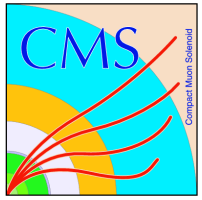
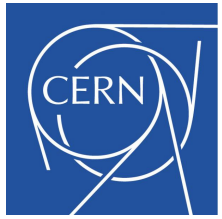
Hard probes in heavy ion collisions with CMS



Kaya Tatar
CERN
for the CMS Collaboration



ICHEP, Bologna
July 8, 2022

Energetic partons as probes of QGP

Calculations related a parton's energy loss to quark gluon plasma (QGP) properties a long time ago

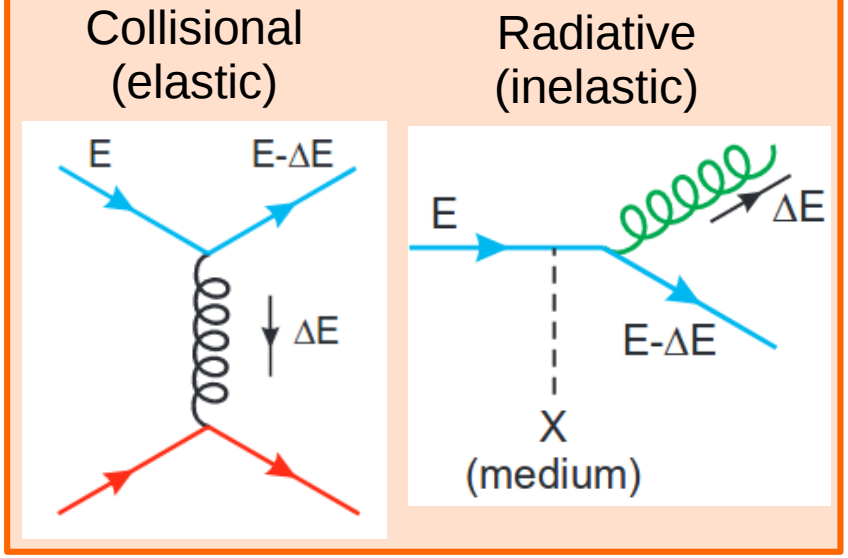
Bjorken $$-\frac{\mathrm{d}E_{\mathrm{coll}}}{\mathrm{d}x} \propto \alpha_{\mathrm{s}}^2\, T^2$$

BDMPS $$-\frac{\mathrm{d}E_{\mathrm{rad}}}{\mathrm{d}x} \propto \alpha_{\mathrm{s}}\, \hat{q}\, L \qquad \hat{q} \propto \frac{m_D^2}{\lambda}$$

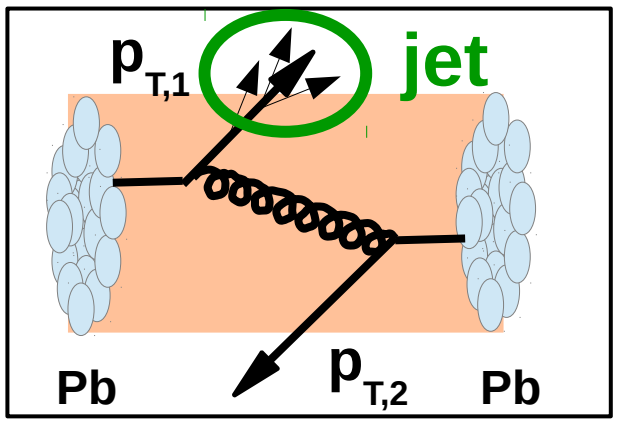
α_s : Strong coupling const
T : Temperature
λ : Mean free path

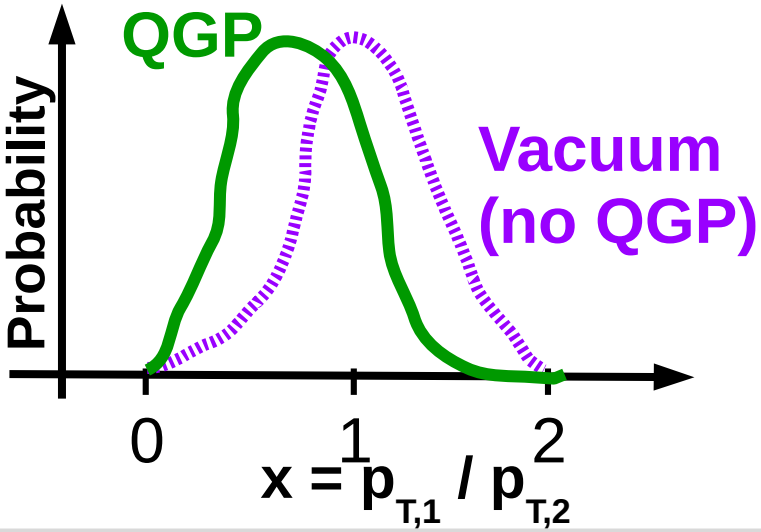
Bjorken : FERMILAB-PUB-82-059-THY
BDMPS : Nucl.Phys.B484:265-282,1997

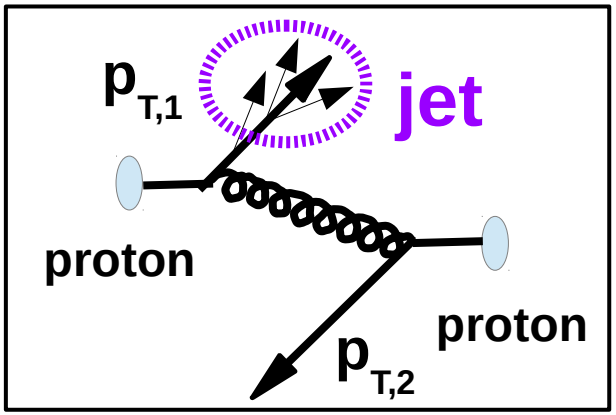
Energy loss in QGP



Experiment method : Compare measurements of energetic partons btw PbPb and pp

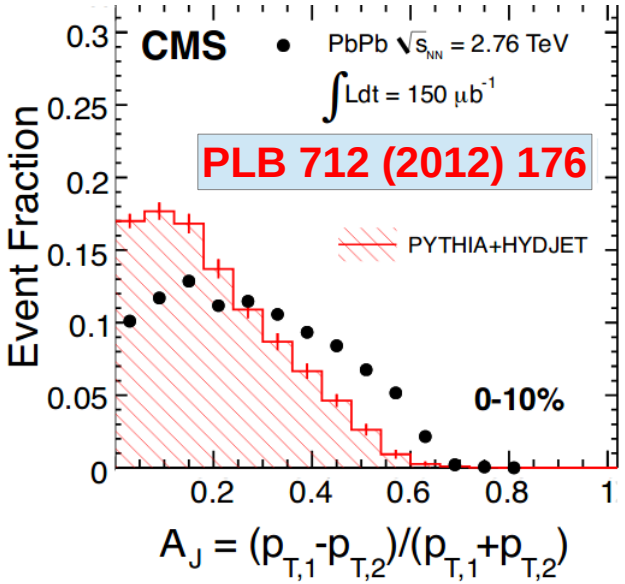






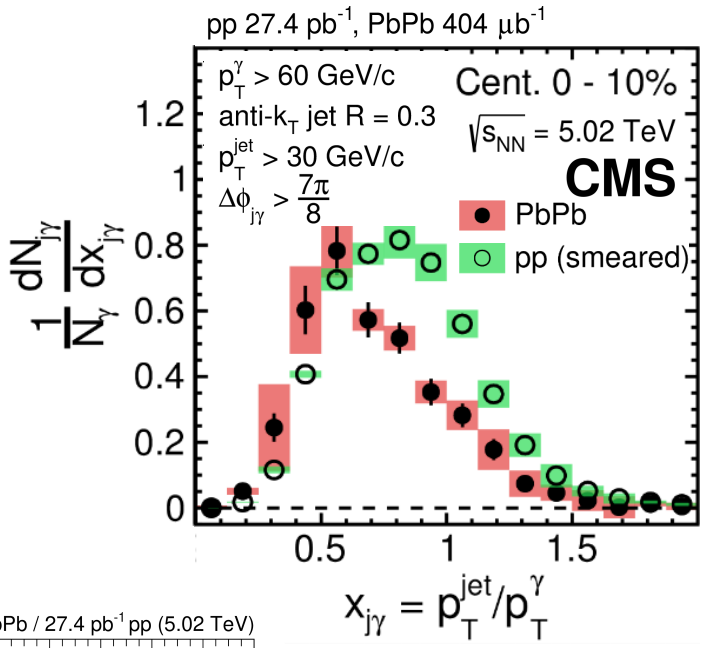
Hard probes in CMS up to now

First observations of energy loss using for fully reco jets

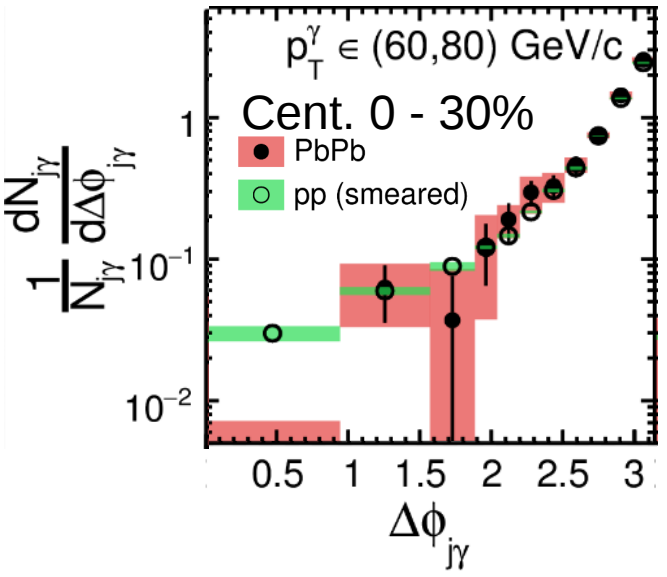


Quantify energy loss using jets recoiling from photons

PLB 785 (2018) 14

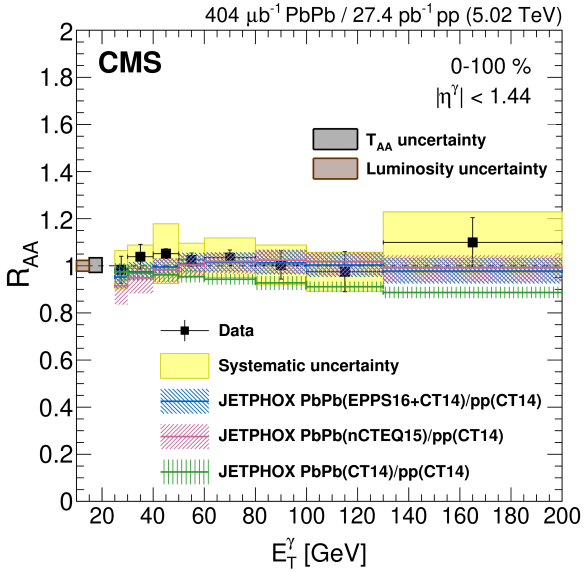


No sign of $p_\perp$-broadening

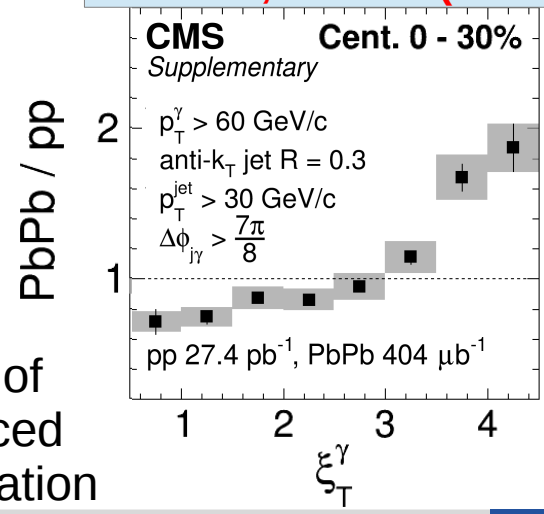


No significant modification of isolated photon production in QCD medium

JHEP 07 (2020) 116



PRL 121, 242301 (2018)

