Prospectives QGP-France

Irfu/DPhN/LQGP

Outline

- General Motivations
- HIC at Irfu/DPhN/LQGP
  - 2010–2019
  - 2020–2029
  - 2030–…
- Summary

General Motivation

- "Investigate high-density QCD and the Quark-Gluon Plasma (QGP) towards four main goals:
  - Characterizing the macroscopic long-wavelength properties of the QGP with unprecedented precision.
  - Accessing the microscopic parton dynamics underlying QGP properties.
  - Developing a unified picture of QCD particle production from small (pp) to larger (pA and AA) systems.
  - Probing nuclear parton densities in a broad (x, Q^2) range, searching for the possible onset of parton saturation."

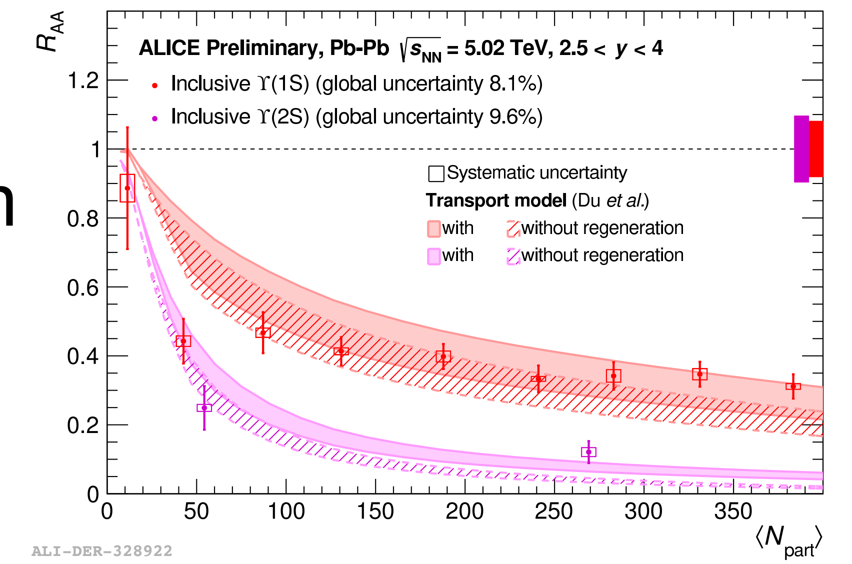
HL-LHC Yellow Report (arXiv:1812.06772)

HIC @ Irfu

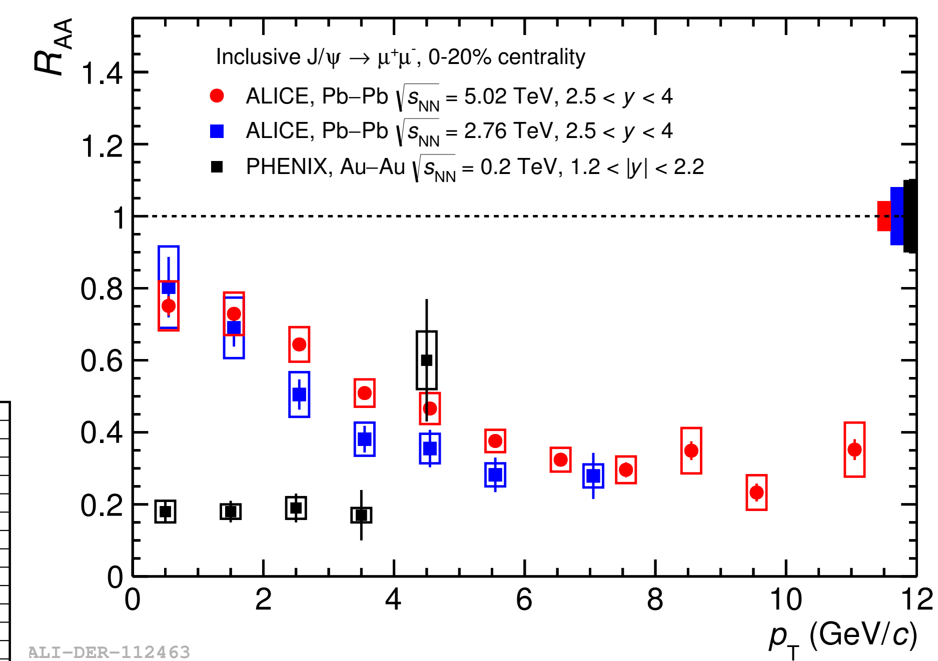
2010–2019

LHC Run 1 & Run 2 in three figures

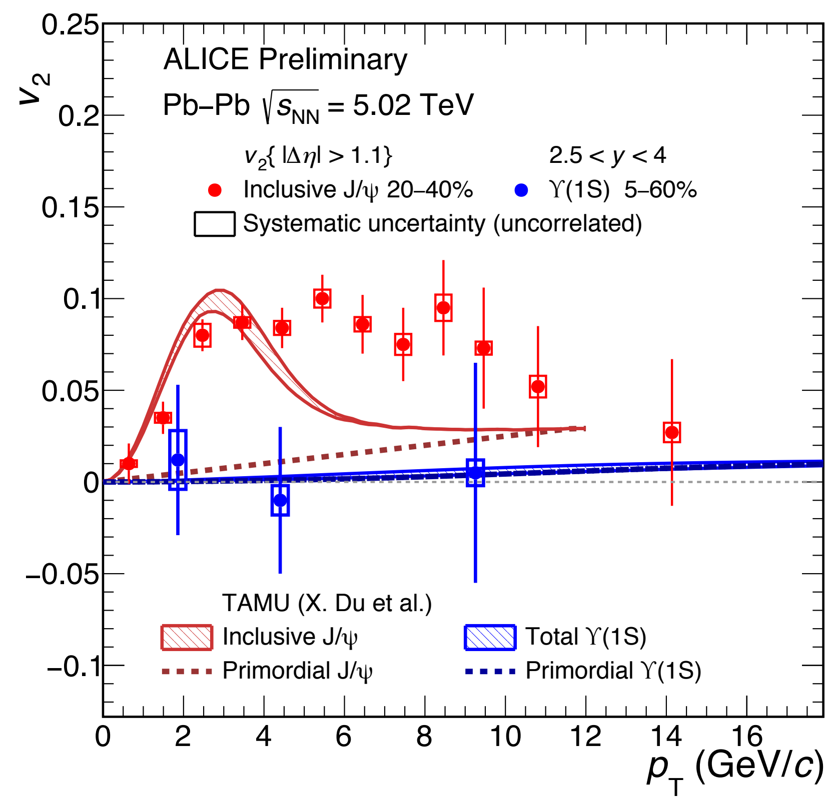
- Υ(1S) and Υ(2S) R_{AA}
  - Stronger suppression of less bound quarkonium states



- J/ψ R_{AA}
  - Recombination of charm quarks



- Quarkonium v_2
  - Intriguing

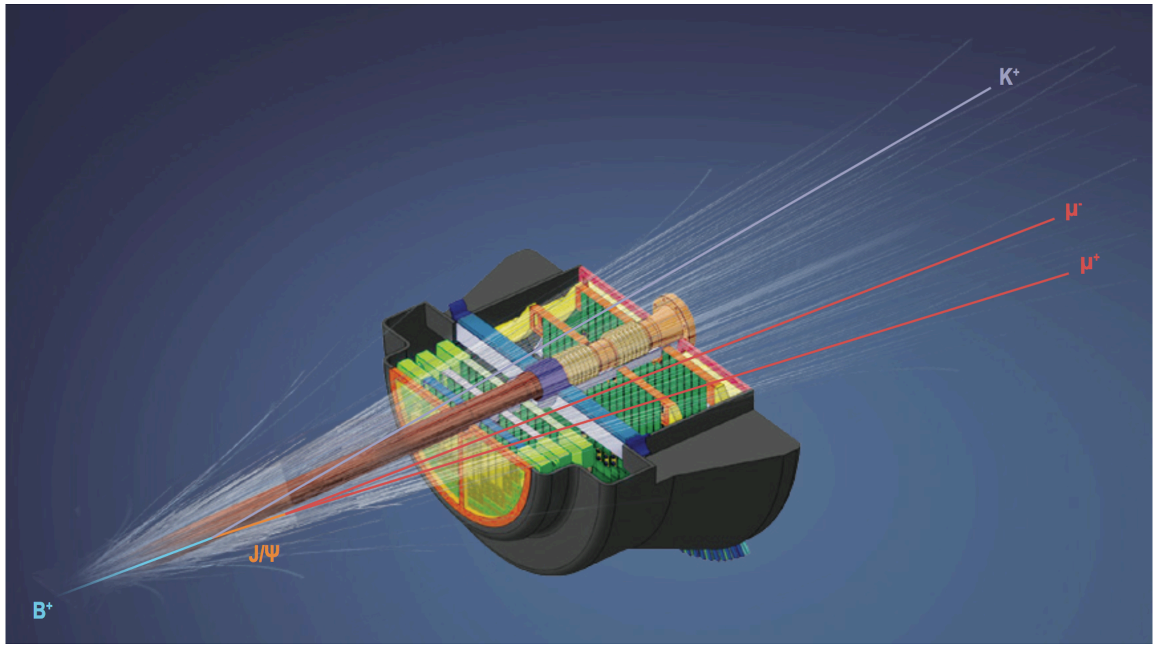


HIC @ Irfu

2020–2029

LHC Run 3 and Run 4 – Upgrade

- Committed to the successful exploitation of the HL-LHC
- For heavy ions, the HL-LHC starts in Run 3 with the capacity of the machine to deliver an integrated luminosity of 3/nb in one month of Pb-Pb
- With the aim of utilizing the full potential of the LHC, an ambitious upgrade plan was proposed, discussed, approved and is being implemented during LS2, in particular
  - Continuous read-out of the ALICE muon spectrometer
  - Addition of a pixel detector (MFT) in front of the ALICE muon spectrometer



LHC Run 3 and Run 4 – Physics Program

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- Program already approved and extensively discussed elsewhere, e.g. HL-LHC Yellow Report

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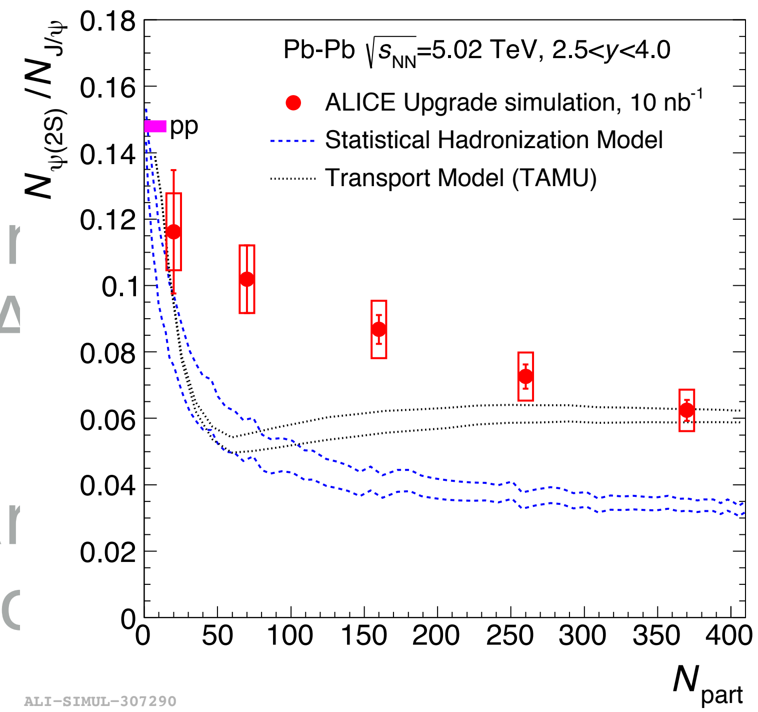
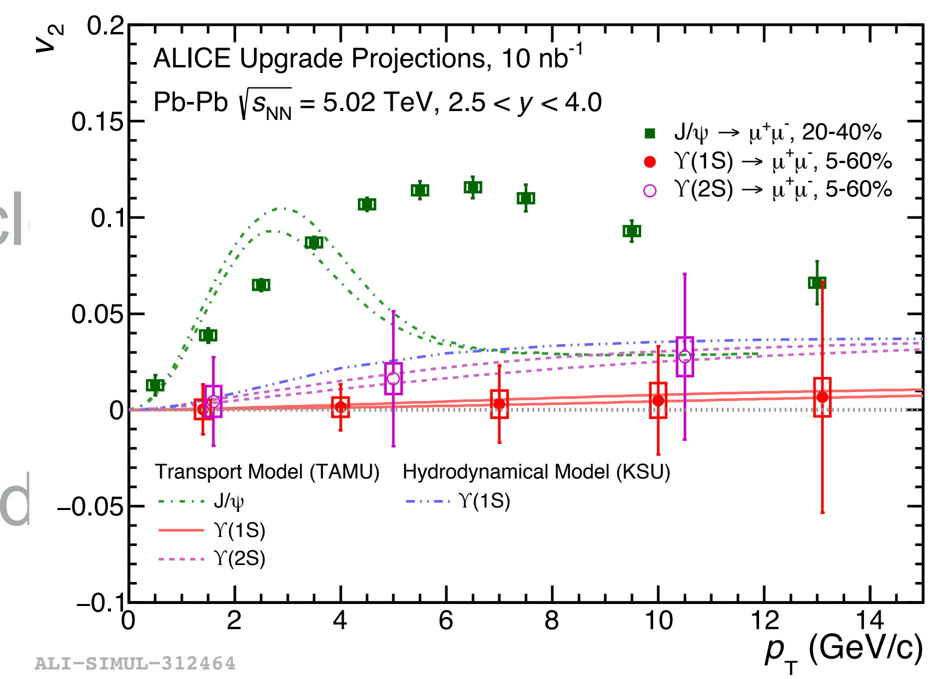
  – Accessing the microscopic parton dynamics underlying QGP properties.

