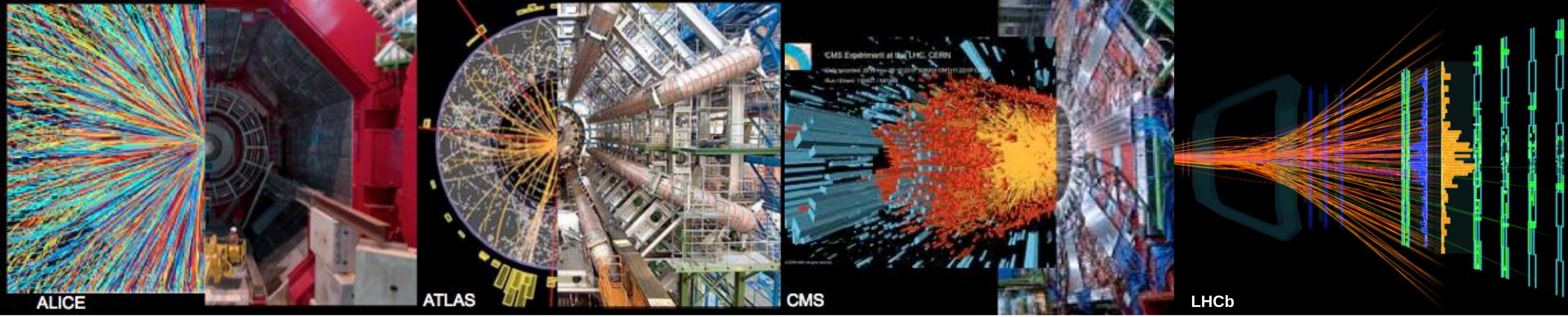


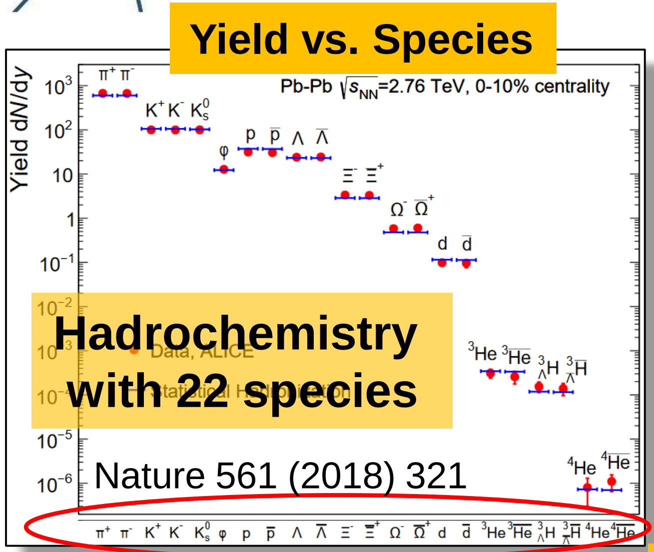
Future physics opportunities for high-density QCD with ions and protons

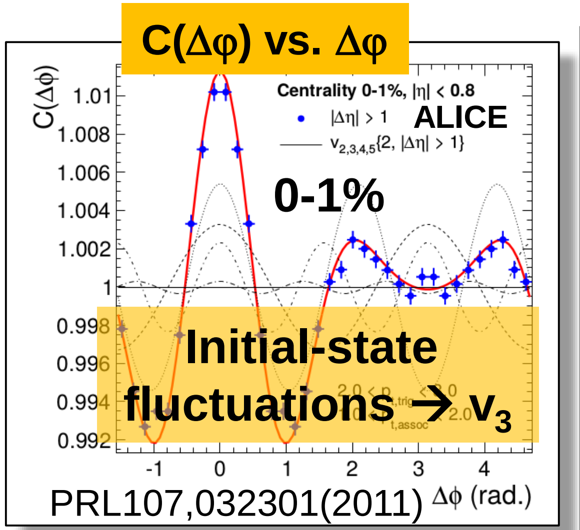
HL/HE-LHC WG Report

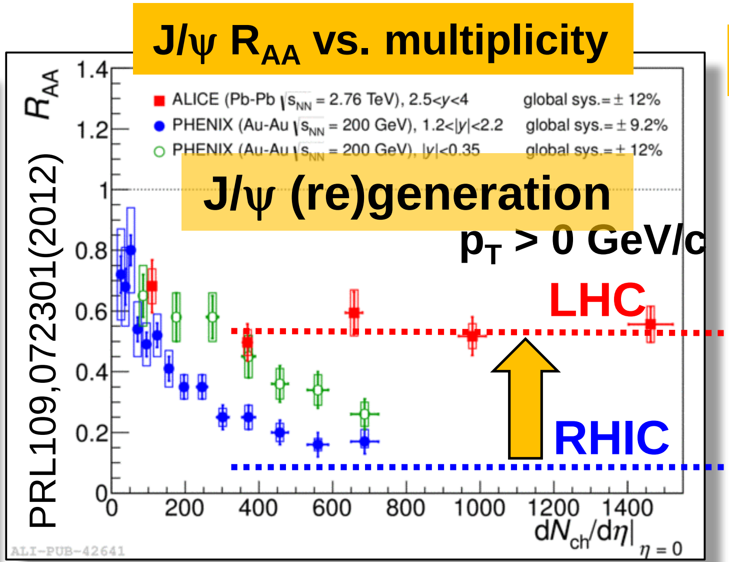
Jan Fiete Grosse-Oetringhaus, CERN
on behalf of WG5

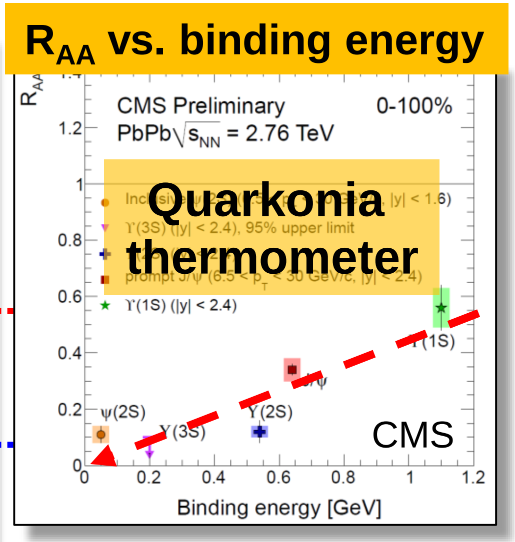
Town Meeting, CERN
24.10.18

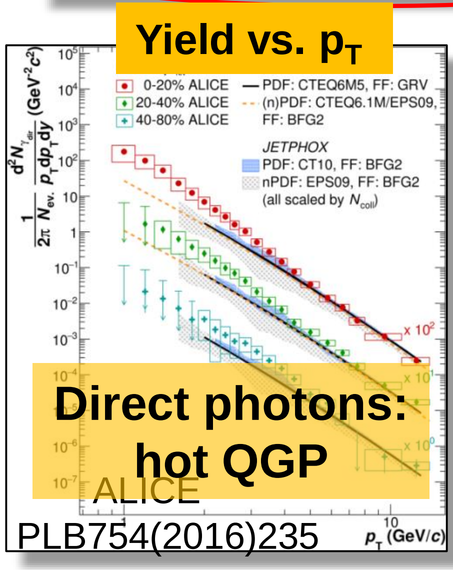
Eight Years of Exciting Heavy-Ion Physics @ LHC

