J/ψ-in-jets with CMS

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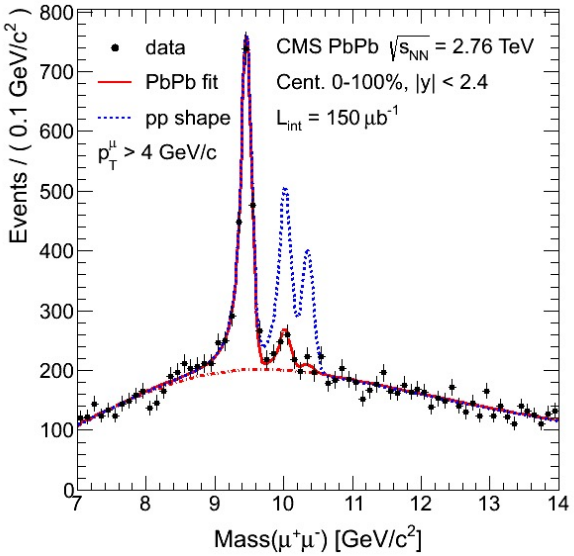
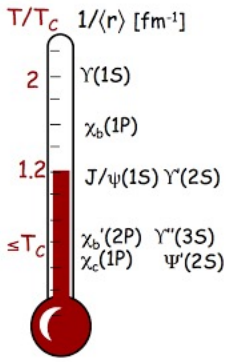
PhD thesis project of Dr. Batoul Diab

Hot nuclear matter effects

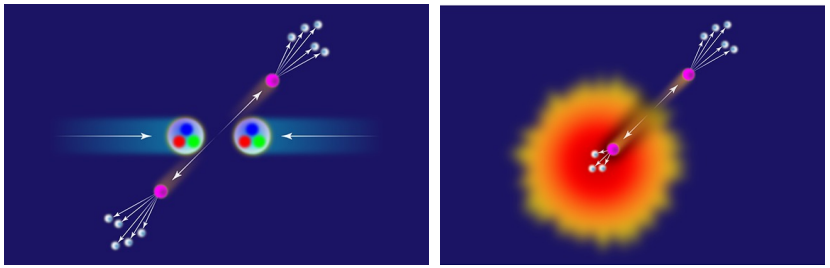
Quarkonium dissociation

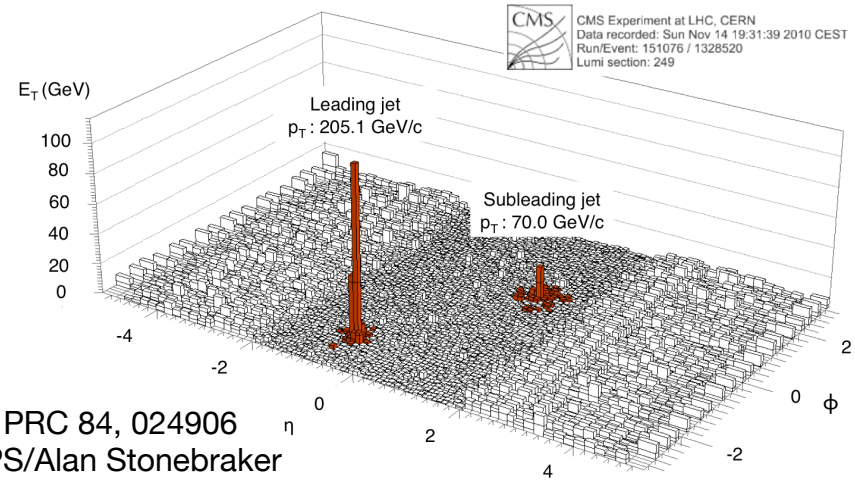




Data from CMS, PRL 109, 222301
Cartoon from Mocsy, EPJC 61 (2009) 705

Jet quenching



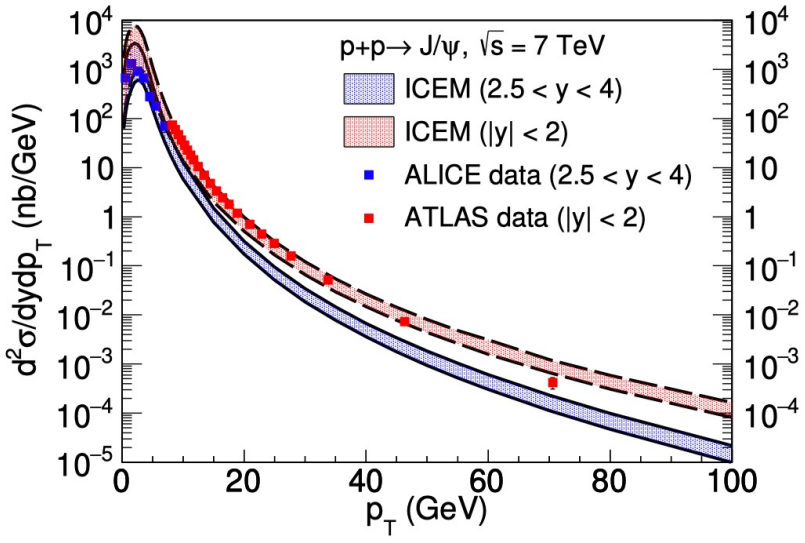


Data from CMS, PRC 84, 024906
Cartoon from APS/Alan Stonebraker

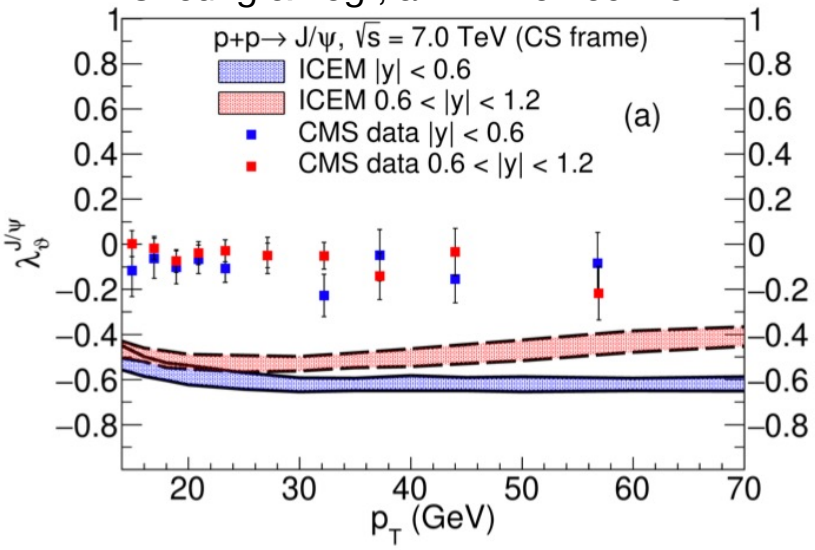
- Two phenomena closely tied to QGP formation in heavy-ion collisions
- First observed at the SPS & RHIC; intensely studied at the LHC
- No obvious connection between these phenomena, a priori

Quarkonium production puzzle

- Determination of nuclear effects requires accurate description of baseline from pp
- Heavy-quark pair x-section calculable, but not transition to color-singlet bound state
- Vast literature w/ many different approaches to hadronization, e.g., CEM, NRQCD etc.