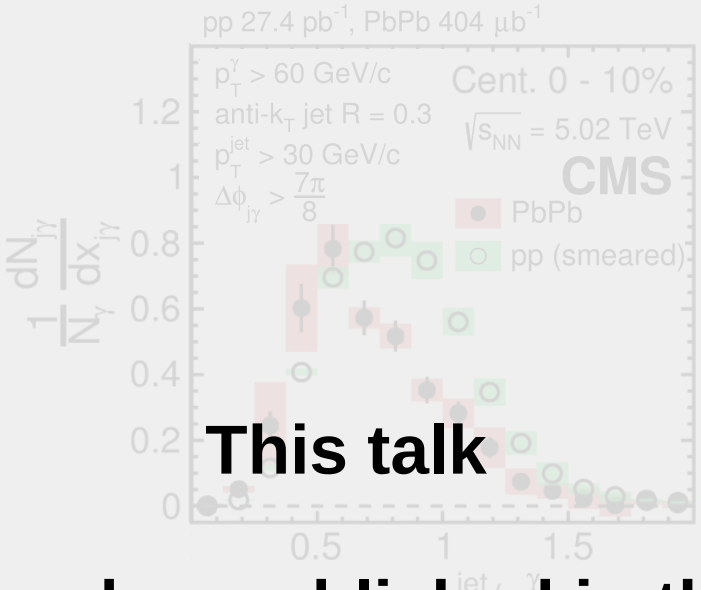


Observation of medium-induced shower modification

First observations of energy loss using for fully reco jets

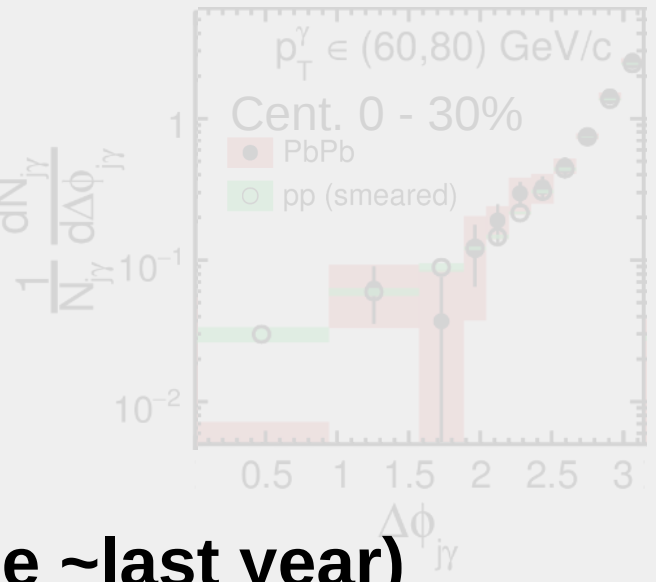
PLB 712 (2012) 176

Quantify energy loss using jets recoiling from photons



PLB 785 (2018) 14

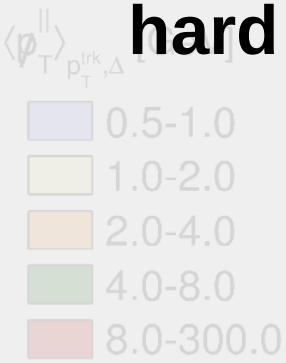
No sign of $p_\perp$-broadening



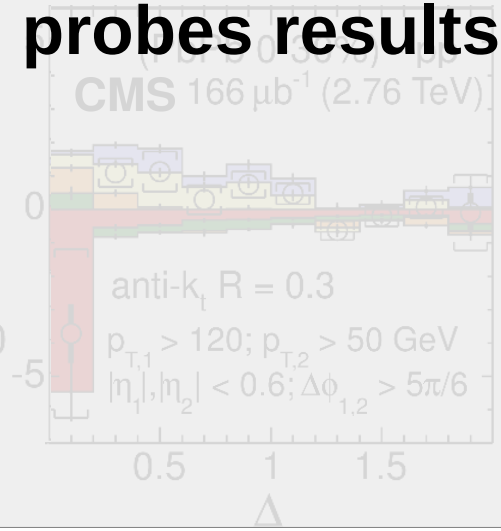
This talk

Recent (finalized or published in the ~last year) hard probes results from CMS

Jet energy radiated to large angles in form of low energy particles

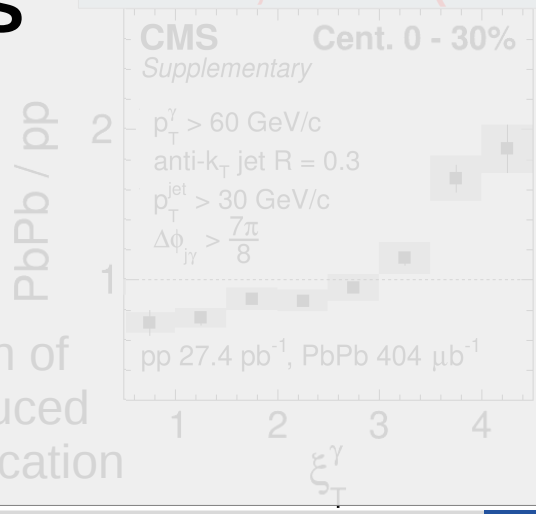


JHEP 01 (2016) 006



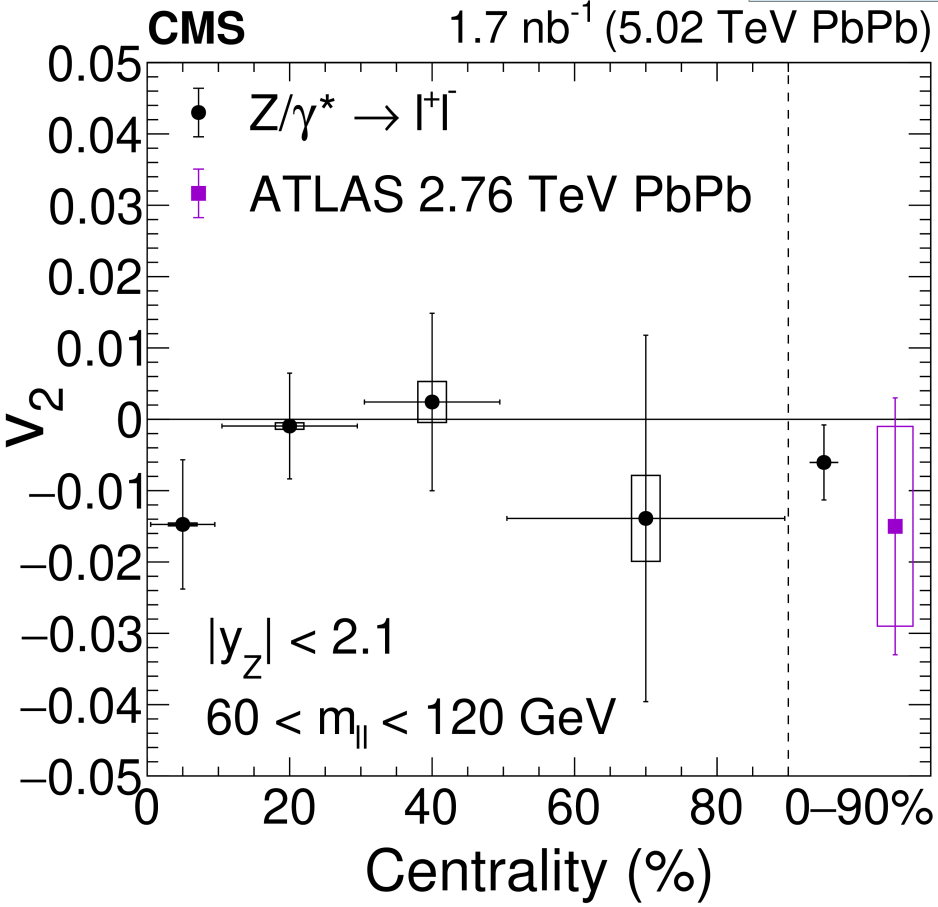
PRL 121, 242301 (2018)

Observation of medium-induced shower modification

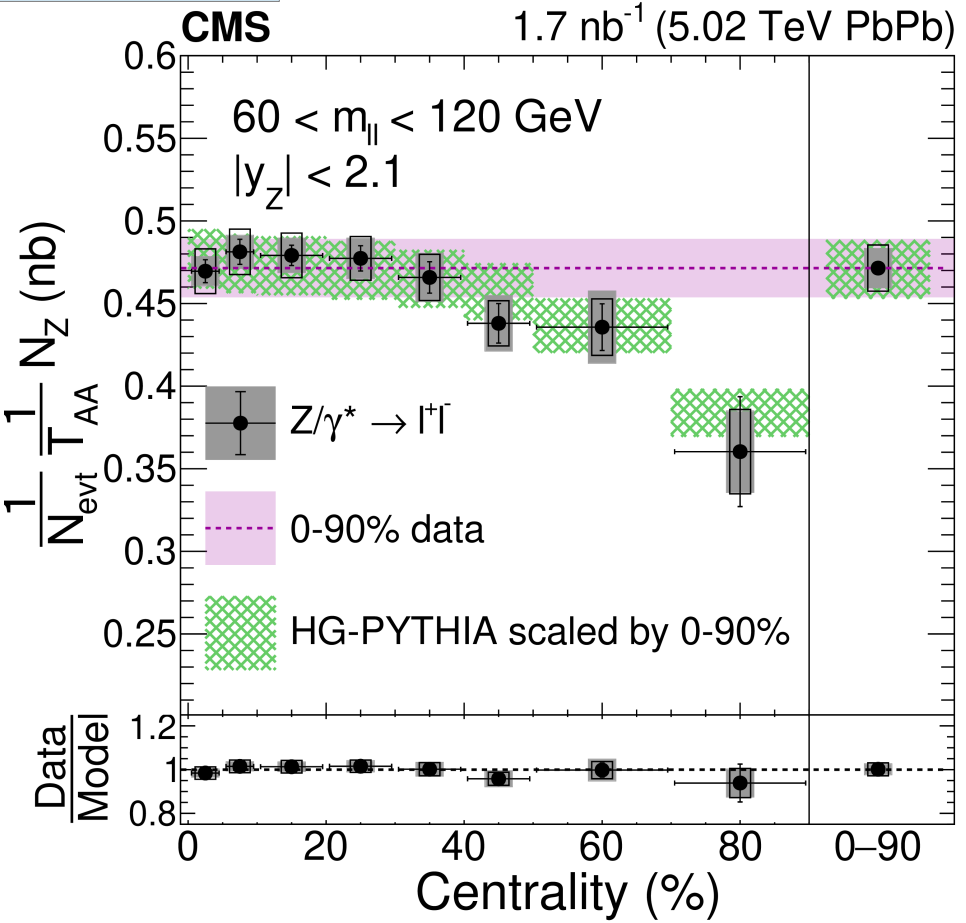


Constraining initial state via Z bosons

PRL 127 (2021) 102002



- v_2 measured via 3-subevent method using forward calorimeters and tracks
- Consistent with Z boson production not being modified by QCD medium

