New results on hard probes in heavy-ion collisions from CMS

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Bologna, Italy

CMS

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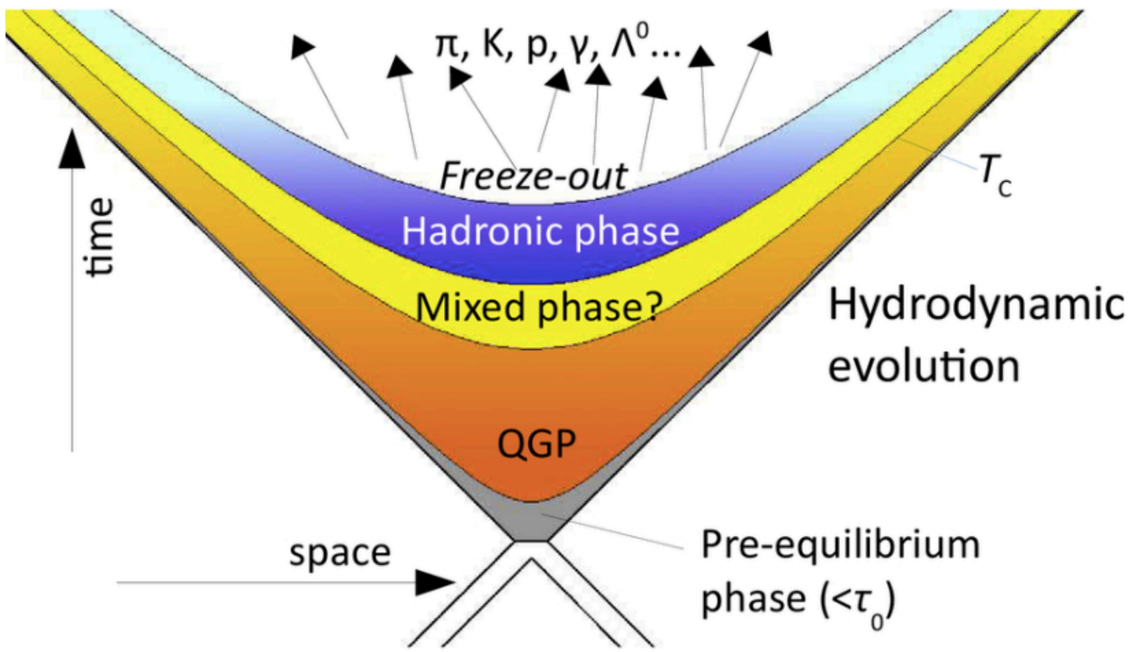
Outline

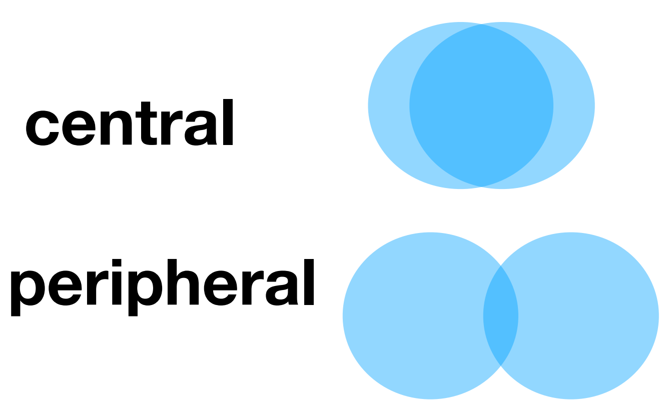
- Hard probes for studies of the Quark Gluon Plasma
- Energy Loss in hot QCD medium:
  - Nuclear modification factors for jets and hadrons
  - Suppression of Charm and Beauty
  - New studies of system size effects
- Melting Quarkonia
- Jet quenching and modification of jet properties in QGP
  - Medium effects on Jet Mass
  - Jet shapes and Fragmentation Functions
  - Energy redistribution in Photon-tagged jets
  - In-jet Flavor production in Heavy Ion collisions

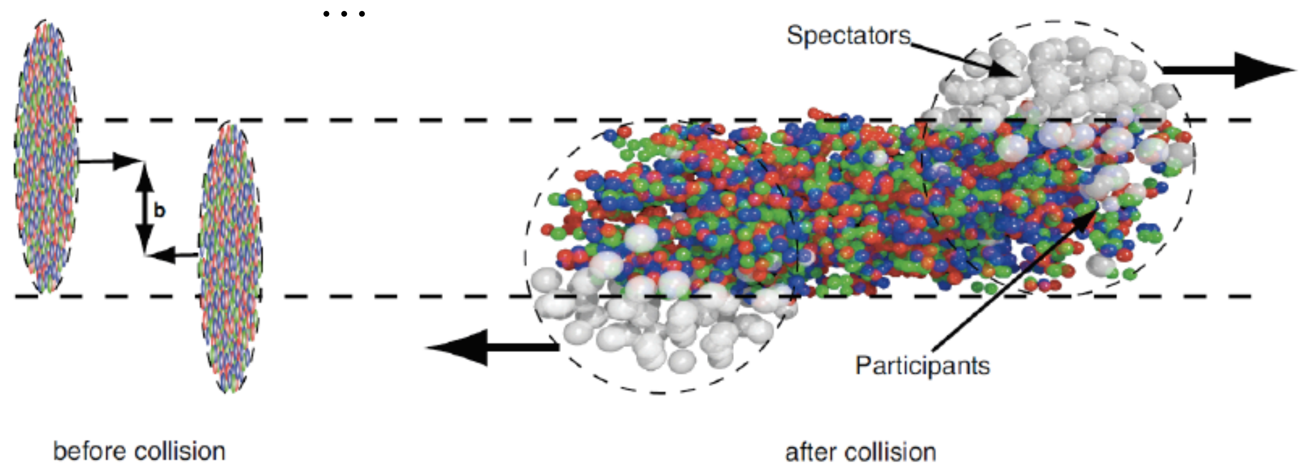
Heavy Ion Collision



- Energy densities and temperatures achieved in Heavy Ion collisions at RHIC and LHC exceed QCD predicted critical values for deconfinment
- Creation of strongly-interacting Quark Gluon Plasma (QGP) in such collisions is firmly established through multitude of experimental results
- Hard probes (high-scale processes: high momentum transfer, high p_T/E_T, high mass) are in-situ tomographic probes for QGP
- Provide experimental means to study:
  - Medium properties and interaction strength
  - Energy loss and redistribution
  - Degree of thermalization
  - …

Characterizing Heavy Ion Collisions





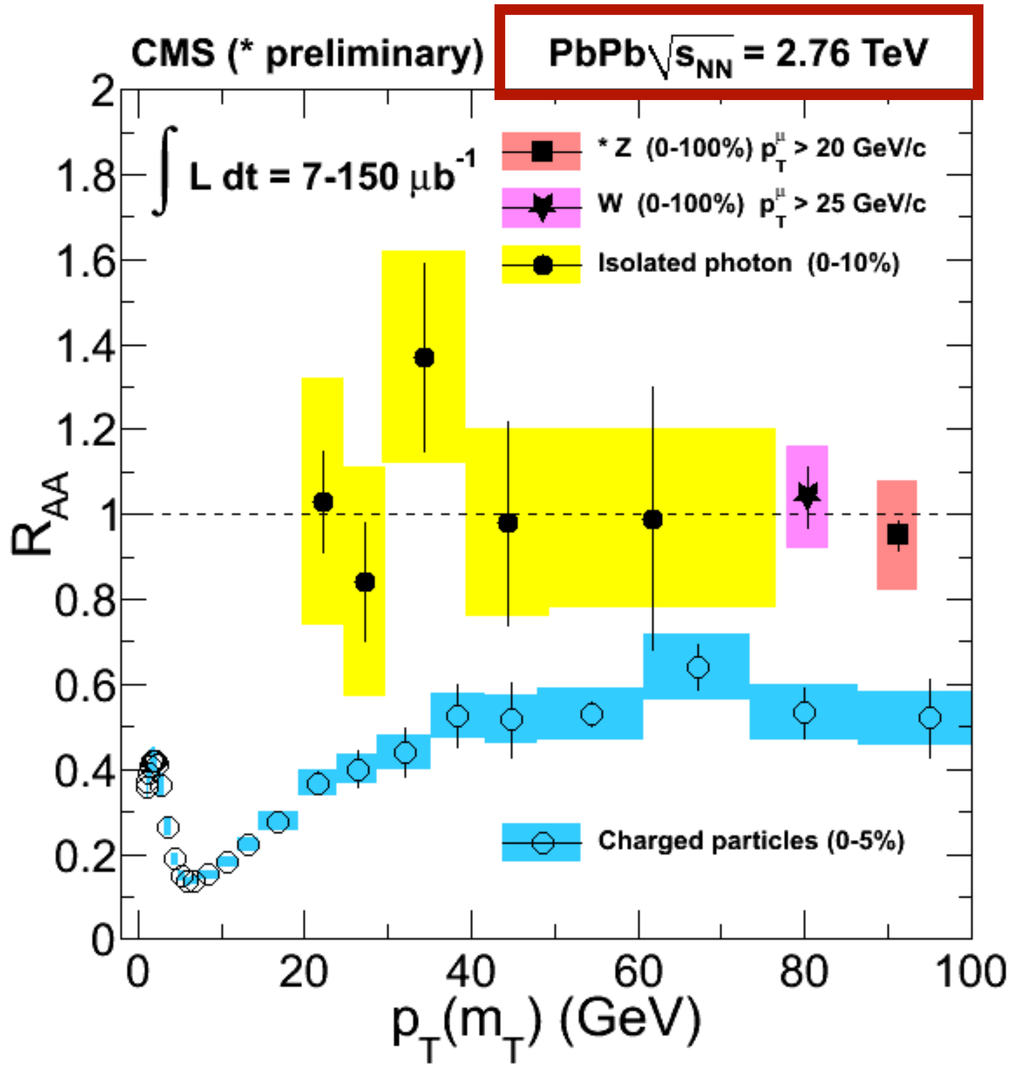
N_{part} – #of participating nucleons: characterizes volume of the interaction region

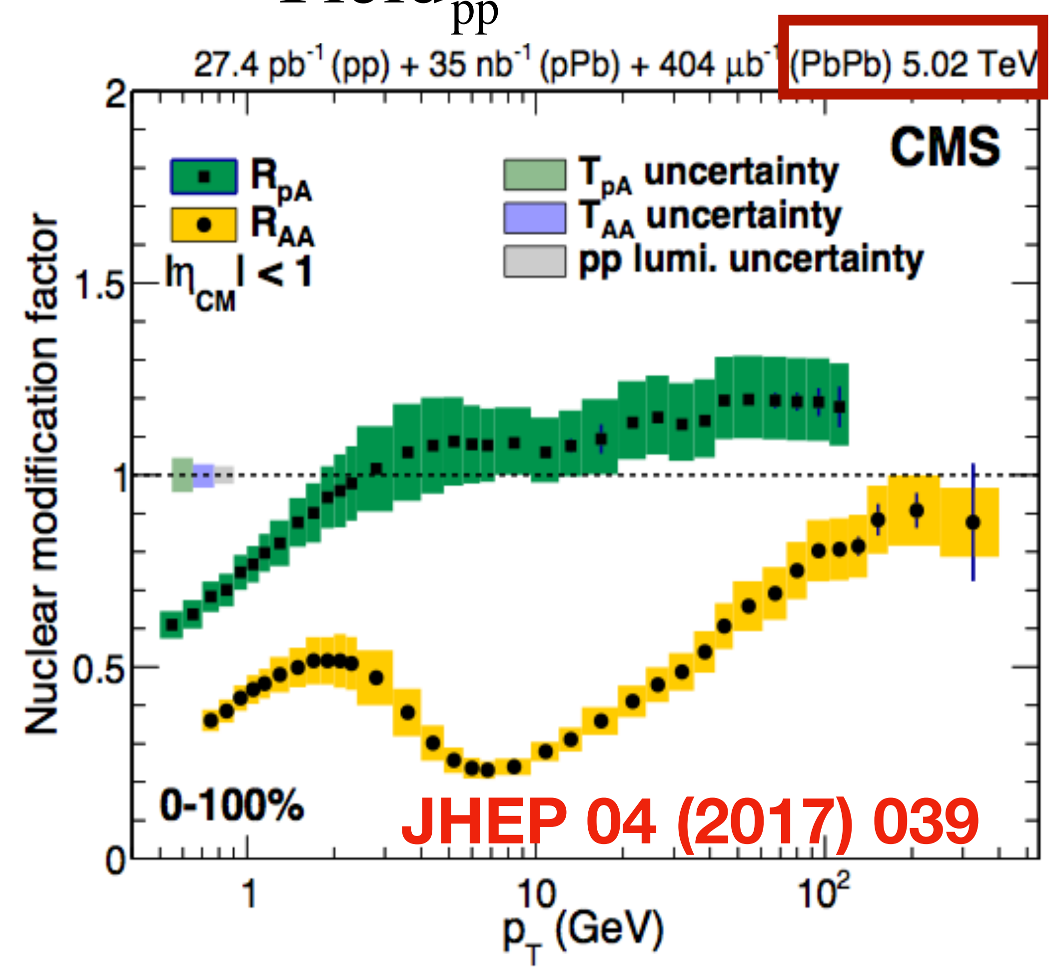
N_{coll} – # binary collisions: expected scale for hard processes

Energy Loss in QGP

- **Nuclear modification factors are used to express the strength of nuclear effects:**

$$R_{AA} = \frac{\mathrm{Yield}_{AA} / \langle N_{binary} \rangle_{AA}}{\mathrm{Yield}_{pp}}$$





- Partonic energy loss in QGP is evident in strong suppression of high p_T hadrons
- Colorless probes (isolated photons, Z^0, W) confirm expected N_{coll} scaling
- Cold nuclear matter effects are constrained by pPb data

