U.S. DEPARTMENT OF ENERGY
Office of Science

KU THE UNIVERSITY OF KANSAS

CMS

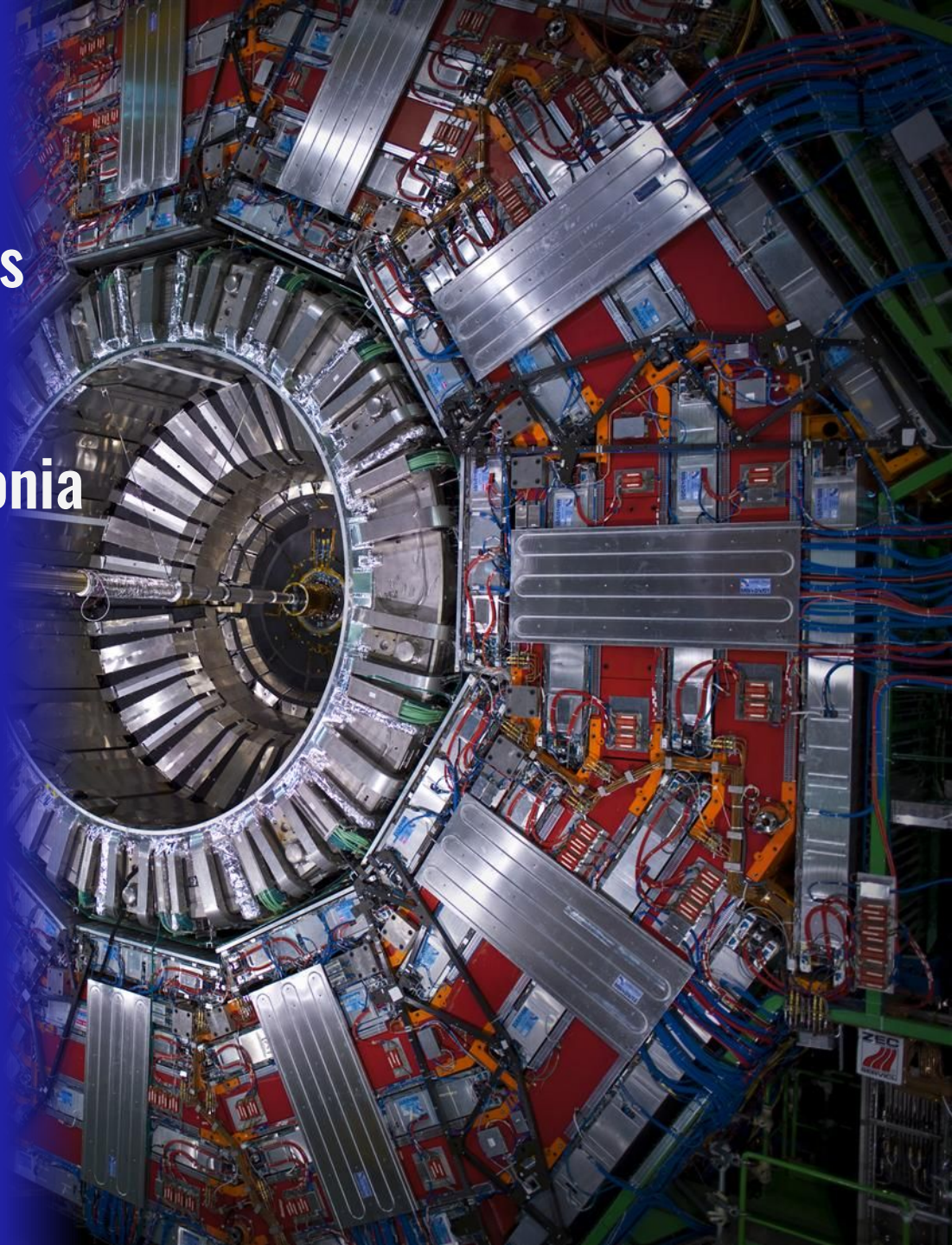
CMS experimental highlights

Georgios K Krintiras (on behalf of the CMS Collaboration)
The University of Kansas

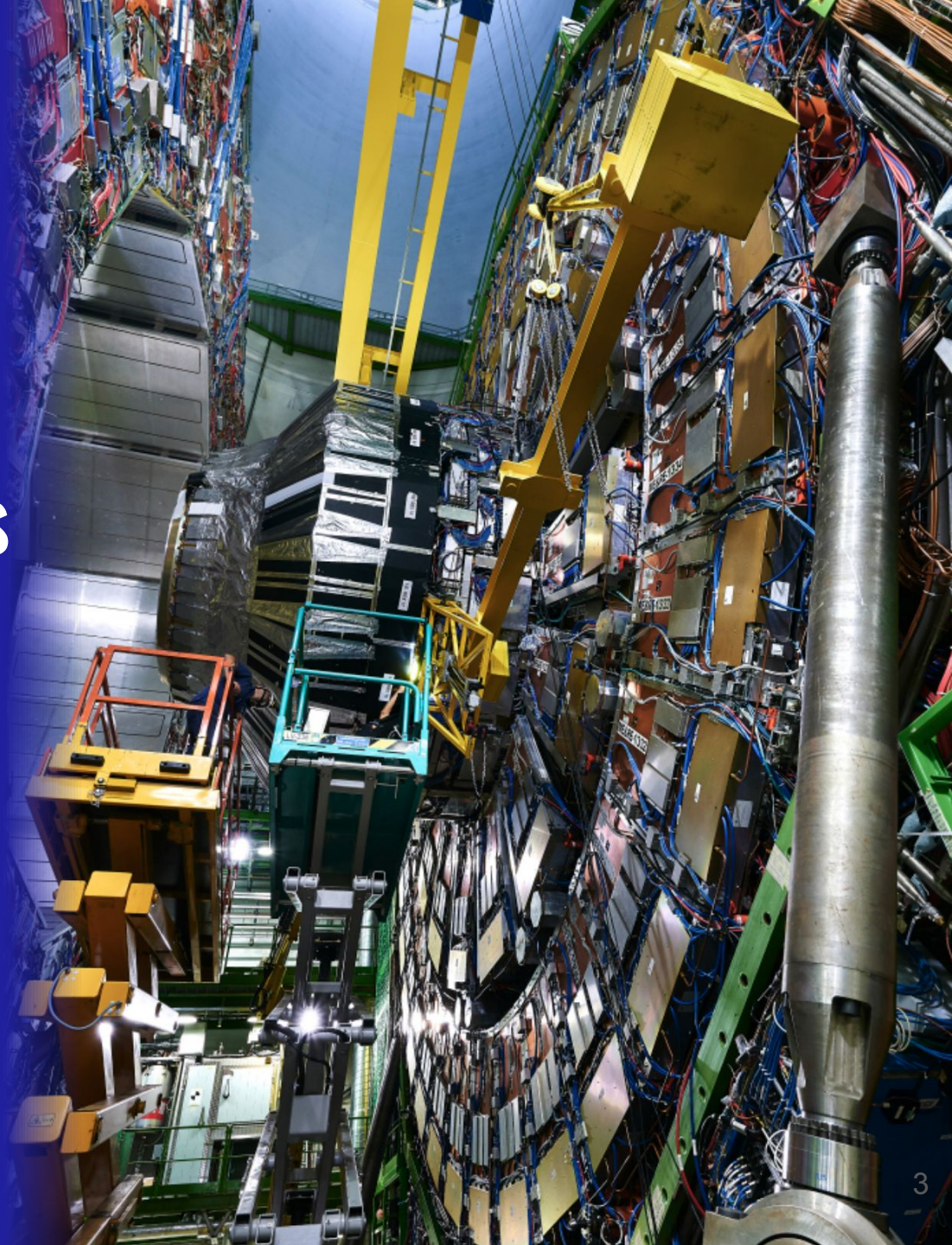
11th International Conference on Hard and Electromagnetic Probes

Outline–the probes

- Early dynamics and nPDFs
  - E/W bosons
  - J/ψ, dijets, v_n (UPC)
- Heavy quarks and quarkonia
  - ψ(2S), D^0, Λ_c^+
  - b($\rightarrow D^0$), B_s^0,B_c^+, Υ(ns)
- Medium modifications
  - dijet & b jet shapes
  - dijet v_n
- Rare/BSM probes
  - X(3872), tops, τ leptons
- Run 3 & beyond

