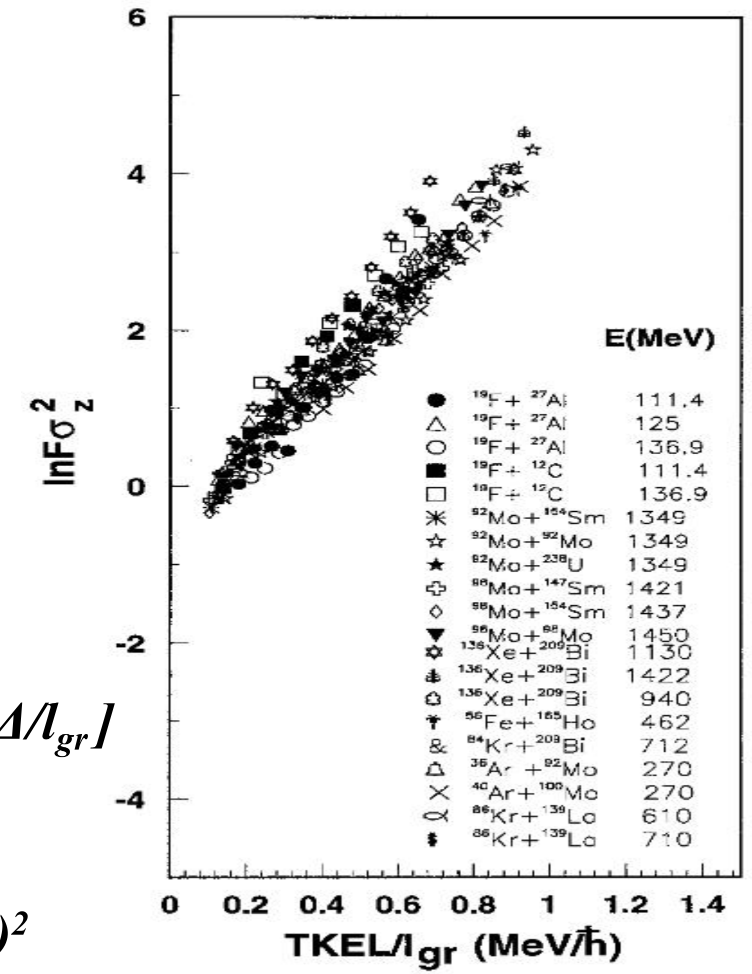


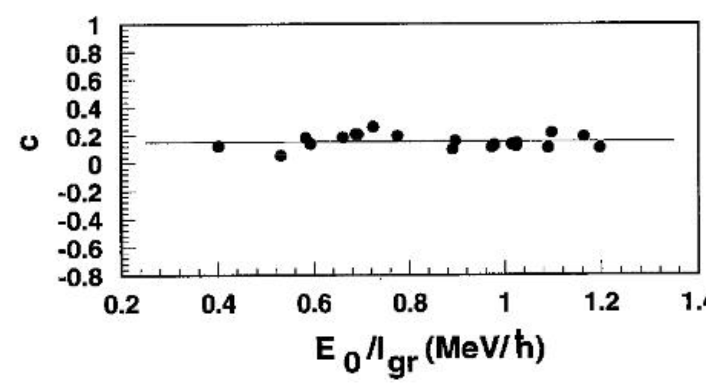
$$\ln[F\sigma_Z^2] = s[TKEL/l_{gr} - \Delta/l_{gr}]$$

$$F = s(m/\mu)\alpha(E_0/l_{gr})(A/Z)^2$$

$$\Delta = c \cdot l_{gr}$$

$$E_0 = E_{cm} - V_{coul}$$





Theoretical models

- Particle exchange picture based on Fermi gas with long mean free path

- J.Blocki et al., Ann.Phys. (NY) 113(1978)330
- J.Randrup, Nucl.Phys. A327(1979)490; A383(1982)_468
- H.Feldmeier, Rep.Prog.Phys. 50(1987)915
  and ref. therein

- Time dependent Hartree-Fock model TDHF

- K.T.R.Devis et al., Tretease on Heavy Ion Science, ed. D.A.Brompley, vol.3,
  Plenum Press N.Y. & London (1985)
- J.A.Marun et al., Nucl.Phys. A270(1976)471
- S.E.Koonin et al., Phys.Rev. C15(1977)1359
  and ref. therein

- Landau-Vlasov - BUU

- G.F.Bertsch et al., Phys.Rep. (1988)189
- W.Bauer et al., Phys.Rev. C34(1986)2127
- A.Bonasera et al., Proc. XXVII Winter Meeting Bormio (1989)
  and references therein

- QMD

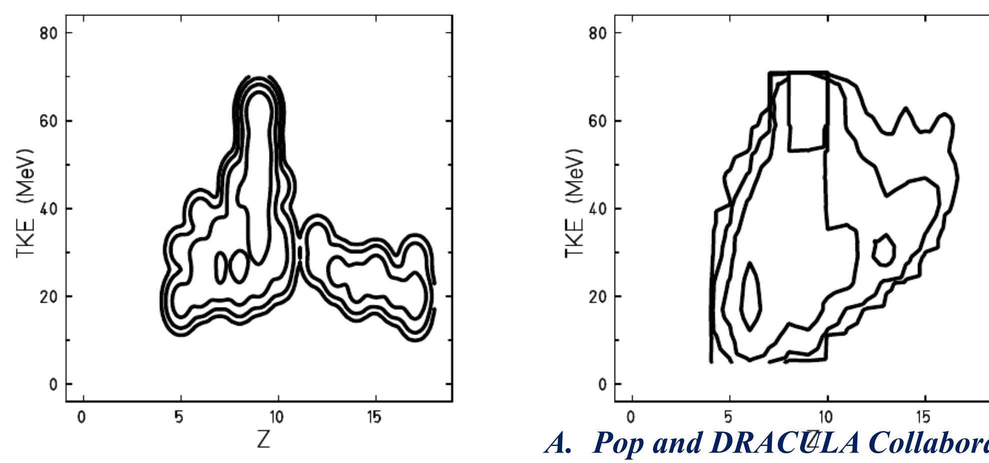
- J.Aichelin, Phys.Rep. 202(1991)233
  and references therein

- FMD

- H.Feldmeier et al.,
  Progress in Particle and Nuclear Physics 39(1997)393
  and ref. therein

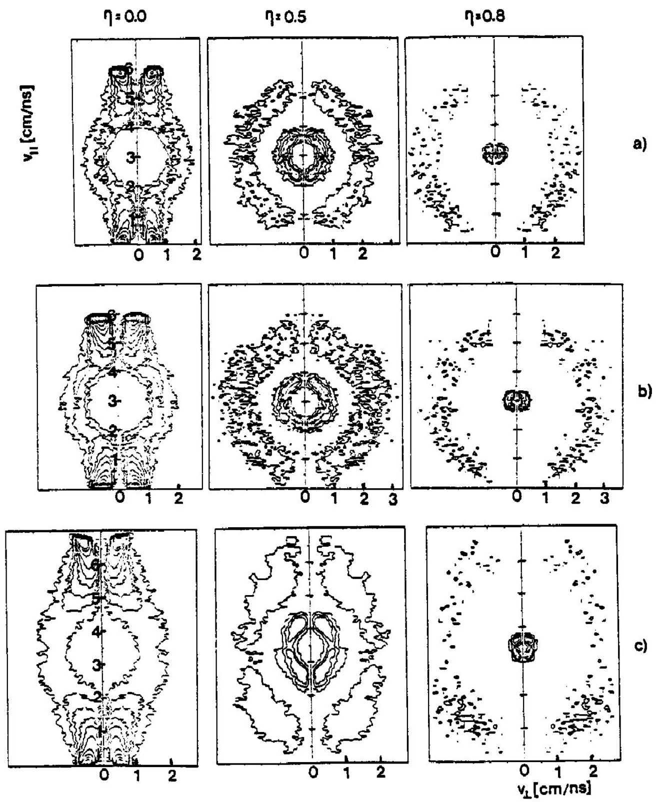
^{27}F + ^{27}Al

Theory **Exp.**



A. Pop and DRACULA Collaboration,
Nucl.Phys A679(2001)793

Incomplete Dissipative Processes - preequilibrium processes



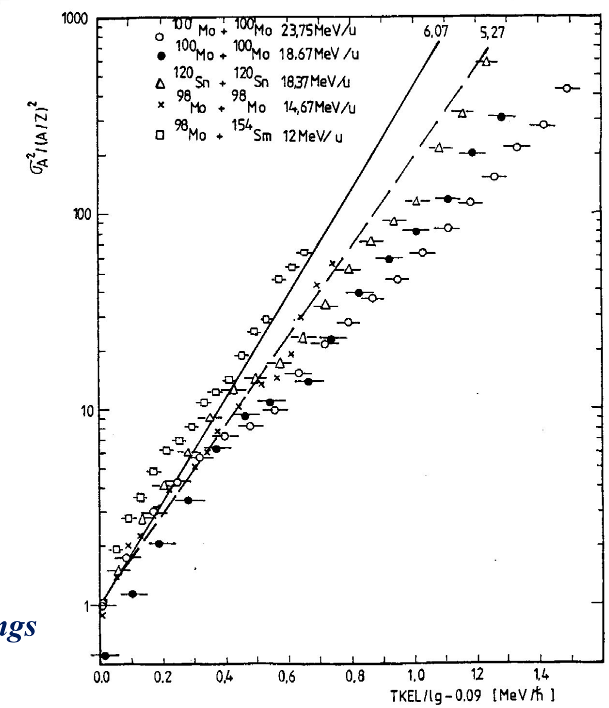
- ***Incomplete deep inelastic processes in medium mass heavy ion collisions at 18 and 24 MeV/u***
  M.Petrovici – invited talk at International Simposium Nikko 1991 – „Towards a Unified Picture of Nuclear Dynamics"

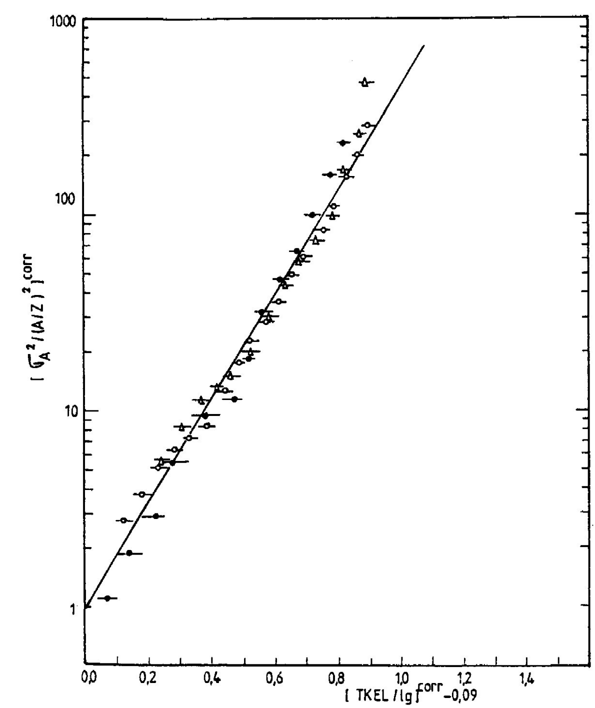
- ***Fast particle emission in incomplete deep inelastic collisions***
  A. Pop, M. Petrovici
  Rom. Jorn. of Phys. 38(1993)437
  1993

a) $^{100}Mo+^{100}Mo$ at 18.67 MeV/u

b) $^{120}Sn+^{120}Sn$ at 18.34 MeV/u

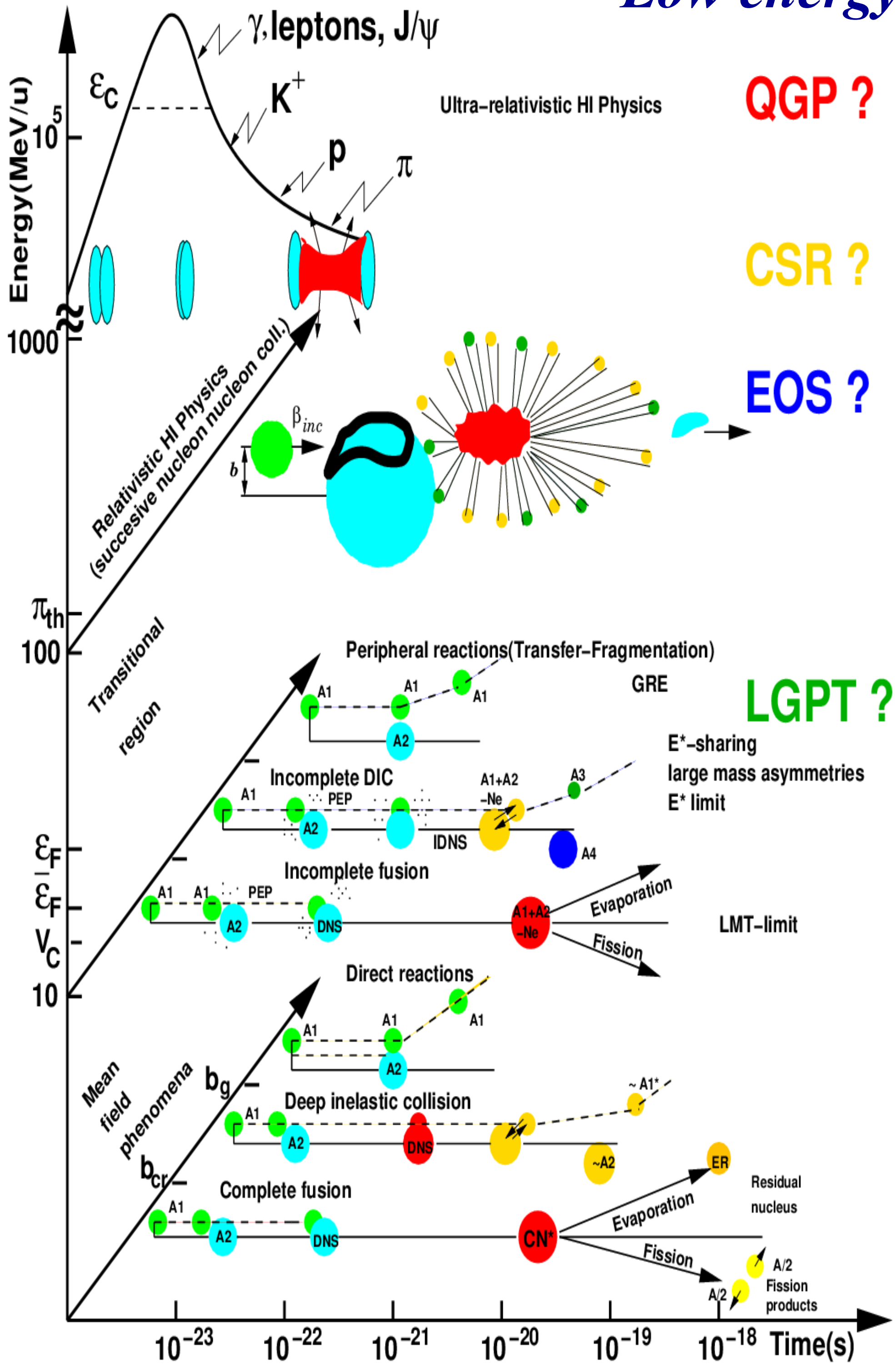
c) $^{100}Mo+^{100}Mo$ at 23.75 MeV/u

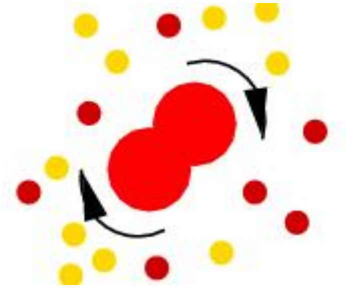




M.Petrovici, Nikko, Japan 1991, AIP Conference Proceedings 250((1992)187

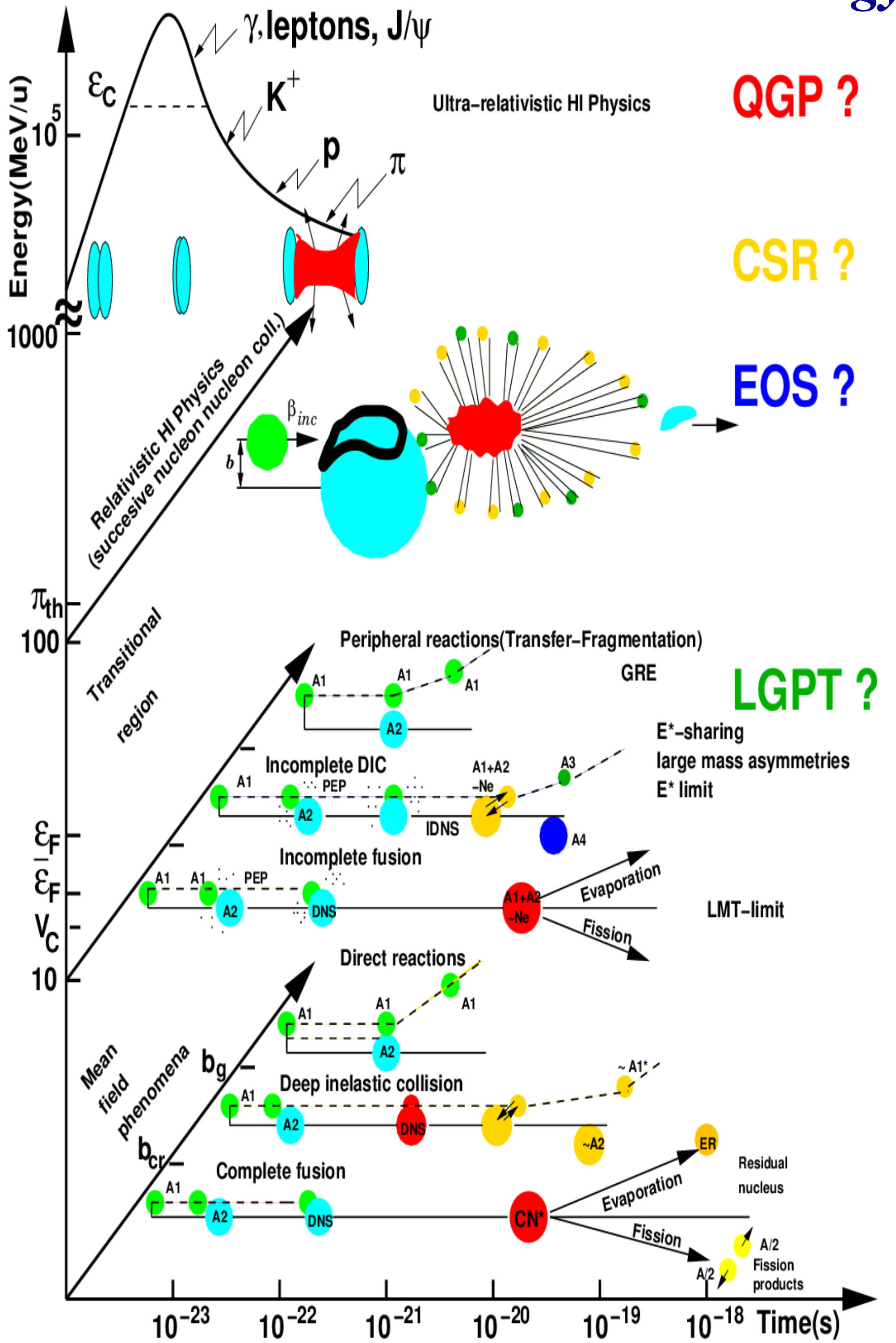
Low energy Heavy Ion Collisions

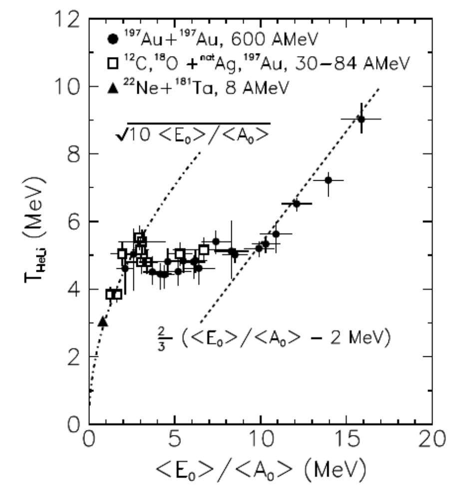




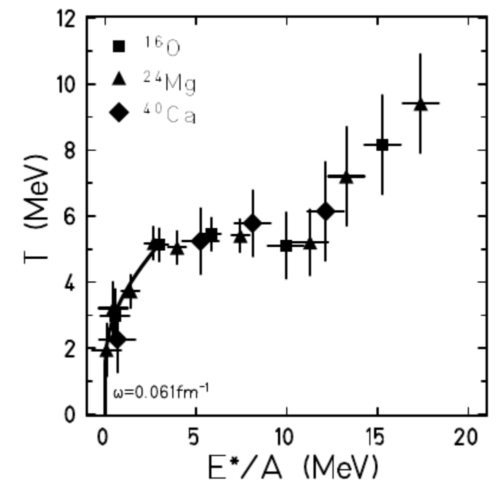
< 100 A•MeV

Low energy Heavy Ion Collisions



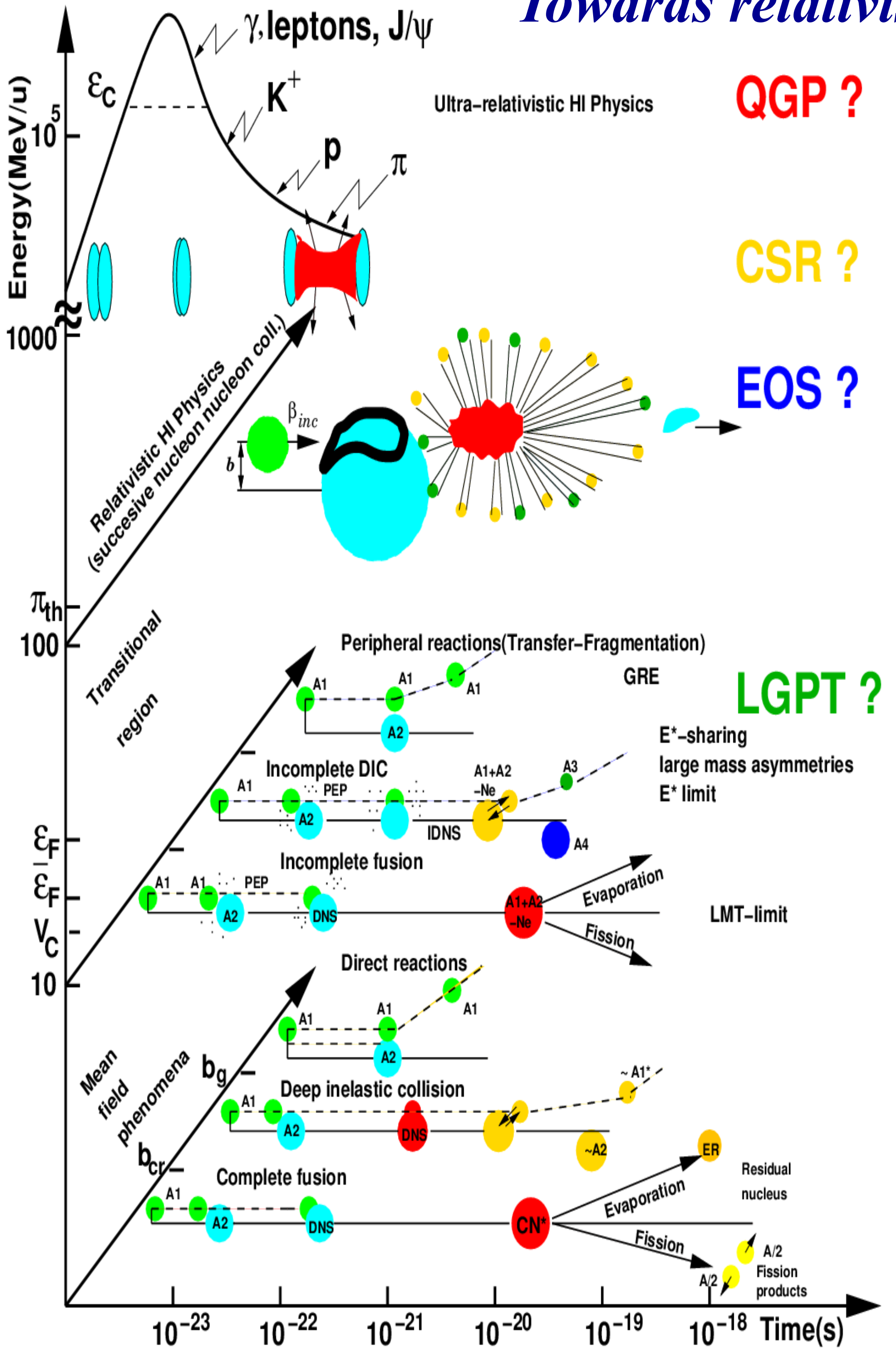


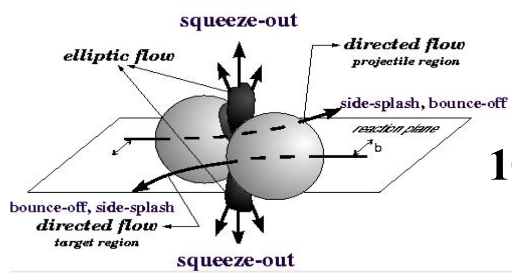
J.Pochodzalla et al.,
arXiv:[nucl-ex]9607.004



H.Feldmeier et al.,
Prog. in Part. and Nucl. Phys.
39(1997)393

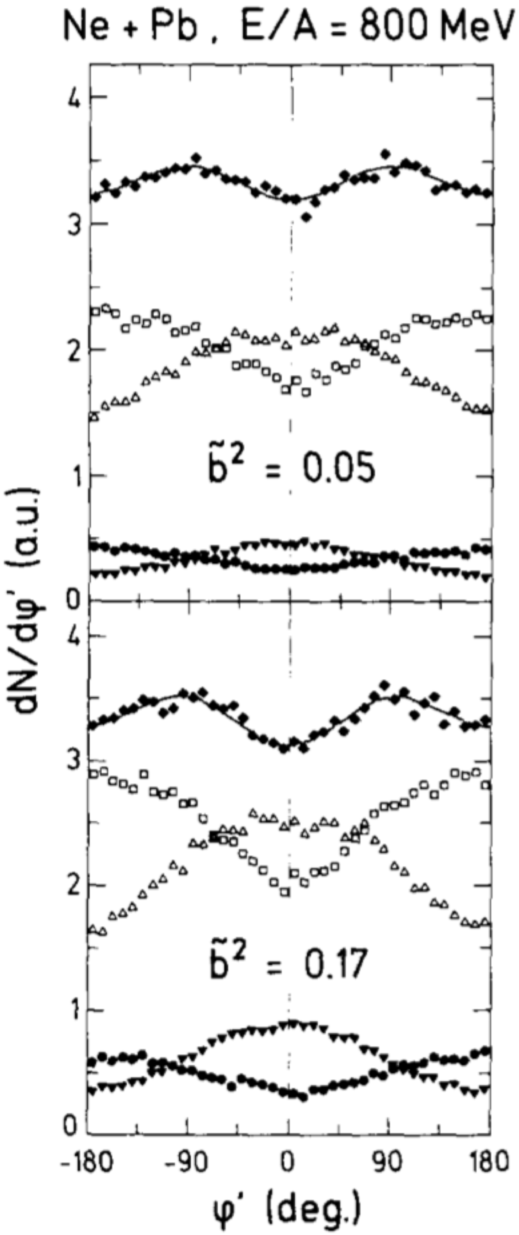
Towards relativistic heavy ion collisions



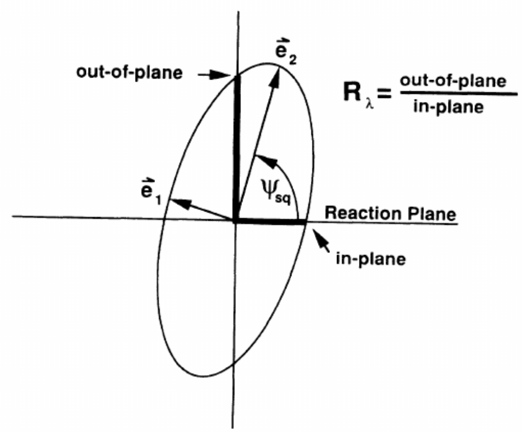


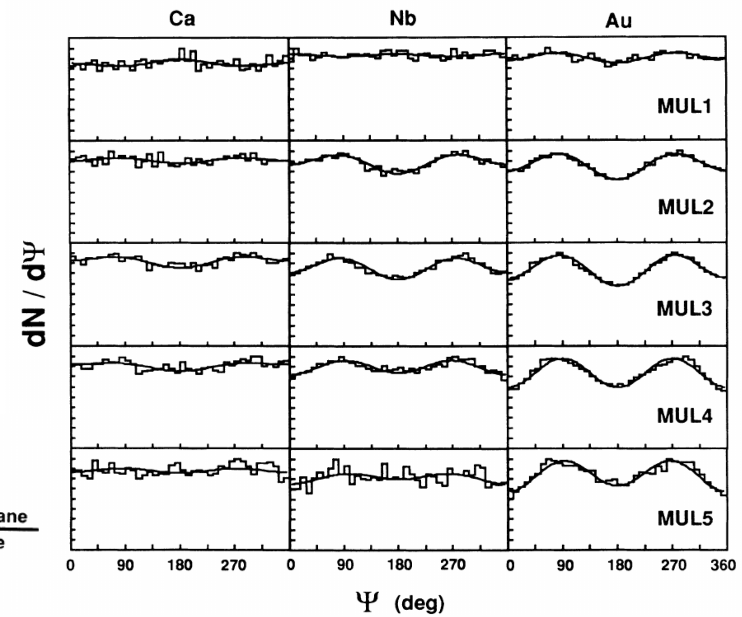
100 A•MeV - ~600 A•MeV

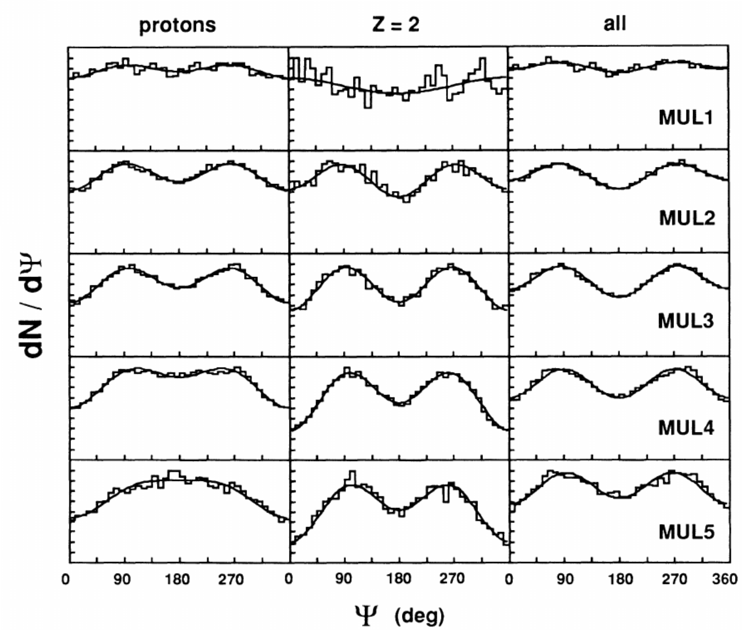
Towards relativistic heavy ion collisions
Azimuthal distributions



M.Demounlins et al., Phys.Lett. 241B(1990)47
(received 19 December 1989)





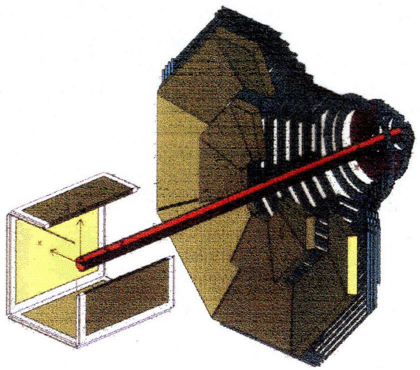


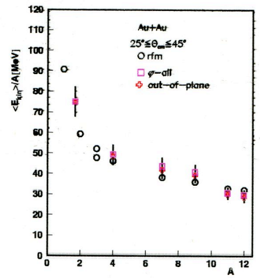
H.H.Gutbrod et al., Phys. Rev. 42C(1990)640
(received 8 January 1990)

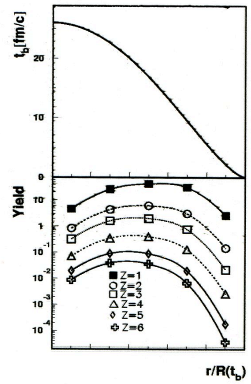
Towards relativistic heavy ion collisions

FOPI COLLABORATION

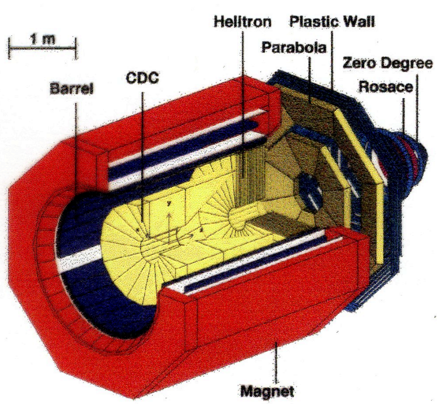
Phase I

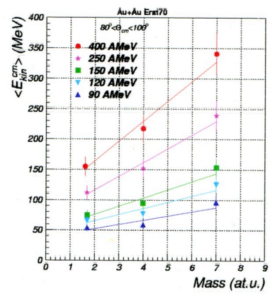


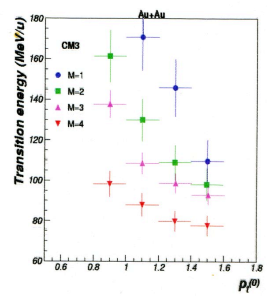


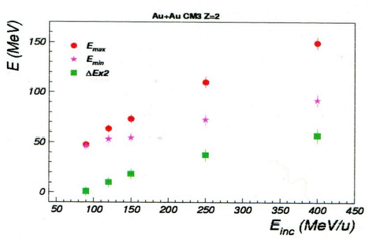


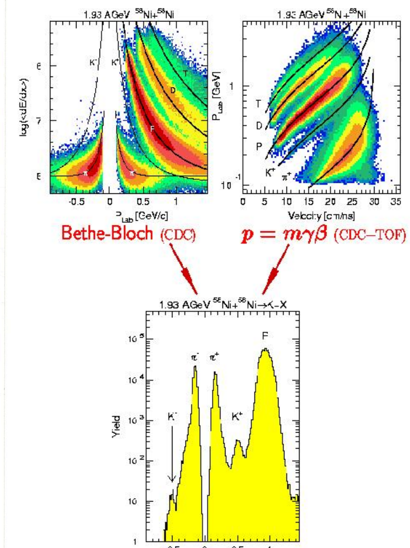
Phase II



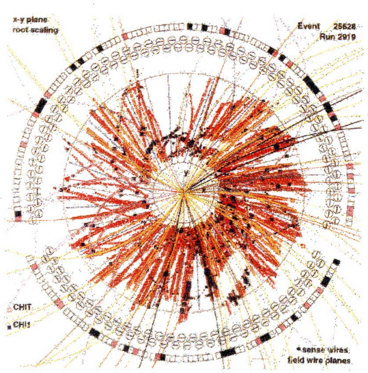


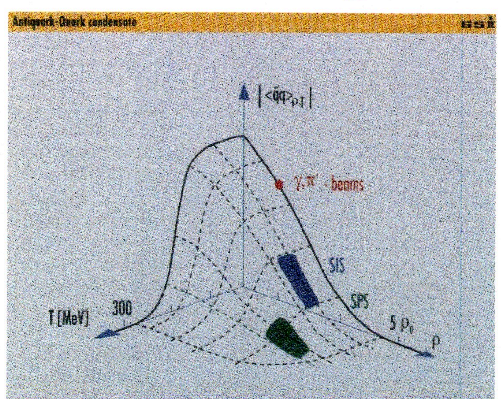


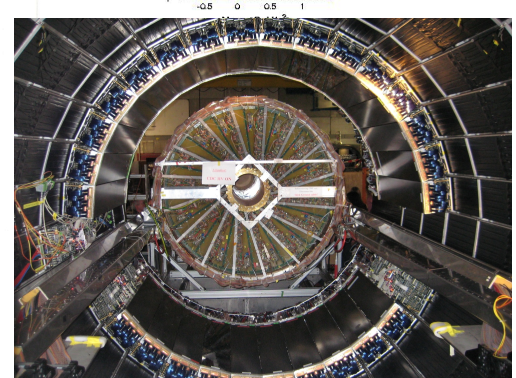


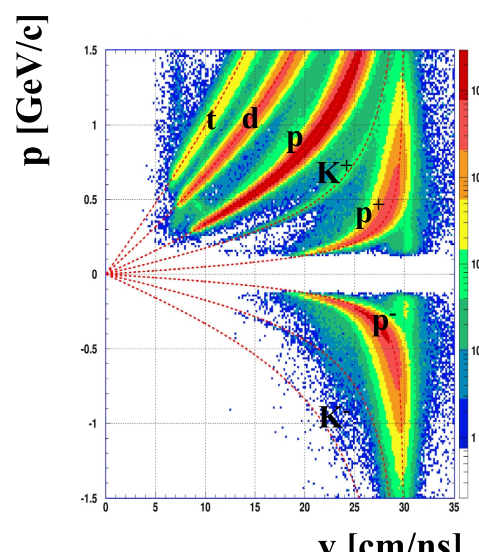


Phase III









Radial expansion of compressed baryonic matter

Semi analytical radial flow model
&
SM at break-up moment

M.Petrovici et al., Phys.Rev.Lett. 74(1995)5001

RFM

$$\begin{cases} u_t + u u_r = -p_r/\rho \\ \rho_t + \rho_r u + \rho(u_r + 2u/r) = 0 \\ (\delta/\delta t + u\,\delta/\delta r)(p\rho^{-\gamma}) = 0 \end{cases}$$