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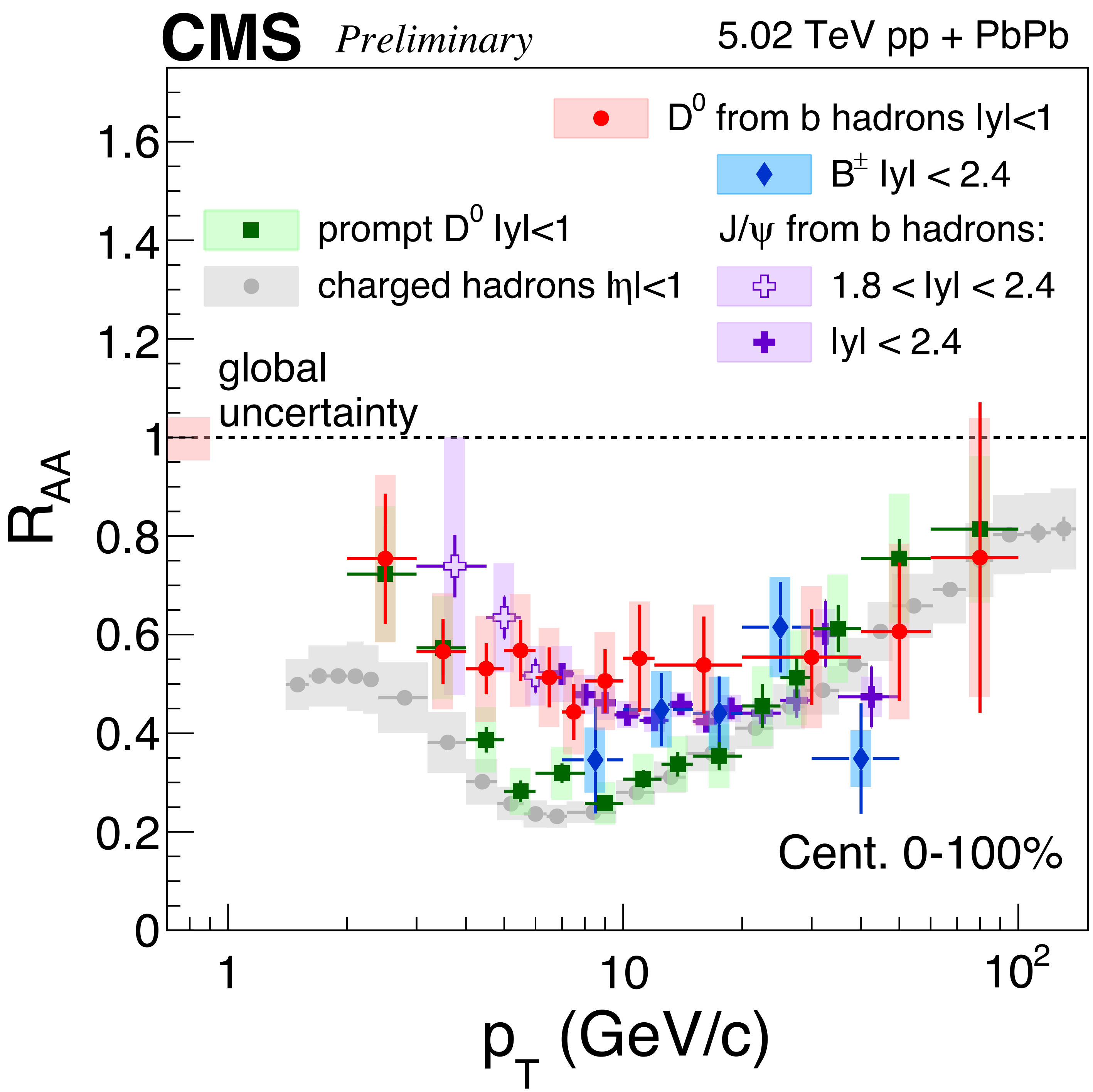
Flavor Dependence of Energy Loss

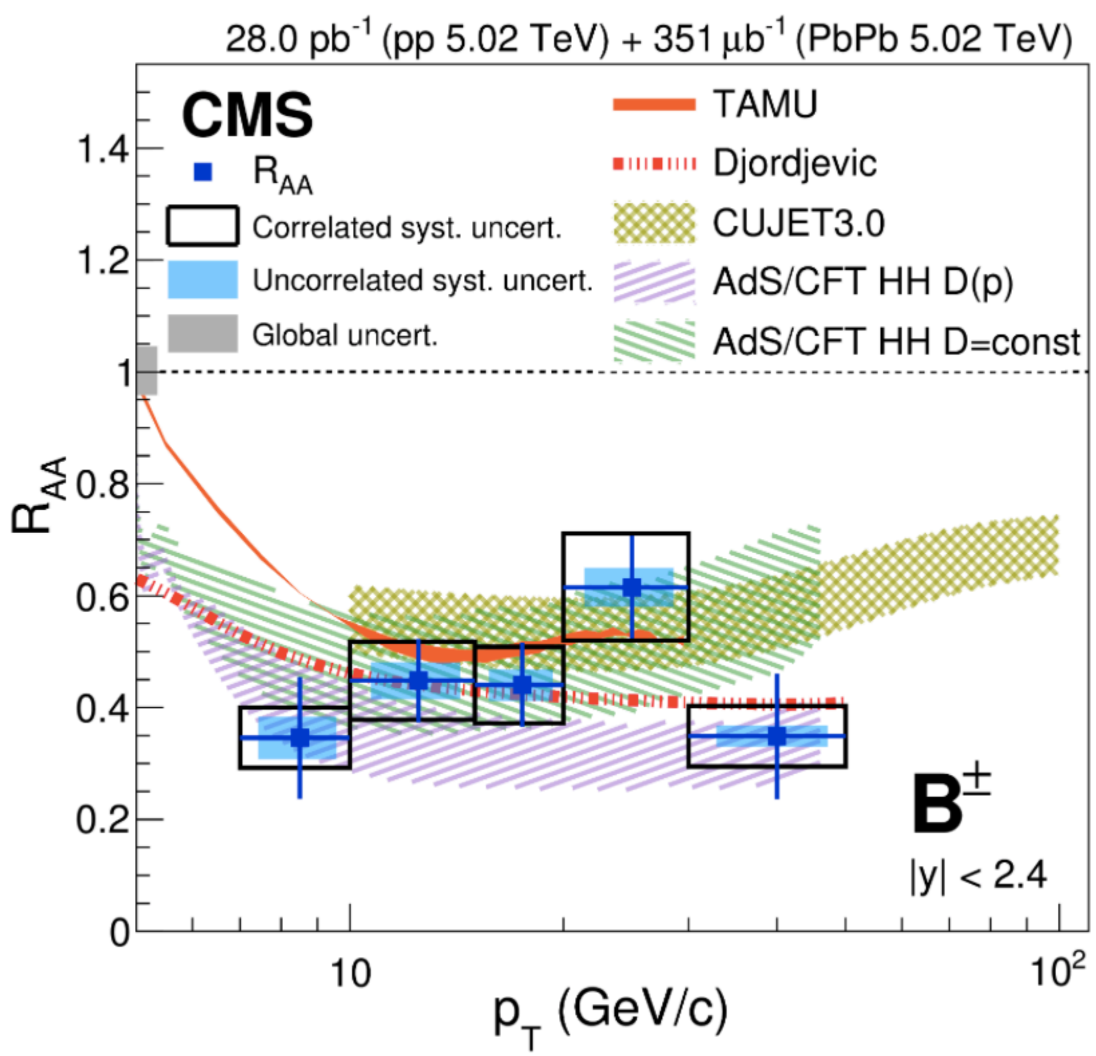


- **Gluons and Light Quarks**:
  - dominant contributions to charged hadrons
  - strongest suppression at intermediate p_T
- **Charm**:
  - assessed through prompt D0
  - similar suppression level with light hadrons
- **Beauty**:
  - non-prompt J/Ψ, B± mesons
  - less suppressed at intermediate p_T
  - at high p_T parton mass seems no longer important

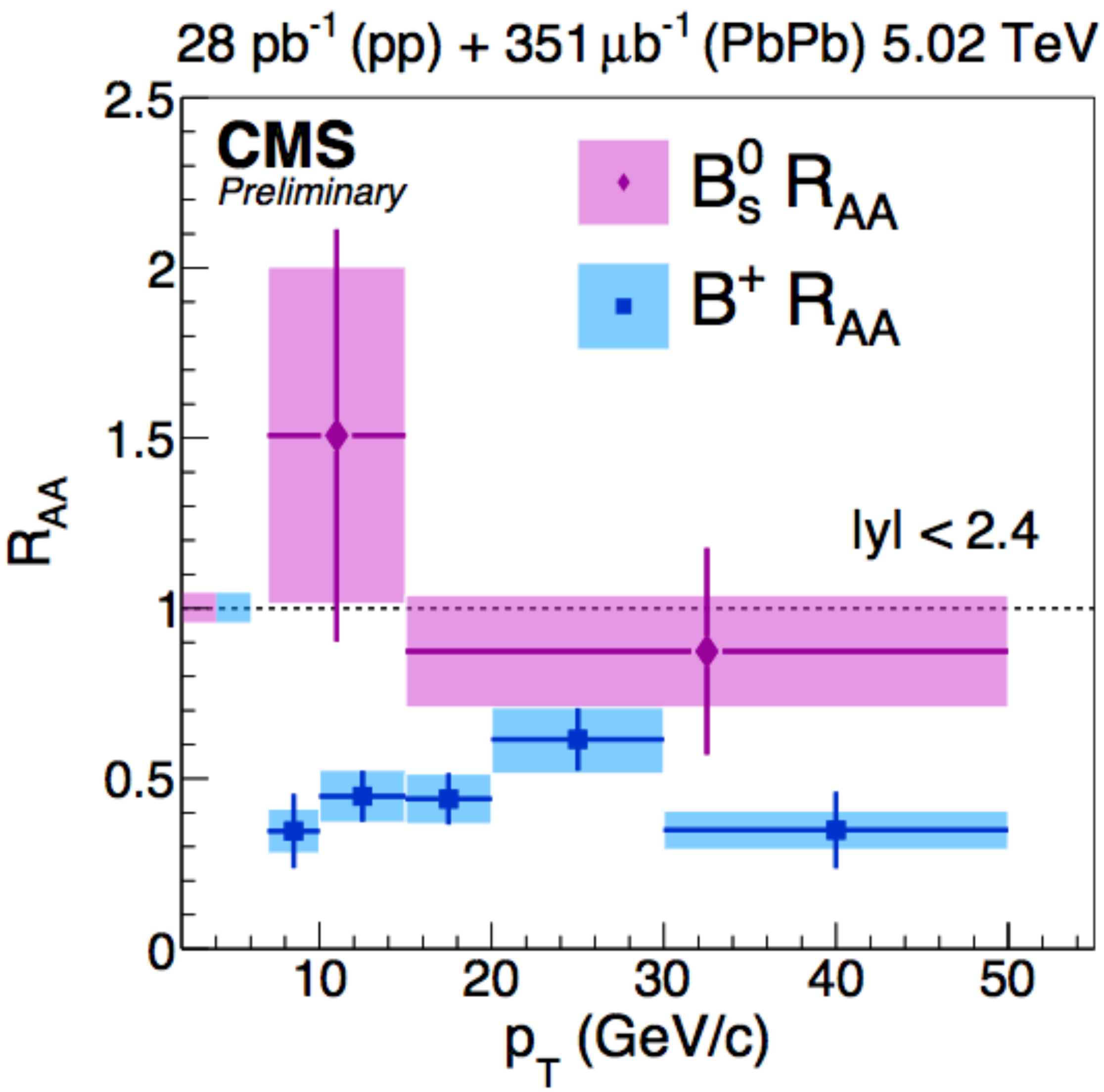
CMS-PAS-HIN-16-016

More on Beauty Suppression

- First direct reconstruction of B mesons observation in heavy ion collision
- Significant suppression of $B^{\pm}$ yields in PbPb data compared to pp
- Hint of smaller B_s^0 suppression – could be related strangeness enhancement (a known QGP signature) and quark recombination mechanism of particle production



Phys. Rev. Lett. 119, 152301



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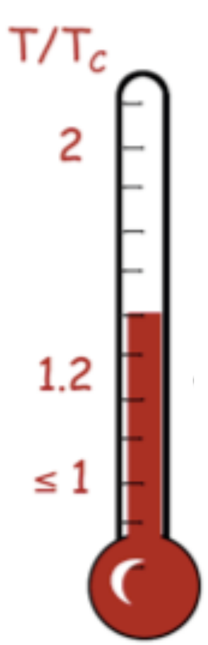
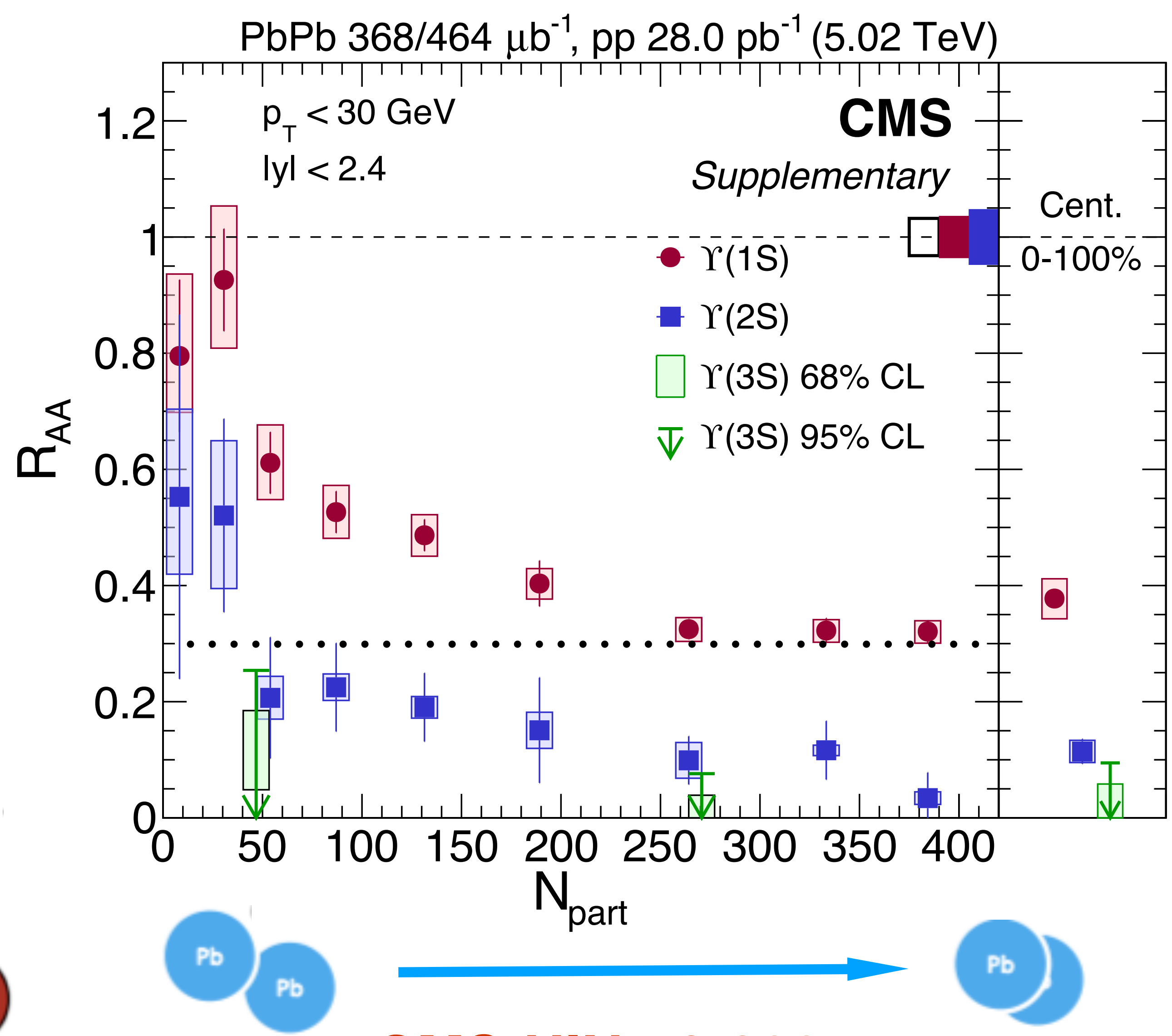
Melting Quarkonia

- Theory predicts sequential "melting" of Quarkonium species based on binding energy vs medium temperature
- Observed ordering of R_{AA} levels is generally consistent with this expectations
- Details of centrality dependence – not straightforward to relate to expected temperature change





