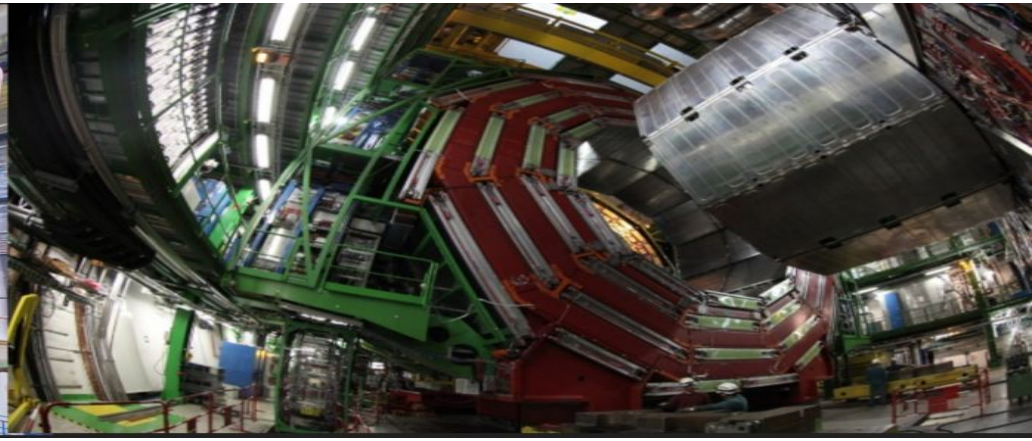
U.S. DEPARTMENT OF ENERGY
Office of Science

KU THE UNIVERSITY OF KANSAS

ATLAS EXPERIMENT

CMS



ATLAS & CMS turned 30

Results on QGP by ATLAS and CMS

Georgios K Krintiras (on behalf of the ATLAS and CMS collaborations)

The University of Kansas

20th International Conference on Hadron Spectroscopy and Structure

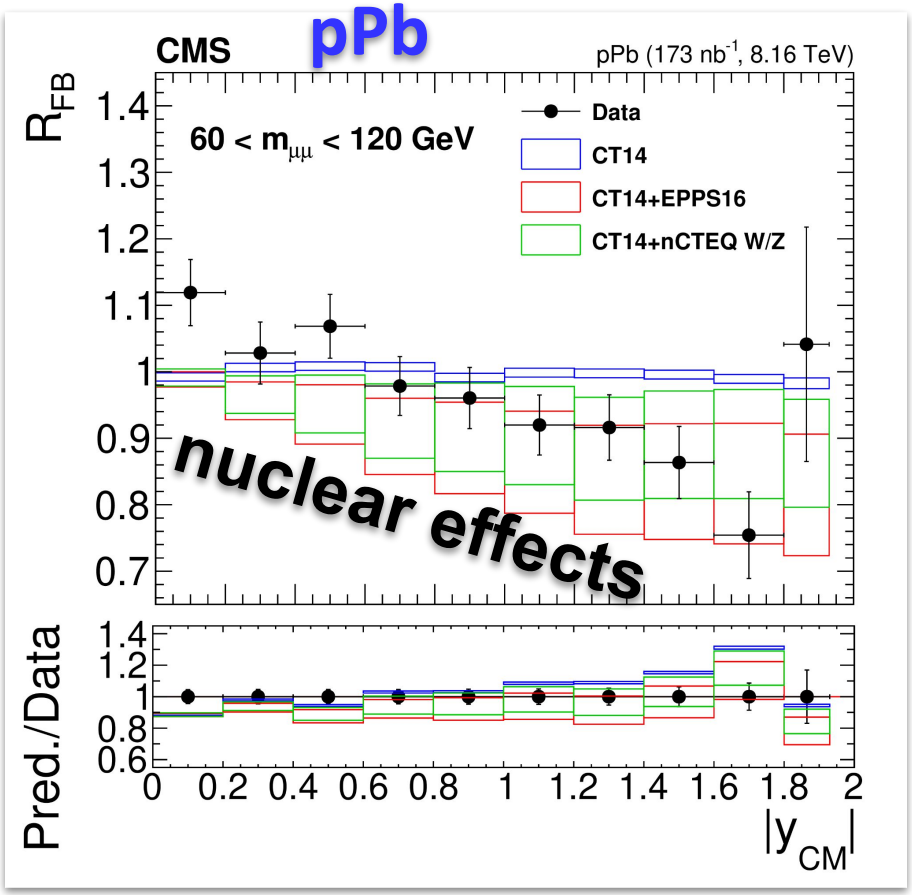
Outline–the probes

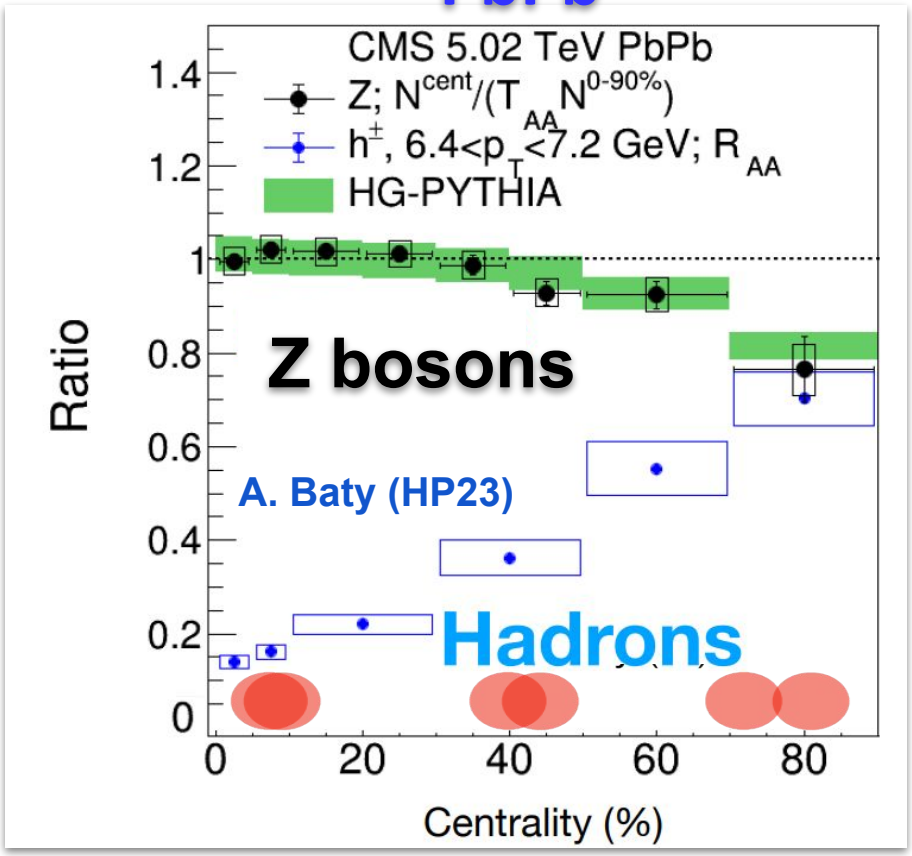
- Early dynamics and nPDFs
  - E/W bosons
  - J/ψ, flow in very small systems
- Heavy quarks and quarkonia
  - Υ(ns), B_s^0,B_c^+
  - J/ψ, Λ_c^+
- Medium modifications
  - R_{AA} & extensions
  - en. loss in small systems
- Rare/BSM probes
  - X(3872), tops, τ leptons
- Run 3 prospects

Early time dynamics and nPDFs

Z/γ* production in pPb and PbPb

JHEP **05** (2021) 182
PRL **128** (2022) 122301

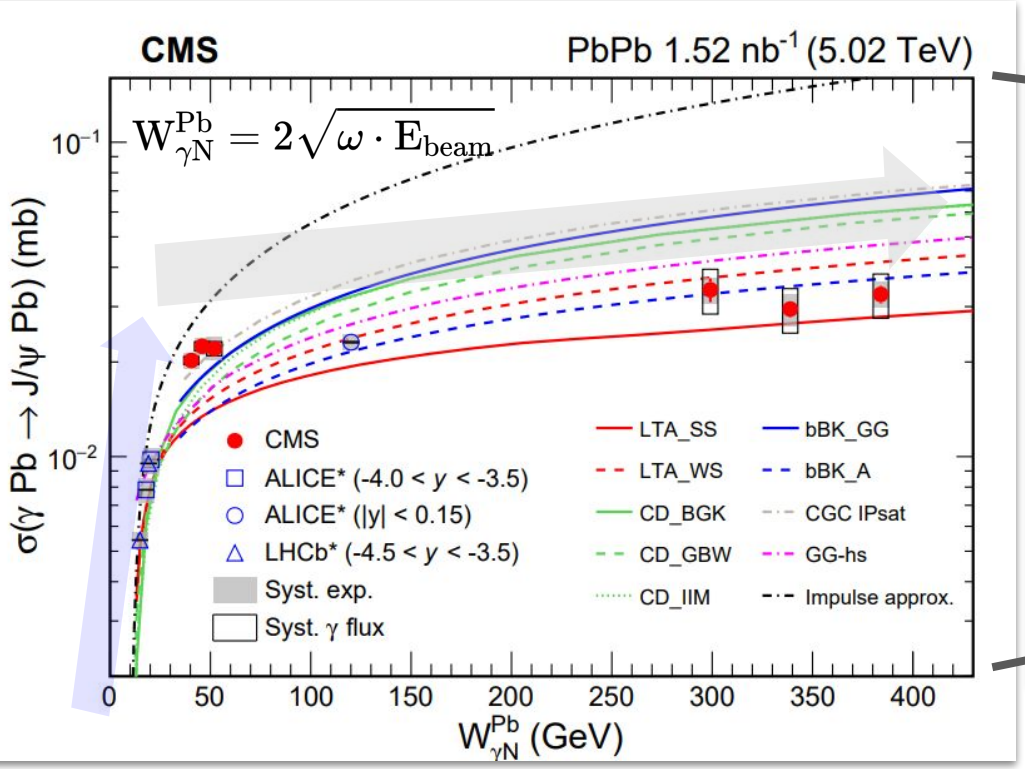


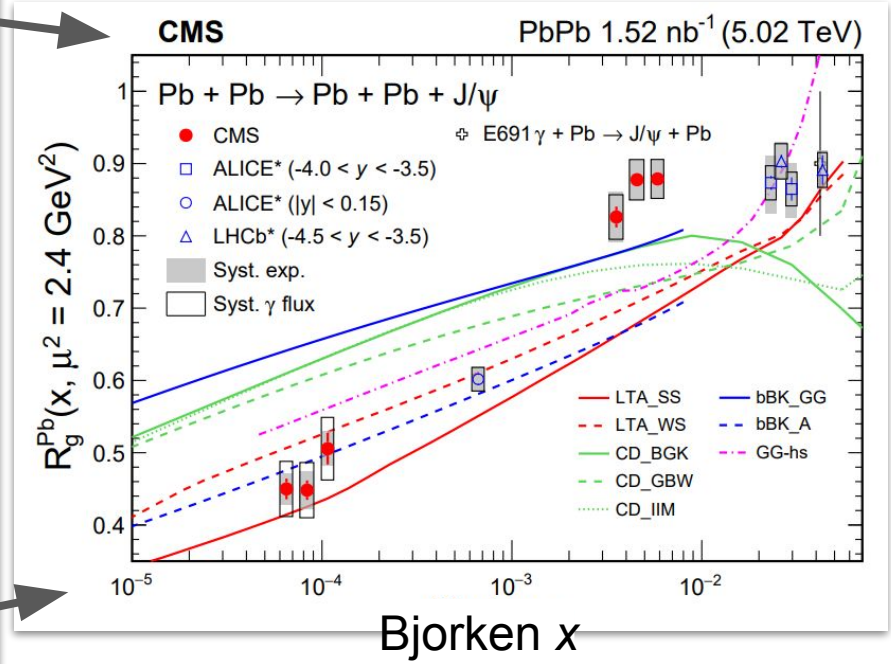


- Forward-backward σ ratio $R_{FB} \equiv 1$ in the absence of nuclear effects
- W bosons, dijets, top quarks sensitive to gluon modifications at different *x*
- EW bosons in PbPb mostly unmodified as compared to hadrons (R_{AA}!=1)

Coherent J/ψ production in UPC PbPb

arXiv:2303.16984
(submitted to PRL)





- **Using ZDCs, higher energy photons are extracted w/o increasing √s**
  - experimental uncertainty **correlated** across or $W_{\gamma N}^{Pb}$
    - flattening of coherent σ(J/ψ) vs. $W_{\gamma N}^{Pb}$ not predicted by models
- **An unprecedentedly low-*x* gluon regime is probed (10^{-4}–10^{-5})**
  - LHC data seem to consistently point to a common *x* evolution

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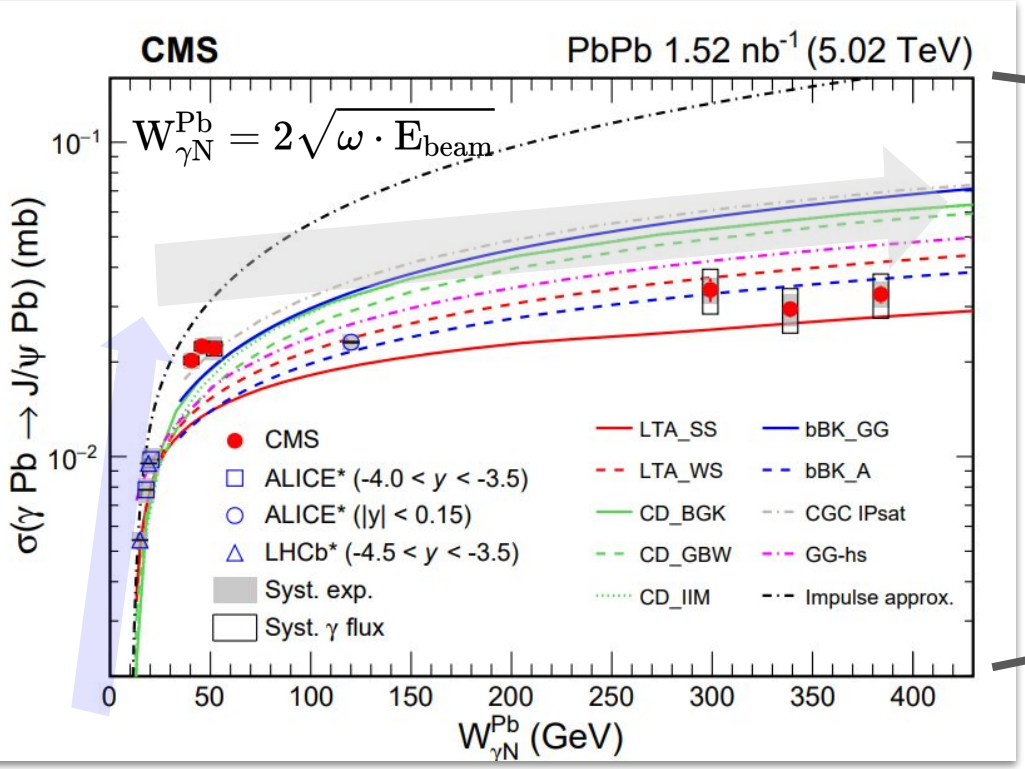

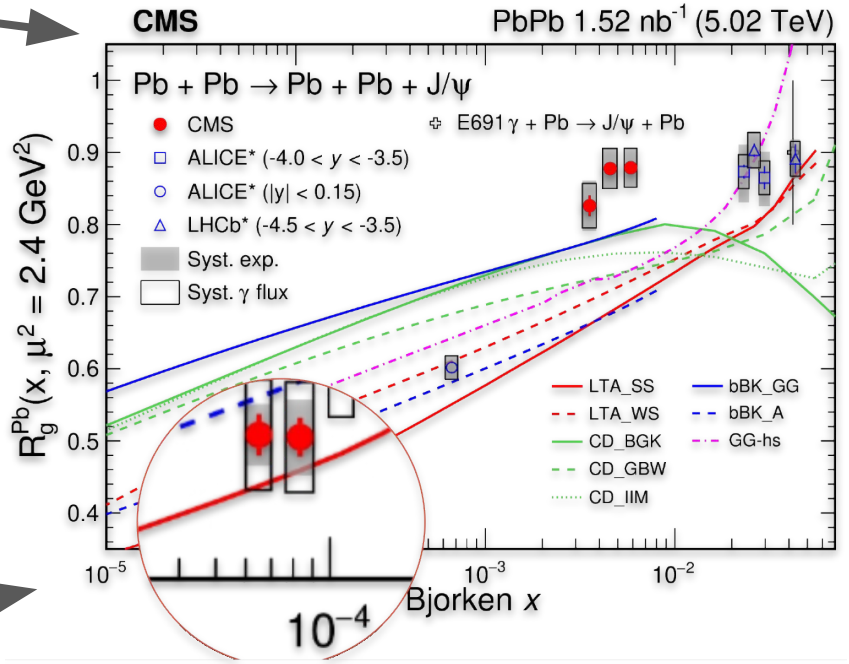

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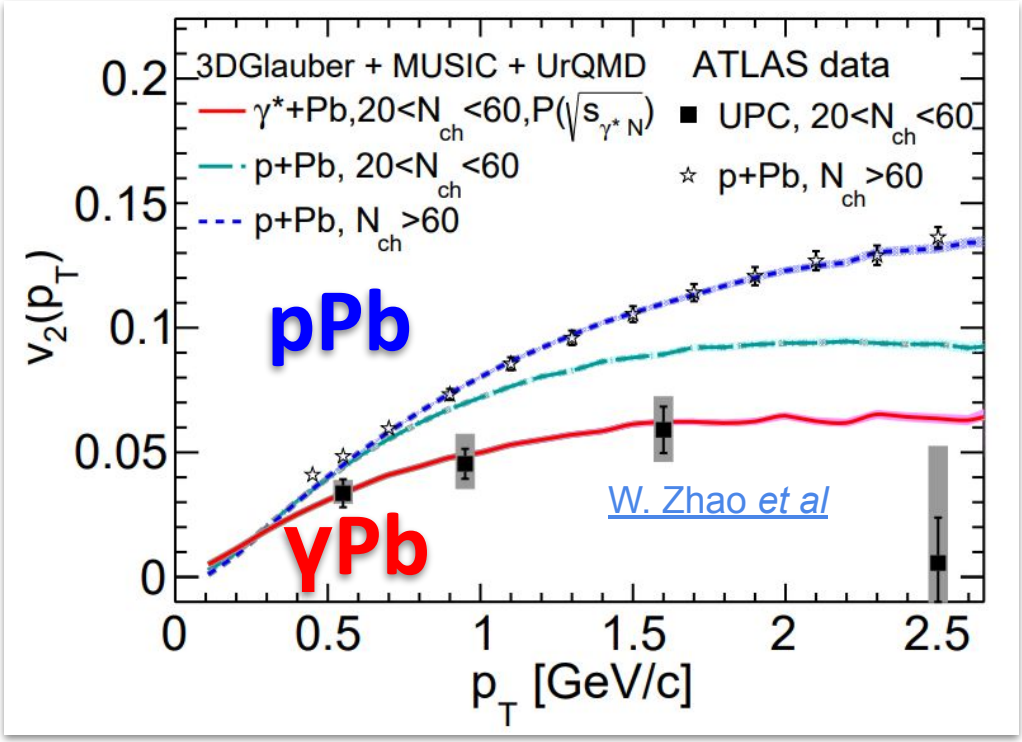
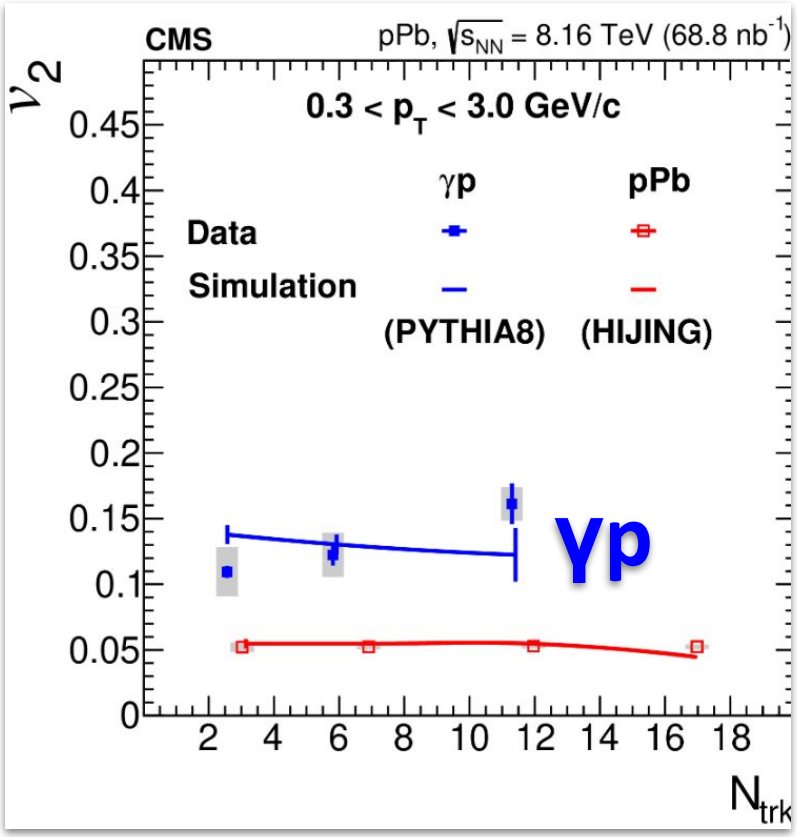
Angular correlations in γPb and γp

