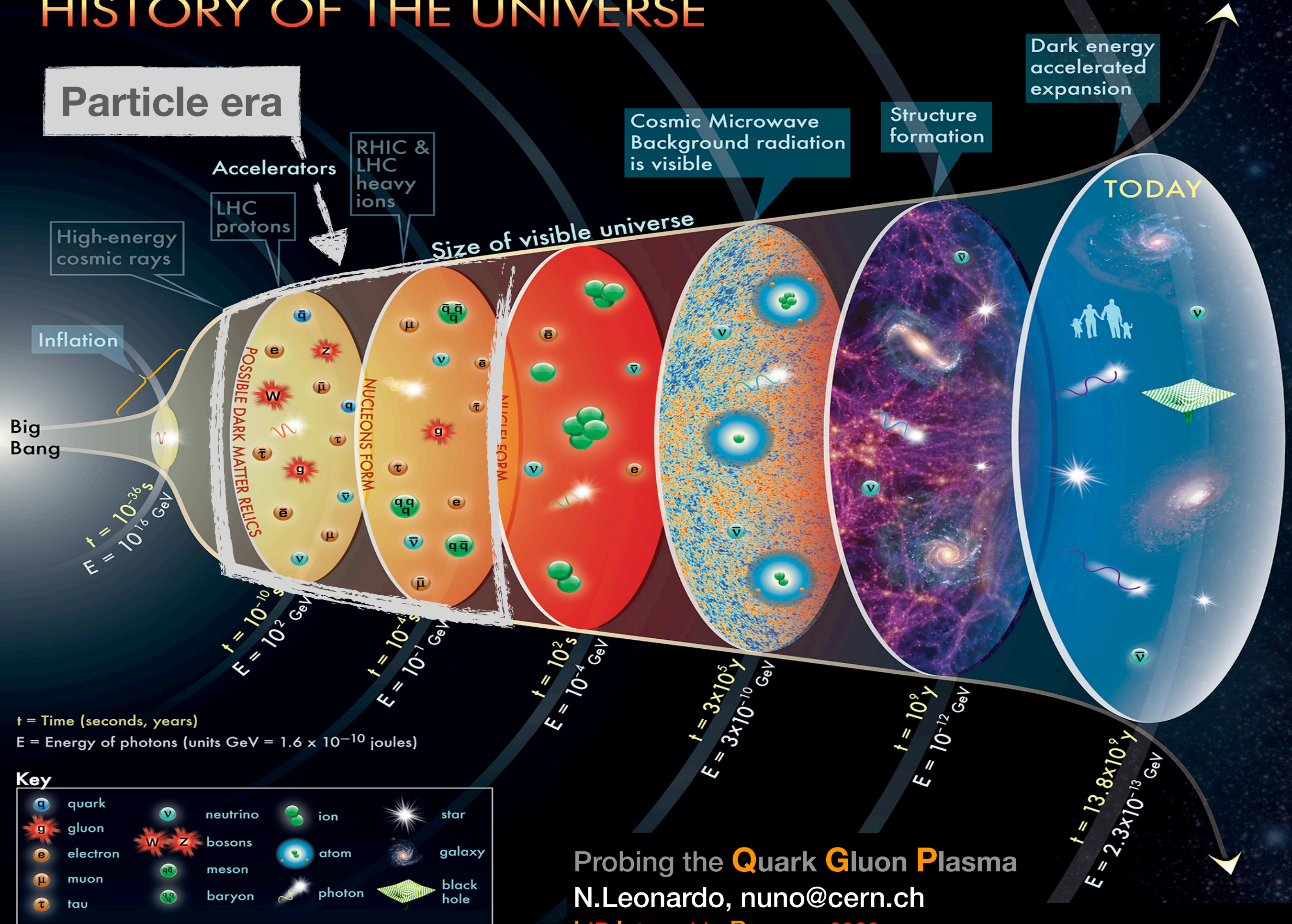


HISTORY OF THE UNIVERSE

Particle era



t = Time (seconds, years)
 E = Energy of photons (units GeV = 1.6×10^{-10} joules)

Key

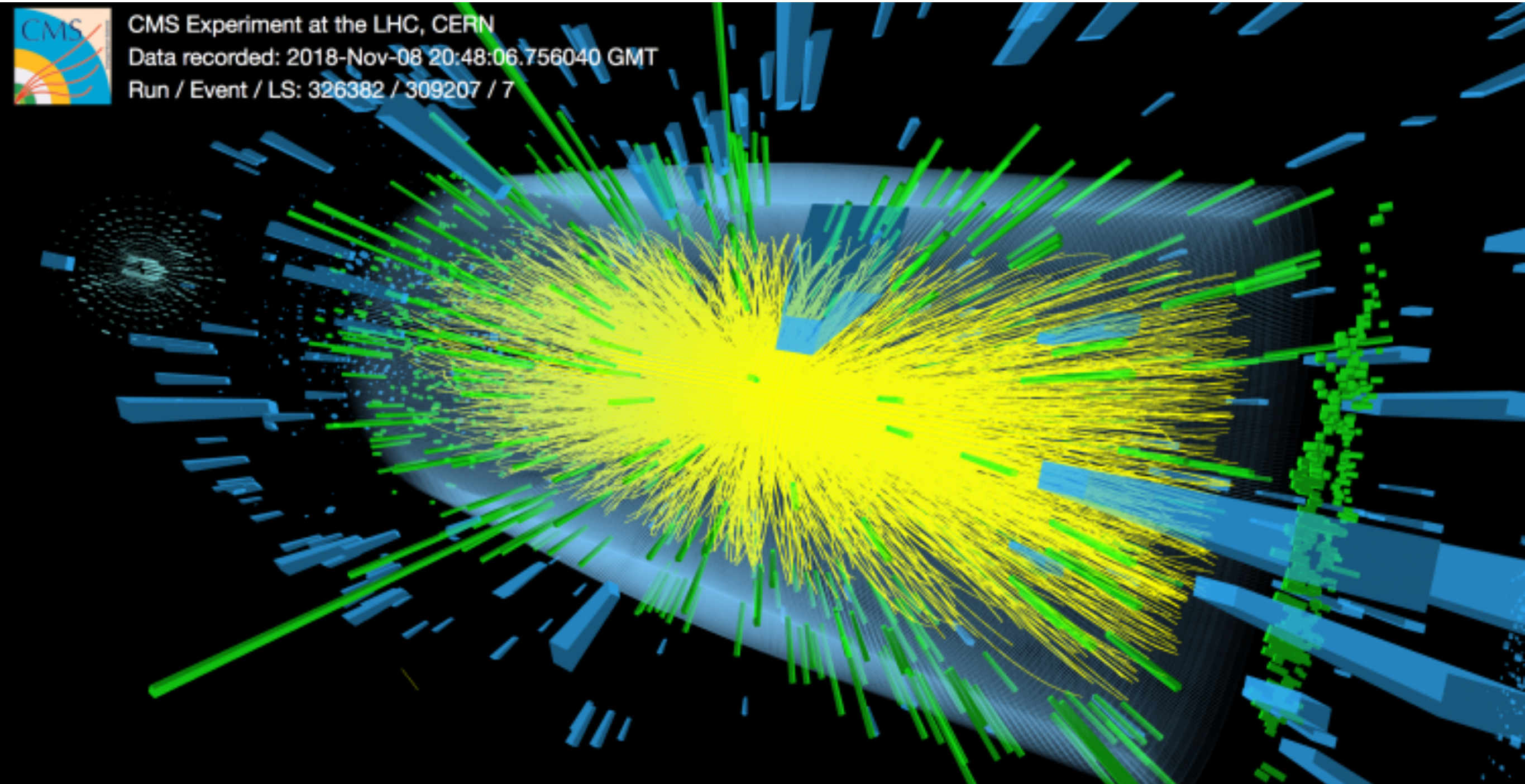
quark	neutrino	ion	star
gluon	bosons	atom	galaxy
electron	meson	photon	black hole
muon	baryon		
tau			

Probing the **Q**uark **G**luon **P**lasma
 N.Leonardo, nuno@cern.ch
 LIP Internship Program 2020

The concept for the above figure originated in a 1986 paper by Michael Turner.

