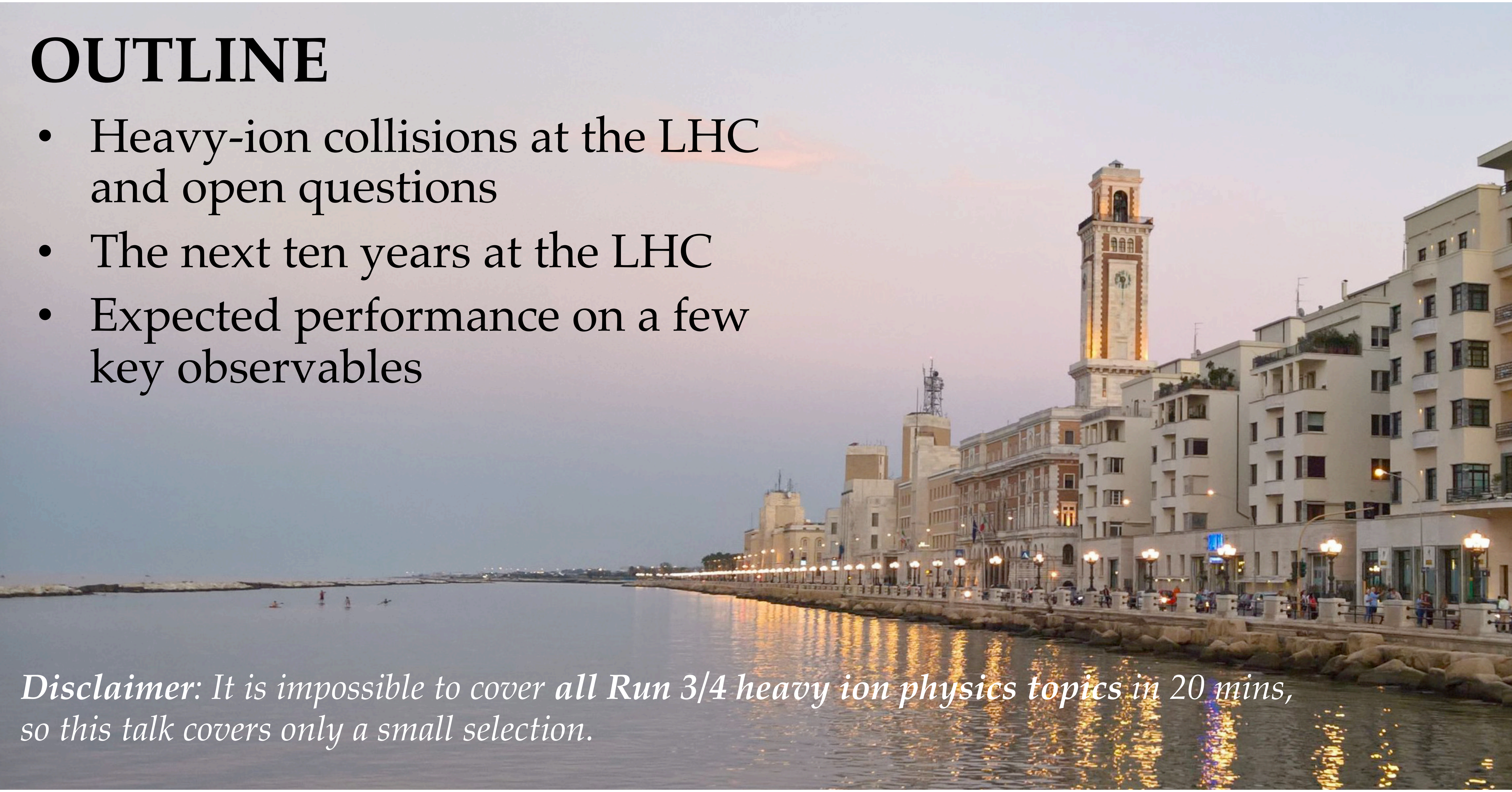
PHYSICS WITH THE DETECTOR UPGRADES AT THE LHC

Michael Weber
Stefan Meyer Institute, Vienna
SQM 2019, Bari / Italy, 14.06.2019

Special thanks to:
Jan Fiete Grosse-Oetringhaus / Andrea Dainese / Alexander Kalweit (ALICE),
Zvi Citron (ATLAS), Yen-Jie Lee (CMS), Michael Winn (LHCb -> ALICE)



OUTLINE

- Heavy-ion collisions at the LHC and open questions
- The next ten years at the LHC
- Expected performance on a few key observables

Disclaimer*: It is impossible to cover* ***all Run 3/4 heavy ion physics topics*** *in 20 mins, so this talk covers only a small selection.*

Slides mainly based on HL-LHC WG5 yellow report:
CERN-LPCC-2018-07 ***arXiv:1812.06772***

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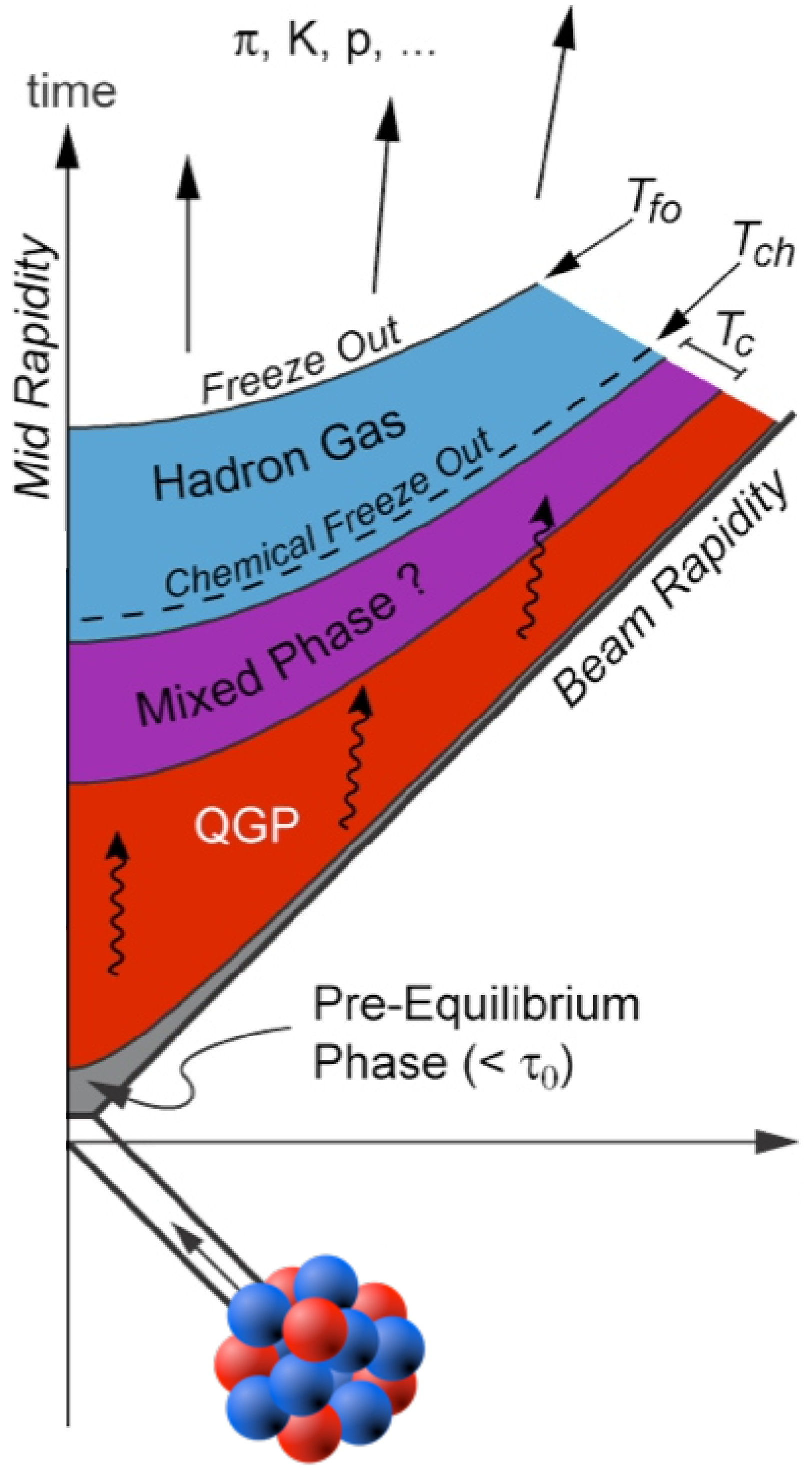
HEAVY IONS AT THE LHC

and open questions



Initial state

- Nuclear parton distributions not strongly constrained
- Importance of initial state fluctuations
- ➢ **Characteristics of the initial state?**

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HEAVY IONS AT THE LHC

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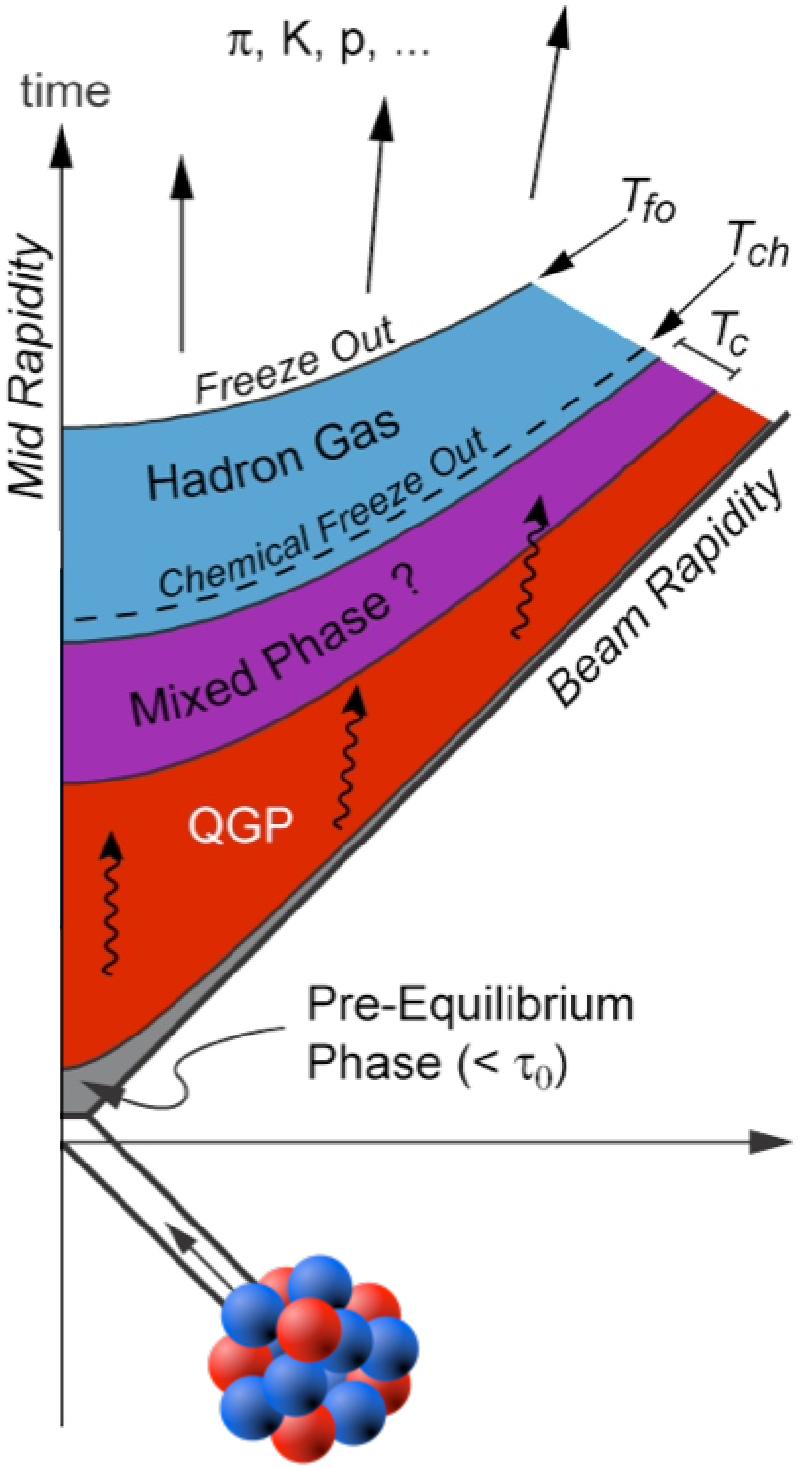

Macroscopic properties (long wavelength characterisation)

- Description in terms of fluid- and thermodynamics
- Next level of precision and new observables (flow correlations,…)
- ➢ **Properties of QCD matter and the transition between phases?**

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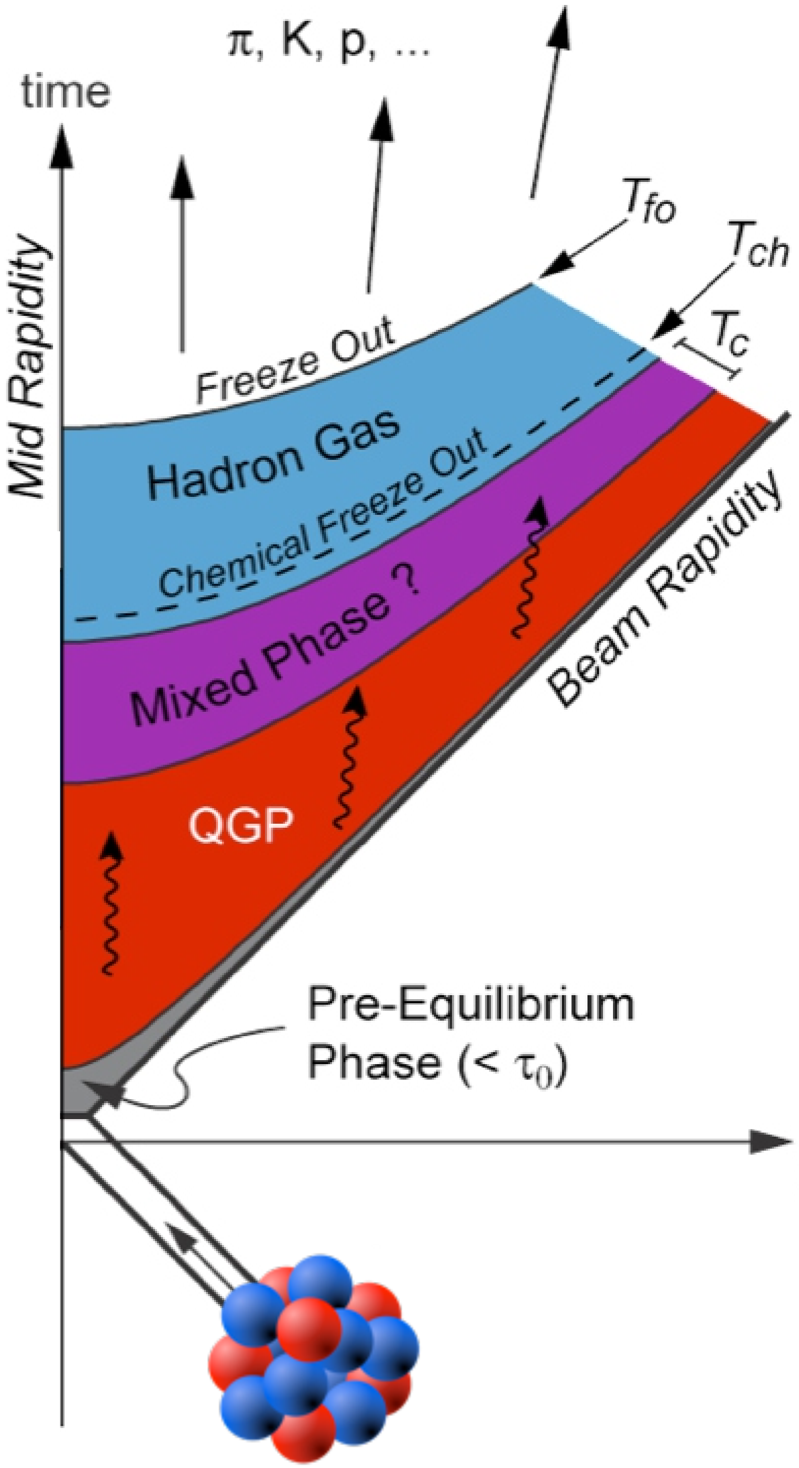

Microscopic dynamics (short wavelength characterisation)

- Strong energy loss for hard partons
- New jet substructure observables (splitting function, jet mass,…)
- Quarkonium suppression and regeneration
- ➢ **Degrees of freedom at which stage and their interactions?**

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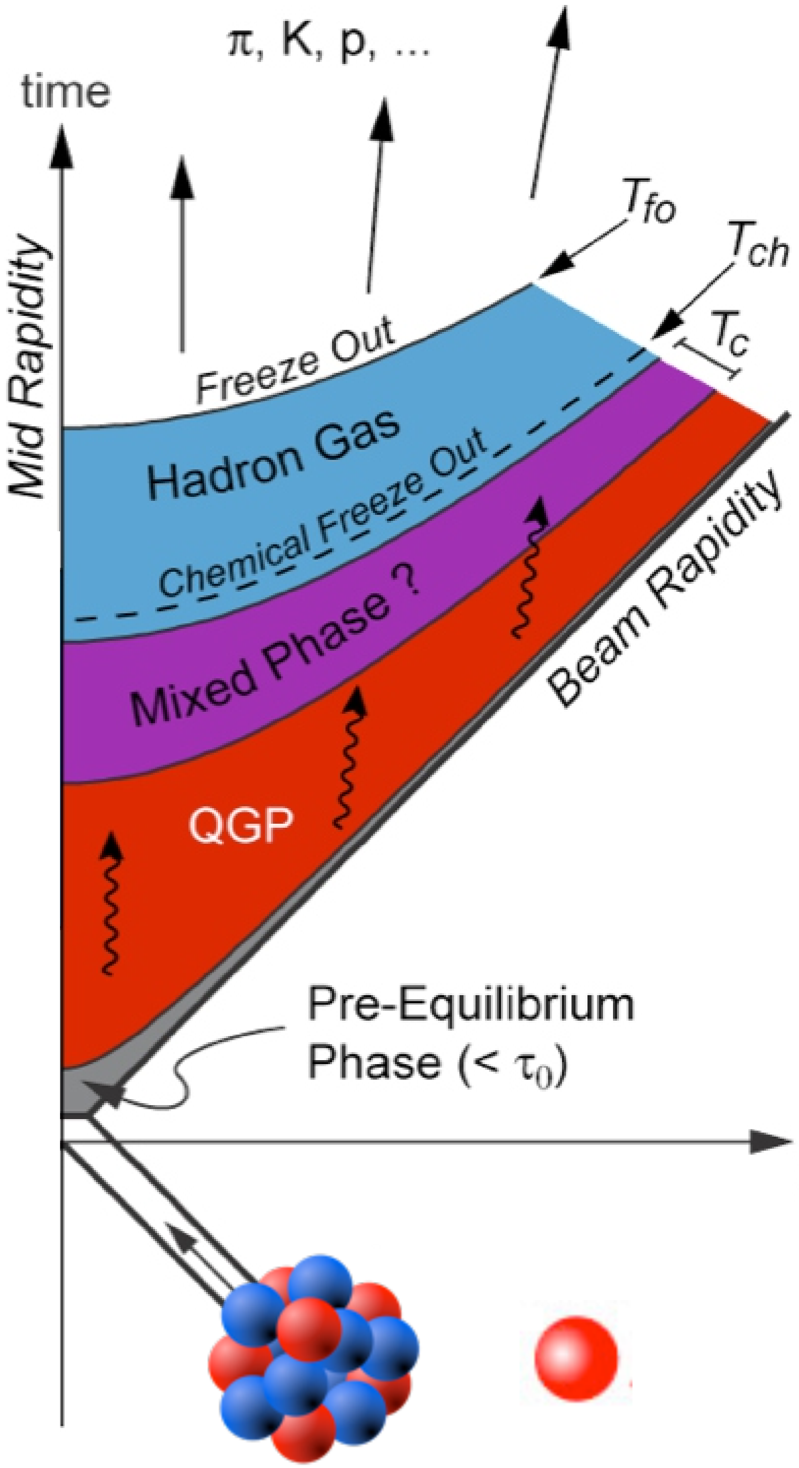

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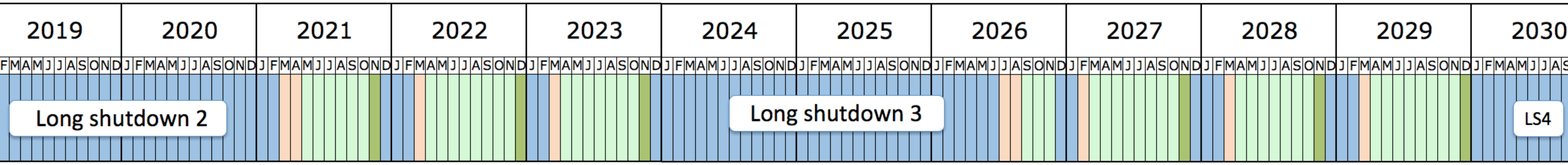
➢ **Characteristics of the initial state?**

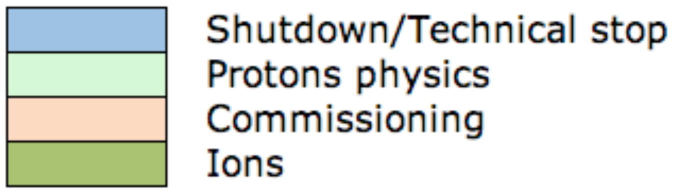
Small systems

- Surprises in pp and p-Pb collisions ("flow", "strangeness enhancement")

➢ **Is there a unified picture of QCD particle production from small (pp) to larger (p-A and A-A) systems?**

THE NEXT TEN YEARS





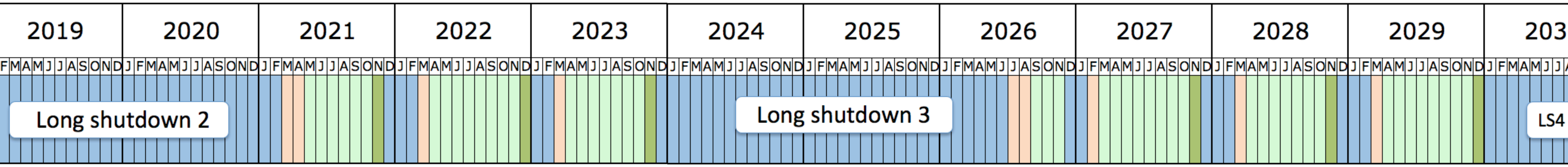
- **13 nb^{-1} Pb-Pb collisions**
  - ≈ 10 × combined Run 1/2 luminosity
  - ≈ × 100 for soft probes (new ALICE read-out)

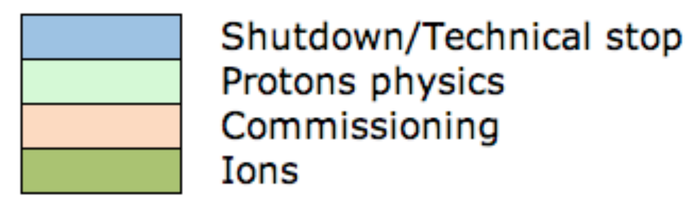
- **Complemented by (proposal of HL-LHC WG5)**
  - Larger p-Pb samples: 1.2 pb^{-1} ATLAS/CMS, 0.6 pb^{-1} ALICE/LHCb & pp references
  - pp running for high-multiplicity events: 0.2 fb^{-1}
  - Pilot-like O-O and p-O collisions run

- **Proposal for lighter ions, e.g. Ar–Ar (A = 40), running in Run 5 (2030+) to sample much larger luminosities**

CERN-LPCC-2018-07

THE NEXT TEN YEARS





Upgrades (LS 2):

ALICE

- **50 kHz Pb-Pb readout** (O^2)
- New Inner Tracking System (ITS2)
- GEM readout for TPC
- Muon Forward Tracker
- Fast Interaction Trigger (FIT)

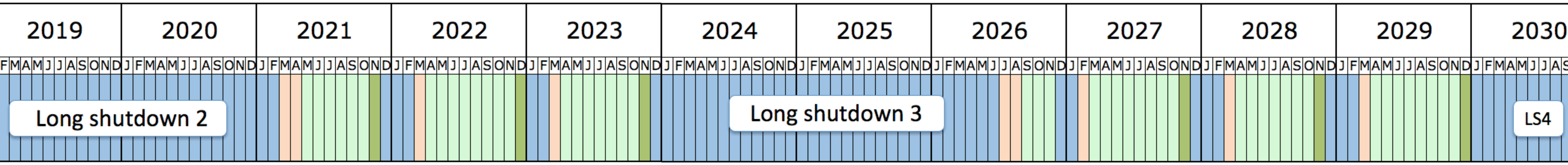
ALICE-TDR-015 ALICE-TDR-016 ALICE-TDR-017 ALICE-TDR-018 ALICE-TDR-019

LHCb

- **Fixed-target upgrade** to sample 10-100 larger luminosity
- **New tracking detectors** and read-out for 5× pp pile-up

LHCb-PUB-2018-015 LHCB-TDR-013 LHCB-TDR-015

THE NEXT TEN YEARS



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Upgrades (LS 3):

ATLAS EXPERIMENT

ATLAS-TDR-025

ATLAS-TDR-030

CMS

CMS-TDR-014

CMS-TDR-020

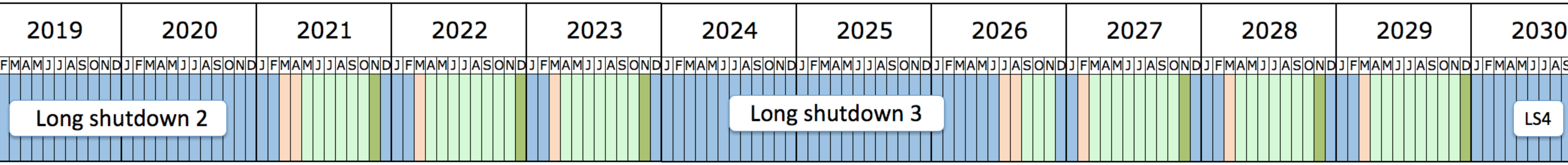
- Upgrade of the ZDCs
- **Larger tracking acceptance** for ATLAS and CMS ($|\eta| < 4$) with better performance
- **Better charged particle tracking** in high-multiplicity events, improving b-tagging of jets, and more selective photon, electron, and muon triggers
- **Extended PID capabilties**

ALICE-PUBLIC-2018-013

ALICE

- Forward Calorimeter?
- Cylindrical silicon detector (ITS3)?