Phys. Rev. C **104** (2021) 014903
arXiv:2204.13486
(accepted by PLB)



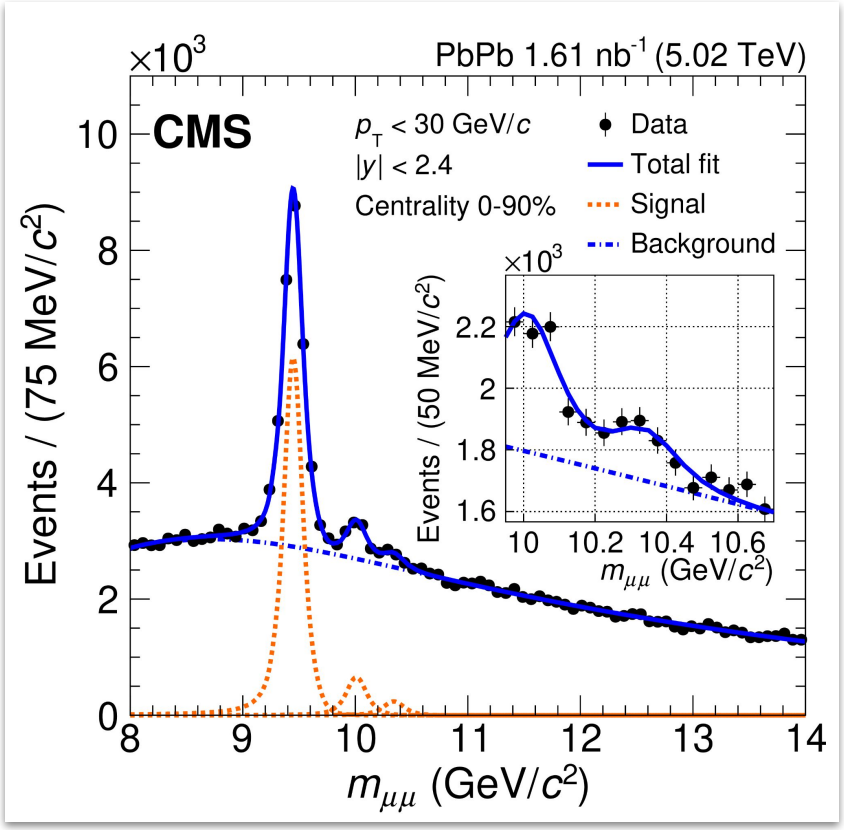


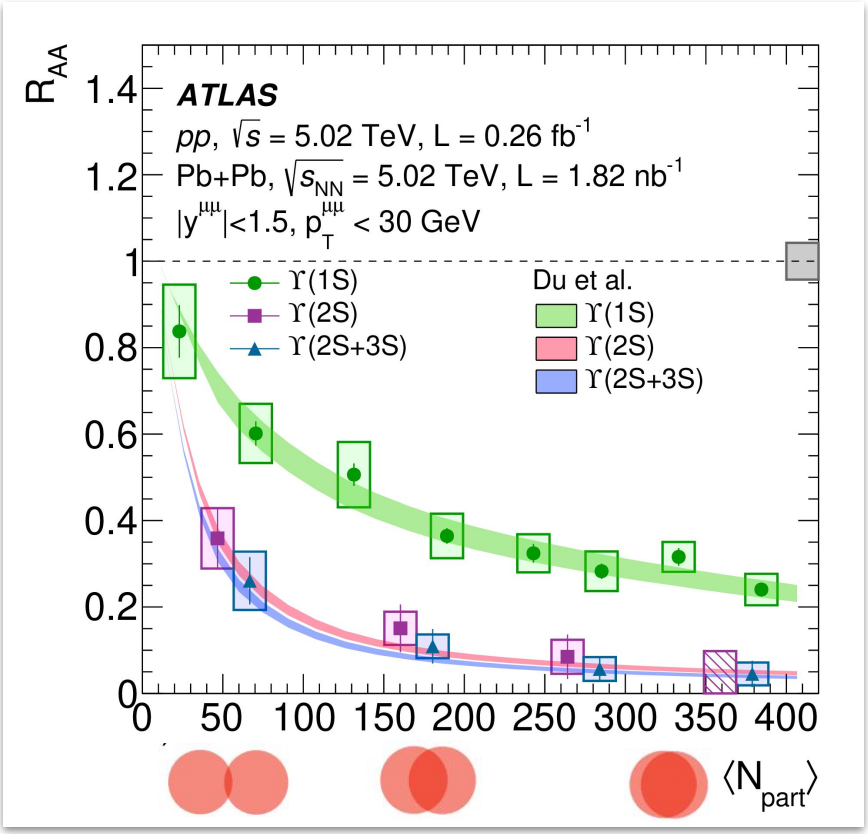
- **Bridging large with exceedingly small systems (UPC PbPb)**
  - hierarchy of flow in **pPb** vs γPb reproduced by (3+1)D dynamical simulations
- **Challenging to go even smaller: tiny flow signal competes with nonflow**
  - PYTHIA8 describes v_2 **in γp** ⟶ jet-like correlations still dominate

Heavy quarks and quarkonia

Y(ns) suppression in PbPb

arXiv:2303.17026 (submitted to PRL)
PRC **107** (2023) 054912

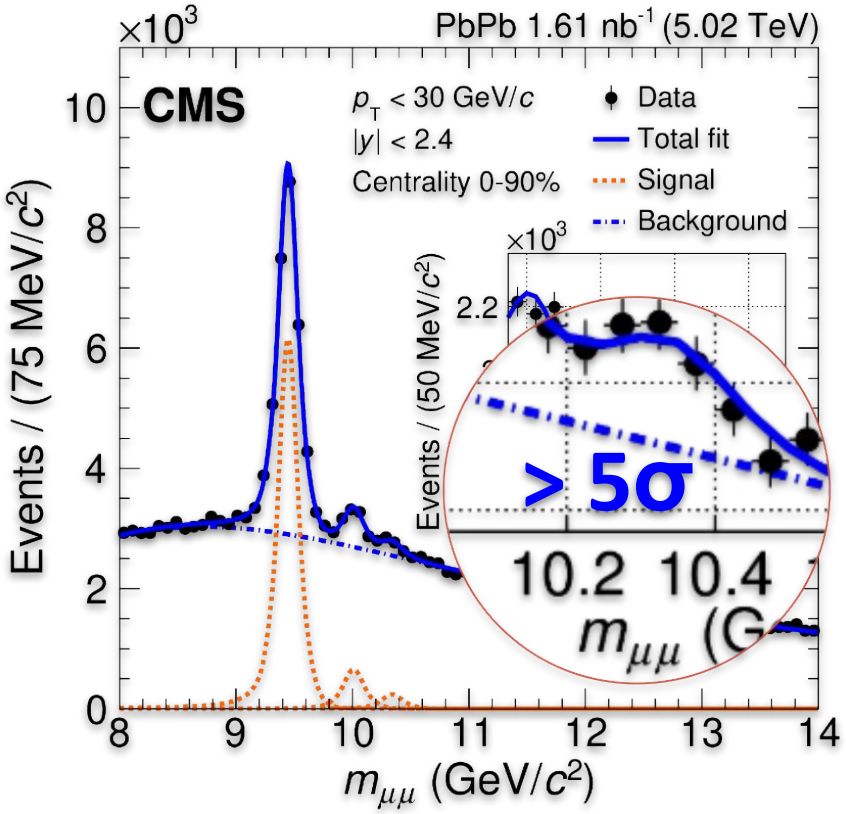


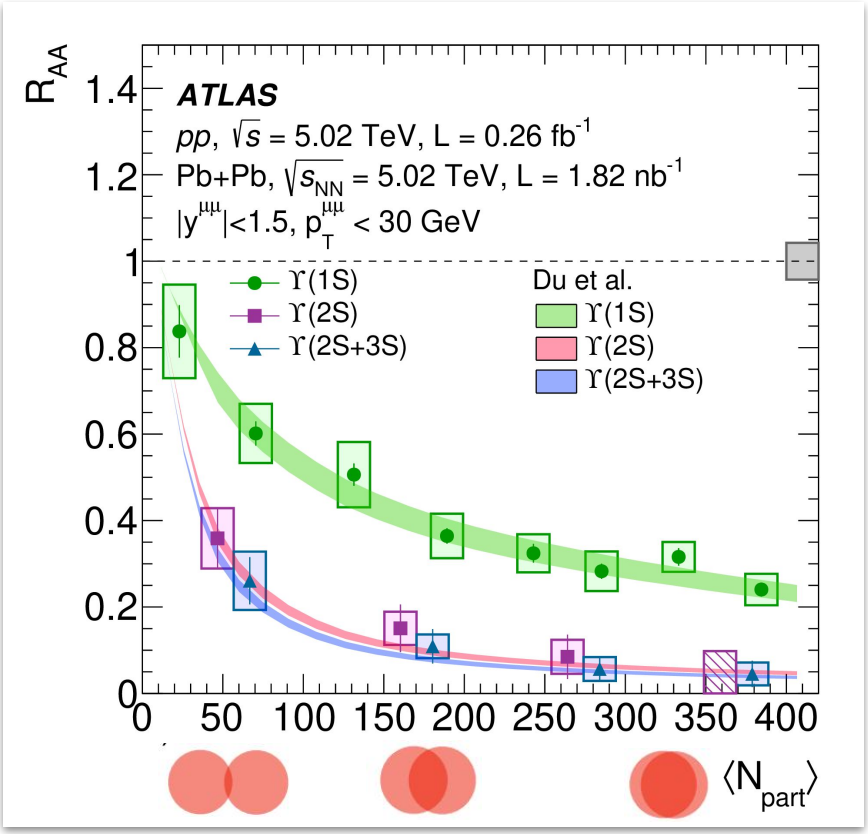


- **Observation of Y(3S) now in PbPb too(!)**
  - indication of ordered (sequential) suppression up to Y(3S)
  - input to a series of models to reproduce Y(3S) R_{AA}>0
- **Excited states can set strong constraints on models**
  - in the study of initial (pPb) & final-state effects

Υ(ns) suppression in PbPb

arXiv:2303.17026 (submitted to PRL)
PRC **107** (2023) 054912





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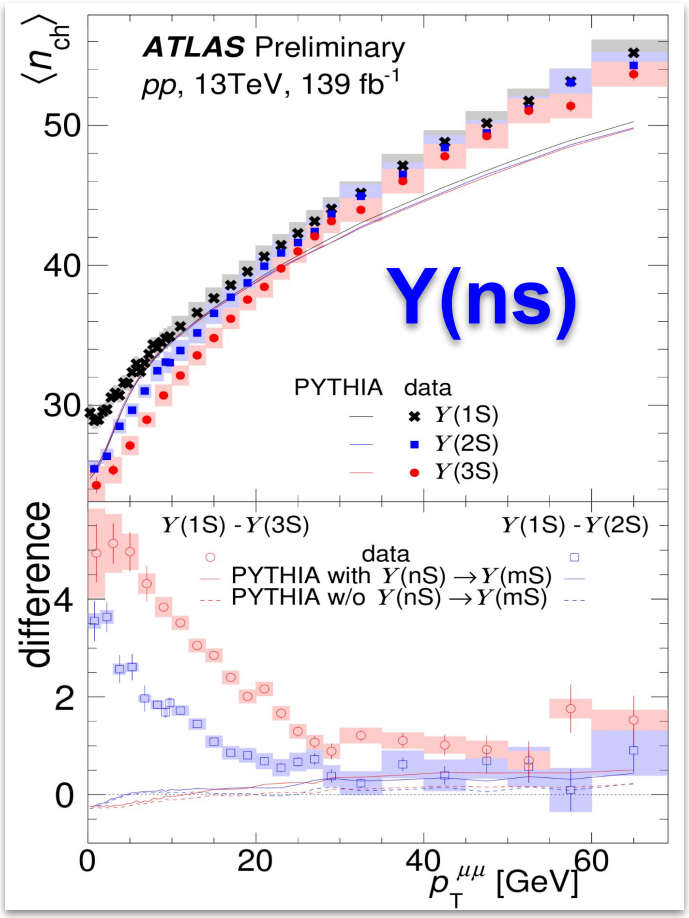
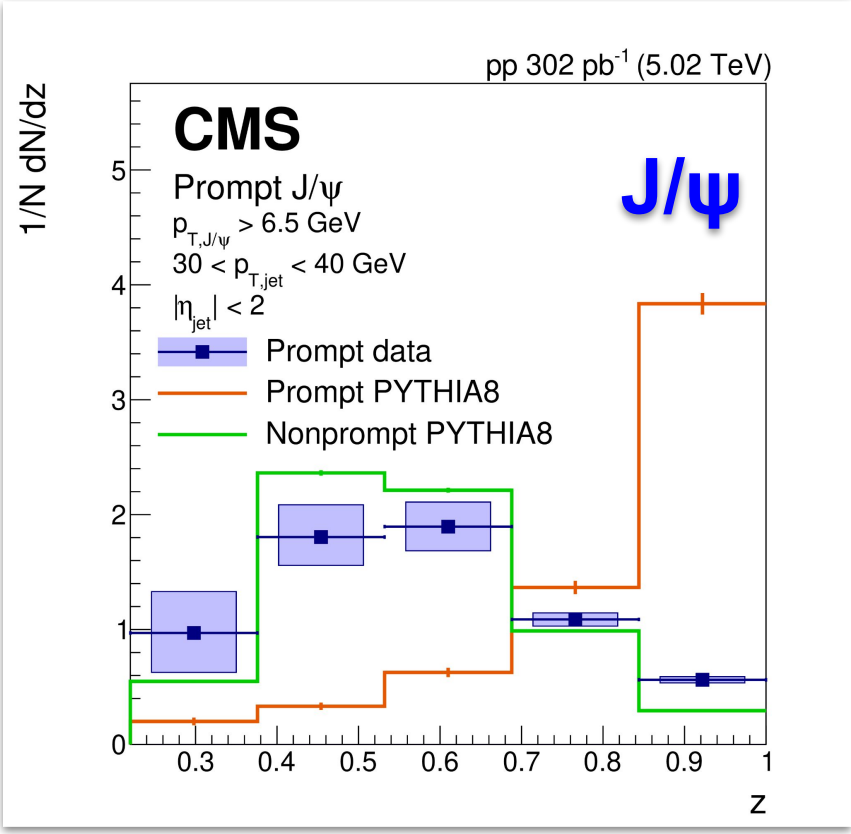
Y(ns) and J/ψ production in pp

ATLAS-CONF-2022-023
PLB **825** (2021) 136842

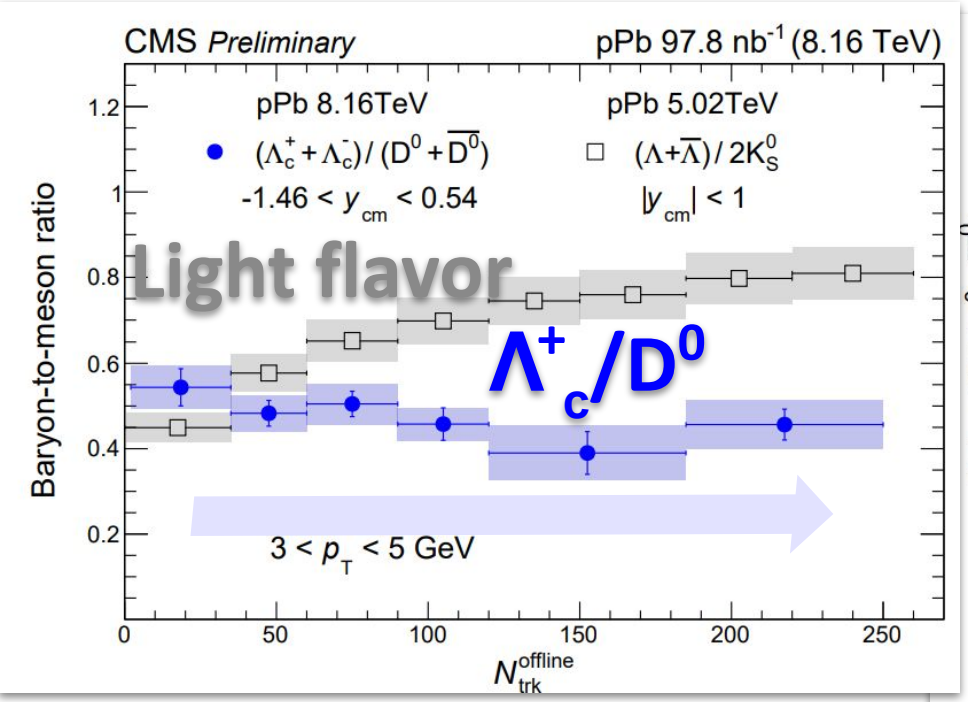


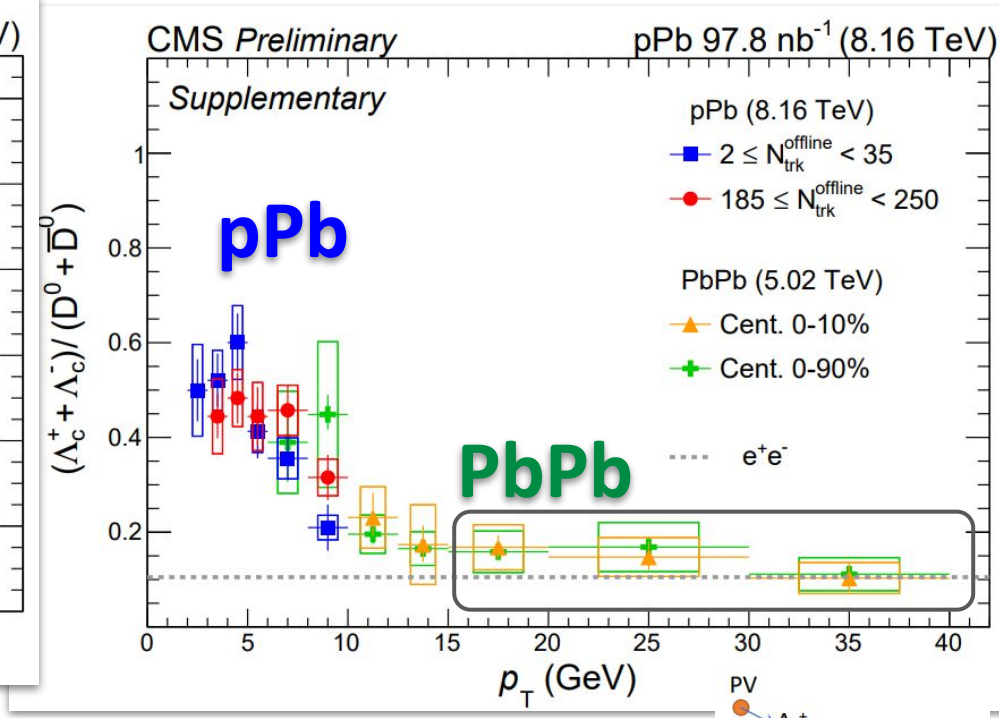


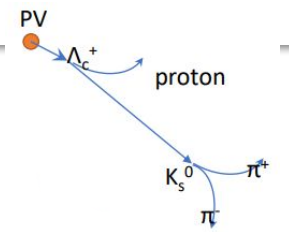
- **At lower Y p_T: the associated $\langle n_{ch} \rangle$ in Y(2S) and Y(3S) events < Y(1S)**
  - correlation between UE and hard processes
- **Prompt J/ψ have more surrounding jet activity than predicted**
  - late production in the parton shower is underestimated