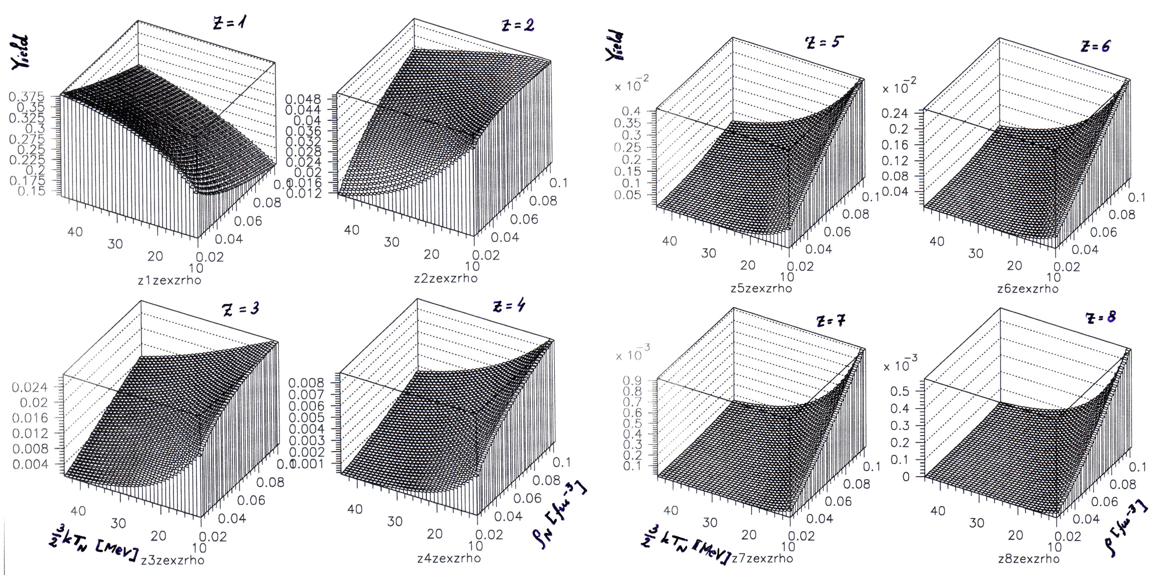
$$u = r \cdot R/\dot{R}$$

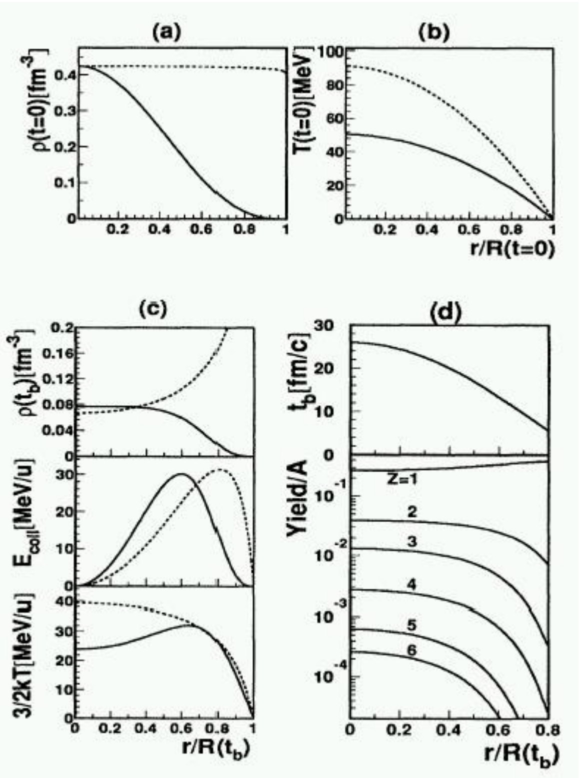
$$x = r/R$$

L.I.Sedov, Similarity and Dimensional Methods in Mechanics

J.P.Bondorf et al., Nucl.Phys. A296(1978)320

SM *G.Fai et al., Comp.Phys.Com. 42(1986)385*

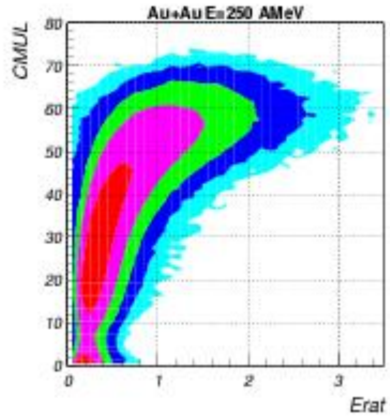


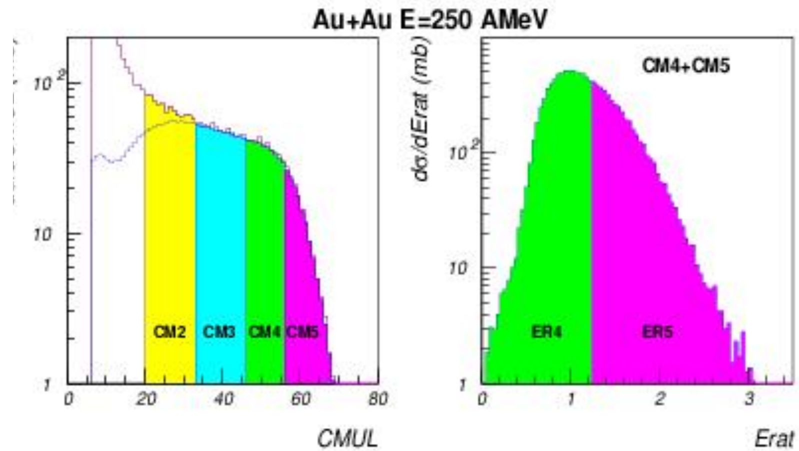


Radial expansion of compressed baryonic matter

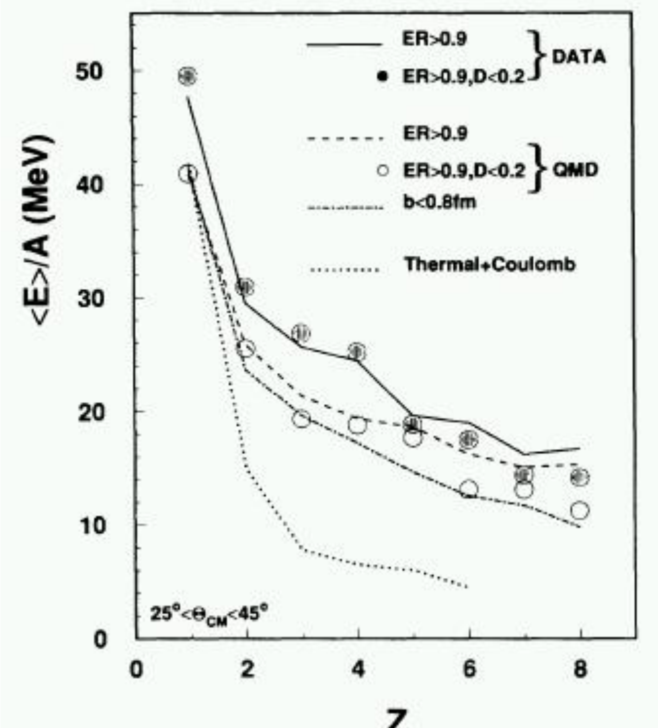
Highly central Au + Au collisions

$$Erat = \sum_i \frac{E_{\perp,i}}{E_{||,i}}$$

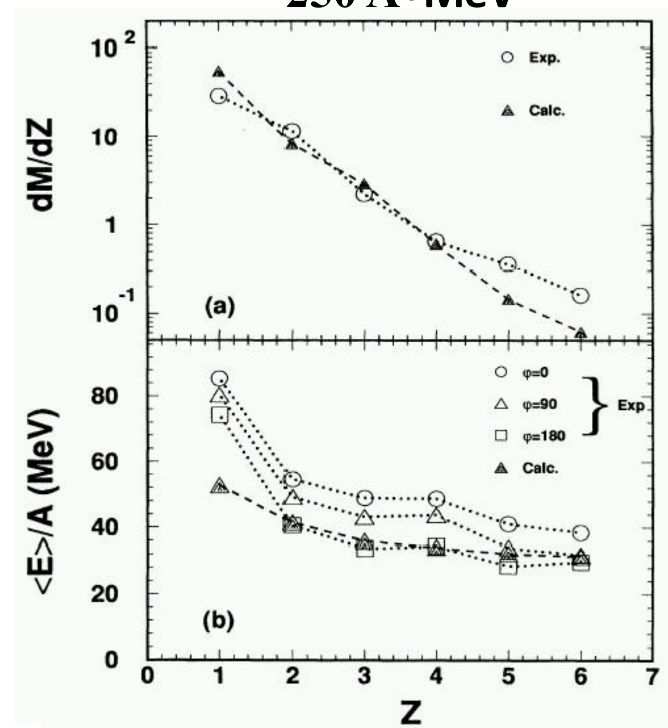




150 A•MeV



250 A•MeV



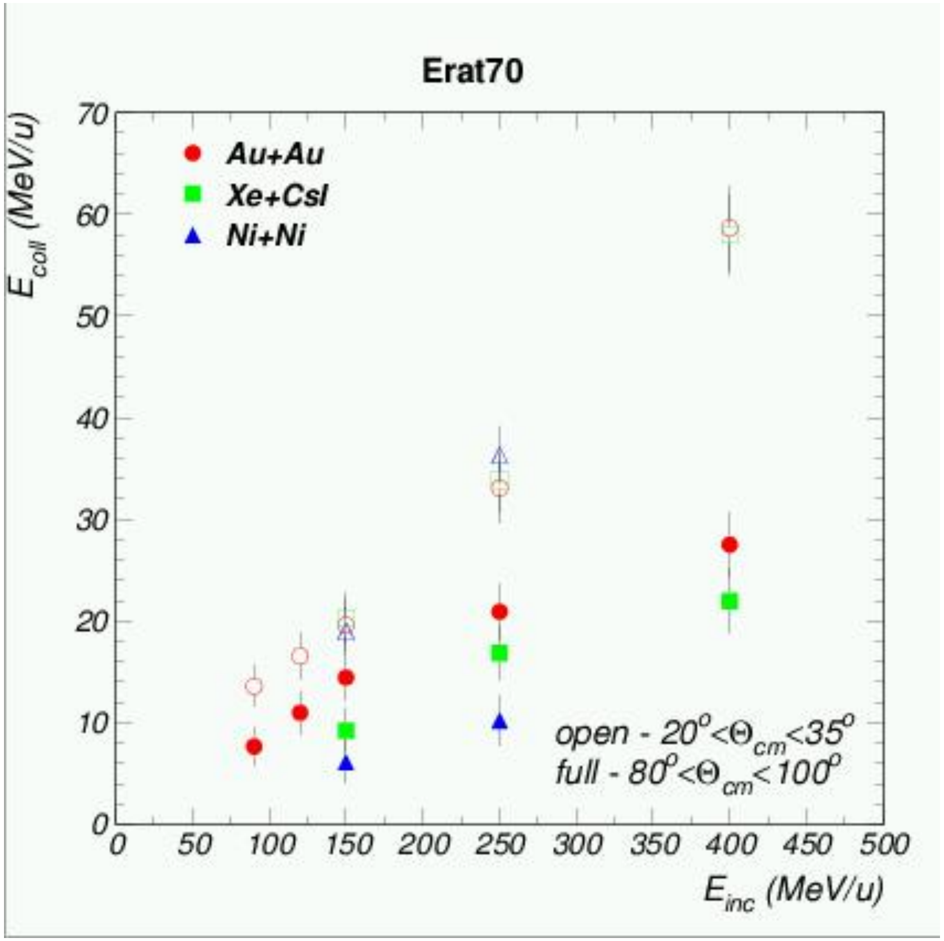
S.C.Jeong & FOPI Coll,
Phys.Rev.Lett. 72(1994)3468

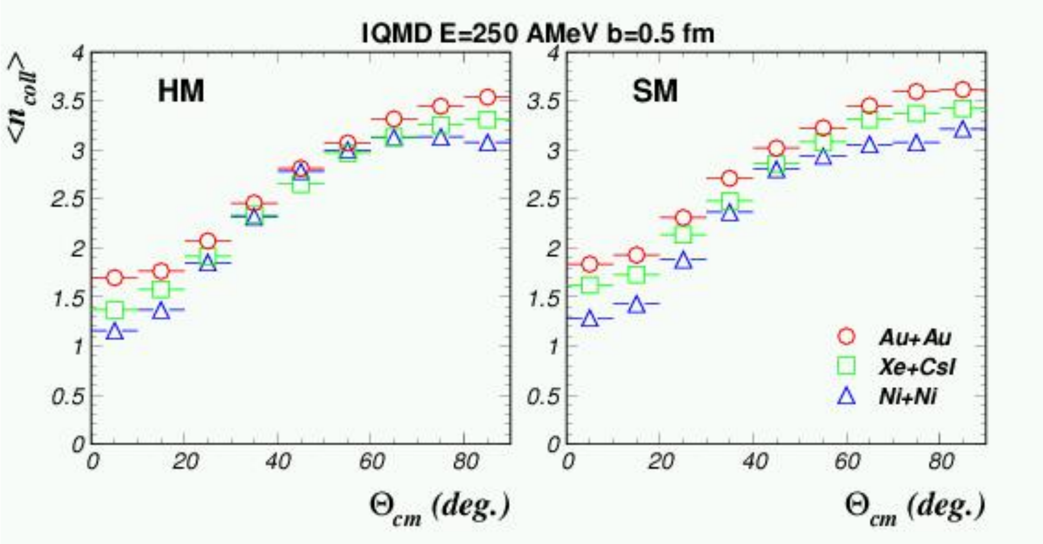
$$\langle E_{kin}^{cm} \rangle \approx \frac{1}{2} m_0 < \beta_{flow}^2 > A_{IMF} + \frac{3}{2} "T"$$

M.Petrovici & FOPI Coll,
Phys.Rev.Lett. 74(1995)5001

Radial expansion of compressed baryonic matter

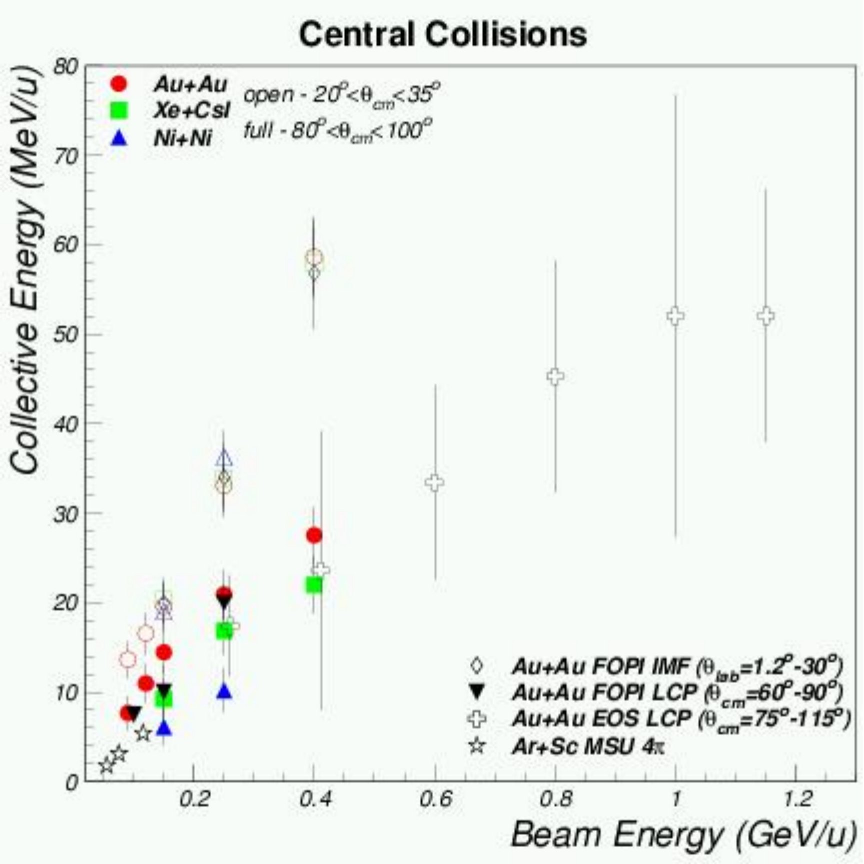
Highly central A-A collisions





M.Petrovici, "Exotic Nuclei and Nuclear/Particle Astrophysics",
AIP Conf.Proc. 972(2004)072303
A.Andronic PhD Thesis

Compilation of different experimental results central collisions



$$\langle T_i \rangle = (\langle \gamma_F \rangle - 1) A_i m_0 + \langle \gamma_F \rangle \langle T_i \rangle_{un}$$

$$\langle T_i \rangle \approx \frac{1}{2} A_i m_0 \langle \beta_F^2 \rangle + \frac{3}{2}\tau$$

$$\frac{dN}{dE} \sim p \exp^{-\gamma E/T} \left\{ \frac{\sinh \alpha}{\alpha} (\gamma E + T) - T \cosh \alpha \right\}$$

$$\gamma = (1 - \beta^2)^{-1/2}, \; \alpha = \gamma \beta p / T$$

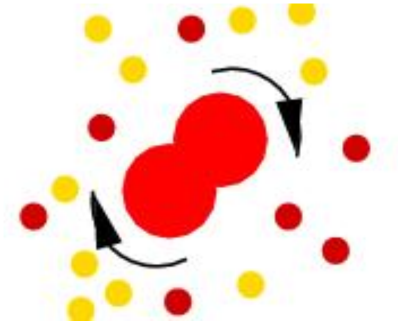
EOS – M.A.Lisa & EOS Coll., PRL 75(1995)2662

MSU - R.Pak et al., PRC 54(1996)1681

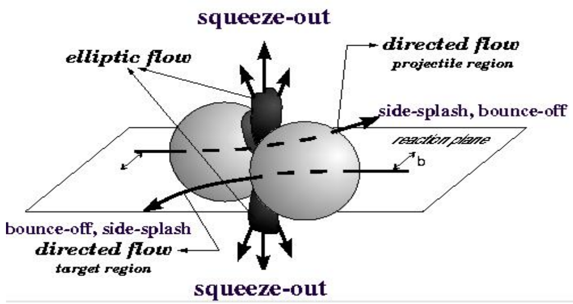
A.Andronic PhD Thesis

Azimuthal distributions

What should be expected as a function of incident energy ?



< 100 A•MeV



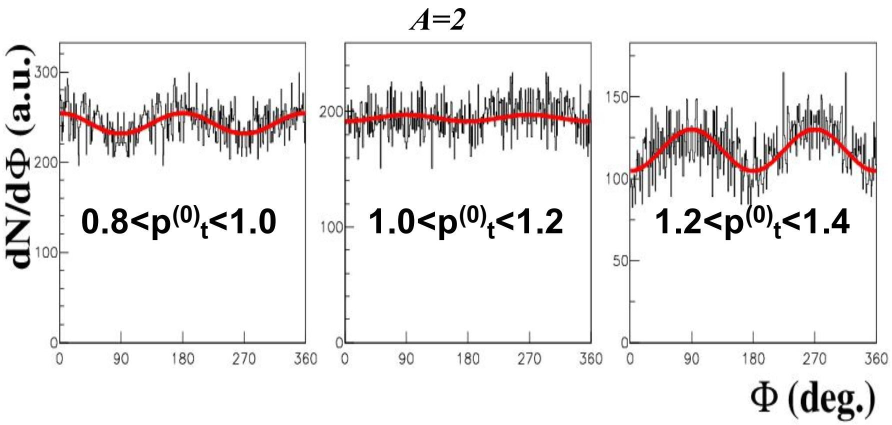
100 A•MeV - ~600 A•MeV

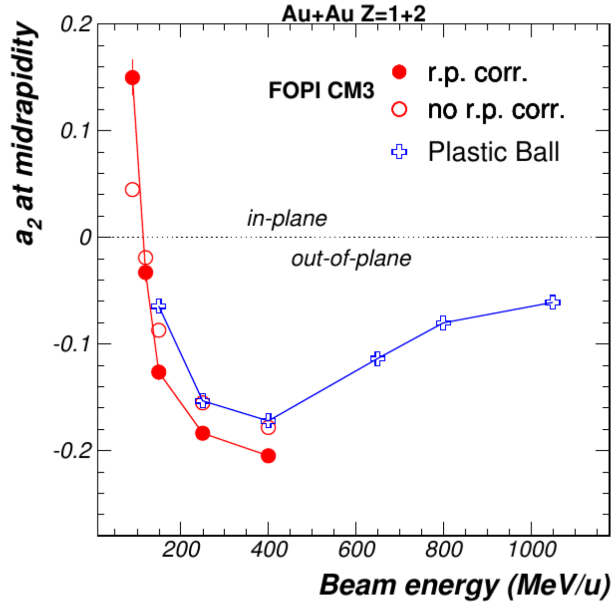
$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n(\phi-\Psi_r)\right)\right)$$

$$v_2=\langle\cos 2(\phi-\Psi_r)\rangle,\quad \phi=\tan^{-1}\left(\frac{p_y}{p_x}\right)$$

The experimental evidences

Au+Au 120 Mev/u, CM3

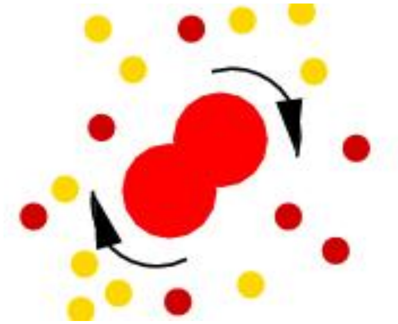




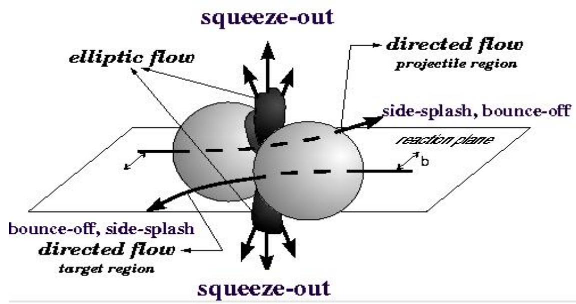
A.Andronic, G.Stoicea, M.Petrovici &FOPI Coll. NPA679(2001)765

Azimuthal distributions

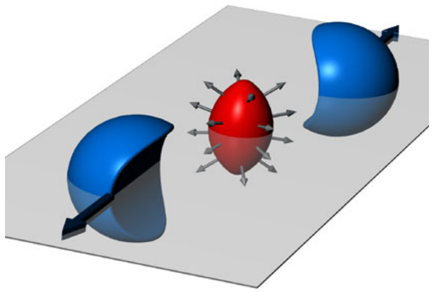
What should be expected as a function of incident energy ?



< 100 A•MeV



100 A•MeV - ~600 A•MeV



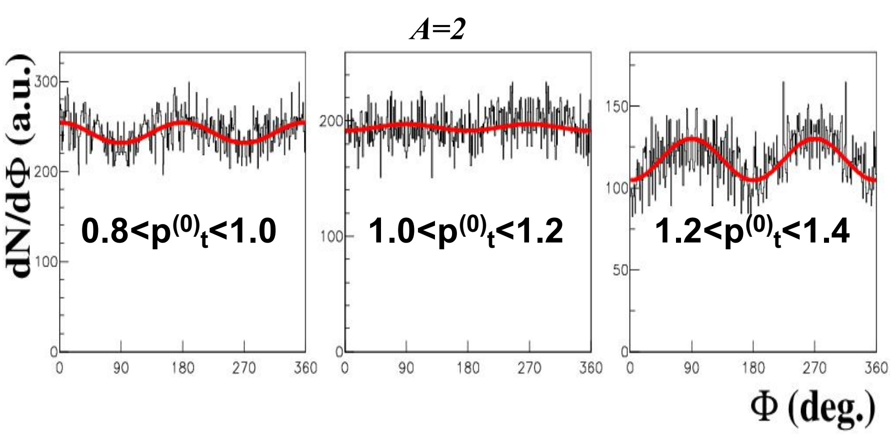
~4 A•GeV

$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n(\phi-\Psi_r)\right)\right)$$

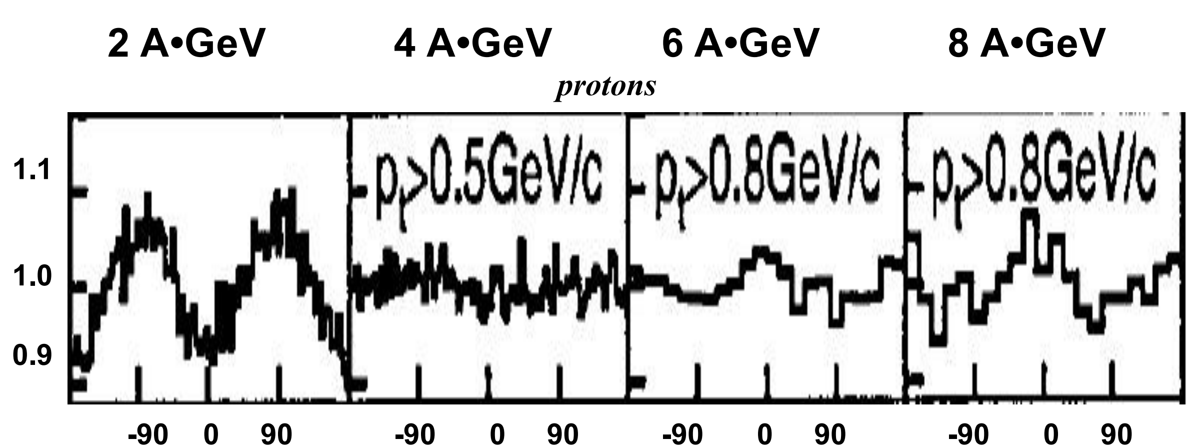
$$v_2=\langle\cos 2(\phi-\Psi_r)\rangle,\quad \phi=\tan^{-1}\left(\frac{p_y}{p_x}\right)$$

The experimental evidences

Au+Au 120 Mev/u, CM3

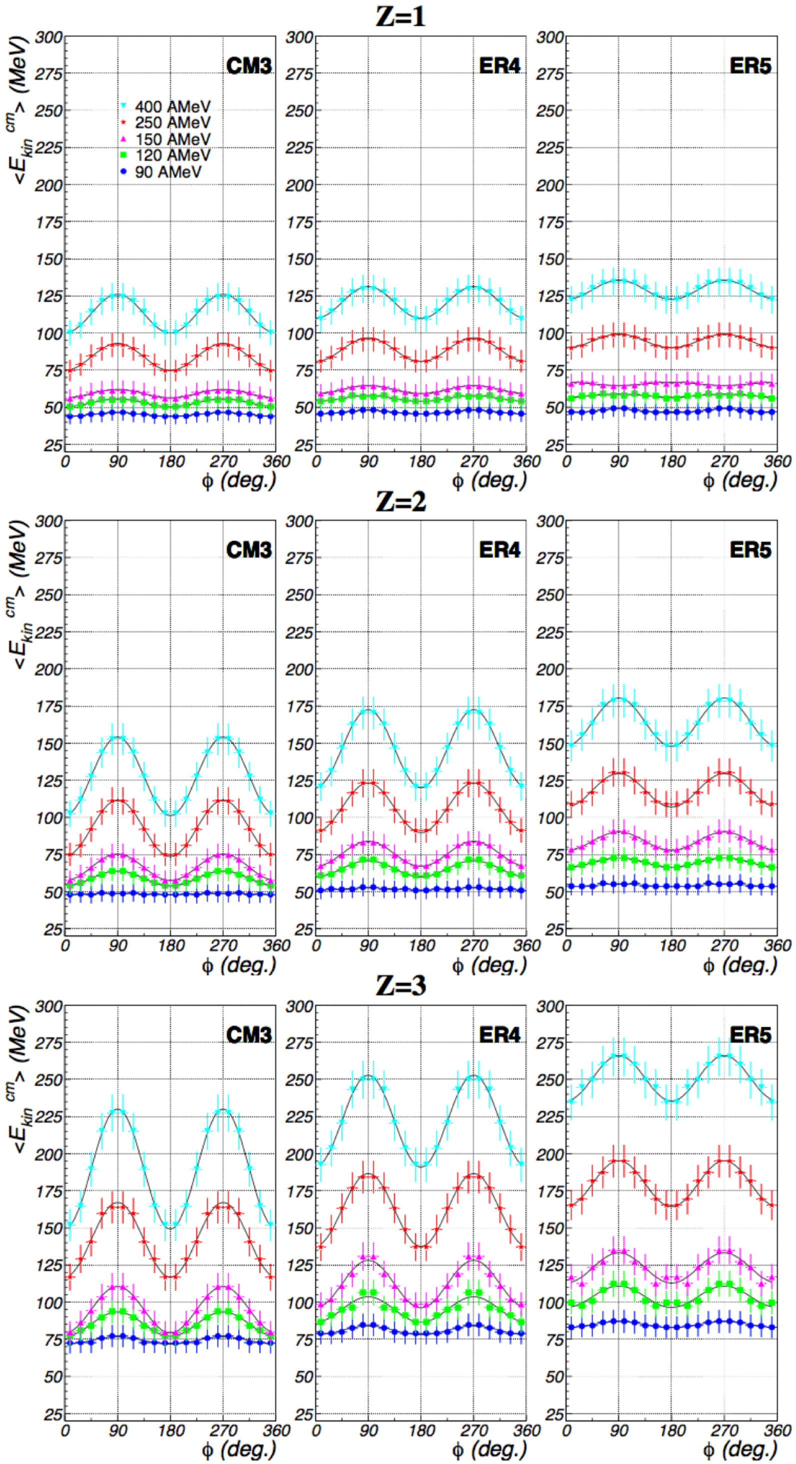


A.Andronic, G.Stoicea, M.Petrovici &FOPI Coll. NPA679(2001)765



C.Pinkenburg & EOS Coll. Phys.Rev.Lett. 83(1999)1295

Mean kinetic energy azimuthal distributions



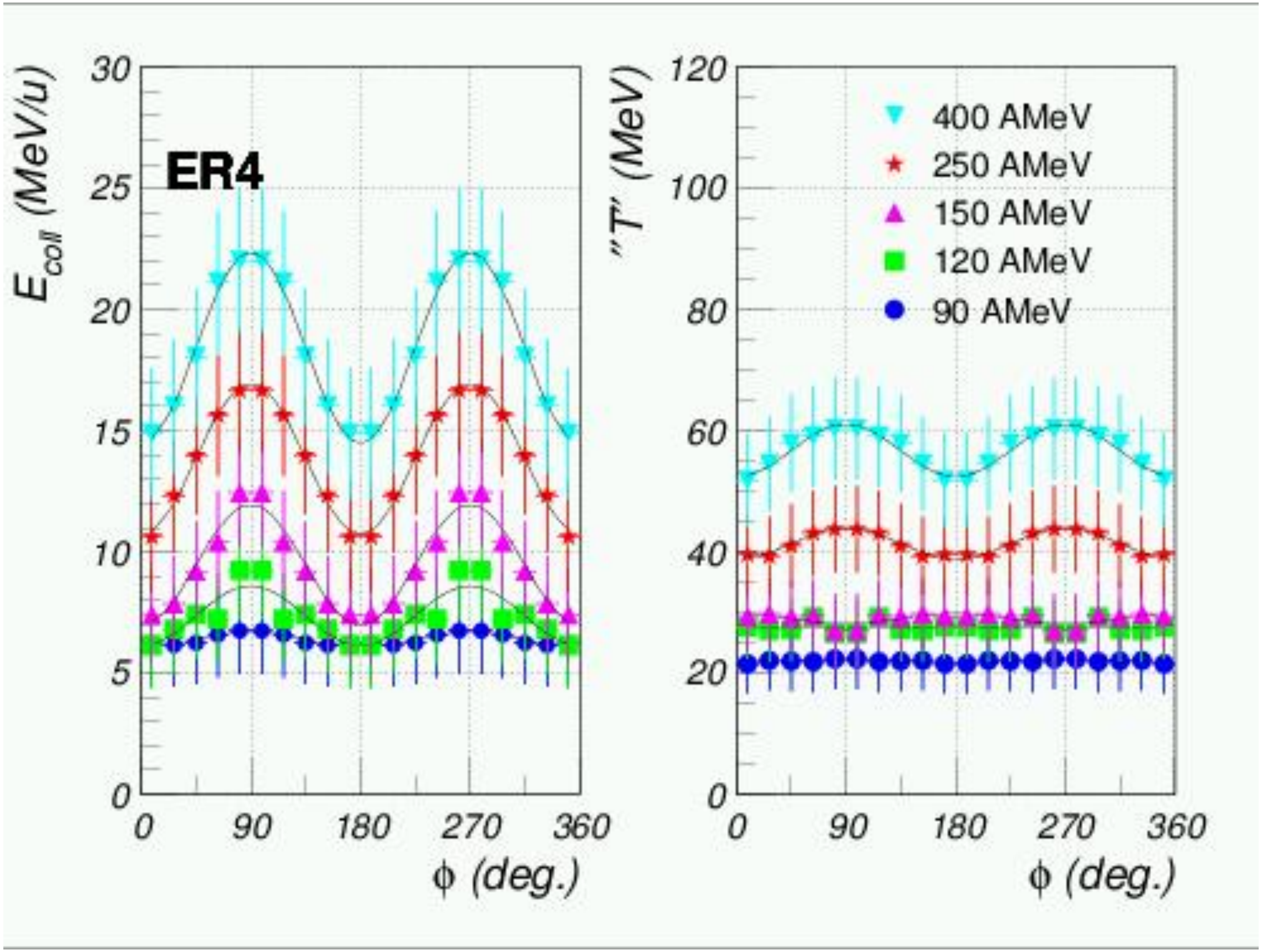
$$\langle E_{kin}^{cm} \rangle \approx \frac{1}{2} m_0 < \beta_{flow}^2 > A_{IMF} + \frac{3}{2} "T"$$

$$E_{coll} = \frac{1}{2} m_0 \langle \beta_{flow}^2 \rangle$$

G.Stoicea, M.Petrovici & FOPI Phys.Rev.Lett. 92(2004)072303

G.Stoicea PhD Thesis

E_{coll} & "T" azimuthal distributions

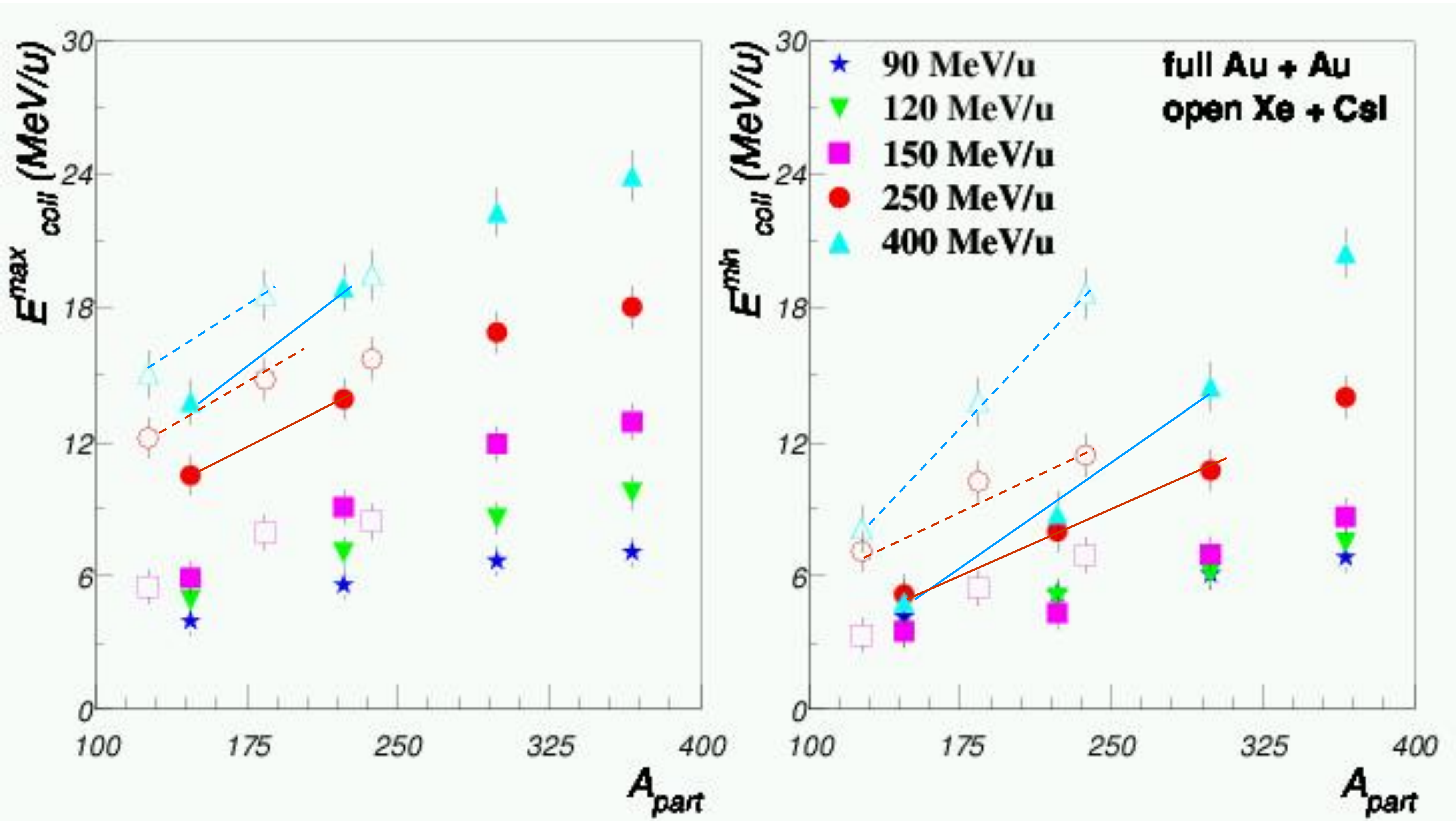


$$E_{coll} = E^0_{coll} - \Delta E_{coll} \cdot \cos 2\Phi$$

$$"T" = "T"_0 - \Delta"T" \cdot \cos 2\Phi$$

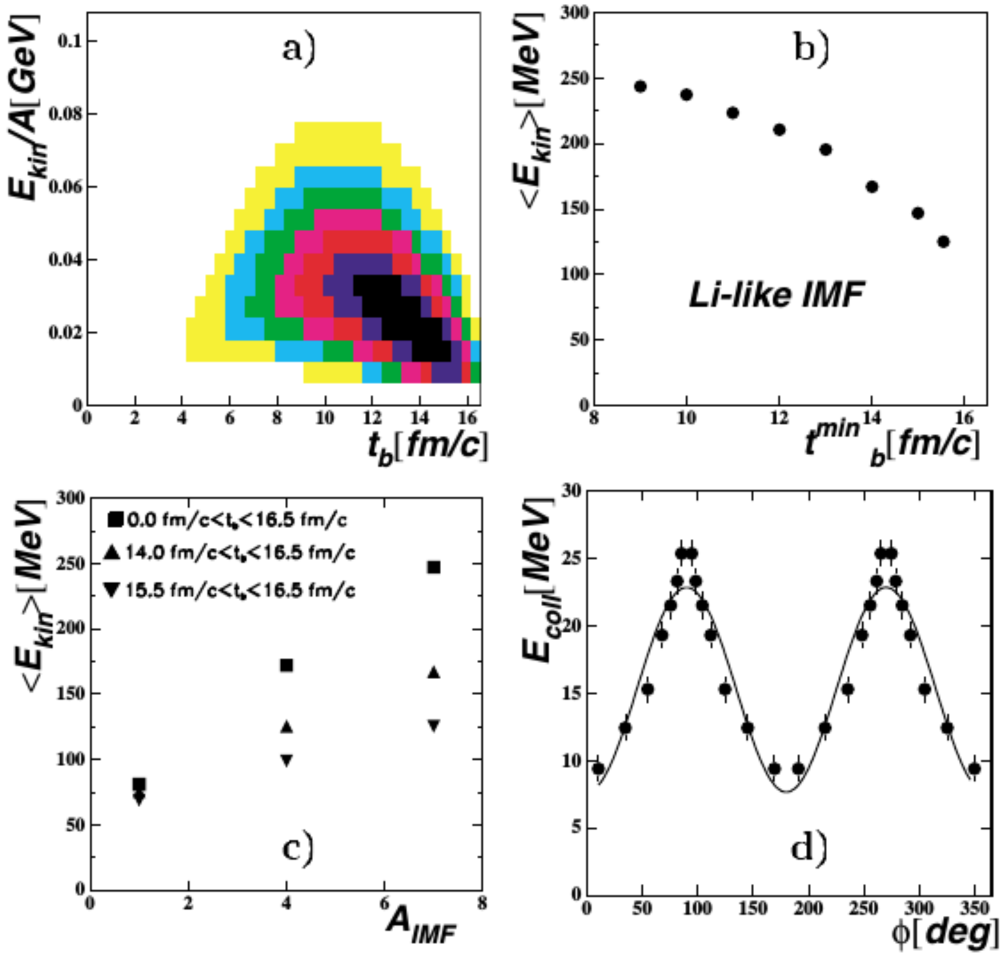
G.Stoicea, M.Petrovici & FOPI Coll., Phys.Rev.Lett. 92(2004)072303

