

Hard-soft correlations with CMS

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on behalf of the CMS experiment

CERN

Hard-soft correlations in hadronic collisions - GDR QCD



- Interactions between hard probes and soft particle production
 - Compare the behaviour of selected hard probes with the bulk
 - Are the same effects present in pp, pPb and PbPb at the same multiplicity?
- “Hard probes” can be heavy flavour (charm, beauty), jets, high p_T particles
- Can study these hard-soft correlations in various ways
 - Production vs multiplicity
 - Angular correlations
 - Fourier harmonics v_n
 - Jet structure: shape, fragmentation

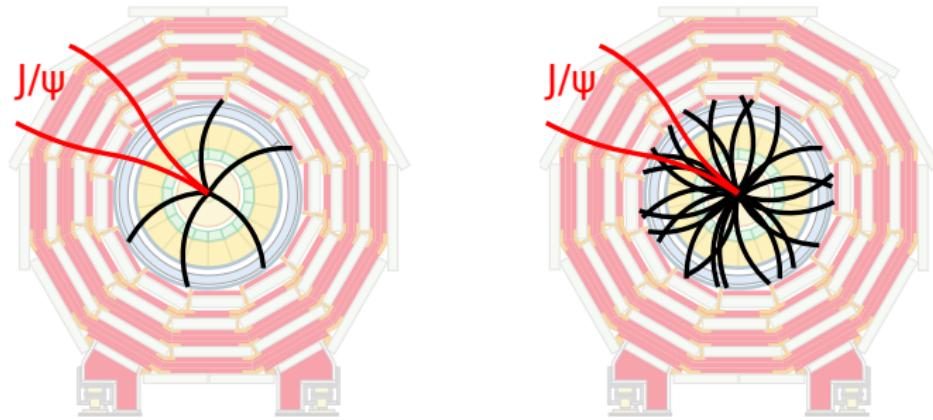


Outline

- ① Quarkonia
- ② Collective flow of heavy and light flavours
- ③ Jet-h correlations and jet structure
 - Heavy flavour mesons in jets
 - Jet structure and fragmentation



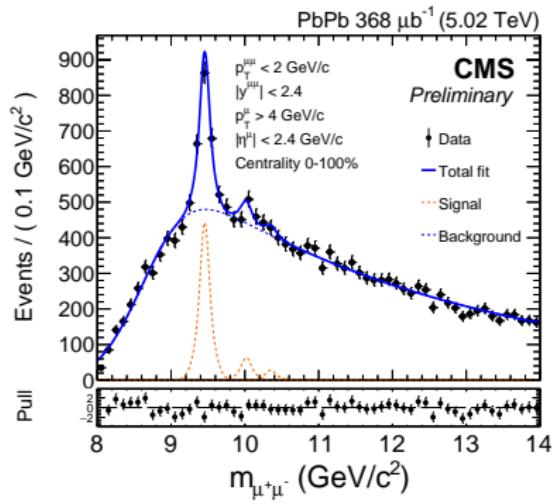
Quarkonia: introduction



- Quarkonia: bound state of heavy quark-antiquark
 - J/ψ , $\psi(2S)$, $\Upsilon(1S,2S,3S)$
- “Long” lifetime: probing the medium evolution
- Affected by the event multiplicity / activity
 - Excited states may be affected differently than the ground state



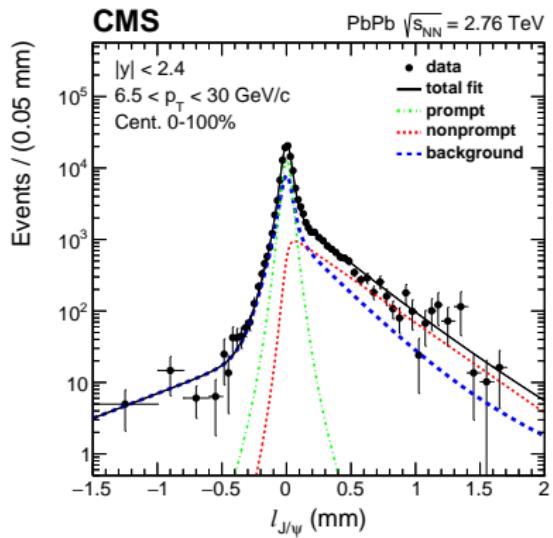
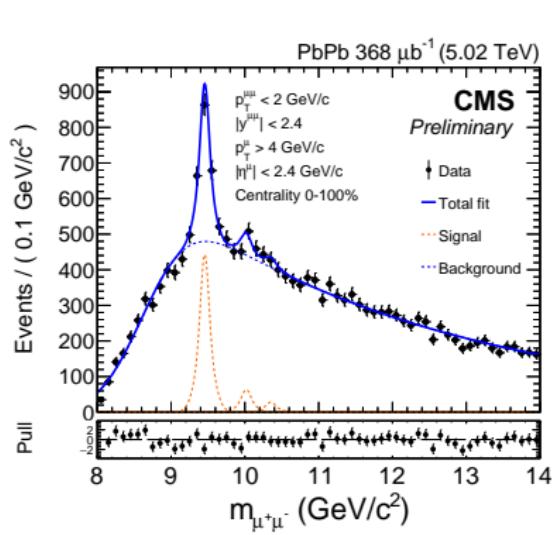
Signal extraction



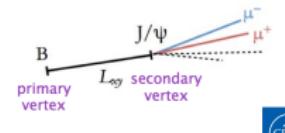
- Extract the different resonances (J/ψ , $\psi(2S)$, $\Upsilon(nS)$) from a fit to $M_{\mu^+\mu^-}$



Signal extraction



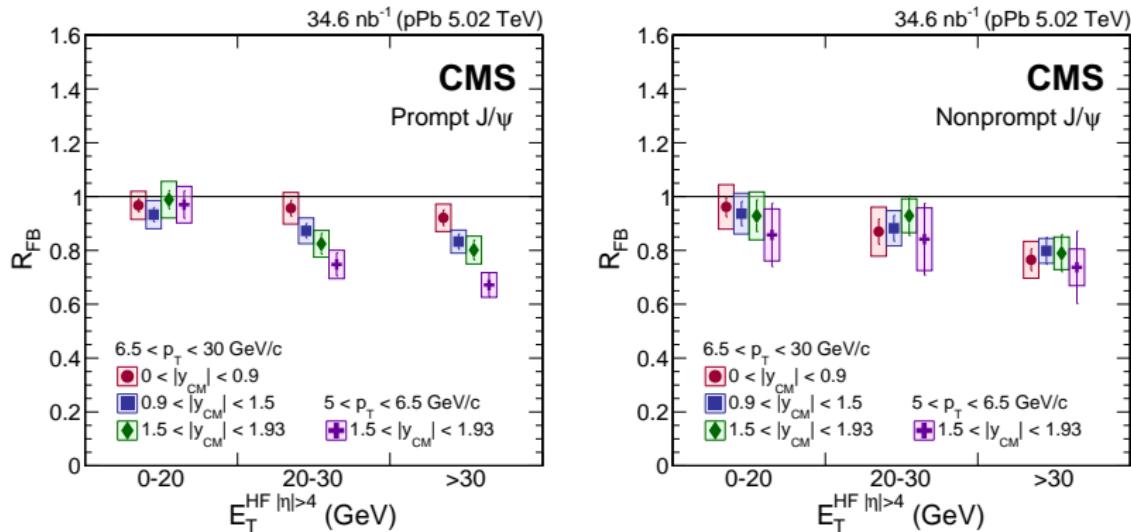
- Extract the different resonances (J/ψ , $\psi(2S)$, $\Upsilon(nS)$) from a fit to $M_{\mu^+\mu^-}$
- B meson feeddown for charmonia: 2D fit of $(M_{\mu^+\mu^-}, \ell_{J/\psi})$ ($\psi(2S)$: cut on $\ell_{J/\psi}$)





