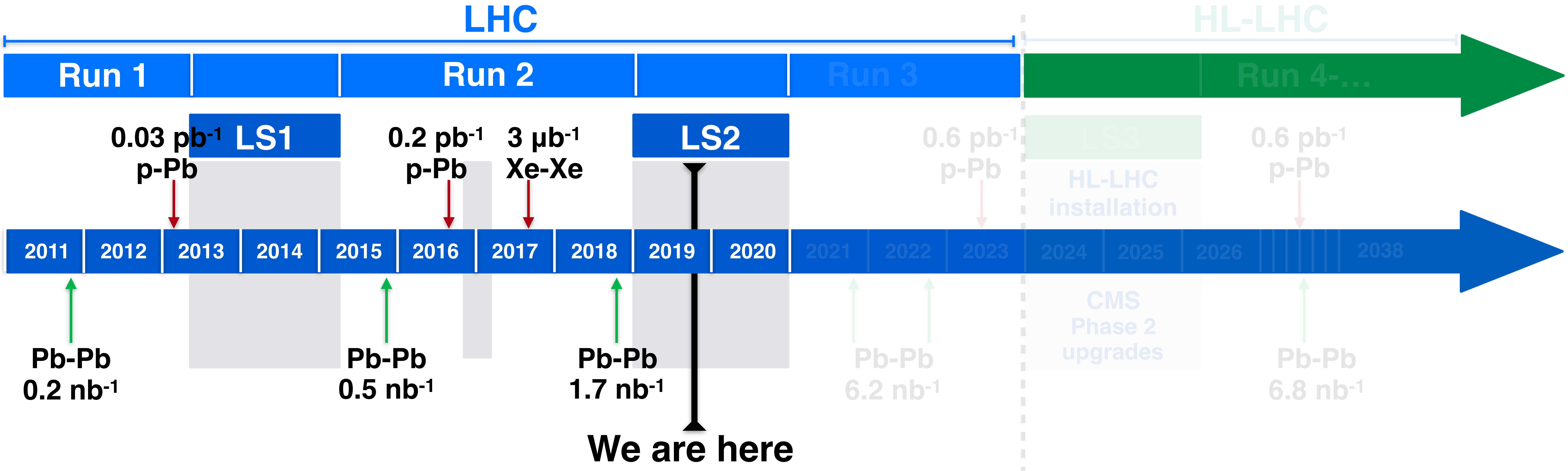
Recent results of HI collisions and future opportunities with fast timing upgrades at CMS

Andre Ståhl
on behalf of the CMS Collaboration

T.W. Bonner Laboratory, William Marsh Rice University

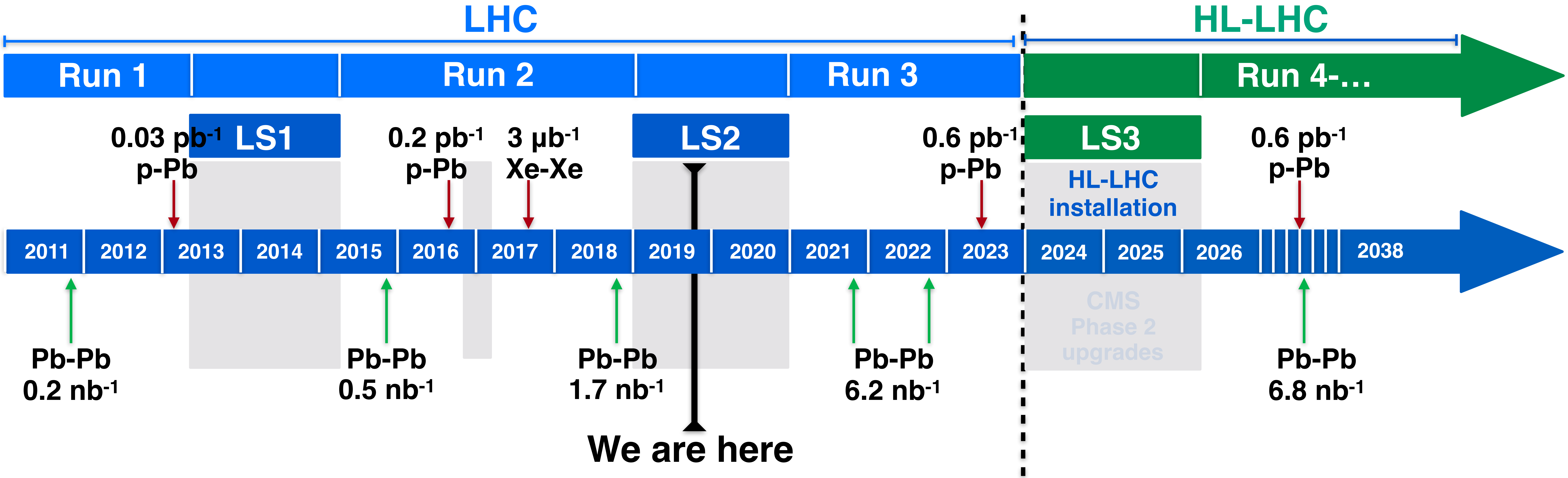
Workshop on Forward Physics and QCD at the LHC,
the future Electron Ion Collider and Cosmic Ray Physics

Heavy Ion Program at LHC



- Successful HI program at LHC: Pb-Pb, Xe-Xe and p-Pb, with all 4 main LHC experiments participating.

Heavy Ion Program at LHC



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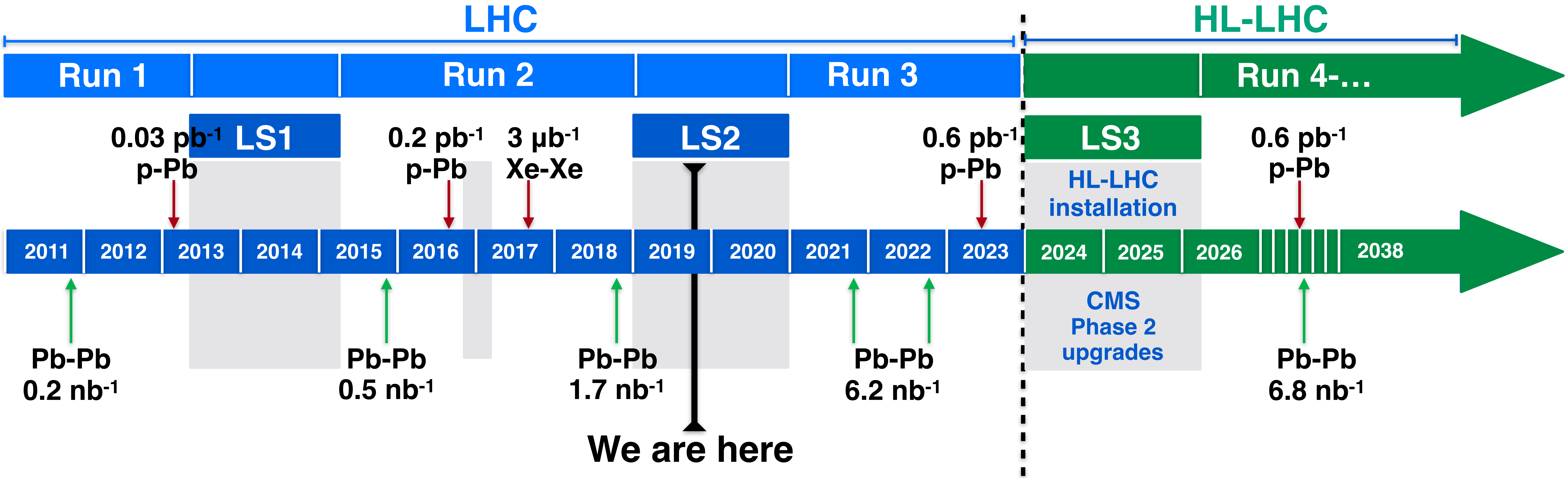
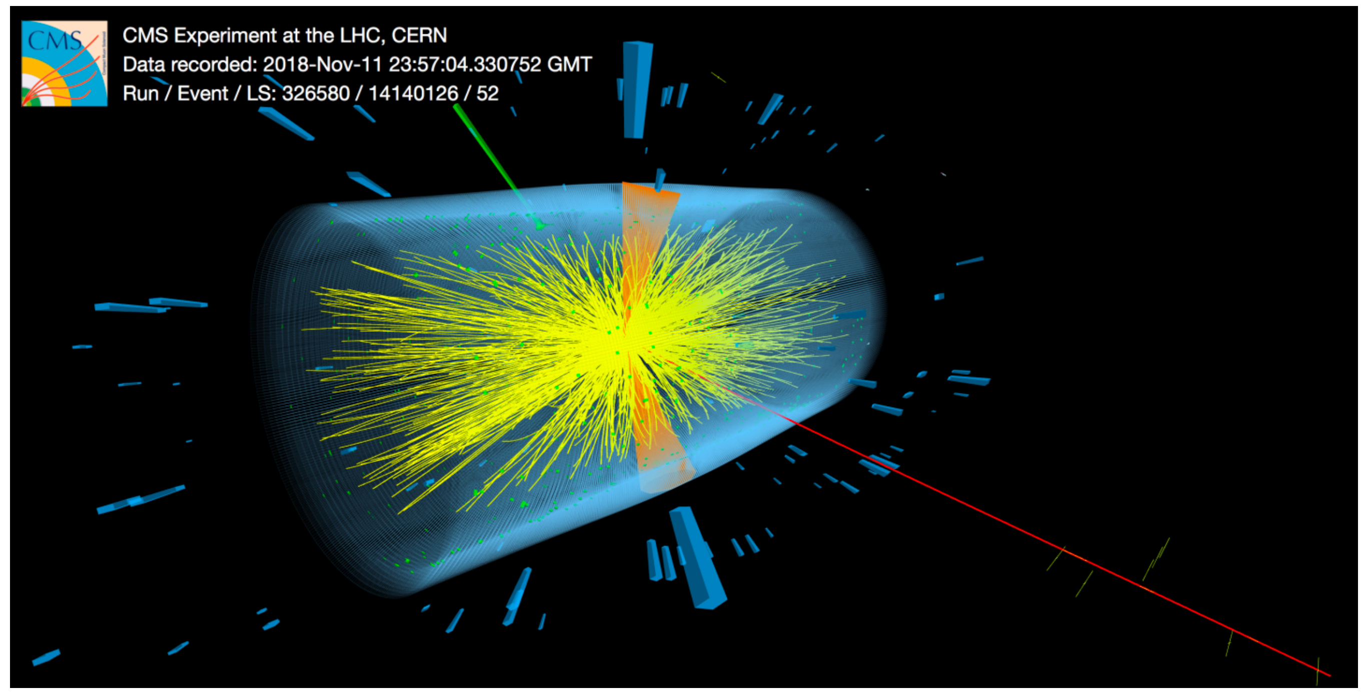
Heavy Ion Program at LHC



- Successful HI program at LHC: Pb-Pb, Xe-Xe and p-Pb, with all 4 main LHC experiments participating.
- By the end of Run 3+4, we expect an increase of 5-7x HI data.
- CMS major upgrade for High Luminosity LHC will bring new opportunities for the HI programme.
  - Large impact on Heavy-Flavour and jet physics.

Outline

- **Recent results in HI collisions:**
  1. **Jets and medium response**
  2. **Heavy-flavour production**
  3. **Heavy-flavour collectivity in large systems**
  4. **Heavy-flavour collectivity in small systems**



- **Future opportunities with fast timing upgrades:**
  1. **HL-LHC and phase 2 upgrades**
  2. **Conceptual design of MTD**
  3. **Applications and performance of MTD**
  4. **Physics impact with MTD**

High Luminosity LHC

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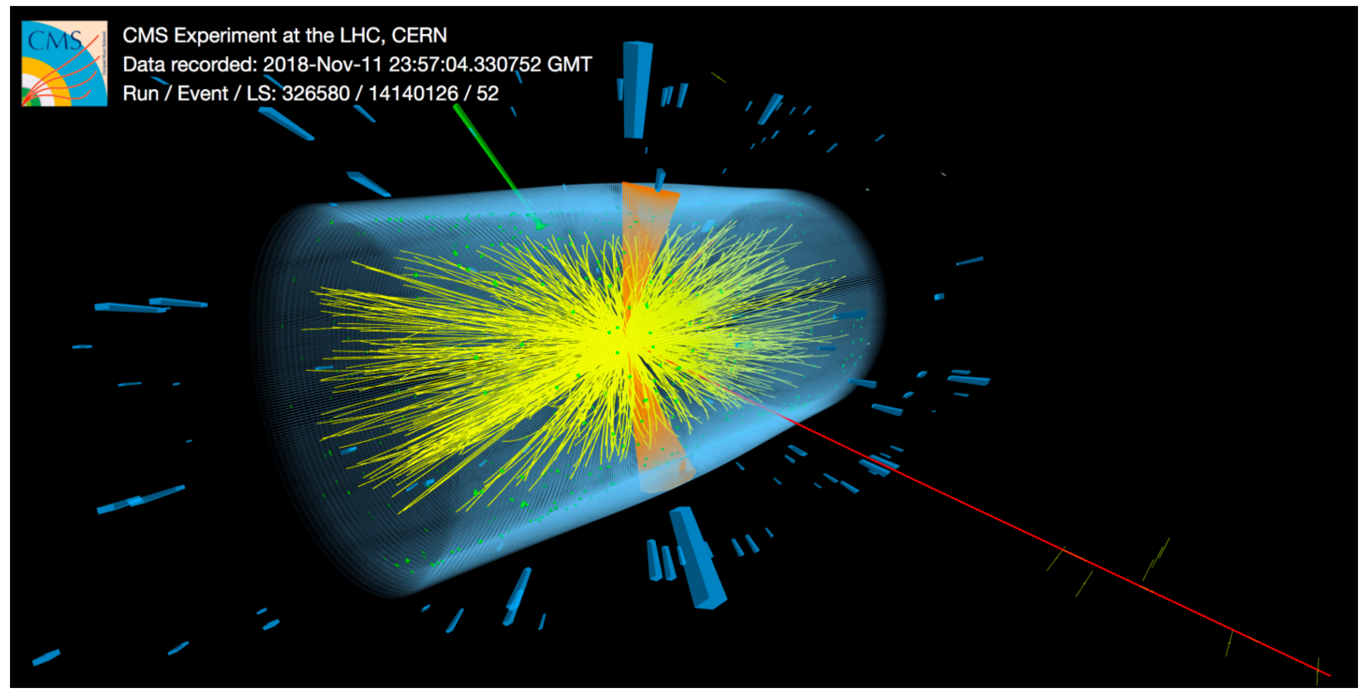

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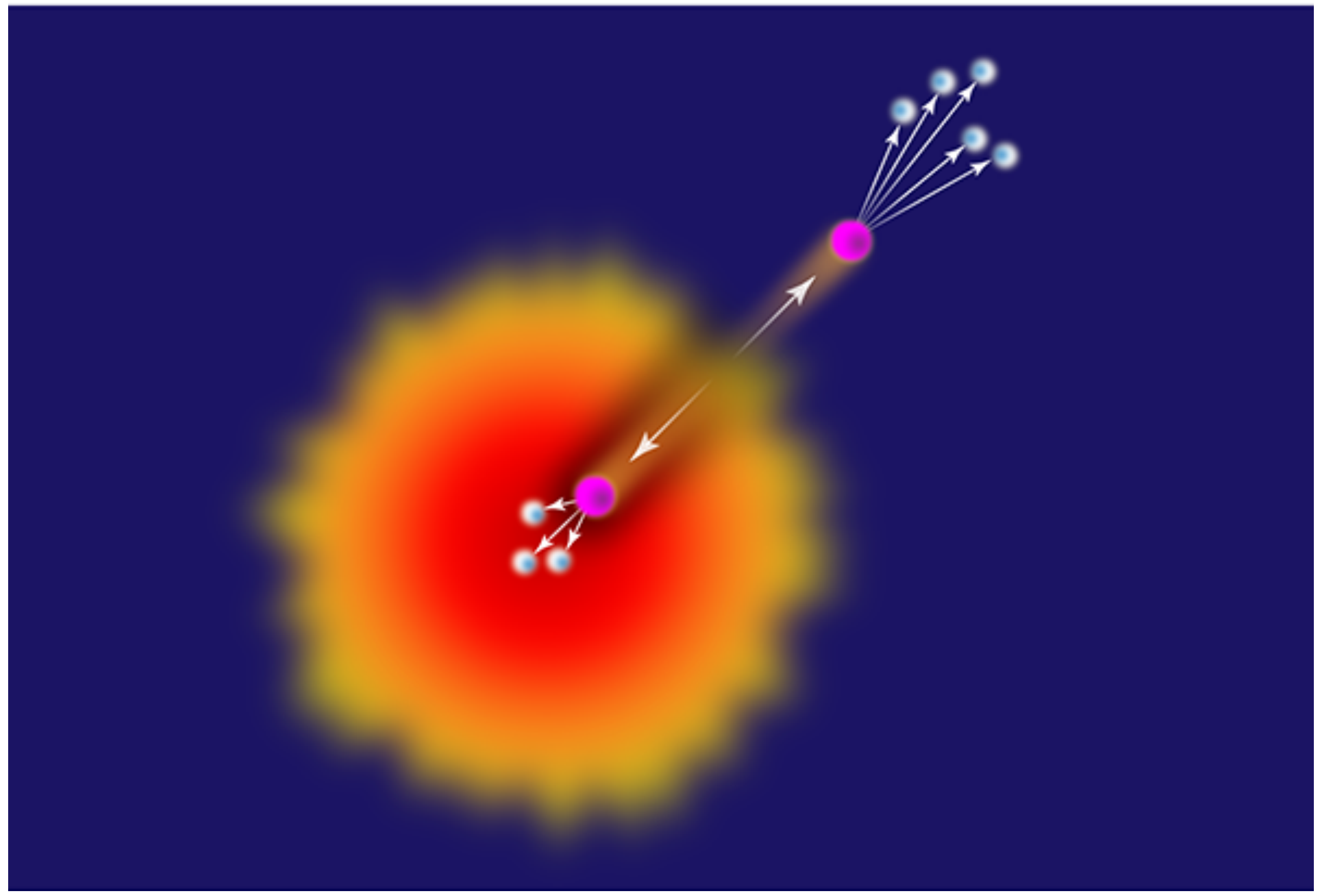
High Luminosity LHC

Jet R_{AA}: jet radius scan



- Jet production in HI probe energy loss of hard probes in the QGP.

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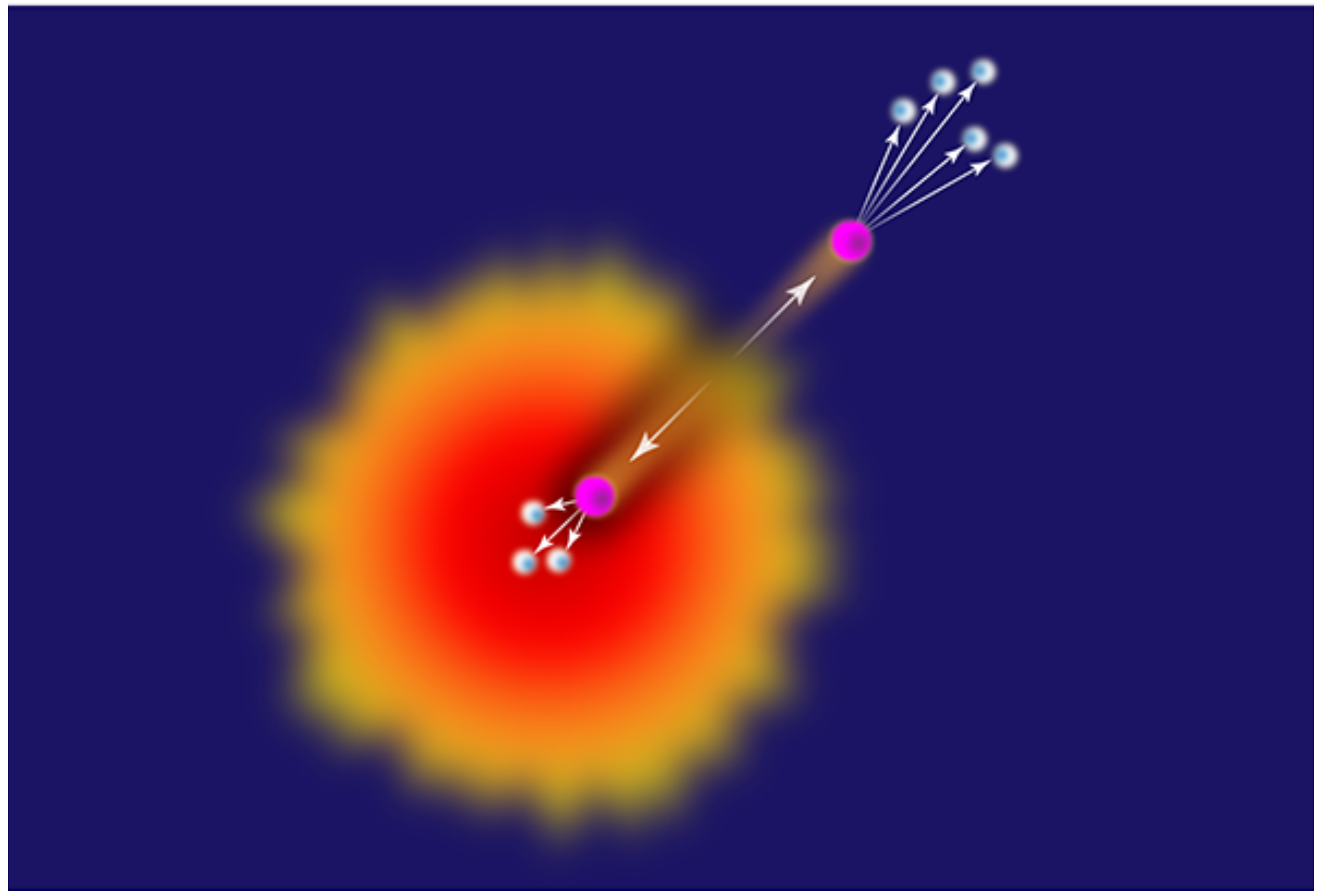
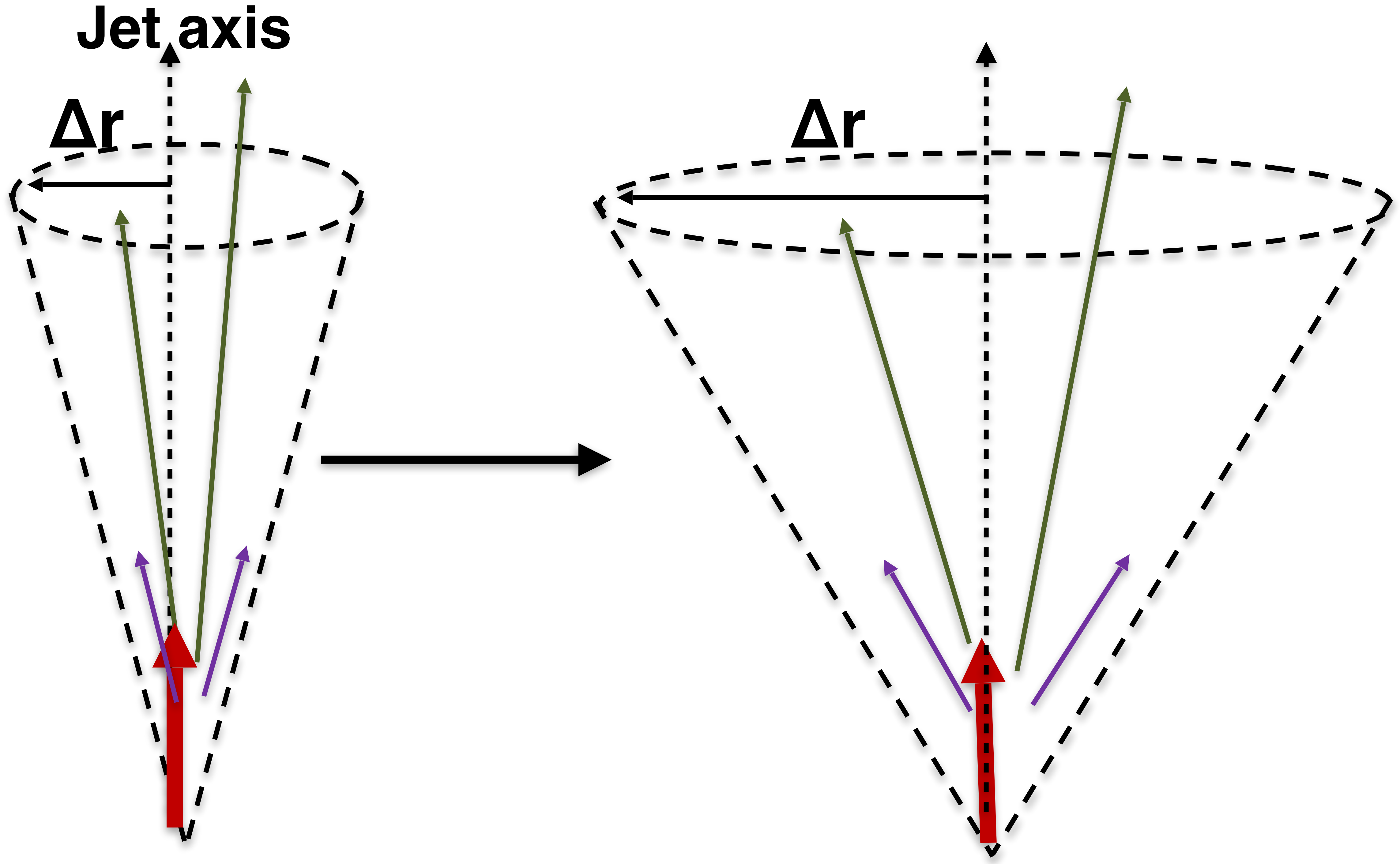
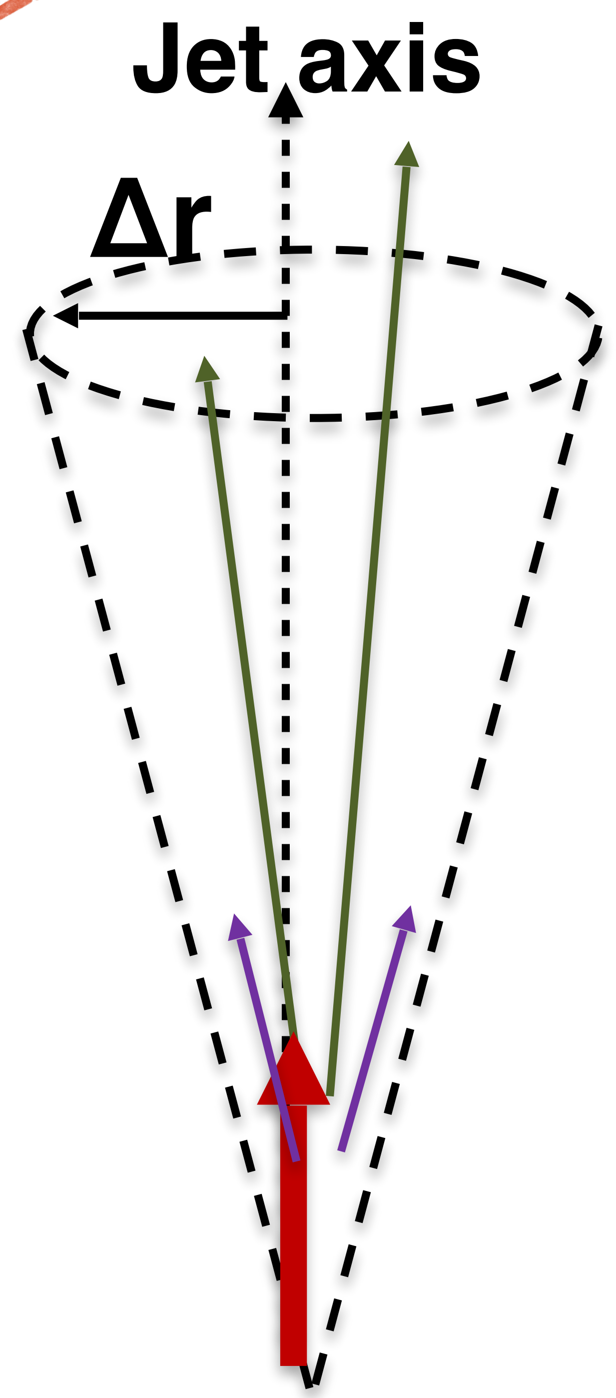
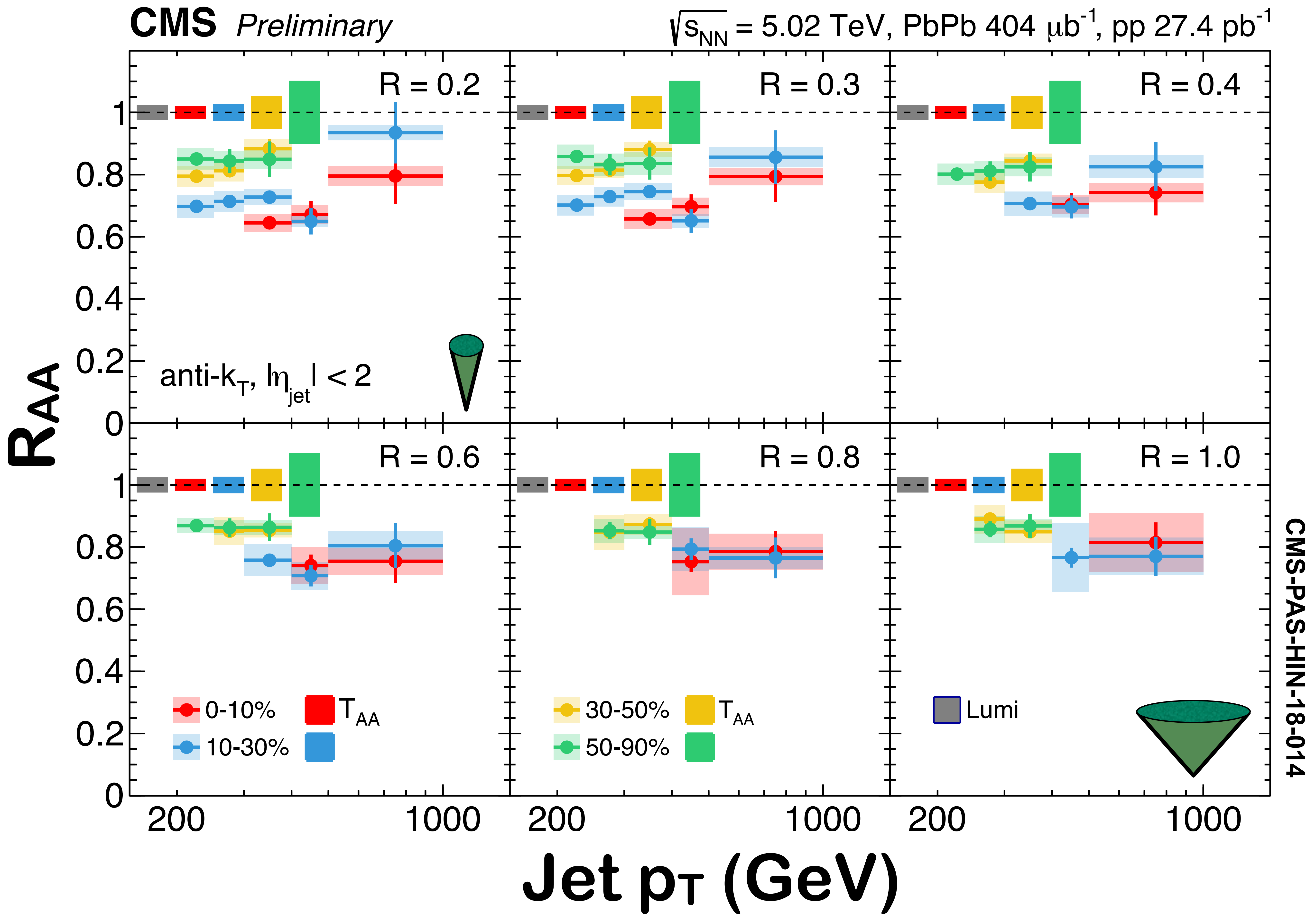




- Jet production in HI probe energy loss of hard probes in the QGP.
- Jet radius scan→ study suppression vs recovery effects of quenched energy.

Jet R_{AA}: jet radius scan





- Jet production suppressed for all jet radius → larger suppression in central collisions.

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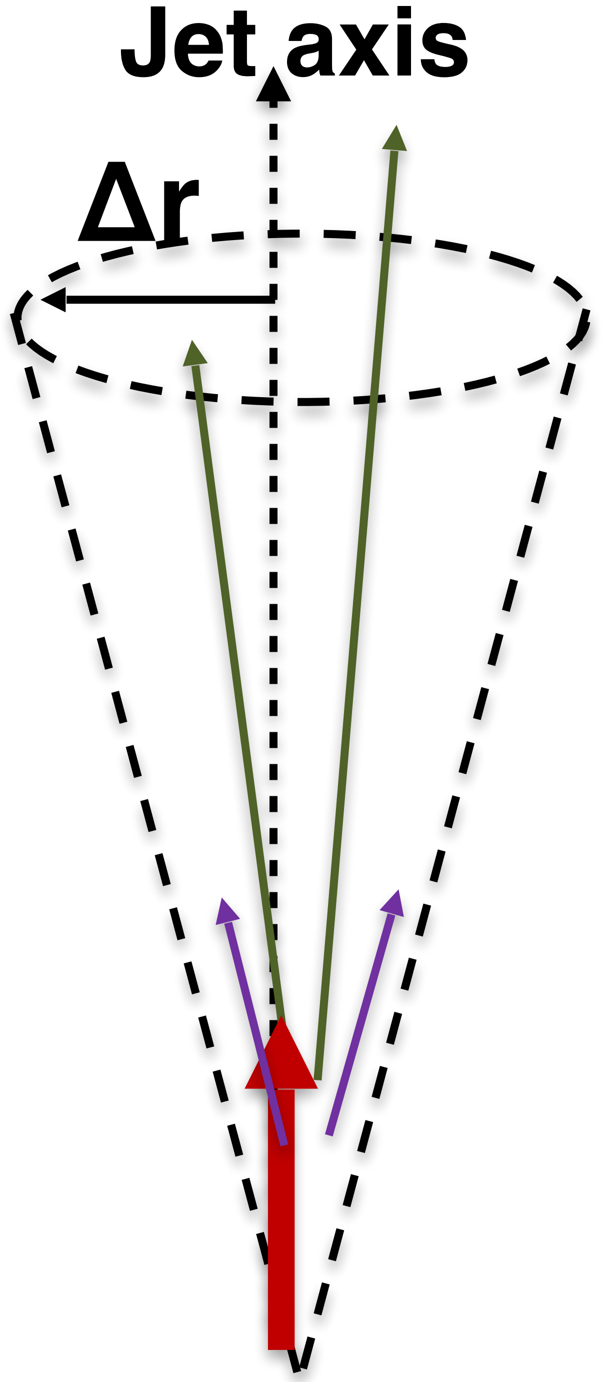

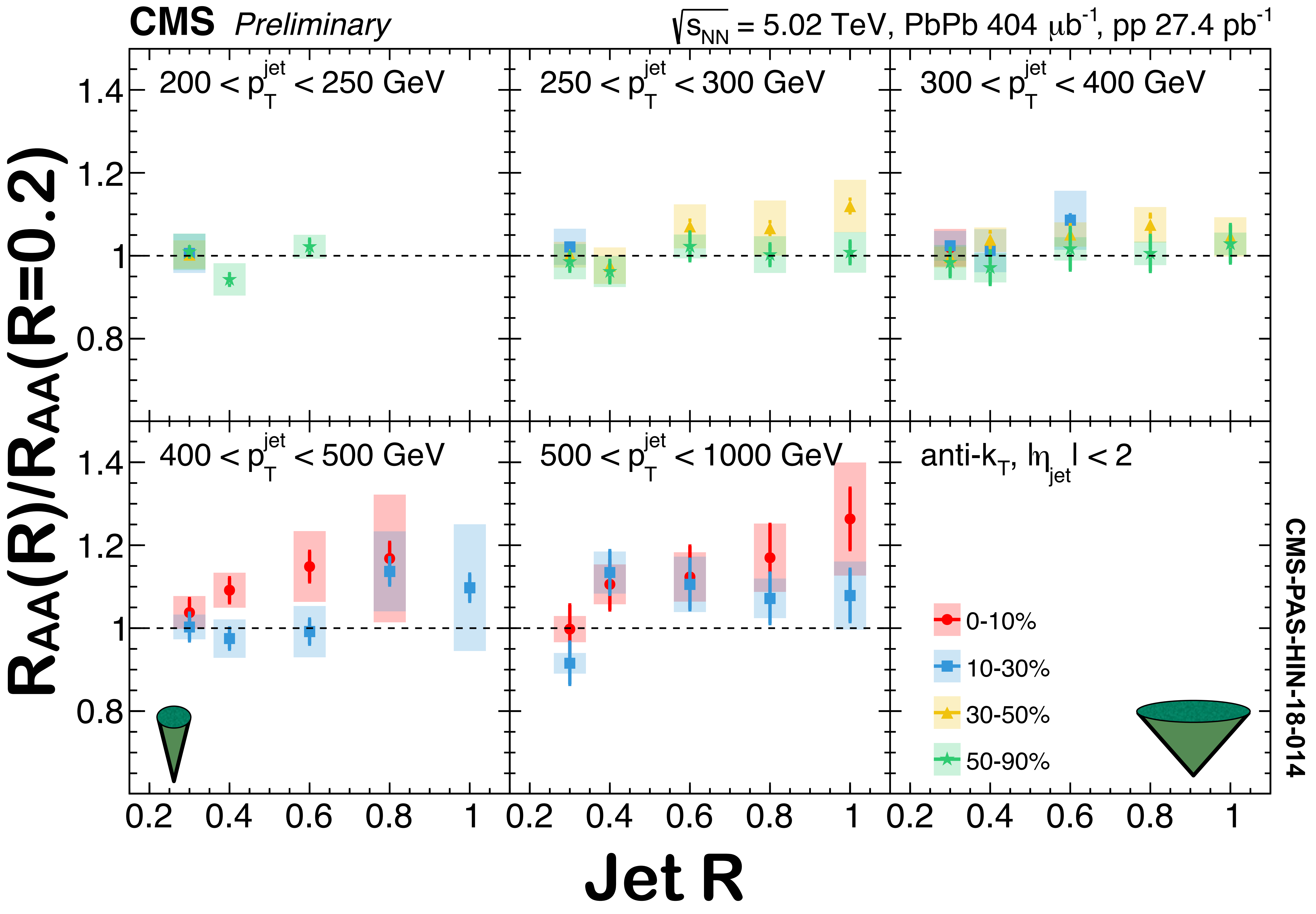

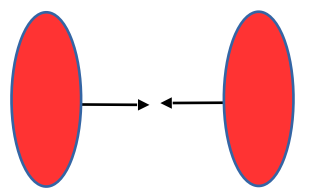

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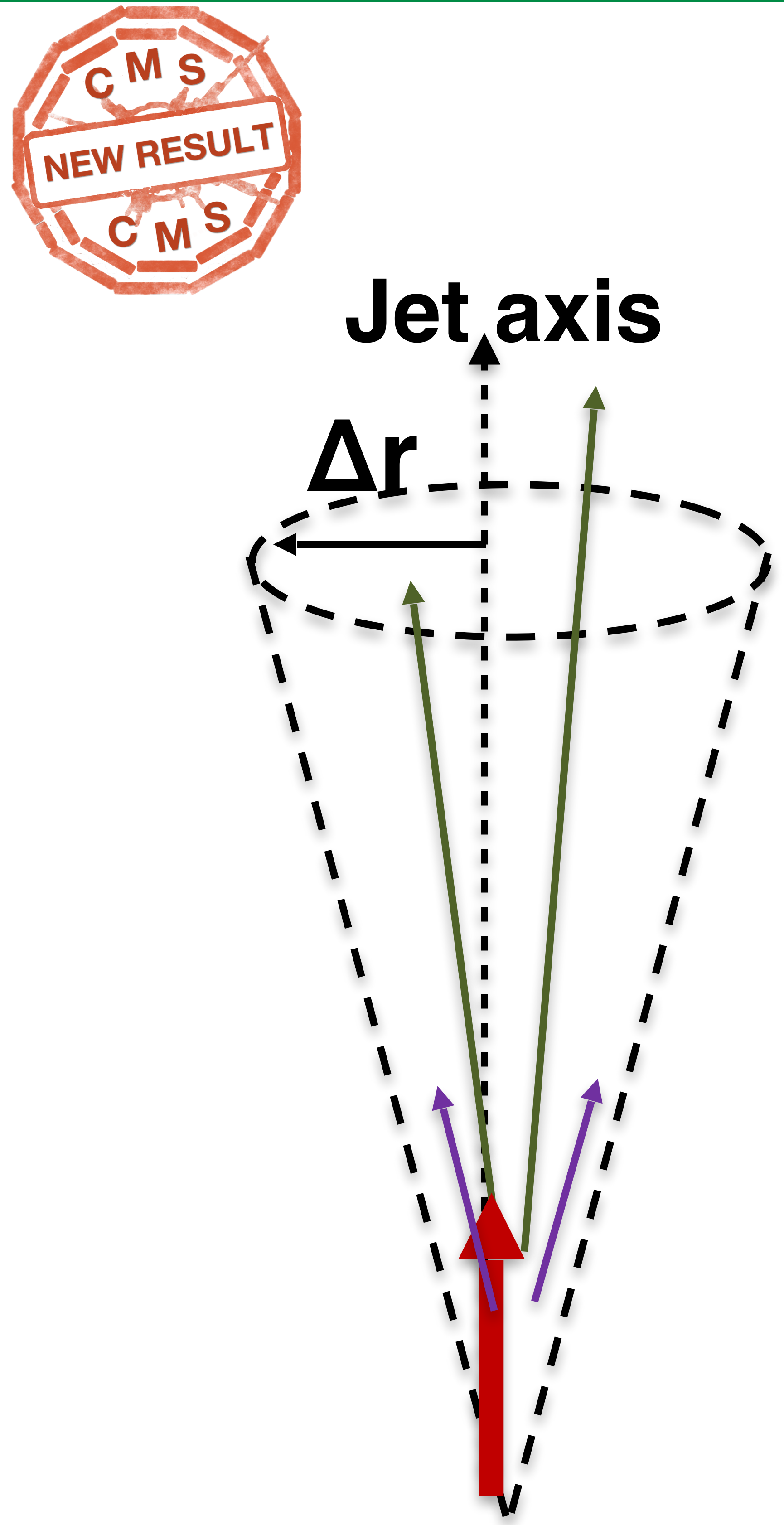
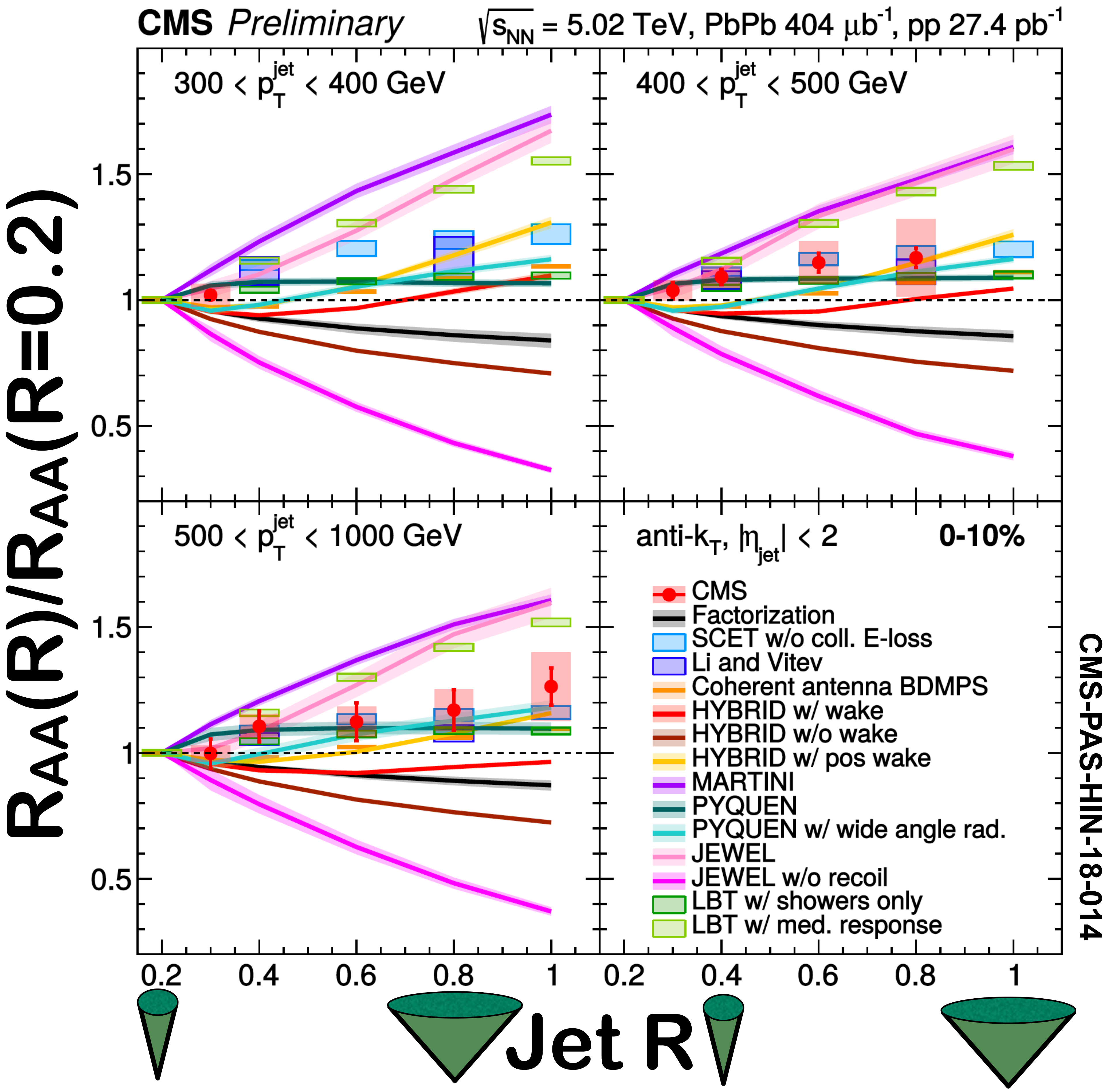
- **R_{AA}(R) / R_{AA}(R=0.2)** ratio shows light recovery at central collisions.

Jet R_{AA}: jet radius scan





- Jet production suppressed for all jet radius → larger suppression in central collisions.
- **$R_{AA}(R)$ / $R_{AA}(R=0.2)$** ratio shows light recovery at central collisions.
- Results provide new constrains on jet quenching models.