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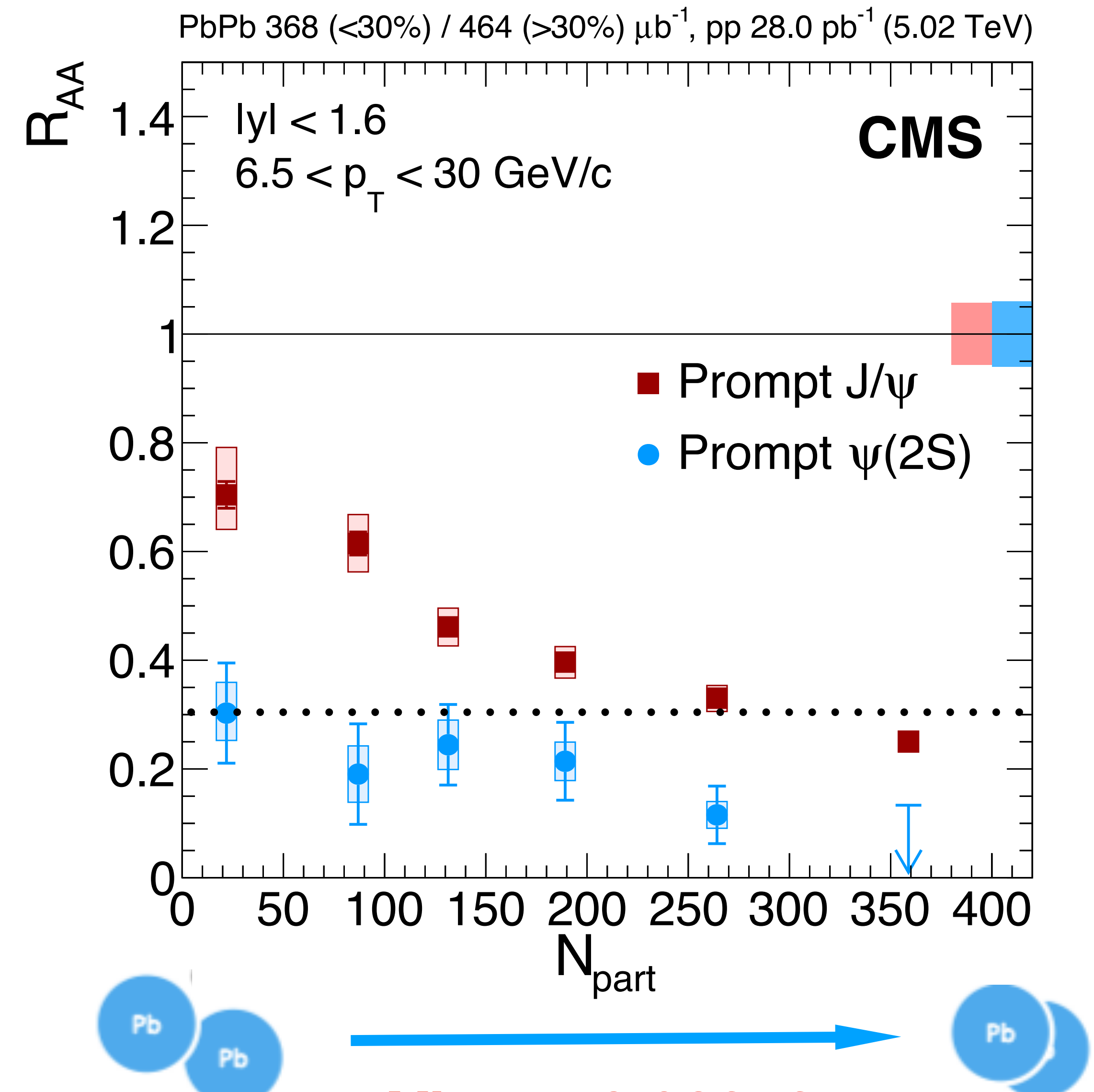

arXiv:1712.08959

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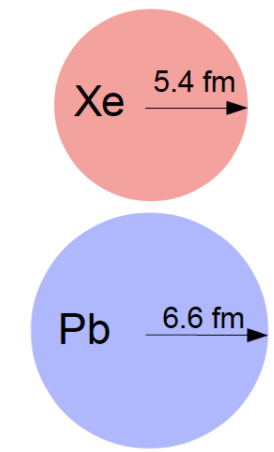
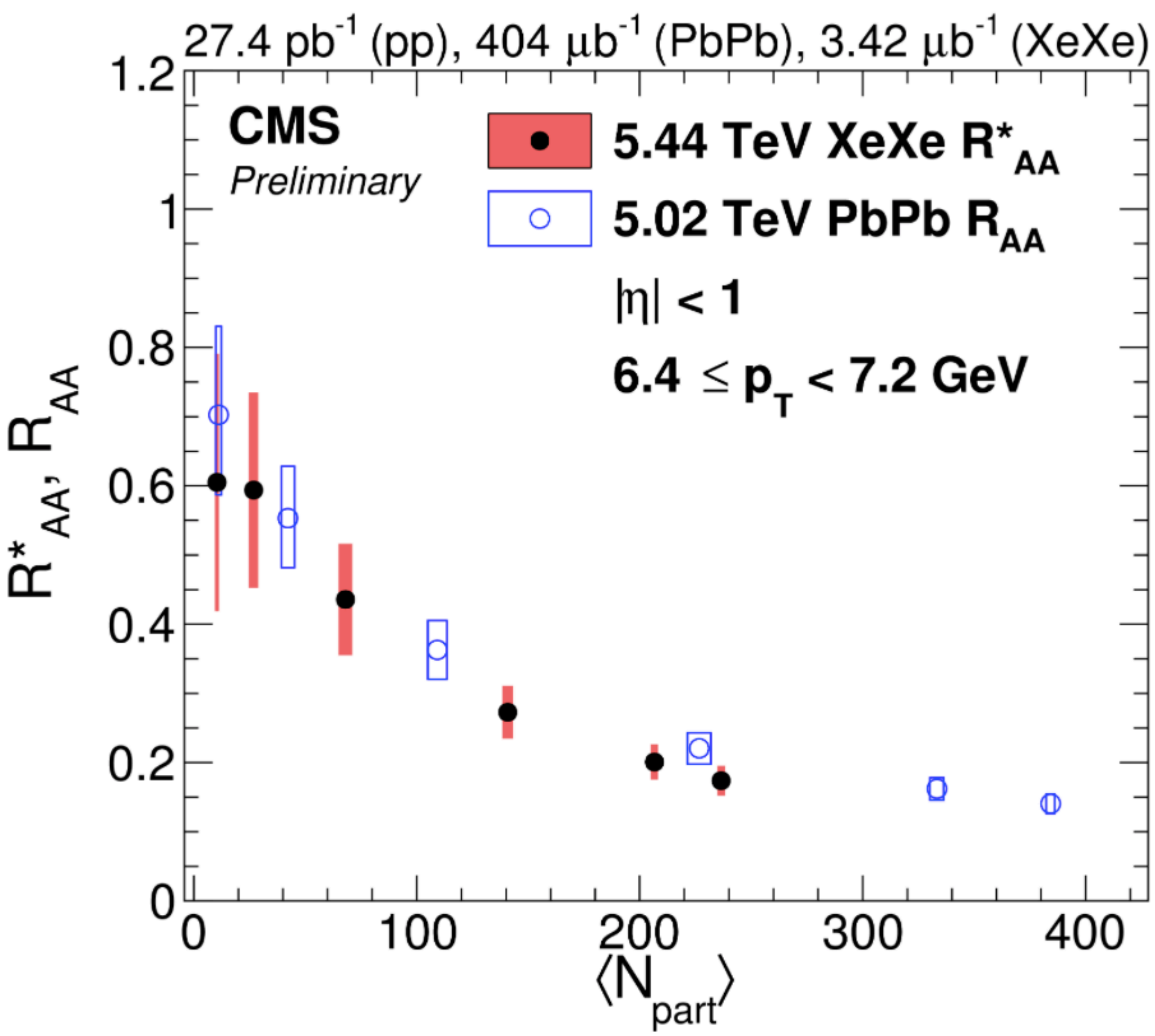
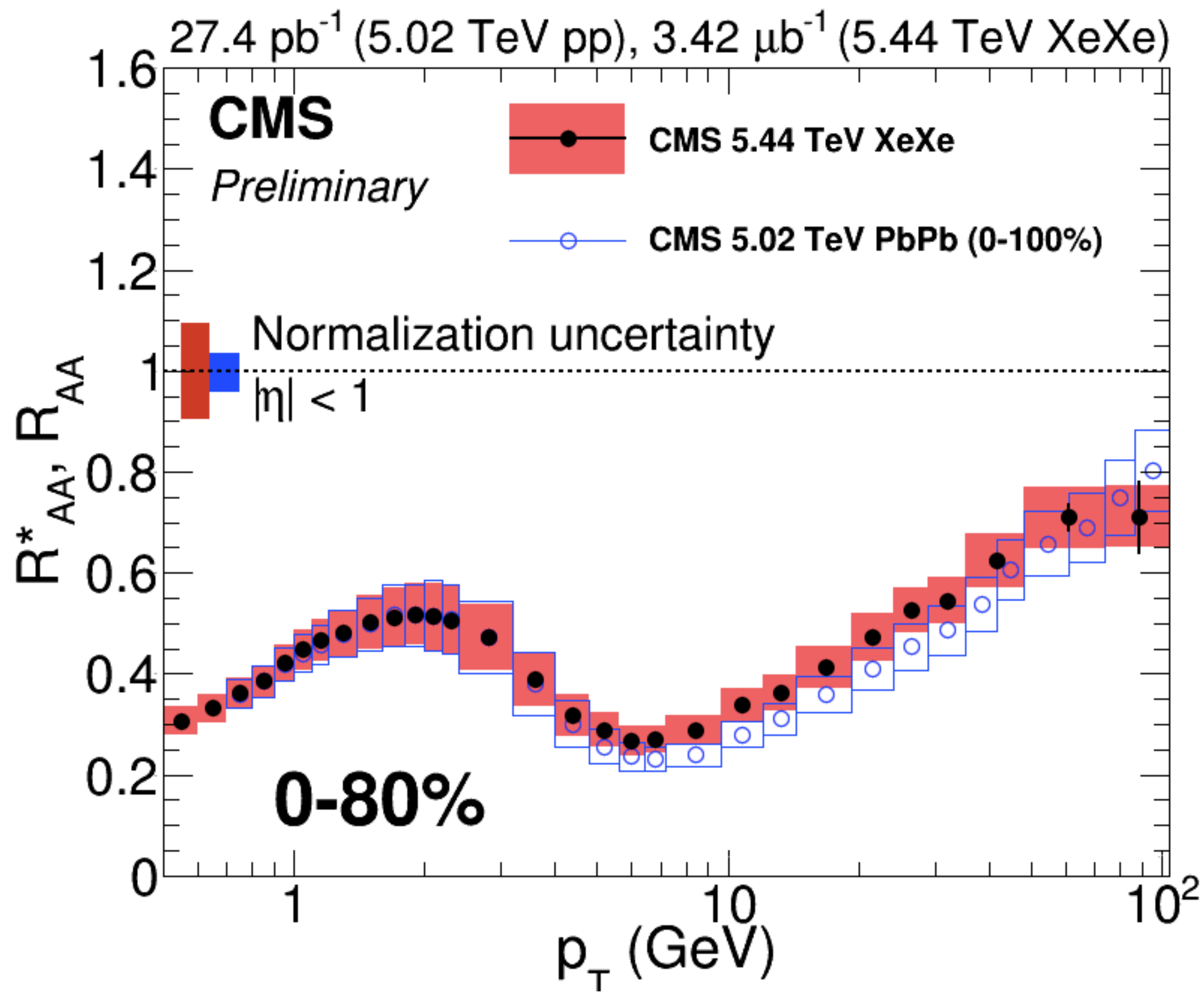
Energy Loss vs System Size

- Short LHC run with a smaller Xeon nuclei allowed to explore details of system size effects on energy loss
- Similar R_{AA} trends with p_T
- Maximum suppression levels follow same trend in $\langle N_{part} \rangle$