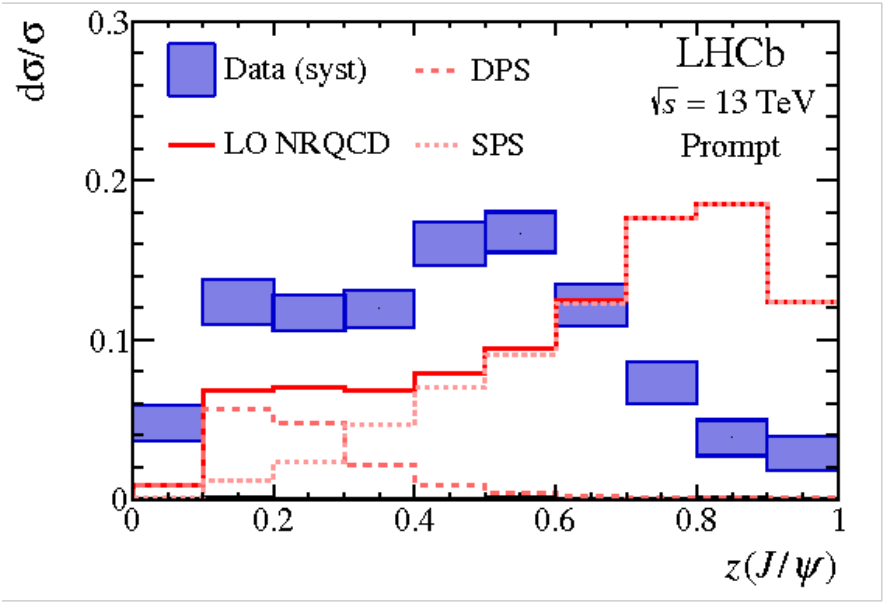
Cheung & Vogt, arXiv:2102.09118

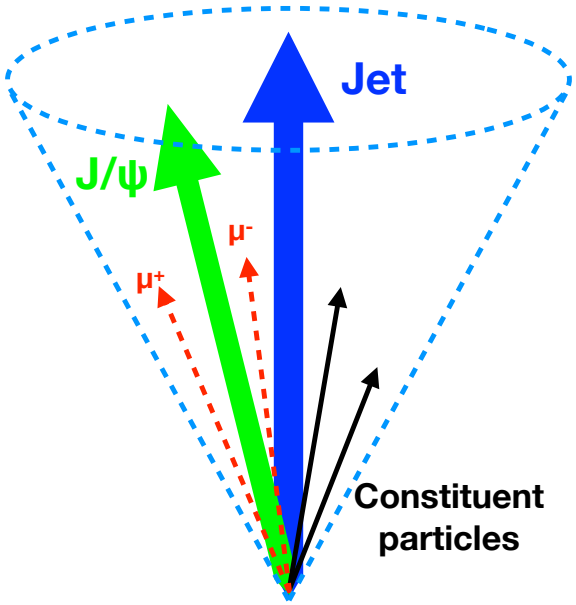


- Models have trouble simultaneously describing p_T–differential x-section & polarization
- Illustrative example: recent results from Improved Color Evaporation Model (ICEM)

A new observable: J/ψ-in-jets

- Not a correlation of J/ψ & jets, rather clustering of J/ψ *into* jets
  → the decay muons are replaced w/ J/ψ before clustering
- Observable is $z = p_T$ (J/ψ) / p_T (jet)



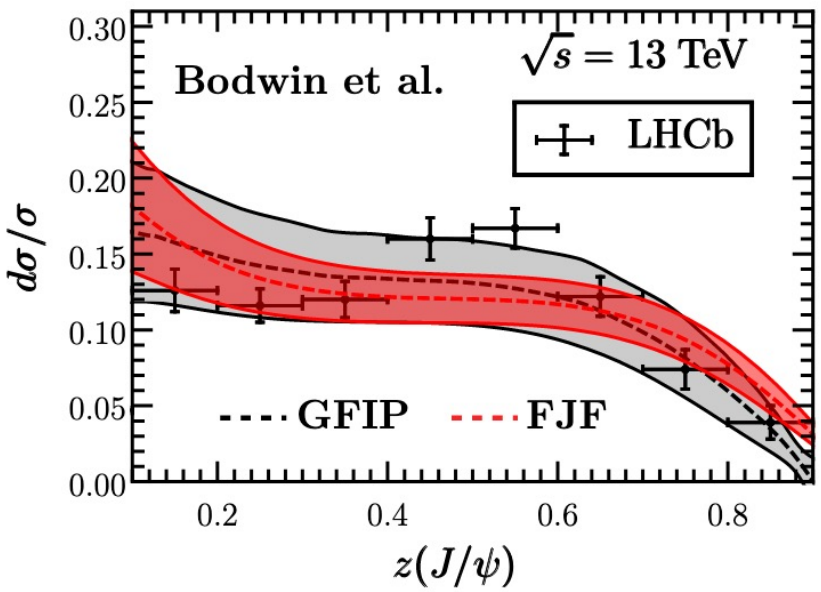


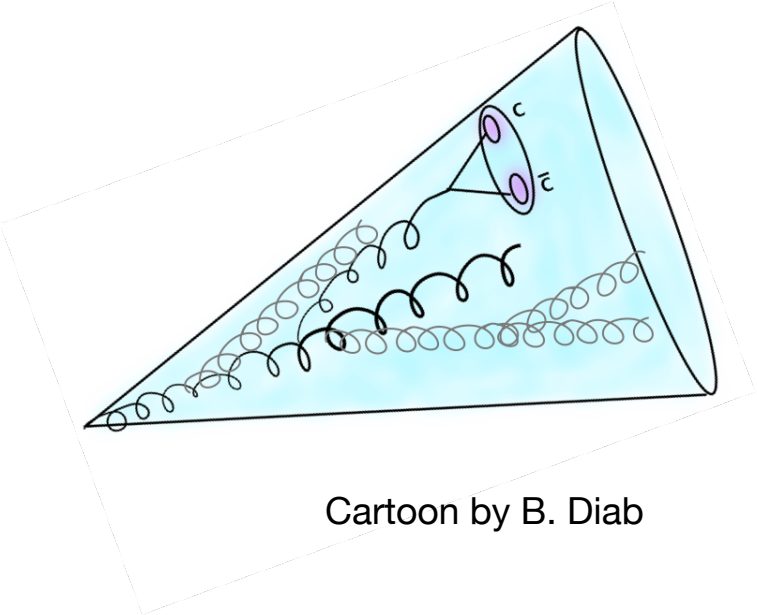
Cartoon adapted from Q. Yang

- J/ψ in pp data fragment softer than models, i.e., more jet activity
- At very low *z*, contribution from double parton scattering

Quarkonium puzzle resolved?

