Highlights on Hard Probes from CMS

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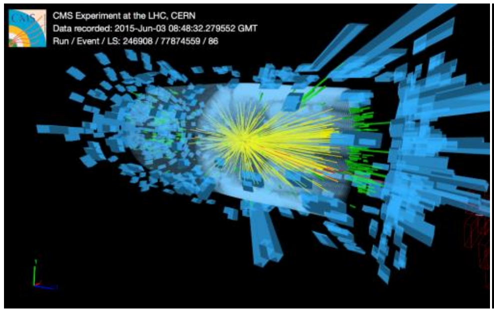
For the CMS collaboration

Hard Probes 2018

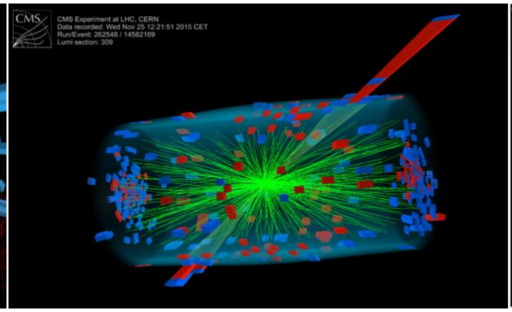
Aix-Les-Bains, Savoie, France

30 September – 5 October, 2018

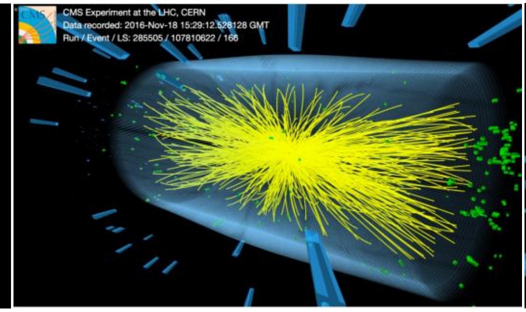
Highlights from CMS



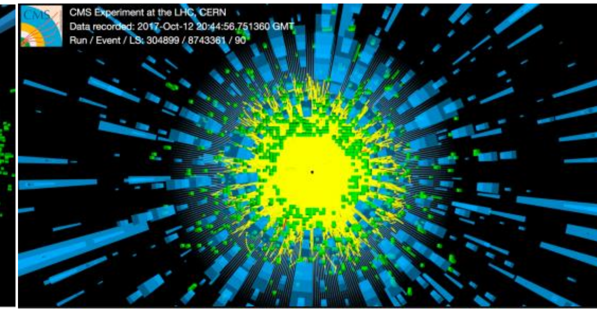
2015+2016 13 TeV pp



2015 5 TeV pp & PbPb



2016 5 & 8 TeV pPb



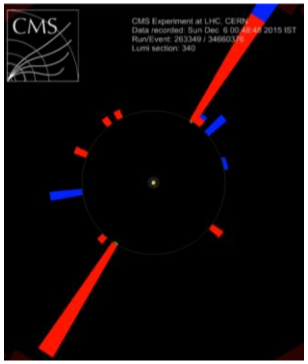
2017 5.44 TeV XeXe

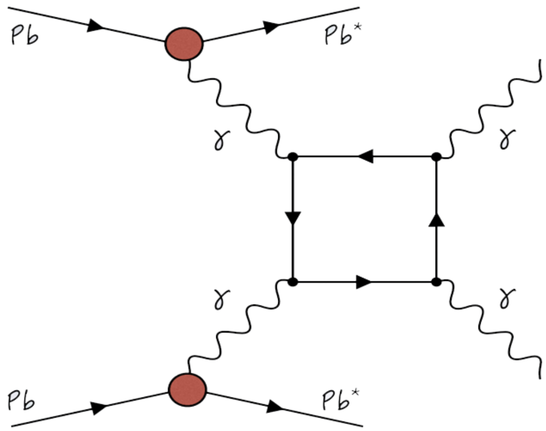
- Light-by-light scattering and search for axion-like particles
- Parton distribution function in Pb
- Parton flavor and shower dependence of energy loss
- Quark-enriched jet substructure in pp and PbPb
- “Sequential suppression” of quarkonia in pp, pPb and PbPb
- Similarity between pp, pPb and PbPb collisions

Exciting new results with LHC Run II data!

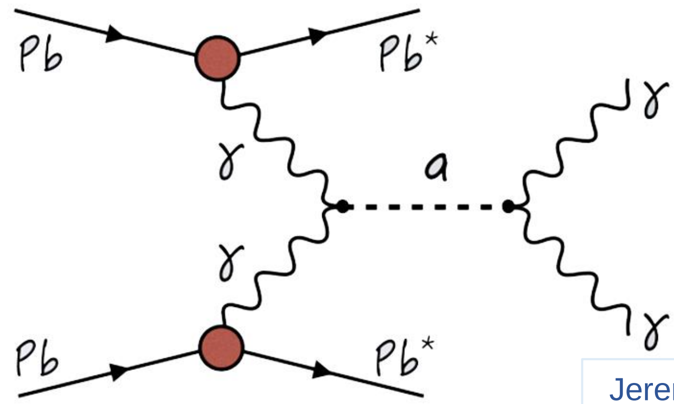
Search for Axion with UPC Event

Observation of **light-by-light scattering**



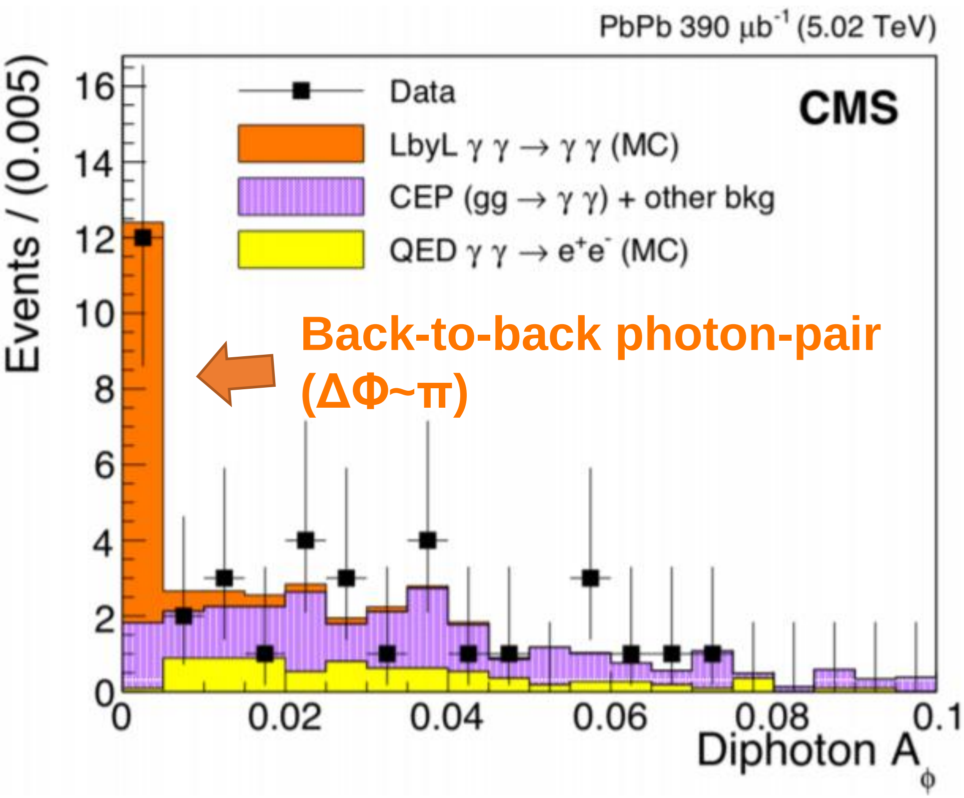


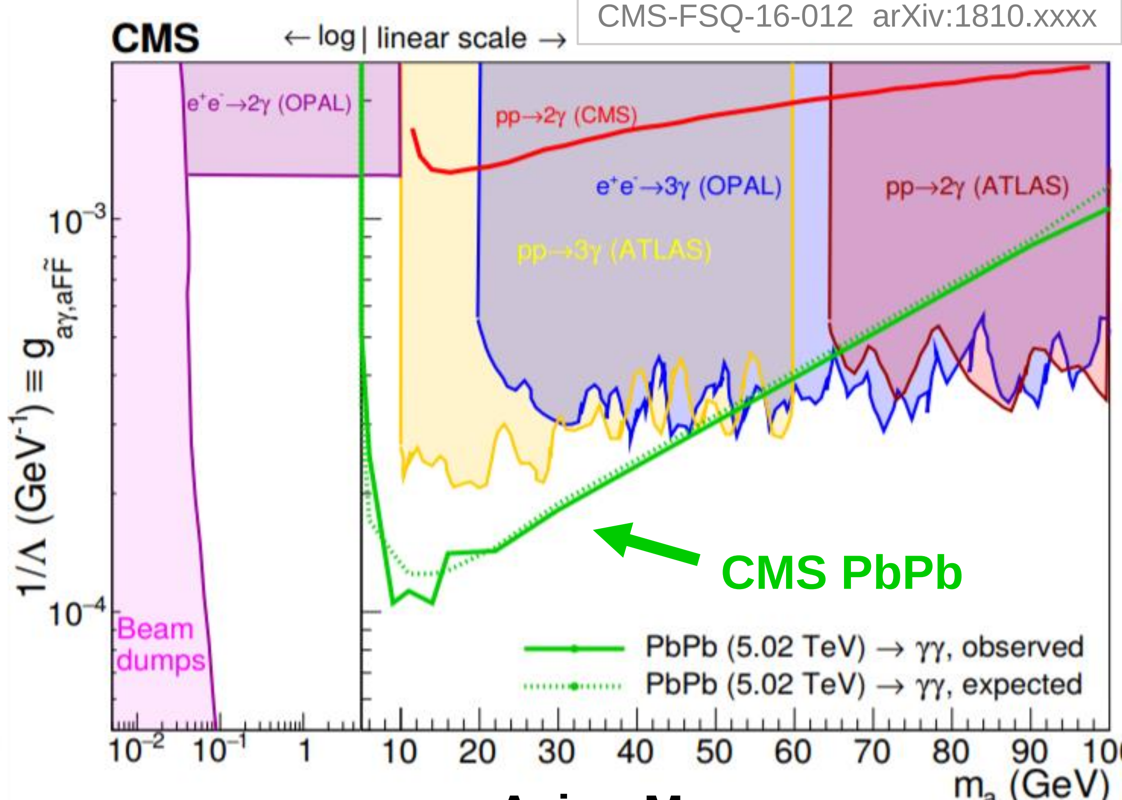
New limit on **axion-like** particle production



Jeremi Niedziela

CMS-FSQ-16-012 arXiv:1810.xxxx

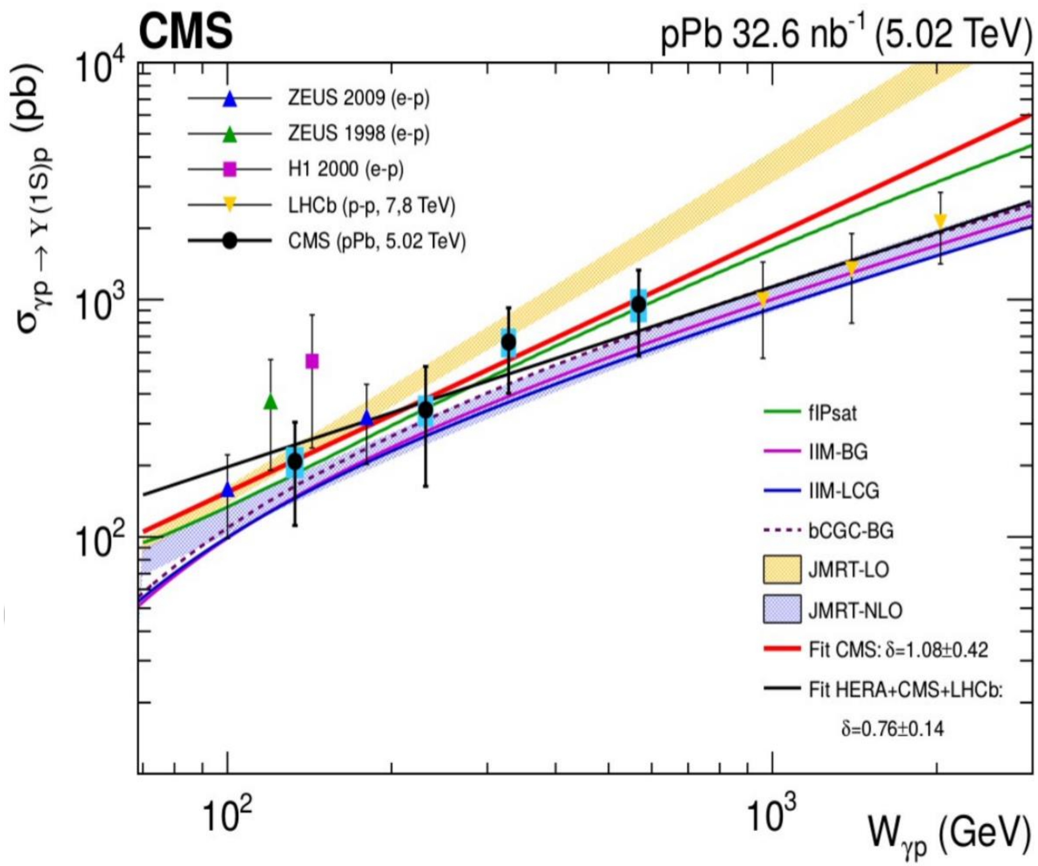




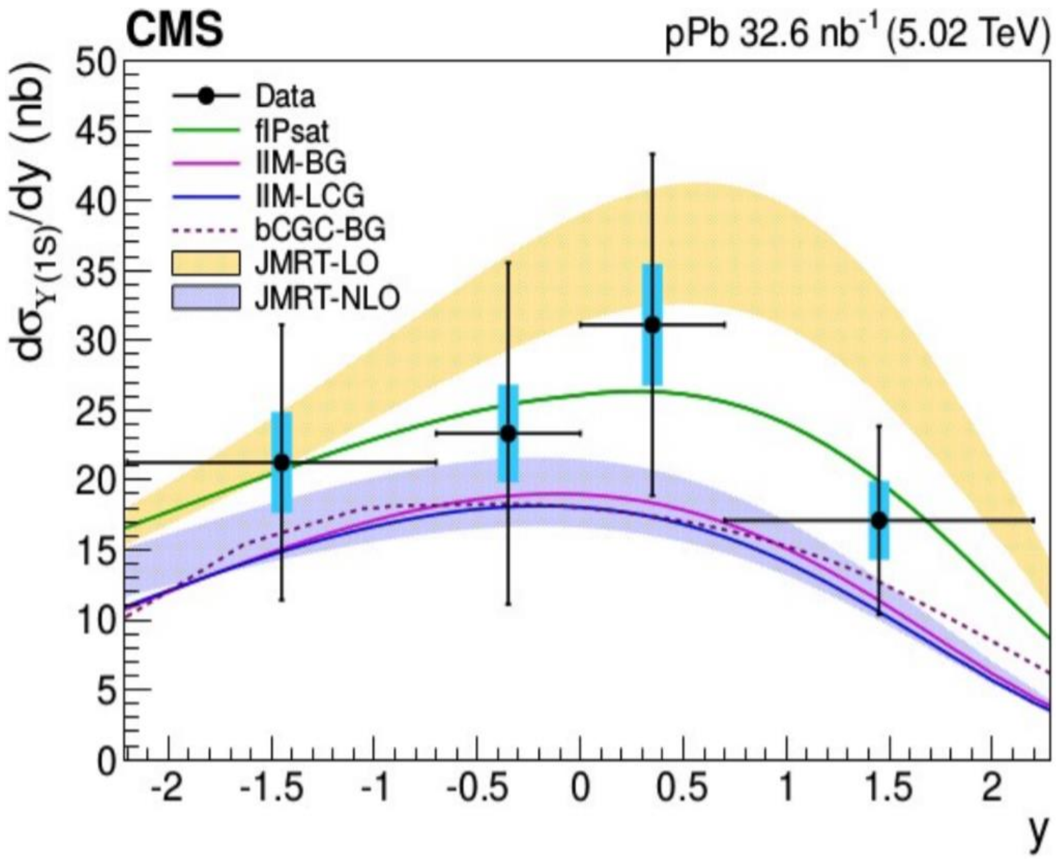
Axion Mass

UPC Upsilon Production in pPb

Y(1S) Cross-Section vs. γγ CM Energy



Y(1S) Rapidity Distribution



- σ_{Y} measured in an unexplored region of γγ CM energy $W_{\gamma p}$ = 91 – 826 GeV
- Cross section follows a power law: $\sigma_{Y}(W_{\gamma p}) = W_{\gamma p}{}^{\delta}$, where **$\delta = 1.08 \pm 0.42$** (ZEUS result: $\delta = 1.2 \pm 0.8$)

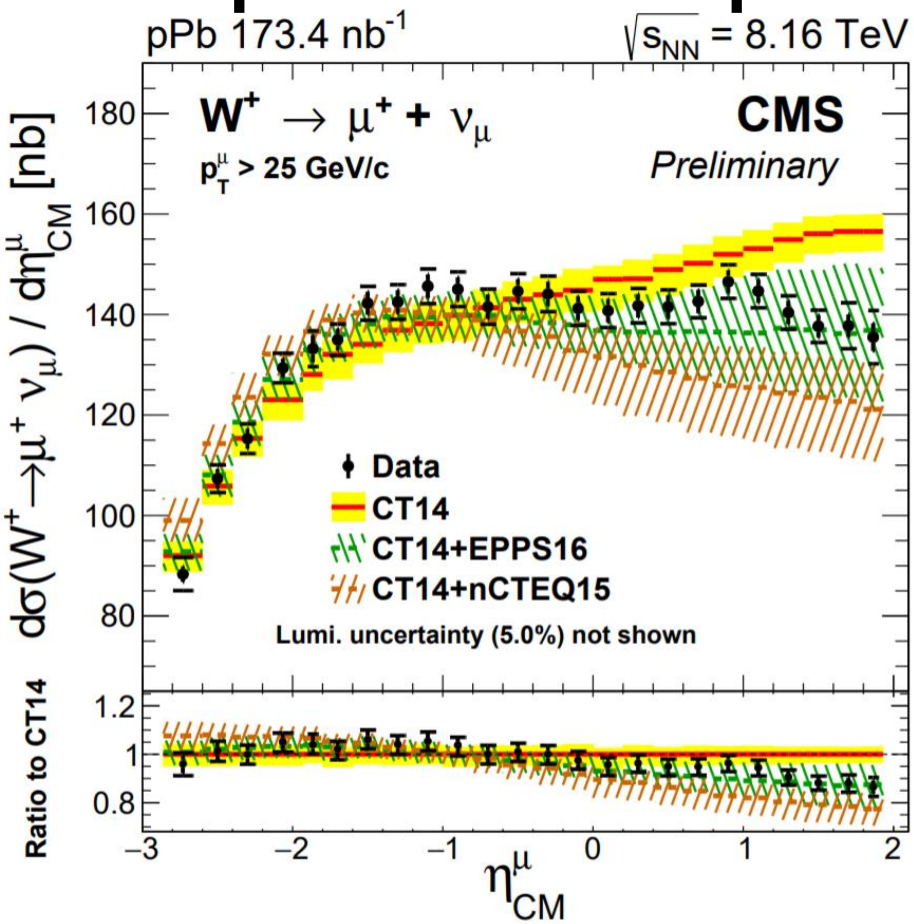
- Y(1S) rapidity distribution consistent with various models