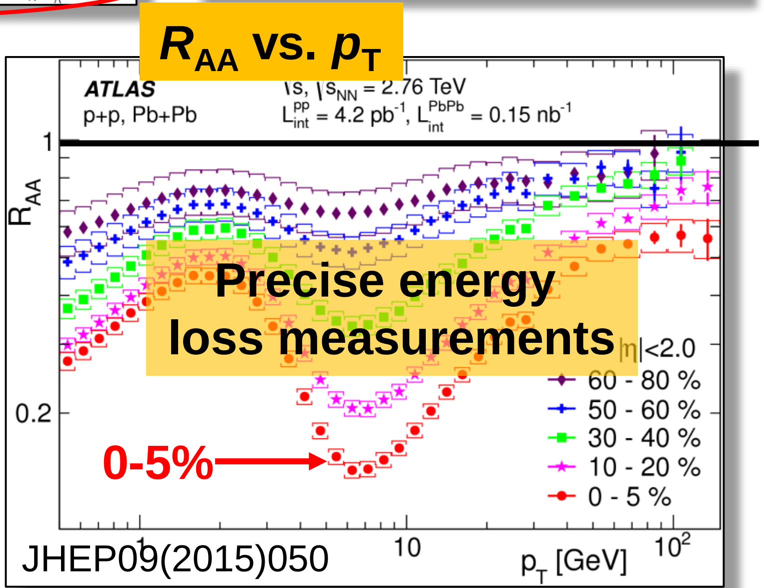


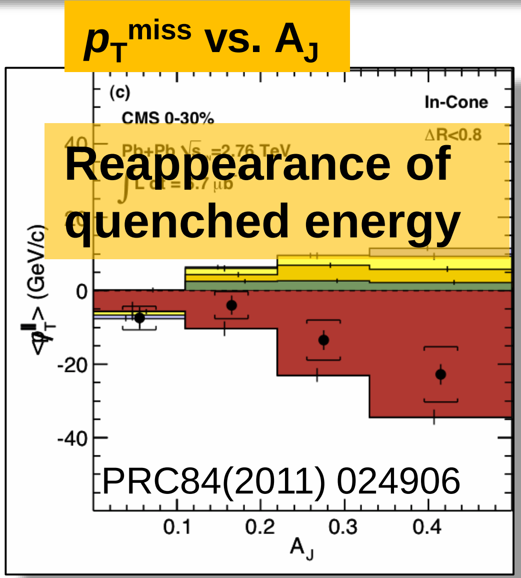


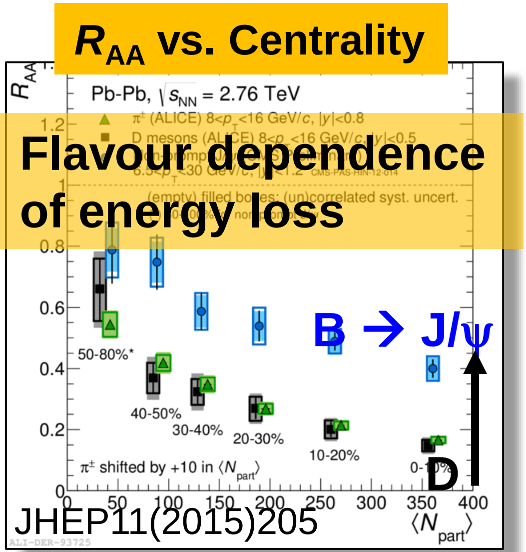




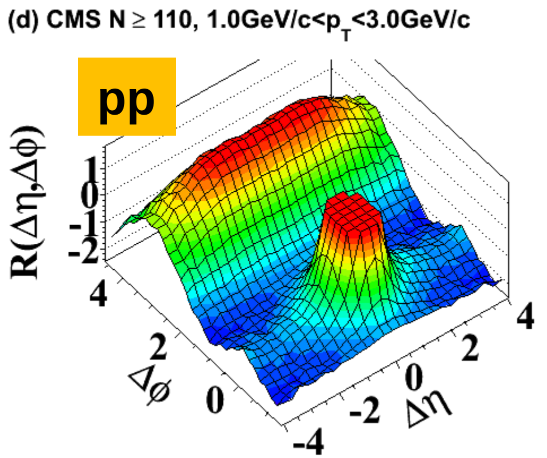




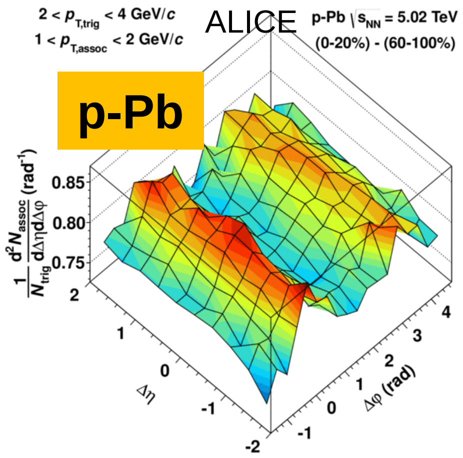




Small Systems



JHEP09(2010)091



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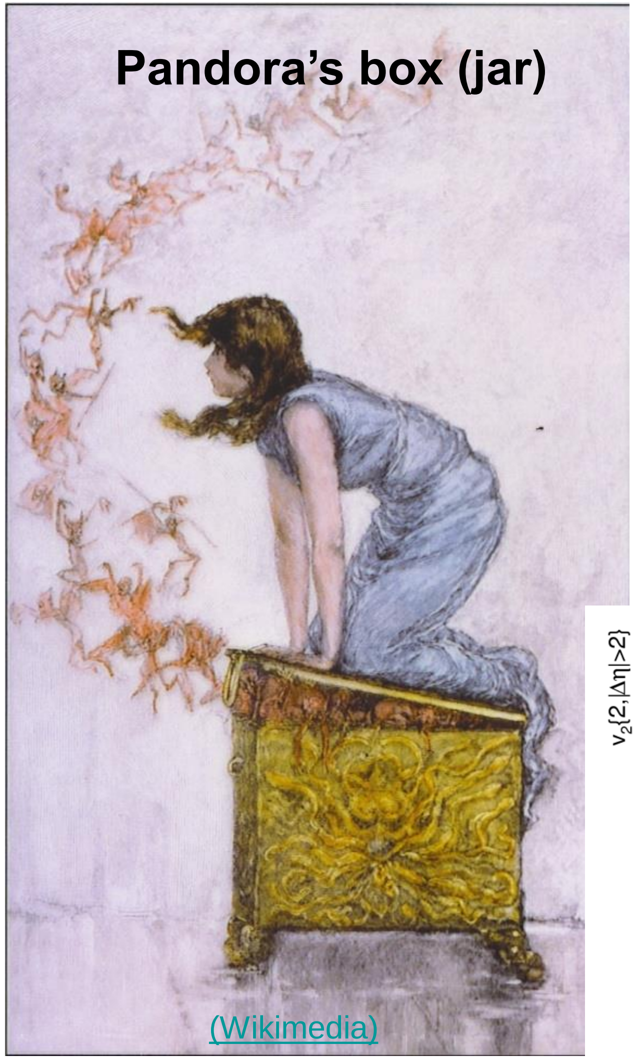

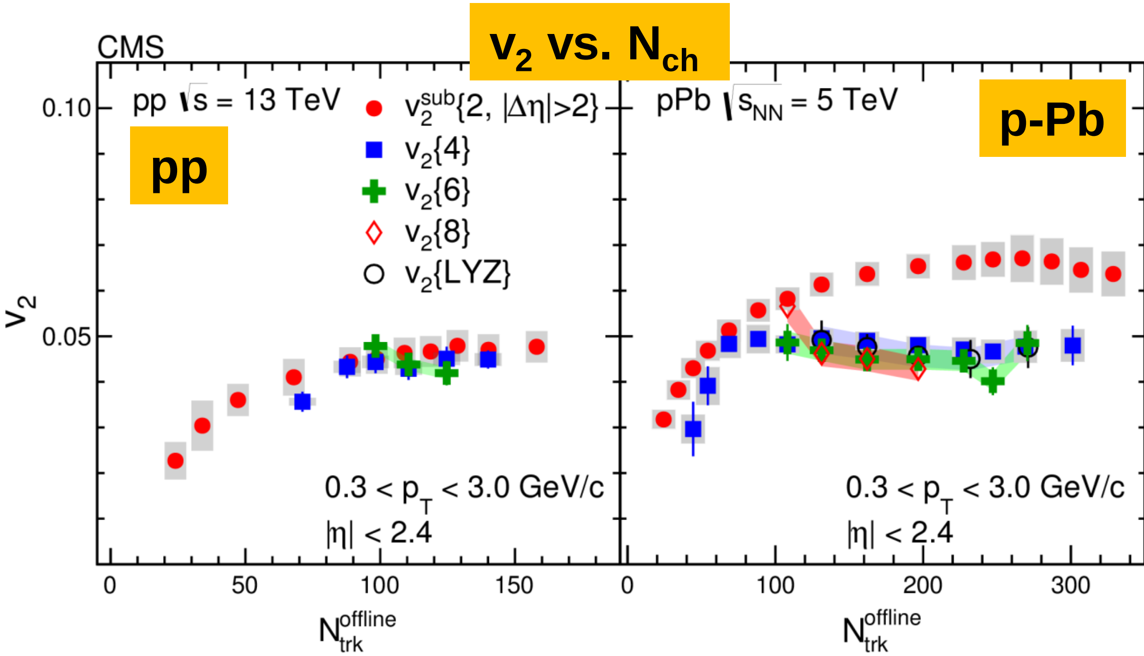

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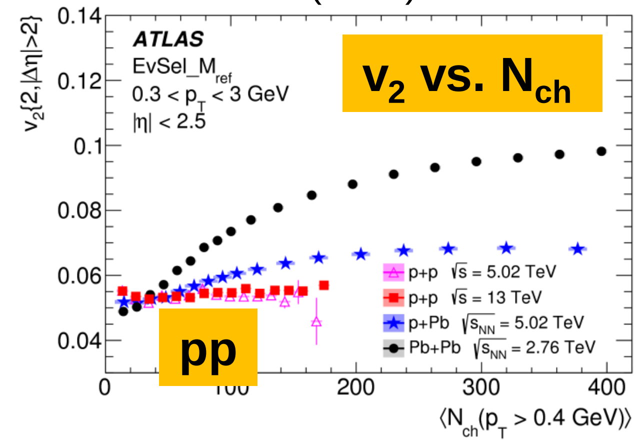
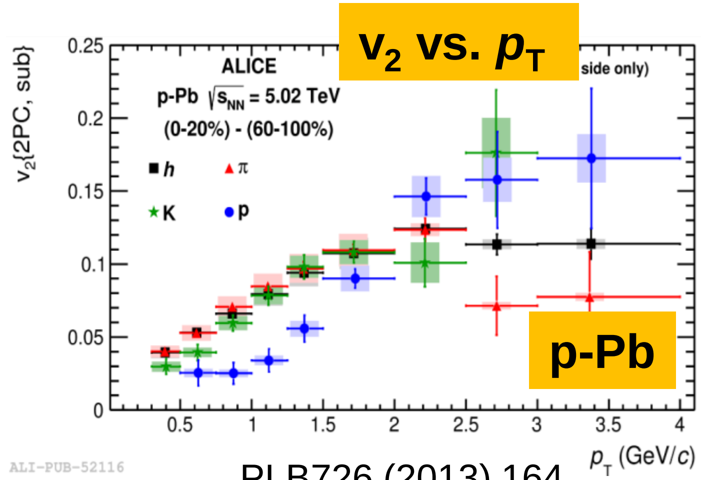
Collective phenomena in pp and p-Pb collisions have caused a paradigm shift

EPJC 77 (2017) 428





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HL/HE-LHC Physics Workshop

- CERN-wide process to document physics programme (→ twiki)
  - for High-Luminosity LHC (from 2021 for HI, from 2026 for pp)
  - for potential High-Energy LHC (doubling the energy, from 2040)
- Yellow report with 5 chapters
  - WG1: SM | WG2: Higgs | WG3: BSM | WG4: Flavour | WG5: Heavy Ions
  - Finalization by the end of this year
  - 10-page summaries (one for HL, one for HE) as input to European Strategy Group
- WG5 HI steered by Zvi Citron (ATLAS), Jan Fiete Grosse-Oetringhaus (ALICE), John Jowett (LHC), Yen-Jie Lee (CMS), Urs Wiedemann (TH), Michael Winn (LHCb) + Andrea Dainese (steering committee)
- General workshops: October 2017 | June 2018 | 1st March 2019
- Next WG5 General Meeting on October 30-31
- Mailing list: hllhc-wg5@cern.ch (→ e-groups)

Timeline
End Oct: Review within WG5
Nov 17th: Cross-review between WGs
Dec 10th: Submission to arXiv

WG5 Yellow Report outline and chapter coordinators

- **Ch. 1: Future physics opportunities for high-density QCD with ions and proton beams at LHC (WG5 conveners)**
- **Ch. 2: Accelerator performance with heavy ions (John Jowett, Michaela Schaumann, Roderik Bruce)**
- **8 chapters "by observable", with experimental projections**
  - Light flavour and nuclei — **Francesca Bellini** (**ALICE**)
  - Flow, polarisation, magnetic effects — **Soumya Mohapatra** (**ATLAS**)
  - Open heavy flavour — **Elena Bruna (ALICE) / Gian Michele Innocenti (CMS)**
  - Jets and energy loss — **Marta Verweij (CMS)**
  - Quarkonia — **Emilien Chapon (CMS) / Anton Andronic (ALICE)**
  - Thermal radiation and di-leptons — **Michael Weber** (**ALICE**)
  - Physics of small systems — **Jan Fiete Grosse-Oetringhaus / Constantin Loizides (ALICE)**
  - Nuclear PDFs and small-x — **Michael Winn** (**LHCb**)
- **Ch. 11 on other opportunities ($\gamma\gamma$ collisions (Iwona Grabowska-Bold (ATLAS)), fixed-target collisions, p-O short run for cosmic rays (Hans Dembinksi))**
- **Ch. 12 on opportunities with HI at HE-LHC (Andrea Dainese, David d'Enterria, Carlos Salgado)**

Open Questions

- The quest for the QGP has turned into a precision exercise
- The questions remain puzzling and exciting

- What is the underlying dynamics?
  - Model describing long wavelength (ideal fluid) and short wave-length ("quenching") behavior
- What are the (relevant) degrees of freedom / microscopic structure?
- How to derive behavior from QCD?