Event activity dependence: $R_{FB}(J/\psi)$

EPJC 77 (2017) 269



$$R_{FB} = \frac{N(y_{CM} > 0)}{N(y_{CM} < 0)}$$

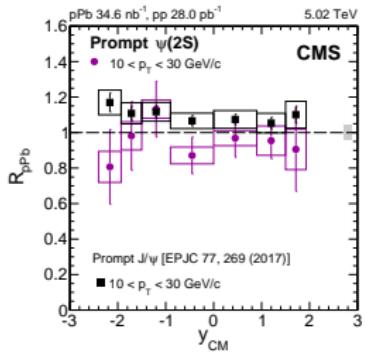
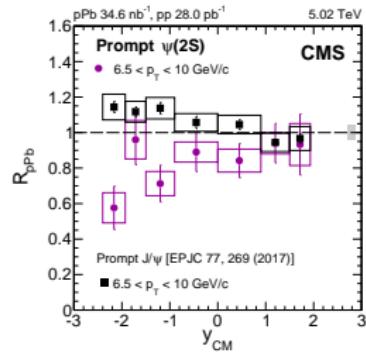
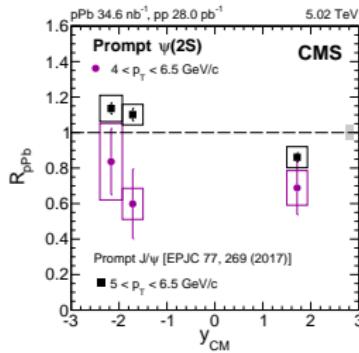
- Some dependence of the forward-backward ratio with forward activity
 - For both prompt (closed charm) and nonprompt (open beauty)
- More pronounced in the **forward region**
- Hinting to other nuclear effects beyond nPDF?





Excited vs. ground state: $\psi(2S)$ vs J/ψ

1805.02248



- Expecting similar effects from nPDF for J/ψ and $\psi(2S)$
- Hint for a different modification in the data
- Is the more “fragile” $\psi(2S)$ destructed by the event multiplicity?
 (“comover” interactions?)

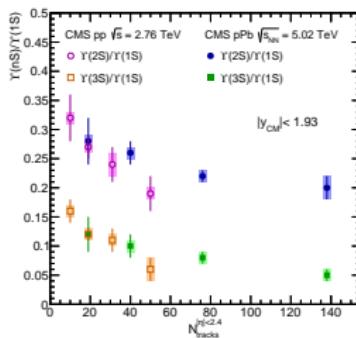
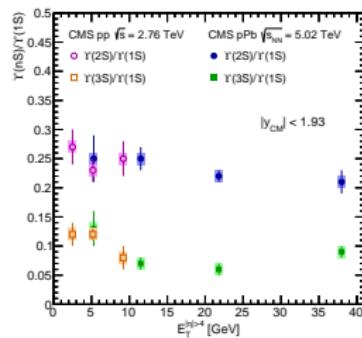




Event activity dependence: excited bottomonium states

JHEP 04 (2014) 103, CMS-PAS-BPH-14-009

Excited state over ground state ratios: $\Upsilon(nS)/\Upsilon(1S)$



- No significant dependence of the $\Upsilon(nS)/\Upsilon(1S)$ ratio with E_{HF}
- Some dependence with N_{tracks} (both in pp and pPb!)

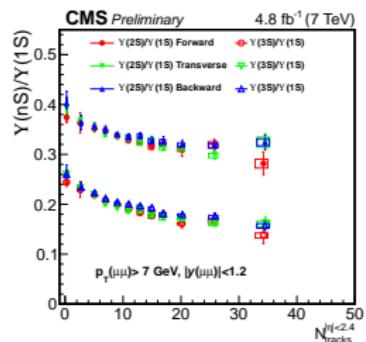
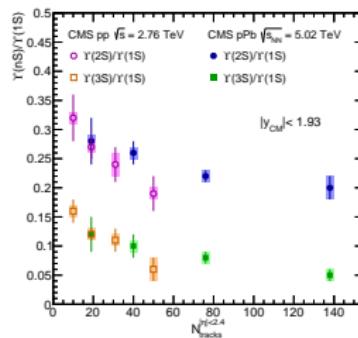
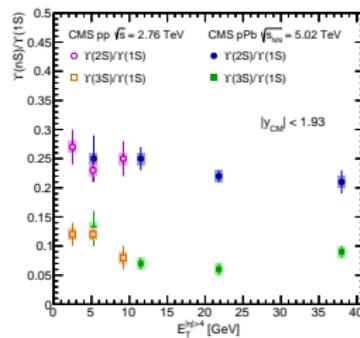




Event activity dependence: excited bottomonium states

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Excited state over ground state ratios: $\Upsilon(nS)/\Upsilon(1S)$



- No significant dependence of the $\Upsilon(nS)/\Upsilon(1S)$ ratio with E_{HF}
- Some dependence with N_{tracks} (both in pp and pPb!)
- Confirmed and investigated more differentially in a larger pp data sample





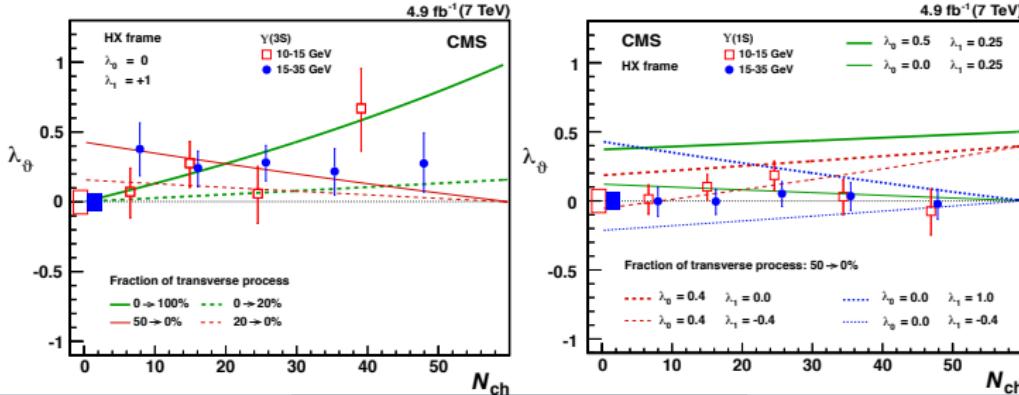
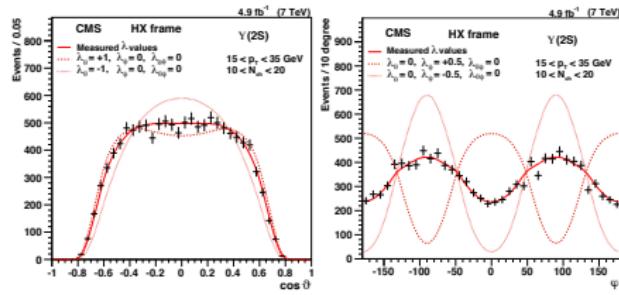
$\Upsilon(1S,2S,3S)$ polarisation vs multiplicity in pp

PLB 761 (2016) 31

Testing factorisation in NRQCD:

- Does quarkonium polarisation depend on multiplicity?
- Do different Fock states dominate depending on multiplicity?