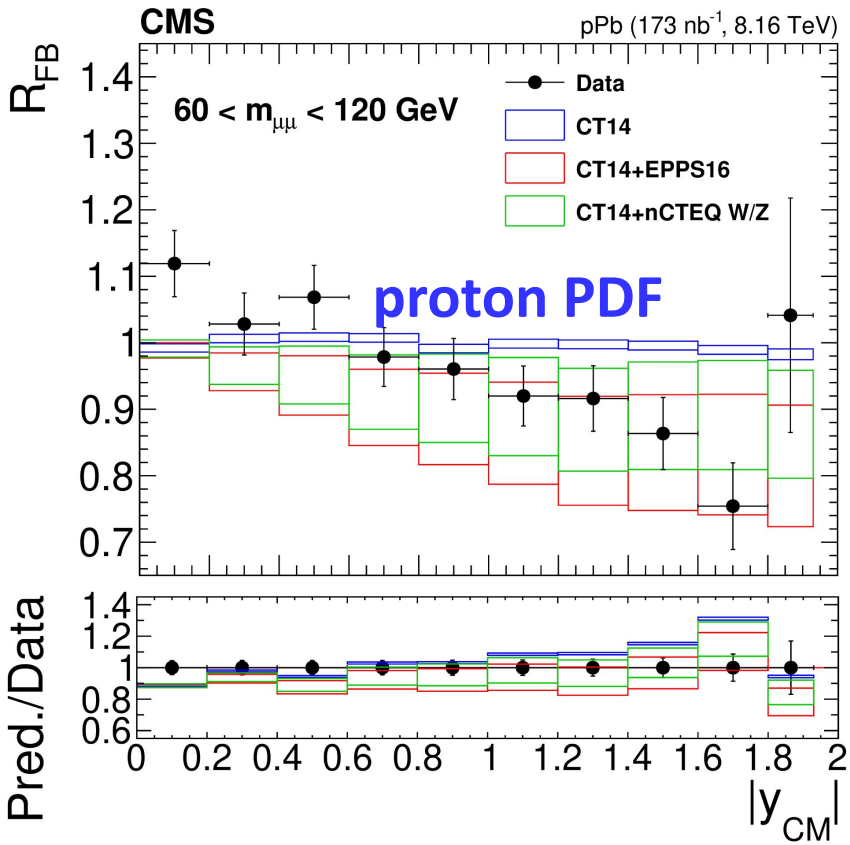


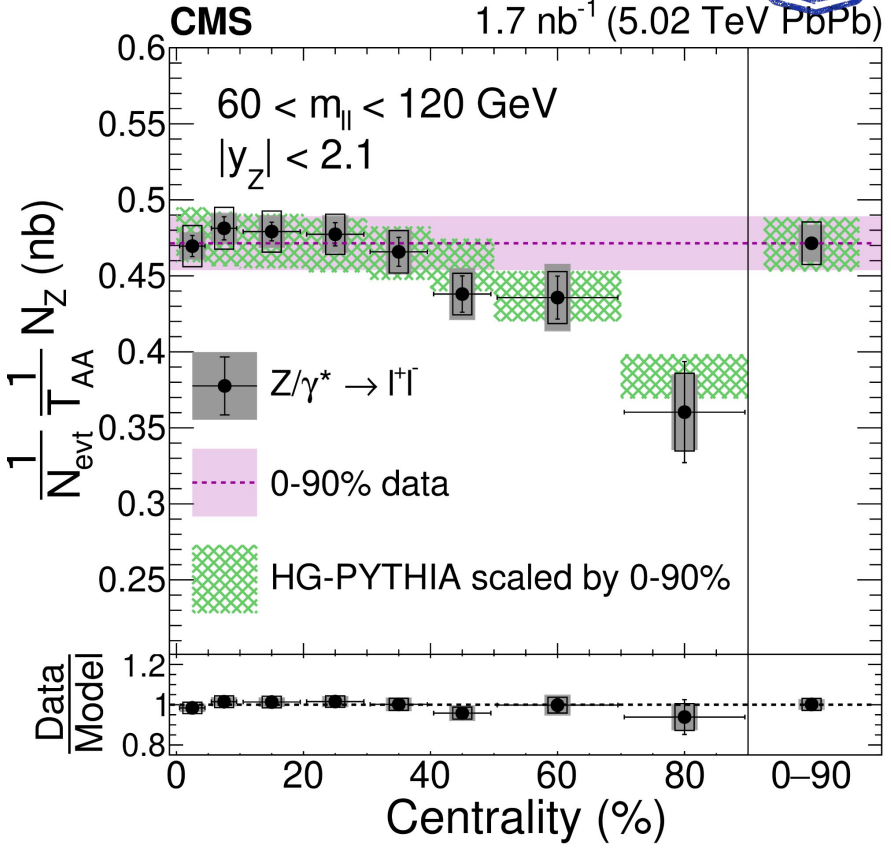
Early time dynamics and nPDFs



Z/γ* production in pPb and PbPb

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



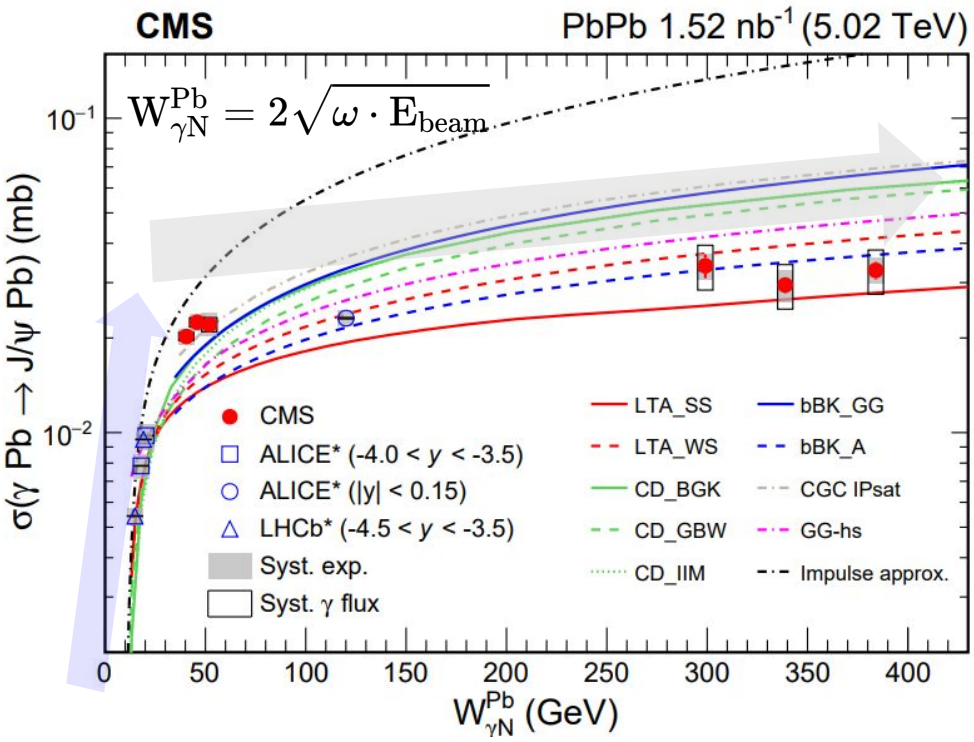


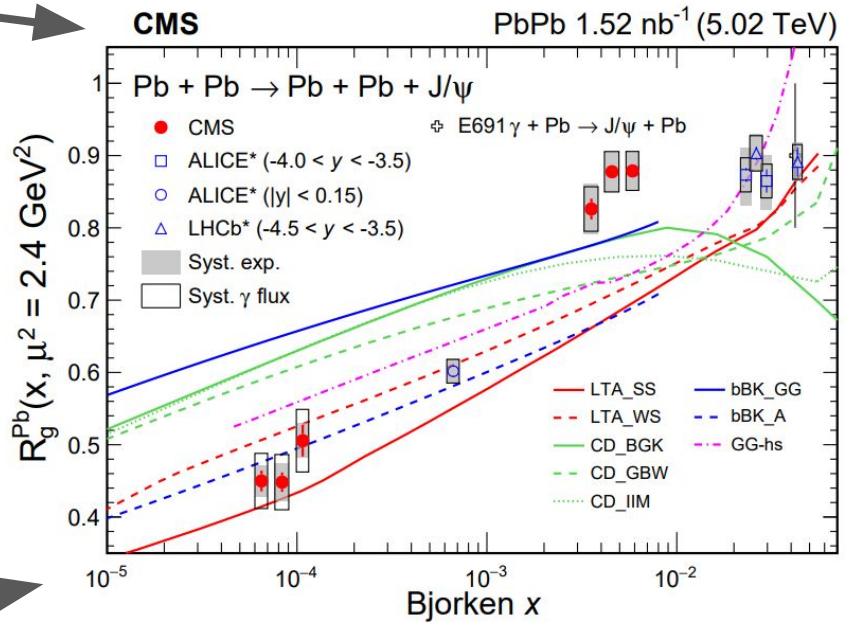
- **Forward-backward ratios $R_{FB} \equiv 1$ in the absence of nuclear effects**
- **HG-PYTHIA grasps centrality evolution → centrality bias in peripheral PbPb**
- **W bosons, dijets, top quarks sensitive to gluons at different *x***

Coherent J/ψ production in UPC PbPb

HIN-22-002
(to appear)

W. Li: Wed 11.10 am

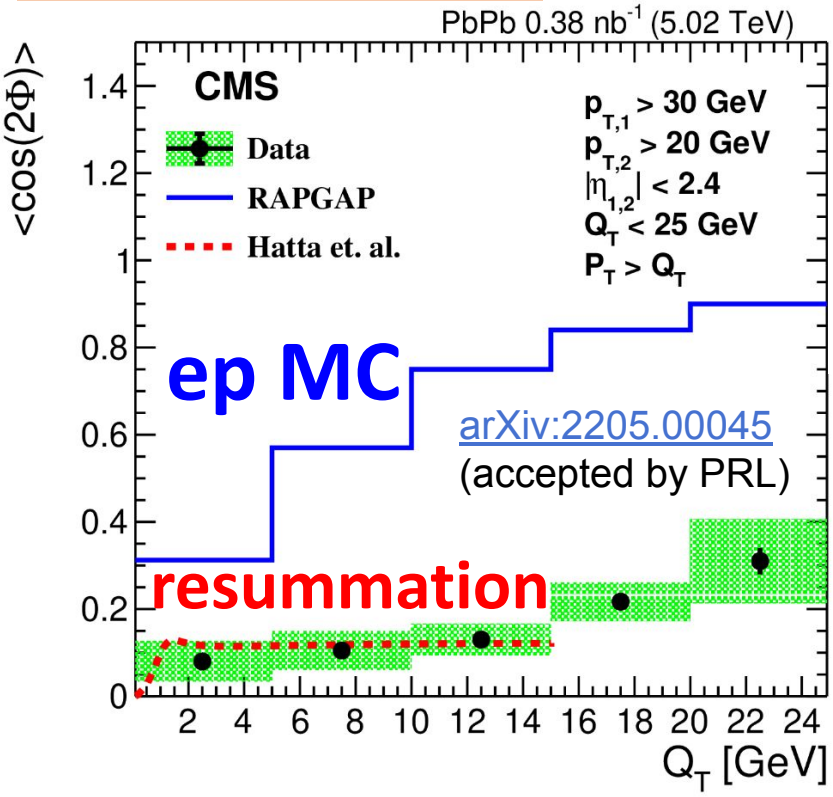


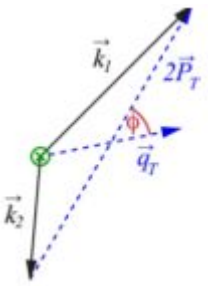


- **Using ZDCs, disentangled low- and high-γ energy contributions**
  - experimental uncertainty **correlated** across or $W^{Pb}_{\gamma N}$
    - flattening of coherent σ(J/ψ) vs. $W^{Pb}_{\gamma N}$ not predicted by models
- **An unprecedentedly low-*x* gluon regime is probed (10^{-4}–10^{-5})**
  - LHC data seem to consistently point to a common *x* evolution

Angular correlations in excl. dijet and γp events

S. Behera: Wed 3.20 pm



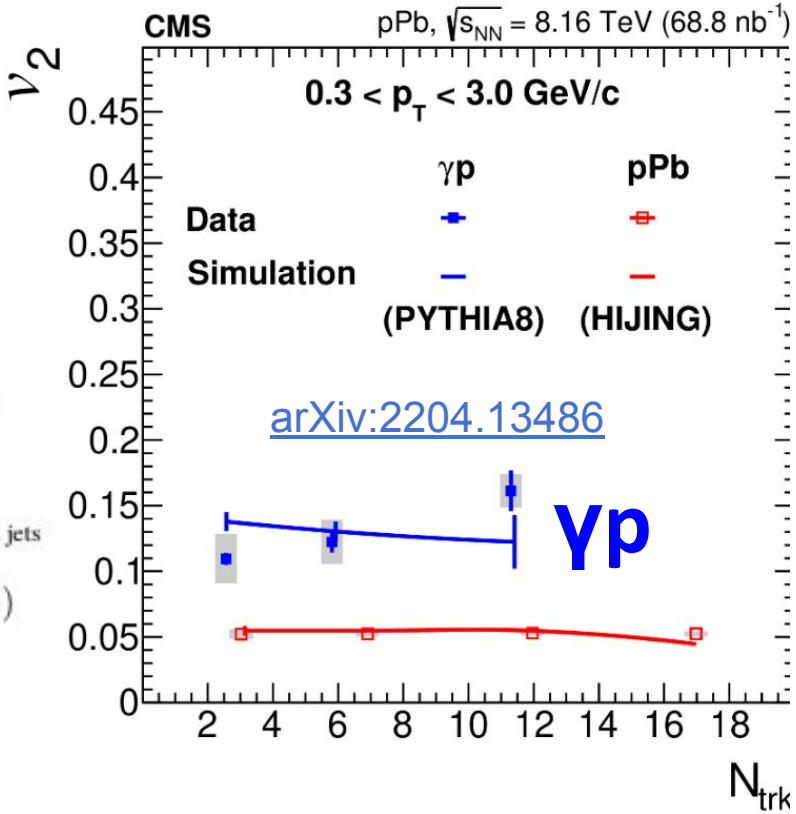


Vector sum of 2 jets:

$$\vec{Q}_T = \vec{k}_1 + \vec{k}_2$$

Vector difference of 2 jets

$$\vec{P}_T = \frac{1}{2}(\vec{k}_1 - \vec{k}_2)$$



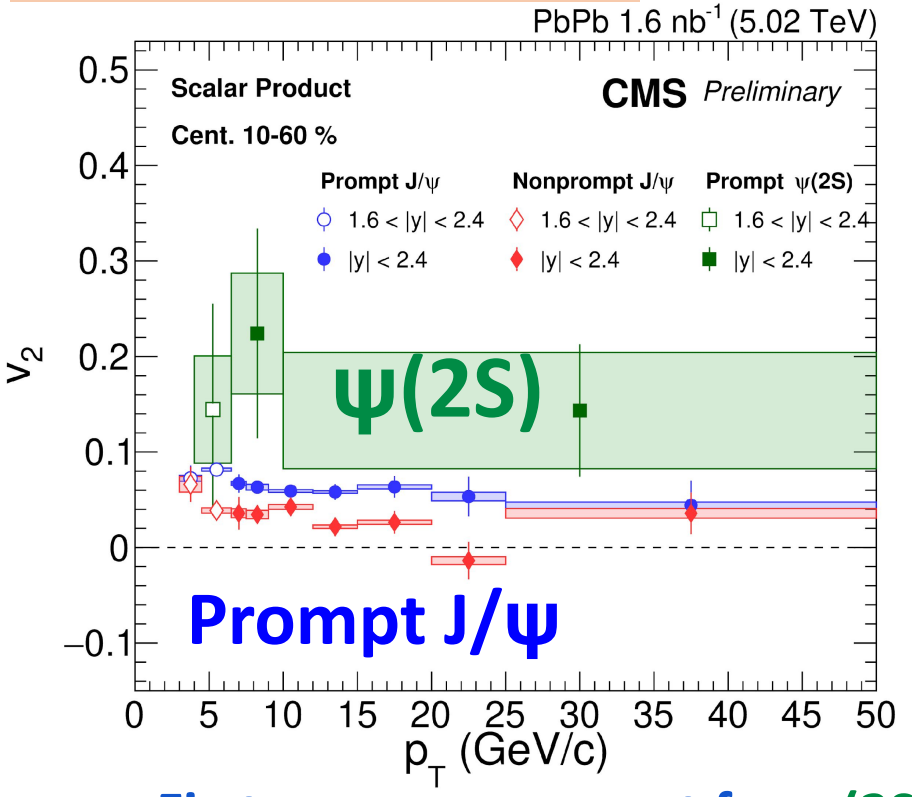
- **<cos(2Φ)> for exclusive dijets not well described by MC tuned in ep**
  - sensitive to primordial asymmetry due to the linearly polarized gluons
- **Bridging large with exceedingly small systems**
  - PYTHIA8 describes v_2 in γp too ⟶ jet-like correlations still dominate

