

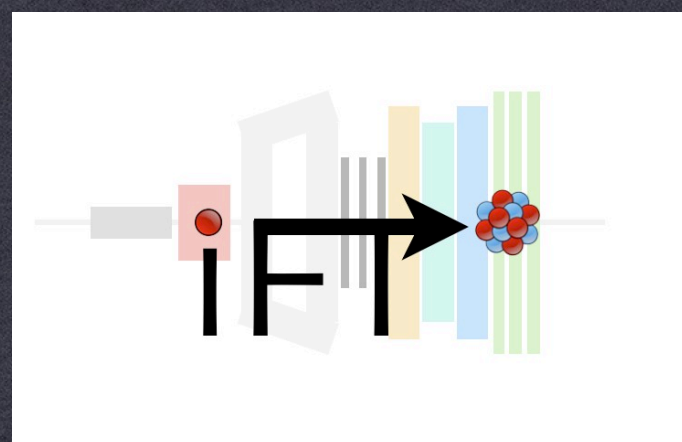
DE LA RECHERCHE À L'INDUSTRIE



## HADRONIZATION IN SMALL SYSTEMS

- FRAGMENTATION, COALESCENCE AND QCD MEDIUM
- SELECTED RESULTS

Benjamin Audurier - LHCb implication workshop - Oct. 25th 2023





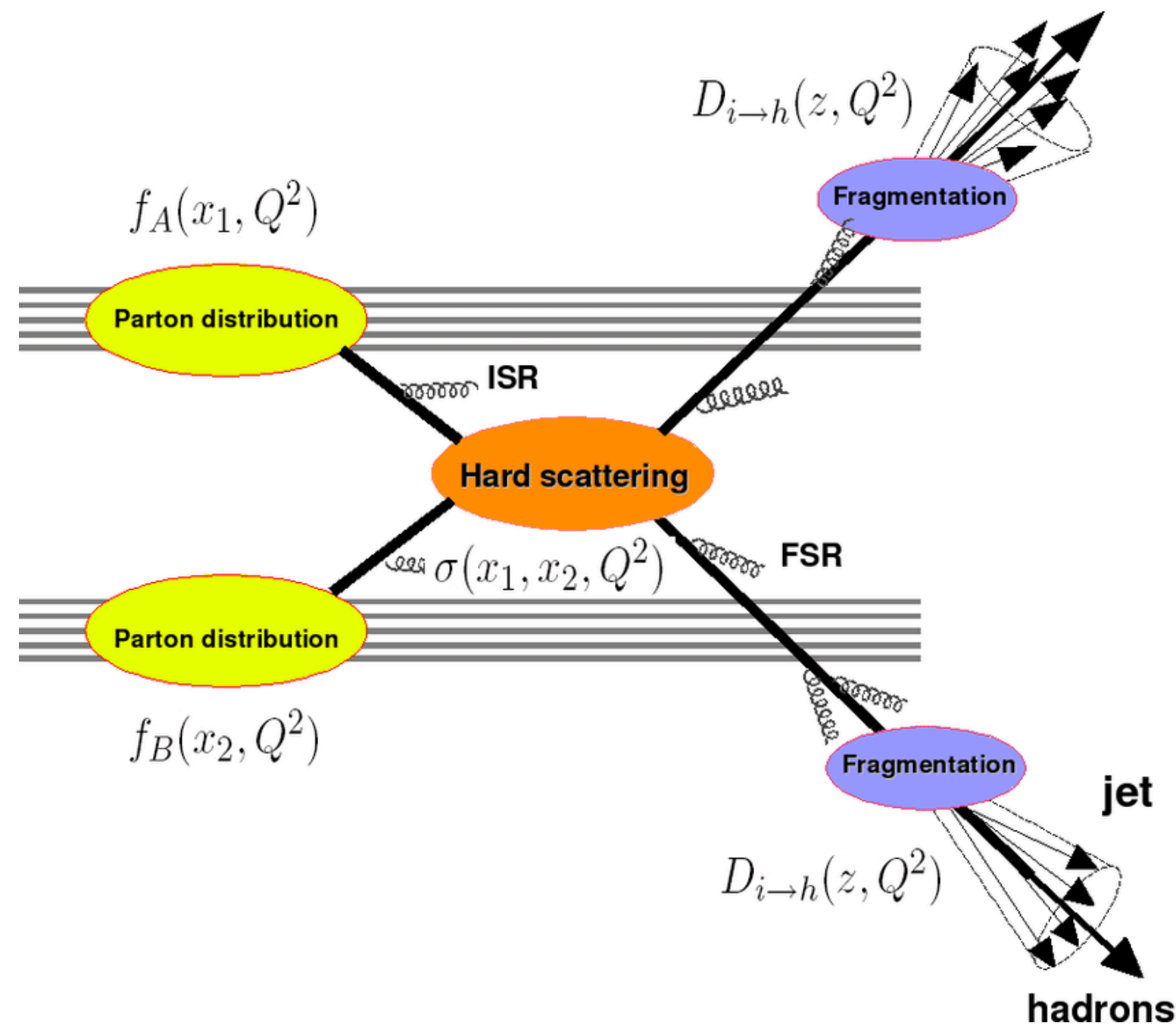
# **FRAGMENTATION, COALESCENCE AND QCD MEDIUM**



