Prospectives QGP-France
Quarkonia, OHF, and dileptons

Acknowledgment & Disclaimer

- The following slides are based on the work of many colleagues, in particular, but not only, in view of the fore-coming yellow report at cern

- Very rich discussions were held among an actually quite large group of interested fellows, my gratitude goes to them
  - Emilien Chapon, Pol-Bernard Gossiaux, Matthew Nguyen, Michael Winn, Nicole Bastid, Philippe Crochet, Cvetan Cheskov, Frederic Fleuret, Hubert Hansen, Raphael Granier de Cassagnac, François Arleo, Antonio Uras, Ginés Martinez, Cynthia Hadjidakis

- Any omission? Blame it on JC!

Outline

- Motivations
- LHC Run 3 and Run 4
- Opportunities at the SPS
- Opportunities at the LHC after Run 4
- Opportunities at higher energies
- Summary

Motivation

- Heavy Flavors (HF), open and closed, as well as low- and intermediate-mass dileptons will allow to understand
  - chiral transition
  - deconfinement
  - properties of the QGP
  - hadronization

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 $M \approx 1.5$ GeV/c^2)

- At lower energies ($\sqrt{s} < 20$ GeV): properties of the deconfinement & chiral transitions
  - Evolution of the fireball temperature (slope of the invariant mass spectrum for $M \approx 1.5$ GeV/c^2) as a function of the energy density: measurement of the caloric curve of the QCD phase transition (never performed)
  - Measurement of the a_1-ρ chiral mixing through the identification of the $\pi a_1 \rightarrow \mu\mu$ structure in the invariant mass spectrum (never performed)

- 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

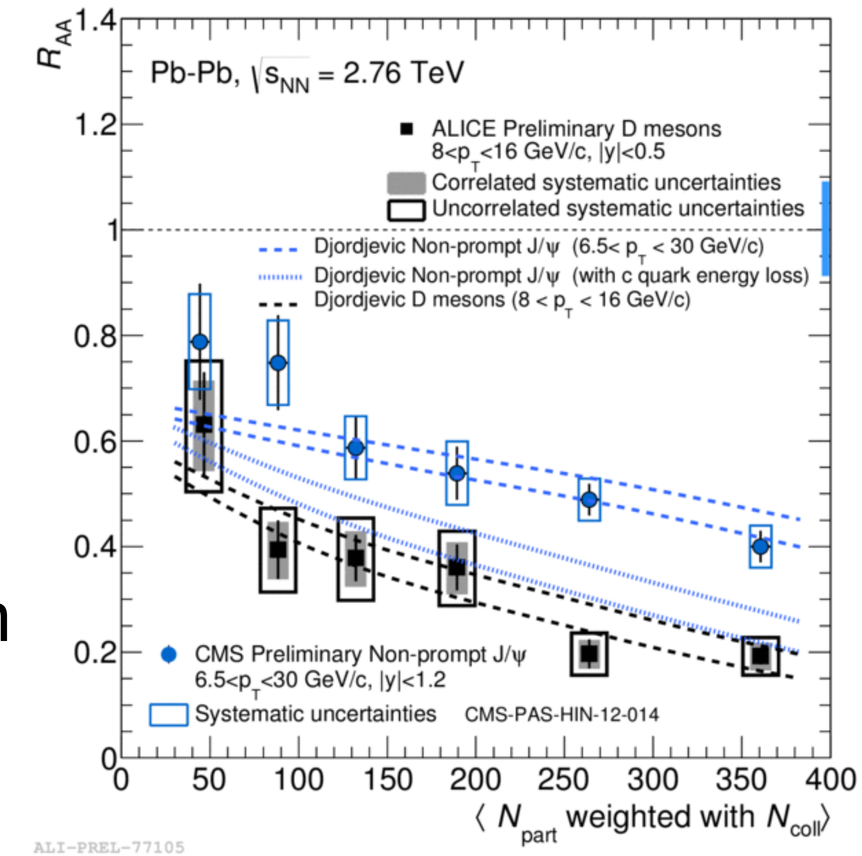
- In short, heavy quarks are produced early by hard collisions and traverse and probe the QGP, ok but …

- 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

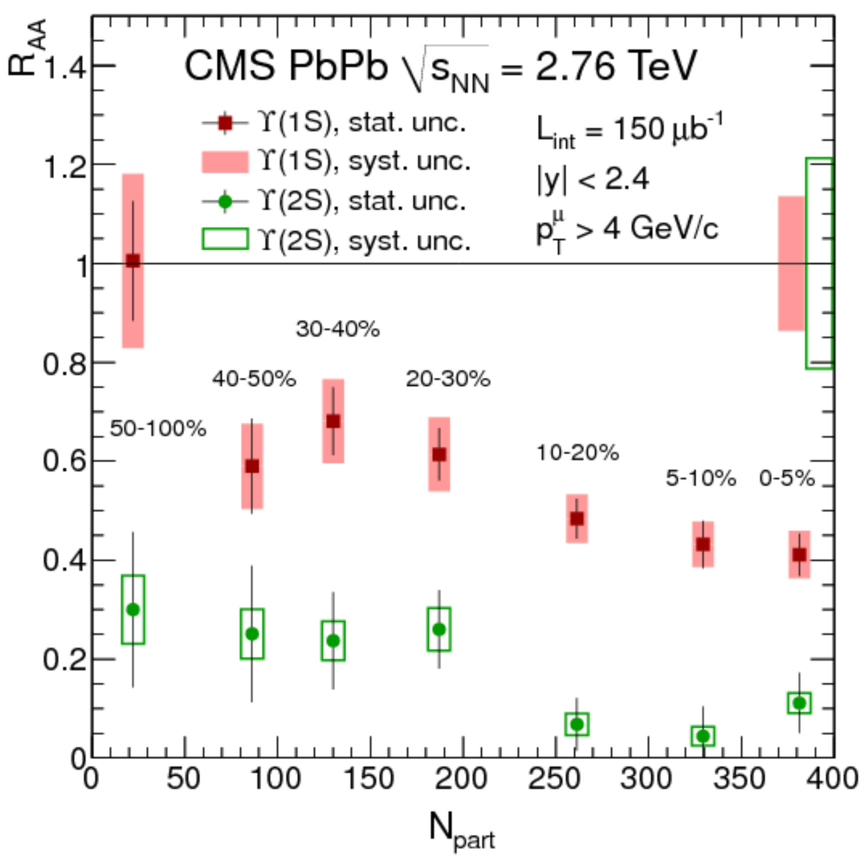
LHC Run 1 and Run 2

Run 1 & Run 2 in three figures

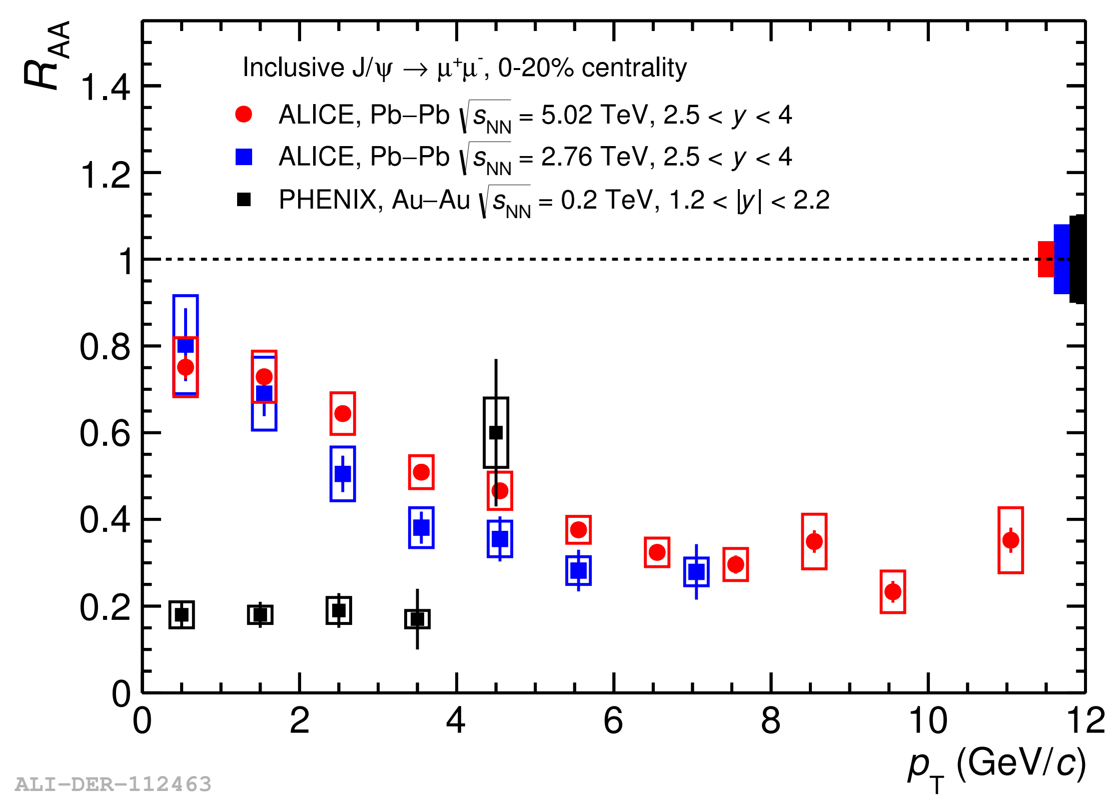
- R_{AA} of D mesons and non-prompt J/ψ
  - Flavour dependence of parton energy loss