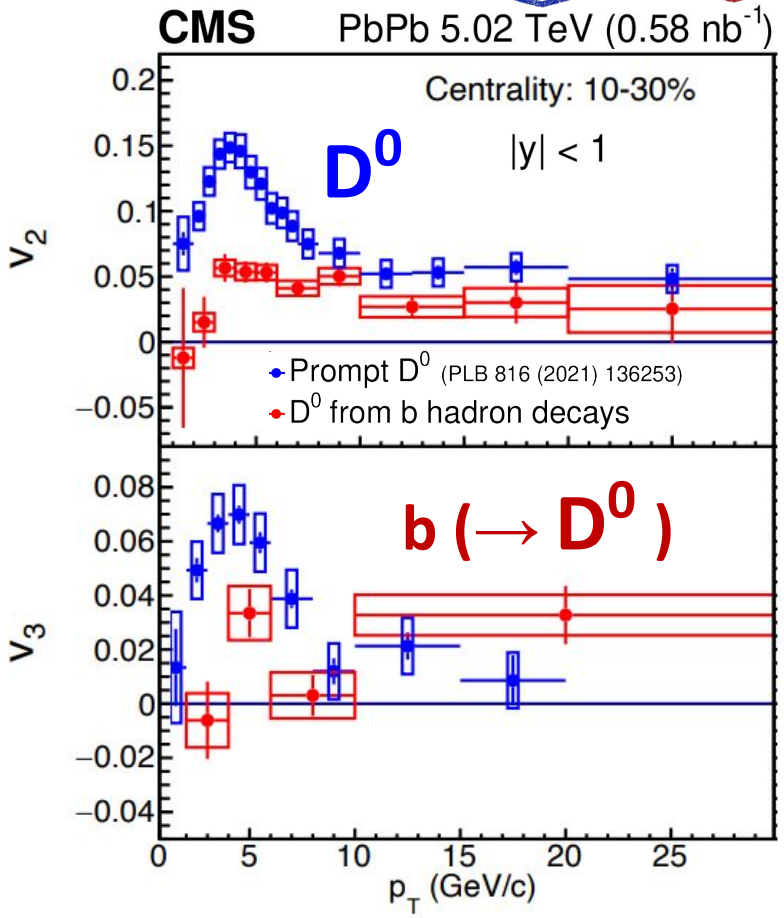
Heavy quarks and quarkonia

Heavy flavor flow in PbPb

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

G. Oh: Tue 11.50 am
M. Stojanovic: Wed 2.00 pm



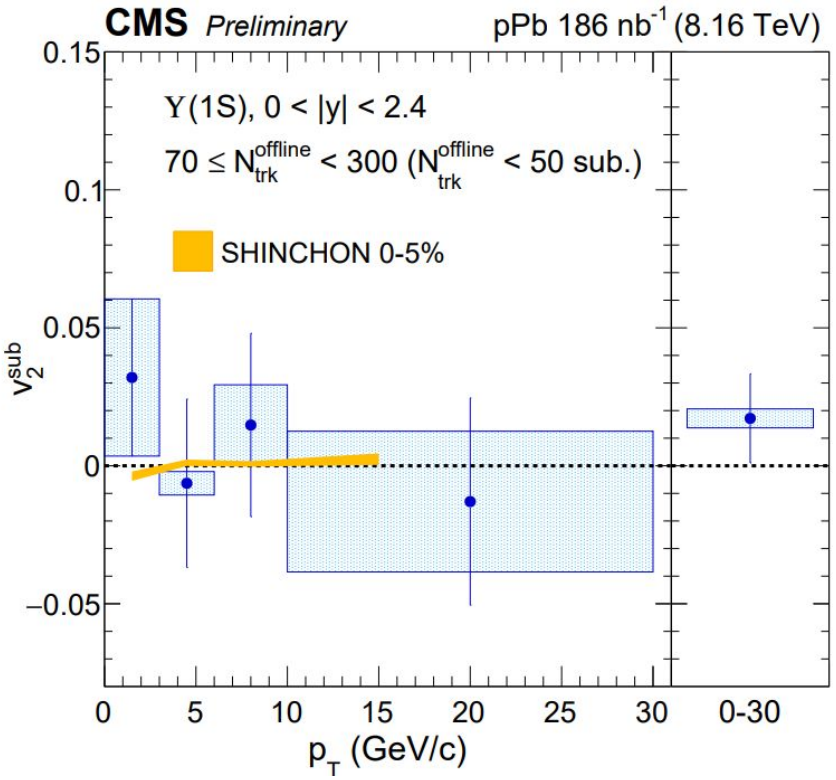


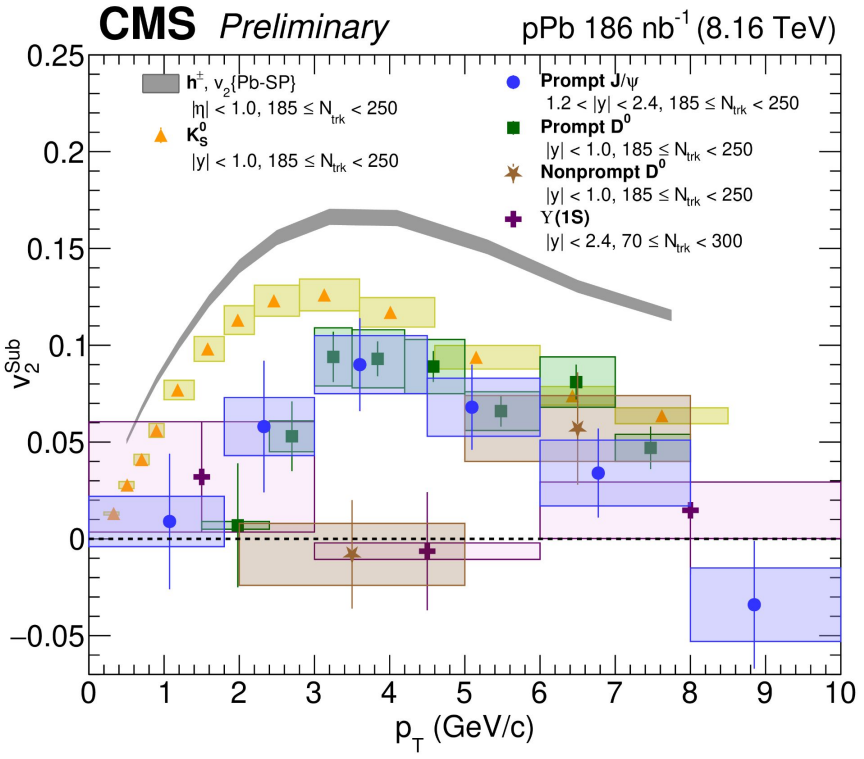
- **First $v_{2,3}$ measurement for ψ(2S)**
  - indication of ψ(2S) v_2 > **prompt J/ψ** v_2 → ψ(2S) from recombination at later stage?
- **First v_2 for b (→ D^0); b quark and D^0 meson p_T well correlated**
  - **charm** > b (→ D^0) v_2, whereas Υ(1S), Υ(2S) $v_2 \approx 0$
  - evidence for b (→ D^0)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

Heavy flavor flow in high-multiplicity pPb

CMS-PAS-HIN-21-001

K. Lee: Tue 11.30 am



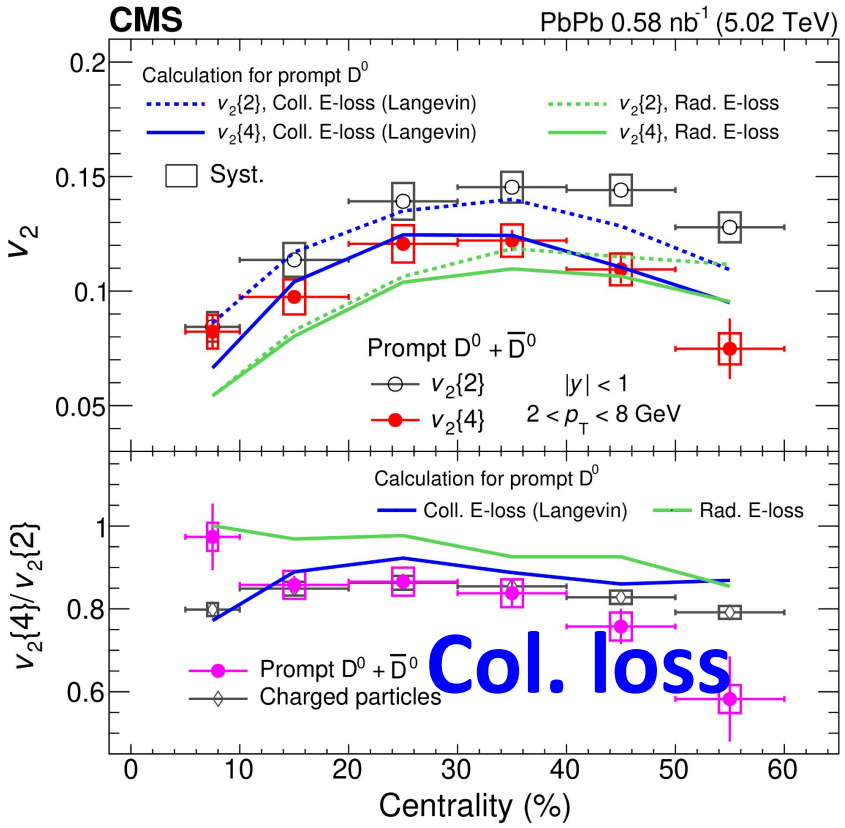


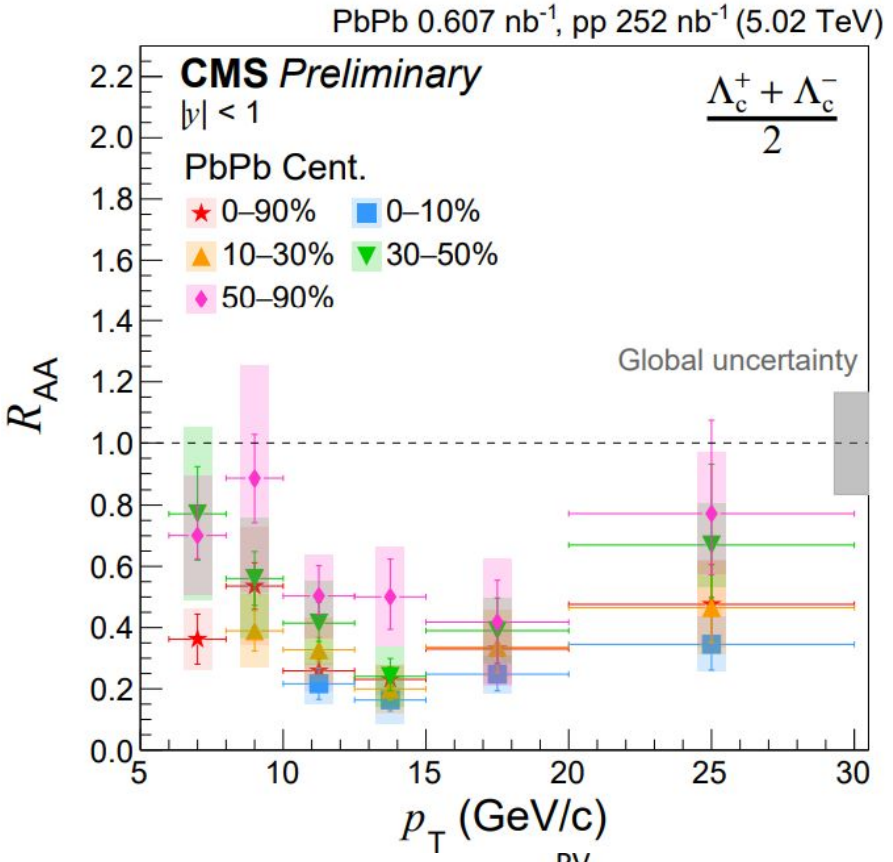
- **First v_2 measurement for Y(1S)**
  - $v_2 \approx 0$ up to 30 GeV(!), similar to a model with final-state interactions only
- **Bridging HF flow measurements in large & small systems**
  - clear **mass hierarchy**: heavier particles flow less
  - open question: do open/closed b hadrons flow in pPb?

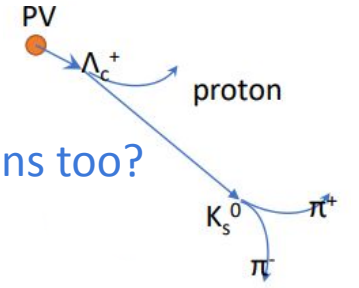
Charm quark energy loss in PbPb

S. Chandra, M. Stojanovic: Poster
M. Stojanovic, Wed 2.00 pm

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





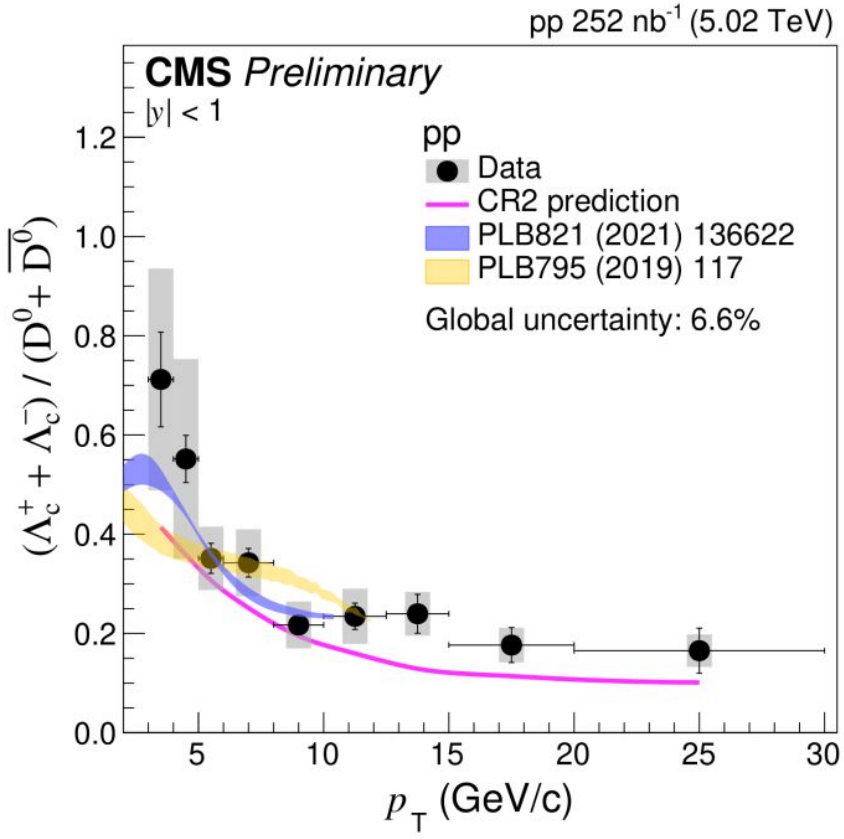


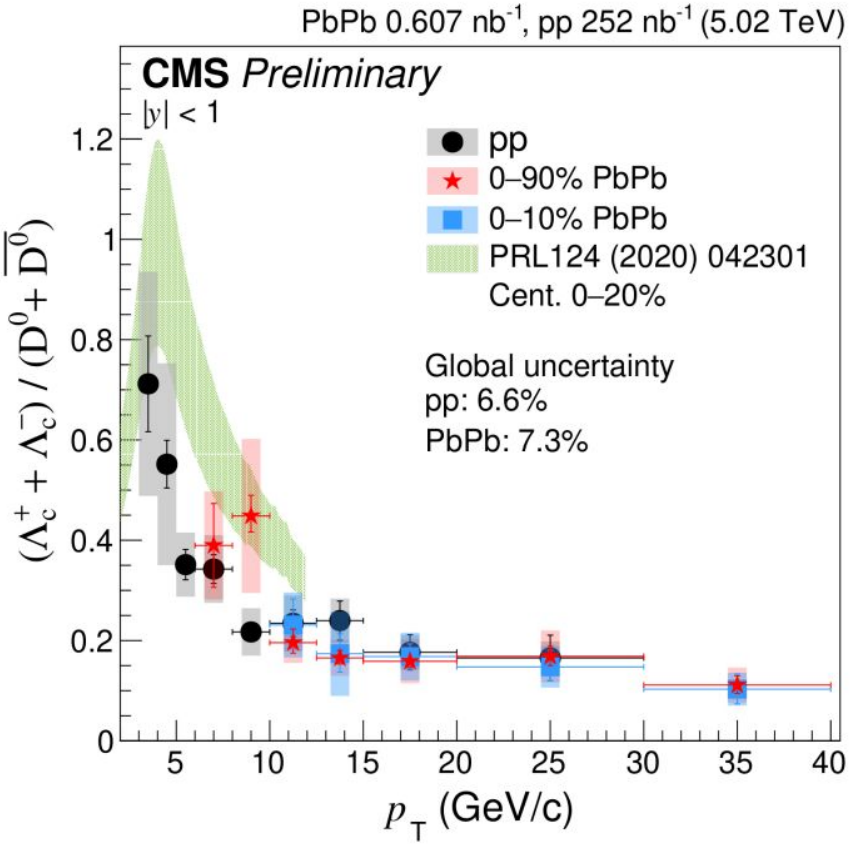
- **First high-precision v_2{4}/v_2{2}(!)**
  - compare D^0 to **light** flavor → v_2 fluctuations due to en. loss fluctuations too?
- **HF en. loss measurement with Λ_c^+ R_{AA}**
  - Large suppression but with min R_{AA} at ≈ 14 GeV contrary to other HF measurements

