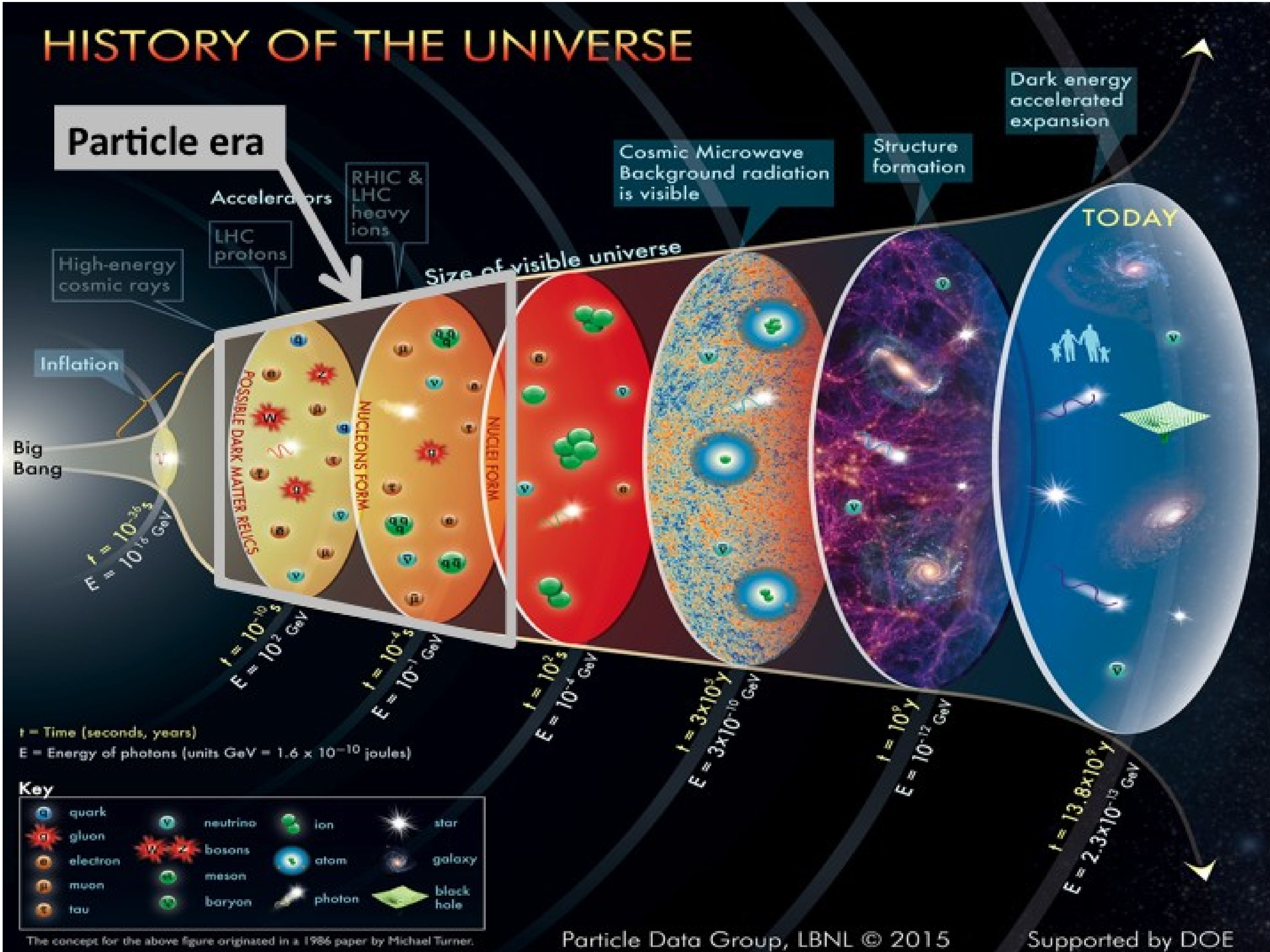
colliding relativistic nuclei: selected remarks on future opportunities and challenges

- introduction and perspective
- the quark-gluon plasma and the early universe
- the baryon-rich region – search for a critical point
- the baryon free region at LHC – deconfinement and restoration of chiral symmetry
- future circular collider
- outlook

Workshop on
accelerators revealing the QCD secrets
Thessaloniki
Sep. 3, 2016

Peter Braun-Munzinger



HISTORY OF THE UNIVERSE
Particle era
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Inflation
Big Bang
Size of visible universe
Cosmic Microwave Background radiation is visible
Structure formation
Dark energy accelerated expansion
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-35 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

time line and matter in the early universe

- inflation up to 10^{-32} s
- 10^{-32} to 10^{-12} s: cosmic matter consists of **massless** particles and fields quarks, leptons, neutrinos, photons, Z, $W^{\pm}$, H ??? lots of speculations
- 10^{-12} s: electroweak phase transition, $T \approx 100$ GeV
- $10^{-12} - 10^{-5}$ s quark-gluon plasma phase
  particles acquire mass through Higgs mechanism, QGP consists of: $\bar{q}qg\bar{l}l\gamma ZW^{\pm}H$, all in equilibrium
- 10^{-5} s QCD phase transition, $T = 155$ MeV
- 10^{-5} s to 1 s annihilation phase, $T(1\ \text{s}) \approx 1$ MeV
  cosmic matter converts into protons, neutrons, leptons, neutrinos, photons
- $t > 1$ s: leptons annihilate and reheat universe, neutrinos decouple, light element production commences

could it be that inflation lasted until t = 1s ???
Figueroa and Byrnes
arXiv:1604.03905
no QGP in early universe?

QGP in the early universe

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\rho$$ cosmological scale factor $a(t)$

Hubble parameter $H(t)$ $$\dot{\rho} = -3H(\rho + p)$$

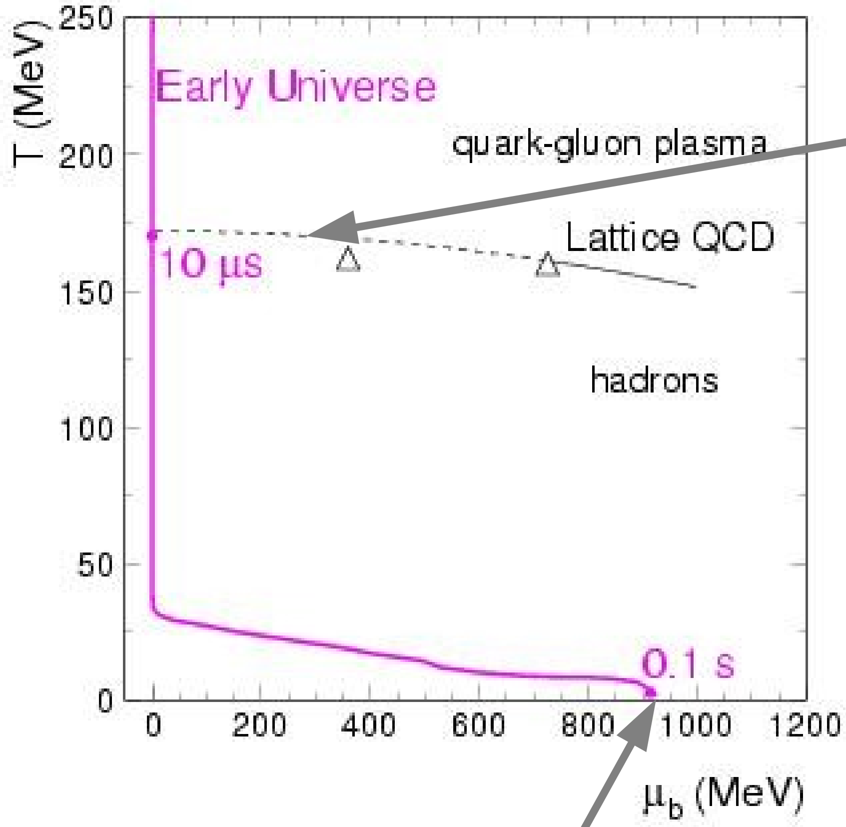
Temperature	New Particles	$4N(T)$
$T < m_e$	γ's + ν's	29
$m_e < T < m_\mu$	$e^\pm$	43
$m_\mu < T < m_\pi$	$\mu^\pm$	57
$m_\pi < T < T_c{}^\dagger$	π's	69
$T_c < T < m_{\text{strange}}$	π's + $u, \bar{u}, d, \bar{d}$ + gluons	205
$m_s < T < m_{\text{charm}}$	$s, \bar{s}$	247
$m_c < T < m_\tau$	$c, \bar{c}$	289
$m_\tau < T < m_{\text{bottom}}$	$\tau^\pm$	303
$m_b < T < m_{\text{W,Z}}$	$b, \bar{b}$	345
$m_{\text{W,Z}} < T < m_{\text{Higgs}}$	$W^\pm, Z$	381
$m_H < T < m_{\text{top}}$	H^0	385
$m_t < T$	$t, \bar{t}$	427

source: RPP 2014

$$\rho = \left(\sum_B g_B + \frac{7}{8}\sum_F g_F\right)\frac{\pi^2}{30}T^4 \equiv \frac{\pi^2}{30}N(T)T^4 = \frac{\pi^2}{30}g_T T^4$$

$$t_{[\text{s}]} = \frac{2.42}{\sqrt{g_T}(T_{[\text{MeV}]})^2}$$

evolution of the early universe and the QCD phase diagram



QCD phase boundary

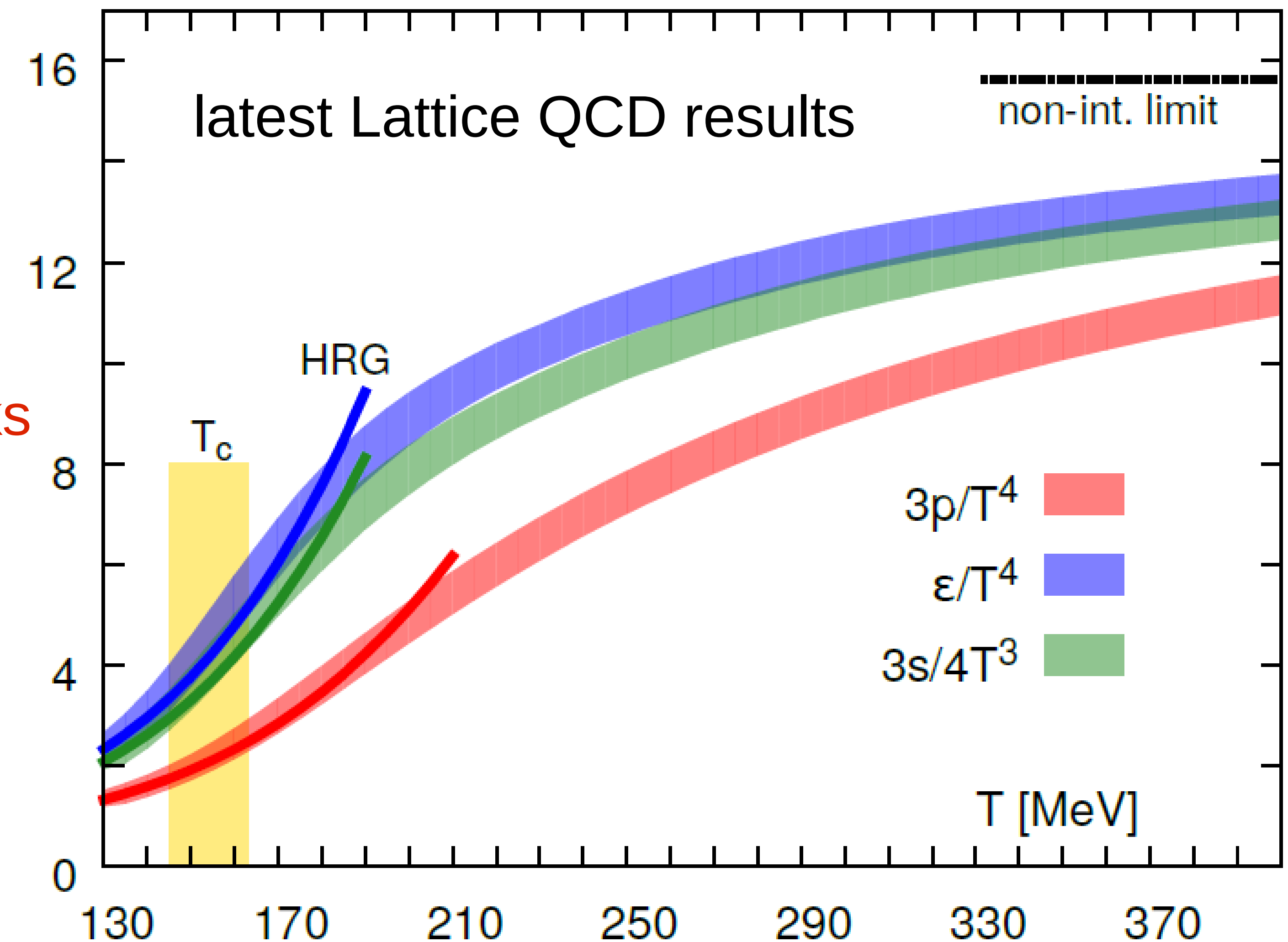
homogeneous Universe in equilibrium, this matter can only be investigated in nuclear collisions

- charge neutrality
- net lepton number = net baryon number
- constant entropy/baryon

neutrinos decouple and light nuclei begin to be formed

the equation of state of hot QCD matter – a chiral (cross over) phase transition between hadron gas and the QGP

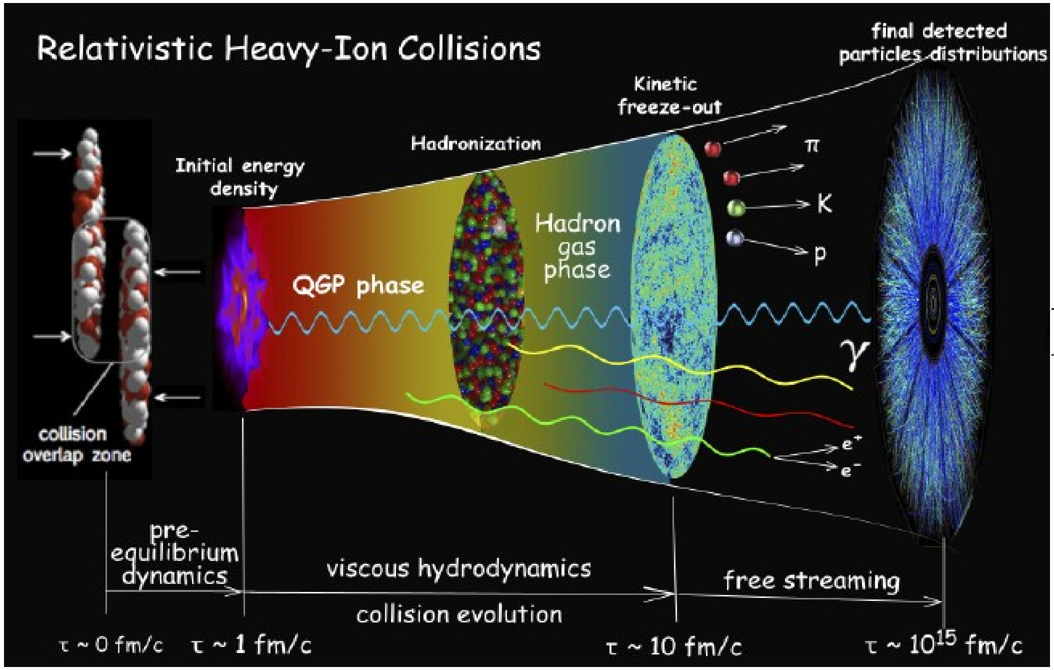
are there free quarks at T << Tc ???

