Future Opportunities for Heavy-flavor and Quarkonia Measurements with CMS

Jing Wang (MIT)
For the CMS Collaboration

Quark-Gluon Plasma Characterisation with Heavy Flavour Probes (ECT*, Trento)
18 November, 2021

MIT HIG group's work was supported by US DOE-NP

Great Success So Far

Heavy Flavor Measurement Compilation Tool

Observable: RAA vs. pT

X-axis range: 0 - 50 Log x

Y-axis range: 0 - 1.5 Log y

Clear all | Random color | Checked only | e.g. open, baryon, lepton

	Prompt D^0	AuAu	200 GeV	STAR	0-10%	$\lvert y \rvert < 1$
	Prompt D^0	AuAu	200 GeV	STAR	10-40%	$\lvert y \rvert < 1$
	Prompt D^0	AuAu	200 GeV	STAR	40-80%	$\lvert y \rvert < 1$
	Prompt D^0	PbPb	5.02 TeV	CMS	0-100%	$\lvert y \rvert < 1$
	Prompt D^0	PbPb	5.02 TeV	CMS	0-10%	$\lvert y \rvert < 1$
	Prompt D_s	PbPb	5.02 TeV	ALICE	0-10%	$\lvert y \rvert < 0.5$
	Prompt D_s	PbPb	5.02 TeV	ALICE	30-50%	$\lvert y \rvert < 0.5$
	Prompt D_s	PbPb	5.02 TeV	CMS	0-100%	$\lvert y \rvert < 1$
New!	Prompt D	PbPb	5.02 TeV	ALICE	0-10%	$\lvert y \rvert < 0.5$
New!	Prompt D	PbPb	5.02 TeV	ALICE	30-50%	$\lvert y \rvert < 0.5$
	Prompt J/ψ	PbPb	2.76 TeV	CMS	0-100%	$1.6 < \lvert y \rvert < 2.4$
	Prompt J/ψ	PbPb	2.76 TeV	CMS	0-100%	$\lvert y \rvert < 2.4$
	Prompt J/ψ	PbPb	5.02 TeV	ATLAS	0-10%	$\lvert y \rvert < 2$
	Prompt J/ψ	PbPb	5.02 TeV	ATLAS	0-80%	$\lvert y \rvert < 2$
	Prompt J/ψ	PbPb	5.02 TeV	ATLAS	20-40%	$\lvert y \rvert < 2$
	Prompt J/ψ	PbPb	5.02 TeV	ATLAS	40-80%	$\lvert y \rvert < 2$
	Prompt J/ψ	PbPb	5.02 TeV	CMS	0-100%	$1.6 < \lvert y \rvert < 2.4$
	Prompt J/ψ	PbPb	5.02 TeV	CMS	0-100%	$1.8 < \lvert y \rvert < 2.4$
	Prompt J/ψ	PbPb	5.02 TeV	CMS	0-100%	$\lvert y \rvert < 0.6$
	Prompt J/ψ	PbPb	5.02 TeV	CMS	0-100%	$\lvert y \rvert < 1.6$

Jing Wang jing.wang@cern.ch

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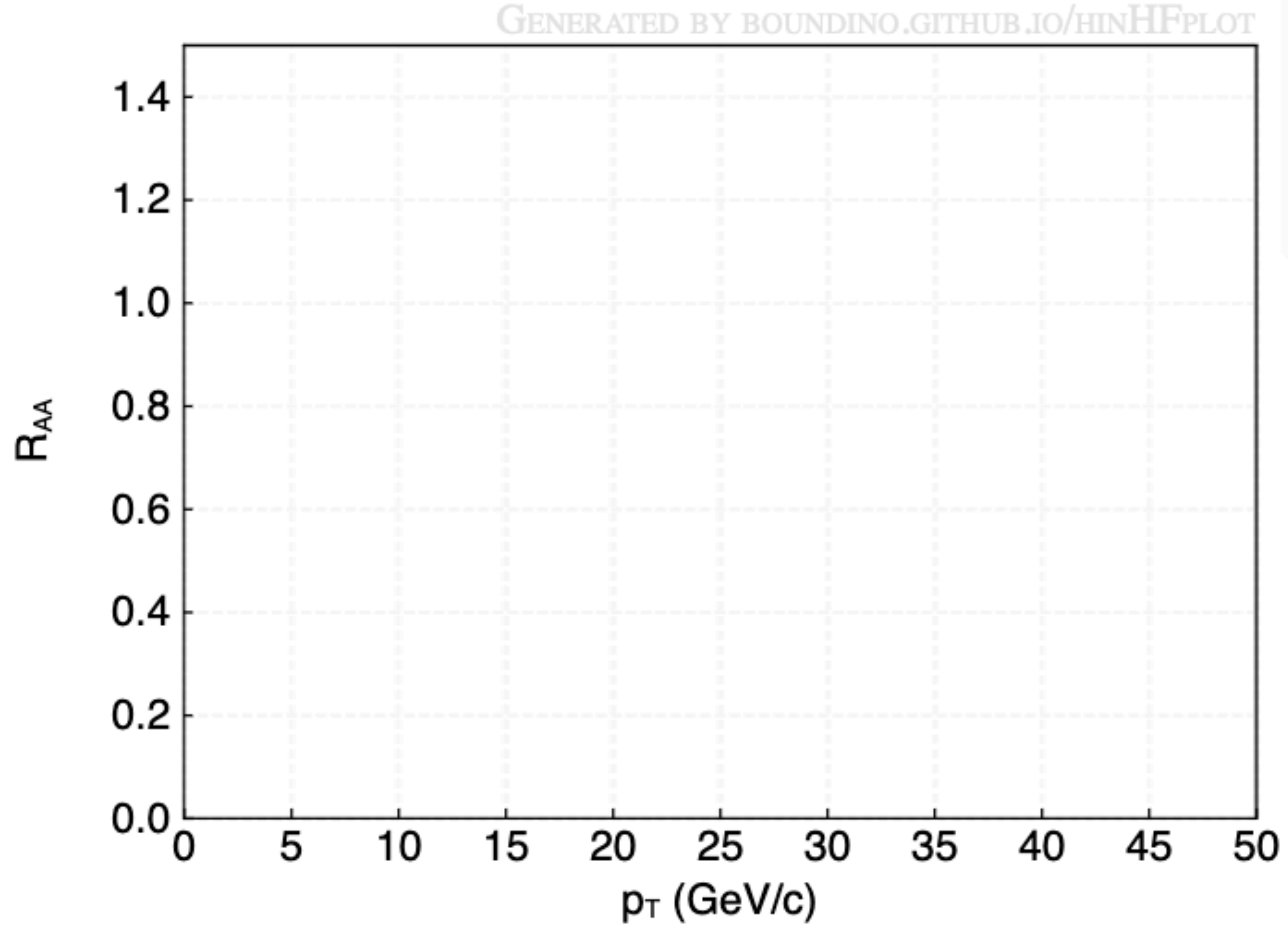
Unify Style | Unity/Zero | Grid | Legend | Save as PNG

Legend x: 25 y: 20



Update (Sep 20):
- Allow to change the height-width ratio of canvas
- Use ⇑ to move to front

Update (Sep 18):
- More marker styles

Update (Sep 16):
- Use to change display style for each dataset separately

Canvas shape: (0.72)

➠ https://boundino.github.io/hinHFplot/

LHC Run 3 & 4

2015 - - 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031

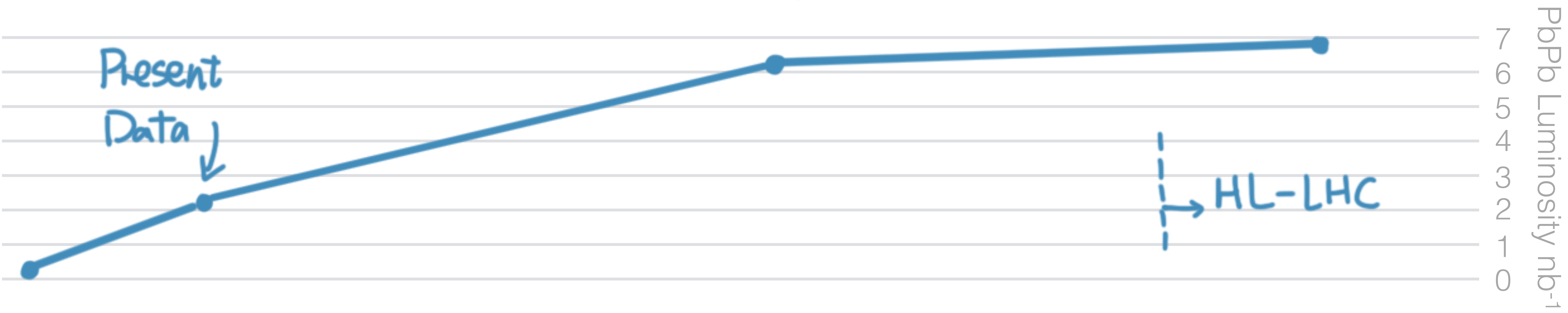
Run 1 | Run 2 | Long Shutdown 2 | Run 3 | LS 3 | Run 4 | LS 4 | Run 5

PbPb
(2.2 nb^{-1})
pPb
(0.18 pb^{-1})

We are here

PbPb
(6.2 nb^{-1})
pPb
(0.6 pb^{-1})
pO/OO

PbPb
(6.8 nb^{-1})
pPb
(0.6 pb^{-1})



LHC Run 3 & 4

Run 1		
Run 2	2015 - 2018	PbPb (2.2 nb^{-1}) pPb (0.18 pb^{-1})
Long Shutdown 2	2019 – 2021	ALICE, LHCb Major upgrades
Run 3	2022 – 2024	**PbPb (6.2 nb^{-1}) pPb (0.6 pb^{-1}) pO/OO**
LS 3	2025 – 2027	**CMS/ ATLAS Phase-2 upgrades**
Run 4	2028 – 2030	**PbPb (6.8 nb^{-1}) pPb (0.6 pb^{-1})**
LS 4	2031	
Run 5		

Not only higher luminosities

But also upgraded detectors!

CMS Phase-2 upgrades for HL-LHC

Table 1: Main features of CMS detector at present and Phase 2 upgrades.

Subdetector	CMS present	CMS Phase-2
Inner Tracker	$\|\eta\| < 2.4$, $100\times150\ \mu\mathrm{m}^2$ pixel size	$\|\eta\| < 4$, $50\times50\ \mu\mathrm{m}^2$ pixel size
Calorimeter	Low-granularity	High-granularity end-cap with silicon sensors
Muon detector	$\|\eta\| < 2.4$	$\|\eta\| < 2.8$

- Significantly improve the resolution
  ➡ Better heavy flavor vertex reconstruction
- Uniquely cover large acceptance studying longitudinal dynamics
  ➡ Study full 3+1D heavy quark dynamics in QGP medium

CMS Phase-2 upgrades for HL-LHC

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Calorimeter	Low-granularity	High-granularity end-cap with silicon sensors
Muon detector	$\|\eta\| < 2.4$	$\|\eta\| < 2.8$
L1 trigger bandwidth	30 kHz for PbPb, 100 kHz for pp and pPb	750 kHz (pass through all PbPb events)
DAQ throughput	6 GB/s	60 GB/s

- High trigger and DAQ rate will allow more sophisticated triggers and collect large number of minimum-bias events (if not all of them)

CMS Phase-2 upgrades for HL-LHC

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Inner Tracker	$\lvert\eta\rvert < 2.4$, $100\times150\ \mu m^2$ pixel size	$\lvert\eta\rvert < 4$, $50\times50\ \mu m^2$ pixel size
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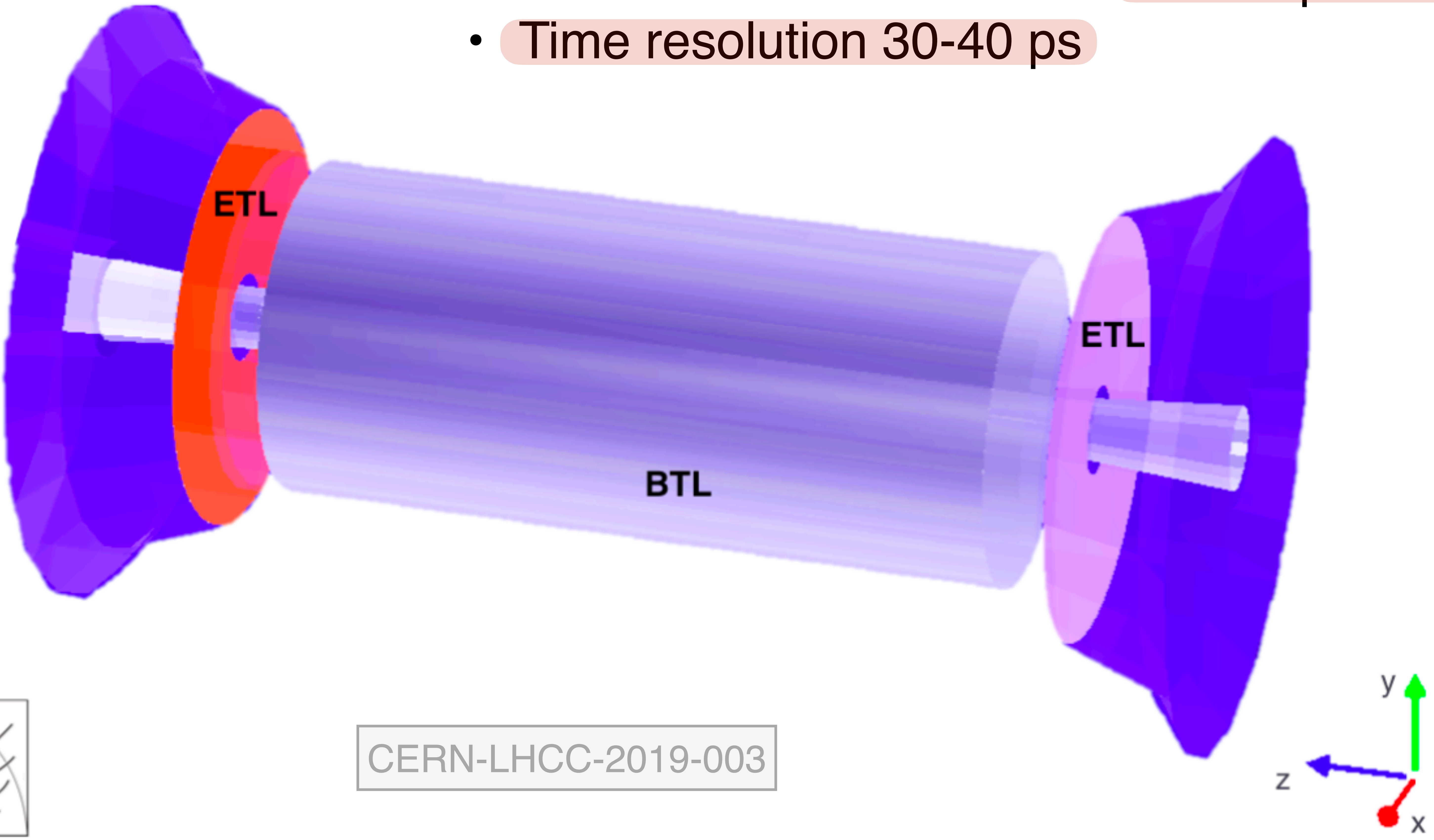
L1 trigger bandwidth	30 kHz for PbPb, 100 kHz for pp and pPb	750 kHz (pass through all PbPb events)
DAQ throughput	6 GB/s	60 GB/s
Time-of-flight for Particle ID	**N/A**	**MTD for charged hadron PID over $\lvert\eta\rvert < 3.0$**

- New MIP Timing Detector (MTD) for TOF-PID!
- Unique PID up to |η| = 3

Precision determination of the arrival time of the signal

CMS MIP Timing Detector (MTD)

- Large acceptance
  ➡ Barrel Timing Layer (BTL): $|\eta| < 1.5$
  ➡ End-cap Timing Layer (ETL): $1.6 < |\eta| < 3$
- Serve as TOF detector for hadron particle identification
- Time resolution 30-40 ps

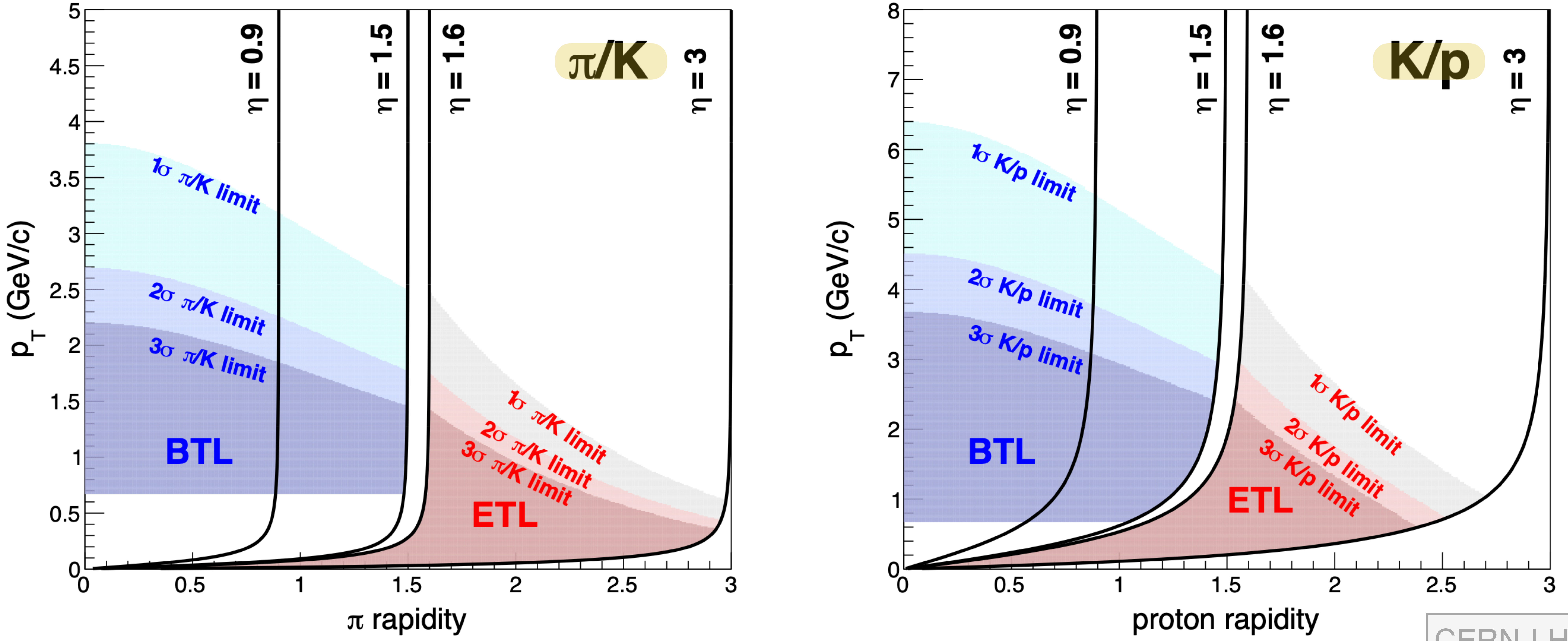


CERN-LHCC-2019-003

Experiment	r (m)	σ_T (ps)	r/σ_T ($\times 100$) ($m \times ps^{-1}$)
STAR-TOF	2.2	80	2.75
ALICE-TOF	3.7	56	6.6
CMS-MTD	1.16	30	3.87

CMS MIP Timing Detector (MTD)

Separation Power vs. kinematic phase space



CERN-LHCC-2019-003

- CMS MTD brings complementarity and uniqueness in PID

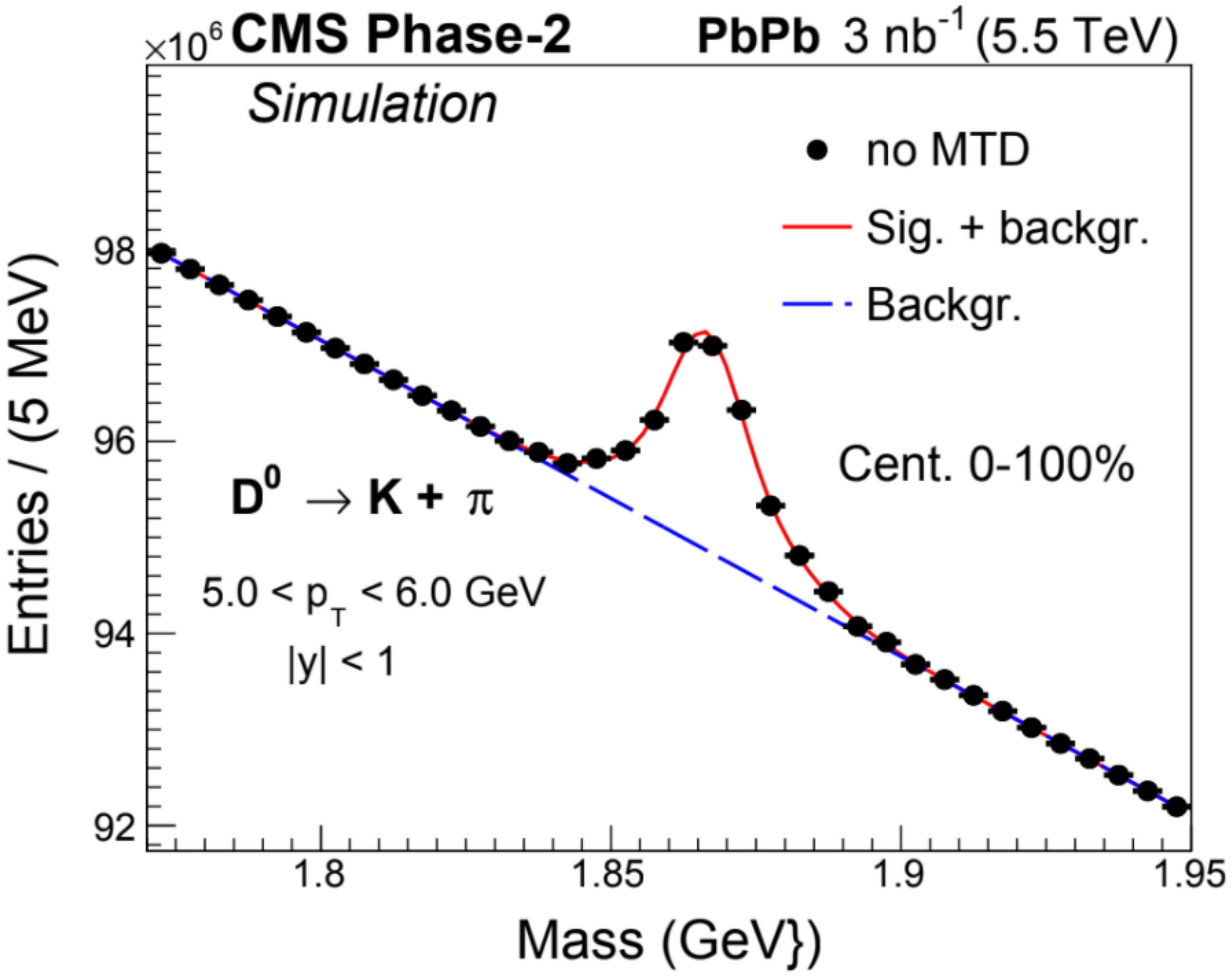
CMS MTD (|η| < 3) vs. ALICE: mid-rapidity (|η| < 0.9)
LHCb: forward (2 < η < 5)

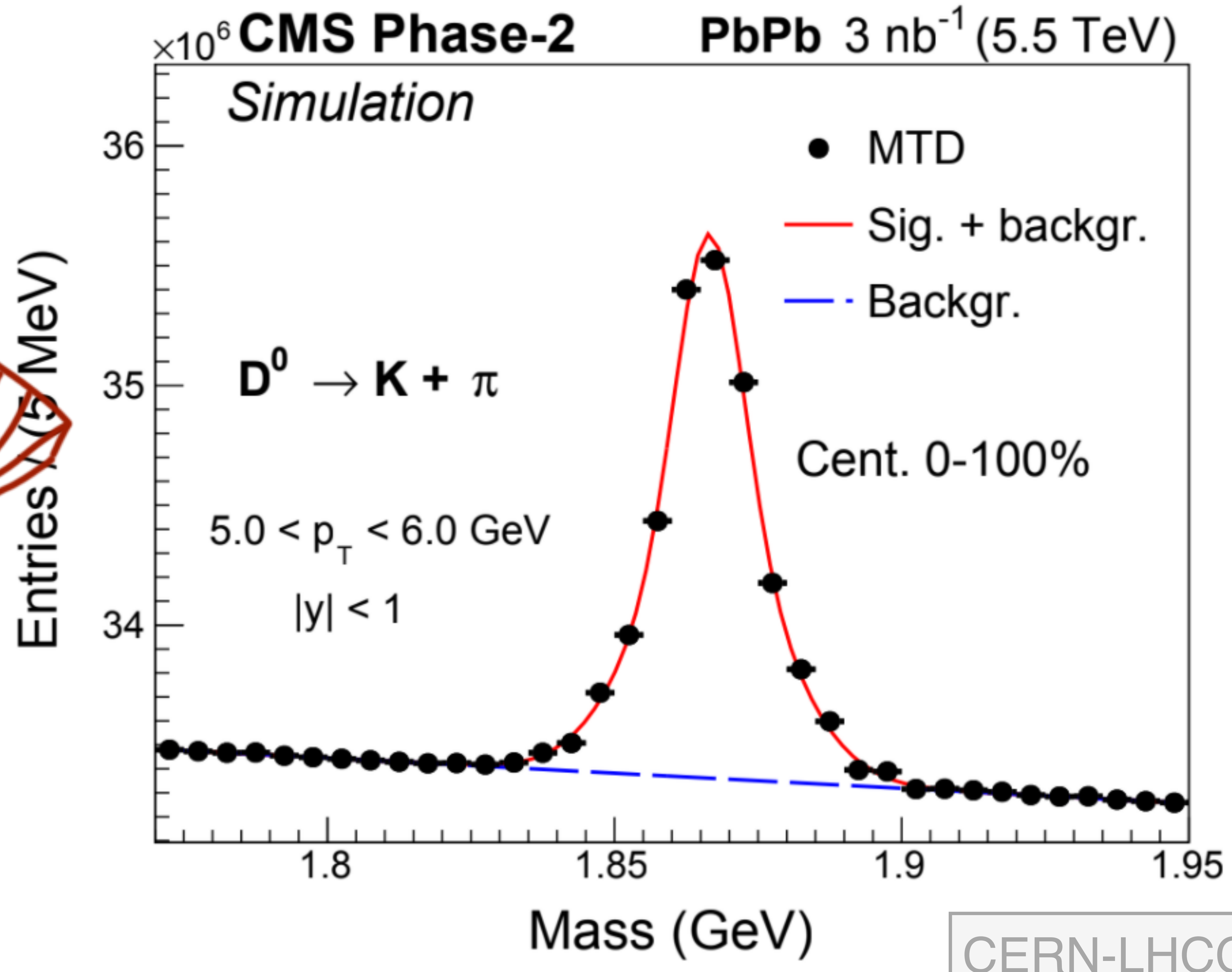
MTD Impact on HF hadron reconstruction

Without MTD

CMS 1 year of Run 4

With MTD





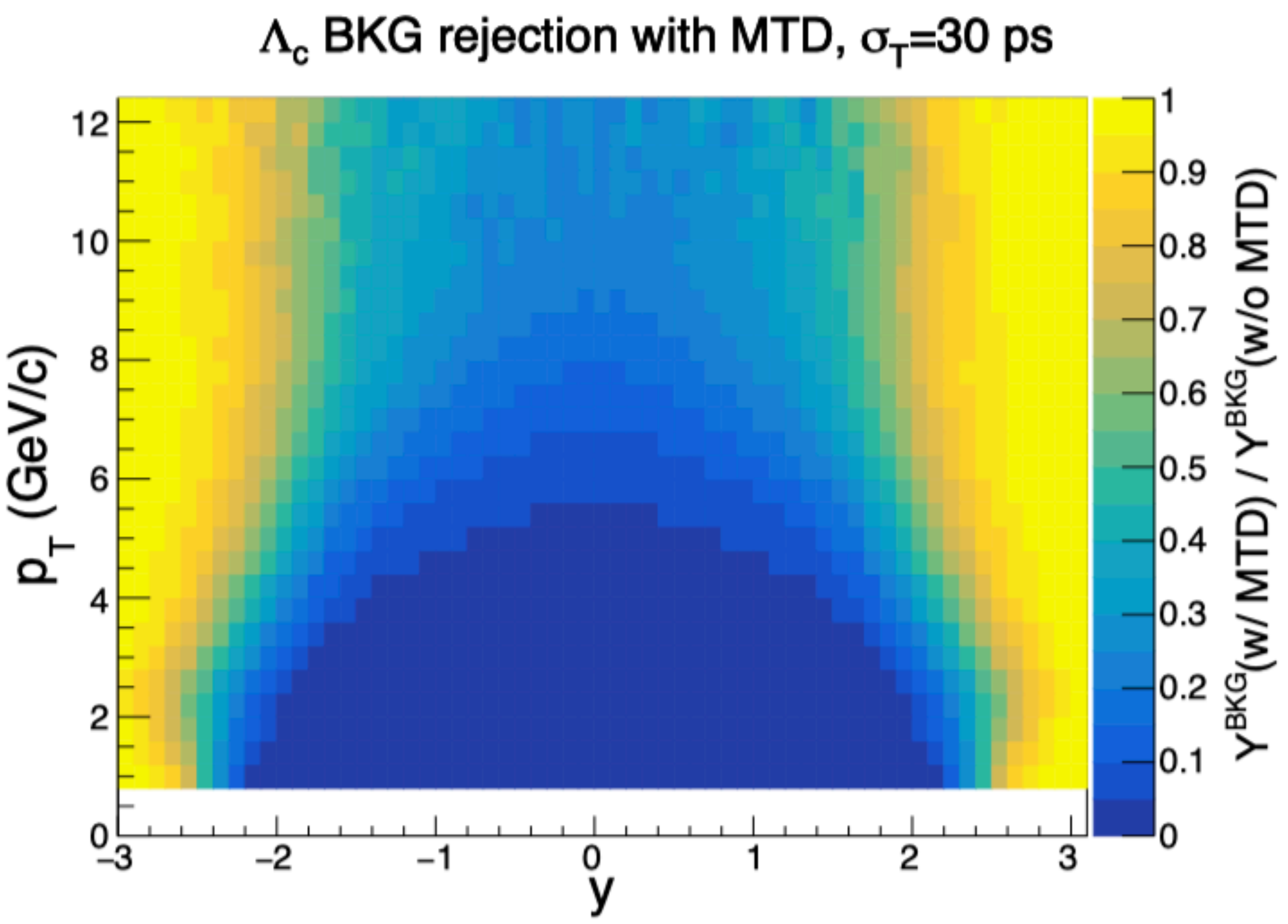
CERN-LHCC-2019-003

- Significant improvement of signal to background ratio with PID information from MTD