Kousik Naskar

arXiv: 1809.11080

Modification of PDF in Pb

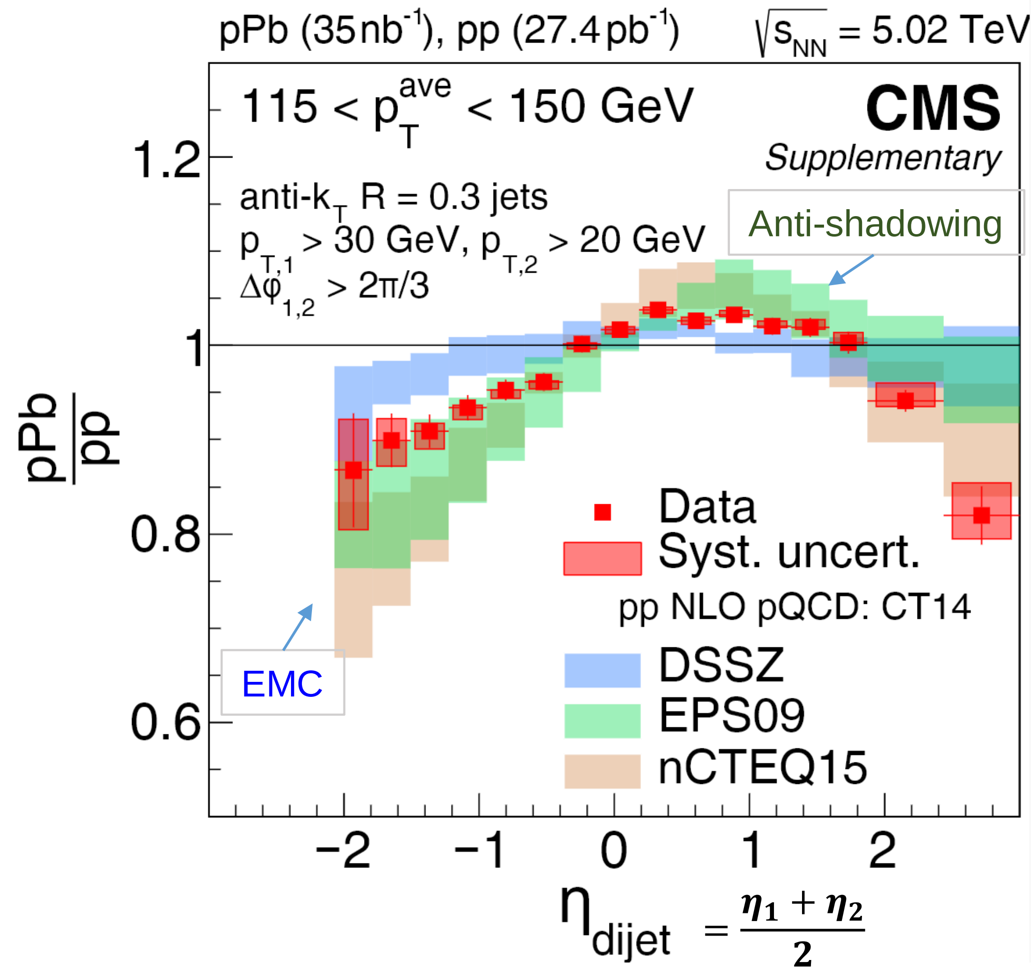
W⁺ production in pPb



Hyunchul Kim CMS-PAS-HIN-17-007

- Constrain quark PDF in Pb

Dijet average η in pPb



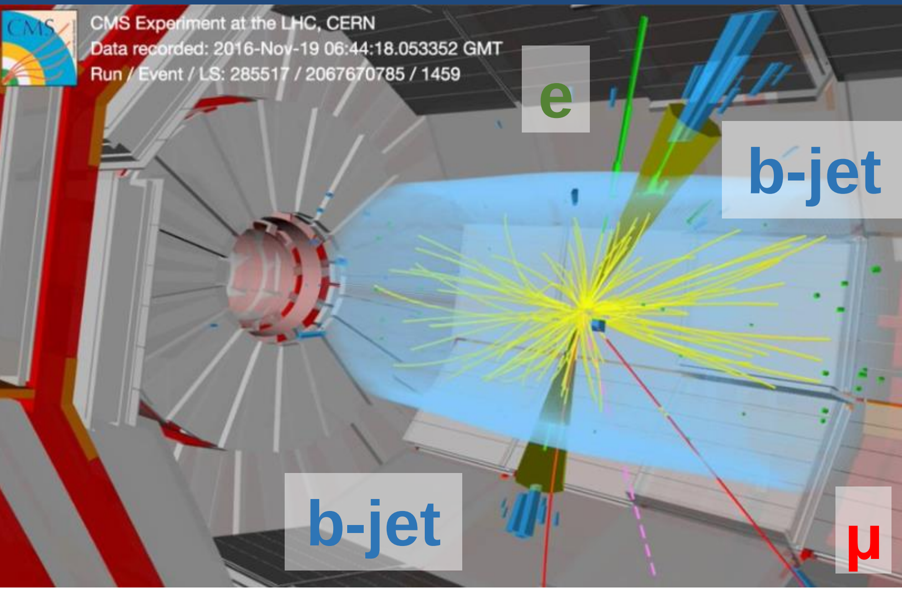
- Evidence of gluon **anti-shadowing** and modification in the EMC region $x > 0.3$

W and dijet data are consistent with **EPS09** and **EPPS16**

Not compatible with **DSSZ**, **nCTEQ15** and **CT14** (nucleon)

Yeonju Go PRL 121 (2018) 062002

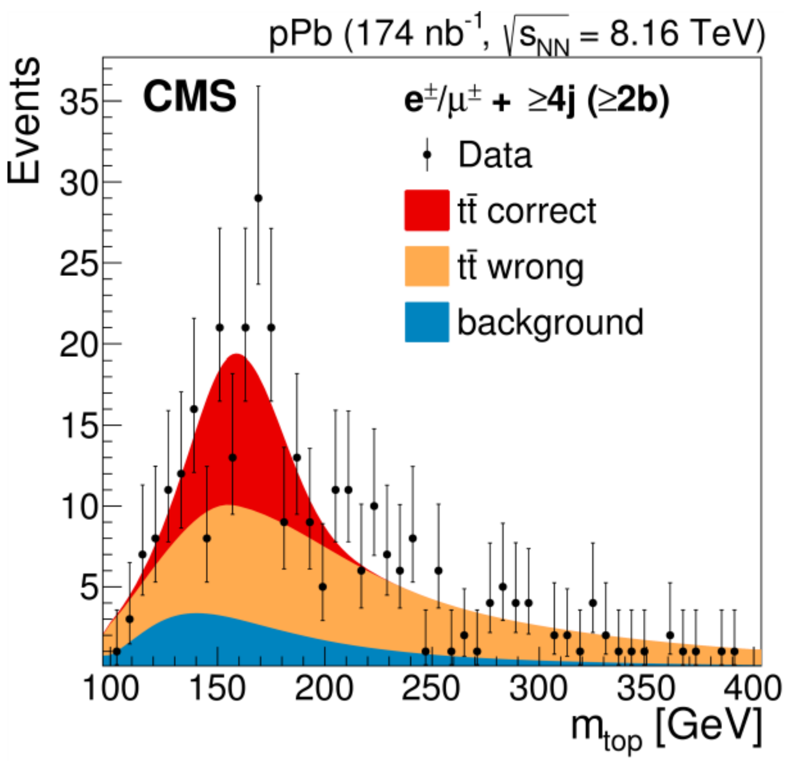
Observation of Top Production in pPb

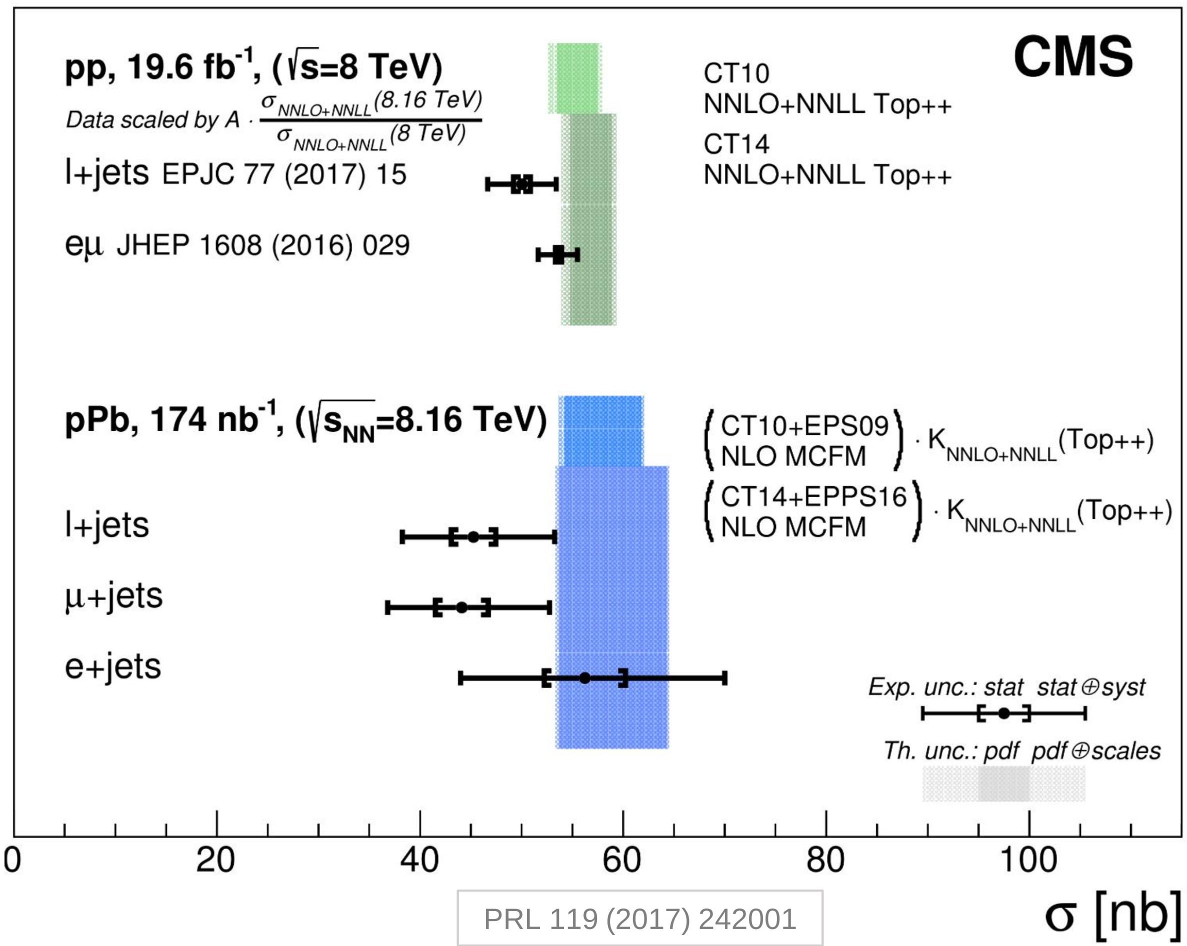


Top pair cross-section in **pPb** at 8.16 TeV

Compatible with pQCD calculations with nPDF

New constraint on gluon PDF at large x

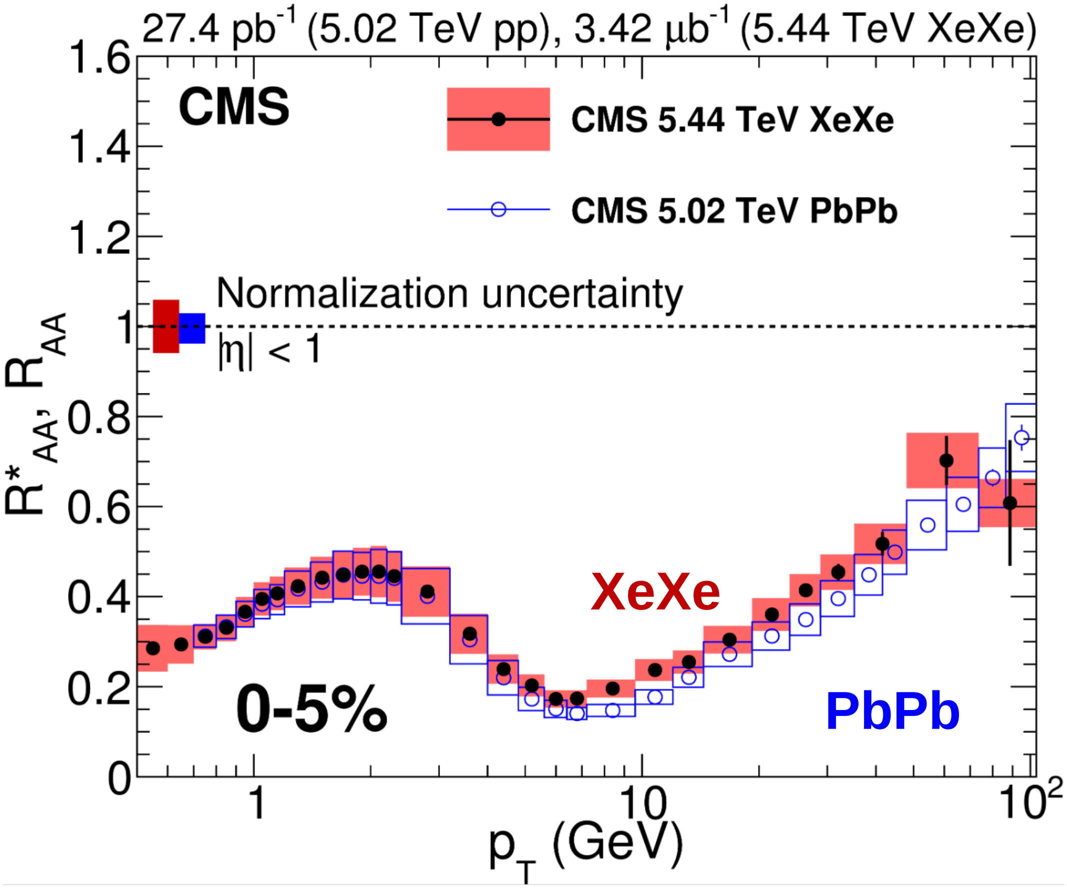




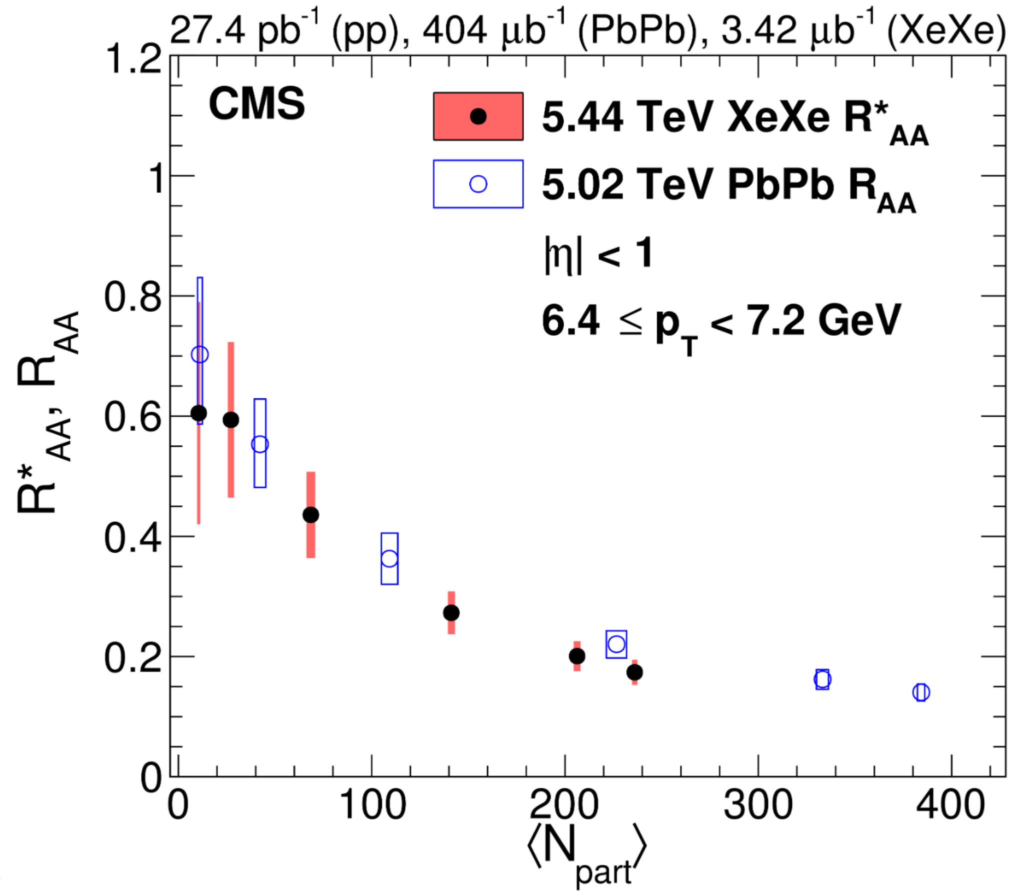
PRL 119 (2017) 242001

Jet Quenching vs. System Size

Charged Particle R_{AA} vs. p_T

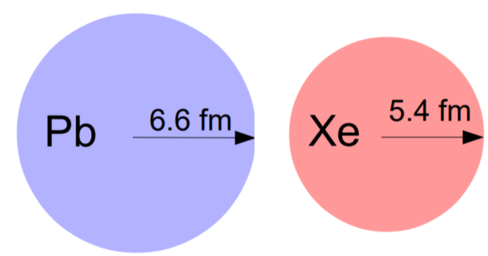


Charged Particle R_{AA} vs. N_{part}



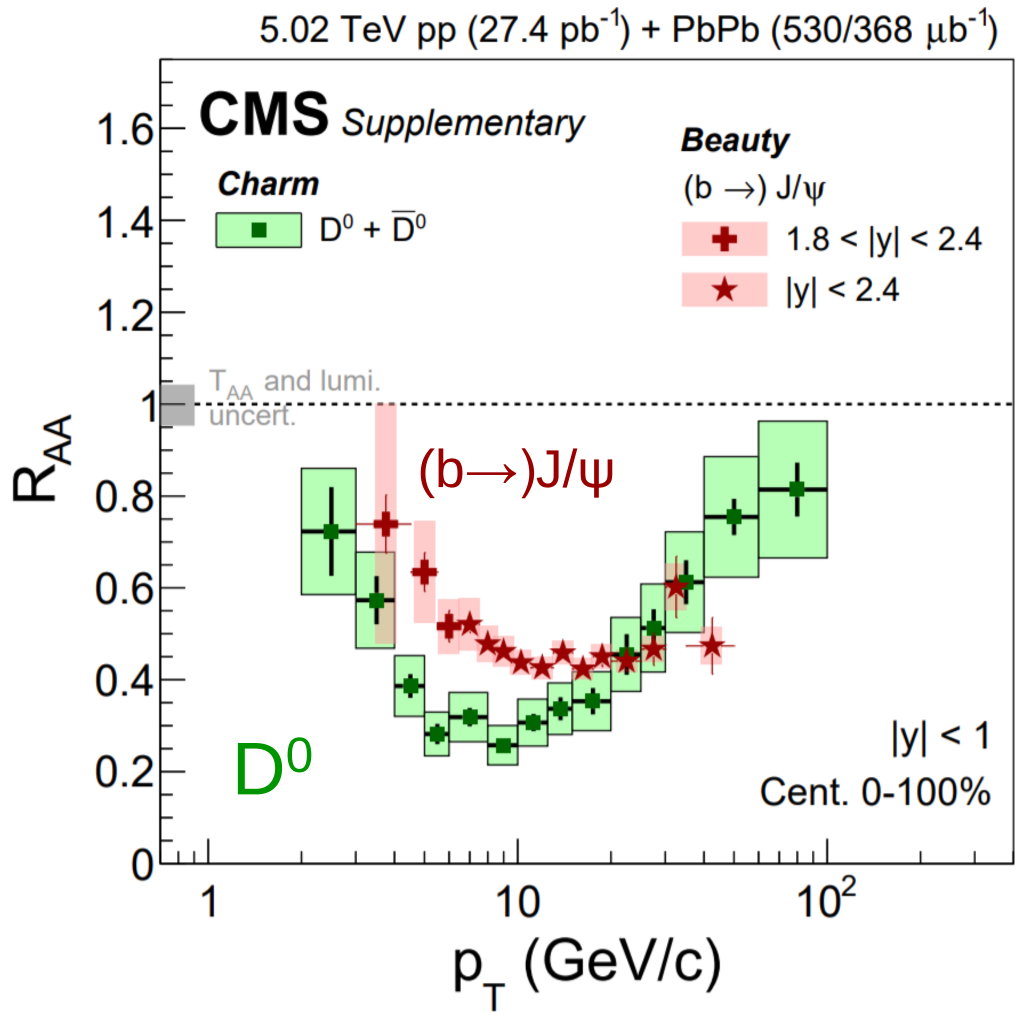
- Similar suppression at low p_T < 5 GeV
- Larger suppression in **PbPb** than **XeXe** at high p_T > 5 GeV

