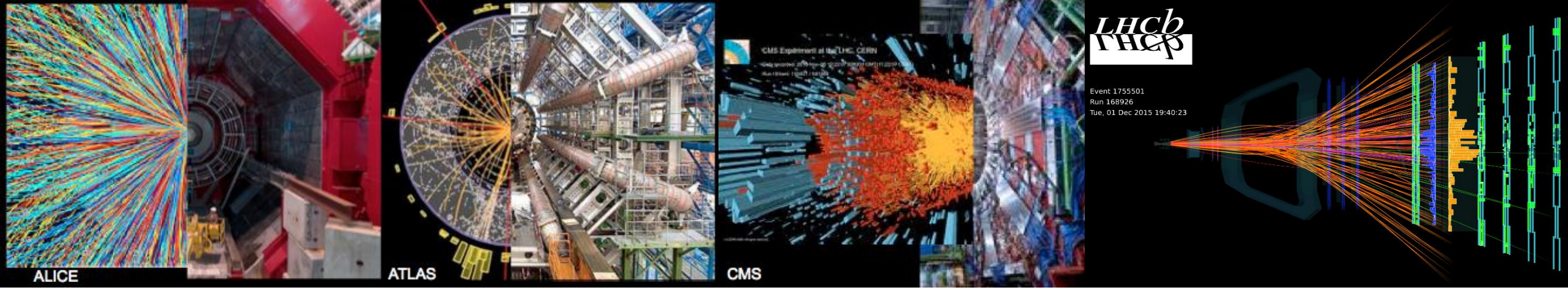


Heavy-Ion Prospects for HL-LHC

Jan Fiete Grosse-Oetringhaus, CERN
(on behalf of ALICE, ATLAS, CMS, LHCb)

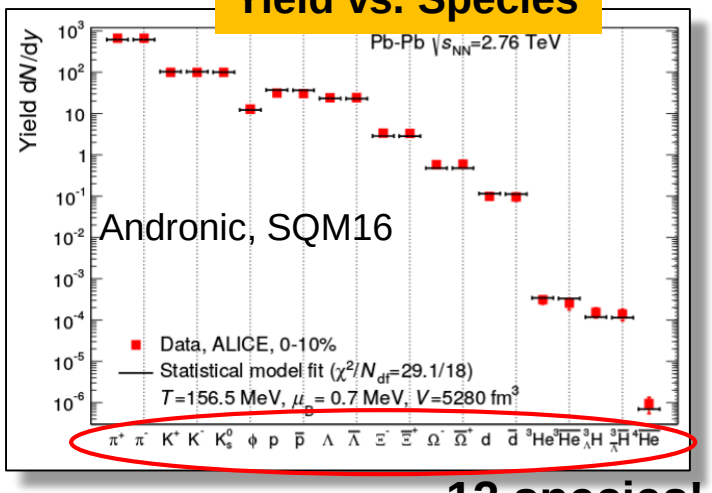
Workshop on the physics of HL-LHC, and perspectives at HE-LHC

30.10.17

Heavy-Ion Physics at the Energy Frontier

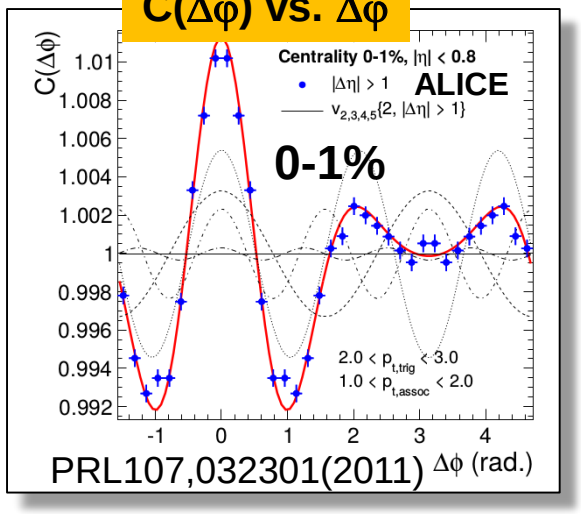
- LHC is precision machine for heavy-ion physics
  - Has set standard for measurements of particle production, collective flow and energy loss

Yield vs. Species



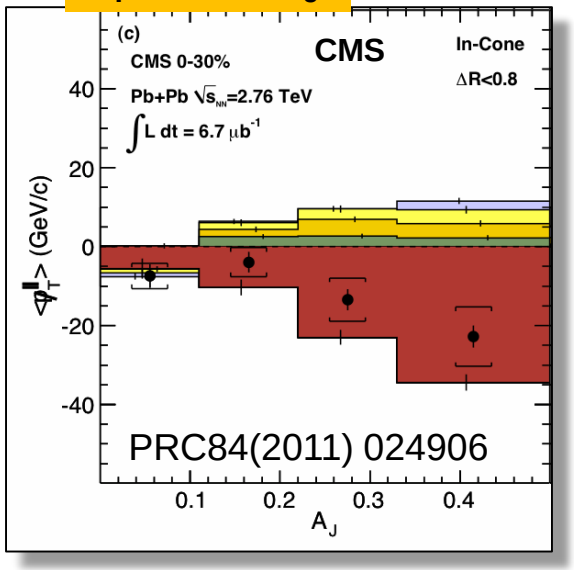
12 species!

C(Δφ) vs. Δφ



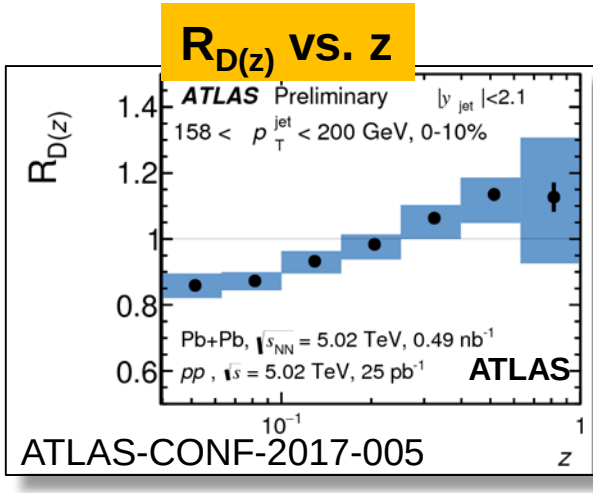
PRL107,032301(2011)