Charm quark hadronization in pPb and PbPb

CMS-PAS-HIN-21-016
CMS-PAS-HIN-21-004



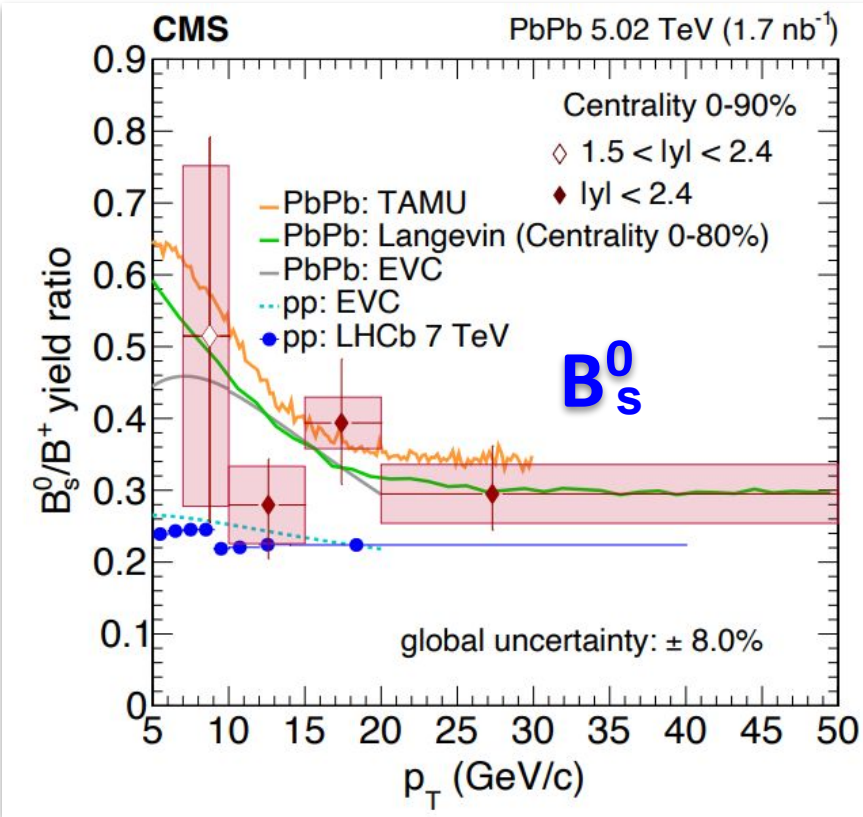


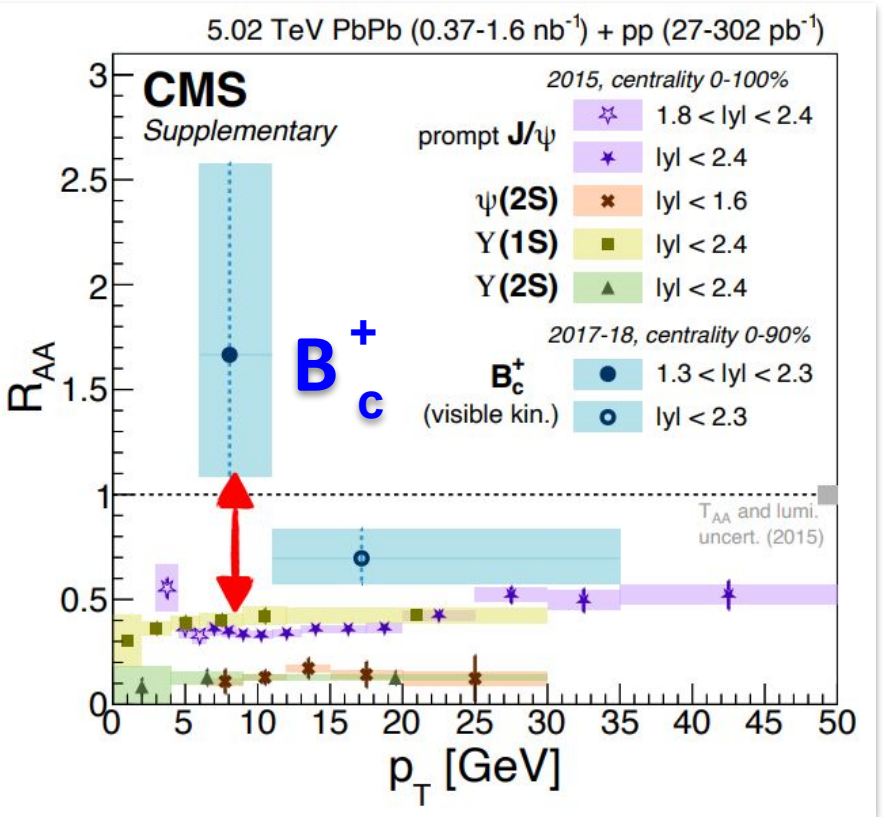


- **First measurement of Λ_c^+/D^0 vs N_{trk}**
  - different trend compared to **strange sector**, i.e., small dependence
- **Extending the system (pPb 8 TeV), p_T (<40 GeV), and centrality (0–90%)**
  - Λ_c^+/D^0 in pPb and MB PbPb consistent at intermediate p_T
  - at high p_T MB and central PbPb approach the ratio from e^+e^- → no coalescence

Beauty hadronization in PbPb

PLB **829** (2022) 137062
PRL **128** (2022) 252301

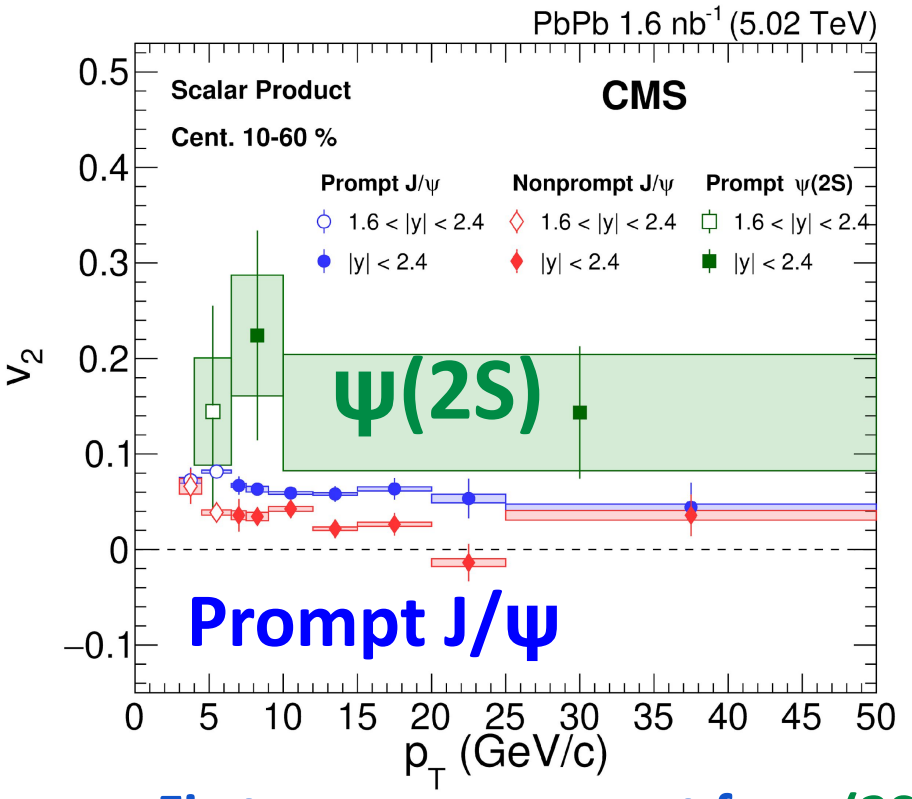


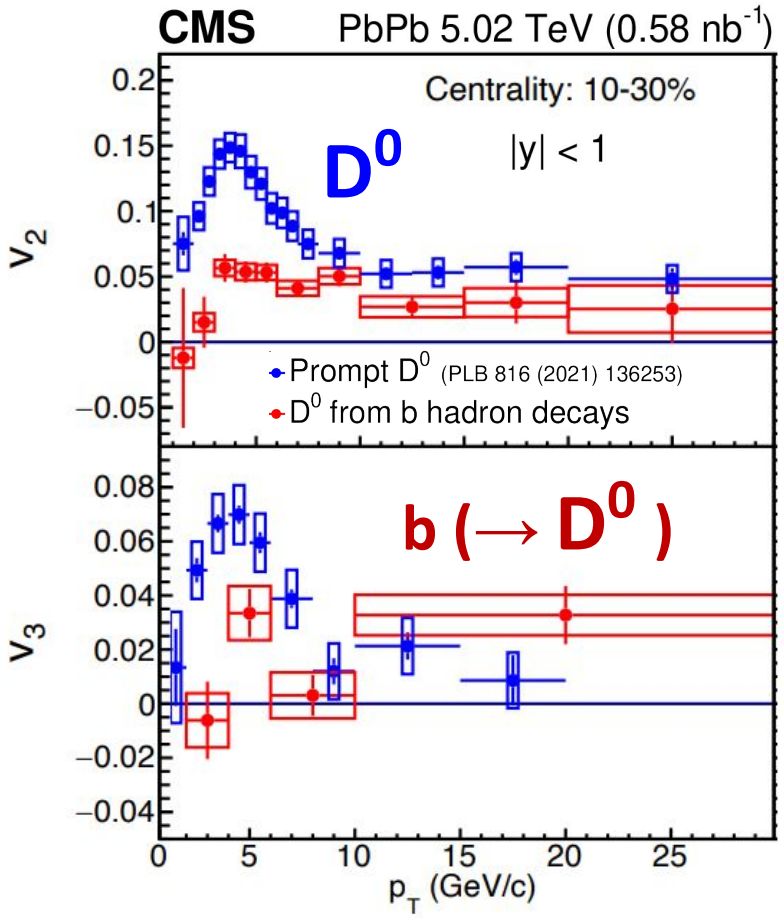


- **Observation** of B_s^0
  - indication of enhanced B_s^0/B^+ in PbPb to **pp** at low p_T
  - similar to models with recombination or coalescence
- **Observation** of B_c^+
  - flavor-dependent R_{AA} : at low/medium p_T: recombination of c and b

Heavy flavor flow in PbPb

arXiv:2305.16928 (submitted to JHEP)
arXiv:2212.01636 (submitted to PLB)

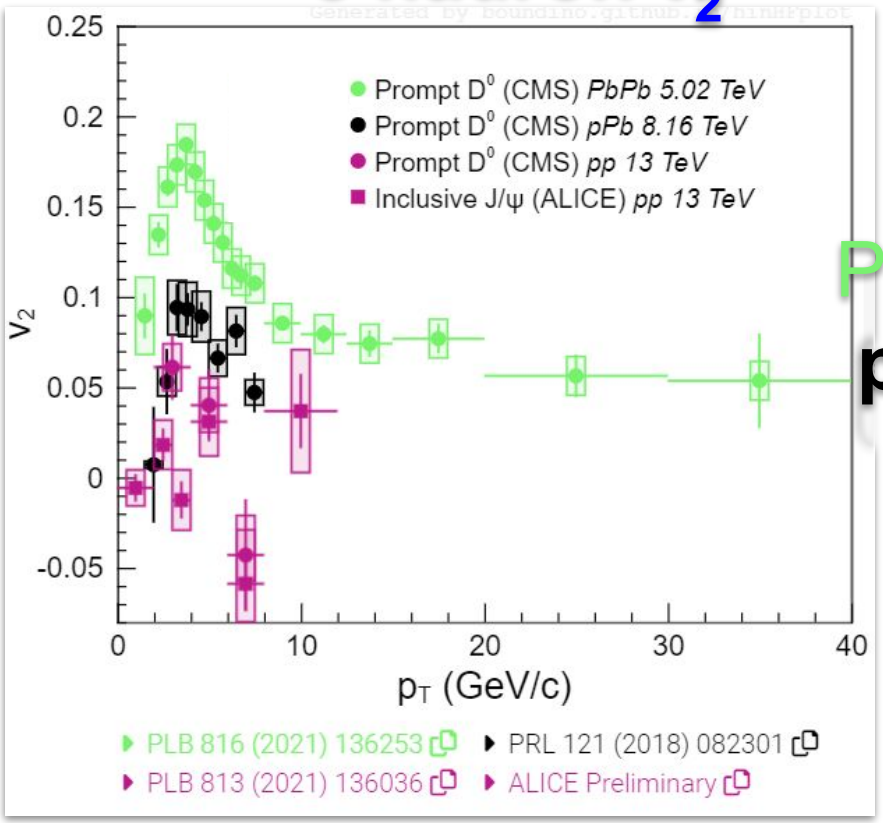




- **First $v_{2,3}$ measurement for ψ(2S)**
  - indication of ψ(2S) v_2 > **prompt J/ψ** v_2 → ψ(2S) from recombination at later stage?
- **First v_2 for b (→ D^0); b quark and D^0 meson p_T well correlated**
  - **charm** > b (→ **D^0**) v_2, whereas Υ(1S), Υ(2S) v_2≈0
  - evidence for b (→ **D^0**) v_3 >0 at intermediate p_T

Heavy flavor flow in all systems

c hadron v_2



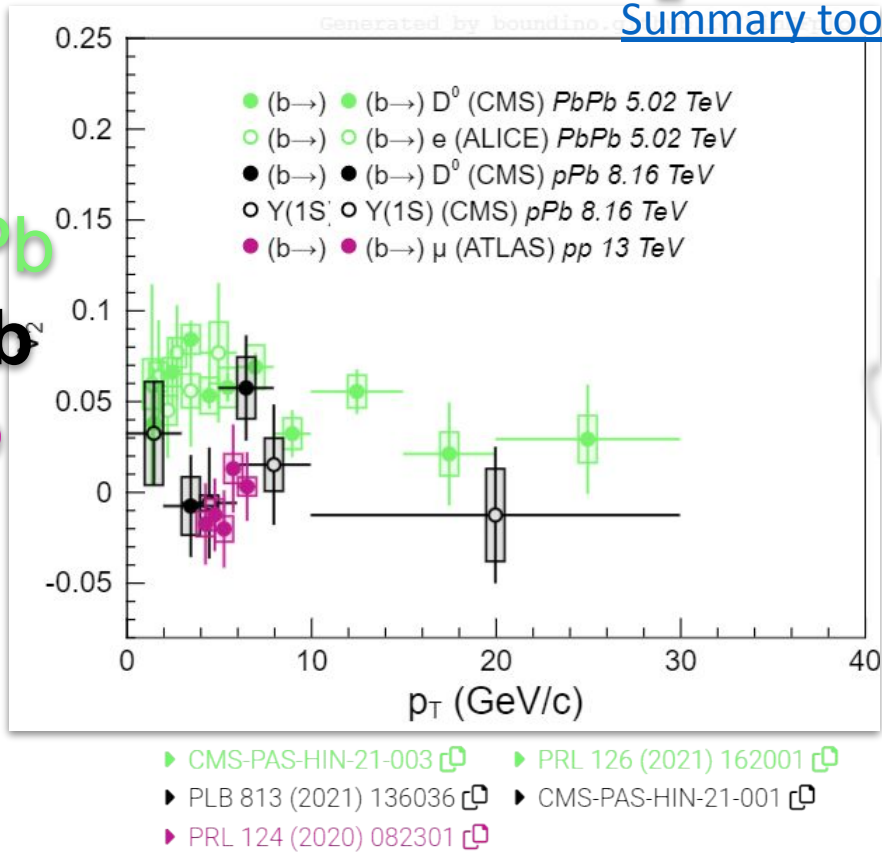
PbPb

pPb

pp

b hadron v_2

Summary too



- **There is charm anisotropy... everywhere**
  - apparent ordering: v_2(PbPb) > v_2(pPb) > v_2(pp)
- **For open bottom hadrons: v_2(PbPb) > 0 but v_2(pPb) ~ v_2(pp) ~ 0**
  - open question whether open/closed b hadrons flow in pPb or not

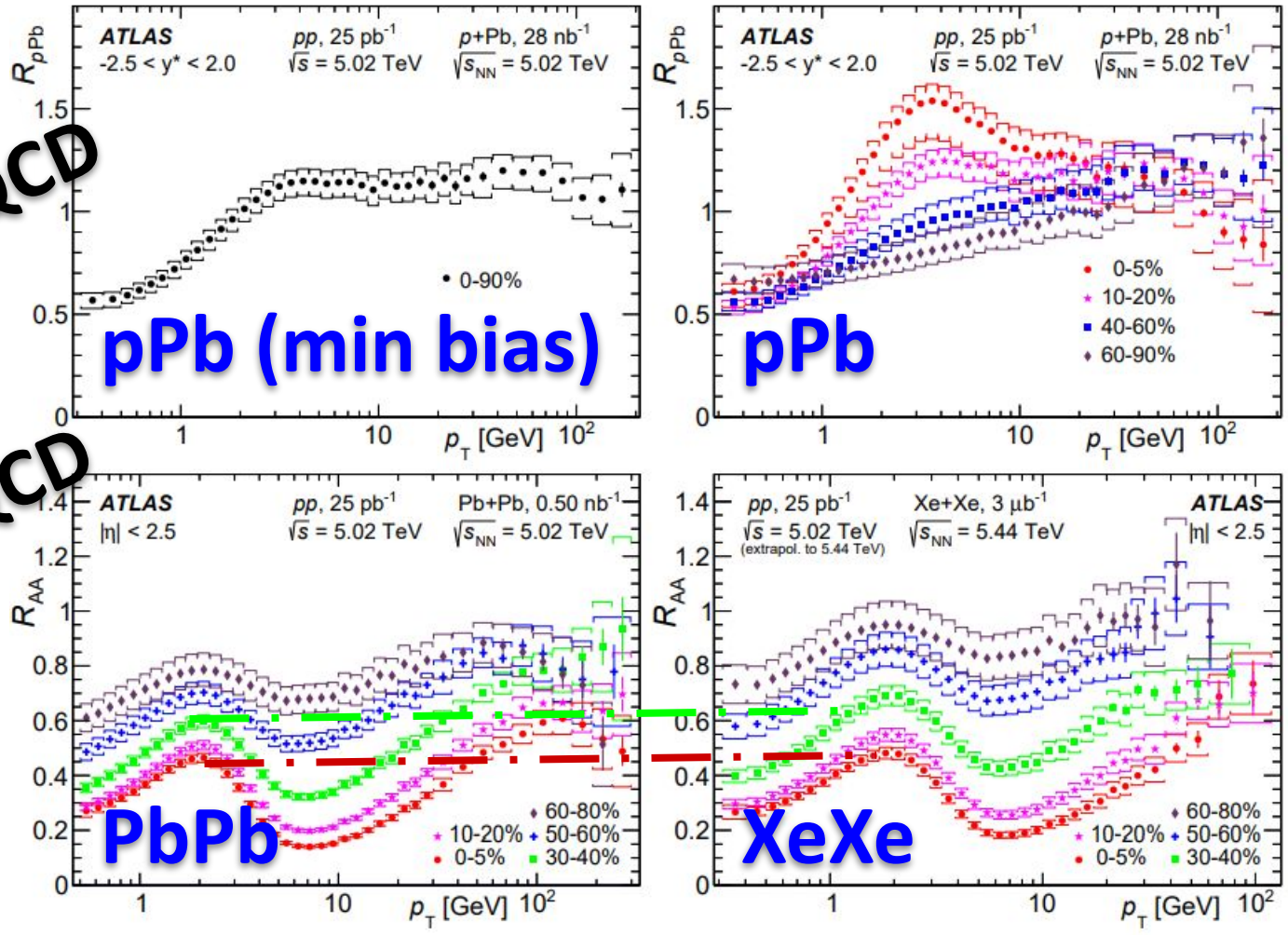
Medium modifications

Charged hadrons in all systems

arXiv:2211.15257
(submitted to JHEP)

