Ultra-relativistic nuclear collisions

Lecture 1

a) light flavors

- introductory remarks and context
- hadron production, statistical model and the QCD phase boundary
- chemical freeze-out and the case of weakly bound objects
- production yields in high energy collisions

FIAS-Frankfurt

54 Cracow School on Theoretical Physics
Zakopane, June 13, 2014

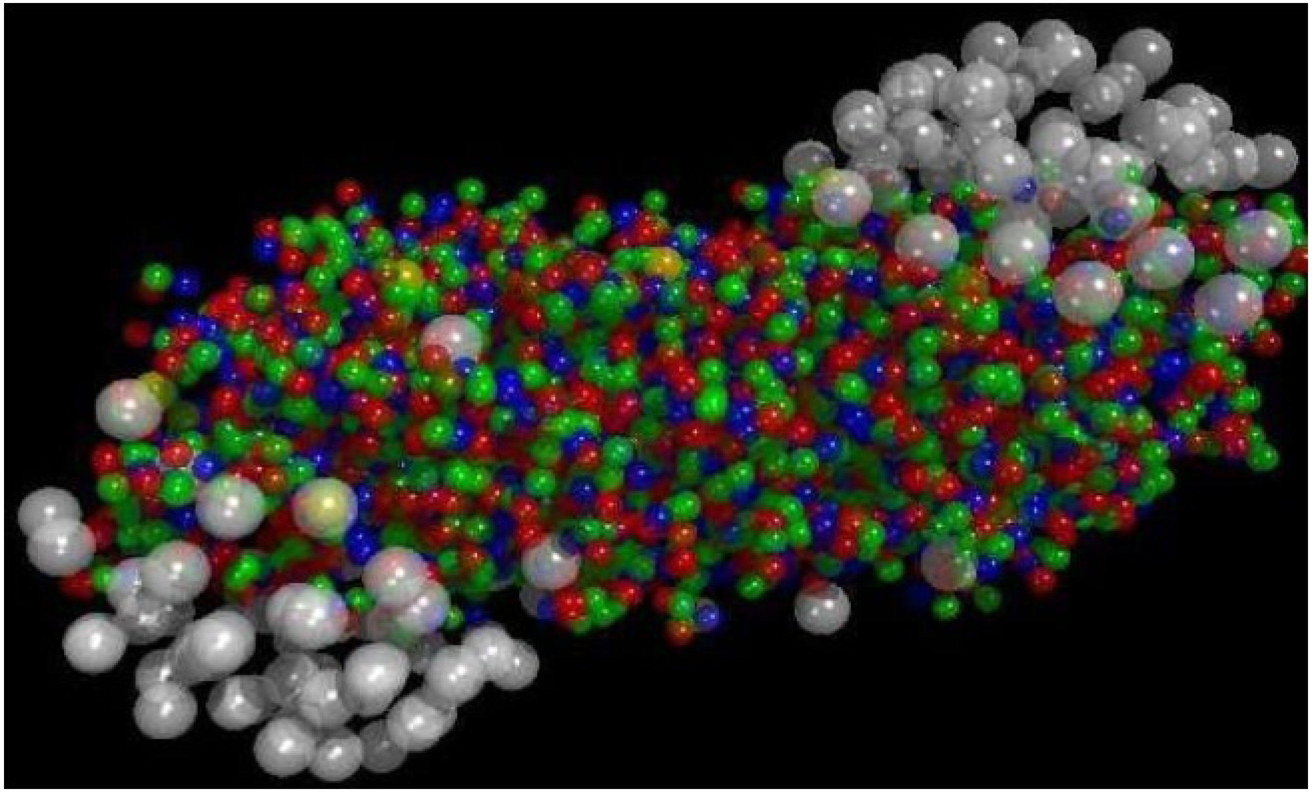
Peter Braun-Munzinger

Lecture 1

b) heavy flavors – hard probes

- reminder of basics
- discussion of time scales and open charm conservation equation
- results for RHIC and LHCenergy in pp collisions
- results for RHIC and LHC energy in AA collisions
- an aside on photon production

Quark-gluon plasma –a new state of matter- deconfined quarks and gluons



in relativistic nucleus-nucleus collisions, a new state of matter is produced, in which colored quarks and gluons roam freely

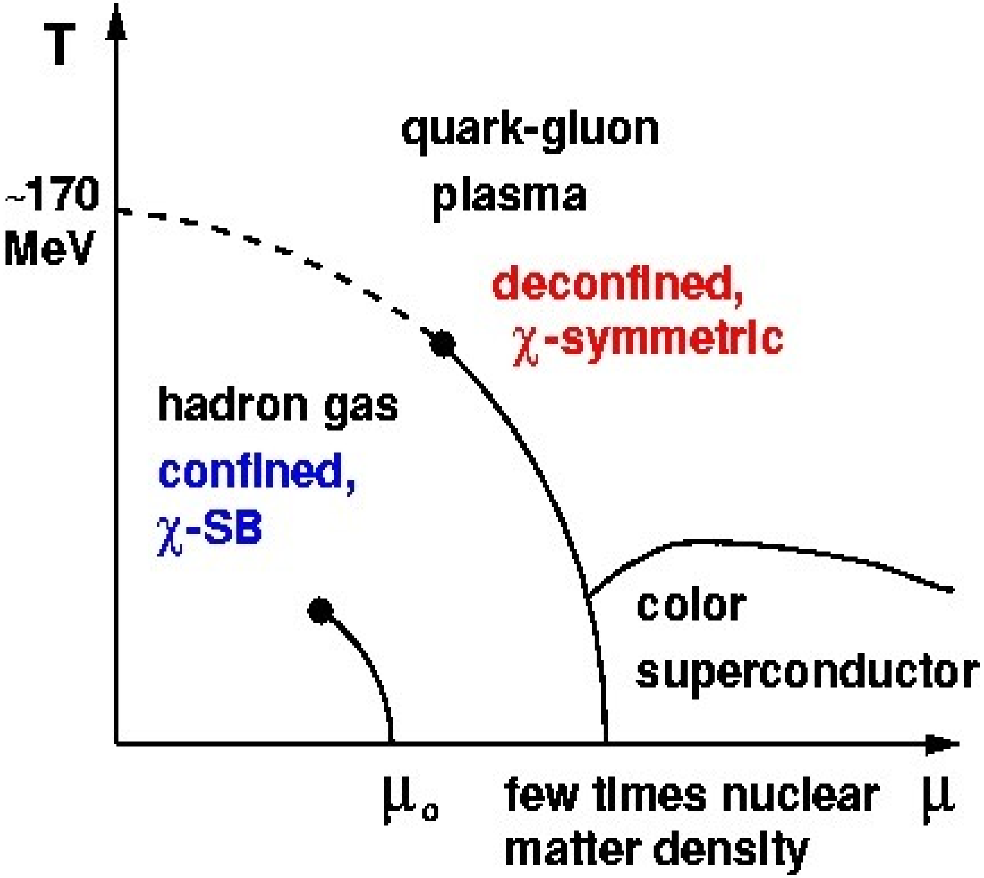
Simulation: UrQMD, Frankfurt

The phase diagram of strongly interacting matter

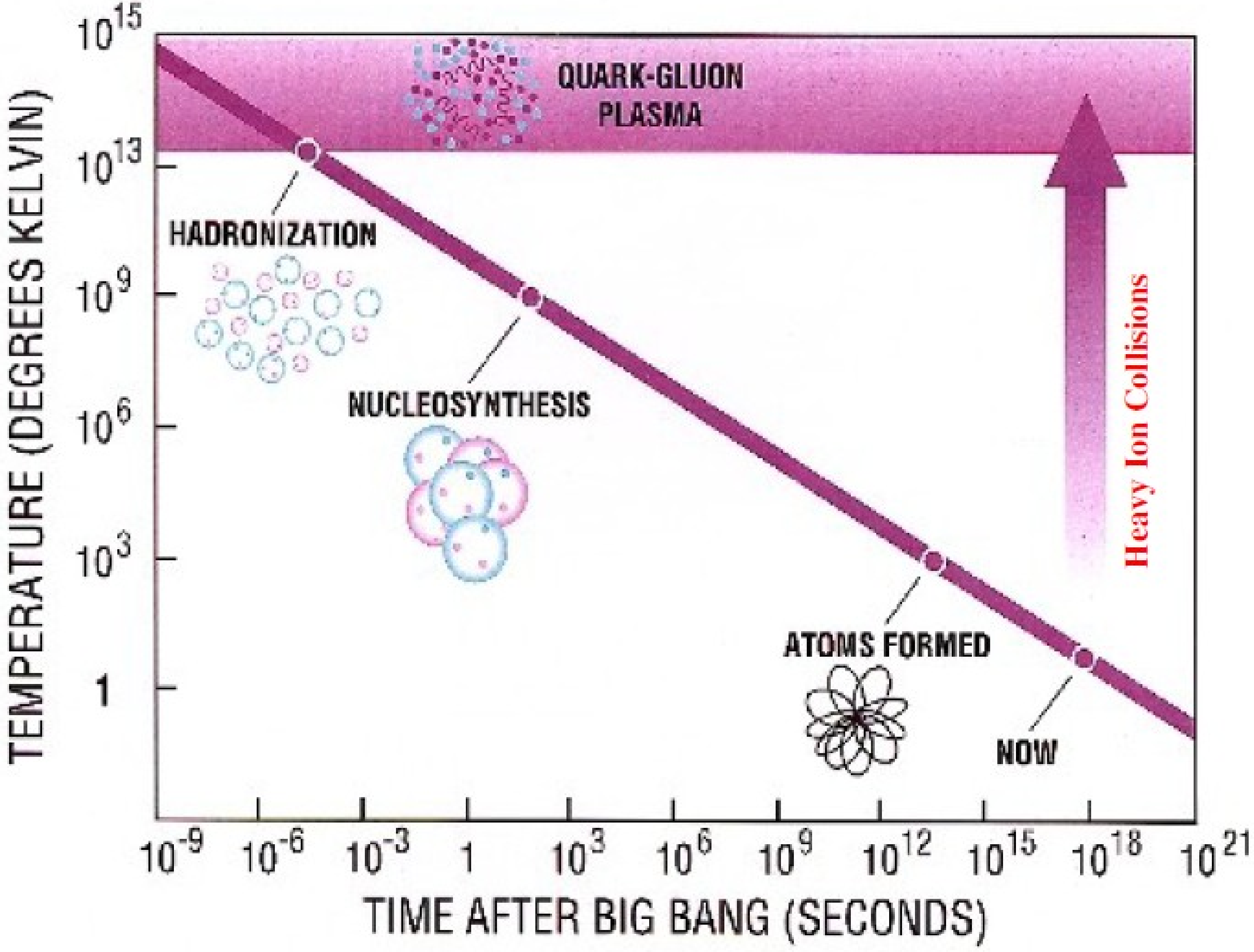
at low temperature and normal density
colored quarks and gluons are bound in colorless hadrons - confinement
chiral symmetry is spontaneously broken (generating 99% of proton mass e.g.)
1972 QCD (Gross, Politzer, Wilczek)
asymptotic freedom at small distances

at high temperature and/or high density
quarks and gluons freed from confinement
-> new state of strongly interacting matter
1975 (Collins/Perry and Cabibbo/Parisi)

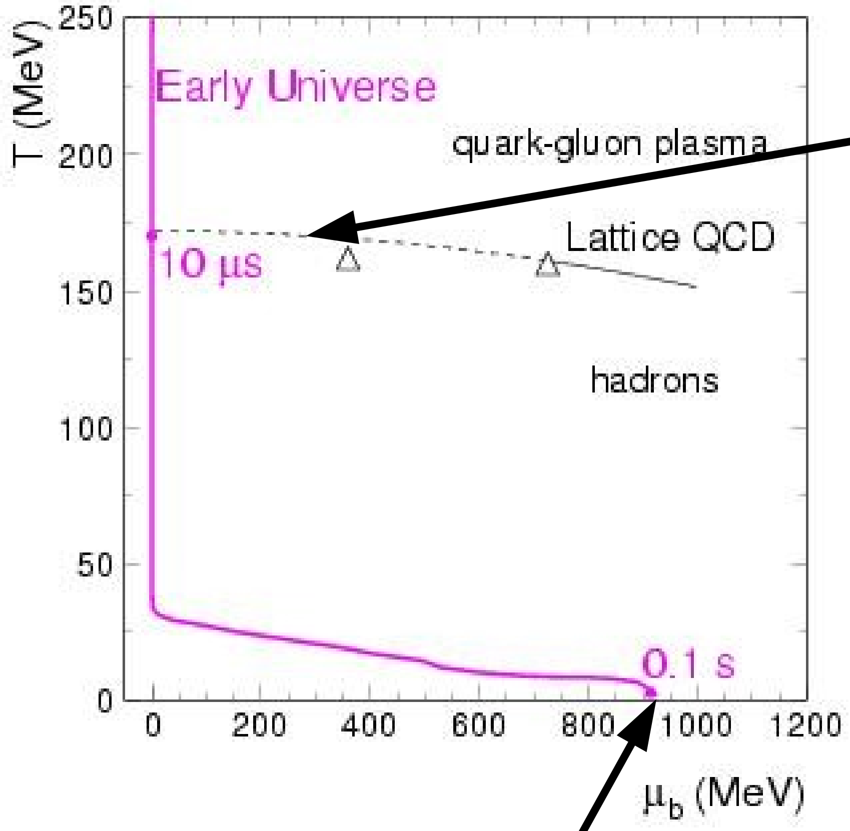
now called **Quark-Gluon Plasma (QGP)**



Quark-gluon plasma and the early universe



Evolution of the Early Universe



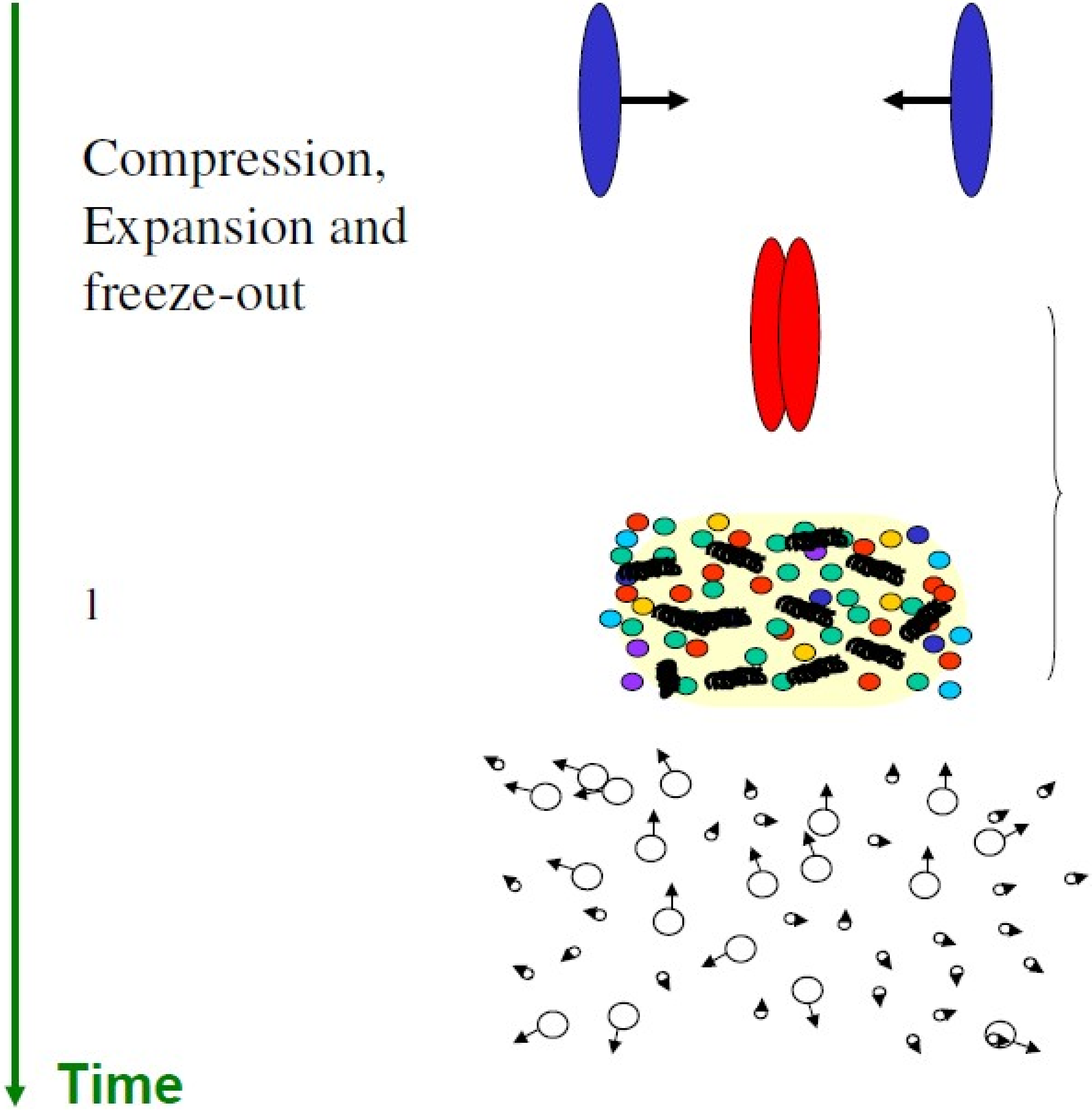
QCD Phase Boundary

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

How to create QGP in the laboratory?



Compression, Expansion and freeze-out

1

Normal nuclear matter

$\rho_0 = 0.17\ /\mathrm{fm}^3$

$\varepsilon_0 = 0.16\ \mathrm{GeV}/\mathrm{fm}^3$

Quark-Gluon Matter
Quark-Gluon Plasma

QGP reached

$\rho = 1.2\ /\mathrm{fm}^3$

$\varepsilon = 3\ \mathrm{GeV}/\mathrm{fm}^3$

Free streaming particles

The Large Hadron Collider (LHC)

27 km long, 8 sectors

1232 dipole magnets (15m, 30 tonnes each) to bend the beams

Cooled with **120 tonnes of He at 1.9 K**

pp: 2808 bunches/ring, each 1.15×10^{11} protons (8 min filling time)

Design luminosity: **10^{34} cm^{-2}s^{-1}**

PbPb: 592 bunches/ring, each 7×10^{7} Pb ions

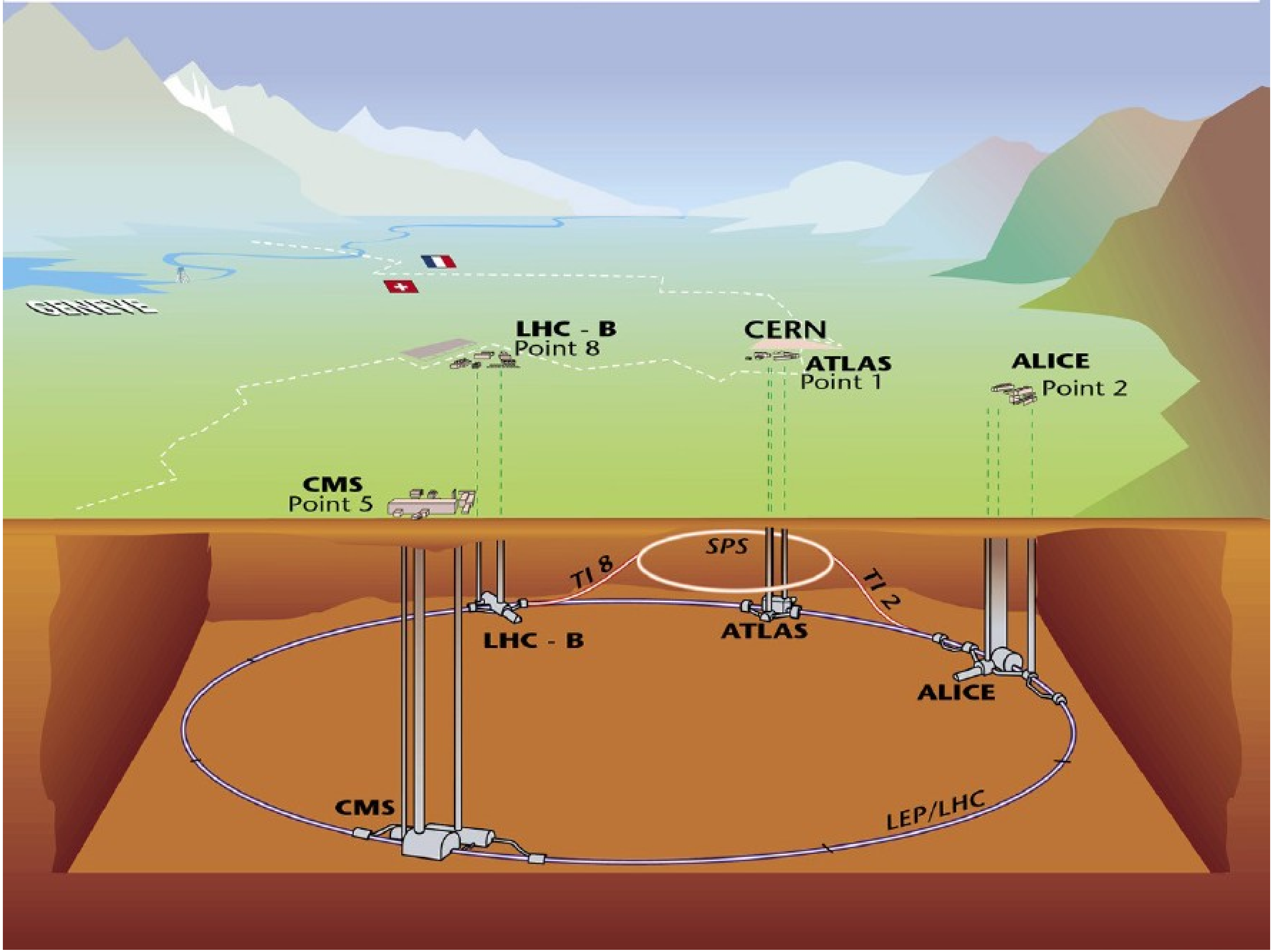
Design luminosity: 10^{27} cm^{-2}s^{-1}

Transverse r.m.s beam size: **16 µm**, r.m.s. bunch length: 7.5 cm

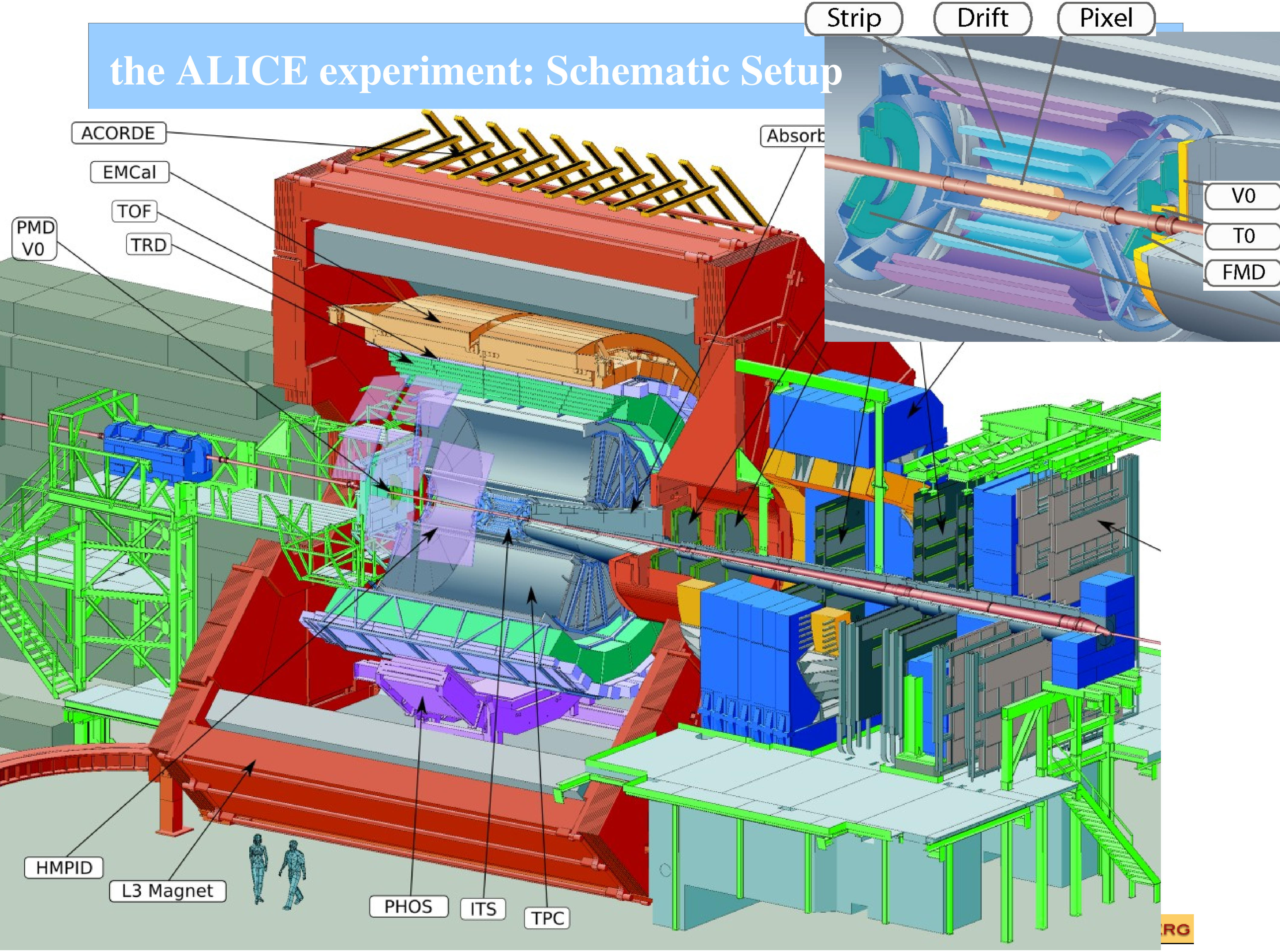
Beam kinetic energy: 362 MJ per beam (1 MJ melts 2 kg copper)

Total stored electromagnetic energy: **8.5 GJ** (dipole magnets only)

Overall view of the LHC experiments.

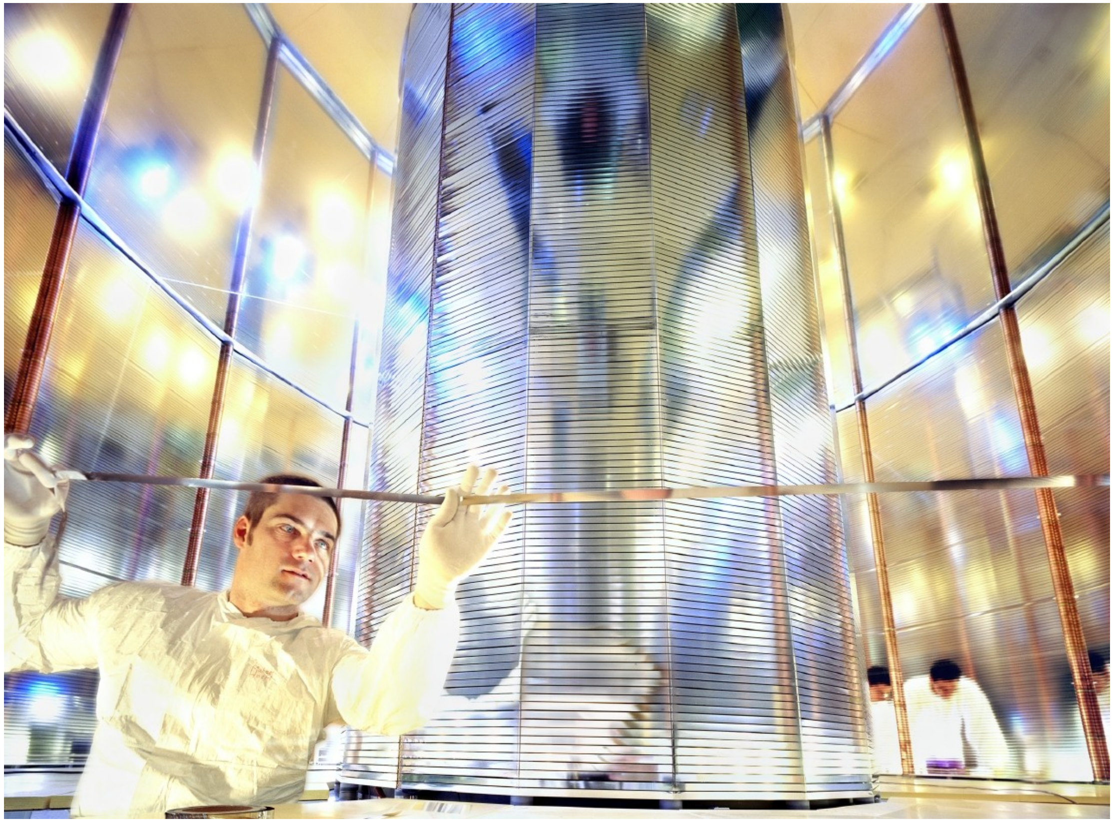


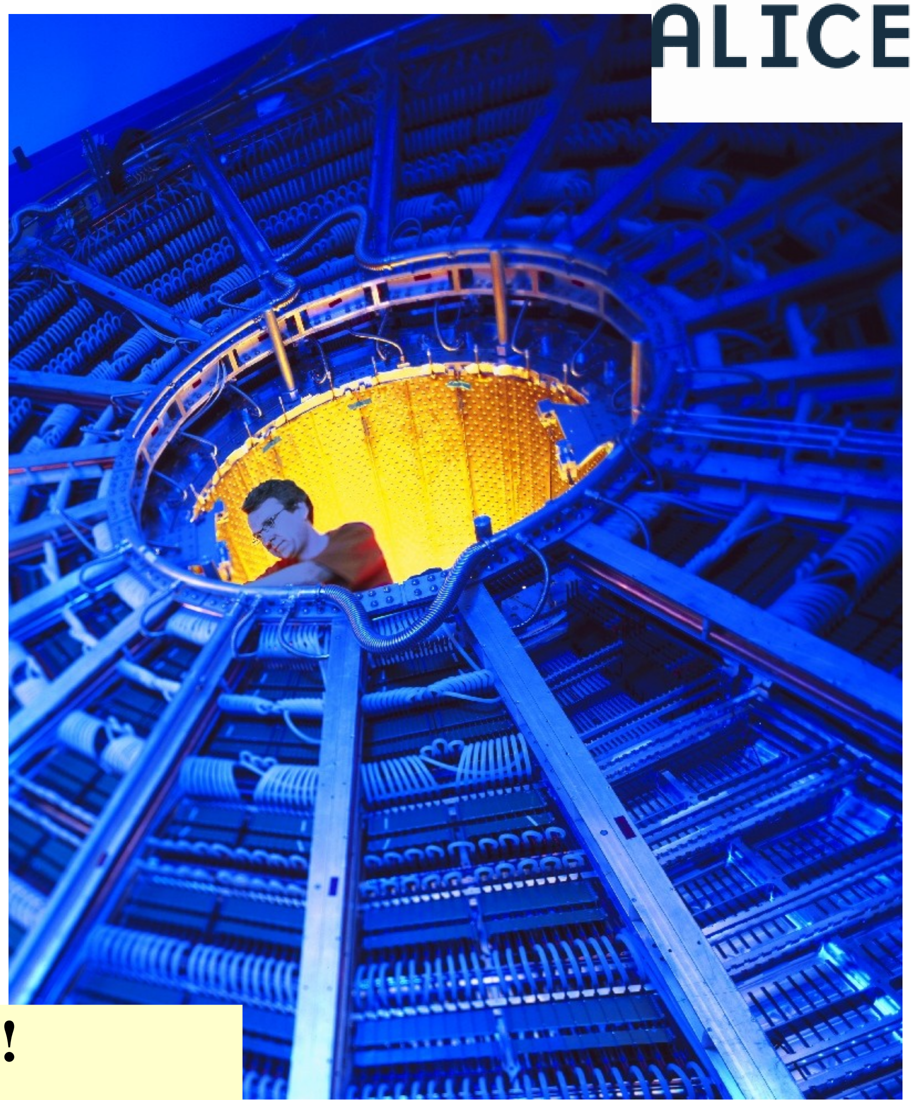
the ALICE experiment: Schematic Setup



the TPC (Time Projection Chamber) - 3D reconstruction of up to 15 000 tracks of charged particles per event

with 95 m^3 the largest TPC ever





560 million read-out pixels!

precision better than 500 µm in all 3 dim.

