# *QGP soft probes in AA: overview and prospective*

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and much more colleague from CERN and elsewhere…

***QGP-France***

*02/07/18*

# Introduction

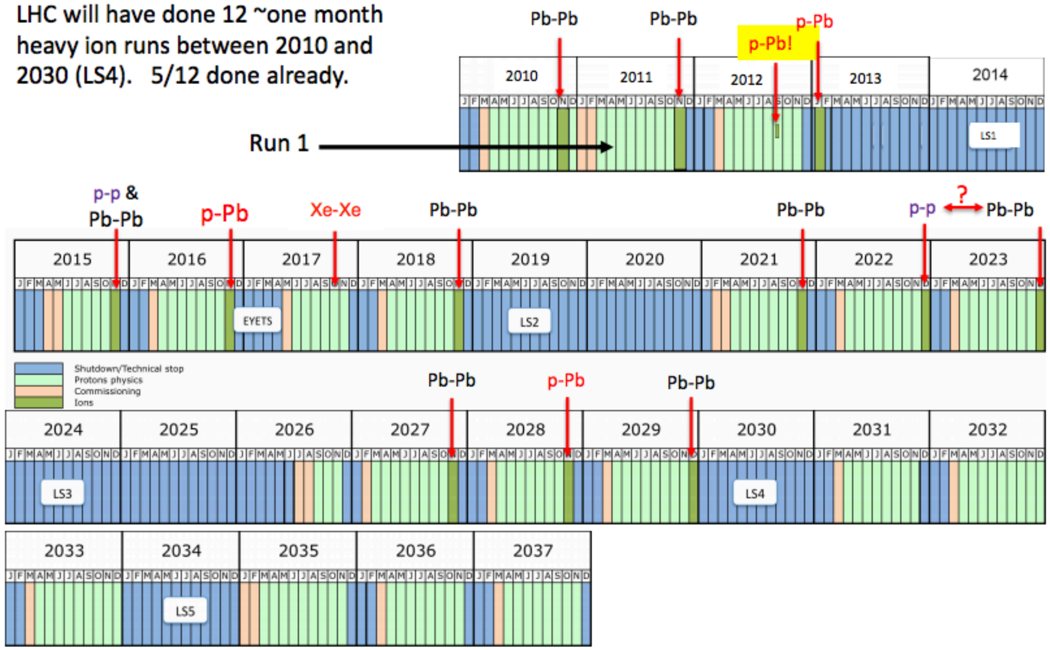
Disclaimer:

- Thermal radiation and chiral restoration are not covered here (see Javier’s talk)
- Small systems soft physics will be covered in a dedicated talk (see Sarah’s talk)

Outline:

- Soft physics definition and main questions
- LHC run1+2
- Prospect for LHC run3+4
- Beyond run 4 at LHC
- Other opportunities
- Summary and conclusions

LHC will have done 12 ~one month heavy ion runs between 2010 and 2030 (LS4). 5/12 done already.



# Nuclear matter phase diagram study

## Scan of the nuclear phase diagram

- Characterization of QGP properties
- Unique opportunity to study QCD under extreme conditions

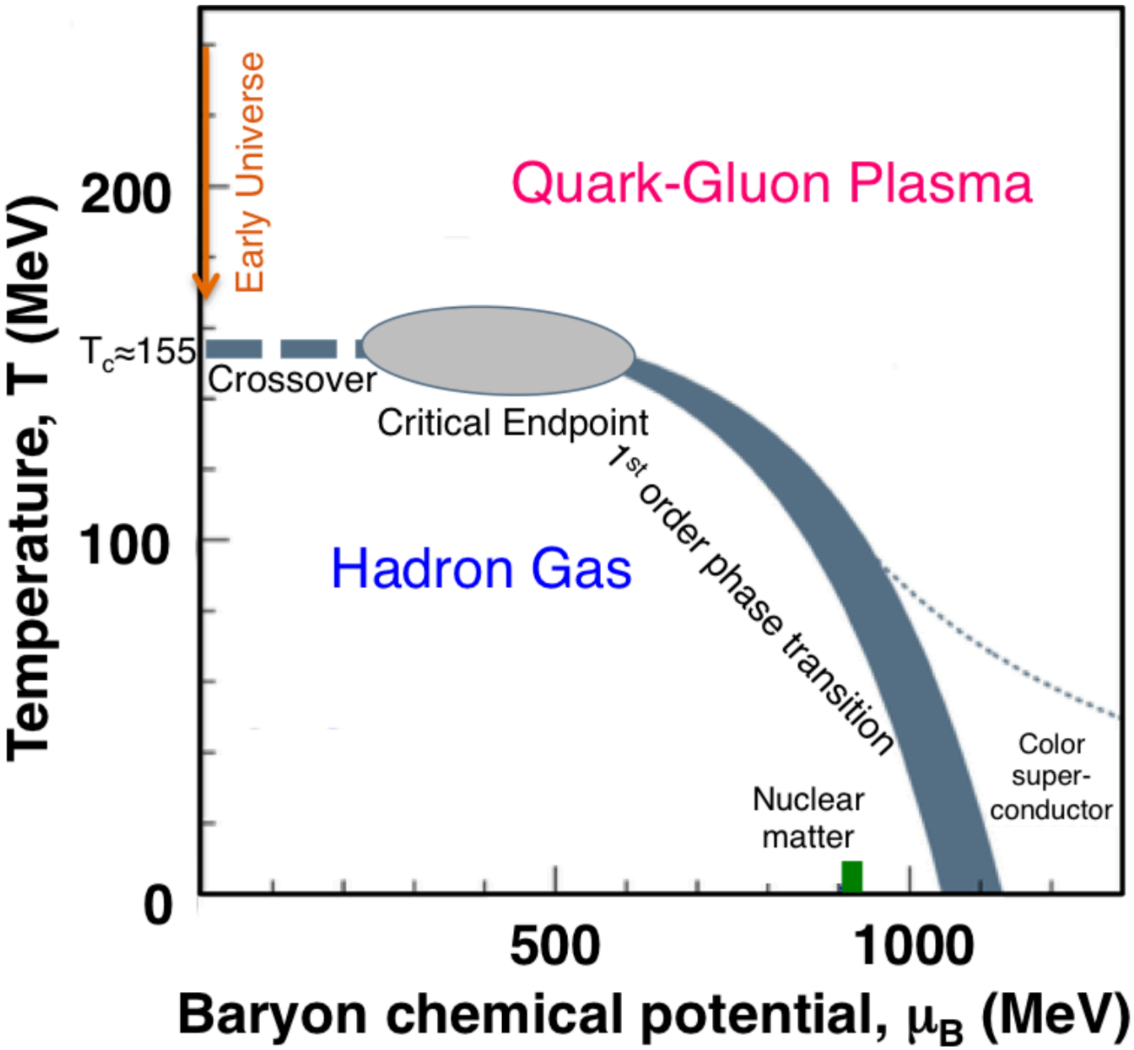
## Search for a critical point

- Is there any?
- Beam energy scan

## What happens at high $\mu_B$?

- Phase transition?
- Understand composition of neutron star

*Taken from: https://goo.gl/ydDc2e*



# What are we trying to probe/constrain?

## QGP: a nearly perfect fluid

- Fluid in a global thermal equilibrium: $T^{\mu\nu} = \epsilon\, u^\mu u^\nu + (p + \pi_{\text{bulk}})\, \Delta^{\mu\nu} + \pi^{\mu\nu}$