  – Developing a ur … articl (pp) to larger (pA

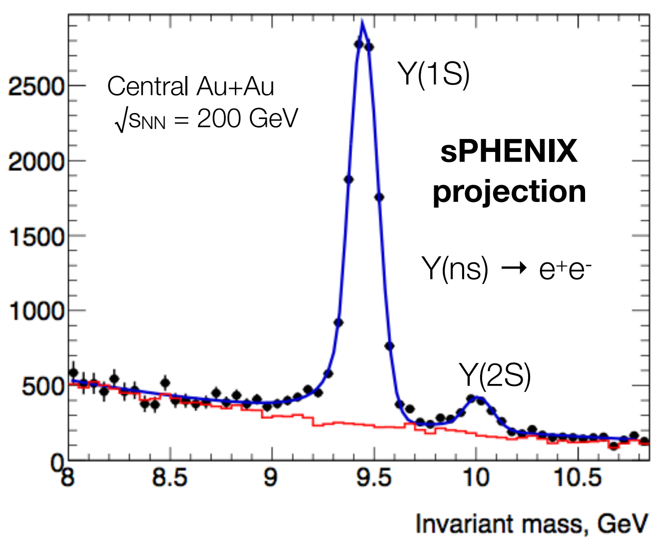
  – Probing nuclear … road for the possible c … on

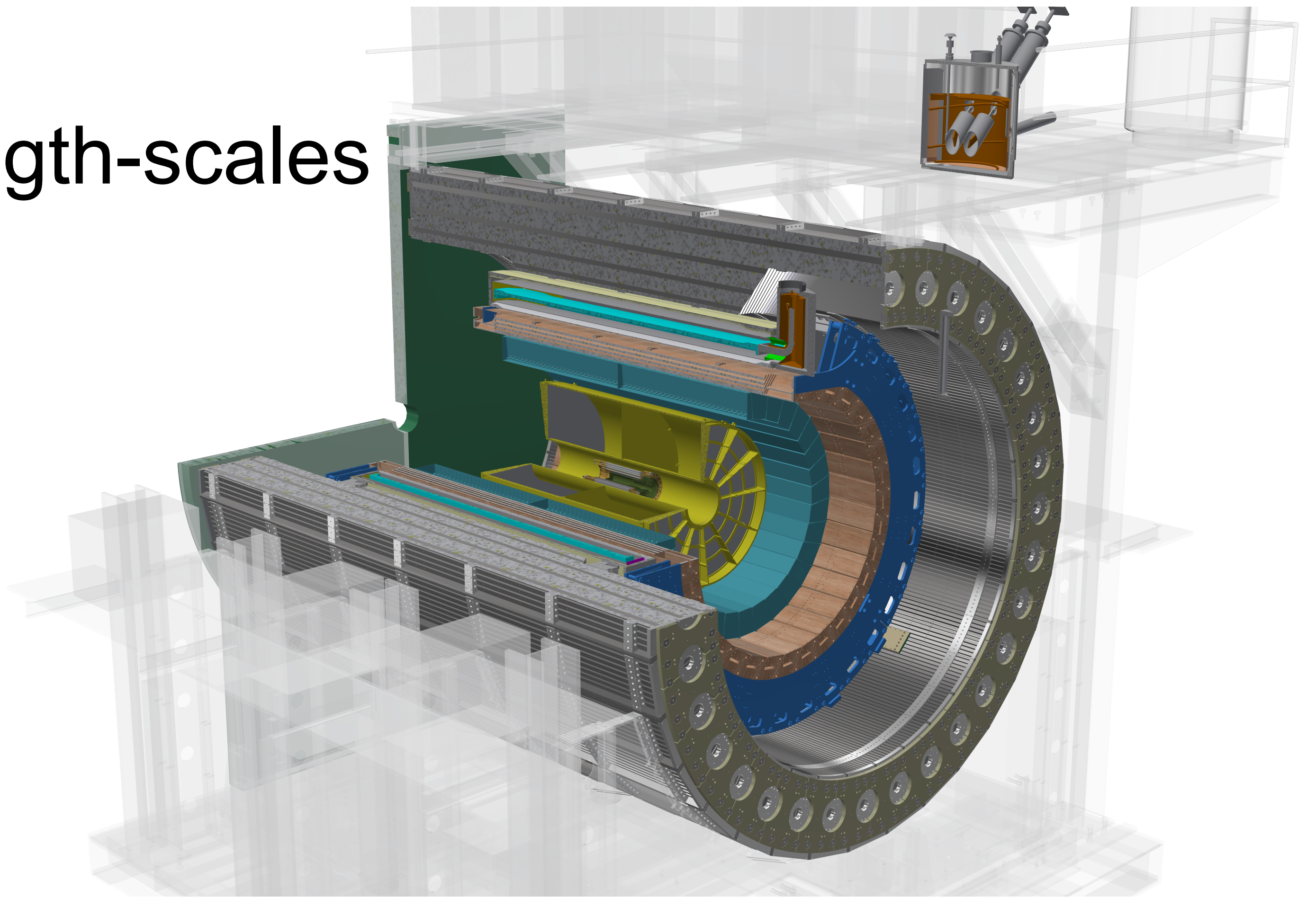




sPHENIX

- Involved in the sPHENIX program at RHIC
- R&D for TPC readout
- Software development
- Probe the QGP at various length-scales
  - Jets
  - Quarkonia





- Timeline
  - 2023 start physics data taking
  - 3+2 years data taking campaigns

HIC @ Irfu

2030–…

Open questions by 2030

- Characterizing the macroscopic long-wavelength properties of the QGP with unprecedented precision.
  - Precise temperature and time evolution of the system
    - Thermal radiation of the QGP

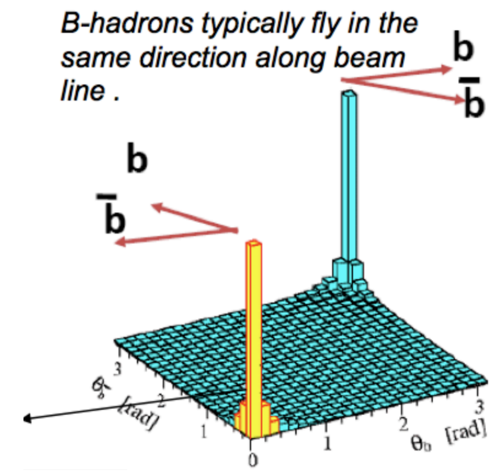
- Accessing the microscopic parton dynamics underlying QGP properties.
  - Precise experimental assessment of the in-medium QCD force and hadronization mechanism
    - Heavy-flavor probes

- Developing a unified picture of QCD particle production from small (pp) to larger (pA and AA) systems.
  - Broad mapping of system-size and energy dependence of collective effects
    - Also heavy quarks?

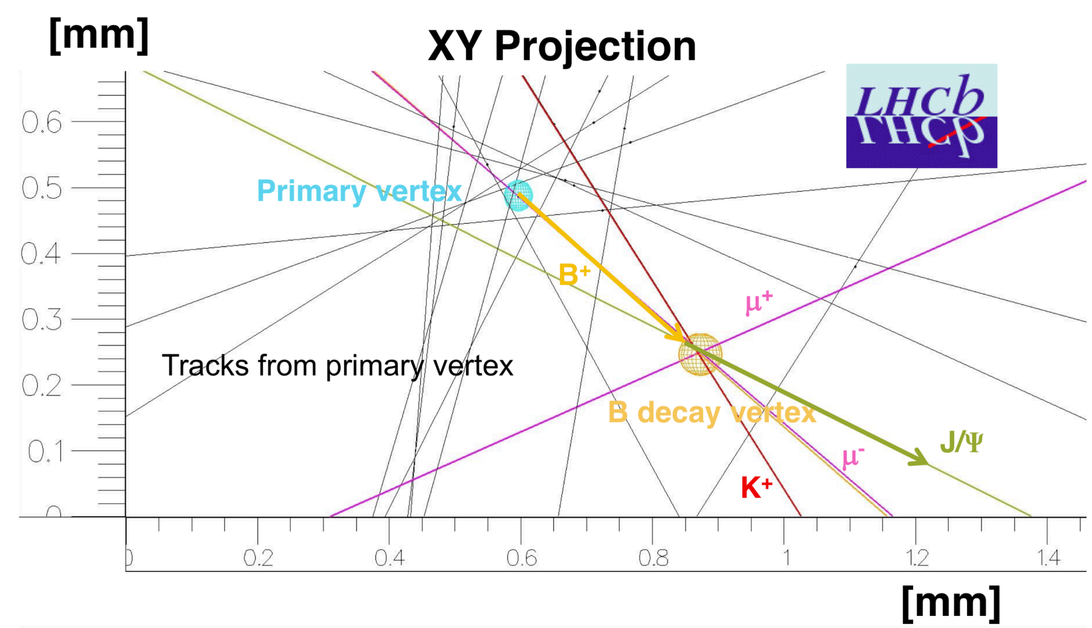
- Probing nuclear parton densities in a broad (x, Q^2) range, searching for the possible onset of parton saturation
  - Precise characterization of the initial state and its influence on the system evolution
    - nPDF, saturation, geometry

LHCb Upgrade II

- LHCb Upgrade II, including SMOG2, appears as the most promising place
  - Boost (fully instrumented in $2 < \eta < 5$)
    - Gives access to low transverse momenta
  - Precision
    - High Interaction Rate
    - Excellent vertex and track resolution
    - Good Particle Identification
  - Flexibility
    - Full software trigger (RTA)
    - Adapt to seize opportunities
    - Leave room for the unexpected
  - Potential
    - Collider mode
    - Fixed target
    - Broad and rich physics program
    - …



