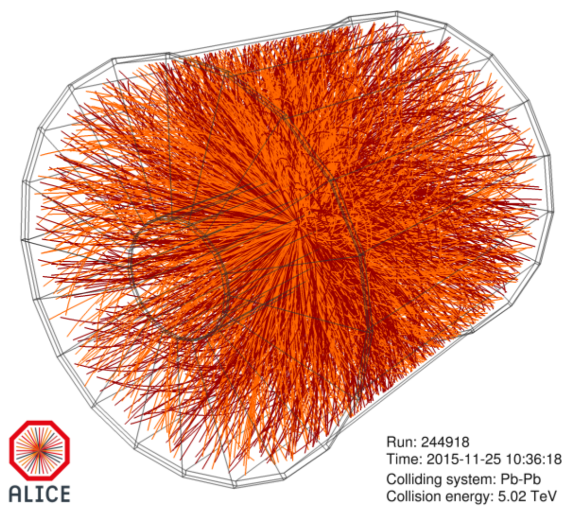
Physics at the LHC

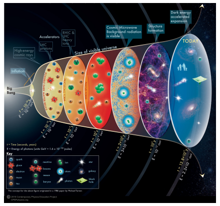
Hot QCD matter produced in ultra-relativistic heavy-ion collisions

Lecture 4
January 22, 2020

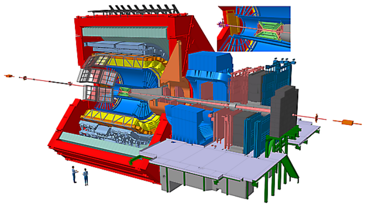


Silvia Masciocchi
GSI Darmstadt and Heidelberg University

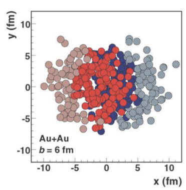
Outline



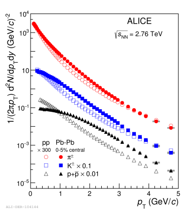
Heavy-ion collisions: Little Bangs



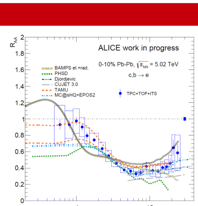
Experimental program at the LHC, ALICE



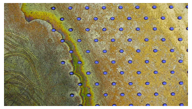
Global characteristics



Bulk particle production



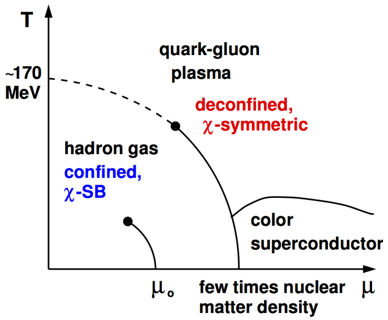
Quark-gluon plasma tomography with hard probes



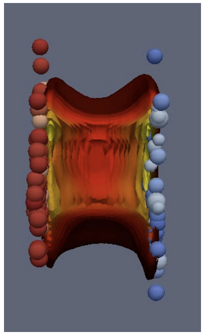
Research plans for near and further future

Outline

- Historical view: experimental opportunities, first theoretical ideas
- Thermodynamics of strongly interacting matter and phase diagram
- QCD matter under extreme conditions in nature and in the lab
- Global characteristics: centrality, energy density, multiplicities



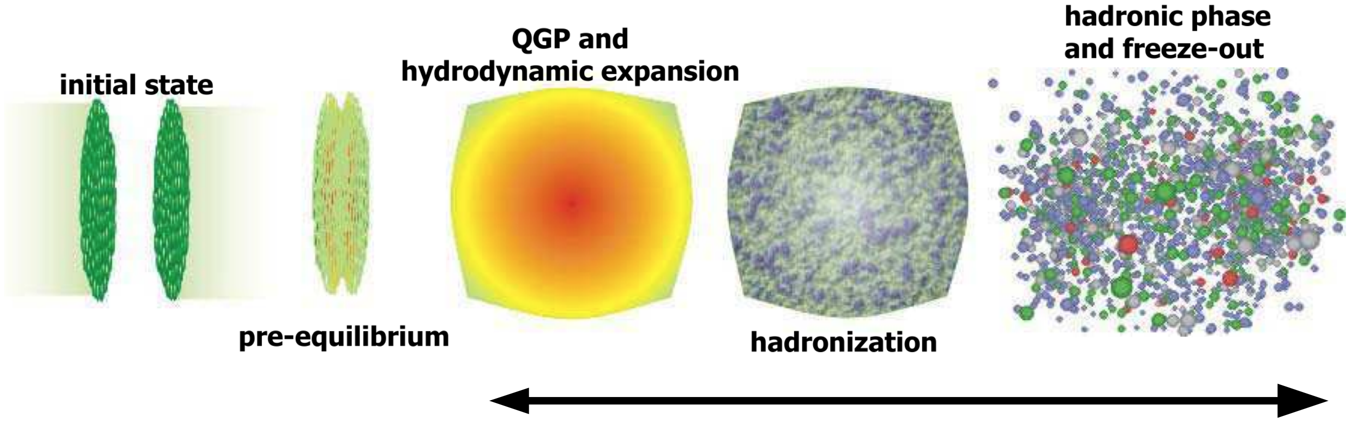
- Bulk (soft) particle production
  - Thermal model, particle yields and chemical freeze-out
  - Hydrodynamics, flow and correlations
  - Small systems



TODAY

- Hard probes: jets, heavy quarks and quarkonia
  - Tomography of the medium, parton energy loss
  - Nuclear modification factor R_{AA}
  - Open heavy flavors, J/ψ
- Future, near and far

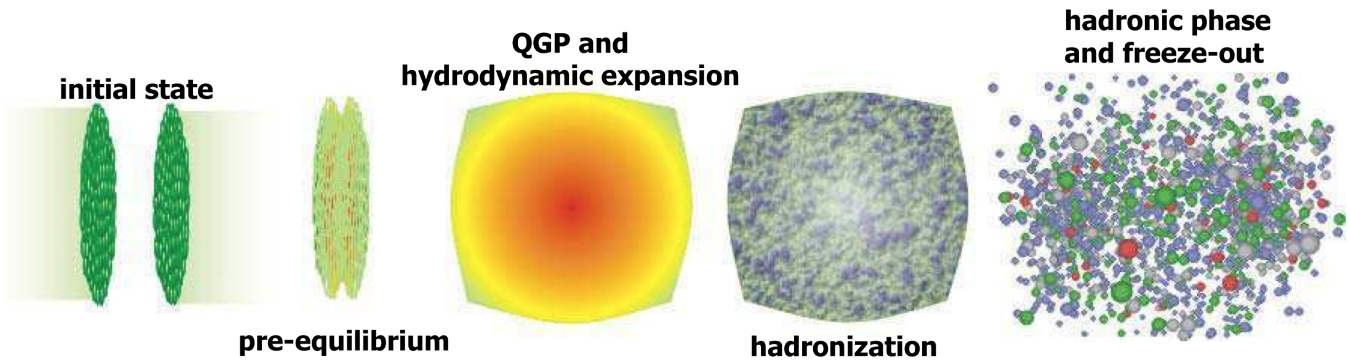
Bulk particle production



Particles emerging from the medium

Low momenta (0 to ~3 GeV/c)

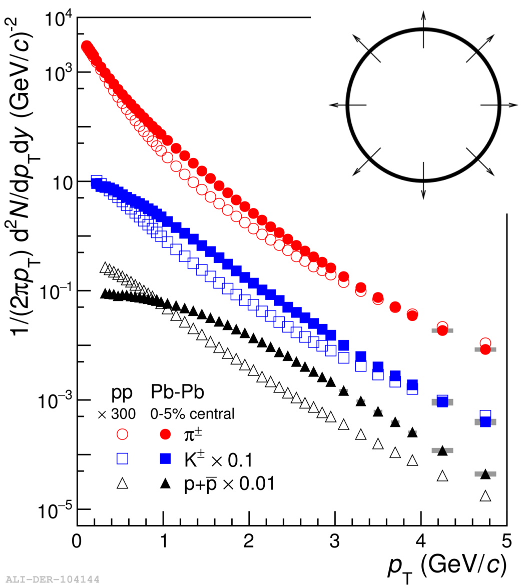
Bulk particle production



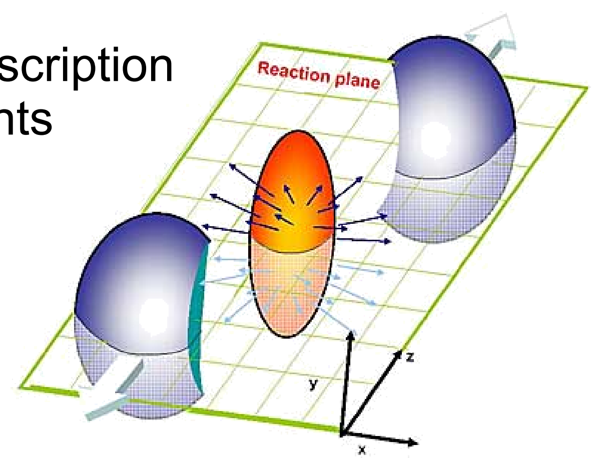
Particles emerging from the medium

Low momenta (0 to ~3 GeV/c)

Spectra (radial flow)



Hydrodynamic description
and flow coefficients

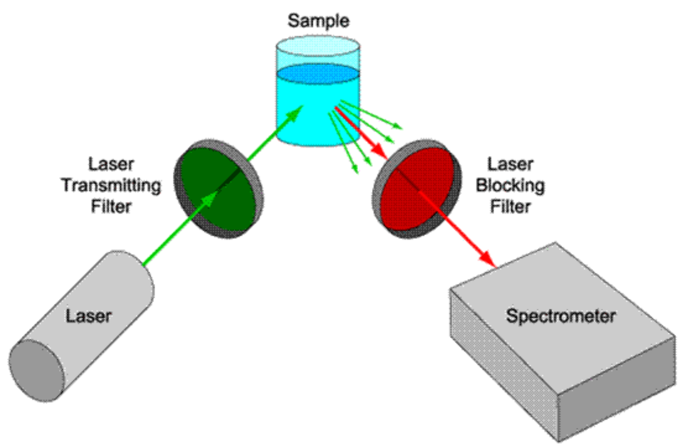


External probes?

Study internal structure and properties via penetrating probes

X-rays

Laser



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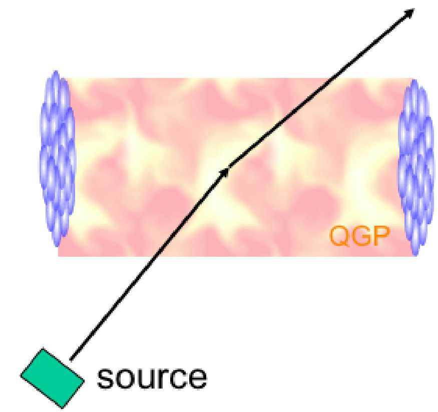
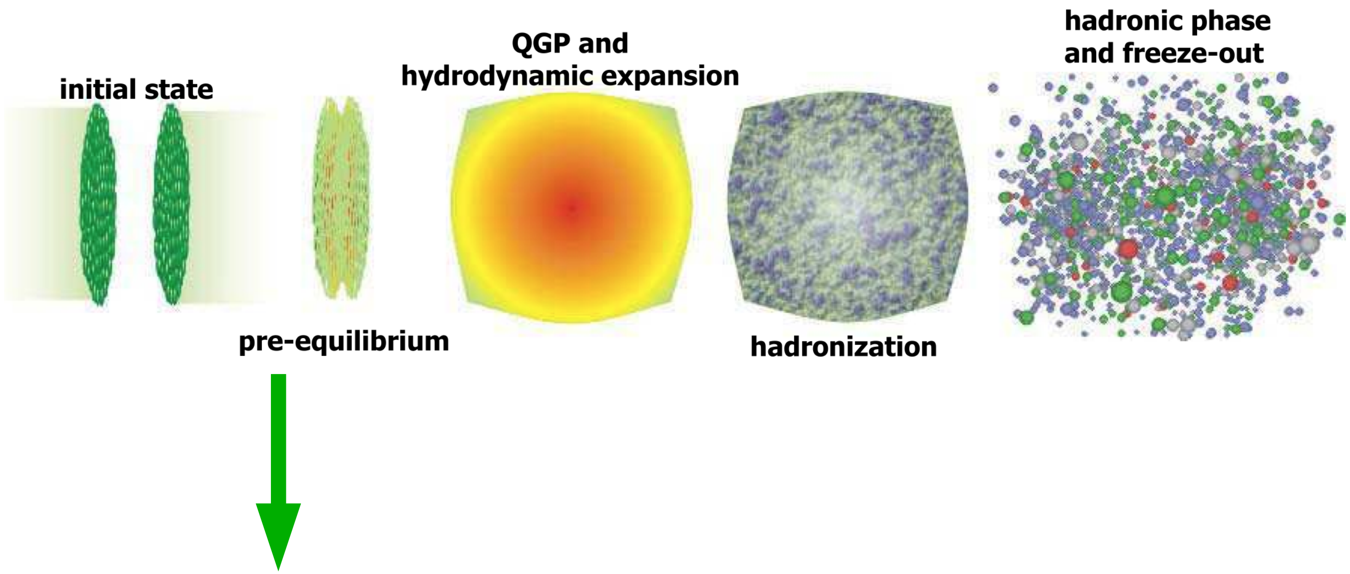


Courtesy of Yen-Jie Lee

The lifetime of the QGP (10^{-22} s) is too short to use an external source

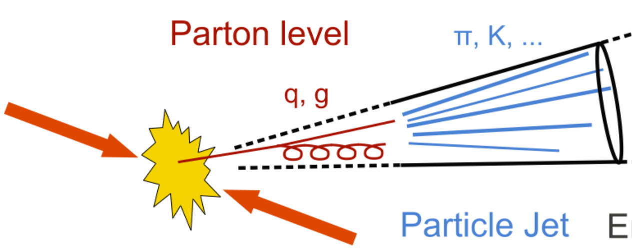
→ Use auto-generated (hard) probes !

External (hard) probes



HERE !
Hard parton scatterings → LARGE Q^2

- Partons with very large momentum → jets
- Heavy quarks, charm and beauty

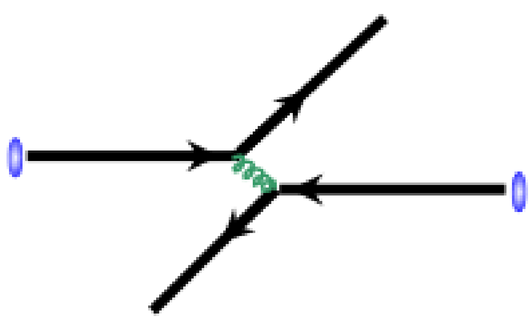


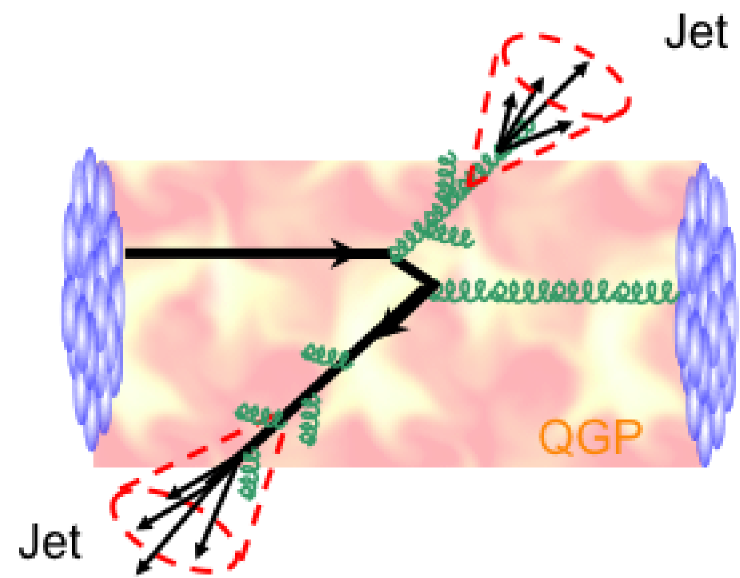
Hard probes: medium tomography

Hard scattering processes (large Q^2) in the **early** stages of the collisions

- Jets
    - Leading hadron
- Heavy quarks

Vacuum QCD	→	Parton interactions with quark-gluon plasma
Proton-proton collisions		Energy loss in medium, in Pb-Pb collisions

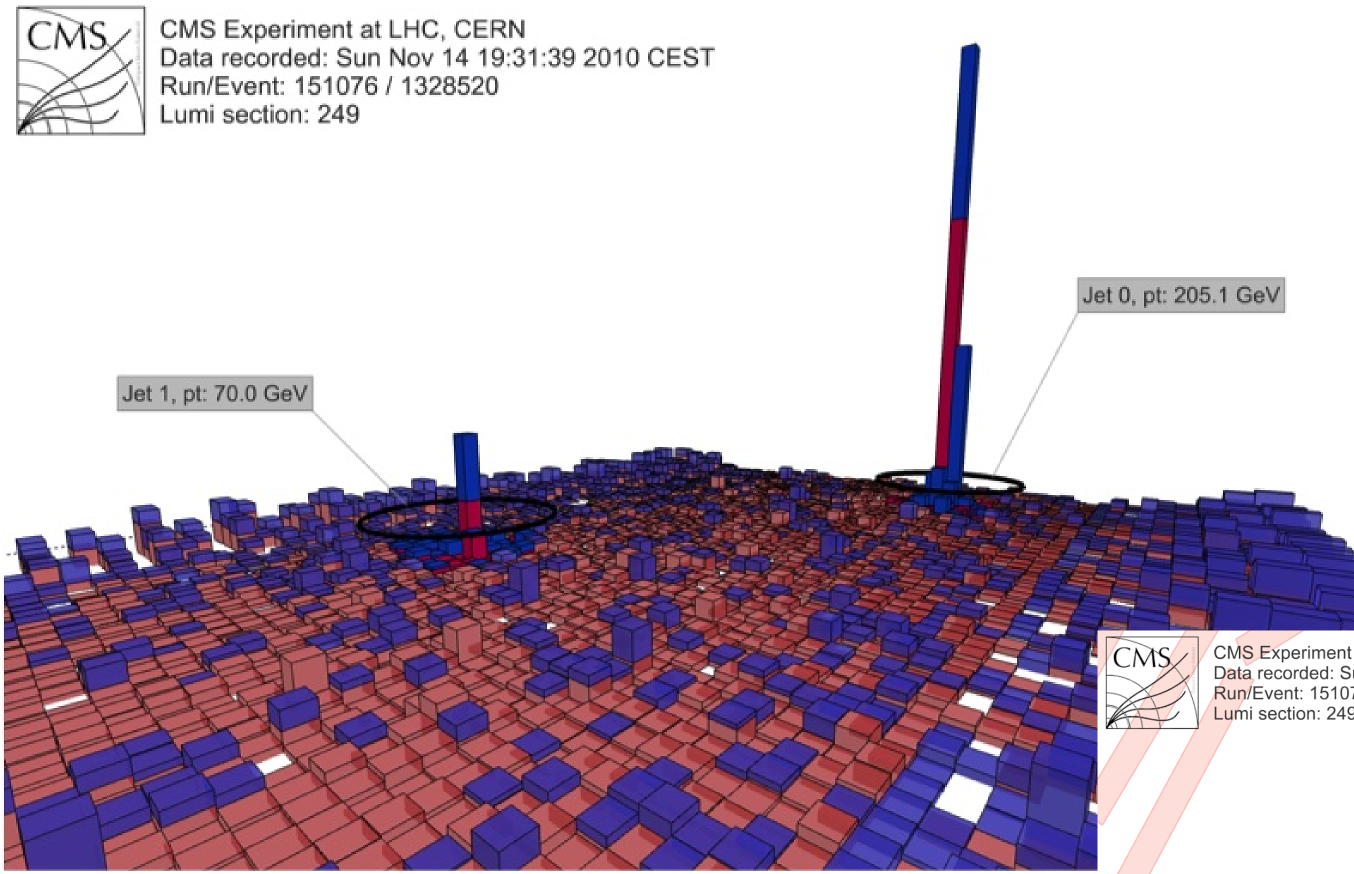


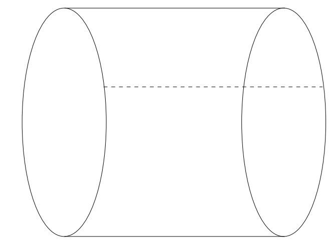


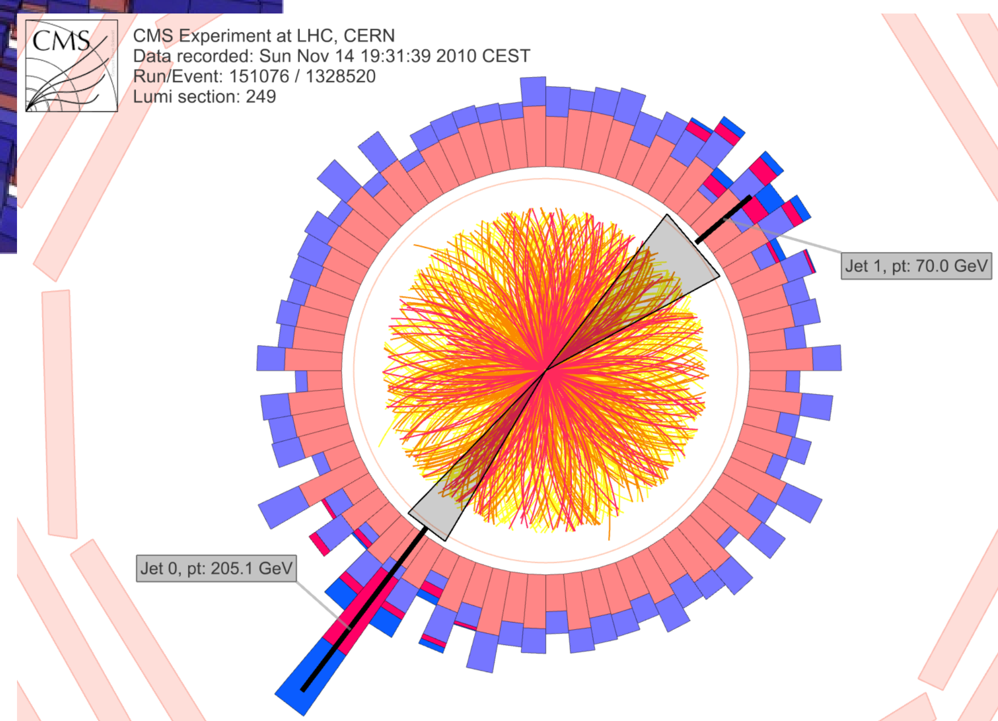
Courtesy of Yen-Jie Lee

Jet quenching

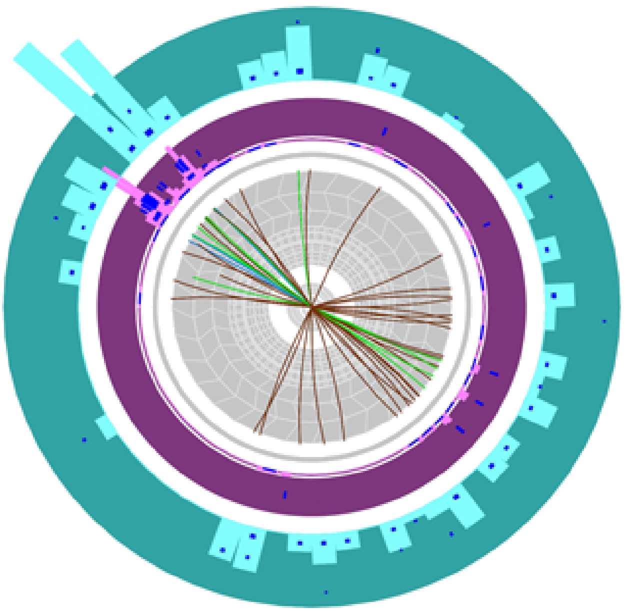
Hard probes: jet quenching

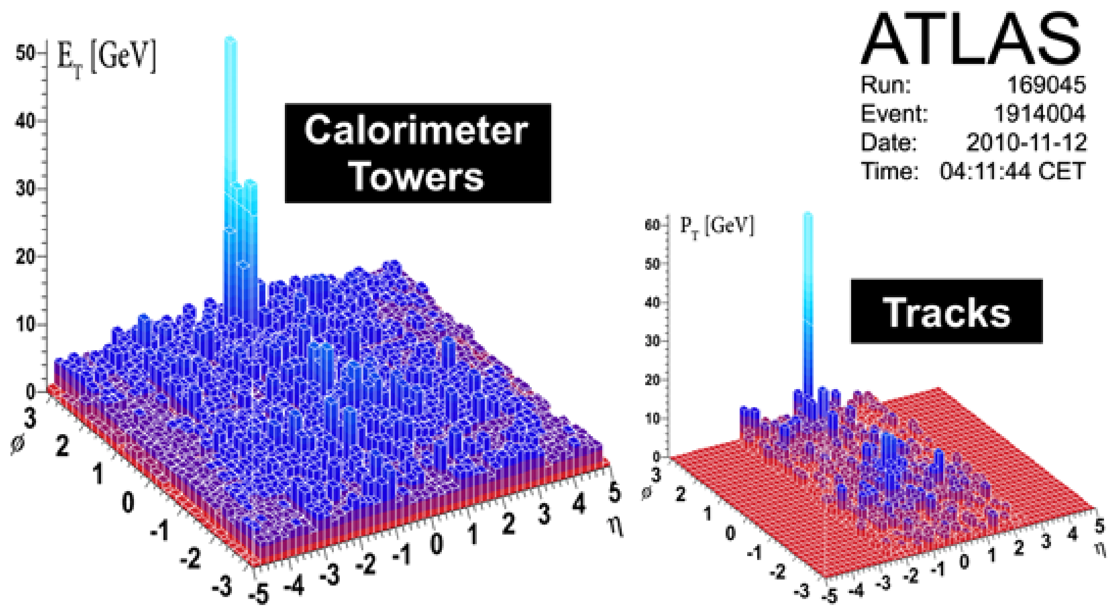




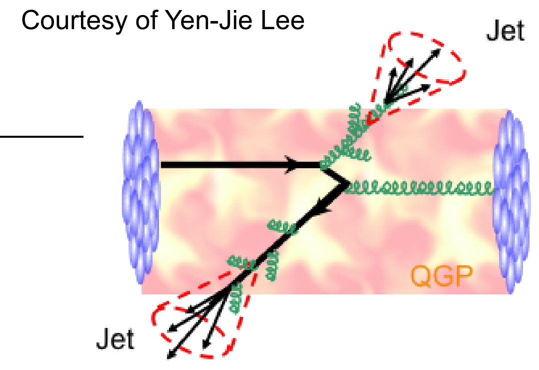


Hard probes: jet quenching





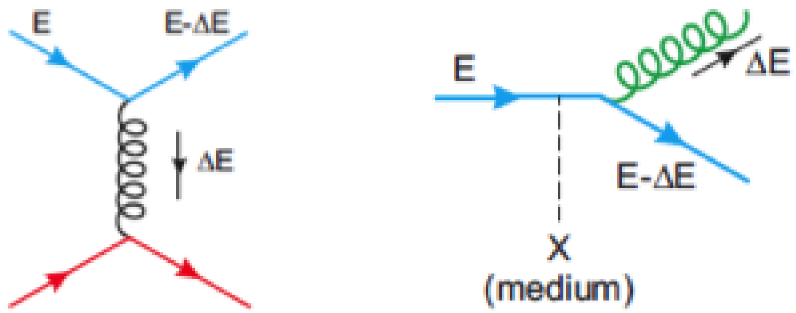
In-medium parton energy loss



Energy loss by:

- Collisions with medium constituents
- Medium-induced gluon radiation

Collisional and radiative energy loss



Depends on:

Colour charge $\Delta E_{gluon} > \Delta E_q \rightarrow$

Parton mass $\Delta E_c > \Delta E_b \rightarrow$

Compare:

heavy to light hadrons

charm and beauty

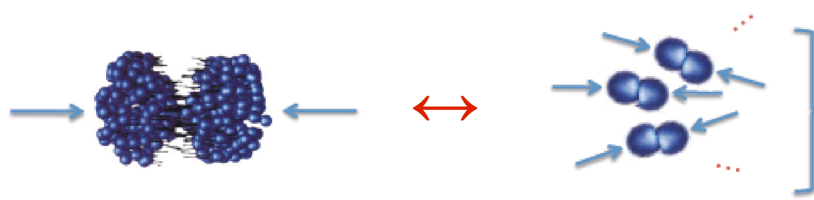
In-medium parton energy loss

Quantifier: the **nuclear modification factor**

as function of p_T, rapidity and centrality

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

Without nuclear effects and interactions with the QCD medium, a heavy-ion collision would be the superposition of independent nucleon-nucleon collisions:



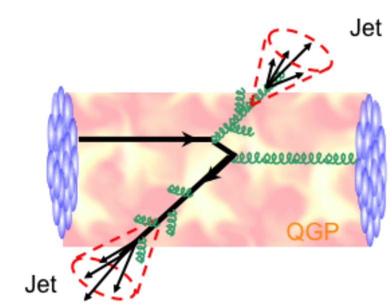
$\mathbf{N_{coll}}$

binary collisions (Glauber)