- QGP “onset” in light of the discoveries in small systems

  - Collectivity in small systems challenges two paradigms at once!
    1. How far down in systems size does the ”SM of heavy ions” remain?
    2. Can the standard tools for min bias pp remain standard?

  Christian Bierlich, Workshop on physics at HL-LHC, 31.10.17

  - Collective effects in small and dilute systems?

Goals for HL-LHC Era

1 **Characterize the macroscopic long-wavelength QGP properties with unprecedented precision**

2 **Access the microscopic parton dynamics underlying the QGP properties**

3 **Probing partonic content in nuclei and search for possible onset of parton saturation**

4 **Investigate unified picture of particle production from small to large systems**

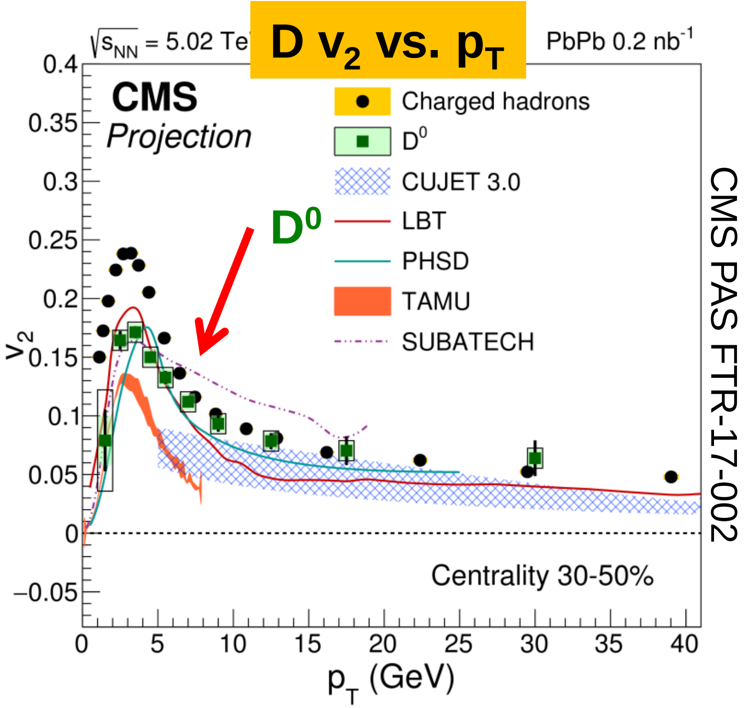
Goal 1

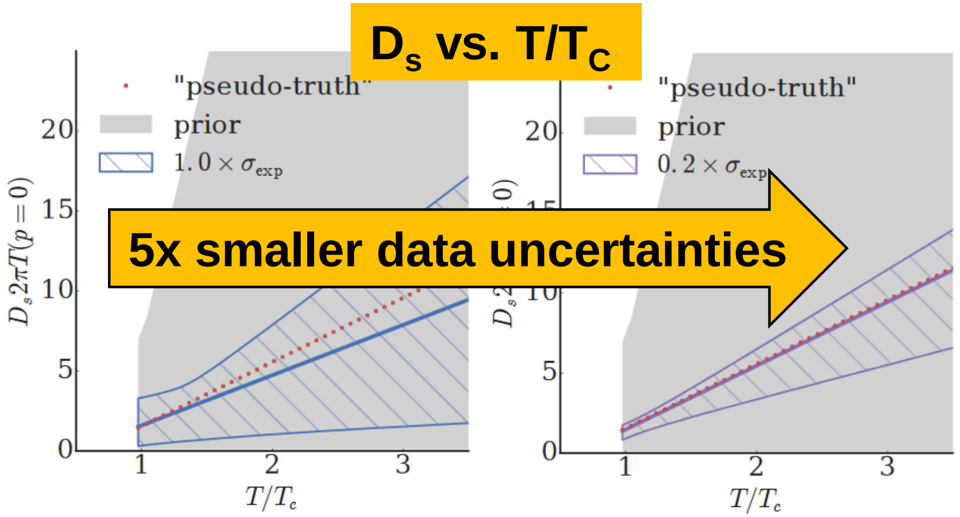
Characterize the macroscopic long-wavelength QGP properties with unprecedented precision

Temperature, QGP transport coefficients like viscosity, heavy quark diffusion, electric conductivity, …

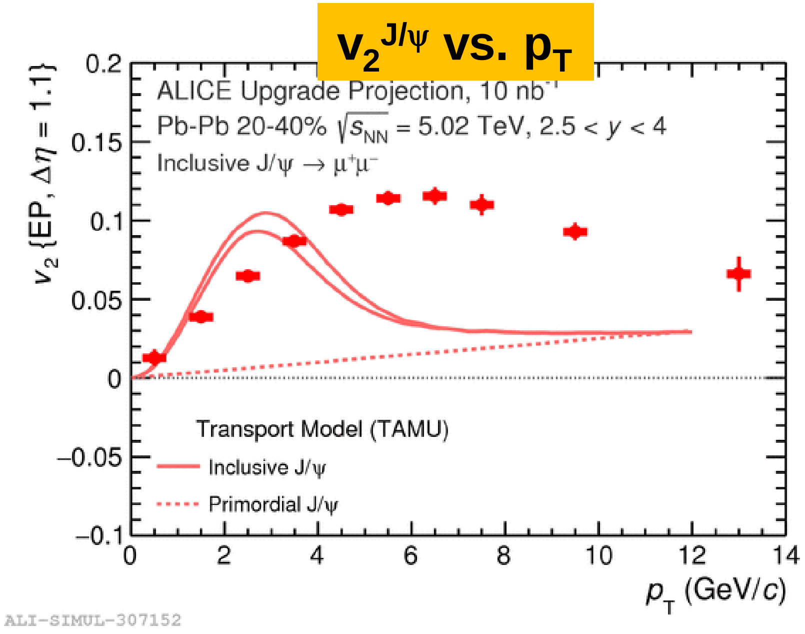
Heavy Quarks

- Do heavy quarks thermalize?
  → Charm and beauty v_2 down to $p_T = 0$
- Correlation of light and heavy-quark flow
- Constrain temperature dep. of diffusion coefficient
- Heavy Quark coefficients compared to lattice QCD





Stefan Bass, WG5 HI Meeting, 06.03.18

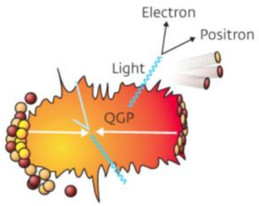


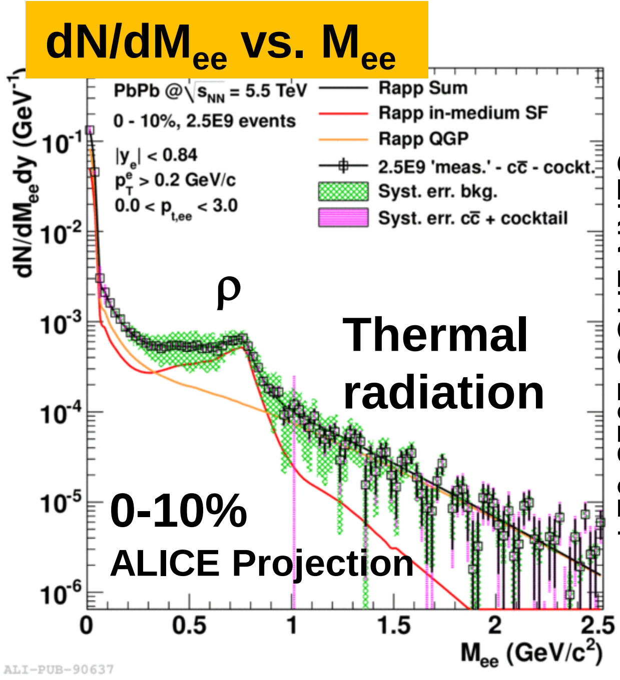
Medium Temperature

- Thermal radiation at vanishing μ_B
- Access space-time evolution of medium
  - Temperature (→ 20% uncertainty)
  - Radiation from all stages of the expansion
  - v_2 of thermal photons (1% abs. uncertainty on v_2)
- Change of ρ spectral function connected to chiral symmetry restoration
- Sequential bottomonia dissociation?

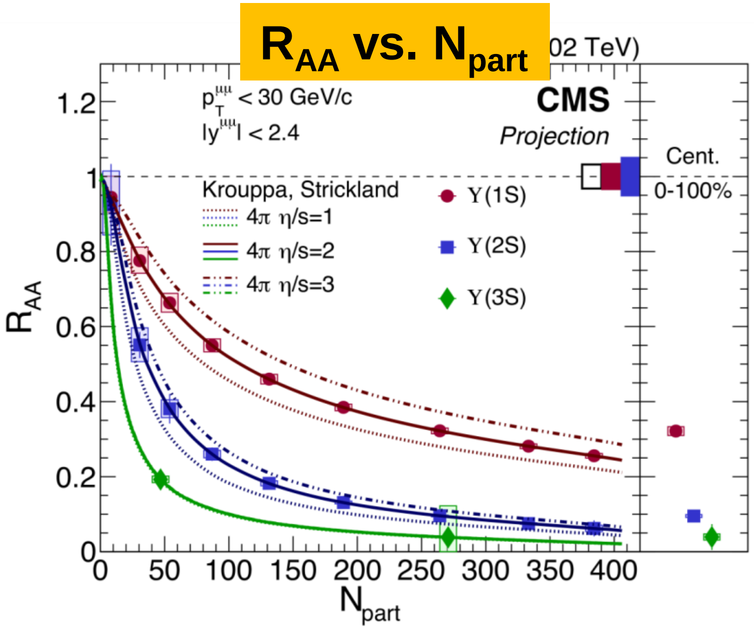
Υ(1S)	Υ(2S)	Υ(3S)
270k	40k	7k?