"Cold" QCD

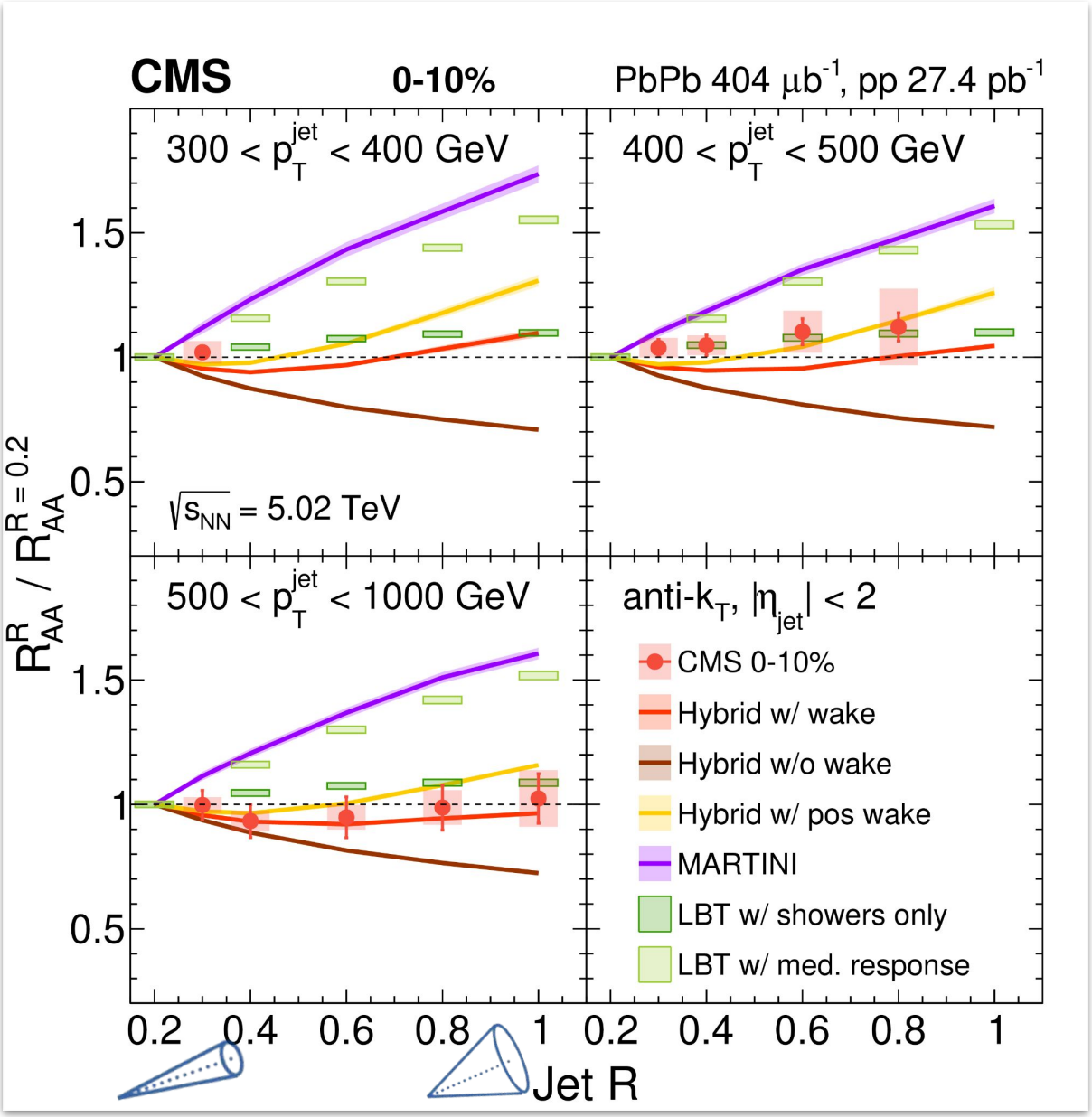
"Hot" QCD



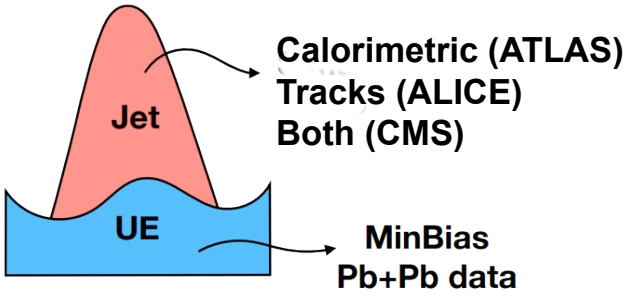
- **Extensive study on charged hadron production in pPb, PbPb & XeXe**
  - R_{pPb}: peak (pT <≈ 3 GeV) and plateau (pT>≈ 10 GeV) regions, centrality dependent
  - R_{AA}< 1 with local max (min) at p_T≈3 (7) GeV; significant centrality dependency

Jet quenching depends on jet radius?

JHEP **05** (2021) 284

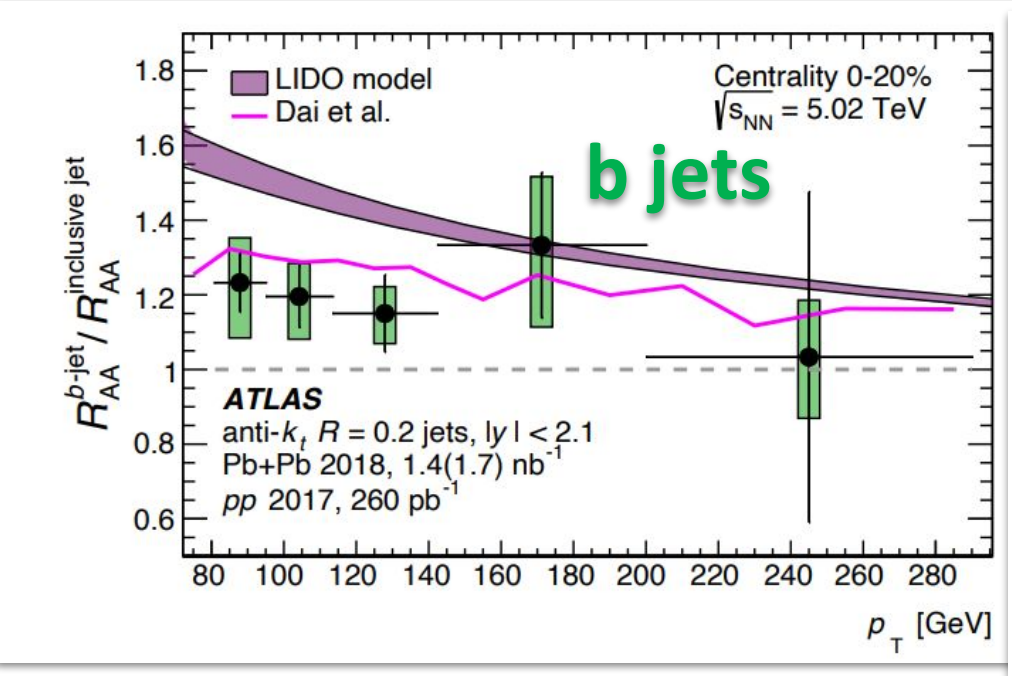


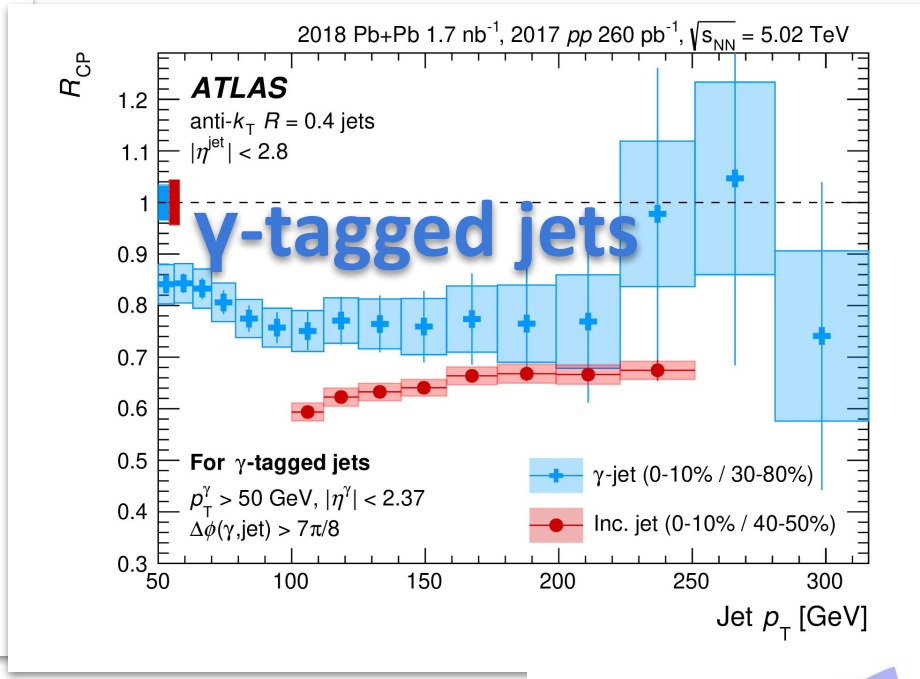
- Larger jet R ⟶ wider area to recover lost energy
  - but **R-independent** suppression seen
- Cross experiment effort
  - Different jet collections and UE treatment

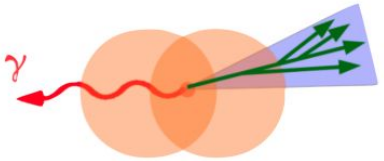


Mass and color-charge dependence

arXiv:2204.13530 (submitted to EPJC)
arXiv:2303.10090 (submitted to PLB)



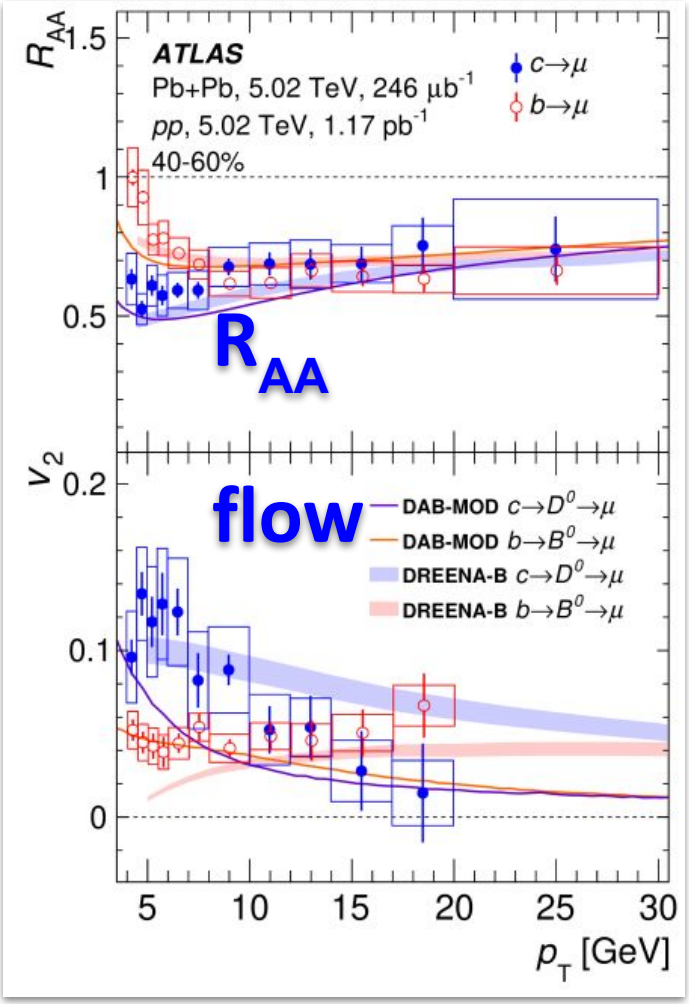


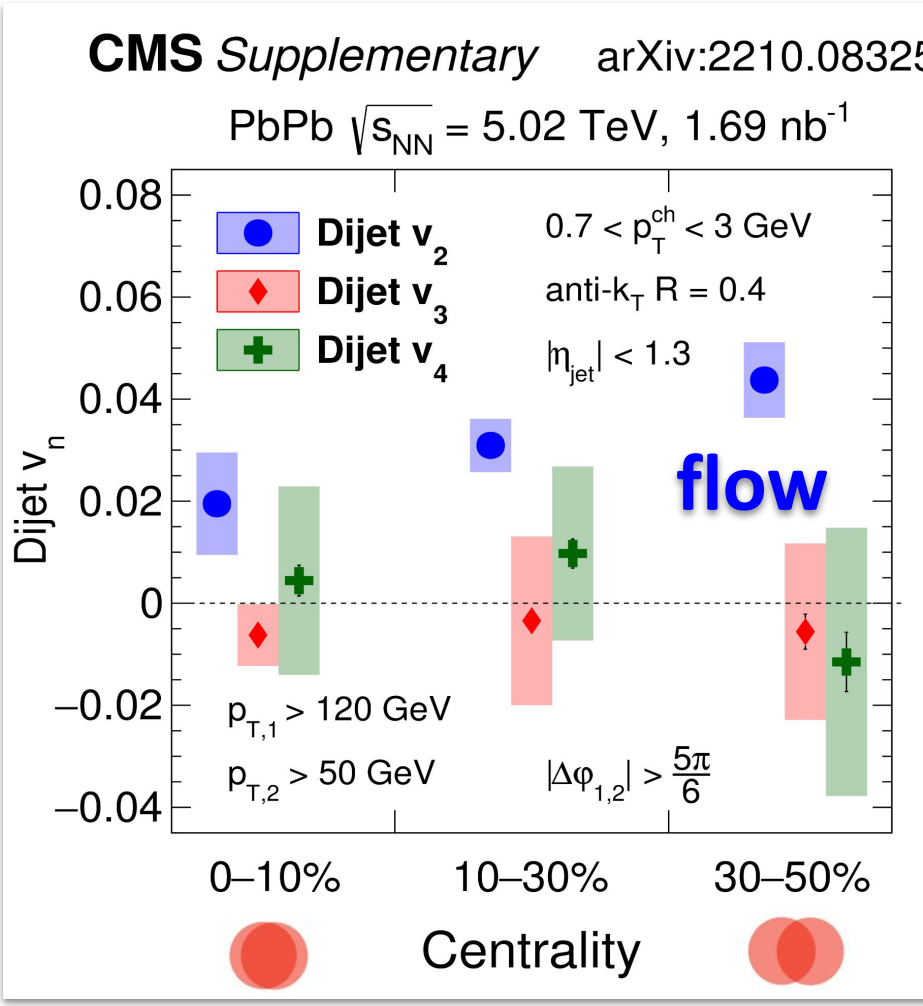


- **Parton mass and color-charge play a major role in energy loss**
  - **b jets** and **γ-tagged** (i.e., quark-initiated) jets less suppressed than inclusive jets
- **Jets with different substructure may experience different energy loss**
  - recent measurements on
    - substructure-dependent suppression and in-jet particle-momentum distributions

Easy interpretation of flow and R_{AA}

PLB **829** (2022) 137077
arXiv:2210.08325 (accepted by JHEP)

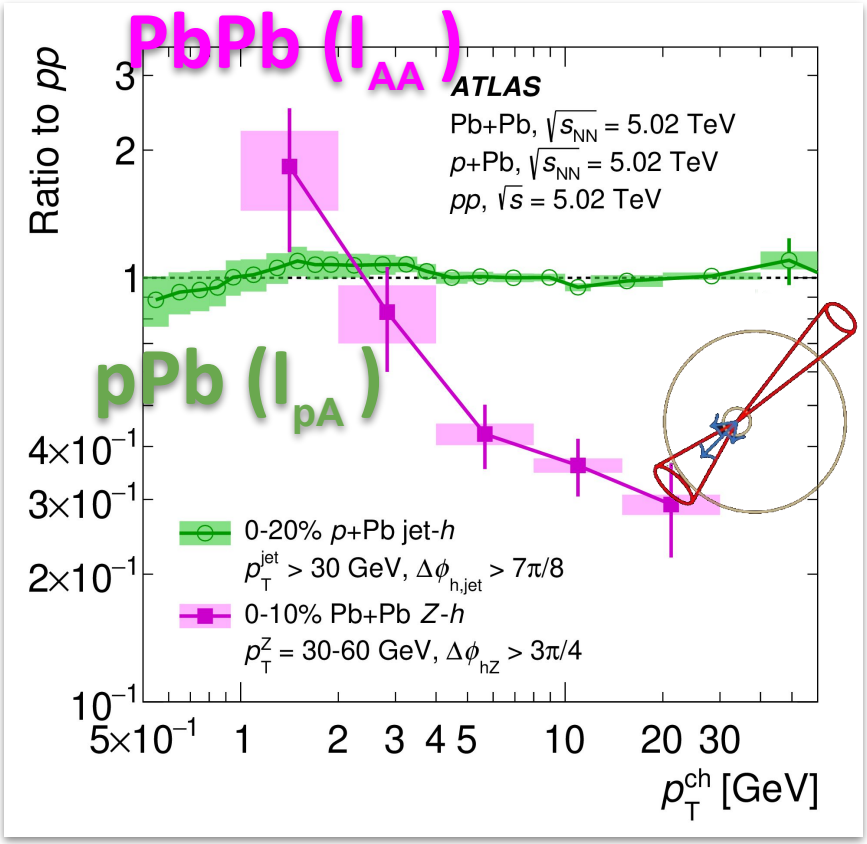




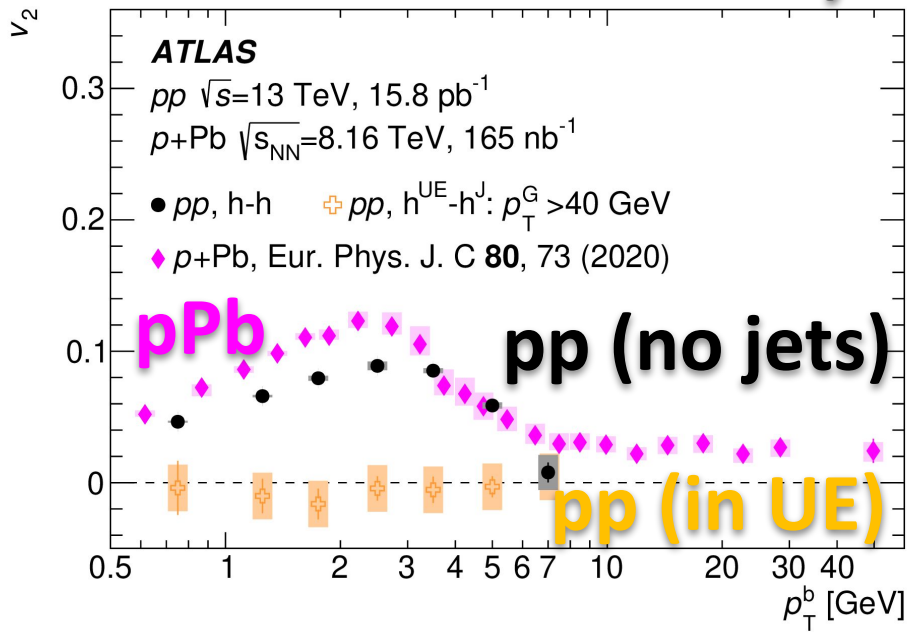
- **Combining/extending traditional observables**
  - **Simultaneous measurement** of R_{AA} and v_2 for **charm** and bottom
    - mass splitting at low p_T but converge at high p_T ($\gg$ mb)
  - **Dijet flow**: **v_2**>0, consistent with high-p_T hadron v_2; **v_3**,**v_4**≈0 → not yet sensitive(?)

