colliding ultra-relativistic nuclei at the LHC - results and perspectives

and comments on some EIC relevant topics

- intro
- selected results from LHC Run1 and LHC Run2
- plans and projections until 2030
- brief final remarks

NAS e-ion panel
April 19, 2017
Irvine, Ca

UNIVERSITÄT HEIDELBERG
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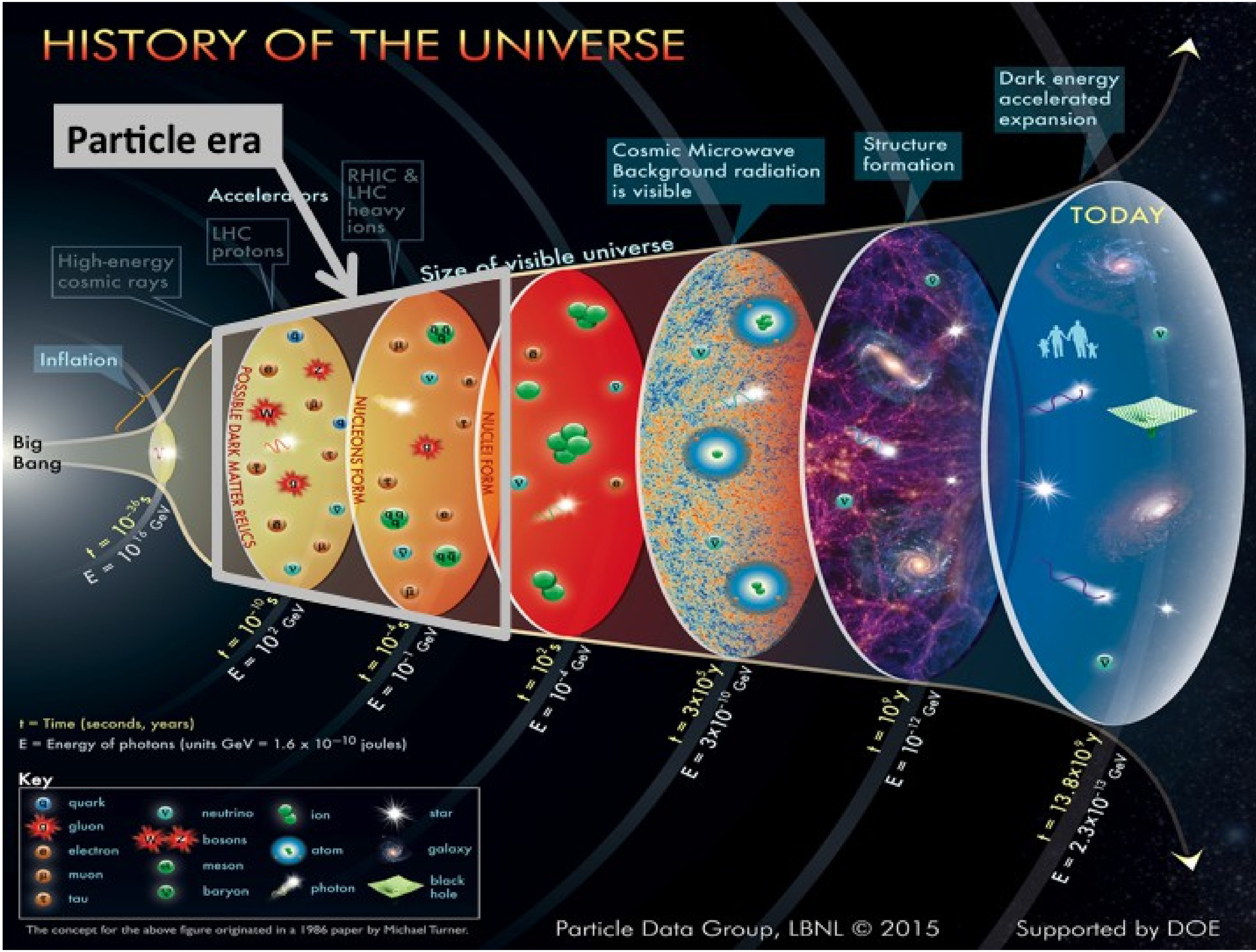
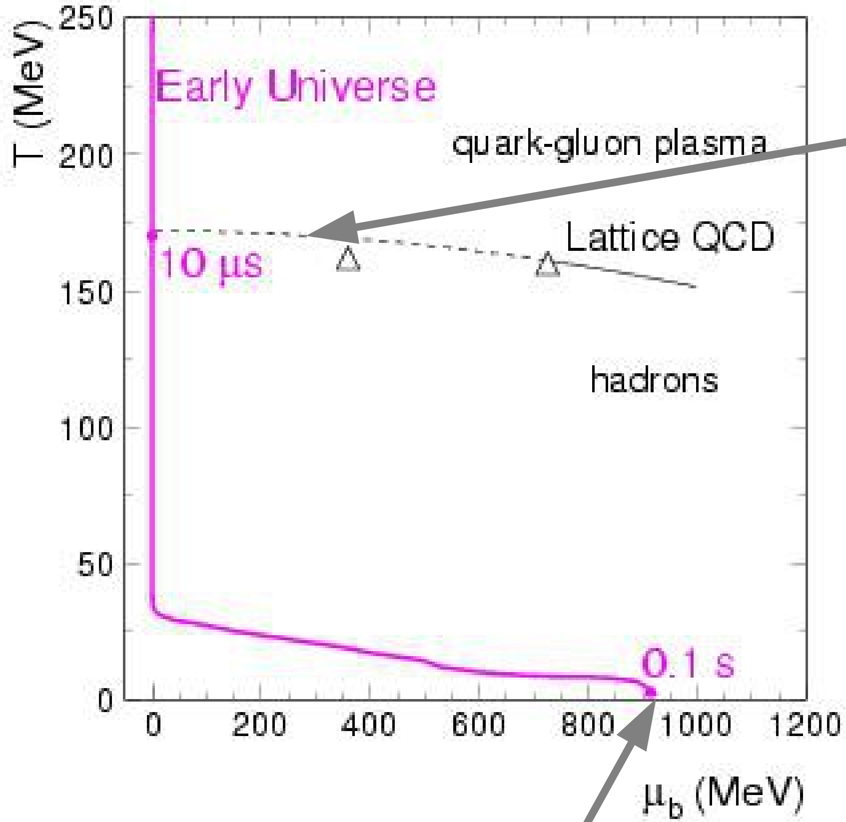


HISTORY OF THE UNIVERSE
Particle era
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Inflation
Big Bang
Size of visible universe
Cosmic Microwave Background radiation is visible
Structure formation
Dark energy accelerated expansion
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 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

evolution of the early universe and the QCD phase diagram



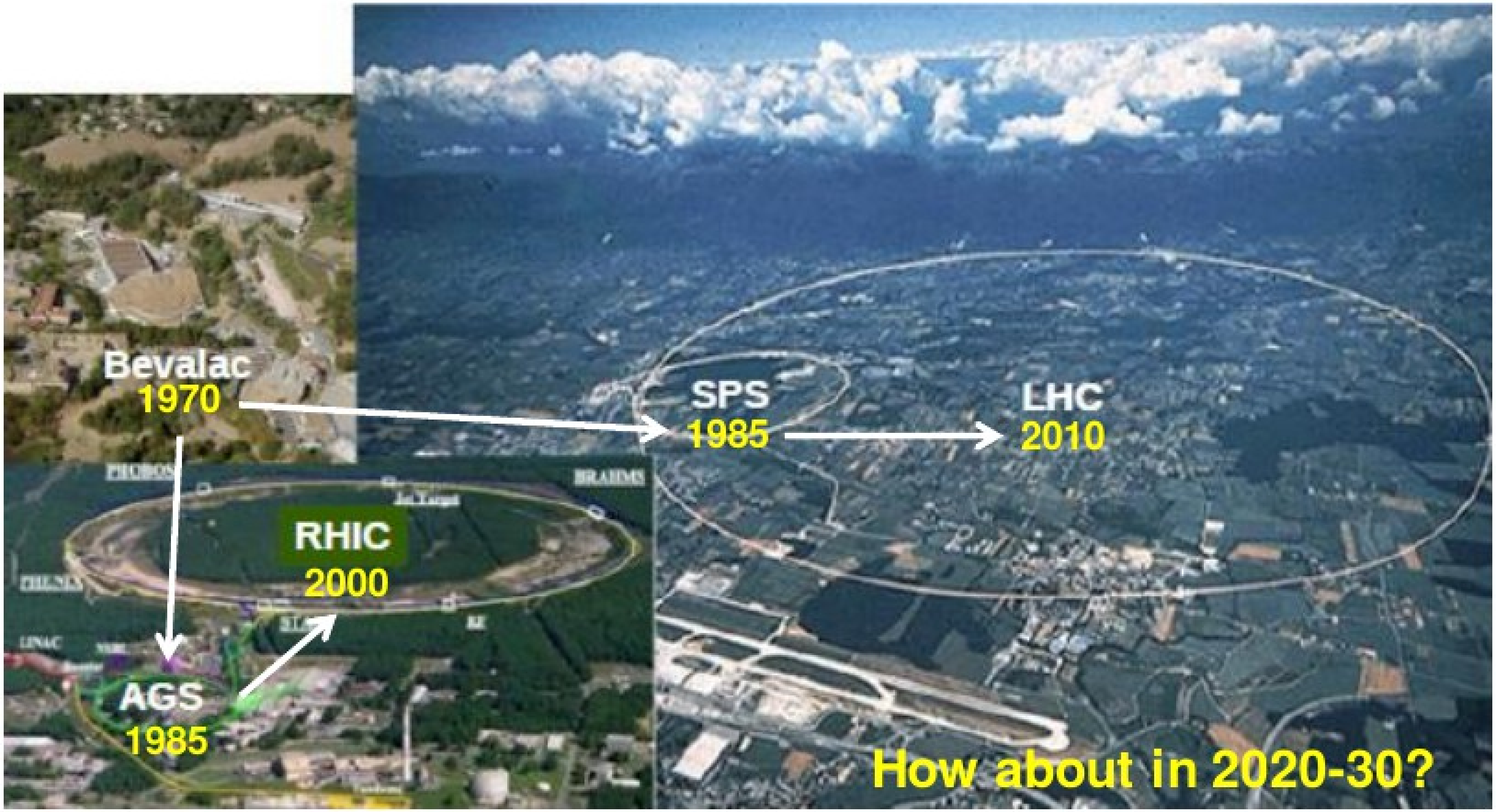
QCD phase boundary

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

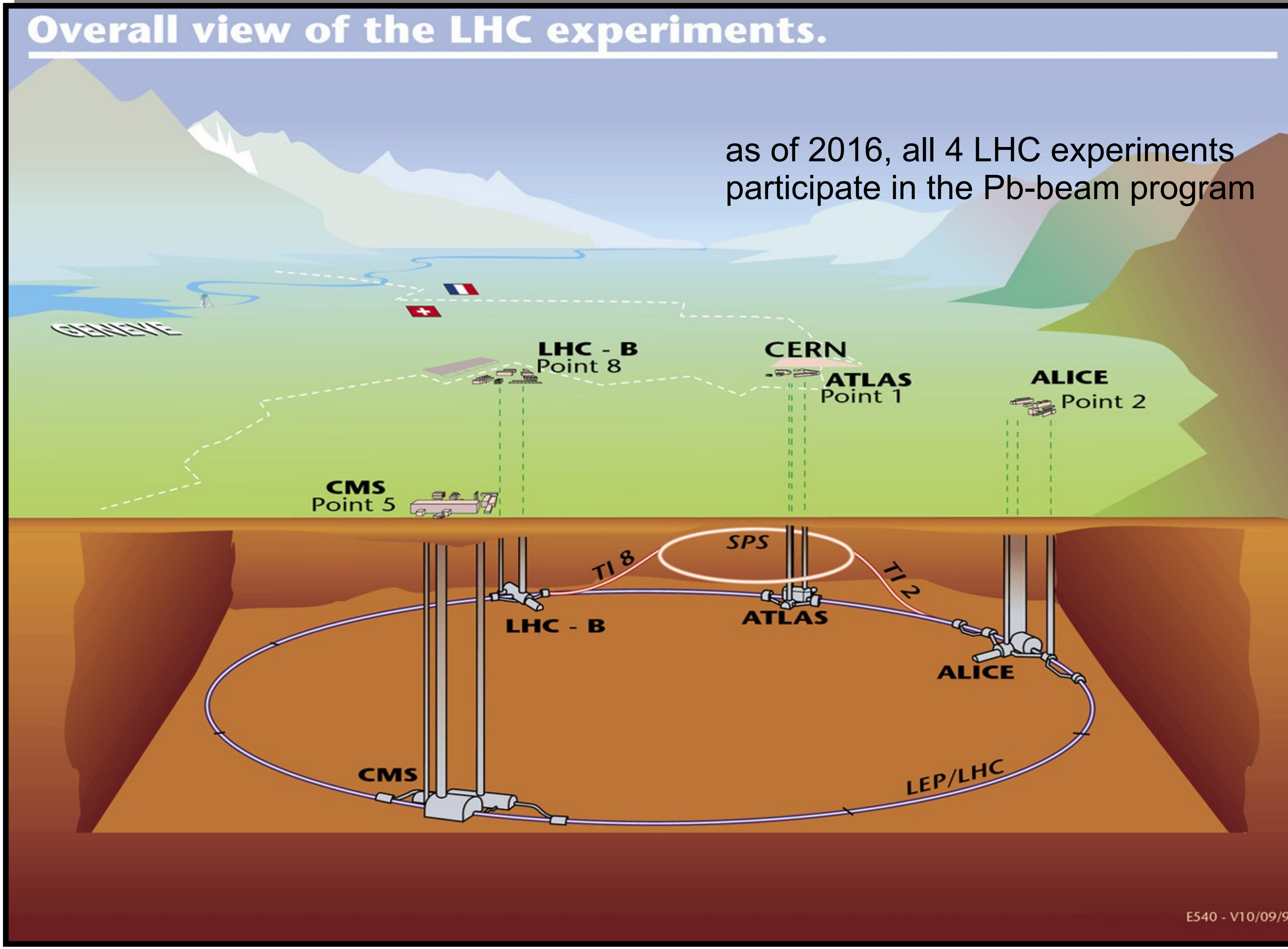
- charge neutrality
- net lepton number = net baryon number
- constant entropy/baryon

neutrinos decouple and light nuclei begin to be formed

The landscape of accelerators

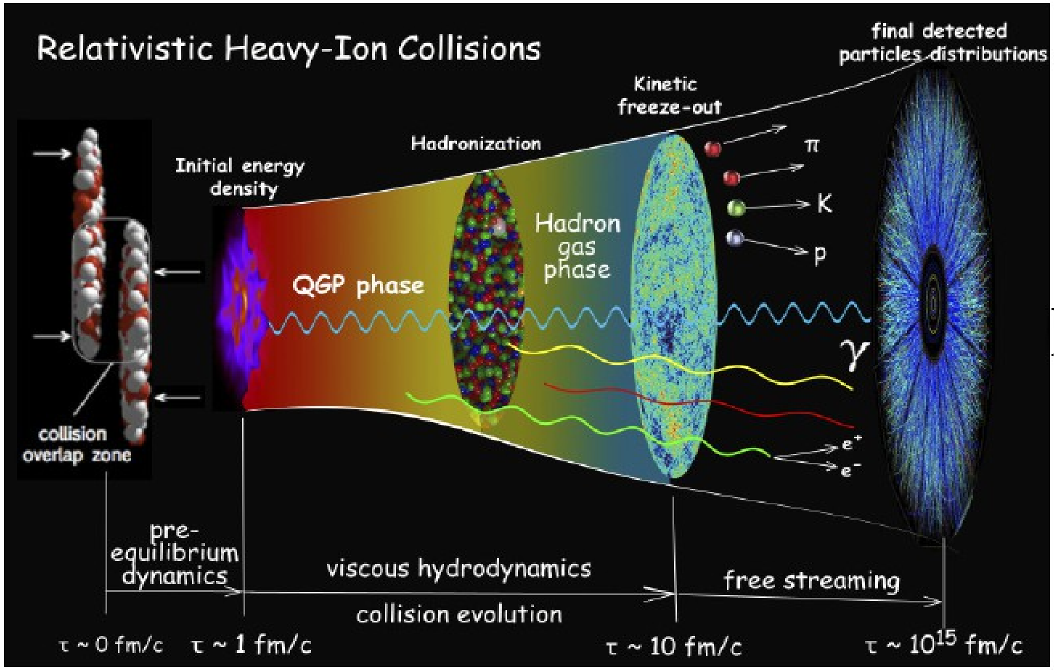


(Figure provided by M. Gyulassy)

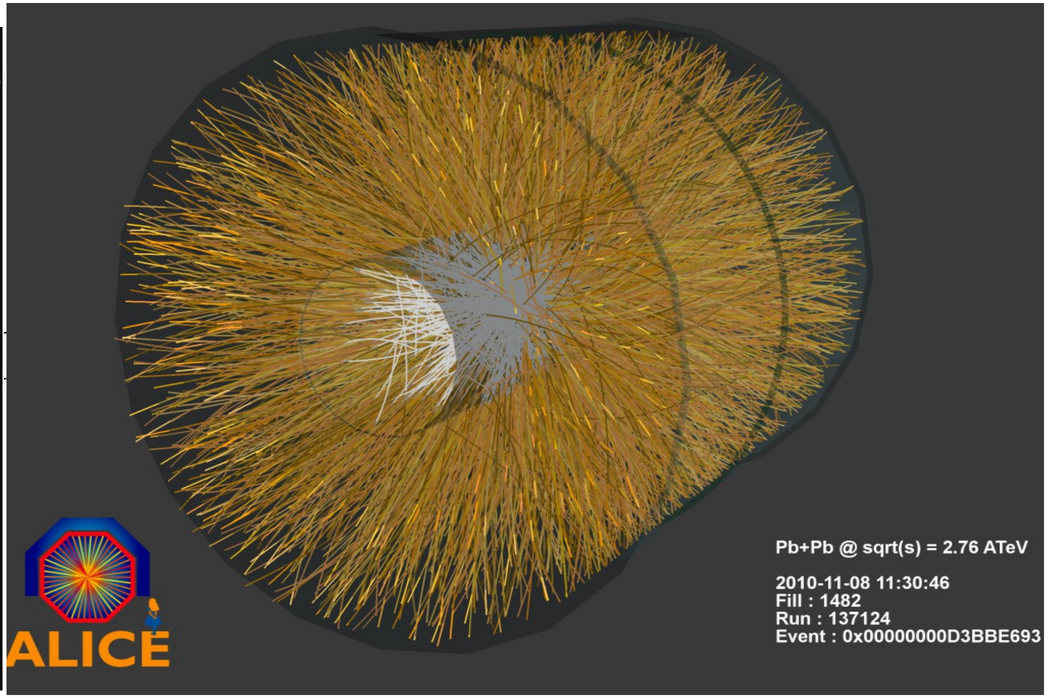


as of 2016, all 4 LHC experiments participate in the Pb-beam program

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



Paul Sorensen and Chun Shen

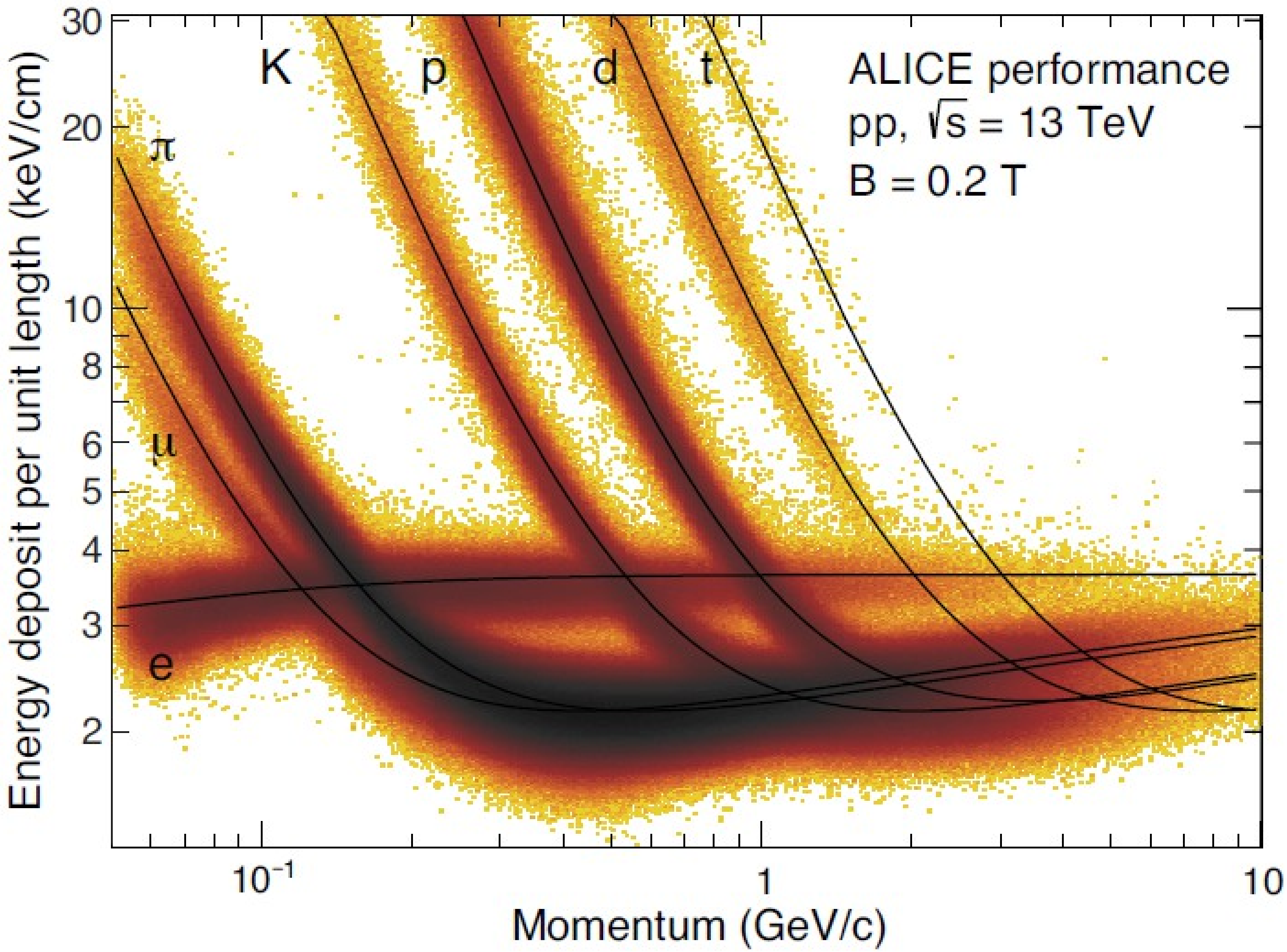


a few selected topics from LHC Run1 and Run2 2010 - 2018

- hadron production, QCD phase boundary and search for critical fluctuations
- energy loss of high momentum partons (quarks and gluons) in the QGP matter
- seeding the QGP with heavy (charm and beauty) quarks
- ultra-peripheral and photon-photon collisions

particle identification with the ALICE TPC

from 50 MeV to 50 GeV



hadron production and the QCD phase boundary

part 1: the hadron resonance gas

duality between hadrons and quarks/gluons (I)