(CMS L_{int} = 10 nb^{-1})



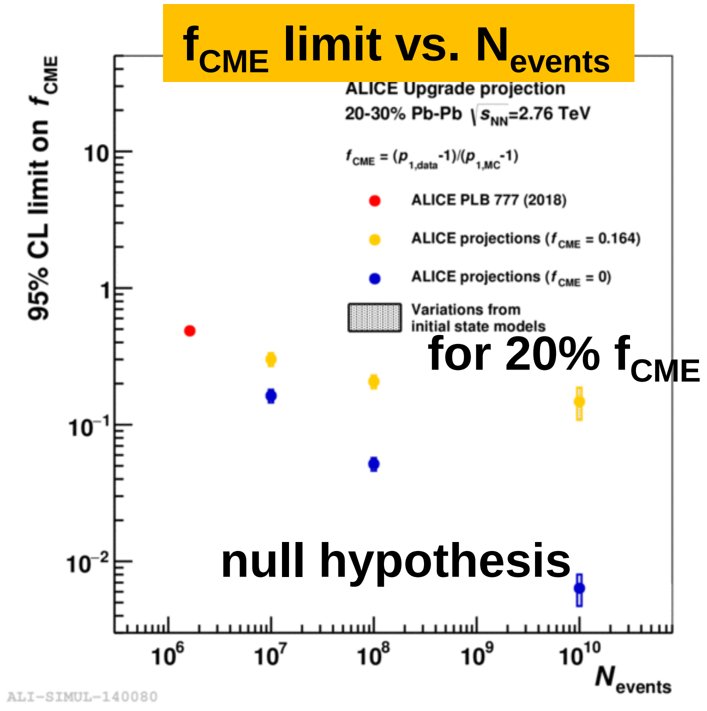


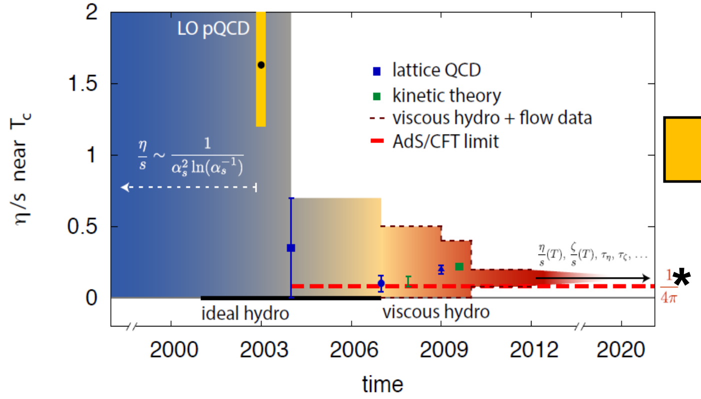
CERN-LHCC-2013-024



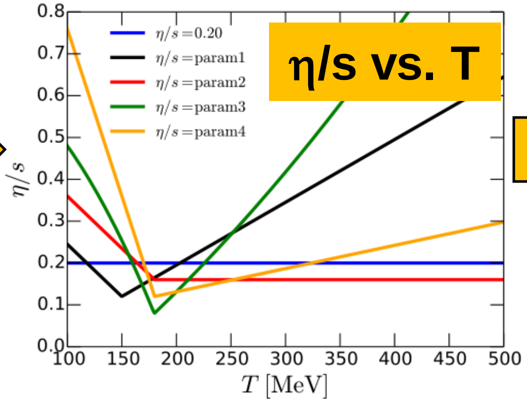
Correlations & Fluctuations

- Insight into parity violation in the strong interaction
  - Charge dependent v_1 with h and D's (→ magnetic field)
  - Chiral magnetic effect (→ upper limit on background), <1% limit!
- Fluctuations of conserved charges
  - Higher moments (χ_6/χ_2) ~ criticality
  - Direct comparison to LQCD
- Temperature dependence of medium properties and their interplay
  - Differential and precise flow measurements (higher-order, longitudinal fluctuations)

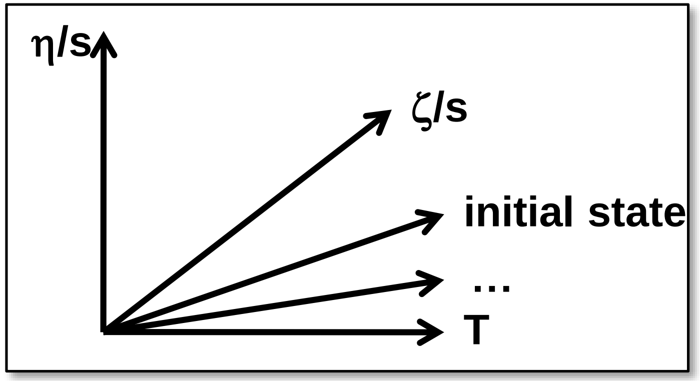




* neglecting Kurkela, Wiedemann, Wu, arXiv:1803.02072



Niemi, Eskola, Paatelainen, PRC93,024907(2016)



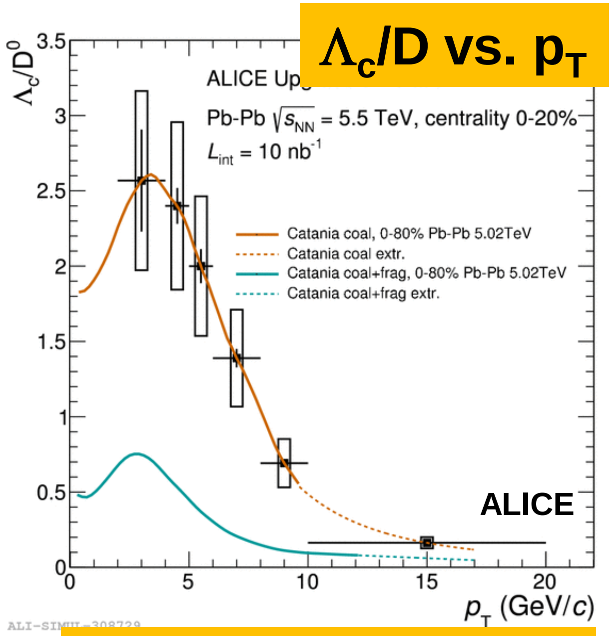
Goal 2

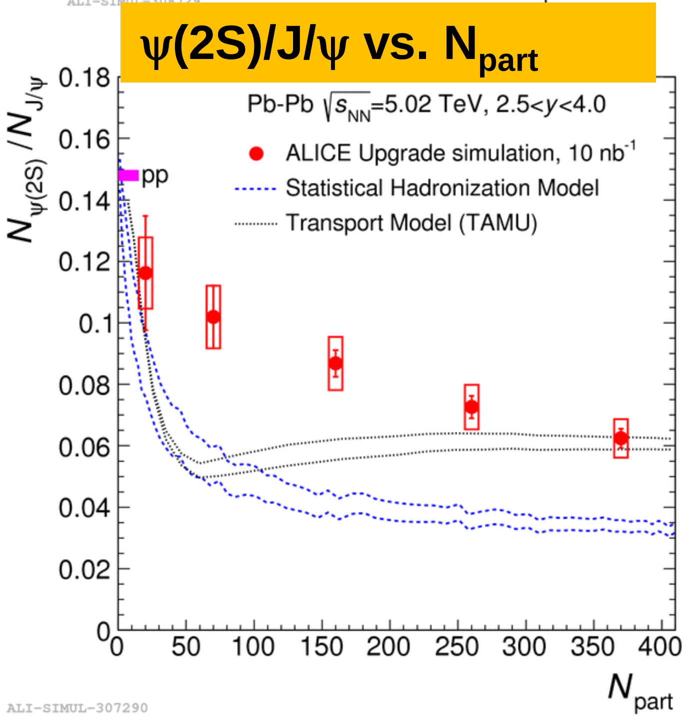
Access the microscopic parton dynamics underlying the QGP properties

What are the effective constituents and inner length scales?

Charm Hadronization

- How does charm form in the QGP?
  - Baryon/meson ratios D_s/D, Λ_c/D, Λ_b/B
  - Very challenging: e.g. Λ_c $c\tau$ ~ 60 μm
- Influence of recombination and radial flow
- Influence of melting and (re)generation
  - Compare states with different binding energy
- Charm cross-section to p_T = 0
  → reduce (re)generation model uncertainties
- Validation of quarkonium evolution within QGP and heavy quark hadronisation, e.g. recombination and coalescence



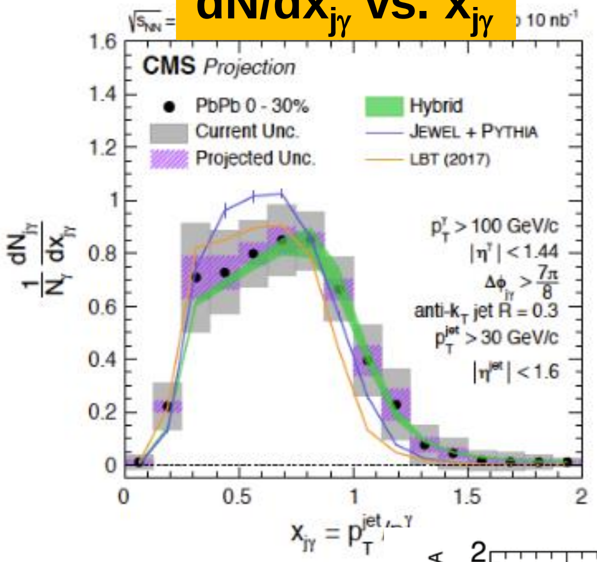


Jets: Precision Medium Tomography

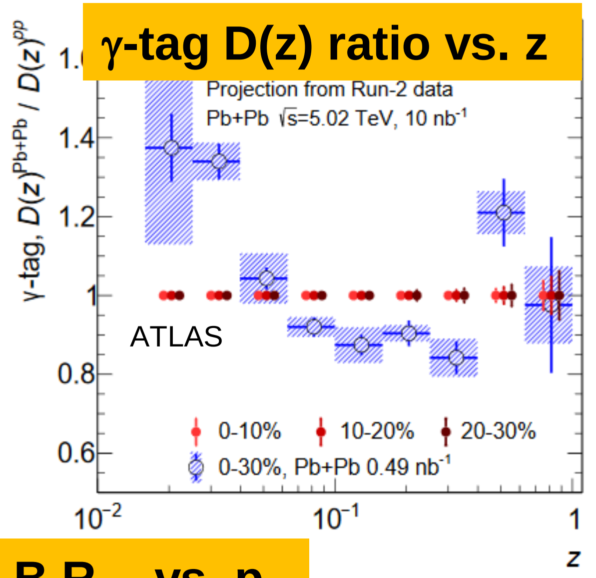
- Light quark sector
  - Suppression from GeV to TeV
  - Path-length dependence with event-shape engineering
  - Di-jet imbalance, γ-jet, Z^0-jet

- Heavy quark sector (c & b)
  - Quark-mass dependence
  - Flavour identified fragmentation functions
  - Path-length dependence through v_2