  with,

$$p = p(\epsilon)$$

$$\pi_{\text{bulk}} = -\zeta \nabla_\mu u^\mu + \ldots,$$

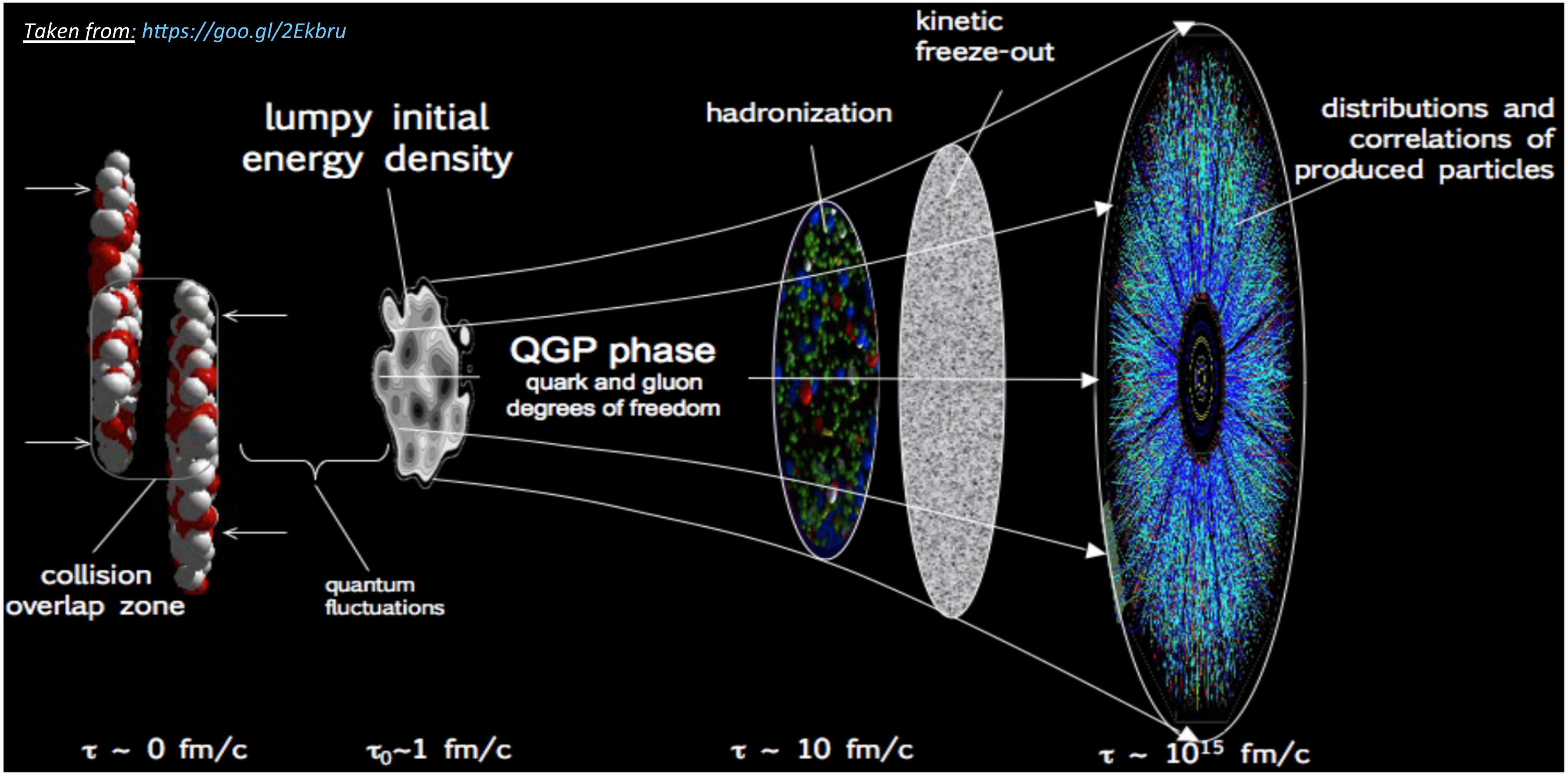
$$\pi^{\mu\nu} = -2\eta \left( \tfrac{1}{2}\Delta^{\mu\alpha}\Delta^{\nu\beta} + \tfrac{1}{2}\Delta^{\mu\beta}\Delta^{\nu\alpha} - \tfrac{1}{3}\Delta^{\mu\nu}\Delta^{\alpha\beta} \right) \nabla_\alpha u_\beta + \ldots$$

- Macroscopic fluid properties
  - Thermodynamic equation of state: p(T, μ)
  - Shear viscosity: η(T, μ)
  - Bulk viscosity: ζ(T, μ)
  - …

## Thermodynamic and particle/nuclei production

- QGP thermodynamic equation of state rather well understood
  - T and μ extracted from data using measured particle abundances
- Details of some particle/nuclei production still under investigation
  - Thermal production vs. coalescence

# The little bang



# What is a soft probe?

## Either global or rather low $p_T$ probe/observable

- Low $p_T$ usually mean < 3 GeV/c
- Can be identified particle or not

## Particle involving soft/low mass quarks

- p, K, π, …
- Strange particles
- (hyper-)nuclei and corresponding anti-nuclei

## Possible observable

- Particle spectra and meson/baryon ratio
- Flow and correlations
- Strangeness enhancement
- …

# What are the experimental needs?

**Current experiments:**

- LHC (ALICE/ATLAS/CMS/LHCb)
- RHIC (PHENIX/STAR)
- SPS (NA61/Sunshine)
- SIS (HADES)

**Approved/Proposed experiments:**

- FAIR (CBM)
- NICA (MPD, BM@N)
- RHIC (sPHENIX)

## Large acceptance detector with efficient tracking

- This is particularly important for correlation measurements
- Precise tracking down to low $p_T$ is the key

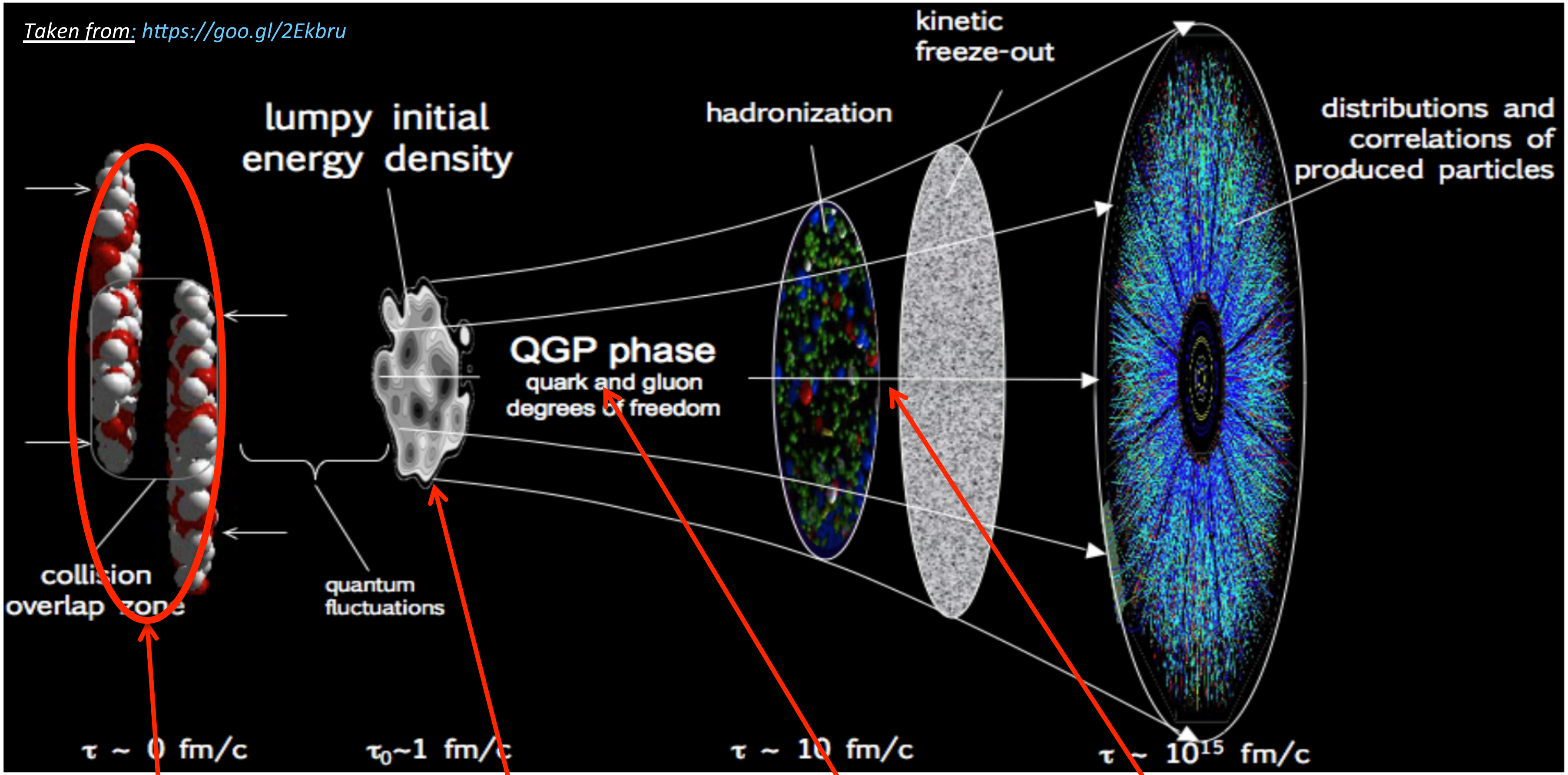
## PID capability

- Important to identify particle at low $p_T$
- At LHC, ALICE is unique on that respect at mid-rapidity