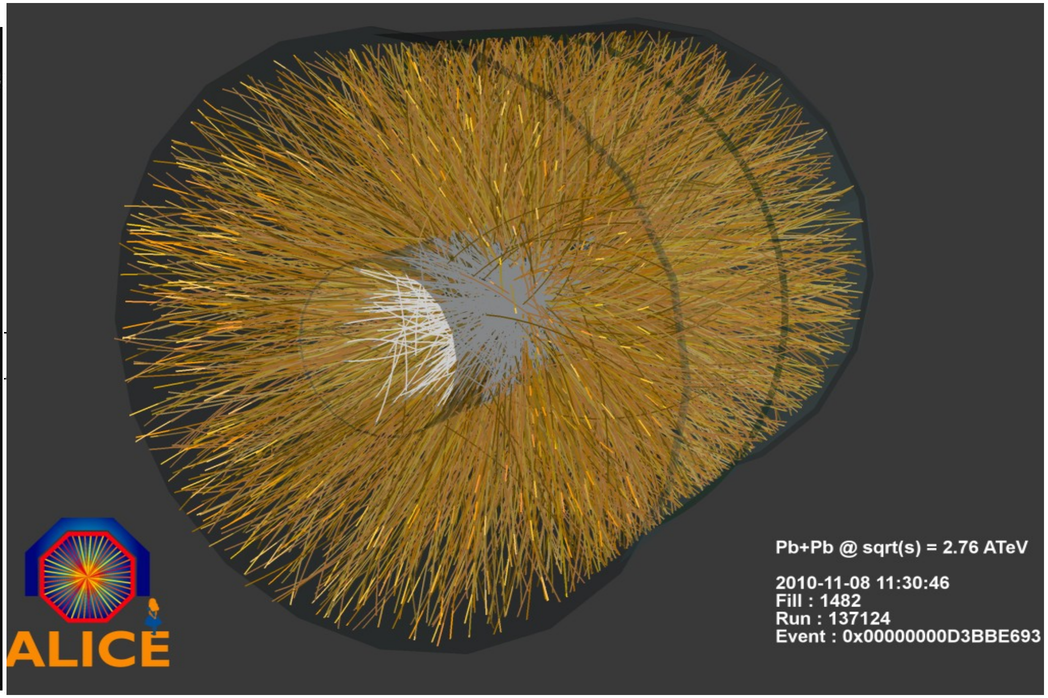


critical region: $T_c = (154 \pm 9)$ MeV $\varepsilon_{crit} = (340 \pm 45)$ MeV/fm^3

HOTQCD coll., Phys.Rev. D90 (2014) 9, 094503

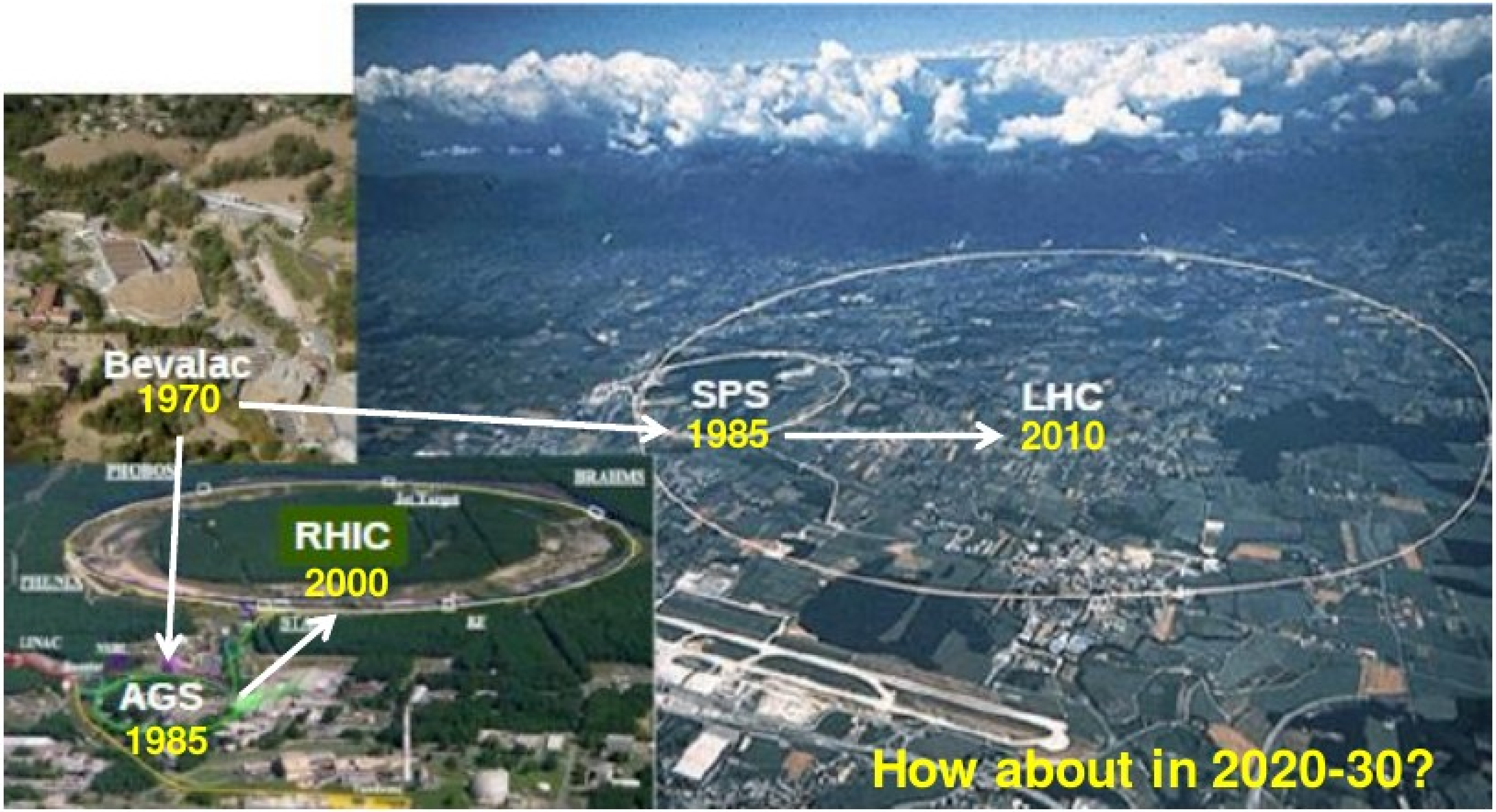
the Quark-Gluon Plasma formed in nuclear collisions at very high energy





Paul Sorensen and Chun Shen

The landscape of accelerators



(Figure provided by M. Gyulassy)

Low-Energy Heavy-Ion Programs

Accelerator	Type	Beam energy (AGeV)	C.M. energy √s(AGeV)	Beam rate / Luminosity	Interaction rate (sec^{-1})	Year of experiment
RHIC Beam Energy Scan (BNL)	Collider		7.7-62	10^{26} -10^{27} $cm^{-2}s^{-1}$ (√s=20AGeV)	600~6000 (√s=20AeV) (σ_{total}=6b)	2004-2010 2018-2019 (e-cooling)
NICA (JINR)	Collider Fixed target	0.6-4.5	4-11 1.9-2.4	10^{27} $cm^{-2}s^{-1}$ (√s=9AGeV Au+Au)	~6000 (σ_{total}=6b)	2019- 2017-
FAIR SIS100 (CBM)	Fixed target	2-11(Au)	2-4.7	1.5x10^{10} $cycle^{-1}$ (10s cycle,U^{92+})	10^5-10^7 (detector)	2021-2024
J-PARC	Fixed target	1-19(U)	1.9-6.2	10^{10} -10^{11} $cycle^{-1}$ (~6s cycle)	10^7-10^8 ? (0.1% target)	?

remarks on dilepton measurements

'standard description': melting of the rho meson near (pseudo-)critical temperature leads to enhanced dilepton radiation

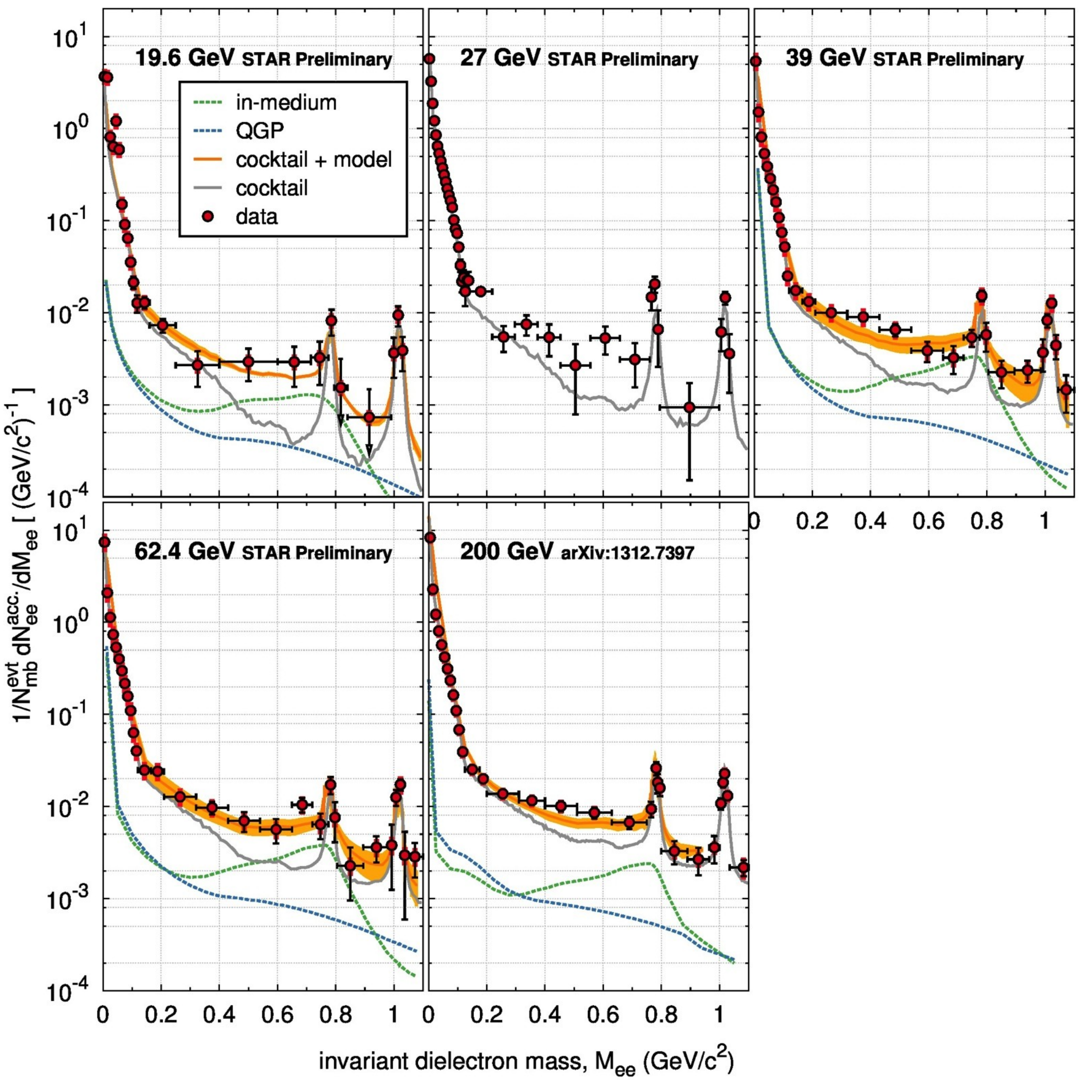
see

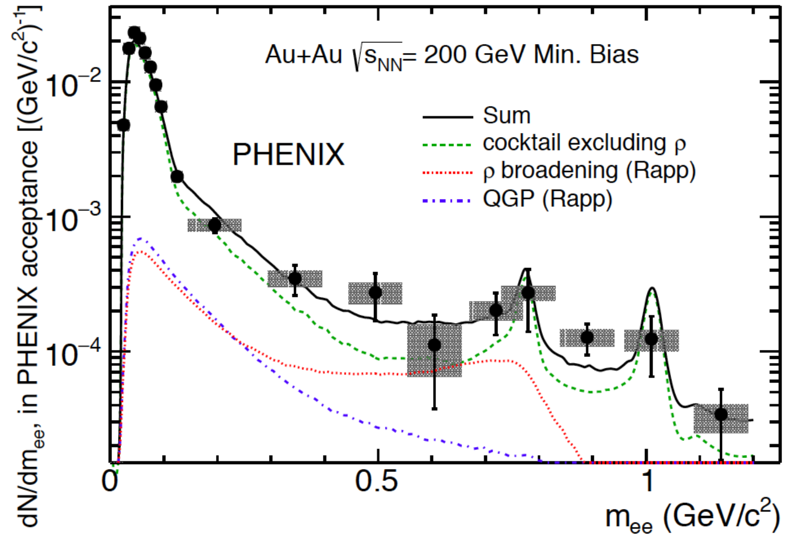
Thermal Electromagnetic Radiation in Heavy-Ion Collisions

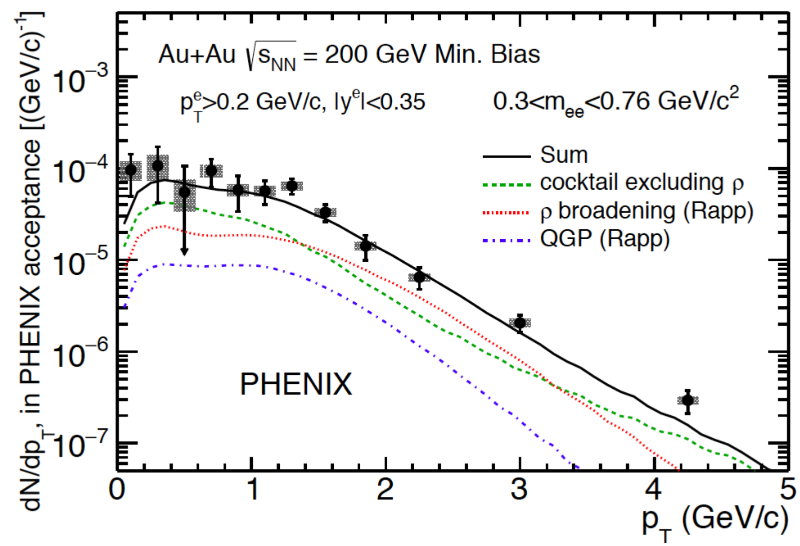
R. Rapp, H. van Hees. Aug 18, 2016. 5 pp.