Challenging interpretation of flow and R_{pA}

arXiv:2206.01138 (submitted to PRL)
arXiv:2303.17357 (submitted to PRL)



"Jet hadrochemistry"



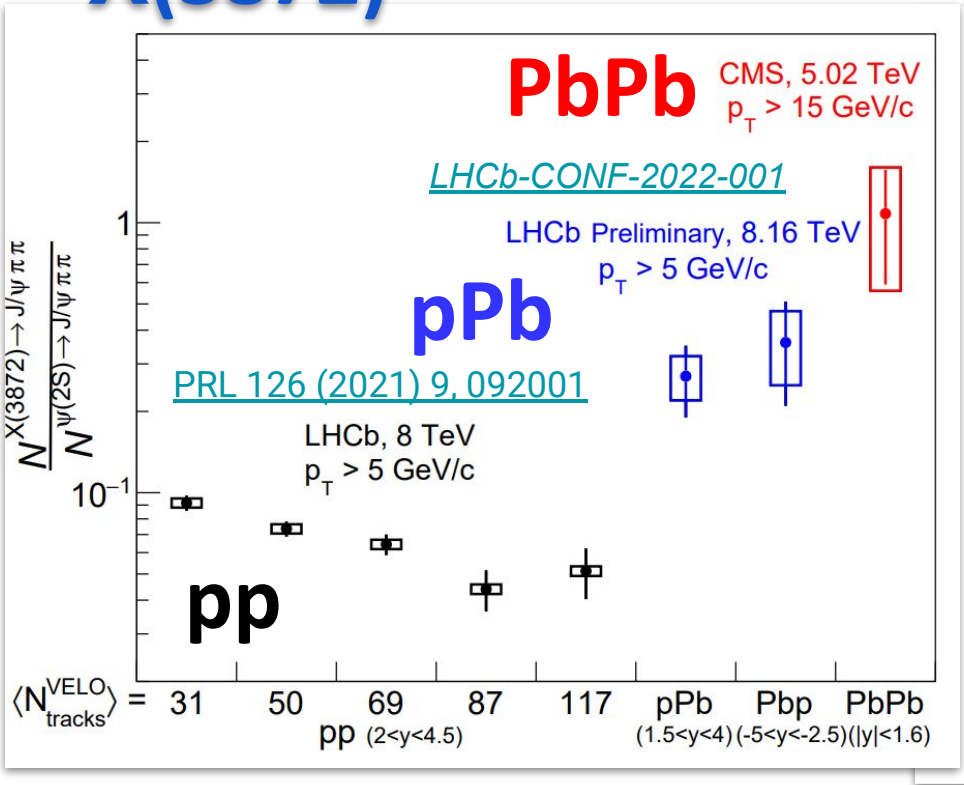
- **v_2 >0 up to high p_T but no modifications of hadron yields**
  - for p_T<8 GeV "factorization" between hard scattering and long range correlations
  - further studies to higher p_T to check whether such factorization is broken or not
  - **OO collisions** (pilot run in 2024) key guidance for jet quenching in lighter systems

Rare/BSM probes

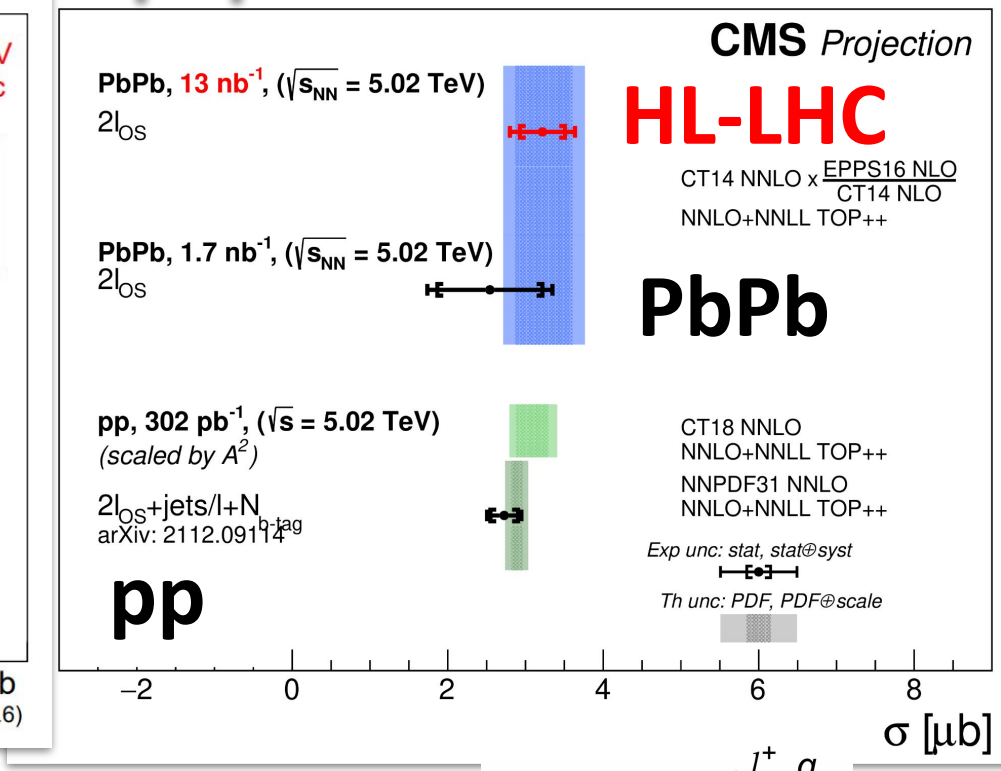
Exotic hadrons and top quarks in PbPb

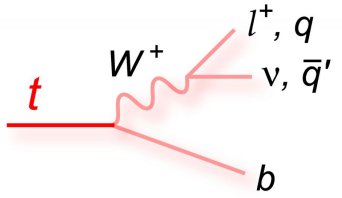
PRL **128** (2022) 032001
PRL **125** (2020) 222001

X(3872)



Top quark

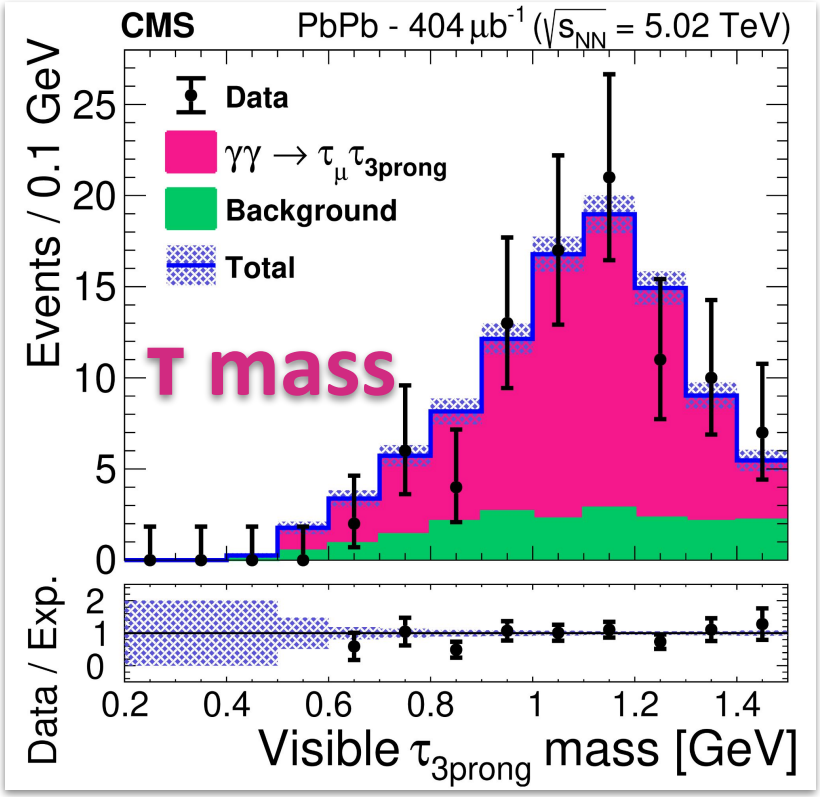


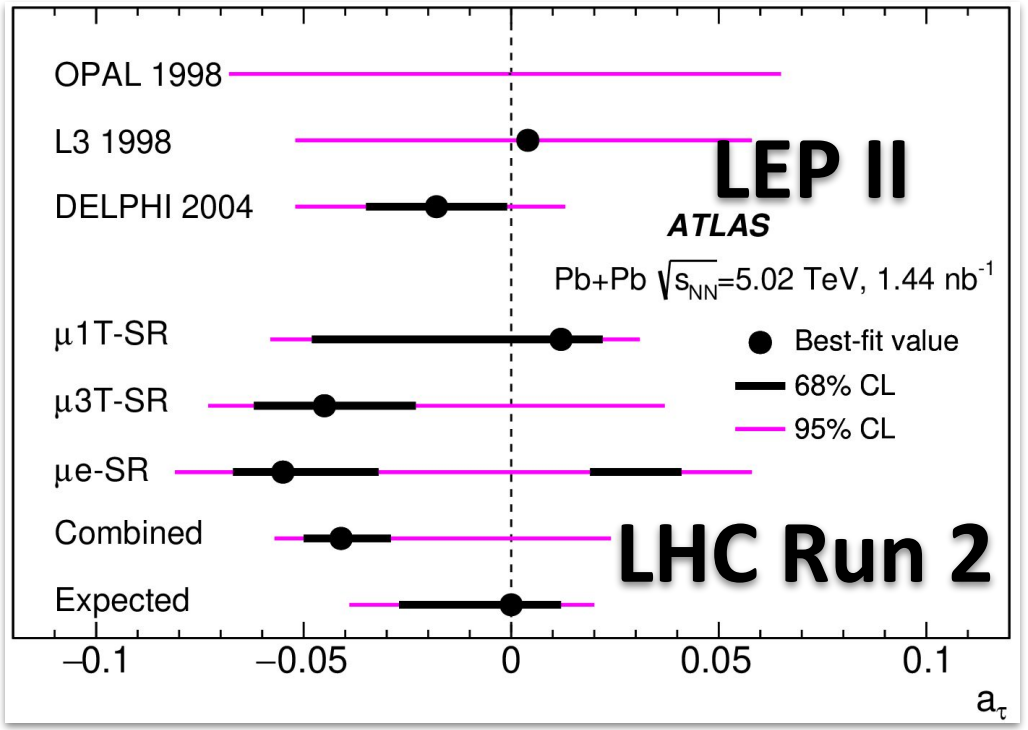


- **Evidence of X(3872) production**
  - its quark configuration remains elusive
  - X(3872)/ψ(2S): non-monotonic N_{trk} trend in pp & more pronounced in larger systems?
- **Evidence of top quark pair production**
  - uncertainty at HL-LHC competes with nPDF uncertainty; tool for QGP time profile

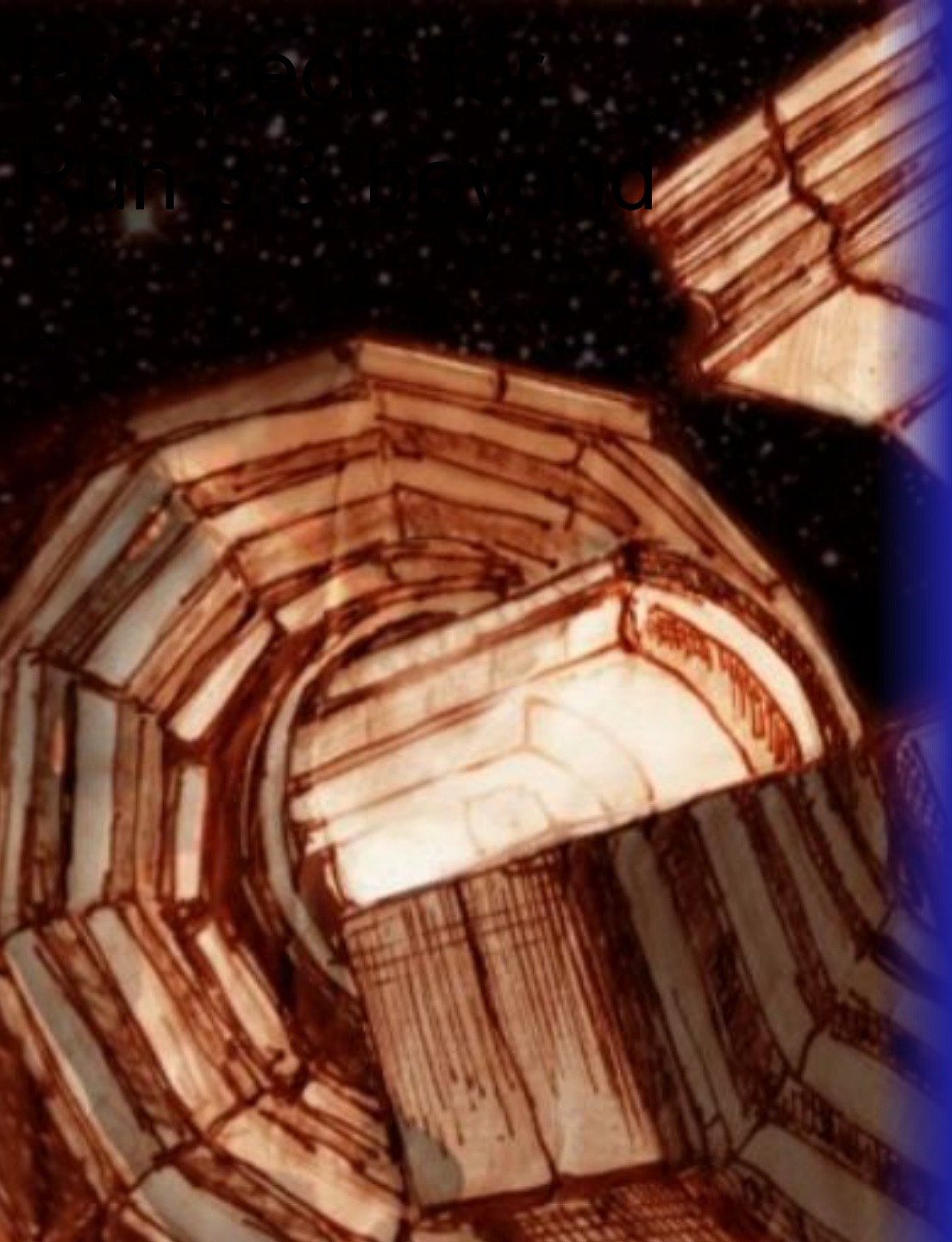
τ lepton pair production in UPC PbPb

arXiv:2204.13478
arXiv:2206.05192
(both accepted by PRL)





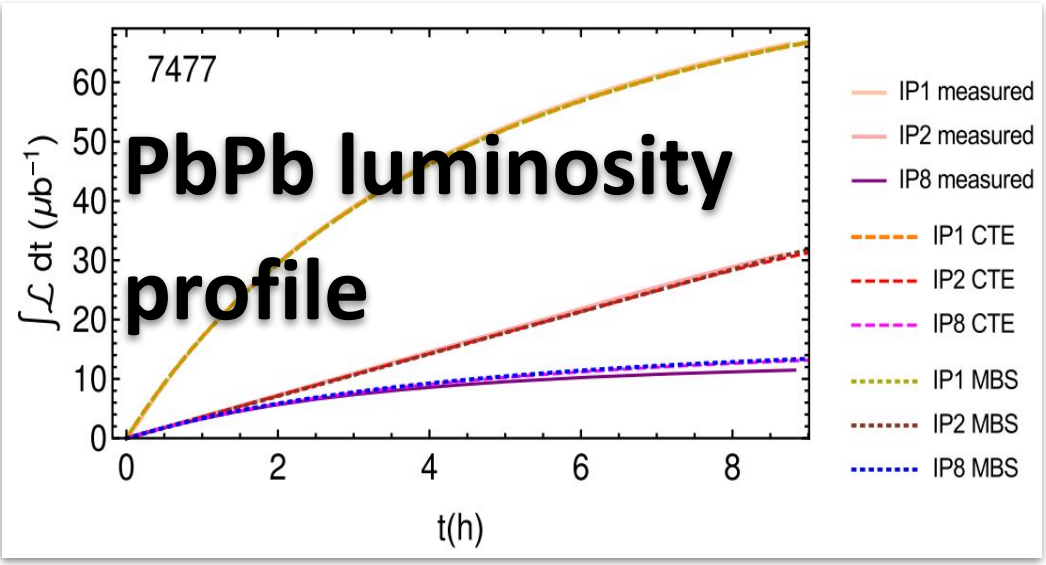
- **Observation of γγ → τ⁺τ⁻ at LHC**
  - ATLAS: full Run 2, multiple final states
  - CMS: part of Run 2, with a single but clean final state
- **Model-dependent constraints on a_τ obtained**
  - already competing with LEP II limits
  - further improvements on projected a_τ at HL-LHC with more final states