# Hadronization mechanism

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# Hadronization mechanism

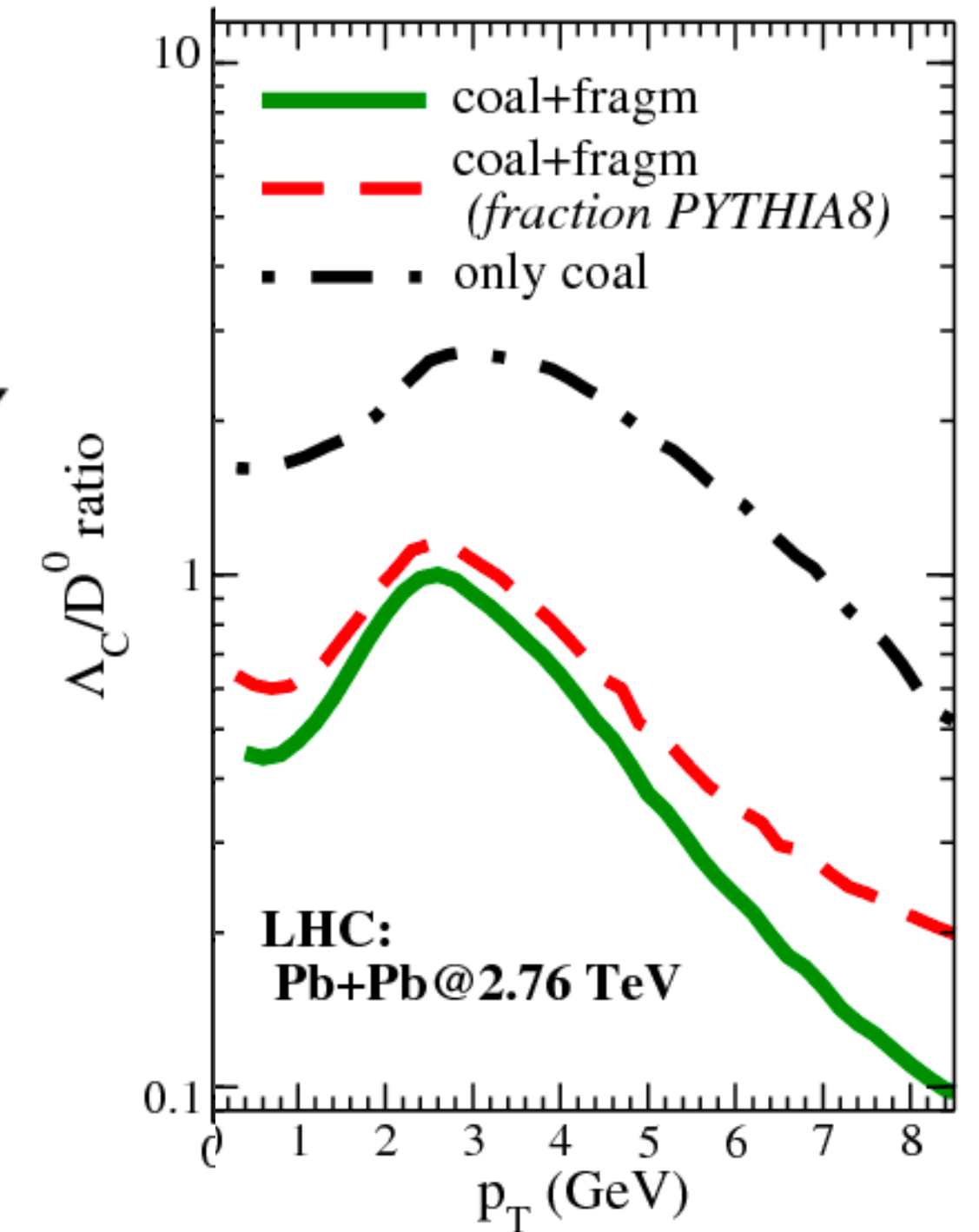
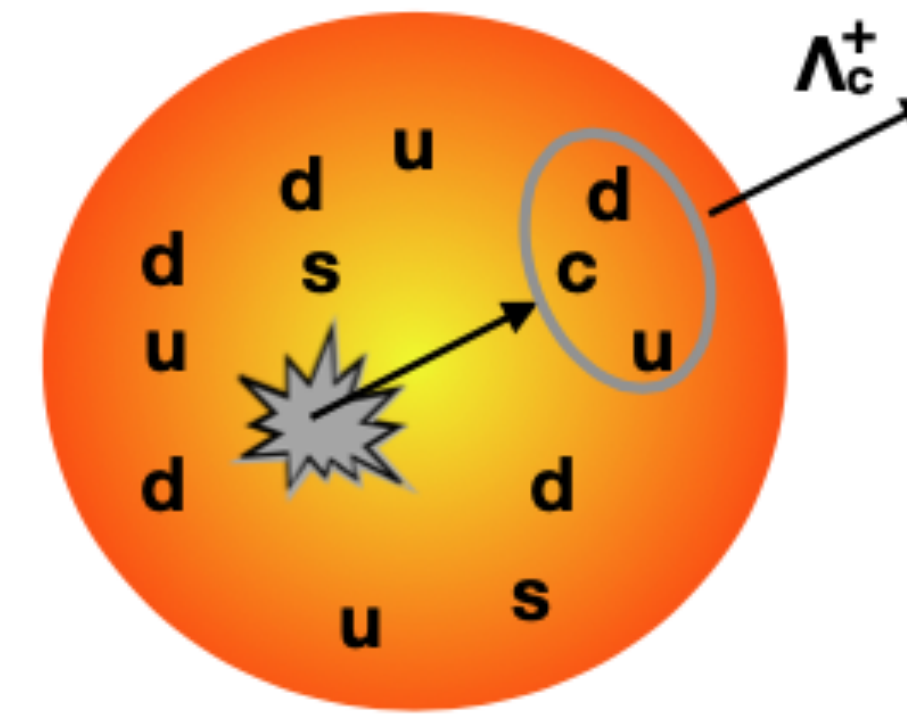
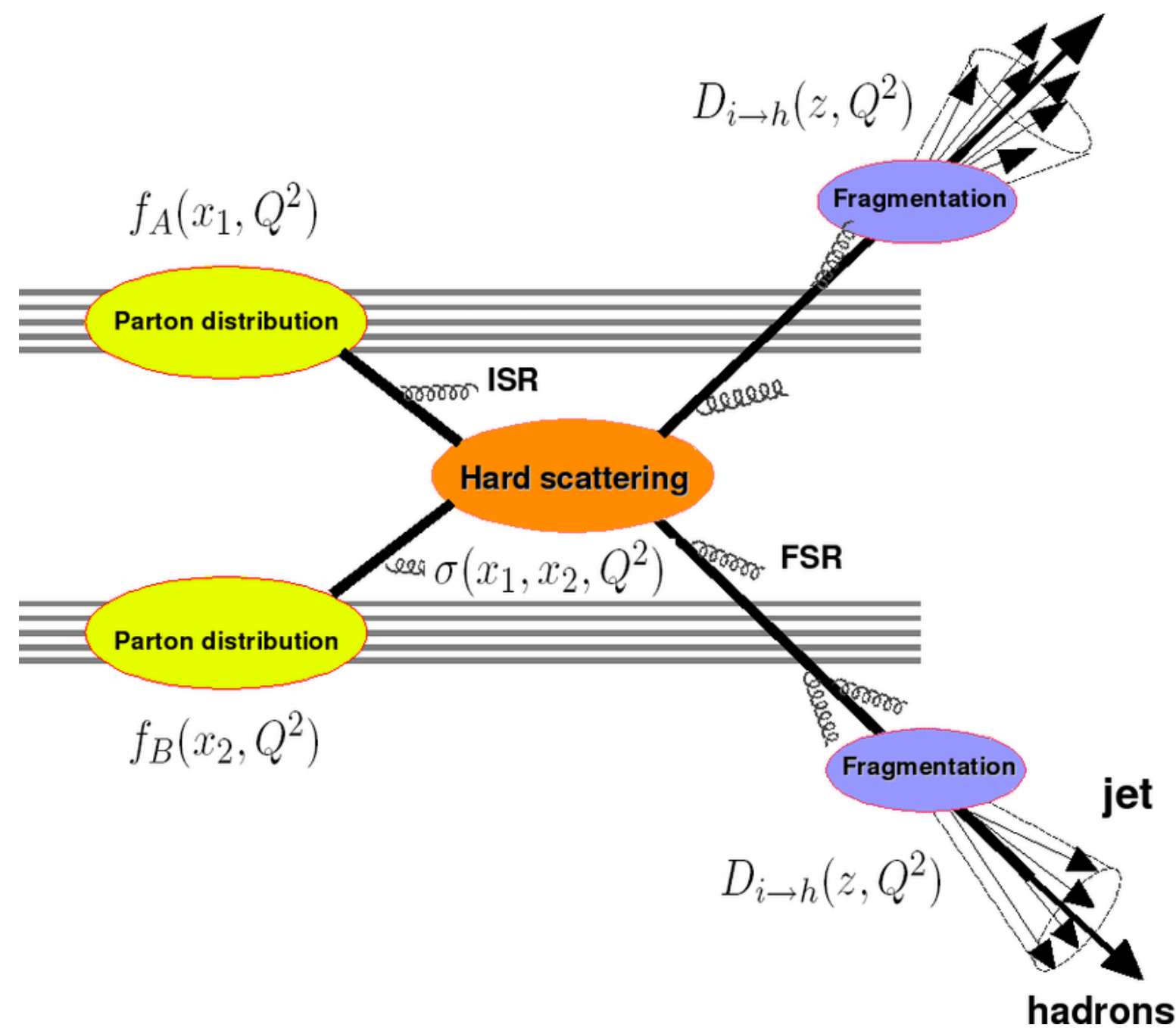


## \* pQCD factorization formula:

- Jet production.
- Universality of the PDFs.
- Universality of the Fragmentation Functions  $D_{i \rightarrow h}(z_q, Q^2)$ .