No medium effect $\rightarrow$ $R_{AA} = 1$

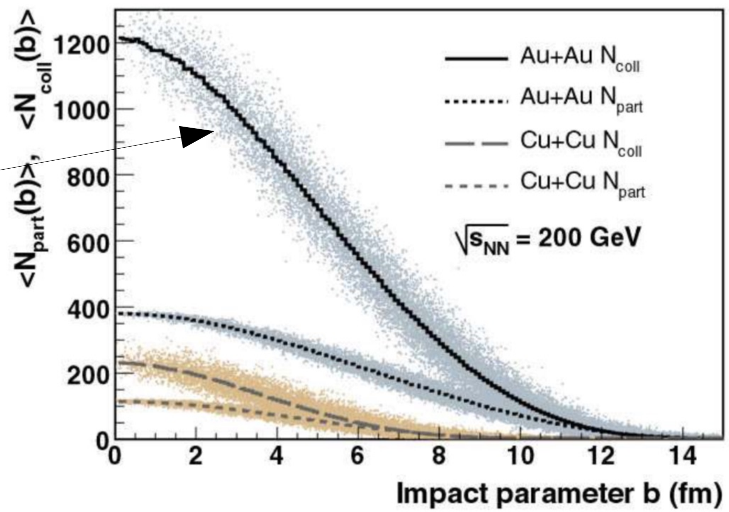
Medium effect $\rightarrow$ medium "slows" down particles

$\rightarrow$ $R_{AA} \neq 1$



Number of binary collisions

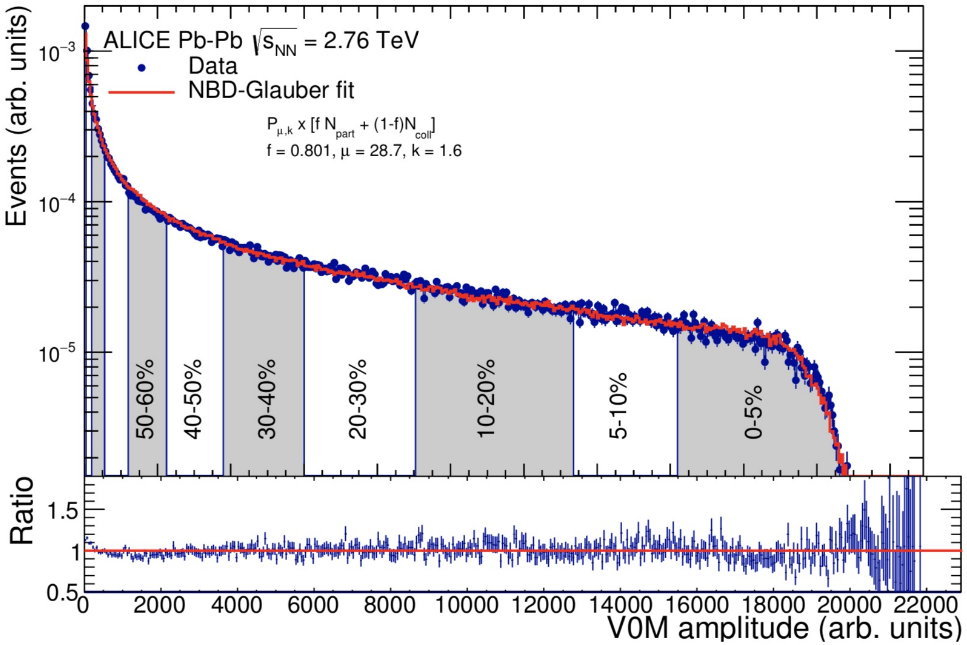
- Number of nucleon-nucleon collisions
- Computed with MC Glauber

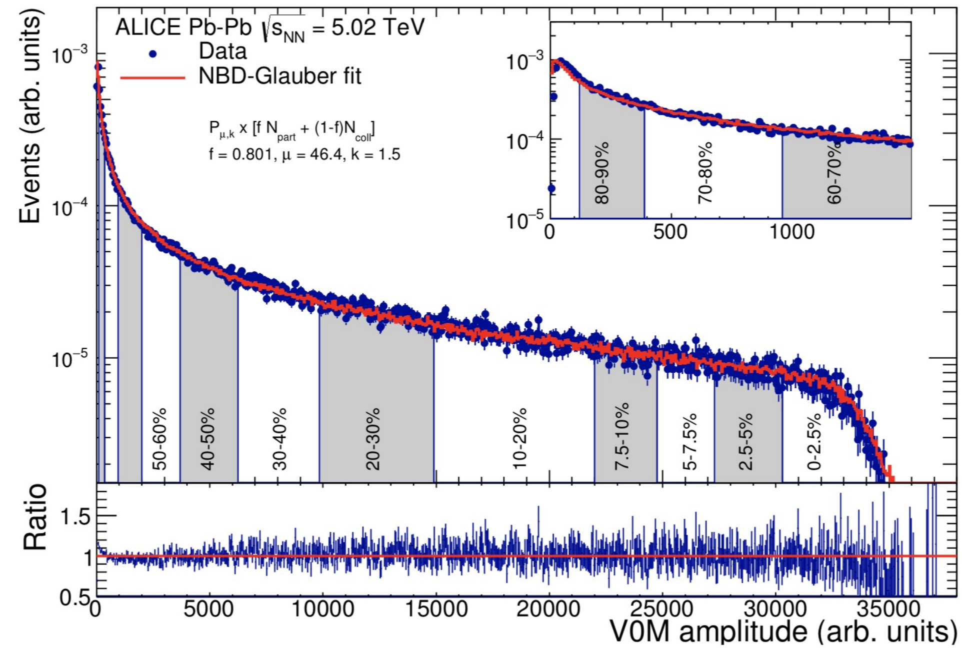


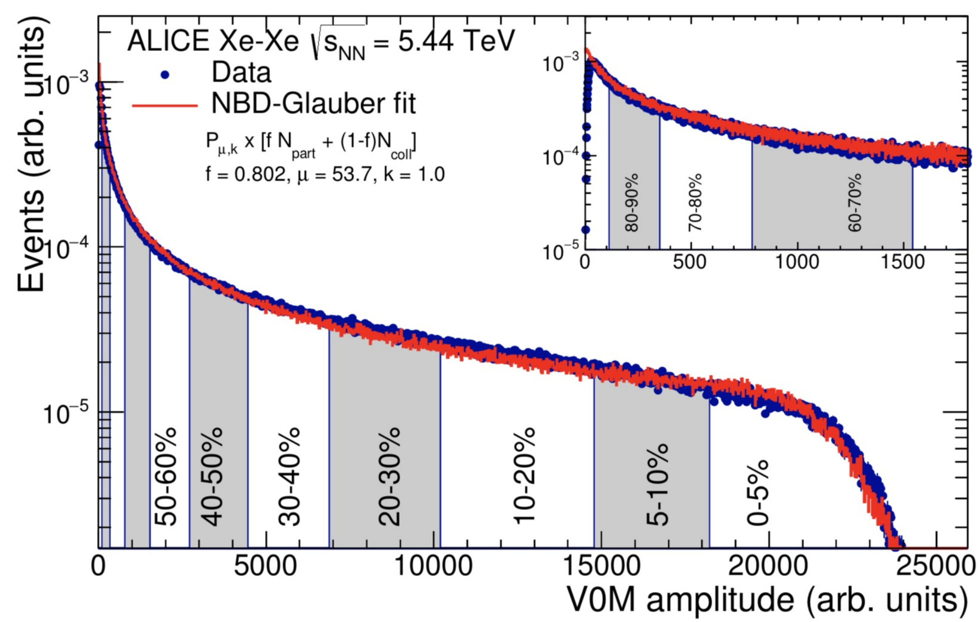
arXiv:nucl-ex/0701025

- Soft processes (soft particle production) scale with the number of participants
- In contrast, a scaling with the number of binary collisions is expected for hard processes

Centrality: ALICE







cds.cern.ch/record/2636623?ln=en

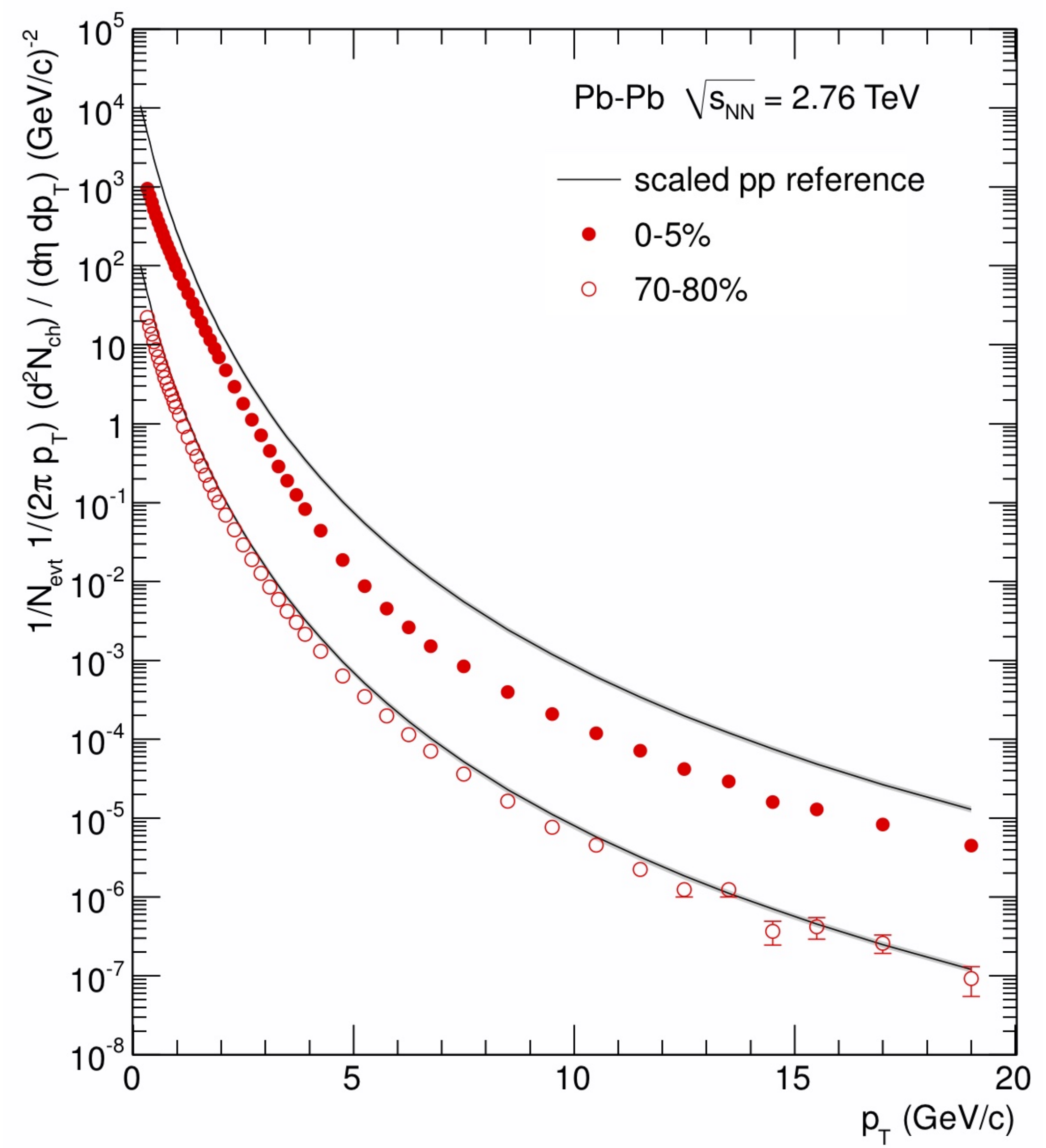
Nuclear modification factor

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

Charged-particles:
Parton energy loss in the medium

- Slowing down of the emerging hadrons, which appear with lower p_T
- Modification of the shape of the spectrum

- Effect stronger in central collisions, weaker and weaker with decreasing centrality



PLB 696 (2011) 30-39

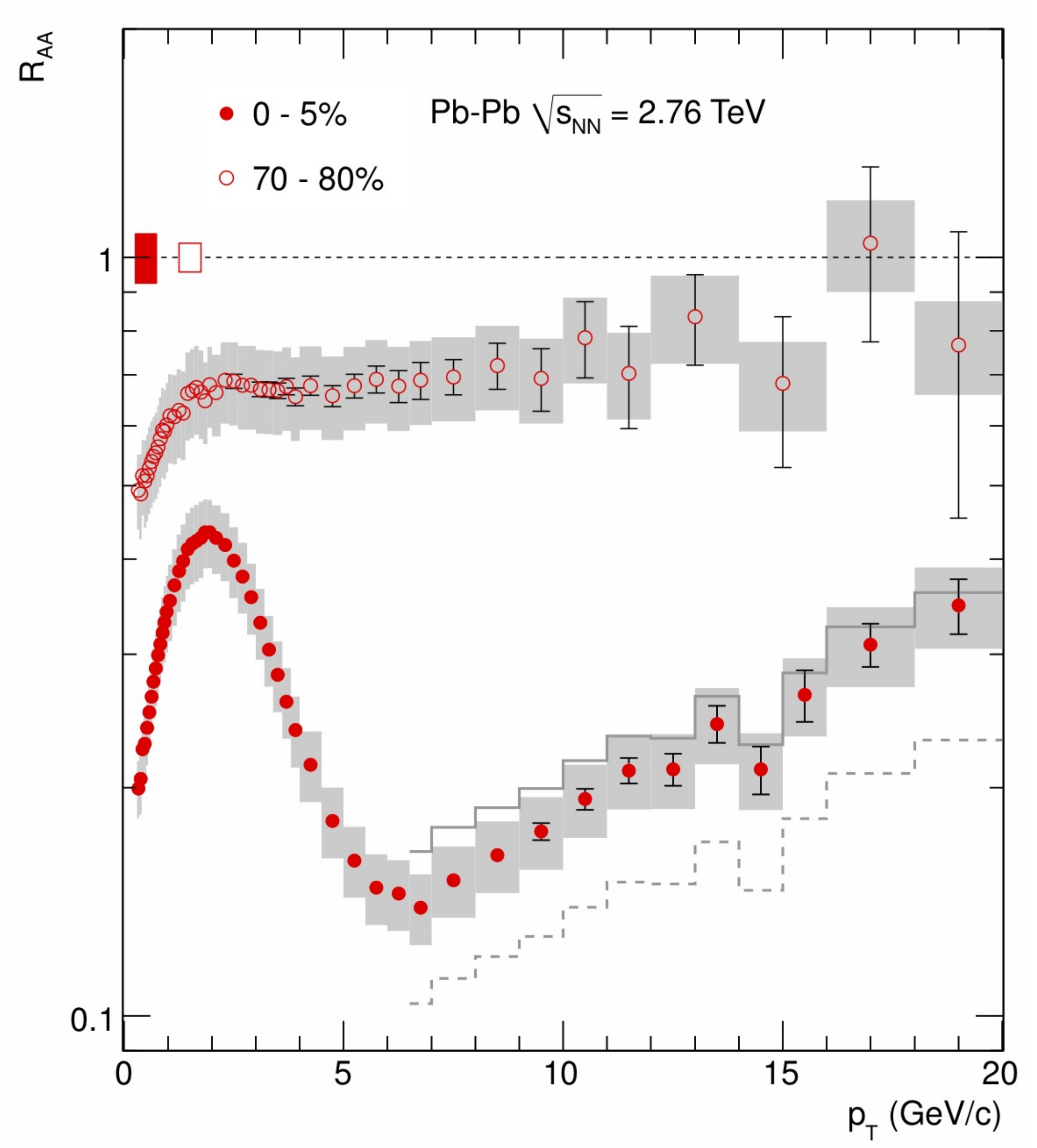
Nuclear modification factor

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

Charged-particles:

- Very strong suppression in the most central collisions ...
- ... strongly reduced in peripheral collisions

- Low transverse momentum region dominated by soft particle production: different particle composition in Pb-Pb vs pp, radial flow, shadowing



PLB 696 (2011) 30-39

Nuclear modification factor

No medium effect → $R_{AA} \approx 1$

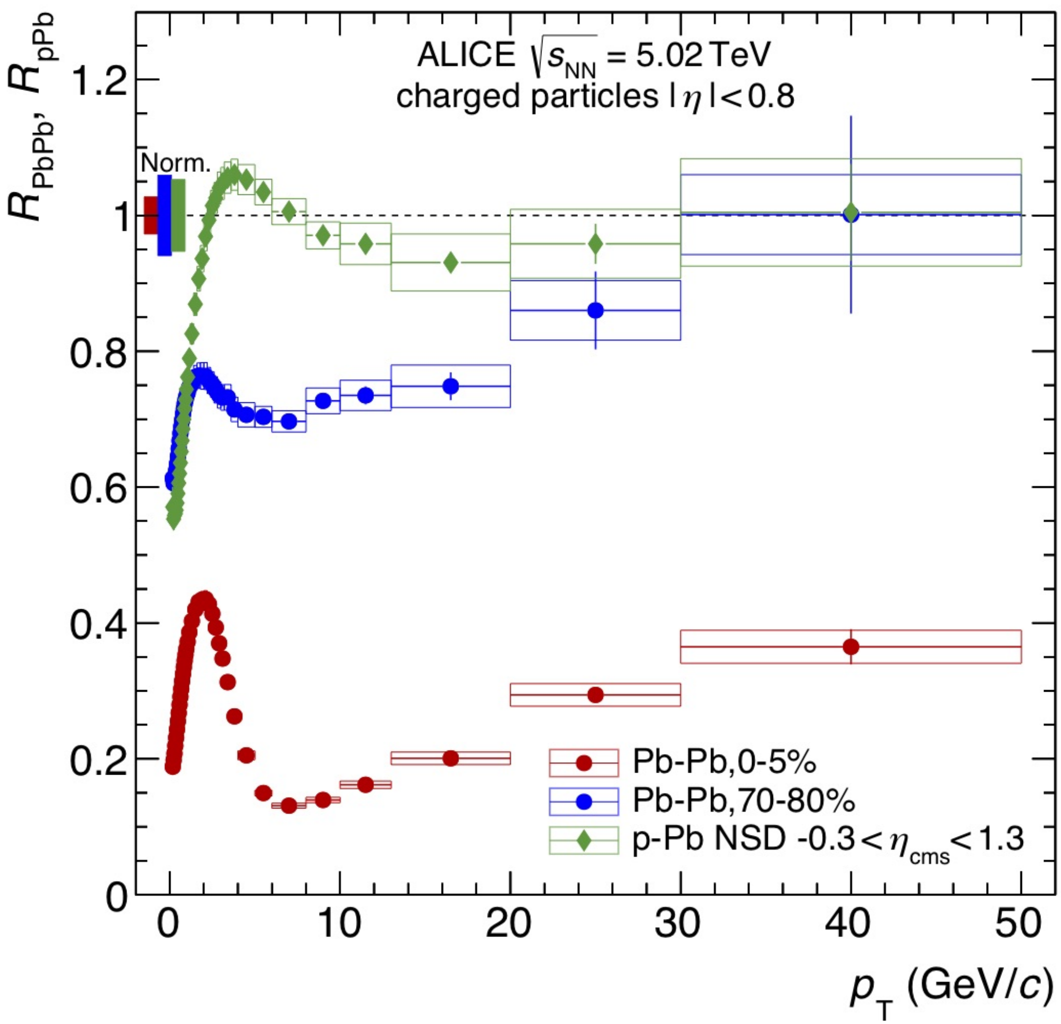
Medium effect → medium "slows" down particles

→ $R_{AA} \neq 1$

Pb-Pb 5.02 TeV data and
p-Pb 5.02 TeV !!

Low p_T: shadowing, particle composition, radial flow, ...

High p_T: suppression in Pb-Pb clearly a final state effect



arXiv:1802.09145

Nuclear modification factor

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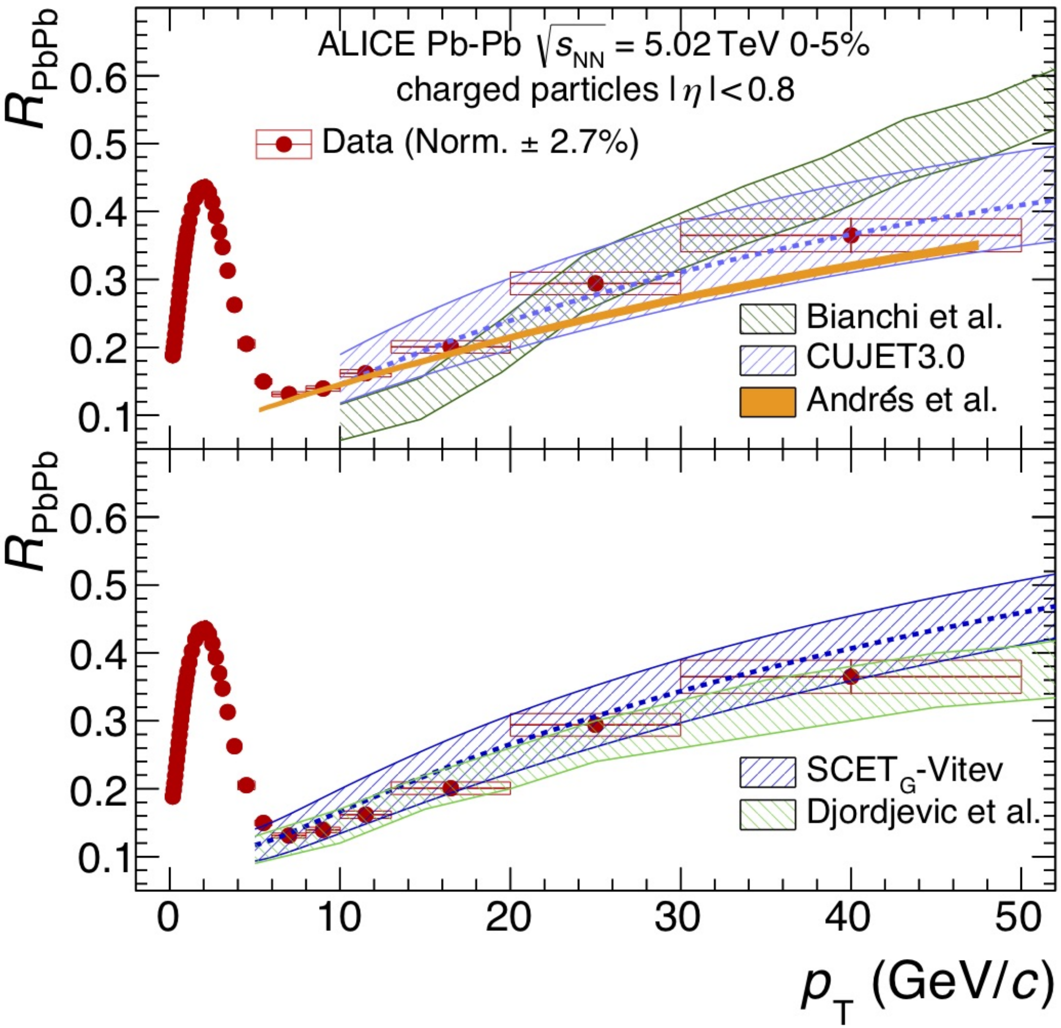
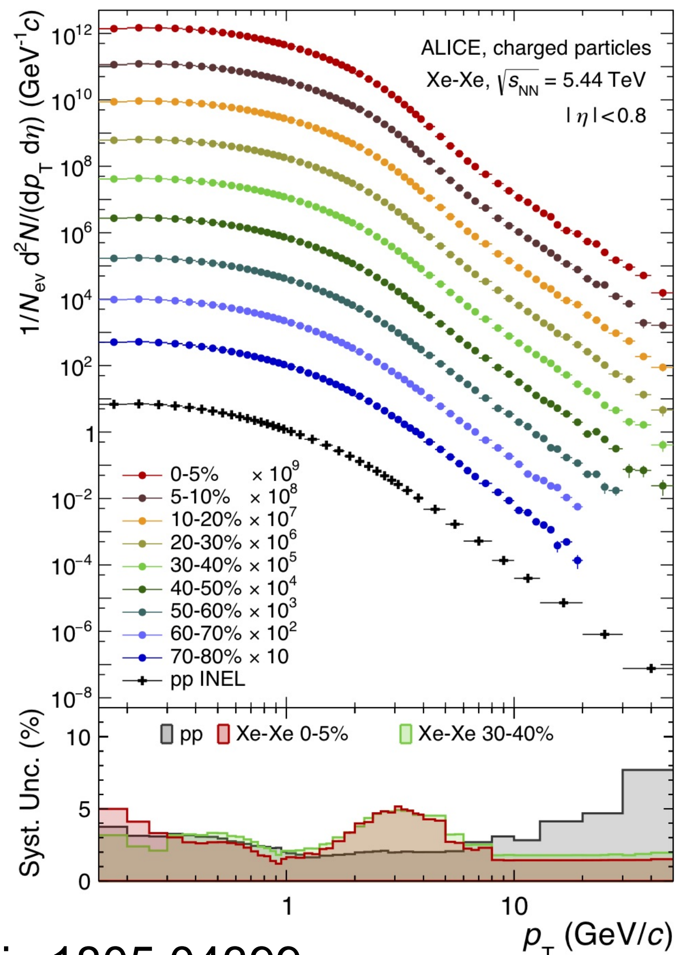
Comparison to theoretical calculations modeling parton energy loss in the medium



arXiv:1802.09145

Nuclear modification factor: Pb-Pb vs Xe-Xe

	Xenon	Lead
Very short run in 2018:	A=129	A=208
Half density radii for the nuclear charge distribution	5.36 fm	6.62 fm
	deformed	spherical



arXiv:1805.04399

Nuclear modification factor: Pb-Pb vs Xe-Xe

	Xenon A=129	Lead A=208
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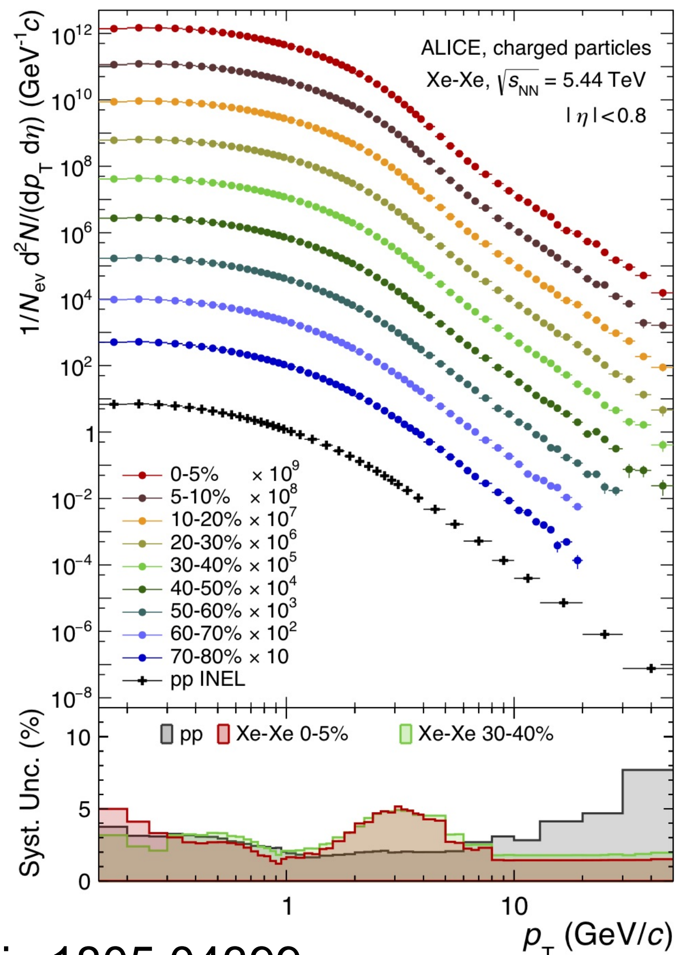
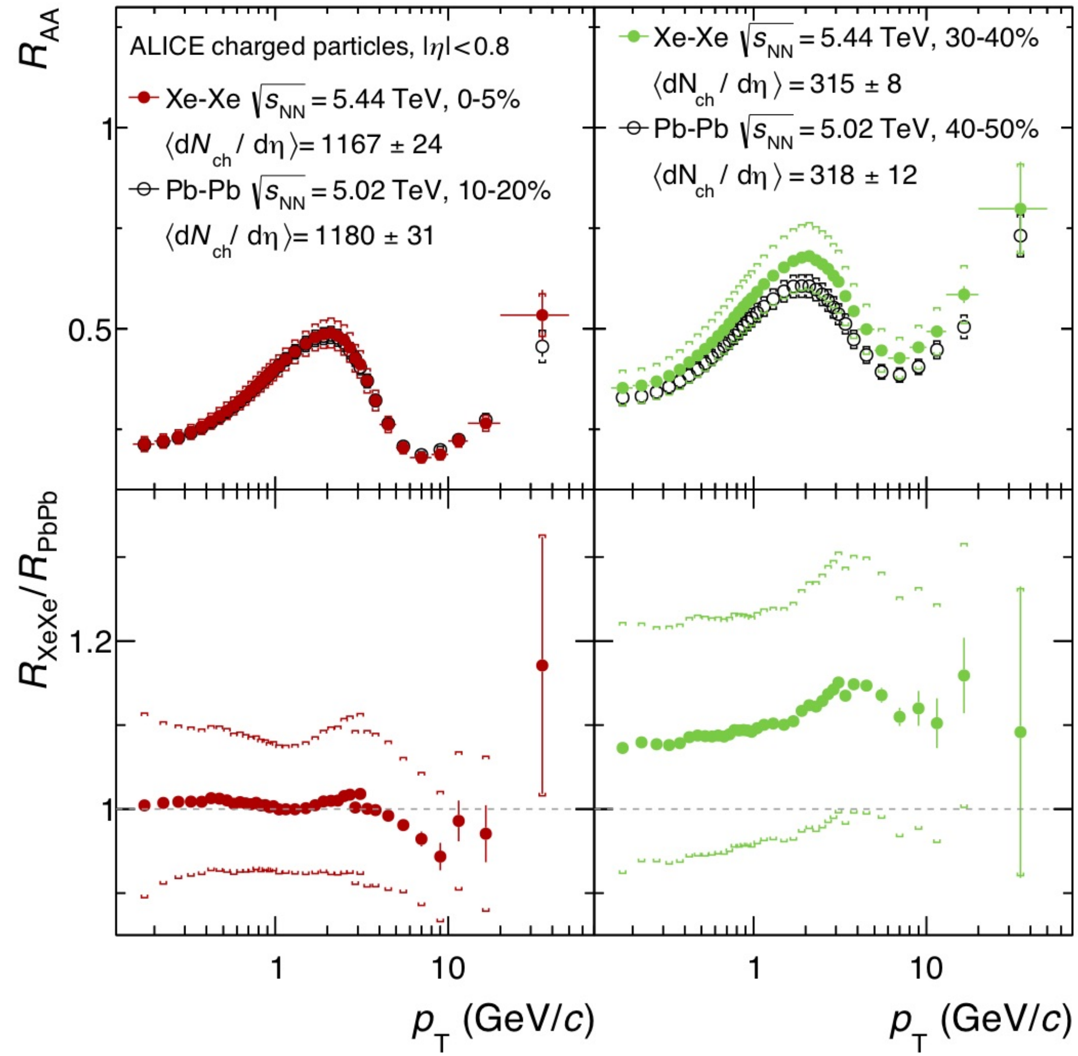
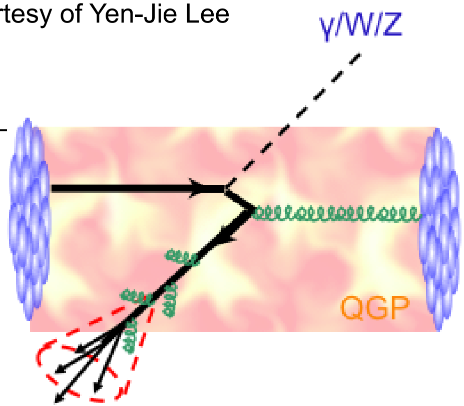