## At LHC, no ideal detector for soft probes

- Each of them have their own pros and cons
- How each of them can be improved in the future need to be part of the discussion

# The little bang




Initial conditions

Initial state and fluctuations

Hydrodynamic evolution

Particle/nuclei production

# LHC Run 1+2: What have we learned?

## *QGP Hydrodynamic and Initial state fluctuations*

**Hydro evolution quite well understood now**

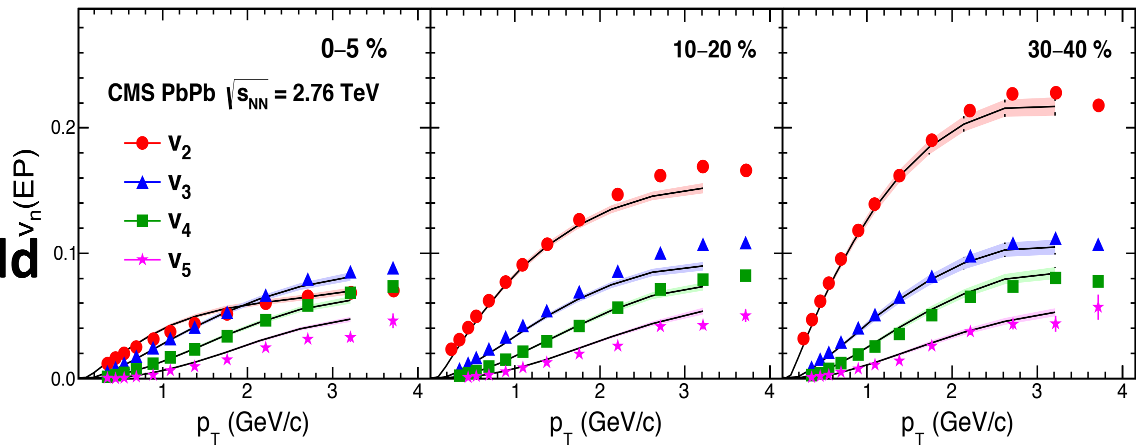
- Tighter constraint on shear viscosity: $0.07 < \eta/s < 0.2$

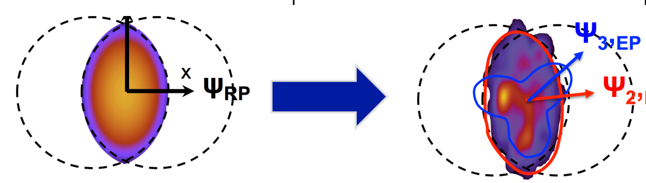
**From RHIC already non-zero odd harmonic**

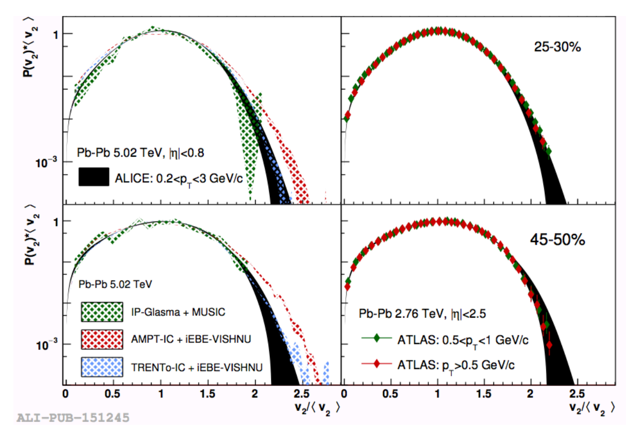
- Initial state fluctuations
- Lumpy initial state generates factorization breaking
  - EP angle depends on $p_T$ and $\eta$

**Precision era with more refined methods**

- Gain control on IS and fluctuations
  - Different initial conditions needed
- Flow distribution measurements
  - More data, larger acceptance
- More direct comparison with theory
  - New methods



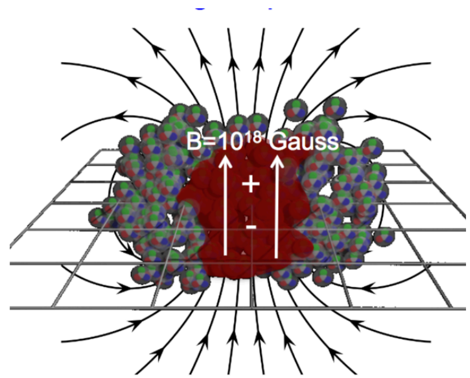



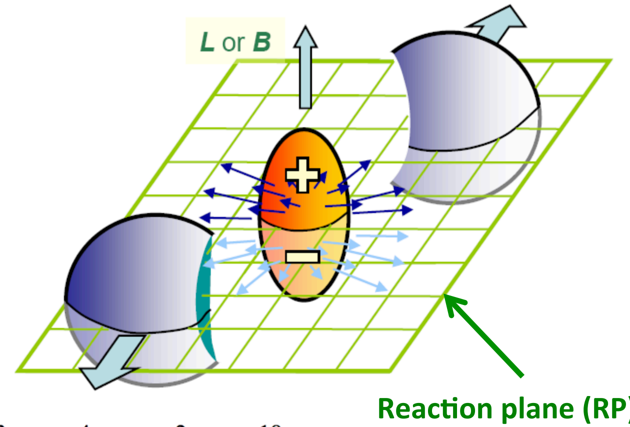



# LHC Run 1+2: What have we learned?

## *Chiral Magnetic effect (CME)*

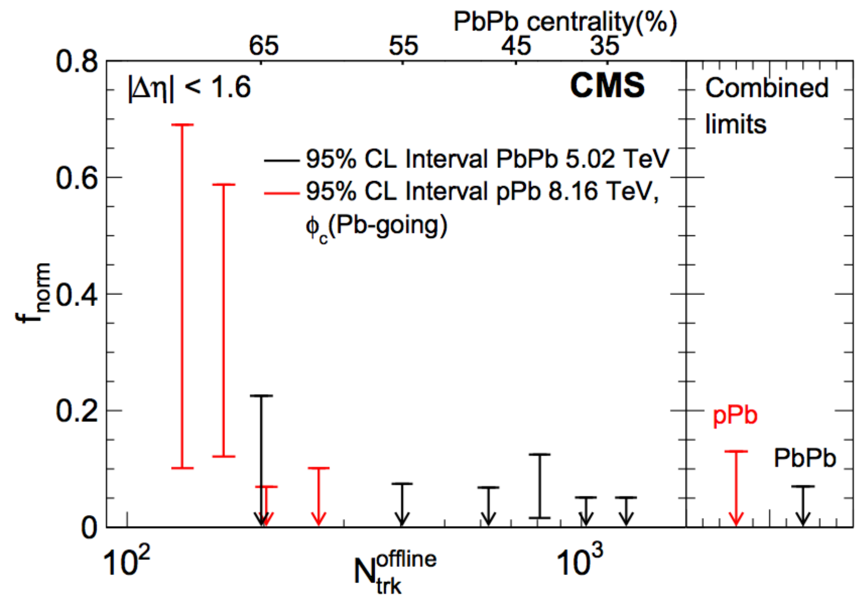
**Large B field predicted at the collisions**
- Induced current
- Charge separation along the RP is expected




$$eB(\tau = 0.2\ \mathrm{fm/c}) \approx 10^3 \sim 10^4\,\mathrm{MeV}^2 \approx 10^{18}\,\mathrm{G}$$