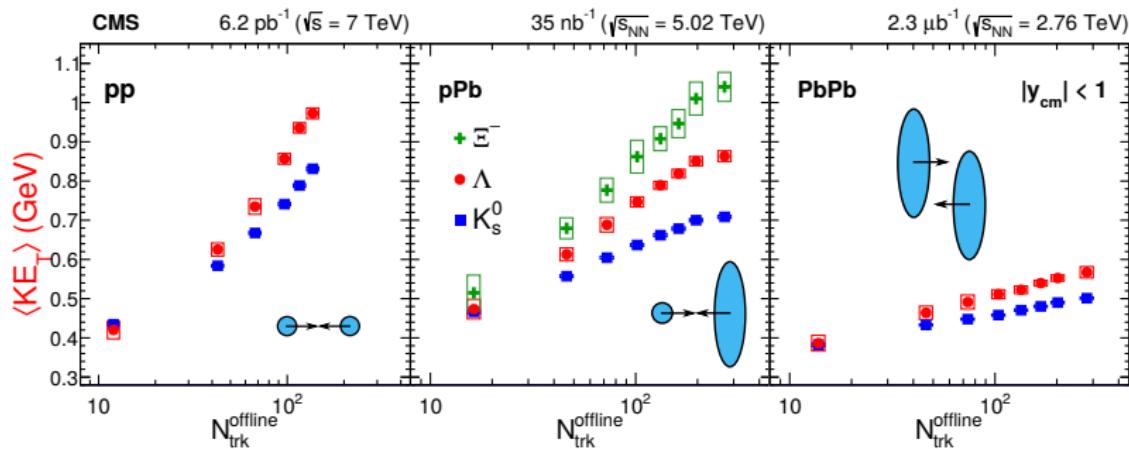
No dependence found on multiplicity





En passant: strangeness vs multiplicity

PLB 768 (2017) 103

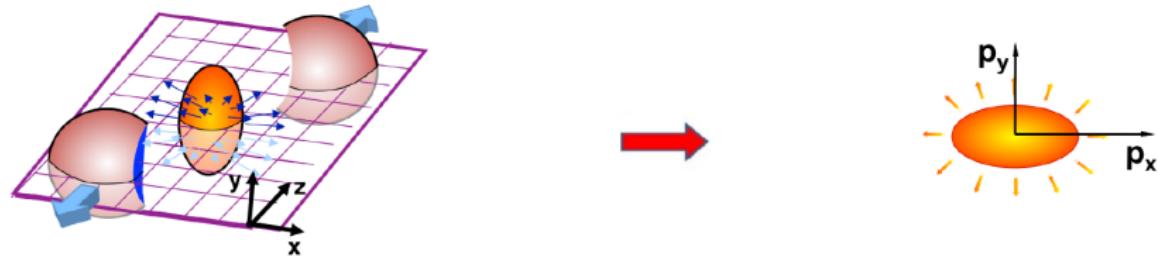


Strangeness production studied in pp, pPb and PbPb collisions as a function of multiplicity

- Higher transverse kinematic energy $\langle KE_T \rangle$ at higher multiplicities for all systems
- Faster increase for heavier particles and smaller systems



Collective flow

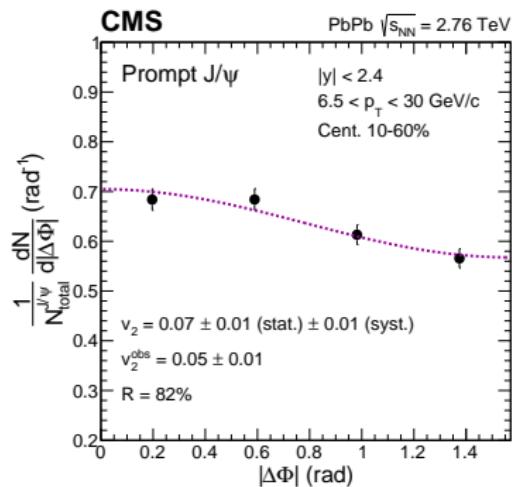
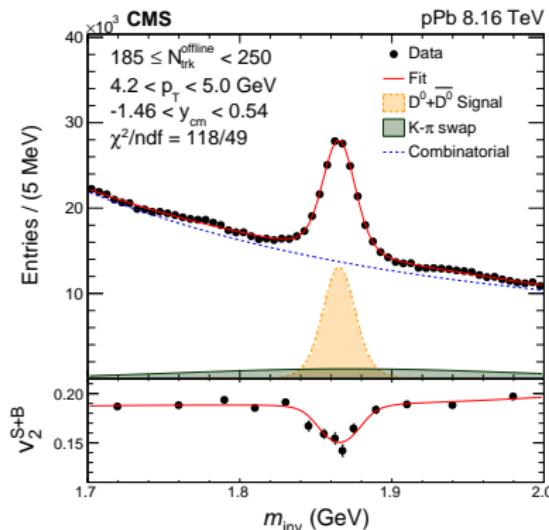


- Lenticular overlapping region \rightarrow space anisotropy \rightarrow momentum space anisotropy
- What is the flow of soft vs hard probes (D mesons, J/ψ , high p_T hadrons)?



v_2 extraction for D and J/ ψ mesons

1804.09767, EPJC 77 (2017) 252



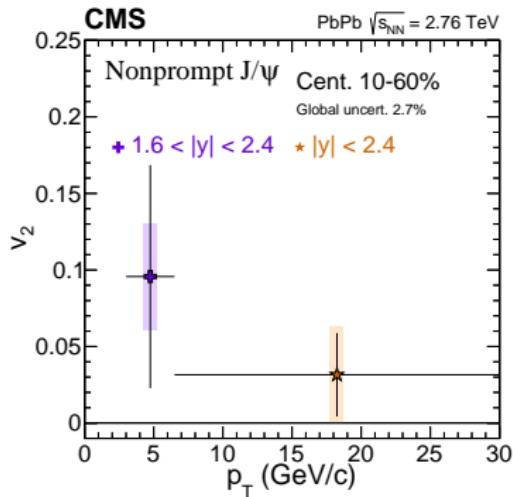
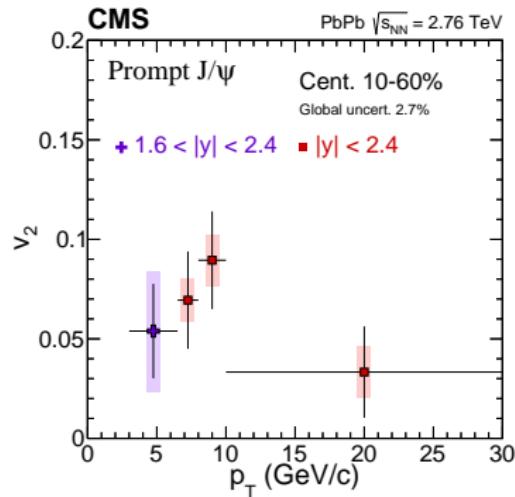
- Simultaneous fit to the invariant mass spectrum and $v_2^{S+B}(m_{\text{inv}})$
- J/ ψ v_2 in PbPb: fit of $\Delta\Phi(\text{J}/\psi, \text{event plane})$





$J/\psi v_2$ in PbPb (2.76 TeV)