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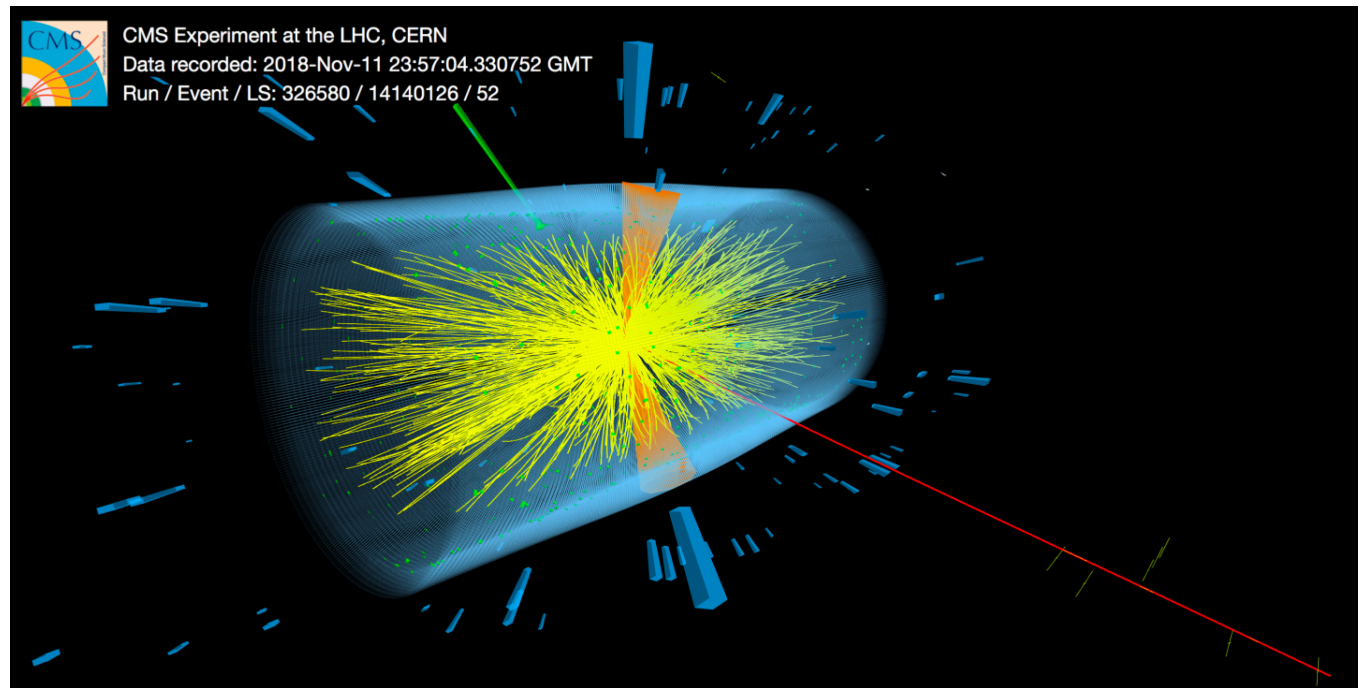

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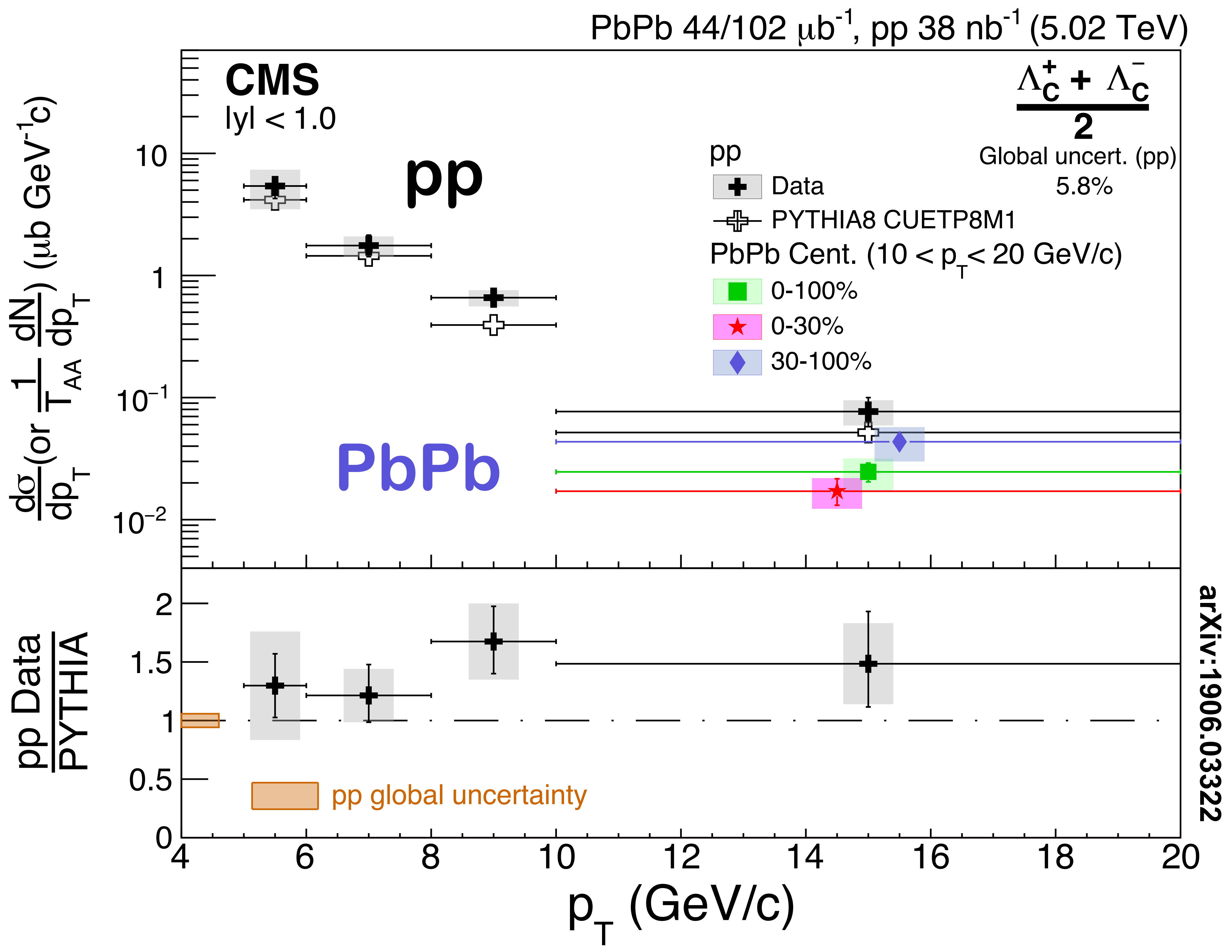
Λ_c in pp and PbPb

$$\Lambda_c^+ \rightarrow \pi^+ + K^- + p$$

Submitted to PLB.



- Measurements of Λ_c p_T spectrum down to 5 GeV in pp and 10 GeV in PbPb.
- Λ_c p_T spectrum in pp consistent with PYTHIA.

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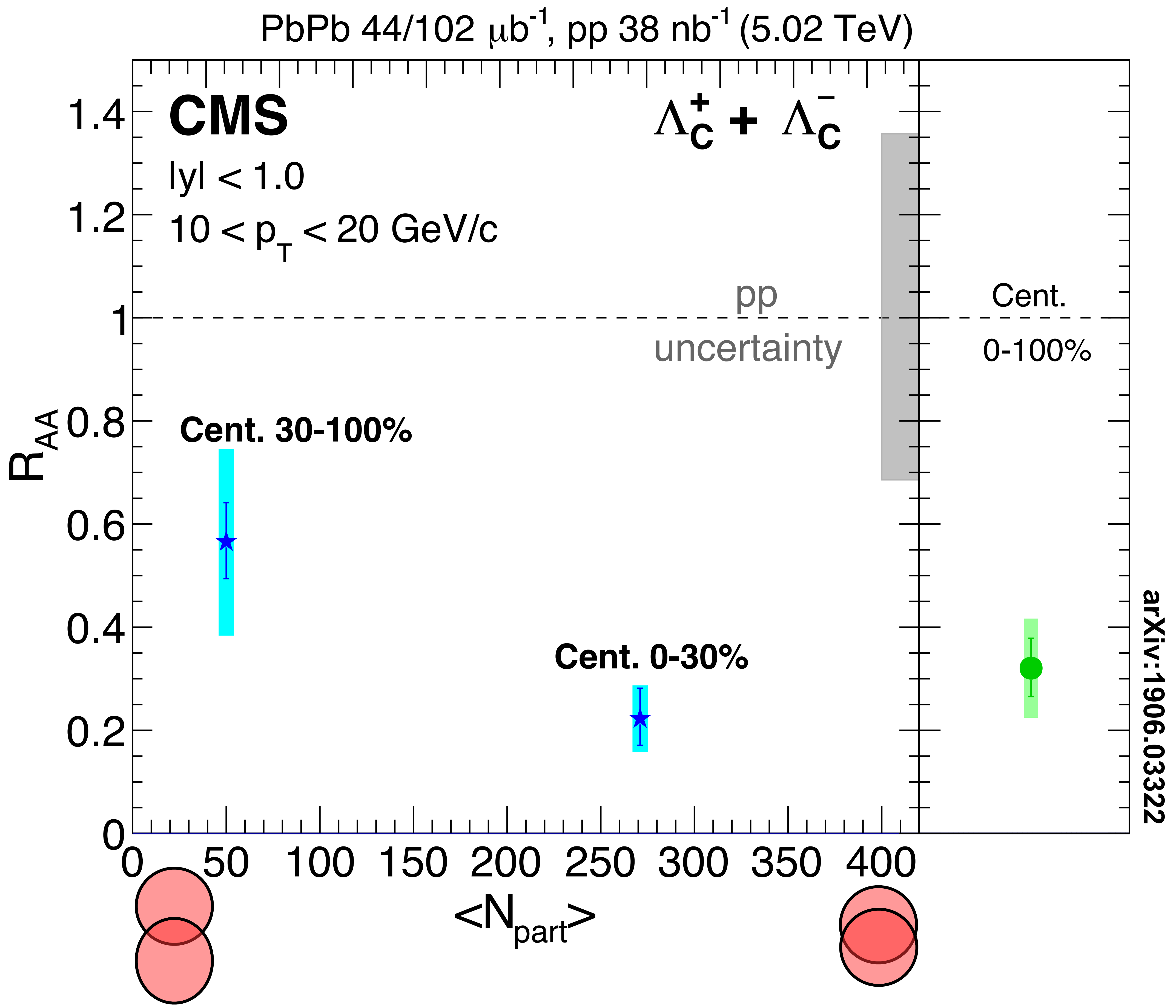

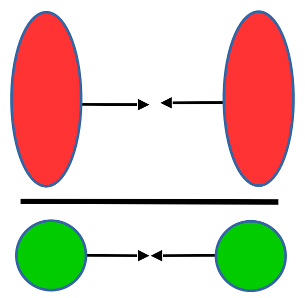

- Hint of Λ_c suppression in PbPb, though pp uncertainties large.
- Larger suppression in more central PbPb collisions.

Λ_c / D_0 ratio in PbPb

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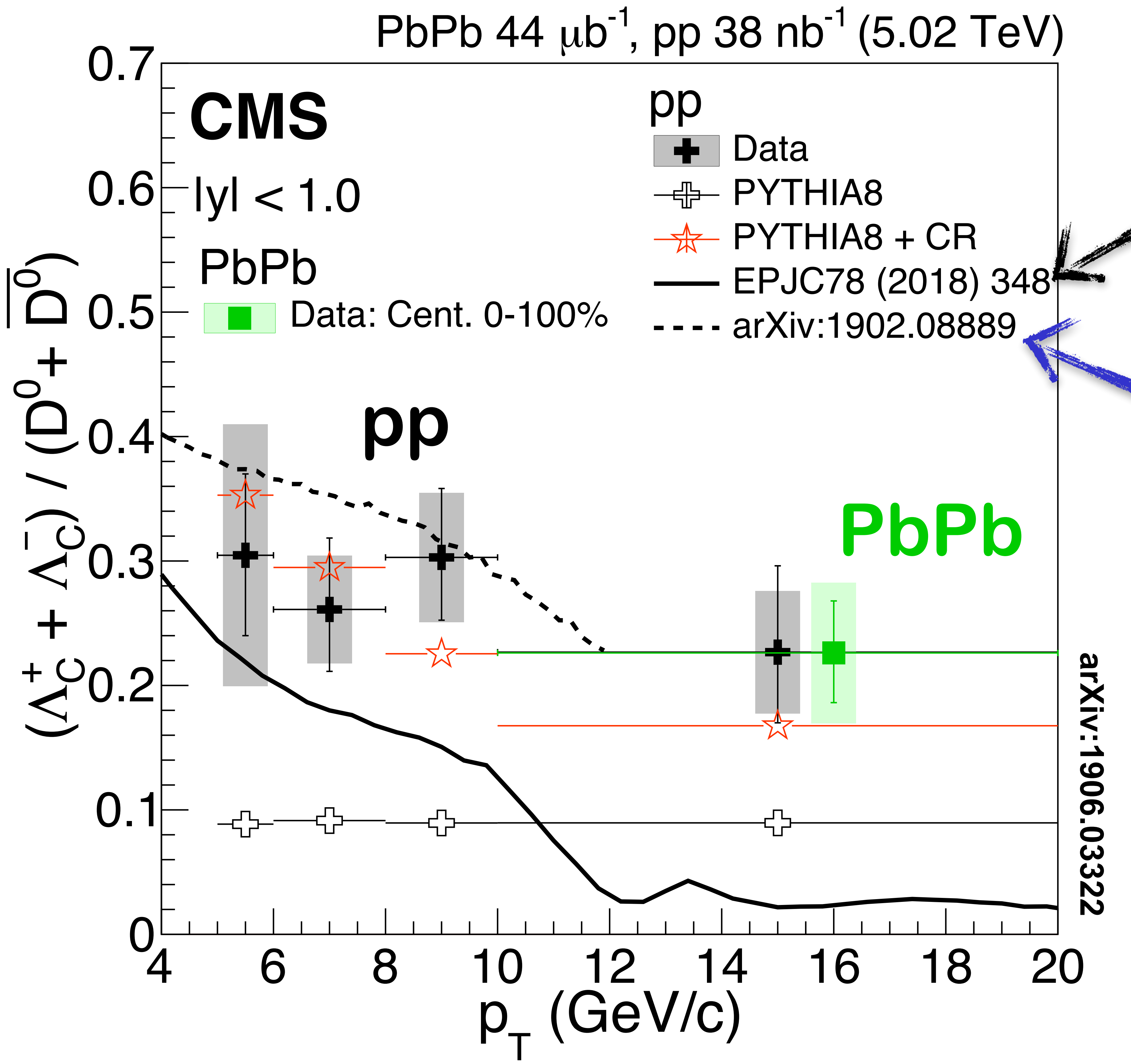
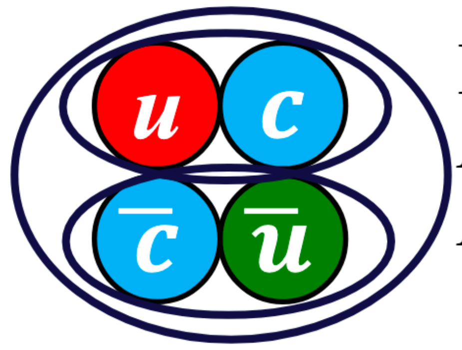


Coalescence + fragmentation in pp

Decay of excited charm baryon states not in PYTHIA8

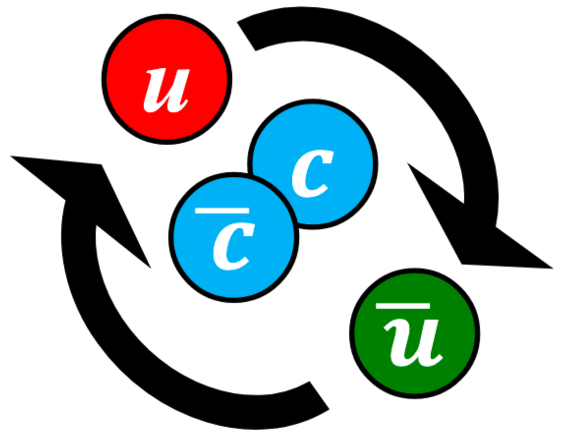
- Λ_c/D_0 ratio in pp consistent with PYTHIA + colour reconnection (CR).
- Results in PbPb similar to pp:
  - No significant contribution from coalescence at p_T > 10 GeV in PbPb.

Compact tetraquark/pentaquark



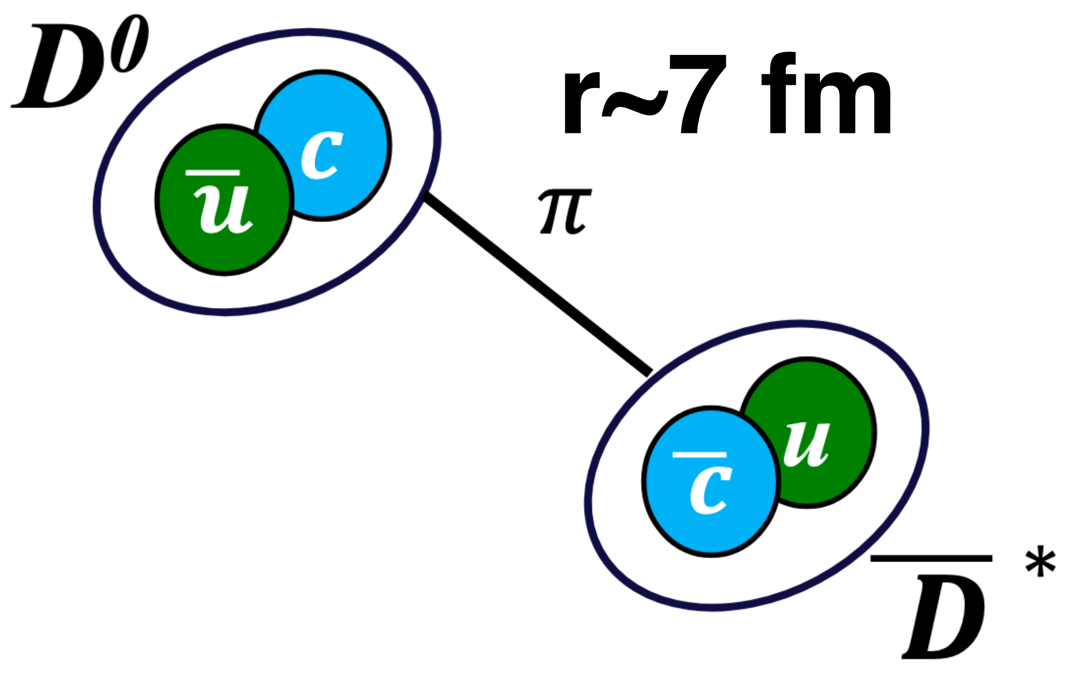
Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)

r~1 fm



Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

Hadronic Molecules
PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)



Mixtures of exotic + conventional states

$$X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle$$

PLB 578 365 (2004)
PRD 96 074014 (2017)

- Exotic quarkonium state first observed by Belle and later confirmed by LHCb.
- Structure not understood yet: tetraquark or hybrid state or hadron molecule?

Exotic charmonium state: X(3872)

Compact tetraquark/pentaquark

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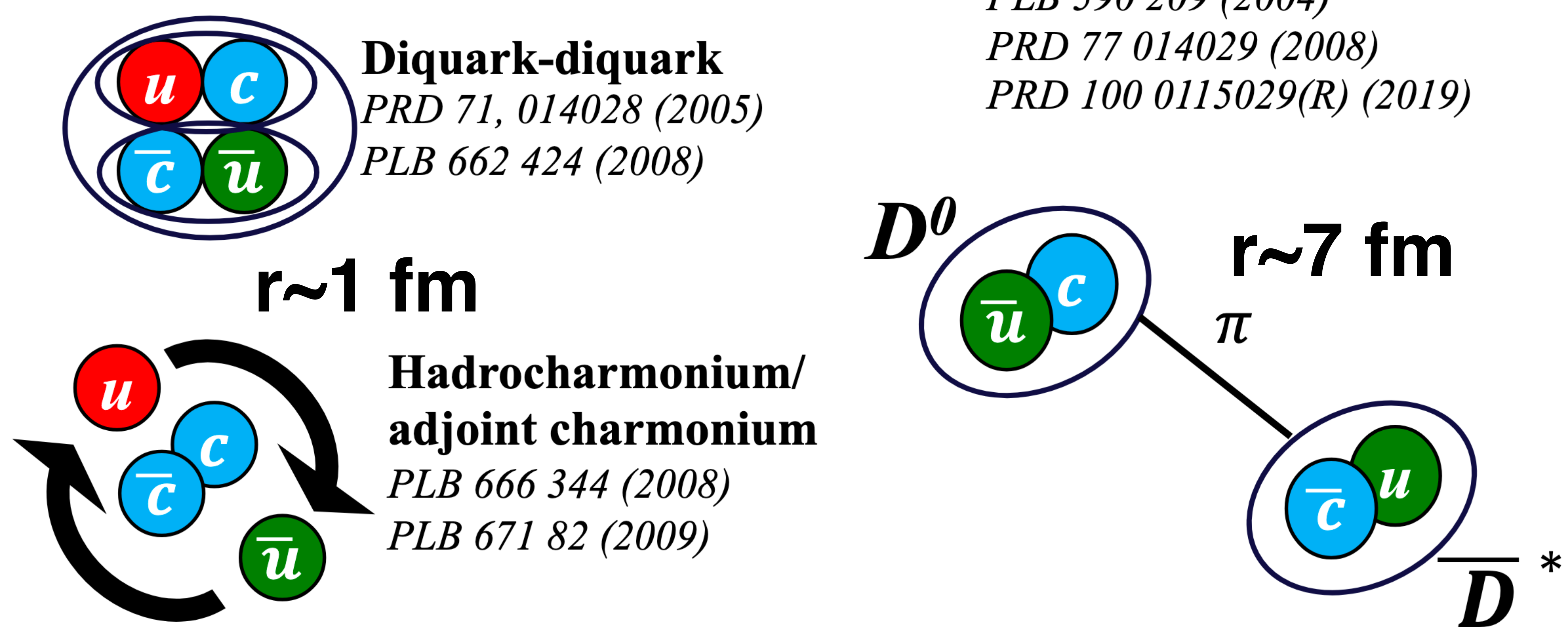

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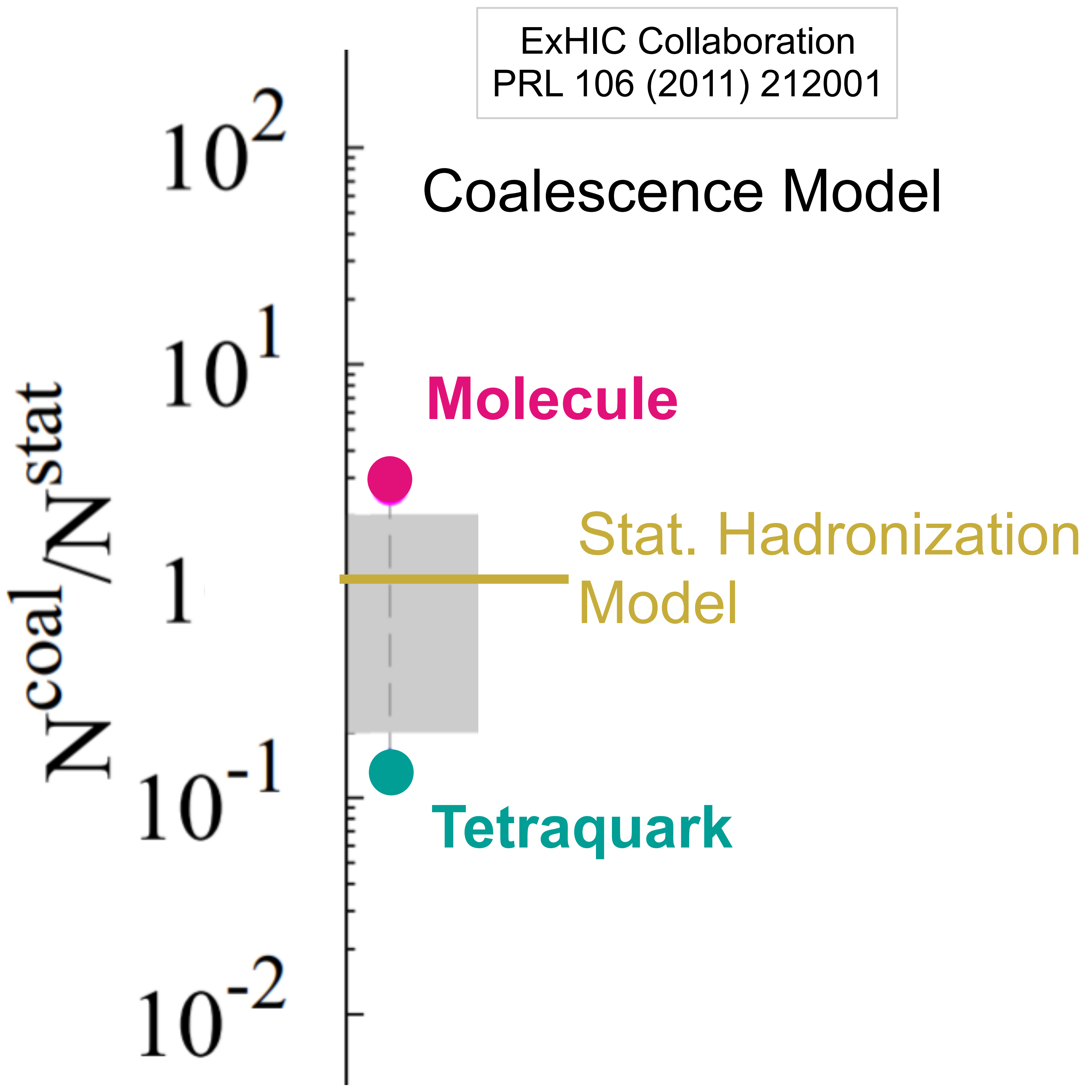
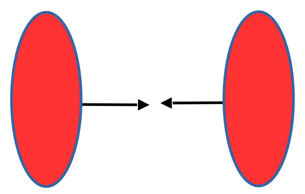
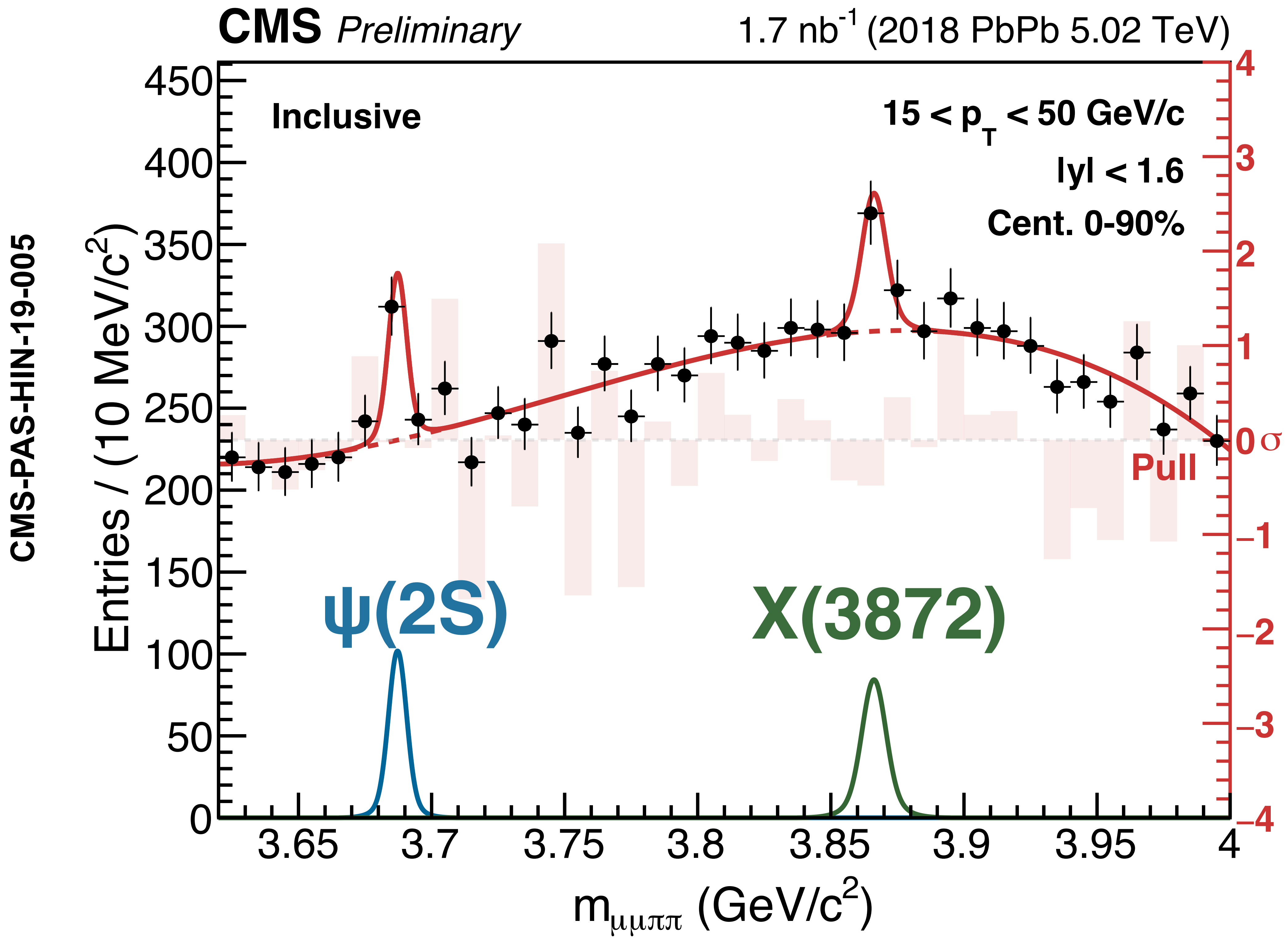


- Exotic quarkonium state first observed by Belle and later confirmed by LHCb.
- Structure not understood yet: tetraquark or hybrid state or hadron molecule?
- Production yield in QGP strongly reflects internal structure.

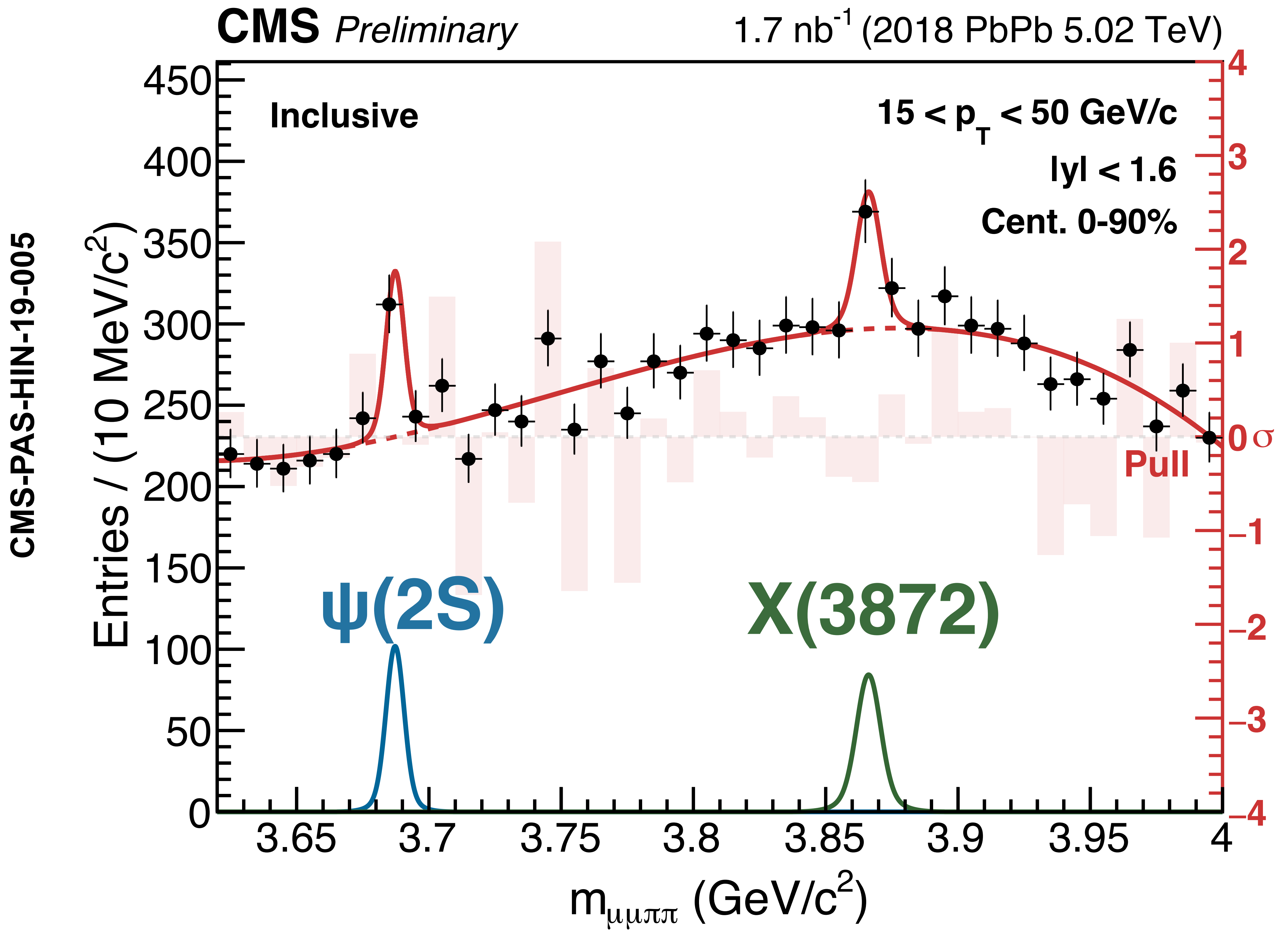
$X_c \to J/\psi + \pi^- + \pi^+$



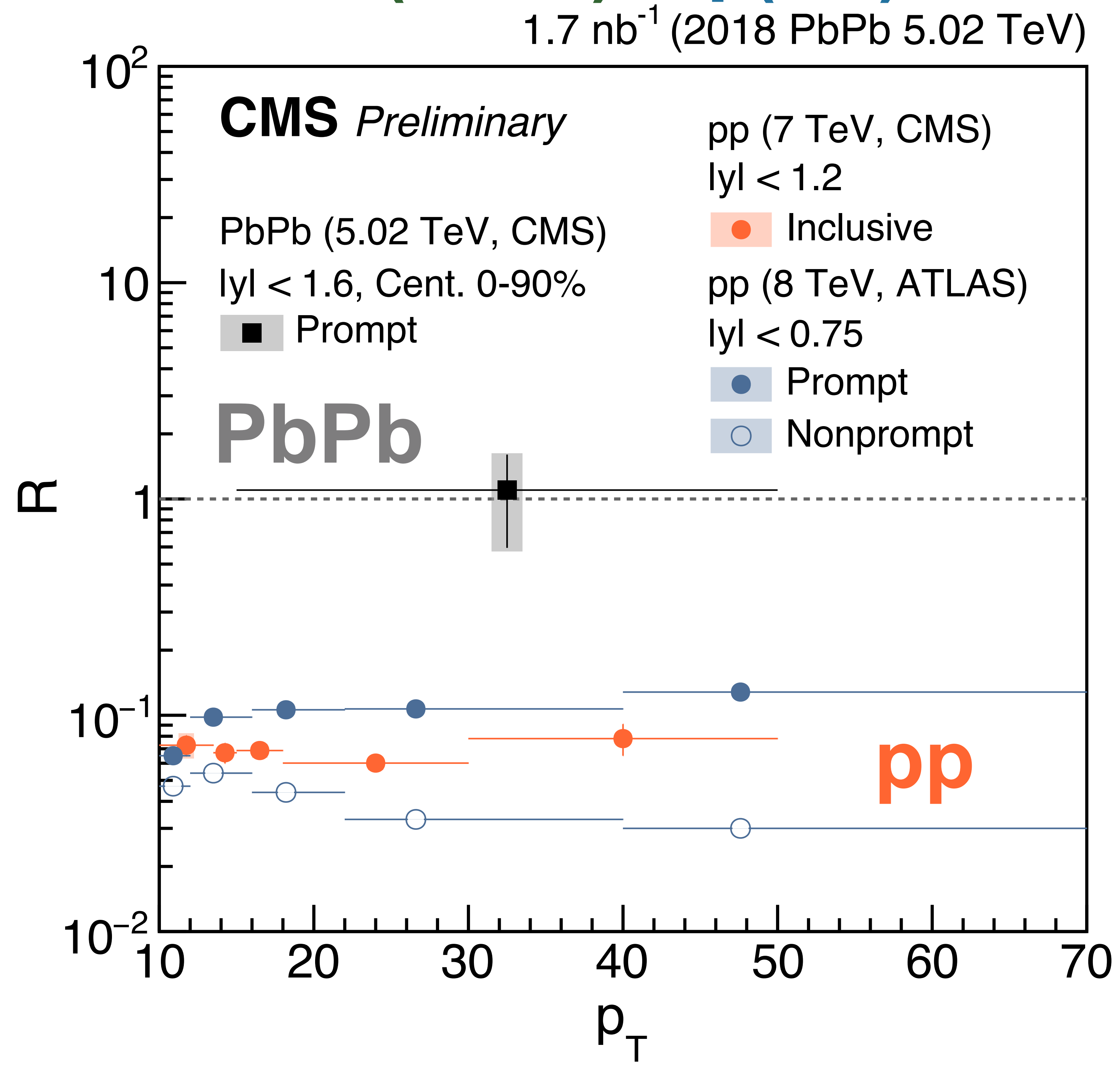


- First evidence of inclusive **X(3872)** production in heavy ion collision (>3 s.t.d).

$X_c \rightarrow J/\psi + \pi^- + \pi^+$



X(3872) / ψ(2S)



- First evidence of inclusive **X(3872)** production in heavy ion collision (>3 s.t.d).
- Hint of **X(3872)** to **ψ(2S)** ratio enhancement in PbPb.

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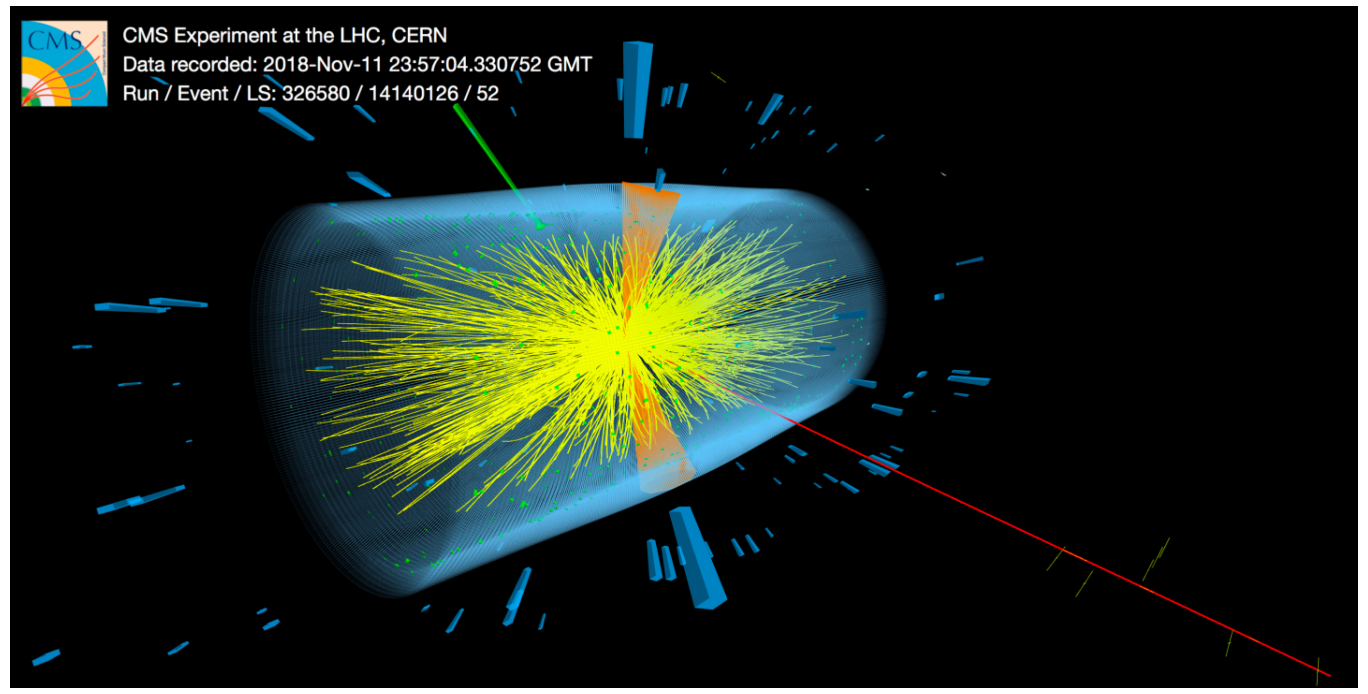

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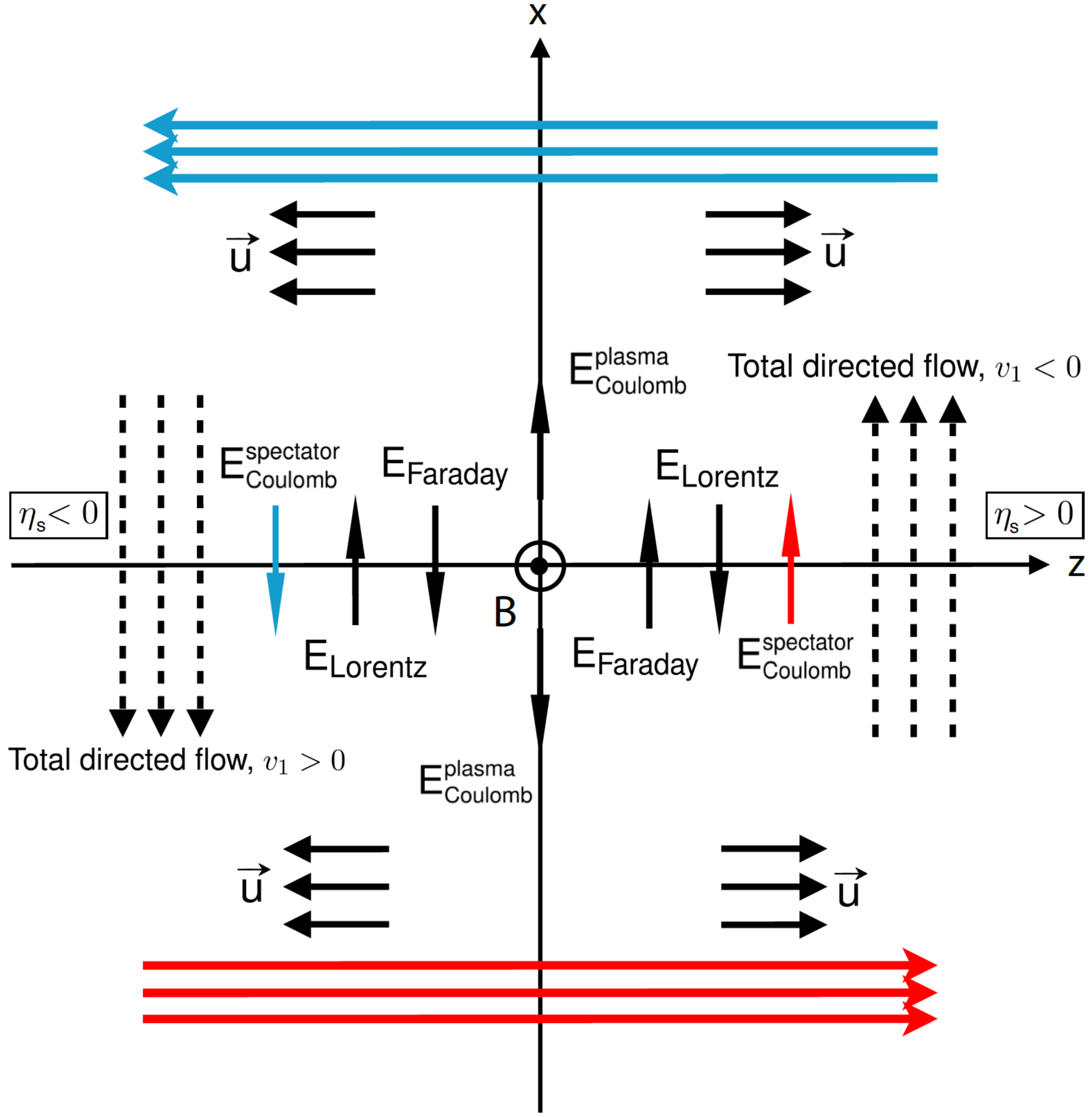
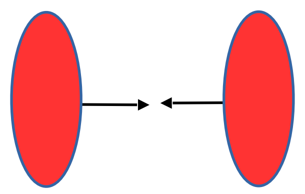
High Luminosity LHC

Phys. Rev. C 98, 055201 (2018)

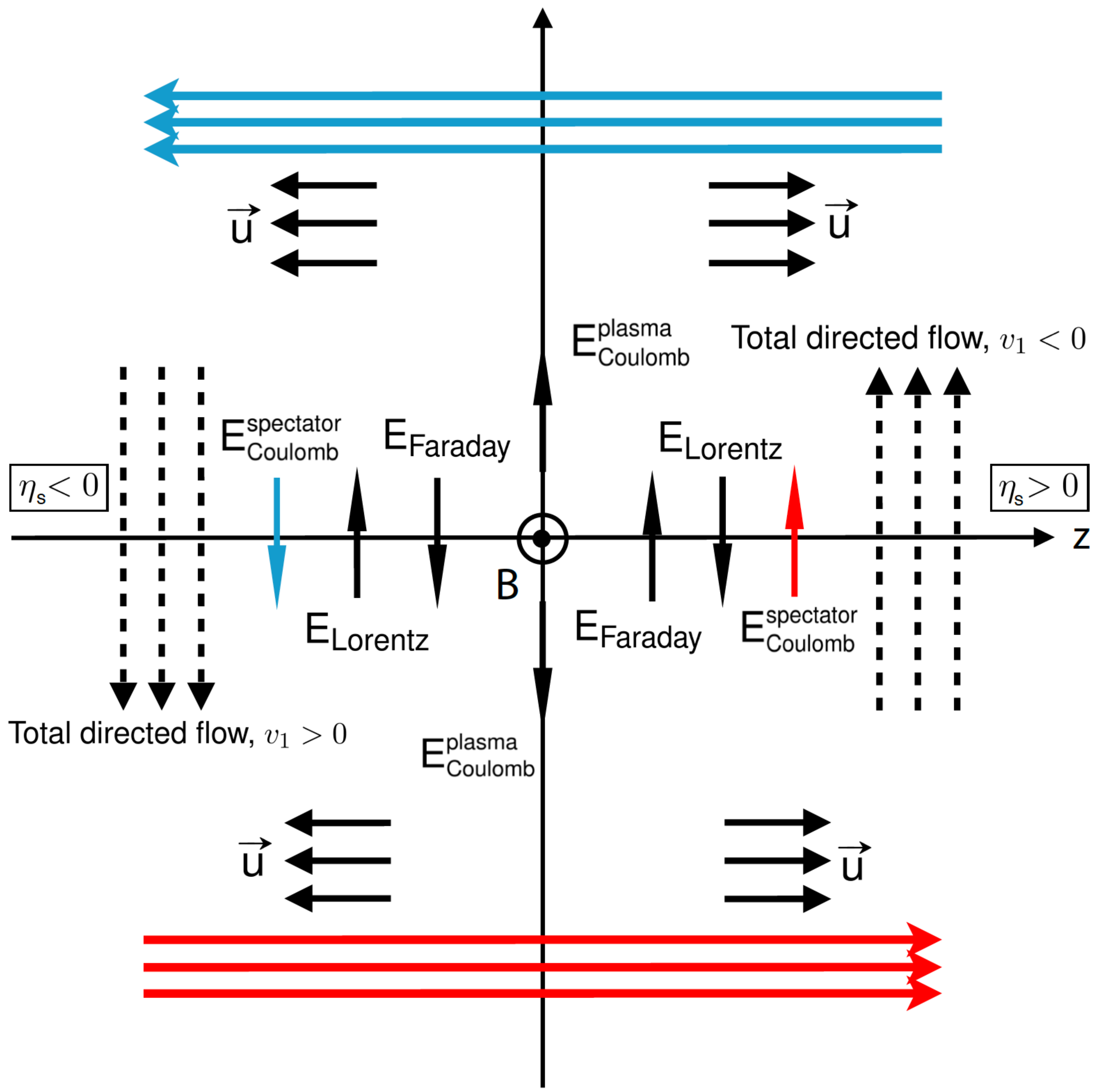




- Strong and short-lived EM fields in PbPb at LHC → Non-zero Δv_n for opposite-charge.