Bain et al., PRL 119 (2017) 032002



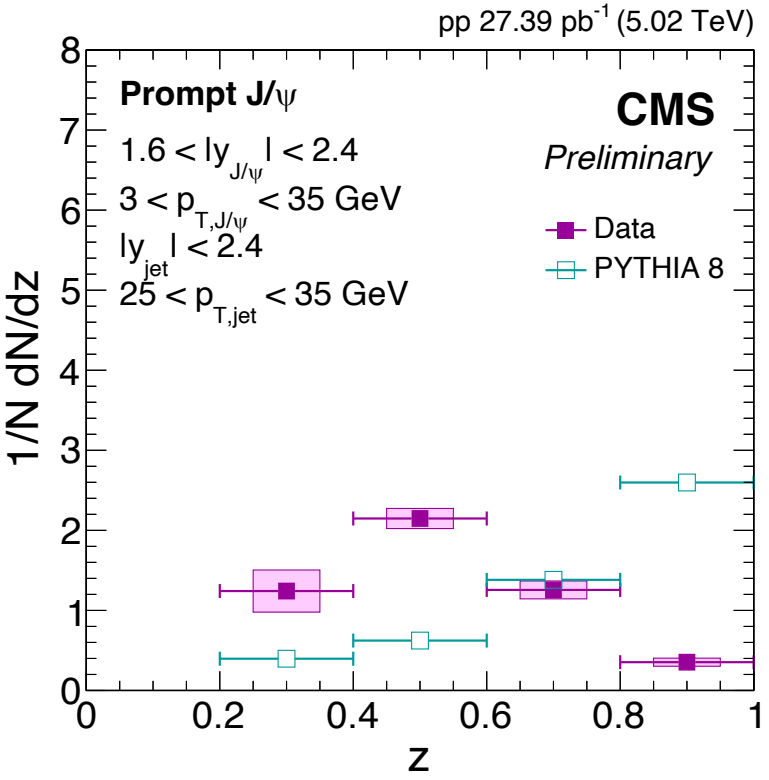


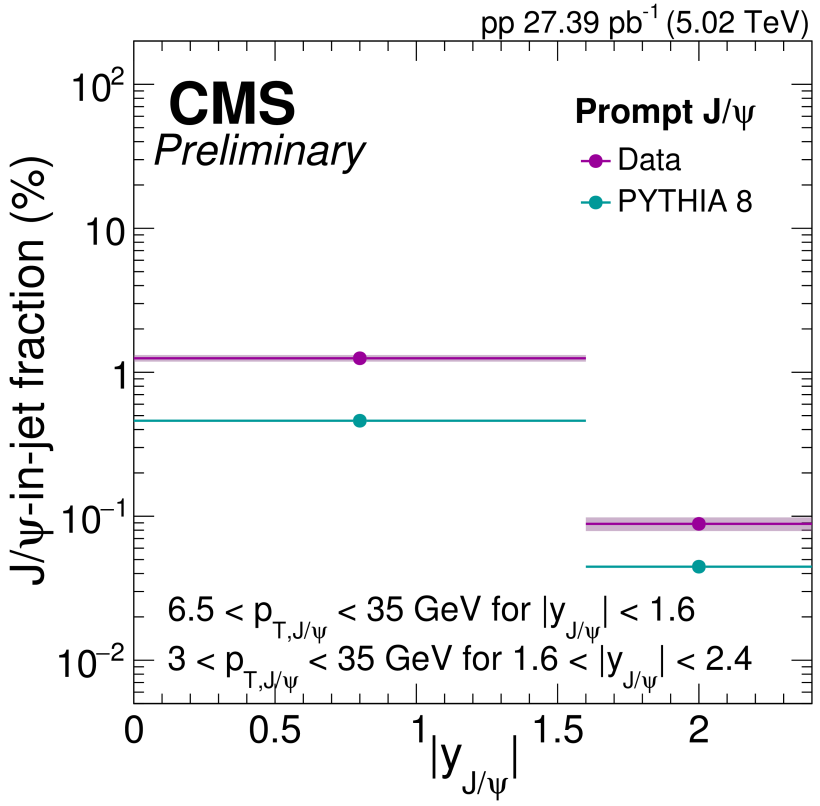
Cartoon by B. Diab

- Resummed calculations (NLL') describe J/ψ production in parton showers
- GFIP and FJF are two prescriptions for matching these calculations to Pythia
- Calculations shown for one choice of NRQCD matrix elements (Bodwin et al.)

➢ Reproduces data well, with a large jetty component to J/ψ production

pp measurement from CMS

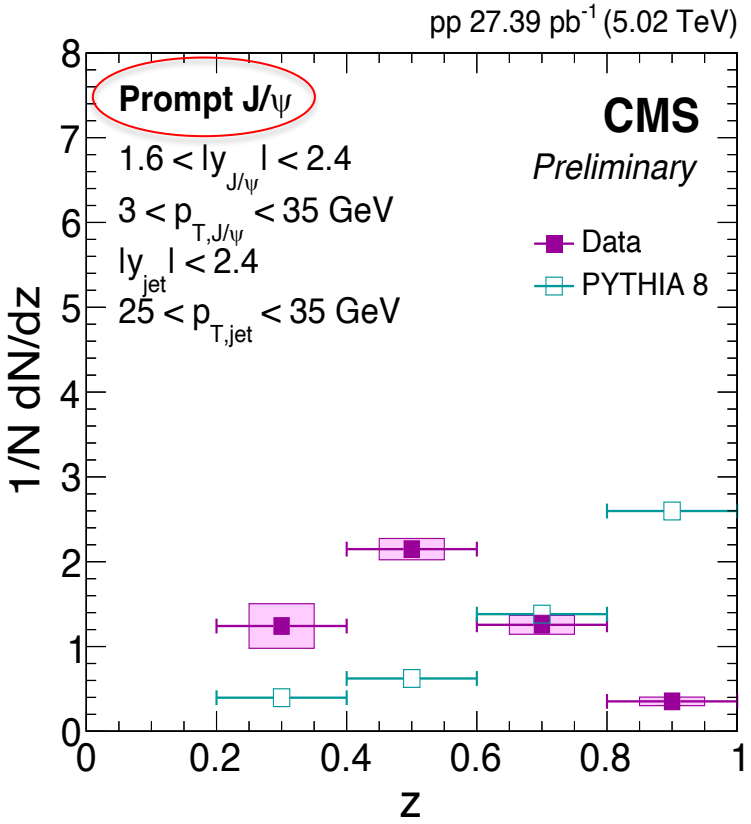


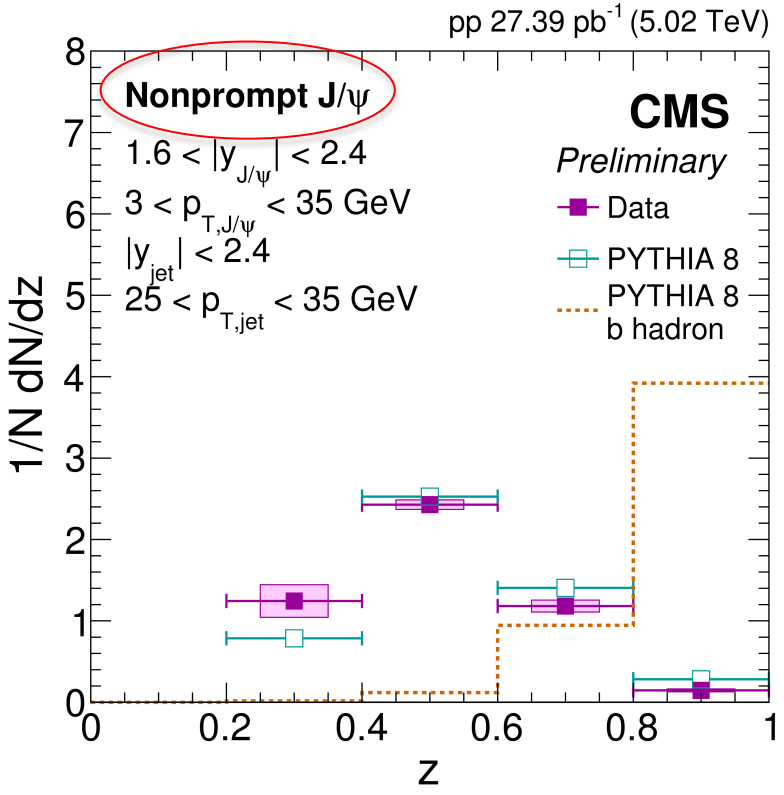


CMS-PAS-HIN-18-002

- Preliminary CMS results used 2015 pp data
- Larger gluon fragmentation component w.r.t. charm, compared to LHCb kinematics
- Observe same qualitative difference btwn data and Pythia (based on NRQCD)
- Fraction of J/ψ in high p_T jet is small & underestimated by simulation