# Hadronization mechanism



Eur. Phys. J. C (2018) 78:348

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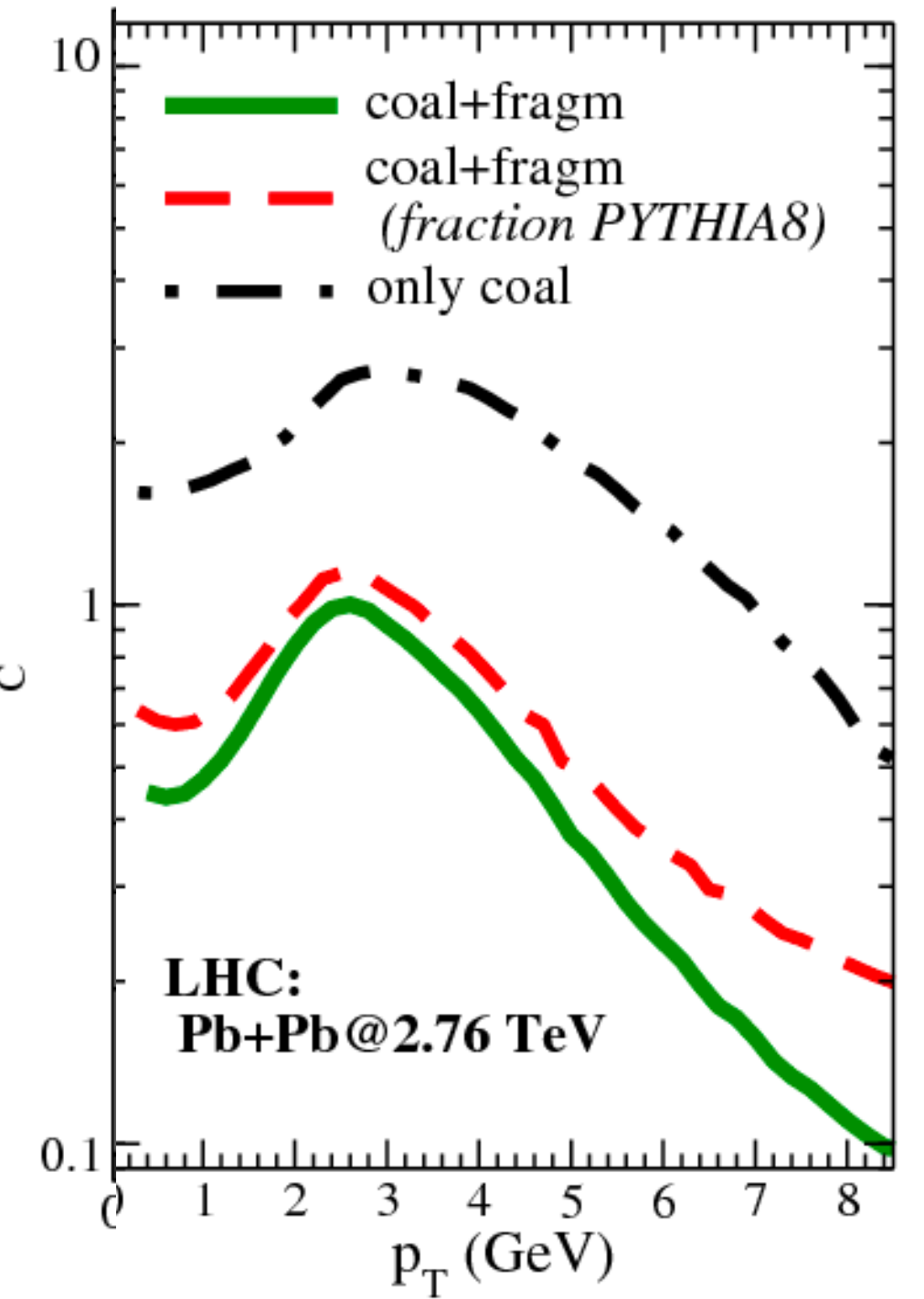
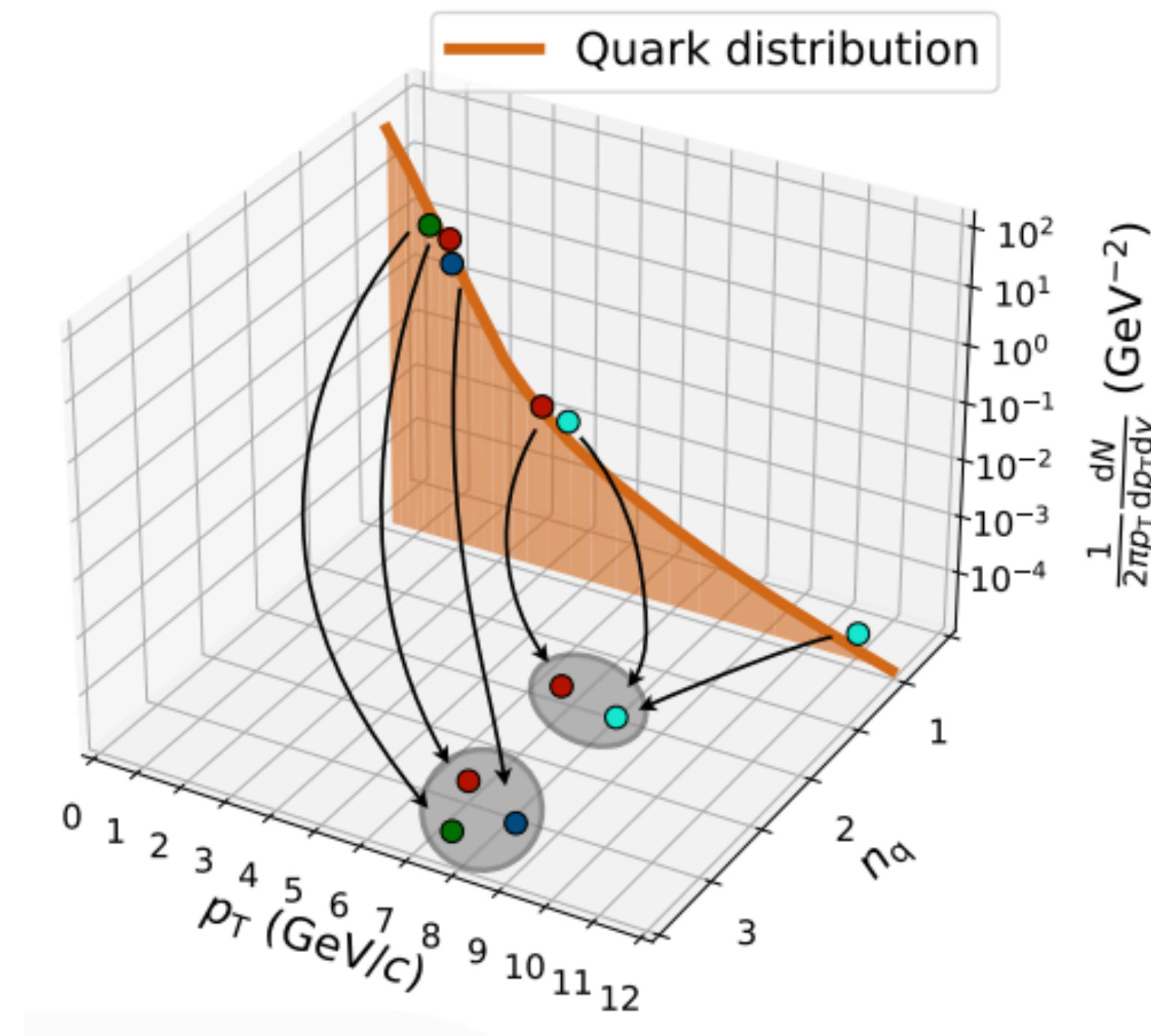
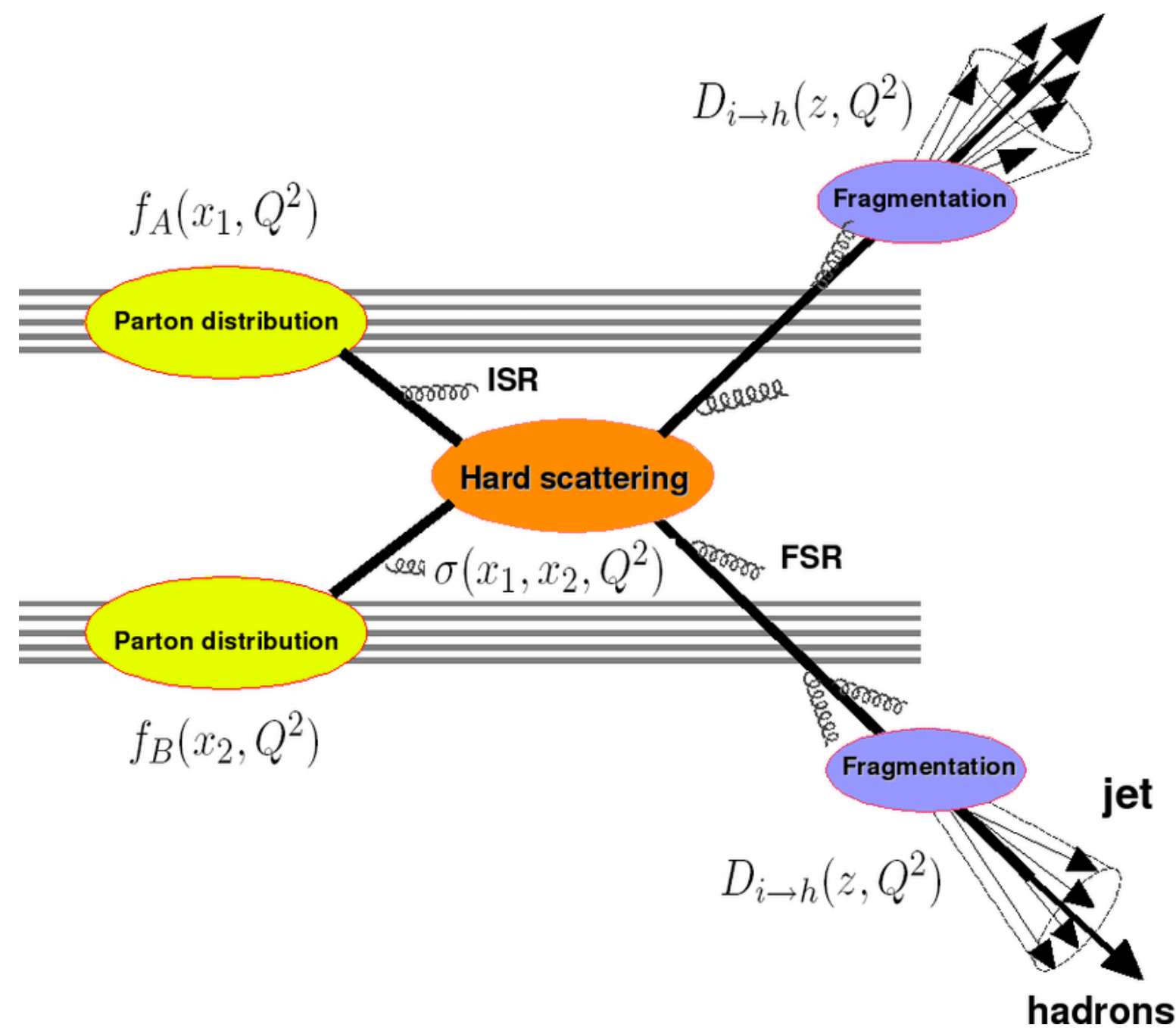
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- Partons close in phase space can recombine.
- Best experimental signature: baryon-to-meson ratios enhancement at intermediate  $p_T$ .
- Need a QCD medium (QGP ?).