arXiv:1805.04399

Nuclear modification factor

Courtesy of Yen-Jie Lee



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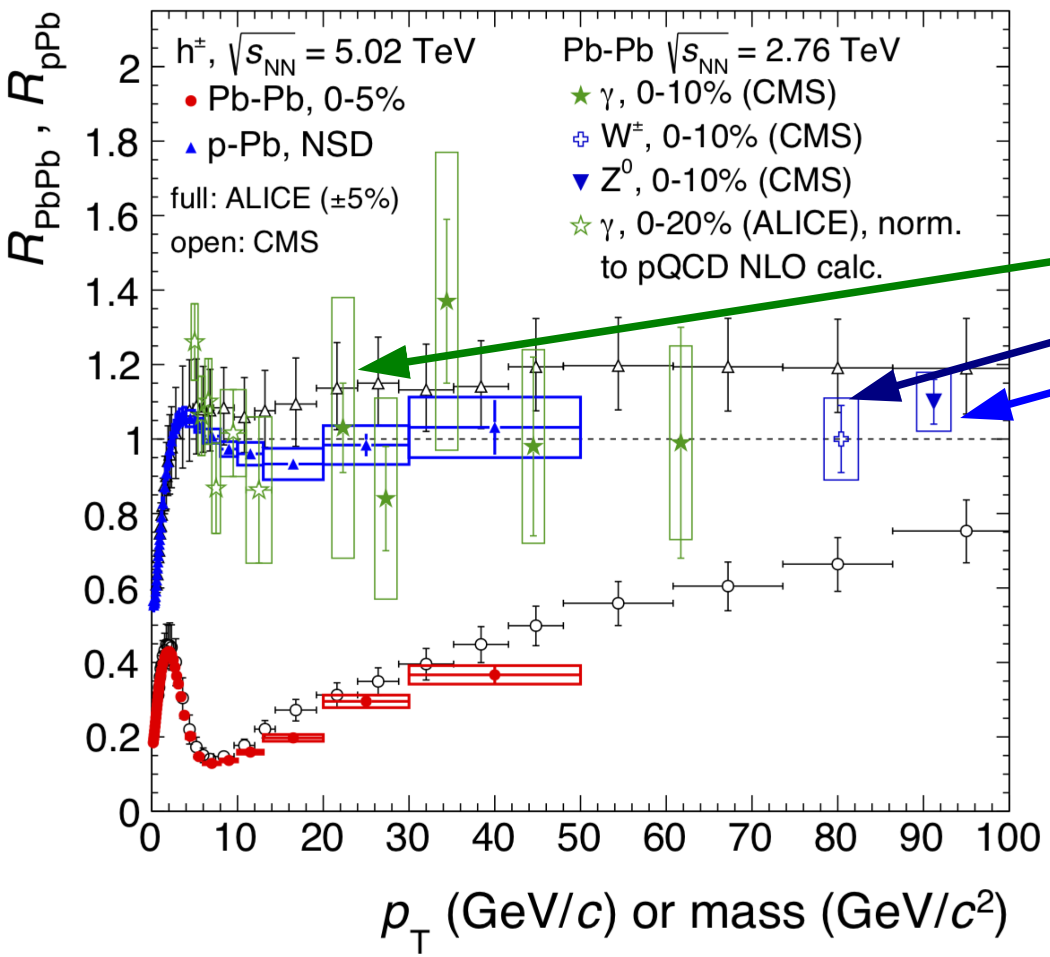


- No modification for EW bosons: γ $W^{\pm}$ Z^0
- Strong suppression for charged hadrons, still significant at 100 GeV/c !
- Look at charm and beauty

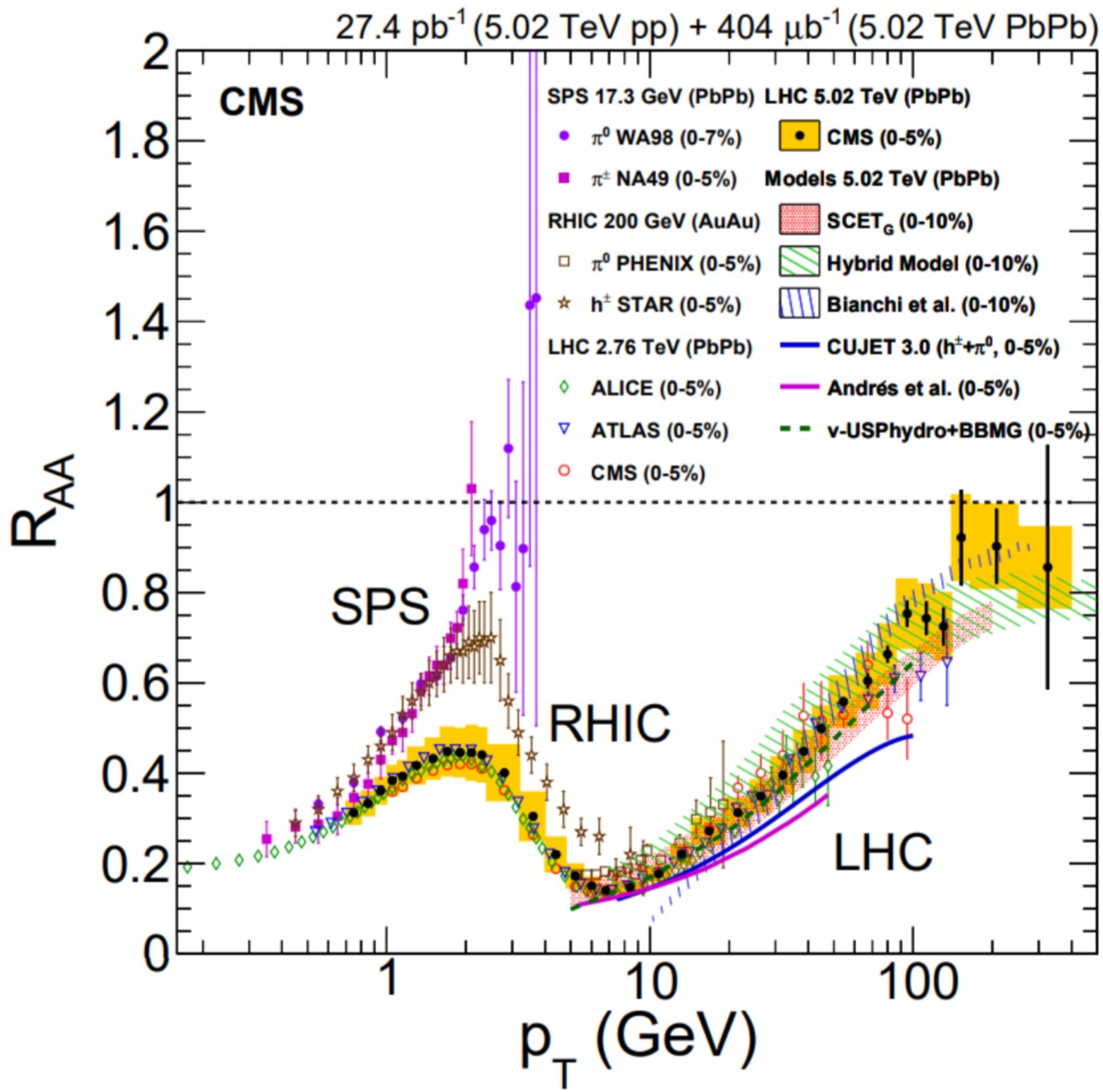
Anton Andronic

Parton energy loss: theory models

Extensive theoretical work to describe the parton propagation and energy loss in dense, strongly interacting matter

Variety of models with

- Weak (pQCD) or strong coupling to the medium
- Full jet MC simulation or coupling analytical solution to hydro computations
- Recoil medium or not
- ...



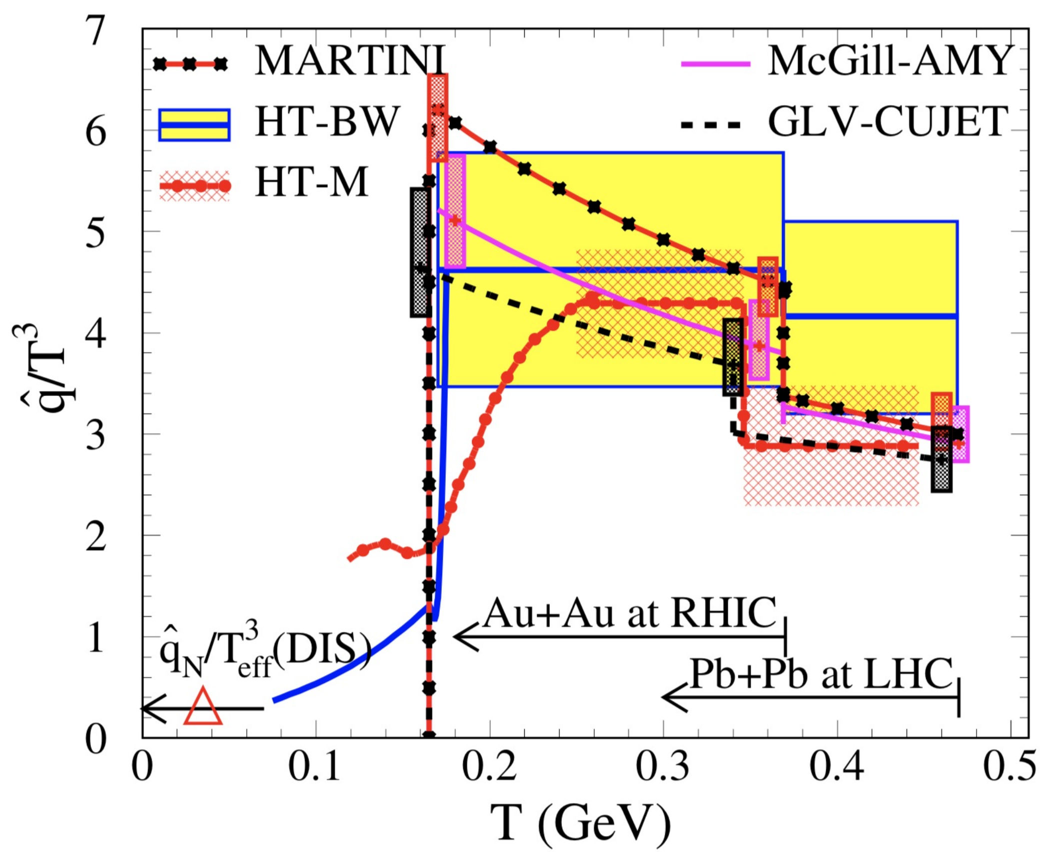
Parton energy loss: the Jet Collaboration

Compilation of experimental results
and 5 different theoretical descriptions

$\hat{q}$: jet transport parameter

mean-squared transverse momentum broadening per unit path length

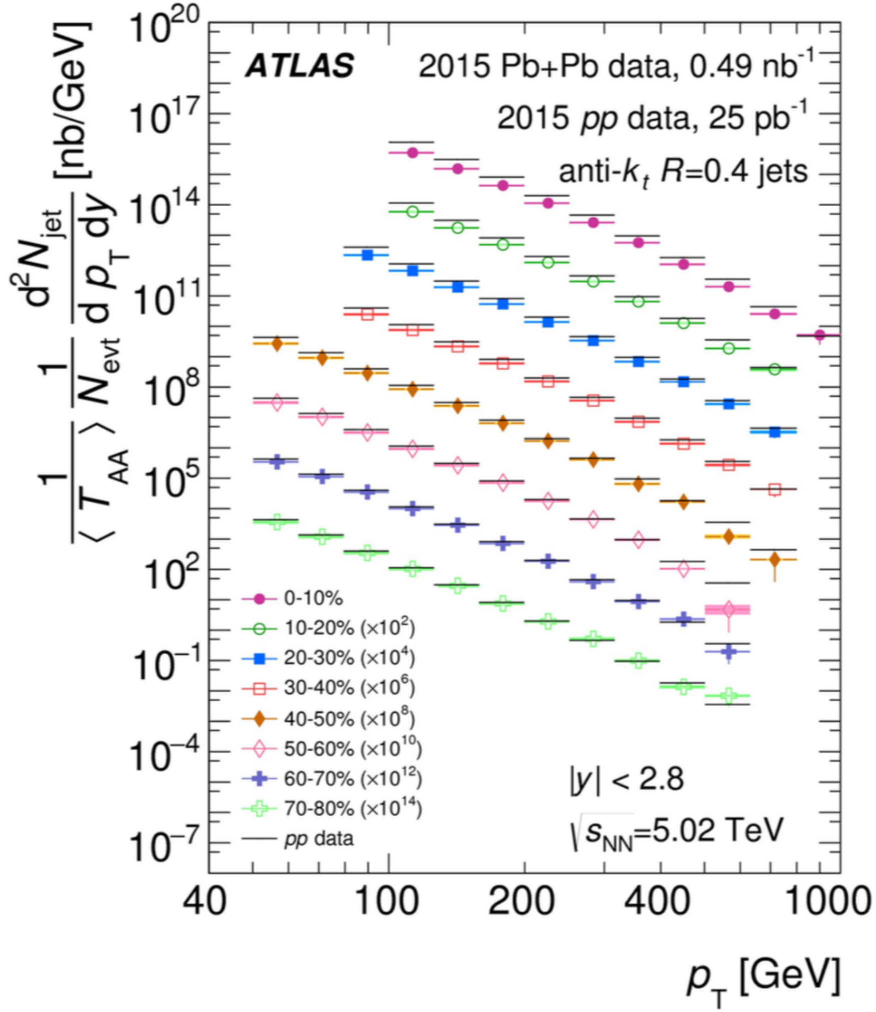
Quark of 10 GeV initial energy:
Au-Au 200 GeV: $\hat{q} \approx 1.2 \pm 0.3$ GeV^2/fm
Pb-Pb 2.76 TeV: $\hat{q} \approx 1.9 \pm 0.7$ GeV^2/fm
at t_0=0.6 fm/c.

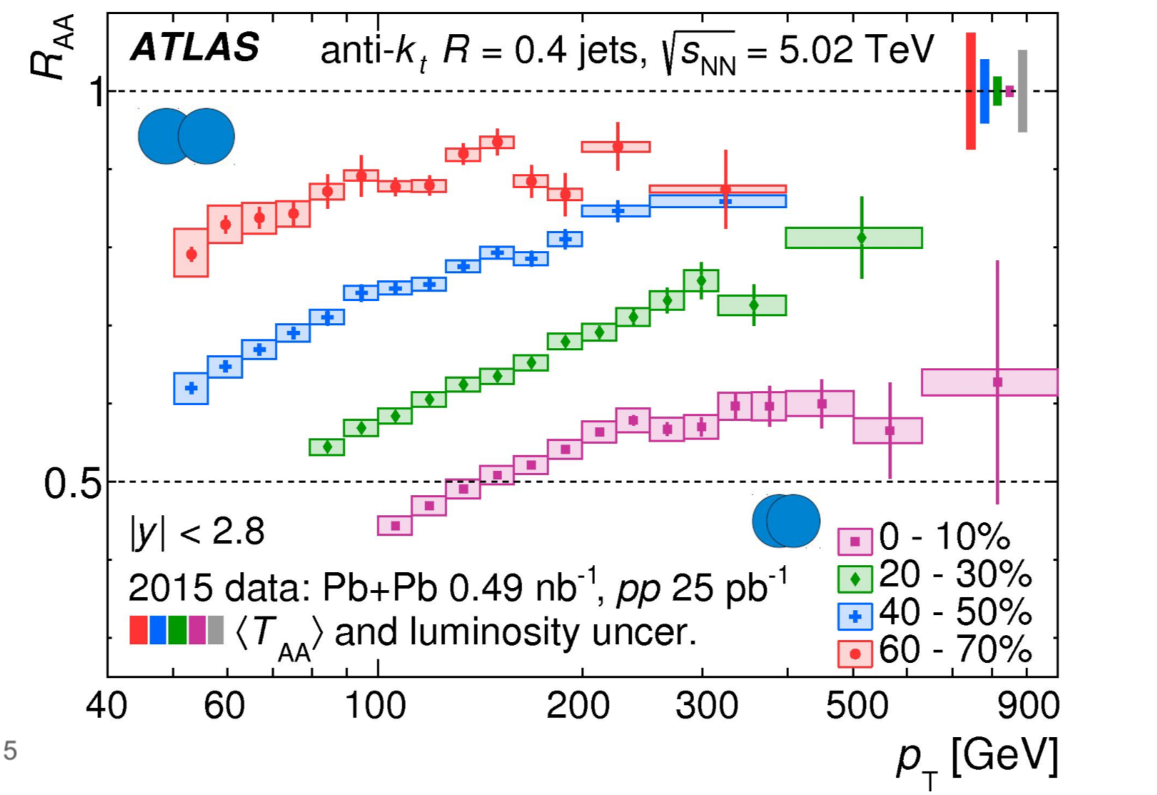


arXiv:1312.5003

Jet R_{AA}

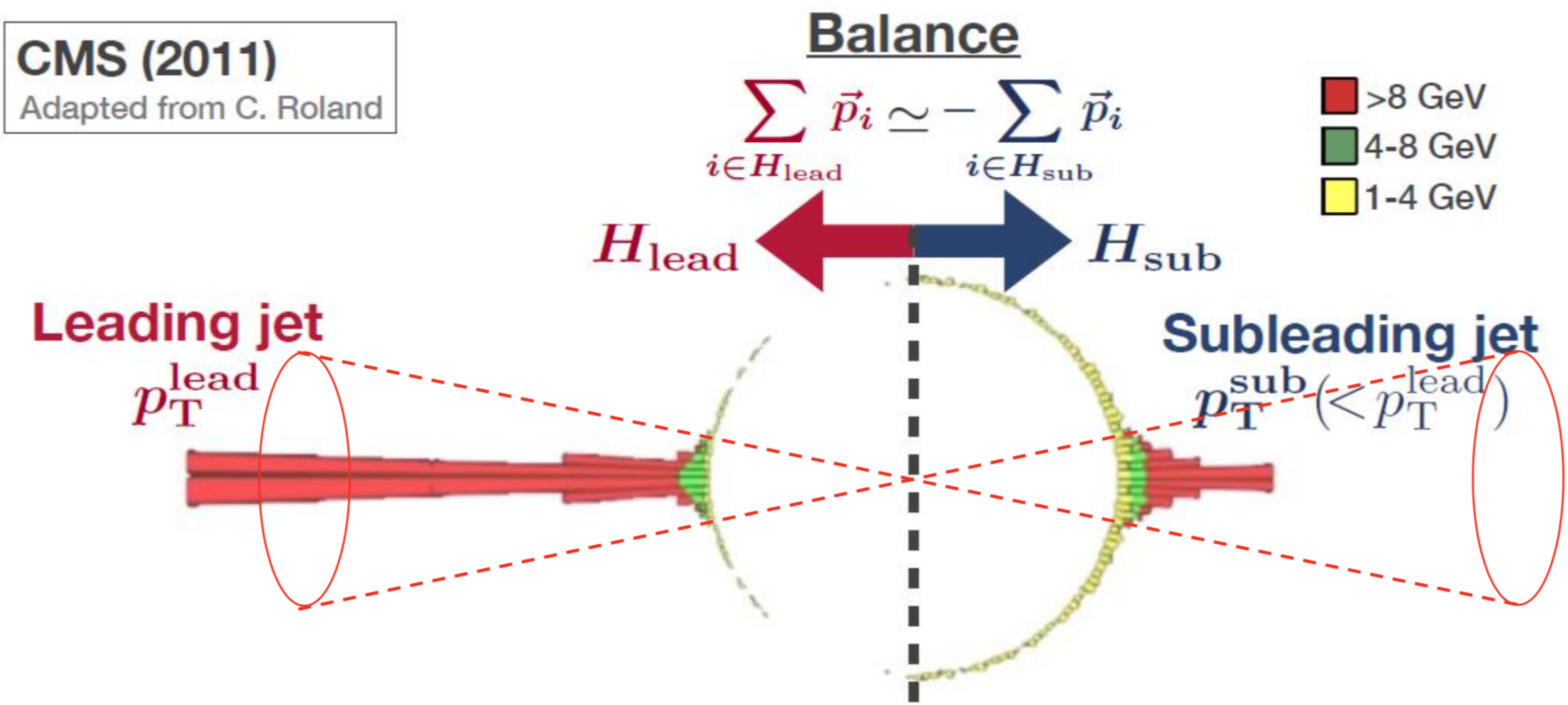
arXiv:1805.05635





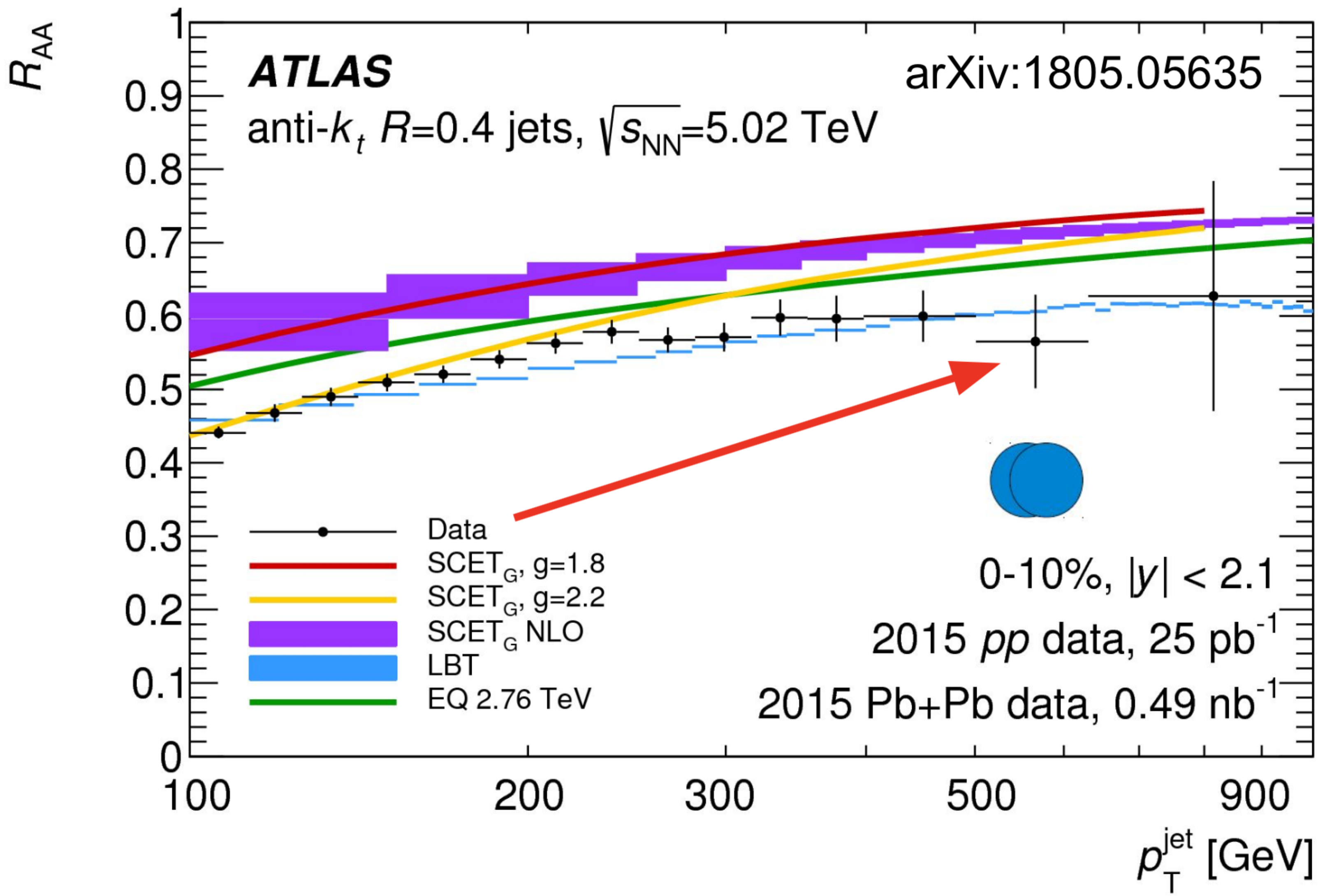
Jet R_{AA}

The energy and momentum deposited by the jet shower into the medium appear at large angles away from the jet axis



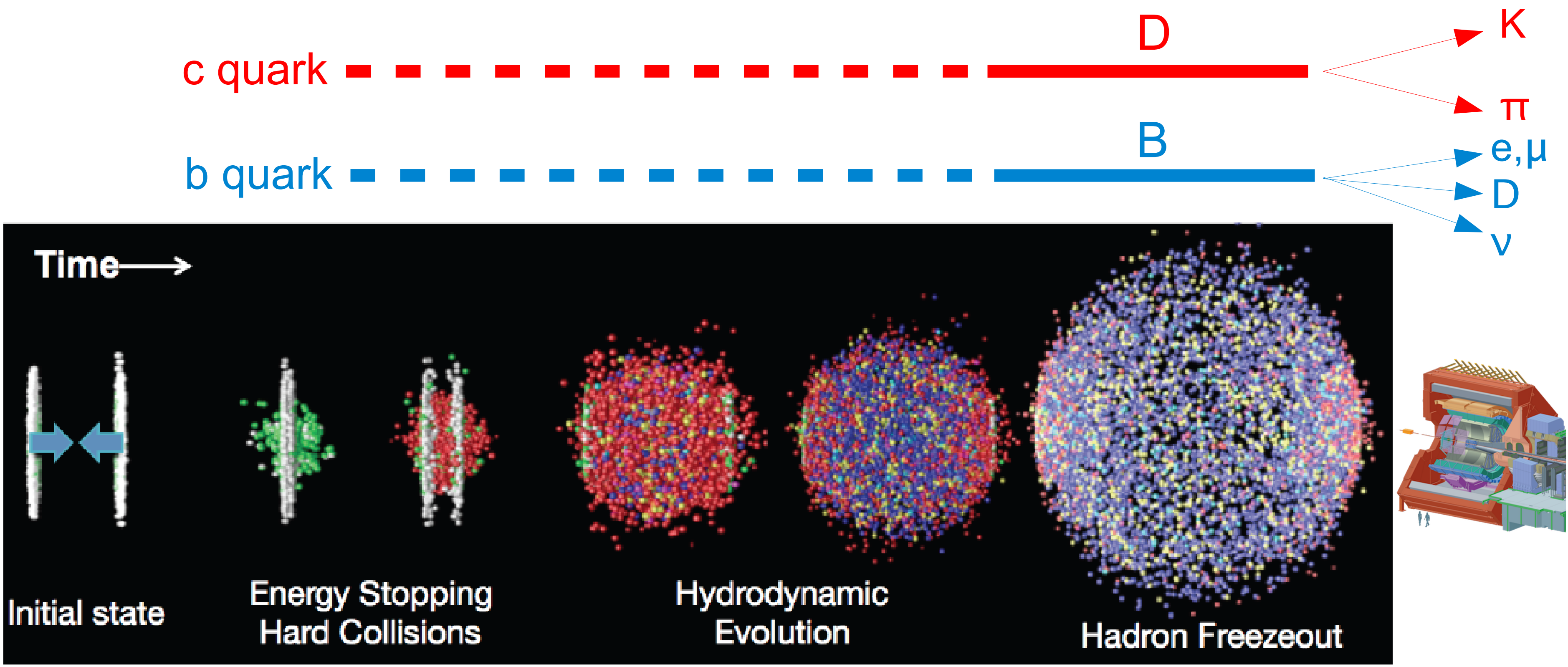
Jet R_{AA}

General trend of jet RAA reproduced by models: constraints more and more possible



Heavy quarks: probes of the QGP

- Produced in initial hard scattering processes, before the thermalized QPG phase
- Flavor is conserved by the strong interaction
- Hard probes down to (almost) p_T ~ 0 GeV/c



Heavy flavors experience the full evolution of the deconfined medium
→ QGP properties

Open heavy flavors

Provide important information from different p_T ranges:

- **Low p_T**: spectra and elliptic flow are influenced by the degree of participation of the charm and beauty quarks to the collective motion of the medium. Do the heavy quarks fully **thermalize**? (constrain the diffusion coefficient D_s)

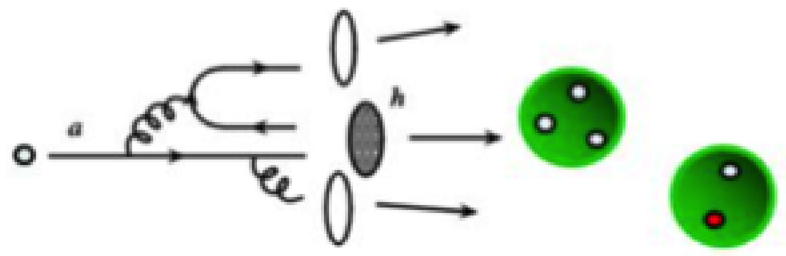
- **Medium p_T**: study the **hadronization** process of heavy quarks (fragmentation, recombination/coalescence)

- **High p_T**: study the heavy quark **energy loss**, constrain the jet transport parameter q. Is there a dependence of energy loss on the parton mass? (dead cone effect: for causality reasons, within a certain angle from the direction of motion of the heavy quark, no gluon can be emitted → lower energy loss the higher the **mass** of the quark is)

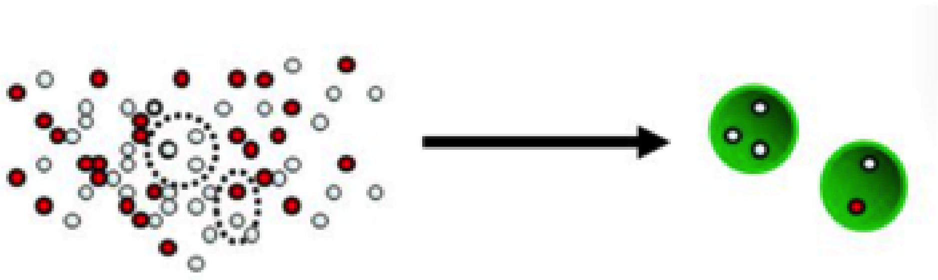
Open heavy flavors: hadronization

- Non-perturbative process
- No first principle calculation yet

High momentum heavy quarks fragment into hadrons [*fragmentation* mechanism: Petersen, FONNL, Pythia, etc.]



