GdL "Precision SM measurements": Heavy Ions

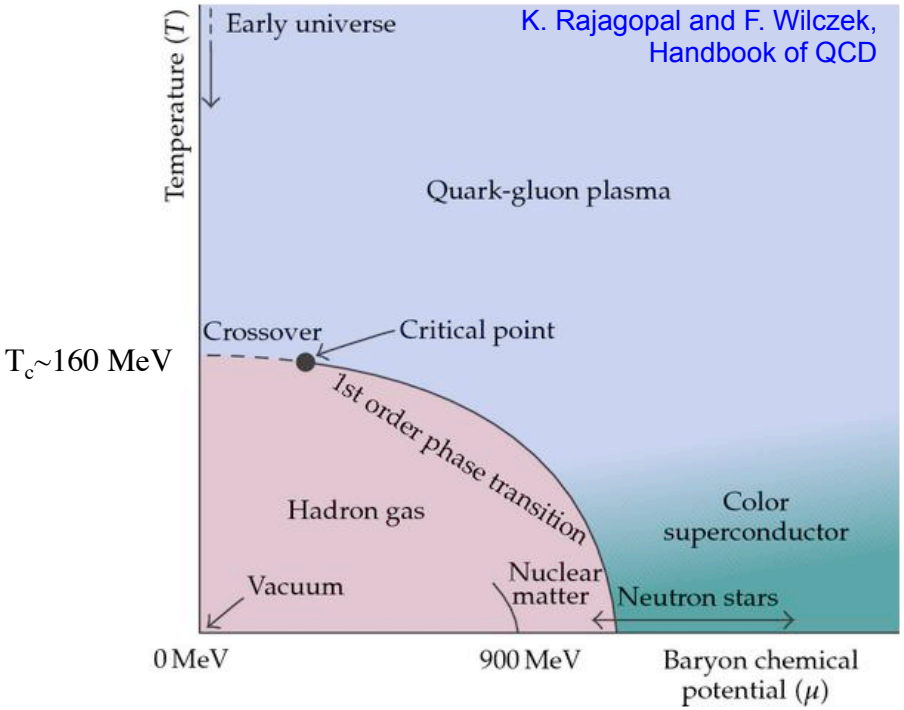
WHO & WHAT ?

- *Mailing list* *whatnextqgp@lists.infn.it*
  - *ALICE community + QCD/QGP theorists*
- *Round table discussion on March 18*

- Long-term plan at LHC (ALICE upgrade)
- Theoretical developments
- Possible new fixed target experiments at CERN
- Future Circular Collider: opportunities with heavy ions
- Heavy ions and searches for dark photons

WHY ?

Exploring the phase diagram of strongly-interacting matter



[~ Density of baryons – anti-baryons]

- At high energy density ε →phase transition to the QGP
  - Colour confinement removed
  - Chiral symmetry approx. restored
- Lattice QCD (so far limited to small densities):
  - ε_c ~ 1 GeV/fm^3
  - Transition is a crossover at low μ_B
- Field theo. approaches (at high densities):
  - Existence of QCD critical point
  - 1st order phase transition at high μ_B

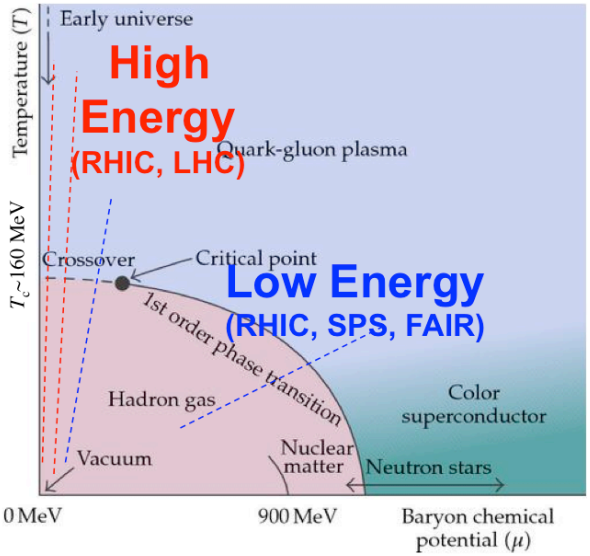
High-energy heavy-ion collisions:

→ **Unique opportunity** to verify the basic predictions of **QCD** and characterize it as a many-body theory in the **non-perturbative** regime

Current status:

The QGP as seen at RHIC/LHC:

- Energy density > 10 GeV/fm^3
- Colour charge deconfined
- Strong energy loss for hard partons
- Expands hydro-dynamically like a very-low viscosity liquid
- Hadronizes as in thermal equilibrium



Future directions:

High Energy collisions (RHIC,LHC):

- Quantify properties of QGP fluid
- How is collectivity developed? can it be developed also in “small systems” (pA)?

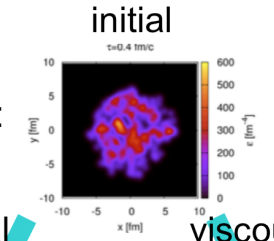
Low Energy collisions (RHIC,SPS,FAIR):

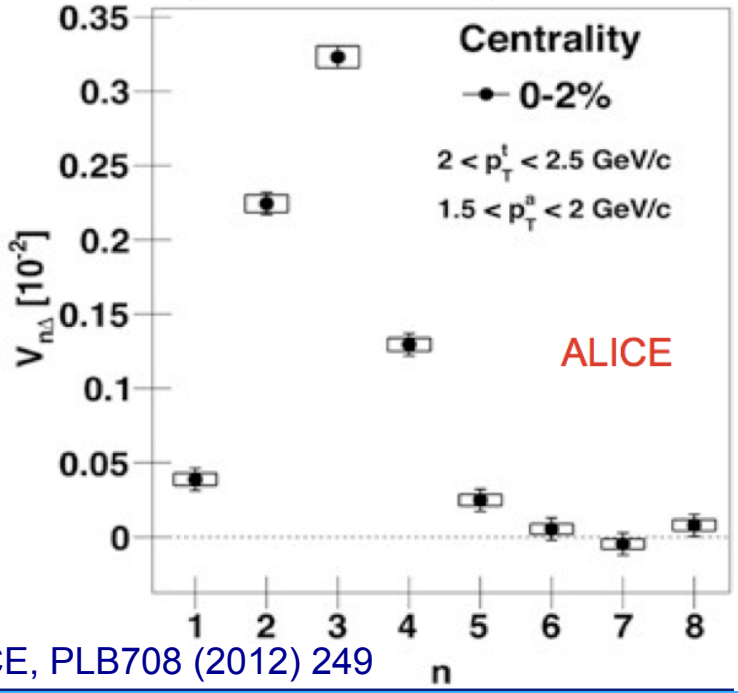
- Onset of deconfinement
- Search for the critical point

- **Experiment** → move **from observation to precision**; exploit detector technology development; systematic scan of the phase diagram
- **Theory** → comparison of **first-principle calculations** (e.g. lattice QCD) with data; for example, **for QGP transport parameters** and viscosity