Z: full QCD partition function

all thermodynamic quantities derive from QCD partition functions

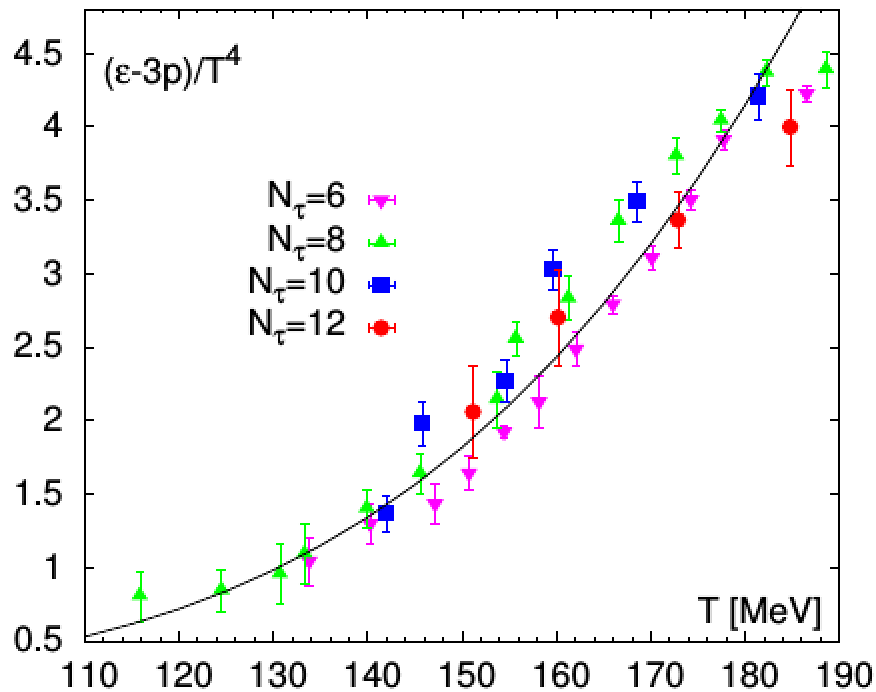
for the pressure we get:

$$\frac{p}{T^4} \equiv \frac{1}{VT^3} \ln Z(V,T,\mu)$$

comparison of trace anomaly from LQCD
Phys.Rev. D90 (2014) 094503
HOTQCD coll.

with hadron resonance gas prediction
(solid line)

LQCD: full dynamical quarks with realistic pion mass

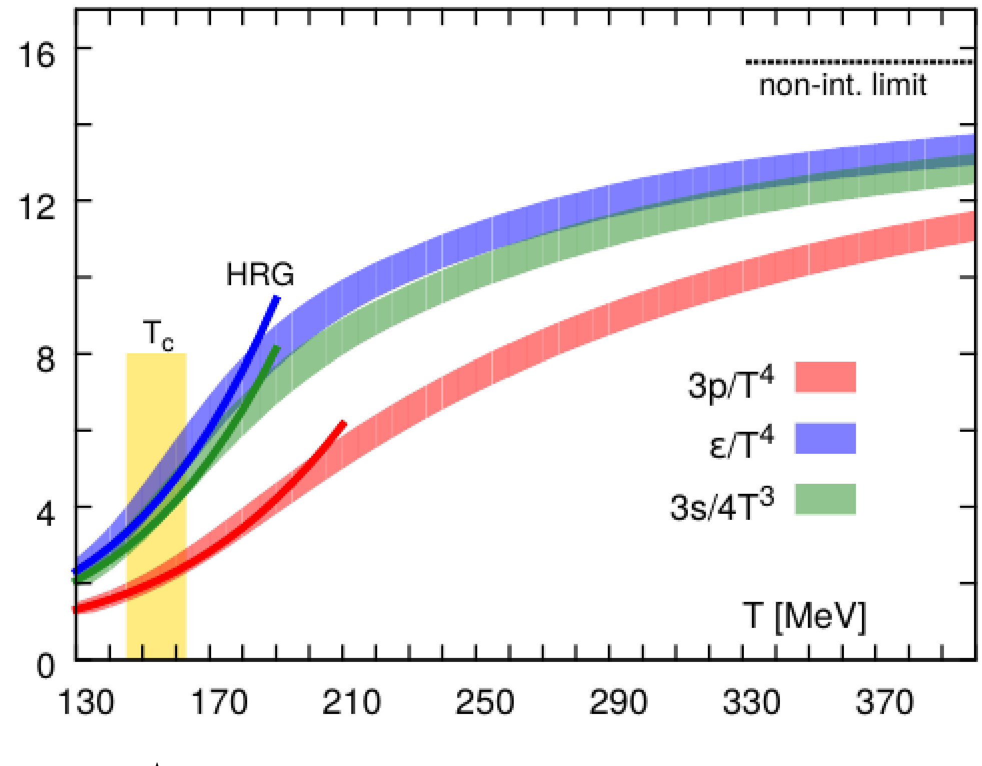


duality between hadrons and quarks/gluons (II)

comparison of equation of state from LQCD
Phys.Rev. D90 (2014) 094503
HOTQCD coll.

with hadron resonance gas predictions (colored lines)

essentially the same results also from Wuppertal-Budapest coll.
Phys.Lett. B730 (2014) 99-104



pseudo-critical temperature

$$T_c = (154 \pm 9)\ \mathrm{MeV}$$

$$\varepsilon_{crit} = (340 \pm 45)\ \mathrm{MeV/fm^3}$$

$$\varepsilon_{nucl} = 450\ \mathrm{MeV/fm^3}$$

duality between hadrons and quarks/gluons (III)

in the dilute limit T < 165 MeV:

$$\ln Z(T,V,\mu) \approx \sum_{i\in\ mesons} \ln \mathcal{Z}^{M}_{M_i}(T,V,\mu_Q,\mu_S) + \sum_{i\in\ baryons} \ln \mathcal{Z}^{B}_{M_i}(T,V,\mu_b,\mu_Q,\mu_S)$$

where the partition function of the hadron resonance model is expressed in mesonic and baryonic components. The chemical potential μ reflects then the baryonic, charge, and strangeness components $\mu = (\mu_b, \mu_Q, \mu_S)$.

thermal model of particle production and QCD

partition function Z(T,V) contains sum over the full hadronic mass spectrum and is fully calculable in QCD

for each particle i, the statistical operator is:

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 \mathrm{d}p \ln[1 \pm \exp(-(E_i - \mu_i)/T)]$$

particle densities are then calculated according to:

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i - \mu_i)/T] \pm 1}$$

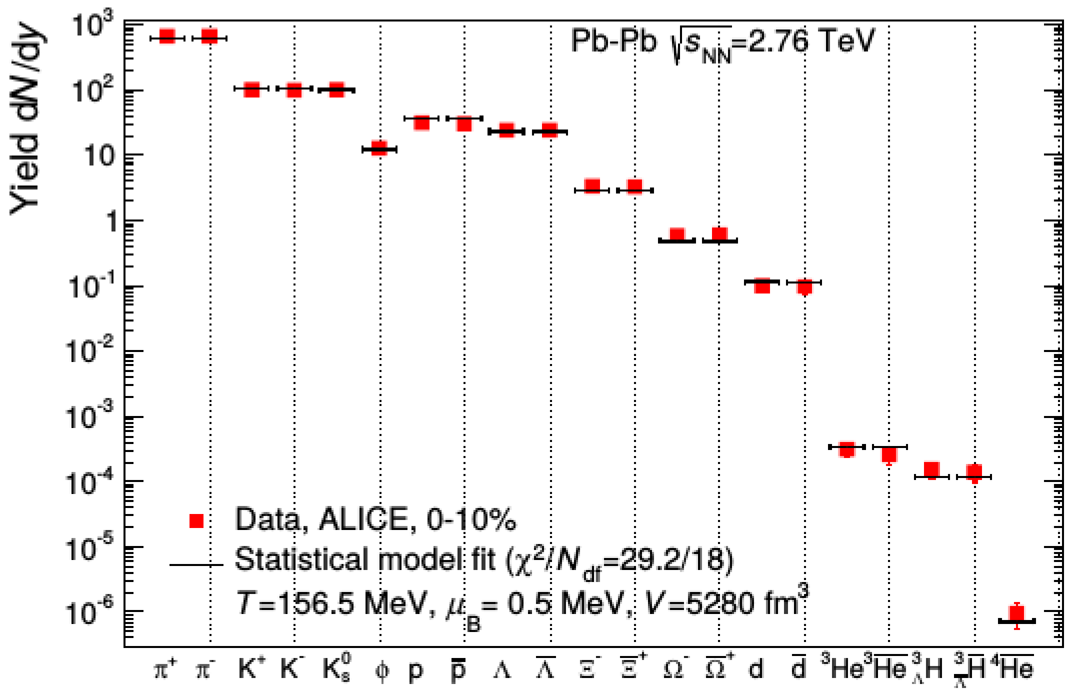
from analysis of all available nuclear collision data we now know the energy dependence of the parameters T, mu_b, and V over an energy range from threshold to LHC energy and can confidently extrapolate to even higher energies

in practice, we use the full experimental hadronic mass spectrum from the PDG compilation (vacuum masses) to compute the 'primordial yield'

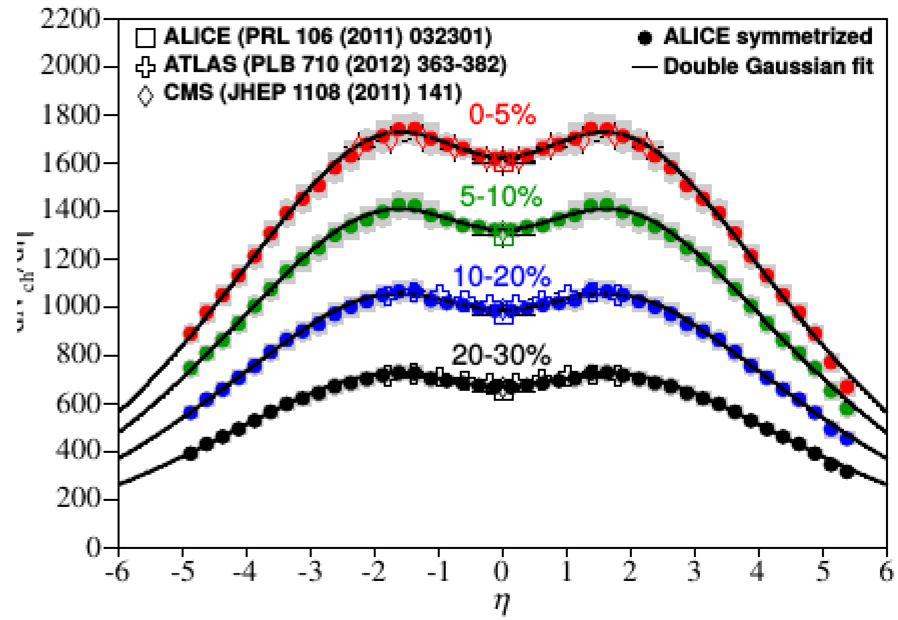
comparison with measured hadron yields needs evaluation of all strong decays

May 2016 update: excellent description of ALICE@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

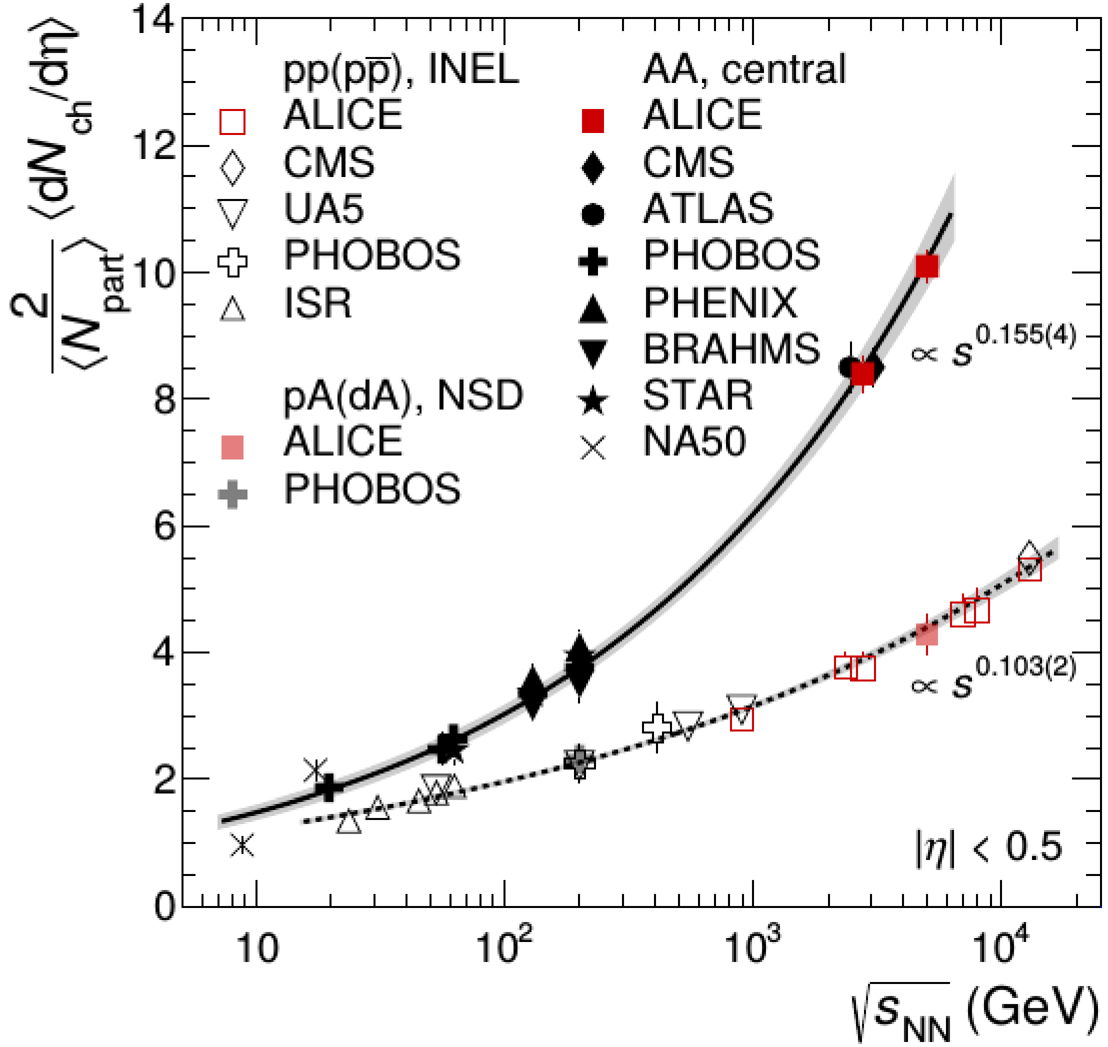
J. Stachel, A. Andronic, P. Braun-Munzinger and K. Redlich, Confronting LHC data with the statistical hadronization model, J.Phys.Conf.Ser.**509** (2014) 012019, arXiv:1311.4662 [nucl-th].

energy dependence of hadron production in central Pb-Pb (Au-Au) collisions

total number of hadrons produced

2.76 TeV
N_had = 25800

5.02 TeV
N_had = 32300



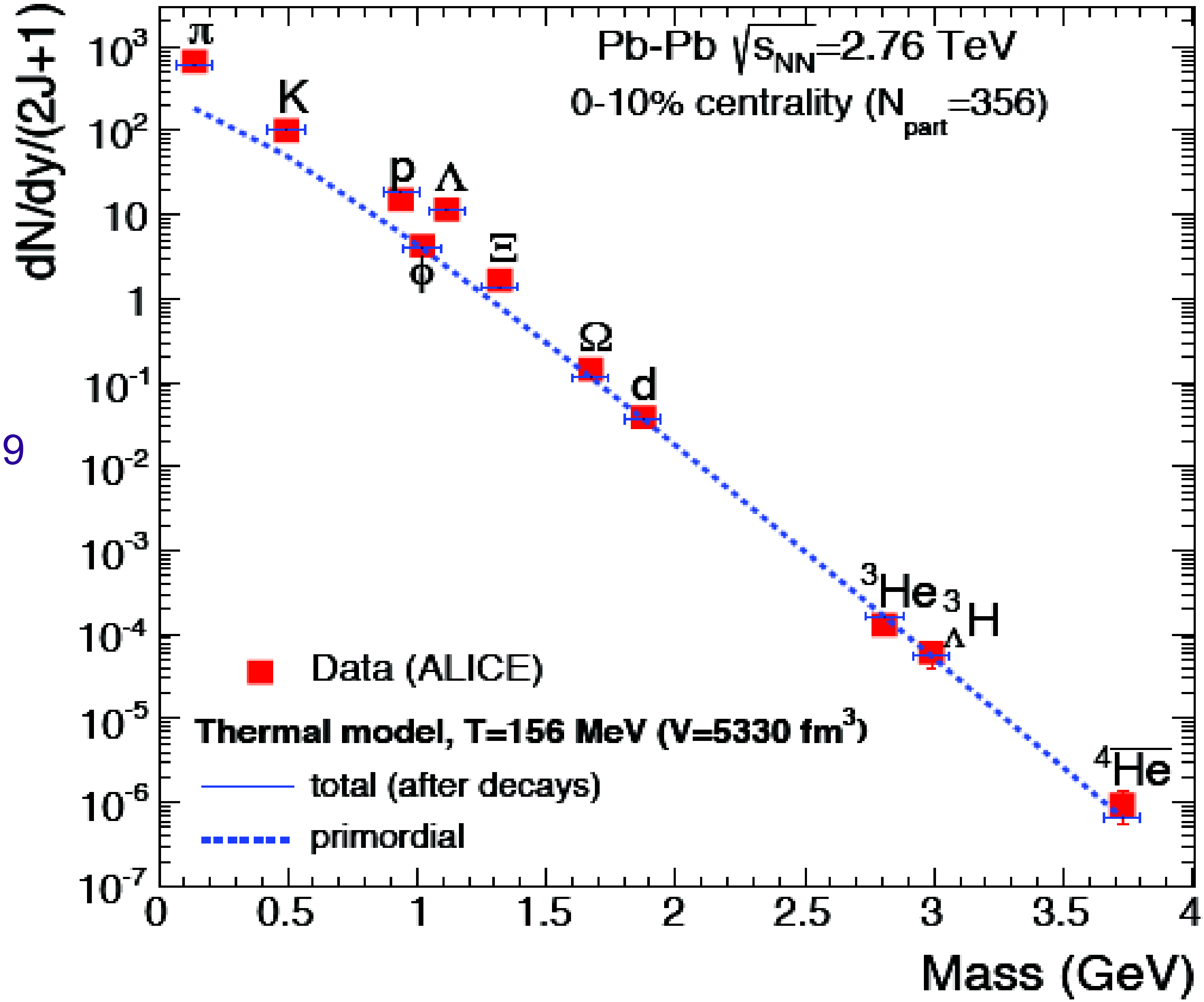
data from LHC run1 and run2

ALICE coll., Phys.Rev.Lett. 116 (2016) no.22, 222302

note: exponent in energy dependence is different for pp and PbPb; not anticipated in saturation models