Electromagnetic fields in PbPb

Phys. Rev. C 98, 055201 (2018)



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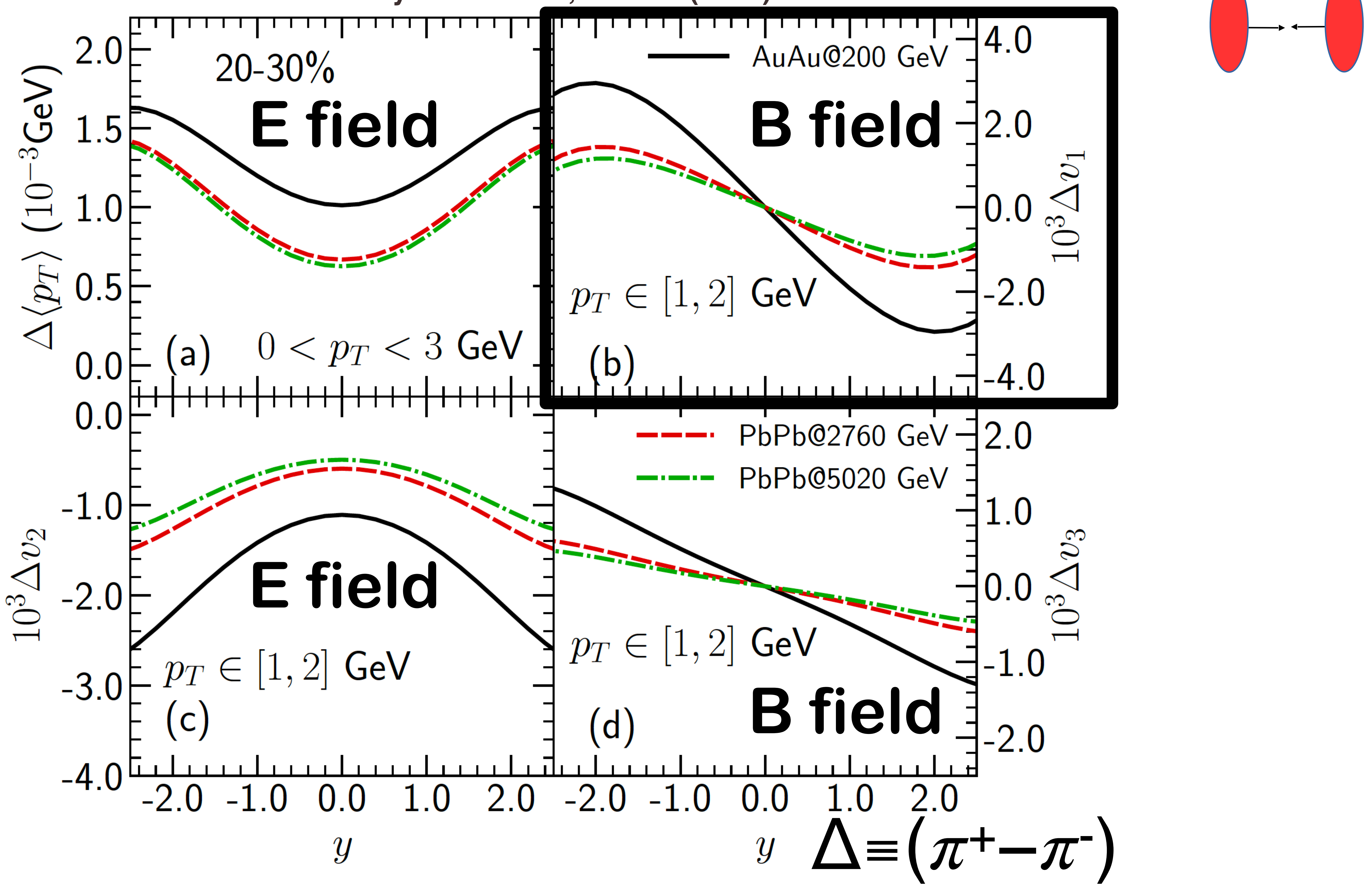

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- **Impact on D0 Δv_1**: mainly due to magnetic field from spectators.

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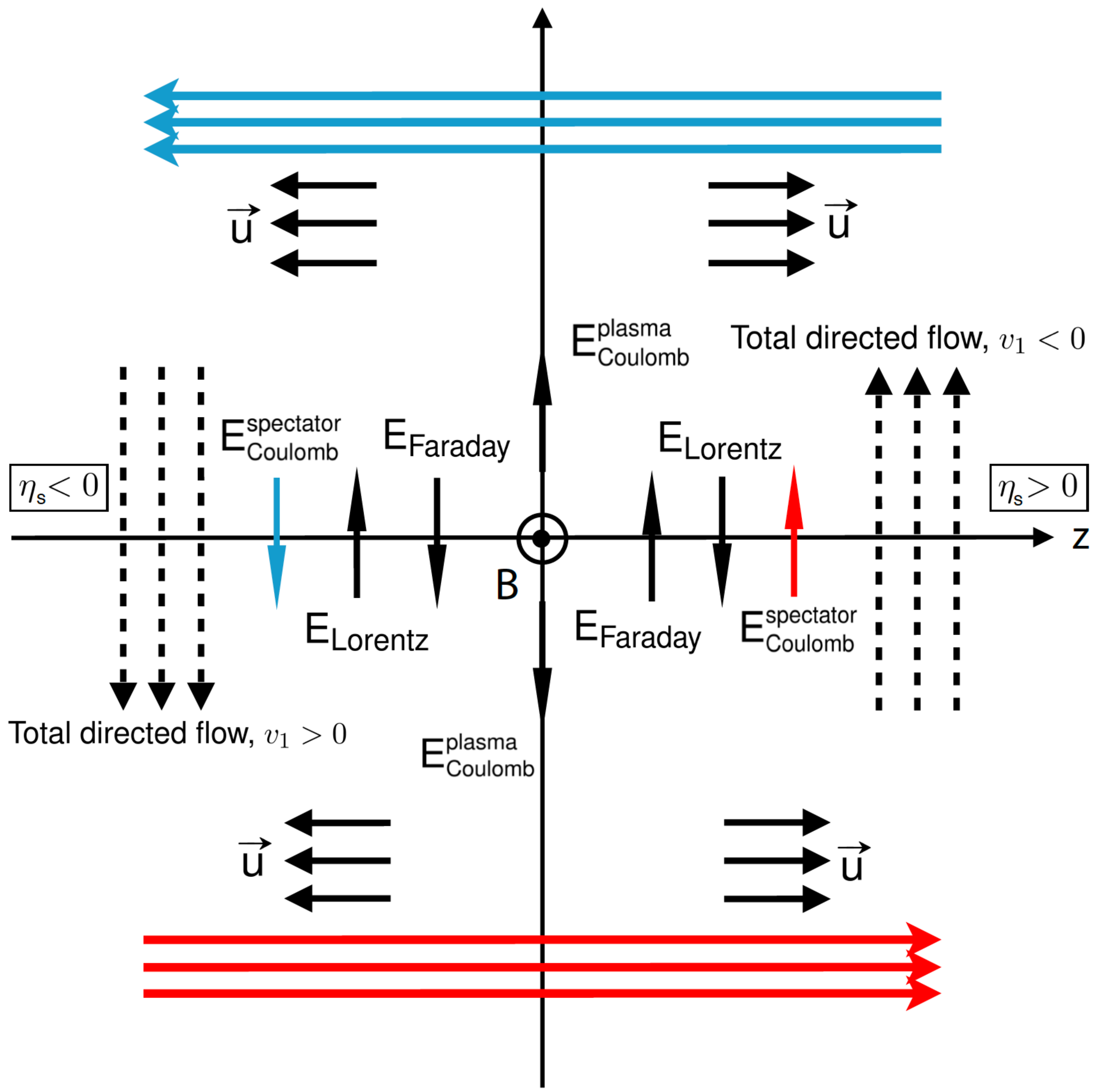

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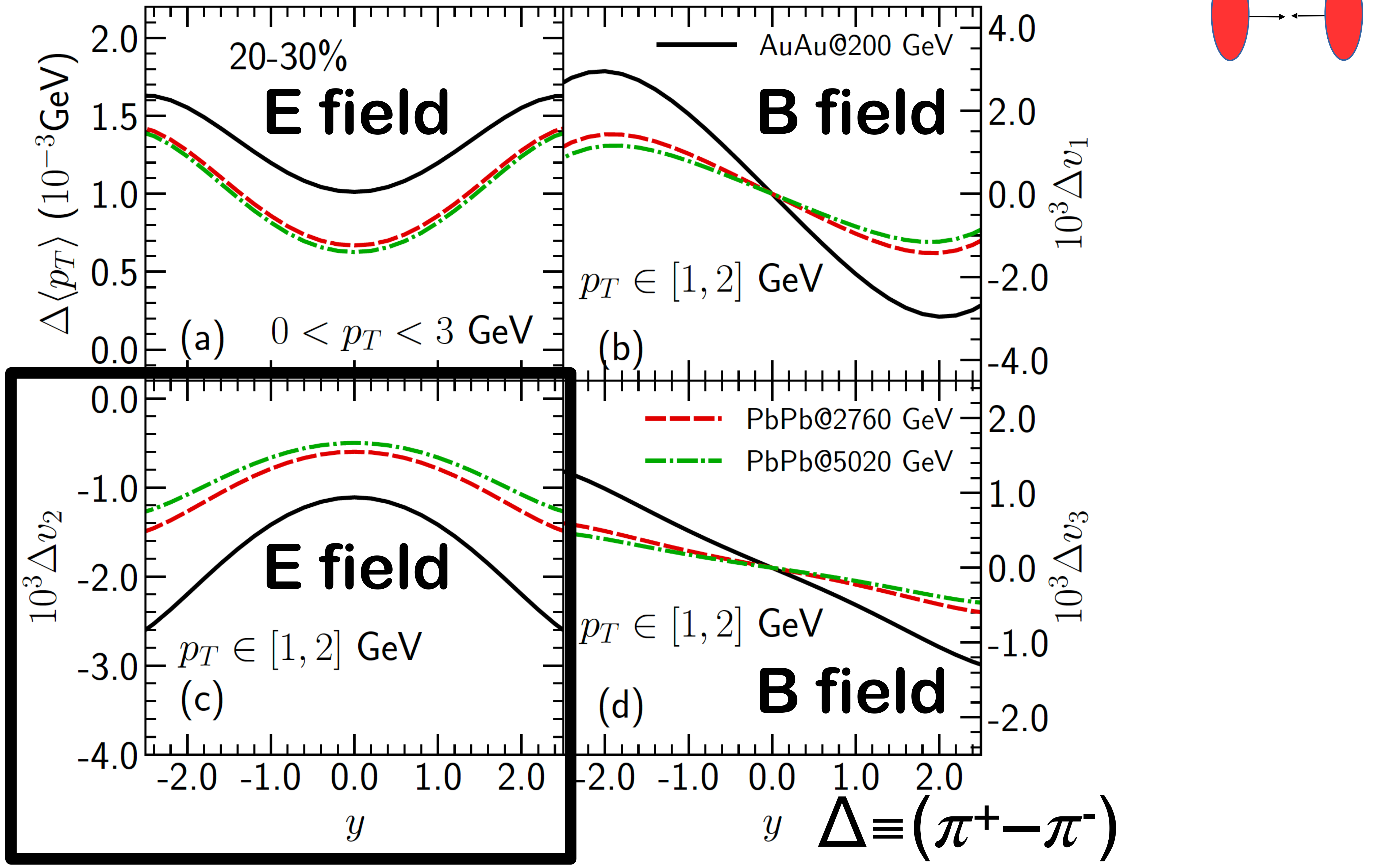
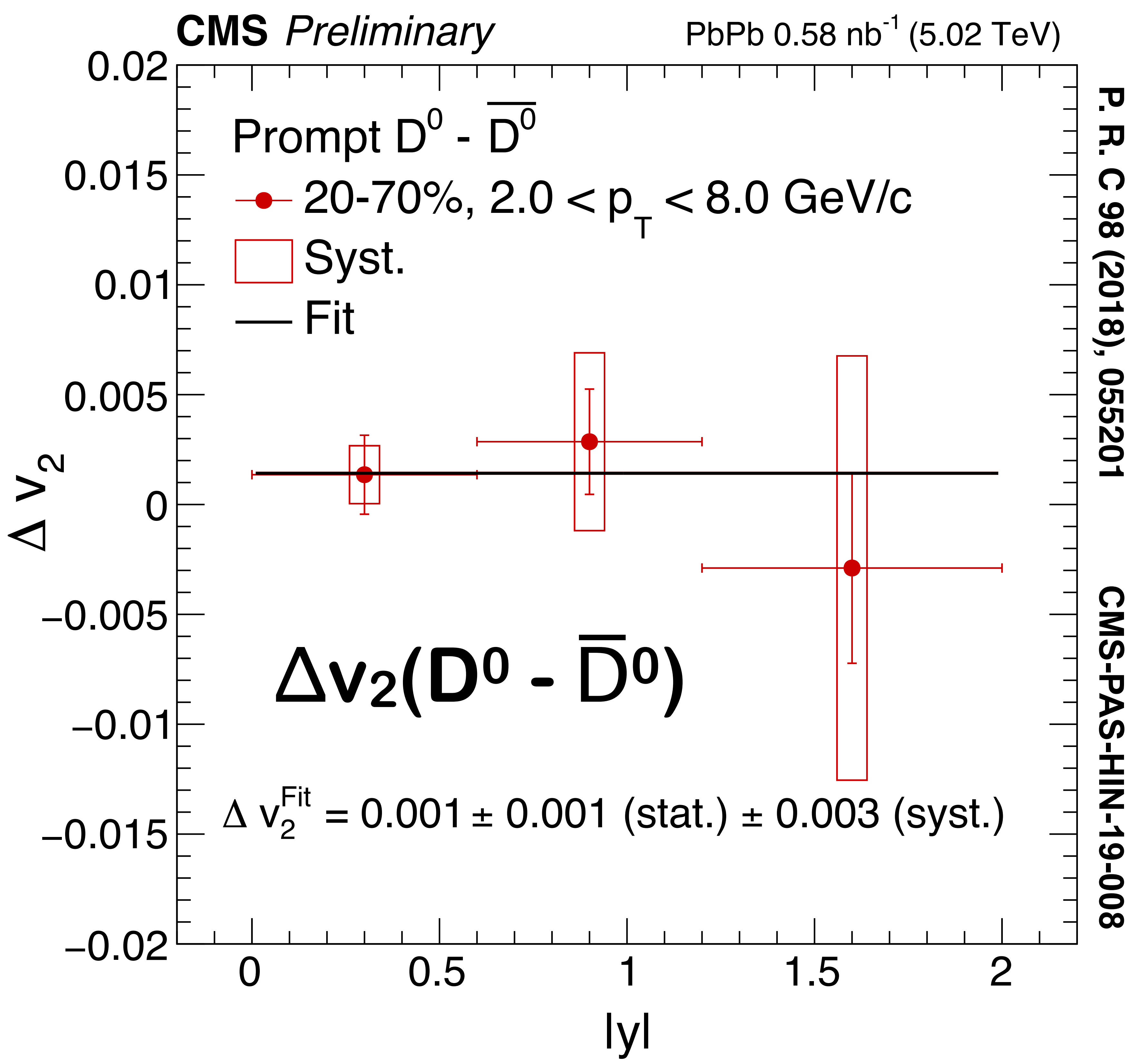
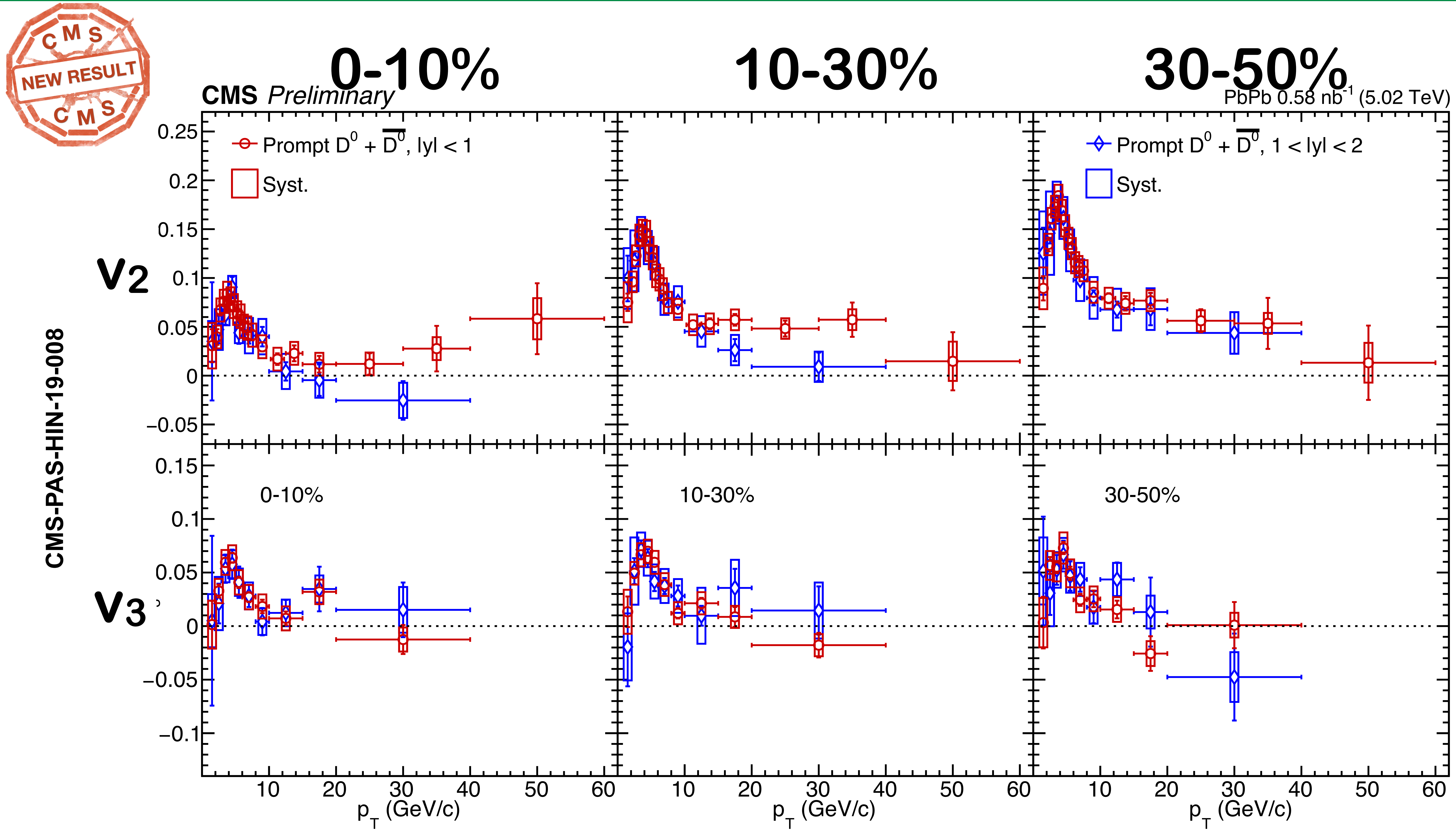


- Strong and short-lived EM fields in PbPb at LHC → Non-zero Δv_n for opposite-charge.
- Impact on D0 Δv_1: mainly due to magnetic field from spectators.
- **Effect on D0 Δv_2**: mostly produced by electric field from collision participants.



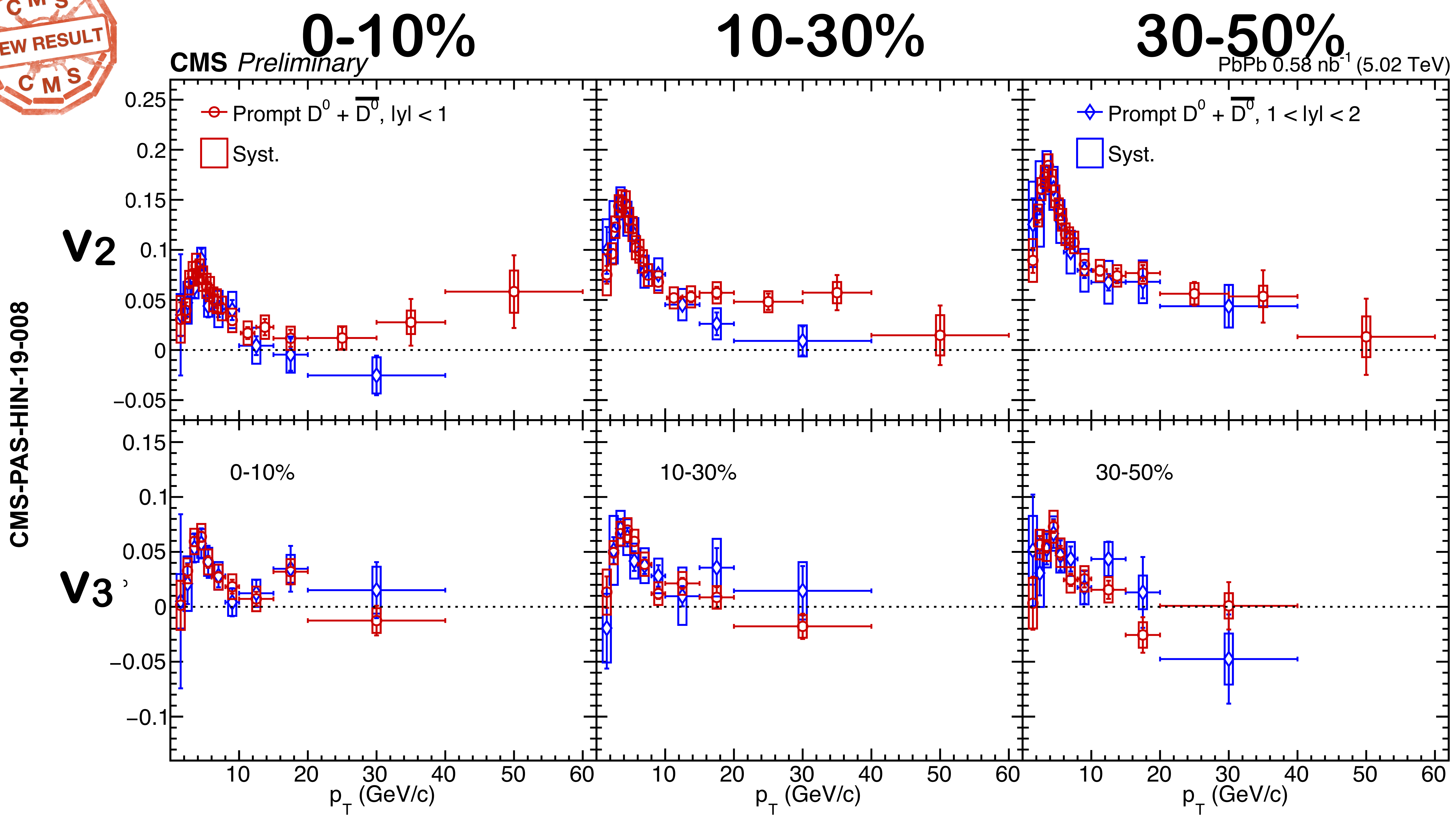
- No sign of rapidity dependence→ average $\Delta v_2(D^0 - \bar{D}^0) = 0.001 \pm 0.001$(stat) ± 0.003(syst).
- Results compatible with calculations for charged hadrons ($\Delta v_2 \sim 0.0001$).

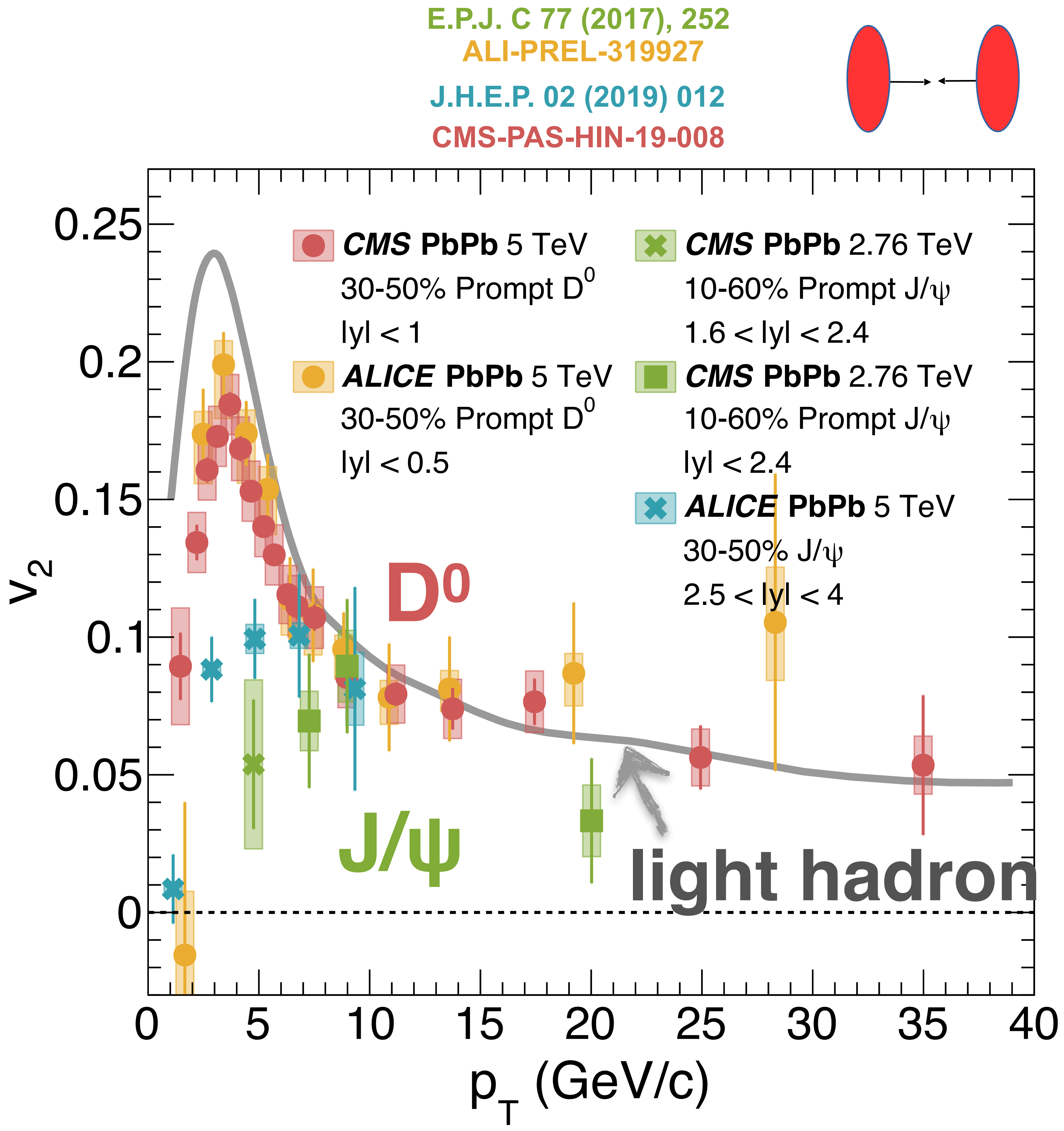
Prompt D^0 v_2/v_3 in PbPb



- Similar trend across rapidity regions → D^0 v_n trend expected from collision geometry.

Prompt D^0 vs J/ψ v_2 in PbPb





- Similar trend across rapidity regions → D^0 v_n trend expected from collision geometry.
- $v_2(D^0)$ > $v_2(J/\psi)$, in agreement with ALICE results.

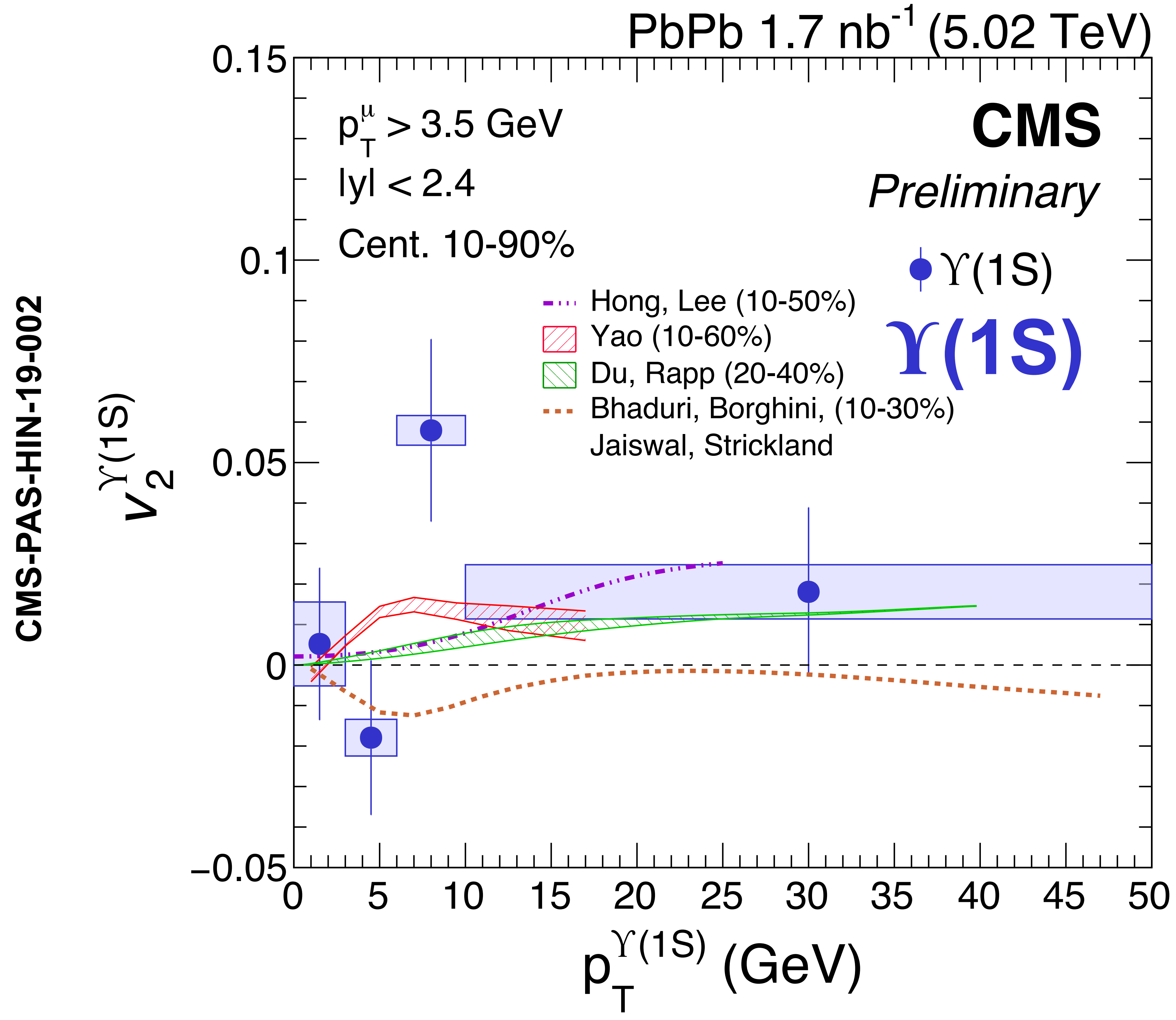
Υ(nS) v_2 in PbPb

Hong, Lee [arXiv:1909.07696]: HTL perturbation theory

Yao [N.P. A 982 (2019) 755]: Boltzmann transport model

Du, Rapp P.R. C 96 (2017) 054901]: kinetic-rate equation

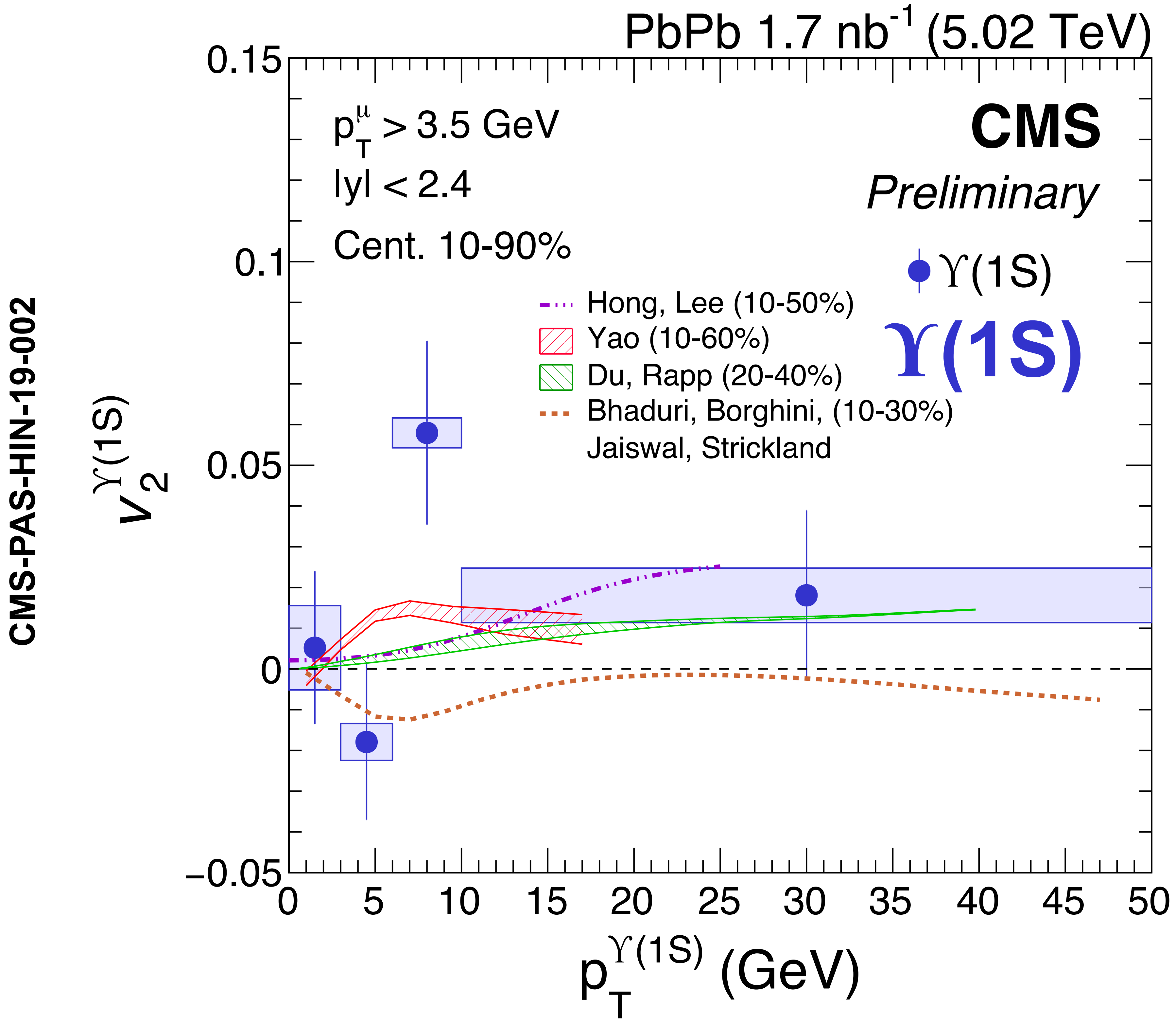
Bhaduri et al [arXiv:1809.06235]: 3+1d aHydro model



- Precise Υ(1S) v_2 measurements compatible with zero within 2.5 s.t.d.

Υ(nS) v_2 in PbPb

Hong, Lee [arXiv:1909.07696]: HTL perturbation theory	Yao [N.P. A 982 (2019) 755]: Boltzmann transport model	Du, Rapp P.R. C 96 (2017) 054901]: kinetic-rate equation	Bhaduri et al [arXiv:1809.06235]: 3+1d aHydro model



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- Model calculations in good agreement with data.

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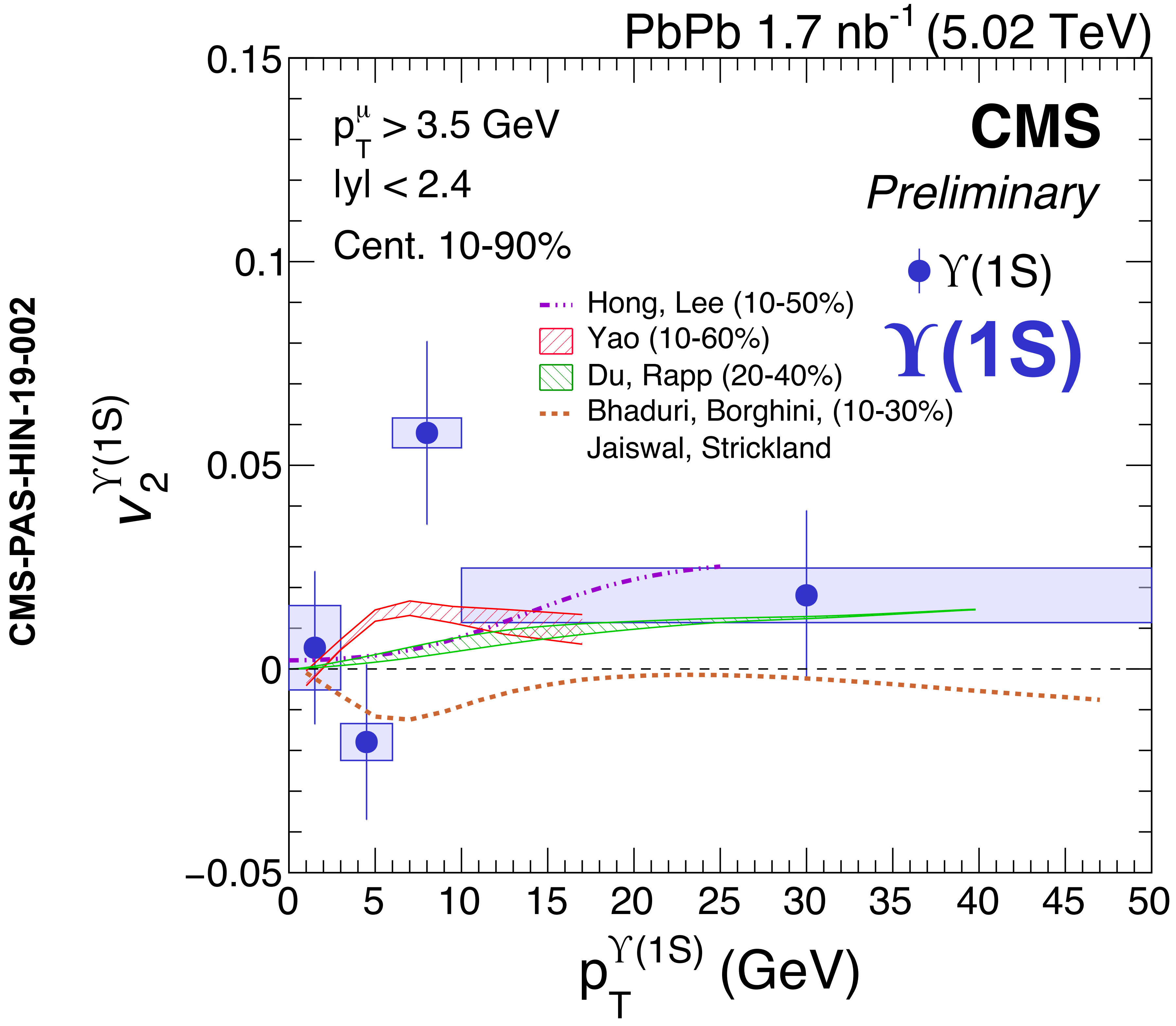
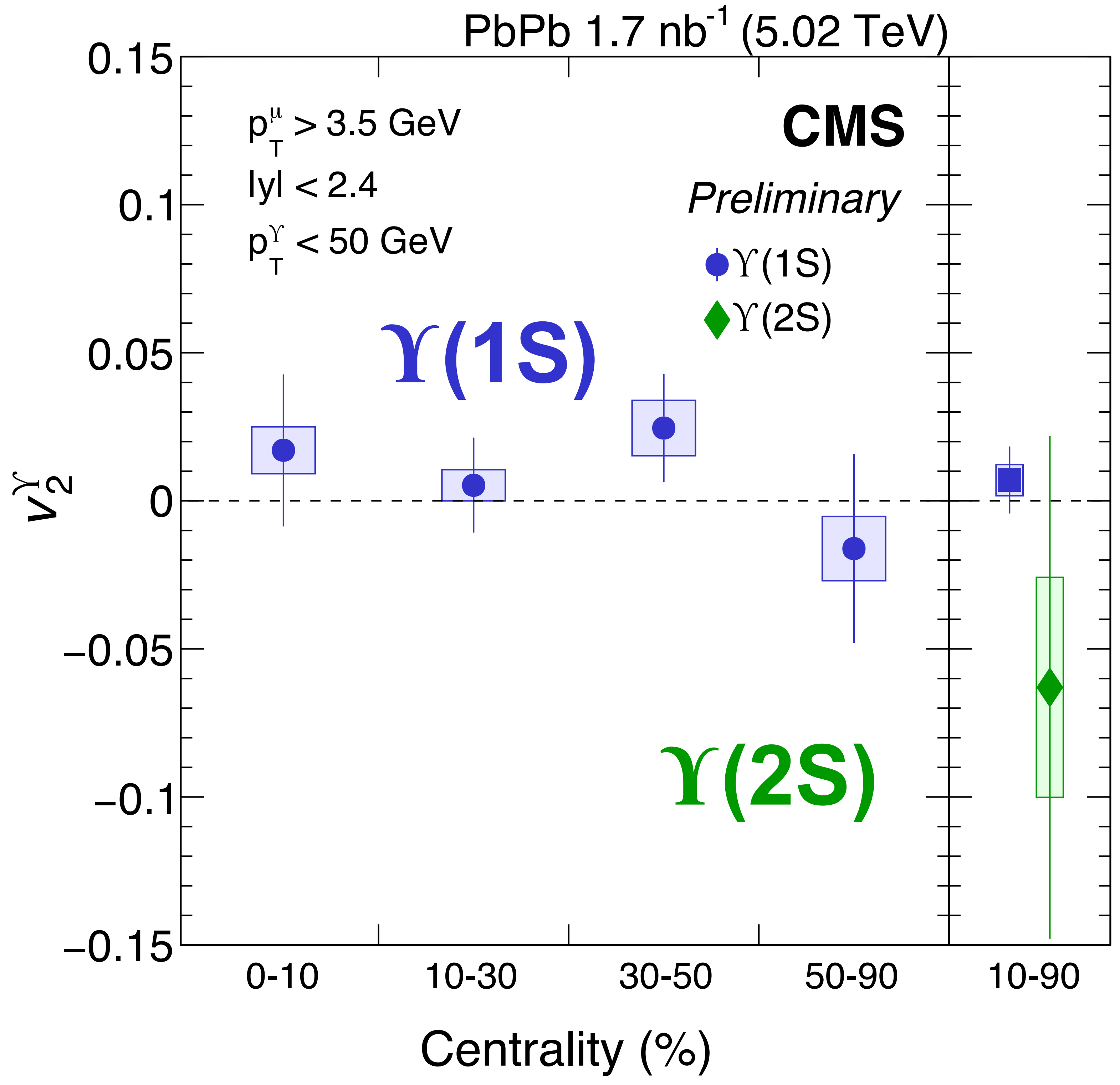
[arXiv:1909.07696]:	**[N.P. A 982 (2019) 755]:**	**P.R. C 96 (2017) 054901]:**	**[arXiv:1809.06235]:**
HTL perturbation theory	**Boltzmann transport model**	**kinetic-rate equation**	**3+1d aHydro model**





- Precise **ϒ(1S) v_2** measurements compatible with zero within 2.5 s.t.d.
- Model calculations in good agreement with data.
- First measurement of **ϒ(2S) v_2**.