Example:
QGP viscosity via final-state harmonic decomposition

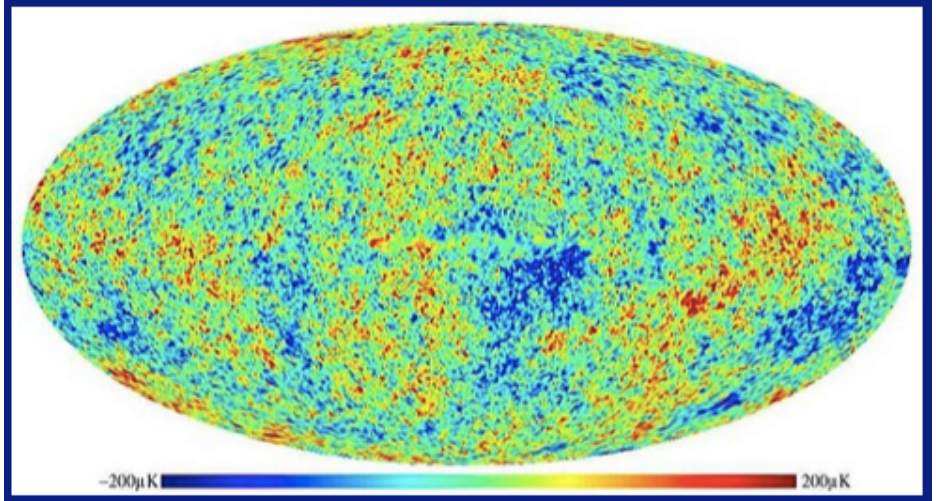
Energy density profile in the transverse plane:

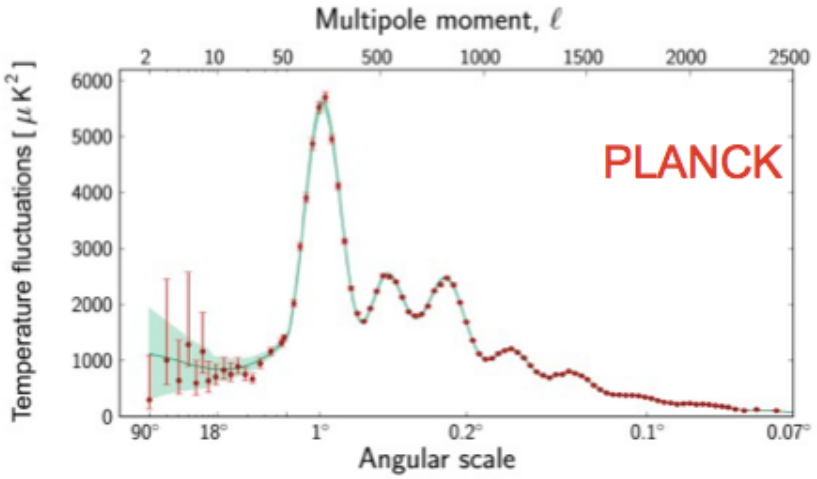




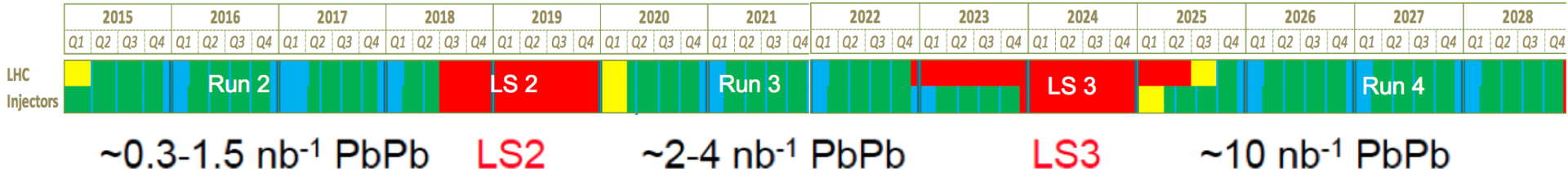
ALICE, PLB708 (2012) 249

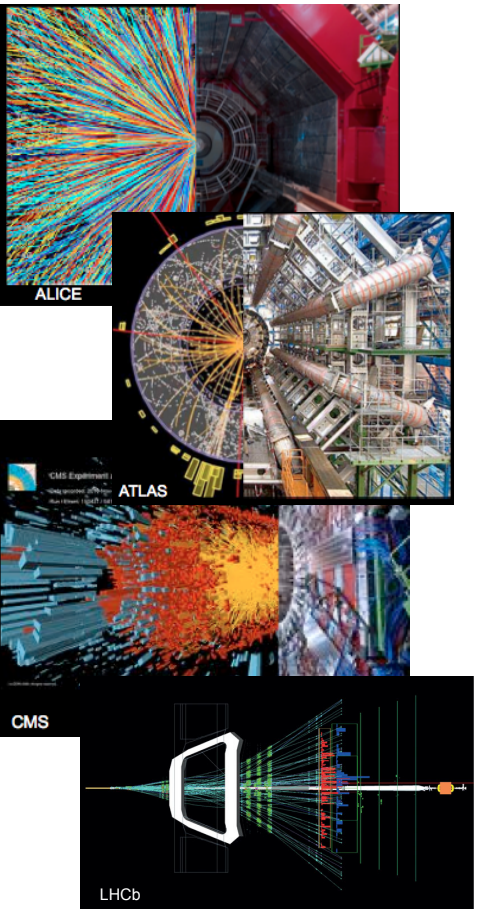
Similar to CMB anisotropies!





HI programme at the LHC





- HI programme till 2028 with all 4 experiments (LHCb pA only)
- After LS2 ALICE aims at collecting x100 larger minimum-bias sample than in Run 2

→ Focus on <u>precision measurements of rare probes</u>, study their coupling with QGP medium

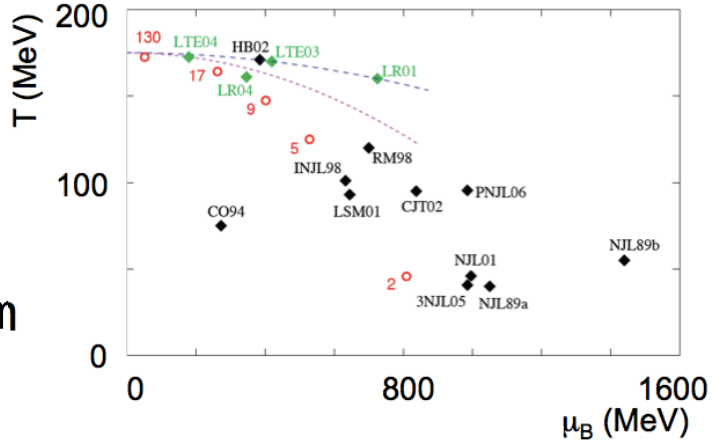
WHAT ELSE ?

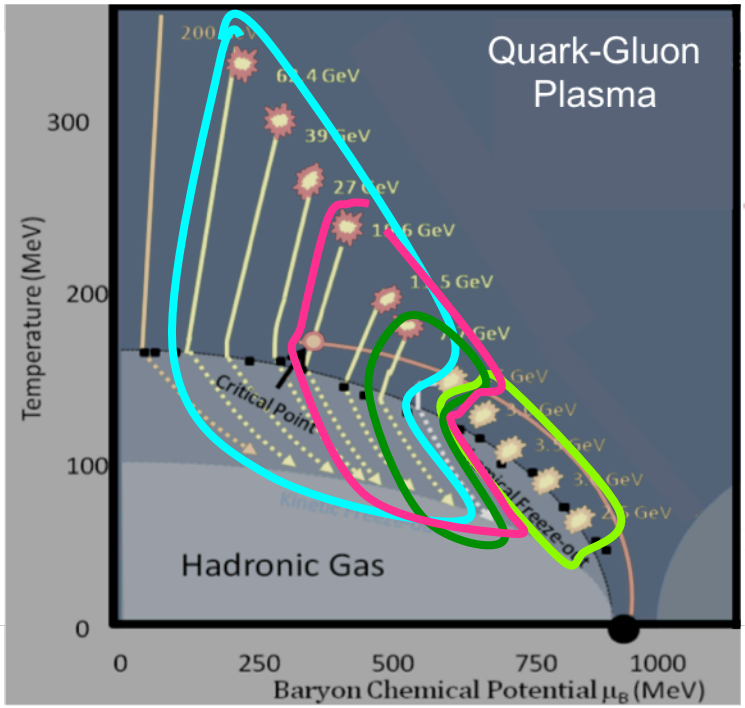
Onset of deconfinement and critical point at SPS

