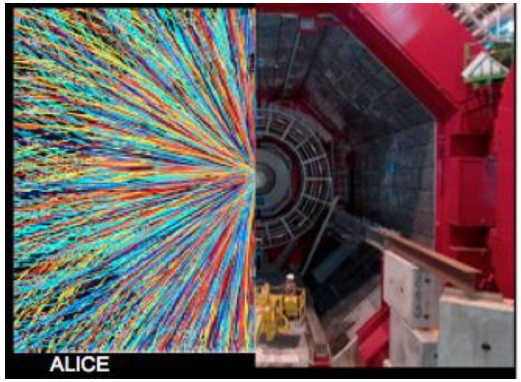
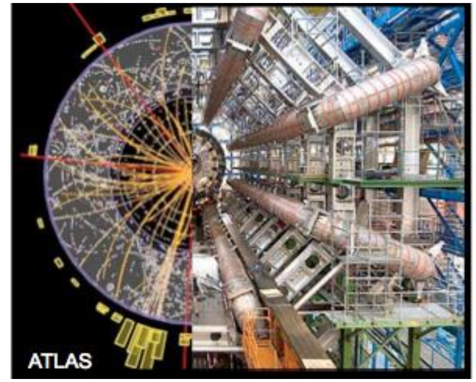
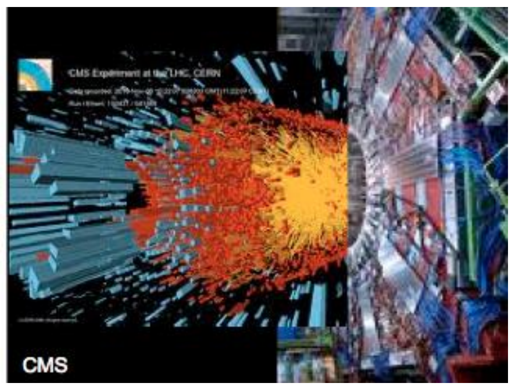
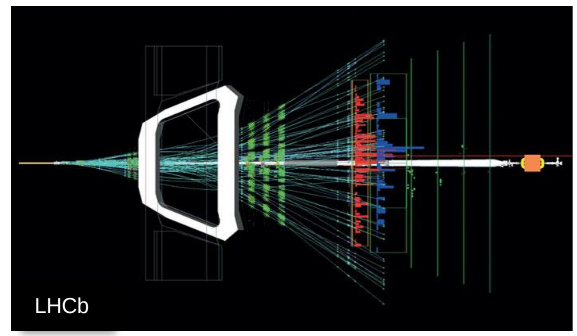
Heavy Ion Plans: Experiments Perspective

- Heavy Ion Physics Highlights from Run 1
- Heavy Ion Parameters and Schedule for Run 2
- Upgrades and Perspective after LS2



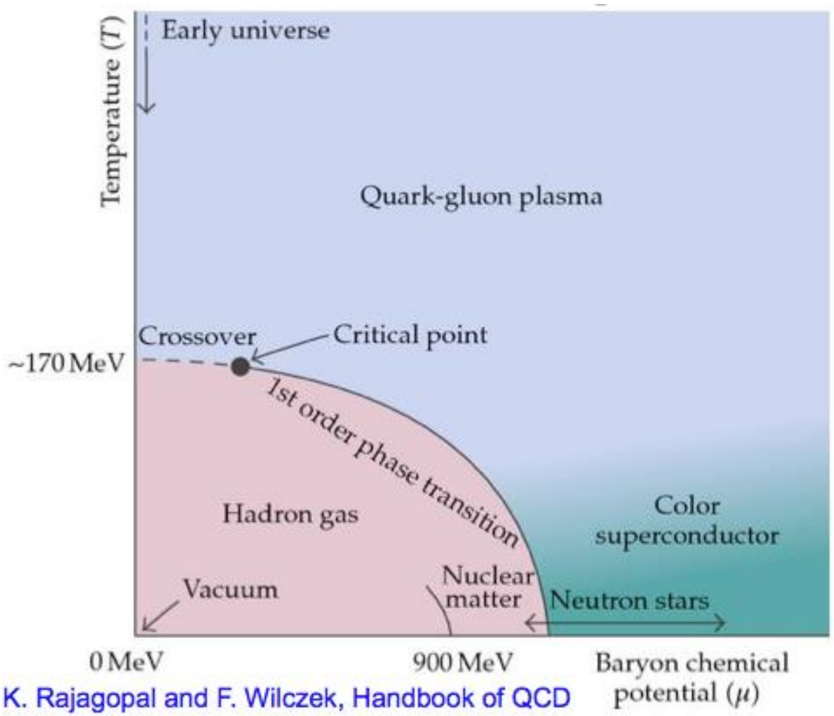






HIGHLIGHTS FROM THE HI PHYSICS PROGRAM

Heavy Ion Physics



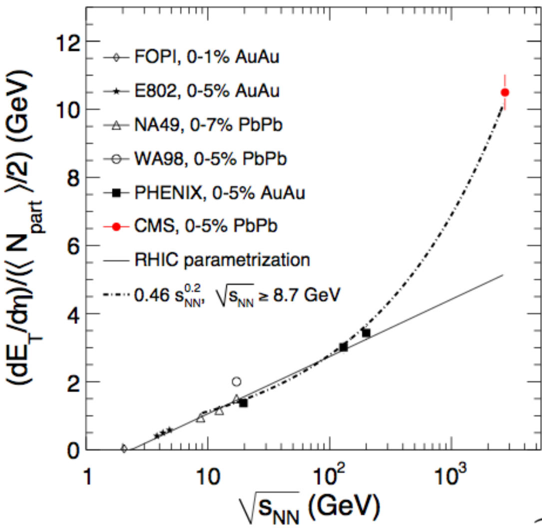
K. Rajagopal and F. Wilczek, Handbook of QCD