Low momentum quarks combine with thermal partons into hadrons [*recombination* (*coalescence*) mechanism]



Shanshan Cao, Hard Probes 2018

Prompt charm: R_{AA}

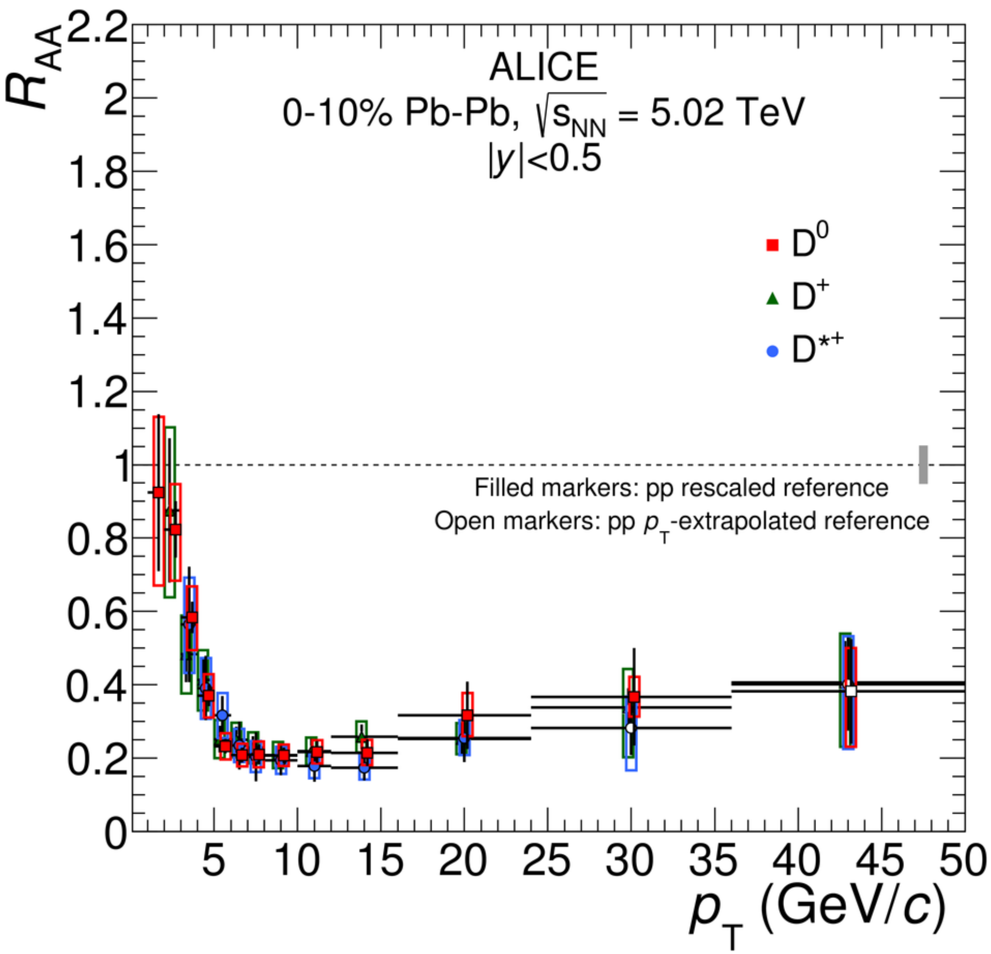
Strong suppression of charm mesons (increasing with centrality)

Significant energy loss of charm quark in the QGP

$D^0 \rightarrow K^- \pi^+$

$D^+ \rightarrow K^- \pi^+ \pi^+$

$D^{*+} \rightarrow D^0 \pi^+$



arXiv: 1804.09083

Prompt charm: R_{AA}

Strong suppression of charm mesons

Average of:

$D^0 \rightarrow K^- \pi^+$

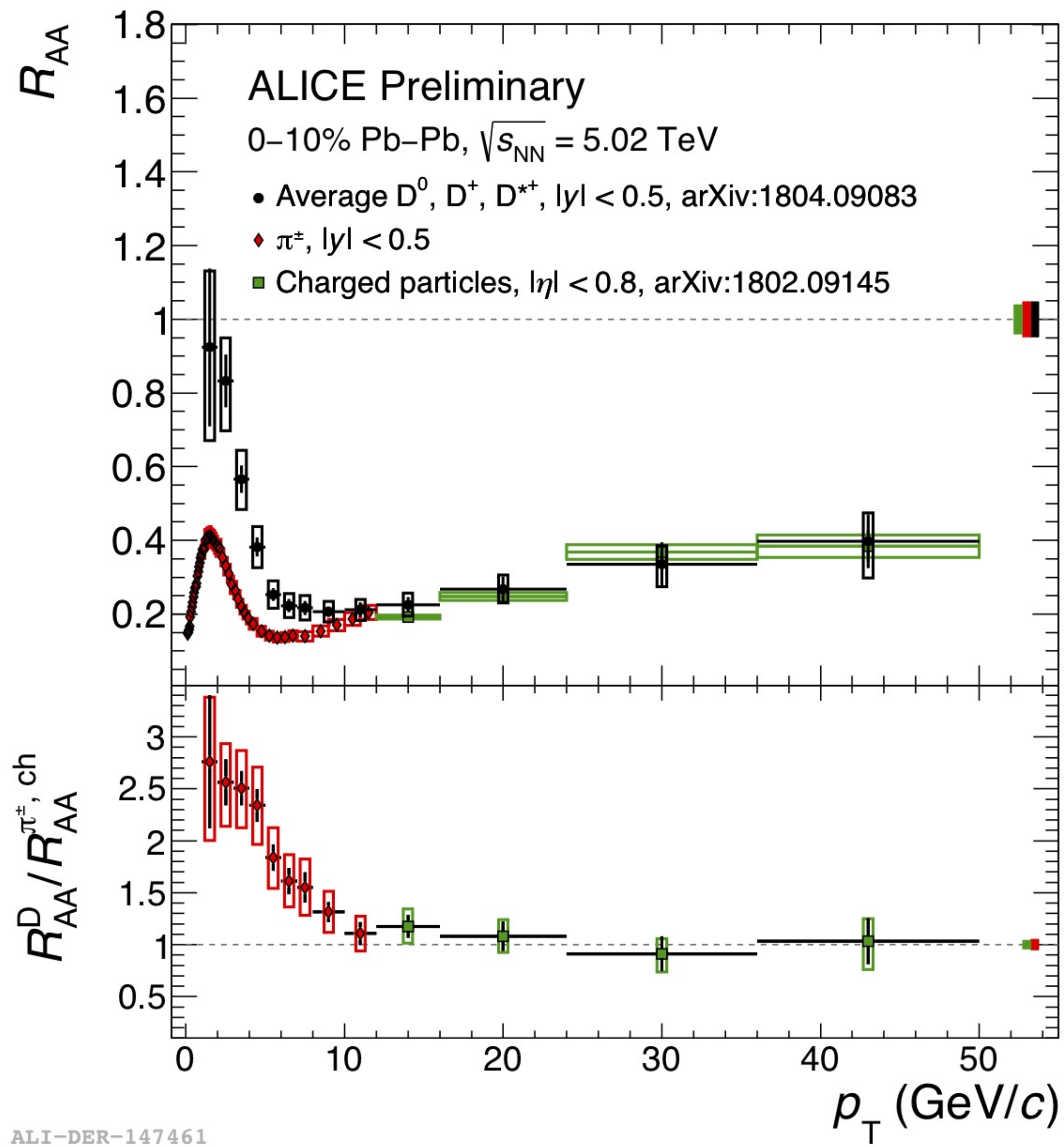
$D^+ \rightarrow K^- \pi^+ \pi^+$

$D^{*+} \rightarrow D^0 \pi^+$

compared to

charged particles and

charged pions



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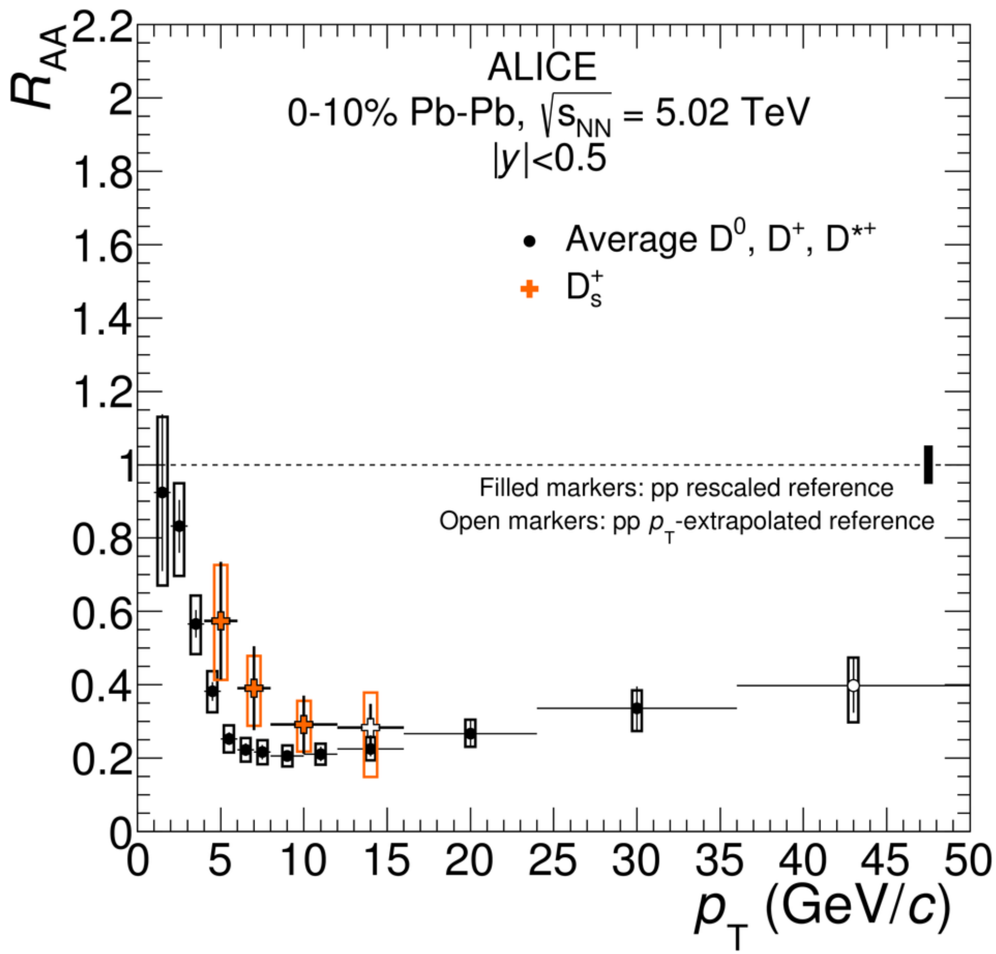
$D^{*+} \rightarrow D^0 \pi^+$

$\mathbf{D_s^+ \rightarrow \varphi\pi \rightarrow K^+K^- \pi^+}$

Modification of hadronization in presence of a medium?
fragmentation vs recombination

Abundance of strange quarks in the medium → possible enhanced production of D_s at low p_T?



arXiv: 1804.09083

Prompt charm: R_{AA}

Strong suppression of charm mesons (increasing with centrality)
Significant energy loss of charm quark in the QGP

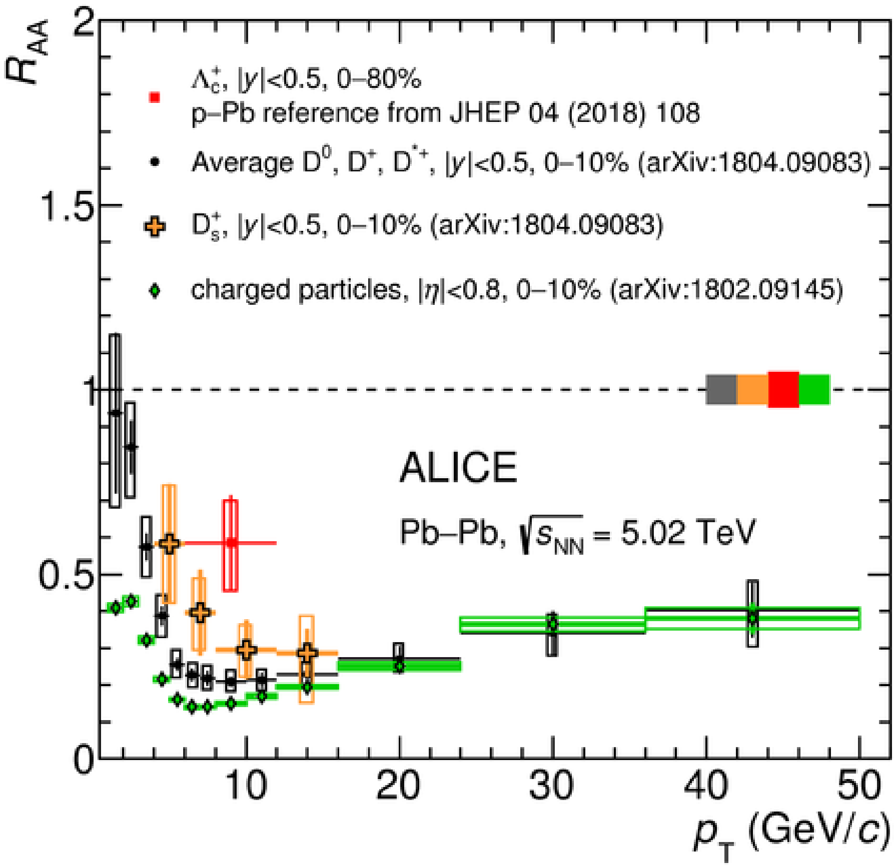
ALICE

$D^0 \rightarrow K^- \pi^+$
$D^+ \rightarrow K^- \pi^+ \pi^+$
$D^{*+} \rightarrow D^0 \pi^+$
$D_s^+ \rightarrow \varphi\pi \rightarrow K^+K^- \pi^+$

$\Lambda_c \rightarrow p\, K^0_s$
Baryon / meson ratio:

$$\left(\frac{\Lambda_c}{D^\cdot}\right)_{PbPb} > \left(\frac{\Lambda_c}{D^0}\right)_{pp}$$

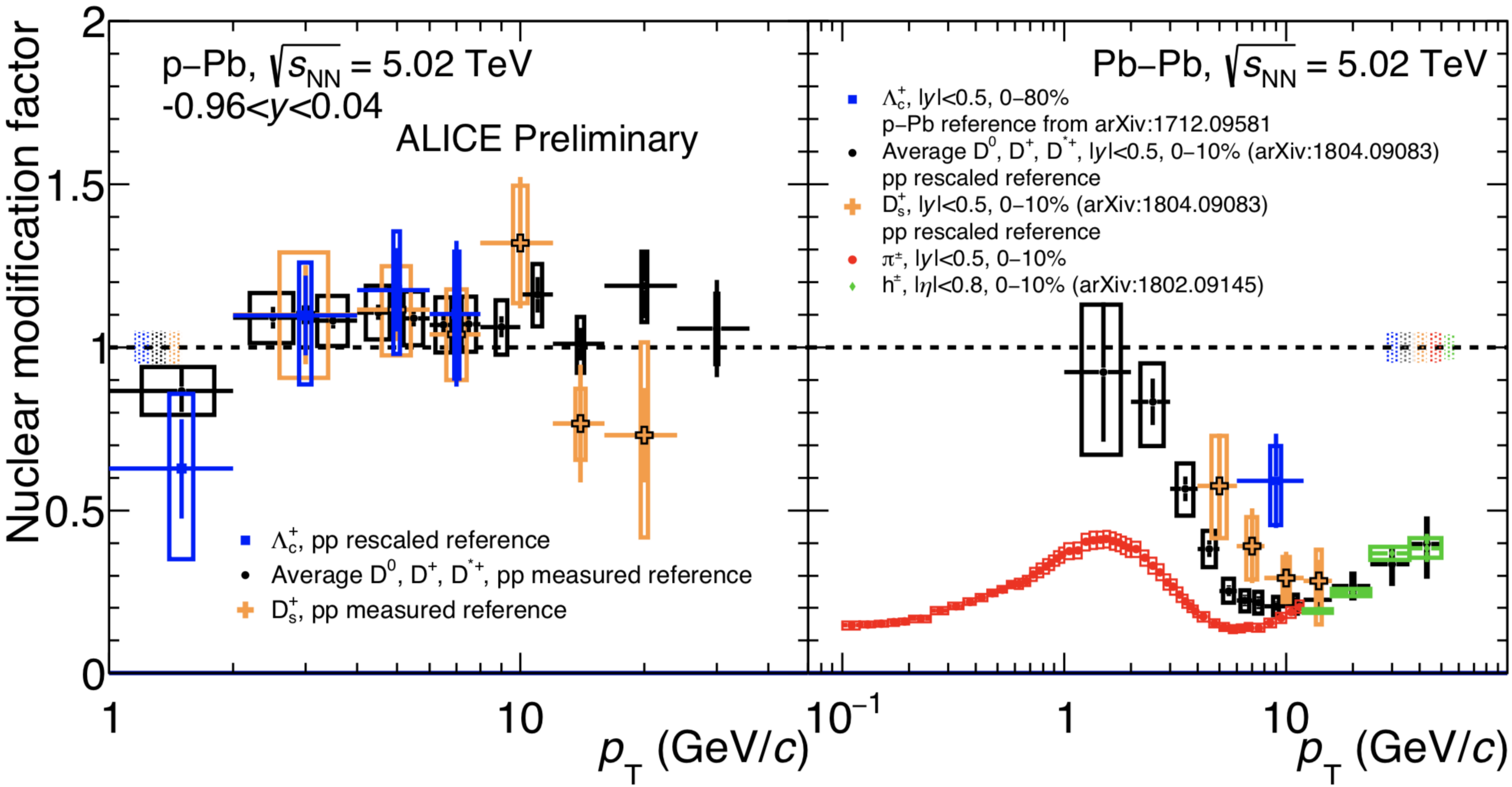
Hadronization mechanism: coalescence?
Indication of charm hadron formation in the medium



arXiv: 1804.09083, arXiv:1809.10922

Prompt charm: R_{AA}

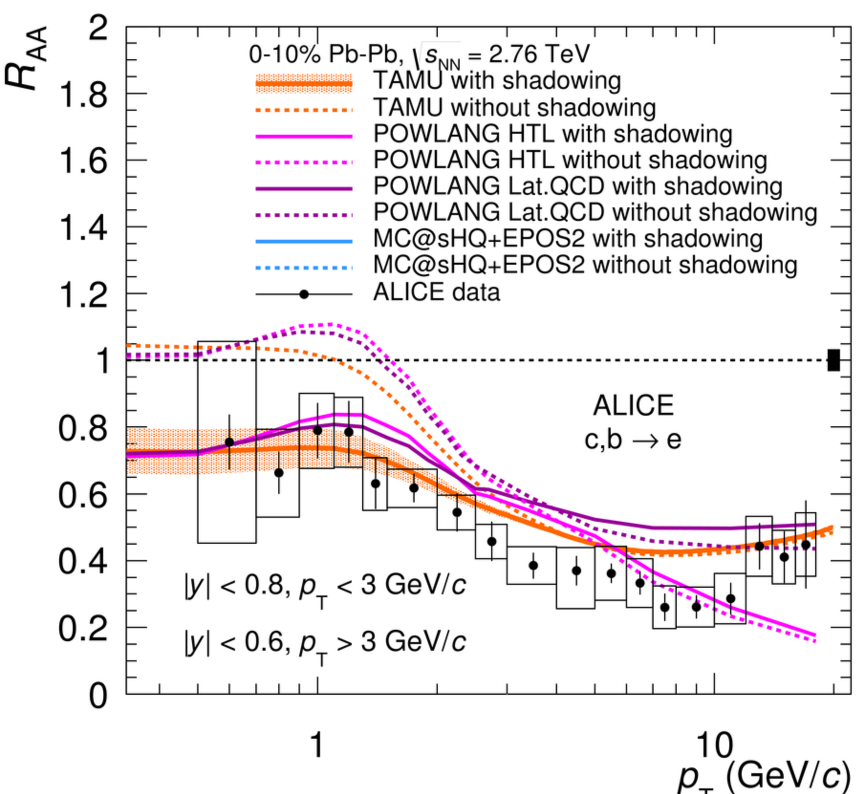
Charm family portrait



Charm and beauty: semi-leptonic decays

Hadrons with charm, hadrons with beauty → e (μ) + X

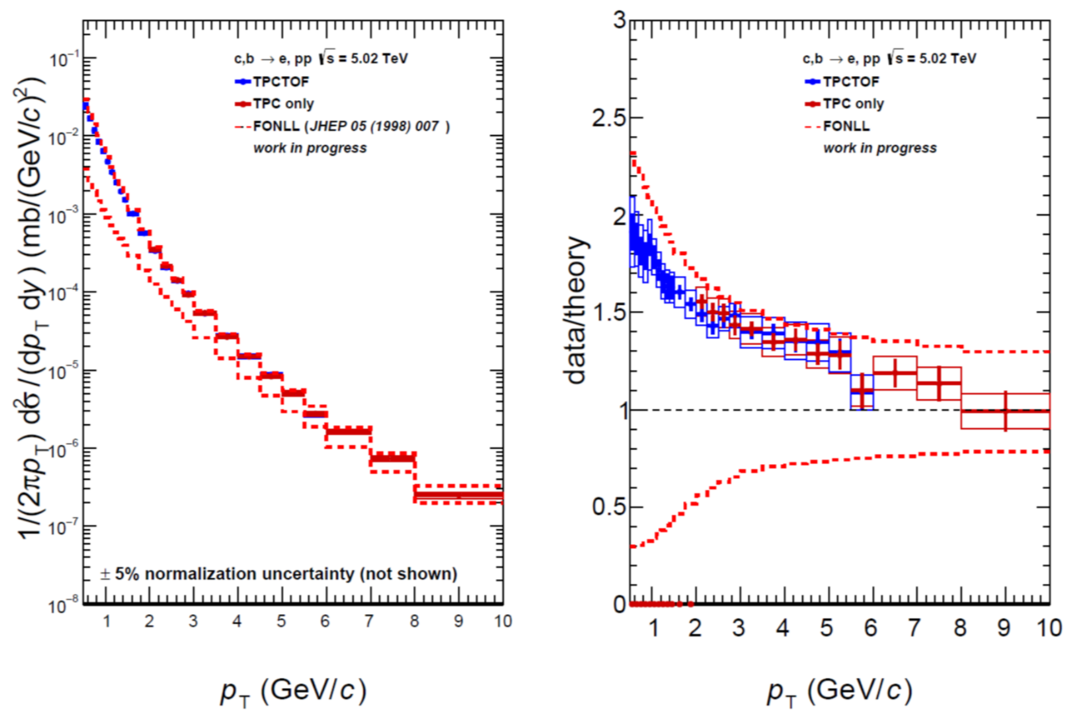
R_{AA}: Pb-Pb / pp



JHEP 1810 (2018) 061

Production cross-section in pp compared with FONLL pQCD calculation (Cacciari et al.)

