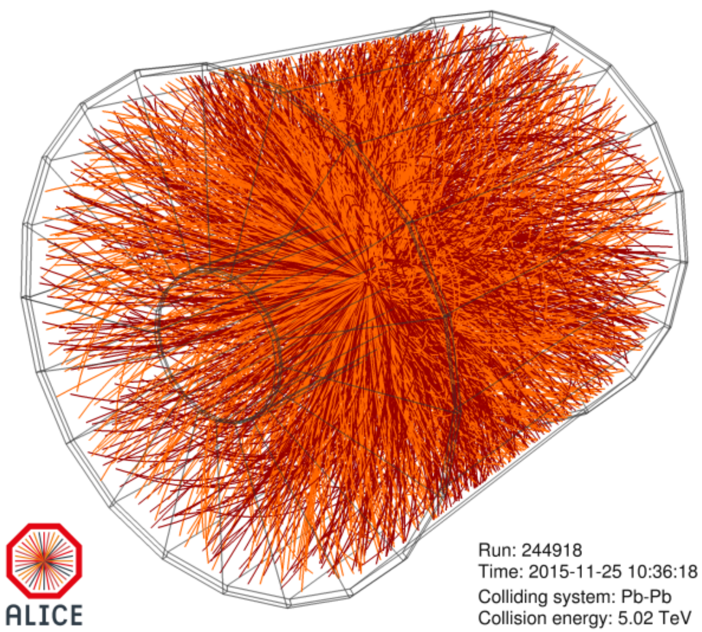
Heavy-ion physics at the high-energy frontier

Silvia Masciocchi
GSI Darmstadt and Heidelberg University

EMMI Physics Day 2017, GSI, November 28, 2017

Outline

- Heavy-ion physics:
  the high temperature and low baryon density regime
- Experimental program at the LHC: from now ...
- ... to the high-luminosity LHC era
- Heavy ions at the Future Circular Collider:
  physics opportunities

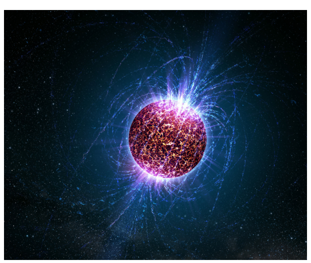


Explore strongly-interacting matter at extreme conditions

Extreme temperatures

≈ 160 MeV ≈ 2 x 10^{12} K (Sun core: 15 x 10^{6} K)

and/or



Extreme densities

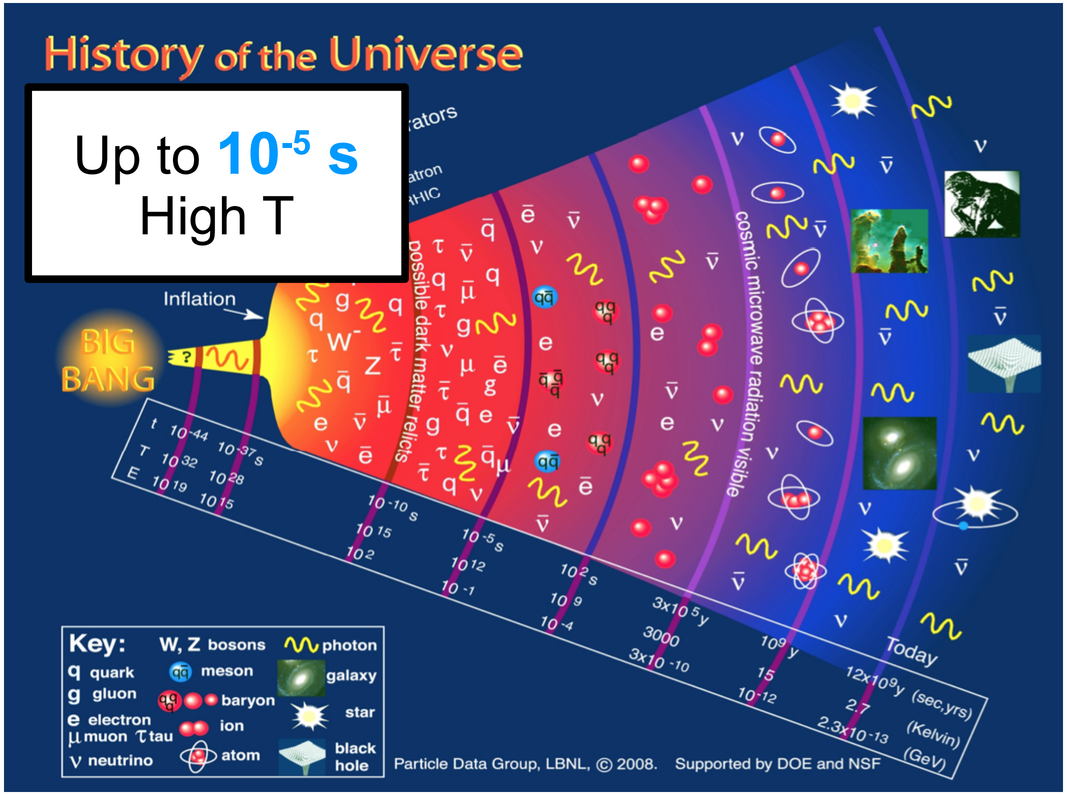
≈ few GeV/fm^3 (few times ground-state nuclear matter. ε_{proton} ≈ 0.44 GeV/fm^3)

to study fundamental properties of QCD:

compressibility of nuclear matter, confinement, QCD-matter phases, hadronization, transport coefficients, etc.

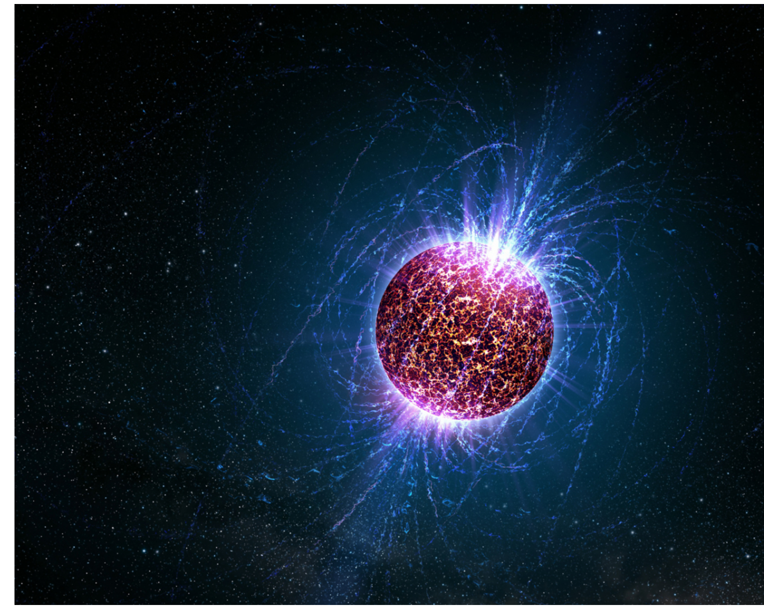
Extreme conditions

In nature



Up to 10^{-5} s
High T

Very high density (~ GeV/fm^3) matter in **neutron** stars



Extreme conditions

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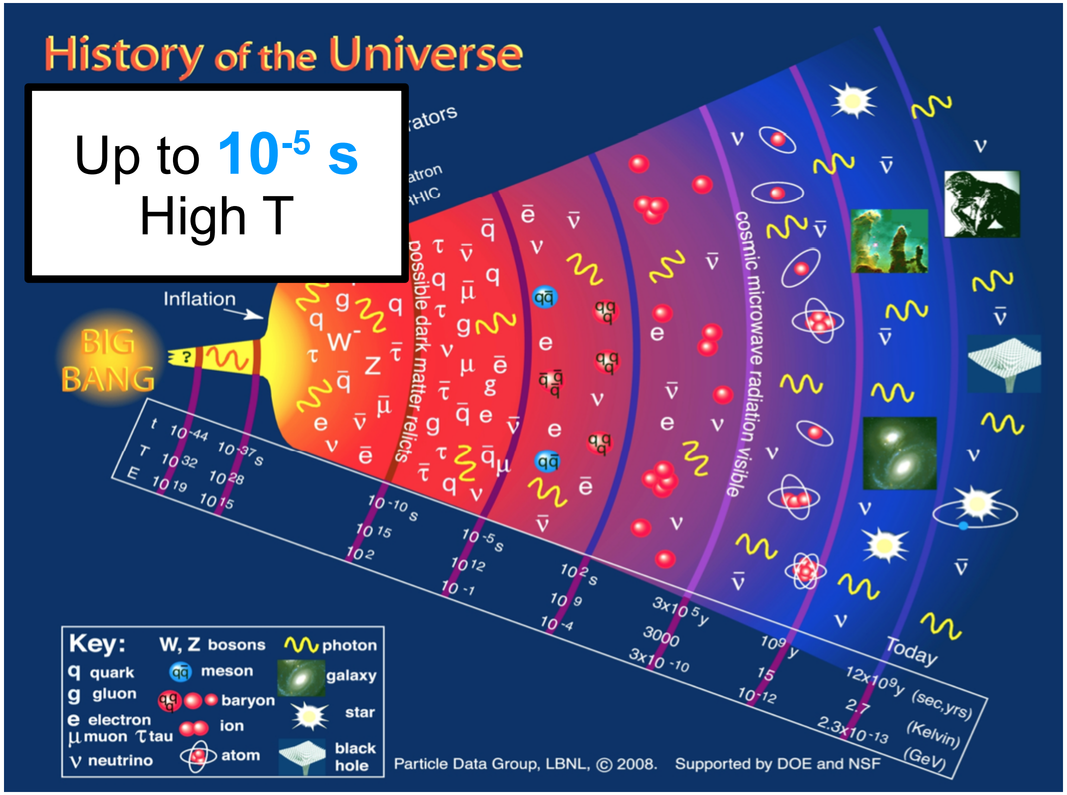

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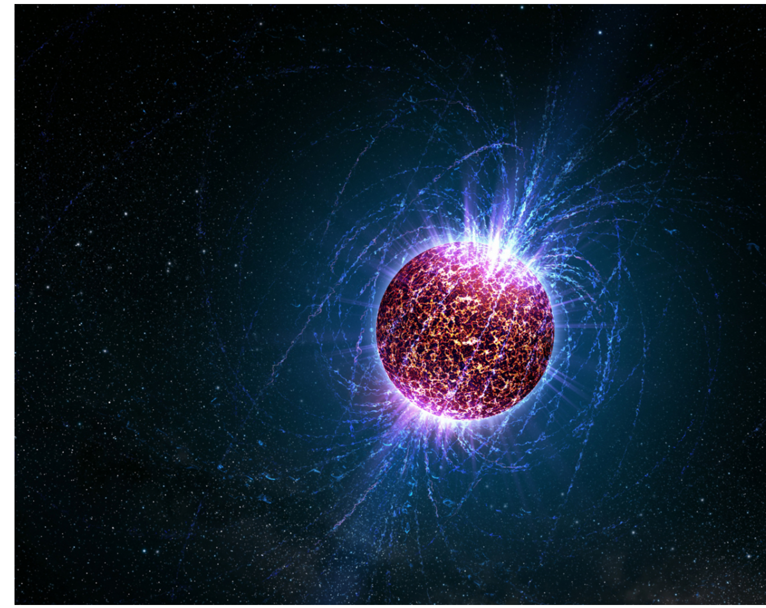
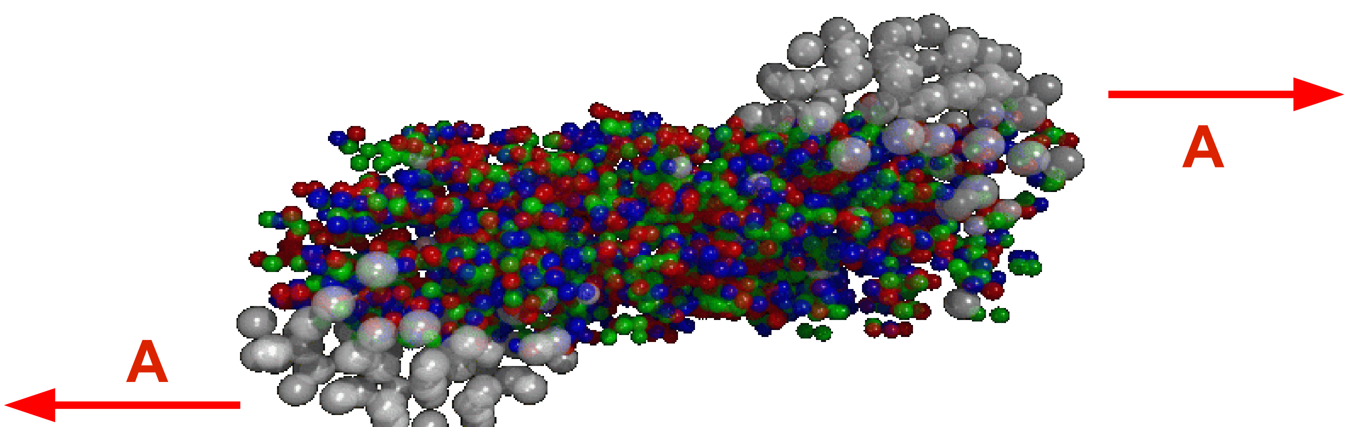
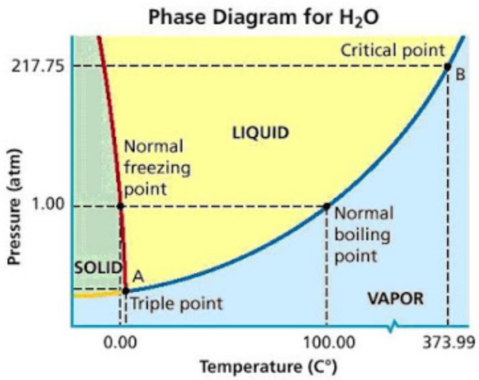