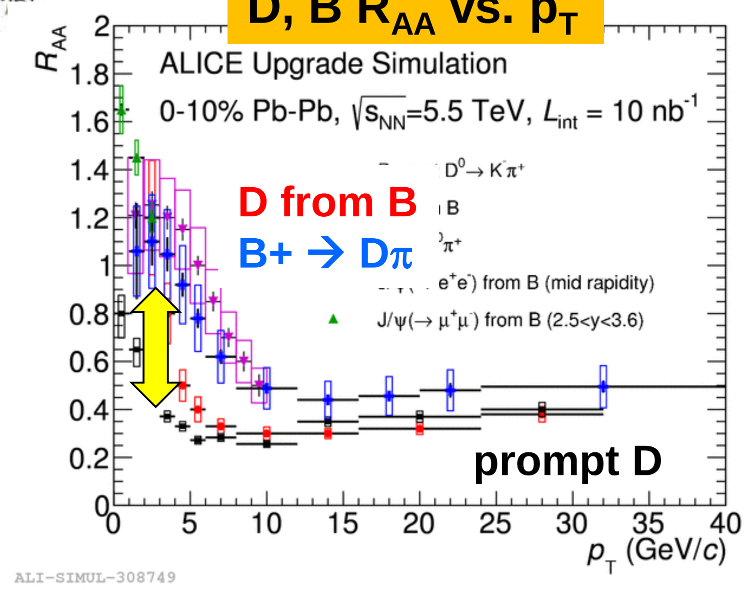
dN/dx$_{j\gamma}$ vs. x$_{j\gamma}$



γ-tag D(z) ratio vs. z



D, B R_{AA} vs. p_T



Jets: Differential Measurements

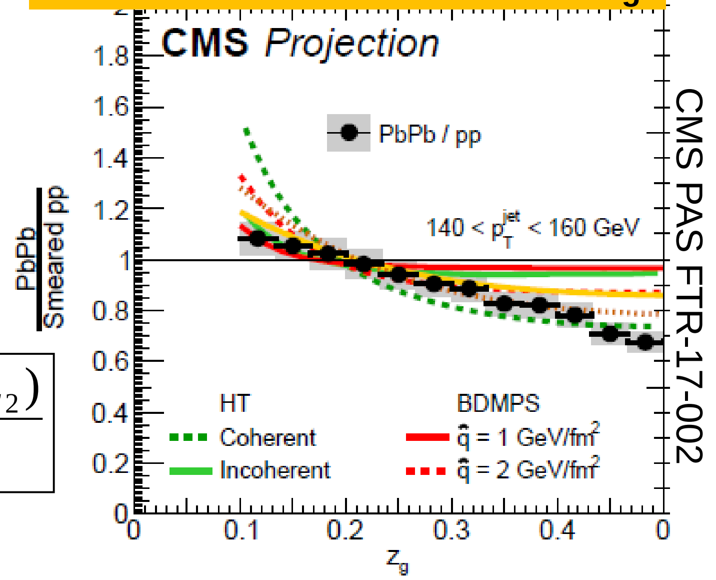
- Inter-jet modifications
  - Broadening through azimuthal correlations
  - Sensitivity to qhat*L at low Q^2

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

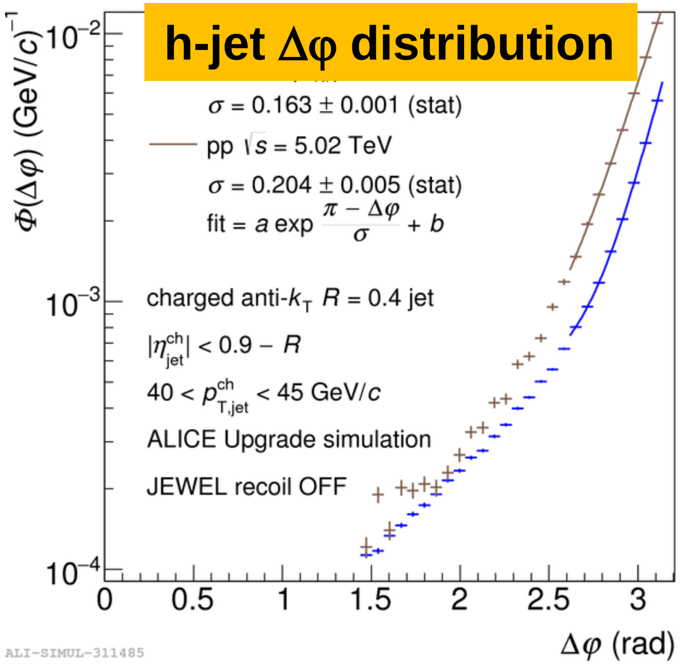
- Intra-jet modifications (jet substructure)
  - Differential probing of splitting phase space with Lund diagram (“emitter transverse momentum vs. angle”)
  - Isolate regions where medium effects are strongest E.g. grooming [Dasgupta et al, JHEP09 (2013) 029; Larkoski et al, JHEP05(2014)146]
  - Understand mechanism of in-medium energy loss

- Large-angle “Molière” scattering [Kurkela, Wiedemann, PLB740(2015)172; Eramo et al, JHEP05(2013)031]
  - Can we see point-like quarks/gluons at large Q^2?

Splitting in PbPb/pp vs. z_g



h-jet Δφ distribution

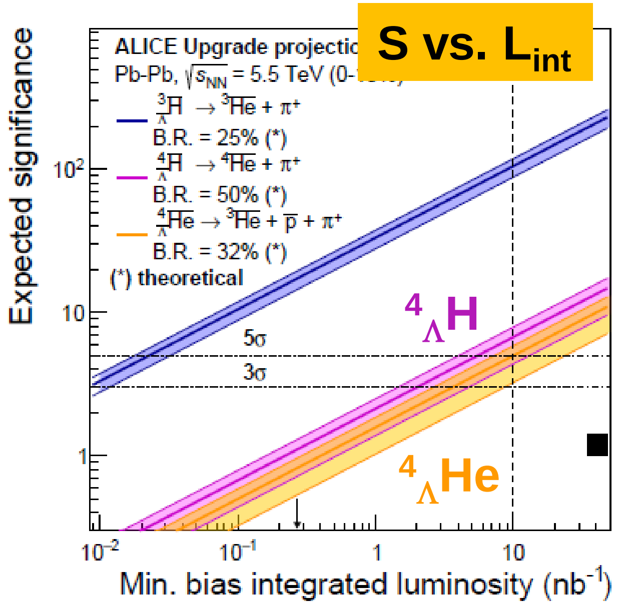


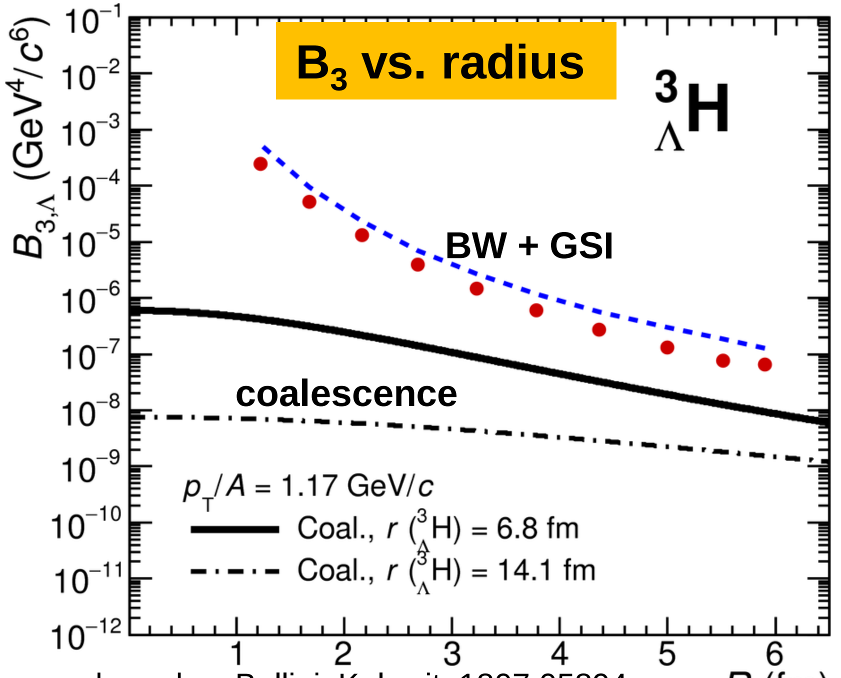
(Anti-)(hyper-)nuclei

- Precision era for (anti-)(hyper-)nuclei production
  - Abundant d, ^{3}He, $^{3}_{\Lambda}$H; > 1000 ^{4}He
  - Significance above 5σ for $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He
  - v_2 for loosely-bound objects (e.g. hypertriton)

- Production mechanism
  - (Advanced) coalescence vs. thermal model

- Astrophysical background in dark matter searches use anti-d and anti-^{3}He data (AMS)



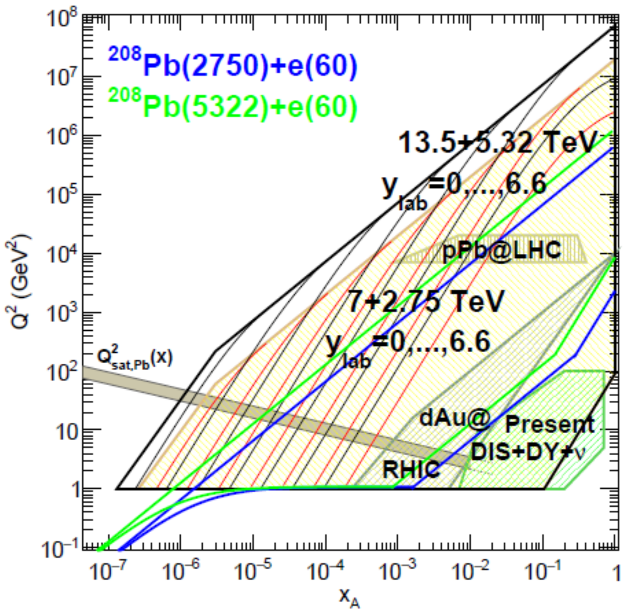


based on Bellini, Kalweit, 1807.05894

Goal 3

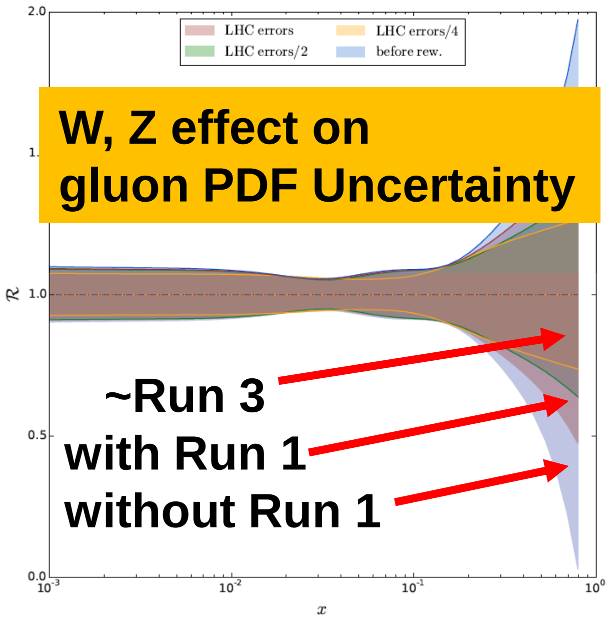
Probing partonic content in nuclei and search for possible onset of parton saturation