**CME effect not observed at LHC**
- Pure background observed
- ALICE and CMS have set a limit



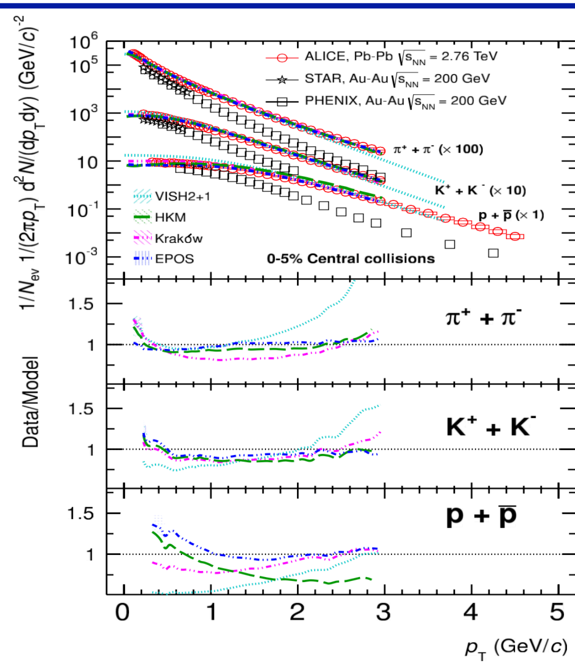

**B field might have a too short lifetime at LHC**
- High transparency of incoming nuclei
- What about high $\mu_B$?
  - Influence of B field and quantum anomaly on fluid dynamics

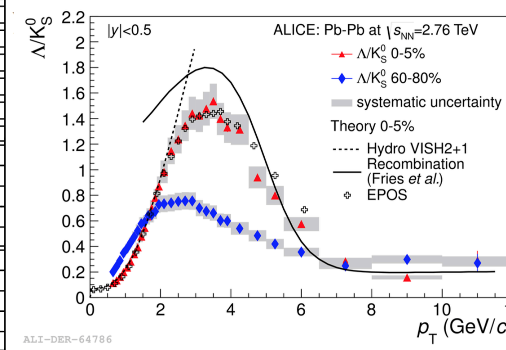
# LHC Run 1+2: What have we learned?

## *Bulk and Particle production*

### (Nearly) thermalized medium and common flow velocity

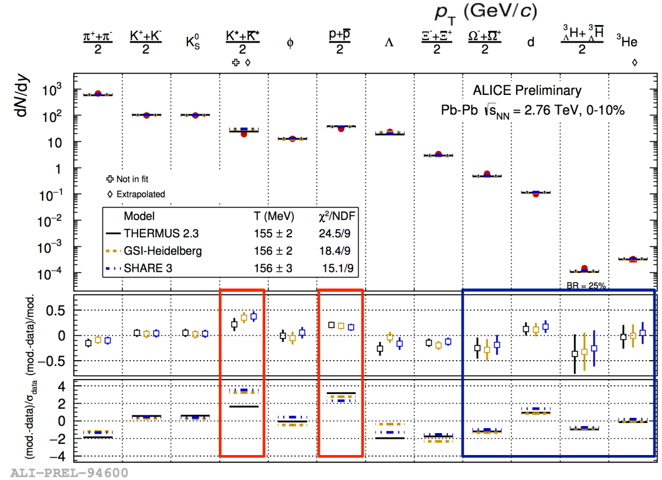
- Boosted $p_T$ spectrum
- Mass ordering
  - Hardening of spectra as function of centrality
  - More pronounced for heavier particles




### Baryon to meson ratio (B/M)

- Low-$p_T$ described by hydro
- B/M in jets significantly lower
- Arise from the bulk




### Thermal production

- T = 156 ± 2 MeV

# LHC Run 1+2: What have we learned?

## *Strangeness enhancement*

**Thermal limit reached**

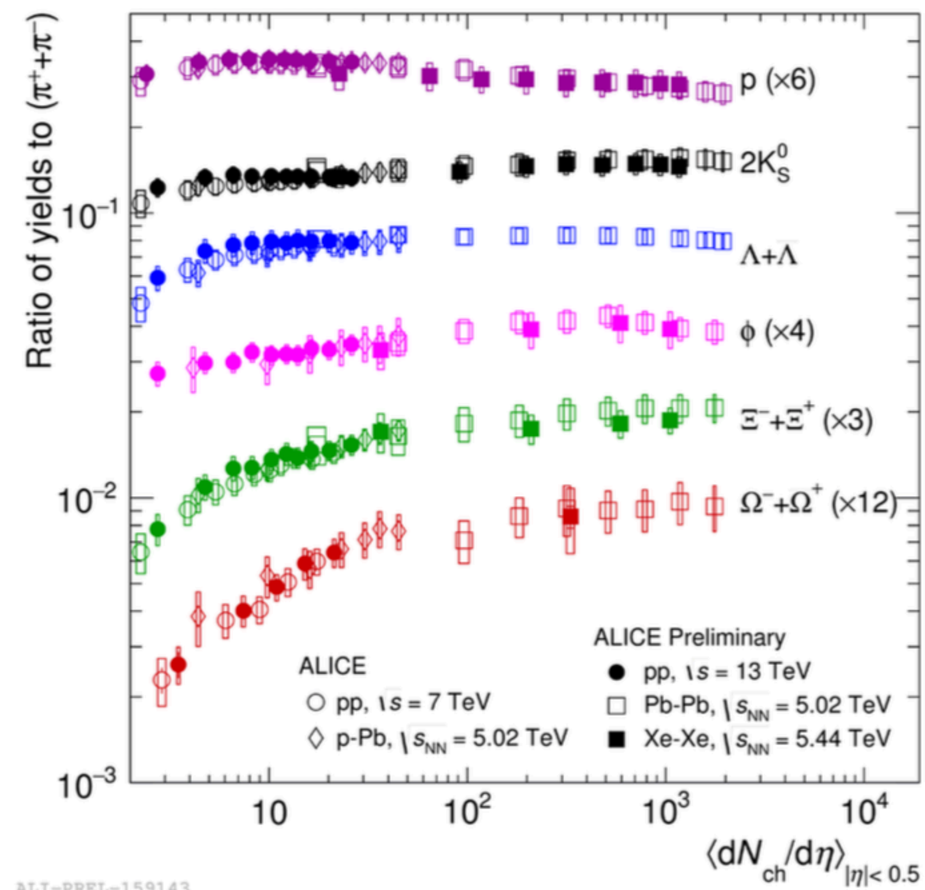
- Most central or high multiplicity events
- Strangeness thermalized at sufficiently high energy