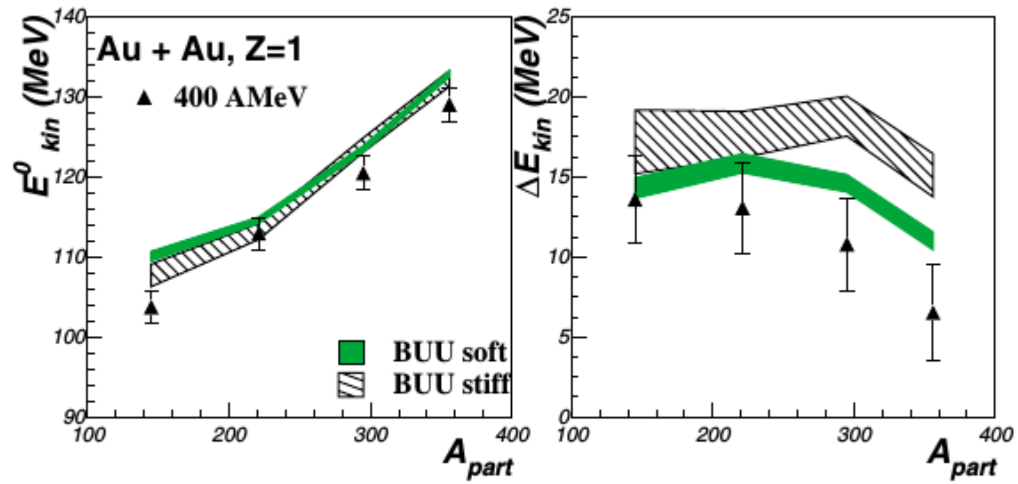
Fireball shape & shadowing effects at SIS18



G.Stoicea, M.Petrovici & FOPI Coll., Phys.Rev.Lett. 92(2004)072303

Shadowing effects - EoS





M.Petrovici et al., Phys.Rev.Lett. 74(1995)5001

G.Stoicea, M.Petrovici & FOPI Coll., Phys.Rev.Lett. 92(2004)072303

P.Danielewicz, Nucl.Phys. A6873(2000)375 and ref. therein

Expectations based on QCD

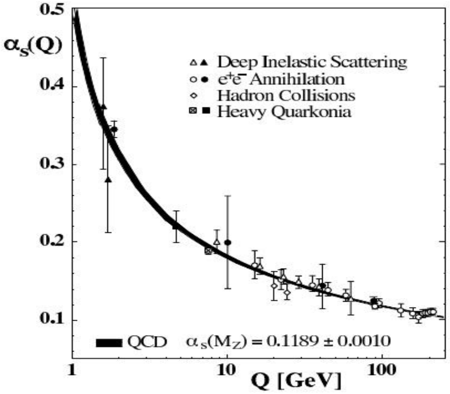
QCD – non-Abelian gauge theory & asymptotic freedom

D.J.Gross, H.D.Politzer and F.Wilczek - Nobel Prize 2004

QCD - running coupling constant $$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi}(33 - 2n_f) log(Q^2/\mu^2)}$$

QCD – intrinsic scale $$\Lambda^2 = \mu^2 exp[\frac{12\pi}{(33 - 2n_f)\alpha_s(\mu^2)}]$$

$$\Rightarrow \quad \alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f) log(Q^2/\Lambda^2)}$$



for $Q^2 \gg \Lambda^2$ α_s *is small* $\Rightarrow$ *a perturbative description in terms of Quarks and Gluons interacting weekly*

$\Rightarrow$

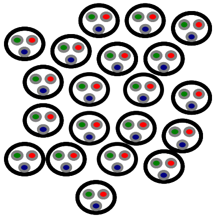
for $Q^2 \sim \Lambda^2$ *Quarks and Gluons arrange themselves in Strongly Bound Clusters - Hadrons*

Since $\Lambda_{QCD} \sim 200$ *MeV a phase transition is expected at:*

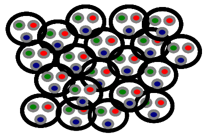
$T \sim \Lambda_{QCD} \sim O(10^{12}\,K)$

or

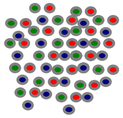
$\rho_B \sim \Lambda_{QCD}^3 \sim 1 fm^{-3}$



Strongly Bound Clusters Hadrons



Phase transition



Weekly interacting Quarks and Gluons

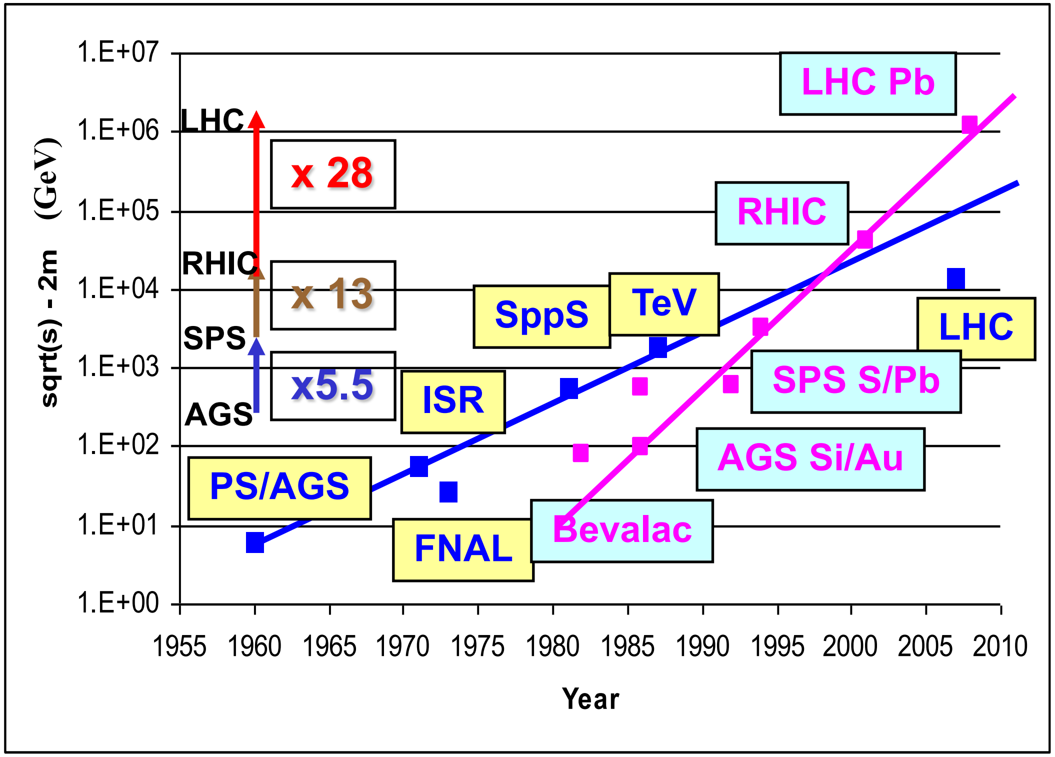
Related theoretical considerations in a chronological sequence

- ***Highly Excited Nuclear Matter*** *- G.F. Chapline et al., Phys.Rev. D8(1973)4302*
  - *It is suggested that very hot and dense nuclear matter may be formed in a transient state in "head-on" collisions of very energetic heavy ions*
- ***Vacuum stability and vacuum excitation in a spin-0 field theory***
  - *T.D.Lee et al., Phys.Rev. D9(1974)2291*
  - *One can produce the abnormal nuclear state by increasing the nuclear density through high energy collisions between very heavy nuclei*
- ***Super dense matter: Neutrons or asymptotically free quarks ?***
  - *J.C.Collins et al., Phys.Rev. Lett. 34(1975)1353*
  - *The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and early big-bang universe) consist of quarks rather than of hadrons*
- ***Asymtotic freedom and the baryon-quark phase transition***
  - *G.Chapline et al., Phys.Rev. D16(1977)450*
  - *Our calculations show that the baryon-quark transition takes place at densities on the order of 10-20 times that of ordinary nuclei*
- ***On the possibility of making quark-gluon matter in nuclear collisions***
  - *G.Chapline et al., Lawrence Livermore Laboratory (1978) March, CTP #695*
- ***Quark matter transition in the baryon rich domain***
  - *G.Chapline, Lawrence Livermore Laboratory (1984) December, UCRL-91875*
- ***And many others after …***

Experimental facilities

- ***Particle Physics: energy doubling time ~ 4 years***
- ***Heavy Ion Physics: doubling time ~ 2 years***

Total center-of-mass energy versus time

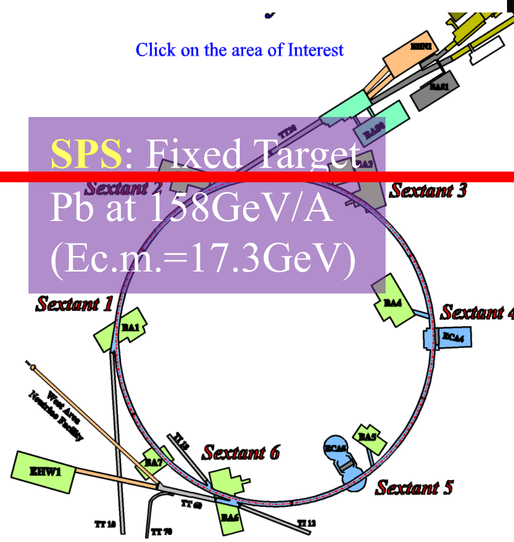


Experimental facilities

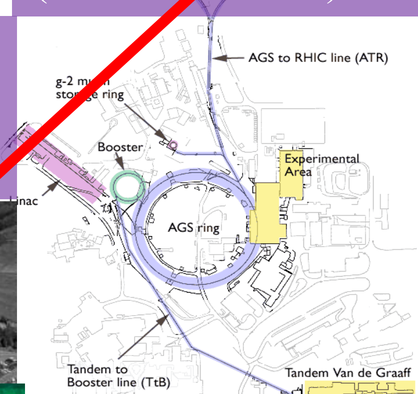
LHC: Collider
Pb+Pb @5500GeV/A

RHIC: Collider
Au+Au @ 200GeV/A

SPS: Fixed Target
Pb at 158GeV/A
(Ec.m.=17.3GeV)



AGS: Fixed Target
Au at 11.7GeV/A
(Ec.m.=4.86GeV)



Bevalac
Fixed Target
1-2GeV/A

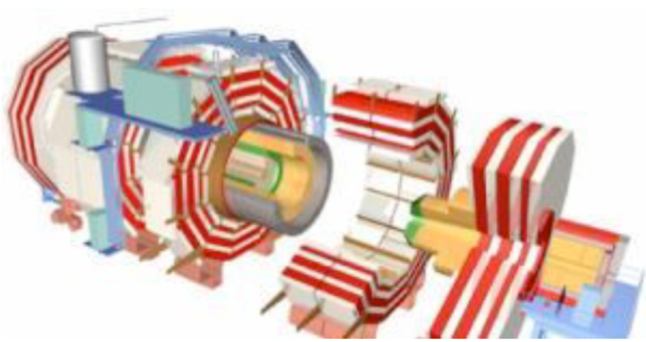
SIS 18

Some of the experiments dedicated to:

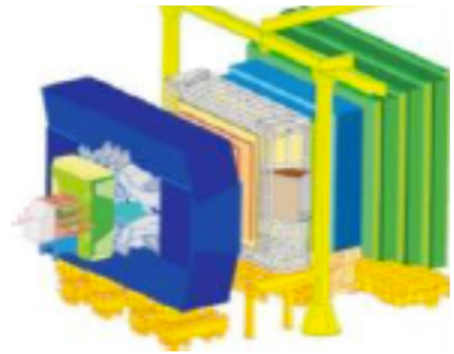
- **EoS**
- **In medium effects**
- **QGP**

studies

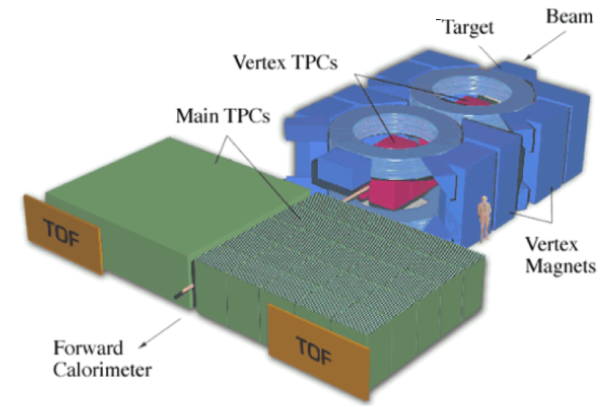
CMS at LHC



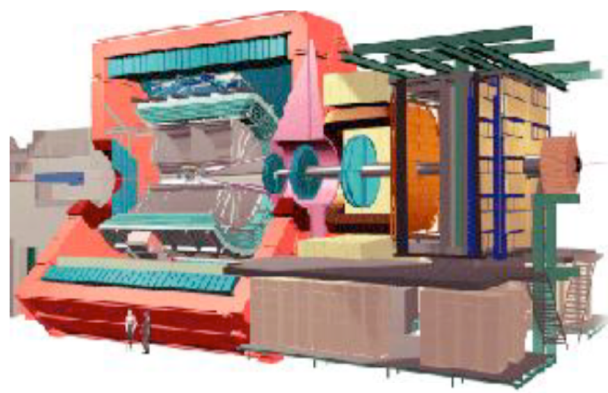
LHCb at LHC



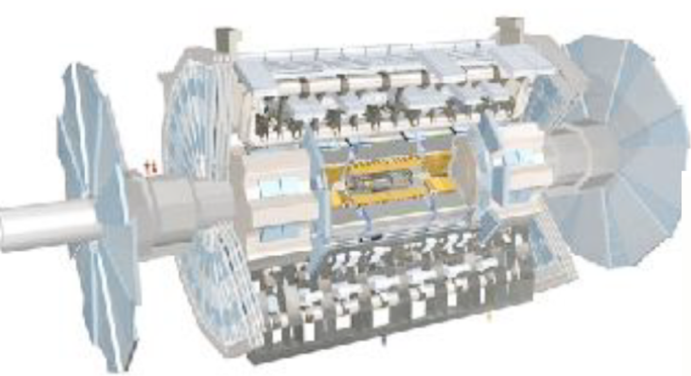
NA49 at SPS



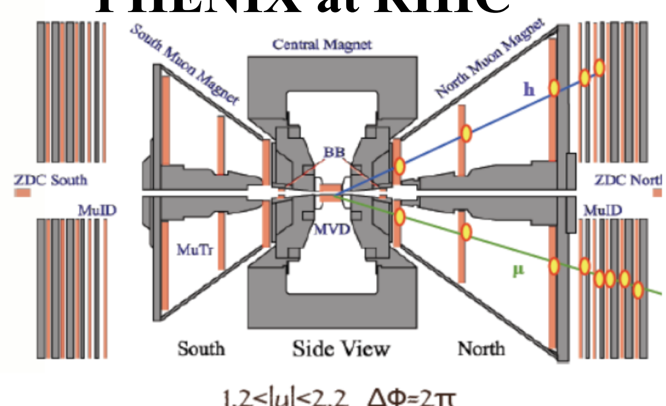
ALICE at LHC



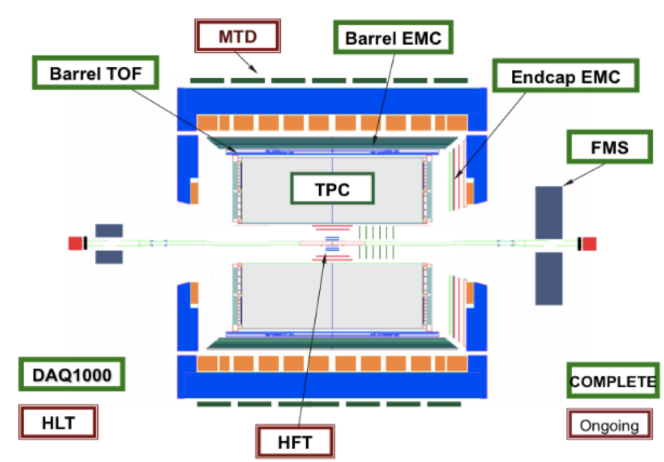
ATLAS at LHC



PHENIX at RHIC

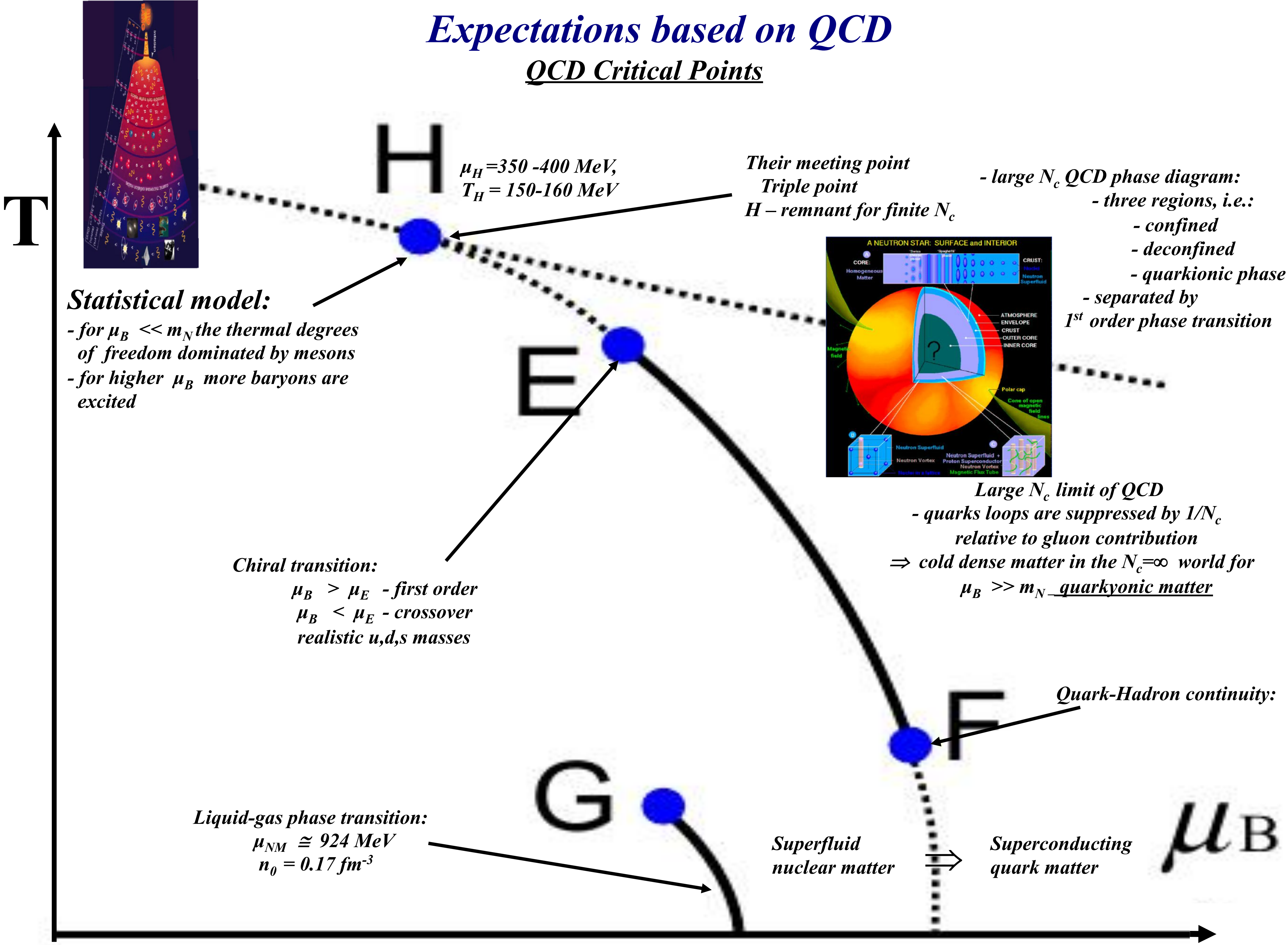


STAR at RHIC

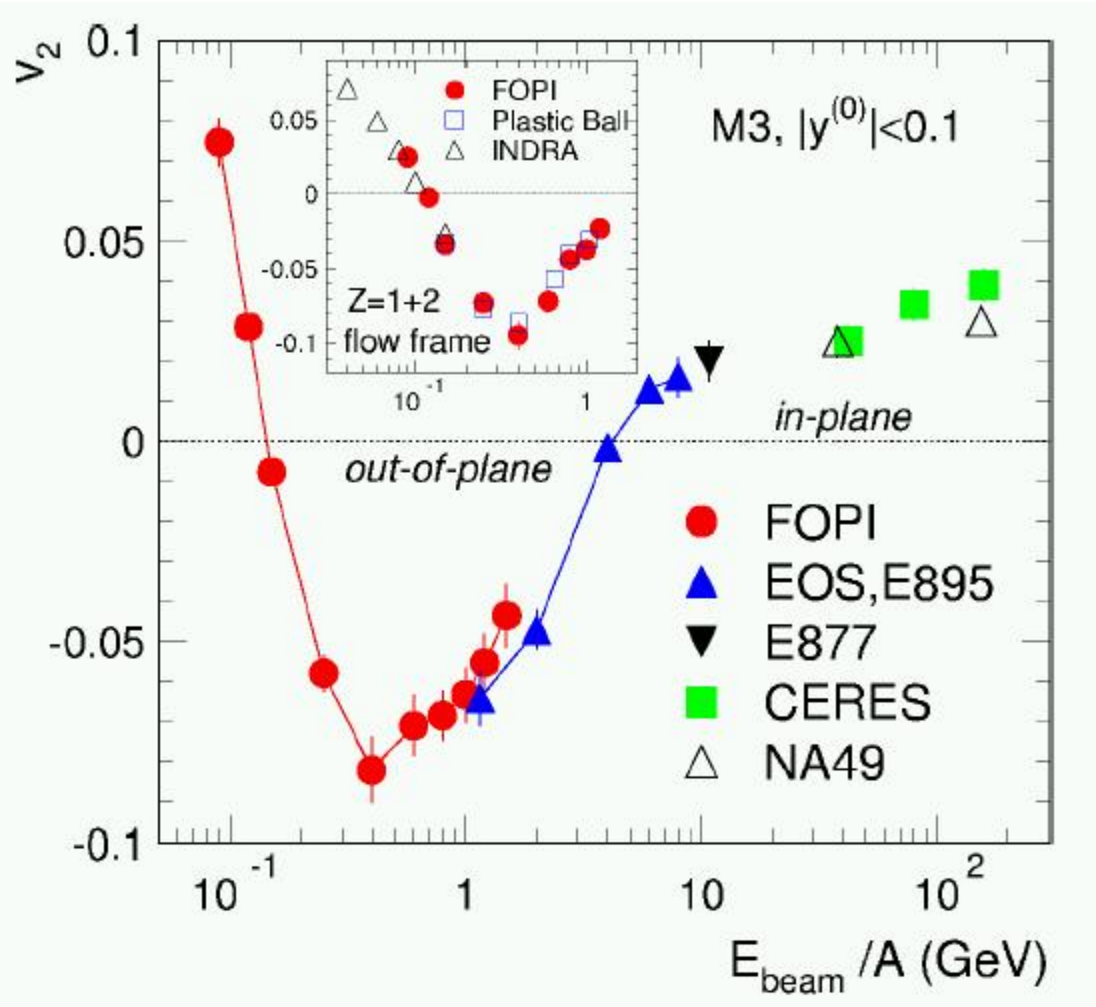


Expectations based on QCD

QCD Critical Points



v_2 excitation function - AGS and SPS



$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\left(\phi-\Psi_r\right)\right)\right)$$

$$v_2=\langle\cos 2(\phi-\Psi_r)\rangle,\quad \phi=\tan^{-1}\left(\frac{p_y}{p_x}\right)$$

FOPI – Z=1 particles

A.Andronic &FOPI Coll., Phys.Lett. B612(2005)173

EOS,E895 – protons

C.Pinkenburg & EOS Coll.

Phys.Rev.Lett. 83(1999)1295

E877 – all charged particles

P. Braun-Munzinger et al., Nucl. Phys. A 638 (1998) 3c

CERES – all charged particles

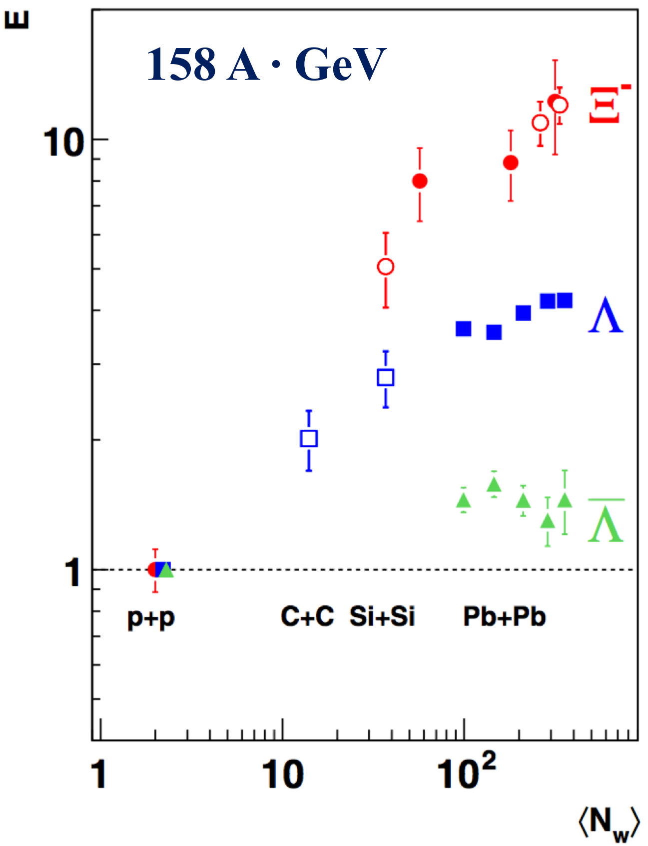
H. Appelshauser et al., Nucl. Phys. A 698 (2002) 253c

NA49 – pions

C. Alt et al., Phys. Rev. C 68 (2003) 034903

Strangeness enhancement - SPS

Exp.

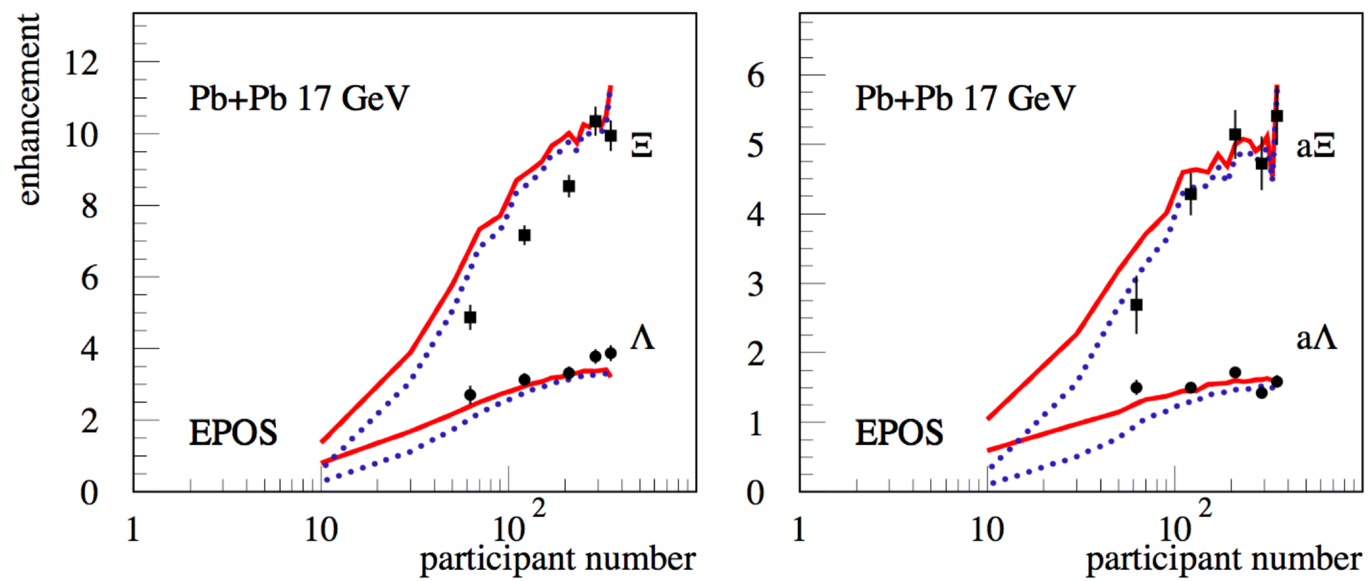


$$E = \left(\frac{1}{\langle N_w \rangle} \frac{\mathrm{d}N(\text{Pb+Pb})}{\mathrm{d}y} \bigg|_{y=0} \right) \Big/ \left(\frac{1}{2} \frac{\mathrm{d}N(\text{p+p})}{\mathrm{d}y} \bigg|_{y=0} \right)$$

C.Blume et al., NA49 Collaboration,

J. Phys. G: Nucl. Part. Phys. 34 (2007) S951

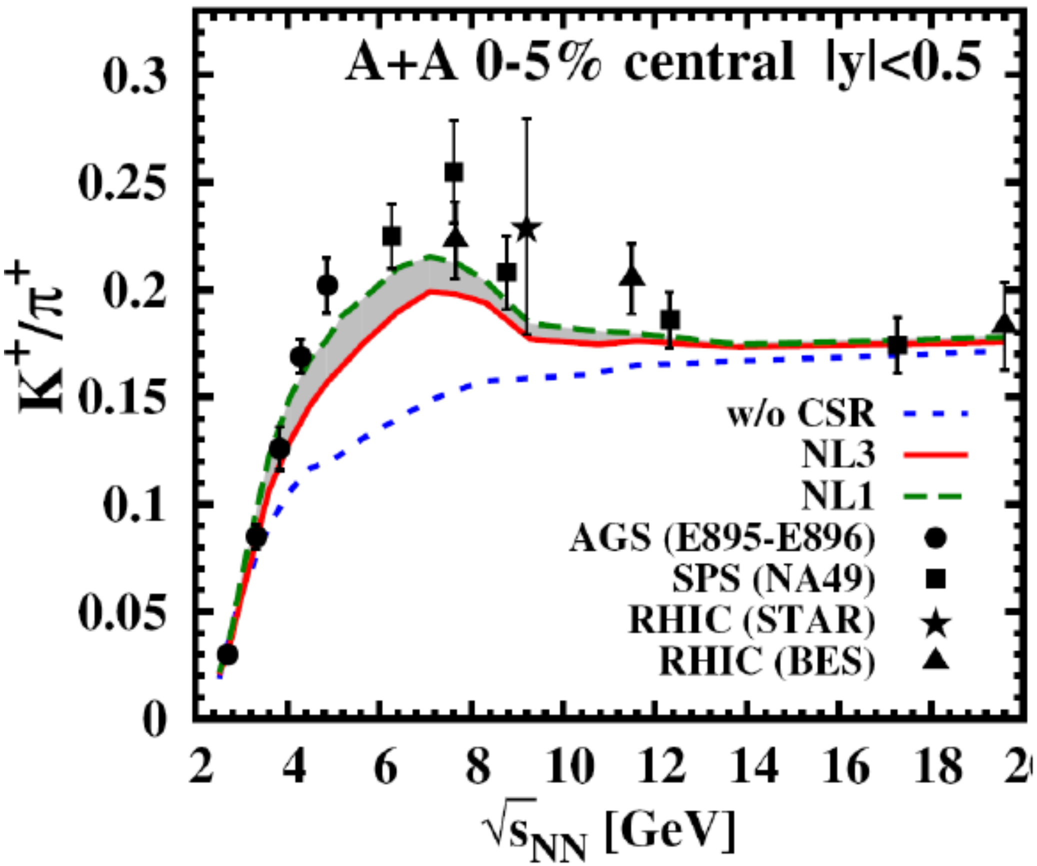
Core-Corona

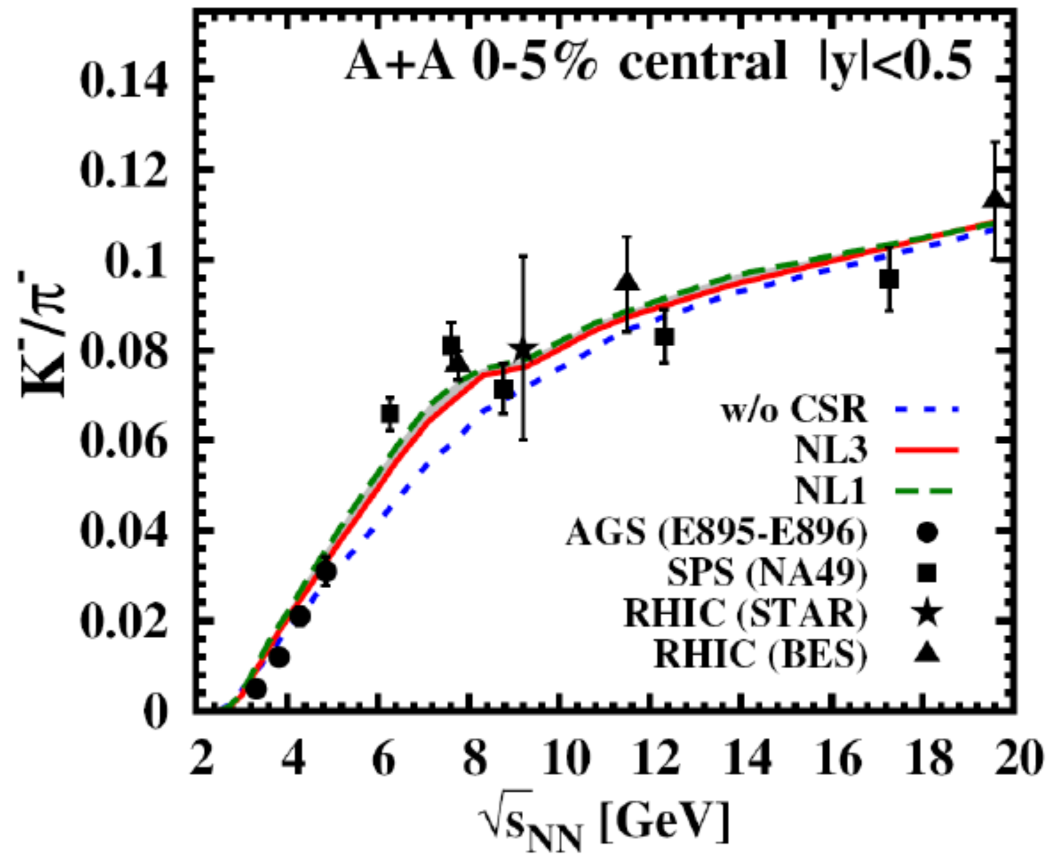


$$M^i(N_{part}) = N_{part}[f(N_{core}) \cdot M^i_{core} + (1 - f(N_{core})) \cdot M^i_{corona}]$$

J.Aichelin et al., Phys.Rev.C79(2009)064907

K/π "horn" - SPS

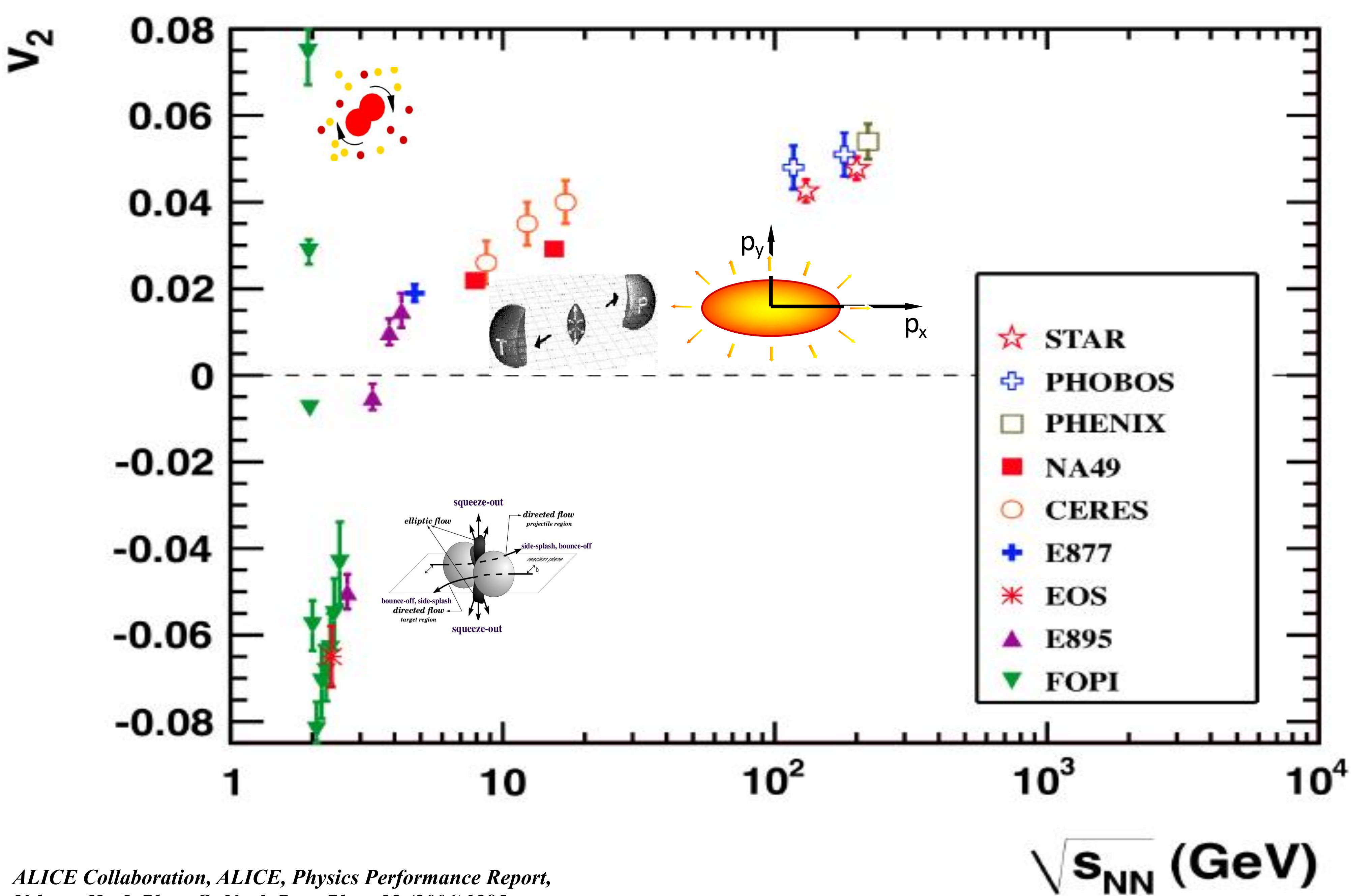




C.Alt et al., Phys.Rev.C77(2008)024903

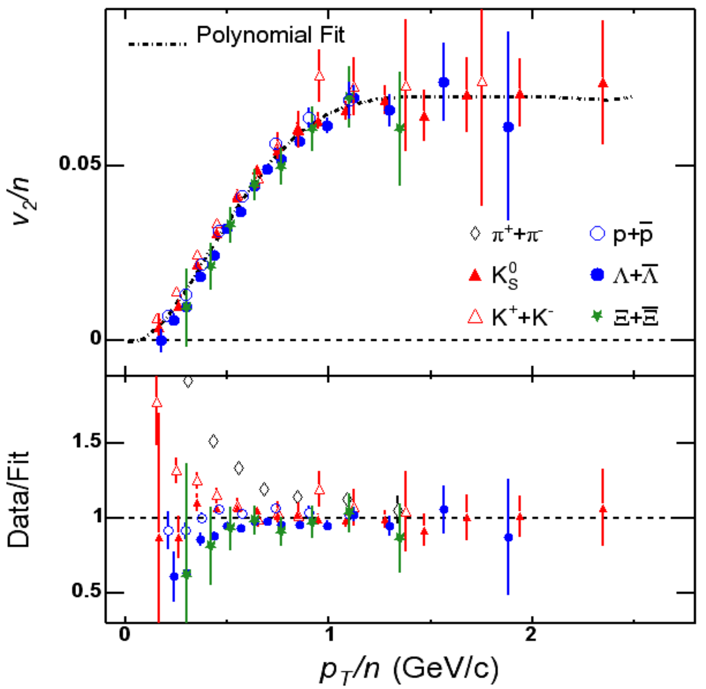
W.Cassing, CBM Collaboration Meeting, April 11, 2016

