

# Heavy Ion physics and projects

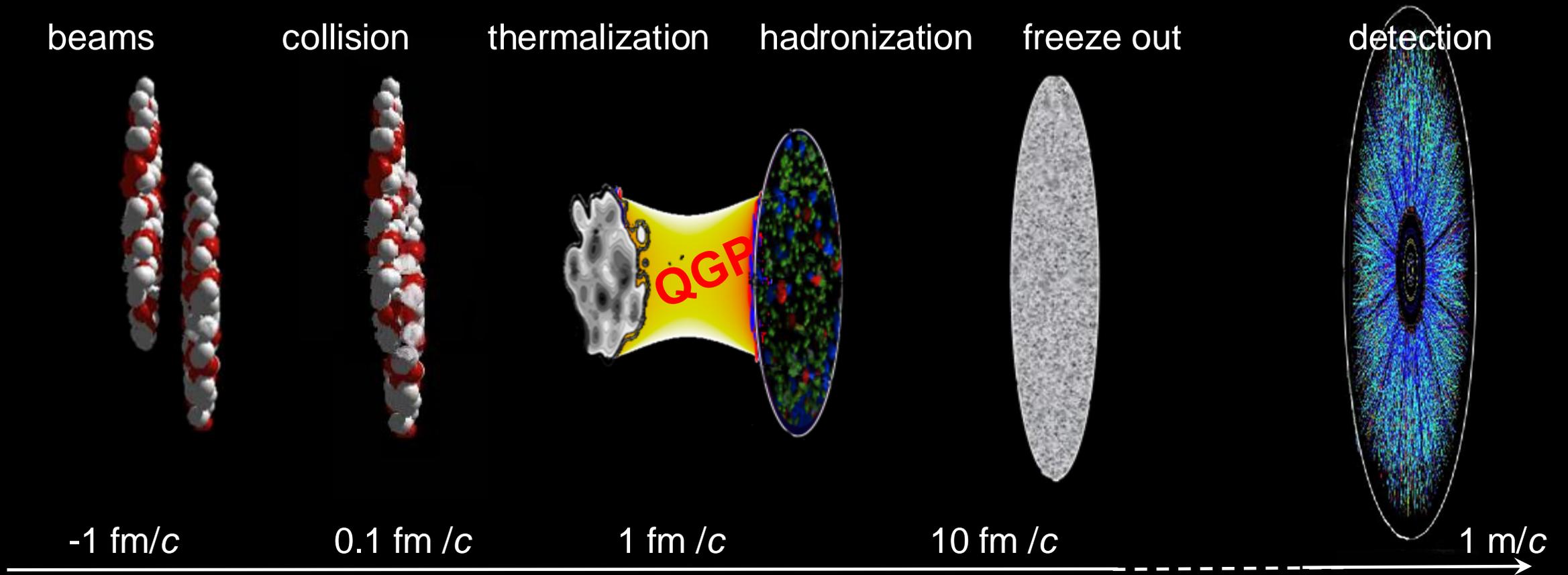


Sasha Milov

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הפקולטה לפיסיקה

# The quark-gluon plasma



Stages of heavy-ion collisions.

# Observables

The problem with HI studies is the absence of the 'QGP peak'. Different measurements must click together to convince the community that the QGP is formed.

Although conceptually, the QGP as a 'strongly coupled nearly ideal liquid' is a widely recognized concept, there are many open questions:

EoS?  
Critical point?  
Minimal conditions?  
etc.

Soft:

Global event characteristics: multiplicity, energy, mean  $p_T$ , speed of sound, baryochemical potential  
Fluctuations, anisotropies, correlations

Hard:

High- $p_T$  hadrons, jets, flavored hadrons, EW bosons

In HI collisions, the impact parameter is essential  
Centrality  
Photonuclear collisions  
Photon-photon collisions

# The big discoveries

## Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions

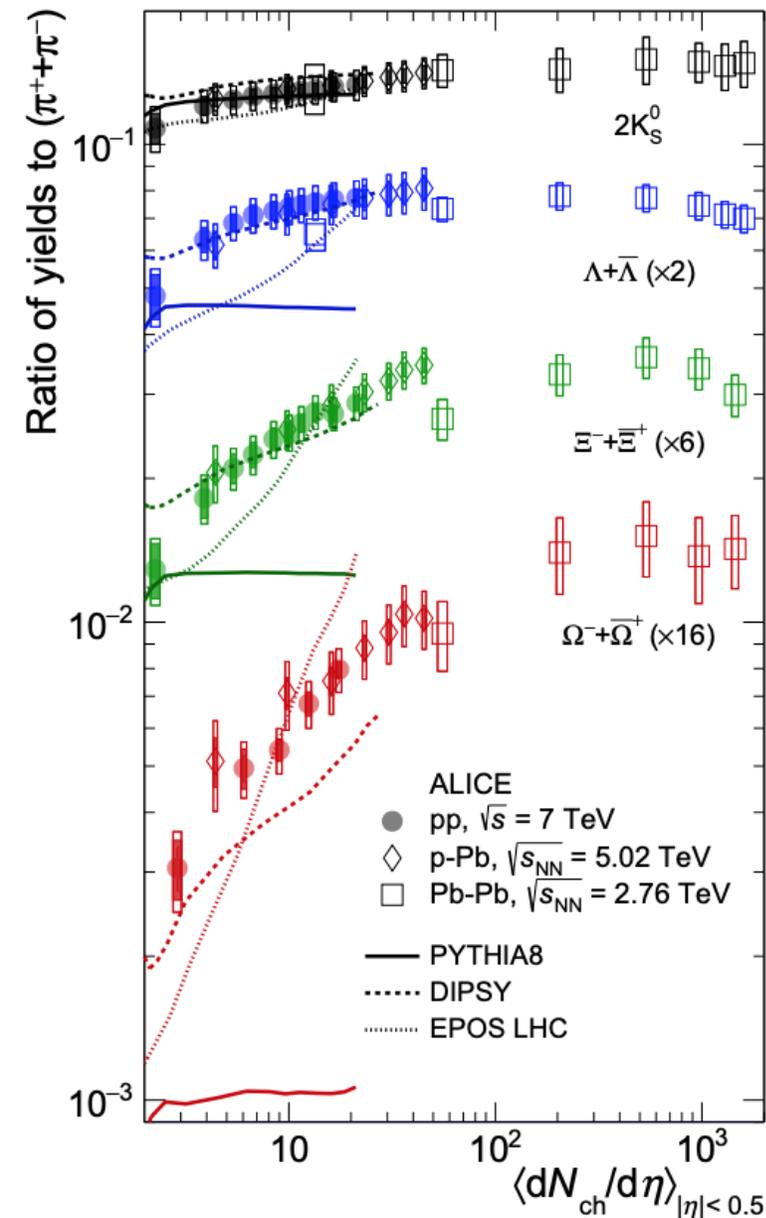
ALICE Collaboration · Jaroslav Adam (Prague, Tech. U.) et al. (Jun 23, 2016)

Published in: *Nature Phys.* 13 (2017) 535-539 · e-Print: 1606.07424 [nucl-ex]

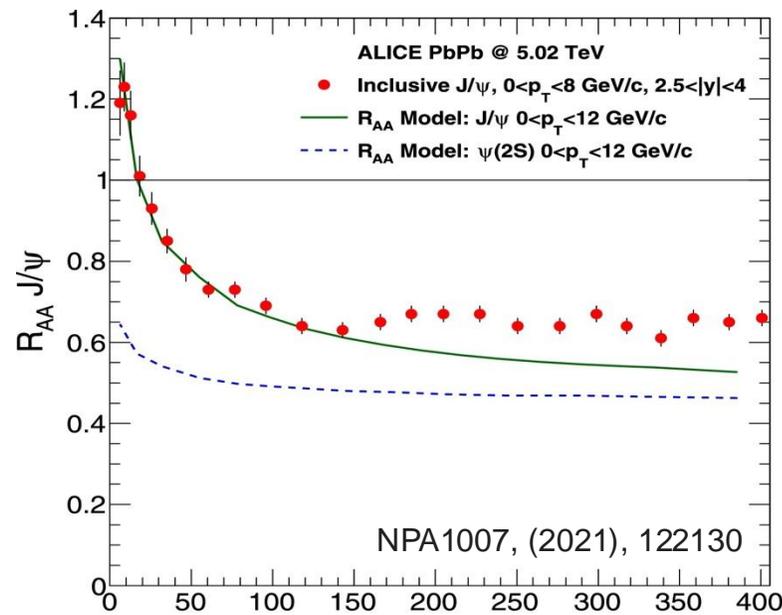
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reference search 833 citations

Formation of strange hadrons depends on the system size  
 The more s-quarks are present, the faster it grows  
 The most rapid development is in small systems



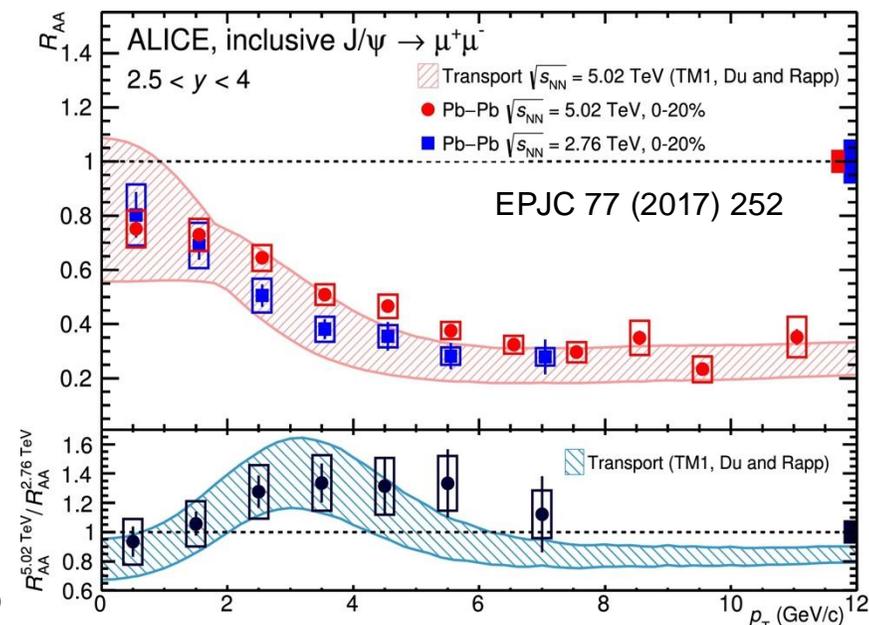
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HI physics and projects

Jan 15, 2025

## Restoration of J/ψ



FF25, HKUST

# The big discoveries

The 2<sup>nd</sup> most cited ATLAS paper,  
 The 3<sup>rd</sup> most cited CMS paper,  
 (except performance and combined) are HI papers

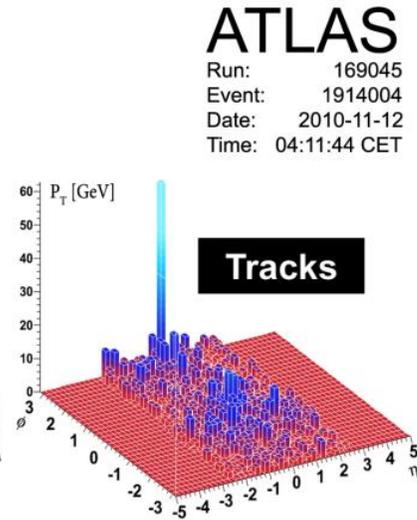
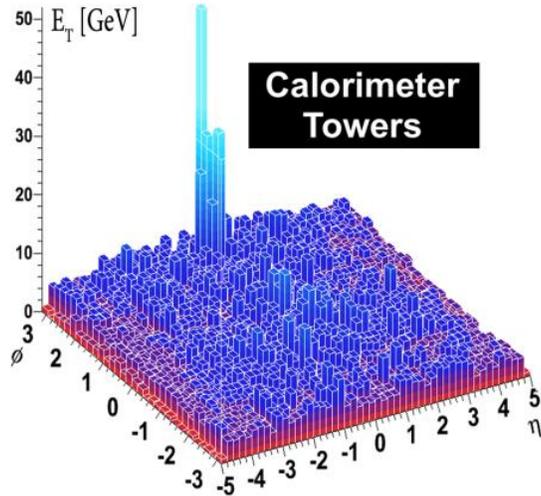
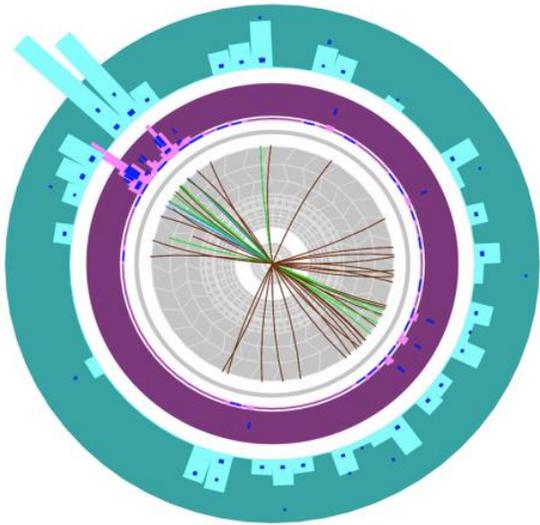
Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at  $\sqrt{s_{NN}} = 2.77$  TeV with the ATLAS Detector at the LHC #13

ATLAS Collaboration · Georges Aad (Freiburg U.) et al. (Nov, 2010)

Published in: *Phys.Rev.Lett.* 105 (2010) 252303 · e-Print: 1011.6182 [hep-ex]

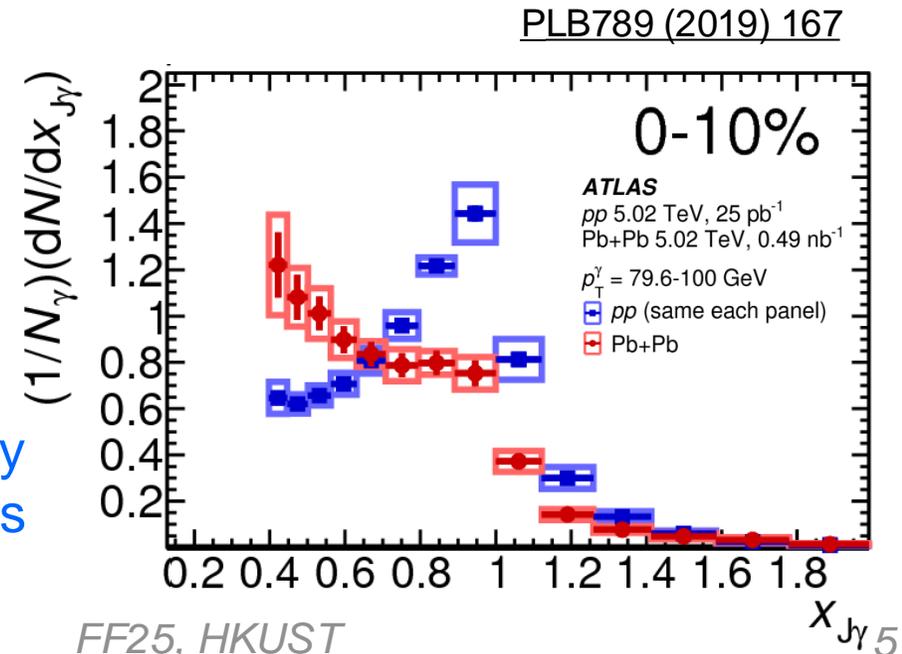
pdf links DOI cite datasets reference search 998 citations

Jet disbalance in Pb+Pb



**ATLAS**  
 Run: 169045  
 Event: 1914004  
 Date: 2010-11-12  
 Time: 04:11:44 CET

Jets lose energy wrt photons

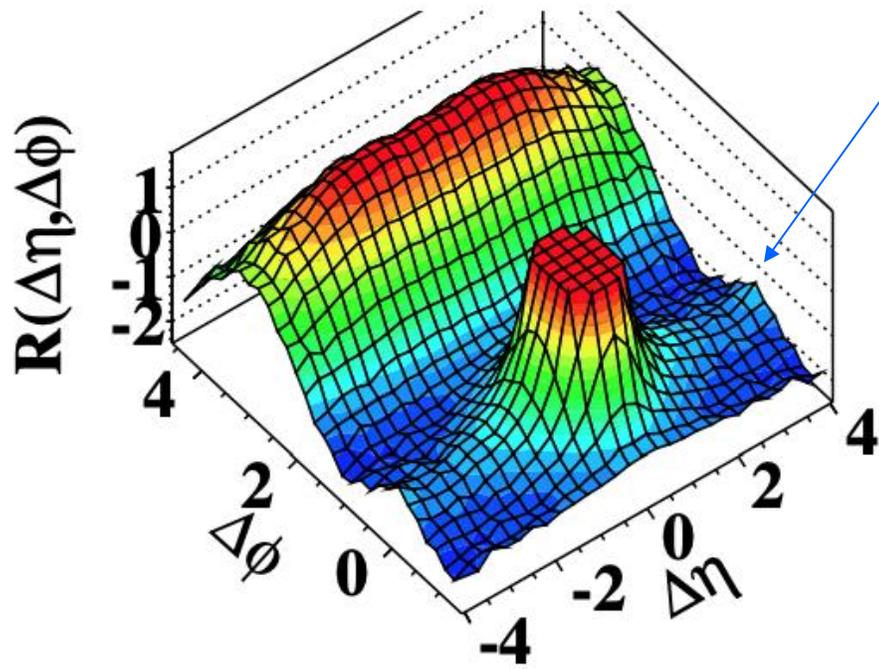


# The big discoveries

The 2<sup>nd</sup> most cited ATLAS paper,  
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 (except performance and combined) are HI papers