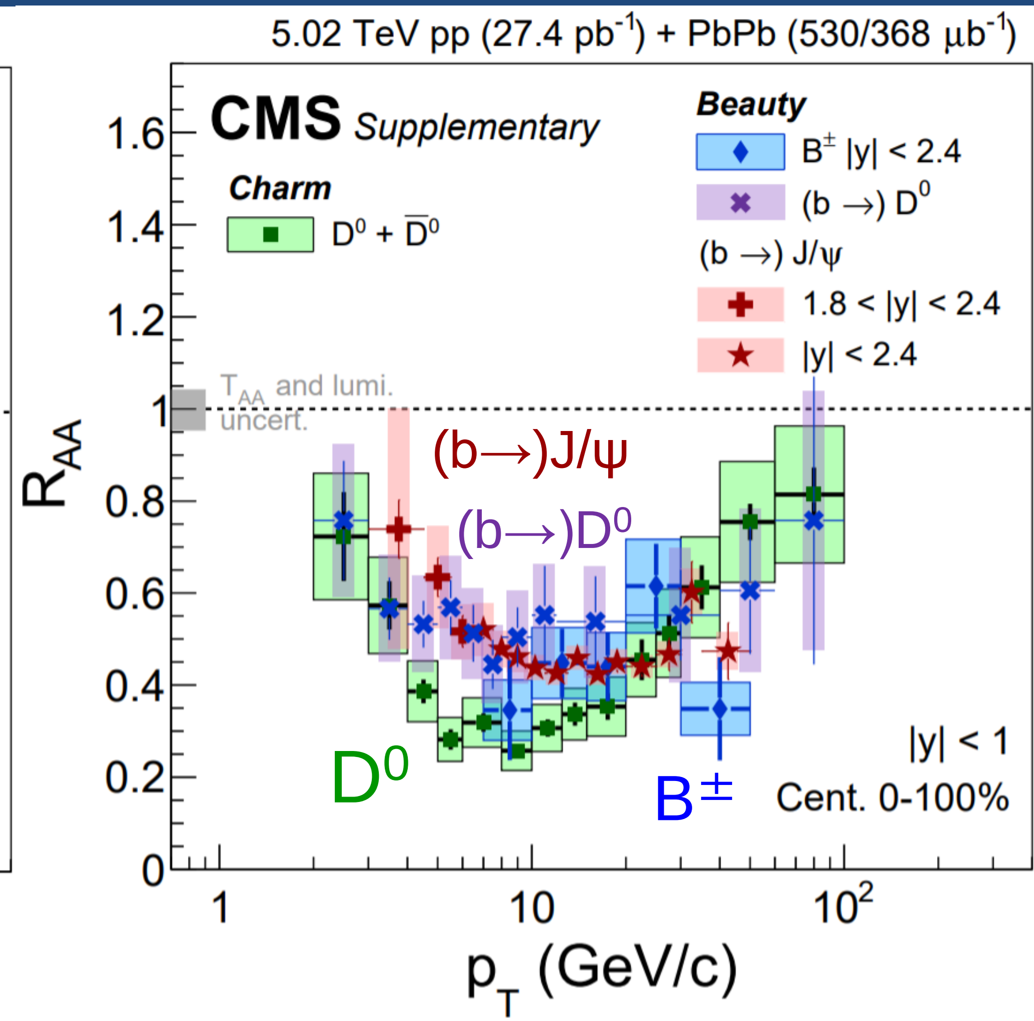
- **PbPb** and **XeXe** R_{AA} at the same N_{part} are similar



Austin Baty | PbPb JHEP 04 (2017) 039 | XeXe arXiv:1809.00201

Charm vs. Beauty Energy Loss





- **Prompt D^0** are significantly more suppressed than **b→J/ψ** at low p_T < 15 GeV

- **Prompt D^0** are more suppressed than **non-prompt D^0**
- Confirmation of the **b→J/ψ** results

Consistent with parton mass dependence of energy loss

D^0 PLB 782 (2018) 474 | J/ψ EPJC 77 (2017) 269 | $B^\pm$ PRL 119 (2017) 152301 | b→D^0 CMS-PAS-HIN-18-010 | Hao Qiu

Flavor Dependence of Parton Energy Loss

D^0 PLB 782 (2018) 474

J/ψ EPJC 77 (2017) 269

b→D^0 CMS-PAS-HIN-18-010

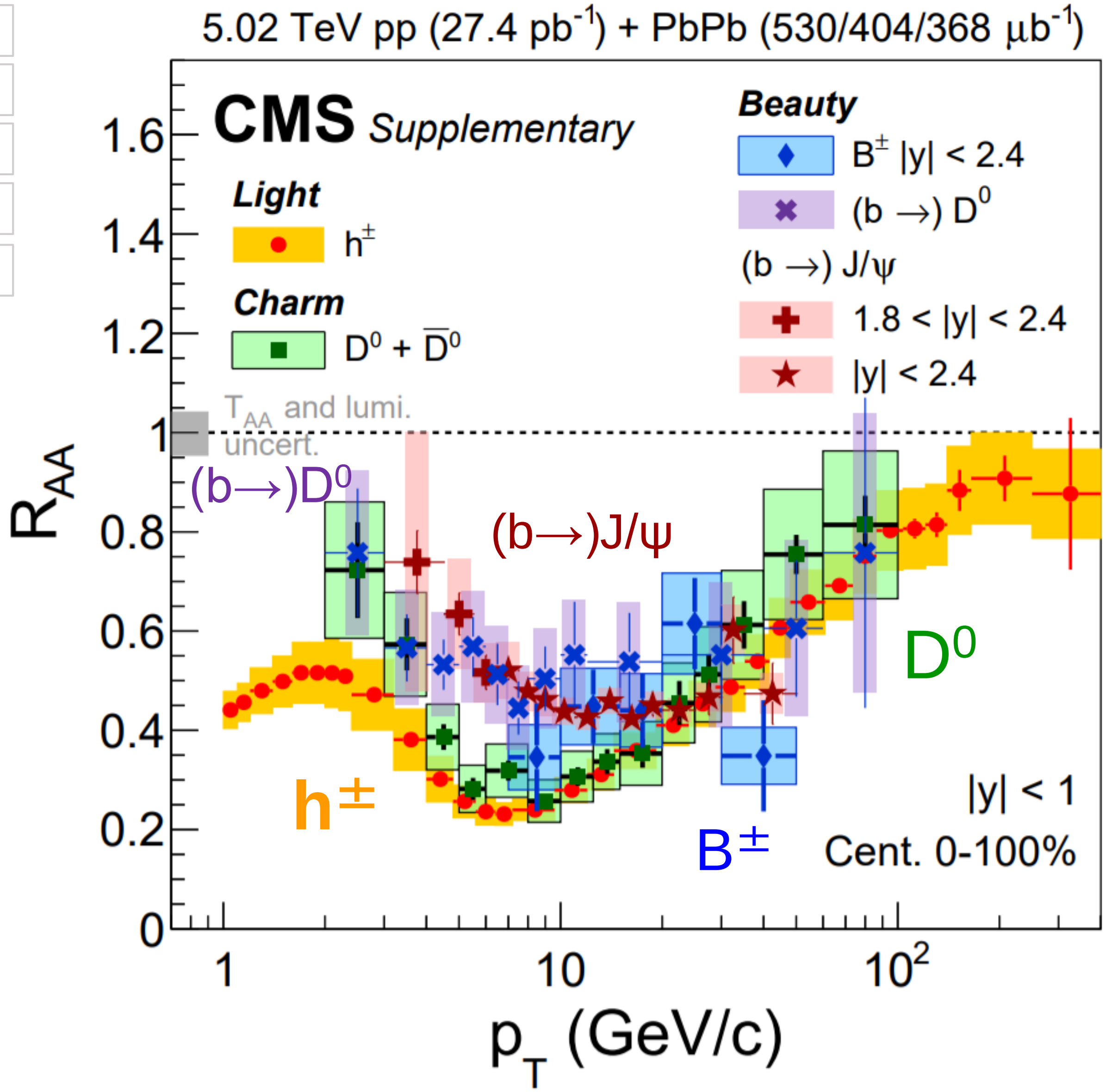
$h^{\pm}$ JHEP 04 (2017) 039

$B^{\pm}$ PRL 119 (2017) 152301

Rui Xiao

Cheng-Chieh Peng

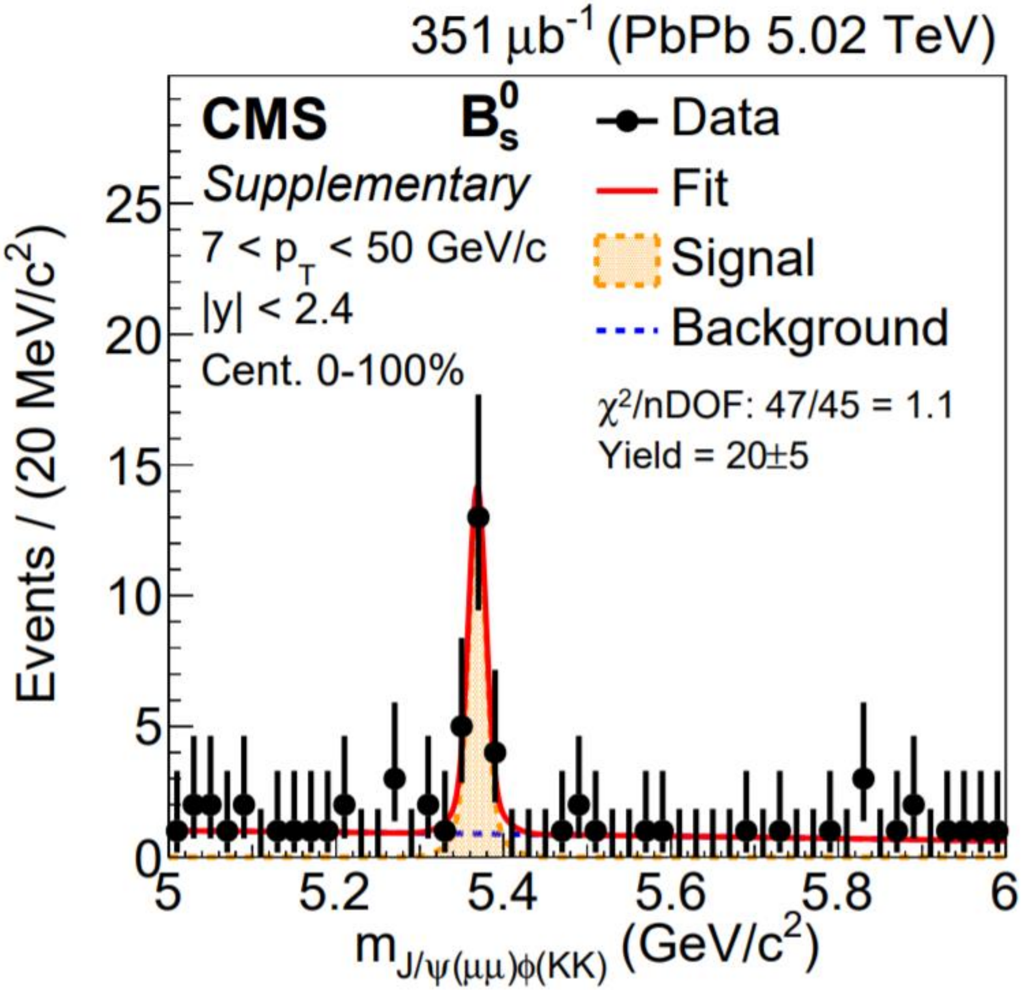
Hao Qiu

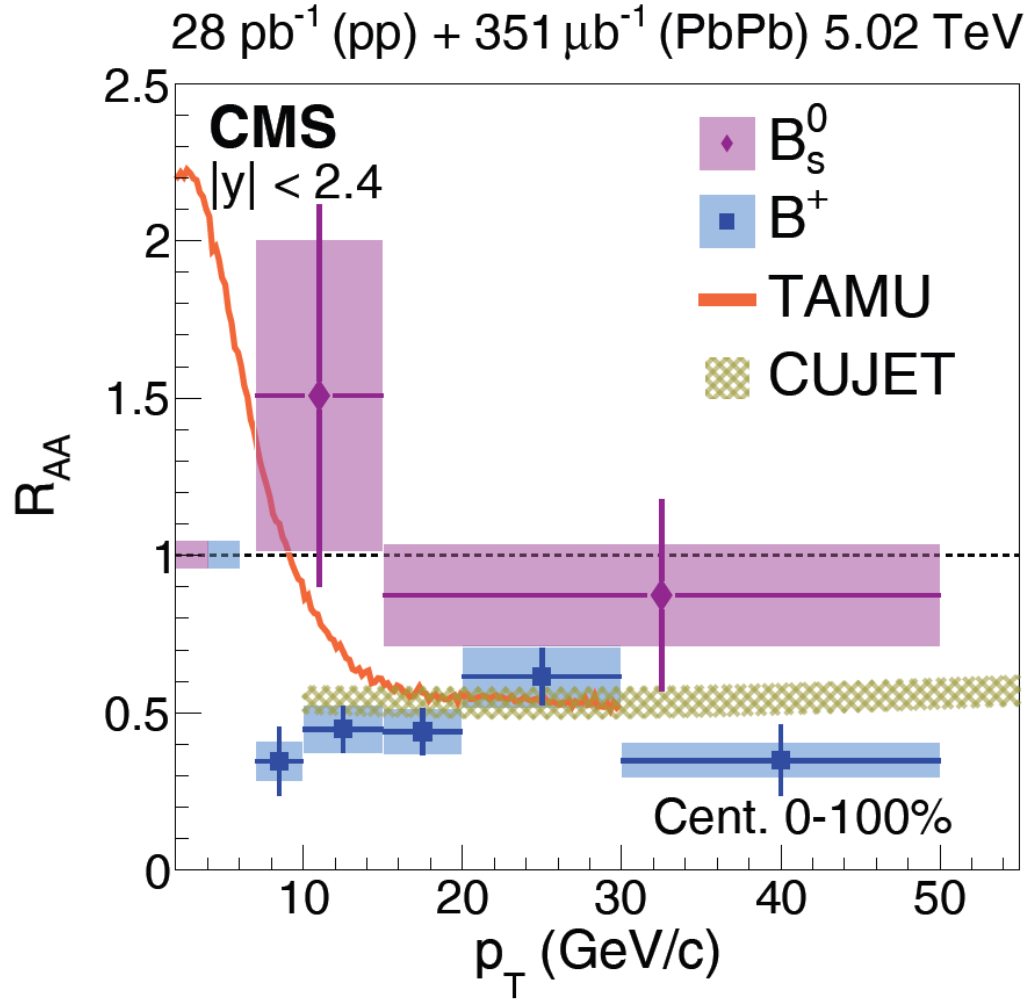


Meson flavor dependent R_{AA} at low p_T, disappearance of this effect at high p_T

Unprecedented info about parton mass dependence of energy loss

Hadronization of Beauty Quarks in QGP





$$B_s^0 \to J/\psi\, \phi \to \mu^+\mu^-K^+K^-$$

- Evidence of B_s^0 production in PbPb

- Indication of **B_s^0** enhancement in PbPb
- Consistent with expectation from beauty+strange coalescence model