In the lab

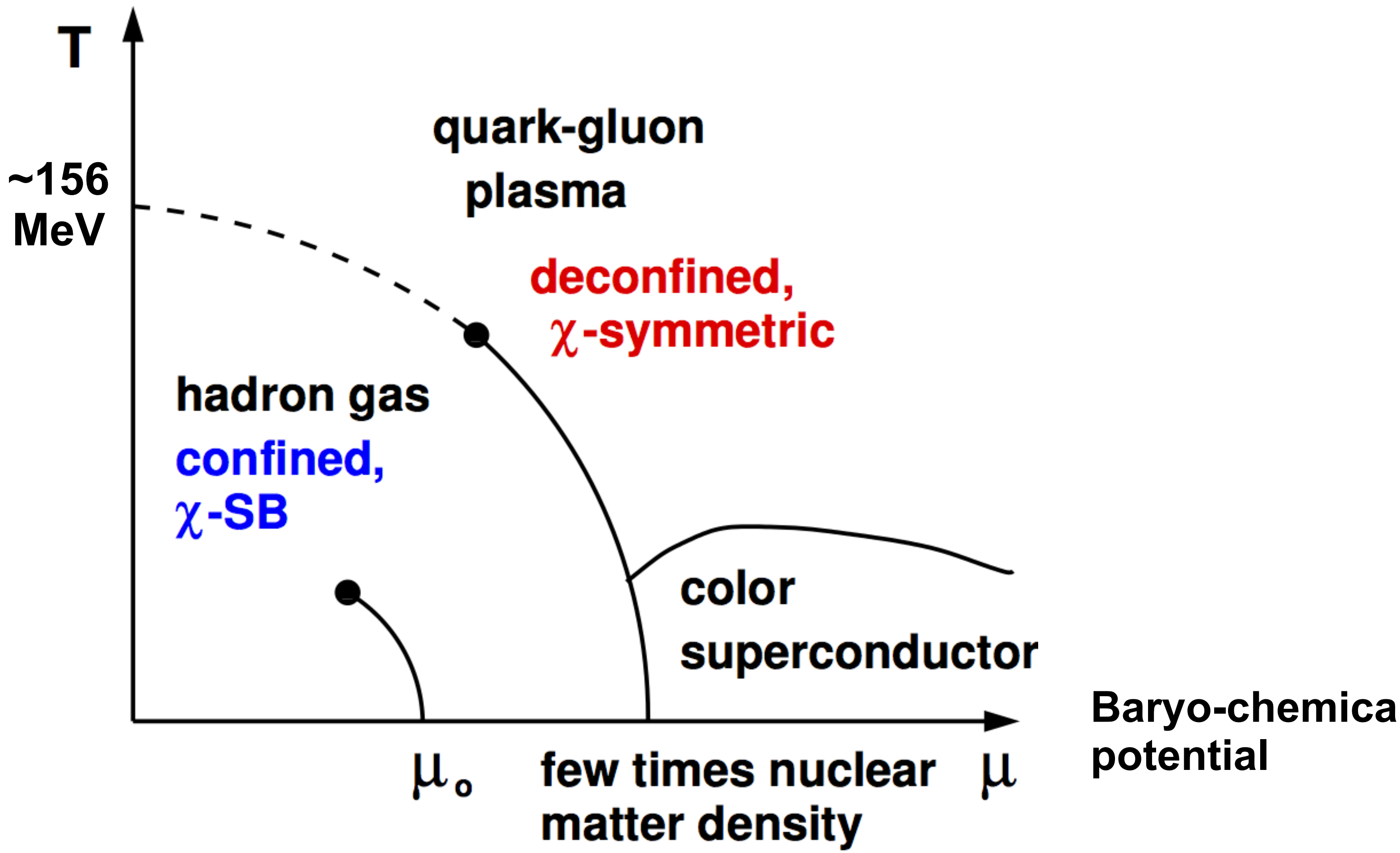


The QCD phase diagram

H_20

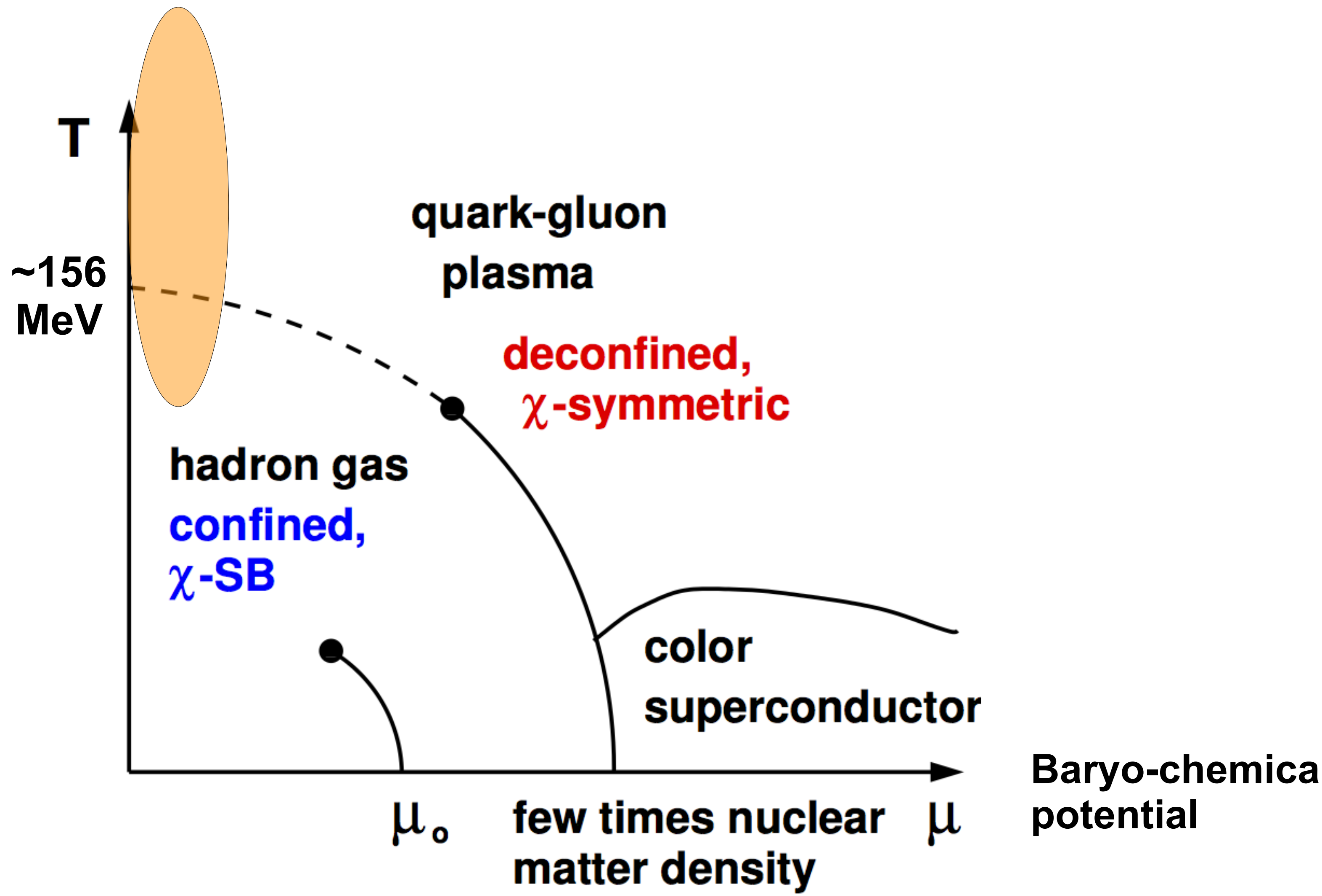


Phases of matter



The QCD phase diagram

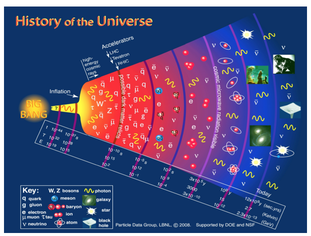
High temperature and low net baryon density region

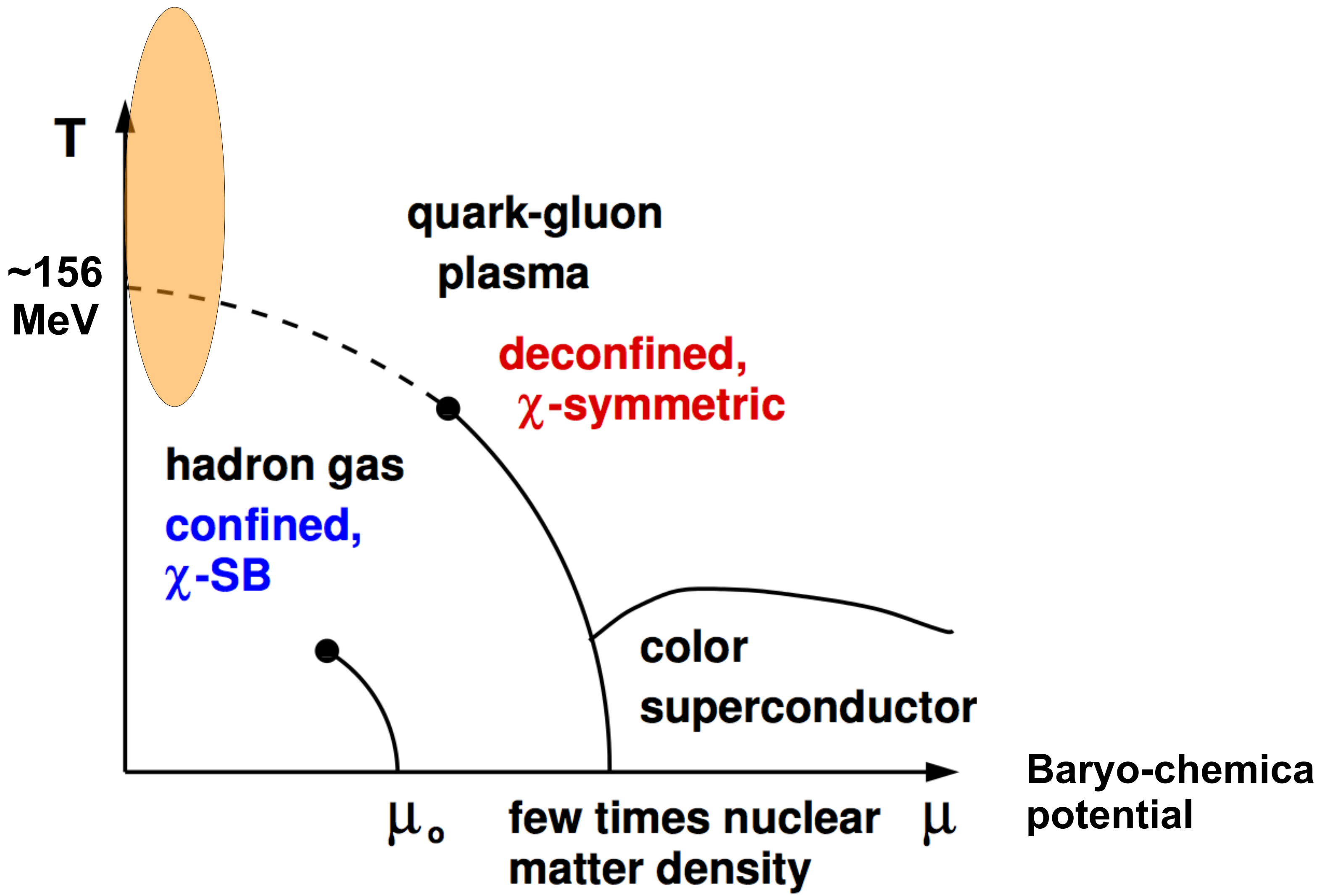


The QCD phase diagram

High temperature and low net baryon density region

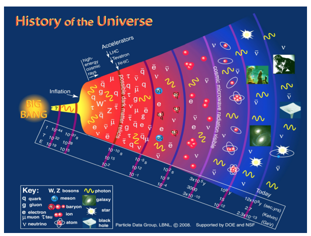
Early universe (few μs after the Big Bang)





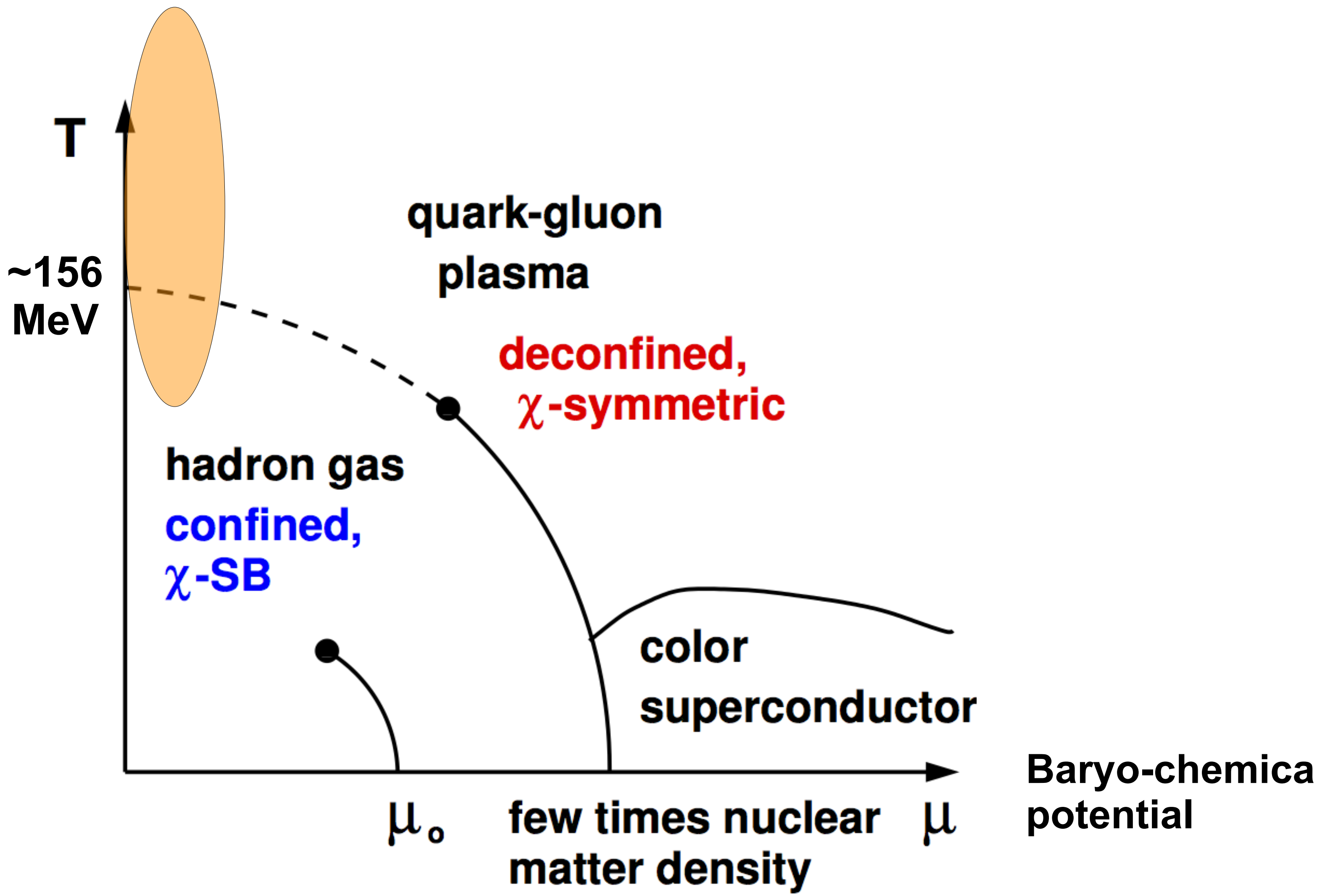
The QCD phase diagram

Early universe (few μs after the Big Bang)



Heavy-ion collisions at the LHC (TeV)

High temperature and low net baryon density region



Heavy ions at the LHC: Run 2 (2015-2018)

^{208}Pb ions:

E_b = 6.37 Z TeV

$\sqrt{s} = 2\ E_b > 1$ PeV

$\sqrt{s_{NN}}$ = 5.02 TeV

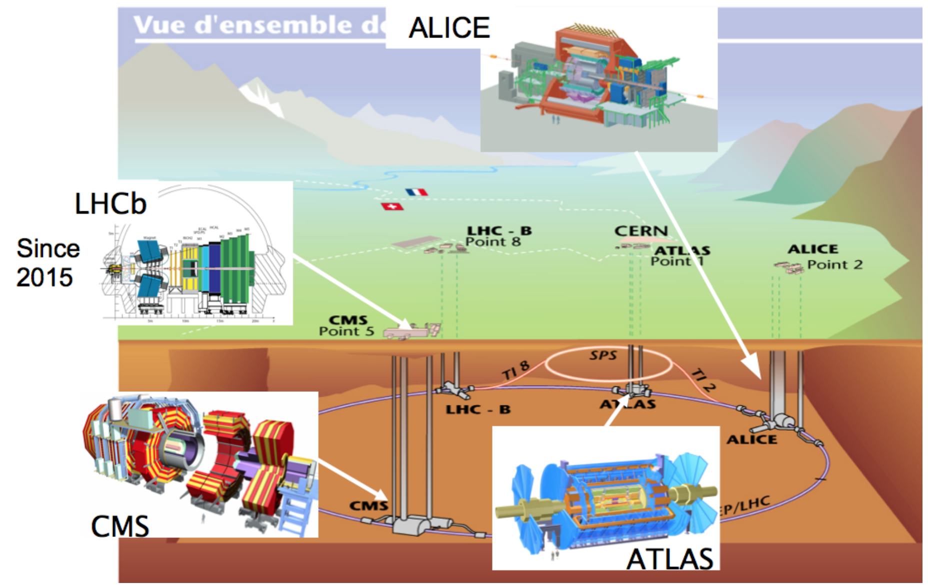
Design luminosity: 1 x 10^{27} $cm^{-2}s^{-1}$
surpassed by factor 2-3.6

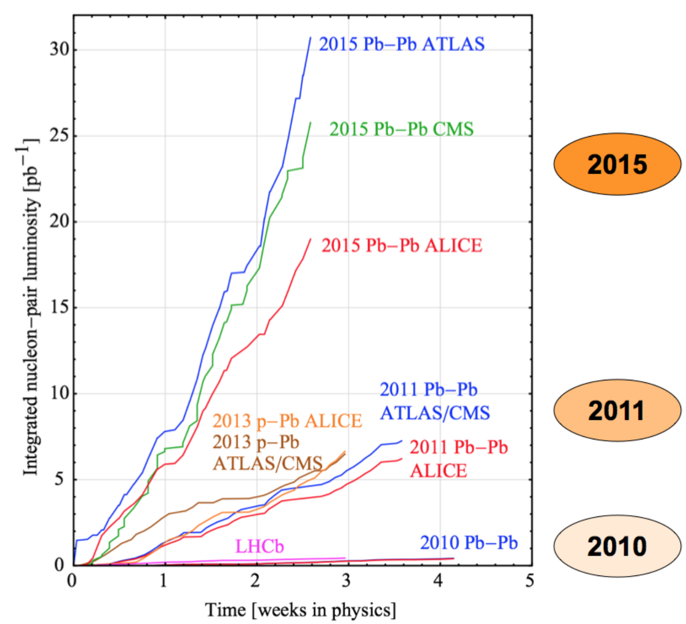
LHC superb performance

Goal (including 2018):

~1 nb^{-1} integrated luminosity

(including rare triggers)

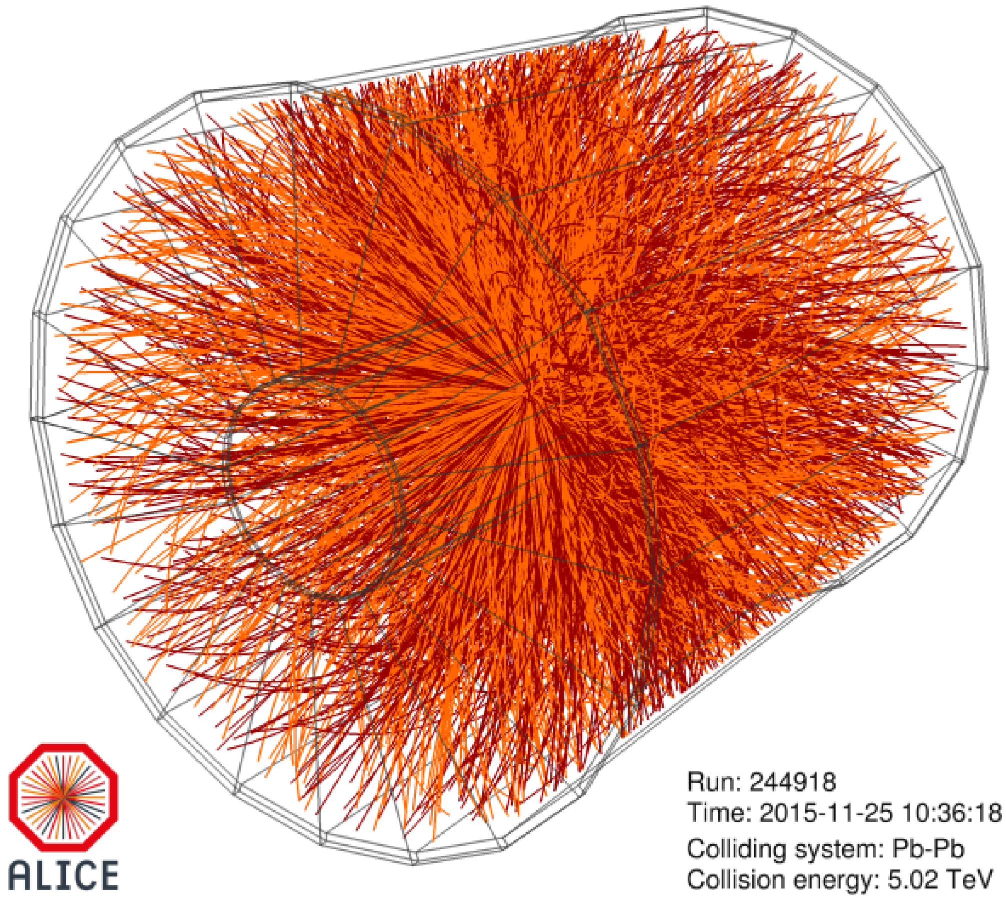




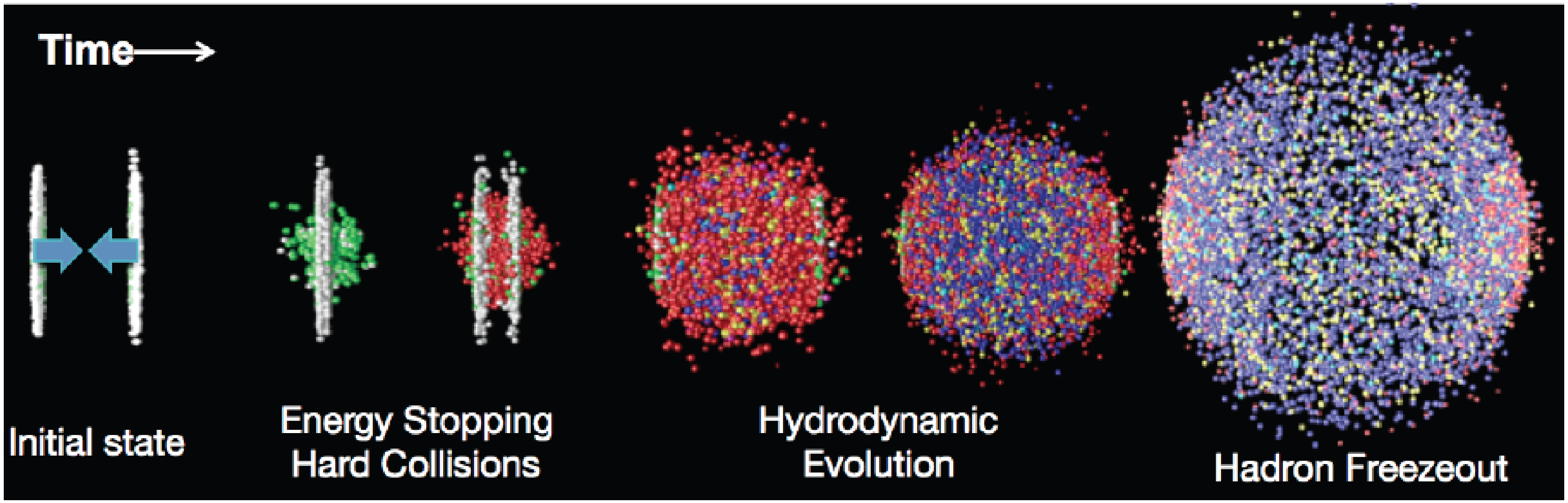
Nucleon-nucleon integrated luminosity

DOI: 10.18429/JACoW-IPAC2016-TUPMW027

Heavy-ion collisions at the LHC



Heavy-ion collision evolution



Non-equilibrium evolution at early times:

- Gluon dominated, fast thermalization

Local thermal and chemical equilibrium: QGP

- Evolution ↔ relativistic fluid dynamics
- Expansion, dilution, cooling

Chemical freeze-out:

- Below a critical temperature, hadrons are formed
- Inelastic collisions cease → particle yields

Kinetic freeze-out:

- Elastic collisions cease → spectra

Therm. time ~ O(0.1 fm/c)

T_0 ~ O(500 MeV)

Homog. Volume ~ 5000 fm^3

Decoupling time ~ 10 fm/c

Questions

- Transport properties
  Parton energy loss
- Deconfinement / confinement
  Phase boundary
- Hadronization mechanism
  Loosely bound objects

Hot QCD matter

Questions

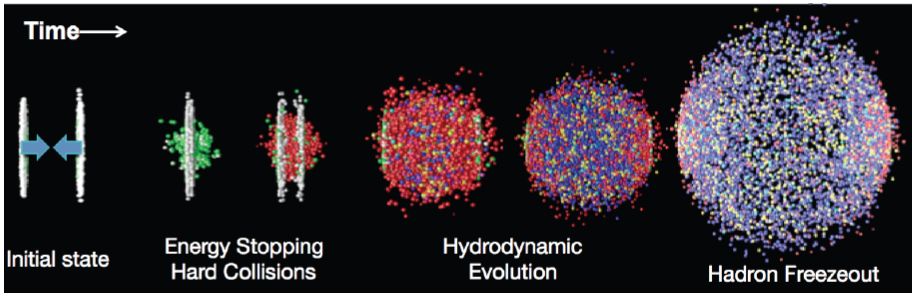
- Transport properties
  Parton energy loss
- Deconfinement / confinement
  Phase boundary
- Hadronization mechanism
  Loosely bound objects

Observables

- Light and heavy hadrons nuclear modification factor
- Charmonium production
- (Anti-)(hyper-)nuclei production

Parton energy loss ↔ tomography

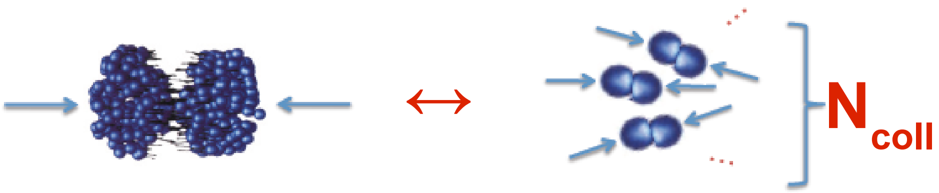
- Medium-induced gluon radiation
- Collisions with medium constituents



Quantifier: the **nuclear modification factor**

$$R_{AA} = \frac{\text{Yield in AA}}{\text{Yield in pp}} \cdot \frac{1}{N_{coll}}$$

as function of $p_{T,}$ y and centrality

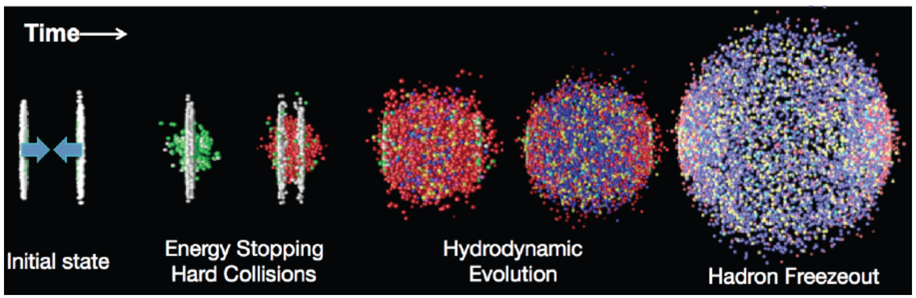


binary collisions (Glauber)

Parton energy loss $\leftrightarrow$ tomography

Probes:

- Vector bosons (do not interact strongly!)
- Light-quark hadrons



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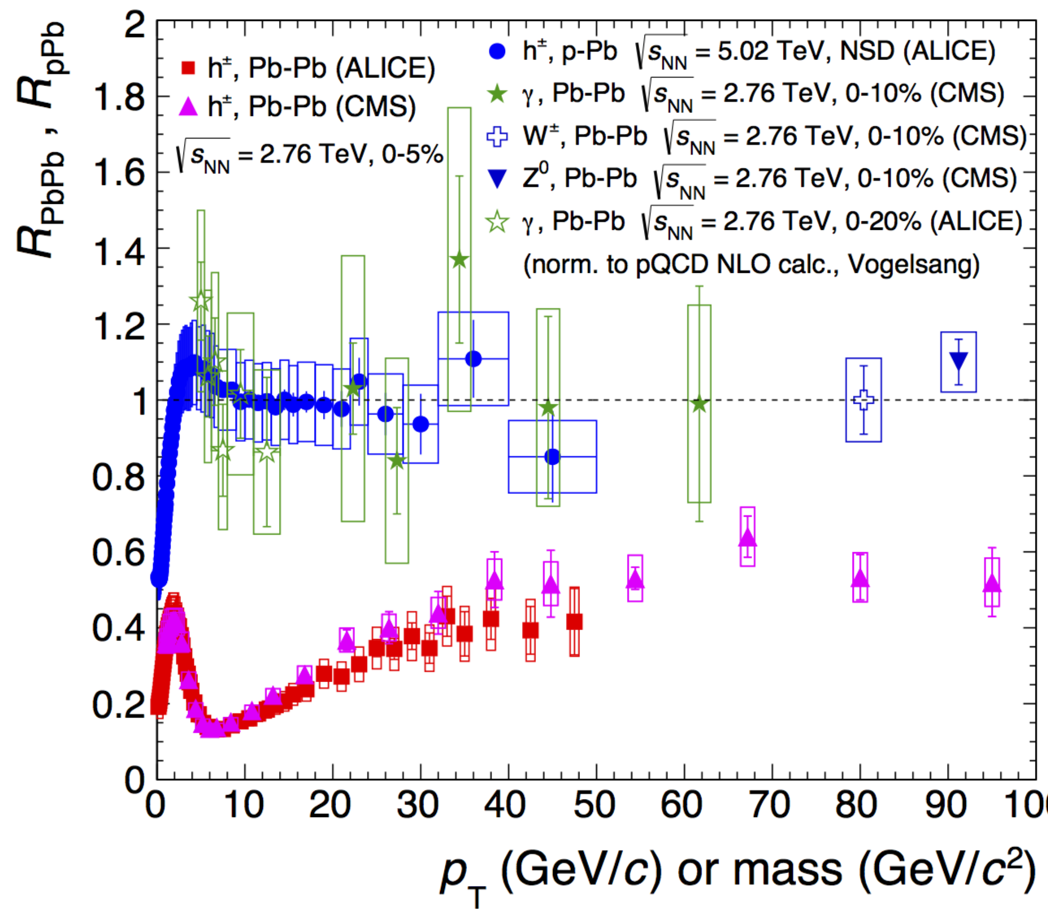
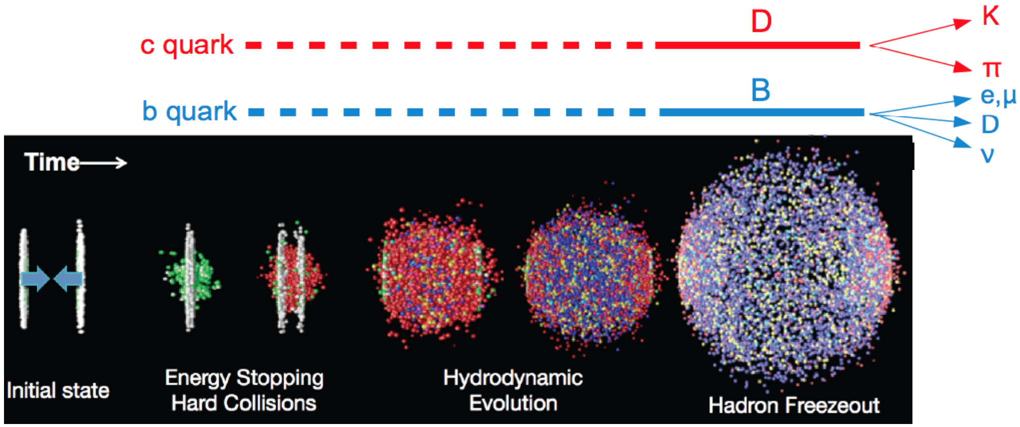


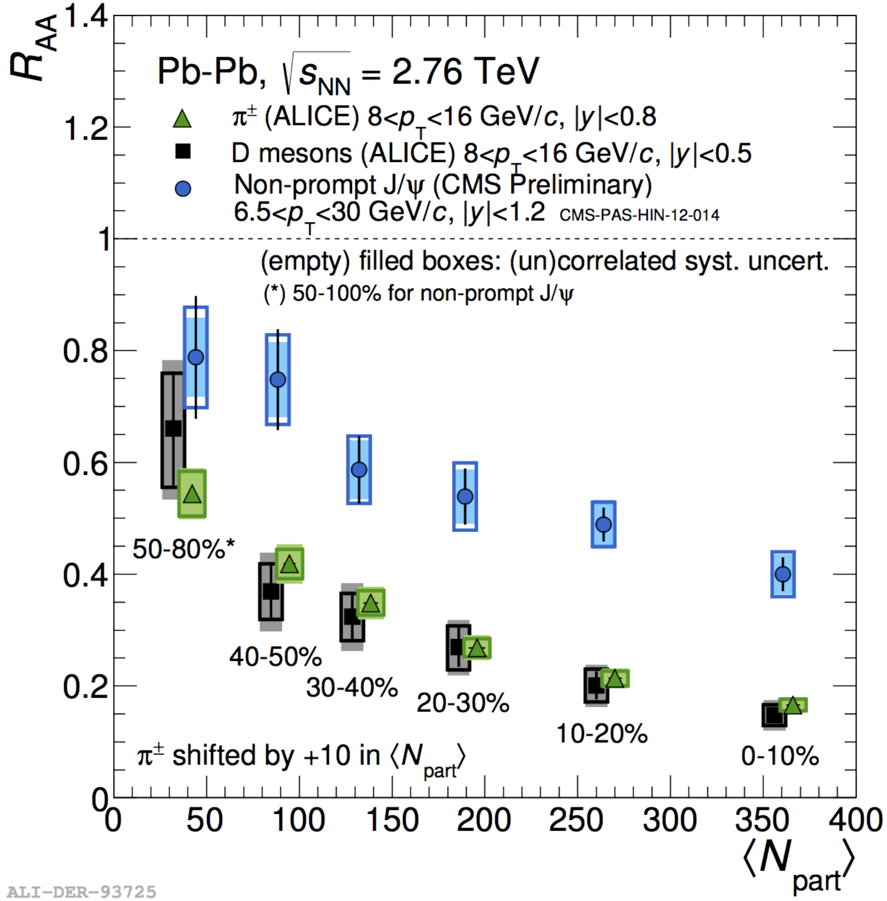
Parton energy loss ↔ tomography

Probes:

- Charm and beauty quarks

  Dependence on color charge (q/g) and parton mass





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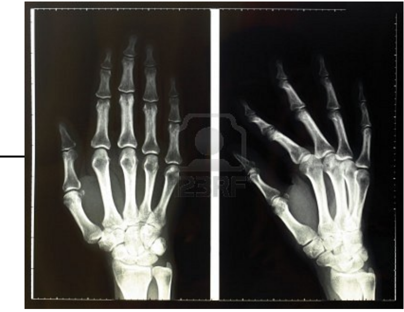
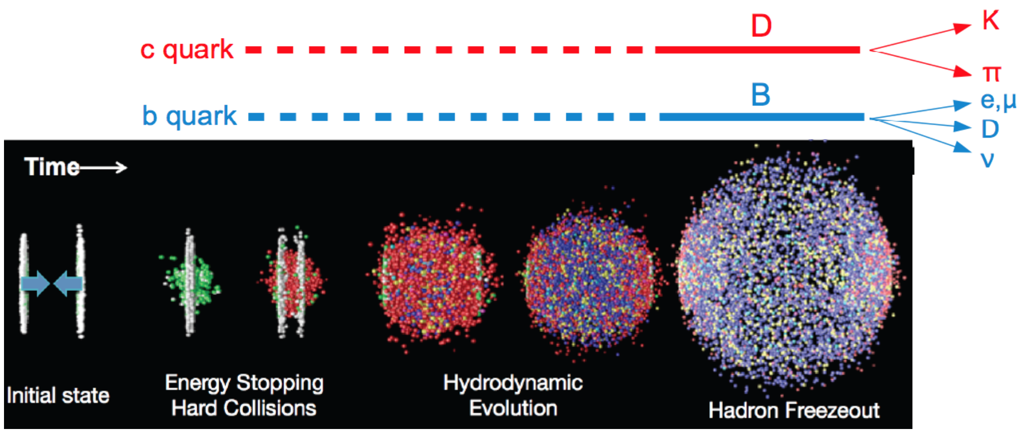


Probes:

- D and D_s mesons: Modification of hadronization in presence of a medium? fragmentation vs recombination



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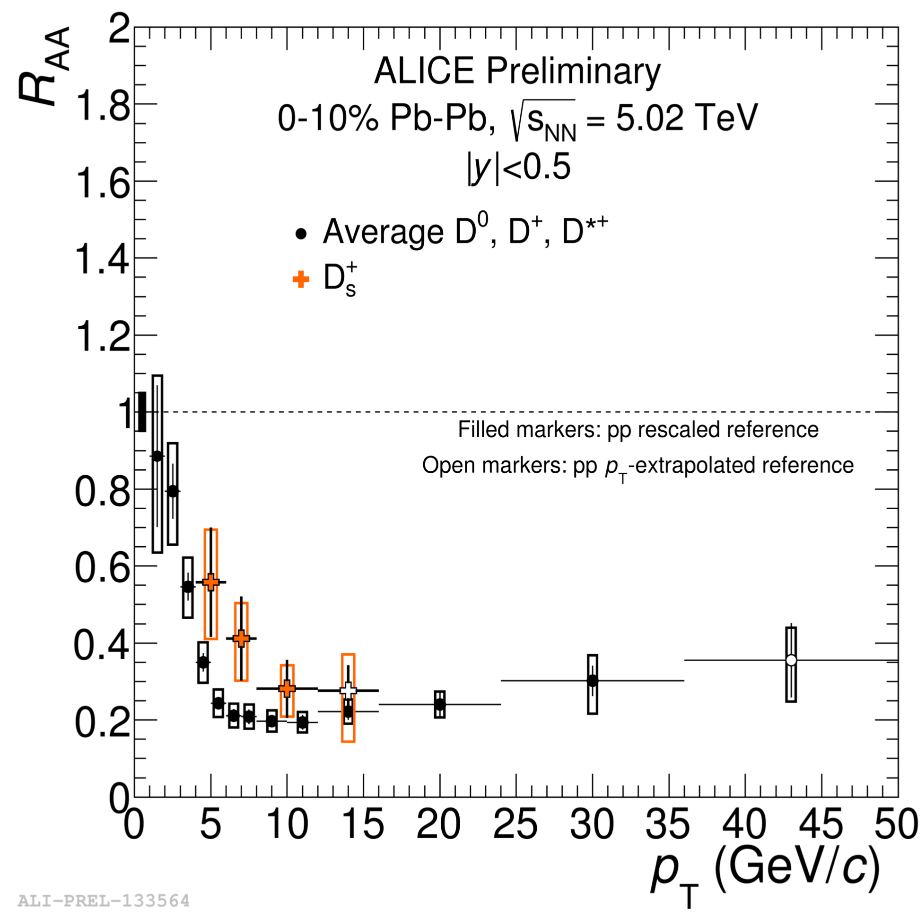
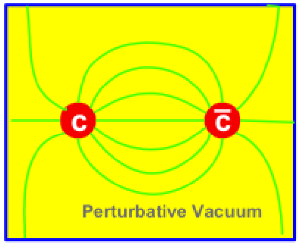
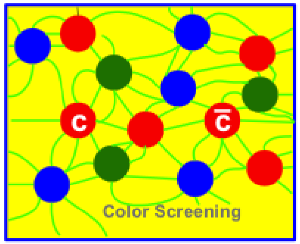
as function of $p_{T,}$ y and centrality