- pp physics probes quarks and gluons as “free particles”
- Nuclear physics studies the bound states
- HI physics studies the intermediate phases of QCD matter which prevailed shortly after the big-bang

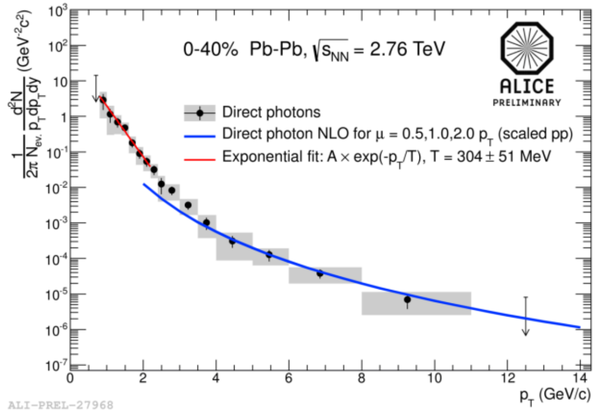
- QGP: what is it
  - A theoretical model of the phase of matter where partons are not (completely) confined
  - Produced in High-energy nucleus-nucleus interactions
  - Large energy density (~15 GeV/fm^3 at LHC) over a large volume (~ 5000 fm3 at LHC)
  - Very high equivalent temperature (T~300 MeV)
  - Strongly interacting
- How it is studied
  - **Jets:** energy loss mechanism - collective effects in QCD, medium density
  - **Heavy flavour:** mass dependence of energy loss - probe the medium transport properties
  - **Quarkonium:** quarkonium dissociation and regeneration - probes deconfinement and medium temperature
  - **Low-mass di-leptons:** thermal radiation γ (→e+e-) - to map temperature and evolution
  - **Proton-Ion**: collective effects

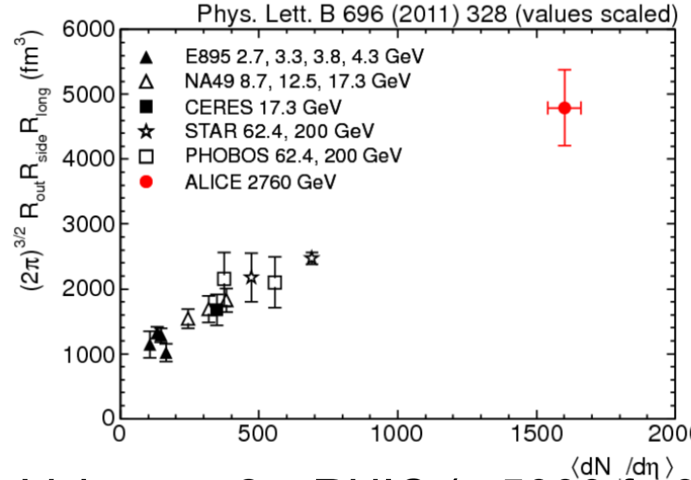
Global Properties of QGP

Energy density
3 x RHIC (≈ 12 GeV/fm3)