Elliptic flow (v_2) - excitation function including RHIC results



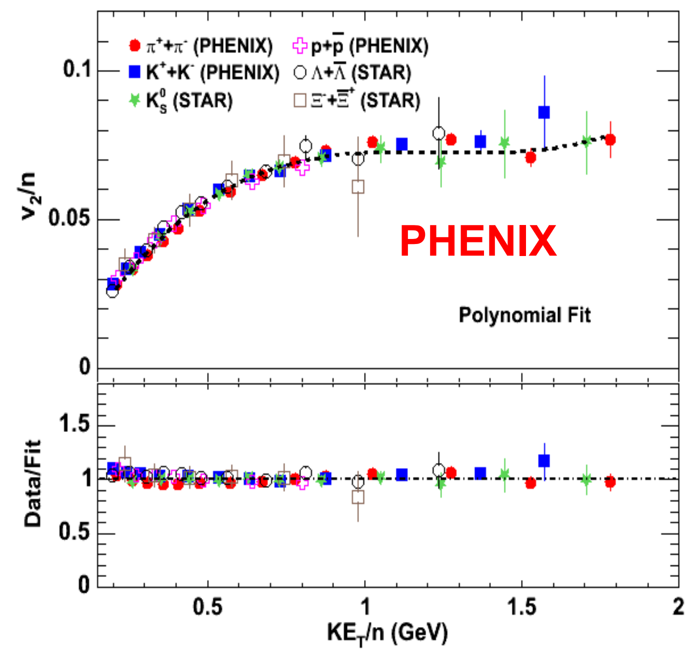
ALICE Collaboration, ALICE, Physics Performance Report, Volume II , J. Phys. G: Nucl. Part. Phys. 32 (2006)1295

Elliptic Flow - Quark Number Scaling

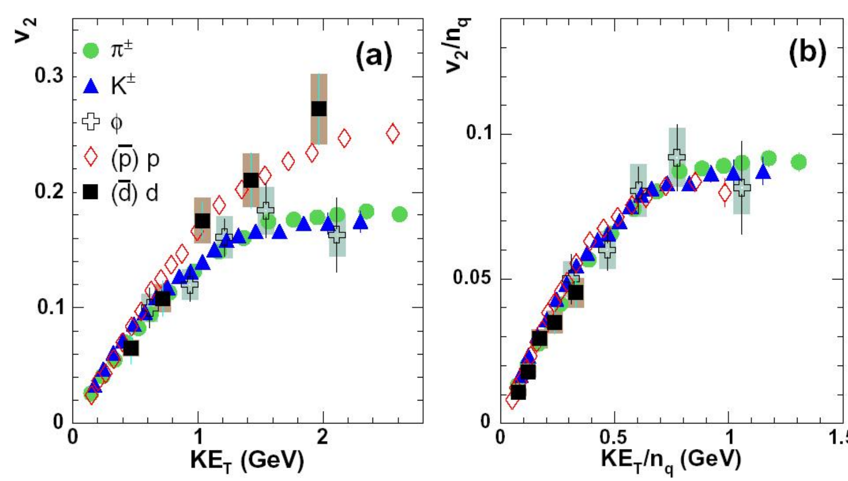


S.S.Adler et al., PHENIX Coll., Phya.Rev.Lett. 91 (2003) 182301

J.Adams et al., STAR Coll., Phys.Rev.Lett. 92 (2004) 052302



A.Adare et al., PHENIX Coll., Phys.Rev.Lett. 98(2007)162301



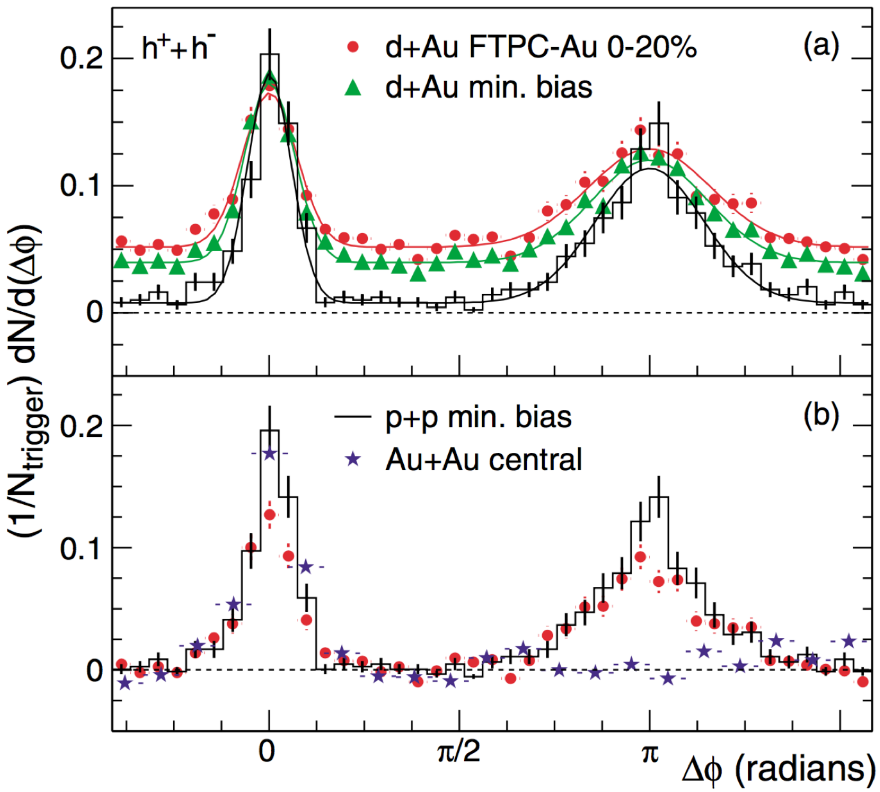
S.Afanasiev et al., PHENIX Coll., Phys.Rev.Lett. 99(2007)052301

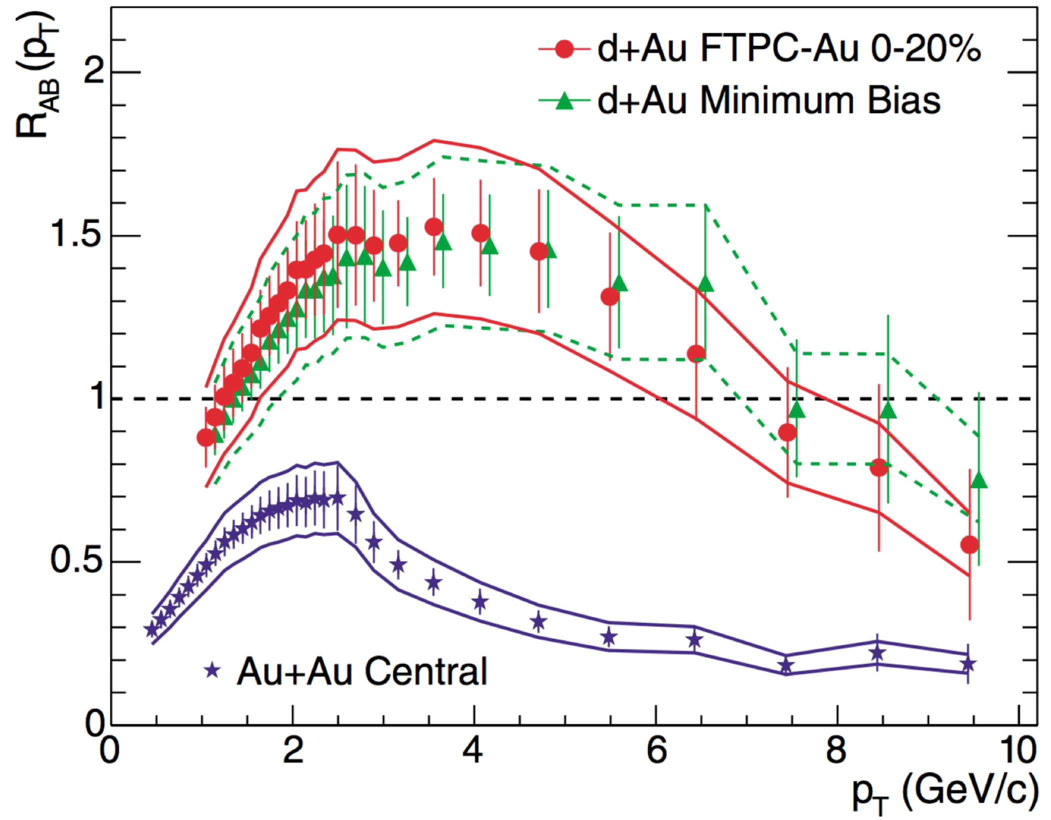
- **At the moment of hadronization in nucleus-nucleus collisions at RHIC the dominant degree of freedom is related to number of constituent (valence) quarks**
- **These 'constituent quarks' exhibit an angular anisotropy resulting from collective interactions**
- **Hadrons seem to be formed from coalescence or recombination of the 'constituent quarks'**

Final-state suppression of high-p_T hadrons

Au-Au, d-Au and pp collisions at $\sqrt{s_{NN}}$ 200 GeV

$$4 < p_T(\text{trig}) < 6\ \text{GeV}/c$$
$$2 < p_T < p_T(\text{trig})$$





$$D(\Delta\phi) = A_N \frac{e^{-(\Delta\phi)^2/2\sigma_N^2}}{\sqrt{2\pi}\sigma_N} + A_B \frac{e^{-(|\Delta\phi|-\pi)^2/2\sigma_B^2}}{\sqrt{2\pi}\sigma_B} + P$$

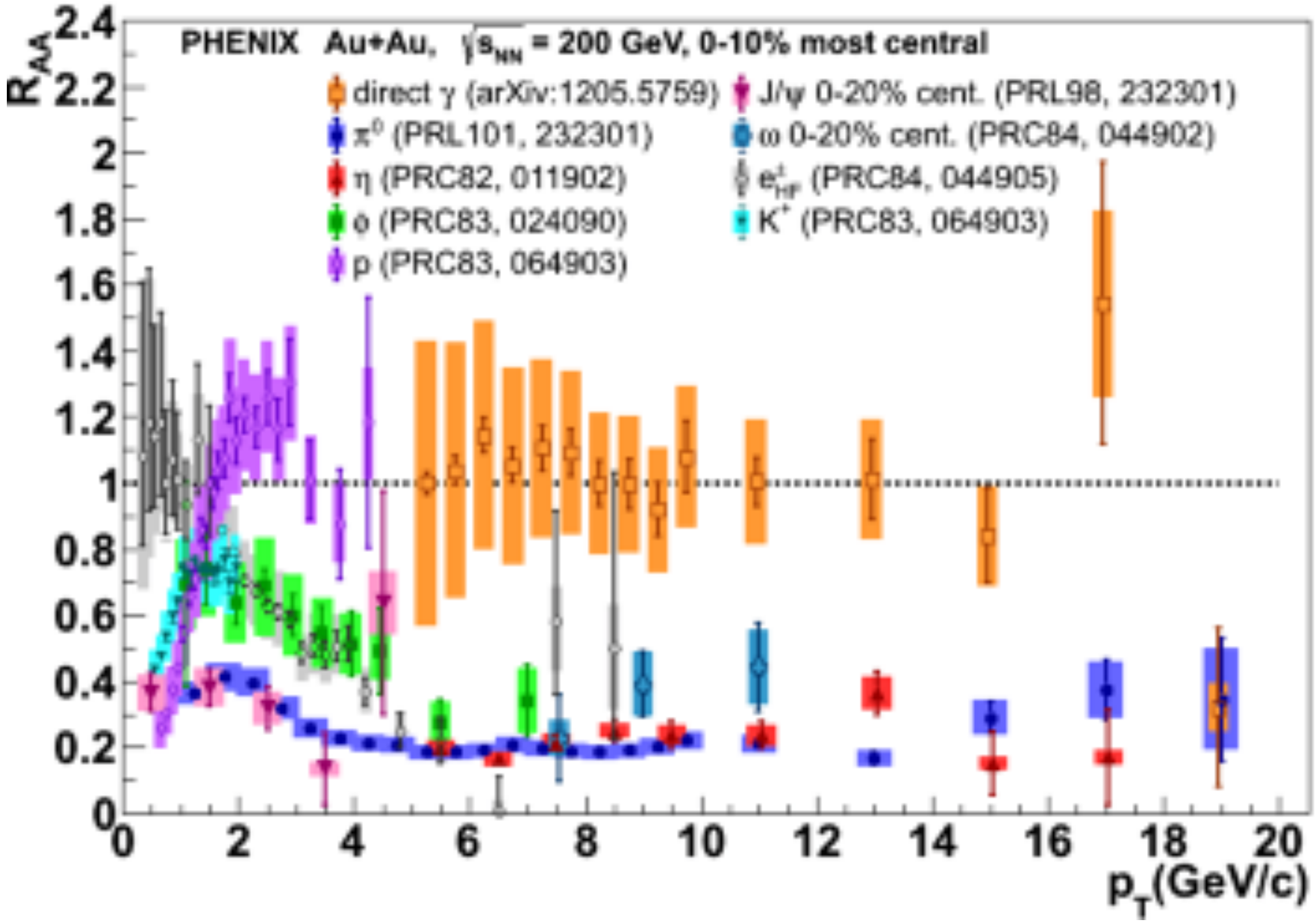
$$R_{AB}(p_T) = \frac{d^2N/dp_T d\eta}{T_{AB} d^2\sigma^{pp}/dp_T d\eta}$$

$$T_{AB} = \langle N_{\text{bin}} \rangle / \sigma_{\text{inel}}^{pp}$$

J.Adams et al., STAR Coll., Phys.Rev.Lett. 91(2003)072304

Final-state suppression of high-p_T hadrons

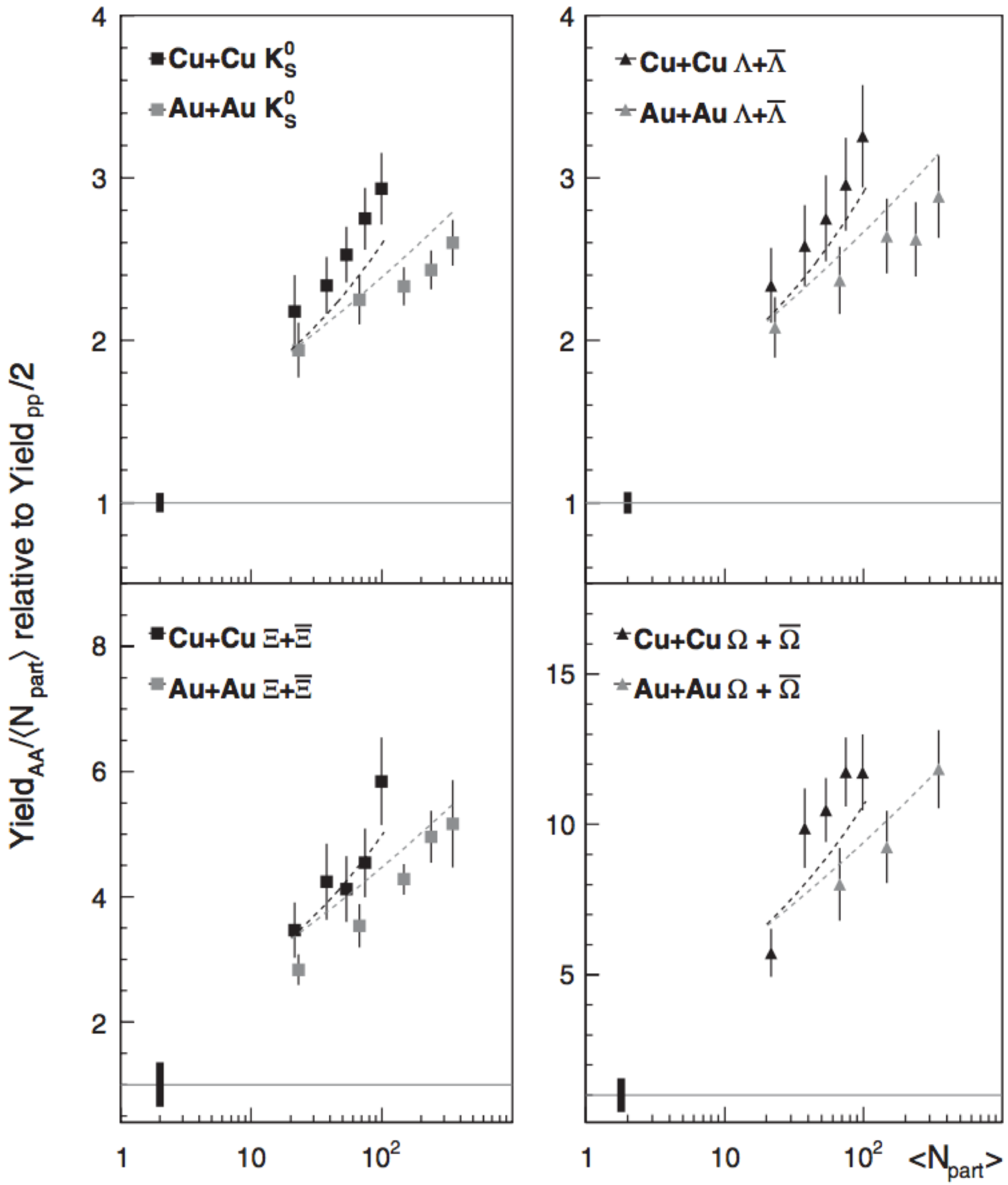
Au-Au, d-Au and pp collisions at $\sqrt{s_{NN}}$ 200 GeV



D.Sharma et al., PHENIX Coll., J.Phys. G: Nucl.Part.Phys. 38(2011)124082

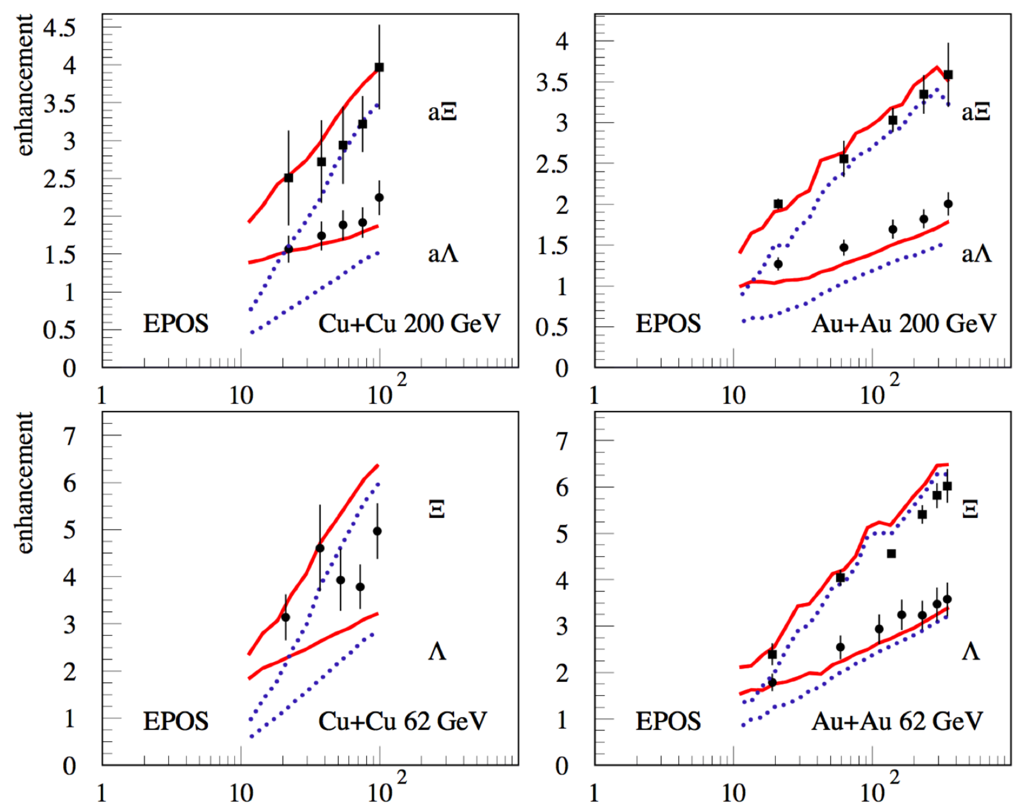
Strangeness enhancement at RHIC

Cu-Cu and Au-Au at $\sqrt{s_{NN}}$ 200 GeV



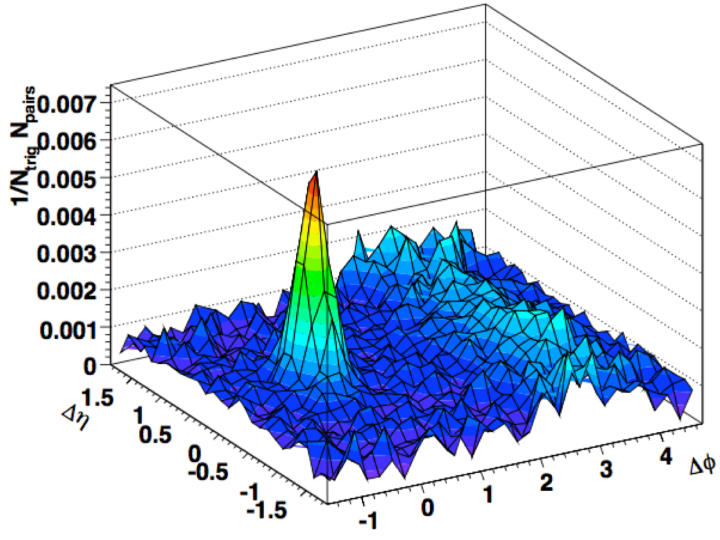
G. Agakishiev et al., STAR Coll., Phys.Rev.Lett. 108(2012)072301

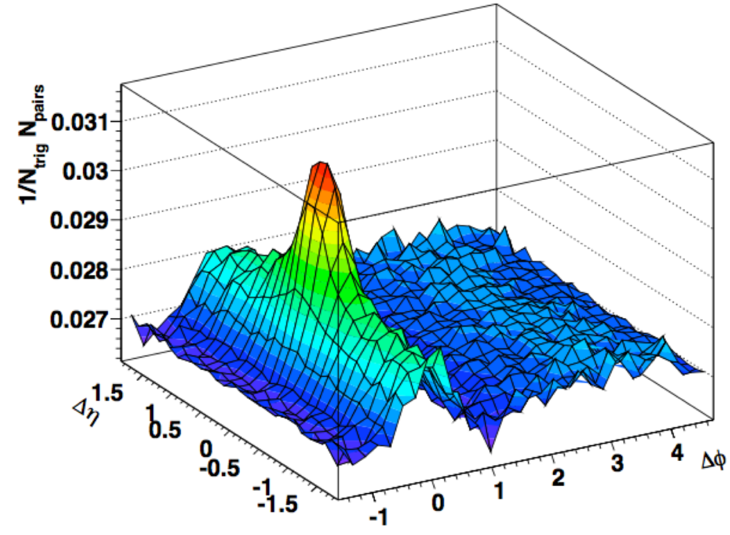
Core-Corona



J.Aichelin et al., Phys.Rev.C81(20010)029902

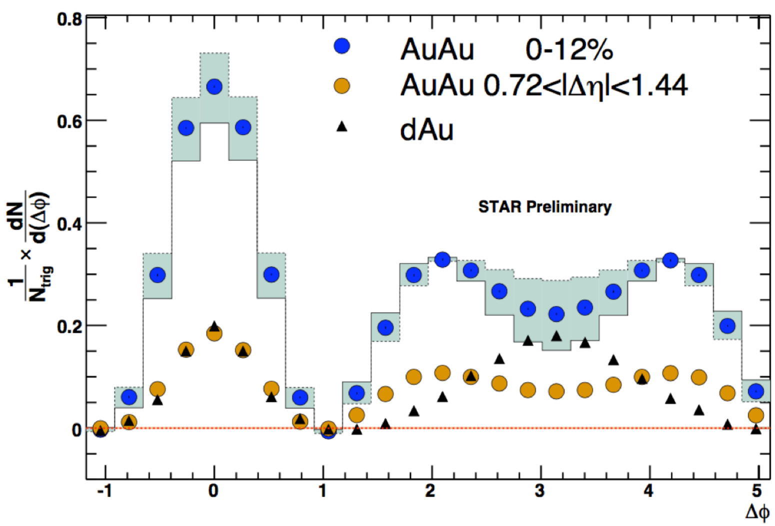
Two-particle correlations at RHIC

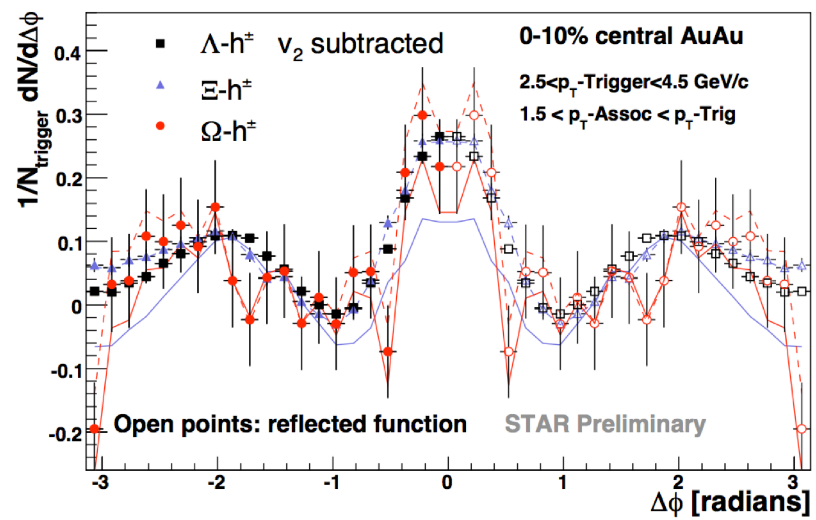




Two-particle angular correlations ($\Delta\varphi, \Delta\eta$): a) d+Au and b) central (0-10%) Au+Au collisions at $\sqrt{s_{NN}}$ =200GeV for 3<p_{trig} <6GeV/c and 2GeV/c<p_{asso} <p_{trig}

2.5 < p_{trig} < 4.0 GeV/c and 1.0 < p_{asso} < 2.5 GeV/c

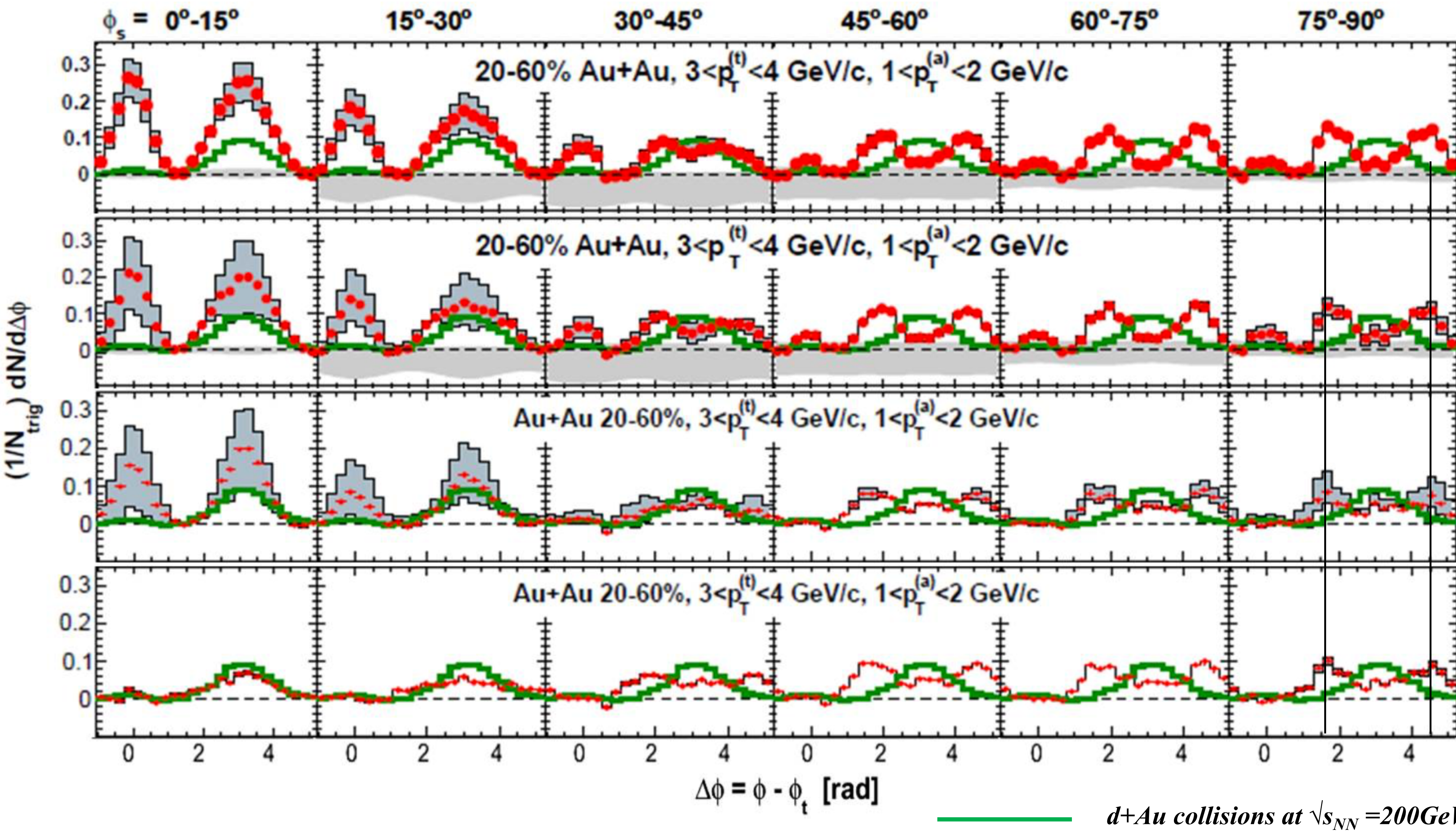




M. Bombara et al., STAR Coll., Journal of Physics: Conference Series 110 (2008) 032003

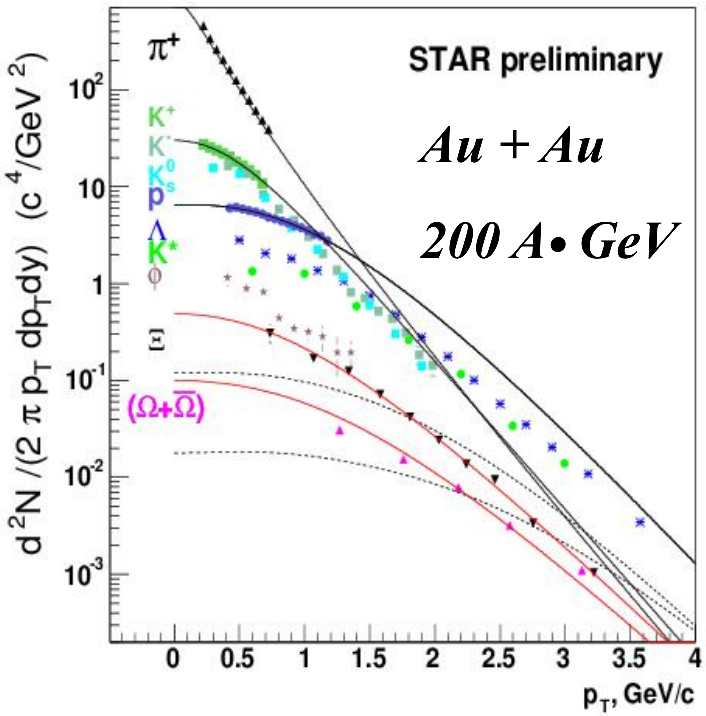
Two particle correlations at RHIC

Two-particle angular correlations Au+Au collisions at $\sqrt{s_{NN}}$ =200GeV



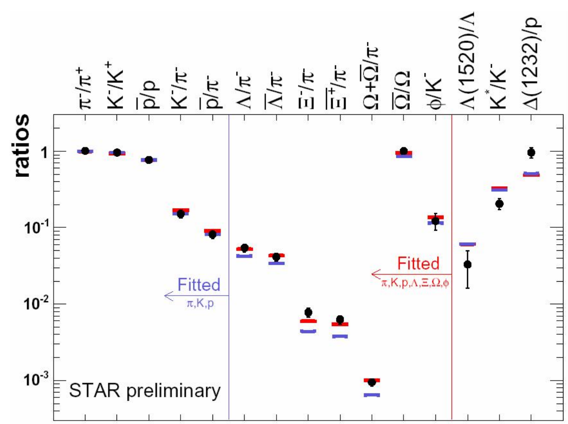
F.Wang, STAR Collaboration, arXiv:[nucl-ex]1309.4515

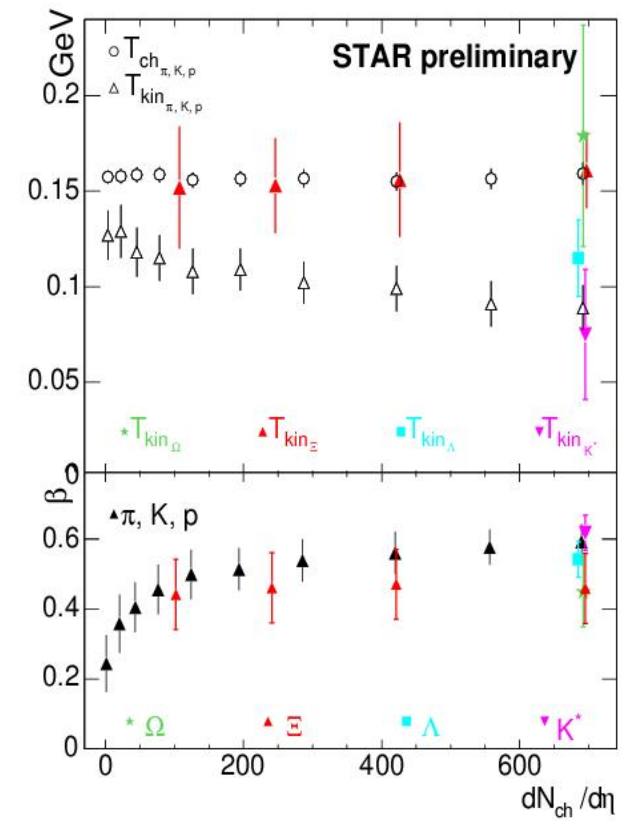
Transverse Flow at RHIC



nucl-ex/0403014

Particle	T_{kin} (MeV)	$\langle\beta\rangle$ (c)
π, K, p	89 ± 10	0.59 ± 0.05
K^*	75 ± 35	0.62 ± 0.05
Λ, $\bar{\Lambda}$	115 ± 20	0.54 ± 0.05
Ξ^-, $\bar{\Xi}^+$	161 ± 20	0.46 ± 0.10
Ω, $\bar{\Omega}$	179 ± 60	0.45 ± 0.10





$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right) I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right)$$

$$\rho = \tanh^{-1}\beta_r \quad \beta_r = \beta_s\left(\frac{r}{R}\right)^{\alpha} \quad \alpha = 0.5, 0.7, 1, 2$$

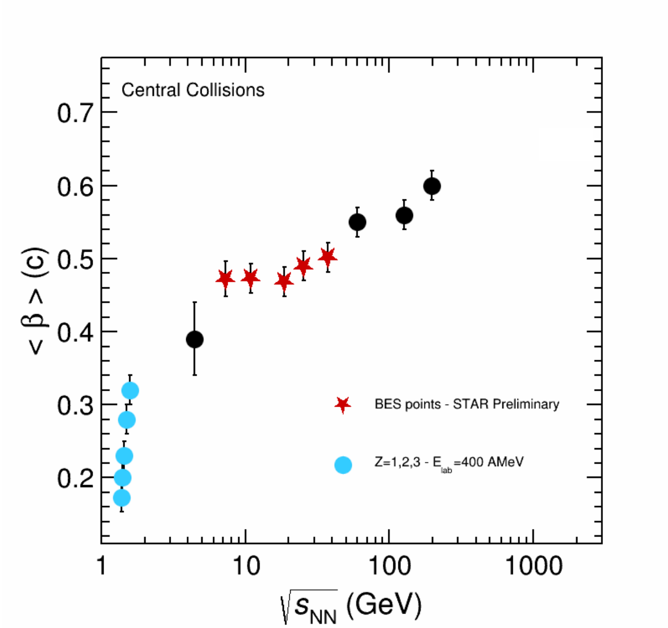
Shnedermann,Sollfrank,Heinz, nucl-th/9307020

Compilation including SIS18, SPS and RHIC central collisions

$$E\frac{d^3N}{dp^3} \sim f(p_t) = \int_0^R m_T K_1(m_T cosh\rho/T_{fo}) I_0(p_T sinh\rho/T_{fo}) r dr$$

$$n = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial\mu} = \frac{VTm_i^2 g_i}{2\pi^2}\sum_{k=1}^{\infty}\frac{(\pm 1)^{k+1}}{k}\left(e^{\beta k\mu_i}\right)K_2\left(\frac{km_i}{T}\right)$$

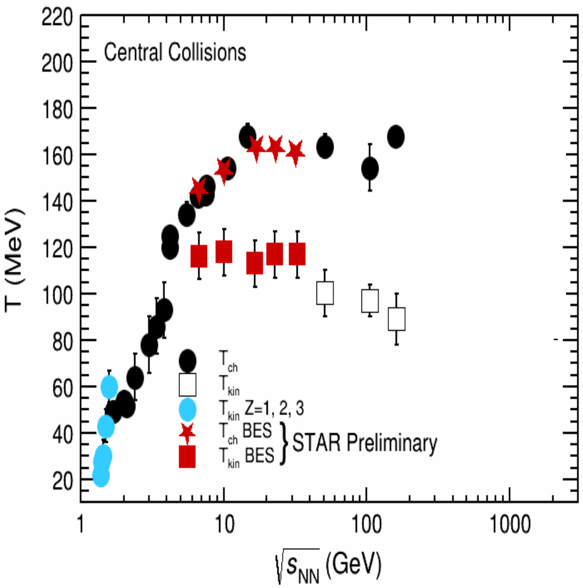
where $m_T = \sqrt{m^2 + p_T^2}$; $\beta_r(r) = \beta_s(\frac{r}{R})^n$; $\rho = tanh^{-1}\beta_r$.



