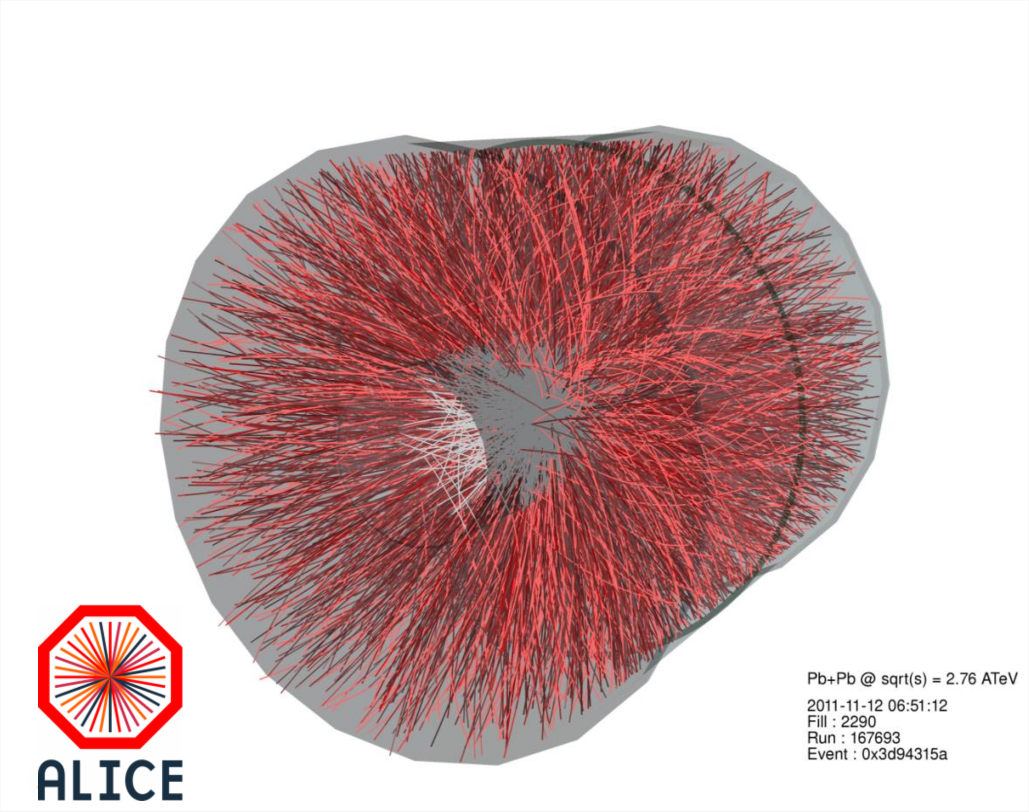
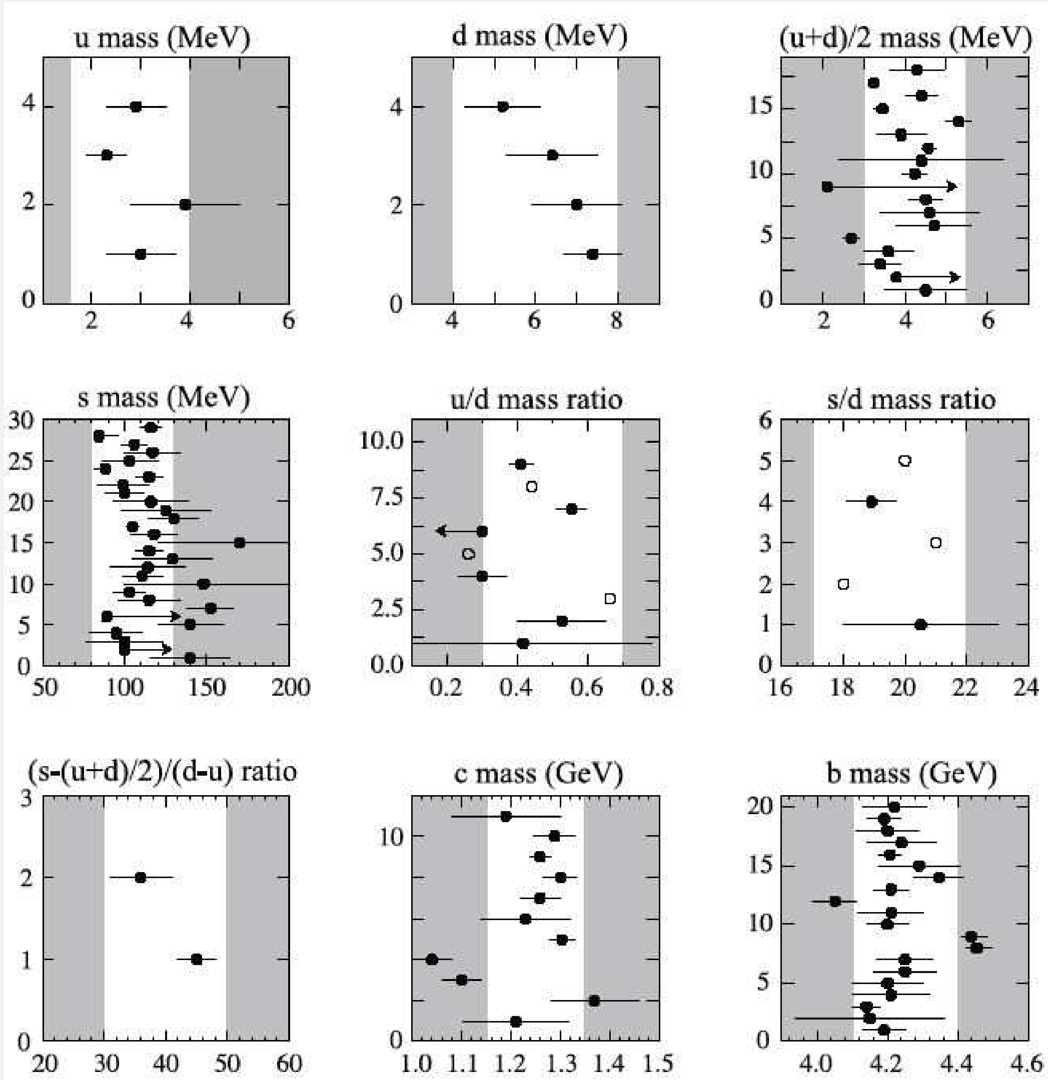
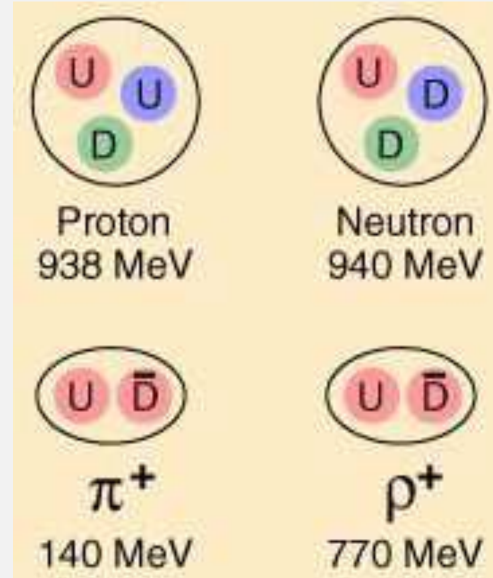
Fyzika s ťažkými iónmi alebo malý tresk



Karel Šafařík, CERN

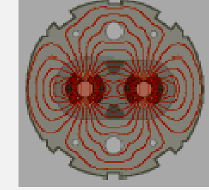
Hmotnosť nukleónov





Σ hmotnosti kvarkov ~
~ 1 % hmotnosti p/n !

väzbová energia



Vákum v QED a QCD
kvantová elektrodynamika: QED
kvantová chromdynamika: QCD

- **Energia páru nábojov spontánne narodených vo vákuu – kvantová fluktuácia (h = 1, c = 1):**

$$E_{kin} = p \sim 1/r \qquad (p \times r \geq 1)$$

$$E_{pot} = -\, q^2/(4\pi r) \qquad (q = e \text{ or } q = g_s)$$

$$E = E_{kin} + E_{pot} = (1/r)\times(1 - q^2/4\pi)$$

- **v QED toto je pravda pre lubovlonú “škálu” (už po Planckovu “škálu” ~ 10^{-20} fm)**

- **v QCD to je však správne len pre velmi malé vzdialenosť, niekoľko fm (10^{-13} cm)**

Prípad QED

- **v QED**

$$q^2 = e^2 = 4\pi\alpha_{em}$$

  - α_{em} sa mení zo vzdialenosťou (polarizácia vákua)
  - **kde pre velké vzdialenosti** $\alpha_{em} = 1/137$
  - **pri EW (elektro-slabej) škále (r = 2×10^{-3} fm)** $\alpha_{em} = 1/128$
  - **pri Planckovej "škále" (r = 10^{-20} fm)** $\alpha_{em} = 1/76$

- **To znamená, ze číselný faktor pred 1/r:** $(1 - q^2/4\pi)$ **sa mení zo vzdialonosť'ou, ale**
  - **len málo, medzi 0.987 – 0.993 (i.e. 0.6%) ak meníme vzdialenosť od Planckovej "škály" až po nekonečno…**

Prípad QCD

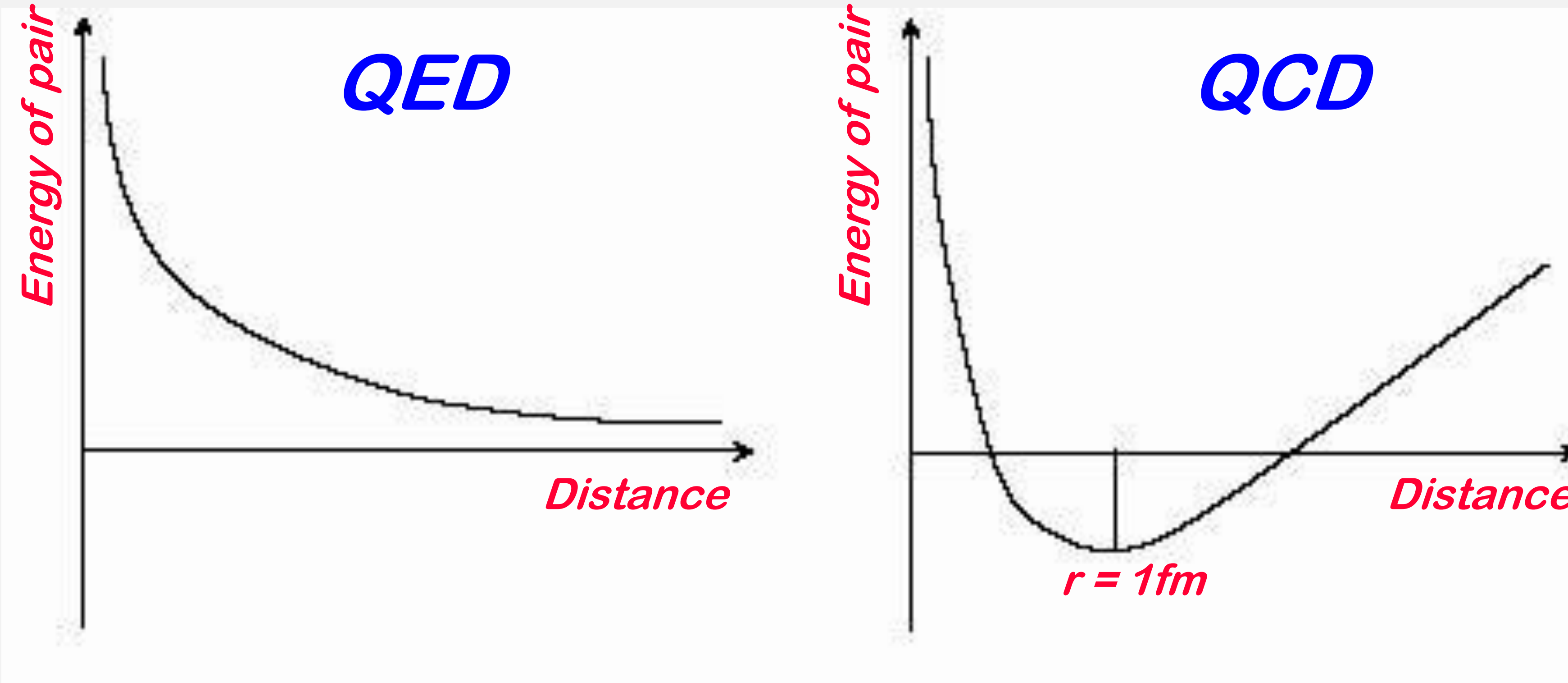
- **v QCD**

$$q^2 = g_s^2 = 4\pi\alpha_s$$

  - **kde α_s sa zmenšuje vel'mi rýchlo zo vzdialonost'ou (asymptotická sloboda)**
  - **pri Planckovej škále** $\alpha_s = 0.04$
  - **pri elektro-slabej skále** $\alpha_s = 0.118$
  - **pri $\Lambda_{QCD} \approx 0.2$GeV ($r \approx 1$ fm)** $\alpha_s \approx 1$

- **numerický faktor** $(1 - q^2/4\pi) = 1 - \alpha_s$
  - **sa znižuje so vzdialenost'ou, pri Planckovej škále je 0.96**
  - **ale pozor, pre $r \approx 1$ fm uz je záporný !**
- **pri vačších vzdialenostíach** je $E = \sigma\times r$ ($\sigma \approx 1$ GeV/fm)
  - **a tento faktor je opät' kladný**

QED versus QCD



Kinetická energia stále dominuje nad potenciálnou (pole je slabé)
virtual páry

Energia skrytá v poli prevázi pri nejakej vzdialenosti kinetickú
reálne páry – vakuový kondensát

Symetrie QCD

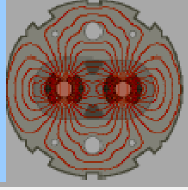
- **QCD má dve približné symetrie:**
  - Z_3–(centre) symetriu (pre čisto kalibračnú toer, v limite $m_q \to \infty$)
  - chirálnu symetriu (obnovenú pre nulové hmotnosti, t.j. $m_q \to 0$)

- **Pri vel’kých hustotách a teplotách sa nakoniec**
  - Z_3–symetria naruší (prechod od confinementu k deconfinementu)
  - chirálna symetria obnoví (chirálny fázový prechod)

- **Otázky:**
  - existuje jeden spoločný fázový prechod alebo dva nezávislé?
  - akého druhu je tento (tieto) fázový(é) prechod(y)
    - prvého druhu (má latentné teplo) ?
    - druhého druhu (len zlom) ?
    - alebo je to len cross-over prechod ?