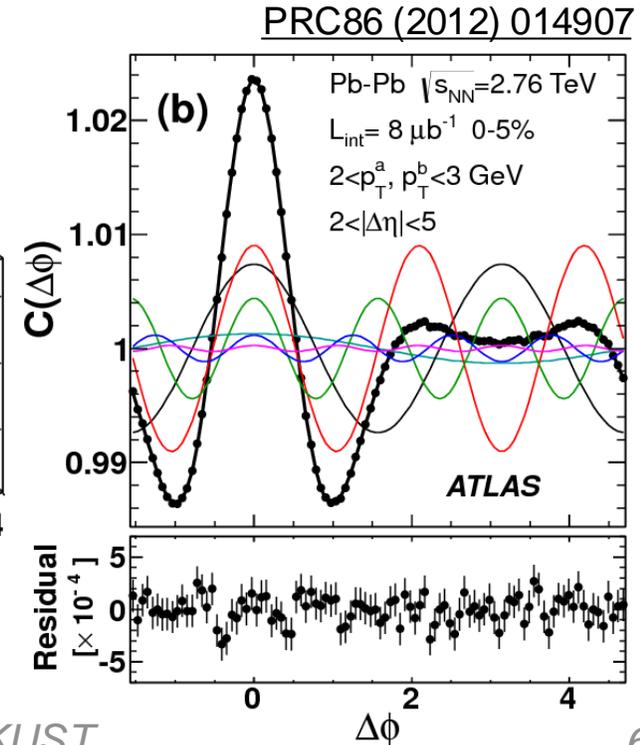
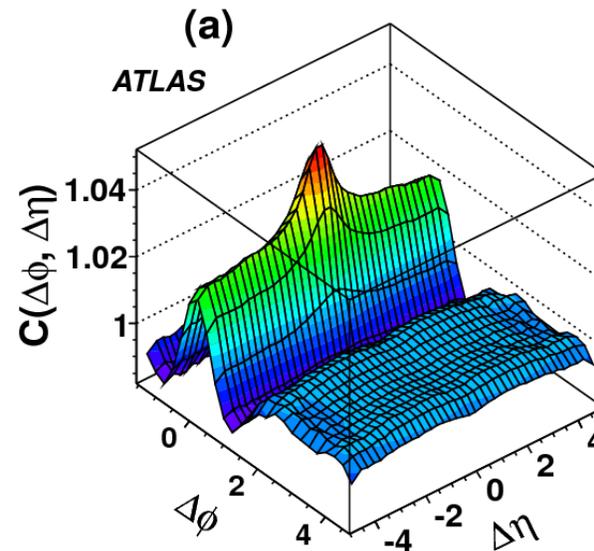
Observation of Long-Range Near-Side Angular Correlations in Proton-Proton Collisions at the LHC #15  
 CMS Collaboration · Vardan Khachatryan (Yerevan Phys. Inst.) et al. (Sep, 2010)  
 Published in: *JHEP* 09 (2010) 091 · e-Print: 1009.4122 [hep-ex]  
[pdf](#) [links](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [1,268 citations](#)

(d) CMS  $N \geq 110$ ,  $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$

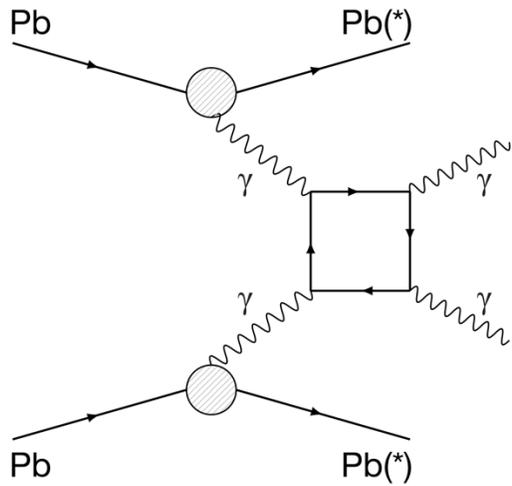


Ridge structure in  $pp$ ?

The effect is well-studied in A+A collisions,  
 where it is explained as a collective motion.



# The big discoveries



Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

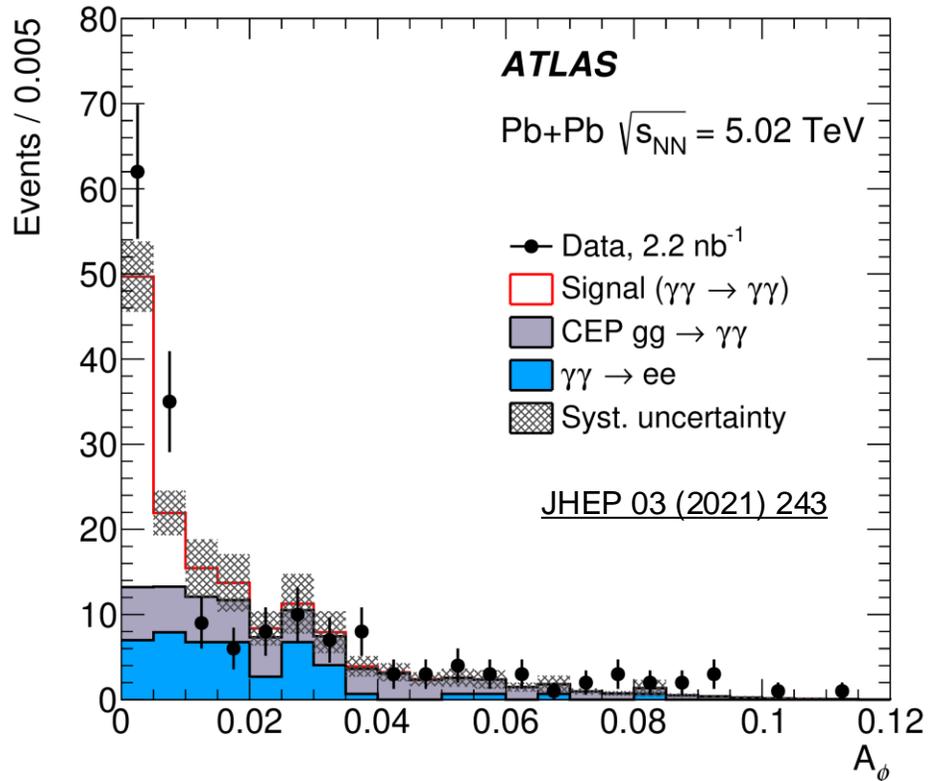
#106

ATLAS Collaboration • Morad Aaboud (Oujda U.) et al. (Feb 6, 2017)

Published in: *Nature Phys.* 13 (2017) 9, 852-858 • e-Print: [1702.01625](https://arxiv.org/abs/1702.01625) [hep-ex]

[pdf](#) [links](#) [DOI](#) [cite](#) [datasets](#)

[reference search](#) [394 citations](#)

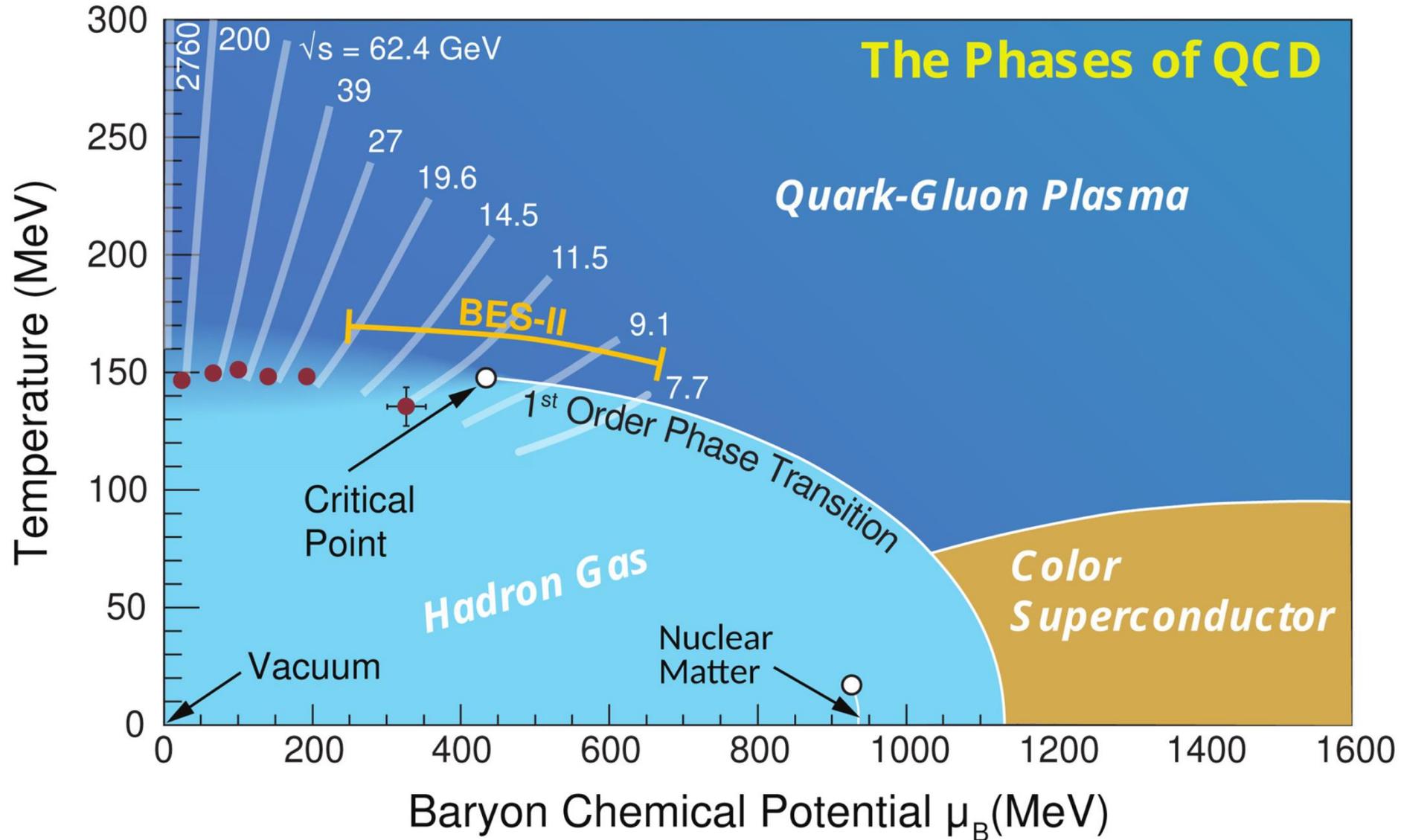


In A+A interactions, the EM fields of the nuclei are enhanced due to  $Z=82$  and collide with the incoming nuclei, producing photonuclear and  $\gamma\gamma$  interactions.

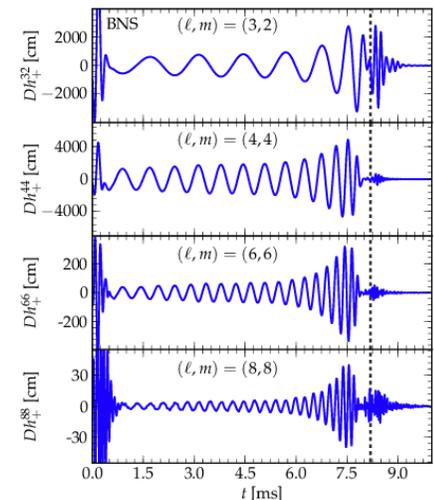
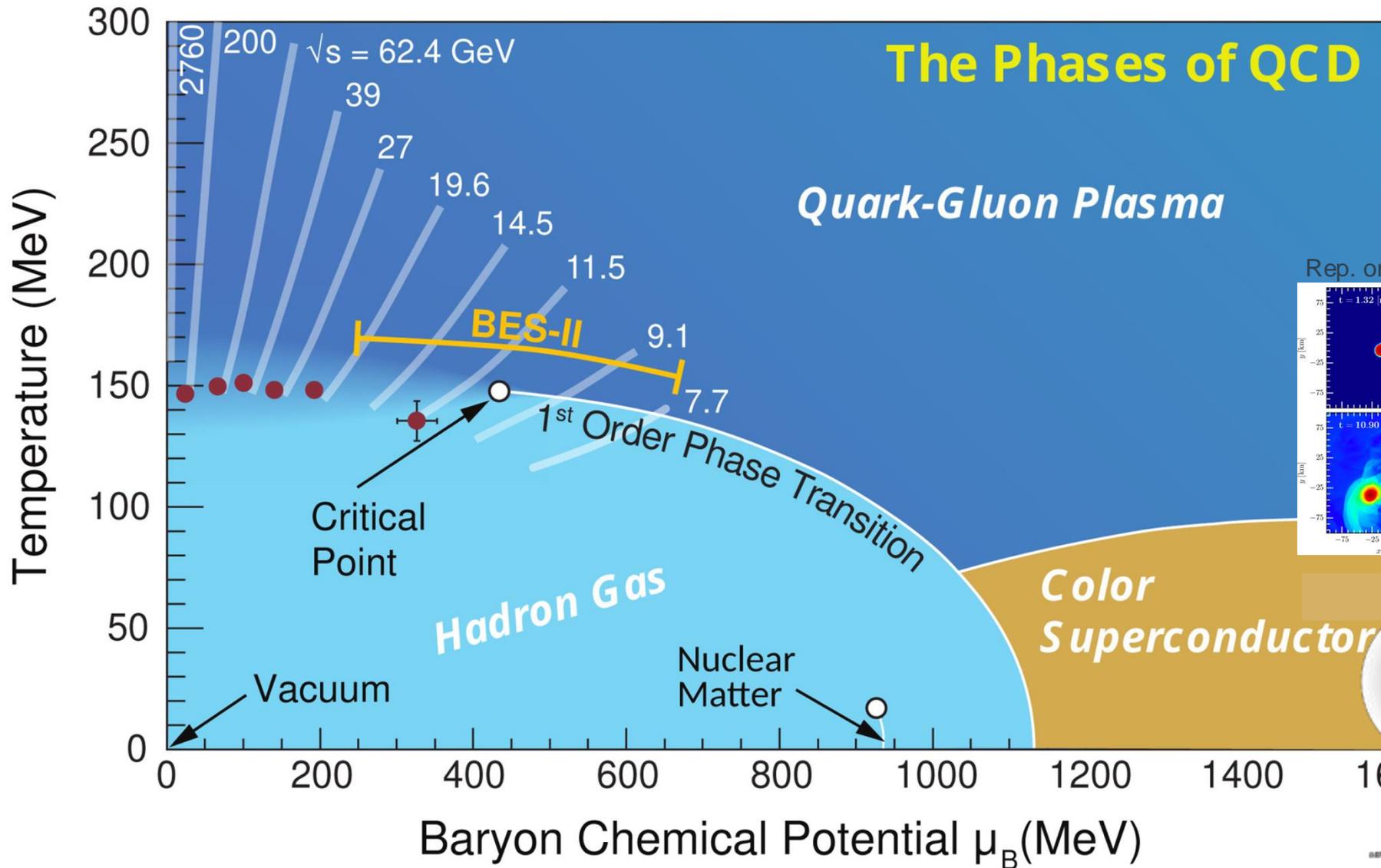
At LHC, the photonuclear interactions determine the luminosity lifetime.

High-energy HI collisions are  $\gamma\gamma$ -colliders

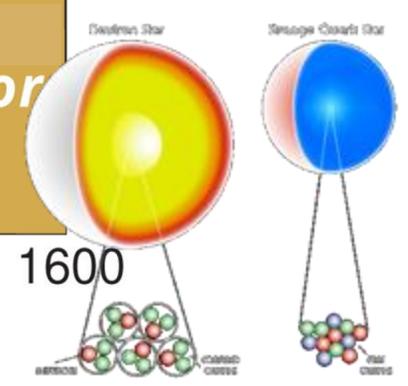
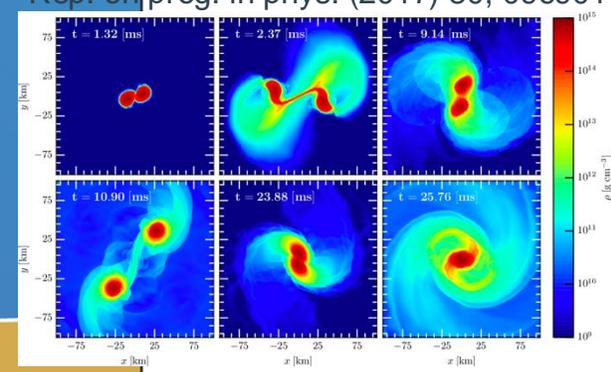
# The phase diagram