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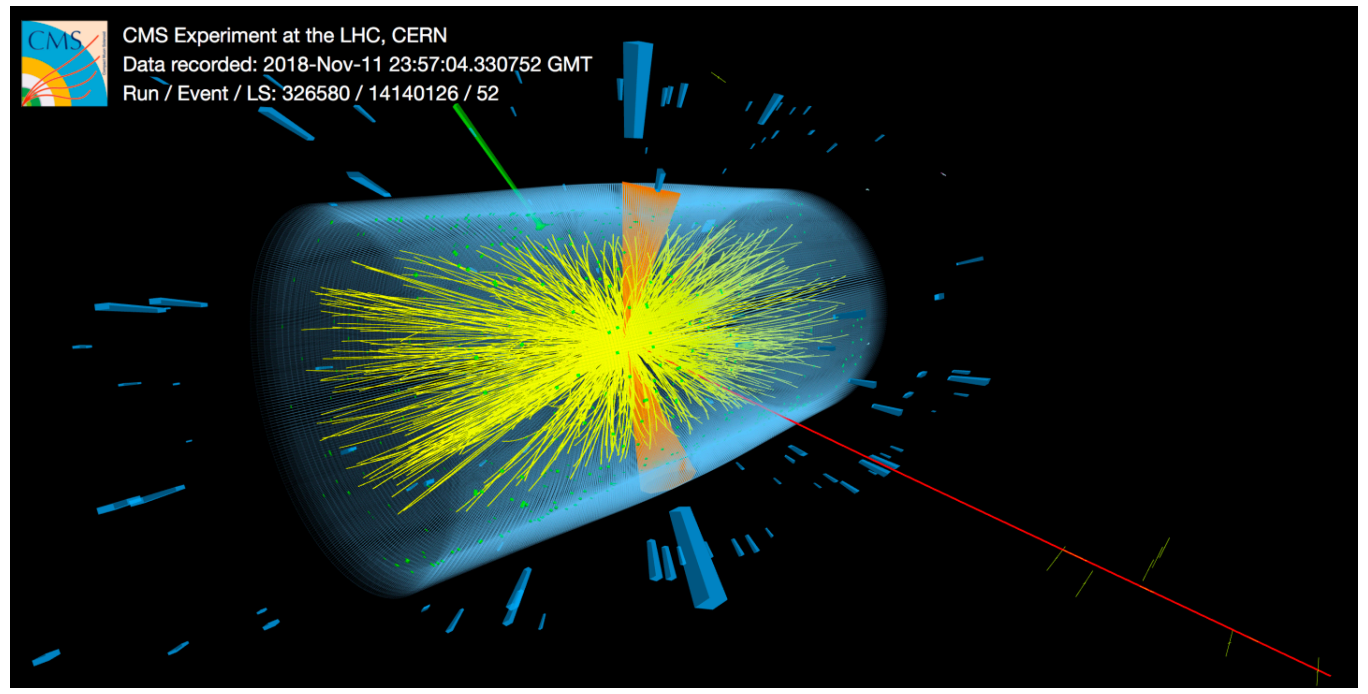

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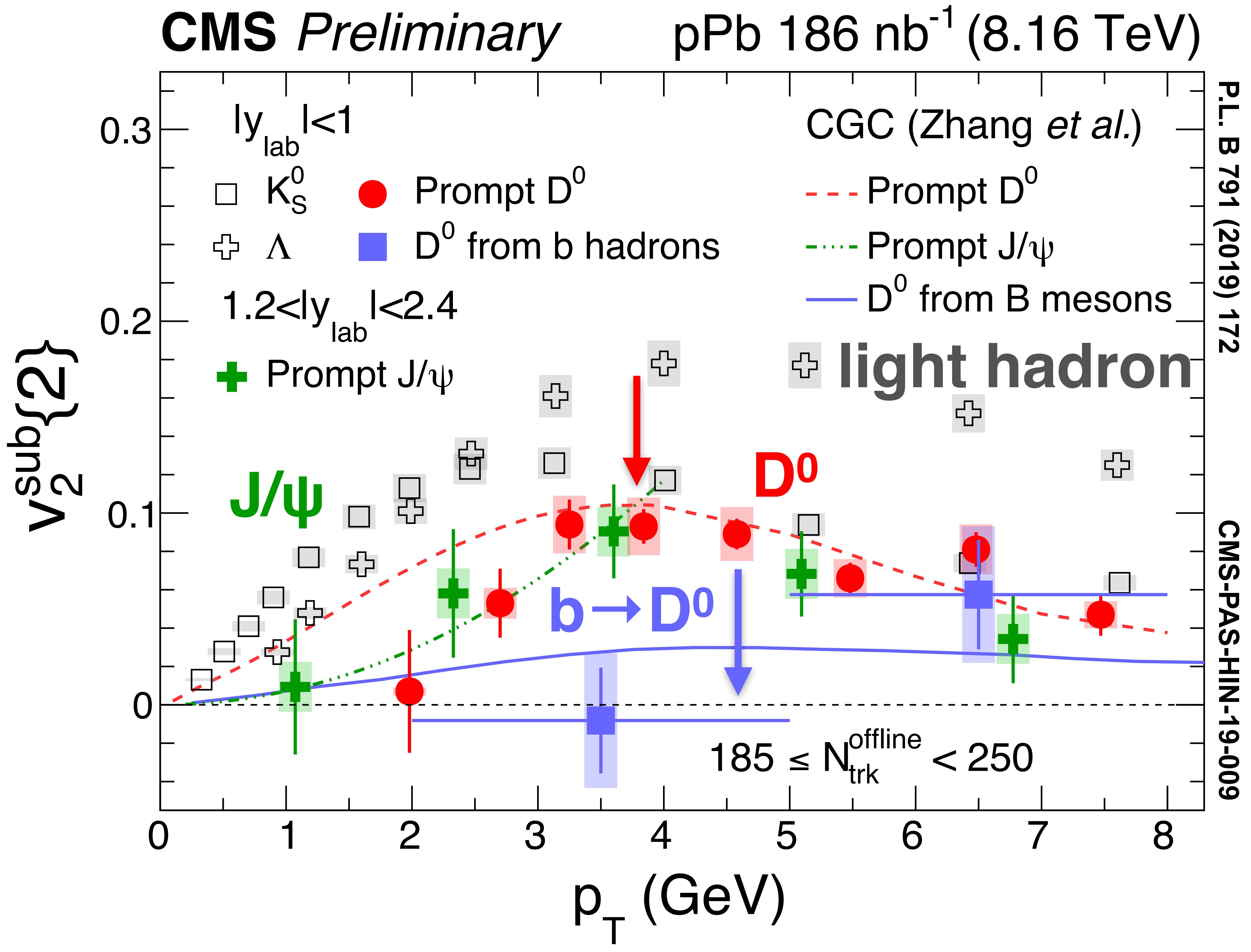
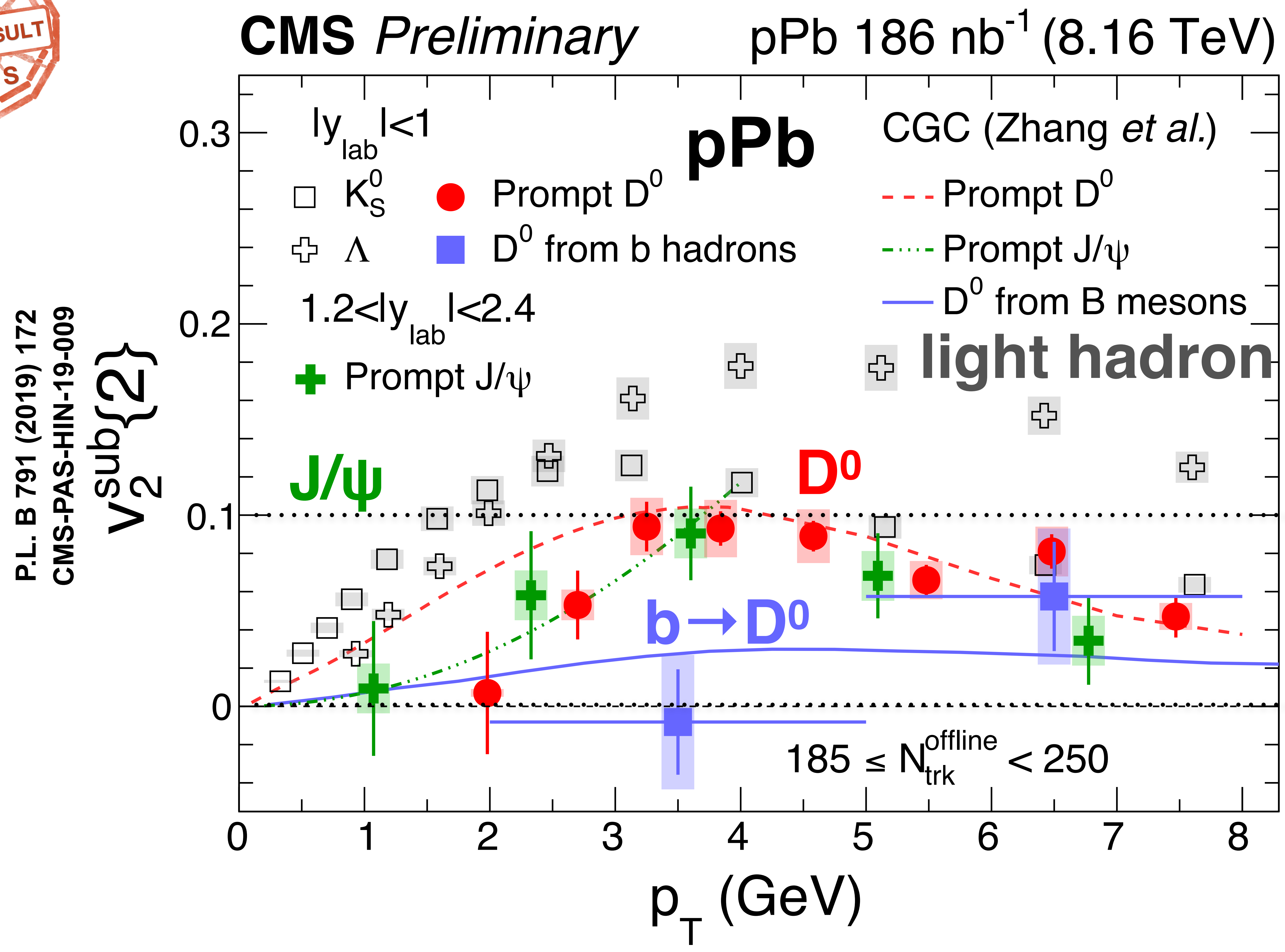
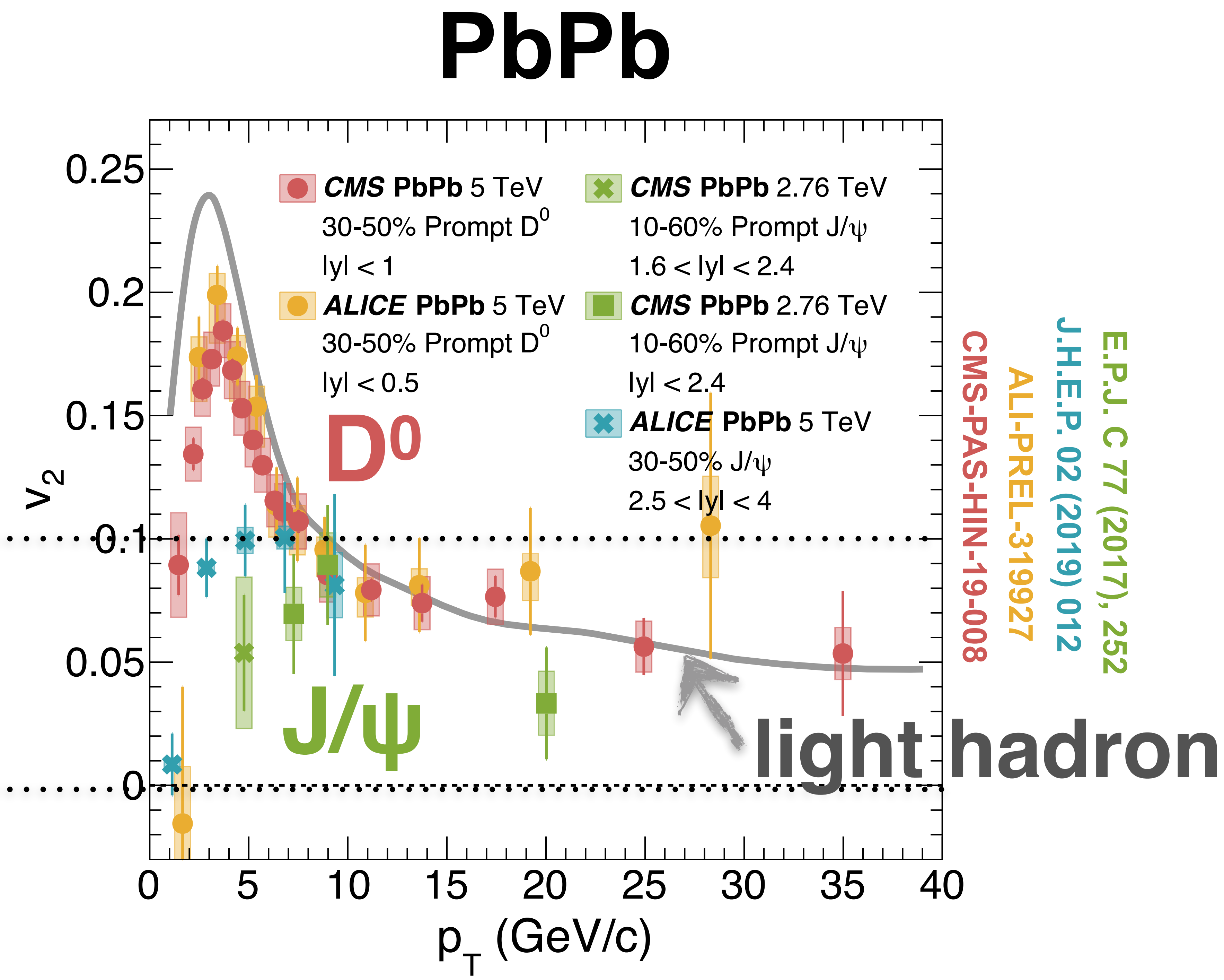


- Observation of prompt **J/ψ** and **D⁰** flow in high-multiplicity pPb → **charm collectivity**.
- **pPb**: $v_2(b\to D^0) \sim 0$ **<** $v_2(J/\psi)$ **~** $v_2(D^0)$ **<** v_2(light hadron) → **beauty collectivity ~ 0**.





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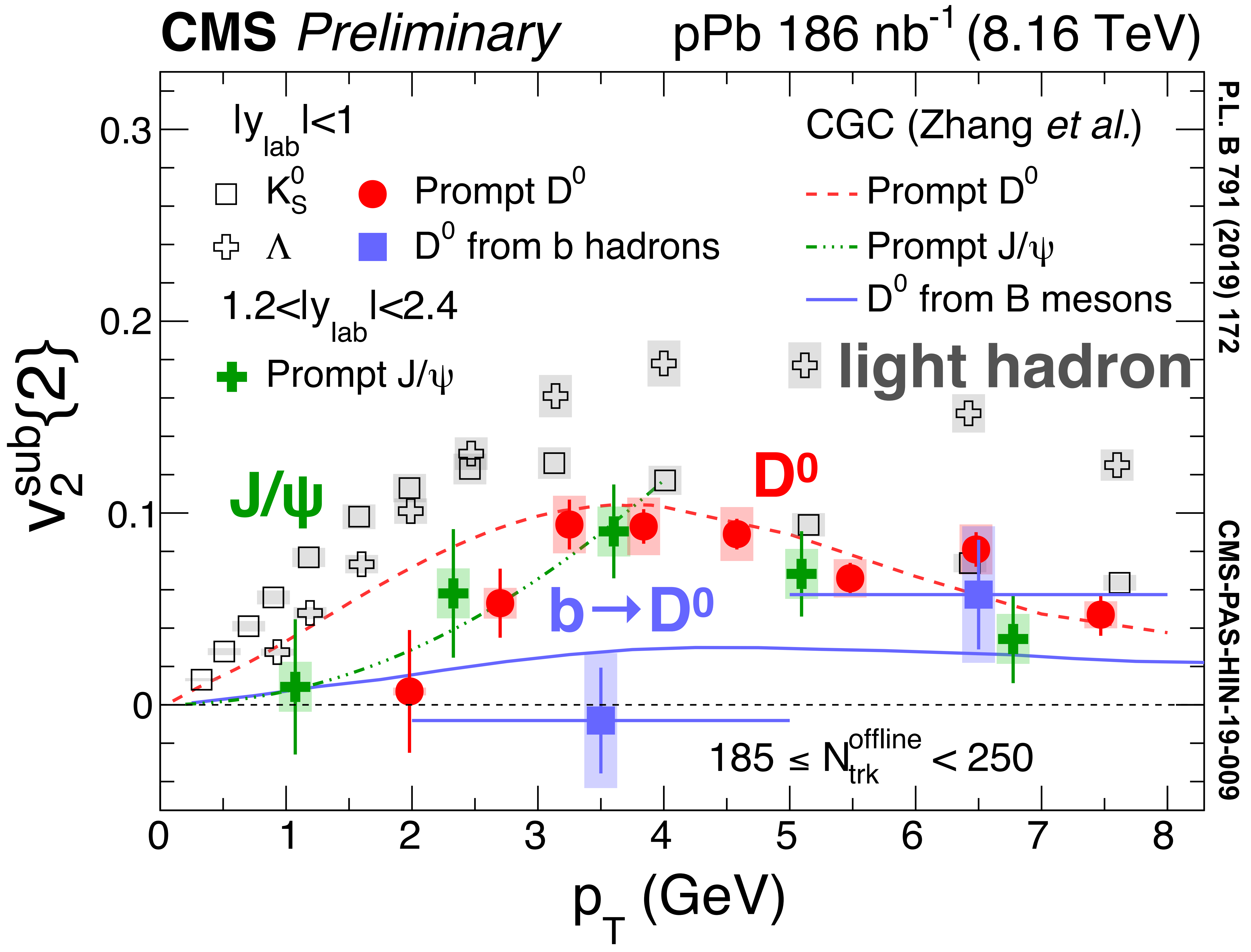
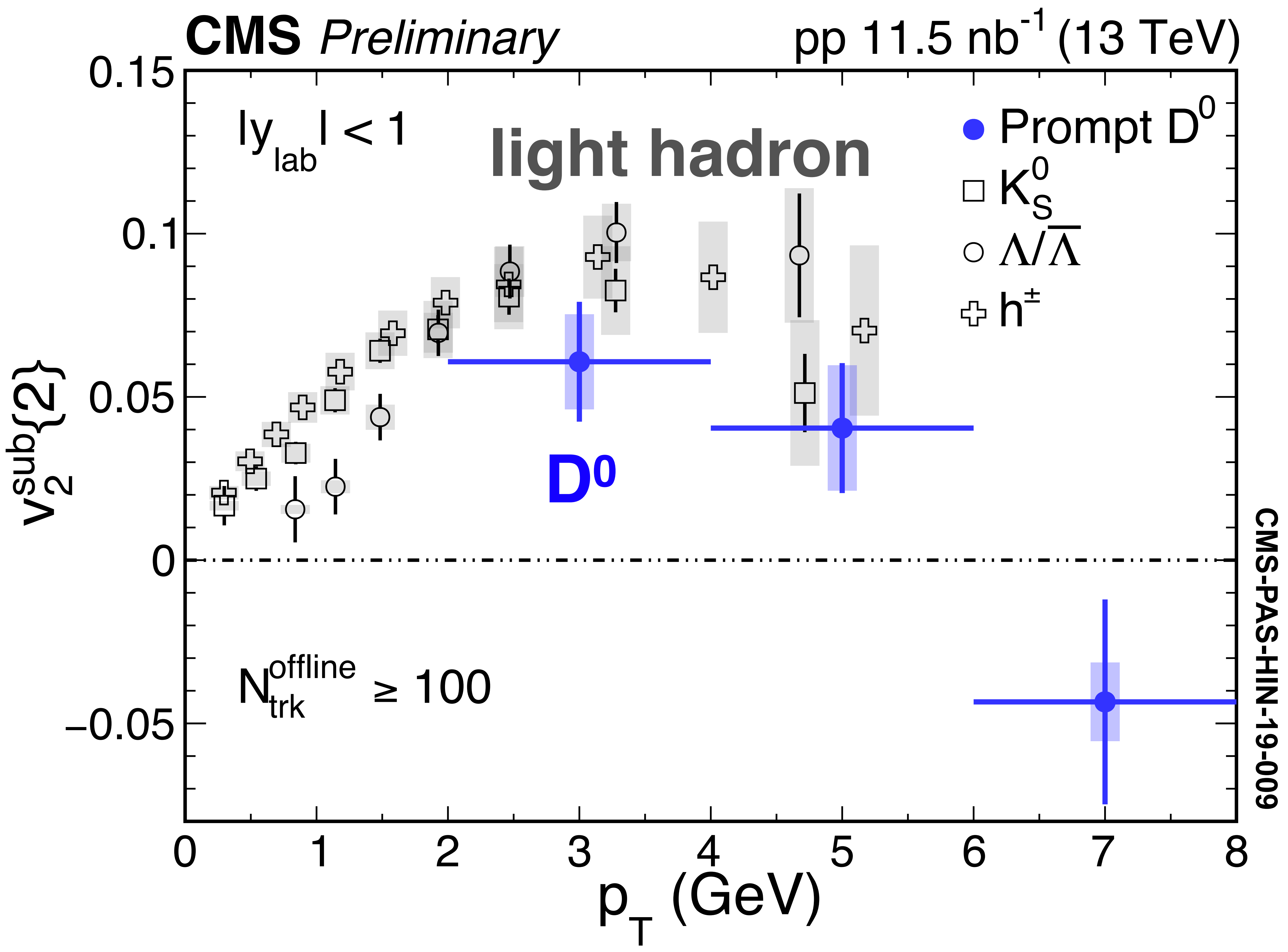
- **PbPb**: $v_2(J/\psi)$ **<** $v_2(D^0)$ → pPb results not explained by final state coalescence effects.

Heavy-flavour collectivity in pPb



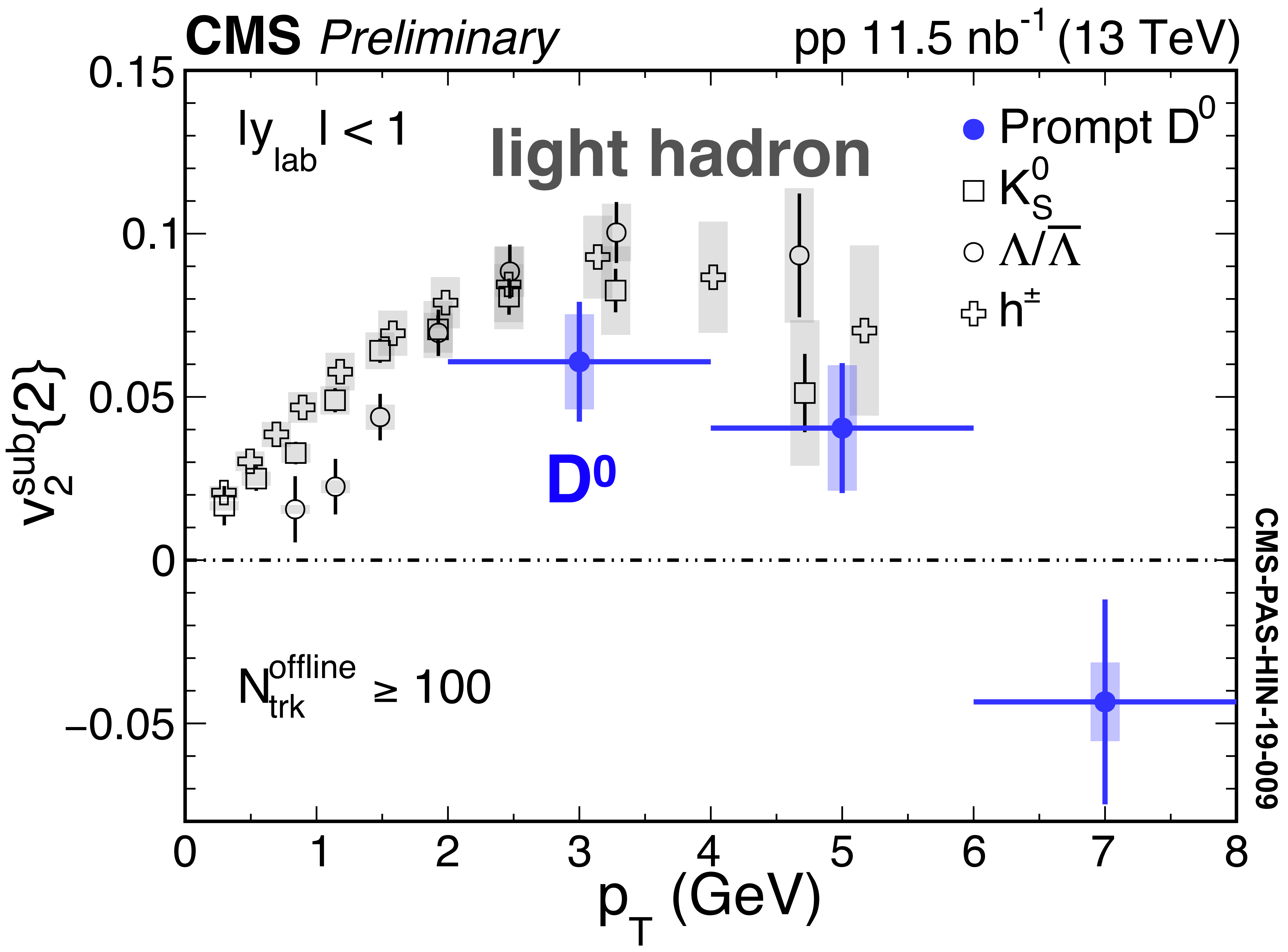
- Observation of prompt **J/ψ** and **D^0** flow in high-multiplicity pPb → **charm collectivity**.
- **pPb**: **$v_2(b \to D^0) \sim 0$ < $v_2(J/\psi)$ ~ $v_2(D^0)$ < v_2(light hadron)** → **beauty collectivity ~ 0**.
- Initial state Colour Glass Condensate (**CGC**) calculations in **agreement** with **data**.

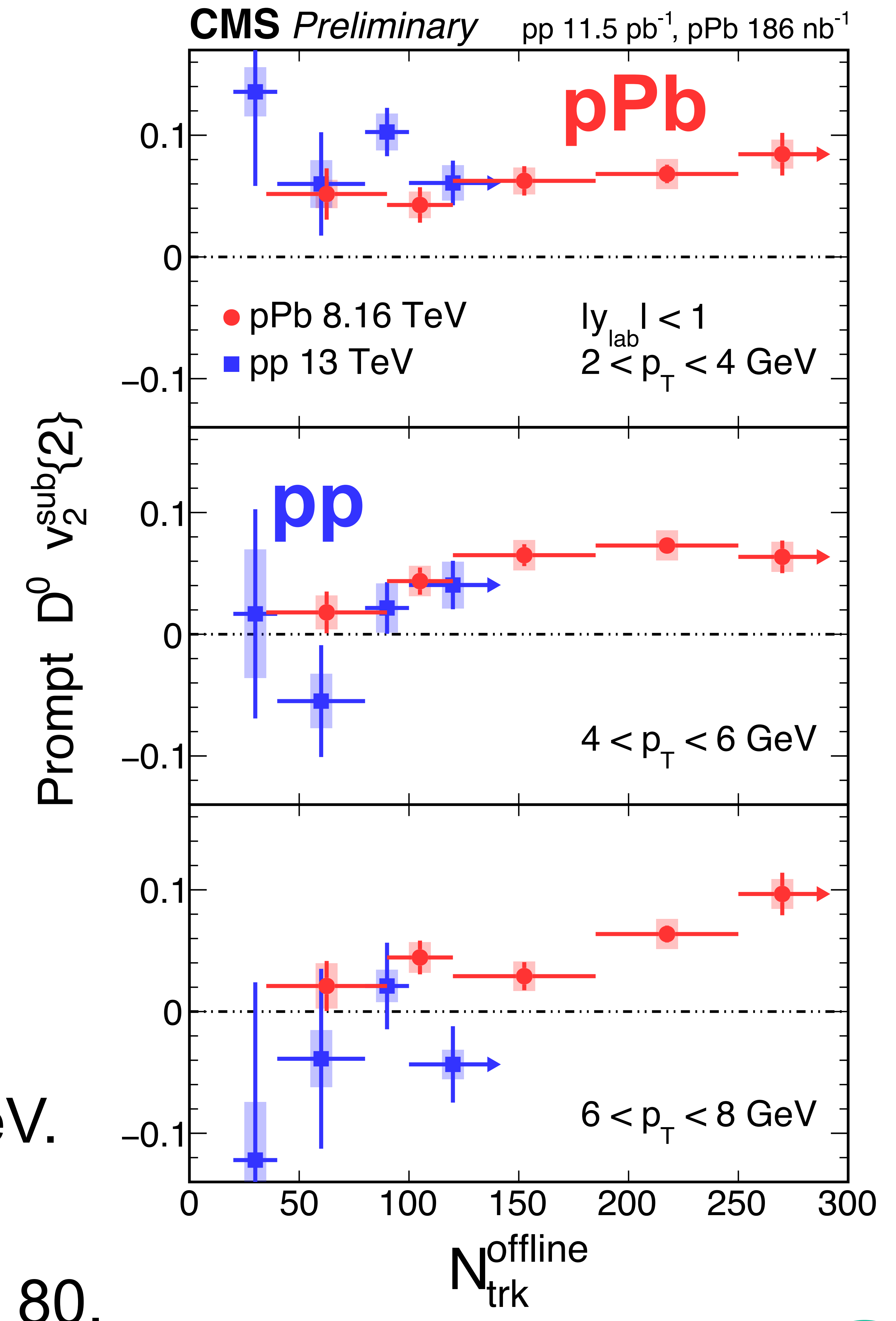
Prompt D^0 collectivity in pp



- Similar collectivity between D^0 and light hadrons.

Prompt D^0 collectivity in small systems





- Similar collectivity between D^0 and light hadrons at $p_T < 6$ GeV.
- First measurement of D^0 v_2 vs N_{trk}
  - Compatible D^0 v_2 in pp and pPb → D^0 $v_2 > 0$ at $N_{trk} > 80$.

Outline

- Recent results in HI collisions:
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  2. Heavy-flavour production
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- **Future opportunities with fast timing upgrades:**
  1. **HL-LHC and phase 2 upgrades**
  2. Conceptual design of MTD
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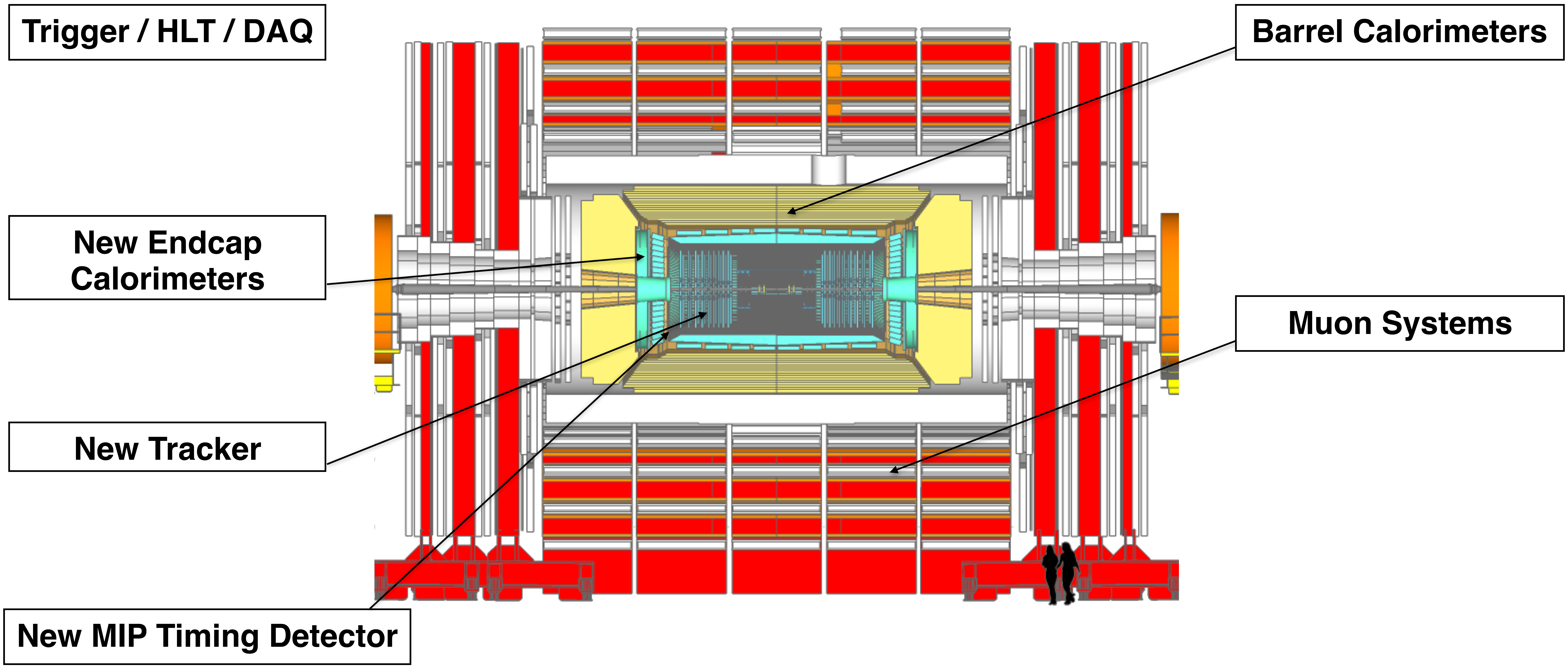
CMS Phase 2 upgrades for HL-LHC

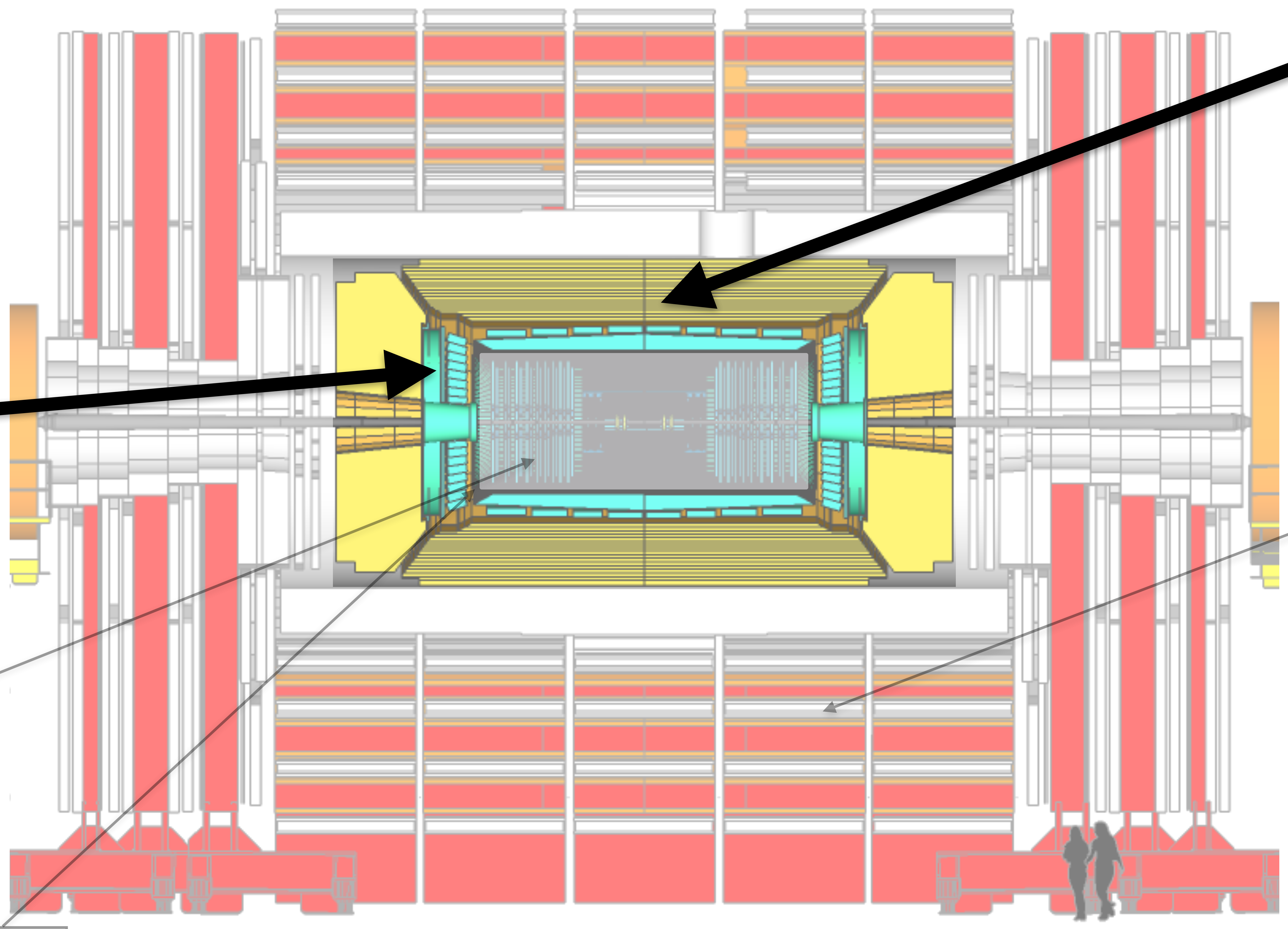


CMS Phase 2 upgrades for HL-LHC

Trigger / HLT / DAQ

Barrel Calorimeters
- Replace FE/BE electronics

New Endcap Calorimeters
- Radiation tolerance
- High granularity



Muon Systems

New Tracker

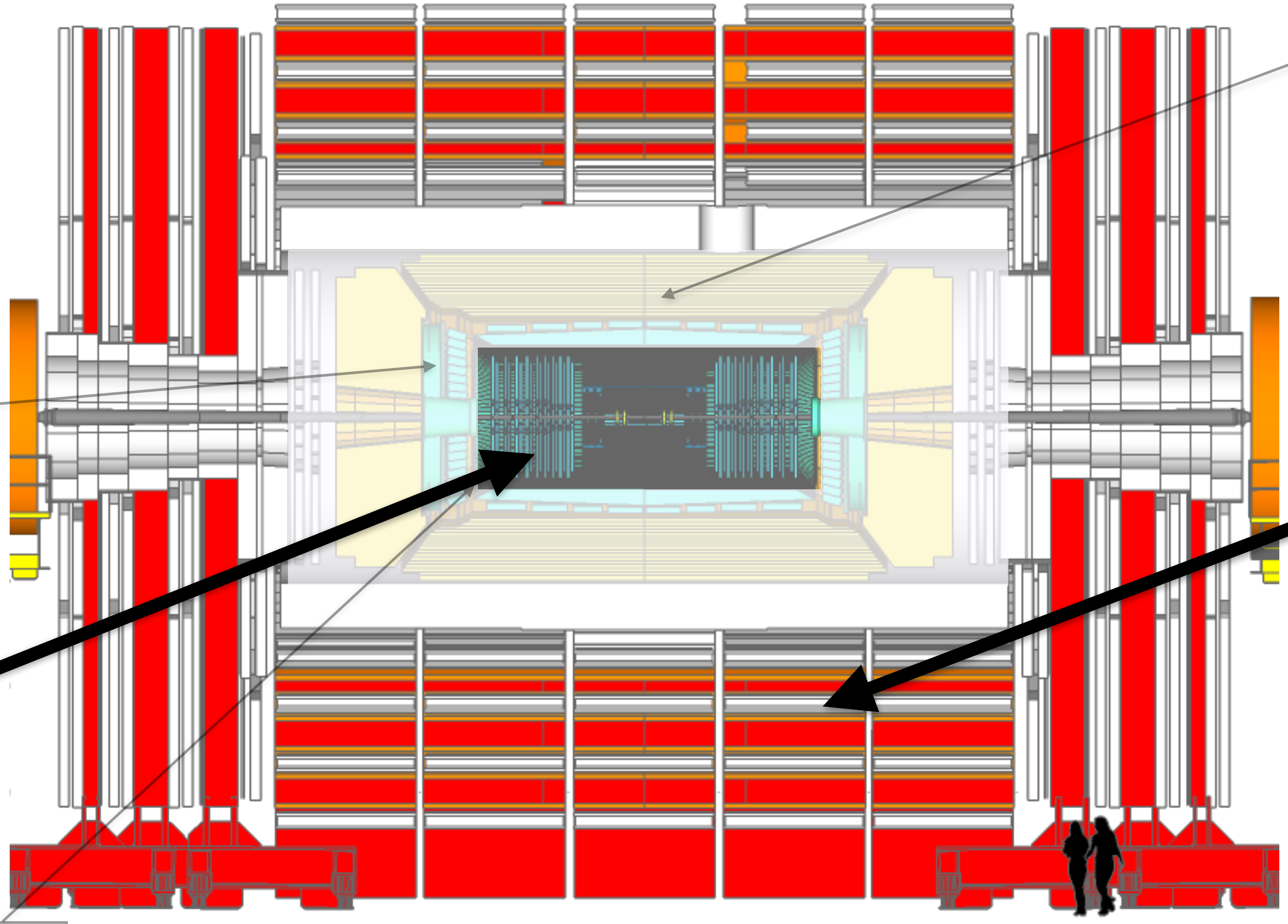
New MIP Timing Detector

CMS Phase 2 upgrades for HL-LHC

Trigger / HLT / DAQ

Barrel Calorimeters

New Endcap Calorimeters



Muon Systems

- $|\eta| < 2.4 \rightarrow |\eta| < 3.0$

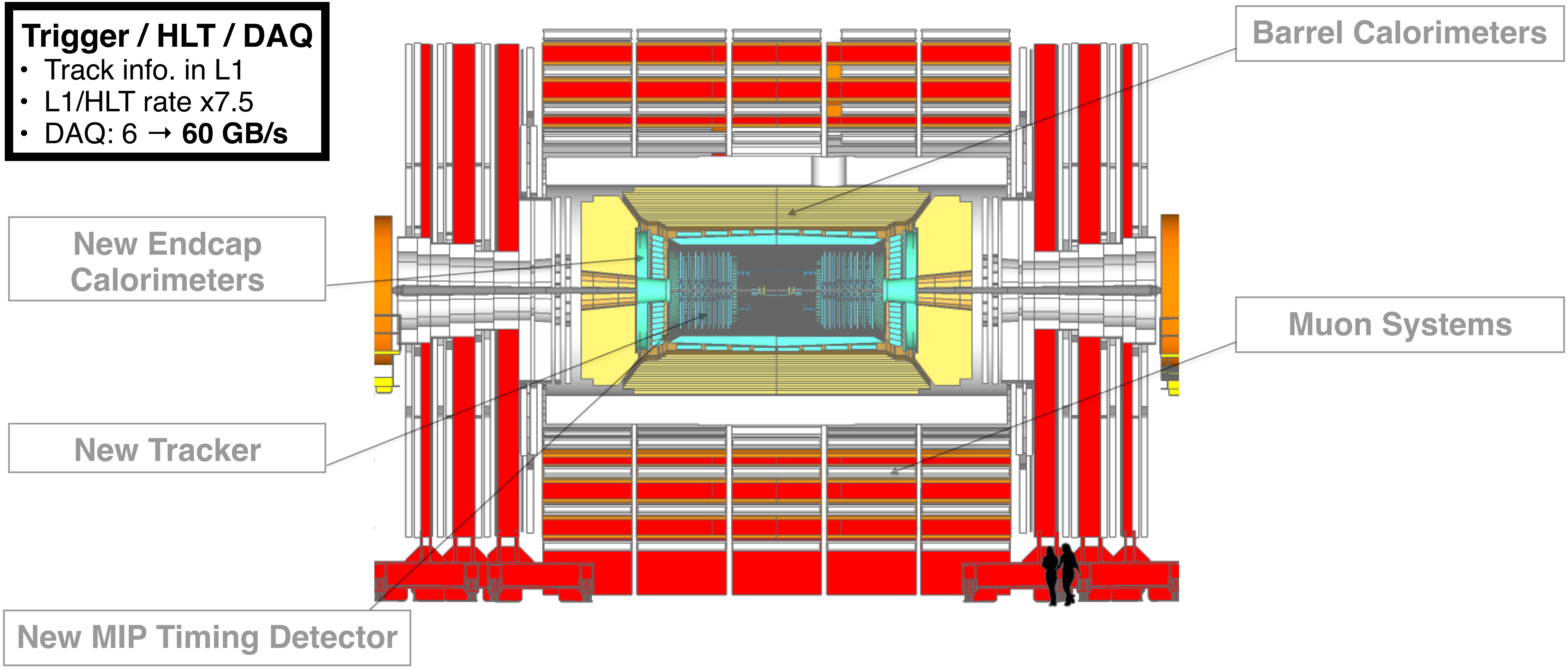
New Tracker

- Radiation tolerance
- High granularity
- $|\eta| < 2.4 \rightarrow |\eta| < 4.0$

New MIP Timing Detector

CMS Phase 2 upgrades for HL-LHC

Trigger / HLT / DAQ
- Track info. in L1
- L1/HLT rate x7.5
- DAQ: 6 → **60 GB/s**



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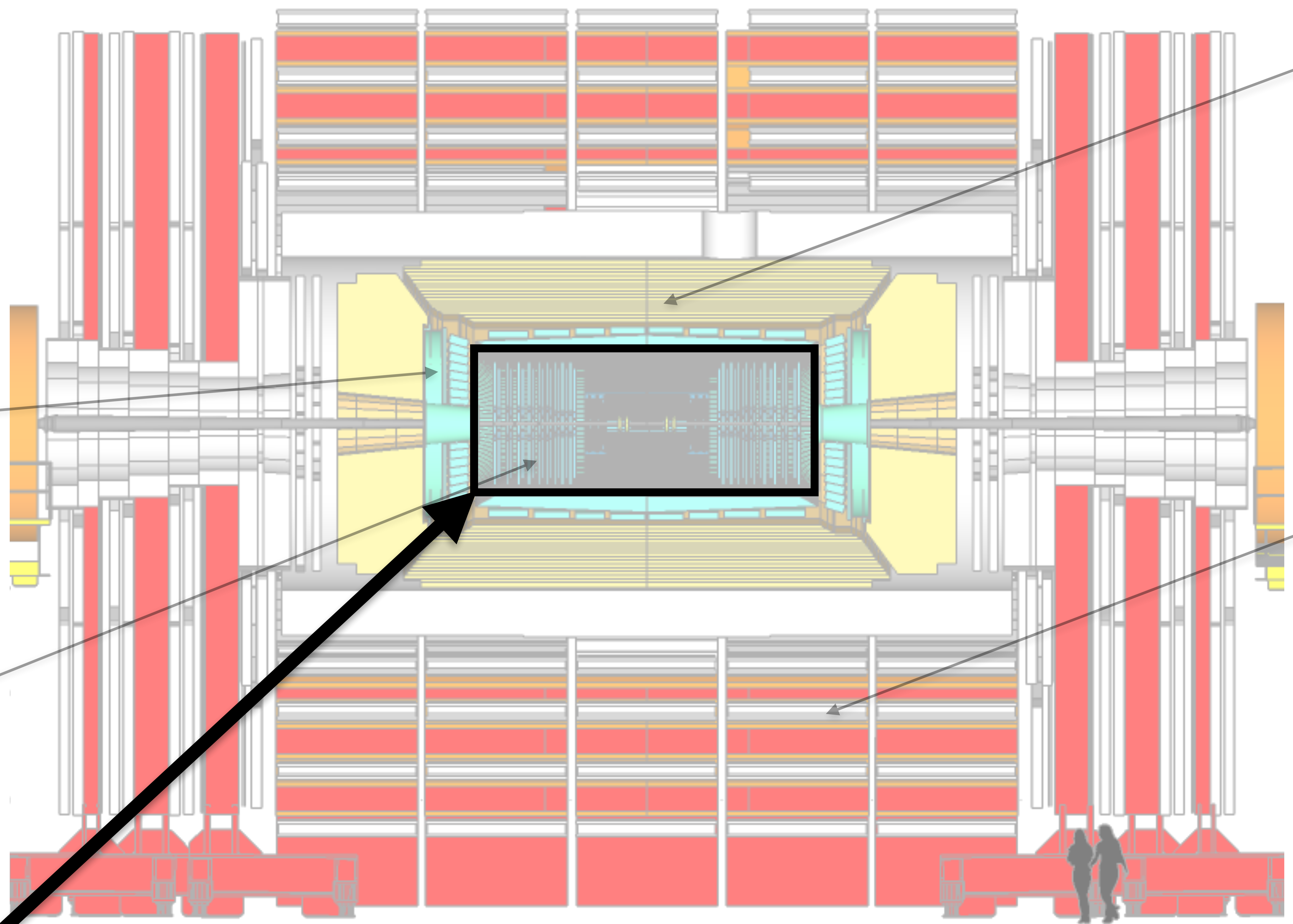

New MIP Timing Detector
- Precision timing
- **$|\eta| < 3.0$**

Outline

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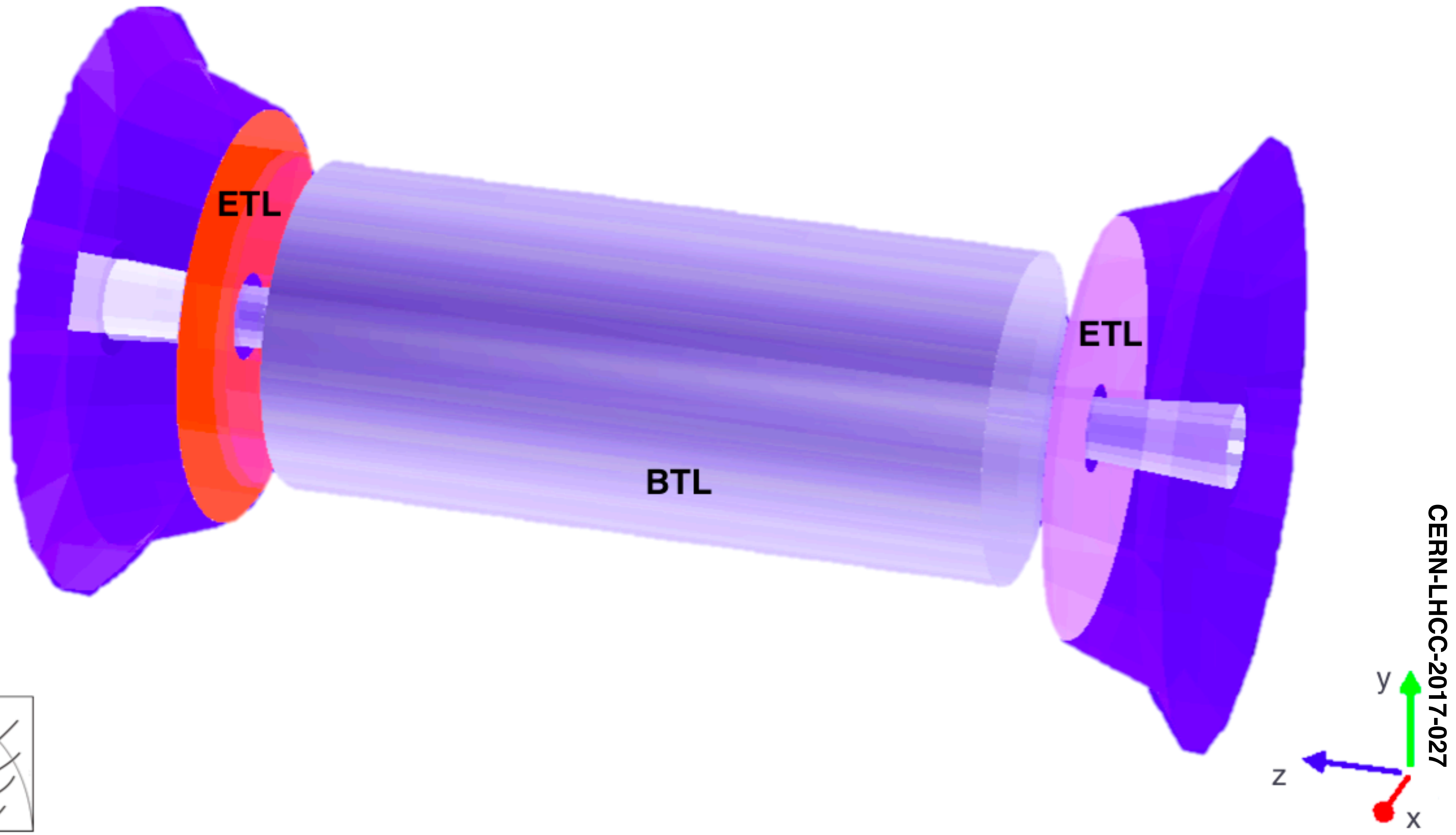
CMS MIP Timing Detector (MTD)



- One barrel section (BTL) and two end-cap disks (ETL).
- Coverage for tracks: p > 0.7 GeV at $|\eta| < 3.0$, and time resolution: ~30 ps
- Installation planned for HL-LHC: 2022 for BTL and 2024 for ETL.