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



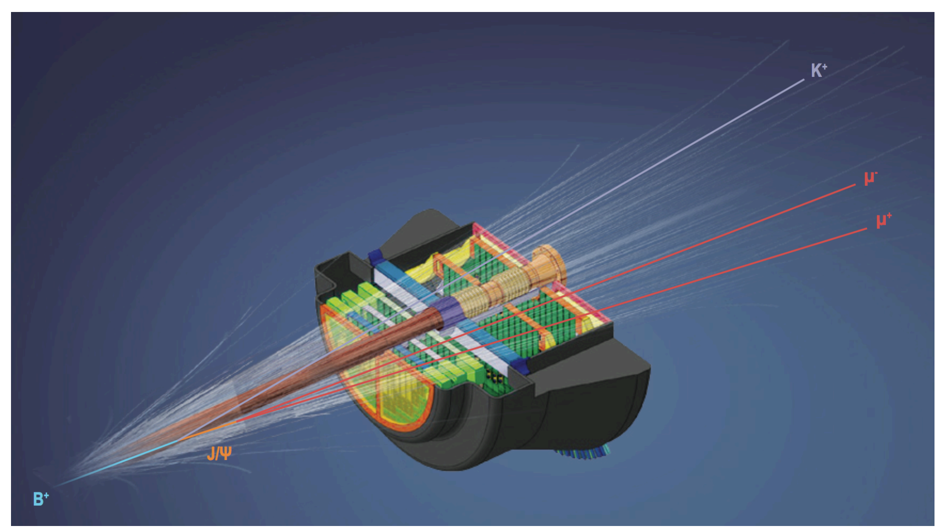
- J/ψ R_{AA}
  - Recombination of charm quarks



LHC Run 3 and Run 4

Detector Upgrades

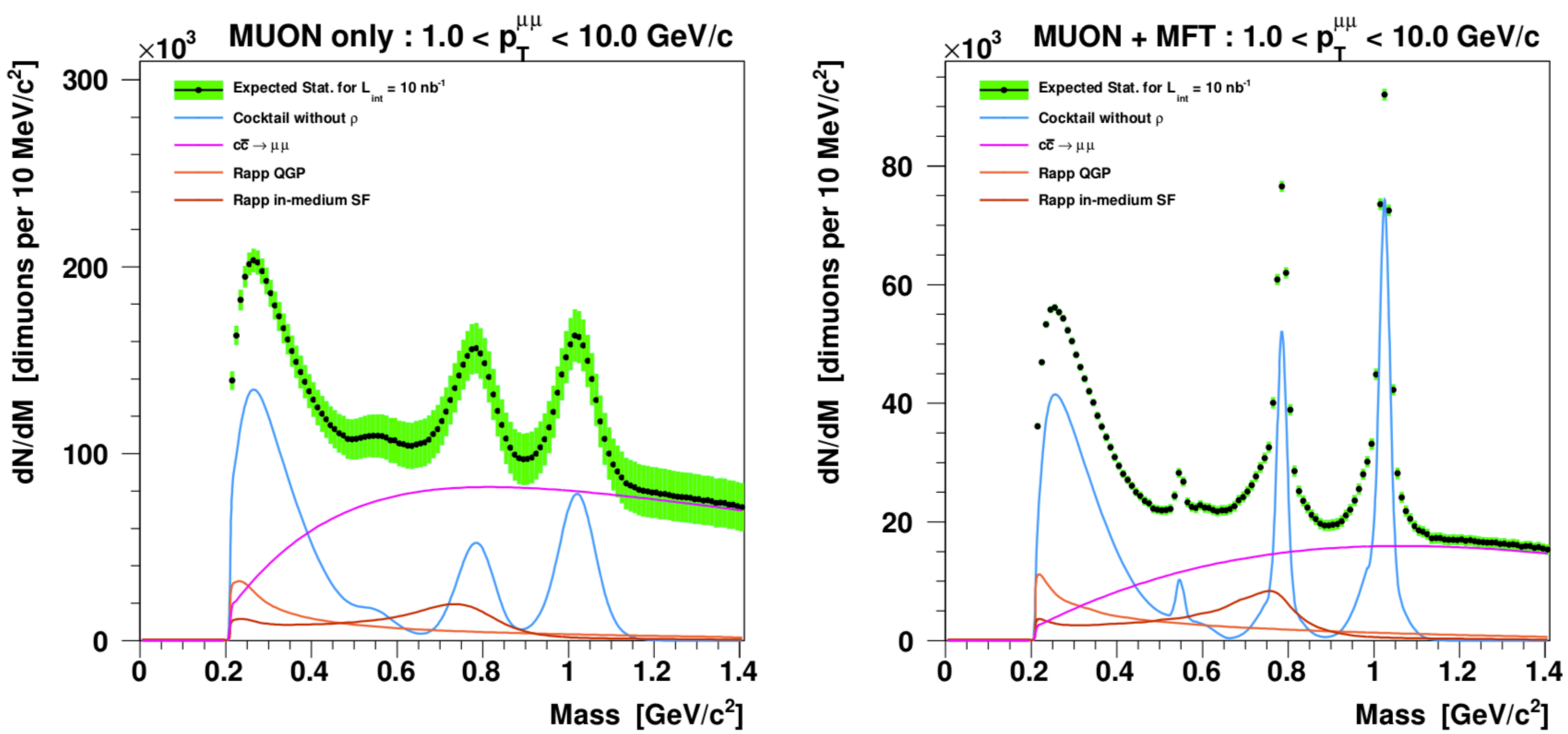
- For heavy ions, the HL-LHC starts in Run 3 with the capacity of the machine to deliver an integrated luminosity of 3/nb in one month of Pb-Pb
- With the aim of utilizing the full potential of the LHC, an ambitious upgrade plan was proposed, discussed and approved to be implemented during LS2, in particular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



- Other detector upgrades in CMS and LHCb primarily driven by pp physics will also benefit the heavy-ion programs.
  – Some are only expected after LS3

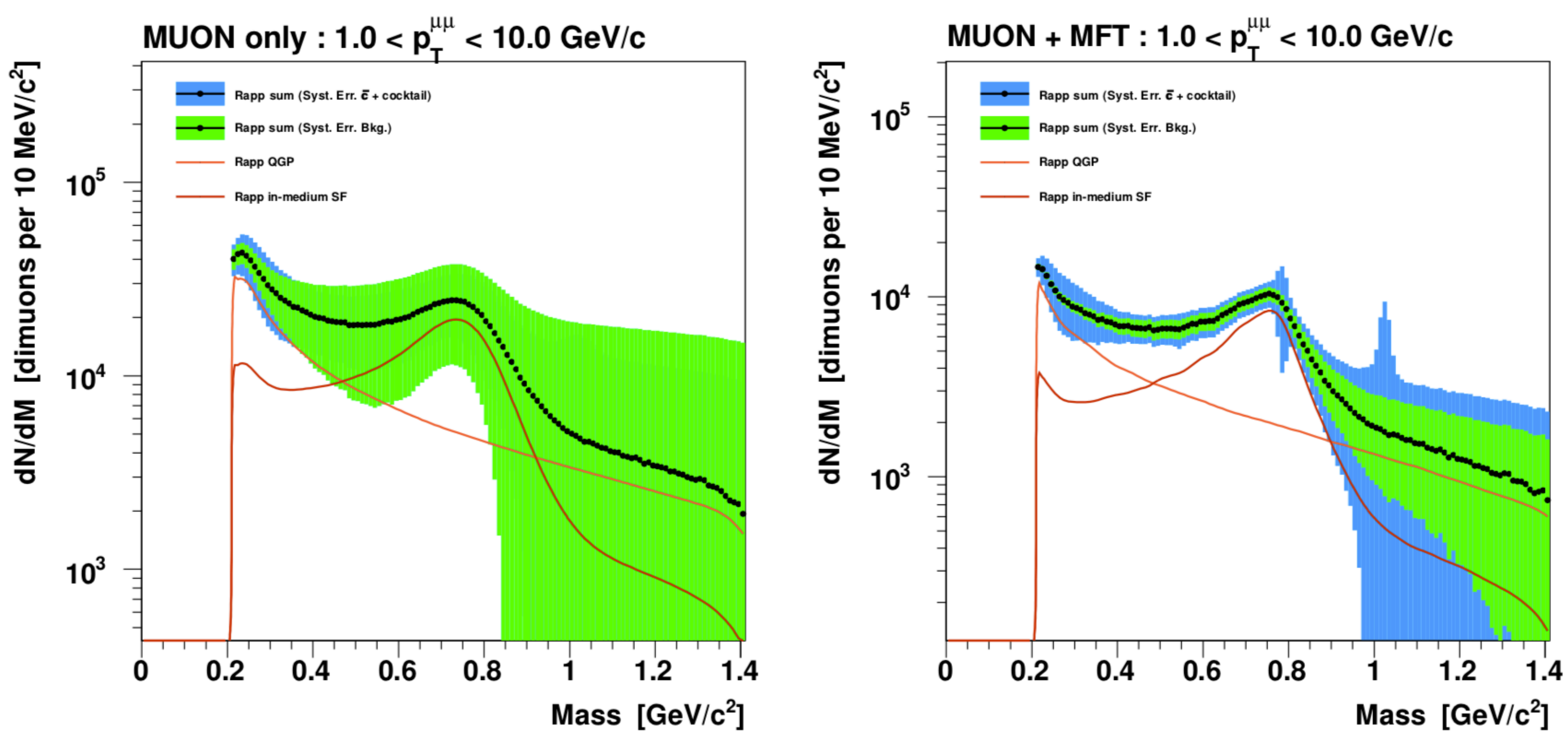
Low and Intermediate-Mass dileptons

- Strong case for the upgrades of ALICE for Runs 3 and 4
- Discussed in length in the LoI and TDR of the upgraded detectors including performance plots
- In particular, the addition of the MFT will
  - bring significant improvement in the rejection of non-prompt dilepton sources