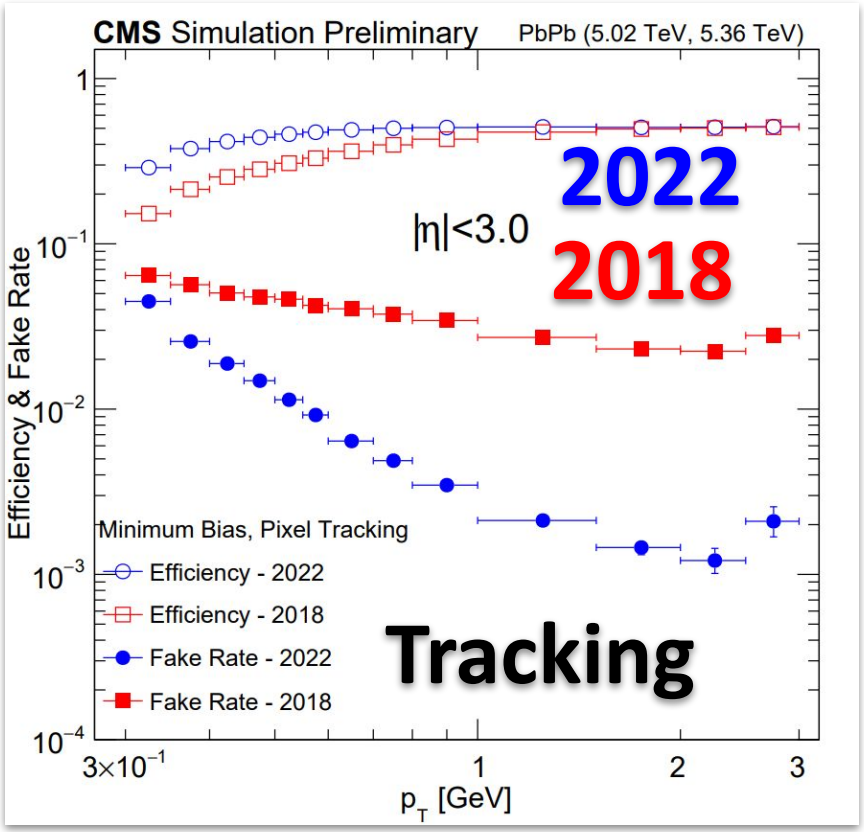


Luminosity prospects for Run 3

Improvements in Run 3 pPb and PbPb

EPJ.Plus **136** (2021) 7
CMS-DP-2023-011





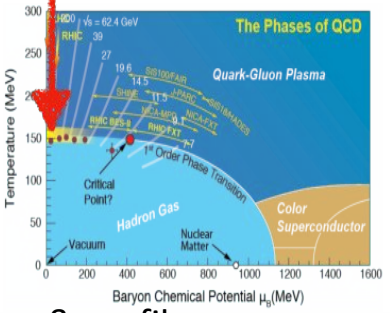
- **Based on benchmarked models (agree remarkably well with LHC data)**
  - 1 month of PbPb > Run 2 PbPb data
  - 1 month of pPb ≈ 3× Run 2 pPb data
- **Some extra improvements expected already in Run 3, e.g.,**
  - better low-p_T tracking, increased MB trigger rate, etc

From "smoking guns" to high precision

LHC for heavy-ion physics

- **Unique potential**
  → high T, low μ_B, large HF yields
- **Progress enabled** by
  - increased **luminosity**
  - improved **detector performance**, e.g. vertexing, acceptance

Goals for high-T/low-μ_B QCD matter	Experimental tools
Controlling initial conditions	EW bosons, dijets, VM's in UPC, R_{pA}
From early phase to hydrodynamization	Flow, femtoscopy, balance functions
Transport properties and hadronization	Heavy flavor transport, quarkonia, exotics
Quenching and connection to smaller systems	R_{AA}, $I_{(p/A)A}$, high-p_T probes, jet (sub)structure & profiles
Pinning down hydro-like behavior	v_n in γA, γp
Precision QED and BSM searches	Photon-induced processes



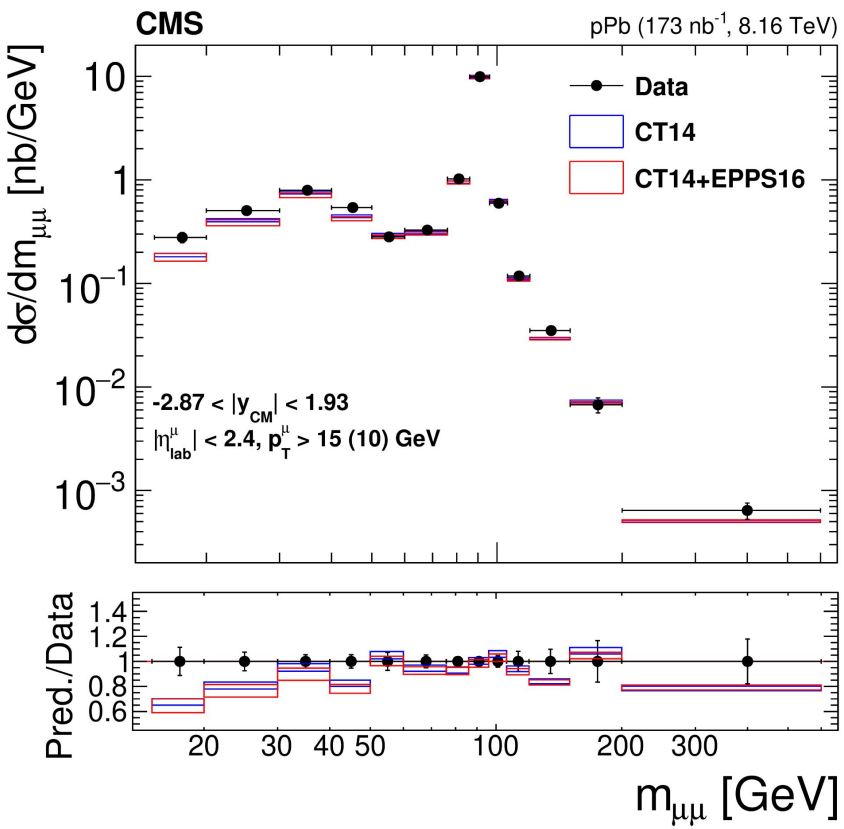
Further input in
WG5 HL-LHC, ATLAS+CMS Snowmass'22,
QCD Town Meeting WP, CMS HIN

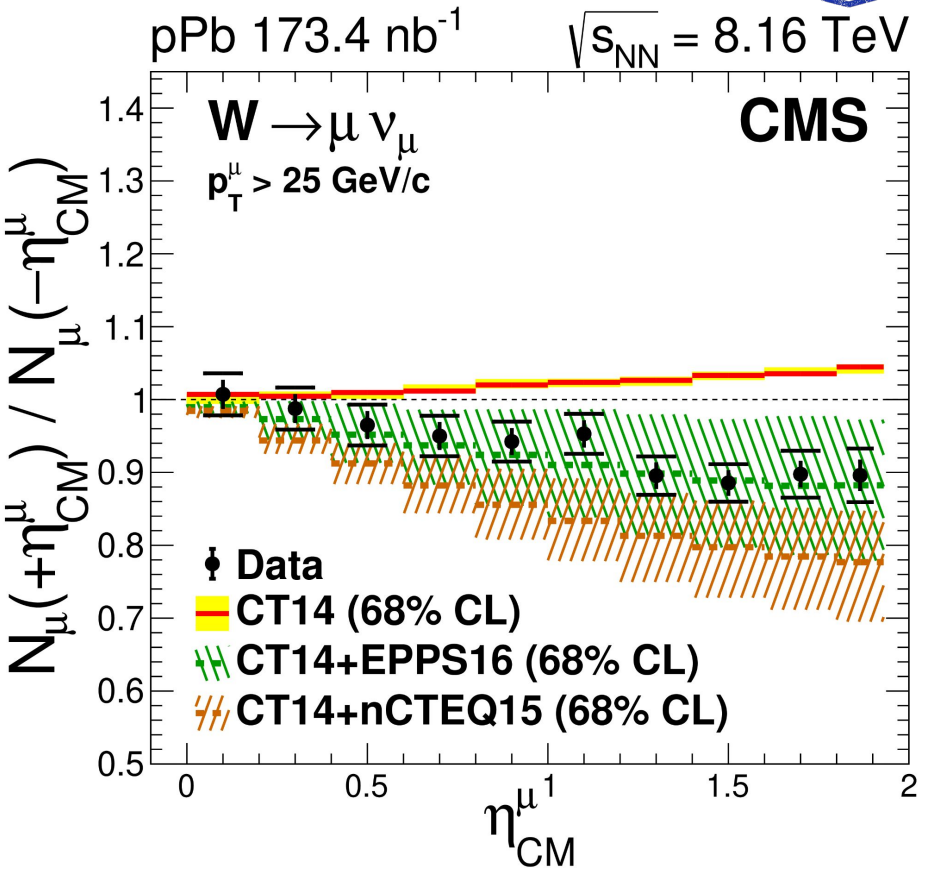
Nonexhaustive list

slides

Z/γ* & W production in pPb

JHEP 05 (2021) 182
PLB 800 (2020) 135048





- **First Z/γ* study in an extended m$_{\mu\mu}$ range**
  - low m$_{\mu\mu}$ sensitive to NNLO corrections
  - on-shell production less well described: statistical fluctuations(?)
- **Observation of nuclear effects in W boson production**
  - included in all recent nPDF fits

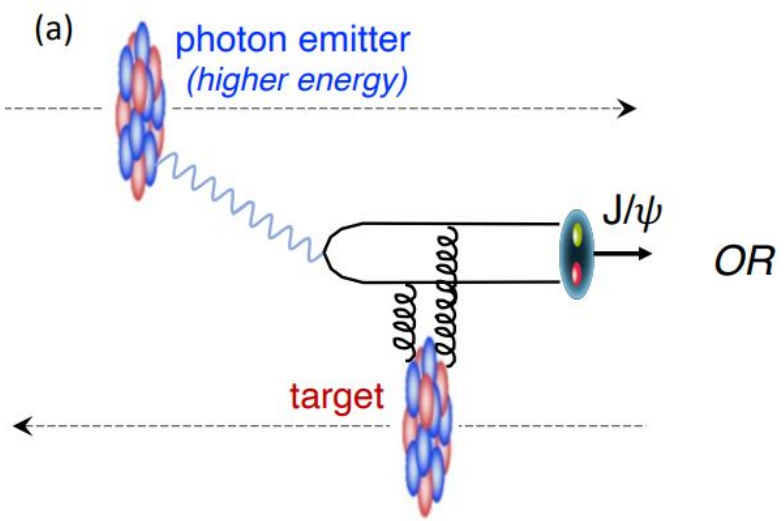
Key characteristics of the nPDF global fits

	KSASG20	nCTEQ15WZSIH	TUJU21	EPPS21	nNNPDF3.0
Order in α_s	NLO & NNLO	NLO	NLO & NNLO	NLO	NLO
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓		✓	✓	✓
pA DY	✓	✓		✓	✓
πA DY				✓	
RHIC dAu π^0,$\pi^\pm$		✓		✓	
LHC pPb π^0,$\pi^\pm$,$K^\pm$		✓			
LHC pPb dijets				✓	✓
LHC pPb D^0				✓	✓ reweight
LHC pPb W,Z		✓	✓	✓	✓
LHC pPb γ					✓
Q, W cut in DIS	1.3, 0.0 GeV	2.0, 3.5 GeV	1.87, 3.5 GeV	1.3, 1.8 GeV	1.87, 3.5 GeV
p_T cut in D^0,h-prod.	N/A	3.0 GeV	N/A	3.0 GeV	0.0 GeV
Data points	4353	948	2410	2077	2188
Free parameters	9	19	16	24	256
Error analysis	Hessian	Hessian	Hessian	Hessian	Monte Carlo
Free-proton PDFs	CT18	~CTEQ6M	own fit	CT18A	~NNPDF4.0
Free-proton corr.	no	no	no	yes	yes
HQ treatment	FONLL	S-ACOT	FONLL	S-ACOT	FONLL
Indep. flavours	3	5	4	6	6
Reference	PRD 104, 034010	PRD 104, 094005	arXiv:2112.11904	arXiv:2112.12462	arXiv:2201.12363

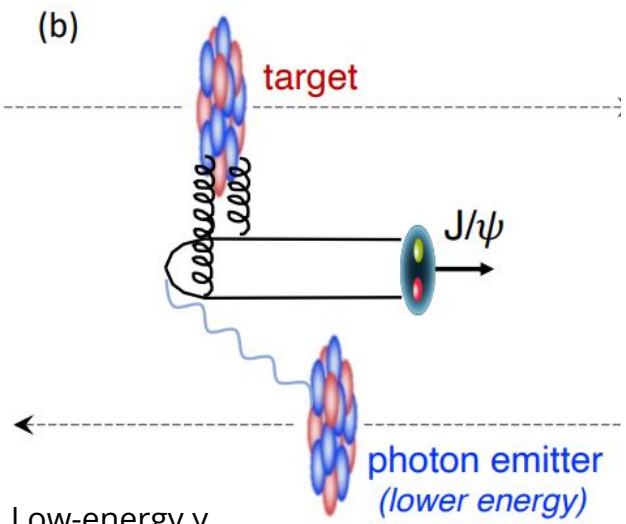
P. Paakkinen (DIS22)

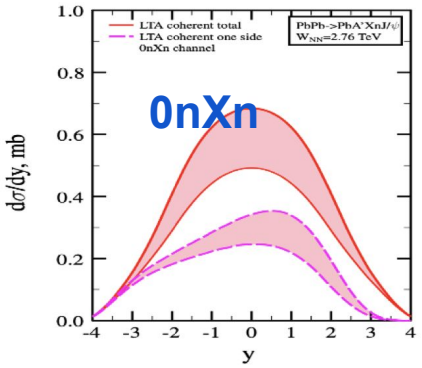
How to unambiguously access low-x gluons? The theo. solution

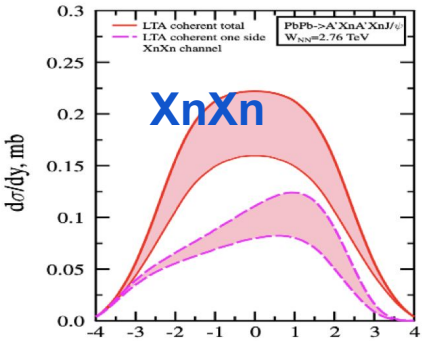
Guzey et al., **EPJC 74 (2014) 2942**



OR







High-energy γ

$$w_2 = \frac{M_{VM}}{2} e^{+y}$$

The issue

Low-energy γ

$$w_1 = \frac{M_{VM}}{2} e^{-y}$$

The exp. solution

What is measured **Photon flux from theory** **What we want to extract**

$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = N^{0nXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0nXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

$$\frac{d\sigma^{XnXn}_{AA\to AA'J/\psi}}{dy} = N^{XnXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{XnXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

Entering a new regime of small x ~ 10^{-4}-10^{-5} in nuclei w/o the need to increase the energy!

HF transport models: ingredients

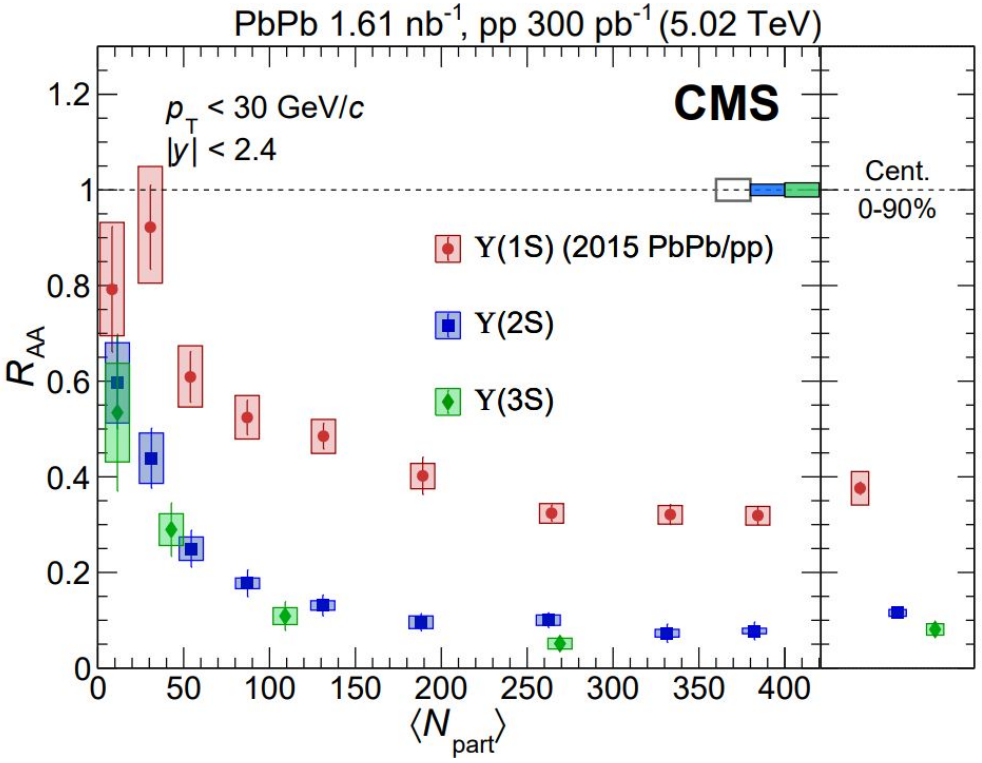
	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF
TAMU	✅	❌	✅	✅	✅
LIDO	✅	✅	✅	✅	✅
PHSD	✅	❌	✅	✅	✅
DAB-MOD	✅	✅	✅	✅	❌
Catania	✅	❌	✅	✅	✅
MC@sHQ+EPOS	✅	✅	✅	✅	✅
LBT	✅	✅	✅	✅	✅
POWLANG+HTL	✅	❌	✅	✅	✅
LGR	✅	✅	✅	✅	✅

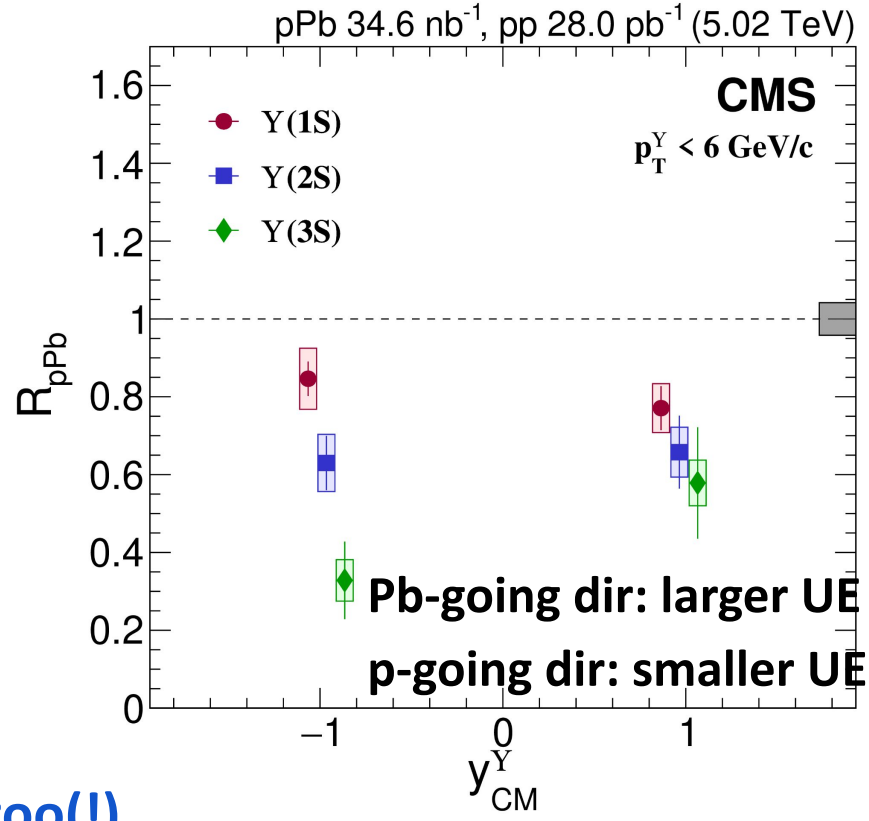
But more importantly: different **implementations** and **input parameters**.