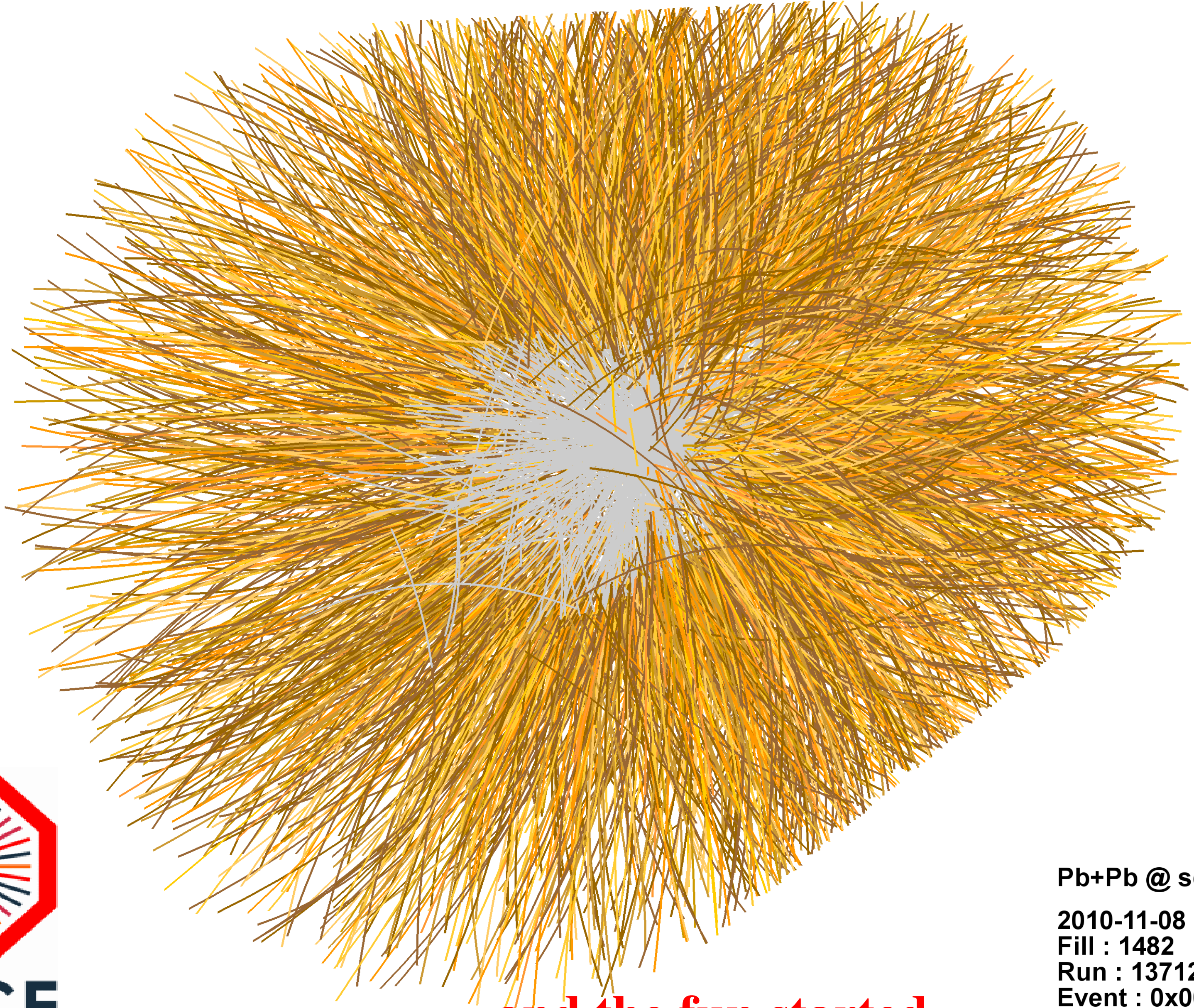
180 space and charge points per track

The interior of the TPC, 2004

first PbPb collisions at LHC at $\sqrt{s}$ = 2.76 A TeV

setup for ion collisions: November 4
first collisions with stable beams:
November 8 until Dec 6

already in Dec 2010
5 publications in PRL and PLB

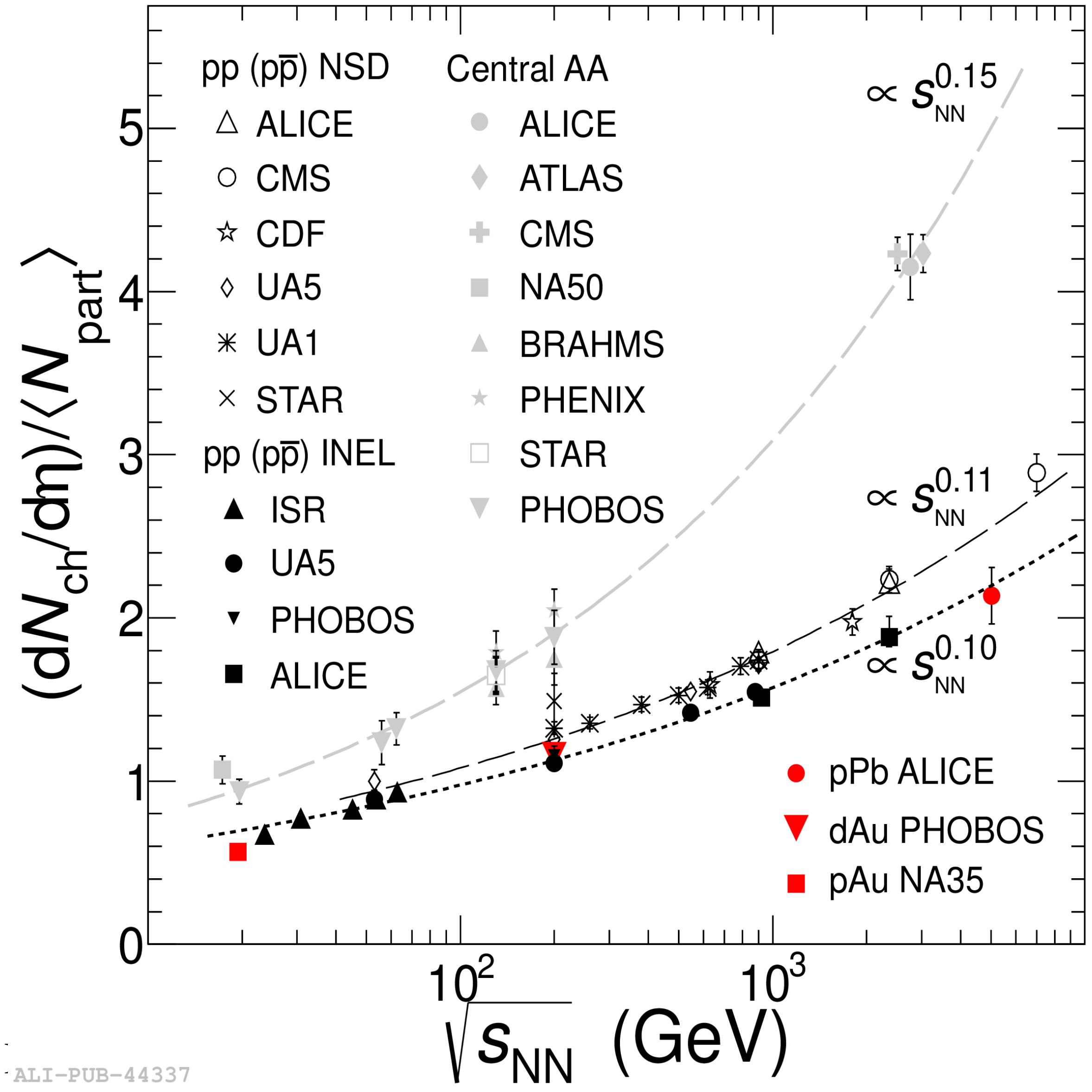


Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

and the fun started

Charged particle multiplicity in pp, pPb and central PbPb collisions



increase with beam energy significantly steeper than in pp

can the fireball formed in central nuclear collisions be considered matter in equilibrium?

Equilibration at the phase boundary

- Statistical model analysis of (u,d,s) hadron production: an important test of equilibration of quark matter near the phase boundary, **no equilibrium → no QGP matter**

- Would also imply: no (strangeness) equilibration in hadronic phase

- Present understanding: multi-hadron collisions near phase boundary bring hadrons close to equilibrium – supported by success of statistical model analysis

pbm, Stachel, Wetterich, Phys.Lett. B596 (2004) 61-69

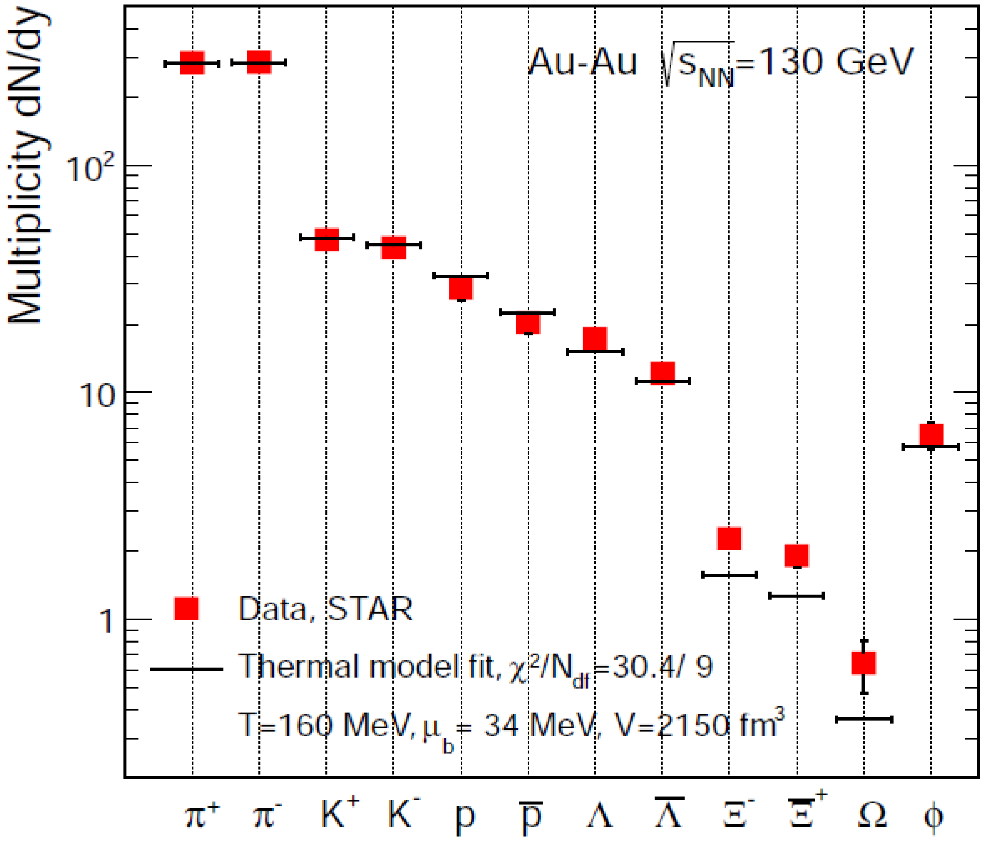
- This implies little energy dependence above RHIC energy

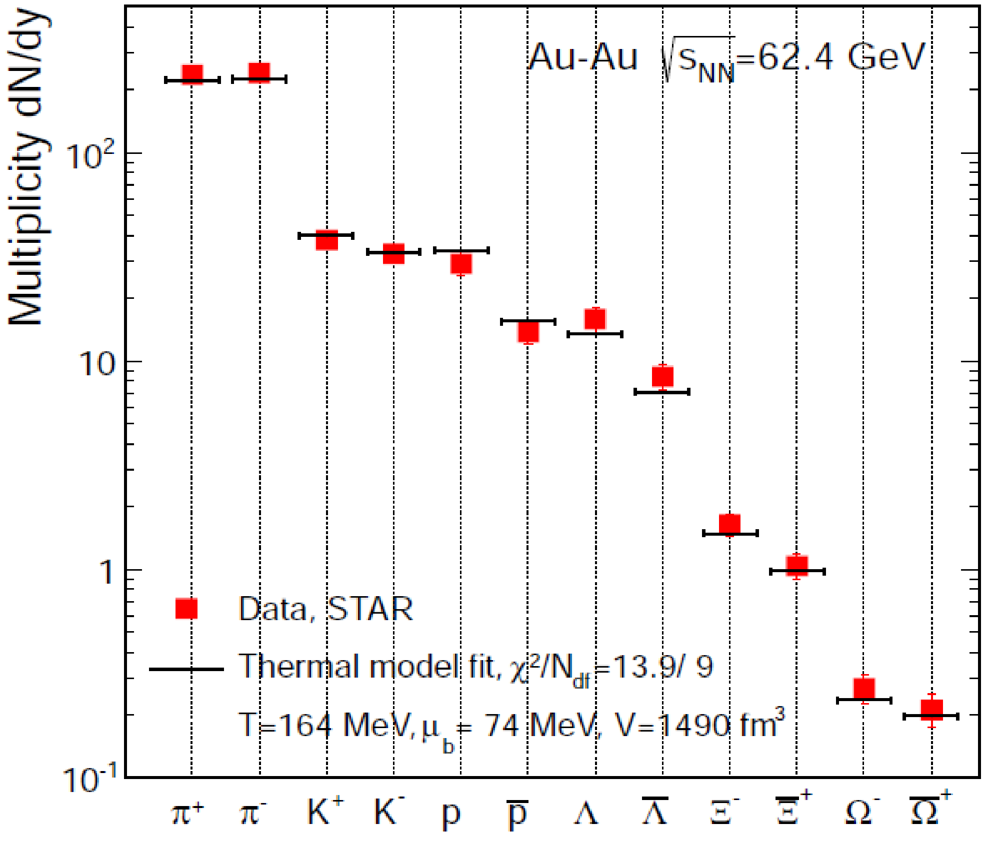
- Analysis of hadron production → determination of T_c

Is this picture also supported by LHC data?

Summary of pre-LHC era

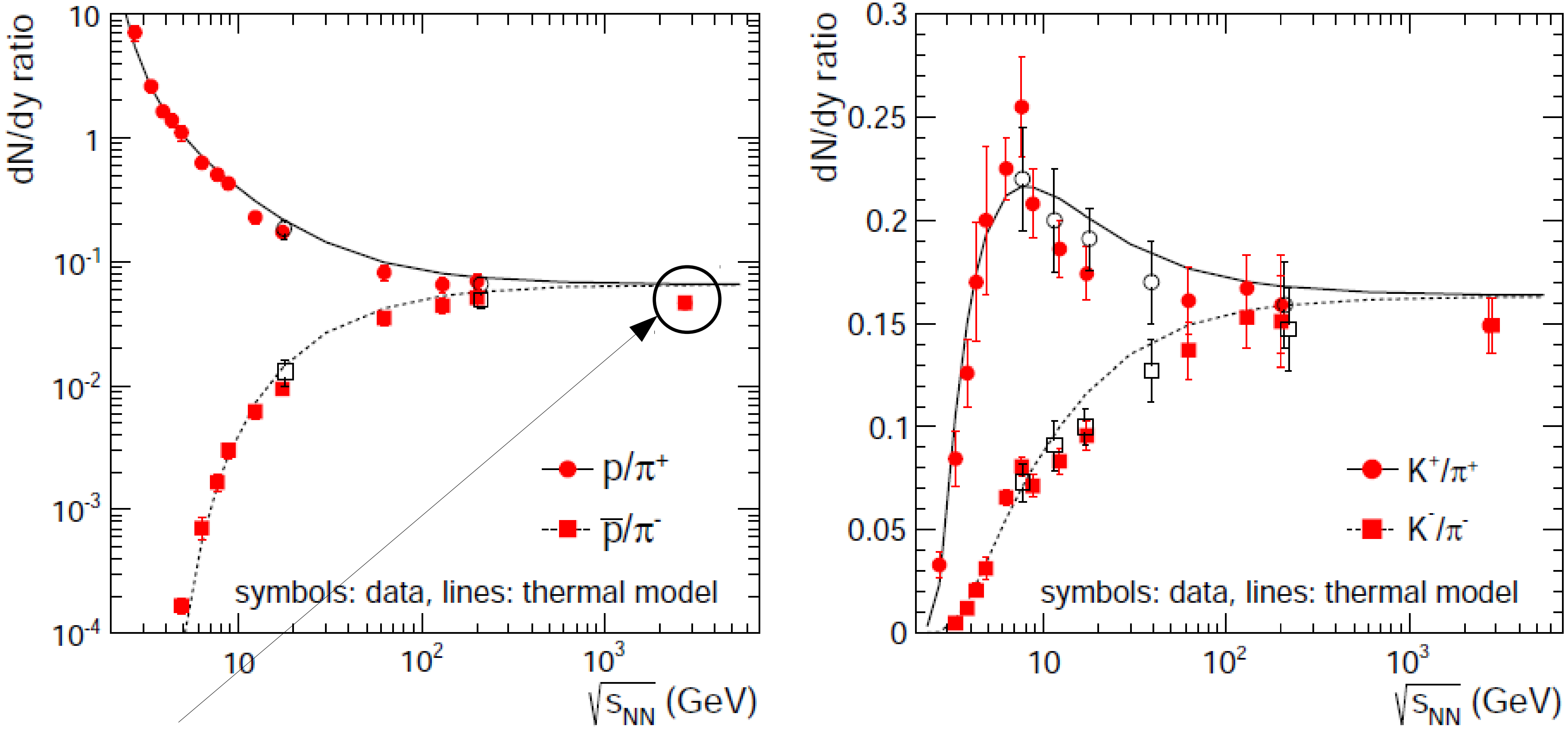
example of thermal fits: RHIC lower energies, STAR data alone





good fits, T = 160 – 164 MeV

overall systematics, including ALICE data, on proton/pion and kaon/pion ratios



proton anomaly?

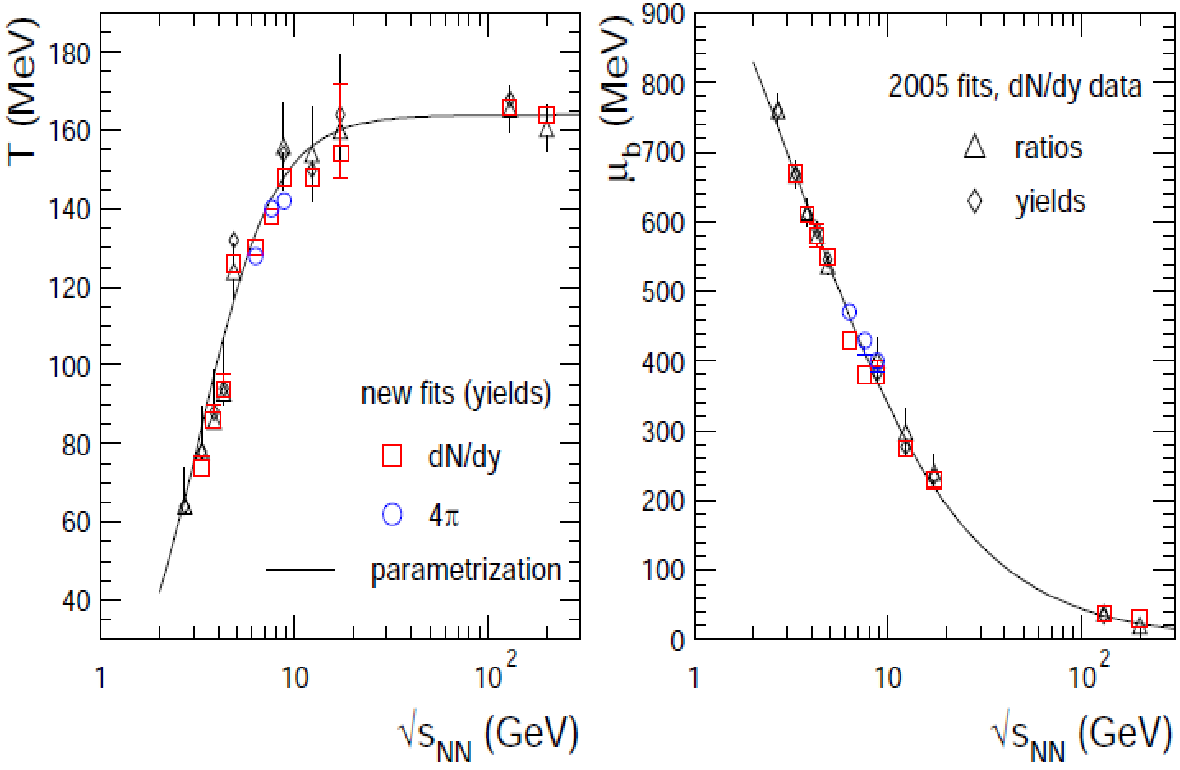
Parameterization of all freeze-out points before LHC data

note: establishment of limiting temperature

T_{lim} = 161 +/- 4 MeV

get T and μ_B for all energies

for LHC predictions we picked T = 161 MeV and, later, 164 MeV

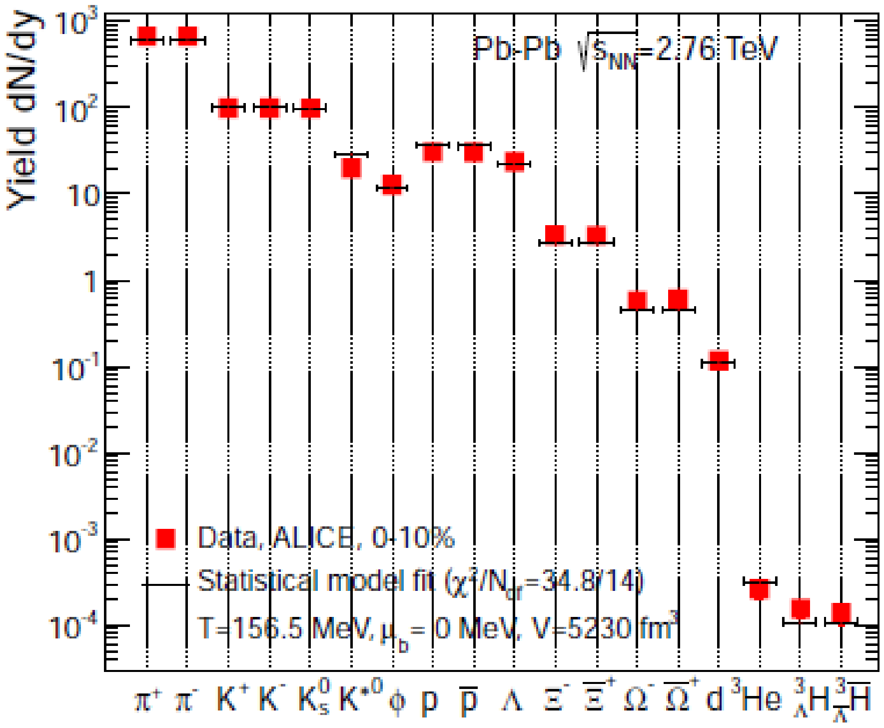


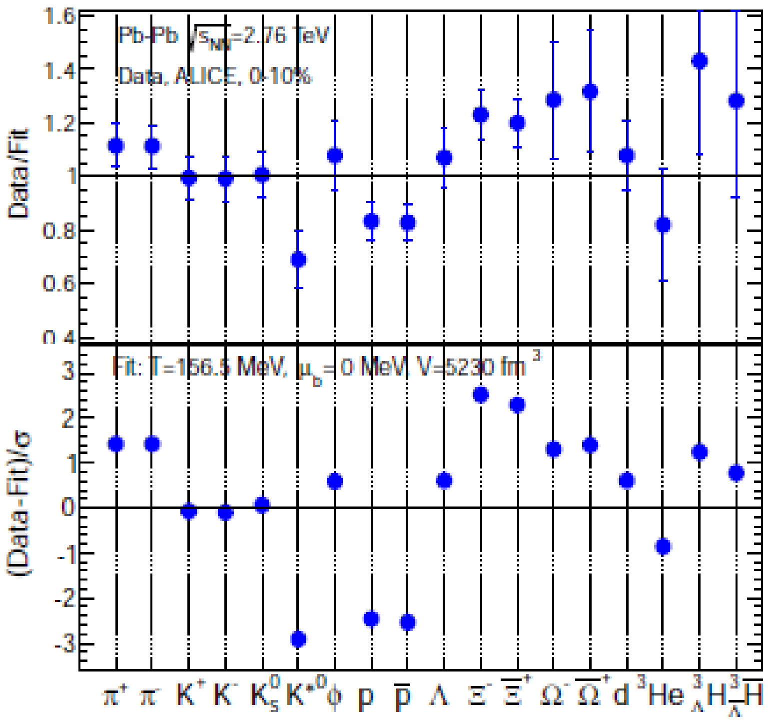
A. Andronic, pbm, J. Stachel,
Nucl. Phys. A772 (2006) 167, nucl-th/0511071 ,
J. Phys. G38 (2011) 124081

T_{lim} = 161 MeV is close to the QCD phase transition temperature

update April 2014 incl. 3He and hypertriton

LHC, Pb–Pb, 0-10%





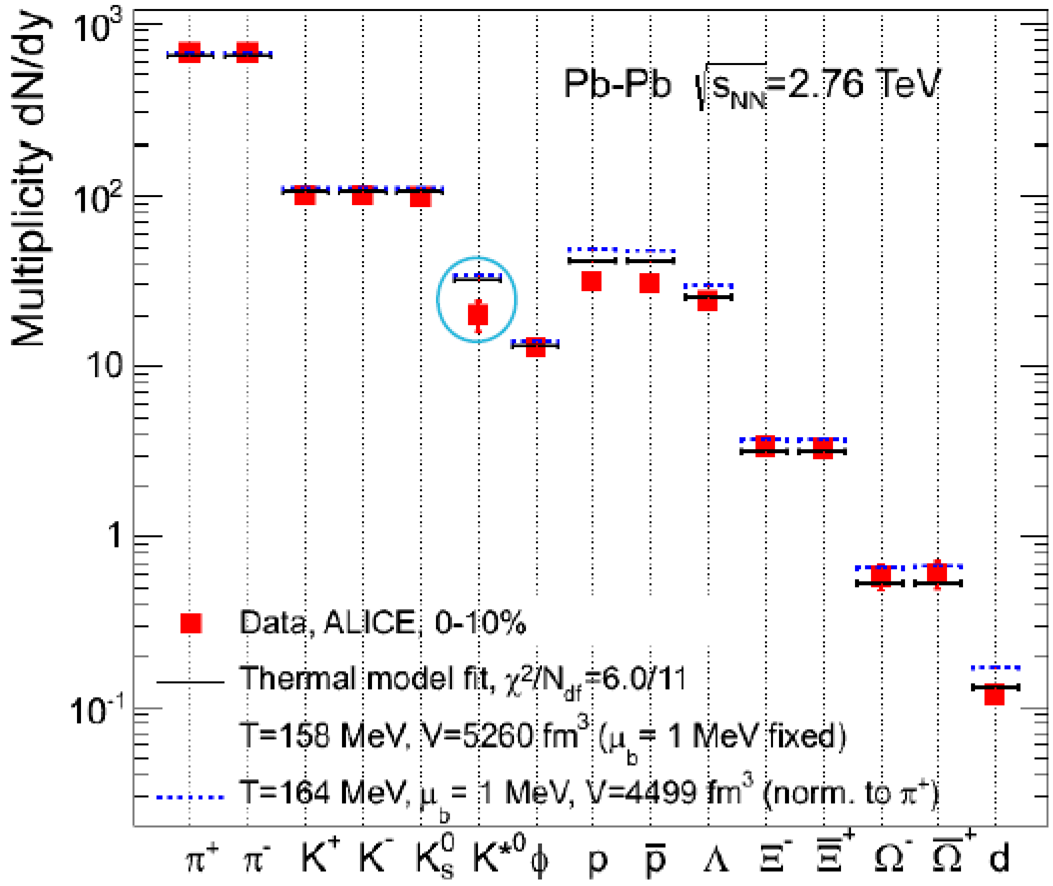
K^* not in fit

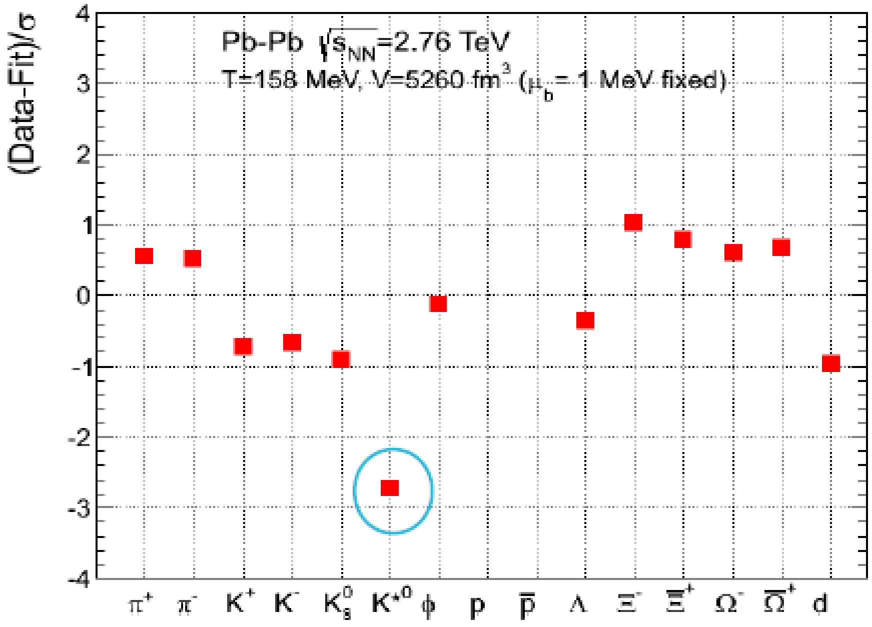
$T = 156.5 \pm 1.5$ MeV, $V = 5230 \pm 420$ fm^3

π, $K^\pm$, K^0 from charm included (0.7%, 2.6%, 2.9% for best fit)

[no π in fit: $T = 158 \pm 1.5$ MeV, $V = 4730 \pm 380$ fm^3, χ^2/N_{df}=30.3/12]

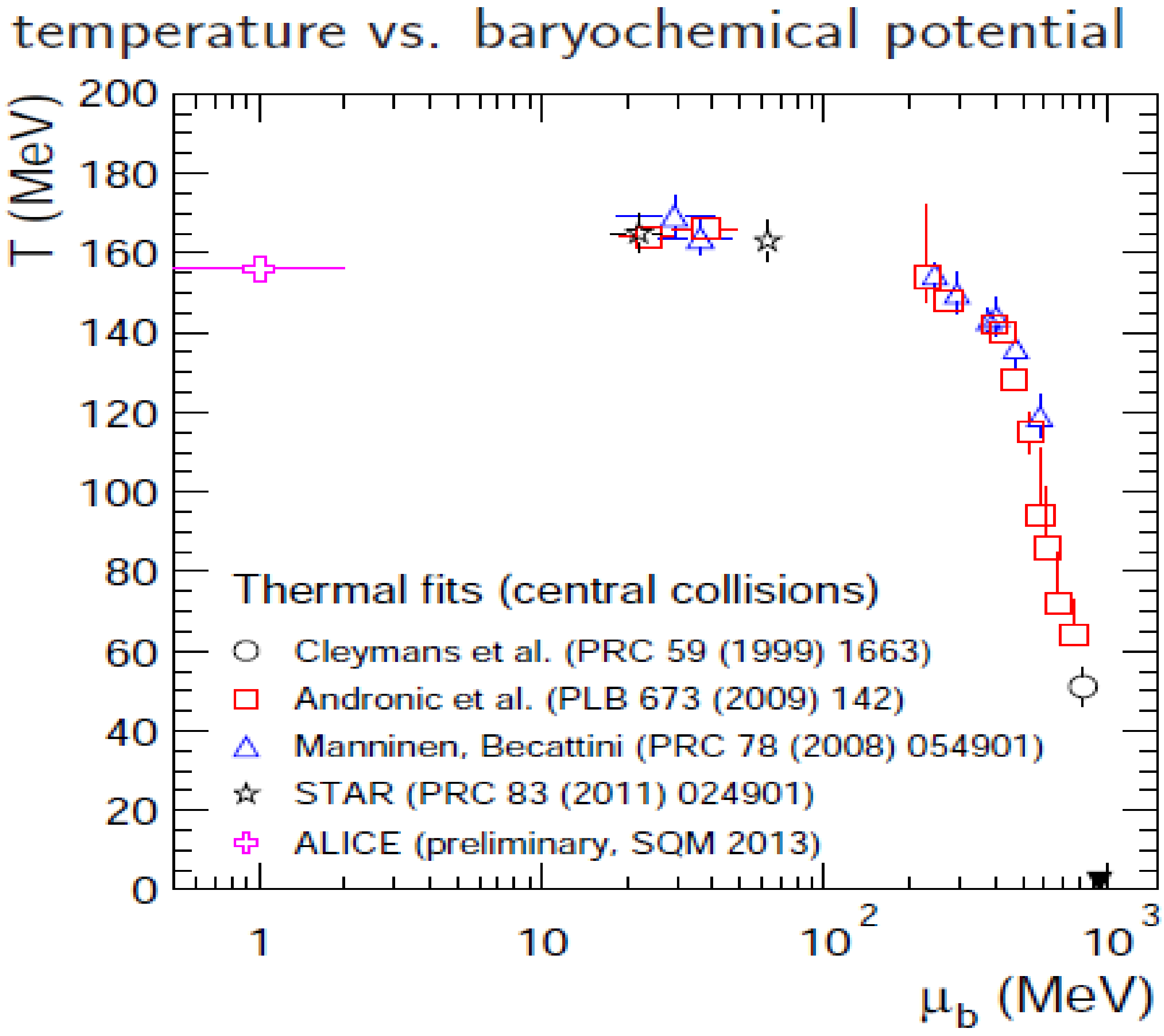
fit to data excluding protons





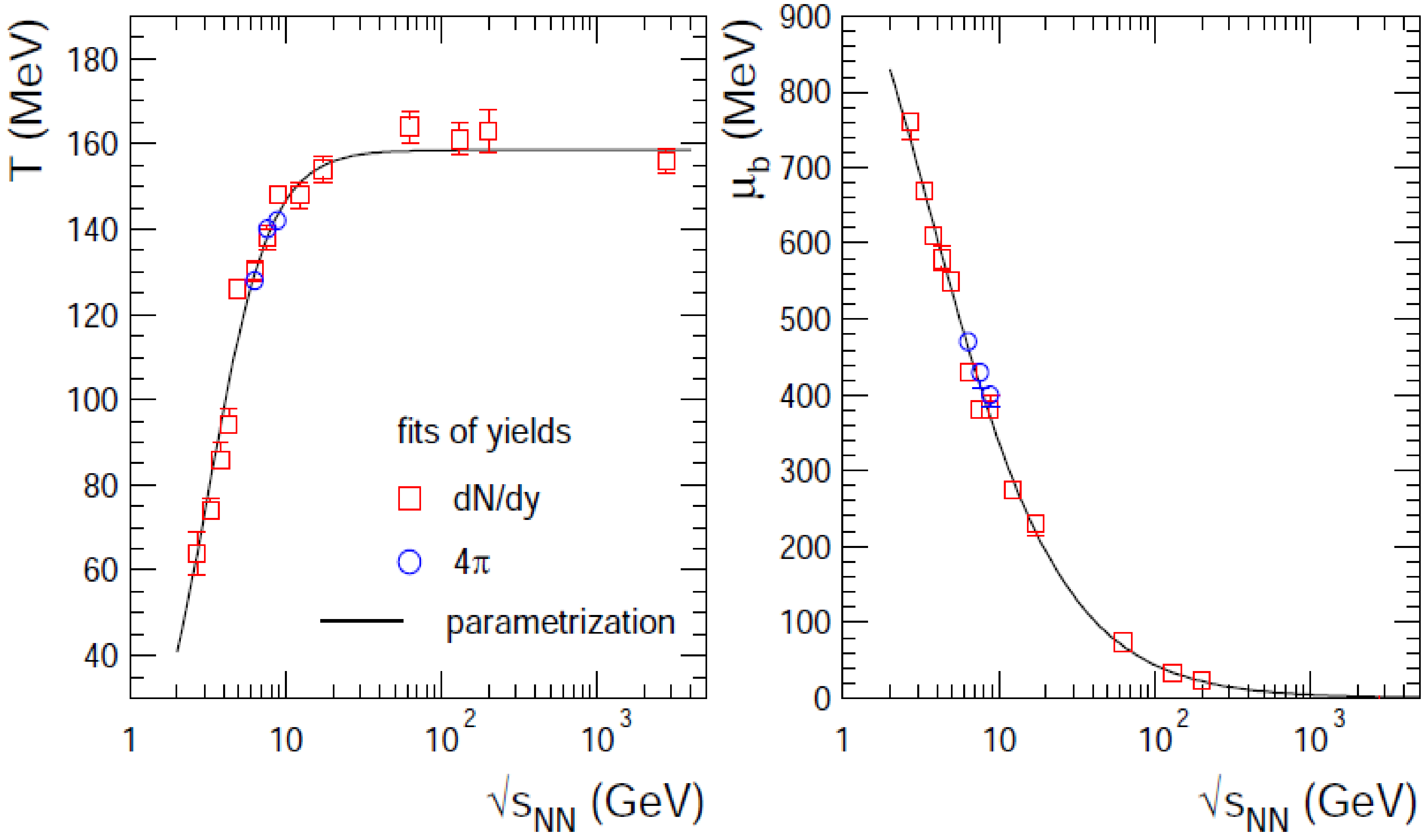
excellent fit, T = 158 MeV chi^2/ndf < 1

The newest T-mu plot including LHC data



Newest global fit

LHC data imply slightly lower T_{lim} compared to RHIC data extrapolations



where are we?

since QM2012, discrepancy between protons and thermal fit went from 7 sigma to 2.9 (2.7) sigma

T went from 152 to 156.5 MeV

fit without protons yields slighty higher T = 158 MeV, driven by hyperons

the 'proton anomaly' and production of light nuclei

can the measurement of d, t, 3He and 4He settle the issue?
what about hypertriton?

important to realize: production yield of deuterons is fixed at $T = T_{chem} = 156$ MeV even if $E_B(d) = 2.23$ MeV!

entropy/baryon is proportional to $-\ln(d/p)$ and is conserved after T_{chem}

good agreement with LHC d and hyper-triton yield implies: there is no shortage of protons and neutrons at chemical freeze-out, inconsistent with annihilation scenario

The thermal model and loosely bound, fragile objects

successful description of production yields for d, d_bar, 3He
hypertriton, …
implies no entropy production after chemical freeze-out

hypertriton binding energy is 130 keV << T_chem = 156 MeV

use relativistic nuclear collision data and thermal model
predictions to search for exotic objects

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stoecker, Production of light nuclei, hypernuclei and their antiparticles in relativistic nuclear collisions, Phys. Lett. B697 (2011) 203, arXiv:1010.2995 [nucl-th].