CMS-PAS-HIN-18-004

Energy Loss vs System Size

- Short LHC run with a smaller Xeon nuclei allowed to explore details of system size effects on energy loss
- Similar R_{AA} trends with p_T
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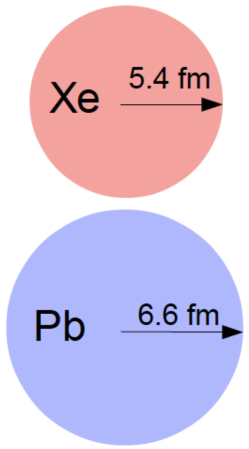
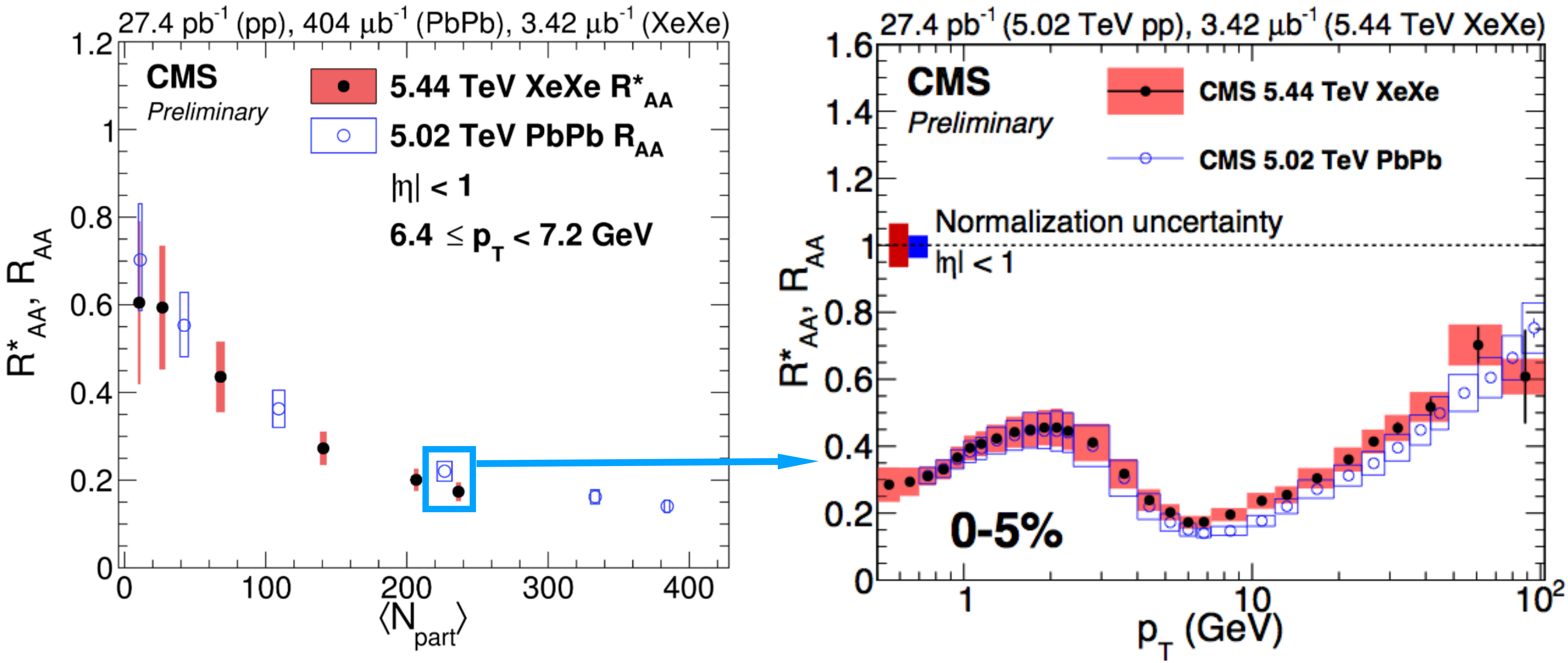
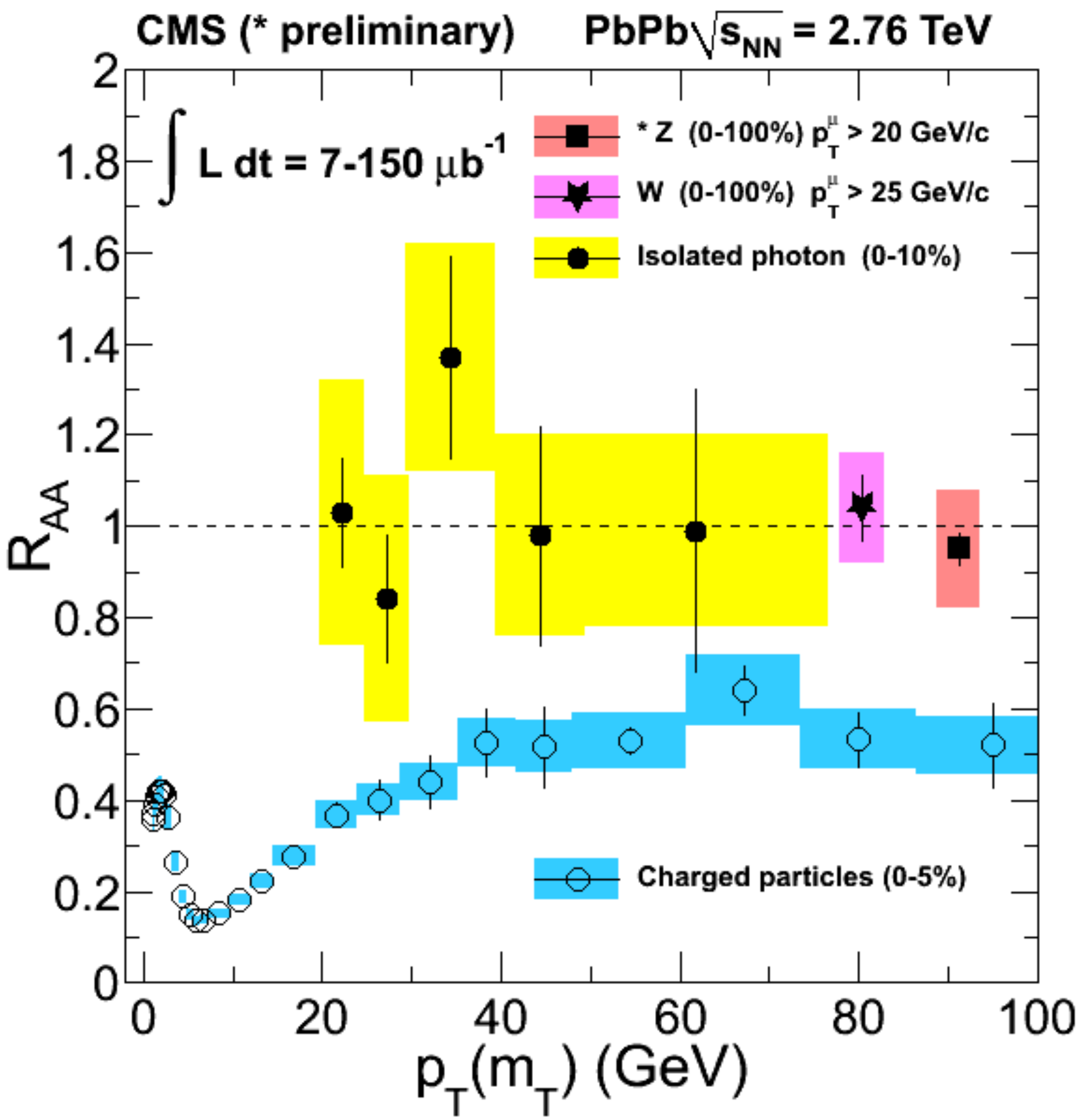




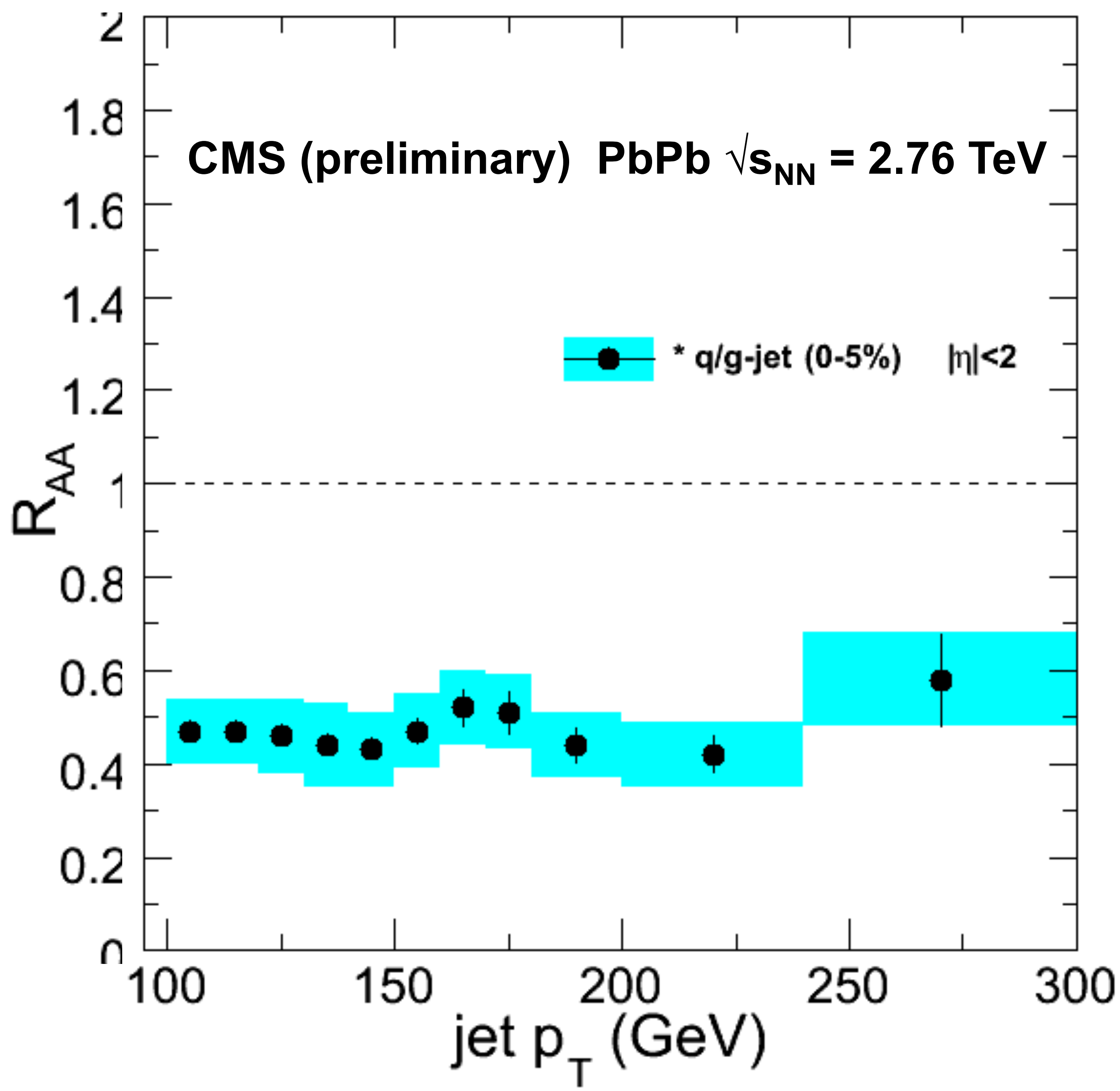
CMS-PAS-HIN-18-004

Jet Quenching

- Energy loss in QGP could be assessed more closely with jet studies: jet energy has closer connection to initial parton
- Jet R_{AA} shows significant suppression over the entire p_T range assessed
- What happens to this “quenched” energy?



CMS-RAA-Zoo



CMS-HIN-12-004

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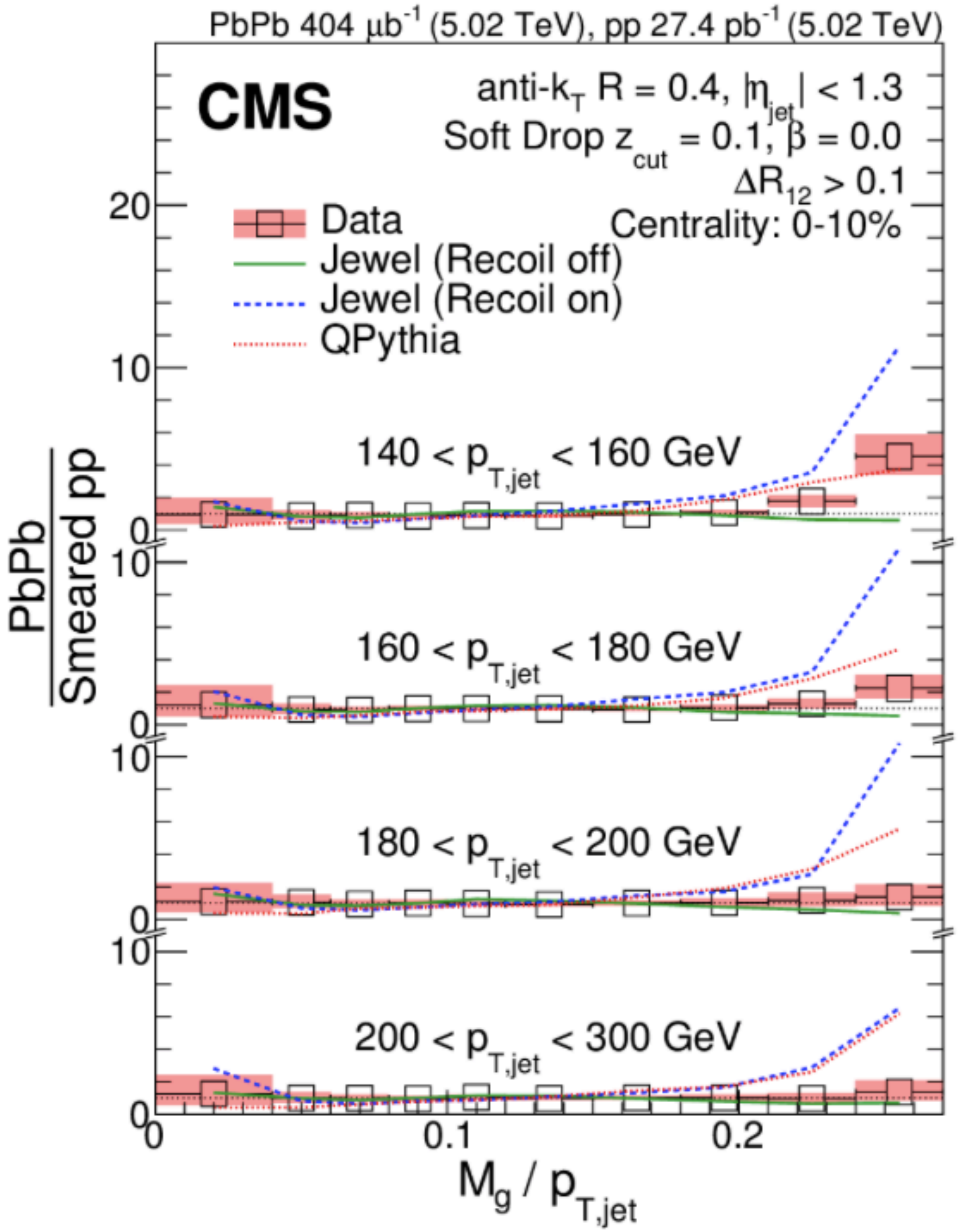
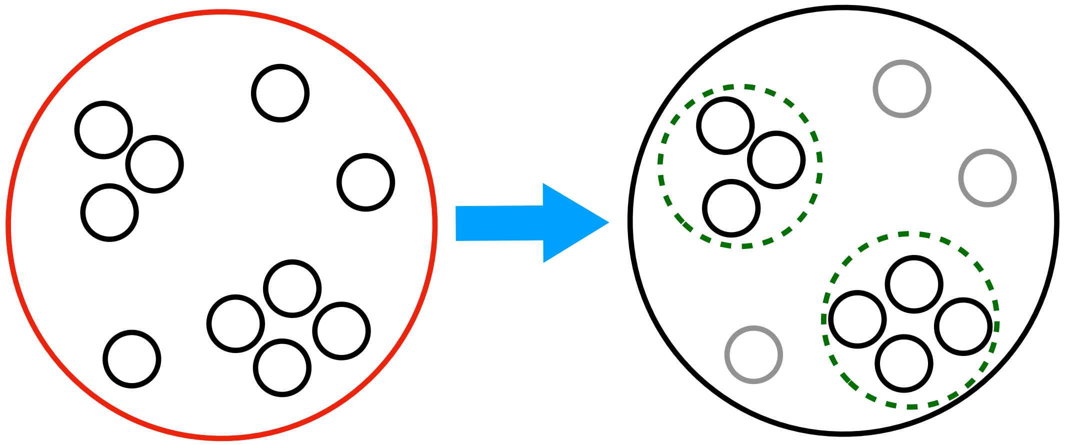
Modification of Jet Substructure