excellent agreement over 9 orders of magnitude

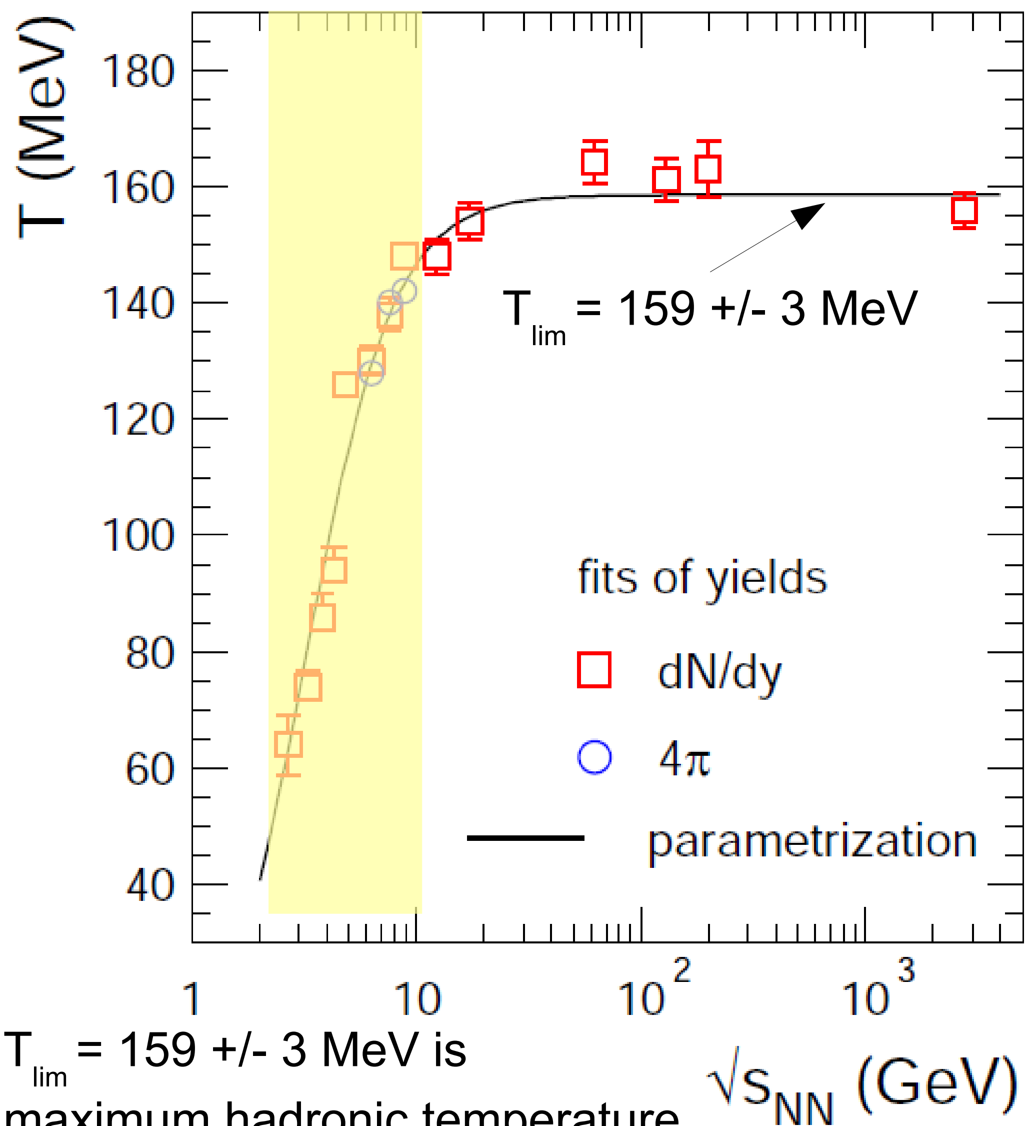
agreement over 9 orders of magnitude with QCD statistical operator prediction



yield of light nuclei predicted in: pbm, J. Stachel, J.Phys. G28 (2002) 1971-1976,
J.Phys. G21 (1995) L17-L20

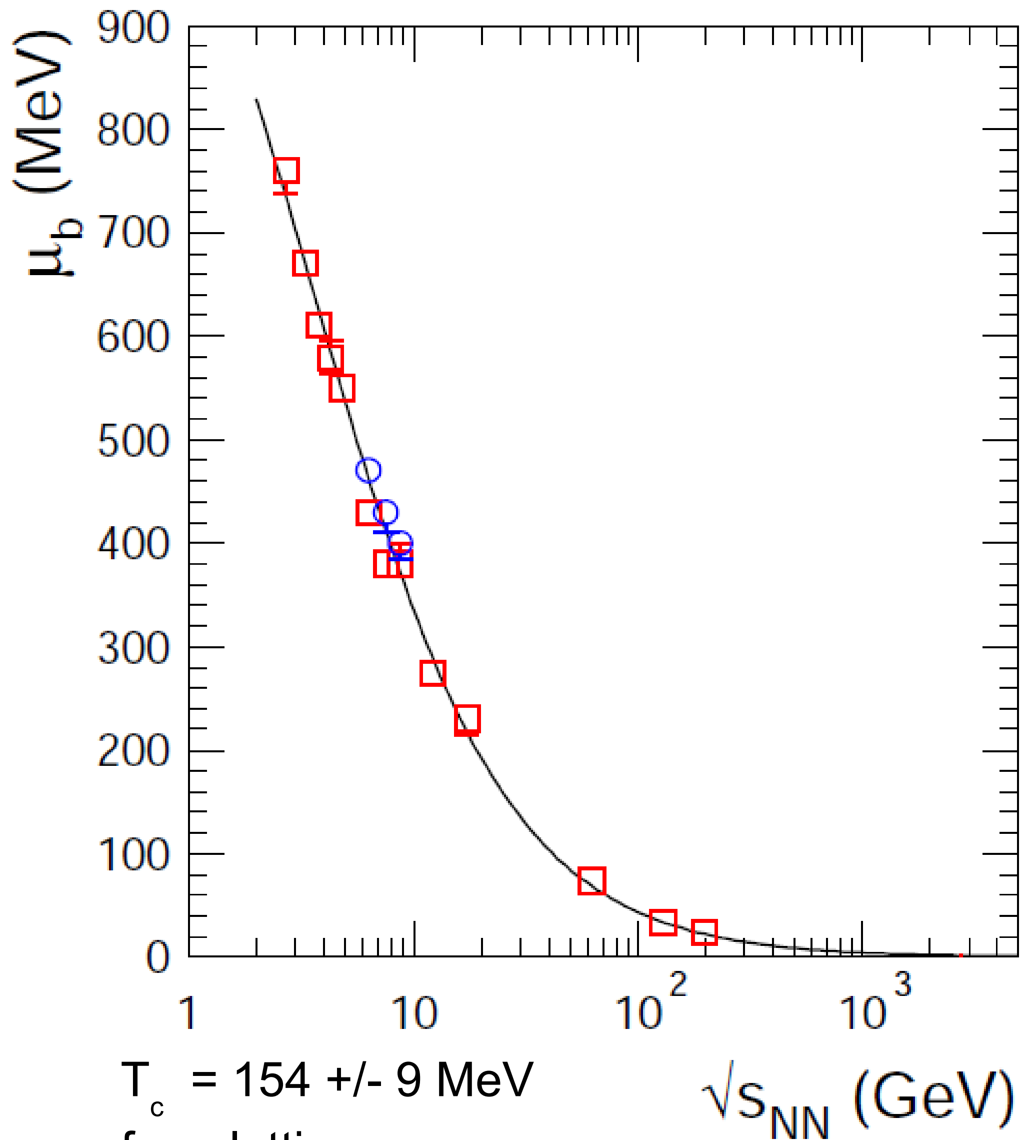
energy dependence of temperature and baryo-chemical potential

energy range from SPS down to threshold



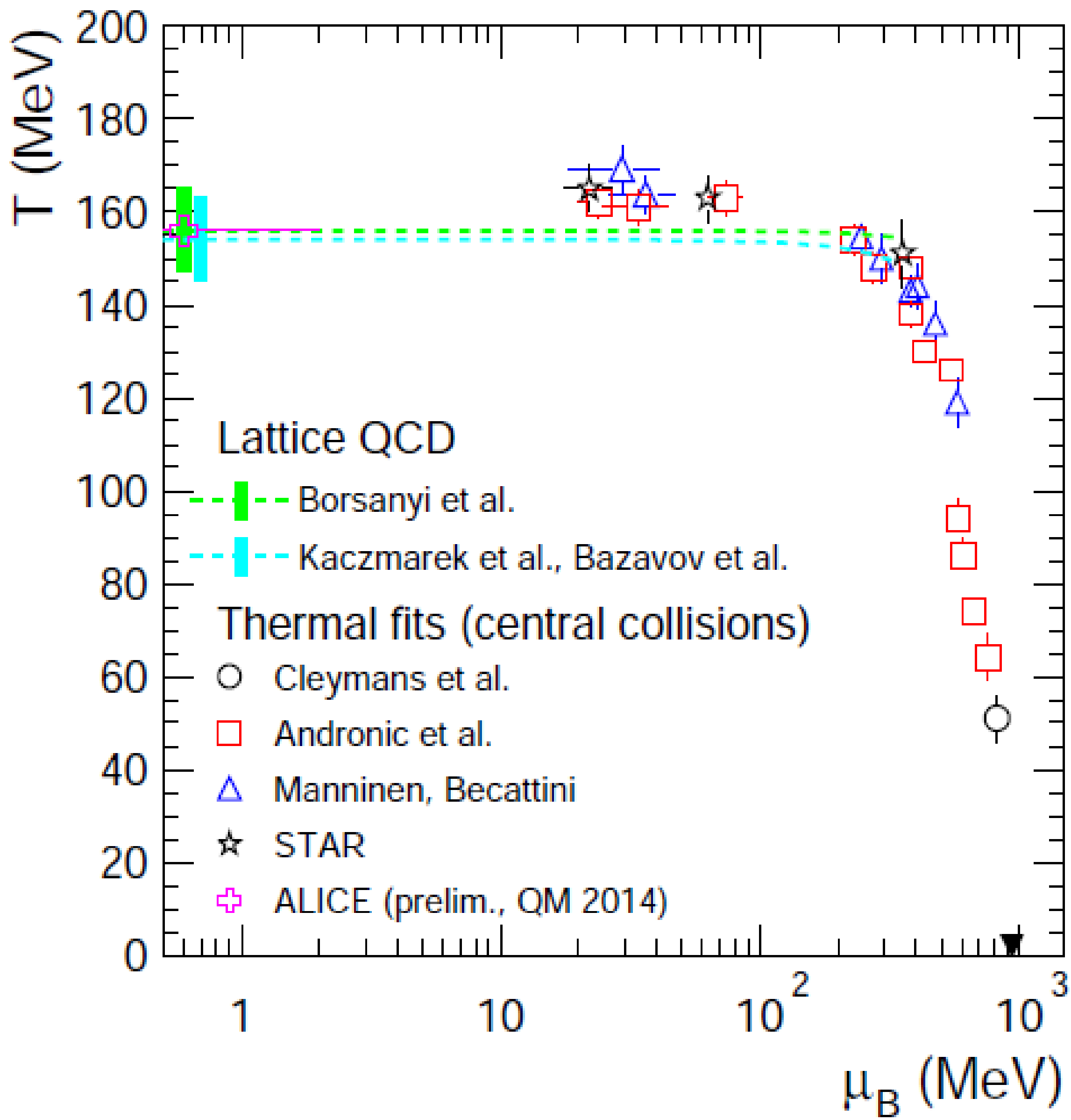
T_{lim} = 159 +/- 3 MeV is maximum hadronic temperature

is phase boundary ever reached for $\sqrt{s_{NN}}$ < 10 GeV?



T_c = 154 +/- 9 MeV from lattice

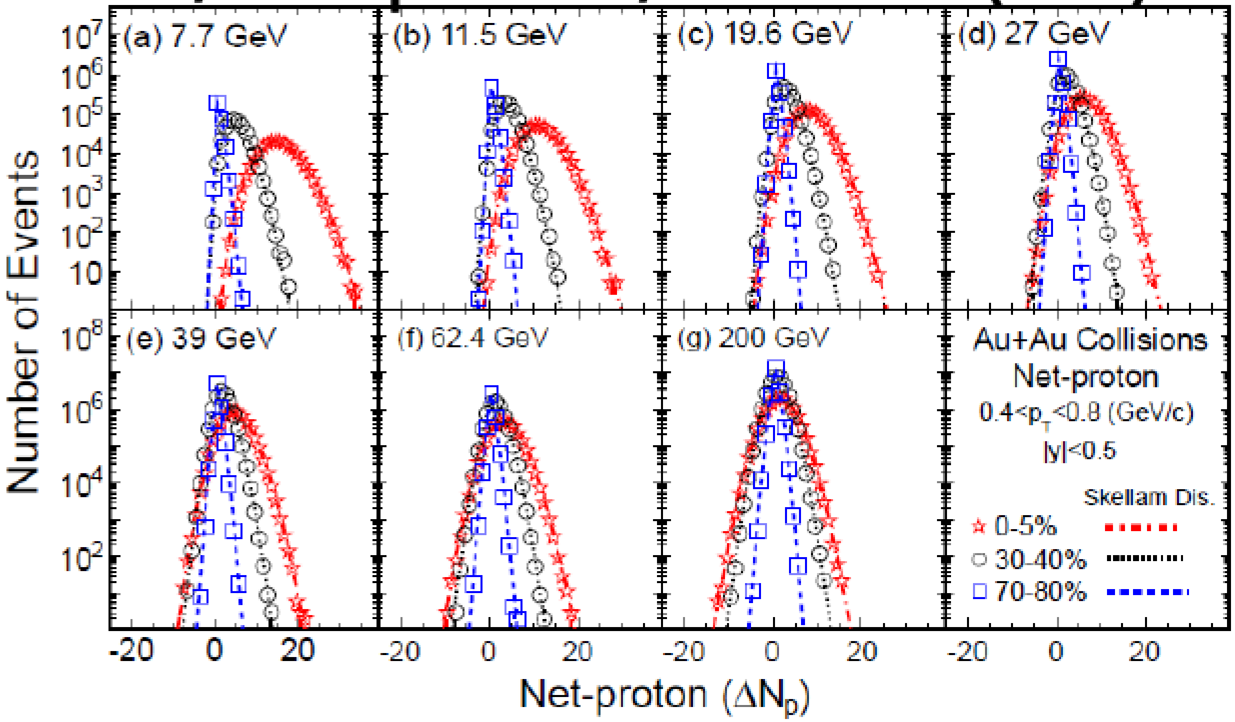
the QGP phase diagram, LQCD, and hadron production data



quantitative agreement of chemical freeze-out parameters with LQCD predictions for baryo-chemical potential < 300 MeV

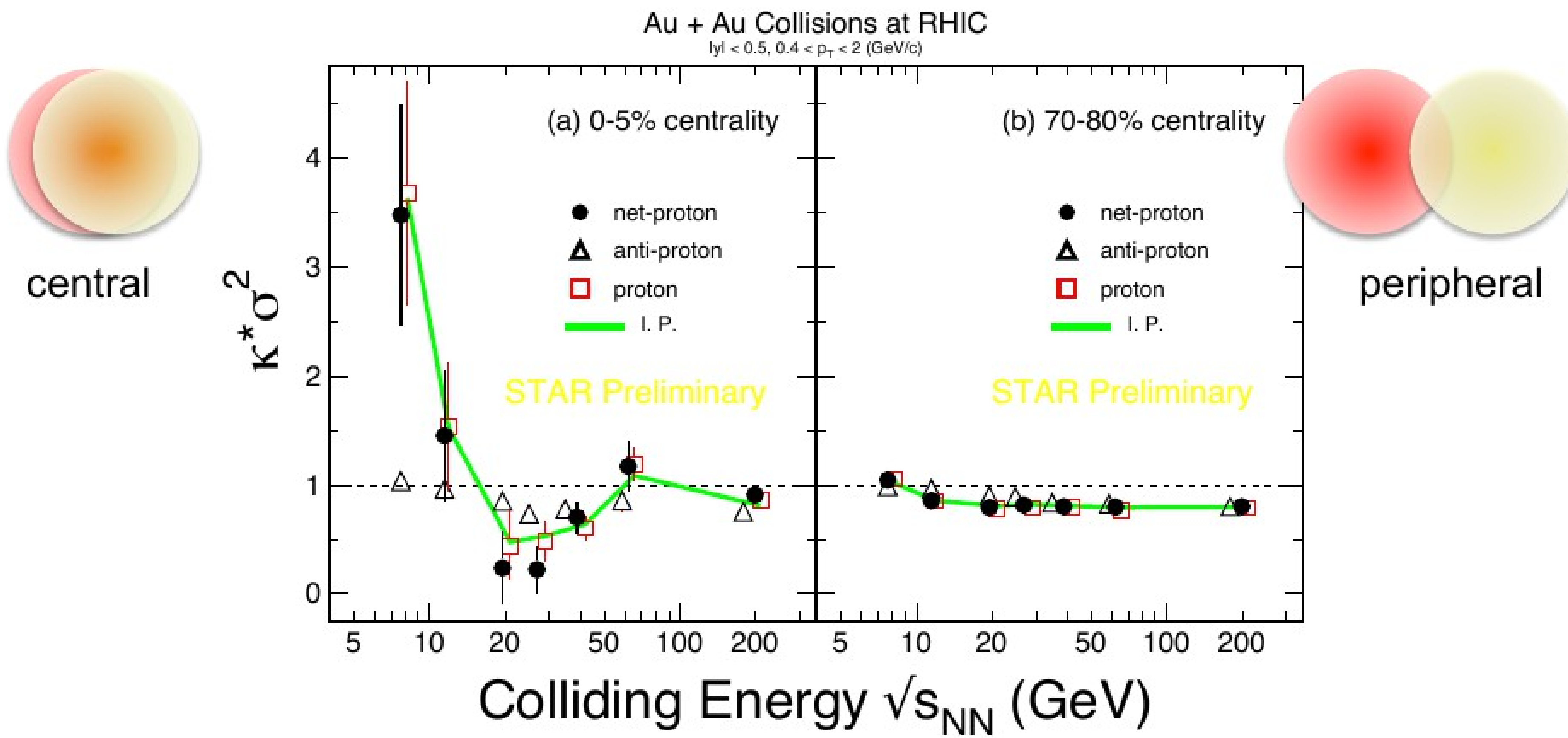
now: remarks on measurements and interpretation of higher moments

STAR, net-proton, PRL112 ('14)



search for a critical point in the QCD phase diagram

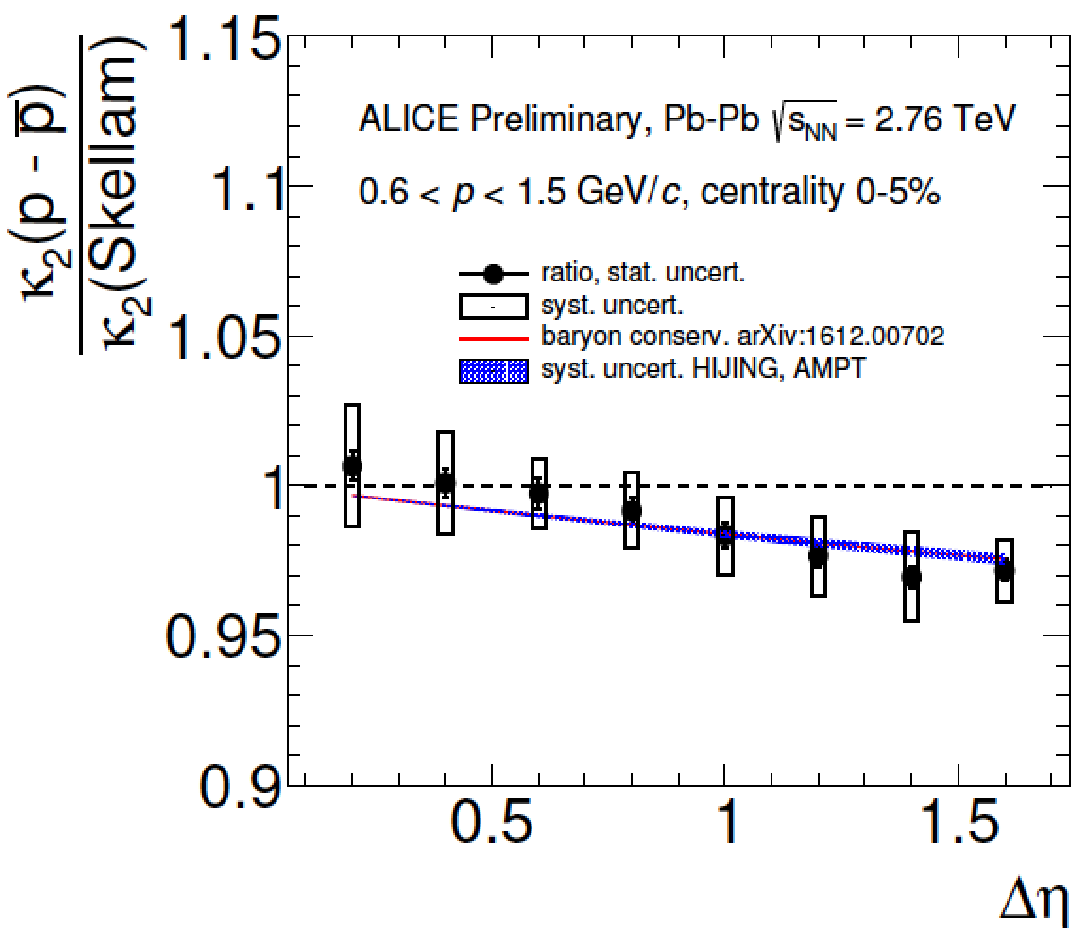
is this non-monotonic behavior a first indication?