Low and Intermediate-Mass dileptons

- Strong case for the upgrades of ALICE for Runs 3 and 4
- Discussed in length in the LoI and TDR of the upgraded detectors including performance plots
- In particular, the addition of the MFT will
  - bring significant improvement in the rejection of non-prompt dilepton sources
  - give access to
    - QGP radiation of thermal dimuons
    - In-medium modification of spectral shape of low-mass resonances



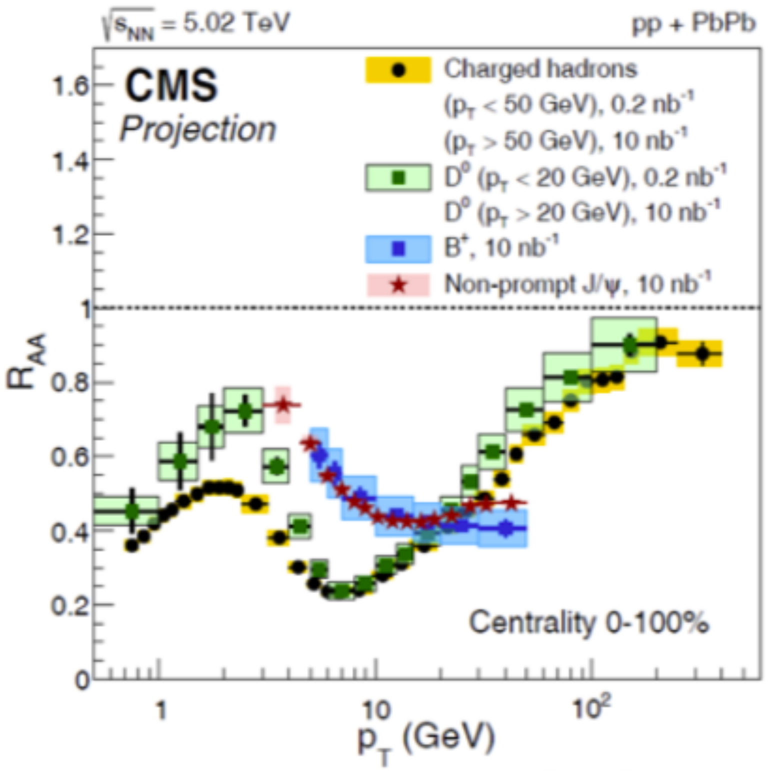
Low and Intermediate-Mass dileptons

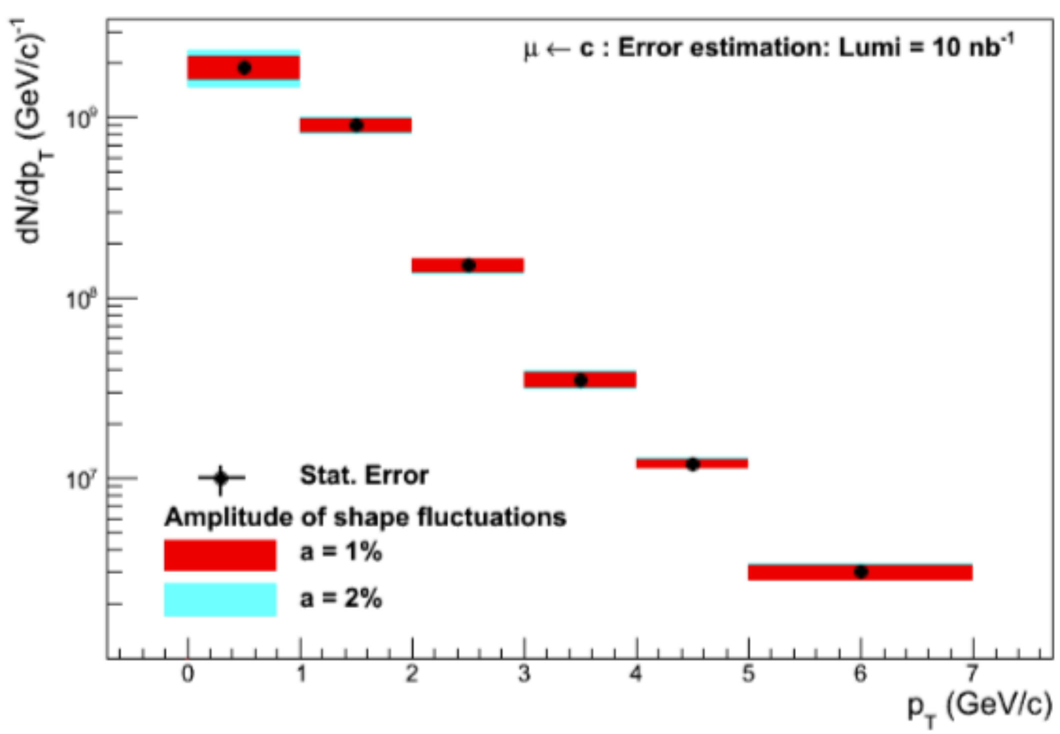
- CMS and ATLAS:
  - Still out of the game (no coverage at low-p_T where the bulk of the in-medium modification of the spectral functions and the thermal dilepton production will be concentrated)

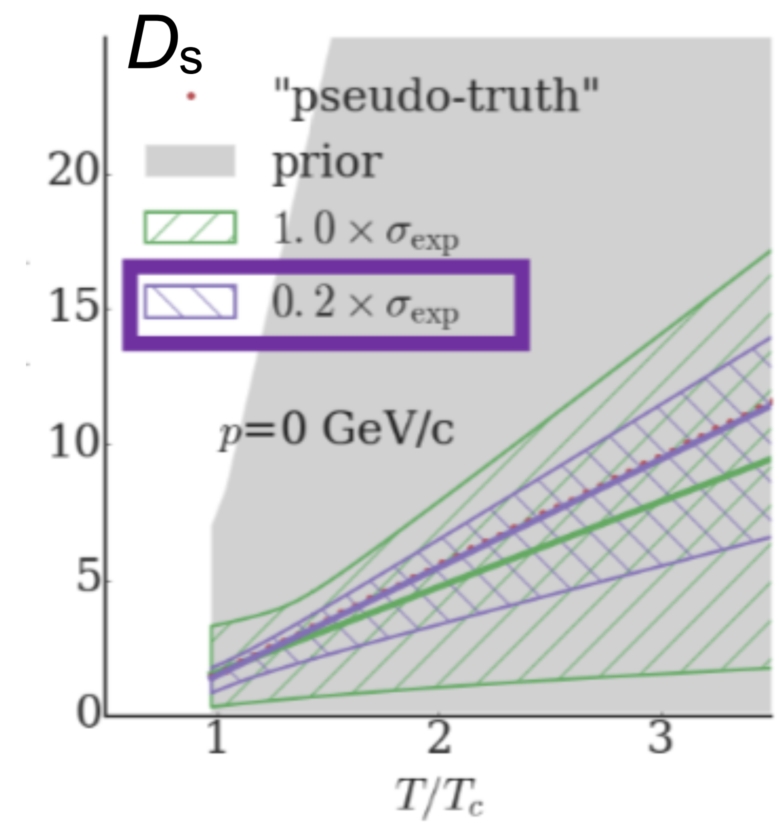
- LHCb:
  - In principle, similar acceptance and performance as the ALICE muon spectrometer can be expected, with even stronger rejection power for non-prompt sources, both for the measurement of the spectral functions and the QGP temperature
  - No performance available, at the moment

OHF – energy loss and collectivity

- Goal: address the transport properties of heavy quarks in the QGP
  - Transport coefficients, e.g. diffusion coefficient D_s
  - Transport parameter, q-hat
  - Collisional vs radiative energy loss
- Observables
  - R_{AA} and v_2 of D and B mesons
  - Separation of single muons from c and b decays (MFT)
  - Event-shape engineering for D mesons