Charmonium production

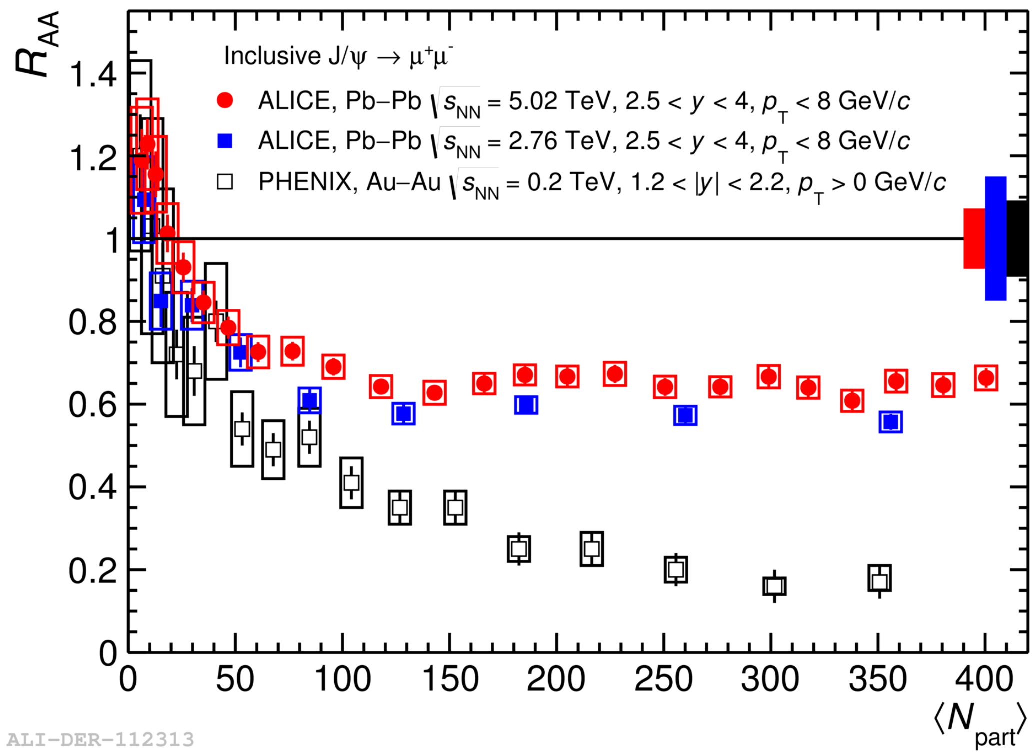


Screening of the strong interactions in the QGP!



ALICE
$\sqrt{s_{NN}}$ = 2.76 TeV
$\sqrt{s_{NN}}$ = 5.02 TeV

PHENIX
$\sqrt{s_{NN}}$ = 0.2 TeV



Event centrality

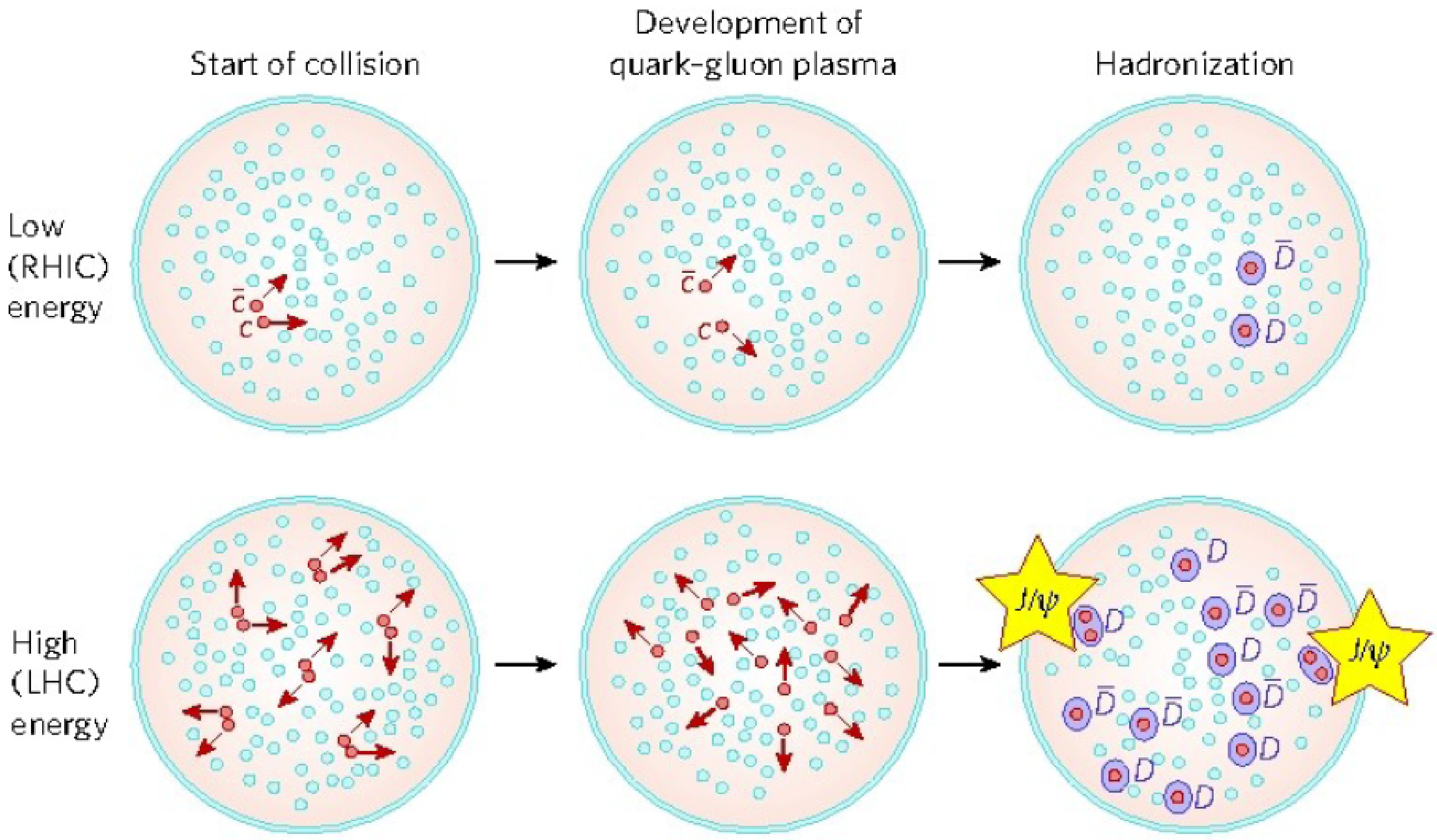
Suppression + new production mechanism !

Suppression

PLB734(2014)314
PLB766(2017)212

Charmonium production

Idea already proposed before the LHC: abundance of charm and deconfinement

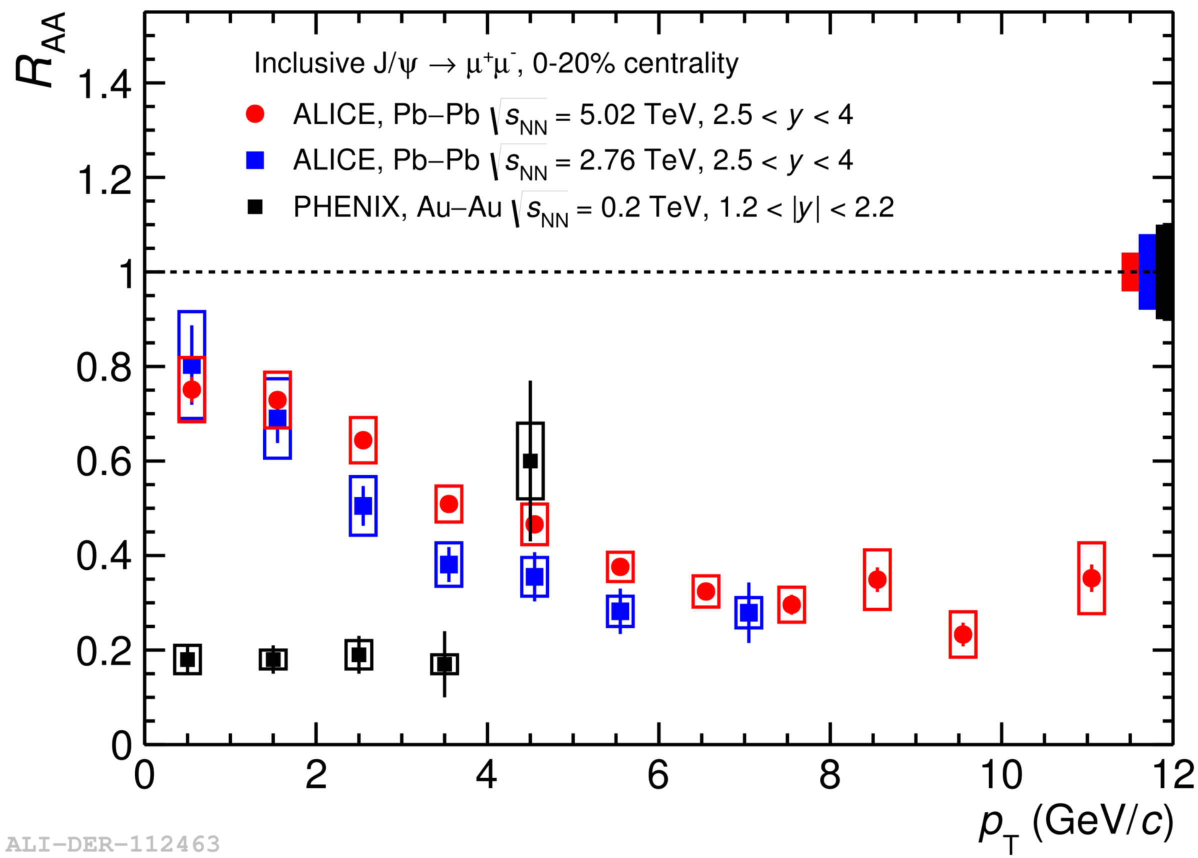


Braun-Munzinger, Stachel, Nature 448 (2007) 302-309

Charmonium production

Abundance of J/ψ regenerated in the QGP or newly generated at the phase boundary by statistical hadronization, at low p_T

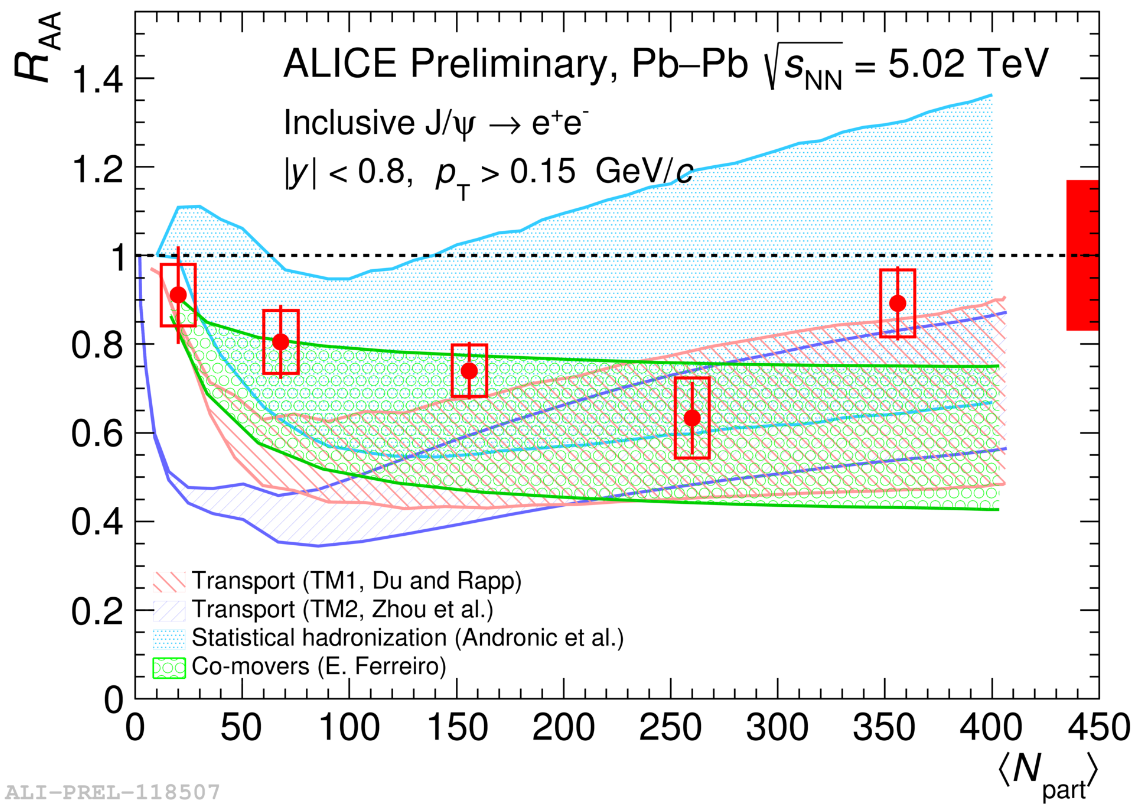
→ signature of deconfinement



PLB734(2014)314
PLB766(2017)212

Charmonium production

J/ψ regenerated in the QGP or newly generated at the phase boundary: statistical hadronization, transport models, co-movers



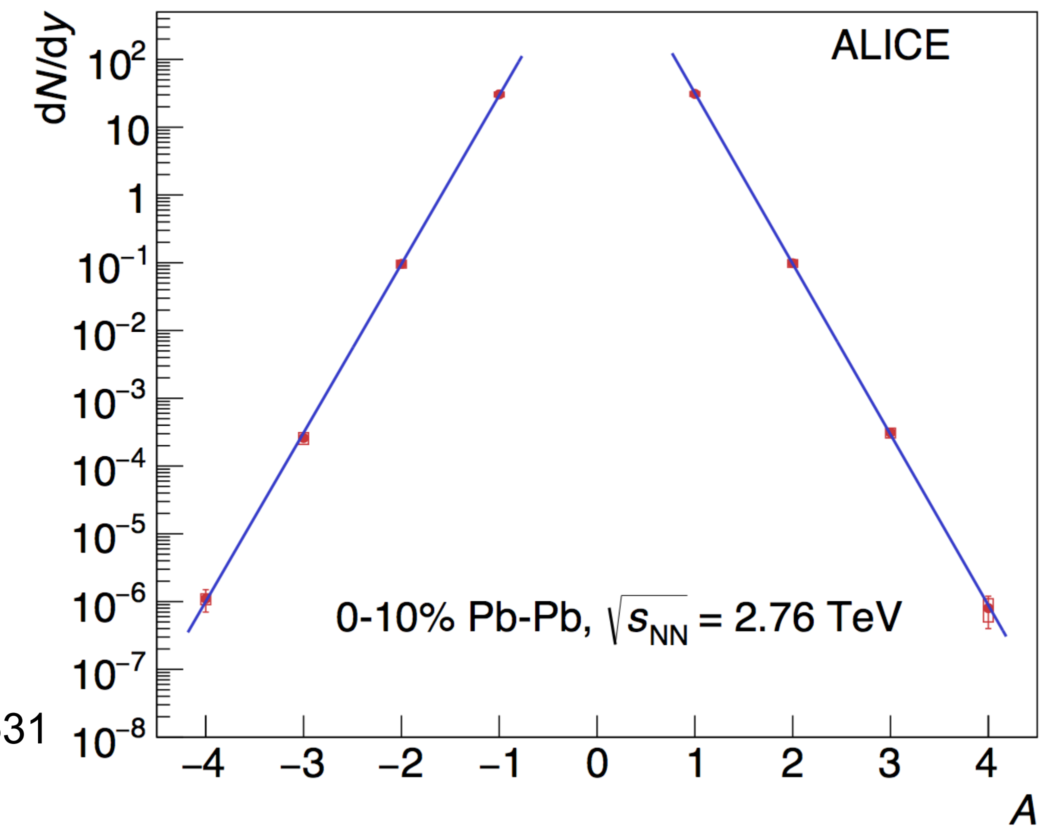
Large uncertainties: shadowing, open charm cross section

Progress on both theory and experiment sides needed to reach a more precise description

(Anti-)(hyper-)nuclei production

Abundant production of light nuclei:

- ➔ A=2: deuteron (many)
- ➔ A=3: ^{3}He, $^{3}_{\Lambda}$H (good statistics)
- ➔ A=4: ^{4}He (few)



arXiv: 1710.07531

- Hadronization mechanism?
  Thermal production or coalescence?
- Some very loosely bound (Λ separation energy in $^{3}_{\Lambda}$H is ~ 0.13 MeV): how do they get formed at a freeze-out at 154 MeV?
- Precise lifetime and BR measurements needed

EMMI workshop, Torino, 2017 https://indico.gsi.de/event/6301/

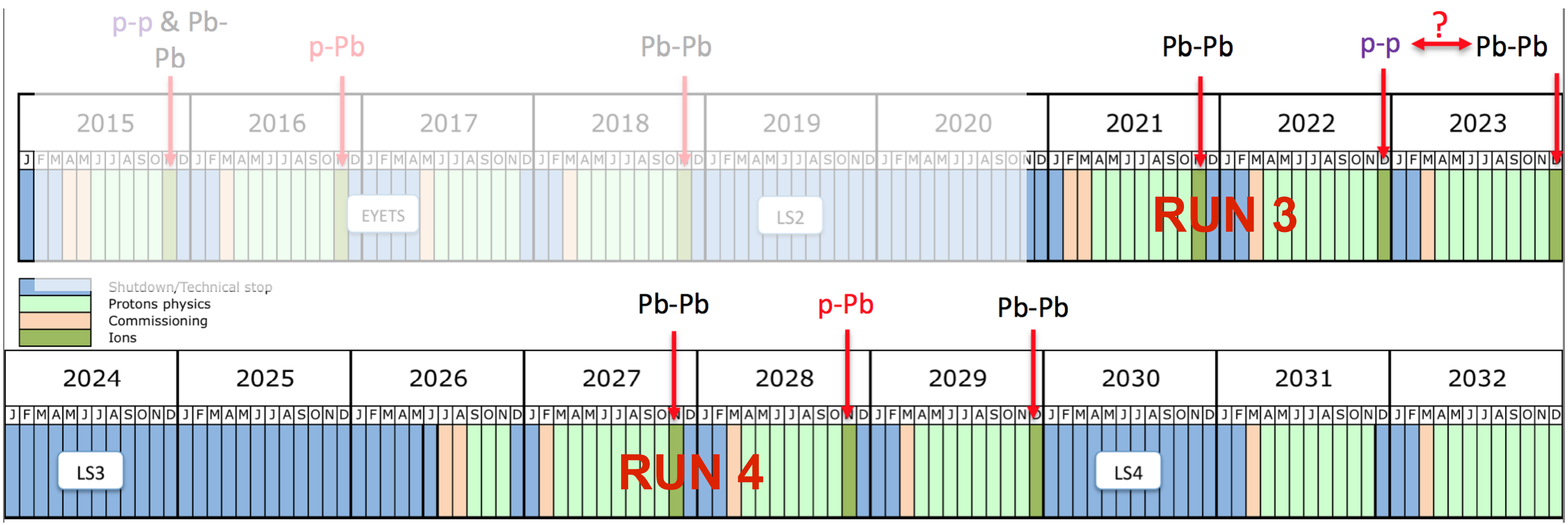
Heavy-ion high-luminosity LHC

During the Long Shutdown 2 (2019-2020) at the LHC:

- Increase total number of lead nuclei stored
- Upgrade of LHC collimators

→ Peak Luminosity > 6×10^{27} $cm^{-2}s^{-1}$ → **50 kHz Pb-Pb interaction rate**

Foreseen integrated luminosity ~ **3 nb^{-1} / month**



HL-LHC for heavy ions starts in 2021 !