# Hadronization mechanism



Eur. Phys. J. C (2018) 78:348

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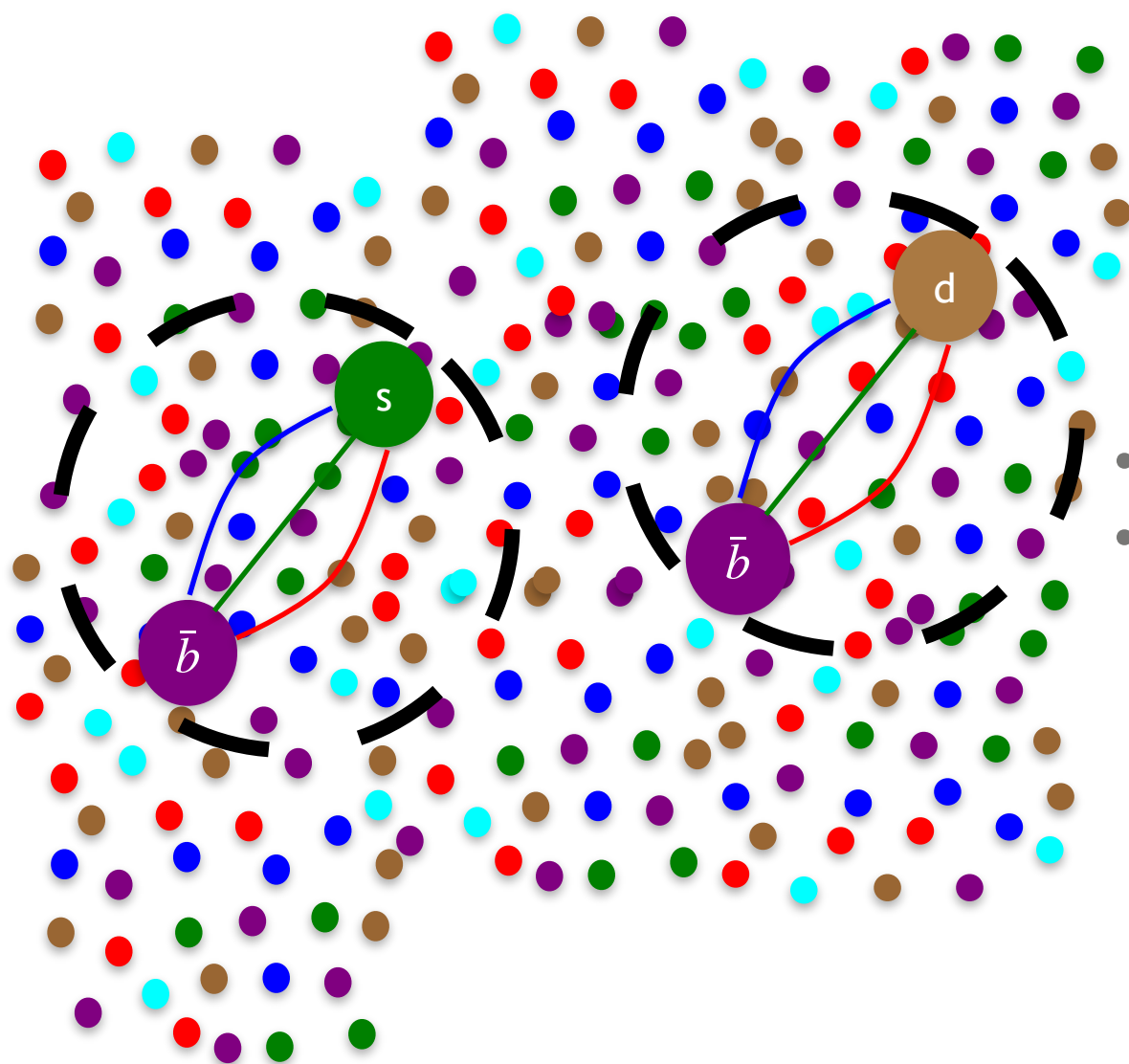
# Few questions on coalescence in small system

JHEP 368 08 (2015) 003  
 Phys. Rev. C 79 (2009) 044905  
 Eur. Phys. J. C 78, 348 (2018)

\* If coalescence is a « simple association » of nearby quarks in phase space:

- Need the quark degree of freedom or equivalent:
  - \* Two approaches in small system: « Small fireball » vs « color reconnection ».
  - \* Sensitive to quark density → sensitive to charged particle multiplicity?
- Production sensitive to medium hydrochemistry:
  - \* Sensitive to strangeness enhancement due to QGP production?

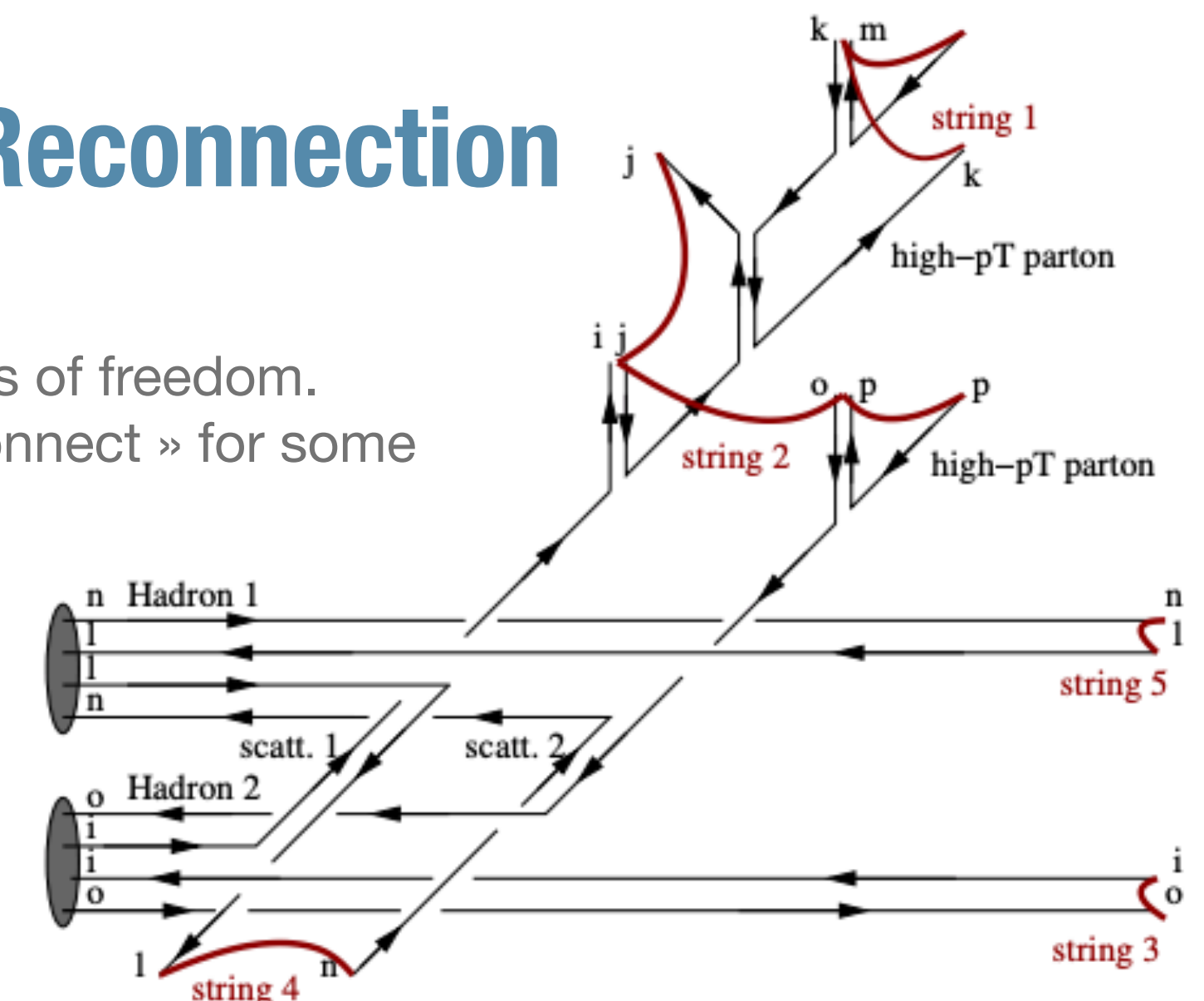
## « fireball » coalescence



- Transport equation in QGP medium.
- Wigner function at the hadronization stage.