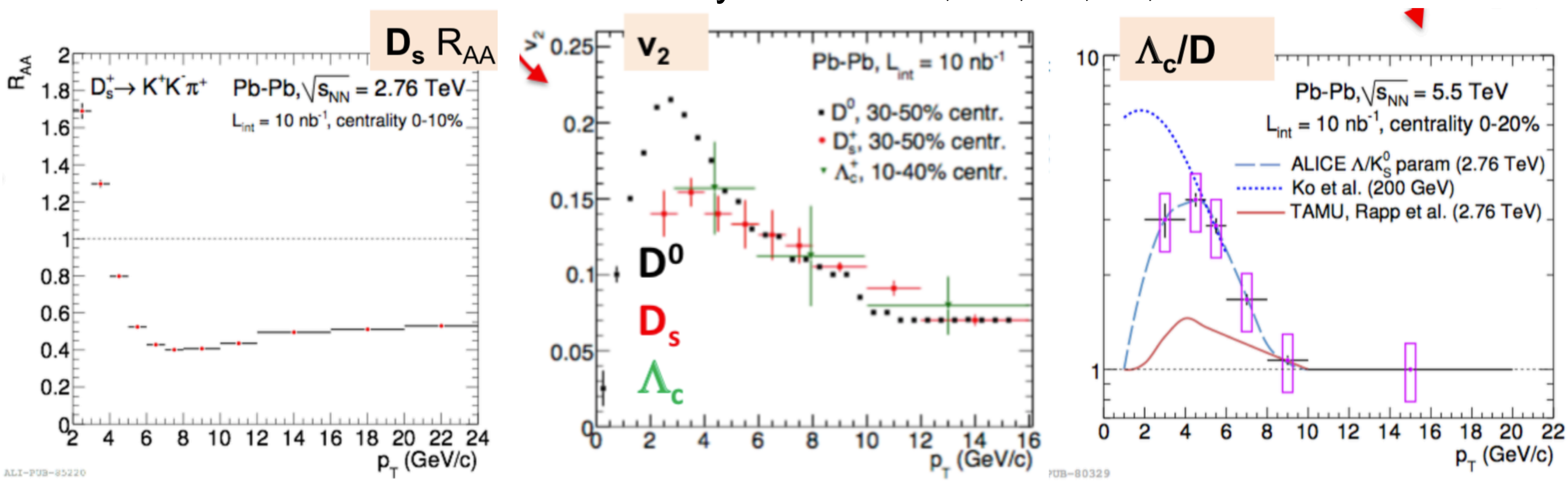




- Parallel development of theory is critical
  - Use of bayesian approach to extract model parameters from data should be extended

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, …

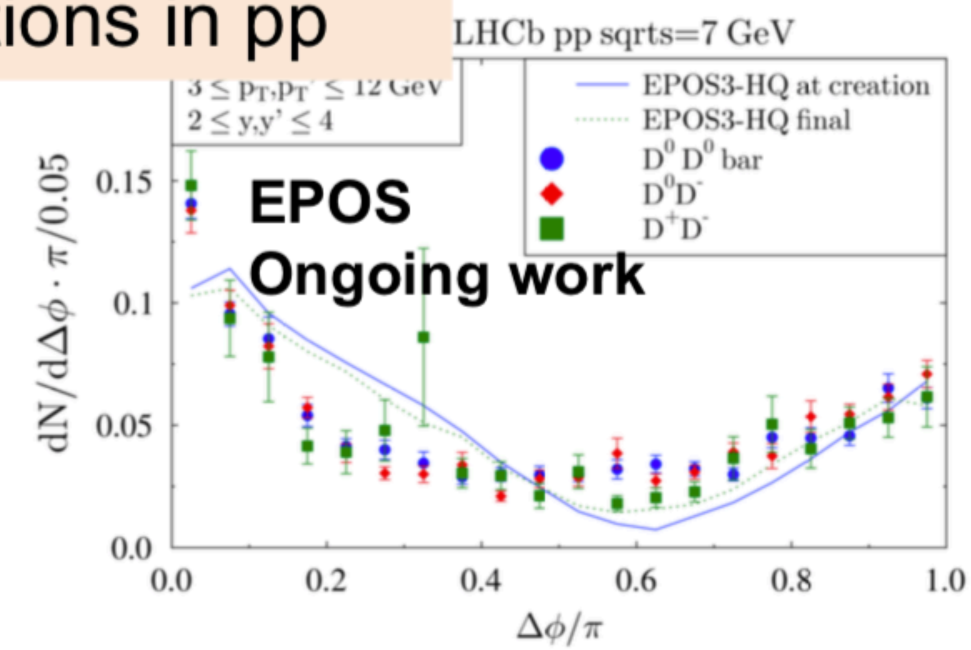


- Parallel development of theory is critical
  - Rigorous treatment of recombination is difficult (if any)

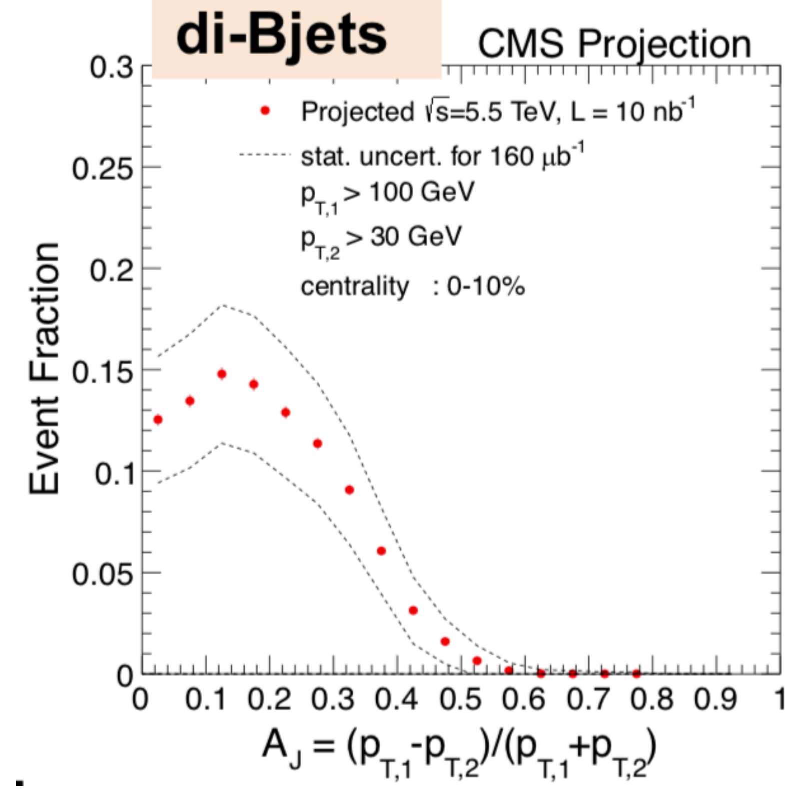
OHF – Correlations and jets

- 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: Δϕ,Δy D$\overline{\text{D}}$
correlations in pp