# The phase diagram



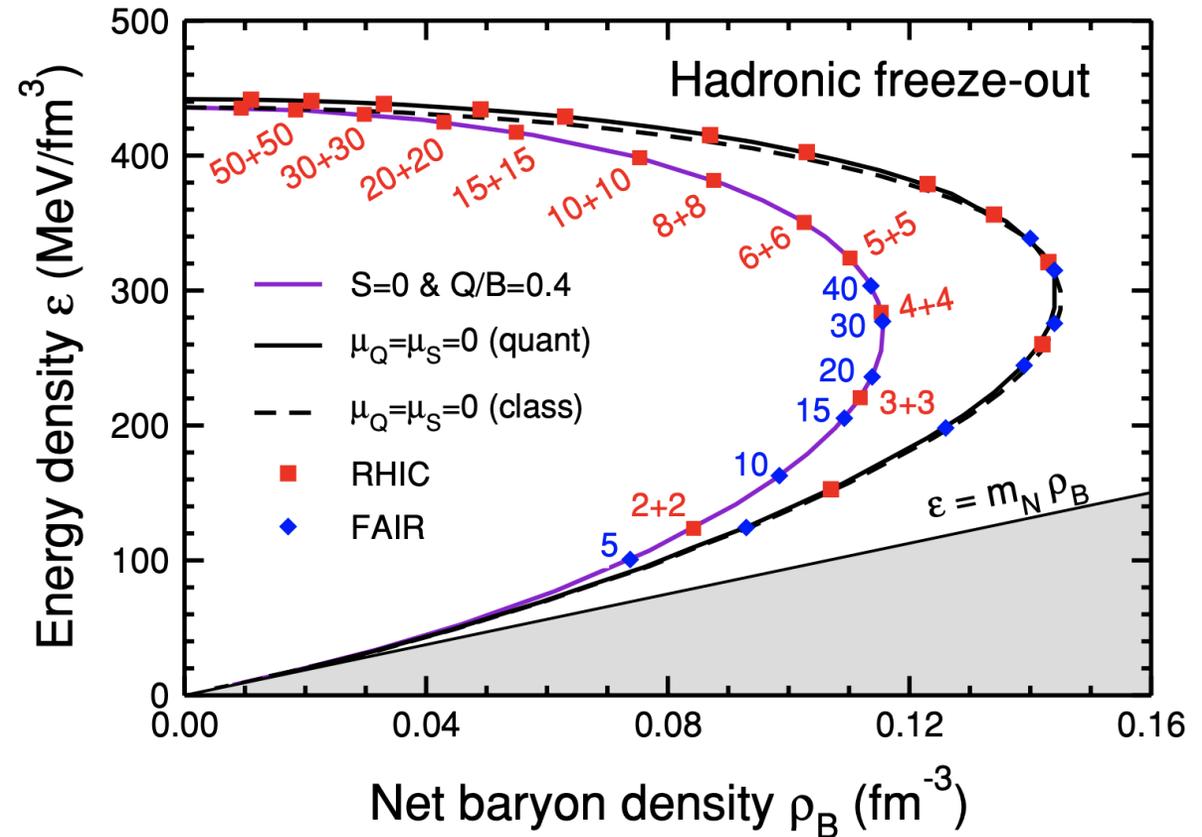
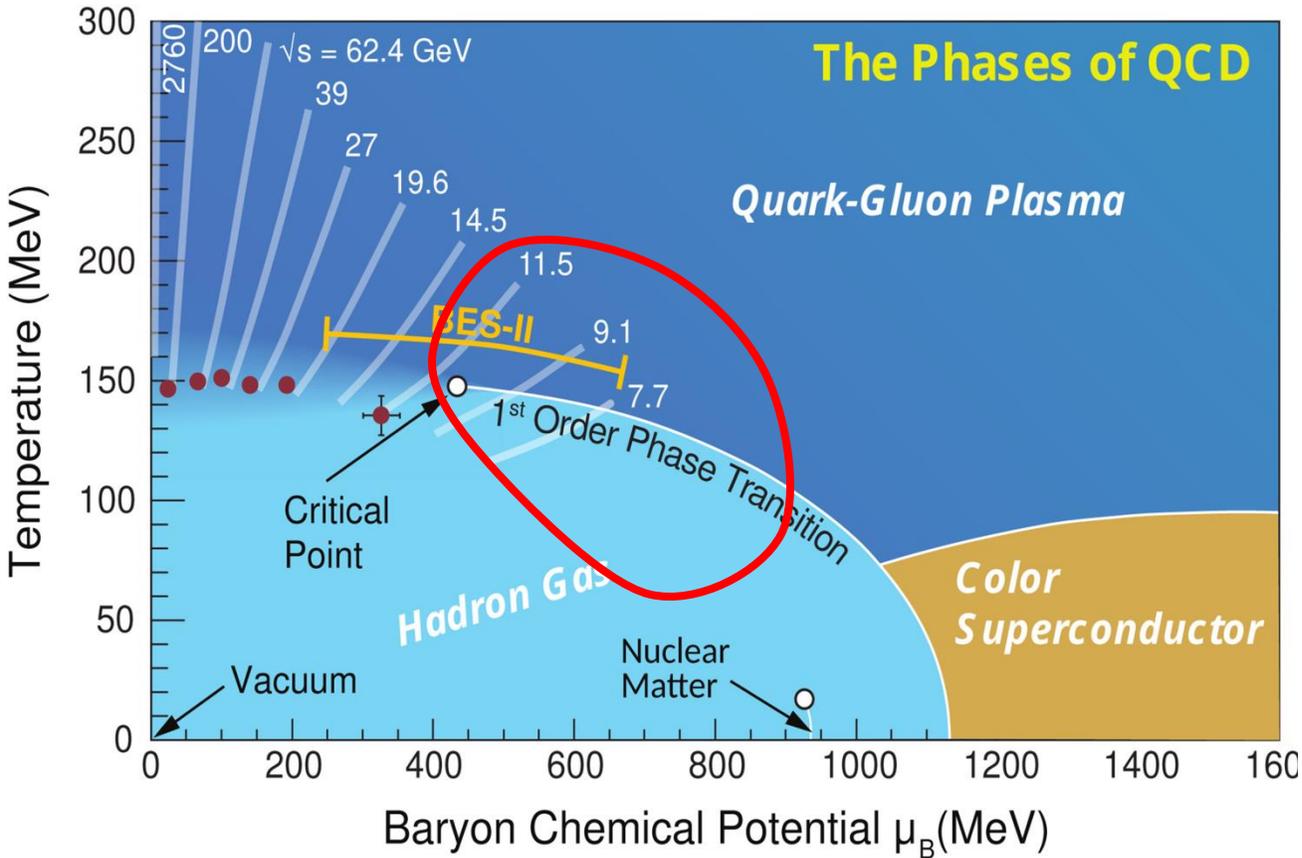
Rep. on prog. in phys. (2017) 80, 096901



# Heavy Ion Experiments

Machine	Lab	$\sqrt{s_{NN}}$ [GeV]	Config.	From	To	Experiment
BEVELAC	LBNL	2.2	Fixed target	1972	1984	DLS
NICA	JINR	2.2	Fixed target	2016	present	BM@N
SIS18	GSI	2-3	Fixed target	1990	present	HADES
HIAF	HFRS	2-3	Fixed target	2025	future	HI spectrometer
FAIR	GSI	2.2-4	Fixed target	2028	future	CBM
J-PARC	KEK	7.7	Fixed target	2008	present	J-PARC HI
AGS	BNL	4.8	Fixed target	1988	1996	E864/941, E802/859/866/917, E814/877, E858/878, E810/891, E896, E910 ...
NICA	JINR	4-11	Collider	2025	future	MPD
SPS	CERN	4-17	Fixed target	1986	present	NA35/49, NA38/50/51, NA44, NA45, NA52, NA57, NA60, WA97, WA80/98, ...
Tevatron	FNAL	40	Fixed target	1981	1993	E772, E789/P865
LHC	CERN	76-115	Fixed target	2018	present	SMOG
RHIC	BNL	7-200	Collider	2000	2025	BRAMS, PHOBOS, STAR, s(PHENIX)
LHC	CERN	2760-8160	Collider	2010	present	ALICE, LHCb, ATLAS, CMS

# Low energy regime

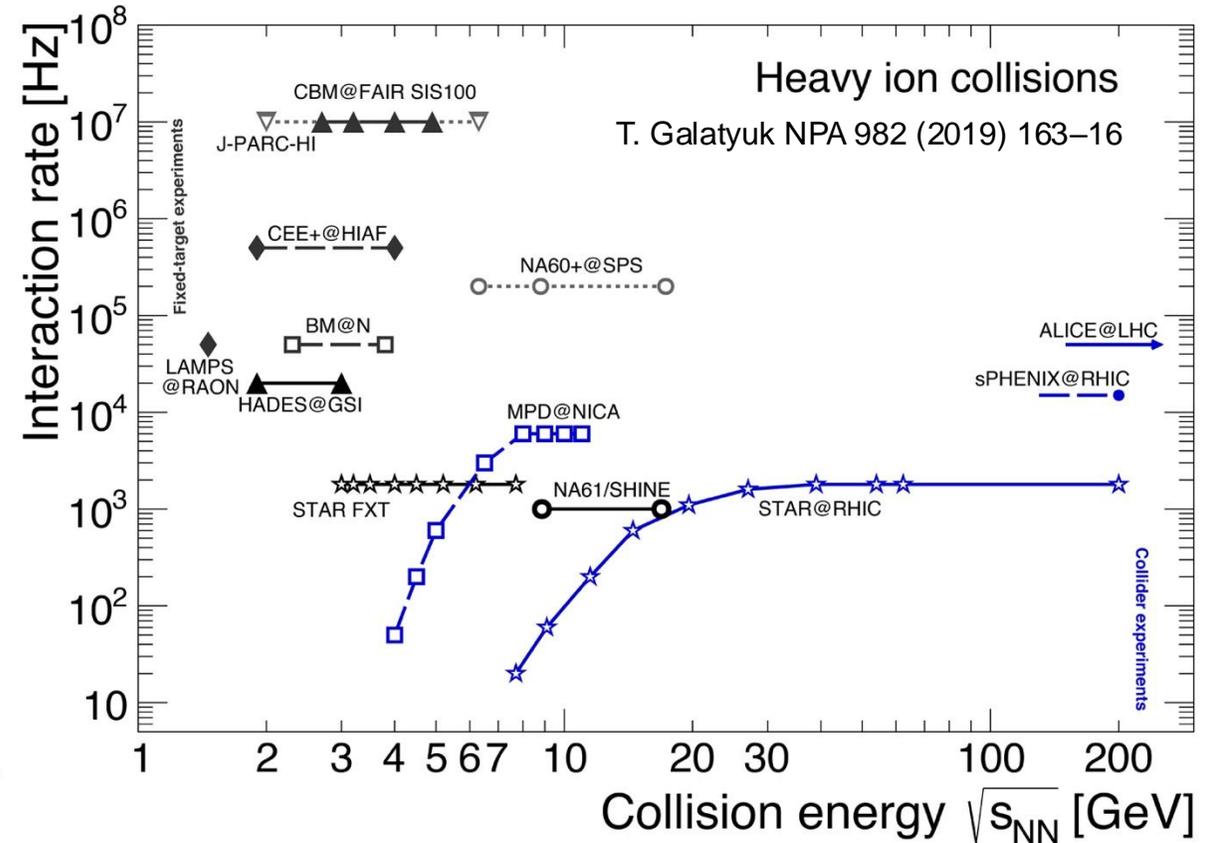
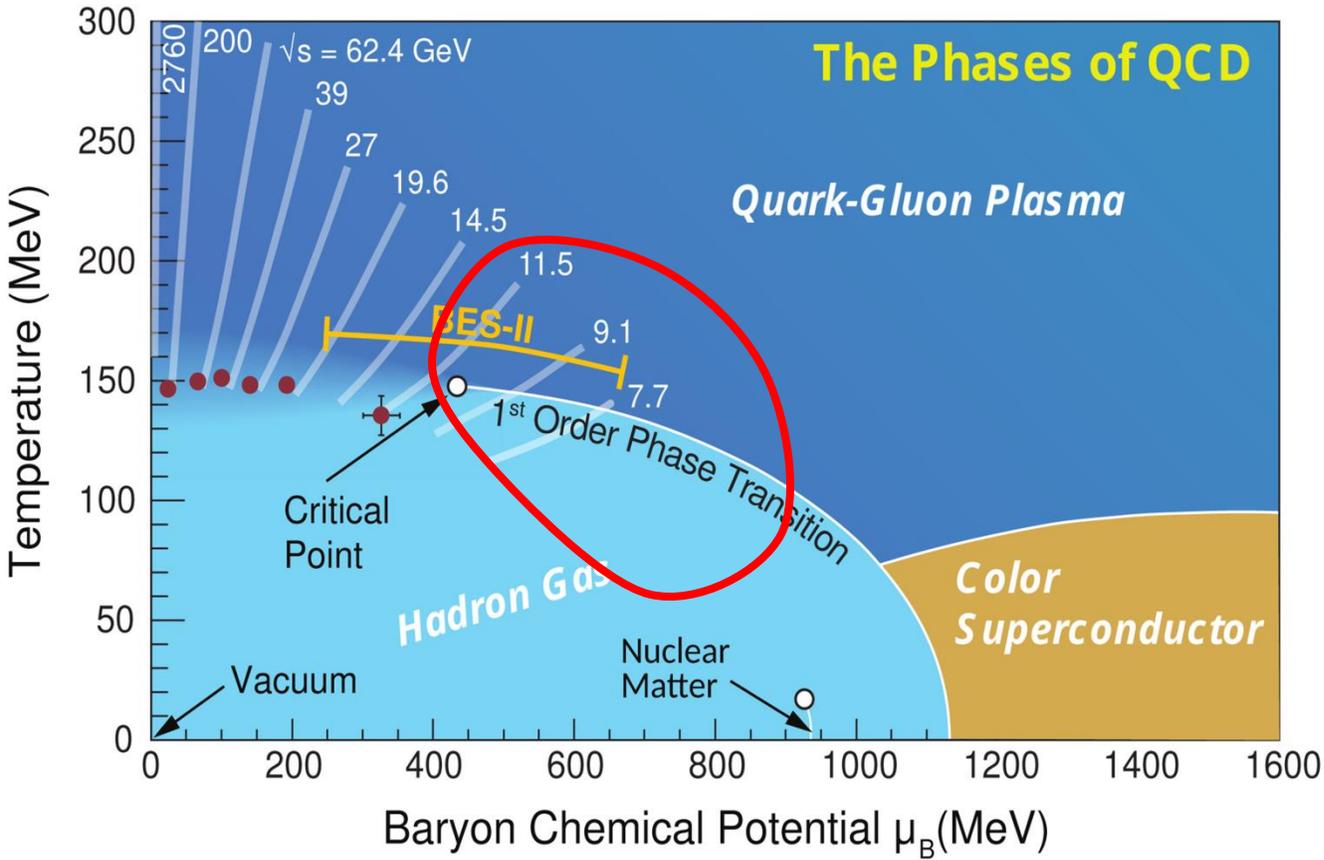


Exploring matter at extreme densities.

Present: HADES @ GSI, BM@N, STAR @RHIC Beam Energy Scan

Future: MPD @ NICA, CBM @ FAIR

# Low energy regime

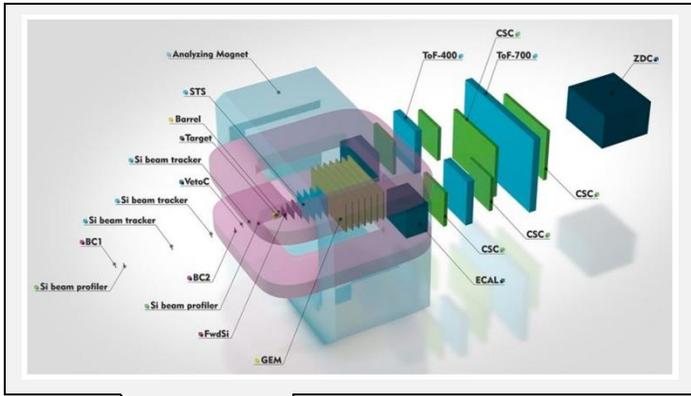


Exploring matter at extreme densities.

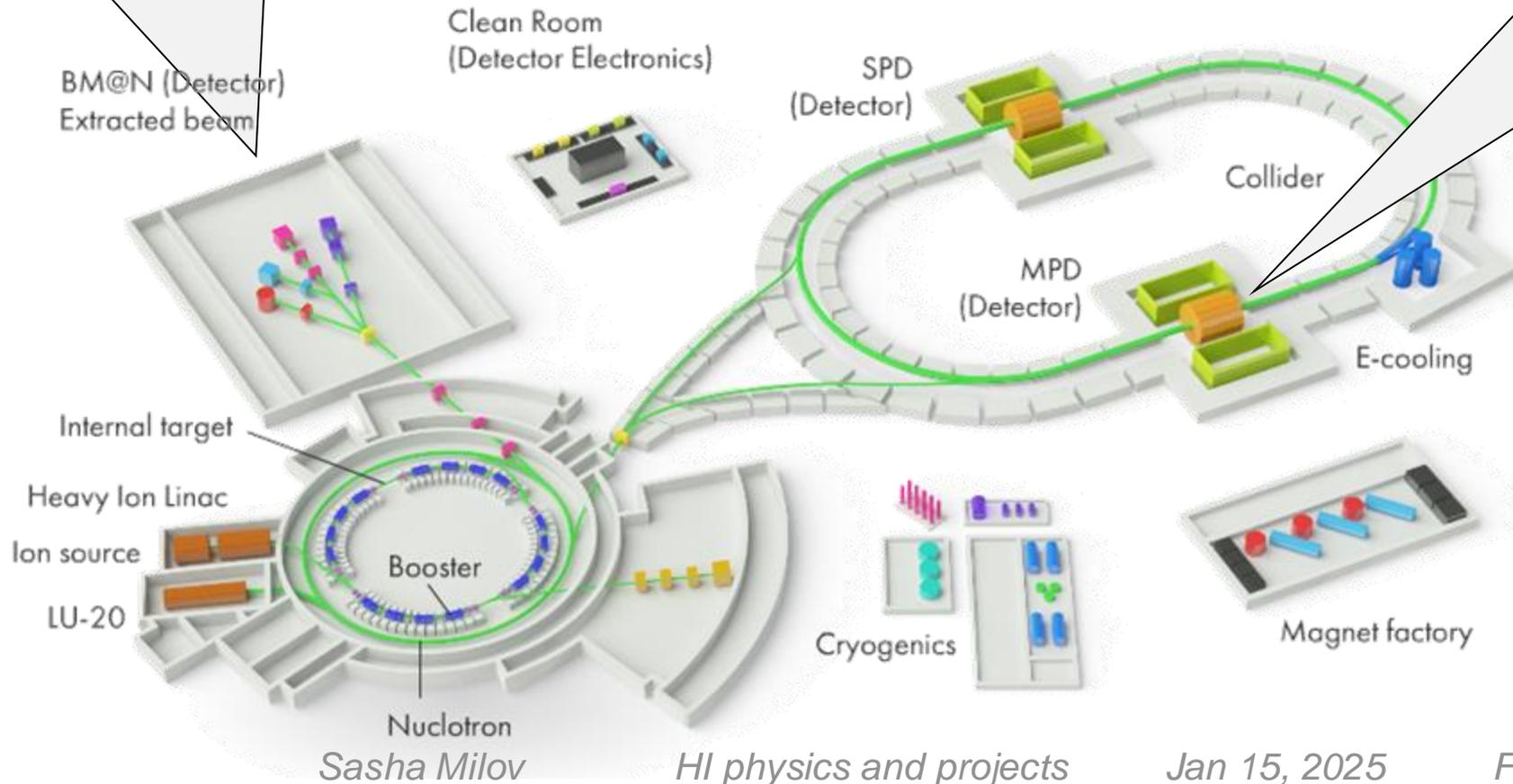
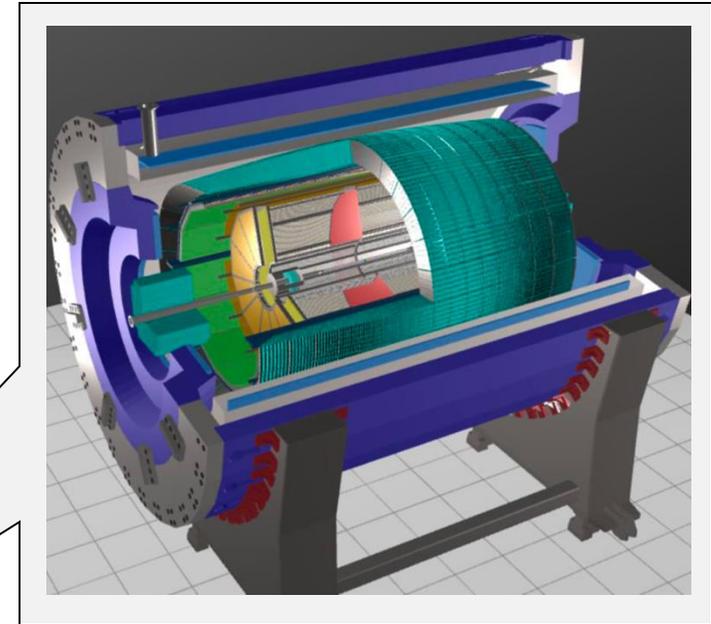
Present: HADES @ GSI, BM@N, STAR @RHIC Beam Energy Scan