Flat grooming



- Groomed jet mass explores earliest hard splitting of emerging parton shower
- For high-p_T jets the PbPb results are consistent with pp measurements
- For lower p_T jets enhanced fraction of high mass jets is observed in PbPb
- Theoretical calculations predict same qualitative trend but miss the details of p_T and mass dependence

arXiv:1805.05145

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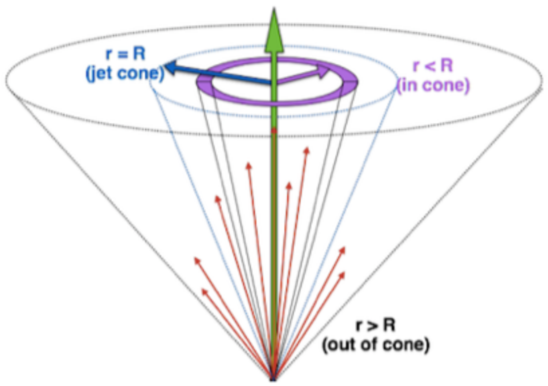
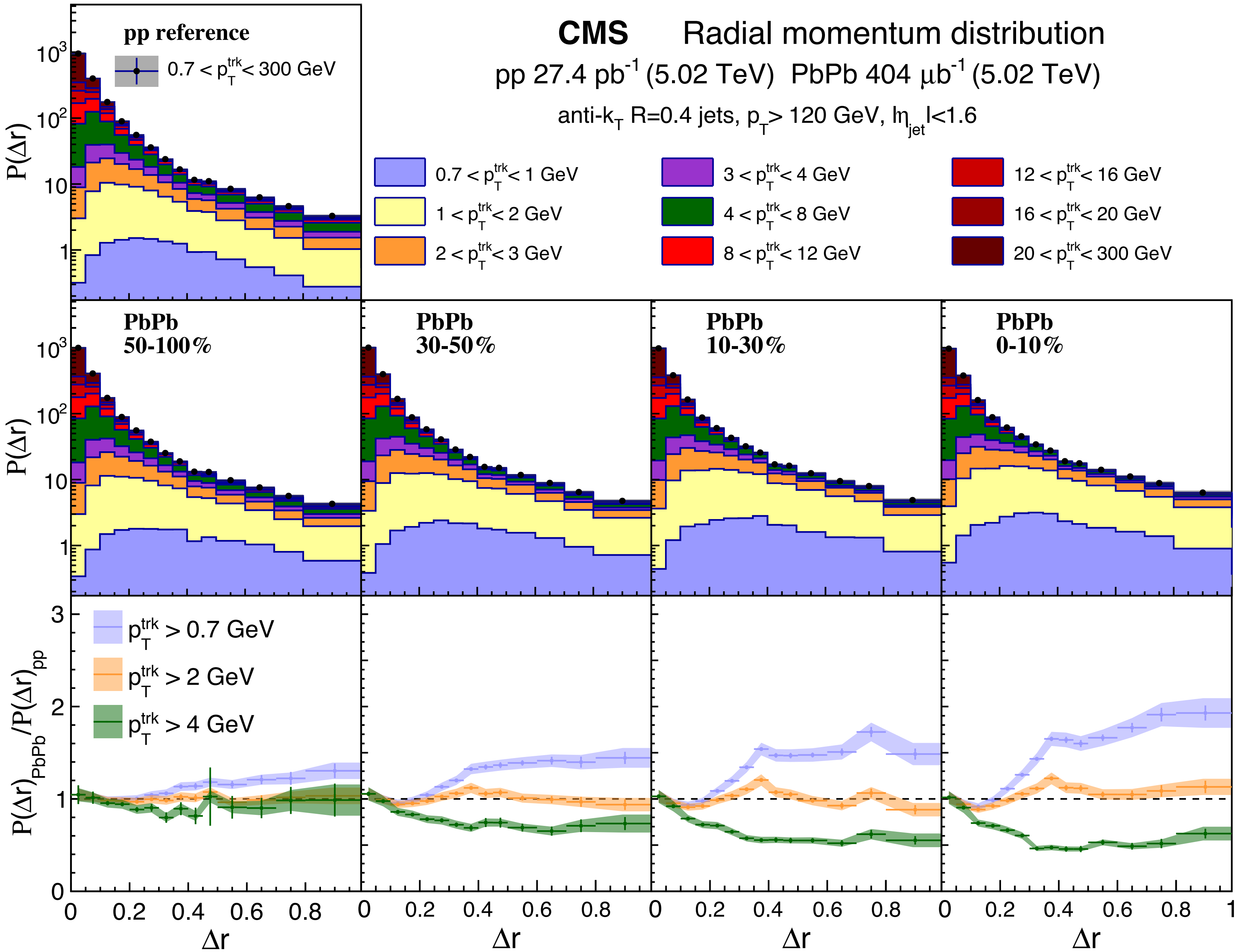
Modifications of Jet Shapes





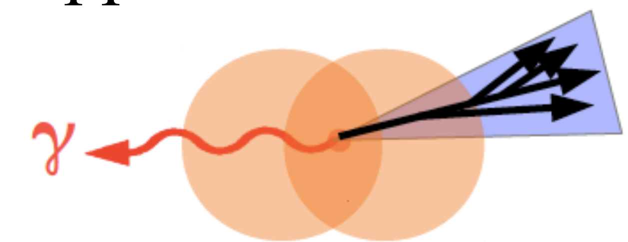
JHEP05(2018)006

- Radial distribution of transverse momenta is measured differentially in p_T
- Peripheral PbPb collisions: most similar to pp, small momentum excess in soft sector
- Central PbPb collisions: enhancement of large Δr contributions in soft sector, loss of momenta in hard constituents →

Jet energy is redistributed towards softer fragments and large radii

Jet Shapes for γ+Jets

- γ+jet events provide an unbiased reference selection for PbPb and pp data
- Jet shape results show similar trends with inclusive jets:
  - Peripheral PbPb – similar to pp reference
  - Central PbPb – energy shift towards larger radii



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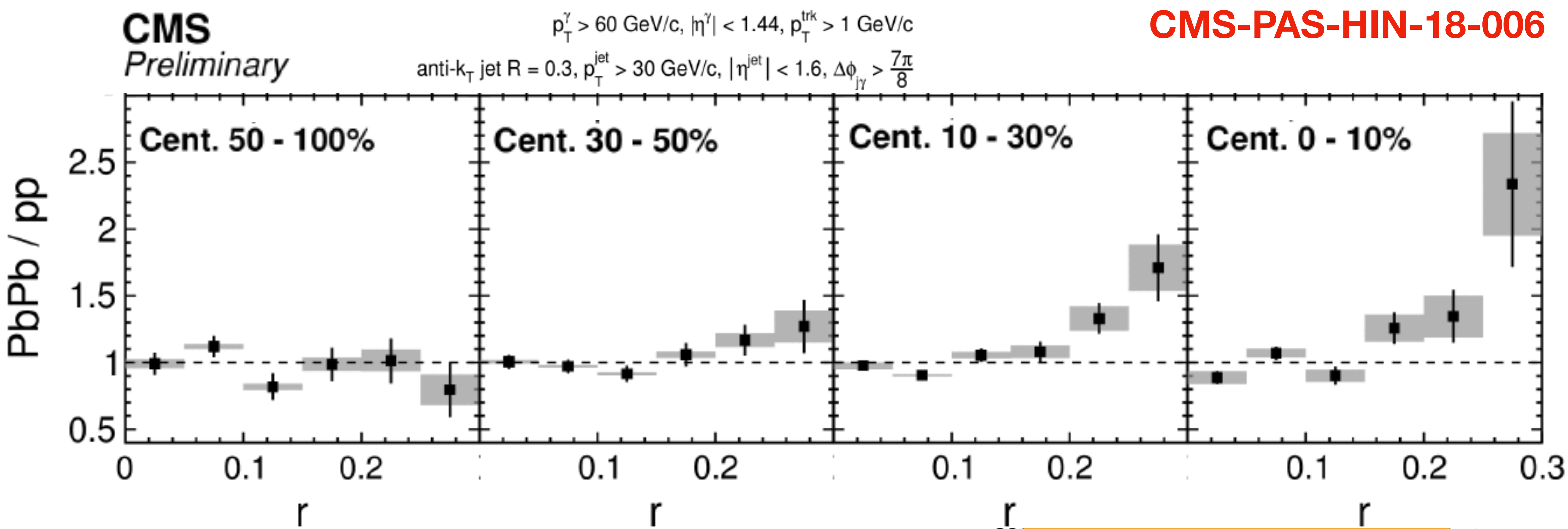
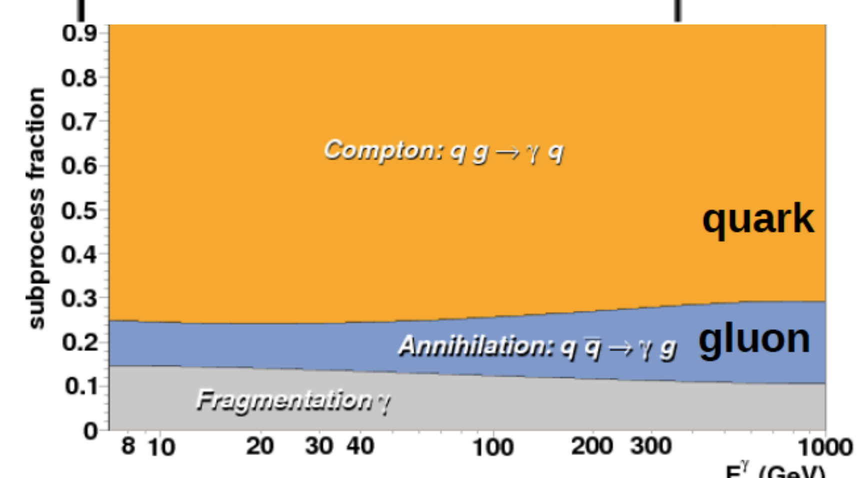


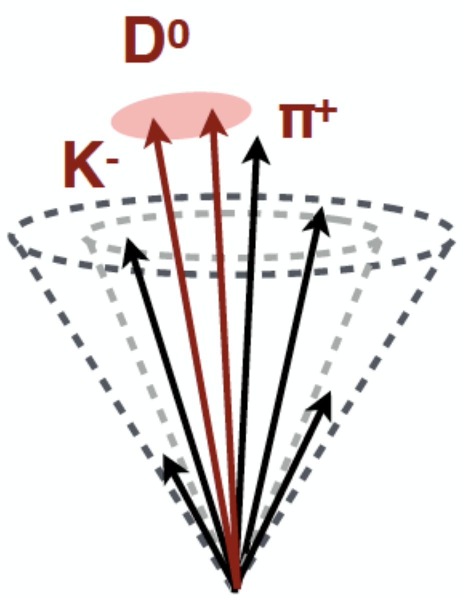
- γ+jet events are dominated by quark jets
- Comparative analysis with gluon-dominated inclusive jets will provide further constraints on q vs g energy loss



Nucl.Phys. B860 (2012) 311

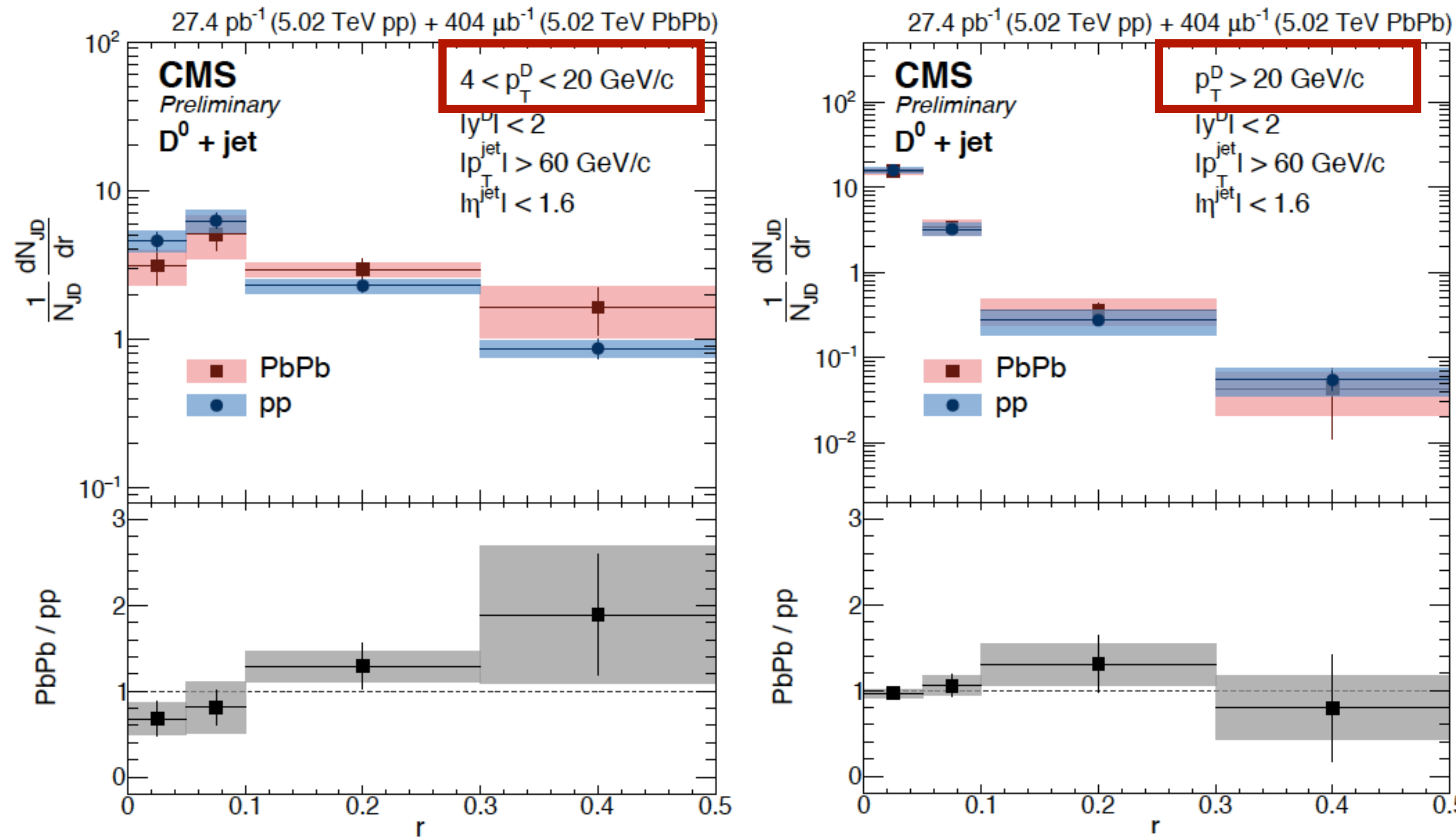
In-jet Flavor Production

- Radial distribution of D^0 mesons wrt jet axes initiated the study of charm production in jets
- At high p_T radial D^0 distribution inside jet cone is consistent with vacuum reference
- At lower p_T → hint of "pushing out" towards larger r?