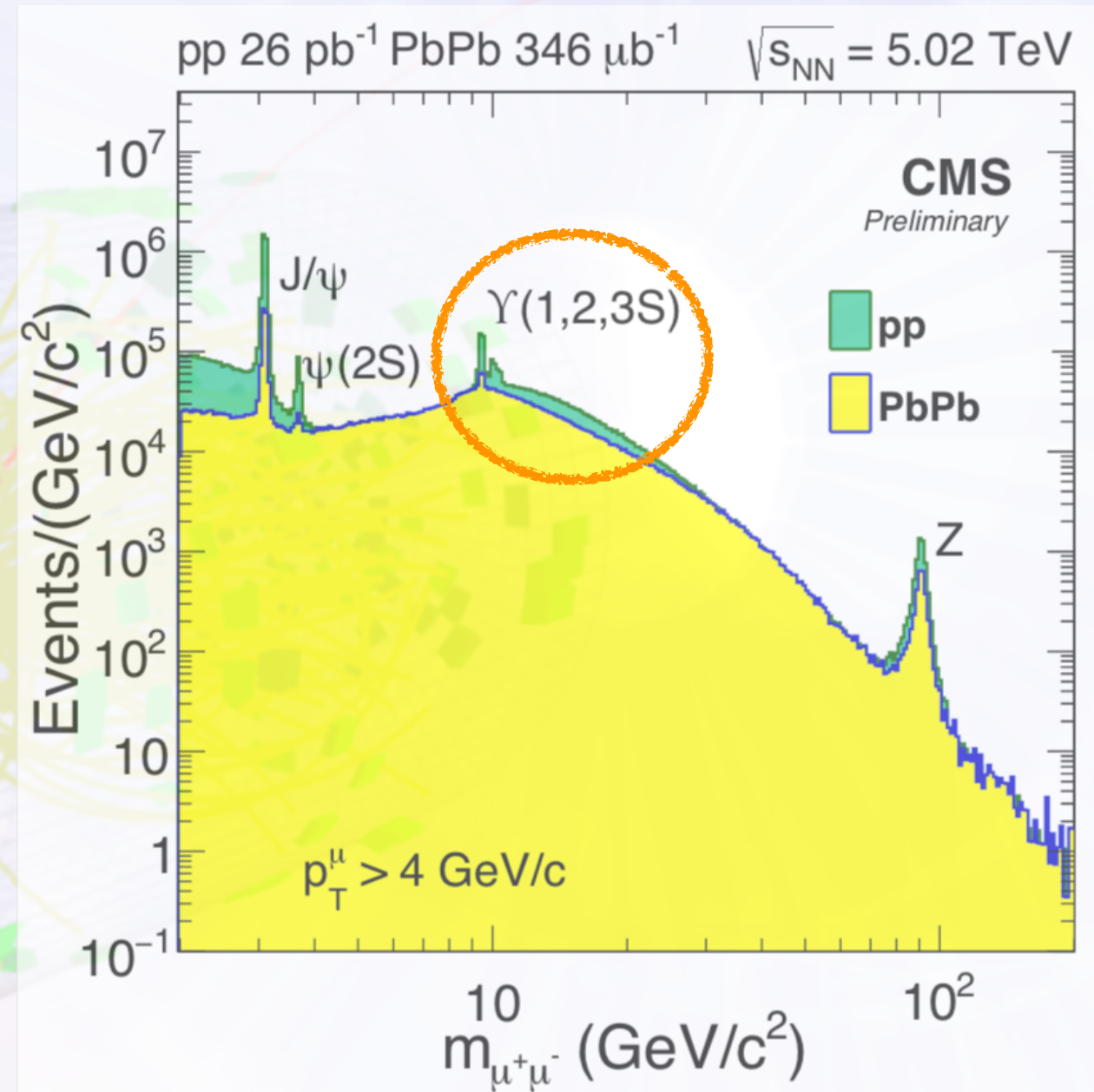
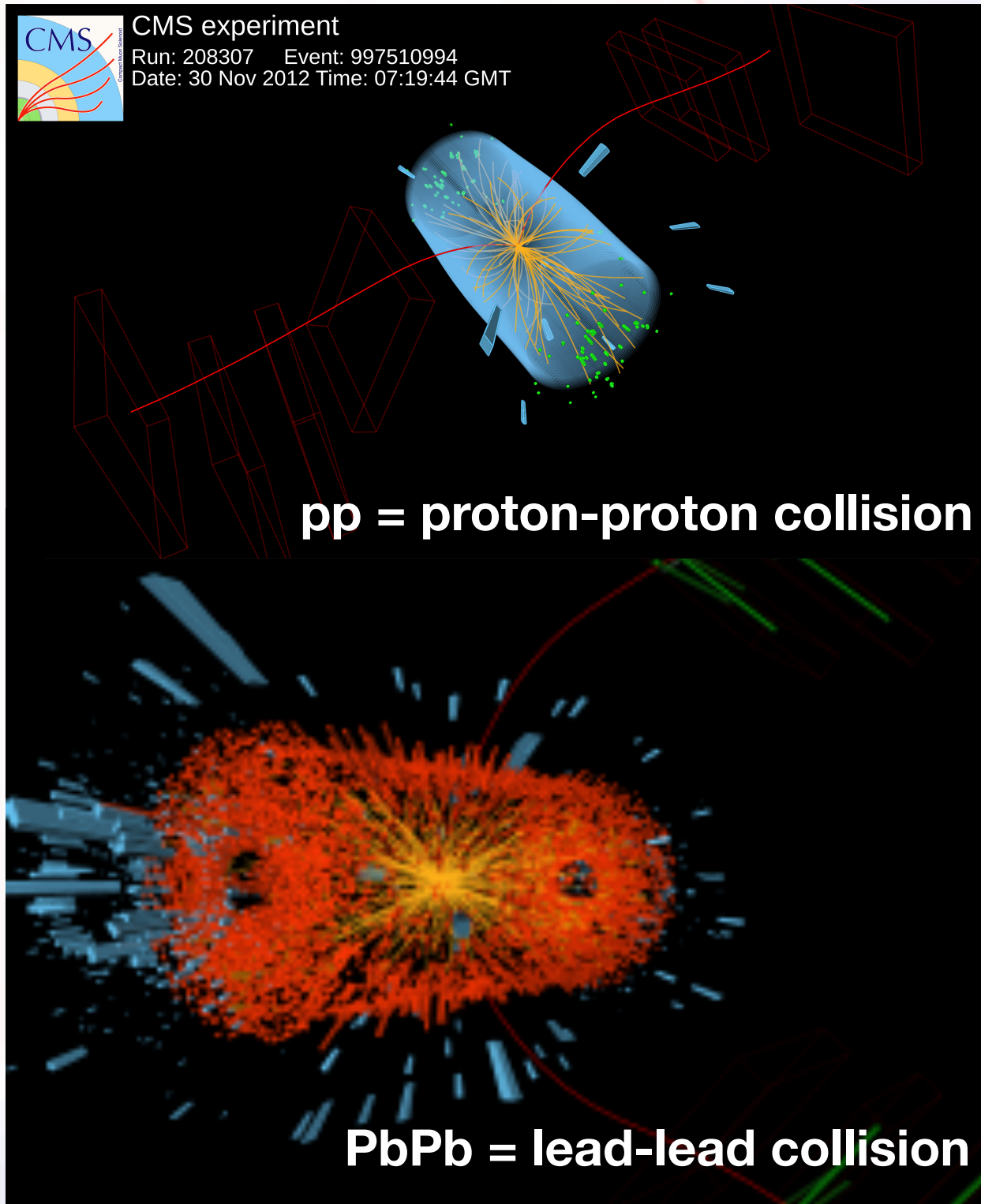
heavy ion collisions

November 2018



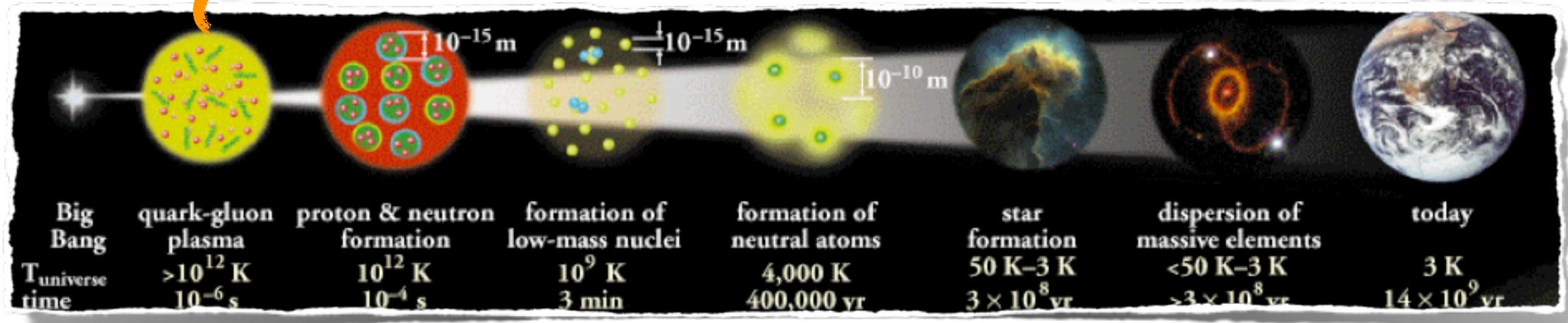
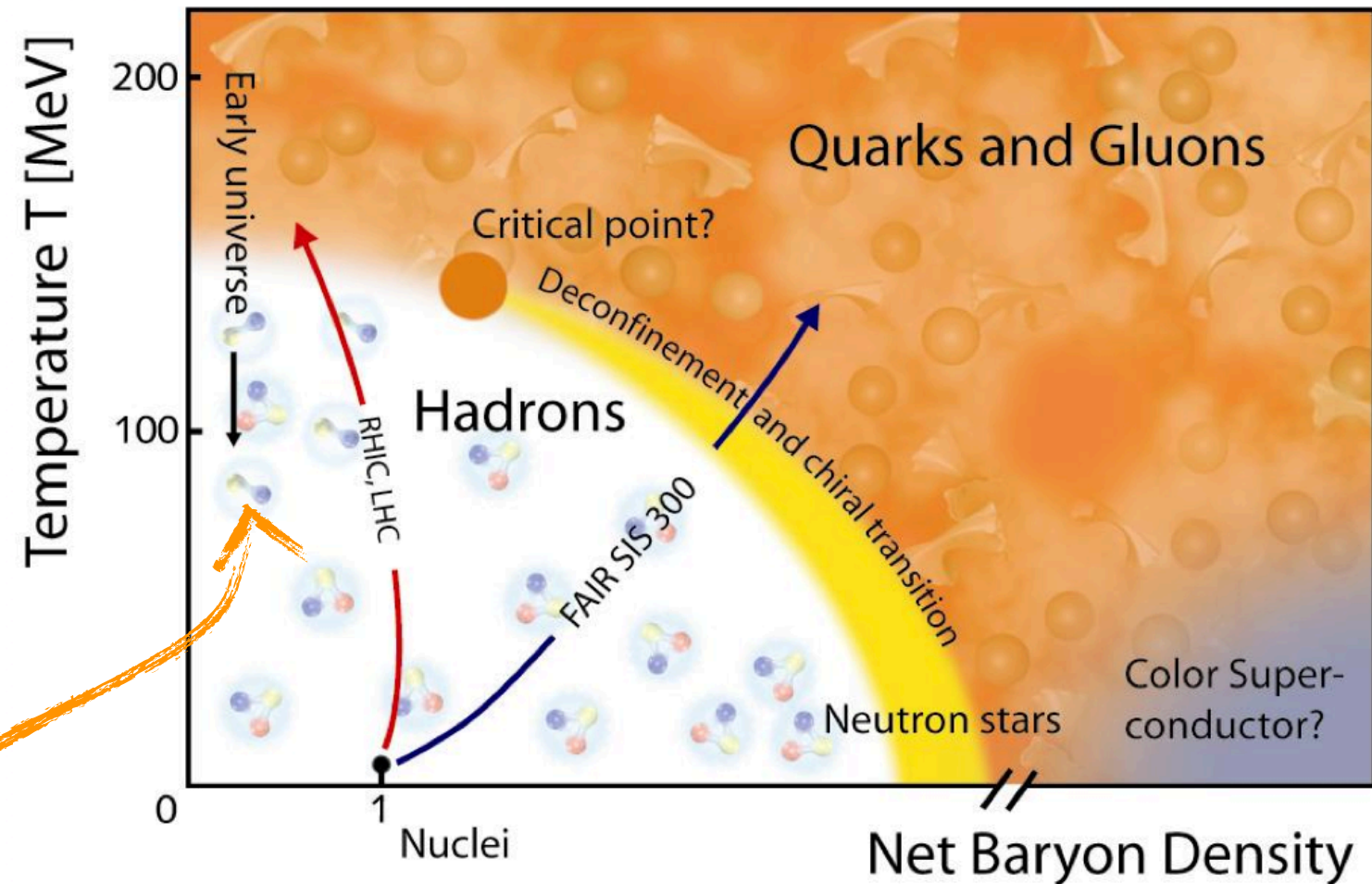
CMS Experiment at the LHC, CERN
Data recorded: 2018-Nov-08 20:48:06.756040 GMT
Run / Event / LS: 326382 / 309207 / 7

Di-muon pairs: a robust signature in pp & in PbPb collisions!