Some historical context on cluster production in relativistic nuclear collisions

P.J. Siemens and J.I. Kapusta, Phys. Rev. Lett. 43 (1979) 1486.

here the provocative statement was made that cluster formation probability is determined by the entropy of the fireball in its compressed state, i.e. for example:

entropy/baryon is proportional to -ln(d/p)

ENTROPY AND CLUSTER PRODUCTION IN NUCLEAR COLLISIONS

László P. CSERNAI* and Joseph I. KAPUSTA

PHYSICS REPORTS (Review Section of Physics Letters) 131, No. 4 (1986) 223–318.

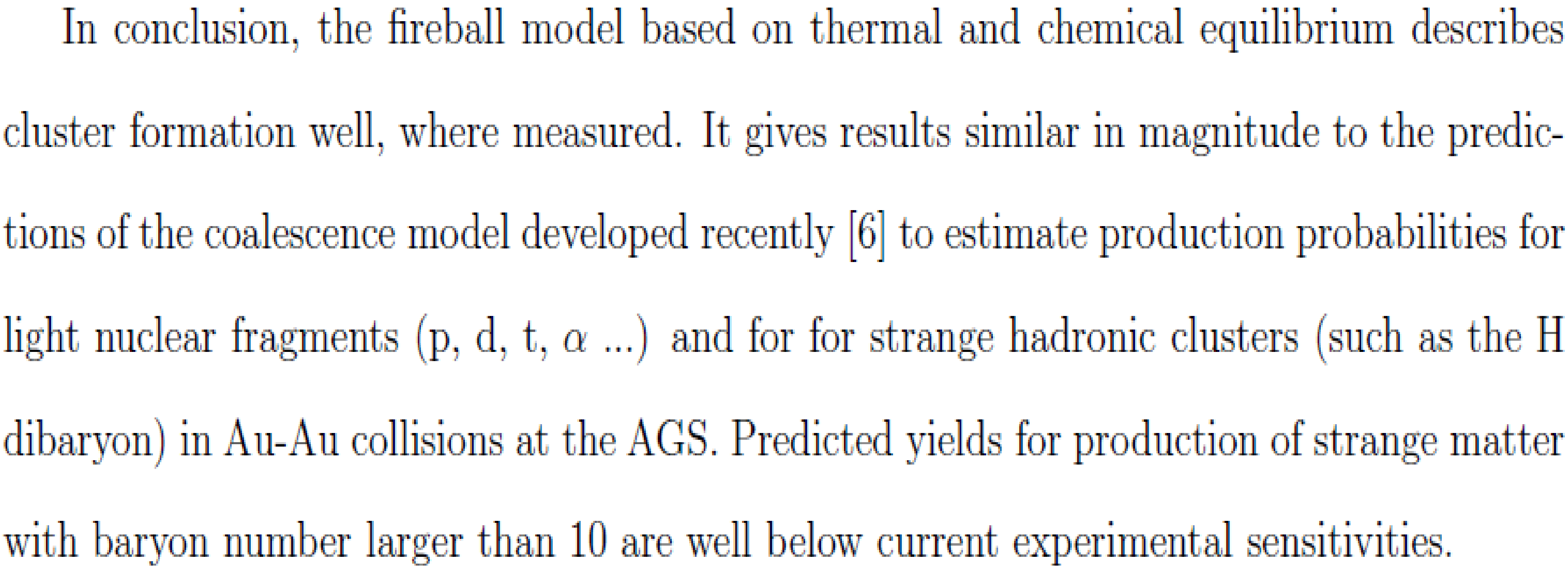
Very concise summary, including an elucidation of the relation between thermal fireball model and coalescence model

The 'snowball in hell' story

Production of strange clusters and strange matter in nucleus-nucleus collisions at the AGS

P. Braun-Munzinger, J. Stachel (SUNY, Stony Brook). Dec 1994. 9 pp.

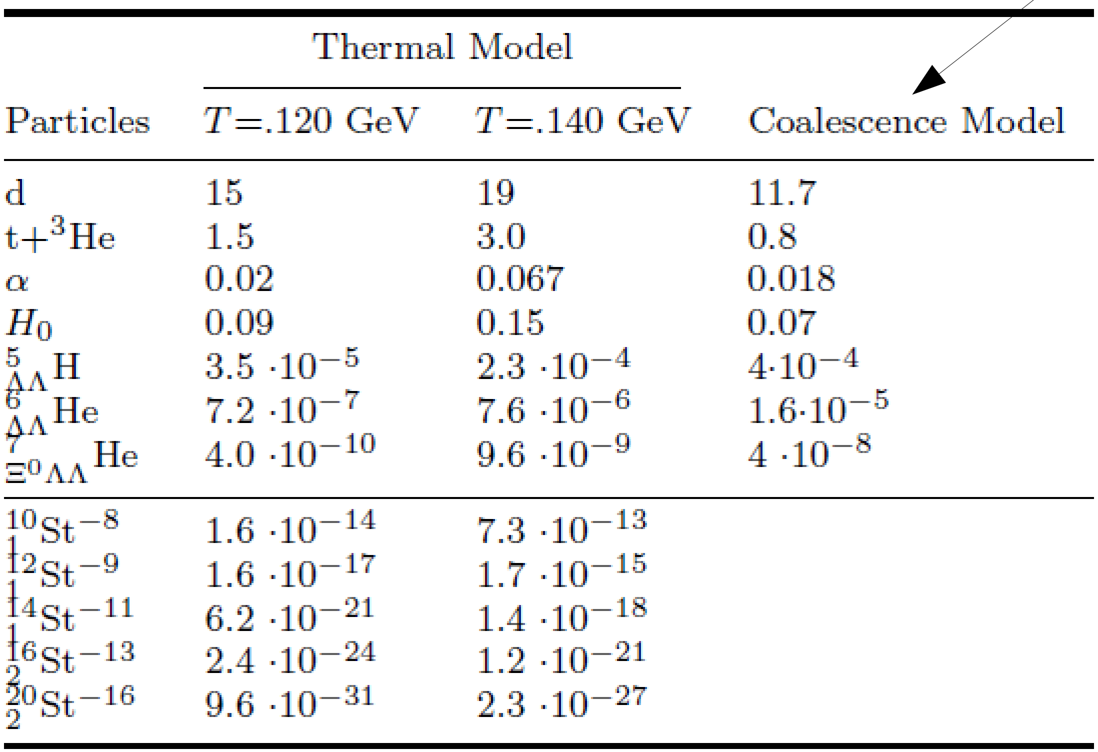
Published in J.Phys. G21 (1995) L17-L20



In conclusion, the fireball model based on thermal and chemical equilibrium describes cluster formation well, where measured. It gives results similar in magnitude to the predictions of the coalescence model developed recently [6] to estimate production probabilities for light nuclear fragments (p, d, t, α ...) and for for strange hadronic clusters (such as the H dibaryon) in Au-Au collisions at the AGS. Predicted yields for production of strange matter with baryon number larger than 10 are well below current experimental sensitivities.

Thermal vs coalescence model predictions for the production of loosely bound objects in central Au—Au collisions

A.J. Baltz, C.B. Dover, et al., Phys. Lett. B315 (1994) 7



	Thermal Model		
Particles	T=.120 GeV	T=.140 GeV	Coalescence Model
d	15	19	11.7
t+^{3}He	1.5	3.0	0.8
α	0.02	0.067	0.018
H_0	0.09	0.15	0.07
$^{5}_{\Lambda\Lambda}$H	$3.5 \cdot 10^{-5}$	$2.3 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
$^{6}_{\Lambda\Lambda}$He	$7.2 \cdot 10^{-7}$	$7.6 \cdot 10^{-6}$	$1.6 \cdot 10^{-5}$
$^{7}_{\Xi^0\Lambda\Lambda}$He	$4.0 \cdot 10^{-10}$	$9.6 \cdot 10^{-9}$	$4 \cdot 10^{-8}$
$^{10}_{1}\mathrm{St}^{-8}$	$1.6 \cdot 10^{-14}$	$7.3 \cdot 10^{-13}$	
$^{12}_{1}\mathrm{St}^{-9}$	$1.6 \cdot 10^{-17}$	$1.7 \cdot 10^{-15}$	
$^{14}_{1}\mathrm{St}^{-11}$	$6.2 \cdot 10^{-21}$	$1.4 \cdot 10^{-18}$	
$^{16}_{2}\mathrm{St}^{-13}$	$2.4 \cdot 10^{-24}$	$1.2 \cdot 10^{-21}$	
$^{20}_{2}\mathrm{St}^{-16}$	$9.6 \cdot 10^{-31}$	$2.3 \cdot 10^{-27}$	

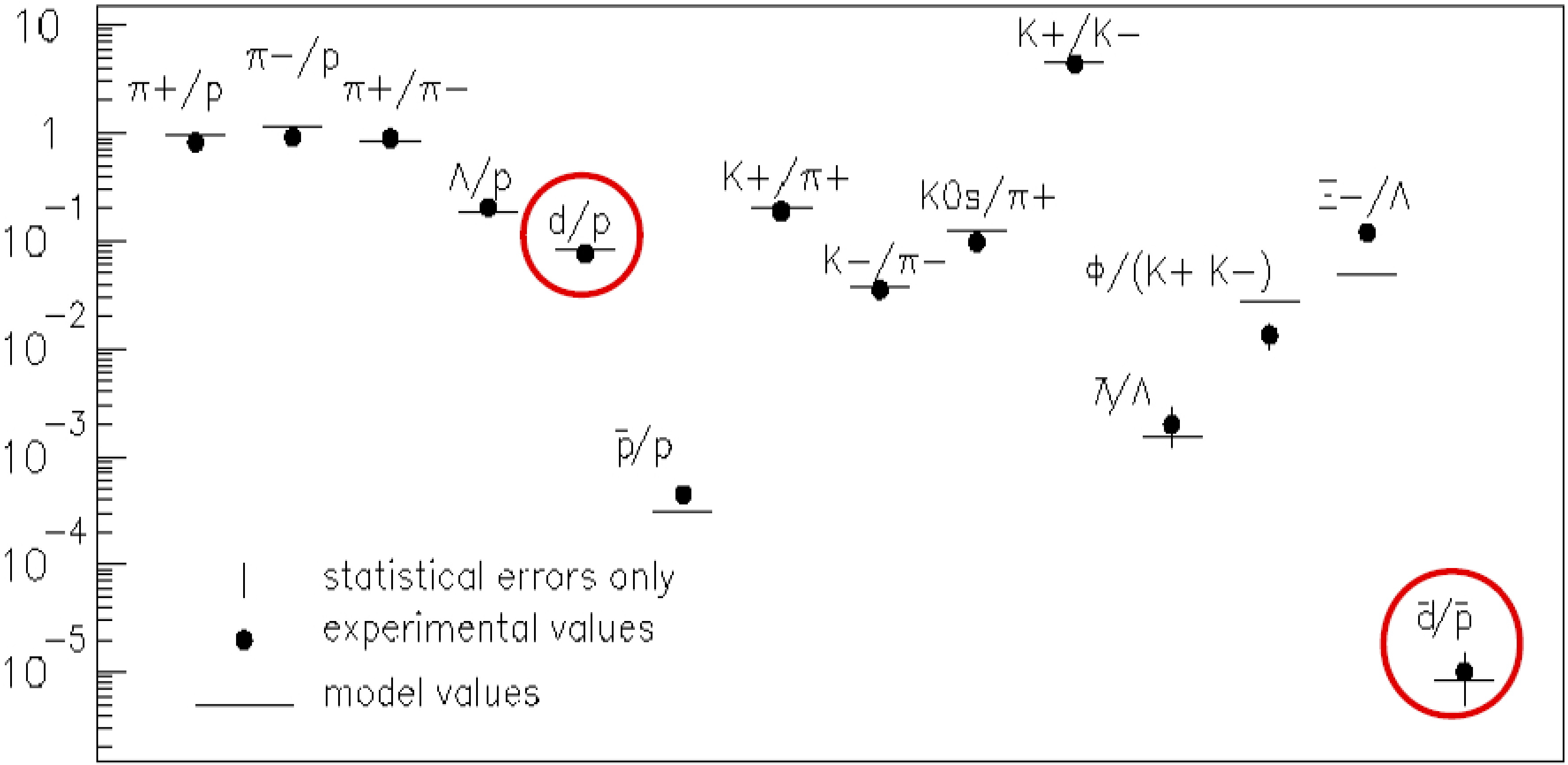
P. Braun-Munzinger, J. Stachel, J. Phys. G **28** (2002) 1971 [arXiv:nucl-th/0112051]

J.Phys. G21 (1995) L17-L20

deuterons and anti-deuterons also well described at AGS energy

14.6 A GeV/c central Si + Au collisions and GC statistical model

P. Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu, PLB 1994



dynamic range: 9 orders of magnitude! No deviation

Thermal model and production of light nuclei at AGS energy

data cover 10 oom!

addition of every nucleon

-> penalty factor $R_p = 48$

but data are at very low pt

use m-dependent slopes following

systematics up to deuteron

-> $R_p = 26$

GC statistical model:

$R_p \approx \exp[(m_n \pm \mu_b)/T]$

for T=124 MeV and $\mu_b = 537$ MeV

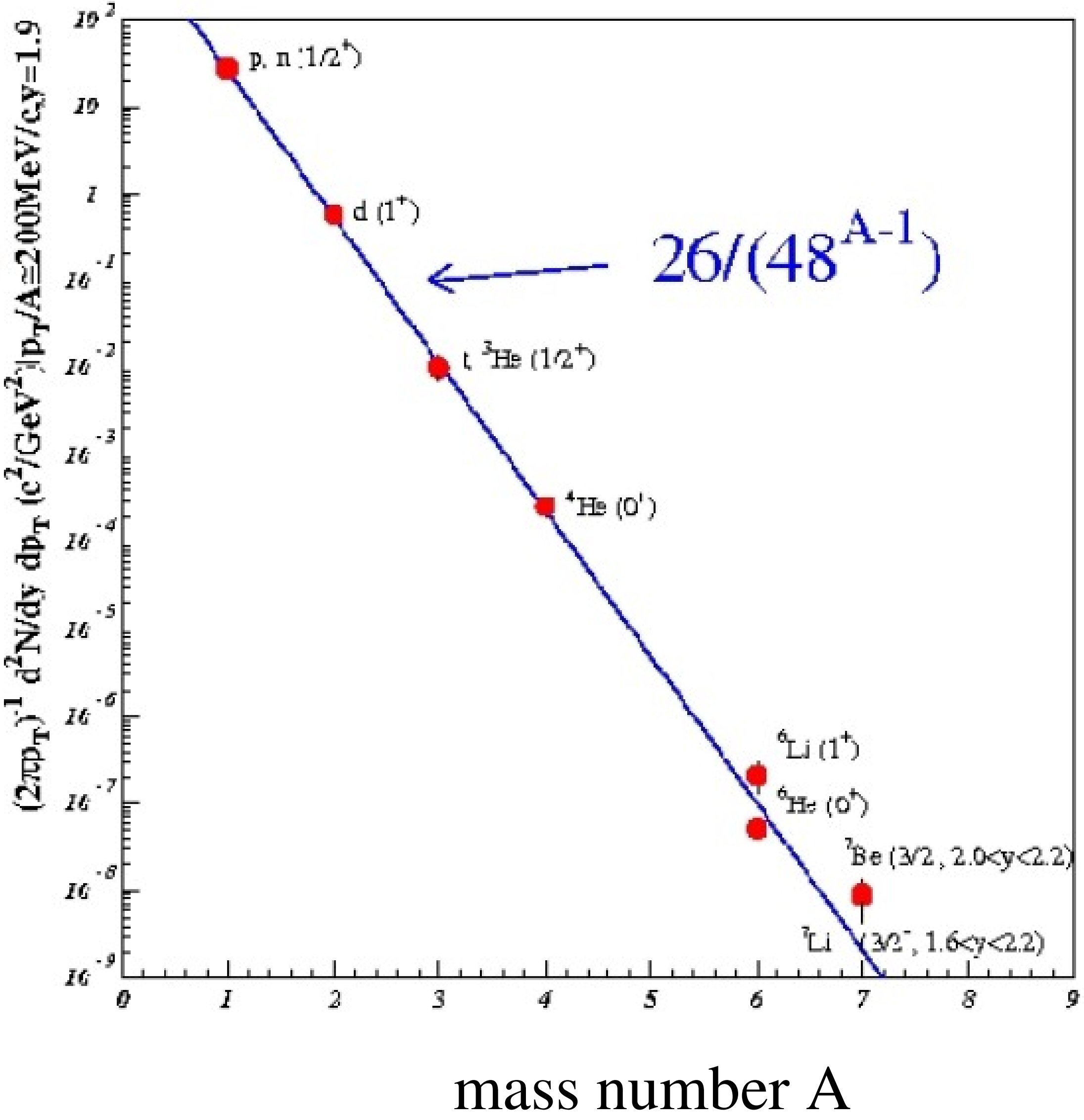
$R_p = 24$ good agreement

also good for **antideuterons**:

data: $R_p = 2 \pm 1 \cdot 10^5$ SM: $1.3 \cdot 10^5$

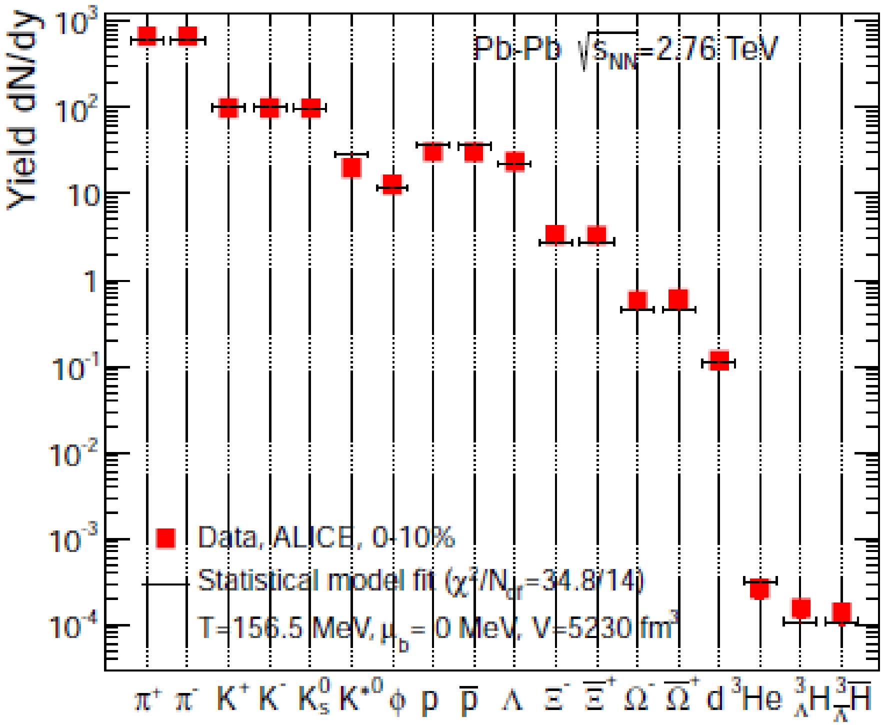
P. Braun-Munzinger, J. Stachel,
J. Phys. G28 (2002) 1971

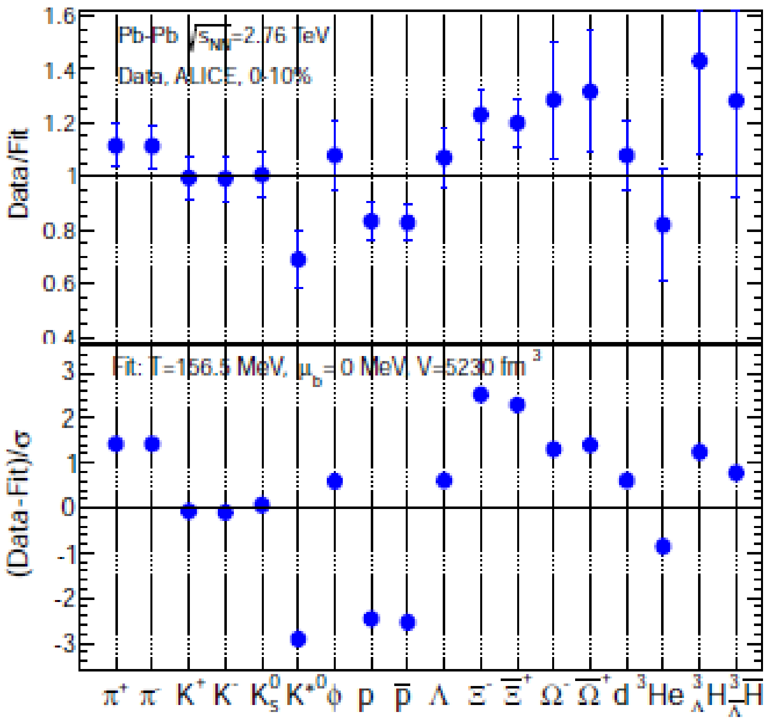
E864 Coll., Phys. Rev. C61 (2000) 064908



update April 2014 incl. 3He

LHC, Pb–Pb, 0-10%





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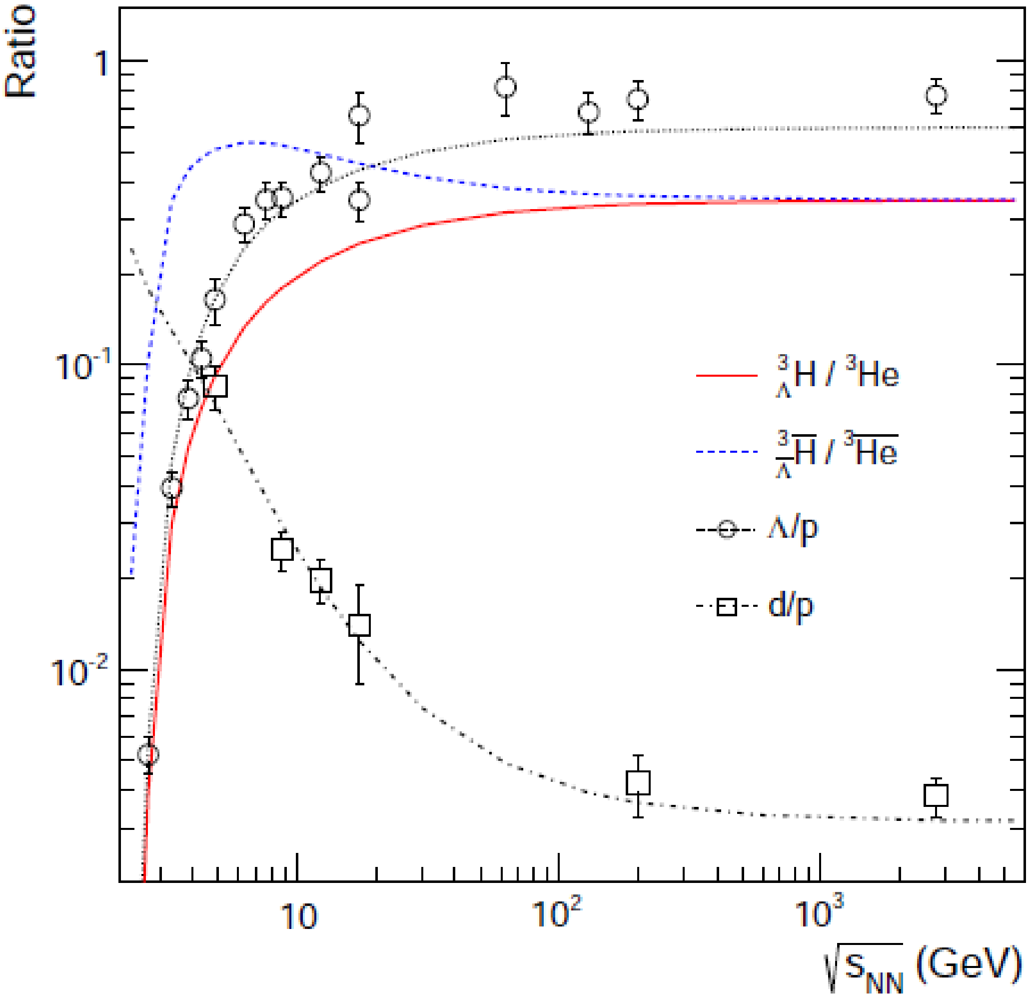
energy dependence of d/p ratio and thermal model prediction



agreement between thermal model calculations and data from Bevalac/SIS18 to LHC energy

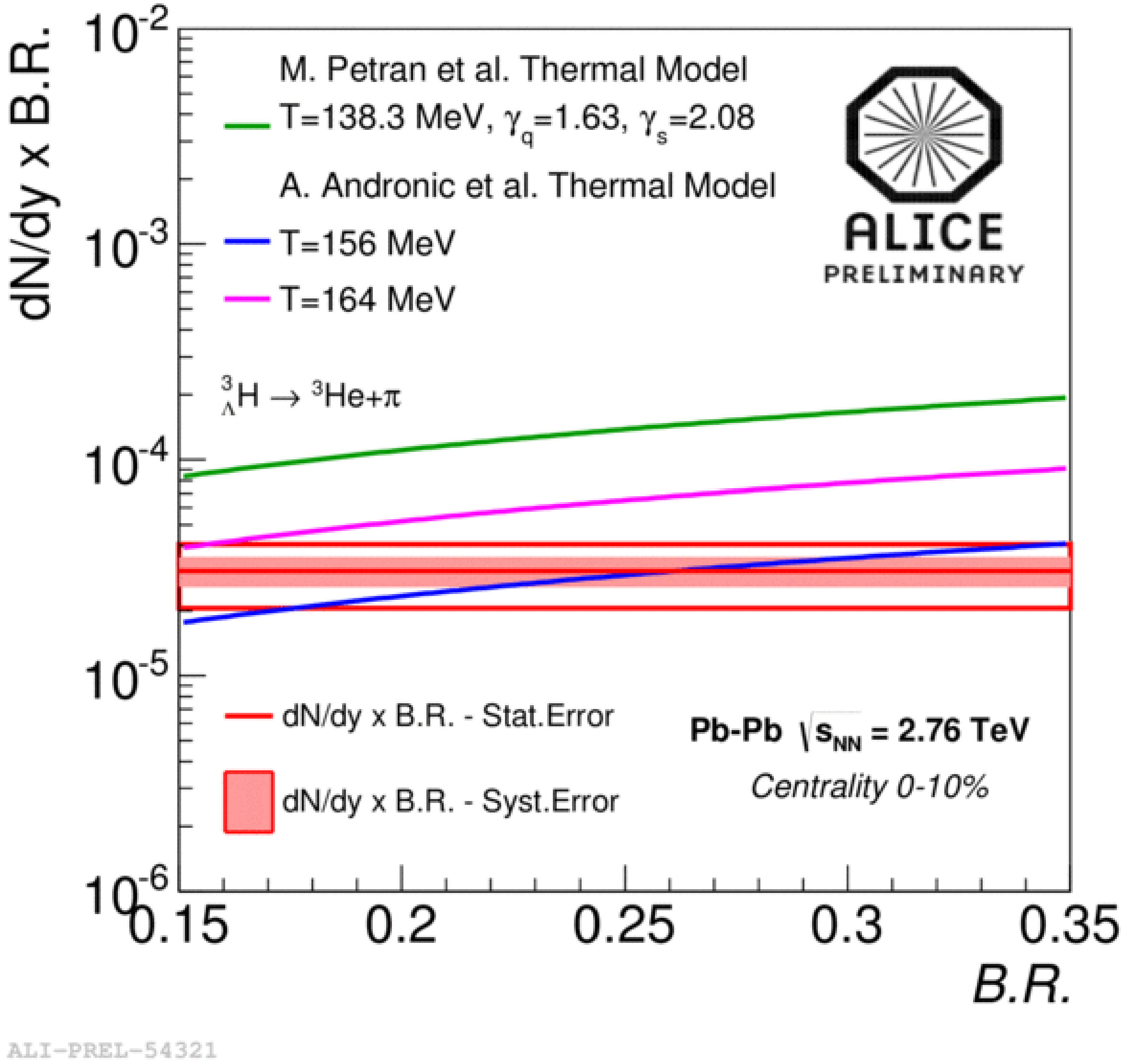
A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stoecker, Phys. Lett. B697 (2011) 203, arXiv:1010.2995 [nucl-th].