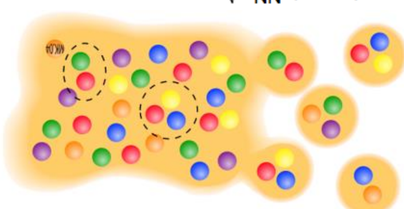
T ≈ **+30% (≈ 300 MeV)**

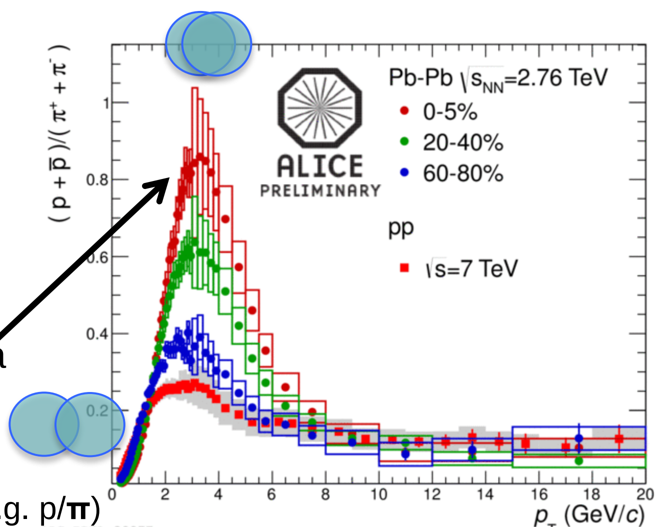


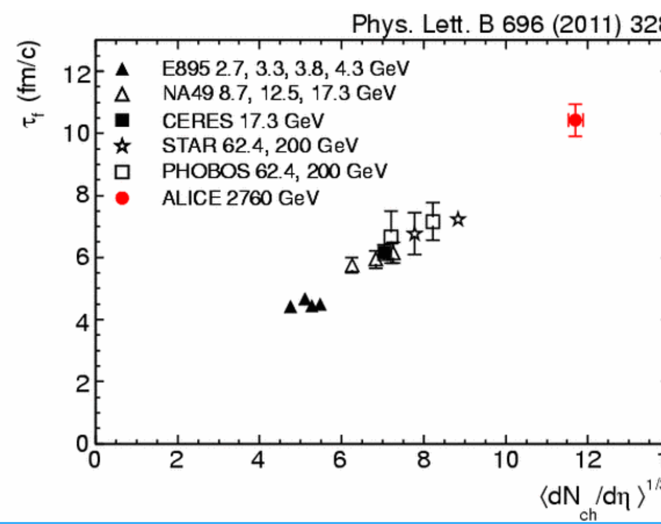


Volume ≈ 2 x RHIC (≈ 5000 fm3)

Lifetime ≈ +20% (≈ 10 fm/**c**)







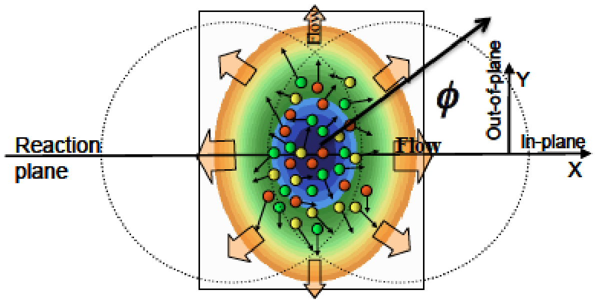
Hadron yields suggest hadronization occurs from a system with partonic degrees of freedom

Baryon(3**q**)/Meson(2**q**) ratios (e.g. p/**π**) enhanced at intermediate pT

ECFA HL-LHC, Aix-les-Bains, 01.10.13 Andrea Dainese

Hydrodynamic Properties

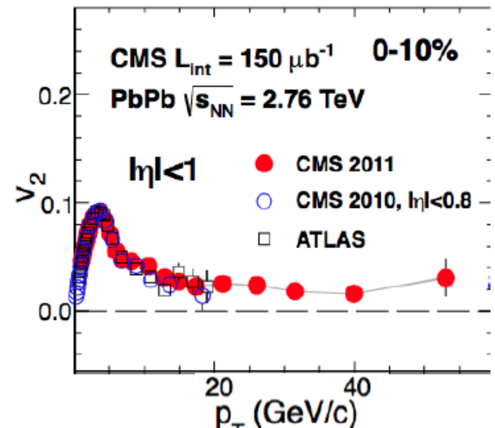
Features of medium: anisotropy



- System geometry asymmetric in non-central collisions
- Expansion under azimuth-dep. pressure gradient results in azimuth-dep. momentum distributions
- Measured by the elliptic flow parameter $v_2(p_T)$

$$\frac{dN}{Nd\phi} \sim 1 + 2v_2 \cos\left(2(\phi - \Psi_{RP})\right) + \textit{higher harmonics } (v_3, v_4, \ldots)$$

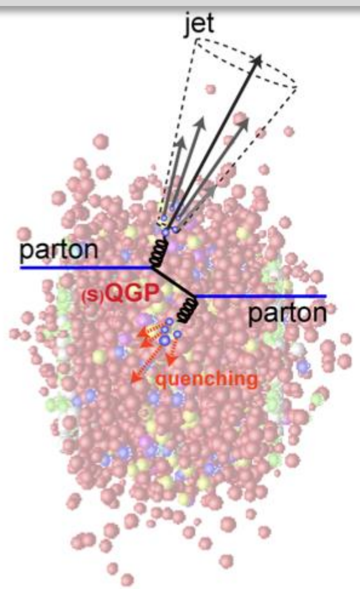
- v_2 at low p_T provides a measure of the strength of collectivity (mean free path of outgoing partons)

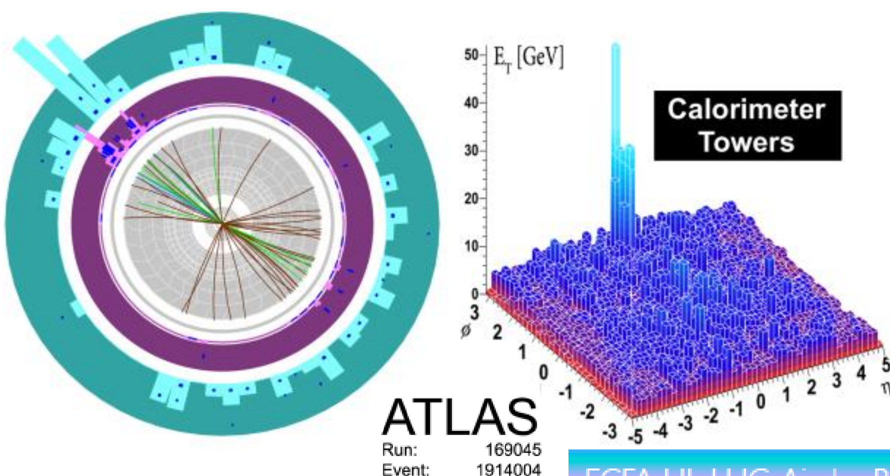


- v_2 decreases at large p_T
  - Hydrodynamic expansion not effective
- But remains >0 up to 50 GeV/c
  - Path length dependent energy loss