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

Nu Xu, CPOD2016

at LHC energy, 2nd moments only exhibit baryon number conservation effects, as predicted by Lattice QCD



a Skellam distribution is the difference between 2 uncorrelated Poisson distributions

charmonium as a probe for the properties of the QGP

the original idea: (Matsui and Satz 1986) implant charmonia into the QGP and observe their modification, in terms of suppressed production in nucleus-nucleus collisions with or without plasma formation – sequential melting

new insight (pbm, Stachel 2000) QGP screens all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders – signal for deconfined, thermalized charm quarks production probability scales with $N(_{ccbar})^2$

reviews: L. Kluberg and H. Satz, arXiv:0901.3831

pbm and J. Stachel, arXiv:0901.2500

both published in Landoldt-Boernstein Review, R. Stock, editor, Springer 2010

nearly simultaneous: Thews, Schroeder, Rafelski 2001

formation and destruction of charmonia inside the QGP

n.b. at collider energies there is a complete separation of time scales

$t_{coll} << t_{QGP} < t_{Jpsi}$

implanting charmonia into QGP is an inappropriate notion

this issue was already anticipated by Blaizot and Ollitrault in 1988

the idea

heavy quarks are not thermally produced, since their mass m >> T

at collider energies, heavy quarks are copiously produced through QCD hard scattering

the developing hot fireball formed in the collision thermalizes the heavy quarks

all charmed hadrons and charmonia are deconfined near T_c

the fireball expands and cools until it reaches the phase boundary

there, charmonia are formed with thermal/statistical weights

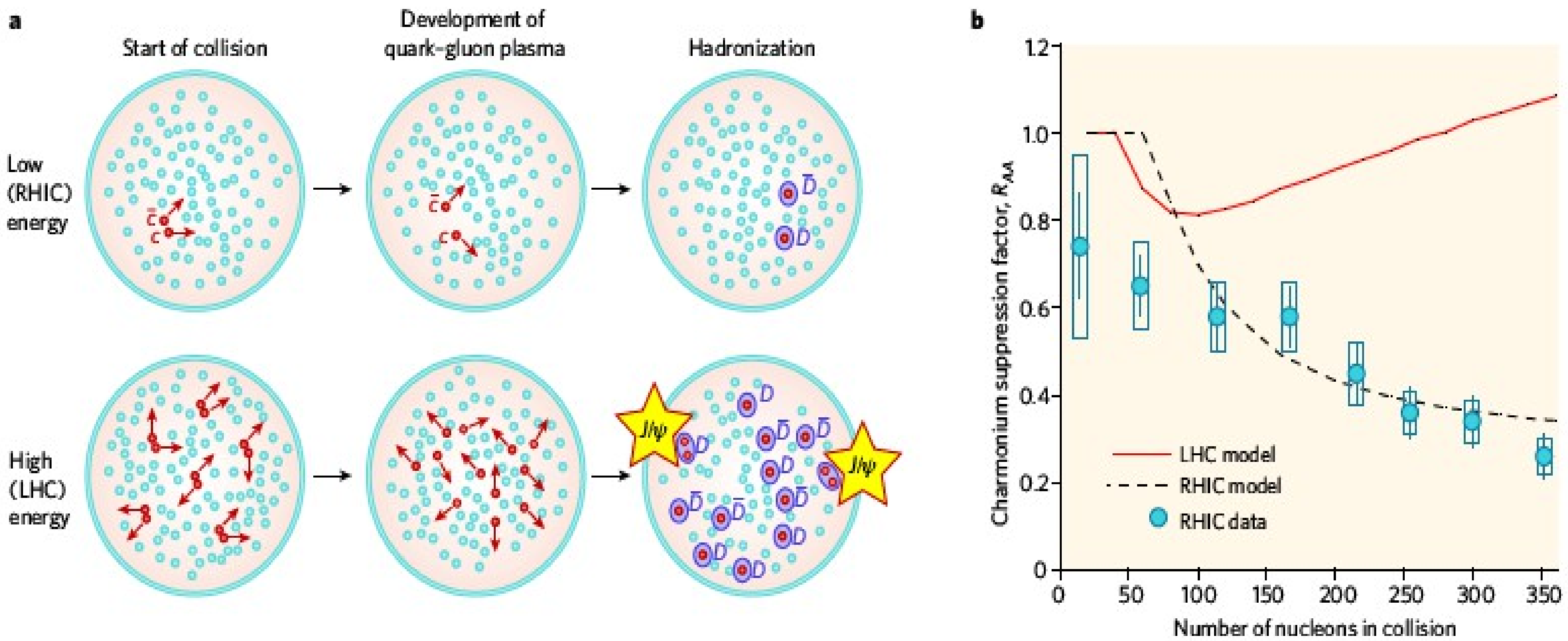
since charmonium formation scales with $N(_{ccbar})^2$ and since the charm cross section increases strongly with energy, we expect enhanced charmonium production at collider energy

this brings the thermal model into the heavy quark era with a large heavy quark fugacity

note: mass of charm quark is about 300 times heavier than mass of light quarks

quarkonium as a probe for deconfinement at the LHC
the statistical (re-)generation picture

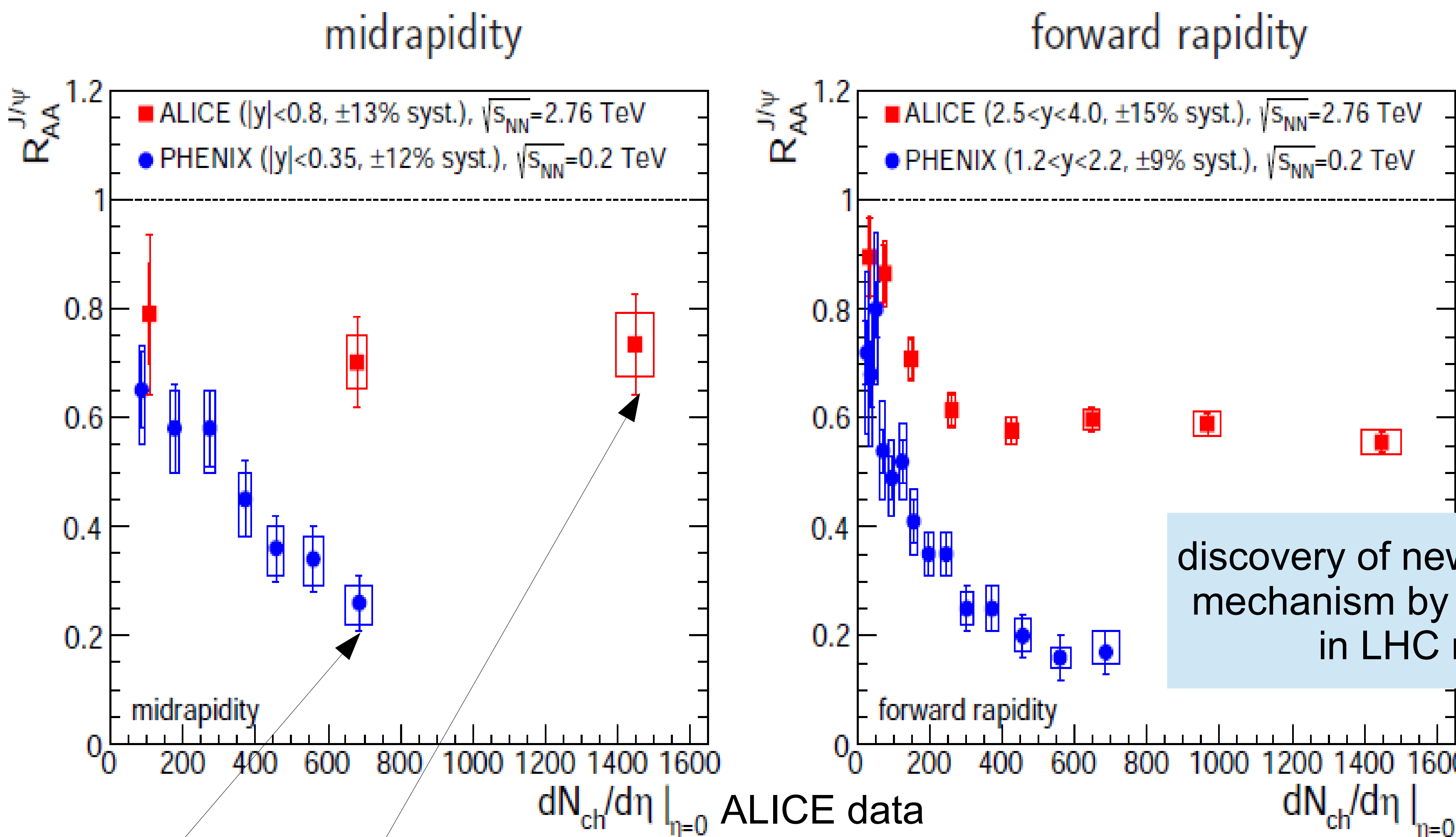
P. Braun-Munzinger, J. Stachel, The Quest for the Quark-Gluon Plasma, Nature **448** Issue 7151, (2007) 302-309.



charmonium enhancement as fingerprint of color screening and deconfinement at LHC energy

pbm, Stachel, Phys. Lett. B490 (2000) 196
Andronic, pbm, Redlich, Stachel, Phys. Lett. B652 (2007) 659

less suppression when increasing the energy density



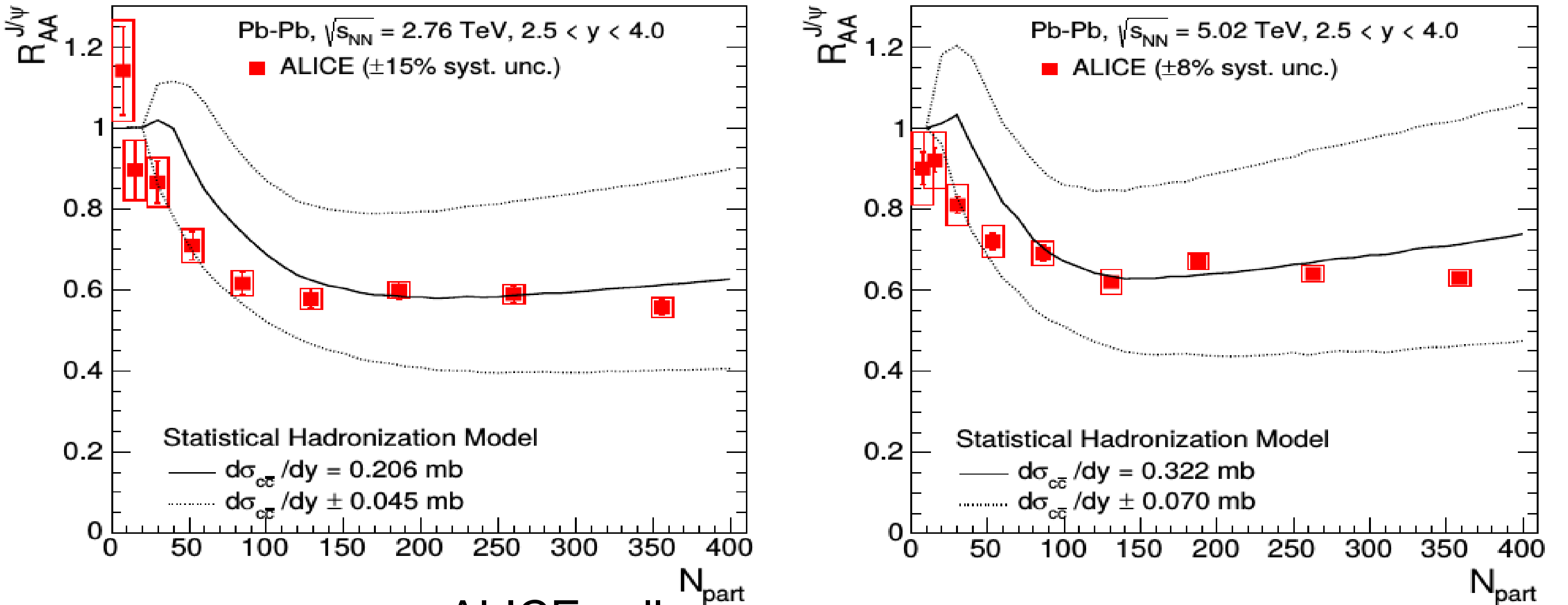
discovery of new production mechanism by ALICE coll. in LHC run1

ALICE data
arXiv:1311.0214
Phys.Lett. B734 (2014) 314-327

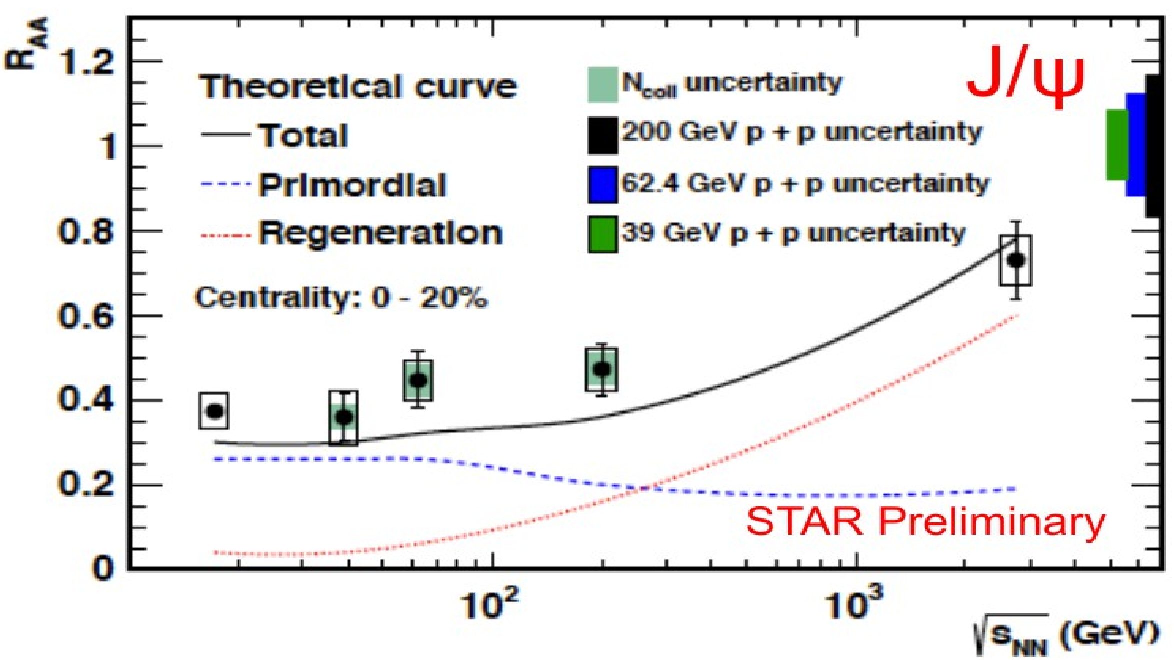
from here to here more than factor of 2 increase in energy density, but R_{AA} increases by more than a factor of 3

2007 prediction impressively confirmed by LHC data

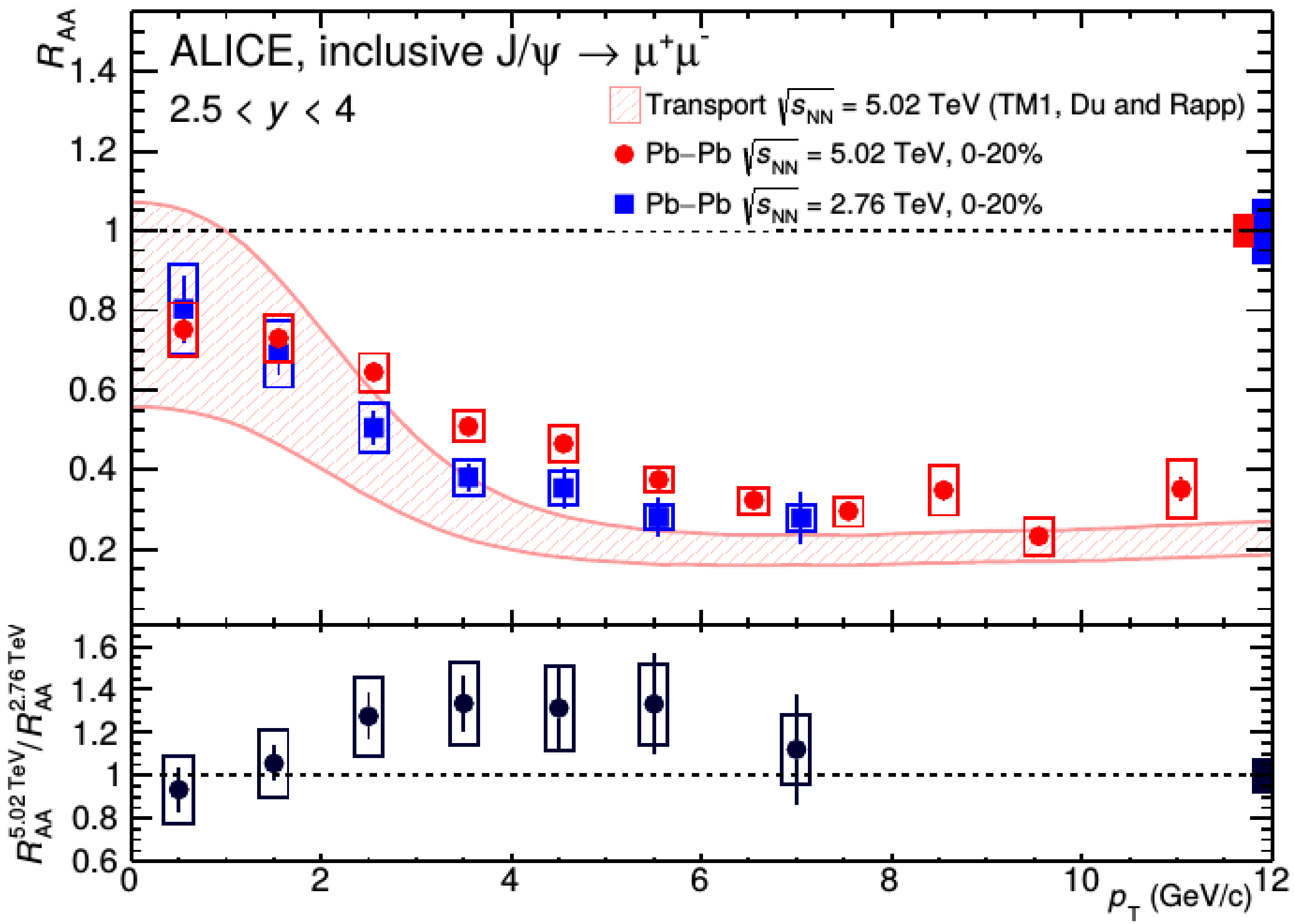
predictions from 2000/2007 beautifully confirmed by RHIC and LHC data