EPJC 77 (2017) 252

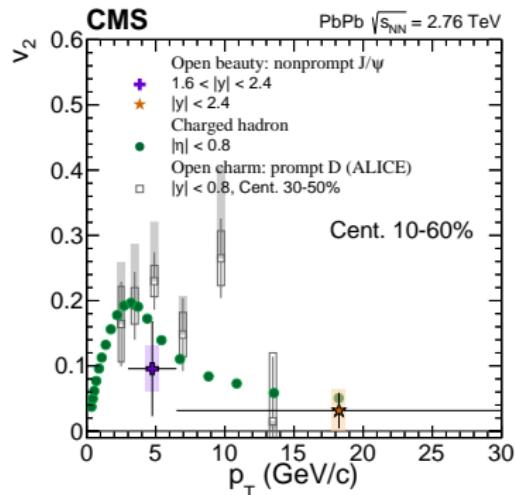
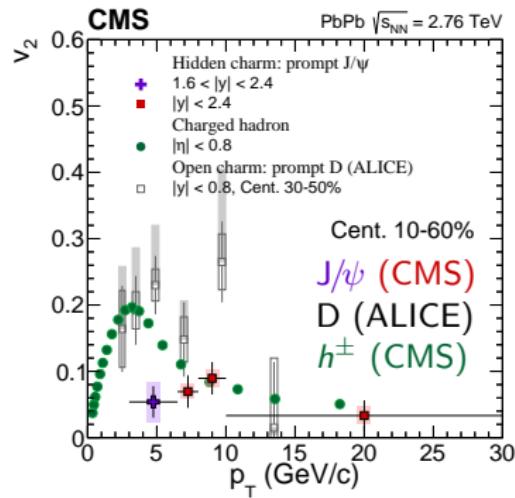


$|y| < 2.4, 6.5 < p_T < 30$ GeV/c, 10–60% centrality:

$$v_2(\text{prompt}) = 0.066 \pm 0.014(\text{stat}) \pm 0.014(\text{syst}) \pm 0.002(\text{global})$$

- Significant non-zero v_2 at high p_T (3.3σ)
- Large uncertainties for nonprompt J/ψ



$J/\psi v_2$ in PbPb (2.76 TeV)

Comparing hidden charm (prompt J/ψ , CMS) and open beauty (nonprompt J/ψ , CMS) to open charm (D, ALICE):

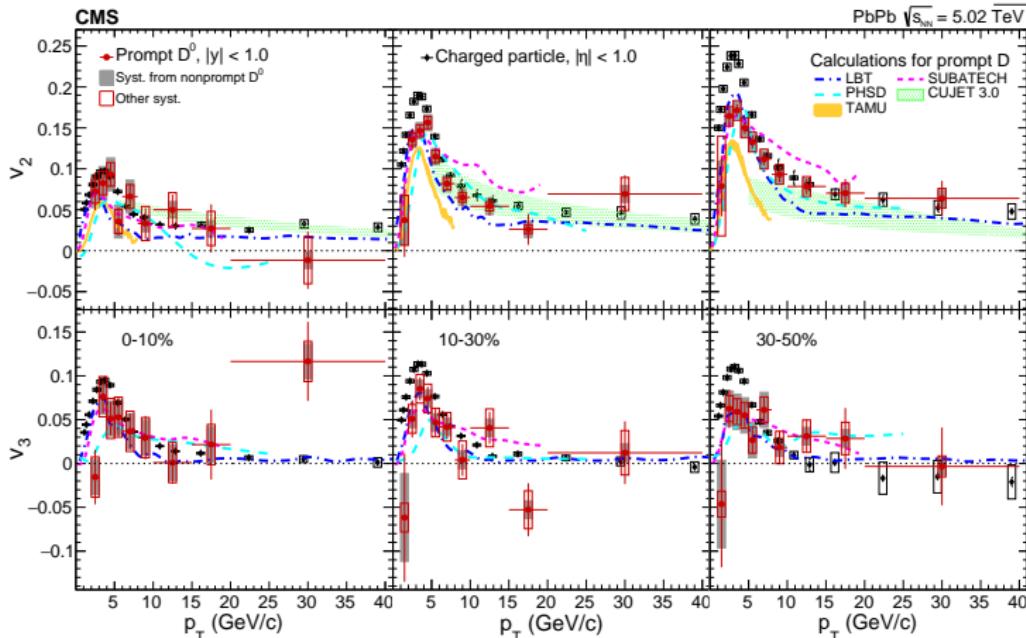
- Smaller v_2 at low p_T , similar at high p_T ?
- Flavour independence of energy-loss path-length dependence?





D meson v_2 and v_3 in PbPb

PRL 120 (2018) 202301



- Positive v_2 from 1 to 40 GeV
- Comparison with light hadrons:
 - low p_T : mass ordering
 - high p_T : similar v_2 (and v_3)! Coincidence, or flavour independence of path length dependence of energy loss?

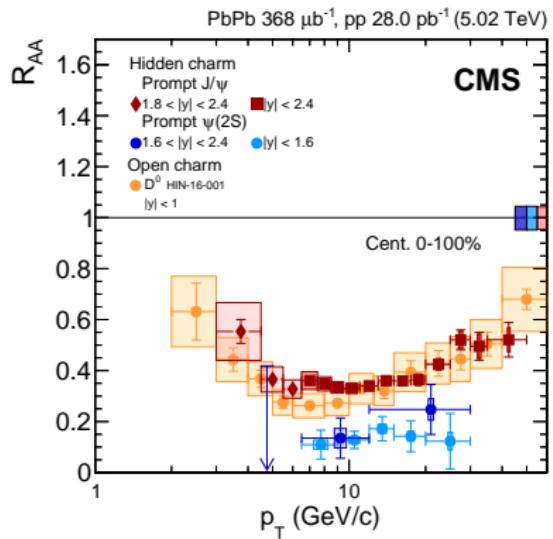




High p_T R_{AA}

JHEP 04 (2017) 039, 1708.04962, 1712.08959, PRL 119 (2017) 152301, EPJC 77 (2017) 252

Hints for **flavour universality** also found in R_{AA} at high p_T : prompt J/ψ and $\psi(2S)$ and D mesons

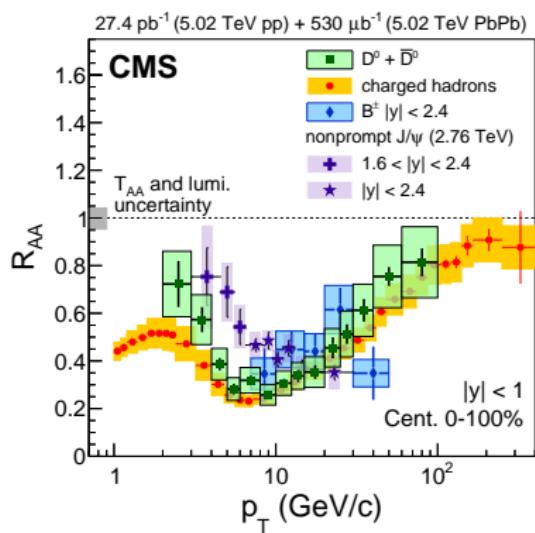
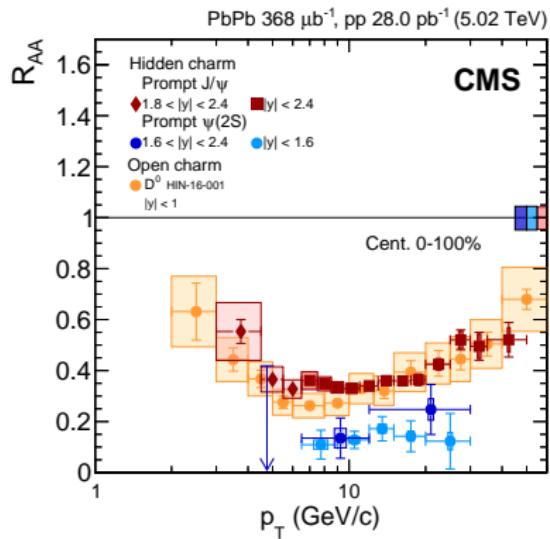