π^+,K^+,p – simultaneous fits

FOPI
E866
STAR

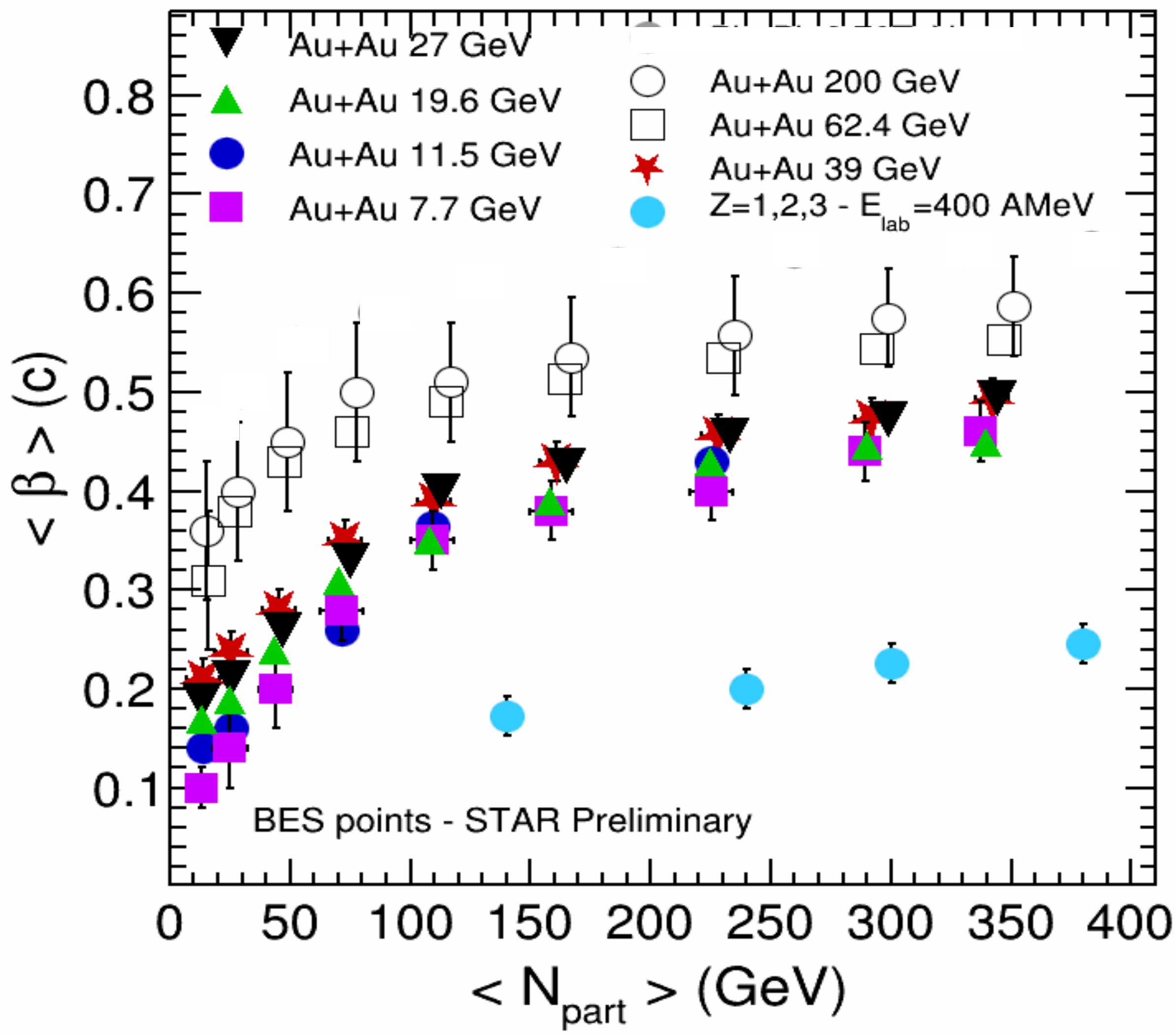
7.7 GeV
11.5 GeV
19.6 GeV
27.0 GeV
39.0 GeV



L. Kumar, STAR Coll., QM2014

M.Petrovici, Carpathian Summer School of Physics
July 23, 2014 - Sinaia, Romania

Compilation of SIS and RHIC
<β> – N_{part} dependence

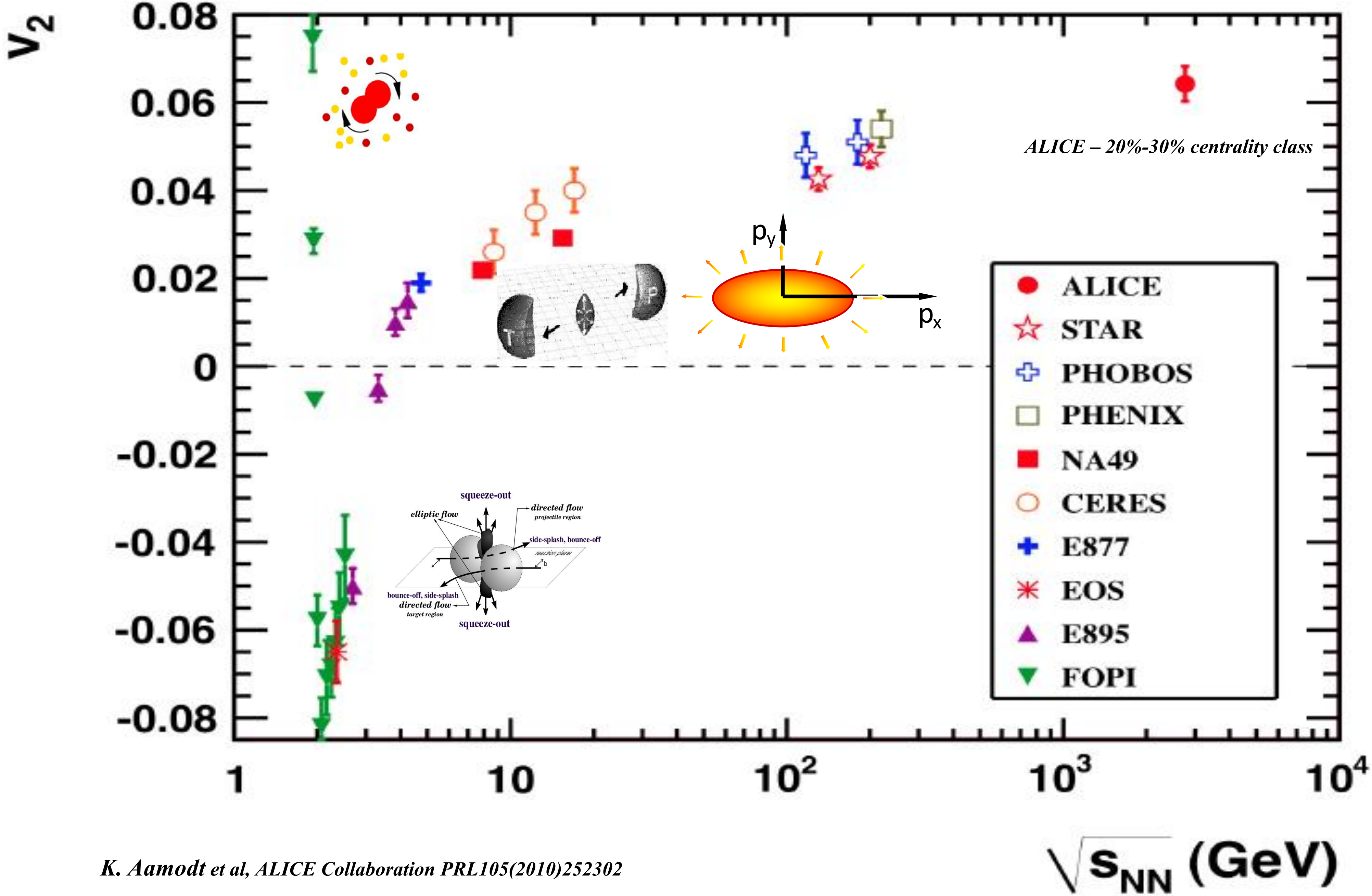


Z=1,2,3 – E_{lab}=400 A•MeV FOPI

7.7 GeV
11.5 GeV
19.6 GeV
27.0 GeV
39.0 GeV

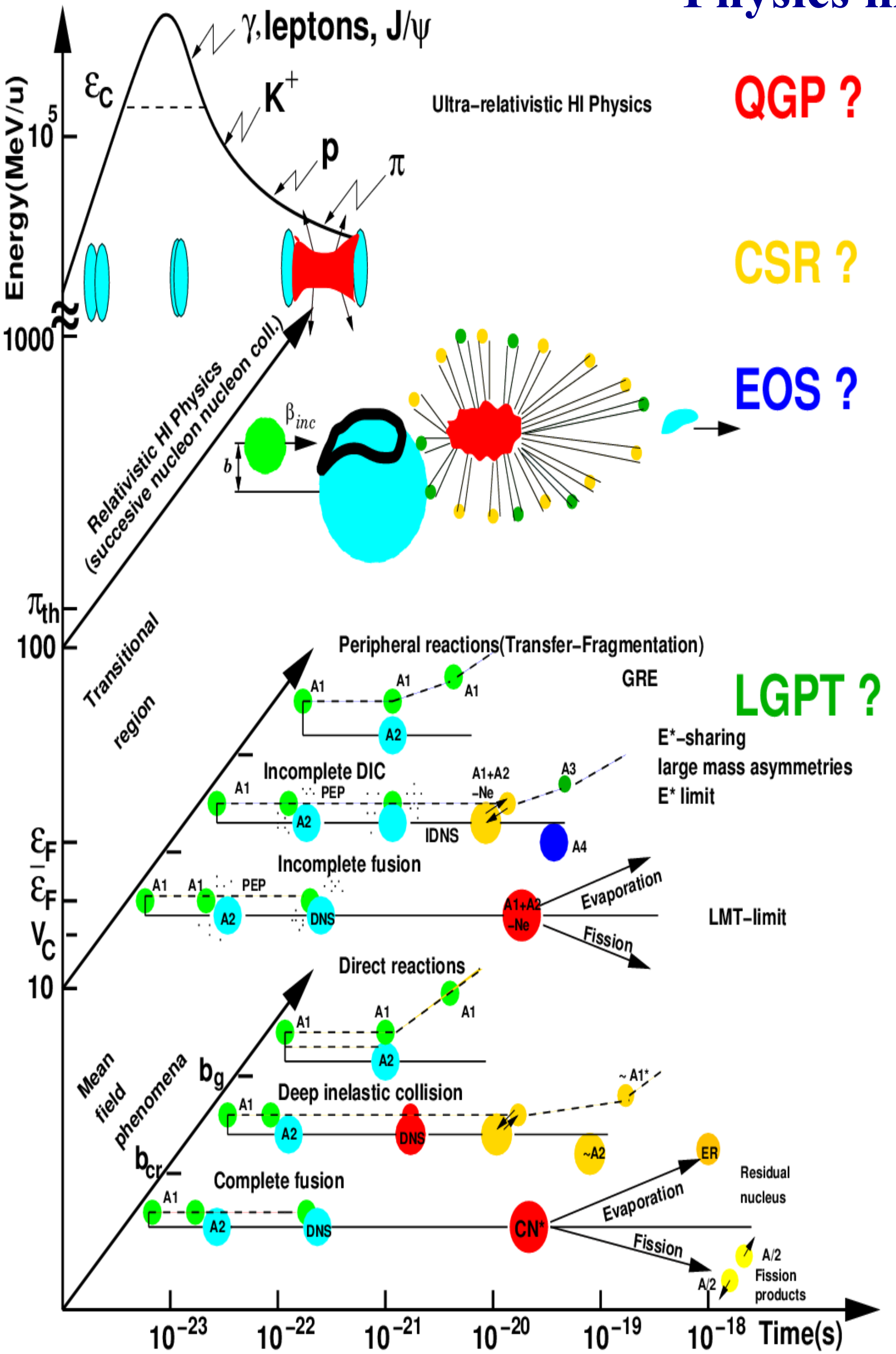
L. Kumar, STAR Coll., QM2014

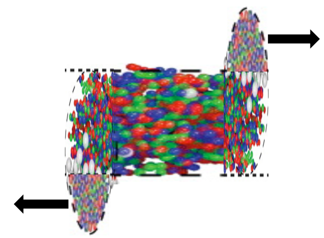
Elliptic flow (v_2) – excitation function including LHC results

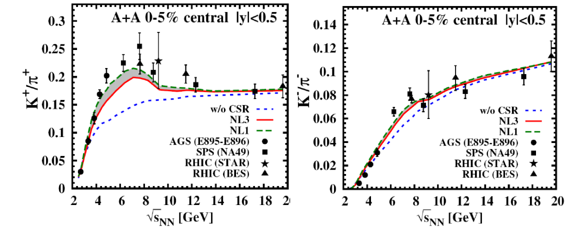


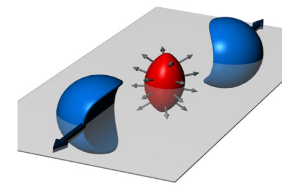
K. Aamodt et al, ALICE Collaboration PRL105(2010)252302

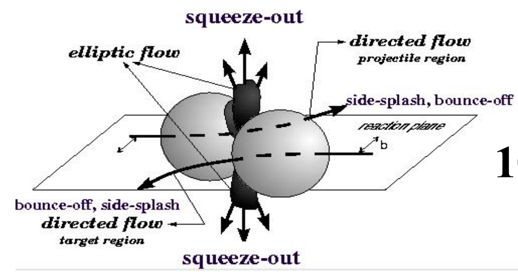
Physics motivation



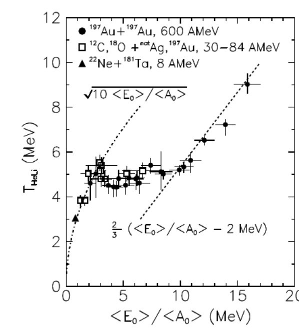


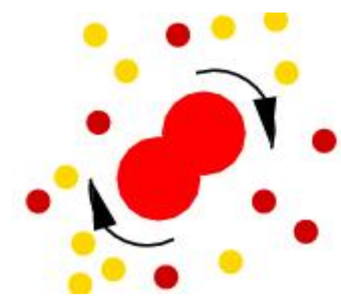






100 A•MeV - ~600 A•MeV

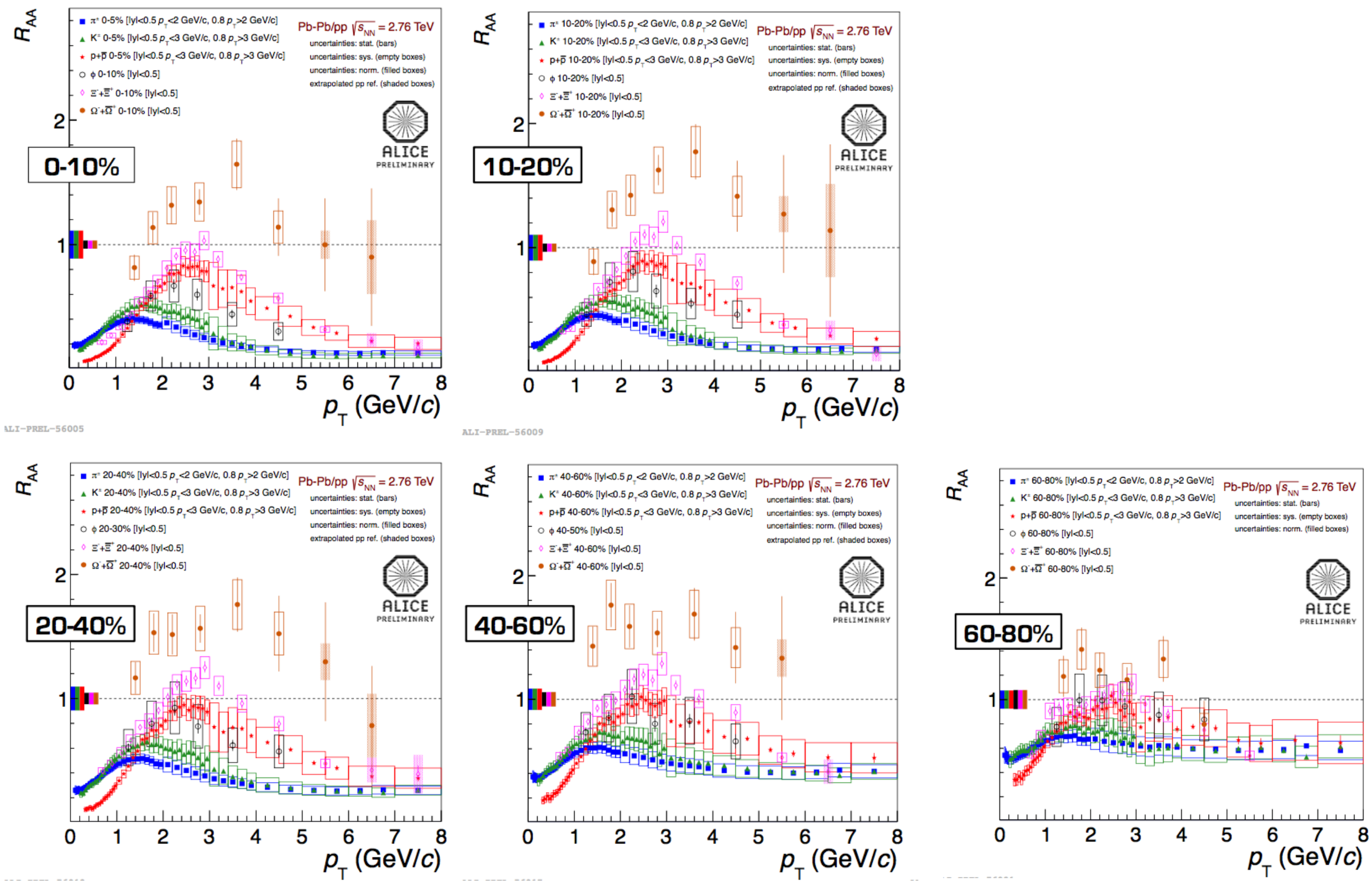




< 100 A•MeV

Suppression of high-p_T hadrons at LHC

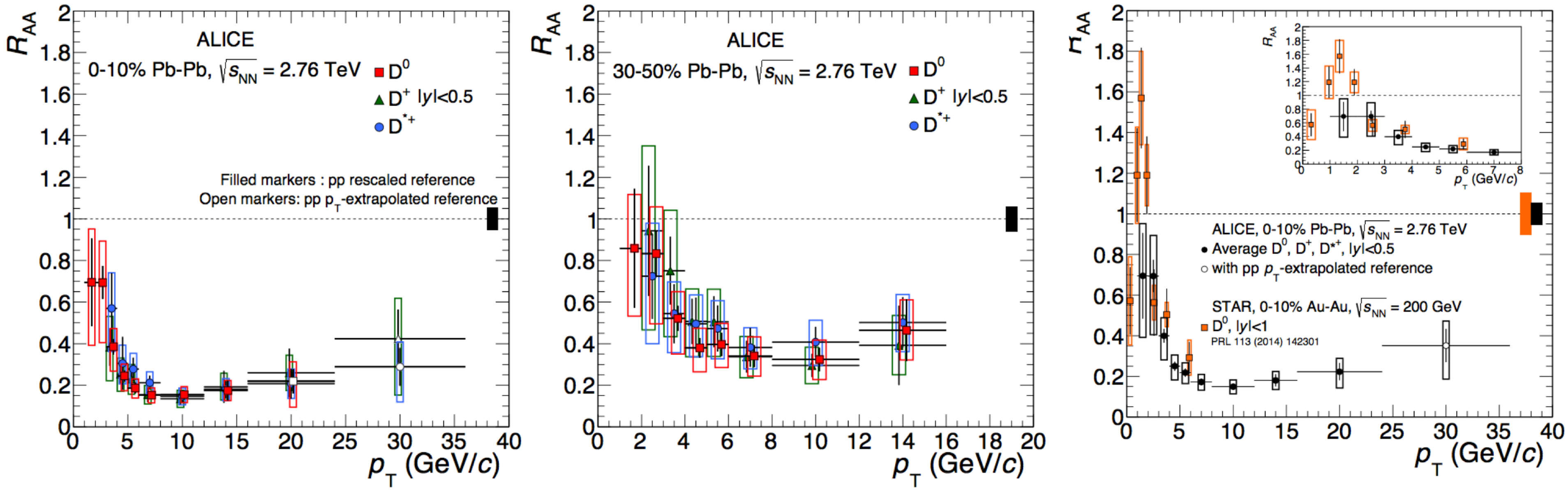
Pb-Pb collisions at $\sqrt{s_{NN}}$ =2.76 GeV



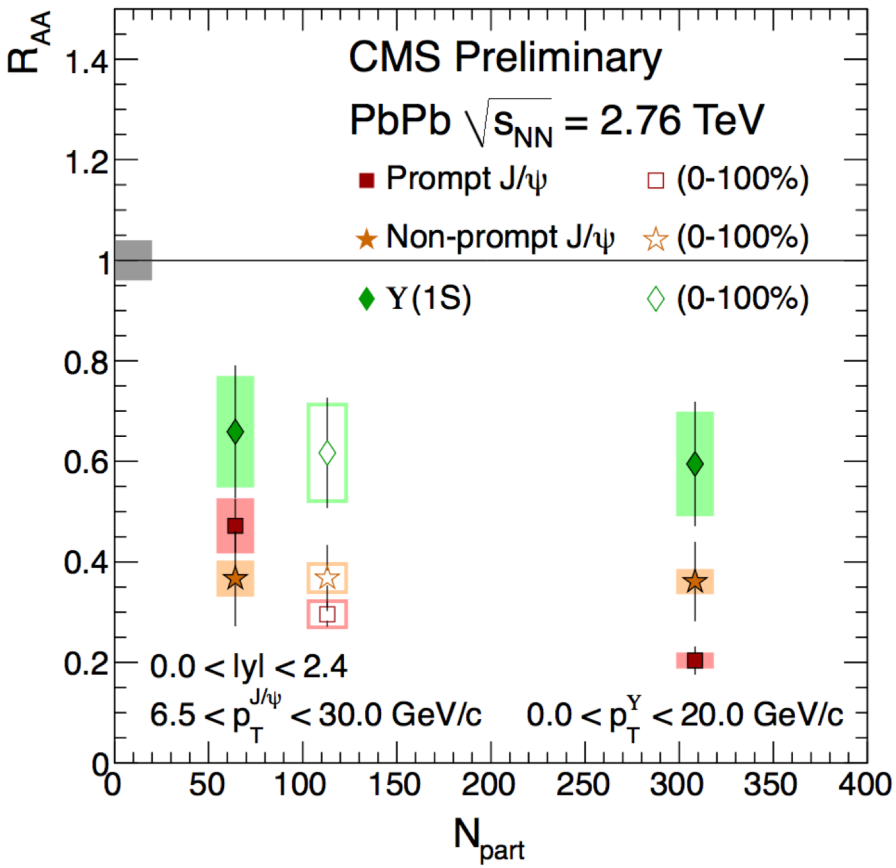
D.Collela et al., ALICE Collaboration, SQM July 22-27, 2013

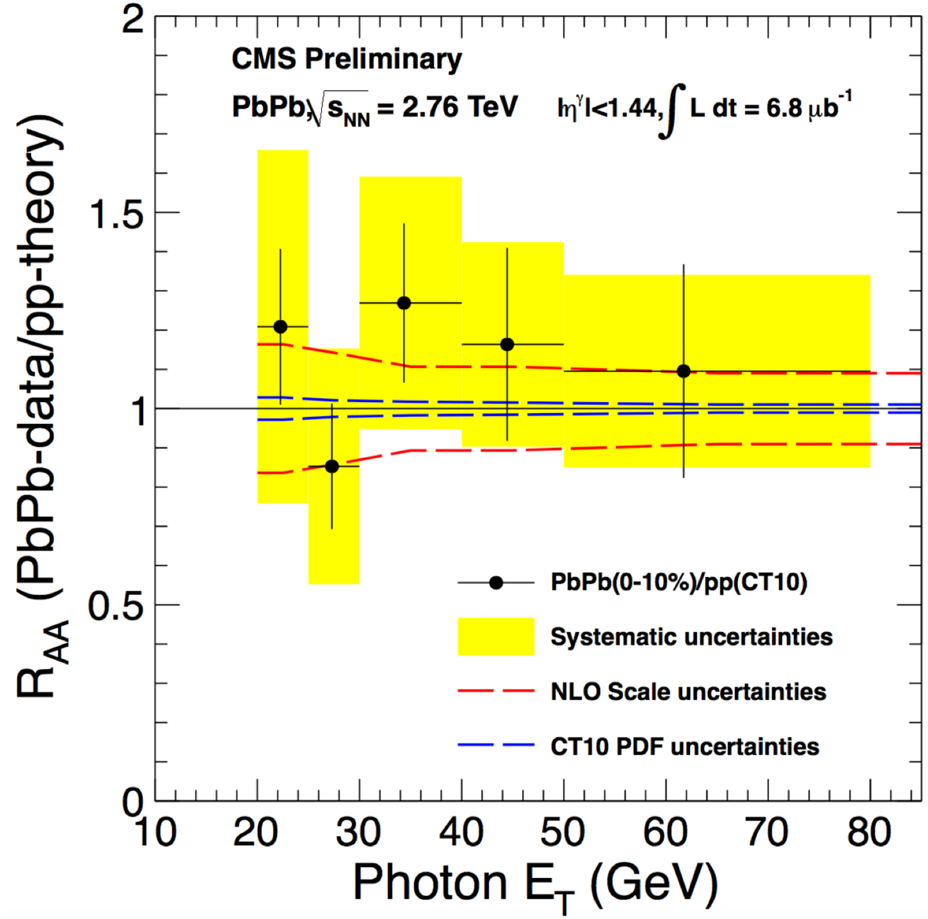
Suppression of high-p_T hadrons at LHC

Pb-Pb collisions at $\sqrt{s_{NN}}$ 2.76 GeV



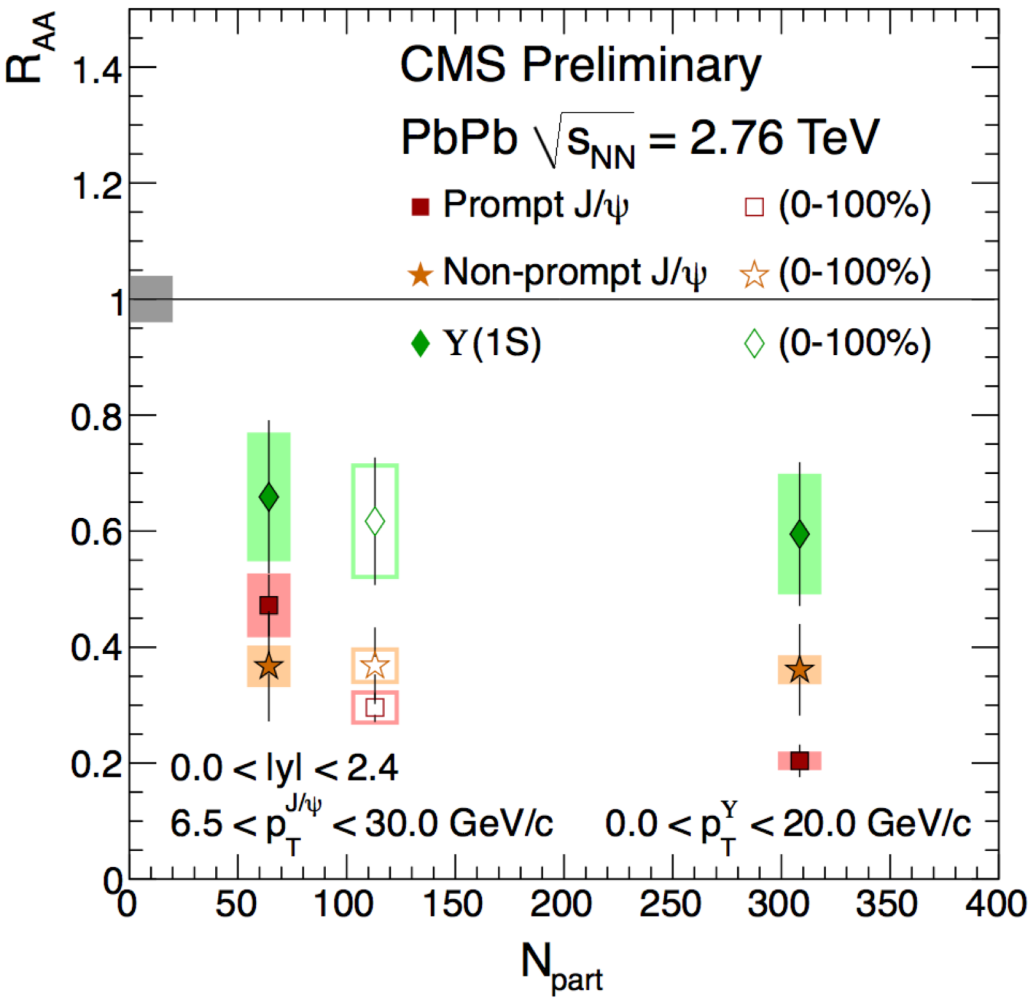
J.Adam et al., ALICE Collaboration, JHEP 03 (2016) 081

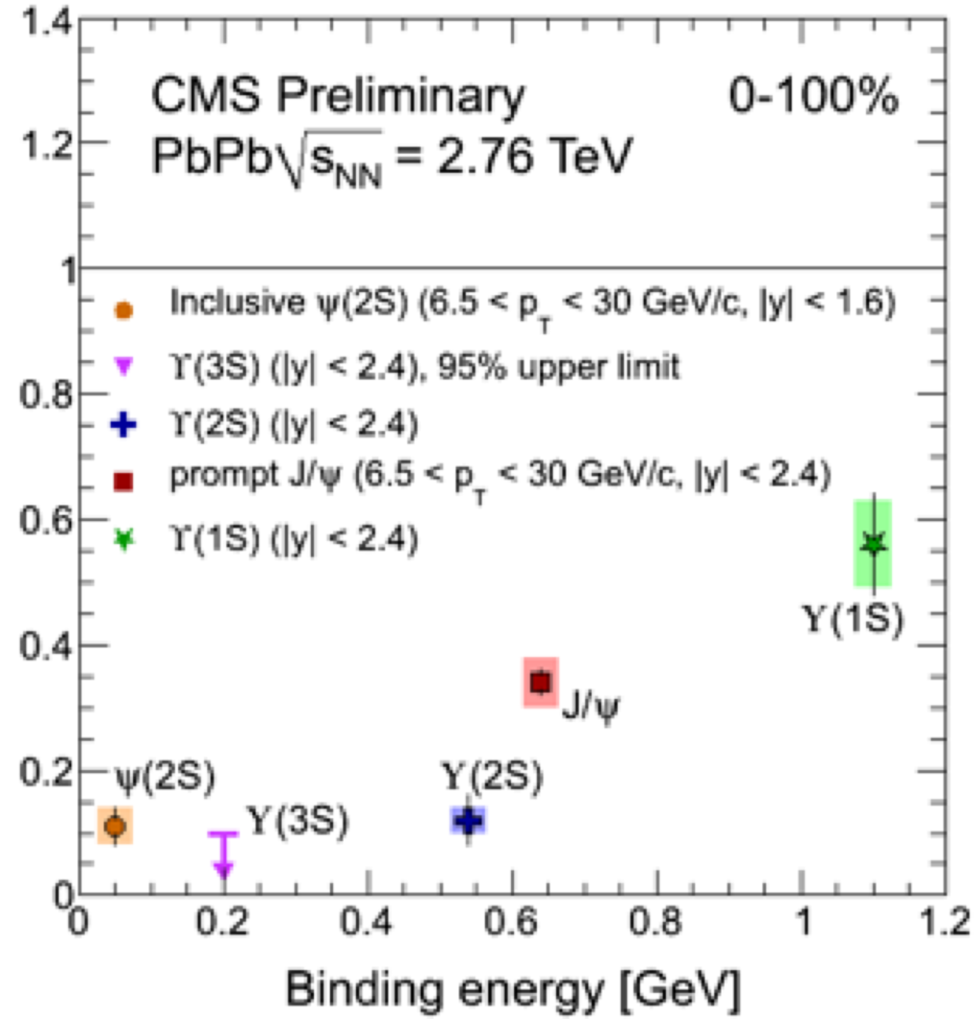

CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Prompt J/ψ
(0-100%)
Non-prompt J/ψ
(0-100%)
Υ(1S)
(0-100%)
0.0 < |y| < 2.4
$6.5 < p_T^{J/\psi} < 30.0$ GeV/c
$0.0 < p_T^{\Upsilon} < 20.0$ GeV/c
R_{AA}
N_{part}


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
$|\eta^{\gamma}|<1.44, \int L\,dt = 6.8\ \mu b^{-1}$
PbPb(0-10%)/pp(CT10)
Systematic uncertainties
NLO Scale uncertainties
CT10 PDF uncertainties
R_{AA} (PbPb-data/pp-theory)
Photon E_T (GeV)

Suppression of high-p_T hadrons at LHC

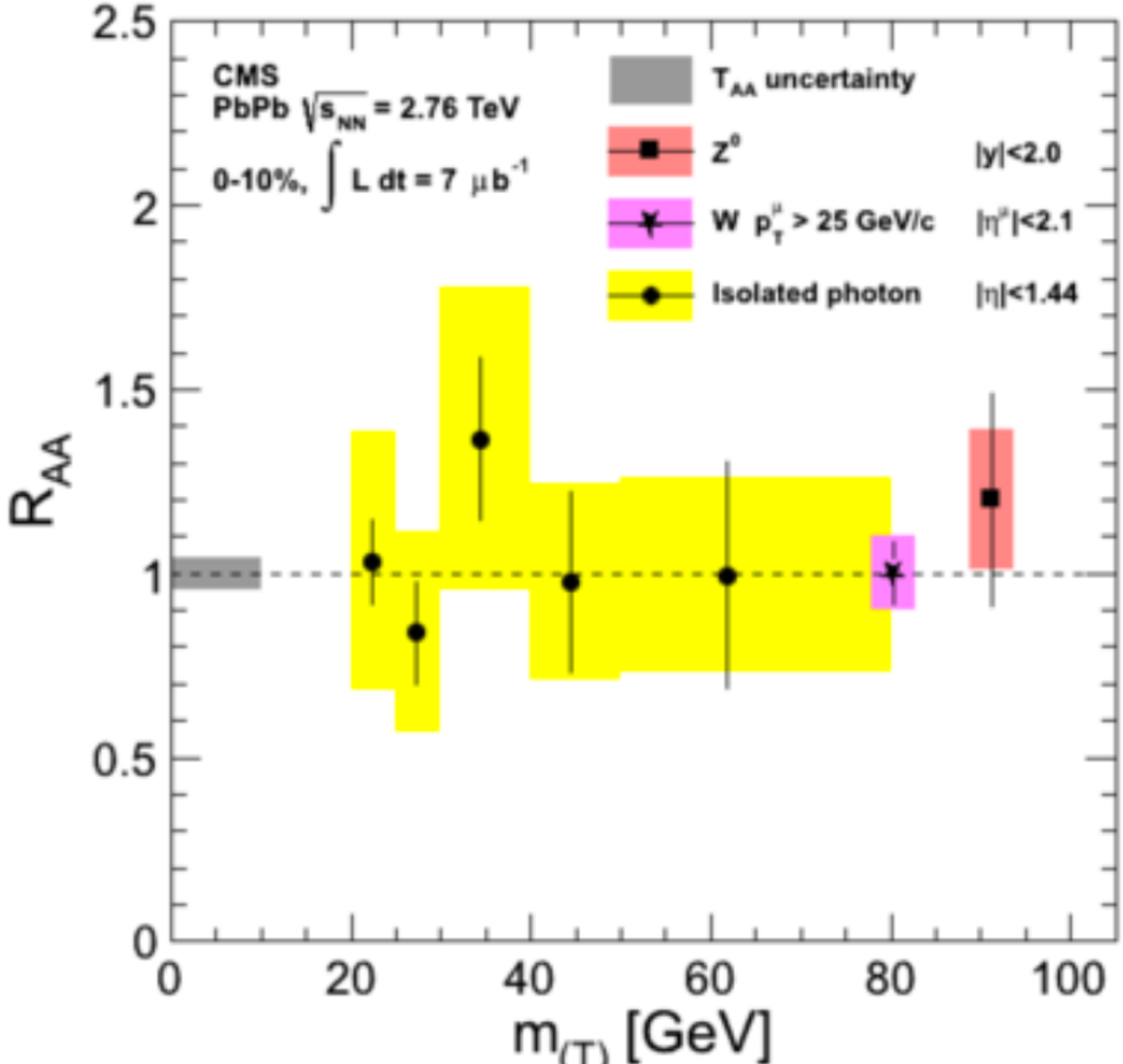
The suppression factors, as a function of the binding energy of the respective quarkonium state





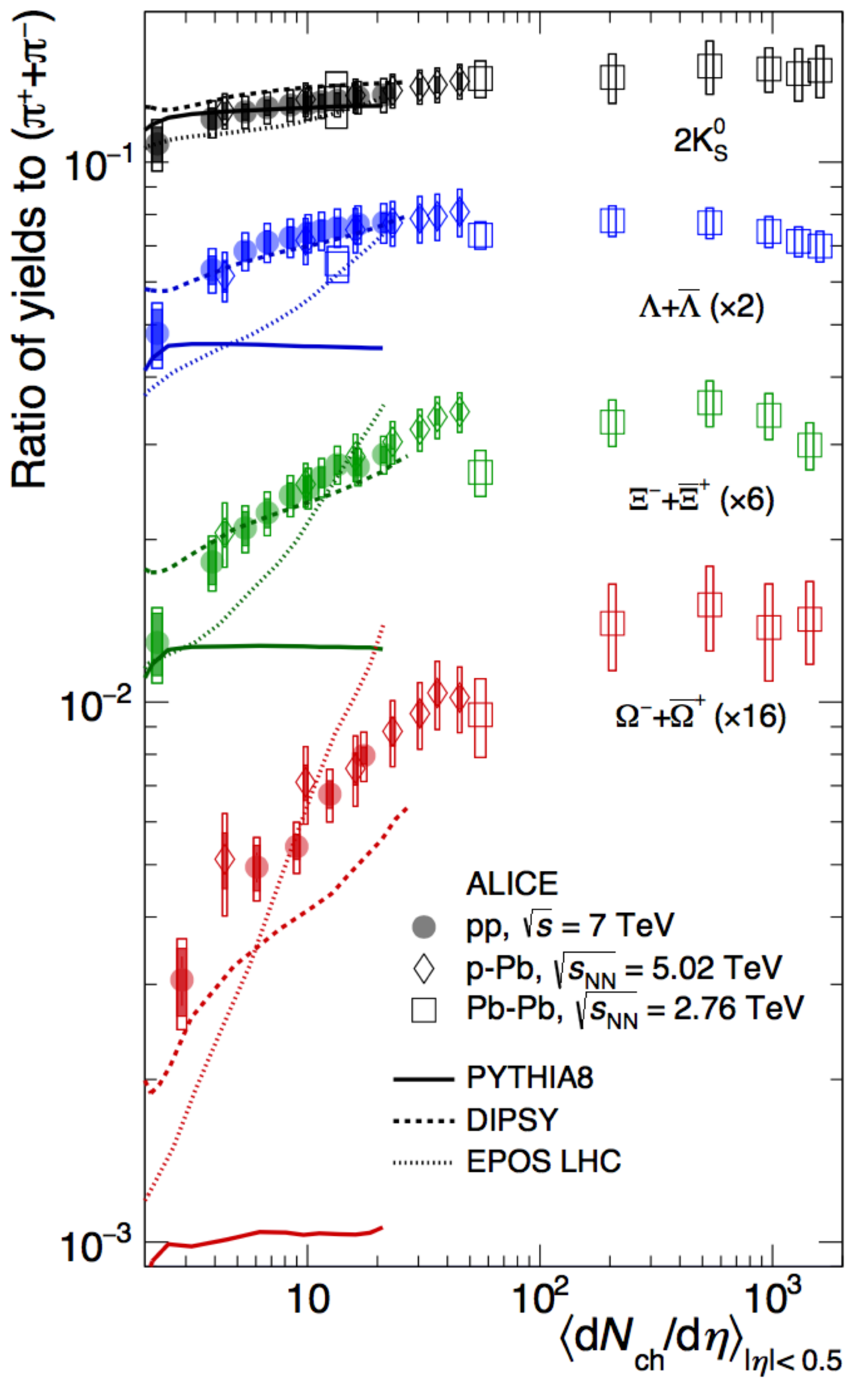
L.Taylor et al., CMS Collaboration, 2012-08-13, Quark Matter 2012