Charm quark hadronization in pp and PbPb

CMS-PAS-HIN-21-004

Y. Zhang: Tue 5.30 pm
S. Chandra, M. Stojanovic: Poster



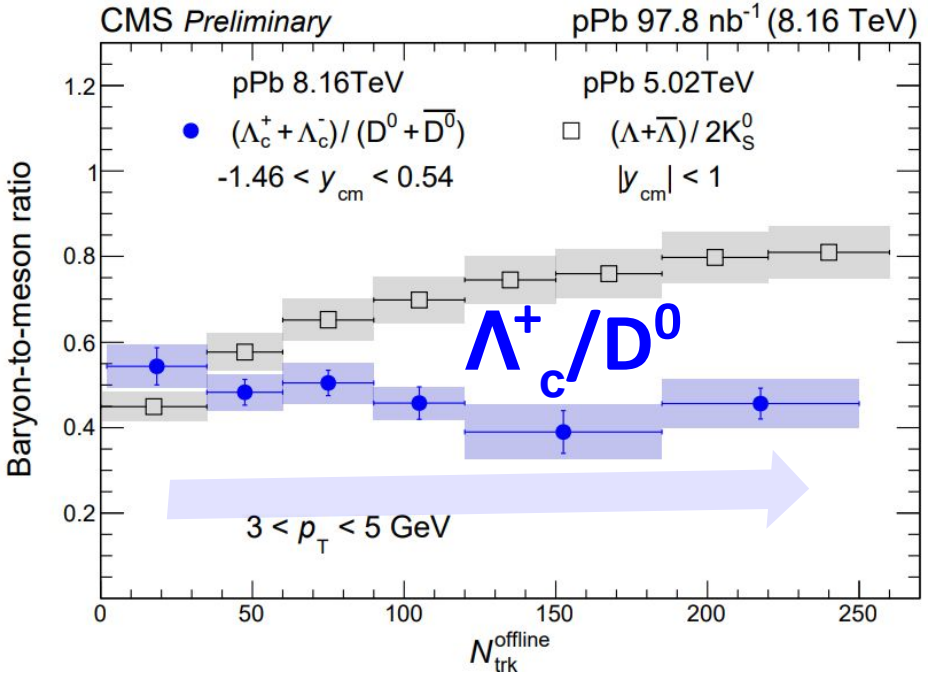


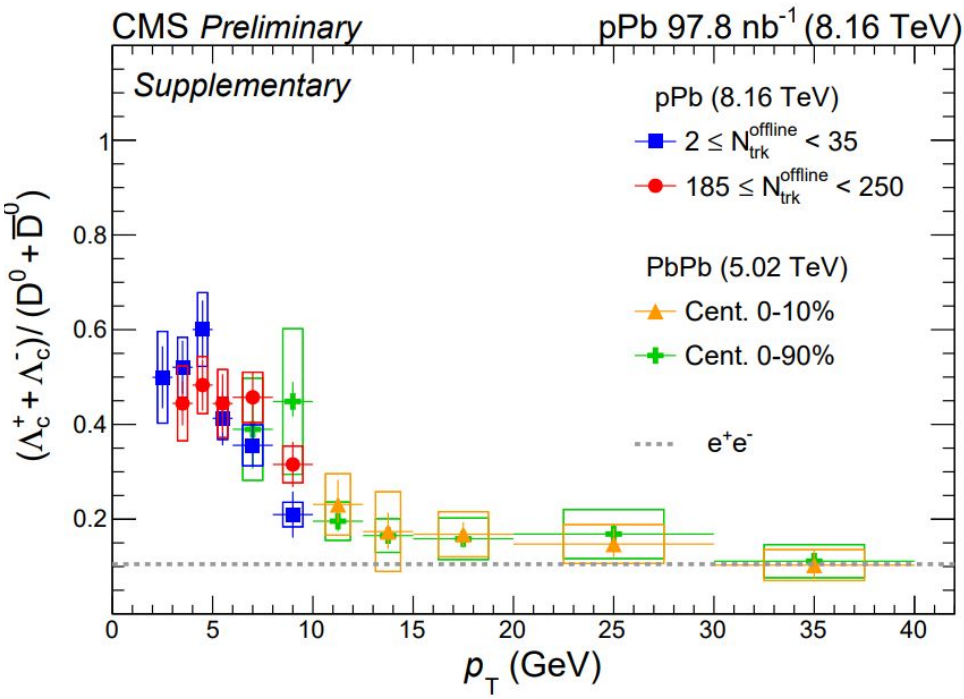
- **PYTHIA8+CR describes Λ_c^+/D^0 at p_T <10 GeV in pp, similar to models**
  - containing decays of **excited c baryons**; involving **coalescence and fragmentation**
- **Extending the p_T (<40 GeV) and centrality (0–90%) reach in PbPb**
  - Λ_c^+/D^0 in pp and PbPb consistent → no significant contribution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

Charm quark hadronization in pPb and PbPb

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

Y. Zhang: Tue 5.30 pm
S. Chandra, M. Stojanovic: Poster



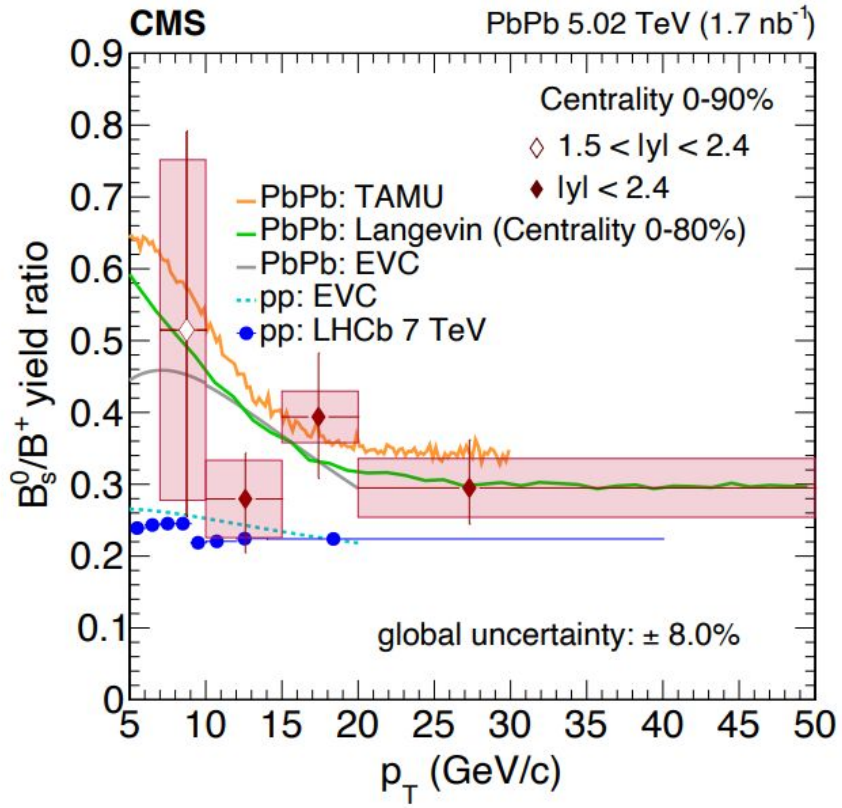


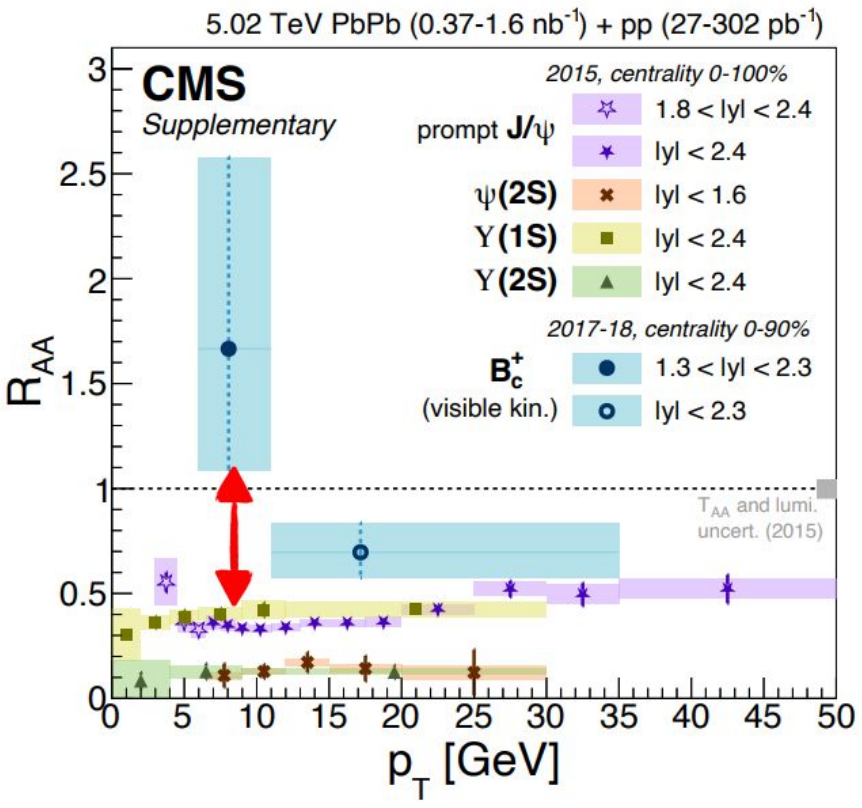
- **First measurement of Λ_c^+/D^0 vs N_{trk}**
  - different trend compared to **strange sector**, i.e., small dependence
- **Extending the system (pPb 8 TeV), p_T (<40 GeV), and centrality (0–90%)**
  - Λ_c^+/D^0 in pPb and MB PbPb consistent at intermediate p_T
  - at high p_T MB and central PbPb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

Beauty hadronization in PbPb

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

Tzu-An Sheng: Thu 10.20 am



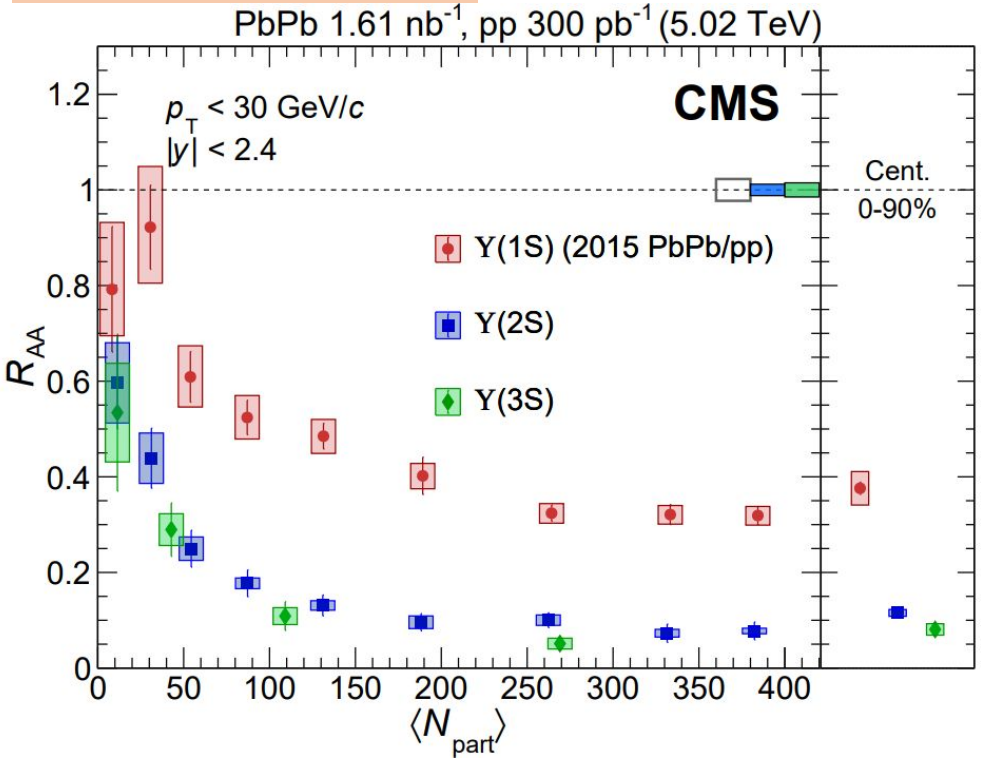


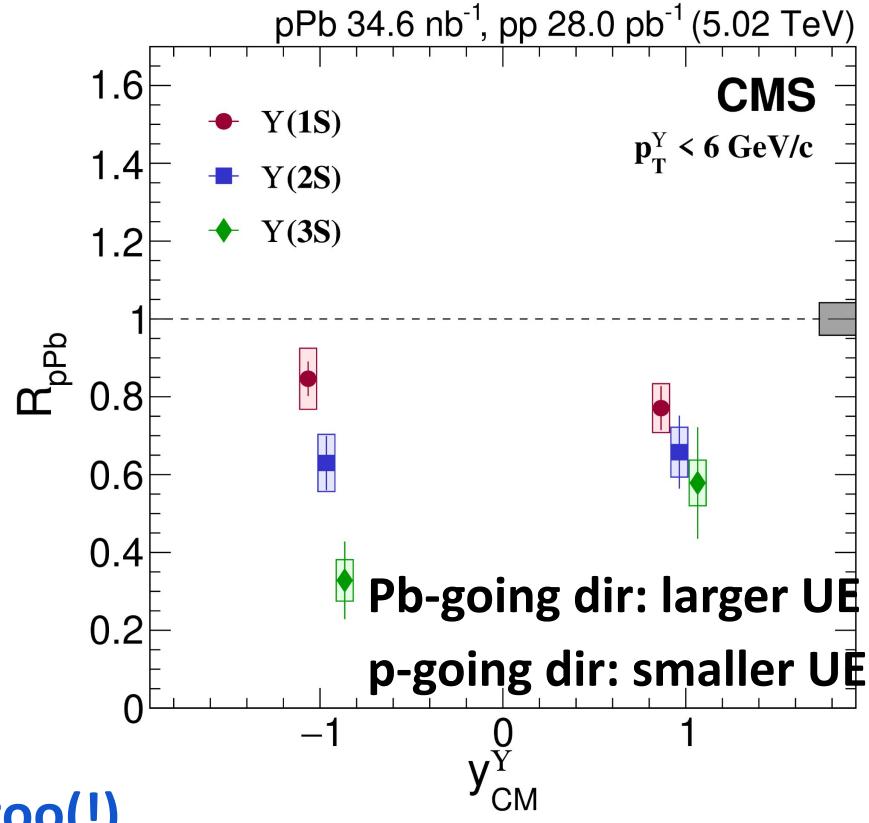
- **Observation** of B_s^0
  - indication of enhanced B_s^0/B^+ in PbPb to **pp** at low p_T
  - similar to models with recombination or coalescence
- **Observation** of B_c^+
  - flavor-dependent R_{AA} : at low/medium p_T: recombination of c and b