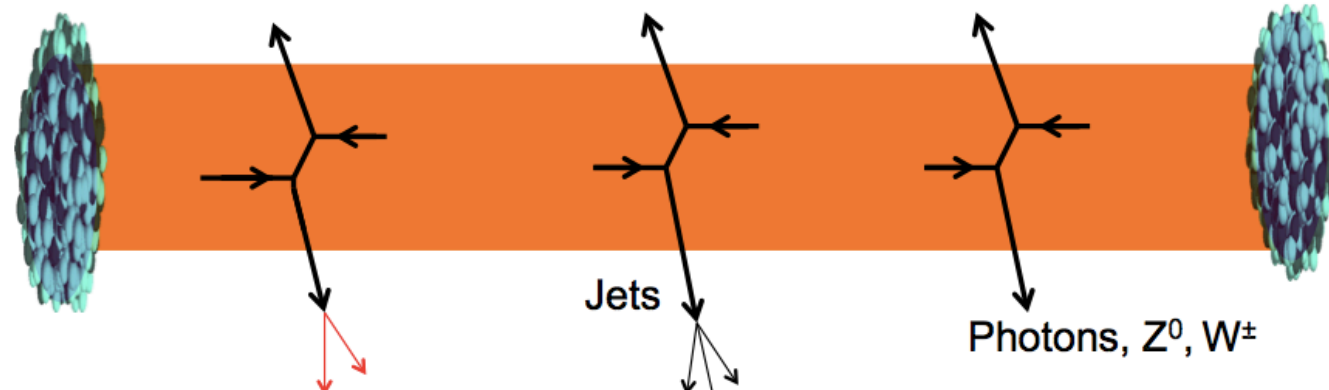


the quark-gluon plasma (QGP)

probe the properties of matter at the highest temperatures



probing a hot soup of quarks and gluons



Quarkonia
(Prompt)

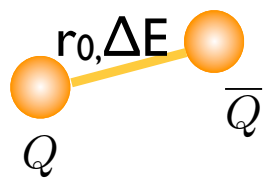
Jets
Non-Prompt J/ψ
Hadrons

Photons, Z^0 , W^\pm

Unperturbed
(do not couple to color)

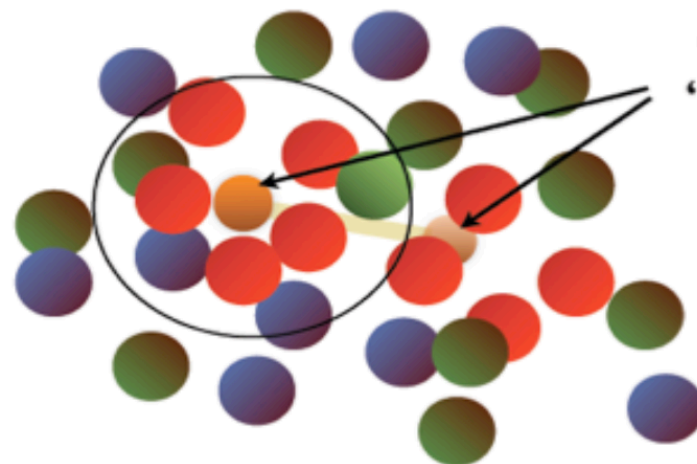
Melting
(color screening)

Energy loss
(as partons traverse medium)



PLB178, 416 (1986)

Screening in a deconfined medium:
effective charge of Q and \bar{Q} reduced

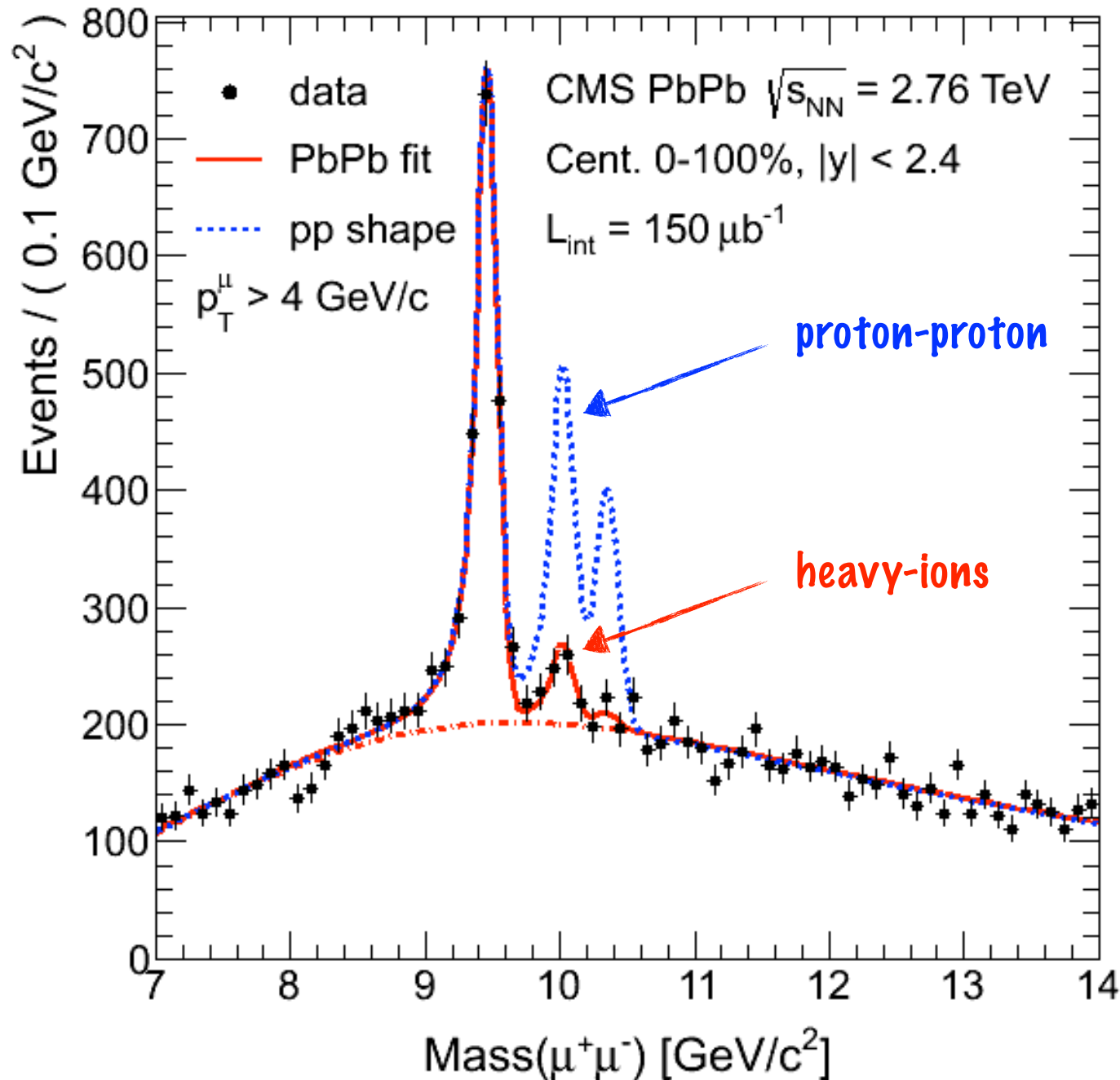


Q and \bar{Q} cannot
"see" each other
 $r_D < r_{Q\bar{Q}}$

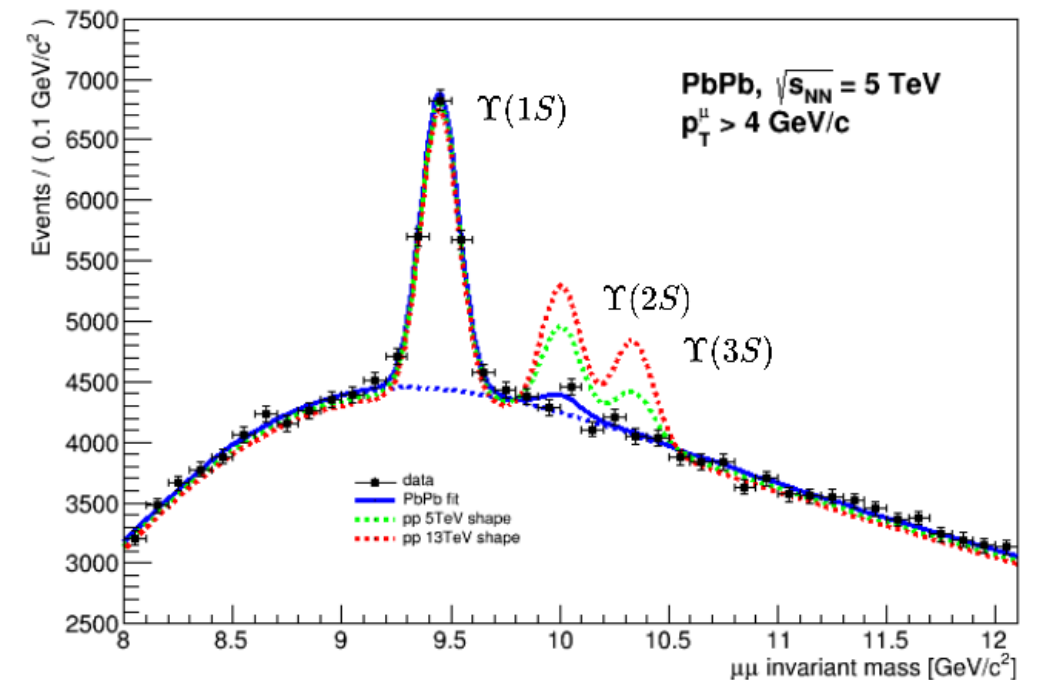
hadrons melt ! (sequentially)

flagship LHC observation!