PRECISION



Ongoing
(master thesis)

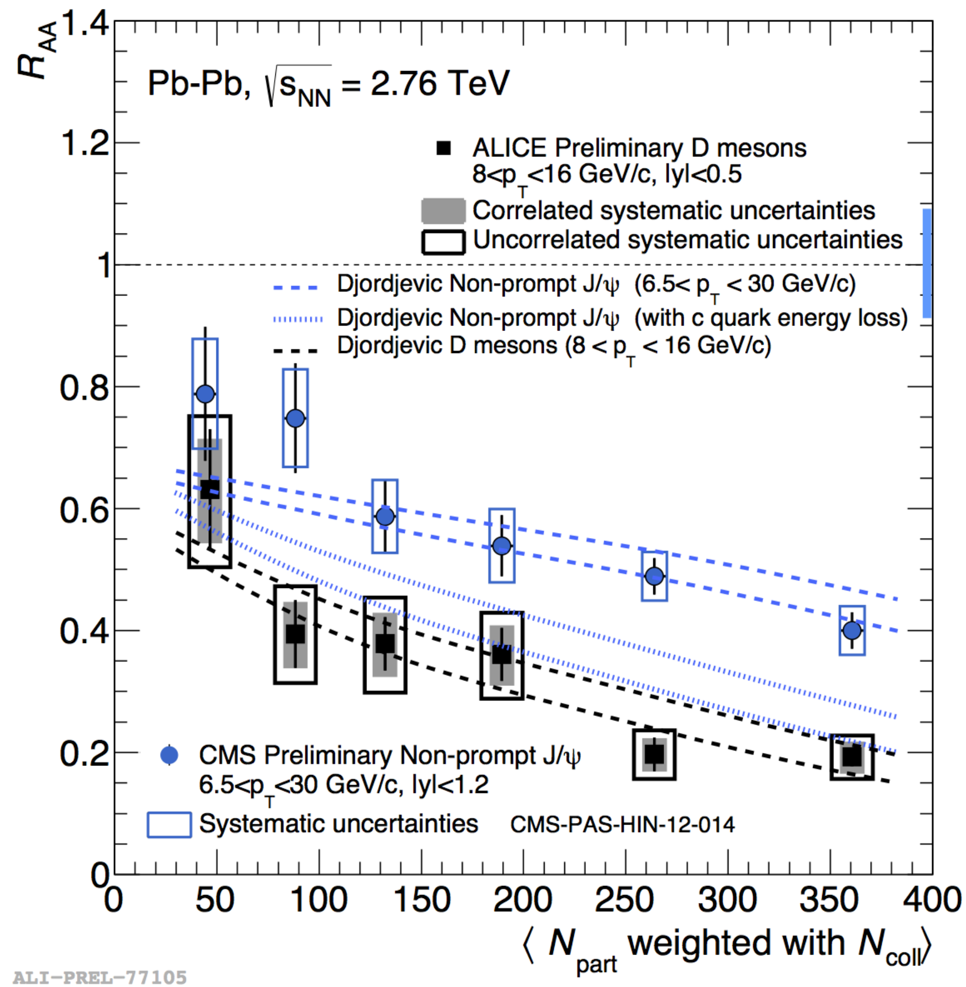
Beauty, charm and light quarks

Beauty: non-prompt J/ψ

CMS-PAS-HIN-12-014

Charm: D mesons

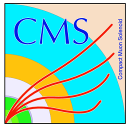
JHEP11(2015)205

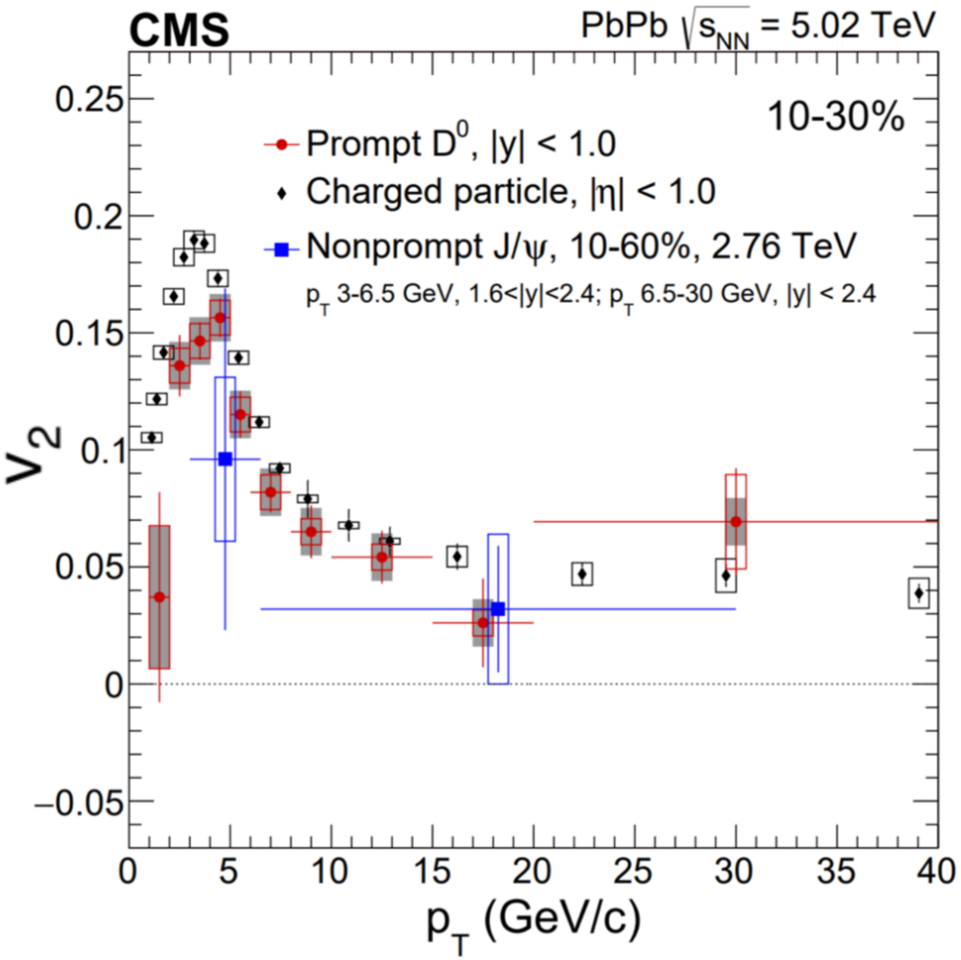


Indication of mass ordering for charm and beauty

fragmentation

Prompt charm: elliptic flow v_2





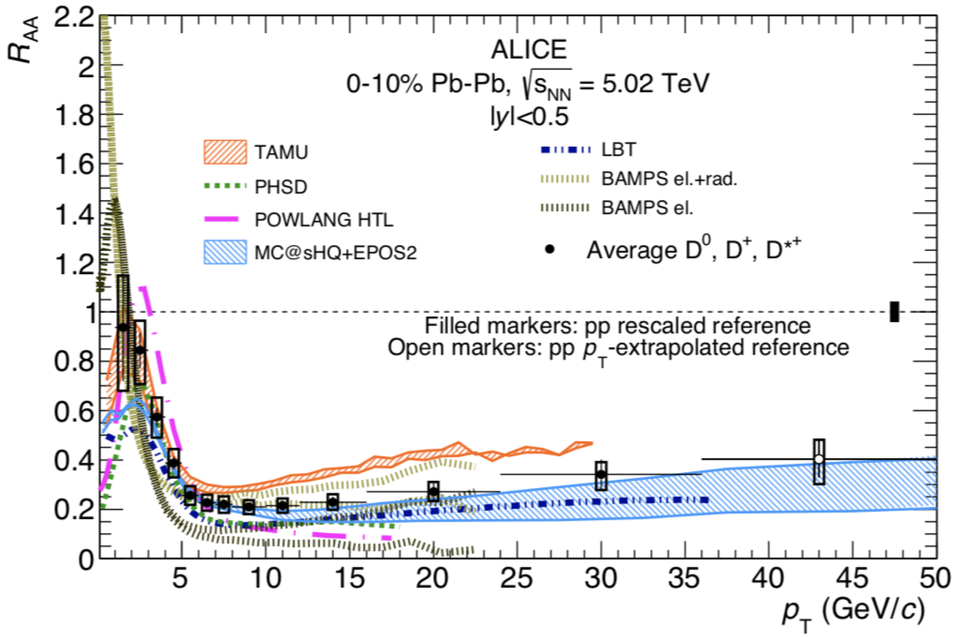
D^0 v_2 follows the same trend as light hadrons

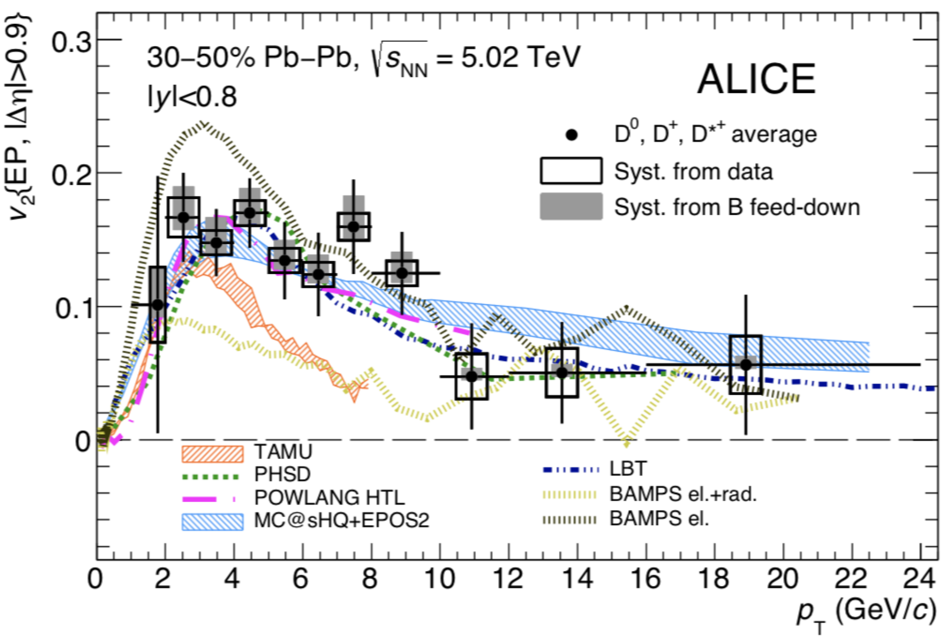
Charm quarks exhibit flow as the light quarks → collective motion

Indication for charm thermalization in the QGP

Prompt charm: comparison with theory models

Important constraints come from describing as many observables as possible at the same time





arXiv: 1804.09083

arXiv: 1707.01005

Open heavy flavors: flash summary

- Aim at more and more **precise and differential measurements** (also at different energies)

  E.g. shadowing, charm production cross section in pp

- Intense theory work to understand interplay of:
  - **collisional and radiative energy loss**
  - **degree of thermalization of charm in QGP**
  - **hadronization** in medium (e.g. coalescence) or fragmentation in vacuum

  to determine **QCD heavy quark drag and diffusion transport coefficients**

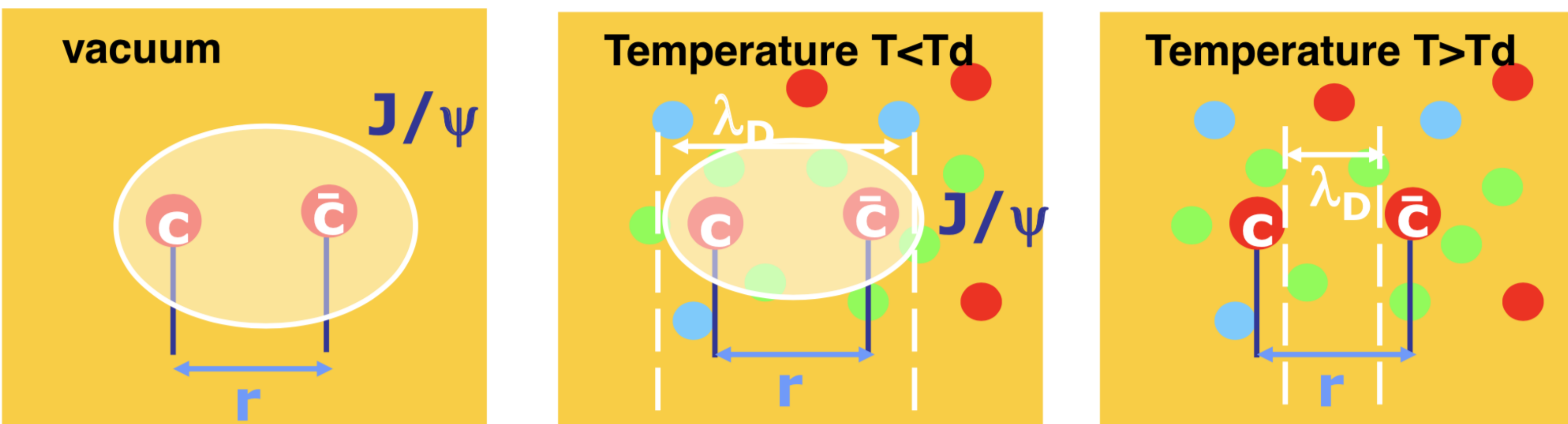
EMMI

Rapid reaction task force, July 2016
"Extraction of heavy-flavor transport coefficients in QCD matter"
Nucl.Phys. A979 (2018) 21-86

Heavy quarkonium states

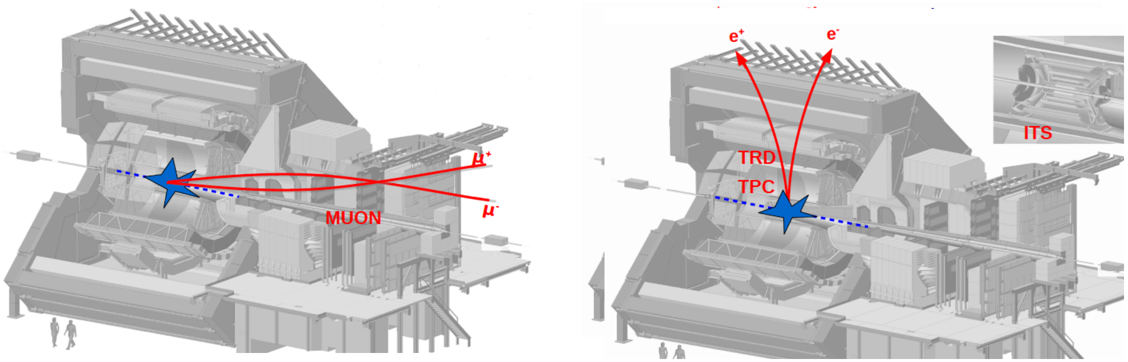
$Q\bar{Q}$ states $\begin{cases} c\bar{c} & J/\psi,\ \psi',\ \chi_c \\ b\bar{b} & \Upsilon(1S),\ \Upsilon(2S),\ \Upsilon(3S),\ \chi_b \end{cases}$

Probes of the medium by excellence!



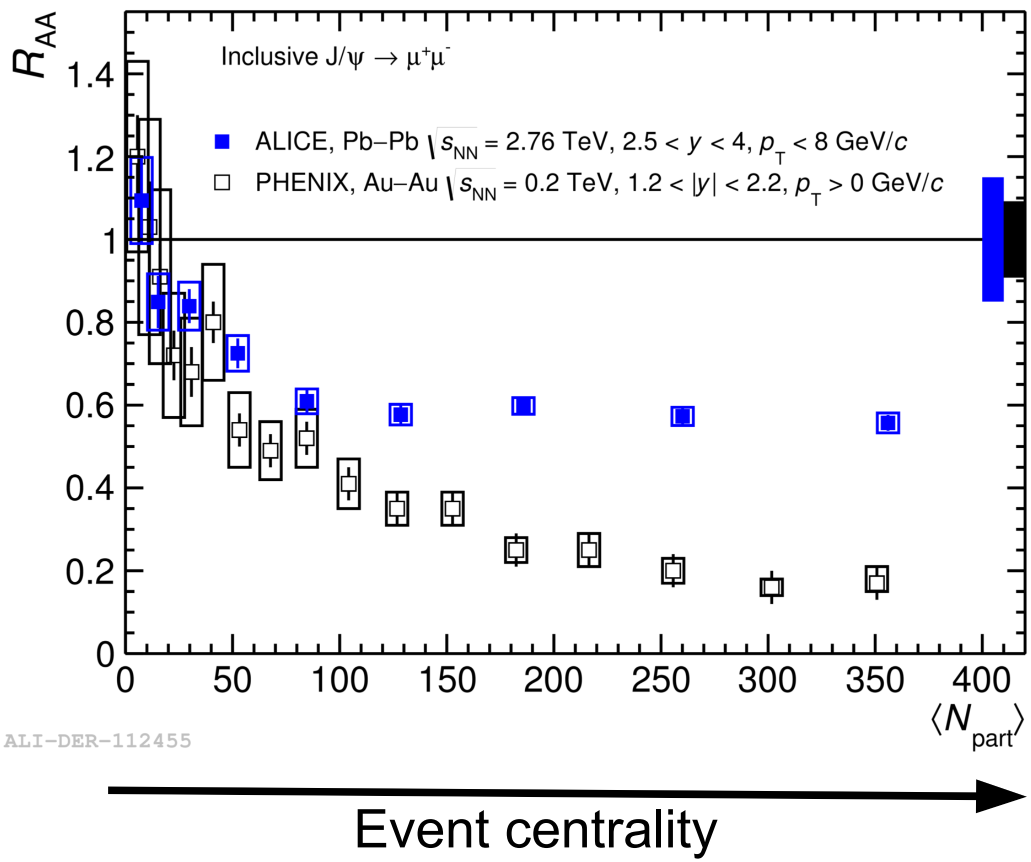
Screening stronger at higher temperatures!

Matsui & Satz



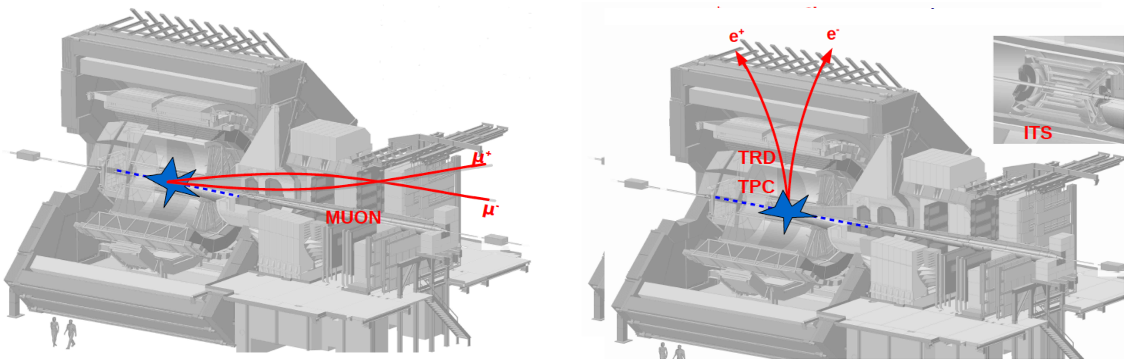
ALICE
$\sqrt{s_{NN}}$ = 2.76 TeV

PHENIX
$\sqrt{s_{NN}}$ = 200 GeV



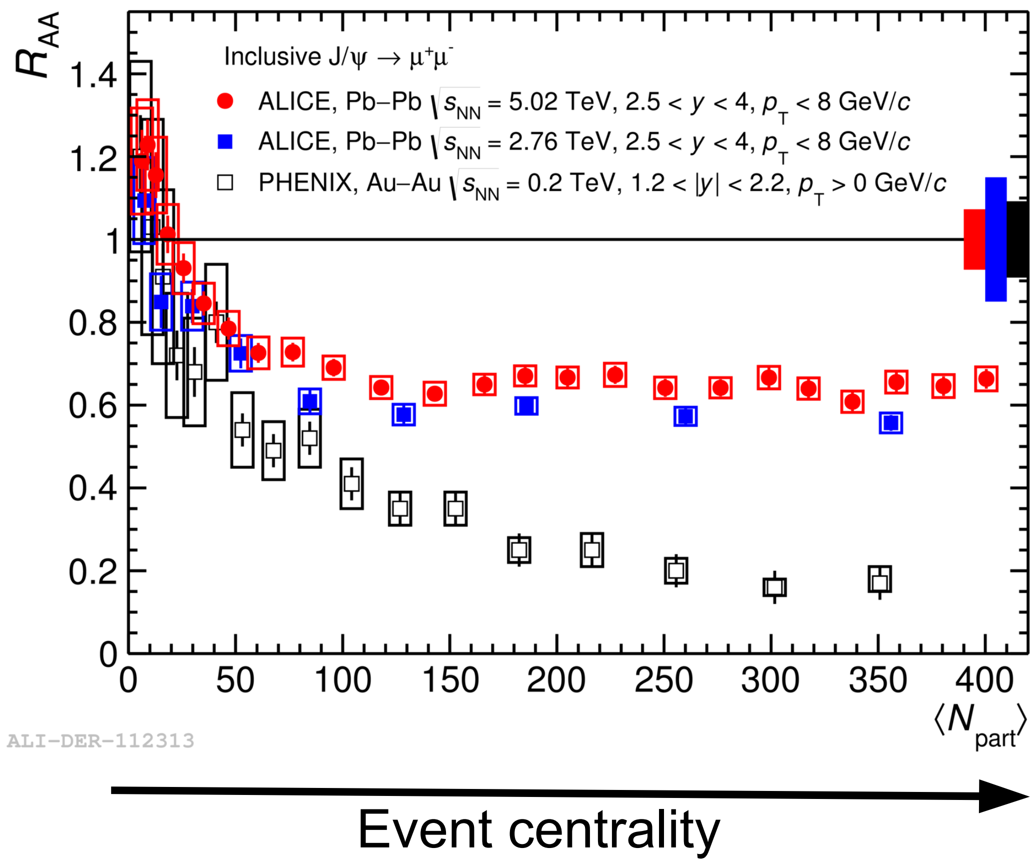
Suppression

PLB734(2014)314



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

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



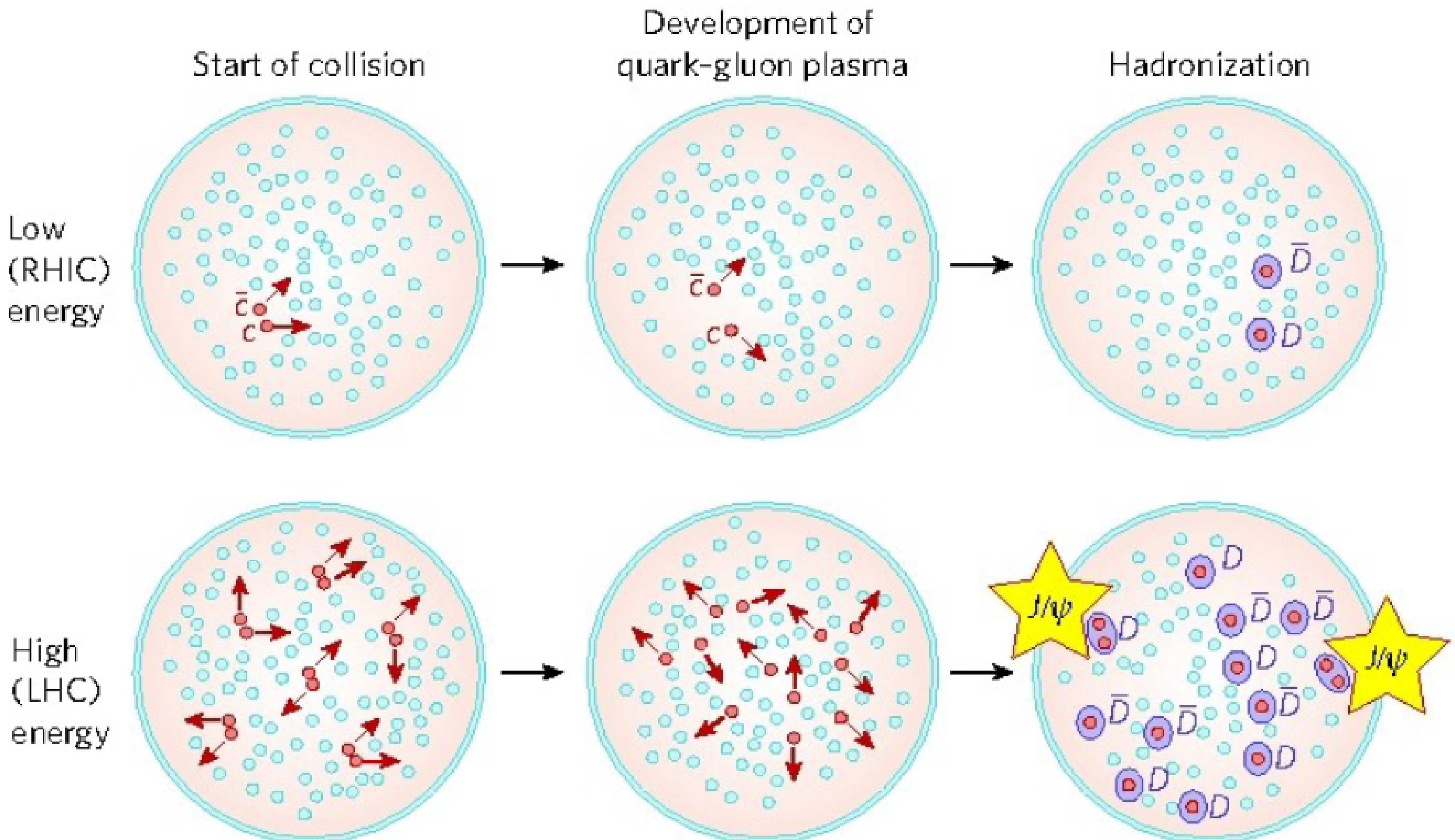
Suppression + new production mechanism !

Suppression

PLB734(2014)314
PLB766(2017)212

J/ψ production mechanism

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

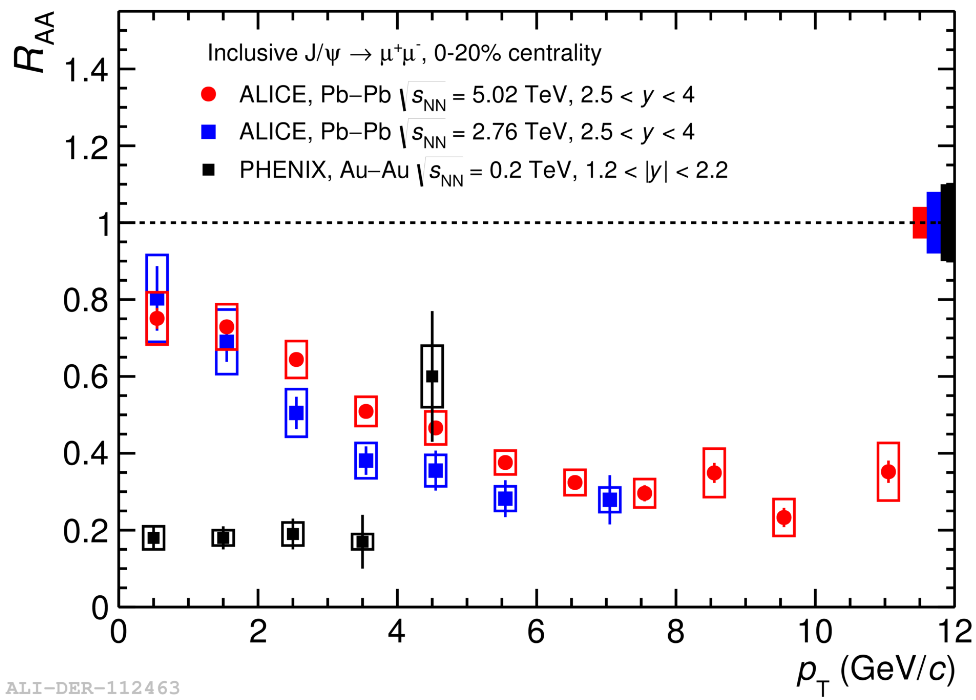


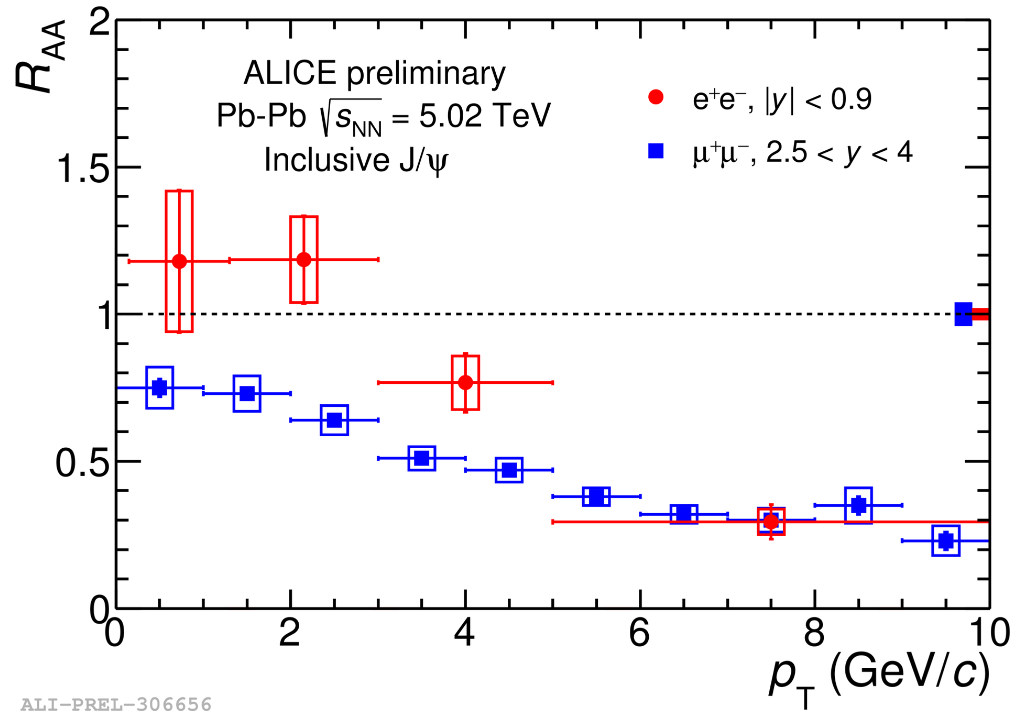
Braun-Munzinger, Stachel, Nature 448 (2007) 302-309