Future: MPD @ NICA, CBM @ FAIR

# Low energy regime: NICA



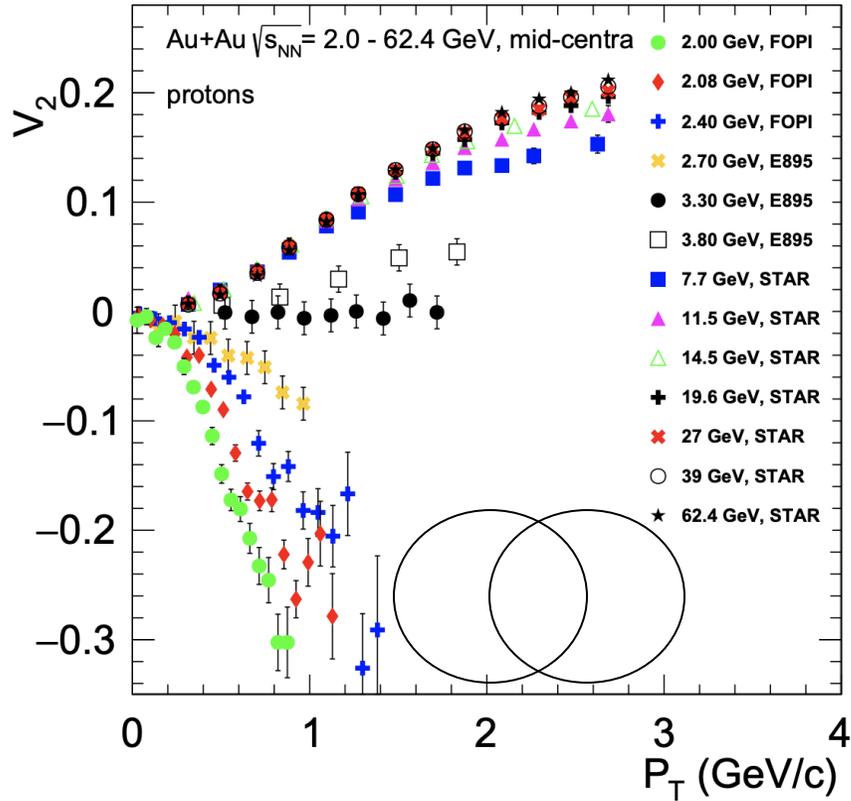
## Nuclotron-based Ion Collider



Synchrotron accelerates ions to 4.5 GeV/N and either drops them on a target (BM@N) or sends them to NICA (MPD)

The second detector (SPD) is for spin physics.

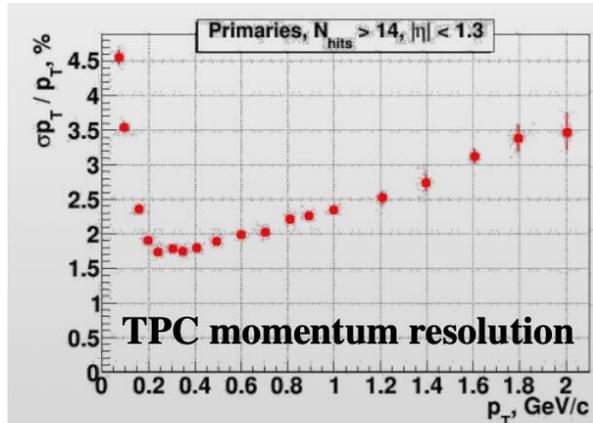
# MPD



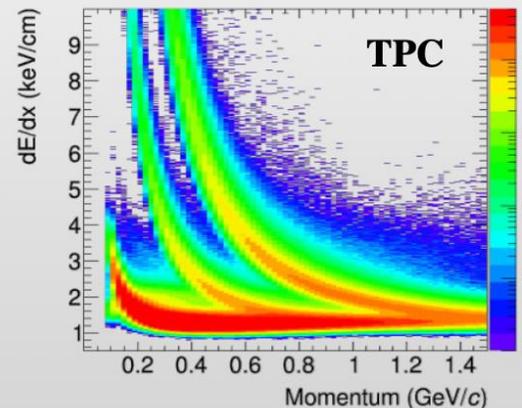
MPD is a Multi-Purpose Detector with the full suite of HI capabilities: precise tracking, pID, calorimetry, and wide coverage of  $\pm 1$  unit of rapidity (a lot at low energy)

MPD is in a very interesting energy spot of an extreme matter density.

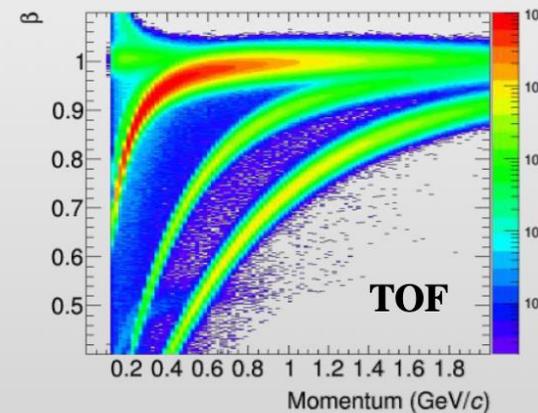
MPD may start this year, possibly as a fixed target experiment with a wire inside the IR.



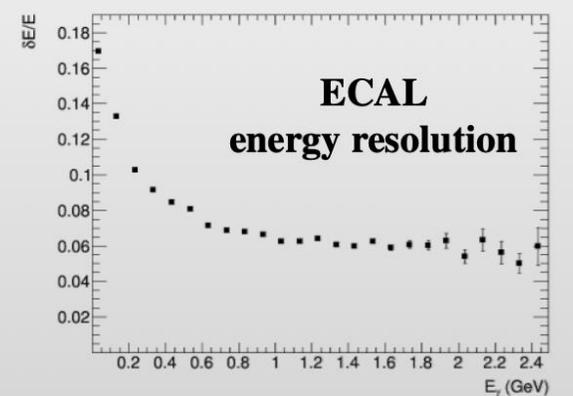
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HI physics and projects



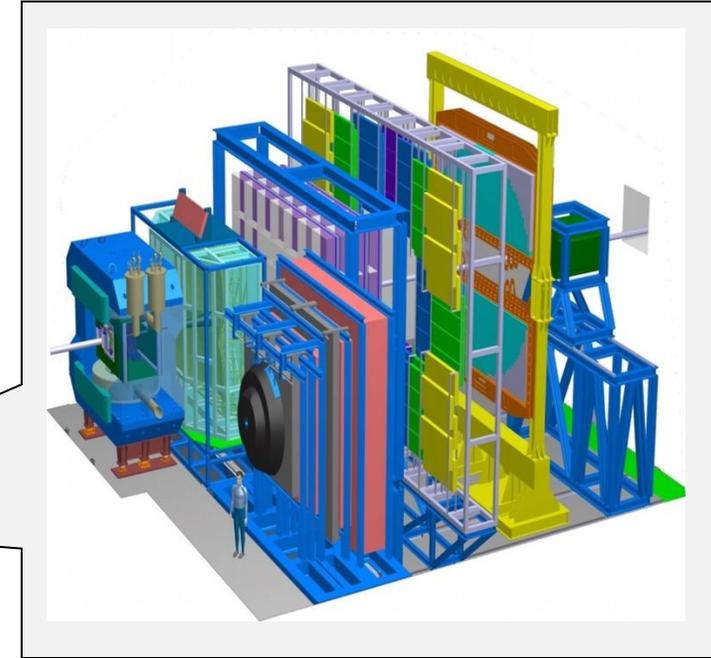
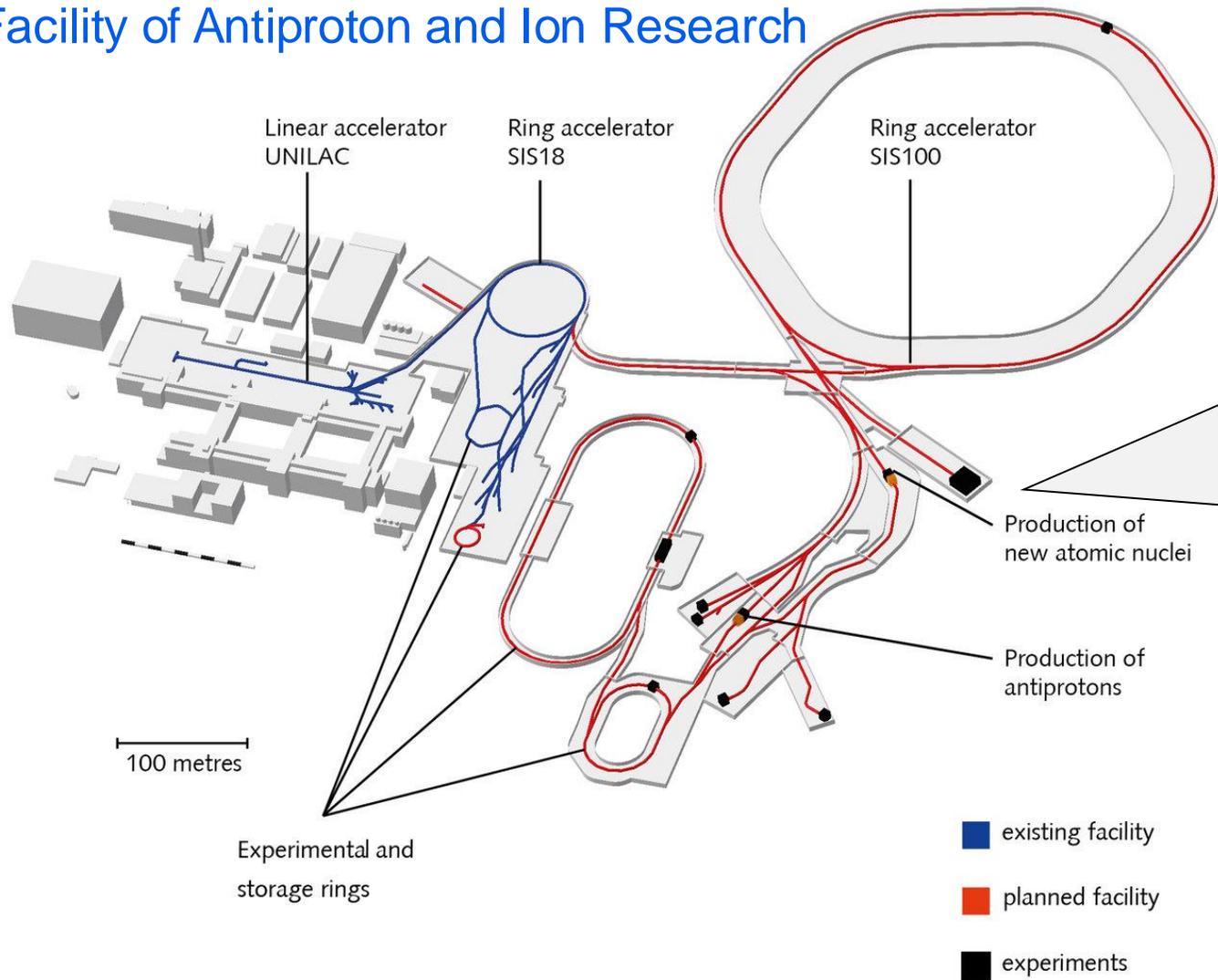
Jan 15, 2025



FF25, HKUST

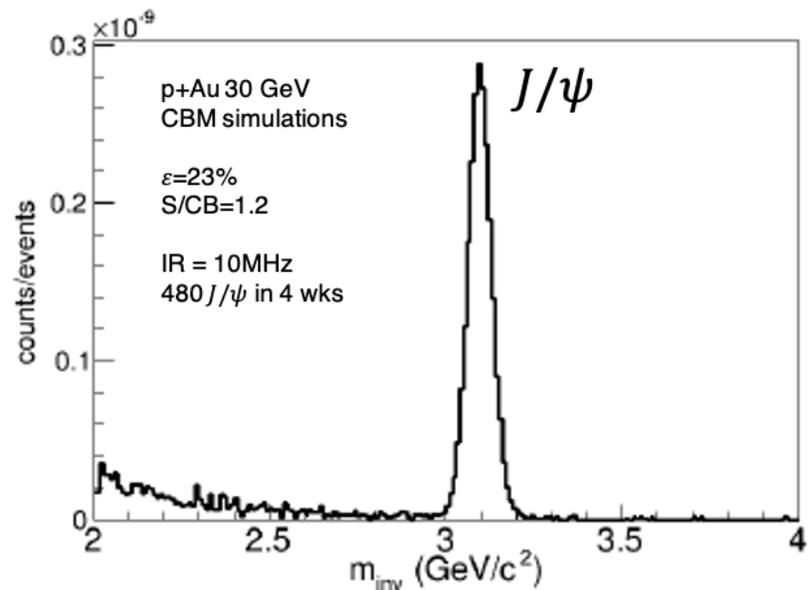
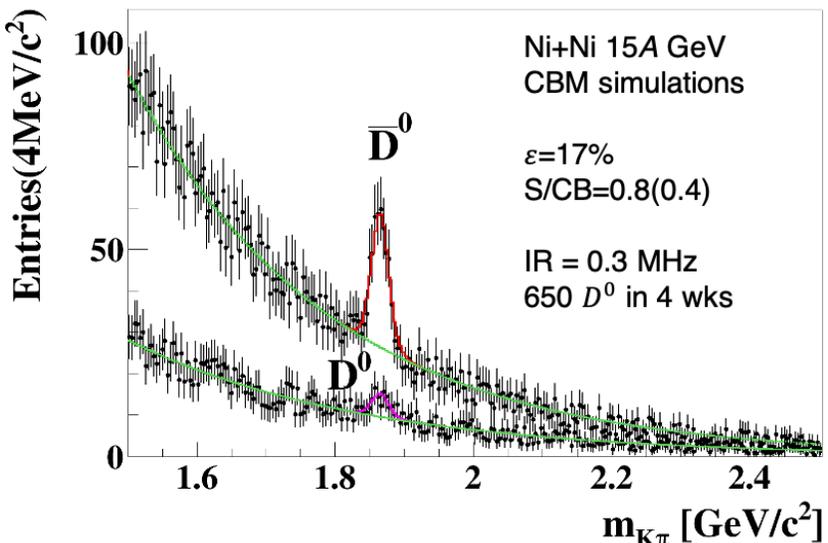
# Low energy regime: FAIR

## Facility of Antiproton and Ion Research



CBM is a fixed target experiment with slightly lower energy (SIS100) than MPD and higher rates.