THE NEXT TEN YEARS



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LHCb-PUB-2018-015 LHCB-TDR-013 LHCB-TDR-015

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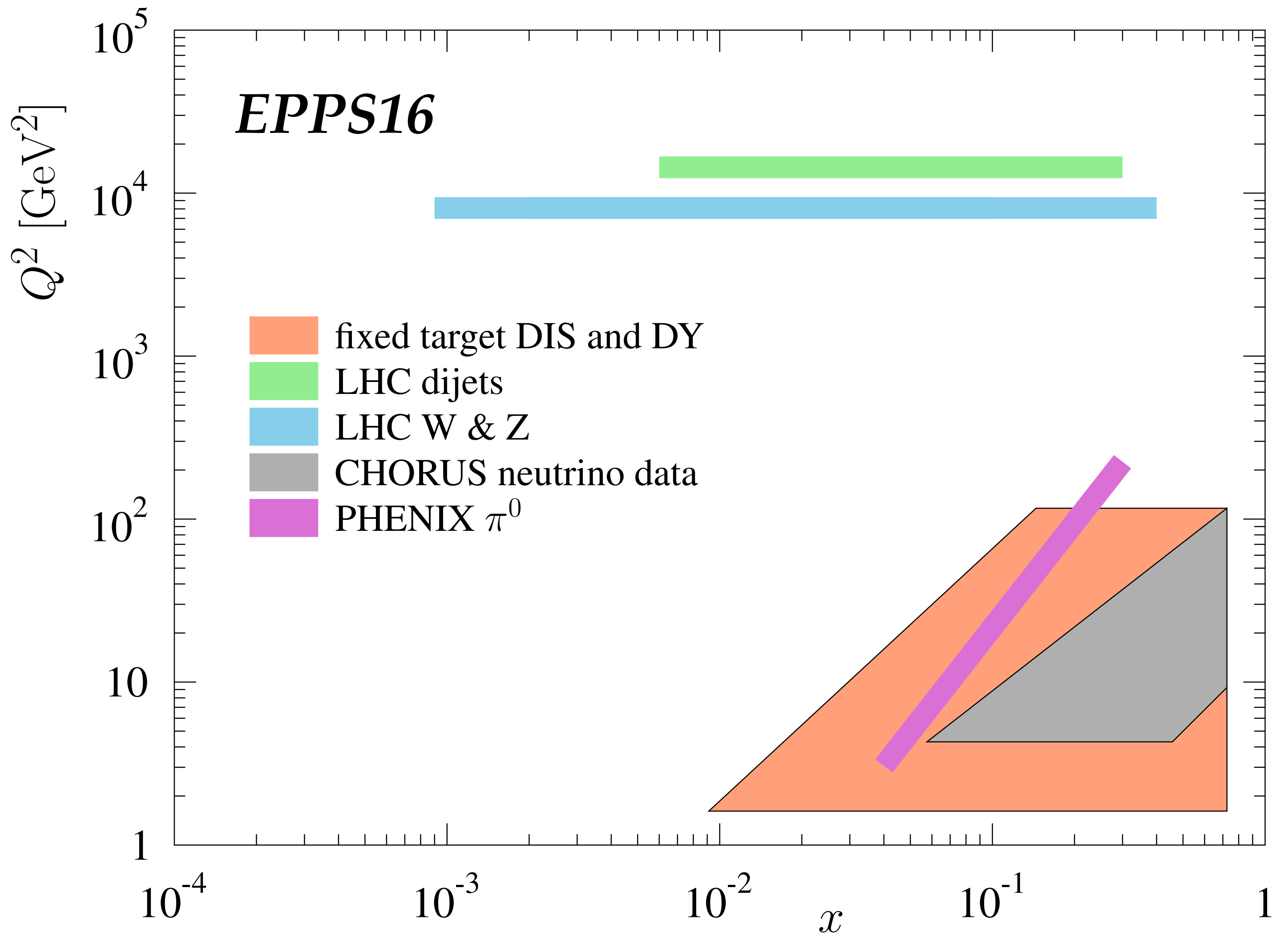
- **LHCb Upgrade-II**
- **New heavy-ion detector at LHC point 2?**

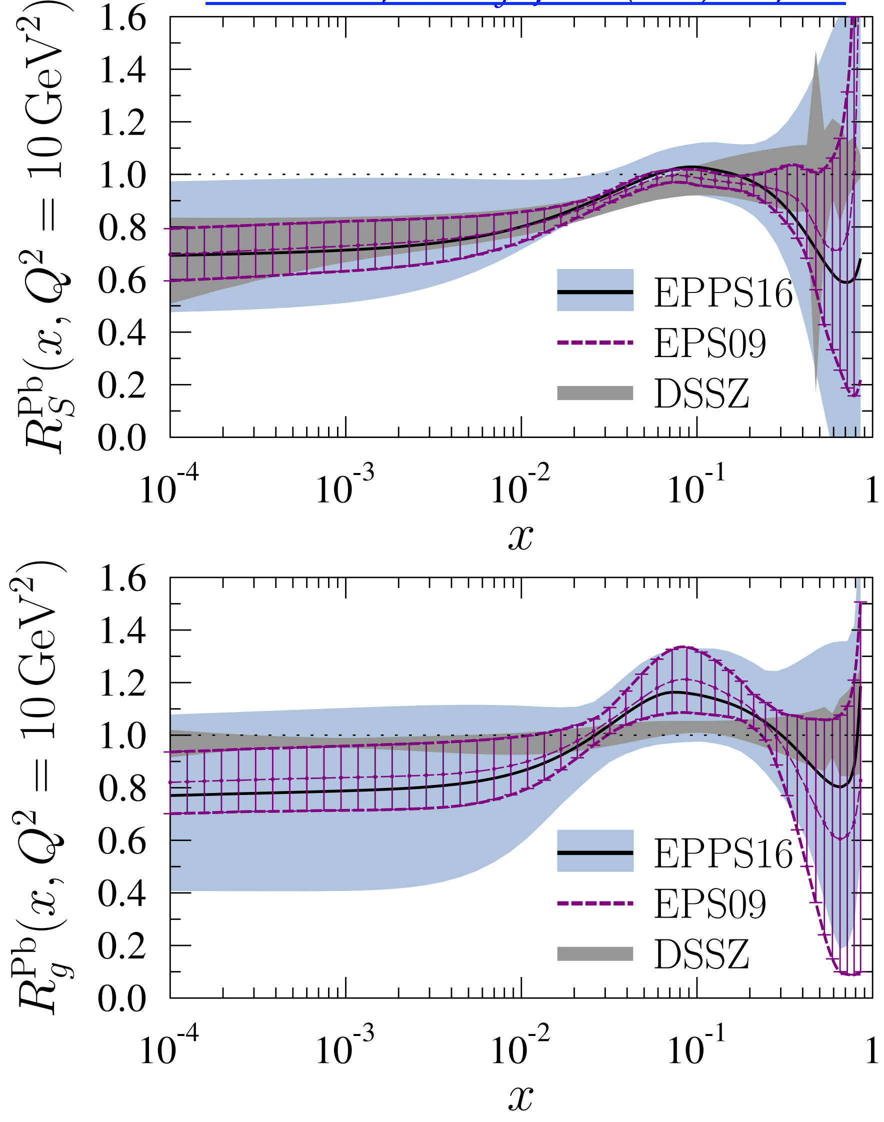
LHCB-PUB-2018-009

arXiv:1902.01211 [physics.ins-det]

INITIAL STATE



Eskola et al., Eur.Phys.J. C77 (2017) no.3, 163



- Nuclear PDFs not strongly constrained
- Probe lowest available Bjorken x
  - ➢ Onset of gluon saturation?

- High-luminosity p–Pb and Pb–Pb (γ–Pb) collisions
  - ➢ Highly-improved precision and kinematic coverage

INITIAL STATE

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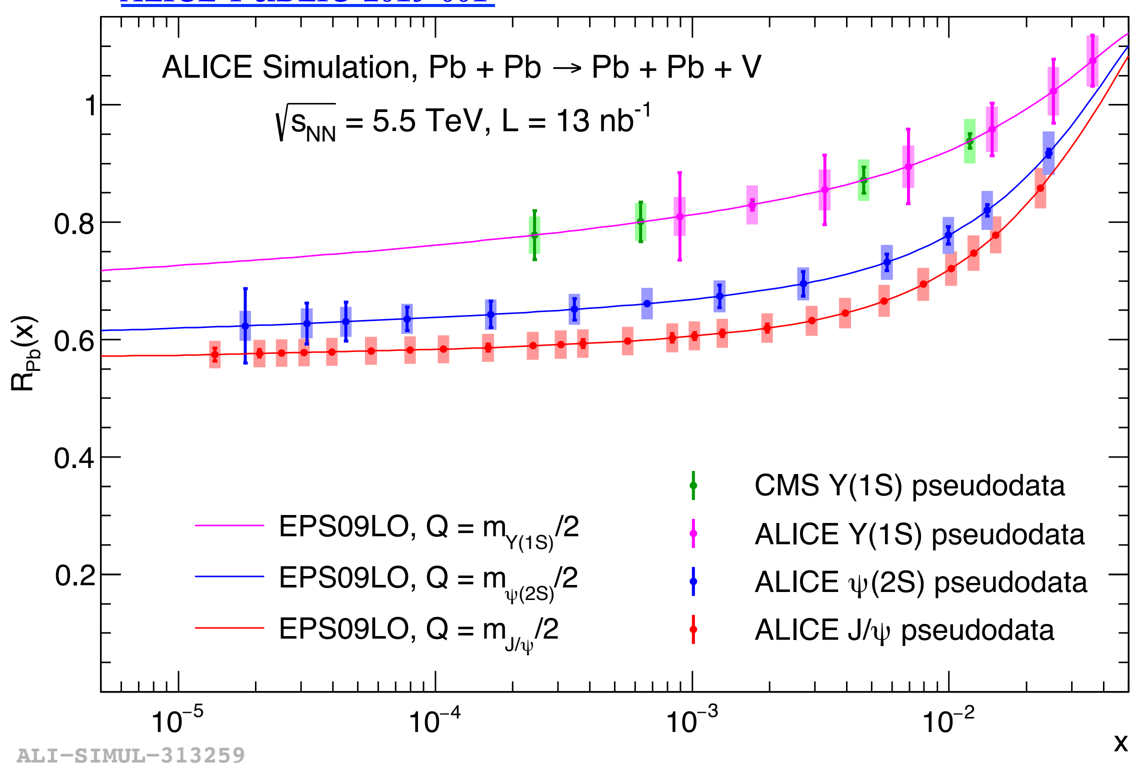

Nuclear PDFs:

- Probe with **quasi-real photon** in ultra-peripheral Pb-Pb collisions

INITIAL STATE

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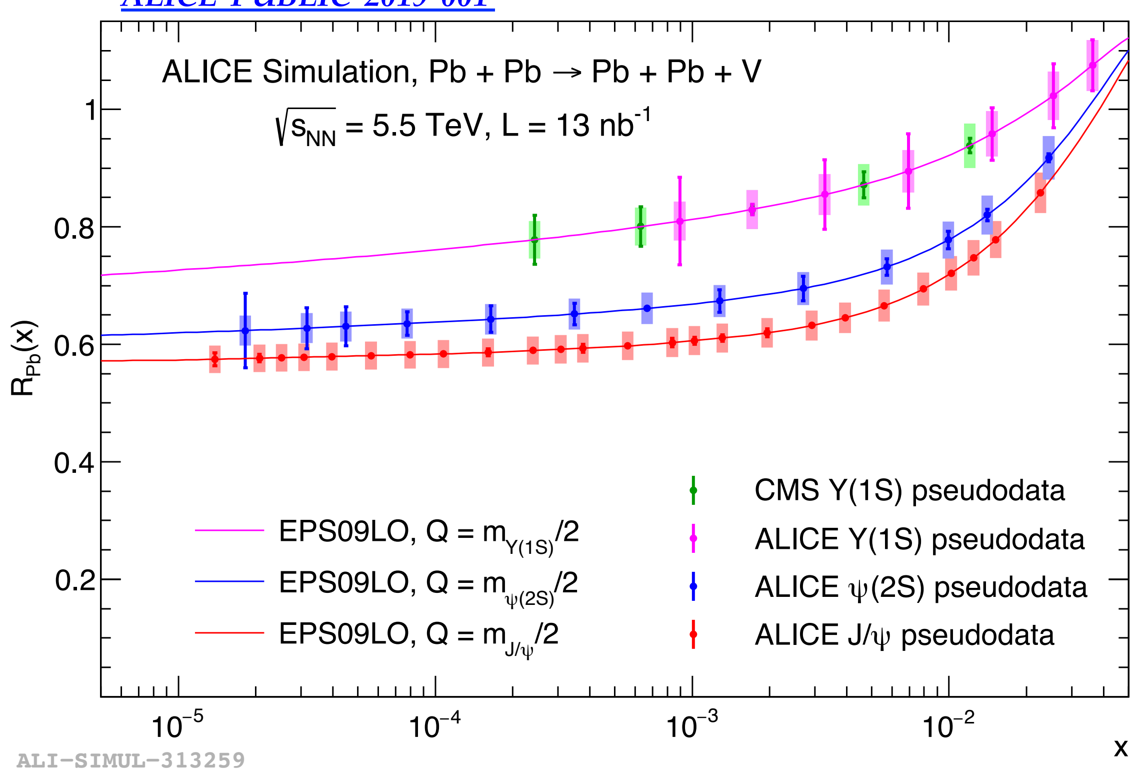
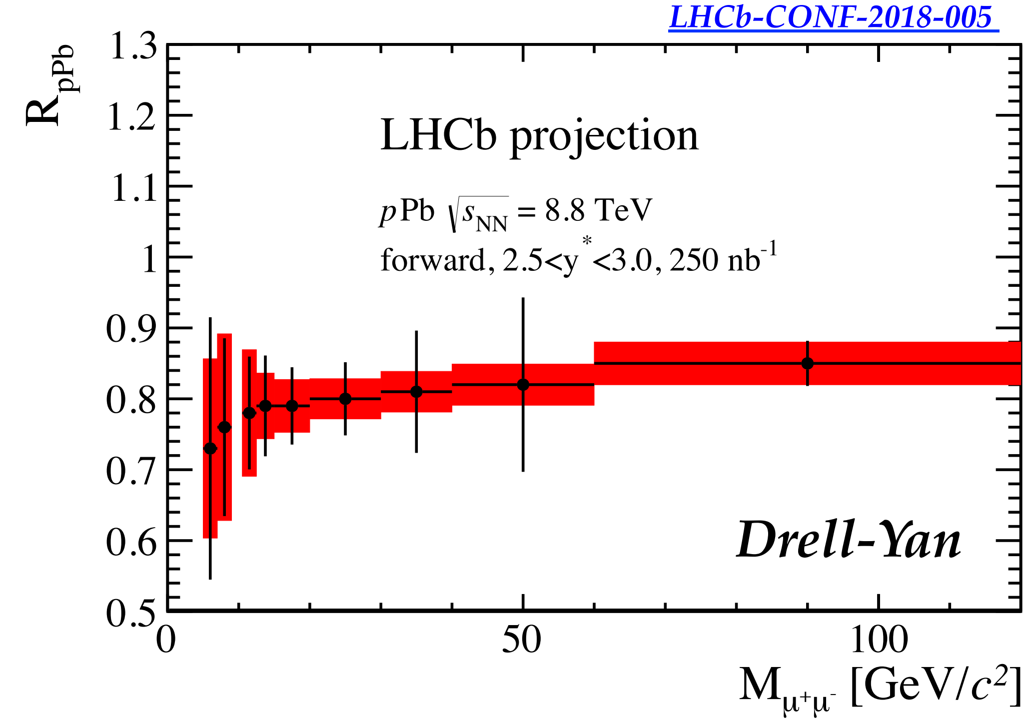
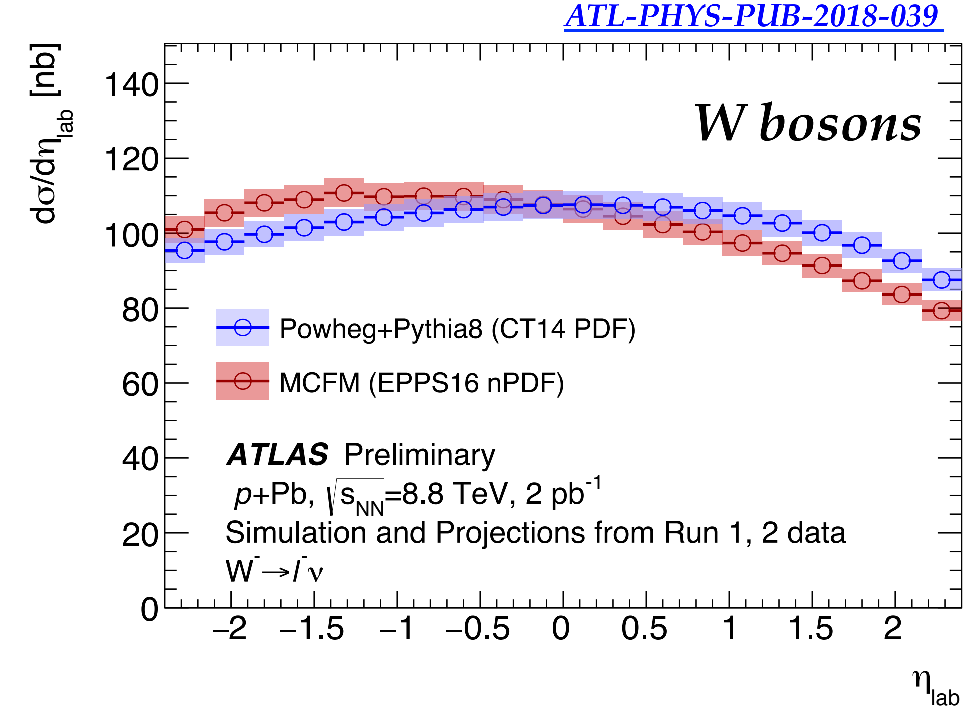


LHCb-CONF-2018-005



ATL-PHYS-PUB-2018-039



Nuclear PDFs:

- Probe with **quasi-real photon** in ultra-peripheral Pb-Pb collisions
- Probe with partons in initial state and **colour neutral final state**