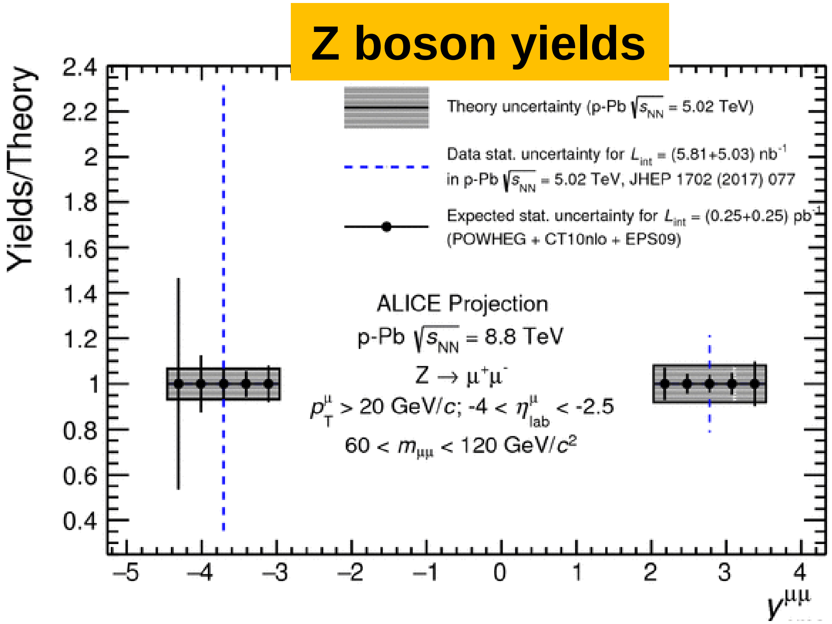
Partonic Content of Nuclei



- State-of-the-art nPDFs: 1000-2000 data points* spread over 14 nuclei (for Pb < 50) [*excluding large-x neutrino data]
  - No fit to a single nucleus possible
  - Compare to proton: ~3100 DIS and ~1200 collider data
  - Input from LHC crucial

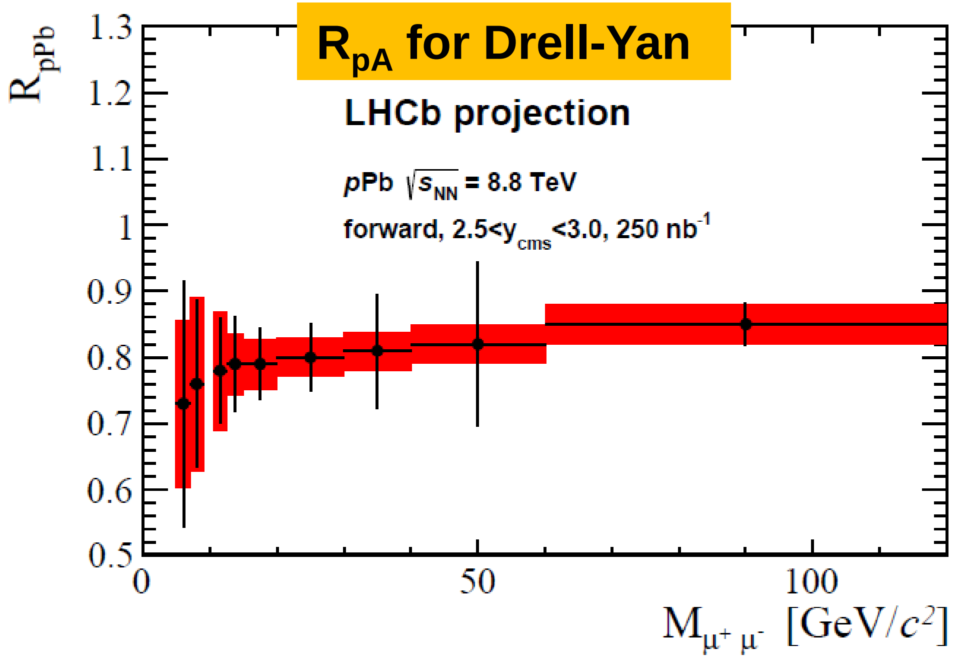
- At large x
  - W, Z, dijets (p-Pb and Pb-Pb)
  - Top quarks
    - "Discovery" in Pb-Pb
    - Constraints with Ar-Ar including A dependence



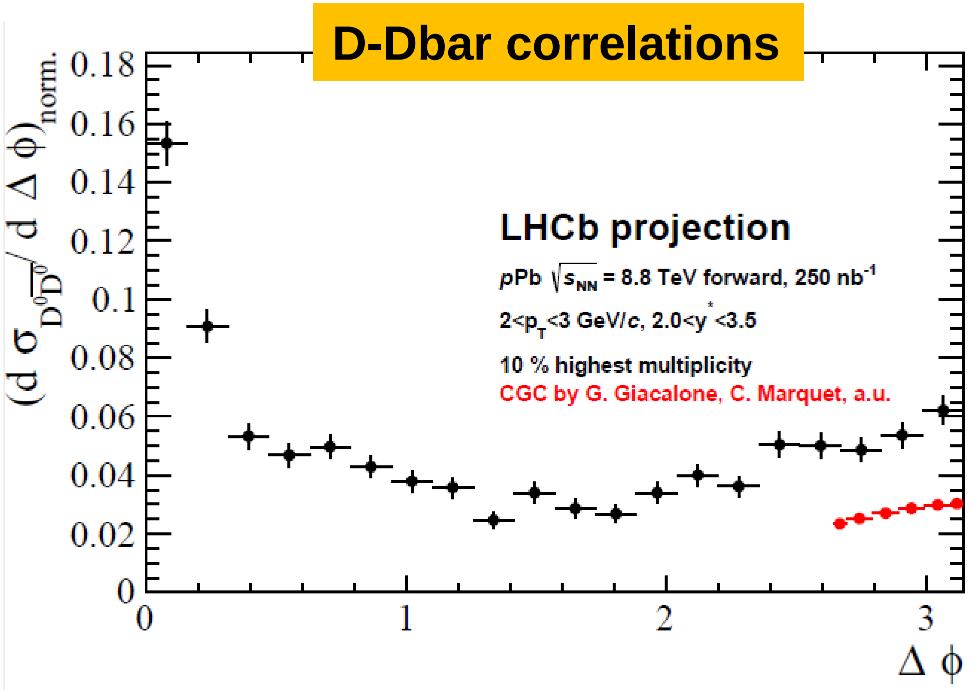


Partonic Content of Nuclei

- At small x
  - Ultra-peripheral collisions
  - Constrain gluon shadowing with quarkonia and open HF
  - Forward Drell Yan and photon production



- Study saturation regime
  - Low-mass Drell Yan
  - Novel signals D-Dbar correlations

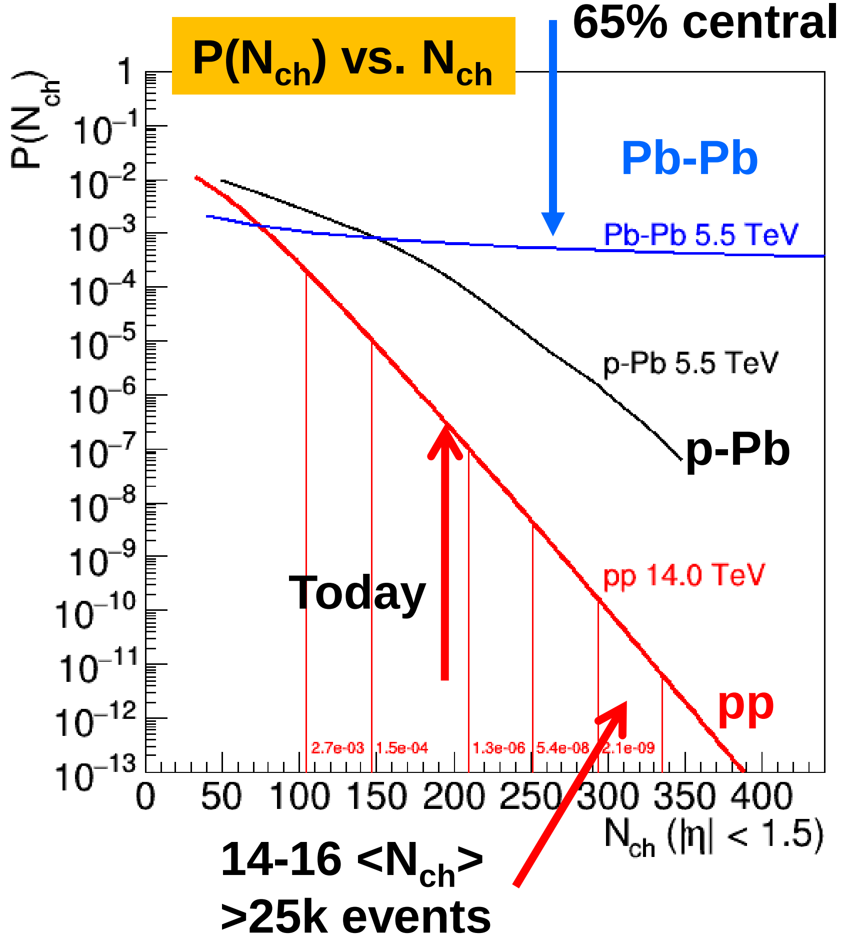


Goal 4

Investigate unified picture of particle production from small to large systems

Collectivity in Small Systems

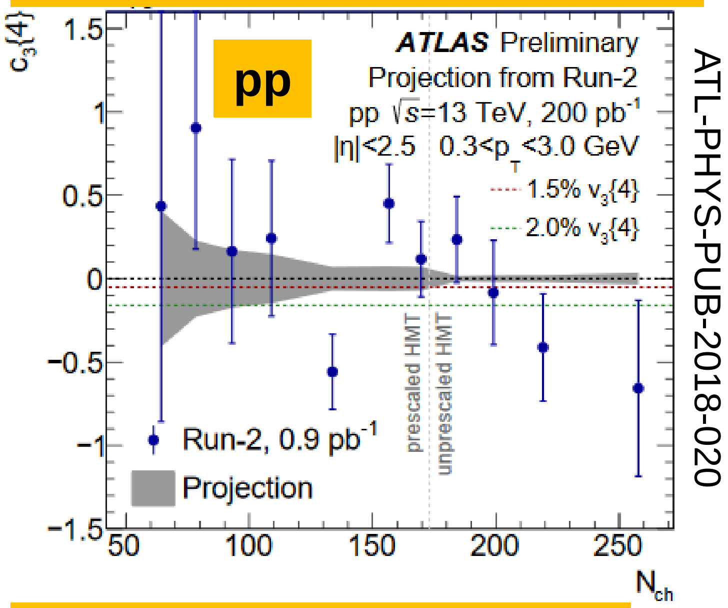
- (Perfect) fluid dynamics ↔ free streaming limit
- Can reach extremely rare (10^{-11}) pp events
  - 200 pb^{-1} | Sampling 10^{13} events
- Significant overlap between pp and PbPb
  - In multiplicity up to ~65% centrality
- If pp behaves HI, we shall see "standard" HI physics
  - Including jet quenching if effects driven by final state
  - If not, we can see the differences
- In addition: MB sample for low-multiplicity limit
  - What is smallest droplet of matter showing collectivity?
  - Origin of collectivity in few particle system?
    (color reconnection, gluon interference, escape, …
    vs. impressively successful hydrodynamic description)