**Strangeness production does not depend on c.m.e. or system size**

- Significant constraint on the underlying mechanisms of microscopic models

**We can also learn a lot from small systems on that particular topic**

- See Sarah's talk



# LHC Run 1+2: What have we learned?

## *(Hyper)nuclei and anti-(hyper)nuclei*

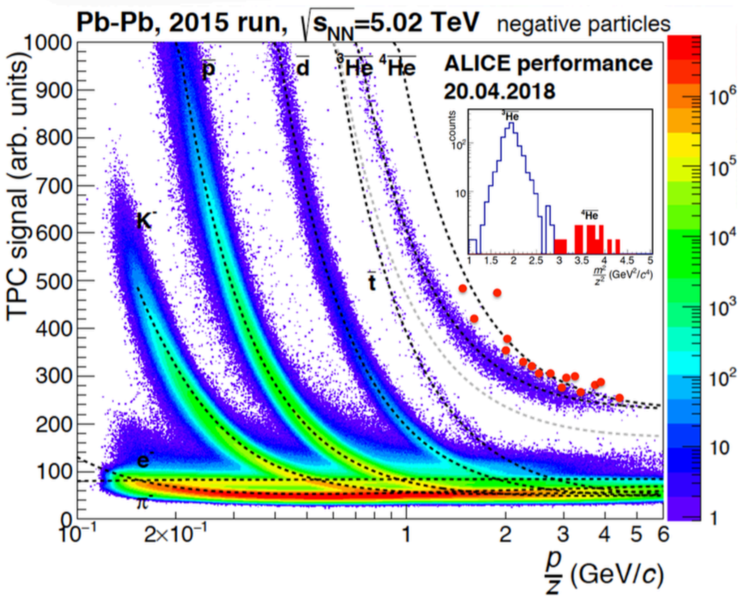
### Thermal production vs. coalescence

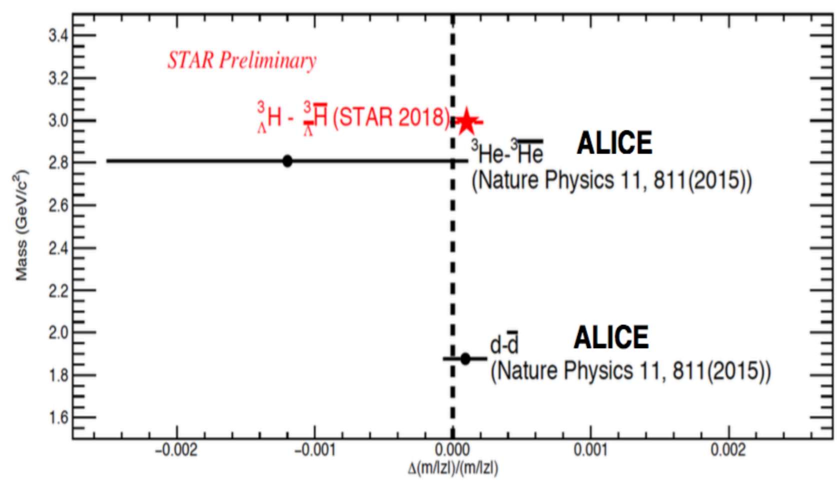
- Sensitive to $T_{ch}$ due to large mass
- Large PID capabilities from ALICE
- Coalescence works (surprisingly?) well for (anti-)nuclei in small systems

### CPT violation studies

- ALICE not build for such measurement
  - .. But still very good results ☺
- Most precise constraint on CPT using heavy nuclei
- A lot of room for improvement
- Follow up with heavier nuclei or hypernuclei

**Large stat. Needed in all cases even in PbPb**



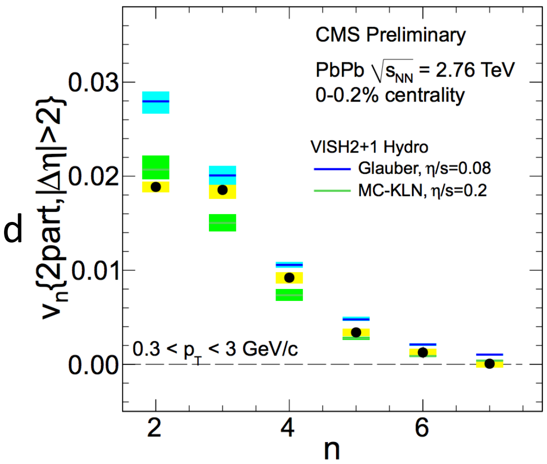
# Brief summary (I)

**At LHC, quantum anomalies such as CME doesn't seem play a big role**

- High transparency on incoming nuclei
- Limit set to 7% max. signal if any
- Is that the case for lower c.m.e. (lower $\mu_B$)? Does it plays a role in fluid dynamics?
- What about other effects such as vorticity? (https://arxiv.org/abs/1701.06657)

**Good understanding of the hydrodynamic behavior of QGP**

- Strong constraint on shear viscosity
- Still devil is in the details
  - The correct descriptions of IS and fluctuation are not clear yet
  - The system size dependence still need to be more precisely investigated
  - The question about the onset of collectivity still need to be answered
  - What about a precise description of non-linear modes? Ultra Central Collision puzzle?
  - …
- More data with different initial conditions are needed



# Brief summary (II)

## Bulk and particle production

- Particle production at LHC globally explained with thermal model
- Extracted temperature compatible with prediction
- Evidence of common flow velocity (radial flow)

## Strangeness

- Thermal limit seems to be reach at LHC temperature
- Production does not depends on system size or c.m.e.
  - Depends on multiplicity?
  - Microscopic mechanisms need more stringent constraint
- Careful comparison spanning the full multiplicity range is needed
  - Comparison at high precision with smaller systems is needed

## (Hyper)nuclei and anti-(hyper)nuclei

- Details of the production mechanisms still under investigation
- Very good test bench for CPT violation

# What are the Run3+4 prospectives?

## Precision measurements

- True and worth it in all areas for soft probes with large sample
- Important to get a more precise knowledge of the soft sector quickly as it is the **underlying events (background) for most of the hard probes**

## Major upgrade on all front at Run3+4

- ALICE tracker upgrade
  - Improved acceptance and tracking precision
  - 50kHz "triggerless" data taking
- CMS/ATLAS tracker upgrade
  - Tracker acceptance extended to 8 units in $\eta$
- PID capabilities in CMS
  - PID using the Mip Timing Detector (MTD) down to low $p_T$ (0.7 GeV/c)
  - Performance comparable to the current ALICE TOF
- LHCb upgrade
  - Better granularity of the tracker and the vertex locator: Going to more central events

# Why these upgrade matters?

**Larger acceptance of tracking systems increase the precision of all spectra/correlation measurements**

- Better understanding of the dynamics in the soft sector

**Precise description of the soft sector is needed to study hard probes**

- Jet underlying events
- Soft-hard correlations
- …

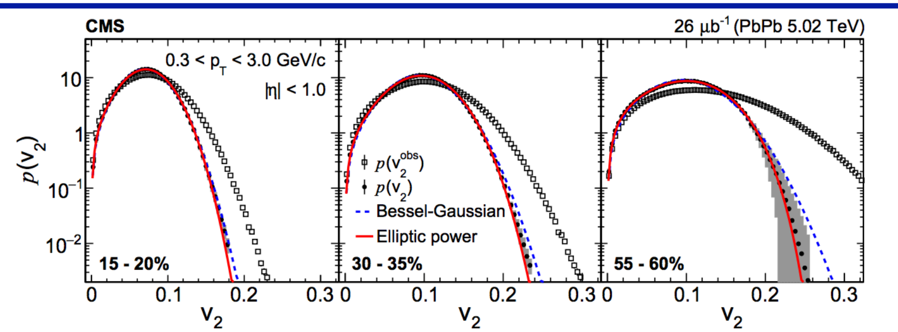
**More complete PID capabilities:**

- ALICE PID capabilities preserved
- Forward pseudo-rapidity region not well known at LHC: LHCb upgrade + its PID capabilities will open up new opportunities
- CMS new PID capabilities will help to measure Soft-hard correlations, …

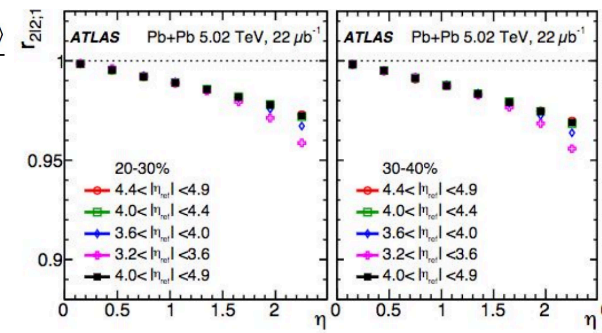
# Some idea of possible measurements for Run3+4

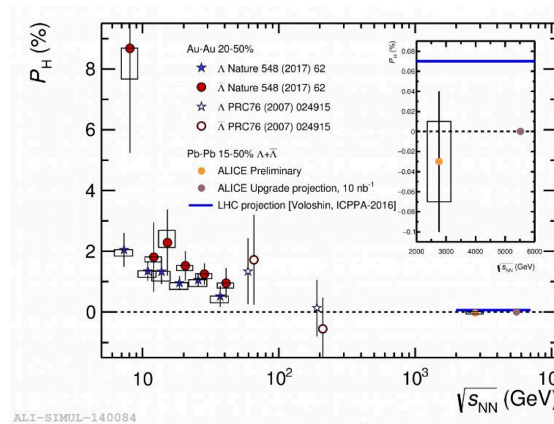
## Flow/correlations

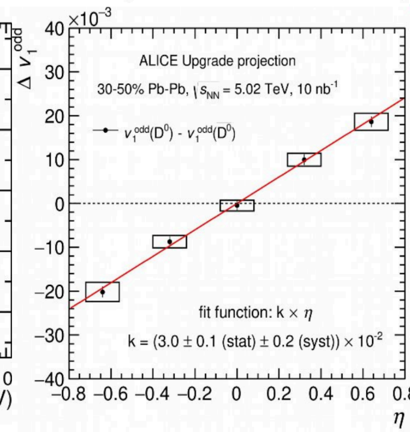
- Characterize the initial state spatial anisotropy and hydro. evolution
  - E-by-E $v_n$ distribution with large tracker acceptance
  - Differential measurement of higher order cumulant with background free methods
  - Differential ($p_T$, η) Principal Component Analysis, study of non linear modes
  - Longitudinal dynamics
- CME search with charge dependent $v_1$
- Vorticity and fluid dynamics
  - Precise measurement of Λ transverse and longitudinal polarization
- Fixed target LHCb program can be interesting here




$$r_{n|n;1}(\eta) = \frac{\langle \mathbf{q}_n(-\eta)\mathbf{q}_n^*(\eta_{\rm ref})\rangle}{\langle \mathbf{q}_n(\eta)\mathbf{q}_n^*(\eta_{\rm ref})\rangle}$$