$$\frac{1}{N_{JD}} \frac{dN_{JD}}{dr}$$

$$r = \sqrt{\Delta\phi_{JD}^2 + \Delta\eta_{JD}^2}$$



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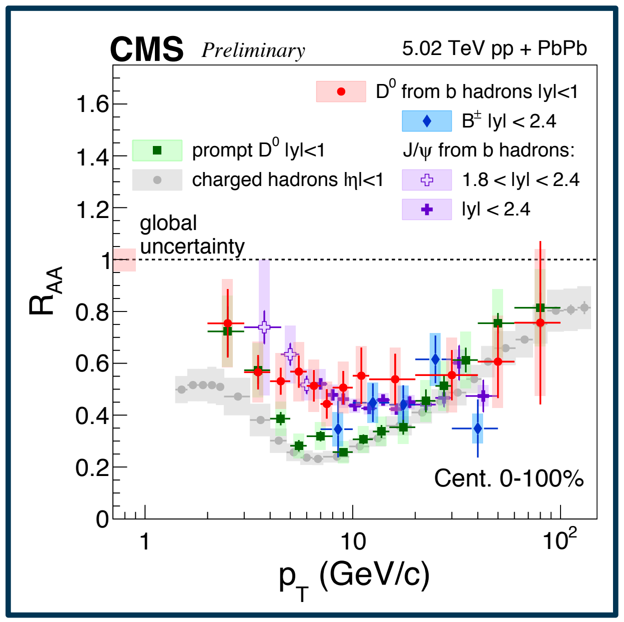
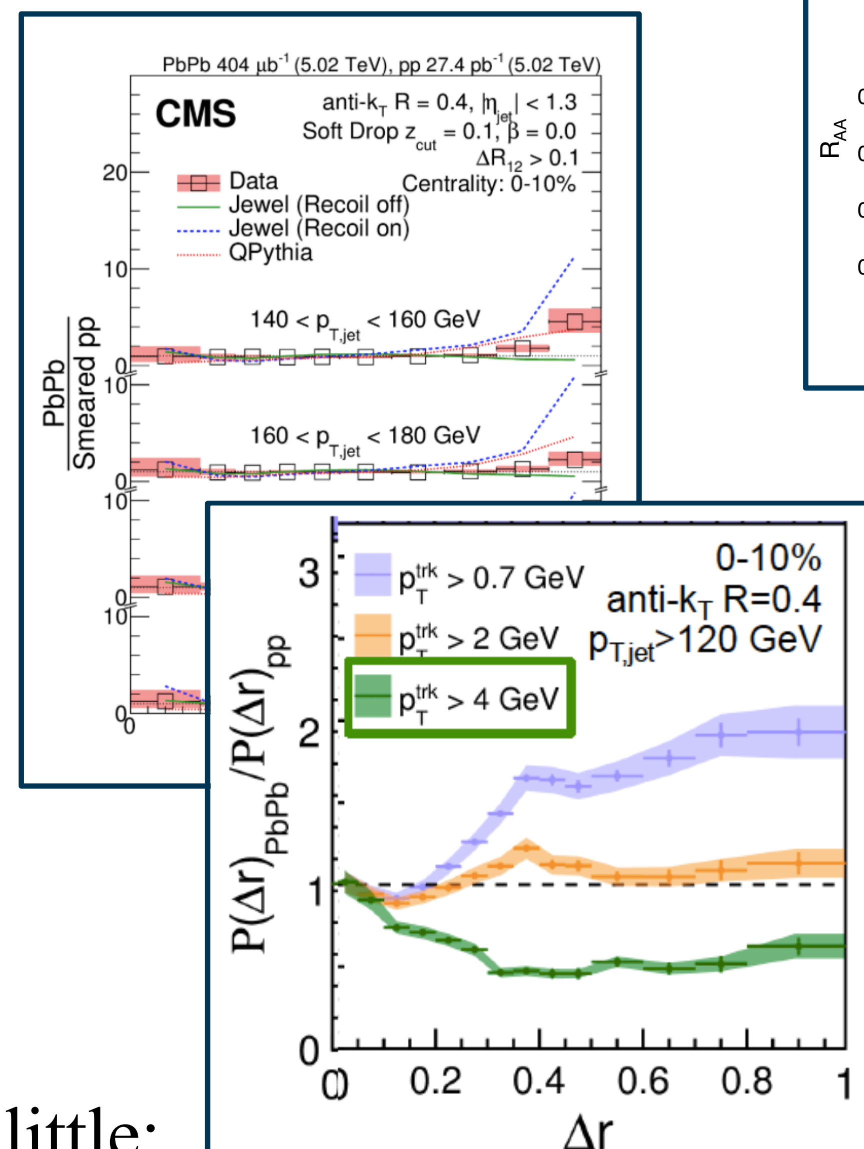
Summary

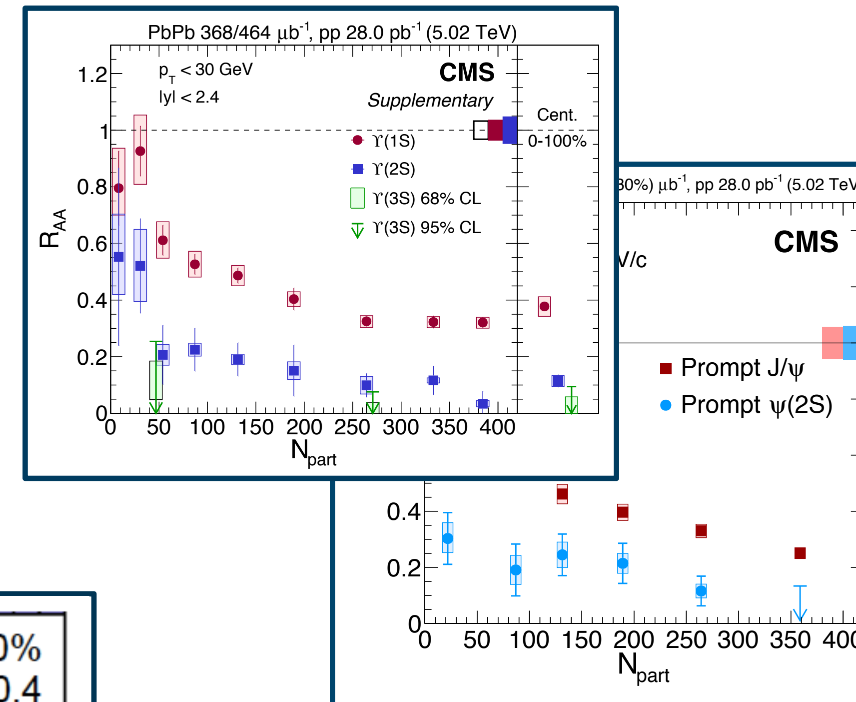
- Hard probes are versatile tools for studying properties of the QGP medium produced in Heavy Ion collisions



1. energy loss (intermediate p_T): u,d,g ~ c > b



2. Jet quenching:
Jet core modified little;
significant energy shifts from hard to soft sector



3. Quarkonia "melting" and medium temperature

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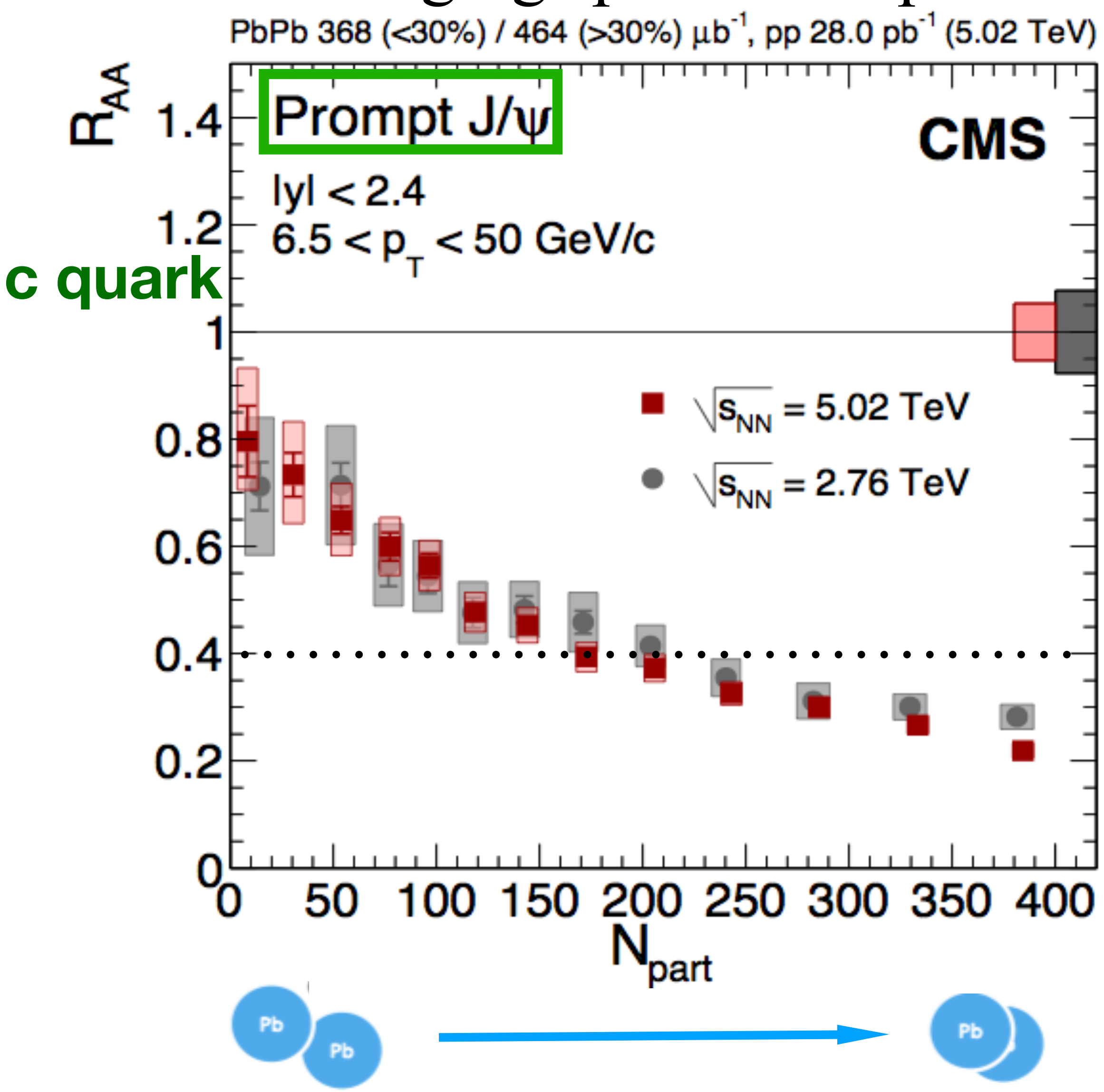
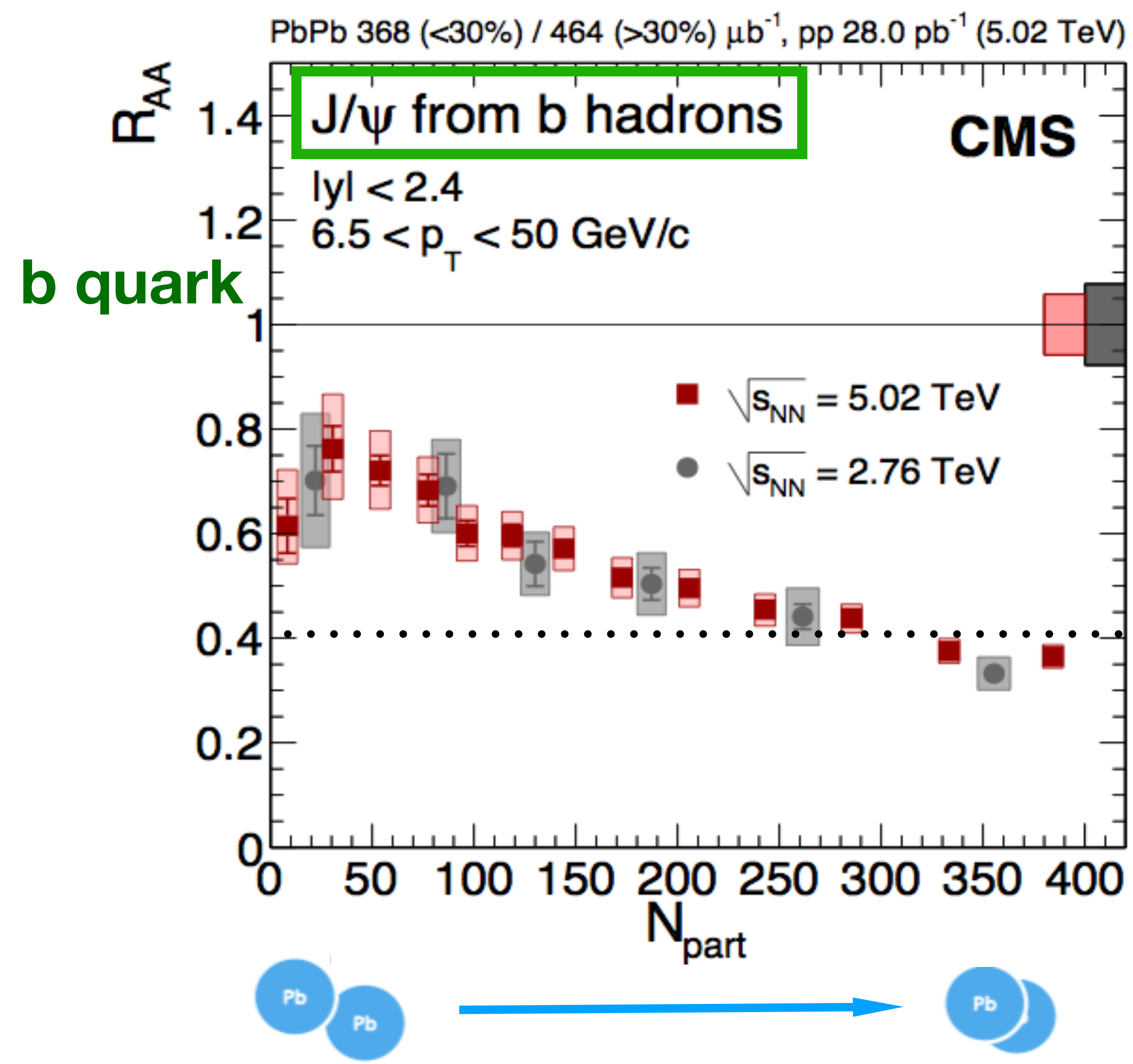
Back up

Charm vs. Beauty

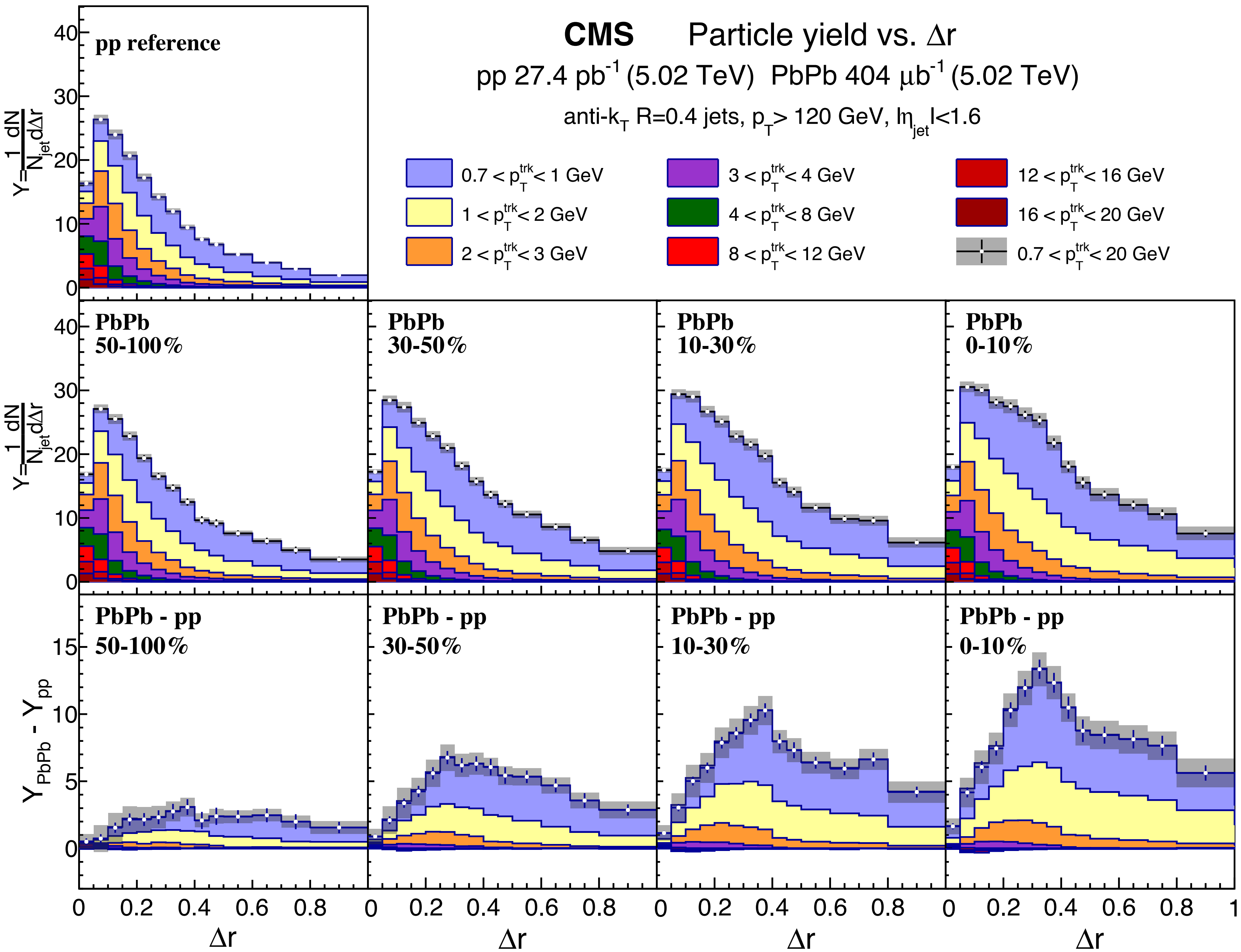
- J/ψ nuclear modification factors are measured separately for prompt (c →J/ψ) and non-prompt (b→J/ψ) components
- Suppression increases with centrality for both components, reaching higher levels for c- than b-related J/ψ
- Similar RAA trends for different collision energies: interplay of higher energy loss with changing spectral shape?