27% of bb in LHCb acceptance

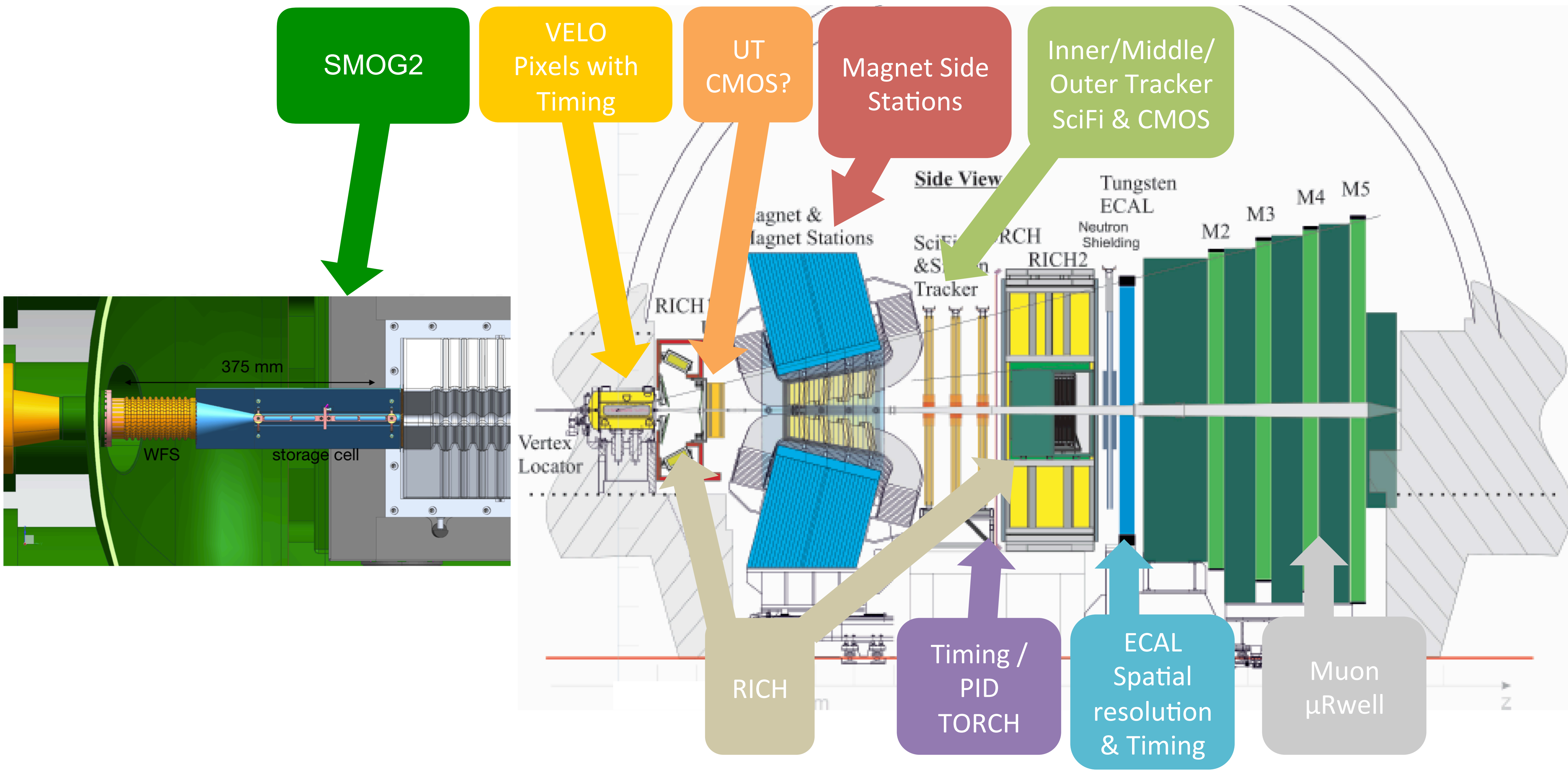


- Workshop on LHCb opportunities for Irfu, Saclay, 8-9 October 2019

LHCb Upgrade II

9 fb^{-1} — Goal: 50 fb^{-1} — Goal: 300 fb^{-1}

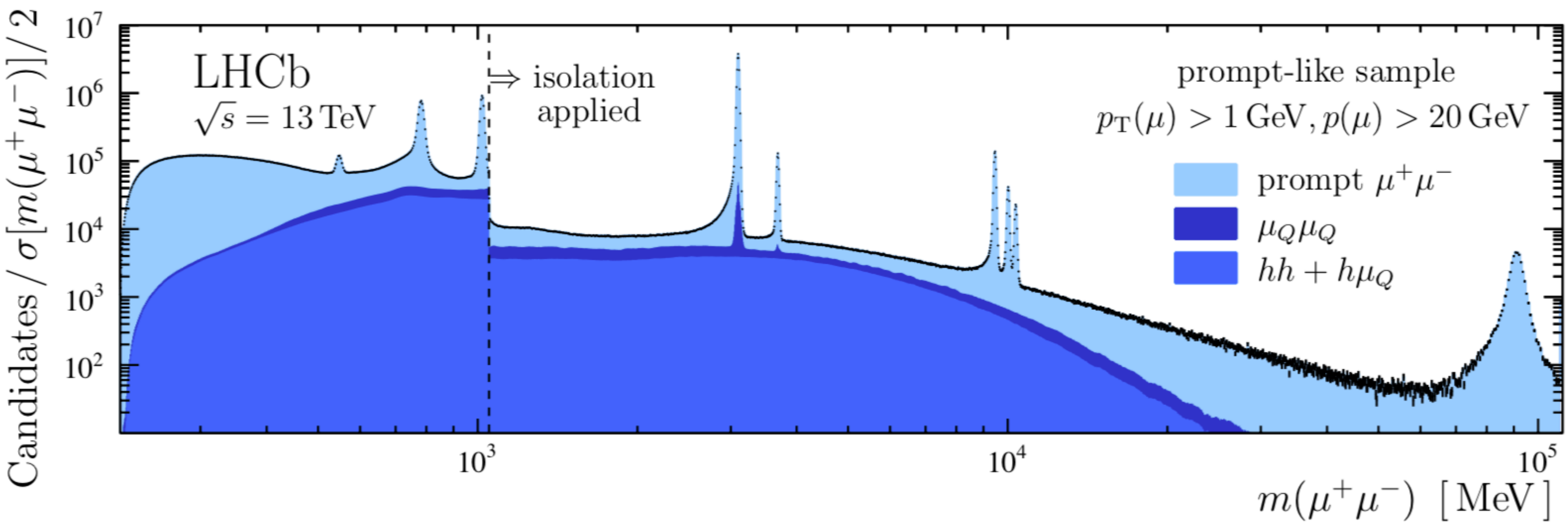
Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
2010 2011 2012	2013 2014	2015 2016 2017 2018	2019 2020	2021 2022 2023	2024 2025	2026 2027 2028 2029	2030	2031 2032 2033	2034	2035 2036 2037
			Upgrade I		Upgrade Ib		Upgrade II			



Addressing open questions with LHCb UII

- Characterizing the macroscopic long-wavelength properties of the QGP with unprecedented precision.
  - Precise temperature and time evolution of the system
    - Thermal radiation of the QGP

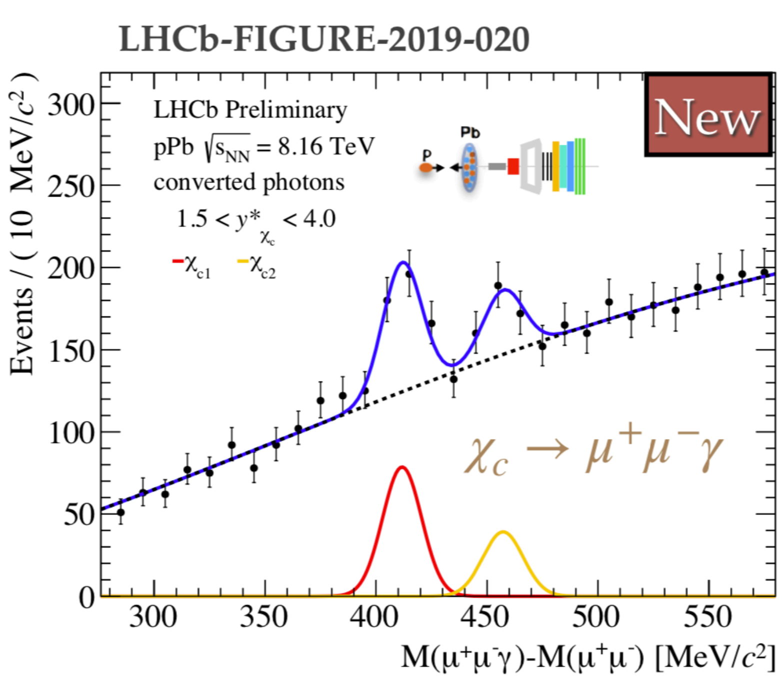
- Dimuon continuum in the intermediate mass range (φ–J/ψ)
  - Strong rejection power of non-prompt sources

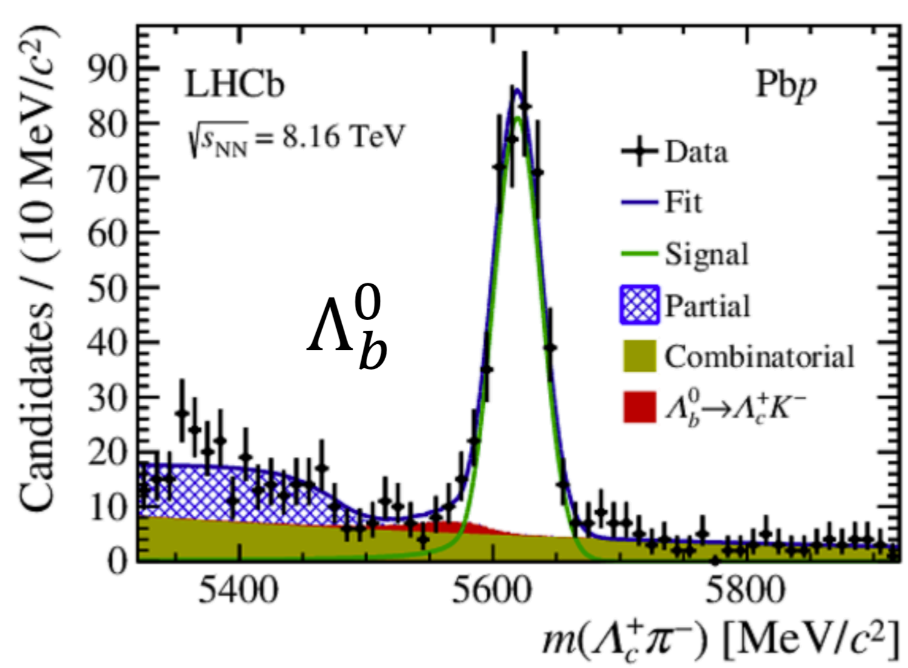


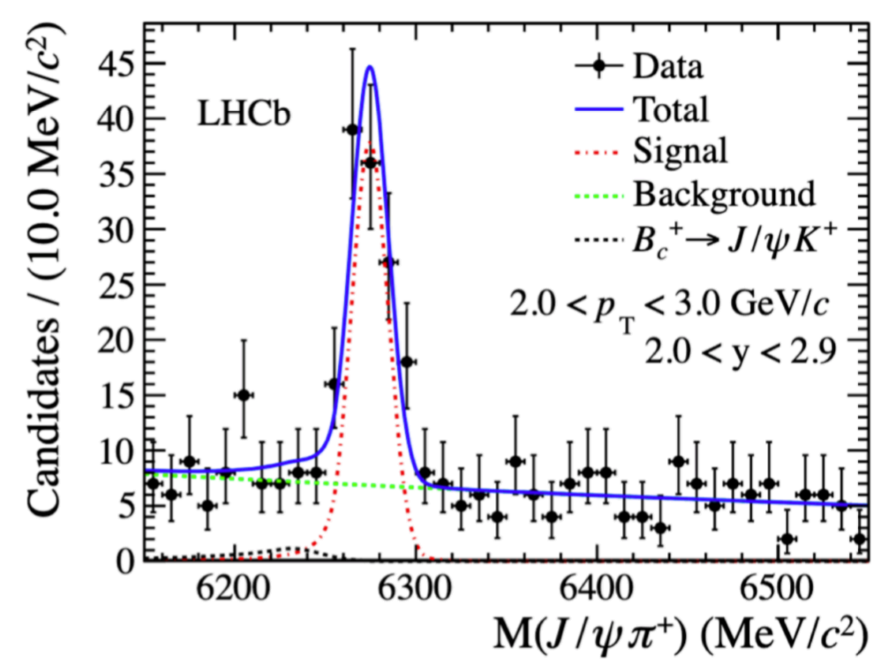
Addressing open questions with LHCb UII

- Accessing the microscopic parton dynamics underlying QGP properties.
  - Precise experimental assessment of the in-medium QCD force and hadronization mechanism
    - Heavy-flavor probes

- Excited heavy vector mesons (ψ(2S),Υ(3S)), non-vector mesons (χ_c)
- Charm and beauty hadrons, multi-heavy-quark hadrons (B_c)
- Exotic charm/beauty
  - Boost gives access to low p_T
  - Excellent vertexing, tracking and PID

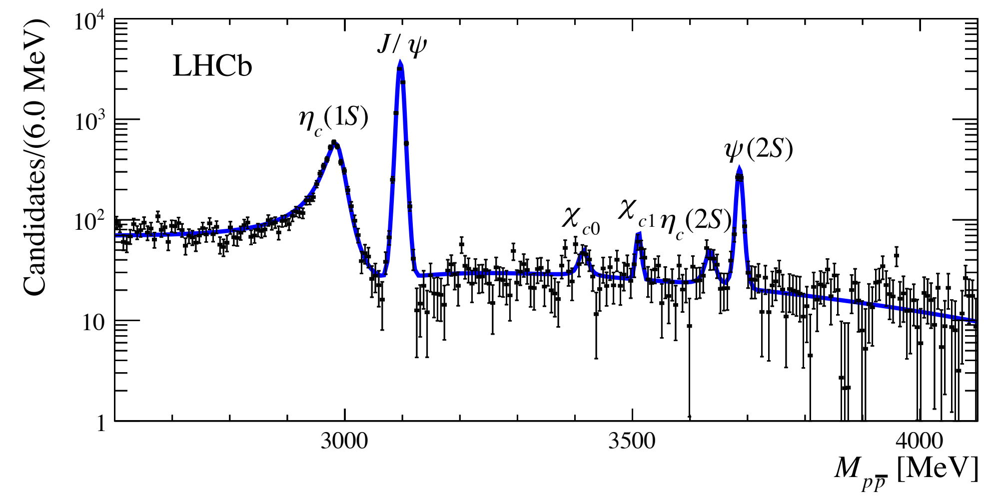






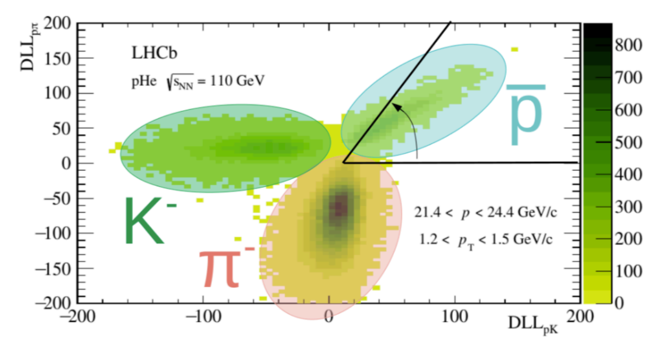
Addressing open questions with LHCb UII

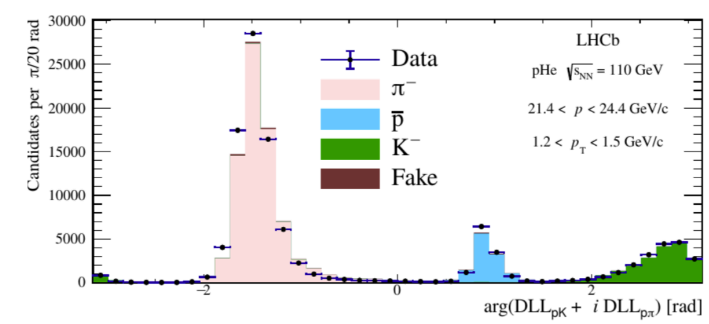
- Developing a unified picture of QCD particle production from small (pp) to larger (pA and AA) systems.
  - Broad mapping of system-size and energy dependence of collective effects
    - Also heavy quarks?