J/ψ production mechanism

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

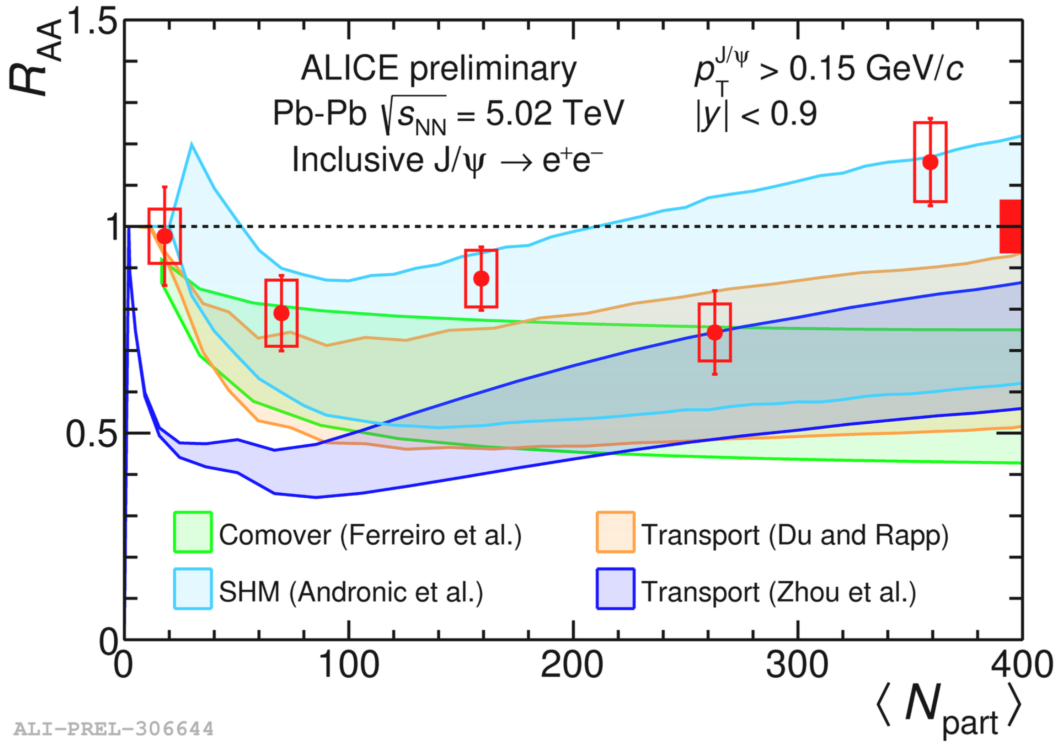


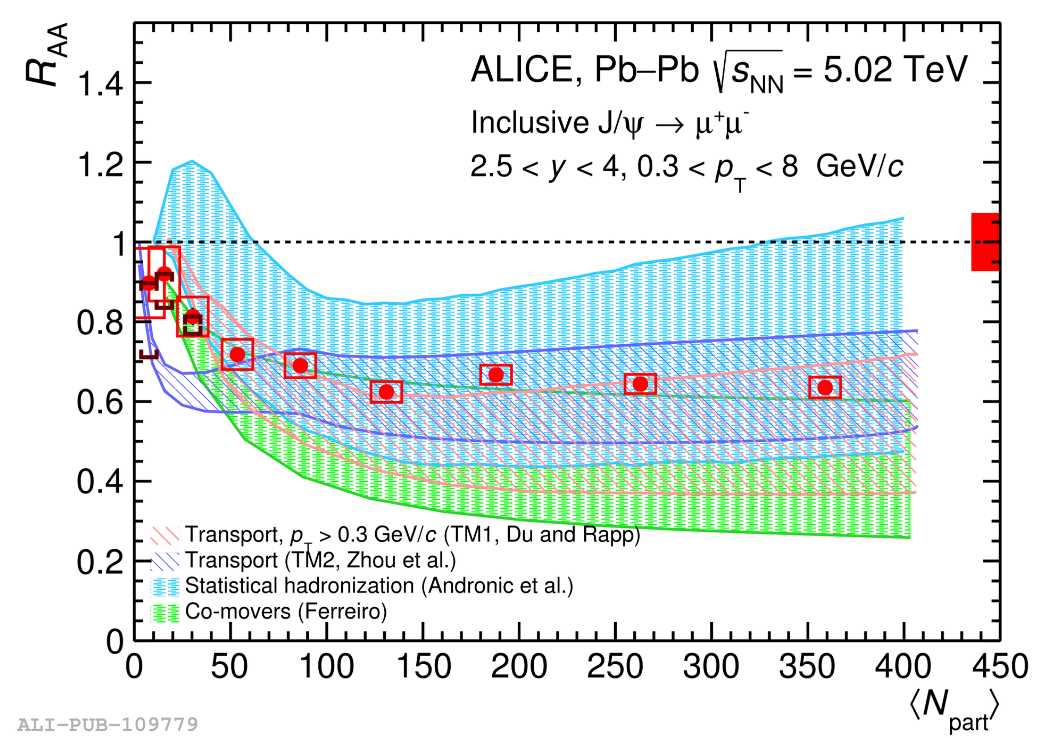


PLB734(2014)314
PLB766(2017)212

J/ψ production mechanism: models

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



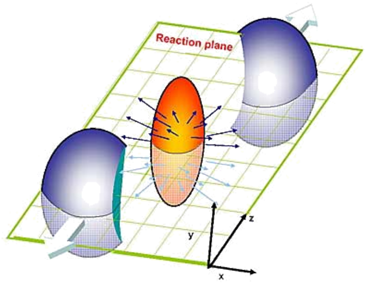


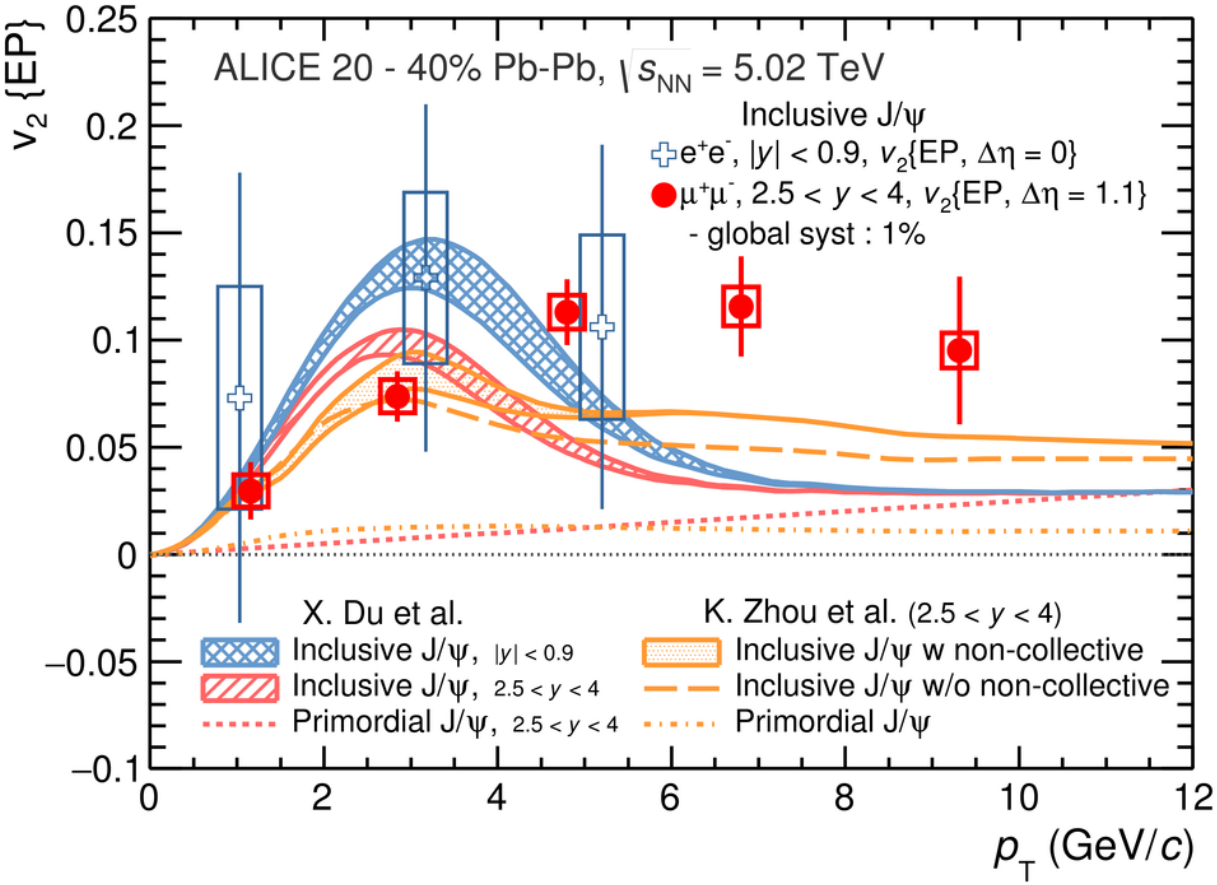
Large uncertainties: shadowing, open charm cross section

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

J/ψ elliptic flow

Non-zero v_2 signal for J/ψ ($c\bar{c}$)





J/ψ participates in the hydrodynamic flow

Charm quarks thermalized in the QGP

Charmonia: flash summary

- New production mechanism of J/ψ by (re-)generation of $c\bar{c}$ pairs
  → deconfinement !!
- Information about the phase boundary
- Thermalization of charm quarks in the QGP

With the data planned for the near future:

- Much larger statistics of charmonia signals
- Measurement of the total charm production cross section
- Possibly improved knowledge of the nuclear PDFs

→ clearer discrimination among production scenarios

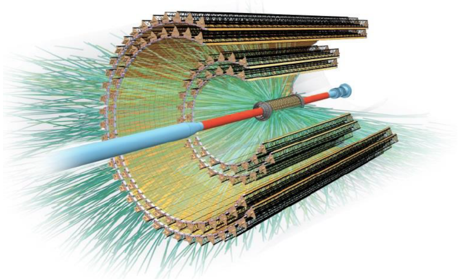
Coming next at the LHC: high luminosity !

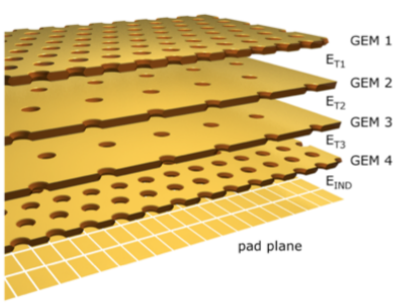
- LS2 (2019-20): improvements to the injection chain
- From 2021 on (Run 3-4): Pb-Pb collisions at 50 kHz

Tremendous physics opportunities!

ALICE UPGRADE:

- detector upgrades to achieve continuous readout
- focus on minimum bias data samples, for low p_T coverage
- 100x min.bias events, 10x integrated luminosity → 10+3 nb^{-1} (goal of Run 1-2: 1 nb^{-1})
- open heavy flavors, heavy quarkonium, light nuclei and exotic states, dilepton spectrum



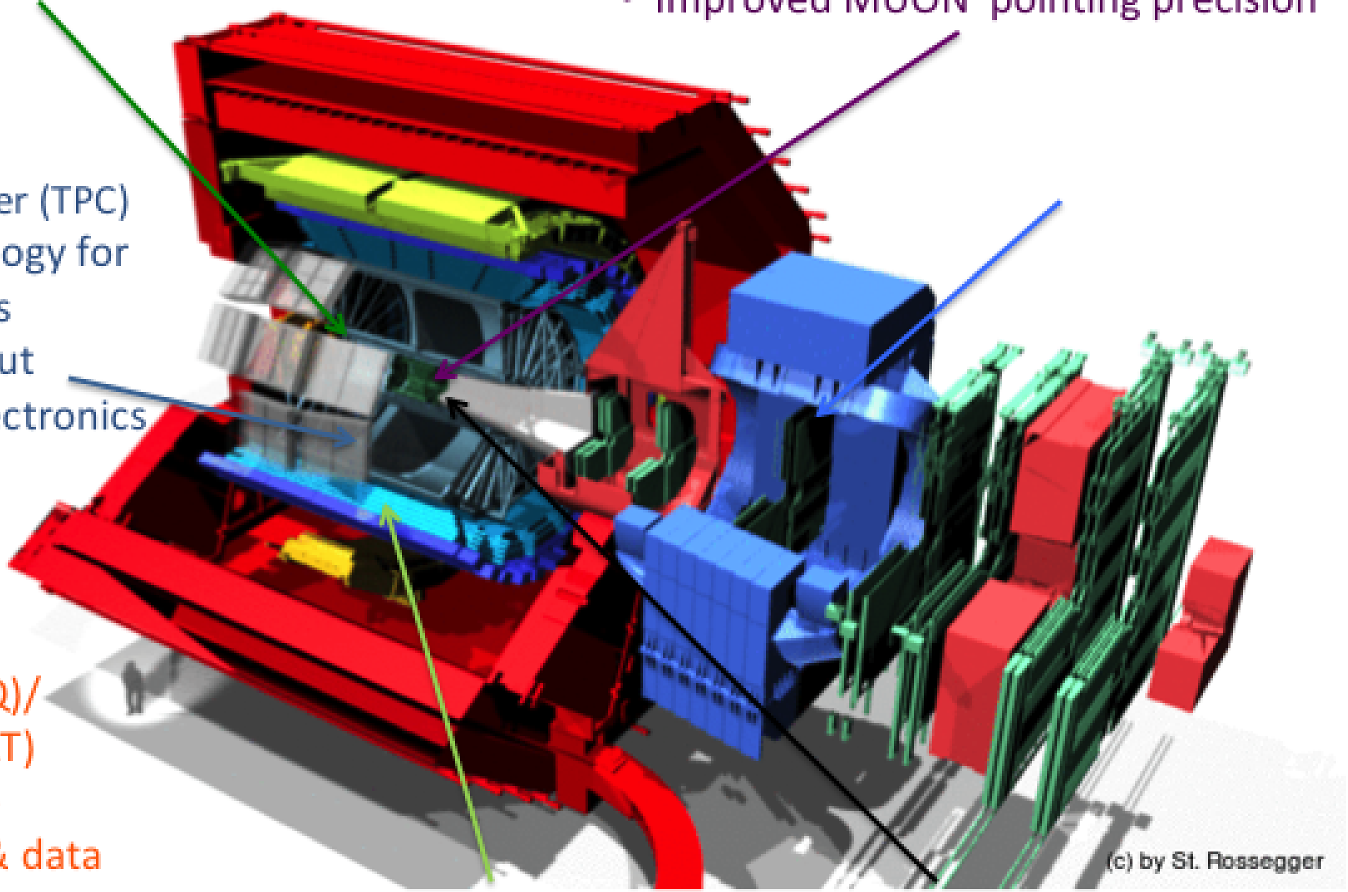


ALICE 2021 - 2029

The LS2 ALICE upgrades

New Inner Tracking System (ITS)
- improved pointing precision
- less material -> thinnest tracker at the LHC

Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision



Time Projection Chamber (TPC)
- new GEM technology for readout chambers
- continuous readout
- faster readout electronics

New Central Trigger Processor

Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz PbPb event rate

TOF, TRD, ZDC
- Faster readout

New Trigger Detectors (FIT)

HI HL-LHC: physics program (some)

Very high statistics, improved detectors:

- **Heavy flavors**
- **Heavy quarkonia production**
- **(Anti-)(hyper-)nuclei production**
- **Low-mass dielectrons**

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, Υ(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 ${}^{3}_{\Lambda}H$
- **Low-mass dielectrons** →
  - Low B field run → low p_T reach
  - High precision measurements

HI HL-LHC

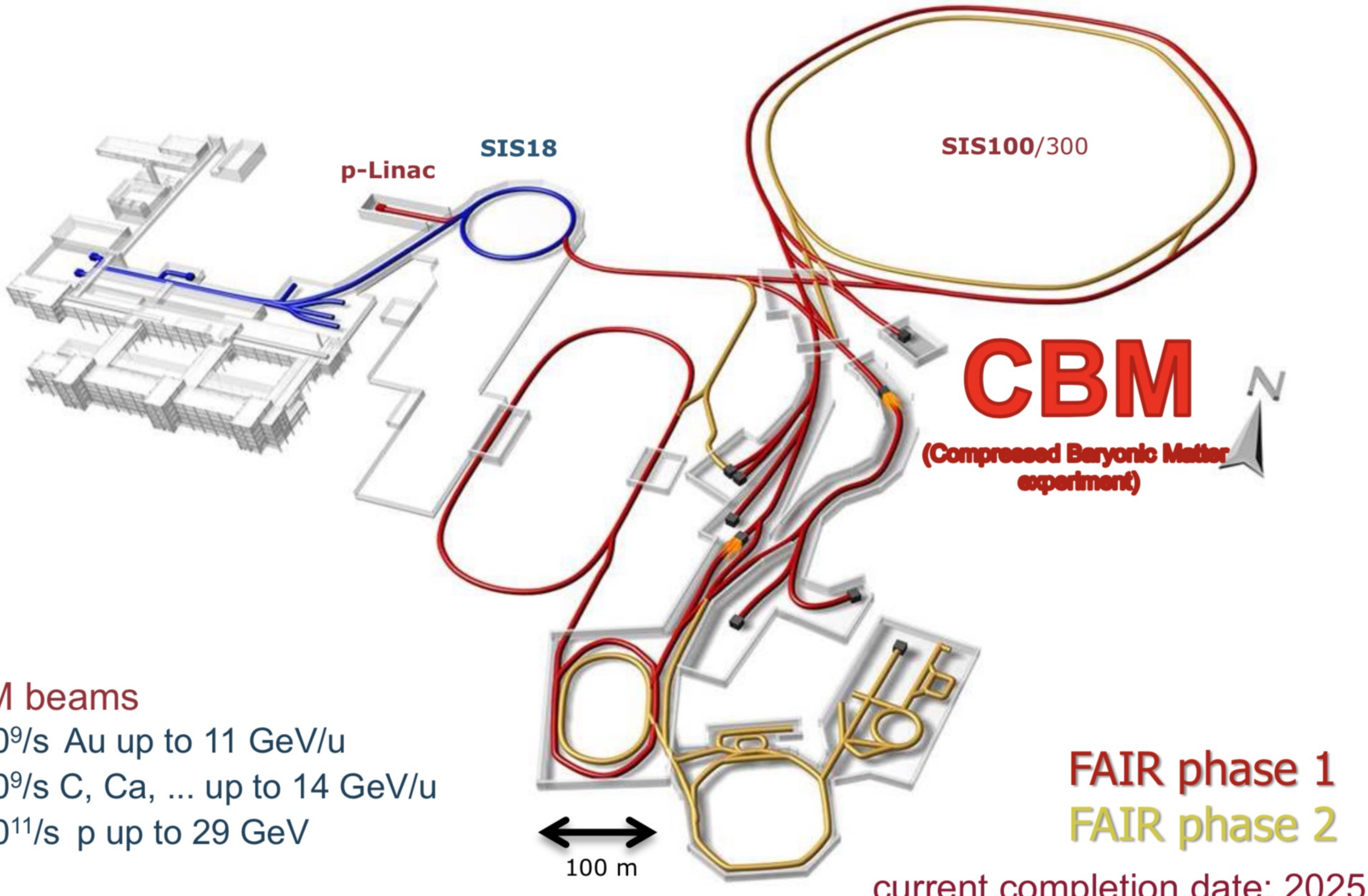
CERN-LPCC-2018-07
December 18, 2018

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

CERN Yellow Report
arXiv:1812.06772

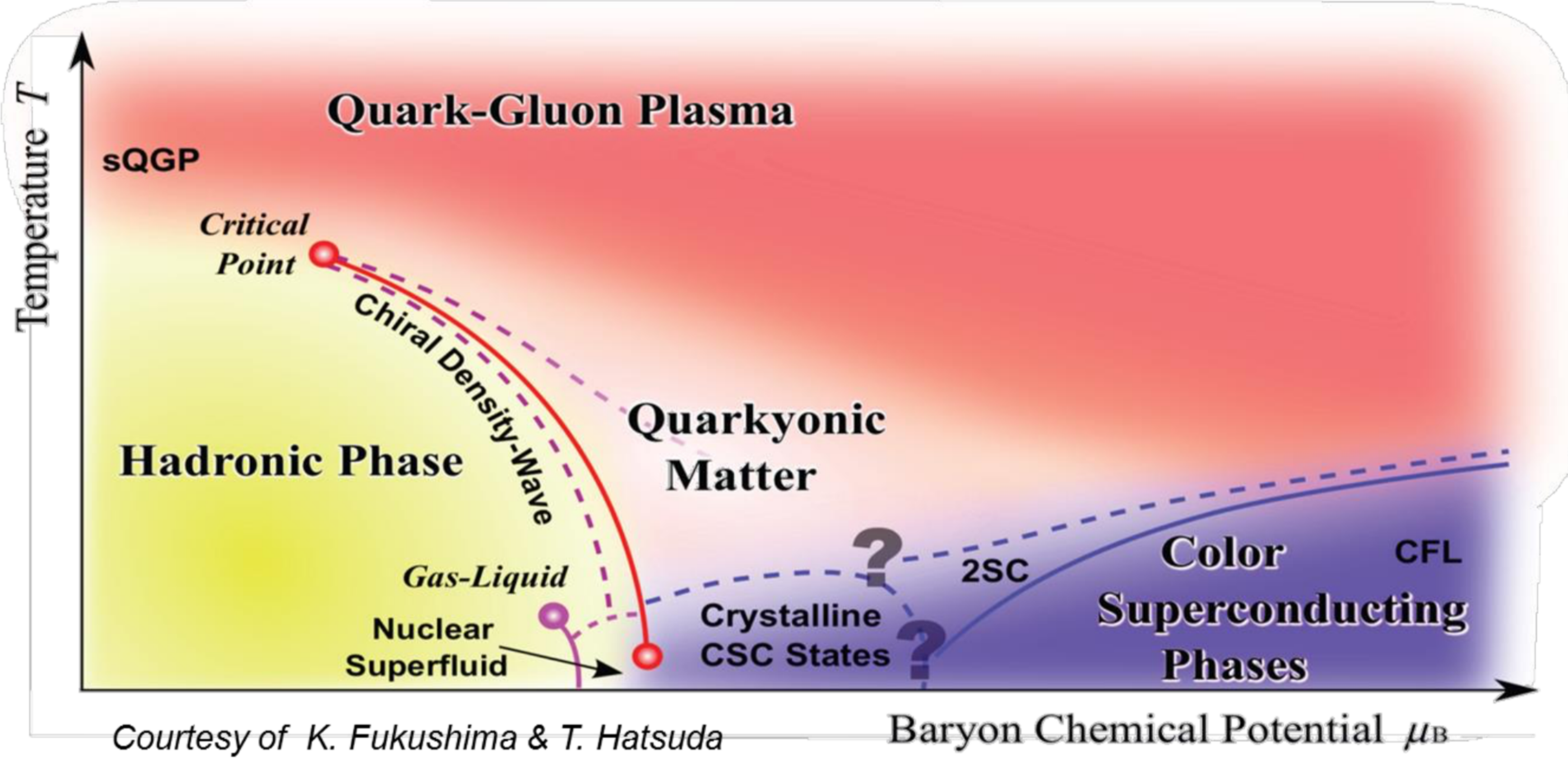
CBM @ FAIR



CBM beams

- 10^9/s Au up to 11 GeV/u
- 10^9/s C, Ca, ... up to 14 GeV/u
- 10^{11}/s p up to 29 GeV

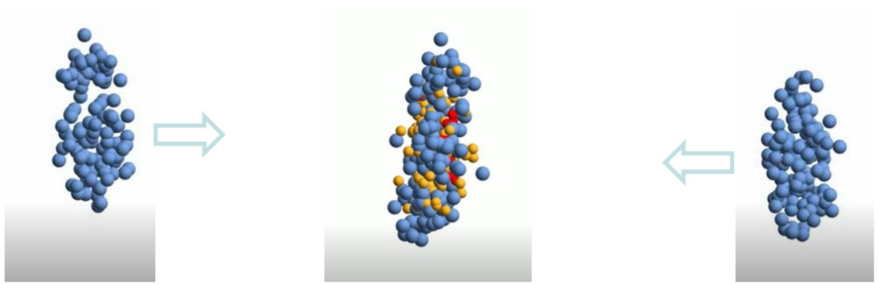
CBM



Explore systematically the QCD phase diagram at high baryon chemical potential, with very high-precision, high-statistics measurements

Material from N. Herrmann, Erice, 2018

Heavy ion collisions at SIS100



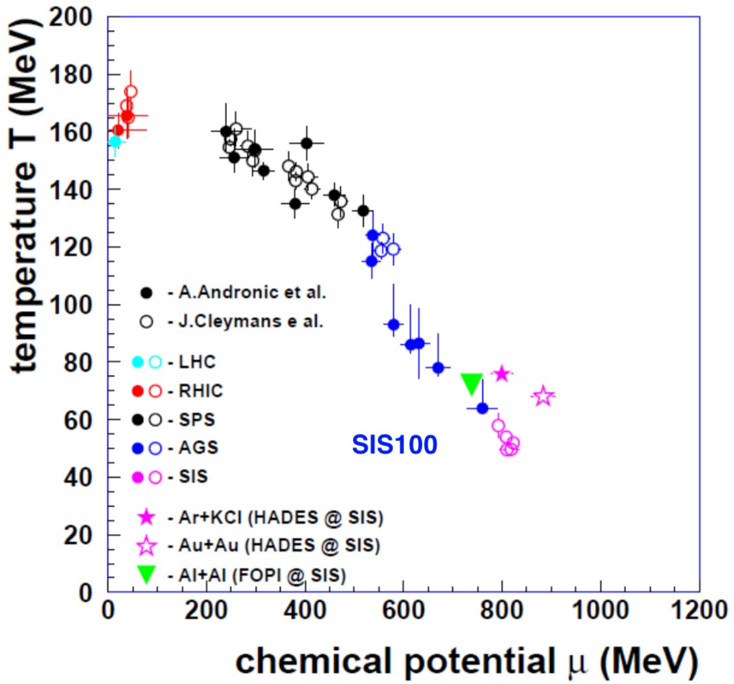
Compressed Baryonic Matter

Temperature
T < 120 MeV

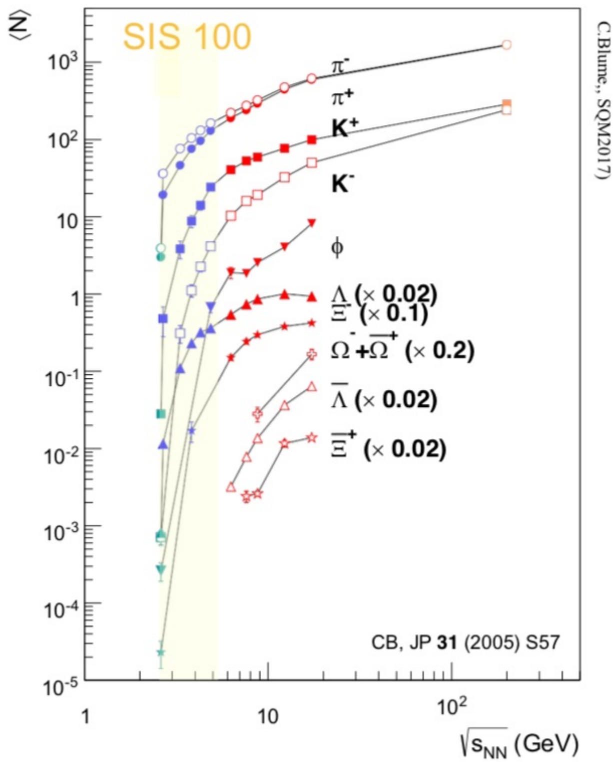
Density
$\rho < 8\rho_0$

Reaction time
$t \sim 10^{-23}$ s

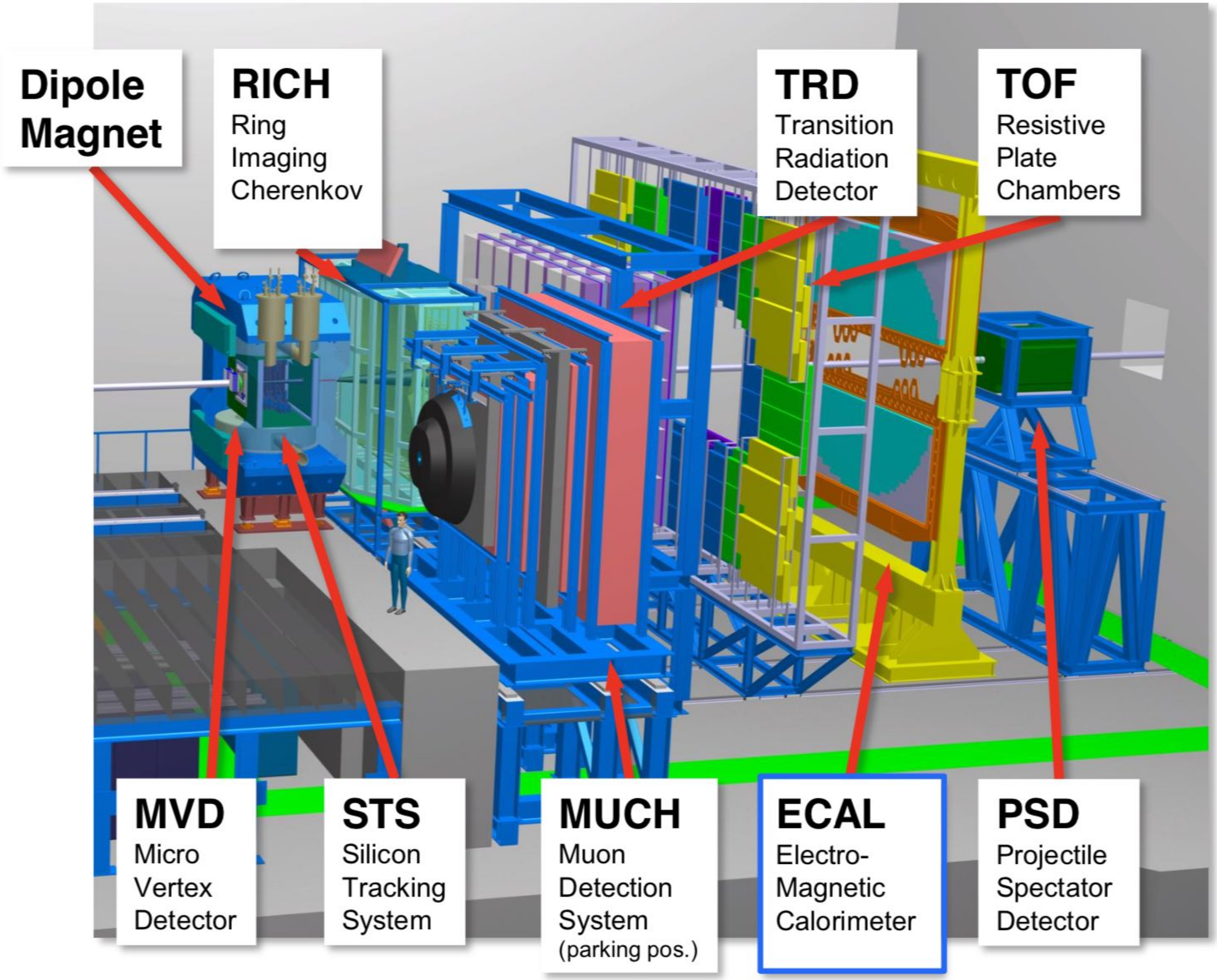
Analyses in framework of Statistical Hadronisation Model



Particle yields from central Au + Au collisions



CBM



- Tracking acceptance: $2^o < \theta_{lab} < 25^o$
- Free streaming DAQ
- R_{int} = 10 MHz (Au+Au)

  $R_{int} \approx 0.5$ MHz
  full bandwith:
  Det. – Entry nodes
  reduced bandwidth
  Entry nodes – Comp. farm

  with
  R_{int} (MVD)=0.1 MHz
- Software based event selection

Day-1 setup = MSV setup – Compute Performance - ECAL
Phase-1 = Day1 with full Compute Performance + ECAL

Day-1 funding: ~ 90% secured

FAIR construction side: January 19, 2019

CBM

Key technology towards new physics frontiers

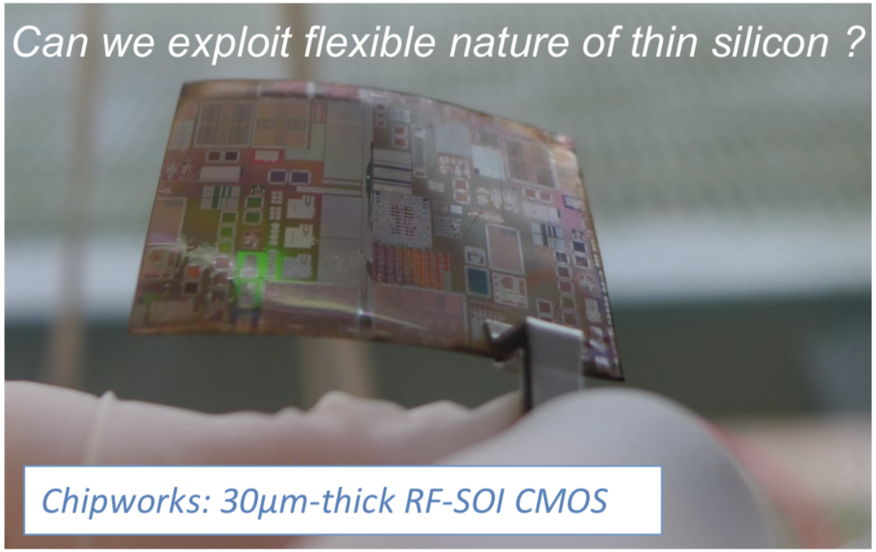
Technological innovation of silicon detectors for a fast and light future experiment.