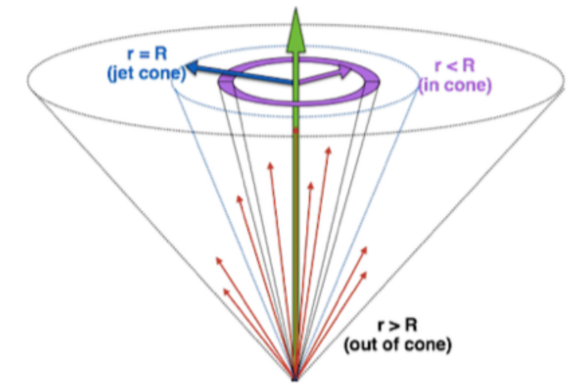




arXiv:1712.08959 (5.02 TeV),
EPJC 77 (2017) 252 (2.76 TeV)

Modifications of Jet Fragmentation





- Radial distribution of correlated particle yields is measured differentially in p_T
- Peripheral PbPb collisions: most similar to pp, small excess of soft hadrons around the jet
- Central PbPb collisions: large excess of soft correlated yields + depletion of high p_T particles near jet access →

modifications of jet fragmentation pattern

JHEP05(2018)006

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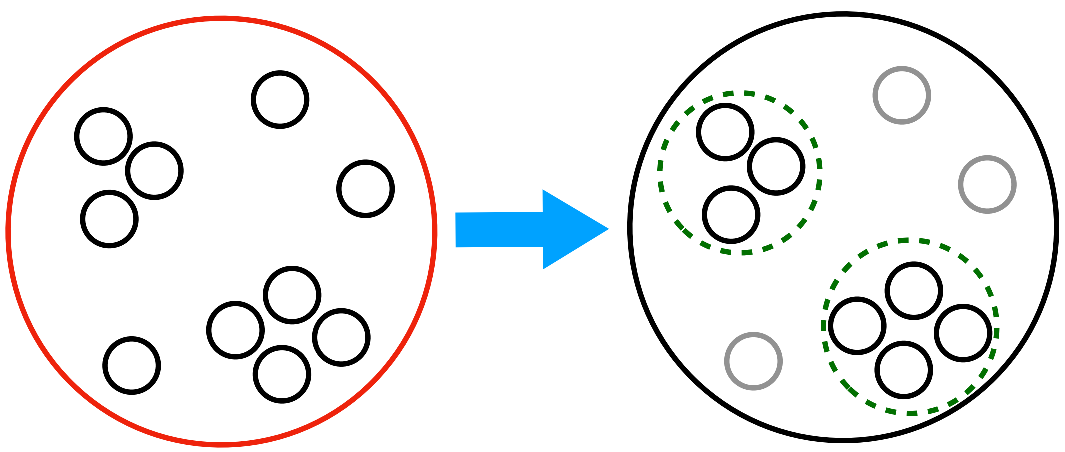
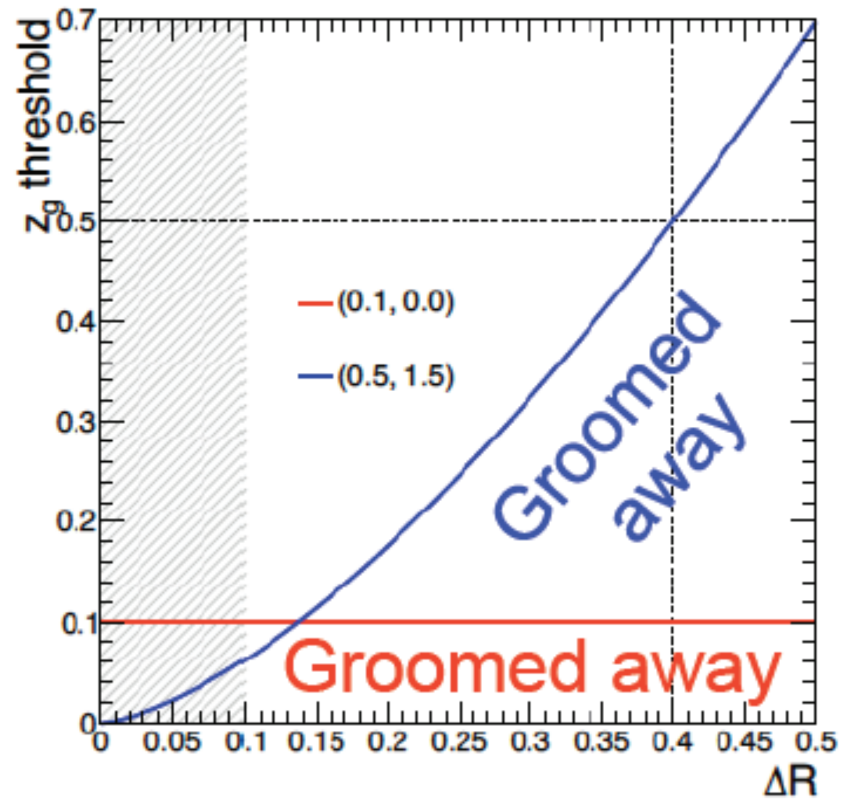
Jet substructure

Groomed jet mass: $M_{\mathrm{g}}^2 \equiv p_{1\mu} p_2^{\mu}$

Observable: $M_{\mathrm{g}} / p_{\mathrm{T}}^{\mathrm{jet}}$



To remove the soft radiation



Large angle grooming

Flat grooming

$$z_g \equiv \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} \geq z_{\mathrm{cut}} \left(\frac{\Delta R_{1,2}}{R_0} \right)^{\beta}.$$

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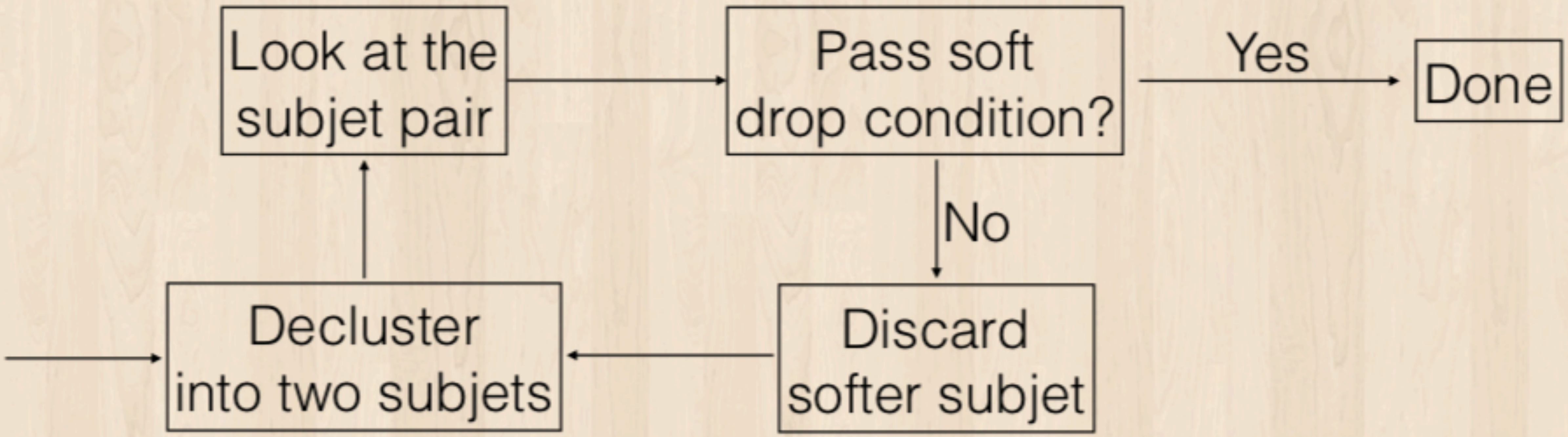
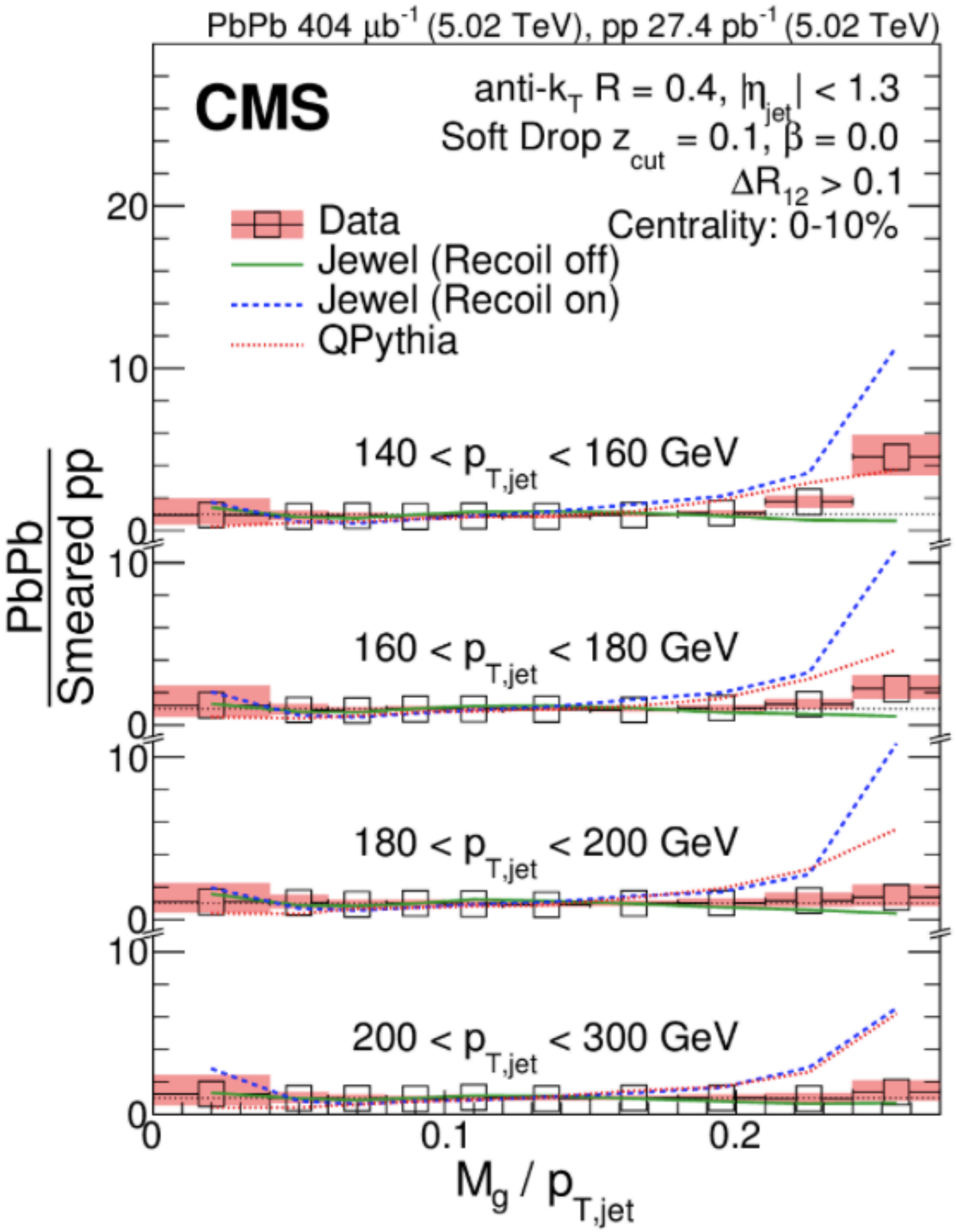
Soft drop algorithm

Soft drop condition: $z_g \equiv \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$