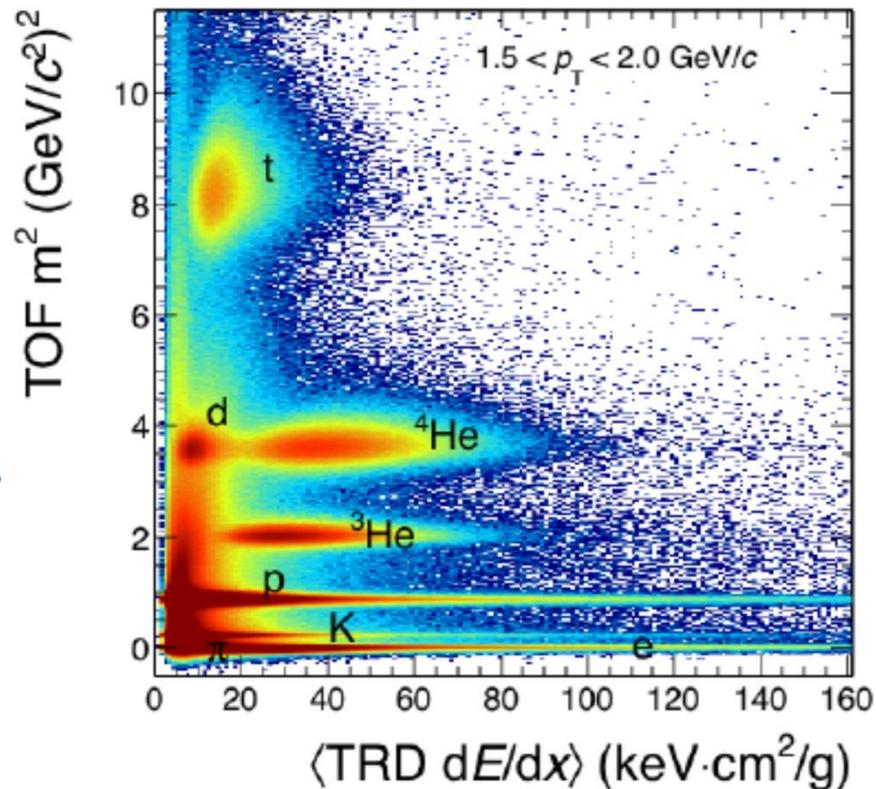
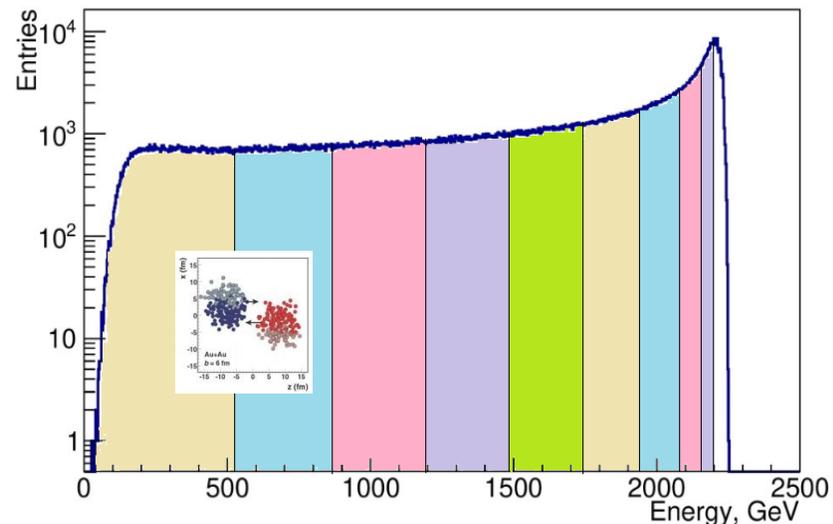
# CBM



CBM benefits from higher rates. Besides excellent pID, it has spectator detectors that allow good centrality determination.

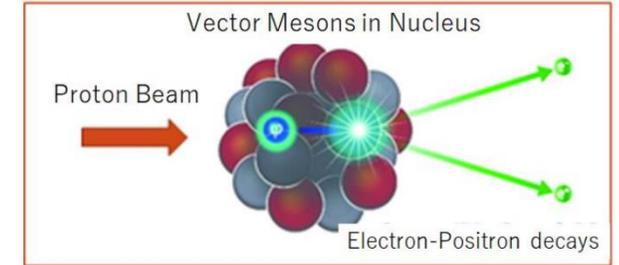
In the past, CBM and MPD have had complimentary physics programs and close cooperation between the teams and laboratories

CBM may go online in 2028.

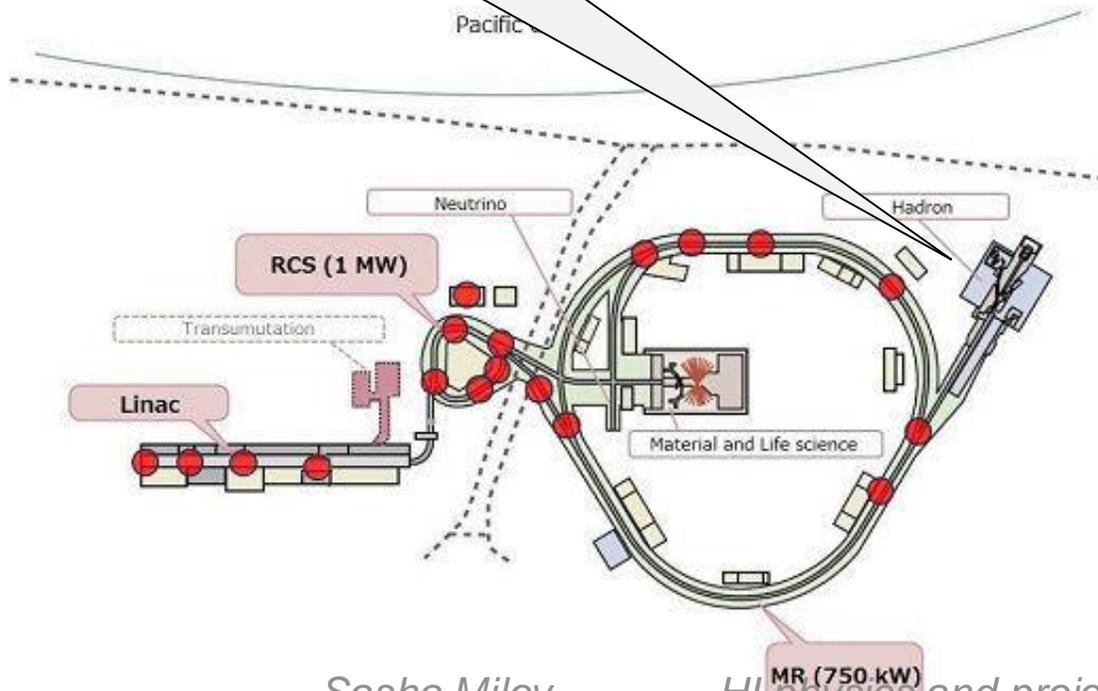


# Low energy regime: J-PARC

Japan Proton Accelerator Research Facility



Measurements of vector meson mass spectra in  $p+A$  collisions and its modifications due to chiral symmetry restoration in CNM



Upgrading plan

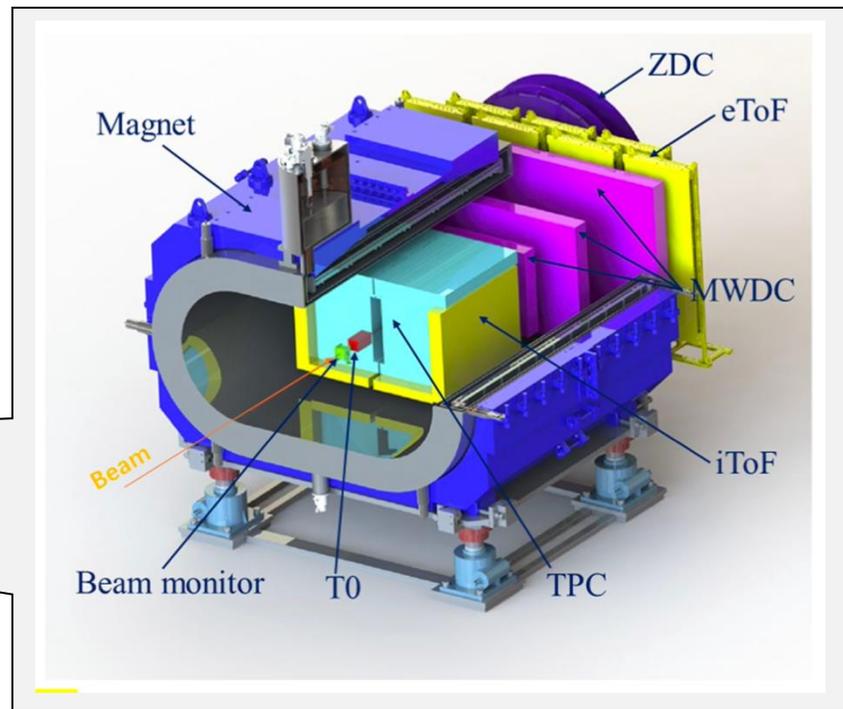
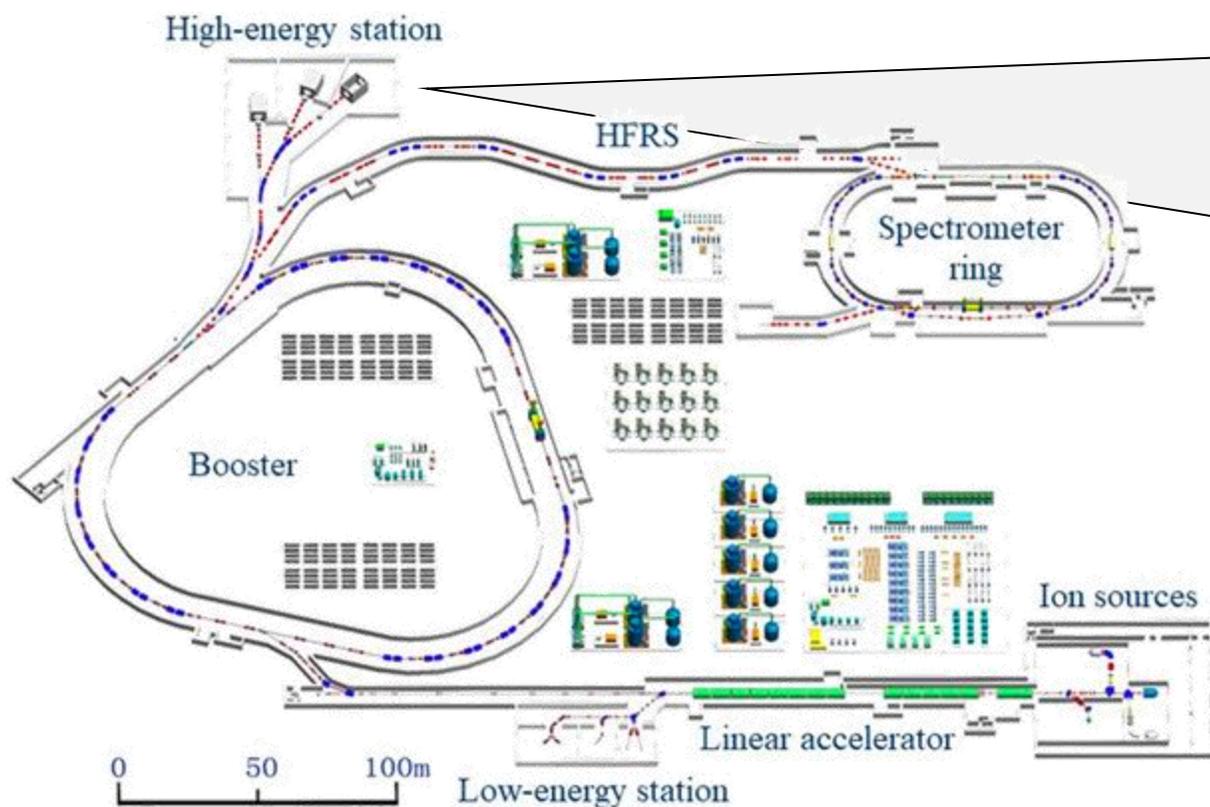
Spectrometer upgrades (ongoing)

New LINAC and reuse of KEK-PS booster  
Upgrades of the existing spectrometer (~2029)

New Booster and New spectrometer (~2032)

# Low energy regime: HIAF

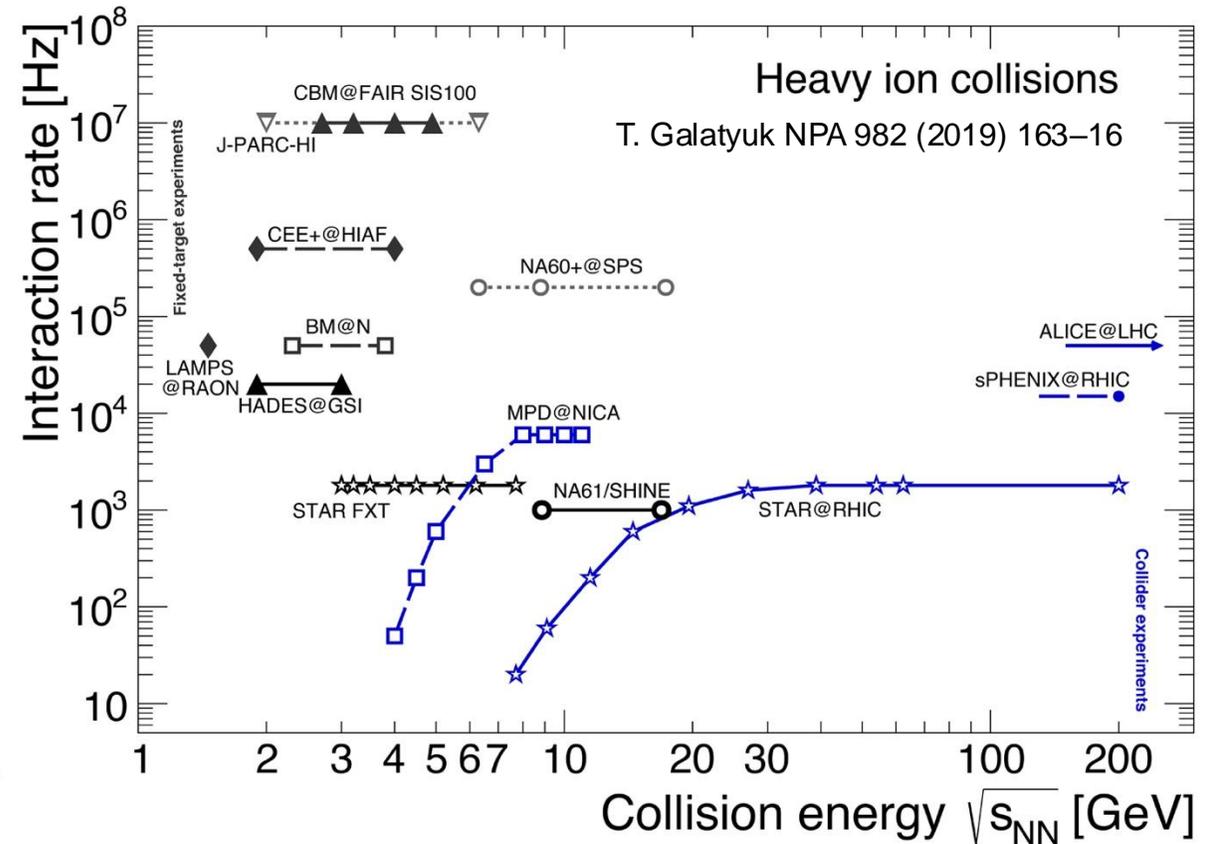
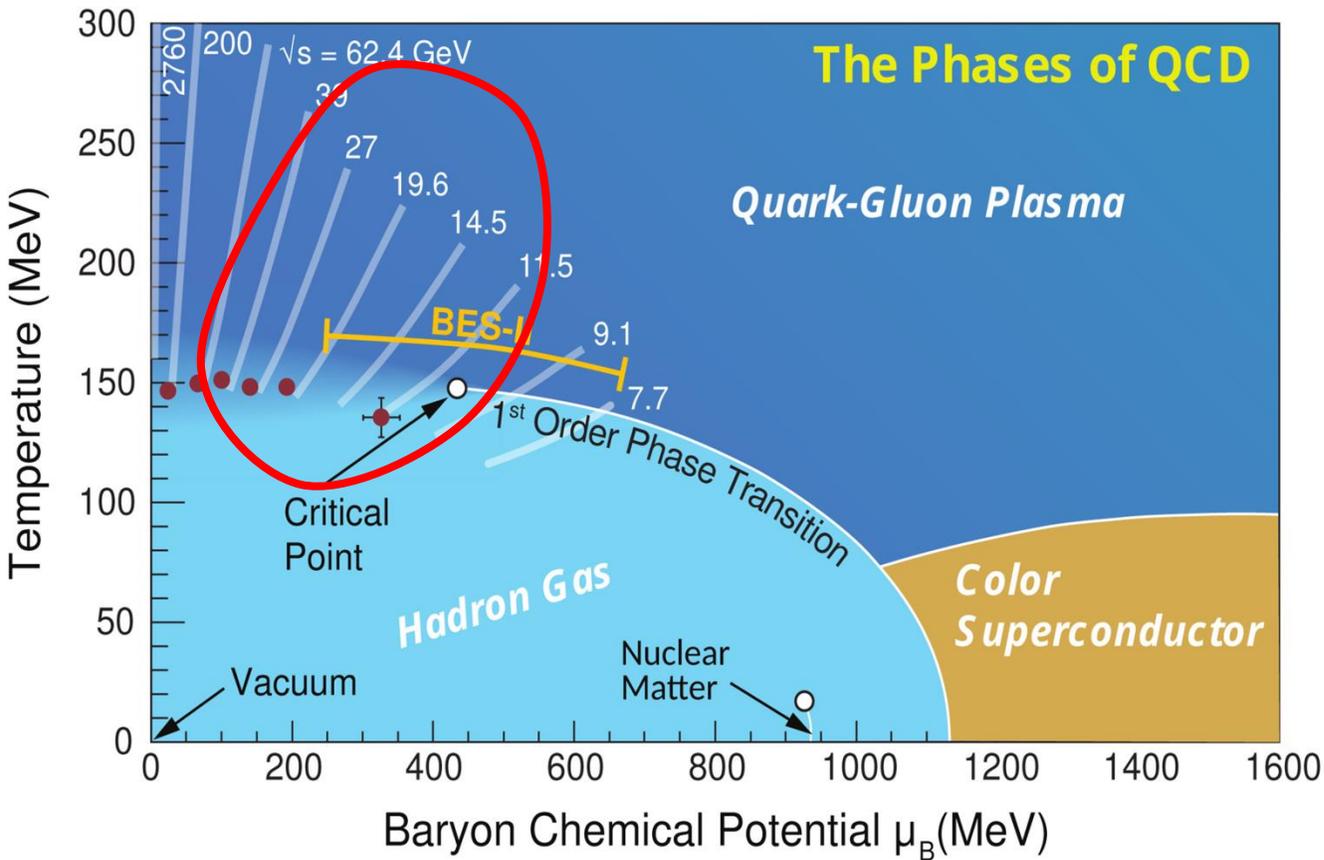
High-Intensity Heavy-Ion Accelerator Facility



Search for the QCD critical point via beam energy scan measurements at HIAF.