- High-multiplicity pp and pA

- Fixed-target program





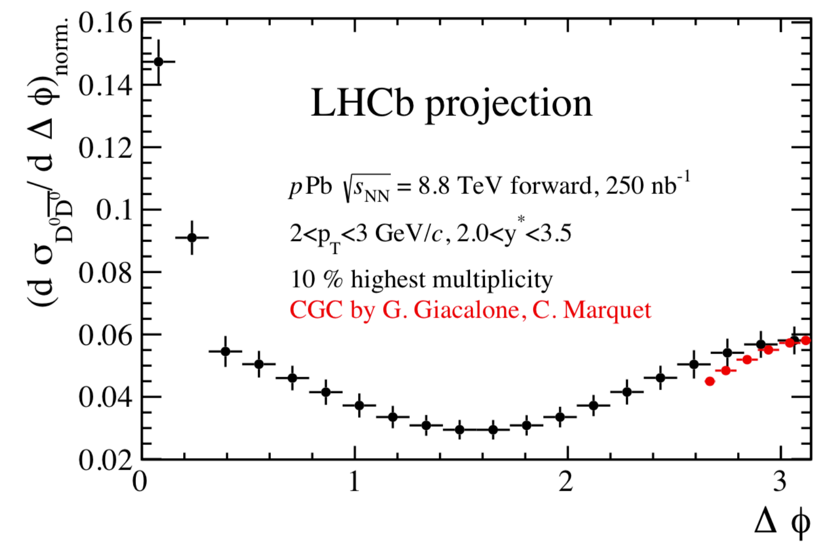
- Lighter ions

- In all cases, exploit full luminosity thanks to
  - Flexible trigger
  - Track to vertex association

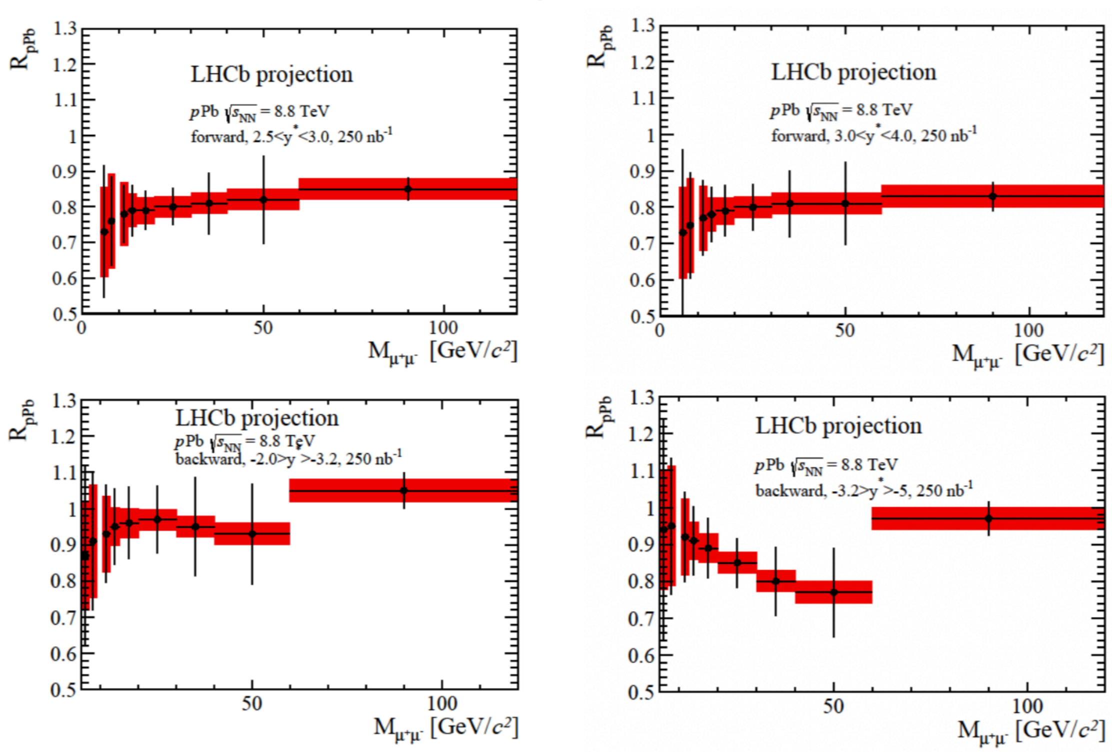
Addressing open questions with LHCb UII

- Probing nuclear parton densities in a broad (x, Q^2) range, searching for the possible onset of parton saturation
  - Precise characterization of the initial state and its influence on the system evolution
    - nPDF, saturation, geometry

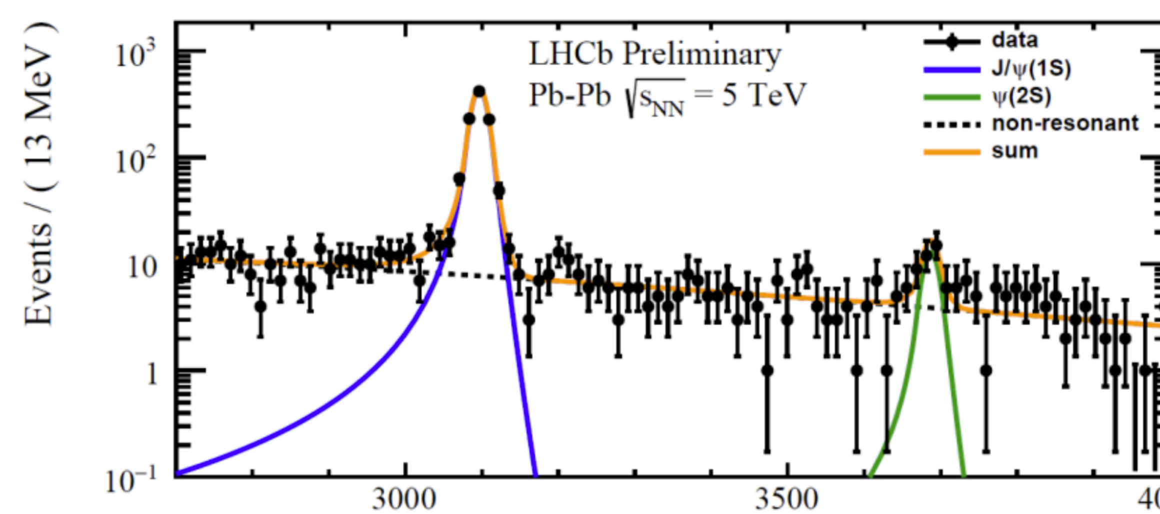
- Heavy-quark correlations
- Drell Yan at forward y
- UPC
  - Ideal kinematic region



EPPS16 nPDF prediction at NLO



LHCb-CONF-2018-005



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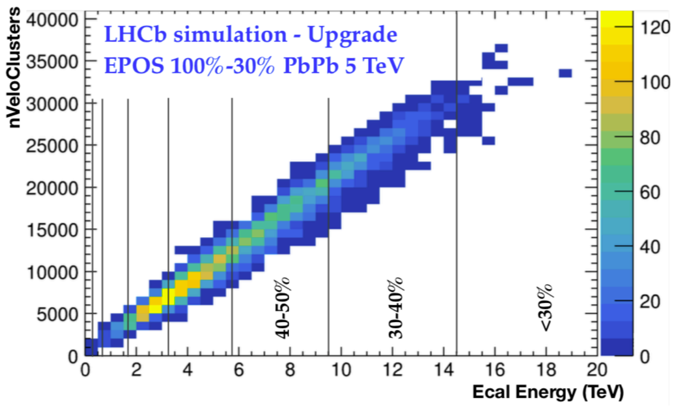
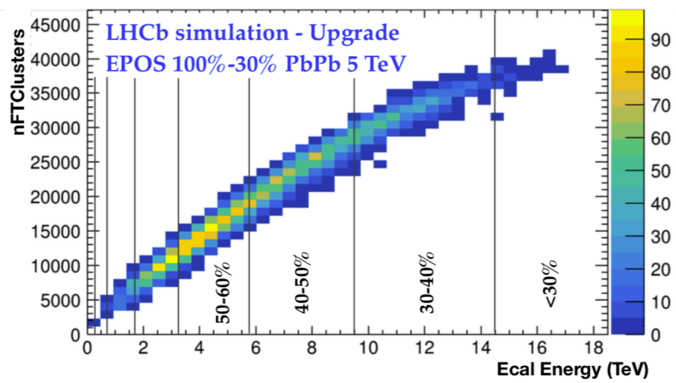
On the critical path for HI

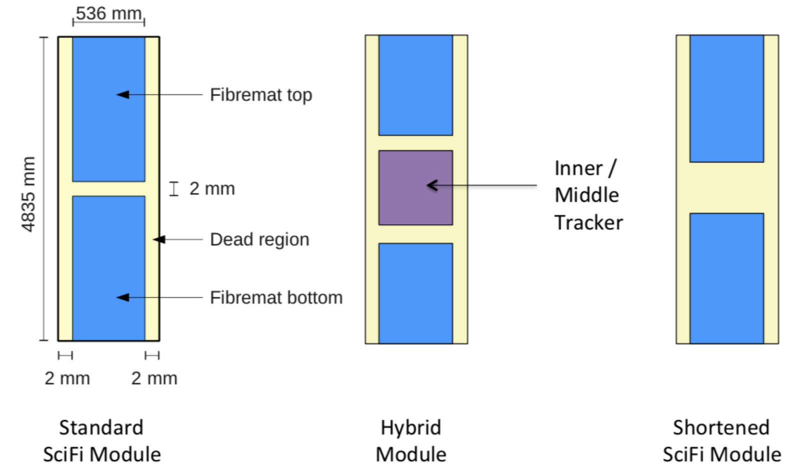
Occupancy

Velo

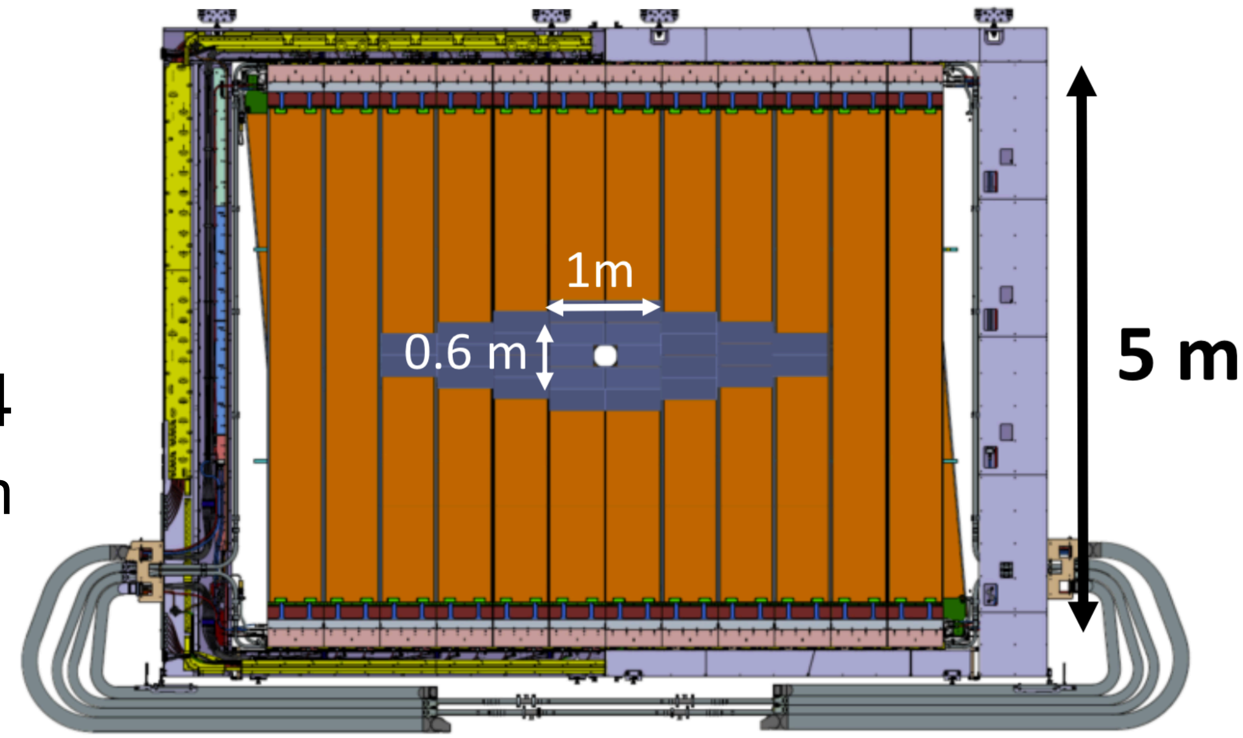


SciFi





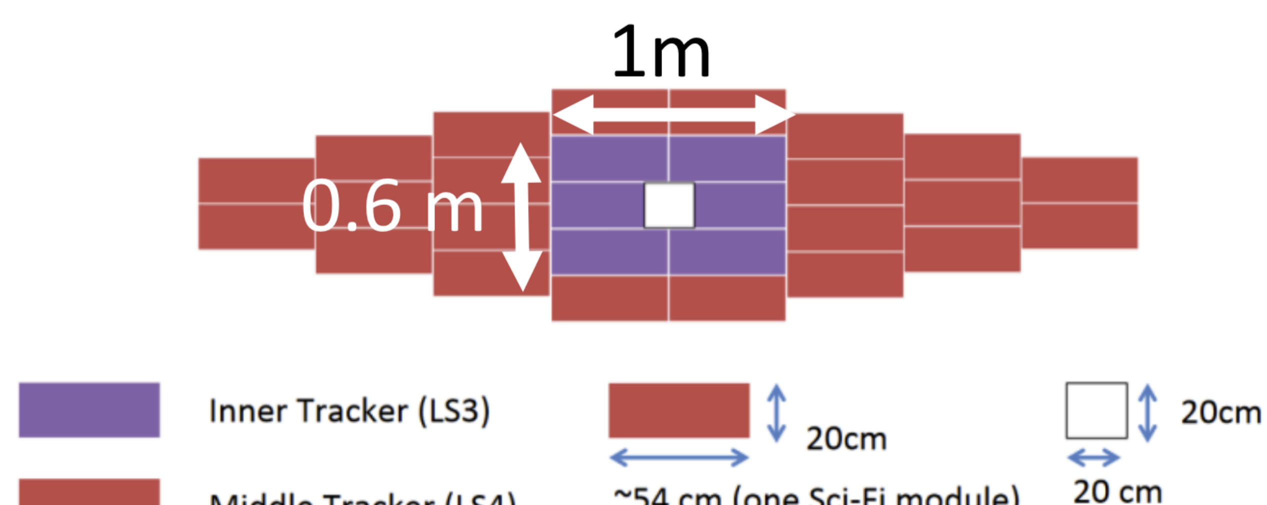
Hybrid Technology Tracker
- Scintillating fibres
- CMOS