di-Bjets

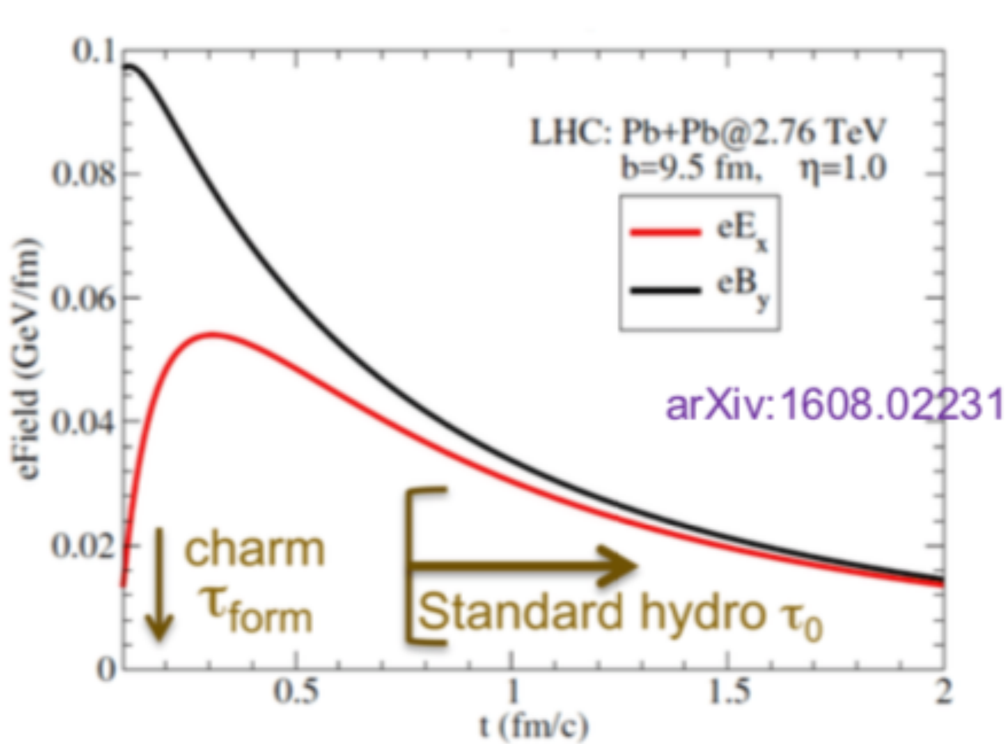


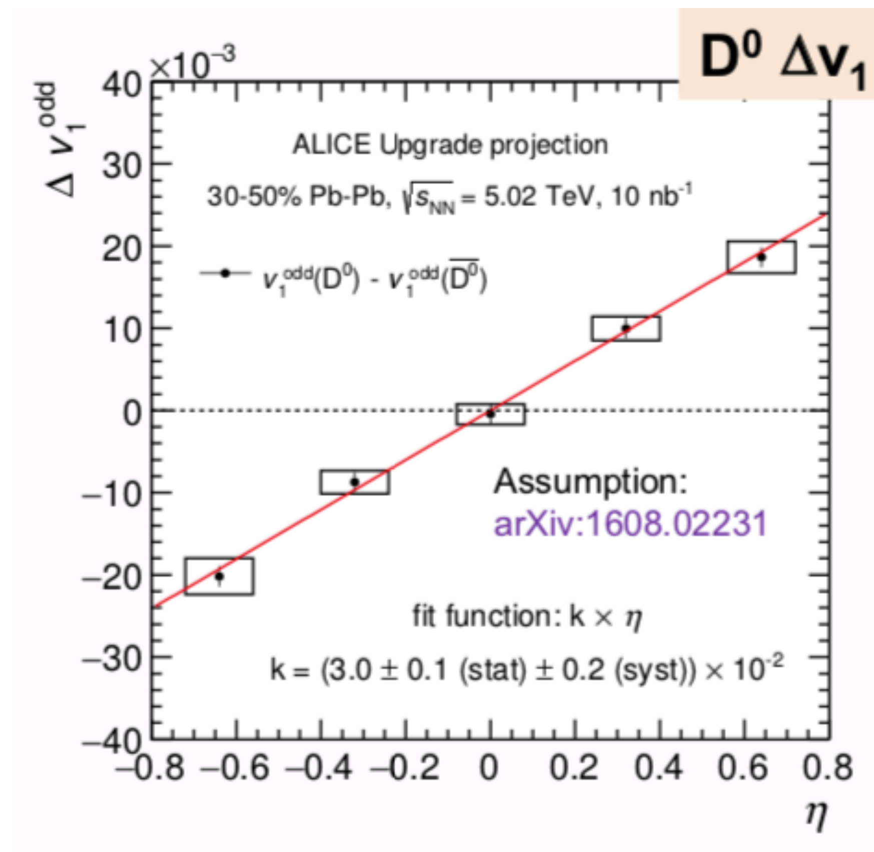
- Parallel development of theory is critical