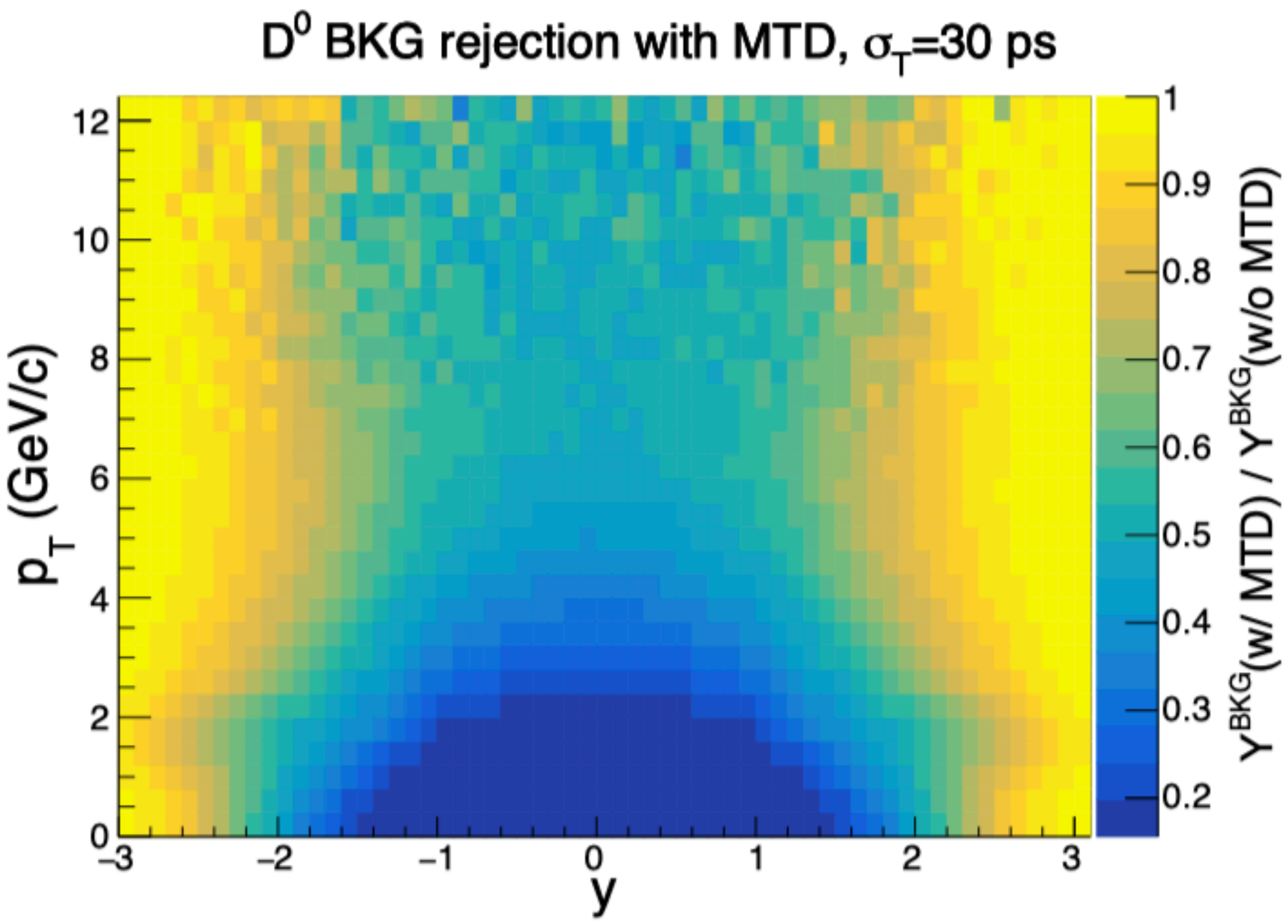
MTD Impact on HF hadron reconstruction

CERN-LHCC-2019-003

$\Lambda_c \to pK\pi$

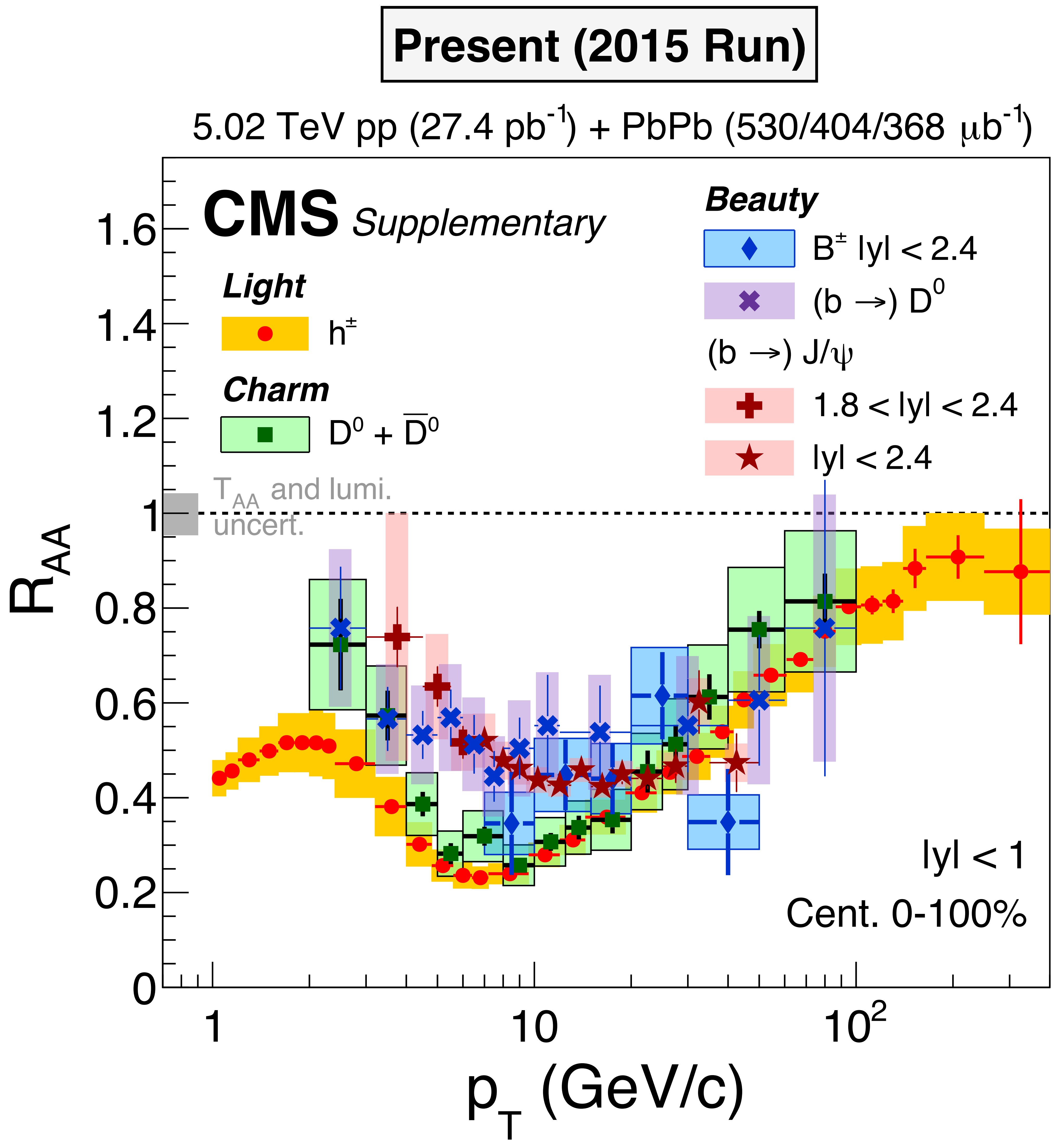


$D^0 \to K\pi$



- More significant improvement for Λ_c (3 daughters) with PID information from MTD
- Enable new probes e.g. $B^+ \to D\pi \to K\pi\pi$

Present CMS Open HF R_{AA} Family



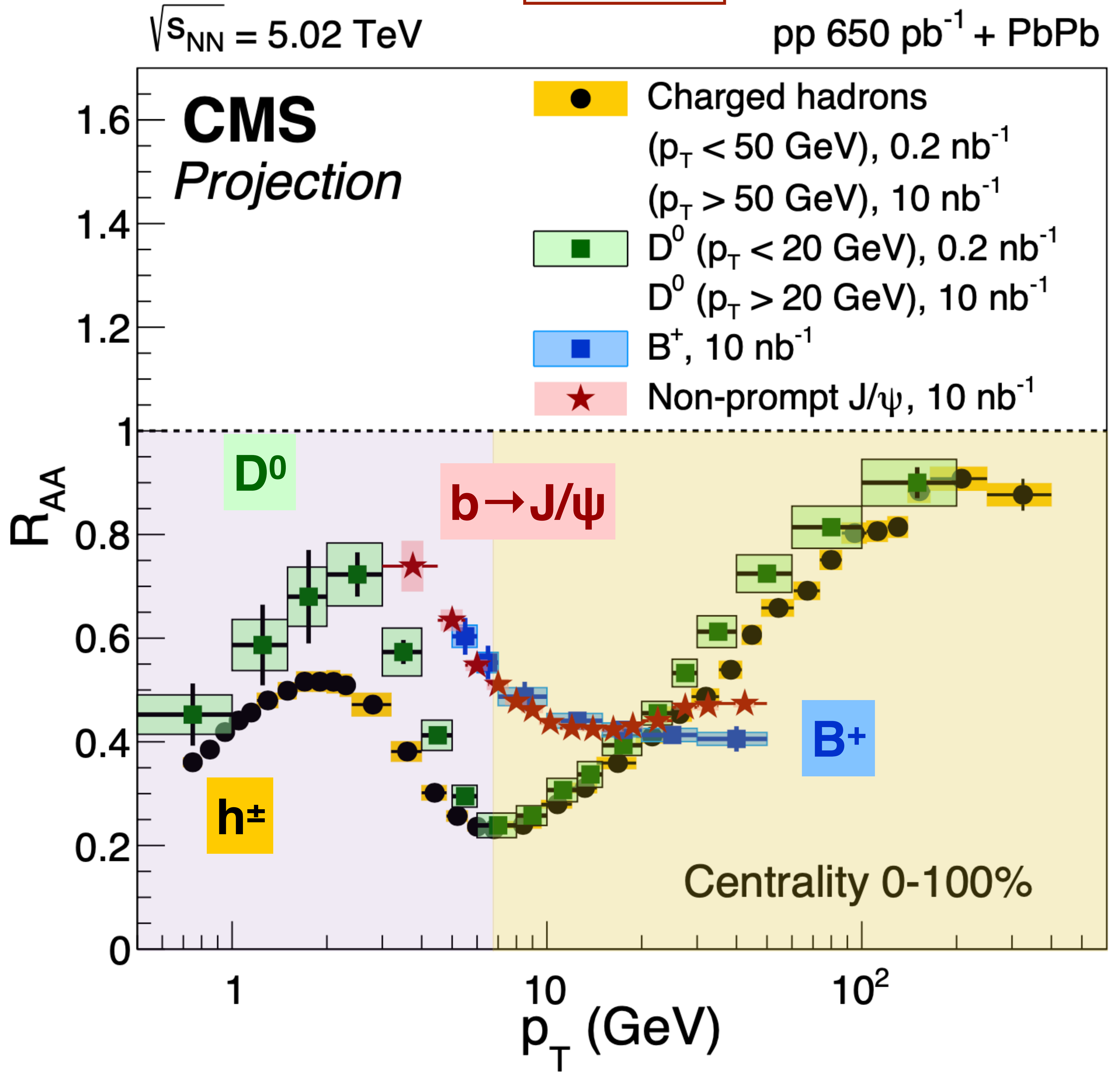
$$R_{AA} = \frac{dN_{AA}/dp_T}{T_{AA}\, d\sigma_{pp}/dp_T}$$

- Preliminary picture of flavor dependence of parton energy loss in the medium

JHEP 04 (2017) 039
PRL 123 (2019) 022001
PLB 782 (2018) 474
PRL 119 (2017) 152301
EPJC 78 (2018) 509

Precise R_{AA} over wide kinematics

HL-LHC



*Luminosity at low p_T here too conservative

- Precise R_{AA} measurements over wide kinematics of light and heavy flavor hadron
  - ➡ Capability to reach low p_T (< 1 GeV)
  - ➡ CMS unique access to high p_T (> 100 GeV)
- ✳ MTD improvement not reflected
- More differential measurements enabled
- ➡ Full picture of relative relevance of collisional and radiative processes and the microscope mechanisms of heavy quark interaction with the medium

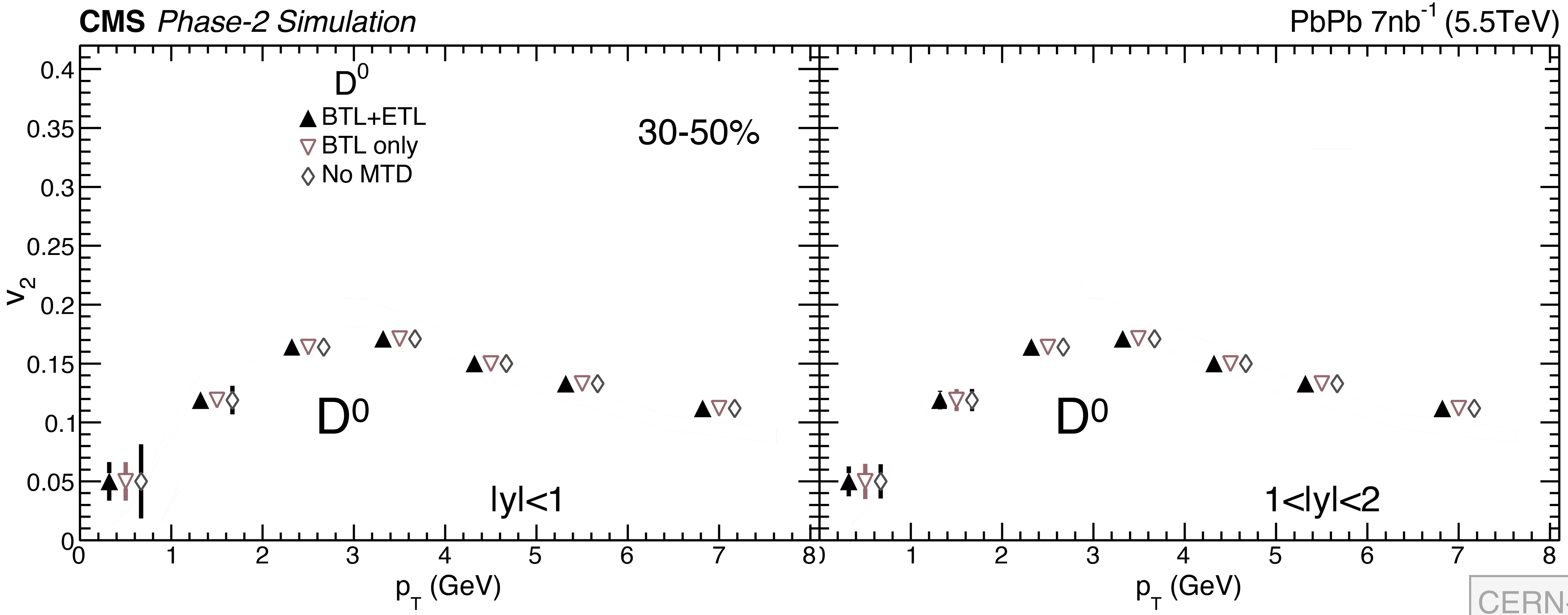
arXiv:1812.06772

D^0 Azimuthal Anisotropy v_2

|y| < 1

HL-LHC

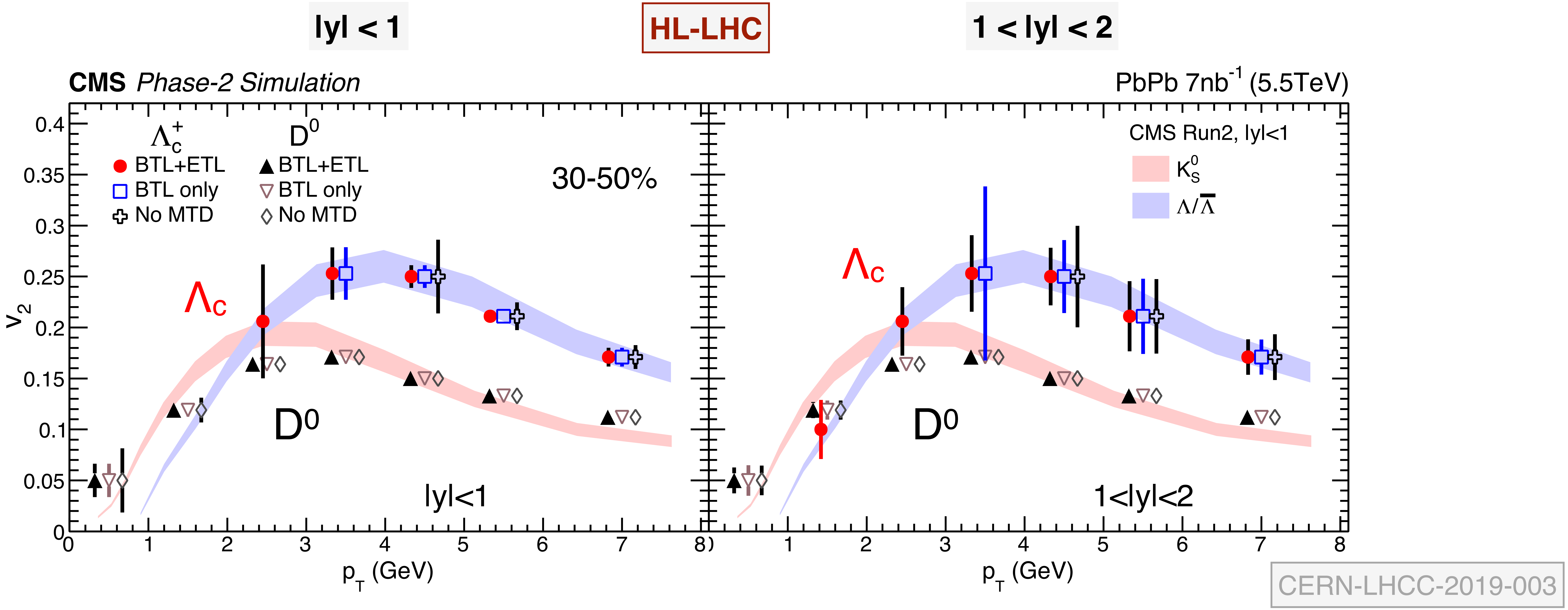
1 < |y| < 2



CERN-LHCC-2019-003

- High-precision measurements of D^0 v_2 down to 0 p_T with MTD

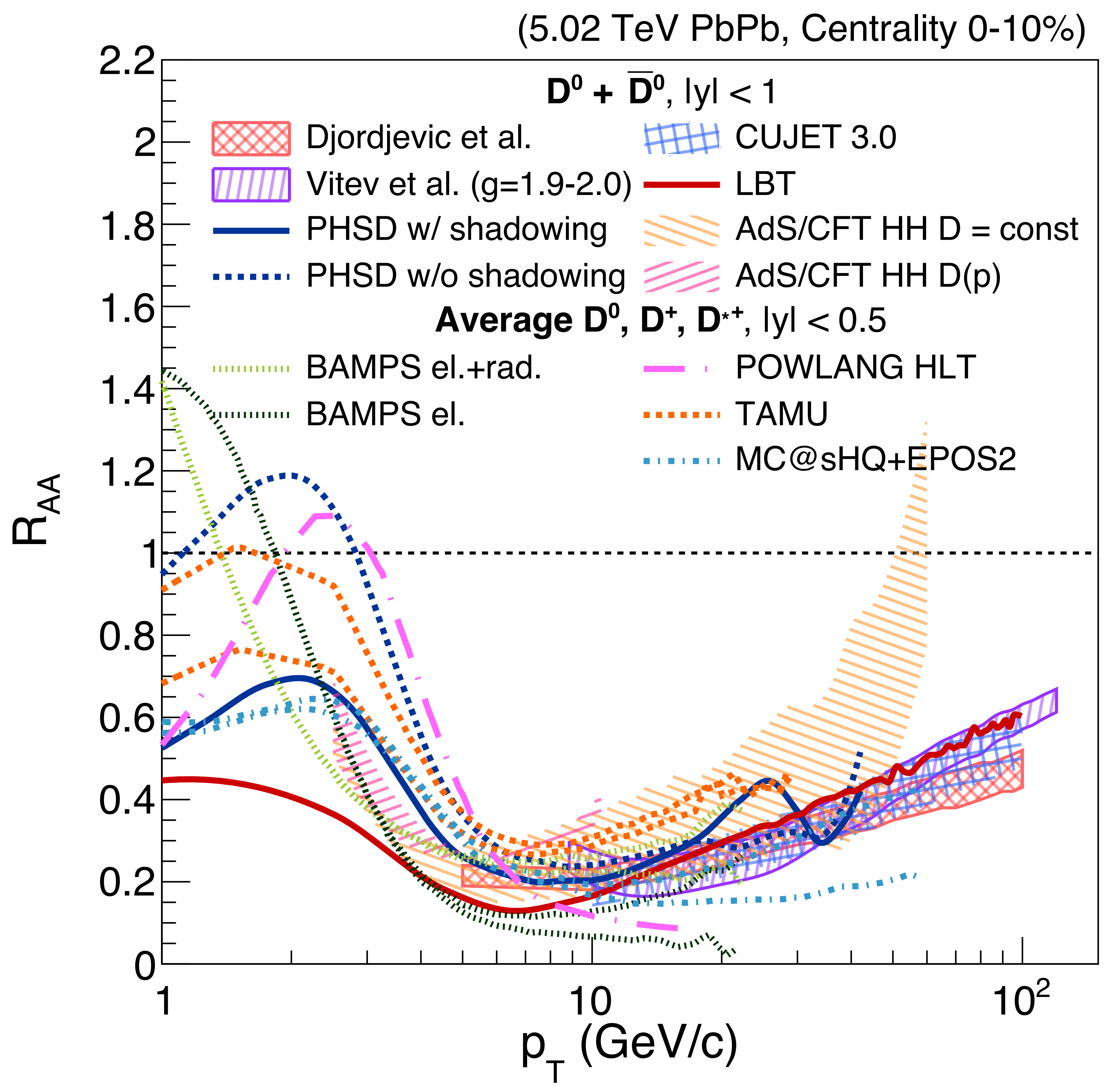
Λ_c Azimuthal Anisotropy v_2



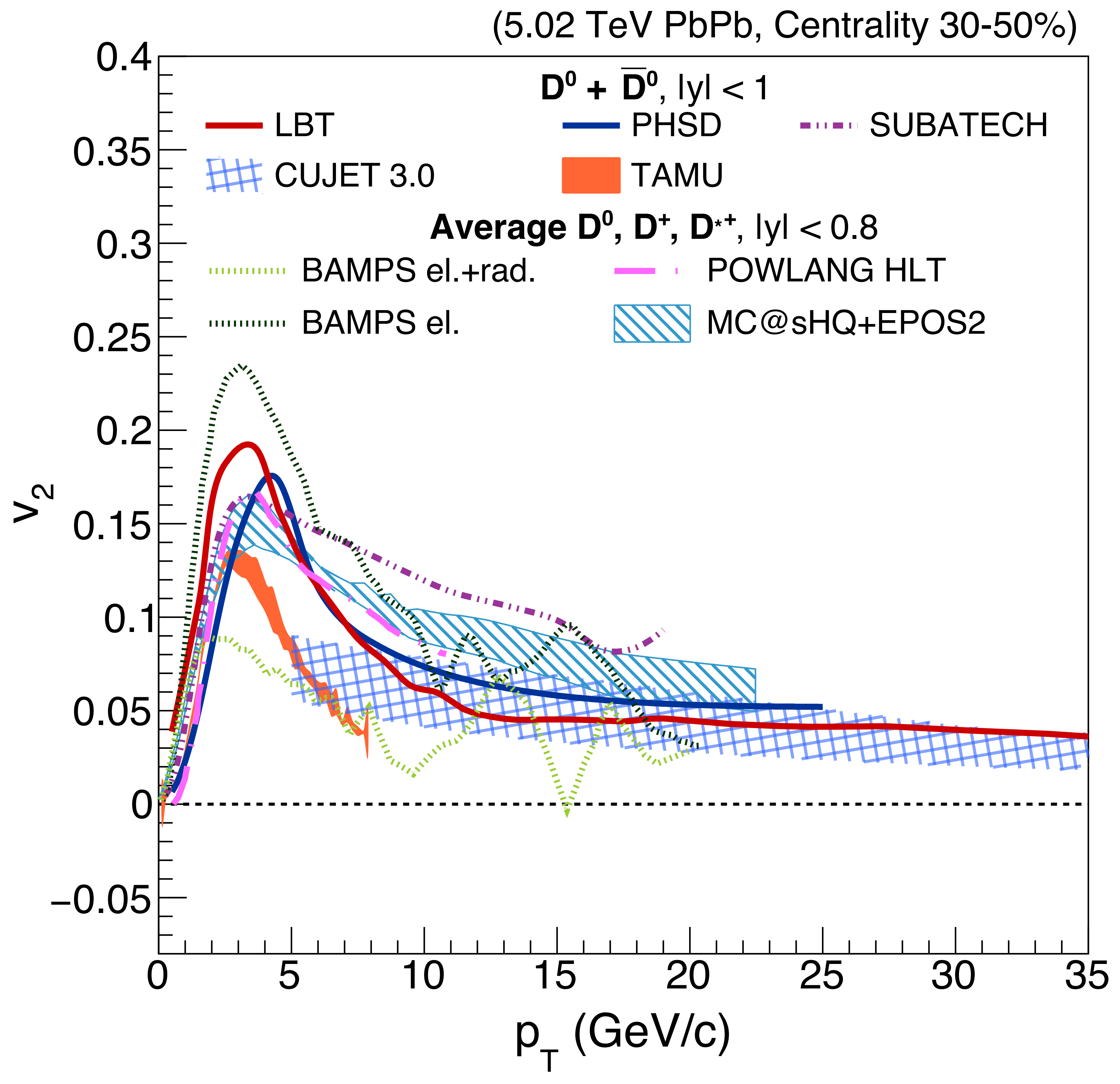
- High-precision measurements of D^0 v_2 down to 0 p_T with MTD
- MTD allows measurements of Λ_c v_2 down to 1 GeV
- Test of the n_q scaling universalness in the charm sector