Chirálna symetria

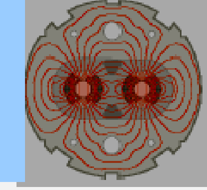
- **Pre $m_q \rightarrow 0$ helicita kavarkov sa zachováva**
  - **pretože gluóny majú helicity ±1 QCD teória v tejto limite má $SU(3)_L \times SU(3)_R$ symetriu**
    - **QCD svet sa rozpadol na dva svety ktoré navzájom nekomunikujú – lavácky svet a pravácky**
  - **ak dáme do QCD vákua nehmotný lavotočivý kvark, on môže anihilovat' s lavotočivým anti-kvarkom z vákuového kondenzátu – tým sa ale oslobodí pravotočivý kvark**
    - **pre vzdialeného pozorovatela naš testový kvark spontánne zmenil helicitu a preto musel nejako získat' dynamickú hmotnost' !**
    - **QCD kvark—anti-kvarkový kondenzátate generuje dynamické kvarkové hmotnost a narušuje chirálnu symetriu**
  - **ak zvýšime teplotu kinetická energia nabitého páru (nad nejakou hodnotou) prevýši potenciálnu energiu**
    - **kvark—anti-kvark kondenzát zmizne z vákua**
    - **chirálna symetria sa obnoví nad nejakou kritickou teplotou**
    - **hodnota $\langle 0|q\bar{q}|0\rangle$ je “order parameter” fázového prechodu**



Confinement (uveznenie)

- **hmotné kvarky v čisto gluónovom vákuume pri nulovej teplote**
  - **nie sú viditelné detektorom kvôli deštruktívnej inerferencii**
  - **expectation hodnota pre stopu kvarkového propagátoru – 3–hodnotový path integrál s rôznými fázami**

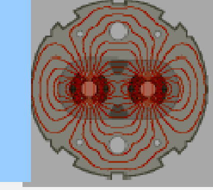
    $\exp(i \times 2\pi j/3)$, $j=1,2,3$ (generátory Z_3)
  - **zvyšujúc teploty** T **až po nejakú hodnotu toto zostane tak**
    - **až pokial gluónové pole bude mat' dostatok času sledovat' (koherentný rearangement) náš testový farebný náboj**
  - **Dalšie zvýšenie teploty (nad nejakú kritickú hodnotu) gluónové pole nebude mat' dostatok času**
    - **Interferencia troch ciest sa naruší**
    - **test farebný náboj sa stane detekovatelný, bude deconfinovaný**
  - **Toto sa dá spočítat' analytickým predlžením kvarkového propagátoru v komplexnom case** ($t = +i/T$) **– Polyakov loop – ktorý sa stane nenulovým pre** $T > T_c$
    - **Polyakov loop je "order parameter" fázového prechodu**



Symetrie QCD

- **Obidve symetrie sú narušené dynamicky**
  - **Z_3 symmetria je narušená kinetickou energiou (pri vysokej T)**
    - **order parameter (Polyakov loop) je nulový pod T_c a nenulový nad**
    - **je to "order – disorder" fázový prechod, Z_3 je narušená nad T_c**
  - **chirálna symetria je narušená potenciálnou energiou (pri nizkej T)**
    - **order parameter (kvark—anti-kvarkový kondenzát) je nenulový pod T_c a nulový nad**
    - **je to "disorder – order" fázový prechod, chirálna symetria je obnovená nad T_c**
- **Obidve sú však narušené aj explicitne – hmotnosť'ou**
  - **pre malosť' m_q je reálne že scénar ohl'adom chirálnej symetrie zostane dobrým priblížením**
  - **ale čo so Z_3 symetriou, prečo nie je úplne zničená malosť'ou m_q ?**

Obnovenie konfinementu



- **Ked sa snažíme znižiť m_q z nekonečna na ich vlastnú (malú) hodnotu to co sa stane závisí od teploty:**
  - **pri nízkych teplotách m_q sa efektívne prestane znižovať keď prídeme pod dynamickú hmotnosť kvarku $M_q \approx 350$ MeV pretože chirálna symetria je narušená**
  - **Z_3 symetria zostane približnou symetriou pri nízkych teplotách aj po takomto tvrdom pokuse o explictné narušenie**
  - **narušenie chirálnej symetrie efektívne zvyšuje hmotnosti kvarkov a preto riadi obnovenie Z_3 symetrie**
  - **toto je argument preto, aby obidva fázové prechody nastali v tom istom bode**

Fázy QCD – hračkársky model

- **uvážme**
  - **fázu v confinemente (hadrónový plyn, HG) z piónov**
  - **deconfinovanú fázu (kvark—gluónovú plazma, QGP) z gluónov a dvoch typov (vôní) kvarkov**
  - **stavové rovnica pre ideálny plyn**

$$\varepsilon = (g/30)\,\pi^2 T^4\,,\quad p = \varepsilon/3 = (g/90)\,\pi^2 T^4$$

kde $g = n_b + (7/8)\, n_f$

- **pre HG** $n_b = 3$, $n_f = 0$

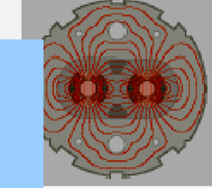
$$p_{HG} = (1/30)\,\pi^2 T^4$$

- **pre QGP:** $n_b = 16$, $n_f = 24$ ale teraz **máme aj vonkajší tlak od QCD vákua** B

$$p_{QGP} = (37/90)\,\pi^2 T^4 - B$$

- **na hranici dvoch fáz – tlak musí byt'rovnaký**

$T_c = (90B/34\pi^2)^{1/4} = 144$ MeV **pre** $B^{1/4} = 200$ MeV (**MIT bag model**)



Fázy QCD – poruchová teória

- **pri nenulovej baryónovej hustote – prvý rád p-QCD**

ε = [16(1 – 15α_s/4π) + (7/8)12n_q(1 – 50α_s/21π)] (1/30) $\pi^2 T^4$ +

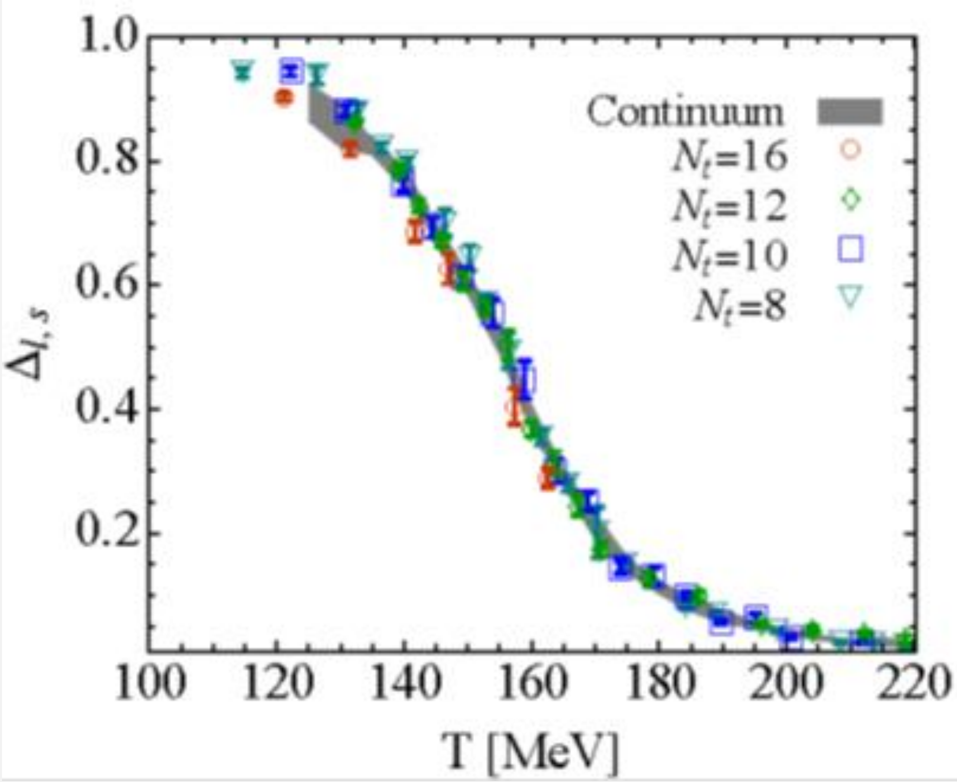
+ Σ_q 16(1 – 15α_s/2π) (3/ π^2)μ_q^2($\pi^2 T^4$ + μ_q^2(/2)

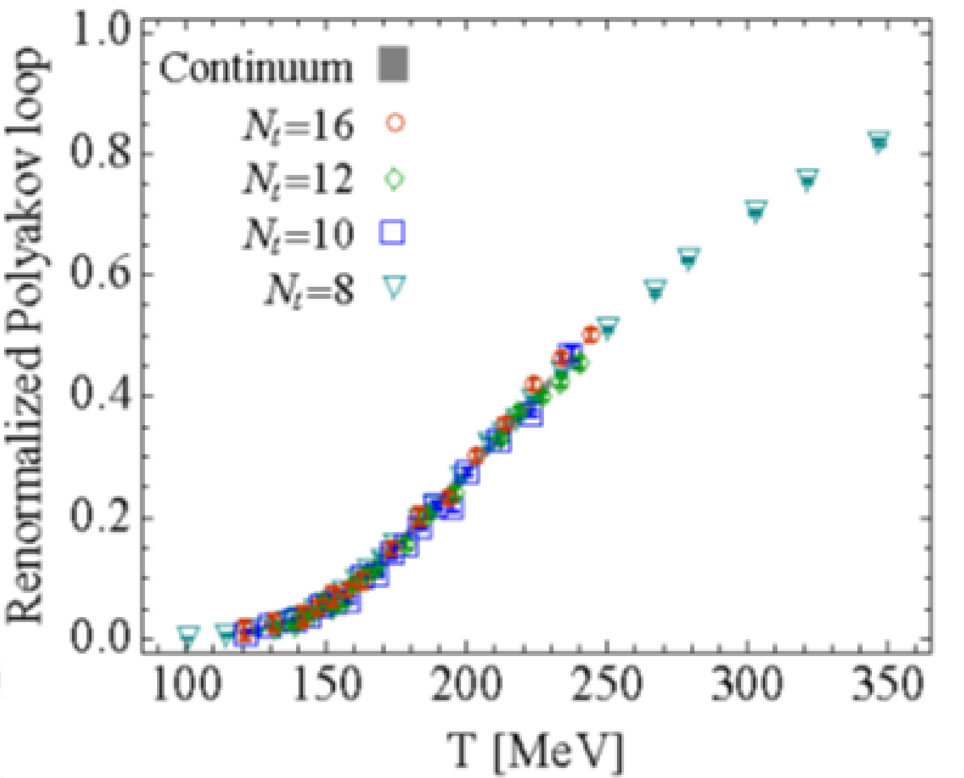
(pre μ_q = 0, α_s = 0, **a** n_q = 2 **dostaneme náš hračkársky model)**

použijúc α_s = 0.4 **tou istou cestou dostaneme** T_c = 164 MeV

- Dnes analytické výpočty existujú aj pre vyššie rády

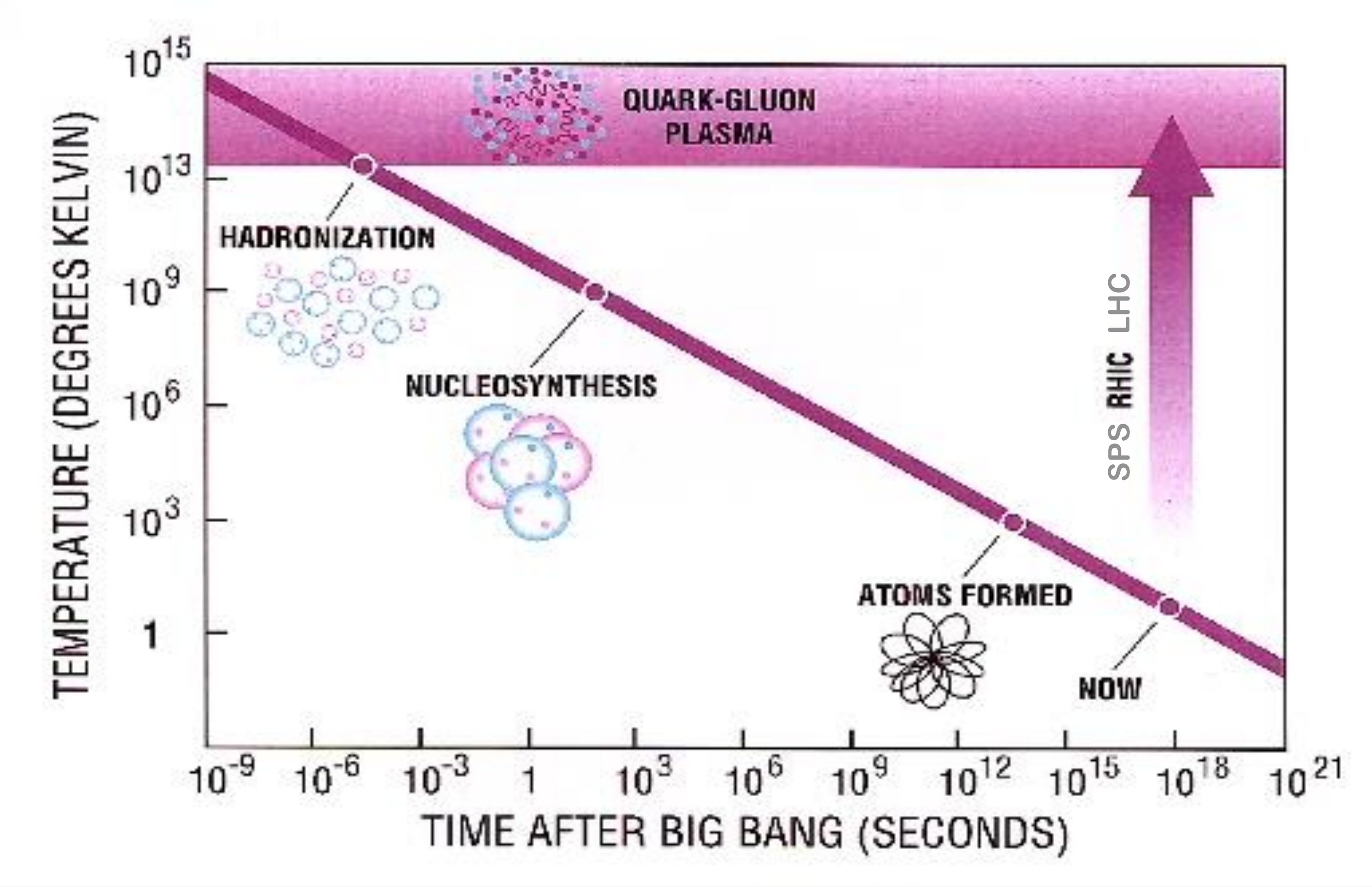
Lattice QCD at high temperature



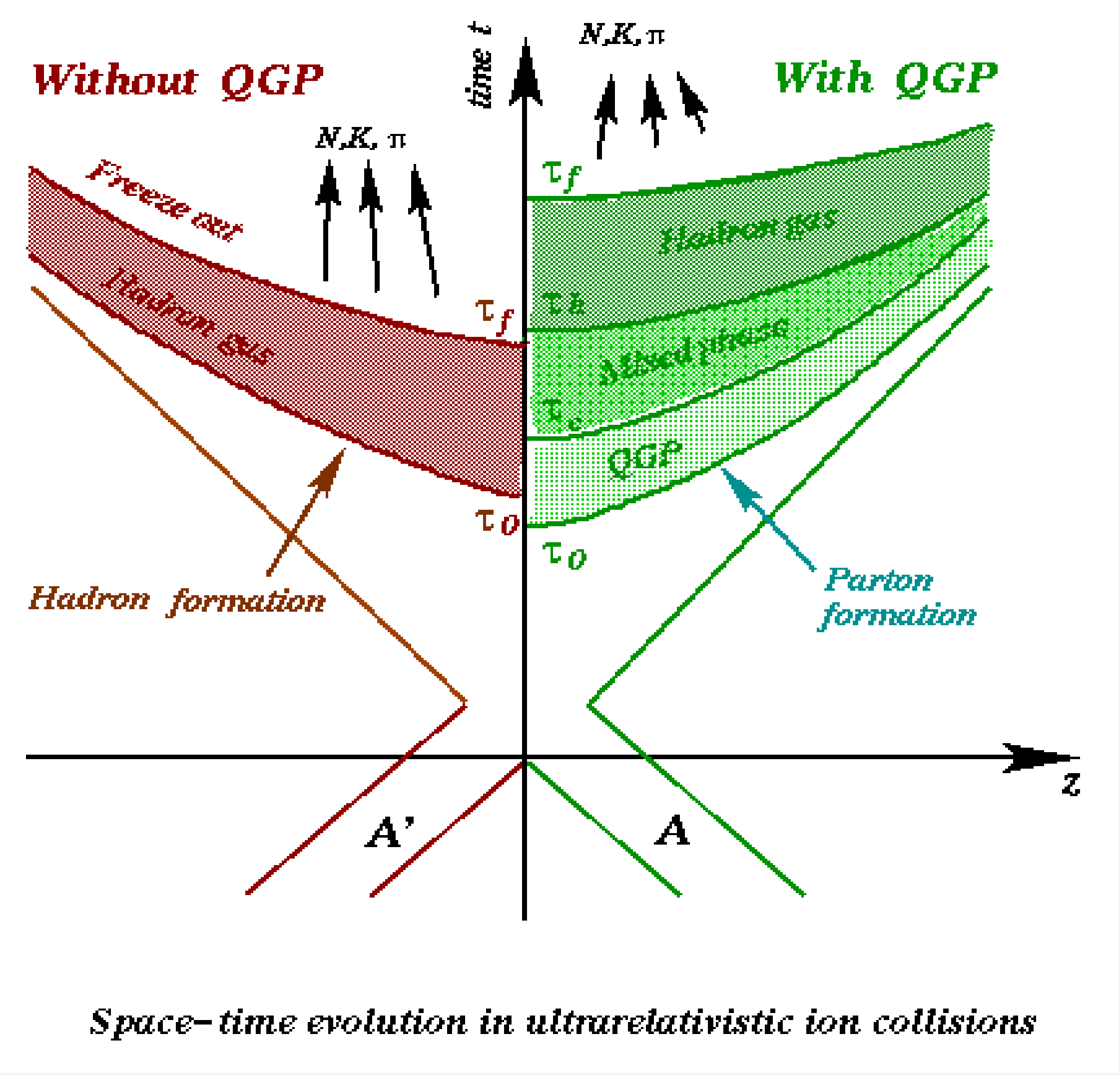


- Order parameters of QCD phase transitions:
  - quark – antiquark vacuum condensate
    - chiral phase transition in limit $m_q \rightarrow 0$
  - expectation value of Polyakov loop
    - deconfinement phase transition in limit $m_q \rightarrow \infty$