ALICE coll.,
arXiv:1606.08197

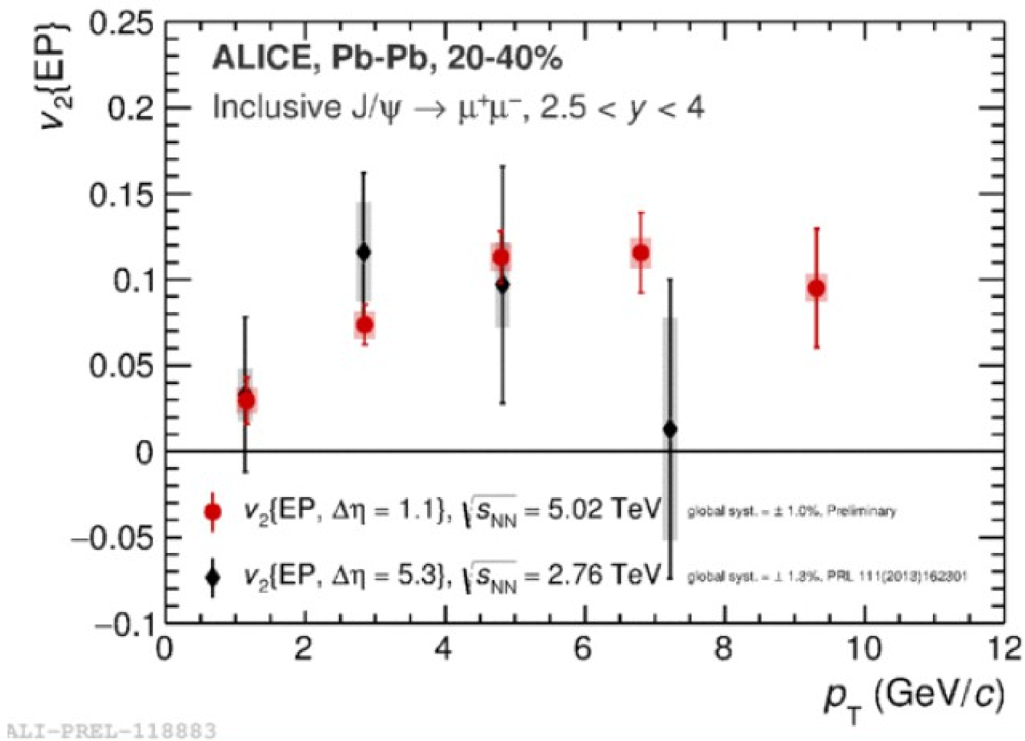


...and the dependence on transverse momentum



ALICE coll., arXiv:1606.08197

elliptic flow of charmonium



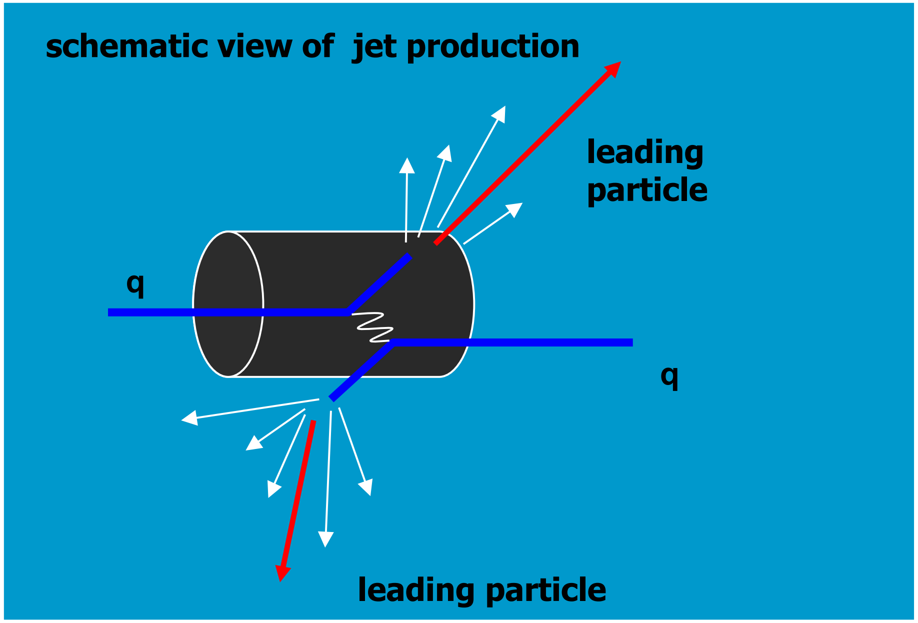
p_T (GeV/c)	0-2	2-4	4-6	6-8	8-12
Δη=1.1	2.2σ	6.3σ	7.4σ	5.0σ	2.8σ
Δη=5.3	1.4σ	6.2σ	5.0σ	3.3σ	1.3σ

most recent LHC Run2 result,
charm quarks participate in the hydrodynamical evolution of the QGP fireball
support for statistical hadronization of deconfined charm quarks

energy loss of partons in the QGP

jets of hard partons as probe of the hot medium

- hard parton scattering observed via leading particles
- expect strong $\int \varphi=\pi$ azimuthal correlations



however, the scattered partons may loose energy (~ several GeV/fm) in the colored medium

a) momentum reduction (fewer high p_T particles in jet)
b) no jet partner on other side

jet quenching

the nuclear modification factor R_AA

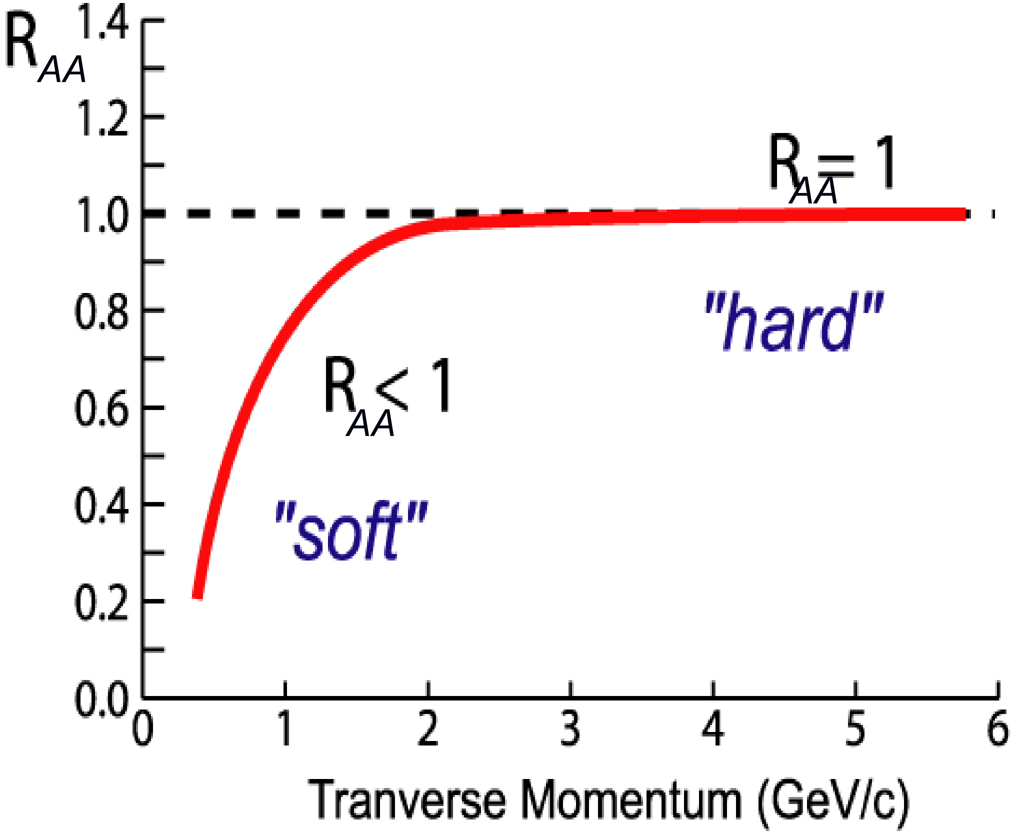
The R_{AA} function:

$$R_{AA}(b) = \frac{\frac{\mathrm{d}^2 N^{AA}}{\mathrm{d}p_t^2 \mathrm{d}y}}{N_{coll}^{AA}(b) \cdot \frac{\mathrm{d}^2 N^{NN}}{\mathrm{d}p_t^2 \mathrm{d}y}}$$

if hard scattering only:

$$R_{AA}(b) = 1$$

qualitative expectations

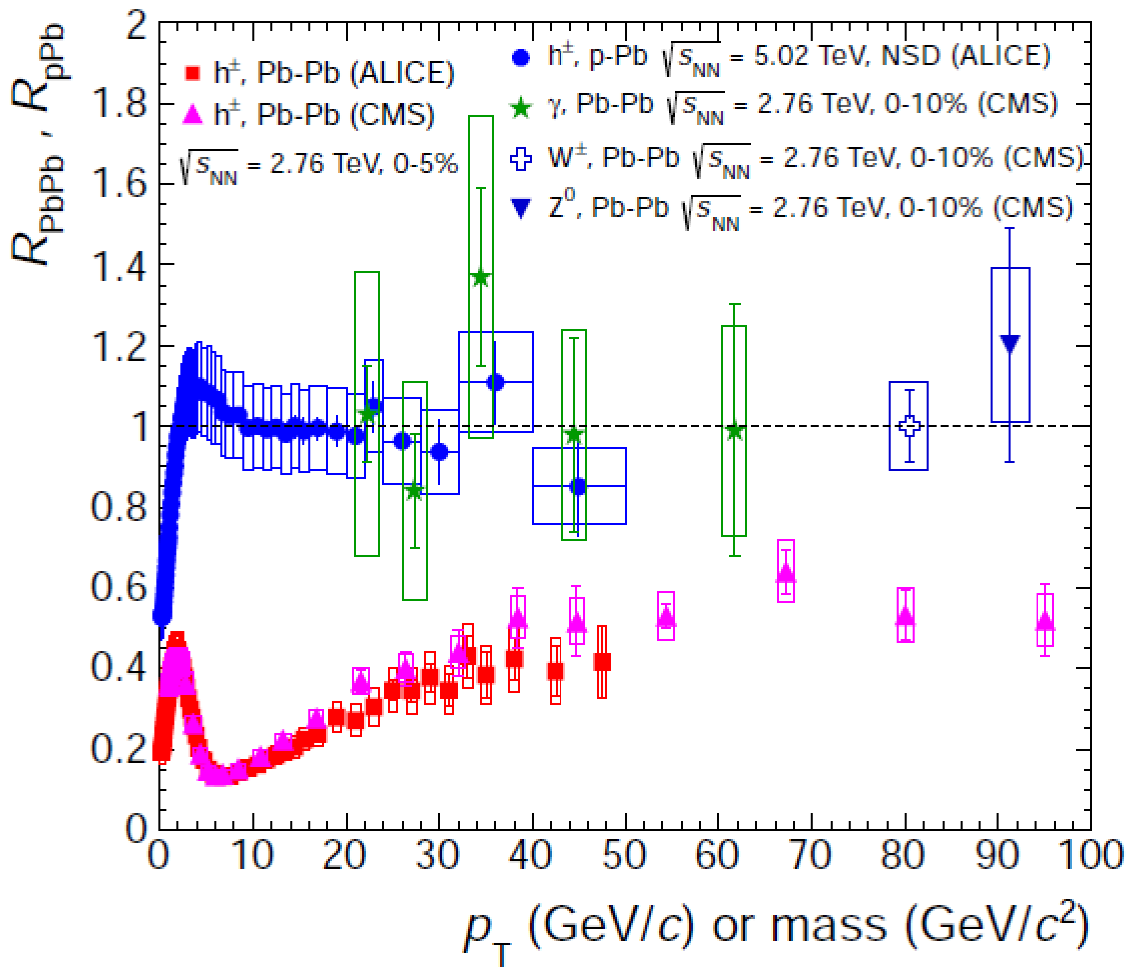


no medium effects:
- $R_{AA} < 1$ in regime of soft physics
- $R_{AA} = 1$ at high-p_T where hard scattering dominates

Suppression:
- $R_{AA} \ll 1$ at high-p_T

synopsis of energy loss measurements for hard probes

no suppression in pPb, QGP opaque for high energy partons



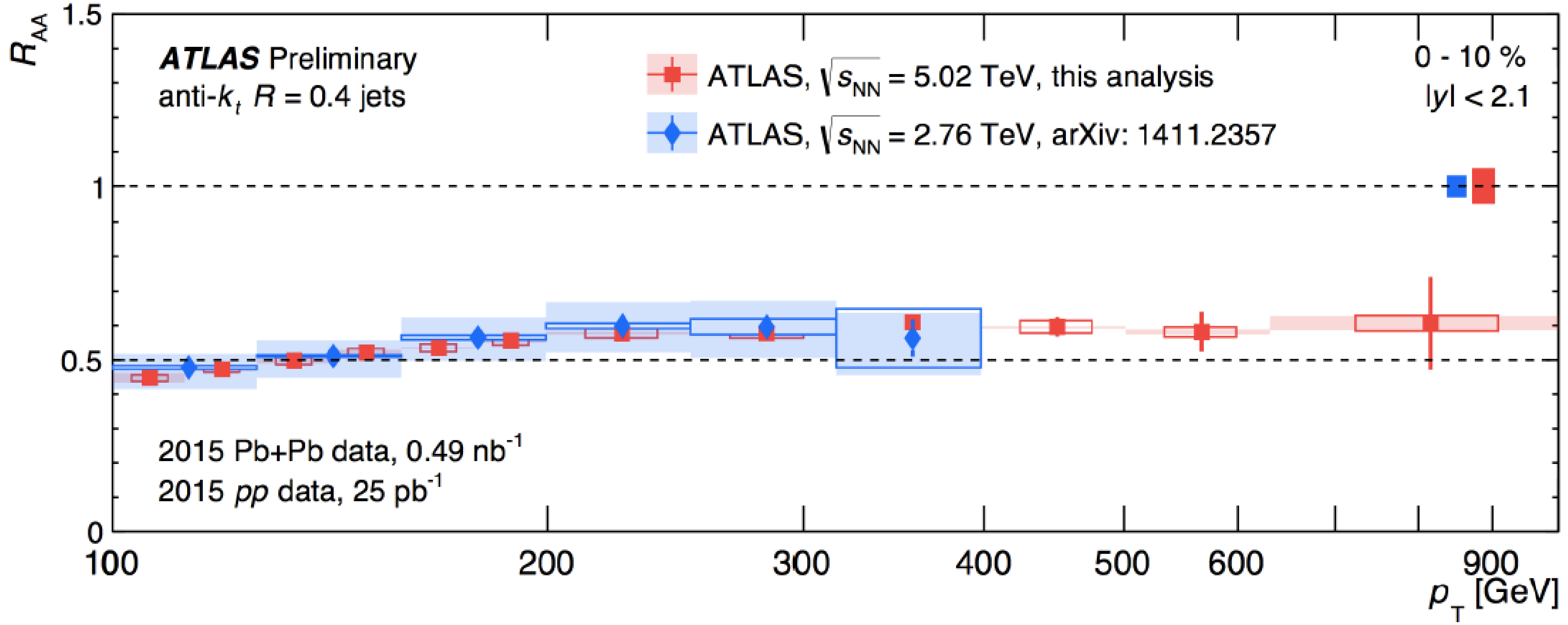
Alice coll.,

arXiv:1405.2737

photons, Z and W scale with number of binary collisions in PbPb – not affected by medium

→ demonstrates that charged particle suppression is medium effect: energy loss in QGP

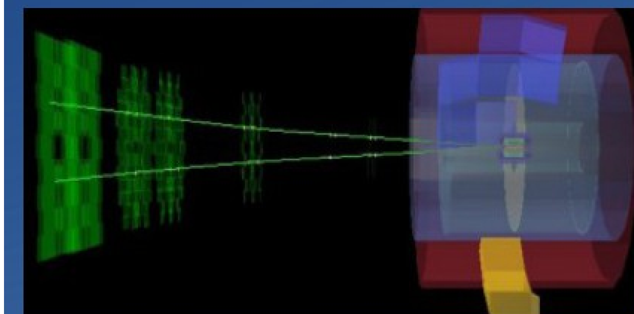
ATLAS measurement of jet quenching direct reconstruction of jets



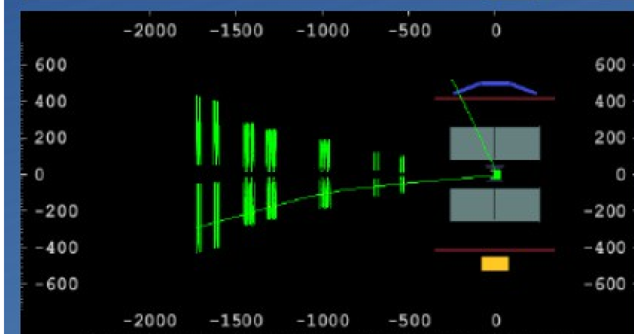
even at jet (parton) momenta of 900 GeV suppression is still strong
the QGP medium modifies the jet at all momentum scales

Some remarks on ultra-peripheral collisions in pp, pPb and Pb-Pb

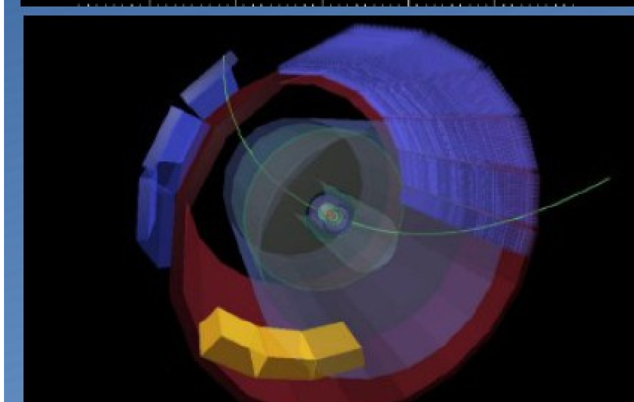
3 possibilities in ALICE: Forward, Semi-forward, and Central



Both muons in muon arm
J/ψ rapidity: $-4.0 < y < -2.5$
γ+p CM energies:
$21 \leq W_{\gamma p} \leq 45$ GeV (p+Pb)
$550 \leq W_{\gamma p} \leq 1160$ GeV (Pb+p)



One muon in muon arm, one in central barrel
J/ψ rapidity: $-2.5 < y < -1.3$
γ+p CM energies:
$45 \leq W_{\gamma p} \leq 82$ GeV (p+Pb)
$300 \leq W_{\gamma p} \leq 550$ GeV (Pb+p)



Both muons/electrons in central barrel
J/ψ rapidity: $-0.9 < y < 0.9$
γ+p CM energies:
$100 \leq W_{\gamma p} \leq 250$ GeV (p+Pb/Pb+p)

$W_{\gamma p}$ - γ-p center of mass energy

ultra-peripheral collisions -some selected aspects

Ultra-peripheral collisions (UPCs)

- Heavy nuclei carry strong electric and magnetic fields
  - Fields are perpendicular -> treat as nearly-real virtual photons
    - $E_{max} = \gamma hc/b$
  - Photonuclear interactions
  - Two-photon interactions
- Visible when b>~2R_A, so there are no hadronic interactions;
  - STAR & ALICE also see photon interactions in peripheral nuclear collisions

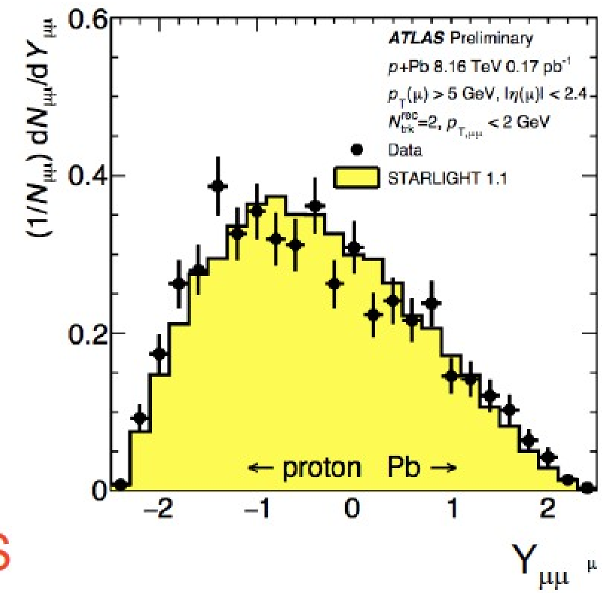
Energy	AuAu RHIC	pp RHIC	PbPb LHC	pp LHC
Photon energy (target frame)	0.6 TeV	~12 TeV	500 TeV	~5,000 TeV
CM Energy $W_{\gamma p}$	24 GeV	~80 GeV	700 GeV	~3000 GeV
Max $\gamma\gamma$ Energy	6 GeV	~100 GeV	200 GeV	~1400 GeV

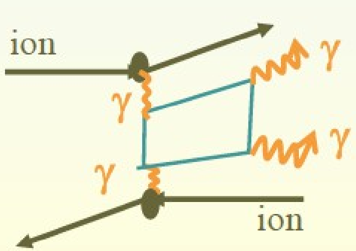
*LHC at full energy √s=14 TeV/5.6 TeV

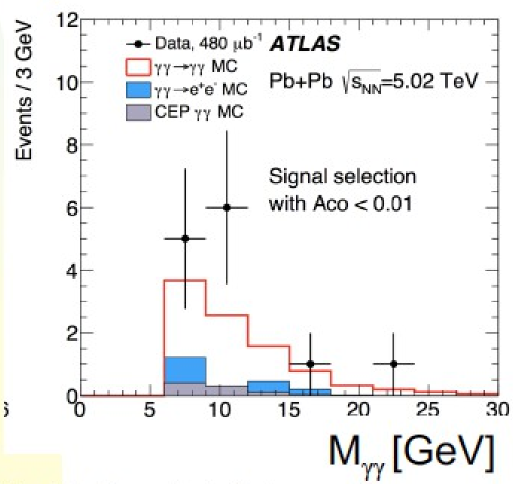
next 4 slides from Spencer Klein, talk at QM2017, Chicago,
see also arXiv:1704.04715 (from yesterday)