Design:

- 72 trays covering a surface of ~38 m^2
- Material budget: < 0.4 X_0
- Rapidity coverage: $|\eta| < 1.5$
- Timing resolution: ~ 30 ps

Sensors:

- **L(Y)SO:Ce crystal** bars as scintillator**:**
  - Excellent radiation tolerance, high signal and fast response time.
- **Silicon Photomultipliers** as detectors:
  - Compact, fast and insensitive to magnetic fields.

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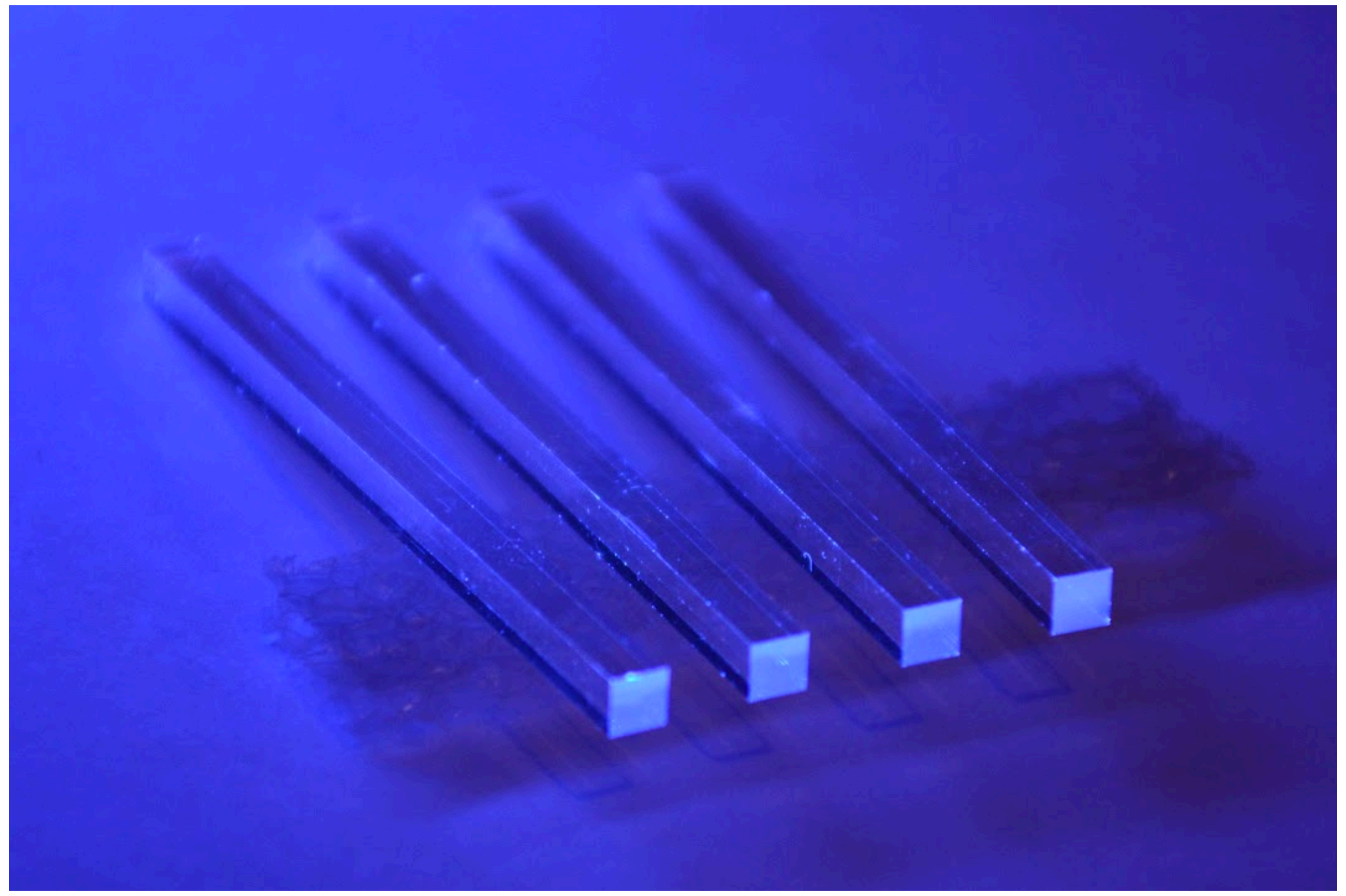
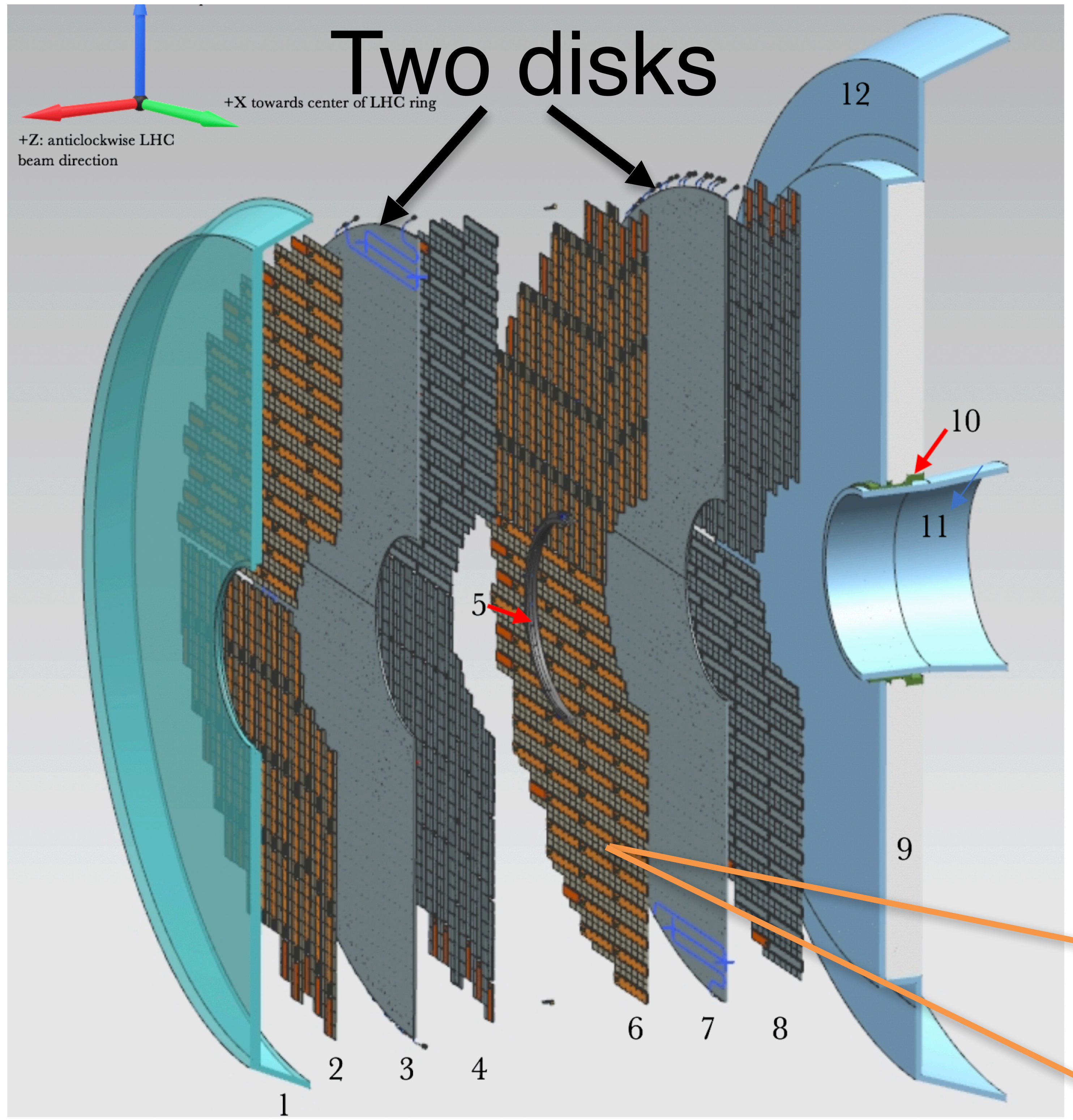


Endcap Timing Layer (ETL)



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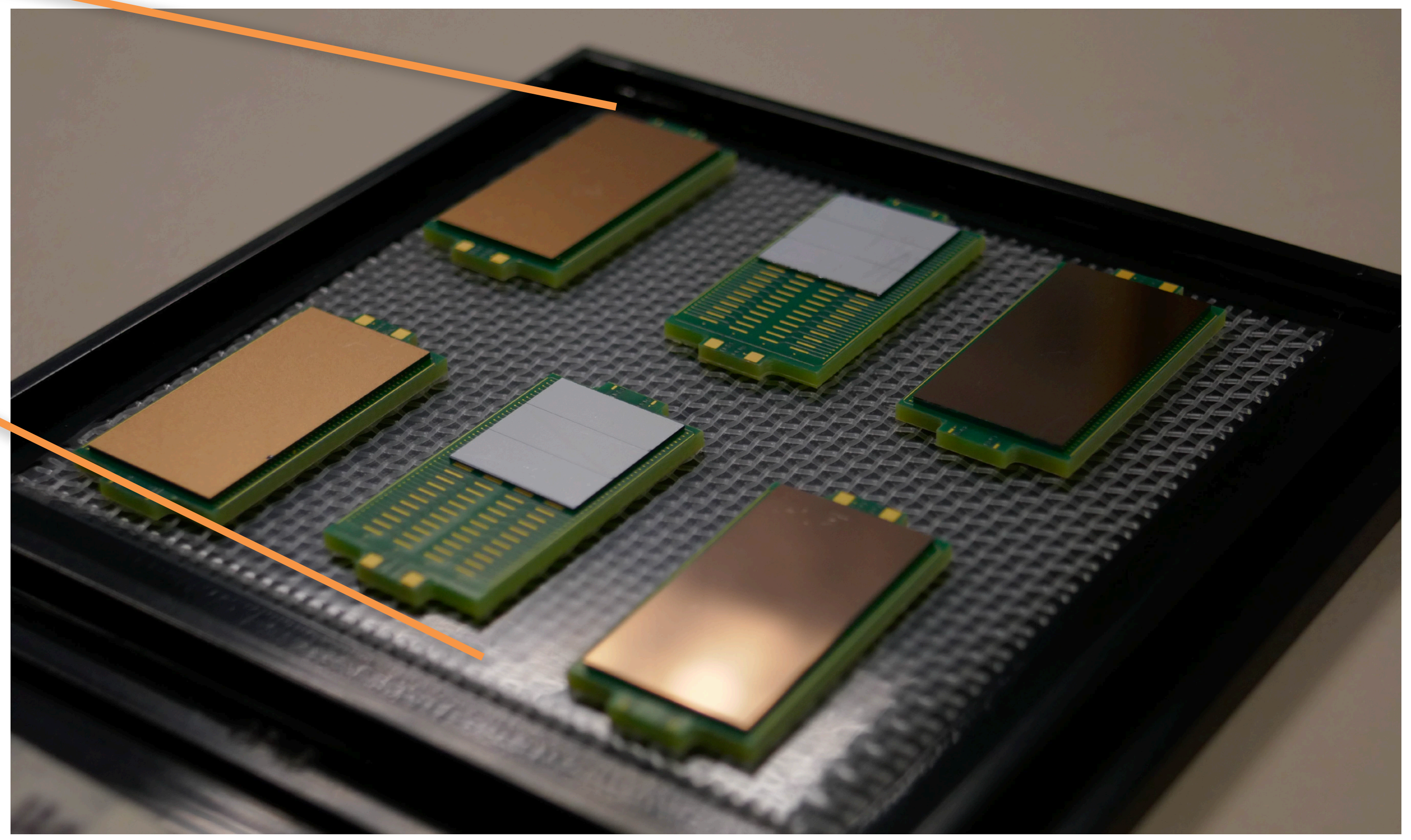
Design:

- 2 disks covering a surface of ~14 m^2
- Material budget: < 0.2 X_0
- Rapidity coverage: 1.6 < |η| < 3.0
- x10 higher radiation level than BTL
- Timing resolution: ~ 30-50 ps

CERN-LHCC-2017-027



Sensors:

- **Ultra fast silicon detectors:**
  - Low gain avalanche diodes optimised for precision timing.

Outline

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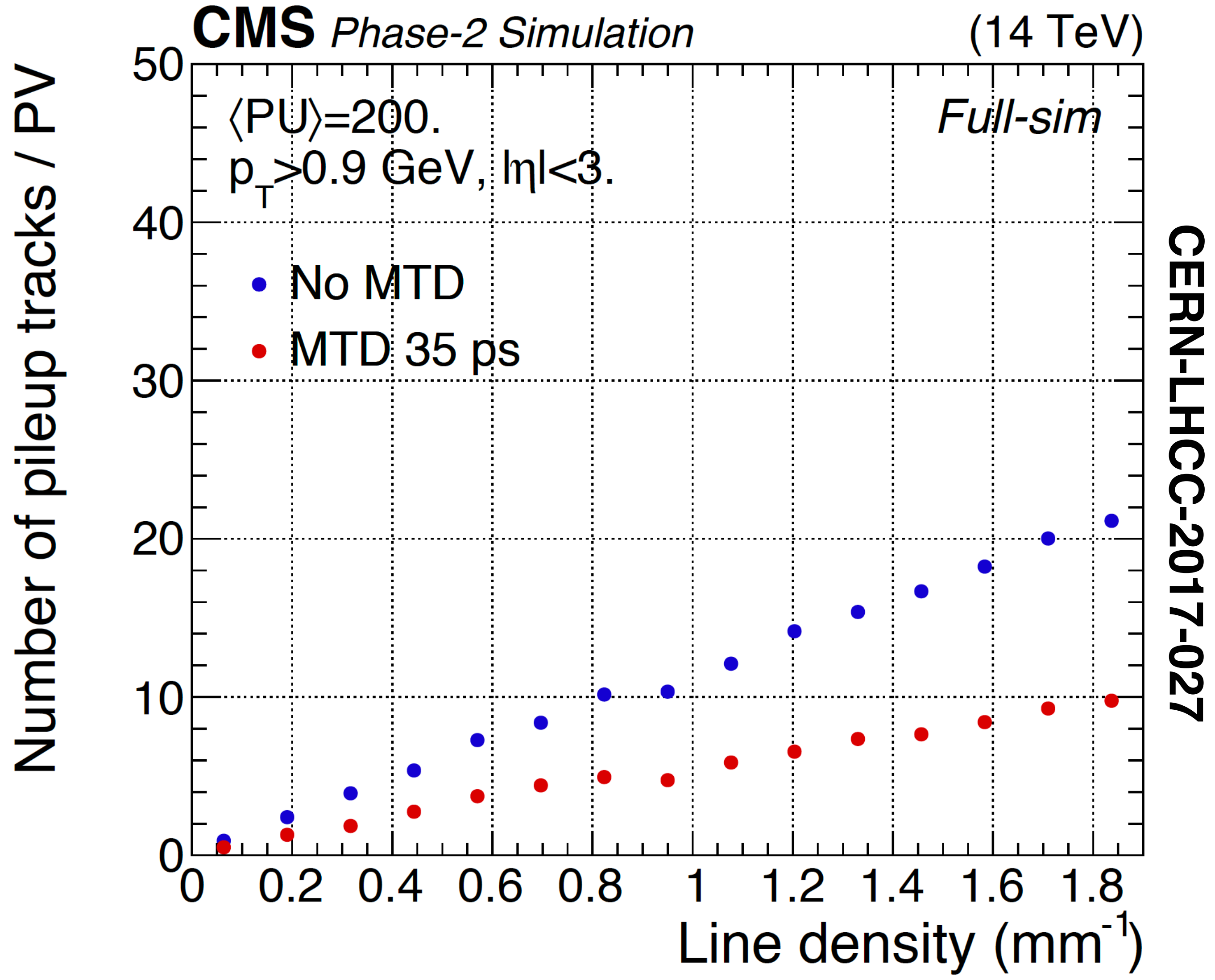
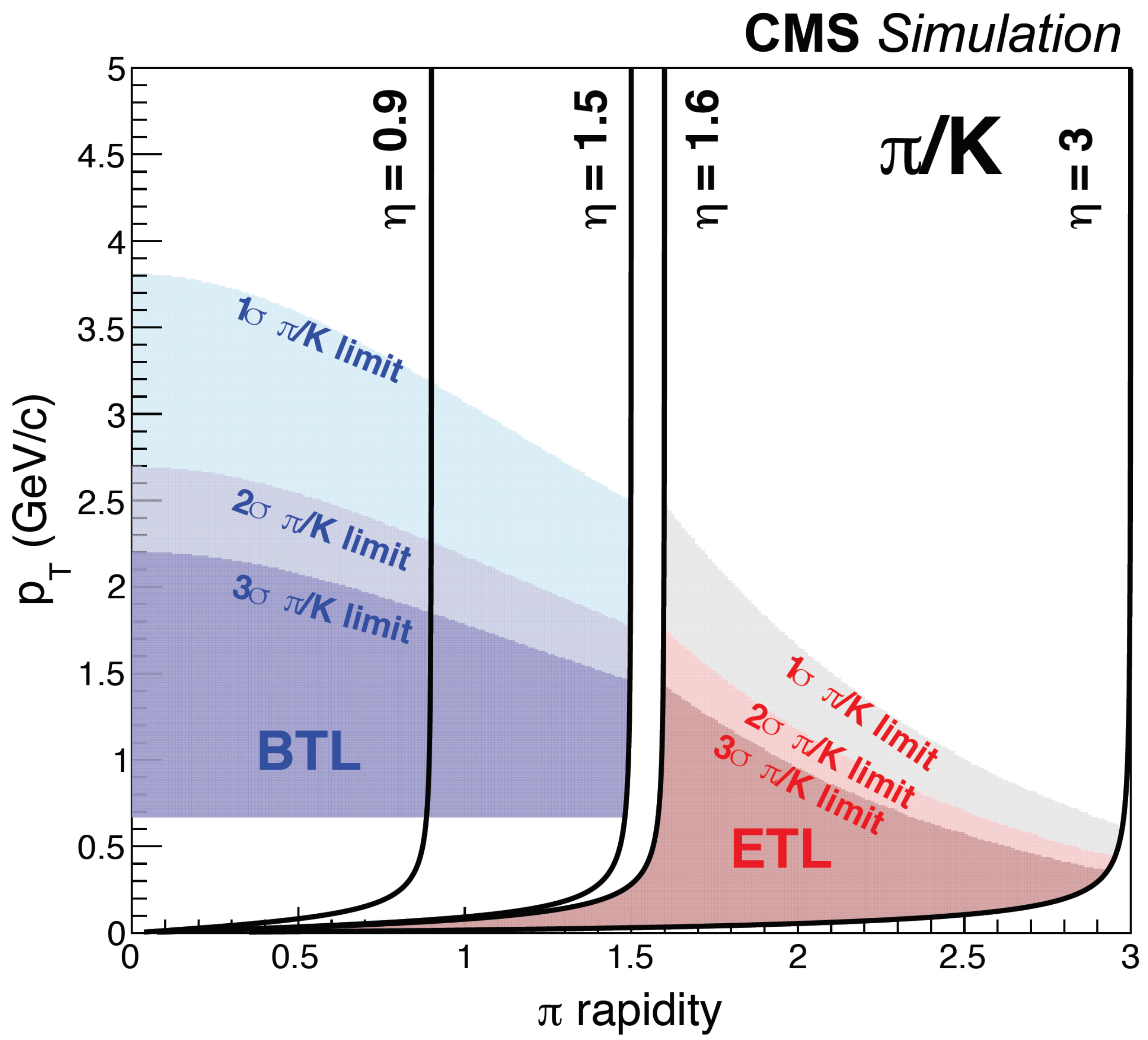
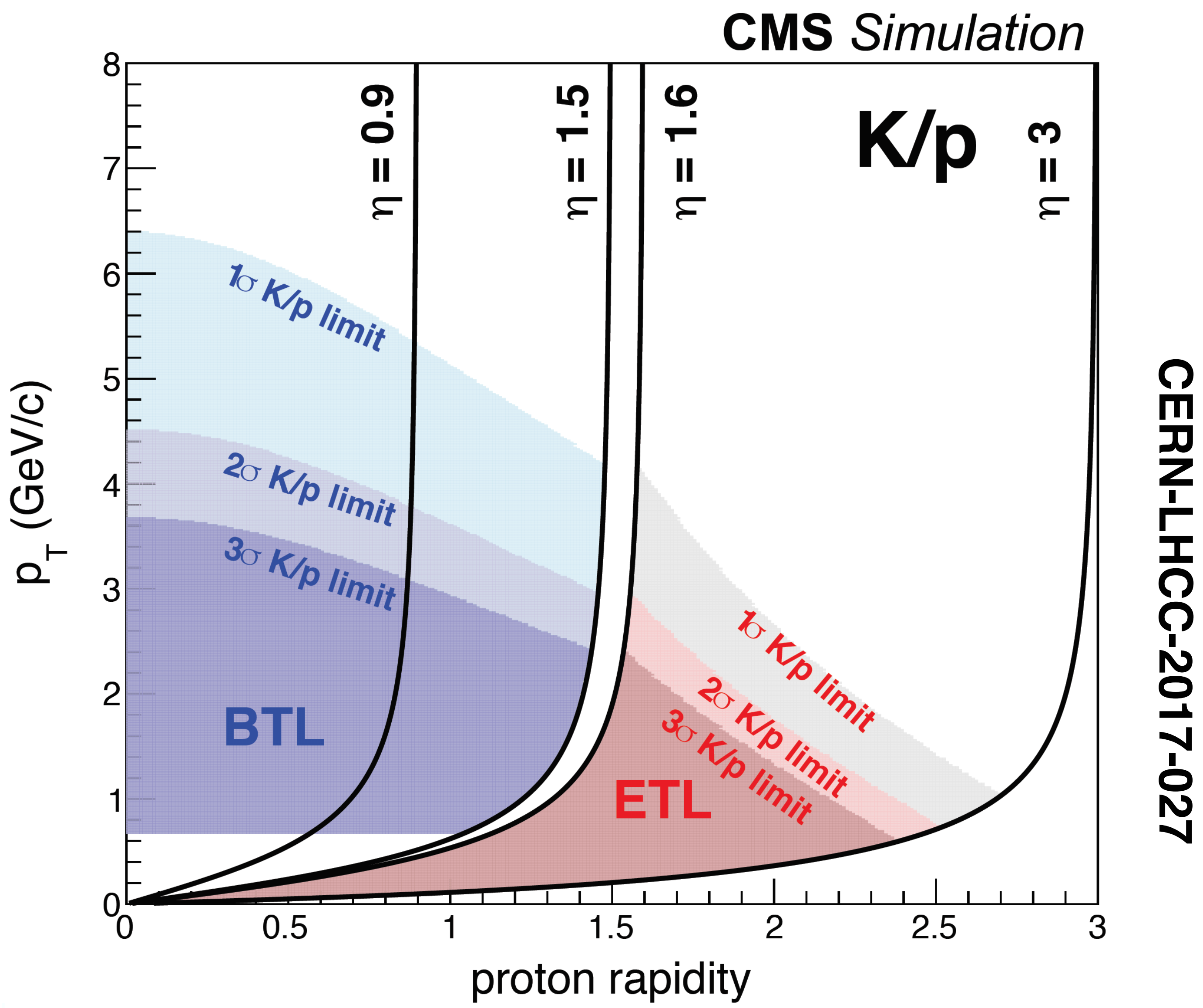
High Luminosity LHC

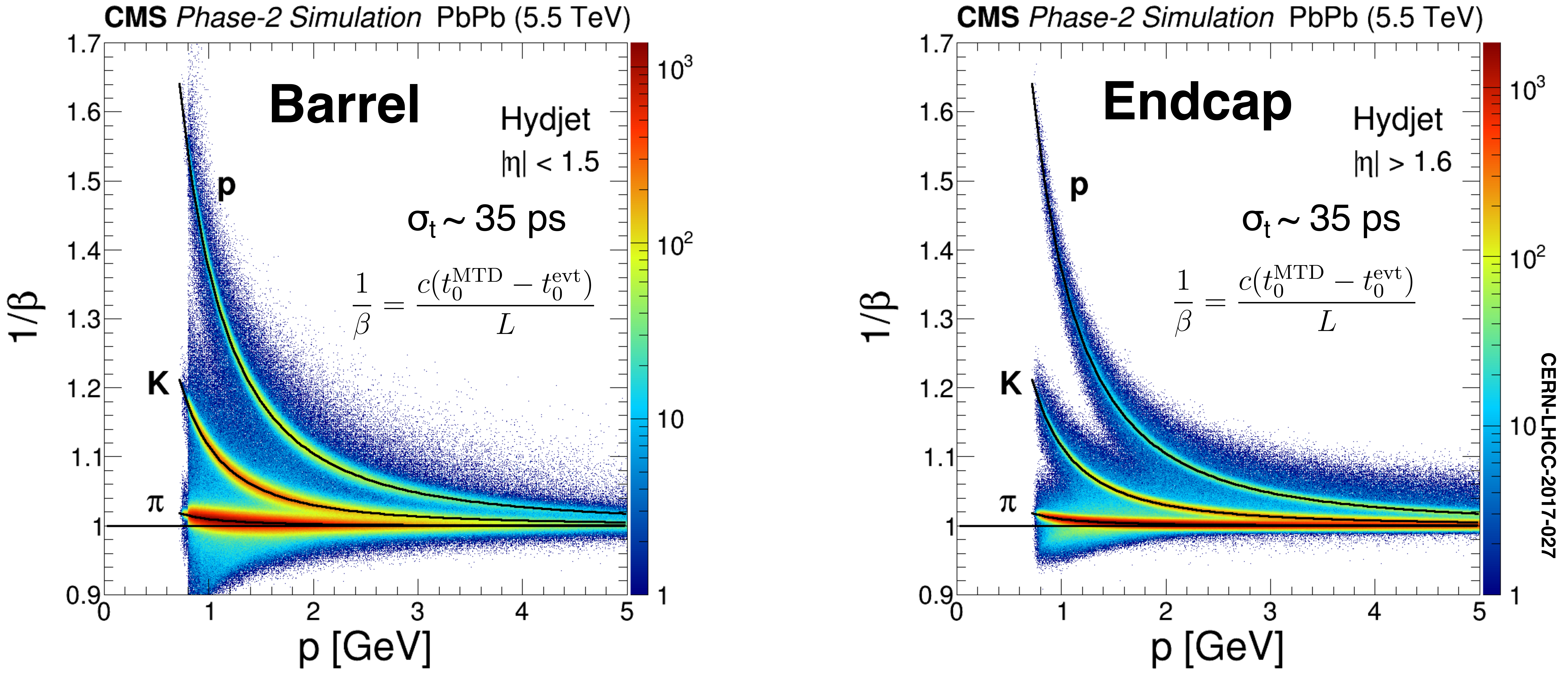
- Time compatibility for track-vertex association:
  - Suppress impact of pile-up in pp collisions.
- 4D vertex reconstruction:
  - Improved reconstruction of displaced products (B decays) or long-lived particles (BSM).
- Measurement of velocity of low p_T hadrons:
  - Particle identification via Time-of-Flight (TOF) of charged hadrons (π, K, p) down to p = 0.8 GeV.





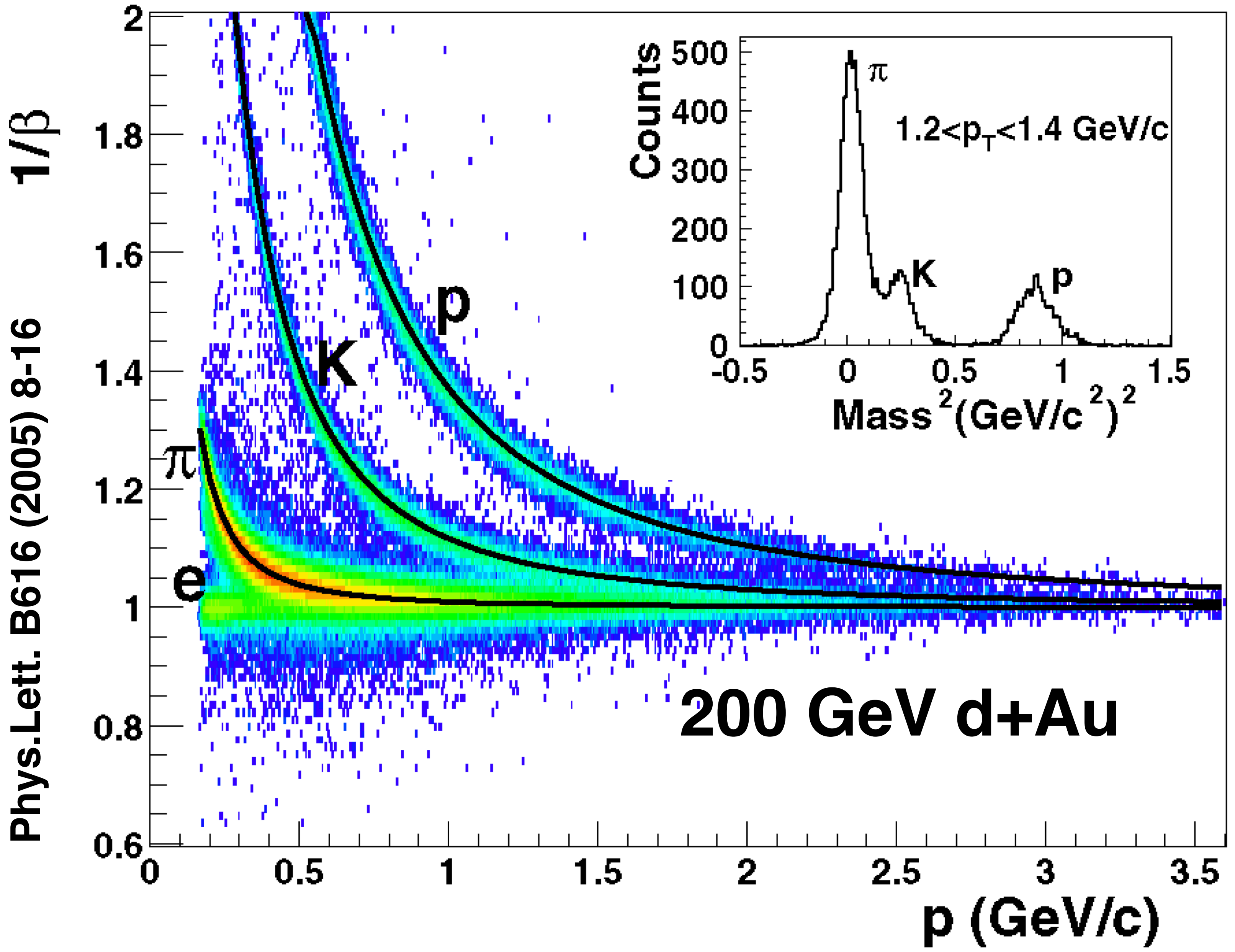


TOF-PID performance with MTD

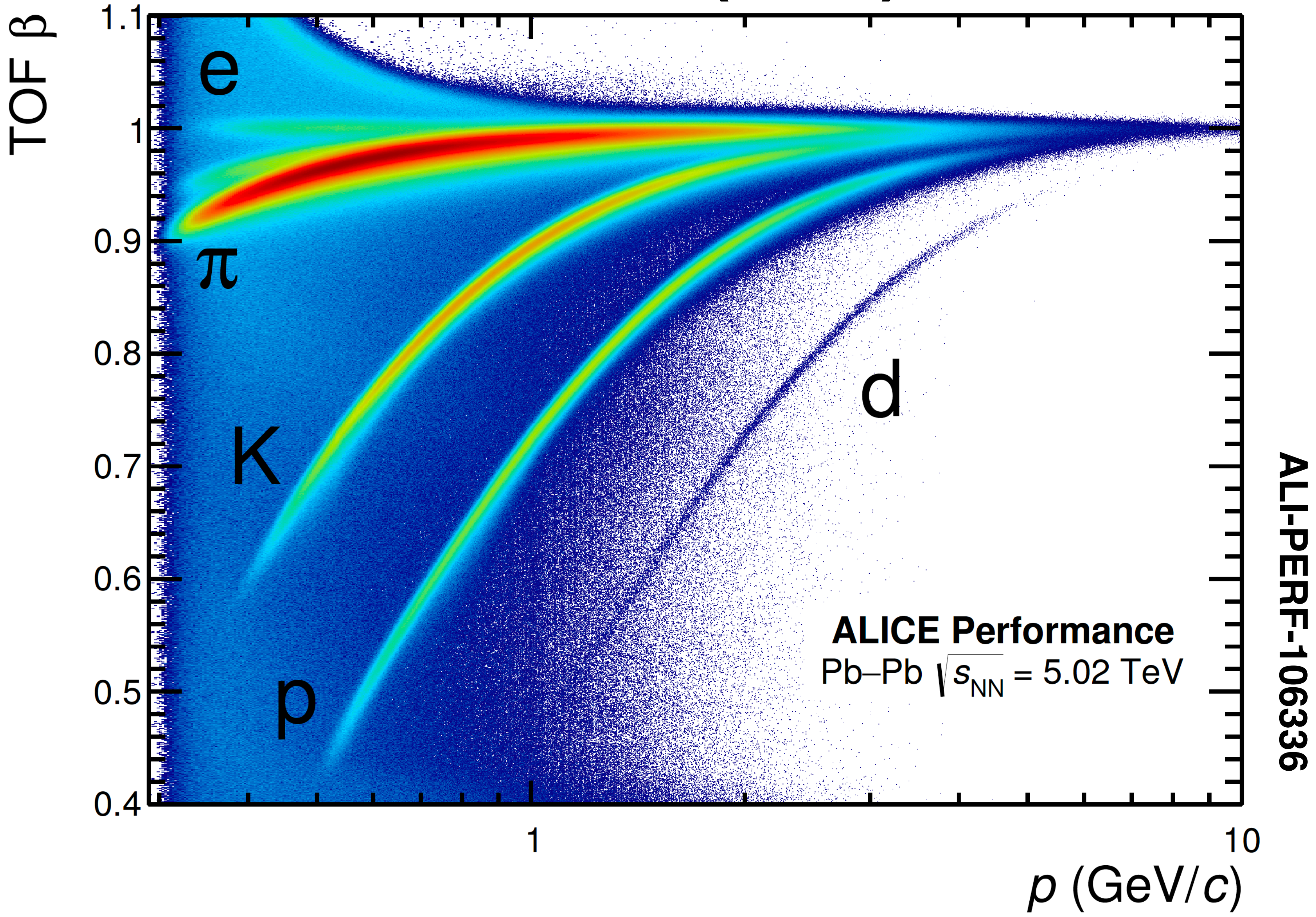


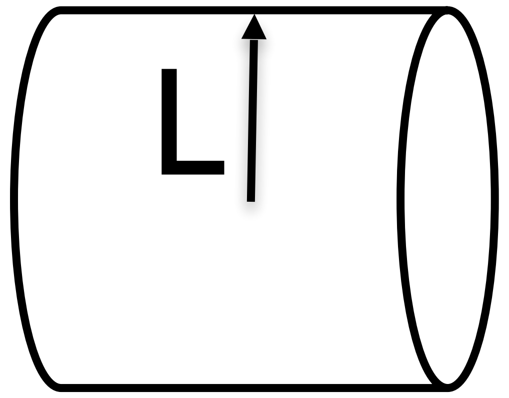
- Clear identification of π/K up to p ~ 2.5 GeV and p/K up to p ~ 5 GeV.
- Hermetic coverage over |η| < 3

STAR (RHIC)



ALICE (LHC)





Experiment	η coverage	L at $\eta = 0$ (m)	σ_T (ps)	L/σ_T ($\times 100$)
CMS	$\lvert\eta\rvert < 3.0$	1.16	30	3.9
ALICE	$\lvert\eta\rvert < 0.9$	3.7	56	6.6
STAR	$\lvert\eta\rvert < 0.9$	2.2	80	2.2

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- Competitive momentum coverage compared to ALICE and STAR
- **Unique wider rapidity coverage**

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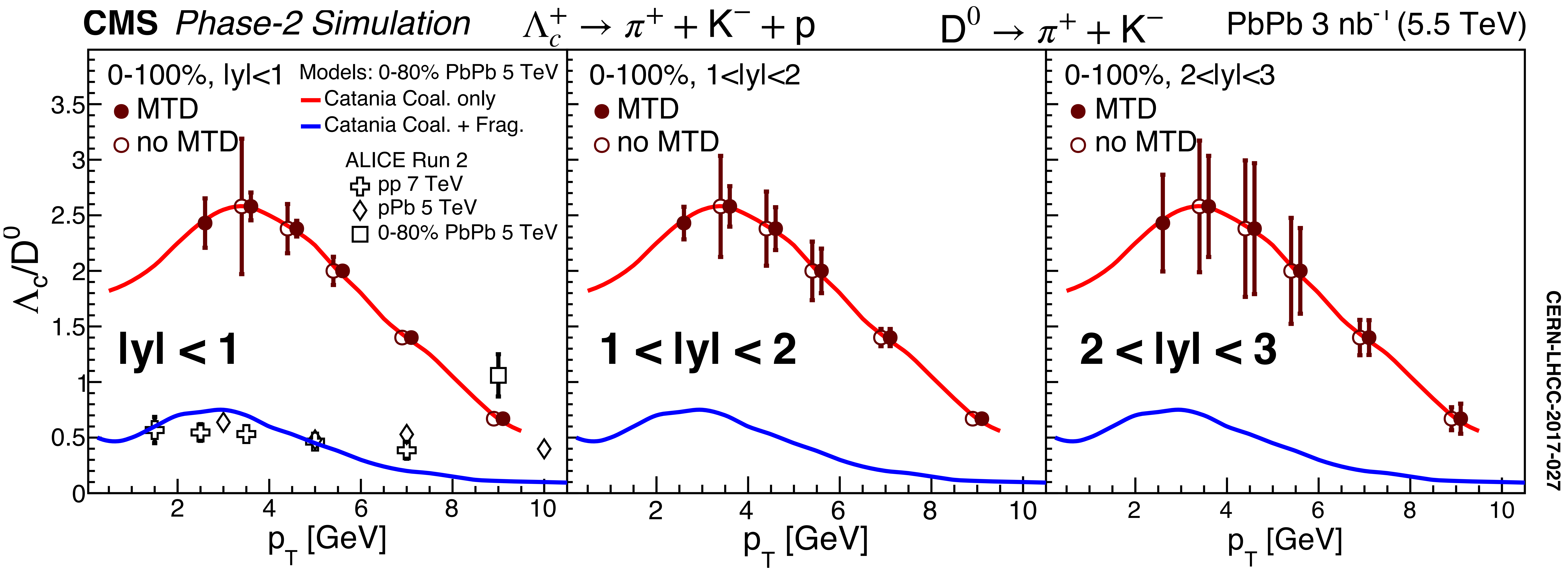
High Luminosity LHC

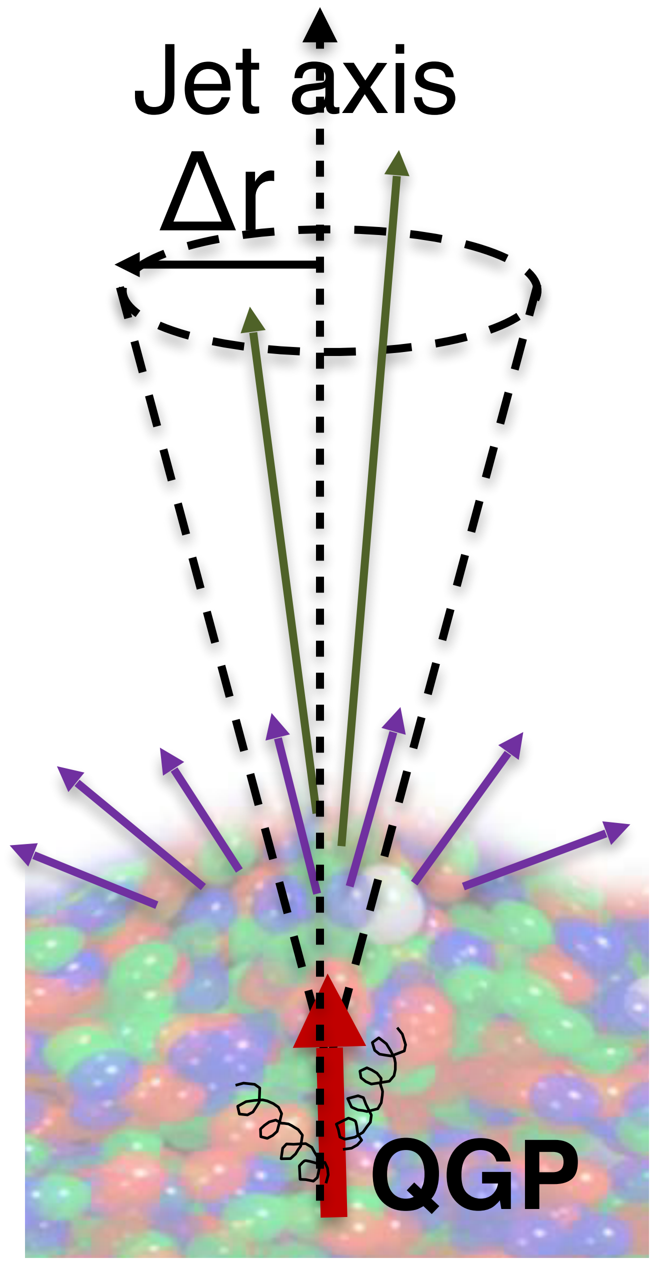
Heavy quark dynamics in QGP



- CMS will be able to study c- and b-hadrons over 6 units of rapidity (|η| < 3) with MTD.
- Measurements of the production yield and correlation will constrain the 3D HF dynamics in QGP.

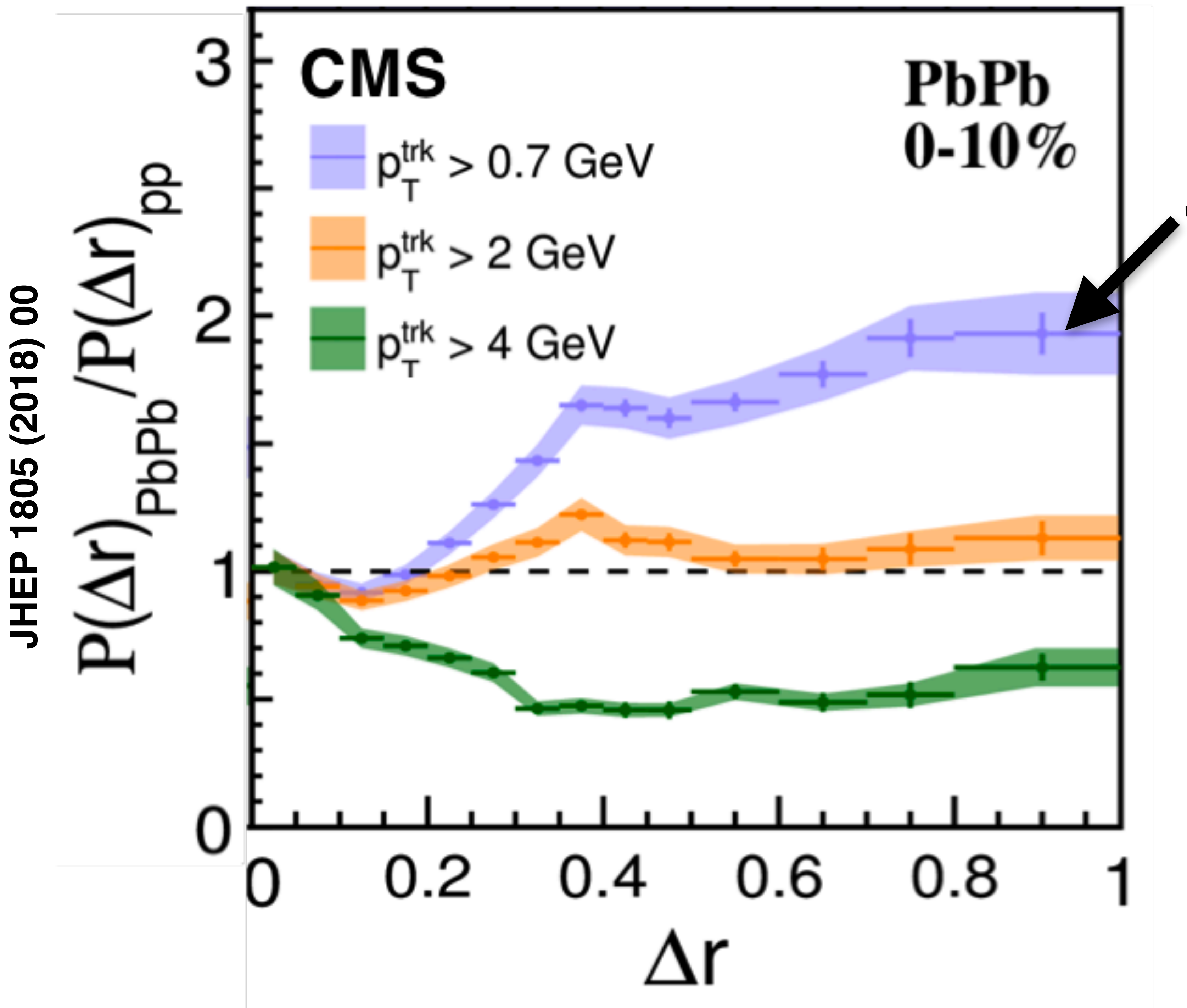
QGP response to parton energy loss

Radial momentum distribution

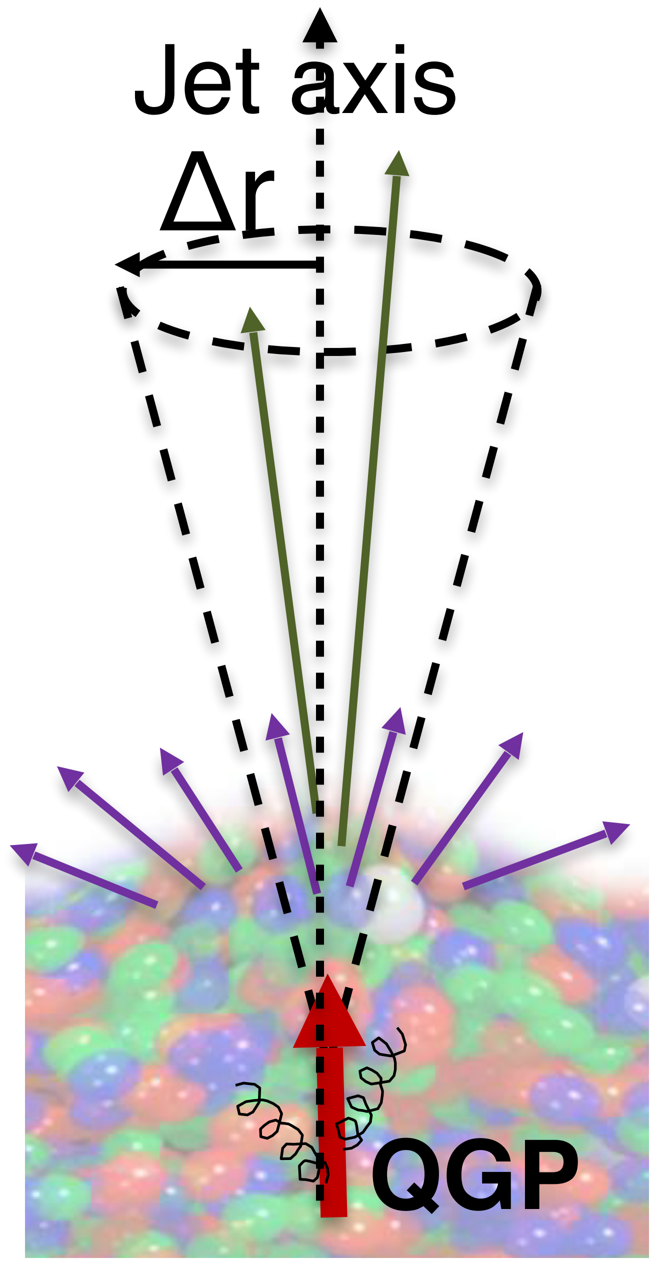


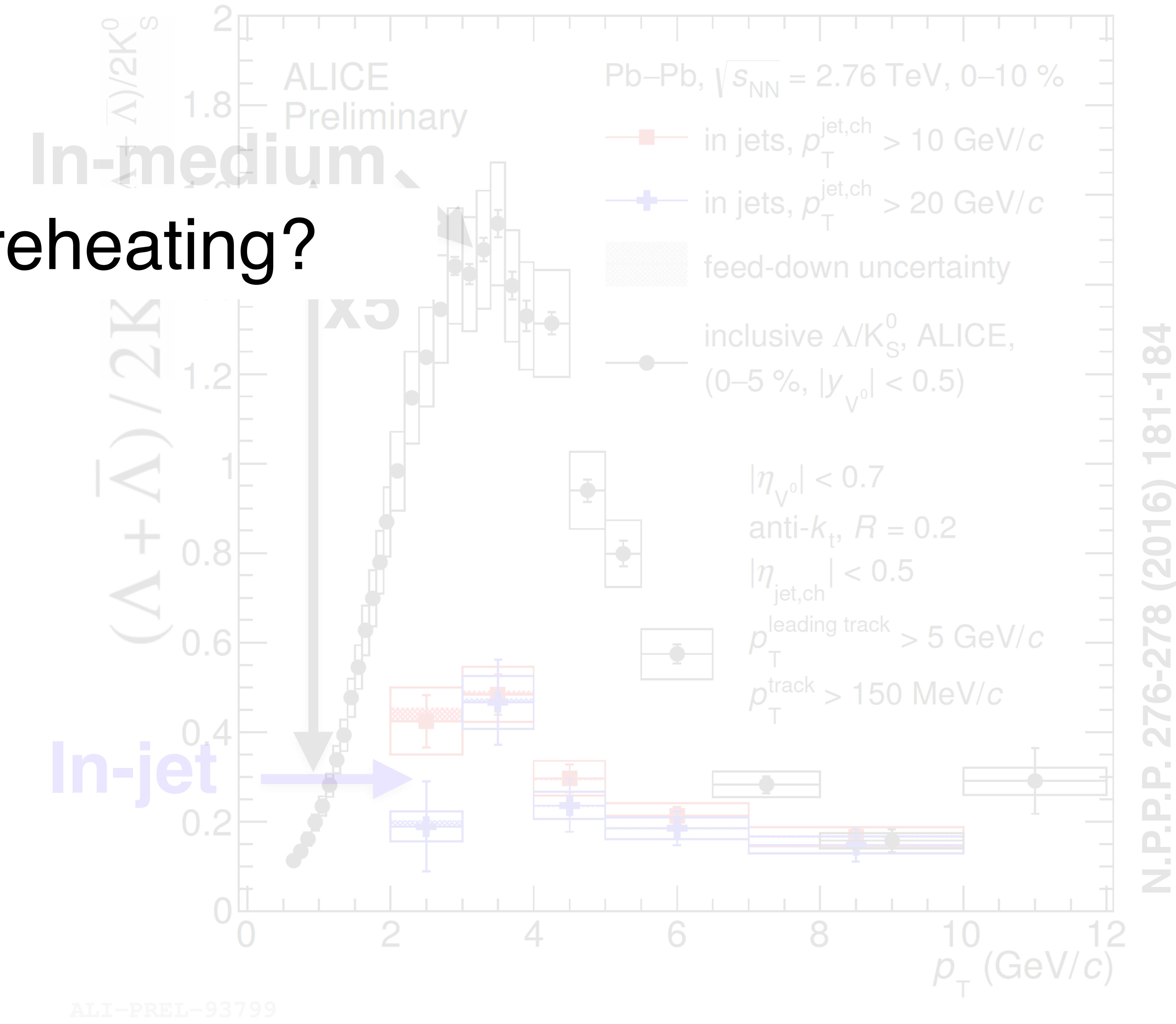
- CMS HL upgrades + MTD provides a unique opportunity to measure baryon-to-meson ratios differential in jet radii, distinguishing between QGP medium effects and jet fragments.