Big Bang


QUARK-GLUON PLASMA
HADRONIZATION
NUCLEOSYNTHESIS
ATOMS FORMED
NOW
SPS RHIC LHC
TEMPERATURE (DEGREES KELVIN)
10^{15}
10^{13}
10^{9}
10^{6}
10^{3}
1
10^{-9} 10^{-6} 10^{-3} 1 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18} 10^{21}
TIME AFTER BIG BANG (SECONDS)

Priestorovo-časový vývoj



R_{AA} and v_n – definitions

- R_{AA} – ratio of p_T spectrum in AA collisions to that in pp – properly normalized by number of binary collisions

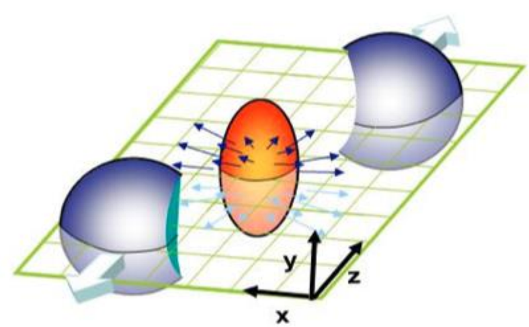
$$R_{AA} = \frac{(\mathrm{d}\sigma/\mathrm{d}p_T)_{AA}}{N_{bin}(\mathrm{d}\sigma/\mathrm{d}p_T)_{pp}} = \ \ldots$$

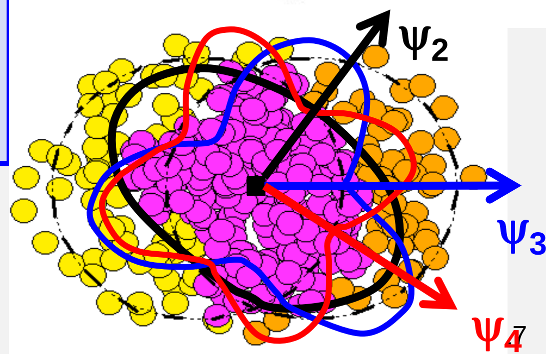
if AA would be just a superposition of pp collisions $R_{AA} = 1$

- v_n – Fourier coefficients of particle distributions in azimuthal angle φ with respect to n-th reaction plane

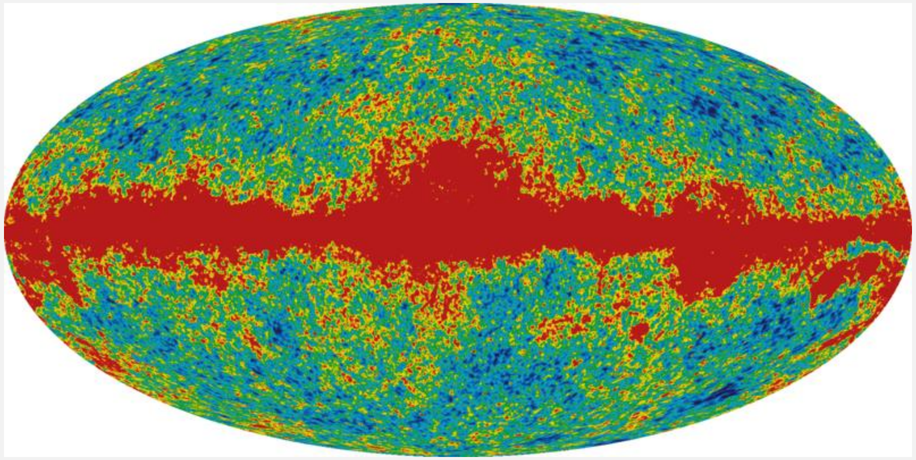
$$\frac{dN}{d\varphi}(\ldots) \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \psi_n)$$

$v_n = 0$ would mean azimuthally symmetric distribution



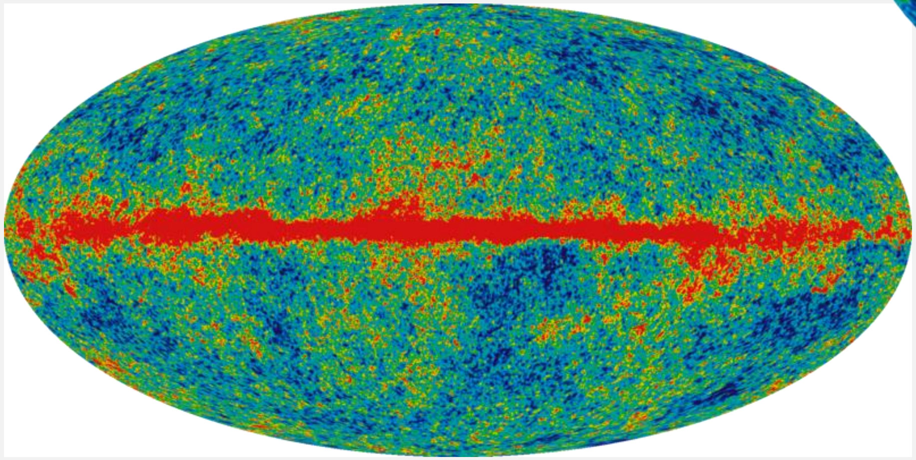


CMB maps

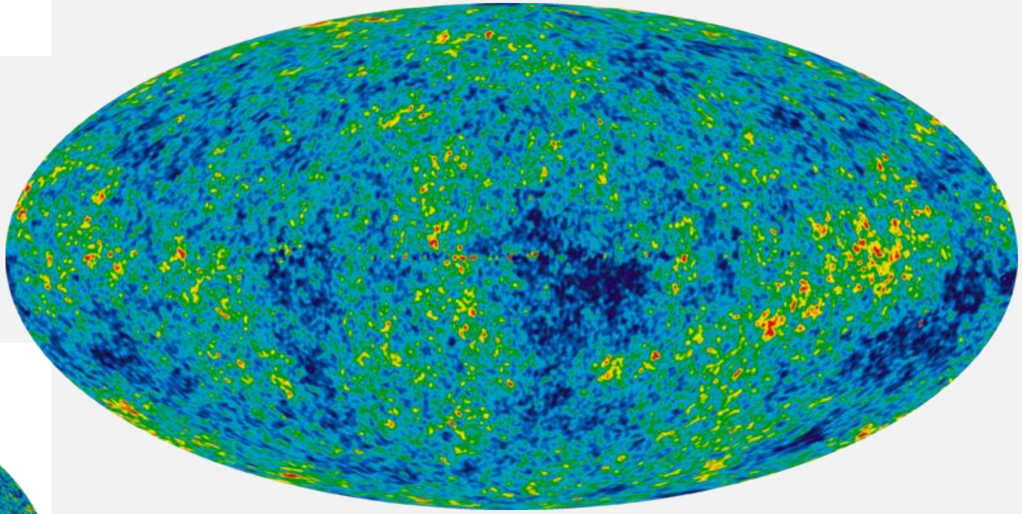


33 GHz with foreground

94 GHz with foreground



Final result, 7-years data
foreground subtracted



Inhomogeneities ~10^{-4} – 10^{-5}

WMAP results

- CMB power spectrum

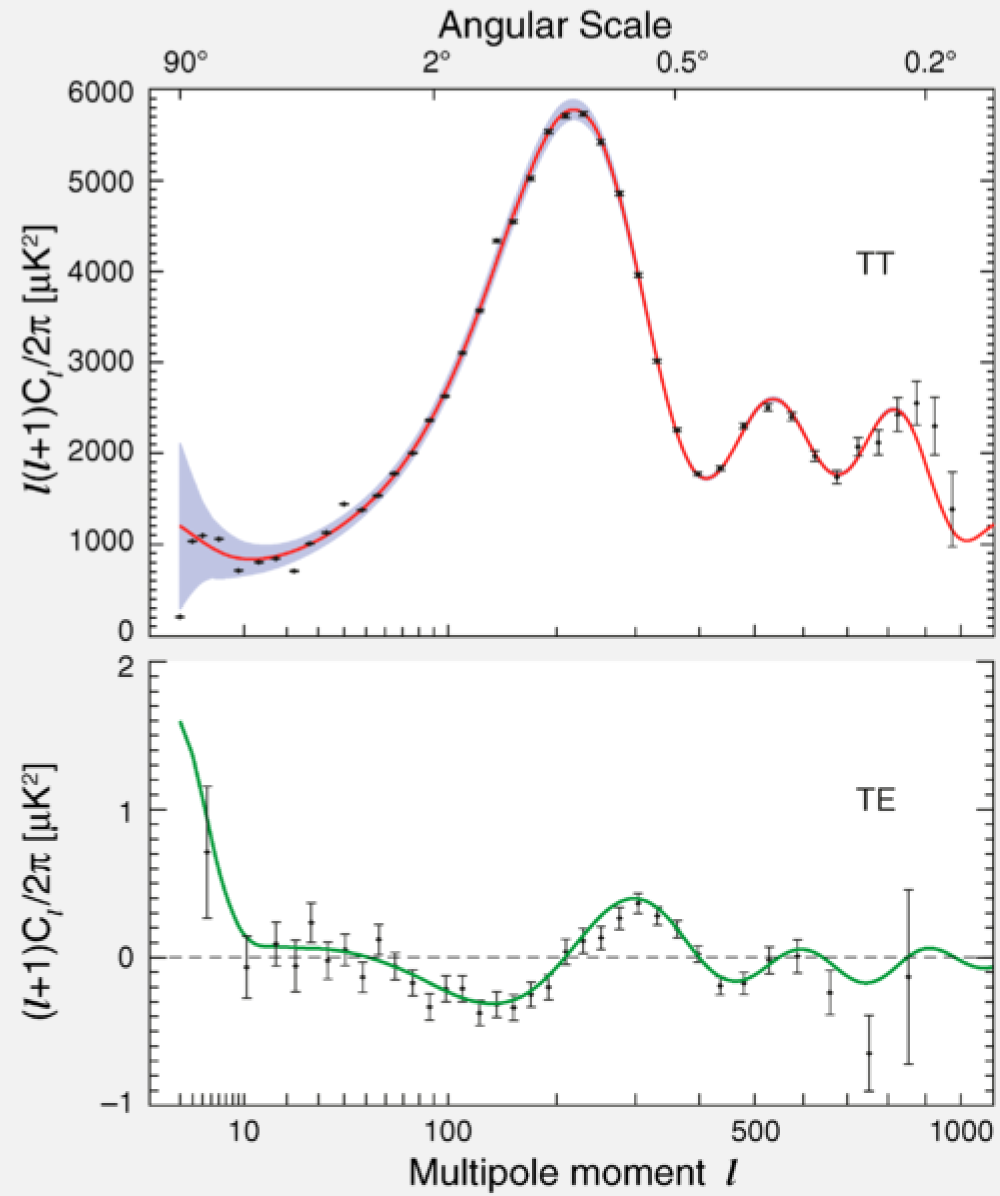
dipole moment gives our velocity 627±22 km/s

age of the Universe 13.75±0.11 x 10^9 years

total density of the Universe $1.0023^{+0.0056}_{-0.0054}$

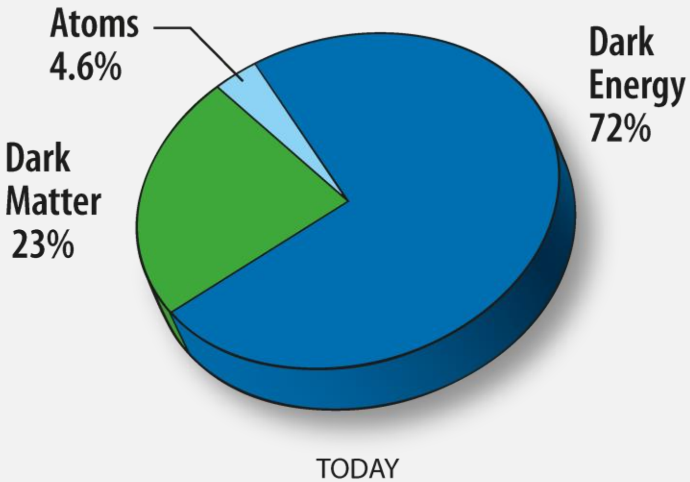
Hubble's constant $70.4^{+1.3}_{-1.4}$ (km/s) / Mpc

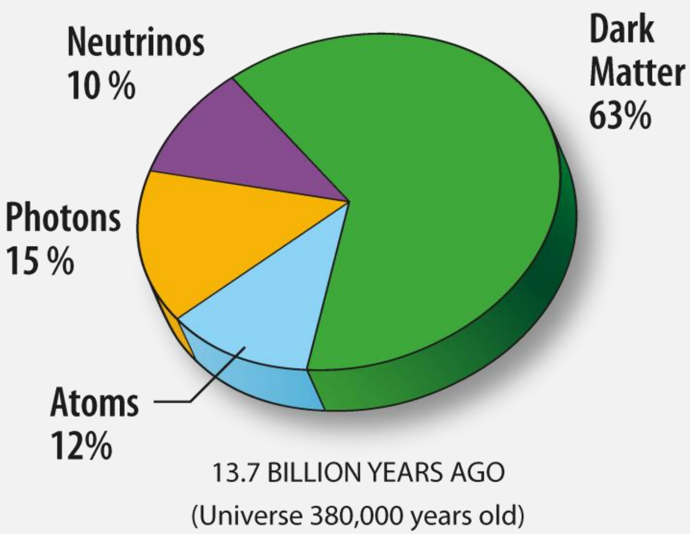
CMB temperature 2.725 K



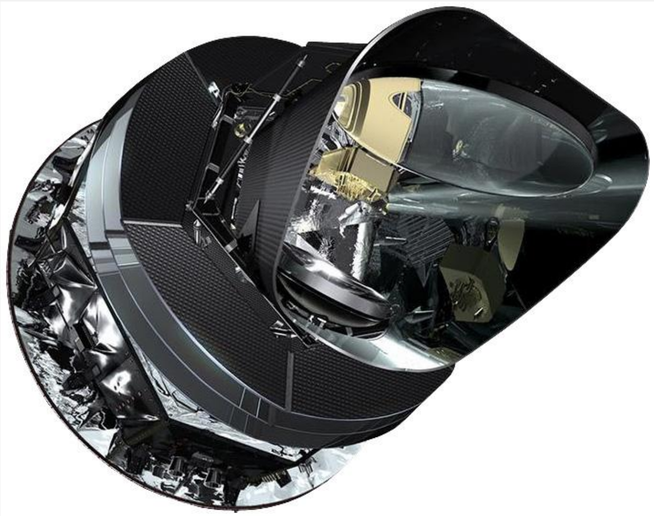
Composition of matter

- today 72% of matter of the Universe – dark energy
- before ~7 x 10^9 years the Universe accelerated its expansion
- vacuum energy? scalar field? cosmological constant?
- 23% is (cold) dark matter, what is it?