Y(ns) suppression in PbPb and pPb

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

J. Park: Tue 3.40 pm





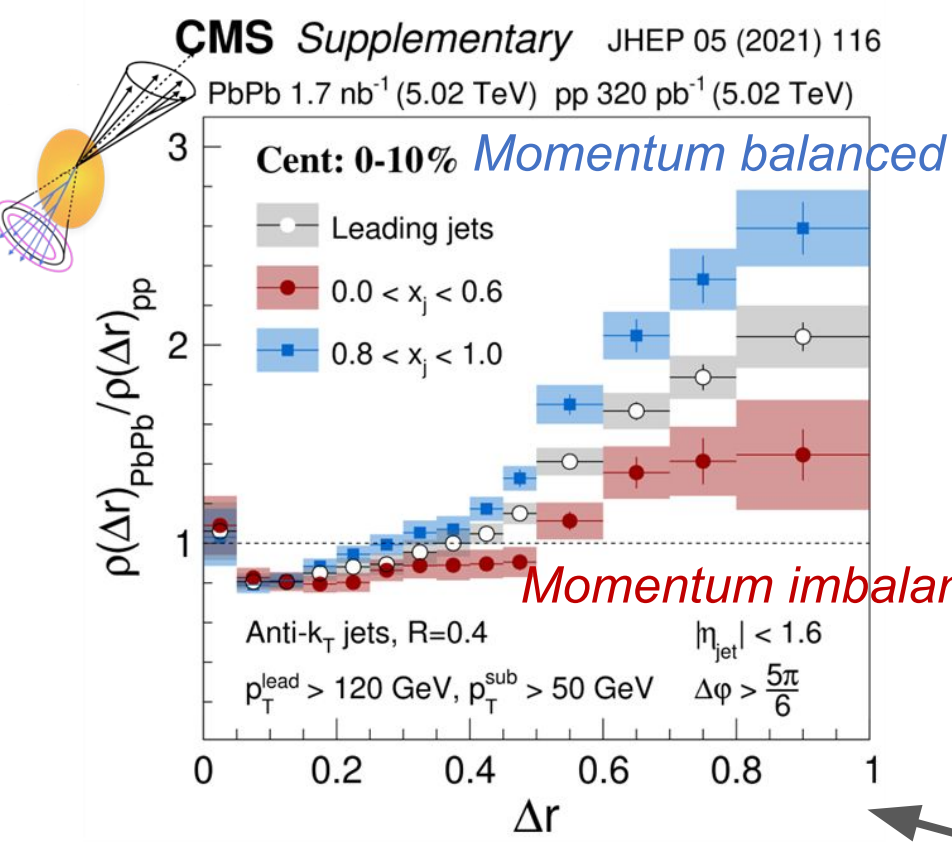
- **Observation of Y(3S) now in PbPb too(!)**
  - indication of ordered (sequential) suppression up to Y(3S) in both systems
  - strong challenge for models to reproduce Y(3S) $R_{AA}>0$
- **Excited states set strong constraints on models**
  - In the study of initial-/final-state effects

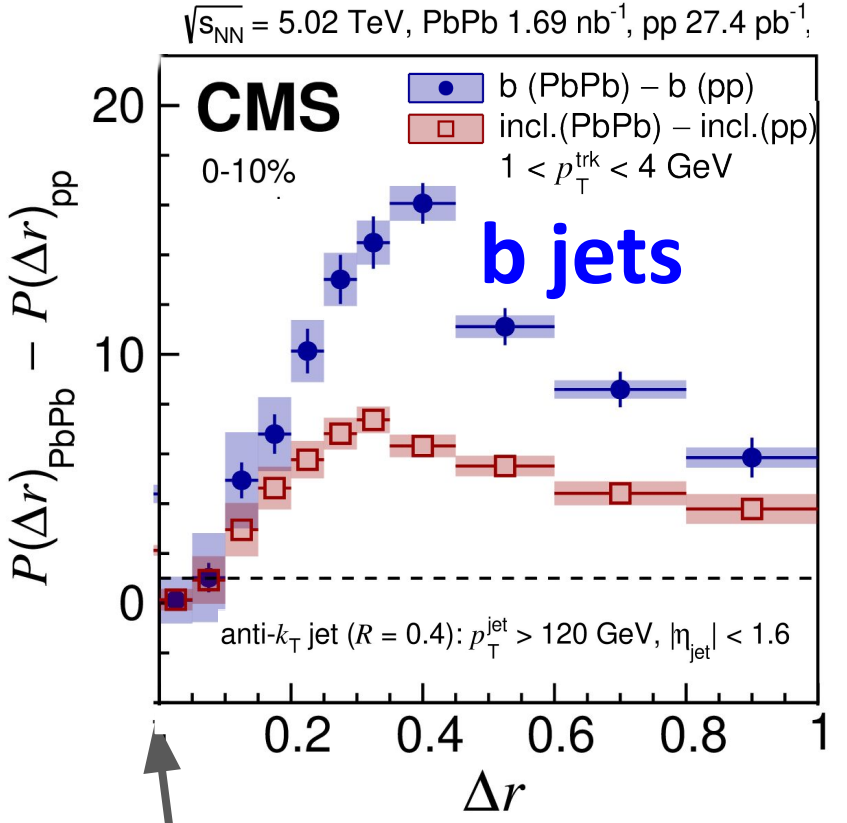
Medium modifications

How energy loss is distributed?

L. Kalipoliti: Wed 12.10 pm

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

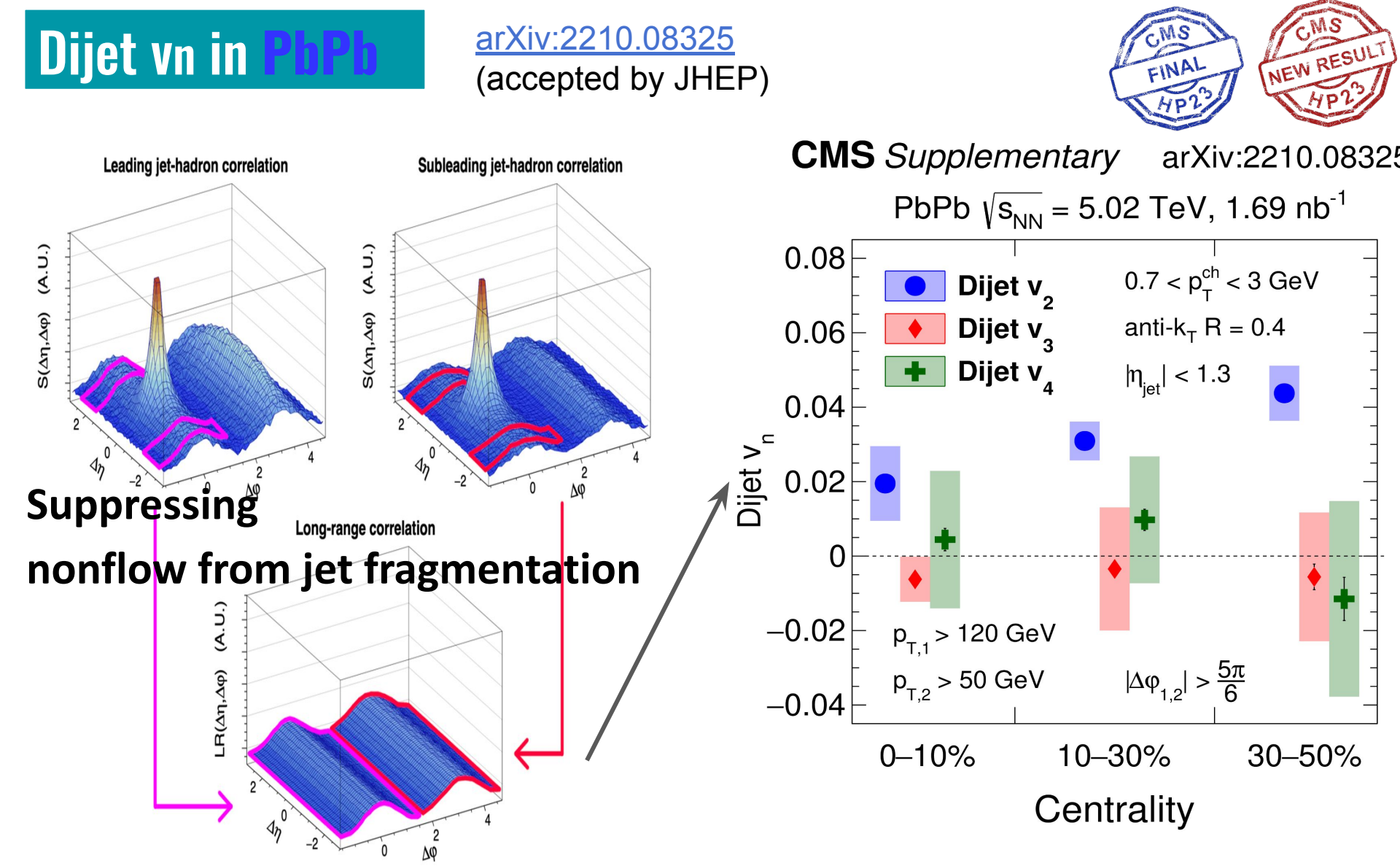




- **Jet shape: radial profile of particles in dijets, b jets**
  - in-medium path length for leading jets is larger when $x_J \approx 1$ (vice versa for subleading)
  - for b jets
    - small-Δr depletion: sensitive to dead-cone effect
    - large-Δr enhancement: enhanced medium response to b quarks

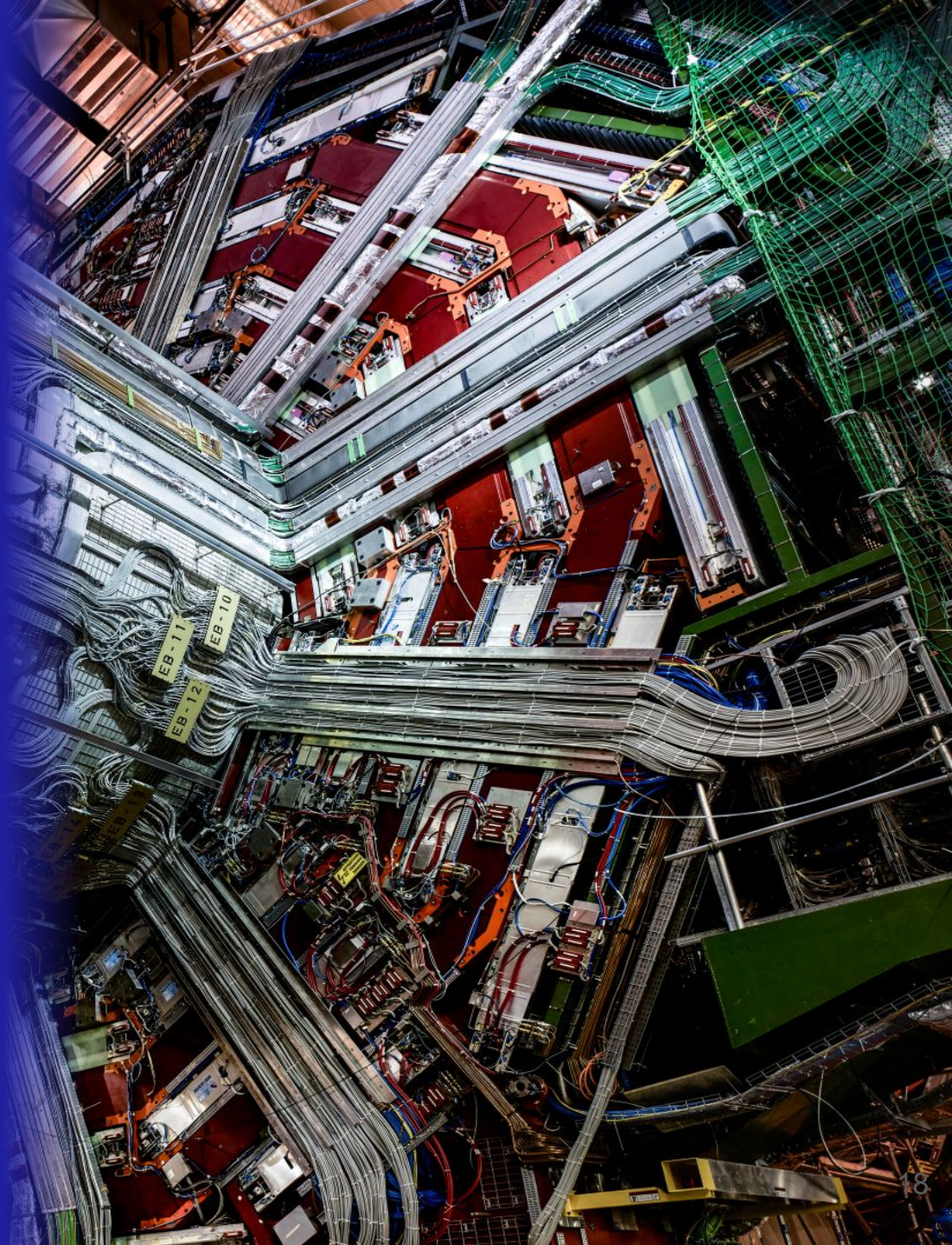
Dijet vn in PbPb

arXiv:2210.08325
(accepted by JHEP)