INITIAL STATE

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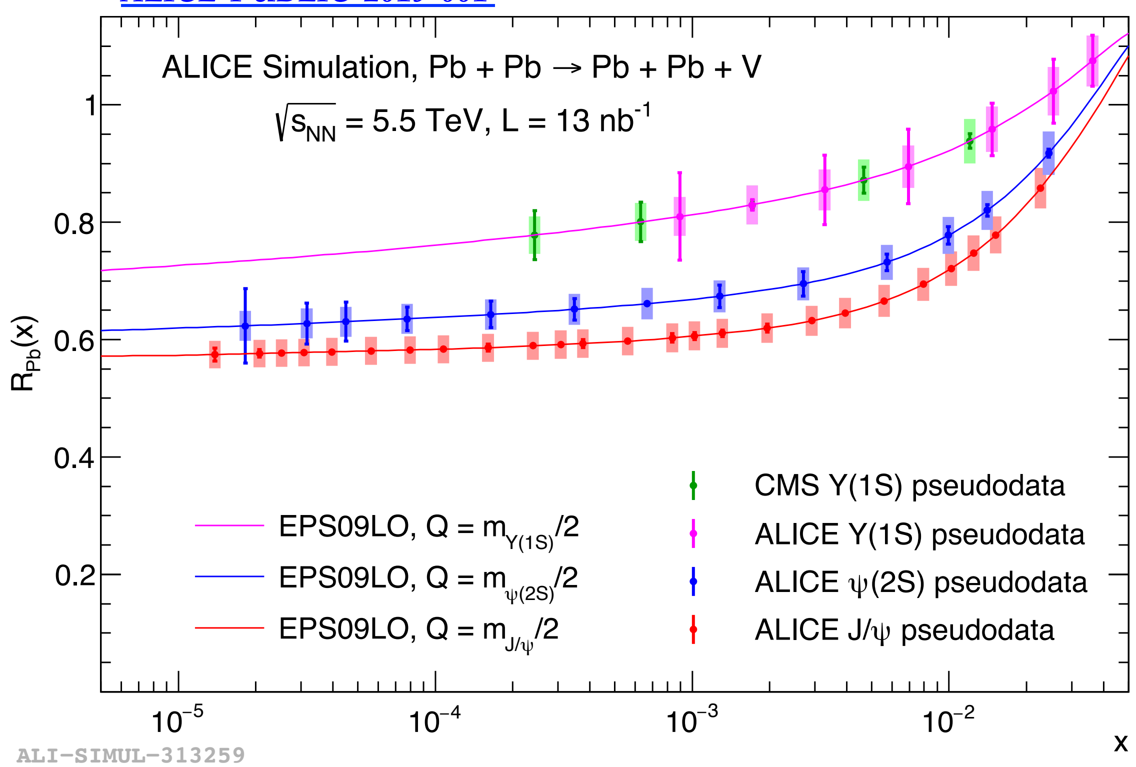
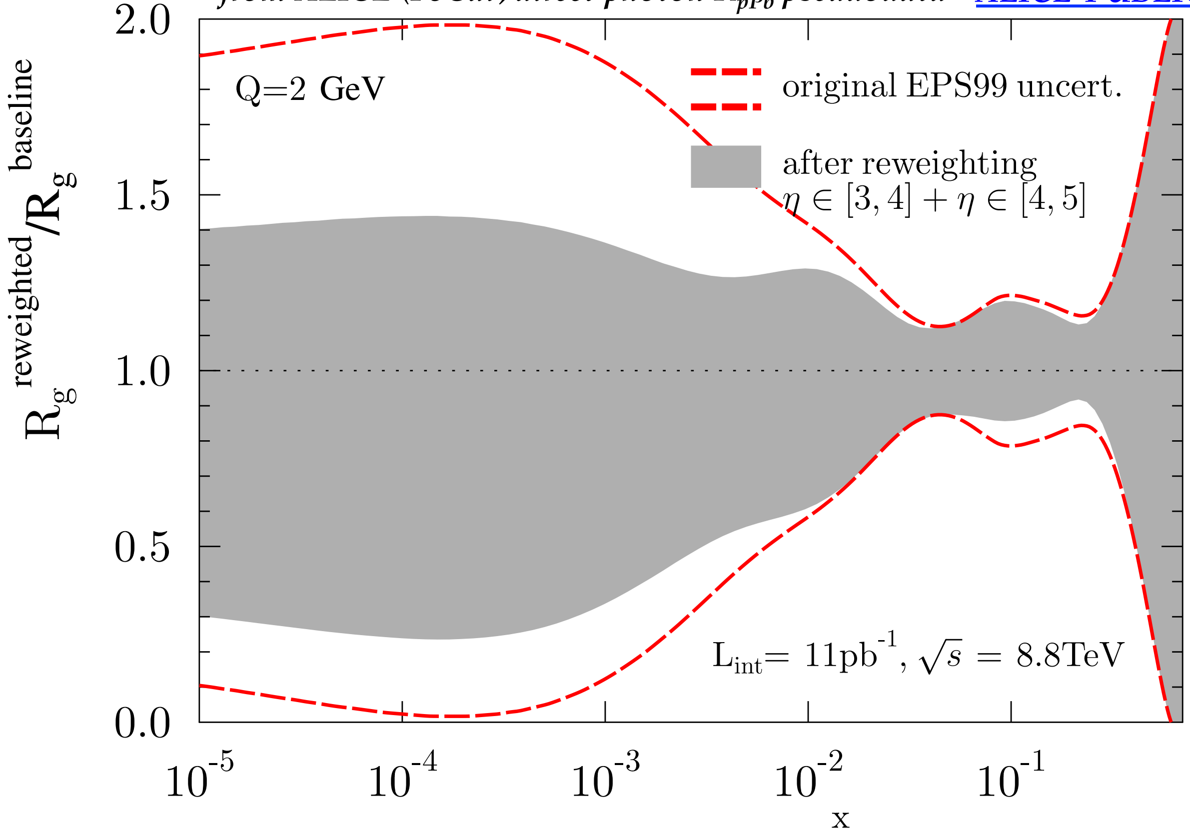


from ALICE (FoCal) direct photon R_{pPb} pseudodata ALICE-PUBLIC-2019-001



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- Probe with **quasi-real photon** in ultra-peripheral Pb-Pb collisions
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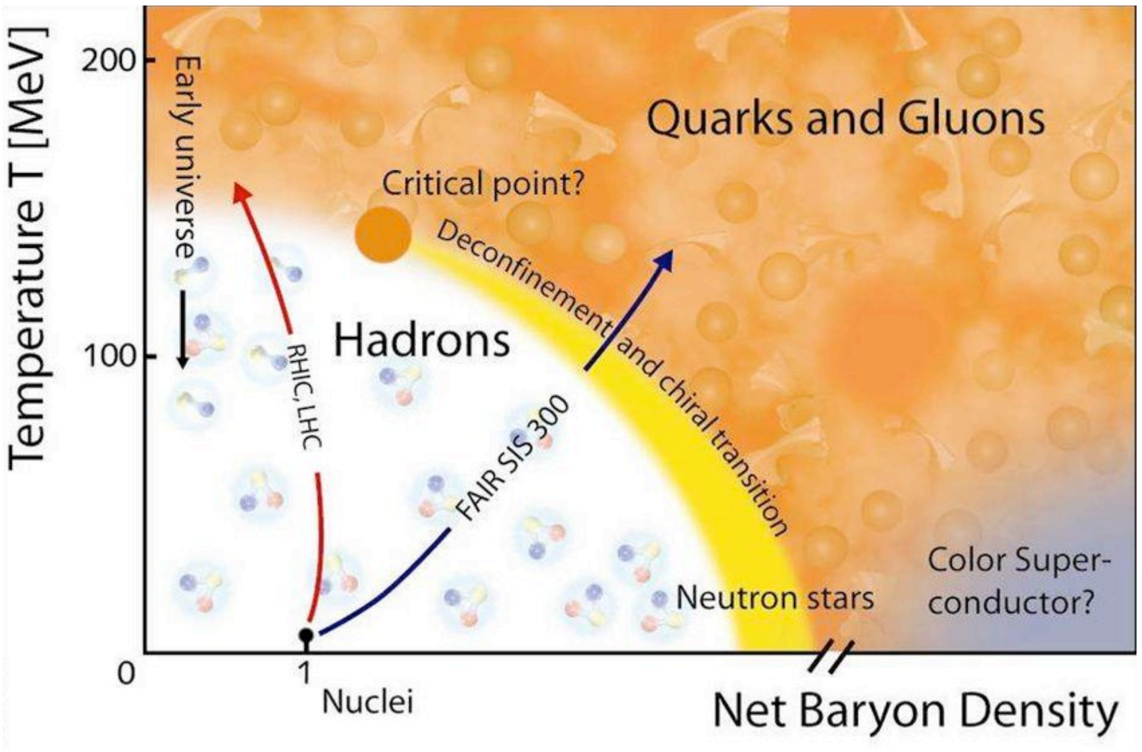
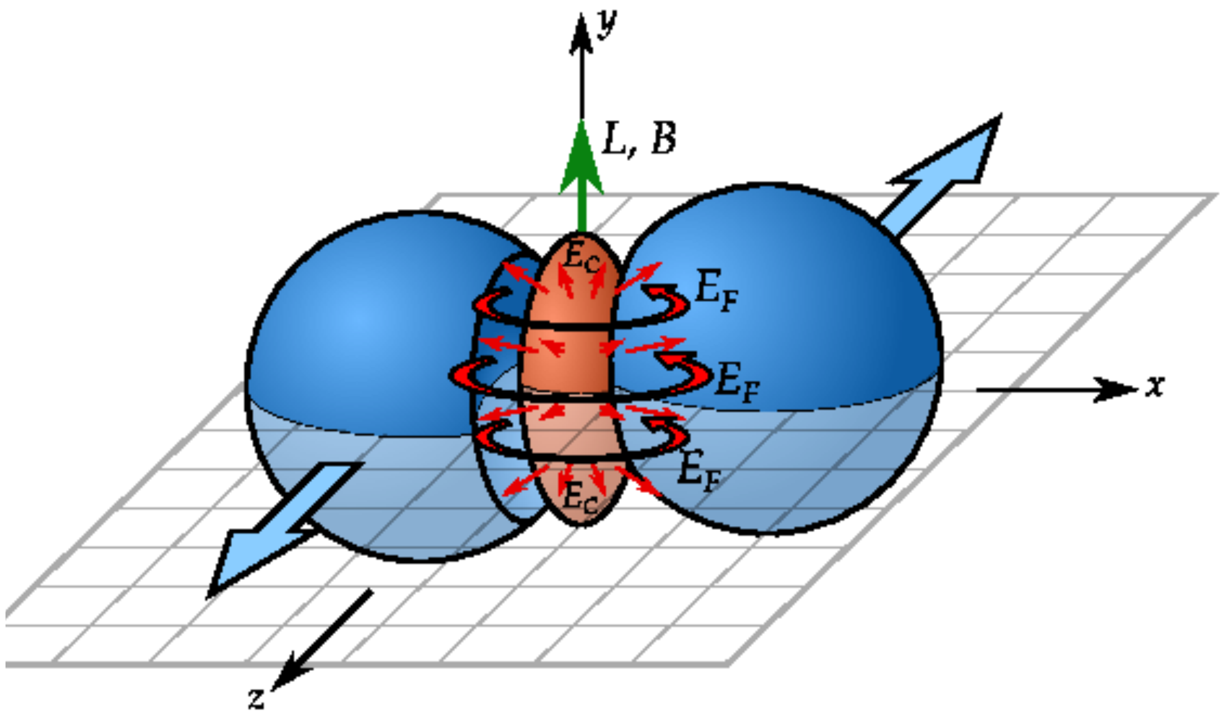
Gluon saturation:

- Nuclear modification of the gluon distribution
- Direct photon measurement in p–Pb collisions accessible in possible ALICE Forward Calorimeter

MACROSCOPIC PROPERTIES





- Signatures of phase transitions at $\mu_B = 0$ (Lattice QCD)

- Hydrodynamic transport coefficients
- Temperature (evolution)
- Magnetic field

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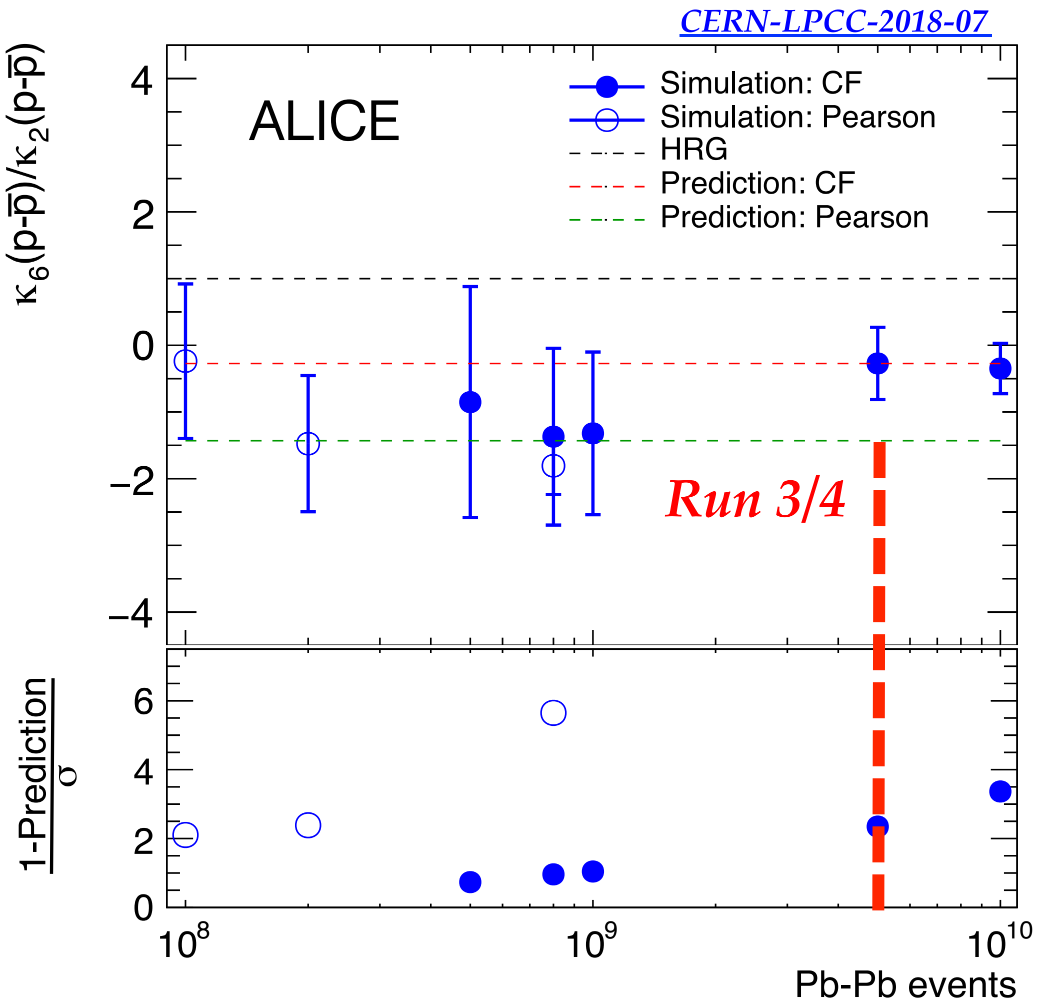
MACROSCOPIC PROPERTIES



Phase transition

- Event-by-event net-proton number fluctuation as proxy for baryon susceptibility
- 6th moment predicted to be sensitive to critical behaviour at chiral phase transition

Macroscopic Properties

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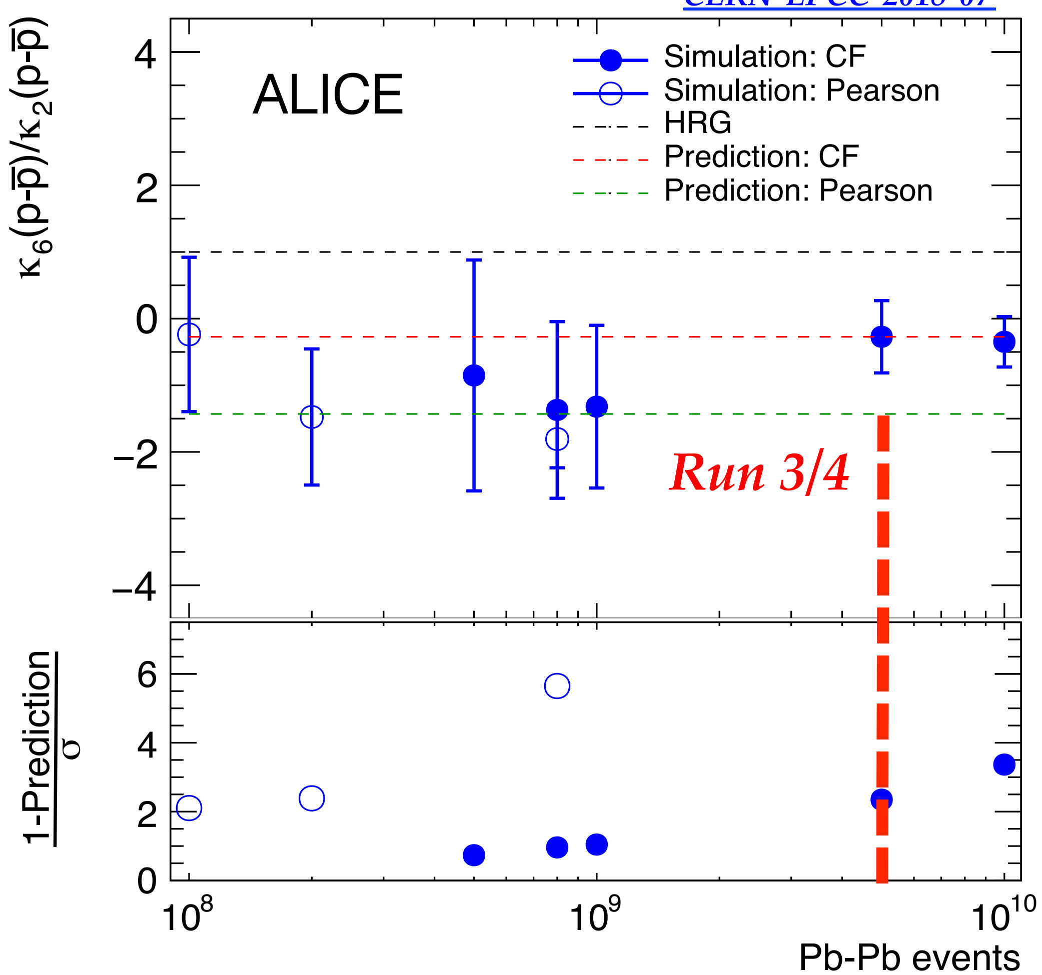
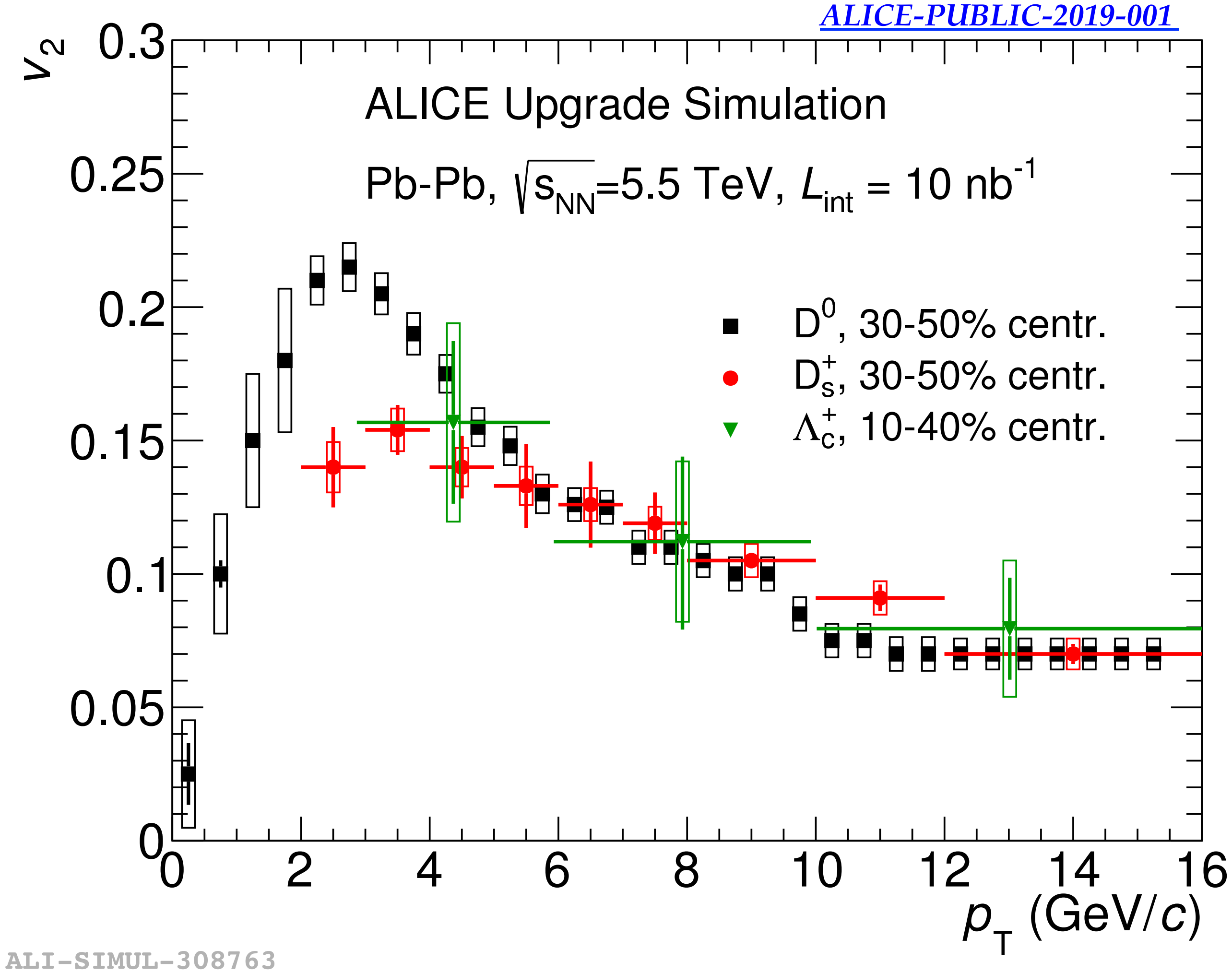


ALICE-PUBLIC-2019-001



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Transport coefficients

- Heavy quark diffusion coefficient by combining R_{AA} and v_2 of heavy flavour particles

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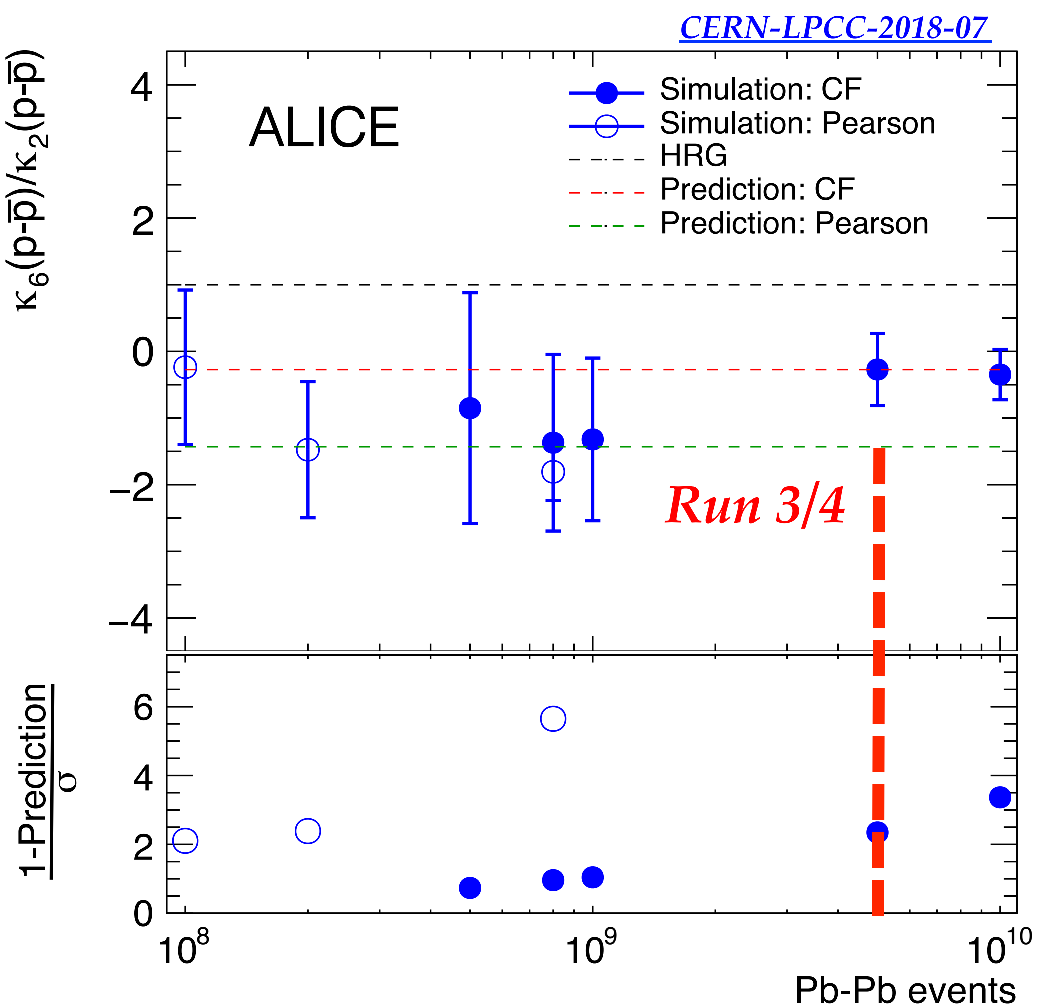