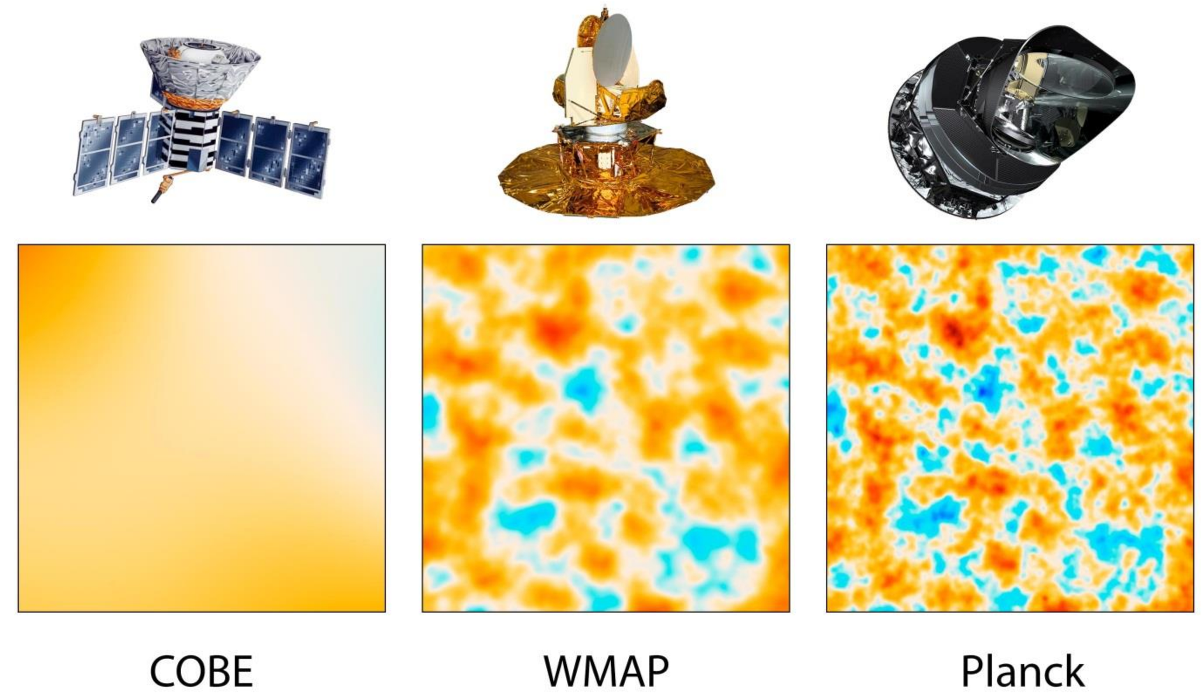
Planck satellite



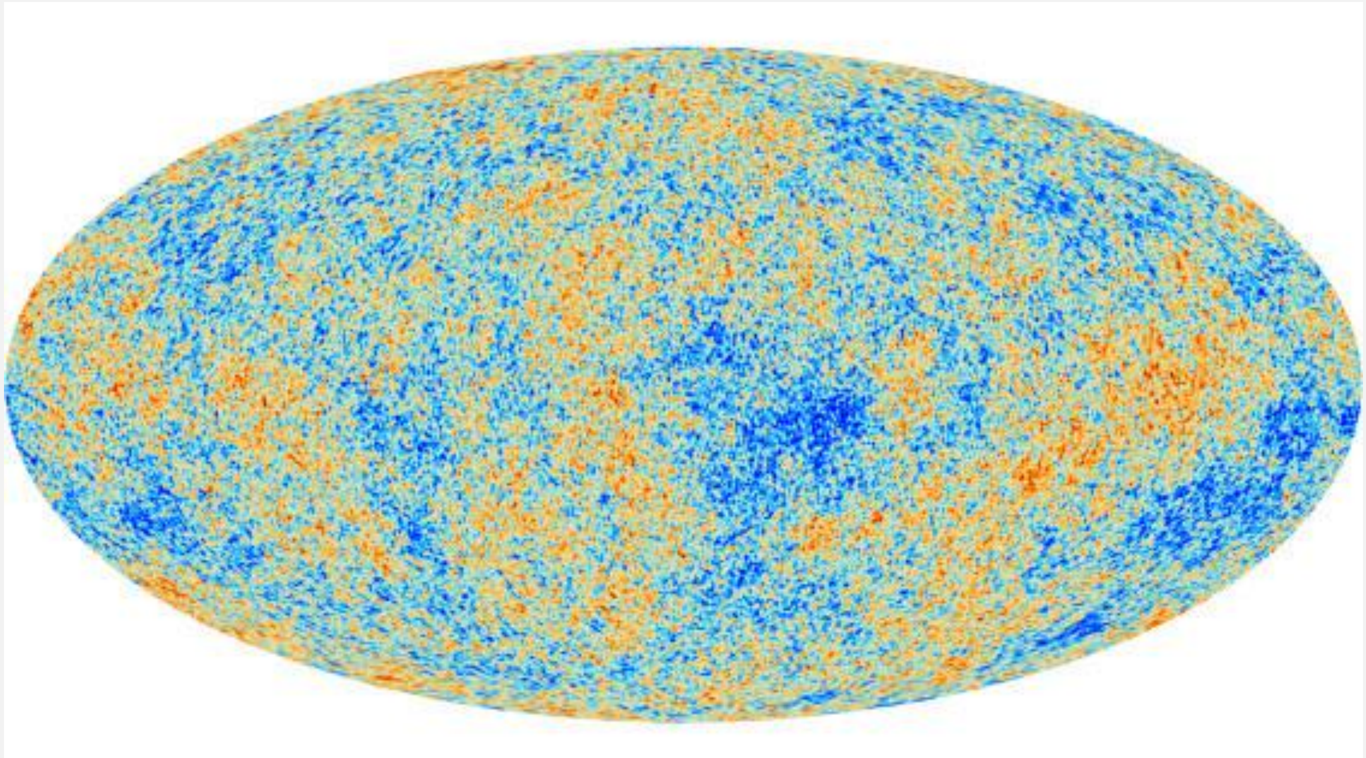
Porovnanie rozlíšania:

10 x lepšie rozlíšenie než WMAP

9 frequency band (WMAP 5)



Planck – prvé výsledky

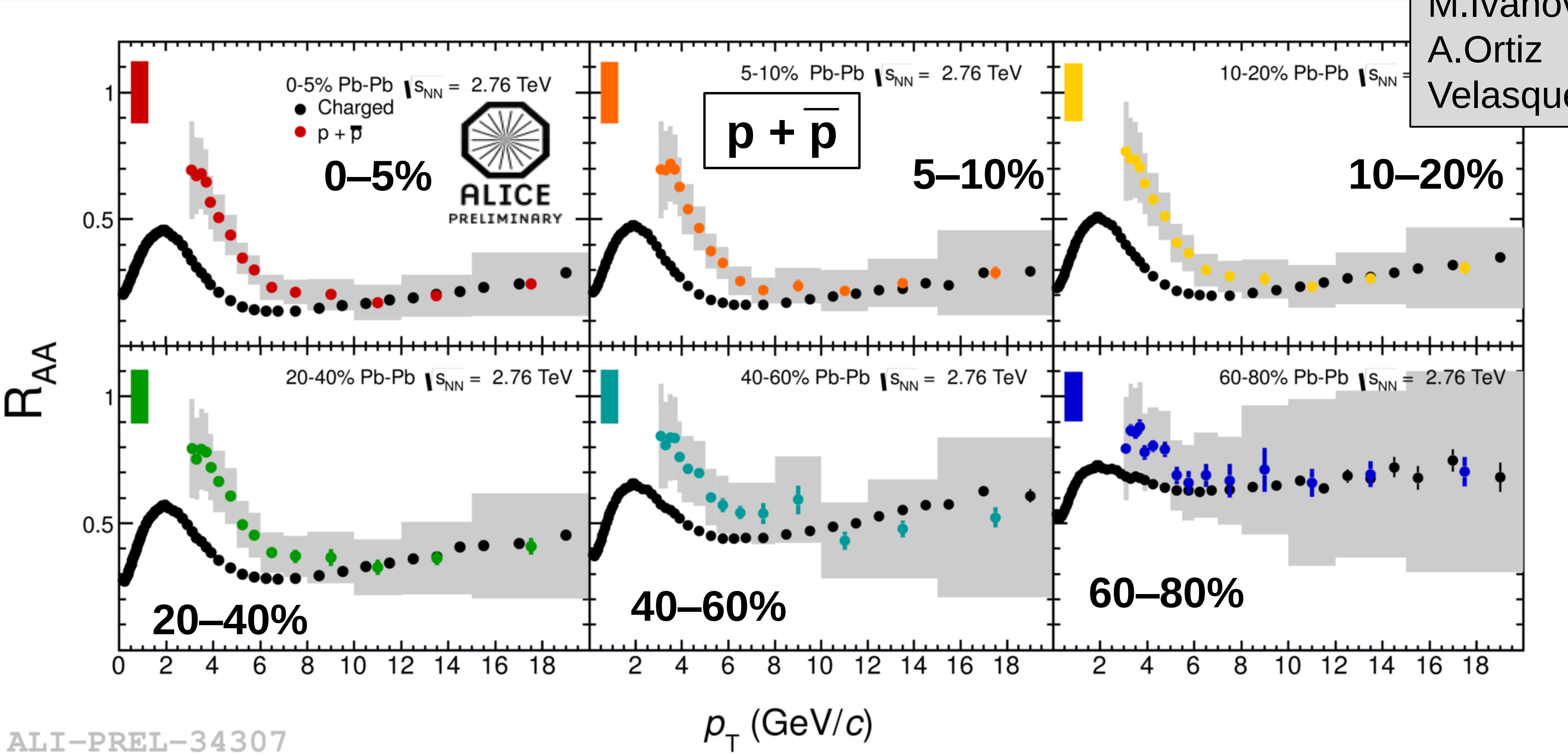


Age of Universe: 13.798 ± 0.037 x 10^9 years
Hubble constant: 67.80 ± 0.77 (km/s)/Mpc
Ordinary matter: 4.9 %
Dark matter: 26.8 %
Dark energy: 68.3%

Identified particles at intermediate p_T

● charged particles ●●●●●● different centralities for identified particles

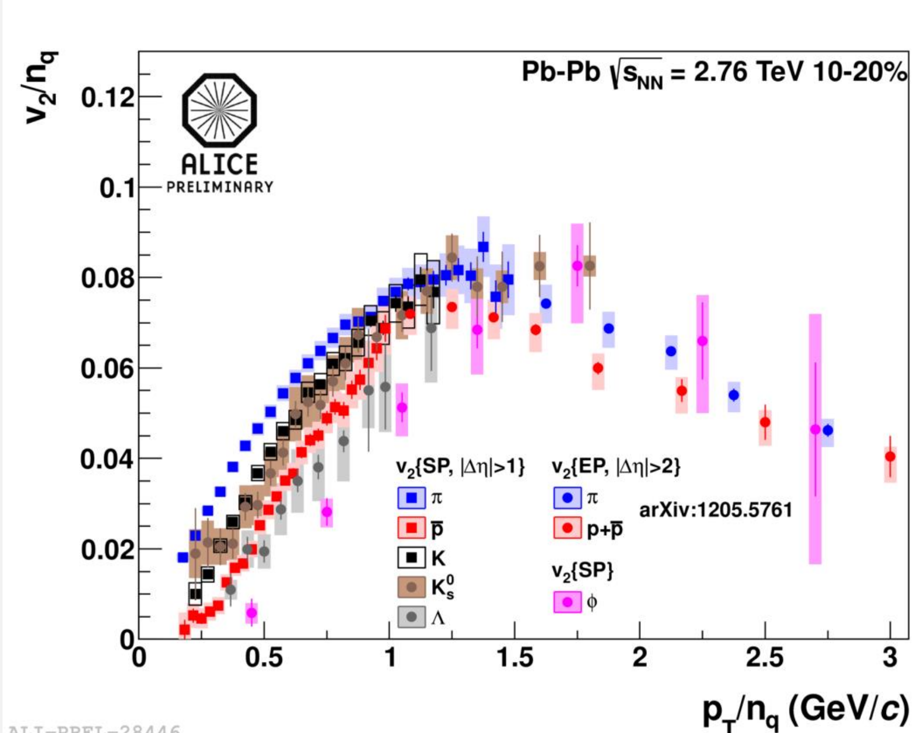
Talks by M.Ivanov A.Ortiz Velasquez

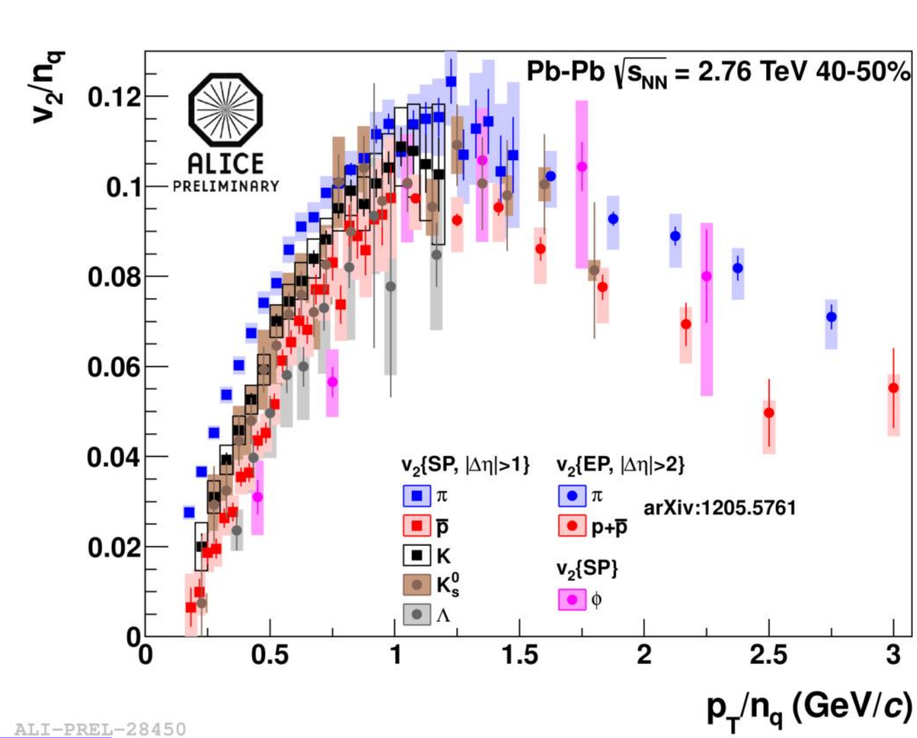


For p_T below ~ 7 GeV/c: $R_{AA}(\pi) < R_{AA}(h^{\pm})$, $R_{AA}(K) \approx R_{AA}(h^{\pm})$, $R_{AA}(p) > R_{AA}(h^{\pm})$