- Large spread of predictions on the position of the phase transition line and critical point

  For illustration: compiled by M. Stephanov →

- Th: extend lattice QCD to high μ_B (sign problem)
- Exp: cover a large portion of the phase diagram





RHIC collider energy scan: good coverage, but much lower statistics than fixed-target experiments

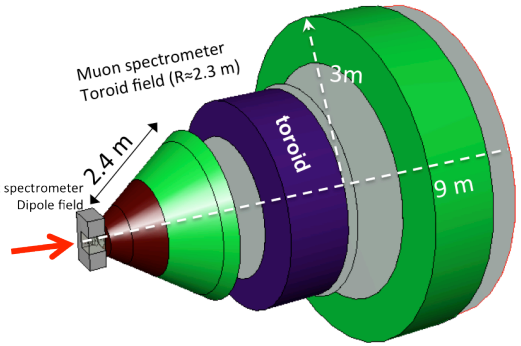
FAIR (CBM):
SIS-100 (>2020) limited coverage
SIS-300 better coverage but unclear timeline

SPS: better coverage than FAIR; existing facility; other AA experimental programmes are ongoing (NA61) and could offer interesting opportunities

WHAT ELSE ?

New experiment at SPS?

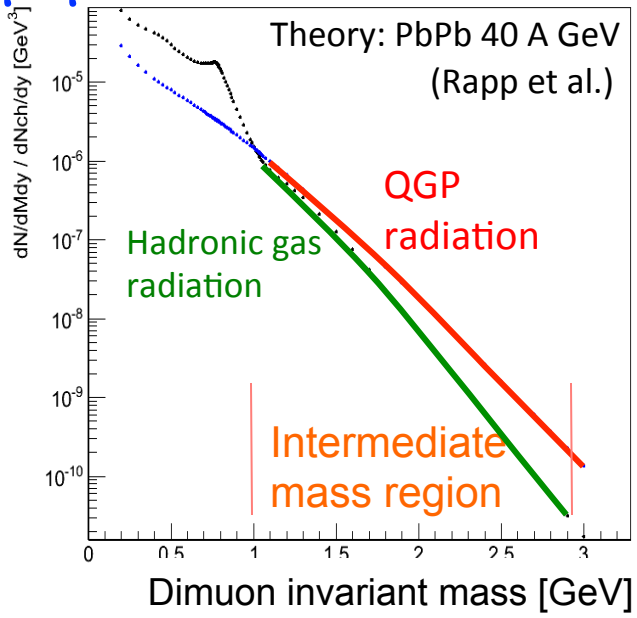
- Precise measurement of electromagnetic radiation and charmonium over full SPS energy range $11<E_{beam}<160$ GeV/nucleon and with different nuclei
  - Onset of deconfinement and first order phase transition
  - Chiral symmetry restoration
- Successor of NA60 (2001-2004)
  - Dimuon spectrometer with pixel tracker)
  - First simulation studies carried out (G. Usai, PRIN2009)



Onset of deconfinement: thermal radiation $\gamma^* \rightarrow \mu^+\mu^-$

- $\mu\mu$ mass distribution has contributions from radiation by the QGP and radiation by the hot hadronic gas
- Onset of deconfiment: QGP radiation dominant

Example measurement: slope of mass spectrum dN/dM → temperature T of the source with few MeV precision
E_{Beam} scan → T scan around T_c~150 MeV