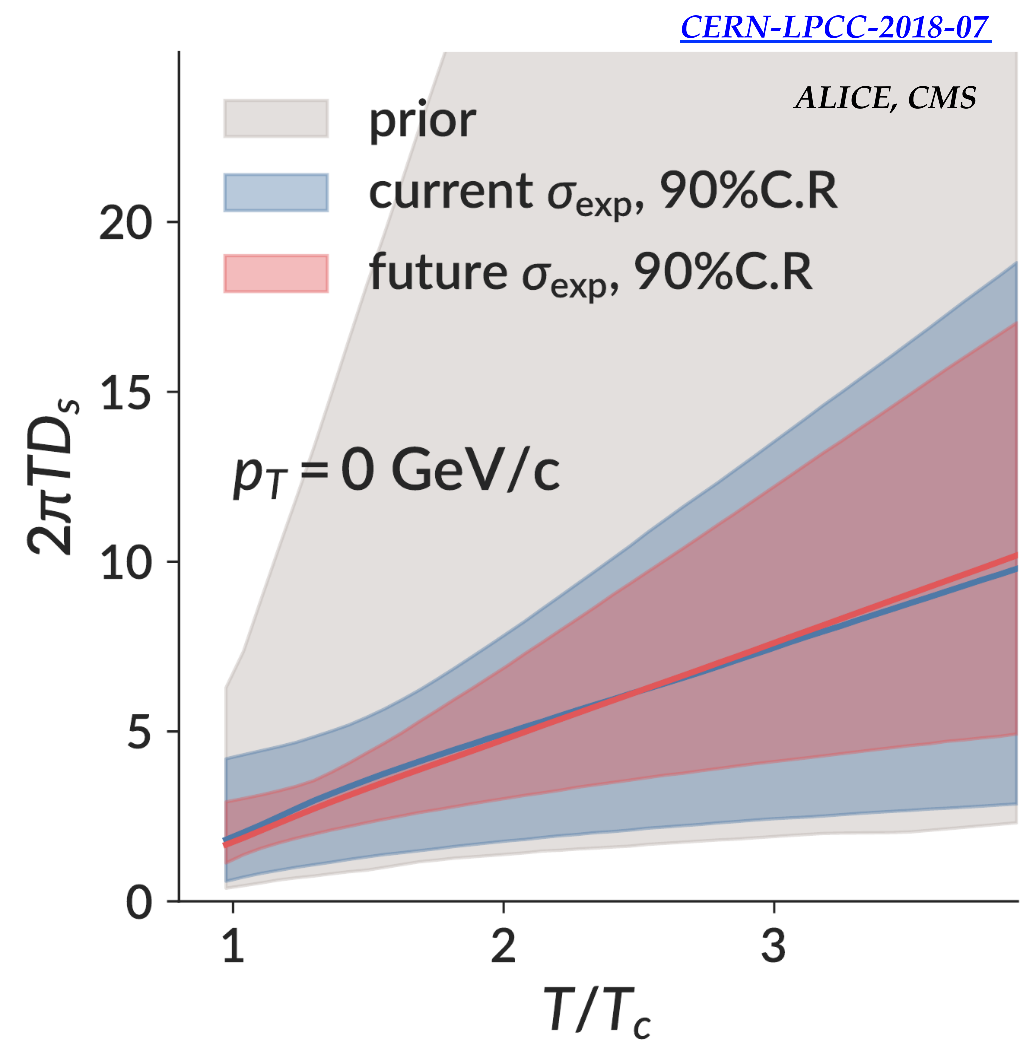

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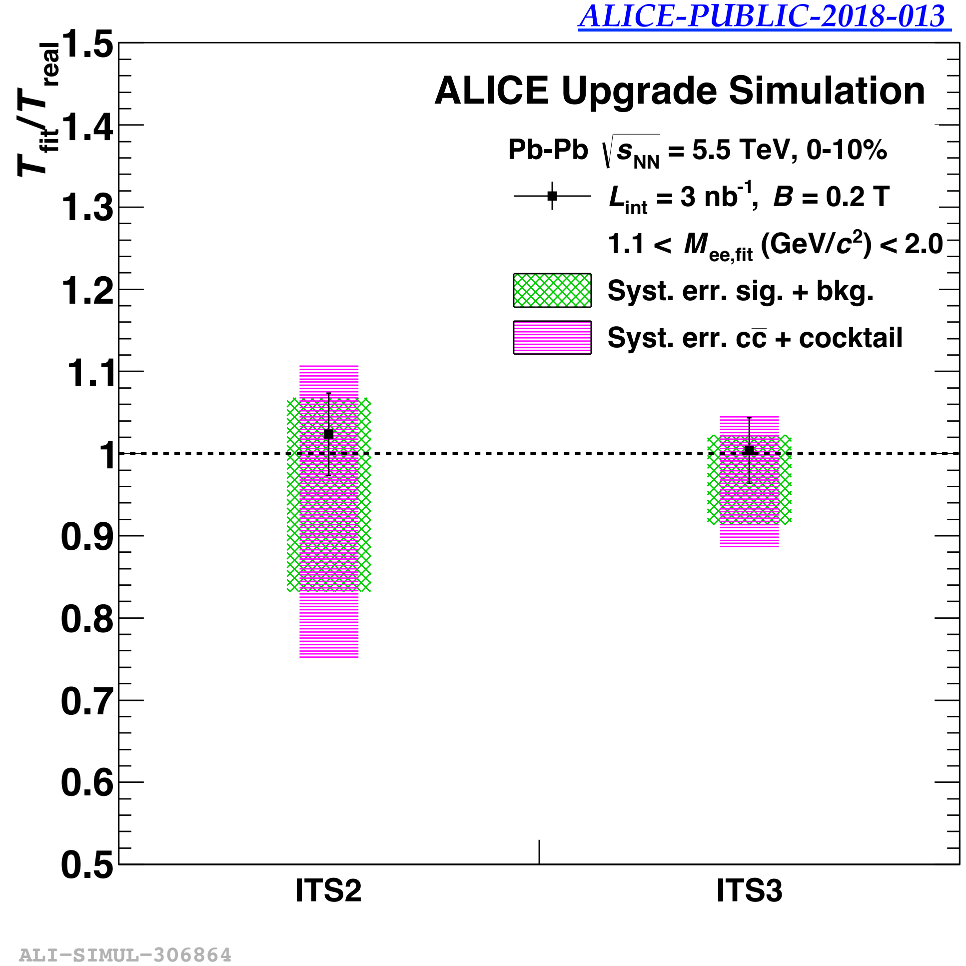
ALICE-PUBLIC-2018-013

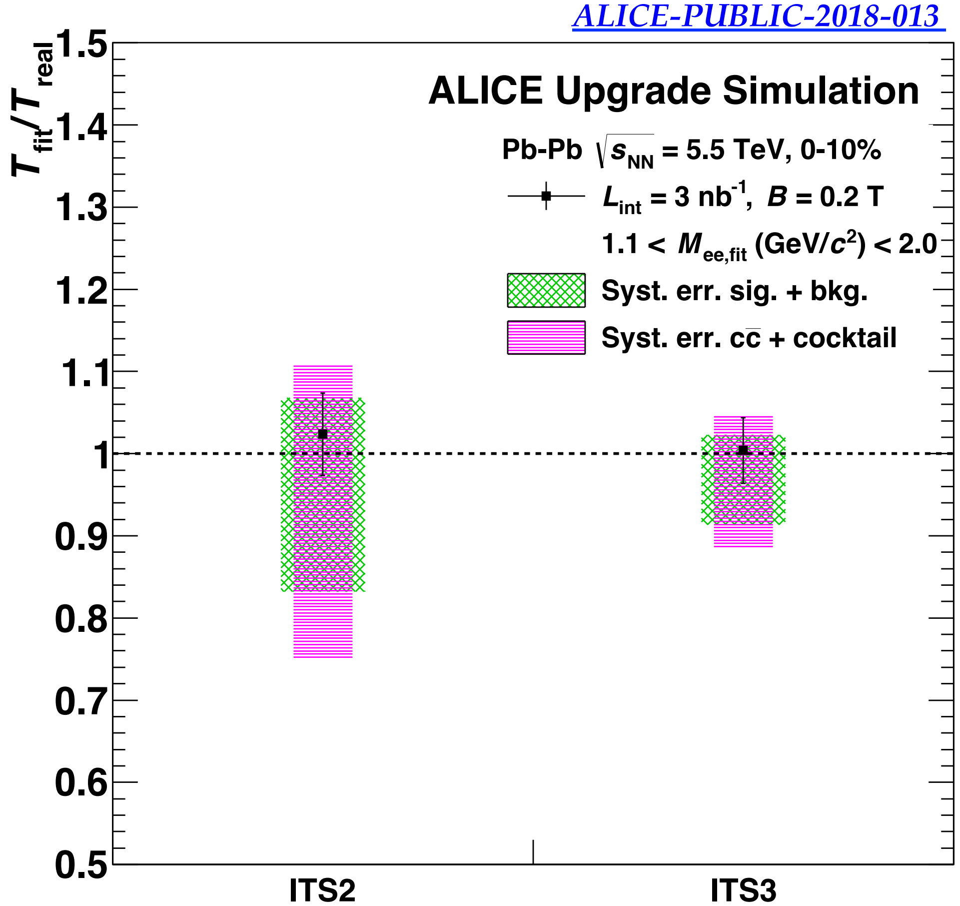


Temperature

- Measured with (virtual) photons
- Possible improvement with further ALICE upgrade (ITS3)

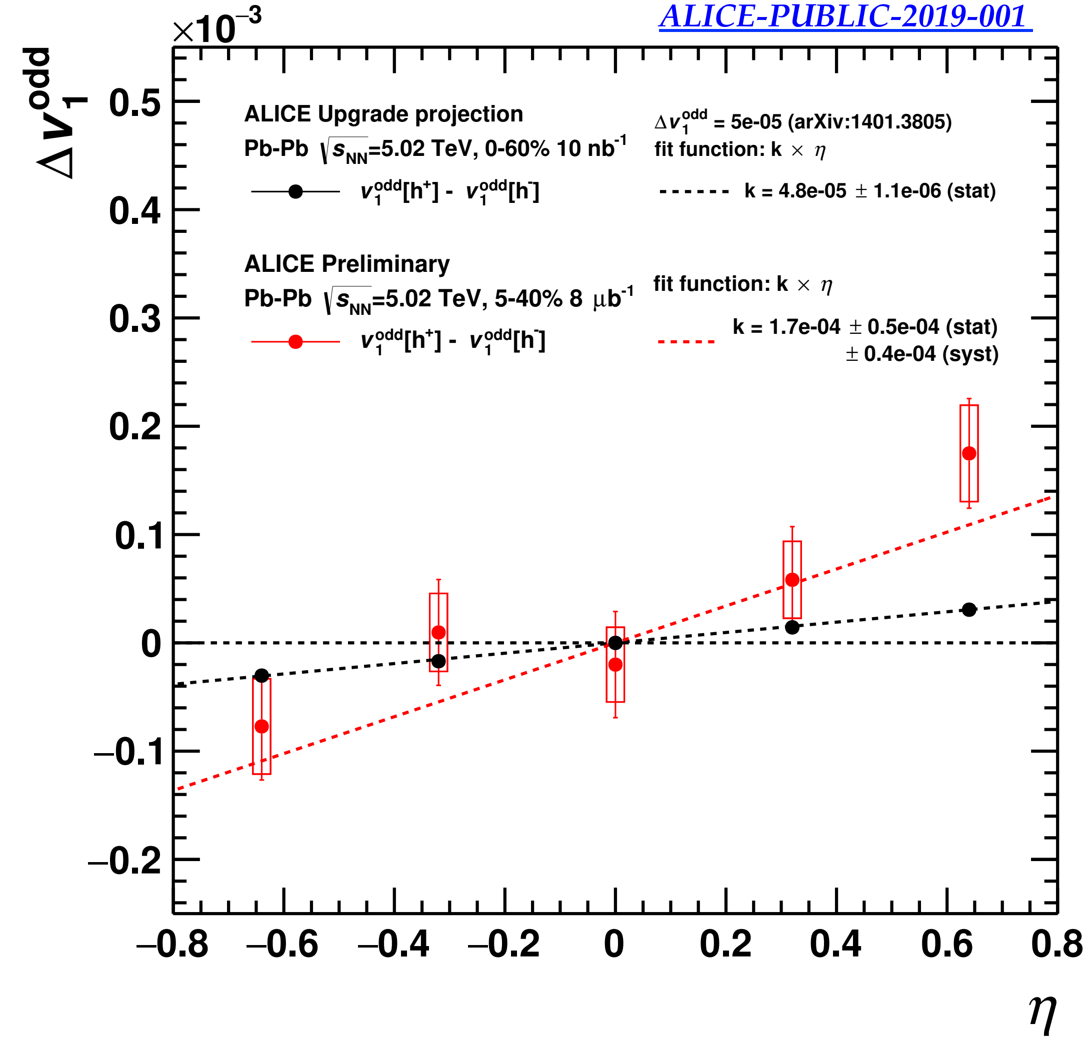
MACROSCOPIC PROPERTIES

ALICE-PUBLIC-2018-013



ALI-SIMUL-306864

ALICE-PUBLIC-2019-001

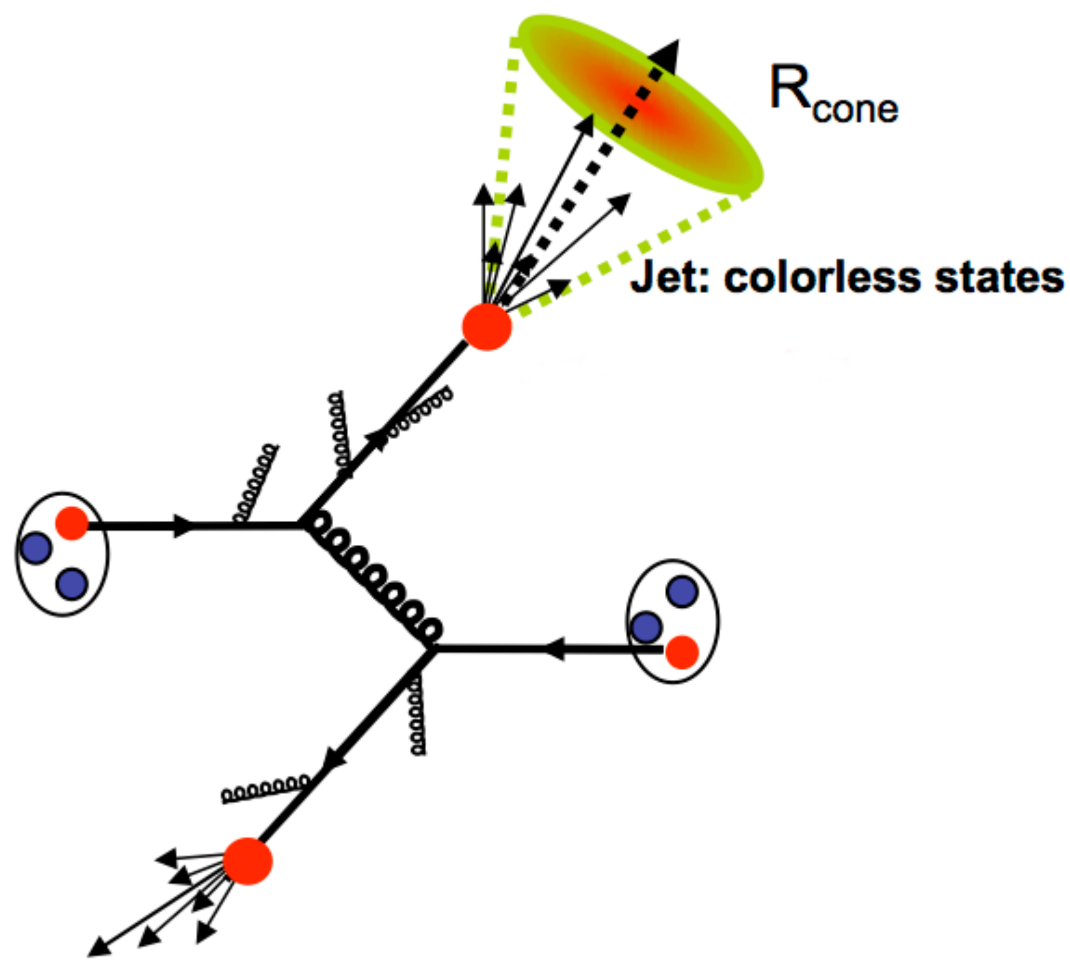


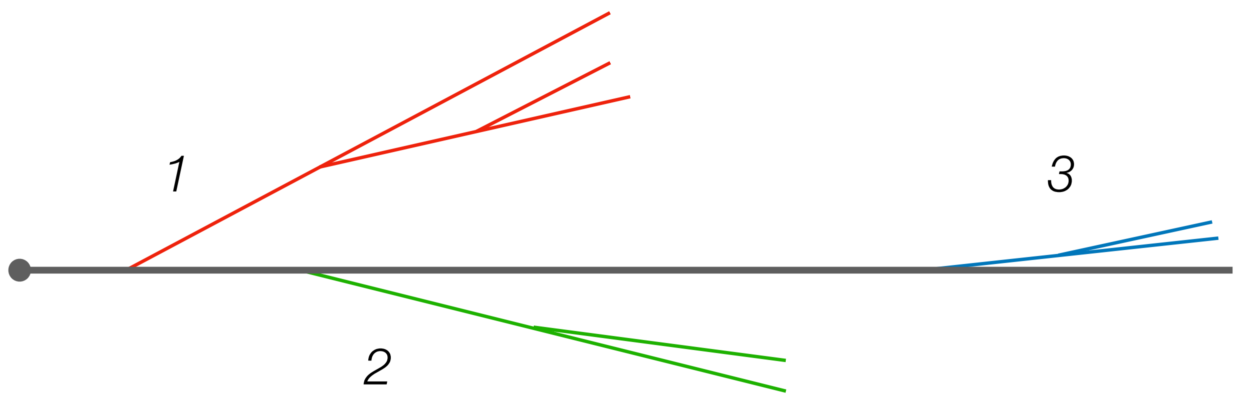
ALI-SIMUL-140076

Temperature
- Measured with (virtual) photons
- Possible improvement with further ALICE upgrade (ITS3)

Strong electromagnetic fields
- Measurable in the charge dependent direct flow of charged particles
- A larger effect is predicted for heavy quarks

MICROSCOPIC DYNAMICS



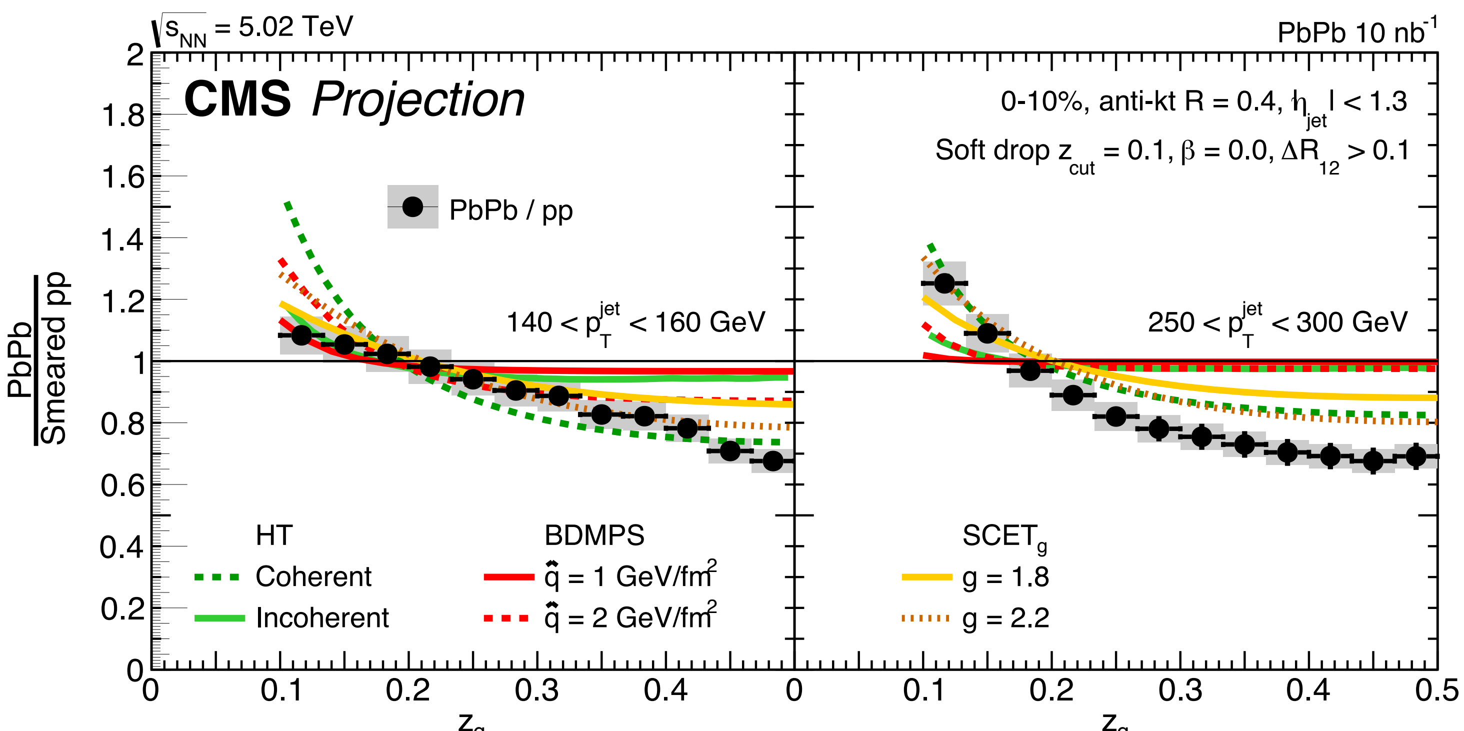


Parton (in-medium) radiation

- Effective constituents of QCD matter (characteristic length scales)?
- Interaction with medium?