Aside: Nonprompt J/ψ

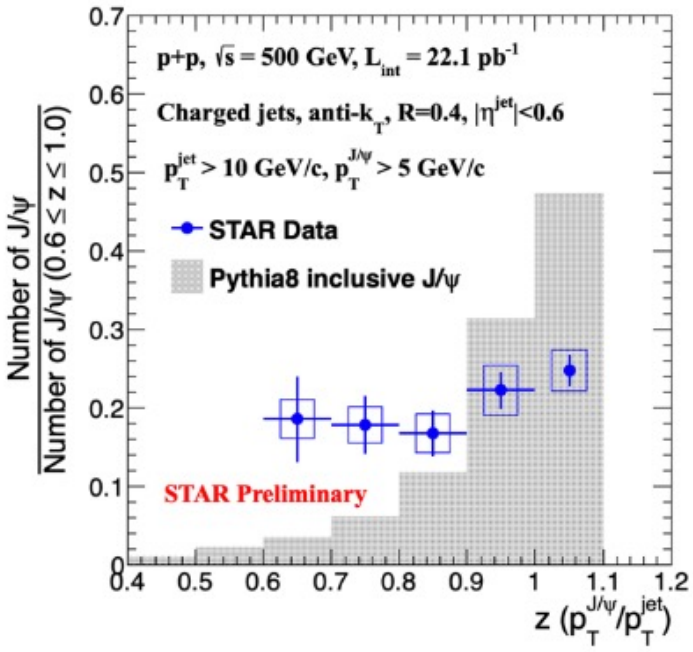


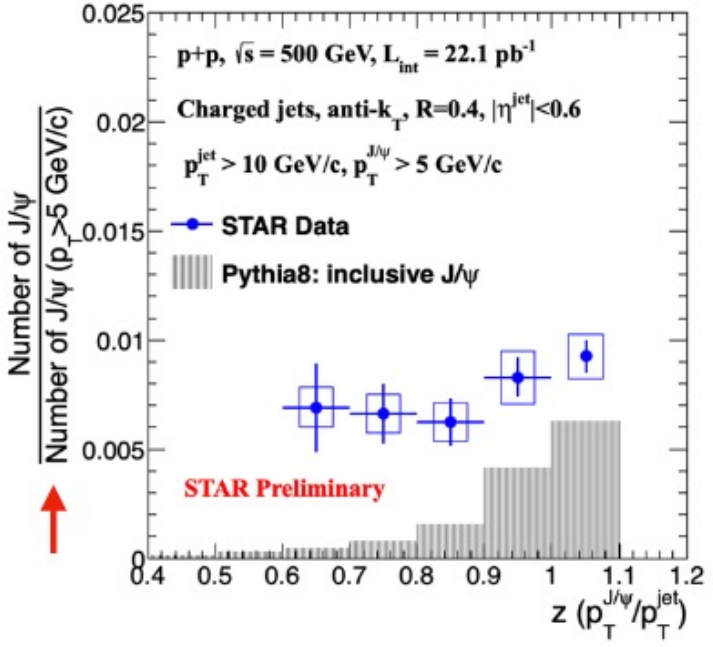


- Nonprompt J/ψ are from b-hadron → J/ψ + X, with a wide variety of channels
- In contrast to prompt J/ψ, such decays are very well modeled by generators
- The z distribution ends up being very similar for prompt and nonprompt J/ψ
- Coincidental, as nonprompt *z* distribution driven by b-hadron decay kinematics
- Well-known from LEP that for b-hadrons, $< z > \approx 0.8 – 0.9$

STAR joining the game

- Several differences w.r.t. CMS: $\sqrt{s}$, p_T & rapidity selections, jet reconstruction & resolution unfolding, prompt/nonprompt separation
- Nevertheless, qualitatively similar conclusions:





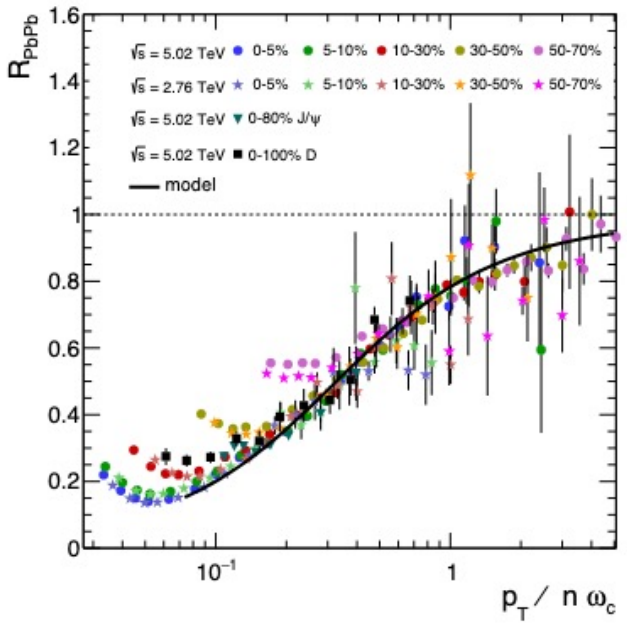
Fragmentation softer than models

Fraction in high p_T jets underestimated

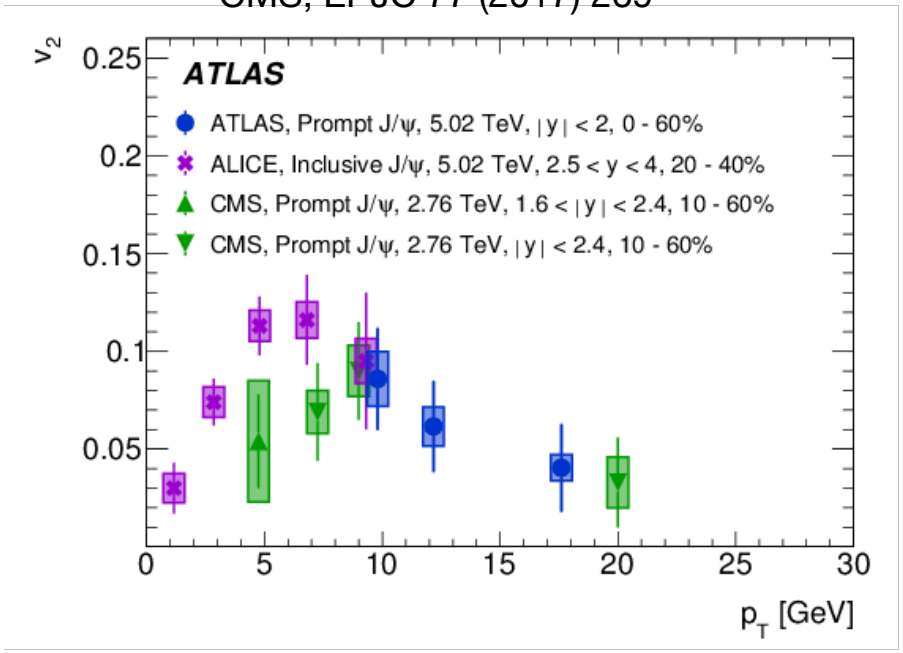
NB: Point at z > 1 corresponds to exactly z =1, displaced for clarity