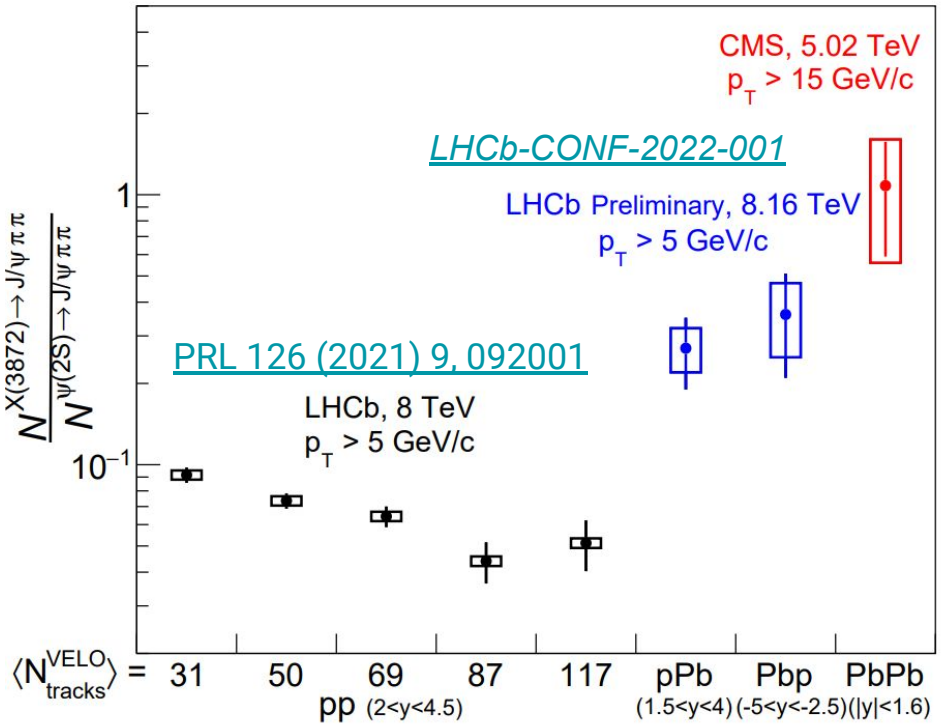
- **Path-length dependent energy loss & its fluctuations**
  - dijet v_2>0 with expected centrality dependence; consistent with high-p_T hadron v_2
  - dijet v_3, v_4≈0 → not yet(?) sensitive to initial-state/en. loss fluctuations

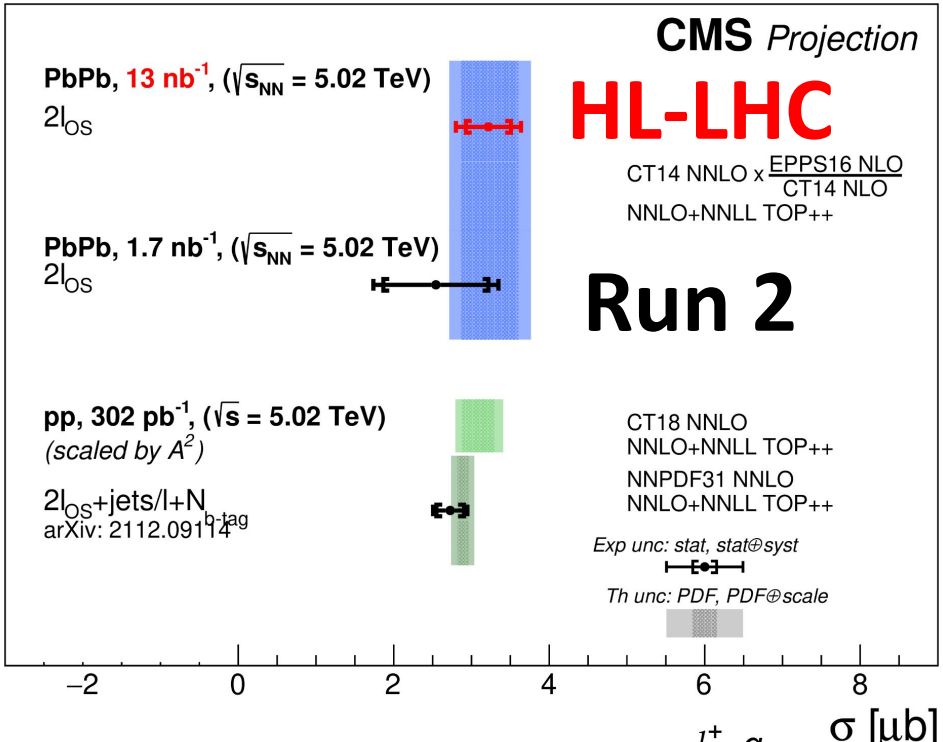
Rare/BSM probes

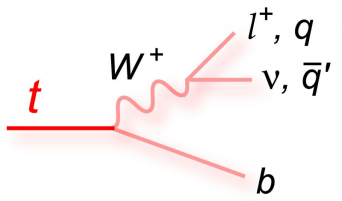


Exotic hadrons and top quarks in PbPb

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



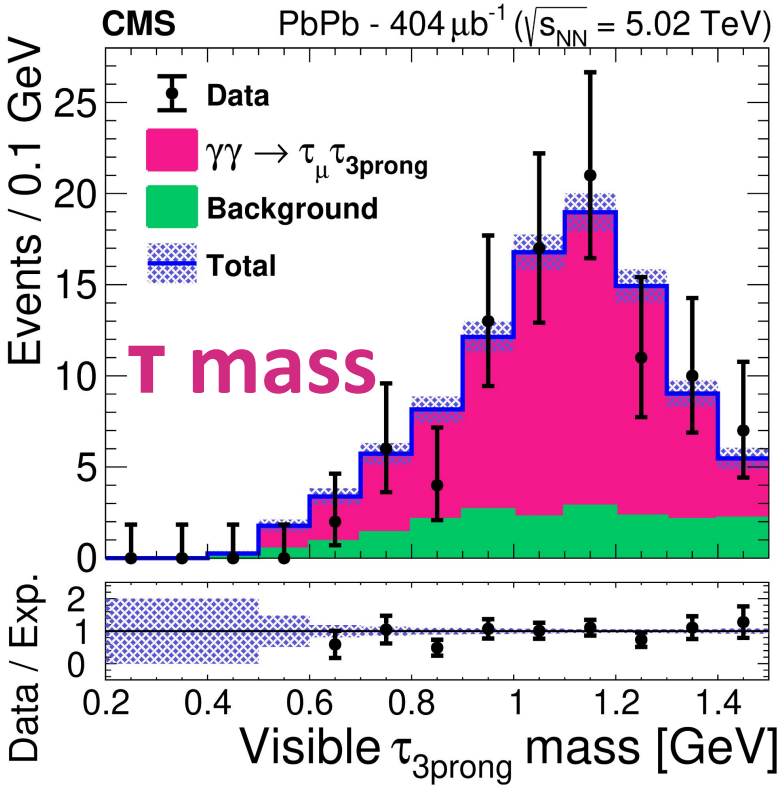


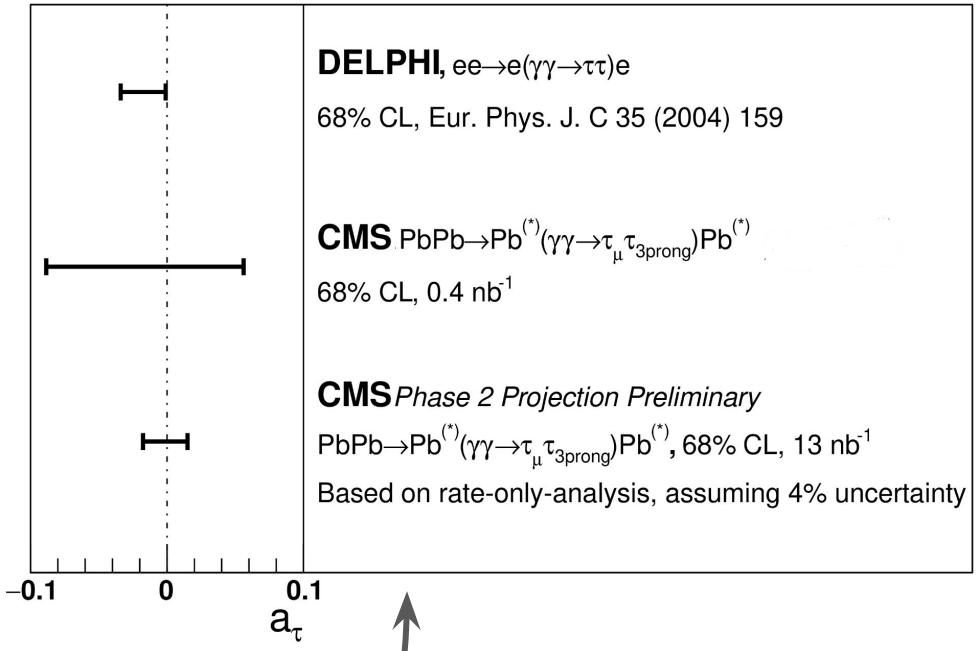


- **Evidence of X(3872) production**
  - its quark configuration remains elusive
  - X(3872)/ψ(2S): non-monotonic N_{trk} trend in pp & more pronounced in larger systems?
- **Evidence of top quark pair production**
  - uncertainty at HL-LHC competes with nPDF uncertainty; tool for QGP time profile

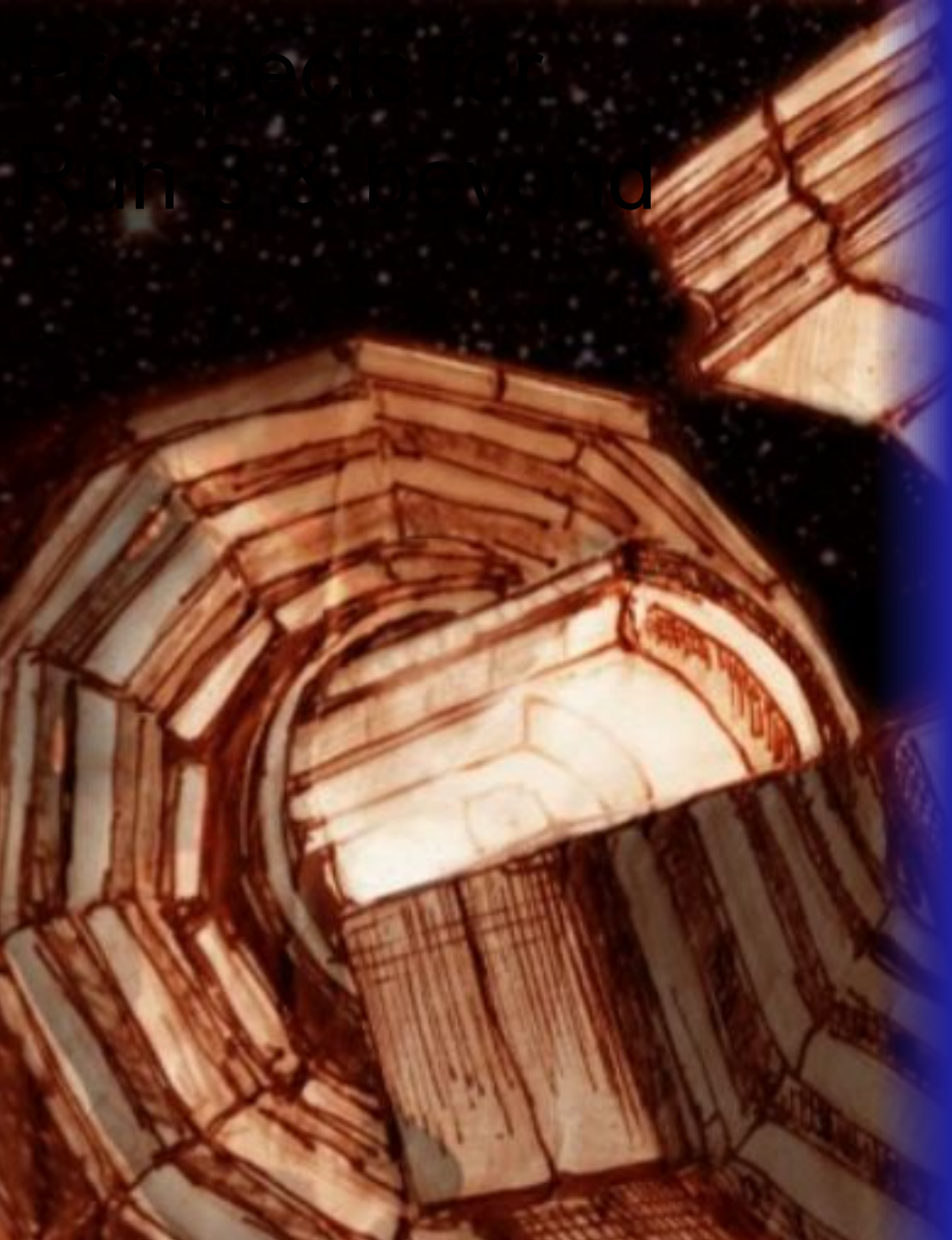
τ lepton pair production in UPC PbPb

arXiv:2206.05192
(accepted by PRL, editor's suggestion)