Exploring EoS around the produced density 2-3 times the nuclei density.

# Intermediate energy regime

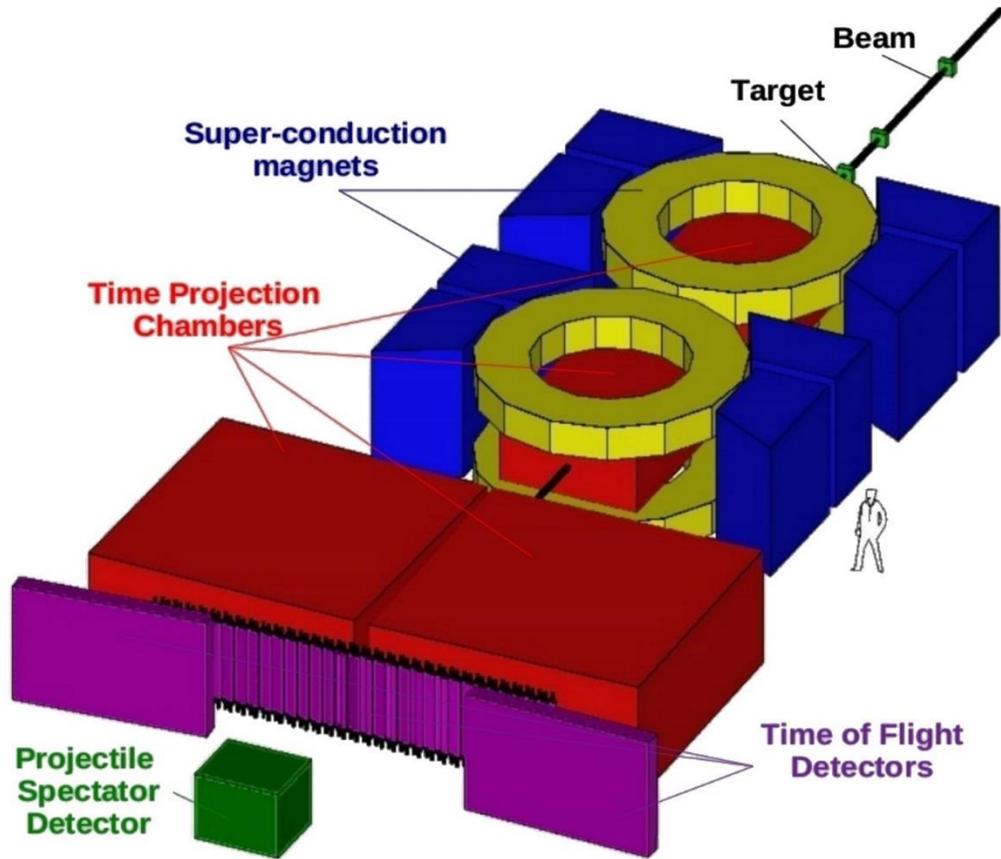


Search for the critical point, onset of QGP

Present: NA61 @ SPS

Future: NA60+ @ SPS

# Intermediate energy regime: SPS – NA61



LS2 upgrades:  
Vertex Detector based on ALPIDE sensors  
TPC readout electronics & DAQ  
Data-taking the rate from 80 Hz  $\rightarrow$  1.2 kHz

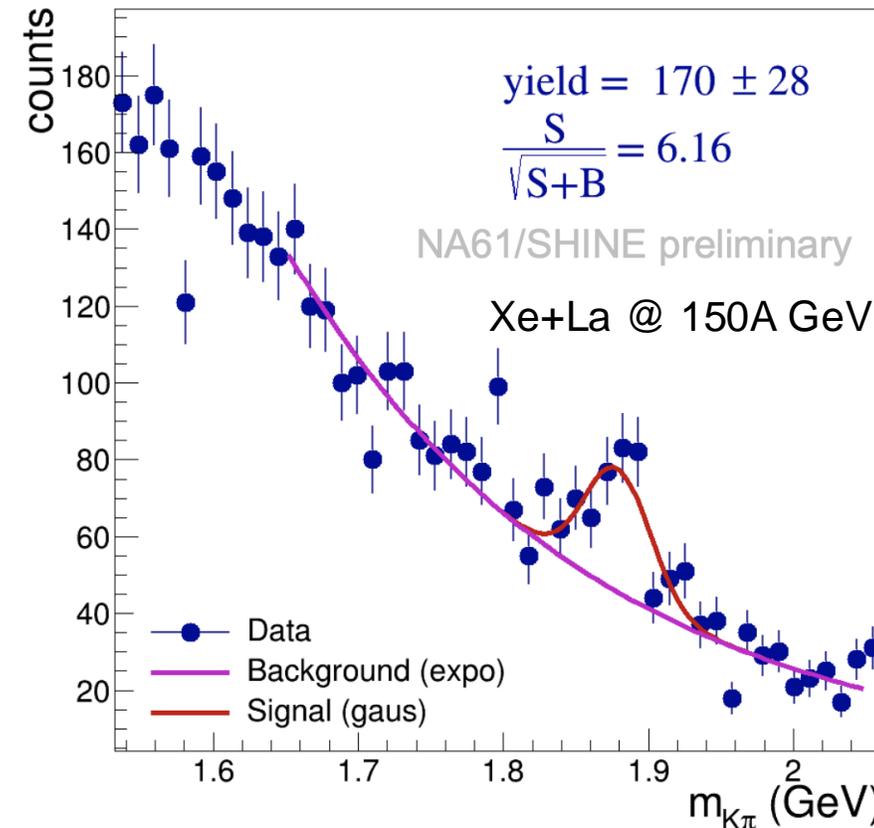
## Measurements of Cross Sections and Charged Pion Spectra in Proton-Carbon Interactions at 31 GeV/c

NA61/SHINE Collaboration • N Abgrall (Geneva U.) et al. (Feb, 2011)

Published in: *Phys.Rev.C* 84 (2011) 034604 • e-Print: 1102.0983 [hep-ex]

[pdf](#) [DOI](#) [cite](#) [datasets](#)

[reference search](#) [306 citations](#)



2022-23 data has enough statistics to make differential  $D^0$  studies

# Intermediate energy regime: SPS – NA60+

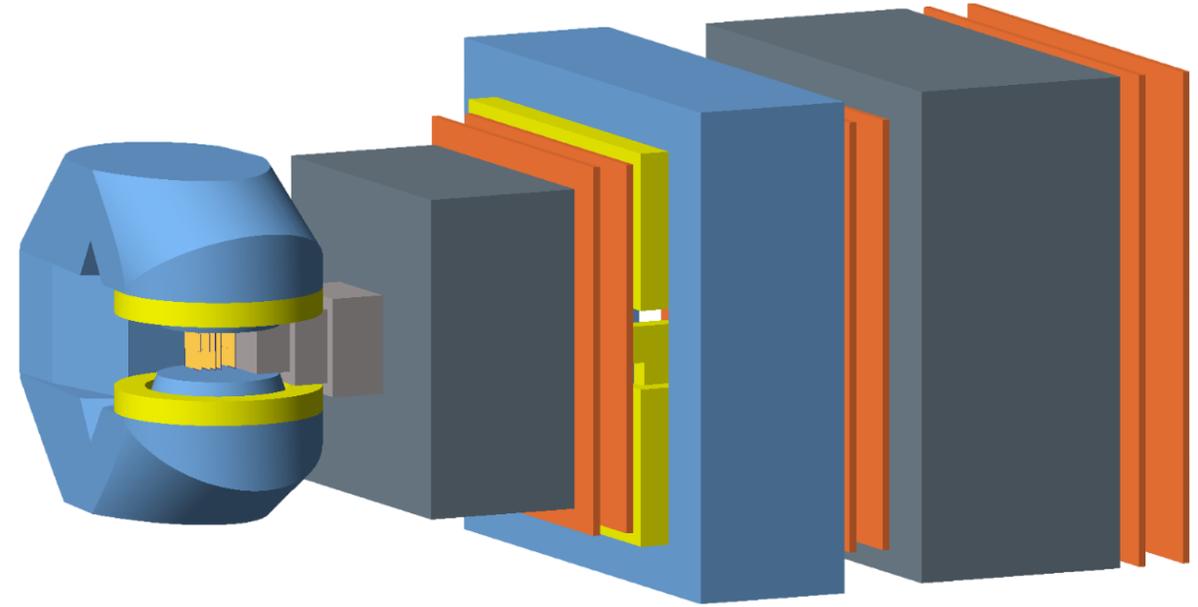
Caloric curve of QGP: thermal dimuons to measure temperature vs  $\sqrt{s_{NN}}$

Charmonium suppression vs.  $\sqrt{s_{NN}}$   $c\bar{c}$  melting

Chiral symmetry restoration via  $\rho$ - $a_1$  mixing in the dimuon channel

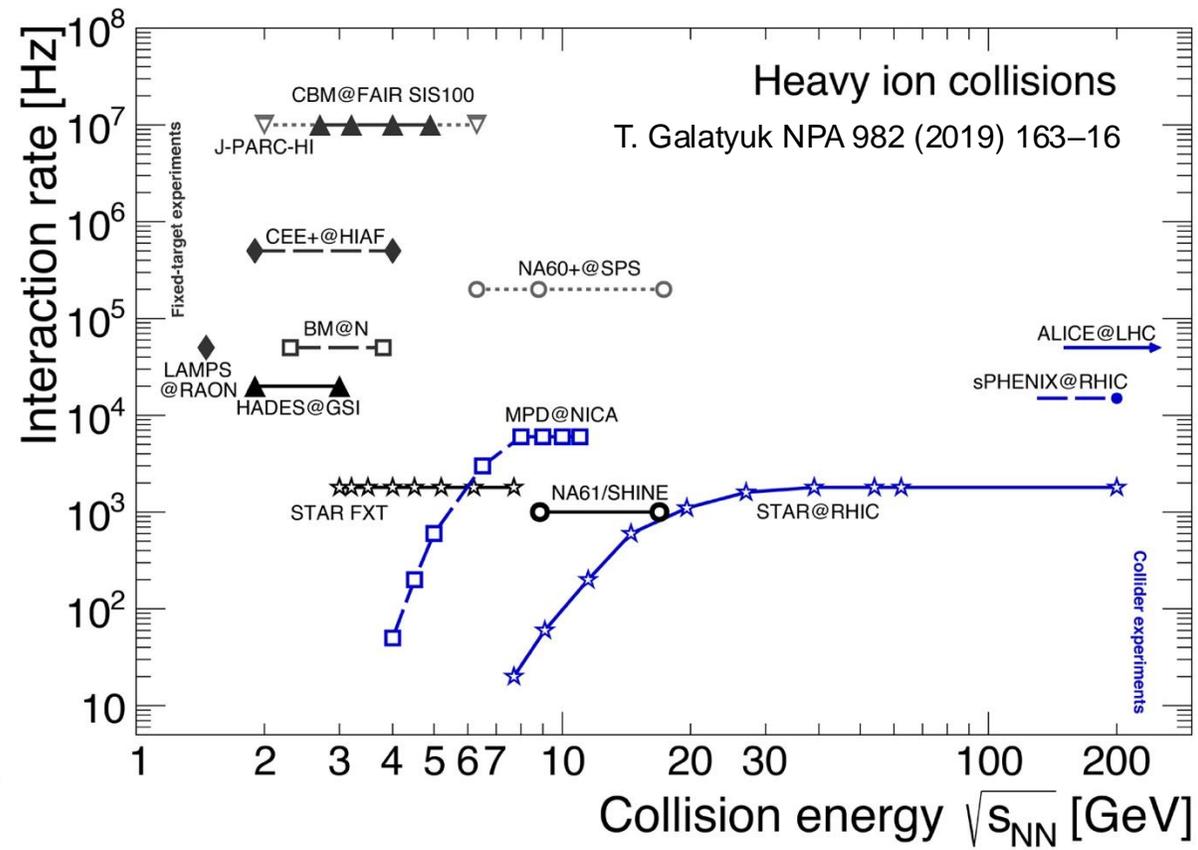
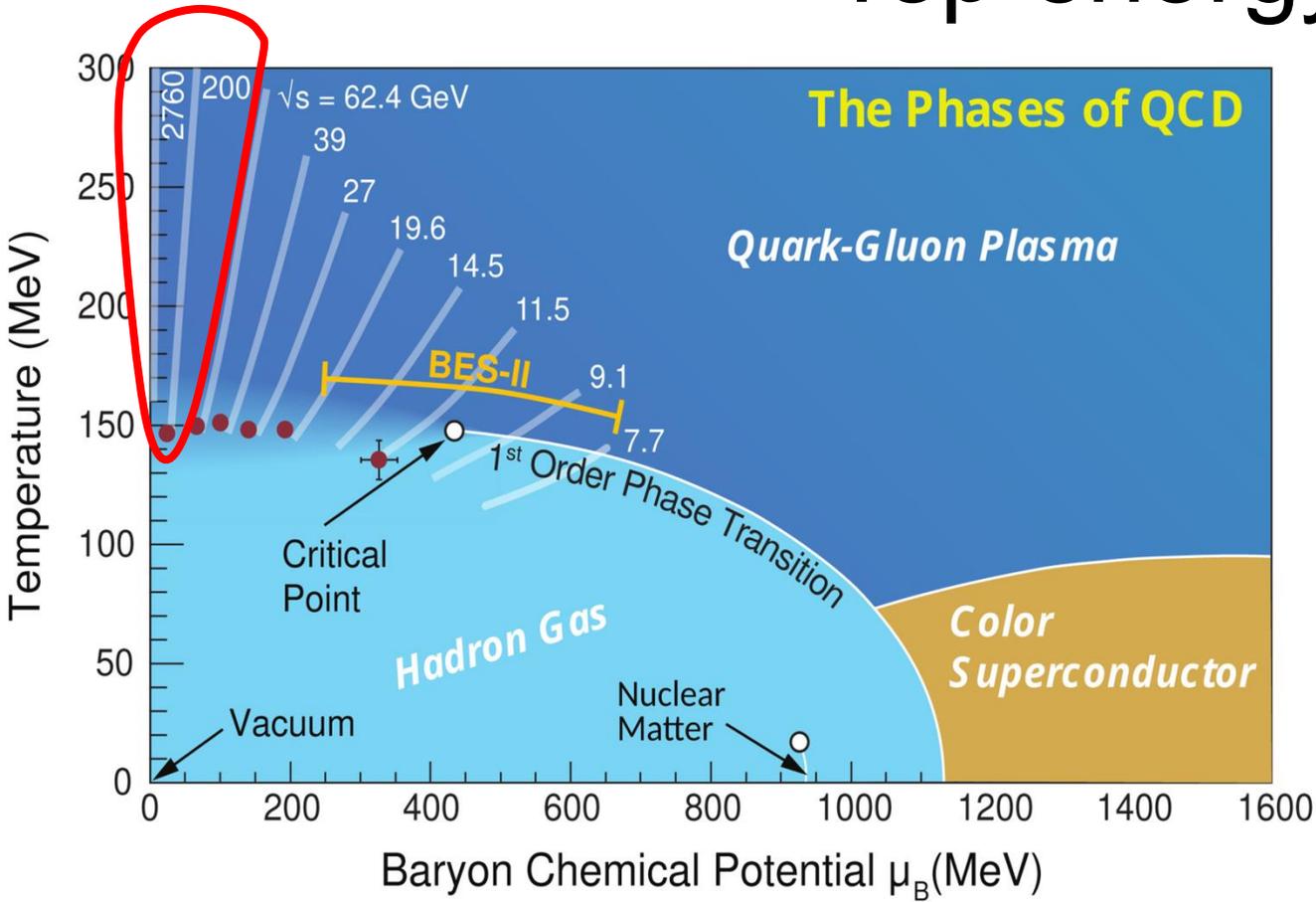
Hadronic decays of open HF to measure QGP transport coefficients and charm hadronization