Motivation for a PbPb measurement

Arleo, PRL 119 (2017) 062302



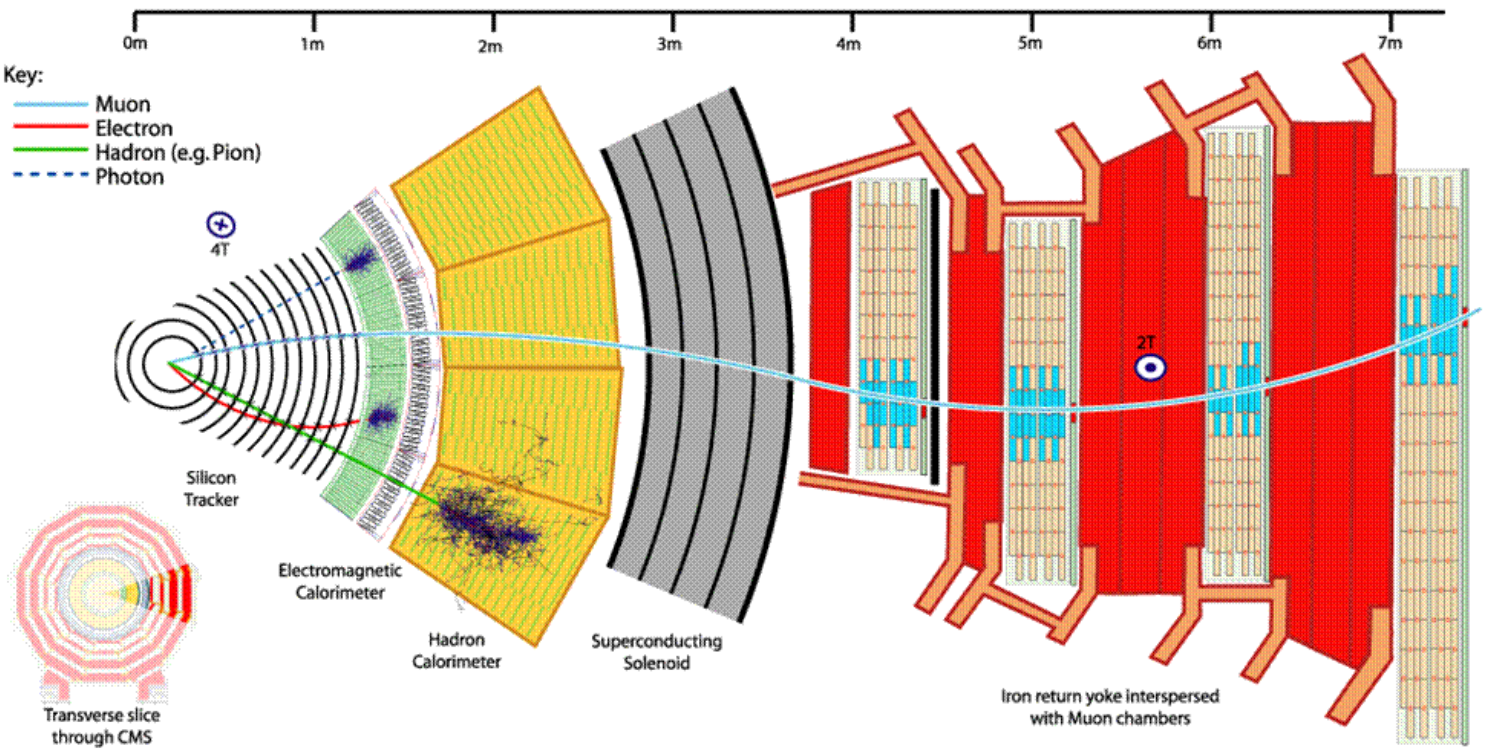
ATLAS, EPJC 78 (2018) 762
ALICE, PRL 119 (2017) 242301
CMS, EPJC 77 (2017) 269



- J/ψ suppression vs. p_T exhibits same rising trend as other hadron species
- Consistent w/ a universal trend that is well-described by parton-energy loss

J/ψ v_2 has a non-zero value at large p_T, where energy-loss thought to dominate

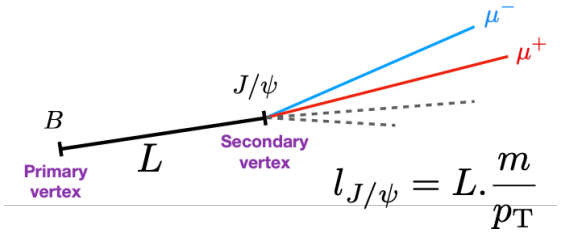
The CMS experiment

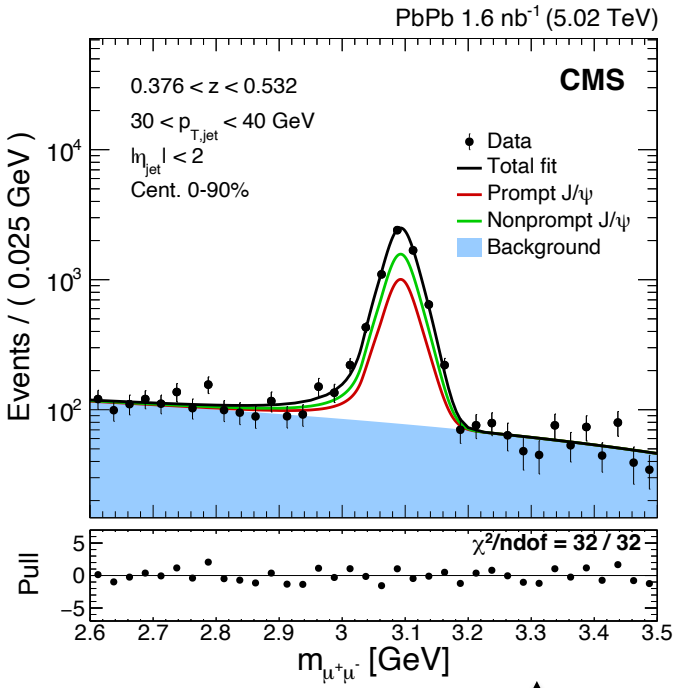


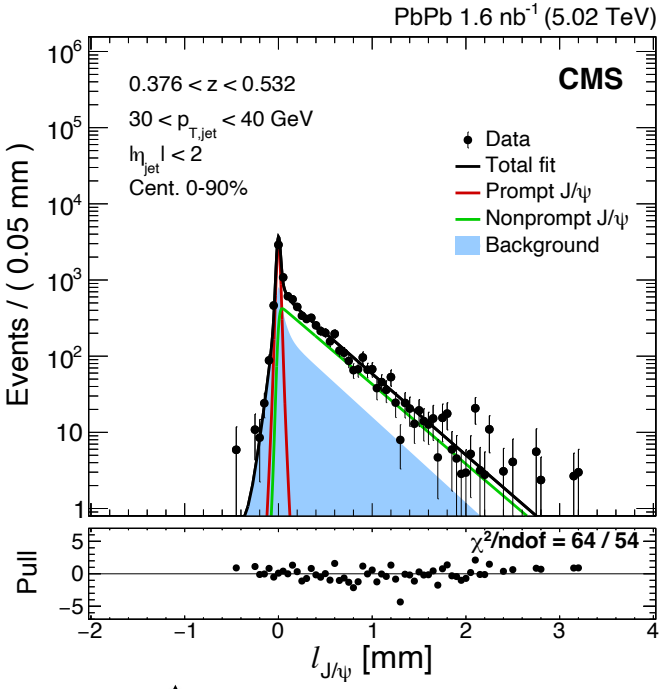
- Muon detection: silicon tracking in 4T B-field + muon chambers
- Jet measurement: Hermetic ECAL + HCAL combined w/ tracking ("particle flow")
- Large acceptance: Full R = 0.4 jets inside $|\eta| < 2$, w/ full muon coverage
- Data consists of dimuon triggered events using 1.6 nb^{-1} of PbPb data (2018) & 302 pb^{-1} of pp data (2017), both at collision energy of 5 TeV