CMS, PRL 109 (2012) 022301
ATLAS, PLB 707 (2012) 330

Features of medium: opacity/viscosity

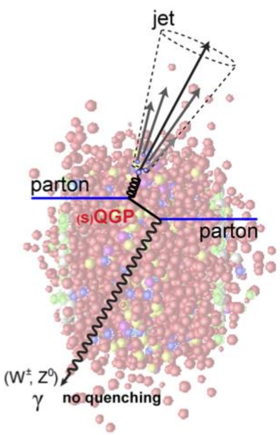




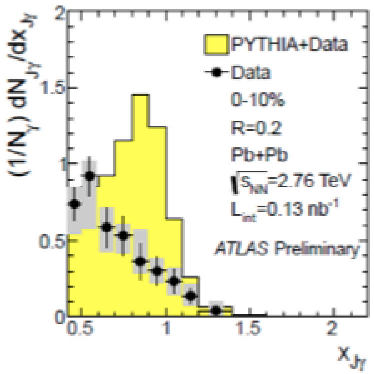
Parton Energy Loss by medium-induced gluon radiation
collisions with medium gluons
p' = p − ΔE(ε medium)

ECFA HL-LHC, Aix-les-Bains, 01.10.13 Andrea Dainese

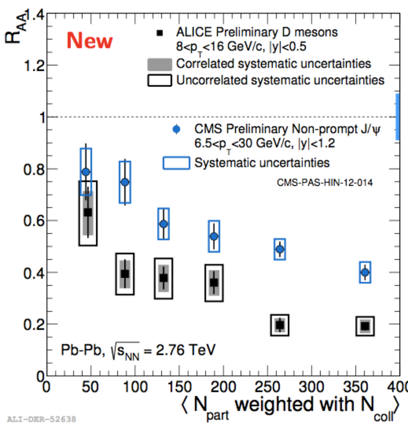
Experimental Techniques



jet-boson (γ, Z) correlation



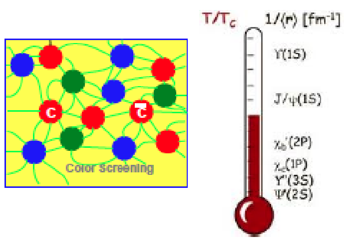
- High statistics:
- Precise measurement of the medium-modified fragmentation function
- Differential studies as a function of event geometry

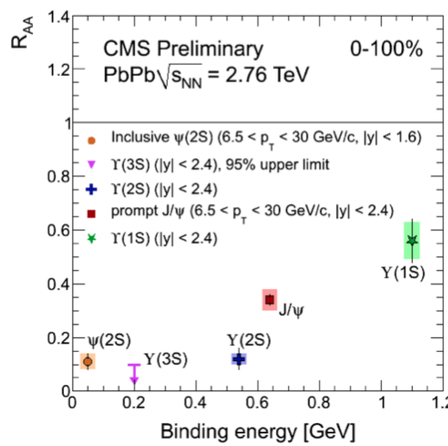


Heavy quark probes

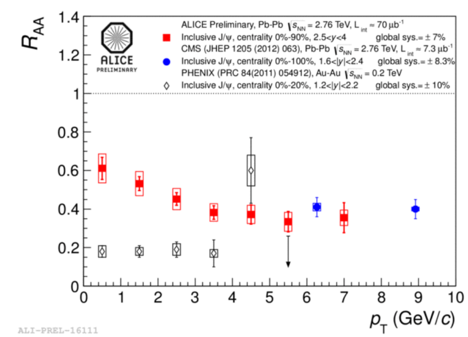
Energy loss expected to depend on parton mass
First indication at LHC:

R$_{AA}$ B (CMS) > **R**$_{AA}$ D (ALICE)





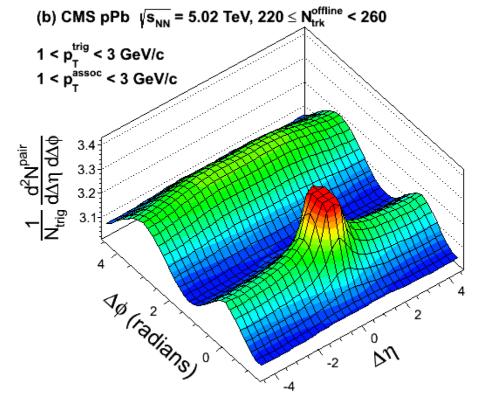
Low-Pt charmonium…
Regeneration?