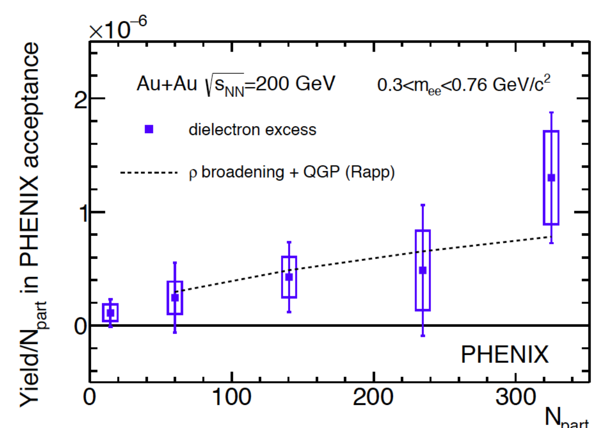
Published in Eur.Phys.J. A52 (2016) no.8, 257

and refs. there – 'Rapp-Wambach model'





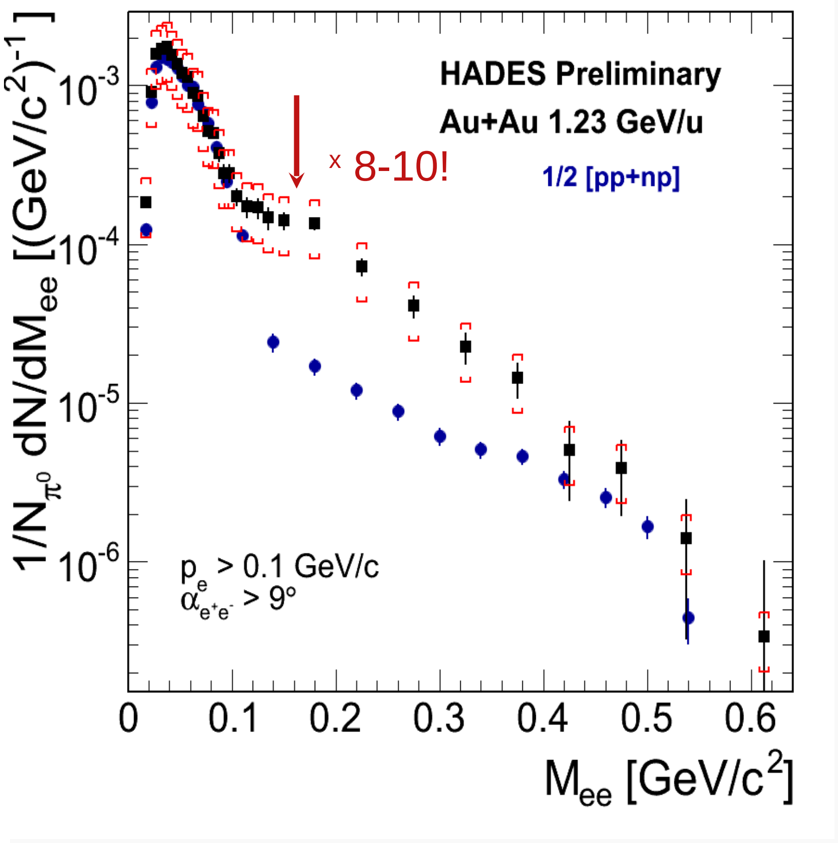


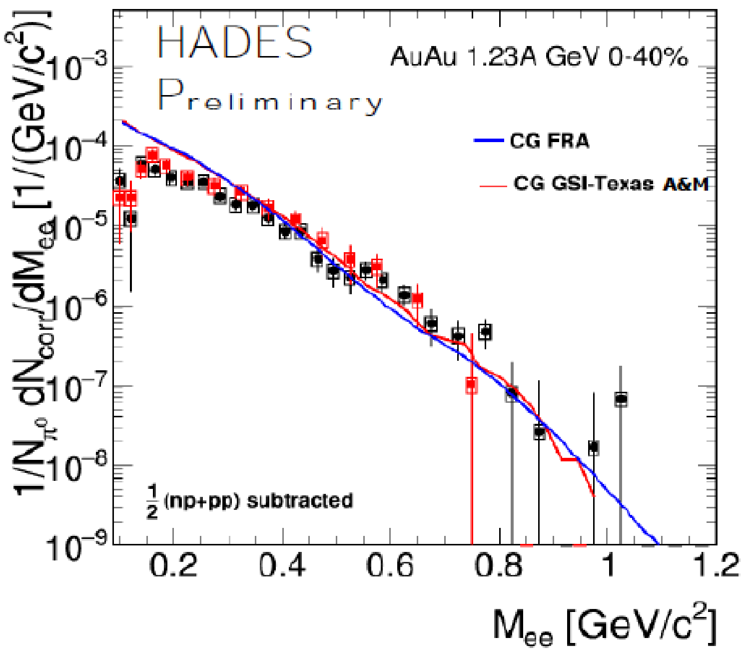


status of dilepton measurements after CERES and NA60: all data consistent with 'standard' Rapp-Wambach description of rho broadening

dileptons from SPS to RHIC energies

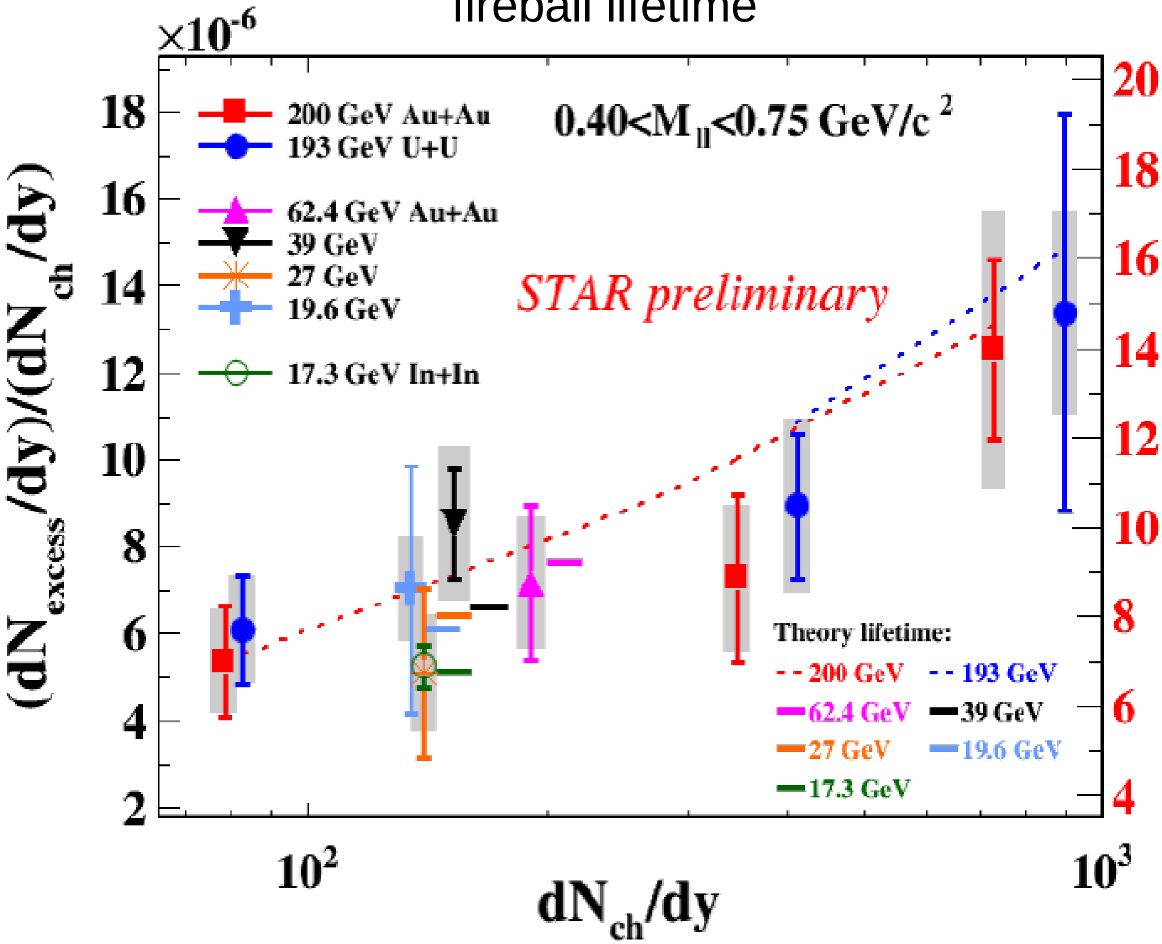
Dileptons at SIS energy



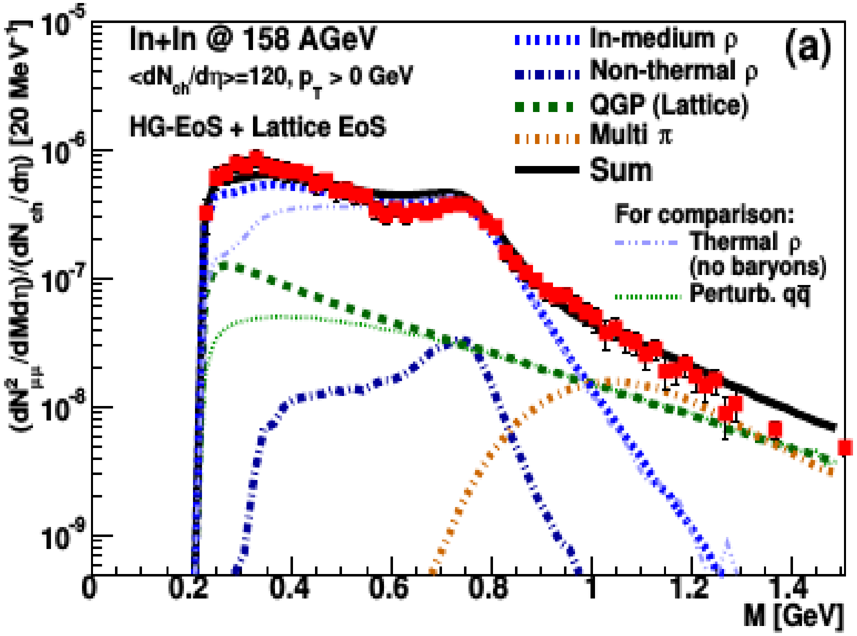


still very good description, QGP component negligible energy dependence – structureless rise with rising energy

fireball lifetime



QGP thermometer



Thermal Dileptons as Fireball Thermometer and Chronometer

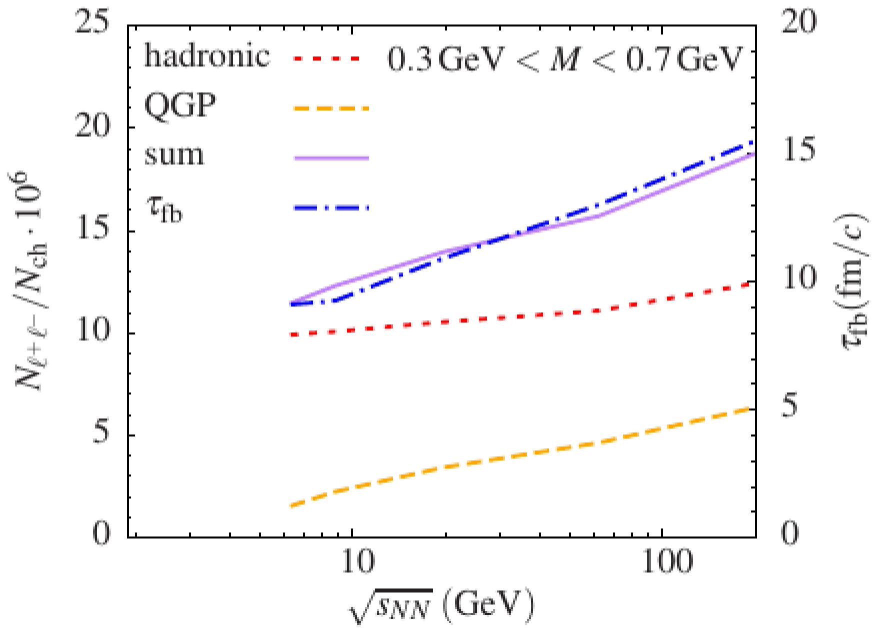
Ralf Rapp (Texas A-M, Cyclotron Inst. & Texas A-M), Hendrik van Hees (Frankfurt U. & Frankfurt U., FIAS). Nov 17, 2014. 5 pp.