Yield extraction

- Sizeable fraction of J/ψ from decays of b-hadrons
- Component separated w/ 2D fit to mass & decay length







Fit model:

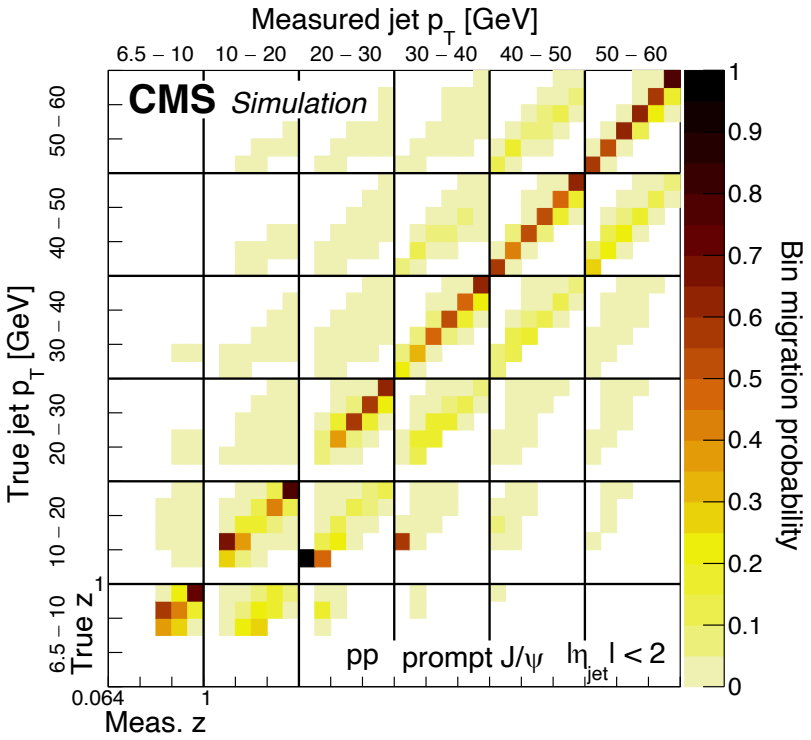
Double Crystal Ball + polynomial

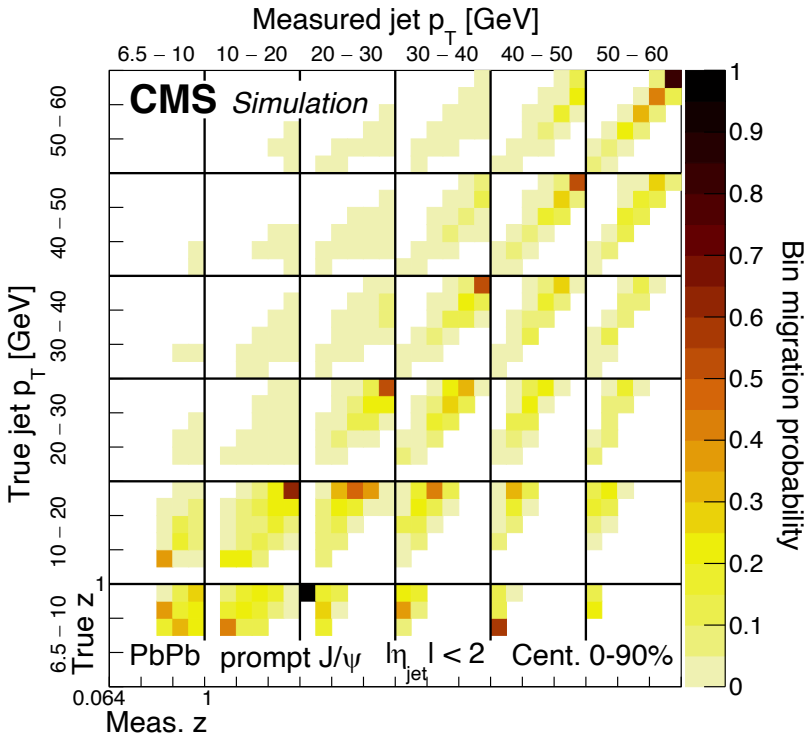
Exponential + Delta + Gaussian smearing

- Muon efficiency corrected in-situ using the tag-and-probe technique

Bin migration from jet resolution

Jets: anti-k_T, R = 0.4 "Constituent subtraction"* for PbPb underlying event

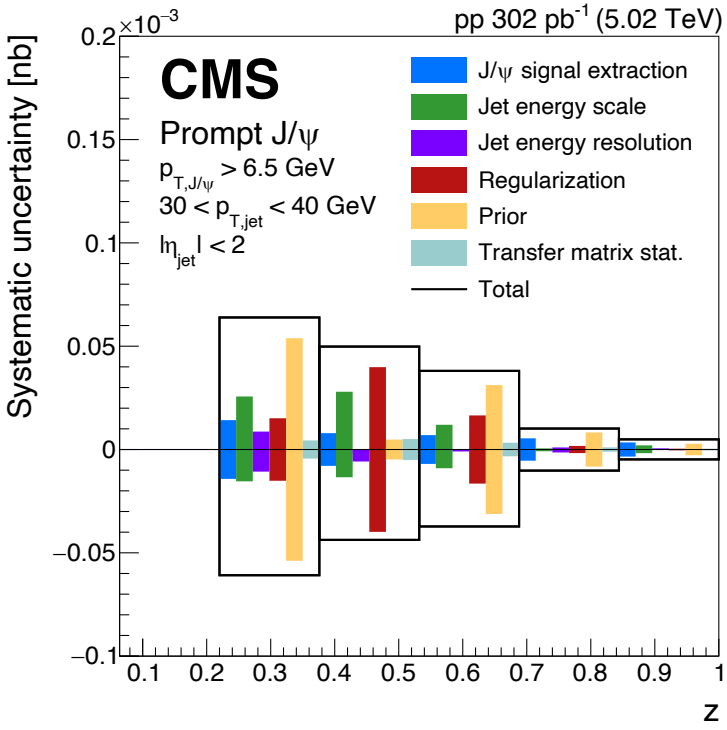




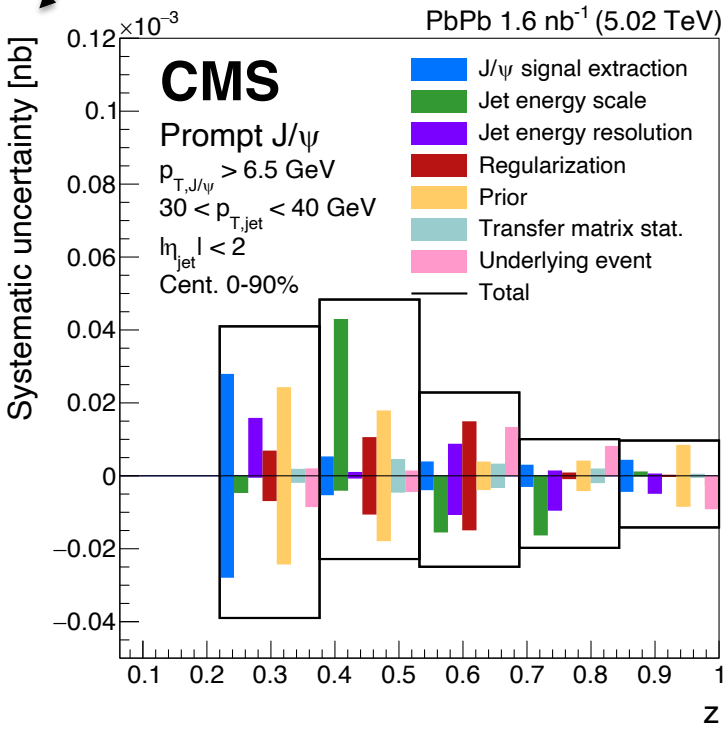
- Wide jet resolution causes bin migration both in *z*, but also in jet p_T
- 2D unfolding performed with iterative D'Agostini algorithm
- Jet energy scale and resolution calibrations
  - Applied only to non-J/ψ component of jet