3 key ingredients:

- Thinning of wafers to realize curved silicon chips
- Stitching to fabricate wafer scale sensors
- Ultra-fast CMOS pixels for time-of-flight measurements for particle identification

Key 1: exploit flexibility of thin silicon layers → < 0.05% X_0 per layer

R&D Luciano Musa (CERN) with IZM ALPIDE ongoing



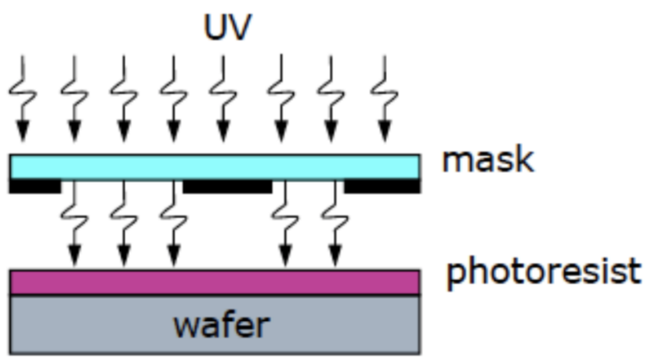
Ultra-thin chip (<50 um): flexible with good stability

Key 2: use the stitching technology to fabricate sensors of large as the entire silicon wafer

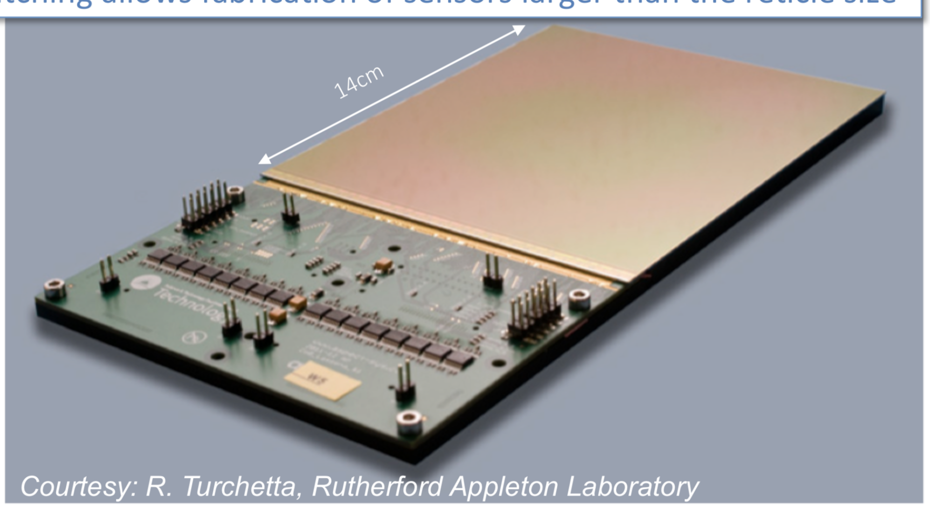
CMOS photolithographic process defines wafer reticles size

⇨ Typical field of view O(2 x 2 cm²)

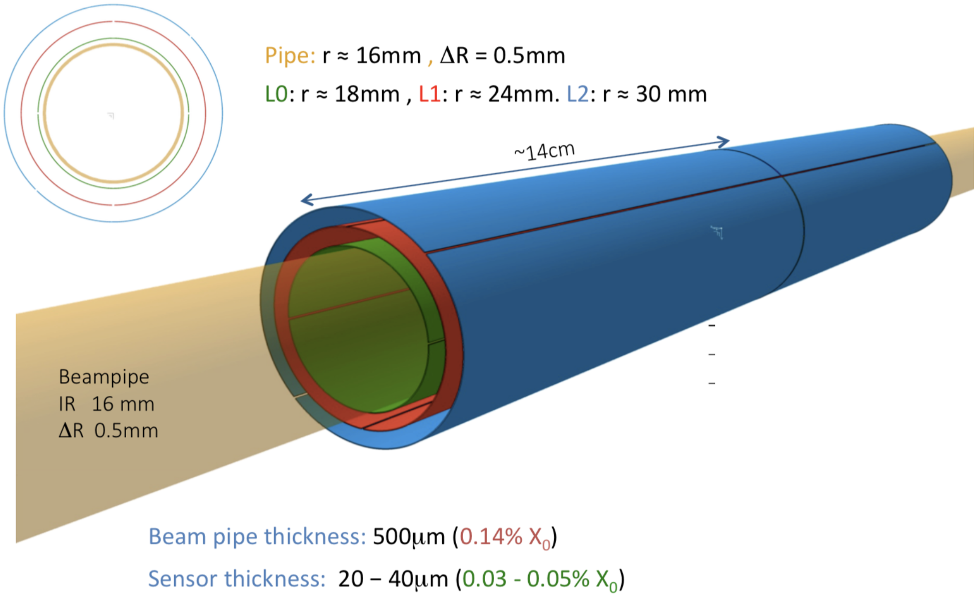
Reticle is stepped across the wafers to create multiple identical images of the circuit(s)



Stitching allows fabrication of sensors larger than the reticle size



Courtesy: R. Turchetta, Rutherford Appleton Laboratory



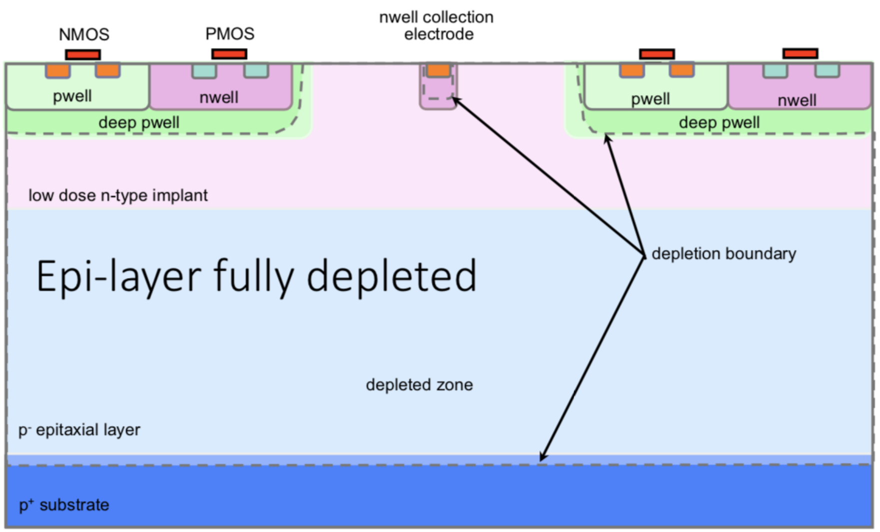
Key technology to reach new physics frontiers

Key 3: ultra-thin O(10 μm) fully depleted CMOS sensors with 10V reverse bias:

- reduces charge collection time (<1ns)
- enhances radiation hardness (~ 10^{15} n/cm^2)

promises time resolution (single layer) of the order **σ_t < 27 ps**

(effect of signal shape fluctuations inside sensor under study)



Modified process CERN/Tower

Also: other technologies for timing layers for ATLAS and CMS: LYSO crystals + SiPM, and Low-Gain Avalanche Diode (LGAD)

Ultra-light all-silicon detector

Ideas for a new heavy-ion experiment for Run 5 (from 2031), after LS4

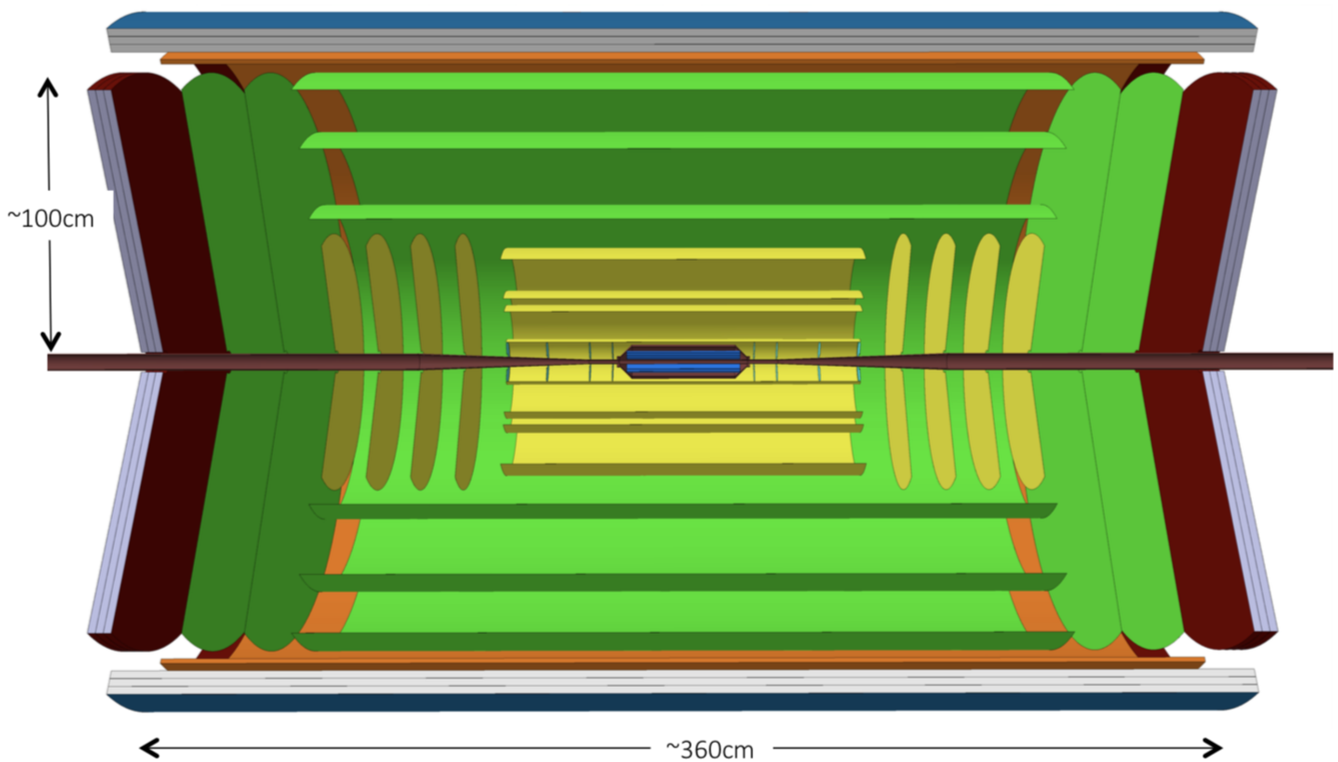
capable to handle extremely high rates for rare probes (heavy flavors, heavy quarkonia, light (anti-)(hyper-)nuclei), and measure ultra low p_T particles

Tracker: ~10 tracking barrel layers (blue, yellow and green) based on CMOS sensors

Hadron ID: TOF with outer silicon layers (orange)

Electron ID: pre-shower (outermost blue layer)

Extended rapidity coverage: **up to 8 rapidity units**
+ FoCal



L. Musa (CERN) – ALICE Physics Week, 23 Oct 2018

Preliminary studies

Magnetic Field
- B = 0.5 or 1 T

Spatial resolution
- Innermost 3 layers: $\sigma \sim 1\mu m$
- Outer layers: $\sigma \sim 5\mu m$

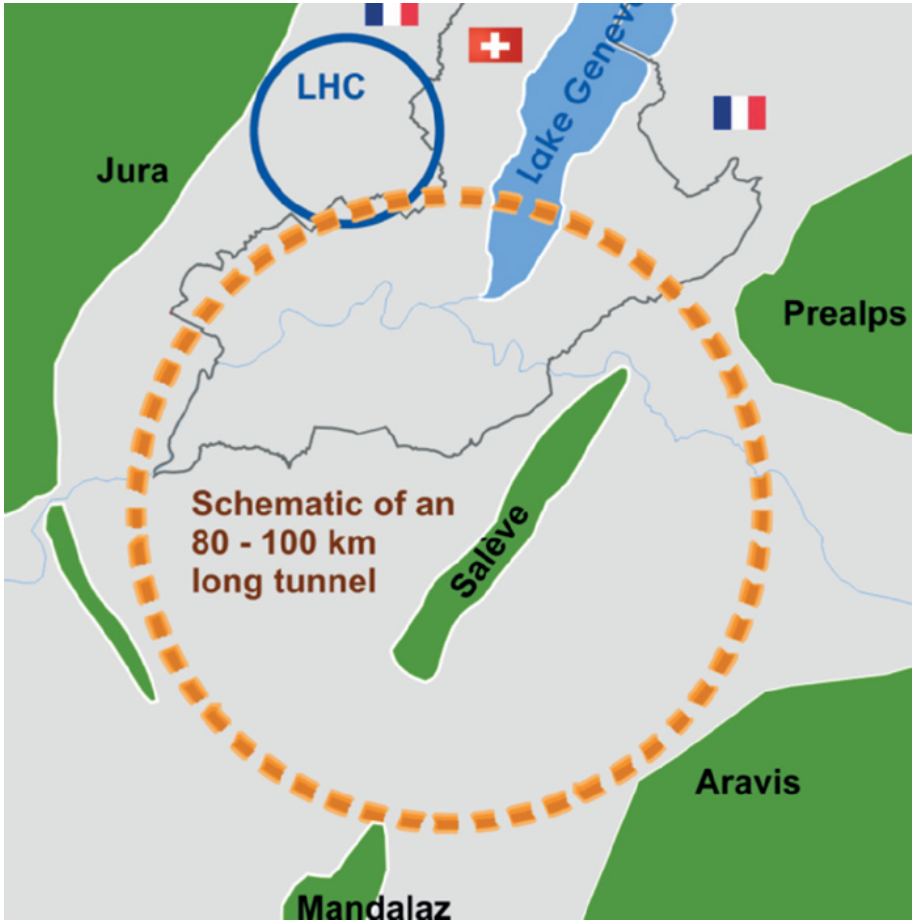
Time Measurement
Outermost layer integrates high precision time measurement ($\sigma_t < 30ps$)

arXiv:1902.01211

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

Future Circular Collider

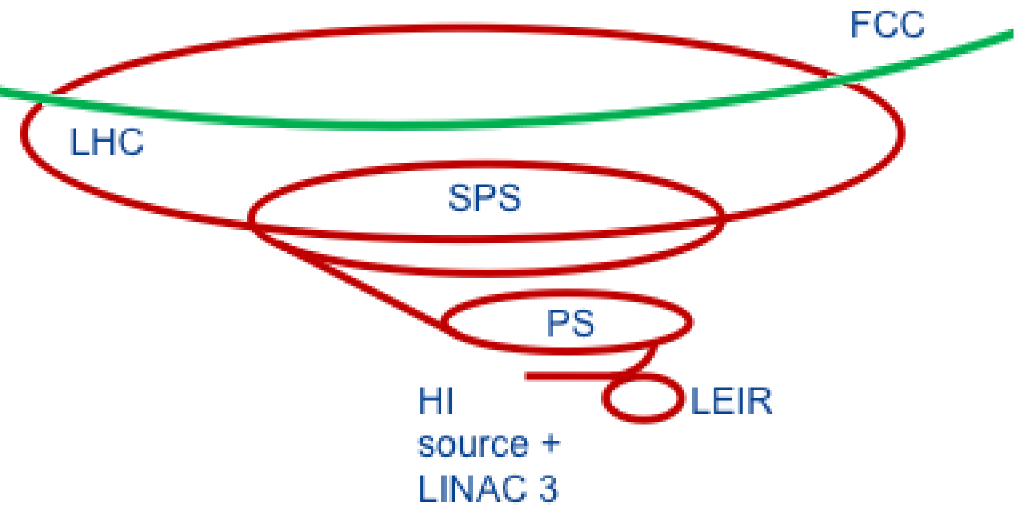
- Proton-proton collider (FCC-hh)
  ~16 T → 100 TeV pp in 100 km
  ~20 T → 100 TeV pp in 80 km
  → defining infrastructure requirements
- e^+e^- collider (FCC-ee) as potential intermediate step
- p-e (FCC-he) option
- **Ion program!**



Scope: CDR and cost review for the next European strategy (2019)
Starting date targeted for ~2045 (?)

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

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 GeV/fm^3	16–17 GeV/fm^3	35–40 GeV/fm^3

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

$dE_T/d\eta$ x 2.2

volume x 1.8

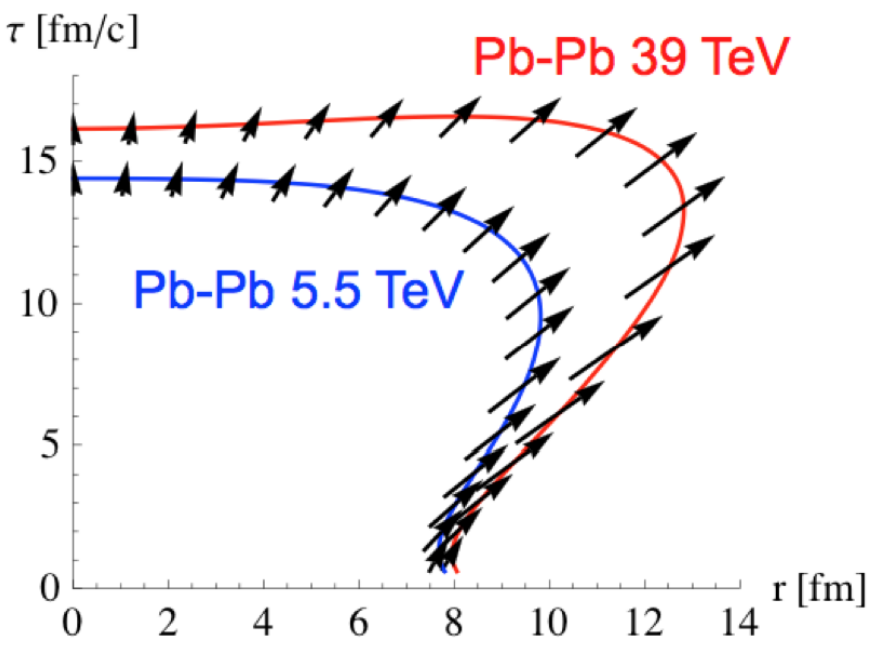
d. time x 1.3

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

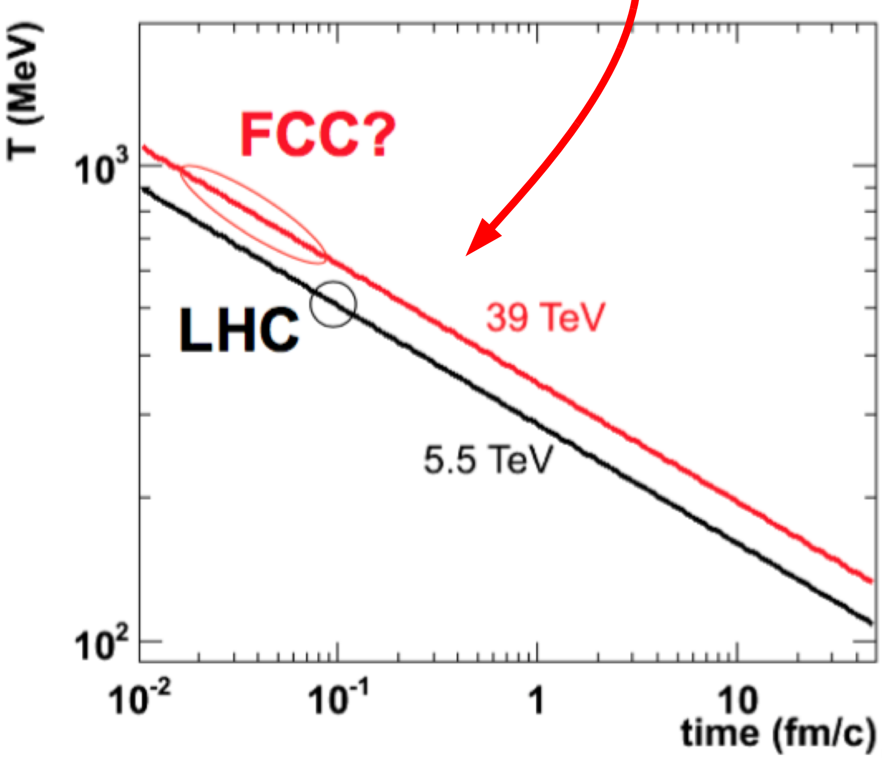
Global properties at $\sqrt{s_{NN}}$ = 2.76 TeV (0-5% centrality interval) extrapolated to 5.5 and 39 TeV

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



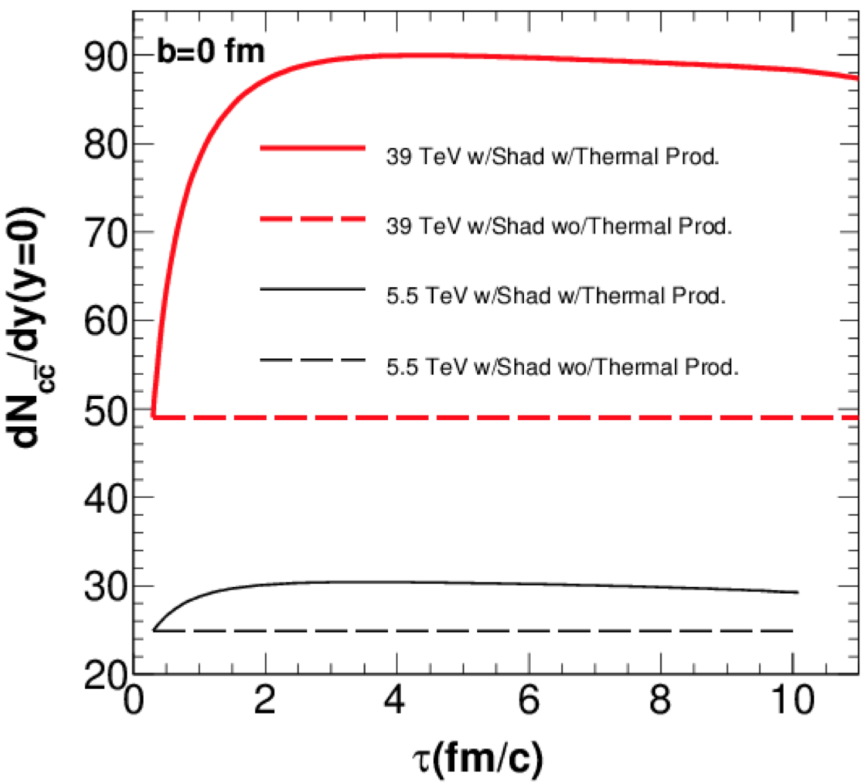
QGP temperature evolution on basis of Bjorken relation and Boltzmann equation

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)



K. Zhou et al. PLB758 (2016) 434

New relevant dof
Effect on the QGP equation of state?
Under debate

Conclusion

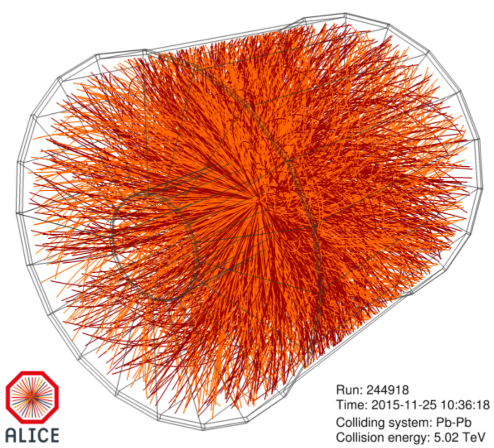
Heavy-ion collisions provide an essential window to access fundamental properties of QCD matter

Extremely dynamic field

Deep collaboration between theory and experiment

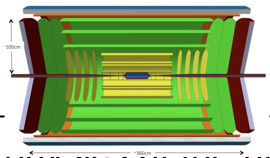
Remarkable progress in the last years

Field accompanied by fantastic detector (and computing) challenges and developments



Timeline

	CERN	ALICE	FAIR	
2019 2020	Long Shutdown 2			
2021 2022 2023	Run 3 Pb-Pb 5.5 TeV, 50 kHz	Approved physics program to 10 nb^{-1}		
2024 2025	Long Shutdown 3	**ITS3 ?** Possible new inner-most vertex det layers with curved silicon	CBM	Beam on target
2026 2027 2028 2029	Run 4 Pb-Pb 5.5 TeV, 50 kHz			
2030	Long Shutdown 4			
2031		New experiment ?		



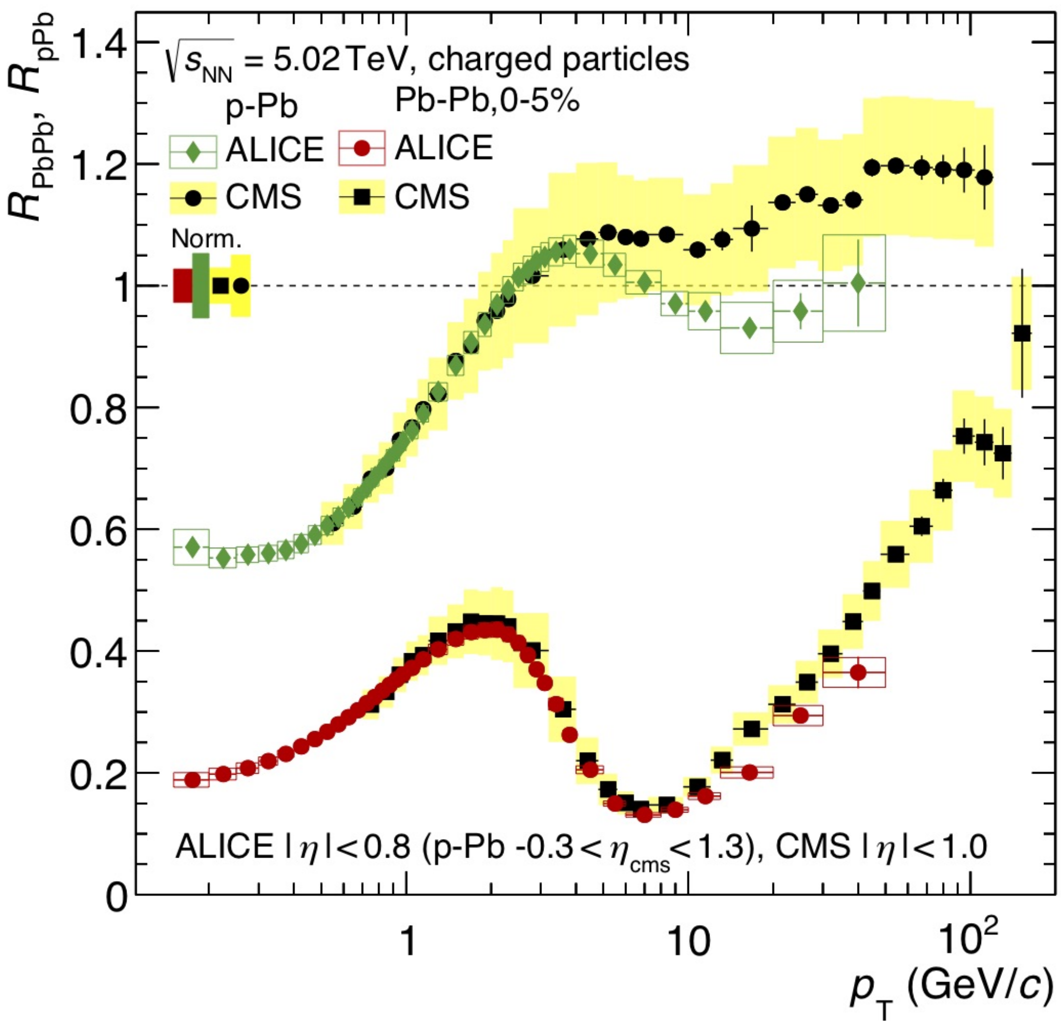
Nuclear modification factor

No medium effect → $R_{AA} \approx 1$

Medium effect → medium "slows" down particles

→ $R_{AA} \neq 1$

Comparison ALICE - CMS

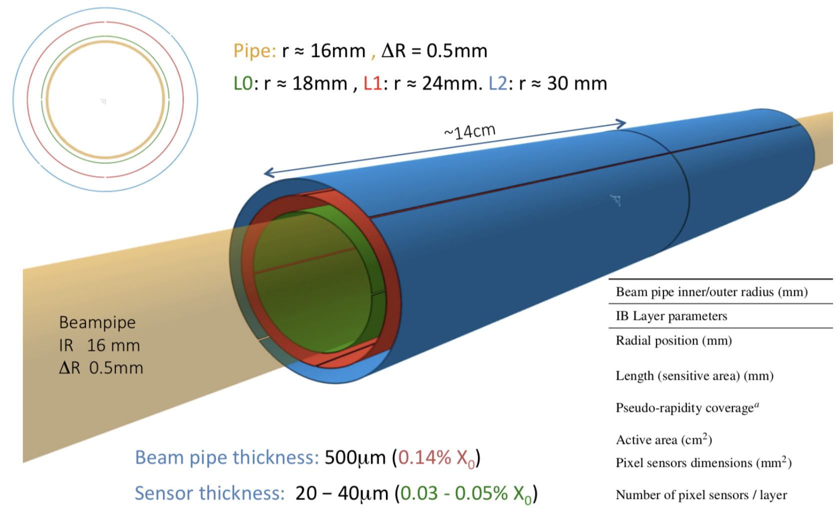


arXiv:1802.09145, accepted by JHEP

And after that ?