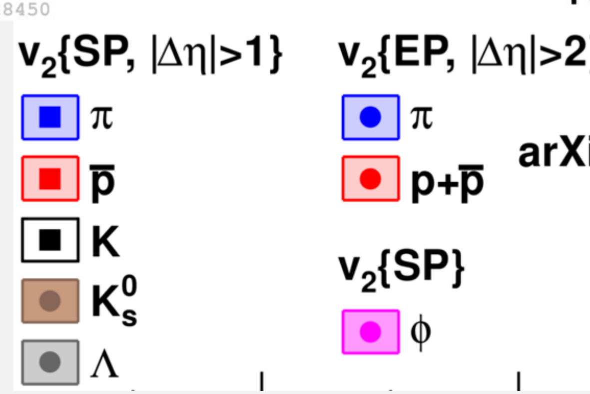
At higher p_T: R_{AA} are compatible

Identified-particle v_2





v_2 for π, p, K$^{\pm}$, K^0_s, Λ, ϕ (not shown for Ξ, Ω)
ϕ at low p_T (<3 GeV/c) follows mass hierarchy – at higher p_T joins mesons
overall qualitative agreement with hydro up to p_T 1.5–3 GeV/c (π–p); quantitative precision needs improvements – hadronic afterburner



arXiv:1205.5761

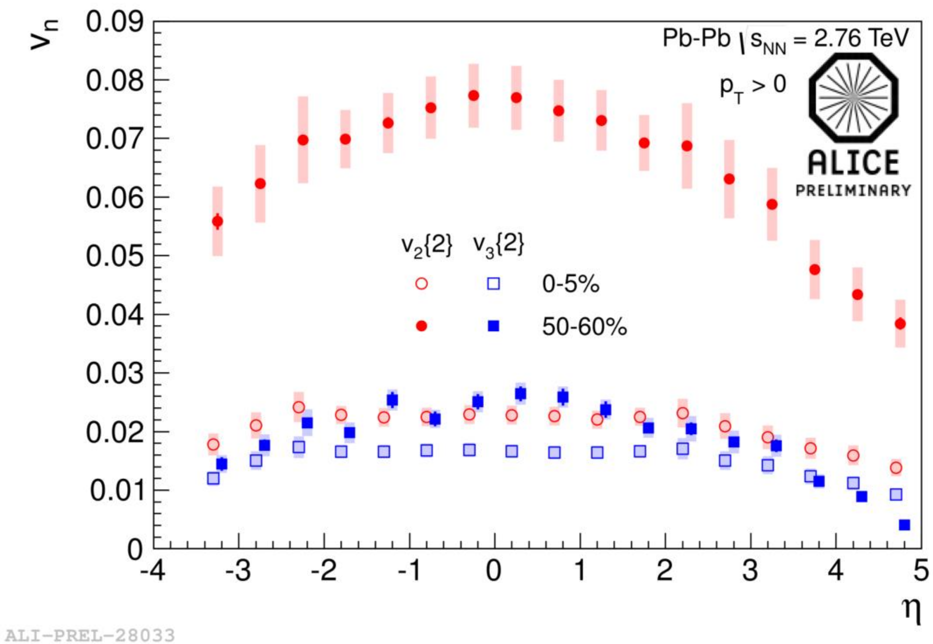
Talks by
S.Voloshin
F.Noferini

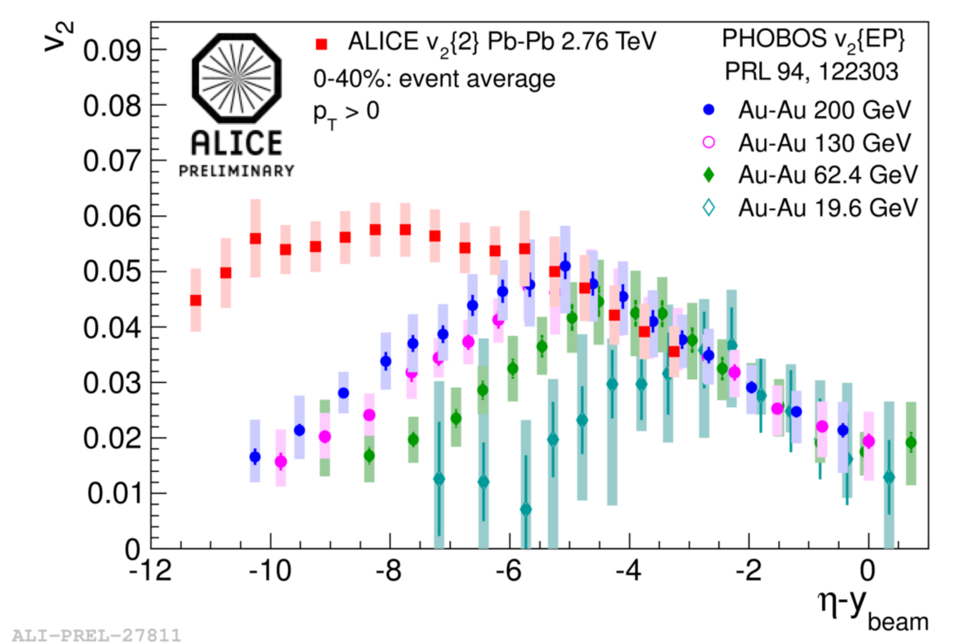
$n_q(m_T)$-scaling worse than at RHIC

$n_q(p_T)$-scaling at p_T > 1.2 GeV/c violation 10–20%

v_2 and v_3 versus η

ALICE





v_2 and v_3 measurements extended up to η = 5
observed plateau in pseudorapidity (|η| < 2)
very good agreement between ALICE and CMS for v_2 in |η| < 2.4

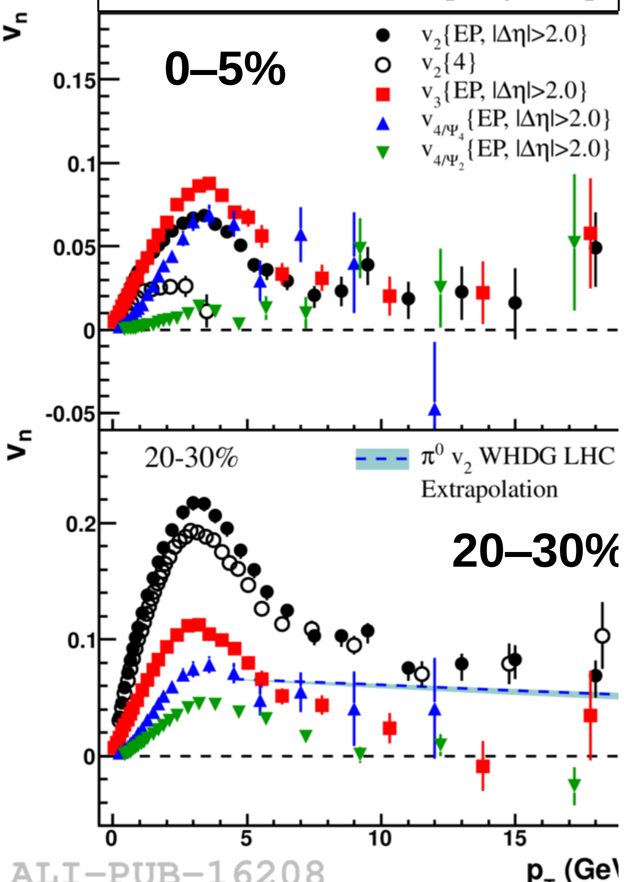
consistent with longitudinal scaling in $\eta - y_{beam}$ with PHOBOS data

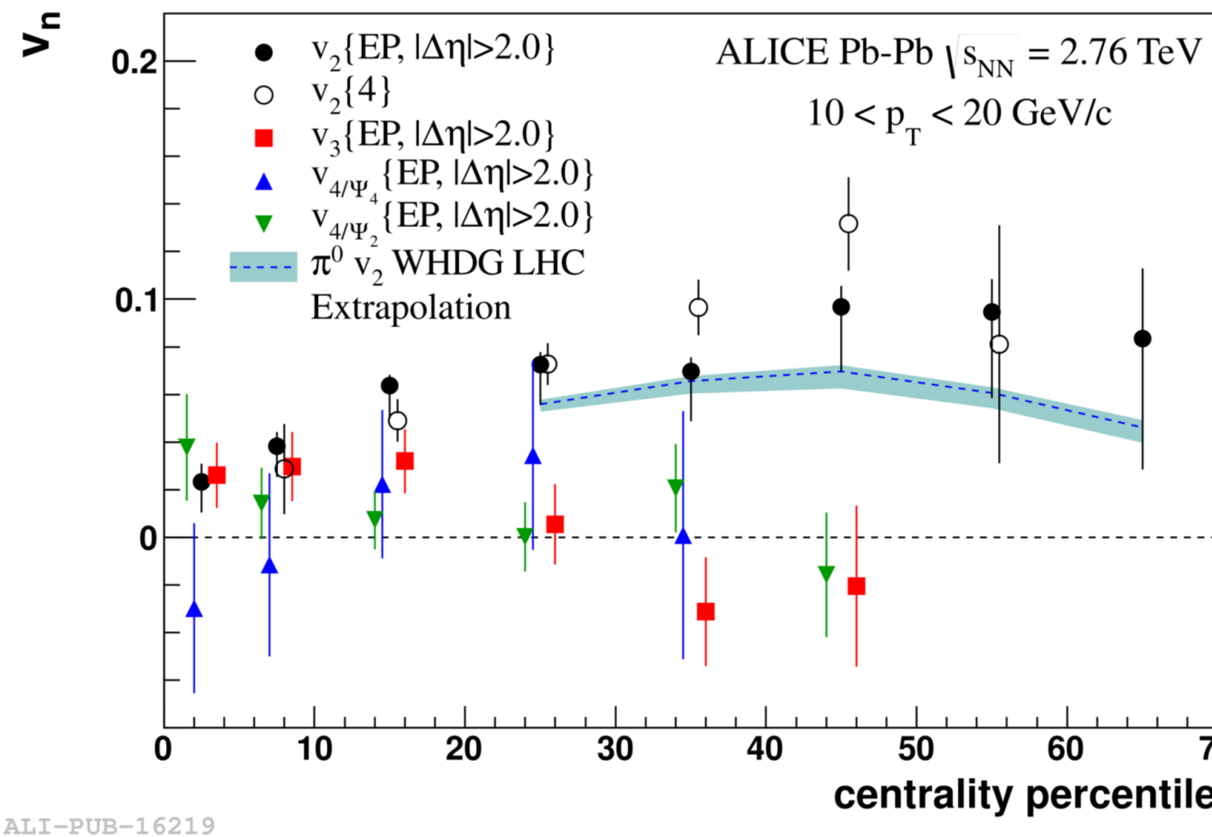
Talks by
S.Voloshin
A.Hansen

v_2 , v_3, v_4 versus p_T

arXiv:1205.5761 [hep-ex]

W.Horowitz,M.Gyulassy, J.Phys. G38 124114



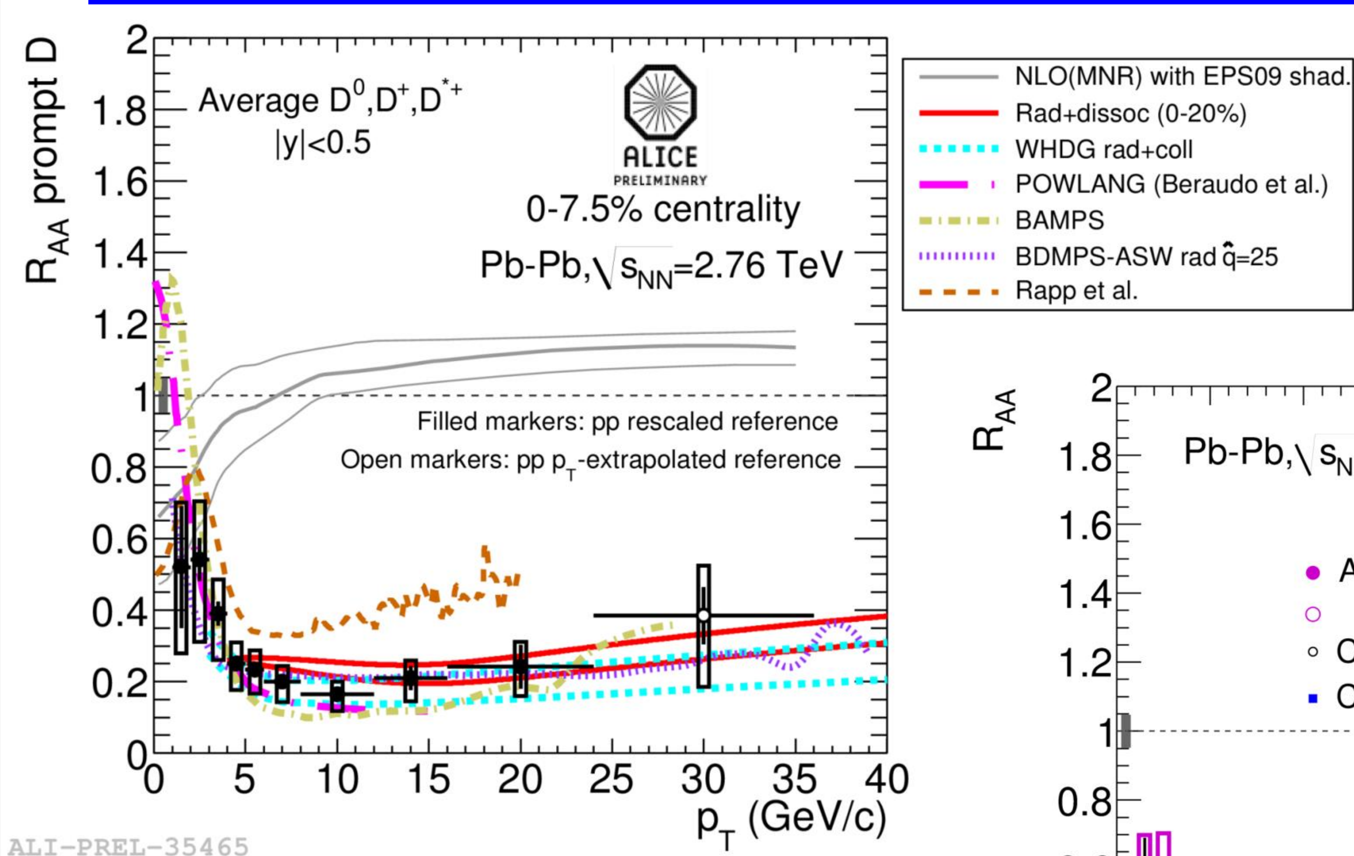


v_n measurements up to 20 GeV/c – where dominated by jet quenching
Non-flow effects suppressed by rapidity gap or using higher cumulants
Non-zero value of v_2 at high p_T both for $\Delta\eta$ > 2 and 4-particle cumulant