N.LEONARDO ET AL'2012

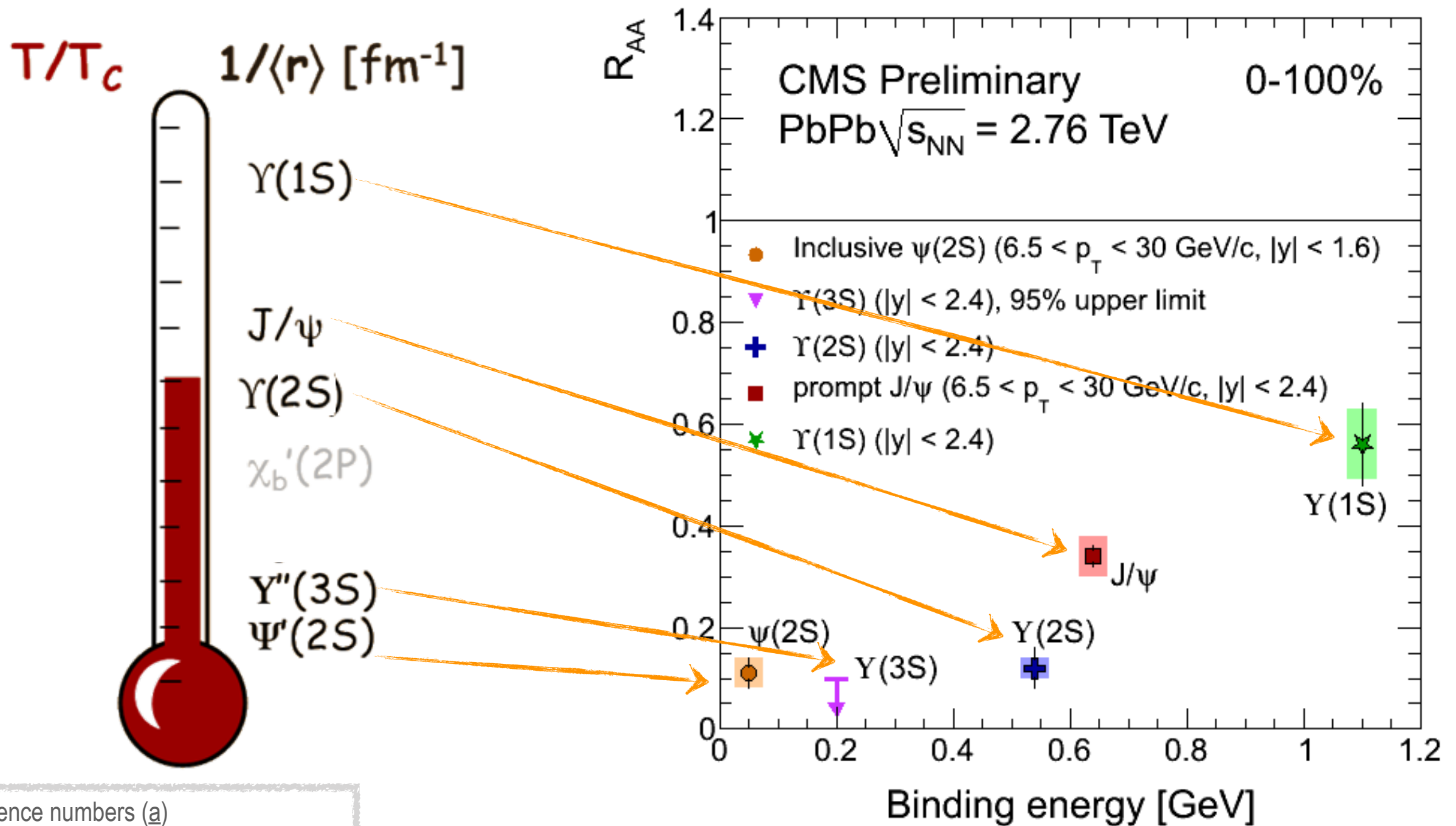


W/J.LOURENÇO, LIP2'2018



- 3 $\Upsilon(nS)$ states reconstructed for the *first time* in ion collisions
- Excited states (2S,3S) suppressed in PbPb compared to pp

a thermometer of the medium



Reference numbers (a)
 Tomato soup (hottest) $\sim 60^\circ\text{C} \sim 10^2$ K
 Sun (core) $\sim 10^7$ K
 QGP phase transition ~ 160 MeV $\sim 10^{12}$ K
[CMS observes melting](#)
[New temperature probe of QGP](#)

- all onia states are suppressed in the medium, *sequentially!*
 the least tightly bound states are suppressed the most

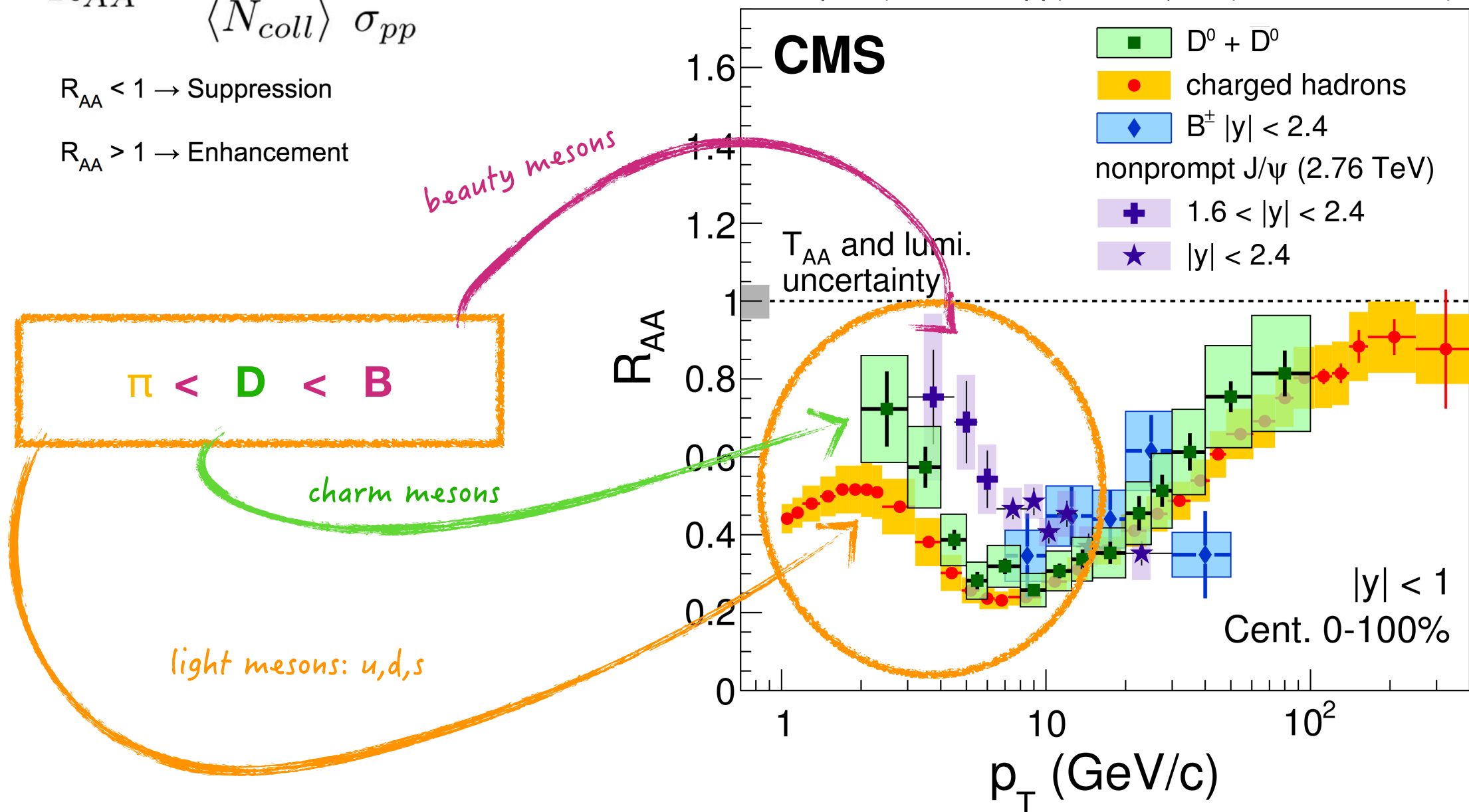
hadrons loose energy! (sequentially)