Heavy-ion high-luminosity LHC from 2021!

Same collision energy $\sqrt{s_{NN}}$ = 5 - 5.5 TeV

ALICE physics case:

- Low transverse momentum observables (reduced material budget)
- Minimum bias data taking (no triggers) → 100 x statistics
- Need for continuous readout of detectors → >3 TBytes/s

  → online data processing with strong volume reduction

13 nb^{-1}

Letter of intent: https://cds.cern.ch/record/1475243/
ITS TDR: https://cds.cern.ch/record/1625842?ln=en

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CMS ATLAS EXPERIMENT LHCb

Workshop on the physics of HL-LHC, and perspectives at HE-LHC

30 Oct 2017, 09:00 → 1 Nov 2017, 19:00 Europe/Zurich

500-1-001 - Main Auditorium (CERN)

https://indico.cern.ch/event/647676/

General strategy and running plans in discussion in the HL-LHC heavy-ion working group

→ document by end of 2018 as input for the European Strategy discussion

HI HL-LHC: physics program (some)

Very high statistics, improved detectors:

- **Heavy flavors**
- **Heavy quarkonia production**
- **(Anti-)(hyper-)nuclei production**

HI HL-LHC: physics program (some)

Very high statistics, improved detectors:

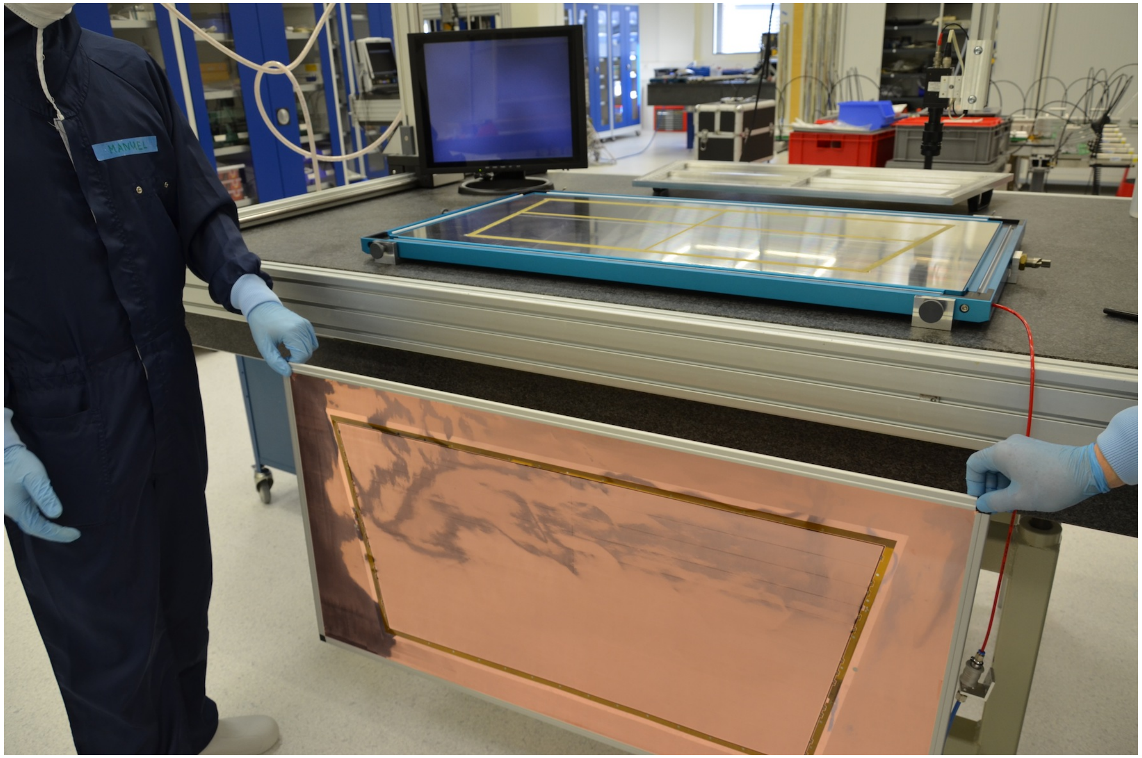
- **Heavy flavors** →
  - Precision measurements c, b hadrons
  - Baryons/mesons: hadronization mech.
  - New observables (e.g. D^0 v_1 ↔ B field)

- **Heavy quarkonia production** →
  - Large statistics J/ψ, ψ(2S) → pin down production mechanism
  - X_c, Y(1S,2S,3S), flow

- **(Anti-)(hyper-)nuclei production** →
  - What is now done for A=2,3 will be extended to A=4: ${}^4_\Lambda H$, ${}^4_\Lambda He$
  - Precision measurements: 40k ${}^3_\Lambda H$

ALICE upgrades: work at GSI

Framing and testing of large area GEM foils



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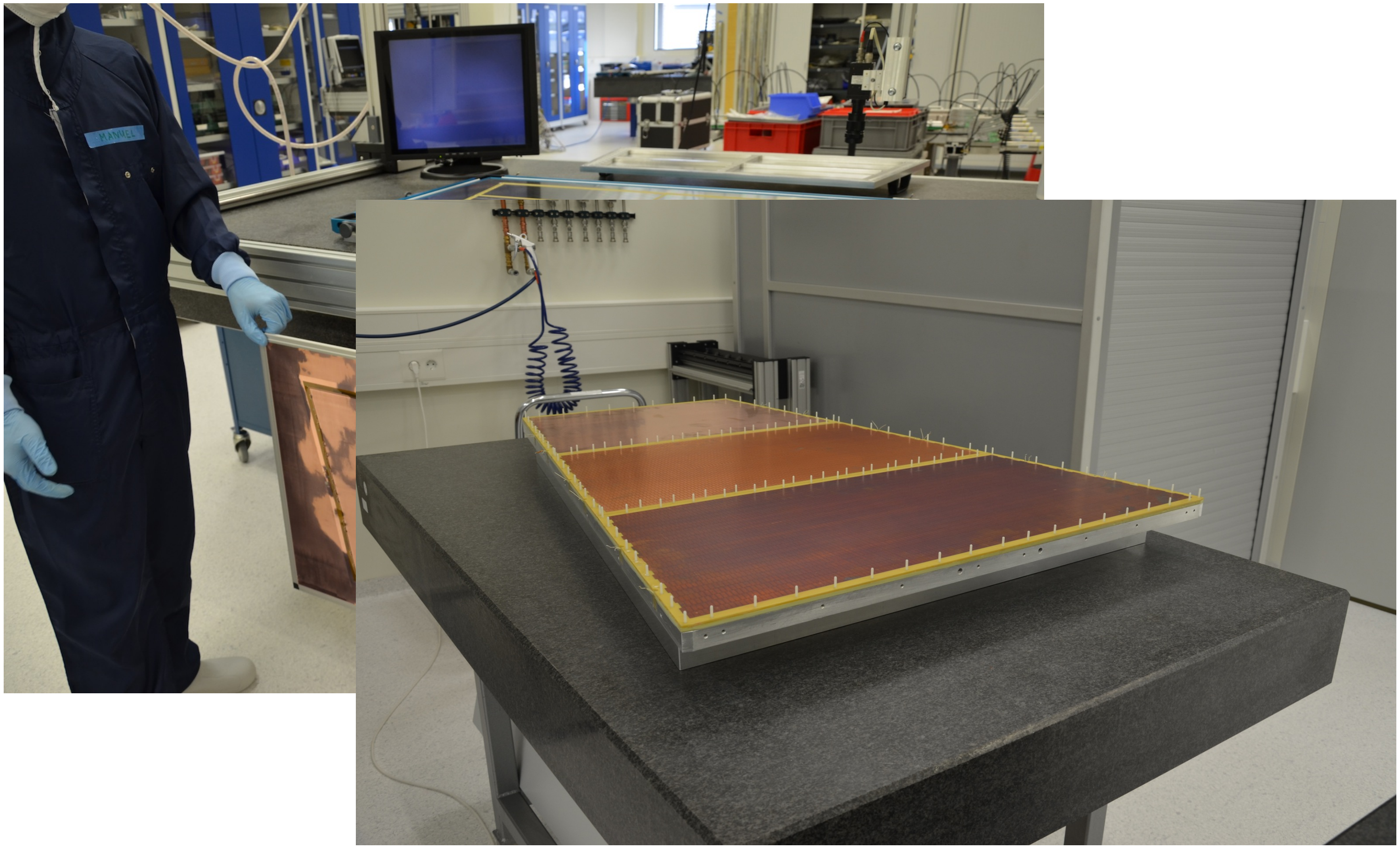
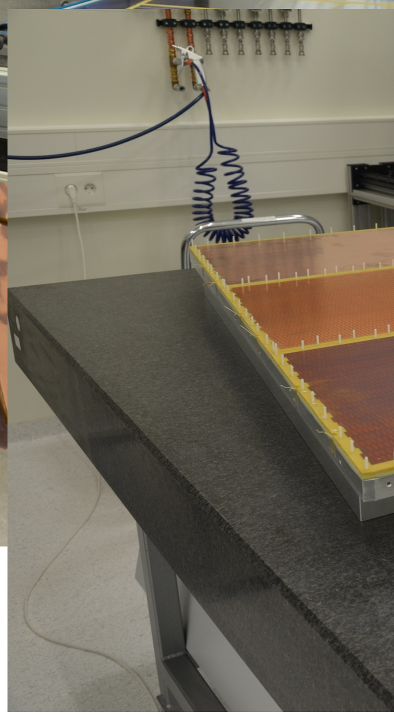


Chamber body
prepared (Hd, F)

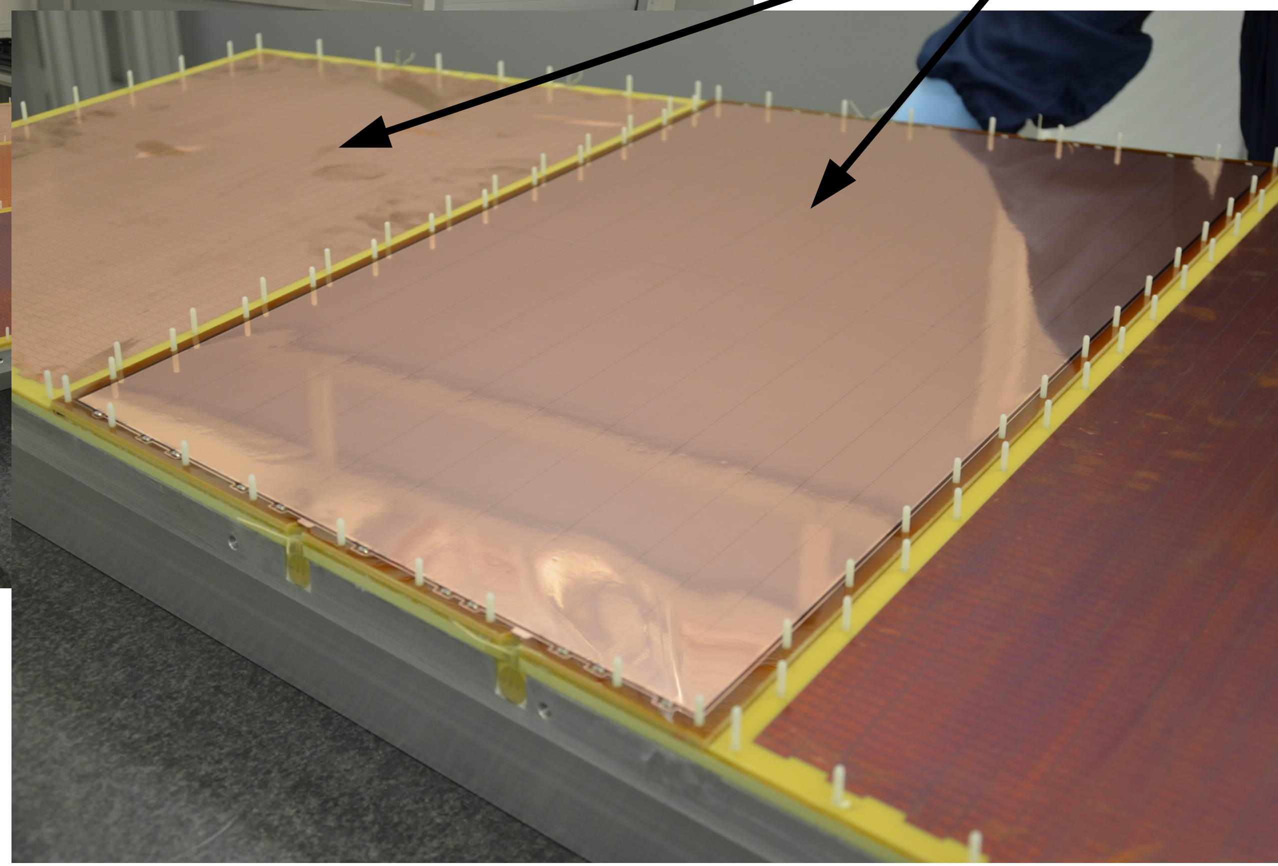
ALICE upgrades: work at GSI

Framing and testing of large area GEM foils



Chamber body
prepared (Hd, F)

GEM quadruple
stacks mounted

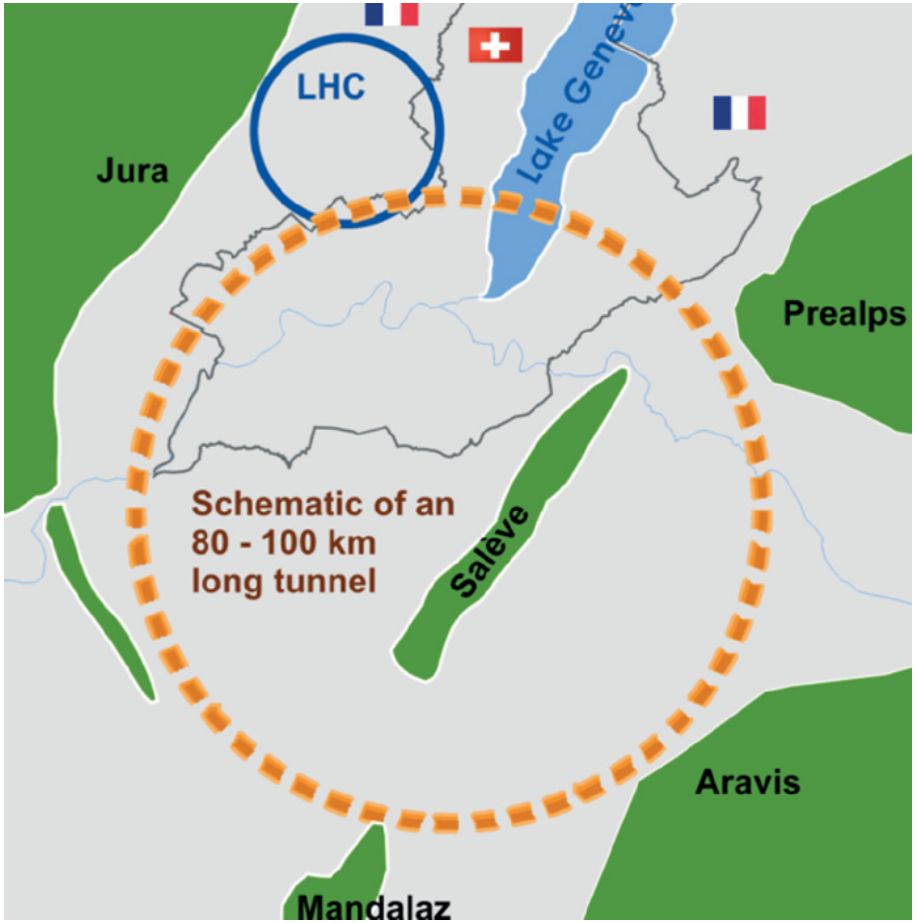


Beyond the LHC

Design study by international collaboration, initiated by CERN in 2014, for a

Future Circular Collider

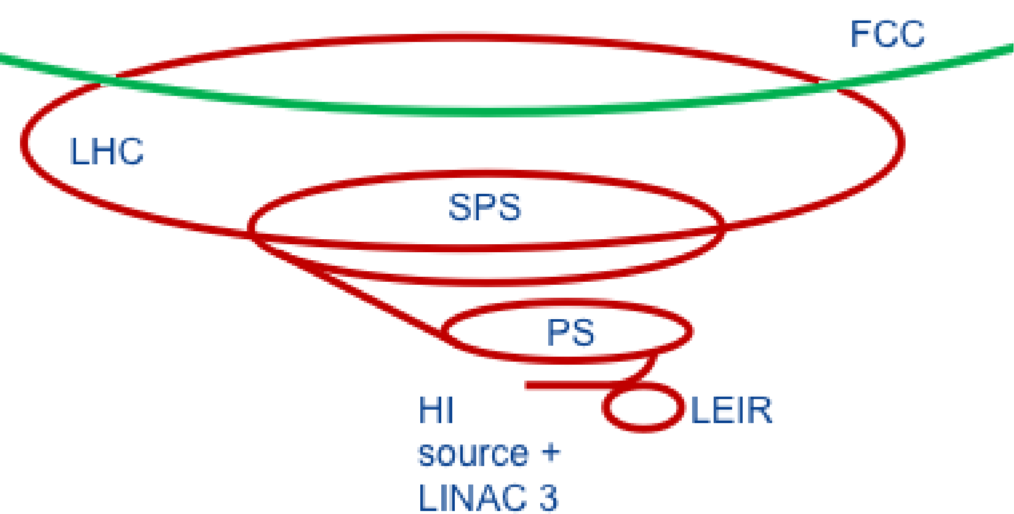
- Proton-proton collider (FCC-hh)
  ~16 T → 100 TeV pp in 100 km
  ~20 T → 100 TeV pp in 80 km
  → defining infrastructure requirements
- e^+e^- collider (FCC-ee) as potential intermediate step
- p-e (FCC-he) option
- **Ion program!**



Scope: CDR and cost review for the next European strategy (2019)
Starting date targeted for 2035-2040

Heavy ions at the FCC (FCC-hh → FCC-HI)

John M. Jowett
Michaela Schaumann



Hadron beams: protons and Pb ions

E_b = 50 Z TeV

- pp: $\sqrt{s}$ = 100 TeV

➔ Pb-Pb: $\sqrt{s_{NN}}$ = 39.4 TeV

➔ p-Pb: $\sqrt{s_{NN}}$ = 62.8 TeV

Pre-accelerator chain for ions to be studied. 1 or 2 experiments.