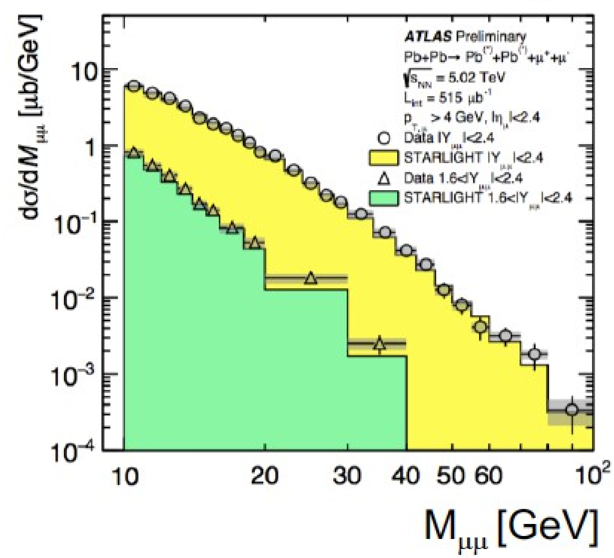
γγ -> Dileptons

- Large samples from ALICE, ATLAS & STAR
- Data is in excellent agreement with lowest order QED
  - STARlight Monte Carlo
  - $Z\alpha \sim 0.6$, so perturbation theory might fail
- Light-by-light scattering seen by ATLAS
  - Sensitive to new particles



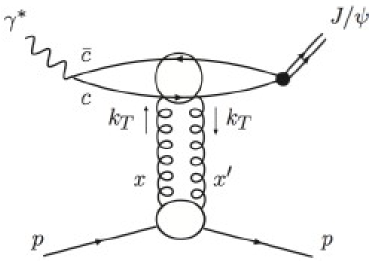






ATLAS: arXiv:1702.01625; M. Dyndal, this conference

VM photoproduction in pQCD



- In 2-gluon model, leading order pQCD

$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\, p)\Big|_{t=0} = \frac{\Gamma_{ee} M^3_{J/\psi}\pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right]^2\left(1+\frac{Q^2}{M^2_{J/\psi}}\right).$$

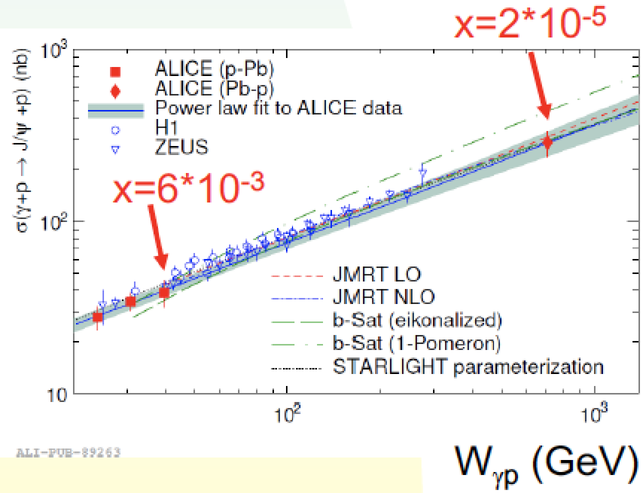
- With $\bar{Q}^2 = (Q^2 + M^2_{J/\psi})/4,\qquad x = (Q^2 + M^2_{J/\psi})/(W^2+Q^2)$
  - Vector meson mass provides hard scale
- Some caveats
  - pQCD factorization does not strictly hold
    - Two gluons have different x values (with x' ≪ x ≪ 1)
      - Use generalized (skewed) gluon distributions – smallish correction.
      - Can do exactly with Shuvaev transform
  - Photon is not pure $q\bar{q}$ dipole
  - Choice of scale μ
  - "Absorptive corrections" for pp akin to b>R_A+R_b

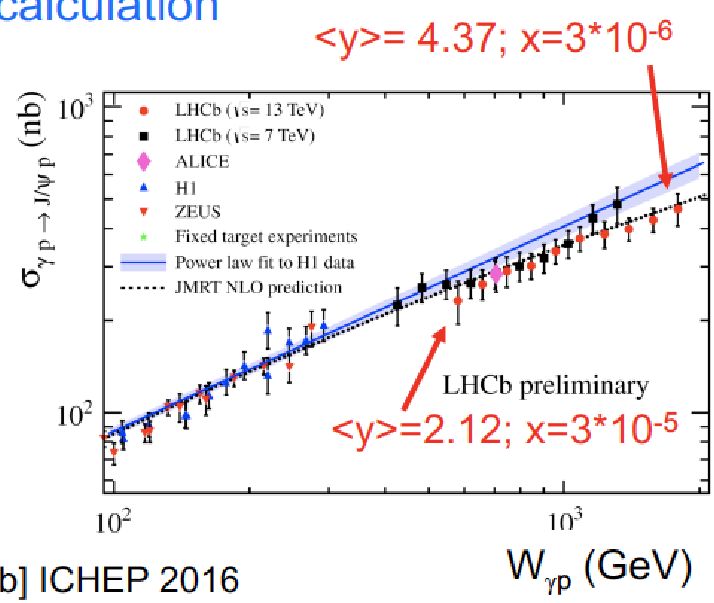
Jones, Martin, Ryskin and Teubner ("JMRT"), JHEP 1311, 085 (2013); and others

11

σ(γp-> J/ψ p)

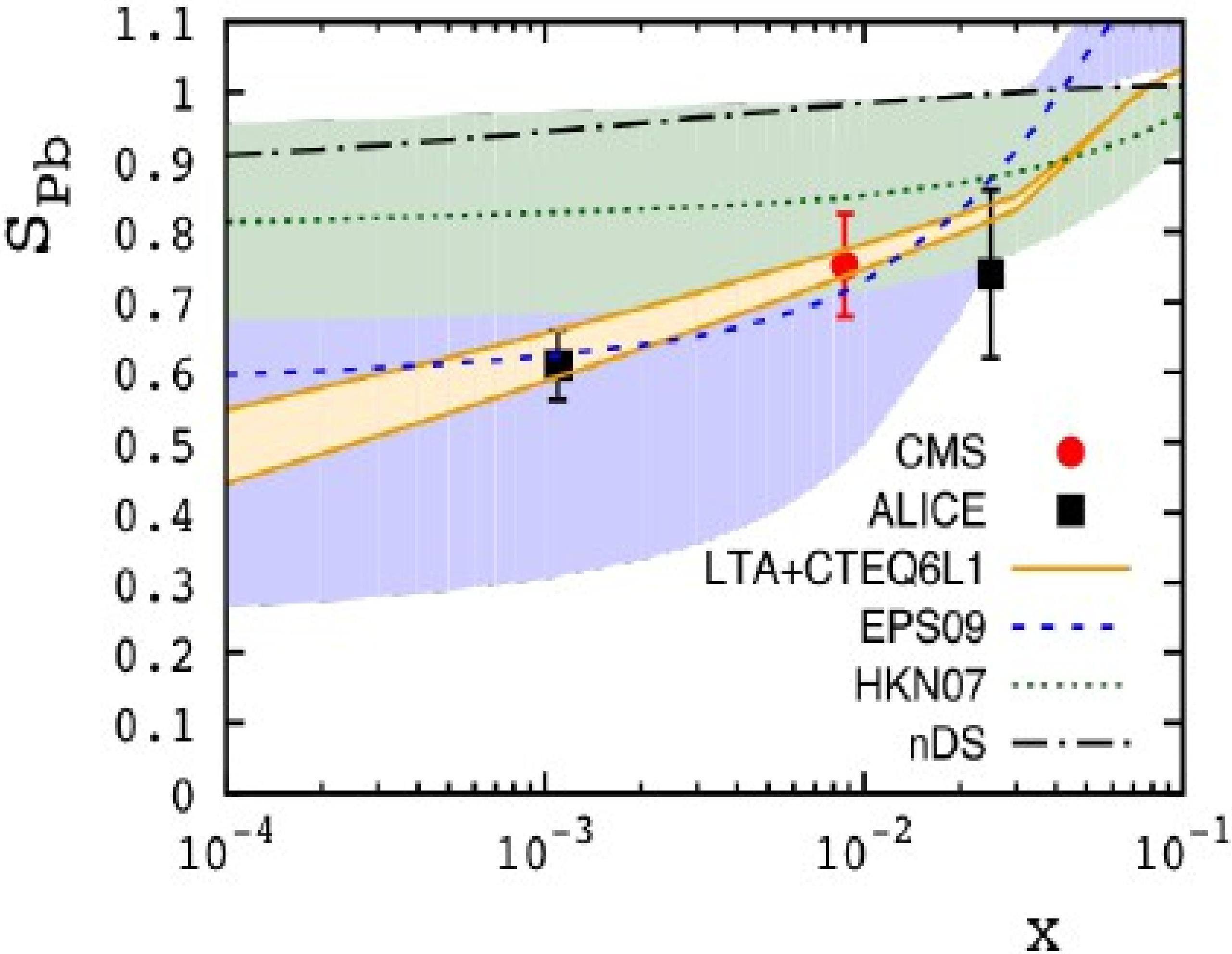
- Data up to $W_{\gamma p}$= 1.5 TeV -5 times the HERA maximum
- ALICE sees good pA agreement with HERA data
- LHCb 13 TeV-beam data somewhat below 7 TeV data?
  - LHCb uses bootstraps from HERA range for 2-fold ambiguity
- NLO calculation predicts a small down-turn from power law prediction at energies above ~ 300 GeV
  - 13 TeV data agrees well with NLO calculation





J. Adams [ALICE], DIS 2016; R. McNulty [LHCb] ICHEP 2016

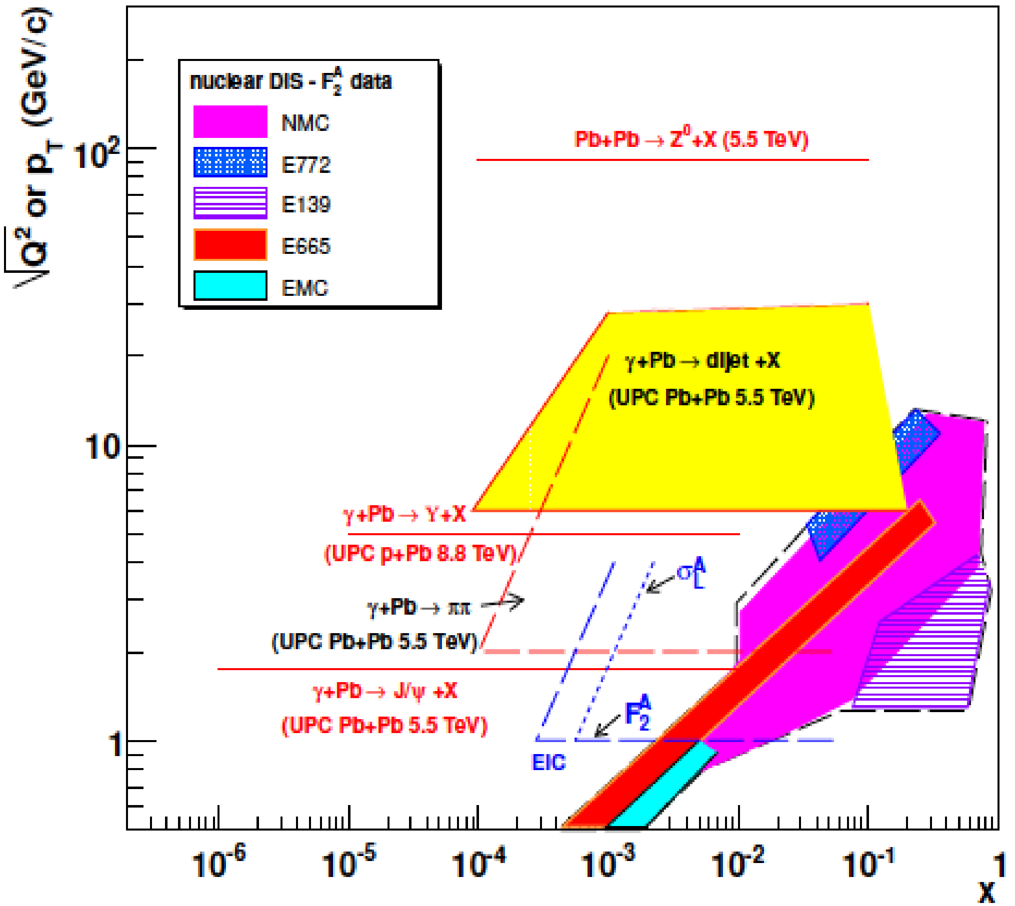
Shadowing extracted from J/psi production in UPC Pb-Pb vs pp



Results constrain EPS09 shadowing calculations and agree with recent leading twist (LTA) calculations. Fig. Taken from Vadim Guzey V. Guzey and M. Zhalov, JHEP **1310**, 207 (2013)

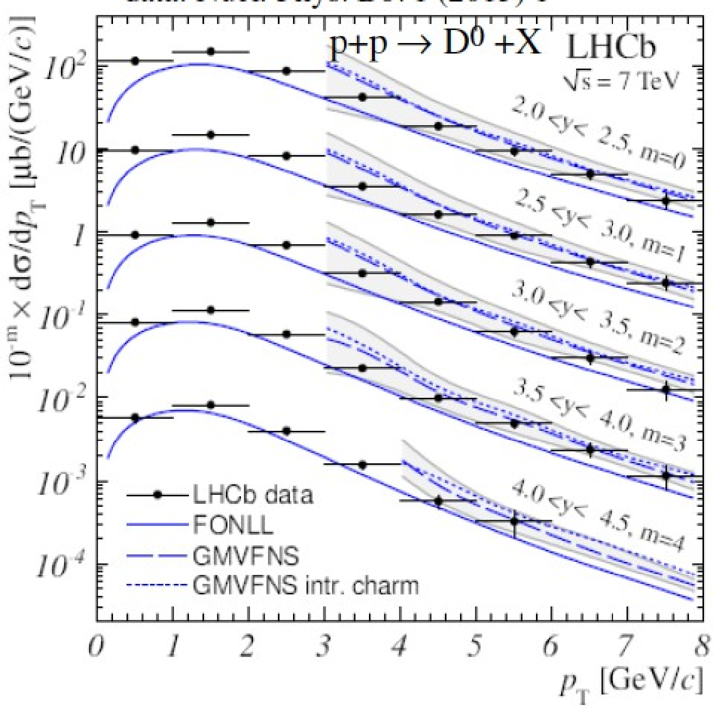
LHC reach for gluon distributions in nuclei from ultra-peripheral collision studies

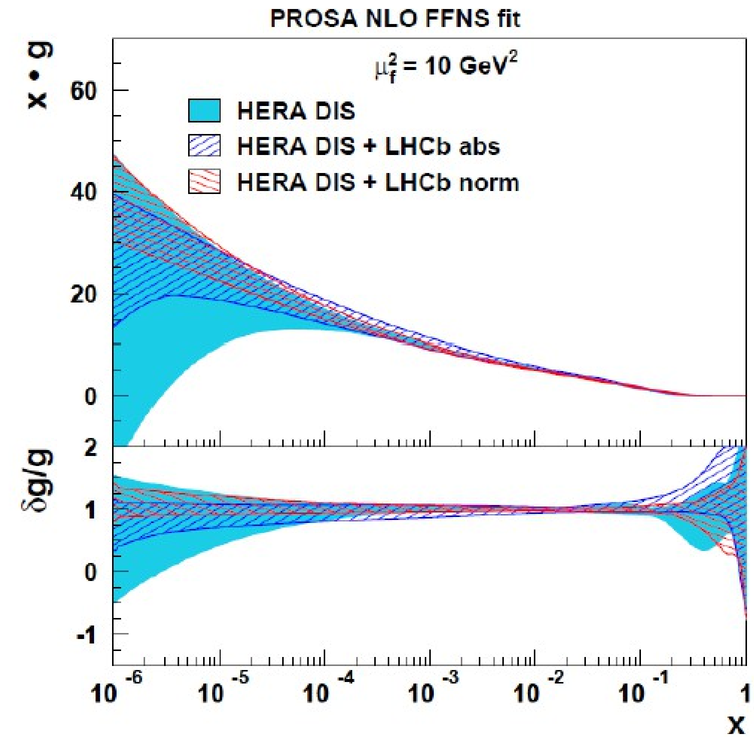
Fig. taken from Baltz et al., Phys. Reports 458 (2008)1 with the additional domain opened by p-Pb collisions



precision measurement of open charm production by LHCb measurement at forward rapidity provides input on low-x gluon PDFs

data: Nucl. Phys. B871 (2013) 1





for a recent summary of data and pQCD predictions see:
Guzzi, Geiser, Rizatdinova, 1509.04582 and Beraudo, 1509.04530
additional constraint of gluon PDF in particular at low x (down to 5 10^{-6})

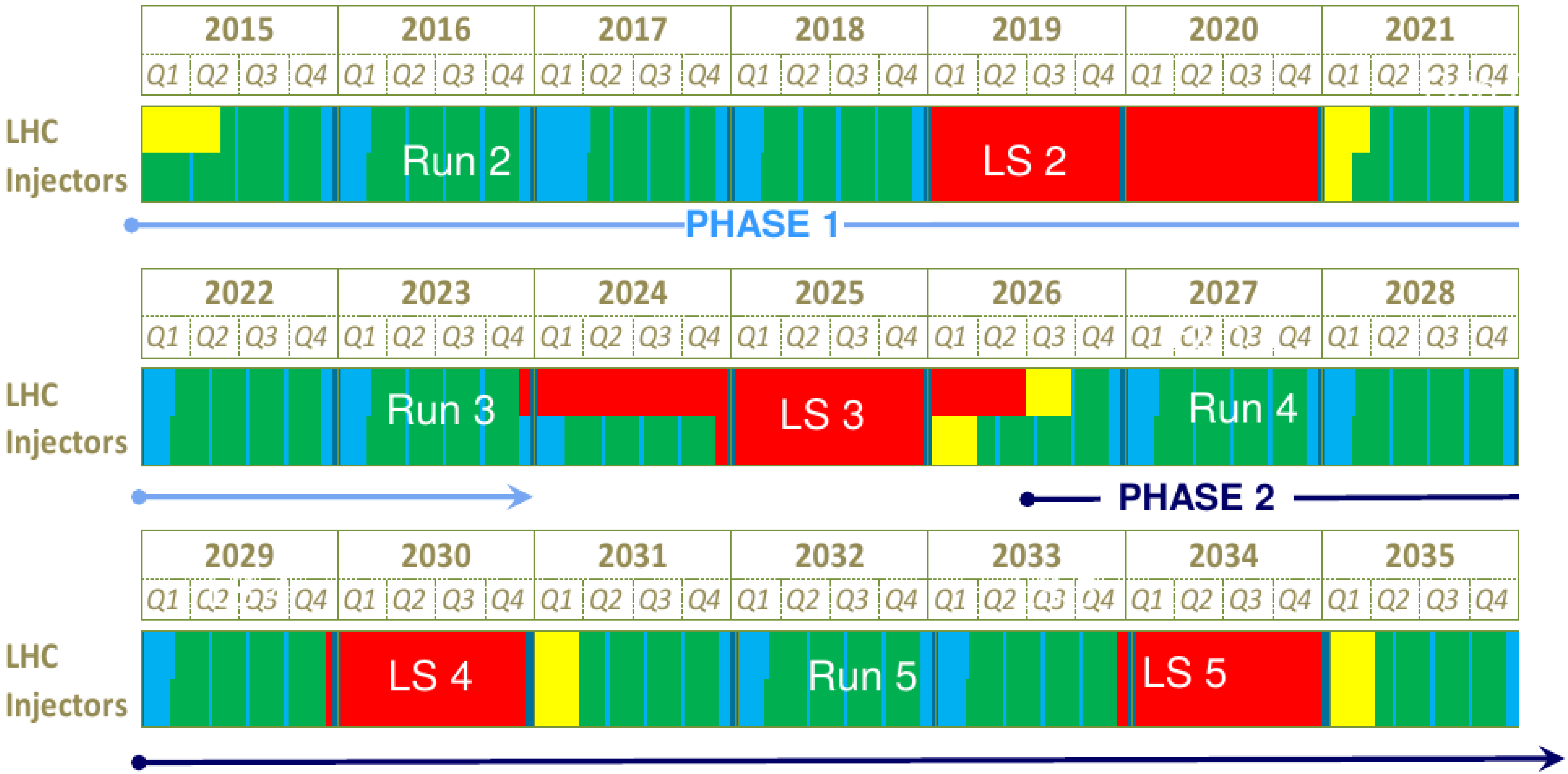
LHC ion program for Run3 and Run4

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

ALICE

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. $L = 6 \times 10^{27}\ cm^{-1}s^{-1}$), 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)