Theoretical calculation of R_{AA} and v_2

D R_{AA}

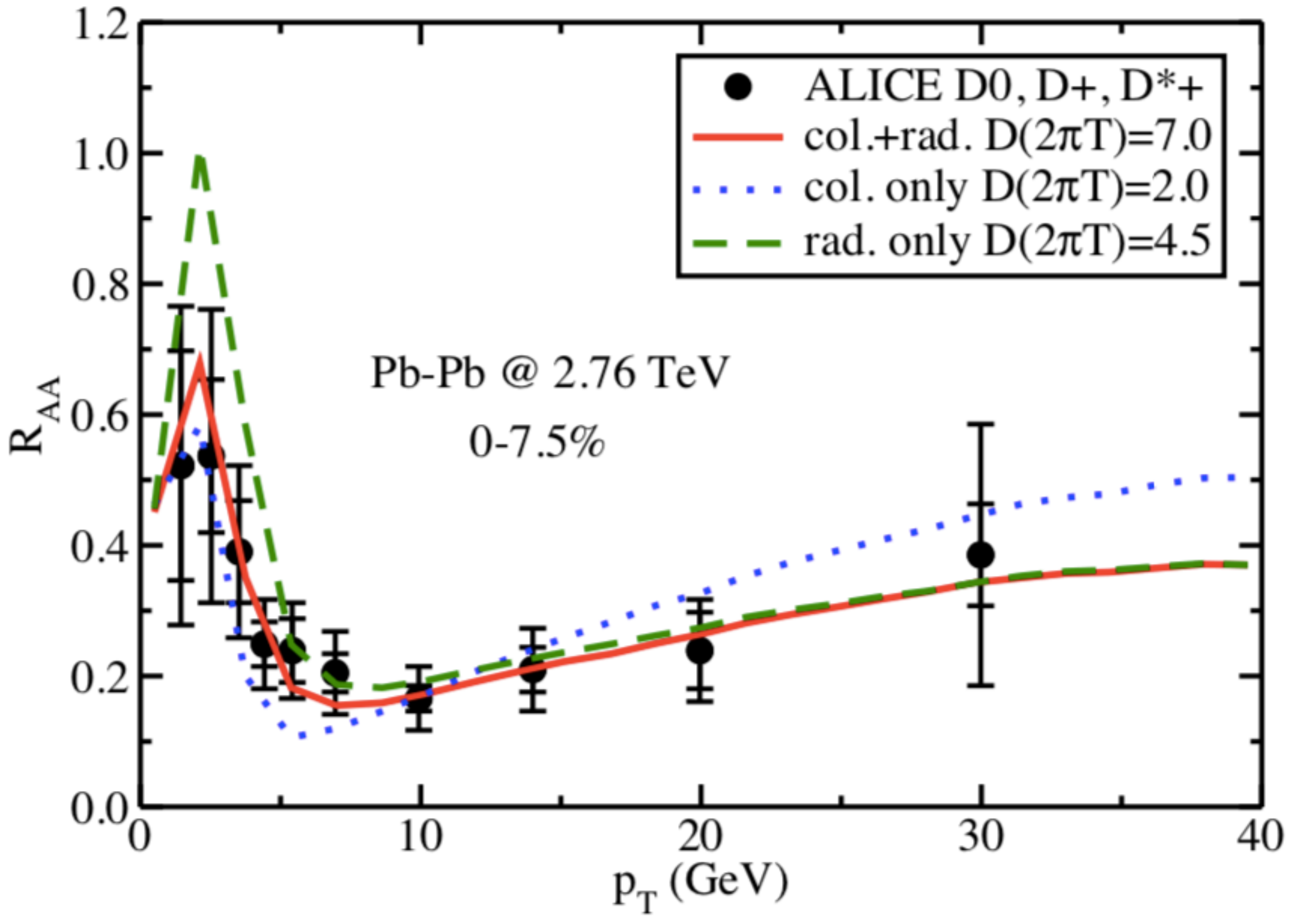


D v_2

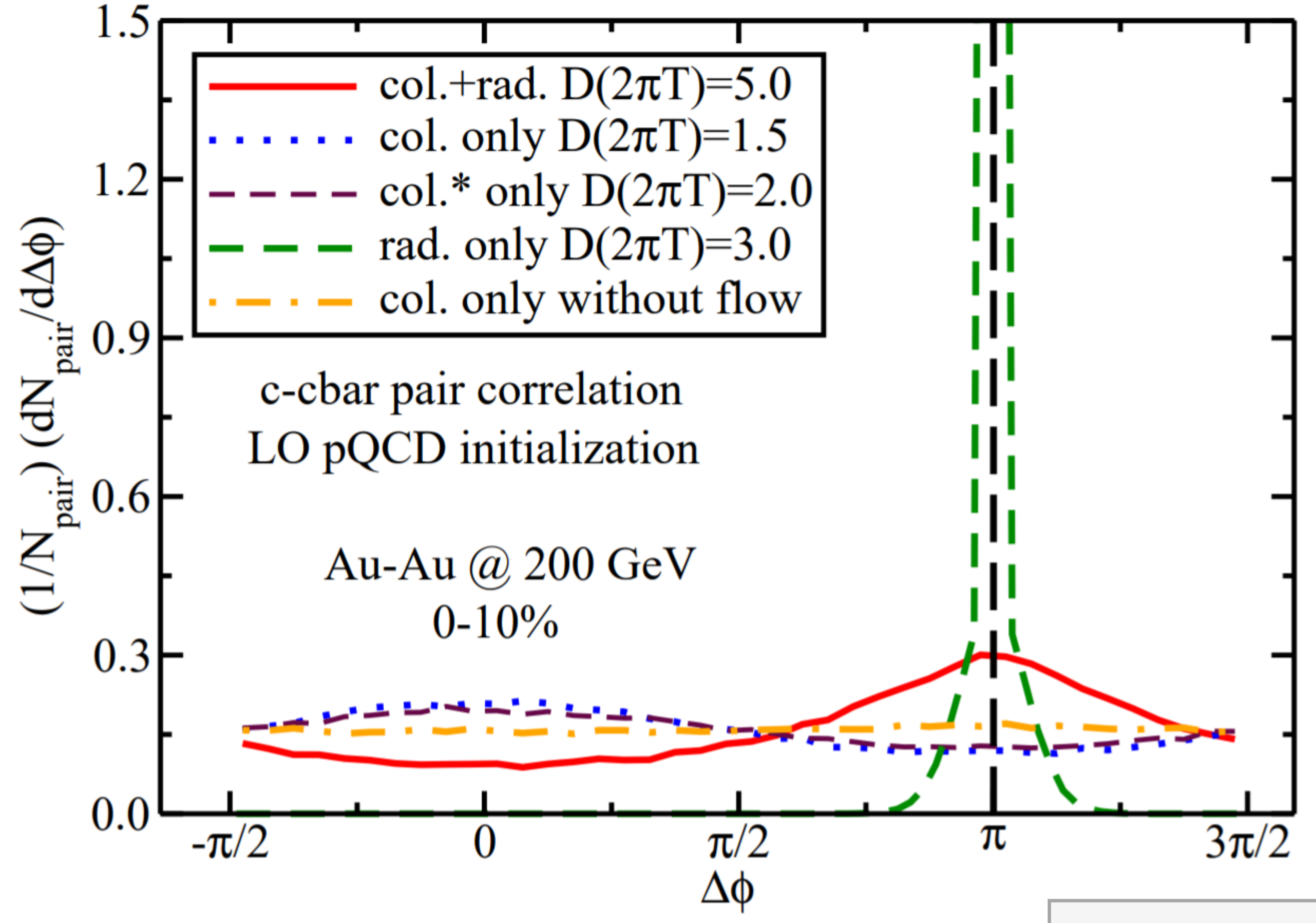


- CMS precise R_{AA} and v_2 measurements have strong discrimination power of theoretical calculations

R_{AA}



c-c̄ correlation



PRC 92 (2015) 054909

Different
- Diffusion coefficient
- Energy loss mechanisms

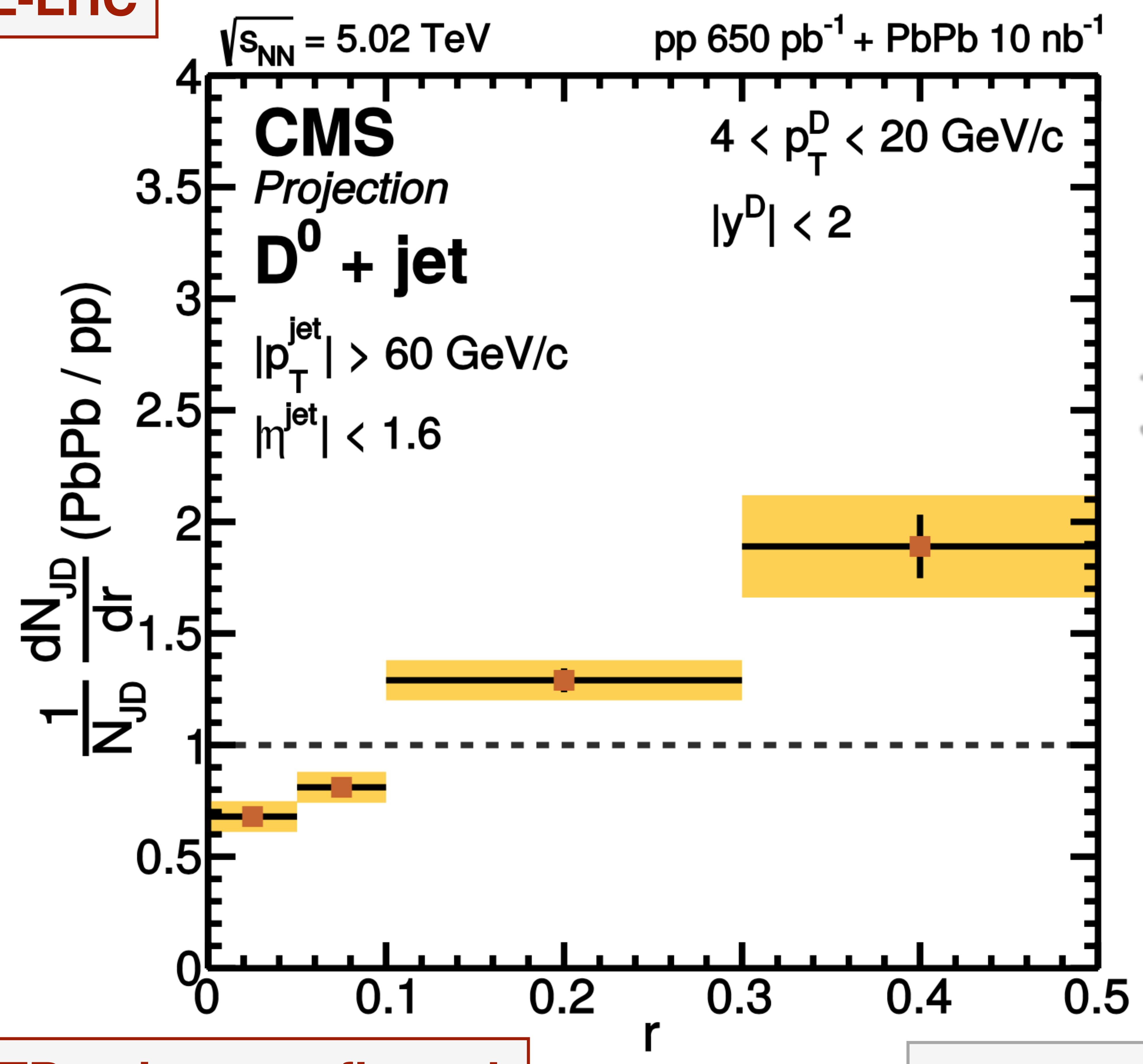
← R_{AA}

→ c-c̄ correlation

HF Correlation with Hard Probes

D⁰-jet correlation

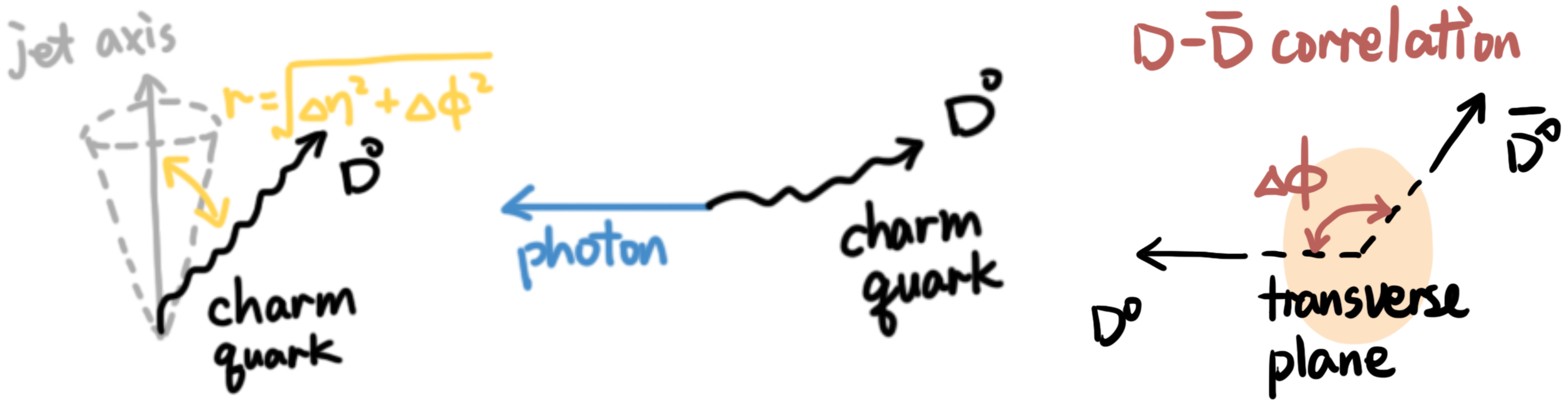
HL-LHC



MTD gain not reflected

arXiv:1812.06772

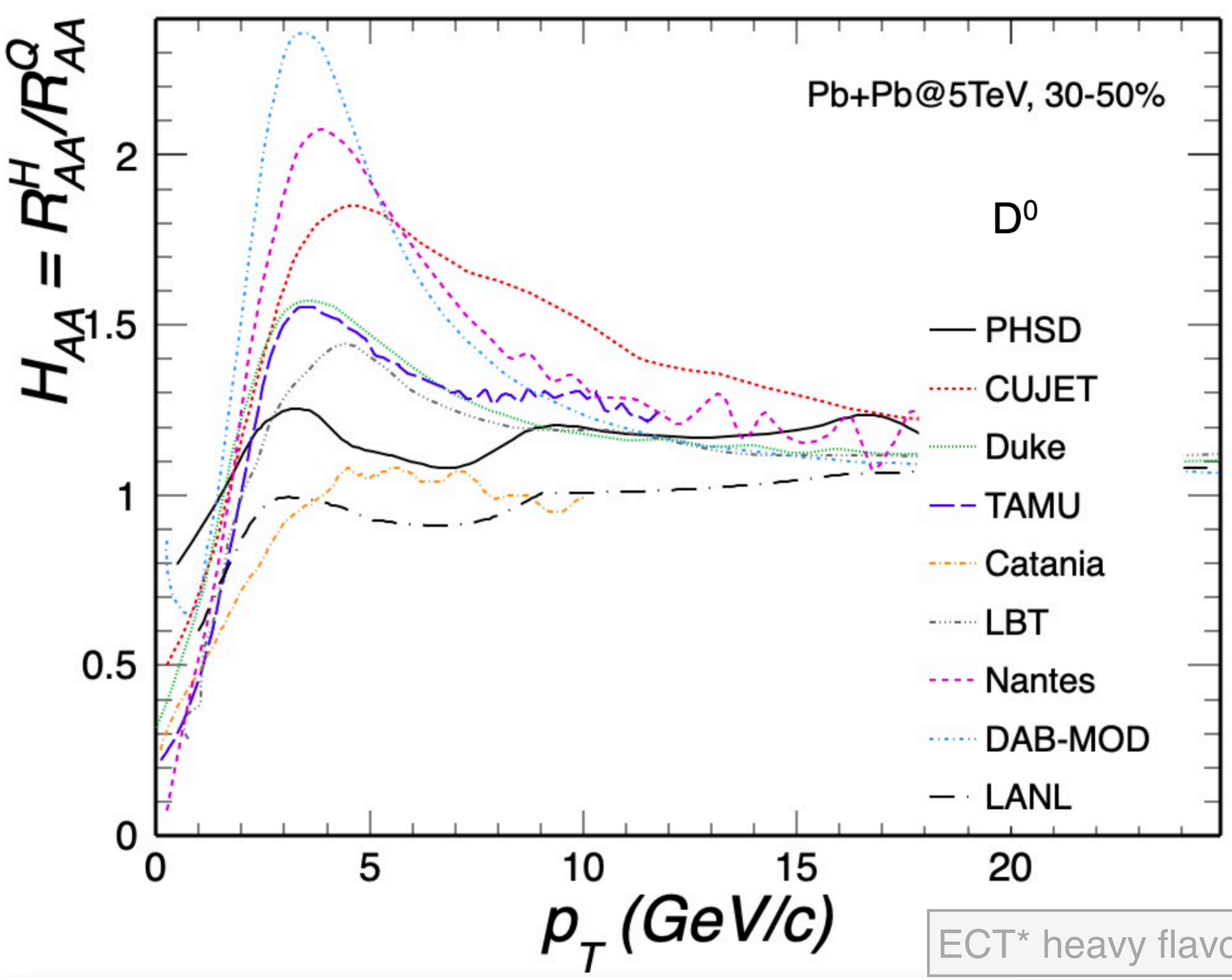
- Correlation as a more sensitive observable than R_{AA} and v_2
- Higher-precision Jet-D^0 correlation is expected
- Enable photon-D^0, D^0-$\bar{D}^0$ correlation measurements



➡ New measurements of charm diffusion signal in QGP

Heavy Quark Hadronization

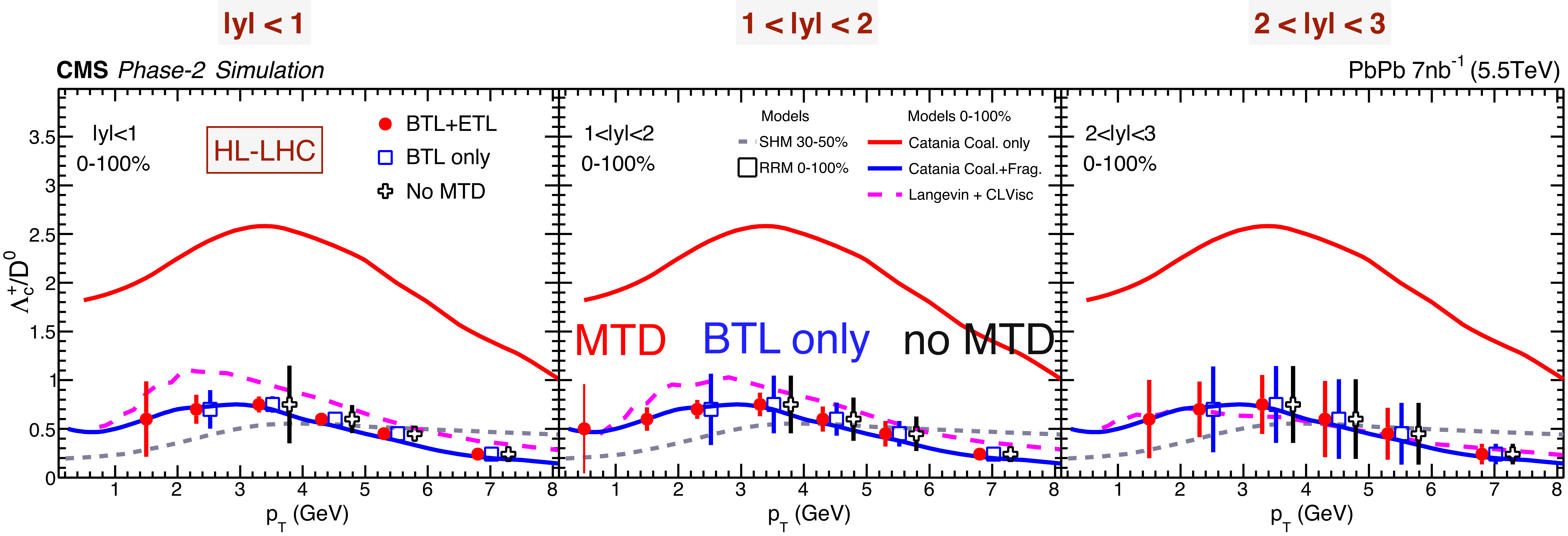
RAA (Hadron) / RAA (Quark)



ECT* heavy flavor workshop in April

- Still significant disagreement on hadronization mechanisms between models

Wide Rapidity Coverage of Λ_c/D^0 (PbPb)

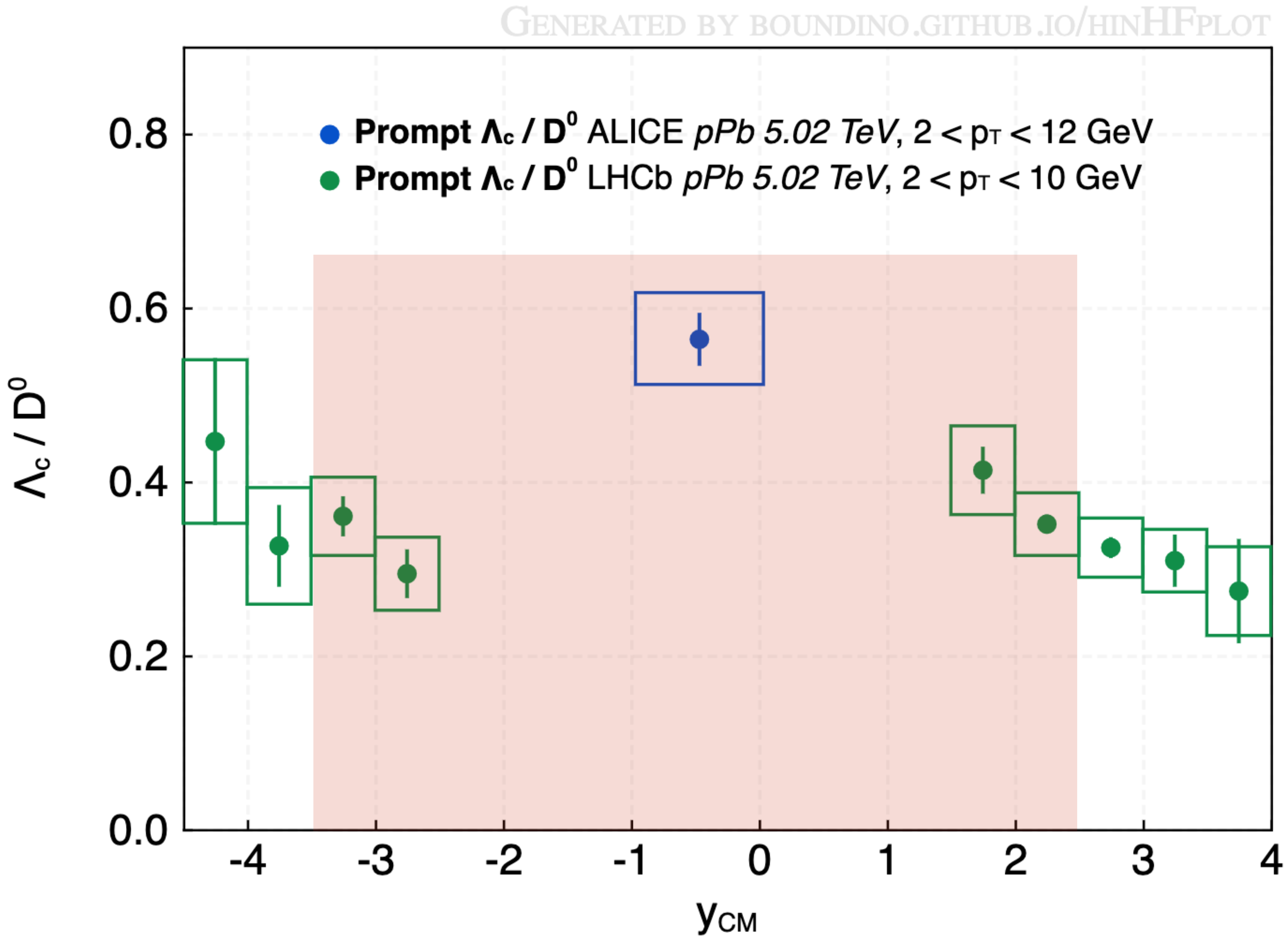


CERN-LHCC-2019-003

- Unique capability of CMS due to the large inner tracker and MTD acceptance
- Capability to access low p_T (down to 0) ➡ Total charm cross-section
- Except for Langevin+CLVisc, other models shown assume boost invariant in the longitudinal direction

➡ Provide the strongest constraint on the heavy quark hadronization mechanism

Wide Rapidity Coverage of Λ_c/D^0 (pPb)