OHF – magnetic effects on HQ

- Goal: address strong magnetic field created in peripheral heavy-ion collisions

- Observables
  - Direct flow v_1 of D mesons

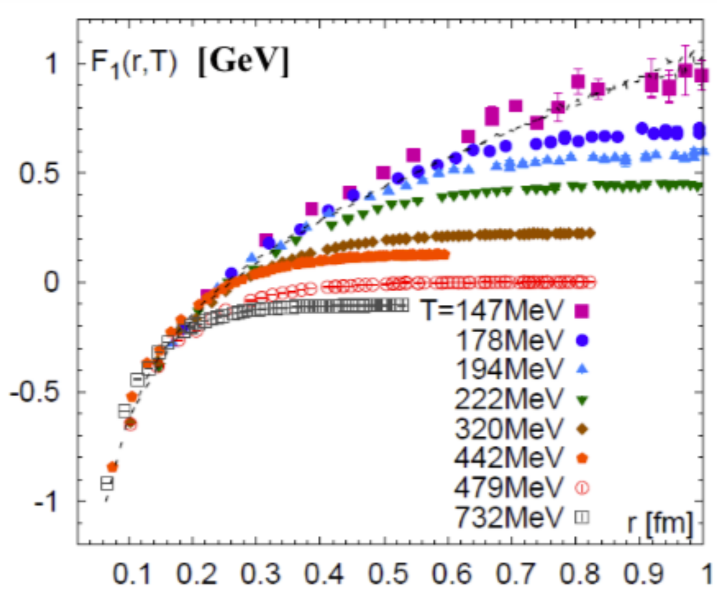


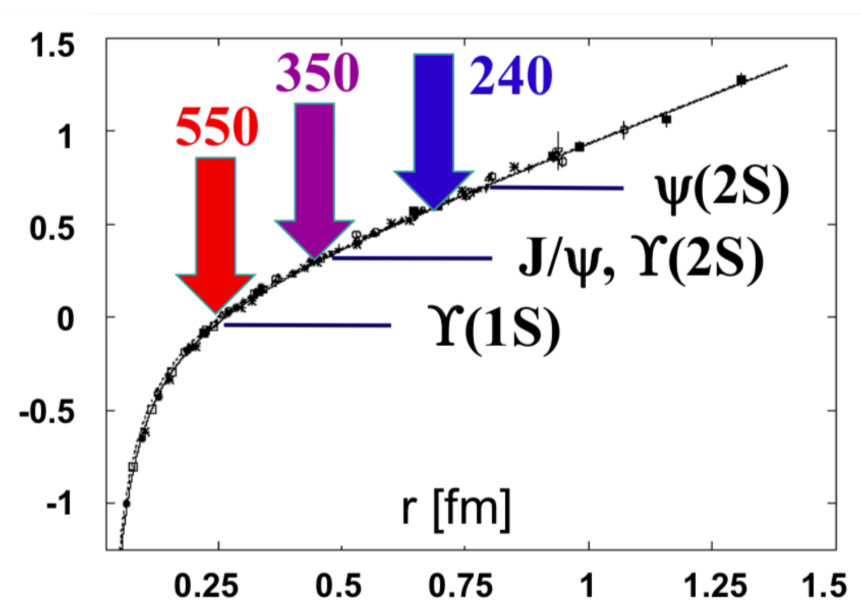


- HQ appears to be more sensitive to early magnetic field than light quarks

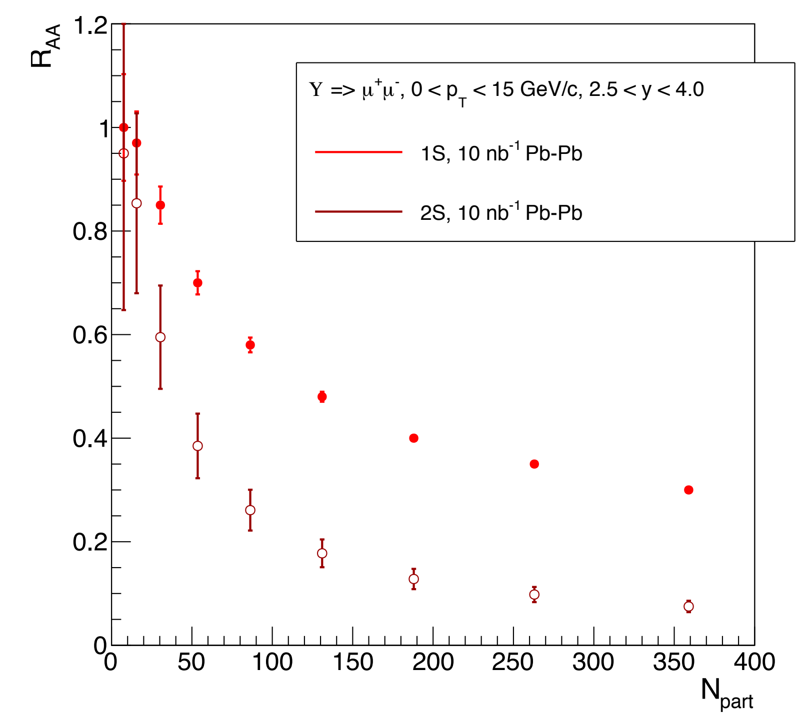
Quarkonia – deconfinement

- 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



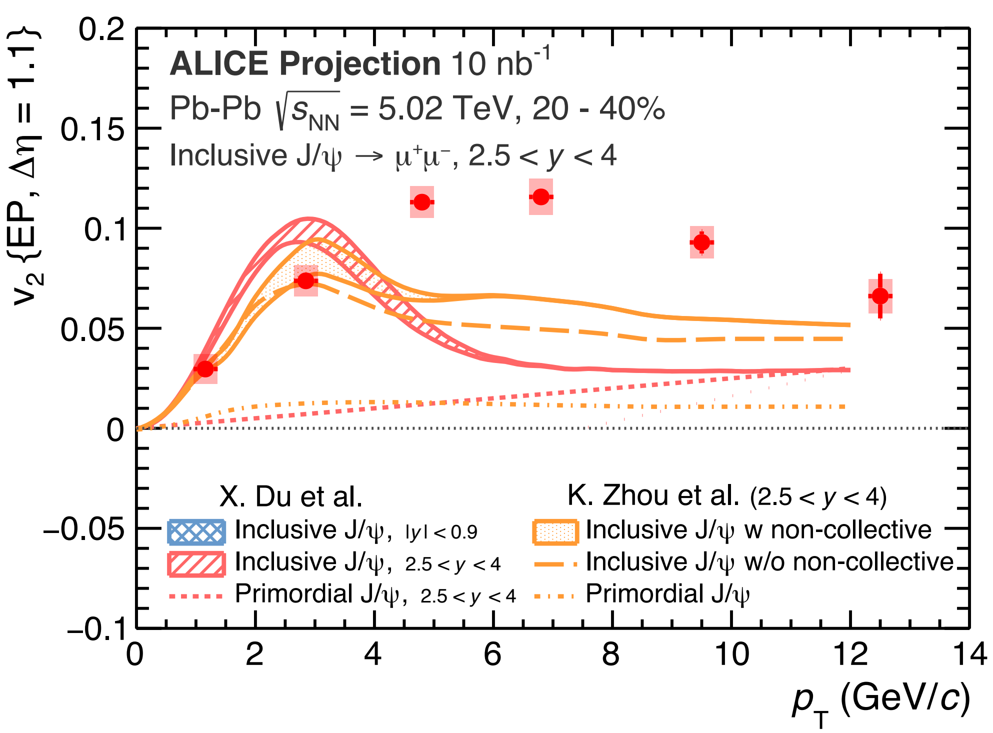


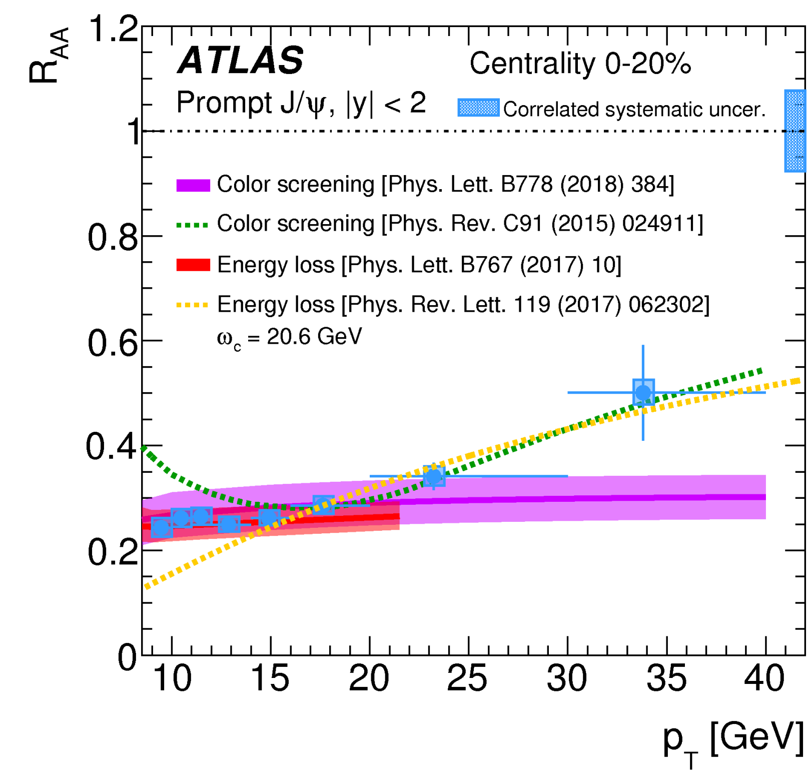
ALICE Projection



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

- 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



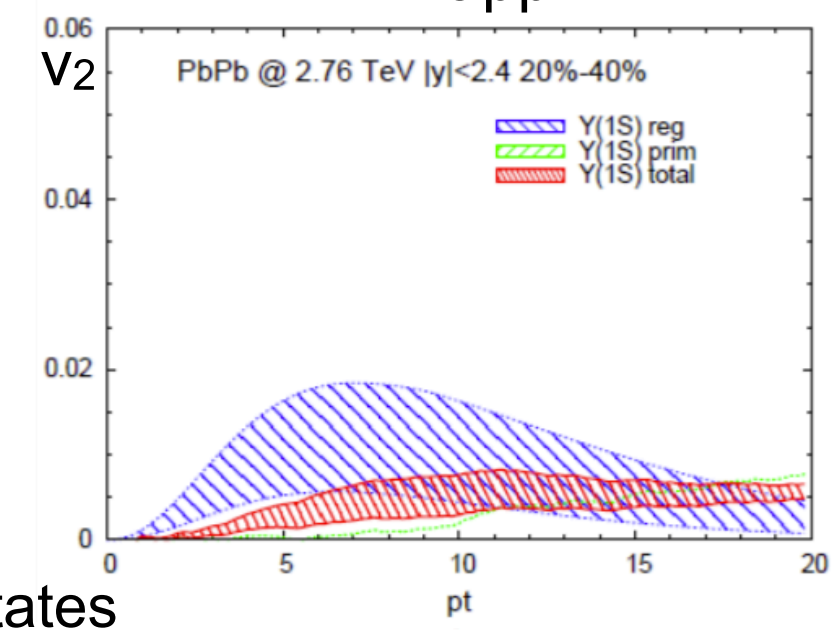


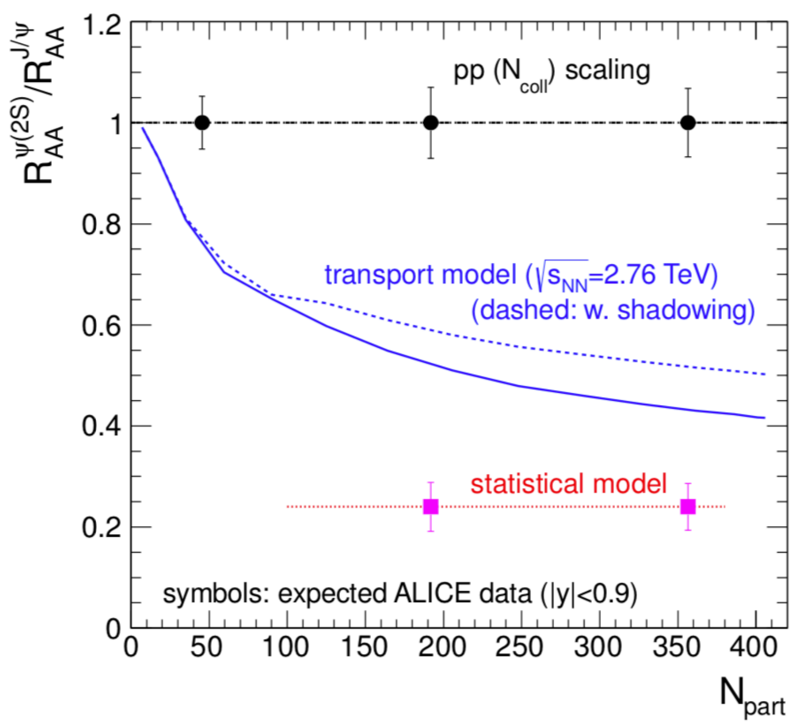
- Parallel development of theory is critical
  - Link between OHF and quarkonia theory is mandatory

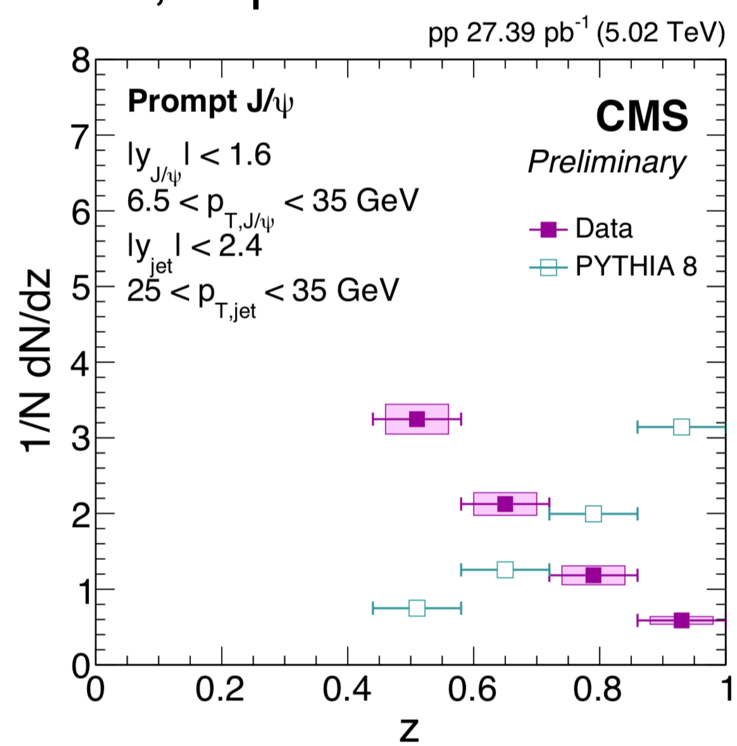
Quarkonia – hadronization mechanism

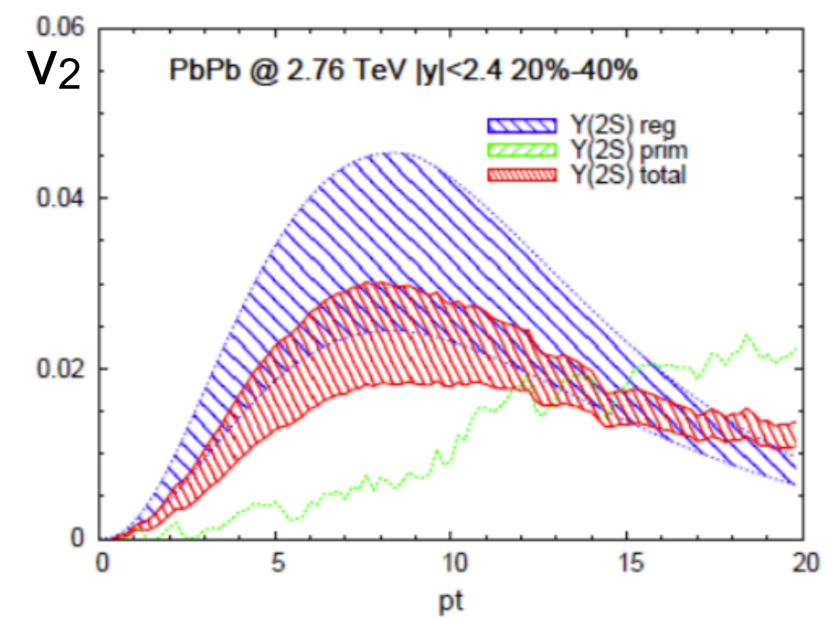
- Goal: understand quarkonium hadronization
  - Initial production
  - Heavy quark recombination / statistical hadronization
  - Fragmentation
  - Suppression and formation time
- Observables
  - R_{AA} and v_2 of charmonia
  - J/ψ in jets
  - p_T dependence of quarkonium states, in particular excited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