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{AA}}{\sigma_{pp}}$$

$R_{AA} < 1 \rightarrow$ Suppression

$R_{AA} > 1 \rightarrow$ Enhancement

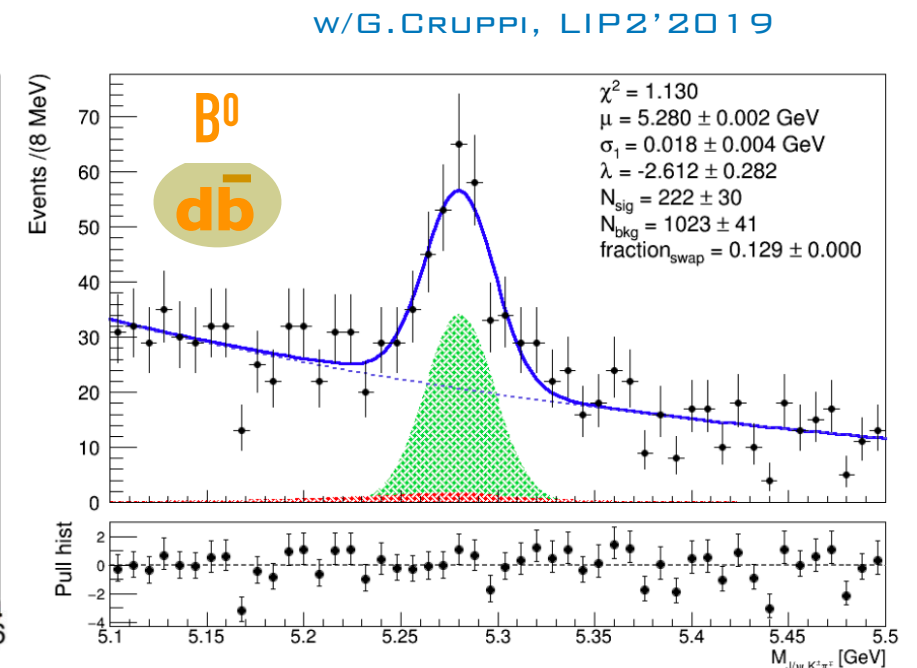
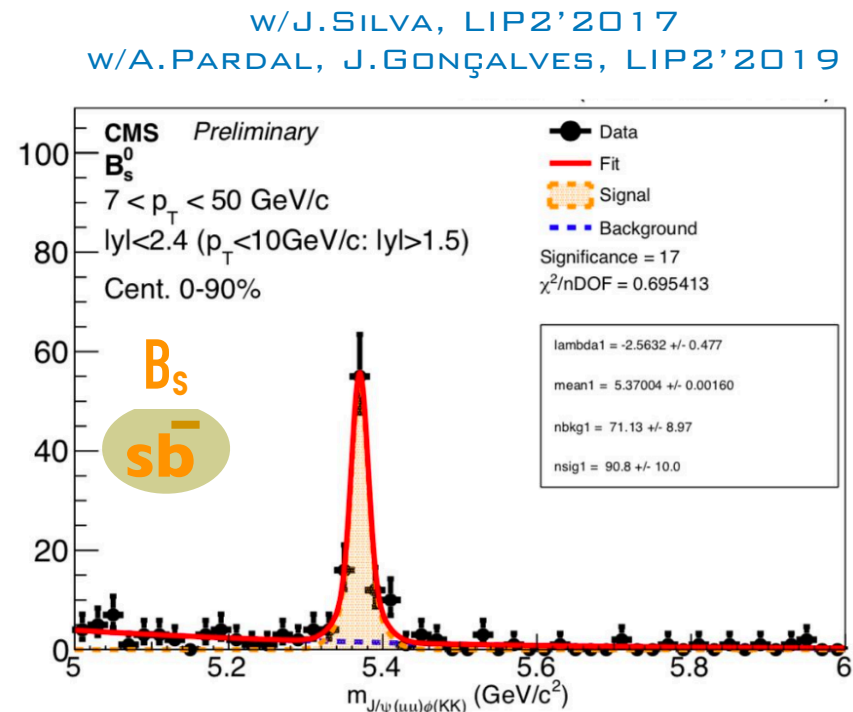
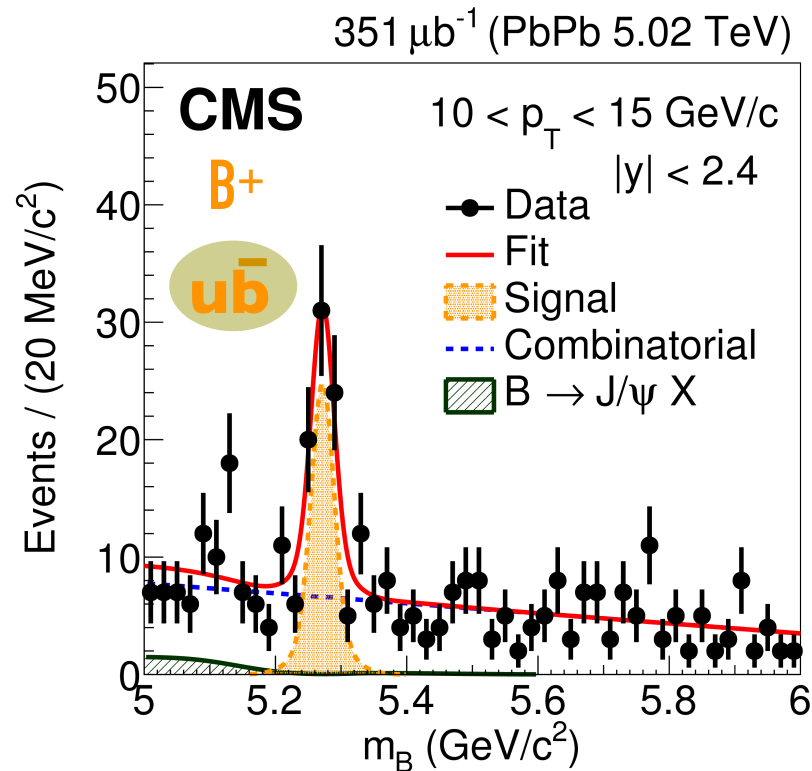
27.4 pb⁻¹ (5.02 TeV pp) + 530 μb⁻¹ (5.02 TeV PbPb)



partons loose energy as they traverse the QGP medium ... but heavier quarks loose less!

beauty in QGP

3 new observations !

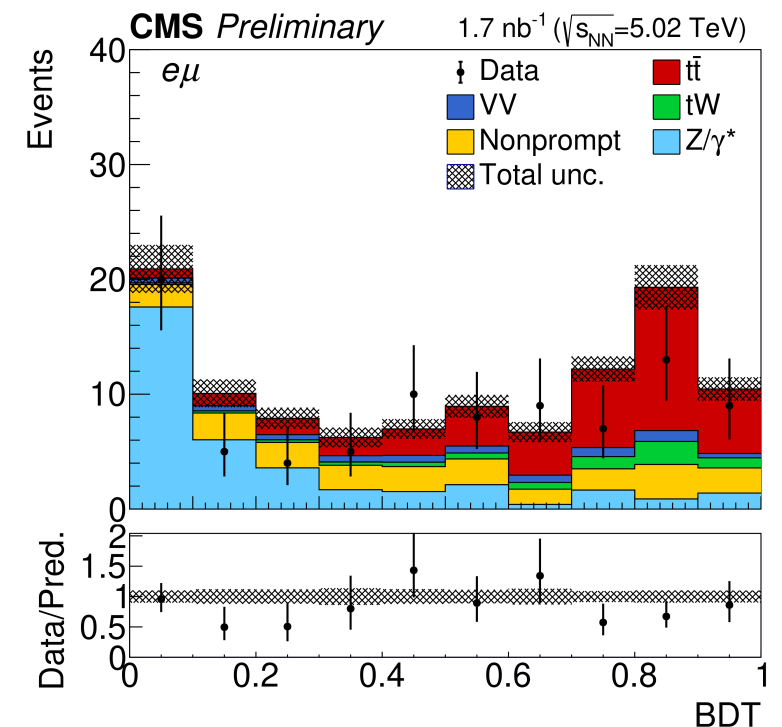
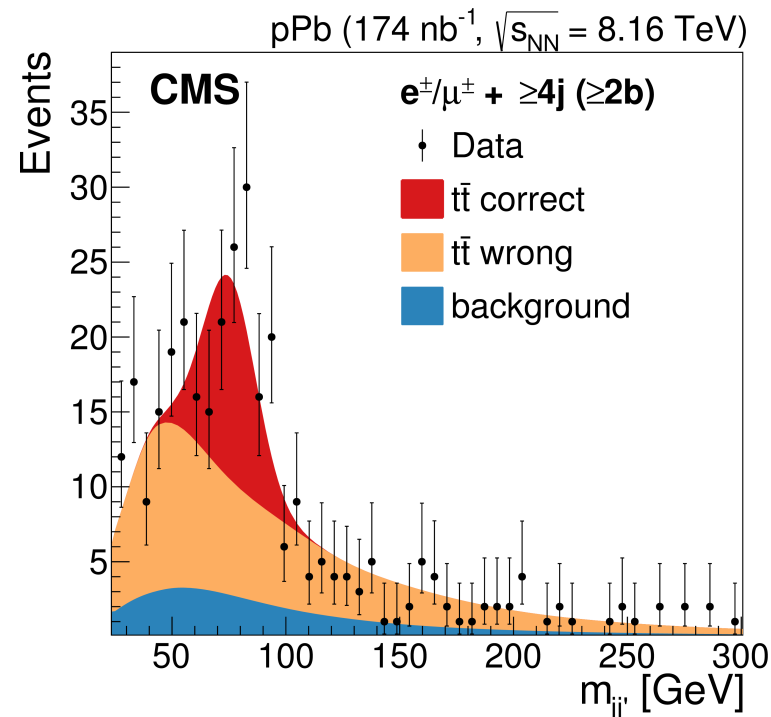
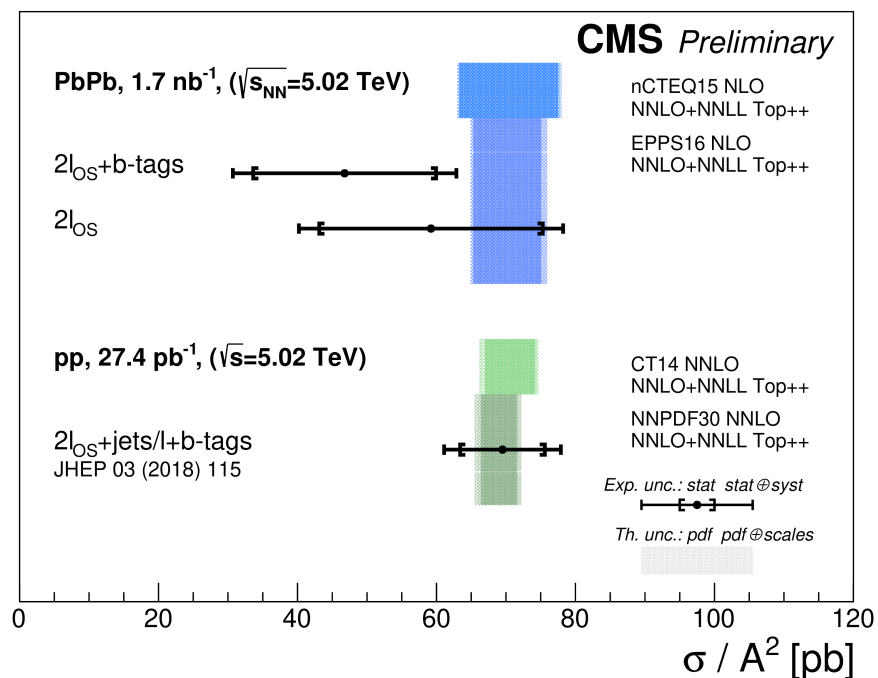
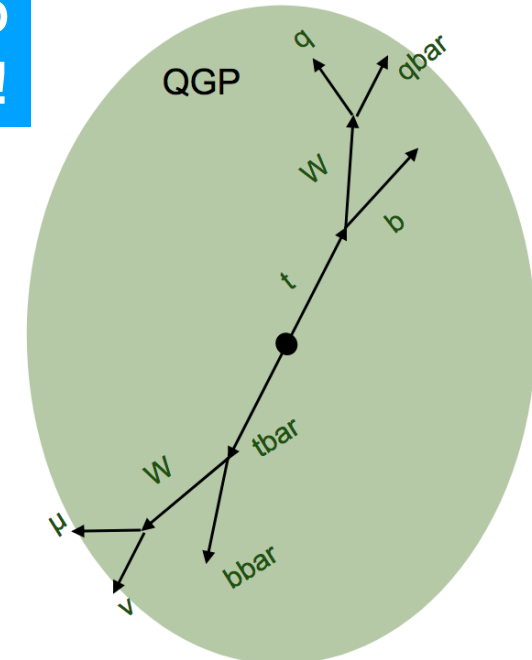