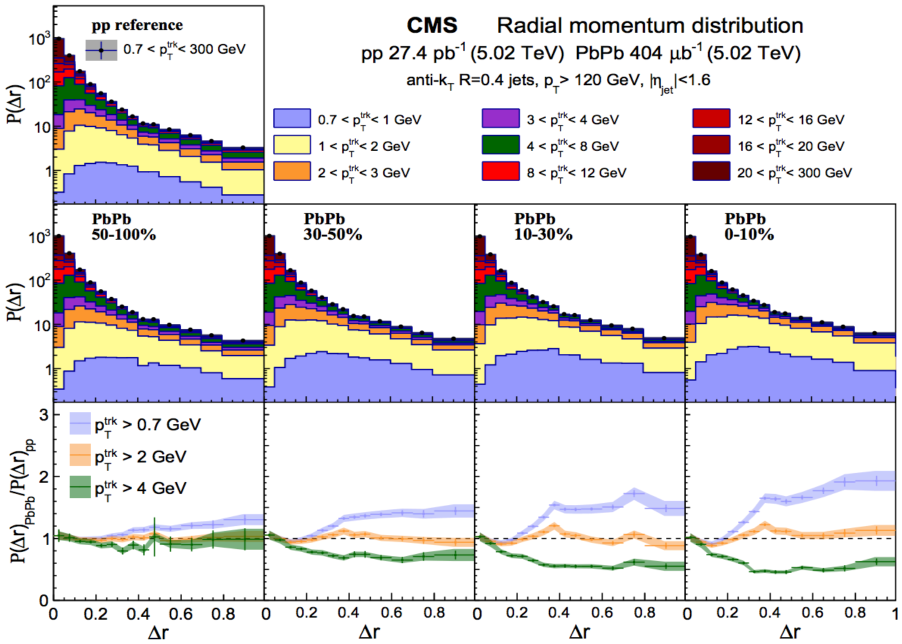



# Some idea of possible measurements for Run3+4

## Bulk and particle production

- p, K, π correlation with jets
  - Low $p_T$-track excess at large angle in PbPb compared to pp
  - What is the origin of this excess?
- Strange particle measurement will also be possible in CMS through the Φ to KK channel



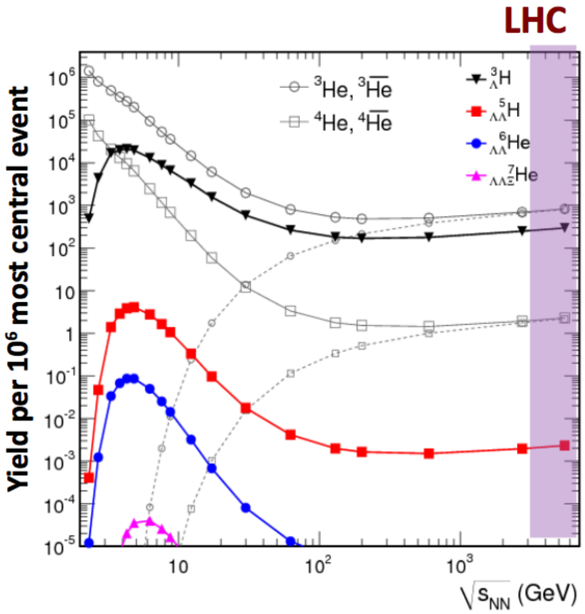

What is the exact mechanism?

- Bulk effect
- Related to jet fragmentation?

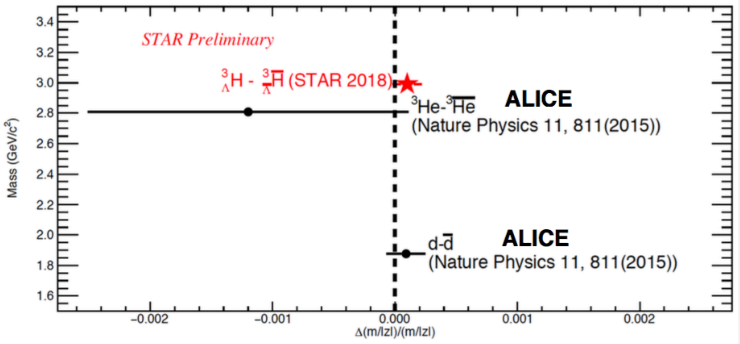
# Some idea of possible measurements for Run3+4

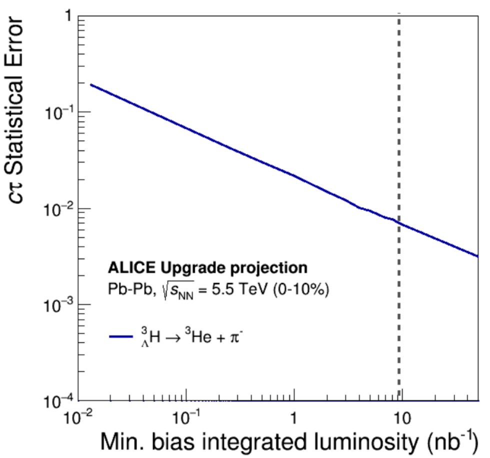
## (Hyper)nuclei

- More precise measurement and to higher masses will help to clarify production mechanisms




High precision




- Huge opportunity to improve the limit on CPT violation

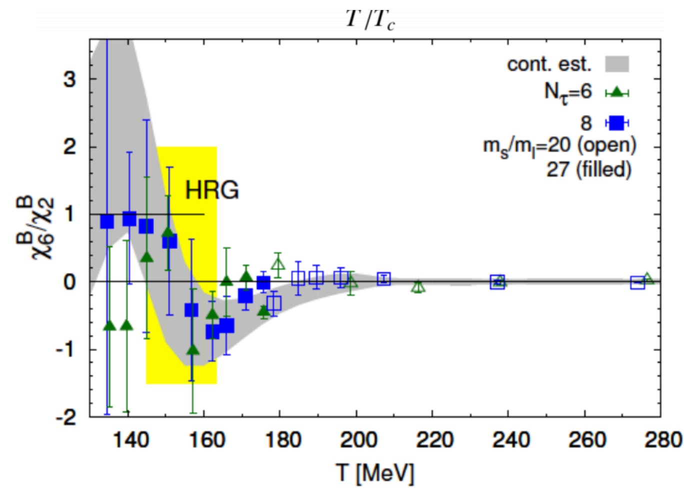
# Critical phenomena and comparison to ℓQCD

$$\chi_n^B = \frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}$$

Susceptibility directly link to **EoS**

**E. By E. fluctuation predicted** in Grand Canonical Ensemble

Sensitive to critical phenomena




$$\kappa_2(N_B - N_{\bar{B}}) = \left\langle (N_B - N_{\bar{B}})^2 \right\rangle - \left\langle N_B - N_{\bar{B}} \right\rangle^2$$

$$\Delta N_B = N_B - N_{\bar{B}}$$

Net baryon fluctuations via cumulant measurement

$$\kappa_1 = \langle \Delta N_B \rangle = VT^3 \chi_1^B$$

$$\kappa_2 = \left\langle (\Delta N_B - \langle \Delta N_B \rangle)^2 \right\rangle = VT^3 \chi_2^B = \sigma^2$$

$$\kappa_3 = \left\langle (\Delta N_B - \langle \Delta N_B \rangle)^3 \right\rangle / \sigma^3 = \frac{VT^3 \chi_3^B}{(VT^3 \chi_2^B)^{3/2}} = S$$

$$\kappa_4 = \left\langle (\Delta N_B - \langle \Delta N_B \rangle)^4 \right\rangle / \sigma^4 - 3 = \frac{VT^3 \chi_4^B}{(VT^3 \chi_2^B)^2} = k$$