p_T^{miss} vs. A_J



PRC84(2011) 024906

$R_{D(z)}$ vs. z

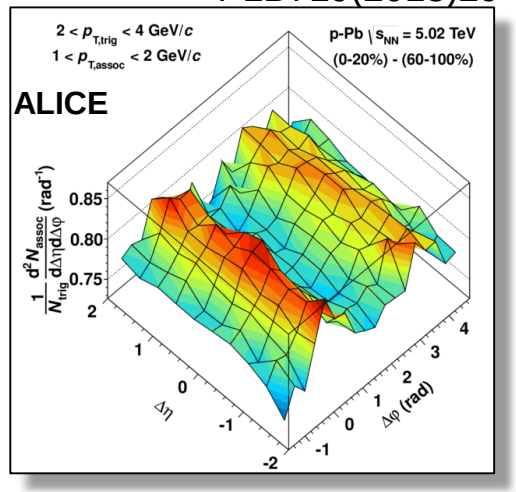


ATLAS-CONF-2017-005

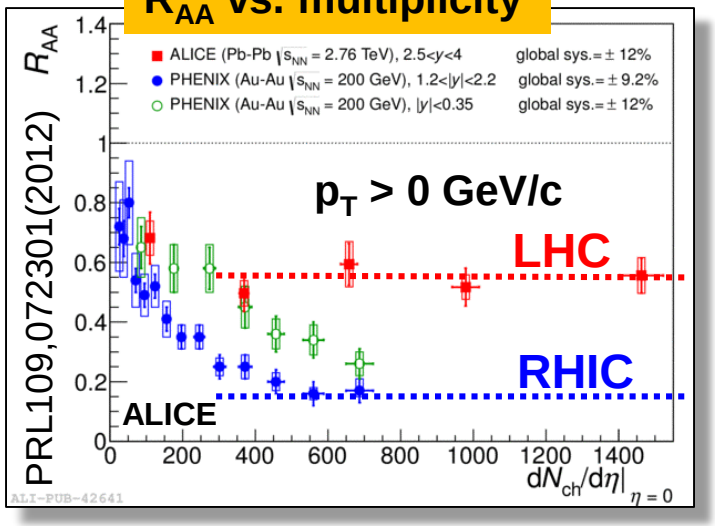
Heavy-Ion Physics at the Energy Frontier

- LHC is a discovery machine for heavy-ion physics
  - Quarkonia melting and J/ψ regeneration
  - Collective-like effects in small systems

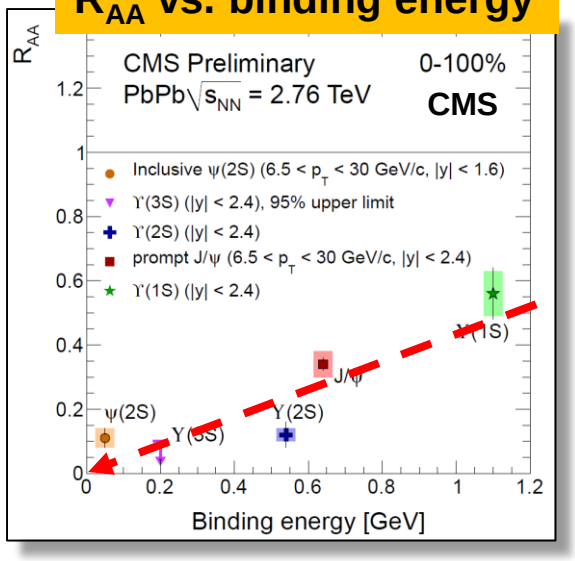
PLB719(2013)29



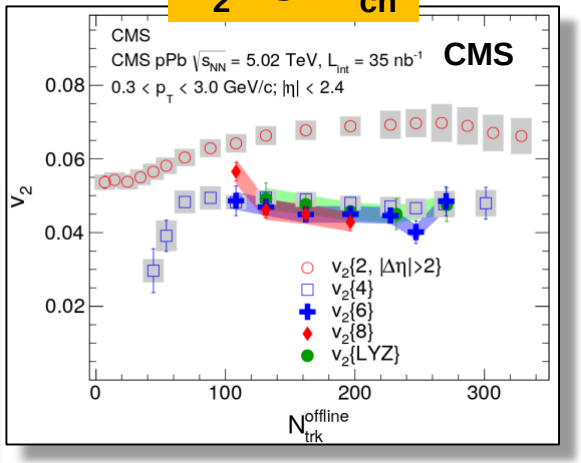
R_{AA} vs. multiplicity



R_{AA} vs. binding energy

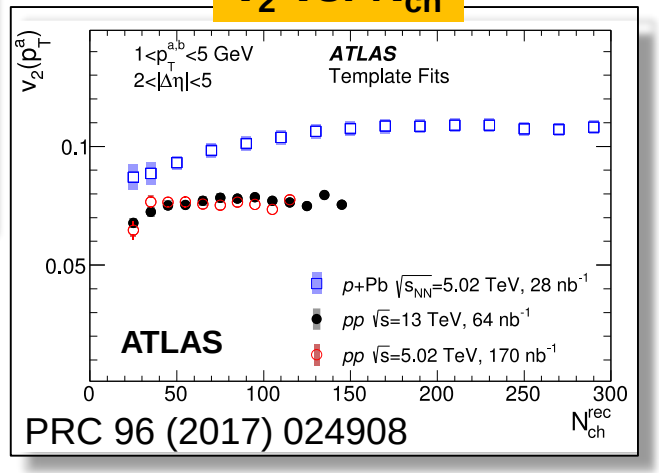


v_2 vs. N_{ch}



PRL 115 (2015) 012301

v_2 vs. N_{ch}



PRC 96 (2017) 024908

Open Questions

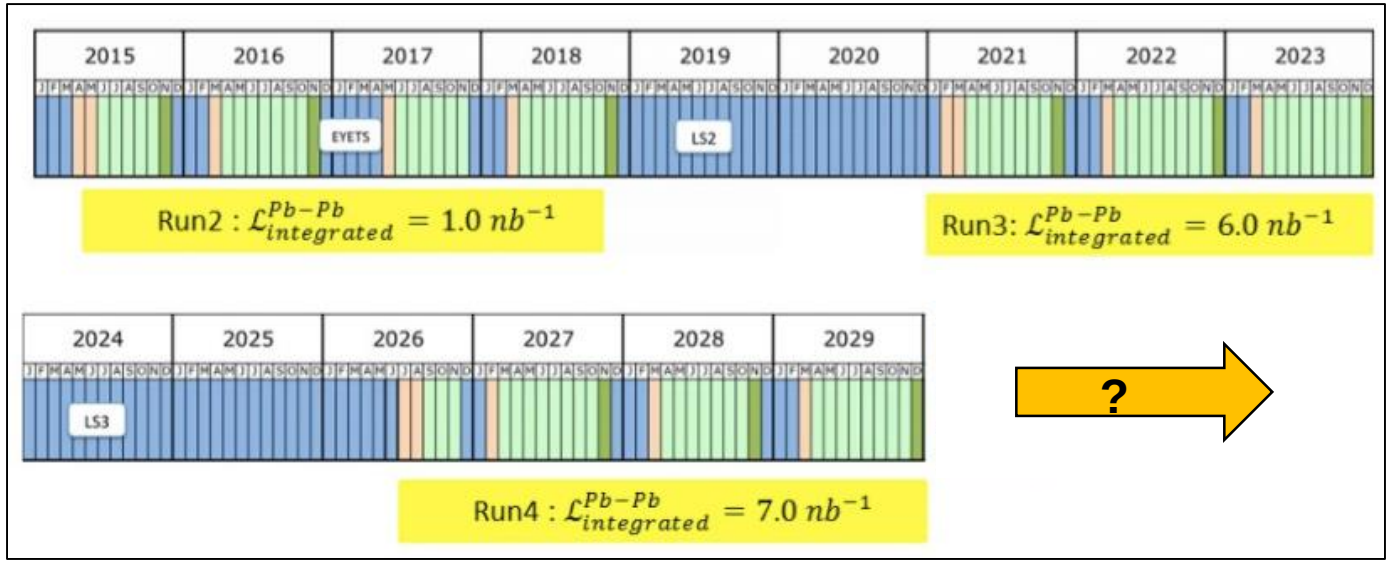
- Underlying dynamics
  - Macroscopic QGP transport properties measured with accuracy
  - What is the underlying dynamics? I.e. the model describing long wavelength (ideal fluid) and short wave-length ("quenching") behavior
  - What are the (relevant) degrees of freedom / microscopic structure?
  - How to derive behavior from QCD?
- QGP onset (as a function of system size)
  - Traditionally, onset of QGP physics expected (leading to postulation of smoking gun observables). Reality more complex…
  - Smooth onset to first order in many observables, with some fine structure to second order
  - Huge potential to learn about underlying dynamics, i.e. non-perturbative QCD