Suppression of high-p_T hadrons at LHC



B.Cruz et al., CMS Collaboration, Nucl. Phys. A 910–911(2013)139

Strangeness enhancement at LHC

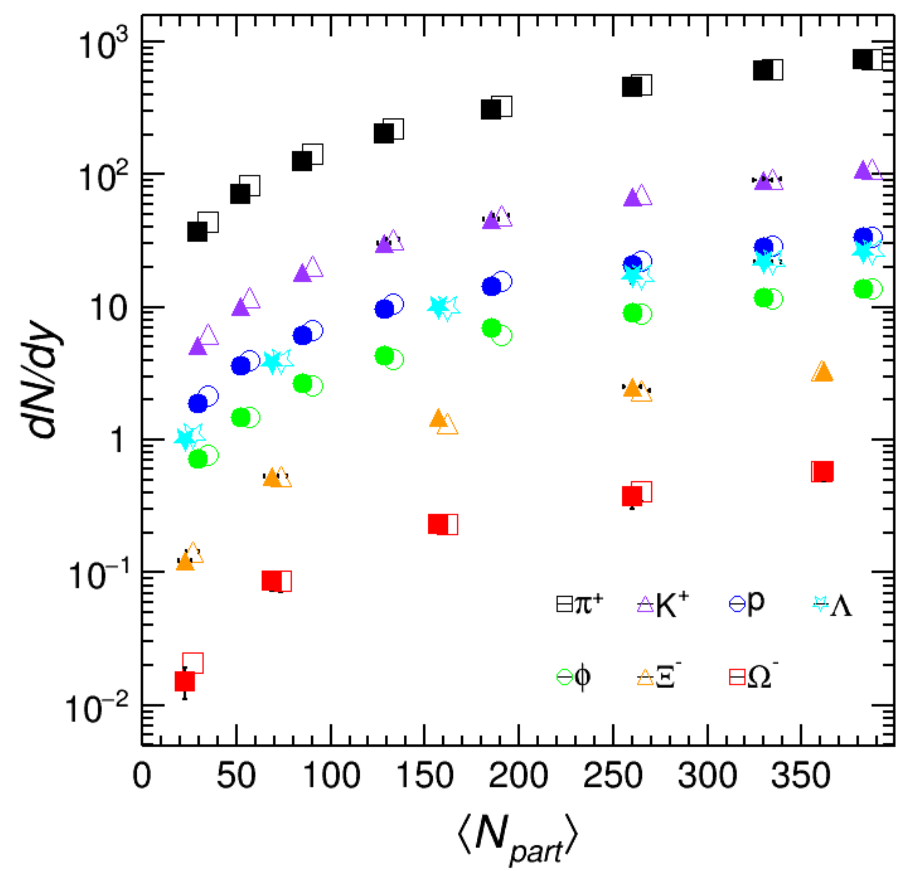


J.Adam et al., ALICE Collaboration, Nature Physics 13 (2017) 535-539

Core-Corona effect

$$\left(\frac{dN}{dy}\right)_i^{cen} = N_{part}[(1-f_{core})M_i^{ppMB} + f_{core}M_i^{core}]$$

$$M_i^{ppMB} = \frac{1}{2}(dN/dy)_i^{ppMB}$$



M. Petrovici, I. Berceanu, A. Pop, M. Târzila, and C. Andrei, Phys.Rev. C96(2017)014908

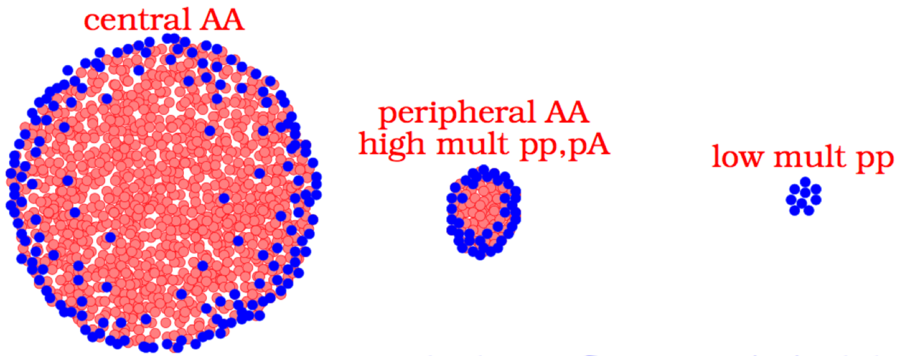
Core-corona in pp

Core-corona picture in EPOS

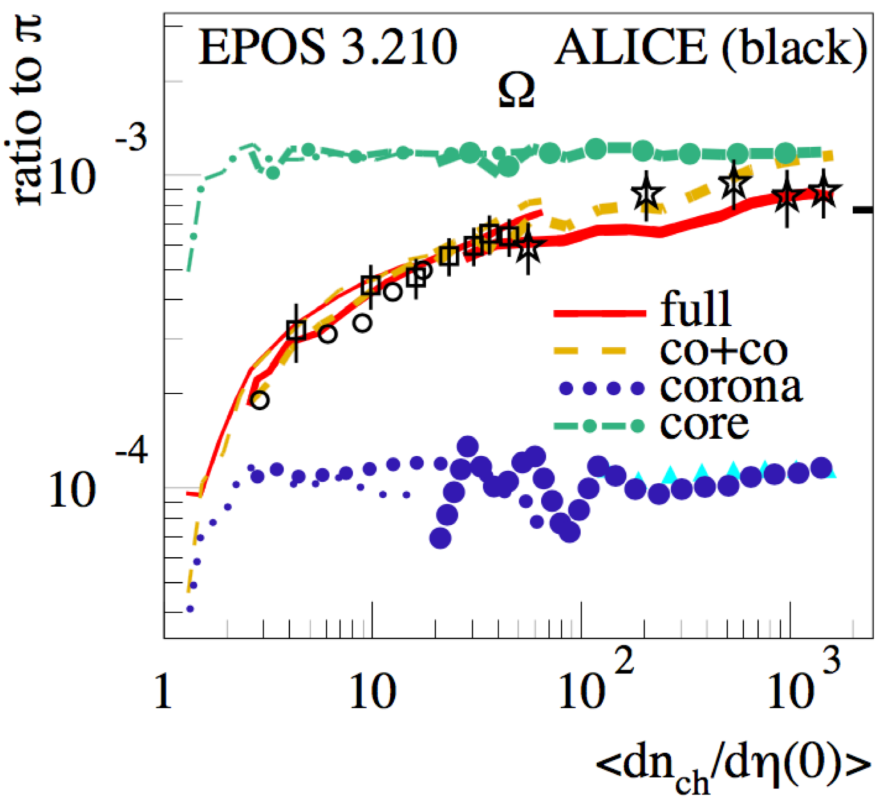
Phys.Rev.Lett. 98 (2007) 152301, Phys.Rev. C89 (2014) 6, 064903

K. Werner, SQM 2017, July 10-15 2017, Utrecht

Gribov-Regge approach => (Many) kinky strings
=> core/corona separation (based on string segments)

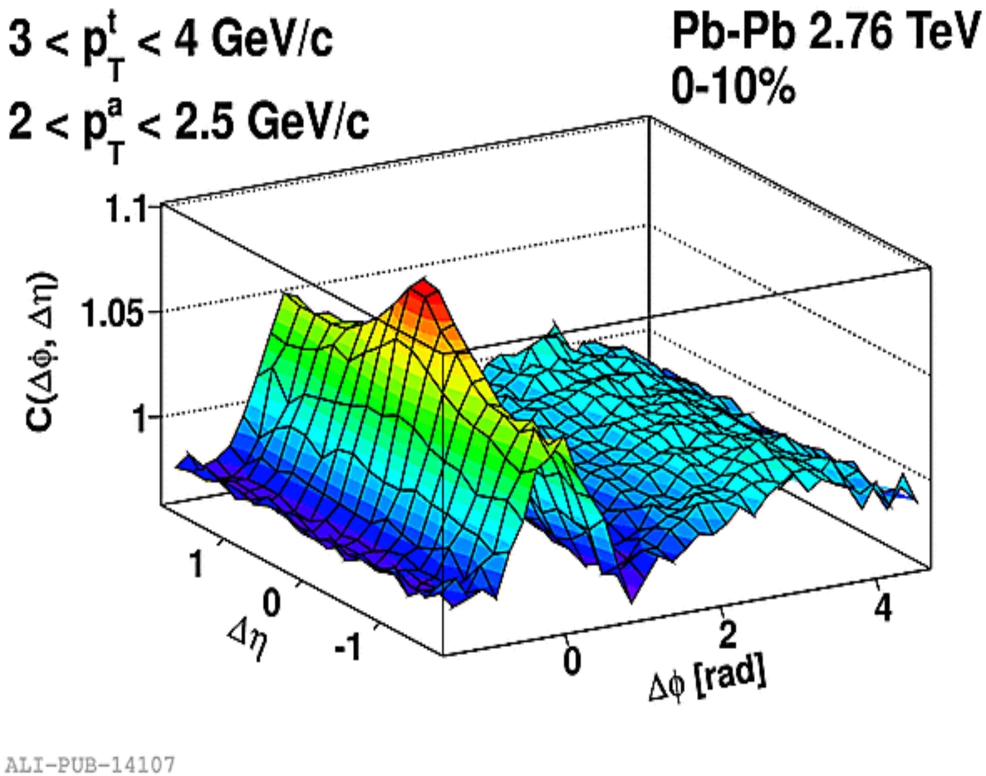


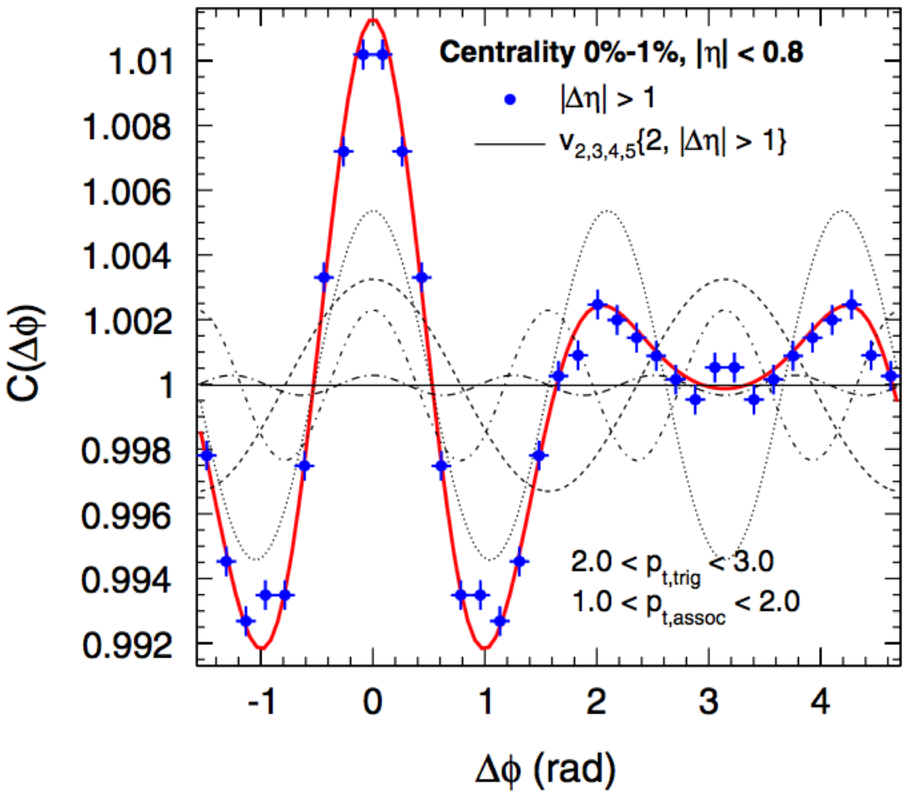
core => hydro => flow + statistical decay
corona => string decay



thin lines = pp (7TeV)
intermediate lines = pPb (5TeV)
thick lines = PbPb (2.76TeVVV)
circles = pp (7TeV)
squares = pPb (5TeV)
stars = PbPb (2.76TeV)

Two-particle correlations at LHC

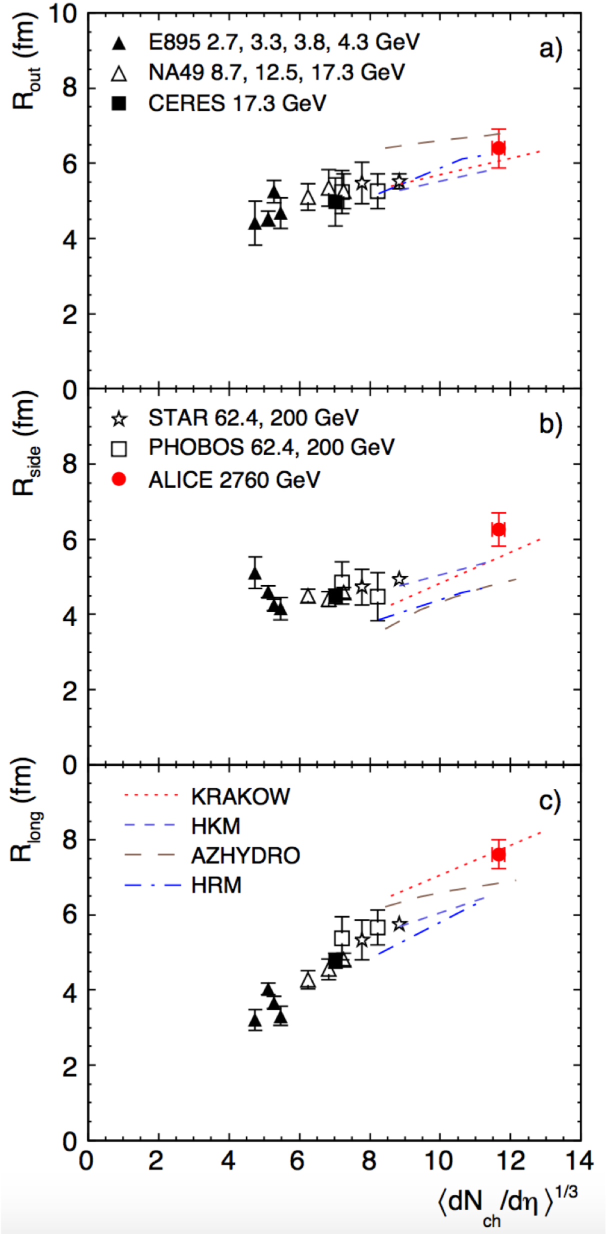


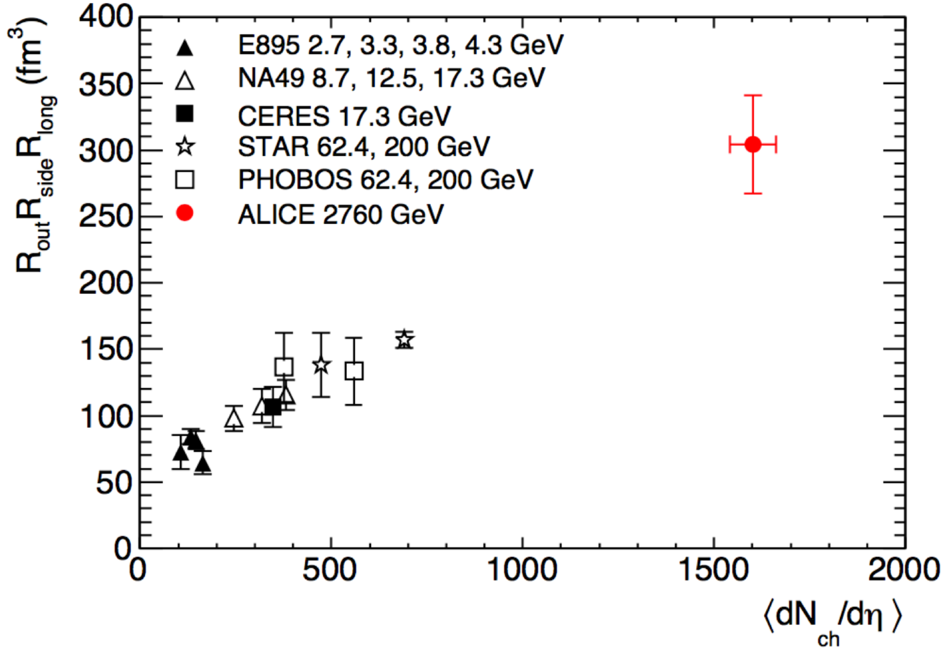


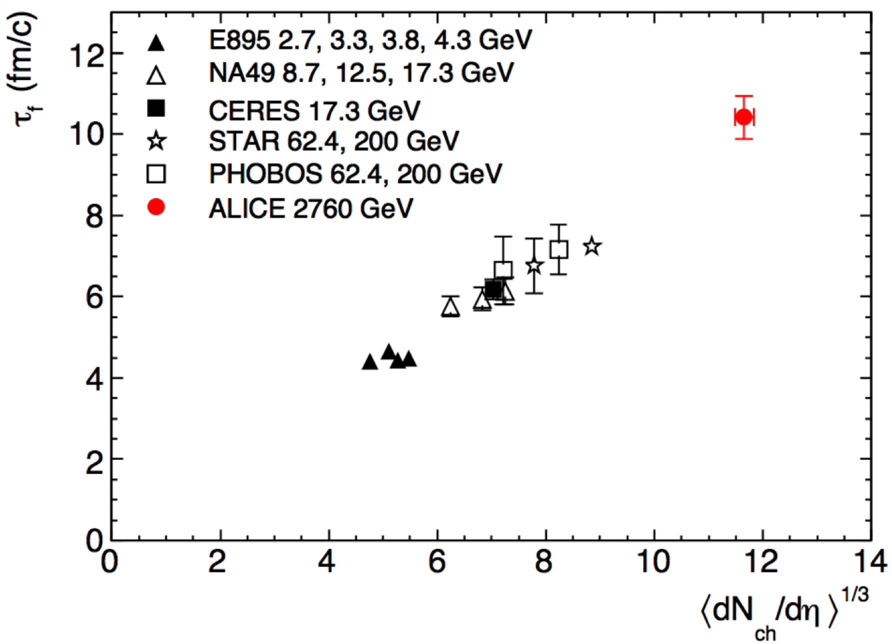
I.G.Altsybeev et al., ALICE Collaboration, arXiv:[nucl-ex]1611.10090

K.Aamodt et al., ALICE Collaboration Phys.Rev.Lett. 107(2011)032301

Bose-Einstein correlations at AGS, SPS, RHIC and LHC

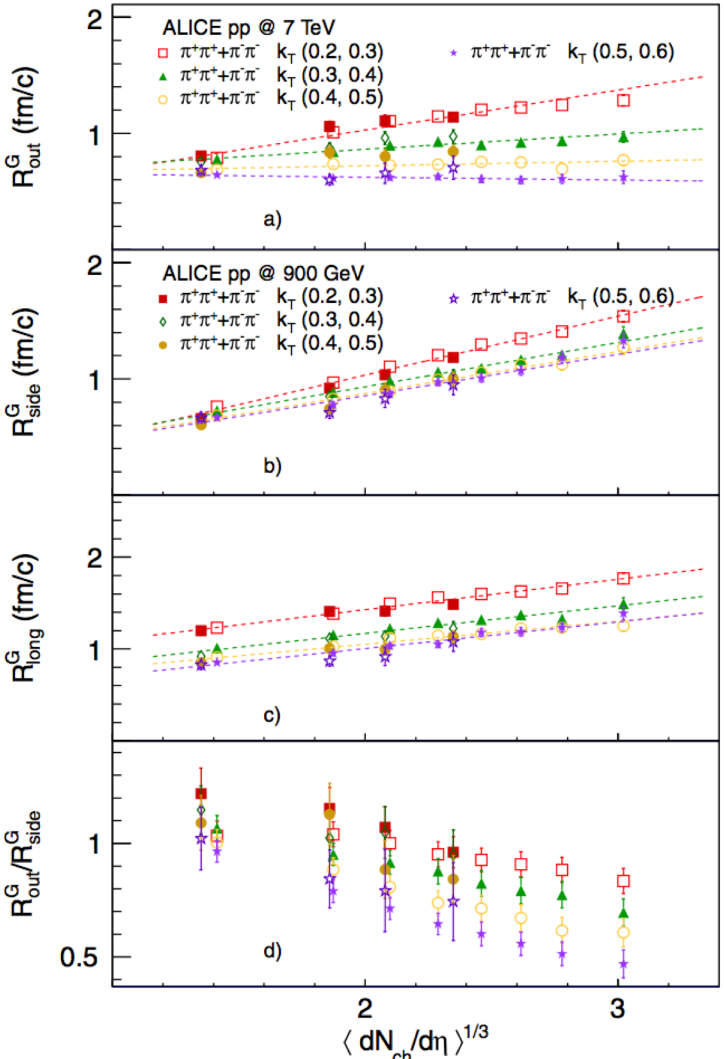


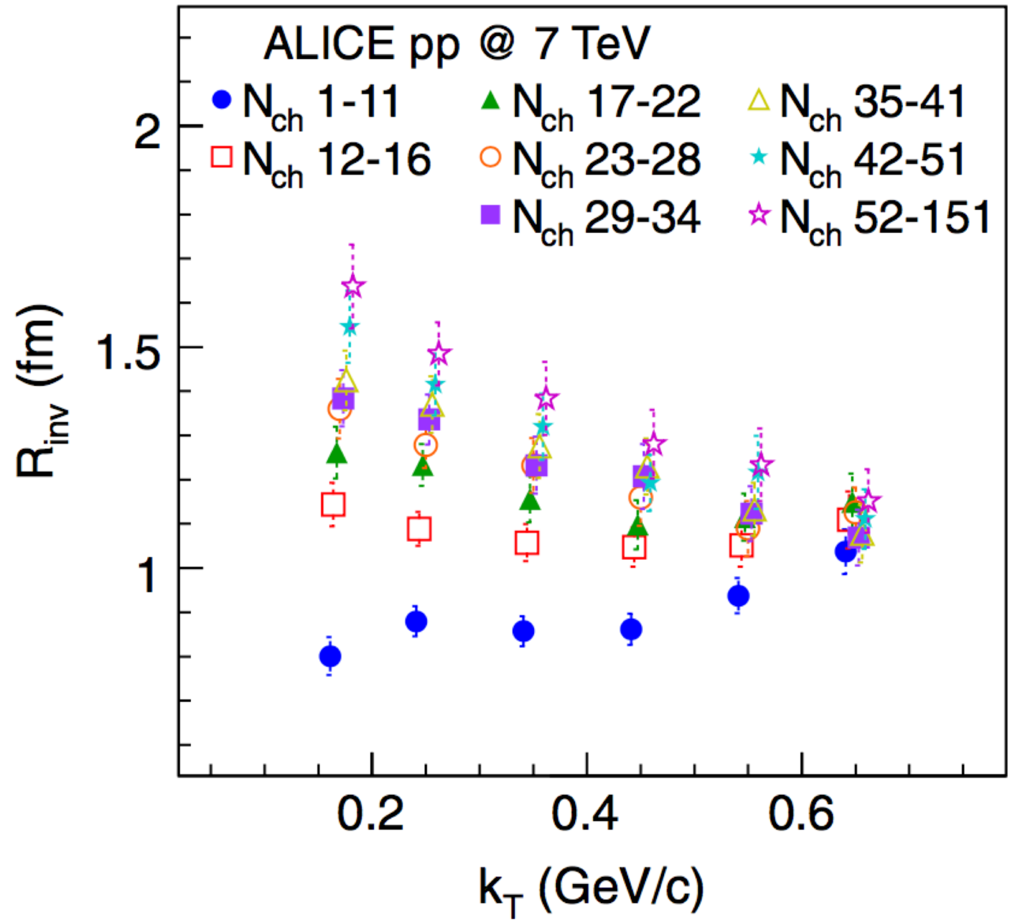




K.Aamodt et al., ALICE Collaboration, Phys.Lett. B696(2011)328

Bose-Einstein correlations for pp collisions at LHC





$C(\mathbf{q})=A(\mathbf{q})/B(\mathbf{q})$

- $A(\mathbf{q})$ measured two-particle distribution of a pair momentum difference $\mathbf{q}=\mathbf{p}_2-\mathbf{p}_1$
- $B(\mathbf{q})$ similar with $A(\mathbf{q})$ but for pairs from different event
- $k_T=|\mathbf{p}_{T,1} + \mathbf{p}_{T,2}|/2$

q_{long} is parallel to the beam, q_{out} is parallel to the pair transverse momentum, and q_{side} is perpendicular to q_{long} and q_{out}

$C(q_{inv}) = [((1-\boldsymbol{\lambda})+\boldsymbol{\lambda}K(q_{inv})(1+\exp(-R^2_{inv}q^2_{inv})]B(q_{inv})$

K.Aamodt et al., ALICE Collaboration, Phys.Rev. D84(2011)112004

Bjorken energy density

$$\varepsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{S_T\tau}$$

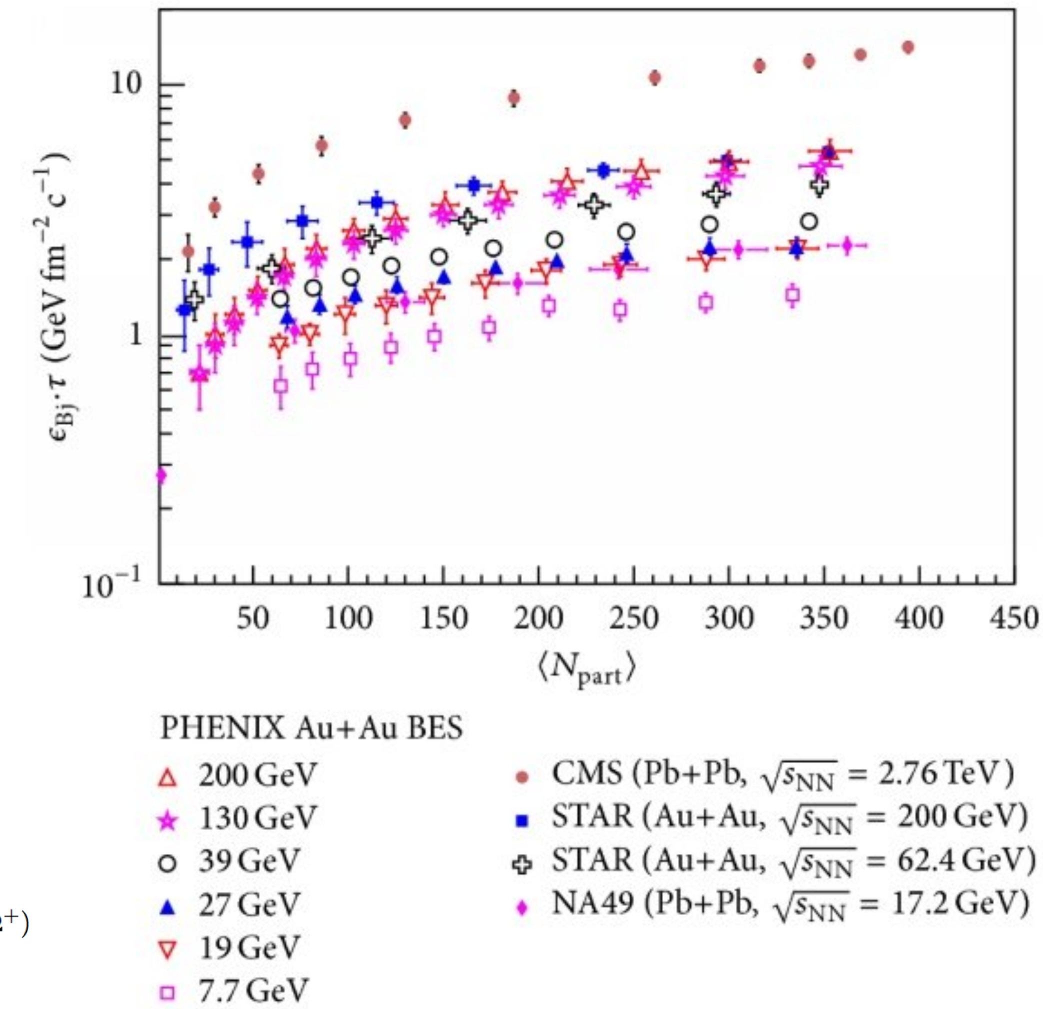
$$\frac{dE_T}{dy} \approx \frac{3}{2}(< m_T > \frac{dN}{dy})_{\pi^\pm} + 2(< m_T > \frac{dN}{dy})_{K^\pm,p,\bar{p}}$$

$$< m_T > = \sqrt{< p_T >^2 + m_0^2}$$

$$\frac{dN}{dy} \simeq \frac{3}{2}\frac{dN}{dy}^{(\pi^+ + \pi^-)} + 2\frac{dN}{dy}^{(K^+ + K^-, p+\bar{p}, \Xi^- + \bar{\Xi}^+)} + \frac{dN}{dy}^{(\Lambda+\bar{\Lambda})}$$

$$\frac{dN}{dy} \simeq \frac{3}{2}\frac{dN}{dy}^{(\pi^+ + \pi^-)} + 2\frac{dN}{dy}^{(K^+ + K^-, p+\bar{p}, \Xi^- + \bar{\Xi}^+)} + \frac{dN}{dy}^{(\Lambda+\bar{\Lambda}, \Omega^- + \bar{\Omega}^+)}$$

$$\frac{dN}{dy} \simeq \frac{3}{2}\frac{dN}{dy}^{(\pi^+ + \pi^-)} + 2\frac{dN}{dy}^{(p+\bar{p}, \Xi^- + \bar{\Xi}^+)} + \frac{dN}{dy}^{(K^+ + K^-, K_S^0 + \bar{K_S^0}, \Lambda+\bar{\Lambda}, \Omega^- + \bar{\Omega}^+)}$$

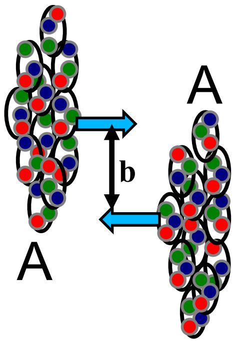


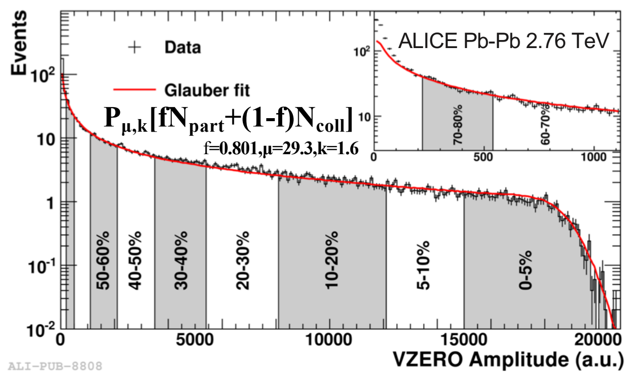
R.Sahoo et al., arXiv:[nucl-ex]1408.5773

A few considerations

Pb-Pb collisions at $\sqrt{s_{NN}}$ 2.76 GeV

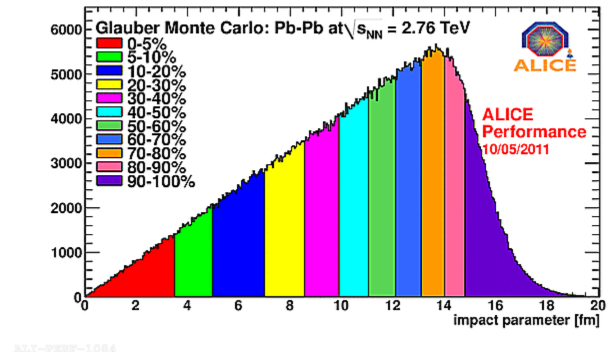
Experimental Multiplicity

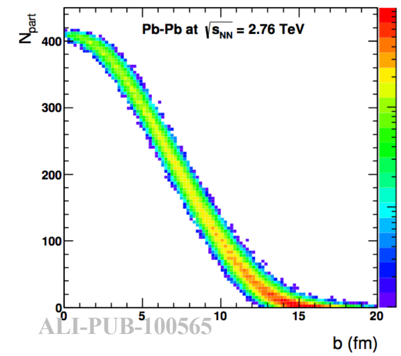


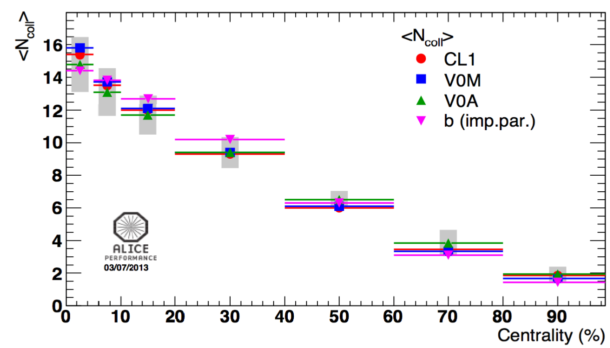


ALICE Collaboration, Phys. Rev. Lett. 106, 032301

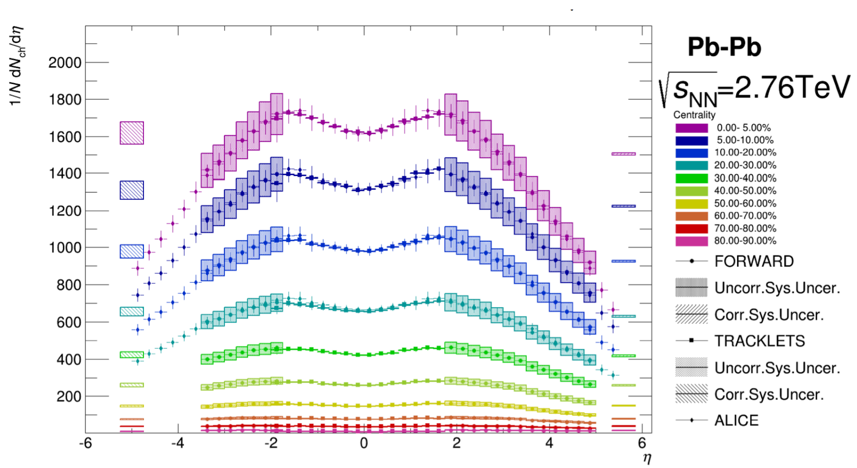
Glauber MC

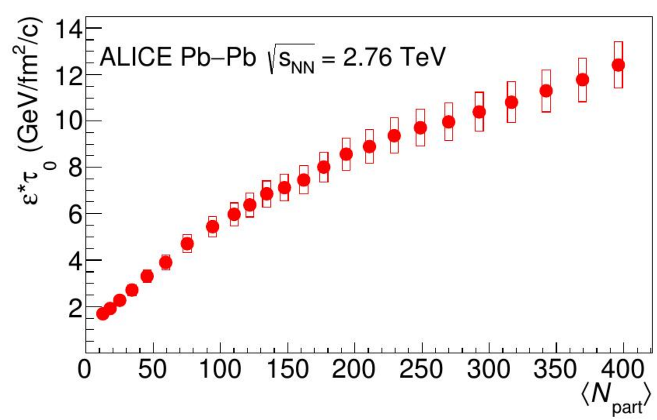




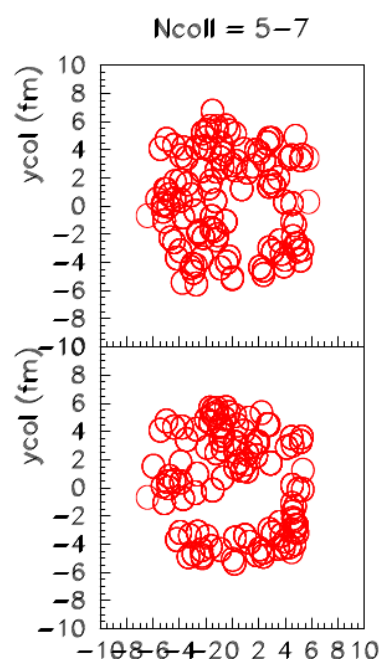


- highly non-homogeneous initial state
- Bjorken energy estimate is based on S_T supposing a uniform distribution