Guilaume Falmagne

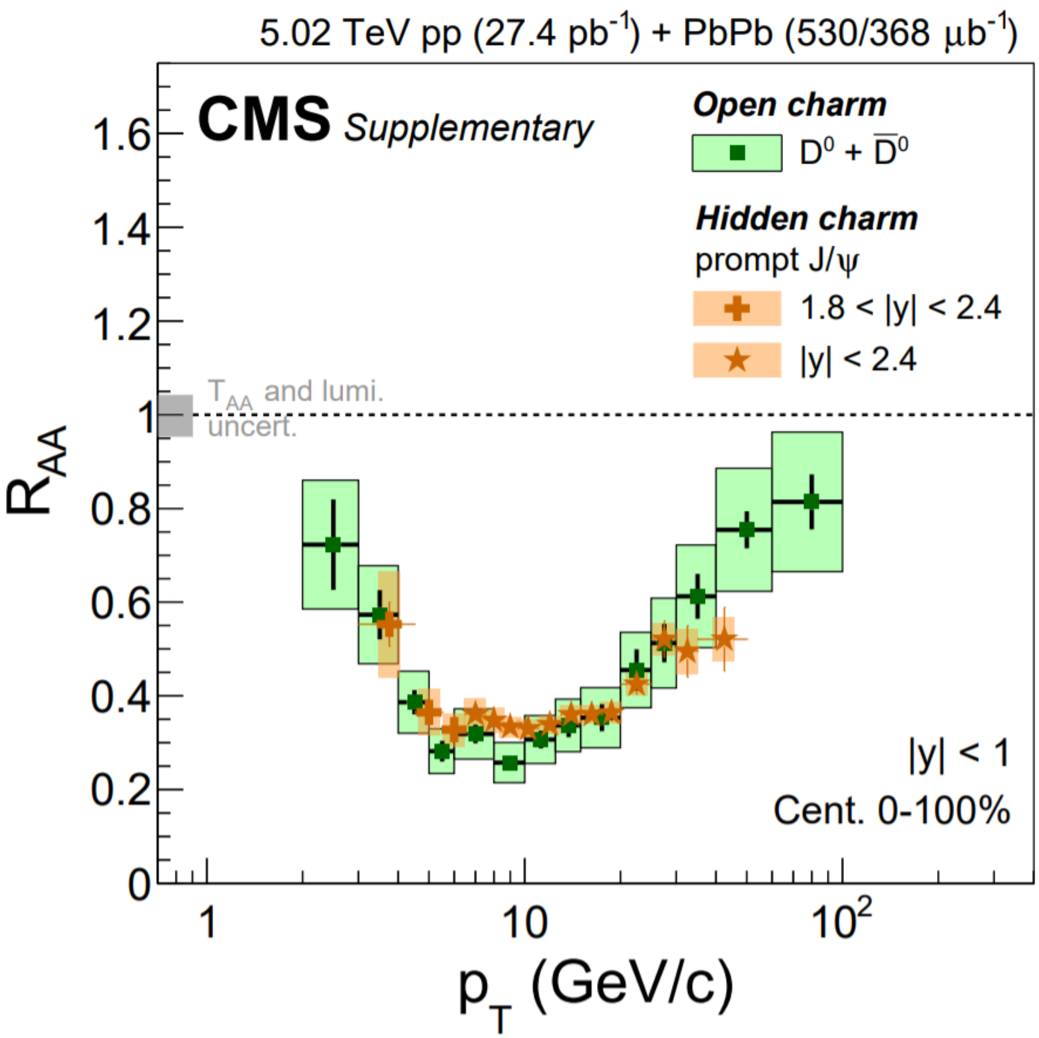
B_s^0 arXiv:1810.xxxx

B± PRL 119 (2017) 152301

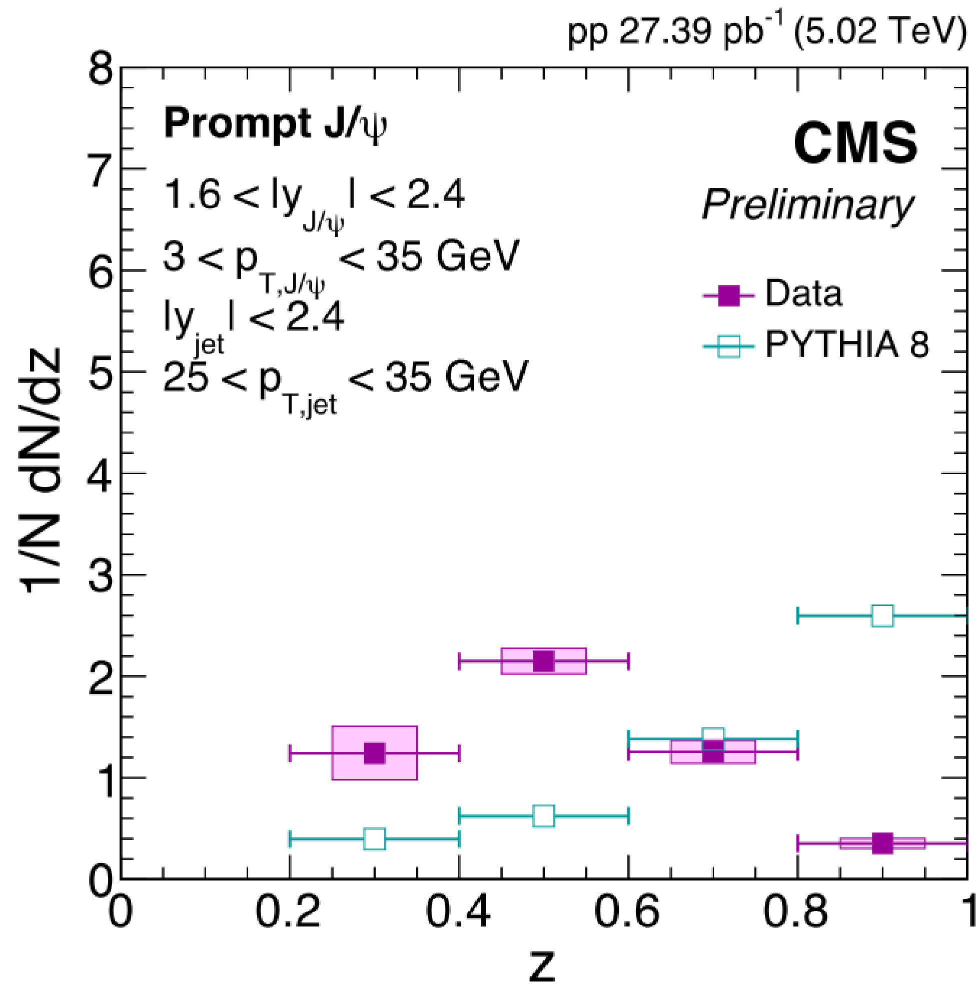
HARD PROBES 2018

Prompt J/ψ Production

Nuclear Modification Factors in PbPb



Jet to J/ψ fragmentation function in pp



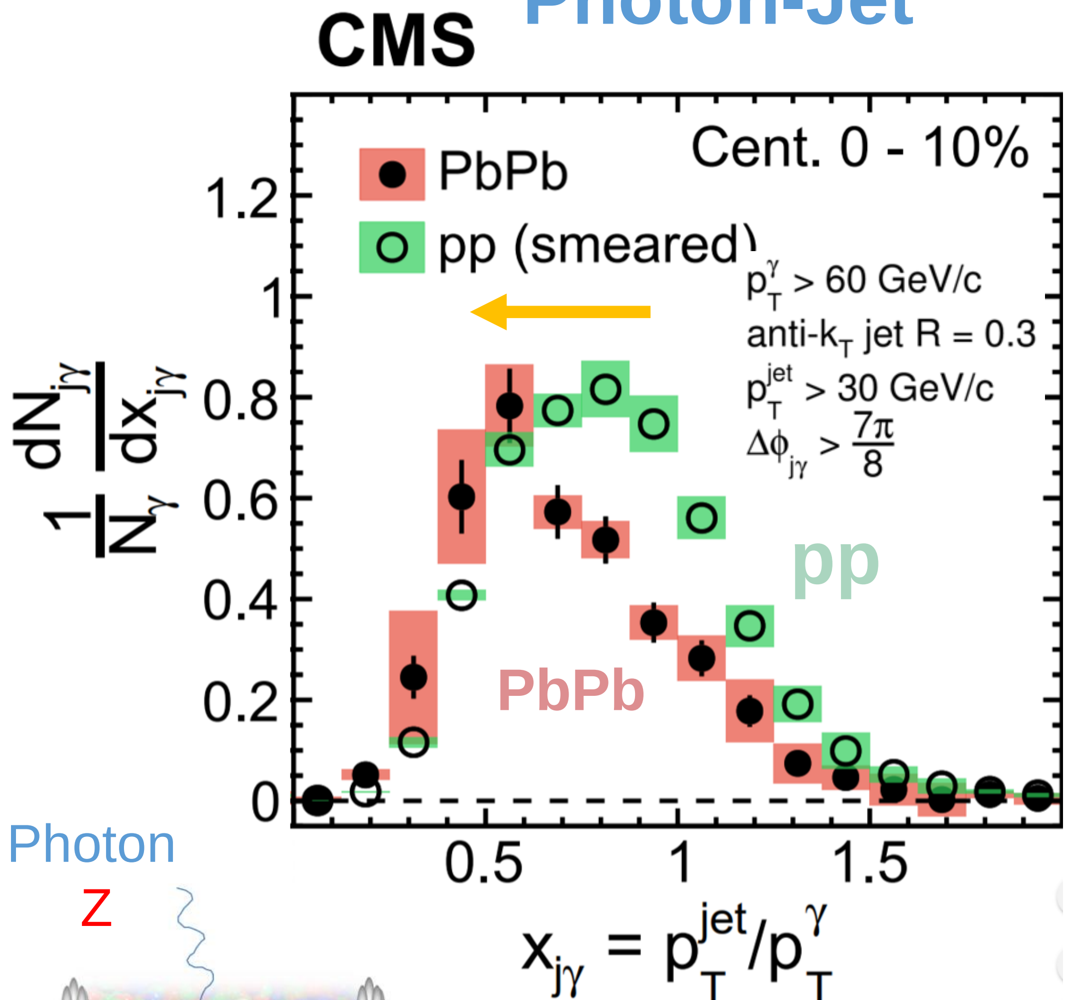
Similar R_{AA} between **open charm** (D^0) and **hidden charm** (prompt J/ψ)

J/ψ FF in pp: not described by **PYTHIA8**
Significantly less isolated

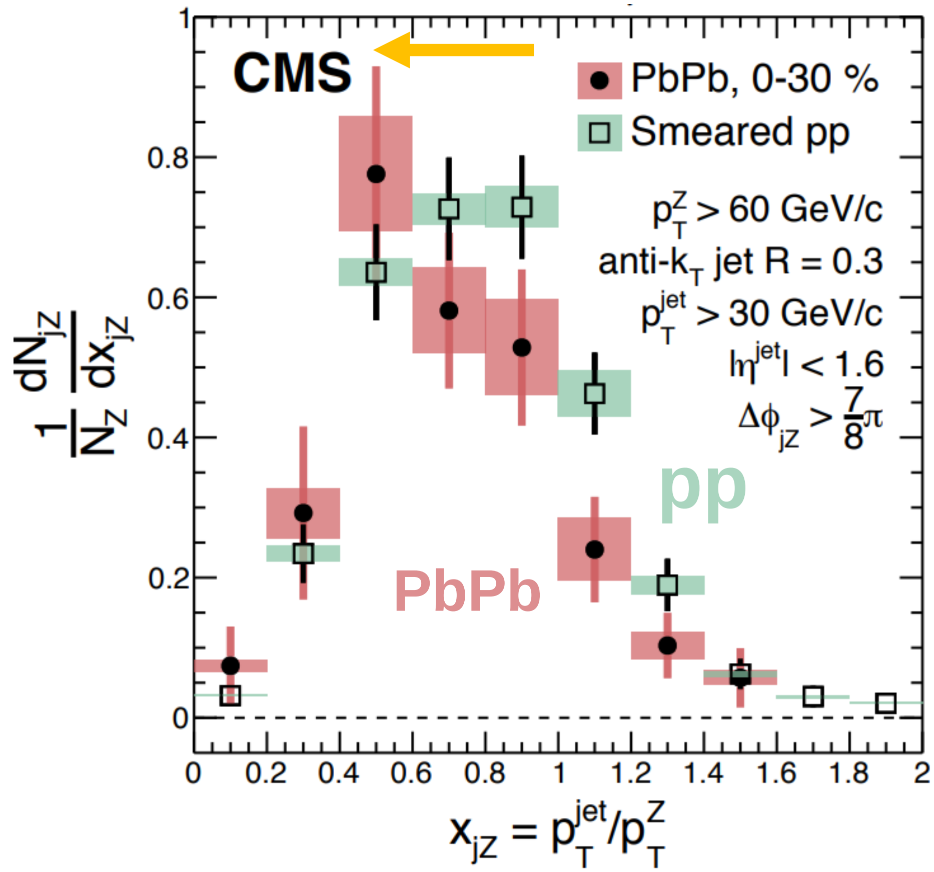
D^0 PLB 782 (2018) 474 | J/ψ EPJC 77 (2017) 269 | J/ψ in Jet CMS-PAS-HIN-18-012 | Batoul Diab

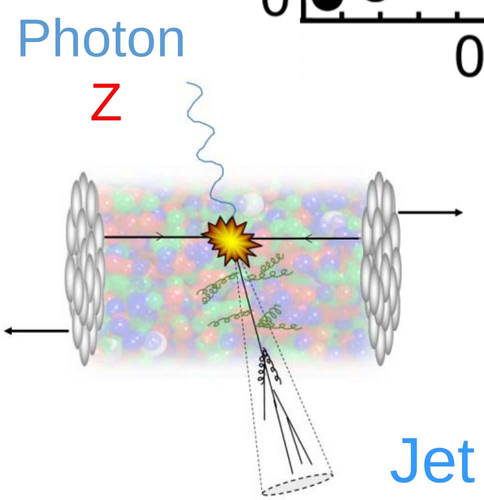
Boson-Jet Momentum Ratio in PbPb at 5 TeV

Photon-Jet



Z-Jet





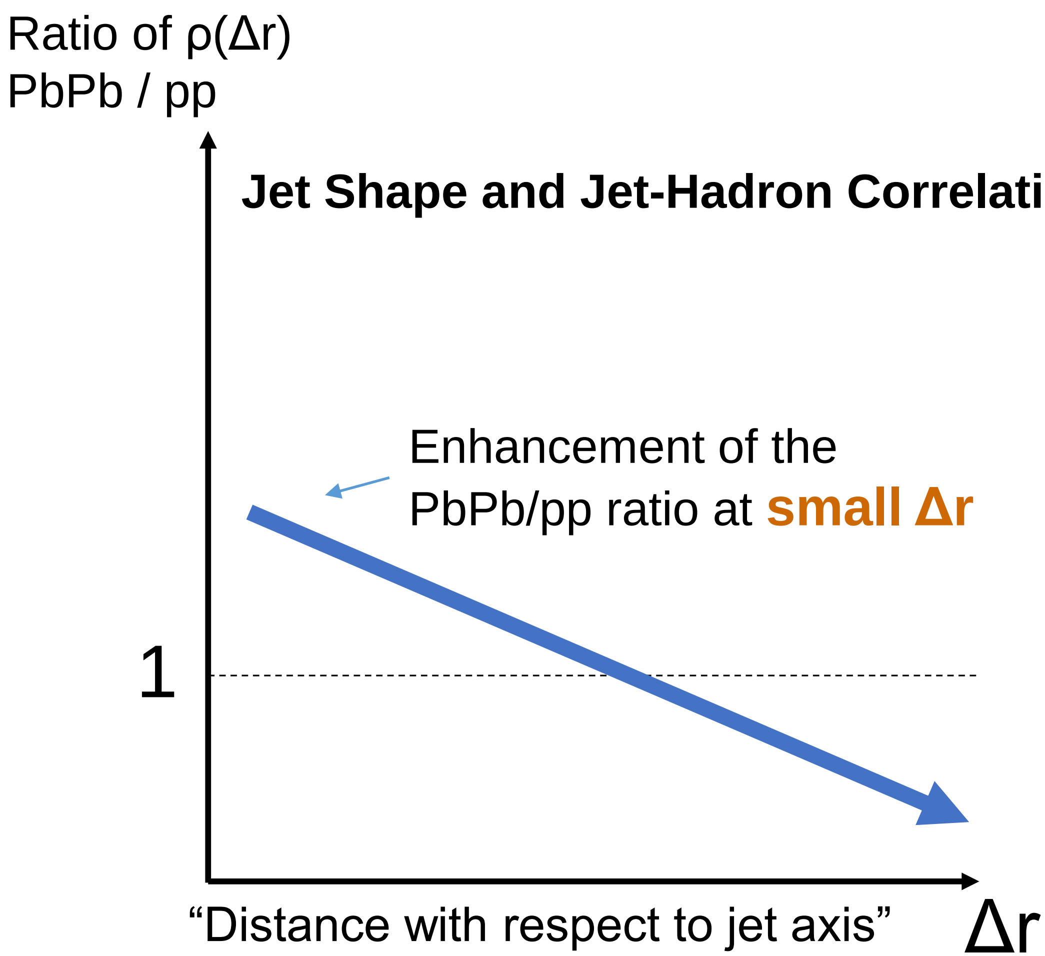
- Measured “**absolute energy loss**” (out of the jet cone) by comparing photon/Z and jet transverse momentum
- **Quark enriched away-side jet sample** (~70%)

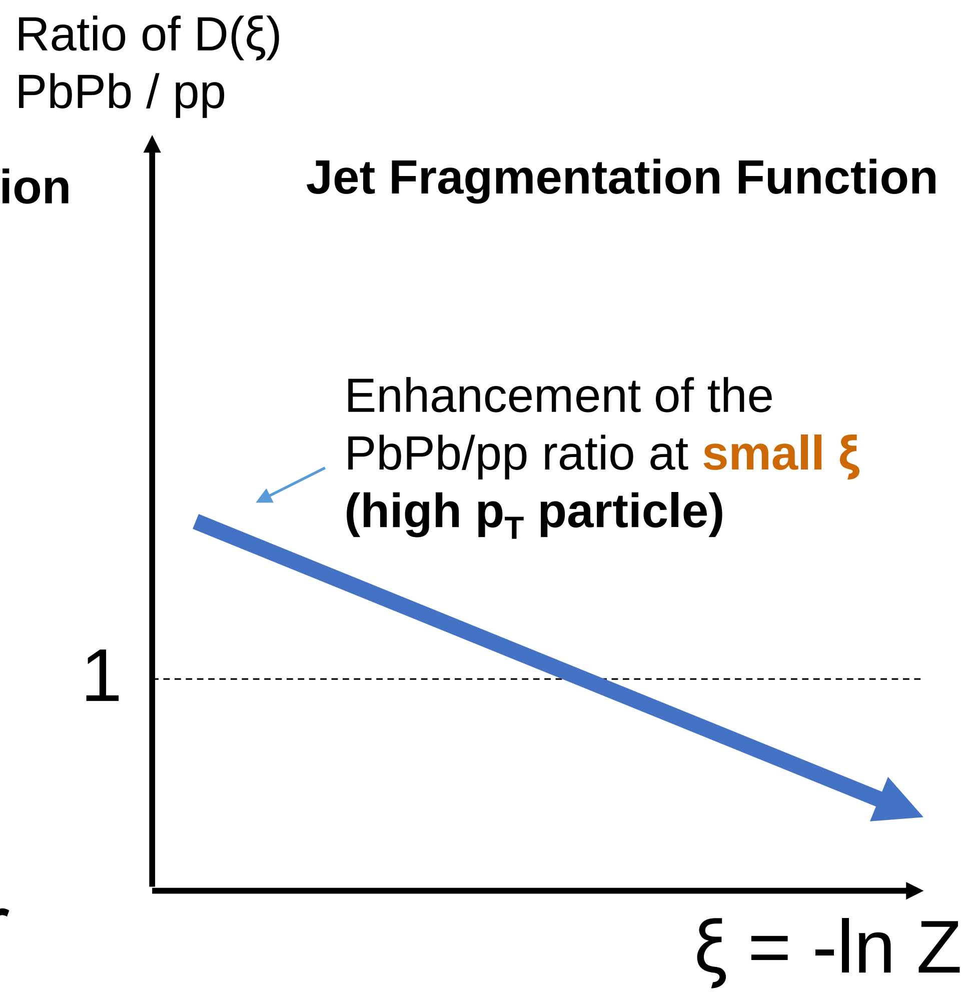
γ-Jet PLB 785 (2018) 14
Z-Jet PRL 119 (2017) 082301