  - Residual in-situ corrections from boson-jet and dijet balancing

*Berta et al, JHEP 1406 (2014) 092

Systematic uncertainties

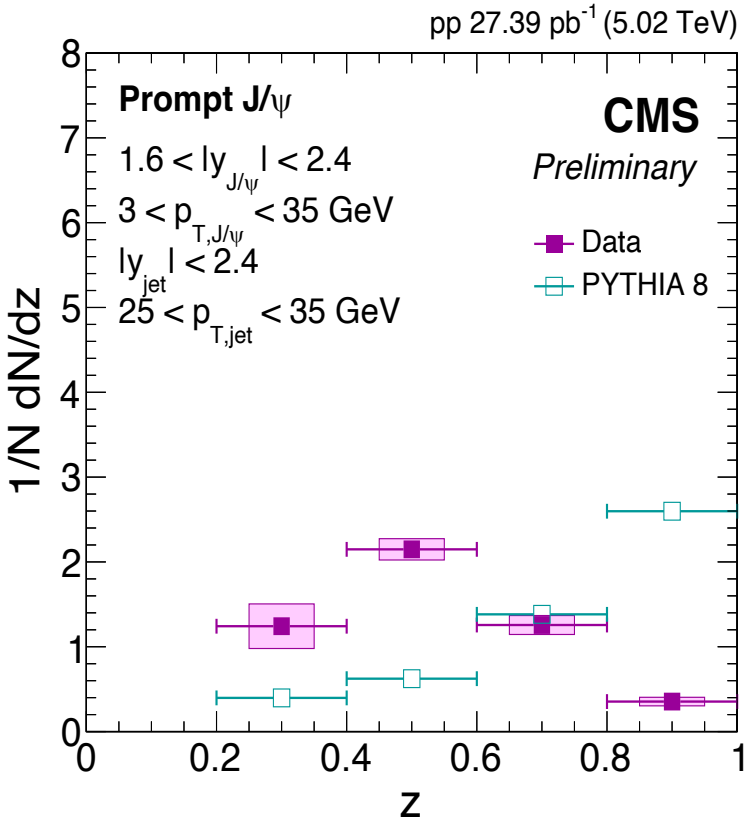


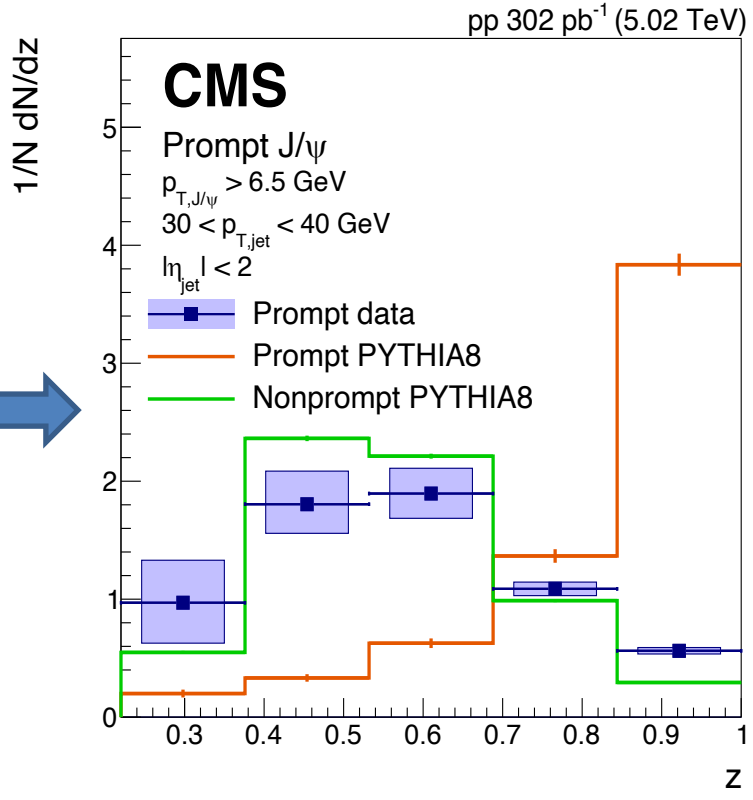
Plotted as absolute errors



- Jet uncertainties dominate for most bins
  - Unfolding uncertainties include variation of prior & choice of regularization
  - Jet energy scale and resolution important contributions in some bins
  - Underlying event modeling included in PbPb (sub-dominant)
- J/ψ extraction uncertainties only dominant in lowest *z* bin in PbPb

Updated pp results





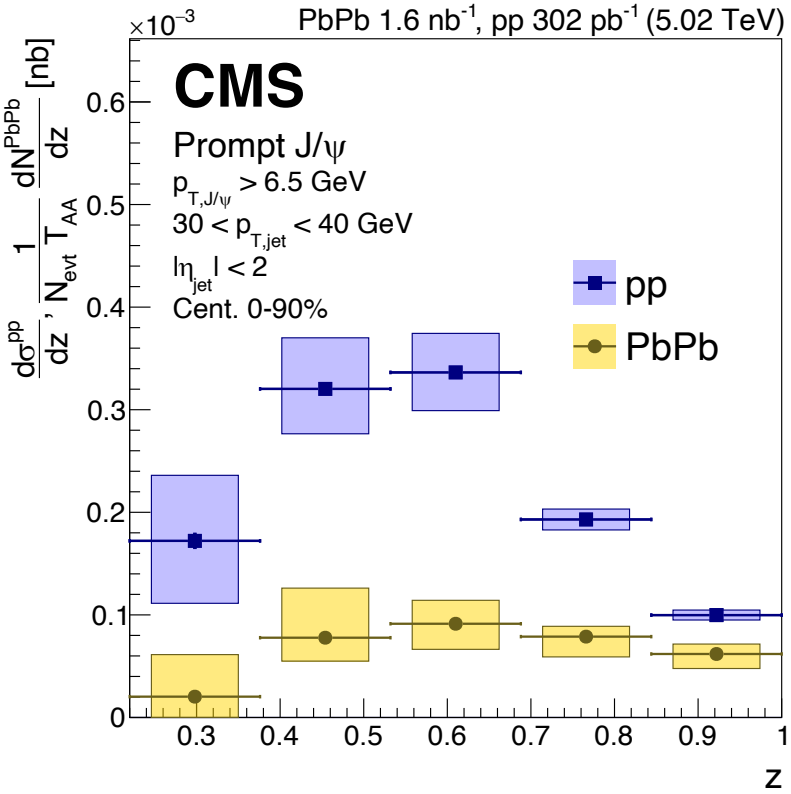
- 10x larger data sample of pp collisions in 2017 w.r.t. 2015
- Kinematic cuts adjusted to take better advantage of CMS acceptance
- Results qualitatively similar to previous ones