Heavy Ions at the LHC

- Run 2:
  - Pb-Pb: few nb^{-1} (0.7 nb^{-1} in 2015, ~1 nb^{-1} in 2018) at $\sqrt{s_{NN}}$ = 5 TeV
  - p-Pb at 5 and 8 TeV (185 nb^{-1} in 2016)
  - pp reference at Pb-Pb energy (5 TeV, Nov 2017)
- LS2:
  - LHC injector upgrades; bunch spacing reduced to 50 ns
  - Pb-Pb interaction rate up to 50 kHz (now <10 kHz)
  - Experiments' upgrades (also LS3)
- Runs 3+4:
  - Request for **Pb-Pb: >10 nb^{-1}**
    (ALICE: 10 nb^{-1} at 0.5T + 3 nb^{-1} at 0.2T)
  - In line with projections by machine:
    3.1 nb^{-1}/month (Chamonix 2017)

$\sigma_{hadr,PbPb}$ = 8 barn !

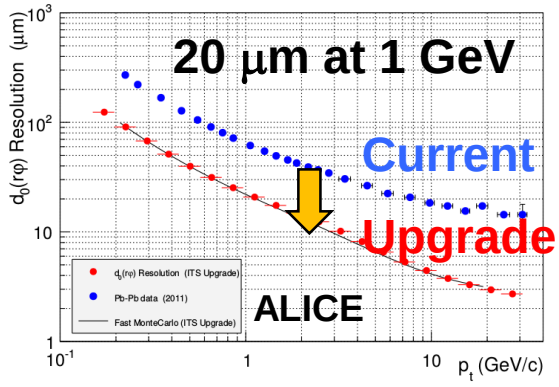
HL-LHC for heavy ions begins in Run 3 !

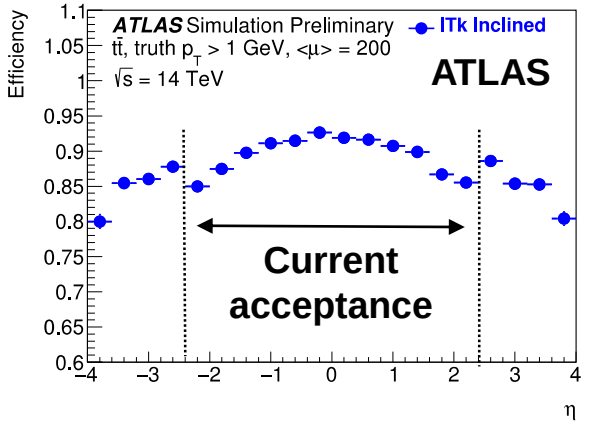


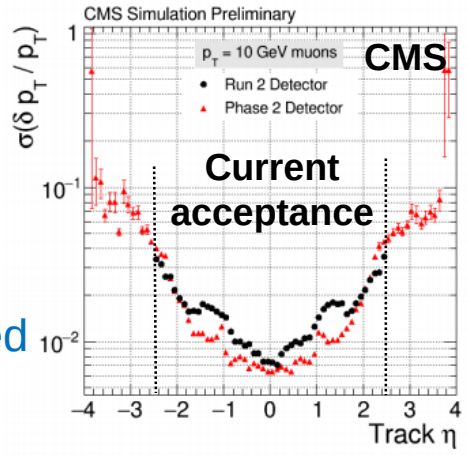
Detector Upgrades

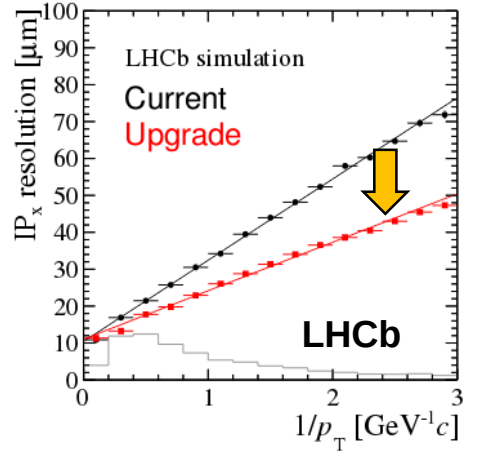
most relevant to heavy-ion physics

- **ALICE** (LS2)
  - New inner tracker: precision and efficiency at low p_T
  - New pixel forward muon tracker: precise tracking and vertexing for μ
  - TPC upgrade + readout + online data reduction x100 faster readout (continuous)
- **ATLAS** (LS2/LS3)
  - Fast tracking trigger (LS2): high-multiplicity tracking
  - Calorimeter and muon upgrades (LS2): electron, γ, muon triggers
  - ZDC replacement planned (LS2): radiation hardness, granularity
  - Completely new tracker (LS3): tracking and b-tag up to η=4
- **CMS** (mainly LS3)
  - Extension of forward muon system (LS2): muon acceptance
  - Completely new tracker (LS3): tracking and b-tag up to η=4
  - Upgrade forward calorimeter (LS3): forward jets in HI
- **LHCb** (LS2)
  - Triggerless readout, full software trigger, higher granularity detectors: impact on tracking performance in Pb-Pb being studied
  - Fixed-target programme with SMOG + possible extensions









Trigger/Readout Strategies

ALICE

- Main focus on “untriggerable” signals (extremely low S/B)
- Trigger approach: write all events at 50 kHz in Pb-Pb
  e.g. ALICE: ~1.1 TB/s → **O^2 facility** → ~90 GB/s (50 kHz)
- Increase of minimum-bias sample x100 wrt Run-2

LHCb

- Similar strategy than ALICE, but rates to be defined

ATLAS/CMS

- Main focus on muon, jet, displaced track triggers
- Trigger approach: strong event number reduction
  e.g. CMS: 50 kHz → **L1** → ~10 kHz → **HLT** → ~3 kHz
- Increase of minimum-bias (rare-trigger) sample x5 (x10) wrt Run-2

Heavy-Ion Physics in Run 3 and 4

Precision Physics

- Energy loss / qhat
  - Jets, b,γ,Z-jets, di-jets, colour/mass dep.
- Probe chiral symmetry restoration at $\mu_B = 0$
- QGP deconfinement and temperature
  - Quarkonia dissociation and regeneration
- Charm interaction with QGP
- Temperature dep. of transport coefficients
- Behaviour across system size
- High Q^2 and high-x nPDFs
- Ultraperipheral collisions
- Production of nuclei