Gluon Jet Suppression in PbPb

- Inclusive jets in pp: mixture of gluon and quark jets
- Due to the color charge, gluon jets are **wider** and **softer**

If gluons are more suppressed than quarks in PbPb…

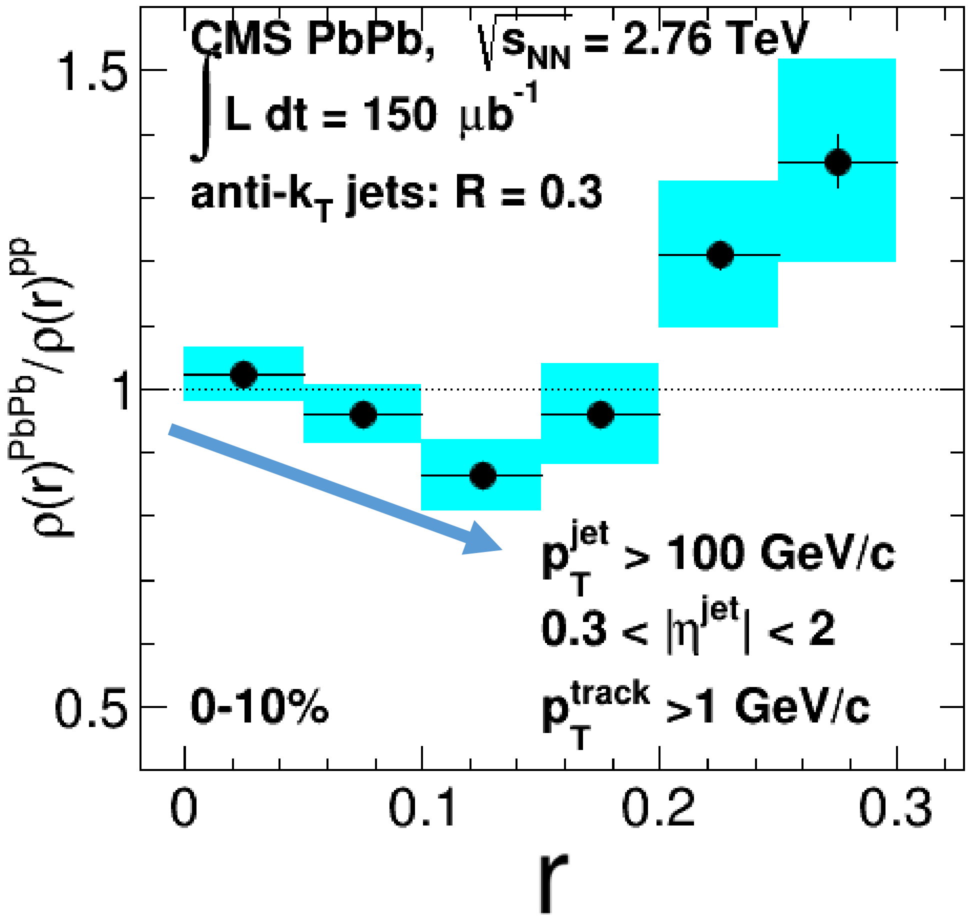




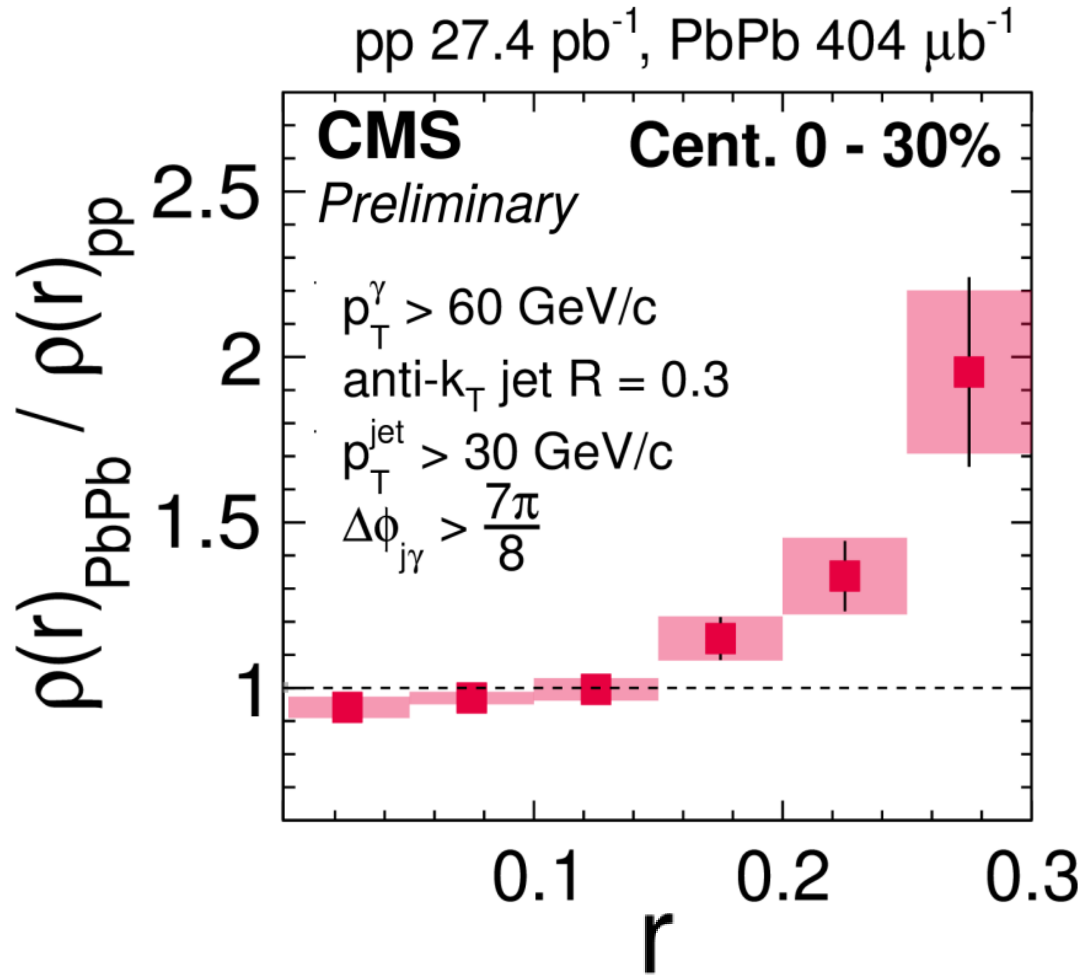
If one start with a purer quark jet sample, these effects will be reduced

Inclusive and Photon-Tagged Jet Shape

Inclusive Jet shape PbPb / pp



Photon-tagged Jet shape PbPb / pp



- Narrowing of the jet core (r<0.15) in inclusive jet shape, consistent with lower gluon fraction in PbPb
- Quark enriched jet shape from **γ-tagged jets**
- **Jet broadening** in PbPb in a purer (>70%) **quark jet** and **lower jet p_T sample**

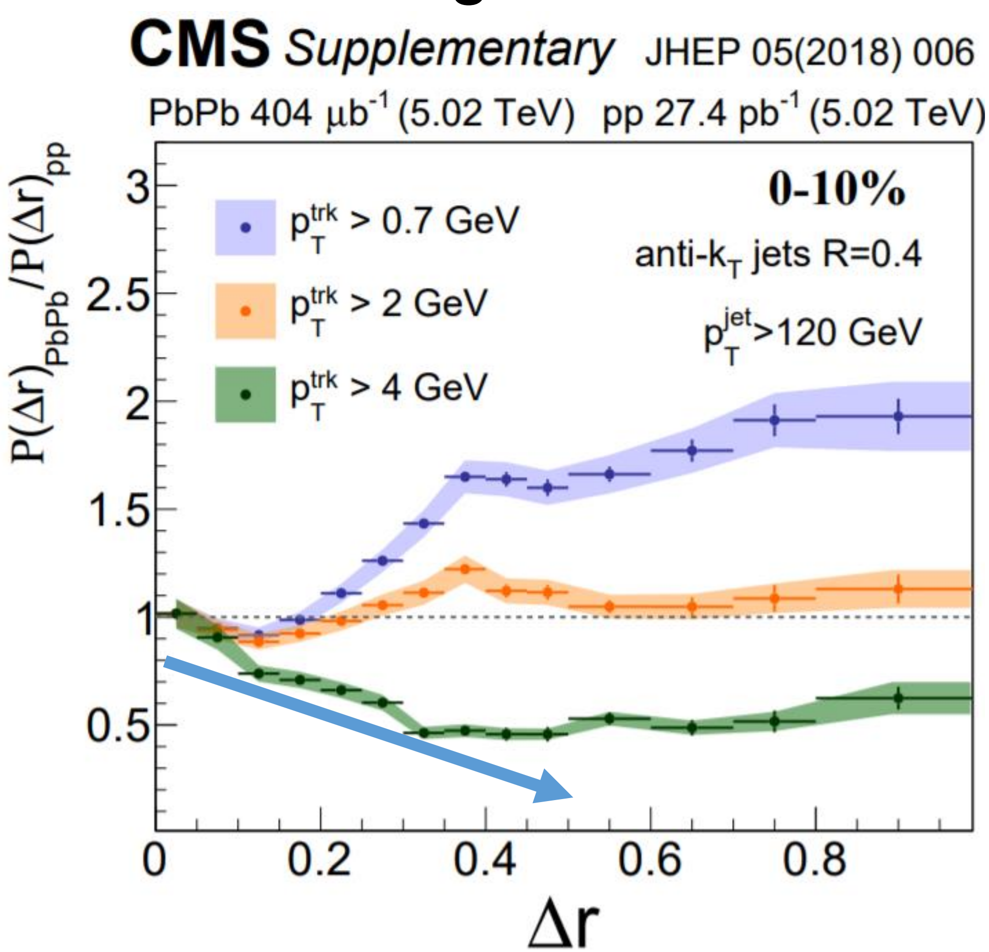
Inclusive Jet Shape PLB 730 (2014) 243

γ-tagged Jet Shape arXiv:1810.xxxx

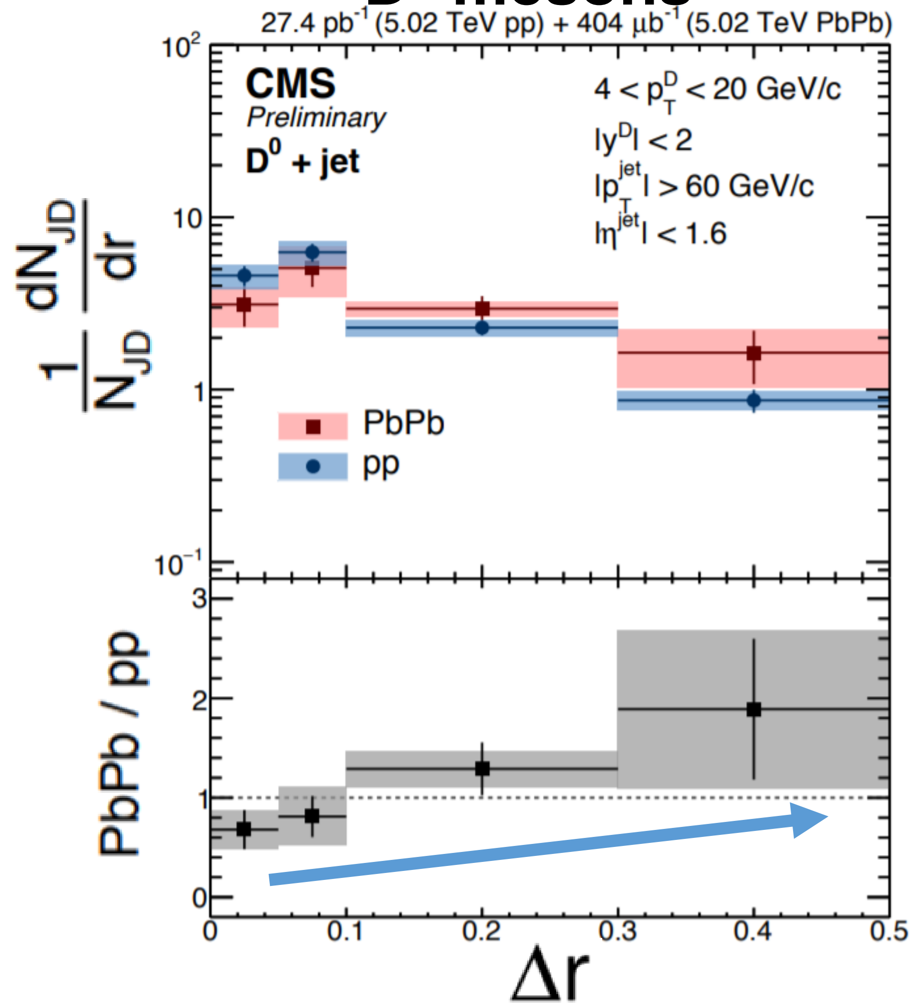
Kaya Tatar

Jet Shape with Light and Heavy Flavor Hadrons

Charged Particles



D^0 mesons

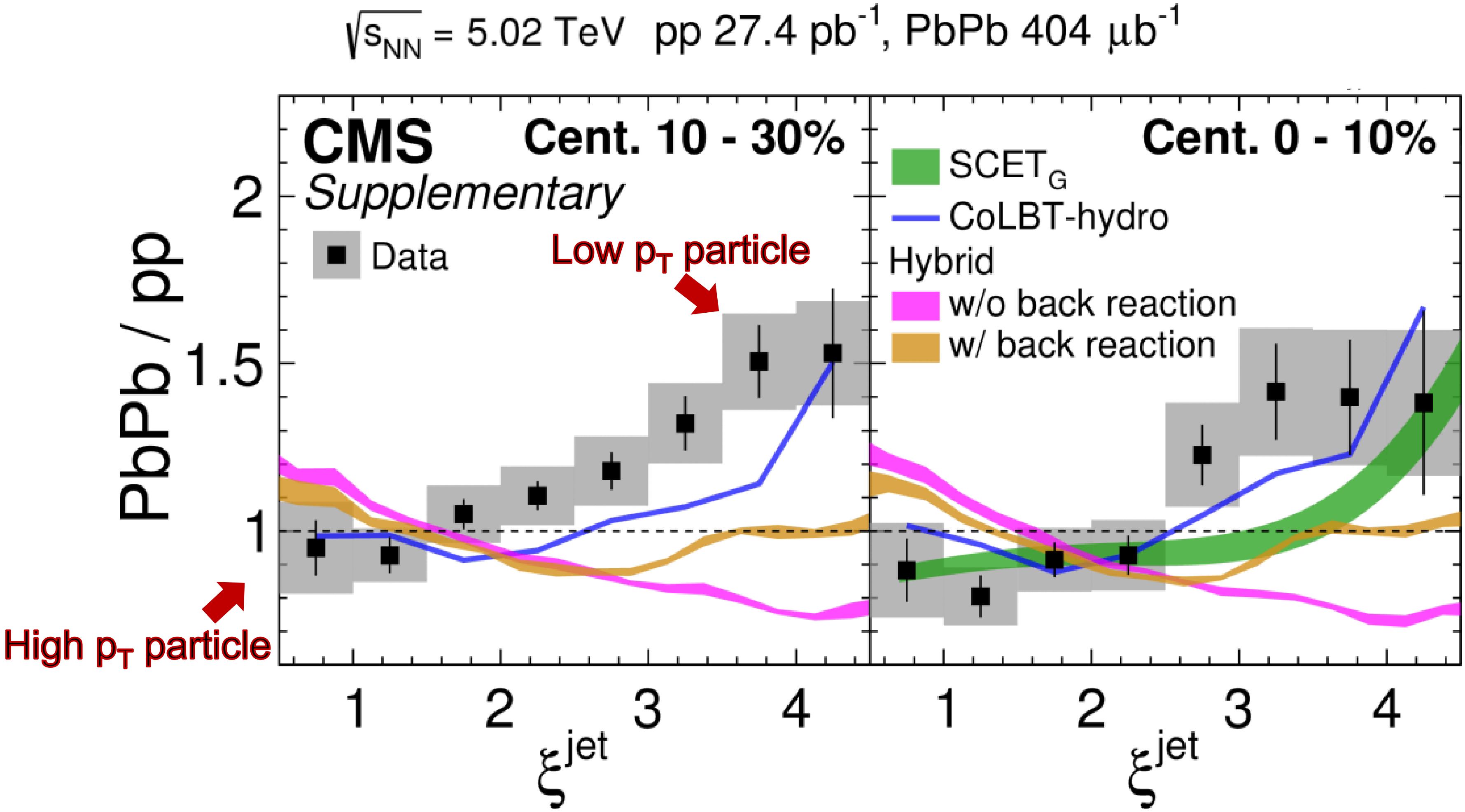


- **High p_T charged particle** suppression at large Δr with respect to jet axis in PbPb
- Due to the lower gluon fraction in PbPb?

- Different pattern compared to light flavor
- Hint of larger distance between D^0 and the jet axis in **PbPb** than **pp**
- Connection to charm diffusion in QGP?