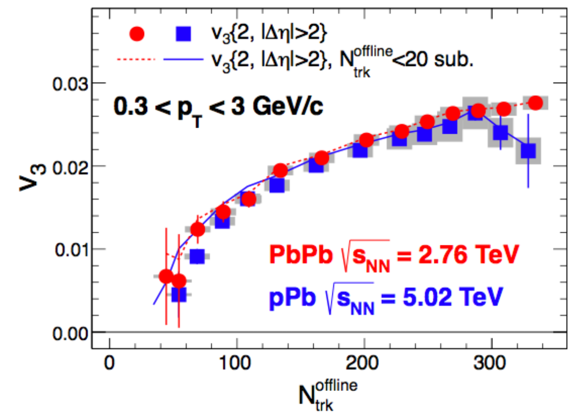


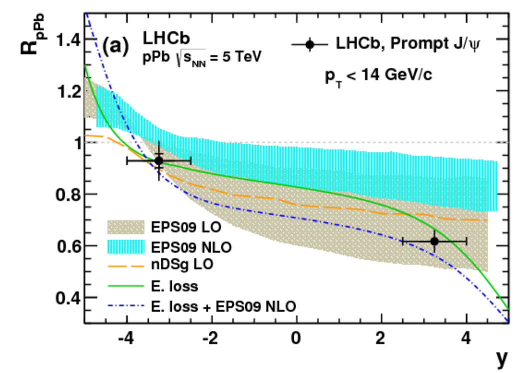
Quarkonium sequential dissociation: direct probe of deconfinement and of the medium temperature – “melting” of bound states

pPb: a Control Experiment

- Motivation for pPb running:
  - Reference for the PbPb data
  - Study the effects of the initial state without the presence of the hot medium
    - nuclear PDFs
    - Cold Nuclear Matter effects
- But also shows exciting new phenomena:
  - Long range Δη correlations
  - Surprisingly similar multipole harmonics
  - (v2, v3) in pPb and PbPb at the same multiplicity
- Hydrodynamic expansion of a strongly coupled medium presently the only theory that explains this observation
- Important constraints on expected "cold nuclear matter" effects

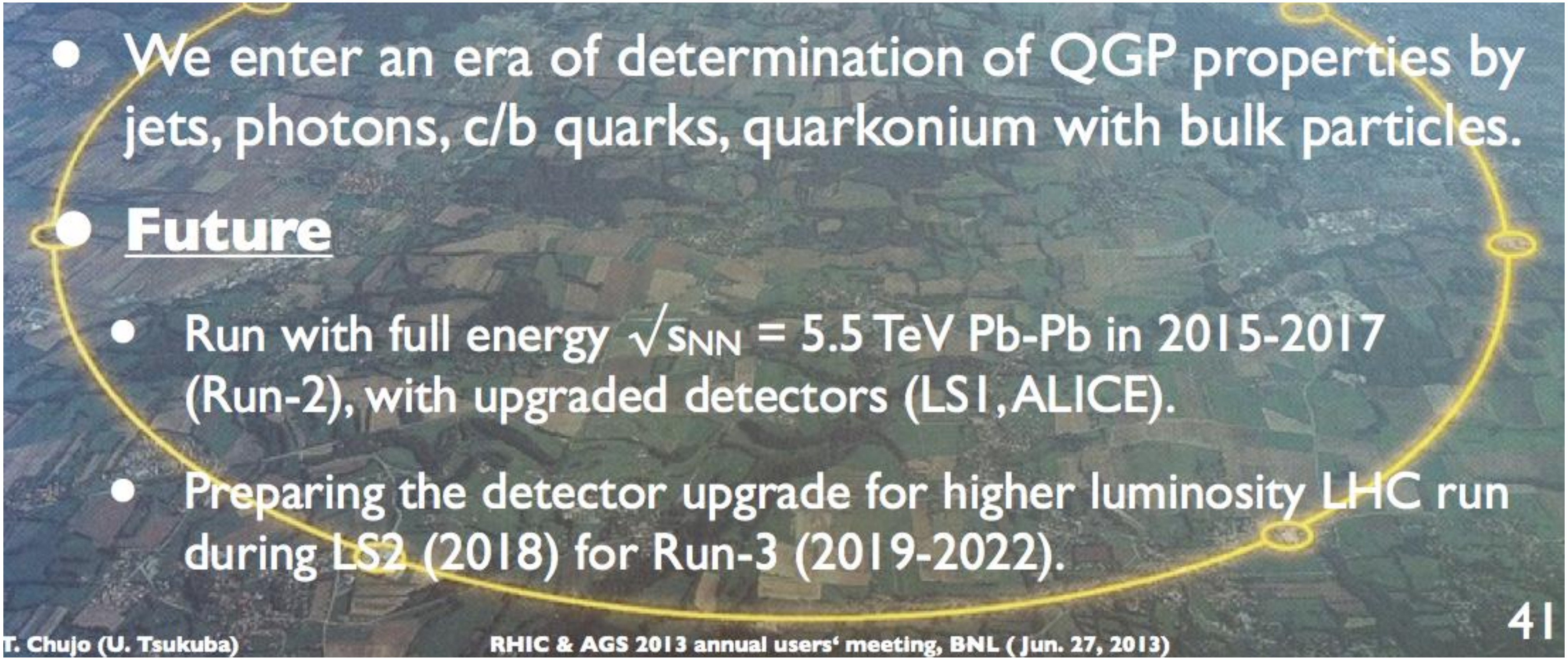






In a nutshell

Thanks to this:



HEAVY ION PARAMETERS FOR RUN 2

Machine Summary
(J.Jowett, Chamonix 2012 and later, with edits by EM)