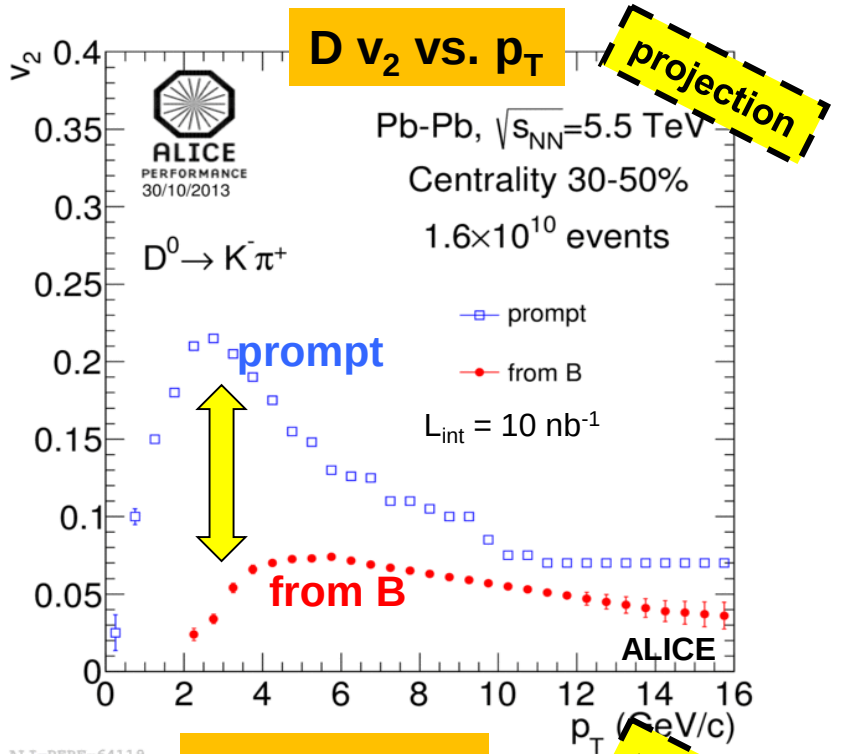
Novel Directions

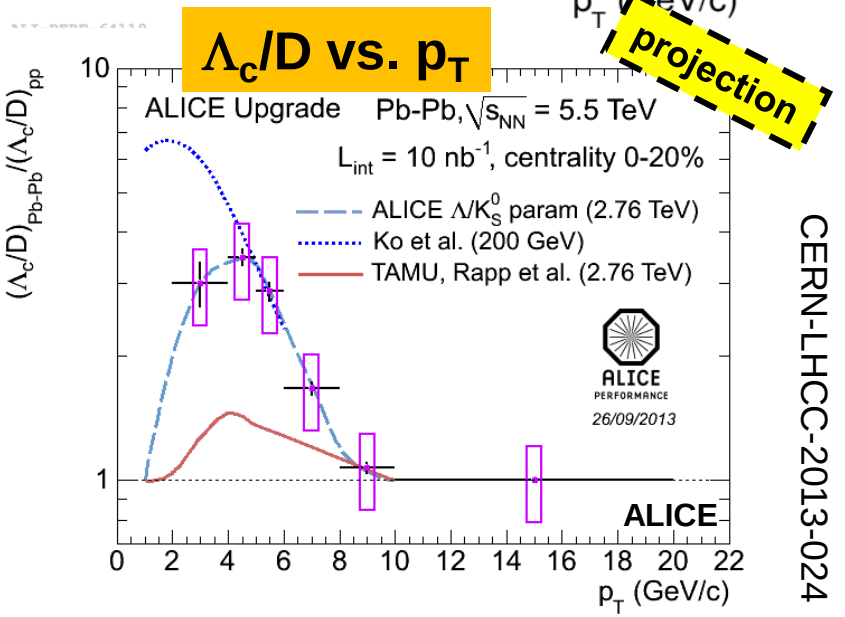
- Jet substructure
  - probe medium degree of freedom
- QGP temperature evolution
- Beauty thermalization
- Critical fluctuations, link to lattice QCD
- Collective behaviour of few particle systems
- Saturation at small x
- Light by light scattering
- Antihypernuclei and dibaryon

Existing documents: **ALICE** Upgrade LOI | MFT | ITS | MTK **ATLAS** projections | ITk **CMS** HI HL-LHC projections HI Town Meeting | Input to ESPG

Heavy Flavour

- Study QGP with tagged probe produced only initially which preserves identity during medium lifetime
- Do heavy quarks thermalize?
  - Charm and beauty v_2 down to $p_T = 0$
- How does charm recombine from the QGP?
  - D_s/D, Λ_c/D, Λ_b/B ratio
- Charm cross-section to $p_T = 0$
  - Reduce regeneration model uncertainties
- Beauty transport compared to lattice QCD





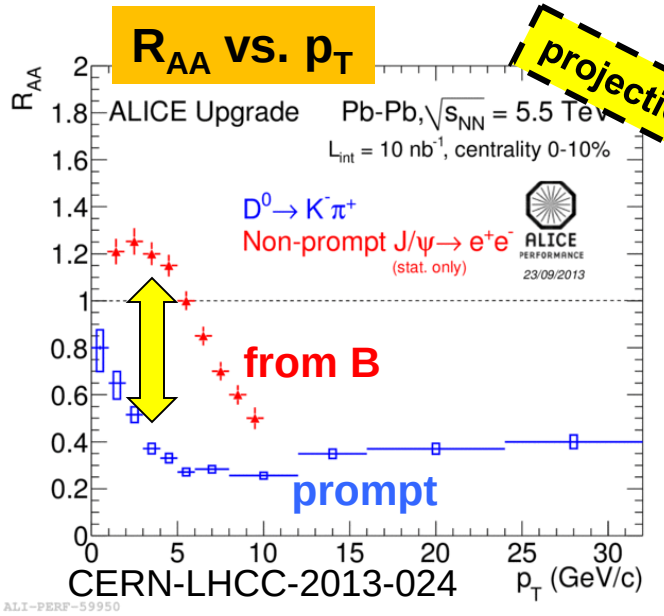
CERN-LHCC-2013-024

Jets / Energy Loss

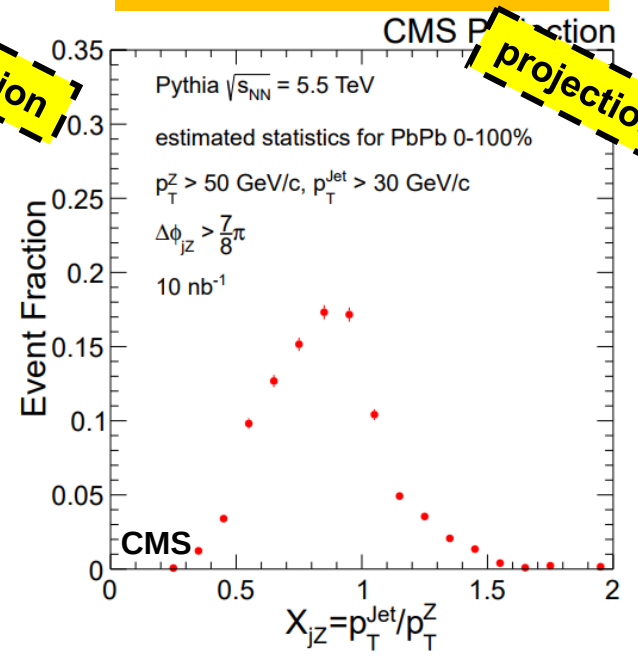
- Flavour dependence of energy loss
  - Charm and beauty R_{AA}
- Precise measurement of photon-jet and Z-jet asymmetry
- Suppression at TeV scale
- Flavour dependence of fragmentation function