Xiao Wang | Jet-hadron JHEP 05 (2018) 006 | D^0 in Jet CMS-PAS-HIN-18-012 | Michael Peters

Photon-Tagged Jet Fragmentation Function



- Observation of medium induced modifications of jet fragmentation
- **Medium response**: important ingredient for the description of large ξ (low charged particle p_T) in **Hybrid** and **CoLBT-hydro**
- **SCET$_G$**: medium induced radiation

arXiv:1801.04895

Kaya Tatar

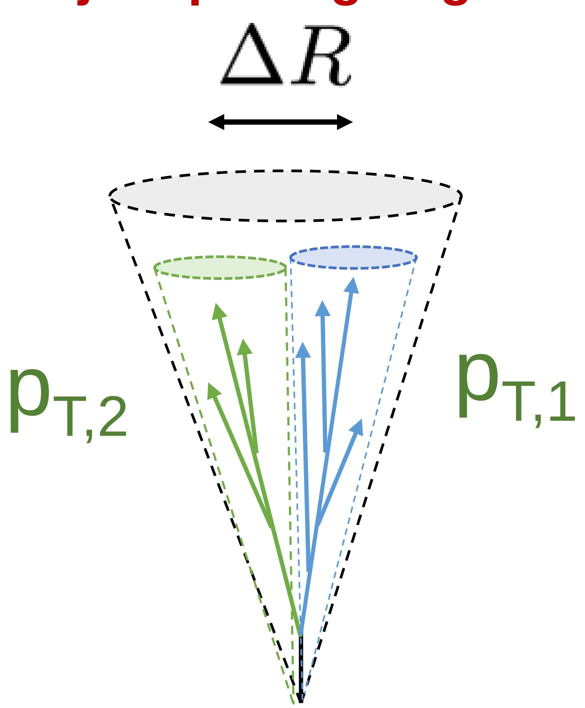
Parton Shower Dependence of Jet Quenching

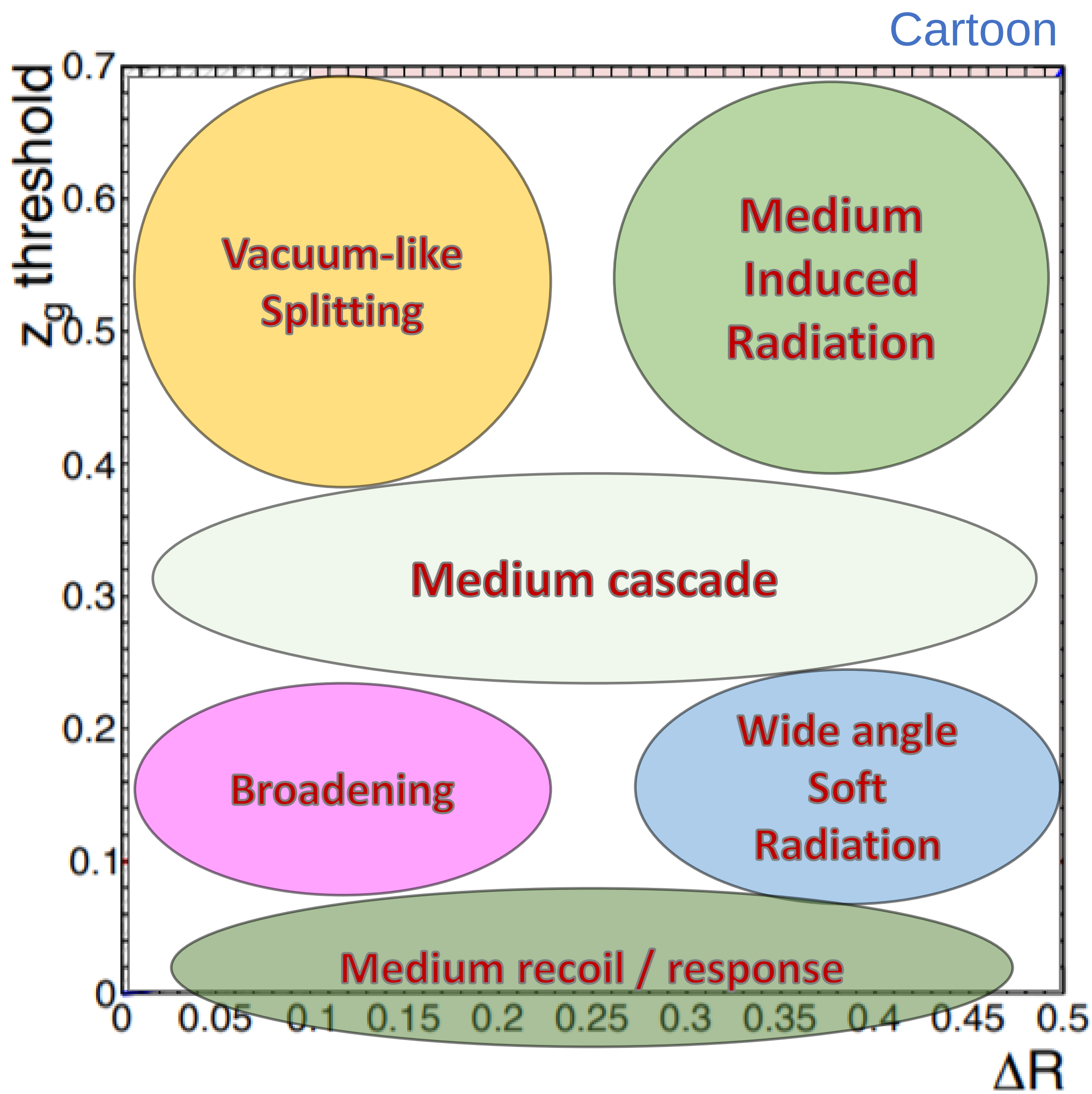
Parton energy loss **depends on its "shower history"** inside QGP

Subjet momentum sharing Z_g

$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

Subjet opening angle ΔR





Ideally, different phase space correspond to different physics…

Parton Shower Dependence of Jet Quenching

Parton energy loss **depends on its "shower history"** inside QGP

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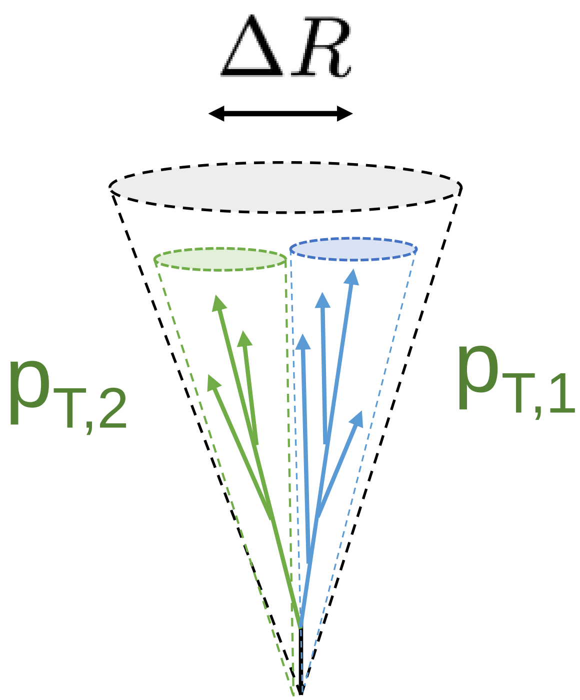
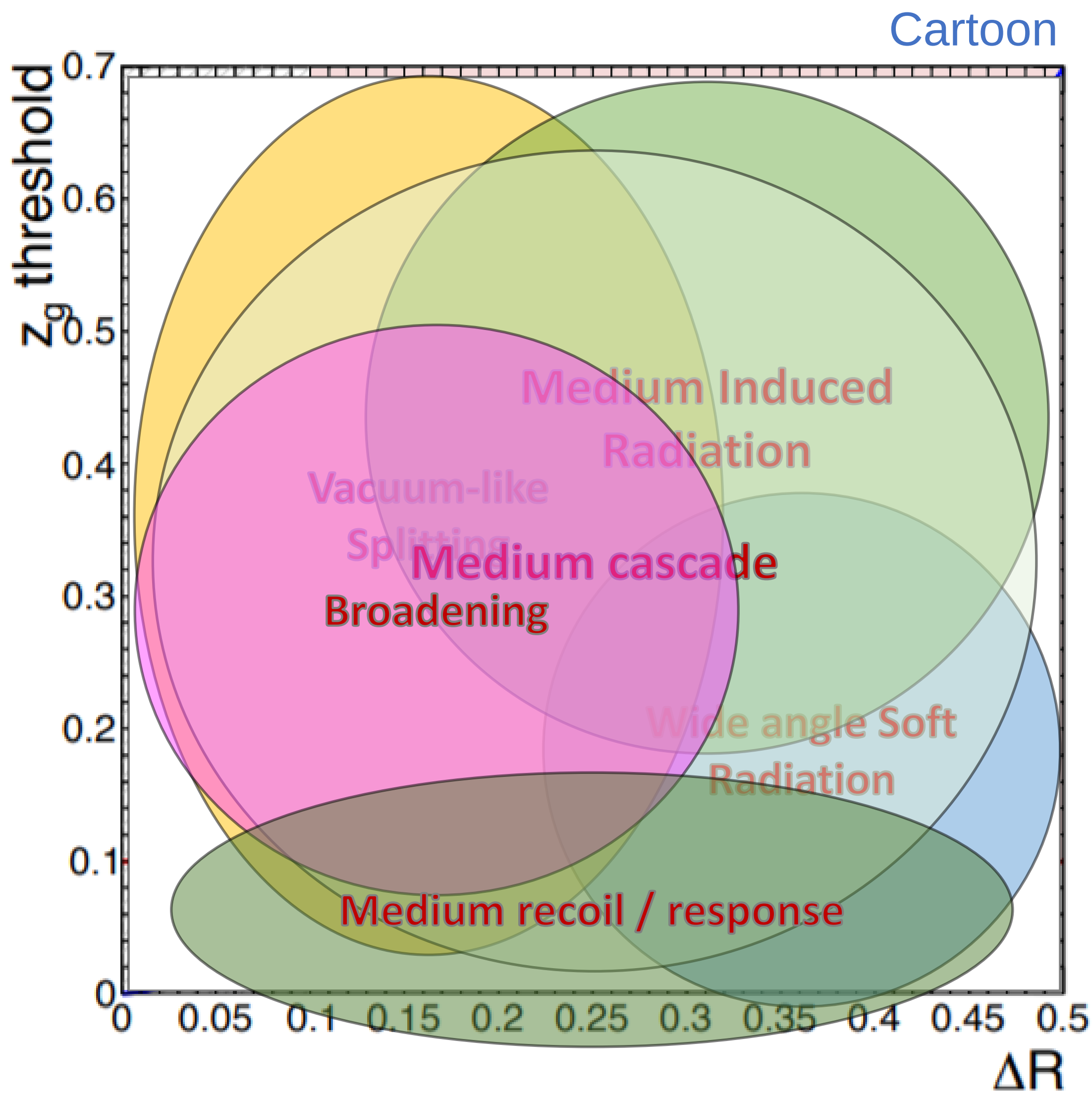
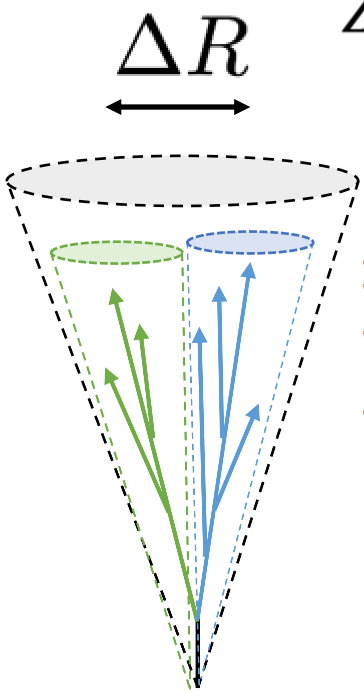




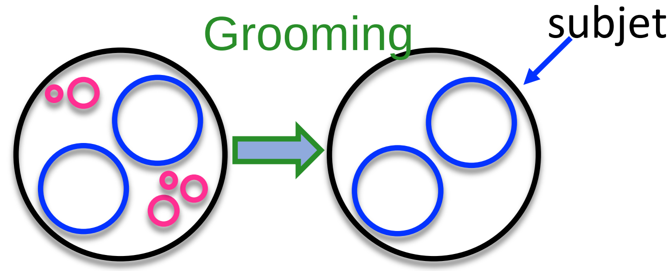
The reality may be more complicated than that

Groomed Jet Substructure with Soft Drop

- Jet grooming: design observables **sensitive to different phase space**
- Two soft drop settings with ΔR>0.1 cut

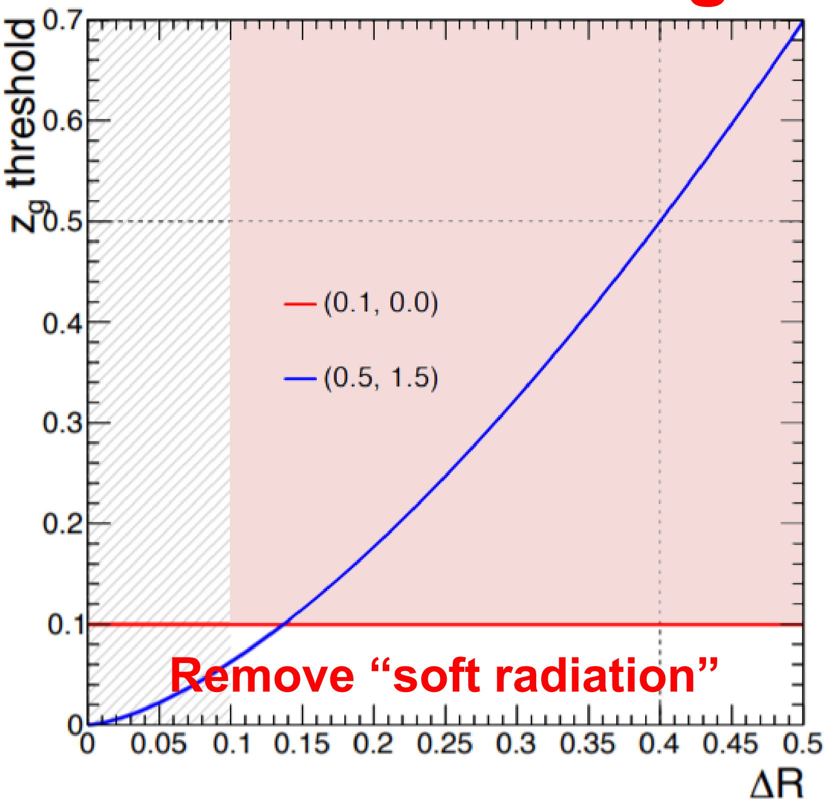


$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} > z_{\mathrm{cut}} \left(\frac{\Delta R}{R_0}\right)^{\beta}$$

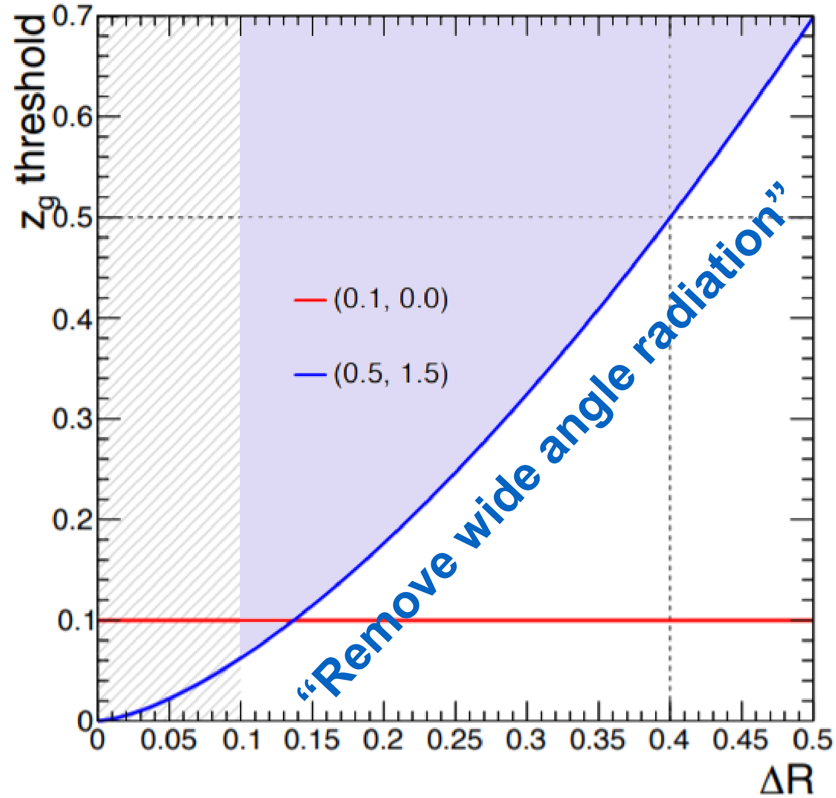


Soft Drop:
JHEP 1405 (2014) 146

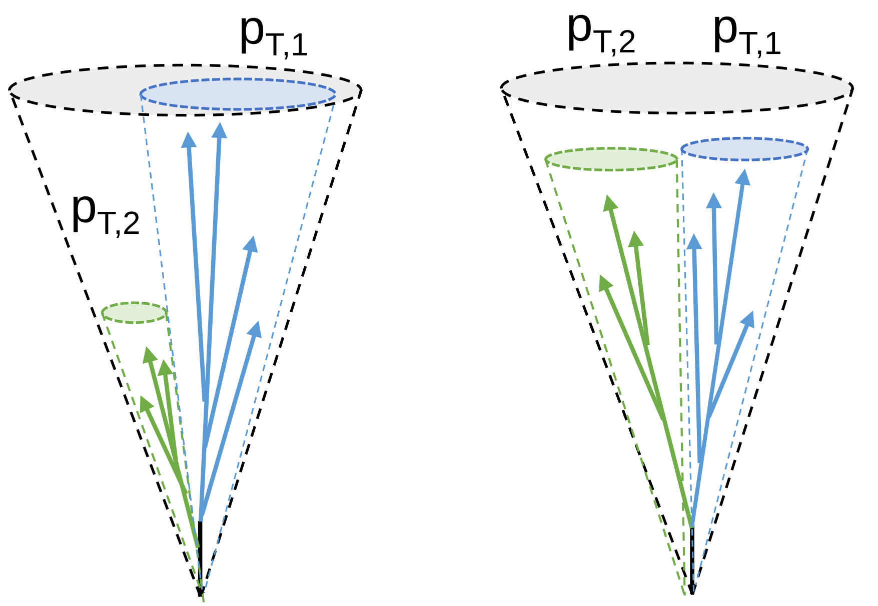
"Flat Grooming"



"Jet Core"

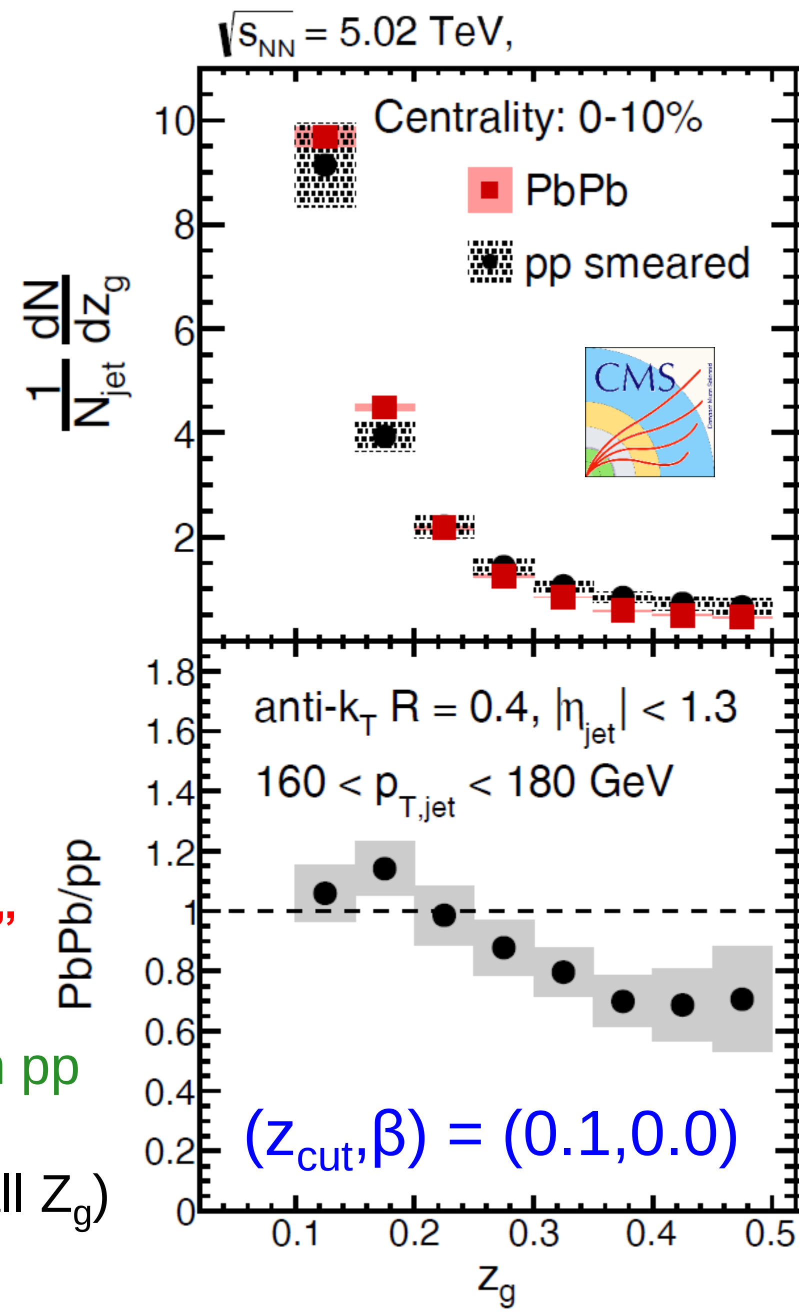


Momentum Sharing of Subjets



$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

"Flat Grooming"