Input from
QM22 conference (Luuk Vermunt)

Y(ns) suppression in PbPb and pPb

HIN-21-007 (to appear)
PLB 835 (2022) 137397

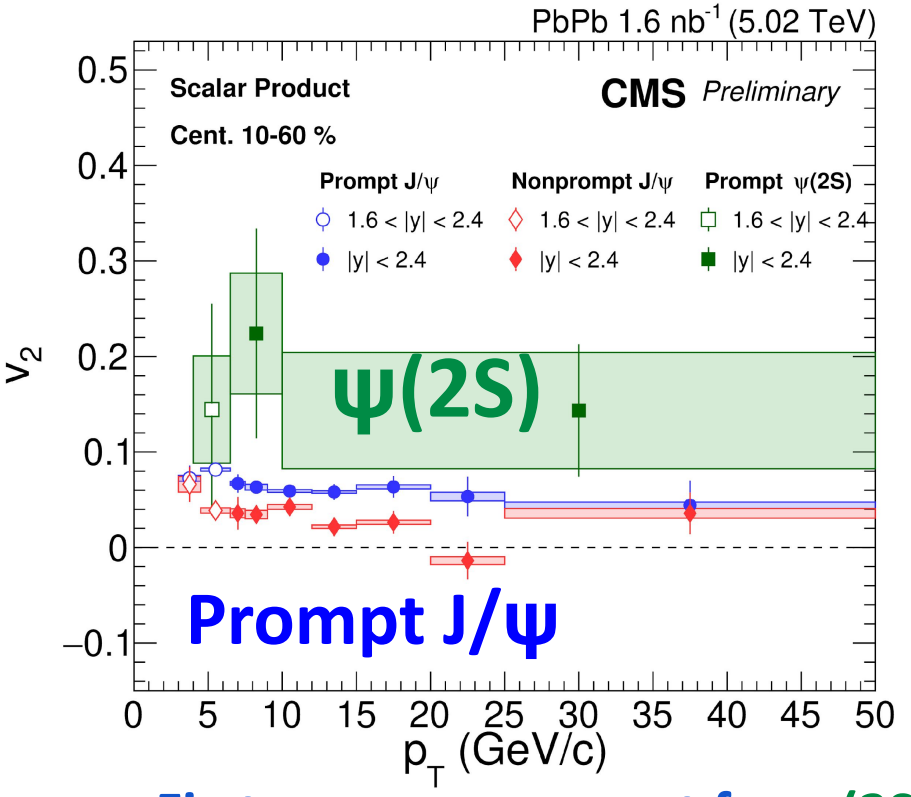


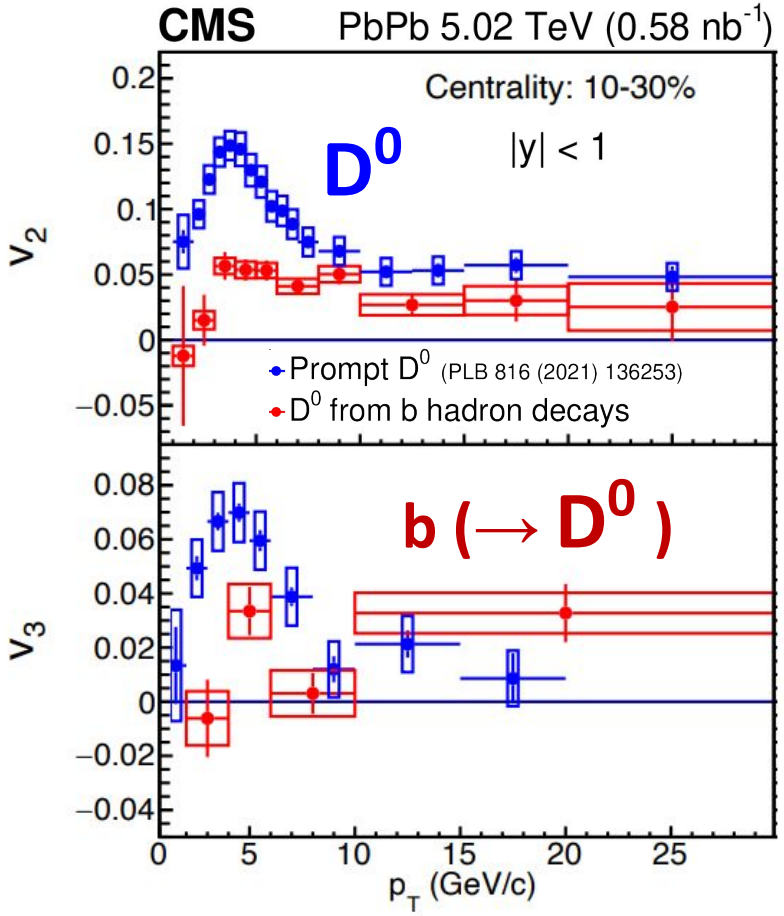


- **Observation of Y(3S) now in PbPb too(!)**
  - indication of ordered (sequential) suppression up to Y(3S) in both systems
  - strong challenge for models to reproduce Y(3S) $R_{AA}>0$
- **Excited states set strong constraints on models**
  - In the study of initial-/final-state effects

Heavy flavor flow in PbPb

CMS-PAS-HIN-21-008
arXiv:2212.01636

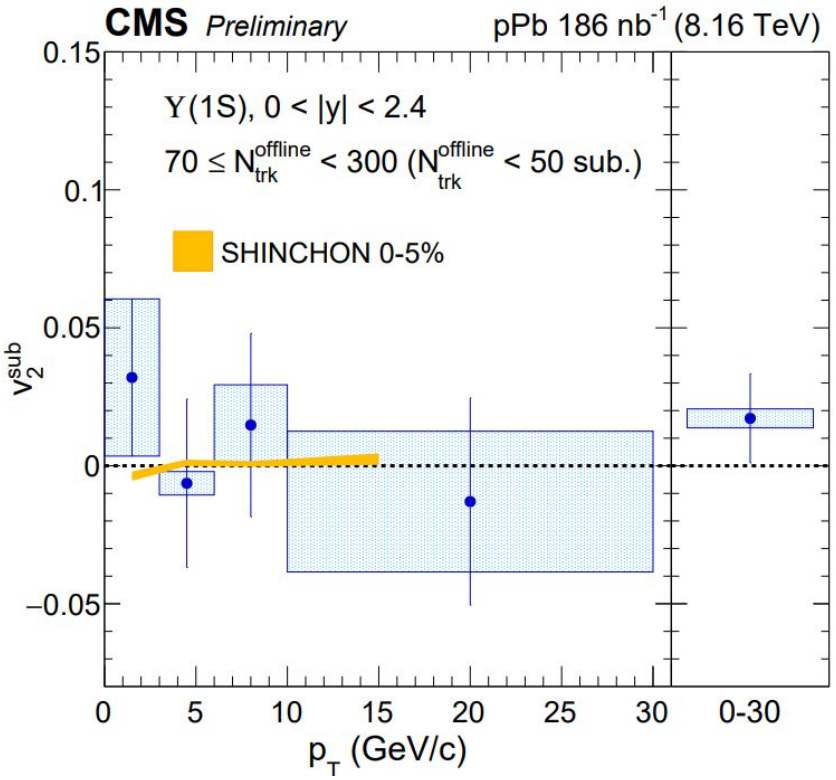


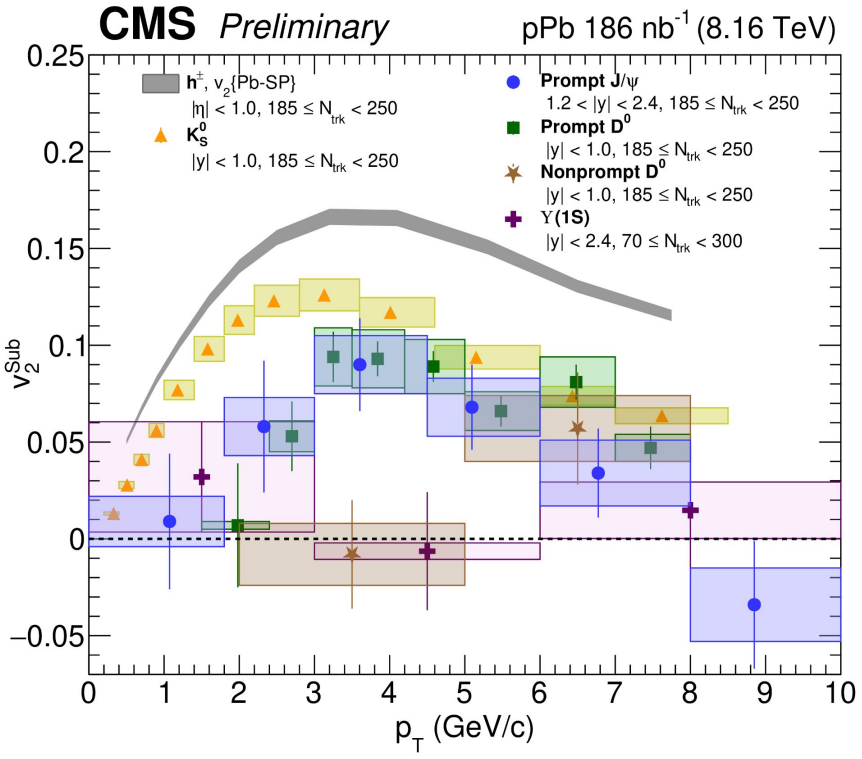


- **First $v_{2,3}$ measurement for ψ(2S)**
  - indication of ψ(2S) v_2 > **prompt J/ψ** v_2 → ψ(2S) from recombination at later stage?
- **First v_2 for b (→ D^0); b quark and D^0 meson p_T well correlated**
  - **charm** > b (→ **D^0**) v_2, whereas Υ(1S), Υ(2S) v_2≈0
  - evidence for b (→ **D^0**) v_3 >0 at intermediate p_T

Heavy flavor flow in high-multiplicity pPb

CMS-PAS-HIN-21-001

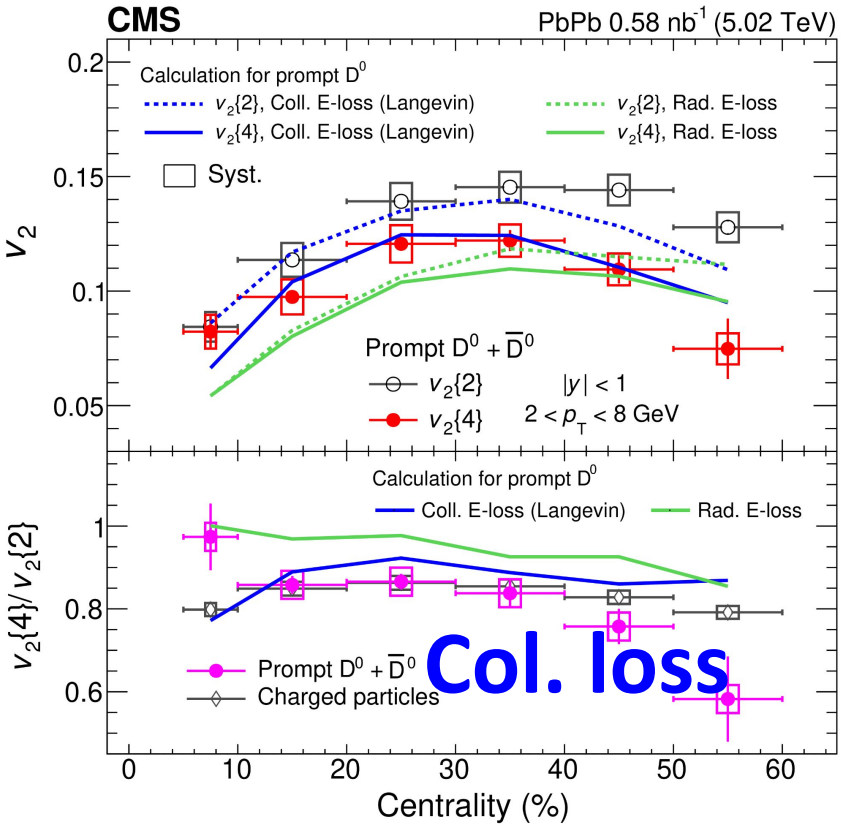


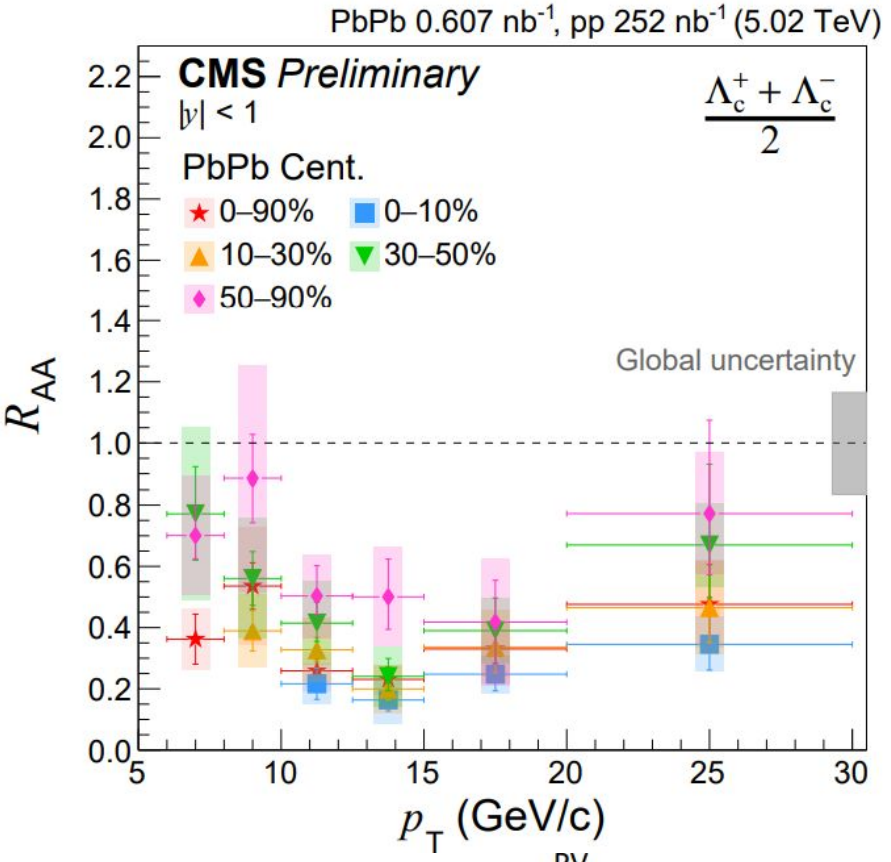


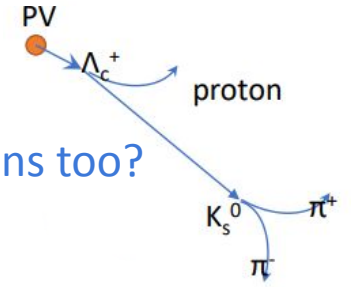
- **First v_2 measurement for Y(1S)**
  - v_2≈0 up to 30 GeV(!), similar to a model with final-state interactions only
- **Bridging HF flow measurements in large & small systems**
  - clear **mass hierarchy**: heavier particles flow less
  - open question: do open/closed b hadrons flow in pPb?

Charm quark energy loss in PbPb

PRL 129 (2022) 022001
CMS-PAS-HIN-21-004



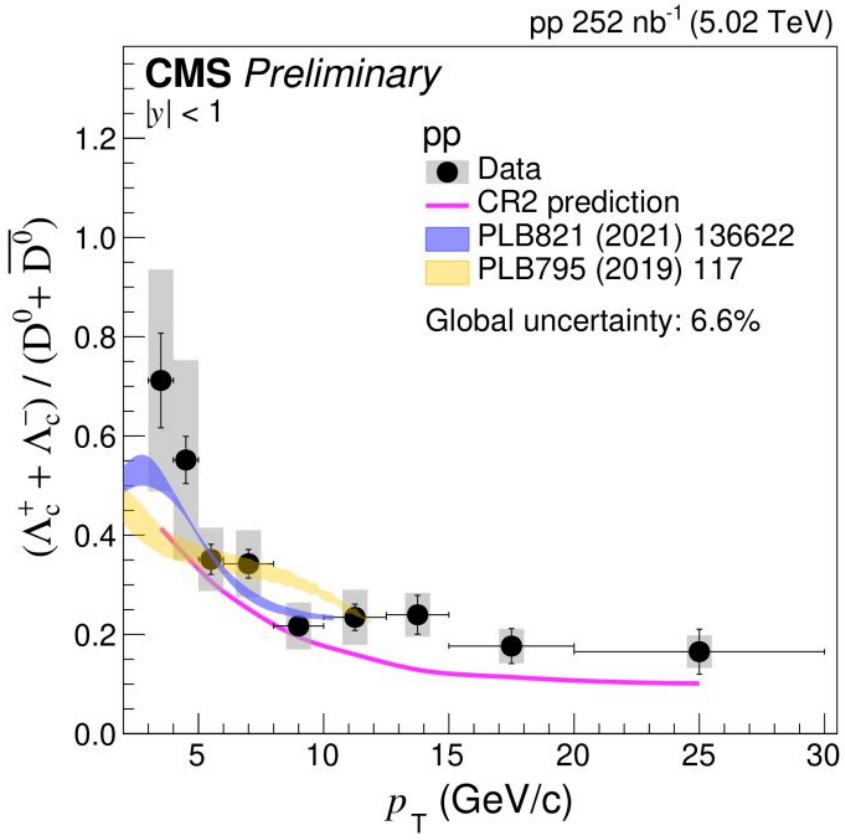


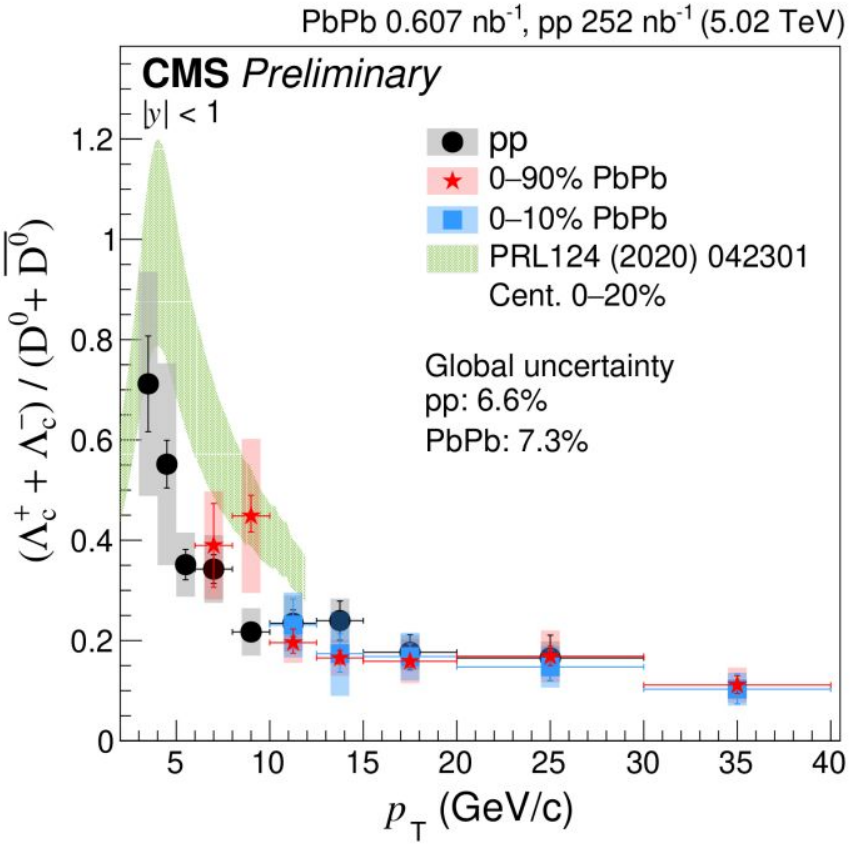


- **First high-precision v_2{4}/v_2{2}(!)**
  - compare D^0 to **light** flavor → v_2 fluctuations due to en. loss fluctuations too?
- **HF en. loss measurement with Λ_c^+ R_{AA}**
  - Large suppression but with min R_{AA} at ≈ 14 GeV contrary to other HF measurements