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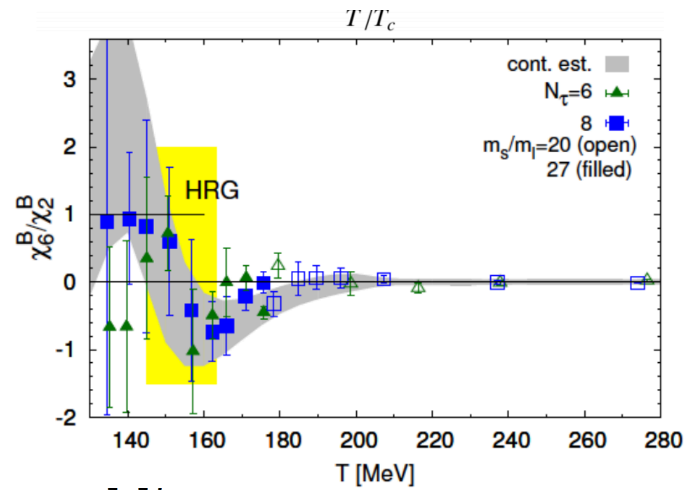
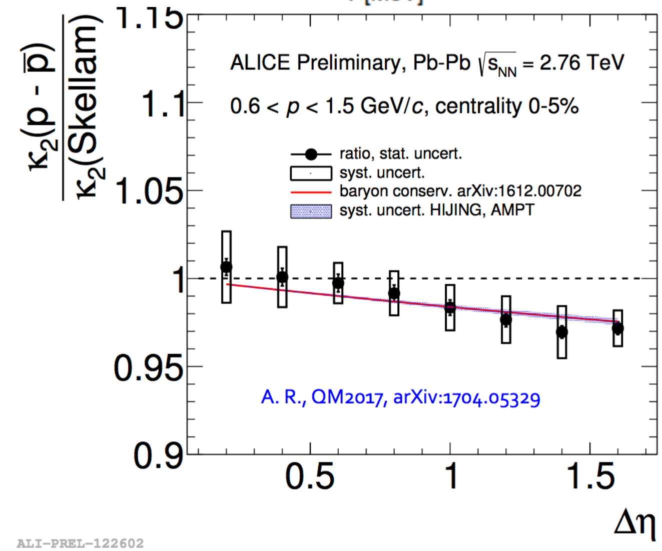
NOT a direct comparison due to **V** fluctuation and **finite acceptance**



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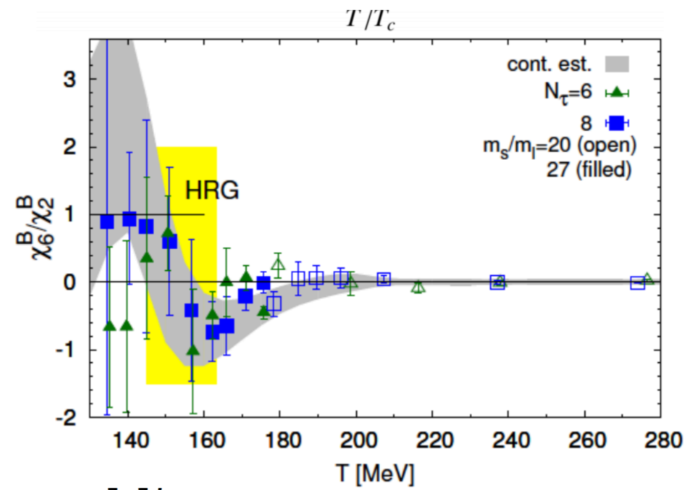


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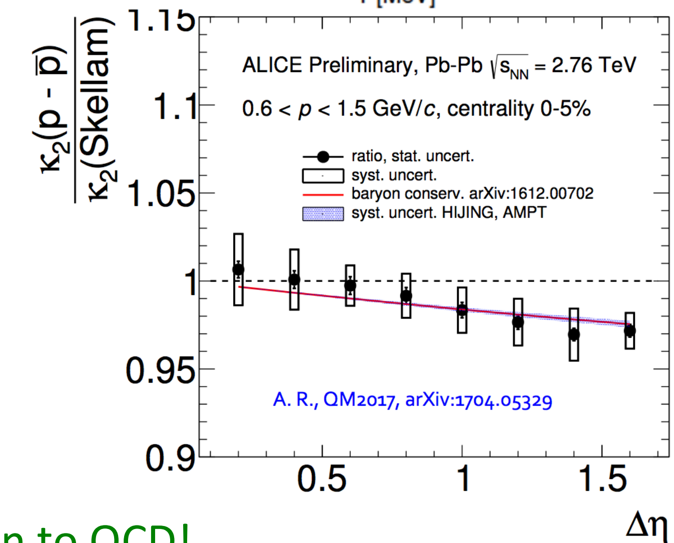



Direct comparison to QCD!

**Even more relevant at RHIC energies!**

# Fixed target experiment at LHC

## From Run 3+4 and beyond

### Proposal to use ALICE in a fixed target mode

- Very high luminosity and more precise tracker
- Flexible nuclear target (Pb+A or p+A collisions)

### LHCb fixed target program

- Polarized fixed target: Spin physics search
- Could be possibly ready for run 4

### Intermediate energy between RHIC and SPS

- Studies at high-$\mu_B$
- Unique opportunity to study longitudinal expansion of the QGP
  - Correlation measurements and particle yields
  - Fragmentation region poorly know so far

# What's next?

**LHC**

- Collider (ALICE/LHCb/CMS/ATLAS)
- Fixed Target (ALICE/LHCb)