- B mesons (b-quark) observed for **first time** in nuclear collisions
- novel probes of the QGP
 - investigate flavor dependence of energy loss mechanisms
 - probe strangeness enhancement (also predicted as QGP signature)

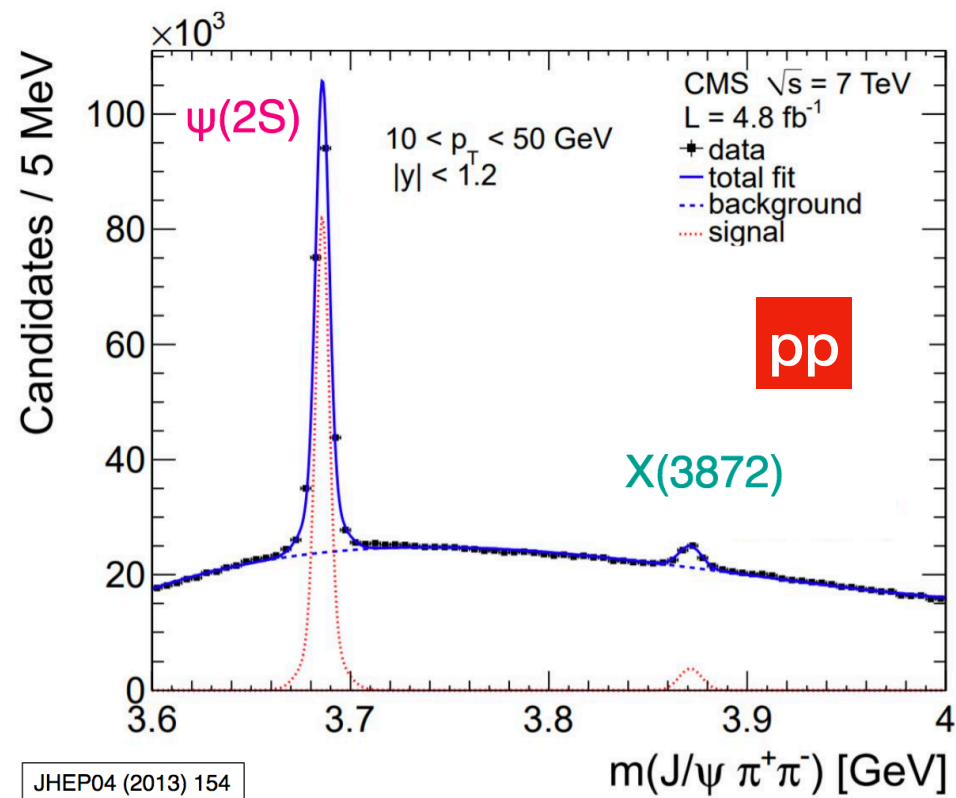
top in QGP

observation in pPb
evidence in PbPb !

- top detected in PbPb collisions
 - significance: 4σ obs., 6σ exp.
 - used signature: e^\pm or μ^\mp plus ≥ 4 jets
- previously observed in p+Pb collisions by CMS
- yet another novel probe of the QGP
- may be used to resolve time dependence of jet quenching effects

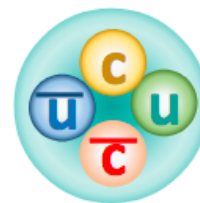


and something more exotic !

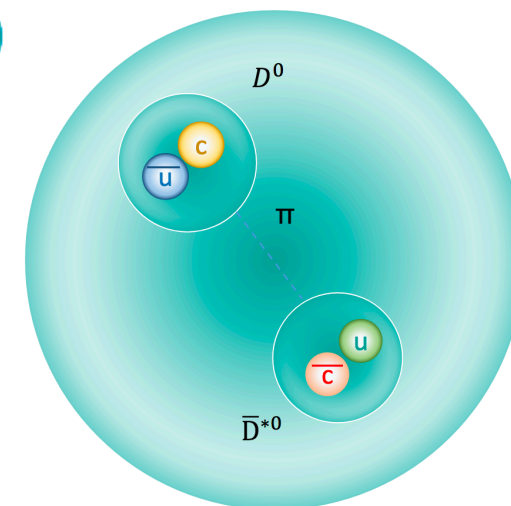


X(3872): observed by BELLE (2003)
 but its nature not yet understood

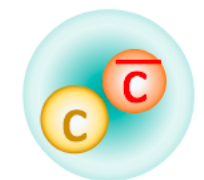
Tetraquark (4q)



$D^0 - \bar{D}^{*0}$ molecule



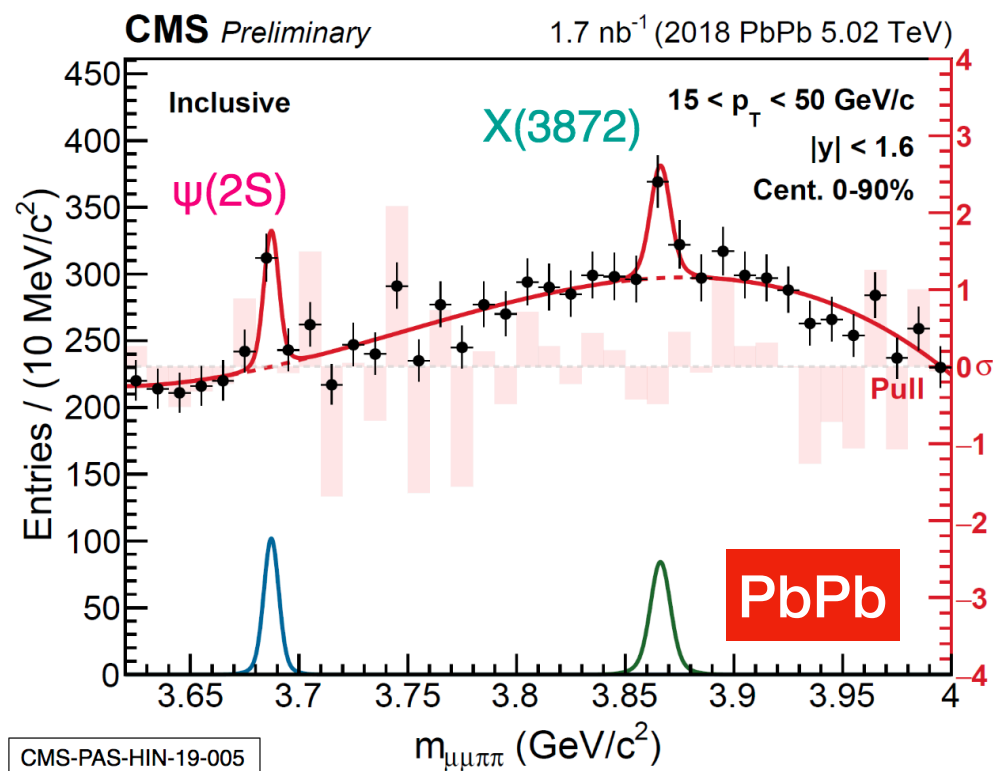
Charmonium



Hybrid



• the latest novel probe of the QGP !

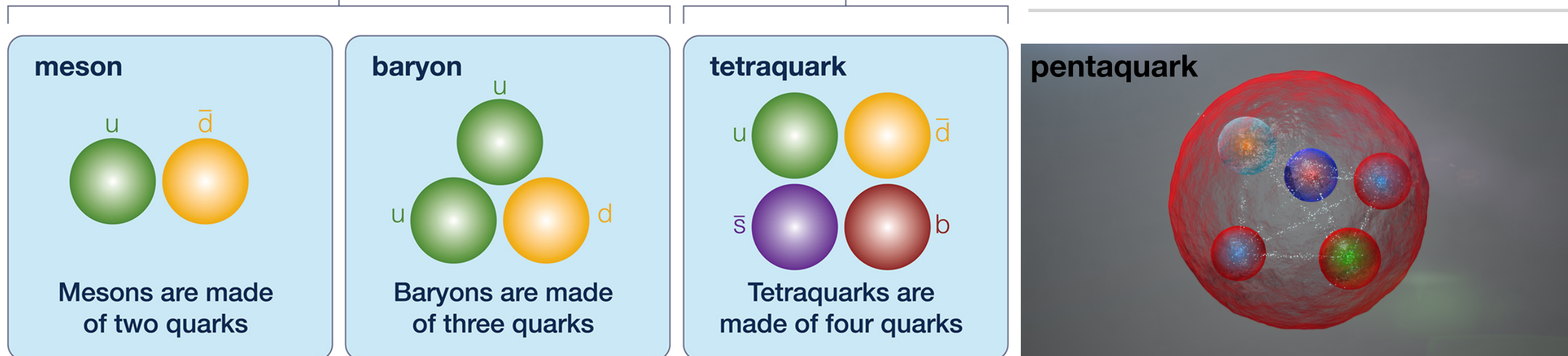


exotic particles

Well understood

New species

Newer species



Shown here is a pion, made of an up and a down quark.