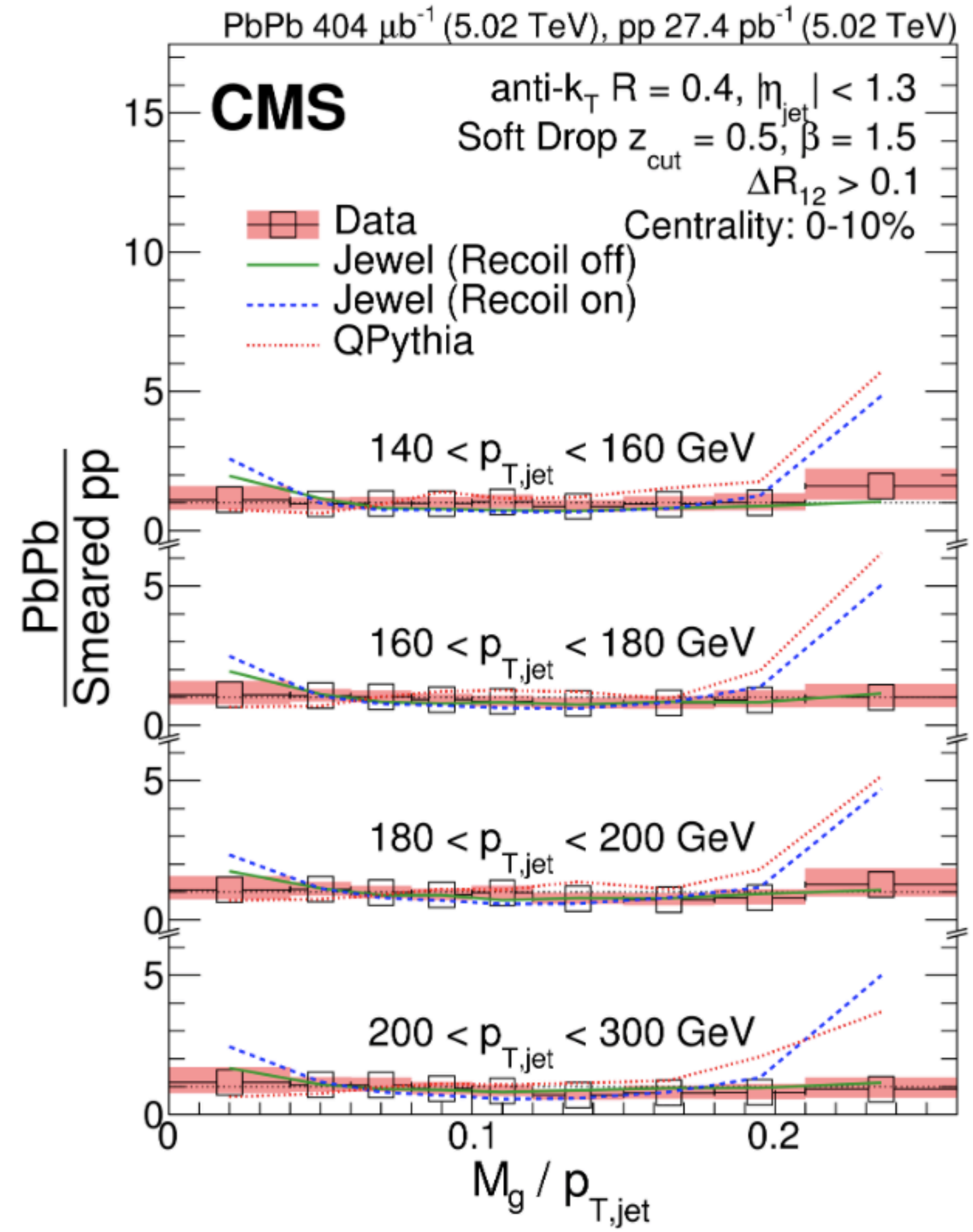


Yi Chen: QM2018

Jet substructure



Flat grooming



Large angle grooming

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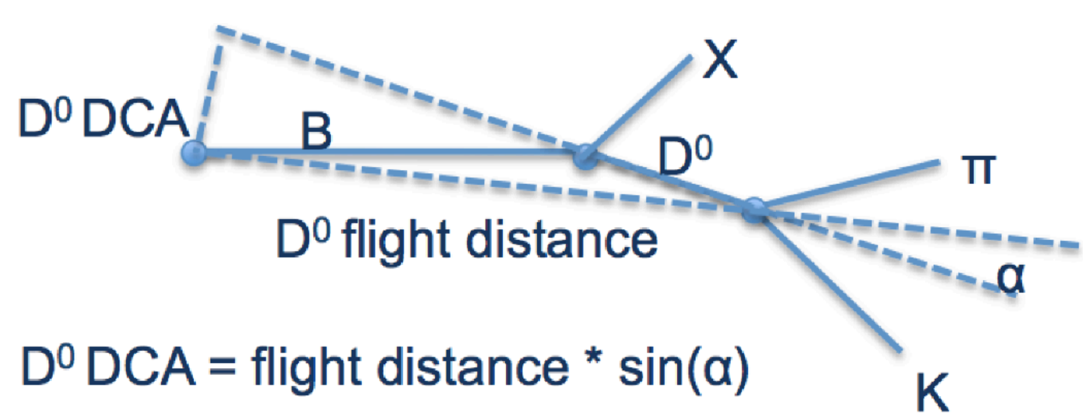
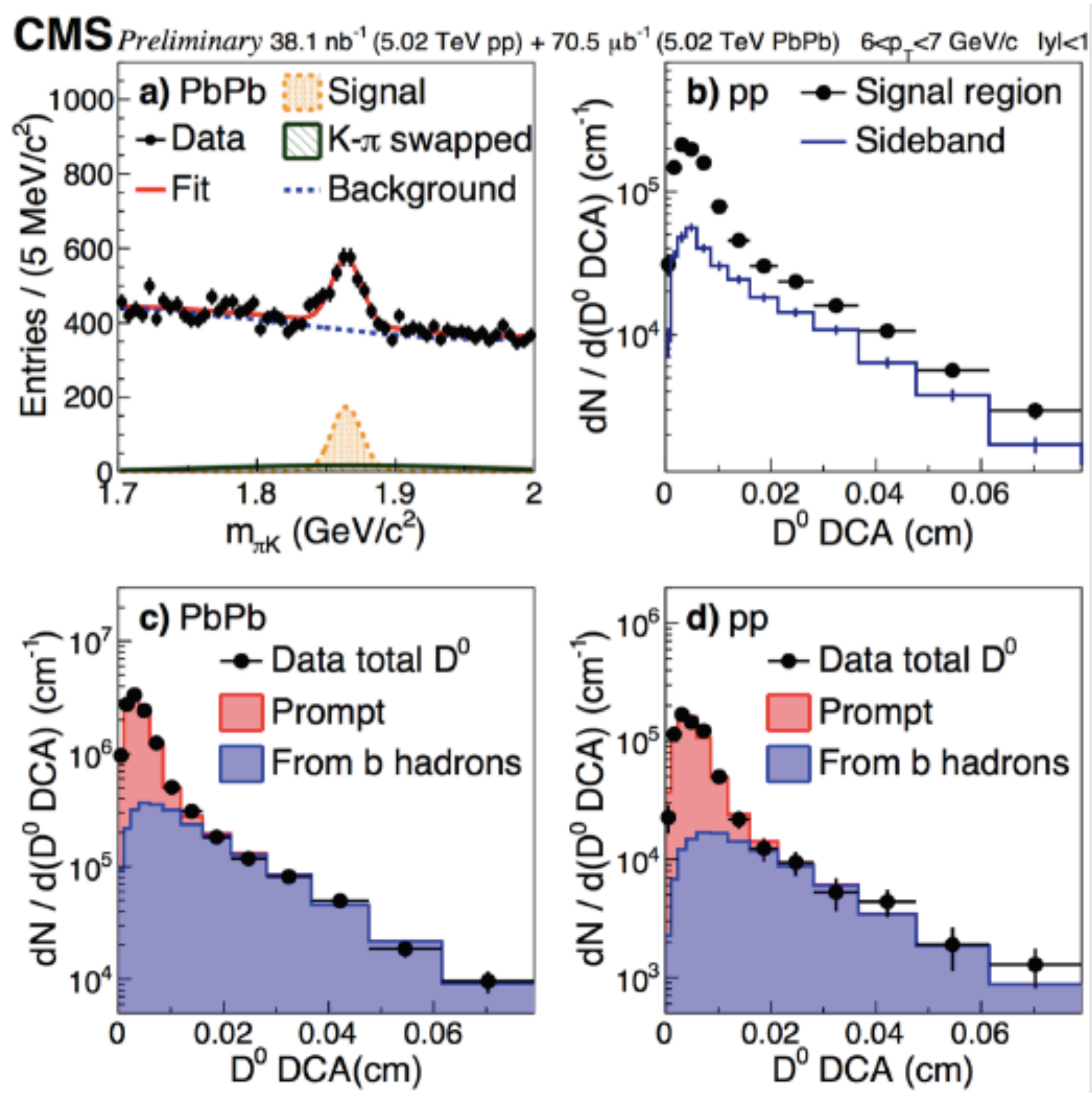
non-prompt D^0 meson



D^0 DCA = flight distance * sin(α)



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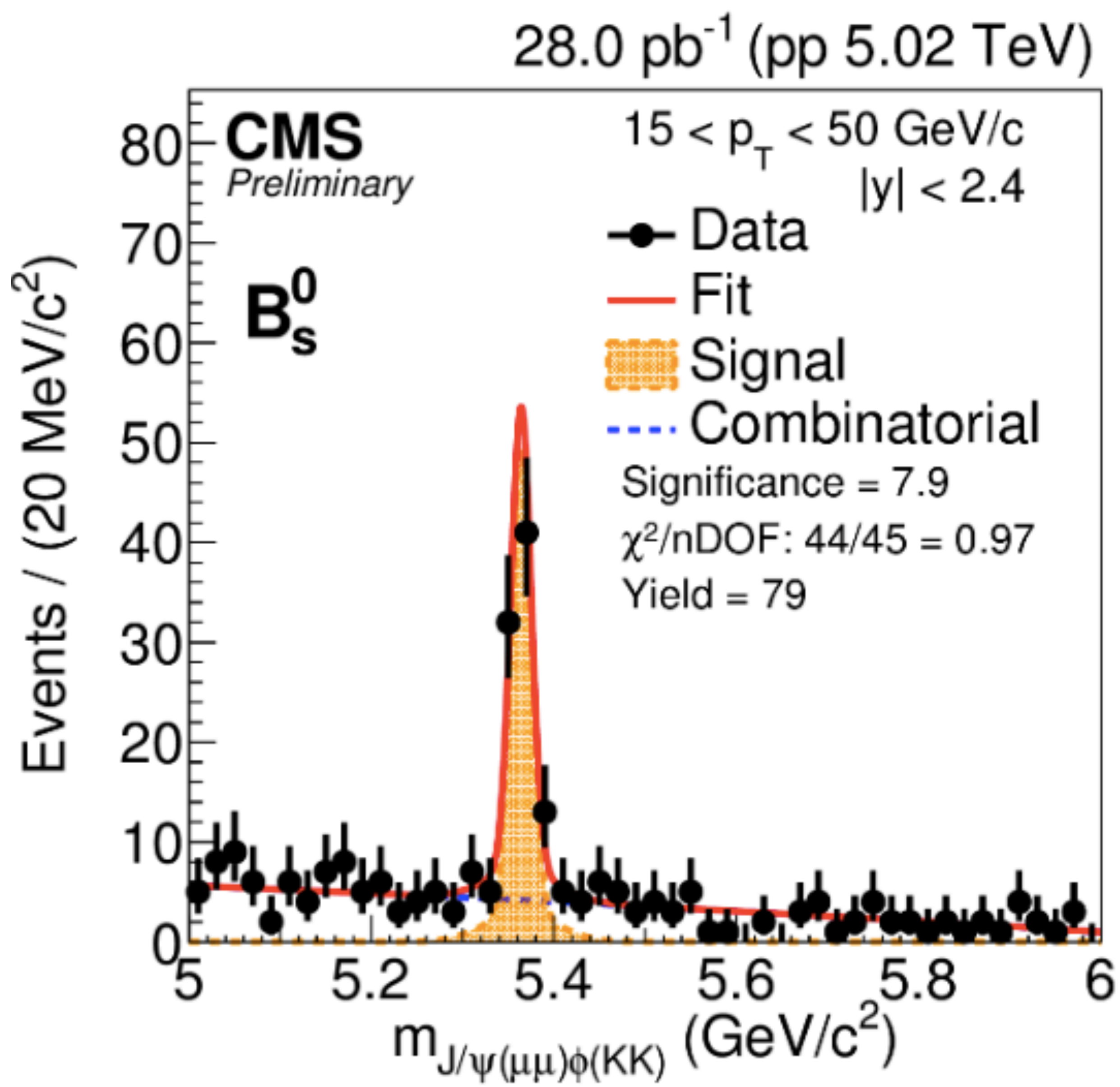
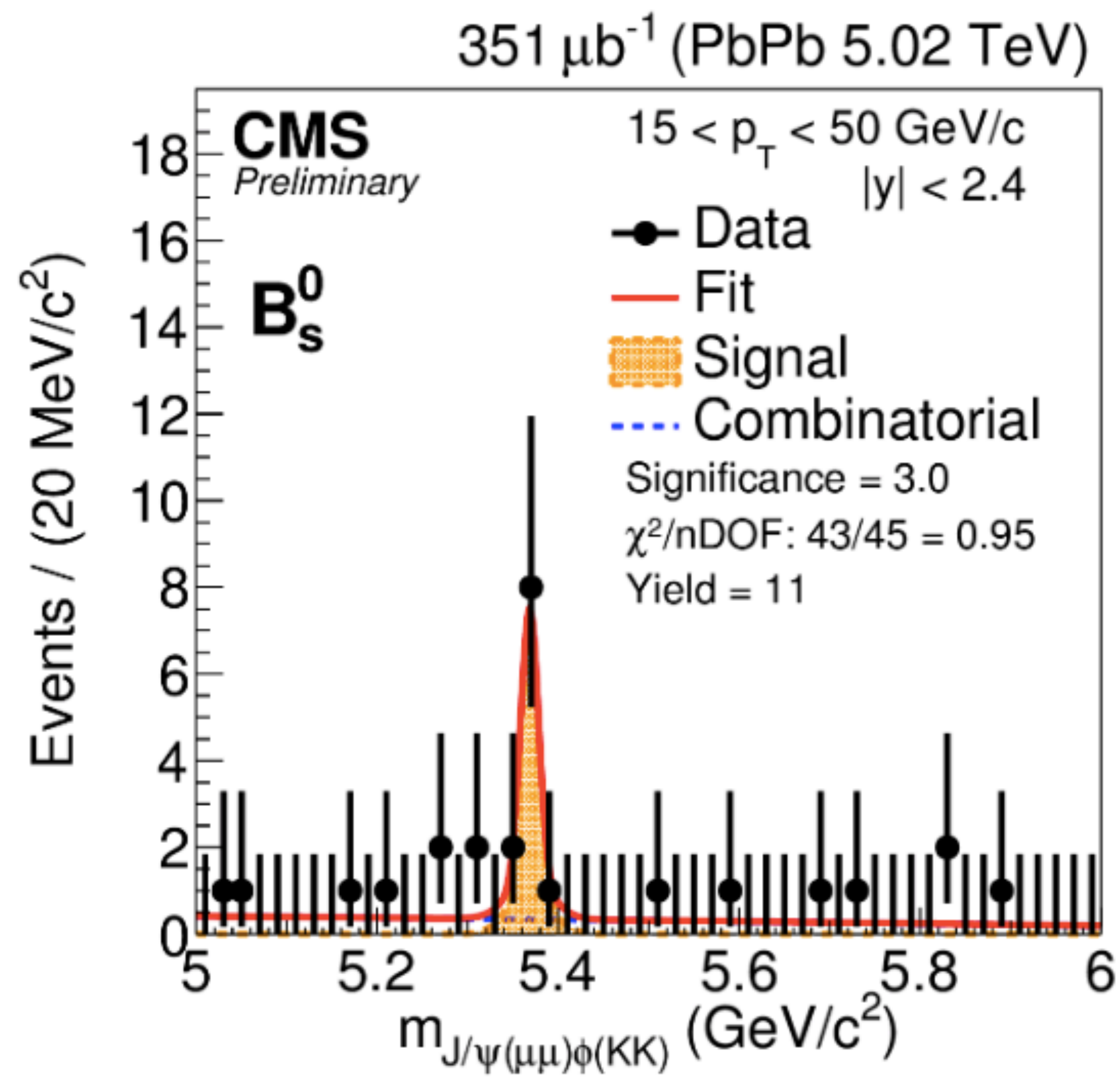
B_s^0 meson reconstruction





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