Glauber MC



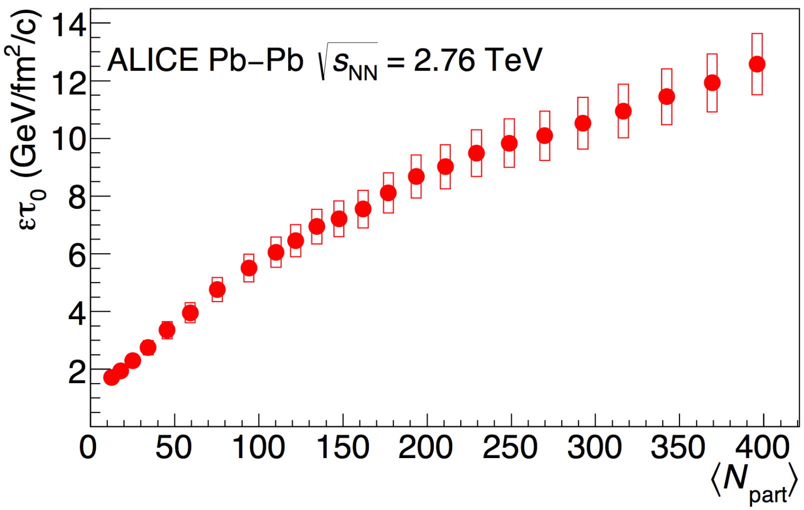
A few considerations

Bjorken energy density - Pb+Pb

$$\varepsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{S_T\tau}$$

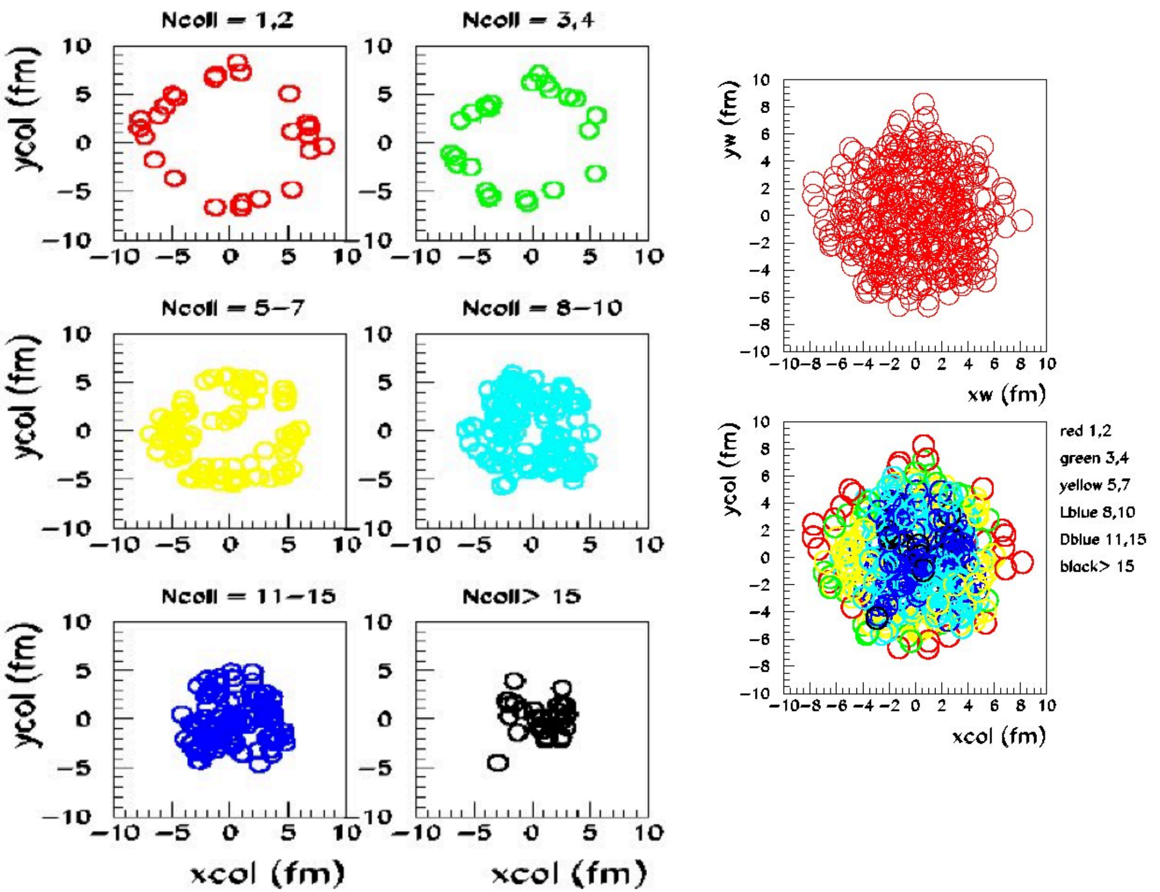
$$\frac{dE_T}{dy} \approx \frac{3}{2}(< m_T > \frac{dN}{dy})_{\pi^\pm} + 2(< m_T > \frac{dN}{dy})_{K^\pm,p,\overline{p}} \qquad < m_T >= \sqrt{< p_T >^2 + m_0^2}$$

Pb+Pb $\sqrt{s_{NN}}$ *2.76 TeV*



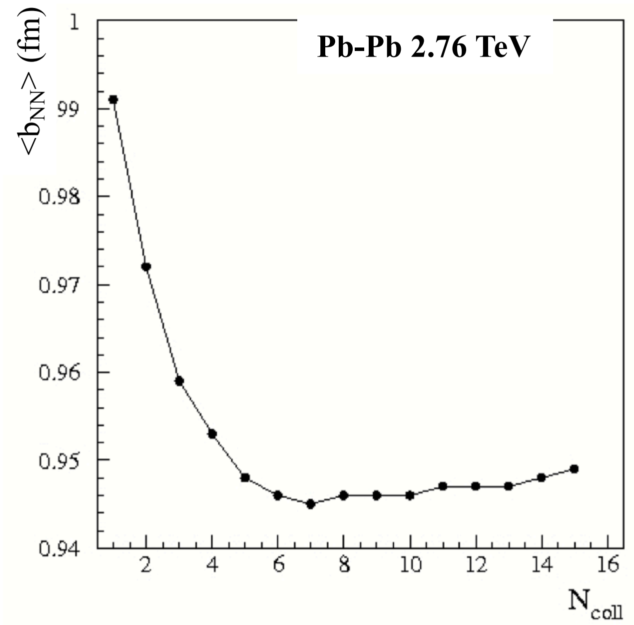
J.Adam et al., ALICE Coll., CERN-EP-2016-071 11 March 2016

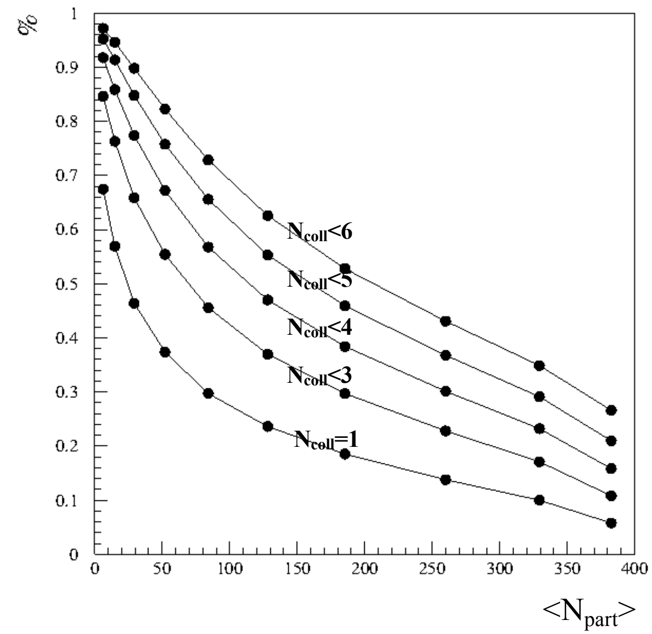
Glauber MC, b=0



A few considerations
Core-Corona effect

Glauber MC





$$\left(\frac{dN}{dy}\right)_i^{cen} = N_{part}[(1-f_{core})M_i^{ppMB} + f_{core}M_i^{core}]$$

$$M_i^{ppMB}=\frac{1}{2}(dN/dy)_i^{ppMB}$$

How should we define "Corona" ?

F.Becattini, J.Manninen, J.Phys.G 35 (2008) 104013, Phys.Lett.B 673(2009)19
J.Aichelin, K.Werner, Phys.Rev.C 79(2009)064907,
J.Phys.G 37(2010)094006,
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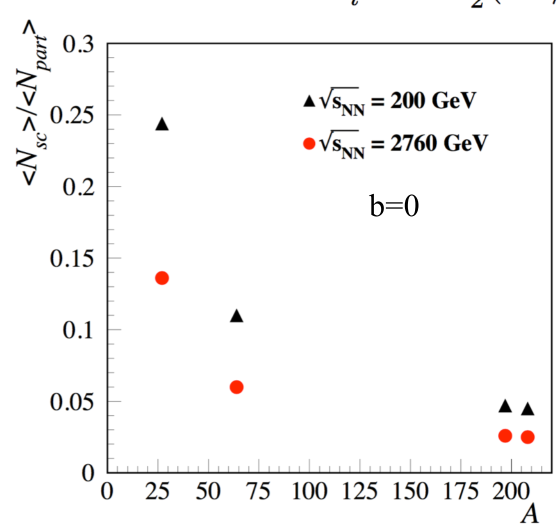
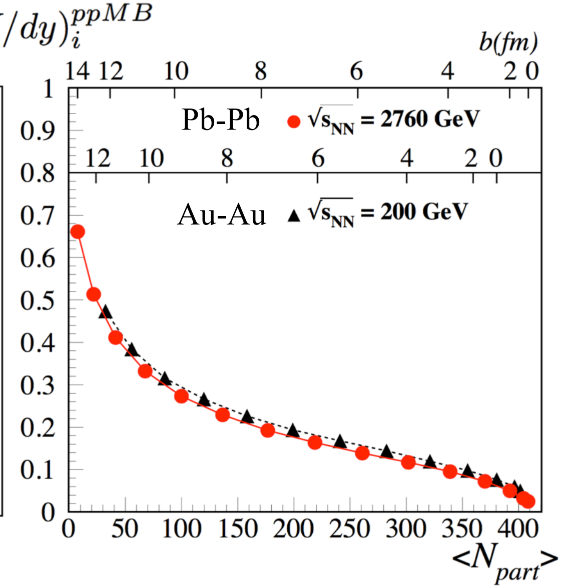
P.Bozek, Phys.Rev.C 79 (2009) 054901
C.Schreiber, K.Werner, J.Aichelin, Phys.Atom.Nucl. 75(2012)640
M.Gemard and J.Aichelin, Astron.Nachr. 335(2014)660





M. Petrovici, I. Berceanu, A. Pop, M. Târzila, and C. Andrei, Phys.Rev. C96(2017)014908

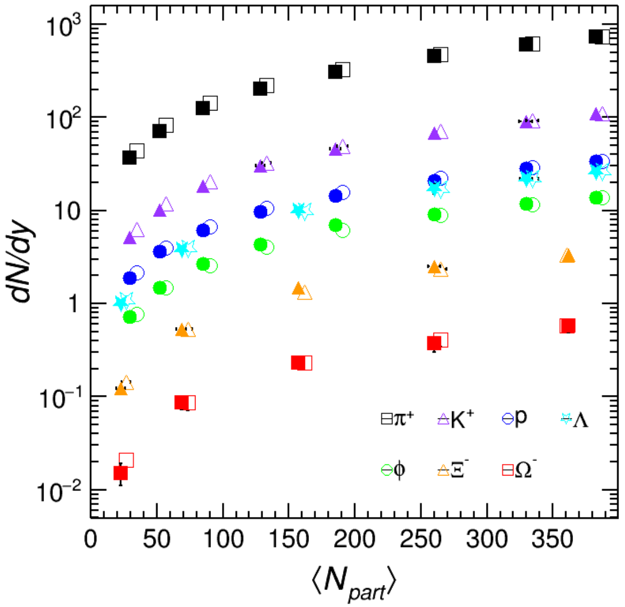
A few considerations

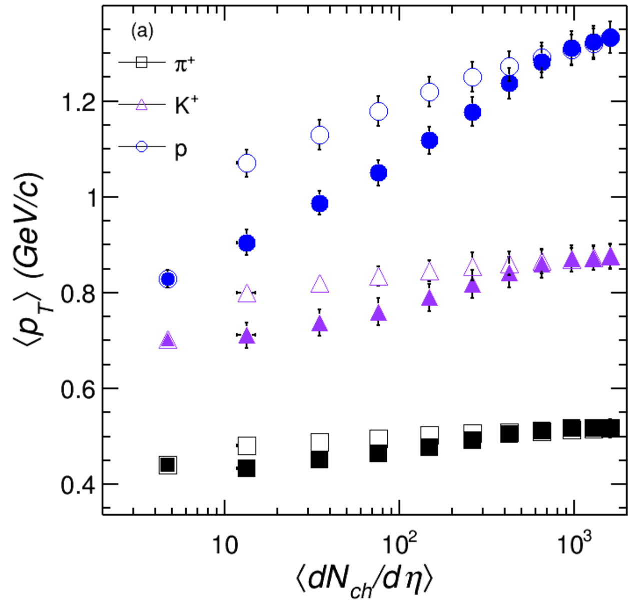
Core-Corona effect

$$\left(\frac{dN}{dy}\right)_i^{cen} = N_{part}[(1-f_{core})M_i^{ppMB} + f_{core}M_i^{core}] \qquad (1)$$

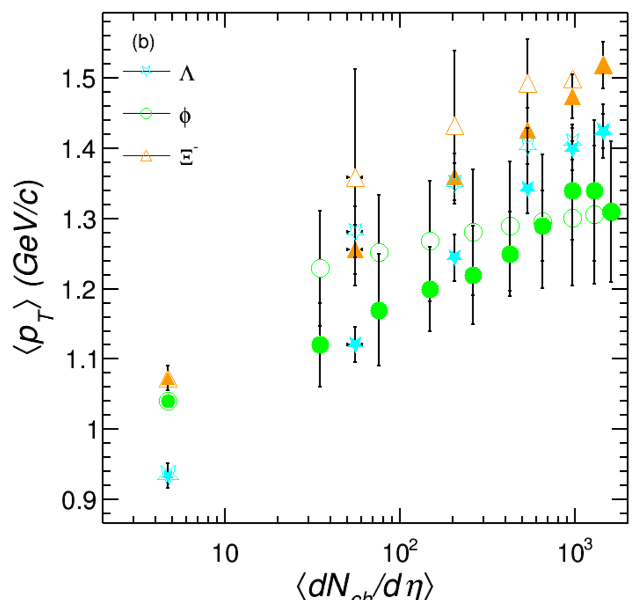
$$M_i^{ppMB} = \frac{1}{2}(dN/dy)_i^{ppMB} \qquad (2)$$

$$\langle p_T\rangle_i^{cen} = \frac{f_{core}\langle p_T\rangle_i^{core}M_i^{core} + (1-f_{core})\langle p_T\rangle_i^{ppMB}M_i^{ppMB}}{f_{core}M_i^{core} + (1-f_{core})M_i^{ppMB}} \qquad (3)$$



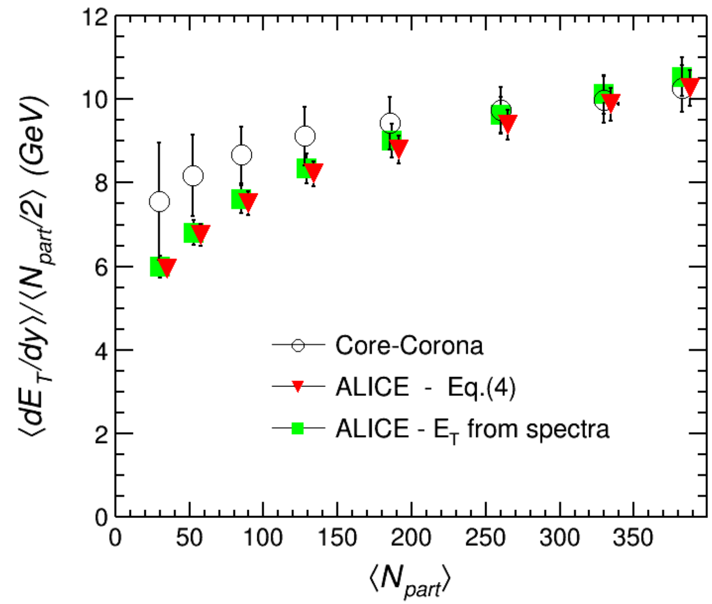


Full symbols - experiment
Open symbols – core-corona interplay



$$\frac{dE_T}{dy} \approx 3\left(\frac{dE_T}{dy}\right)_{\pi^+} + 4\left(\frac{dE_T}{dy}\right)_{K^+,p,\Xi^-} + 2\left(\frac{dE_T}{dy}\right)_{\Lambda,\Omega^-} \quad (4)$$

$$\frac{dE_T}{dy} = \langle m_T\rangle\frac{dN}{dy} \qquad \langle m_T\rangle = \sqrt{\langle p_T\rangle^2 + m^2}$$

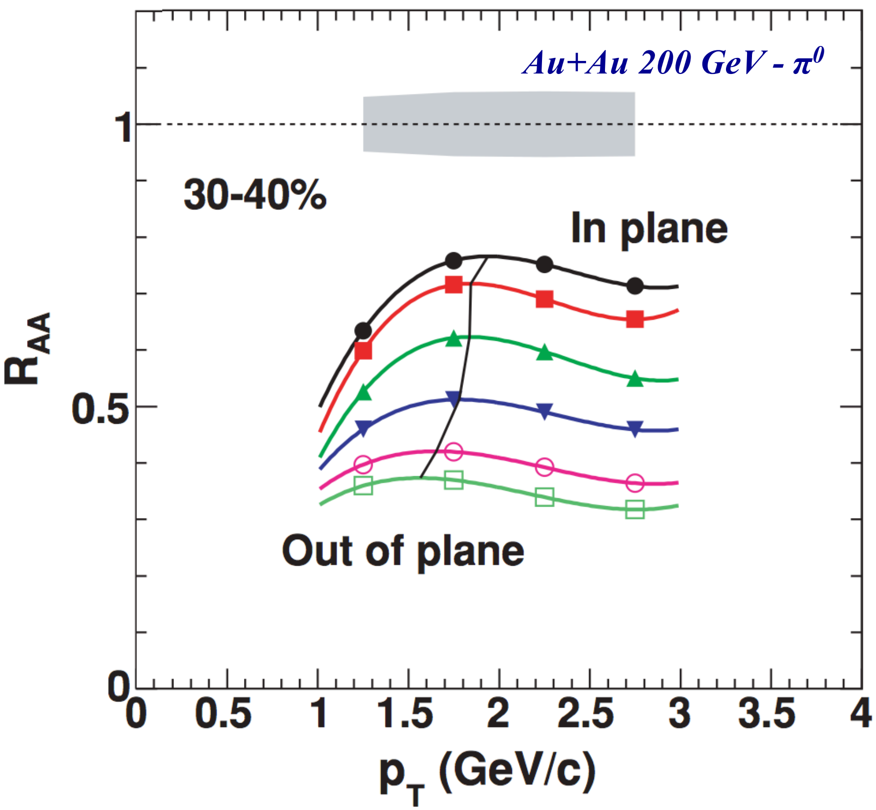


ALICE Coll., Phys.Rev. C88(2013)044910
ALICE Coll., Phys.Rev.Lett 111(2013)222301
ALICE Coll., Phys.Lett. B728(2014)216
ALICE Coll., Phys.Rev. C91(2015)024609
M. Petrovici, I. Berceanu, A. Pop, M. Târzila, and C. Andrei, Phys.Rev. C96(2017)014908

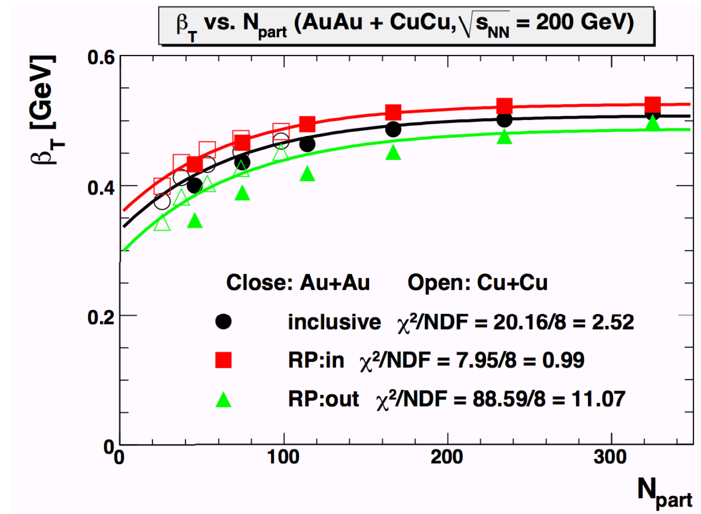
Which is the source of difference between Core-Corona in <p_T> and ration of normalized p_T distributions relative to Core-Corona in yields ?

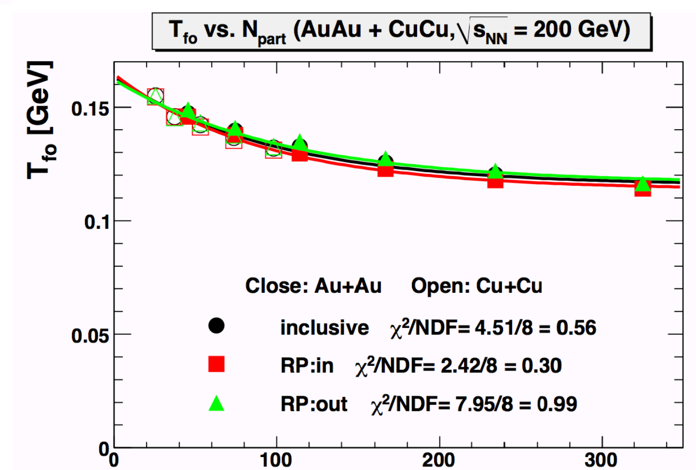
Core <p_T> and ratio of normalized p_T distributions is fireball shape dependent

Which is not included in the simple anzatz used up to now !!!



PHENIX Coll. Phys.Rev. C80(2009)054907

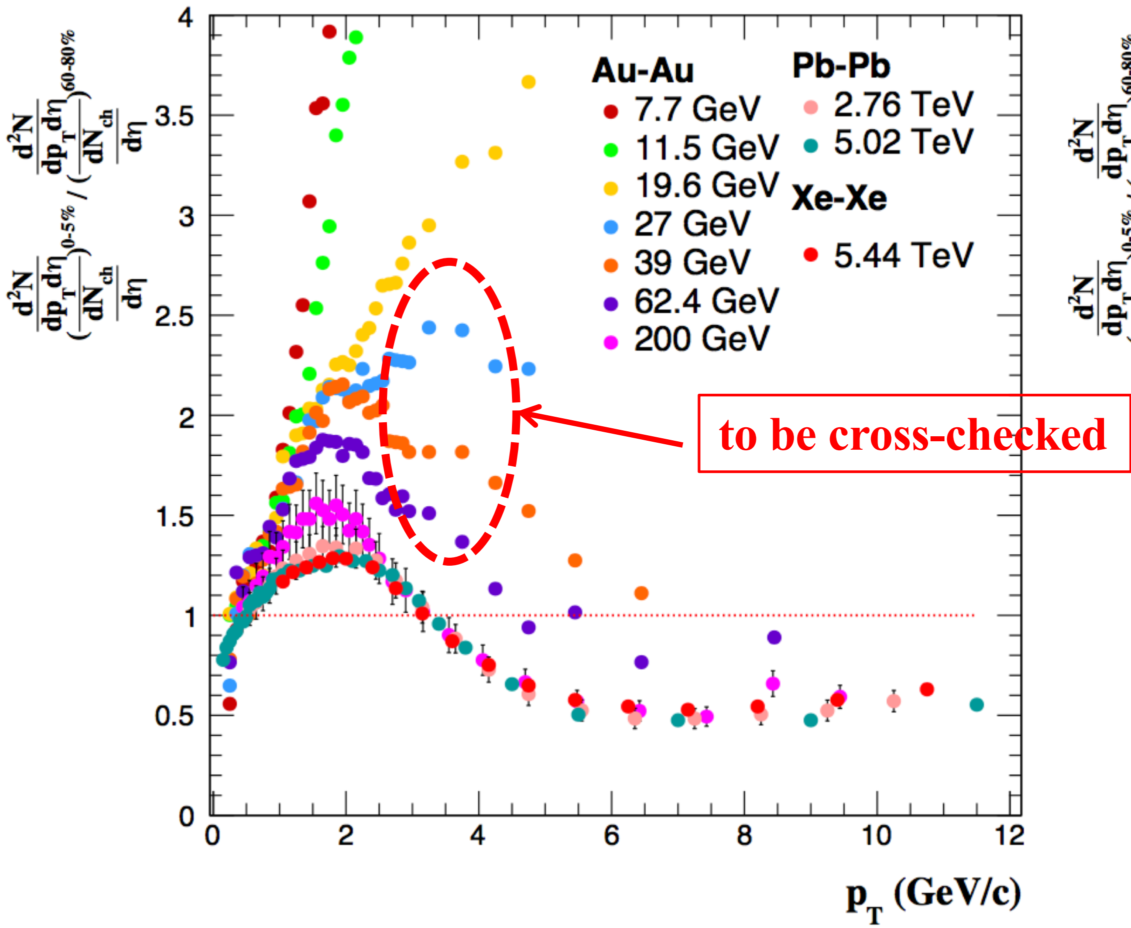


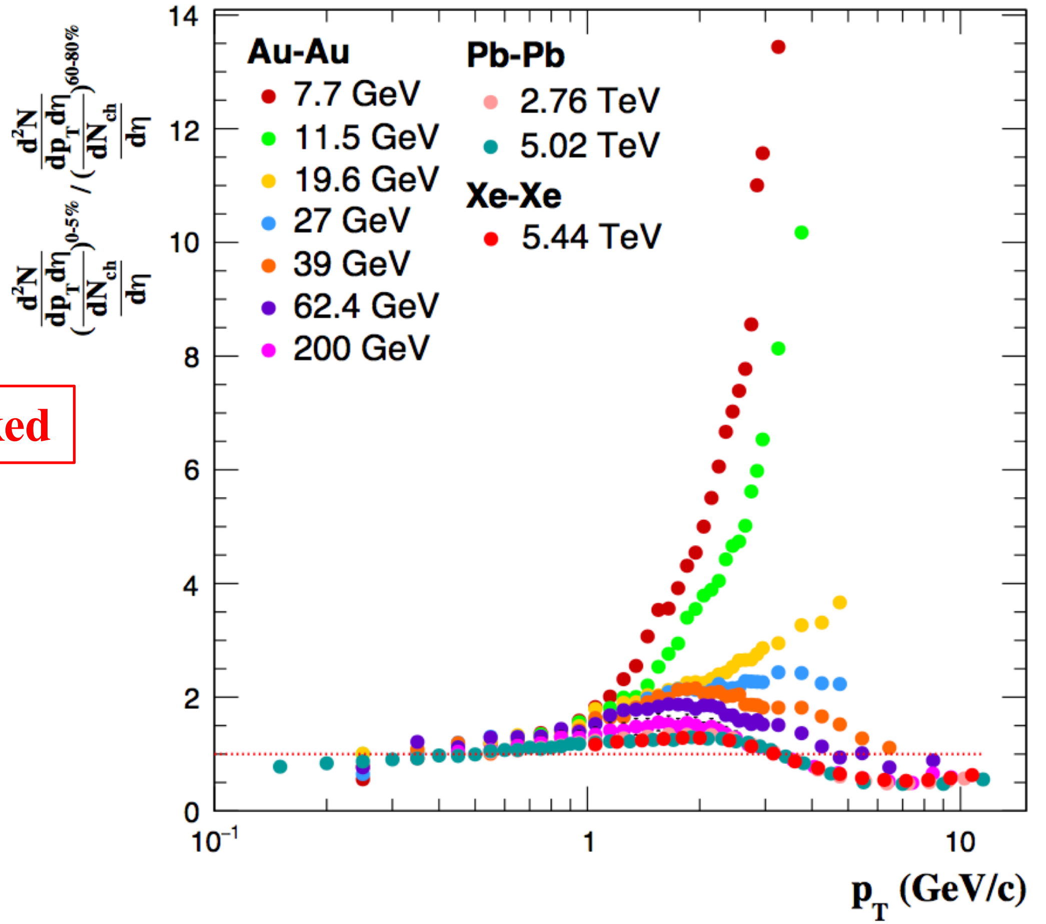


M.Shimomura, PHENIX Coll.
J. of Phys. Conf. Series 270(2011)012041

<u>Could we extract something similar using v2 analysis in Pb-Pb @ LHC ???</u>

(0-5%)/(60-80%) - collision energy dependence





- ***at p_T>~2-2.5 GeV/c - no difference between 200 GeV - 2.76(5.02)TeV***
- ***at ~ 27 GeV at p_T~3-4 GeV/c - a leveling off sets in***
- ***>39 GeV a maximum appears at p_T values decreasing with the collision energy expansion - "suppresion" competition ? - it stays at the same p_T value starting from 200 GeV***

A few considerations

Geometrical scaling

Local parton-hadron duality picture and dimensionality argument

$$\langle p_T \rangle / \sqrt{\frac{dN}{dy}/S_\perp} \sim \frac{1}{n\sqrt{n}}$$

n – *no. of charged part. from a gluon fragmentation*

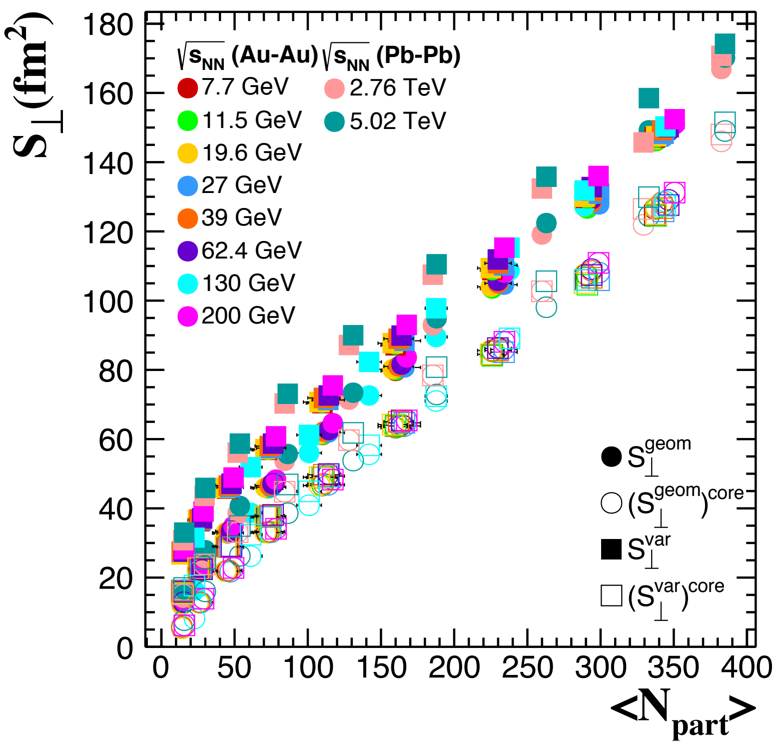
- Y.L.Dokshitzer, V.A.Khoze and S.Troian, J.Phys.G 17 (1991) 1585
- T. Lappi, Eur.Phys.J. C71 (2011) 1699
- E. Levin and A.H. Rezaeian, Phys.Rev.D 83 (2011) 114001

$$\langle p_T \rangle / \sqrt{\frac{dN}{dy}/S_\perp}$$

decreases as a function of:
- **collision energy**
- **centrality**

S_{perp} & dN/dy estimates

Glauber Monte Carlo approach



$$S_\perp^{var} \sim \pi\sqrt{\sigma_x^2\sigma_y^2 - \sigma_{xy}^2}$$

BES

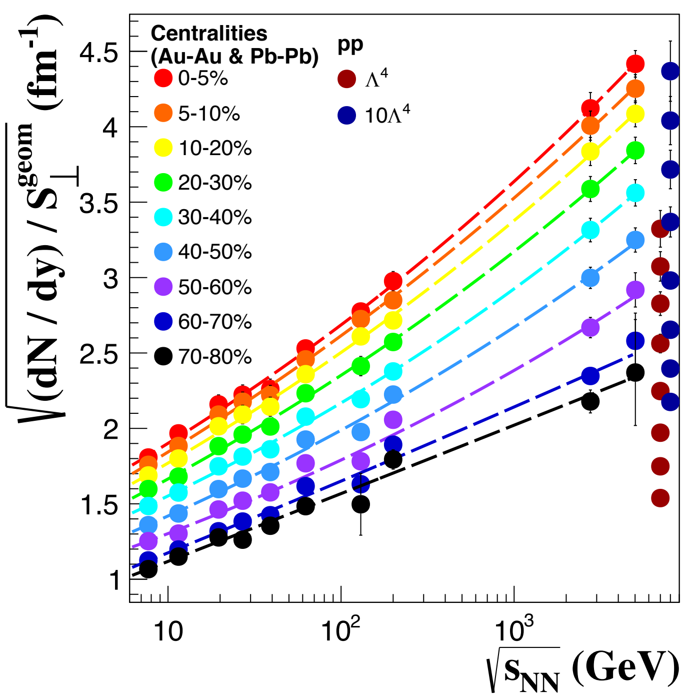
$$\frac{dN}{dy} \simeq \frac{3}{2}\frac{dN}{dy}^{(\pi^+ + \pi^-)} + 2\frac{dN}{dy}^{(K^+ + K^-, p+\bar{p}, \Xi^- + \bar{\Xi}^+)} + \frac{dN}{dy}^{(\Lambda+\bar{\Lambda})}$$

RHIC 62.4; 130; 200 GeV

$$\frac{dN}{dy} \simeq \frac{3}{2}\frac{dN}{dy}^{(\pi^+ + \pi^-)} + 2\frac{dN}{dy}^{(K^+ + K^-, p+\bar{p}, \Xi^- + \bar{\Xi}^+)} + \frac{dN}{dy}^{(\Lambda+\bar{\Lambda}, \Omega^- + \bar{\Omega}^+)}$$

LHC

$$\frac{dN}{dy} \simeq \frac{3}{2}\frac{dN}{dy}^{(\pi^+ + \pi^-)} + 2\frac{dN}{dy}^{(p+\bar{p}, \Xi^- + \bar{\Xi}^+)} + \frac{dN}{dy}^{(K^+ + K^-, K_S^0 + \bar{K}_S^0, \Lambda+\bar{\Lambda}, \Omega^- + \bar{\Omega}^+)}$$

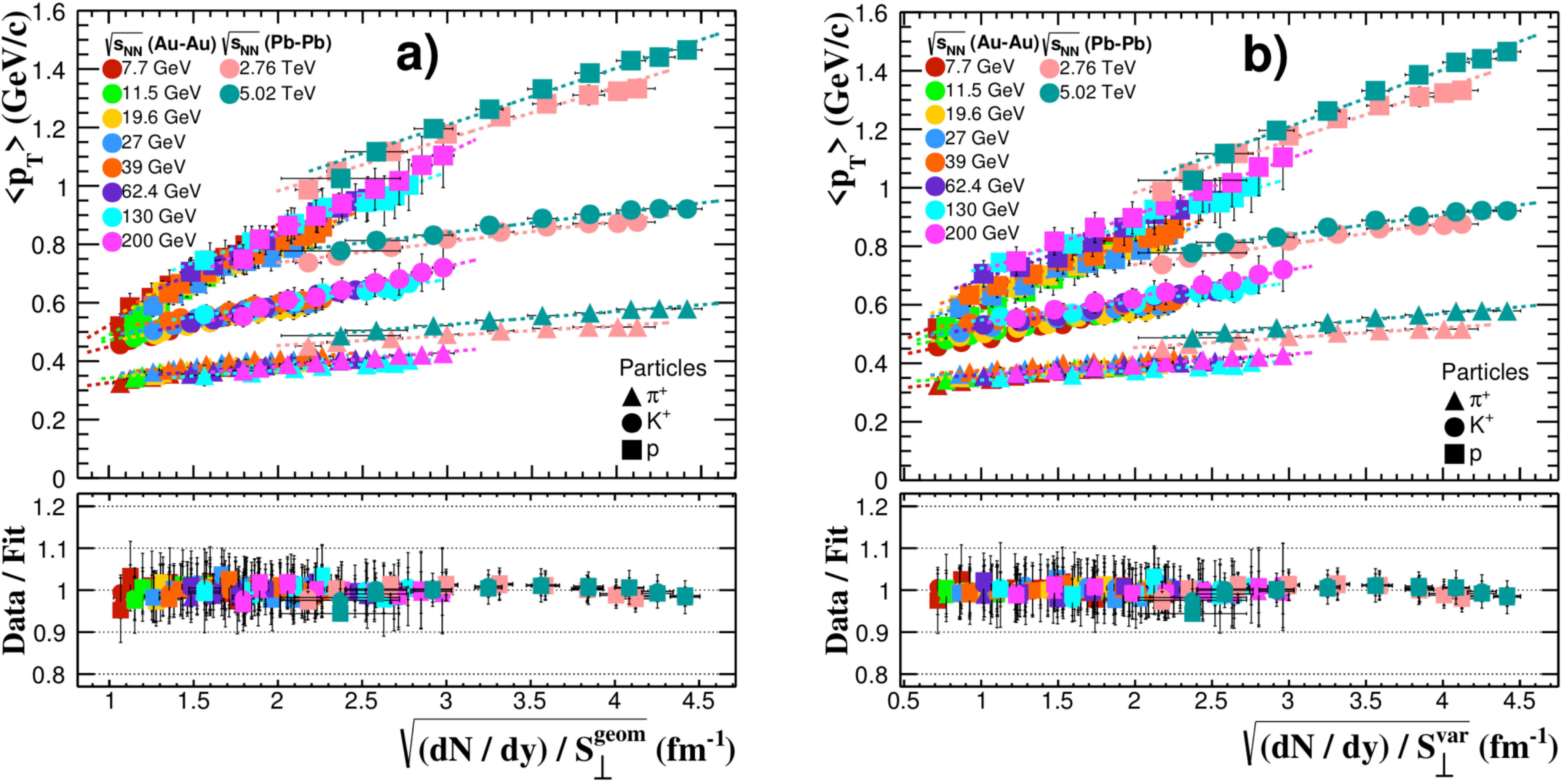


M. Petrovici, A.Lindner, , A. Pop, M. Târzila, and I.Berceanu, arXiv:[hep-ph]1805.04060

A few considerations

Geometrical scaling

$\langle p_T \rangle$ vs. $[(dN/dy)/S_{perp}]^{1/2}$



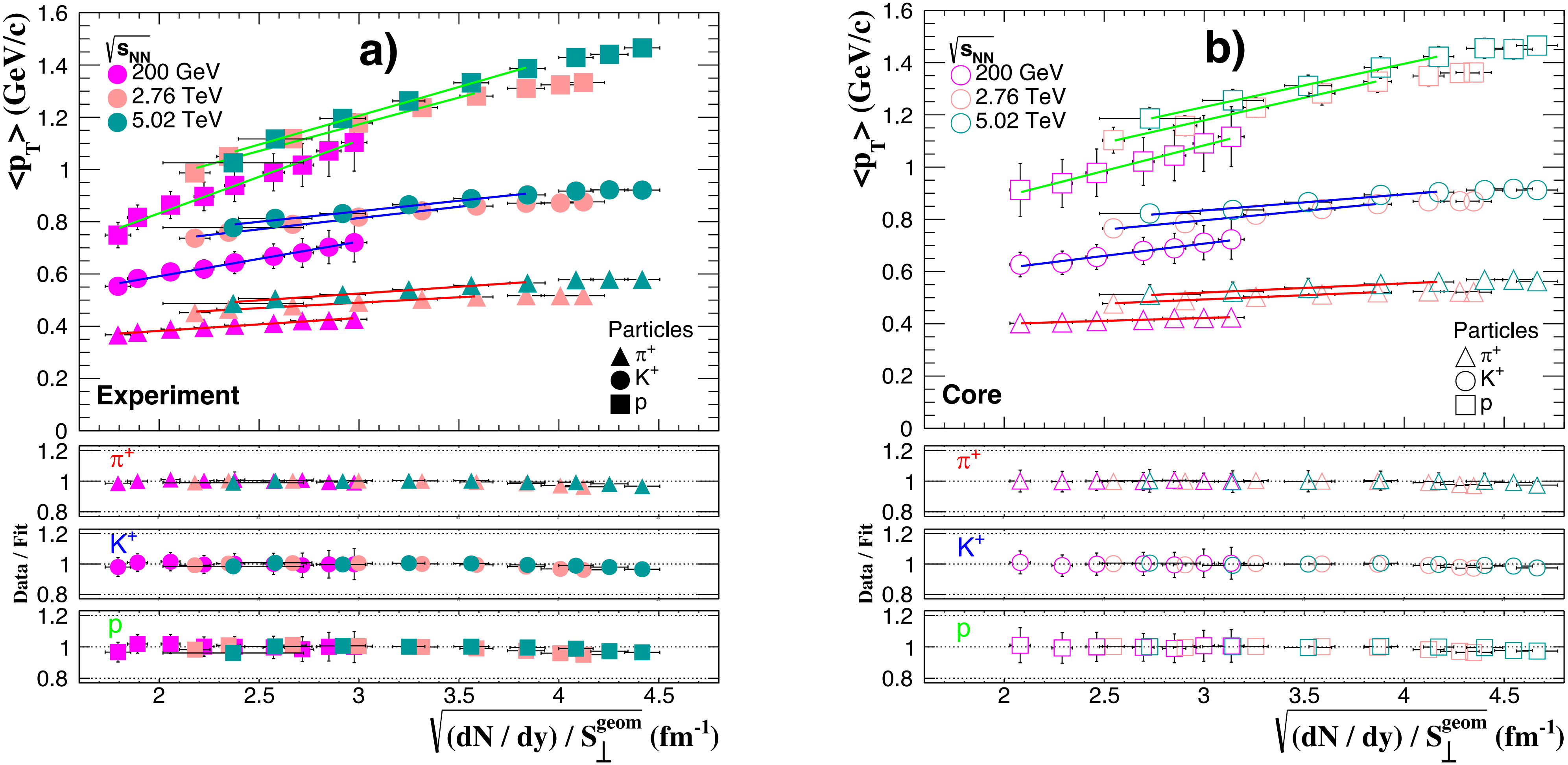
STAR Collaboration, Phys.Rev. C96(2017)044904
STAR Collaboration, Phys.Rev. C79(2009)034909
ALICE Collaboration, Phys.Rev. C}{88}{2013}{044910}
ALICE Collaboration, Phys.Rev.Lett. 116(2016)222302
ALICE Collaboration, Eur.Phys.J. C75(2015)226
A.K.Dash, ALICE Collaboration , 9th Int. Workshop on MPI at LHC, Dec. 11-15, 2017