- In a total of about 8 weeks of LHC operation in the two Pb-Pb runs of 2010-11, the following milestones have been achieved:
  - The peak luminosity has reached twice the design.
  - We have already achieved 15-18% (depending on the experiment) of the overall long-term Pb-Pb luminosity goal of 1 nb^{-1}
- We learned a lot from 2011 Pb-Pb run and have a better understanding of the performance limits of the LHC as a heavy-ion collider
- We have proven the operation of the LHC as a proton-Lead collider and the performance in this configuration has exceeded expectations
- As prospects for exceeding the design luminosity $L>10^{27}$ $cm^{-2}s^{-1}$ after LS1 now appear very good and ALICE is considering an upgrade in LS2 to handle peak luminosities $L \sim 6\ 10^{27}$ $cm^{-2}s^{-1}$ **it will be important to study upgrade measures that may achieve these luminosities in 2019**
- A missing factor 2-3 in peak luminosity might be achieved if we can increase the number of bunches in the ring (reducing the minimum spacing to 50 ns, for example). Alternatively, all, or some fraction, of such an increase could come from measures taken in the LHC, e.g. reduced β* in collision
- The option of running with different ion species will become available

Physics goals

- Differential studies of jets, b-jets, di-jets, γ/Z-jet at very high pT (focus of ATLAS and CMS)
- Flavour-dependent in-medium fragmentation functions (focus of ALICE)
- Low-pT heavy flavour production and elliptic flow of several HF hadron species (focus of ALICE)
- B and b-jets (focus of ATLAS and CMS)
- Low-pT charmonia and elliptic flow (focus of ALICE)
- Multi-differential studies of Y states (focus of ATLAS and CMS)
- (Very) low-pT and low-mass di-electrons and di-muons (ALICE)
- Large integrated luminosity pPb to disentangle QGP effects from cold nuclear matter effects, and to reduce the experimental uncertainty and enable classification of theoretical predictions (focus of LHCb, among others)

Run 2: ALICE

Year	System	Luminosity
2015	pp – min bias (24 weeks)	10^{29}-10^{30} cm^{-2}s^{-1}
	Pb Pb – 4 weeks	10^{27} cm^{-2}s^{-1} - leveled
2016	pp – rare triggers (24 weeks)	5-10 10^{30} cm^{-2}s^{-1}
	Pb Pb – 4 weeks	10^{27} cm^{-2}s^{-1} - leveled
2017	pp – rare triggers (24 weeks)	5-10 10^{30} cm^{-2}s^{-1}
	p Pb – min bias (2 weeks)	0.5-1 10^{28} cm^{-2}s^{-1} - leveled
	p Pb – rare triggers (2 weeks)	1 10^{29} cm^{-2}s^{-1} - leveled
2018	LS 2	

- For 2015 pp need 5 orders of magnitude luminosity reduction in IP2
  - no filling scheme tricks available at 25ns ~all bunches collide in ALICE (except effect of abort gap)
  - Larger β* not an option due to aperture issues in IP2
  - A separation of order 5σ seems to be needed
  - Would the level of background in IP2 be lower than signal? Will depend on quality of vacuum
- ALICE studied the beam-gas background conditions in LSS2-L assuming a 5 10^{-9} vacuum.
  - the result is a rather strong MB trigger contamination (~50%) at L=1 10^{29}. on the other hand the contamination at L=1 10^{30} is ~10%, but a pileup of 10 in the TPC is the price to pay.
  - Further studies of optimization will be performed based on these results

Run 2: ATLAS/CMS

- ATLAS
  - Assume a HI run @ the end of each year as in the baseline LHC schedule
    - A leap of one year, although not desirable, could be acceptable if helping with overall efficiency
  - 2015-2016: PbPb (5 TeV) and corresponding intermediate energy reference pp data – they will also be useful for pPb
    - **Ultimate goal is to collect 2-3 nb-1 before LS3**.
  - pPb: No strong preference - Definitely one run @ 8.2 TeV before LS3
- CMS
  - 2015 PbPb at √sNN = 5 TeV
  - 2016 PbPb at √sNN = 5 (5.5?) TeV
    - Consider having the second high luminosity PbPb run at same energy as the first one, depending on the impact on setup time and achievable instantaneous luminosity
  - 2017 pPb at √sNN = 5 (8.2?) TeV, high luminosity
    - pPb running at the same cms energy as PbPb instead of the top energy possibly preferable: minimize the number of pp reference data sets needed. More studies to balance the gain in high p_T statistics vs availability of reference data
- ATLAS + CMS
  - Intermediate energy pp: Pb+Pb equivalent pp-data set is absolutely required (needed pp integrated lumi **is ~3-4·10^4 the Pb-Pb one**): needs to be kept in sync with Pb+Pb ∫Ldt "steps" --- **not possible to concentrate all pp data taking in a single period** during 2015-2022 running

Run 2: LHCb

- Due to the huge track multiplicity in Pb-Pb collisions in the forward direction ($2 < \eta < 5$), **LHCb plans to participate only in a pPb run**, as in 2013.
- LHCb would appreciate if the p-Pb run comes **not at the end of the HI program of Run II** . . .
- Experience has shown that a pp data sample at the corresponding pPb energies is important, i.e. at 5 TeV and 8.2 TeV.
- LHCb would like to get **at least** 10x the integrated luminosity they had in 2013.
  - In 2013 took data at ~$5 \times 10^{27}/cm^2/s$.
  - Assuming another p-Pb run would last also about 4 weeks, **a luminosity greater than $5 \times 10^{28}/cm^2/s$ should be provided to LHCb**
- To be verified if this is compatible with machine limitations in the pPb scheme