**RHIC**

- sPHENIX program

**NICA and FAIR**

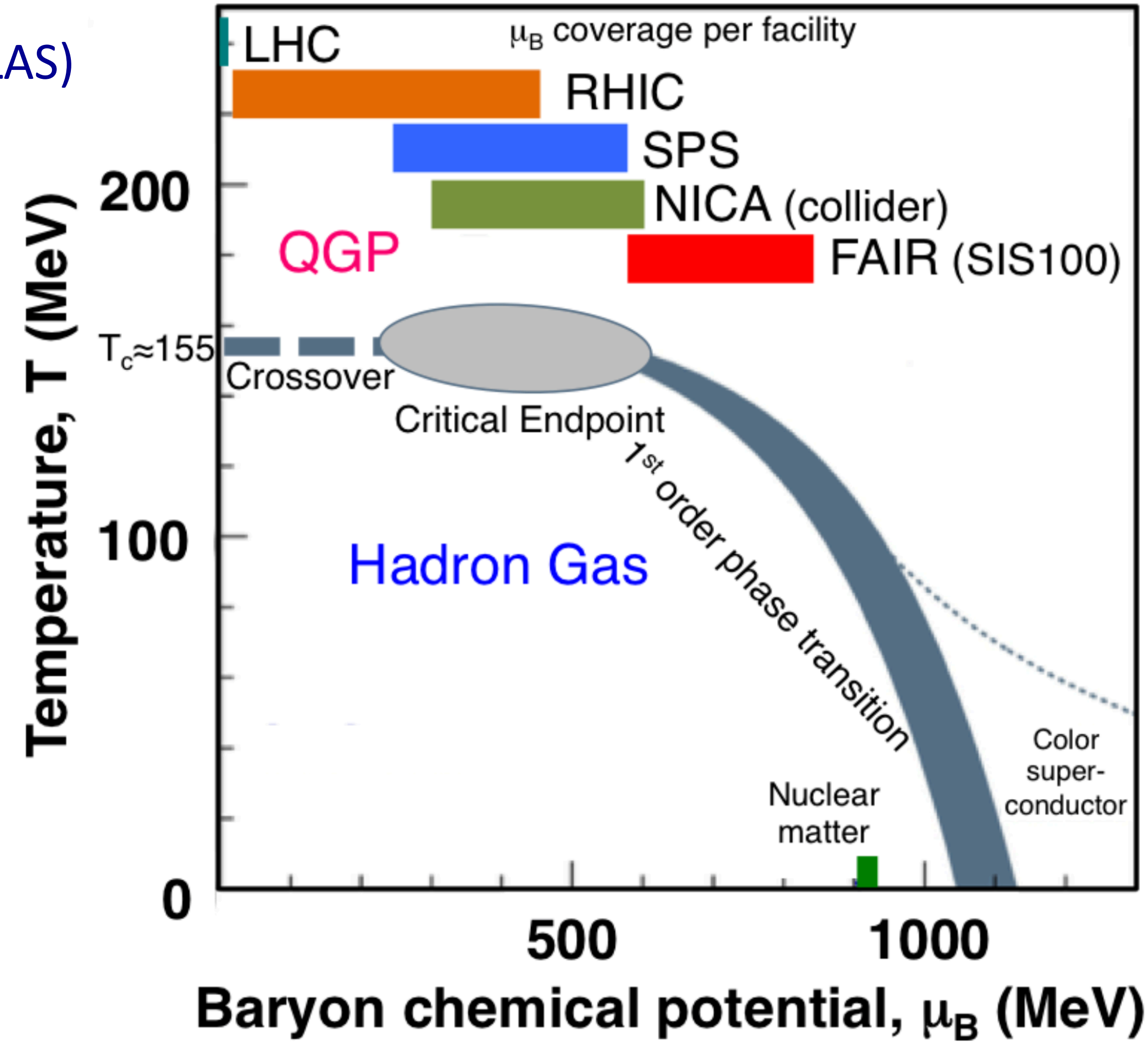
- High $\mu_B$ program

**Scan through the phase diagram!**

**Other facilities:**

- FCC?

*Taken from:* https://goo.gl/ydDc2e



# LHC beyond run 5: collider

**The LHC is tending to be more and more flexible machine**

- Xe-Xe in 2017
- Discussion about O-O this year (not going to happen soon but still…)
- Proposal for Ar-Ar floating around

**One important contribution at LHC energy would be to vary initial condition**

- Initial condition == ion size
- Spanning a range from small ion radii (Ar, O) to large (Pb) will surely increase the constraint on:
  - Hydrodynamic behavior of QGP + IS description
  - Particle production

**Onset of QGP production**

- Can be done extensively at LHC with various ion species
- Need also for a coherent "small system" program to span the full range in system size

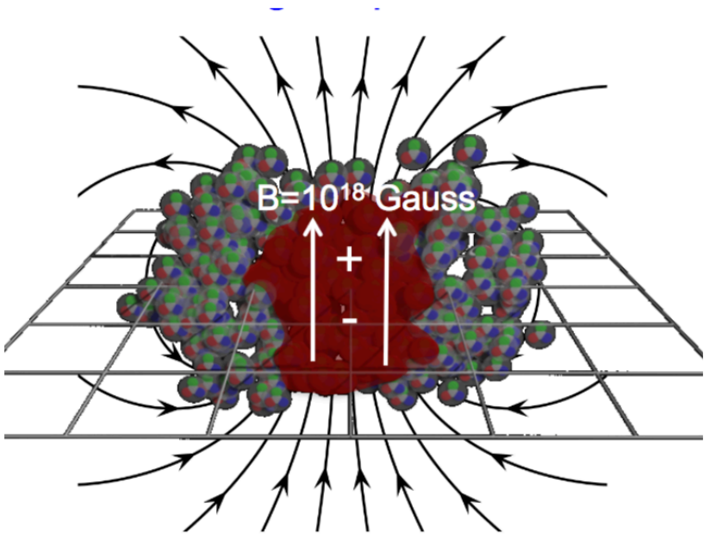
No official plan of upgrade from all the current LHC experiment yet. Need to think about an ideal detector for soft physics

# RHIC and sPHENIX

## RHIC facility

- Flexible in energy: (T, $\mu_B$)
- Flexible on the ion species

## RHIC energies favor CME studies



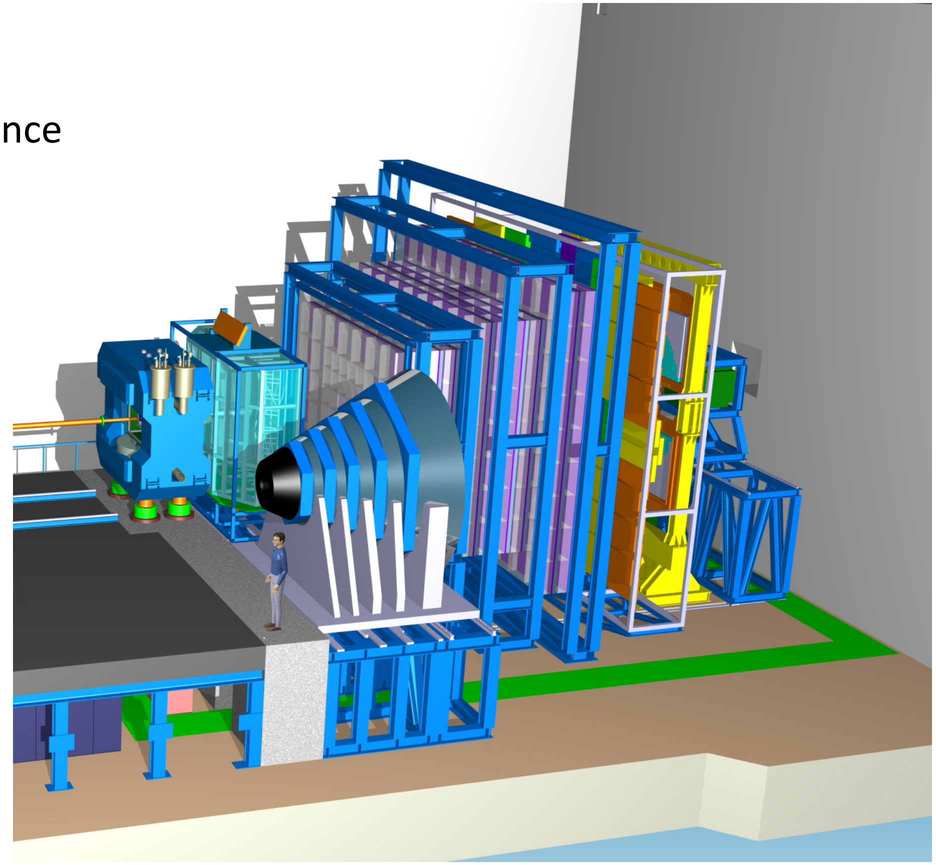

- Non-zero $\mu_B$
  - Incoming ions not fully transparent
  - B field lives longer
- Possibility of colliding isobar
  - Elliptic flow ($v_2$) main background for CME search
  - $v_2$ depends on system size (number of nucleons)
  - B field depends on Z
  - Colliding isobar would vary the CME signal while keeping the background unchanged

# CBM @ FAIR

## Large and rich program at very large $\mu_B$ (3-14 AGeV)

## Test EOS of nuclear matter

- Strangeness production
  - Hypermatter production: Thermal vs. coalescence
- Collective flow of identified particles
  - Is collective flow sensitive to EOS?
- Low mass dilepton production
  - Chiral transition search



# FCC or similar projects

**The FCC interests for our community are**

- Hard probes in HI collisions
- Small system studies

**Regarding Soft physics, there is not much more information at FCC energy**

- Flow/correlation not very sensitive to c.m.e.
- Thermal limit already reach at LHC

**Nevertheless, hard probe studies usually need a precise estimation of the underlying event**

- Basic soft probe measurement are needed at least

# Summary

**Soft probe at LHC are rather well understood BUT…**

- Details of the IS, hydro. evolution and particle production still need to be understood
- With Run3+4 we should be able to address some of the key questions
- Assuming other species available at LHC in Run 5 and beyond
  - Access to the detail of IS and hydro. evolution
  - Common paradigm across hardonic colliding systems

**Other opportunity beyond LHC for soft physics**

- Scan of the phase diagram using multiple facilities running at different energies
- Consistent and complete picture of QGP physics

*Taken from: https://goo.gl/ydDc2e*