- Use multi-differential jet measurements

MICROSCOPIC DYNAMICS



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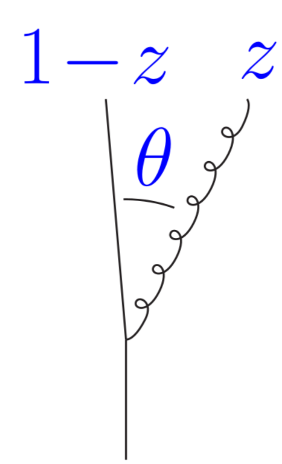
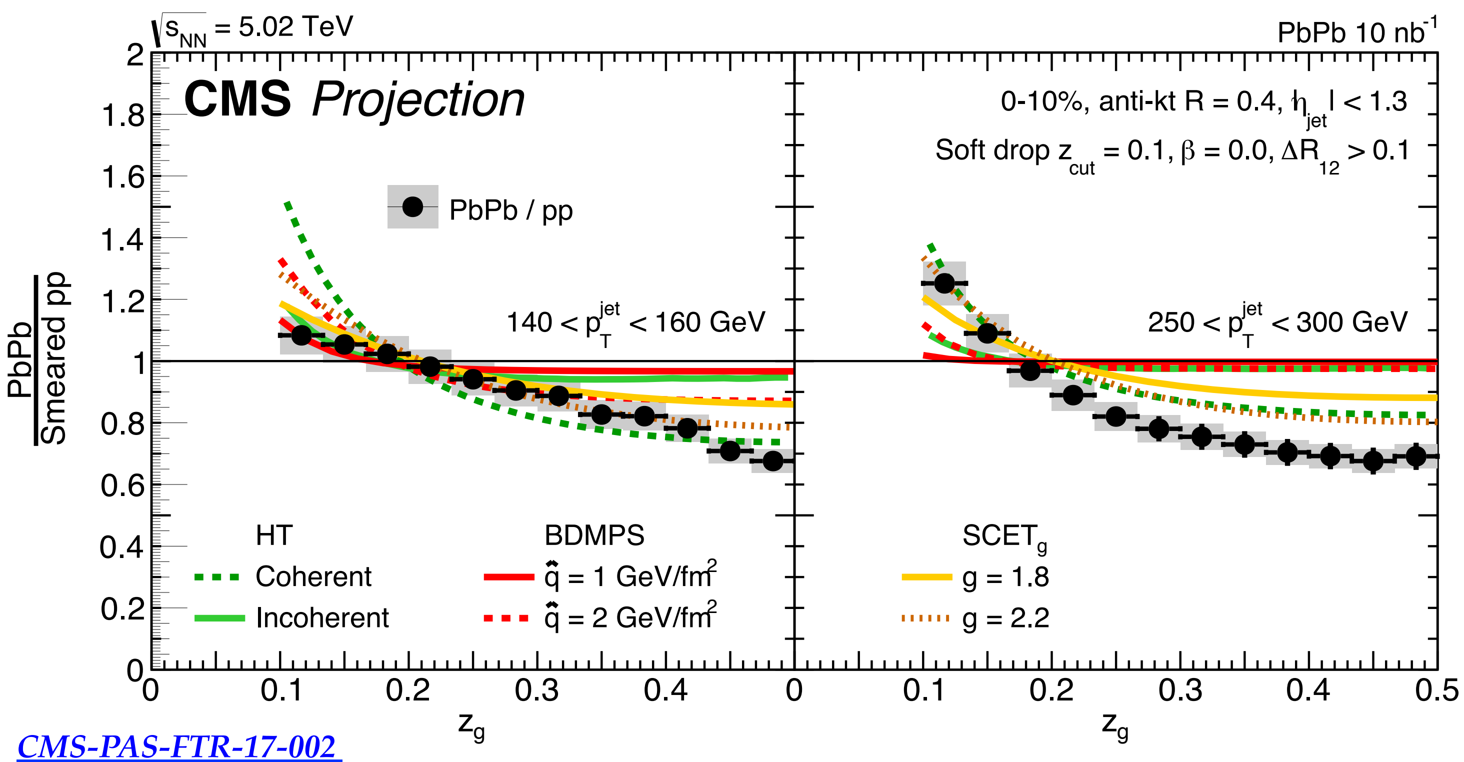


Jet structure measurements

- Momentum sharing fraction z_g
- Constrain in-medium radiation

MICROSCOPIC DYNAMICS



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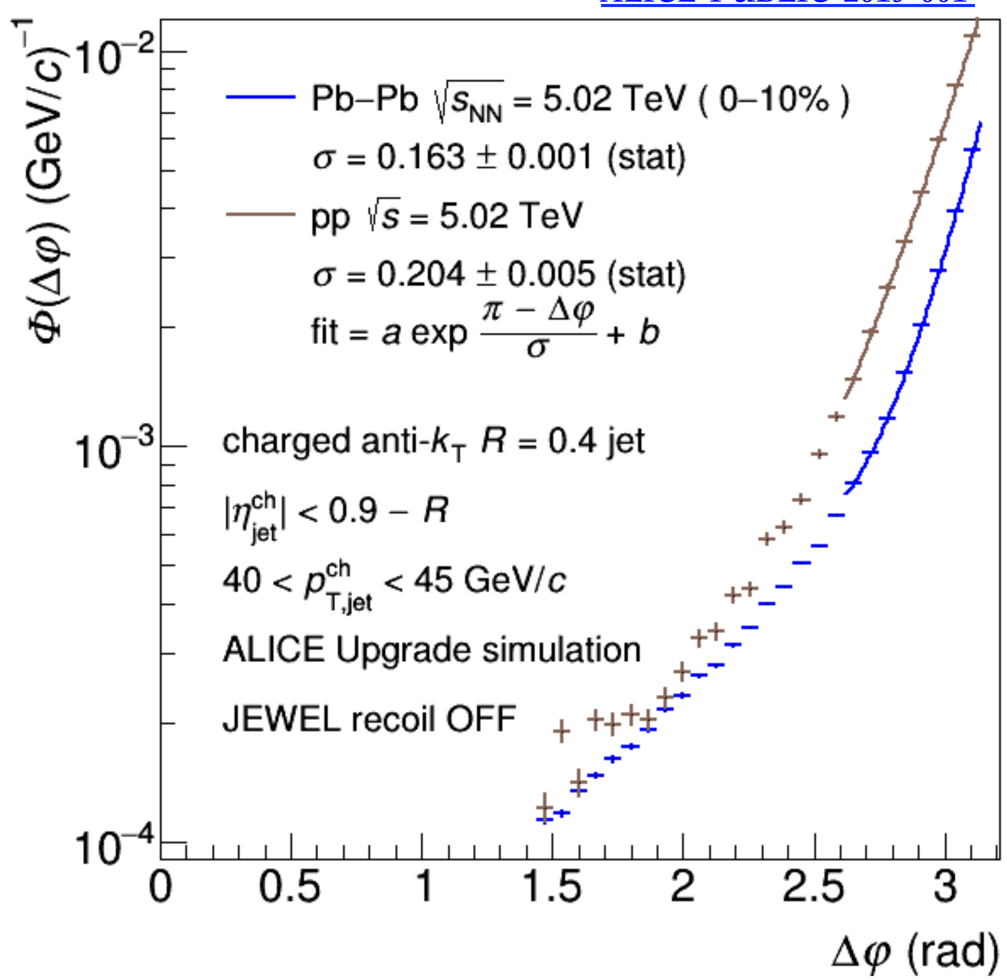
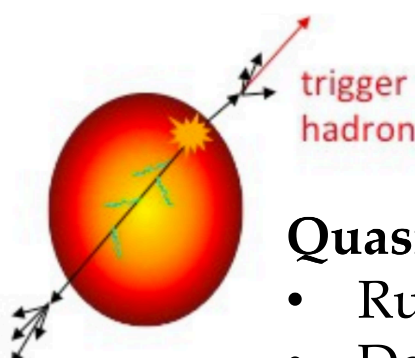


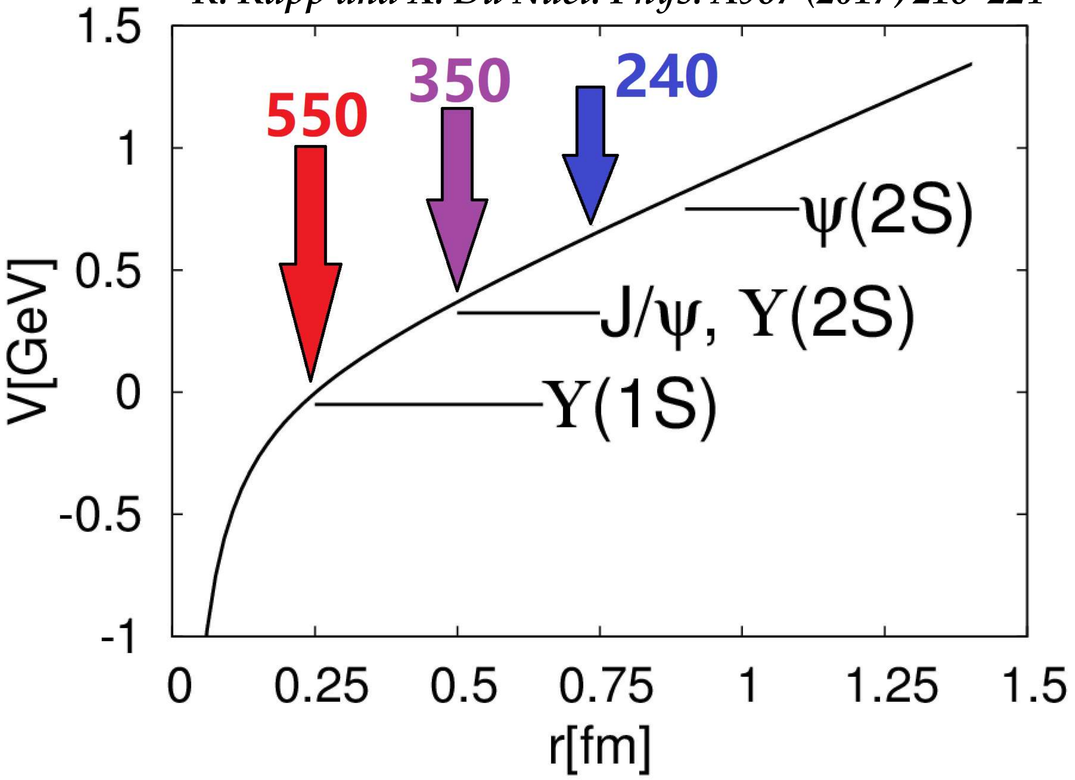


Jet structure measurements
- Momentum sharing fraction z_g
- Constrain in-medium radiation

Quasi particle structure
- Rutherford-type large angle jet–medium scattering
- Detection of recoil or of large angle deflections gives insight into the microscopic structure of the produced matter

MICROSCOPIC DYNAMICS

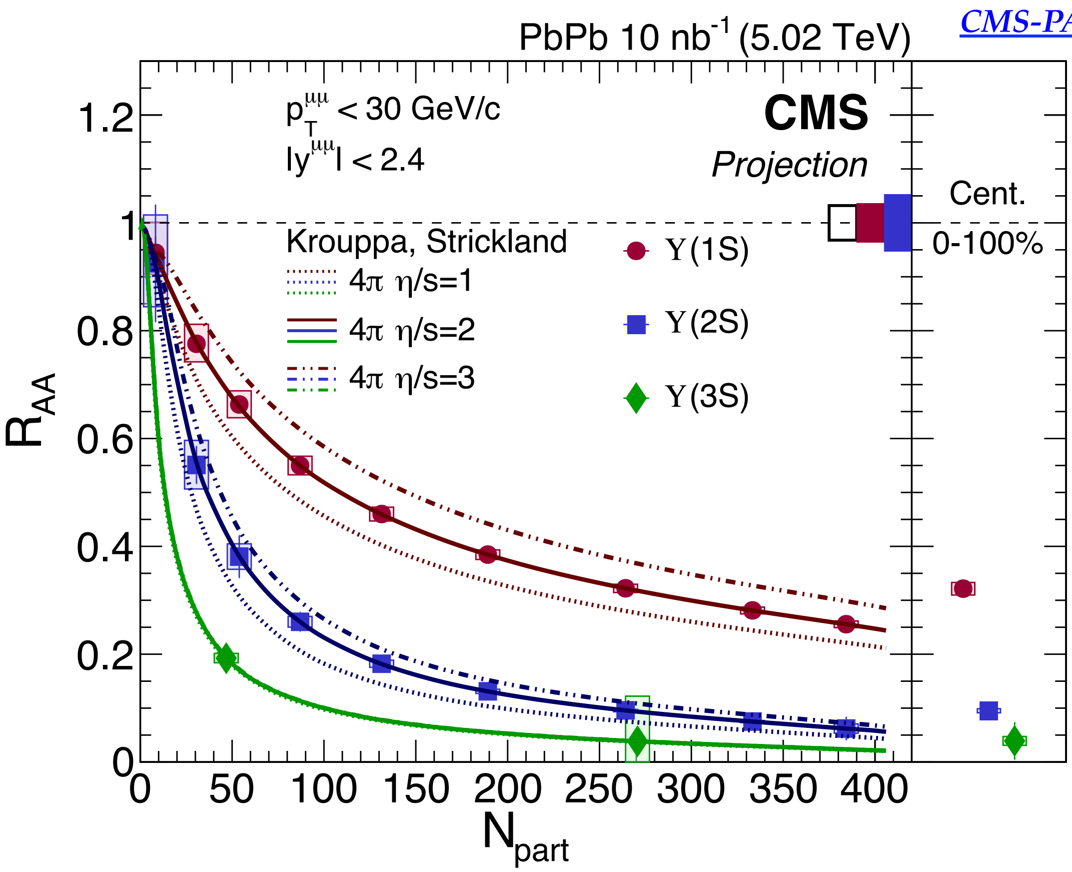
R. Rapp and X. Du Nucl. Phys. A967 (2017) 216–224



- QCD potential and modification in color-deconfined medium
- Quarkonium melting and regeneration

MICROSCOPIC DYNAMICS

CMS-PAS-FTR-17-002

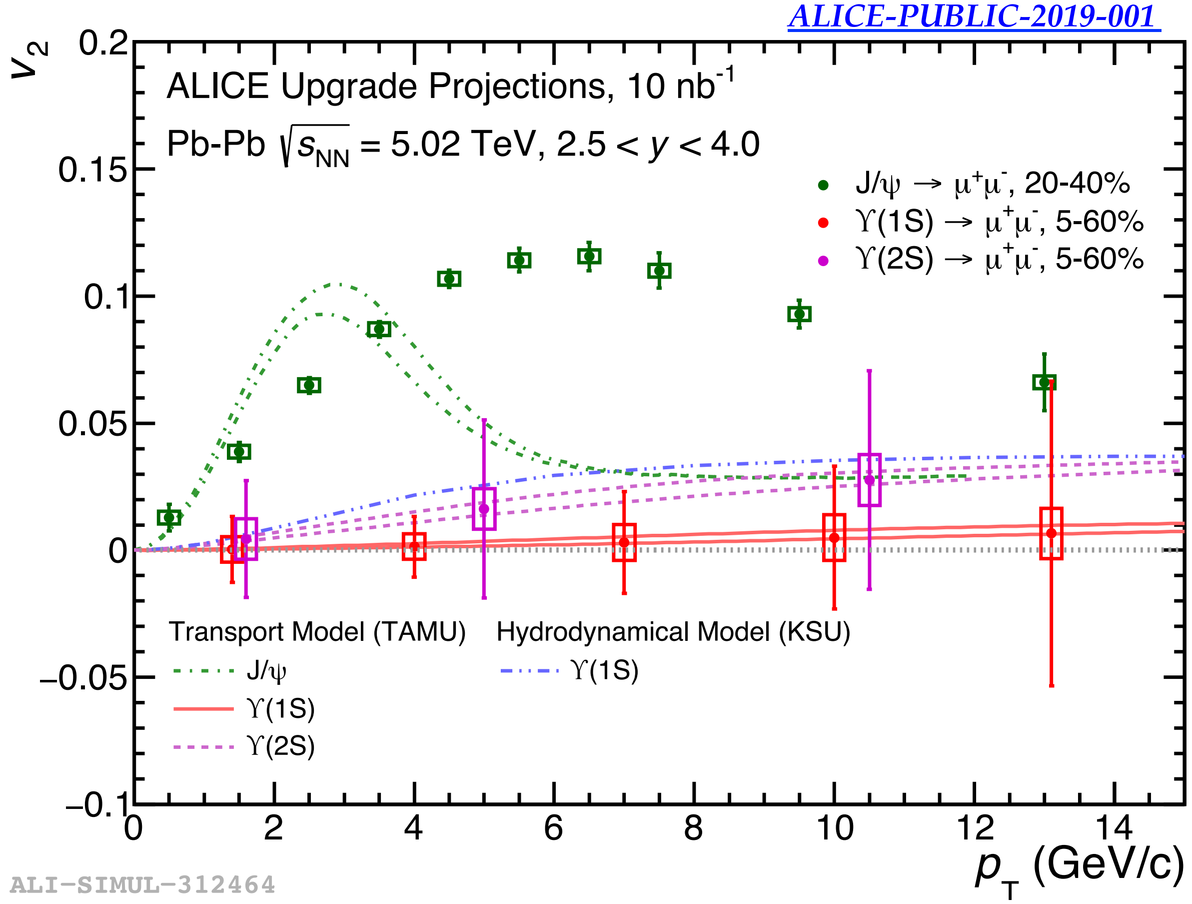


Color screening and regeneration

- R_{AA} of charmonia and bottomonia

Microscopic Dynamics

ALICE-PUBLIC-2019-001

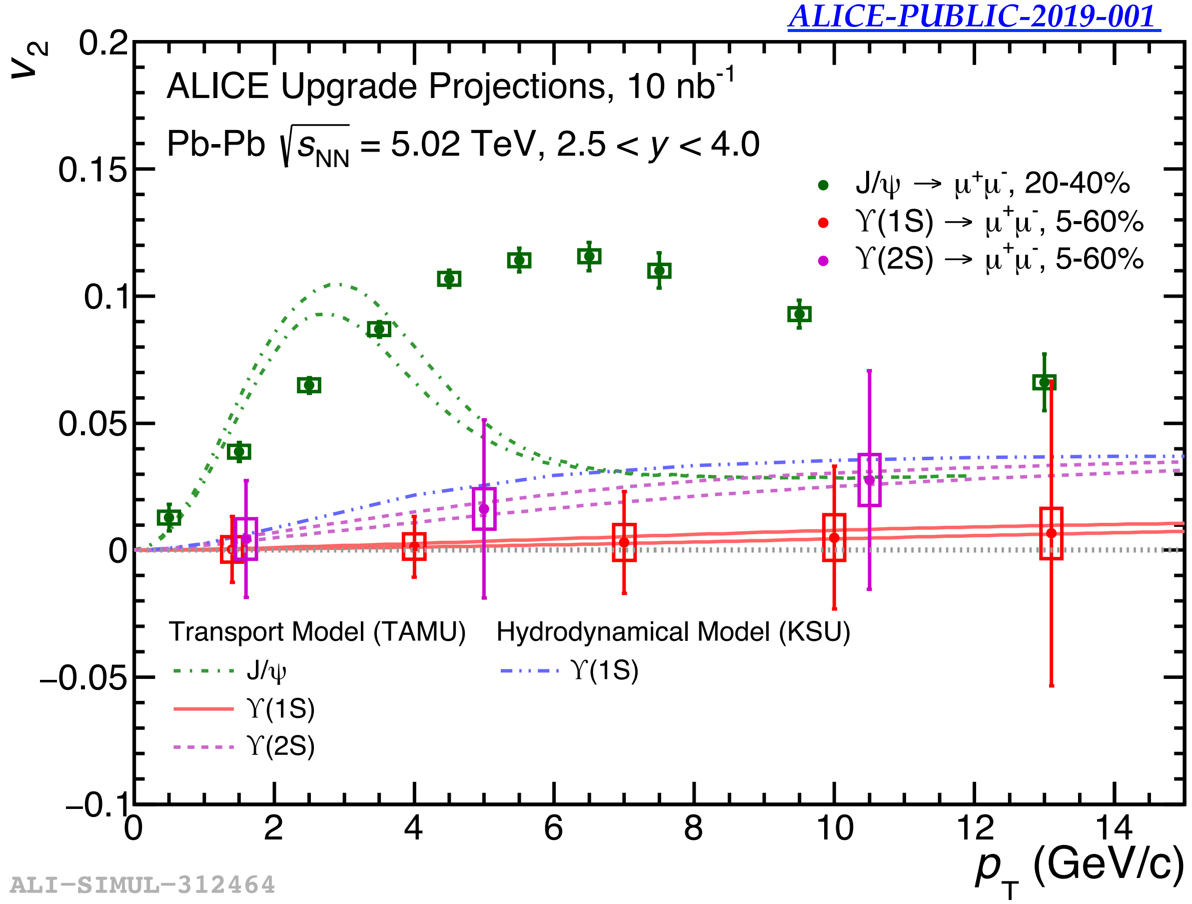


Color screening and regeneration

- R_{AA} and v_2 of charmonia and bottomonia
- **Sensitive to details of heavy quark production**, e.g. thermalisation, time dependence of regeneration, energy loss, rescattering,…

MICROSCOPIC DYNAMICS

ALICE-PUBLIC-2019-001



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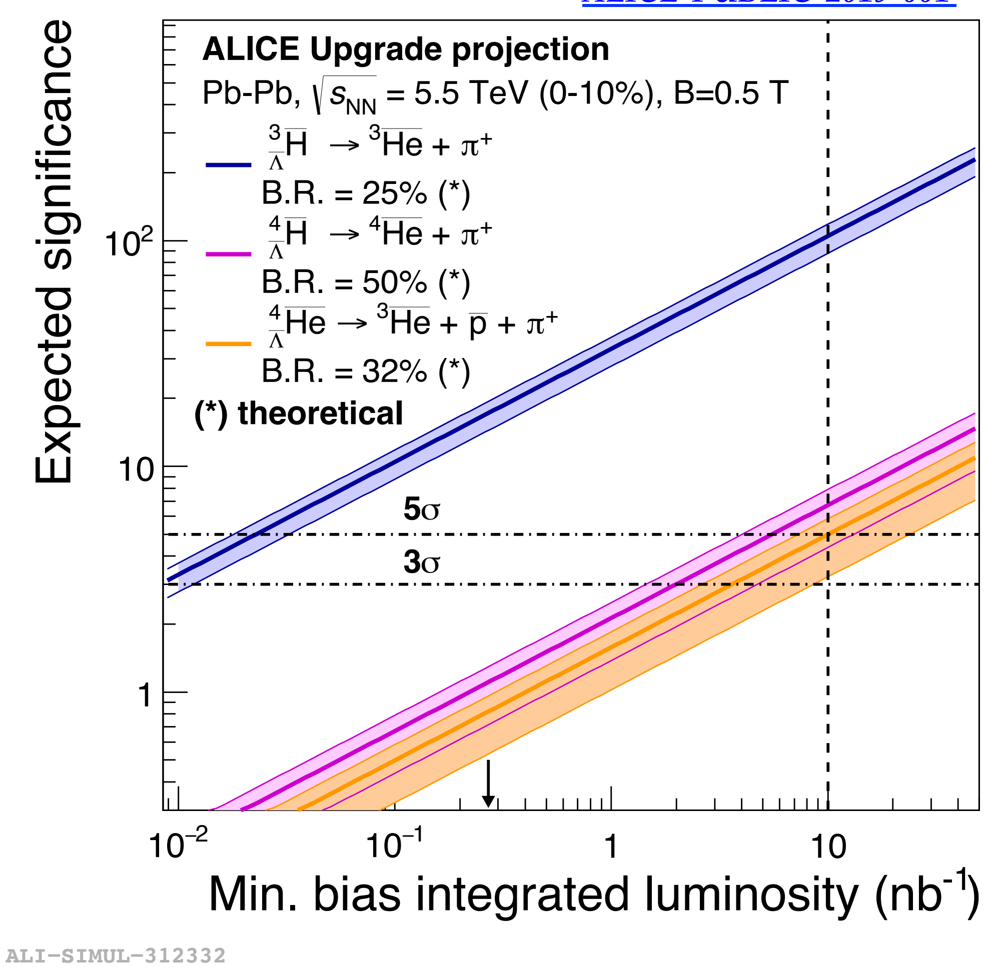