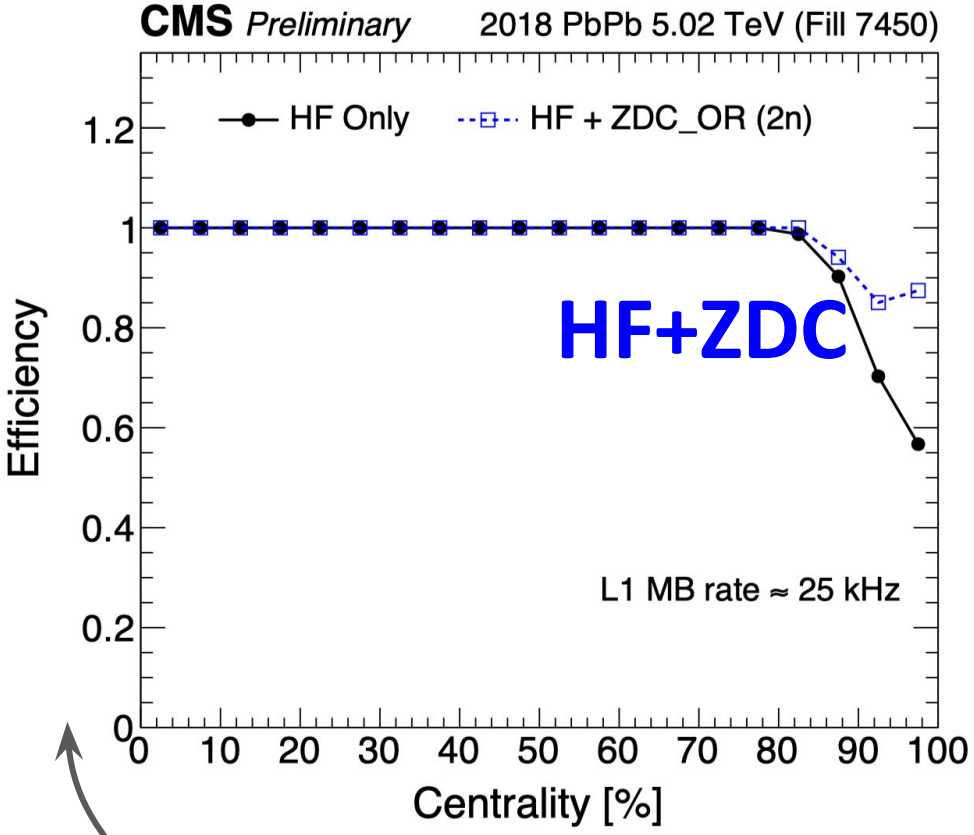
- **Observation of γγ → τ$^+$τ$^-$ at LHC**
  - obtained only with a single, clean final state
- **Model-dependent constraints on a$_τ$ obtained**
  - further improvements on projected **a$_τ$** at HL-LHC with more final states

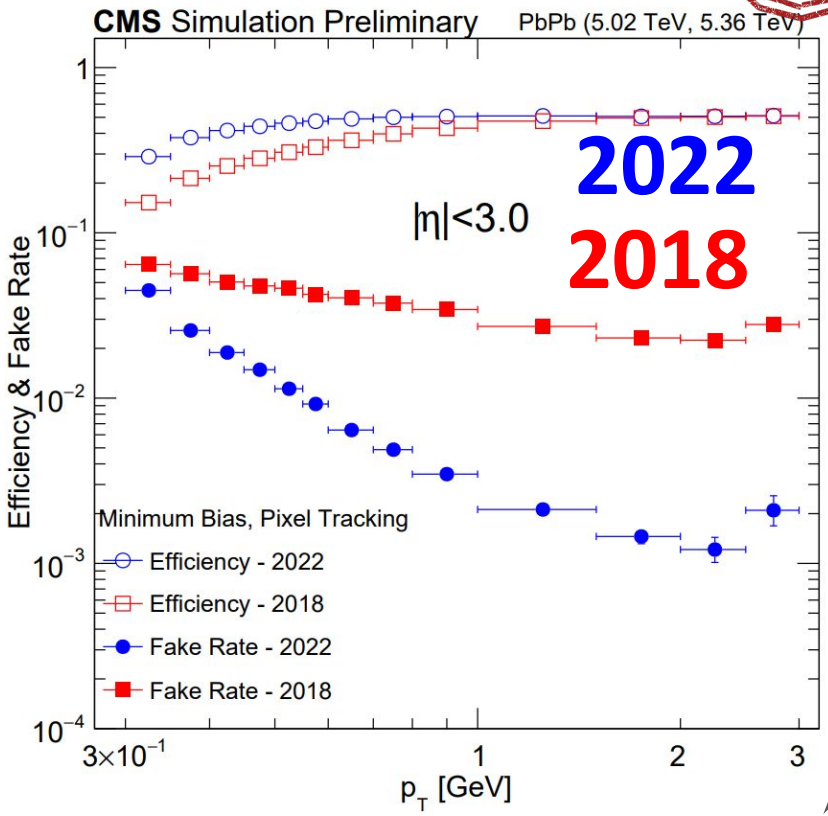


Prospects for Run 3 & beyond

Improvements in Run 3 PbPb

CMS-DP-2023-011
(to appear)





- **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

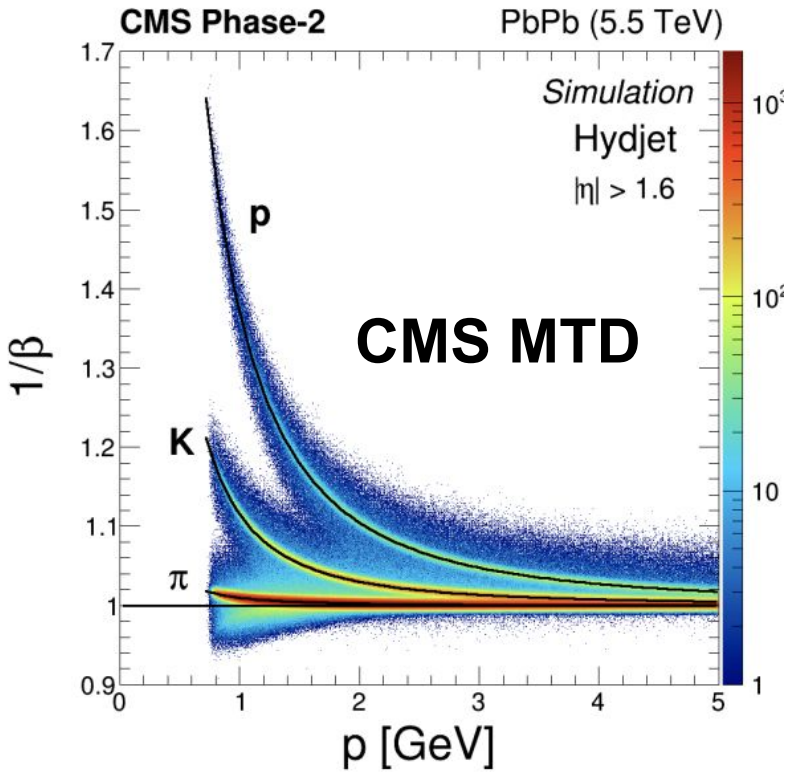
Yen-Jie Lee: Tue 2.00 pm

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

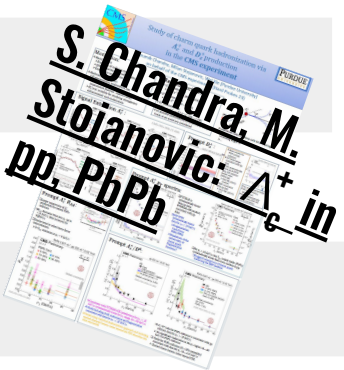


- **Main batch of CMS Upgrades in Run 4**
  - Among others, unique hermetic particle identification coverage by CMS MTD
- **Physics requests documented in past years over a diverse set of reports**
  - WG5 HL-LHC, ATLAS+CMS Snowmass'22, QCD Town Meeting WP, CMS HIN

Summary–the physics

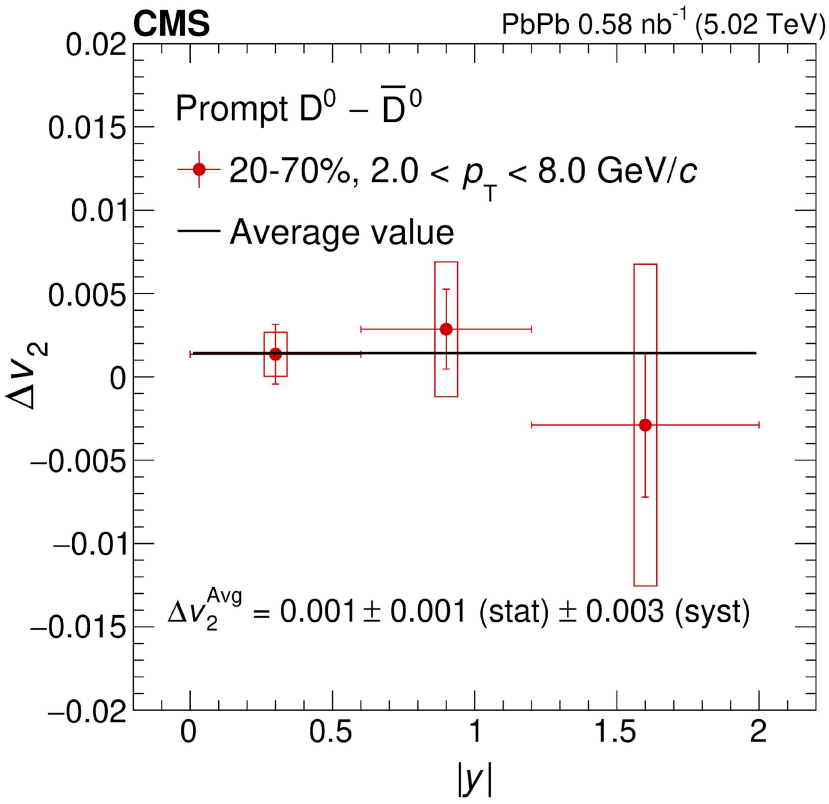
- **Early dynamics and nPDFs**
  - E/W bosons, dijets, top quarks sensitive to nPDFs at different (x,Q^2)
  - very low-*x* gluon regime probed by J/ψ in UPC PbPb
  - theo. dev. needed to extract gluon polarization from excl. dijets
- **Heavy quarks and quarkonia**
  - indication of ψ(2S) v_2 > prompt J/ψ v_2; $v_2\{4\}/v_2\{2\}$ for D^0
  - extending the system (pPb 8 TeV), p_T, and centrality reach for Λ_c^+
  - evidence for b ($\rightarrow D^0$) v_3 >0; Y's v_2 ≈0 in both pPb and PbPb
  - observation of B_s^0, B_c^+, and R_{AA}!=0 for Y(3S)
- **Medium modifications**
  - jet shapes with dijets and b jets input for a more precise energy loss
  - path-length dependent energy loss & its fluctuations with dijet vn
- **Rare/BSM probes**
  - evidence for the X(3872) exotic meson and top quark in PbPb
  - τ leptons as a portal to BSM physics–probing a_T
- **Improved Run 3 & excellent prospects in Run 4**

	Jets and their modification	Heavy flavor and quarkonia	Early-Time Dynamics & nPDFs	Future Facilities
Tue, 11.30 am		K. Lee: $\Upsilon(1S)$, J/ψ v_2 in pPb		
Tue, 11.50 am		G. Oh: J/ψ, $\psi(2S)$ v_n in PbPb		
Tue, 2.00 pm				Y-J Lee: Phase II Opportunities
Tue, 3.40 pm		J. Park: $\Upsilon(nS)$ $R_{pA,AA}$ in pPb, PbPb		
Tue, 5.30 pm		Y. Zhang: Λ_c^+ in pPb		
Wed, 11.10 am			W. Li: J/ψ in UPC	
Wed, 12.10 pm	L. Kalipoliti: b jet shapes in PbPb			
Wed, 2.00 pm		M. Stojanovic: D^0 in PbPb		
Wed, 3.20 pm			S. Behera: v_n in γp	
Thu, 10.20 am		Tzu-An Sheng: B_s^0 and B_c^+ in PbPb		



slides

Prompt D^0 - $\bar{D}^0$ production and v_2 fluctuations



PLB 816 (2021) 136253
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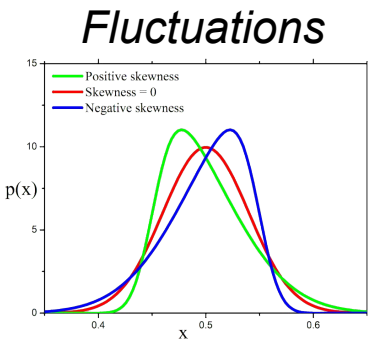

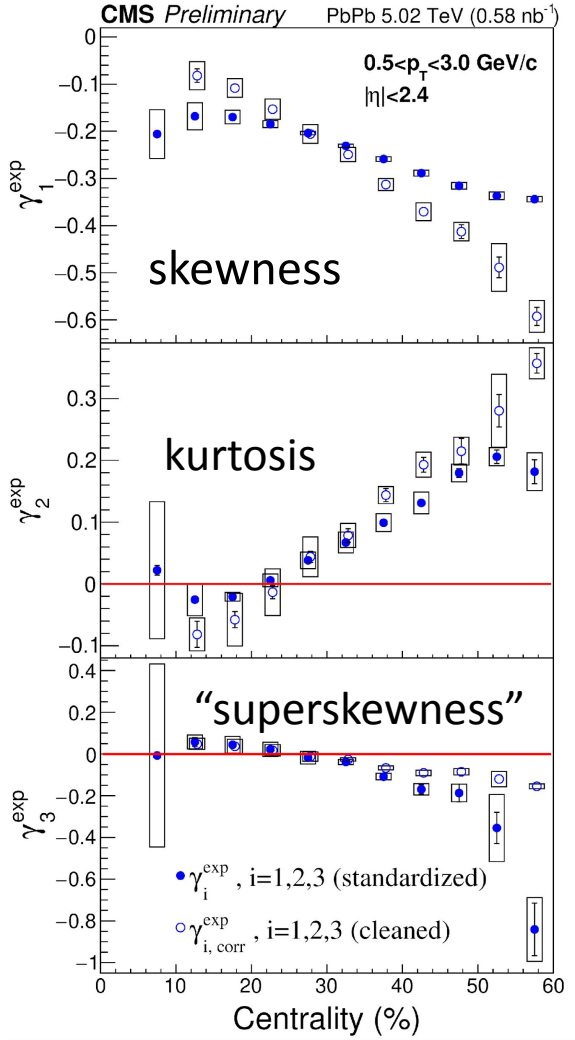

- **First y-dependent Δv_2 measurement for D^0**
  - searching for strong initial Coulomb field
- **Fine splitting up to v_2{10}(!)**
  - higher order moments (γ_{1-3}) in initial state revealed