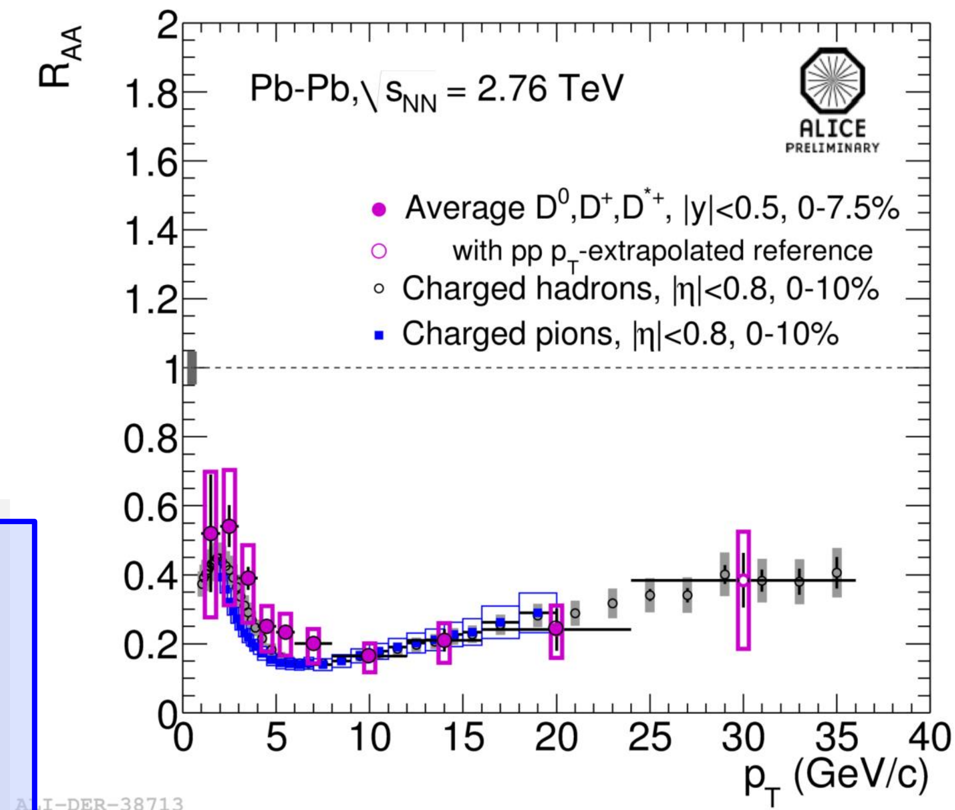
Talk by S.Voloshin

v_3 and v_4 diminish above 10 GeV/c – indication of disappearance of fluctuations at high p_T

D meson R_{AA}

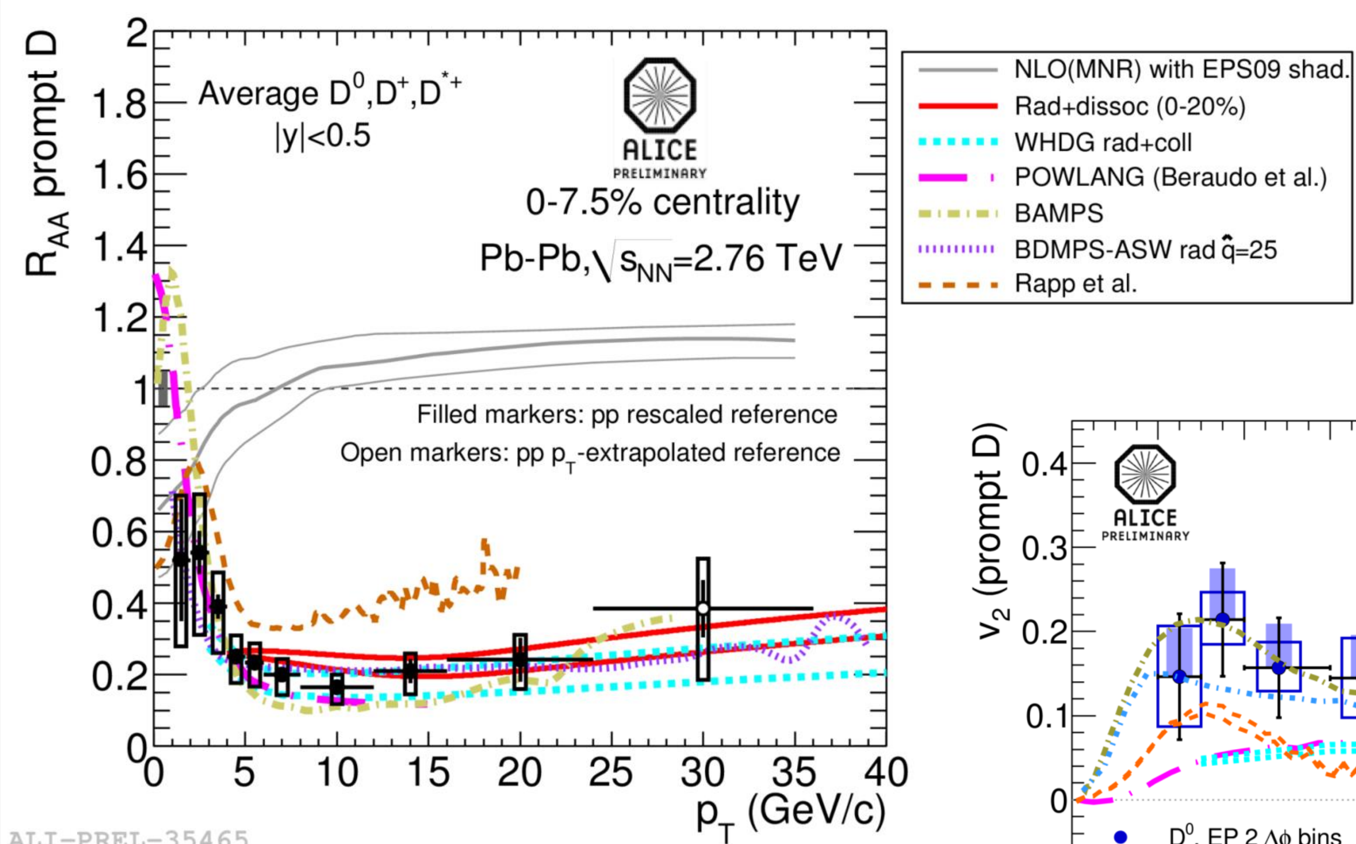


Talks by
Z.Conesa del Valle
A.Grelli

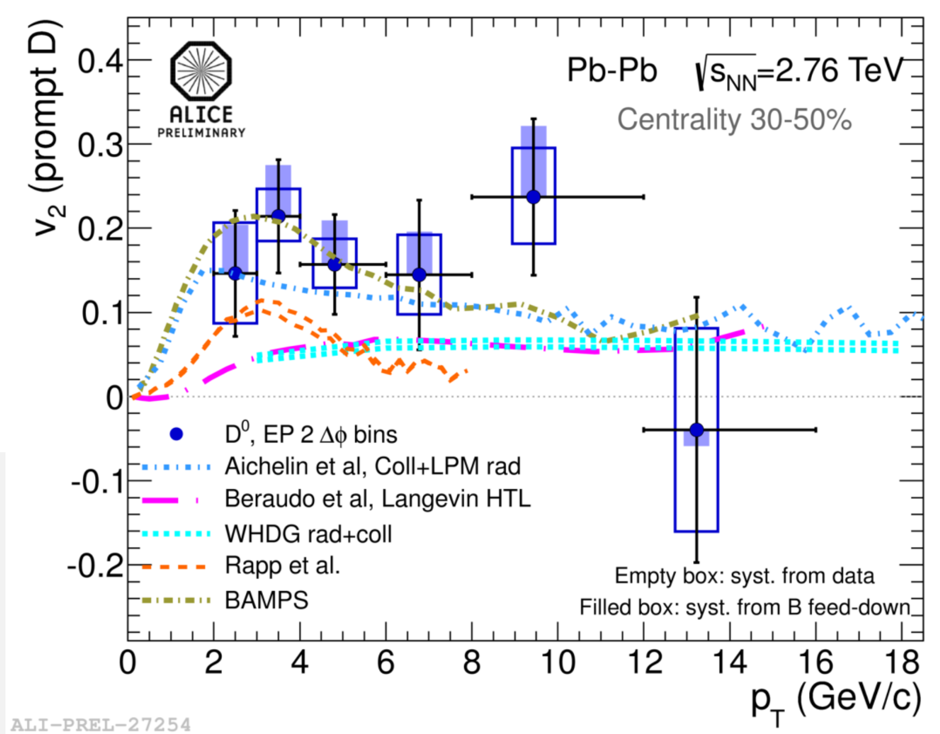


Average D-meson R_{AA}:
– p_T < 8 GeV/c hint of slightly less suppression than for light hadrons
– p_T > 8 GeV/c both (all) very similar
no indication of colour charge dependence

D meson v_2



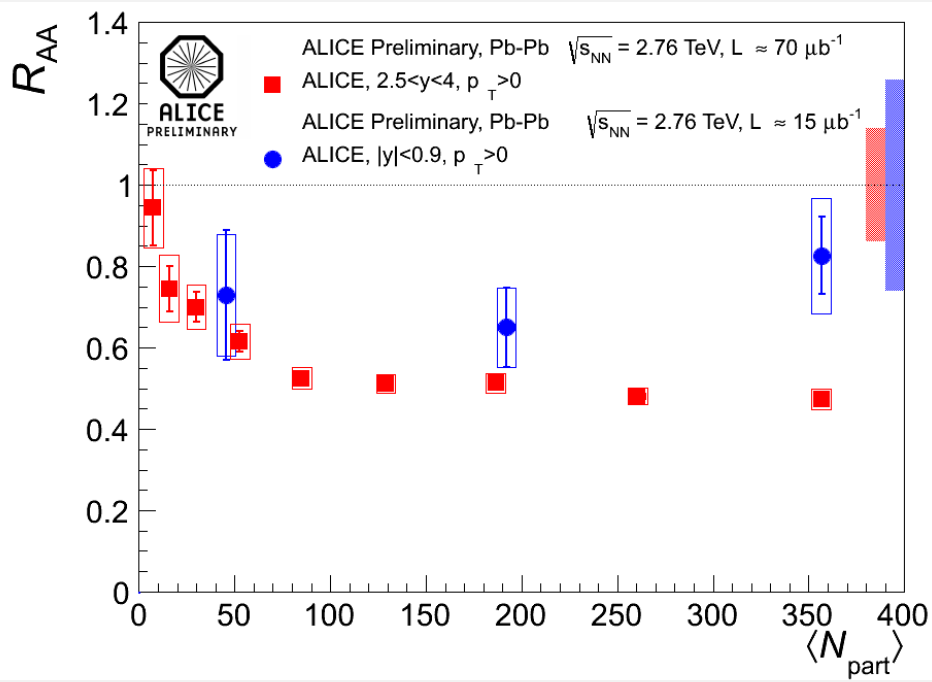
Talks by
Z.Conesa del Valle
D.Caffarri

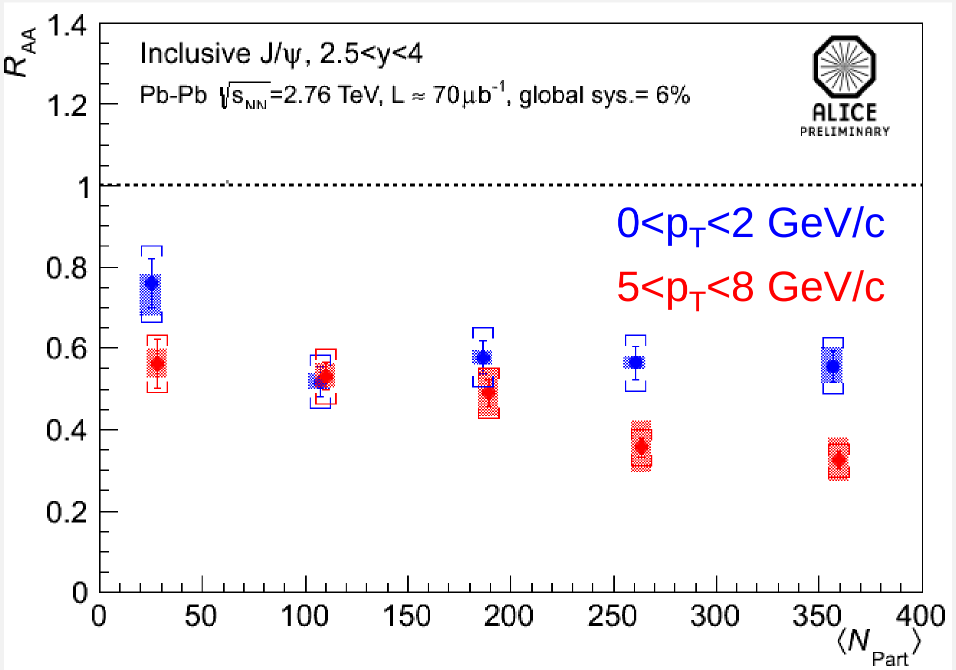


Non-zero D meson v_2 observed
Comparable to that of light hadrons
Expressed as event-plane dependent R_{AA}

Simultaneous description of R_{AA} and v_2
c-quark transport coefficient in medium

J/ψ R_{AA} centrality dependence



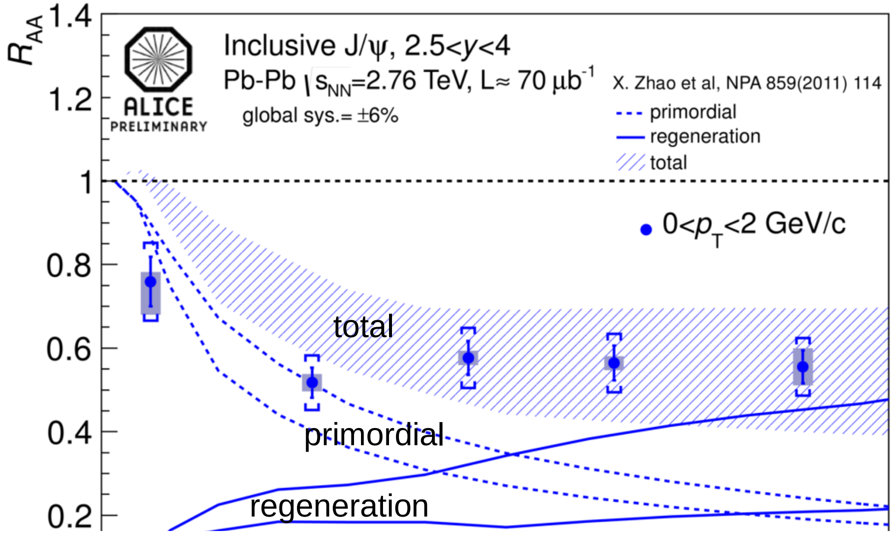


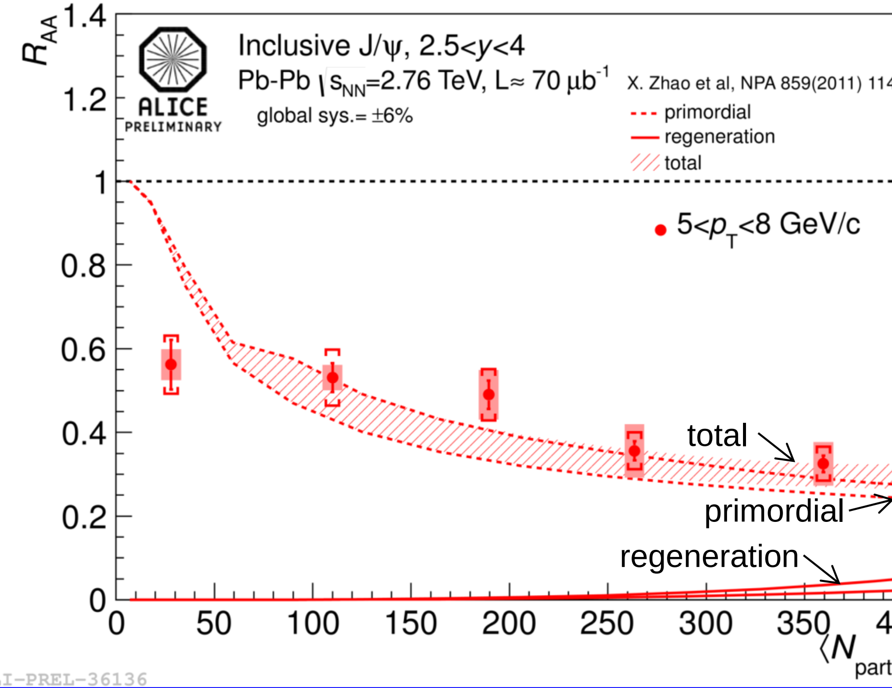
J/ψ suppression measurements both in central and forward regions
– from N_{part} > 100 suppression independent of centrality
– in central collisions, less suppression than at RHIC
– at low p_T (< 2 GeV/c) less suppression than at high p_T, especially in more central collisions