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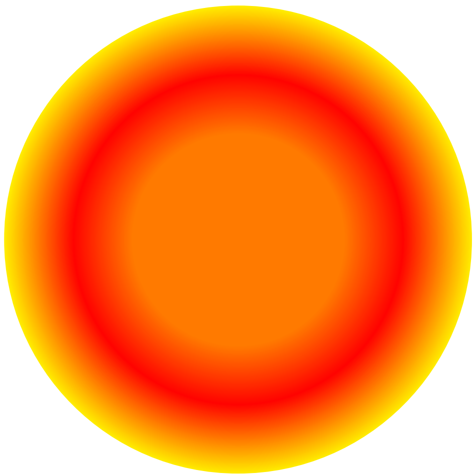
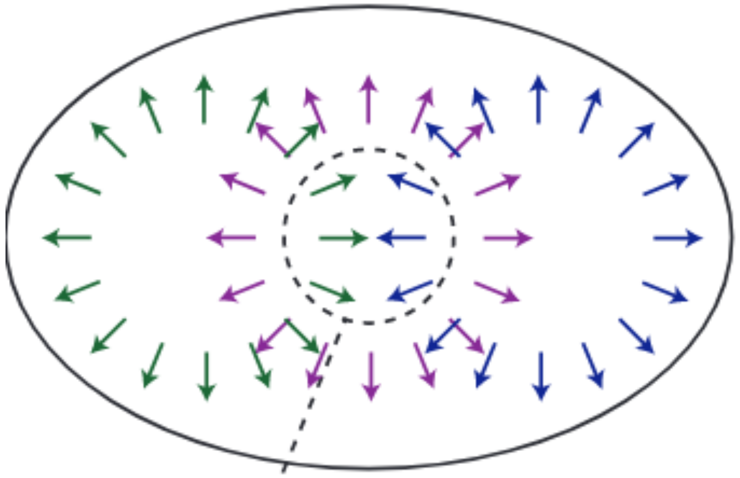
Formation of hadrons and light nuclei

- Coalescence or by statistical hadronization?
- Precise measurements of nuclei and hyper-nuclei (A=3,4)
- Possible observation of exotic baryonic states

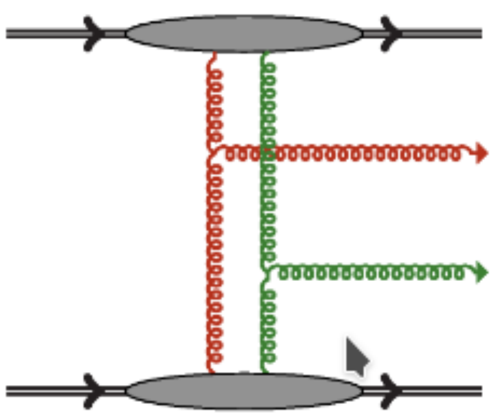
SMALL SYSTEMS

Hydrodynamic evolution | Escape mechanism | Initial-momentum correlations





PLB783(2018) 274



PRD87(2013) 9,094034

Many scatterings ⟷ Few scatterings ⟷ Initial conditions

From JFGO (HL/HE-LHC Physics Workshop: Final Jambore)

SMALL SYSTEMS

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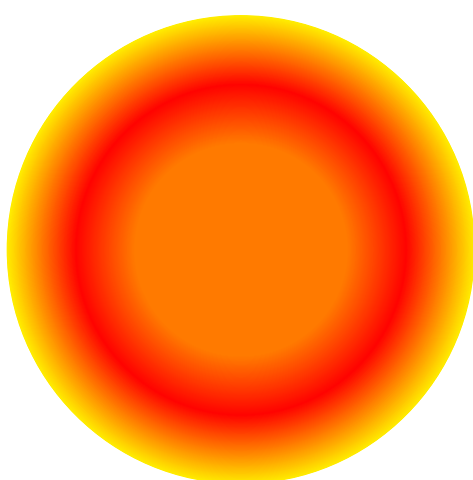

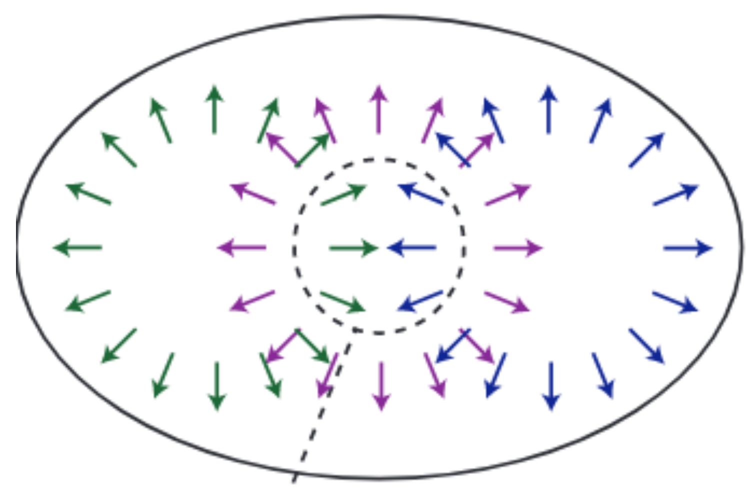

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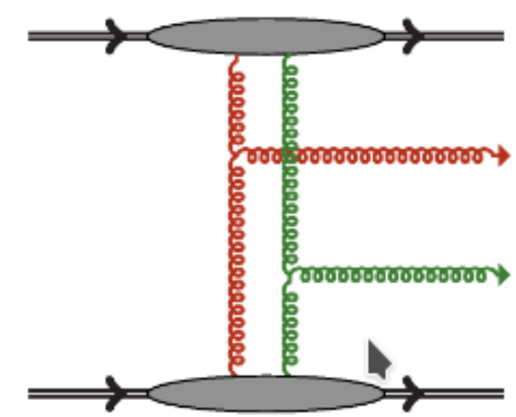


PRD87(2013) 9,094034

Many scatterings ⟷ Few scatterings ⟷ Initial conditions

From JFGO (HL/HE-LHC Physics Workshop: Final Jambore)

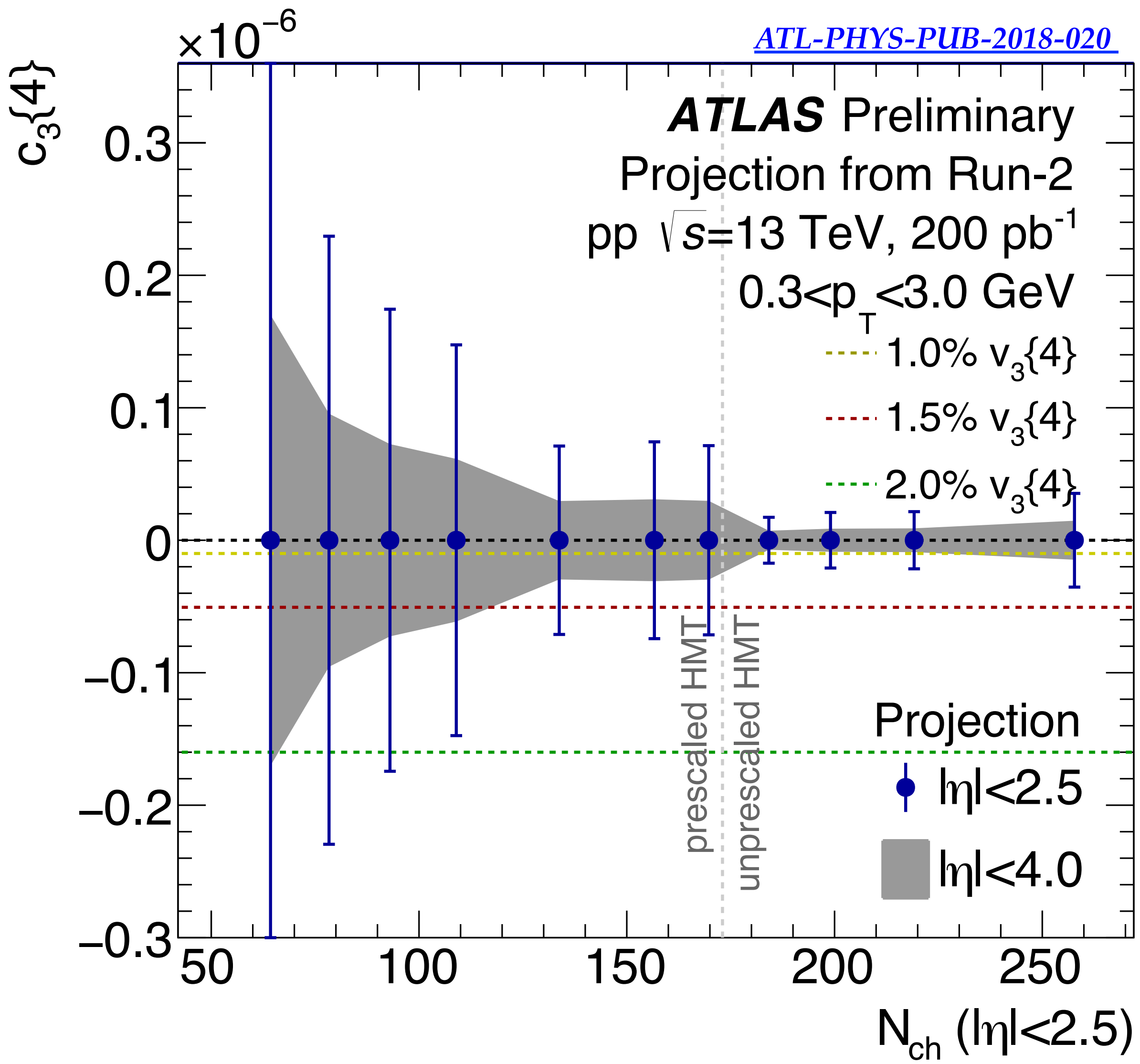
Small systems (pp, p-A) complement studies in A-A collisions

- Is there a unified picture of QCD particle production?
  - **Initial state:** gluon saturation, Color Glass Condensate
  - **Macroscopic:** fluid- and thermodynamics, thermal limit (grand canonical ensemble)
  - **Microscopic:** energy loss

- **Extended and more precise measurements in different collision systems needed**

SMALL SYSTEMS

ATL-PHYS-PUB-2018-020

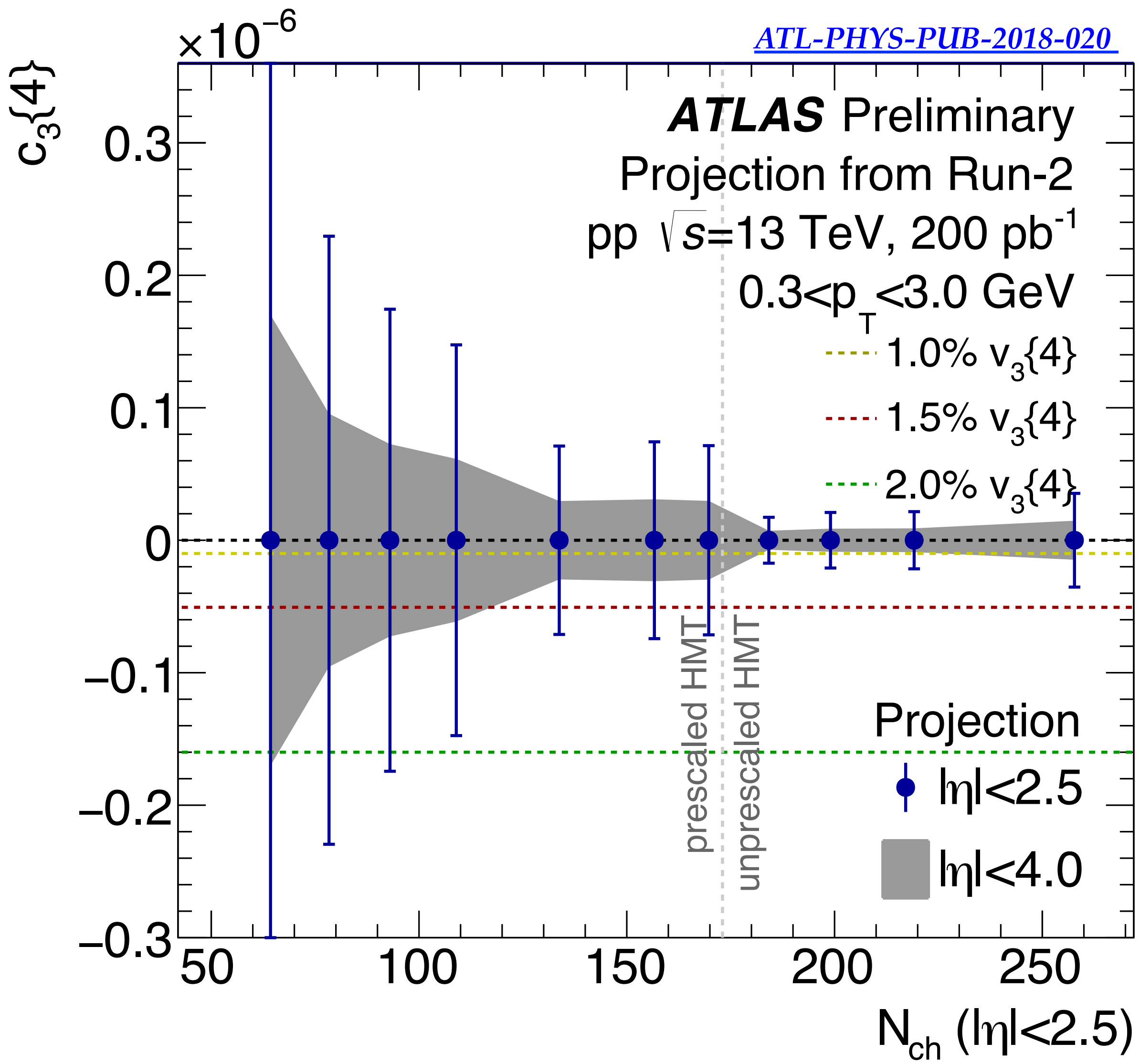


Flow measurements in pp and p-Pb collisions

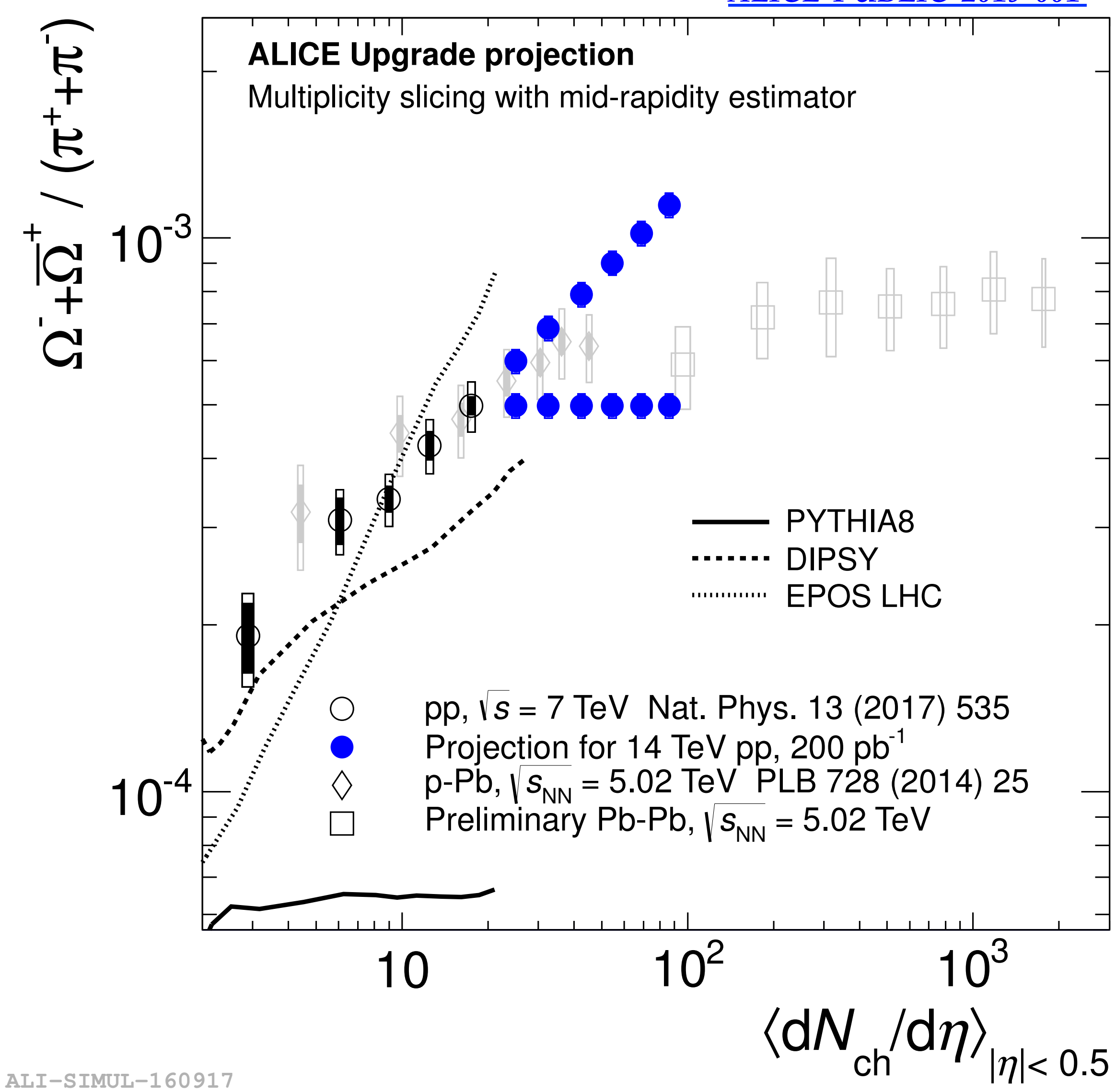
- Larger tracking acceptances for ATLAS and CMS available in Run 4.

Small systems

ATL-PHYS-PUB-2018-020



ALICE-PUBLIC-2019-001



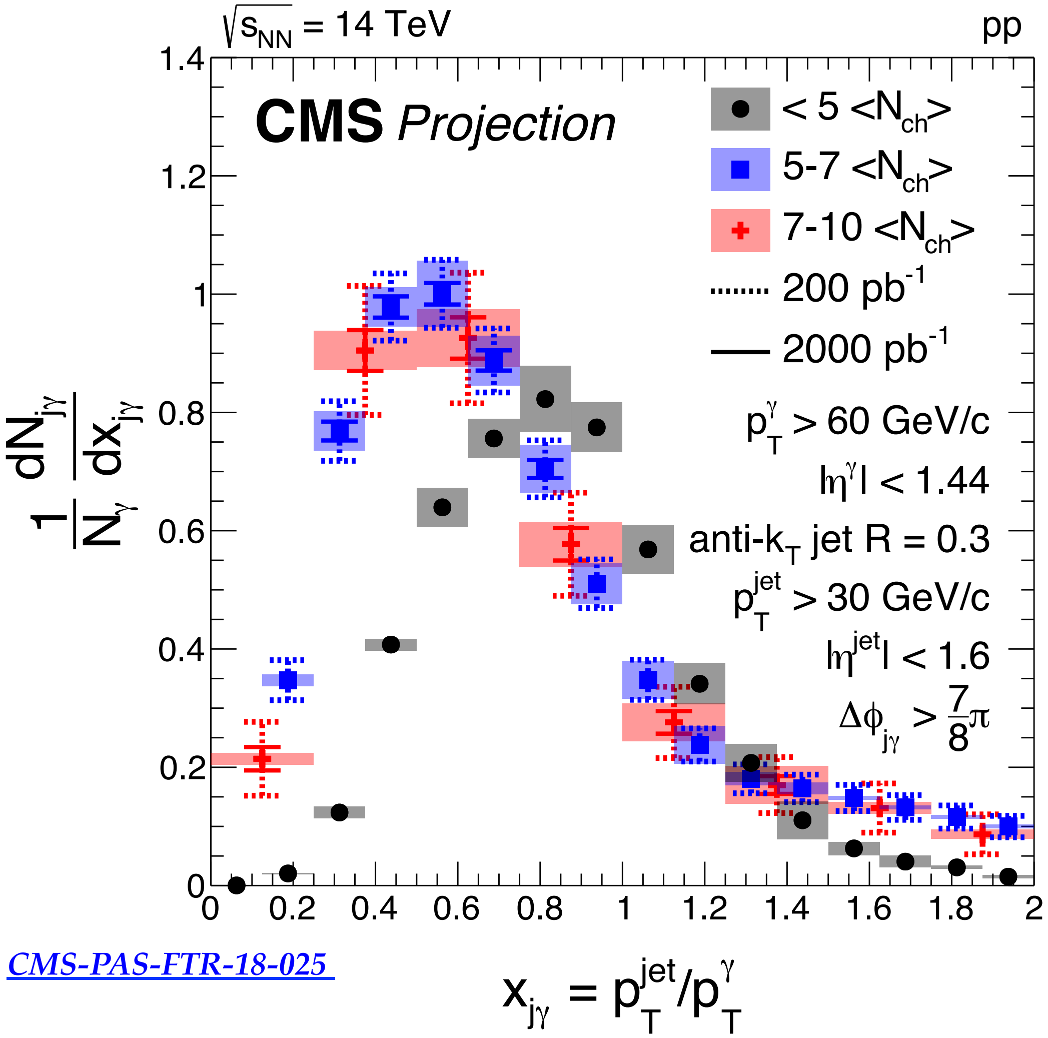
Flow measurements in pp and p-Pb collisions

- Larger tracking acceptances for ATLAS and CMS available in Run 4.