loosely bound objects are formed at chemical freeze-out very near the phase boundary

implies that chemical freeze-out is followed by an isentropic expansion

no appreciable annihilation in the hadronic phase

Hypertriton yield x branching ratio and the thermal model

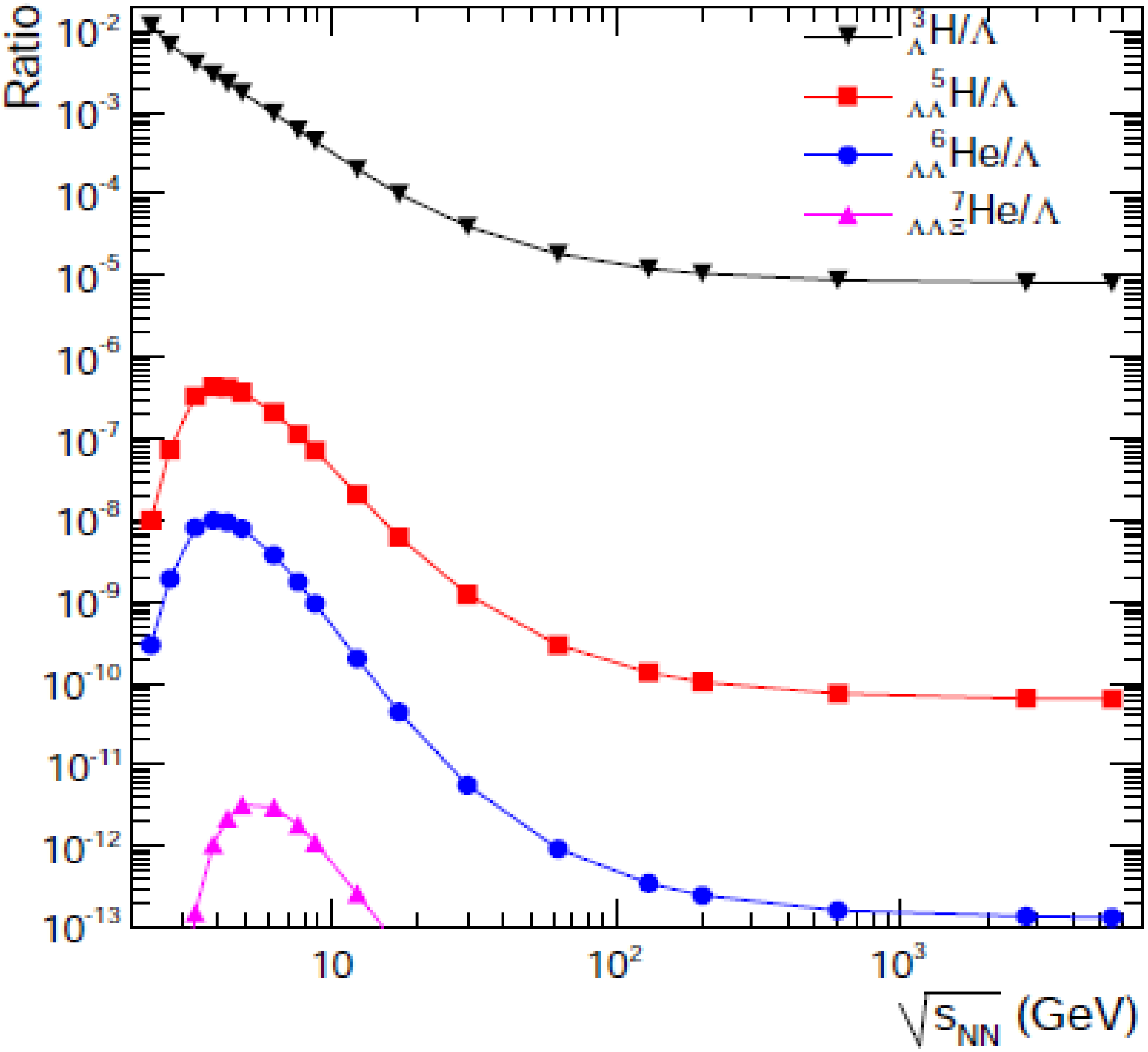


analysis spearheaded by Ramona Lea, ALICE

T = 156 MeV provides very good description

Note: binding energy of hypertriton is 130 keV!!
Most likely B.R. = 0.25 (also used by STAR)

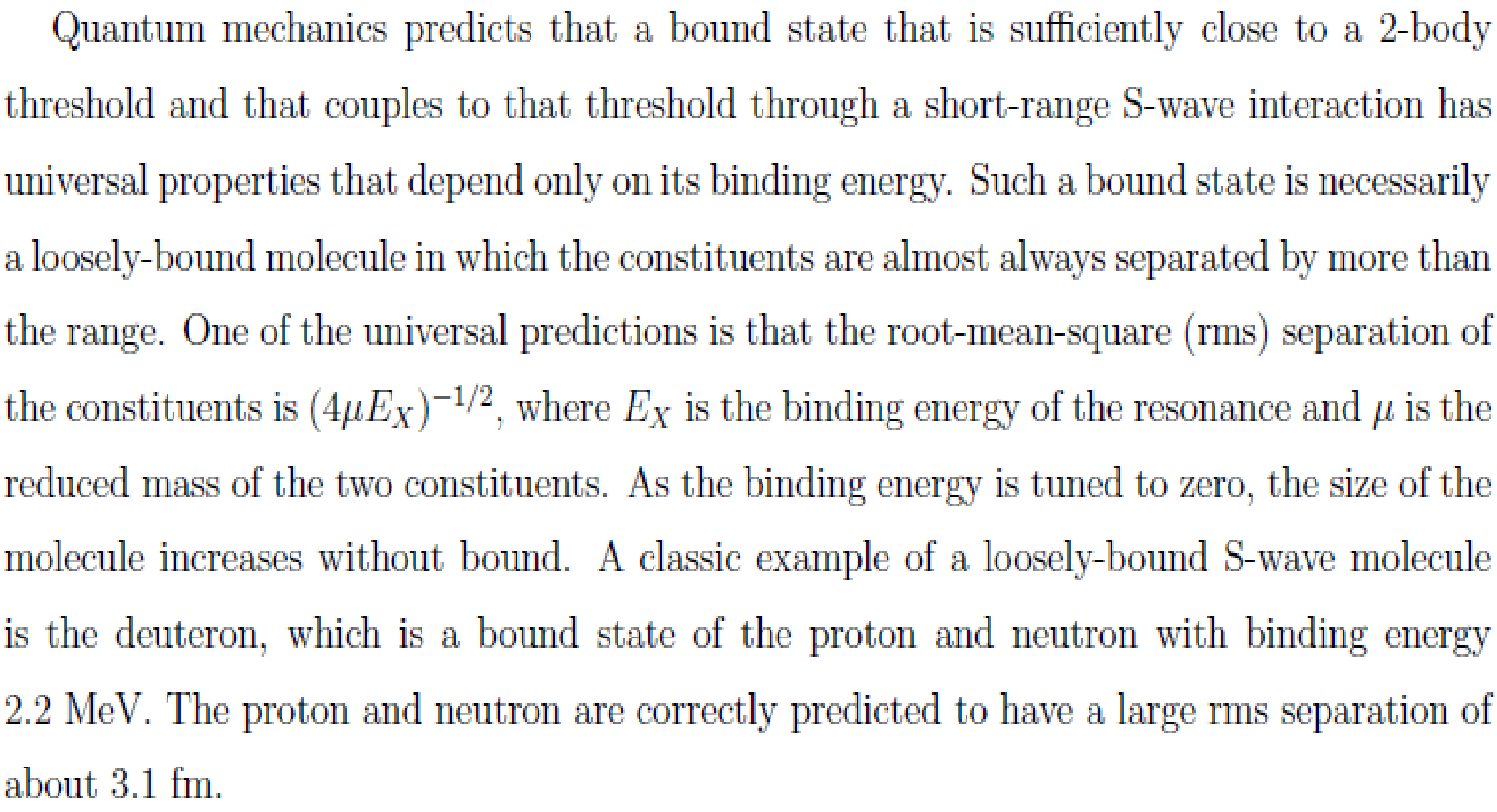
Energy dependence of the yields of exotic objects



note: yield peaks at low (SIS100) energies
an exciting but tough prospect for FAIR

The size of loosely bound molecular objects

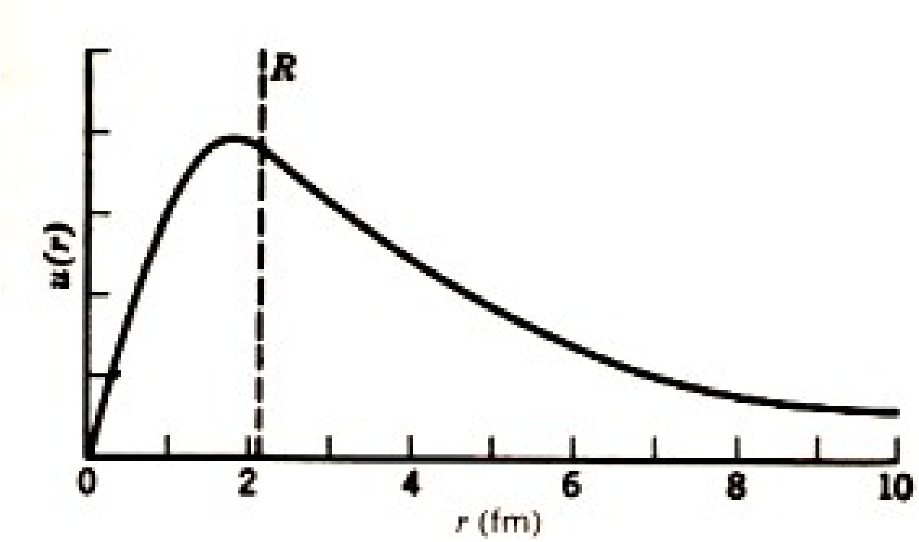
Examples: deuteron, hypertriton, XYZ 'charmonium states, molecules near Feshbach resonances in cold quantum gases



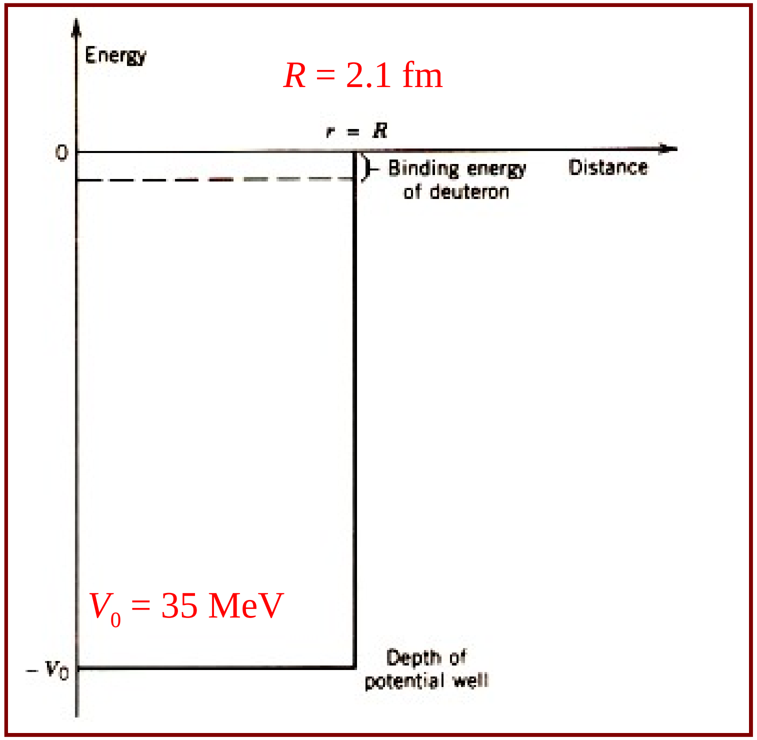
Quantum mechanics predicts that a bound state that is sufficiently close to a 2-body threshold and that couples to that threshold through a short-range S-wave interaction has universal properties that depend only on its binding energy. Such a bound state is necessarily a loosely-bound molecule in which the constituents are almost always separated by more than the range. One of the universal predictions is that the root-mean-square (rms) separation of the constituents is $(4\mu E_X)^{-1/2}$, where E_X is the binding energy of the resonance and μ is the reduced mass of the two constituents. As the binding energy is tuned to zero, the size of the molecule increases without bound. A classic example of a loosely-bound S-wave molecule is the deuteron, which is a bound state of the proton and neutron with binding energy 2.2 MeV. The proton and neutron are correctly predicted to have a large rms separation of about 3.1 fm.

Artoisenet and Braaten, arXiv:1007.2868

The deuteron as a loosely bound object



Mass = 1875 MeV
B.E. = 2.23 MeV
rms radius = 3 fm > range of potential



The Hypertriton

mass = 2.990 MeV

B.E. = 0.13 MeV

molecular structure: (p+n) + Lambda

2-body threshold: (p+p+n) + pi- = ^{3}He + pi-

rms radius = (4 B.E. M_{red})$^{-1/2}$ = 10.3 fm =
rms separation between d and Lambda

in that sense: hypertriton = (p n Lambda) =
(d Lambda) is the ultimate halo state

yet production yield is fixed at 156 MeV
temperature (about 1000 x E.B.)

The X(3872)

mass is below threshold of (D^{*0} D^{0}_{bar}) by (0.42 +/- 0.39) MeV

rms separation = 3.5 – 18.3 fm   structure: $D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}$

should be able to predict the X(3872) production probability in pp collisions at LHC energy with an accuracy of about 30%, uncertainty is due to not very precisely known number of charm quarks

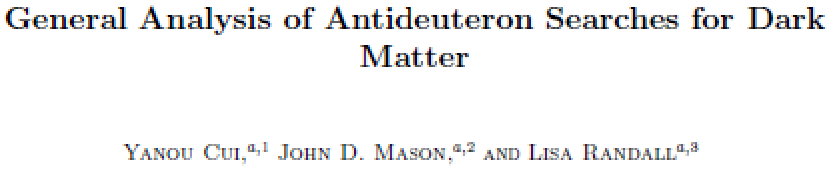
result ready shortly

deuteron and anti-deuteron production in pp collisions at high energy
an important background for dark matter searches

Heavy dark matter states DM can decay via

$DM \rightarrow d\, d_{bar} + X$

Major experiments such as AMS-02 and GAPS search for anti-deuterons in cosmic rays



General Analysis of Antideuteron Searches for Dark Matter

Yanou Cui,[a,1] John D. Mason,[a,2] and Lisa Randall[a,3]

arXiv:1006.0983

background yield from $p + H \rightarrow d_{bar} + X$ and $p + He \rightarrow d_{bar} + X$ should also be well described (better than 50 % accuracy, much better than current coalescence estimates) within thermal model

Summary - part a

the Pb-Pb central collision hadron yields from LHC run1 are well described by assuming equilibrated matter at T = 156 MeV and mu_b < 1 MeV

the original > 7 sigma proton anomaly is now 2.9 (2.7) sigma

success to describe also yields of loosely bound states provides strong evidence for isentropic expansion after chemical freeze-out

These results should be very useful also for dark matter searches and the nature of XYZ states

overall the LHC data provide strong support for chemical freeze-out driven by the (cross over) phase transition at T_c = 156 MeV

The thermal model is alive and well

Exciting prospects for study of loosely bound objects

Lecture 1

b) heavy flavors – a hard probe

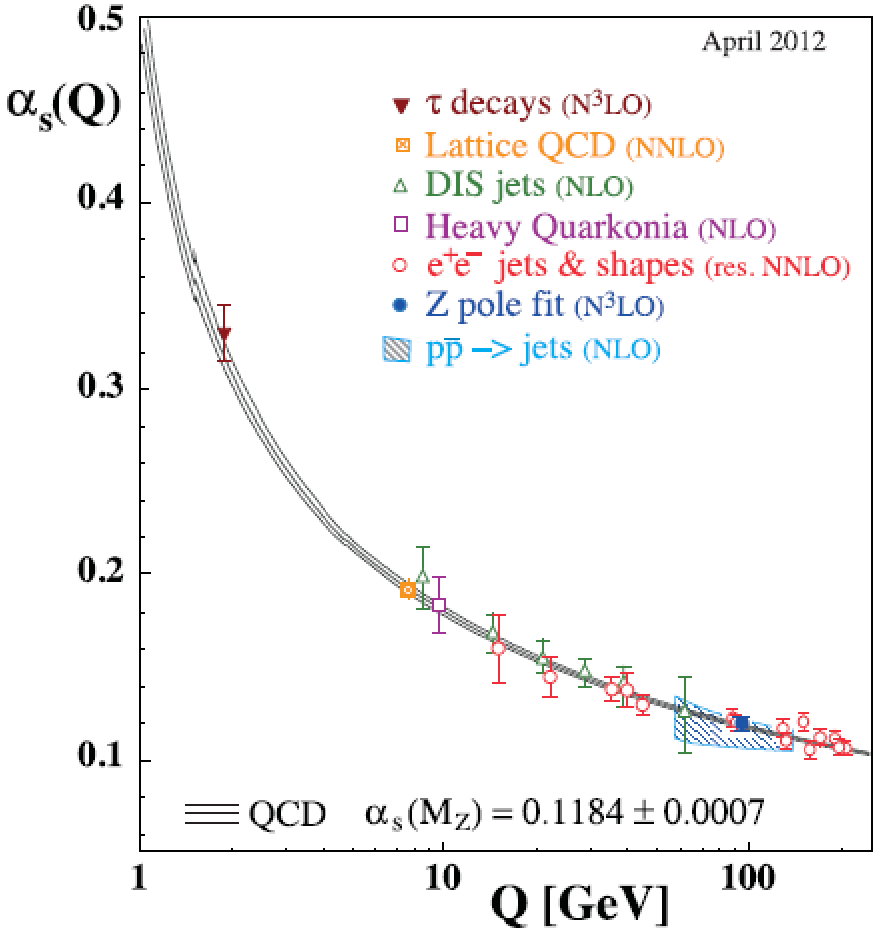
- reminder of basics
- discussion of time scales and open charm conservation equation
- results for RHIC and LHCenergy in pp collisions
- results for RHIC and LHC energy in AA collisions
- an aside on photon production

what are 'hard probes'?

Hard probes are observables which involve an energy or mass scale Q^2 >> (Lambda_QCD)^2

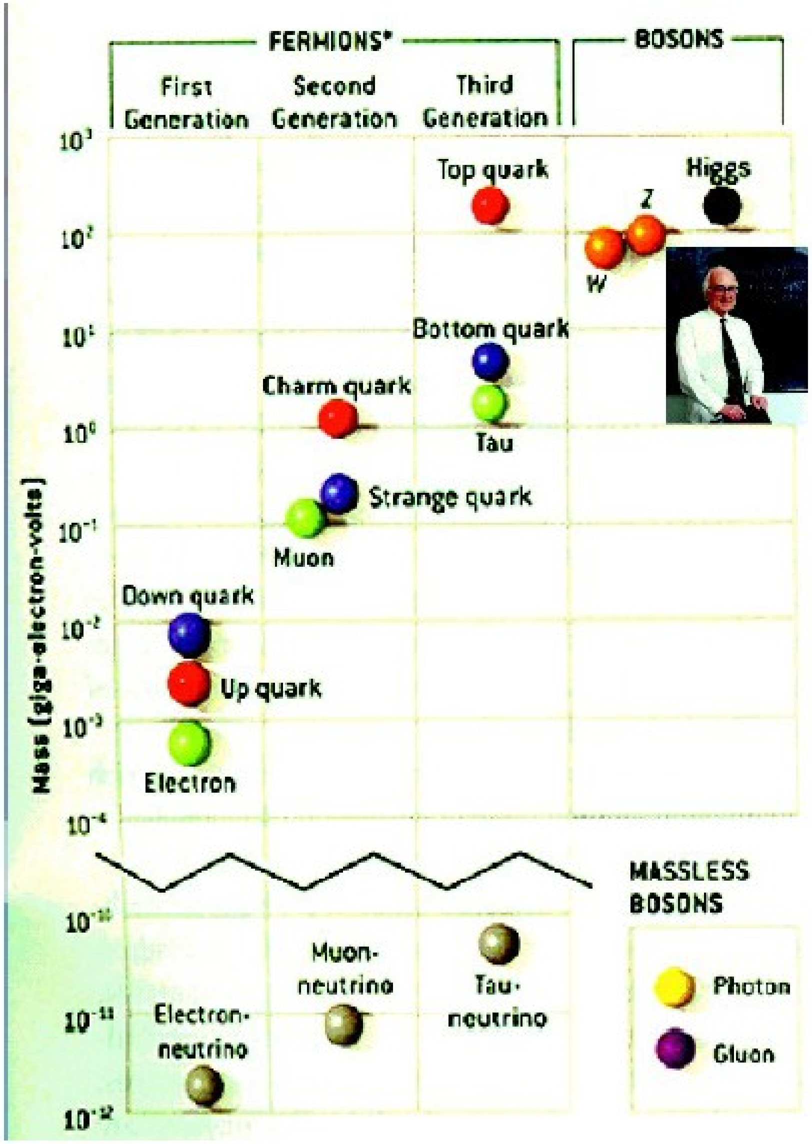
$$\alpha_s(Q^2) = \frac{1}{\beta_0 \ln(Q^2/\Lambda^2)}$$

$$\Lambda \approx 0.1 \text{ GeV for } \alpha_s(M_{Z^0} \equiv 91.2 \text{ GeV}) = 0.12$$



for such processes, production can be precisely computed in pQCD

in QGP physics, we are interested in studying their propagation in and interaction with the QGP medium


FERMIONS*
BOSONS
First Generation
Second Generation
Third Generation
Mass (giga-electron-volts)
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻¹⁰
10⁻¹¹
10⁻¹²
Top quark
Higgs
Z
W
Bottom quark
Charm quark
Tau
Strange quark
Muon
Down quark
Up quark
Electron
MASSLESS BOSONS
Muon-neutrino
Tau-neutrino
Electron-neutrino
Photon
Gluon

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Remarks on production of open charm and charmonia

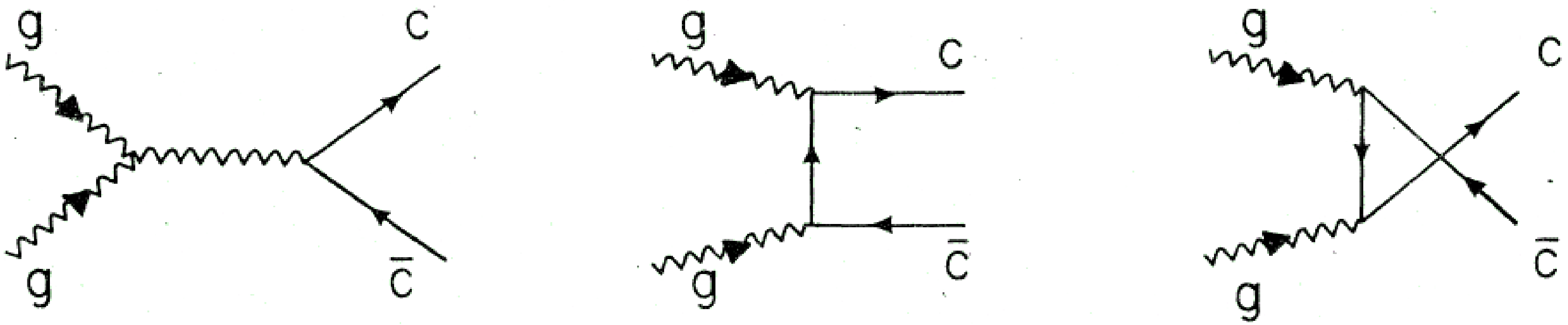
- charm quark mass >> Λ_{QCD} production described in QCD perturbation theory
- all calculations employ gluon fusion as starting point
- argument is energy independent until global energy conservation very close to threshold becomes important
- production of charm quark pairs takes place at timescale $1/m_c$

  $m_c = 1.5$ GeV --> $t_c = 0.13$ fm
- to build up wave function of mesons including those with open charm needs about t = 1fm --> charm production and charmed hadron formation are decoupled
- overall cross section is due to production of charm quark pairs
- time scale is much too short to dress the charm quarks essential to take current quarks

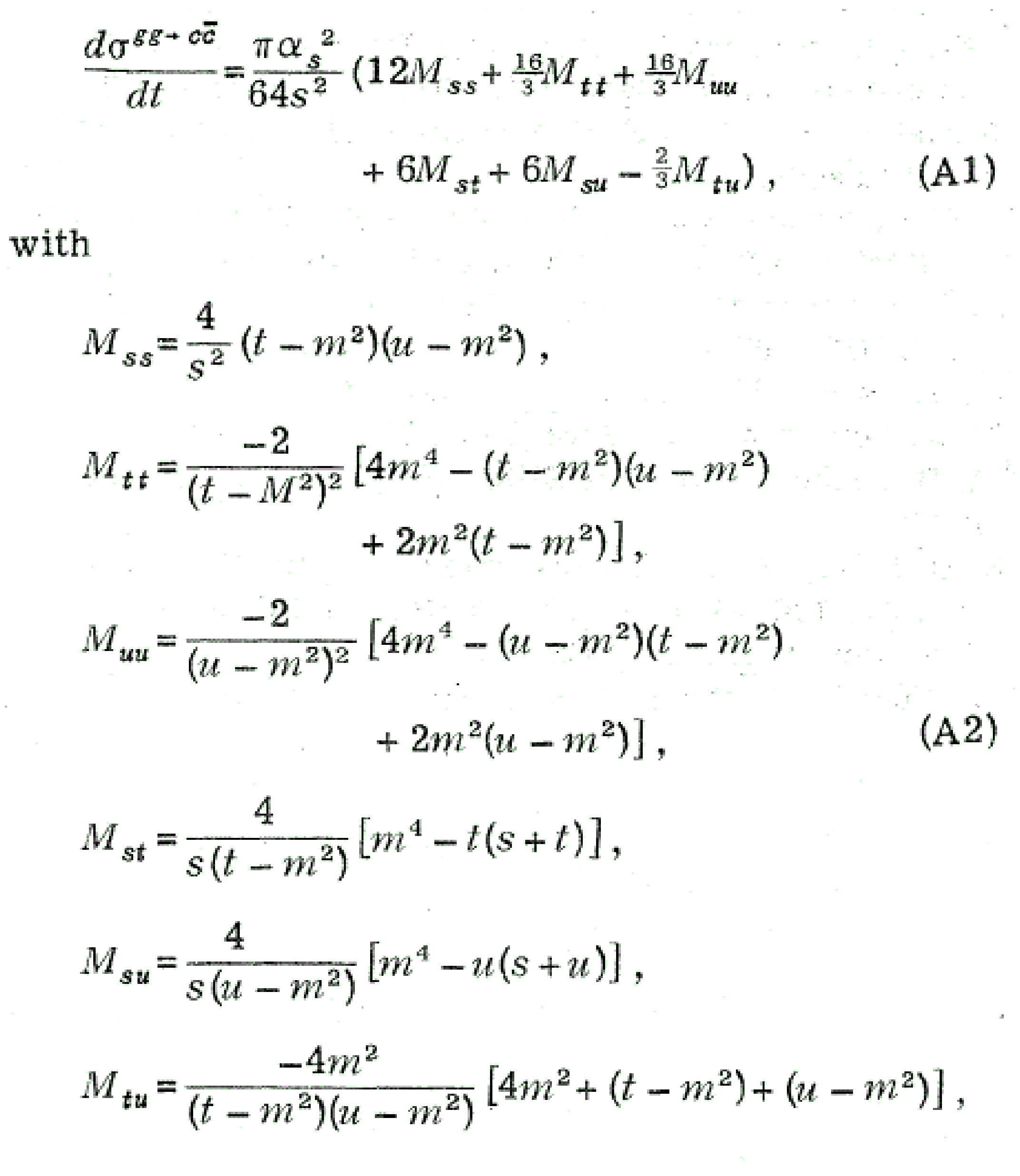
Cross section for charm production

based on M. Glueck, J. F. Owens, E. Reya,
Phys. Rev. D17 (1978) 2324

in leading order there are 3 important diagrams:



differential cross section



$$\frac{d\sigma^{gg\to c\bar{c}}}{dt}=\frac{\pi\alpha_s^{2}}{64s^2}\left(12M_{ss}+\tfrac{16}{3}M_{tt}+\tfrac{16}{3}M_{uu}\right.$$

$$\left.+\,6M_{st}+6M_{su}-\tfrac{2}{3}M_{tu}\right)\,, \qquad \text{(A1)}$$

with

$$M_{ss}=\frac{4}{s^2}(t-m^2)(u-m^2)\,,$$

$$M_{tt}=\frac{-2}{(t-M^2)^2}\left[4m^4-(t-m^2)(u-m^2)\right.$$

$$\left.+\,2m^2(t-m^2)\right]\,,$$

$$M_{uu}=\frac{-2}{(u-m^2)^2}\left[4m^4-(u-m^2)(t-m^2)\right.$$

$$\left.+\,2m^2(u-m^2)\right]\,, \qquad \text{(A2)}$$

$$M_{st}=\frac{4}{s(t-m^2)}\left[m^4-t(s+t)\right]\,,$$

$$M_{su}=\frac{4}{s(u-m^2)}\left[m^4-u(s+u)\right]\,,$$

$$M_{tu}=\frac{-4m^2}{(t-m^2)(u-m^2)}\left[4m^2+(t-m^2)+(u-m^2)\right]\,,$$

total cross section

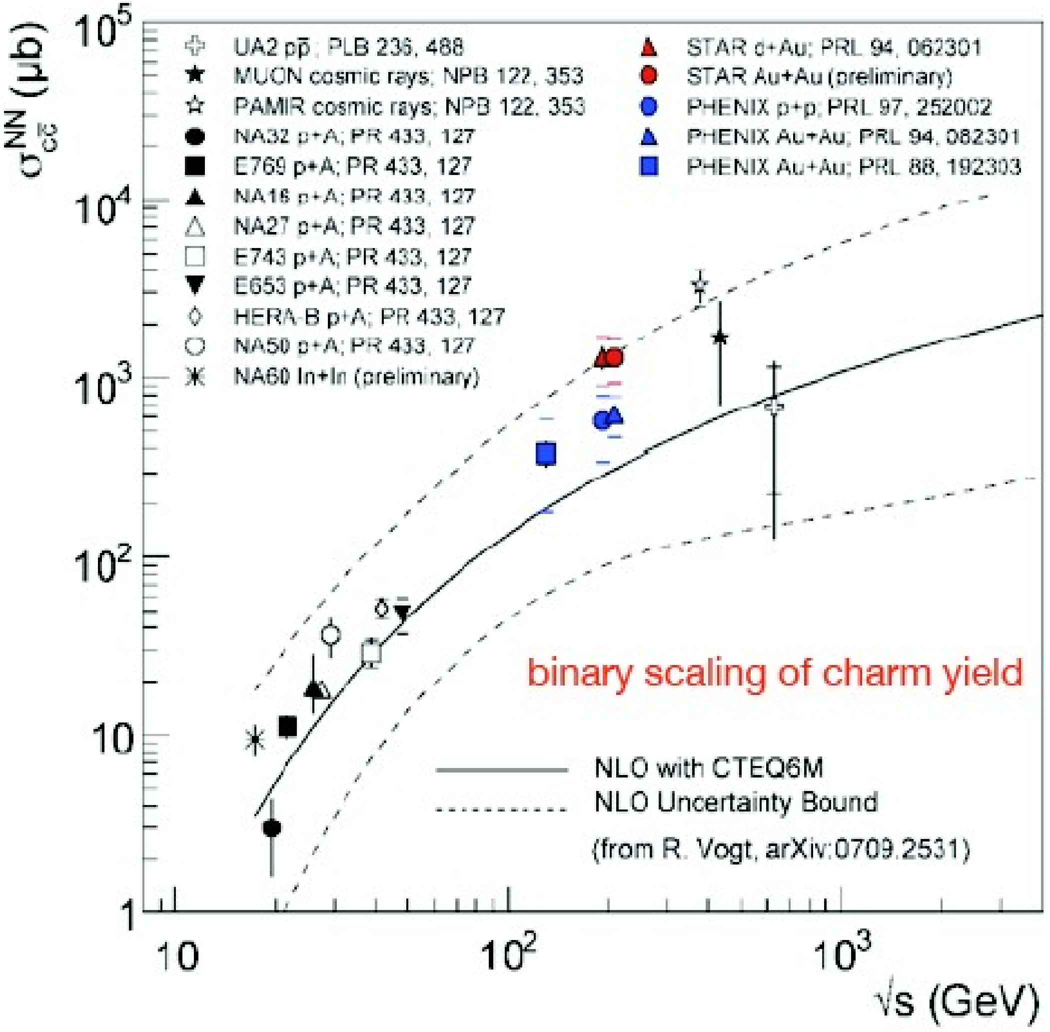
$$\sigma^{gg\to c\bar{c}} = \frac{\pi\alpha_s^{\,2}}{64s}\Bigg[12\left(\tfrac{2}{3}+\tfrac{1}{3}\gamma\right)(1-\gamma)^{1/2}+\tfrac{16}{3}\left((4+2\gamma)\ln\frac{1+(1-\gamma)^{1/2}}{1-(1-\gamma)^{1/2}}-4(1+\gamma)(1-\gamma)^{1/2}\right)$$

$$+\,6\left(2\gamma\ln\frac{1+(1-\gamma)^{1/2}}{1-(1-\gamma)^{1/2}}-4(1+\gamma)(1-\gamma)^{1/2}\right)-\tfrac{2}{3}2\gamma(1-\gamma)\ln\frac{1+(1-\gamma)^{1/2}}{1-(1-\gamma)^{1/2}}\Bigg]$$

with $\gamma \equiv 4m^2/s \leqslant 1$.

this result plus NLO/NNLO/FONLL corrections are currently the basis of all open charm calculations (see, e.g., the calculations by Cacciari et al., discussed below.