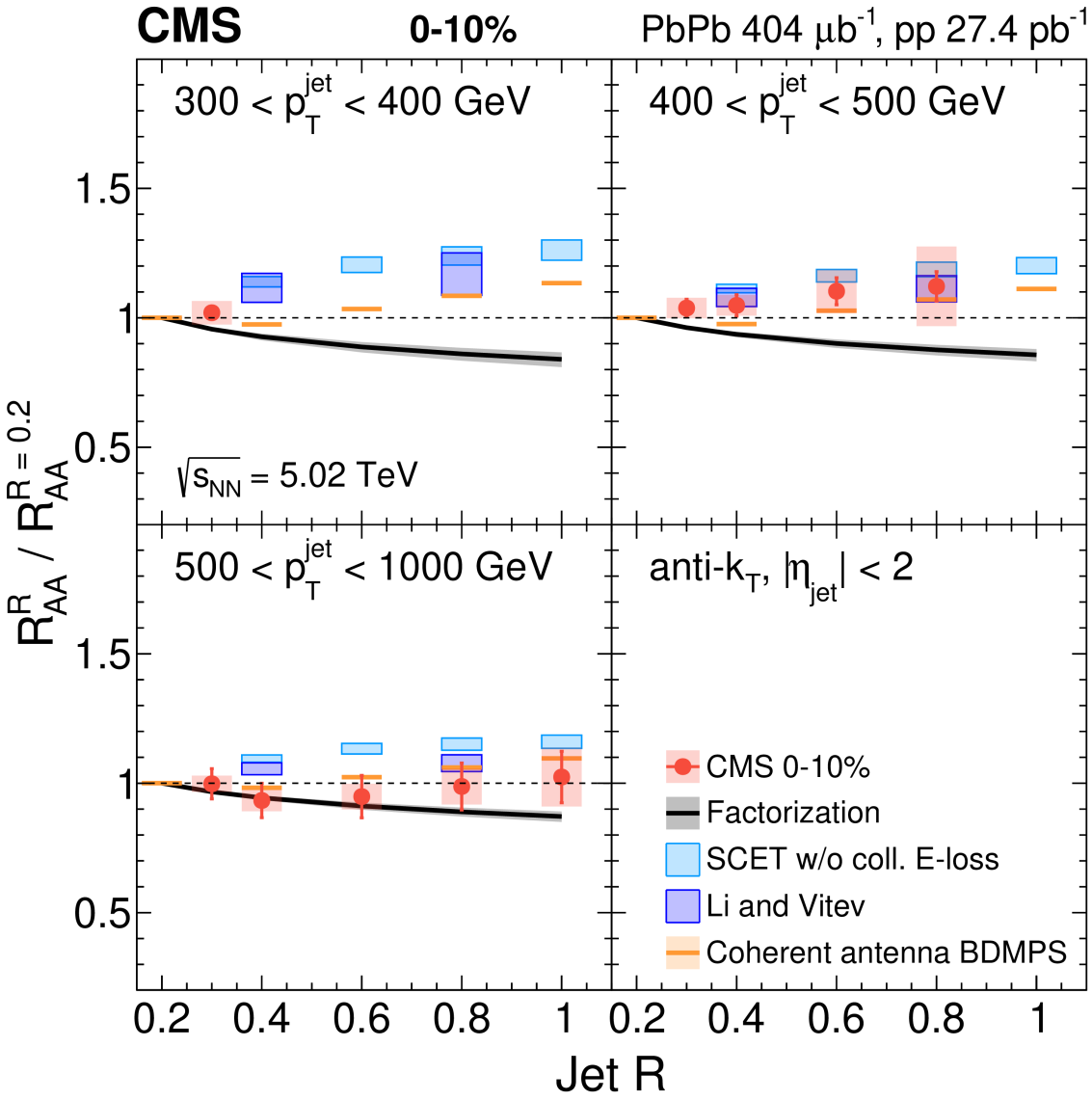


- Yields measured after normalizing for N_{coll}
- Central coll : Consistent with no centrality dependence
- Peripheral coll : captured by **HG-PYTHIA** which considers biases due to
  - Coll geometry and centrality selection

Radius dependence of jet suppression

JHEP 05 (2021) 284

Talk by C. Roland, Thu 7th, 11:15 AM



- Nuclear modification factor (R_{AA}) of jets measured for the **first time up to R=1.0**
- Dependence on R becoming weaker at higher p_T
- Strong constraints on models

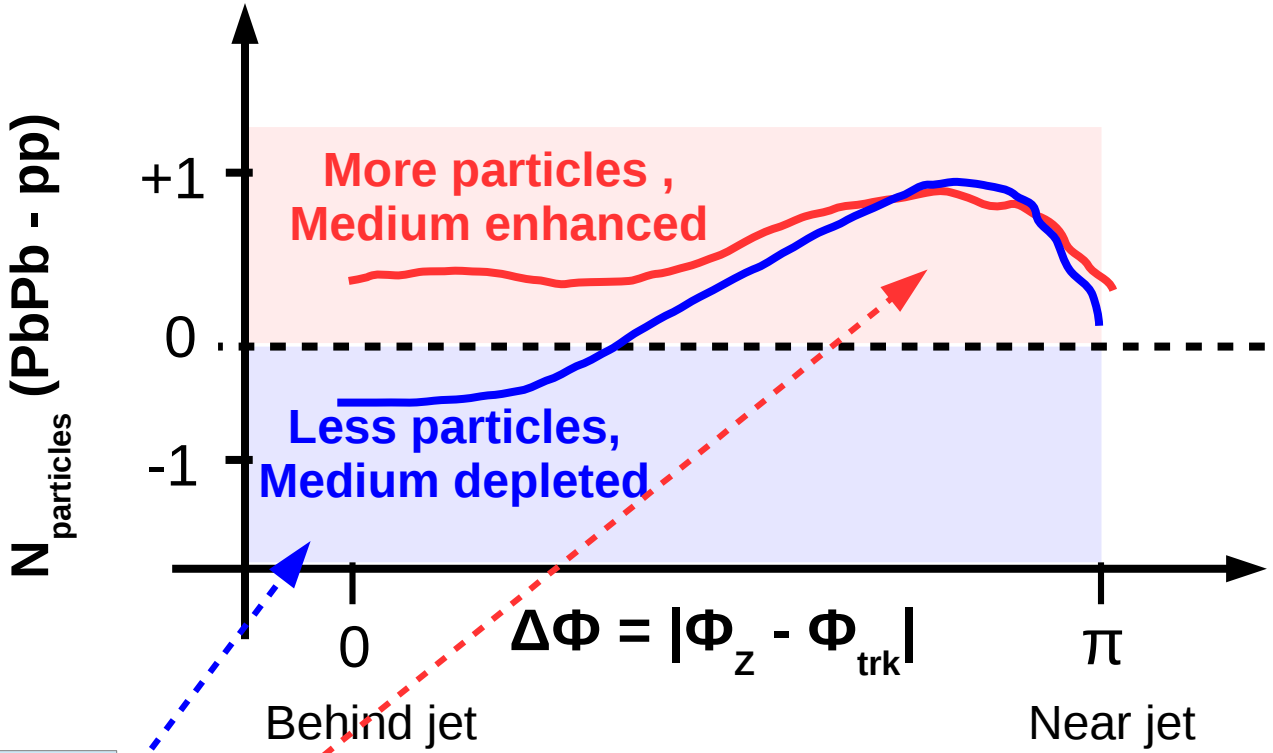
Factorization [PRL 122 (2019) 252301] of jet cross sections
Jet functions from smaller radius jet R_{AA}

SCET$_g$ [JHEP 05 (2016) 023]
Soft collinear effective theory with Glauber gluon interactions

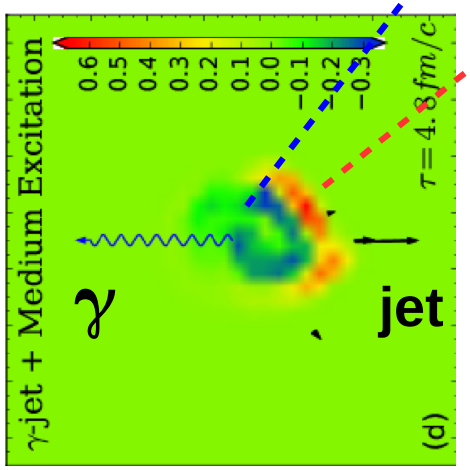
Li and Vitev [JHEP 07 (2019) 148]
SCET$_g$ including collisional energy loss

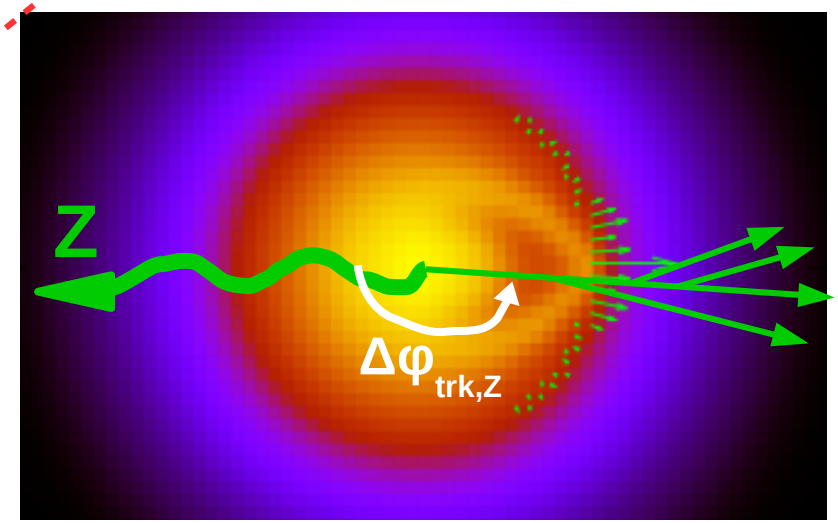
Coherent antenna BDMPS [PLB 345 (1995) 277]
Resums emissions including radiative energy loss and color coherence effects