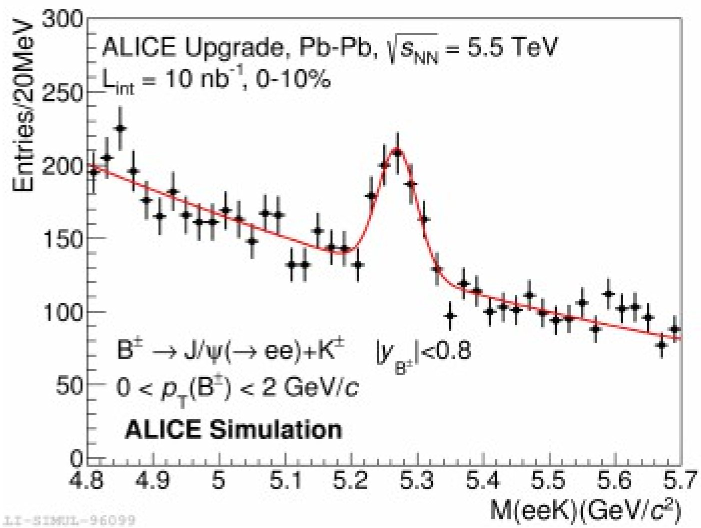
II. Improve vertexing and tracking at low p_T ➔ NEW ITS

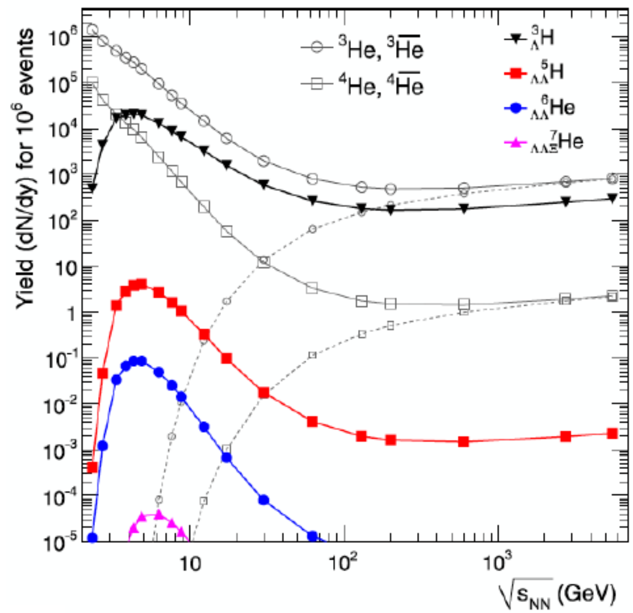
ALICE upgrade: main physics topics for Run3 and Run4

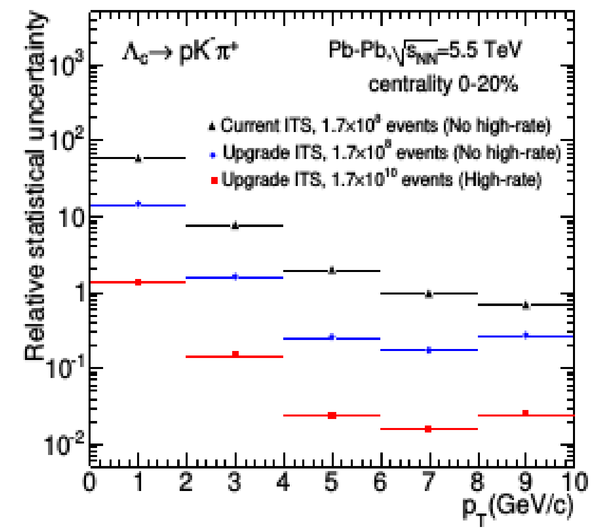
rare probes at low p_T:

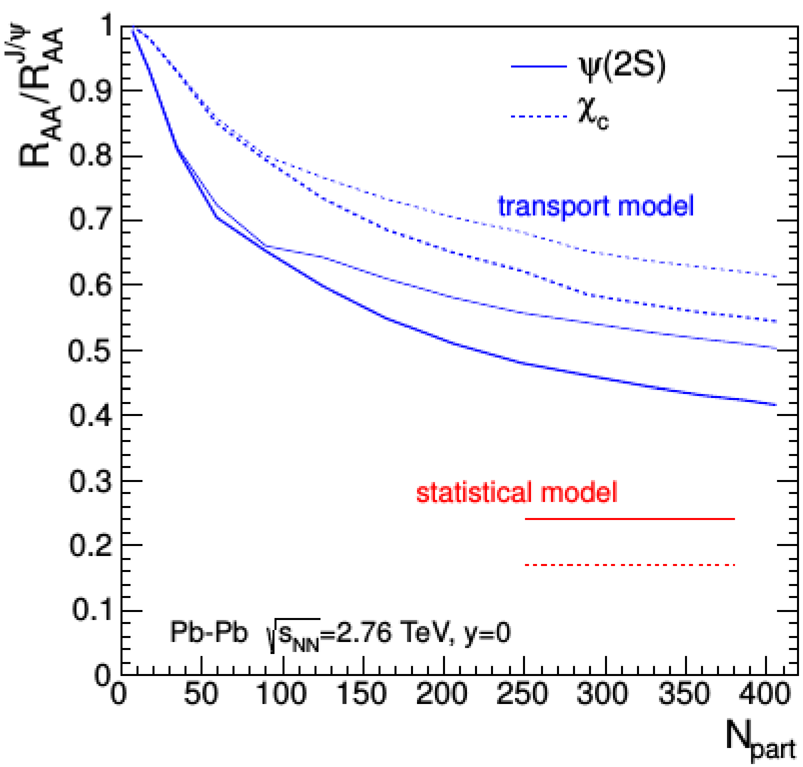
- heavy flavor hadrons
- quarkonia
- di-leptons at low and intermediate mass
- light anti-matter and exotic clusters
- jet physics
- event-by-event fluctuations of conserved quantum numbers
- ultra-peripheral collisions , low x physics, photon-photon collisions

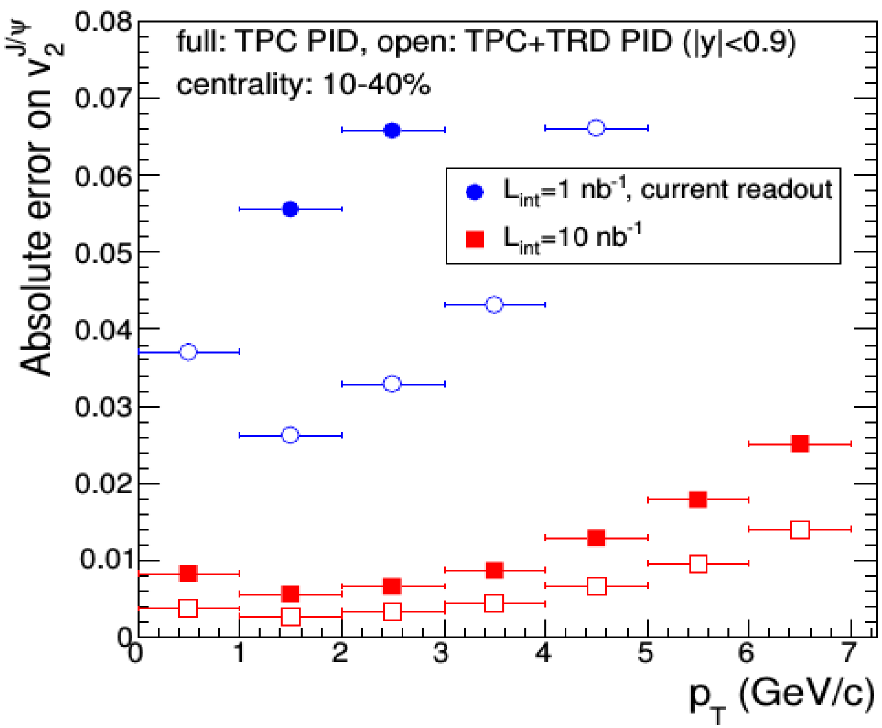
ALICE upgrade – show and tell





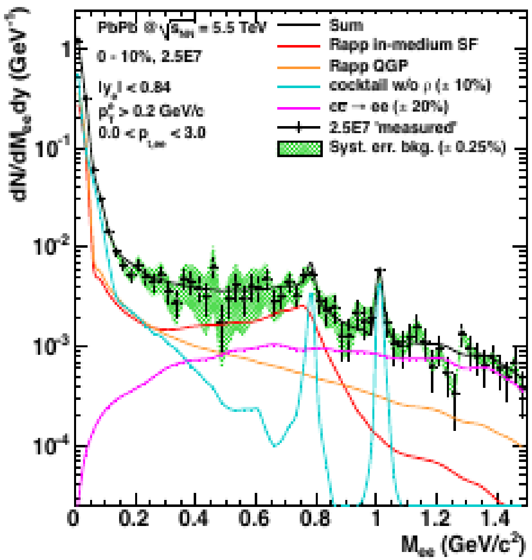


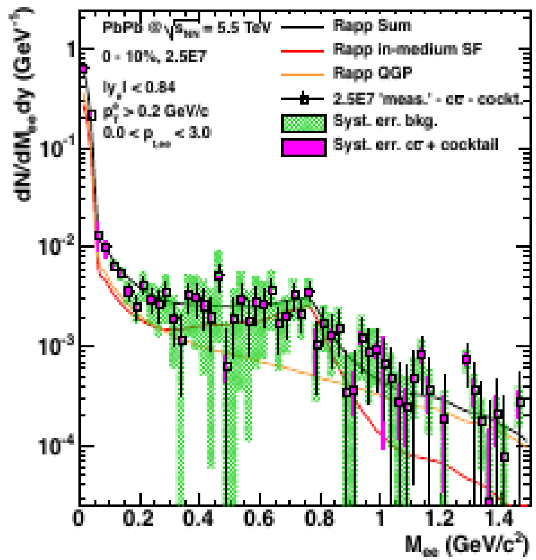




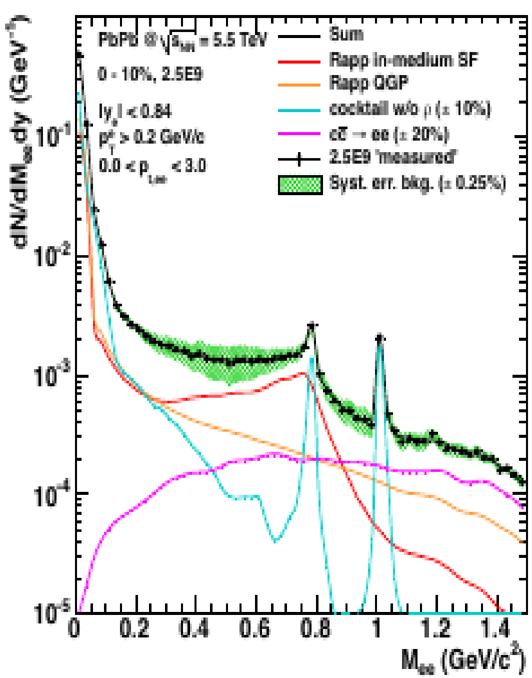
di-electron simulations at mid-rapidity
Rapp-Wambach scenario

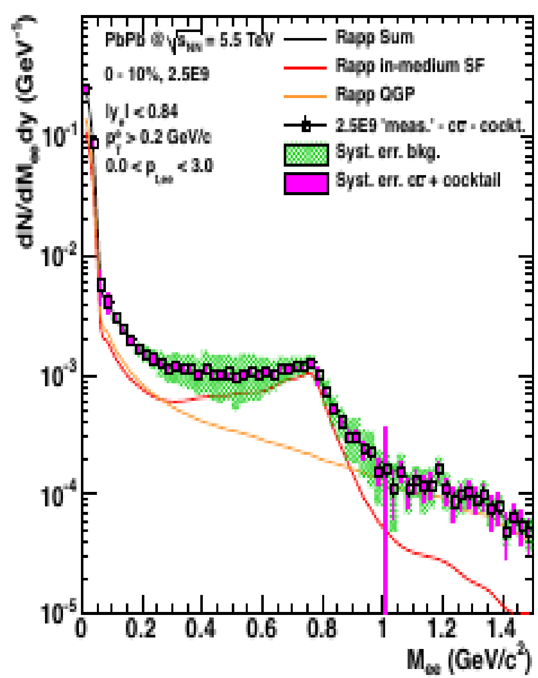
Run 2
current





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

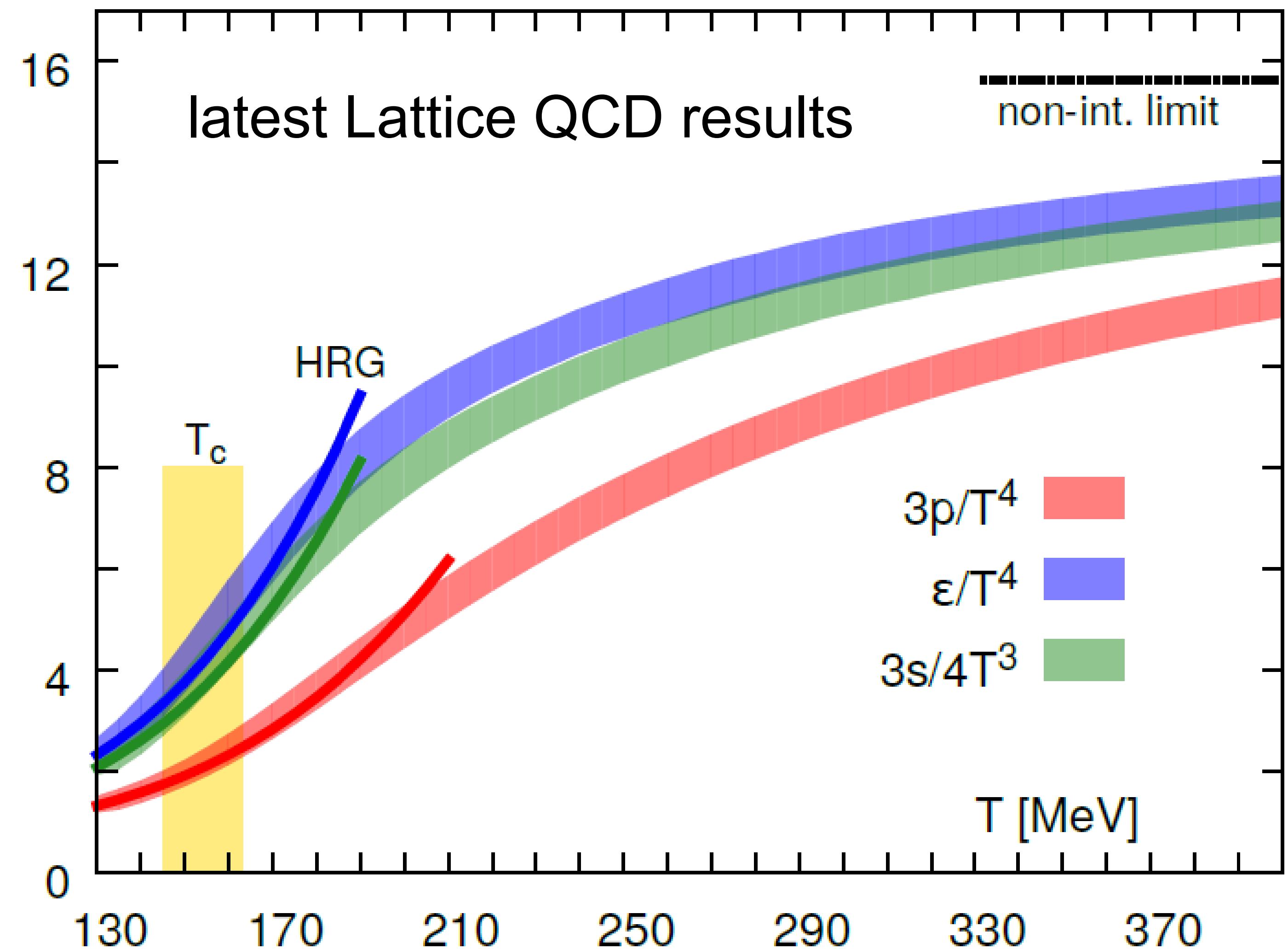
LHC heavy ion program in Run3 and Run4

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

additional slides

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



critical region: T_c = (154 ± 9) MeV ε_{crit} = (340 ± 45) MeV/fm^3

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

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

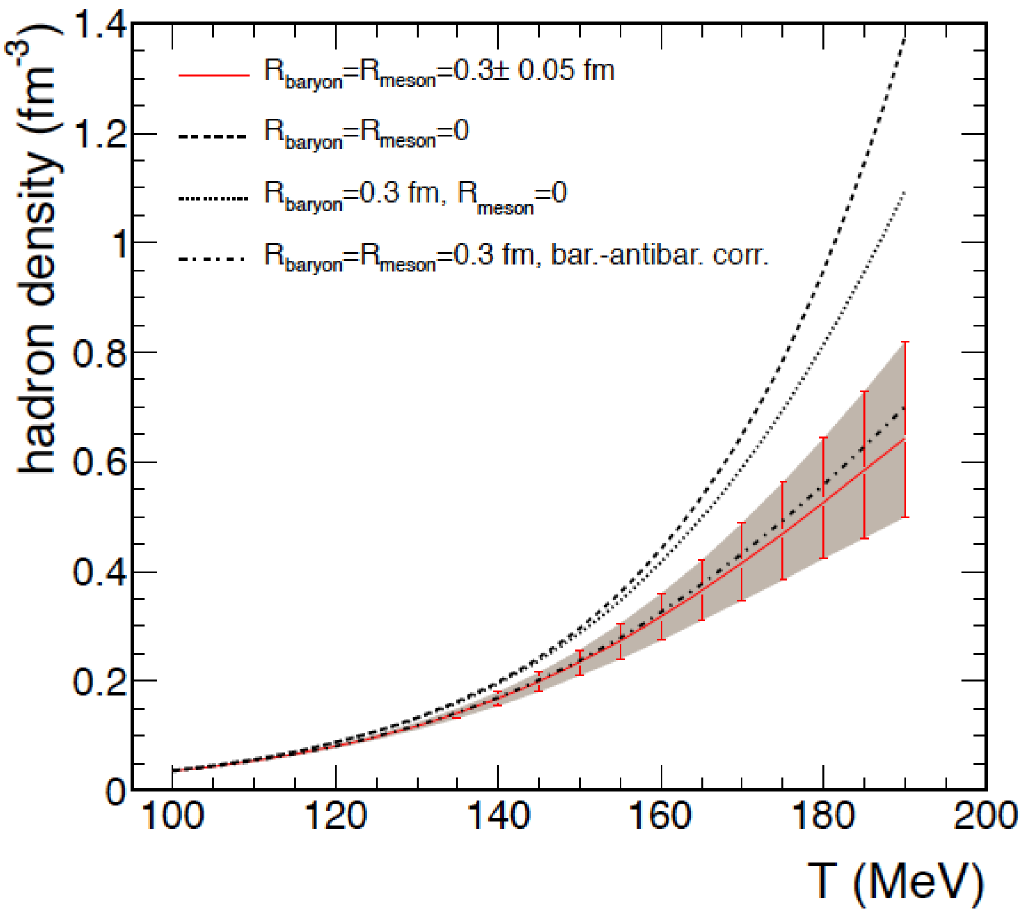
Temperature	New Particles	$4N(T)$
$T < m_e$	γ's + ν's	29
$m_e < T < m_\mu$	$e^\pm$	43
$m_\mu < T < m_\pi$	$\mu^\pm$	57
$m_\pi < T < T_c{}^\dagger$	π's	69
$T_c < T < m_{\text{strange}}$	π's + $u, \bar{u}, d, \bar{d}$ + gluons	205
$m_s < T < m_{\text{charm}}$	$s, \bar{s}$	247
$m_c < T < m_\tau$	$c, \bar{c}$	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