JHEP 02 (2019) 102

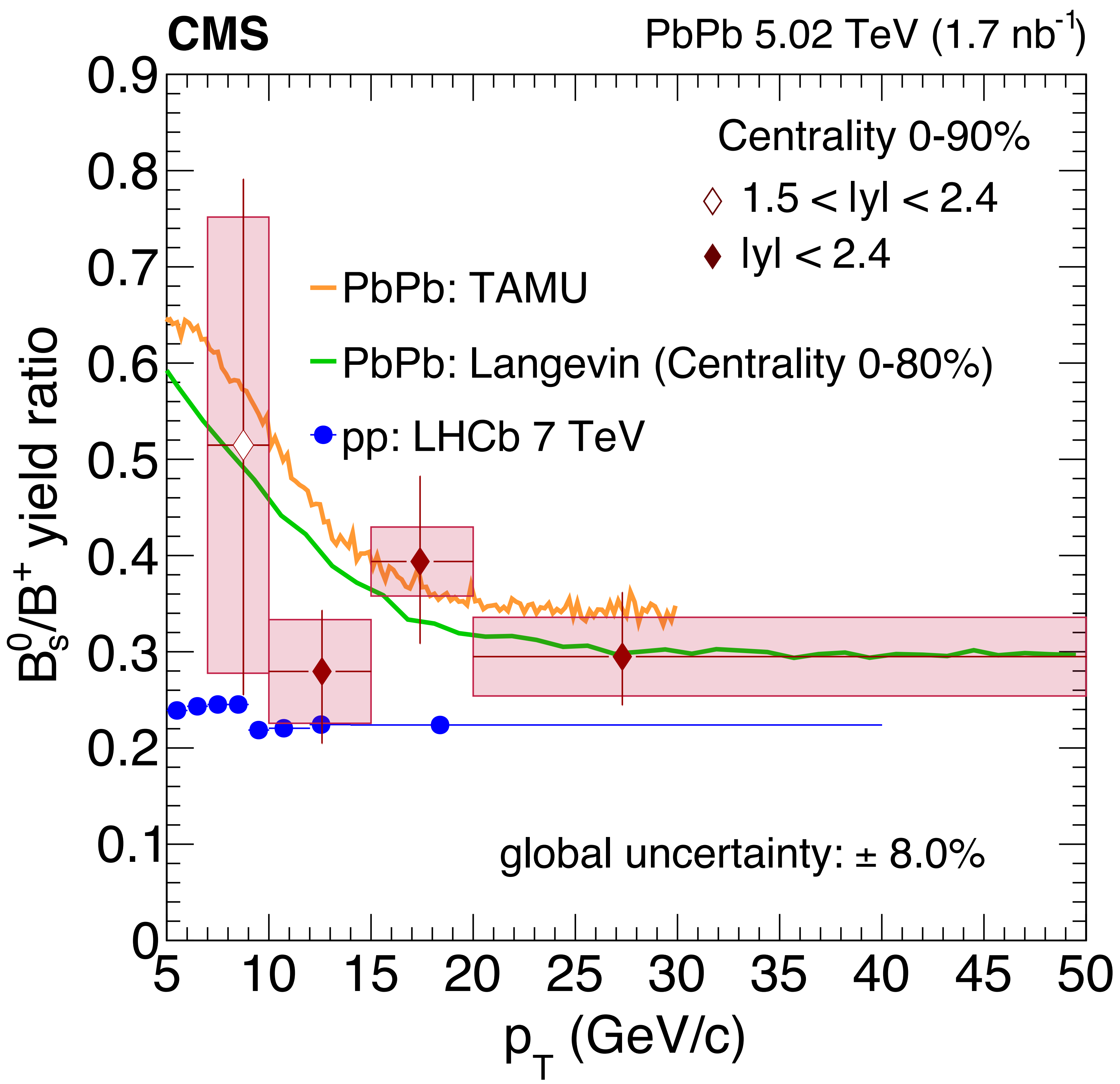
arXiv:2011.06079

- Unique capability of CMS due to the large inner tracker and MTD acceptance

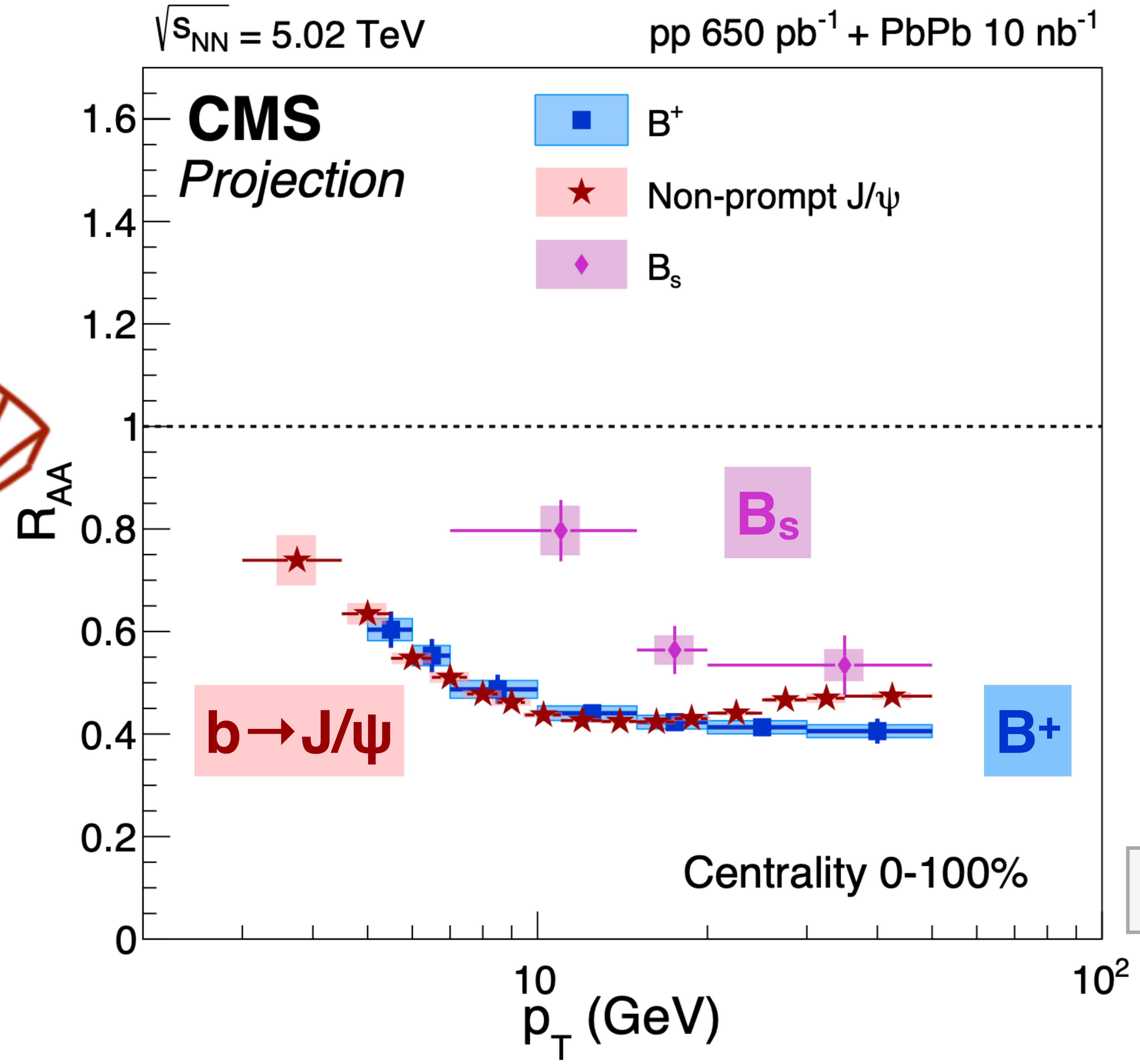
➡ Fill the gap not accessible by ALICE and LHCb

Strangeness HF hadrons

Present Data



HL-LHC

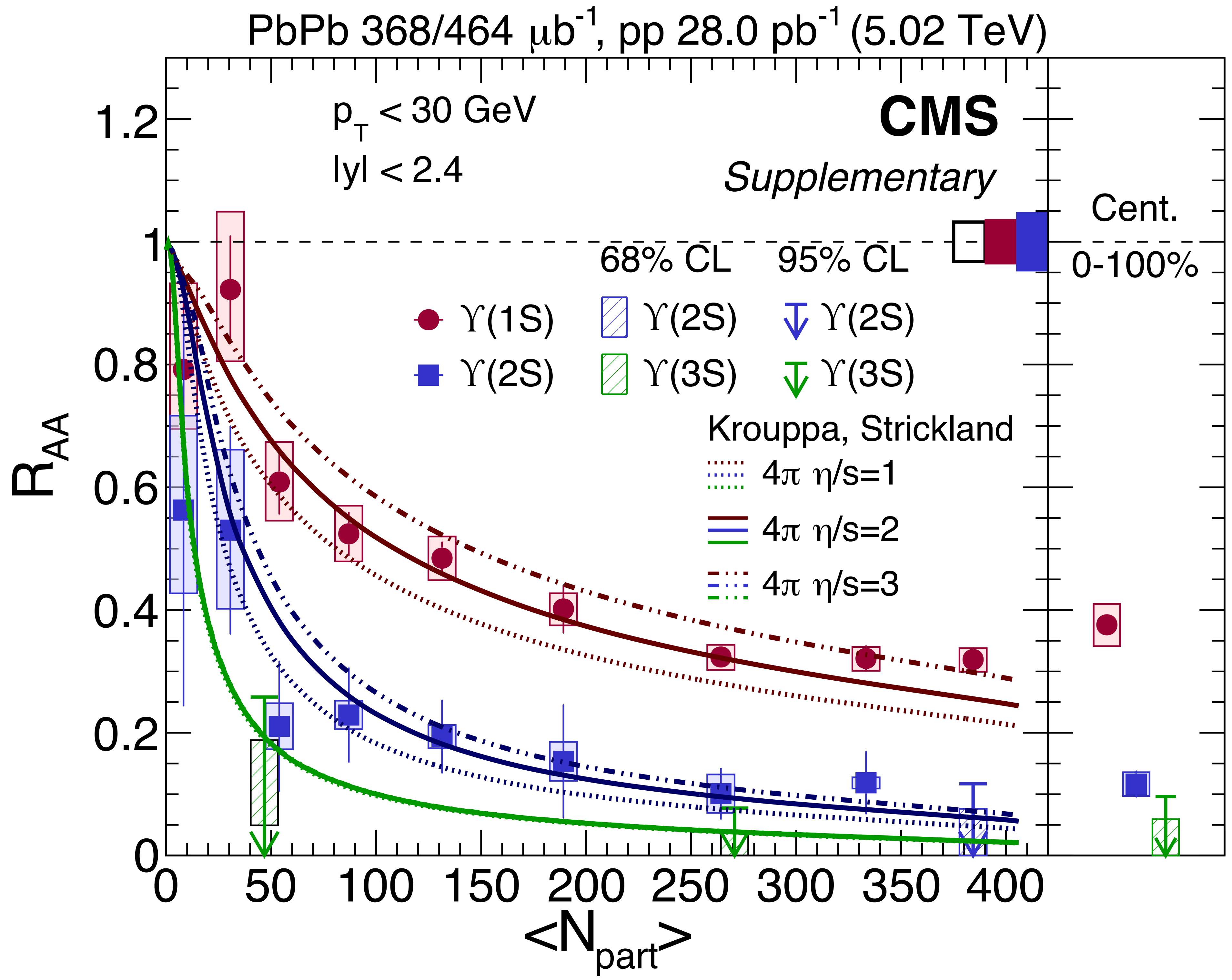


arXiv:1812.06772

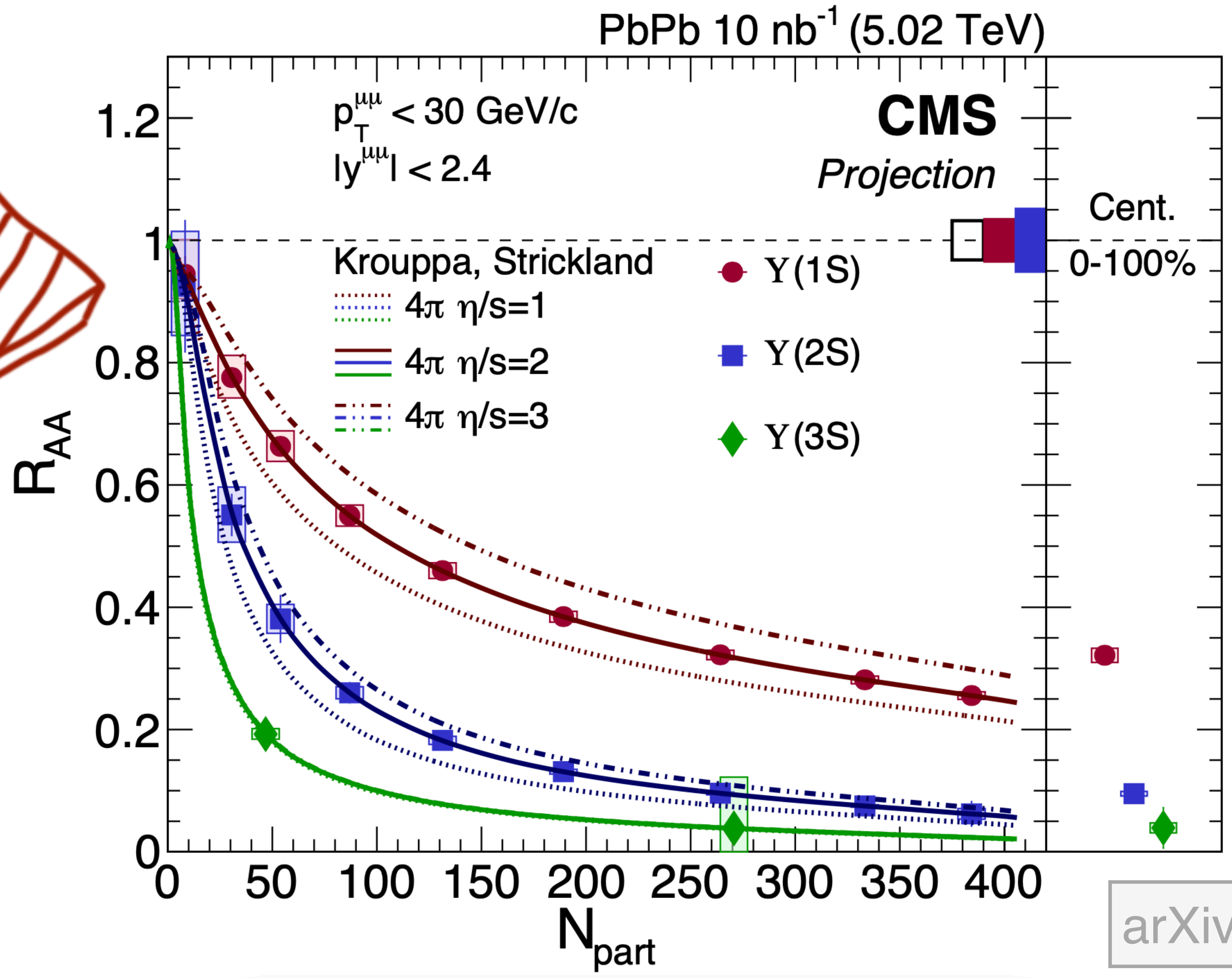
- Strange quark content is enhanced in QGP ← the high temperature
- Strangeness HF mesons (D_s, B_s) could be enhanced via coalescence
- Wider muon detector acceptance improves lower p_T access

Y(nS) Production in PbPb

Present (2015 Run)



HL-LHC



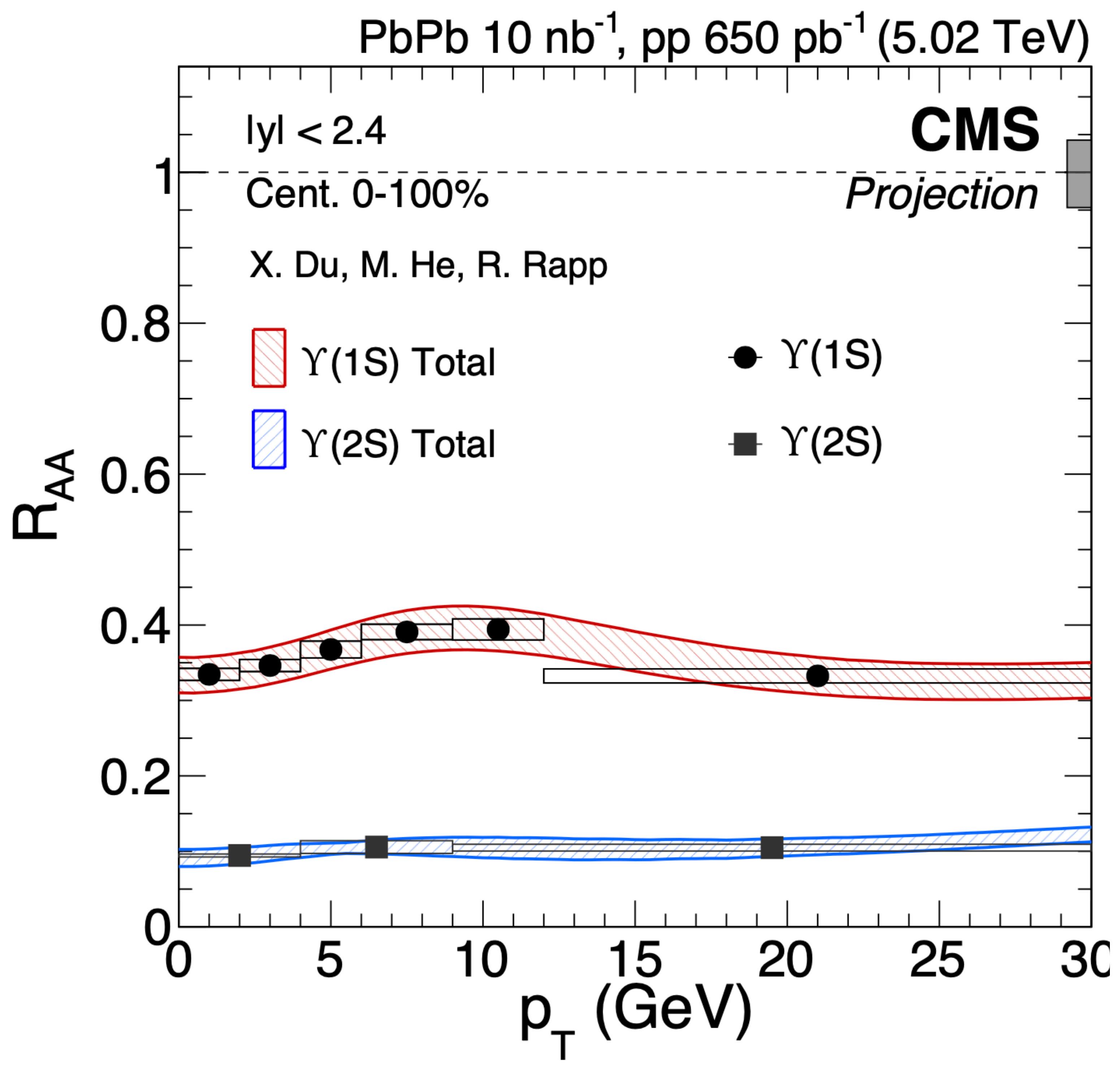
arXiv:1812.06772

- High precision measurements of Y(nS) production
  ➡ Sensitive to the medium shear viscosity and the initial temperature
- Capability of Y(3S) observation

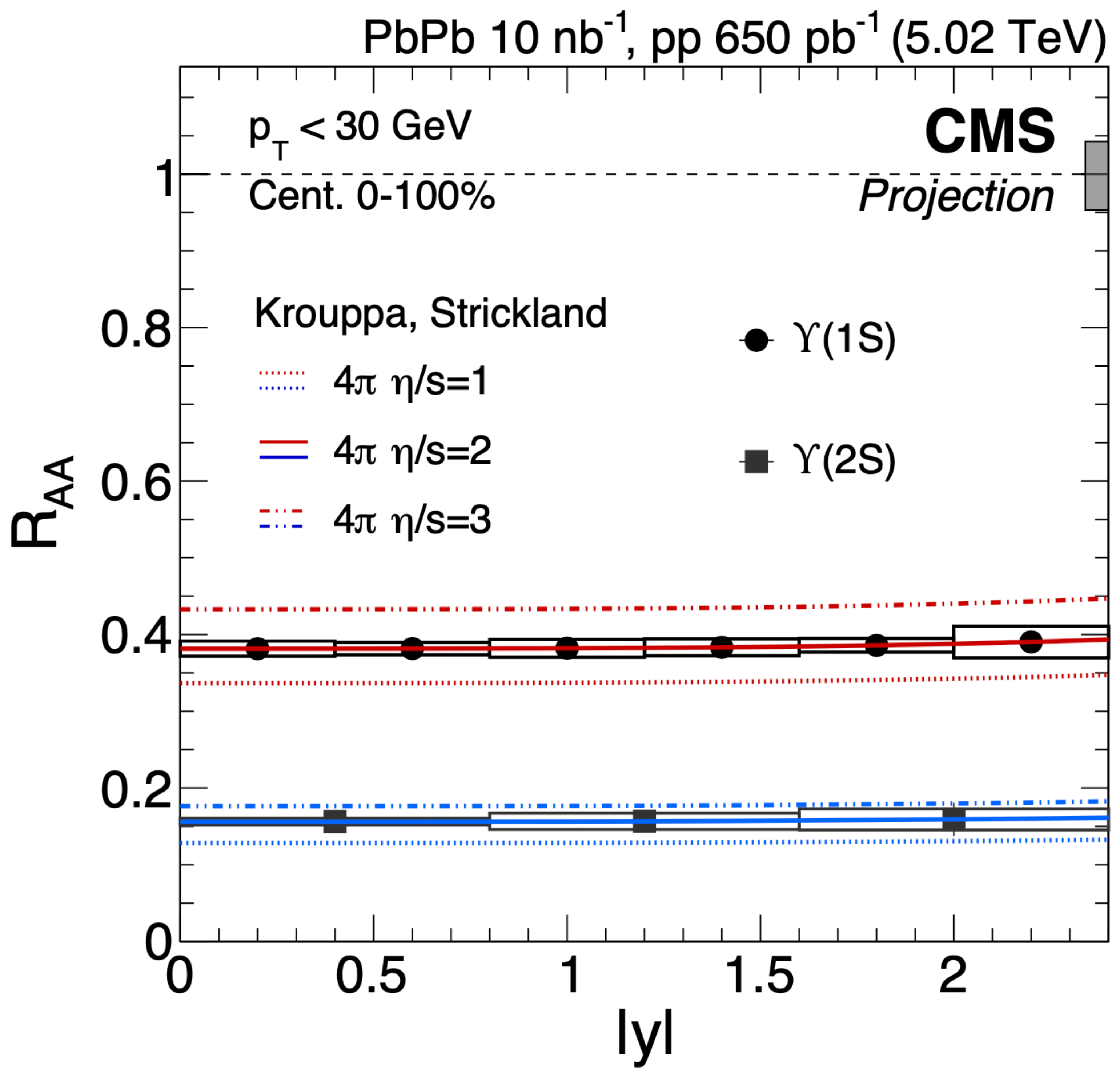
Υ(nS) Production in PbPb

HL-LHC

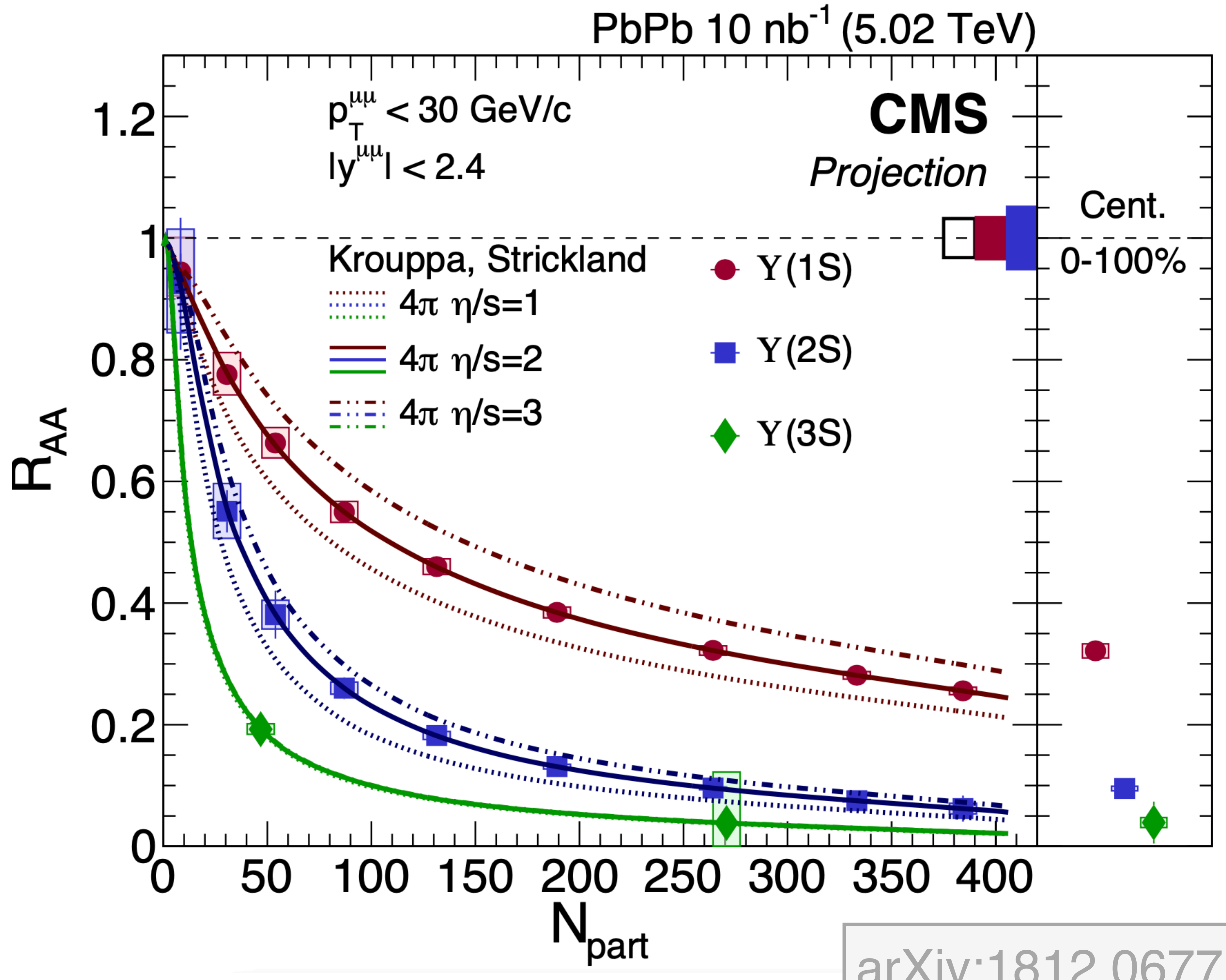
Υ(nS) R_{AA} vs. p_T



Υ(nS) R_{AA} vs. |y|



Υ(nS) R_{AA} vs. N_{part}



arXiv:1812.06772

- High precision measurements of Υ(nS) production
  ➡ Differential: R_{AA} as a function of centrality, p_T and rapidity
- Capability of Υ(3S) observation