High p_T R_{AA}

JHEP 04 (2017) 039, 1708.04962, 1712.08959, PRL 119 (2017) 152301, EPJC 77 (2017) 252

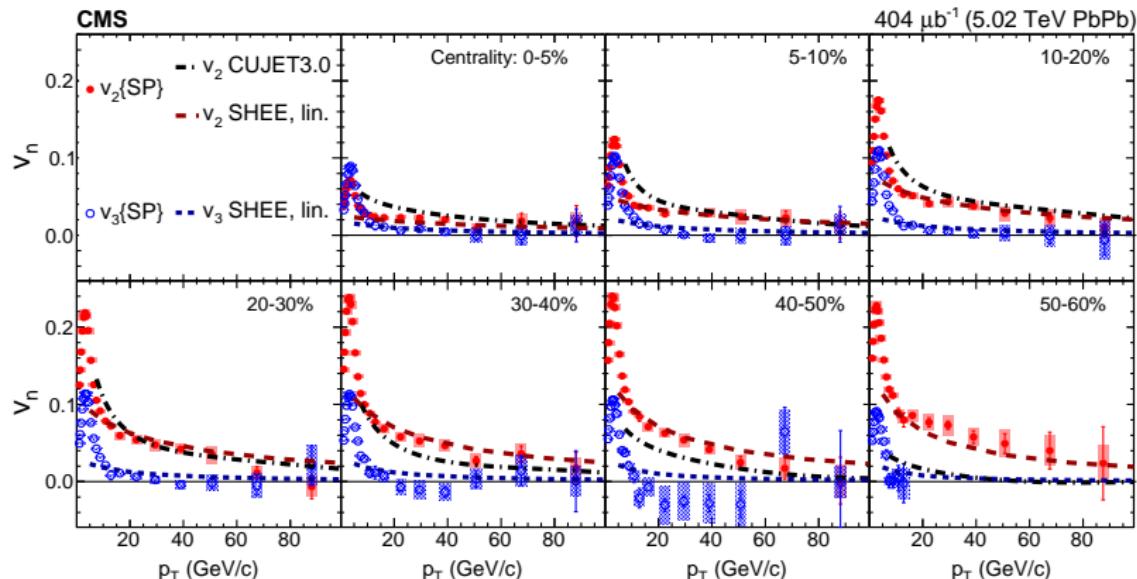
Hints for **flavour universality** also found in R_{AA} at high p_T : prompt J/ψ and $\psi(2S)$ and D mesons, also nonprompt J/ψ , B mesons, charged hadrons





High p_T v_n in PbPb

PLB 776 (2017) 195



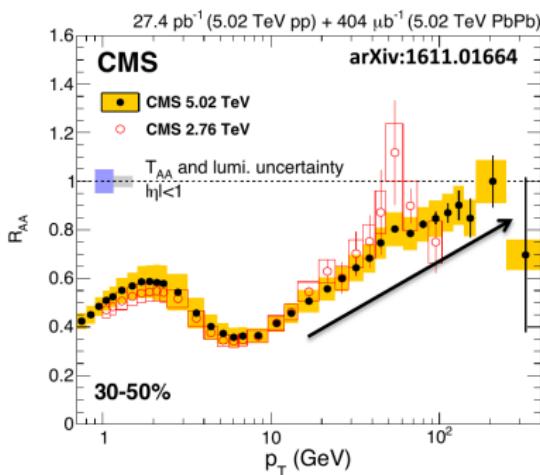
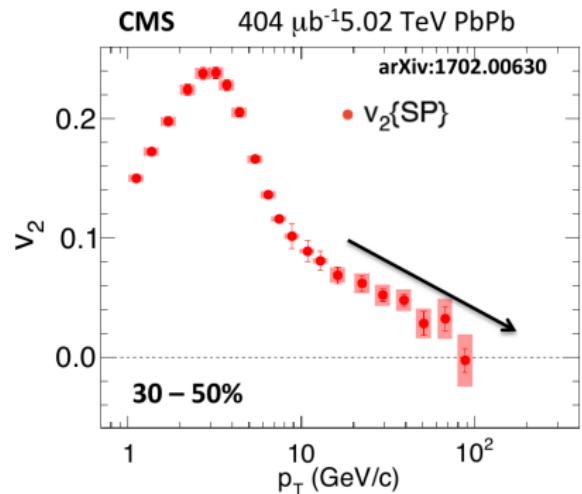
- Probing path-length dependence of energy loss and initial state geometry
- v_2 remains positive up to 100 GeV, v_3 consistent with 0 above 20 GeV





High p_T v_n in PbPb

PLB 776 (2017) 195, JHEP 04 (2017) 039



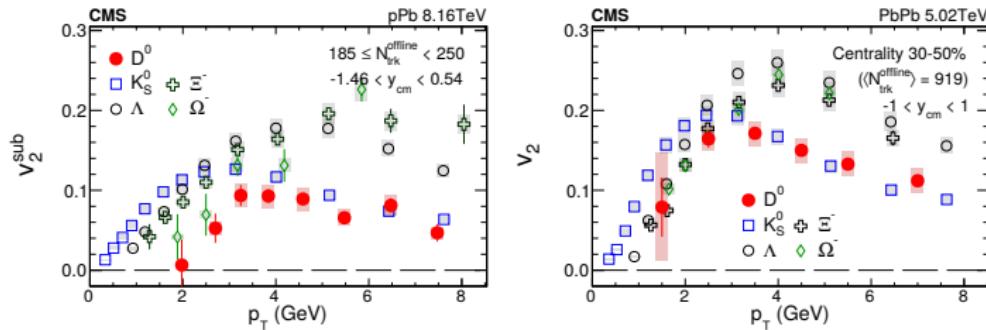
- Probing path-length dependence of energy loss and initial state geometry
- v_2 remains positive up to 100 GeV, v_3 consistent with 0 above 20 GeV
- With fixed centrality at higher p_T , more isotropic ($v_2 \rightarrow 0$), less suppressed





What about pPb? charm v_2 in pPb vs PbPb

1804.09767



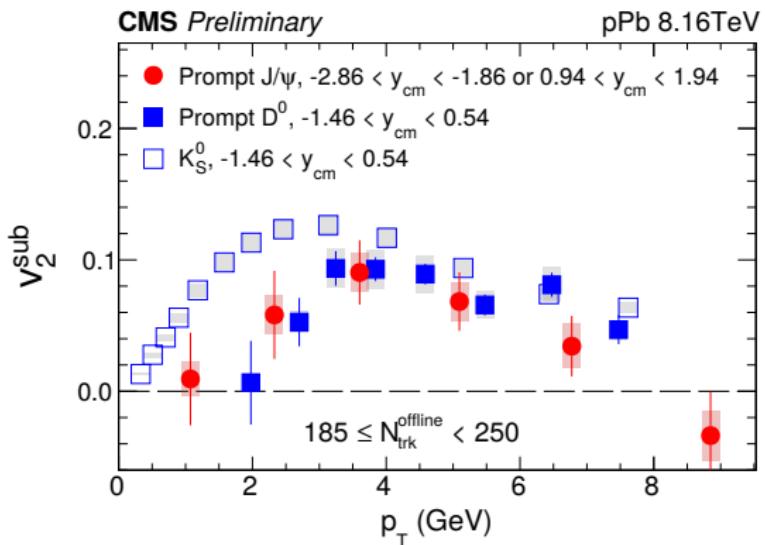
- Significant $D^0 v_2$ both in pPb and PbPb
- Smaller v_2 for charm than strange in pPb
- Weaker coupling between heavy quarks and the medium in pPb than PbPb?