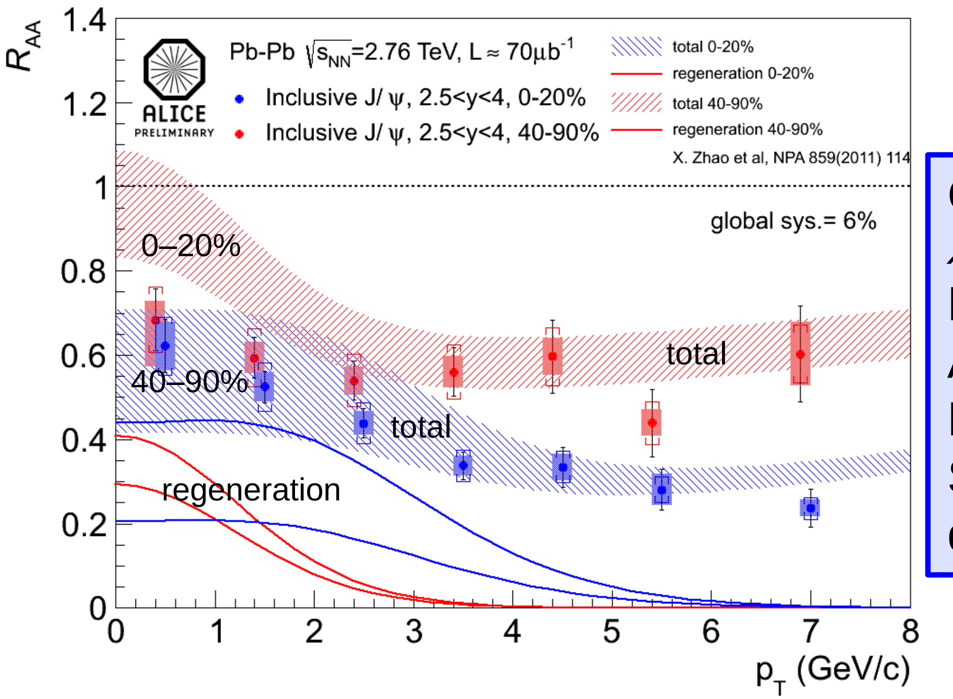
Indication of J/ψ regeneration at low p_T ?

Talks by
E.Scomparin
R.Arnaldi
I.Ch.Arsene

J/ψ R_{AA} vs. centrality and p_T



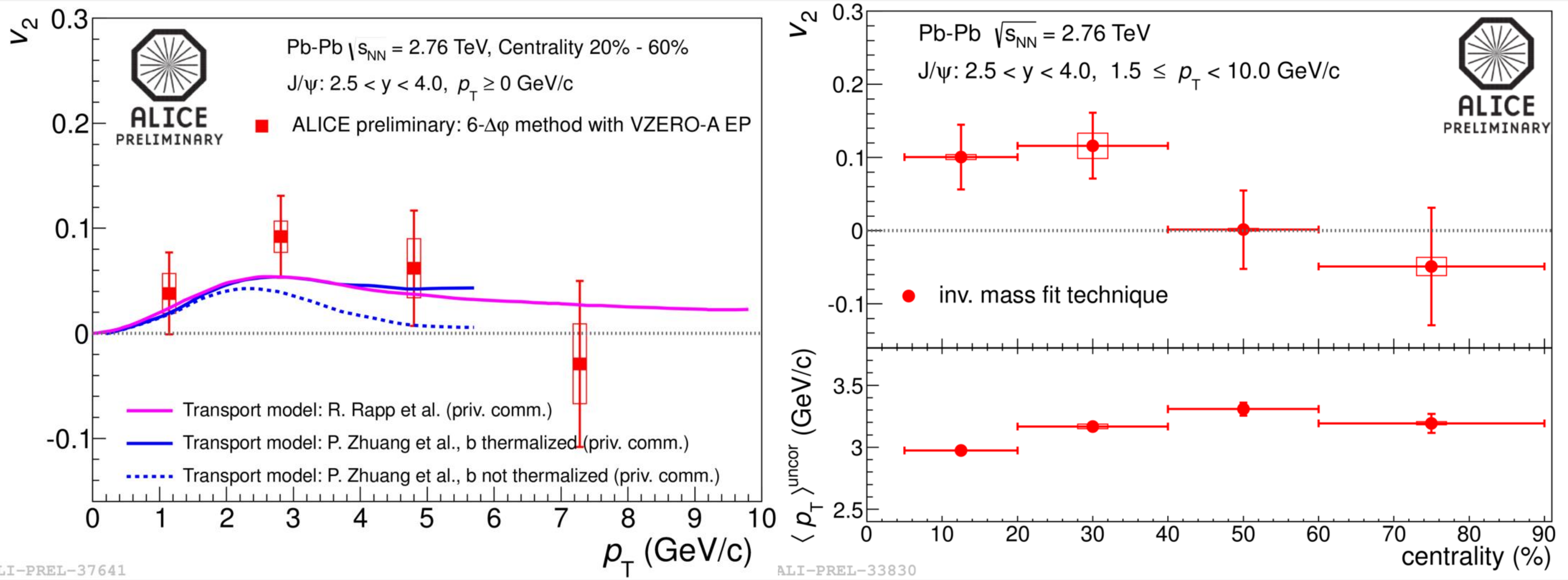




Comparison to regeneration model:
X.Zhao, R.Rapp NPA 859 114
Different suppression pattern at low/high-p_T
At low p_T ~50% J/ψ from recombination
Fair agreement for different centralities
Statistical hadronization model also describes the data: *P.Braun-Munzinger et al.*

Talks by E.Scomparin, R.Arnaldi

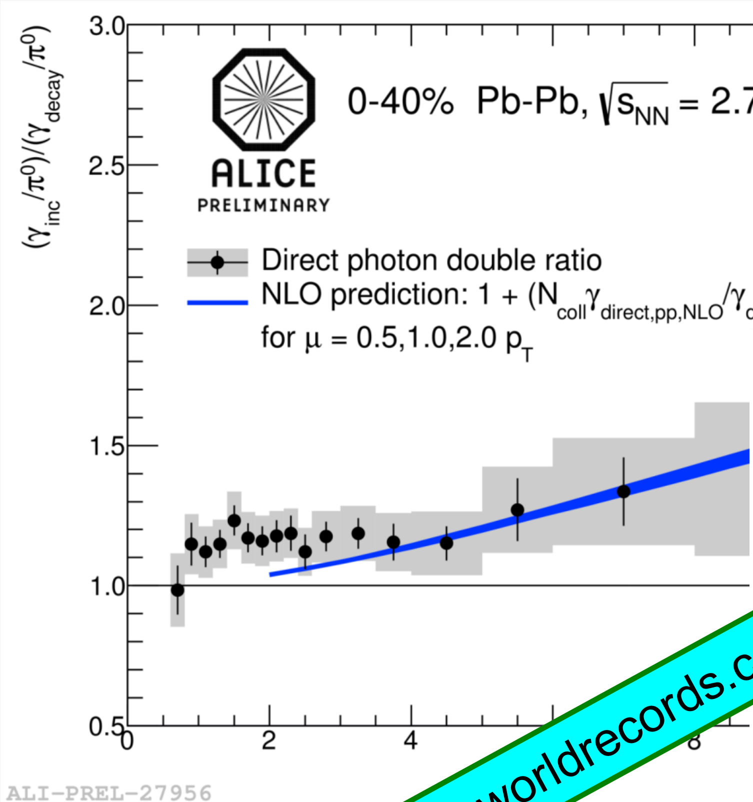
J/ψ elliptic flow



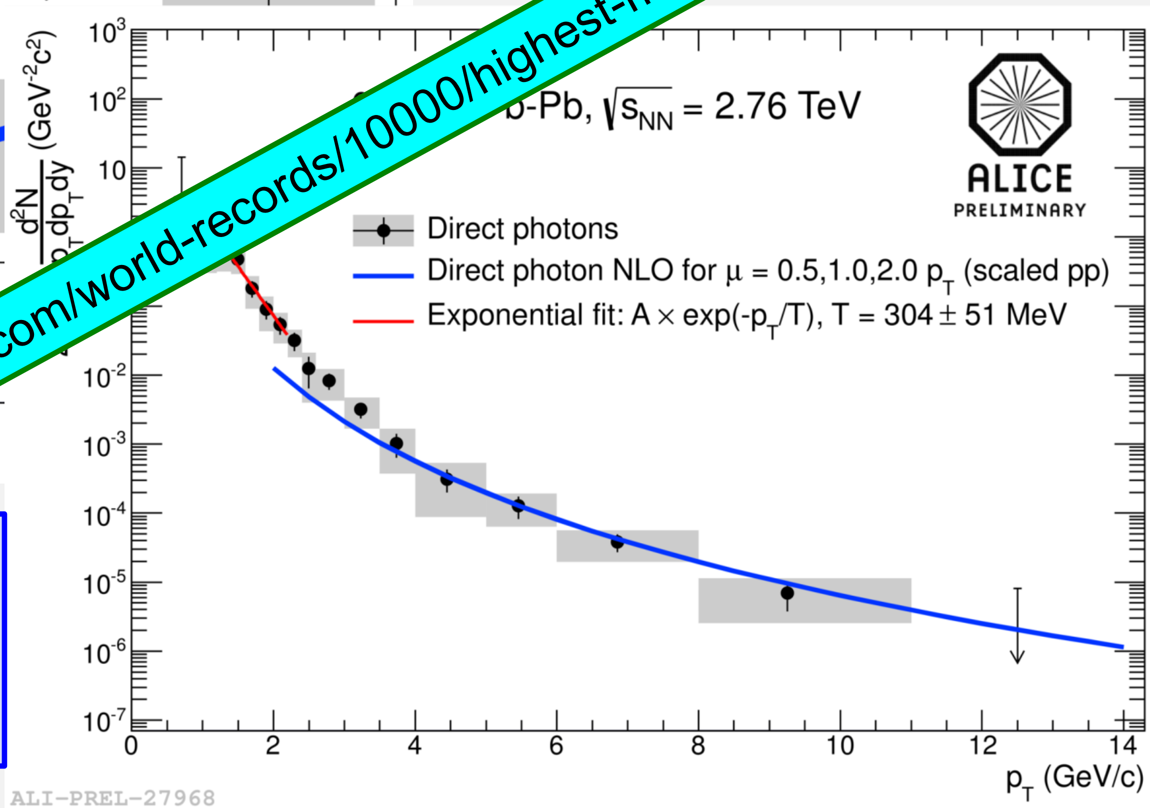
J/ψ produced by recombination of thermalized c-quarks should have non-zero elliptic flow
– measurements give a hint for non-zero v_2
– qualitative agreement with transport models, including regeneration
– complementary to indications obtained from J/ψ R_{AA} studies

Talks by
E.Scomparin
H.Yang

Direct photon production



Exponential fit for p_T < 2.2 GeV/c
inv. slope *T* = 304±51 Me[illegible]
for 0–40% Pb–Pb a[illegible]6 TeV
PHENIX: *T* = 2[illegible]±19 MeV
for 0–20[illegible]u at √*s* 200 GeV



http://www.guinnessworldrecords.com/world-records/10000/highest-man-made-temperature

p_T < 2 GeV/[illegible]
~20% [illegible]s of direct photons
p_T [illegible]eV/c
agreement with N_{coll}-scaled NLO

Talk by M.R.Wilde

ALICE future plans

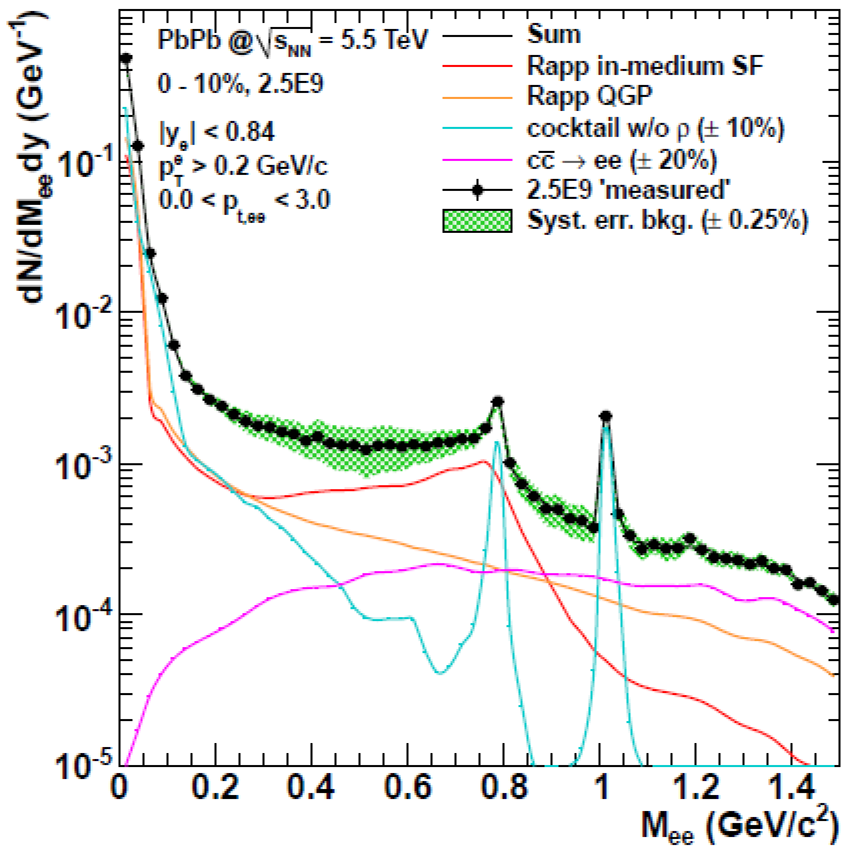
Precision measurement of the QGP parameters at $\mu_b = 0$ to fully exploit scientific potential of the LHC – unique in:

- large cross sections for hard probes
- high initial temperature

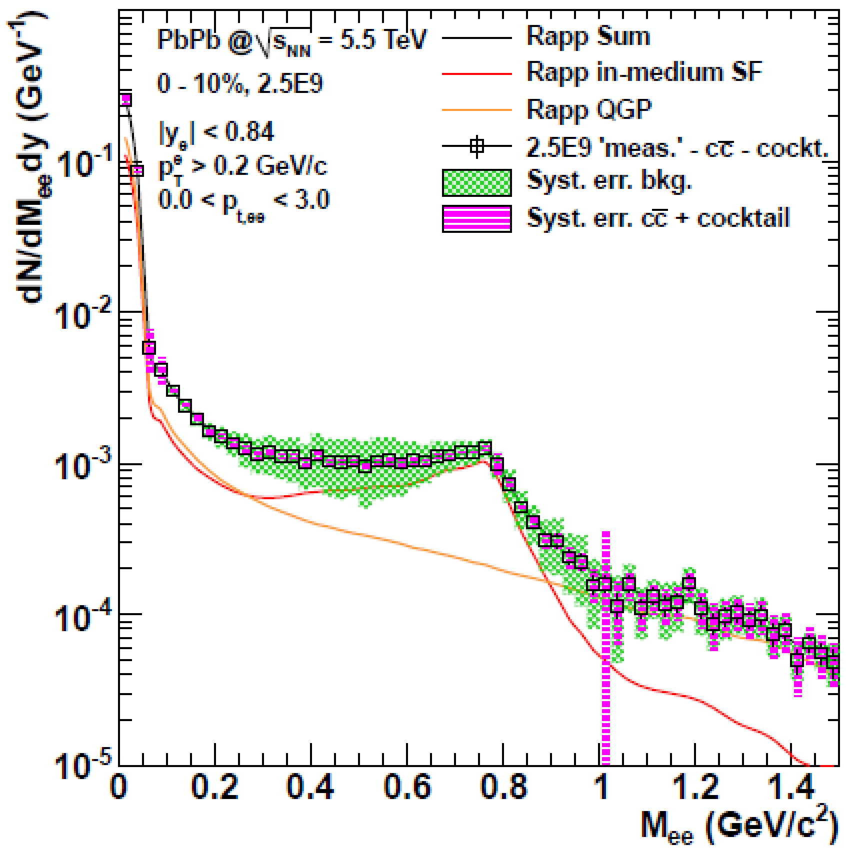
- Main physics topics, uniquely accessible with the ALICE detector:
  - measurement of heavy-flavour transport parameters:
    - study of QGP properties via transport coefficients (η/s, $\hat{q}$)
  - measurement of low-mass and low-p_T di-leptons
    - study of chiral symmetry restoration
    - space-time evolution and equation of state of the QGP
  - J/ψ , ψ', and χ_c states down to zero p_T in wide rapidity range
    - statistical hadronization versus dissociation/recombination

ALICE dielectrons

inclusive dielectron invariant mass



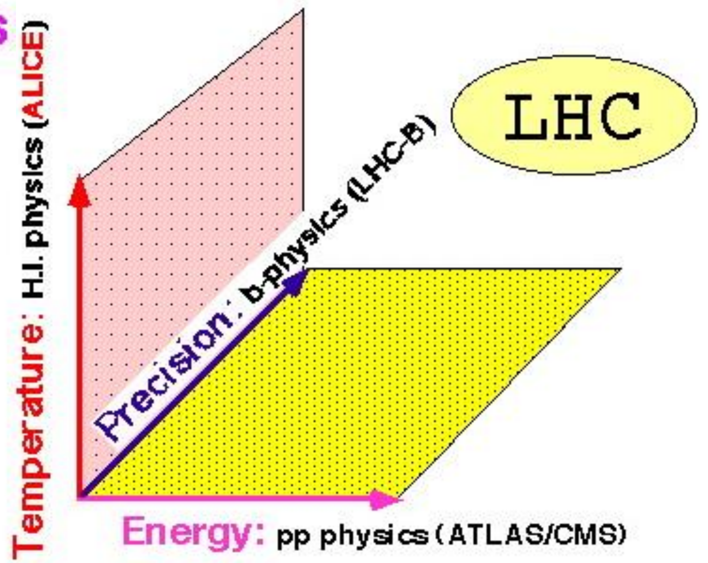
… excess after subtraction



new ITS and high-rate upgrade, with “tight” impact parameter cut…

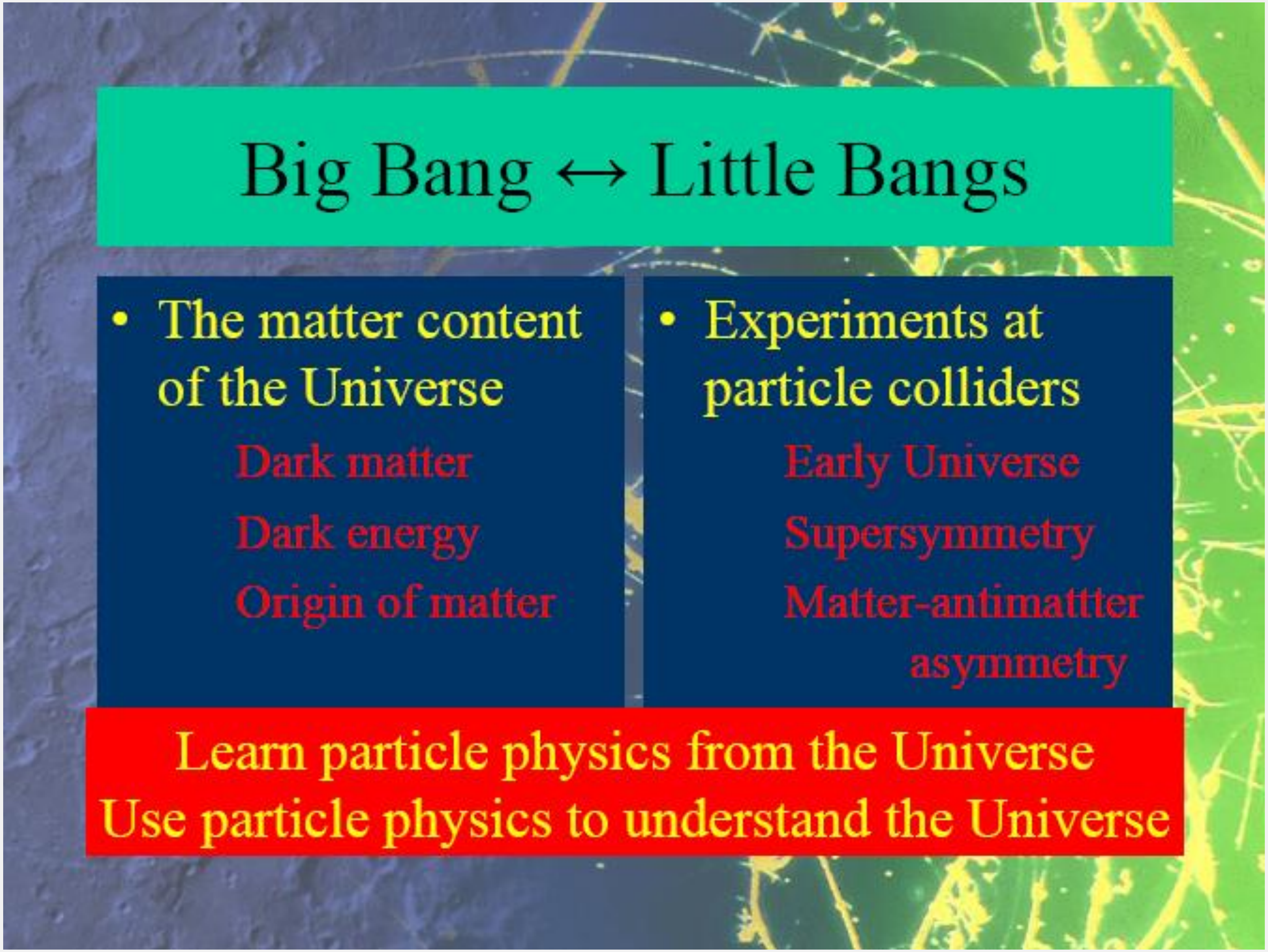
Physics at LHC

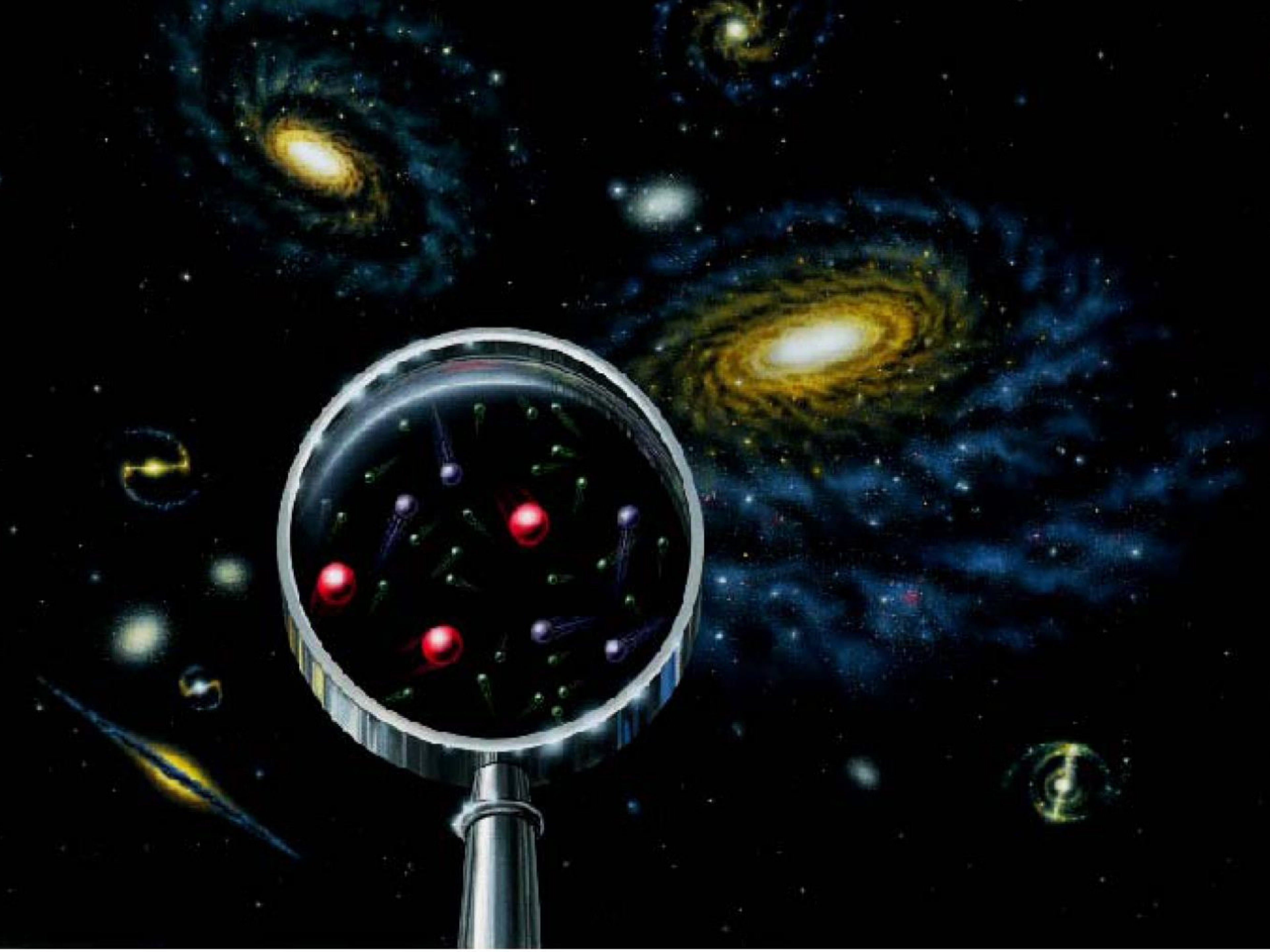
- **Common Questions**
  - generation of mass
    - **elementary** particles => Higgs => ATLAS/CMS
    - **composite** particles => QGP => ALICE
  - missing symmetries
    - **SuperSymmetry**: matter <-> forces => ATLAS/CMS
    - **Chiral Symmetry**: mass of light quarks => ALICE
    - **CP Symmetry**: matter <-> antimatter => LHC-B



- **Different Approaches**
  - 'Concentrated Energy'
    => (single) high mass particles
  - 'Distributed Energy'
    => interaction between matter & vacuum
  - 'Borrowed Energy'
    => indirect effects of very high mass particles

BANGS


Big Bang ↔ Little Bangs
• The matter content of the Universe
Dark matter
Dark energy
Origin of matter
• Experiments at particle colliders
Early Universe
Supersymmetry
Matter-antimattter asymmetry
Learn particle physics from the Universe
Use particle physics to understand the Universe



Zhrnutie

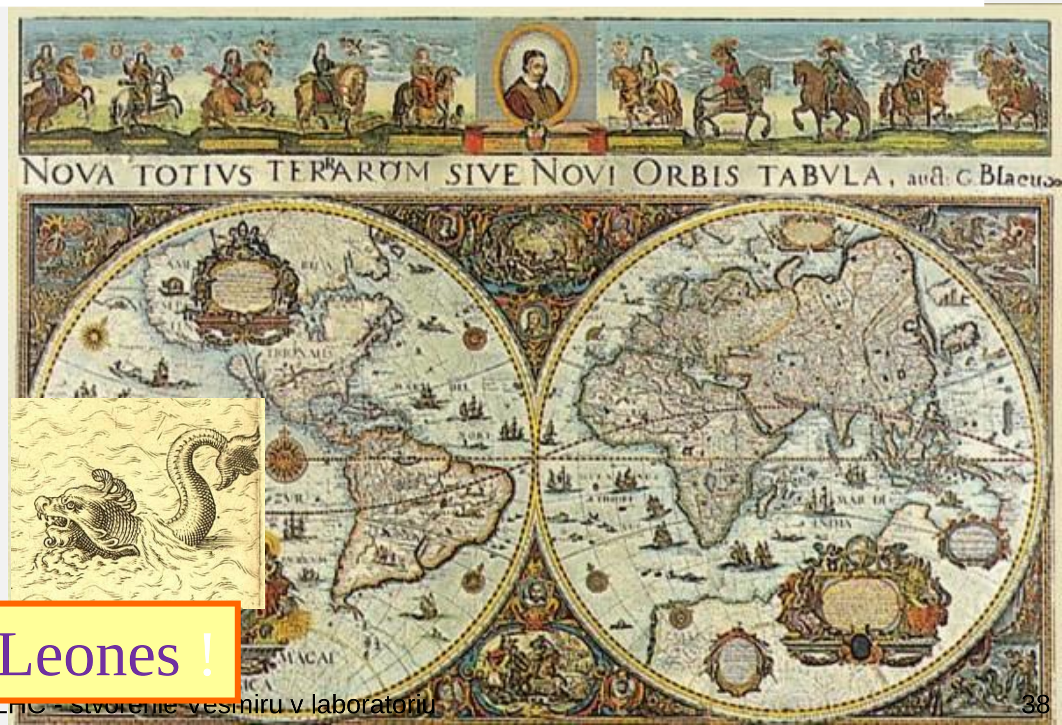
- **LHC a vsetky experimenty pracuju tri roky perfektne**
  - **intezity zvazkov a mnozstvo zaznamenanych zrazok ovela nad ocakavanie**
  - **prve fyzikalne vysledky publikovane**

    presne potvrdenie stadartneho modelu

    Higgsov bozon najdeny – podla predpovedi hmotnost ~ 125 GeV

    fluktacie v pociatocnom stave v zrazkach tazkych ionov

    dosiahnuta teplota v zrazkach tazkych ionov ~ 300 MeV
- **Looking forward to explore the 'terra incognita' at LHC**



Hic sunt Leones !