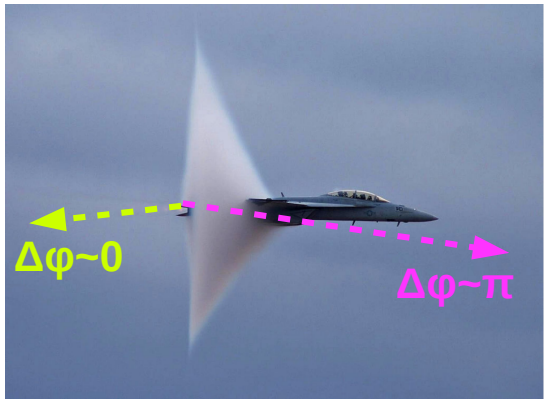
Angular scan of interactions



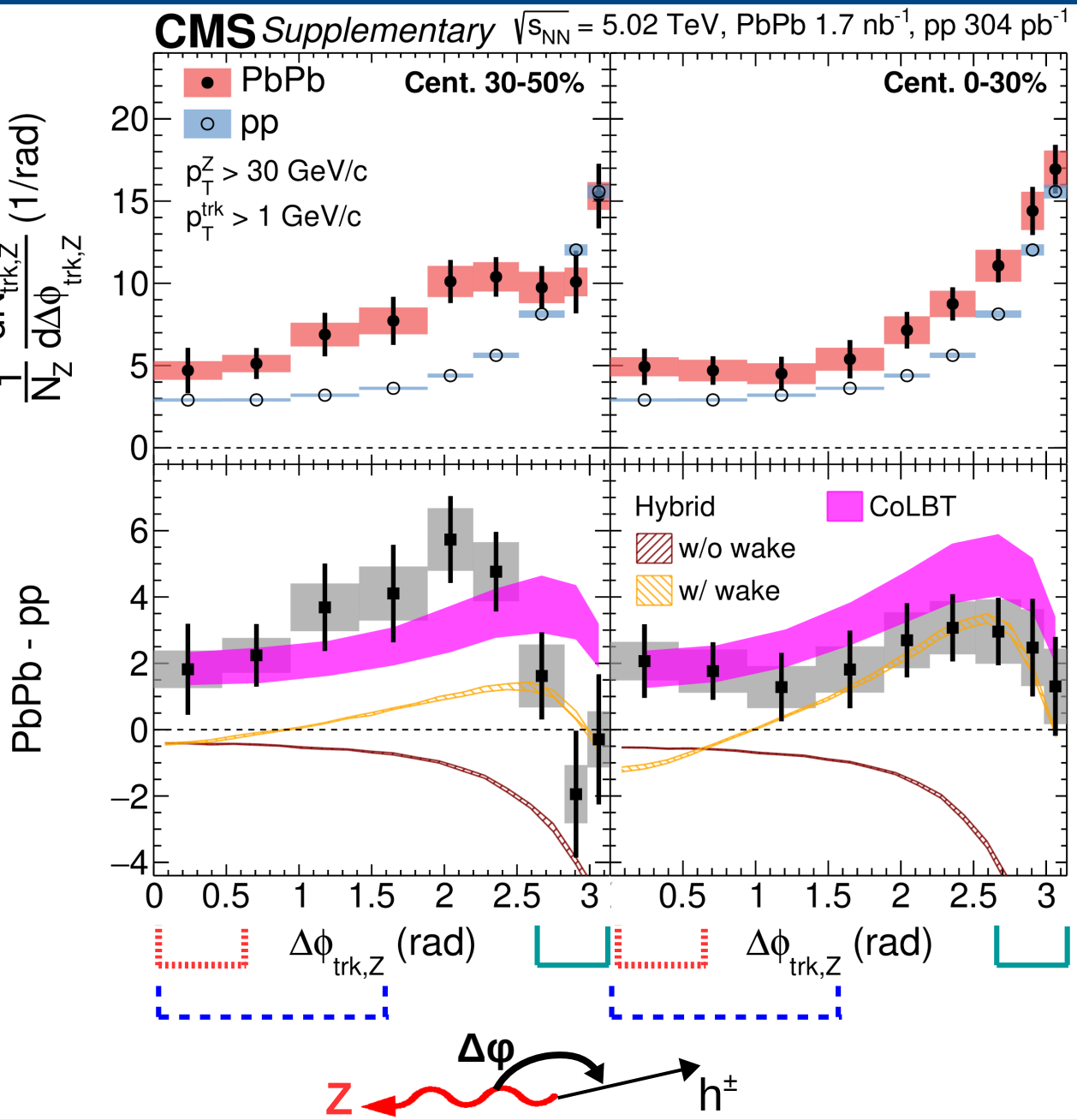
PLB 777 (2018) 86







Particle yield as function of $\Delta\varphi_{trk,Z}$



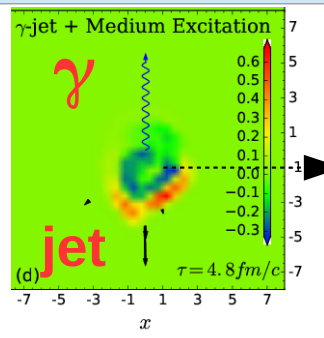
PRL 128 (2022) 122301

$\Delta\varphi_{trk,Z}$ ~ π trend similar when for CoLBT and Hybrid w/ wake

Hybrid tends to undershoot **$\Delta\varphi_{trk,Z}$ < π/2**

$\Delta\varphi_{trk,Z}$ ~ 0
Hybrid → depletion,
(medium response too soft ? [JHEP 05 (2021) 230])
CoLBT → enhancement
(explained by quenching of MPI [PRL 127, 082301 (2021)])

PLB 777 (2018) 86

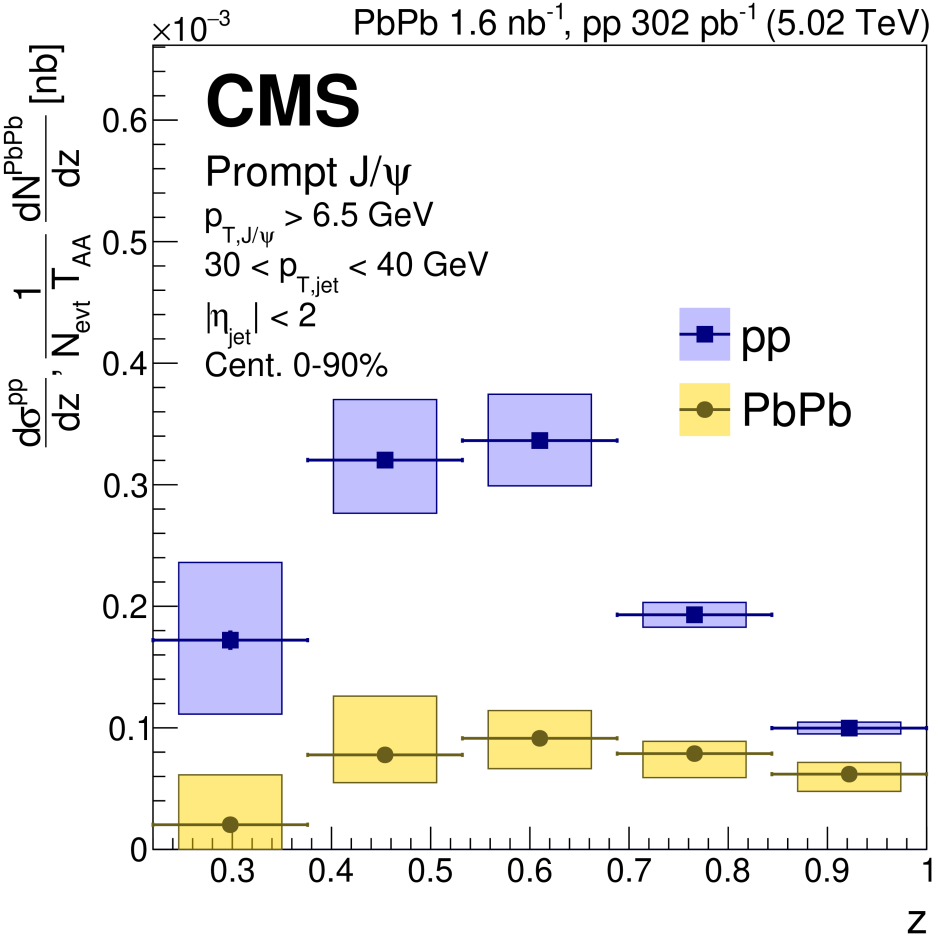


Diffusion wake

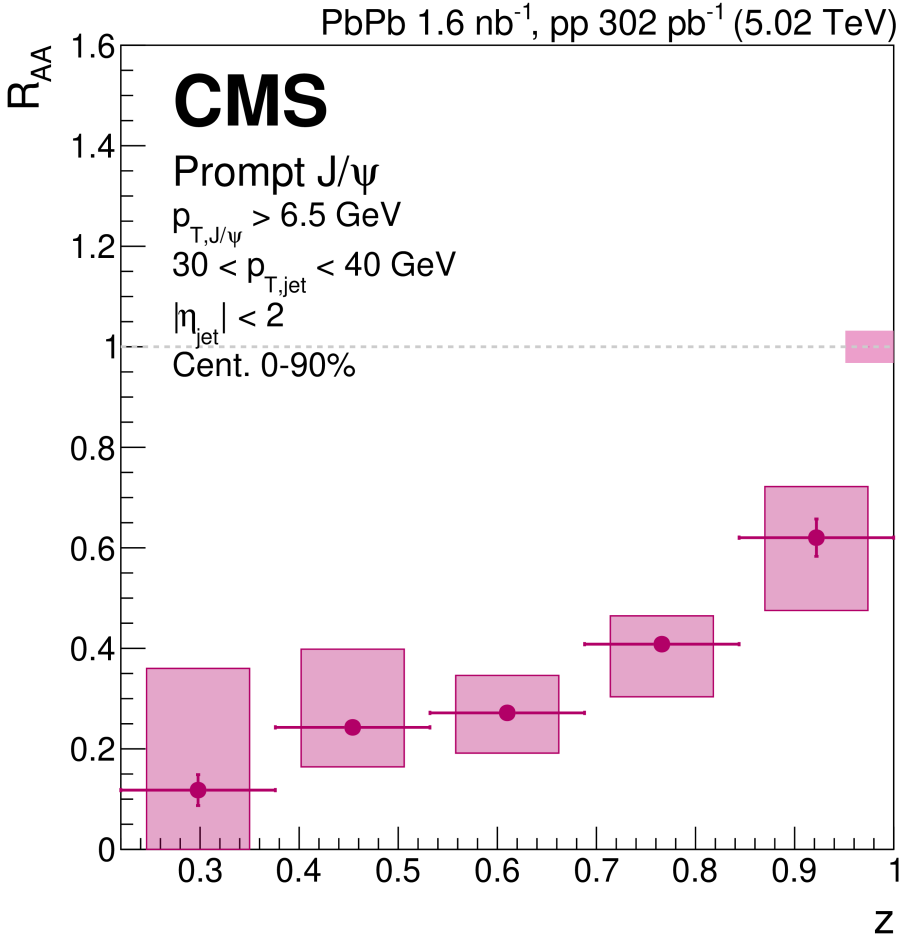
J/Ψ production in jets

Talk by F. Damas, Sat 9th, 9:15 AM

PLB 825 (2021) 136842



- J/Ψ yield measured as function of z = $p_T^{J/\Psi}$ / p_T^{jet}
- Small z –> Large degree of surrounding jet activity



- J/Ψ production more suppressed for small z
- Crucial to include jet quenching mechanisms in J/Ψ suppression calculation

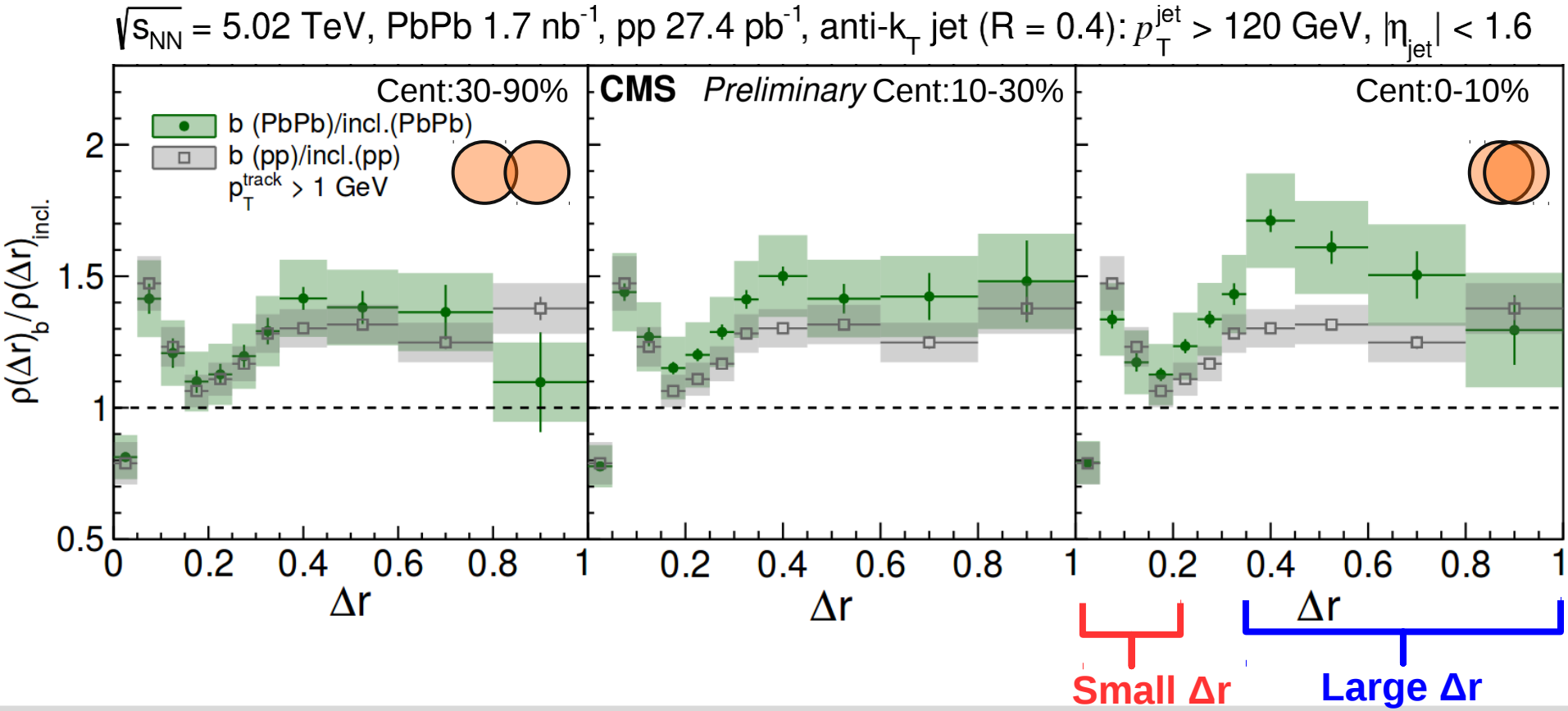
Dead cone effect via b-tagged jet shapes