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

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

Hadron resonance gas and interactions



for T < 165 MeV, the details of the interactions don't matter and the 'low density approximation' is a good assumption

implementation

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i - \mu_i)/T] \pm 1}$$

Latest PDG hadron mass spectrum ...quasi-complete up to m=2 GeV;
our code: 555 species (including fragments, charm and bottom hadrons)

for resonances, the width is considered in calculations

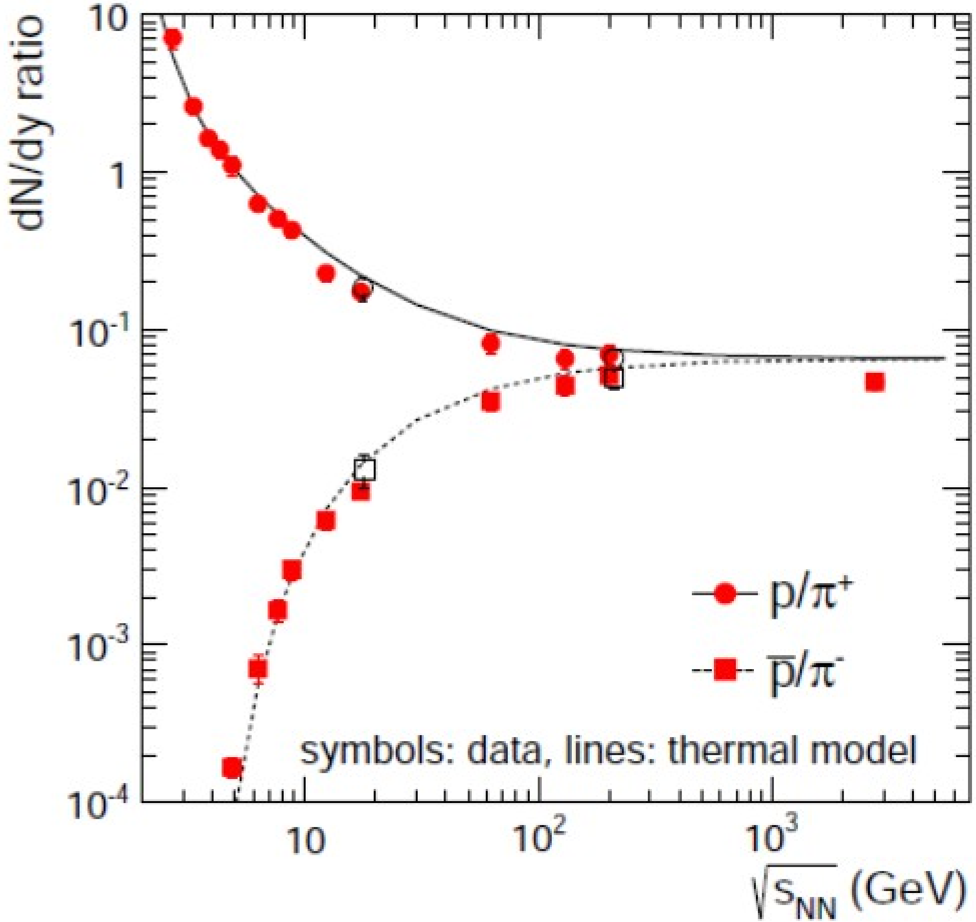
Minimize: $\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$

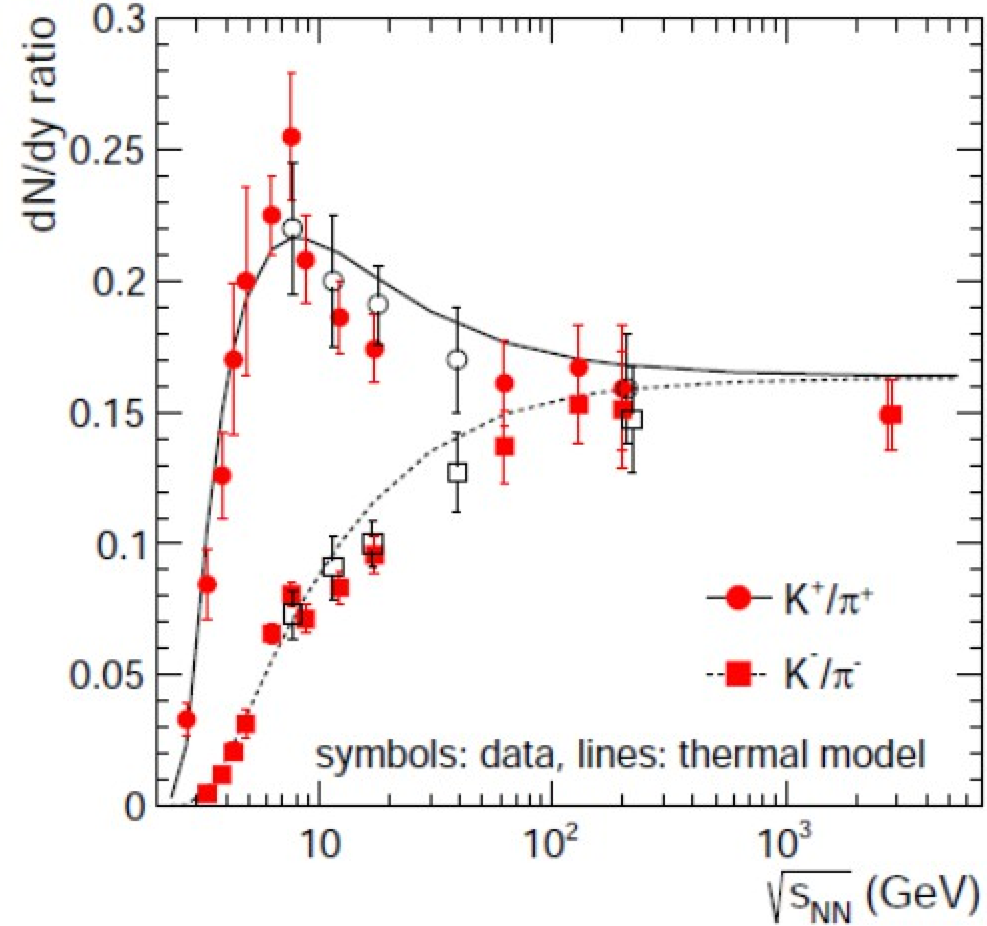
N_i hadron yield, σ_i experimental uncertainty (stat.+syst.)

$\Rightarrow (T, \mu_B, V)$

canonical treatment whenever needed (small abundances)

energy dependence of hadron production described quantitatively





together with known energy dependence of charged hadron production in Pb-Pb collisions we can predict yield of all hadrons at all energies with < 10% accuracy

no new physics needed to describe K+/pi+ ratio including the 'horn'

a note on the chemical freeze-out temperature

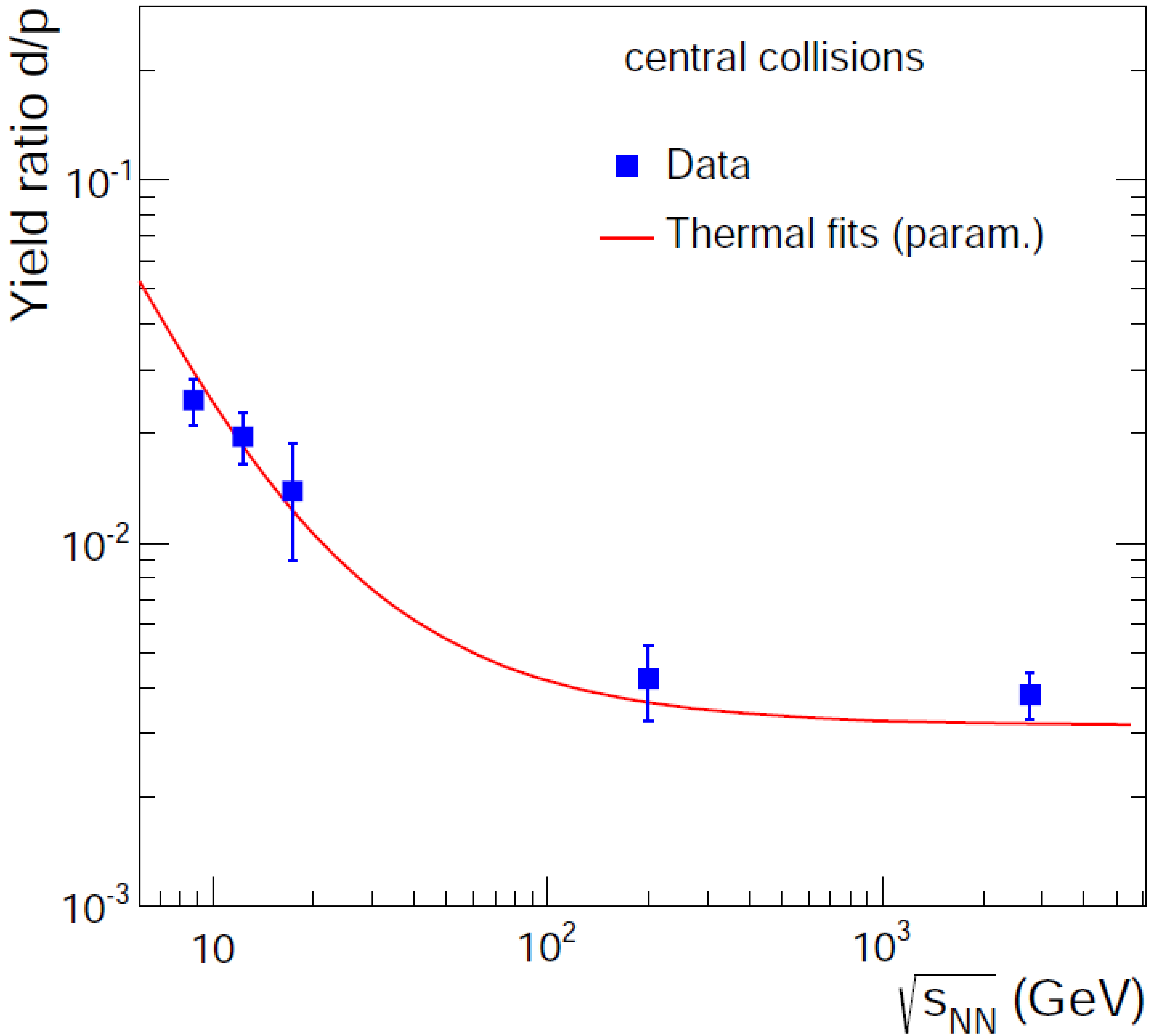
T_{chem} = 156.5 ± 1.5 MeV from fit to all particles

there is an additional uncertainty because of the poorly known hadronic mass spectrum for masses > 2 GeV

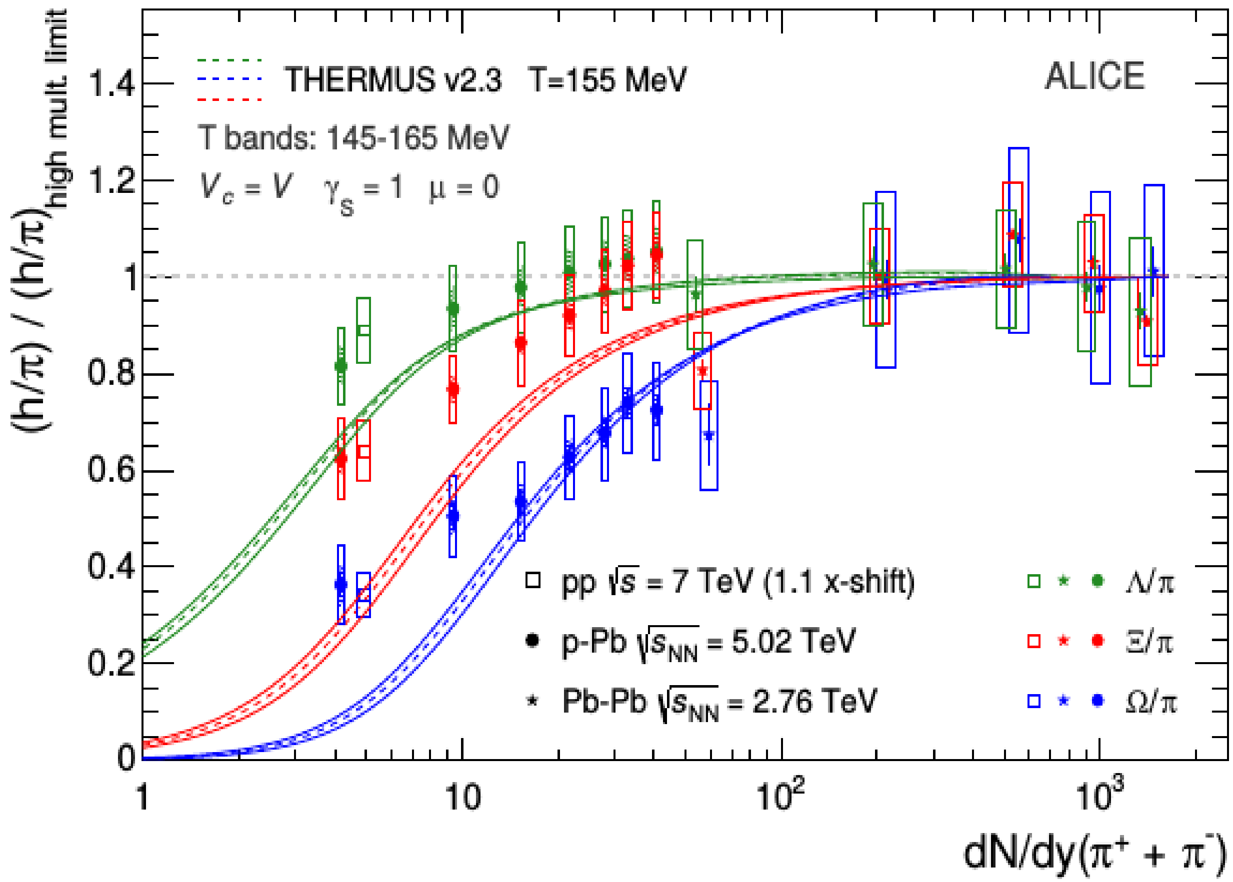
for d, 3He, hypertriton and alpha, there is very little feeding from heavier states and none from high mass states in the hadronic mass spectrum, for these particles the temperature T_{nuc} can be determined 'on the back of an envelope' :

T_{nuc} = 154 ± 5 MeV, independent of hadronic mass spectrum

d/p ratio as function of energy – Pb—Pb collisions

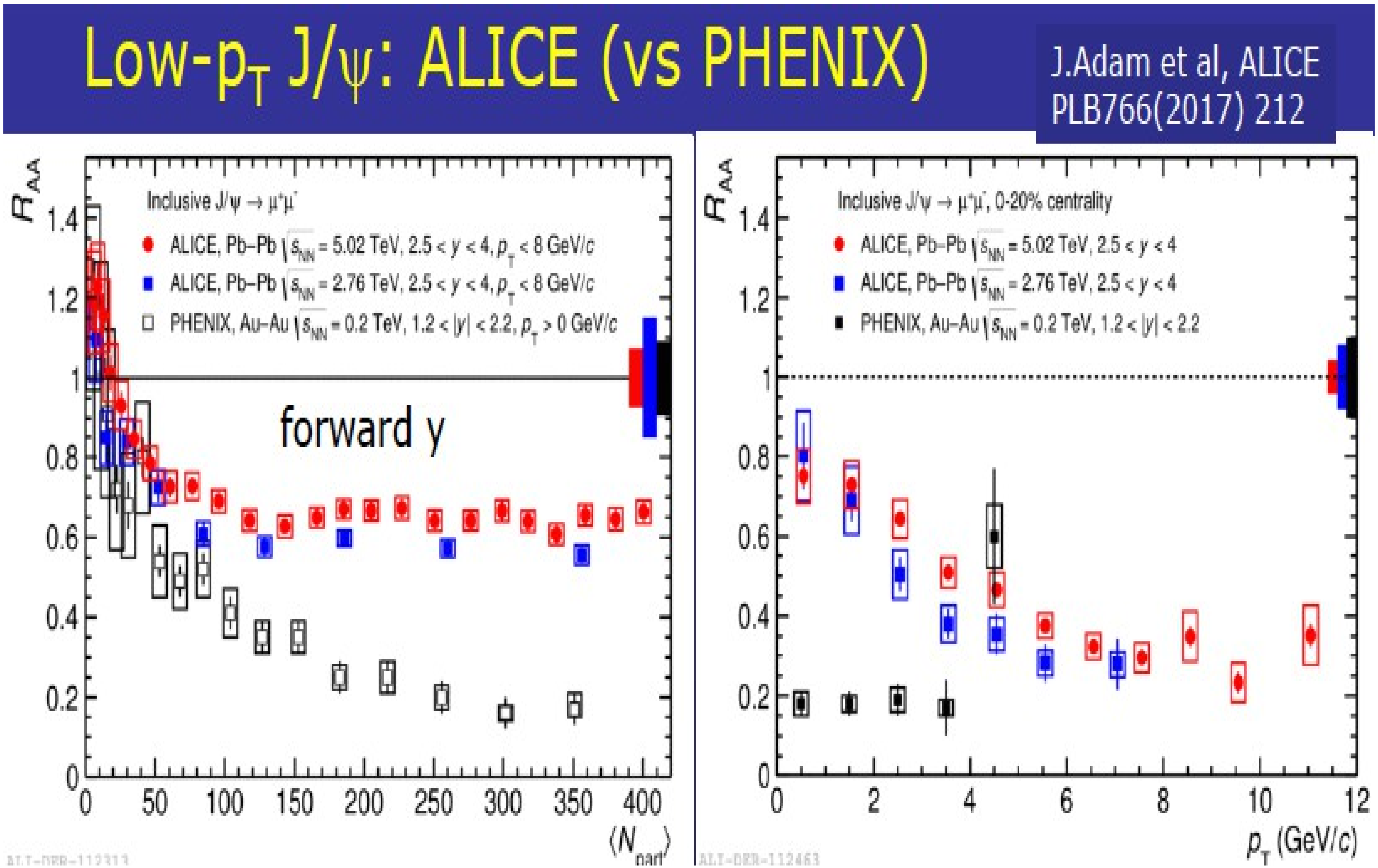


is multiplicity dependence described by canonical thermodynamics?

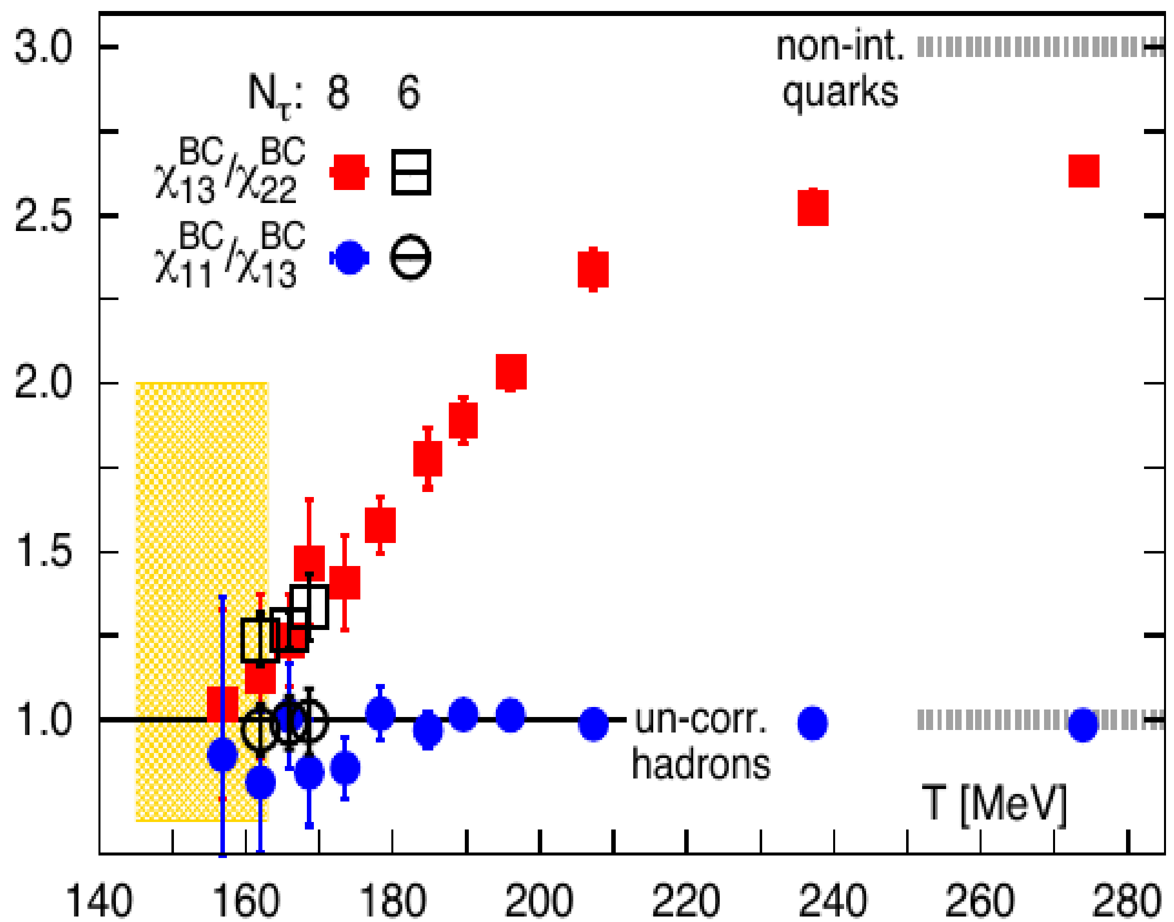


main features, but not details, are captured well – needs further study
arXiv:1512.07227 ALICE

Comparison RHIC vs LHC data



from lattice: charmed hadrons deconfine near T_c



Bazavov et al, PLB 737 (2014) 210

figure courtesy Peter Petrezky