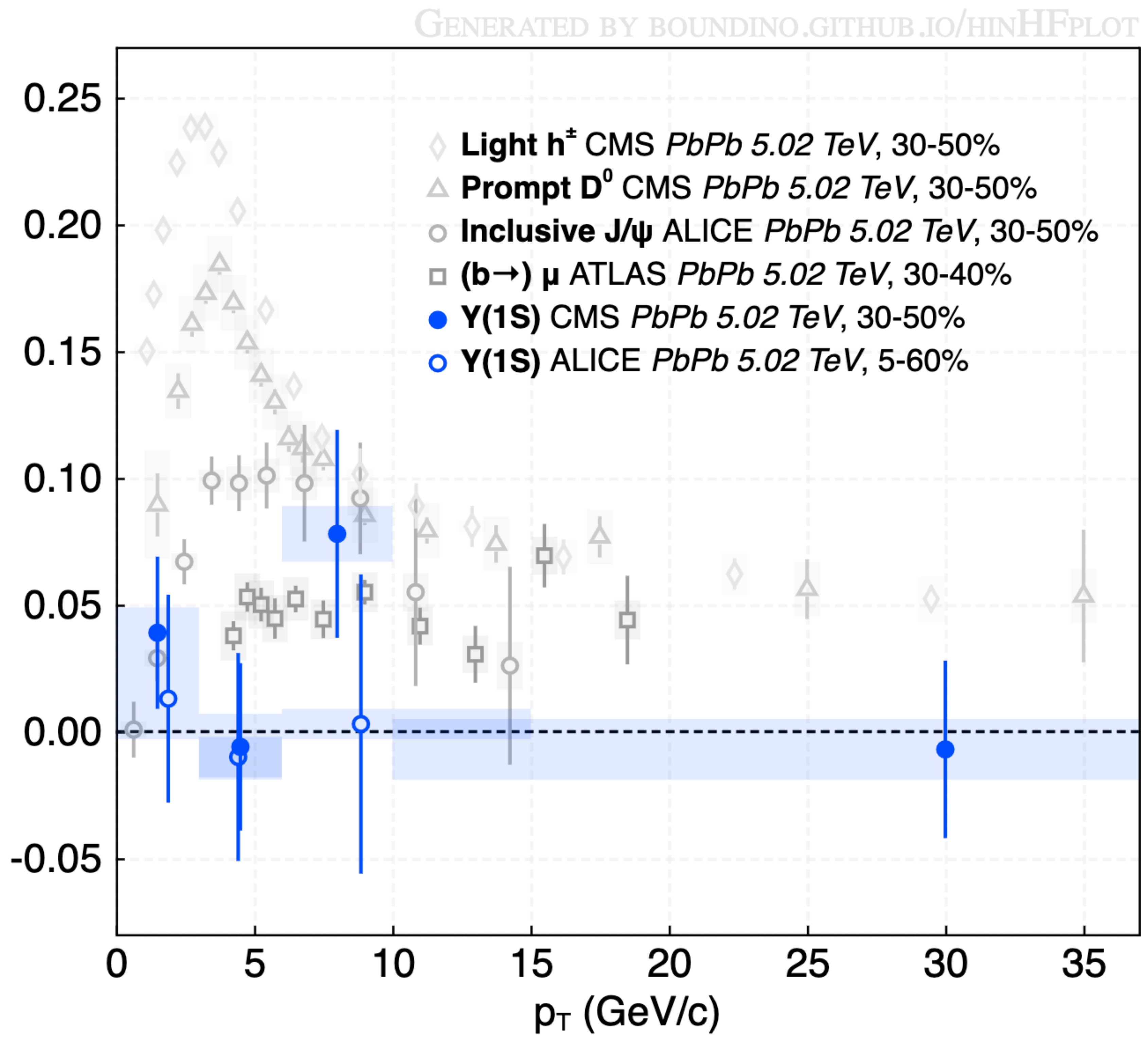
Υ(nS) Azimuthal Anisotropy v_2

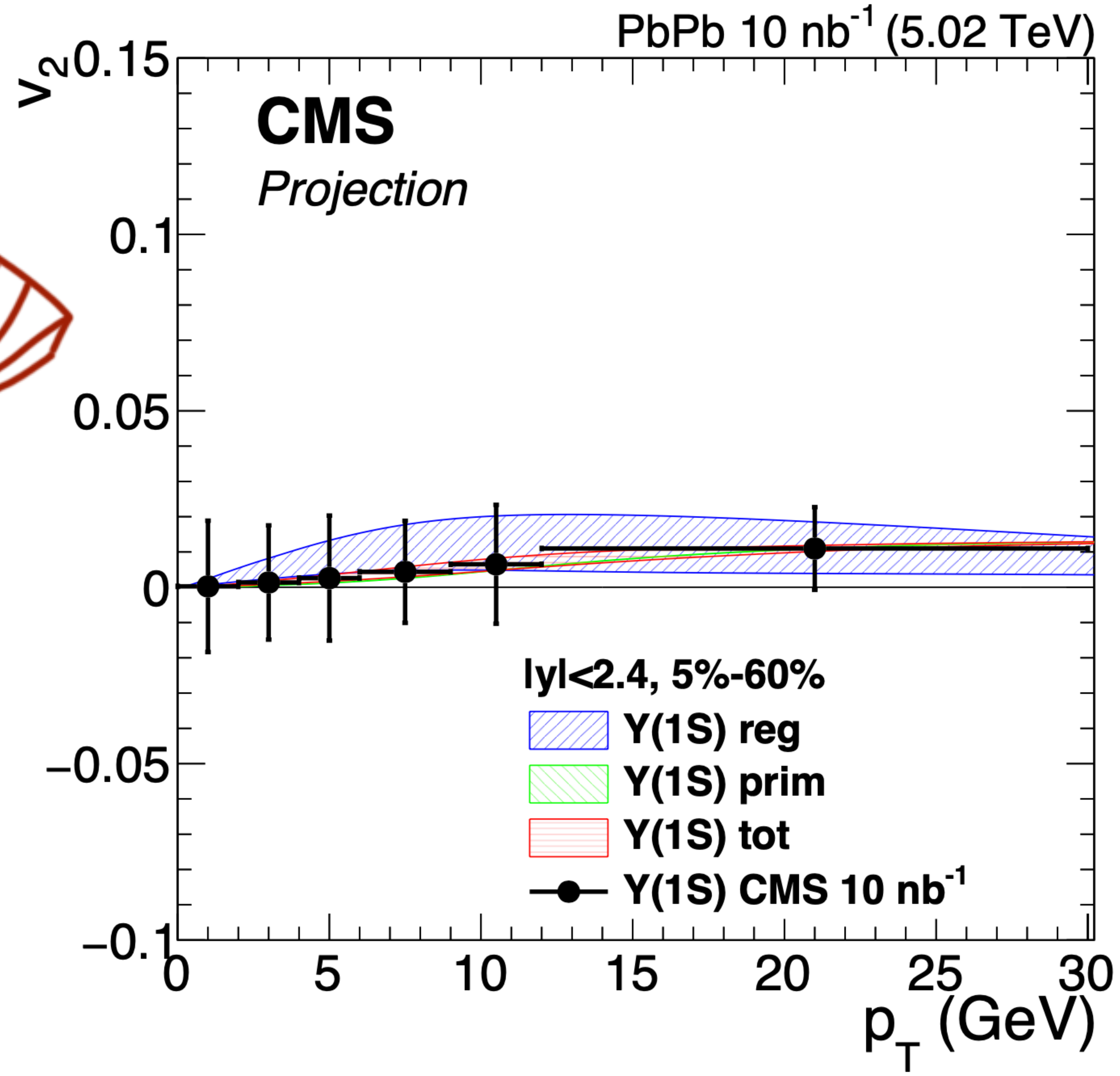
Present

Υ(1S) v_2

HL-LHC

Light
⇓
Open Charm
⇓
Hidden Charm
⇓
Open Beauty
⇓
Hidden Beauty?

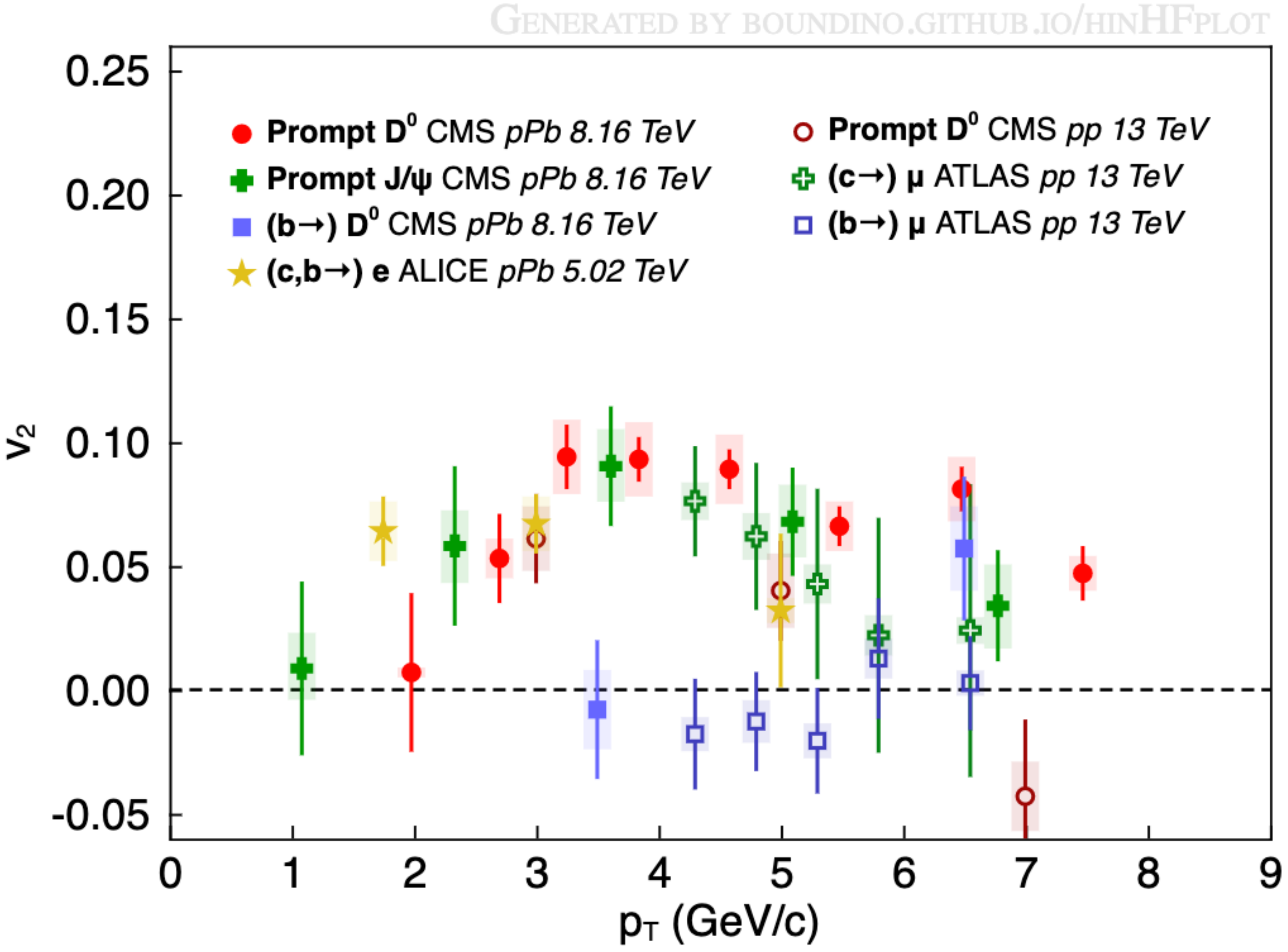




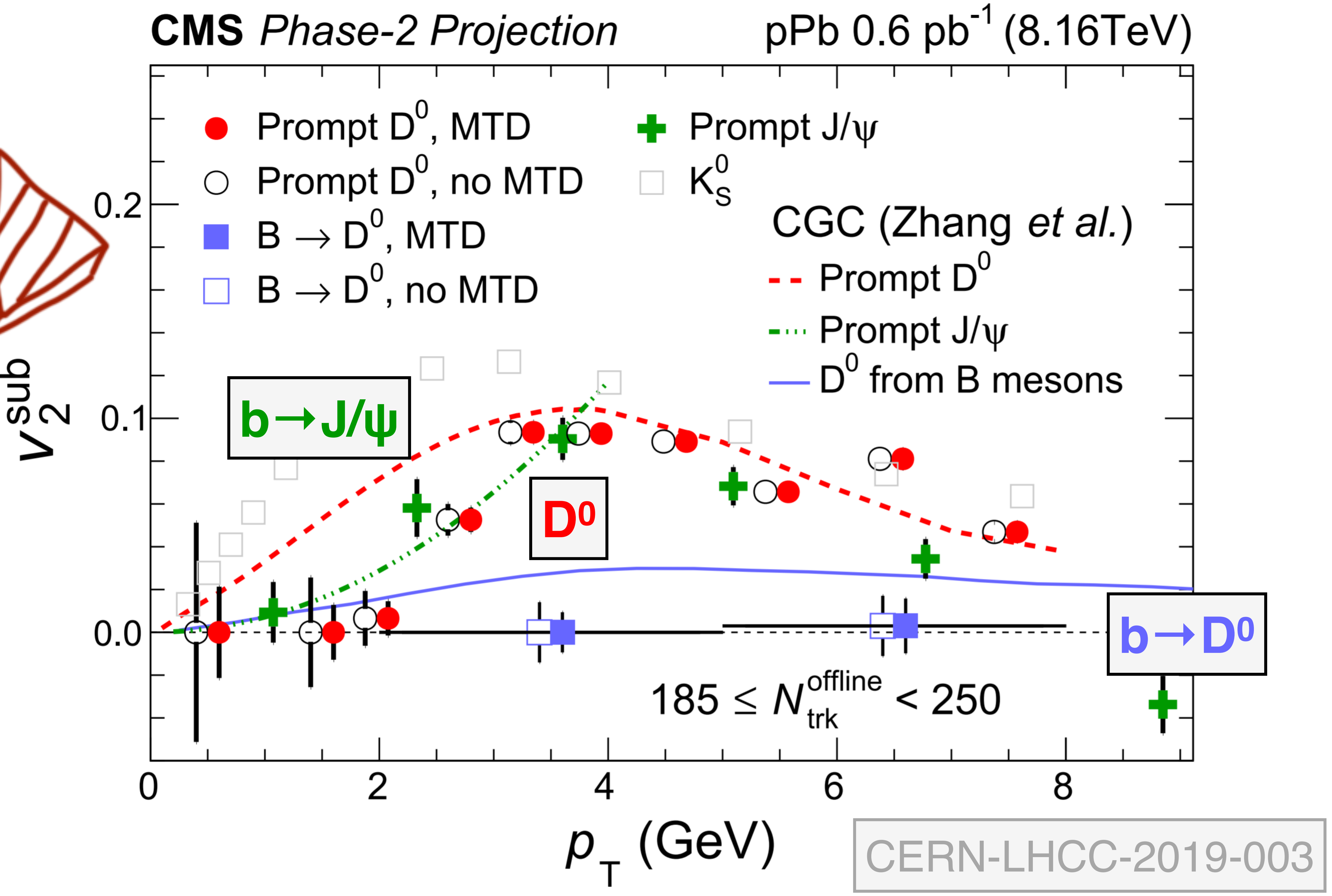
arXiv:1812.06772

- Higher precision and more differential Υ(1S) elliptic flow
- Full picture of collective behavior in all flavor sectors

Present



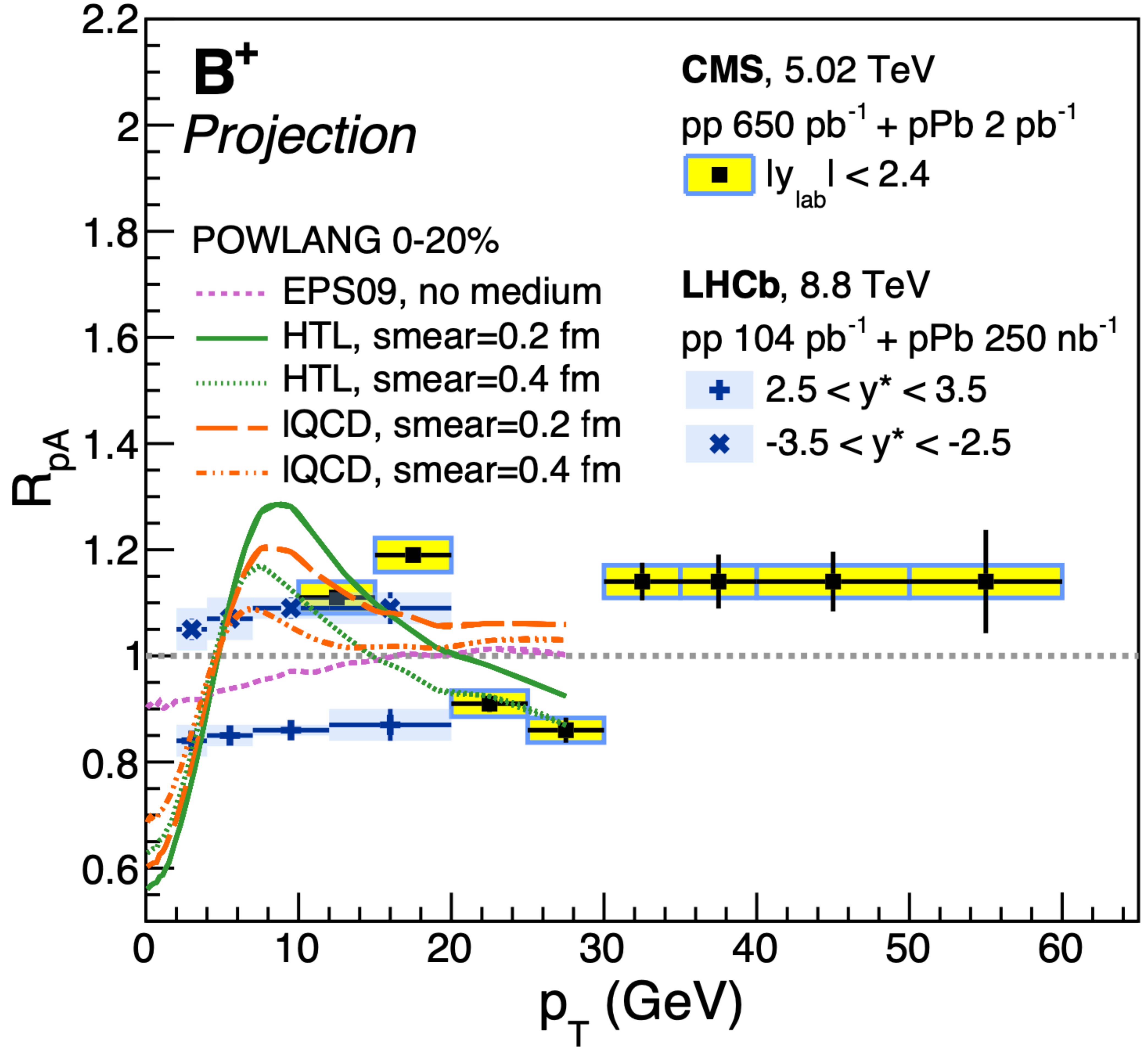
CMS 1-year with MTD



- Unprecedented precision could be achieved over a wider kinematic range with MTD
- Detailed characterization of the heavy flavor hadron collective behavior in small systems
  ➡ Deconfined medium or initial condition effects?
- Enable more differential study scanning multiplicity classes

CNM Effects in pPb Collisions

HL-LHC

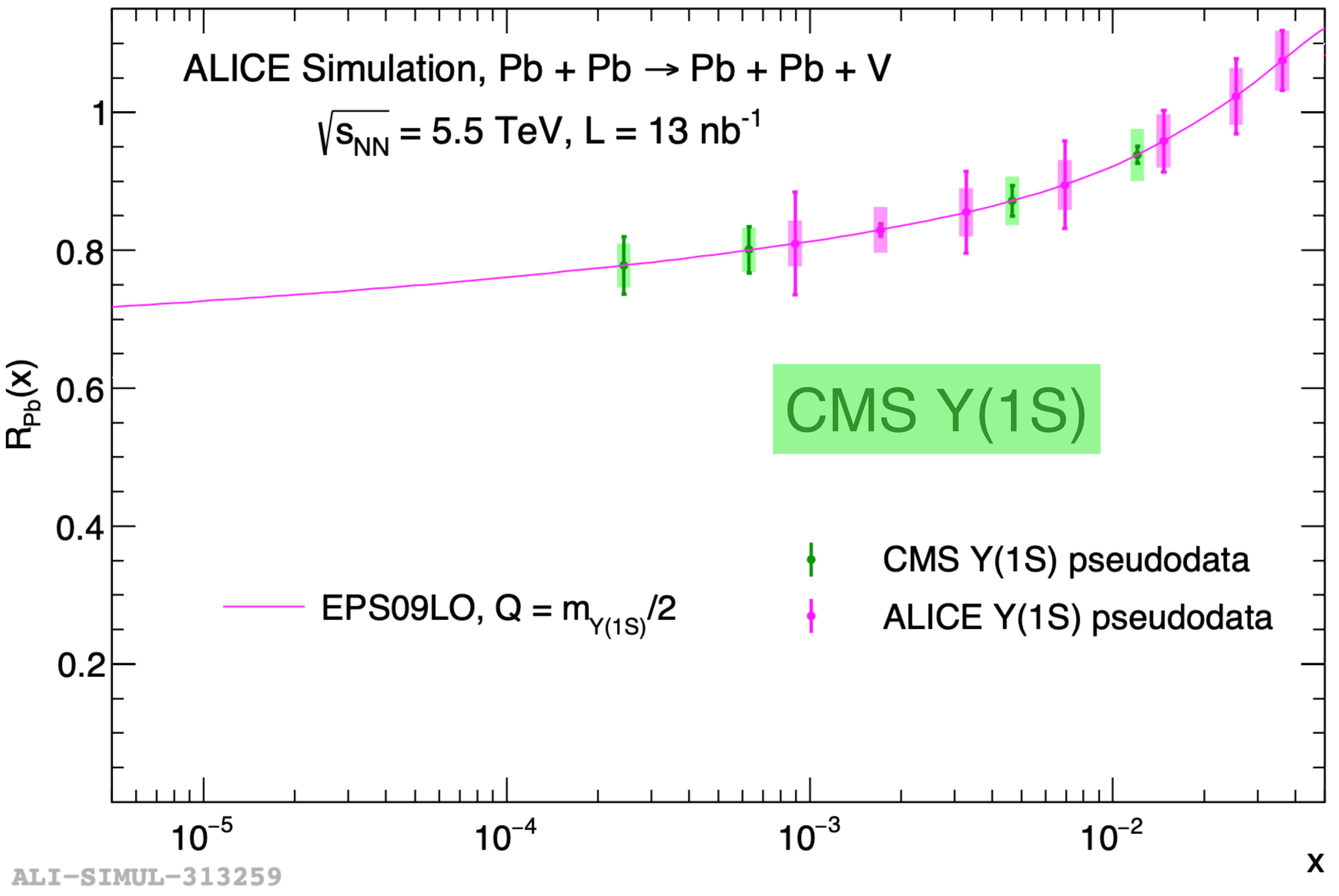


- Precise measurements of heavy flavor hadrons in pPb
- Provide inputs of gluon PDFs
- Distinguish potential hot medium effect from the pure cold matter effects

arXiv:1812.06772

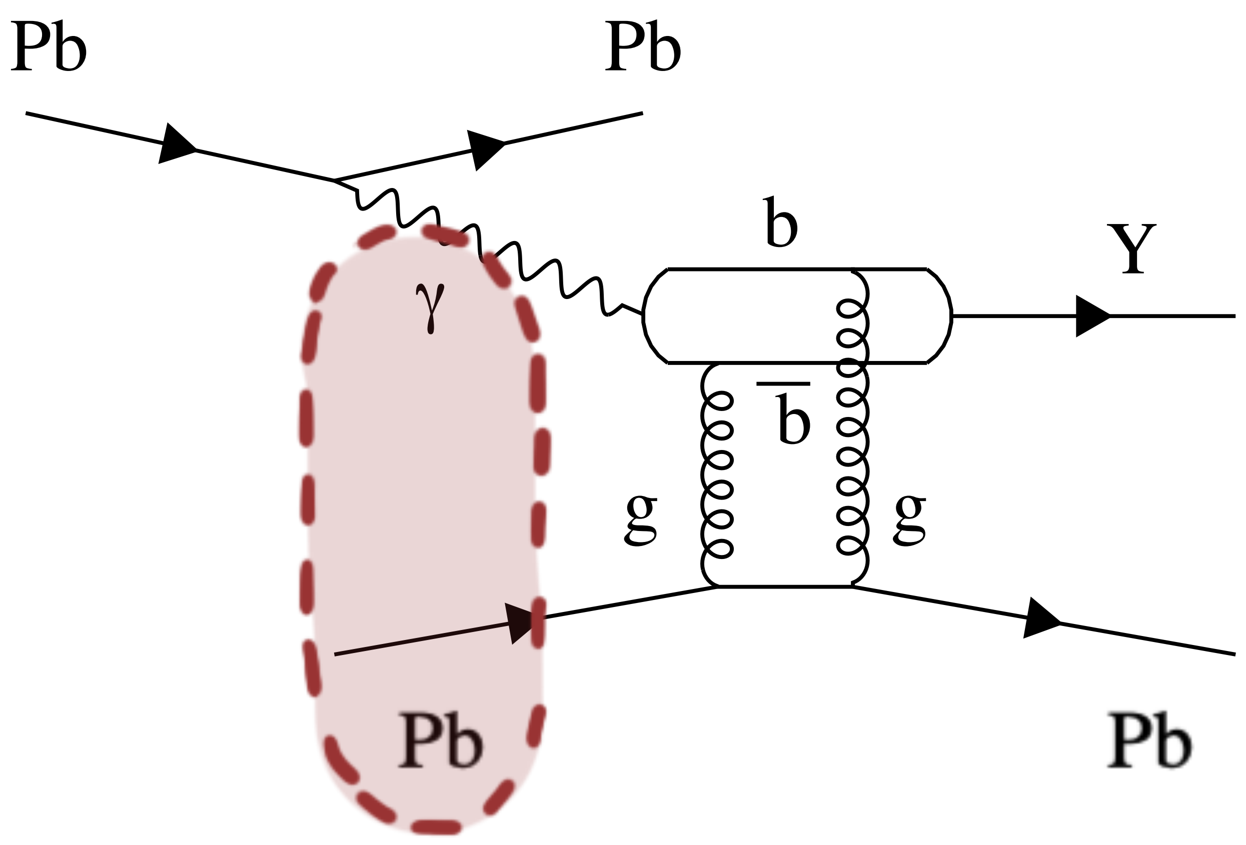
nPDF from Ultra-Peripheral PbPb Collisions