Also discussed: AFTER@LHC

- Extract p/A from beam-halo towards a fixed target experiment
  - Bent crystal extractor R&D at CERN (UA9, LUA9)
  - No impact on LHC operation
  - Centre-of-mass energy: pp 115 GeV, Pb-Pb 72 GeV
- Relevant for QGP physics: **precision** measurements of **heavy quarks and quarkonium** in an energy region where only low-statistics measurements are available (RHIC)
- Competitiveness with RHIC: **high interaction rate** and possibility to make a **A-target scan with p+A and Pb+A**
- But also several other QCD measurements:
  - Heavy quark, quarkonium, photon production
  - Nucleon spin structure using polarized targets

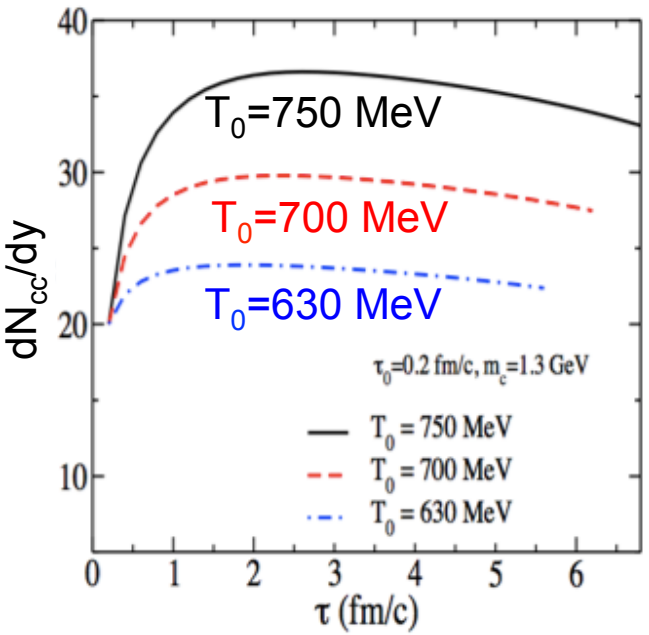
FCC with ion beams?

- Centre-of-mass energy: **LHC x7** → $\sqrt{s_{PbPb}} = 39\ TeV$
- Could aim for a programme of L_{int} ~ 100 nb^{-1} (**LHC x10**)

Potential opportunities:

- Novel reach for study of gluon saturation (probe PDFs down to x~10^{-7} with pA/eA)
- Abundant production of "new" hard probes (e.g. Z+jets, top…)
- Collective effects enhanced (could become important also in pp collisions)
- Initial temperature higher (up to 1 GeV?)

→ e.g. thermal charm production?



Calculation for LHC energy

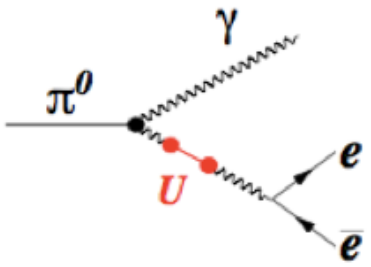
B.-W. Zhang et al. PRC77 (2008)

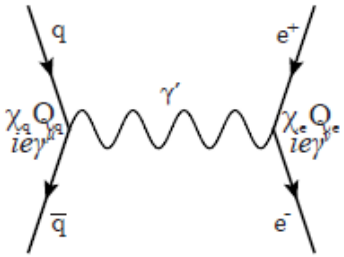
WHY NOT ?

Searching for dark photons with heavy-ion collisions?

- Dark photons can be searched in their decay to a dilepton pair
  a) Dalitz decays, e.g. of π^0
  b) Prompt dileptons, $\overline{q}q \rightarrow l^+l^-$

  Sensitive to coupling to both quarks and leptons





- Some of the HI experiments (e.g. ALICE and PHENIX) collect large samples of π^0 and dileptons (minimum bias pp, pA, AA collisions) and have excellent reconstruction capabilities
- Channel b) could be favoured by larger QGP thermal radiation
- Potentially competitive for searches both at low-masses (<100 MeV) and also at ~1 GeV masses (complementarity with Jlab programme) (see e.g. Davis et al. arXiv:1306.3653)

Synergy with DM GdL in the next months