Run 2 Beam Parameters Summary

- Beam Energy: one clear advantage in choosing a single value of $\sqrt{sNN}$ is the pp reference sample just keeps adding up
  - All experiments seem to consider running PbPb again at 5 TeV acceptable
  - Should the lower energy also be considered for the next pPb run? Physics considerations vs. advantages for reference pp samples…
- ALICE requires leveling during PbPb and pPb running
  - ATLAS/CMS might need to be also leveled to guarantee constant luminosity to ALICE in the presence of large burn-off
  - Same luminosity for all IPs (slightly penalizing for IP1/5)
- The request of LHCb for a factor 10 more luminosity in IP8 requires squeezing of the 4 IPs
  - Not clear how technically difficult this is
  - Other options to be considered ?

Schedule of HI Run 2

- All experiments agree that HI run periods **cannot be grouped**(*)
- Goal is (clearly) as large as possible integrated luminosity for PbPb and pPb
- Run 2: The general goal is to collect **at least 1 nb^{-1}**
  - One HI run period per year 2015-LS2
  - PbPb and pPb only before LS2(**)
- The generally agreed schedule:
  - 2015: PbPb at 5.0(2) TeV
  - 2016: PbPb at 5.0(2) (5.5) TeV (***)
  - 2017: pPb at 5.0(2) (8.2) TeV (***)
  - ArAr…
- All but ALICE consider **reference pp data at equivalent energy** a must
  - $\int Ldt(pp) = 3\text{-}4\ 10^4 \times \int Ldt(PbPb)$ is considered necessary/sufficient
  - ALICE not against pp runs if they do not reduce the allocated time for the HI runs. If there is conflict, their priority would be to collect HI data.

(*) ATLAS considers a one year gap acceptable if proven beneficial for the general program

(**) ATLAS has a slight preference for a possible ArAr run before LS2 – **In any case no request for different species during the same year**

(***) The benefit of higher p_T statistics vs availability of reference data and setup time must be balanced in considering the beam energies for 2016/17

Run 2: Questions to be Addressed

- ALICE operation at very low luminosity during pp
  - Separation
  - Noise level, vacuum quality
- Compatibility of leveled vs. non-leveled operation in IP2 and, respectively 1,5 w.r.t. luminosity lifetime
- pPb: can LHCb get 10 times more luminosity ?
- E-YETS 2016 vs. LS1.5: how does this reflect on the HI schedule ?
- pp reference data taking in Run2: scheduling issues to be addressed
- Need for ALICE polarity reversals

BEYOND LS2

The Race for 10 nb^{-1}

Experiments Plans

- ALICE will install its major detector upgrade during LS2 in 2018
  - The upgrade aims at precision measurements of the Quark Gluon Plasma, with a factor 100 gain in statistics (x10 luminosity, x10 via pipelined readout)
- CMS L1 trigger upgrade implemented during LS1 will enable the experiment to tolerate an interaction rate of up to ~50kHz for PbPb
- ATLAS/CMS Would like to run at the highest possible instantaneous luminosity for PbPb and pPb
  - No lumi leveling – to be verified if this is compatible with ALICE running leveled
  - Support going to a 100ns bunch spacing to increase inst. Luminosity - as early as possible, as long as the development of the SPS injection kickers does not distract from pp upgrades
- LHCb: detector upgrade in LS2 – community interested in HI (pA) physics still small, might build up during Run2

General Expectations

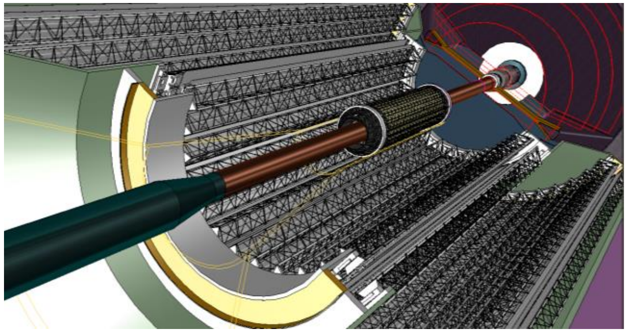
- Collect 2-3 nb^{-1} before LS3.
- The HI community has **strong interest and a physics case for ≥ 10 nb^{-1}**