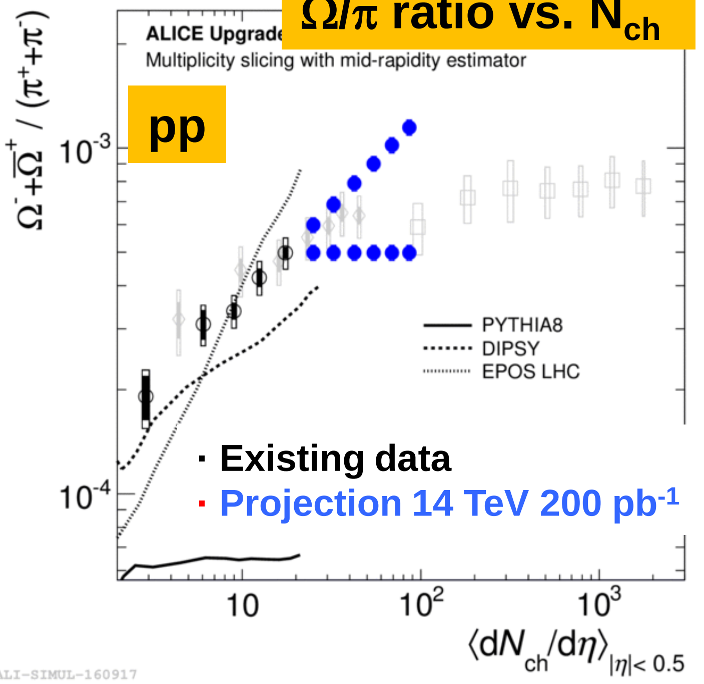
Collectivity in Small Systems

- Non-flow free higher-order correlations
  - Higher order cumulants and subevent method
- Strangeness enhancement. Thermal limit in pp?
- Precise D and J/ψ v_2 in p-Pb
  - and in pp?
- Measure energy loss or put stringent limit
  - h-jet, jet-γ, jet-Z correlations
- Sign of thermal radiation?

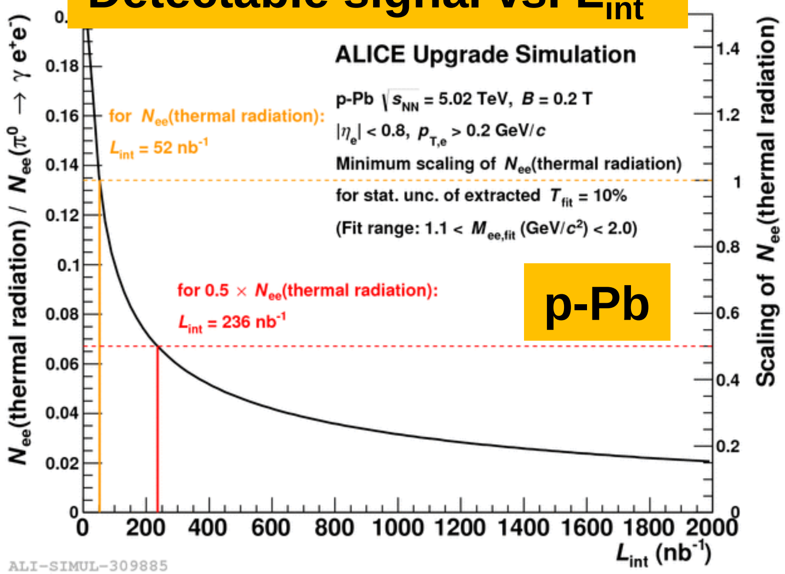
3rd order 4-particle cumulant



Ω/π ratio vs. N_{ch}

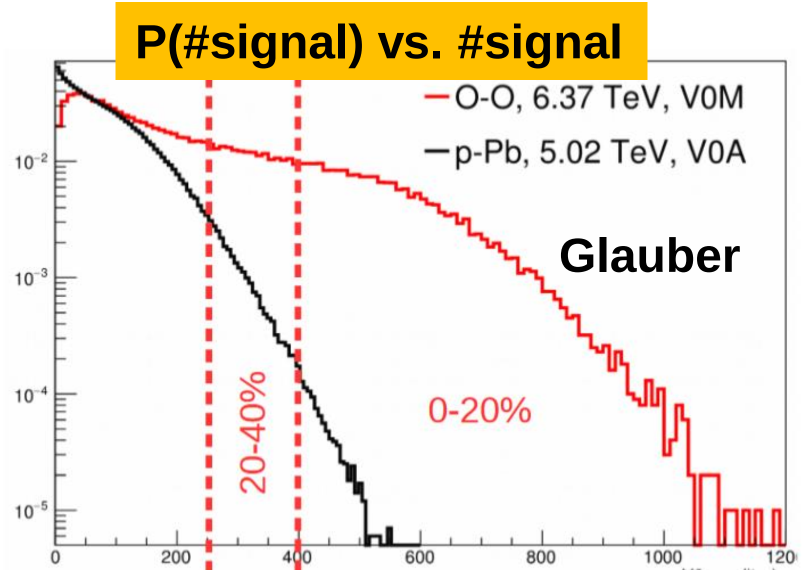


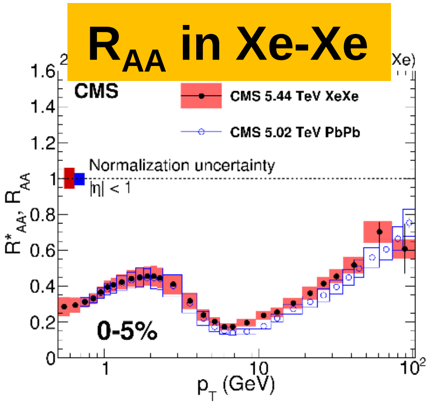
Detectable signal vs. L_{int}



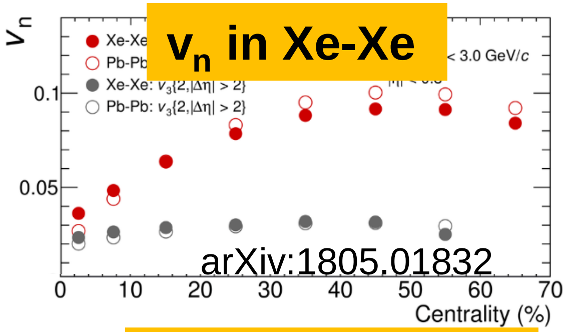
Oxygen-Oxygen Collisions

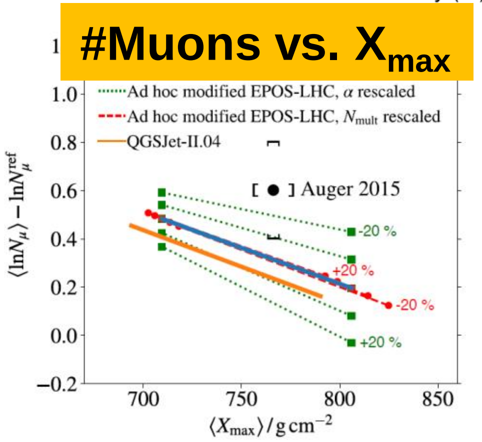
- AA geometry but N_{ch}, N_{part}, N_{coll} as p-Pb
- Centrality shoulder allows geometry selection (N_{coll} and ε_2)
- System large enough to exhibit jet quenching
- O used as carrier gas in accelerator HI source
  - Easier setup and commissioning (for low L_{inst})
  - Few 100 μb^{-1} sufficient for R_{AA}, v_n, … (demonstrated by Xe-Xe)





arXiv:1809.00201



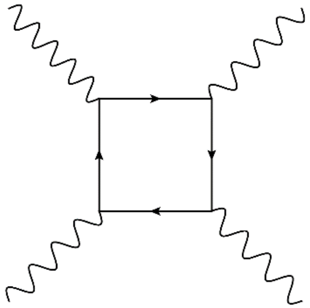


- Cosmic-ray community has expressed strong interest in short p-O run to constrain models describing cosmic-ray showers
  - Could be easily appended to such a run

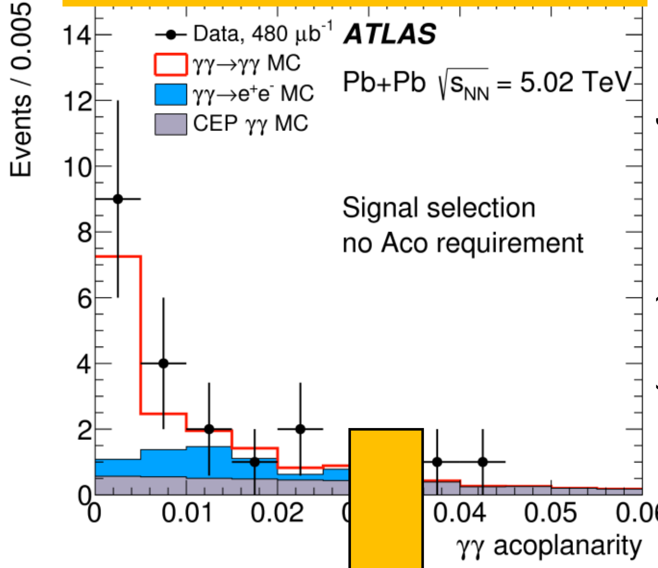
Further Directions

γ-γ Interactions

- Exclusive μμ and ppbar production
  - Precision measurement of photon flux
  - Reach masses not accessible in pp collisions (Z^4 enhancement re pp)
- Rare light-by-light scattering
  - Classically forbidden process
  - 13 events (now) → 640 events
- Axion-like particle search
  - Anomalous contribution γγ → a → γγ



γγ Yield vs. acoplanarity



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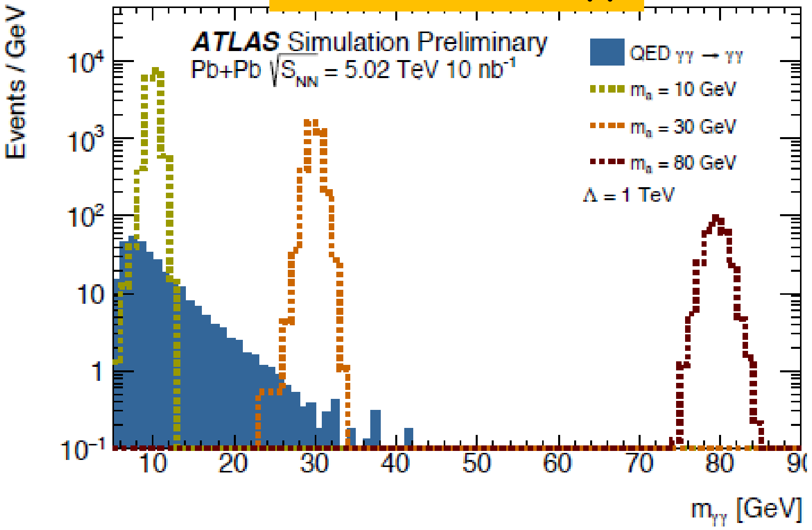
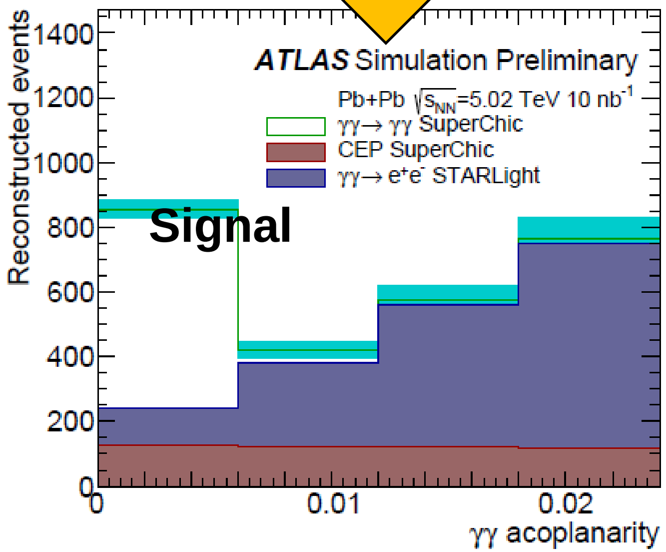
Events vs. mγγ