- Jet substructure observables
  - Medium-modified splitting
  - Colour coherence
  - Probe QGP degrees of freedom (quasiparticles vs. fields)

R_{AA} vs. p_T

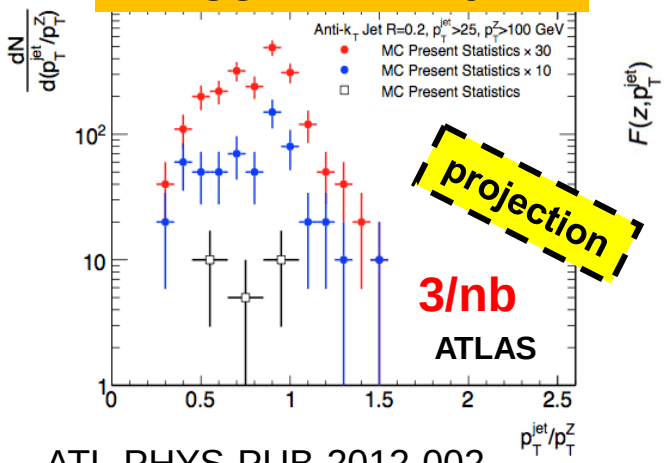


Z tagged recoil jets



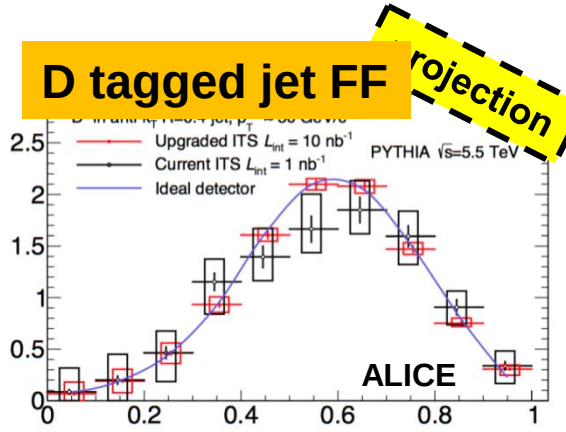
CMS-PAS-FTR-13-025

Z tagged recoil jets



ATL-PHYS-PUB-2012-002

D tagged jet FF



CERN-LHCC-2013-024

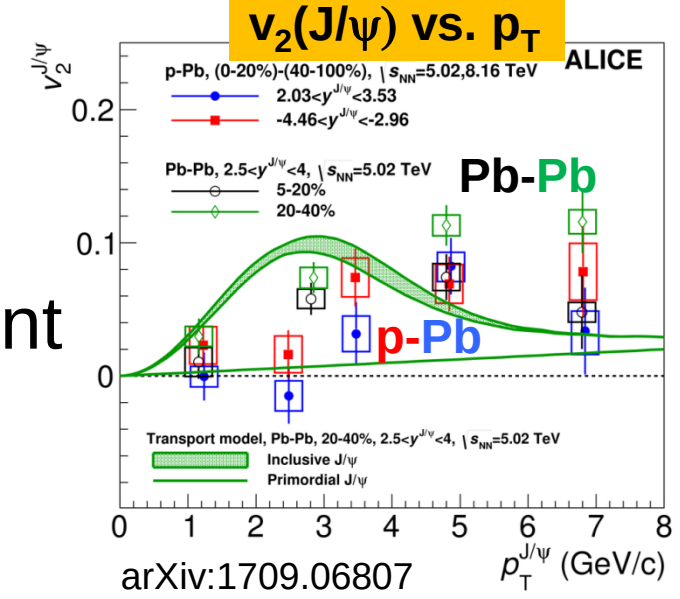
Quarkonia

- J/ψ flow precision measurement
- Compare states with different binding energy
  - Melting and regeneration
  - Formation models
- Bottomonia flow in reach

Υ(1S)	Υ(2S)	Υ(3S)
270k	40k	7k

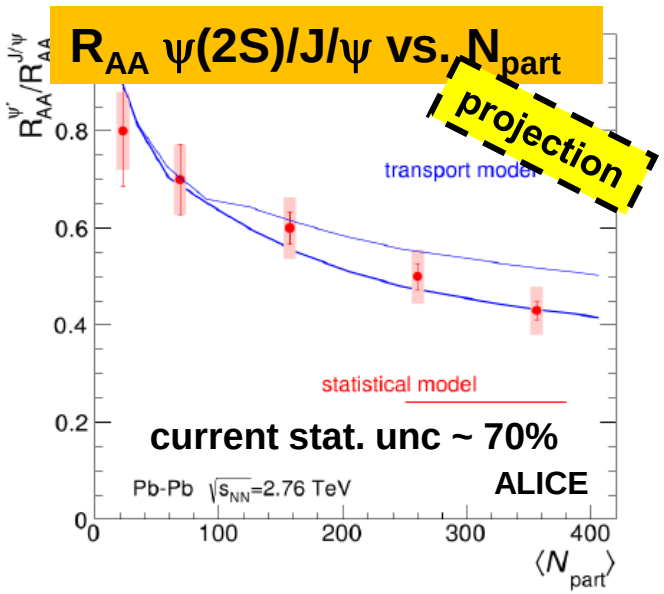
(in CMS in 10nb^{-1})