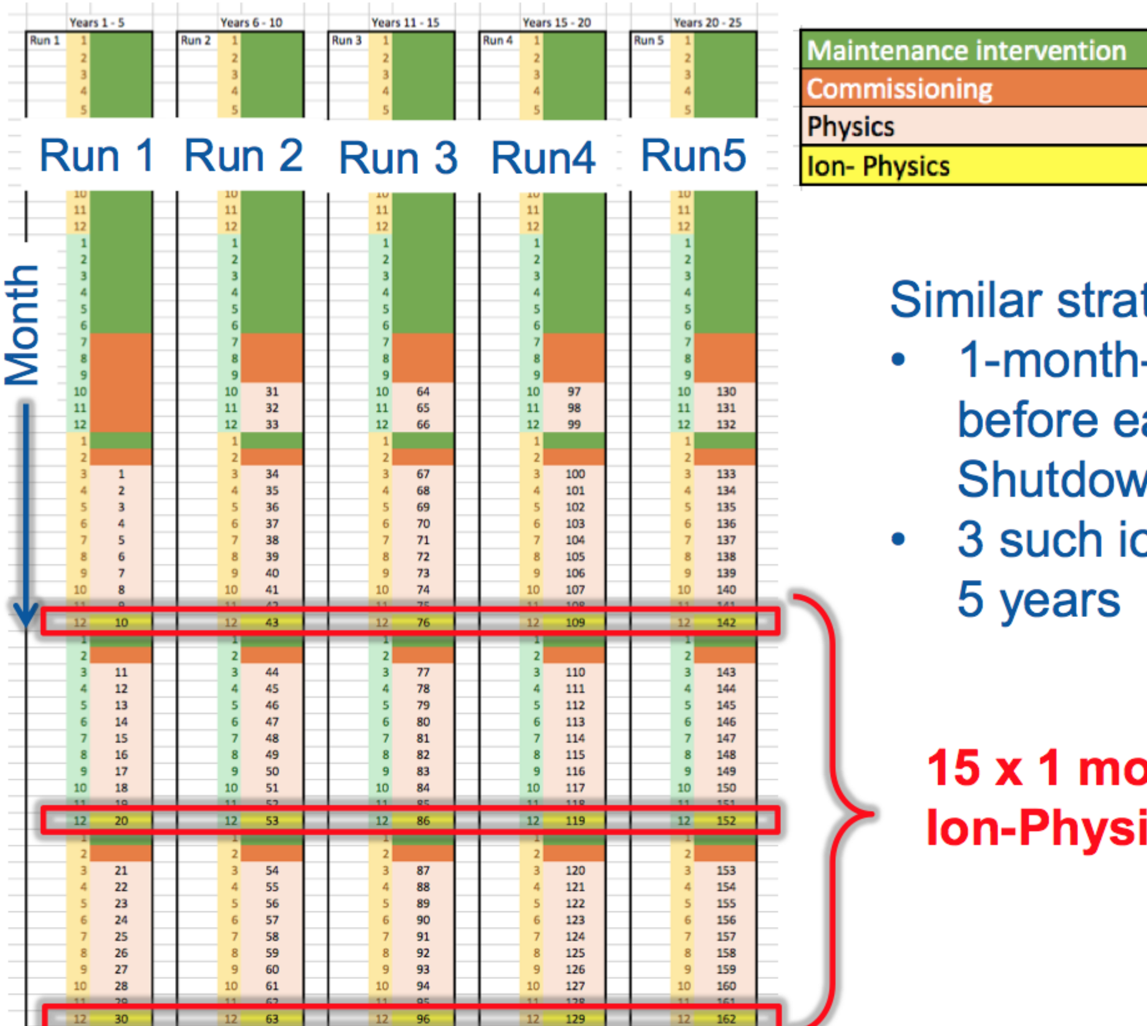
$\int L_{Pb\text{-}Pb}$:

	Baseline:	Ultimate:
1 exp. L_{int}/run:	35nb^{-1}	110nb^{-1}
2 exp. L_{int}/run:	23nb^{-1}	65nb^{-1}

3nb^{-1} at HL-LHC

Heavy ions at the FCC

Tentative Run Schedule



Similar strategy as for LHC:

- 1-month-long Heavy-Ion runs before each Technical Stop or Shutdown
- 3 such ion runs per FCC-Run of 5 years

15 x 1 month Ion-Physics time

29/09/2017 M. Schaumann - Update on FCC-HI Operation and Luminosity 8

FCC-HI: physics opportunities

Wiki: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HeavyIons

HI dedicated meetings: https://indico.cern.ch/category/6068/

Global properties:

CERN Yellow Report (DOI: 10.23731/CYRM-2017-003.635)

Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$\mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta$ at $\eta = 0$	1.8–2.0 TeV	2.3–2.6 TeV	5.2–5.8 TeV
Homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
Decoupling time	10 fm/c	11 fm/c	13 fm/c
ε at $\tau = 1$ fm/c	12–13 $\mathrm{GeV/fm}^3$	16–17 $\mathrm{GeV/fm}^3$	35–40 $\mathrm{GeV/fm}^3$

$dN_{ch}/d\eta$ x 1.8

$dE_T/d\eta$ x 2.2

volume x 1.8

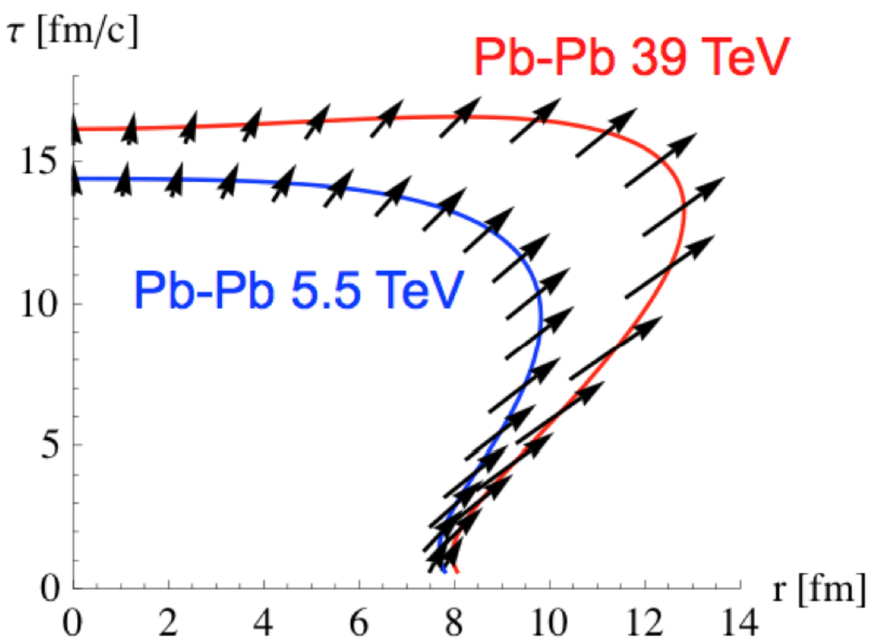
d. time x 1.3

$\varepsilon_{1fm/c}$ x 3

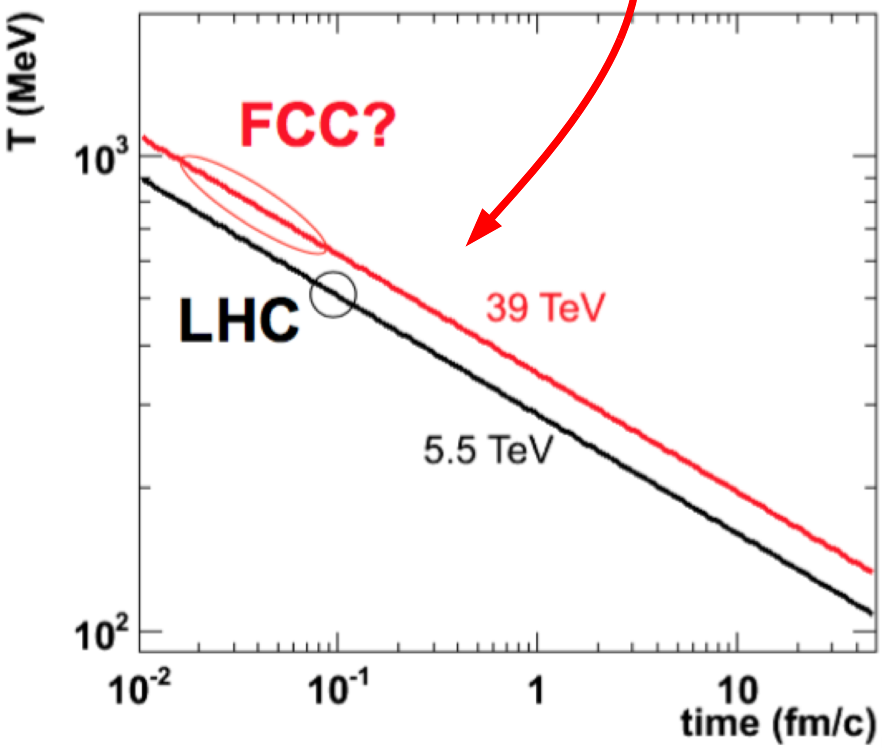
Global properties at $\sqrt{s_{NN}}$ = 2.76 TeV (0-5% centrality interval) extrapolated to 5.5 and 39 TeV

FCC-HI: global properties

Medium: is larger
lives longer
reaches higher energy density and temperatures
equilibrates faster (x2)



Space-time profile at freeze-out from hydrodynamical calculations



QGP temperature evolution on basis of Bjorken relation and Boltzmann equation

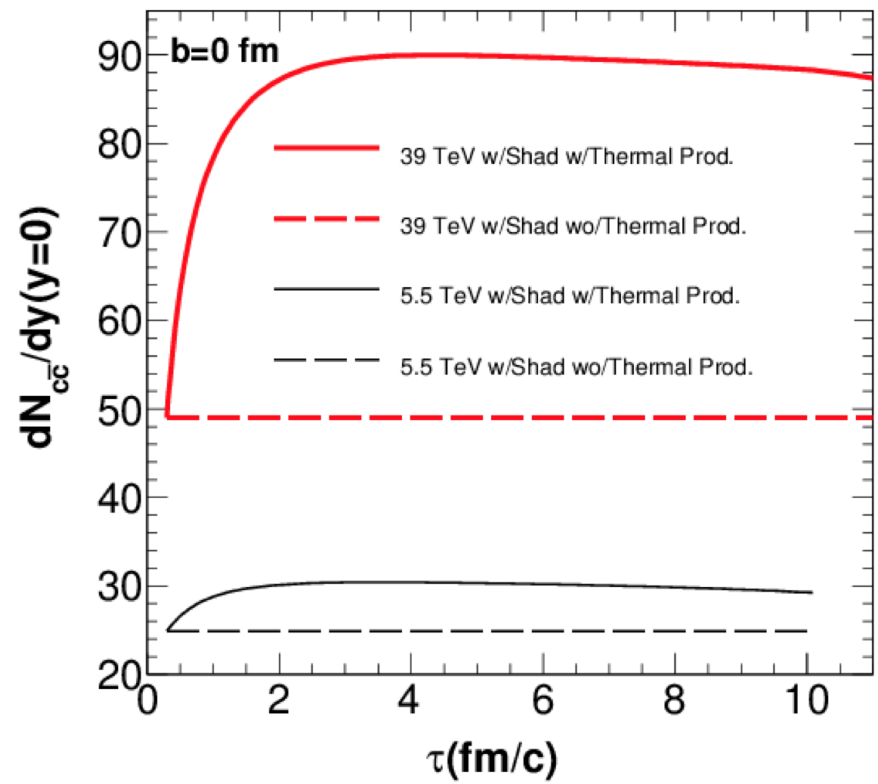
FCC-HI: physics opportunities

High energy → large production cross section for all hard probes

CHARM

Large increase of charm total yield:

- Larger yields of primary charm from hard-scattering processes between partons of the incident nuclei
- Higher QGP temperature → secondary or thermal charm production, from in-medium interacting partons (T > 500 MeV)



New relevant dof

Effect on the QGP equation of state?

Under debate

K. Zhou et al. PLB758 (2016) 434

FCC-HI: physics opportunities

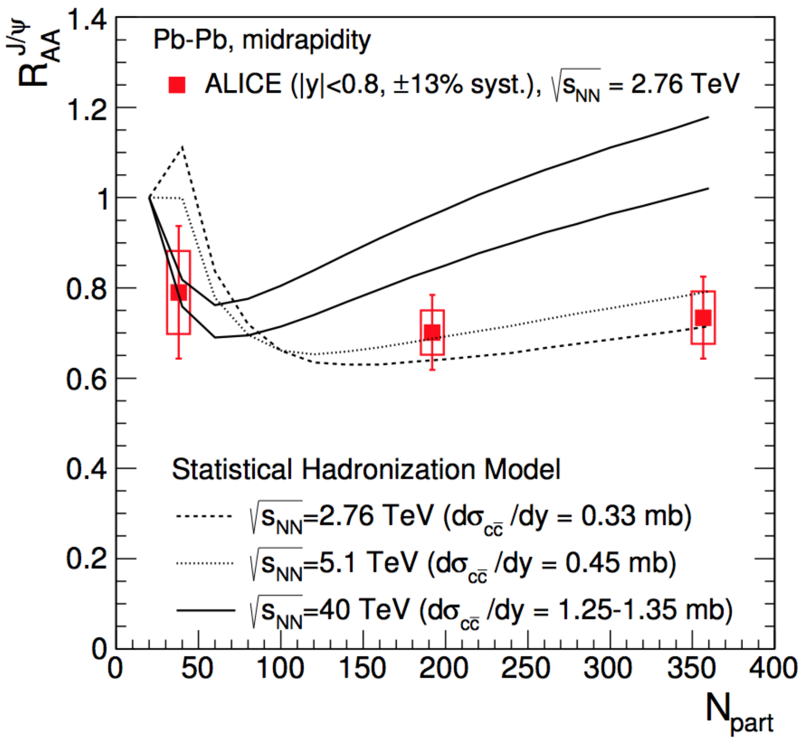
High energy → large production cross section for all hard probes

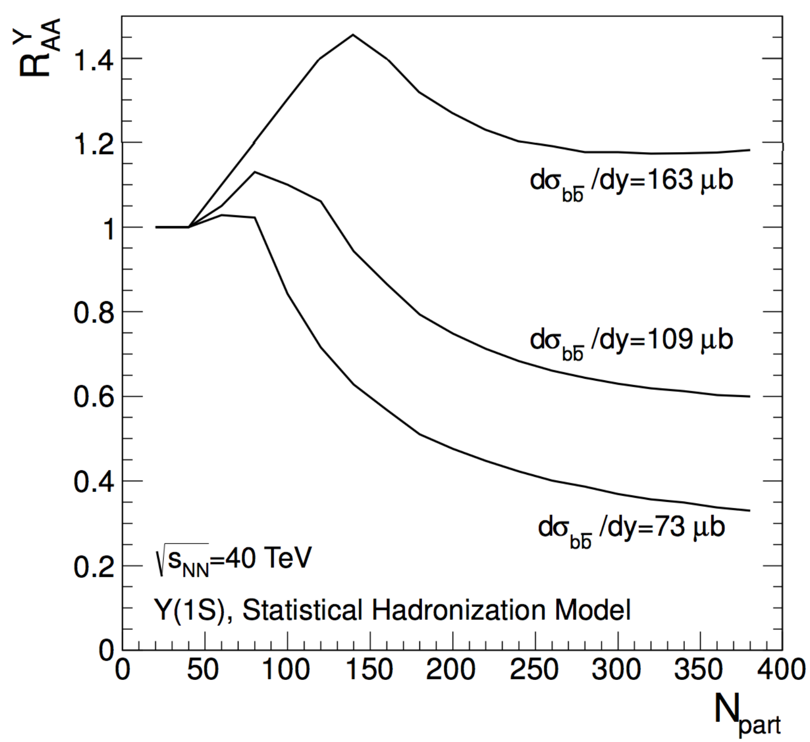
HEAVY QUARKONIA: charmonium and bottomonium

Dissociation by color screening and (re)generation by statistical hadronization: also true for bottom, at FCC temperature and σ_{bb}? Thermalization?