heavy quark production in pp collisions situation before LHC turned on



Measurement of open charm cross section in pp collisions at the LHC

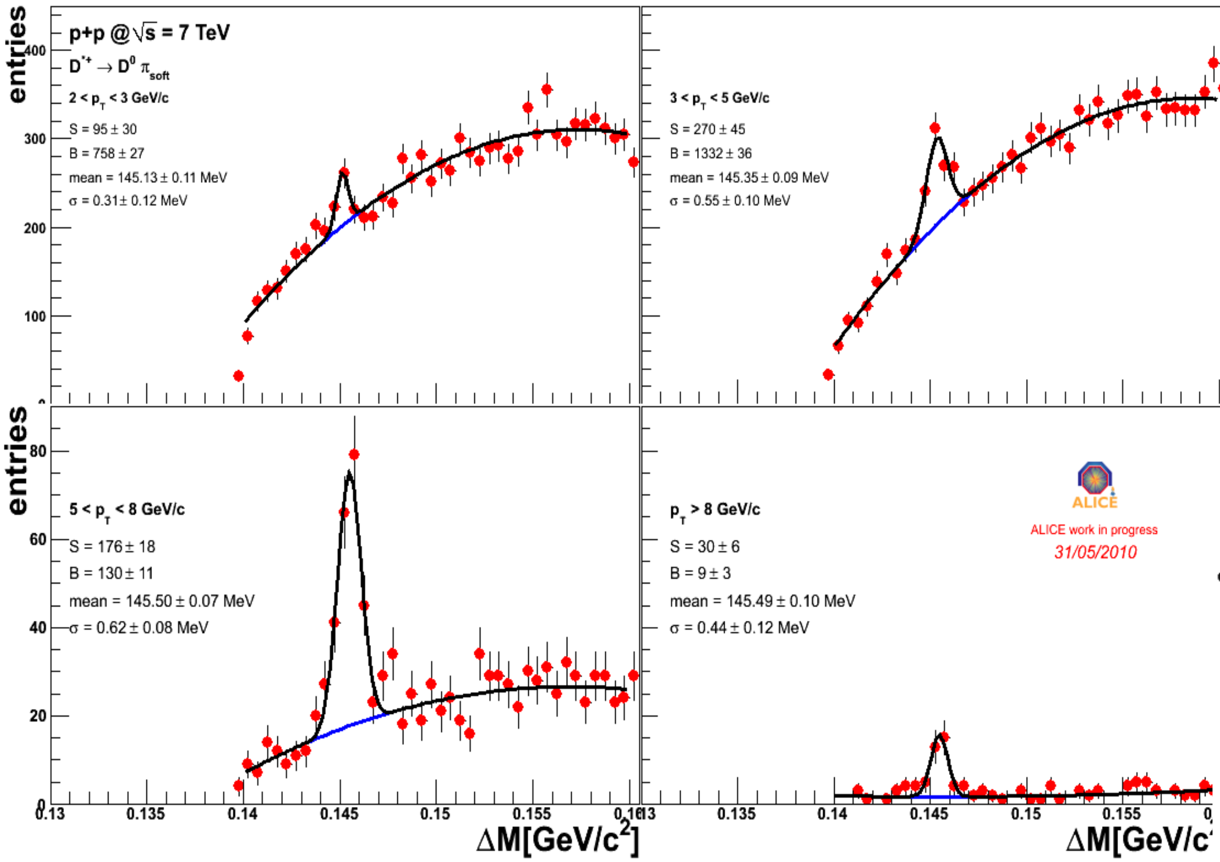
all LHC experiments contribute

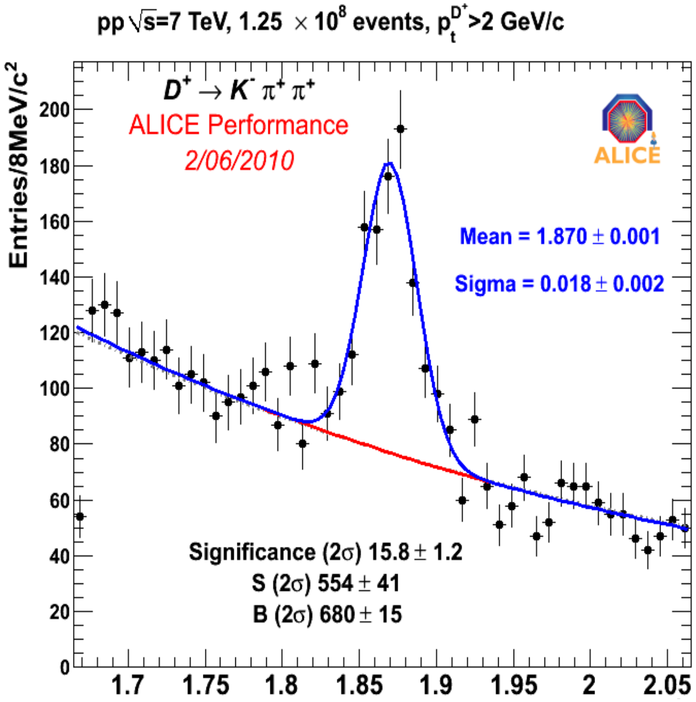
ALICE at $pt > 2$ GeV/c and $0 < y < 4$
ATLAS and CMS at $pt > 6$ GeV/c $0 < y < 2.5$
LHCb at $pt > 2$ GeV/c and $2.5 < y < 4$

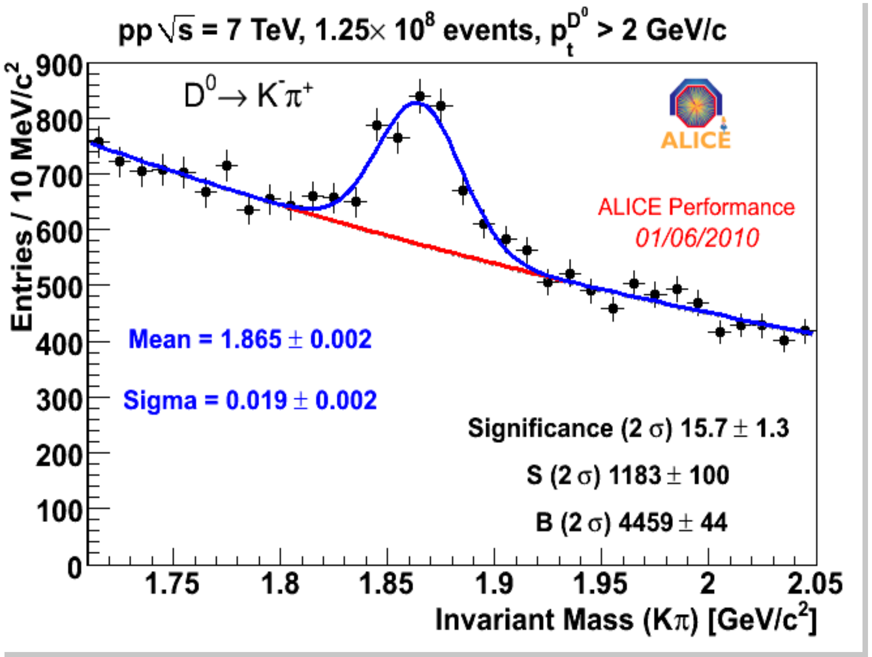
all detectors employ sophisticated Si vertex detectors

D^0, D^+ and D^{0*} in 7 TeV pp data

$1.25\ 10^8$ events

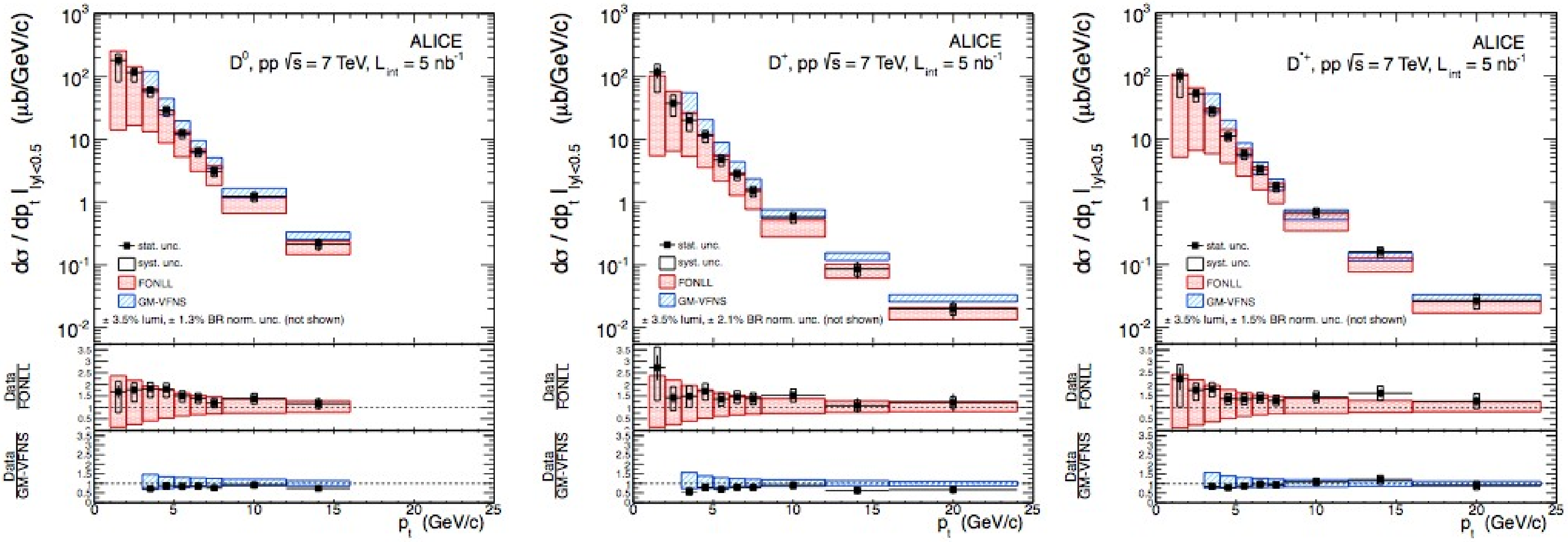






for 10^9 events, expect to measure open charm for $p_t = 0.5 – 15$ GeV/c

measurements agree well with state of the art pQCD calculations



JHEP1201(2012)128

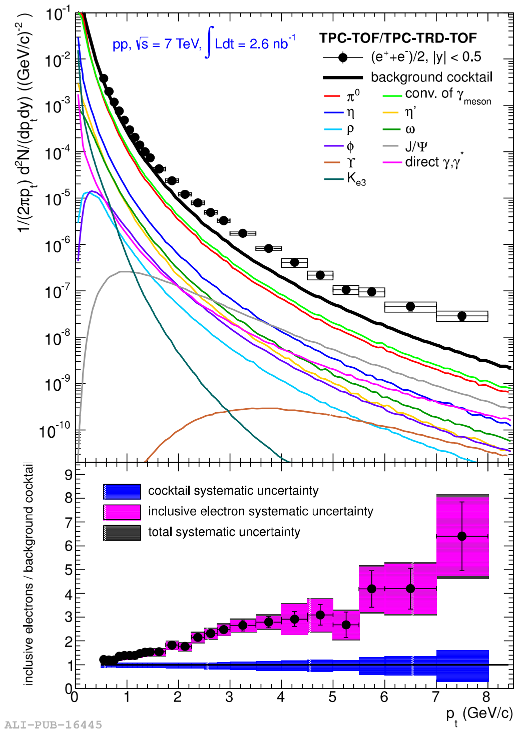
FONLL: Cacciari et al., arXiv:1205.6344
GM-VFNS: Kniehl et al., arXiv:1202.0439

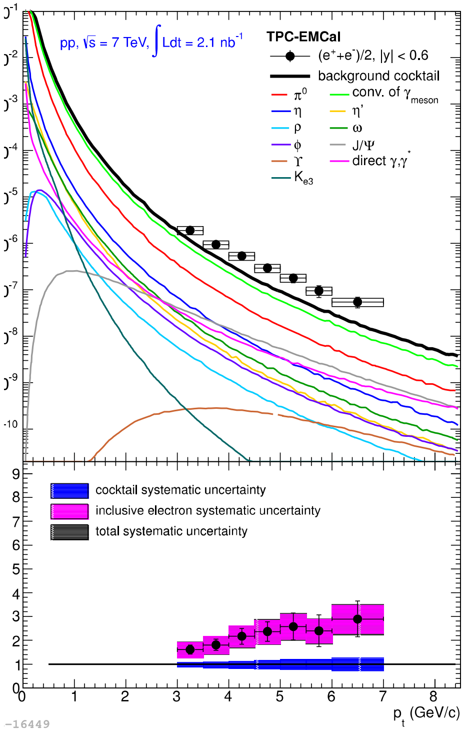
data are compared to perturbative QCD calculations
reasonable agreement
- at upper end of FONLL and at lower end of GM-VFNS

measure 80% of charm cross section for |y| < 0.5

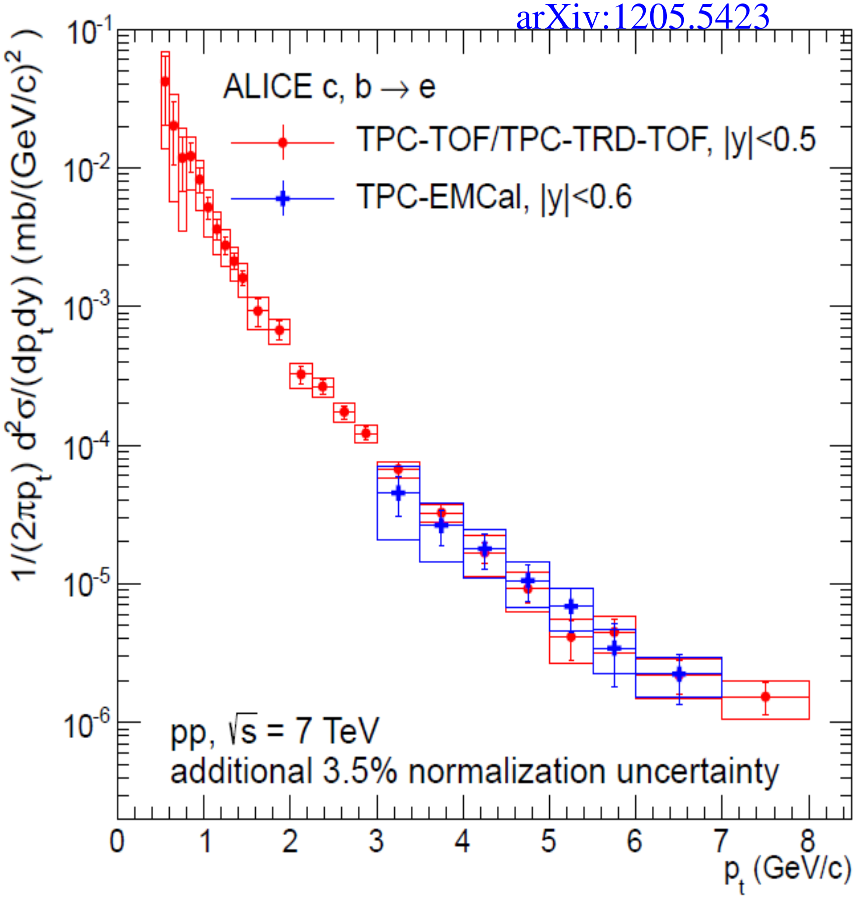
charm and beauty via semi-leptonic decays

Inclusive electron spectrum from 2 PID methods: TPC-TOF-TRD and TPC-EMCAL





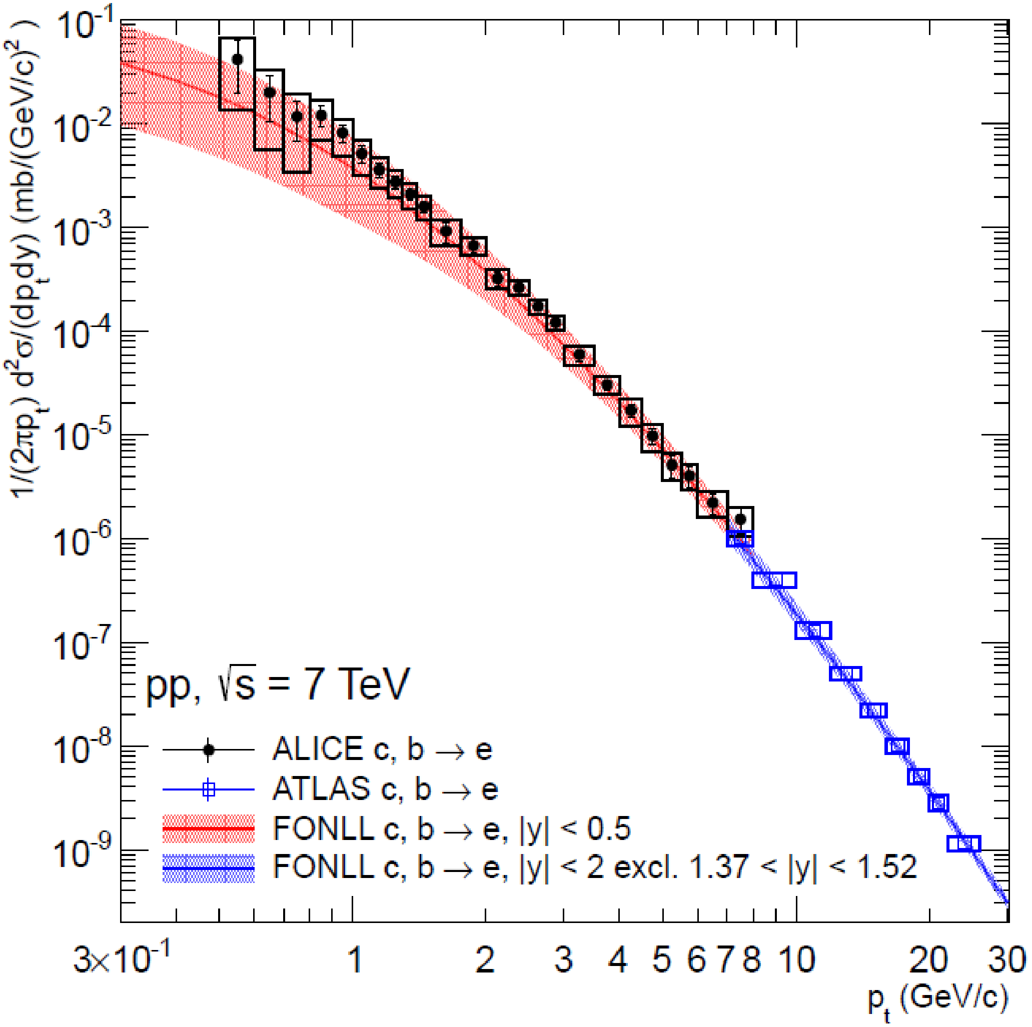
arXiv:1205.5423



subtract hadronic decay cocktail using measurements where possible (π^0, η, m_t scaling for other mesons, J/ψ),
direct γ from pQCD

electrons from c and b decays

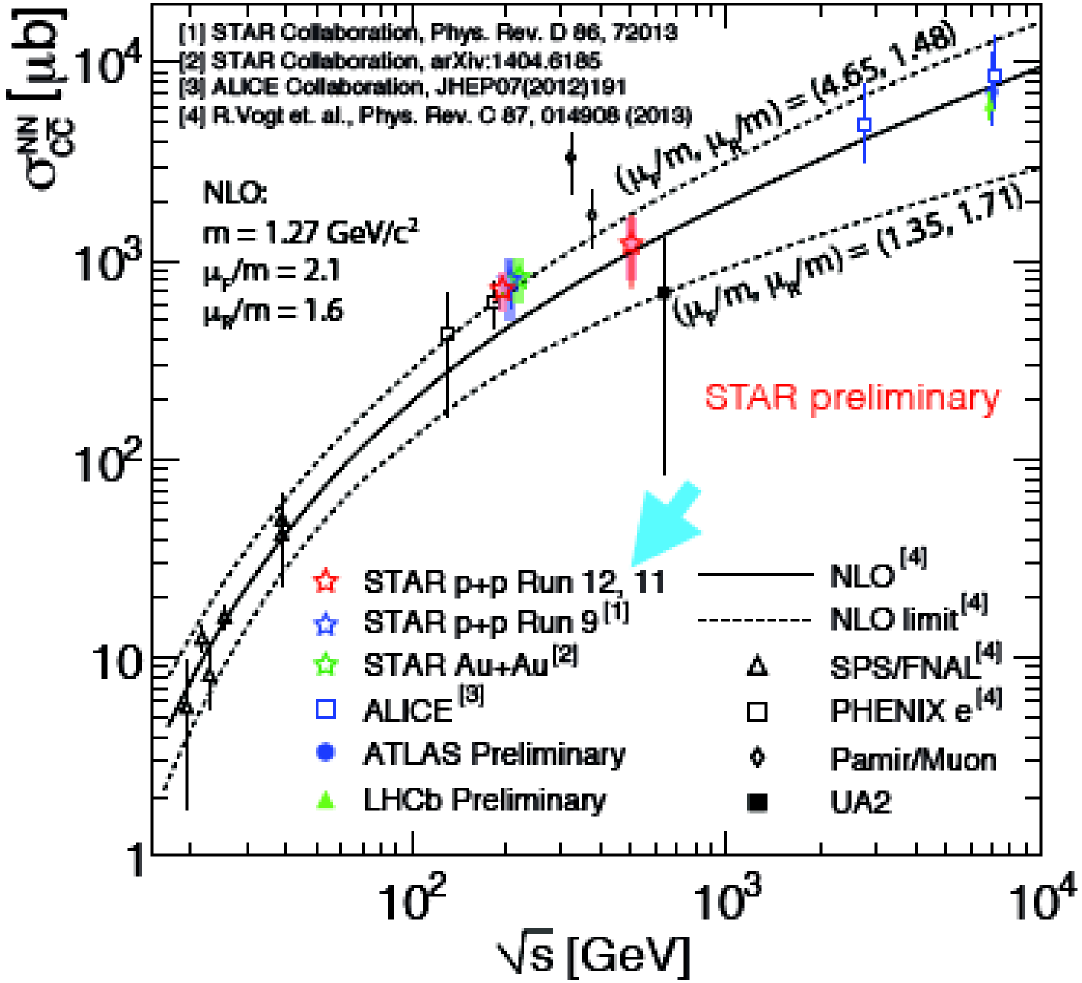
charm and beauty electrons compared to pQCD



- ALICE data complimentary to ATLAS measurement at higher pt (somewhat larger y-interval)
- good agreement with pQCD
- at upper end of FONLL range for $p_t <$ 3 GeV/c where charm dominates

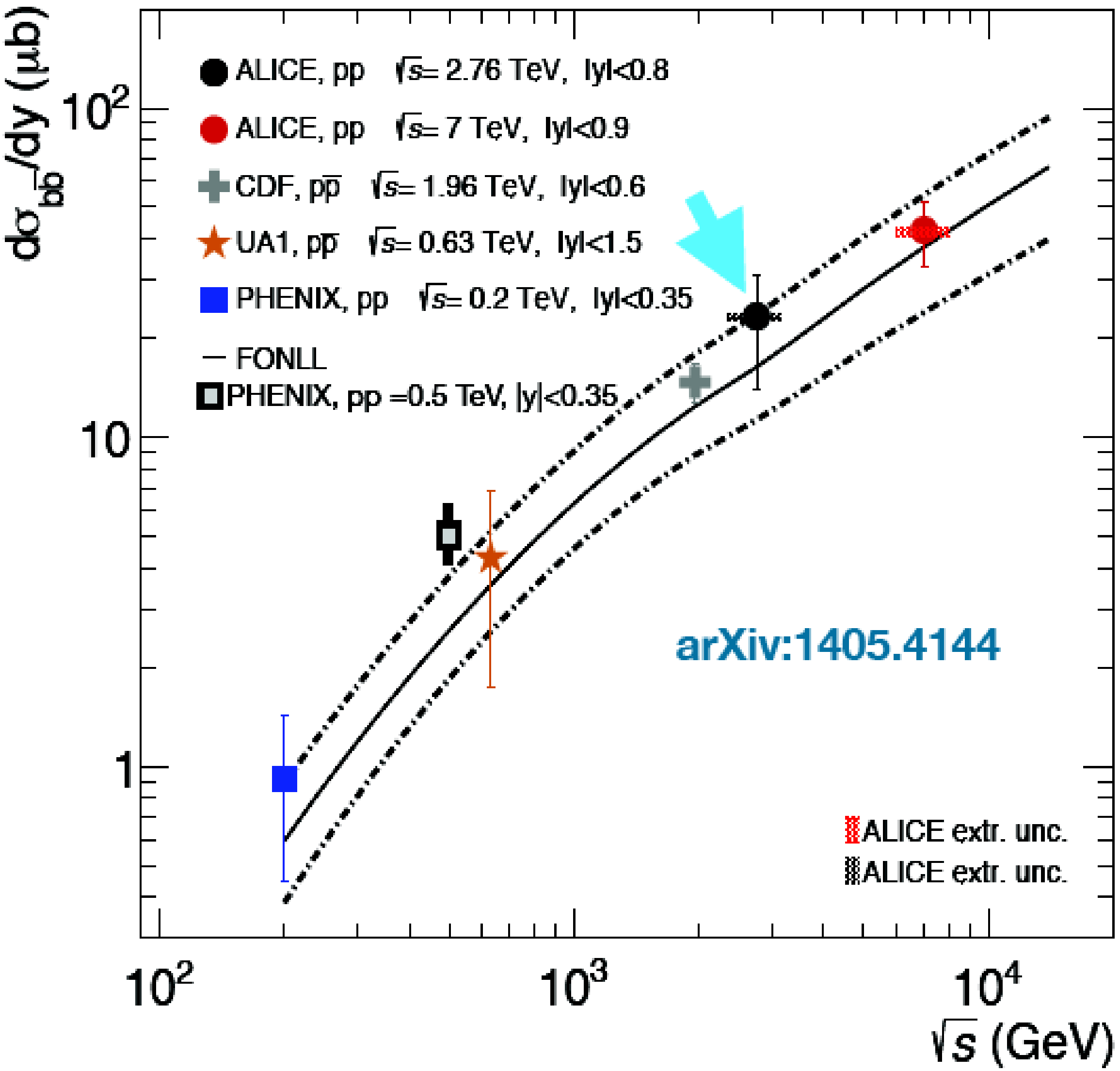
arXiv:1205.5423
ATLAS: PLB707 (2012) 438
FONLL: Cacciari et al., arXiv:1205.6344

the total ccbar cross section in pp collisions as of QM2014



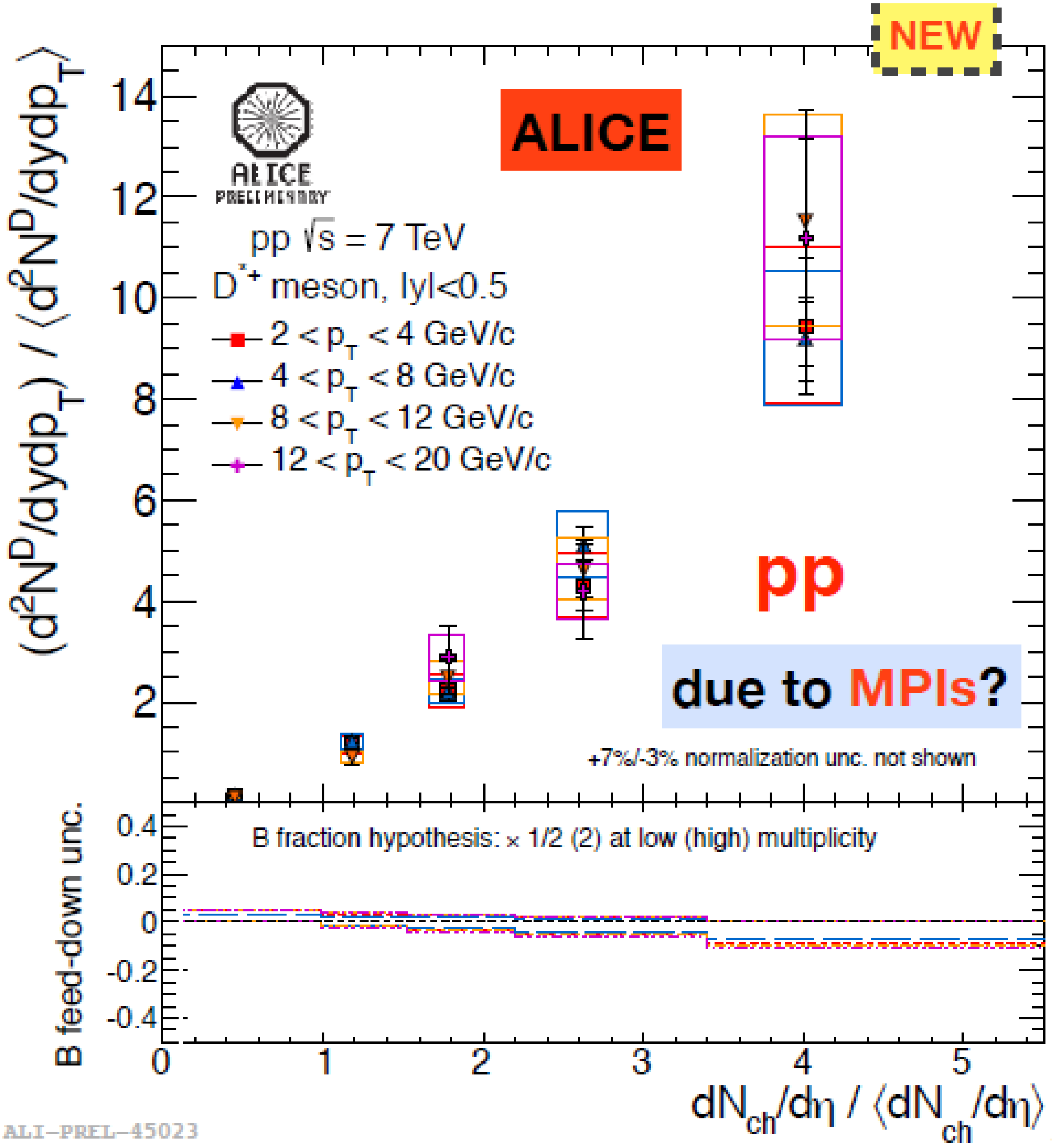
- good agreement between ALICE, ATLAS and LHCb at LHC energy
- large syst. error due to extrapolation to low pt, need to push measurements in that direction
- data factor 2 ± 0.5 above central value of FONLL but well within uncertainty
- beam energy dependence follows well FONLL

beauty cross section in pp and ppbar collisions as of QM2014



arXiv:1405.4144

charm production depends on associated multiplicity

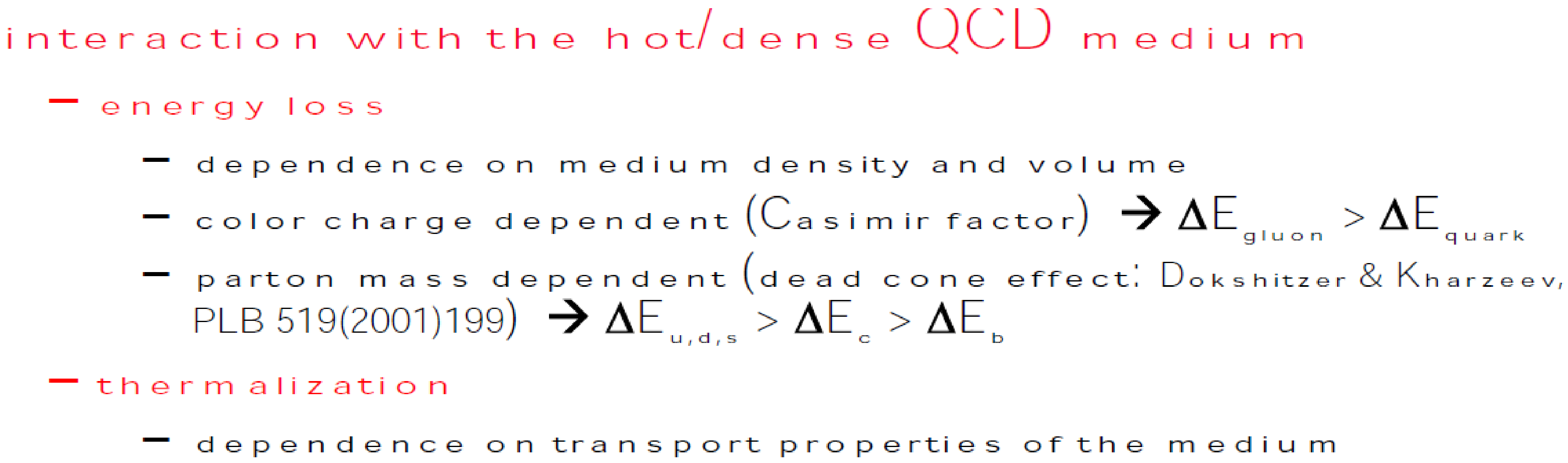


Open heavy flavor production and the QGP

1. m_q >> Lambda_QCD   charm quark production is independent of the medium formed in the collision (see above)

2. propagation of heavy quarks in the medium can be used to diagnose it

energy loss – thermalization – hydrodynamic flow



interaction with the hot/dense QCD medium

- energy loss
  - dependence on medium density and volume
  - color charge dependent (Casimir factor) → $\Delta E_{gluon} > \Delta E_{quark}$
  - parton mass dependent (dead cone effect: Dokshitzer & Kharzeev, PLB 519(2001)199) → $\Delta E_{u,d,s} > \Delta E_{c} > \Delta E_{b}$
- thermalization
  - dependence on transport properties of the medium