v_2(J/ψ) vs. p_T

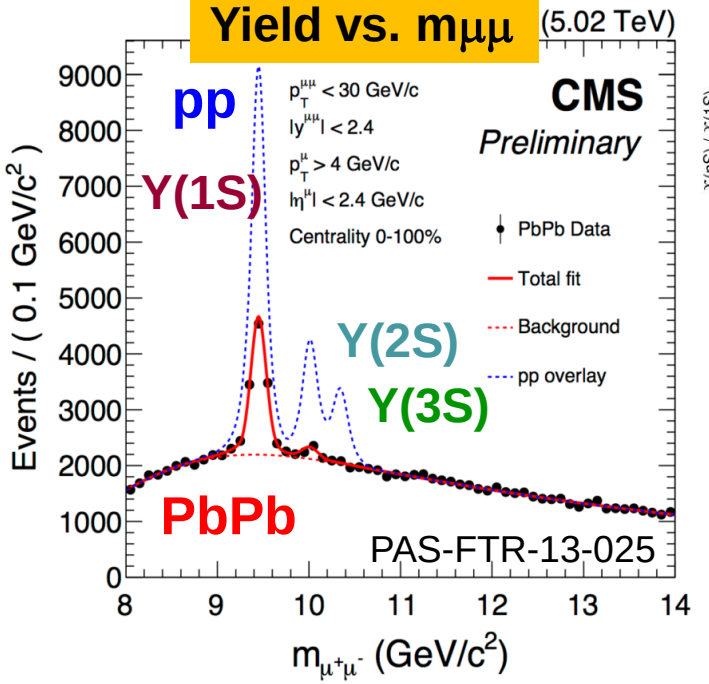


arXiv:1709.06807

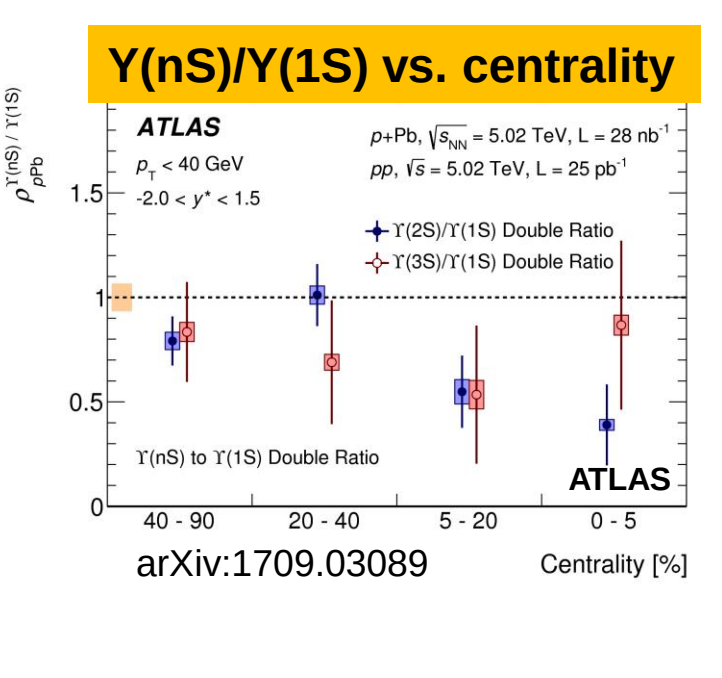
R_{AA} ψ(2S)/J/ψ vs. N_{part}



Yield vs. mμμ

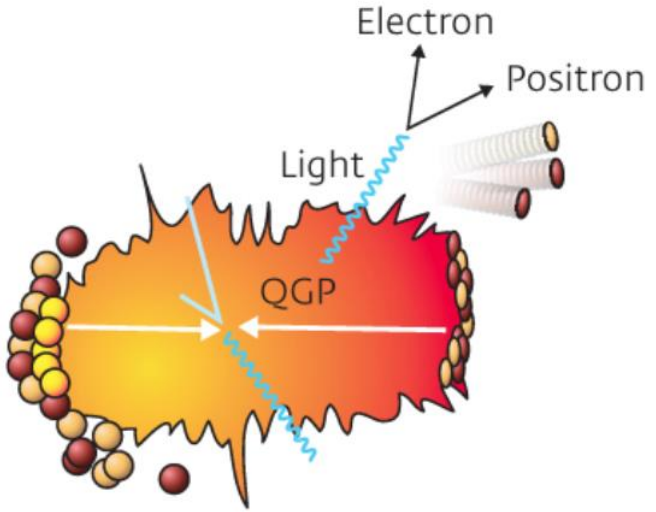


Υ(nS)/Υ(1S) vs. centrality

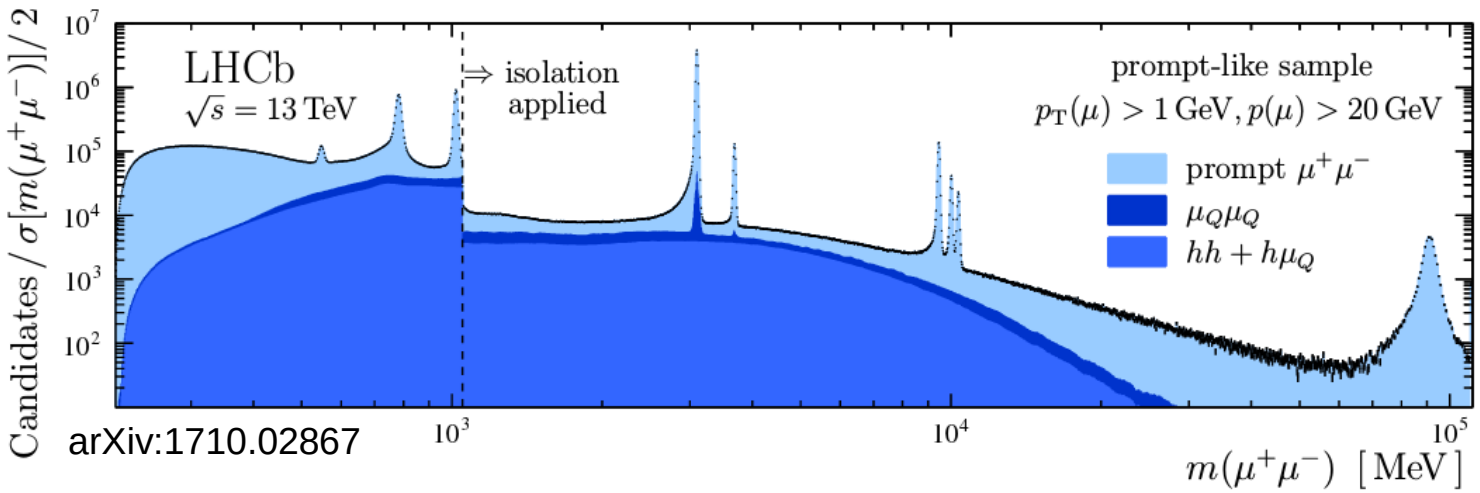


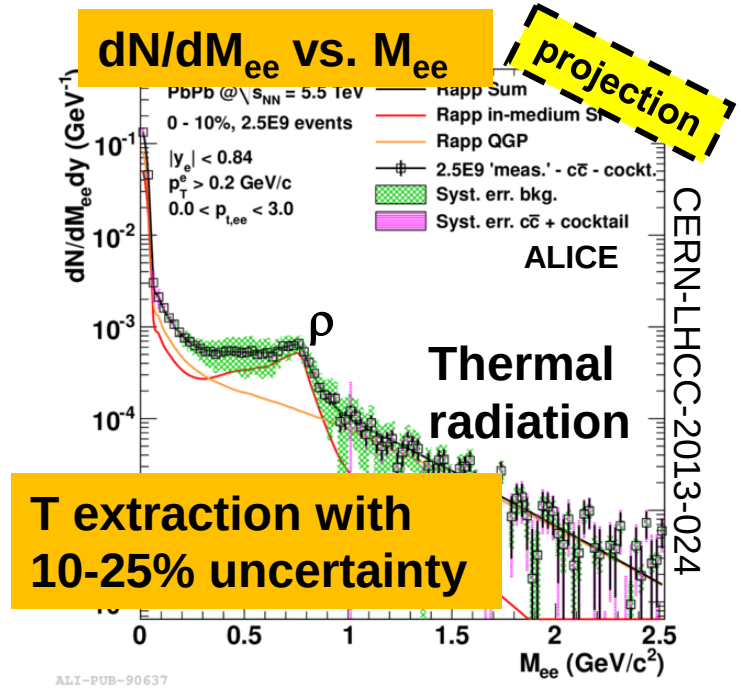
arXiv:1709.03089

(Low-mass) Dileptons



- Time dependence of QGP temperature
  - Black body radiation from QGP
- Change of ρ spectral function when chiral symmetry is restored