## PYTHIA Color Reconnection

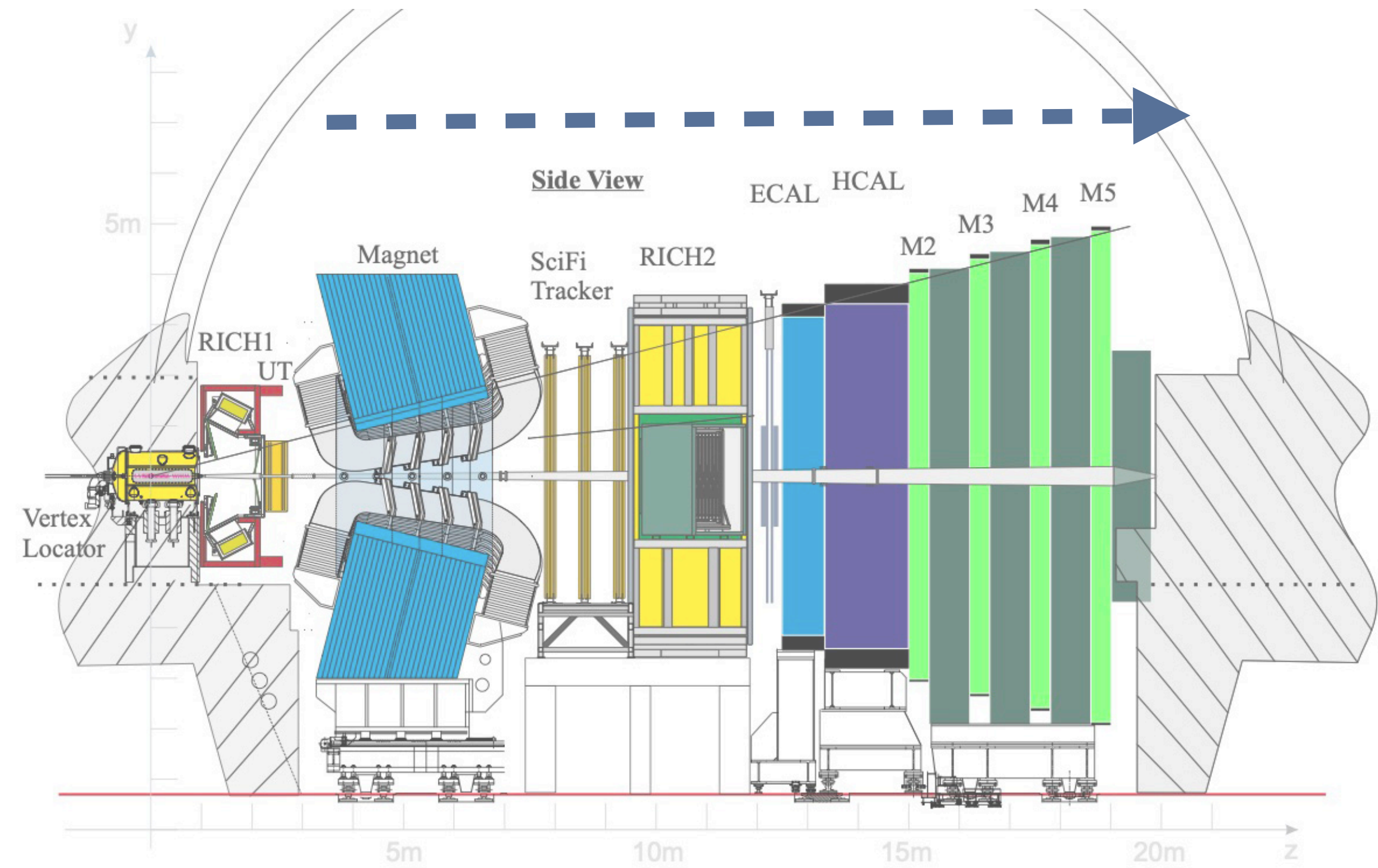
- Strings as degrees of freedom.
- Strings can « reconnect » for some topologies.





# On multiplicity metrics

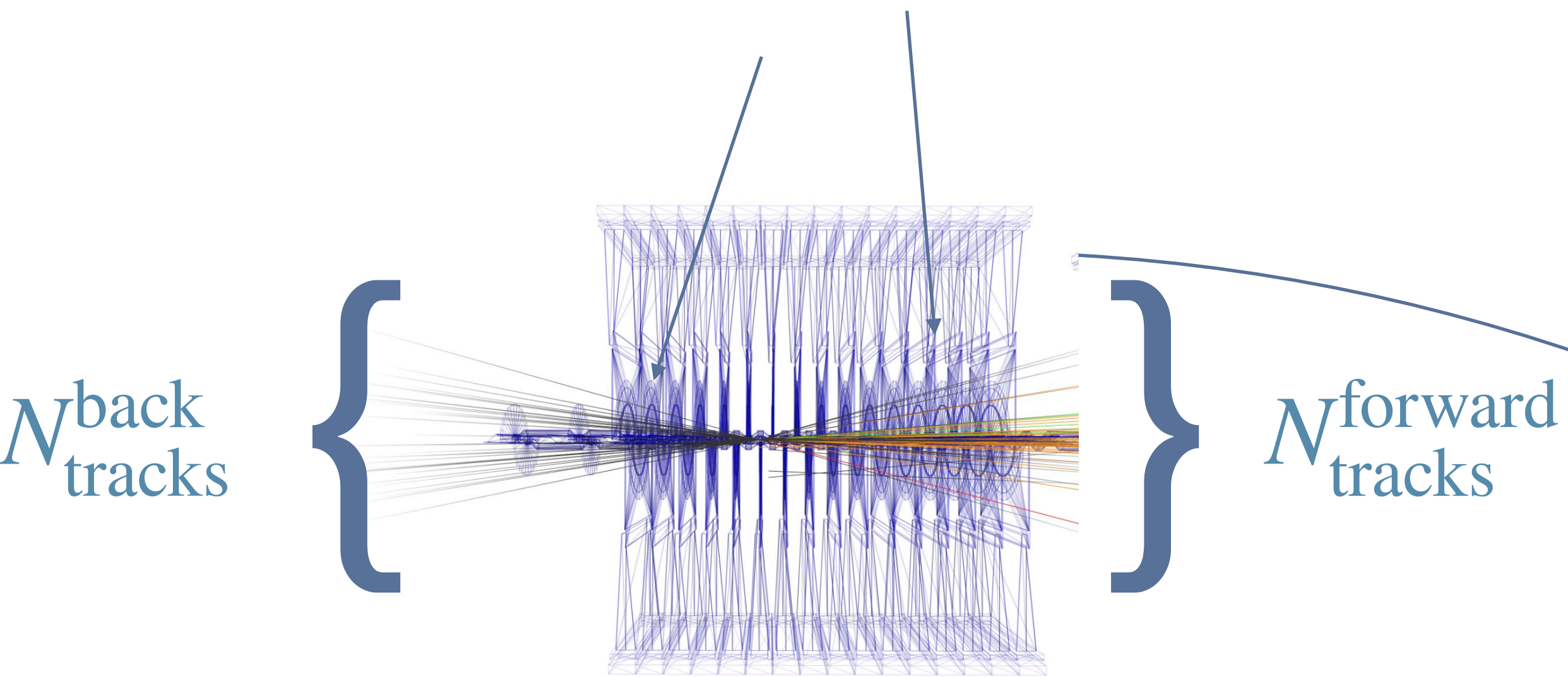
Particles are measured in forward direction