Shown here is a proton, made of two ups and a down.

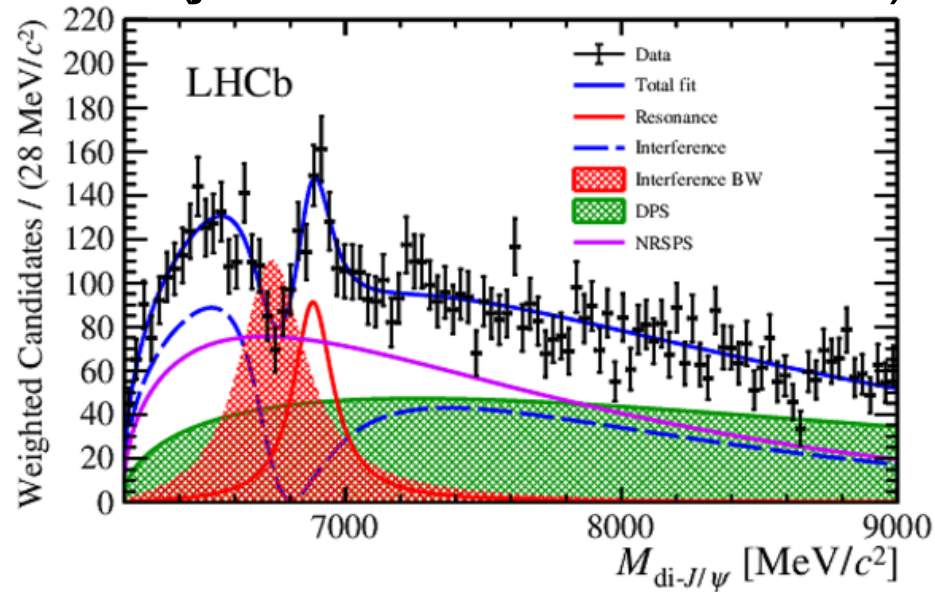
This is X(5568), which is made of an up, down, strange and bottom quark.

since the discovery of the X(3872) almost 2 decades ago, a **zoo of exotic hadron states** has been revealed, understanding of their nature is still lacking but improving with each new measurement,

➔ **NOT UNDERSTOOD = EXCITING !**

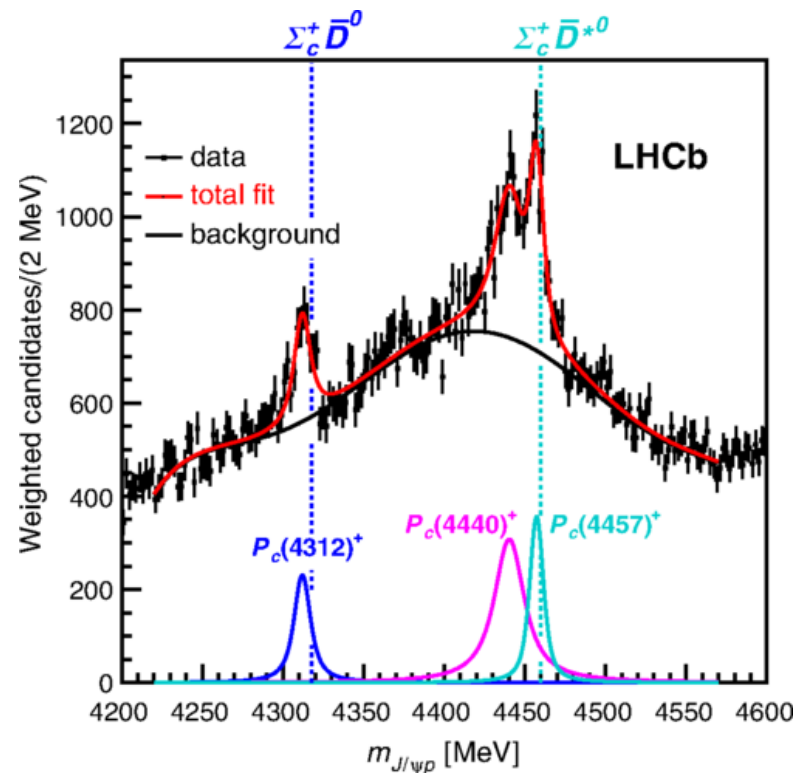
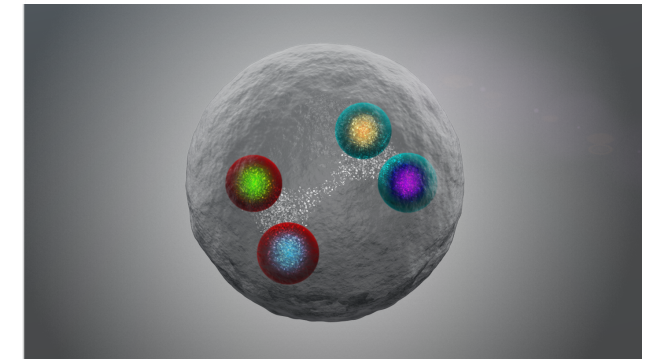
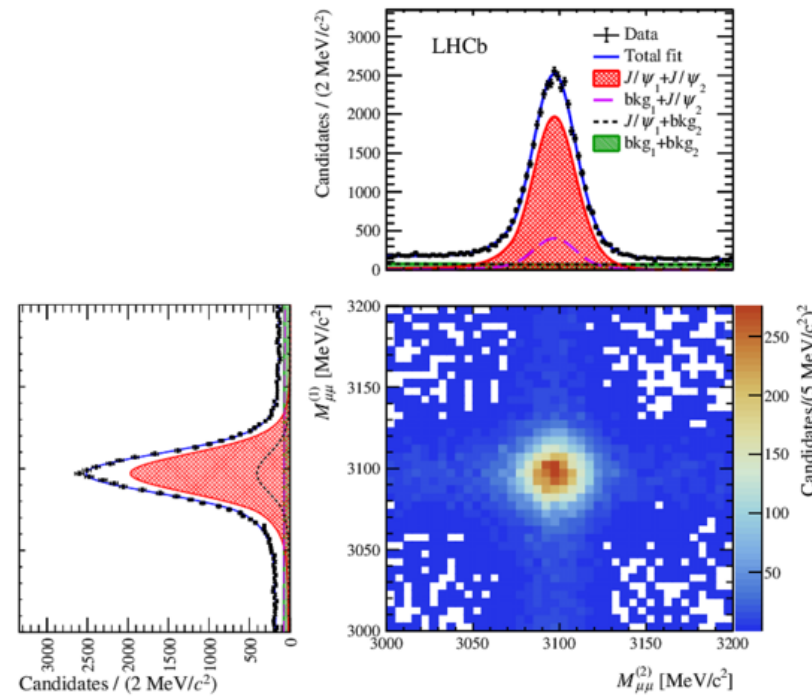
the latest exotic particles from the LHC

new tetraquark LHCb'2020
(just released **this month!**)



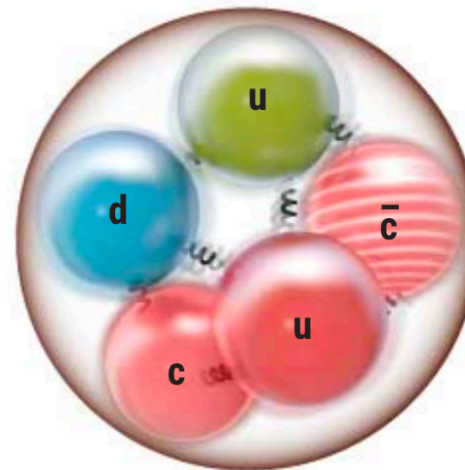
state formed of four charm quarks

in pp
from LHCb

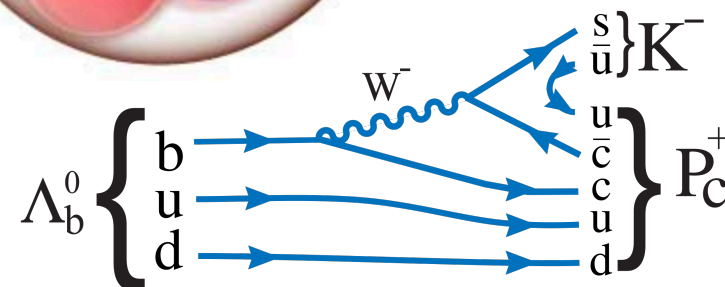
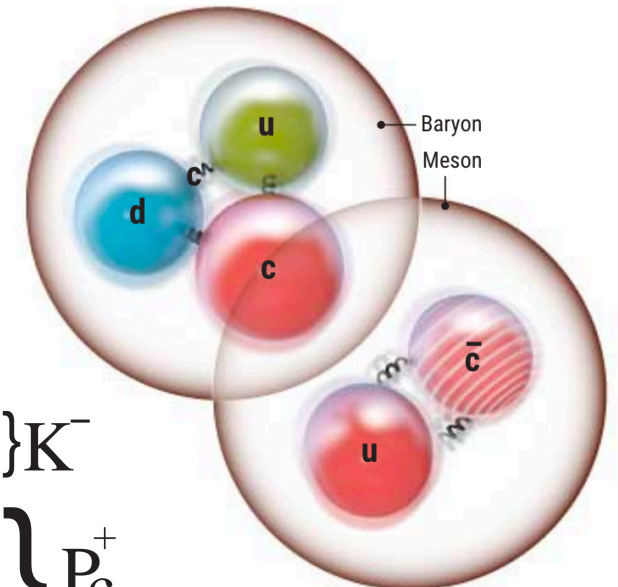