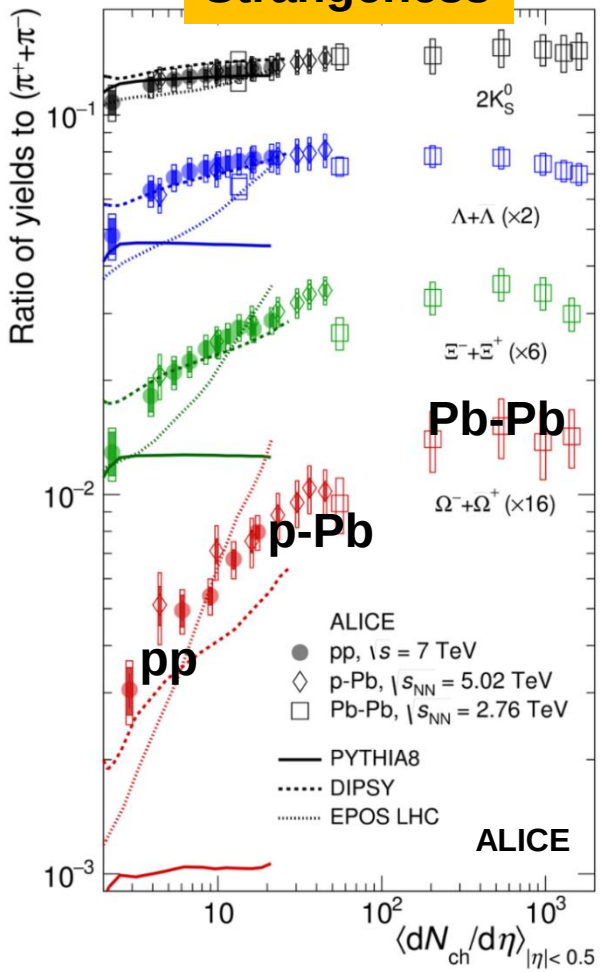


- LHCb potential to be explored (pp, p-Pb, Pb-Pb)

Small Systems

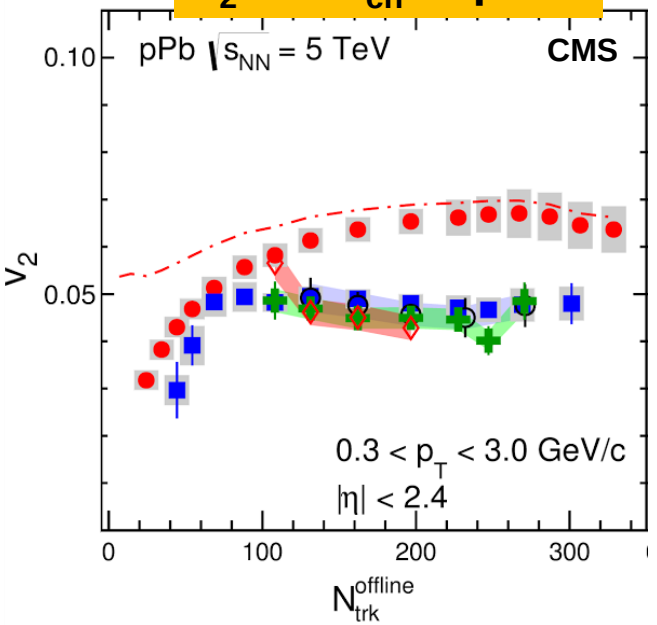
- pp and p-Pb collisions initially only discussed as reference
- Today: *novel* field, studying non-perturbative “heavy-ion” like effects in absence of large medium
- HL: search for collective effects in HF, thermal radiation, quenching
- What is smallest droplet of matter showing collective behavior?
- Origin of collectivity in few particle system? (color reconnection, gluon interference, escape, …)

Strangeness



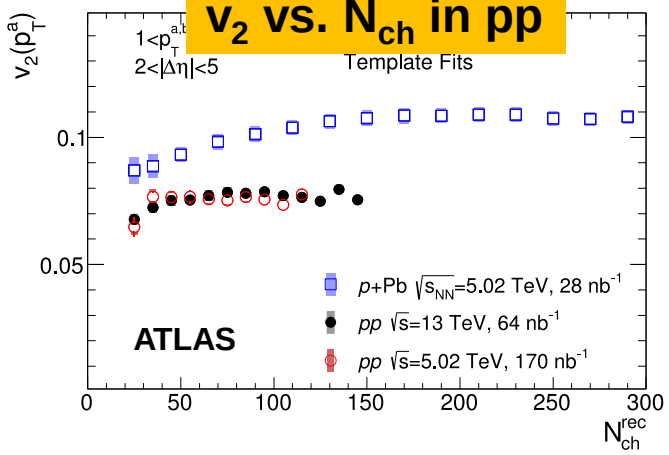
Nat. Phys. 13 (2017) 535

v_2 vs. N_{ch} in p-Pb



PRL115,012301(2015)