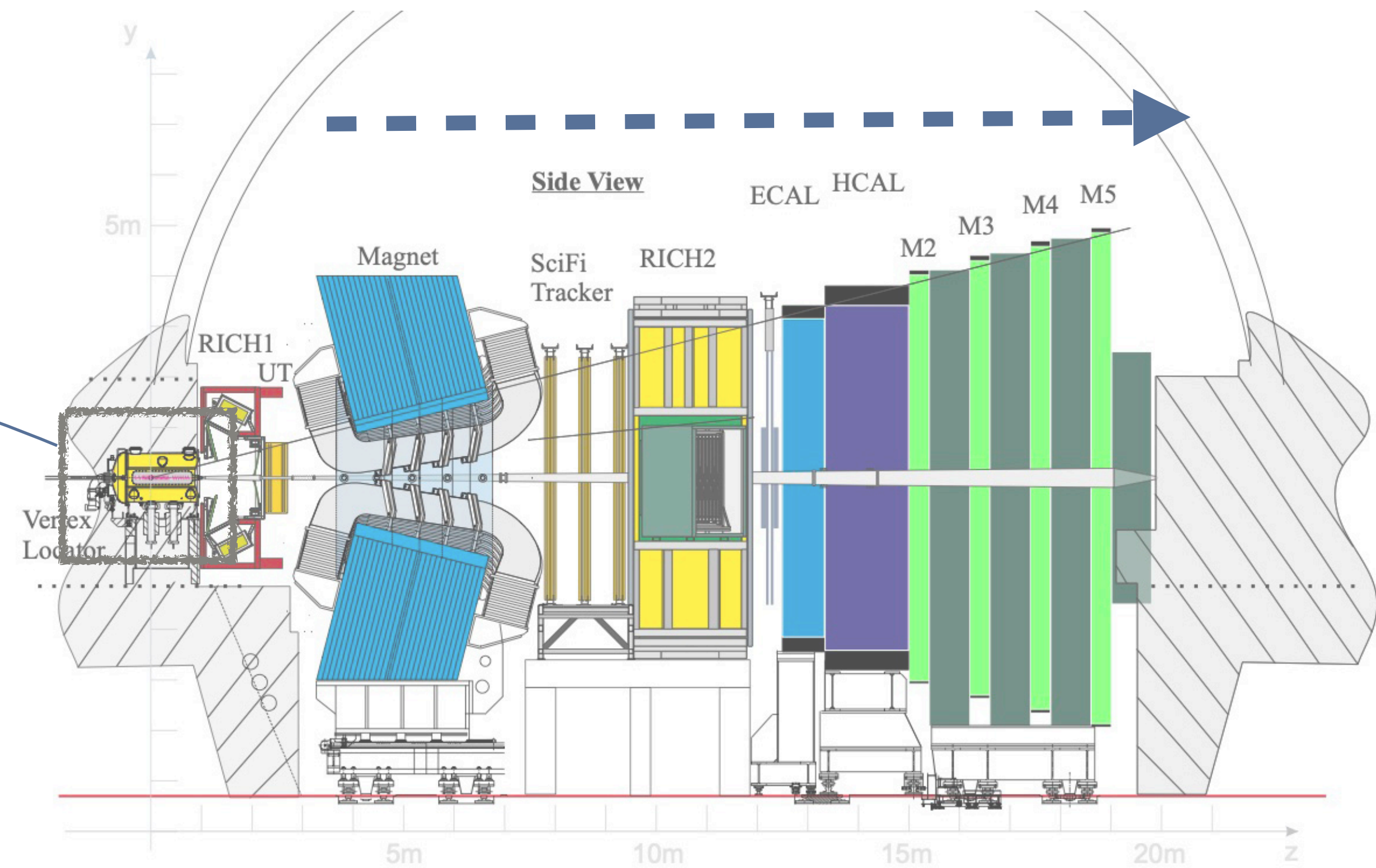
# On multiplicity metrics

$N_{Tracks}^{PV}$  = Number of tracks used to reconstruct primary vertex.