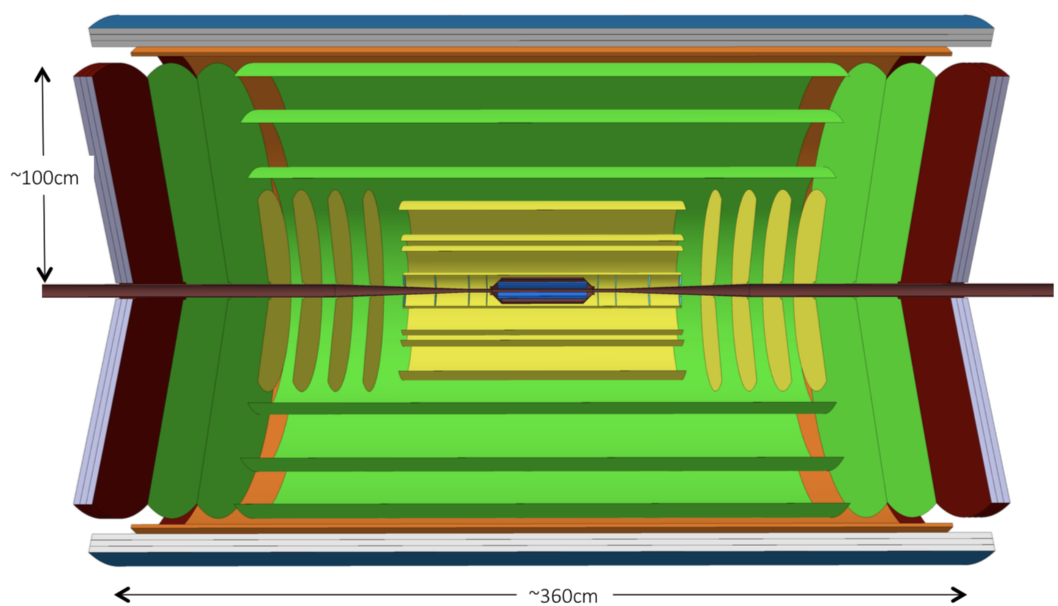
Very exciting technological development of ultra-thin, flexible silicon detectors

Ultra-thin chip (<50 um): flexible with good stability



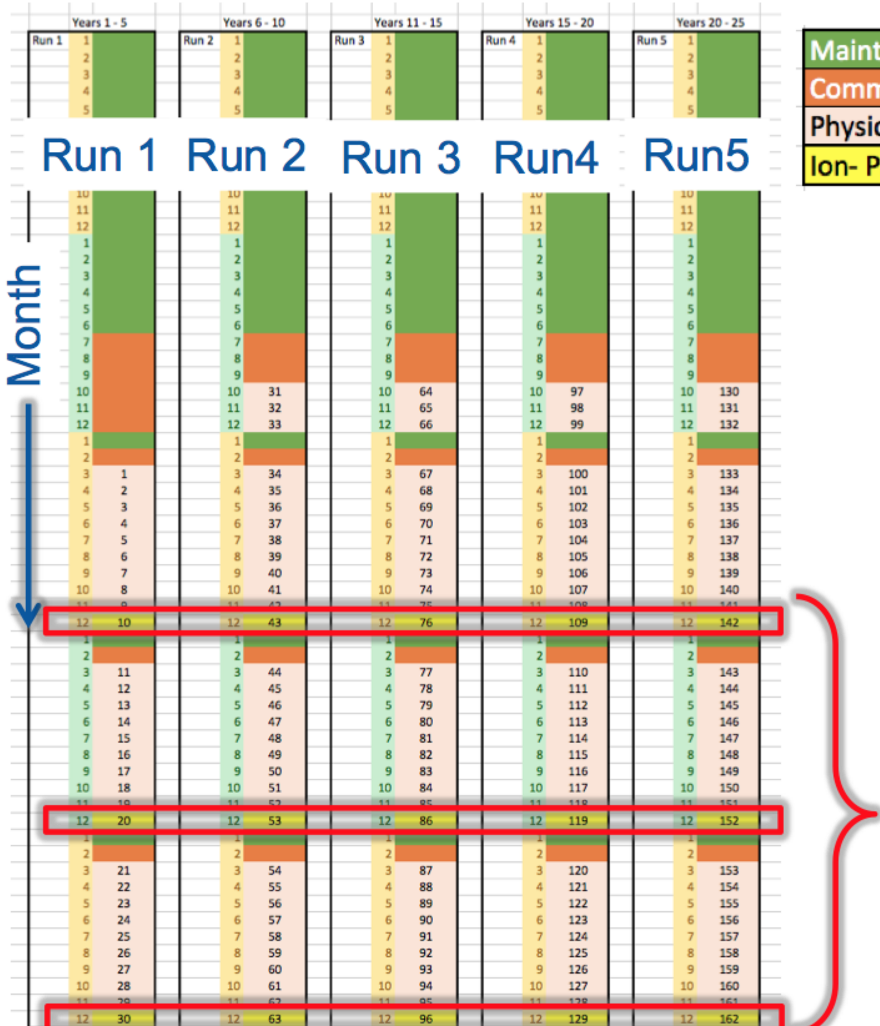
Explore ideas of a new ultra-light experiment:

- Extremely high rates
- Unprecedented reach to VERY low p_T



Luciano Musa (CERN)

Tentative Run Schedule



Maintenance intervention
Commissioning
Physics
Ion- Physics

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

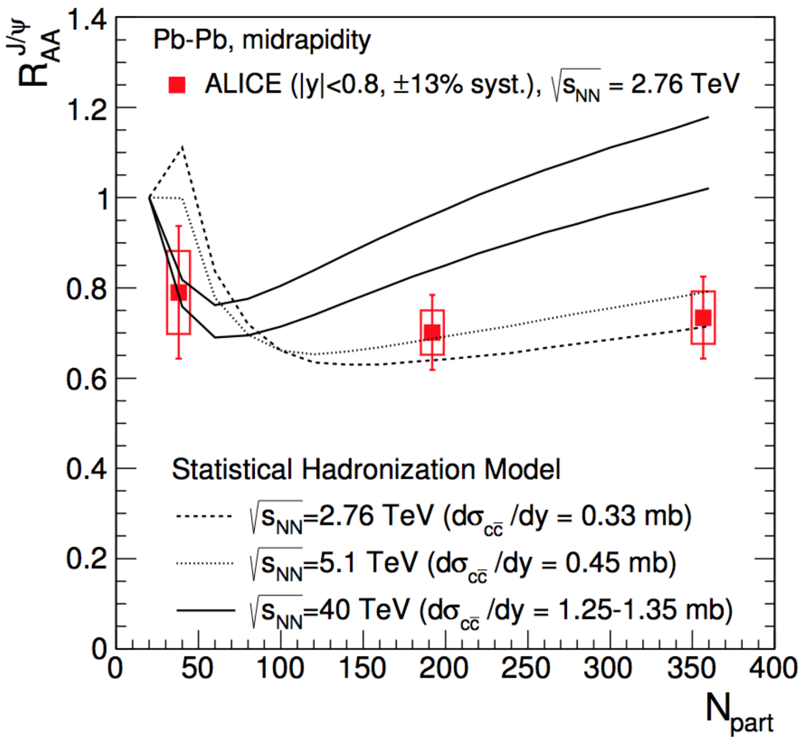
High energy → large production cross section for all hard probes

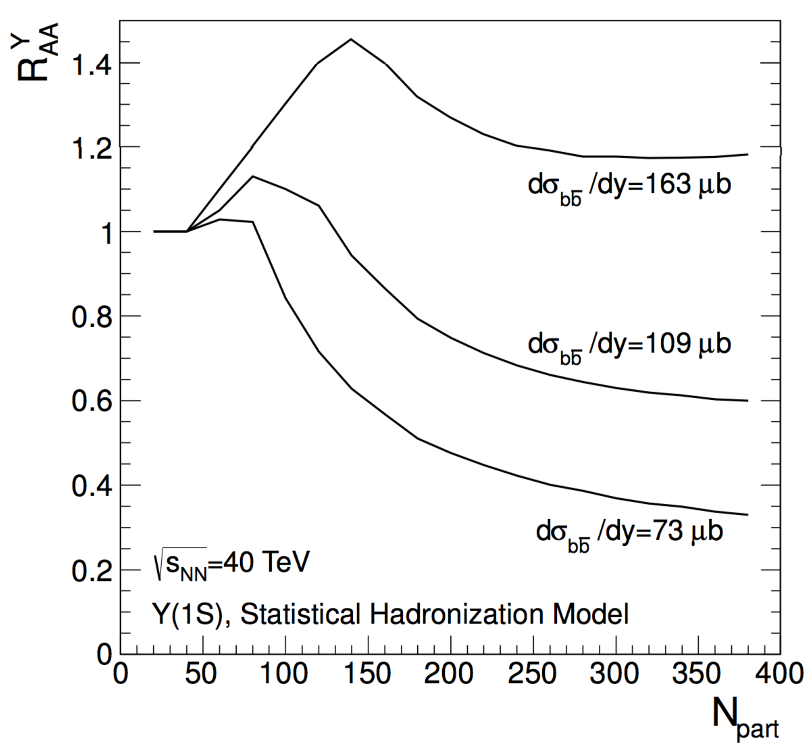
HEAVY QUARKONIA: charmonium and bottomonium

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

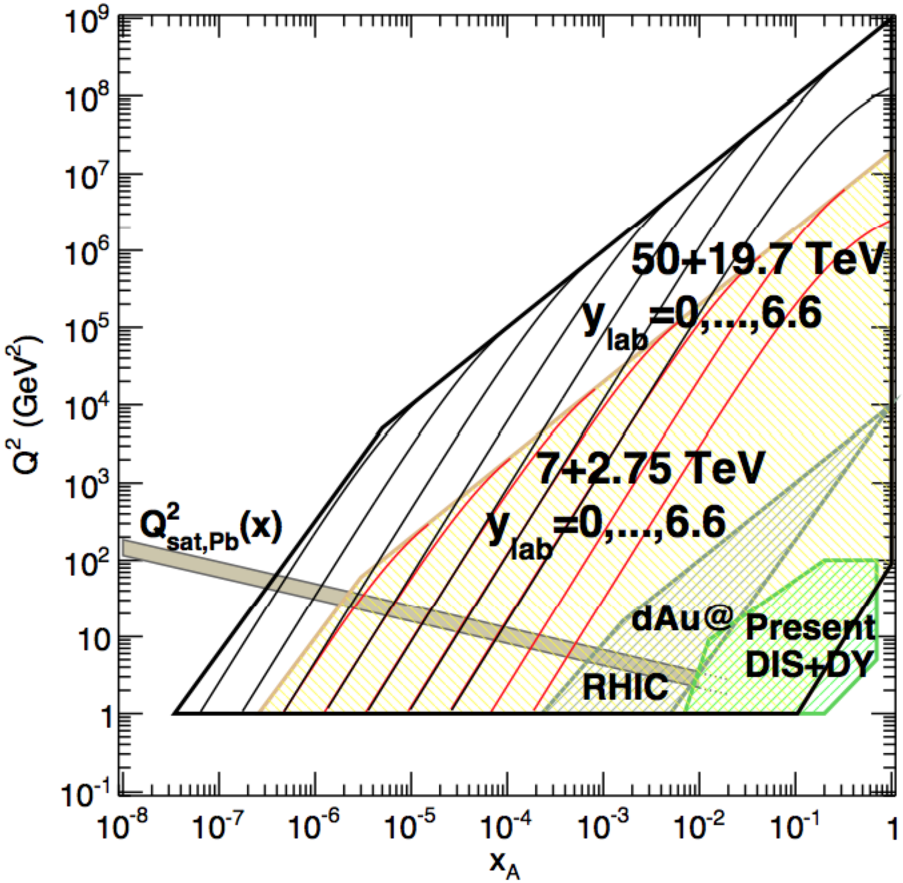


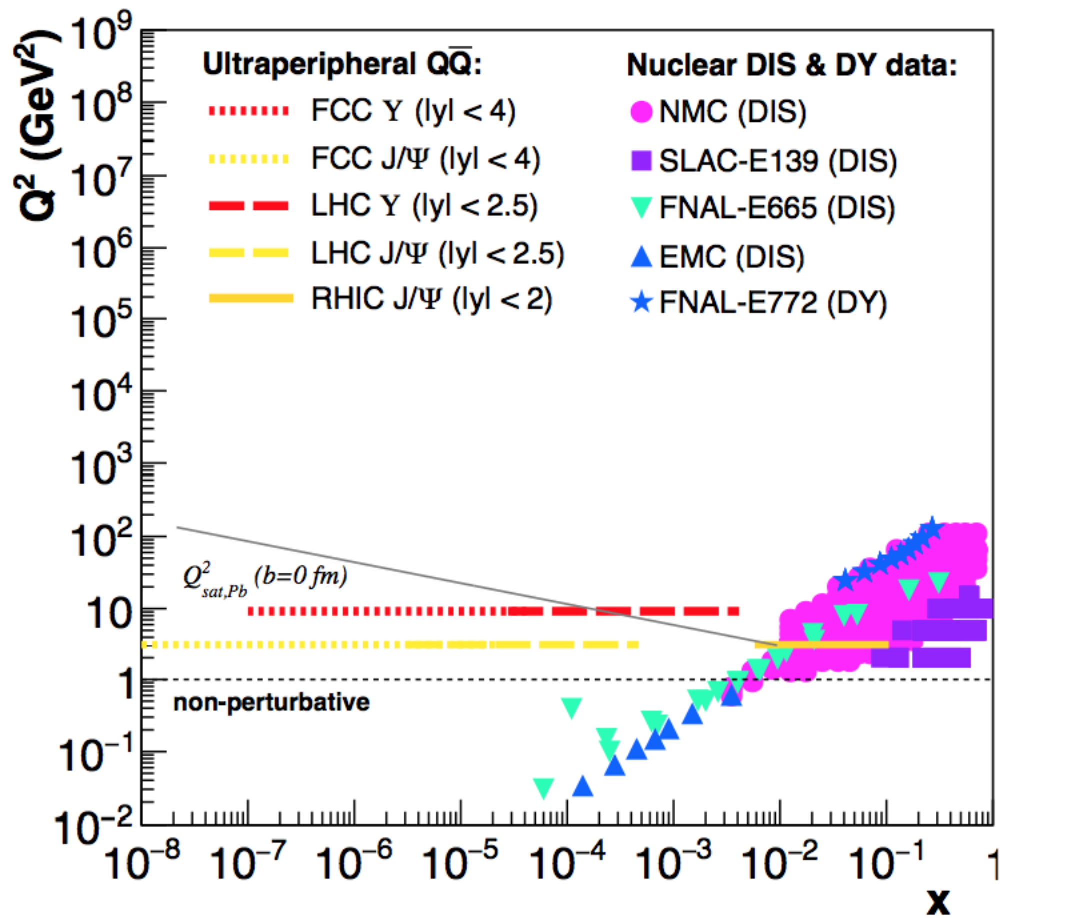


Υ(1S)

FCC-HI: physics opportunities

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

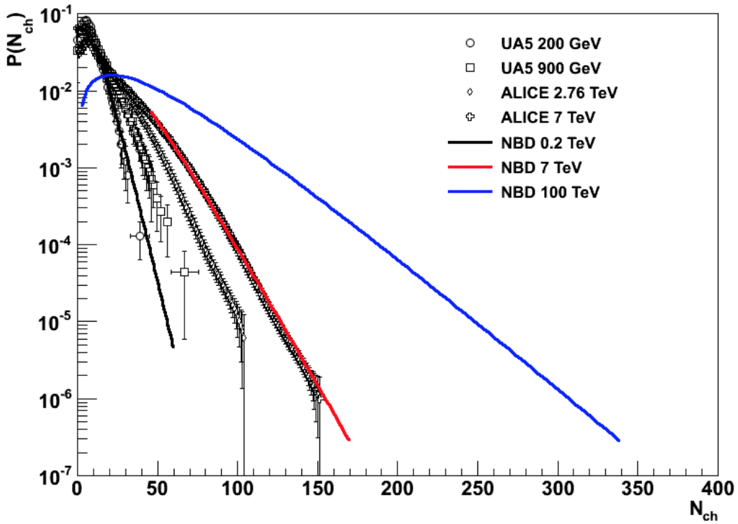




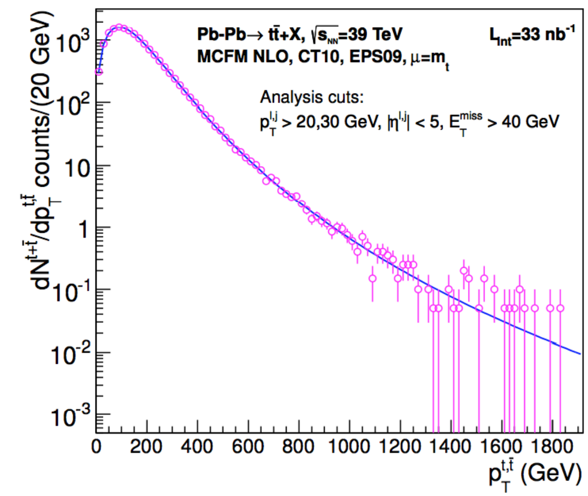
Test whether (perturbative) saturation lies in the accessible kinematic region (coverage of very forward region)

FCC-HI: more physics opportunities

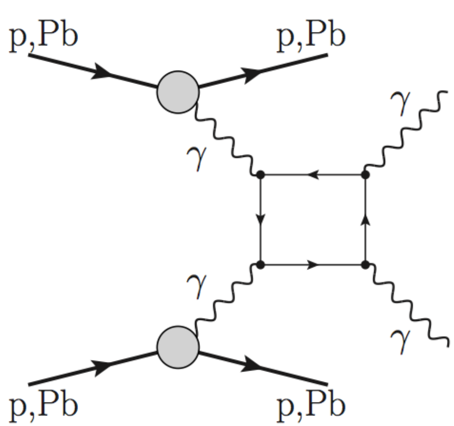
- VERY high multiplicity in pp and p-Pb



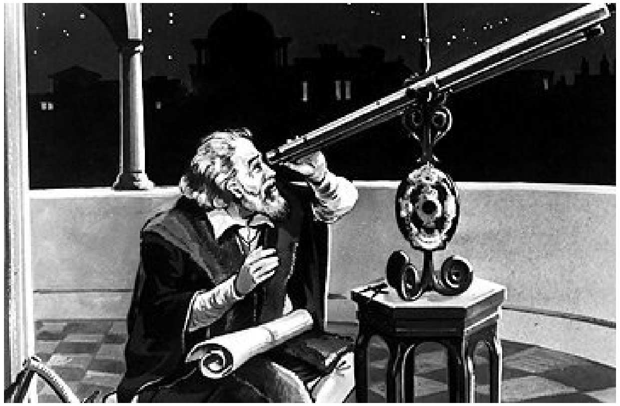
- single- and pair-top production: energy loss, time scales (boosted), nPDF



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

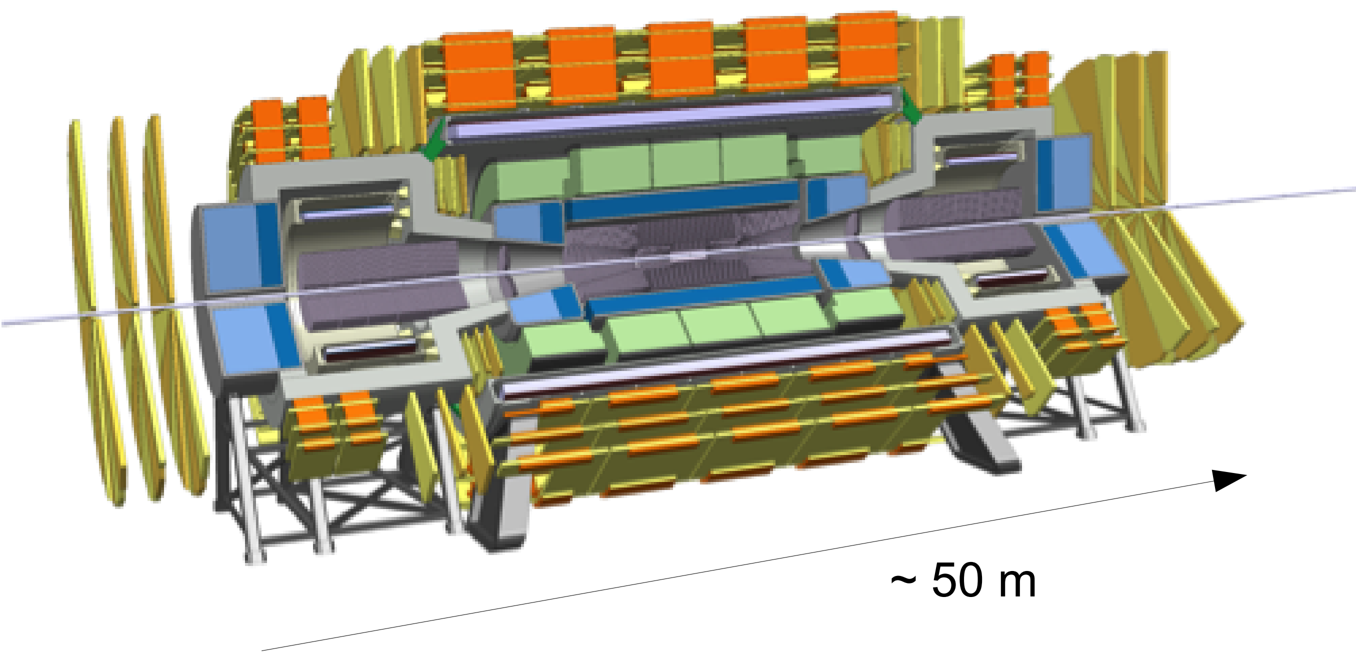


- Stay open for the unknown !!!



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

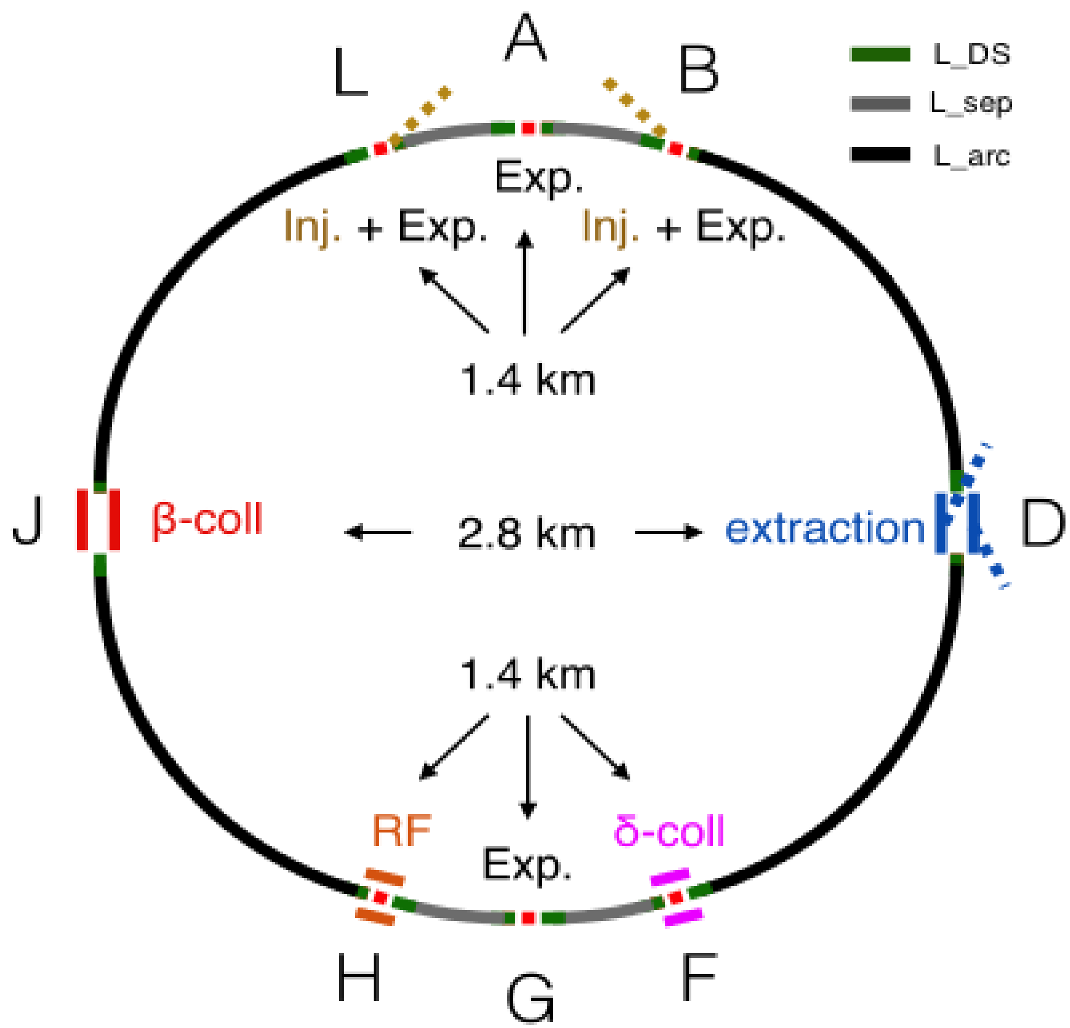
Dedicated experiment necessary?

Special settings for operation with heavy ions?

Focus on forward rapidity?

Werner Riegler

FCC layout

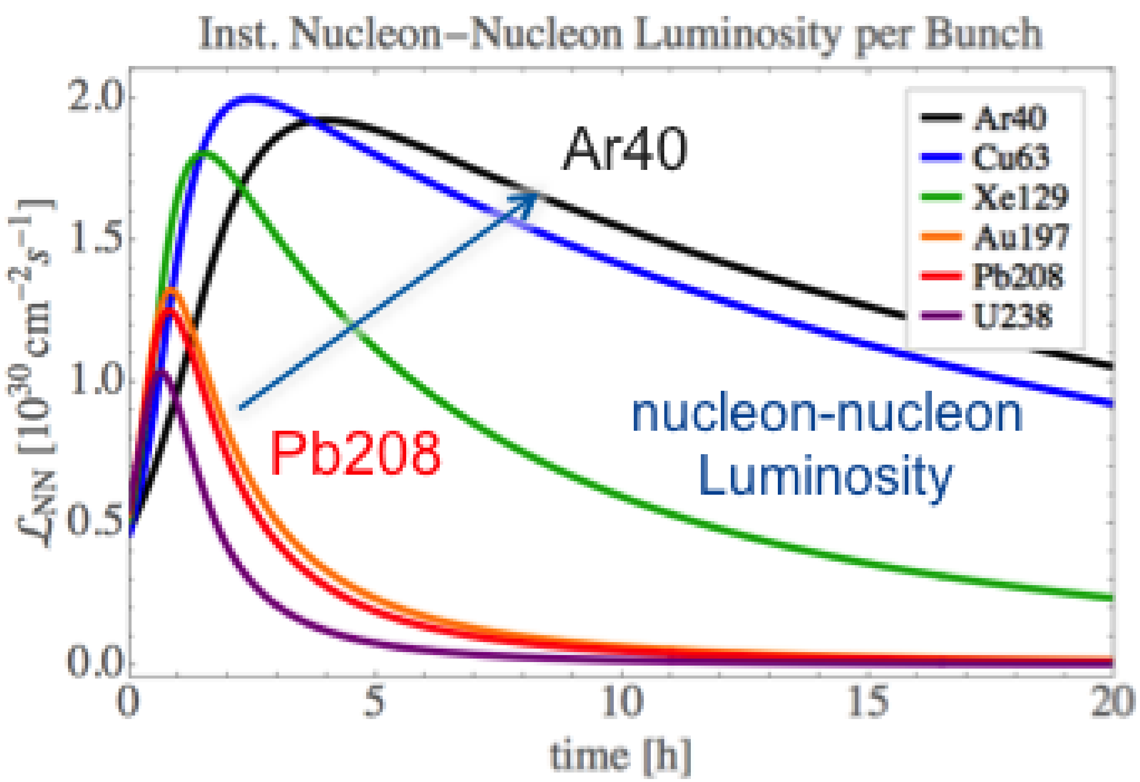


A
L
B
L_DS
L_sep
L_arc
Exp.
Inj. + Exp.
Inj. + Exp.
1.4 km
J
β-coll
2.8 km
extraction
D
1.4 km
RF
Exp.
δ-coll
H
G
F

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