Jet shapes quantified via $\rho(\Delta r) = \frac{1}{\delta r} \frac{\sum_{\text{jet}} \sum_{\text{trk} \in (\Delta r_a, \Delta r_b)} p_{\text{T}}^{\text{trk}}}{\sum_{\text{jet}} \sum_{\text{trk}} p_{\text{T}}^{\text{trk}}}$

CMS-PAS-HIN-20-003

Talk by M. Nguyen, Thu 7th, 3:35 PM

- Large Δr : Modification of b-tagged/inclusive ratio larger in more central **PbPb**
- Depletion in the small Δr where dead-cone effect is expected to be present.
  - No significant difference between **PbPb** and **pp** collisions



Flow (v_n) coefficients for dijets

$$f_{\text{Fourier}}(\Delta\varphi) = A \cdot \left(1 + \sum_{n=1}^{4} 2V_n \cos(n\Delta\varphi)\right)$$

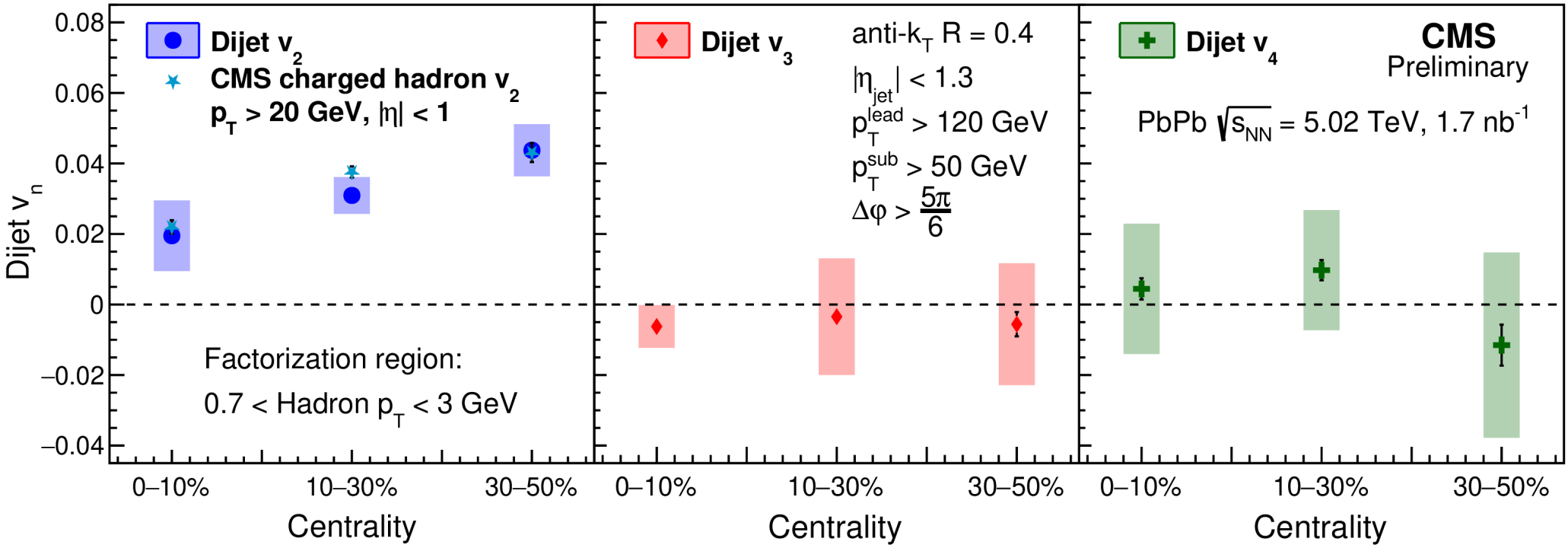
V_n can be factorized as $V_n = v_{n,\text{dijet}} \times v_{n,\text{hadron}}$

where $V_{n,\text{hadron}}$ can be obtained from di-hadron correlations

Talk by S. Tuo, Fri 8th, 5 PM

- Positive and centrality dependent **dijet v_2** : Path-length dependence of energy loss ?
- Dijet **v_3** and **v_4** consistent with zero, not enough precision to comment on effect of initial-state fluctuations

CMS-PAS-HIN-21-002



Summary

New hard probes measurements using Run 2 data

Explored previously uncharted regions

Z bosons: no significant v_2, yields consistent with N_{coll} scaling in central events, and with HG-PYTHIA in peripheral

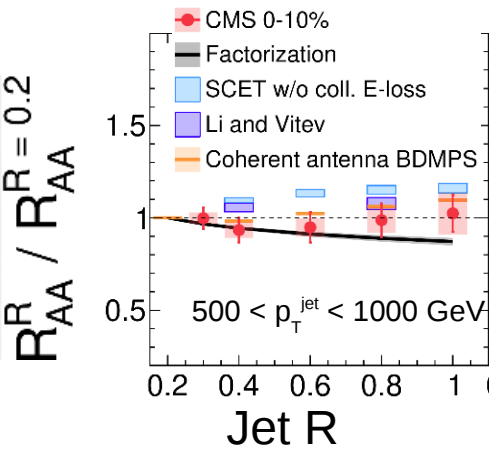
Suppression of large radius jets

Soft particle production in Z-tagged events over all angles

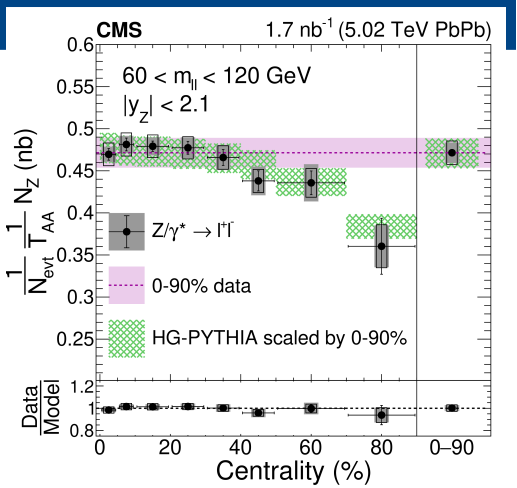
Relation between collision geometry and parton energy loss

New probes (J/Ψ and b-tagged jets) to constrain modification of high-p_T heavy quarks