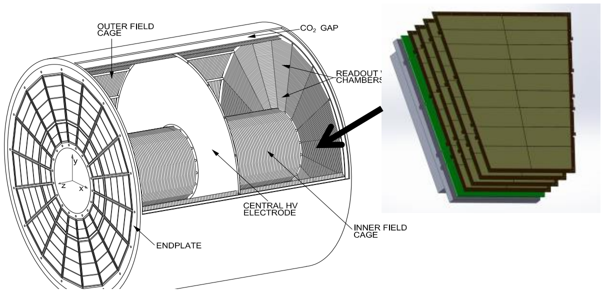
The ALICE upgrade in a nutshell

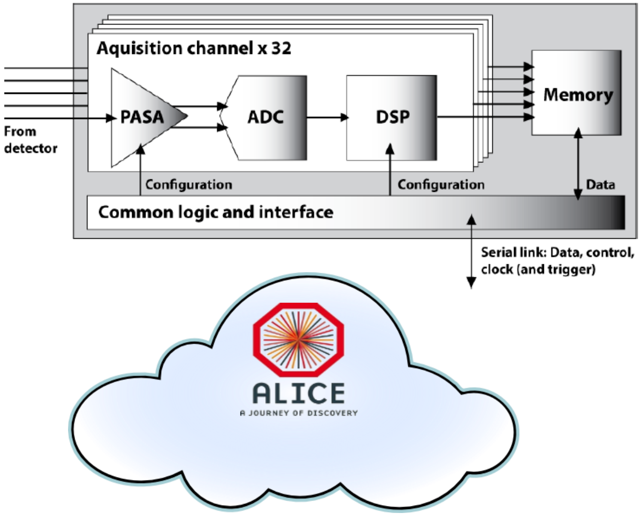
Pb-Pb recorded luminosity $\geq 10\ nb^{-1}$ ➡ 8×10^{10} events (Run2+3)

pp (@5.5 Tev) recorded luminosity $\geq 6\ pb^{-1}$ ➡ 1.4×10^{11} events

- New, ultra-low mass silicon tracker around a very small beam-pipe (ID 34.4 mm)
- Upgrade of the TPC with GEM detectors for continuous (un-gated) readout
- Electronics upgrade of the other sub-detectors
  - read out all Pb-Pb interactions at a maximum rate of 50kHz (i.e. $L = 6 \times 10^{27}\ cm^{-1}s^{-1}$) with a minimum bias trigger
- Major upgrade of the online systems to process all Pb-Pb collisions upon a (minimum bias) interaction trigger
  - Perform online data reduction based on reconstruction of clusters and tracks







Other Upgrades Relevant to HI Physics

- ATLAS
  - Additional pixel layer (LS1), then new tracker (LS3): tracking and b-tag
  - Fast tracking trigger (LS2): high-multiplicity tracking
  - Calorimeter and muon upgrades (LS2): electron, γ, muon triggers
  - TDAQ to allow higher L1 rates and larger data volume
- CMS
  - New pixel tracker (LS2), then new tracker (LS3): tracking and b-tag
  - Extension of forward muon system (LS2): muon acceptance
  - Upgrade of trigger and DAQ (LS2): HI-specific development to reach necessary L1 rejection at 95%, from 50 kHz to <3 kHz (HLT)
- LHCb (LS2)
  - Upgrade includes new vertexing and tracking detectors (not focused on HI)

Heavy Ion Operations after LS2

- Upgrade of SPS injection system
- Installation of collimators in dispersion suppression region around IR2 (possibly also in IR7?) for ions
  - In case the magnet quench limits are reached in IP1/5, the installation of dispersion suppression collimators as in IP2 would be desirable
- ALICE: LHC vacuum in LSS around IP2 needs to be improved by an order of magnitude to mitigate background
- Beam species: Pb-Pb, p-Pb, (Ar-Ar, p-Ar?)
  - Light ion running could be interesting to study jet quenching
    - Lower underlying event multiplicity reduces systematic error on measurements
    - Considered important, especially for jet quenching
    - Potentially higher N_{coll} weighted Luminosity achievable
  - LHCf expresses interest for Nitrogen or Oxygen collisions for cosmic-ray physics
- **The basic assumption is to continue the pattern of one month LHC heavy ion operation per year**

Special needs after LS2

- pp reference at 5.5 TeV required: **ALICE concurs**
  - HF: D and B cross sections can be scaled in √s with pQCD, but large scaling uncertainty for charm at low pT (>50%) Quarkonia: no robust theoretical guidance for interpolating Jets: FF and jet energy scale calibration depends strongly on √s
- Required integrated luminosity for pp at 5.5 TeV
  - ALICE (for HF and charmonia needs): ~10/pb
    - Statistical error on pp reference negligible wrt Pb-Pb (e.g. 1/√2)

      Npp=2 NPbPb [(Sig/ev)PbPb/(Sig/ev)pp]2
    - e.g. 10^6 s at 200 kHz (L leveled at $6x10^{30}$)
  - ATLAS/CMS: match PbPb yields at high pT 10/nb (PbPb)→300/pb (pp)
    - Scaled by N_{coll} (For S>>B, Sig = 1/sqrt(S))
      - S_{PbPb}~ N_{coll} S_{pp} and N_{coll} ~ 1500 in central Pb-Pb at LHC
- pPb, pAr and ArAr:
  - pPb at high luminosity: continue studying collective effects
  - pAr and Ar-Ar certainly on the table after LS2
    priority will be defined based on the outcome of analysis of high statistics PbPb and pPb from Run 2

Run 3 and Beyond

- Run 3 goals: 3 nb-1 of PbPb before LS3, pp reference data…
- Possible running scenario after LS2:
  - 2019 – PbPb 2-3 nb^{-1} (.AND. ArAr as per ATLAS request…?)
    - + pp 60 pb^{-1} (ATLAS/CMS), 3 days (ALICE) ...
  - 2020 – PbPb 2-3 nb^{-1}
    - + pp 60 pb^{-1} (ATLAS/CMS), 3 days (ALICE) …
  - 2021 – pPb/pAr? (1/2) + complete pp reference run (1/2)
  - 2022/2023 LS3
- After LS3
  - HL-HI-LHC…
  - General goal is to collect more than 10 nb^{-1}

CONCLUSIONS