Published in Phys.Lett. B753 (2016) 586-590

remarks

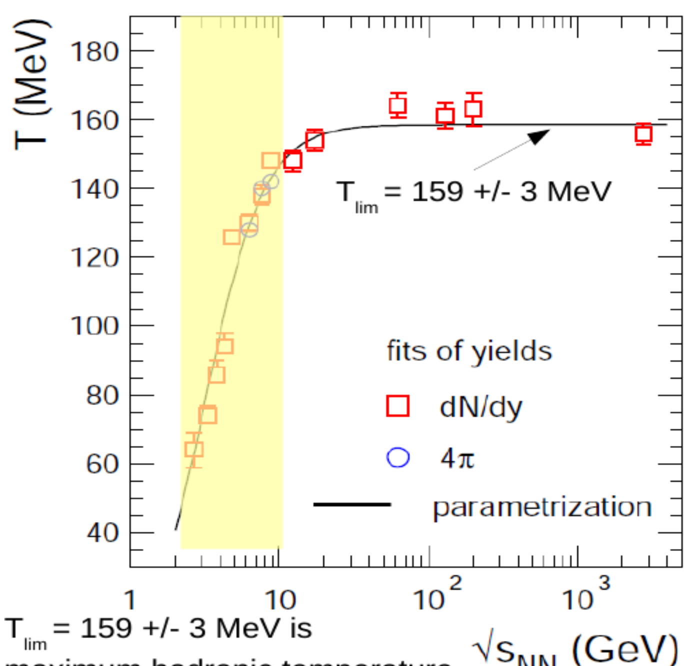
region above 2.5 and below 20 GeV not covered experimentally

without mixed phase or critical point, the enhancement factor or temperature would smoothly decrease until the SIS18 regime is reached

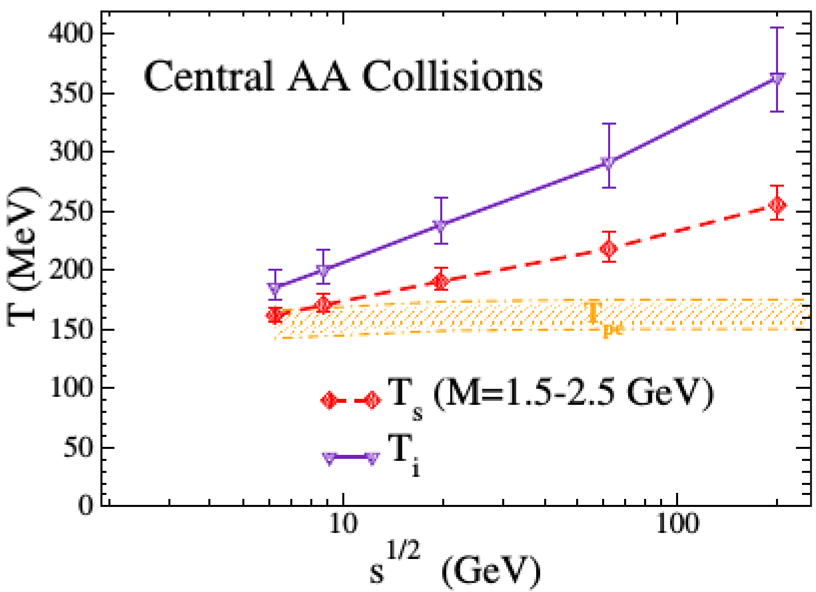


search for deviations from this
NICA, CBM, RHIC BESII
but T_chem decreases smoothly in this region

what about LHC energy? ► ALICE



T_{lim} = 159 +/- 3 MeV is maximum hadronic temperature



Rapp, van Hees 2016

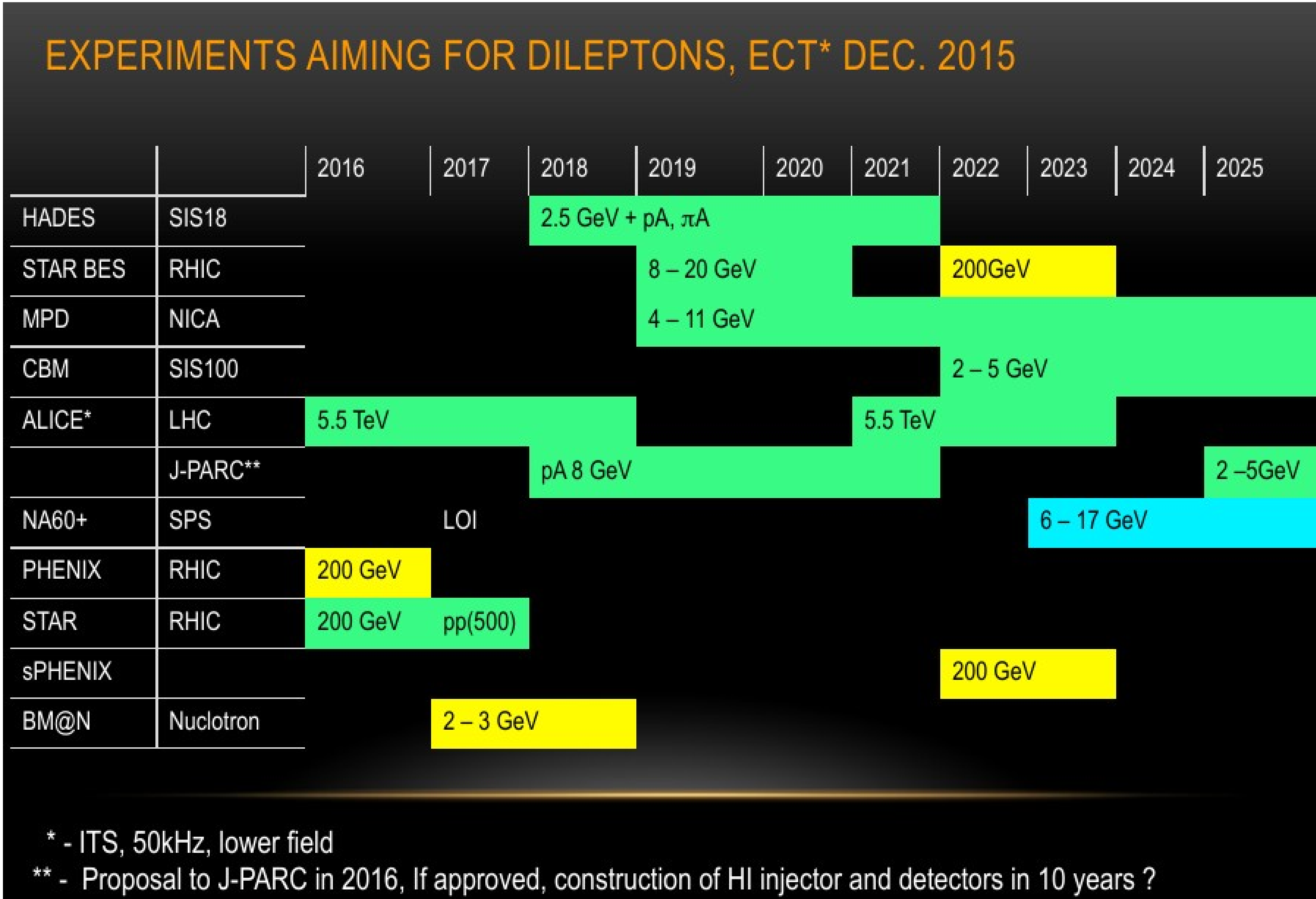


figure fromTetyana Galatyuk 2016

Fluctuations of conserved quantities, susceptibilities, and Lattice QCD

moments of hadron distributions and QCD statistical operator

1st moment = mean yields of all hadrons predicted via statistical hadronization model

2nd moment = variance event-by-event measurements of net charges via LQCD computed susceptibilities

3rd moment = skewness event-by-event measurements of net charges via LQCD computed susceptibilities

4th moment = kurtosis event-by-event measurements of net charges via LQCD computed susceptibilities

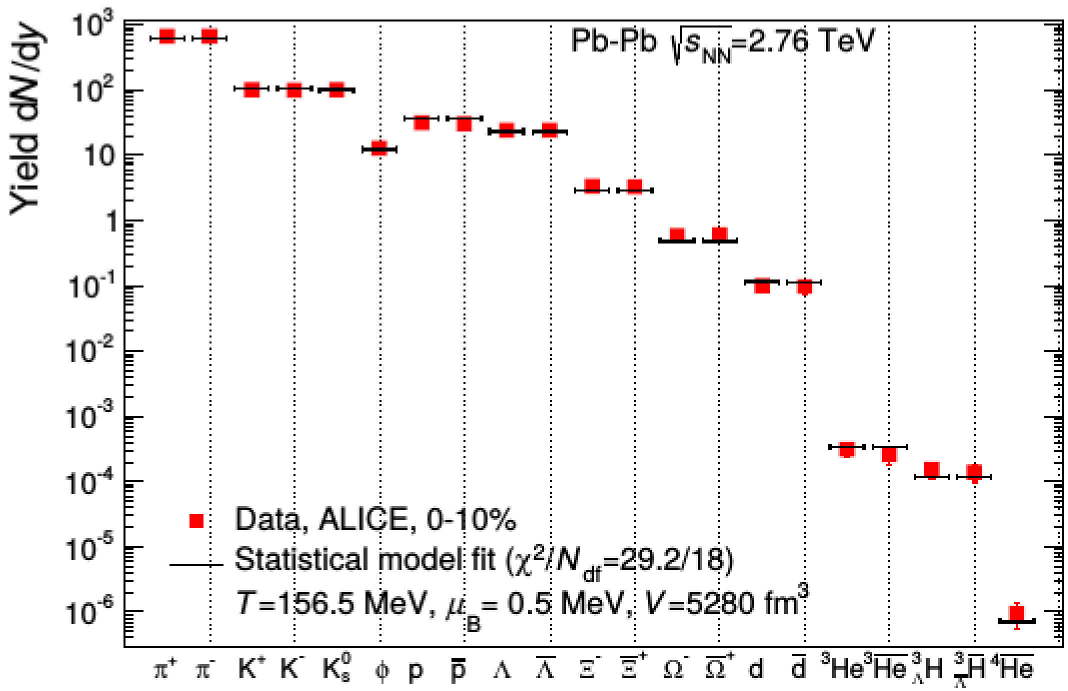
note: higher moments are sensitive to correlation length ξ

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \; \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \; \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