Charm quark hadronization in pp and PbPb

CMS-PAS-HIN-21-004

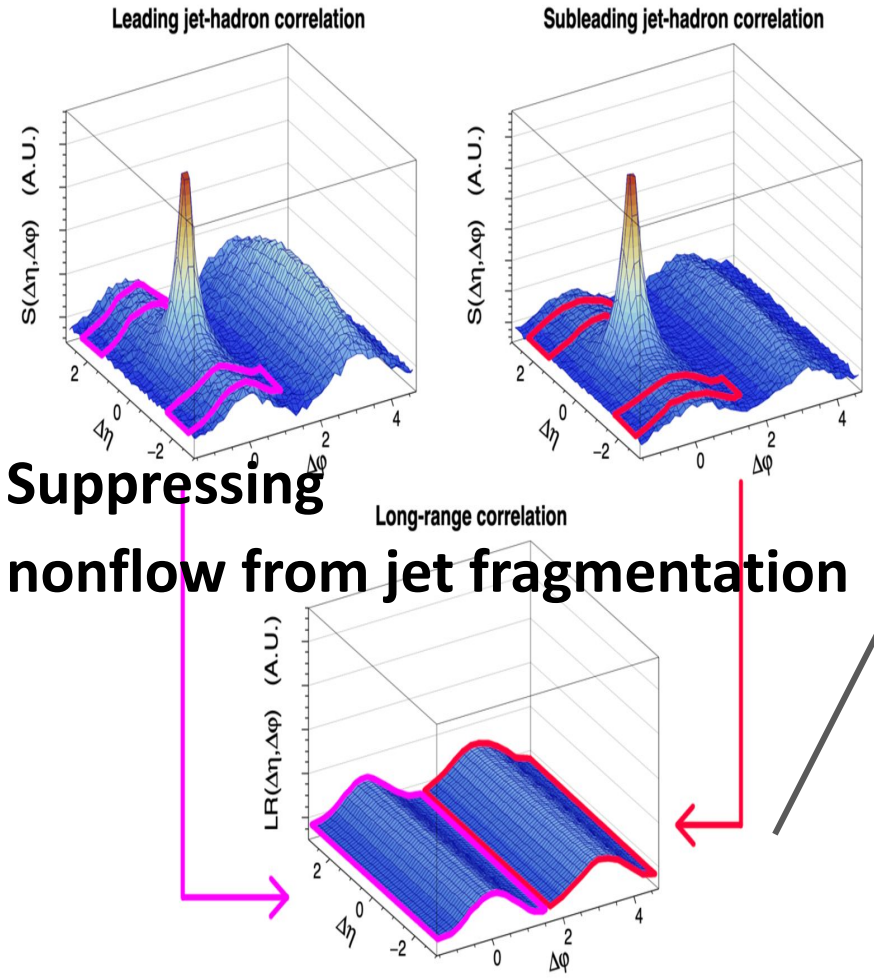




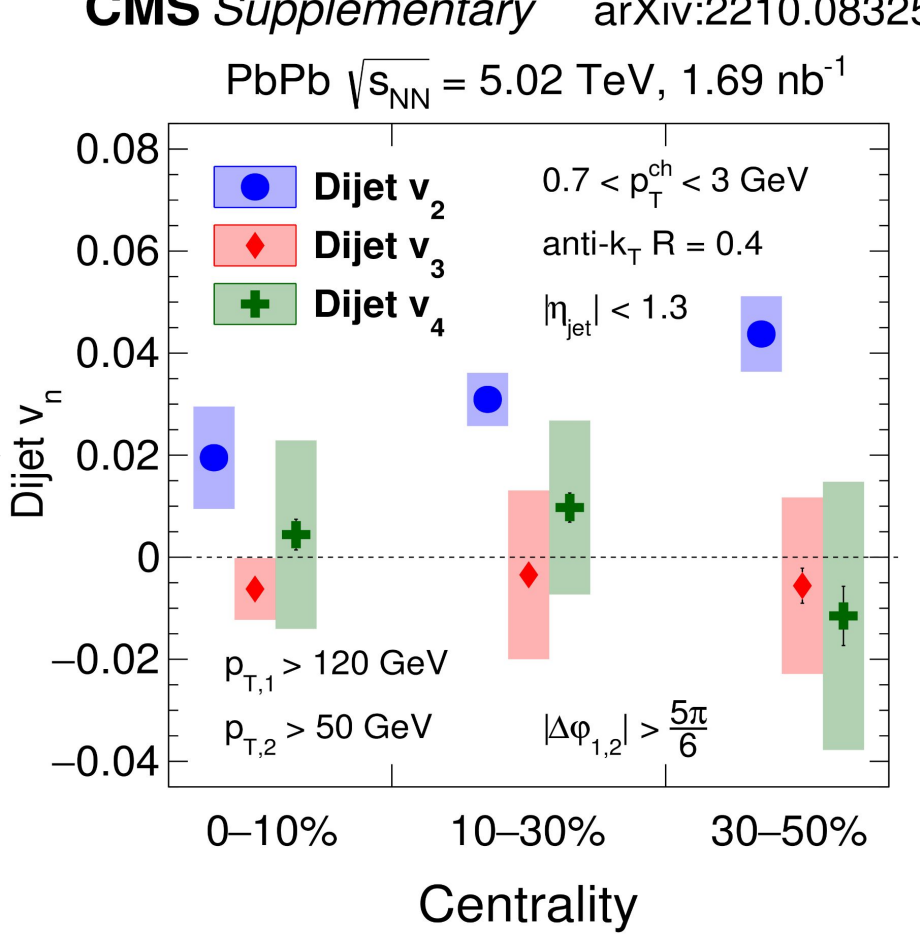
- **PYTHIA8+CR describes Λ_c^+/D^0 at p_T <10 GeV in pp, similar to models**
  - containing decays of **excited c baryons**; involving **coalescence and fragmentation**
- **Extending the p_T (<40 GeV) and centrality (0–90%) reach in PbPb**
  - Λ_c^+/D^0 in pp and PbPb consistent → no significant contribution from coalescence

Dijet vn in PbPb

arXiv:2210.08325
(accepted by JHEP)



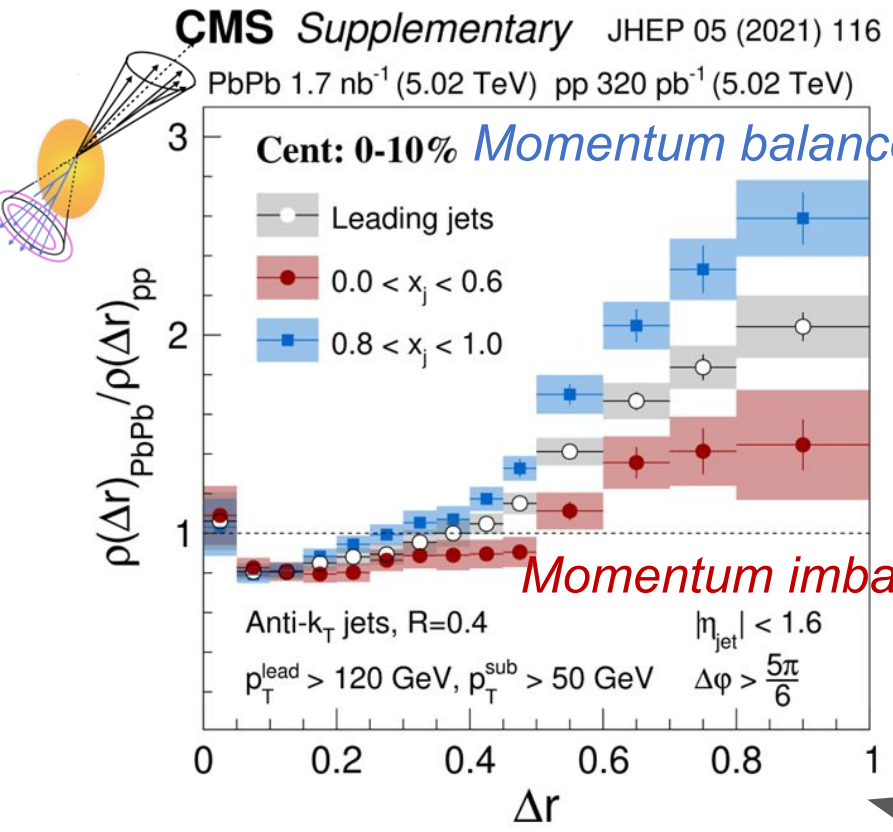
Suppressing nonflow from jet fragmentation

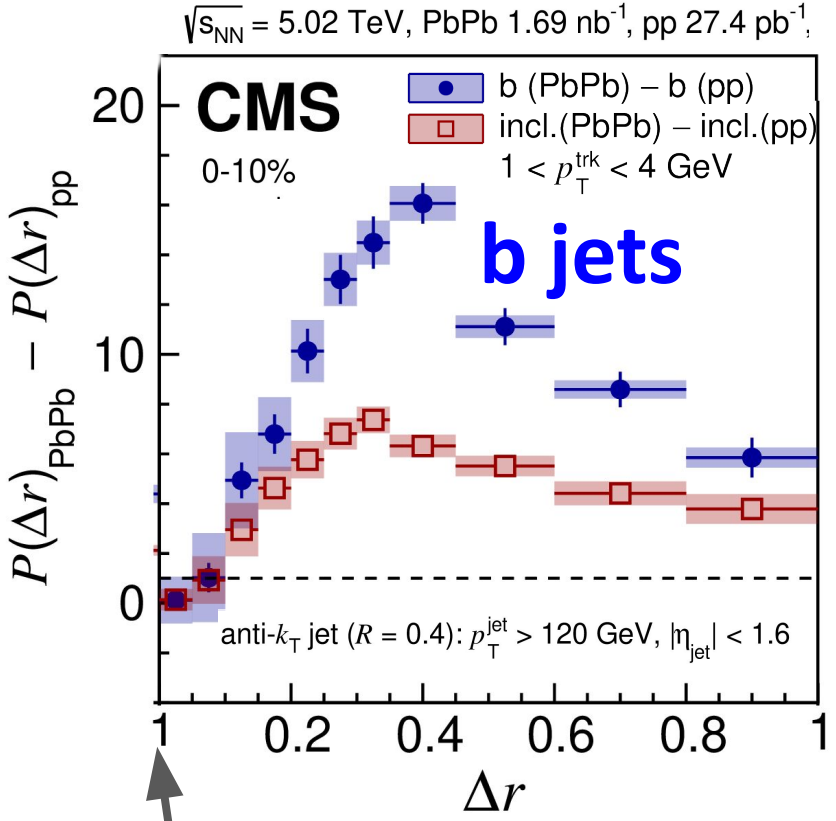


- **Path-length dependent energy loss & its fluctuations**
  - dijet v_2>0 with expected centrality dependence; consistent with high-p_T hadron v_2
  - dijet v_3, v_4≈0 → not yet(?) sensitive to initial-state/en. loss fluctuations

How energy loss is distributed?

JHEP 05 (2021) 116
arXiv:2210.08547
(accepted by PLB)

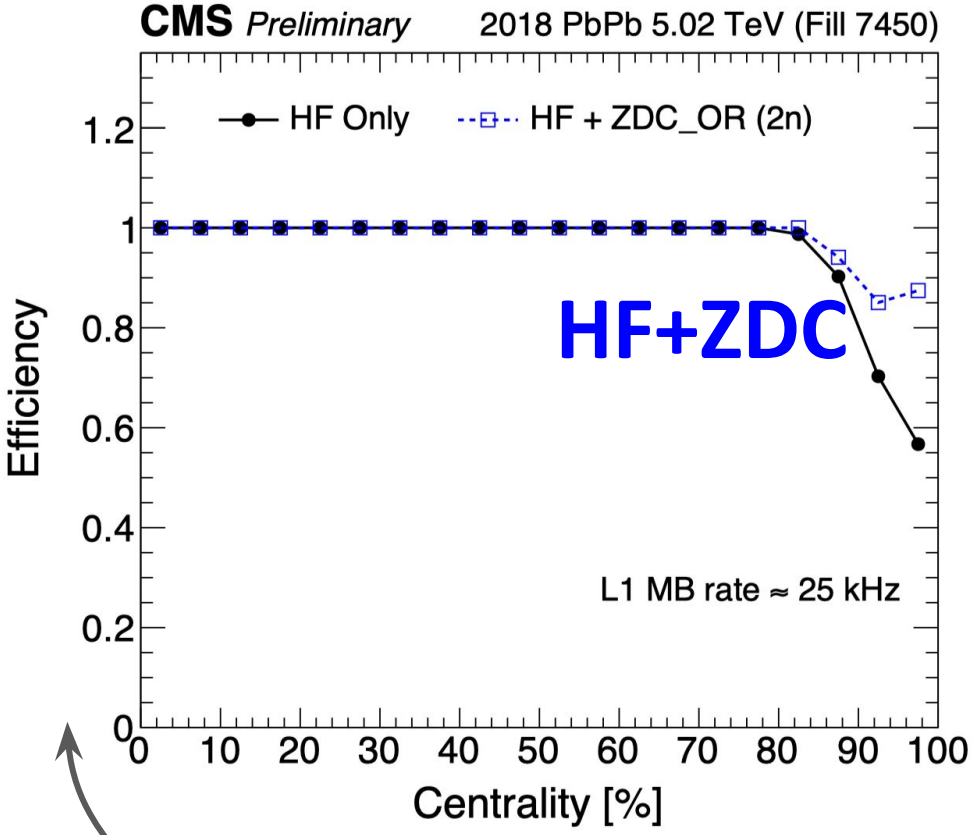


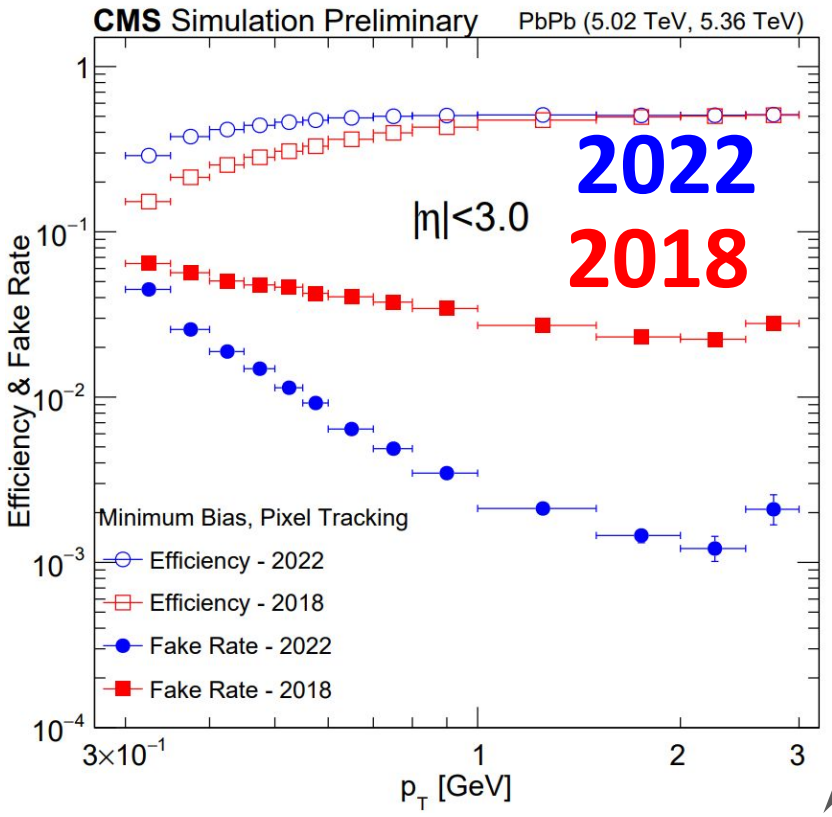


- **Jet shape: radial profile of particles in dijets, b jets**
  - in-medium path length for leading jets is larger when $x_J \approx 1$ (vice versa for subleading)
  - for b jets
    - small-Δr depletion: sensitive to dead-cone effect
    - large-Δr enhancement: enhanced medium response to b quarks

Improvements in Run 3 PbPb

CMS-DP-2023-011





- **Improvements expected already in Run 3, e.g.,**
  - online: increased MB trigger efficiency in peripheral events with ZDC inclusion
  - offline: better low-p_T tracking thanks to innermost pixel layer consideration
- **Overall CMS will record 25 kHz of MB PbPb events**
  - representing an increase of 80x to 2015 and 3x to 2018

CMS Phase 2 Upgrades (HI related)

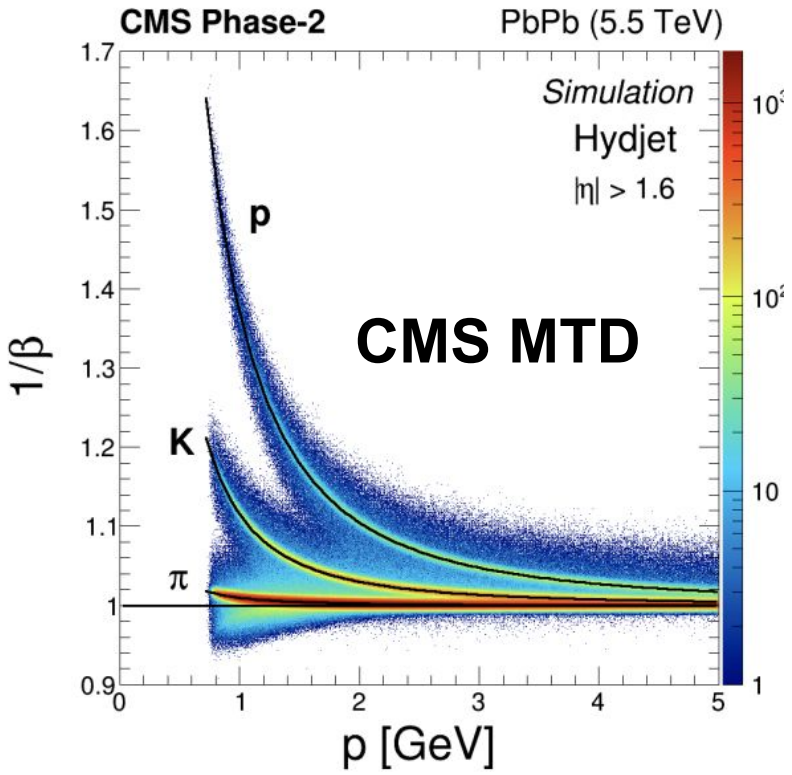
CMS-DP-2021-037

Phase 2 Upgrade

CMS Phase 2 for Run 4

- Tracker **|η|<4**
- Muon ID up to **|η|<2.8**
- High Granularity Calorimeter
- MIP timing detector
  - 4D vertexing
  - **p/K/π PID** (CMS MTD)
- L1 trigger update: 750 kHz for CMS
- DAQ: 51 GB/s for CMS
- L1 track triggers
- ZDC

p/K/π separation



- **Main batch of CMS Upgrades in Run 4**
  - Among others, unique hermetic particle identification coverage by CMS MTD
- **Physics requests documented in past years over a diverse set of reports**
  - WG5 HL-LHC, ATLAS+CMS Snowmass'22, QCD Town Meeting WP, CMS HIN