Z/γ* & W production in pPb

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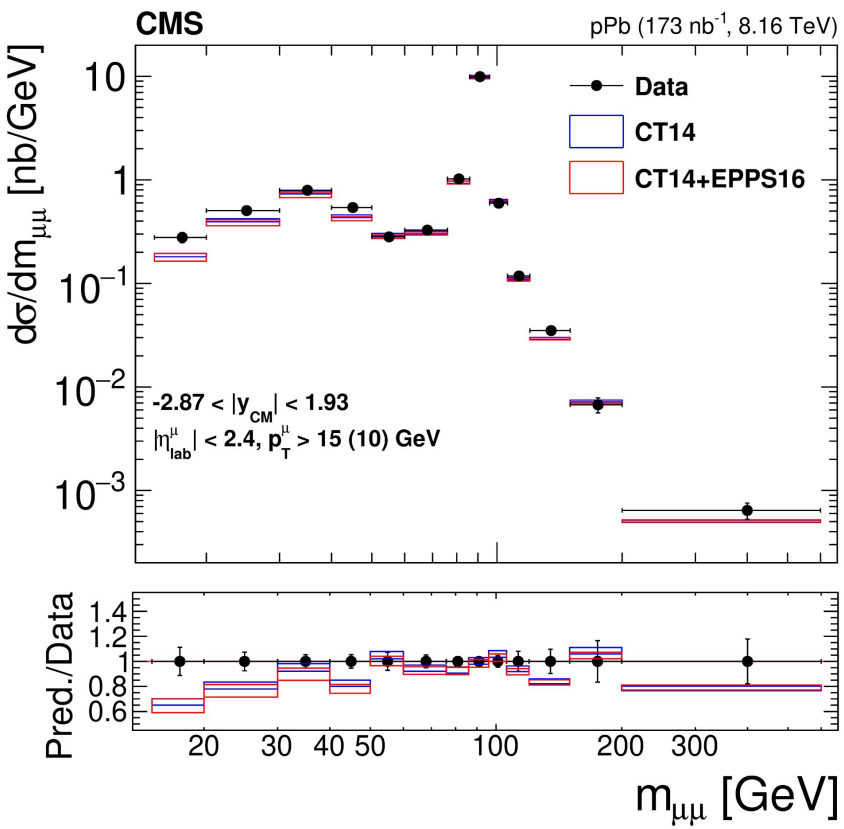
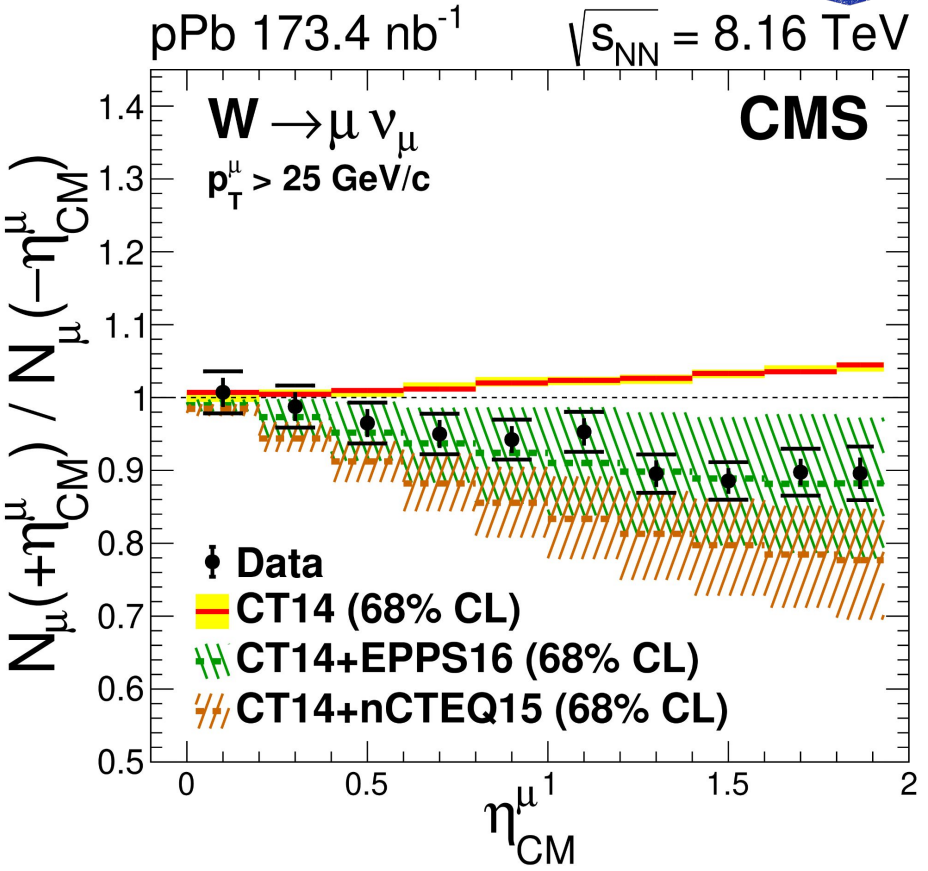




- **First Z/γ* study in an extended m$_{\mu\mu}$ range**
  - low m$_{\mu\mu}$ sensitive to NNLO corrections
  - on-shell production less well described: statistical fluctuations(?)
- **Observation of nuclear effects in W boson production**
  - included in all recent nPDF fits

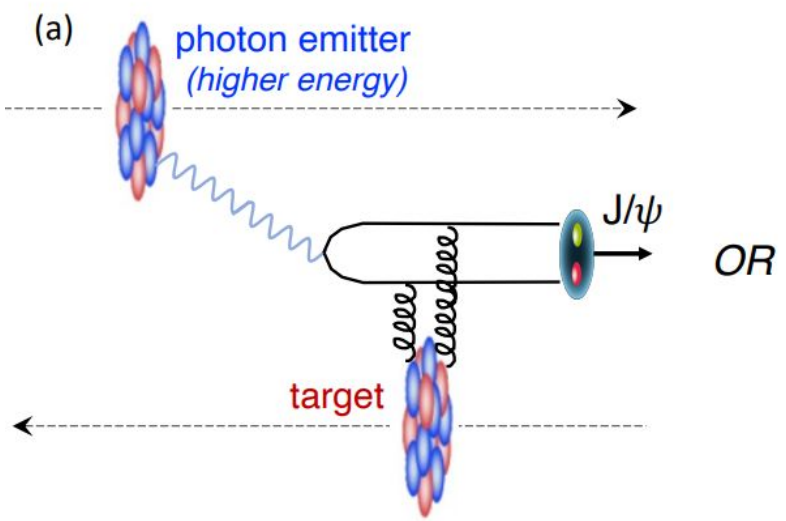
Key characteristics of the nPDF global fits

	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

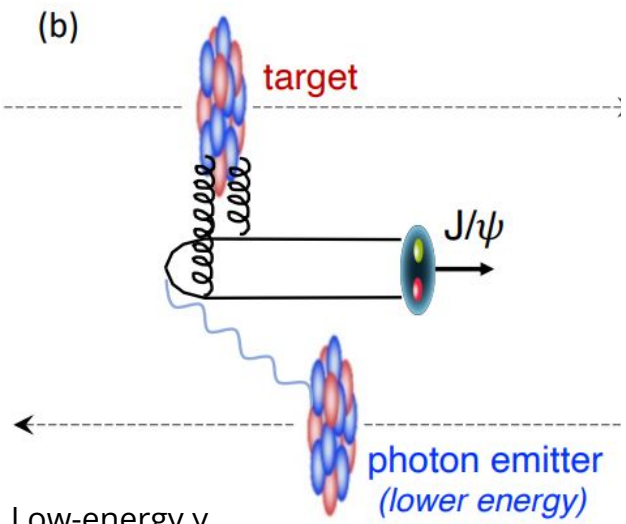
P. Paakkinen (DIS22)

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

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



OR



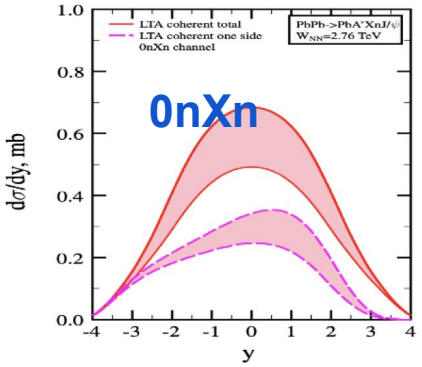
High-energy y

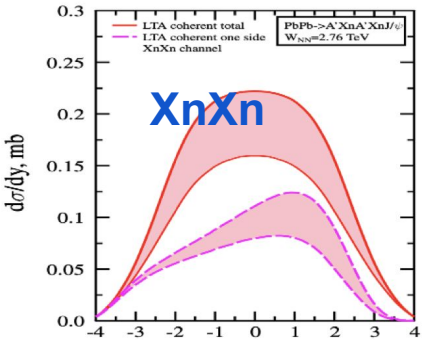
$$w_2 = \frac{M_{VM}}{2} e^{+y}$$

The issue

Low-energy y

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





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)

Jet quenching depends on jet radius?

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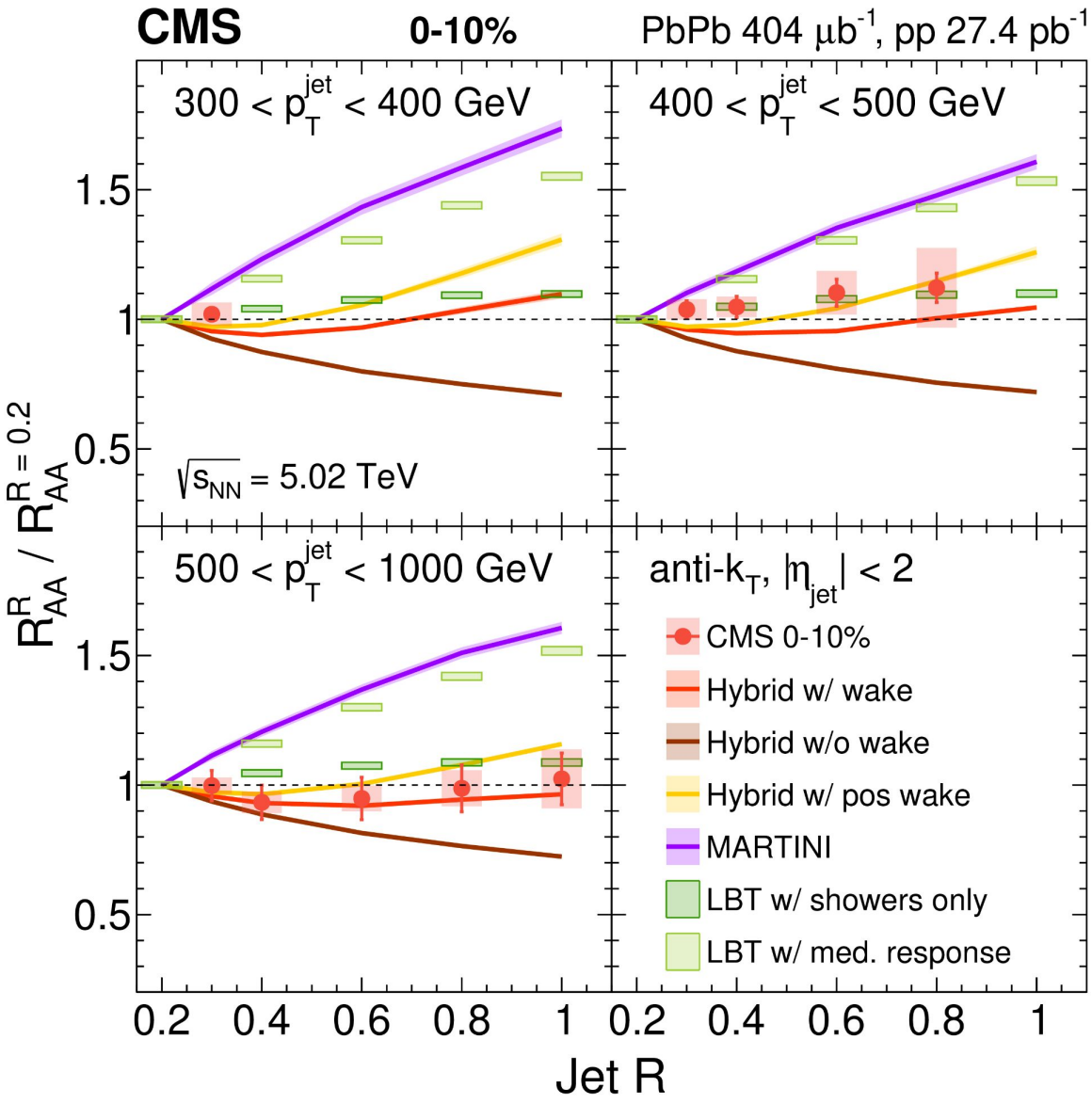

- Larger jet R ⟶ wider area to recover lost energy
  - but **R-independent** suppression seen
- Cross experiment effort
  - Different jet collections and UE treatment