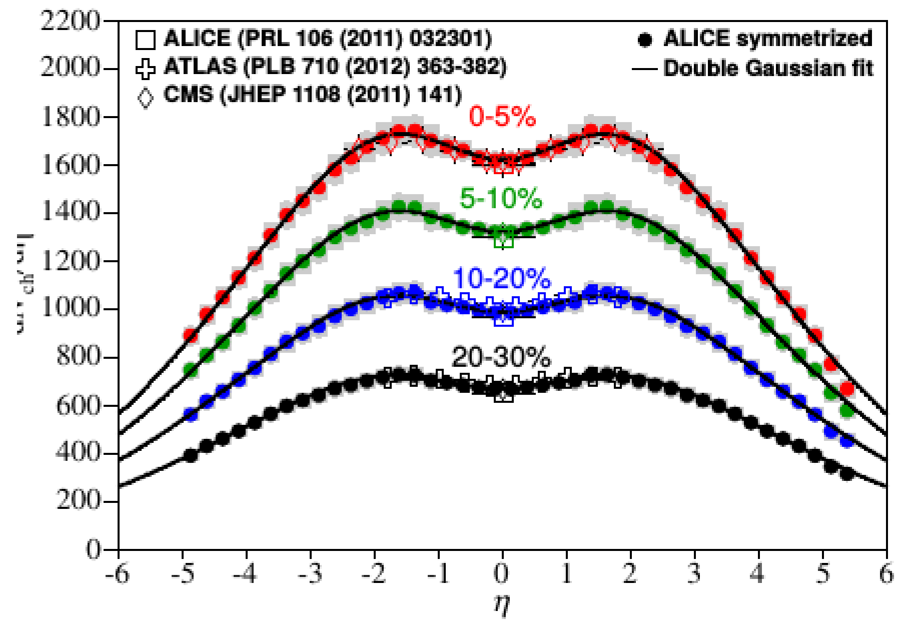
1^{st} moments

May 2016 update: excellent description of LHC data

T, $V(\Delta y = 1)$ from thermal fit



$dN_{ch}/d\eta$ data



ALICE, PLB 726 (2013) 610

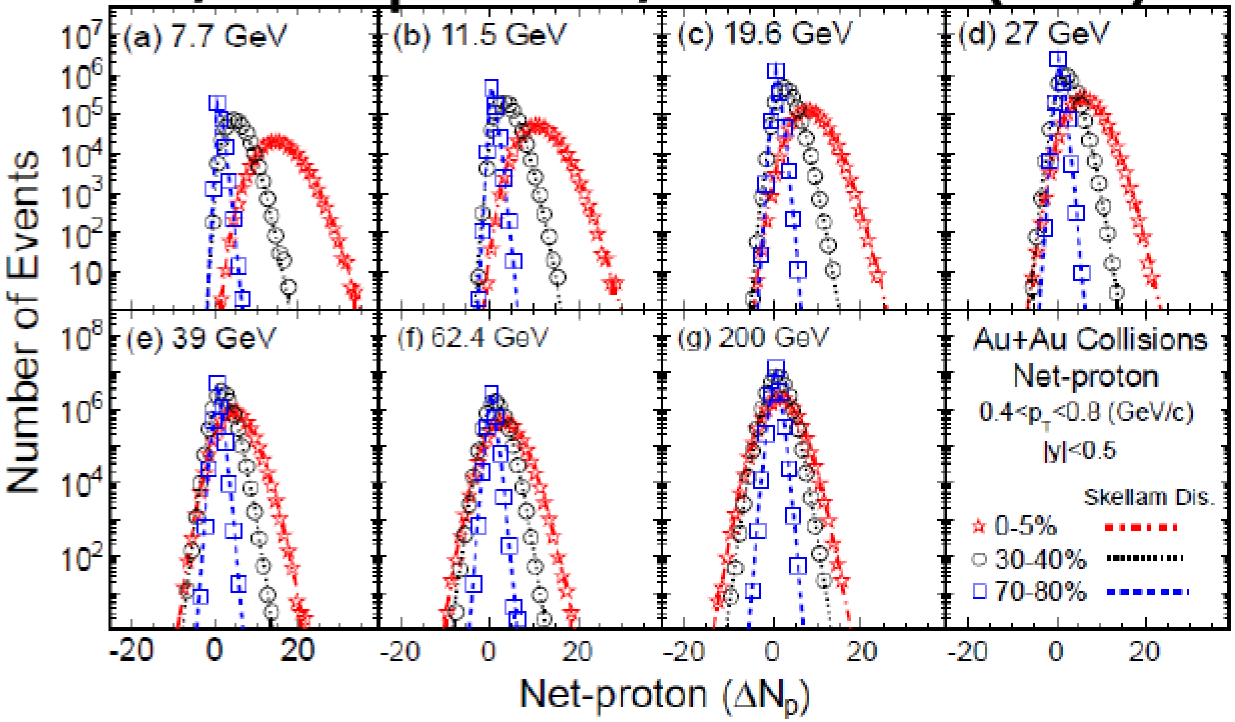
proton discrepancy 2.8 sigma

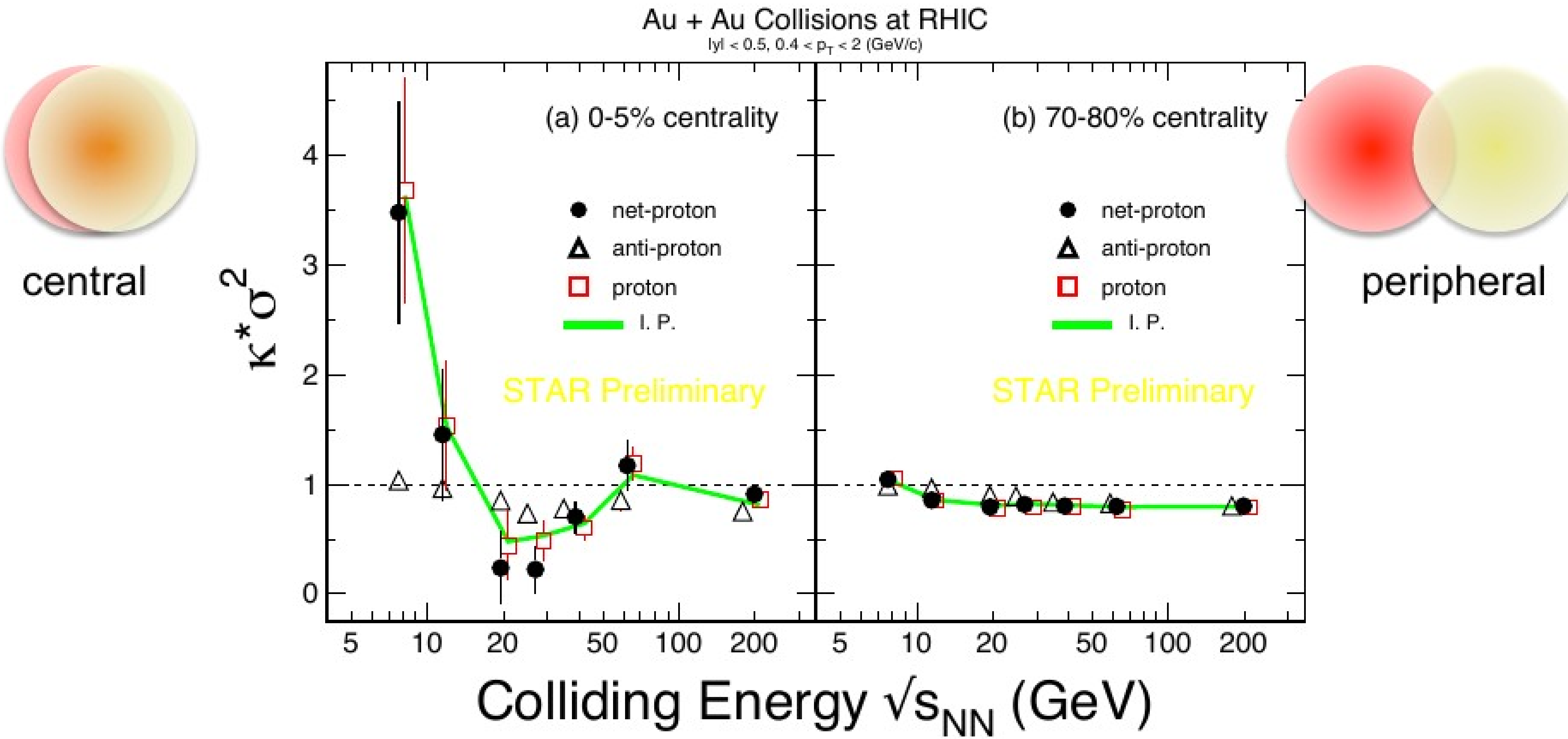
fit includes loosely bound systems such as deuteron and hypertriton
hypertriton is bound-state of (Λ,p,n), Λ separation energy about 130 keV
size about 10 fm, the **ultimate halo nucleus,**
produced at T=156 MeV. close to an Efimov state

J. Stachel, A. Andronic, P. Braun-Munzinger and K. Redlich, Confronting LHC data with the statistical hadronization model, J.Phys.Conf.Ser.**509** (2014) 012019, arXiv:1311.4662 [nucl-th].

now: remarks on measurements and interpretation of higher moments

STAR, net-proton, PRL112 ('14)

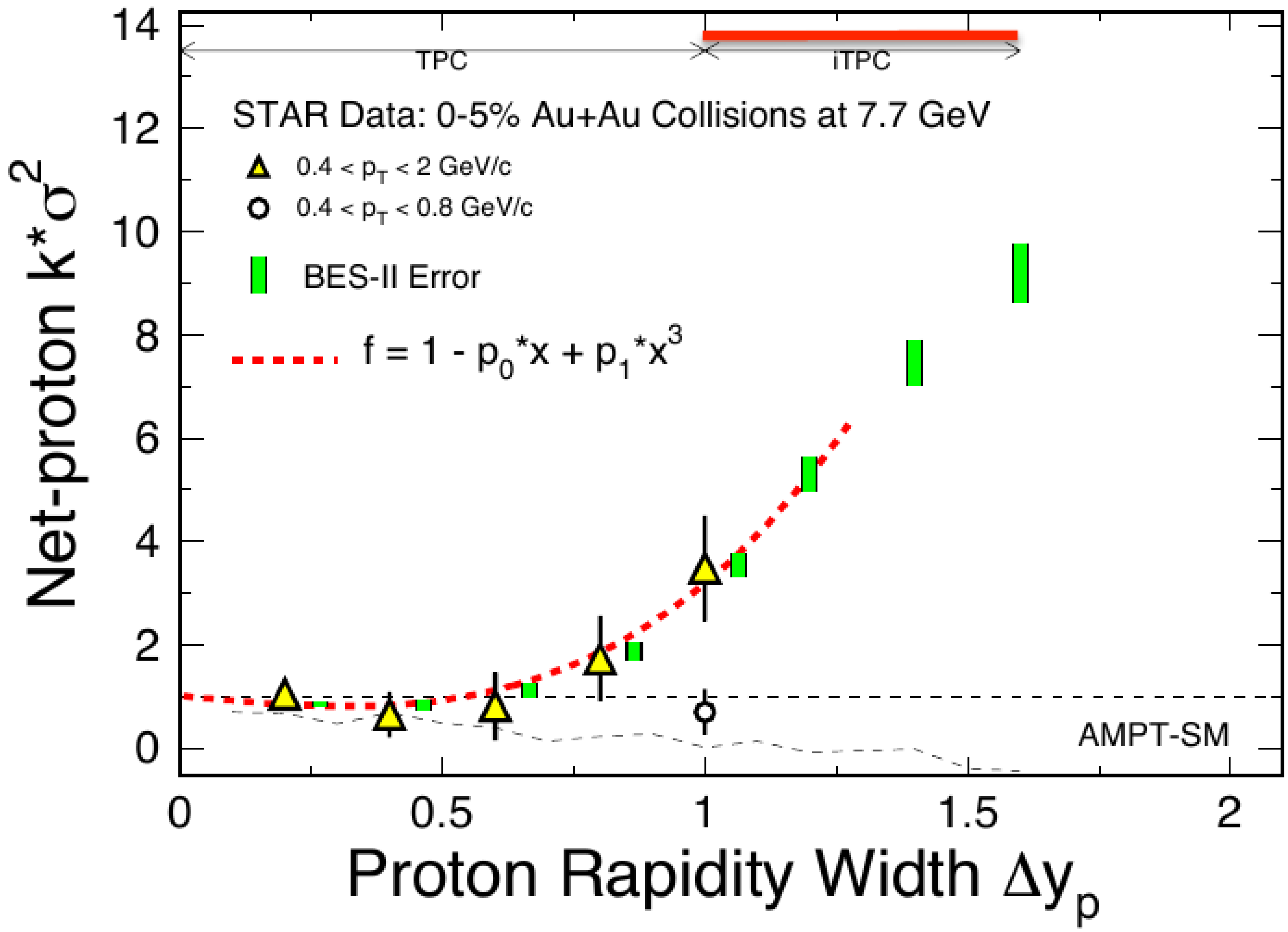




most recent STAR results on 'net protons'
non-monotonic behavior observed

Nu Xu, CPOD2016

outlook for BESII program



BES-I results: Poisson + Baryon conservation + v^3, criticality?

Nu Xu, CPOD2016

a few remarks about analysis of higher moments of conserved charges

- already for second moments there is a delicate balance between influence of conservation laws (at large acceptance) and trivial fluctuations (at small acceptance
  - for small acceptance, delta_eta << 1, probability distributions become Poisson and are not sensitive to critical behavor.
    in this limit all efficiencies are binomially distributed.
  - for large acceptance, delta_eta > 1, effect of conservation laws becomes large. Efficiencies are not anymore binomially distributed. But data are sensitive to dynamical behavior.
  - corrections for baryon number conservation become mandatory
  - impact parameter (volume) fluctuations become largest source of 'trivial' fluctuations, very unpleasant for search for critical endpoint (details see below)
- for higher moments, situation becomes more difficult.
- effect of purity in PID needs to be carefully studied, crucial for higher moment analysis

a few remarks about analysis of higher moments of conserved charges

- volume fluctuations

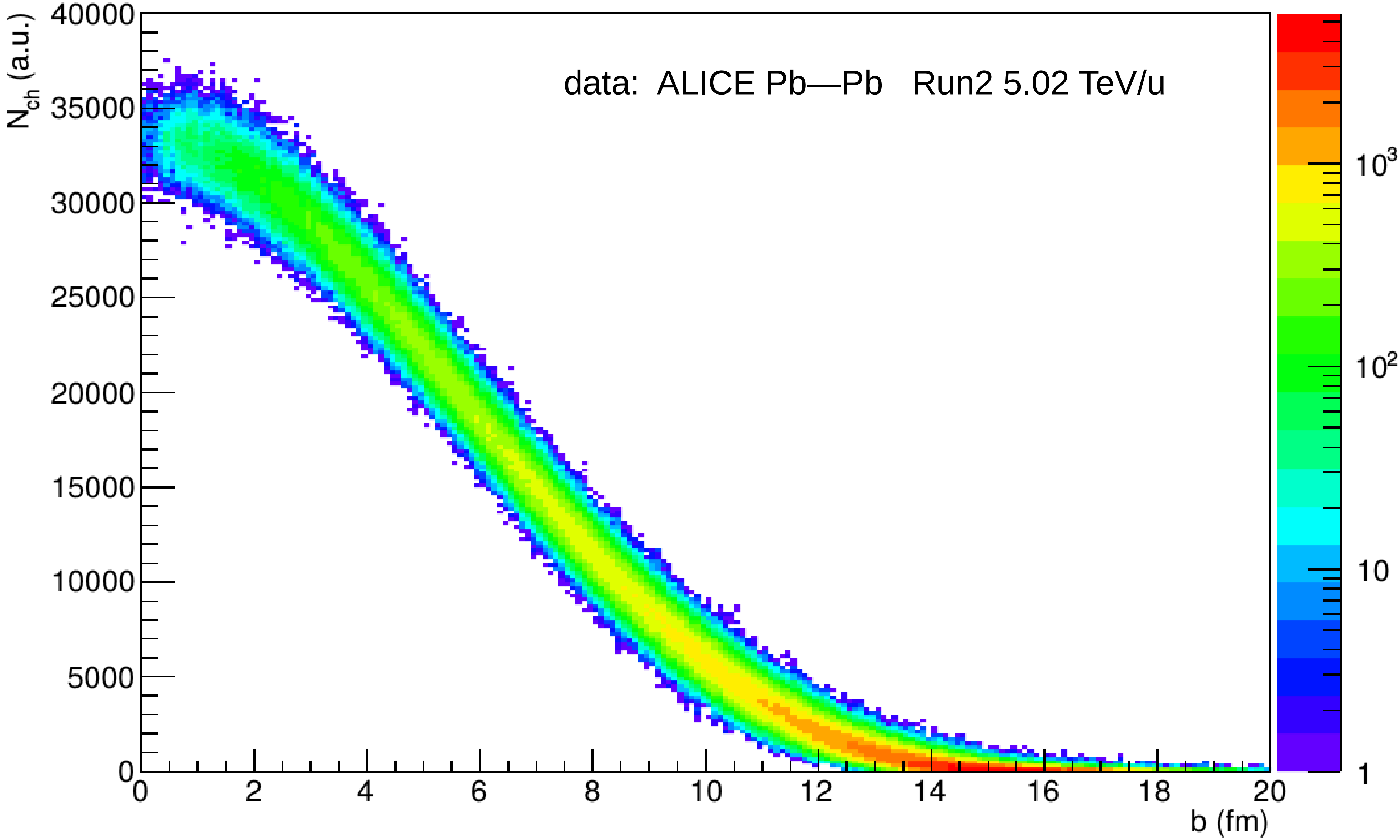
  - independent source model:
  - for N: total number of particles, N_s: number of sources, n: number of particles from a single source

$$c_2(N) = \langle N_s \rangle \, c_2(n) + \langle n \rangle^2 \, c_2(N_s)$$

- 2 limits:
  - (i) <n> = N_p low energy limit, fluctuations dominated by trivial volume fluctuations
  - (ii) <n> = <N_p – N_pbar> = 0 high energy (LHC) limit, volume fluctuations drop out

major advantage at LHC energy: EbE measurements of conserved quantities sensitive to dynamical fluctuations

impact parameter fluctuations in experiment



even for the most central collisions b ranges from 0 – 2 fm

interface between experimental data and LQCD calculations

pbm, Anar Rustamov, Johanna Stachel

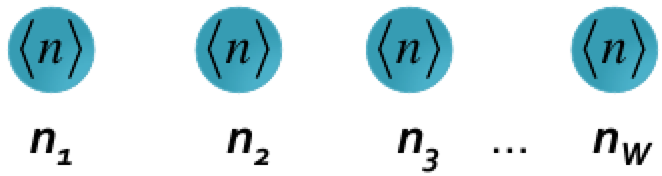
Monte Carlo approach to simulate:

(1) experimental acceptance and centrality determination
(2) volume/impact parameter fluctuations
(3) charge or baryon number conservation corrections

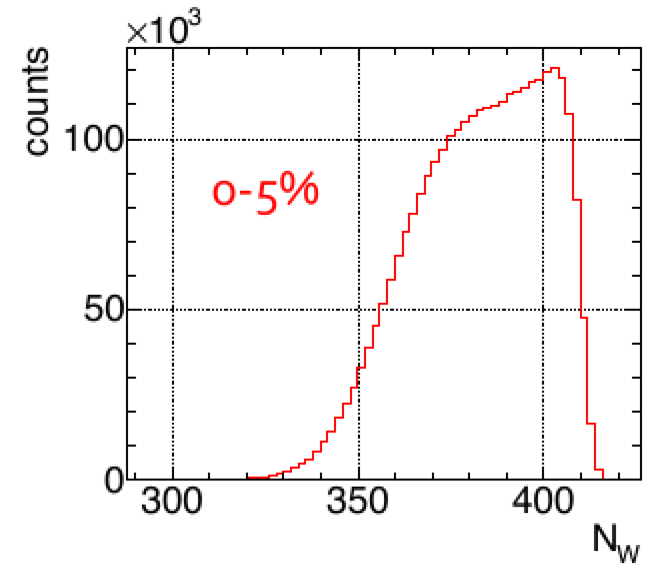
for all higher moments (in practice now up to 6^{th} moment)

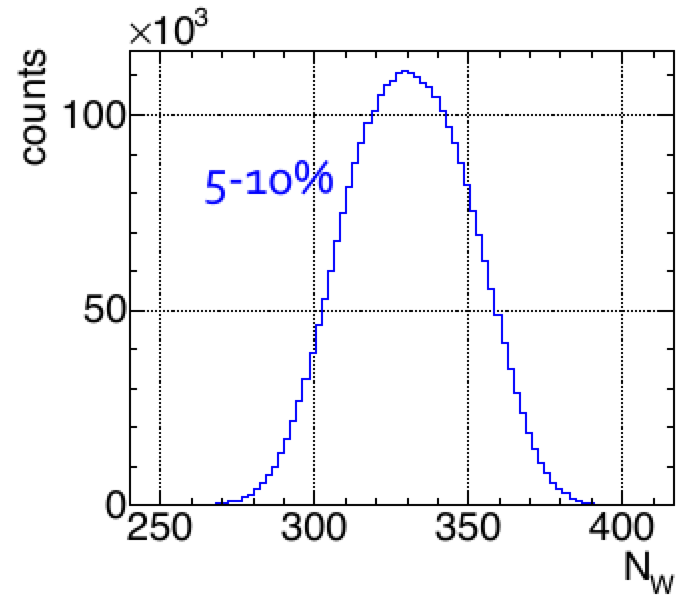
compare measured data to expectations from hadron resonance gas corrected for above effects → dynamical fluctuations

Building the model, Particle production

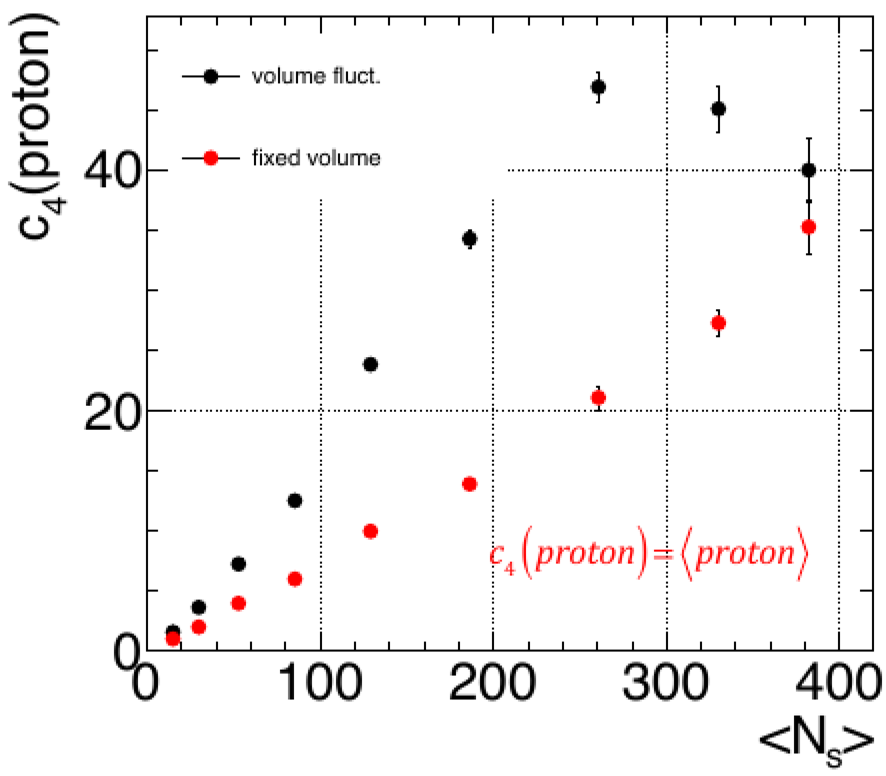


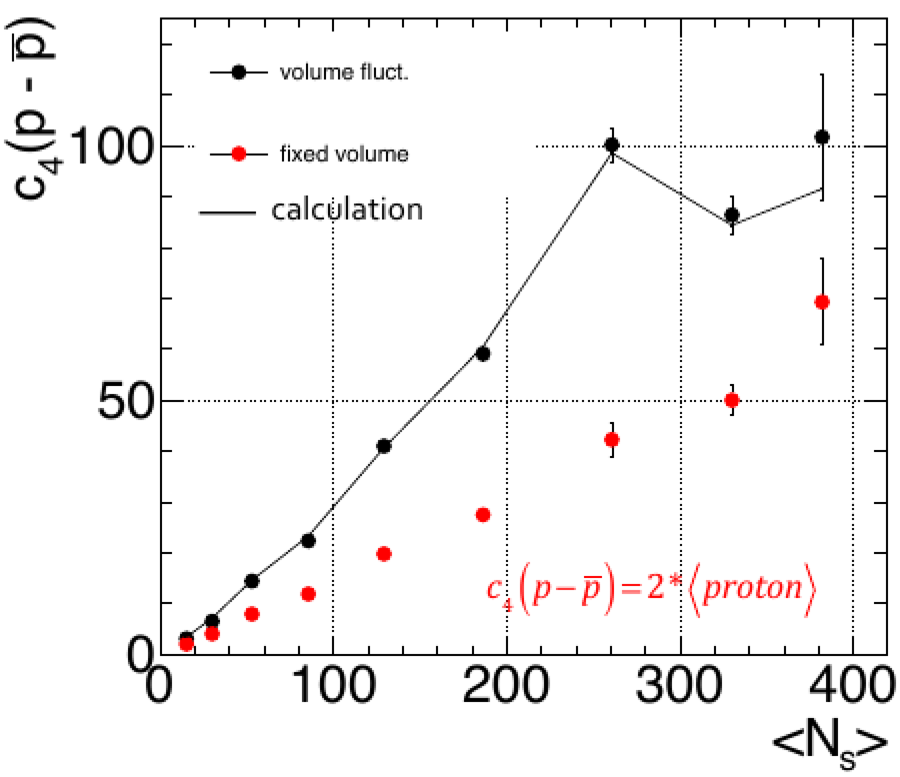
- ***N_W fluctuates with the Glauber initial conditions***
- ***Each source is treated Grand Canonically***
- ***Mean proton multiplicities $\langle p \rangle$, $\langle \overline{p} \rangle$ from ALICE [Pb+Pb@2.76](#) TeV***
- ***Expected results without volume fluctuations:***
  - particles: $c_n = N_w \langle n \rangle = \langle p \rangle = \langle \overline{p} \rangle$
    $c_n / c_2 = 1$
  - net-particles: $c_n = \langle p \rangle + (-1)^n \langle \overline{p} \rangle$
    $c_3 / c_2 = 0, \quad c_4 / c_2 = 1$





examples





LHC energy, net baryon number 0, still big effects from volume fluctuations

examples

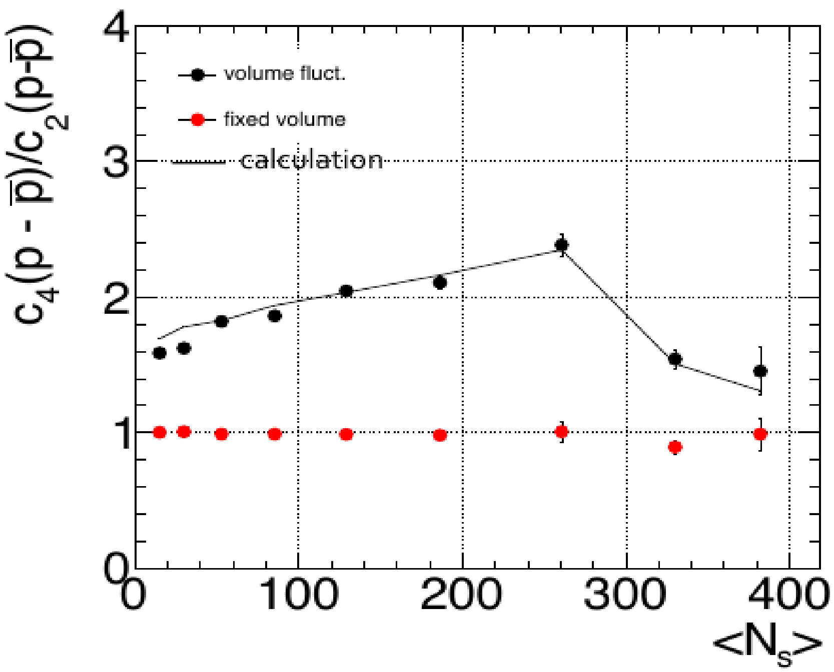
Cumulant Ratios

$$\frac{c_4(p-\bar{p})}{c_2(p-\bar{p})} = \frac{c_4(n-\bar{n})}{c_2(n-\bar{n})} + 3c_2(n-\bar{n})\frac{c_2(N_w)}{\langle N_w \rangle}$$

Additional term due to volume fluctuations

which is missing in famous:

$$\frac{c_4(p-\bar{p})}{c_2(p-\bar{p})} = \frac{\chi_4^B}{\chi_2^B}$$



LHC energy, net baryon number 0, still big effects from volume fluctuations on ratios of susceptibilities, needs to be corrected

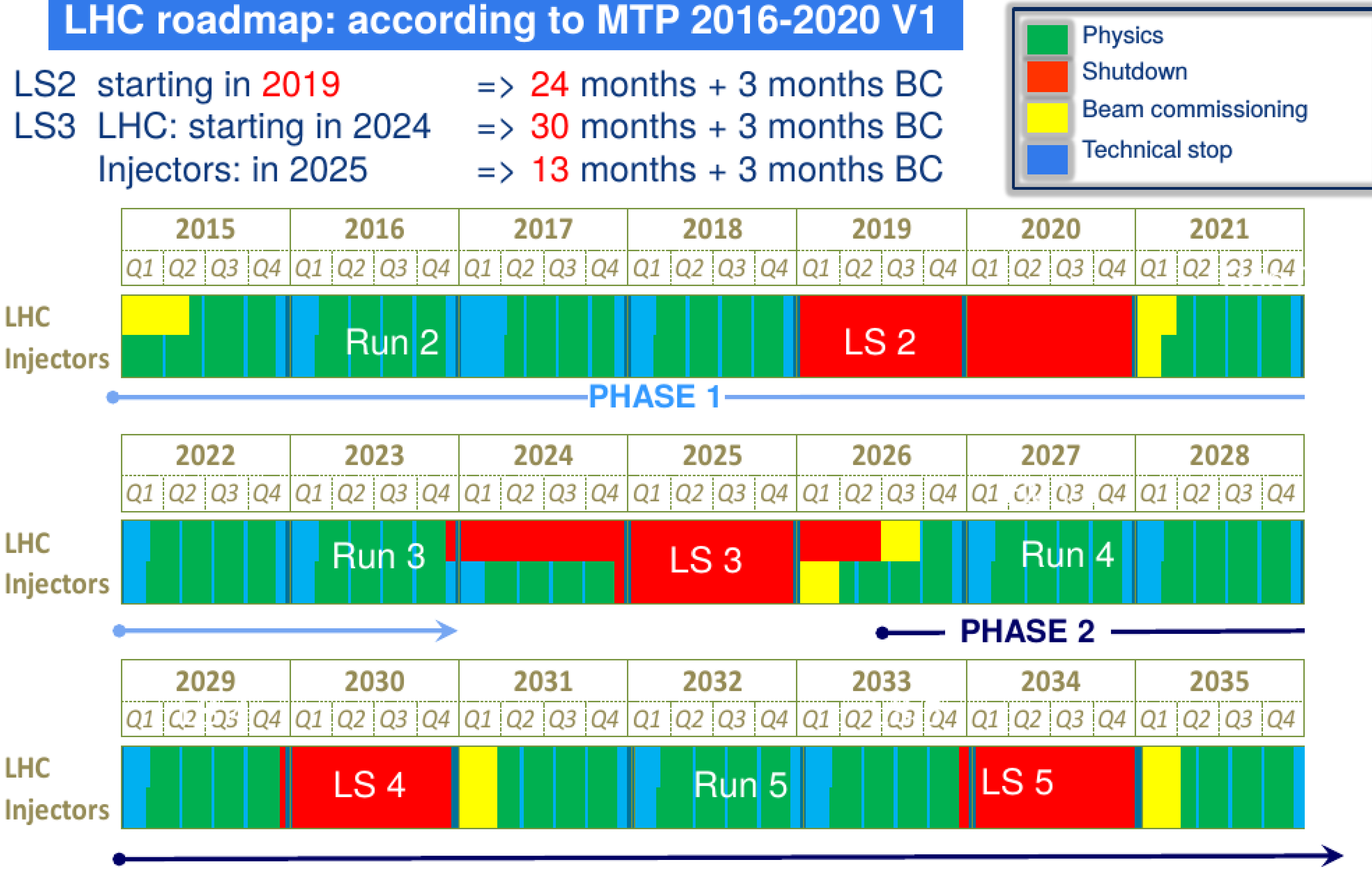
LHC ion program for Run3 and Run4

Main conclusion of the '2013 European Strategy for Particle Physics' process

"Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics ***and the quark-gluon plasma."***