Prompt J/ψ v_2 in pPb

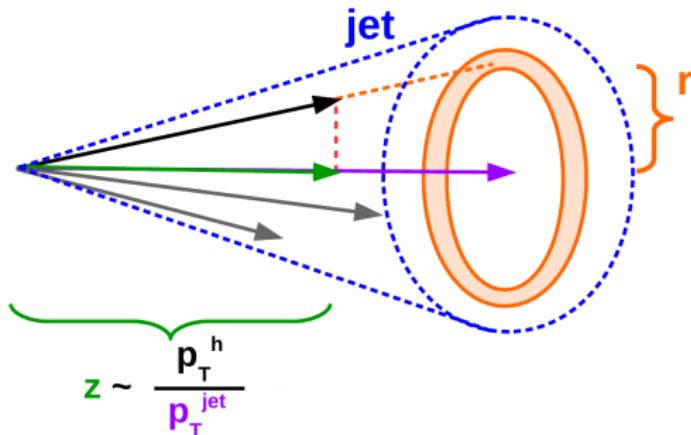
CMS-PAS-HIN-18-010



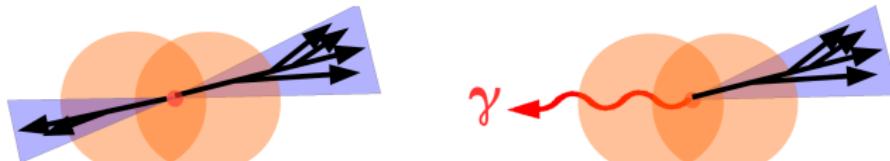
- Clear observation of prompt J/ψ v_2 in high multiplicity pPb collisions
 - Significant positive J/ψ v_2 observed
 - Direct evidence of charm collectivity
- $v_2(K_S^0) > v_2(J/\psi) \rightarrow v_2(\text{light}) > v_2(\text{charm})$
- What is the origin?



Jet shape and fragmentation

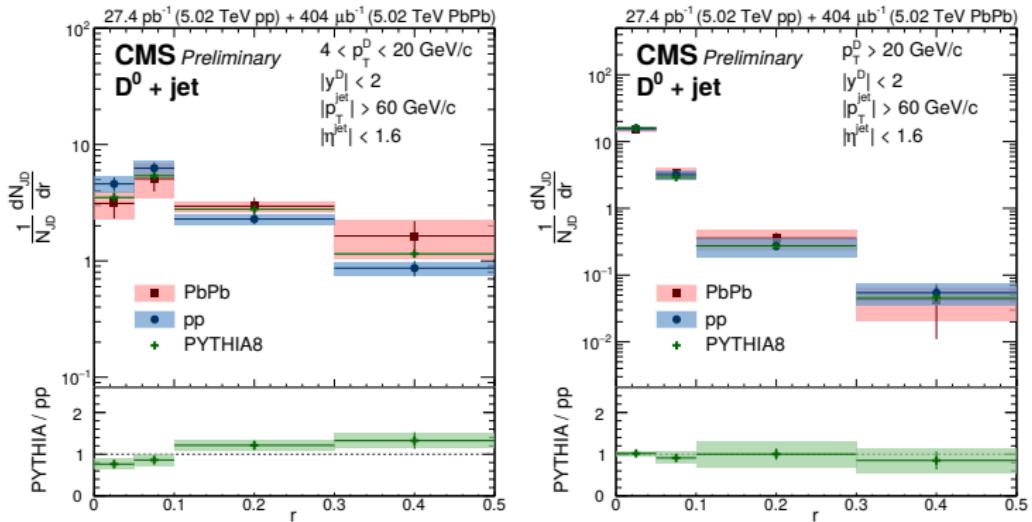


- Correlations between tracks and jets: access to jet structure
 - $\Delta r(\text{trk}, \text{jet})$: **jet shape**
 - $z \sim p_T^{\text{trk}}/p_T^{\text{jet}}, \xi = \ln(1/z)$: **jet fragmentation**
- Can replace the track with a **heavy flavour meson** (J/ψ , D meson)
- Study importance of **quark vs gluon fraction** using γ -tagged jets





D mesons in jets in pp and PbPb



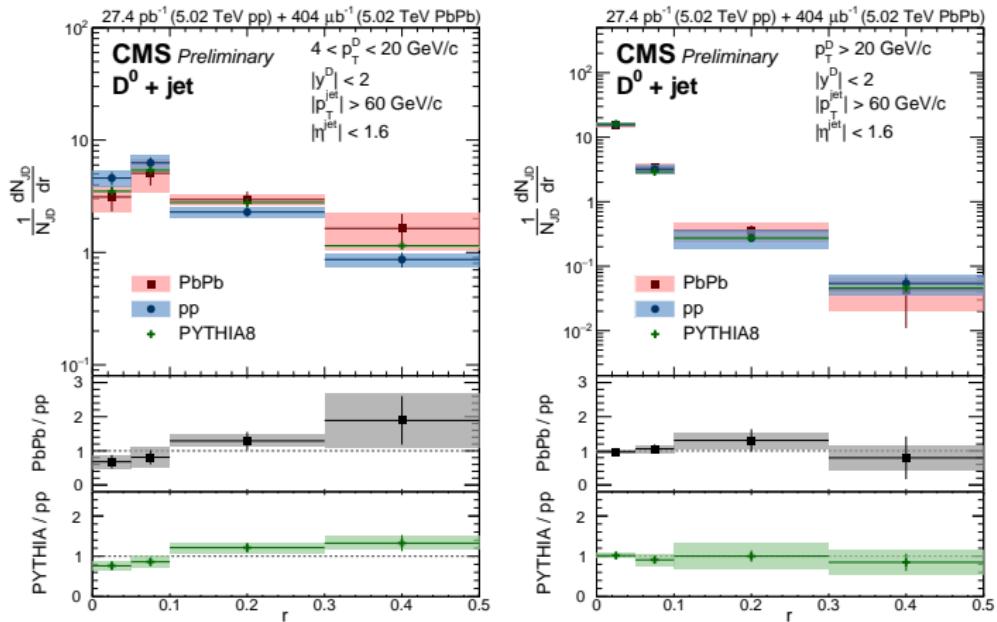
Measuring the radial profile of D mesons in jets

- Low D meson p_T ($4 < p_T^D < 20 \text{ GeV}$):
 - wider radial profile predicted in PYTHIA8, compared to pp
- High D meson p_T ($p_T^D > 20 \text{ GeV}$):
 - good agreement between PYTHIA8 and pp measurements





D mesons in jets in pp and PbPb



Ratio of PbPb to pp:

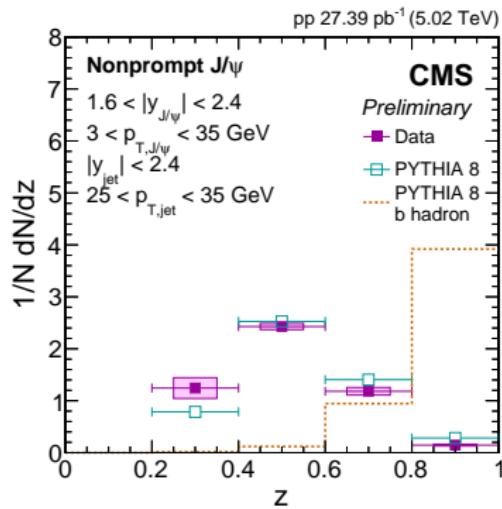
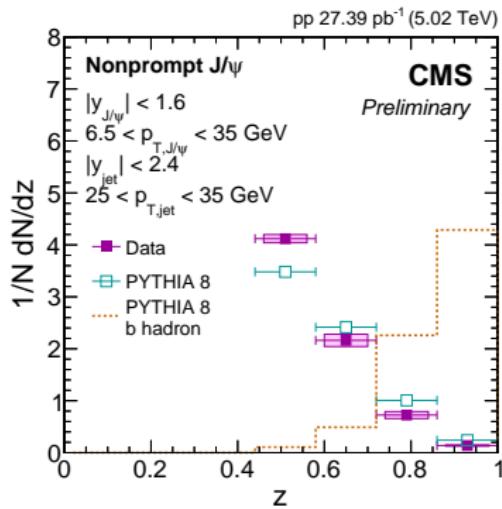
- Low D meson p_T : increase as a function of r
 - Hint that D mesons are further from jet axis in PbPb than pp
- High D meson p_T : consistent with unity