v_2 vs. N_{ch} in pp

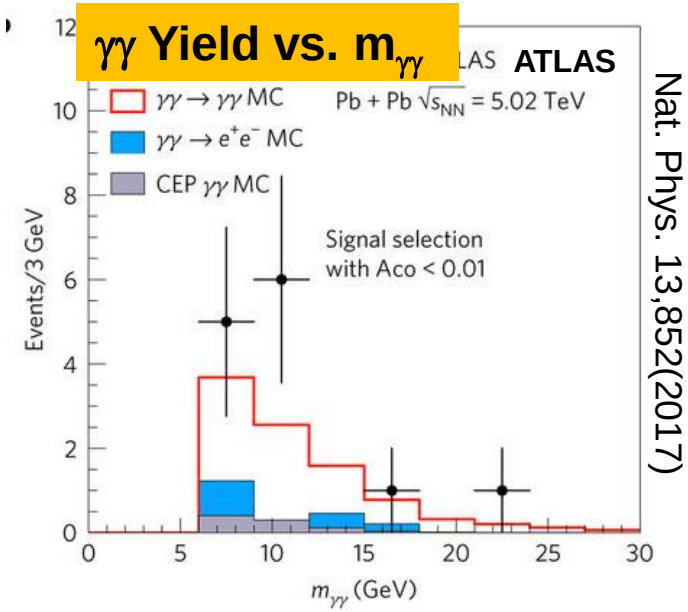


PRC 96 (2017) 024908

Further Directions

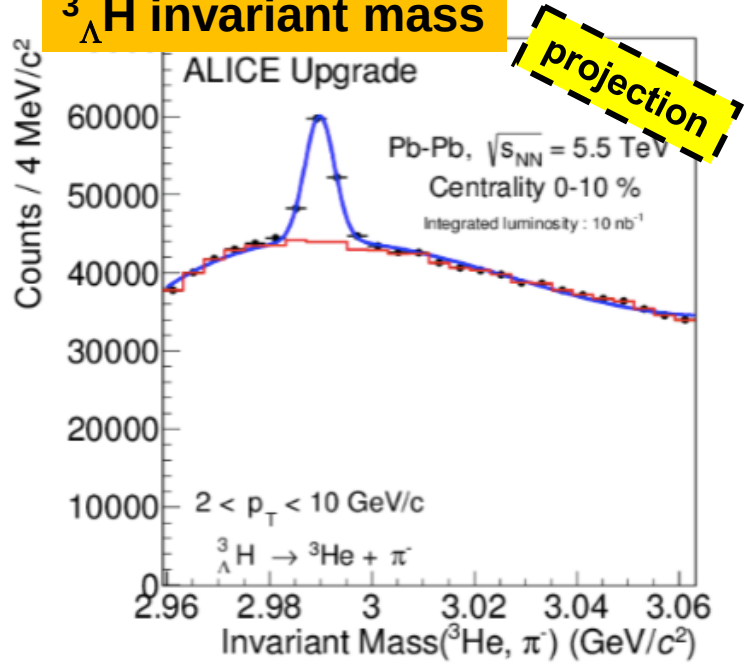
- Ultraperipheral collisions
  - Light-by-light scattering
  - Photo-nuclear collisions → nPDFs
- Light nuclear states
  - Dynamical coalescence vs. statistical thermal production
  - Discovery of (anti-)(hyper-)nuclei and (strange) dibaryons
  - Precision of $^{3}_{\Lambda}$H lifetime and spectrum
- Lighter ions
  - Increase of hard yields and system-size dependence
  - Potential in overall programme and optimal species to be established

γγ Yield vs. $m_{\gamma\gamma}$



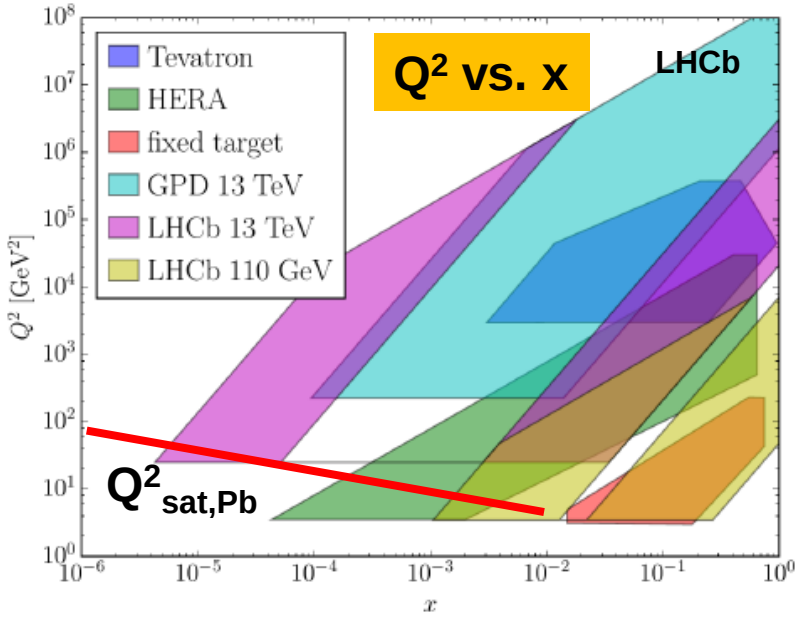
Nat. Phys. 13,852(2017)

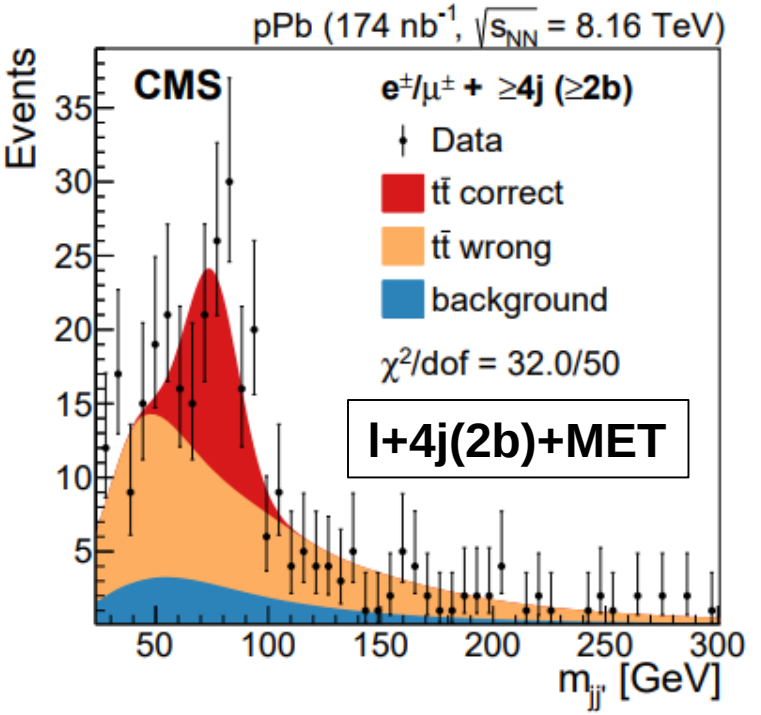
$^{3}_{\Lambda}$H invariant mass



p-Pb and Fixed Target

- Nuclear PDFs
- Saturation
- Forward access to x = 10^{-6}
- Fixed target with SMOG system in LHCb
- Top
  - Recent “discovery” in p-Pb
  - Probe large Q^2 – large x region
  - HL: 10xstats allows rapidity dep. measurement
    - and “discovery” in Pb-Pb (500-900 ttbar rec. expected)





arXiv: 1709.07411

Parallel Session Structure

- WG5 aims
  - Sharpen and document physics program for Run 3 and 4
  - Explore future directions beyond Run 4 and for HE-LHC

Session 1	Tuesday 11:00 – 13:00	4-3-006	Guided discussion: Heavy flavour and Quarkonia Talk: Radiation/low-mass dileptons
Session 2	Tuesday 14:00 – 16:00	160-1-009	Guided discussion: Jets/energy loss Guided discussion: Flow/correlations
Session 3	Tuesday 16:30 – 18:30	160-1-009	Guided discussion: Flow/correlations (cont.) Guided discussion: Small systems
Session 4	Wednesday 9:00 – 10:30	40-S2-A01	Talk: Cosmic ray physics Guided discussion: nPDFs/small-x/UPC
Session 5	Wednesday 11:00 – 13:00	40-S2-A01	Talk: Identified spectra and nuclei Open question session: LHC and beyond

Summary

- Heavy-ion physics addresses fundamental aspects of QCD in particular in the non-perturbative regime

- Heavy ions are and will be an integral part of the LHC program
  - with precision physics and discoveries

- ALICE, ATLAS, CMS and LHCb promise rich physics results

We wish you a productive workshop!