Mighty Tracker

- LS3 (2024–2025) Upgrade Ib → Run 4
  - Stage 1: Inner tracker – 100 µm × 500 µm pixels or 0.1 mm × 100 mm strips
  - Will further extend the (PbPb) centrality coverage

- LS4 (2030) Upgrade II → Run 5,...
  - Stage 2: Inner tracker + Middle tracker



Interesting technical opportunity

Summary

- Run 1 and 2 of the LHC
  - has allowed for significant progress on our understanding of the QGP
  - has raised important questions
- Run 3 and 4 of the LHC
  - a clear scientific program has been proposed, discussed and approved
  - and is being implemented
- Several open question will likely remain in 2030
  - precision will be the key to address them

- LHCb Upgrade II appears as a very promising detector for future QGP physics
  - Boost
  - Precision
  - Flexibility
  - Potential

Panorama

- Some measurements could still be improved after Run 4
  - Measurements of the azimuthal anisotropy of excited quarkonium states will presumably still suffer from low statistics
    - Access to the dynamics of suppression and formation in the QGP
  - Measurements of χ_c will be marginal and/or in a limited kinematical range
    - Important feed-down contribution
  - Measurements of *exotic* charmed and beauty mesons and baryons will still be stat limited
    - Important to understand hadronisation mechanisms, hence QGP d.o.f.
  - Quarkonia in Jets, could be stat limited in bottomonium sector and kinematically limited for all
    - Role of fragmentation

- In addition to more data, improved detectors could be necessary …

And after Run 4?

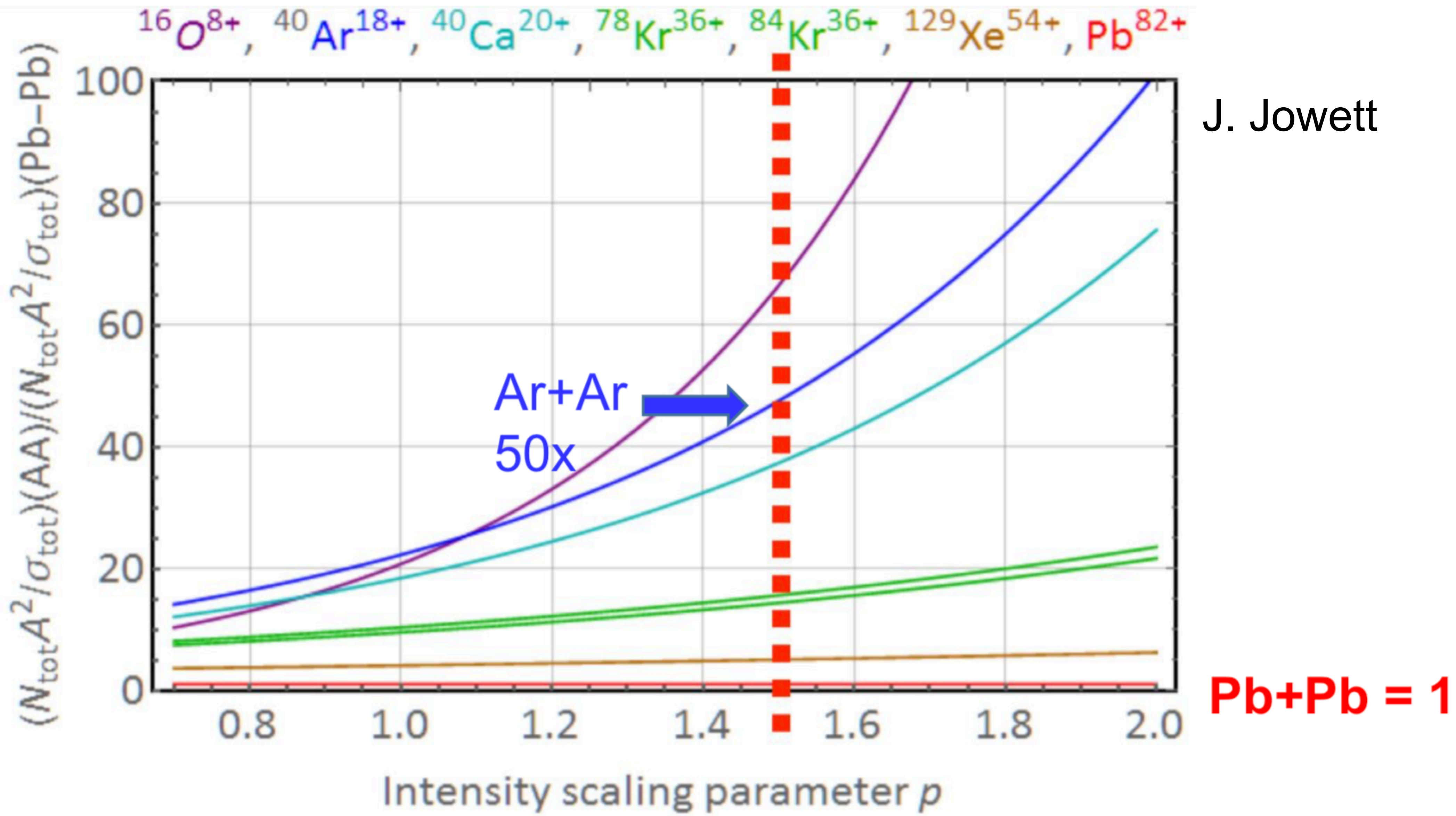
- LHC Run 2 is not over yet
- LHC Run 3 and Run 4 will finish in more than 10 years from now …
  - An ambitious plan is laid down and expected performances have been estimated and are being revisited …
  - We have predicted where we will be at the end of Run 4
  - We can therefore try to predict what will be missing afterwards …
    - …

- Let's also give it a chance to the unexpected, especially since the unexpected has happened
  - Jet suppression
  - J/ψ regeneration
  - QGP-like effects in small systems
  - …

- We can always look for **smoking guns** in **money plots** of **flagship measurements**, and we should, but let's be honest to ourselves, the one lesson from about 30 years of HI physics is that we need systematic and comprehensive program of all observables and probes of the QGP

Lighter ions at the LHC

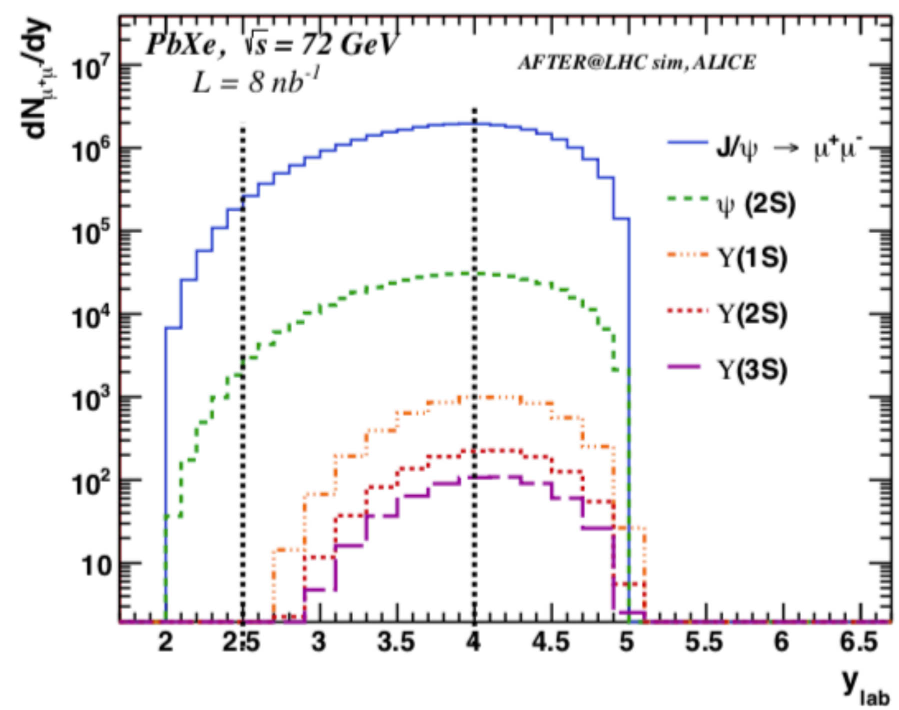
- Could have an intrinsic interest …
- … but does certainly have the practical interest of higher per-nucleon-pair luminosities



LHC at lower energies

- A good theoretical description of the energy dependence of HF production is necessary
- At RHIC energies several measurements are statistically or kinematically limited
  - Total charm and beauty cross sections
  - Excited charmonium states
  - Bottomonia (sPHENIX program)

- Fixed target program at the LHC
  - $\sqrt{s_{NN}} \sim 72$ GeV
  - Flexibility of targets
  - Large integrated luminosities
  - Reach program including open and hidden HF
  - Could complement ongoing (collider-mode) programs in ALICE and LHCb
  - Could start as early as Run 3 (SMOG2 in LHCb)



LHC at lower energies

- A good theoretical description of the energy dependence of HF production is necessary
- Very large gap in energy from RHIC to LHC with the emergence of qualitatively different behavior
  - J/ψ regeneration
  - Collective-like effects in small systems
- LHC run at lower energies, down to injection energies
  - $\sqrt{s_{NN}} \sim 500$–1000 GeV
  - But luminosity decreases with decreasing energy

Motivation – Low- and Intermediate-Mass dileptons

- At the LHC energy: properties of the QGP medium (+ high-multiplicity small systems)
  - In-medium modified spectral function of ρ and ω to provide a reference for LQCD calculations and test predictions from phenomenological models
  - Fireball temperature (slope of the invariant mass spectrum for M ≈ 1.5 GeV/c^2)

- Dileptons can also serve as
  - Clean decay channel for hadrons produced at the freeze-out
  - Complementary channel, although indirect and model-dependent, for the measurement of heavy-flavors at high energies
  - Drell-Yan
  - Bonus: search for dark photons and other beyond-standard-model light bosons

Motivation – Open Heavy Flavor

- In short, heavy quarks are produced early by hard collisions and traverse and probe the QGP, ok but …

- Production through
  - Hard parton-parton (mostly g-g) collisions but
    - gluon radiation
    - Shadowing
    - Initial state correlations
  - gluon fragmentation
- Propagation through the QGP
  - Collisional and radiative energy loss
  - Transport coefficients
    - Medium description
    - LQCD inputs/constrains
  - Could possibly lead to local thermal equilibrium
- Hadronization
  - Recombination
  - Fragmentation
- Propagation through a hadron gas
  - Hadronic cross sections are poorly know