J/ ψ production in jets in pp: nonprompt J/ ψ results



CMS-PAS-HIN-18-012



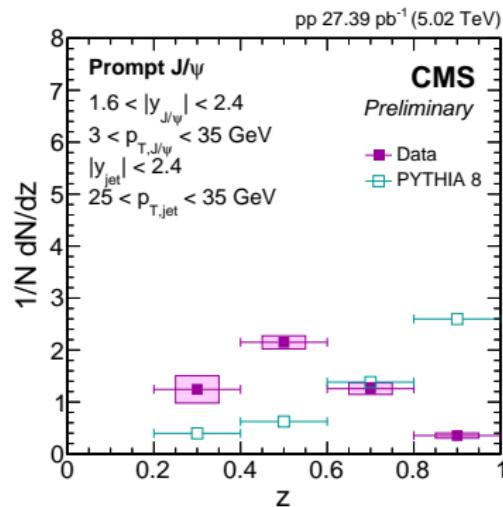
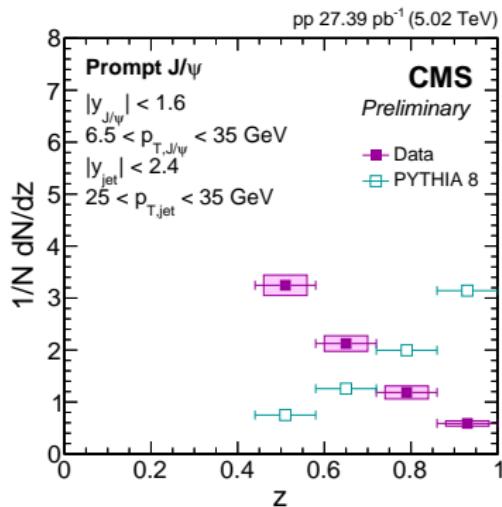
Fully unfolded results (2D unfolding in z and jet p_T)

- Similar behaviour in data and Pythia
- Expected due to decay kinematics



J/ ψ production in jets in pp: prompt J/ ψ results

CMS-PAS-HIN-18-012



Fully unfolded results (2D unfolding in z and jet p_T)

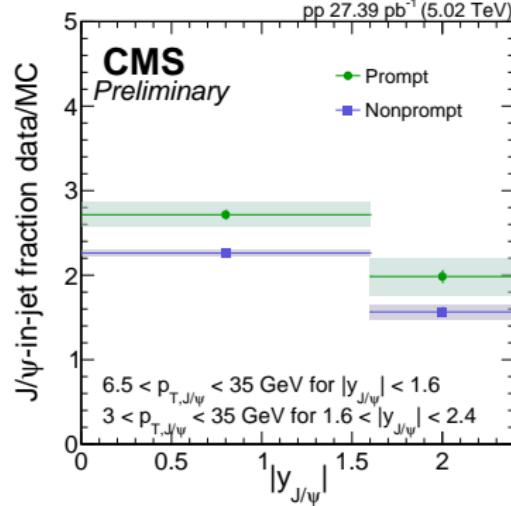
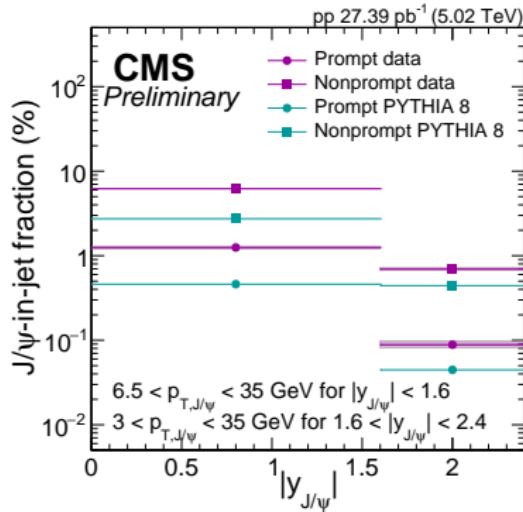
- Different behaviour in **data** and **Pythia**
- J/ ψ** are less isolated in **data**



J/ ψ production in jets in pp: J/ ψ -in-jet fraction



CMS-PAS-HIN-18-012



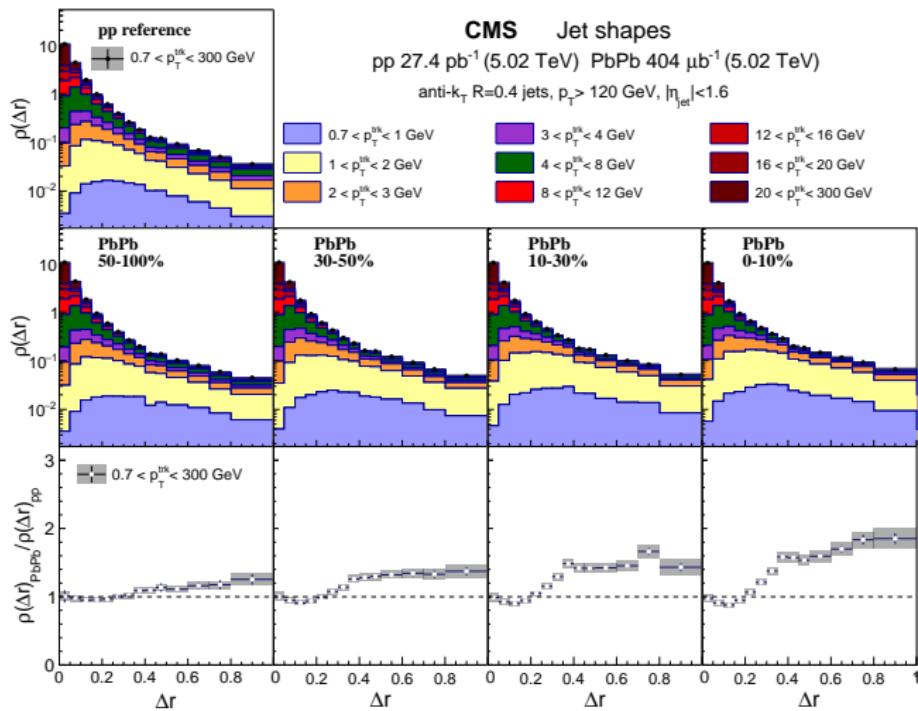
- Less than 7% of J/ ψ produced in jets
- Under-predicted in Pythia