HL-LHC

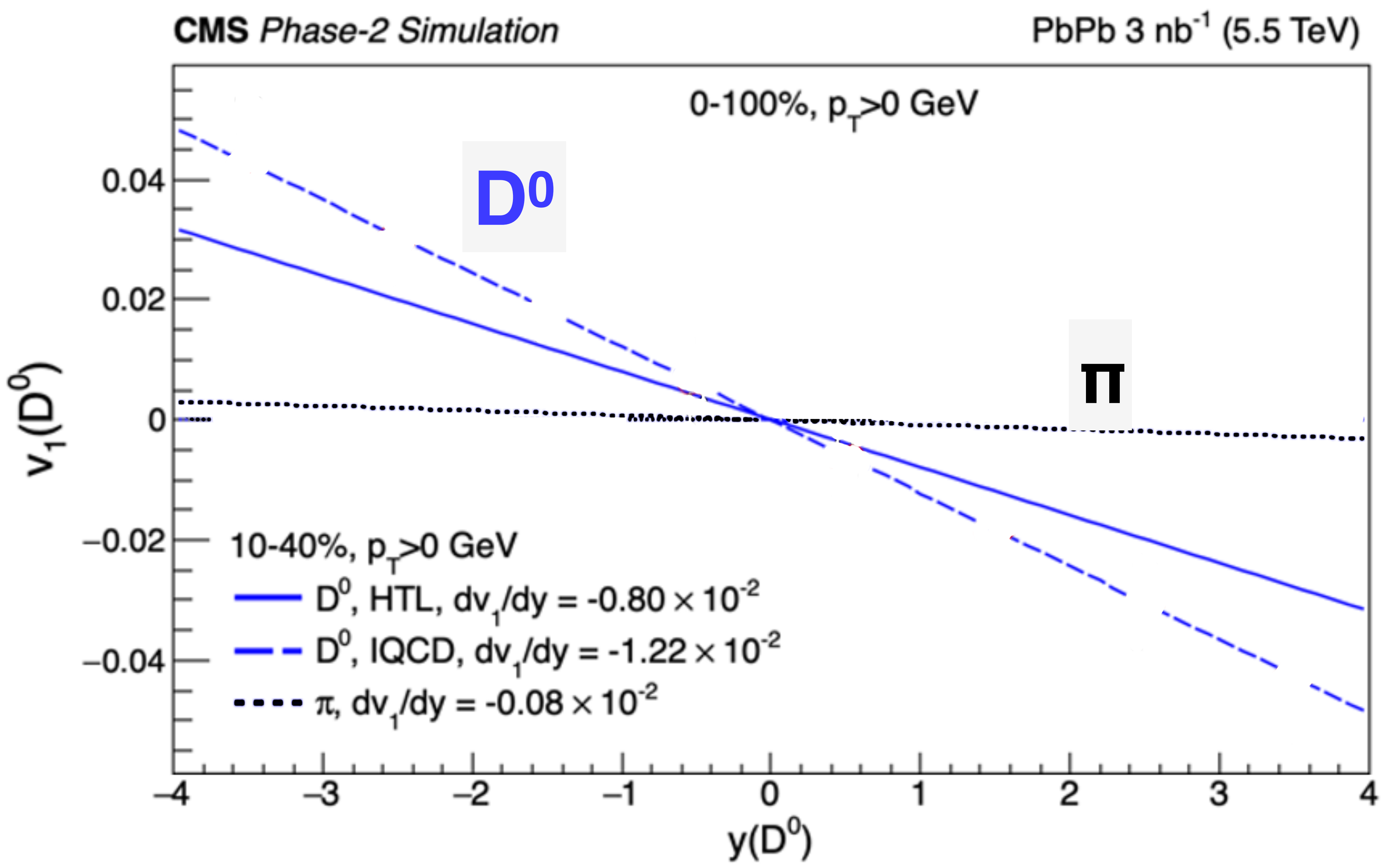


arXiv:1812.06772

- Ultra-Peripheral Collisions(UPC): γ+Pb collisions
- Precise measurements of Y(1S) over a wide x range
  - ➡ Test Q dependence of nuclear modifications with different quarkonion masses
- ➡ Strong constraint on the gluon nuclear PDF

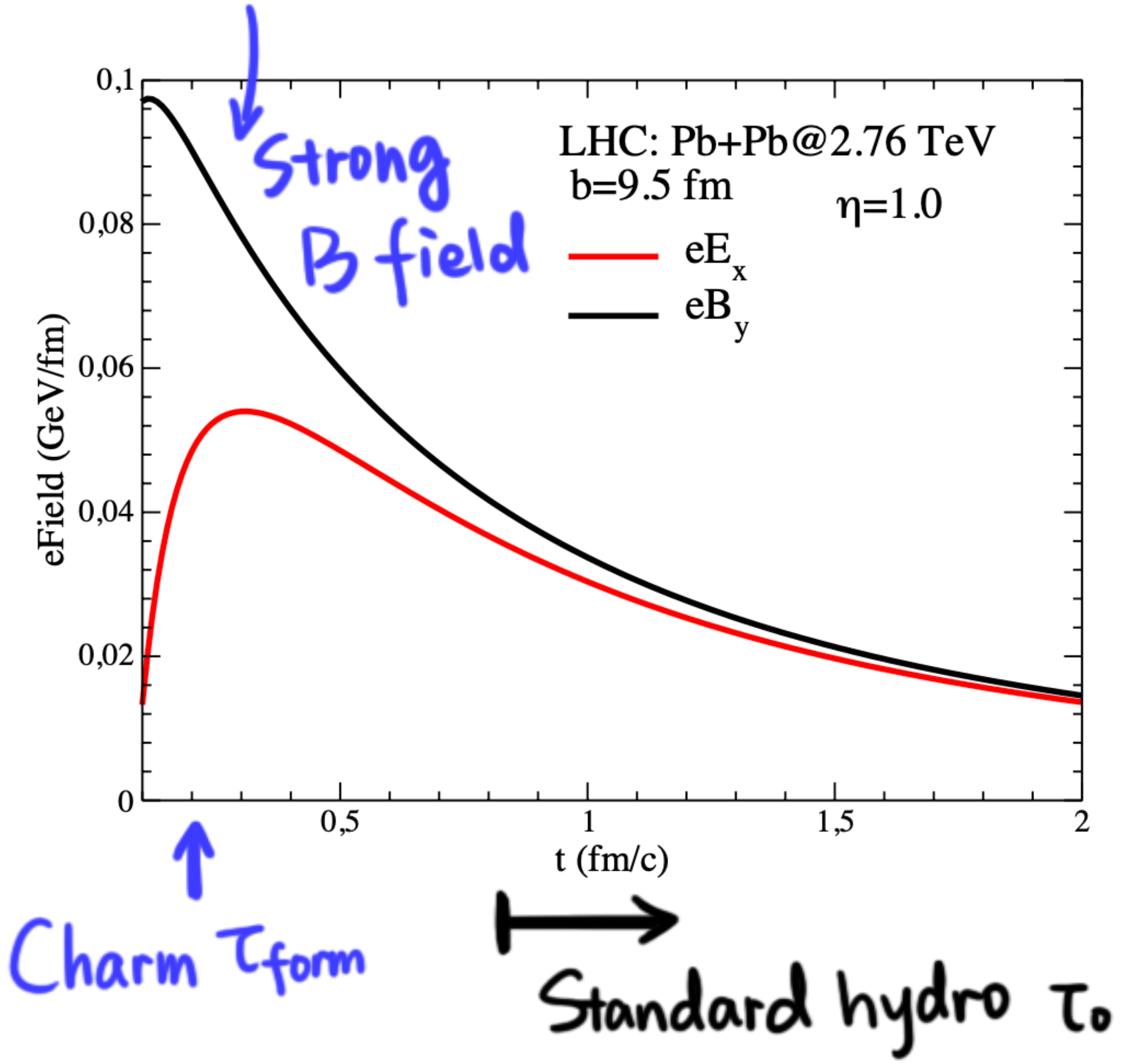


Search for Strong Magnetic Field



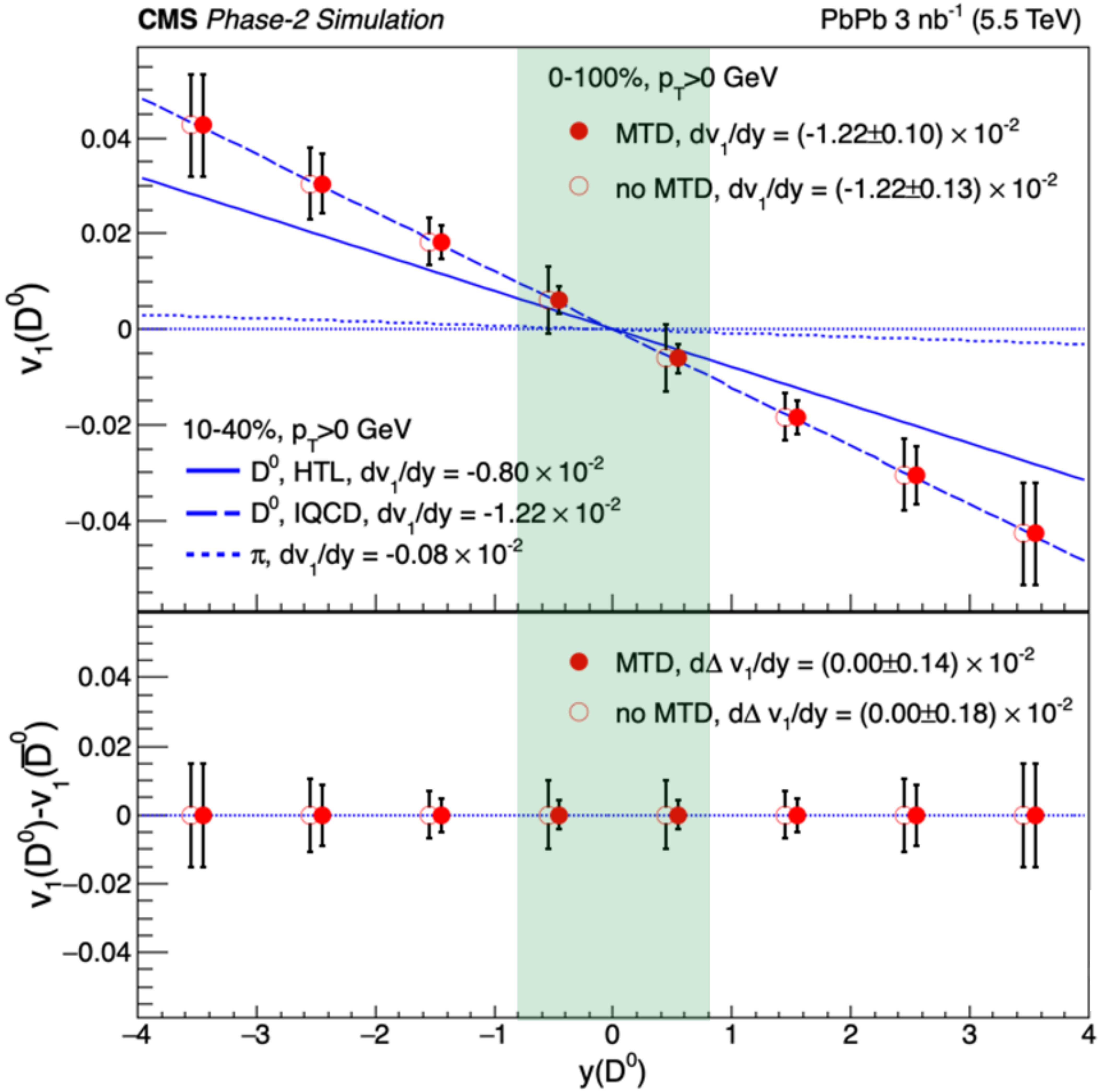
$$\frac{dN}{d\phi} \propto 1 + 2\sum v_n \cos(n(\phi - \Phi_n))$$

- Strong initial electromagnetic field in heavy ion collisions inducing a vorticity in the reaction plane.
  ➡ Heavy quarks produced early as best probes



Search for Strong Magnetic Field

CMS 1-year with MTD



- Strong initial electromagnetic field in heavy ion collisions inducing a vorticity in the reaction plane.
  ➡ Heavy quarks produced early as best probes
- The resultant effects entails a significant directed flow (v_1) and increase vs. rapidity
- Current measurements sticked in midrapidity from ALICE and STAR
- MTD and the large acceptance CMS tracker could provide high precision measurement of D^0 v_1 over 8 units of D^0 rapidity

Summary

HL-LHC: CMS will be the most comprehensive QGP detector

	Wide-coverage Tracking	Precision Vertexing	Full Calorimetry	High Rate	Lepton PID	Hadron PID
CMS	✓ Upgrade	✓ Upgrade	✓	✓ Upgrade	✓	✓ New
ATLAS	✓	✓	✓	✓	✓	
ALICE		✓		✓		✓
LHCb		✓	✓	✓	✓	✓

- High precision production and flow in large and small systems with detector upgrade and HL-LHC
  ➡ Hot and cold nuclear matter effects, wider kinematics and more differential
- New MTD leads to unprecedented precision of D mesons and Λ_c down to 0 p_T
  ➡ Also enable new observables (photon-D correlation, D-$\bar{D}$ correlation)
- Wide rapidity coverage ($|\eta| < 4$) provides new access to study of longitudinal dynamics
  ➡ Full 3+1D heavy quark dynamics in QGP medium


Isabelle
Thanks for your attention!

Back up

Thanks for your attention!

Heavy-ion data in CMS

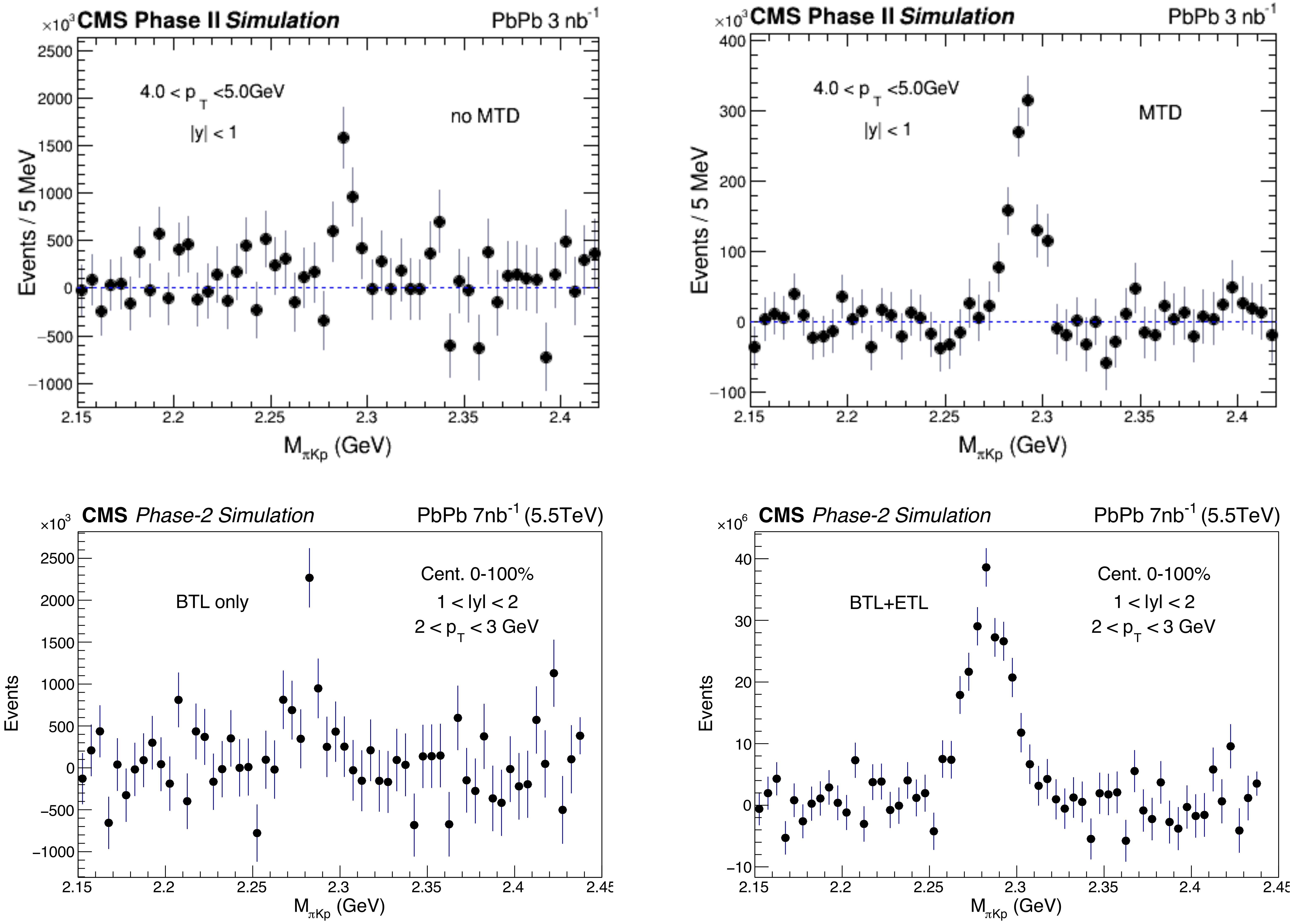
	Collision System	Energy	CMS Recorded	Scale to pp
		Run 1		
2011	Pb-Pb	2.76 TeV	174.3 μb^{-1}	7.5 pb^{-1}
2013	p-Pb	5.02 TeV	35.5 nb^{-1}	7.4 pb^{-1}
		Run2		
2015	p-p	5.02 TeV	28.1 pb^{-1}	28.1 pb^{-1}
2015	Pb-Pb	5.02 TeV	0.55 nb^{-1}	23.8 pb^{-1}
2016	p-Pb	8.16 TeV	180.2 nb^{-1}	37.5 pb^{-1}
2017	Xe+Xe	5.44 TeV	6.0 μb^{-1}	99.8 nb^{-1}
2017	p-p	5.02 TeV	316.3 pb^{-1}	316.3 pb^{-1}
2018	Pb-Pb	5.02 TeV	1.71 nb^{-1}	74.0 pb^{-1}

Heavy-ion data in CMS

Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

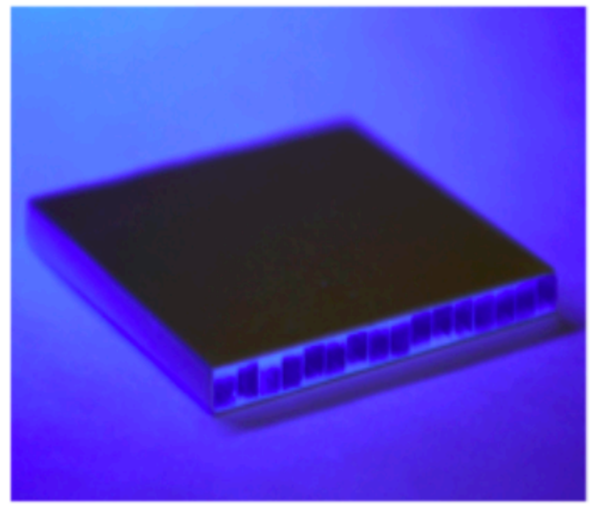
CMS MIP Timing Detector (MTD)

Λ_c Reconstruction with MTD

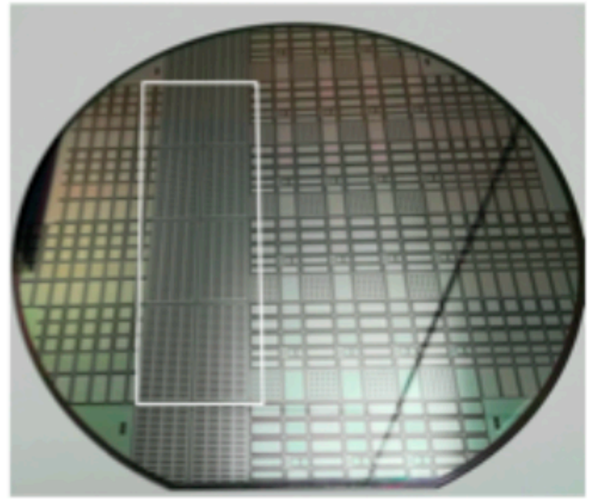


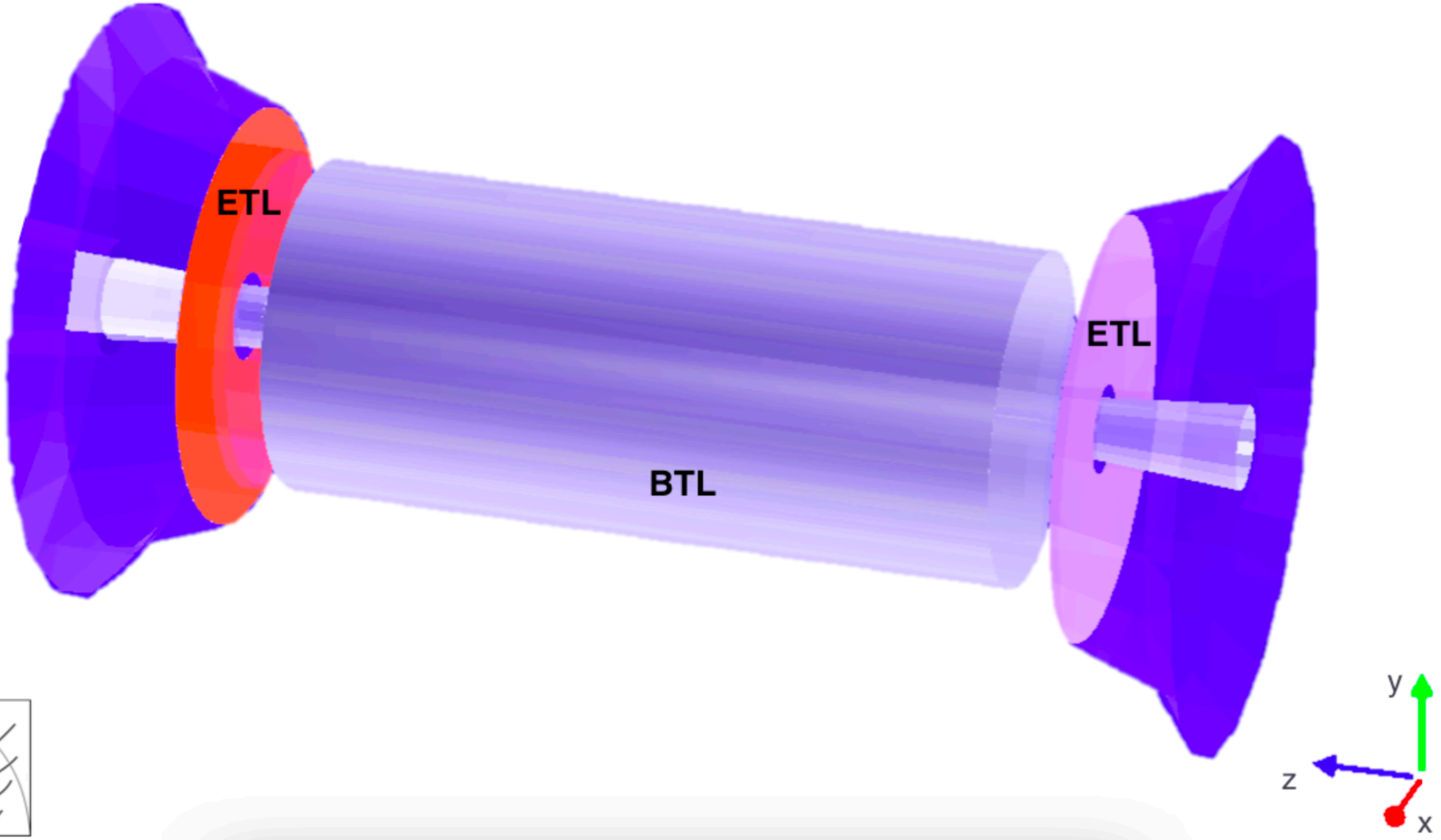
CMS MTD

BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2×10^{14} n_{eq}/cm^2



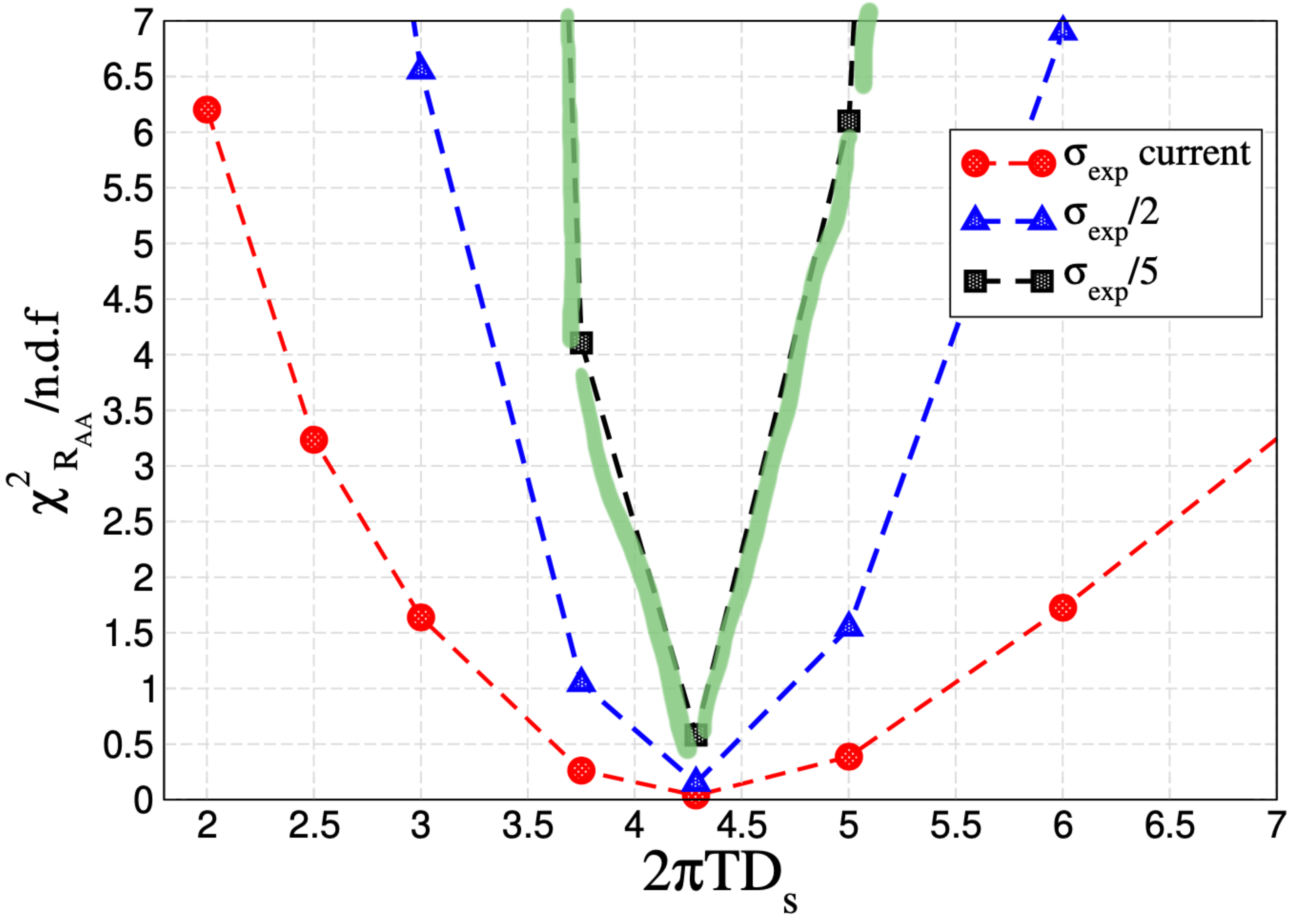
ETL: Si with internal gain (LGAD):
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2