LHC roadmap: according to MTP 2016-2020 V1

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC



approved ALICE program up to and including LHC Run4

ALICE Upgrade Strategy

High precision measurements of rare probes at low $p_{T,}$ which cannot be selected with a trigger, require a large sample of events recorded on tape

Target

- Pb-Pb recorded luminosity $\geq 10\ nb^{-1}$ ➡ 8×10^{10} events
- pp (@5.5 Tev) recorded luminosity $\geq 6\ pb^{-1}$ ➡ 1.4×10^{11} events

Gain a factor **100** in statistics over approved programme

... and significant improvement of vertexing and tracking capabilities

I. Upgrade the ALICE readout systems and online systems to

- read out all Pb-Pb interactions at a maximum rate of 50kHz (i.e. $L = 6\times10^{27}\ cm^{-1}s^{-1}$), with a minimum bias trigger → NEW GEM TPC Readout Planes
- Perform online data reduction based on reconstruction of clusters and tracks (tracking used only to filter out clusters not associated to reconstructed tracks)

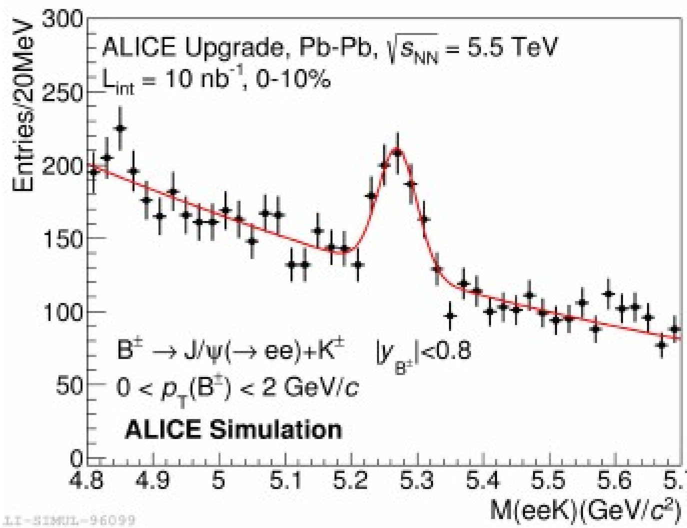
II. Improve vertexing and tracking at low p_T ➔ NEW ITS

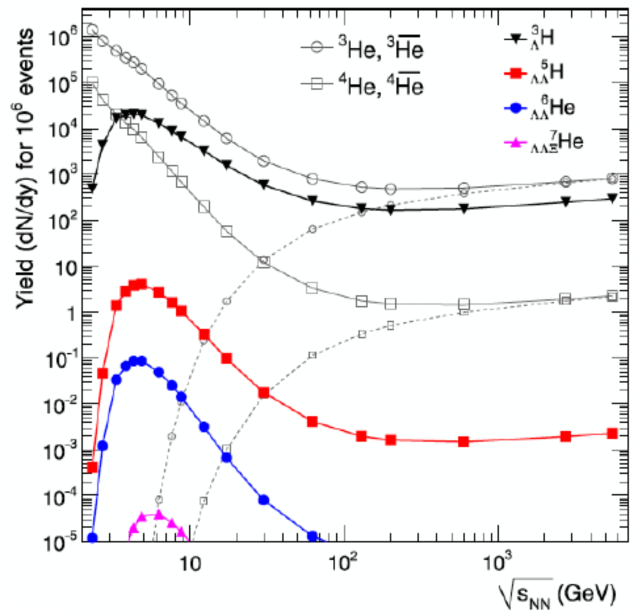
ALICE upgrade: main physics topics for Run3 and Run4

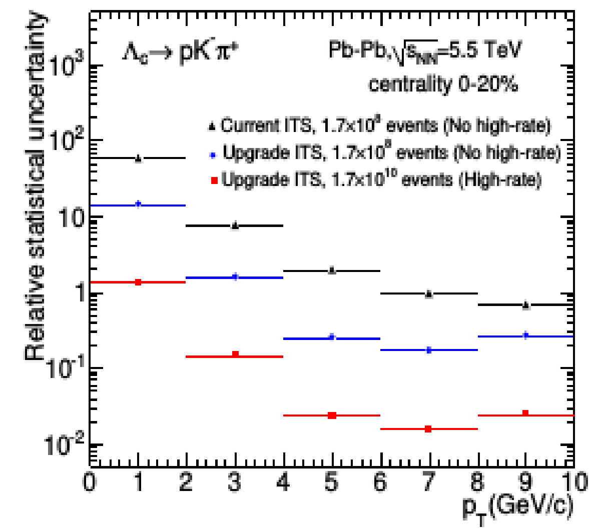
rare probes at low p_T:

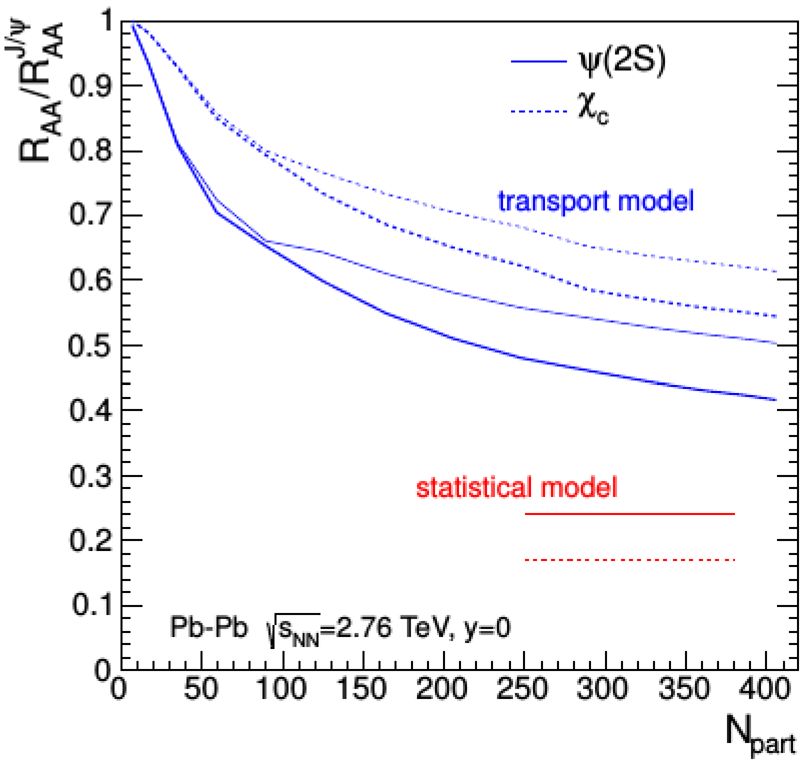
- heavy flavor hadrons
- quarkonia
- di-leptons at low and intermediate mass
- light anti-matter and exotic clusters
- jet physics
- event-by-event fluctuations of conserved quantum numbers

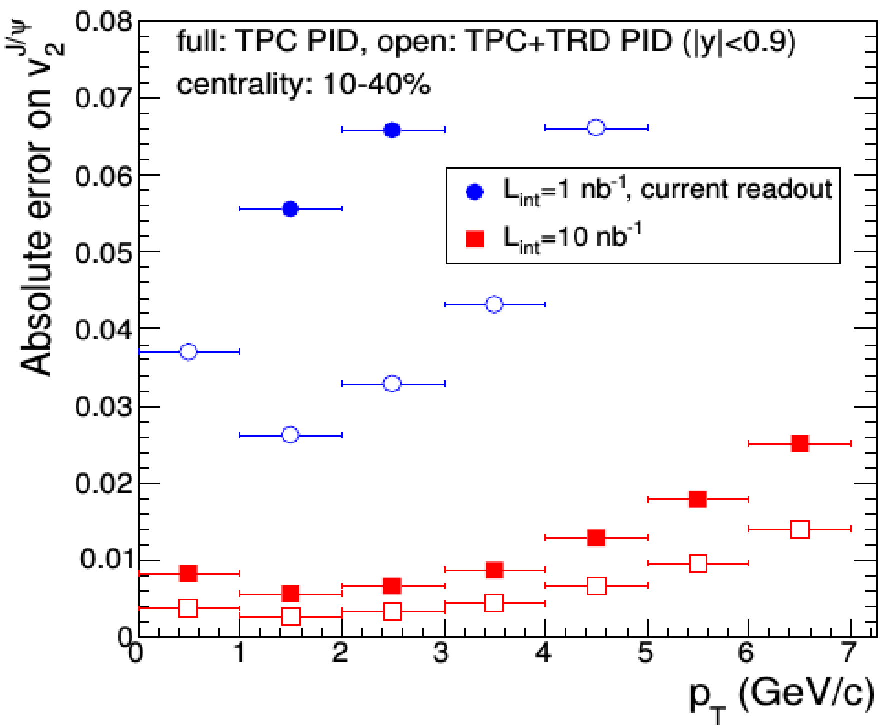
ALICE upgrade – show and tell





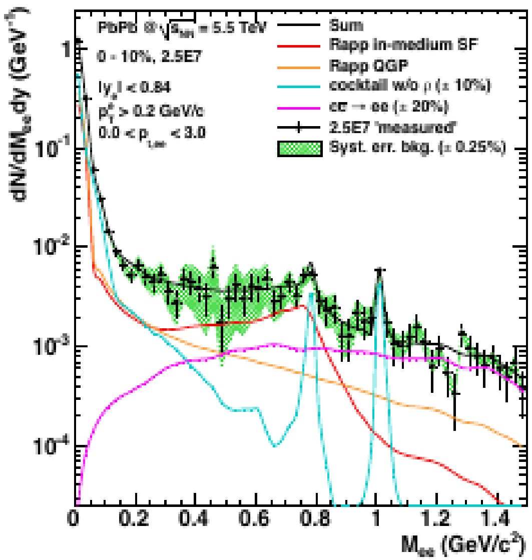


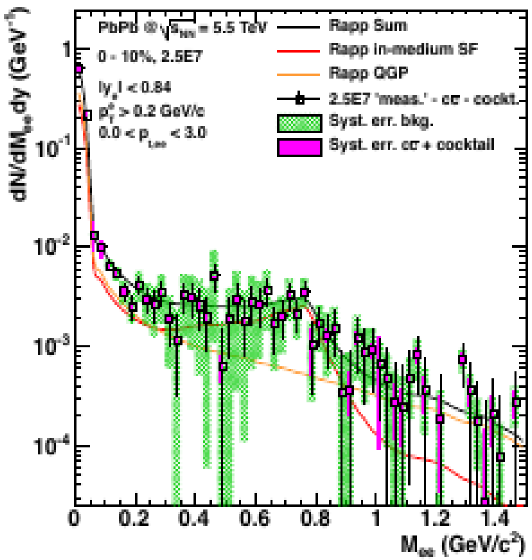




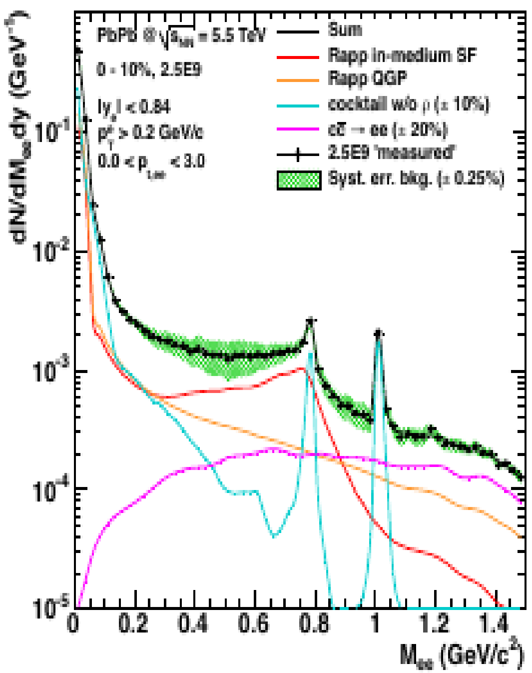
di-electron simulations at mid-rapidity
Rapp-Wambach scenario