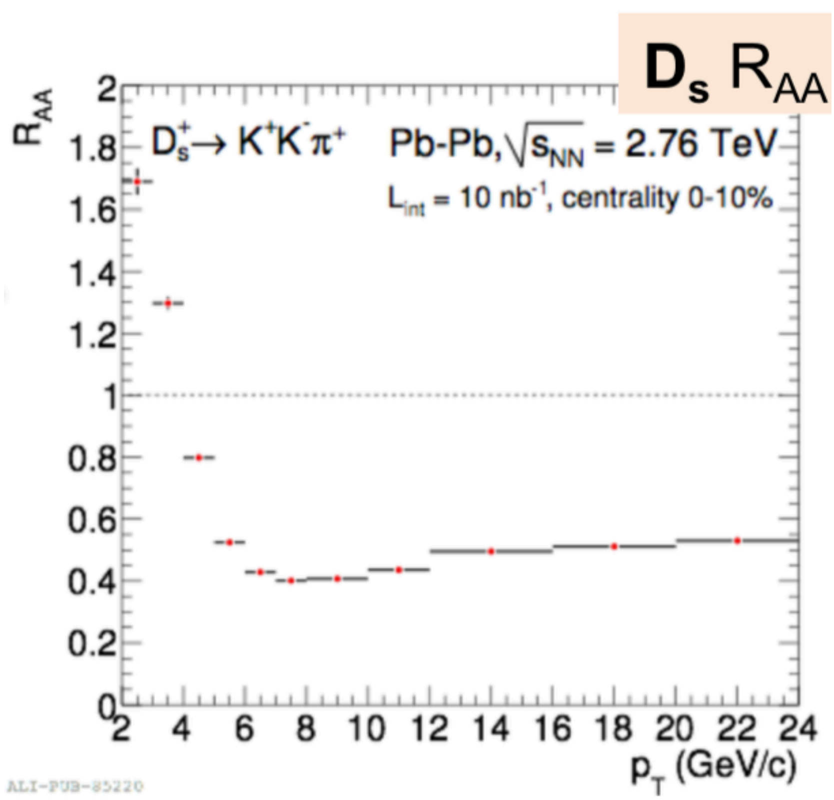
Motivation – Quarkonia

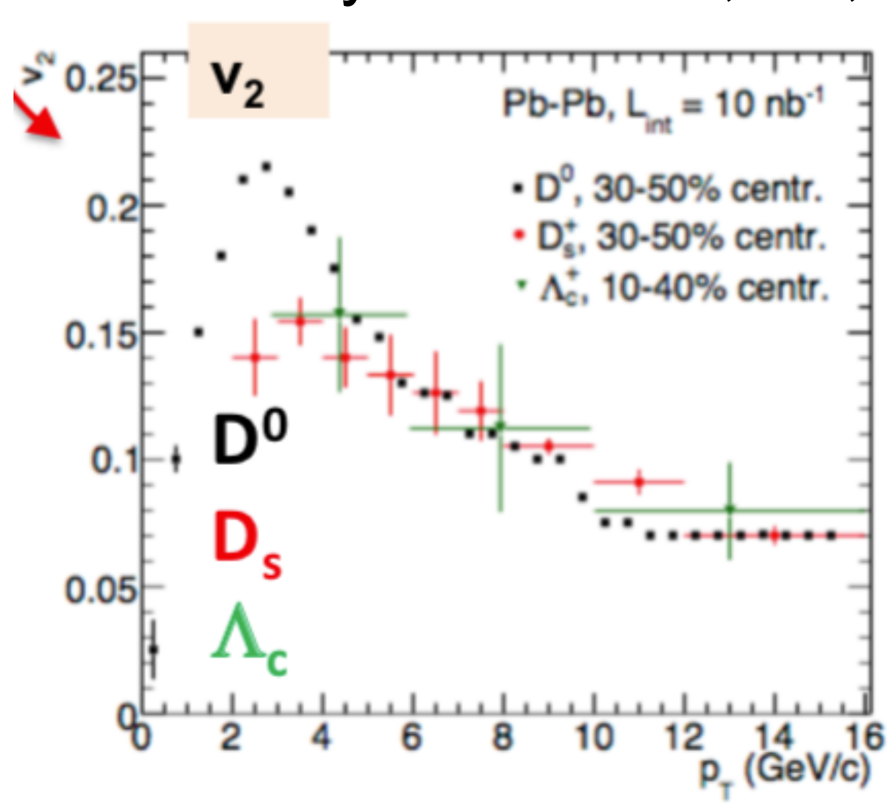
- In short, heavy quarks are produced early by hard collisions and traverse and probe the QGP, ok but …

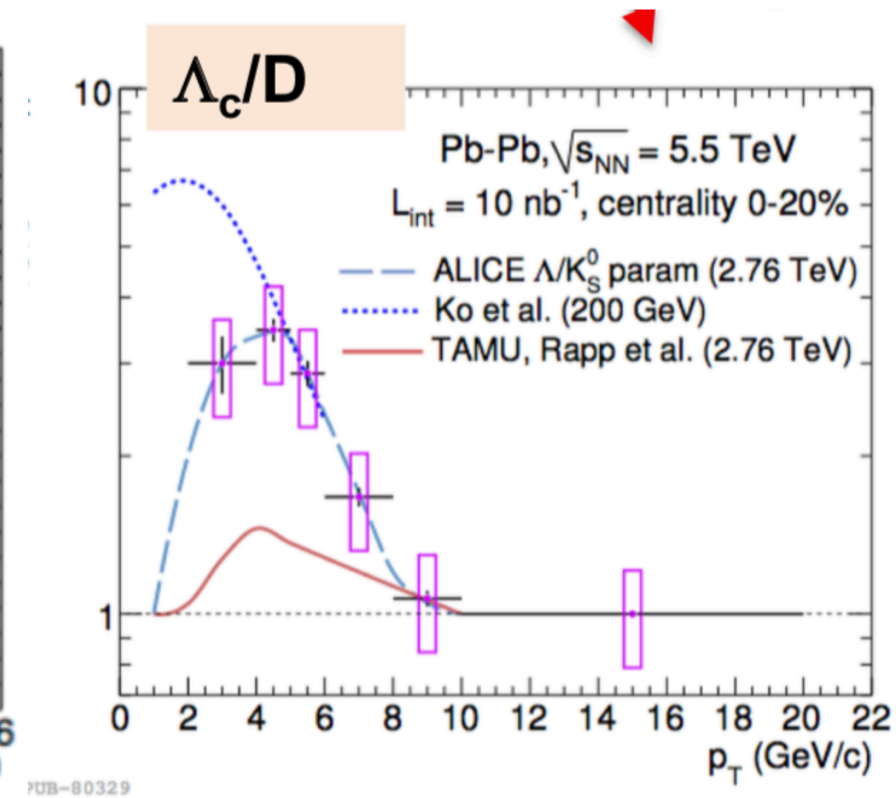
- Production
  - Perturbative: heavy-quark pair production
  - Non-Perturbative: binding of heavy-quark pair into a white quarkonium state
    - Not yet satisfactorily described
  - Fragmentation
- Propagation through the QGP
  - Probe of in-medium QCD force
    - Spectral functions
    - LQCD inputs/constrains
    - Medium description
    - Transport coefficients
- Hadronization
  - Recombination
  - Fragmentation
- Propagations through a hadron gas
  - Hadronic co-movers could play an important role, mostly for excited states

OHF – hadronization mechanism

- Goal: understand HF hadronization
  - Heavy quark recombination at low p_T
  - Fragmentation at high p_T
  - A mix in the middle
- Observables
  - R_{AA} and v_2 of D and B mesons
  - More *exotic* charmed and beauty hadrons Λ_c, Λ_b, D_s, B_s, …





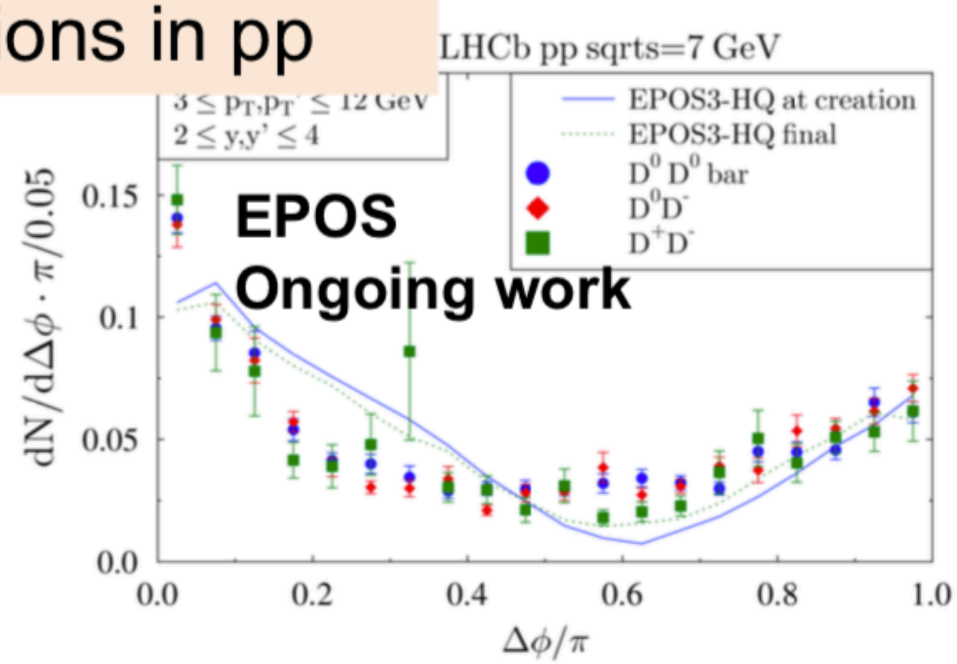


- Parallel development of theory is critical
  - Rigorous treatment of recombination is difficult (if any)

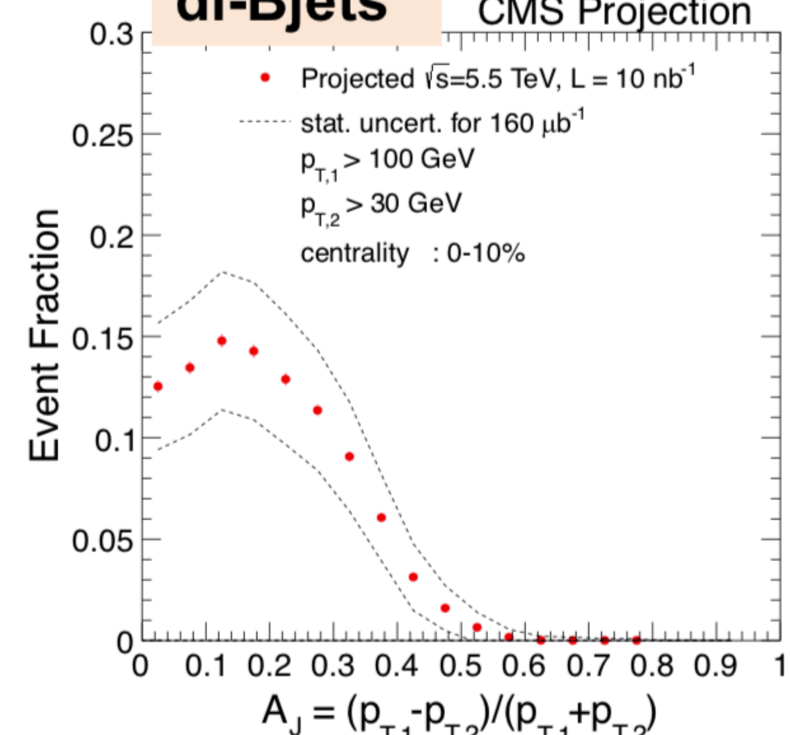
OHF – Correlations and jets

- Goal: understand energy loss
  - Radial distribution of lost energy
  - Mass and parton-type dependence of energy loss
- Observables
  - D-Dbar azimuthal correlations
  - HF-tagged jets
  - D-jet correlations
  - Di b jets