Strangeness production

- Bridge the present gap between pp and Pb–Pb collisions
- Sensitive to origin of enhancement

SMALL SYSTEMS

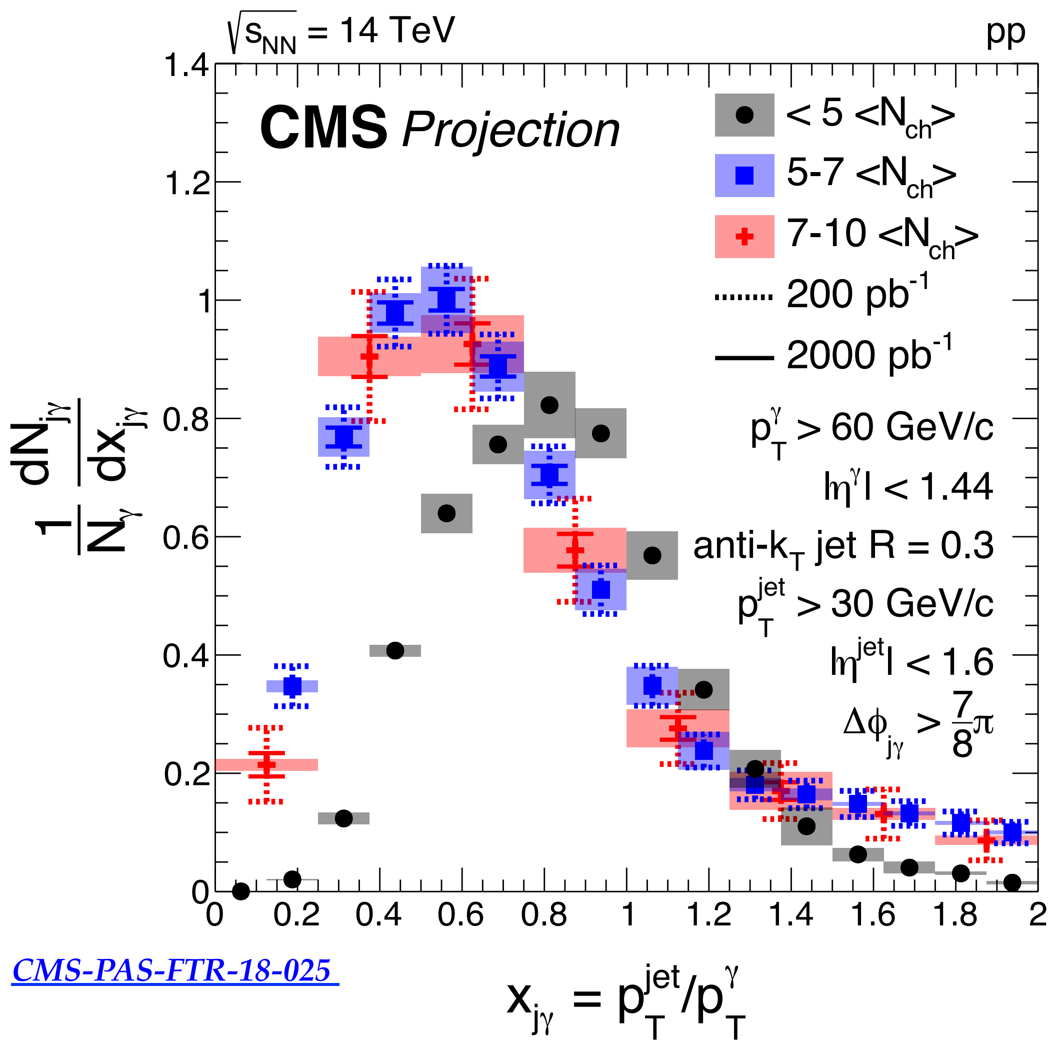


CMS-PAS-FTR-18-025

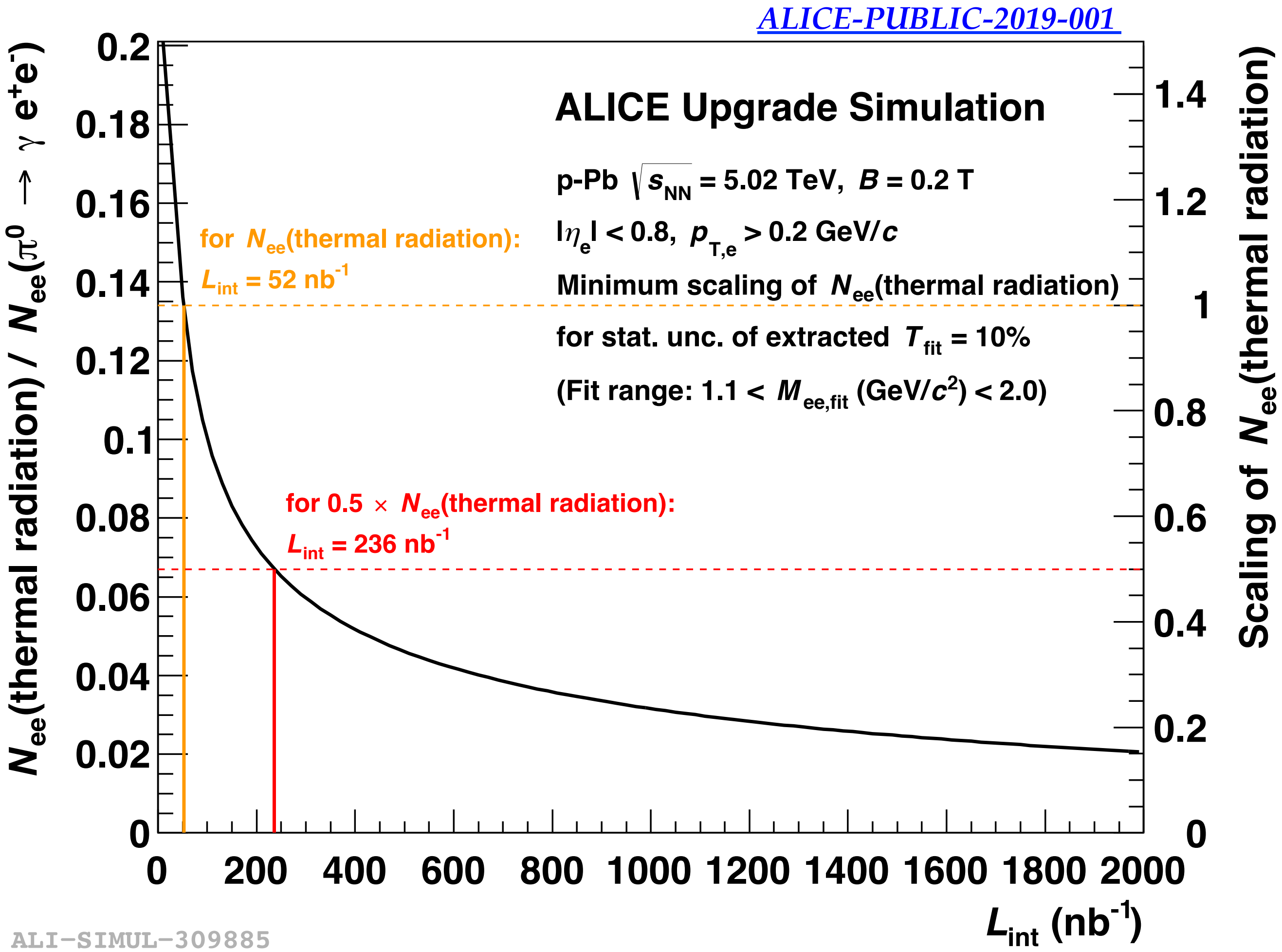
Energy loss

- Correlation of jets and photons
- A potential energy loss acting on the jet would directly alter the momentum fraction x_{jX} distribution

SMALL SYSTEMS



CMS-PAS-FTR-18-025

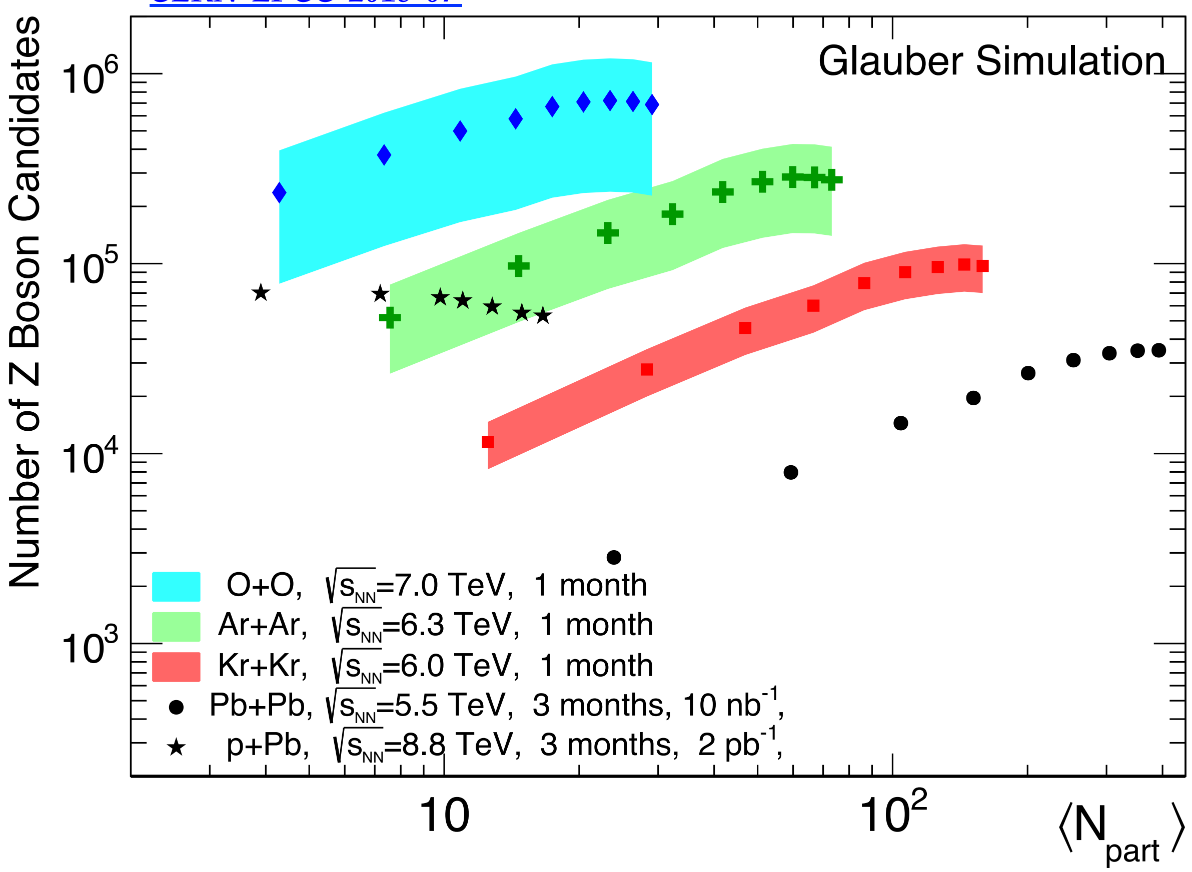


Energy loss
- Correlation of jets and photons
- A potential energy loss acting on the jet would directly alter the momentum fraction x_{jX} distribution

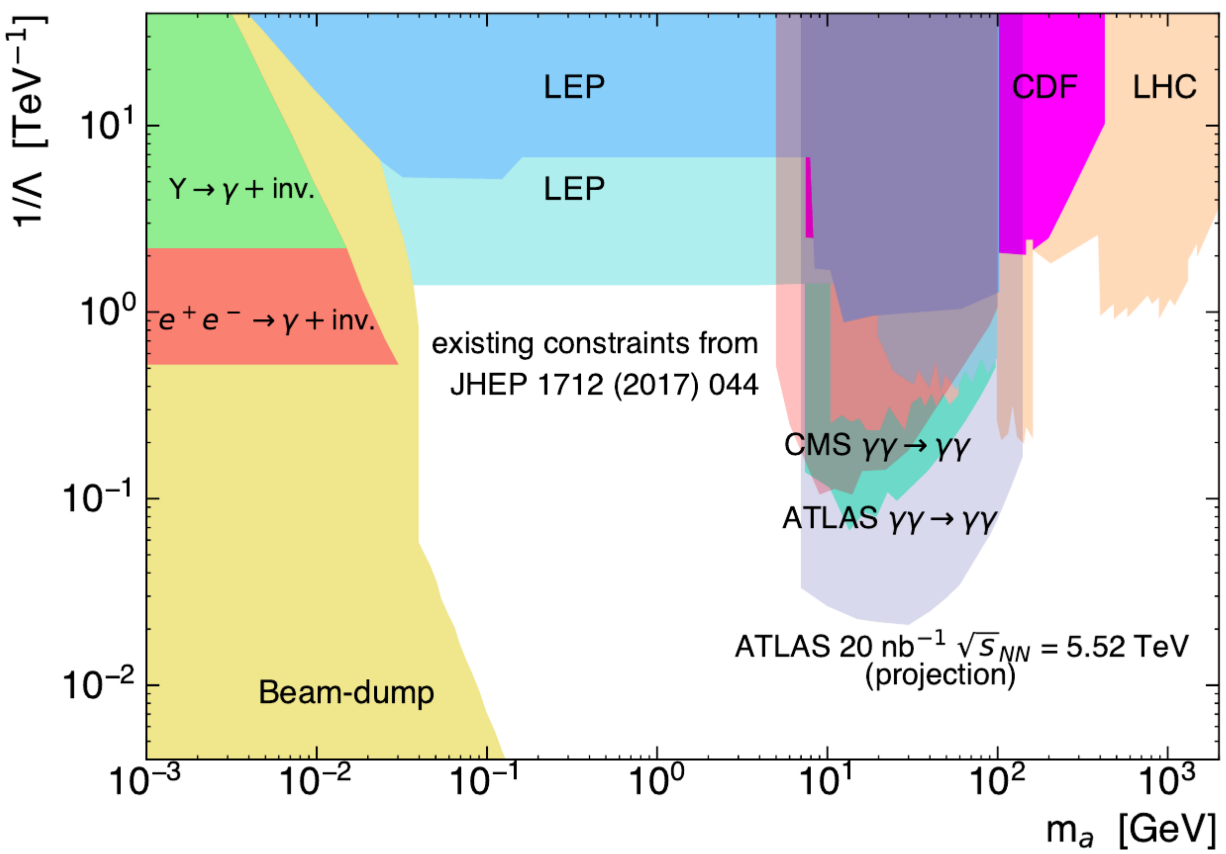
Thermal radiation
- Direct access to temperature of a potential emitting medium
  - ➢ 10% stat. uncertainty in Run 3 for predicted thermal yield

NEW OPPORTUNITIES

CERN-LPCC-2018-07



ATL-PHYS-PUB-2018-018



Lighter ions:

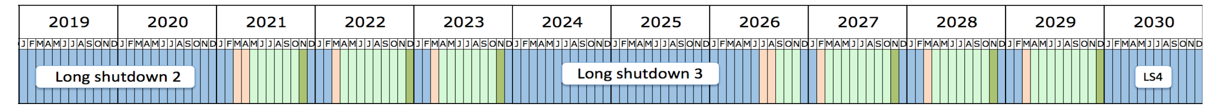
- **Larger NN luminosities, e.g. x8-25 with Ar-Ar**
  - ➢ New probes of the QGP accessible, e.g. boosted top, onset of jet quenching in small systems
  - ➢ With new heavy-ion detector: ultra-soft photons, multi-heavy-flavour hadrons,…
- **Nuclei choice based on physics and accelerator considerations**

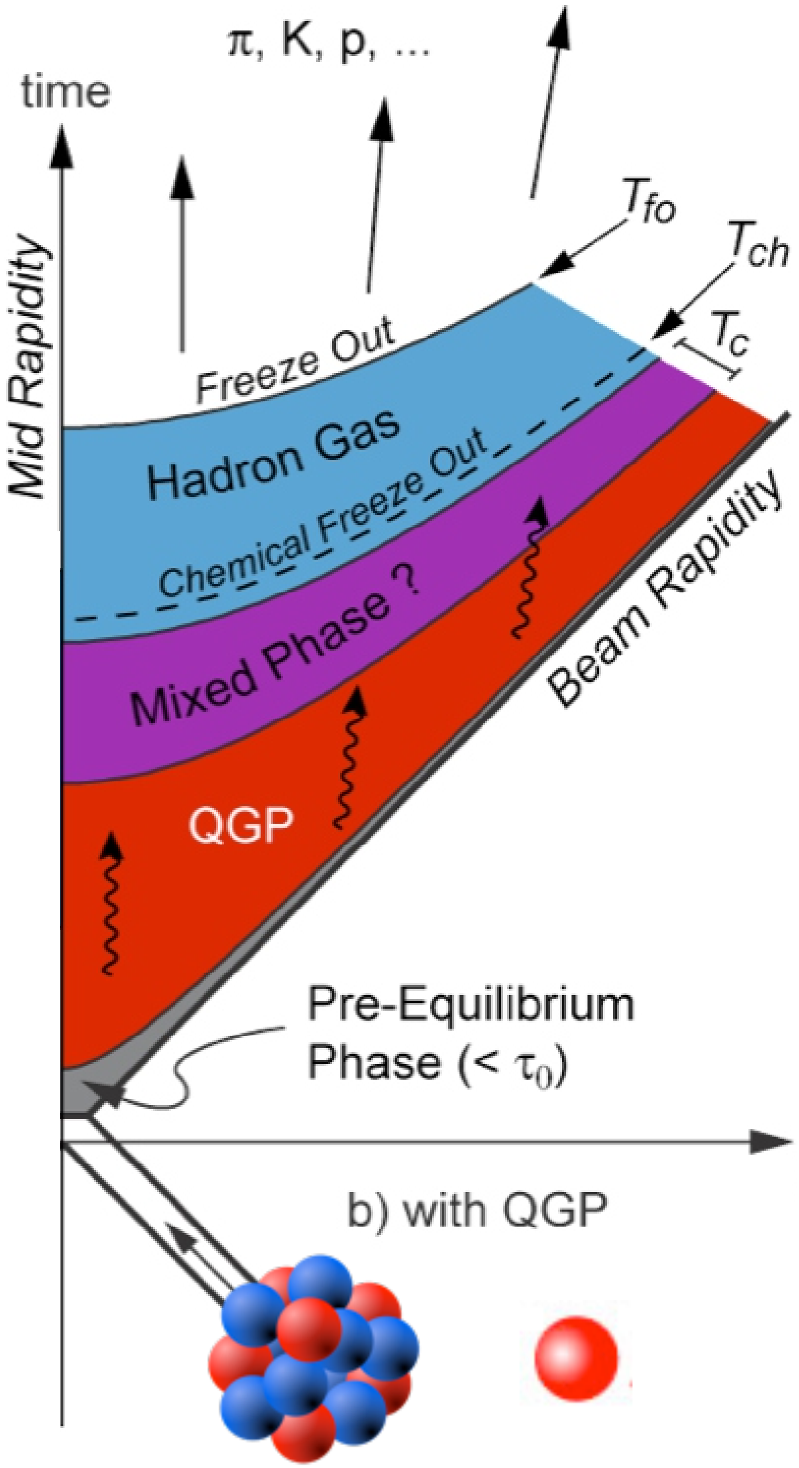
And much more topics

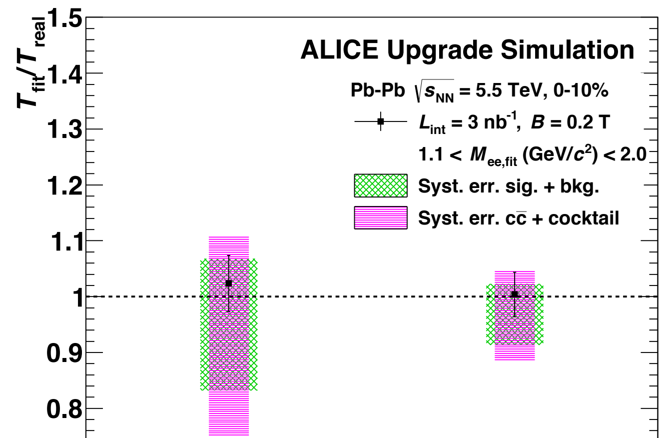
- Light-by-light collision studies
- p-O collisions for cosmic ray related studies
- Further beyond SM physics (e.g. thermal production of magnetic monopoles)
- …

arXiv:1812.07688 [hep-ph]

SUMMARY

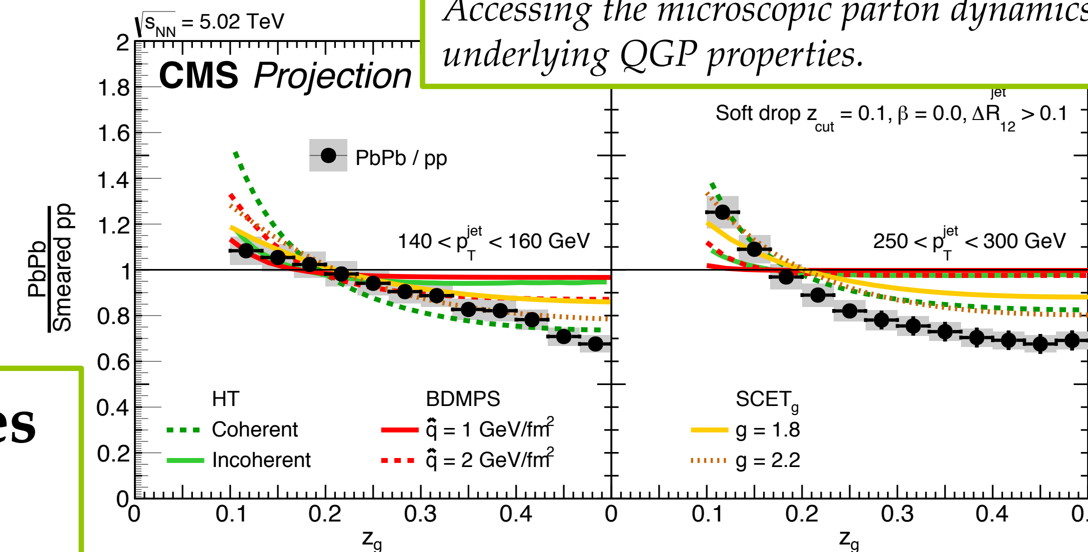






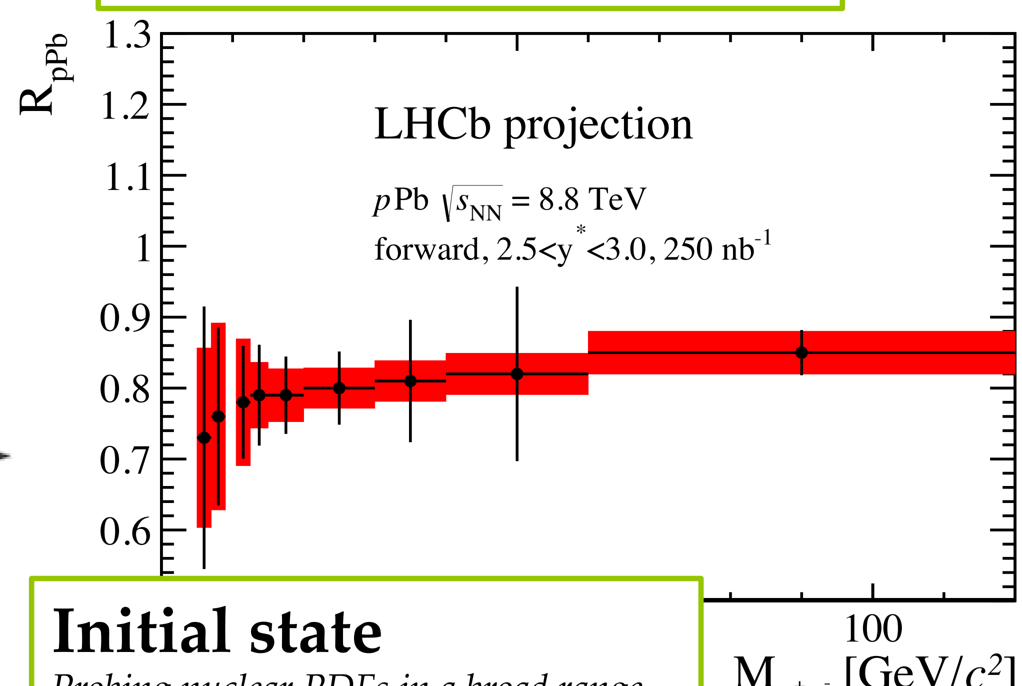
Macroscopic properties

Characterizing the macroscopic long-wavelength properties of the QGP with unprecedented precision.



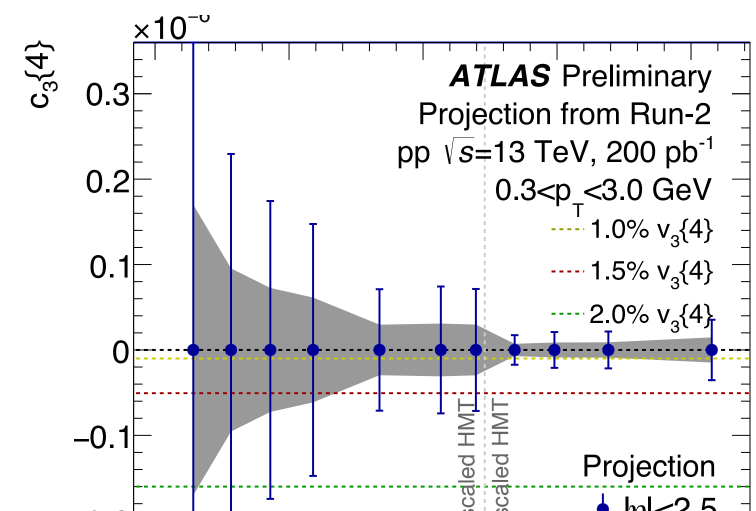
Microscopic dynamics

Accessing the microscopic parton dynamics underlying QGP properties.