Inclusive jet shape in PbPb

JHEP 05 (2018) 006



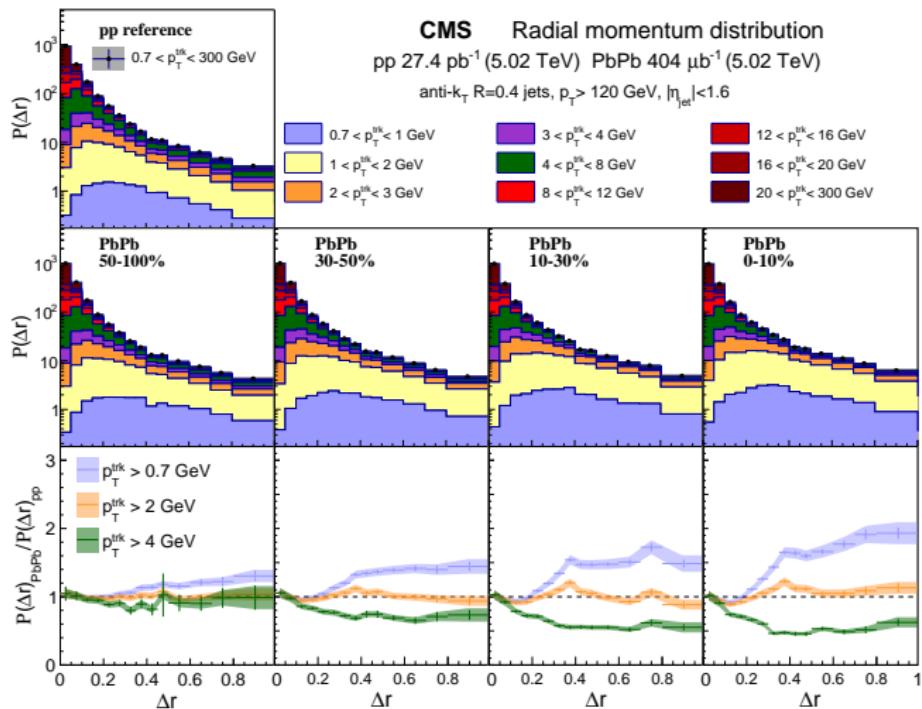
A larger fraction of jet energy is carried at large distance from the jet axis





Inclusive jet shape in PbPb

JHEP 05 (2018) 006



A larger fraction of jet energy is carried at large distance from the jet axis

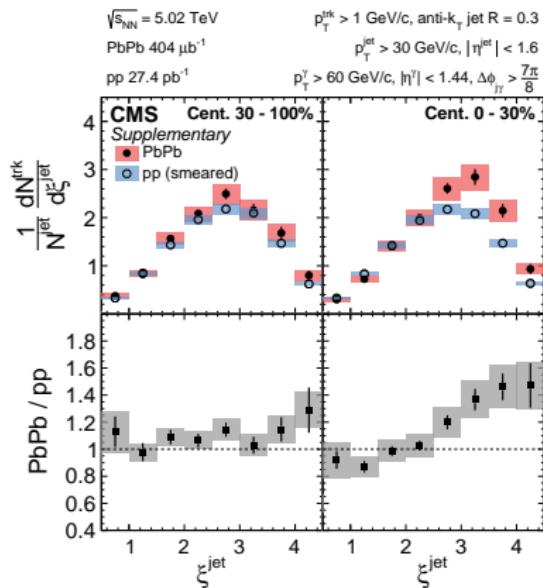
- especially by low p_{T} particles





Gamma-tagged jet fragmentation in PbPb

1801.04895



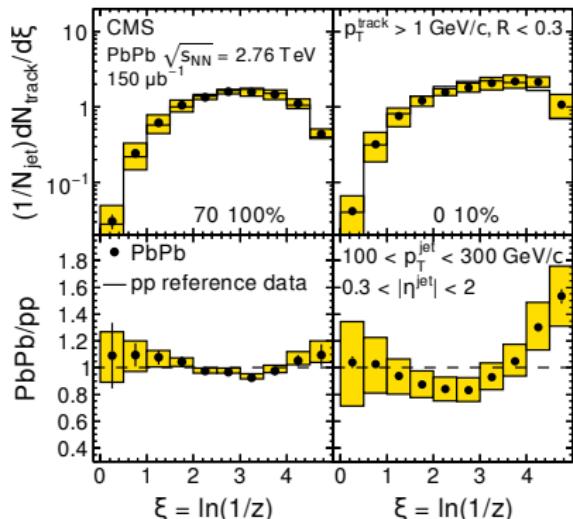
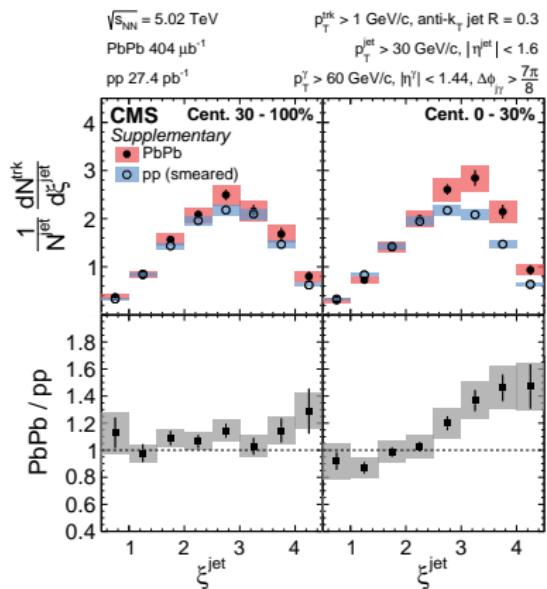
- γ -tagged vs inclusive jets: different quark vs gluon fraction
- In central collisions:
 - enhancement of low p_T particles (high ξ)
 - depletion of high p_T particles (low ξ)





Gamma-tagged jet fragmentation in PbPb

1801.04895, PRC 90 (2014) 024908

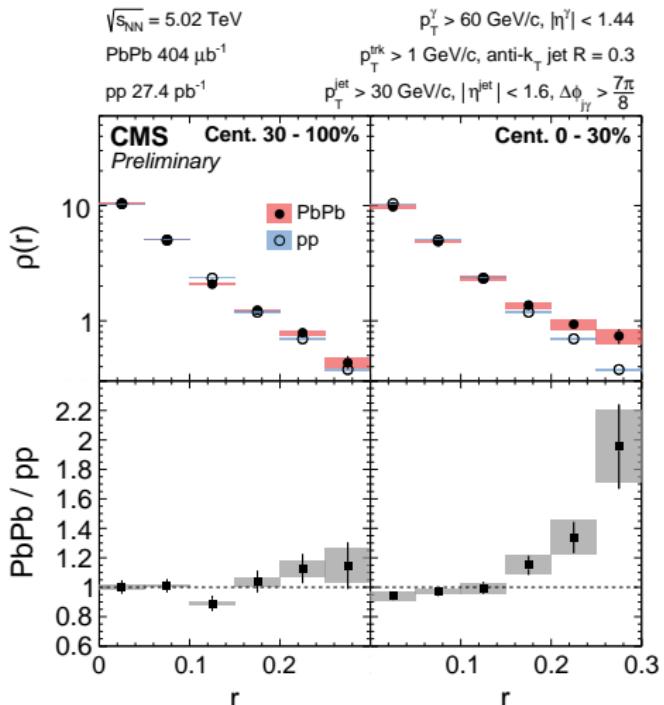


- γ -tagged vs inclusive jets: different quark vs gluon fraction
- In central collisions:
 - enhancement of low p_T particles (high ξ)
 - depletion of high p_T particles (low ξ)
- Qualitatively similar to the observation in inclusive jets





Gamma-tagged jet shape in PbPb



- Larger fraction of jet energy at larger distances from the jet axis
- Again similar observation in inclusive and γ -tagged jets



Summary

Wide spectrum of information from hard-soft correlations

- impact of particle multiplicity on production (e.g. on quarkonia)
- parton energy loss: path-length dependence and its flavour dependence
- production of heavy flavour inside jets
- detailed understanding of jet quenching

Additional material

Not discussed today...

- $b\bar{b}$ correlations
- Electroweak bosons in pp and pPb (soft gluon resummation, nPDF)
- Double parton scattering: (same-sign WW), (W+jj), ...
- Underlying event studies

JHEP 03 (2018) 181, PLB 759 (2016) 36, CMS-PAS-HIN-17-007, JHEP 03 (2018) 172