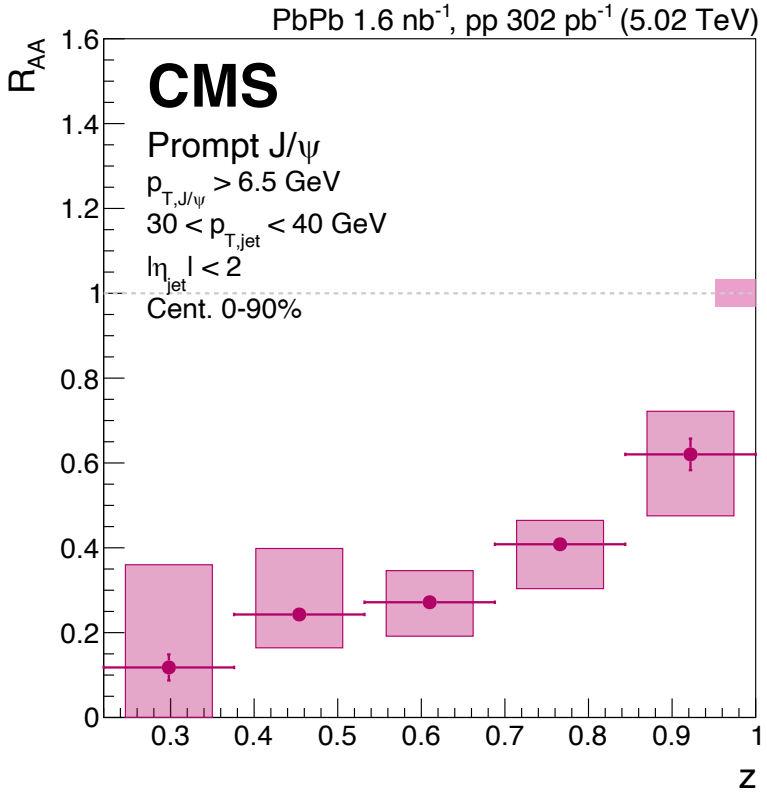
Nuclear modification

$$R_{\mathrm{AA}}(z) = \frac{T_{\mathrm{AA}}^{-1} * N_{\mathrm{evt}}^{-1} * dN^{PbPb}/dz}{d\sigma^{pp}/dz}$$

← Per-event yield in PbPb

← x-section in pp



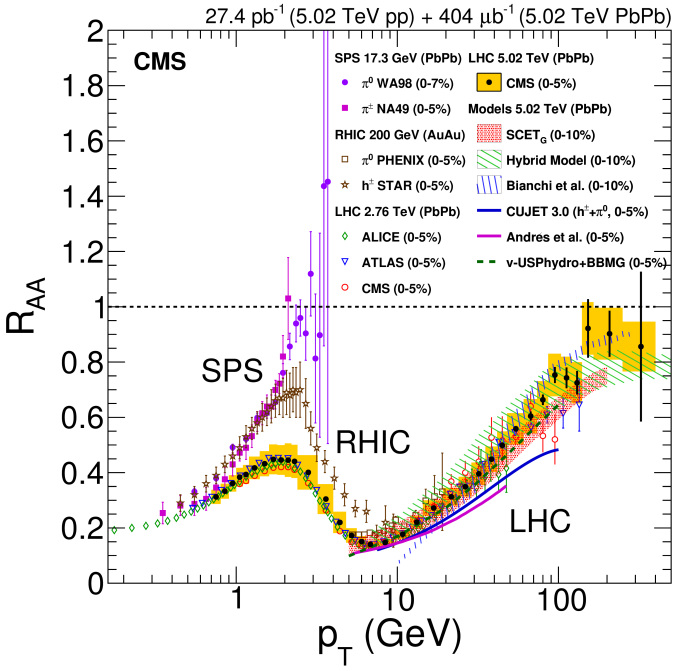


- Yield of J/ψ in PbPb suppressed at all values of *z*, w.r.t. pp
- Systematic uncertainties do not permit a precise statement, but data are consistent with a decreasing suppression with increasing *z*

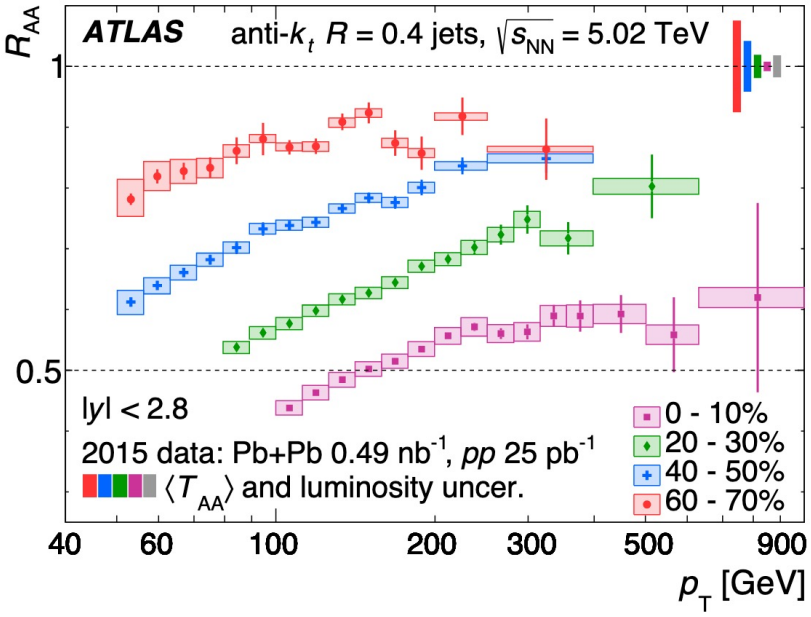
➢ Consistent with picture in which "direct" J/ψ are less suppressed

Connection to light flavor sector?

CMS, JHEP 1704 (2017) 039



ATLAS, PLB 790 (2019) 108



- Whereas inclusive charged hadron R_{AA} rises continually w/ p_T almost to unity, jets flatten out in central events staying suppressed until the largest p_T probed
- One interpretation, similar to J/ψ-in-jet, quenching depends on parton shower multiplicity, such that hard fragmenting jets are less suppressed

Conclusions / Outlook

- J/ψ more jet-like than predicted by most models
  - Potential explanation of long-standing quarkonium puzzle
  - Potential implications for medium effects on J/ψ
- J/ψ jet production now measured in PbPb
  - J/ψ also found to be jet-like in PbPb
  - Consistent w/ decreasing suppression with increasing z, expected if jet quenching depends on parton shower multiplicity
  - Supports picture where jet quenching is relevant for high p_T J/ψ
- Further studies needed to determine where jet quenching effects are relevant
  - J/ψ-hadron correlations at lower p_T
  - ϒ-in-jet measurement to study quark mass effect