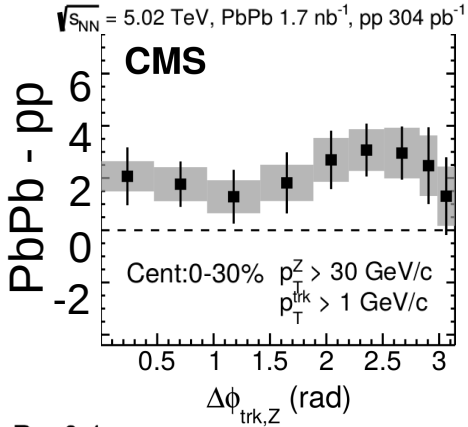
JHEP 05 (2021) 284



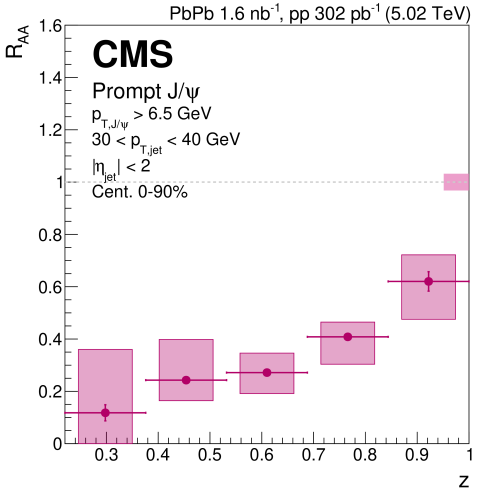
PRL 127 (2021) 102002



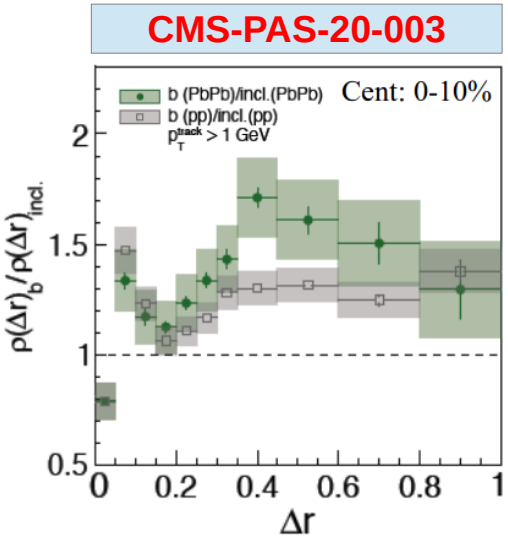
PRL 128 (2022) 122301



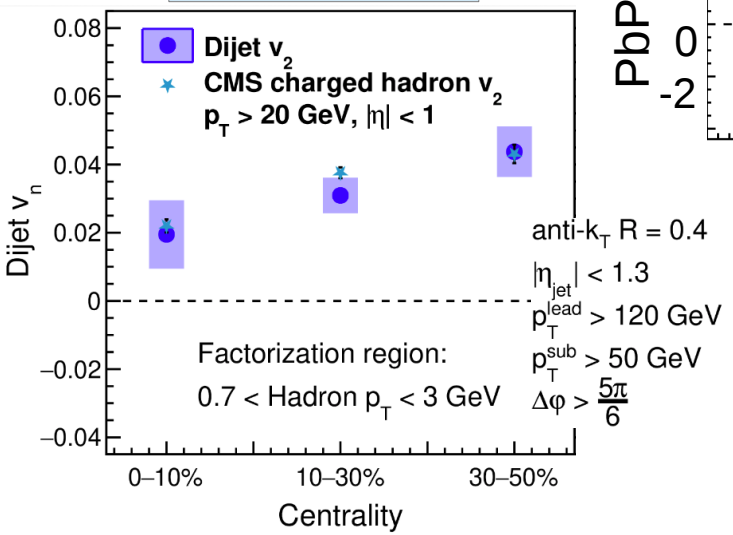
PLB 825 (2021) 136842



CMS-PAS-20-003



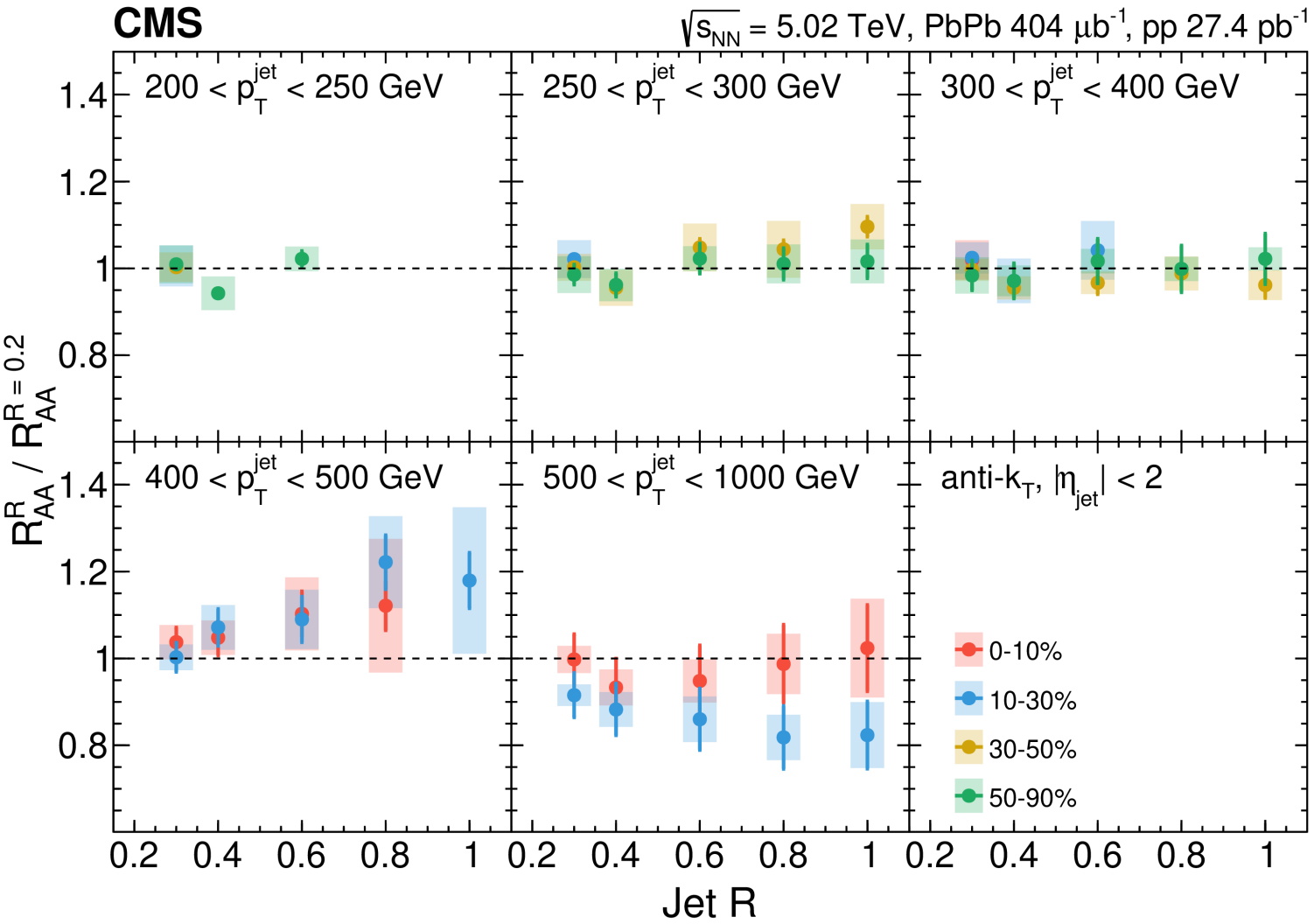
CMS-PAS-21-002



BACKUP

Radius dependence of jet suppression

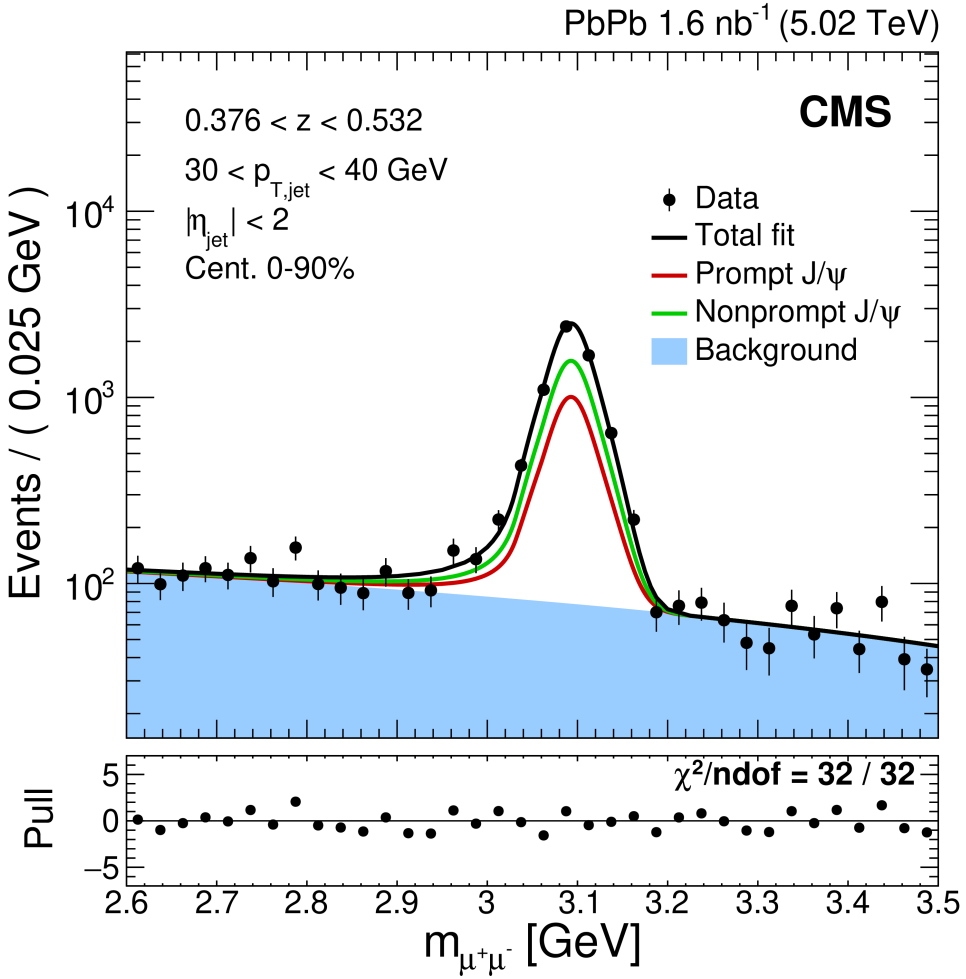
JHEP 05 (2021) 284

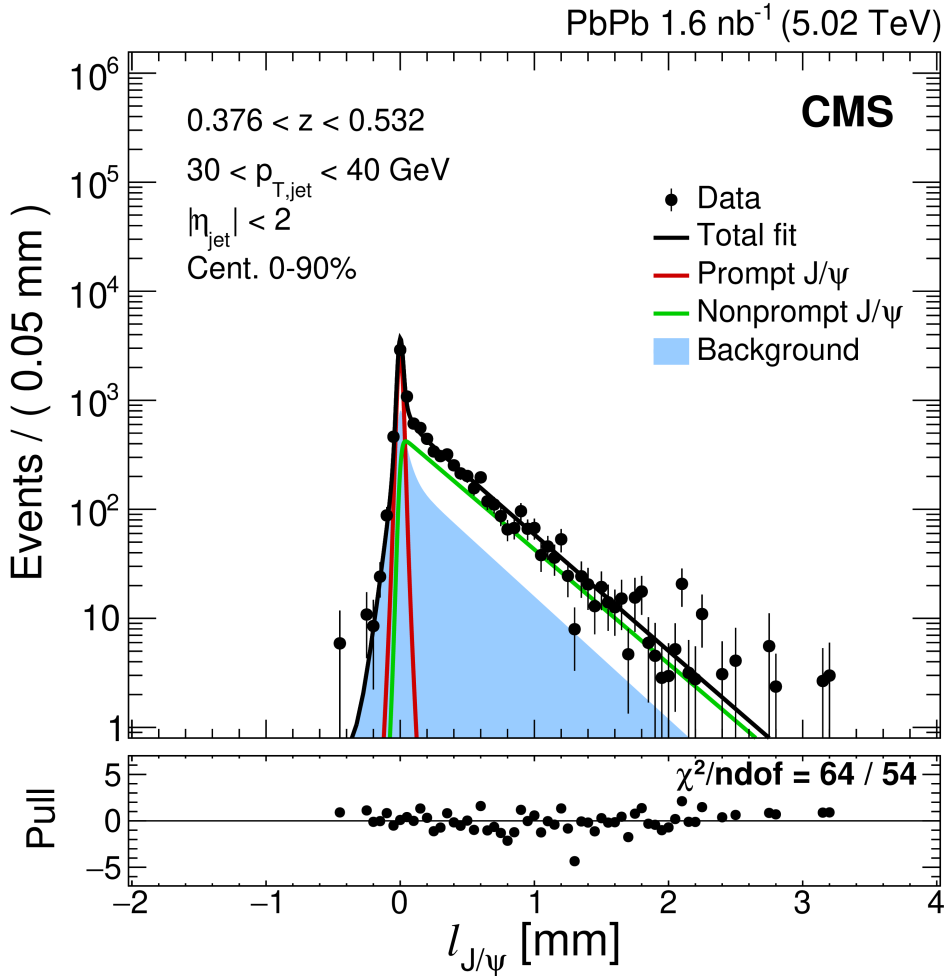


- Nuclear modification factor (R_{AA}) of jets measured for the first time up to R=1.0
- Central collisions : Indication of suppression decreasing with R for jets with p_T < 500 GeV (increasing with R for p_T > 500 GeV)

Prompt J/Ψ in jets : Signal extraction

PLB 825 (2021) 136842





J/Ψ measured via decays into opposite charge muon pairs.

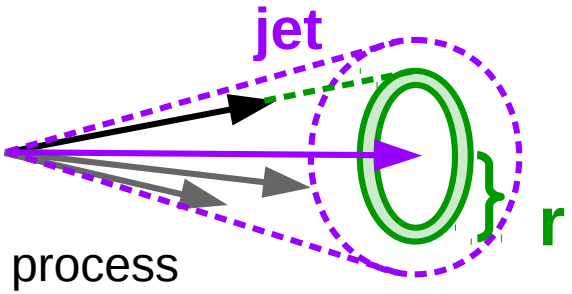
Nonprompt J/Ψ : from b hadron decays
Separated from **prompt** via decay length

Prompt J/Ψ yield extracted via 2D fit to $m_{\mu\mu}$ and $l_{J/\Psi}$ distributions