Formation time of quarkonia

heavy quark velocity in charmonium rest frame:

v = 0.55 for J/ψ see, e.g. G.T. Bodwin et al., hep-ph/0611002

minimum formation time: t = radius/v = 0.45 fm

see also: Huefner, Ivanov, Kopeliovich, and Tarasov, Phys. Rev. D62 (2000) 094022; J.P. Blaizot and J.Y. Ollitrault, Phys. Rev. D39 (1989) 232
formation time of order 1 fm

formation time is not short compared to plasma formation time especially at high energy formation time of open charm hadrons not well understood

presumably similar to charmonia

separation of time scales for initial hard process and late hadronization/hadron formation is called „factorization“

rigorously proven for deep inelastic scattering

charm conservation equation

no medium effect

$$\sigma_{c\bar{c}} = 1/2\ \left[\sigma_{D^+} + \sigma_{D^-} + \sigma_{D^0} + \sigma_{\bar{D}^0} + \sigma_{\Lambda_c} + \sigma_{\bar{\Lambda}_c} \cdots\right]$$

medium effects on charmed hadrons affect redistribution of charm, but not overall cross section

it is not consistent with the charm conservation equation to reduce all charmed hadron masses in the medium for an enhanced cross section

gluon radiation by a quark traversing a medium

from Dokshitzer & Kharzeev, Phys.Lett. B519 (2001) 199-206
we get for the probability of radiation of a gluon with energy ω
by a quark with mass M and energy E

$$dP = \frac{\alpha_s \, C_F}{\pi} \, \frac{d\omega}{\omega} \, \frac{k_\perp^2 \, dk_\perp^2}{(k_\perp^2 + \omega^2 \theta_0^2)^2}, \qquad \theta_0 \equiv \frac{M}{E}$$

$$k_\perp^2 \simeq \sqrt{\hat{q}\,\omega} \qquad \hat{q} \equiv \rho \int \frac{d\sigma}{dq^2} \, q^2 \, dq^2 \qquad C_F = \frac{N_c^2 - 1}{2N_c}$$

here the density of scatterers in the medium is encoded in q^

'dead cone' effect for charm quarks

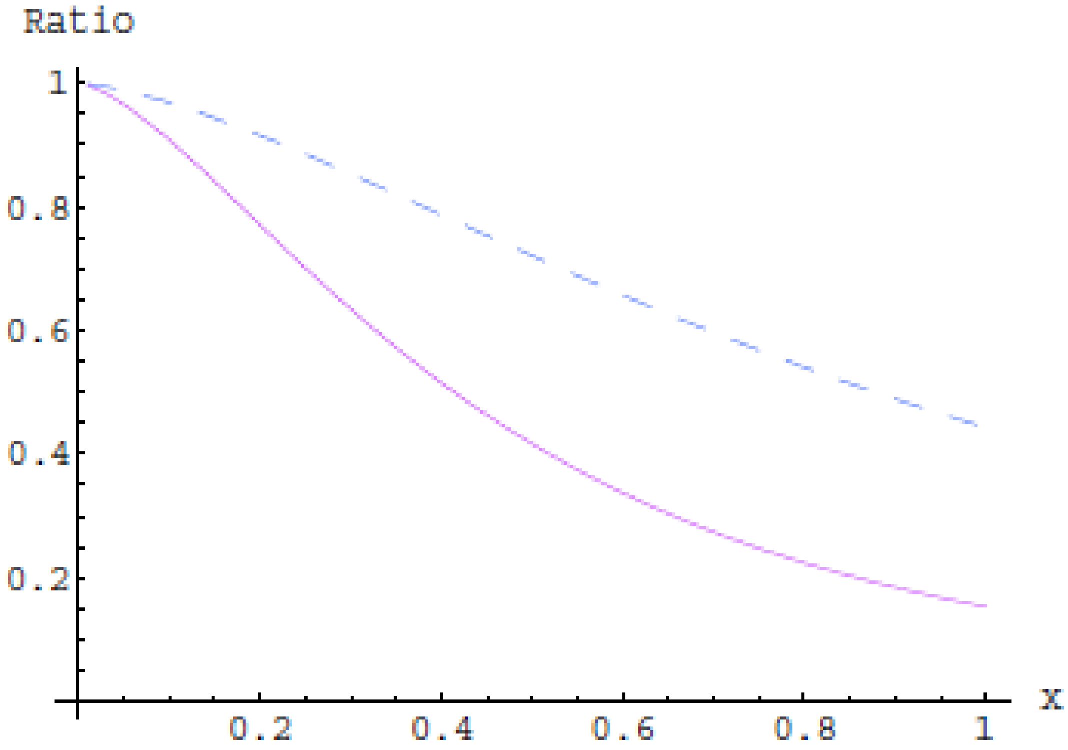


Figure 1: Ratio of gluon emission spectra off charm and light quarks for quark momenta $p_\perp = 10\,\mathrm{GeV}$ (solid line) and $p_\perp = 100\,\mathrm{GeV}$ (dashed); $x = \omega/p_\perp$.

now open charm and open beauty in AA collisions

how to quantify the effect of the medium?

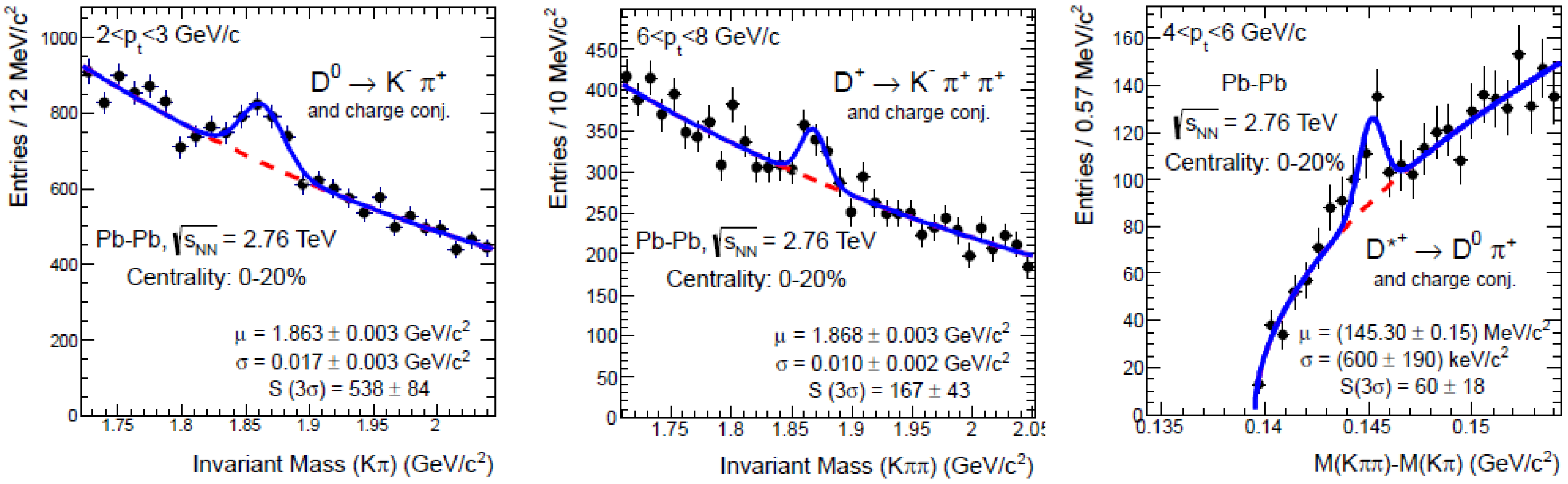
R_{AA}=yield(AA)/(N_{coll} yield(pp))

R_AA = medium/vacuum

R_AA = 1 if no dense medium is formed
or
if one looks at electro-weak probes

D meson signals in Pb Pb collisions

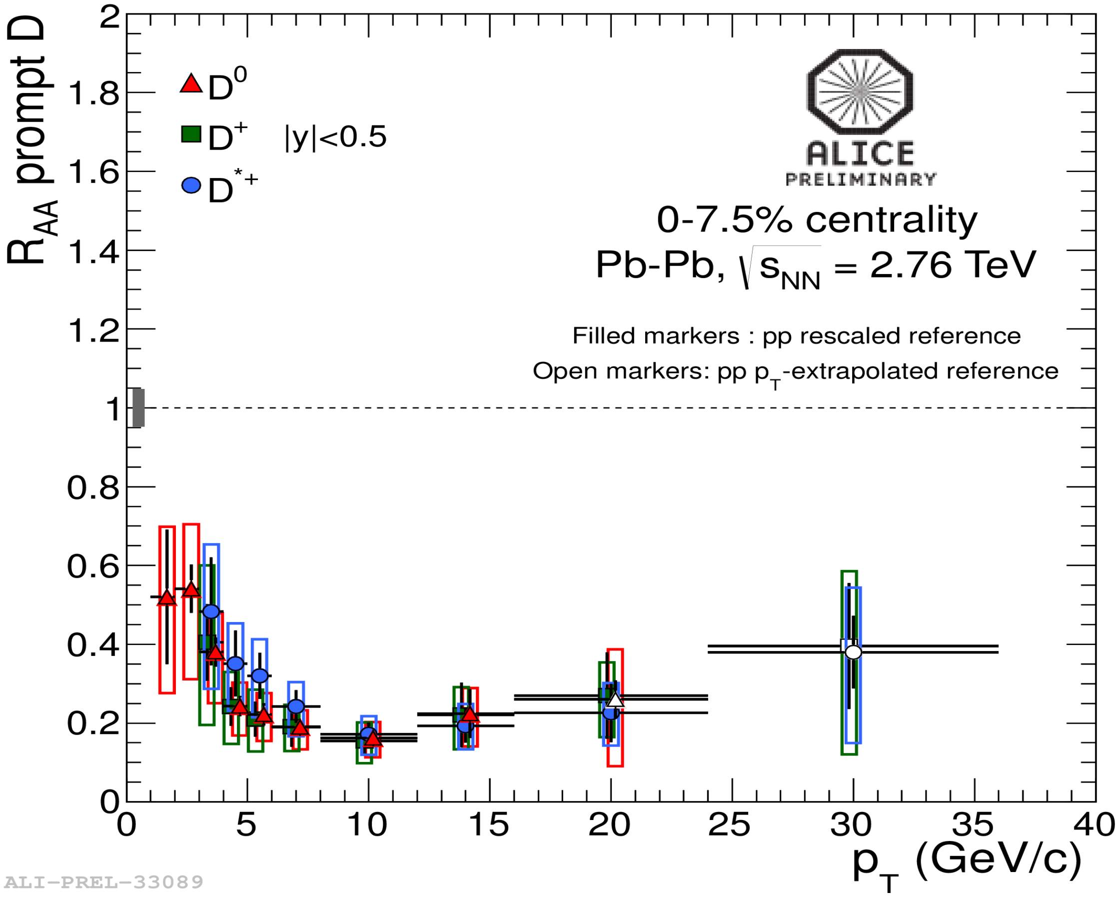
measurement:
reconstruction of hadronic decays of D-mesons (ALICE)
semi-leptonic decays into electrons (ATLAS, ALICE)
“ into muons (ATLAS, ALICE)



data: ALICE arXiv:1203.2160

suppression of charm at LHC energy

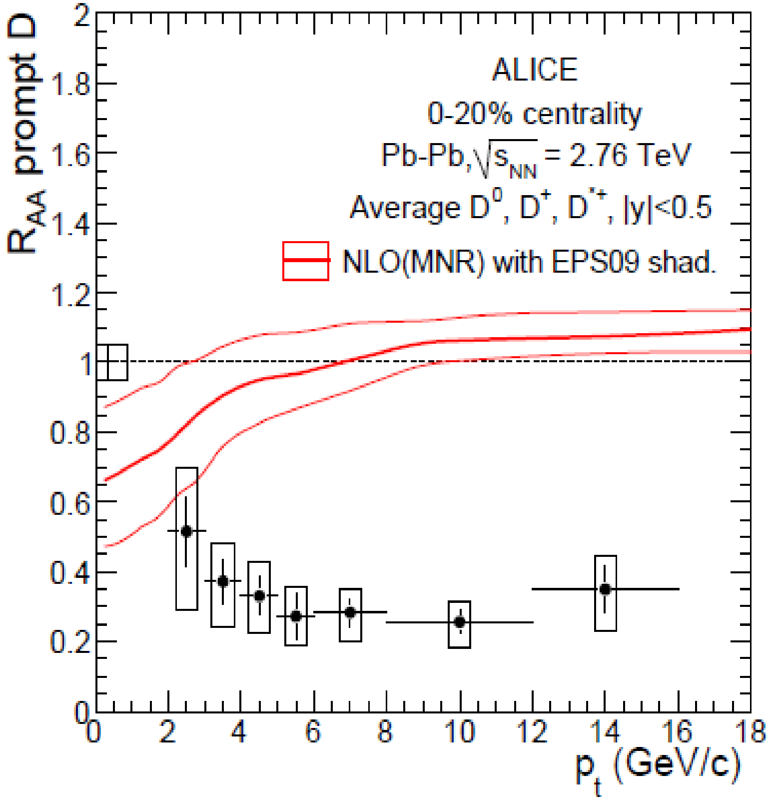
pp reference at 2.76 TeV: measured 7 TeV spectrum scaled with FONLL
cross checked with 2.76 TeV measurement (large uncertainty due to limited luminosity)

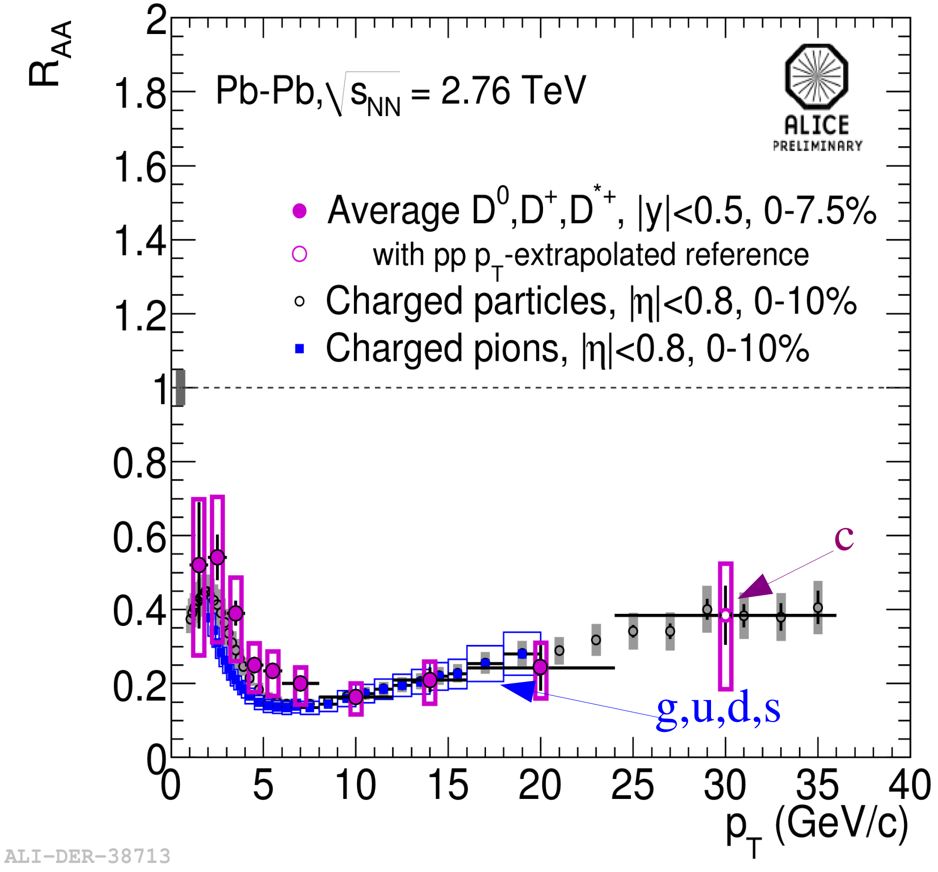


energy loss for all species of D-mesons within errors equal - not trivial
energy loss of central collisions very significant - suppr. factor 5 for 5-15 GeV/c

suppression of charm at LHC energ

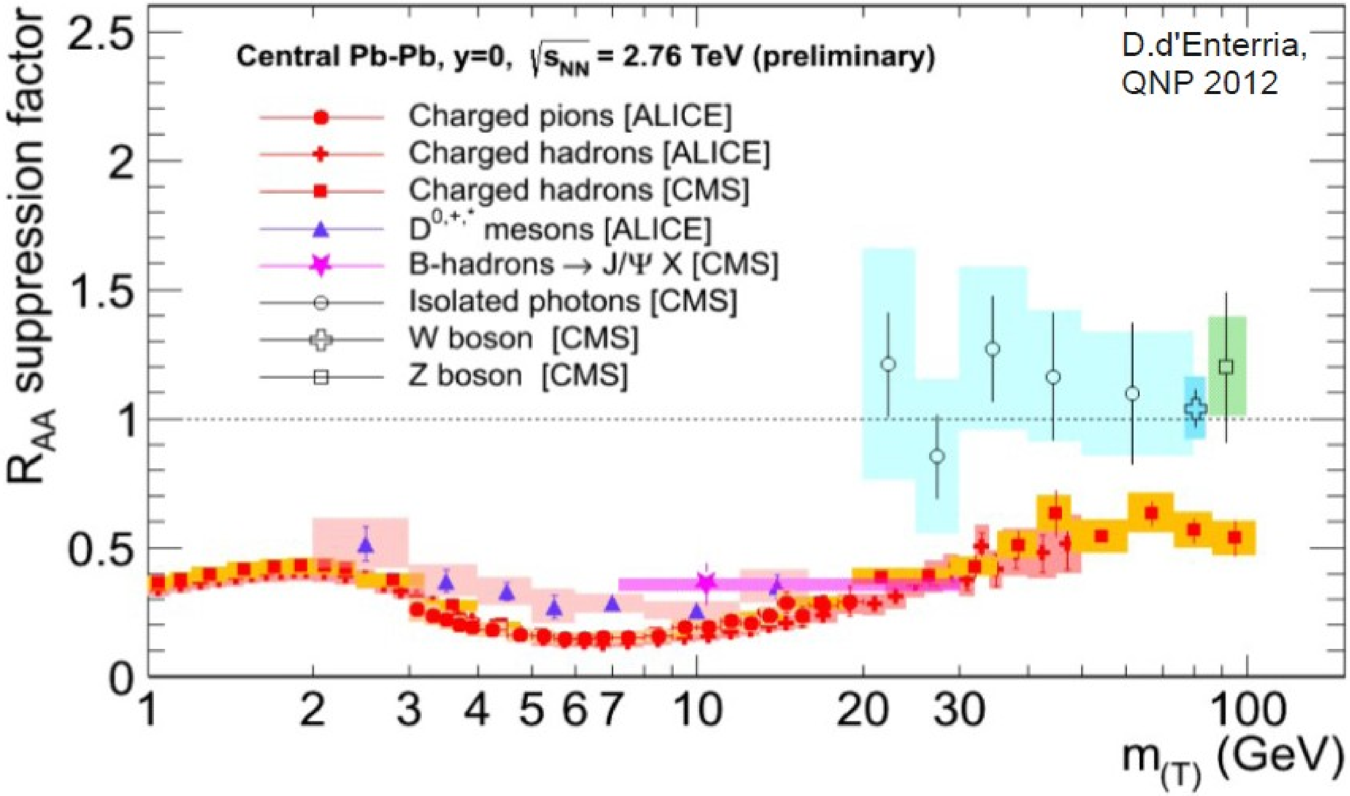
comparison to EPS09 shadowing:
suppression not an initial state effect
will be measured directly in pPb collisions





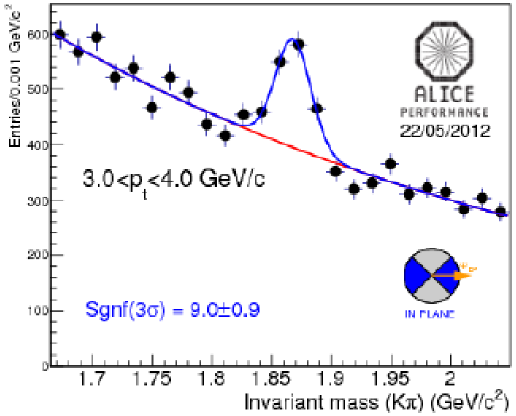
energy loss of charm quarks only slightly less than that for light quark → thermalization

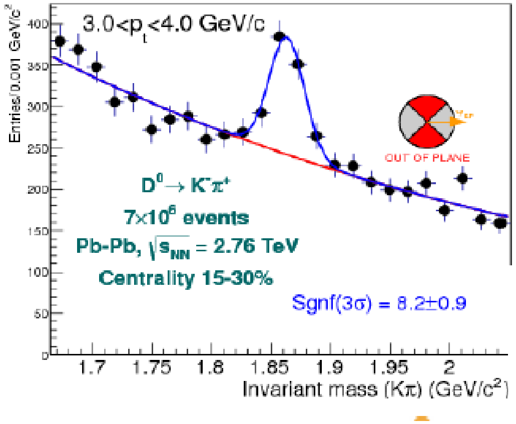
Suppression only for Strongly Interacting Hard Probes



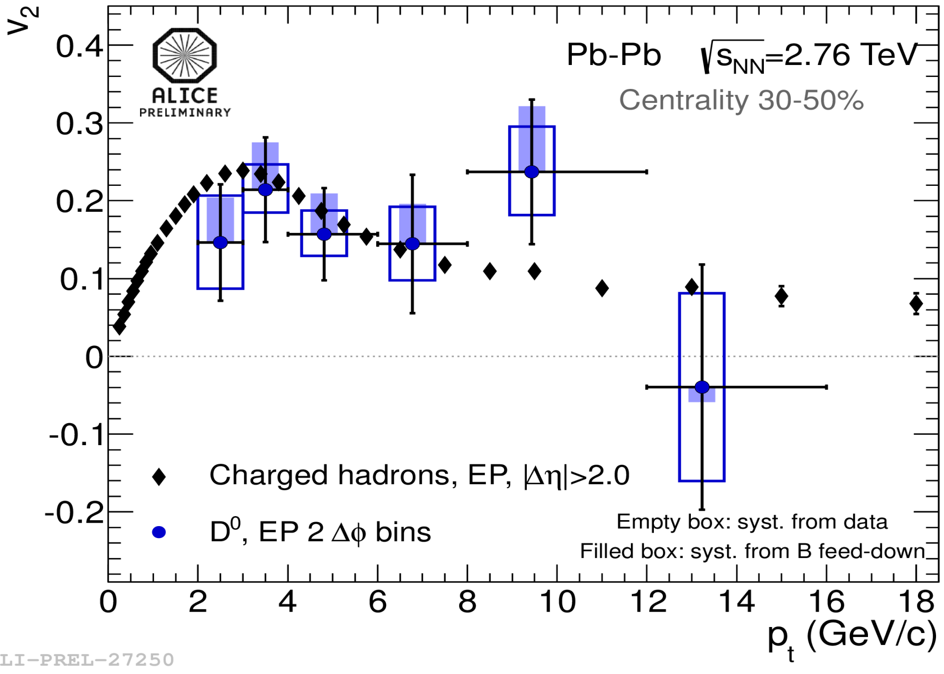
photons, Z and W scale with number of binary collisions in PbPb – not affected by medium
→ demonstrates that charged particle suppression is medium effect: energy loss in QGP

charm Quarks also Exhibit Elliptic Flow





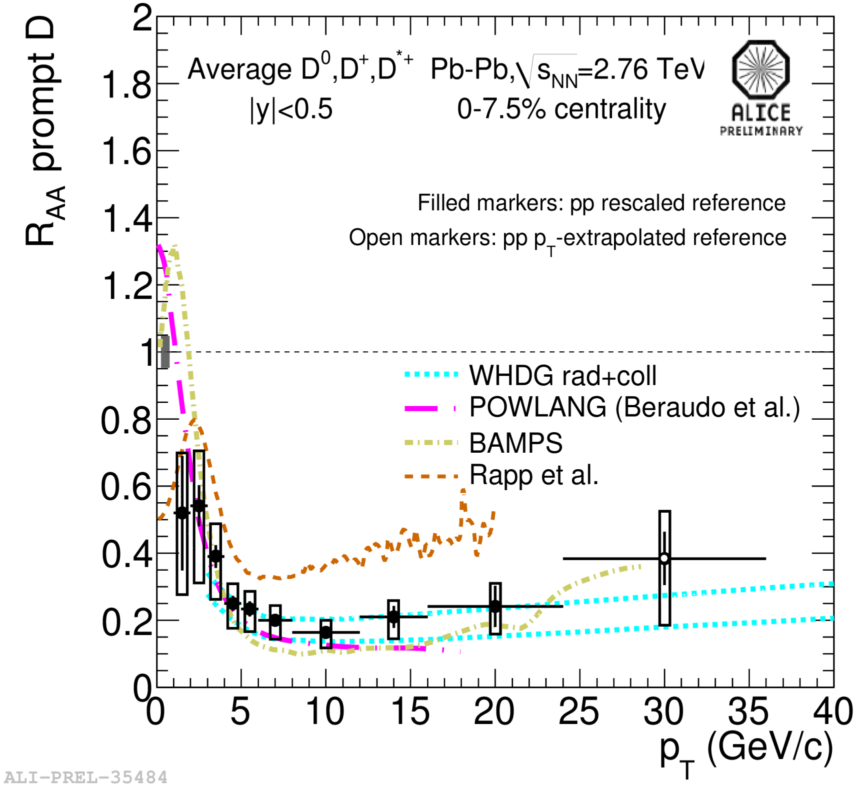
$$v_2 = \frac{\pi}{4}\frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$



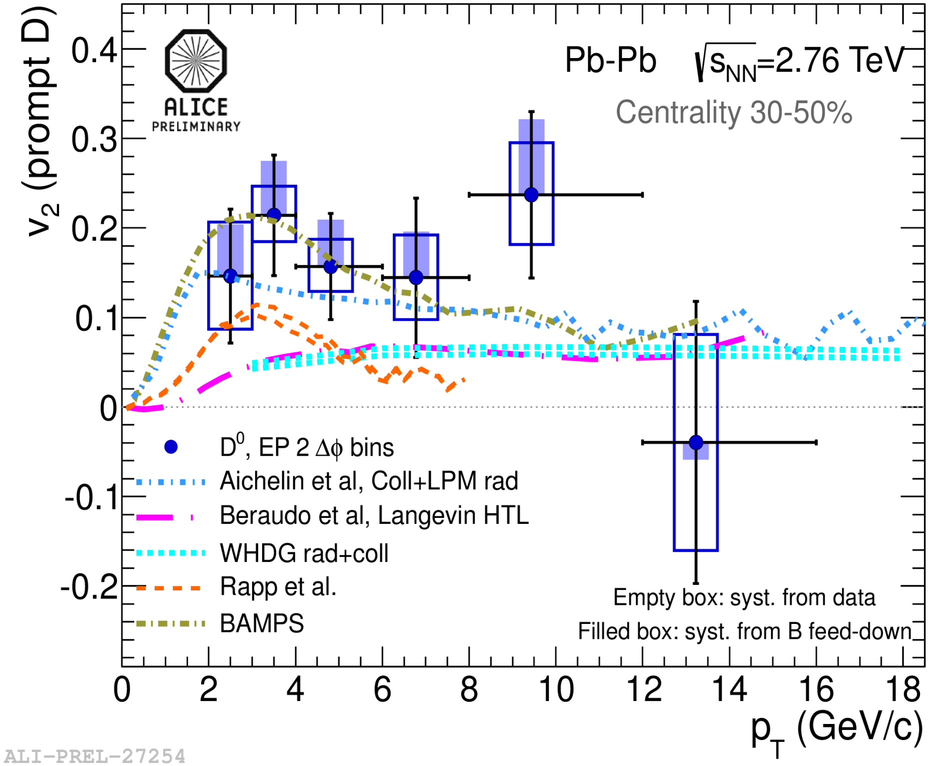
2 centrality classes
event plane from TPC
corrected for B-feed down (FONLL)

non-zero elliptic flow for 3 σ effect for D^0 2-6 GeV/c
within errors charmed hadron v_2 equal to that of all charged hadrons

model description of energy loss and flow of D-mesons



ALI-PREL-35484



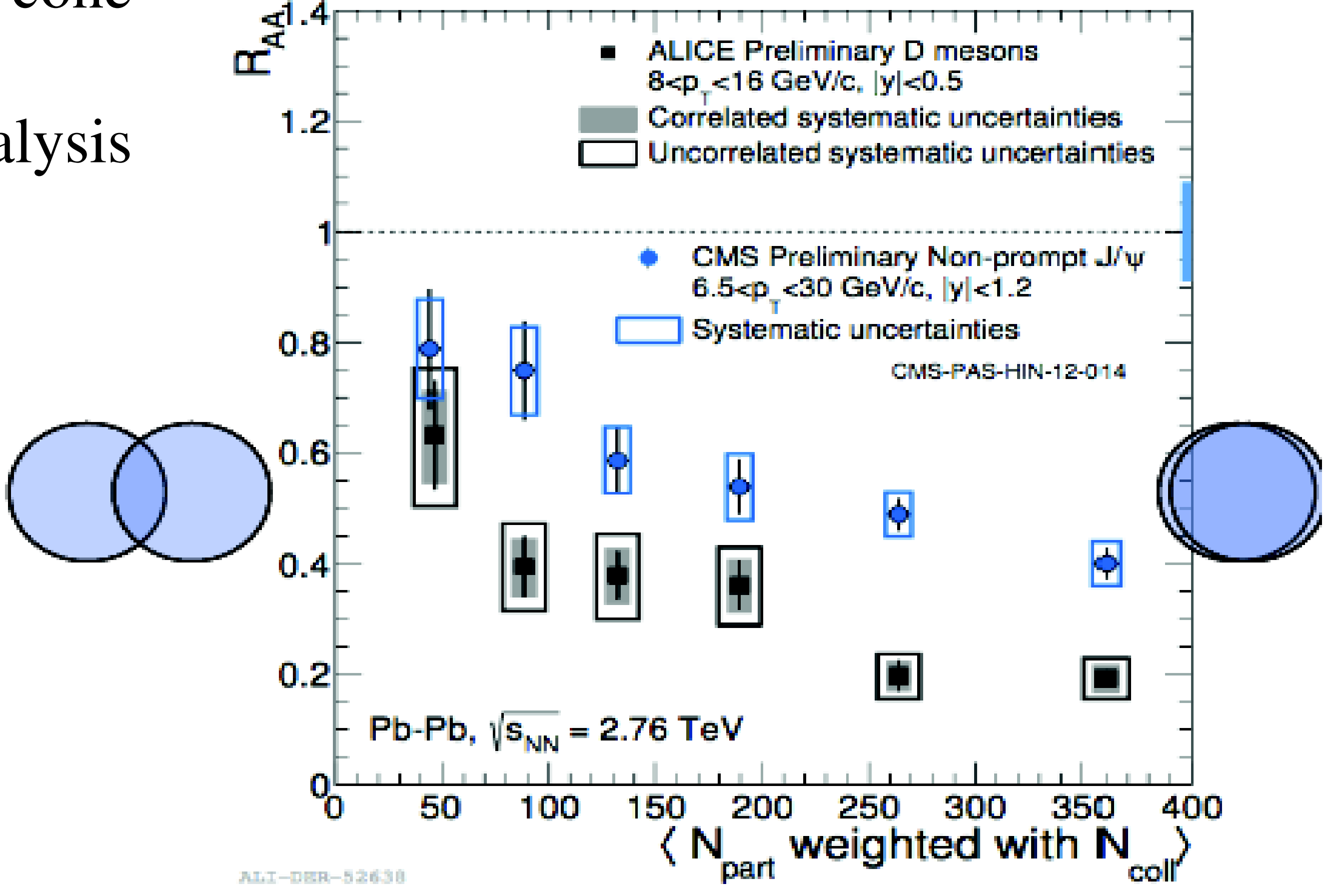
ALI-PREL-27254

both are determined by transport properties of the medium (QGP)
simultaneous description still a challenge for some models

comparison of suppression for b-quarks and c-quarks

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA} / dp_T}{dN_{pp} / dp_T}$$

is this the dead-cone effect? need quantitative analysis



summary - heavy quark production

- heavy quark production in pp collisions is well described within the framework of pQCD

- heavy quark production in pPb and Pb-Pb collisions is only weakly modified – gluon shadowing

- heavy quark propagation in AA collisions is strongly influenced by the fireball's medium – heavy quark energy loss and hydrodynamic flow

additional slides

important note: corrections for weak decays

All ALICE data do not contain hadrons from weak decays of hyperons and strange mesons – correction done in hardware via ITS inner tracker

The RHIC data contain varying degrees of such weak decay hadrons. This was on average corrected for in previous analyses.

in light of high precision LHC data the corrections done at RHIC may need to be revisited.

important note: corrections for weak decays

All ALICE data do not contain hadrons from weak decays of hyperons and strange mesons – correction done in hardware via ITS inner tracker