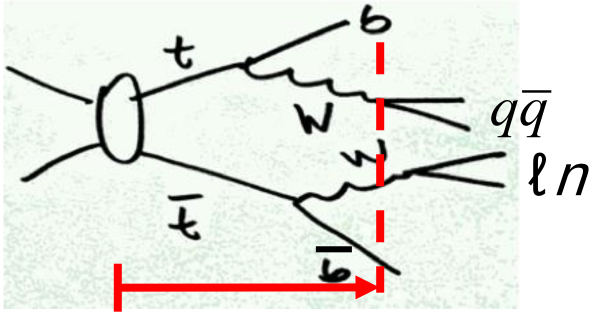


Ar-Ar Collisions

- Collisions of lighter ions can reach much larger instantaneous luminosities
  - Pb-Pb: σ_{had} = 7.8 b vs. σ_{tot} = 508 b (→ 1.5%)
  - Ar-Ar: σ_{had} = 2.6 b vs. σ_{tot} = 3.85 b (→ 68%)

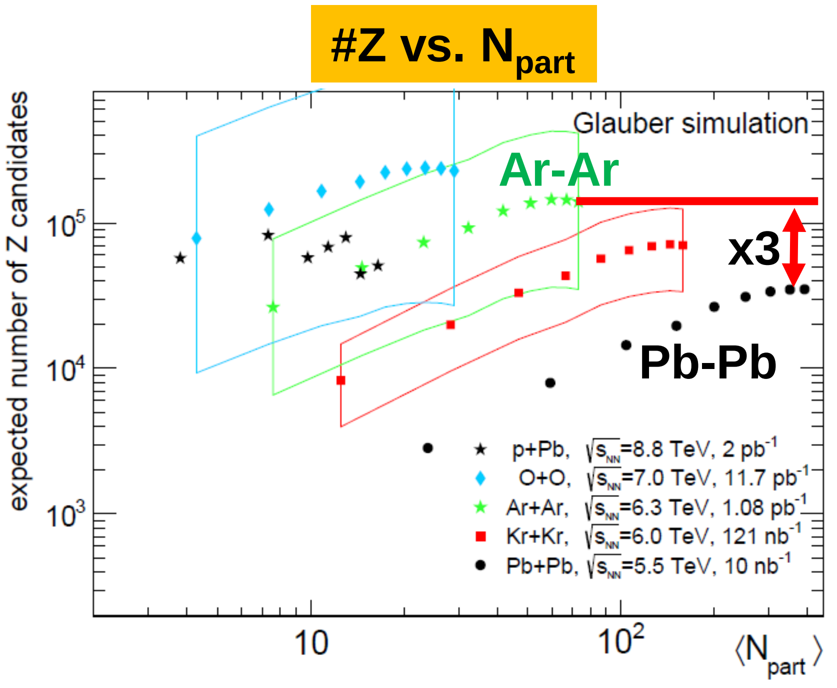
  → much longer beam life time
- Ar-Ar vs. Pb-Pb

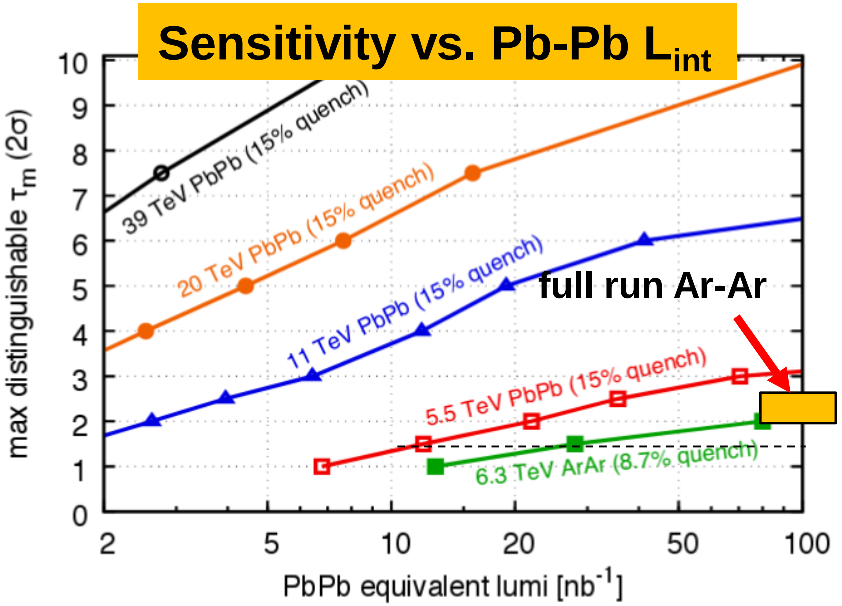
  = more collisions vs. smaller medium (= less quenching)
- Large rate of top quarks for nPDFs
- Time evolution of the QGP w/ boosted (high p_T) top



$$t\bar{t} \rightarrow b\bar{b} + q\bar{q} + \ell + n$$

Time delay before medium interactions





Luminosity Requirements HL-LHC

System	$\sqrt{s_{NN}}$	Baseline	WG5 Report
Pb-Pb	5.5 TeV	13 nb^{-1}	13 nb^{-1}
p-Pb	8.8 TeV	50 nb^{-1}	2000 nb^{-1} (ATLAS/CMS) | 1000 nb^{-1} (ALICE) | 500 nb^{-1} (LHCb)
pp	5.5 TeV	6 pb^{-1}	300 pb^{-1} (ATLAS/CMS) | 50 pb^{-1} (LHCb) | 6 pb^{-1} (ALICE)
	8.8 TeV	-	200 pb^{-1} (ATLAS/CMS) | 100 pb^{-1} (LHCb) | few pb^{-1} (ALICE)
	14 TeV	-	200 pb^{-1} (low μ running)
OO and pO		-	“pilot” running, few 100 μb^{-1} for OO | 1-2 shifts pO
Ar-Ar		-	3000 nb^{-1} → L_{NN} equivalent: 6-18x “Pb-Pb 13 nb^{-1}”

The full programme does not fit in Run 3 and 4. Certainly the Ar-Ar program will extend into Run 5

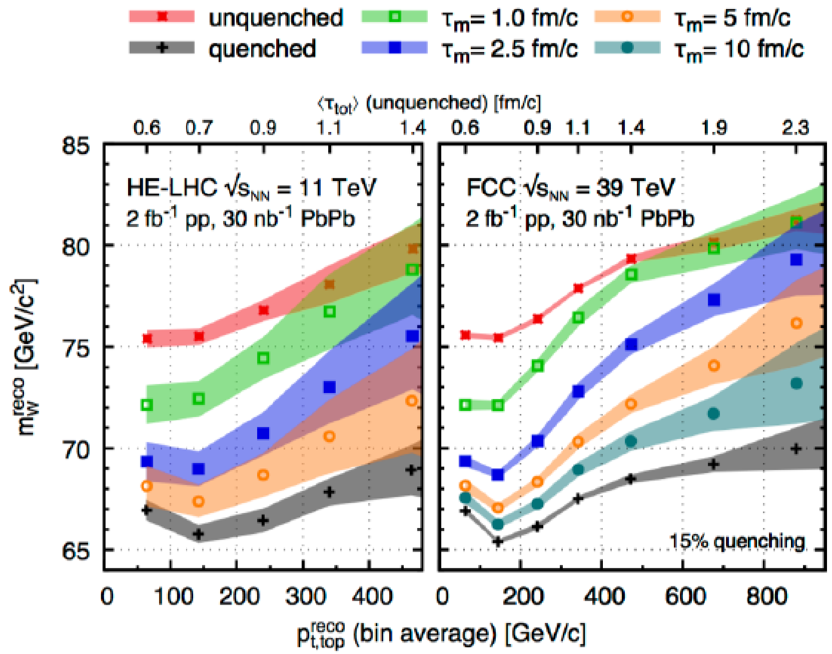
How to put this in a proposed running schedule for 2021-2035 will be discussed during the October 30-31 working group meeting

HE-LHC

	LHC		HE-LHC		FCC
System, $\sqrt{s_{\rm NN}}$ (Tev)	Pb–Pb, 2.76	Pb–Pb, 5.5	Pb–Pb, 10.6	Xe–Xe, 11.5	Pb–Pb, 39.4
$dN_{\rm ch}/d\eta$ at $\eta = 0$	1600	2000	2400	1500	3600
$dE_{\rm T}/d\eta$ at $\eta = 0$ (TeV)	1.7–2.0	2.3–2.6	3.1–3.4	≈ 1.5	5.2–5.8
Homogeneity volume fm^3	5000	6200	7400	4500	11000
Decoupling time (fm/c)	10	11	11.5	10	13
ε at $\tau = 1$ fm/c (GeV/fm^3)	12–13	16–17	22–24	≈ 15	35–40

- Mild increase in N_{ch}, life time and energy density
- Modest increase (~2) in L_{int}, lighter ions preferred
- Hard probes gain: x2 for beauty, x6-8 for top
- Time evolution of the QGP w/ boosted (high p_T) top
- Top as constraint for nPDFs
- First evidence for Higgs boson in Pb-Pb?
- First observation of thermal charm? (→ initial temperature)

$m_{W,reco}$ vs. $p_{T,top}$



Summary

- 2021-29 at LHC promises rich programme along several distinct research lines
  - Measurements comparable with lattice QCD (HQ coefficients, conserved charges)
  - Unprecedented accuracy enables understanding of medium evolution with time: thermalization, hydrodynamization, hadronization
  - Very tight constraints on QGP inner structure and possibly evidence for point-like QGP scattering centres through large-angle scattering
  - Tightly constrained gluon PDF at low and high x through multiple channels
  - Observation of saturation through novel and clean probes at low Q^2: DDbar, low m DY
  - Confirm that unified description from pp to Pb-Pb collisions is feasible
    or show that different mechanisms are justified

- Novel aspects accessible beyond 2030 with Ar-Ar and at HE-LHC