Initial state

Probing nuclear PDFs in a broad range, onset of parton saturation.



Small systems

Unified picture of the underlying QCD from small to large systems.

Thank you

Citron, Z. (Ben Gurion U. of Negev) ; Dainese, A. (INFN, Padua) ; Grosse-Oetringhaus, J.F. (CERN) ; Jowett, J.M. (CERN) ; Lee, Y.-J. (MIT) ; Wiedemann, U.A. (CERN) ; Winn, M. (AIM, Saclay ; Orsay, LAL) ; Andronic, A. (Munster U.) ; Bellini, F. (CERN) ; Bruna, E. (INFN, Turin) ; Chapon, E. (CERN) ; Dembinski, H. (Heidelberg, Max Planck Inst.) ; d'Enterria, D. (CERN) ; Grabowska-Bold, I. (AGH-UST, Cracow) ; Innocenti, G.M. (CERN ; MIT) ; Loizides, C. (LBL, Berkeley) ; Mohapatra, S. (Columbia U.) ; Salgado, C.A. (Santiago de Compostela U., IGFAE) ; Verweij, M. (RIKEN BNL ; Vanderbilt U.) ; Weber, M. (Stefan Meyer Inst. Subatomare Phys.) ; Aichelin, J. (SUBATECH, Nantes) ; Angerami, A. (LLNL, Livermore) ; Apolinario, L. (Lisbon, IST ; LIP, Lisbon) ; Arleo, F. (Ecole Polytechnique) ; Armesto, N. (Santiago de Compostela U., IGFAE) ; Arnaldi, R. (INFN, Turin) ; Arslandok, M. (U. Heidelberg (main)) ; Azzi, P. (INFN, Padua) ; Bailhache, R. (Frankfurt U.) ; Bass, S.A. (Duke U.) ; Bedda, C. (Utrecht U.) ; Behera, N.K. (Inha U.) ; Bellwied, R. (Houston U.) ; Beraudo, A. (INFN, Turin) ; Bi, R. (MIT) ; Bierlich, C. (Lund U. ; Bohr Inst.) ; Blum, K. (CERN ; Weizmann Inst.) ; Borissov, A. (Munster U.) ; Braun-Munzinger, P. (Darmstadt, EMMI) ; Bruce, R. (CERN) ; Bruno, G.E. (Bari Polytechnic ; INFN, Bari) ; Bufalino, S. (INFN, Turin) ; Castillo Castellanos, J. (IRFU, Saclay, DPHN) ; Chatterjee, R. (Calcutta, VECC) ; Chen, Y. (CERN) ; Chen, Z. (Rice U.) ; Cheshkov, C. (Lyon, IPN) ; Chujo, T. (Tsukuba U.) ; Conesa del Valle, Z. (Orsay, IPN) ; Contreras Nuno, J.G. (Prague, Tech. U.) ; Cunqueiro Mendez, L. (LBL, Berkeley) ; Dahms, T. (Munich, Tech. U., Universe) ; Dang, N.P. (Louisville U.) ; De la Torre, H. (Michigan State U.) ; Dobrin, A.F. (CERN) ; Doenigus, B. (Frankfurt U.) ; Van Doremalen, L. (Utrecht U.) ; Du, X. (Texas A-M) ; Dubla, A. (Darmstadt, EMMI) ; Dumancic, M. (Weizmann Inst.) ; Dyndal, M. (DESY) ; Fabbietti, L. (Munich, Tech. U.) ; Ferreiro, E.G. (Santiago de Compostela U., IGFAE) ; Fionda, F. (Bergen U.) ; Fleuret, F. (Ecole Polytechnique) ; Floerchinger, S. (U. Heidelberg (main)) ; Giacalone, G. (IPhT, Saclay) ; Giammanco, A. (Louvain U.) ; Gossiaux, P.B. (SUBATECH, Nantes) ; Graziani, G. (INFN, Florence) ; Greco, V. (Catania U. ; INFN, LNS) ; Grelli, A. (Utrecht U.) ; Grosa, F. (INFN, Turin) ; Guilbaud, M. (CERN) ; Gunji, T. (Tsukuba, Graduate U. Adv. Studies) ; Guzey, V. (Helsinki Inst. of Phys. ; St. Petersburg, INP ; Jyvaskyla U.) ; Hadjidakis, C. (Orsay, IPN) ; Hassani, S. (IRFU, Saclay, DPP) ; He, M. (Nanjing U. Sci. Tech.) ; Helenius, I. (Tubingen U. ; Jyvaskyla U.) ; Huo, P. (SUNY, Stony Brook) ; Jacobs, P.M. (LBL, Berkeley) ; Janus, P. (AGH-UST, Cracow) ; Jebramcik, M.A. (CERN ; Frankfurt U.) ; Jia, J. (Brookhaven Natl. Lab. ; SUNY, Stony Brook) ; Kalweit, A.P. (CERN) ; Kim, H. (Chonnam Natl. U.) ; Klasen, M. (Munster U.) ; Klein, S.R. (LBL, Berkeley) ; Klusek-Gawenda, M. (Cracow, INP) ; Kremer, J. 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Heidelberg (main)) ; Okorokov, V. (Moscow Phys. Eng. Inst.) ; Olness, F. (Southern Methodist U.) ; Paakkinen, P. (Jyvaskyla U.) ; Pappalardo, L. (Ferrara U. ; INFN, Ferrara) ; Park, J. (Korea U.) ; Paukkunen, H. (Helsinki Inst. of Phys. ; Jyvaskyla U.) ; Peng, C.C. (Purdue U.) ; Pereira Da Costa, H. (IRFU, Saclay, DPHN) ; Perepelitsa, D.V. (Colorado U.) ; Peresunko, D. (Kurchatov Inst., Moscow) ; Peters, M. (MIT) ; Pettersson, N.E. (Massachusetts U., Amherst) ; Piano, S. (INFN, Trieste) ; Pierog, T. (KIT, Karlsruhe) ; Pires, J. (Lisbon, CFTP ; Lisbon, IST) ; Płoskoń, M. (LBL, Berkeley) ; Plumari, S. (Catania U. ; INFN, LNS) ; Prino, F. (INFN, Turin) ; Puccio, M. (INFN, Turin ; Turin U.) ; Rapp, R. (Texas A-M) ; Redlich, K. (Darmstadt, EMMI ; Wroclaw U.) ; Reygers, K. (U. Heidelberg (main)) ; Ristea, C.L. (Bucharest, Inst. Space Science) ; Robbe, P. (Orsay, LAL) ; Rossi, A. (INFN, Padua) ; Rustamov, A. (Darmstadt, EMMI ; U. Heidelberg (main) ; NNRC, Baku) ; Rybar, M. 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(Duke U.) ; Zampolli, C. (CERN ; INFN, Bologna) ; Zanoli, H. (Sao Paulo U.) ; Zhou, M. (SUNY, Stony Brook) ; Zhou, Y. (Bohr Inst.)

BACKUP

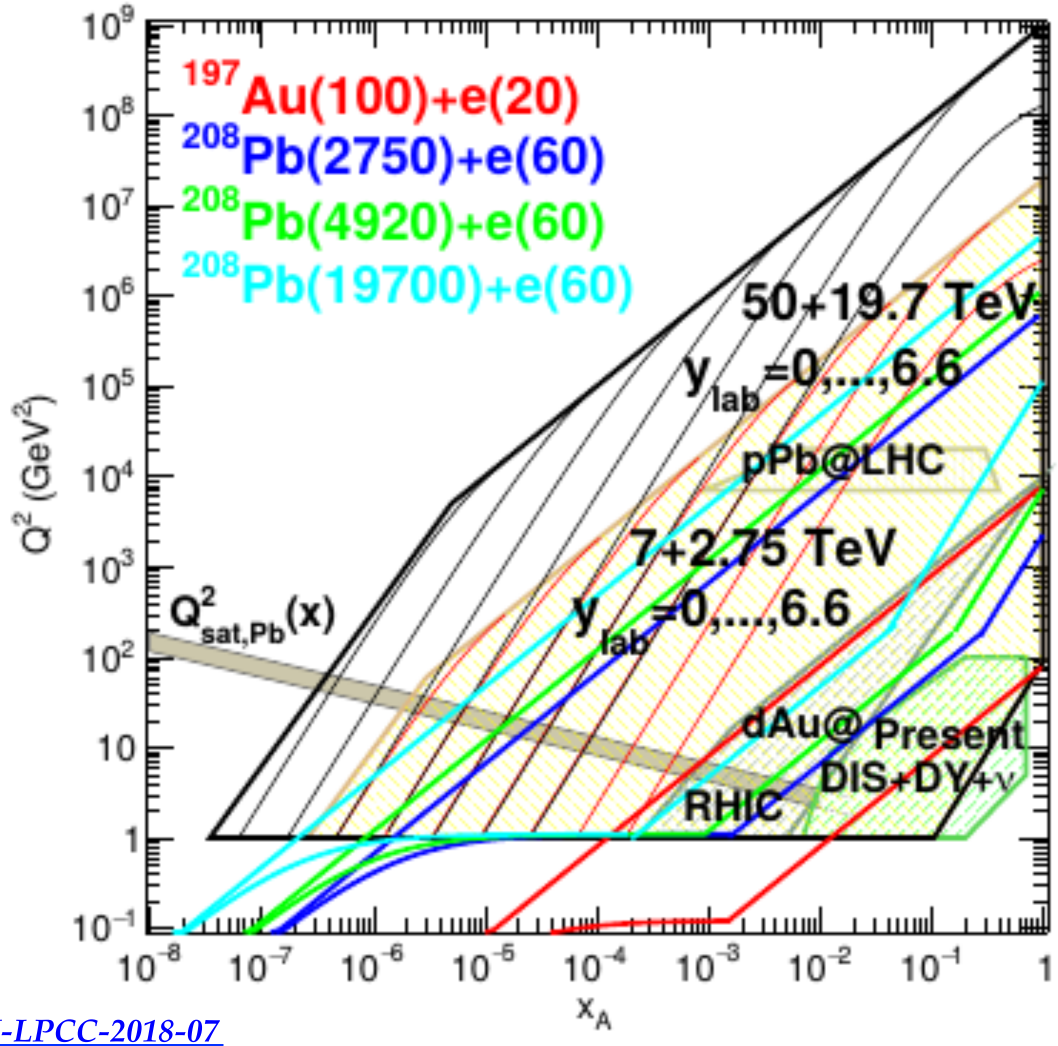
THE NEXT TEN YEARS

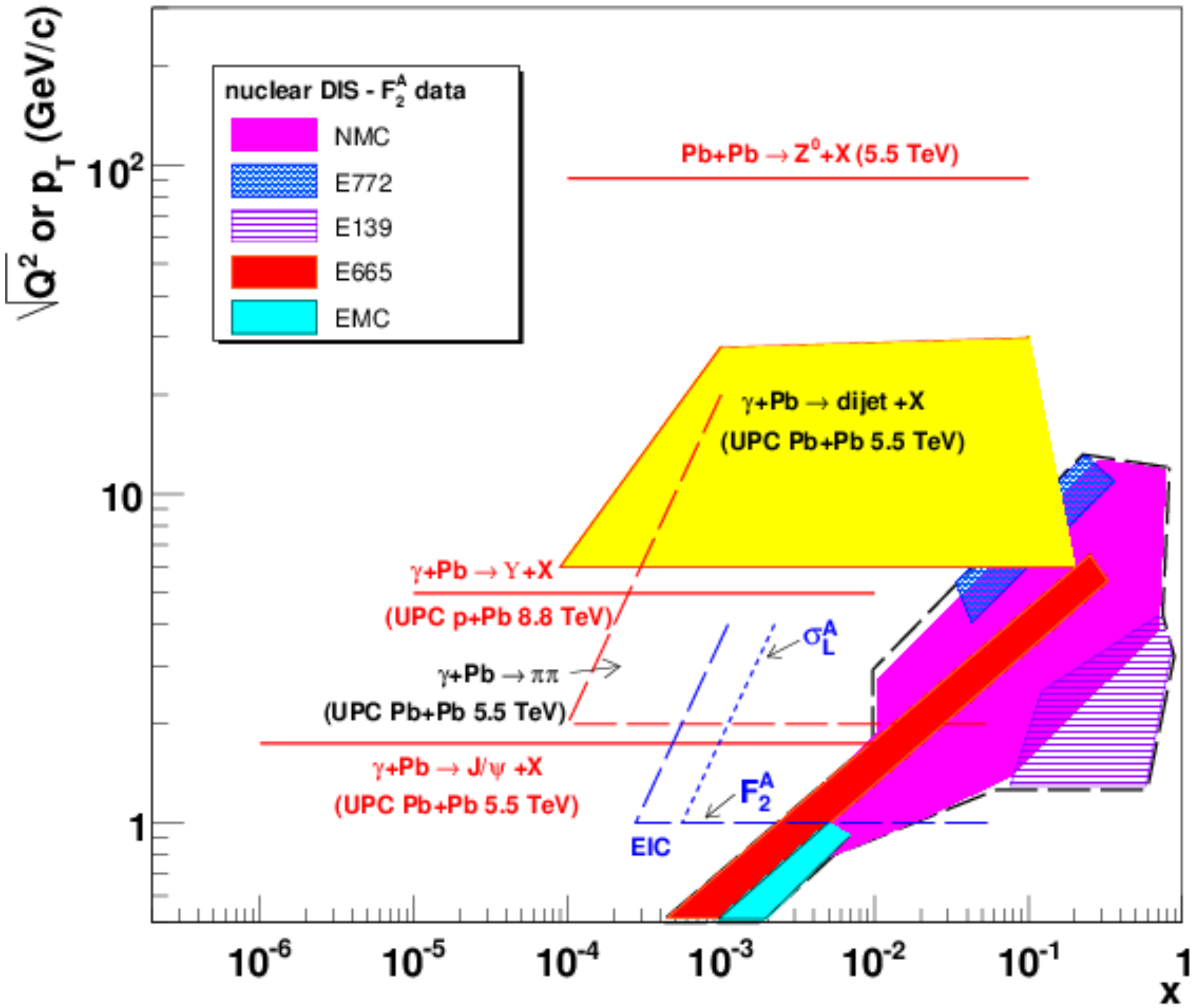
	Year	Systems, time, L_{int}	Total per Run (3 and 4)
RUN 3	2021 (4 weeks)	Pb-Pb 5.5 TeV, 3 weeks pp 5.5 TeV, 1 week	Pb-Pb: 6.2/nb ALICE/ATLAS/CMS, 1/nb LHCb p-Pb: 0.6/pb ATLAS/CMS, 0.3/pb ALICE/LHCb pp 5.5: 300/pb ATLAS/CMS, 25/pb LHCb, 3/pb ALICE pp 8.8: 100/pb ATLAS/CMS/LHCb, 1.5/pb ALICE O-O: 500/μb p-O: 200/μb
	2022 (6 weeks)	p-O + O-O 7 TeV, 1 week (after EYETS?) Pb-Pb 5.5 TeV, 5 weeks	
	2023 (4 weeks)	pp 8.8 TeV, few days p-Pb 8.8 TeV, 3.x weeks	
	LS3	ATLAS/CMS upgrades, ALICE: ITS3? FoCal?	
RUN 4	2027 (4 weeks)	Pb-Pb 5.5 TeV, 3 weeks pp 5.5 TeV, 1 week	Pb-Pb: 6.8/nb, ALICE/ATLAS/CMS, 1/nb LHCb p-Pb: 0.6/pb ATLAS/CMS, 0.3/pb ALICE/LHCb pp 5.5: 300/pb ATLAS/CMS, 25/pb LHCb, 3/pb ALICE pp 8.8: 100/pb ATLAS/CMS/LHCb, 1.5/pb ALICE
	2028 (6 weeks)	Pb-Pb 5.5 TeV, 2 weeks p-Pb 8.8 TeV, 3.x weeks pp 8.8 TeV, few days	
	2029 (4 weeks)	Pb-Pb 5.5 TeV, 4 weeks	

Material

- Public notes:
  - ALICE-PUBLIC-2019-001 (ALICE Run 3/4)
  - LHCb-CONF-2018-005 (p-Pb)
  - LHCb-PUB-2018-015 (fixed target)
  - ATL-PHYS-PUB-2018-018 (UPC)
  - ATL-PHYS-PUB-2018-019 (Jets)
  - ATL-PHYS-PUB-2018-020 (Bulk)
  - ATL-PHYS-PUB-2018-039 (Nuclear Parton Distributions)
  - CMS-PAS-FTR-17-002 (Heavy ions)
  - CMS-PAS-FTR-18-024 (HF)
  - CMS-PAS-FTR-18-025 (Jets)
  - CMS-PAS-FTR-18-026 (small systems)
  - CMS-PAS-FTR-18-027 (Nuclear Parton Distributions)

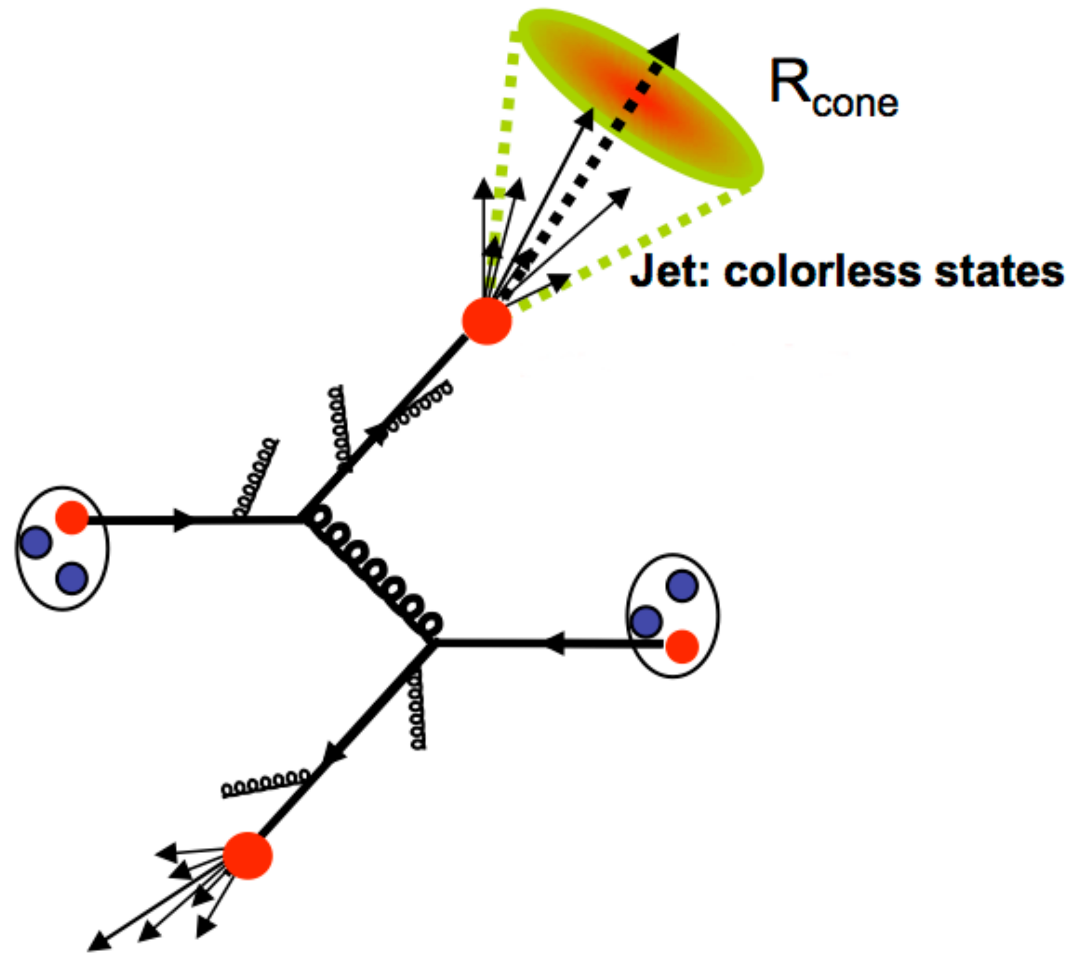
INITIAL STATE



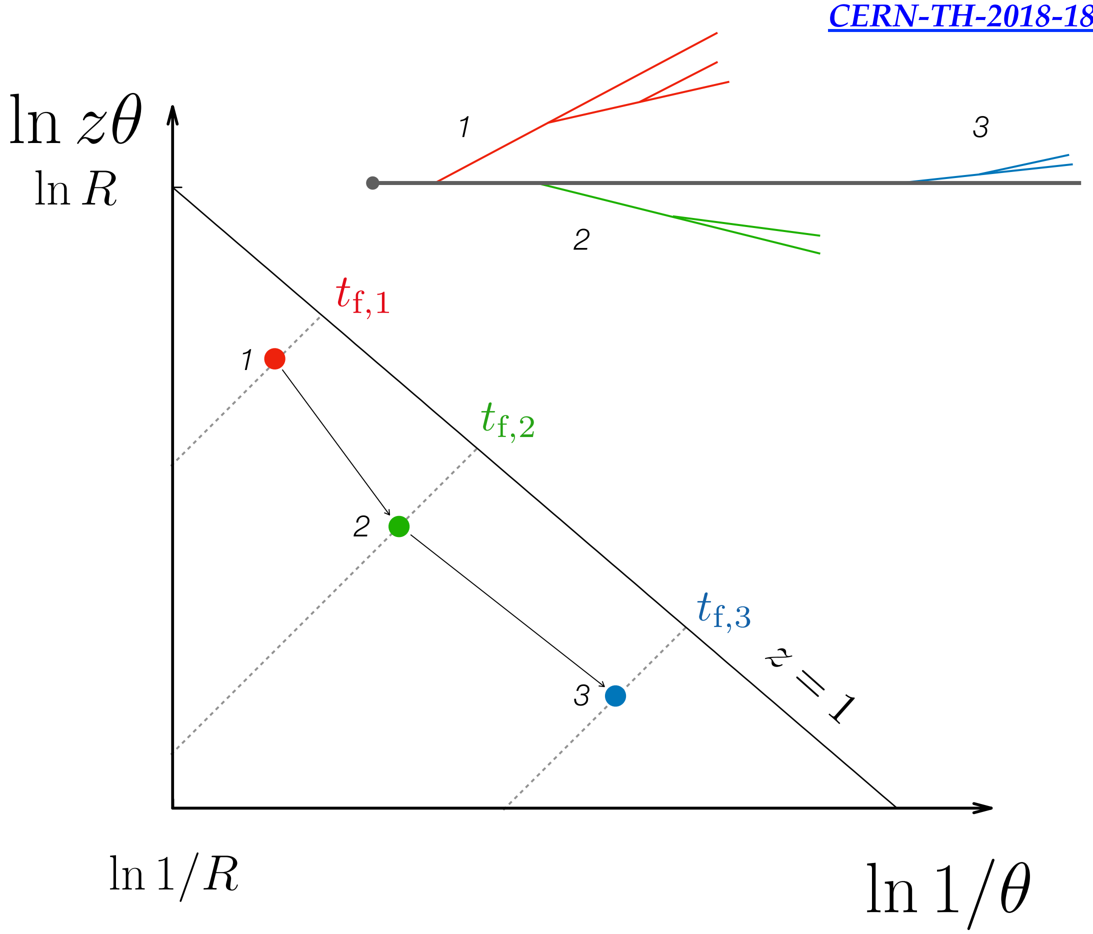


[CERN-LPCC-2018-07]

MICROSCOPIC DYNAMICS



CERN-TH-2018-186



- Effective constituents of QCD matter
- Characteristic length scales
- Use multi-differential jet measurements