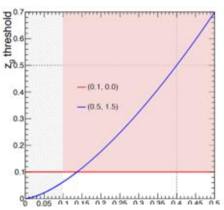


- Quark and gluon Z_g distributions are very similar in pp
- Jets with **two hard subjets** (large Z_g) **"relatively"** more suppressed than jets with a single core (small Z_g)

Dhanush Hangal

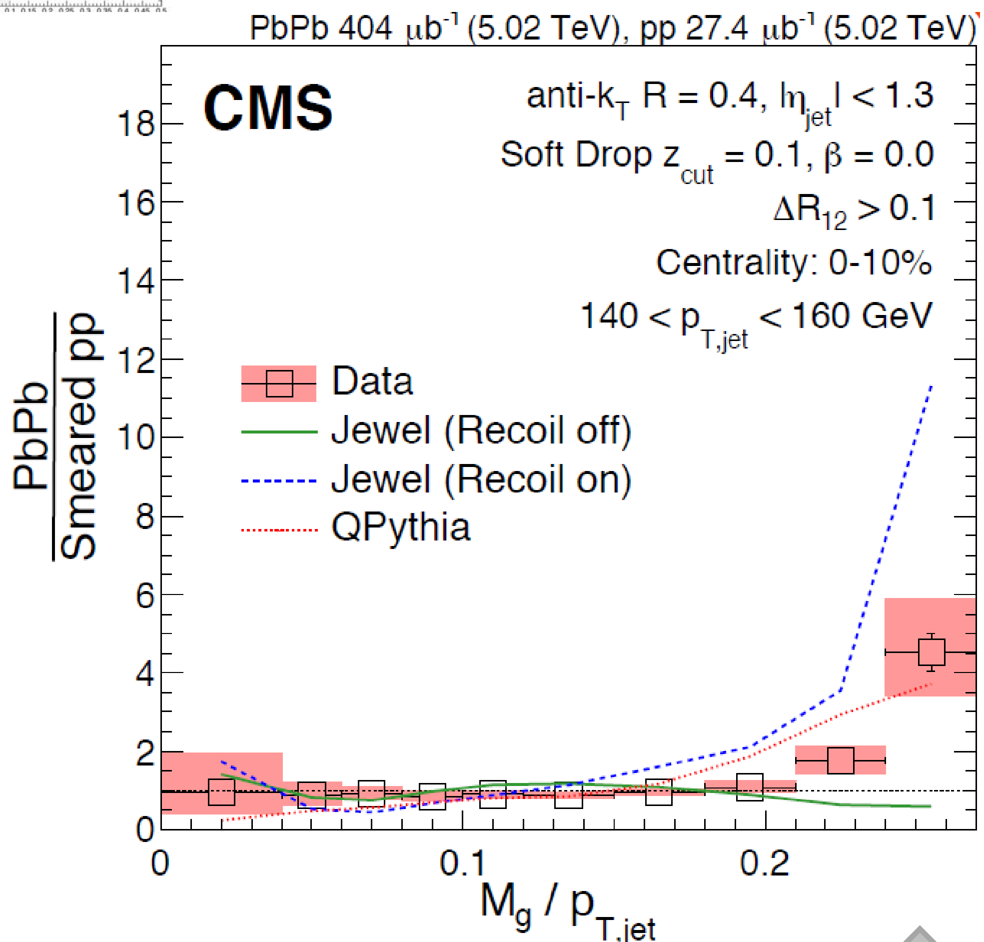
PRL 120 (2018) 142302

Groomed Jet Mass



(z_{cut},β) = (0.1,0.0) ΔR>0.1

"Flat Grooming"

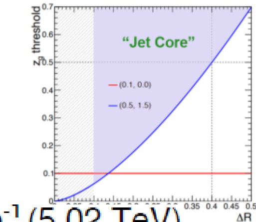


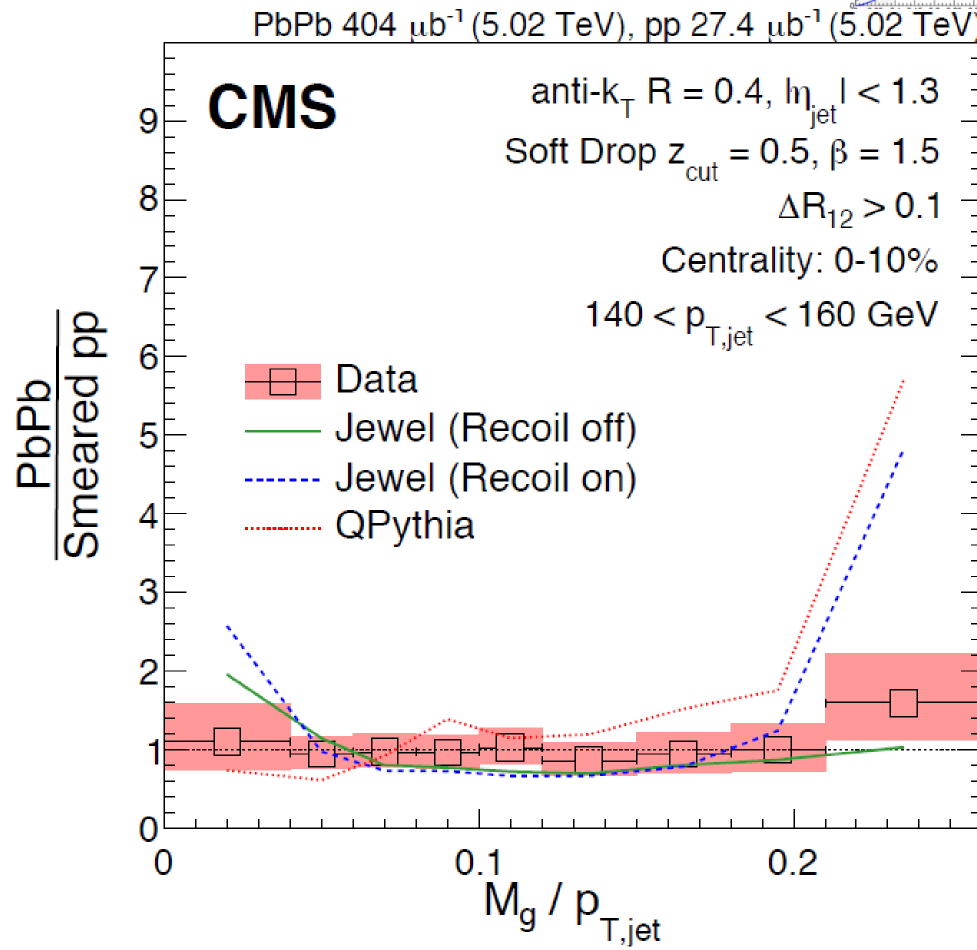
- Enhancement at large mass with flat grooming

arXiv:1805.05145

(z_{cut},β) = (0.5,1.5) ΔR>0.1

"Jet Core"



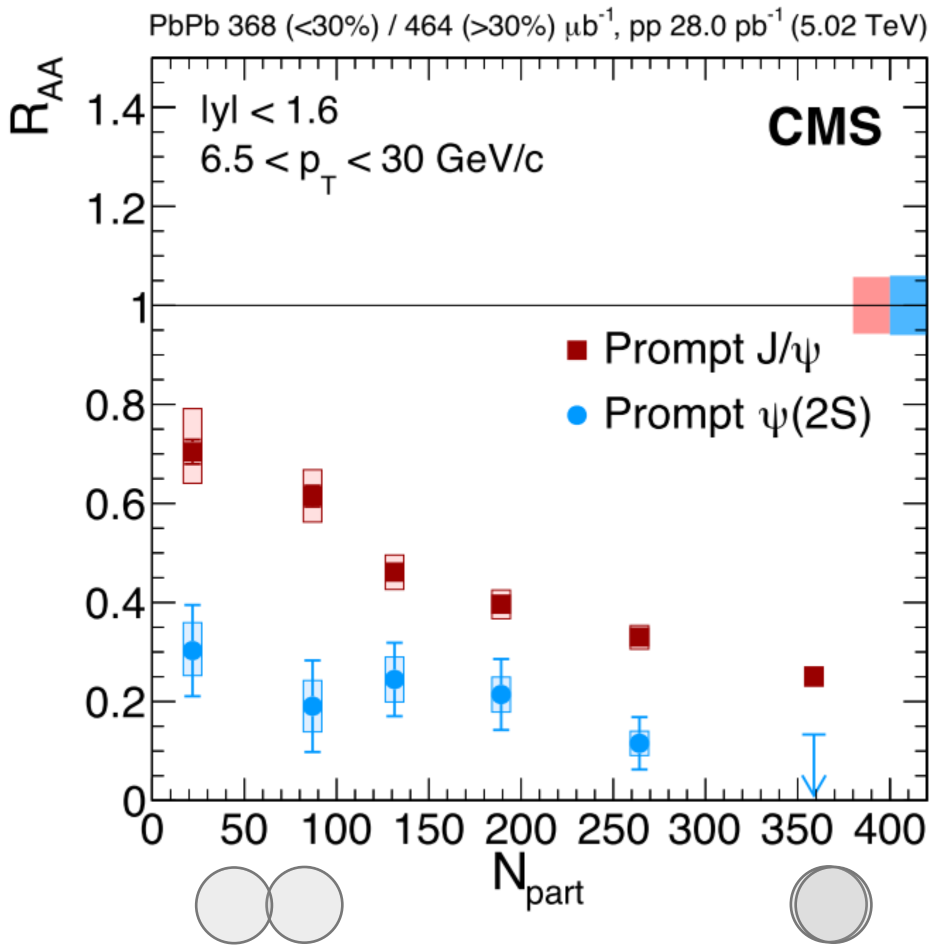


- "More aggressive grooming"
- Smaller or no significant modification of the "jet core"

Dhanush Hangal

Charmonia Production

PbPb at 5 TeV



$R_{AA}\Psi(2S)$ / R_{AA} J/Ψ

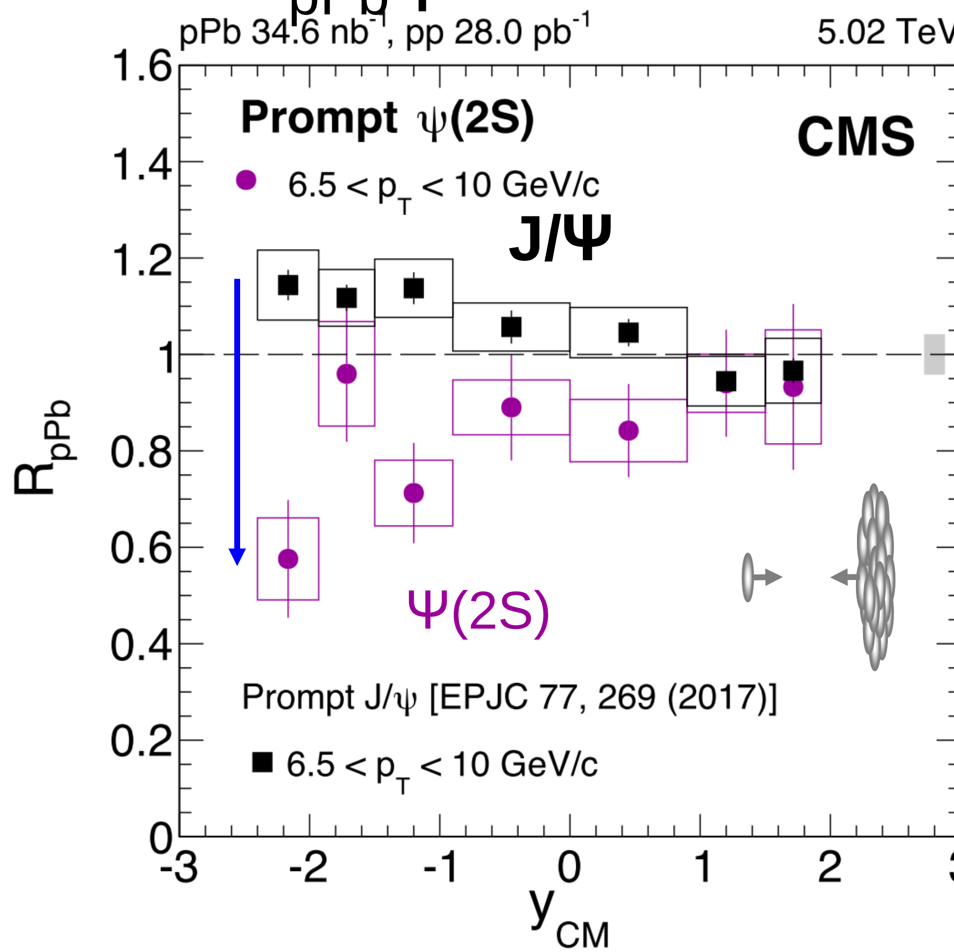
- Prompt Ψ(2S) R_{AA} < J/Ψ R_{AA} in PbPb at 5 TeV

PbPb EPJC 78 (2018) 509

pPb arXiv:1805.02248

Batoul Diab

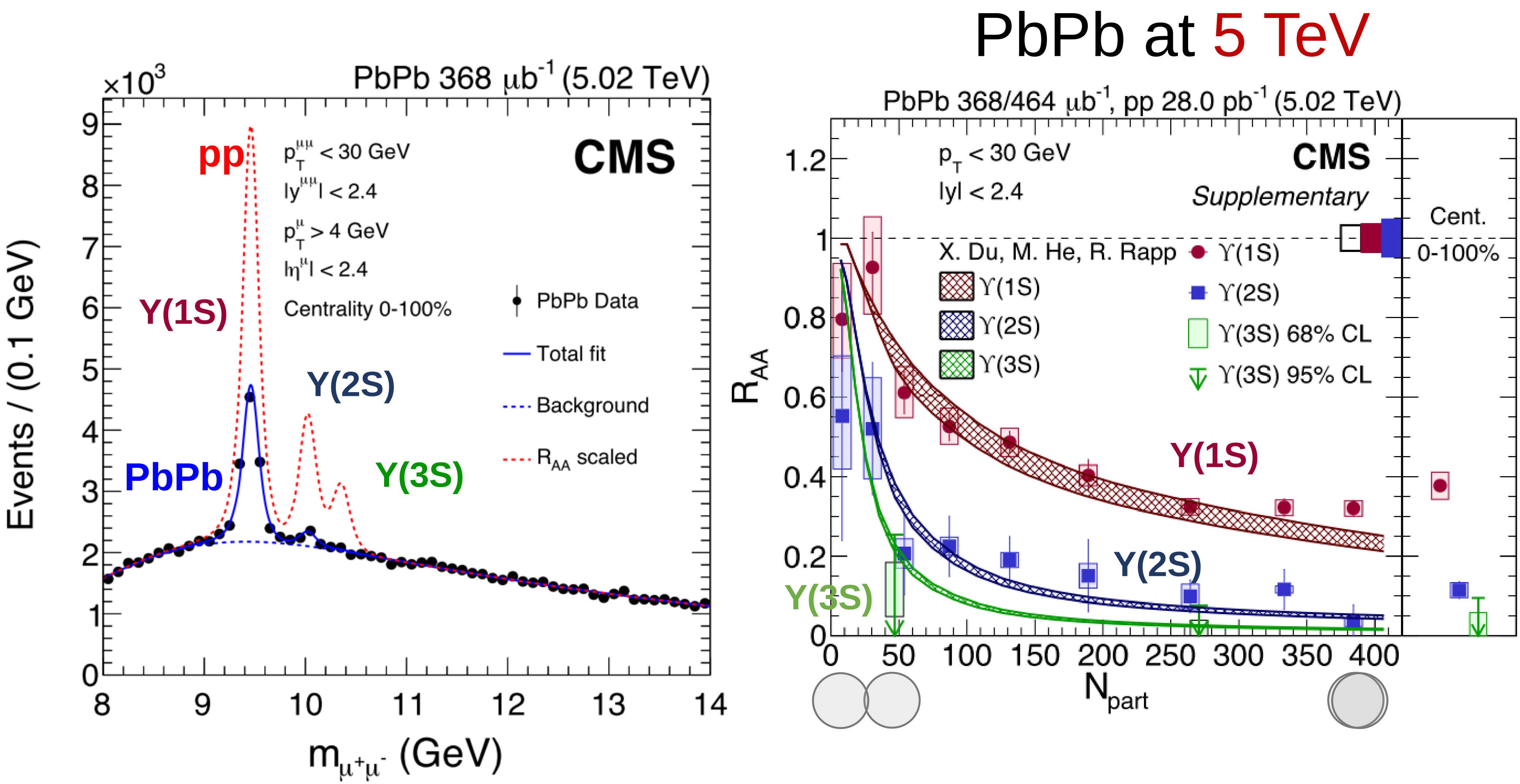
R_{pPb} pPb at 5 TeV



- **J/Ψ** and Ψ(2S) difference increases as we move to backward (lead-going) direction (higher dN_{ch}/dy)
- Can not be explained by nPDF or coherent energy loss model
- Final state effects from comoving (local) medium?