Radial momentum distribution



Jet fragmentation or medium reheating?





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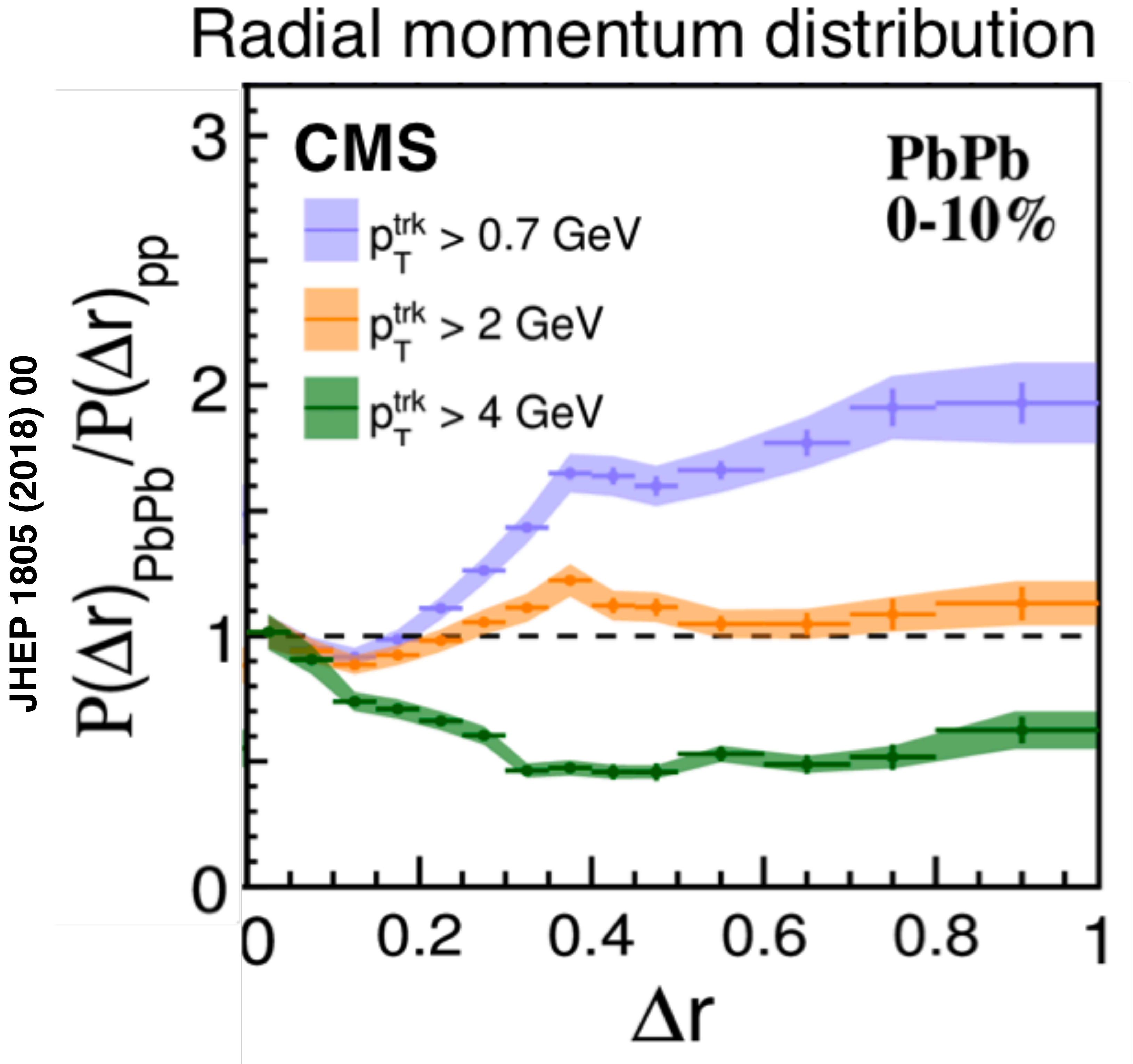

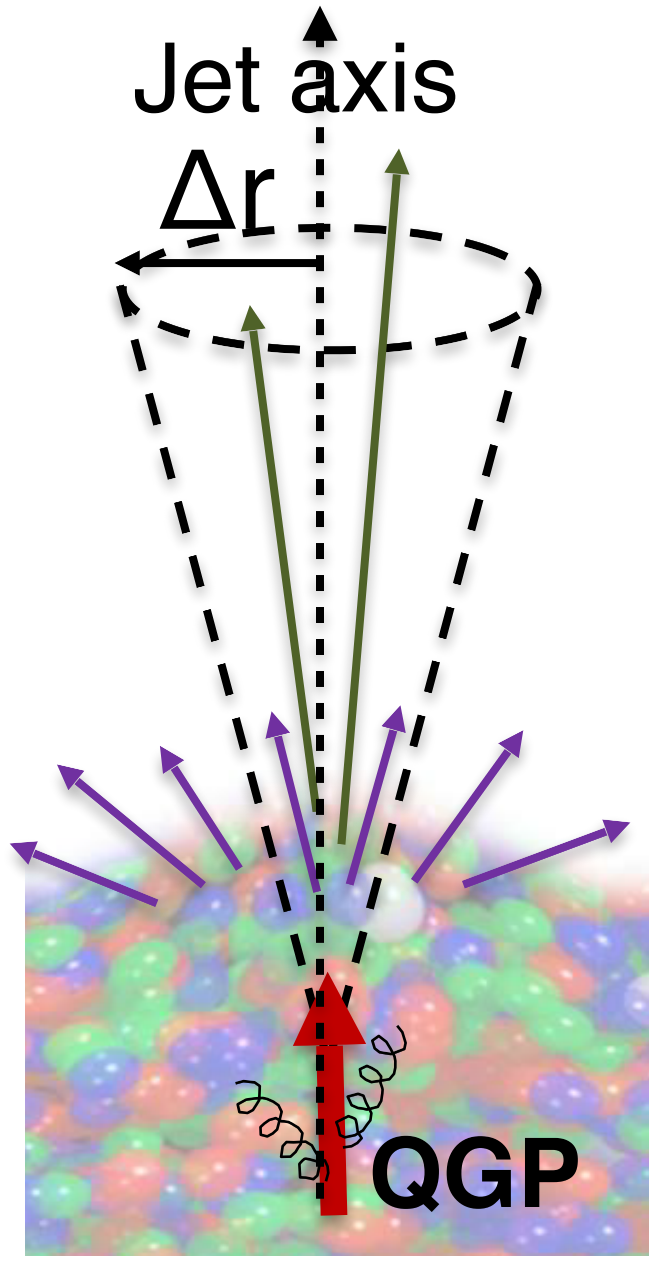

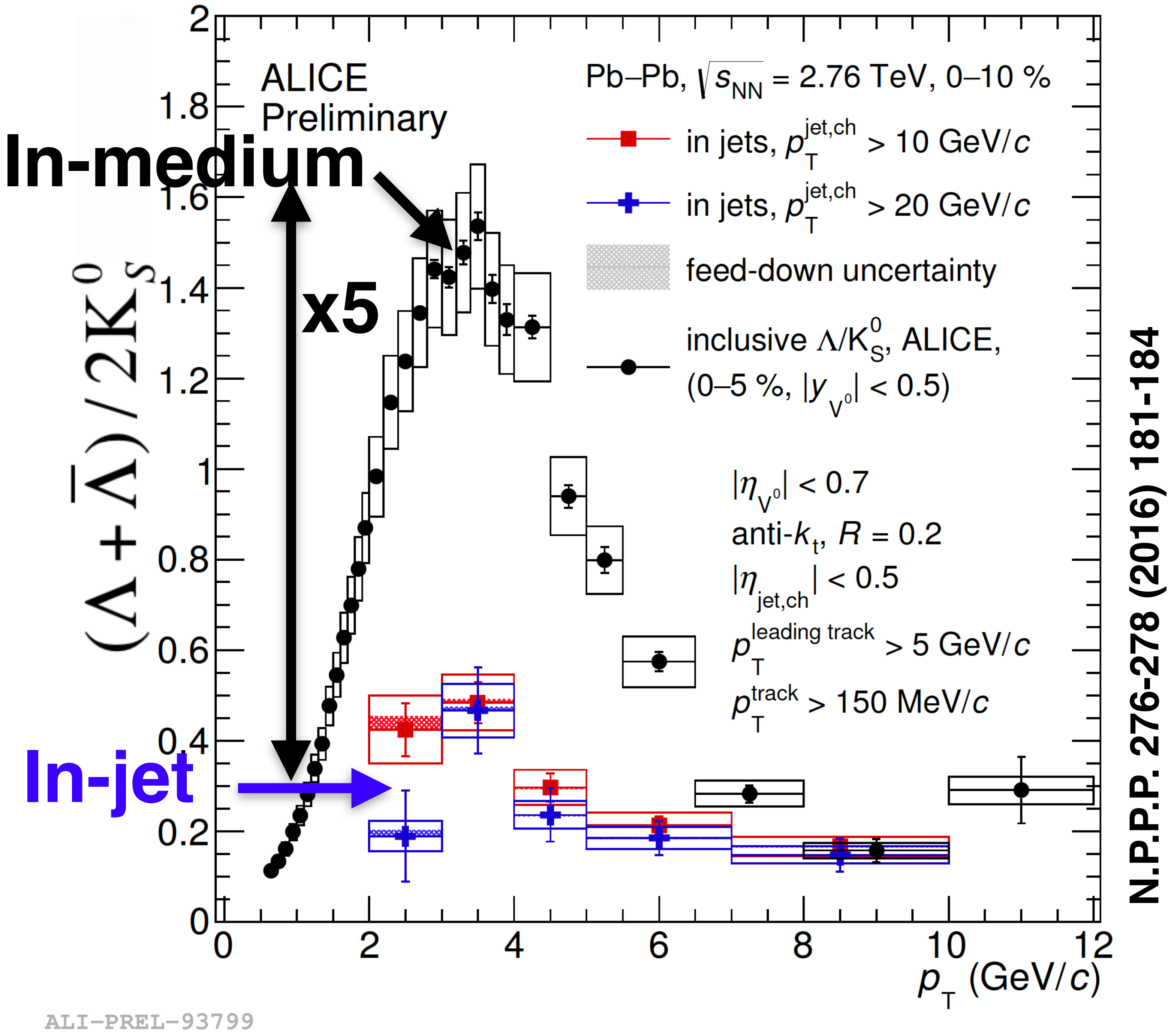

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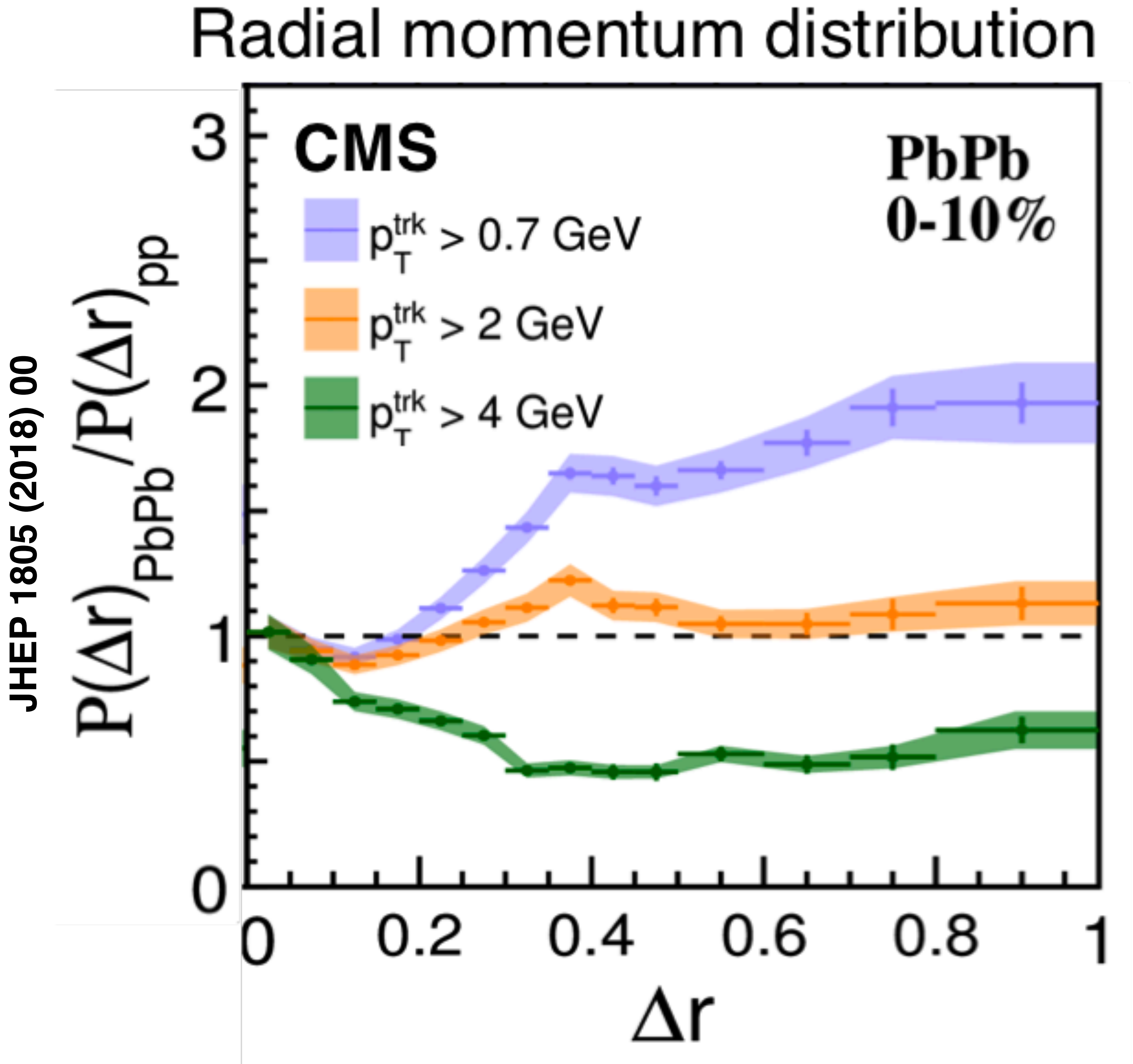

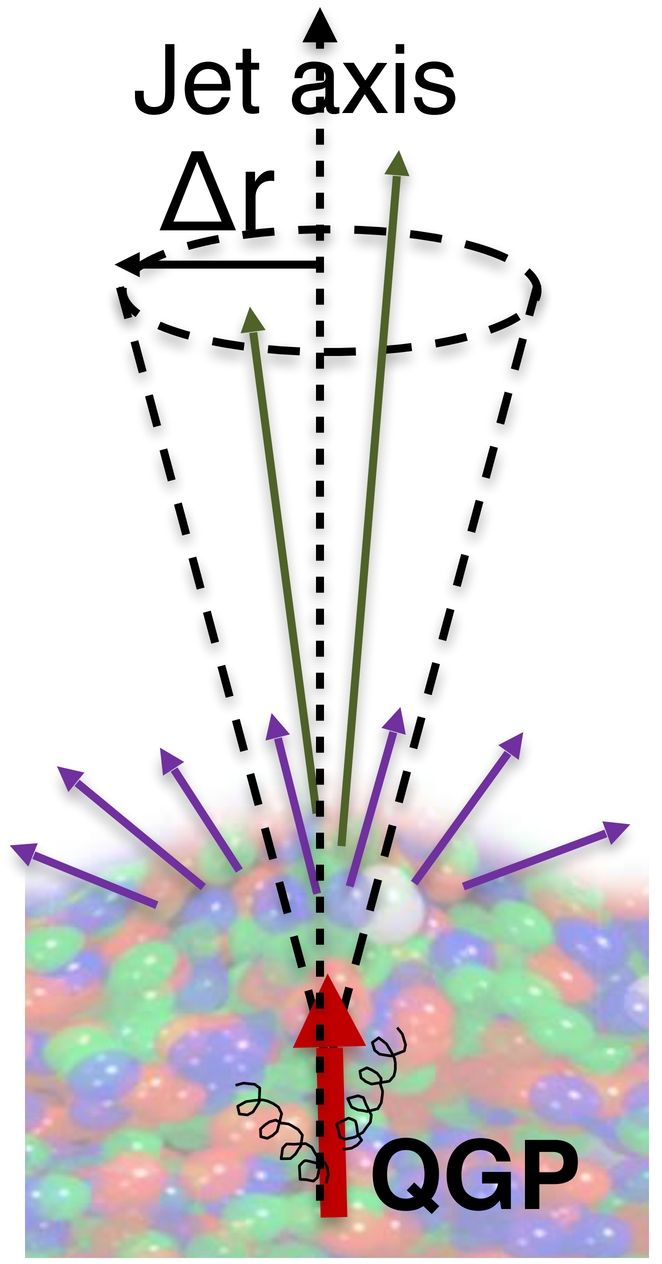

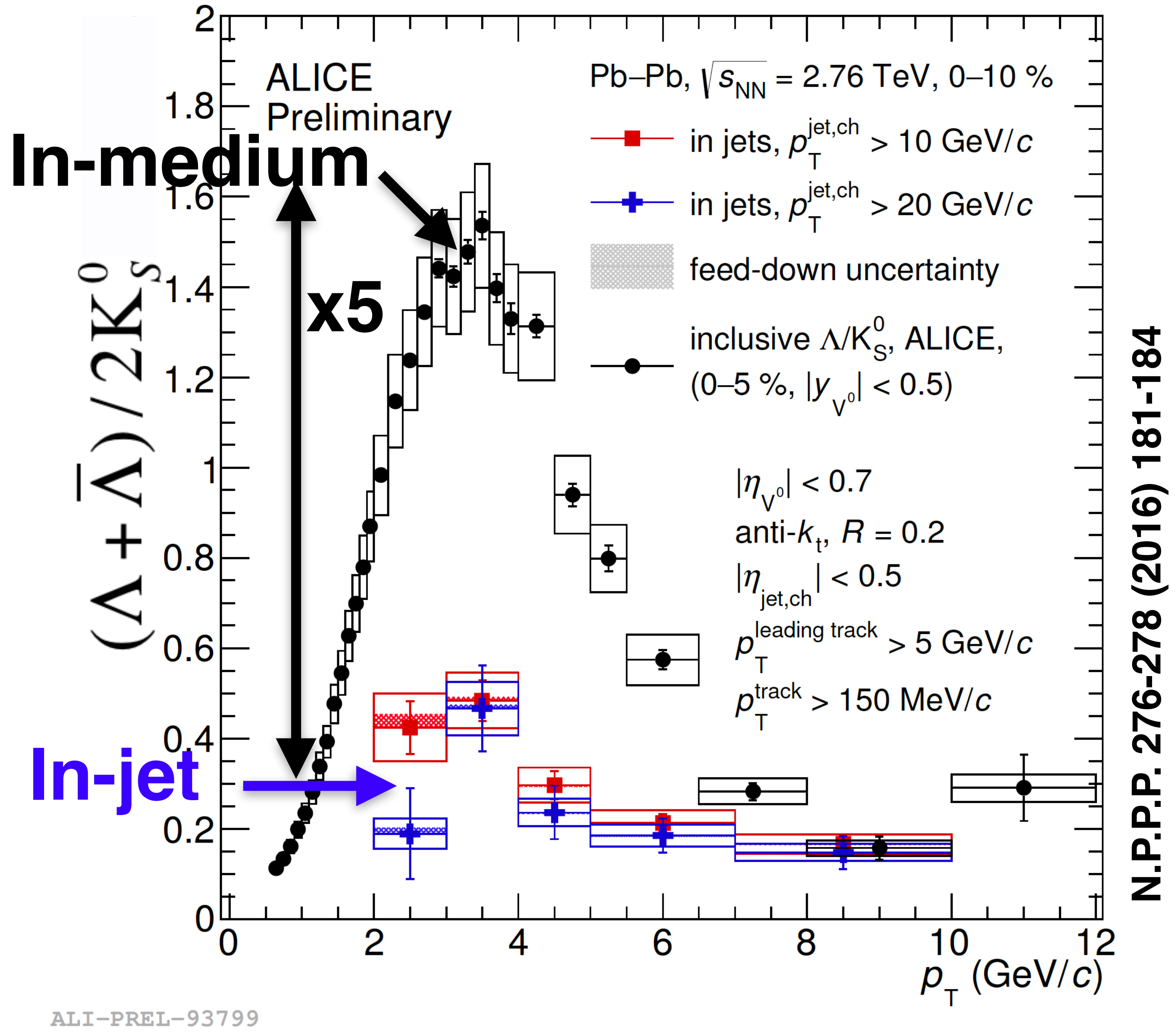

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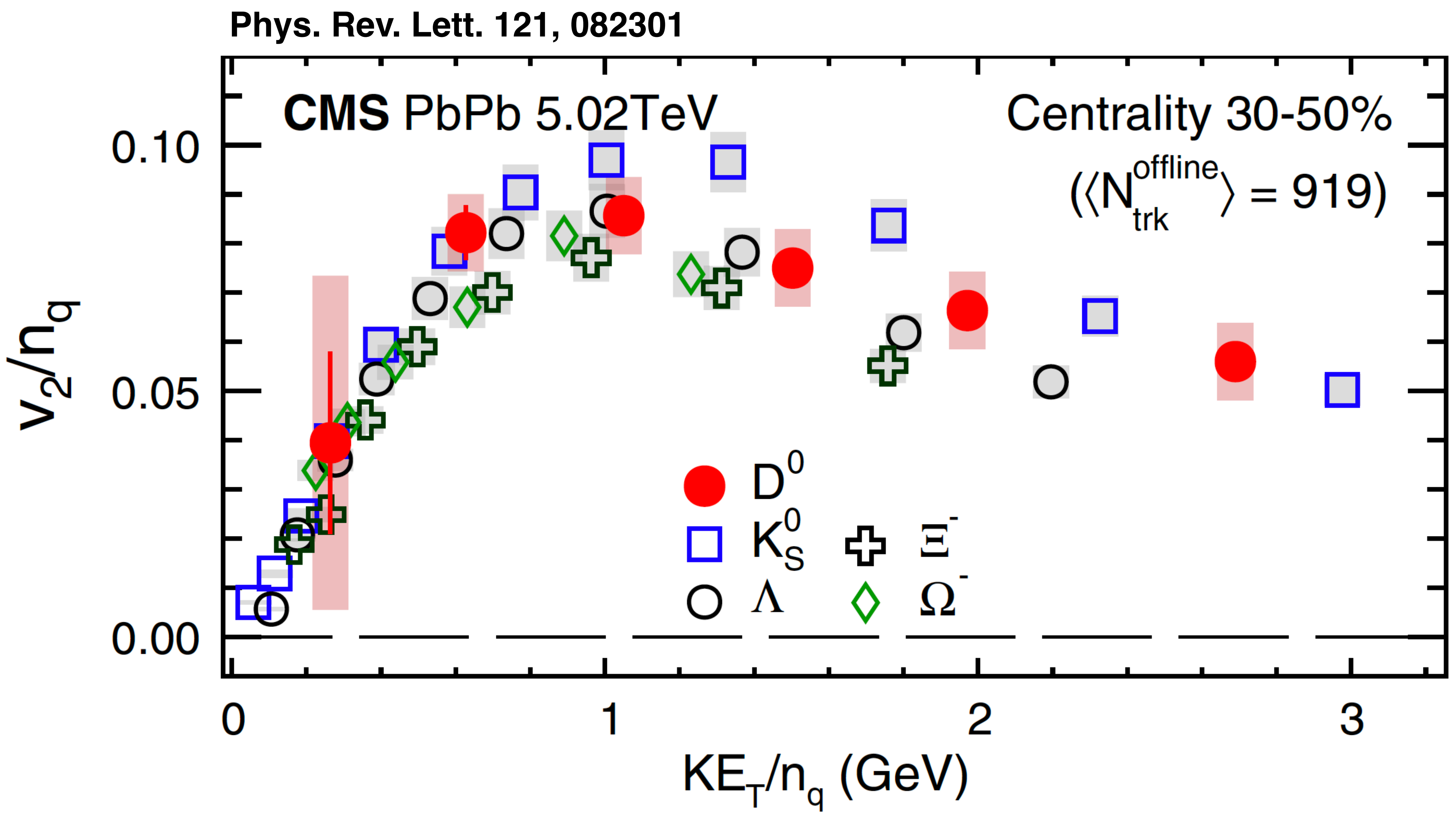
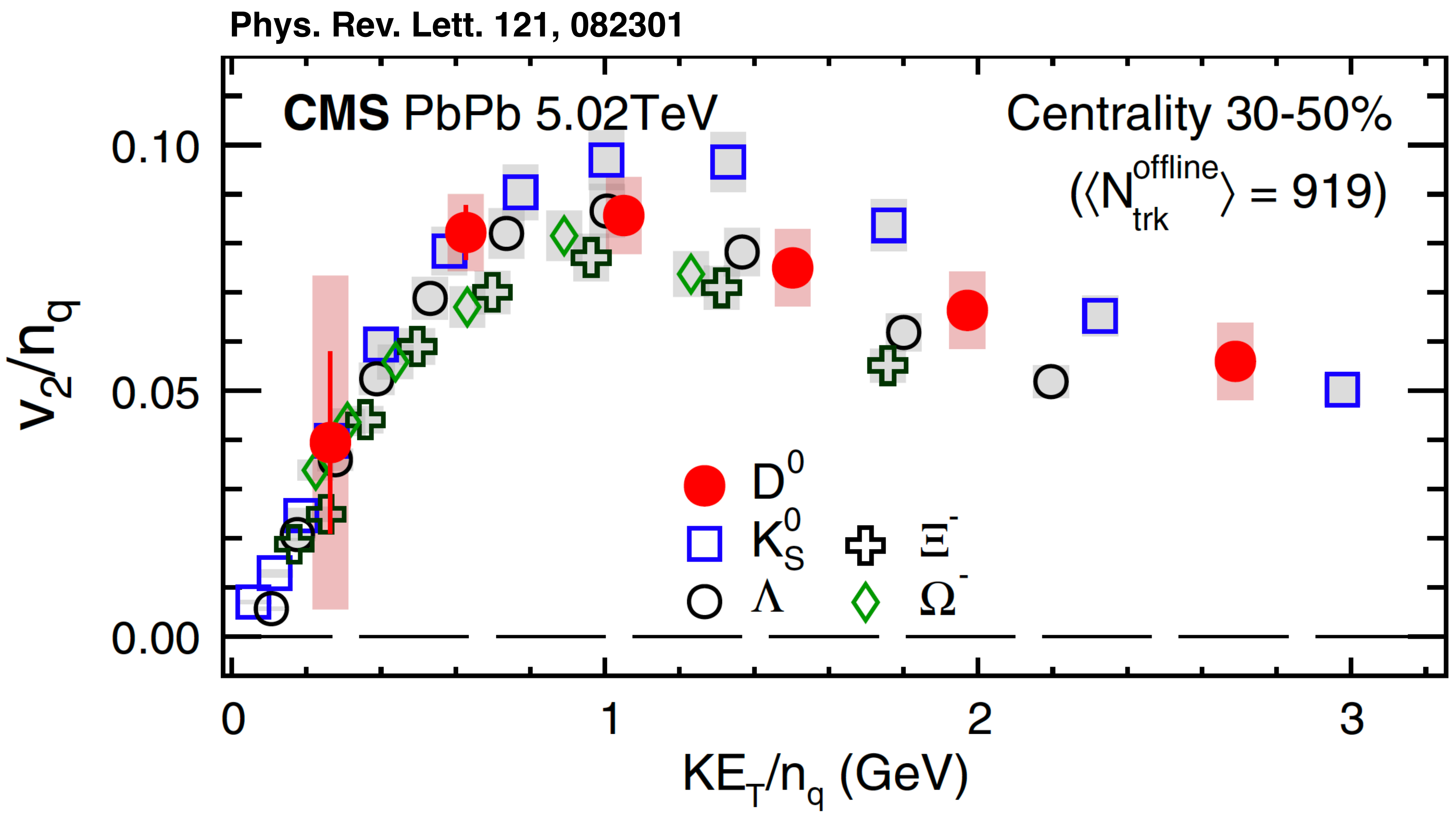
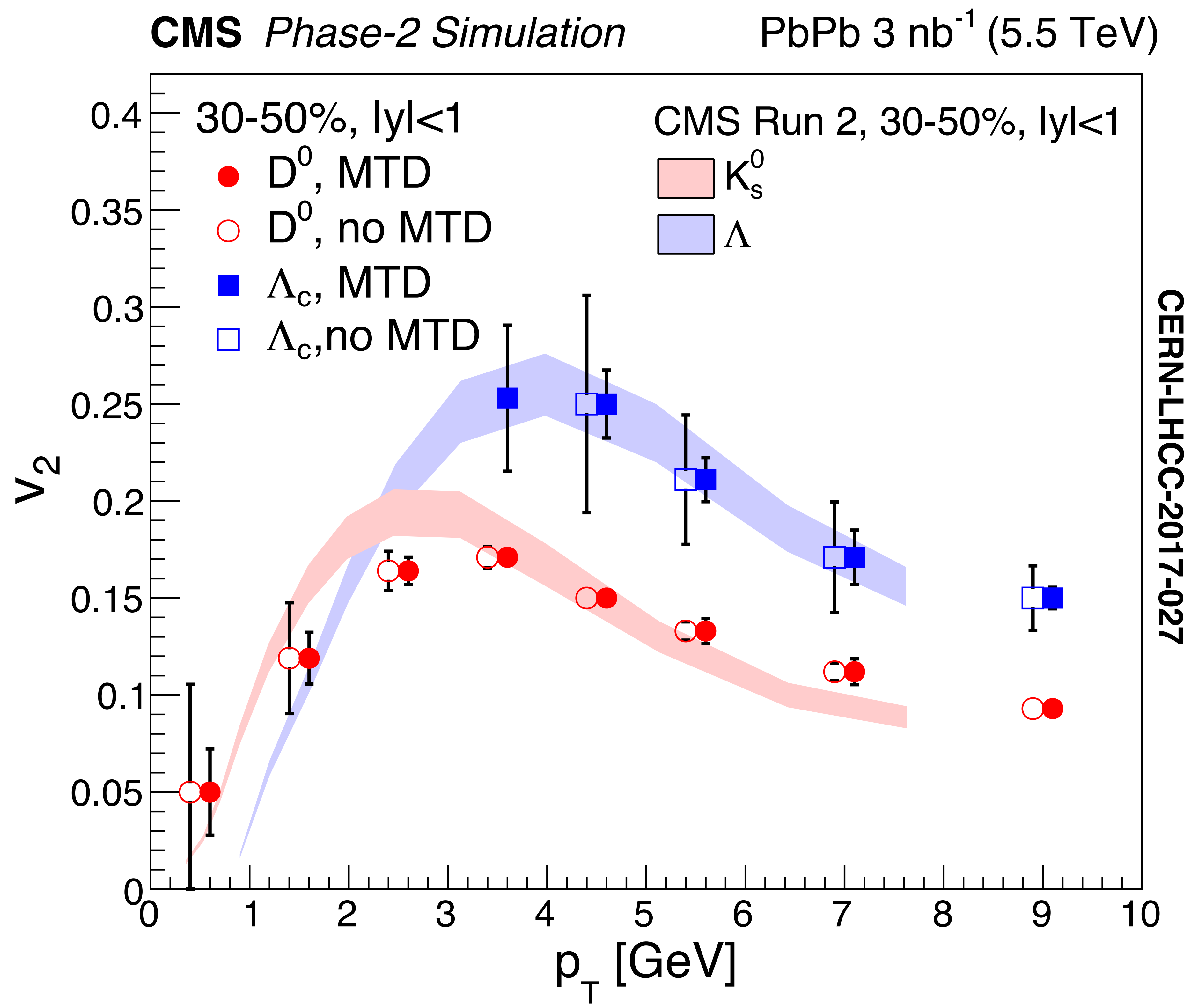
Universal scaling of elliptic flow



- MTD will allow to derive the v_2 of charm baryons and to measure precisely the N_q-scaling of v_2 in the charm quark sector:

$$v_2(\Lambda_c) = \frac{3}{2} v_2(D_0)?$$





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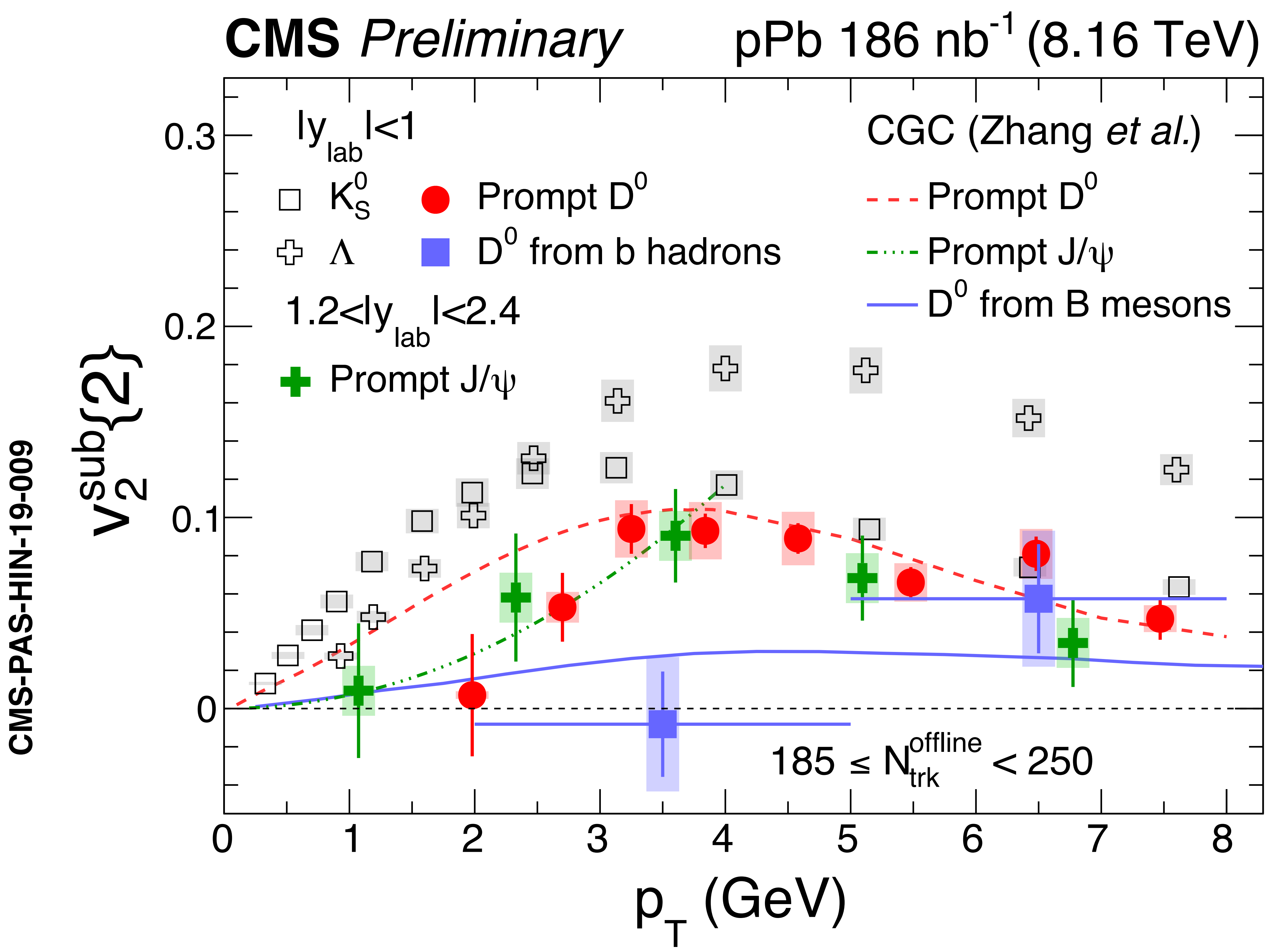
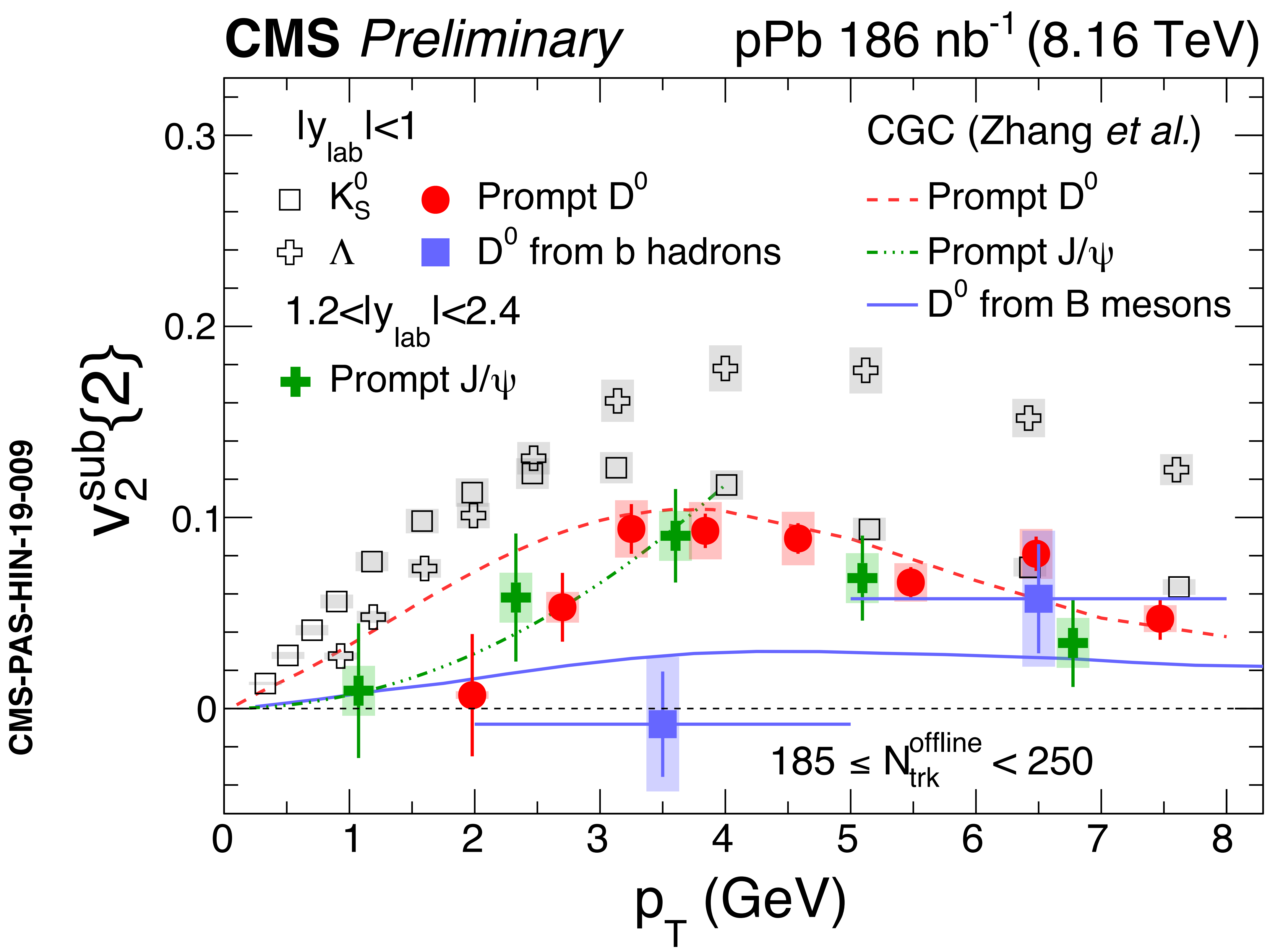
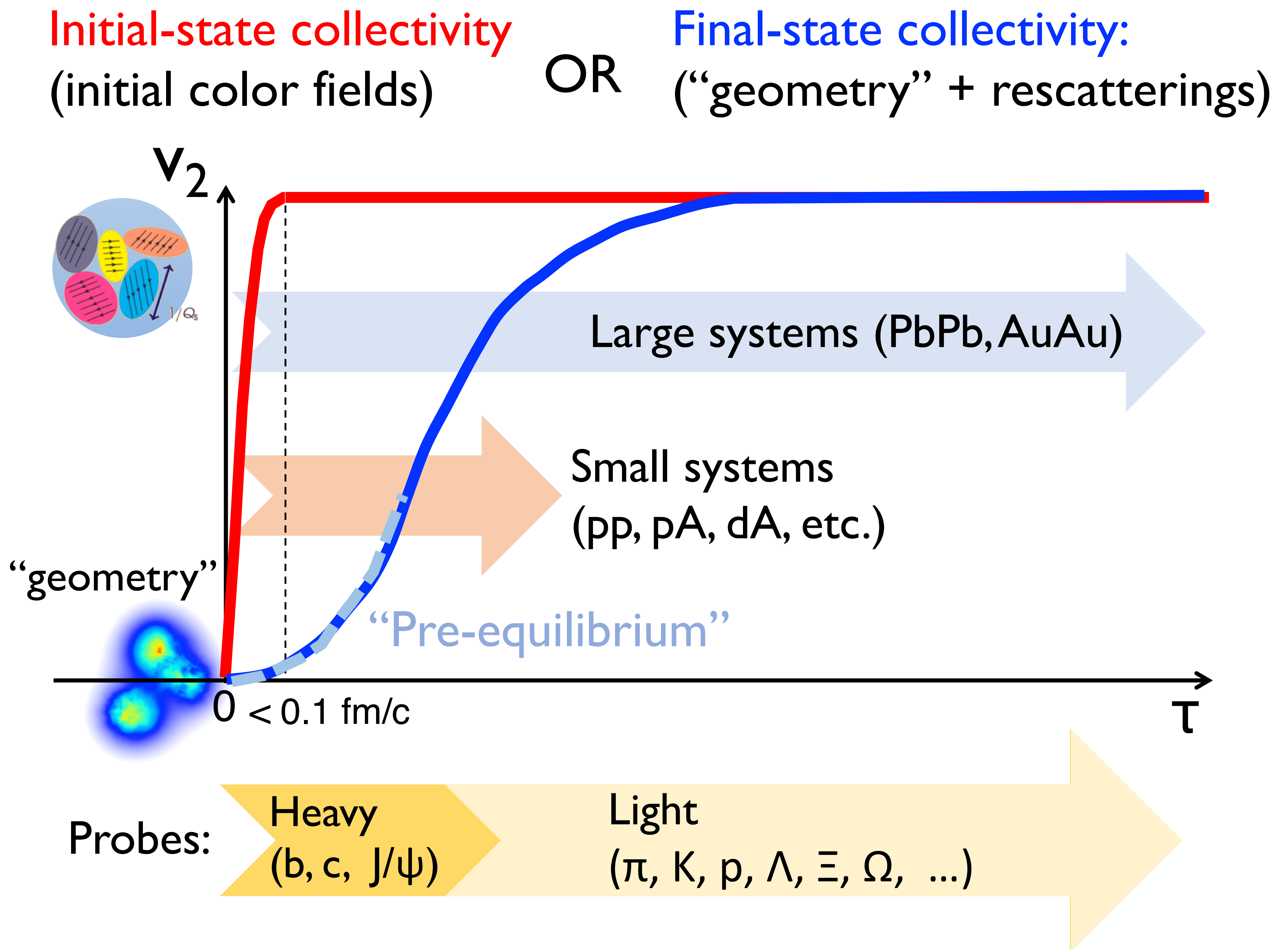
Origin of collectivity in small systems



- Collect more data by triggering on high MIP-multiplicity with MTD.
- Reduce the HF background using TOF-PID, allowing to measure v_2 down to very low p_T for a variety of HF hadrons in small systems.