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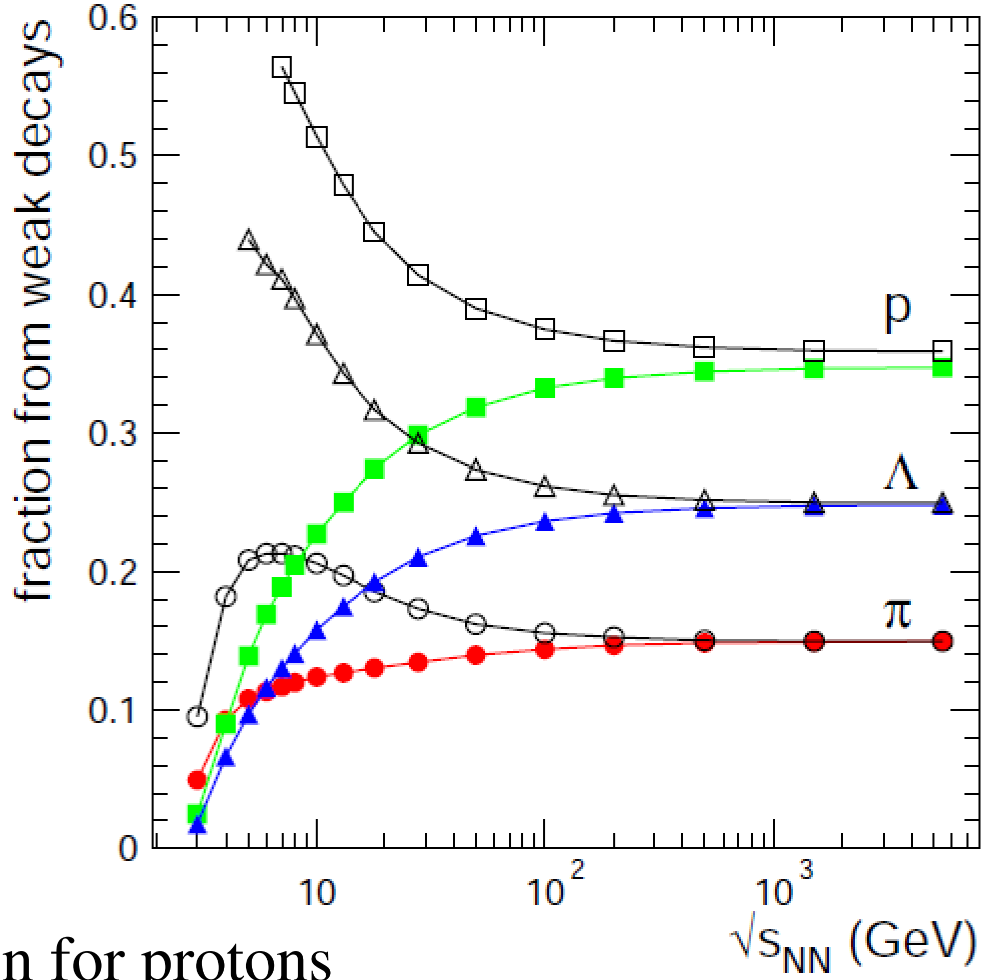
in light of high precision LHC data the corrections done at RHIC may need to be revisited.

treatment of weak decays

fraction of yield from weak decays



biggest correction for protons
done in hardware (vertex cut) at ALICE
software corrections at all lower energies

Re-evaluation of fits at RHIC energies – special emphasis on corrections for weak decays

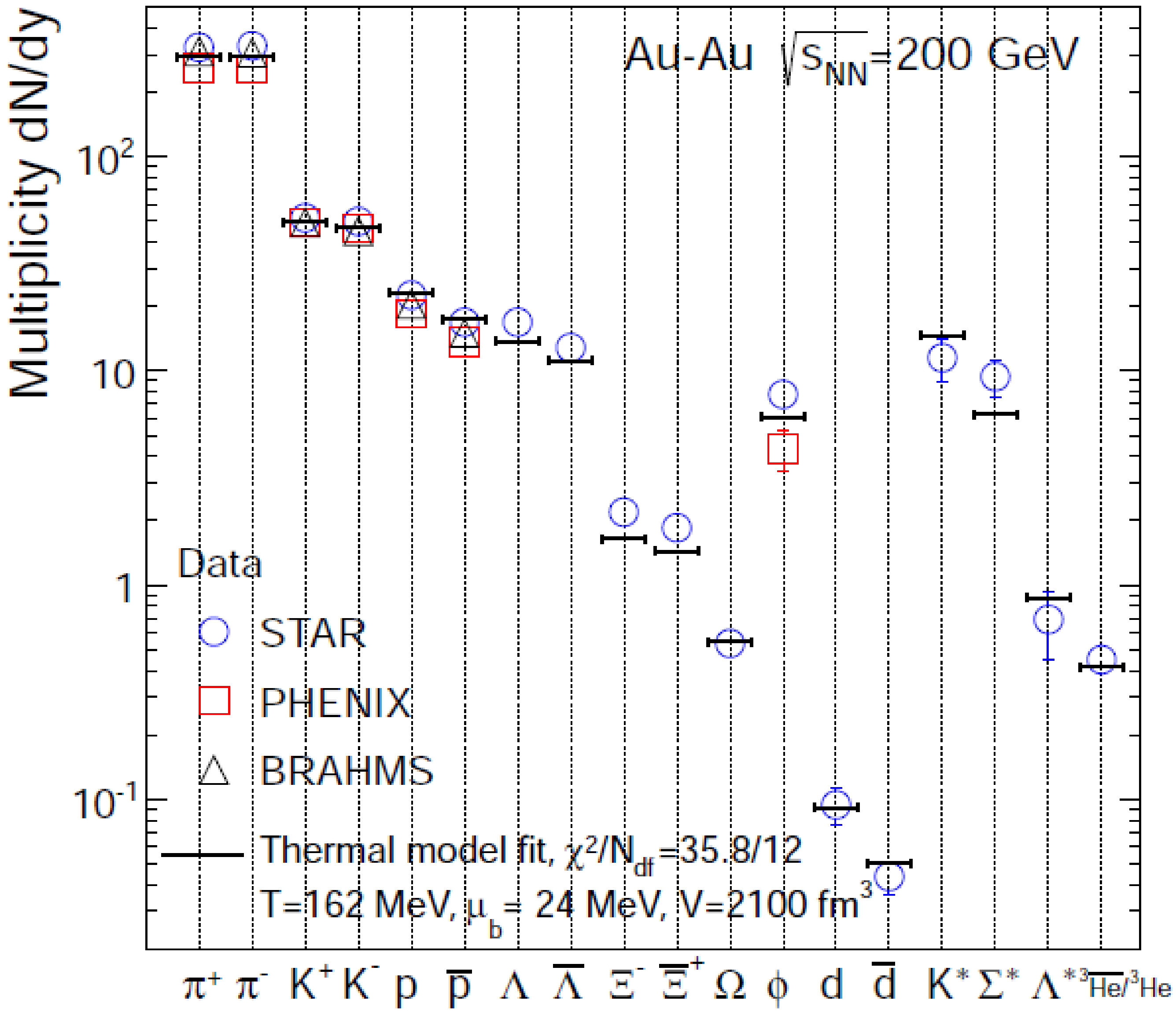
Note: corrections for protons and pions from weak decays of hyperons depend in detail on experimental conditions

RHIC hadron data all measured without application of Si vertex detectors

In the following, corrections were applied as specified by the different RHIC experiments

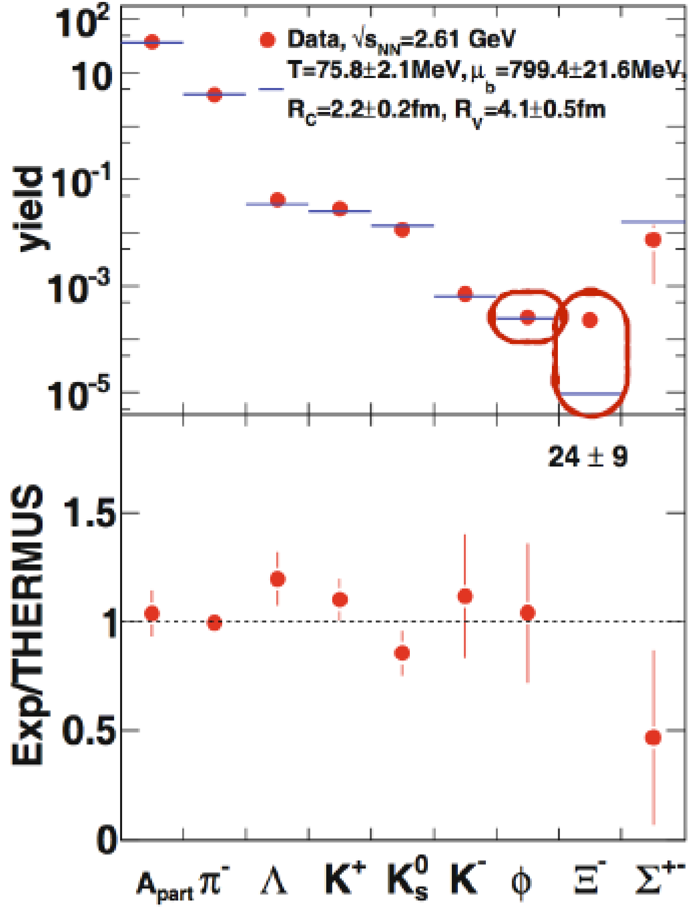
Au+Au central at 200 GeV, all experiments combined

T = 162 MeV



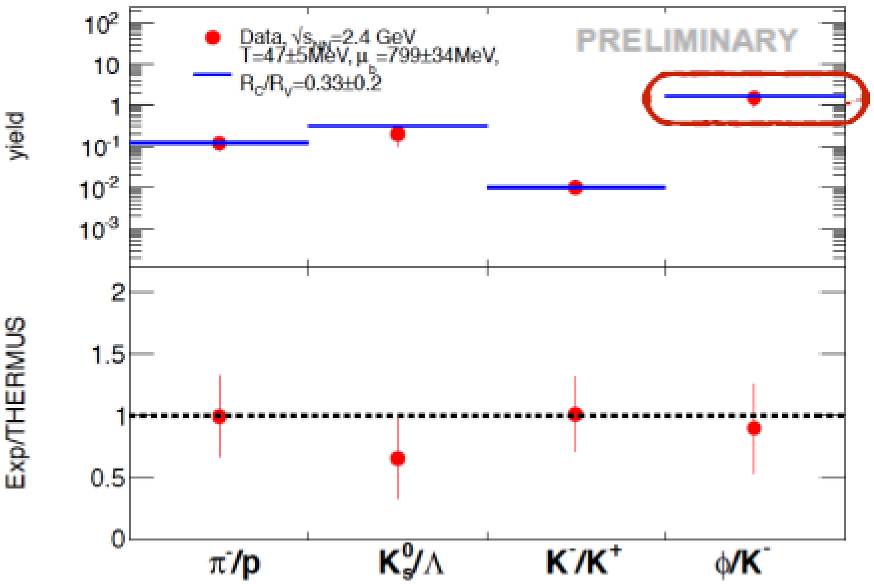
The latest news at very low energy – QM2014 results from HADES

Ar-KCl, $\sqrt{s}$ = 2.61 GeV
(~40+40 nucleons)



EPJ A 47 21 (2011)

Au-Au, $\sqrt{s}$ = 2.4 GeV

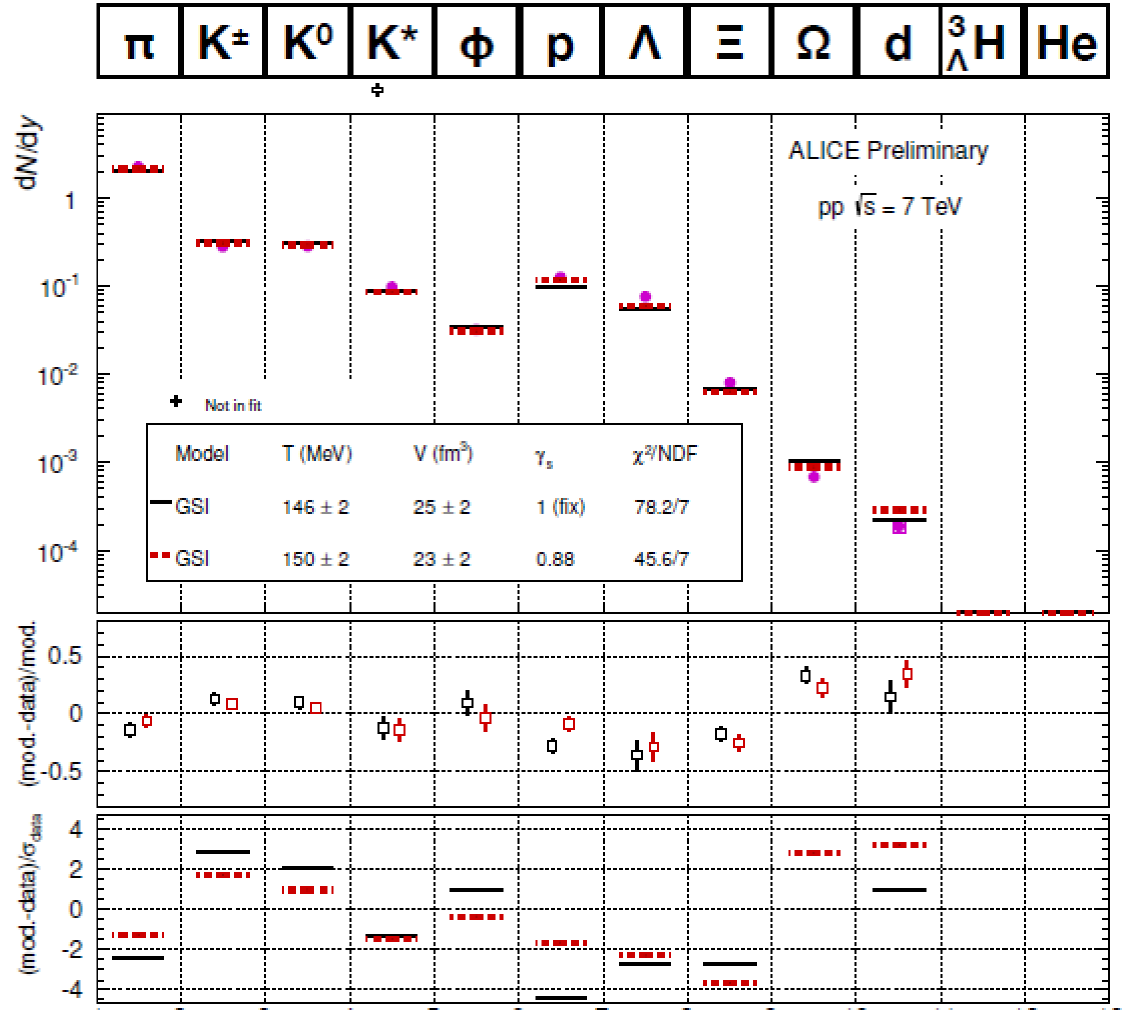


Why does the statistical model work at these low energies?
Strangeness production mechanism?

Rc/Rv ≃ 0.5

from M. Floris
QM2014

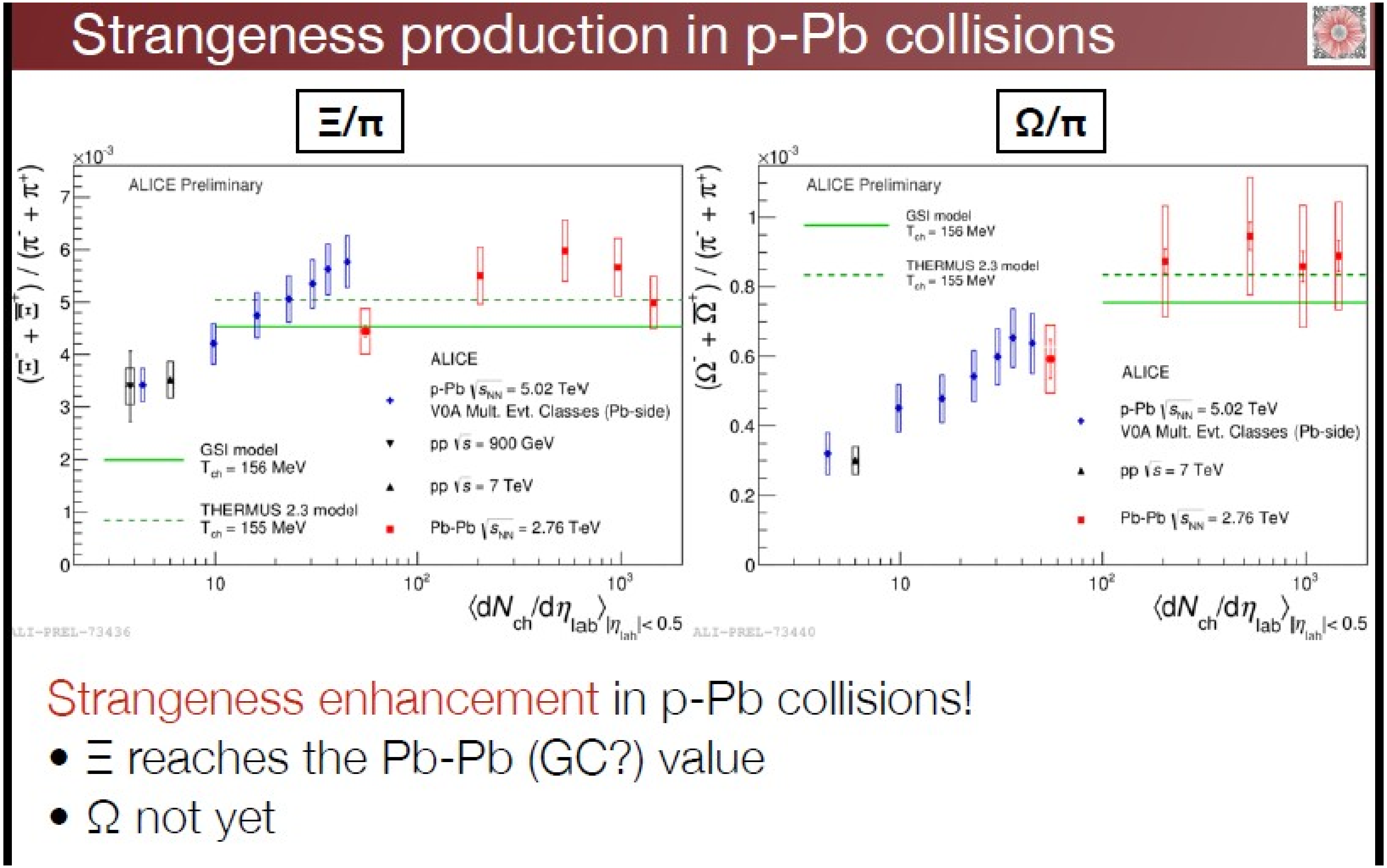
GC fits at the LHC (pp collisions)



Model	T (MeV)	V (fm³)	γ_s	χ^2/NDF
GSI	146 ± 2	25 ± 2	1 (fix)	78.2/7
GSI	150 ± 2	23 ± 2	0.88	45.6/7

ALI-PREL-74533

Poor fit with Grand Canonical ensemble in pp collisions



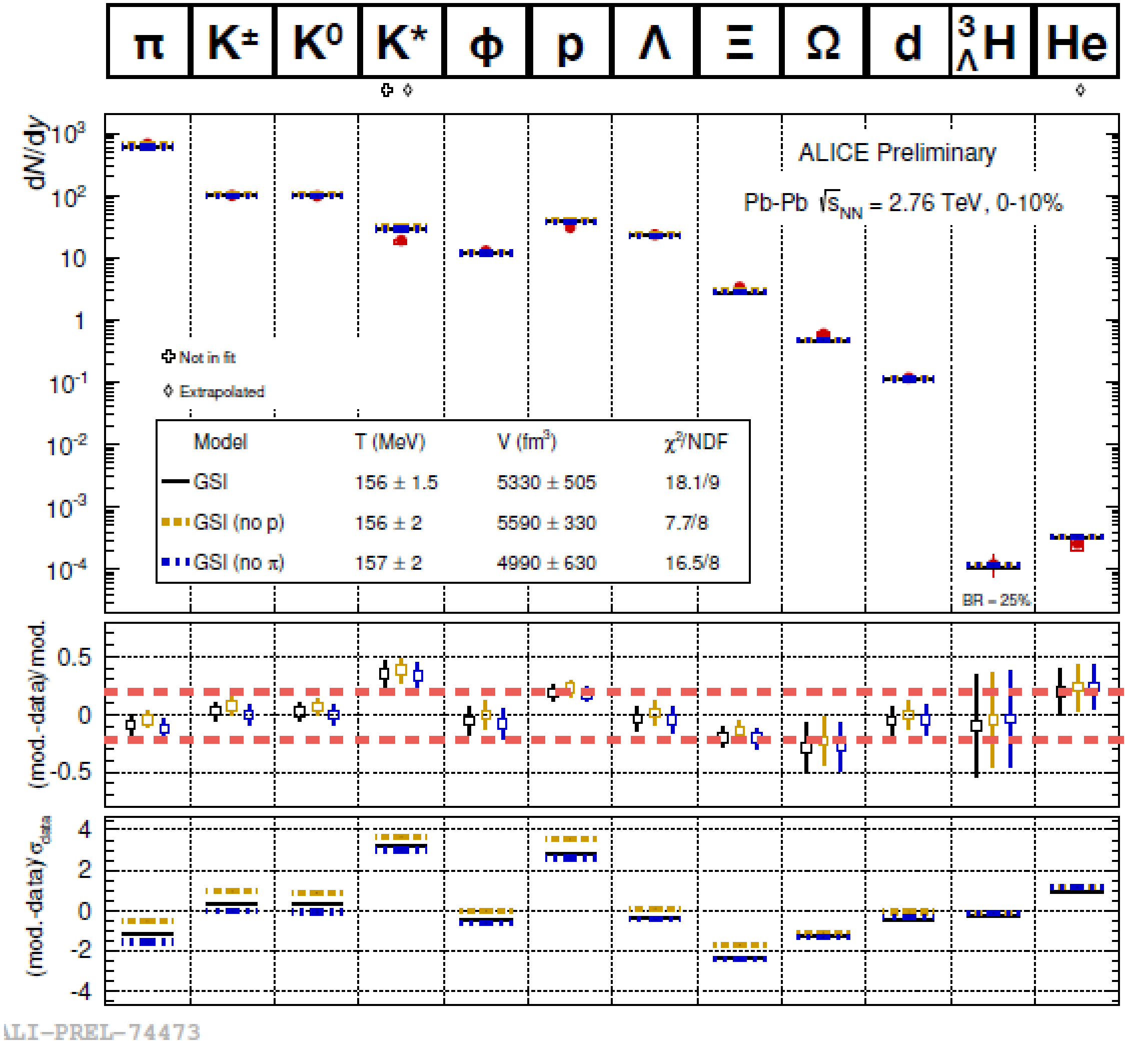
Strangeness production in p-Pb collisions

Strangeness enhancement in p-Pb collisions!

- Ξ reaches the Pb-Pb (GC?) value
- Ω not yet

from M. Floris, QM2014

Excluding protons or pions (GSI)



Model	T (MeV)	V (fm^3)	χ^2/NDF
GSI	156 ± 1.5	5330 ± 505	18.1/9
GSI (no p)	156 ± 2	5590 ± 330	7.7/8
GSI (no π)	157 ± 2	4990 ± 630	16.5/8

ALI-PREL-74473

No π

Fit quality does not improve (no evidence for pion condensate, as opposed to n.eq. model)

No p

Better fit, proton anomaly?

could it be weak decays from charm?

weak decays from charmed hadrons are included in the ALICE data sample

at LHC energy, cross sections for charm hadrons is increased by more than an order of magnitude compared to RHC

first results including charm and beauty hadrons indicate changes of less than 3%, mostly for kaons

not likely an explanation

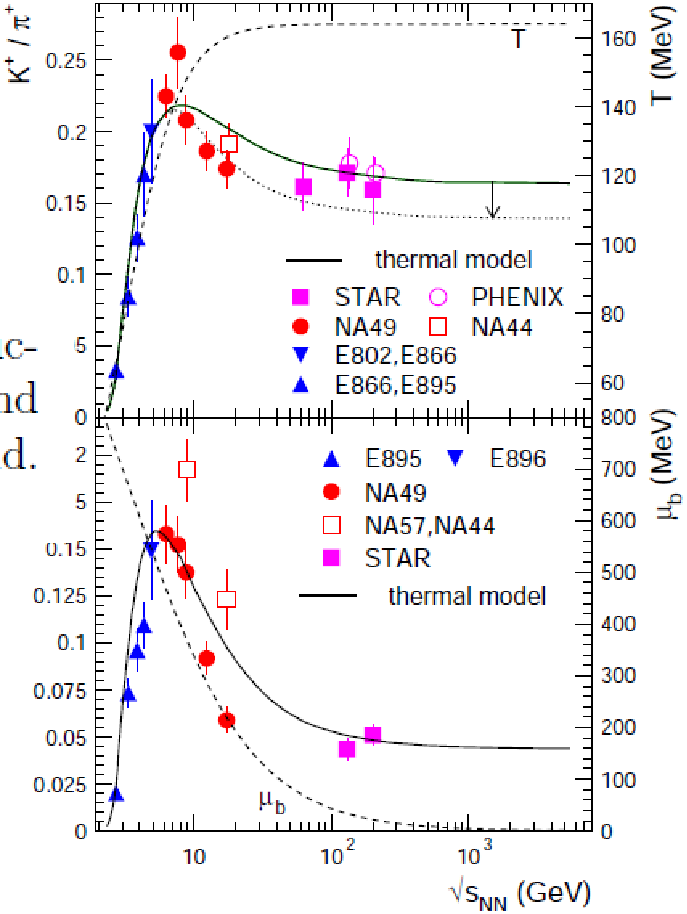
could it be incomplete hadron resonance spectrum?

Note: because of baryon conservation, adding more baryon resonances will decrease in the model the p/pi ratio

An N* will decay dominantly into 1 N + a number (depending on the N* mass) of pions

Same effect seen in
K/pi ratio because of strangeness conservation

A. Andronic, P. Braun-Munzinger, J. Stachel, Thermal hadron production in relativistic nuclear collisions: the sigma meson, the horn, and the QCD phase transition, Phys. Lett. **B673** (2009) 142, erratum ibid. **B678** (2009) 516, arXiv:0812.1186.



could it be proton annihilation in the hadronic phase?

F. Becattini et al., Phys. Rev. C85 (2012) 044921 and arXiv: 1212.2431

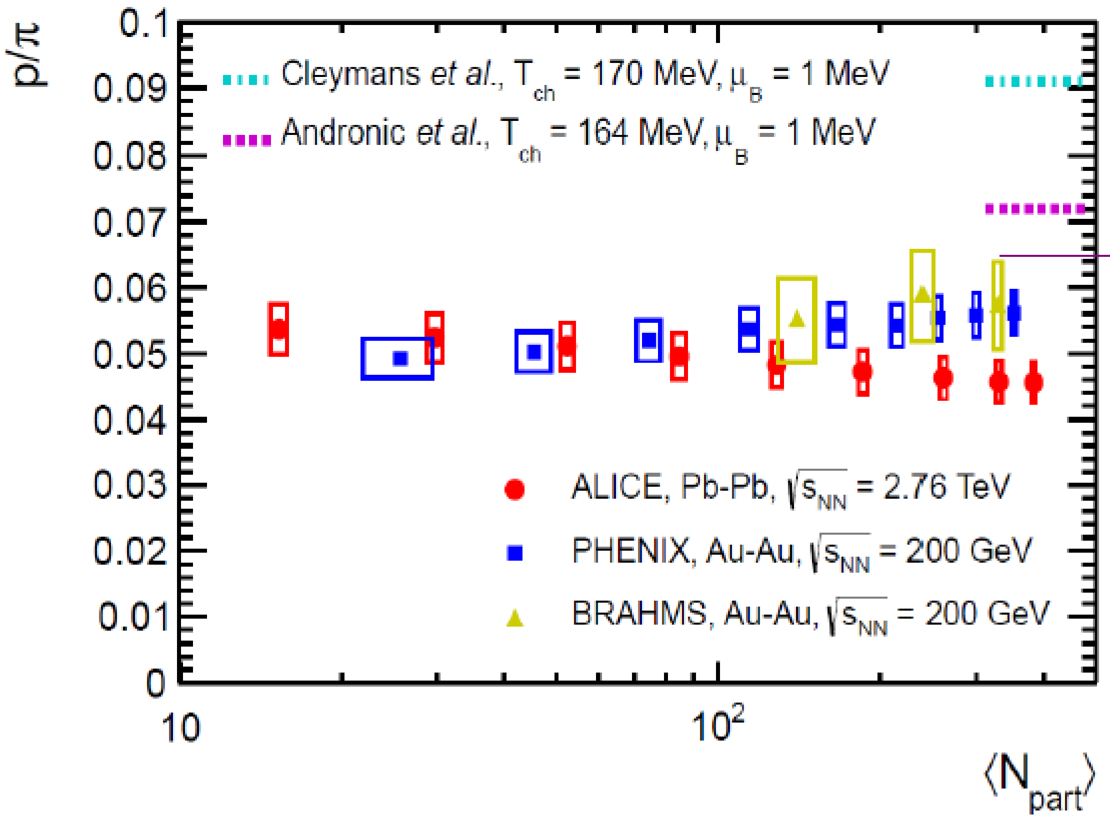
- need to incorporate detailed balance, 5pi → p p_bar
  not included in current Monte Carlo codes (RQMD)

- taking detailed balance into account reduces effect strongly,
see Rapp and Shuryak 1998

- see also W. Cassing, Nucl. Phys. A700 (2002) 618
  and recent reanalysis, by Pan and Pratt, arXiv:

- agreement with hyperon data would imply strongly reduced
hyperon annihilation cross section with anti-baryons → no
evidence for that

centrality dependence of proton/pion ratio



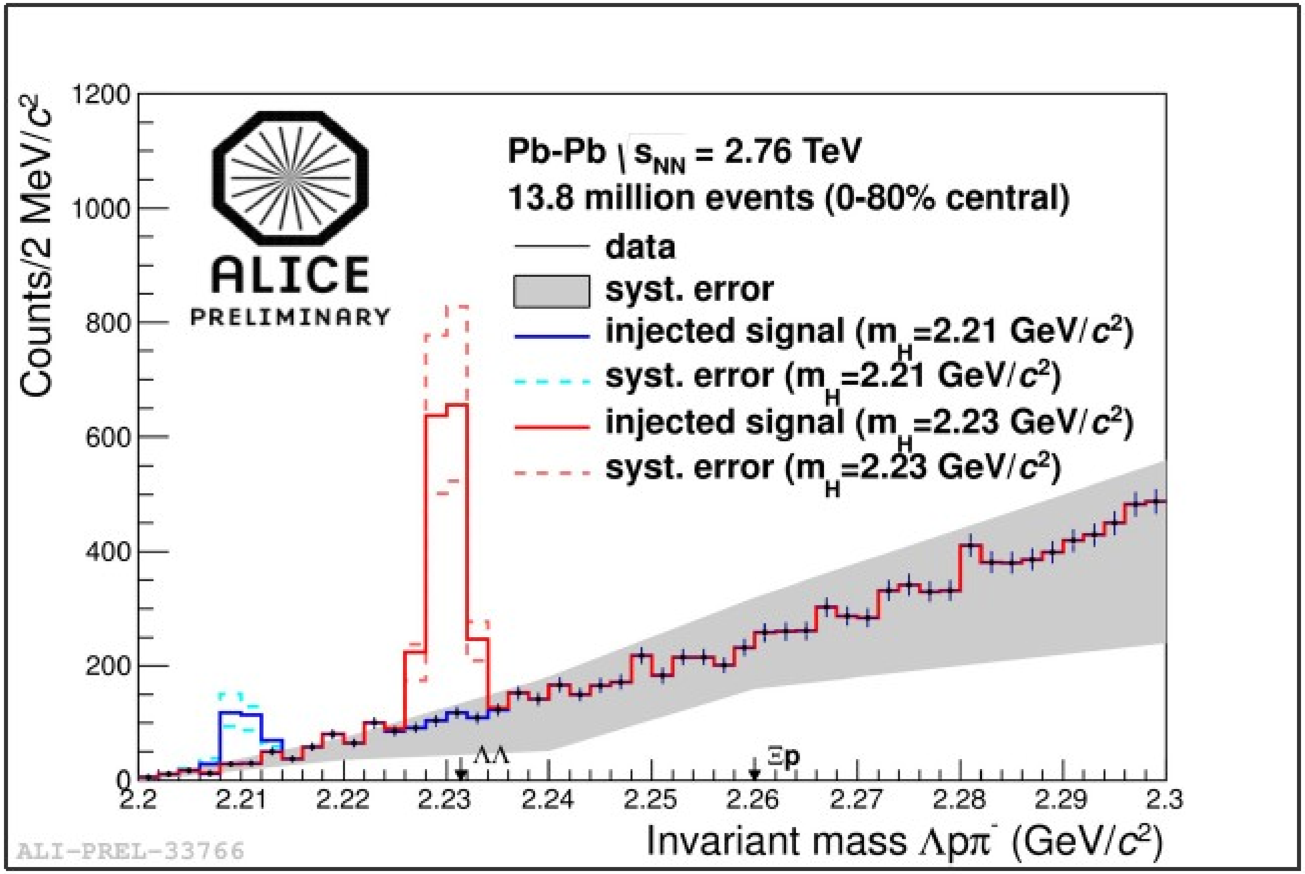
T=156 MeV

different centrality dependence for RHIC and LHC is a real puzzle

- does not support annihilation picture
- is it real? physics origin?