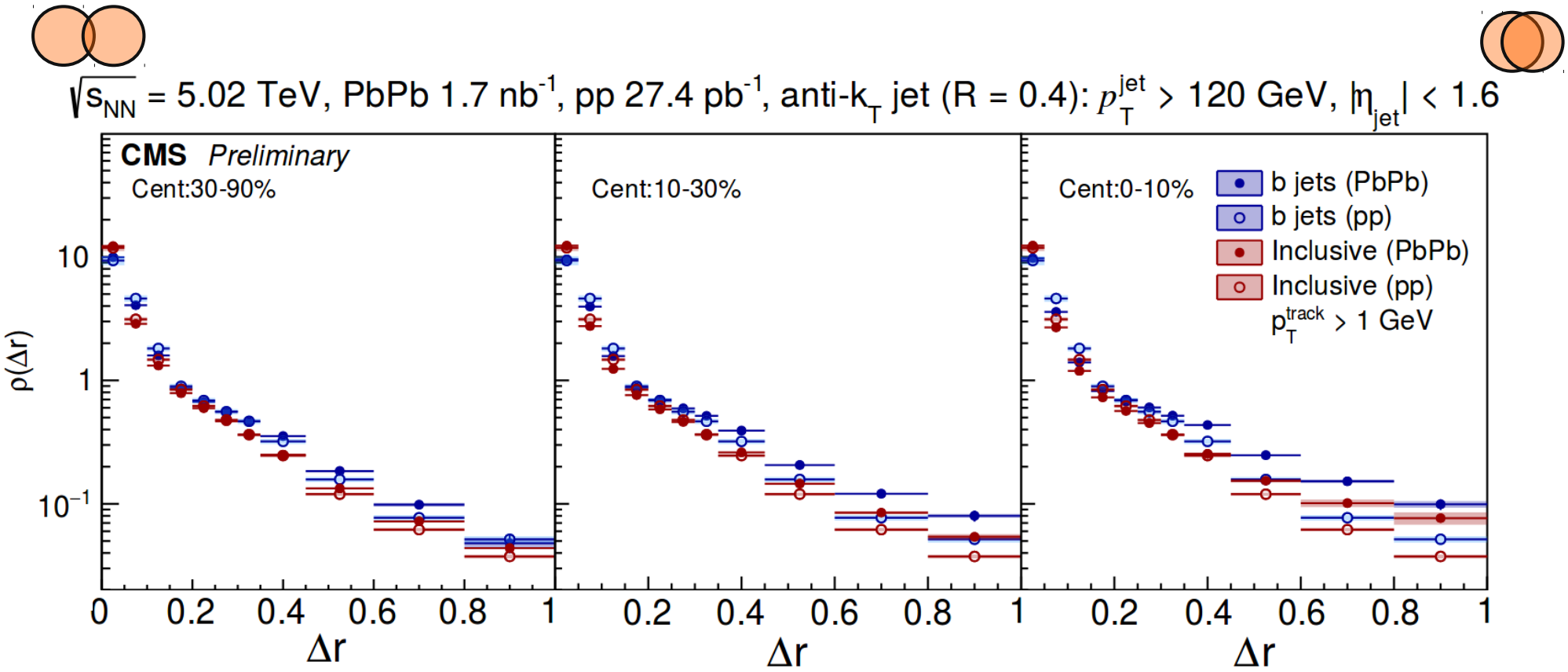
Dead-cone effect via b-tagged jet shapes

CMS-PAS-HIN-20-003

Jet shapes quantified via $\rho(\Delta r) = \frac{1}{\delta r} \frac{\Sigma_{\text{jet}} \Sigma_{\text{trk} \in (\Delta r_a, \Delta r_b)} p_{\text{T}}^{\text{trk}}}{\Sigma_{\text{jet}} \Sigma_{\text{trk}} p_{\text{T}}^{\text{trk}}}$

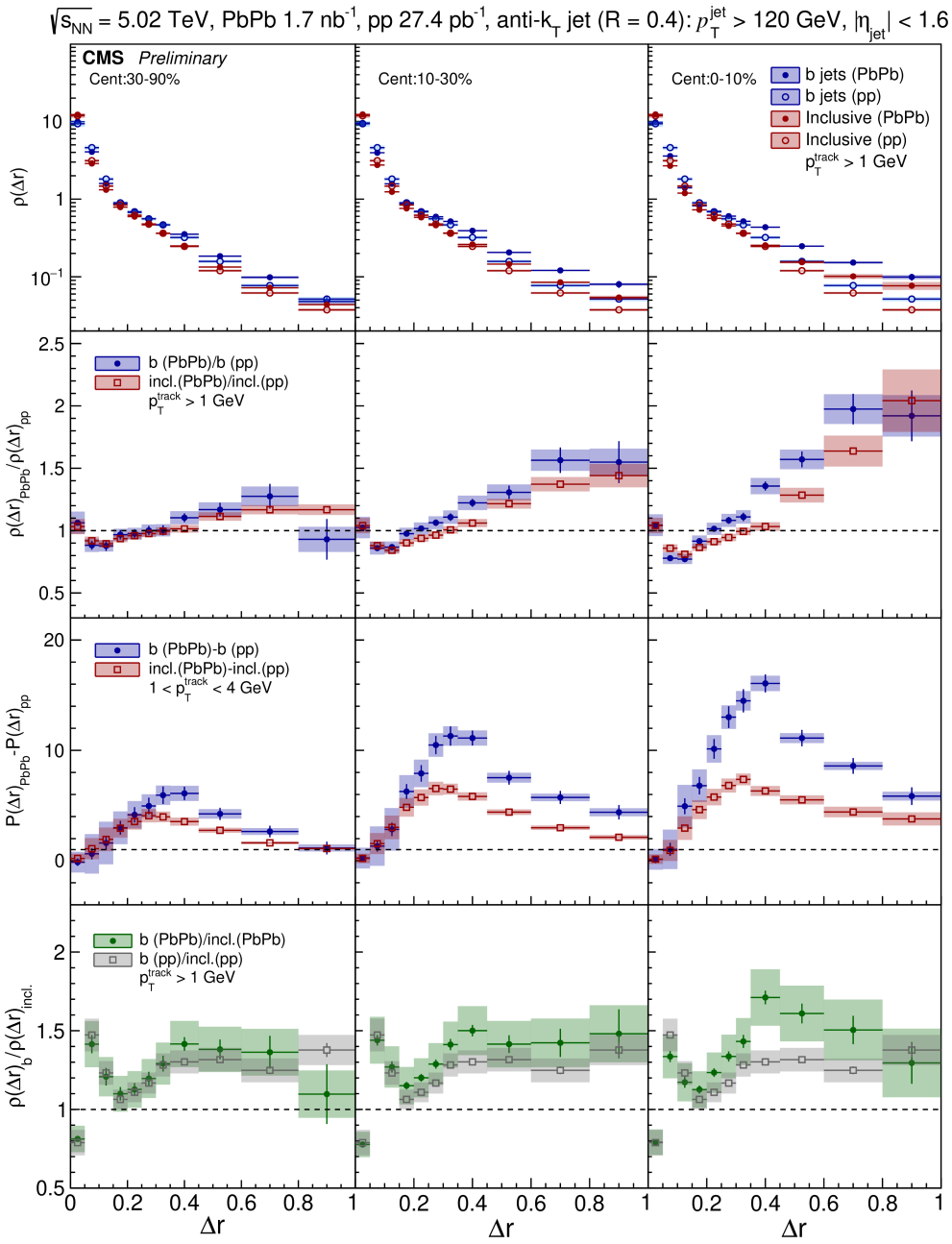


- **b-taggged** jets wider **inclusive** mostly because of gluon splitting process
- **Inclusive** and **b-taggged** jets are wider in PbPb than in pp



b-tagged jet shapes

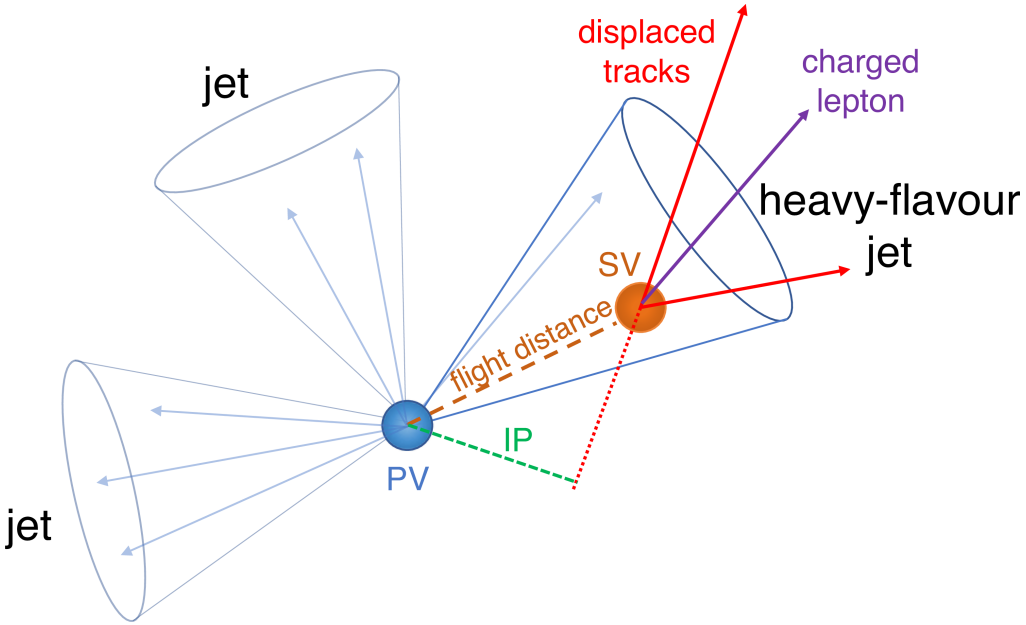
CMS-PAS-HIN-20-003

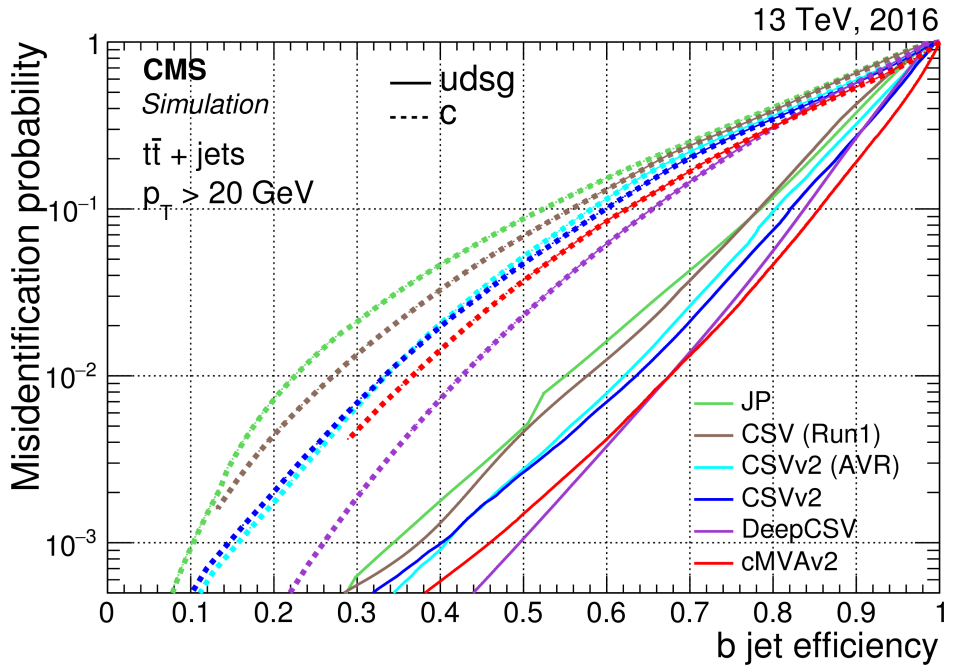


CMS b-tagging

b-jets tagged via a multi-variate discriminator (CSVv2) taking the track and secondary vertex (SV) information