Theory: $\Delta\phi,\Delta y$ $D\overline{D}$
correlations in pp



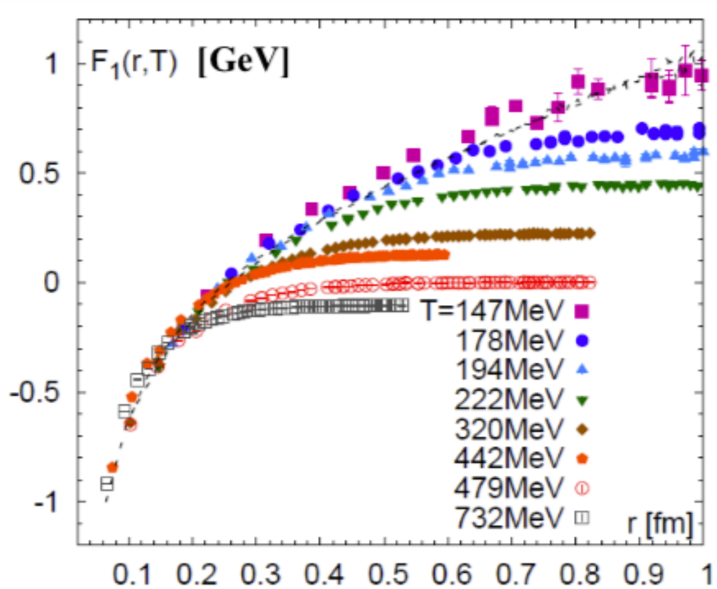
di-Bjets

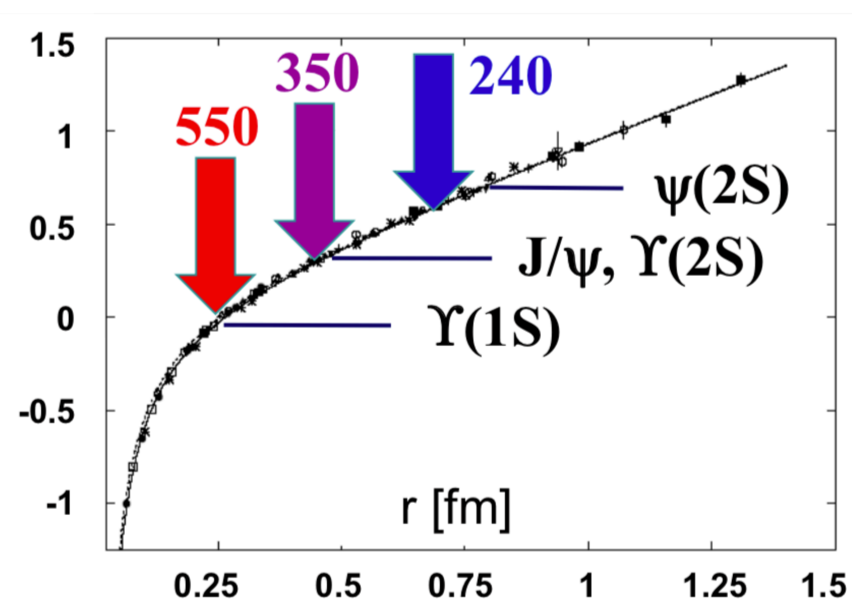


- Parallel development of theory is critical

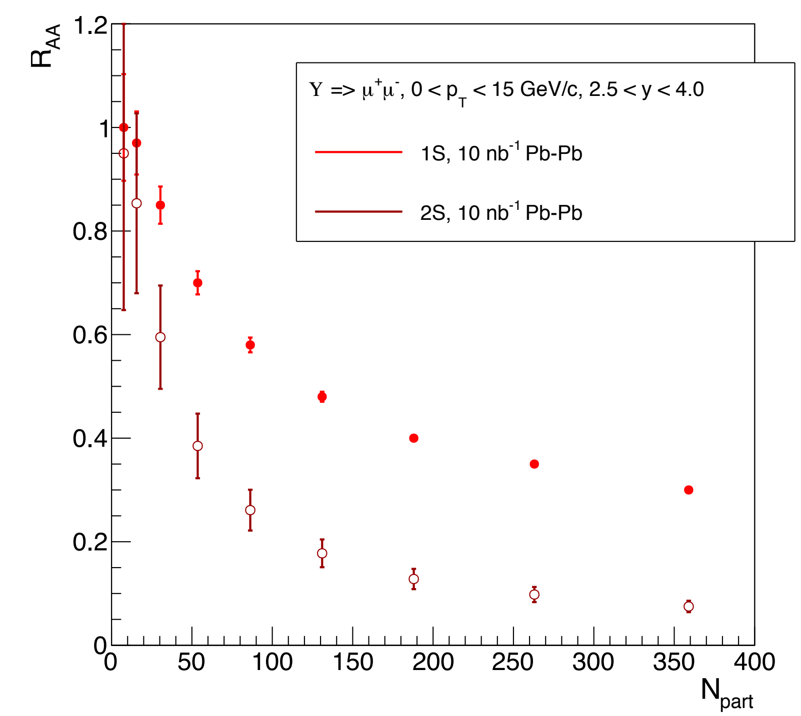
Quarkonia – deconfinement

- Goal: address the deconfinement mechanism
  - Study the in-medium QCD force
  - Access to different regions of the HQ potential
  - Study quarkonium spectral functions
- Observables
  - Suppression of different quarkonium states
    - Y(1S): color-Coulomb
      J/ψ, Y(2S,3S): confining force
    - ψ(2S): barely bound





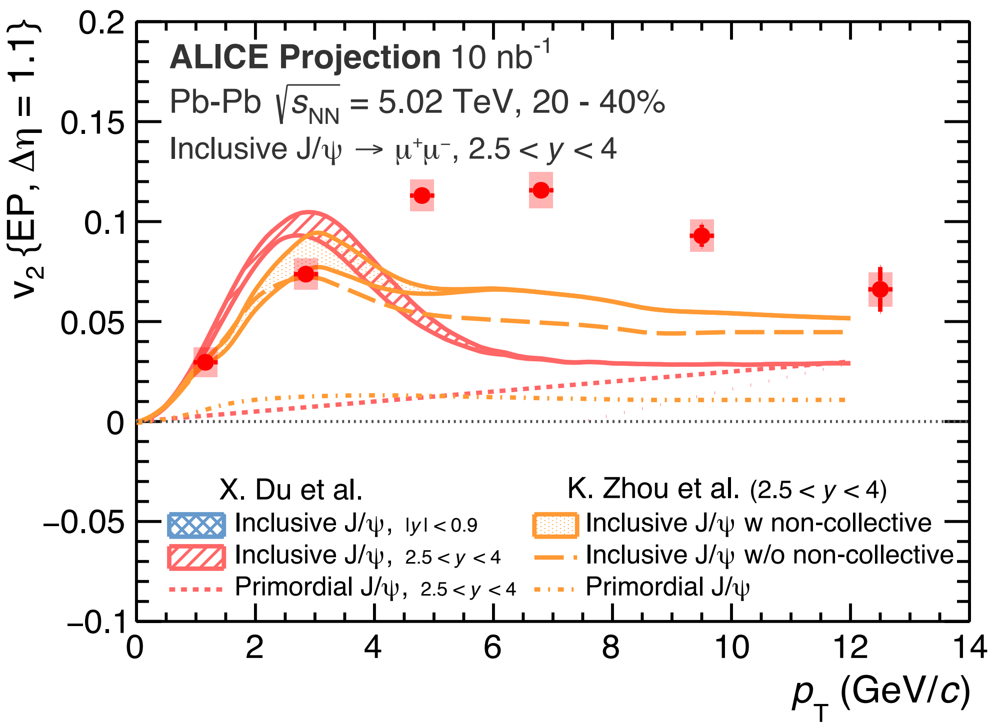
ALICE Projection

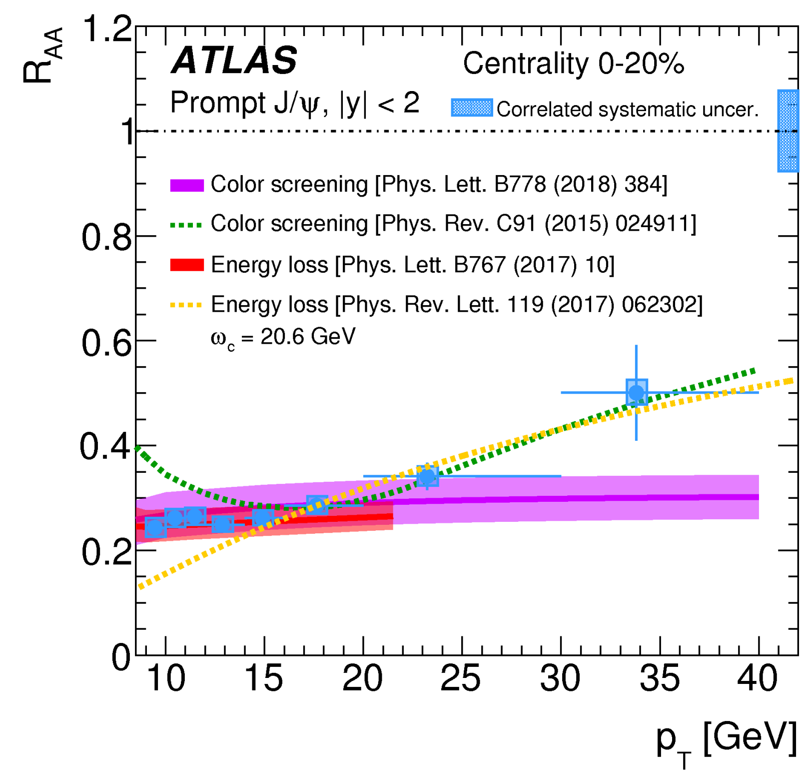


- Parallel development of theory is critical
  - Links and inputs to LQCD, e.g. spectral functions should be more systematic

Quarkonia – energy loss and collectivity

- Goal: address the transport properties of heavy quarks in the QGP
  - Transport coefficient, e.g. diffusion coefficient D_s
  - Collisional vs radiative energy loss
- Observables
  - R_{AA} and v_2 of J/ψ
  - High-p_T J/ψ, prompt and non-prompt



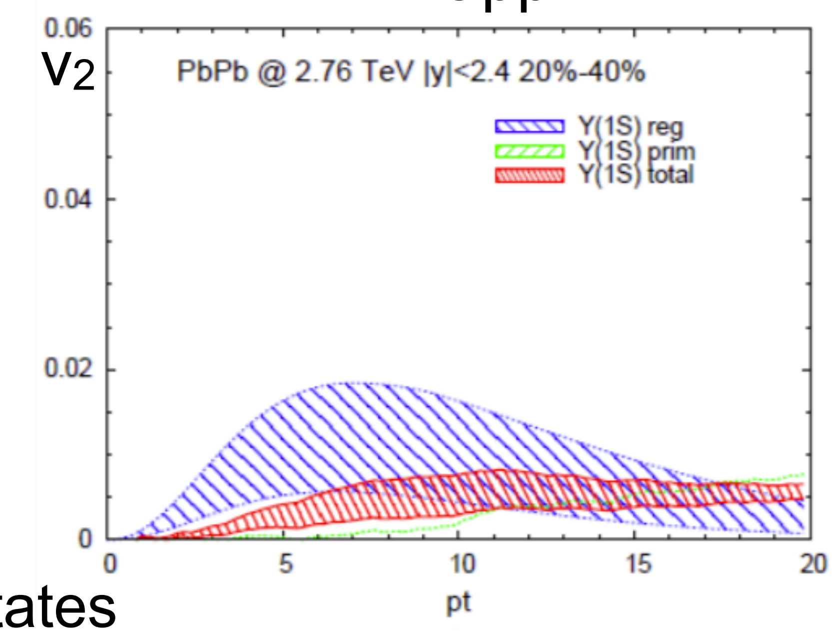


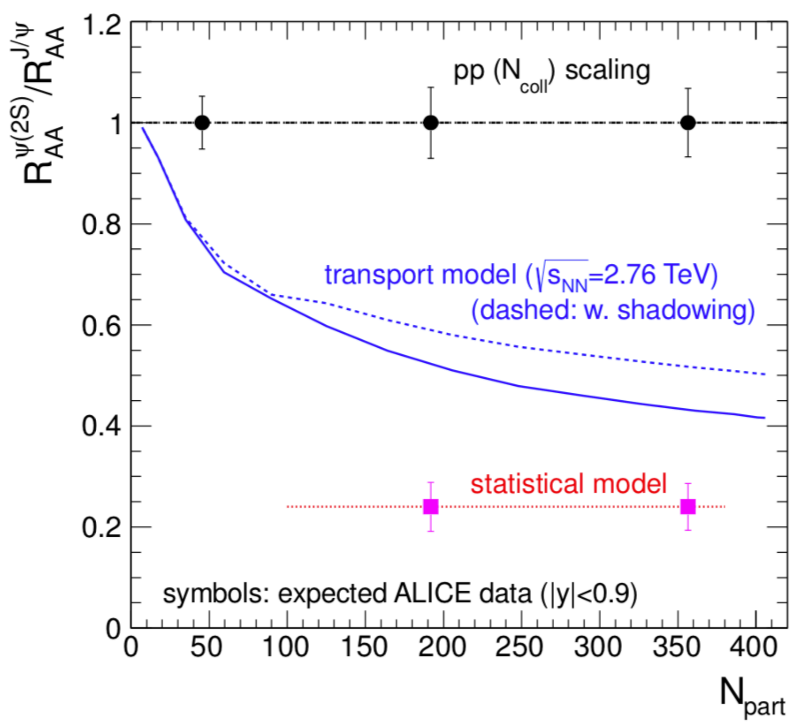
- Parallel development of theory is critical
  - Link between OHF and quarkonia theory is mandatory

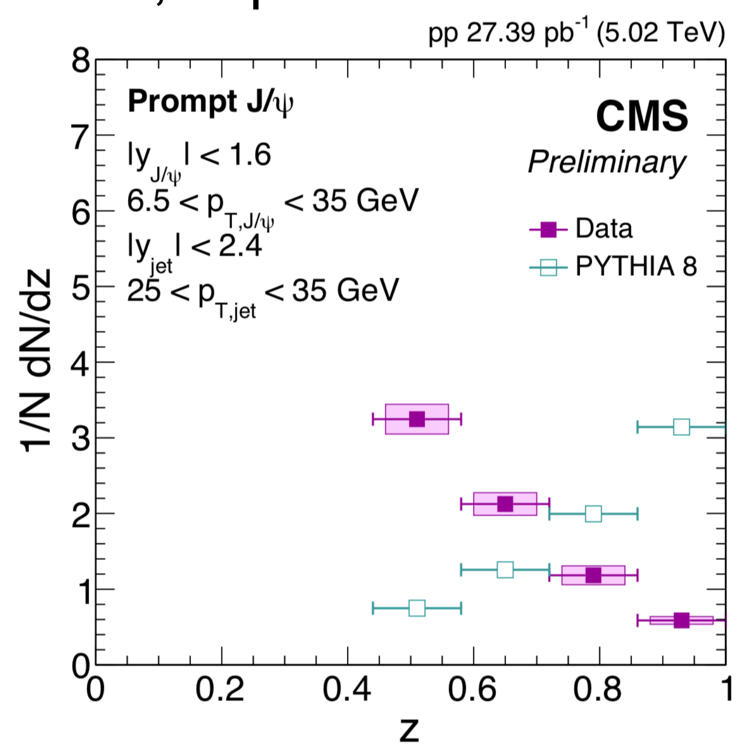
Quarkonia – hadronization mechanism

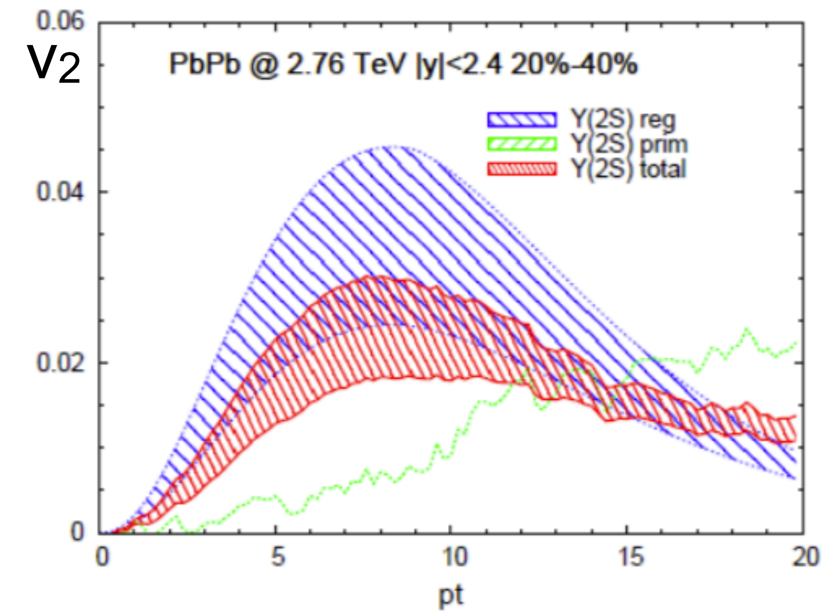
- Goal: understand quarkonium hadronization
  - Initial production
  - Heavy quark recombination / statistical hadronization
  - Fragmentation
  - Suppression and formation time
- Observables
  - R_{AA} and v_2 of charmonia
  - J/ψ in jets
  - p_T dependence of quarkonium states, in particular excited states