new pentaquark(s) LHCb'2019

"Bag of quarks" pentaquark



"Molecule" pentaquark

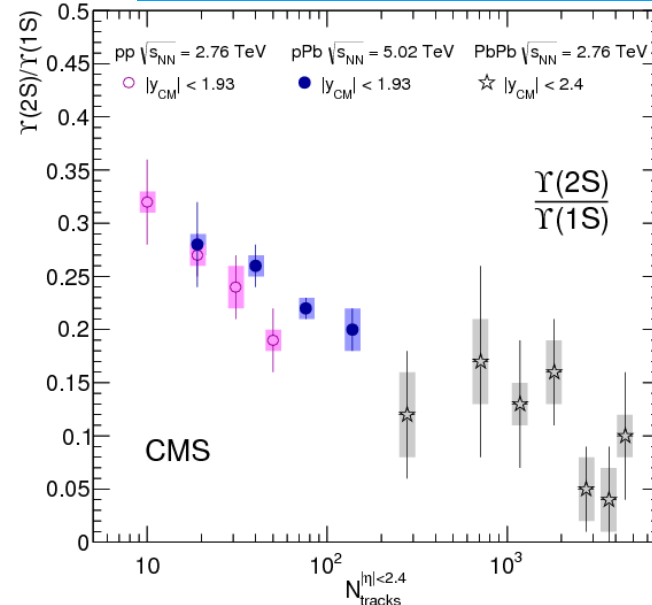


extra: 'collectivity' in 'small systems' ?

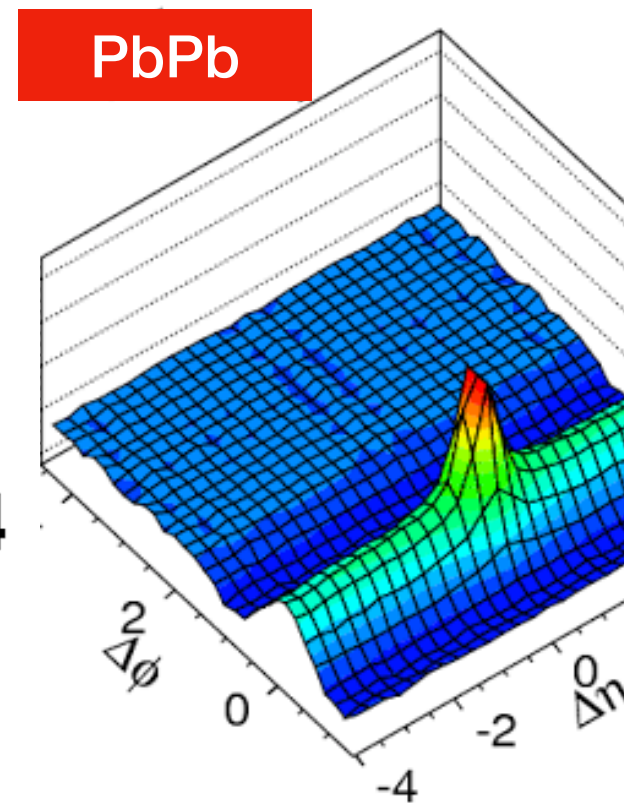
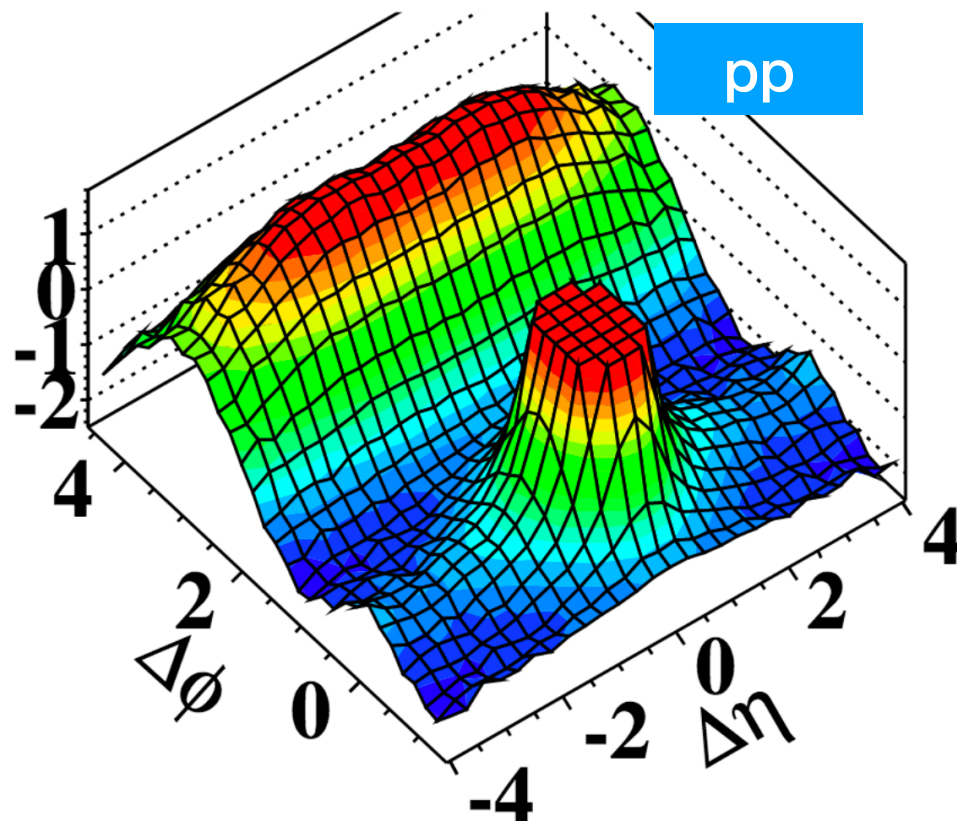
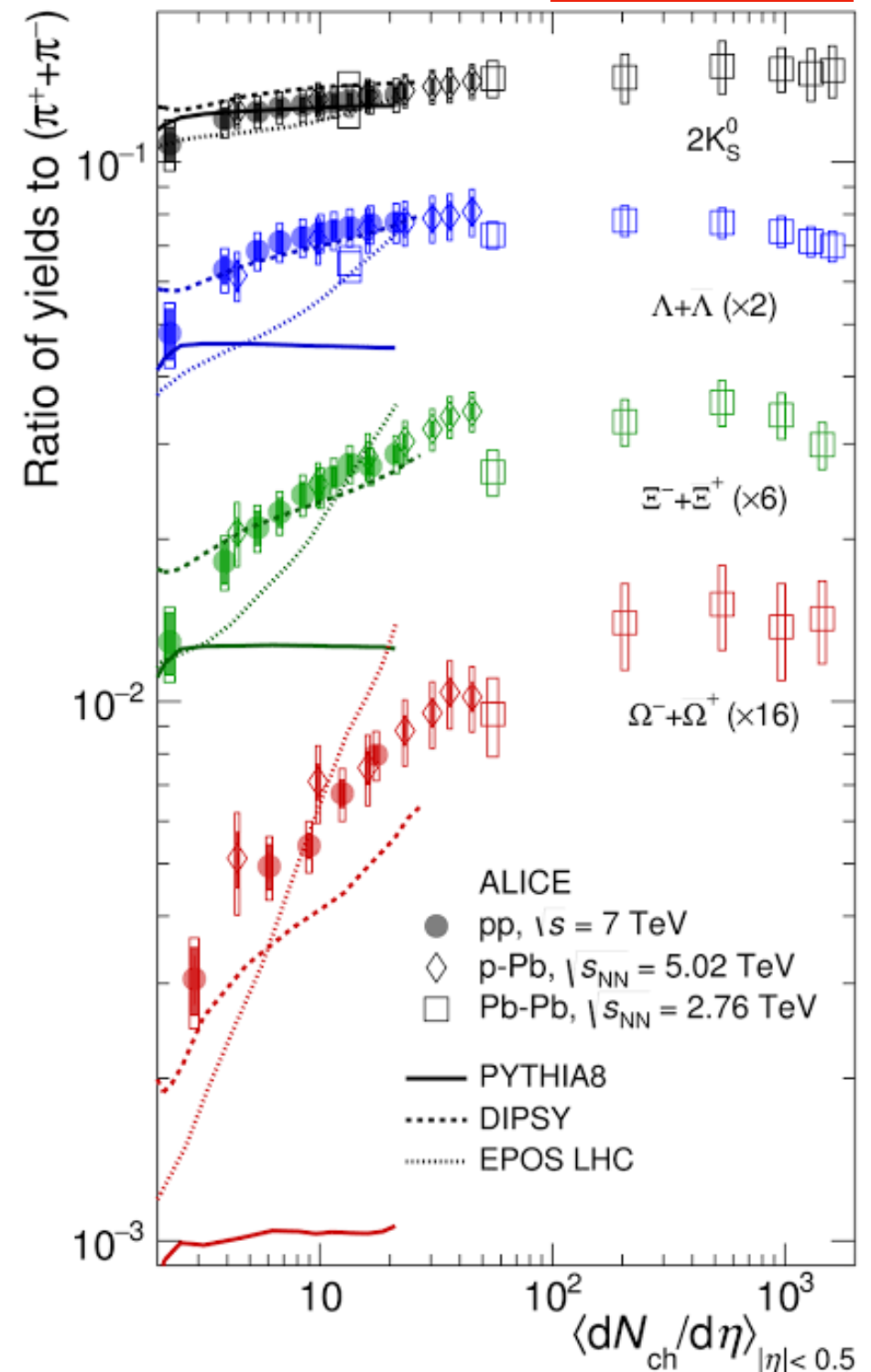
quite unexpected:

- QGP in PbPb ok, ... but hints in small systems: pp and pPb (!?)
- ... or partonic flow
- traditional use of pp as 'vacuum' reference needing revision ?

in pp, pPb, PbPb



from ALICE



→ UNEXPECTED / NOT UNDERSTOOD = EXCITING !