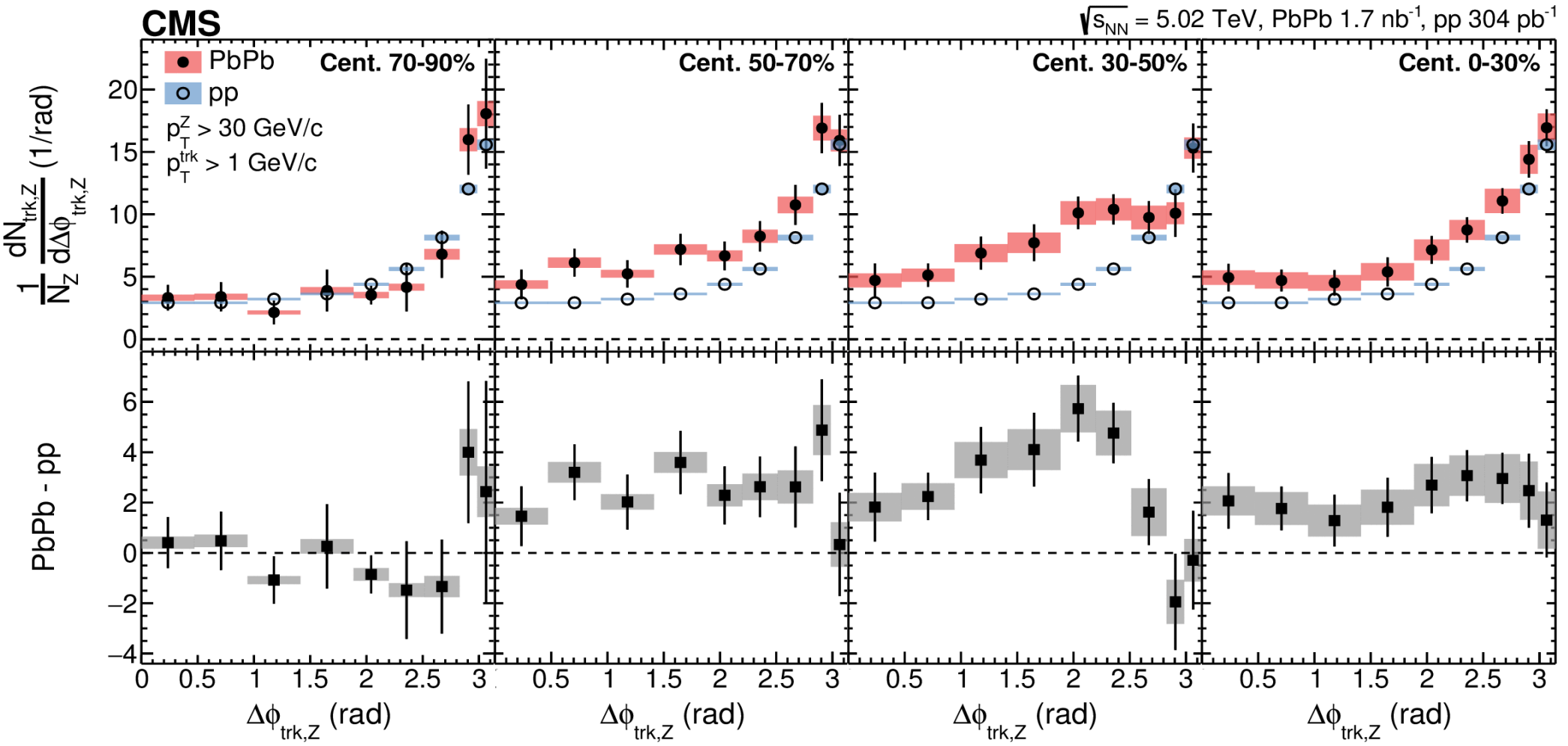
JINST 13 (2018) P05011

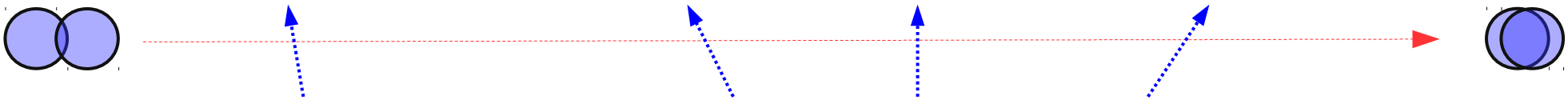




Results : $\Delta\varphi_{trk,Z}$

PRL 128 (2022) 122301



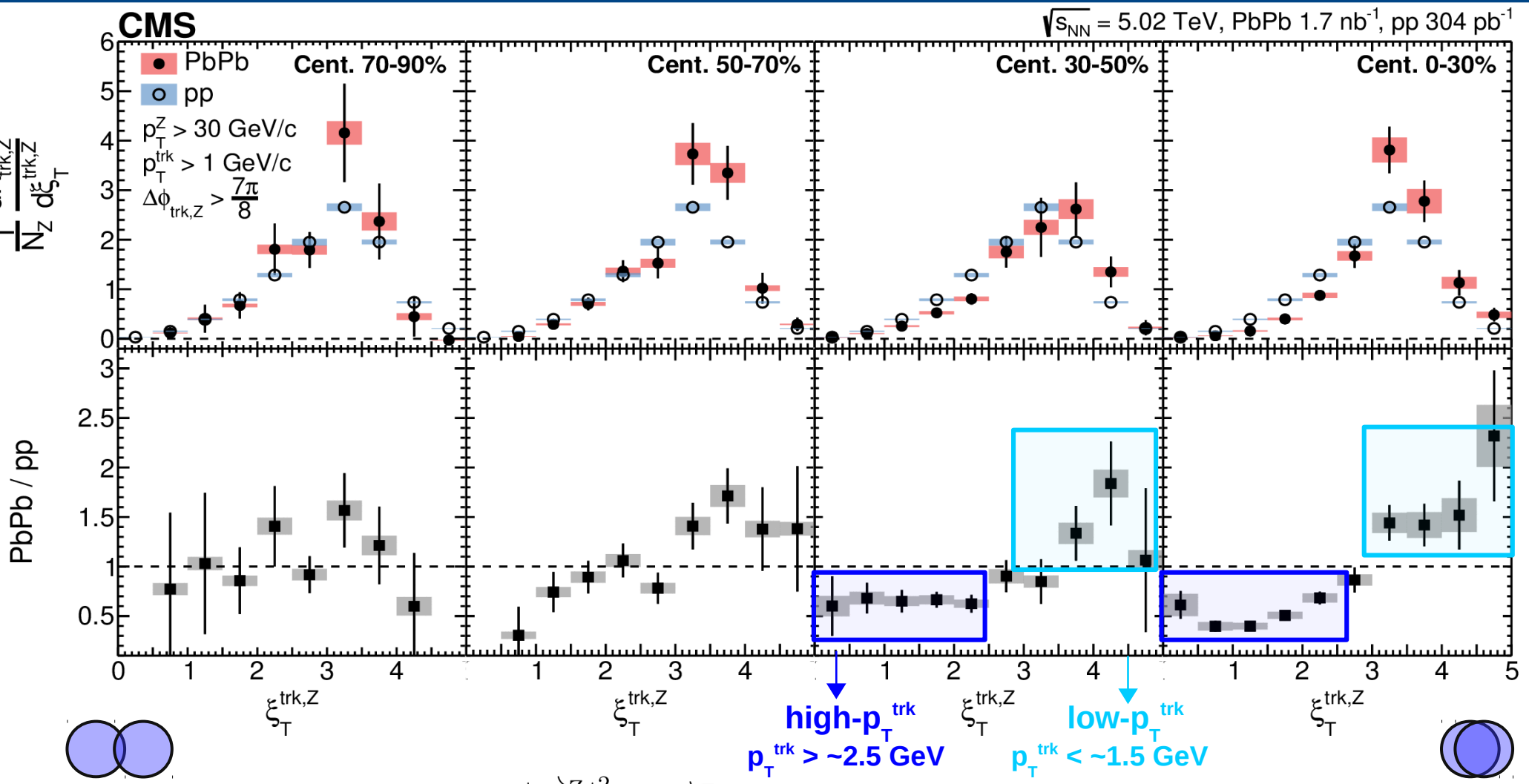


PbPb consistent with pp

Excess of particle yield in PbPb

Results : $\xi_T^{trk,Z}$

PRL 128 (2022) 122301



$$\xi_T^{trk,Z} = \ln \frac{-|\vec{p}_T^{\,Z}|^2}{\vec{p}_T^{\,trk} \cdot \vec{p}_T^{\,Z}}$$

$\vec{p}_T^{\,Z}$: transverse mom. vector of the Z

$\vec{p}_T^{\,trk}$: transverse mom. vector of the track

Excess (**depletion**) of **low** (**high**) -energy particles in central PbPb

Results : p_T^{trk}

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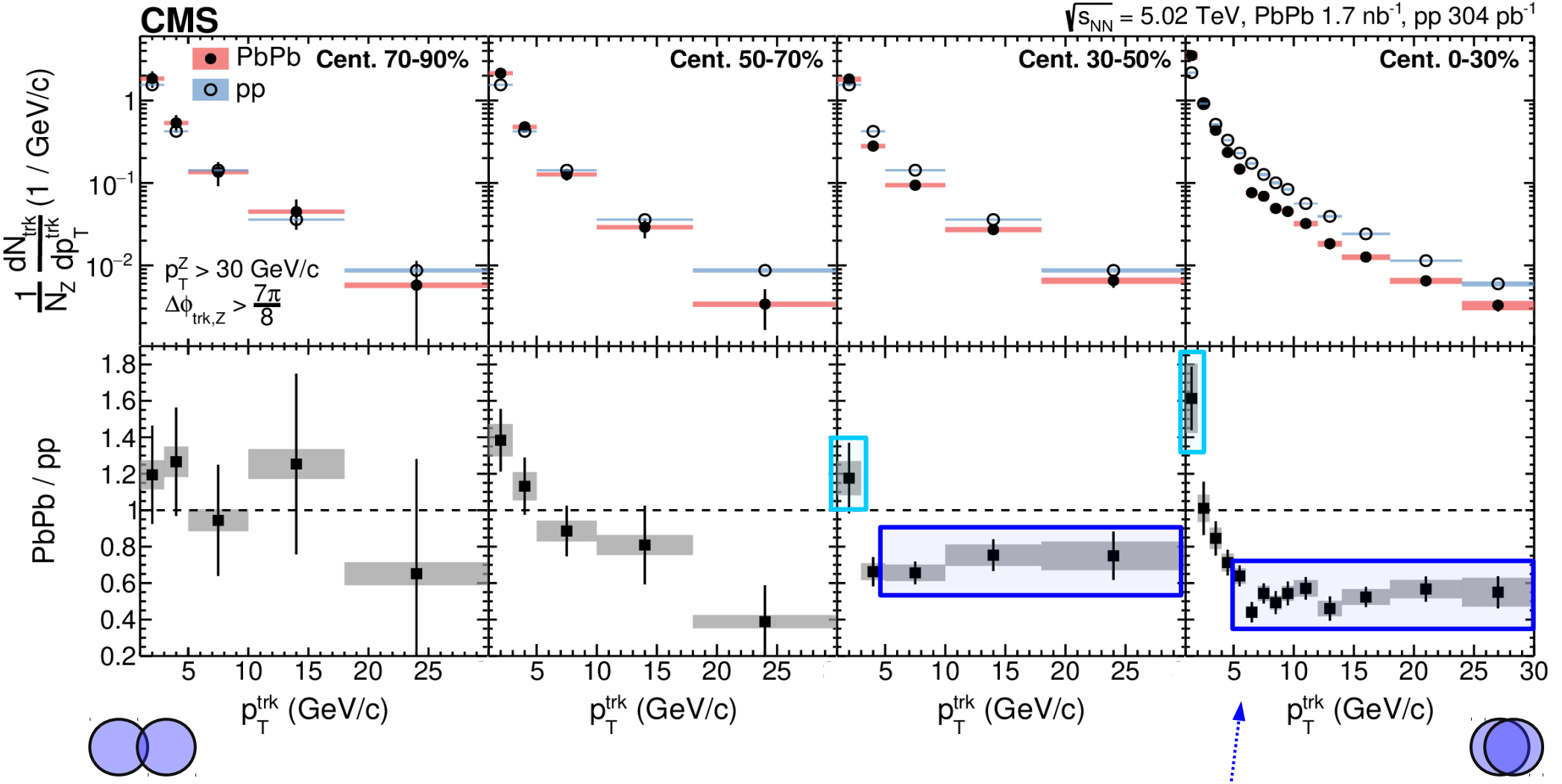

Peripheral PbPb consistent with pp

PbPb / pp ($1 < p_T^{trk} < 2$ GeV) ~ 1.6

($p_T^{trk} > 5$ GeV) ~ 0.4 - 0.6