LoI (arXiv:2212.14452)  
Proposal 1<sup>st</sup> half of 2025



NA60+  
Will start around 2030  
Dimuon experiment

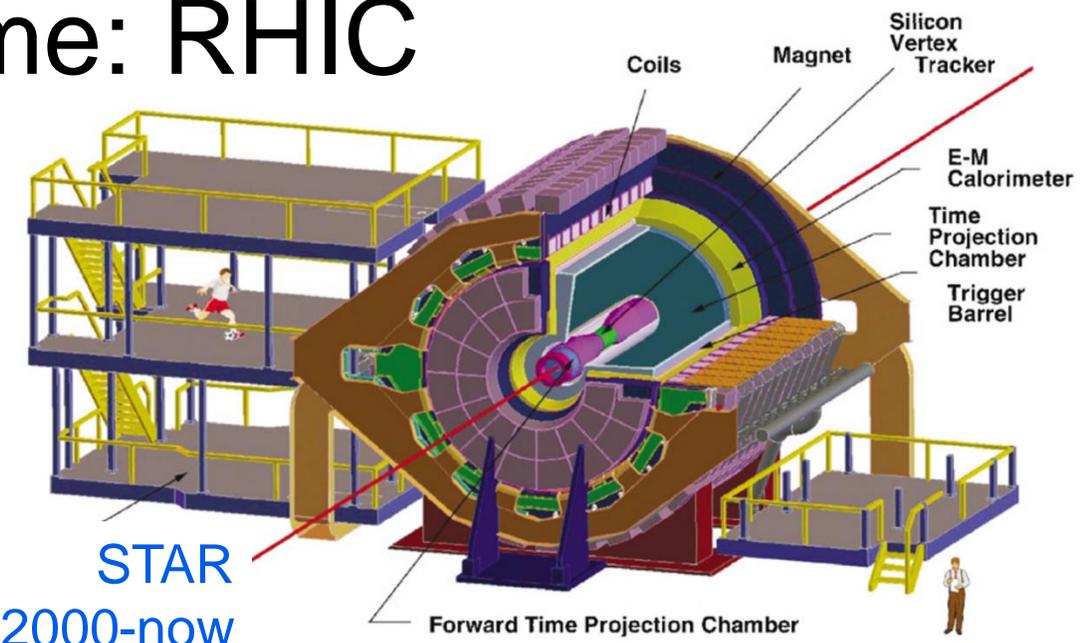
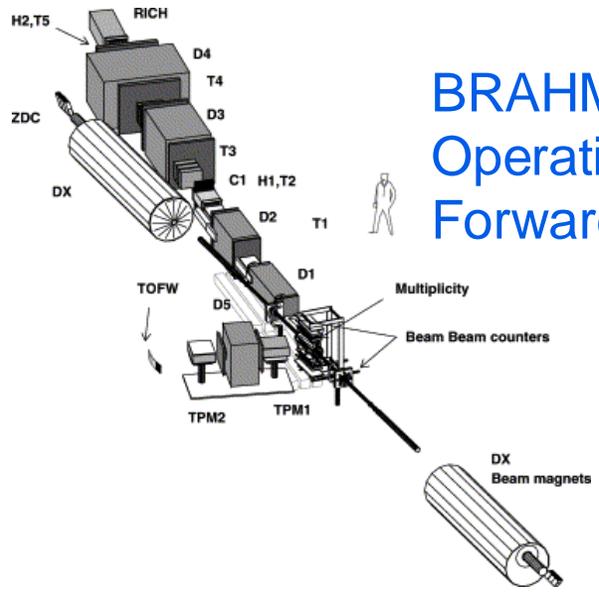
# Top energy regime



Jets and other hard probes. Wider phase space  
 Present: All 4 LHC detectors  
 Future: new ALICE detector + SMOG

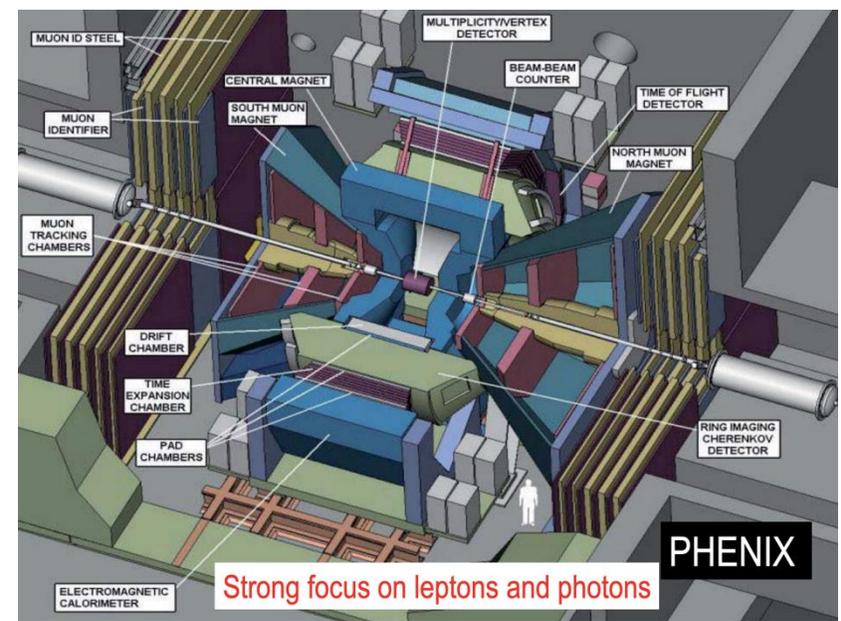
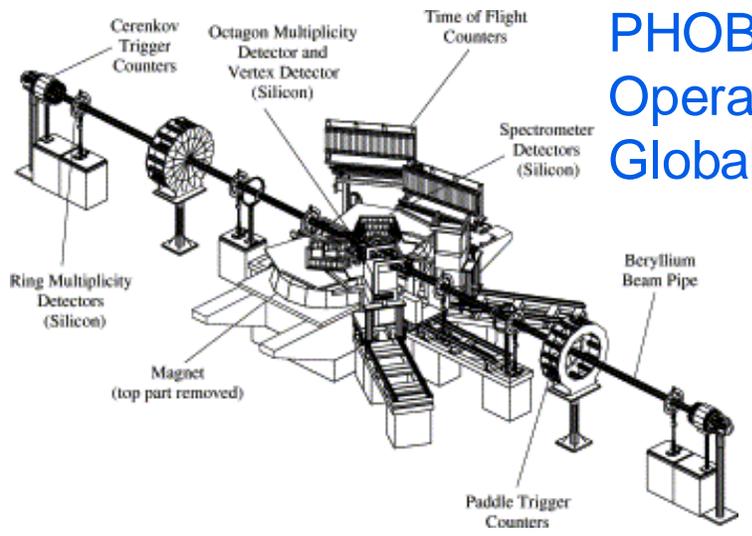
# Top energy regime: RHIC

**BRAHMS**  
Operational 2000-2006  
Forward physics



**STAR**  
Operational 2000-now  
General purpose HI

**PHOBOS**  
Operational 2000-2005  
Global characteristics



**PHENIX**  
Operational 2000-2016  
Rare probes

Strong focus on leptons and photons

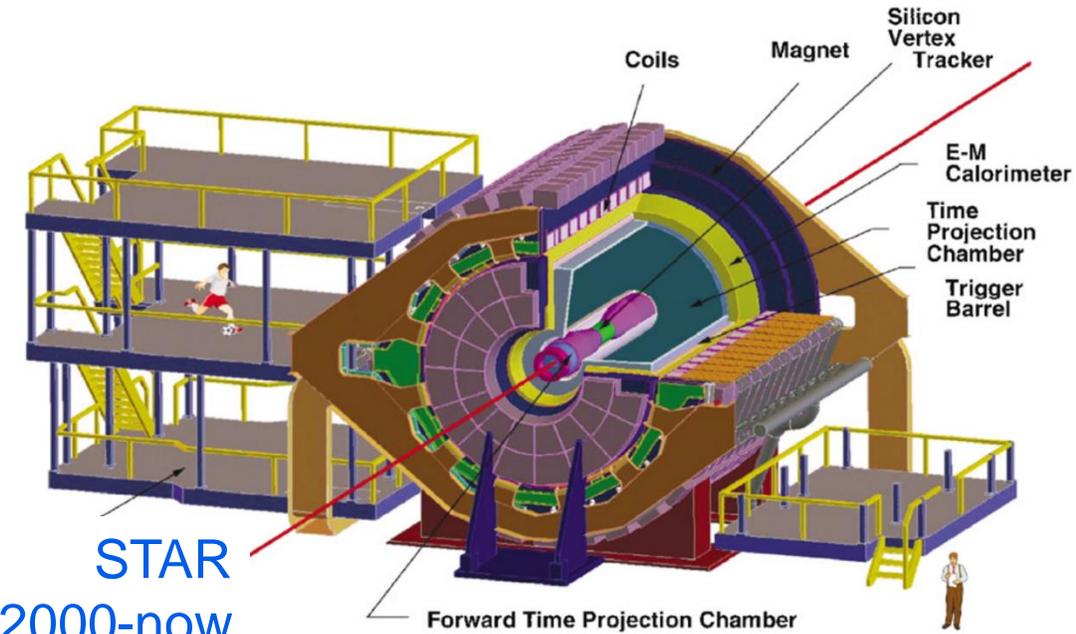
# STAR

## Systematic Measurements of Identified Particle Spectra in $pp$ , $d^+$ Au and Au+Au Collisions from STAR #2

STAR Collaboration • B.I. Abelev (Illinois U., Chicago) et al. (Aug, 2008)

Published in: *Phys.Rev.C* 79 (2009) 034909 • e-Print: [0808.2041](https://arxiv.org/abs/0808.2041) [nucl-ex]

[pdf](#) [links](#) [DOI](#) [cite](#) [datasets](#) [reference search](#) [1,139 citations](#)



STAR  
Operational 2000-now  
General purpose HI

STAR is a 'classical' Heavy Ion experiment

It has a tracking coverage of  $\pm 1$  unit at midrapidity, excellent pID based on TPC, and ToF.

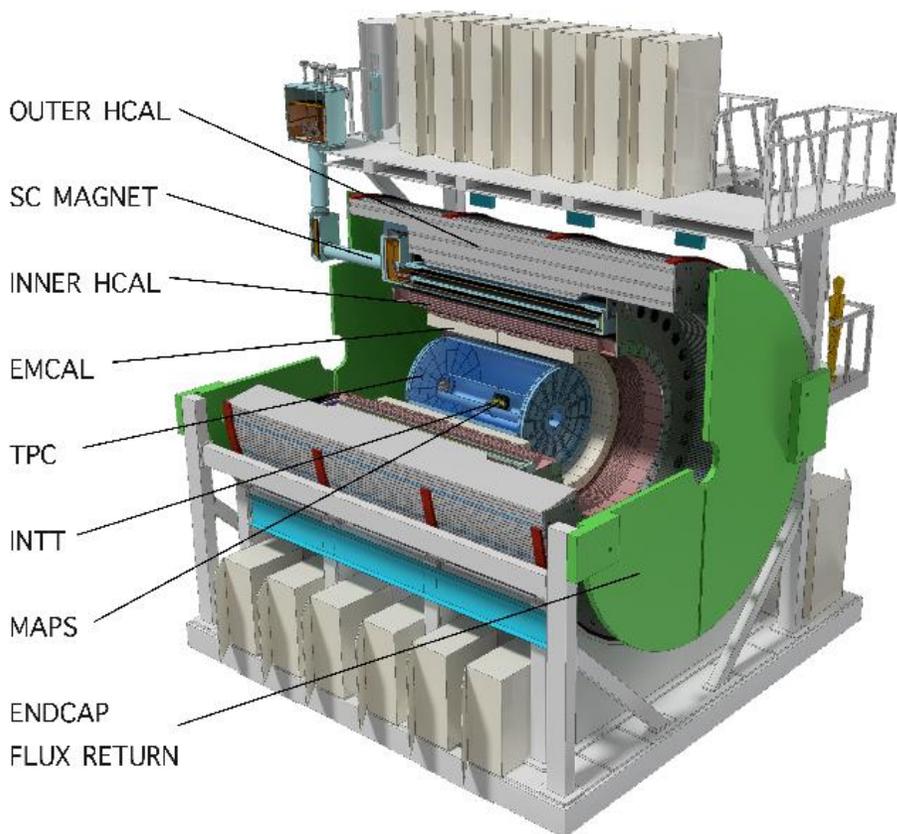
STAR was equipped with some calorimeter coverage

STAR underwent several upgrades, also to extend its tracking into forward rapidity

# (s)PHENIX

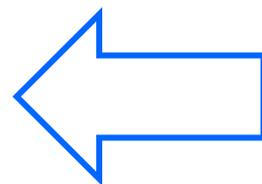
PHENIX was planned as a high-rate electromagnetic and hard probe experiment

It has two forward muon arms,  
two central (midrapidity) arms with an EM calorimeter, and a non-trivial tracking system.  
Central arms covered half of the azimuthal angle.  
PID was based on RICH, ToF and HBD.



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sPHENIX  
Operational 2023-2026  
Jets and Upsilon's



PHENIX  
Operational 2000-2016  
Rare probes

HI physics and projects

Jan 15, 2025

Suppression of hadrons with large transverse momentum in central Au+Au collisions at  $\sqrt{s_{NN}} = 130\text{-GeV}$

PHENIX Collaboration • K. Adcox (Vanderbilt U.) et al. (Sep, 2001)

Published in: *Phys.Rev.Lett.* 88 (2002) 022301 • e-Print: [nucl-ex/0109003](#) [nucl-ex]



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cite



datasets

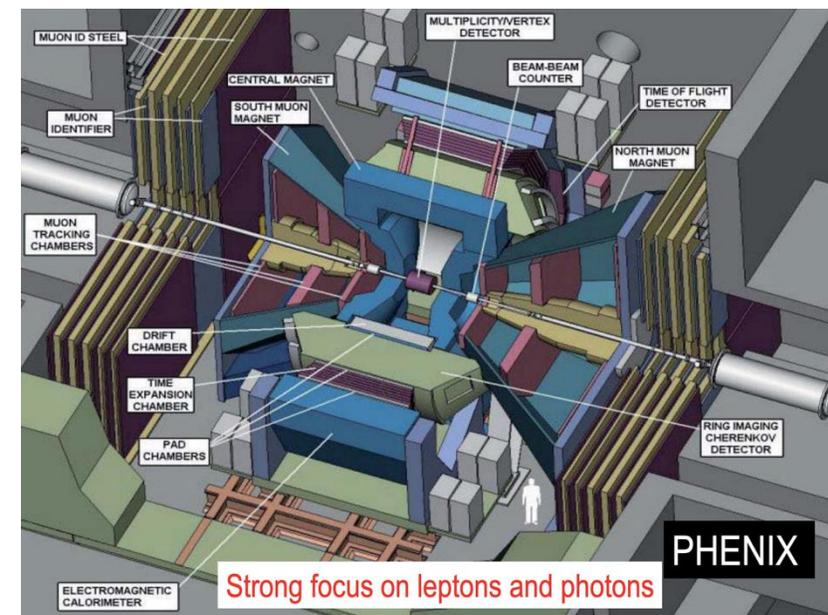


reference search



1,245 citations

#2



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25

# Top energy regime: LHC

I'm not showing ATLAS, CMS, and LHCb in this meeting...

ATLAS + CMS  
Universal HEP detectors  
with excellent HI capabilities

LHCb was a latecomer to the HI program. Due to the huge demand for their data with HI, they now have a strong group and fantastic results, especially in small systems

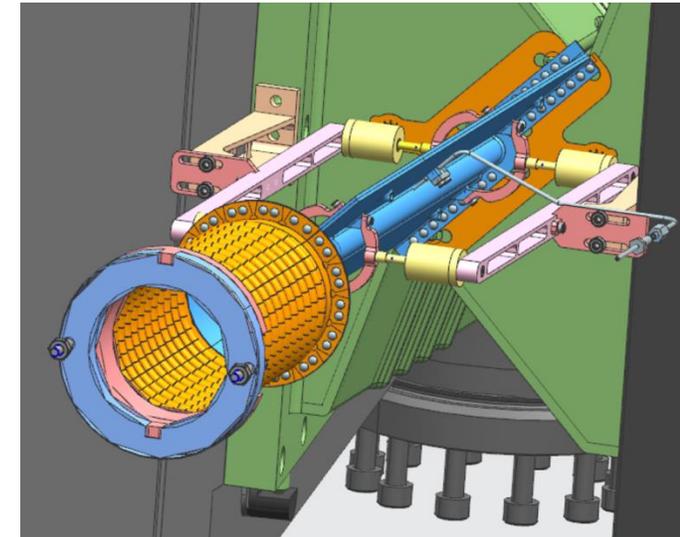
ALICE  
Layout until LS4  
Universal HI detector