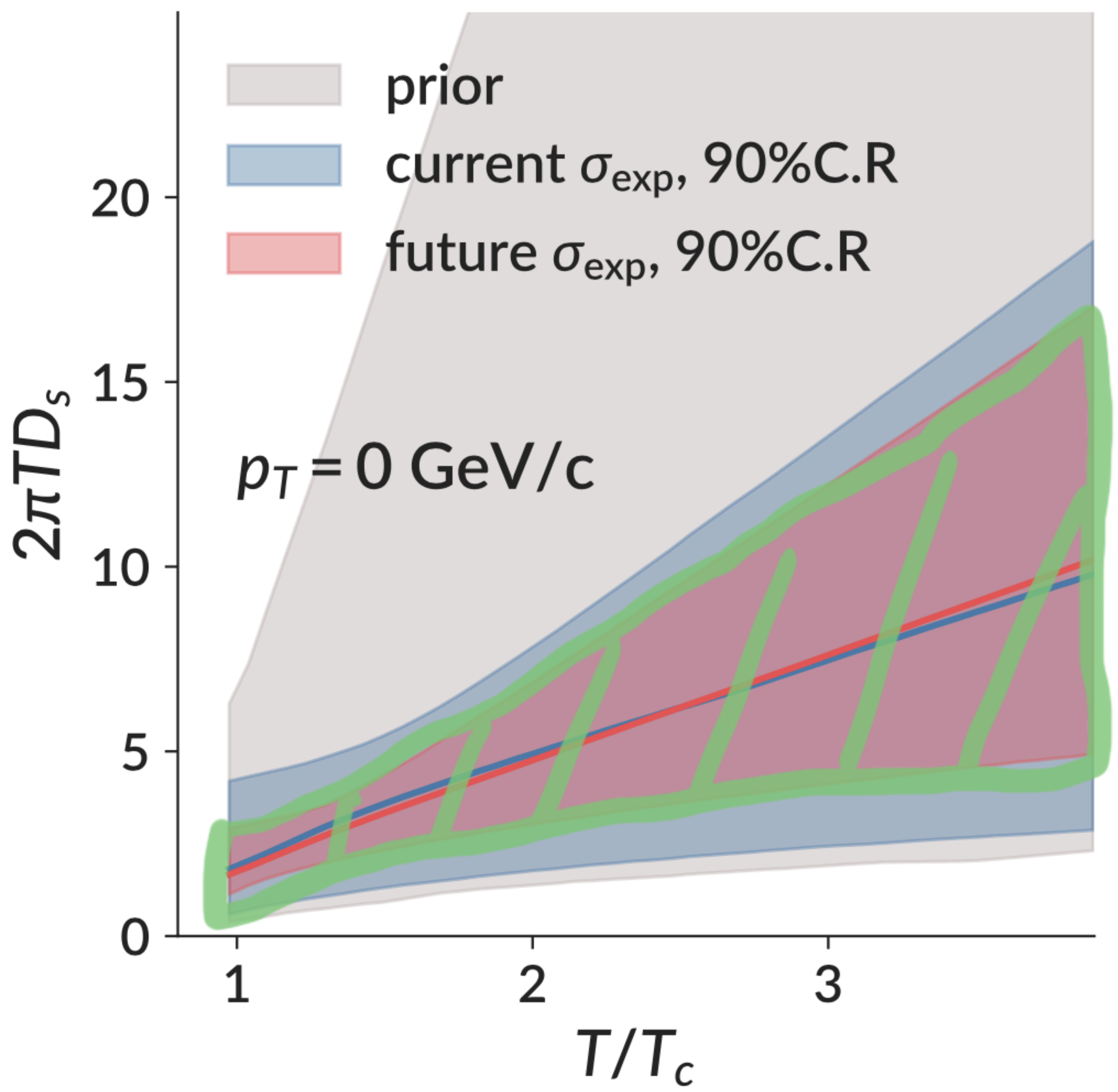


D_s diffusion coefficient

D_s projection after Run 4 (Catania)

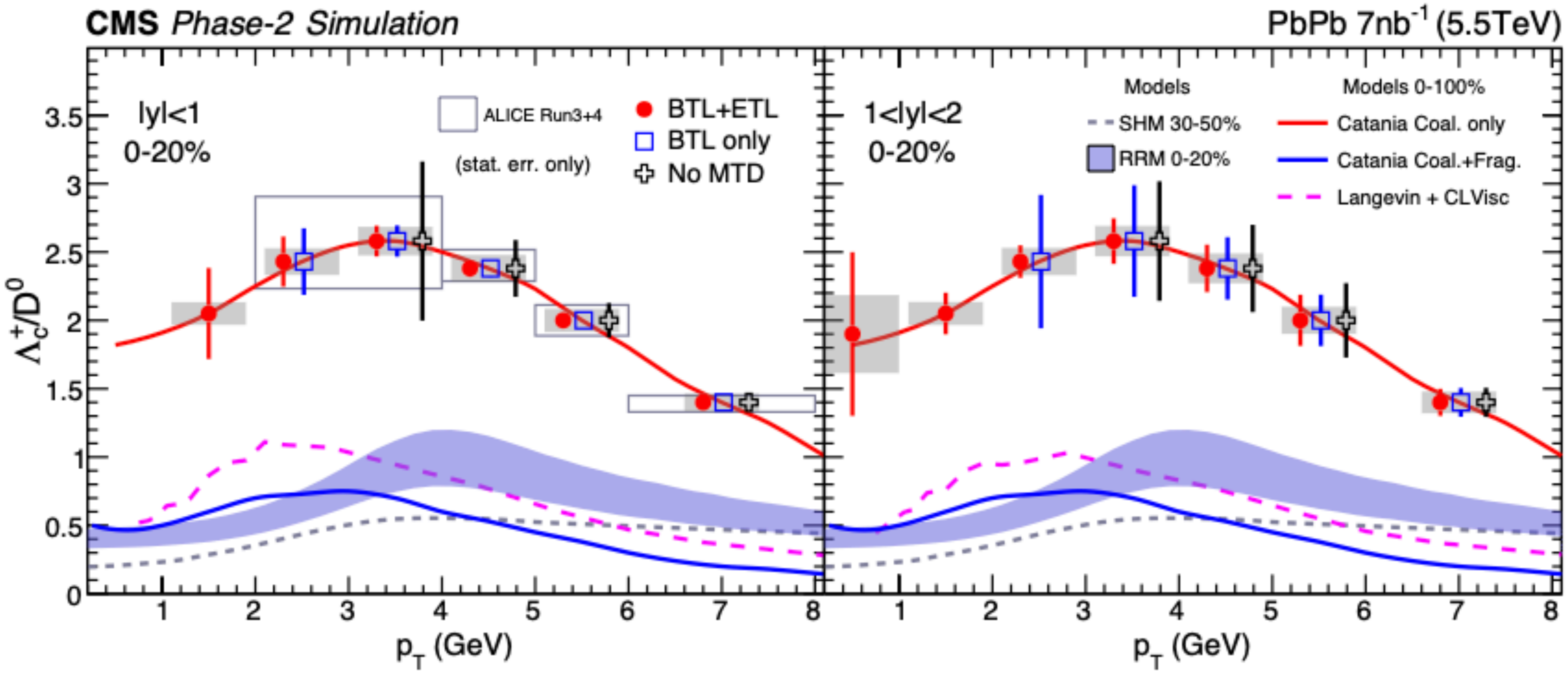


D_s projection after Run 4 (LBT)

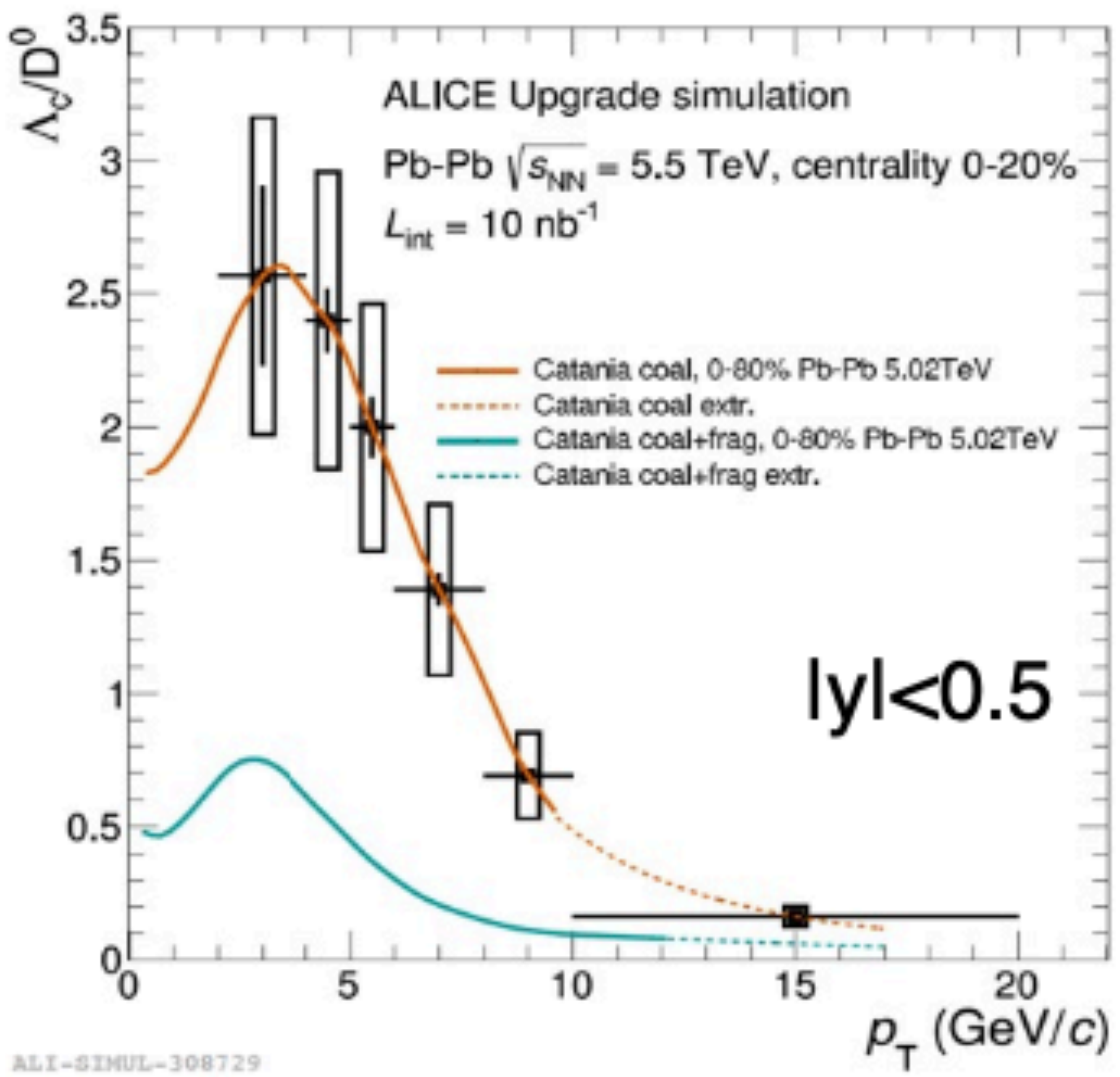


CMS vs. ALICE: Λ_c

CMS Run 4



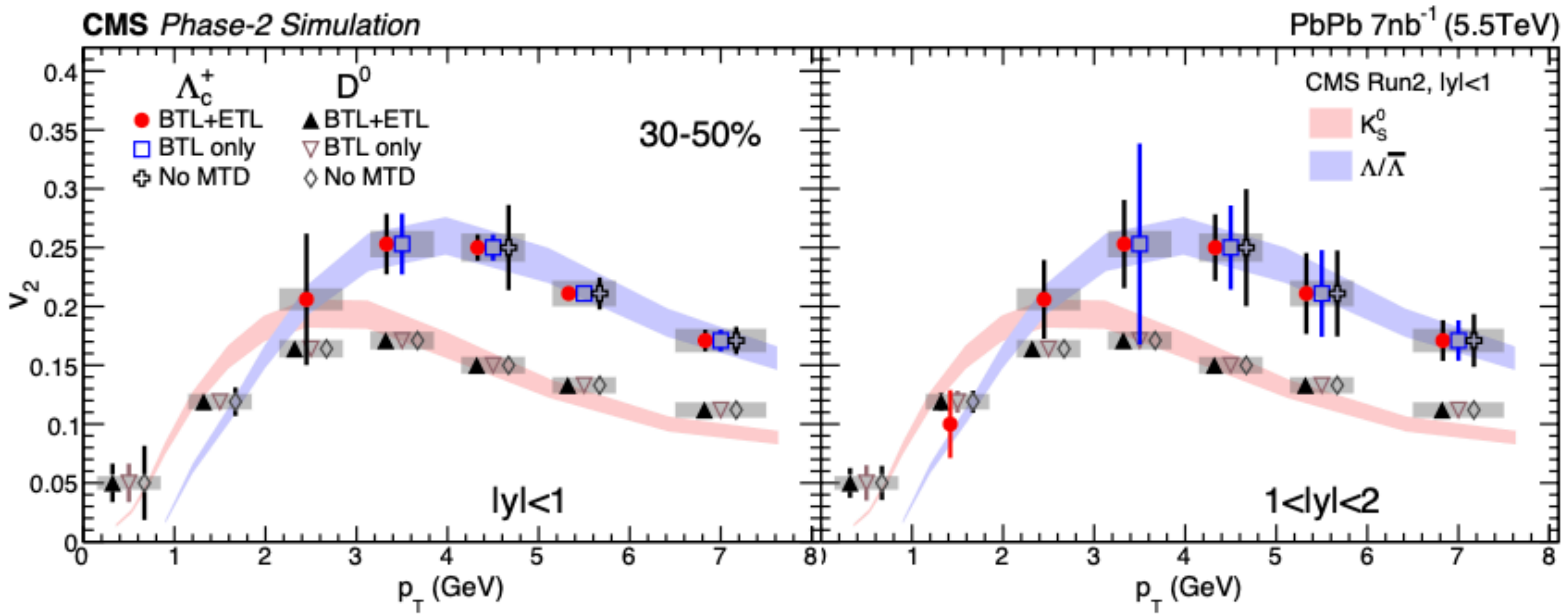
ALICE Run 3+4



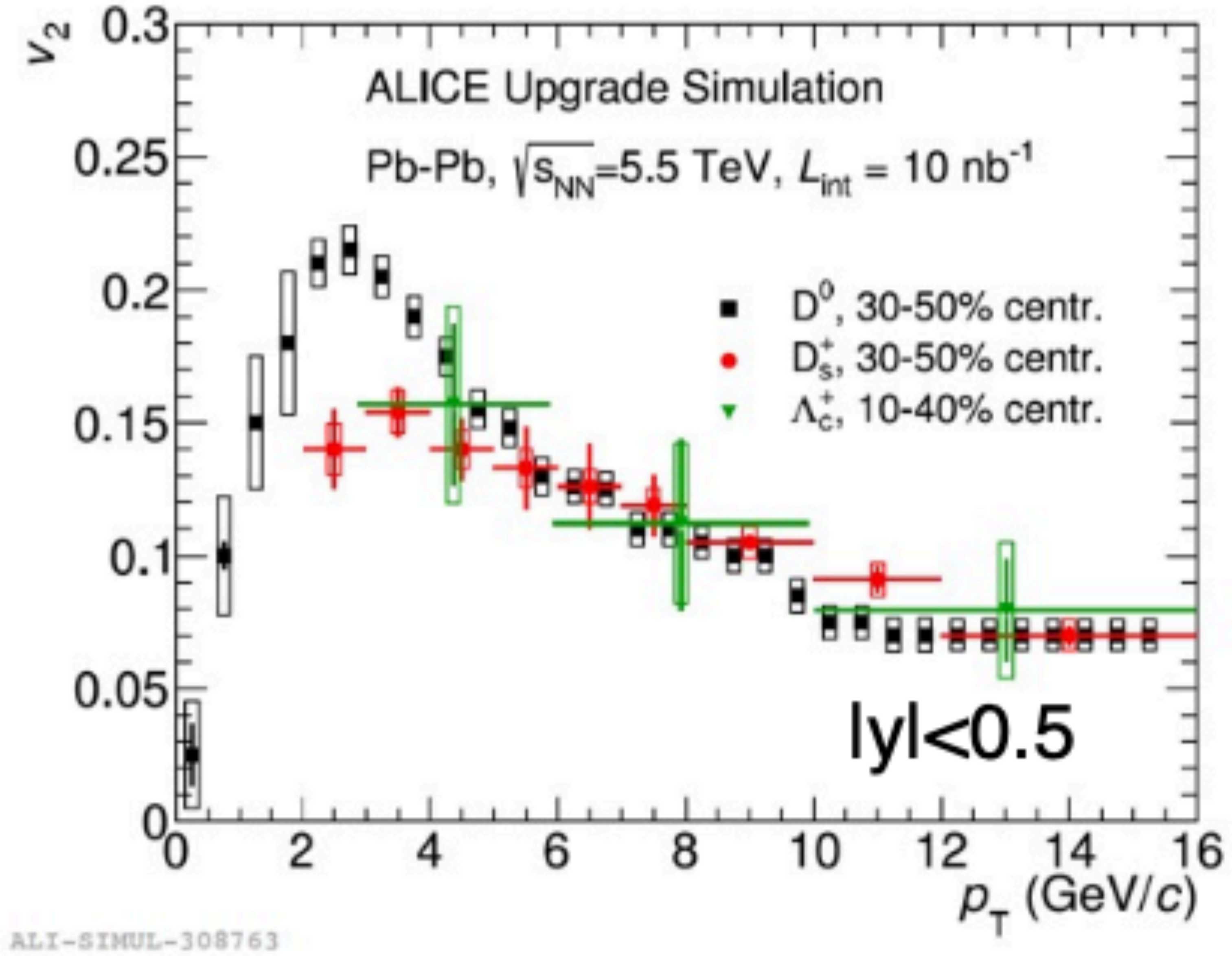
CMS vs. ALICE: Charm v_2

Elliptic flow of charm hadrons

CMS Run 4

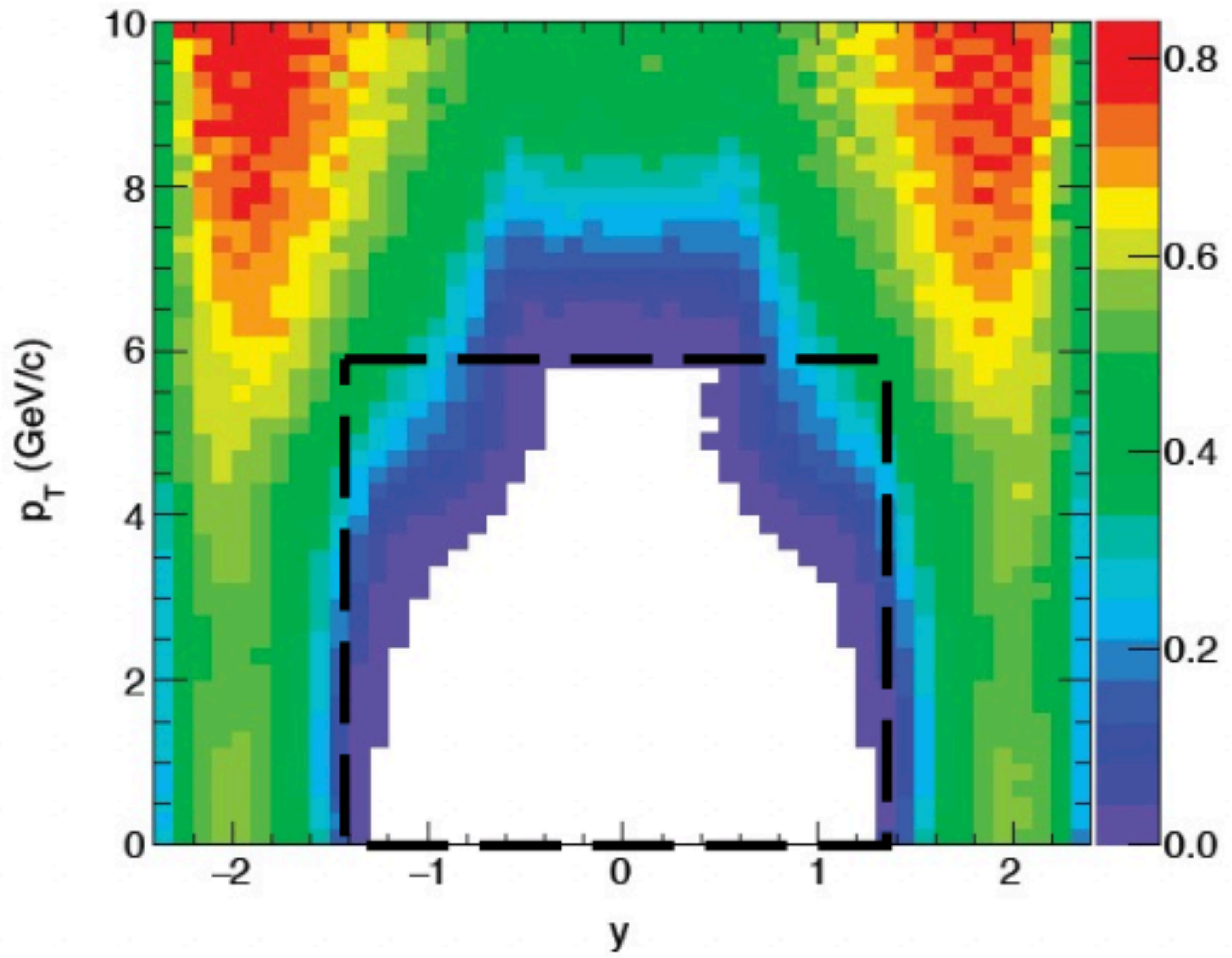


ALICE Run 3+4



Quarkonia with MTD

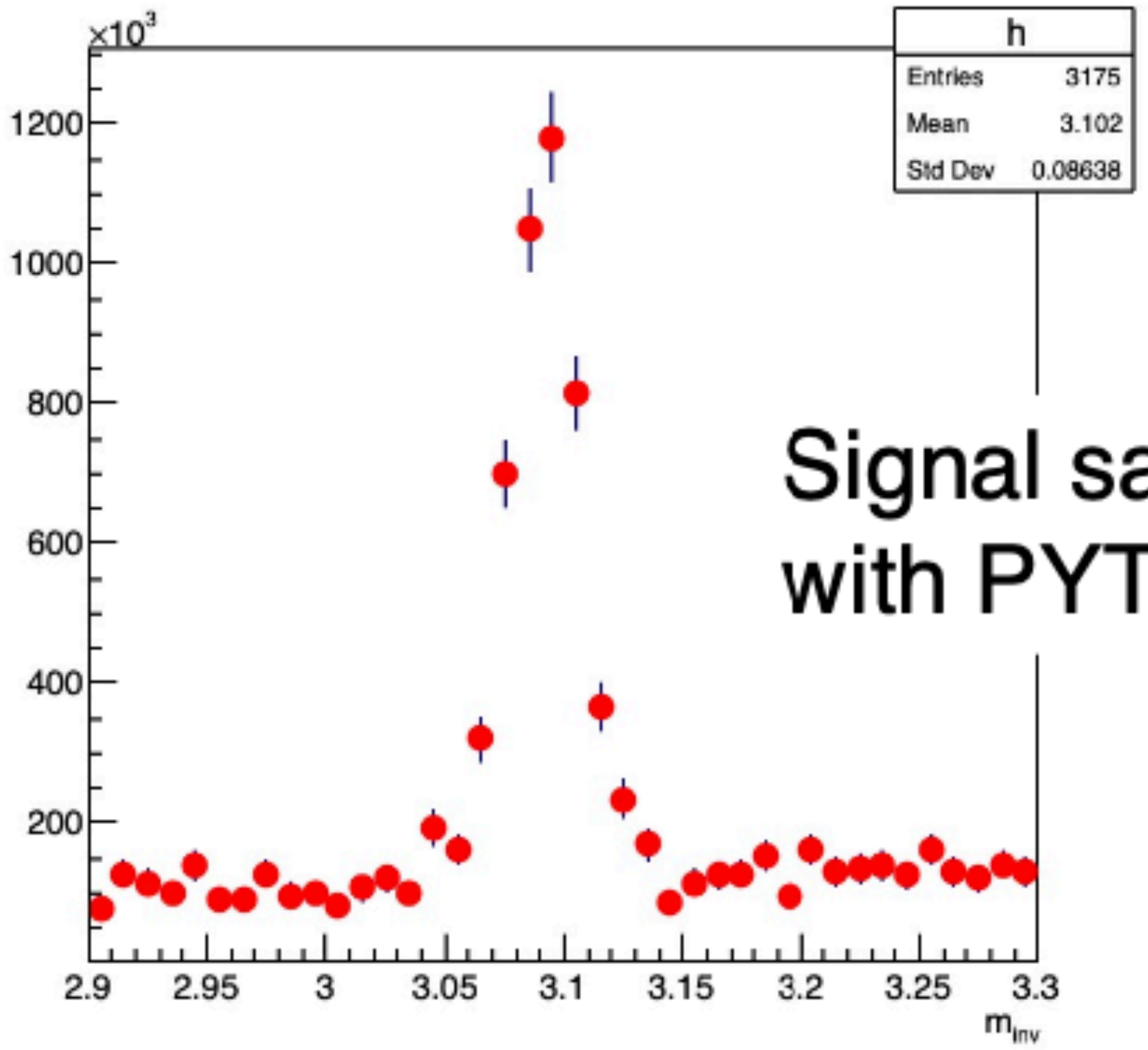
Offline $J/\psi \rightarrow \mu^+\mu^-$ acc*eff
(BR=0.0593)



Missing low-p_T at midrapidity

$J/\psi \rightarrow p\bar{p}$ with MTD
(BR=0.0022)

$|y|<1.5$, $0.15<p_T<1.3$ GeV



Signal sample with PYTHIA 8

From Wei Li

Significance of ~ 20 for MB PbPb with L_{int}=7/nb

12

Multi-HF hadrons

Multi-HF hadron: other channels

3

	B.R.
$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ + K^- + \pi^+ + \pi^-$	5%
$\Lambda_c^+ \rightarrow p + K^- + \pi^+$	6.35%
	0.32%

	B.R.
$\Xi_{cc}^{++} \rightarrow \Xi_c^+ + \pi^+$	5%
$\Xi_c^+ \rightarrow p + K^- + \pi^+$	2.2 ± 0.8% (1)
	0.11%

Ξ_{cc} decays: BR from 1703.09086 (authors claim ~1% < BR < ~10%)

	B.R.
$\Omega_{ccc}^{++} \rightarrow \Xi_{cc}^{++} + \overline{K}^0$	5% x 0.5
$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ + K^- + \pi^+ + \pi^-$	5%
$\Lambda_c^+ \rightarrow p + K^- + \pi^+$	6.35%
$\overline{K}^0 : 50\,\%\, K_s^0 \rightarrow \pi^+ + \pi^-$	70%
	0.0055%

	B.R.
$\Omega_{ccc}^{++} \rightarrow \Xi_{cc}^{++} + \overline{K}^0$	5% x 0.5
$\Xi_{cc}^{++} \rightarrow \Xi_c^+ + \pi^+$	5%
$\Xi_c^+ \rightarrow p + K^- + \pi^+$	2.2 ± 0.8% (1)
$\overline{K}^0 : 50\,\%\, K_s^0 \rightarrow \pi^+ + \pi^-$	70%
	0.0019%

	B.R.
$\Omega_{ccc}^{++} \rightarrow \Xi_c^+ + \mathrm{D}^+$	5%
$\Xi_c^+ \rightarrow p + K^- + \pi^+$	2.2 ± 0.8% (1)
$\mathrm{D}^+ \rightarrow K^- + \pi^+ + \pi^-$	9%
	0.0099%