Statistical hadronization model (A. Andronic et al.)

J/ψ

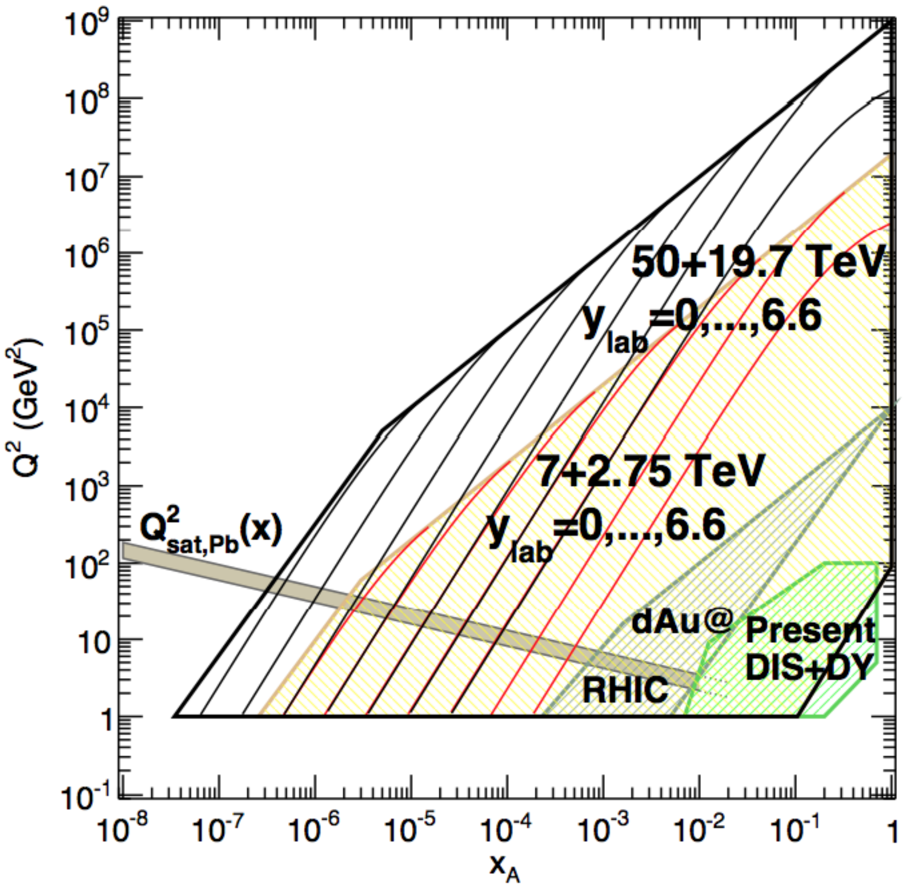


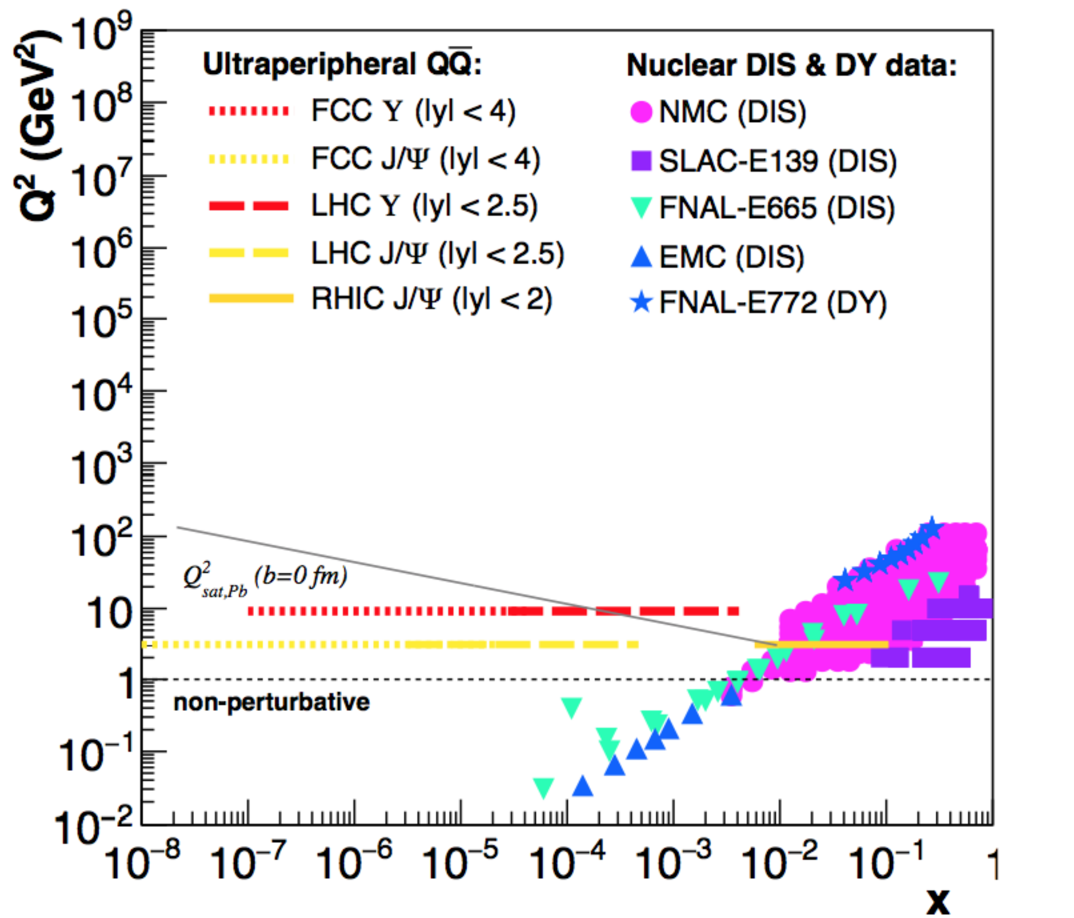


Y(1S)

FCC-HI: physics opportunities

Access to very low x with p-Pb and ultraperipheral Pb-Pb collisions:

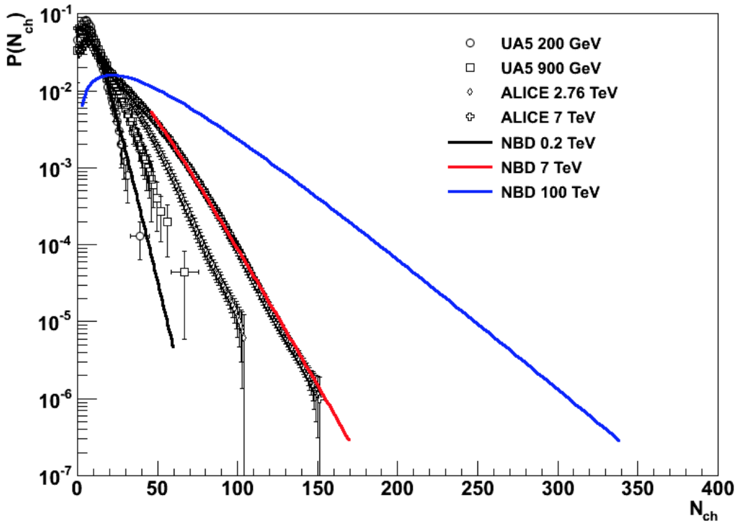




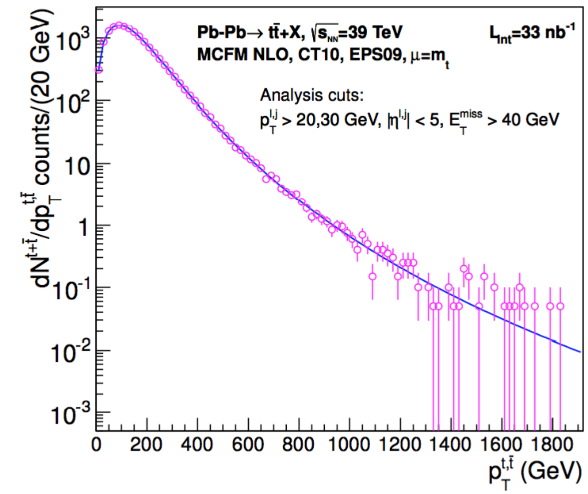
Test whether (perturbative) saturation lies in the accessible kinematic region (coverage of very forward region)

FCC-HI: more physics opportunities

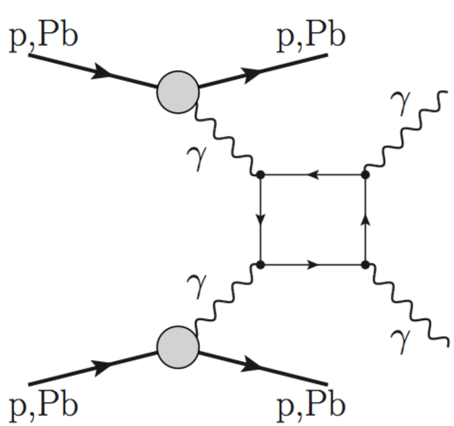
- VERY high multiplicity in pp and p-Pb



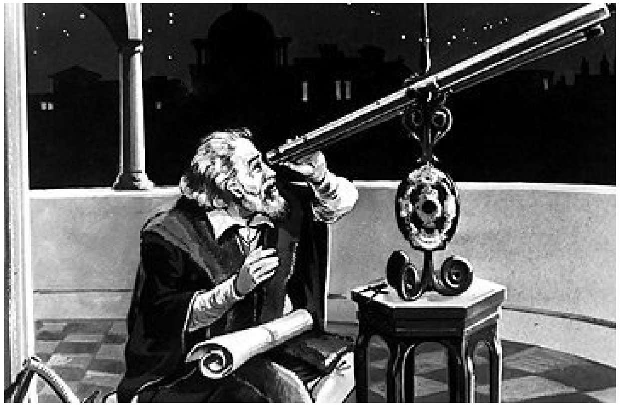
- single- and pair-top production: energy loss, time scales (boosted), nPDF



- Photon-photon scattering in pp, p-Pb, Pb-Pb (UPC)

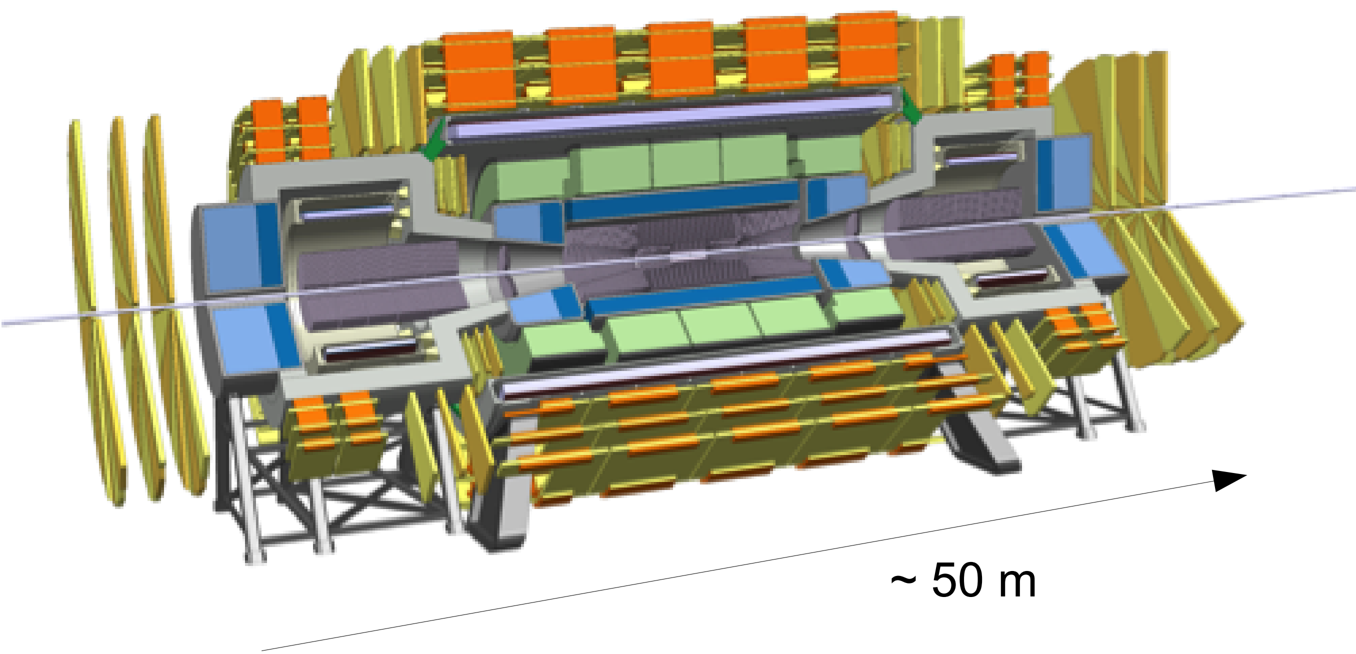


- Stay open for the unknown !!!



FCC-hh: detector options

Reference detector (pp physics driven) for the Conceptual Design Report



- 4T 10m solenoid + forward solenoids: no shielding coil
- Silicon tracker
- Barrel ECAL LAr
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forwards HCAL/ECAL LAr

Needs for heavy-ion physics?

Low (transverse) momentum. Particle identification

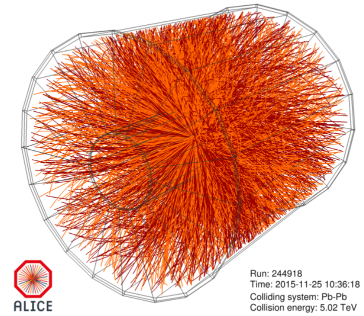
Dedicated experiment necessary?

Special settings for operation with heavy ions?

Focus on forward rapidity?

Werner Riegler

Conclusion



- Heavy-ion physics:
  the high temperature and low baryon density regime

  place of excellence to study non-perturbative QCD, confinement, hadroniz.

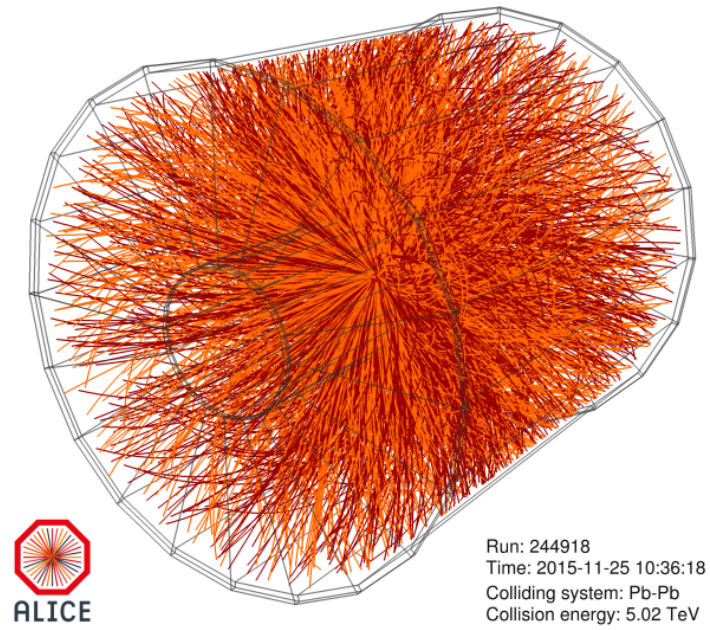
- Experimental program at the LHC:
  now and in the high-luminosity era

  HI HL-LHC: high statistics for precision measurements

- Heavy ions at the Future Circular Collider:
  physics opportunities

  quark-gluon plasma at higher energy densities → access to ultimate precision and new probes

Spares

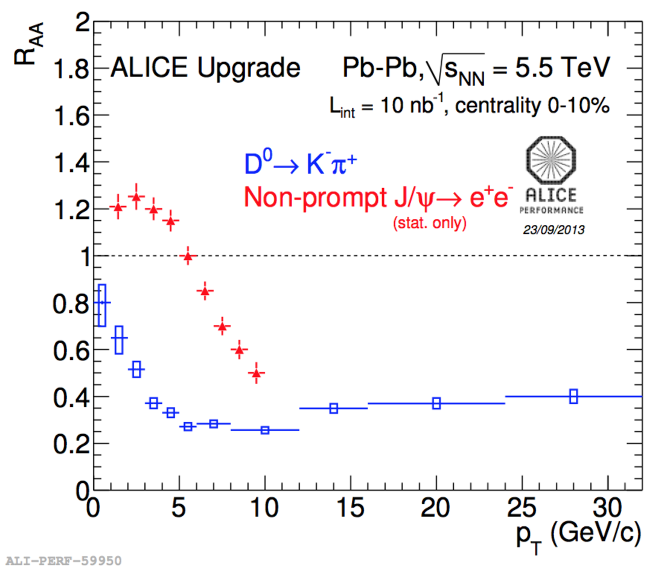

ALICE
Run: 244918
Time: 2015-11-25 10:36:18
Colliding system: Pb-Pb
Collision energy: 5.02 TeV