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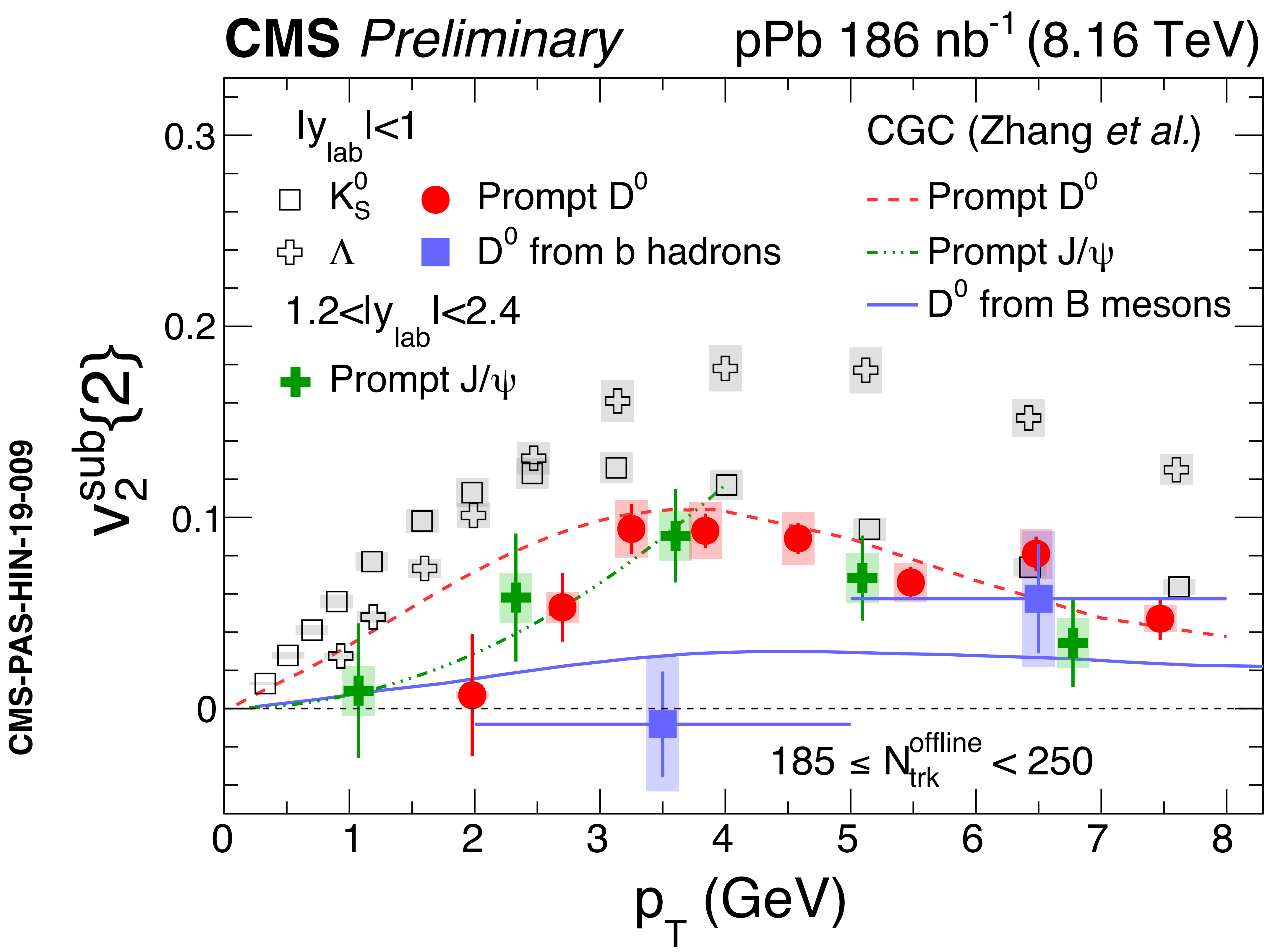

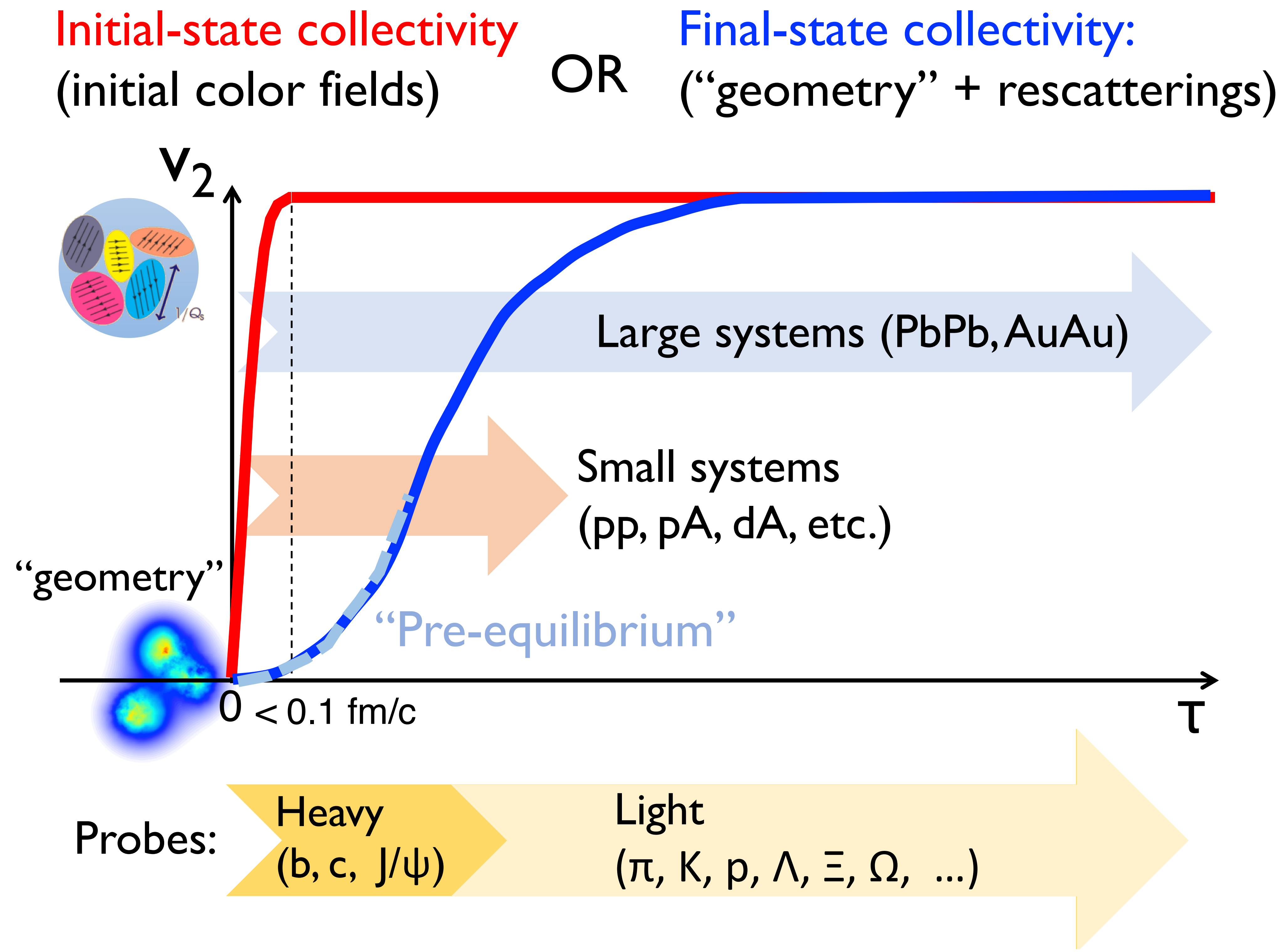

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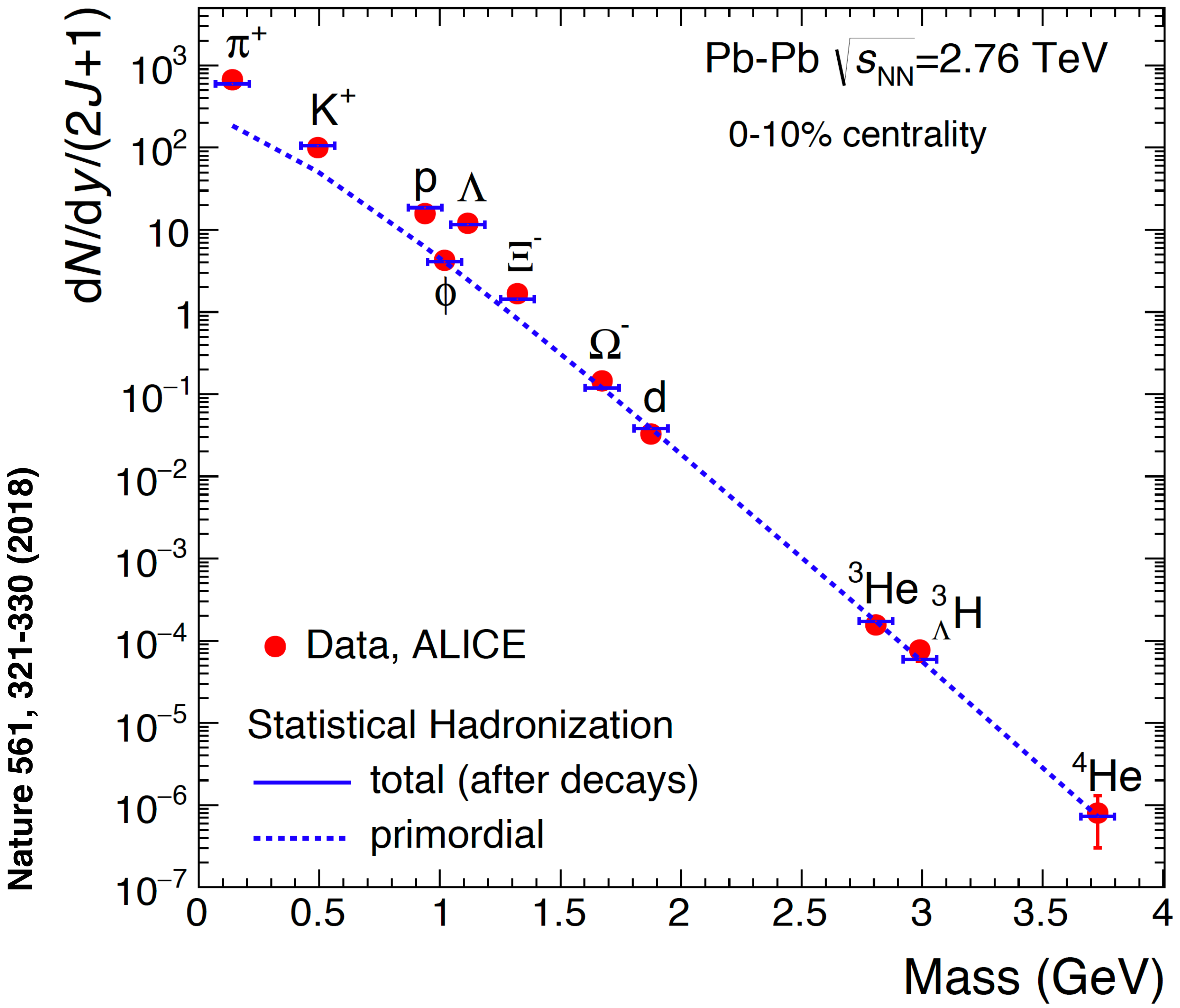
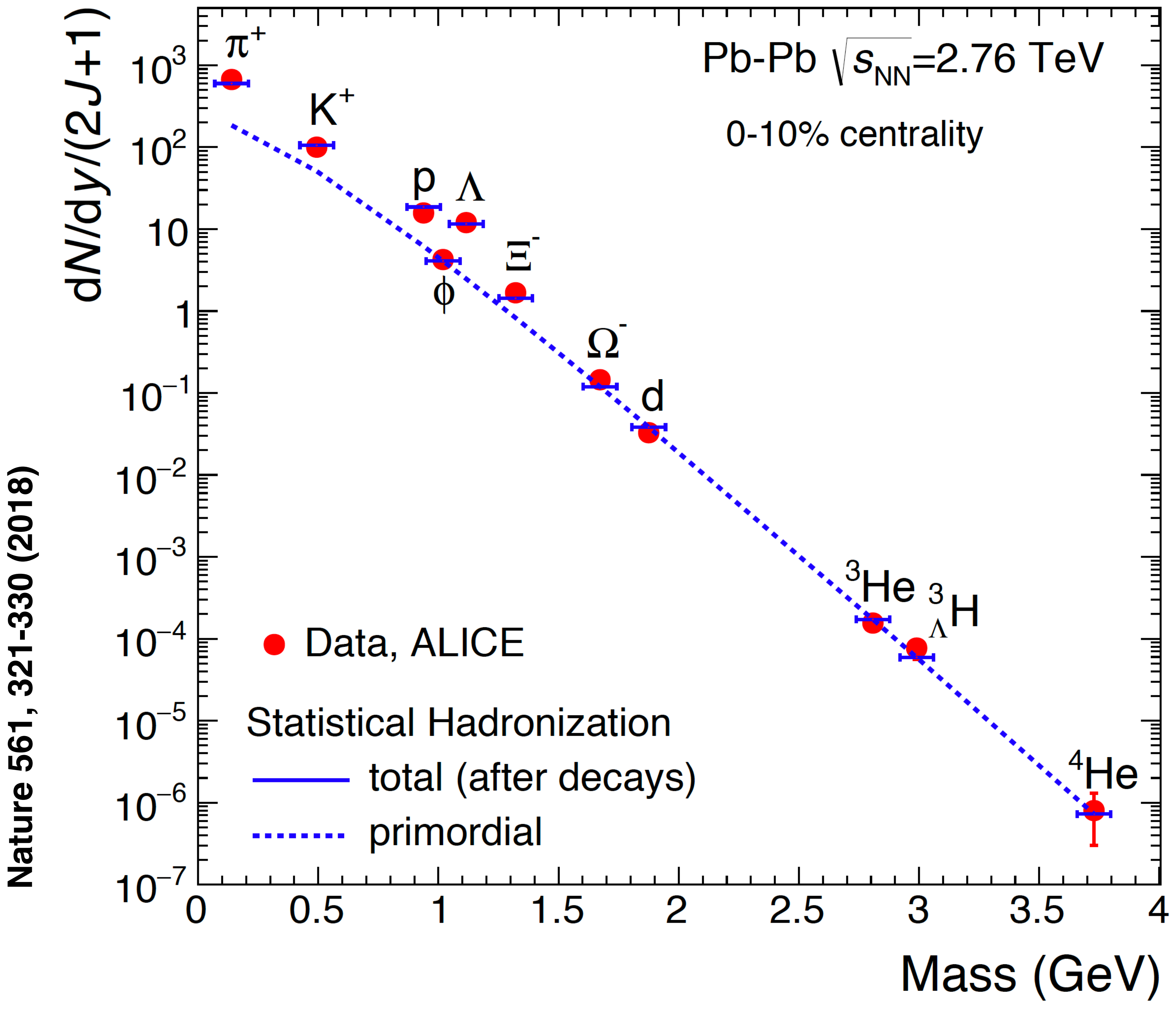
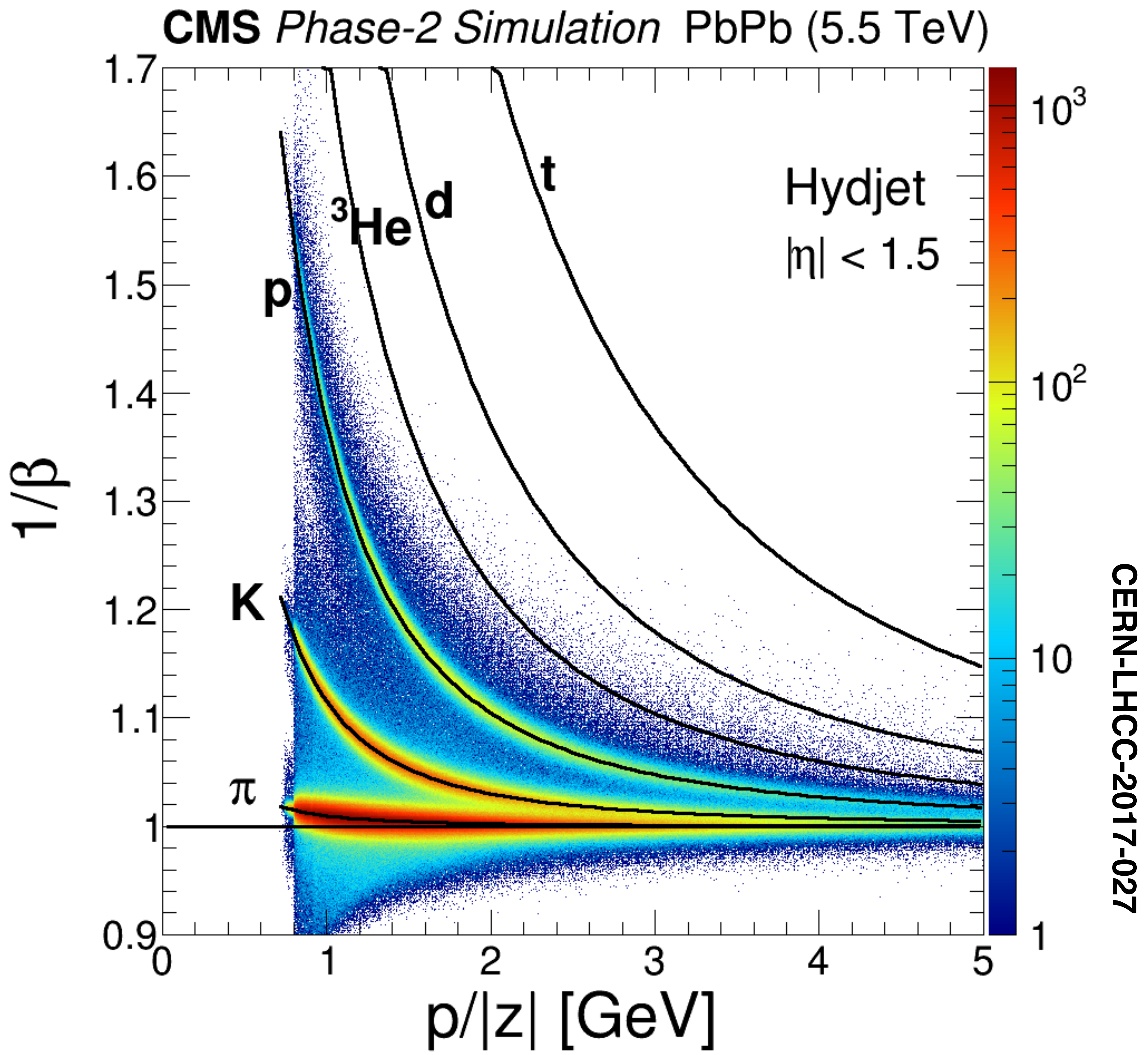


- Light (d, ^{3}He, t) and hyper ($^3_\Lambda$He, $^3_\Lambda$H) nuclei can be identified over a wide kinematic range via TOF using MTD.
- Also provide insights for dark matter searches and astrophysics.

Light (hyper-) nuclei production





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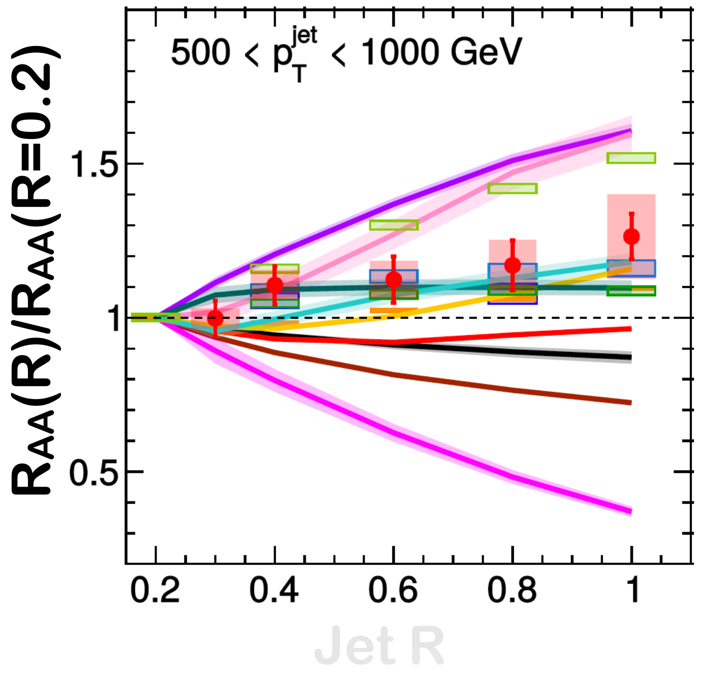
  - First measurement of jet R_{AA} up to R=1.0.
  - Jet R_{AA} vs jet radius constrain jet quenching models.



- **Heavy-flavour production**
  - Λ_c/D_0 ratio in pp consistent with PYTHIA + CR.
  - Similar Λ_c/D_0 results in pp and PbPb.
  - Hint of X(3872) to ψ(2S) ratio enhancement in PbPb.

- **Heavy-flavour collectivity in large systems**
  - $\Delta v_2(D^0\text{-}\overline{D}^0)$ compatible with charged hadron calculations.
  - Bottomonium elliptic flow $v_2(\Upsilon(nS)) \sim 0$.

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  - Large collectivity of prompt J/ψ and D^0 mesons.
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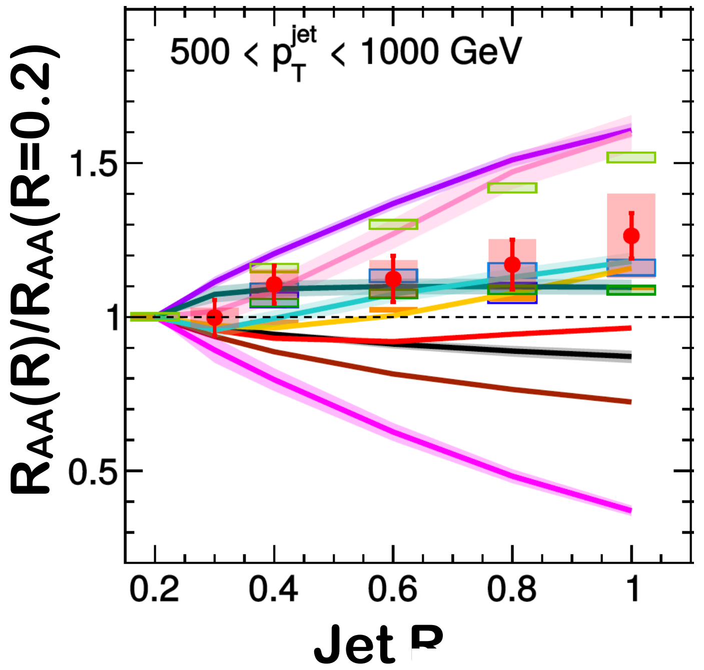

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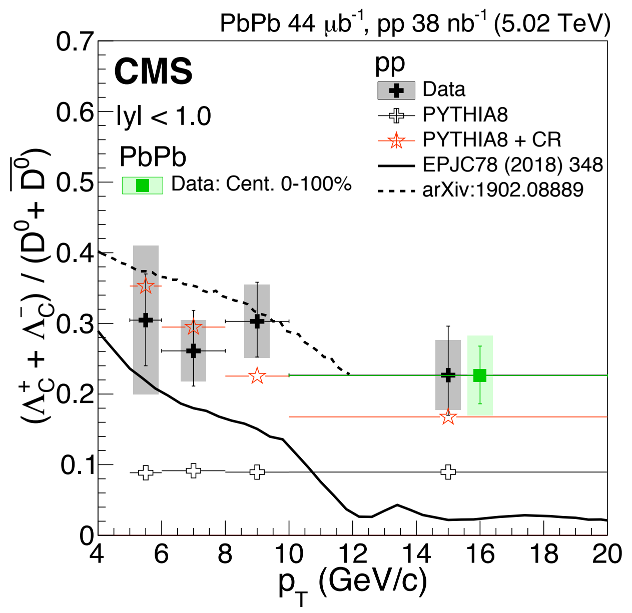

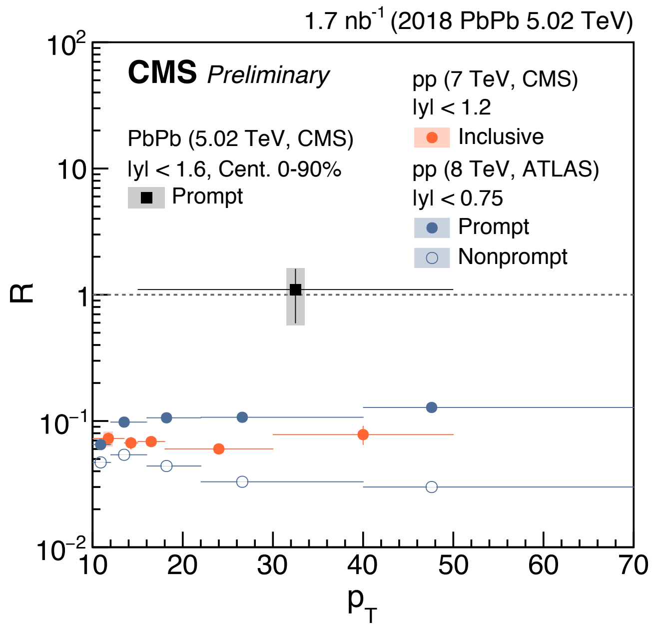

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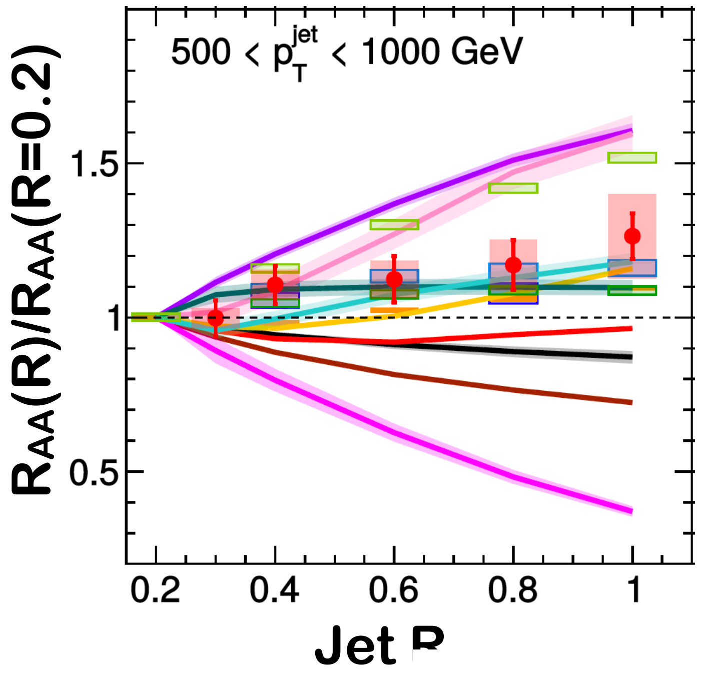

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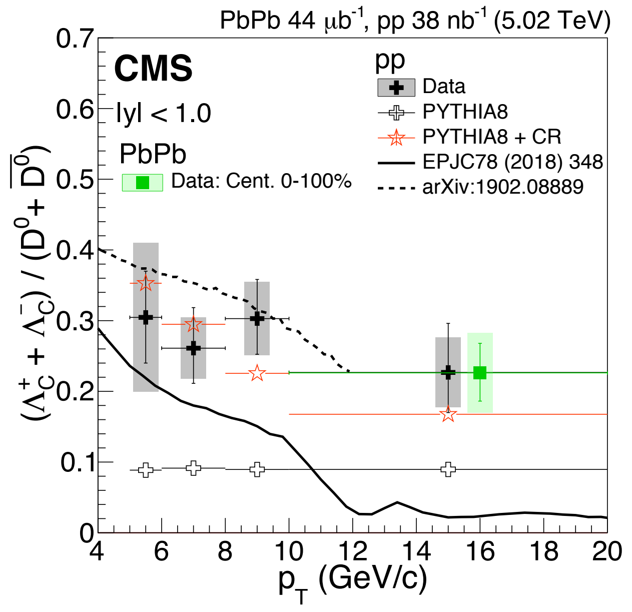

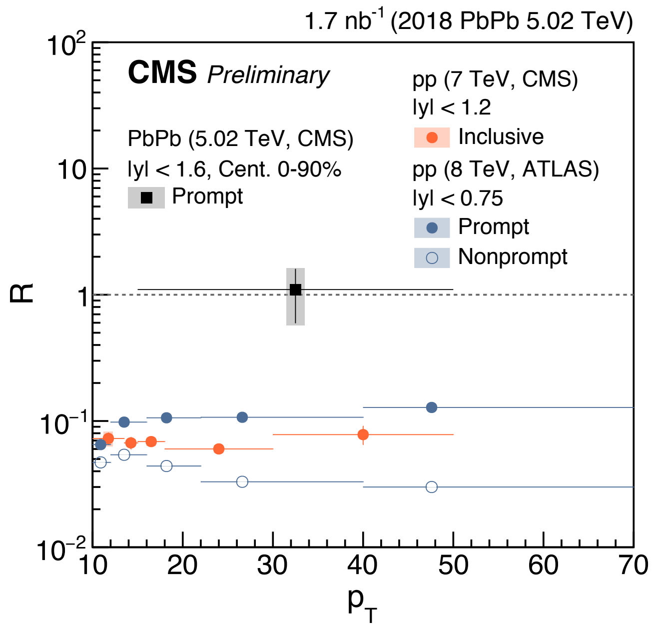

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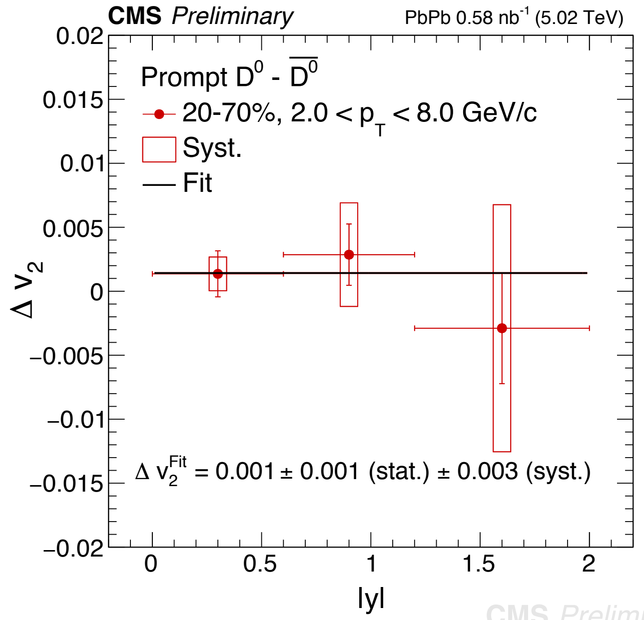
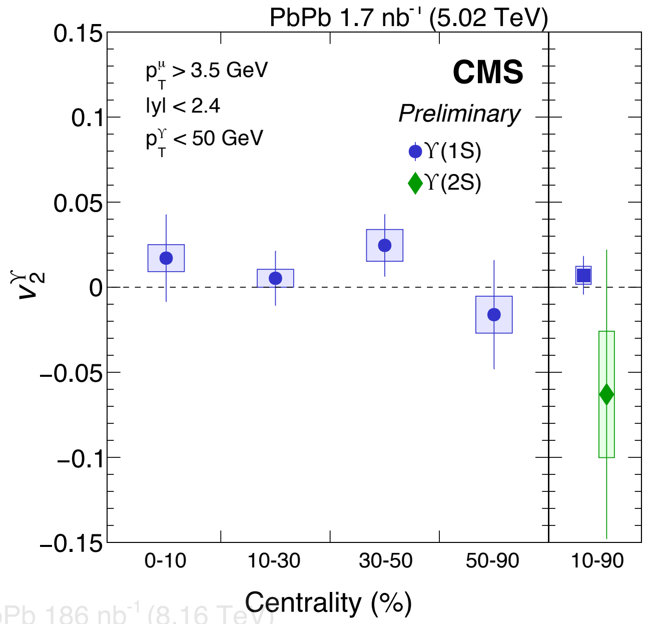
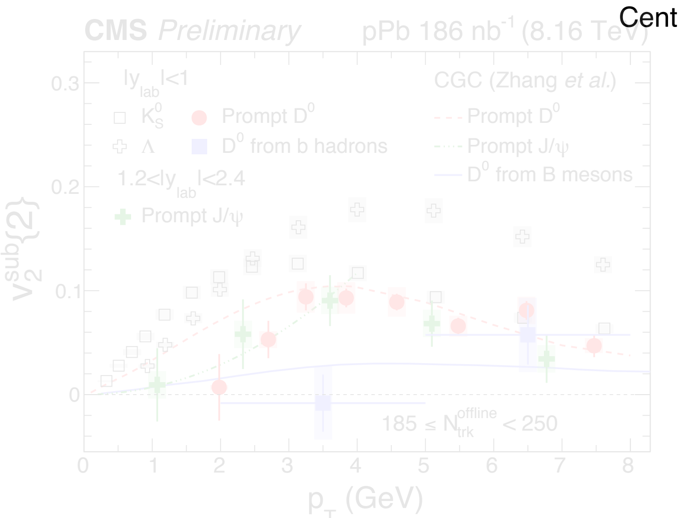


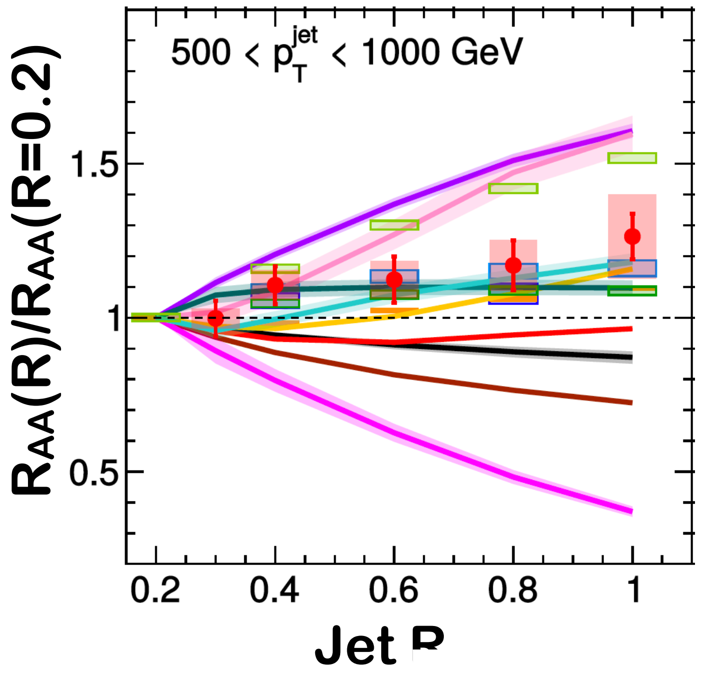


- **Heavy-flavour collectivity in small systems**
  - Large collectivity of prompt J/ψ and D^0 mesons.
  - Non-prompt D^0 collectivity ~ 0 in pPb.

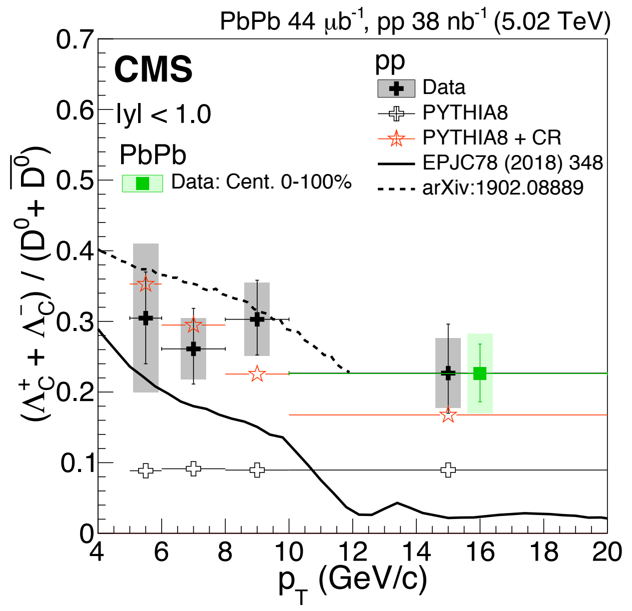


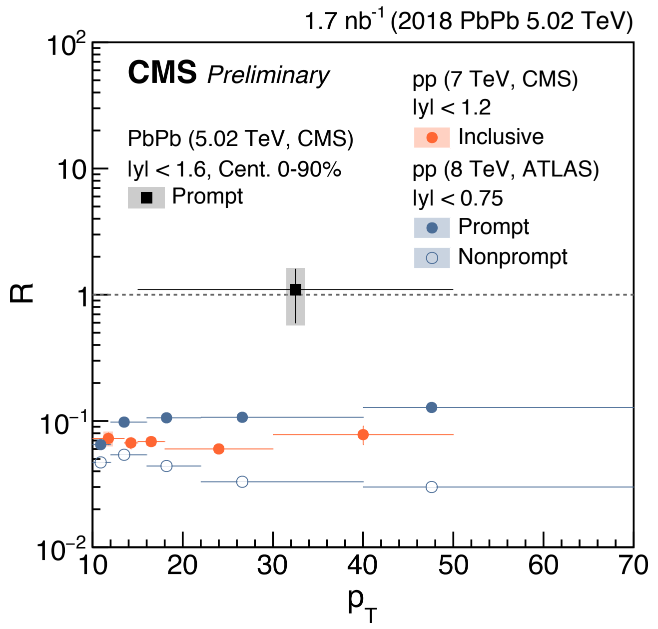
SUMMARY

- **Jets and medium response**
  - First measurement of jet R_{AA} up to R=1.0.
  - Jet R_{AA} vs jet radius constrain jet quenching models.

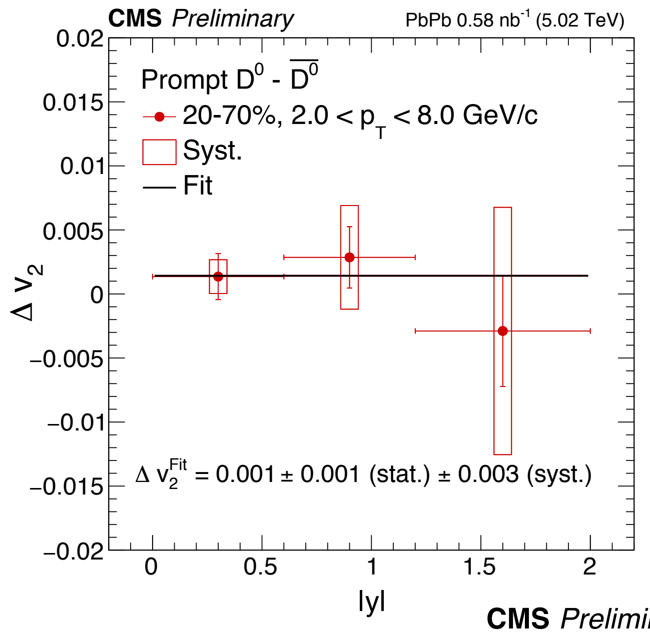


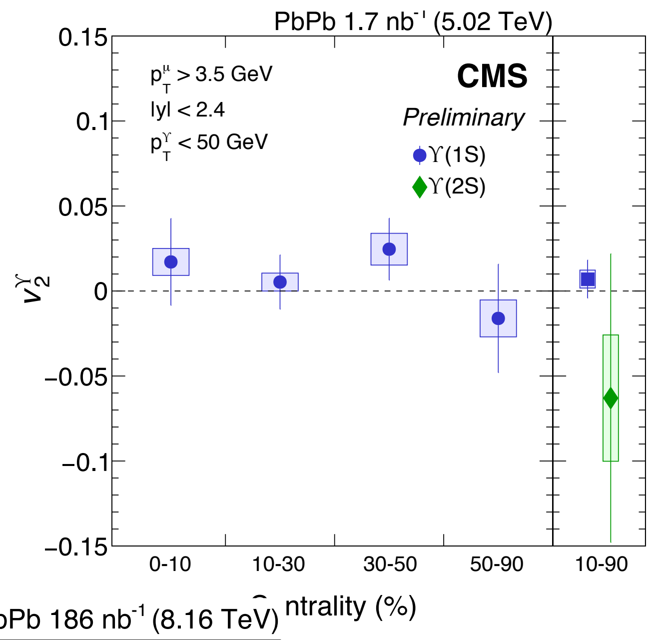
- **Heavy-flavour production**
  - Λ_c/D_0 ratio in pp consistent with PYTHIA + CR.
  - Similar Λ_c/D_0 results in pp and PbPb.
  - Hint of X(3872) to ψ(2S) ratio enhancement in PbPb.



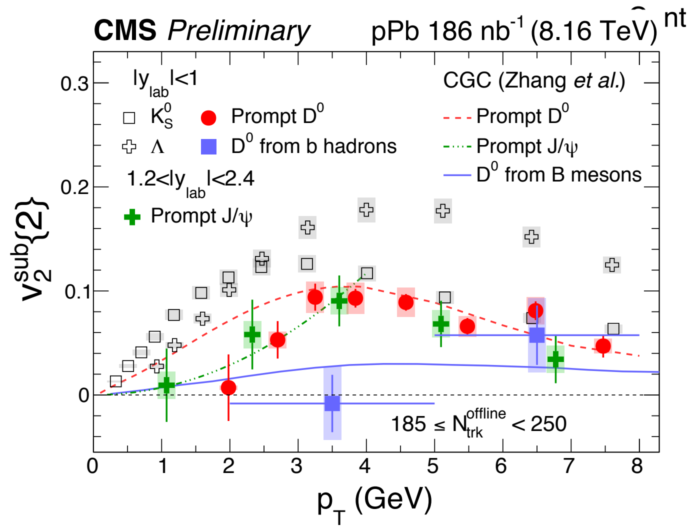


- **Heavy-flavour collectivity in large systems**
  - $\Delta v_2(D^0-\bar{D}^0)$ compatible with charged hadron calculations.
  - Bottomonium elliptic flow $v_2(\Upsilon(nS))$ ~ 0.

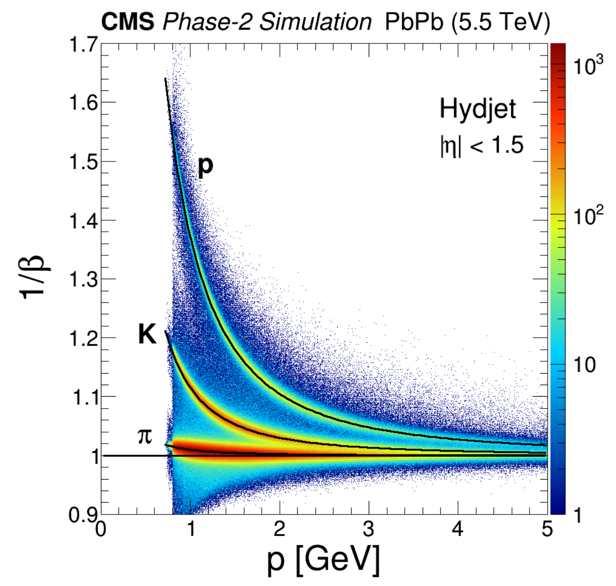


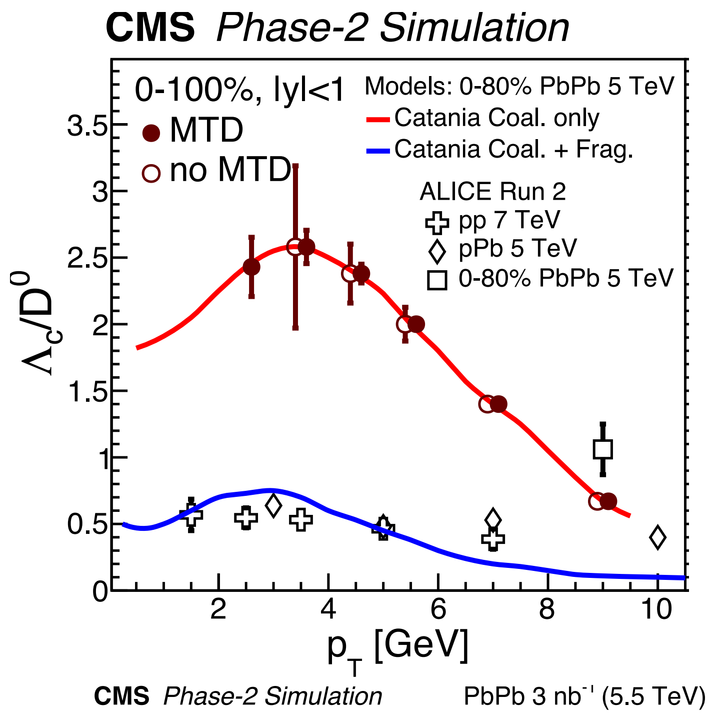


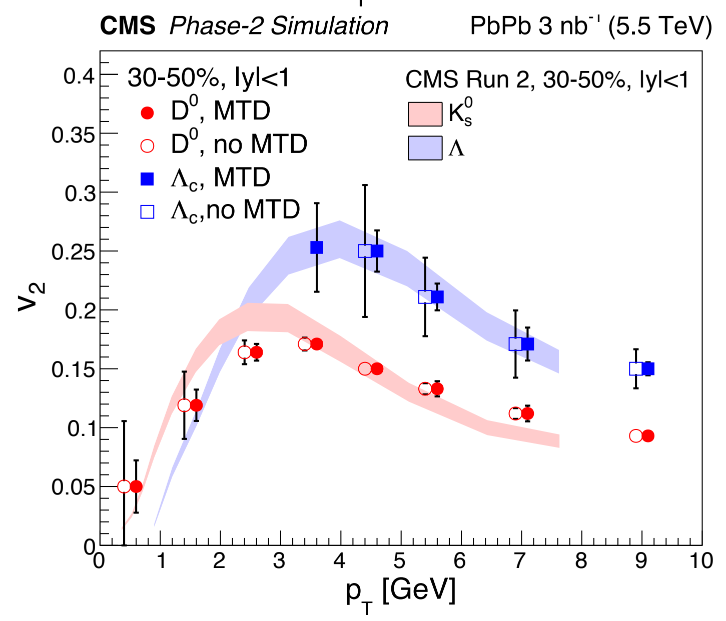
- **Heavy-flavour collectivity in small systems**
  - Large collectivity of prompt J/ψ and D^0 mesons.
  - Non-prompt D^0 collectivity ~ 0 in pPb.



SUMMARY







CMS will add a new precise MIP timing detector for HL-LHC

For more details check: CERN-LHCC-2017-027

MTD will bring a completely new capability to CMS: particle identification via time-of-flight

High impact on CMS Heavy Ion physics program:

- Heavy quark dynamics in QGP → D $p_T > 0$ GeV and Λ_C $p_T > 3$ GeV
- QGP response to parton energy loss
- Universal scaling of elliptic flow
- Origin of collectivity in small systems
- Light (hyper-) nuclei physics
- …. among other topics

Thank you for your attention!