R. Rapp





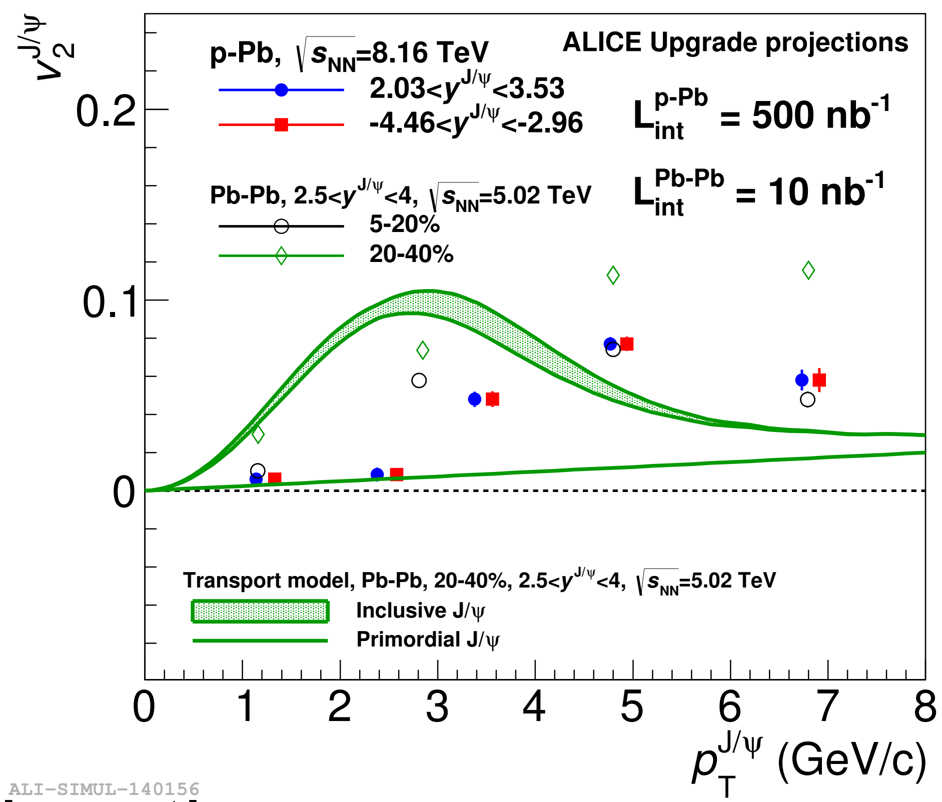




- Parallel development of theory is critical
  - Rigorous treatment of recombination is difficult (if any)

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

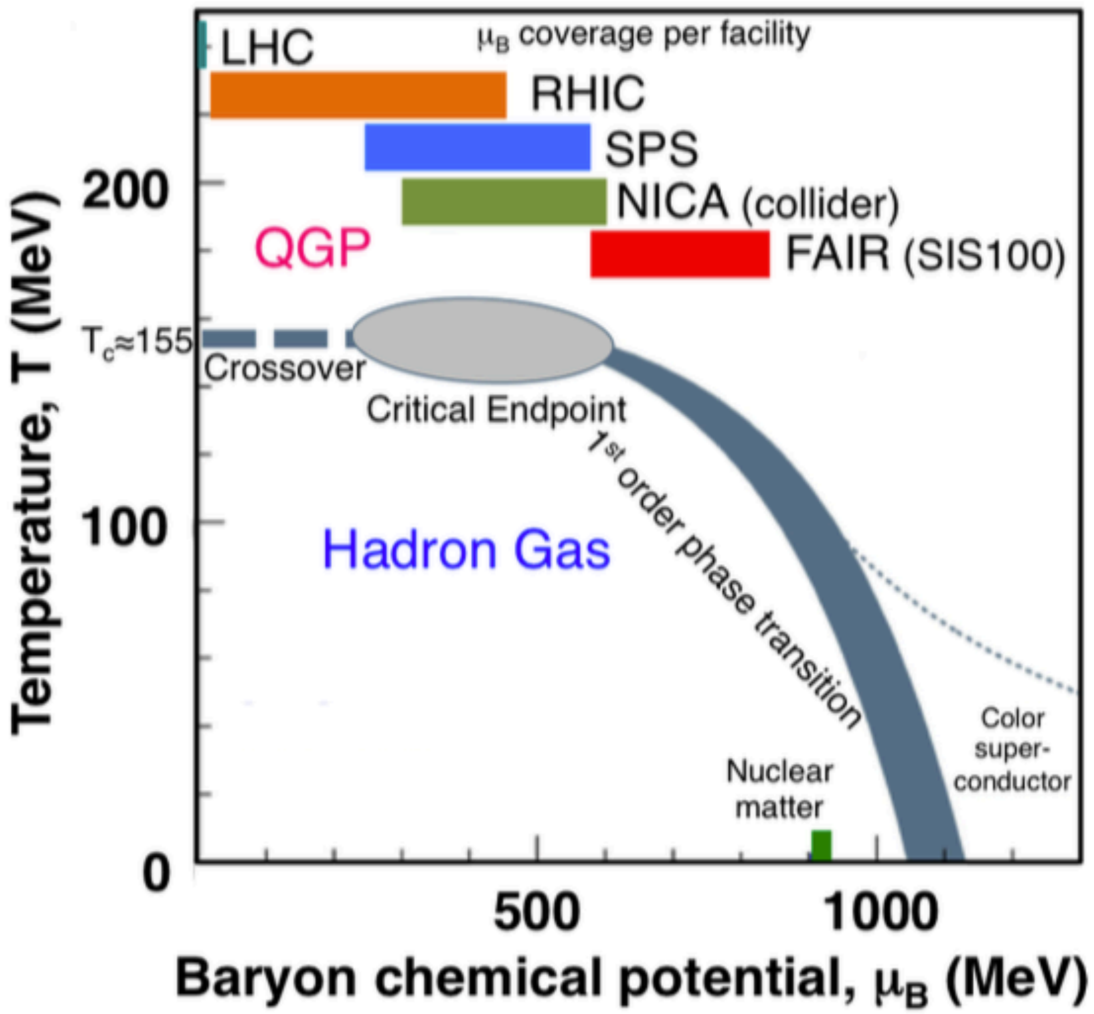
FIXED TARGET AT THE SPS

Search for critical point

- Results from NA60 at SPS and the BES at RHIC suggest the search for the critical point should concentrate below top SPS energy

- Complete hadron and dilepton program in CBM at FAIR
- Existing hadron program at the SPS

- Interests and motivations for a dilepton program at the SPS
  - Fixed target, high-intensity
  - Pb-Pb $\sqrt{s_{NN}}$ = 4.5–17.3 GeV