HI HL-LHC: heavy flavors

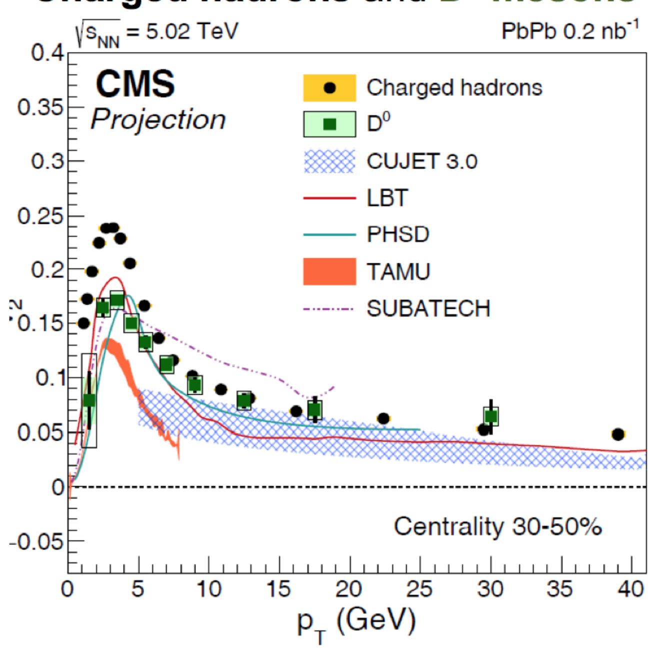
Very high statistics and improved spatial resolution:

- Precision measurements of charm and beauty hadrons
- With heavy-quark baryons, investigation of hadronization mechanism
- Access to new observables: directed flow of D^0 (early time magnetic field)

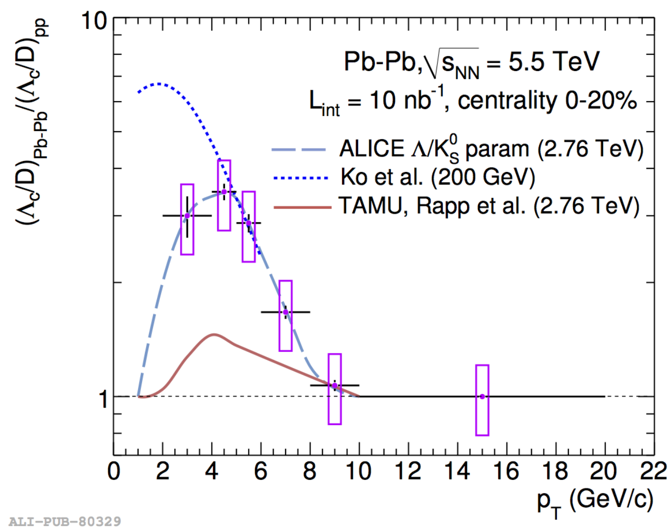
c and b hadrons: Energy loss vs parton mass



D meson elliptic flow: Charm thermalization

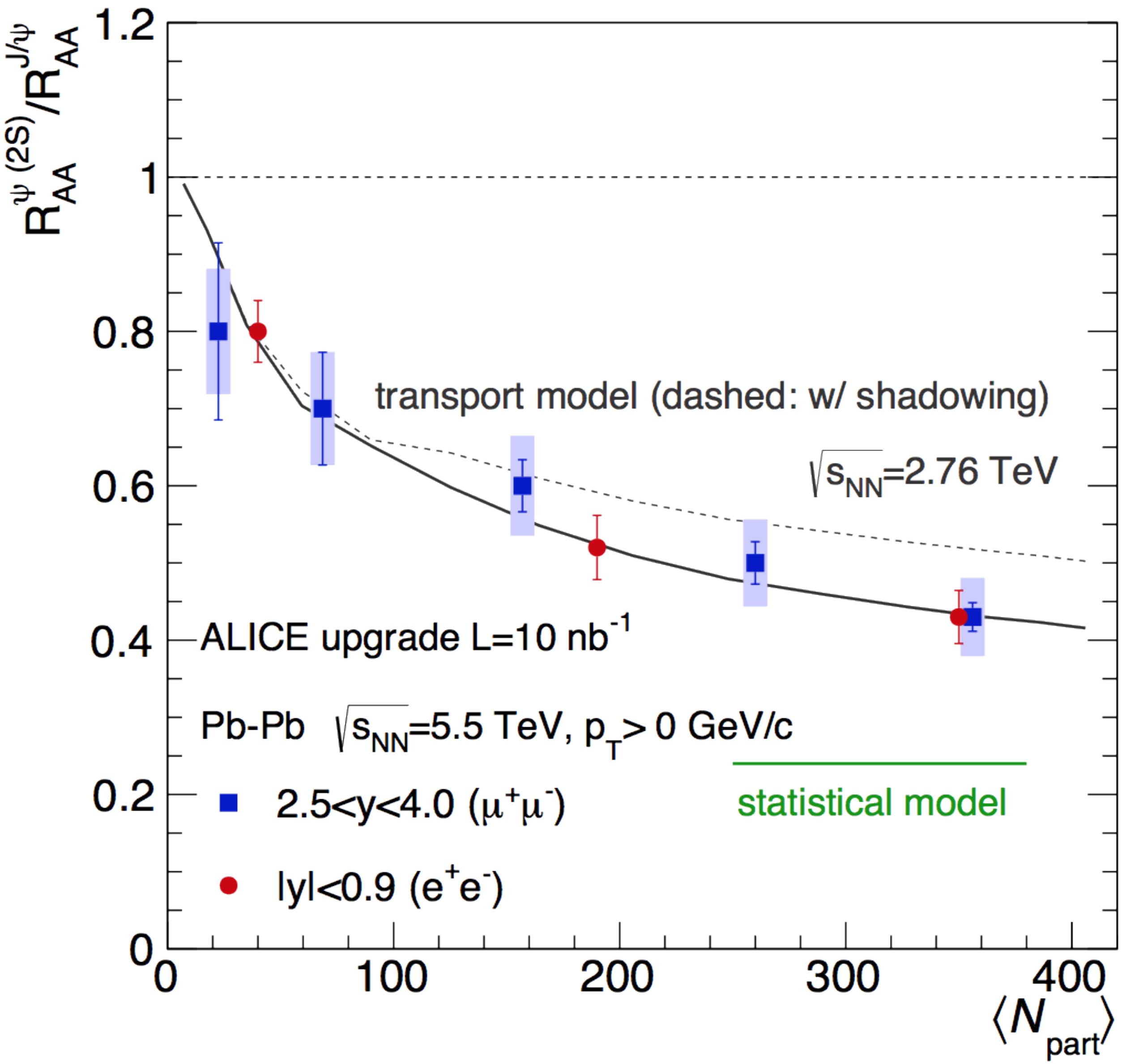


Baryon/meson ratio: hadronization via recombination in medium or fargmentation in vacuum



HI HL-LHC: heavy quarkonia production

Discrimination between different charmonium production mechanisms (models) will be possible with high statistics ψ(2S) measurements



J.Phys. G41 (2014) 087001
LHCC-I-022-ADD-1
EPJ C76 (2016) 3, 107

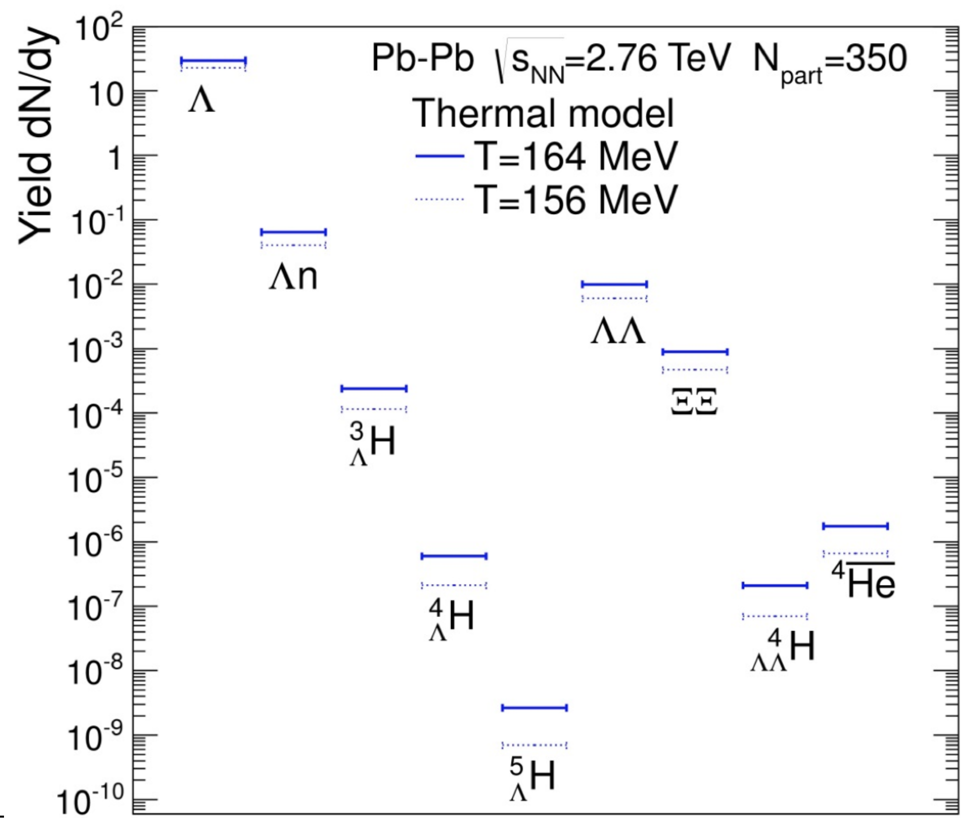
HI HL-LHC: nuclei projections

The physics we can now do for A=2 and A=3 will become possible for

A=4

State	dN/dy [82]	B.R.	$\langle \mathrm{Acc} \times \varepsilon \rangle$	Yield
${}^{3}_{\Lambda}\mathrm{H}$	1×10^{-4}	25 % [83]	11 %	44000
${}^{4}_{\Lambda}\mathrm{H}$	2×10^{-7}	50 % [83]	7 %	110
${}^{4}_{\Lambda}\mathrm{He}$	2×10^{-7}	32 % [84]	8 %	130

Continue exploration of multi-baryon states, including exotic, unknown ones



A. Andronic, priv. comm.

Heavy ions: more than 40 years

1974-1975

GSI-Marburg-Berkeley collaboration

R. Bock, R. Stock, H. Gutbrod et al.

Bevalac / Bevatron: $E_{kin}/A \sim 1$ GeV

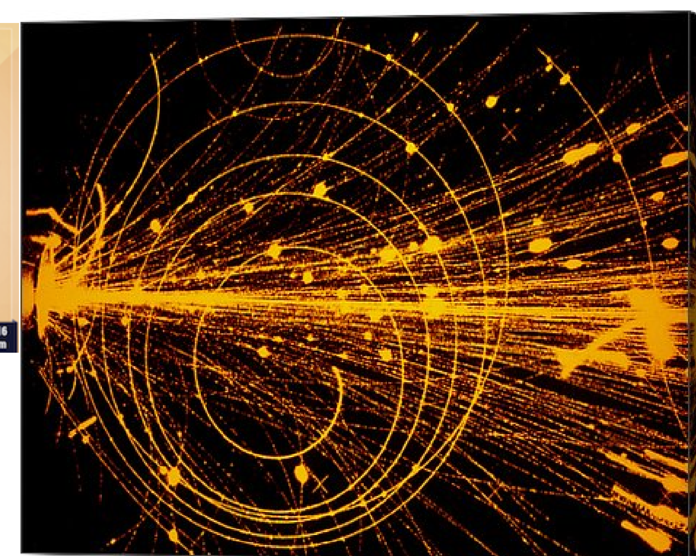
1986: AGS (BNL) and SPS (CERN)

1992: SIS (GSI)

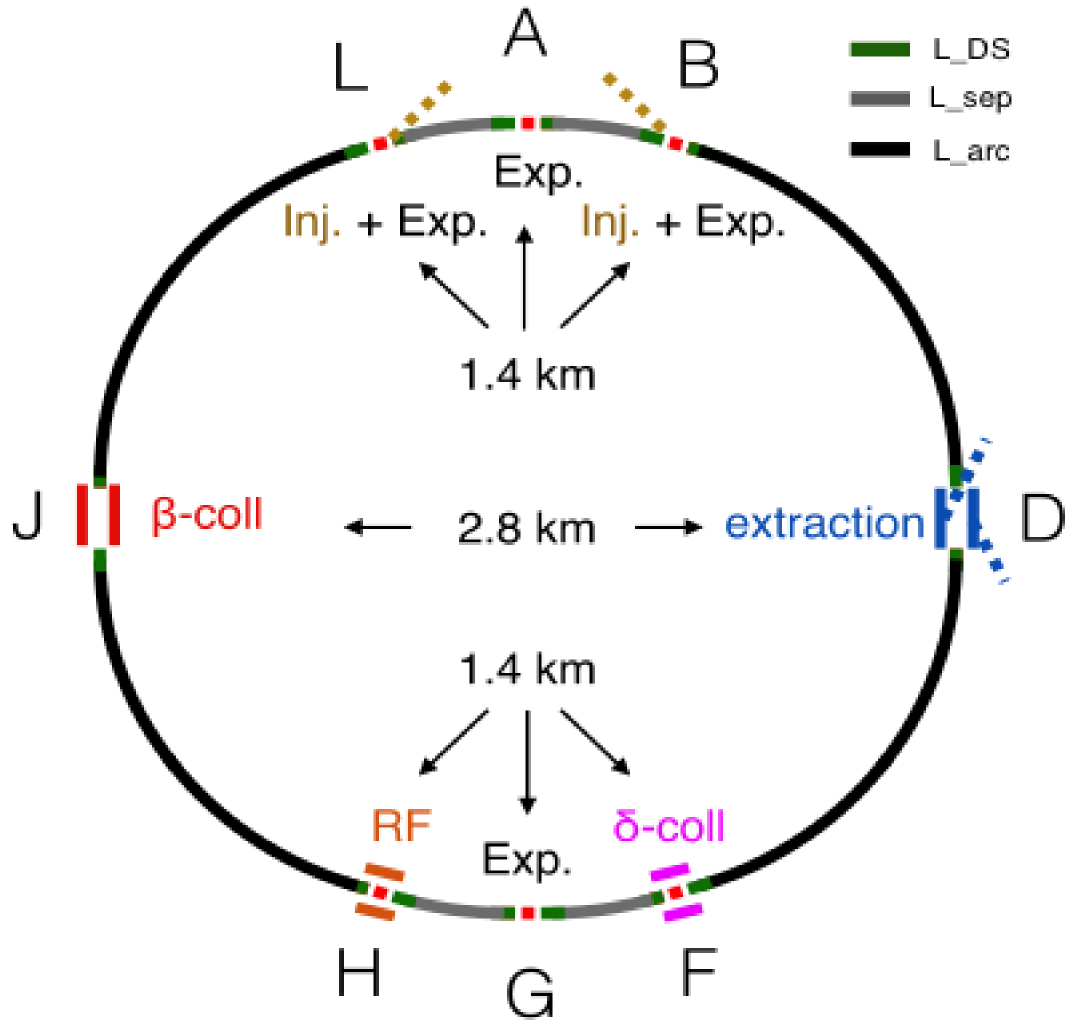
2000: RHIC (BNL)

2010: LHC (CERN)

FUTURE: FAIR, NICA (JINR) .... FCC



FCC layout

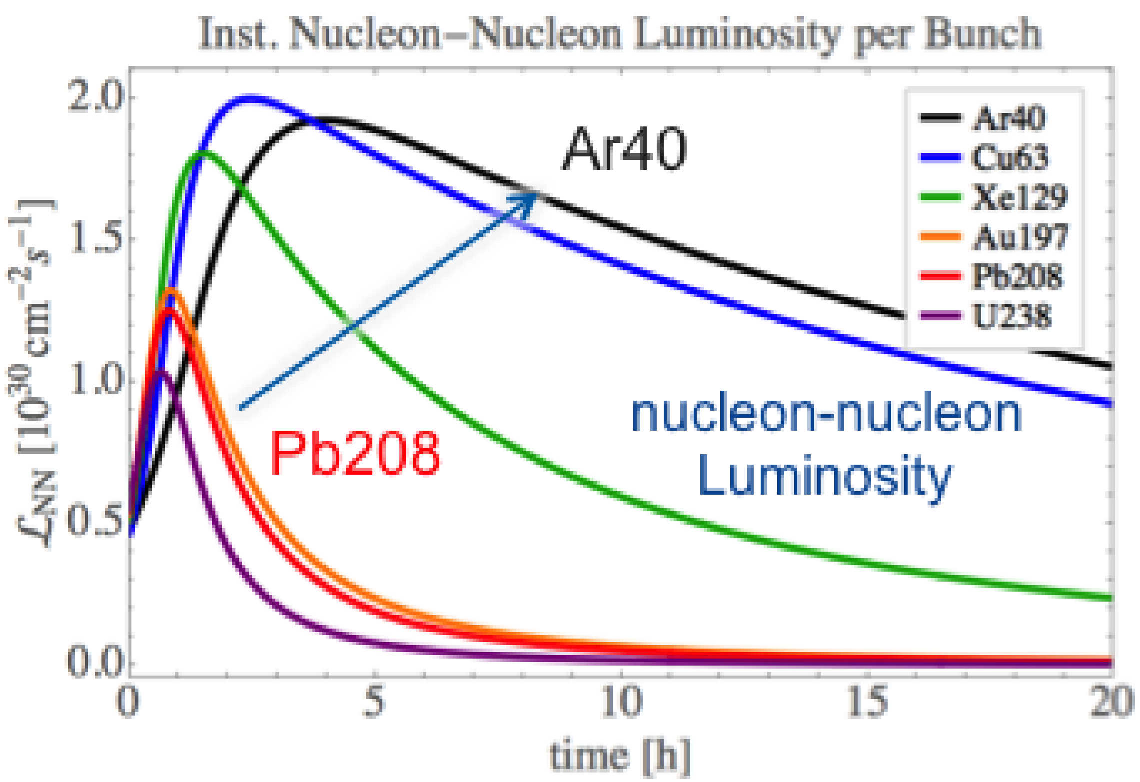


L
A
B
L_DS
L_sep
L_arc
Exp.
Inj. + Exp.
Inj. + Exp.
1.4 km
J
β-coll
2.8 km
extraction
D
1.4 km
RF
Exp.
δ-coll
H
G
F

FCC-HI: other ion species

- From injectors: possibly similar number of charges per bunch → more ions per bunch for lower Z
- Reduced contribution of ultra-peripheral electromagnetic processes:
  σ(bound-free pair production) ~ Z^7 σ(EMD) ~ Z^4

Increased luminosity lifetime:



Physics cases will be studied