R. Rapp





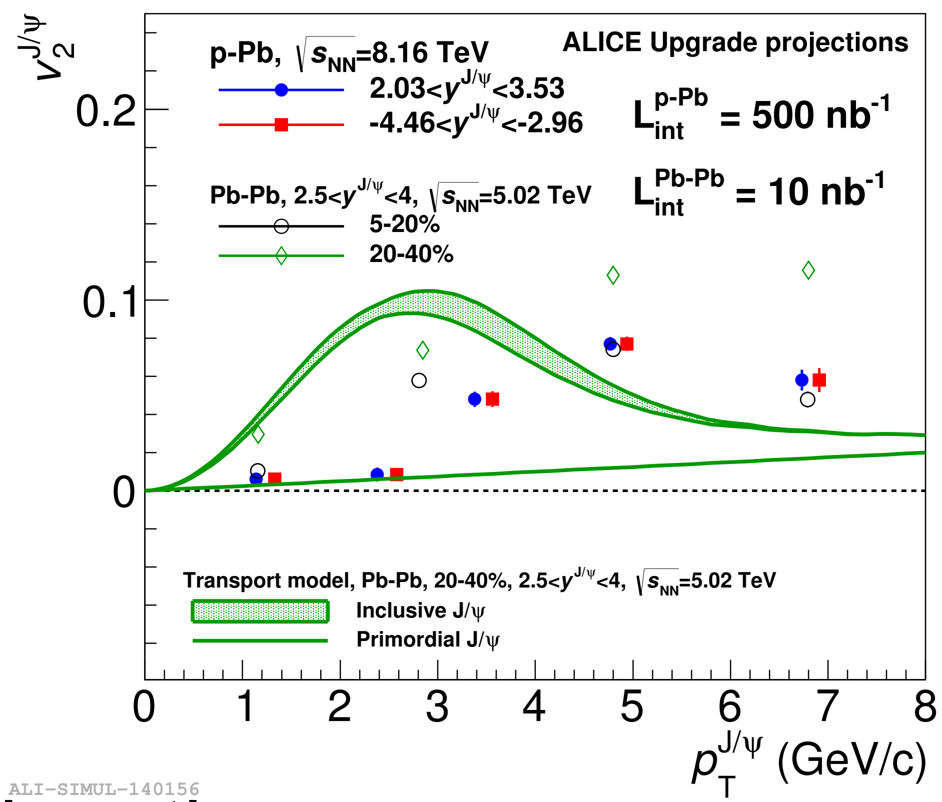




- Parallel development of theory is critical
  - Rigorous treatment of recombination is difficult (if any)

Quarkonia – small systems

- Goals
  - Cold nuclear matter effects
  - Final state interactions
  - Collective-like effects in small systems
- Observables
  - Same as before but in pp, high multiplicity pp, p-Pb, high multiplicity p-Pb collisions
  - Possibly smaller collision systems



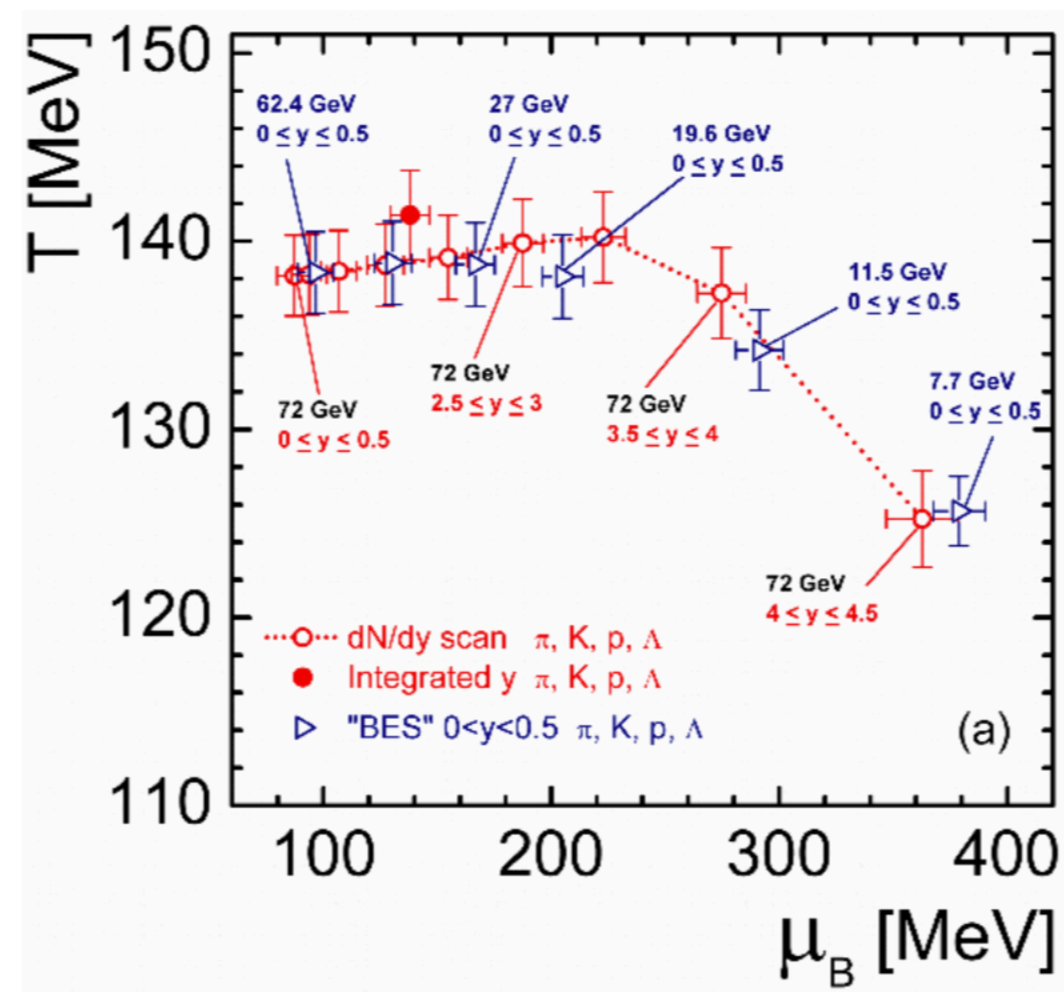
- Also dealt with in the other groups

FIXED TARGET AT THE LHC

Search for critical point

- Rapidity scan to map the phase diagram
  - Complementary to Beam Energy Scan at RHIC

Rapidity scan



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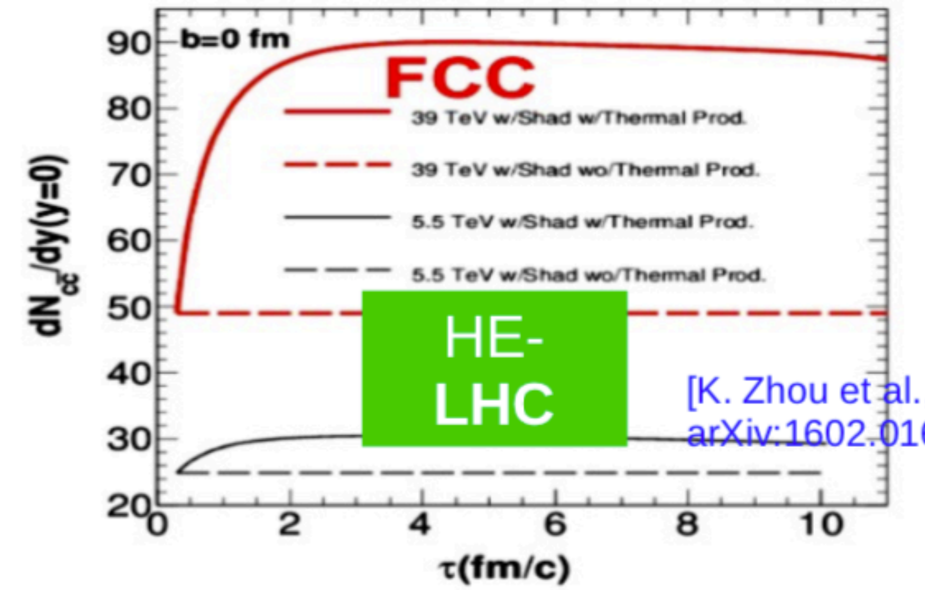
HIGHER ENERGIES

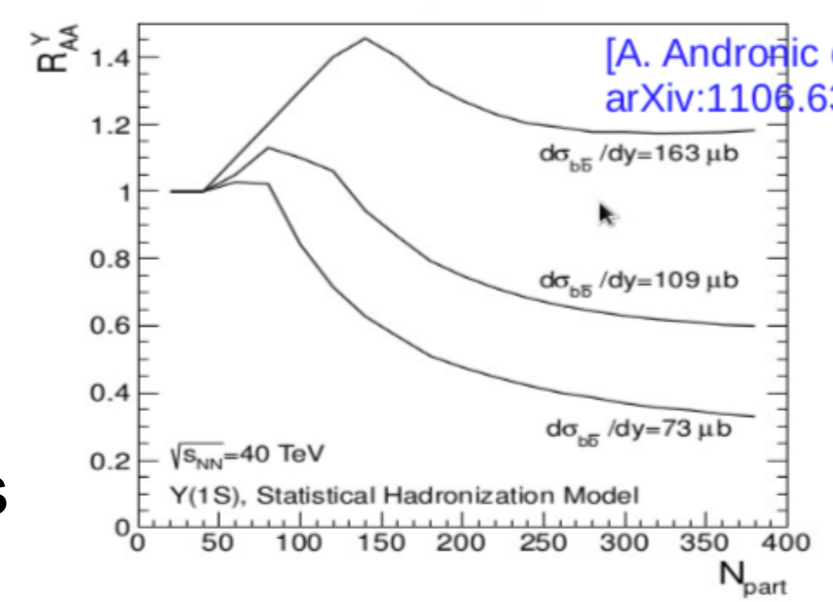
HE-LHC and FCC

- HE-LHC:
  - Energy: 2 x LHC
  - Luminosity: ~ HL-LHC
  - Same tunnel
  - Could start around 2040 (if HL-LHC stoped after Run 5)
- FCC(-hh)
  - Energy: 7 x LHC
  - Luminosity: 30 x LHC
  - New tunnel
  - Could start around 2043



[K. Zhou et al., arXiv:1602.01667]

- HF opportunities
  - At least 1.6 times more charm than at LHC
    - Thermal charm participates in QGP EoS?
  - At least 6 times more bottom than at LHC
    - Y(1S) recombination?
  - More detailed HF energy-loss measurements



[A. Andronic et al., arXiv:1106.6321]

SMALL SYSTEMS

Studying the unexpected

- The unexpected observation of collective-like effects in high multiplicity pp and p-Pb is among the most relevant results of Run 1 and Run 2 of the LHC
- Is there a common paradigm to describe the underlying physics in all colliding systems?
  - If yes: QGP production in small system? Smooth transition from pp to AA?
  - If no: What are the different mechanisms that come into plays?
  - What about an intermediate scenario?

- Search for QGP-like signatures in small systems with systematic mapping between pp and Pb-Pb collisions at similar multiplicity
  - High-multiplicity pp, pA and lighter AA
  - Lighter ions have the added benefit of increased luminosity

- All of our arsenal should be used to study such intermediate systems, in particular
  - Open HF
    - Cross-sections, R_{AA}, azimuthal anisotropy, Jet correlations, …
  - Quarkonia
    - R_{AA}, azimuthal anisotropy, excited states, Jet correlations, …

- An extended lighter-ion program during Run 3 and Run 4 is not feasible
  - Opportunity for Run 5 and Run 6