LHC RUN 5 AND BEYOND

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

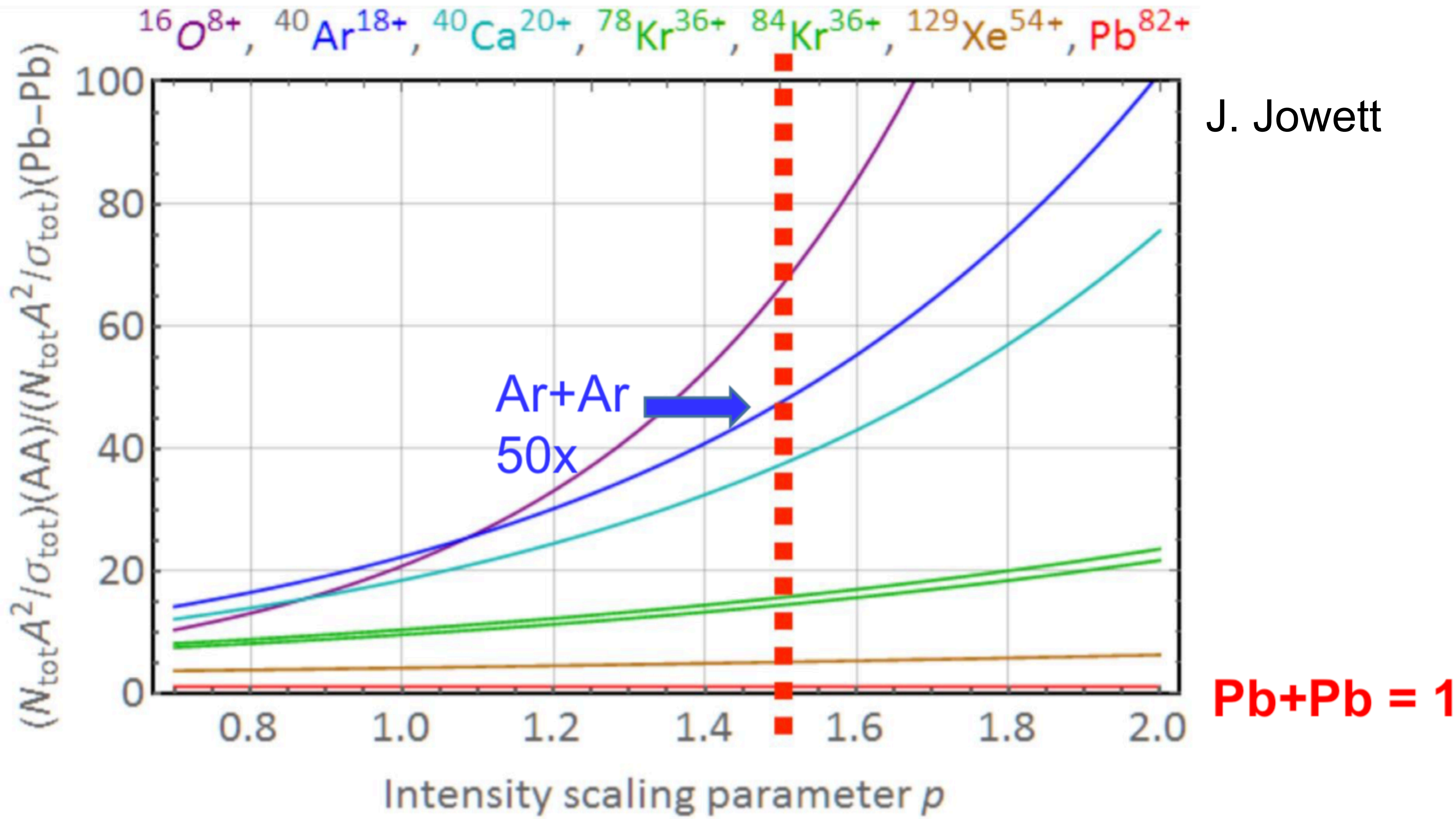
More Pb-Pb at 5 TeV

- 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 …

Lighter ions at the LHC

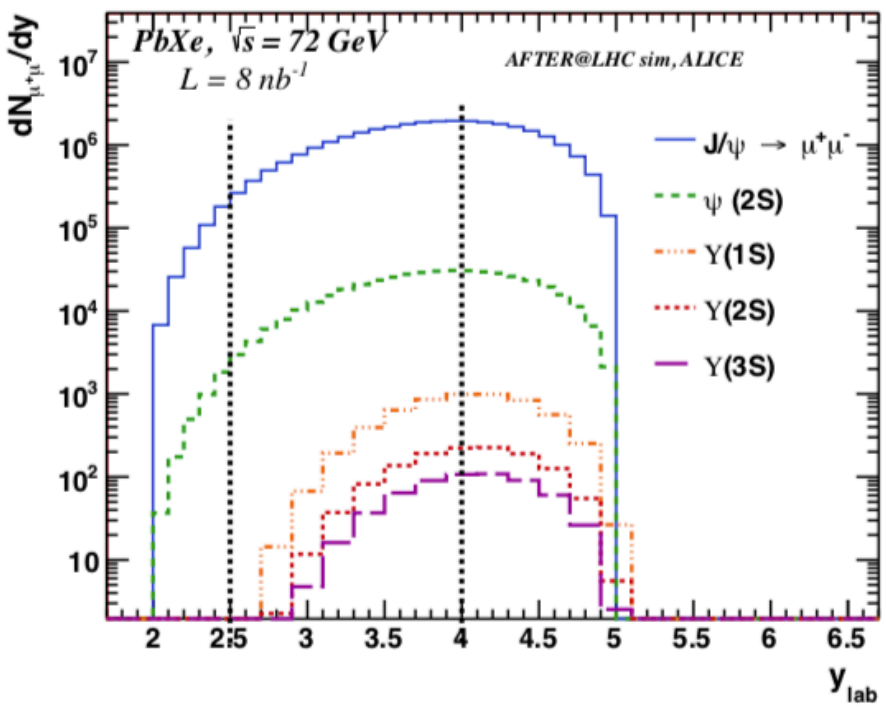
- Could have an intrinsic interest …
- … but does certainly have the practical interest of higher per-nucleon-pair luminosities



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
  - $\sqrt{s_{NN}}$ ~ 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)



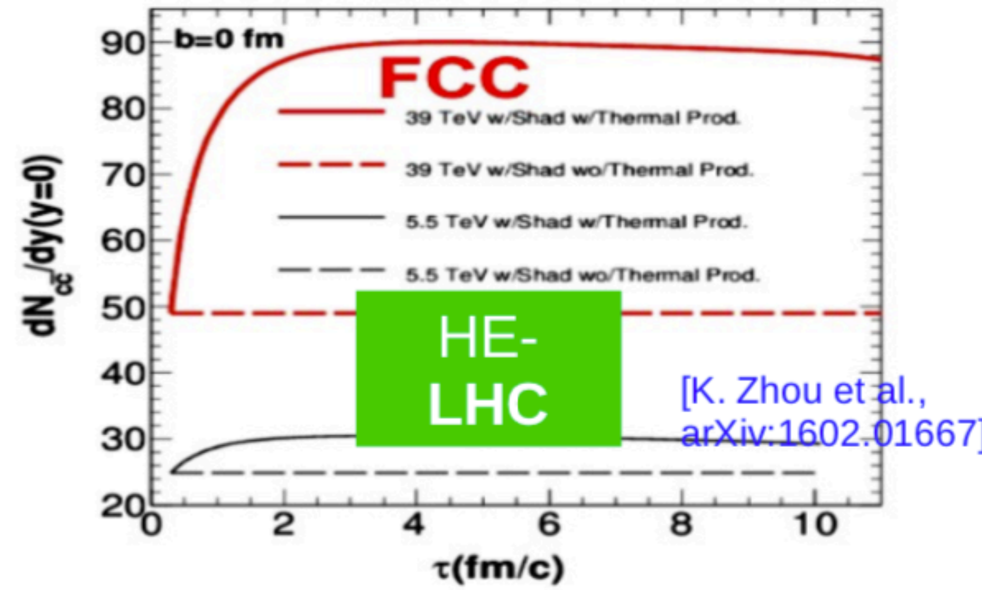
LHC at lower energies

- 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
  - $\sqrt{s_{NN}}$ ~ 500–1000 GeV
  - But luminosity decreases with decreasing energy

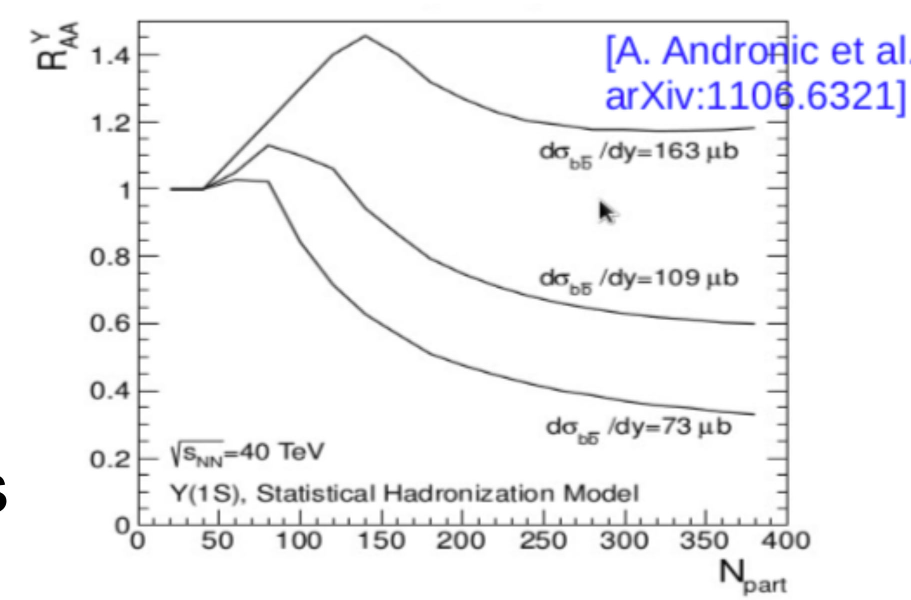
Higher energies

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



- 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



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

Summary

- Very reach physics program for LHC Run 3 + Run 4
  - Must be a success!

- Interest in a dilepton program in fixed target at the SPS
  - Search for the critical point
- Energy scan
  - RHIC-like energies in fixed-target mode at the LHC
    - Precision measurements of c and b deconfinment
  - In between RHIC and top LHC energies
    - Onset of c-cbar recombination
  - HE-LHC/FCC
    - Thermal charm?
    - b-bbar recombination?
- Small systems
  - What does it take to make a QGP?
  - HM pp, p-A but also lighter A-A