example: search for H-Dibaryon

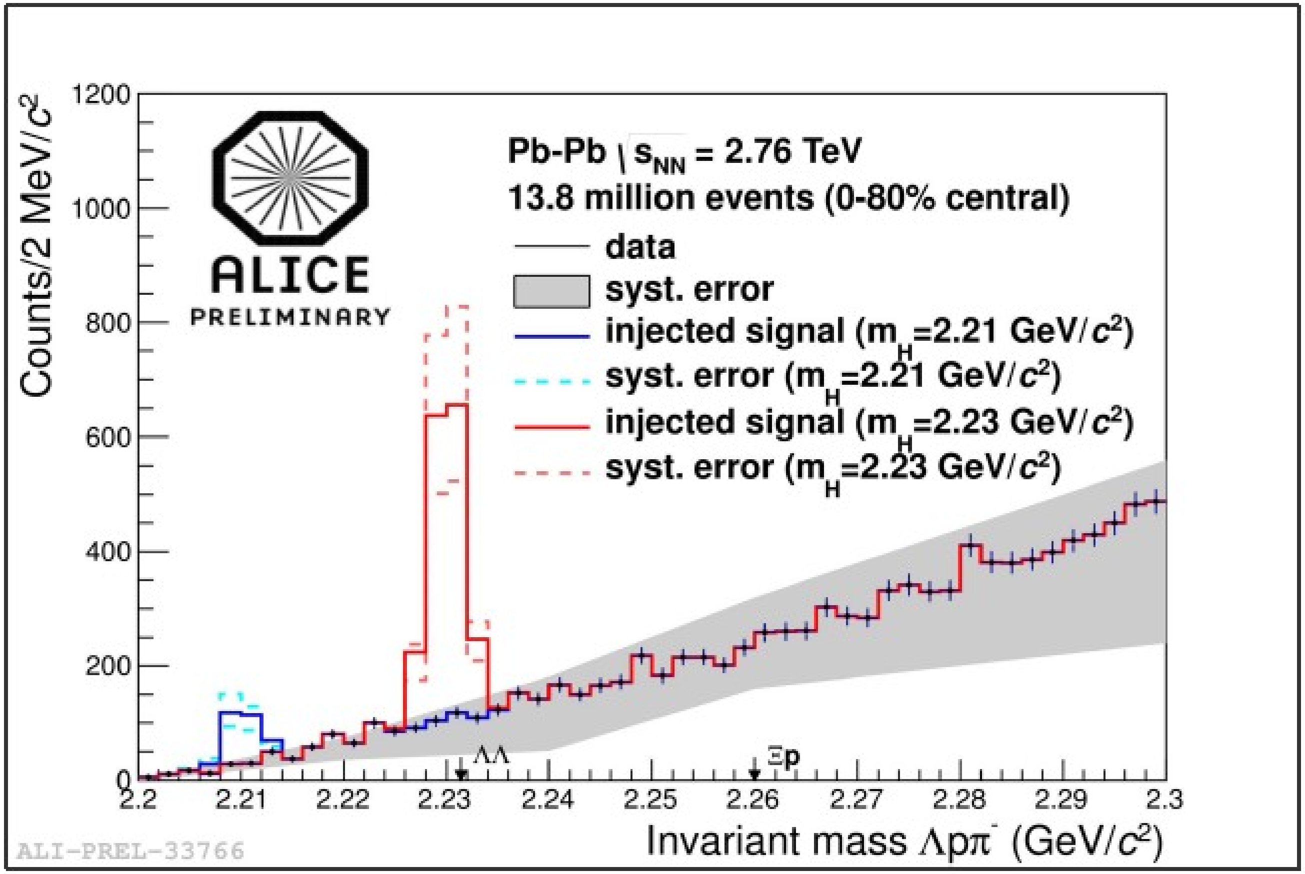
Ramona Lea, SQM2013



No signal observed, H yield is < 0.1 x (thermal model prediction)
Much more stringent limits to come soon

example: search for H-Dibaryon

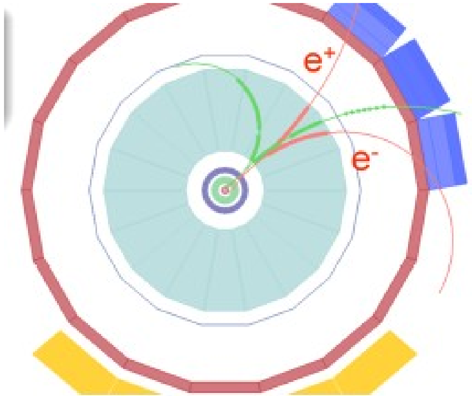
Ramona Lea, SQM2013

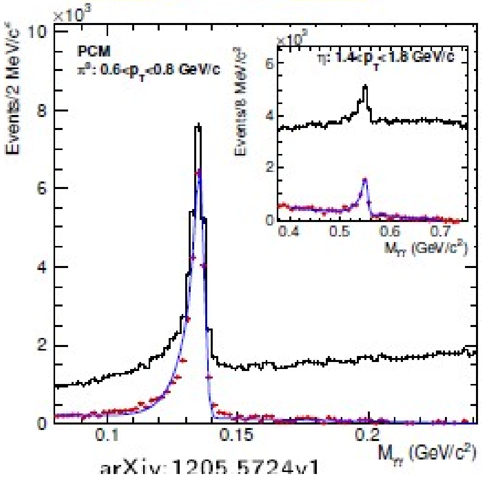


No signal observed, H yield is < 0.1 x (thermal model prediction)
Much more stringent limits to come soon

Measurement of the fireball temperature via photon emission

Photons and neutral mesons measured via the conversion method in the ALICE TPC, see, .e.g, M. Wilde (ALICE coll.) QM2012

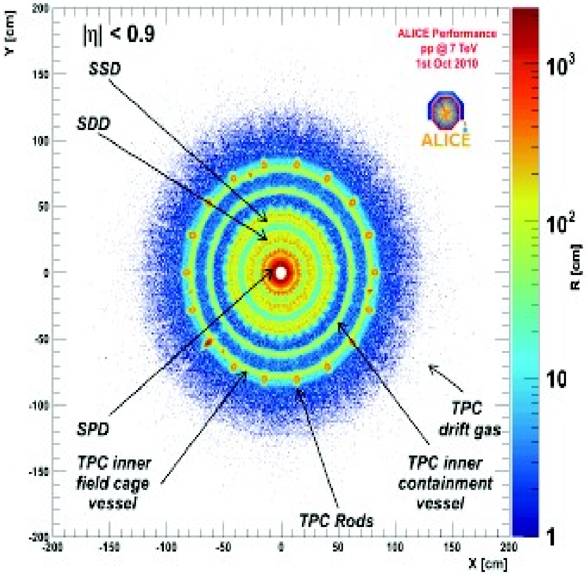


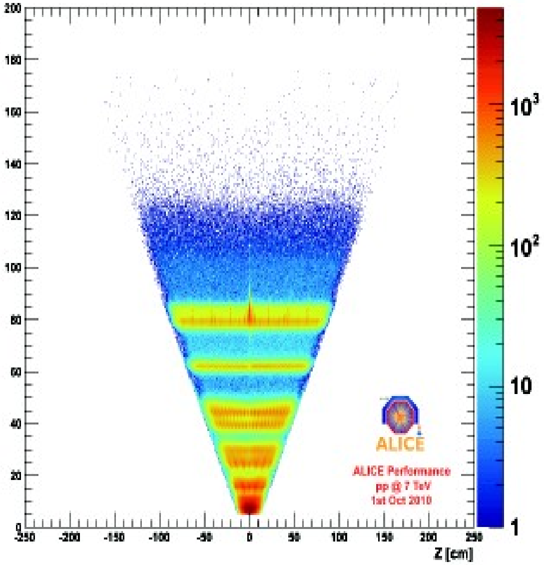


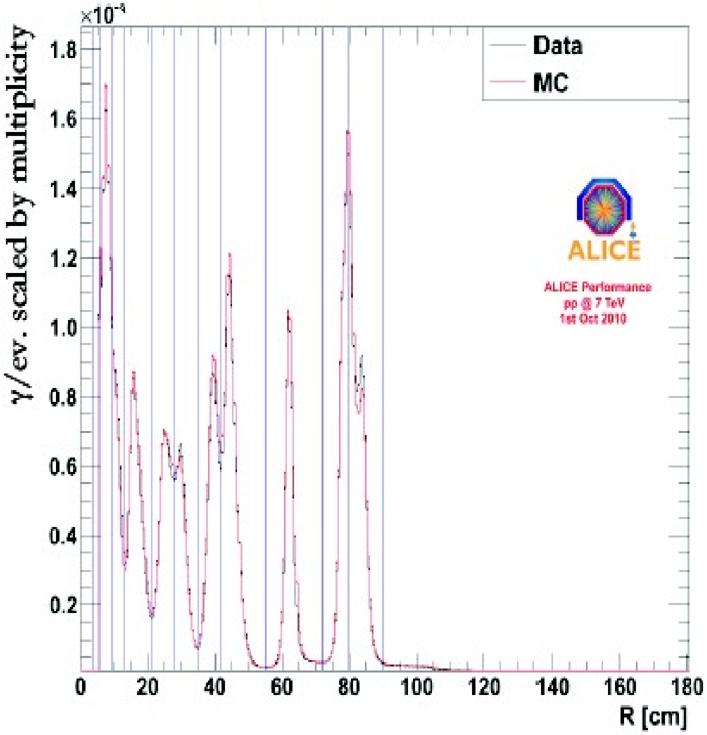
arXiv:1205.5724v1

γ-ray tomography of ALICE

Conversions provide a γ-ray tomography of ALICE.
Very useful tool to check the material budget.
For ALICE this is very well known (down to ± 6% accuracy).







Resolution:
Better than 3 cm in R, 1.5 cm in Z and 2.5 mrad in Φ.

method

- Direct Photon Signal: $\gamma_{direct} = \gamma_{inc} - \gamma_{decay} = (1 - \frac{\gamma_{decay}}{\gamma_{inc}}) \cdot \gamma_{inc}$

- Double Ratio: $\frac{\gamma_{inc}}{\pi^0} / \frac{\gamma_{decay}}{\pi^0_{param}} \approx \frac{\gamma_{inc}}{\gamma_{decay}}$ if > 1 direct photon signal

  $\rightarrow$ cancellation of uncertainties

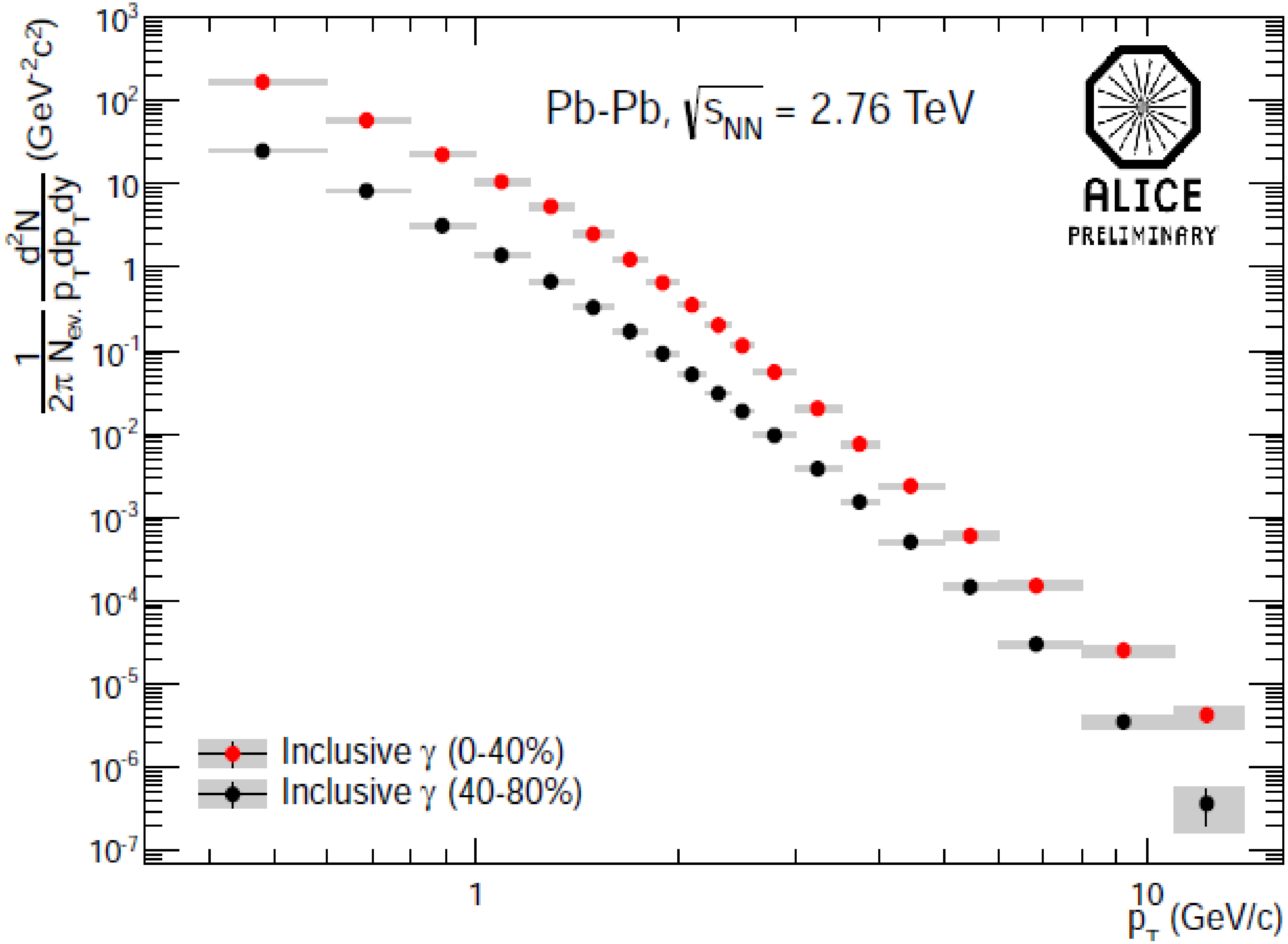
- Numerator: Inclusive γ spectrum per π^0
- Denominator: Sum of all decay photons per π^0

  Decay photons are obtained by a cocktail calculation

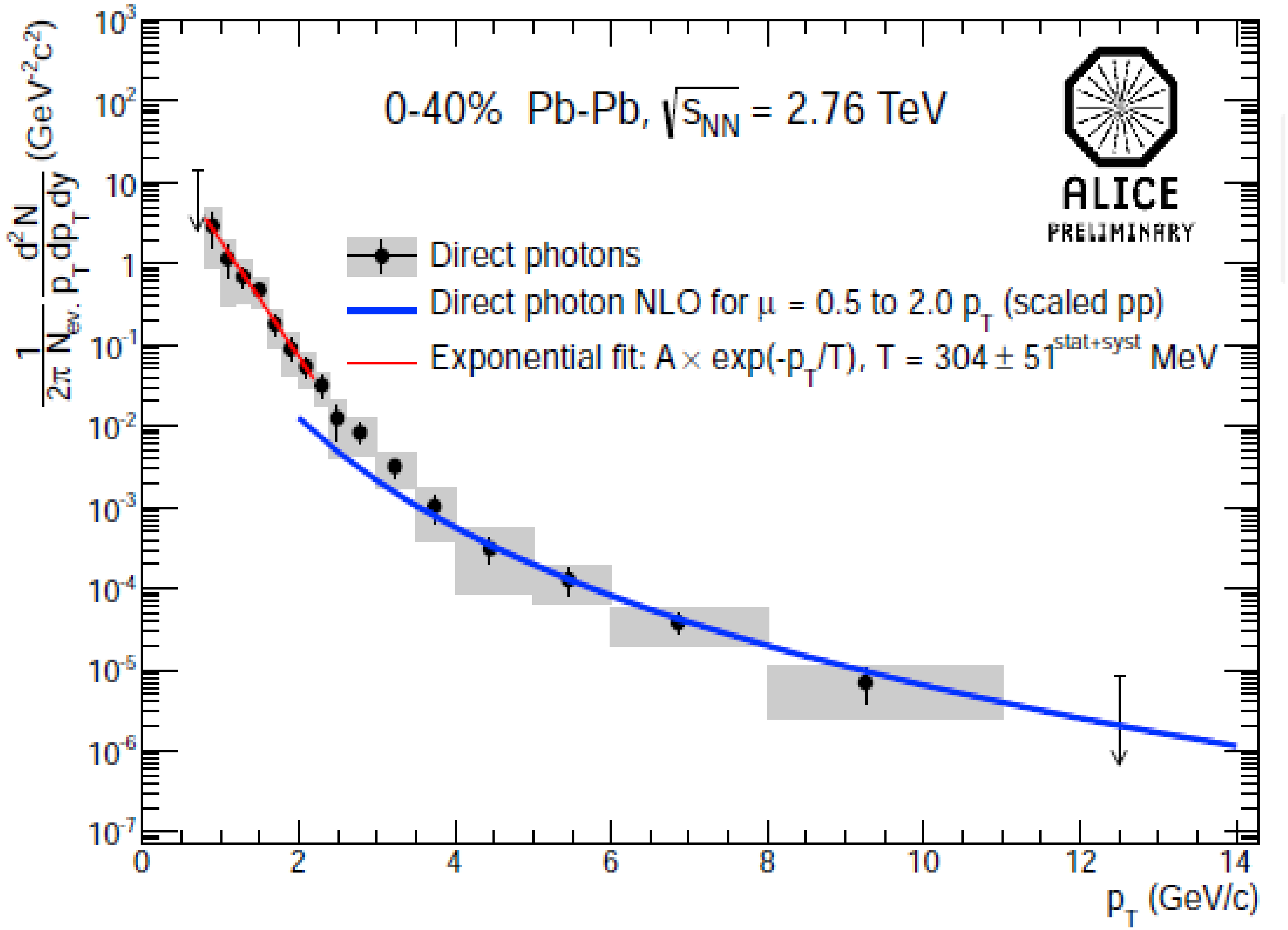
- Photons and π^0s are measured via conversion method

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

Inclusive photon measurement in Pb-Pb collisions



Final result

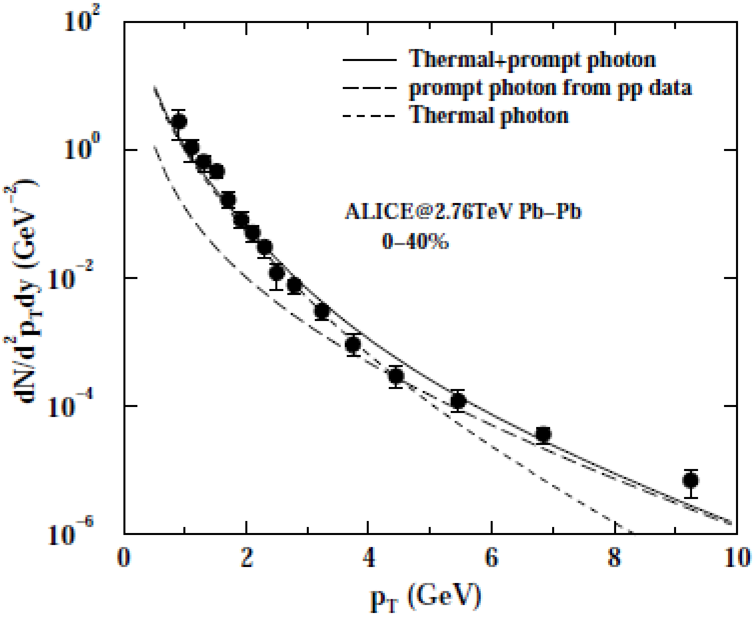


average T = 304 +/- 51 MeV highest ever measured temperature

Interpretation in terms of fireball parameters

Sukanya Mitra, Payal Mohanty, Sabyasachi Ghosh, Sourav Sarkar, Jan-e Alam. Mar 4, 2013.

e-Print: arXiv:1303.0675



note: T_i = 3.2 x T_c

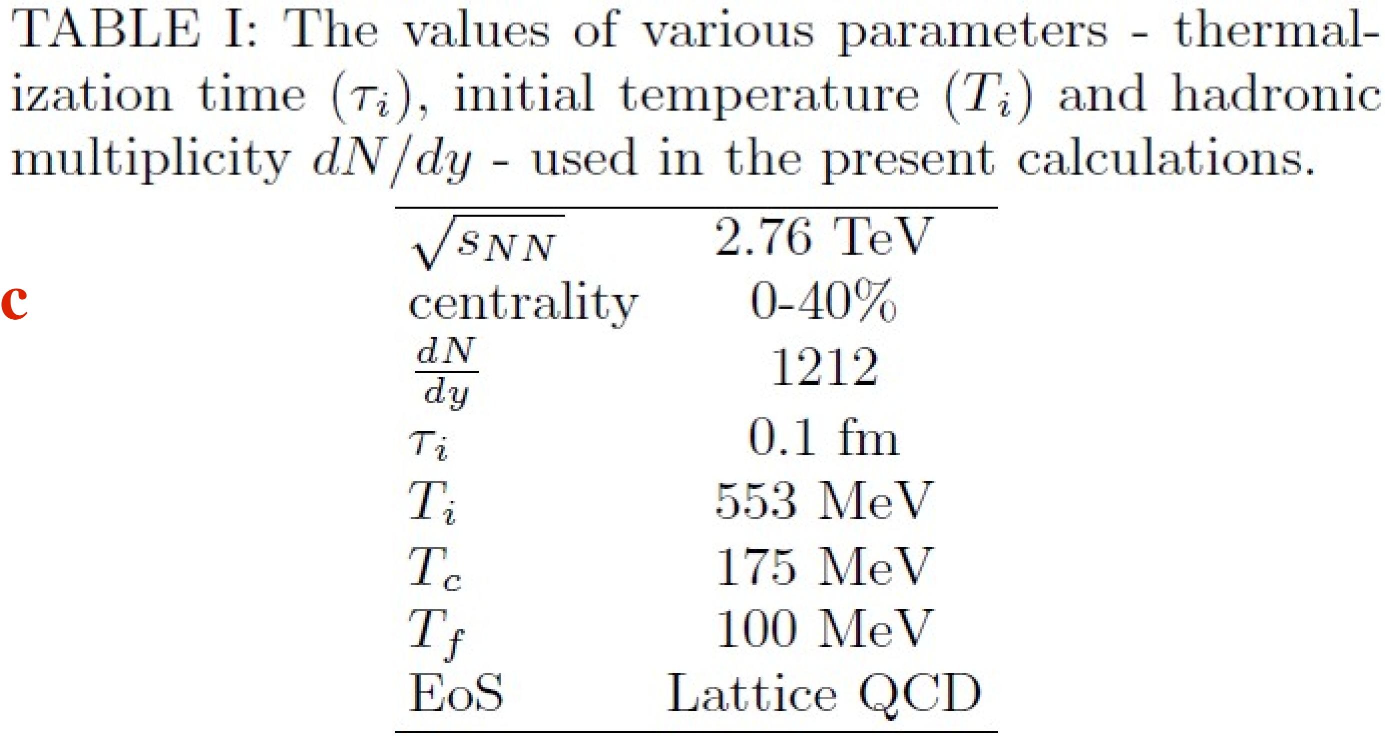


TABLE I: The values of various parameters - thermalization time (τ_i), initial temperature (T_i) and hadronic multiplicity dN/dy - used in the present calculations.

$\sqrt{s_{NN}}$	2.76 TeV
centrality	0-40%
$\frac{dN}{dy}$	1212
τ_i	0.1 fm
T_i	553 MeV
T_c	175 MeV
T_f	100 MeV
EoS	Lattice QCD

Thermal photons also exhibit flow

most hydro-models produce little flow for thermal photons

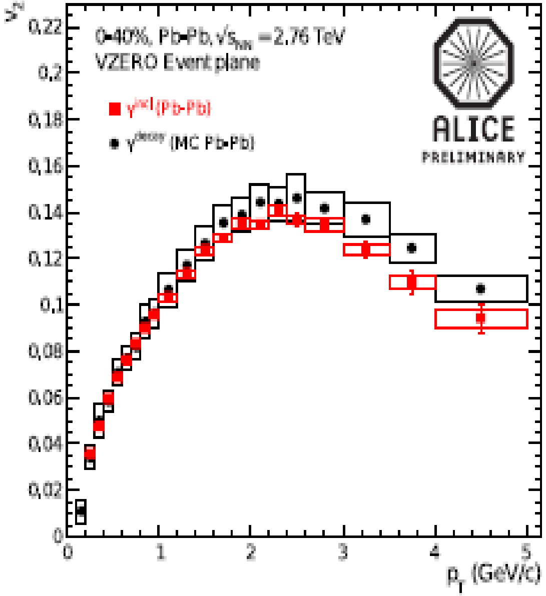


Figure 4: Inclusive photon $v_2^{\gamma,\mathrm{inc}}$ and decay photon $v_2^{\gamma,\mathrm{bg}}$ in 0–40 % Pb-Pb collisions.

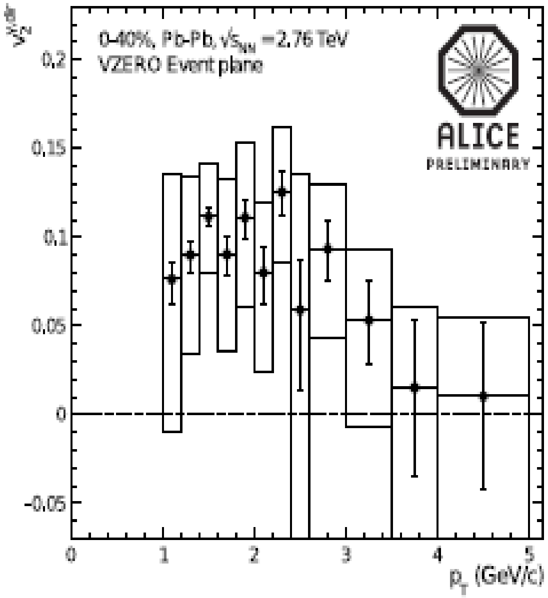


Figure 5: Direct-photon $v_2^{\gamma,\mathrm{dir}}$ in 0–40 % Pb-Pb collisions.

see the 2 papers for a (conflicting) analysis

O. Linnyk, V.P. Konchakovski, W. Cassing, E.L. Bratkovskaya. Apr 25, 2013.

e-Print: arXiv:1304.7030

Ralf Rapp (Texas A-M, Cyclotron Inst. & Texas A-M). Oct 2011. 30 pp.

Published in Acta Phys.Polon. B42 (2011) 2823-2852

Phenix results on thermal photons and Rapp's interpretation
arXiv:1110.4345

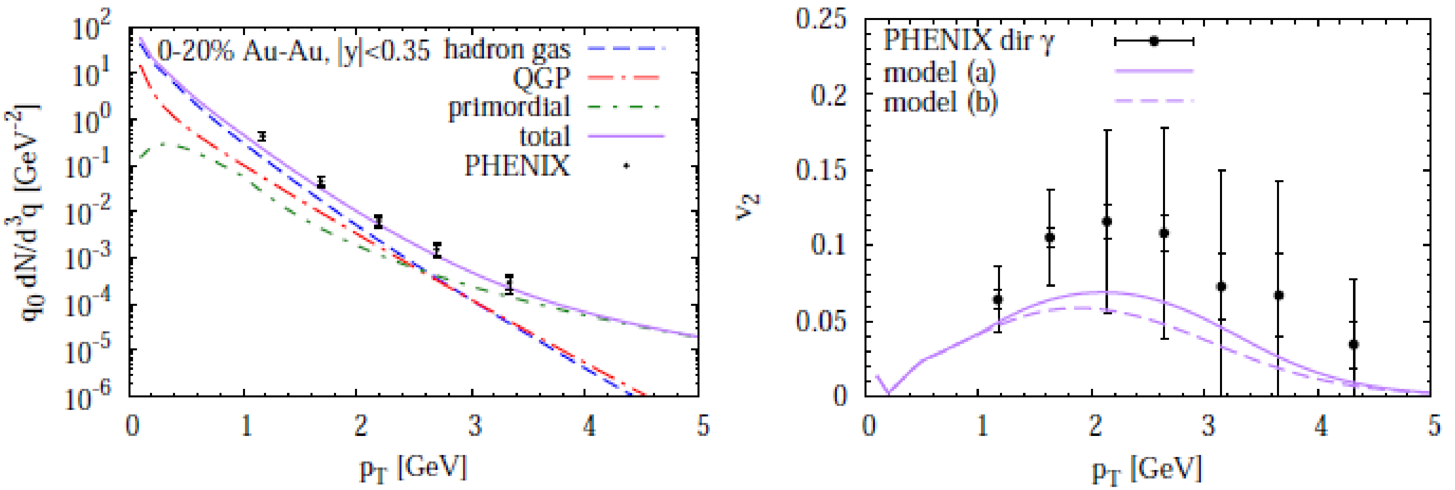
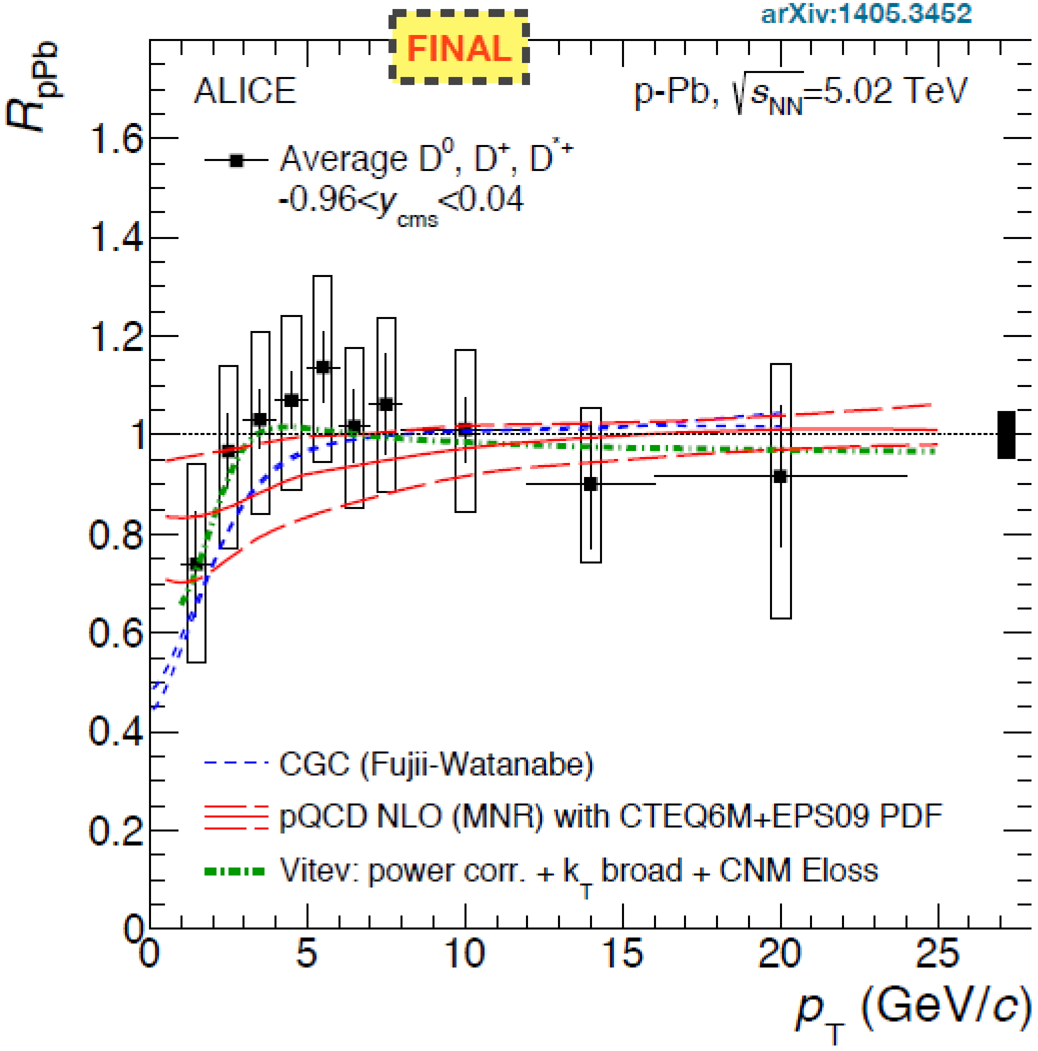


Fig. 14. Transverse-momentum spectra (left panel) and elliptic flow (right panel) of direct photons in 0-20% central Au-Au($\sqrt{s}$=200 AGeV) collisions at RHIC, compared to PHENIX data [49, 54]. The curves are calculations [55] with a realistic fireball evolution employing thermal QGP and hadronic rates which are “dual” around T_c, corresponding to Fig. 9.

In this approach, large initial temperatures are not required, and the spectral shapes are due to very strong radial flow.

Precision measurements are needed to separate the different approaches.


arXiv:1405.3452
FINAL
ALICE
p-Pb, $\sqrt{s_{NN}}$=5.02 TeV
Average D^0, D^+, D^{*+}
-0.96<y_{cms}<0.04
R_{pPb}
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
CGC (Fujii-Watanabe)
pQCD NLO (MNR) with CTEQ6M+EPS09 PDF
Vitev: power corr. + k_T broad + CNM Eloss
0
5
10
15
20
25
p_T (GeV/c)