Acknowledgement

U.S. DEPARTMENT OF
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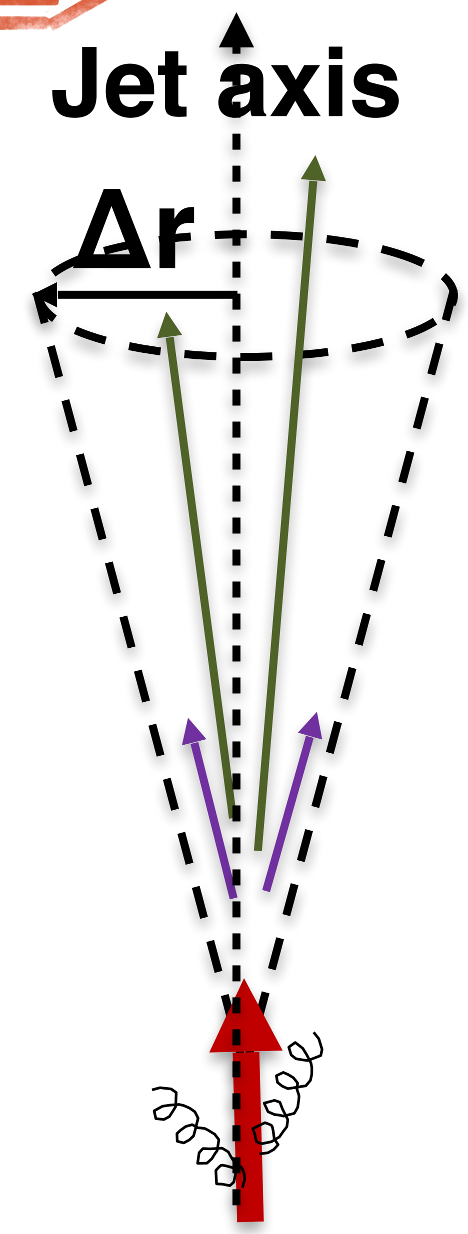
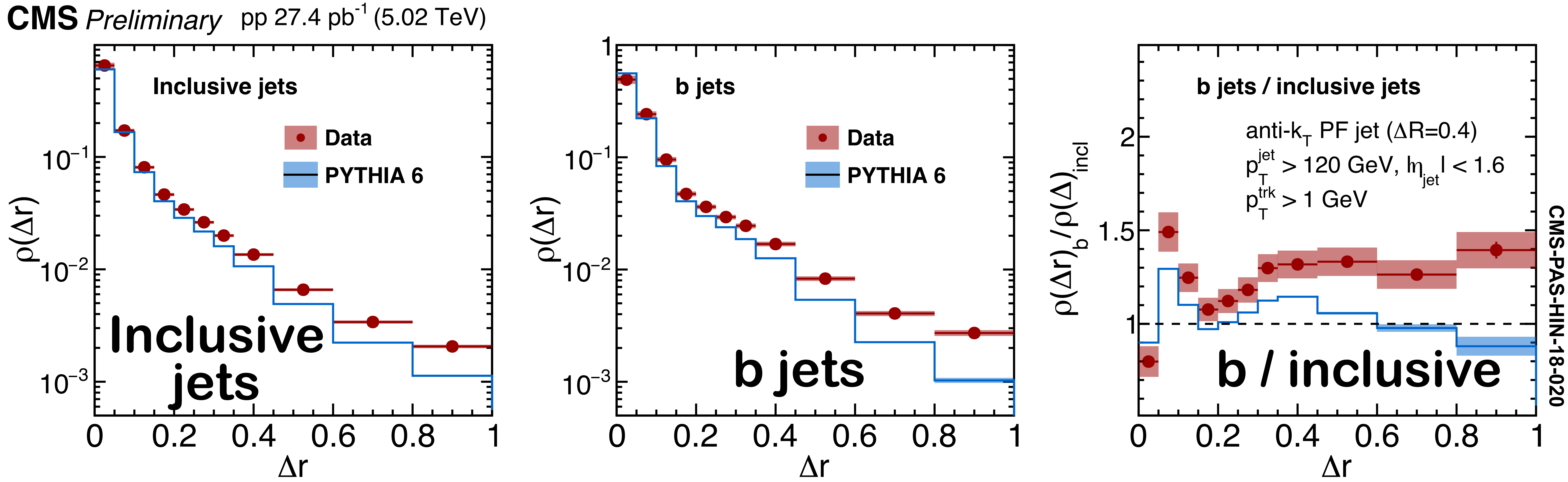
BACKUP

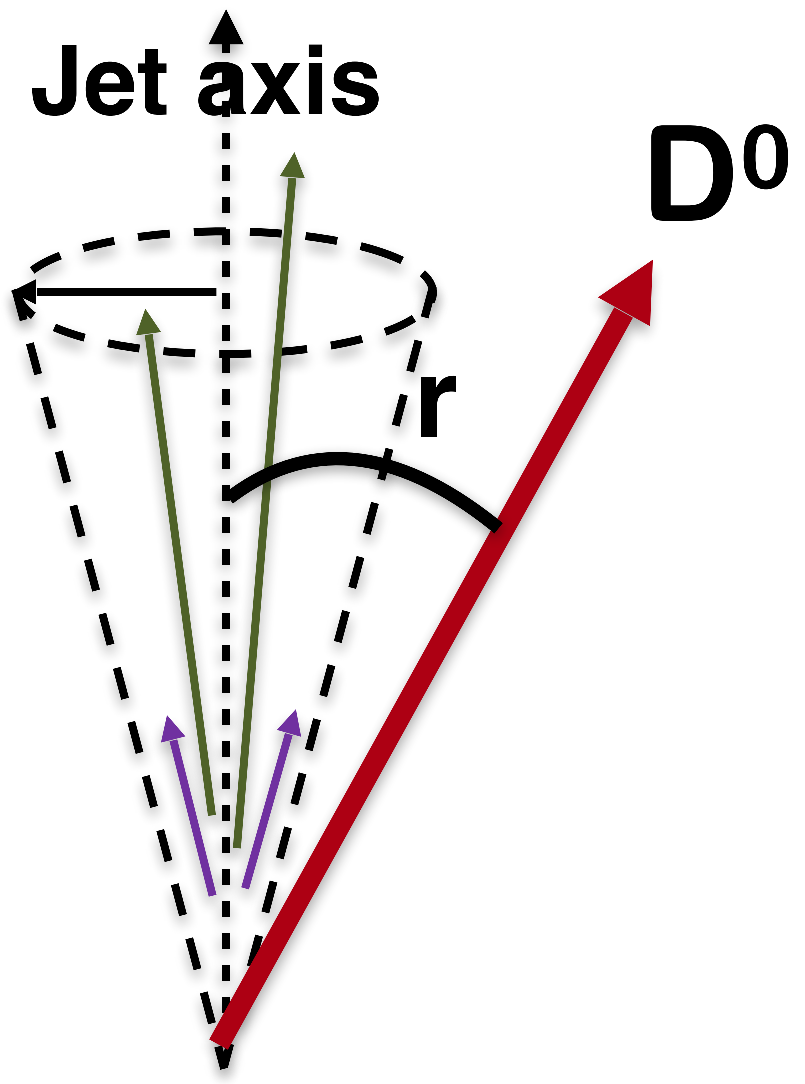
NEW RESULT

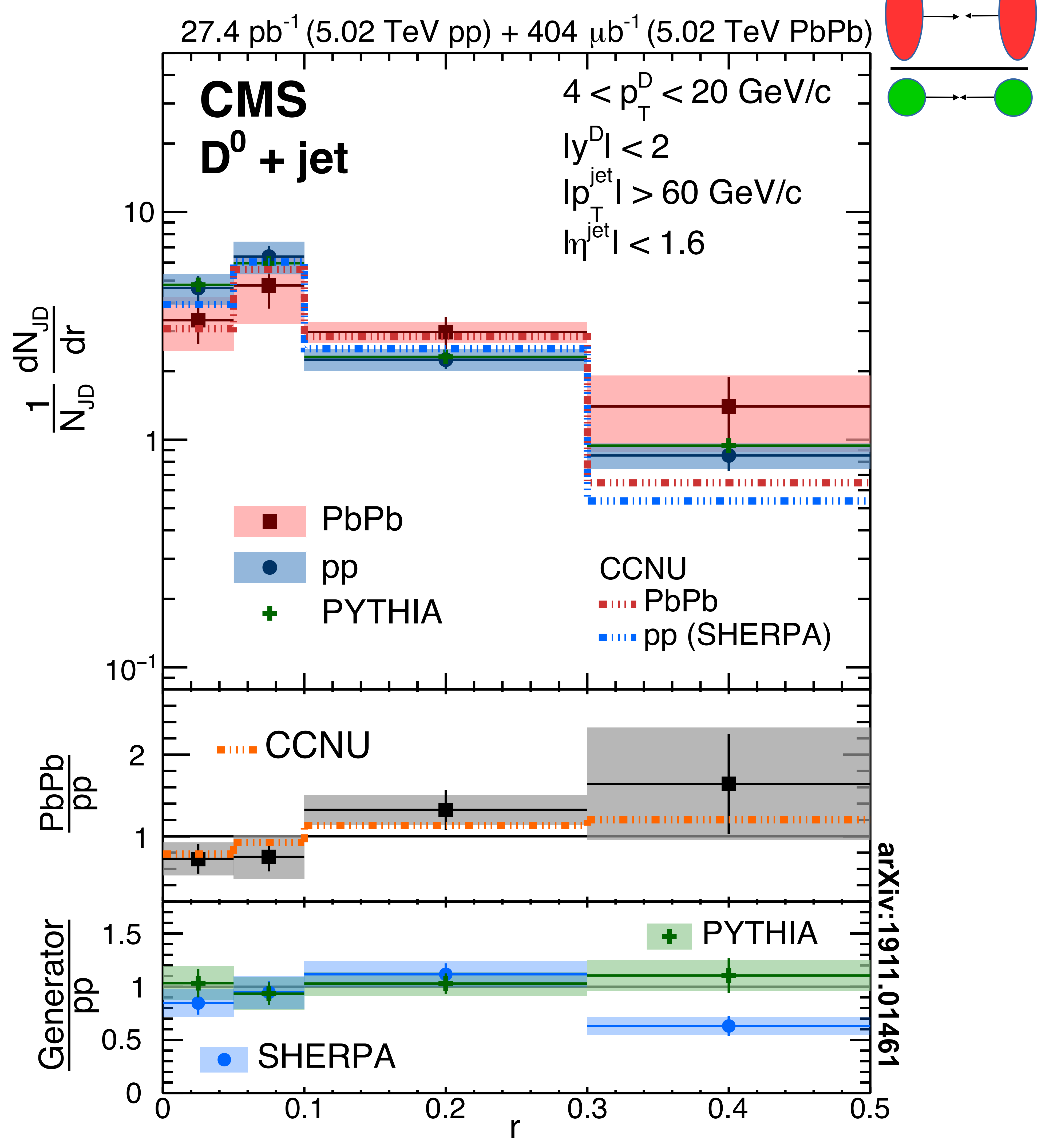




- Different shape with respect to inclusive jets.
- Imperfectly reproduced in PYTHIA.
- Flavour dependence in parton fragmentation

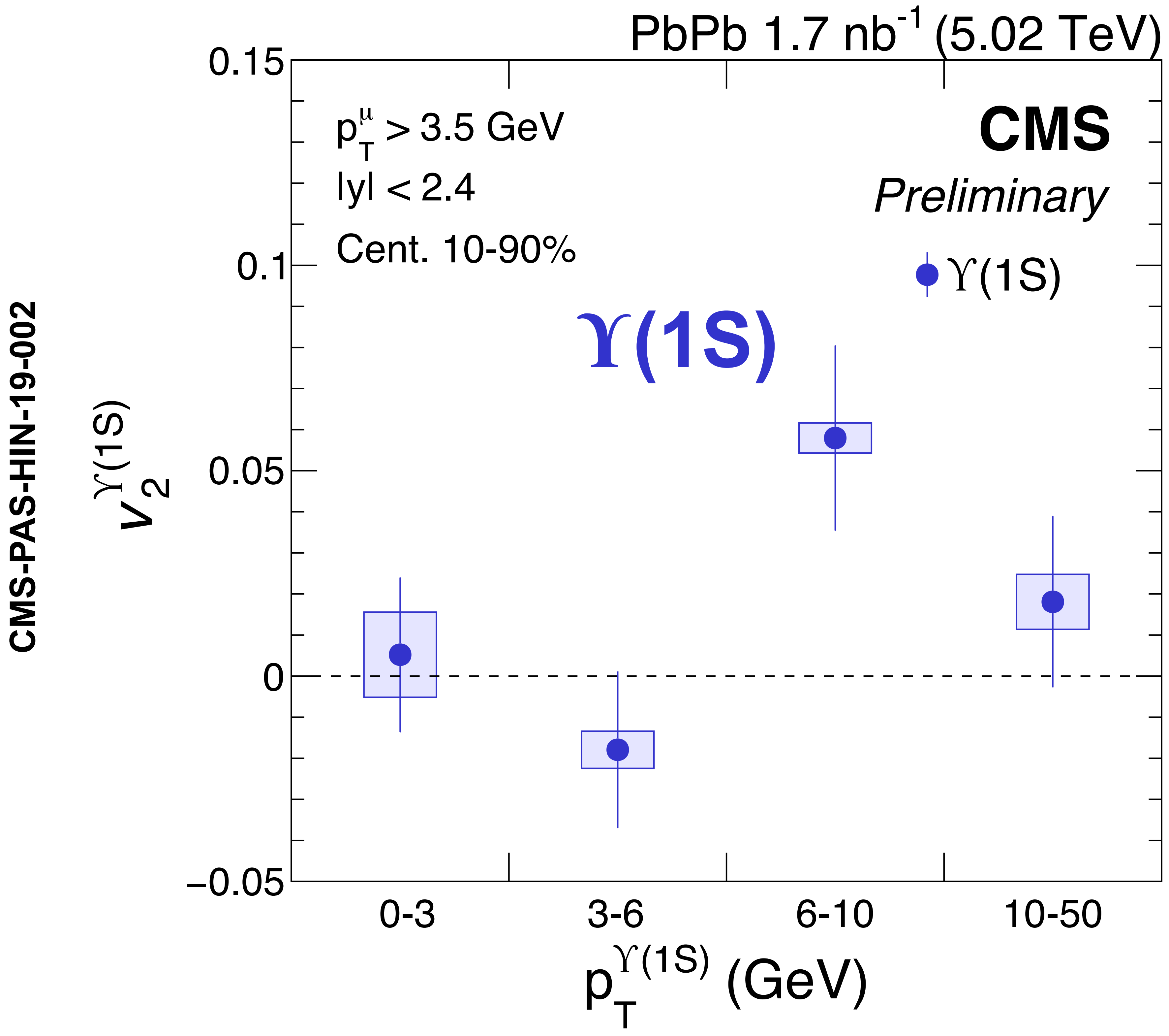
D⁰ mesons in jets in pp and PbPb

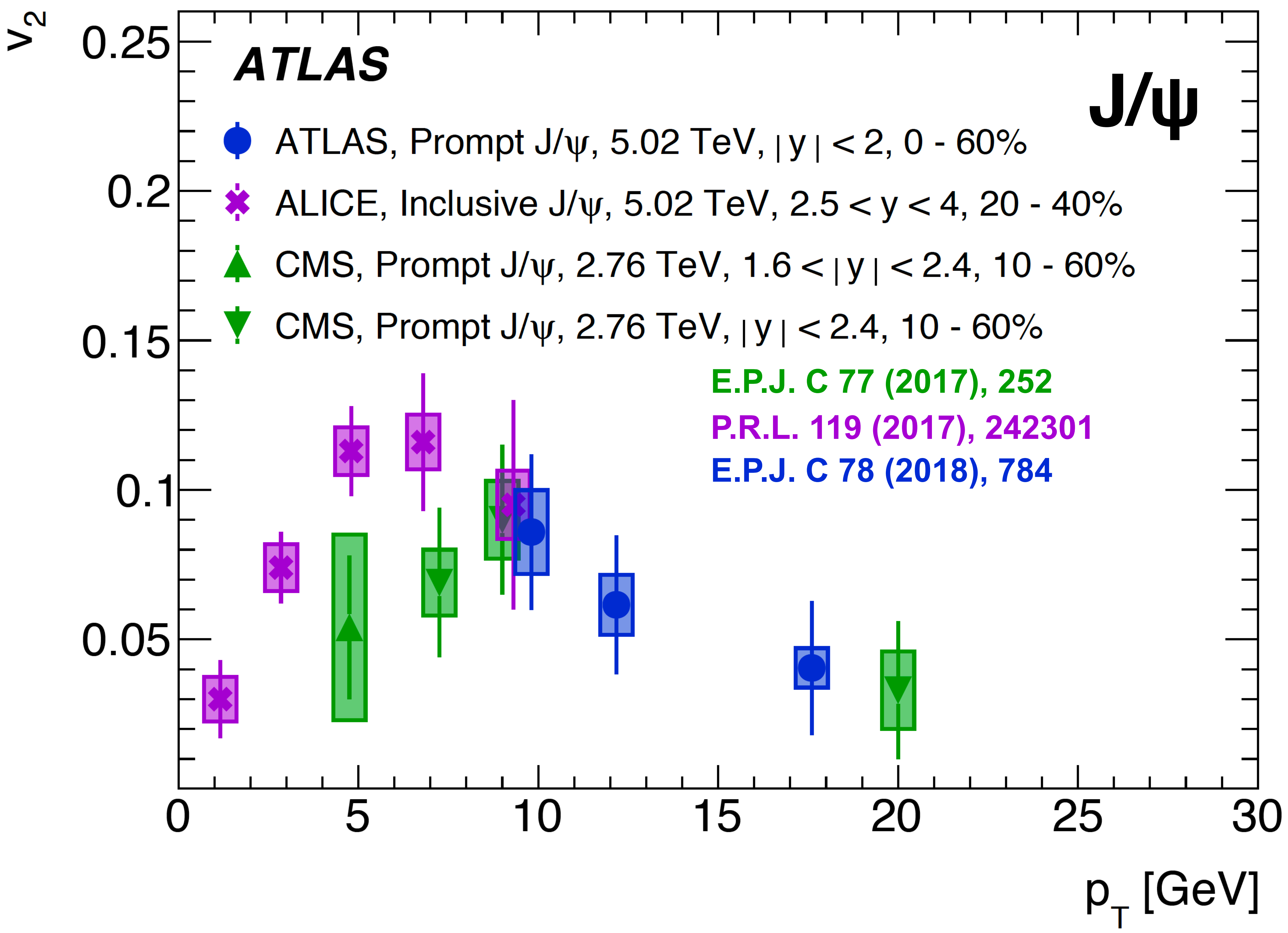




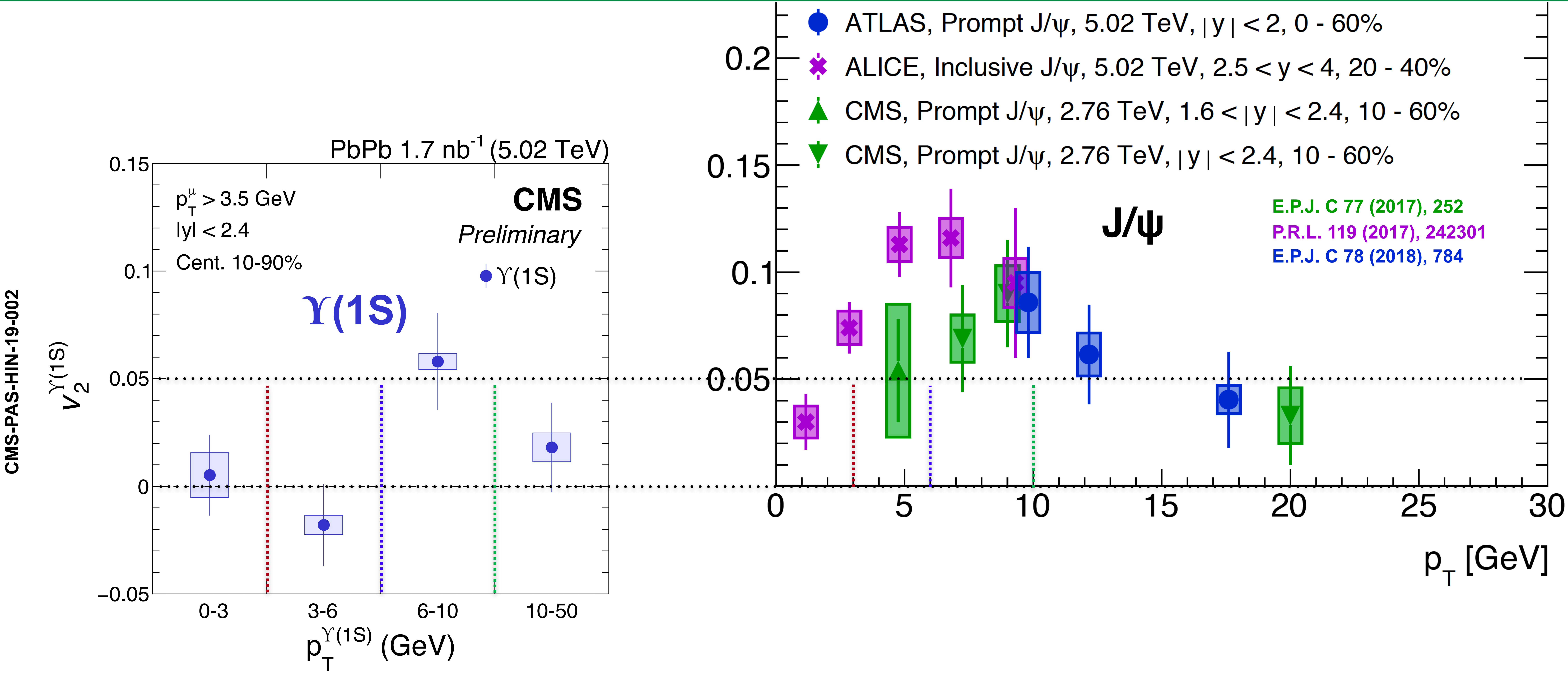
- Radial profile of D⁰ mesons in jets.
- Hint of wider distribution in PbPb than pp at low p_T.
- Charm quark diffusion with respect to the jet axis

ϒ(nS) vs J/ψ v_2 in PbPb





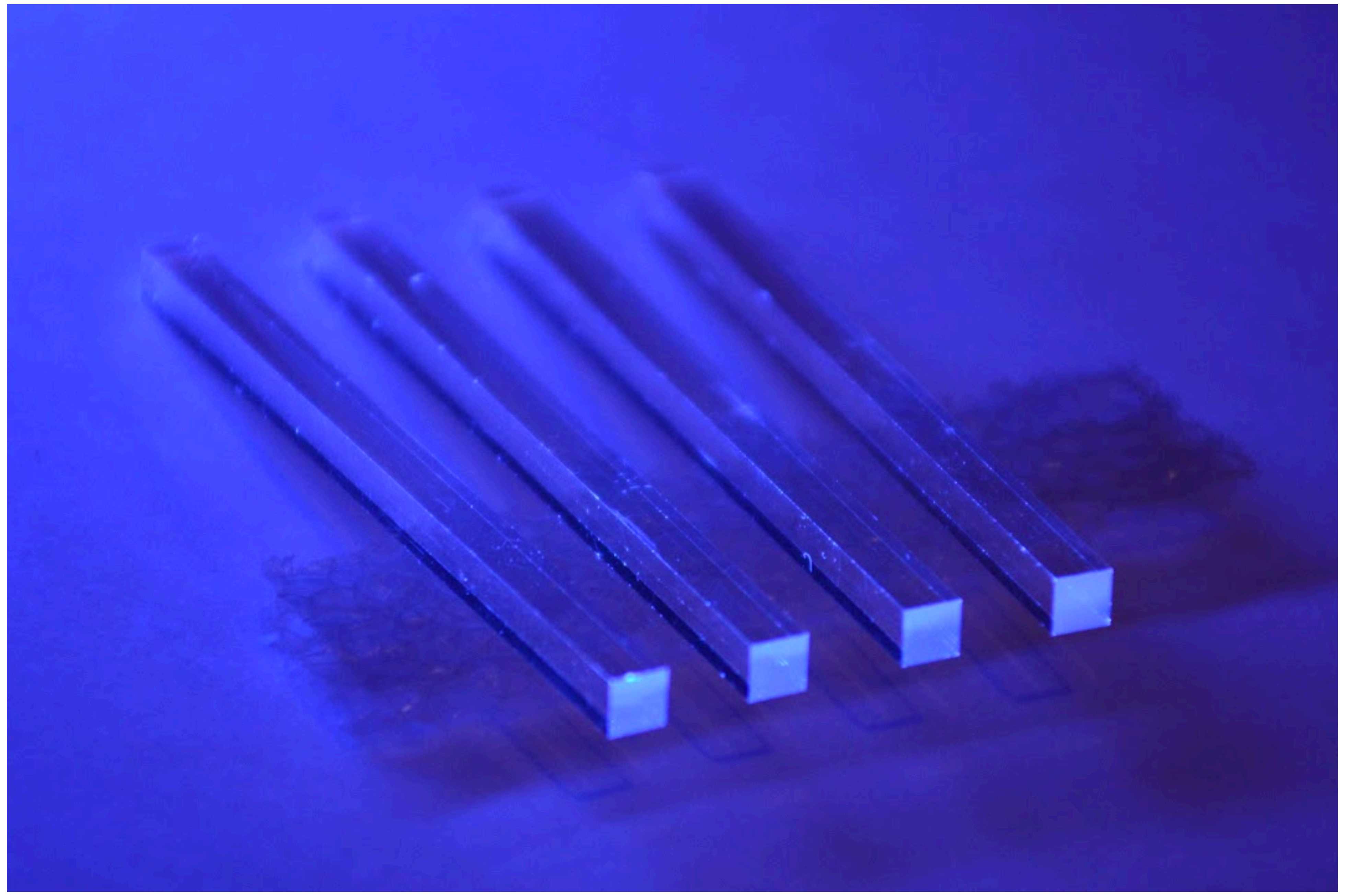
$\Upsilon(nS)$ vs J/ψ v_2 in PbPb

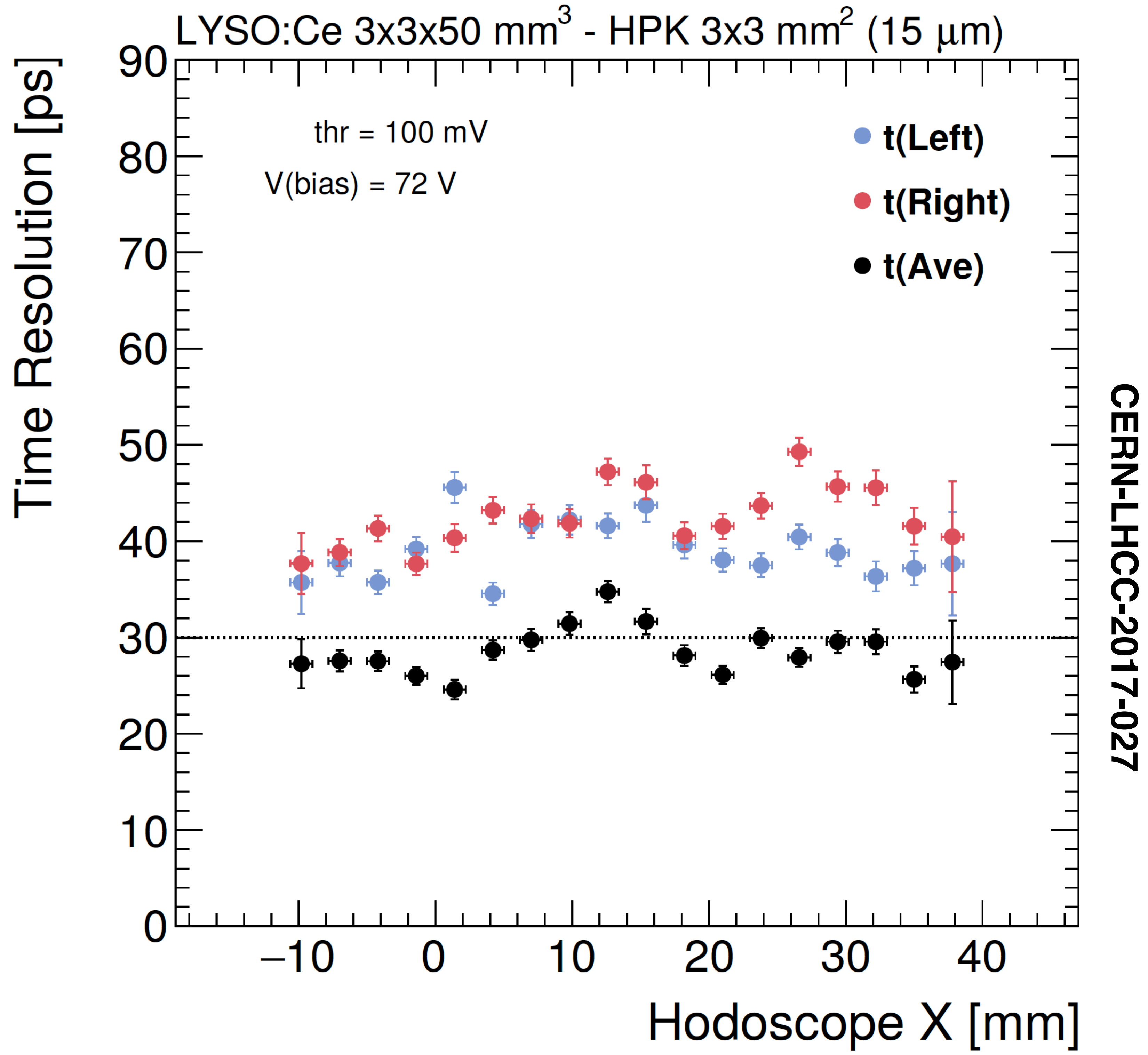


- Lower elliptic flow of **$\Upsilon(1S)$** than **J/ψ**.
    - Different medium effects of charmonia and bottomonia .

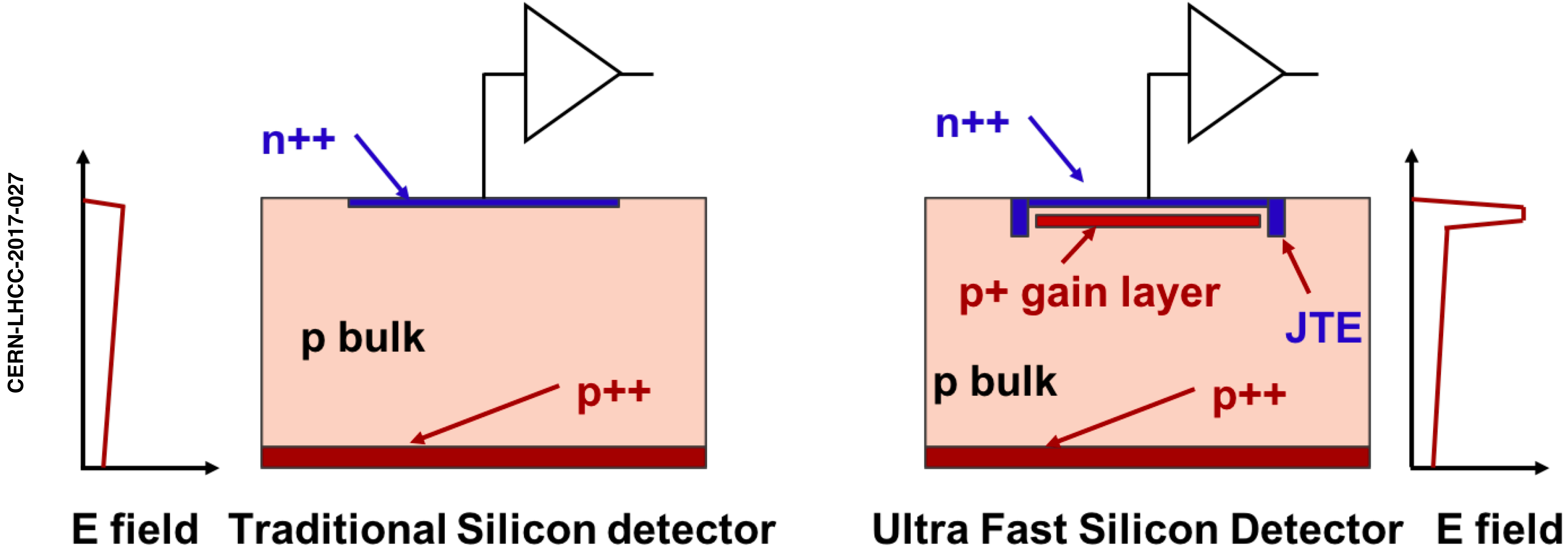
Lutetium-Yttrium Oxyorthosilicate crystal

CERN-LHCC-2017-027



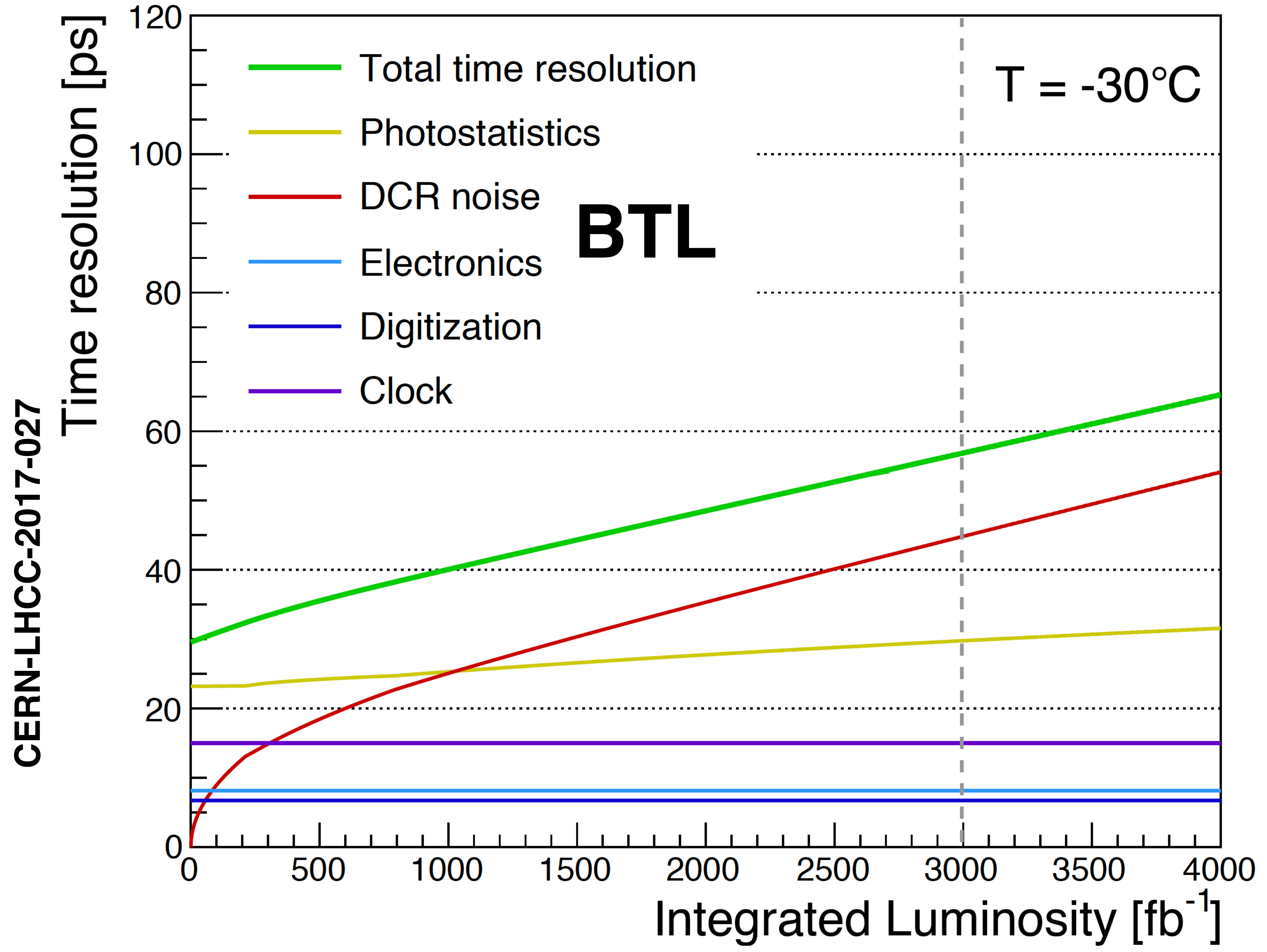


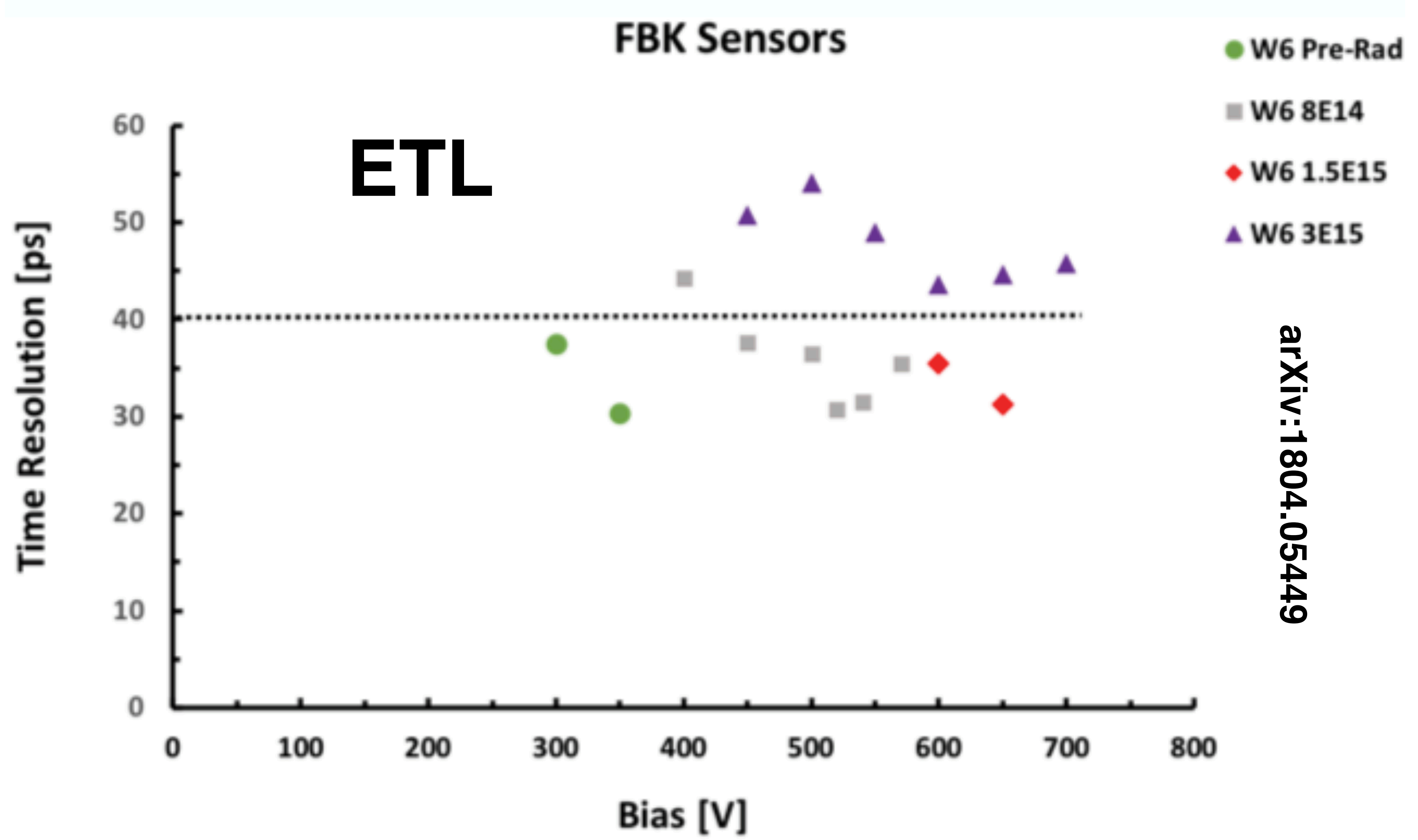
- LYSO:Ce crystal bar size: 3 x 3 x 50 mm^3 and time resolution: ~30 ps.
- LYSO:Ce optimal due to their high light yield (40k photons/MeV), fast scintillation rise time (<100 ps) and short decay time (~40 ns). Also, the light wavelength (420 nm) matches the sensitive range of SiPMs.



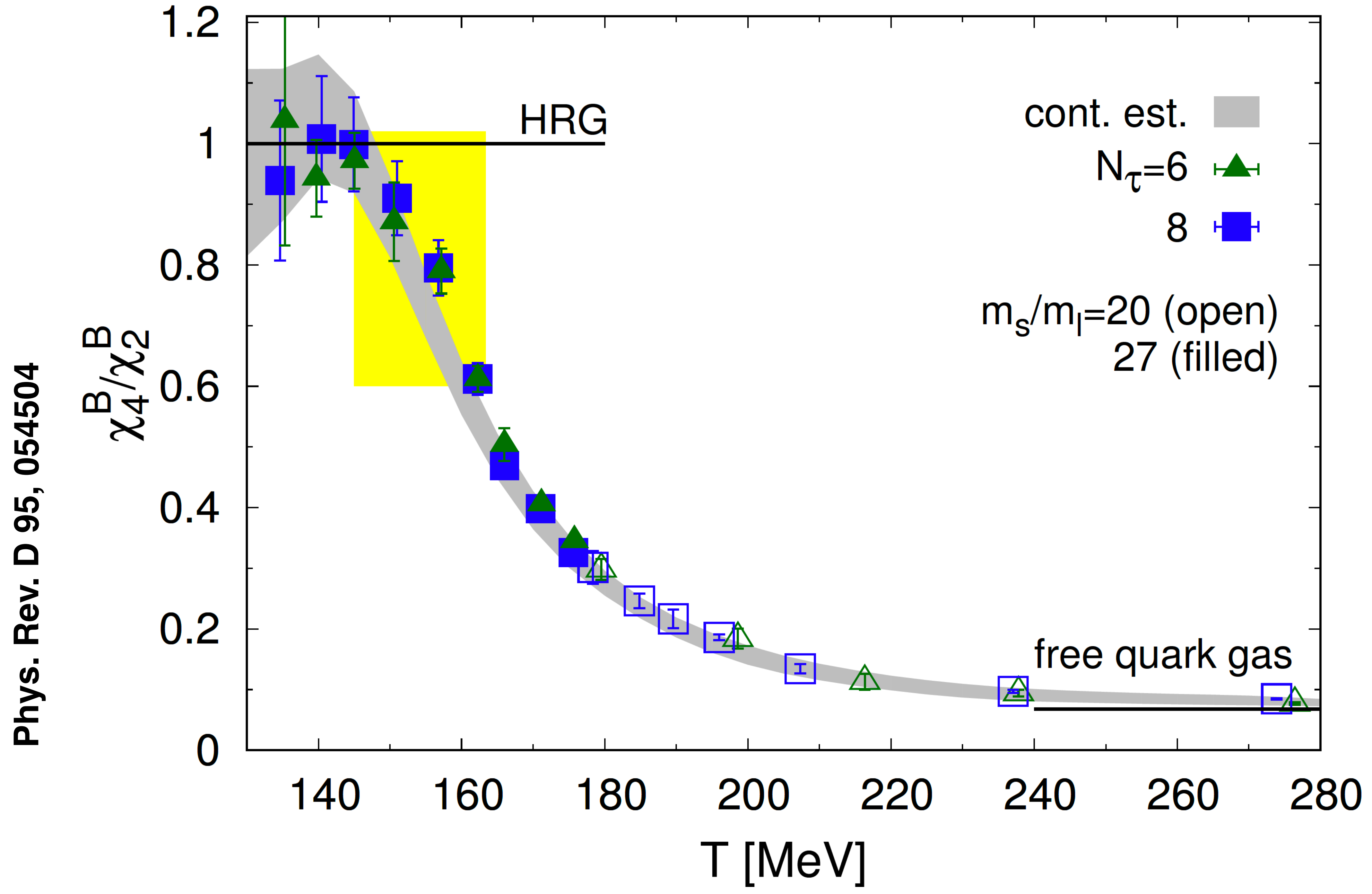
- LGAD sensor pixel size: 1.3 x 1.3 mm^2 and time resolution: 30-50 ps.
- Extra *p*-type implant near the *n*-electrode generates a large electric field, resulting in an electron-avalanche effect that offers a gain factor of 10-30.
- Additional gain allows to extract signals with thinner pixels (depths of 30-50 μm), resulting in: low noise, large slew-rate and fast rising pulse.

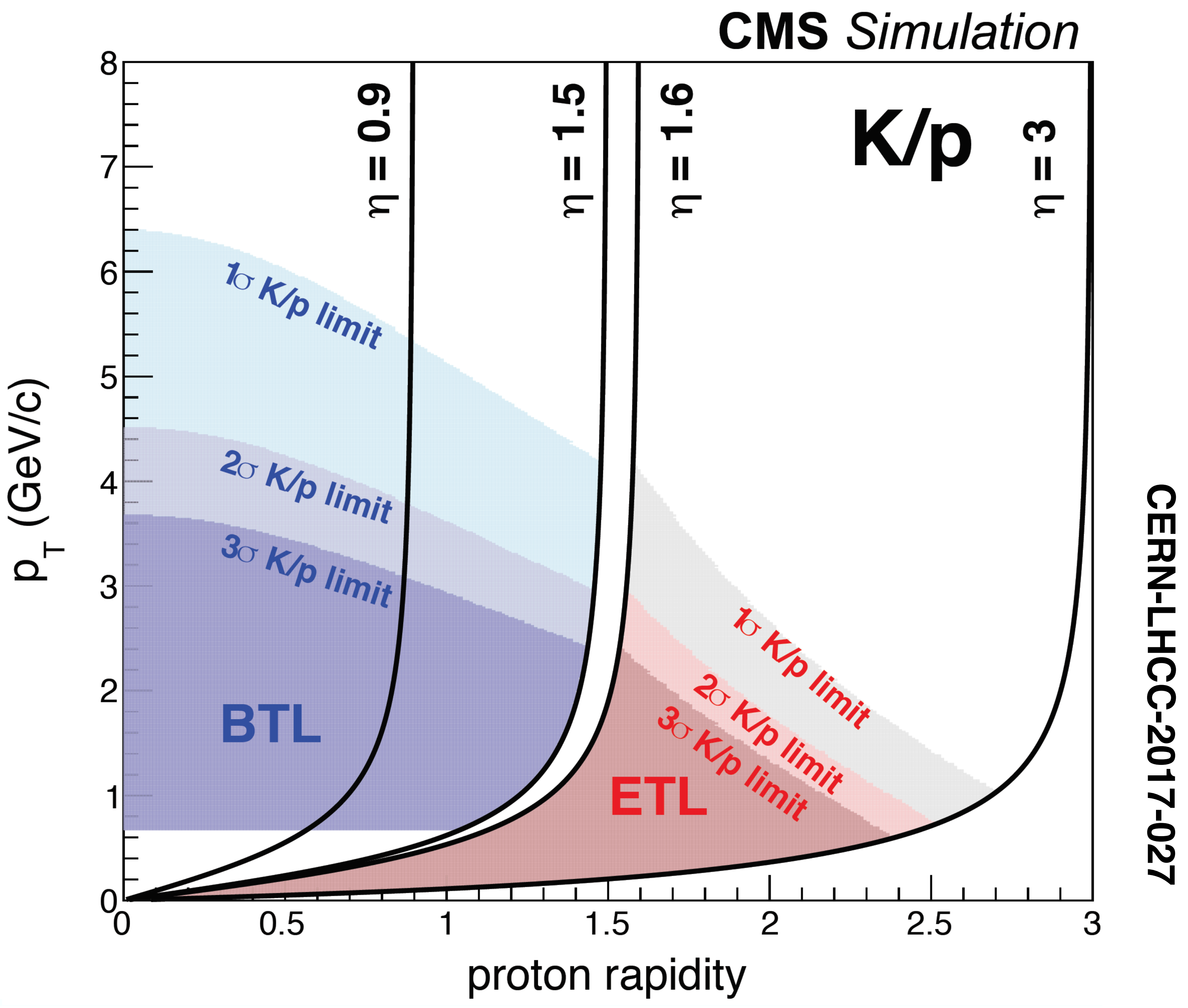
Impact of radiation damage





- **BTL**: Radiation damage leads to worse time resolution up to 60 ps by the end of Run 4. Dominated by the dark count rate (DCR) noise of SiPMs.
- **ETL**: The UFSD is also affected by radiation dose, however the time resolution can be recovered by increasing the bias voltage.





- Can be studied experimentally by measuring the higher cumulants of net strangeness or baryon number (κ_n).
- The PID capabilities of MTD allows to measure the net kaon and proton cumulants in a **wide rapidity range**, directly testing the lattice QCD calculations at LHC energies.

Preliminary proposal of future HI runs

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	

CERN-LPCC-2018-07

Muon acceptance: |η| < 2.4