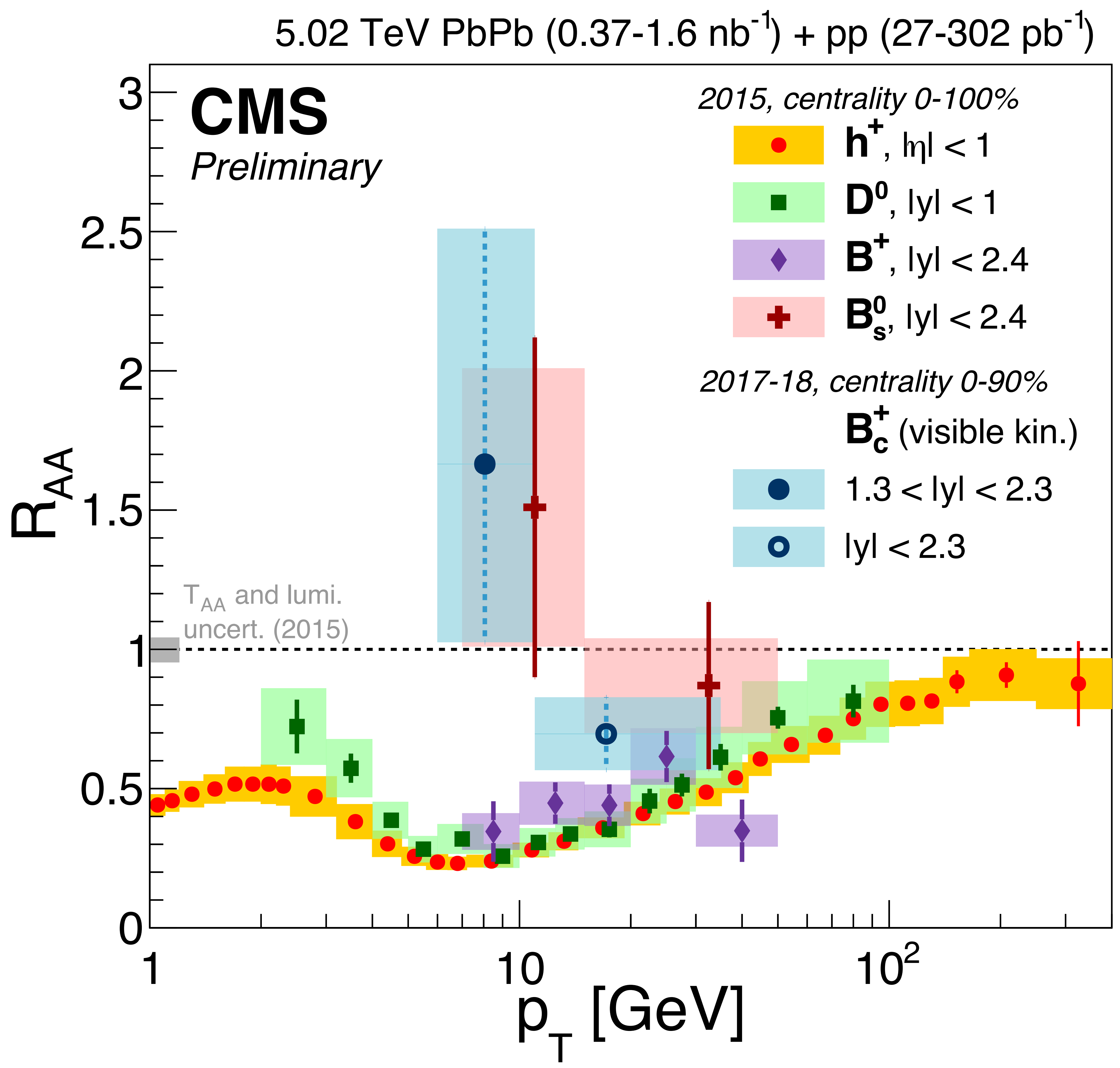
	B.R.
$\Omega_{ccc}^{++} \rightarrow \Omega_{cc}^+ + \pi^+$	5%
$\Omega_{cc}^+ \rightarrow \Omega_c^0 + \pi^+$	5%
$\Omega_c^0 \rightarrow \Omega^- + \pi^+$	5%
$\Omega^- \rightarrow \Lambda + K^-$	67.8%
$\Lambda \rightarrow p + \pi^-$	63.9%
	0.0054%

(1) Belle, B.R. = 0.45 ± 0.22%, PRD 100 (2019) 031101

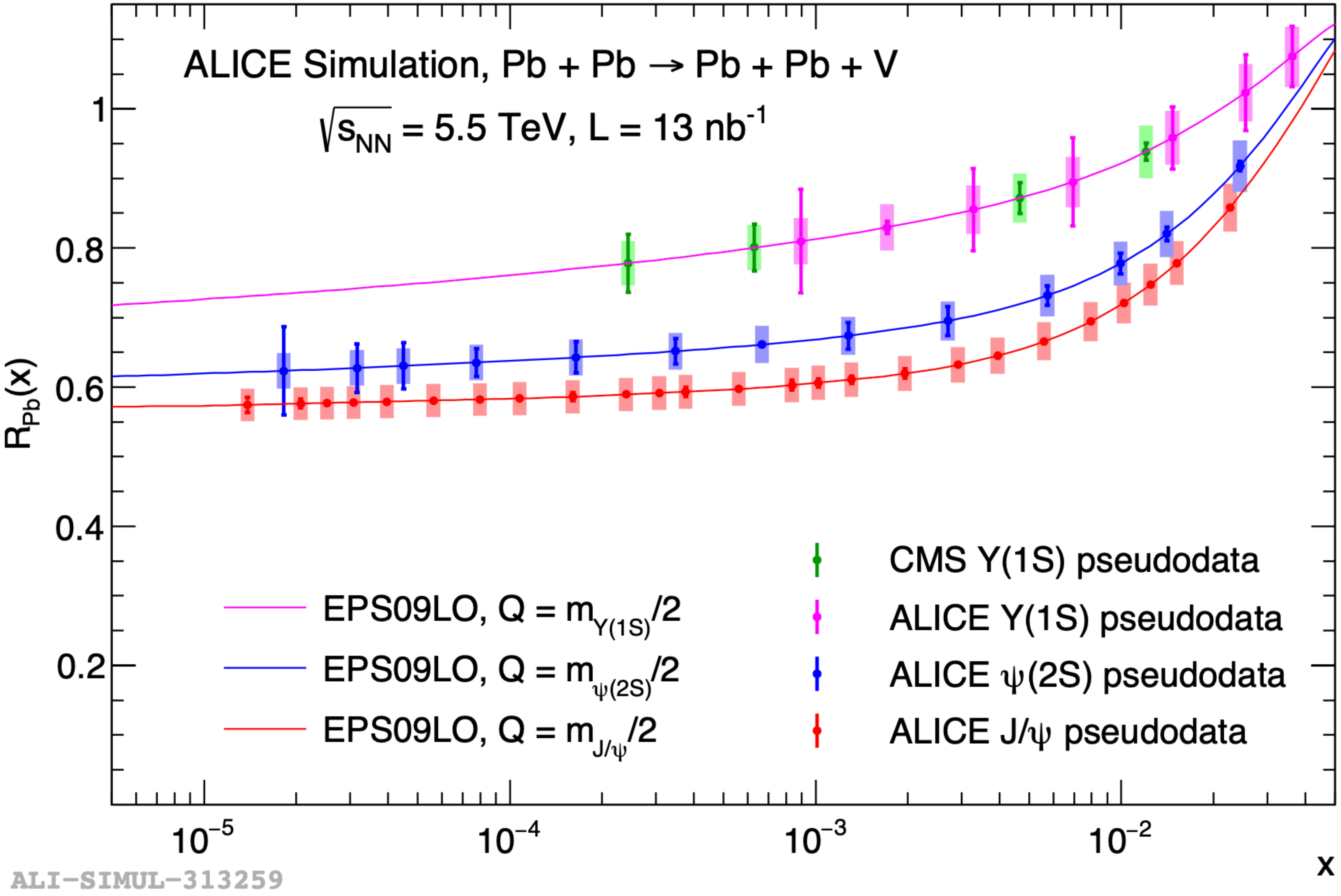
G.M. Innocenti, Prospects for heavy-flavour measurements with ALICE3 44

B_c meson

Present Data



nPDF from Ultra-Peripheral PbPb Collisions

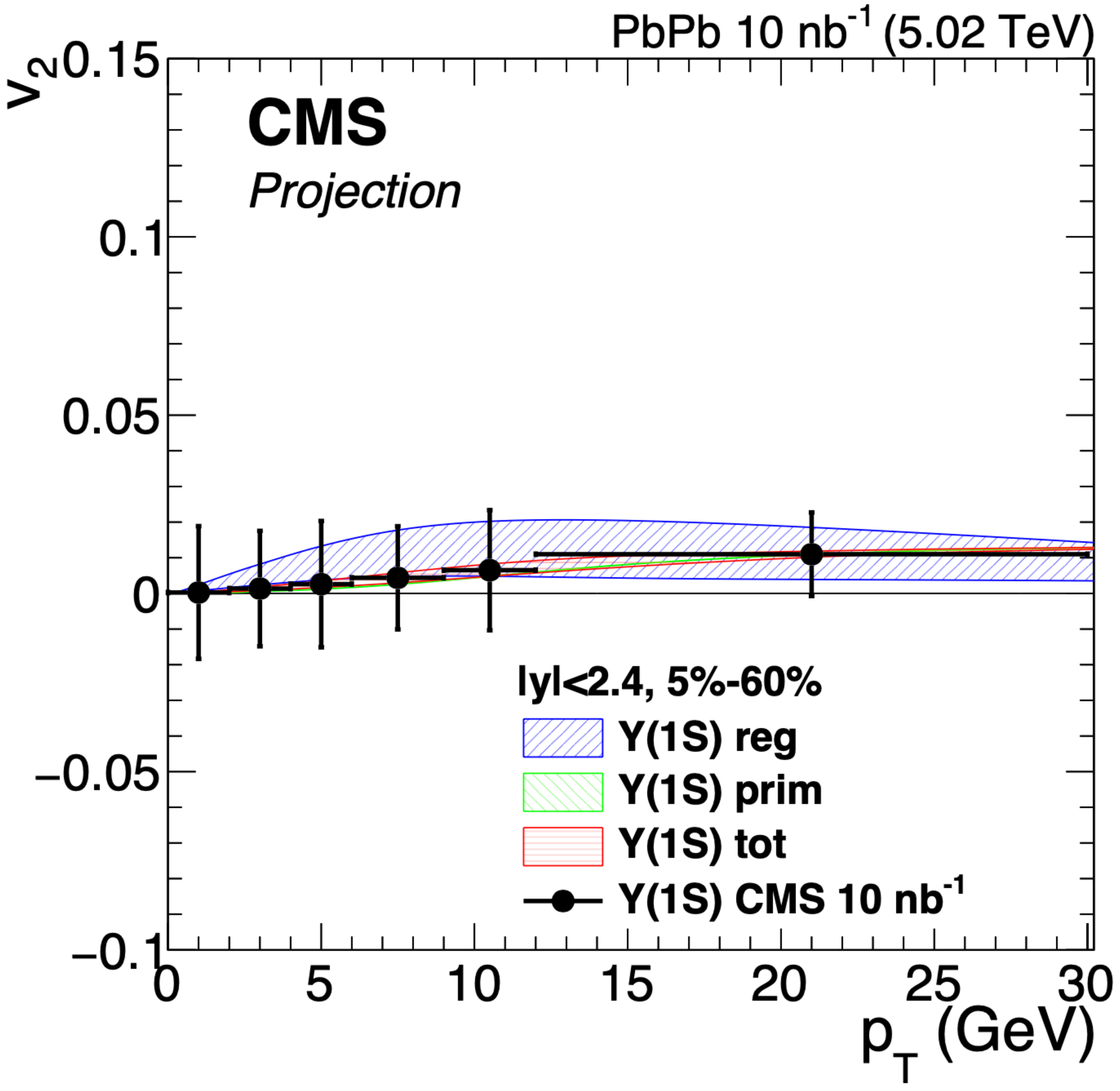


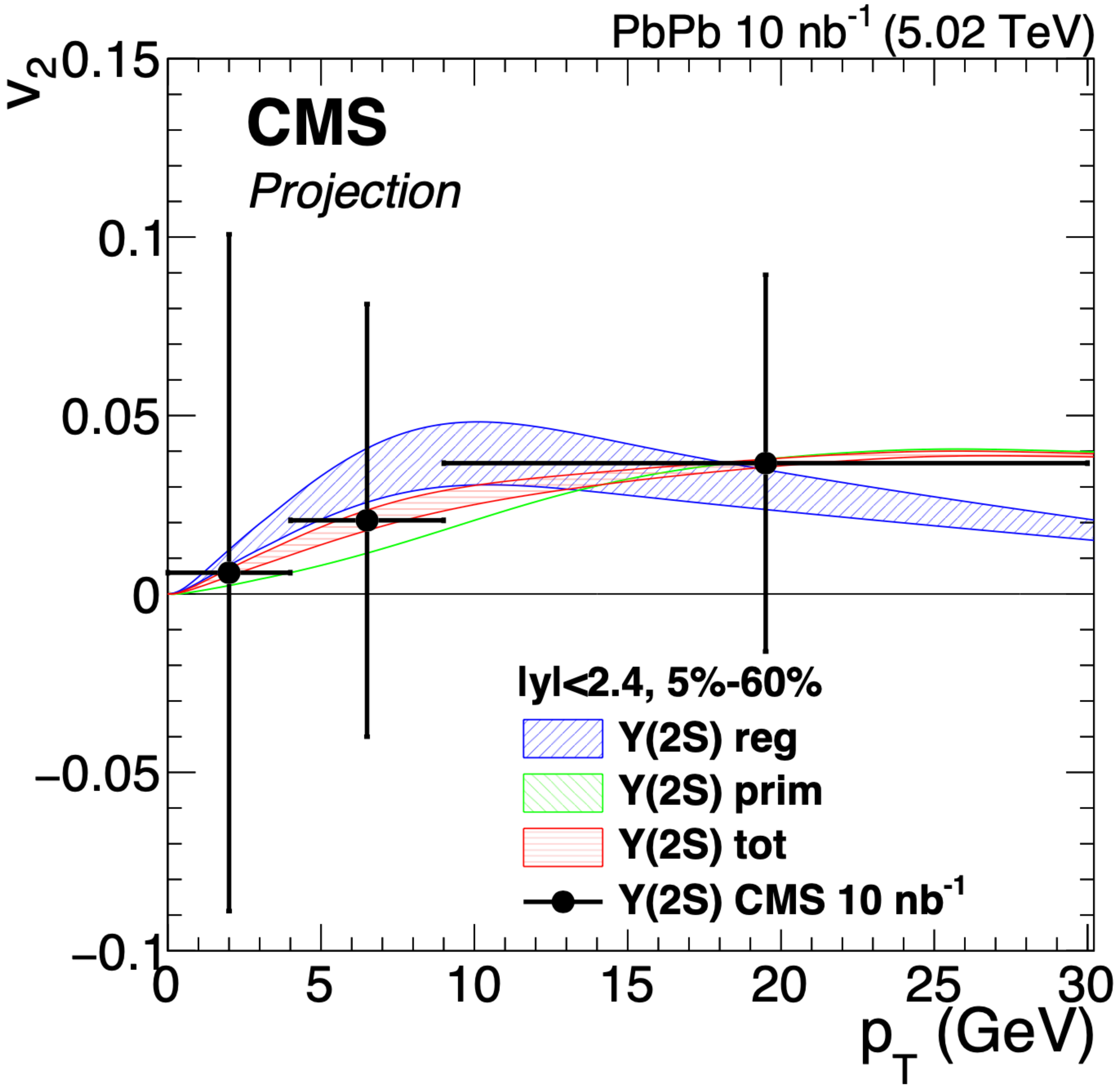
Quarkonion Azimuthal Anisotropy v_2

Y(1S) v_2

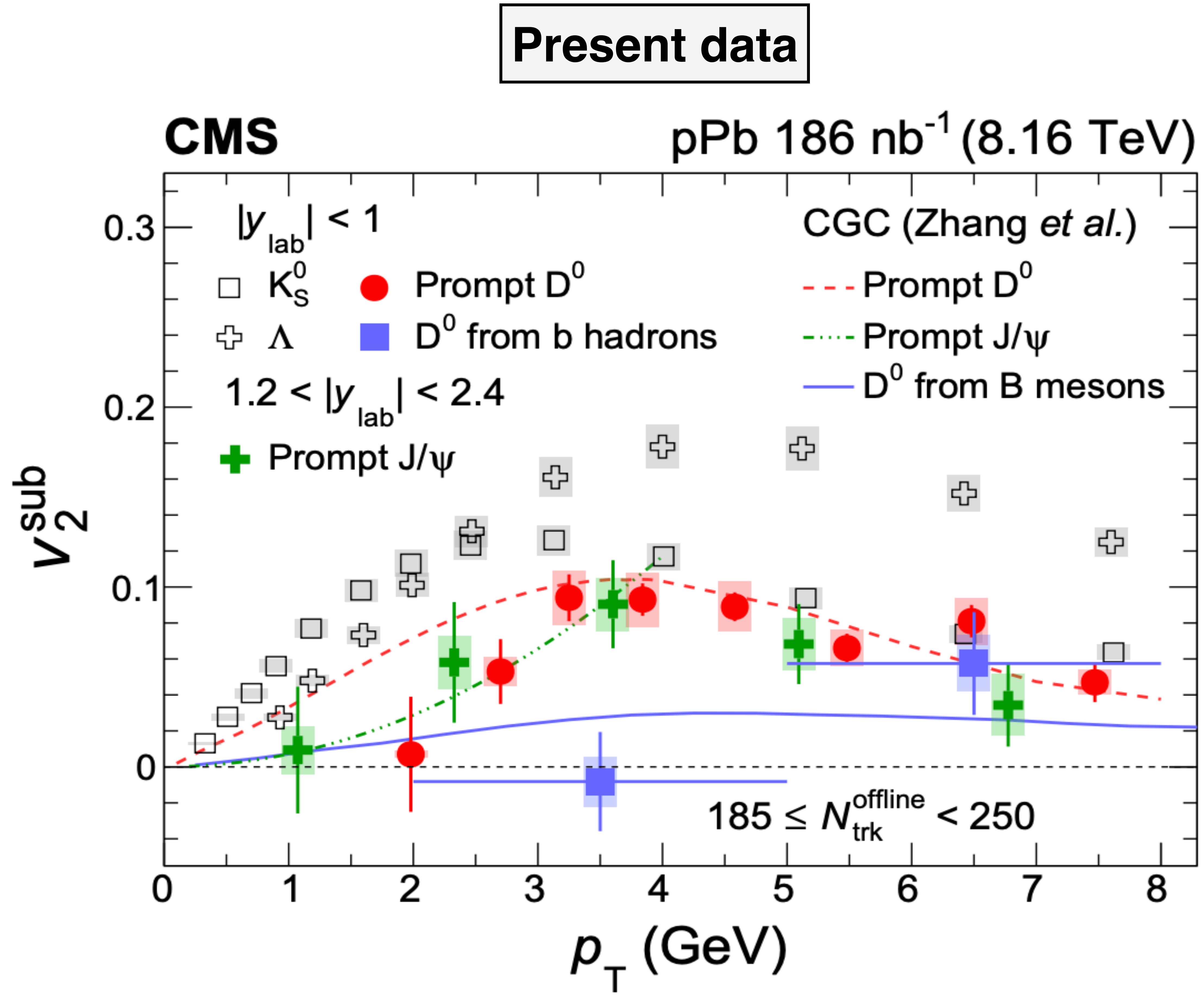
HL-LHC

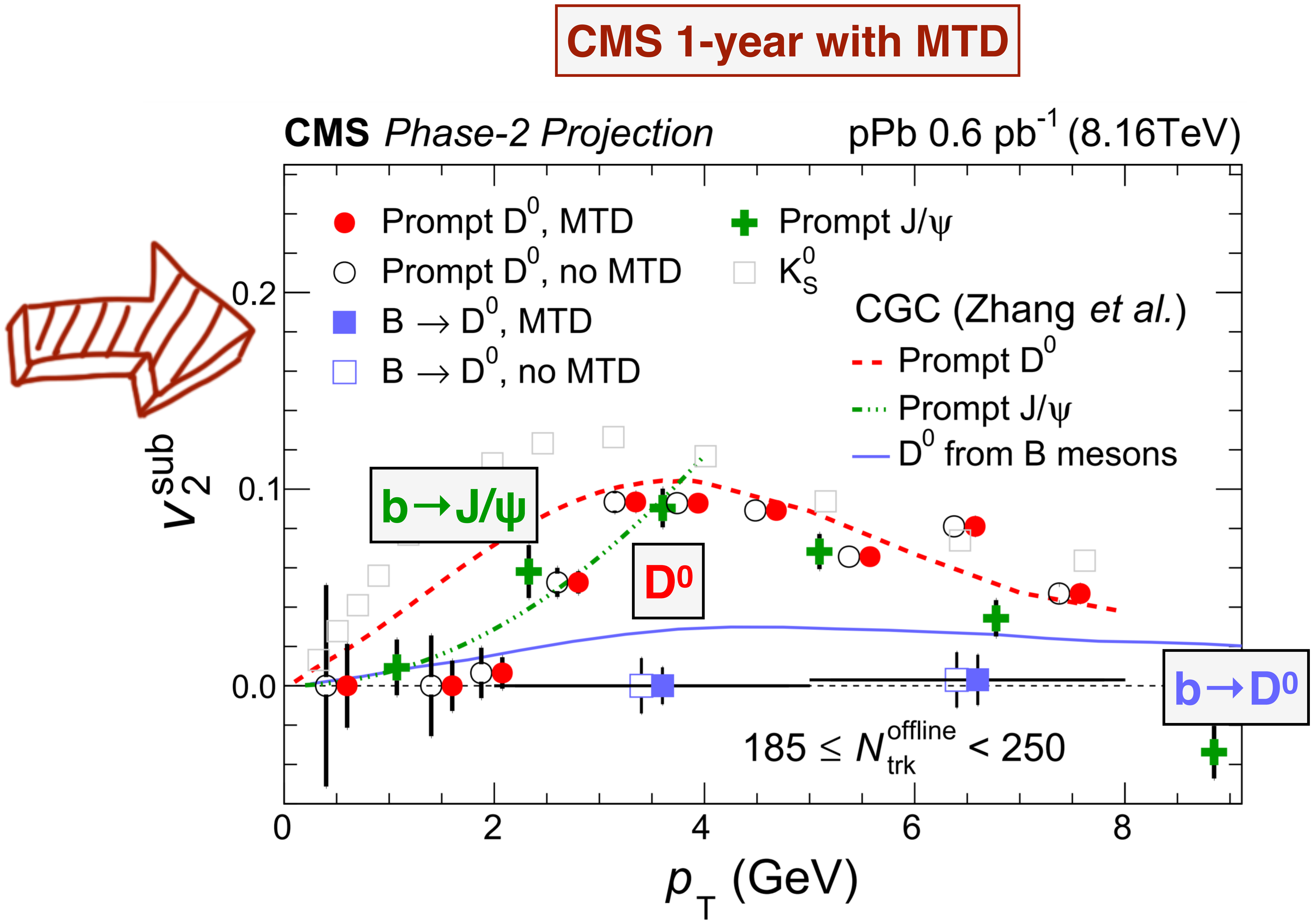
Y(2S) v_2





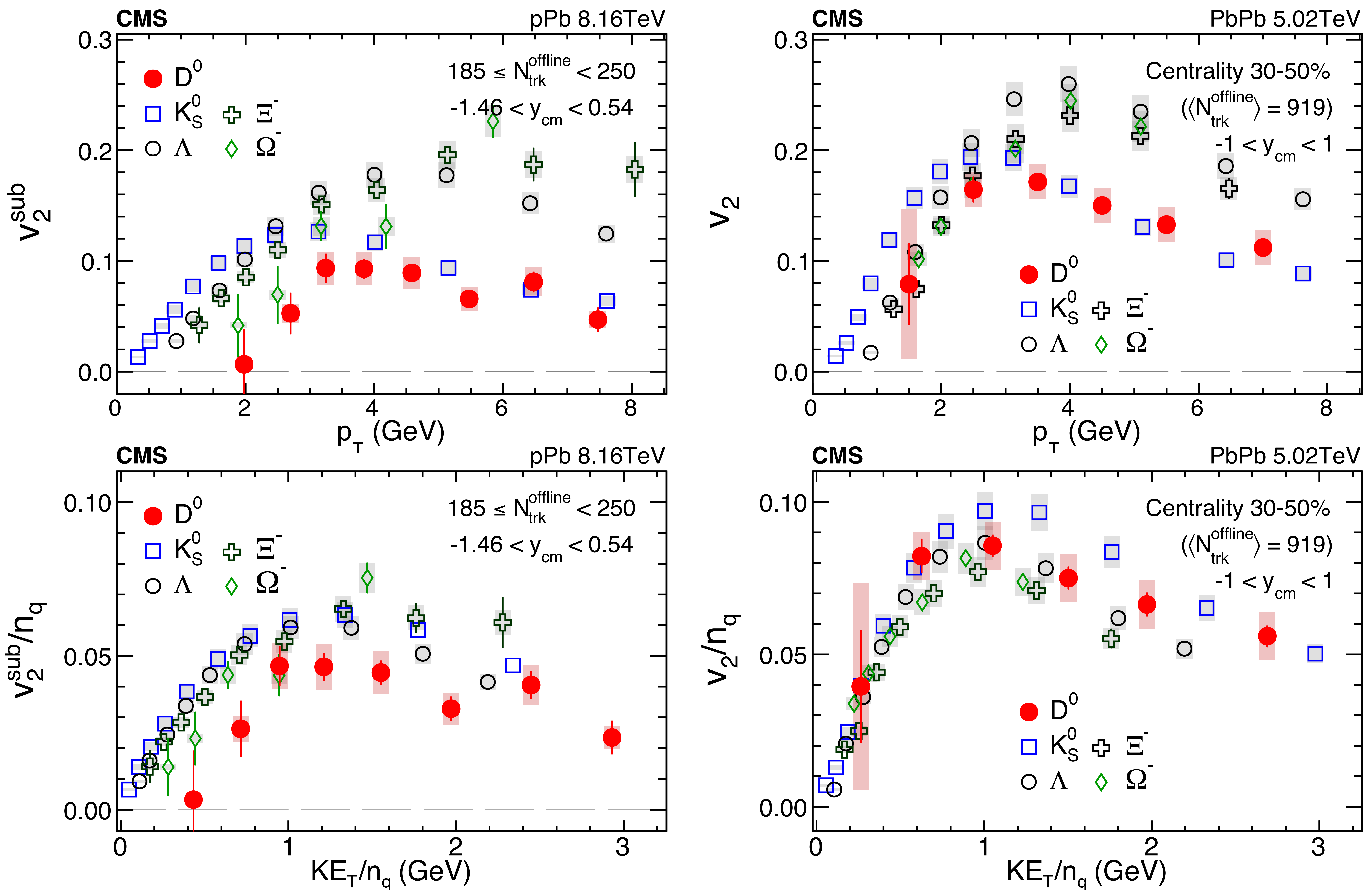
Collectivity in Small Systems





- Unprecedented precision could be achieved over a wider kinematic range with MTD
- Detailed characterization of the heavy flavor hadron collective behavior in small systems
- Enable more differential study scanning multiplicity classes

v_2 n_q Scaling



Return to wonder.
The Wonder Years
NARRATED BY DON CHEADLE
WED 9/22
STREAM ON hulu