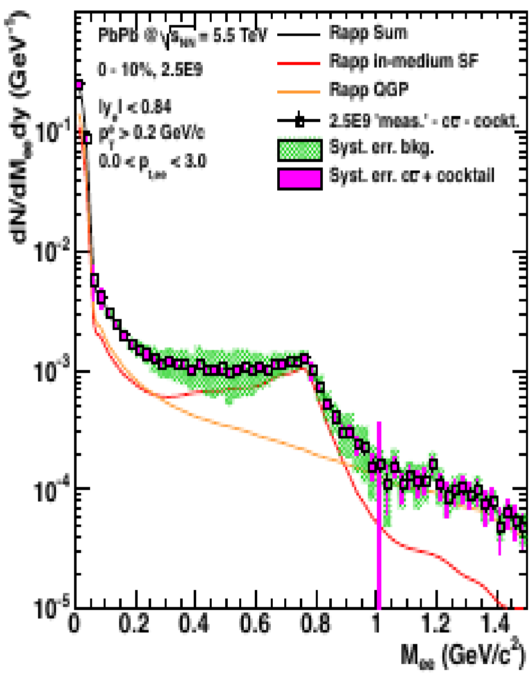
Run 2
current





Run 2
upgrade





ATLAS and CMS heavy ion programs in Run3 and Run4

main themes: rare probes at intermediate and high p_T

- jets
- photon-jet measurements
- EW probes
- quarkonia
- heavy flavor hadrons

LHCb ion program for Run3 and Run4

main theme: collisions at forward rapidity with excellent PID and momentum resolution

expected to be competitive also in central Pb—Pb program

LHC heavy ion program in Run3 and Run4

an exciting mix of upgraded detectors making use of
50 kHz Pb-Pb collisions

more than a decade of forefront research on
QGP and related topics ahead of us

future circular collider

looking far into the future

for an introduction and summary
see Dainese et al.,
arXiv:1605.01389

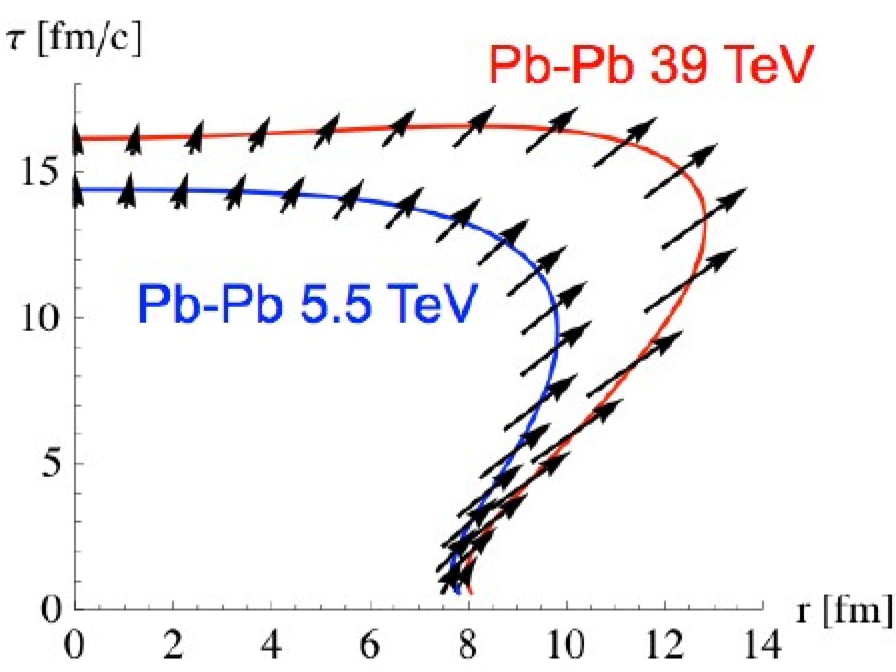
	Unit	FCC Injection	FCC Collision	
Operation mode		Pb	Pb–Pb	p–Pb
Beam energy	[TeV]	270	4100	50
$\sqrt{s_{NN}}$	[TeV]	-	39.4	62.8
No. of bunches per LHC injection	-	518	518	518
No. of bunches in the FCC	-	2072	2072	2072
No. of particles per bunch	[10^8]	2.0	2.0	164
Transv. norm. emittance	[μm]	1.5	1.5	3.75
Number of IPs in collision	-	-	1	1
Crossing-angle	[μrad]	-	0	
Initial luminosity	[10^{27}cm^{-2}s^{-1}]	-	24.5	2052
Peak luminosity	[10^{27}cm^{-2}s^{-1}]	-	57.8	9918
Integrated luminosity per fill	[μb^{-1}]	-	553	158630
Average luminosity	[μb^{-1}]	-	92	20736
Time in collision	[h]	-	3	6
Assumed turnaround time	[h]	-	1.65	1.65
Integrated luminosity/run	[nb^{-1}]	-	33	8000

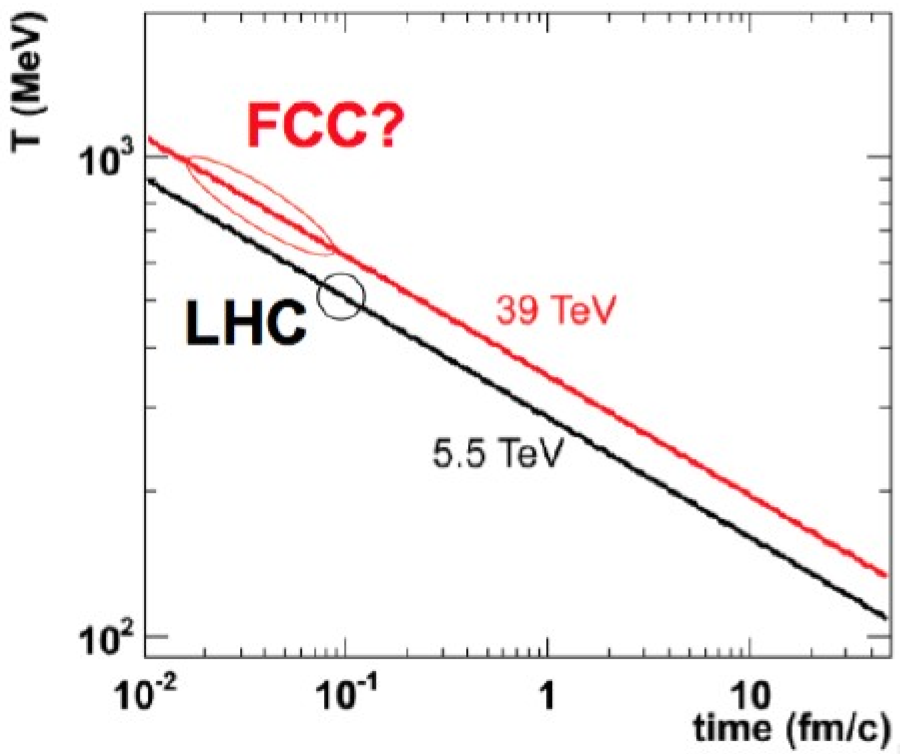
arXiv:1605.01389

Contents

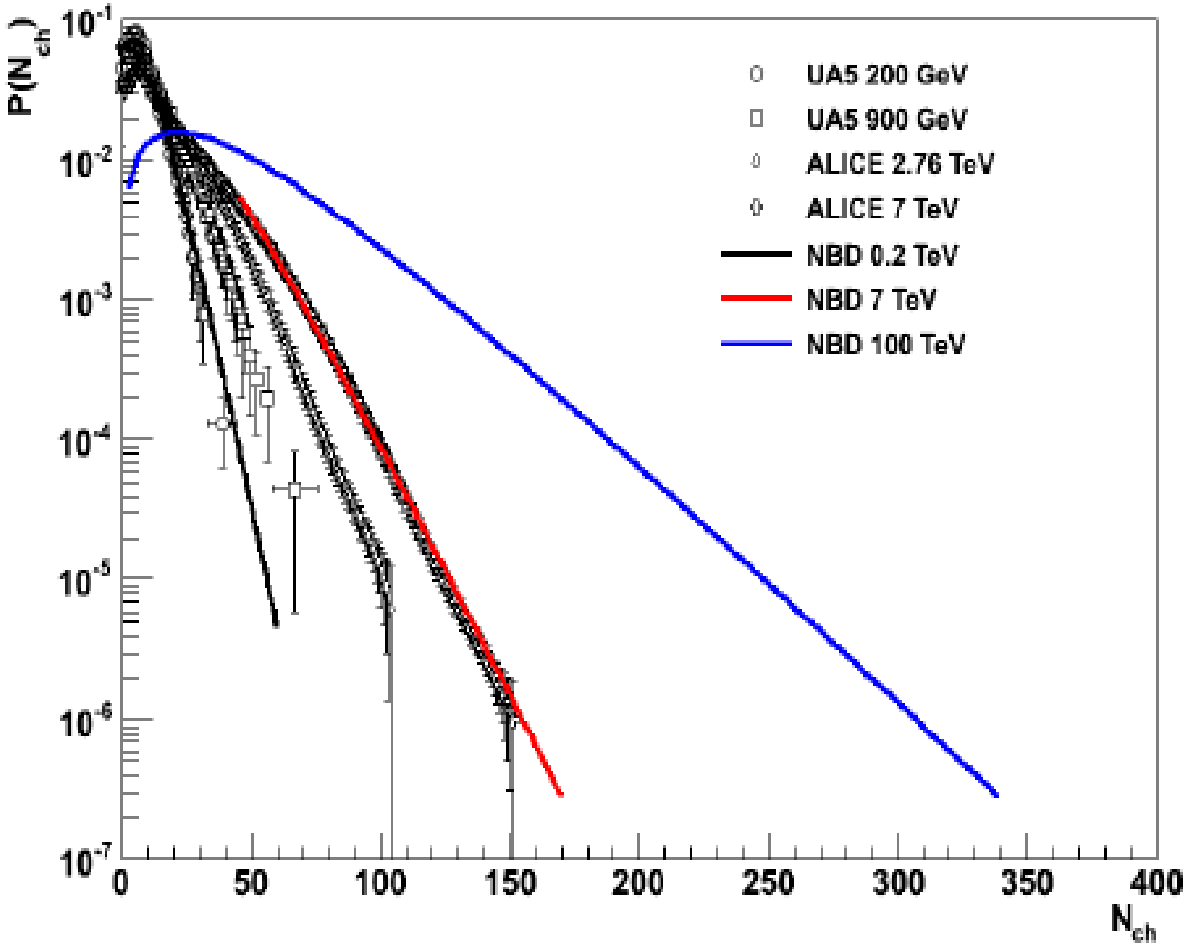
soft physics

Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$\mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta$ at $\eta = 0$	1.8–2.0 TeV	2.3–2.6 TeV	5.2–5.8 TeV
Homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
Decoupling time	10 fm/c	11 fm/c	13 fm/c
ε at $\tau = 1$ fm/c	12–13 $\mathrm{GeV/fm}^3$	16–17 $\mathrm{GeV/fm}^3$	35–40 $\mathrm{GeV/fm}^3$



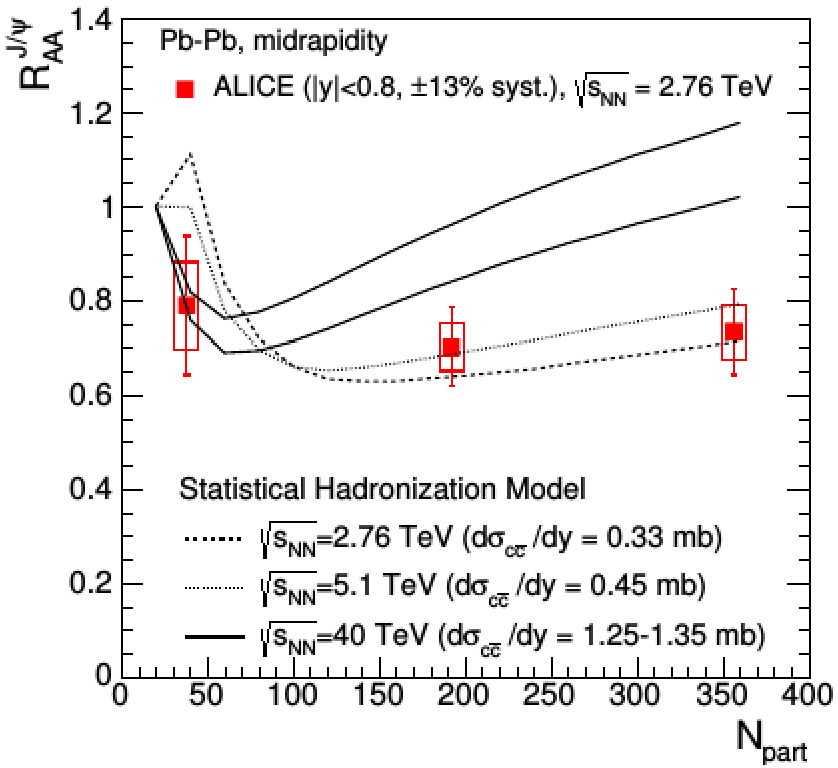


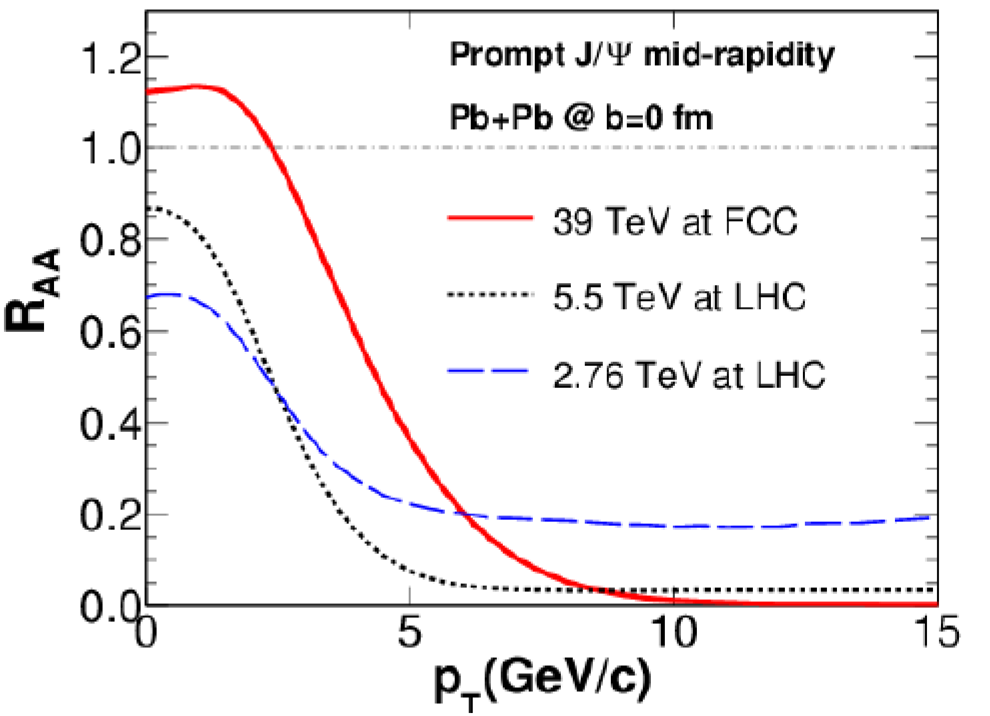
soft physics – pp collisions



can reach multiplicities in pp collisions approaching those in Au—Au collisions at RHIC energy

reaching charmonium enhancement





...maybe also for Y states