Inclusive Upsilon Sequential Suppression

PbPb at 5 TeV



- No sign of **Y(3S)** in the high statistics data
- Consistent with models **with Y(1S) melting** and (with or without) Y regeneration
- Extracted initial medium temperature **550 - 800 MeV** based on models

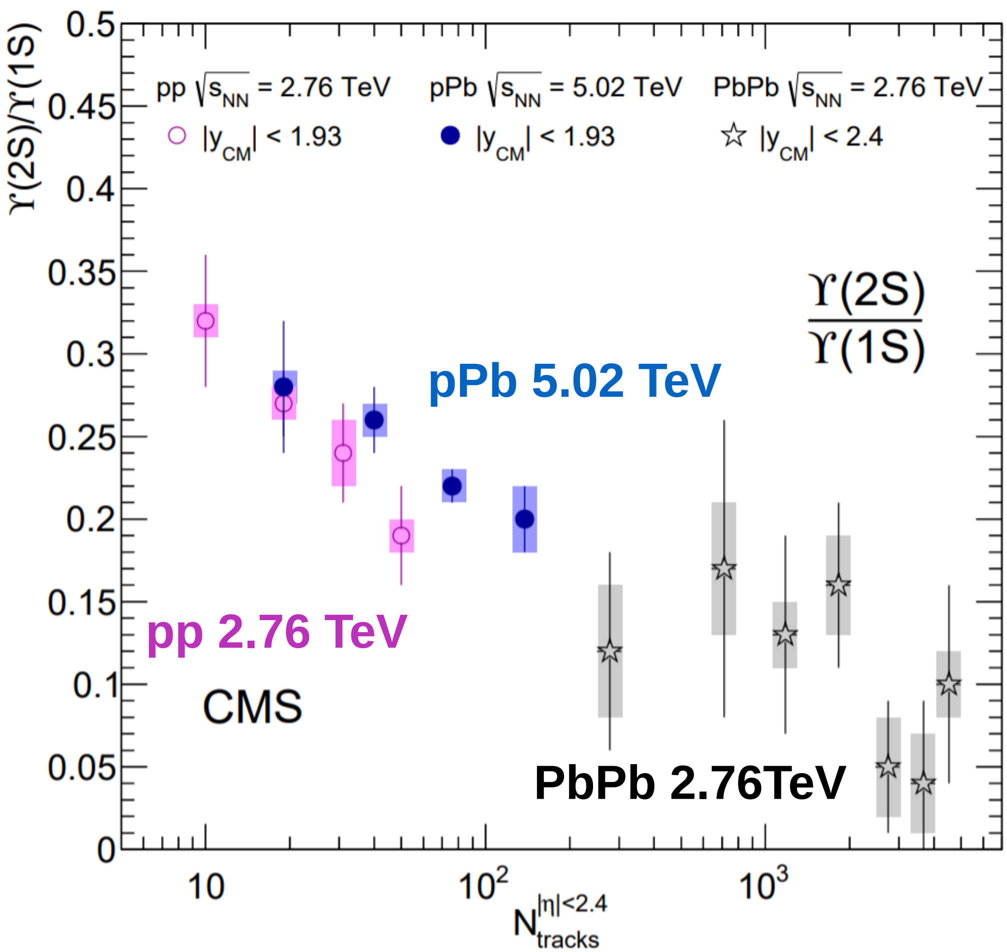
PLB 770 (2017) 357

Jaebeom Park

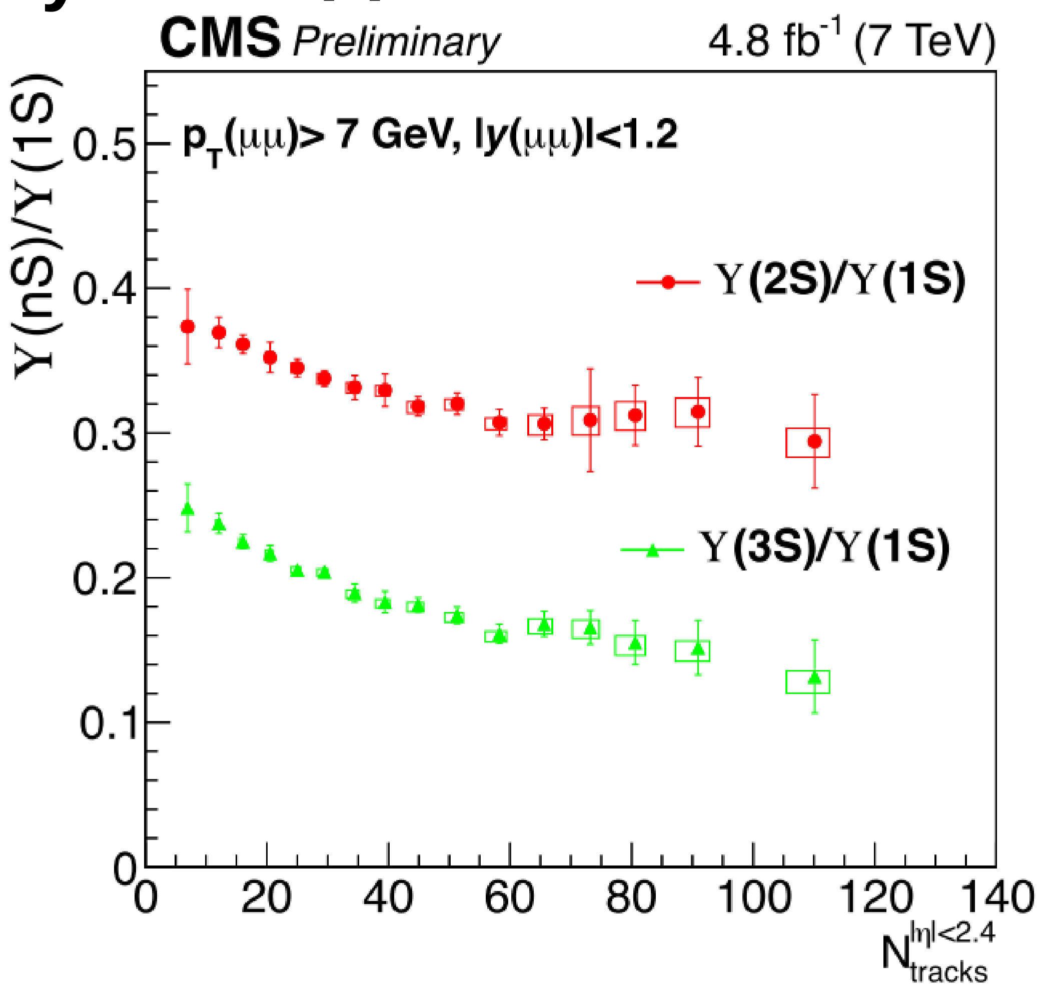
Geonhee Oh [Poster]

Upsilon Sequential Suppression vs. Multiplicity

Υ(2S)/Υ(1S) ratio vs. multiplicity



pp at 7 TeV



- Origin of the sequential suppression in high multiplicity pp events?

JHEP 04 (2014) 103

CMS-PAS-BPH-14-009

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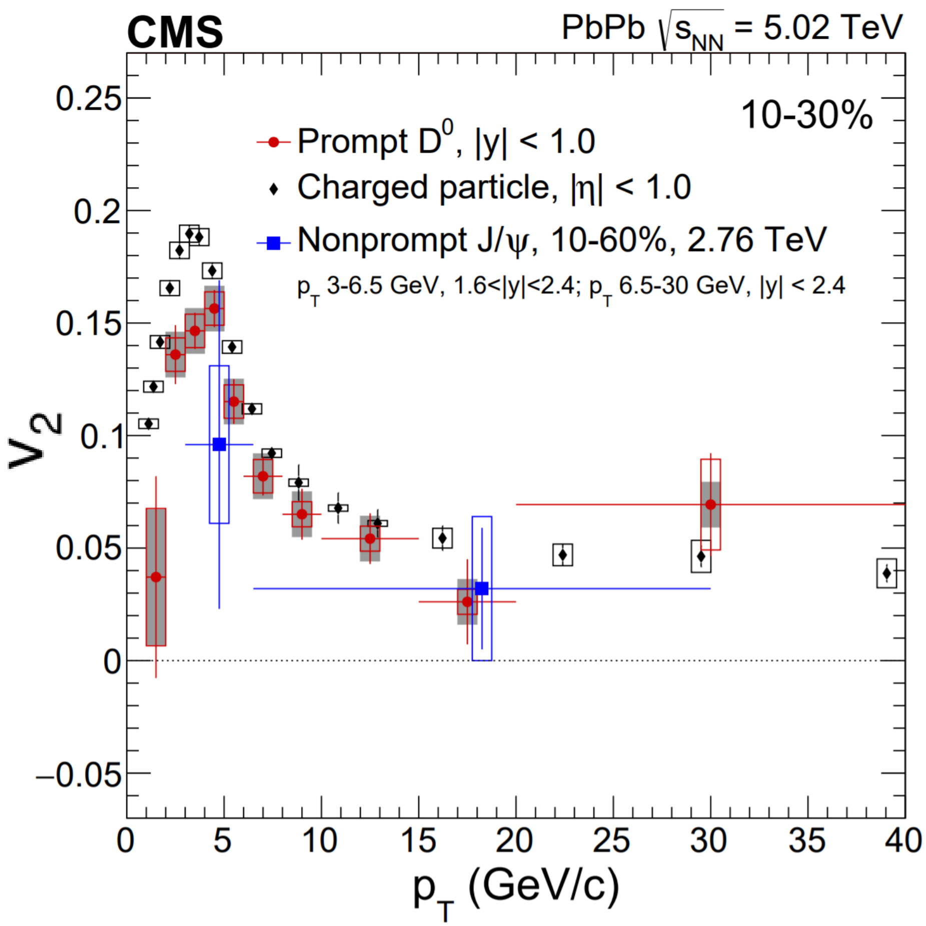
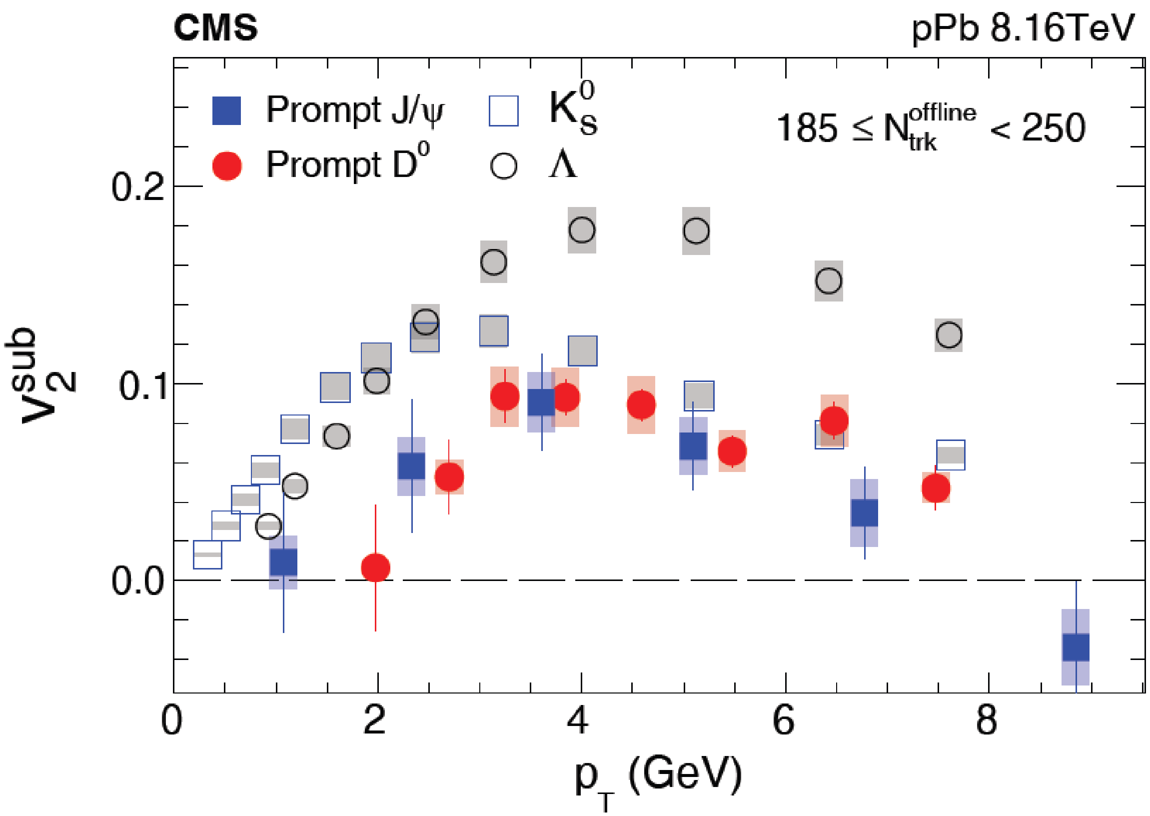
Significant J/ψ and D^0 v_2 in pPb





- Large v_2 signal from prompt J/ψ: charm flow in high multiplicity pPb?
- Origin of the large v_2 at high p_T (up to ~ 8 GeV):
  Indication of jet quenching in pPb?

D^0 pPb PRL 121 (2018) 082301

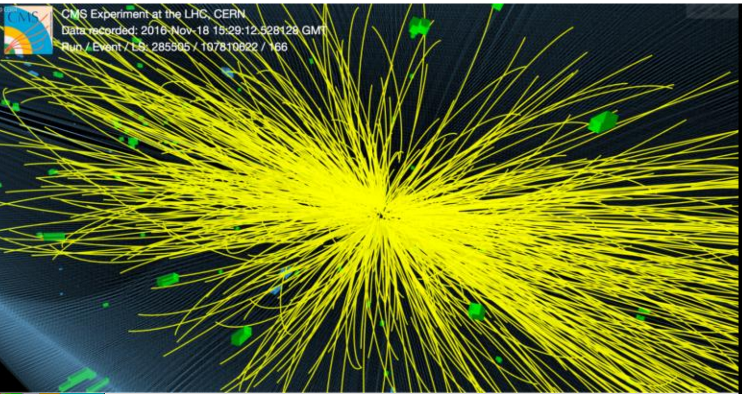
D^0 PbPb PRL 120 (2018) 202301

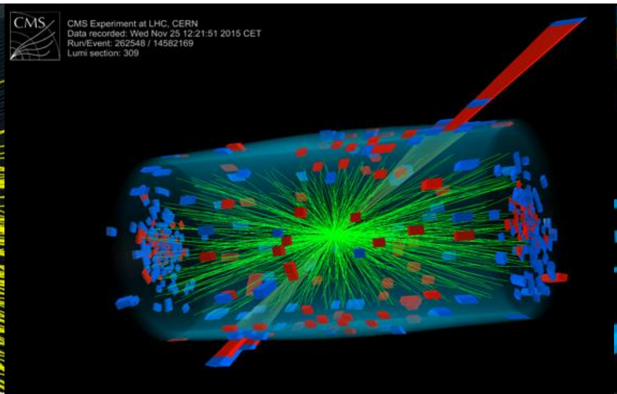
J/ψ pPb arXiv:1810.xxxx

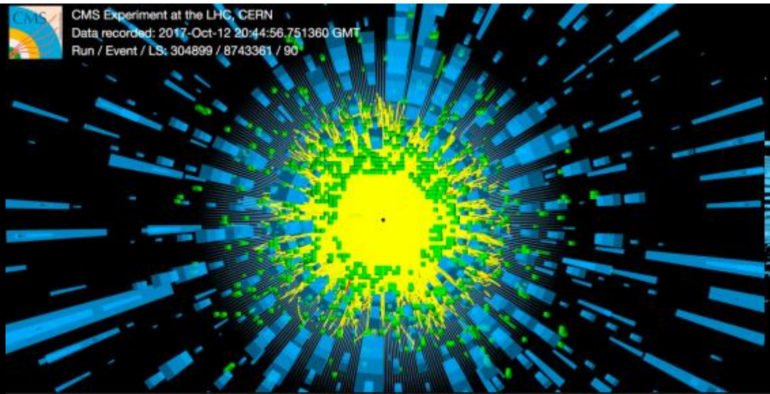
Cheng-Chieh Peng

Take Home Message from CMS

- Observation of **light-by-light scattering** and new limit of axion-like particle coupling strength
- Evidence of **gluon (anti-)shadowing and EMC effects** in Pb
- Observation of modified **quark-enriched jet** fragmentation and shape
- **Parton flavor** and **shower** dependence of parton energy loss
- New info on **beauty hadronization**
- **J/ψ much less isolated** than PYTHIA8
- **Remarkable similarity between pp, pPb and PbPb** on "**Sequential suppression**" of Quarkonia and **Large v_2** signal from **D^0** and **J/ψ**







Physics	CMS Hard Probes 2018 Presentations	Speaker
Initial State and nPDF	nPDF studies with electroweak bosons in pPb at 8.16 TeV with CMS	Hyunchul Kim (Chonnam University)
	Constraints on nuclear parton distribution functions with dijets and isolated photons in pp, pPb and PbPb collisions at 5.02 TeV with CMS	Yeonju Go (Korea University)
	Multiplicity and transverse energy measurements from pp, pPb, PbPb and XeXe collisions with CMS	Michael Murray (Kansas University) [Poster]
Heavy Flavor	Λ_c^+ production in pp and PbPb collisions at 5.02 TeV with CMS	Rui Xiao (Purdue University)
	Studies of beauty suppression via measurements of nonprompt D^0 mesons in PbPb collisions at 5.02 TeV	Hao Qiu (Purdue University)
	D-meson production in jets in pp and PbPb collisions with CMS	Michael Peters (MIT)
	B_s and B^+ meson nuclear modification factors in PbPb collisions at 5.02 TeV with CMS	Guilaume Falmagne (LLR)
	Measurement of strange and non strange charm production in PbPb at 5.02 TeV with CMS	Cheng-Chieh Peng (Purdue University)
Quarkonia	Understanding sequential quarkonium suppression with Υ measurements in pp, pPb and PbPb collisions at 5.02 TeV	Jaebeom Park (Korea University)
	Detailed studies of prompt J/ψ and ψ(2S) production in pp, pPb and PbPb collisions at 5.02 TeV	Batoul Diab (LLR)
	Measurements of Bottomonium production in pp, pPb and PbPb collisions at 5.02 TeV	Geonhee Oh (Chonam University) [Poster]
Jet	Charged particle nuclear modification factors in pPb, PbPb and XeXe collisions with CMS	Austin Alan Baty (MIT)
	Probing properties of the QCD medium using jet substructure techniques in pp and PbPb collisions at 5.02 TeV with CMS	Dhanush Anil Hangal (UIC)
	Measurements of inclusive, boson-tagged, and heavy quark flavor jet energy loss in PbPb collisions at 5.02 TeV with CMS	Xiao Wang (UIC)
	Photon-tagged jet fragmentation functions and jet shapes in pp and PbPb collisions with CMS	Kaya Tatar (MIT)
UPC	Evidence for light-by-light scattering and limits on axion-like-particles from ultraperipheral PbPb collisions at 5 TeV	Jeremi Niedziela (CERN)
	Measurement of exclusive Υ production in pPb collisions with CMS	Kousik Naskar (BARC)

CMS Results Web Pages

- Summary Page of CMS Heavy Ion Results
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN
- Full list of CMS Heavy Ion Journal Publication and Data Tables:
  http://cms-results.web.cern.ch/cms-results/public-results/publications/HIN/index.html
- Full list of CMS Heavy Ion Preliminary Results:
  http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIN/index.html
- Future Performance Projection in HL-LHC Era:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN#Future_Physics_Projections
- Hard Probes 2018 Compilation Plots:
  https://twiki.cern.ch/twiki/bin/view/CMS/HardProbes2018