A few considerations

Geometrical scaling

$\langle p_T \rangle$ vs. $[(dN/dy)/S_{perp}]^{1/2}$

Core-Corona effect



$\sqrt{s_{NN}}$ (GeV)	Slope			Offset		
	π^+	K^+	p	π^+	K^+	p
200	0.05 ± 0.02	0.13 ± 0.04	0.28 ± 0.06	0.28 ± 0.04	0.33 ± 0.09	0.27 ± 0.13
2760	0.04 ± 0.01	0.09 ± 0.02	0.20 ± 0.03	0.37 ± 0.04	0.56 ± 0.07	0.56 ± 0.08
5020	0.05 ± 0.02	0.08 ± 0.02	0.22 ± 0.03	0.37 ± 0.06	0.60 ± 0.07	0.54 ± 0.10

$\sqrt{s_{NN}}$ (GeV)	Slope			Offset		
	π^+	K^+	p	π^+	K^+	p
200	0.02 ± 0.03	0.09 ± 0.06	0.20 ± 0.11	0.36 ± 0.07	0.43 ± 0.15	0.50 ± 0.29
2760	0.03 ± 0.02	0.07 ± 0.03	0.17 ± 0.04	0.40 ± 0.06	0.58 ± 0.10	0.66 ± 0.14
5020	0.03 ± 0.03	0.06 ± 0.02	0.17 ± 0.04	0.41 ± 0.11	0.65 ± 0.08	0.73 ± 0.16

$$\langle p_T \rangle_i^{cen} = \frac{f_{core}\langle p_T \rangle_i^{core} M_i^{core} + (1-f_{core})\langle p_T \rangle_i^{ppMB} M_i^{ppMB}}{f_{core} M_i^{core} + (1-f_{core}) M_i^{ppMB}}$$

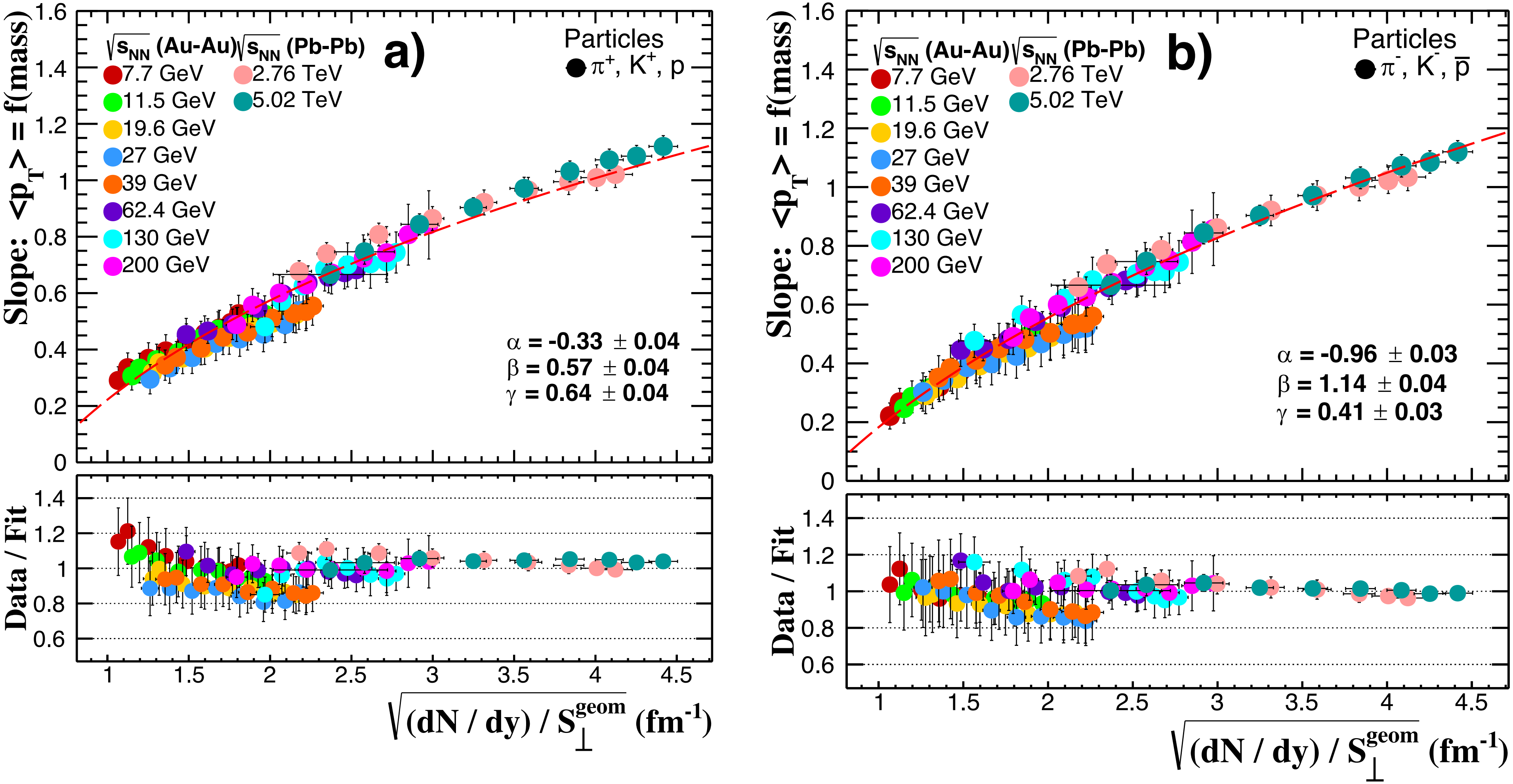
$$\left(\frac{dN}{dy}\right)_i^{cen} = \langle N_{part} \rangle [(1-f_{core}) M_i^{ppMB} + f_{core} M_i^{core}]$$

$$M_i^{ppMB} = \frac{1}{2}(dN/dy)_i^{ppMB}$$

A few considerations

Geometrical scaling

The slope of $<p_T>=f(mass)$ vs. $[(dN/dy)/S_{perp}]^{1/2}$

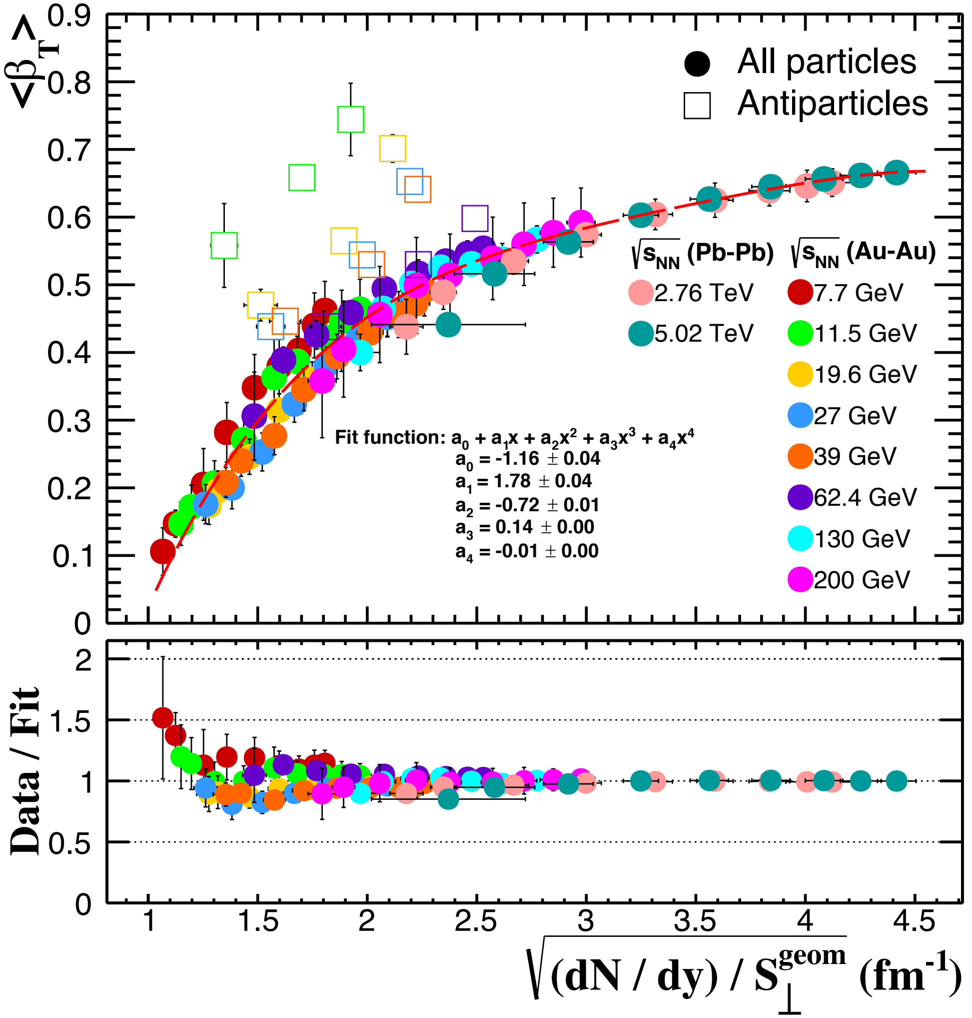


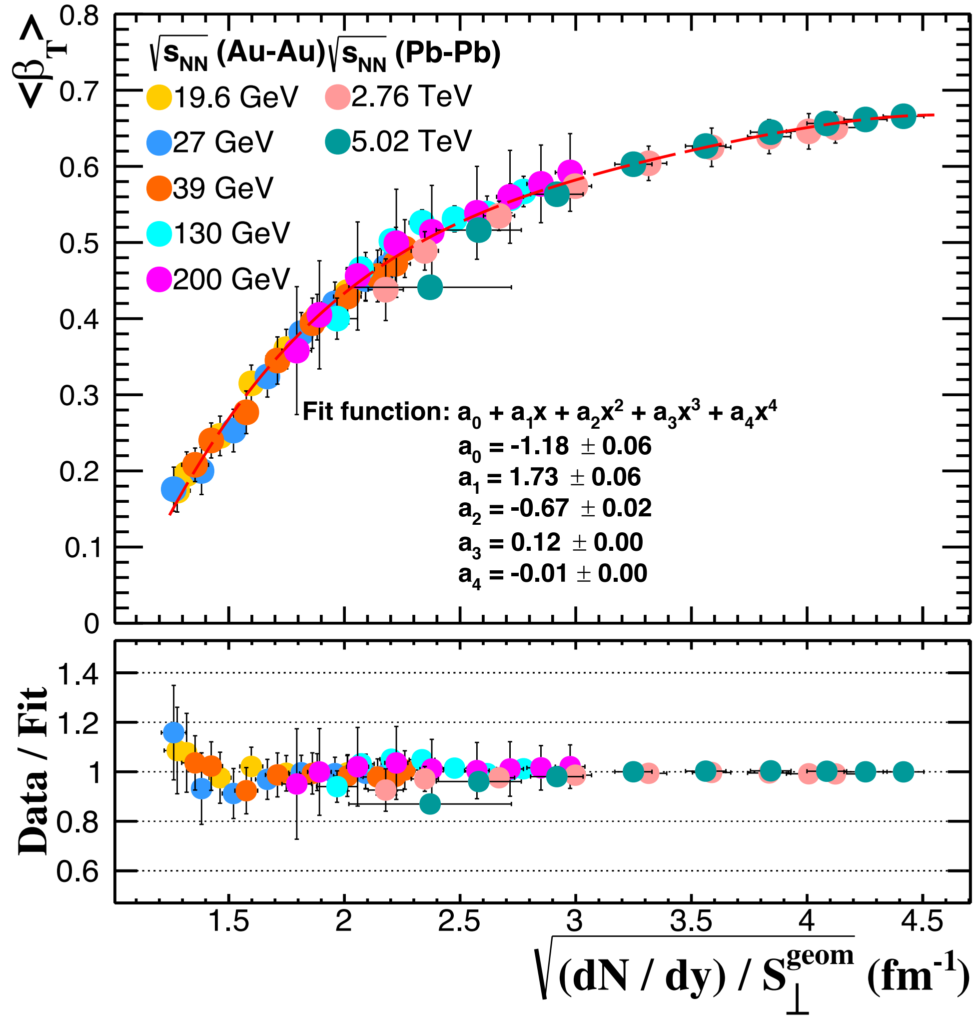
$$Slope_{\langle p_T \rangle = f(mass)} = \alpha + \beta \left(\sqrt{\frac{dN}{dy} / S_{\perp}^{geom}} \right)^{\gamma}$$

A few considerations

Geometrical scaling

$\langle\beta_T\rangle$ from BGBW fits vs. $[(dN/dy)/S_{perp}]^{1/2}$





Boltzmann-Gibbs Blast Wave

$$\frac{1}{2\pi p_T}\frac{d^2N}{dydp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T\sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T\cosh\rho}{T_{kin}}\right)$$

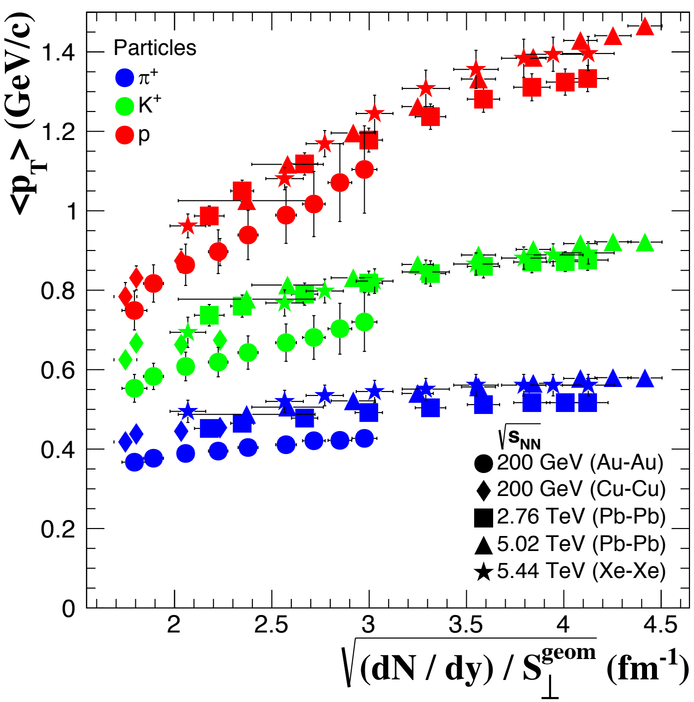
$$\rho = \tanh^{-1}\beta_T = \tanh^{-1}\left[\left(\frac{r}{R}\right)^n \beta_s\right]$$

A few considerations

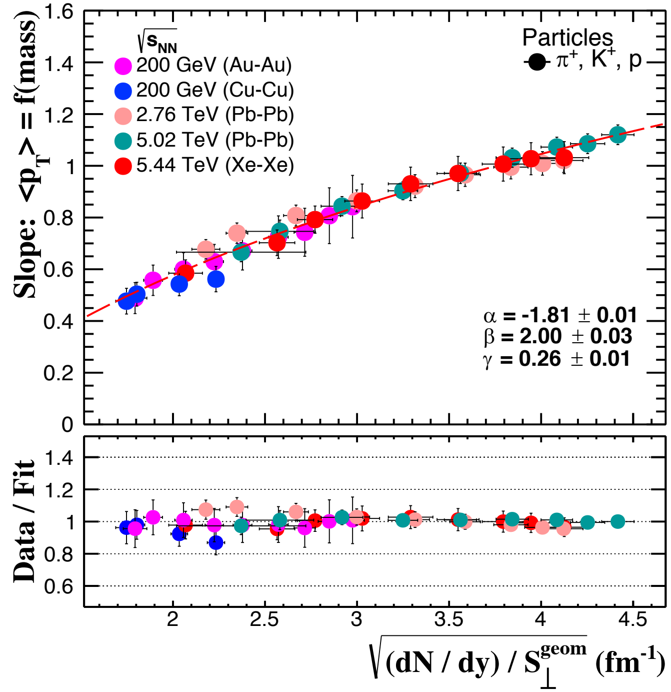
Geometrical scaling

Cu-Cu; Au-Au @ RHIC vs. Xe-Xe and Pb+Pb @ LHC

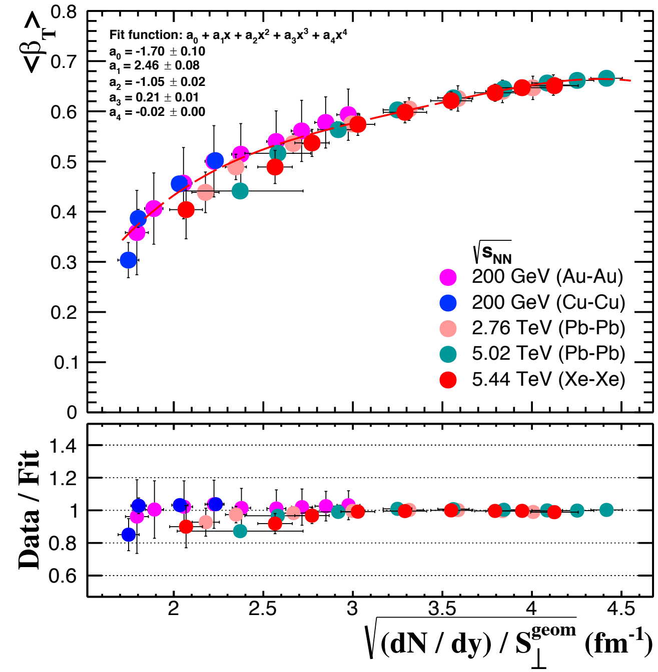
$\langle p_T \rangle$ vs. $[(dN/dy)/S_{perp}]^{1/2}$



The slope of $\langle p_T \rangle$=f(mass) vs. $[(dN/dy)/S_{perp}]^{1/2}$



$\langle \beta_T \rangle$ from BGBW fits vs. $[(dN/dy)/S_{perp}]^{1/2}$



BRAHMS Collaboration, arXic:[nucl.ex]1602.01183

F.Bellini, ALICE Collaboration, QM2018

STAR Collaboration, Phys.Rev. C79(2009)034909

ALICE Collaboration, Phys.Rev. C}{88}{2013}{044910}

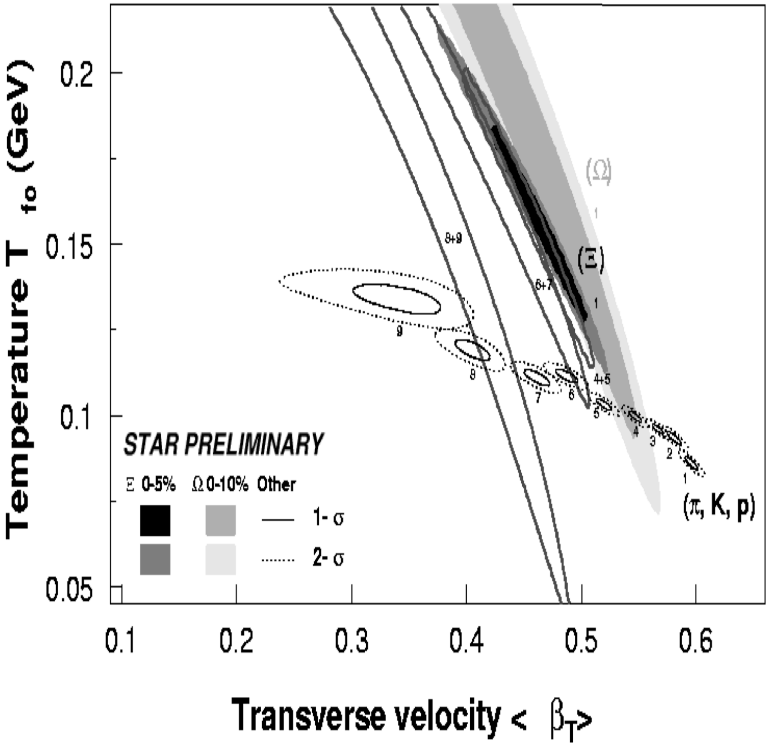
A few considerations

A-A BGBW fits

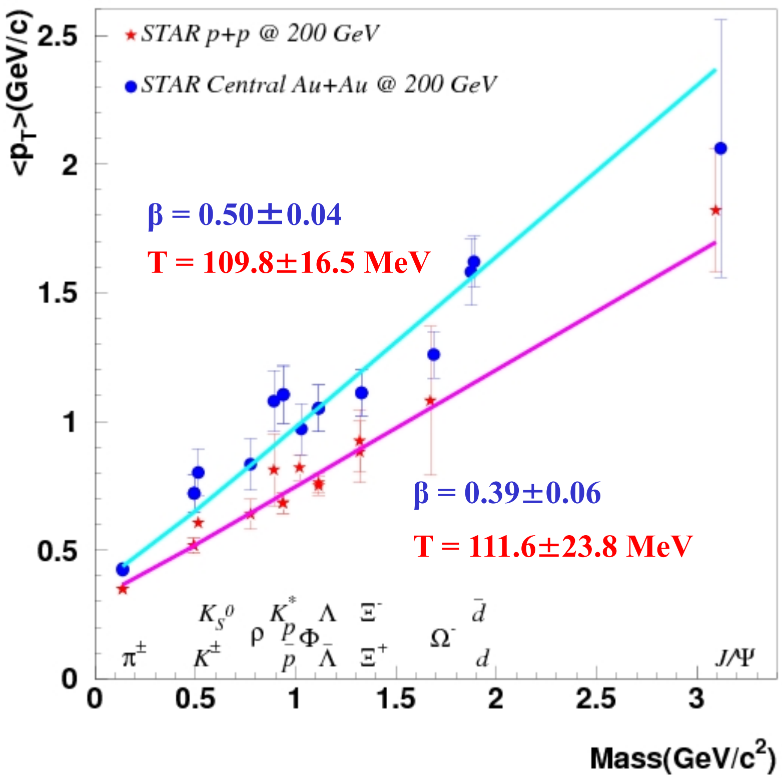
$$f(p_t) \sim \int_0^R r dr m_t I_0\left(\frac{p_t sinh\rho}{T}\right) K_1\left(\frac{m_t cosh\rho}{T}\right)$$

$$< p_t >= \frac{\int_0^\infty p_t^2 f(p_t) dp_t}{\int_0^\infty p_t f(p_t) dp_t}$$

Au-Au 200 GeV



M.Estienne, STAR Coll. arXiv:nucl-ex/0411034

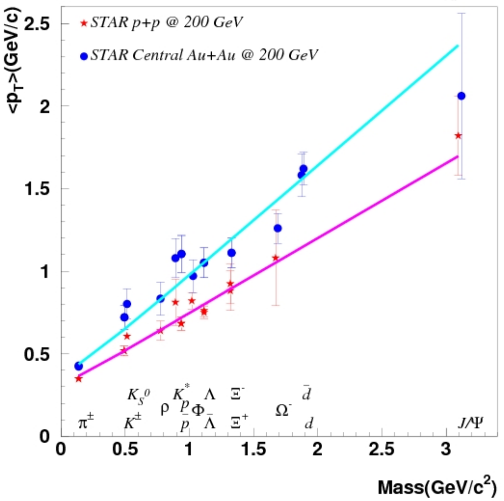


M.Petrovici and Amalia Pop,
AIP Conference Proceedings 972(2008)98

A few considerations

A-A Tsallis BW fits

$$f(p_t) = m_t \int_{-Y}^{Y} cosh(y)dy \int_{-\pi}^{\pi} d\phi \int_{0}^{R} rdr(1+\frac{q-1}{T}(m_t cosh(y)cosh(\rho)-p_t sinh(\rho)cos(\phi)))^{-1/(q-1)}$$



A. Lavagno, Phys.Lett. A301(2002)13
Z. Tang et al, arXiv:0812.1609 nucl-ex

$\pi^{\pm}$, $K^{\pm}$, K^*, K_s^0, $\bar{p}$, Λ, $\bar{\Lambda}$, $\Xi^{\pm}$, Ω^-, d, $\bar{d}$, J/ψ

System	p + p	p + p	Au + Au	Au + Au
Model	BGBW	TBW	BGBW	TBW
T [MeV]	111.6±23.8	78.86±10.13	109.8±16.5	86.8 ±1.54
β	0.39±0.06	0.027±0.10	0.50±0.04	0.48±0.04
q	1.0	1.0874	1.0	1.0247

$\pi^{\pm}$, $K^{\pm}$, K^*, p, $\bar{p}$, d, $\bar{d}$

	Au + Au	Au + Au
	BGBW	TBW
T [MeV]	98.7±19.5	79.05±0.04
β	0.54±0.04	0.53±0.0005
q	1.0	1.0175

Λ, $\bar{\Lambda}$, $\Xi^{\pm}$, Ω^-, J/ψ

	Au + Au
	TBW
T [MeV]	198.0±7.6
β	0.32±0.012
q	1.0247

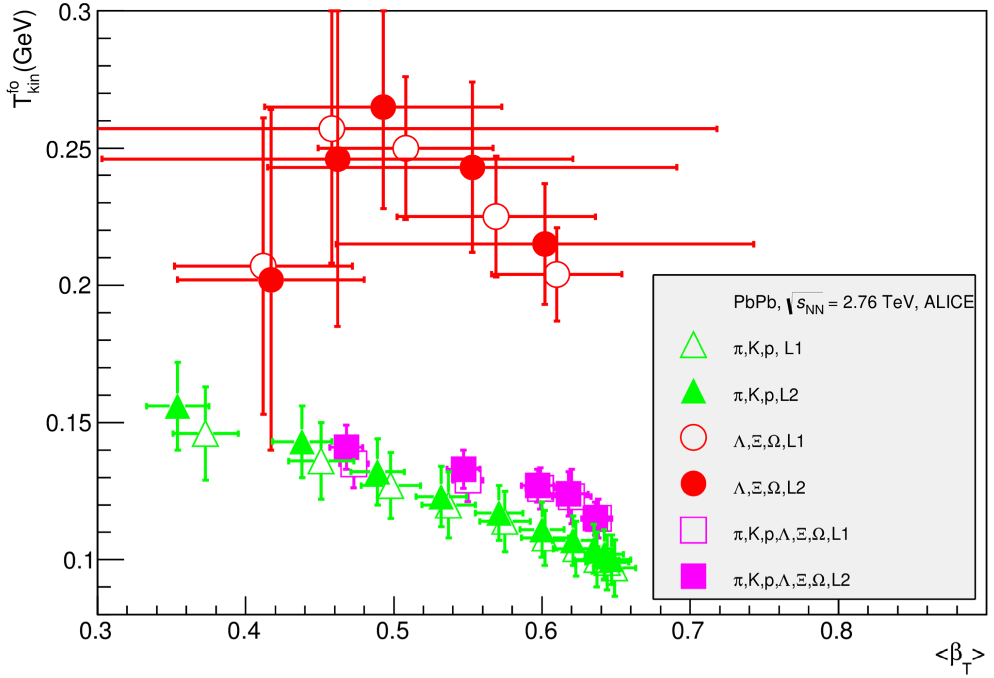
	Au + Au	Au + Au
	BGBW	TBW
T [MeV]	215.5±89.2	200.5±0.1
β	0.37±0.12	0.36
q	1.0	1.021

M.Petrovici and Amalia Pop,
AIP Conference Proceedings 972(2008)98

A few considerations

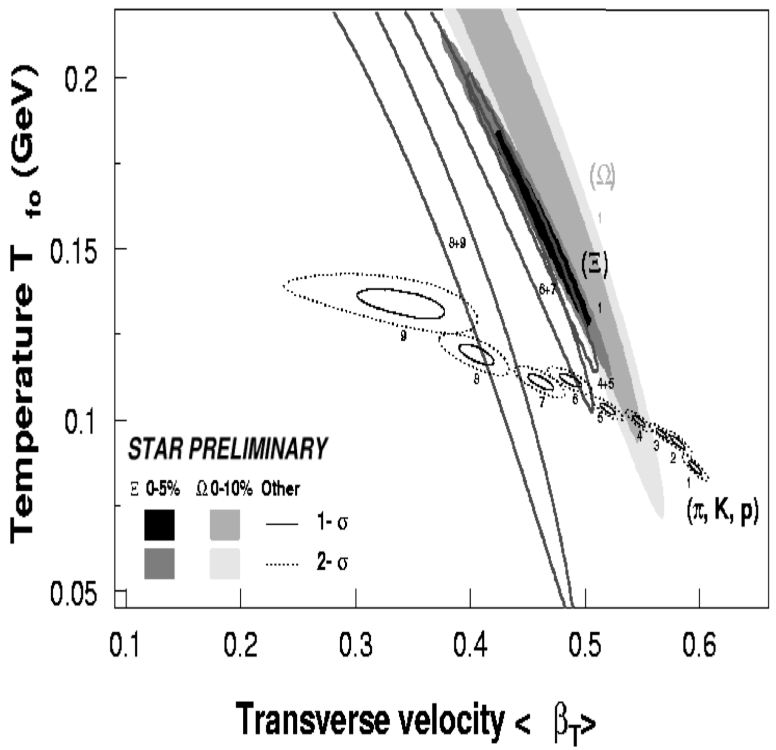
A-A BGBW - fits

Pb-Pb 2.76 TeV



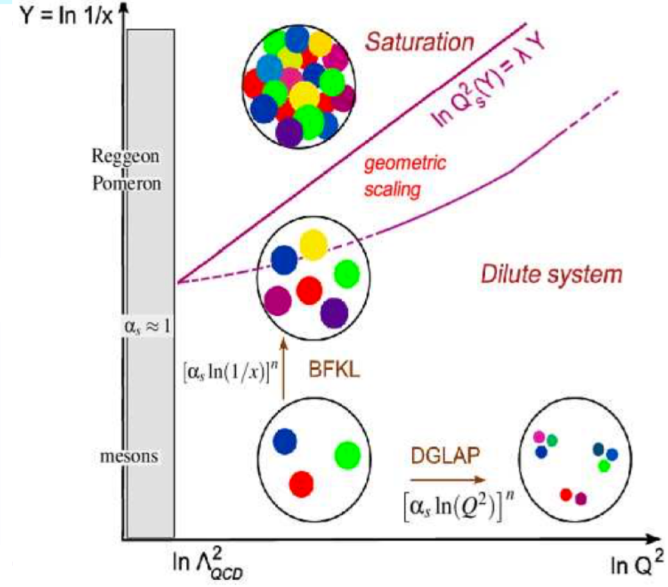
M.Petrovici et al. AIP Conf.Proc. 1852, 050003-1 (2017)

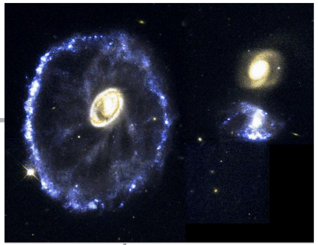
Au-Au 200 GeV



M.Estienne, STAR Coll. arXiv:nucl-ex/0411034

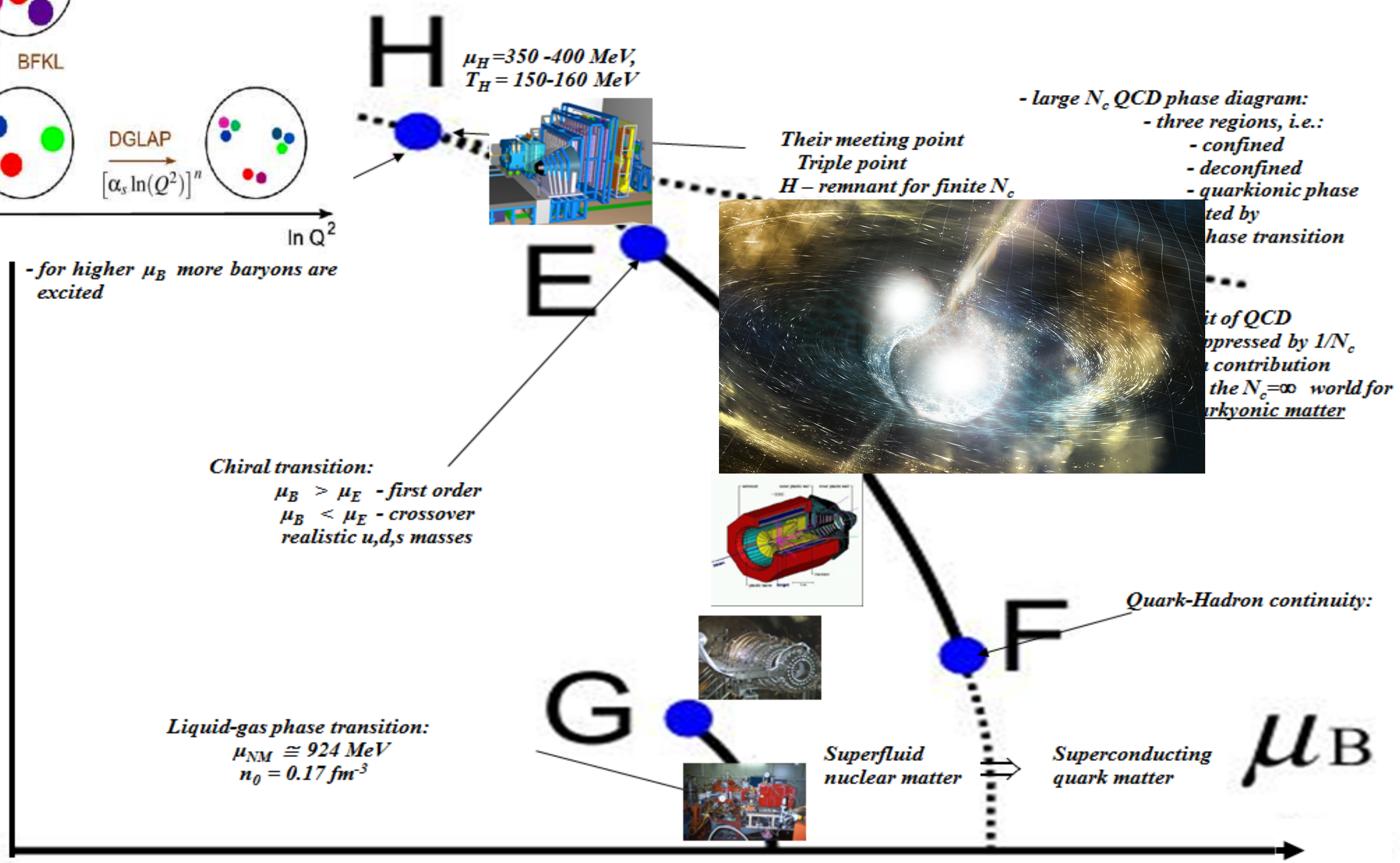
What is really new at LHC ?





Expectations based on QCD

QCD Critical Points



Theoretical approaches - short list of references

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E. Schnedermann, J. Sollfrank, U. Heinz, Phys. Rev. C48(1993)2462
J. Brachmann et al., Nucl. Phys. A619(1997)391

Microscopic (string-, transport-, cascade-, etc.) Models

FRITIOF

B. Anderson et al., Phys. Rep. 97(1983)31

VENUS

K. Werner, Phys. Rep. 232(1993)87

QGSM

N.S. Amelin et al., Sov. J. Nucl. Phys. 51, 327 (1990)

RQMD

H. Sorge, H. Stöcker, W. Greiner, Ann. Phys. (N.Y.) 192, 266 (1989)

Theoretical approaches - short list of references

HIJING ***(Heavy-Ion Jet Interaction Generator) Monte Carlo Model***

- two-component geometrical model of minijet production and soft interaction

- incorporated nuclear effects: nucler modification of parton distribution functions and jet quenching via final state jet medium interaction

X.N.Wang et al., Phys.Rev. D44(1991)34501

M. Gyulassy et al., Comp.Phys.Comm. 83(1994)301

W.T.Deng et al., Phys.Rev. C83(2011)014915

UrQMD *- describes the phenomenology of hadronic interactions at low and intermediate energies ($\sqrt{s}$<5 GeV) in terms of interactions between known hadrons and their resonances*

- *a*t energies $\sqrt{s}$>5 GeV, the excitation of color strings and their subsequent fragmentation in to hadrons *is condsidered*

M.Bleicher et al., J.Phys. G25(1999)1859

Theoretical approaches - short list of references

NeXSPheRIO *- a combination of two codes: - SPheRIO - describes the hydrodynamic evolution*
- NeXus - computes the initial conditions $T_{\mu\nu}$, j^{μ} and u^{μ} on a proper time hypersurface

R.Andrade et al., Acta Phys. Hung. A19(2004)1
arXiv:[nucl-th]0511021

AMPT *- a combination of four models: - HIJING - for generating initial conditions*
- ZPC - Zhang's parton cascade for partonic scatterings
- Lund string fragmentation model
or
quark coalescence model
for hadronization
- ART - relativistic transport model for hadronic scatterings

Z.W.Lin et al., Phys.Rev. C72(2005)064901
J.Xu et al., arXiv:[nucl-th]1103.5187

PHSD *- Parton-Hadron-Sring-Dynamics transport approach, based on dynamical quasiparticle model for partons (DQPM) matched to reproduce lattice-QCD results including partonic equation of state - in thermodynamic equilibrium. The transition from partonic to hadronic degrees of freedom is described by covariant transition rates for the fusion of quark-antiquark pairs or three quarks (antiquarks) obeying flavor current conservation, color neutrality and energy-momentium conservation*

W.Cassing et al., arXiv:[nucl-th]0907.5331
V.P.Konchakovski et al., arXiv:[nucl-th]1201.3220

Theoretical approaches - short list of references

MUSIC *- MUSCL-type (Monotonic Upstream-centered Schemes for Conservation Lawsa combination*
- implementation of ***MUS****cl for heavy* ***I****on Collisions* ***C****ollisions*

B.Schenke et al., Phys.Rev. C82(2010)014903

superSONIC *- a combination of pre-equilibrium flow, viscous hydrodynamic evolution and late stage hadronic rescatterings*

R.D. Weller et al., arXiv:[nucl-th]1701.07145