ALICE vs. ATLAS&CMS

Pros:  
pID  
Low  $p_T$  tracking  
Thickness

Cons:  
Calorimetry  
Rapidity  
Rates

Complementarity of the  
research programs



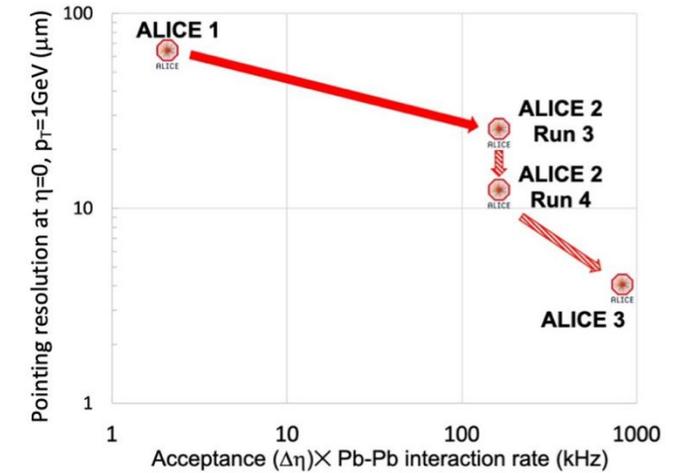
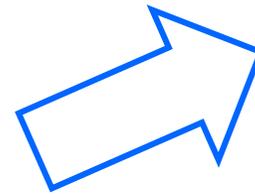
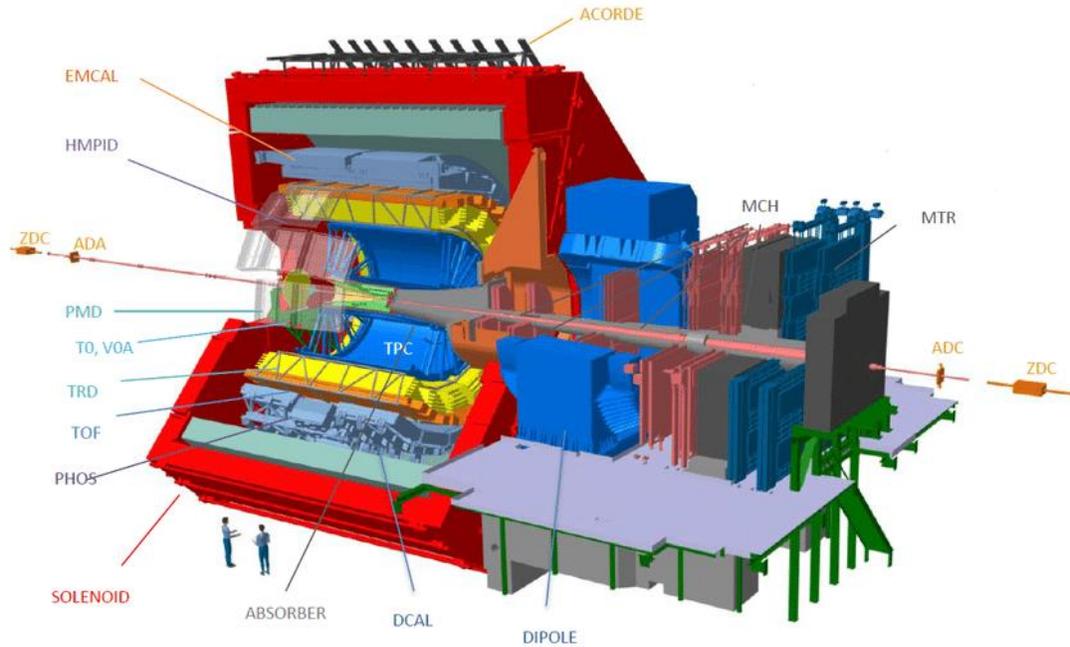
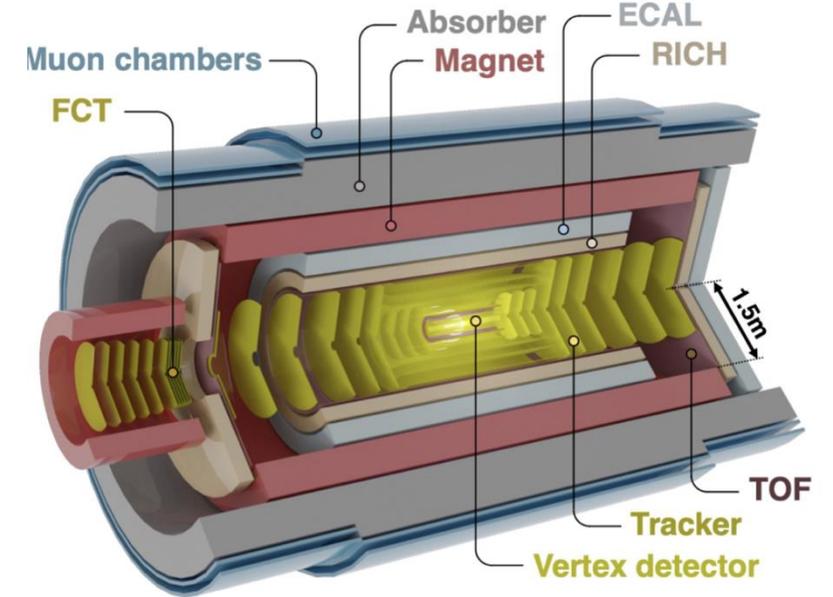
SMOG = A fixed target (gas) experiment at the LHCb  
Pilot runs since 2015

# ALICE

ALICE major upgrades  
 LS2: MWPC TPC  $\rightarrow$  GEM TPC  
 LS3: +FoCal  
 LS3: ITS3

ALICE  
 Layout until LS4  
 Universal HI detector

LS4: new ALICE3 detector

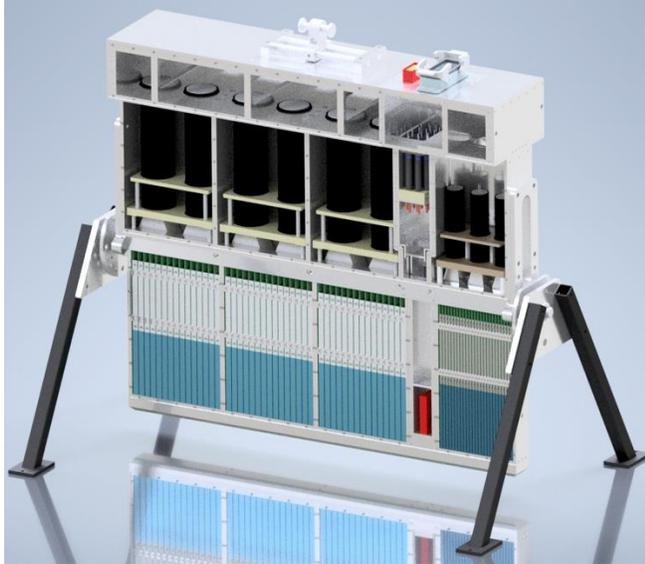


# ATLAS and CMS upgrades

Both experiments have an extensive upgrading program that is driven by HEP demands  
HI program benefits from these improvements

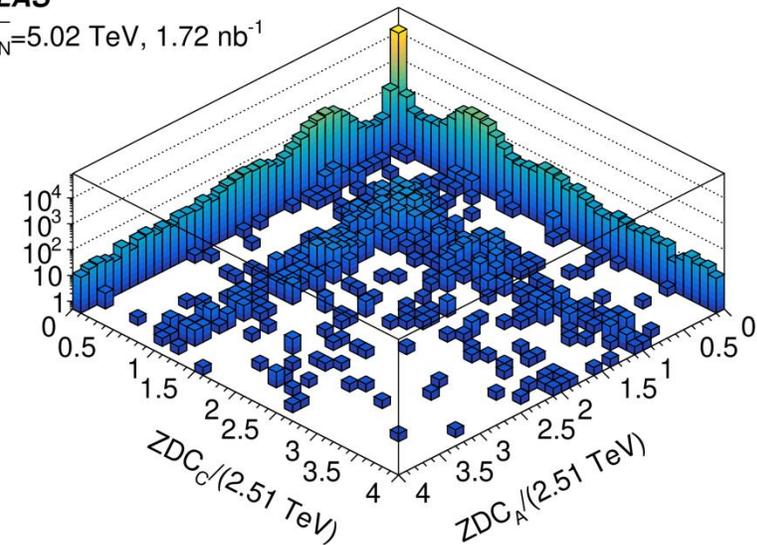
But there is one specific HI-driven upgrade, which is (the only) cooperative project between ATLAS and CMS – the Zero Degree Calorimeter.

The ZDC measures spectator neutrons, which are remnants of colliding ions, ZDC is located downstream from IP. Neutrals reach it, Charged swept away by the magnet



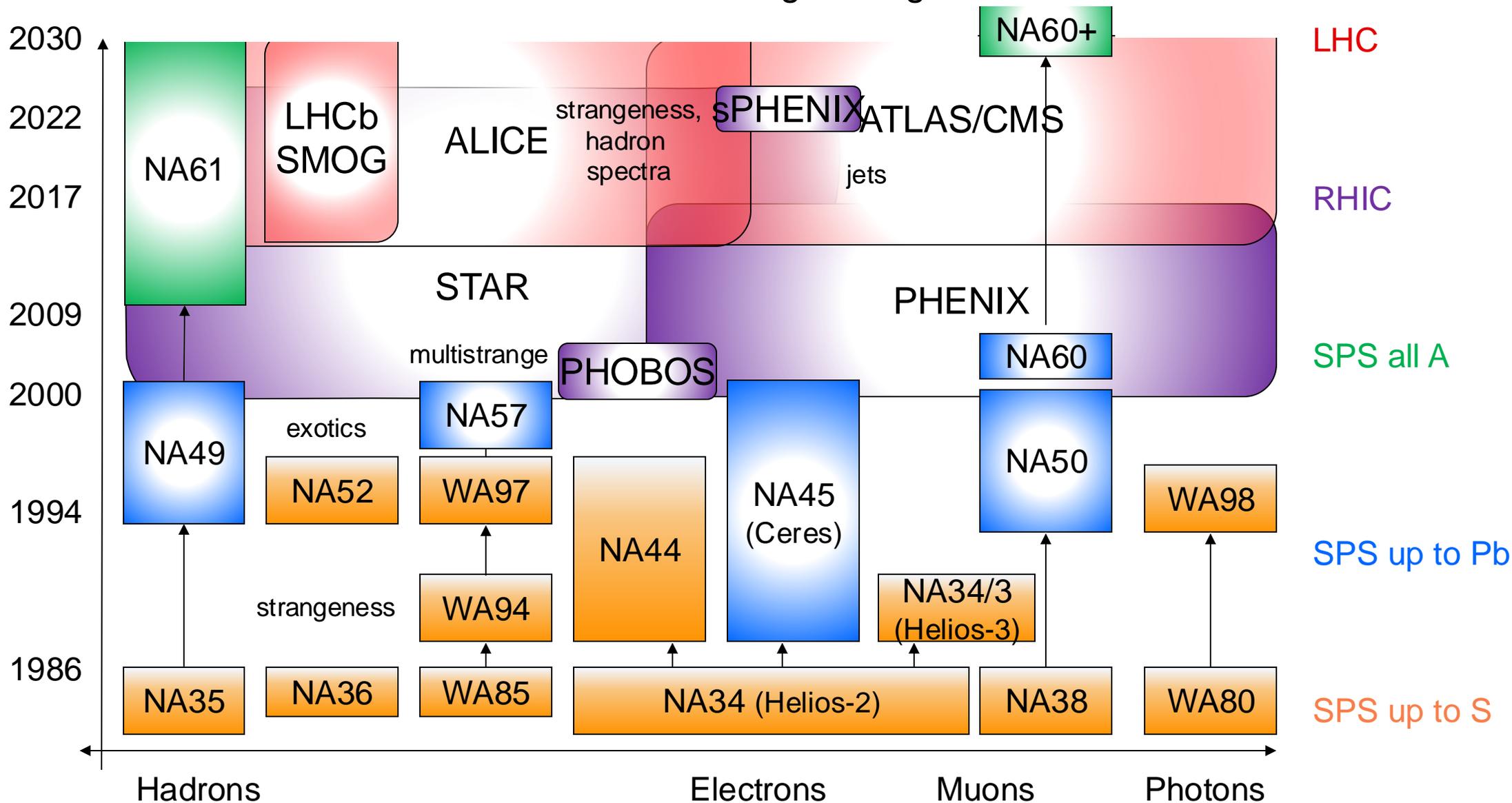
**ATLAS**

$\sqrt{s_{NN}}=5.02$  TeV,  $1.72$  nb $^{-1}$



# Heavy-Ion experimental landscape

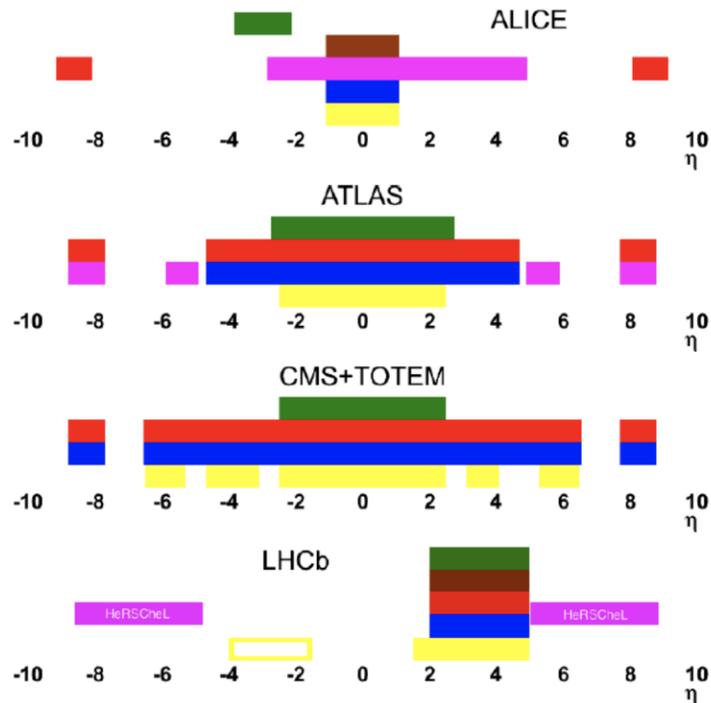
@ Intermediate and high energies



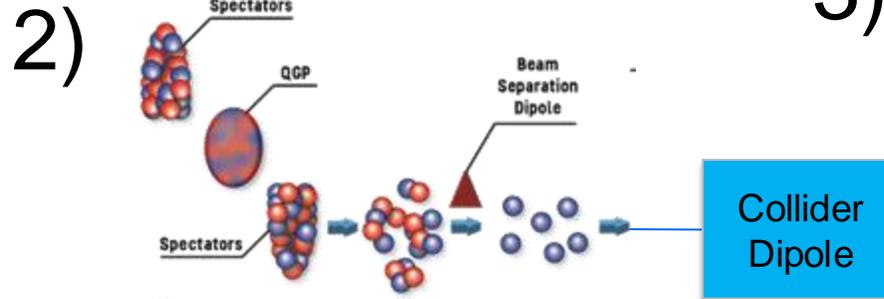
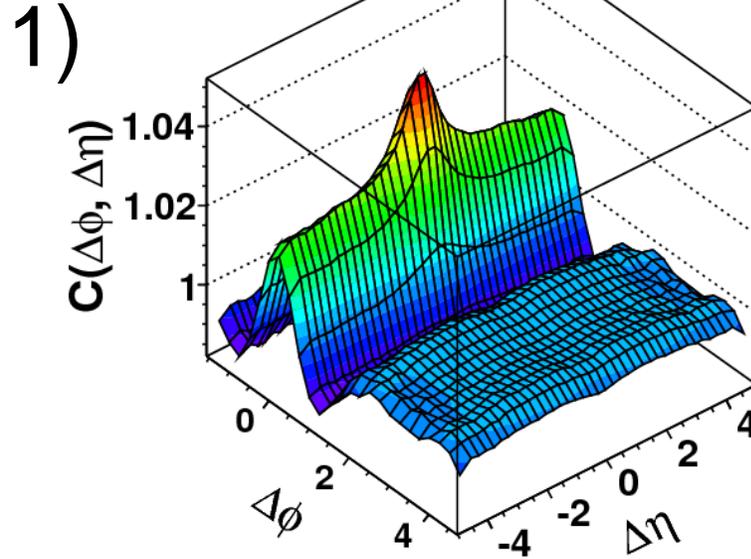
# An ideal HI detector

An ideal HI detector =  
 An ideal HEP detector  
 + pID  
 + zero thickness  
 + low- $p_T$  tracking  
 +  $4\pi$  - coverage

- hadron PID
- muon system
- lumi counters
- HCAL
- ECAL
- tracking



Sasha Milov



$$\sum_{\text{side}}^2 \sum_{A/Z} A_f = 2A - N_{\text{part}}$$

HI physics and projects

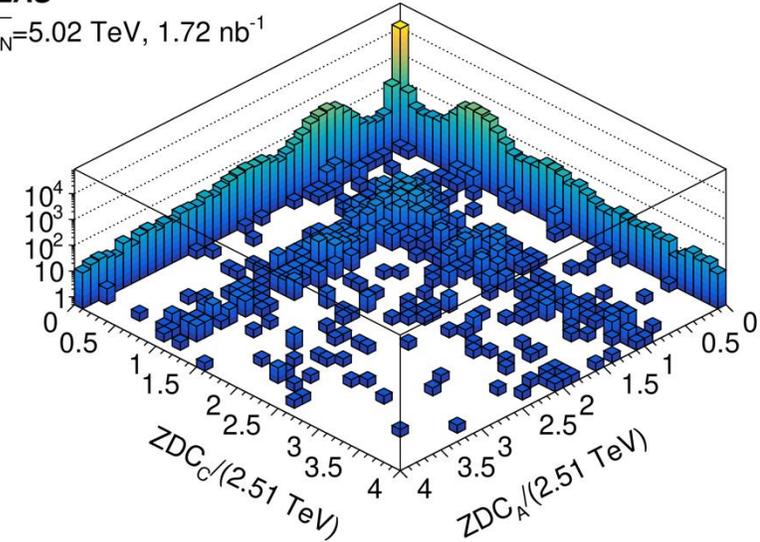
Jan 15, 2025

Detector coverage

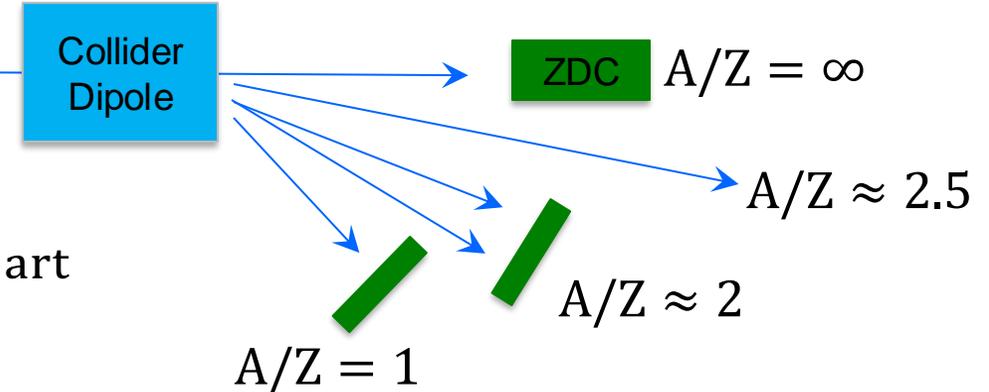
- 1) Helps 2PC
- 2) Separates PN & hh
- 3) Controls geometry

ATLAS

$\sqrt{s_{NN}} = 5.02 \text{ TeV}, 1.72 \text{ nb}^{-1}$



3)



FF25, HKUST

# Summary

Heavy Ion physics addresses the very fundamental questions of physics within the SM.

HI is an exciting, dynamic, and diverse field of HEP / Nuclear physics.

HI research attracts rather high attention. HI community worldwide probably exceeds 1000 scientists.

New facilities have been planned and built for HI physics, and the existing detectors are being upgraded.

Doing HI measurements usually demands the most advanced detectors but not the most generous budgets.

Town hall meeting on HI @ CERN (Feb 17, 2025) <https://indico.cern.ch/event/1483832/>