$$N_{tracks}^{VELO} = N_{tracks}^{forward} + N_{tracks}^{back}$$

Particles are measured in forward direction



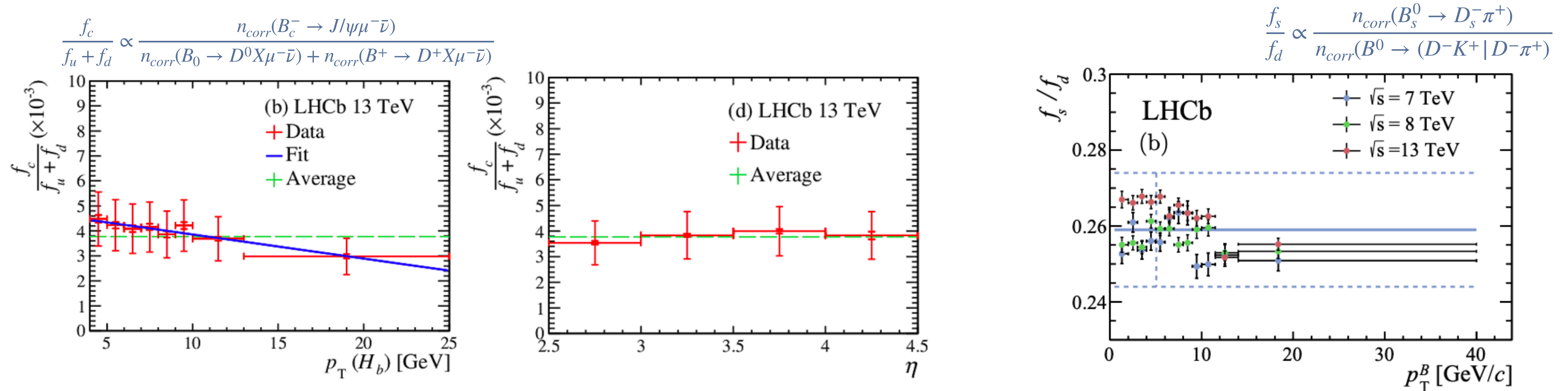


# SELECTED RESULTS

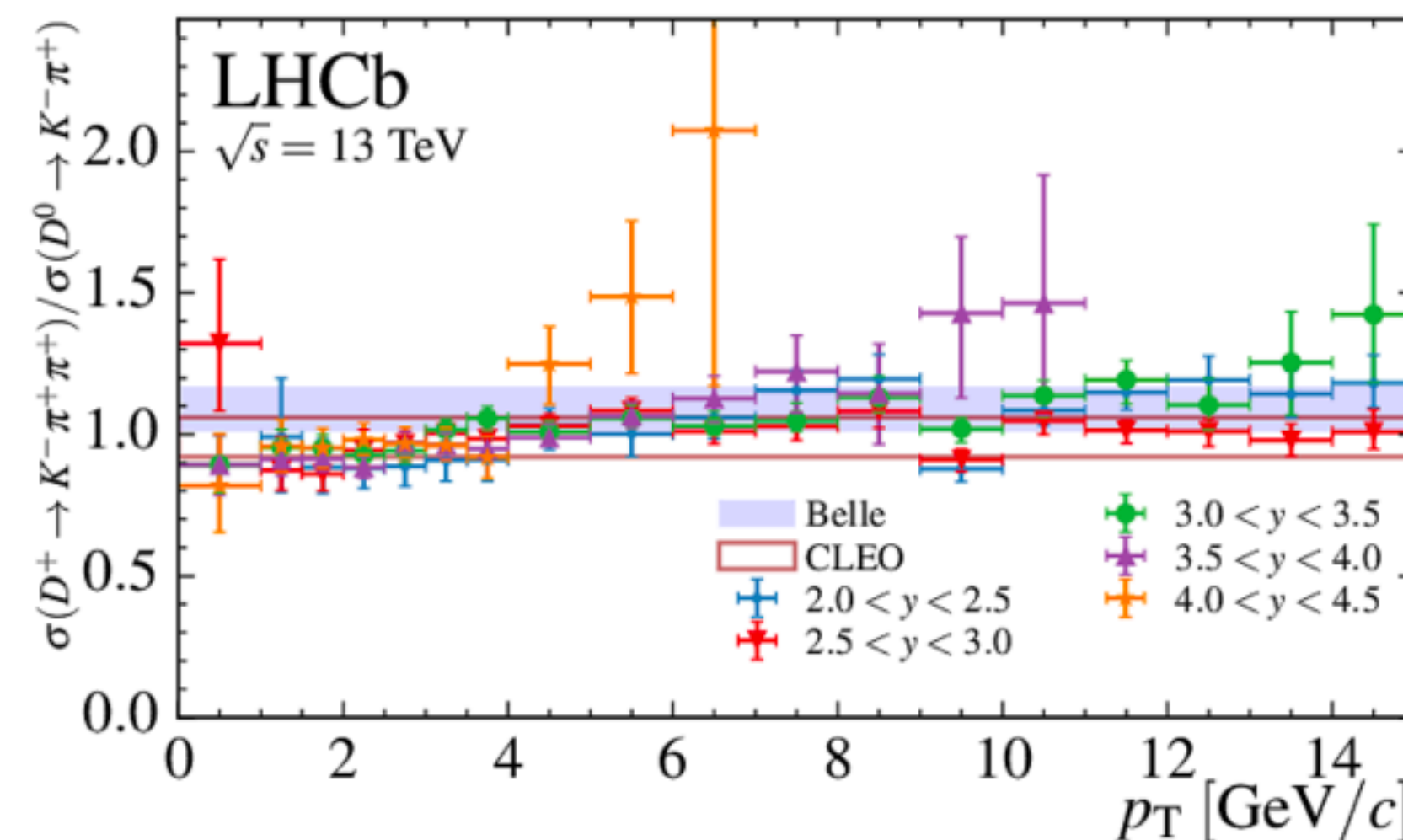


# Fragmentation fraction vs LHCb

PHYS. REV. D100 (2019) 112006  
 Phys. Rev. Lett. 124, 122002 (2020)  
 JHEP 05 (2017) 074



- \* Fragmentation fractions measured with B mesons:
  - Little variations versus  $p_T$ , rapidity and colliding energy.
- \* Ratios between prompt open-charm states:
  - **Good agreement** with measurements in  $e^+e^-$  colliders.
- \* What about coalescence ?
  - Need to look at other observables.

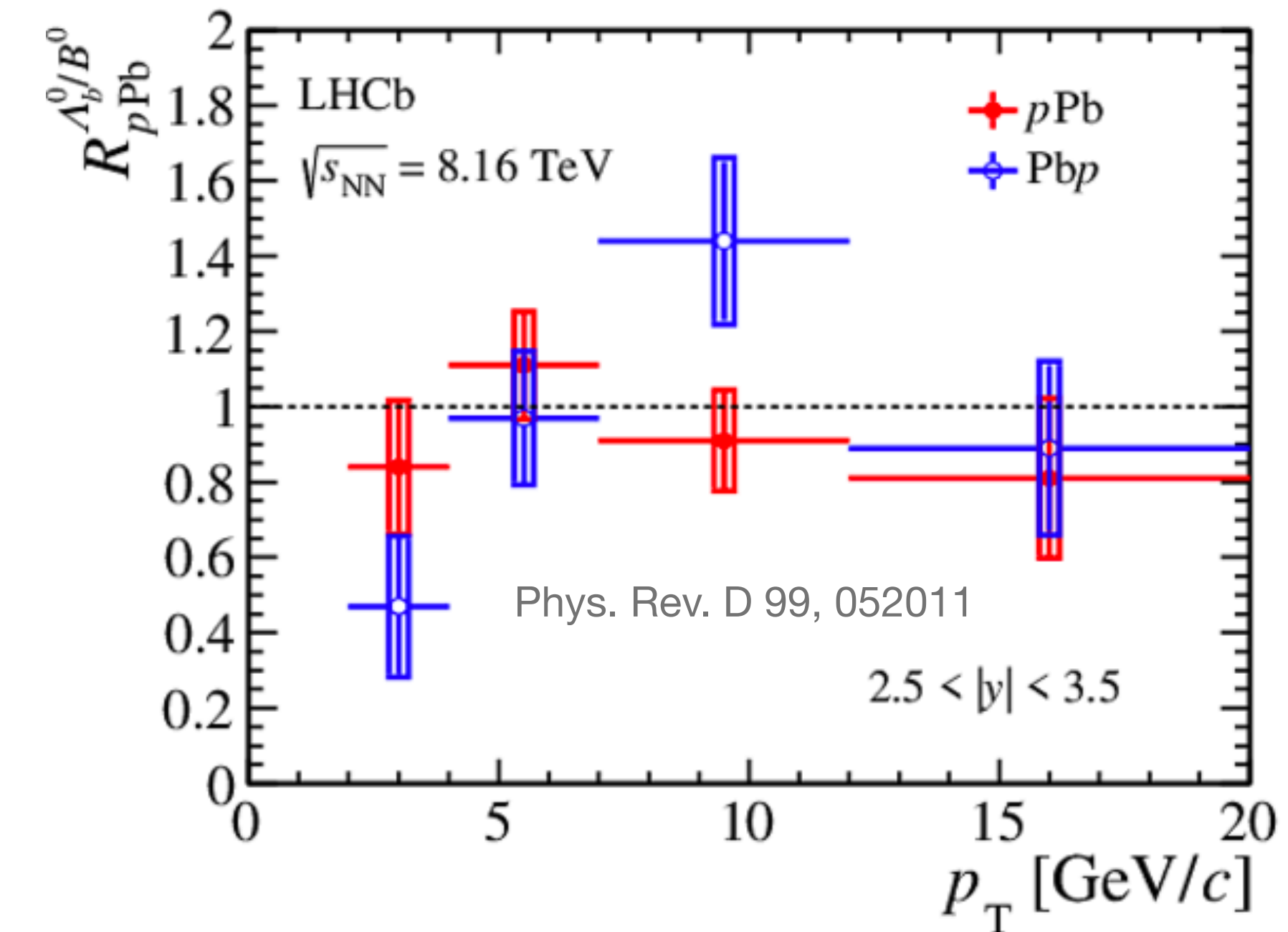




# $\Lambda_b^0/B^0$ versus multiplicity

From first results in pPb and pp...

arXiv:2310.12278

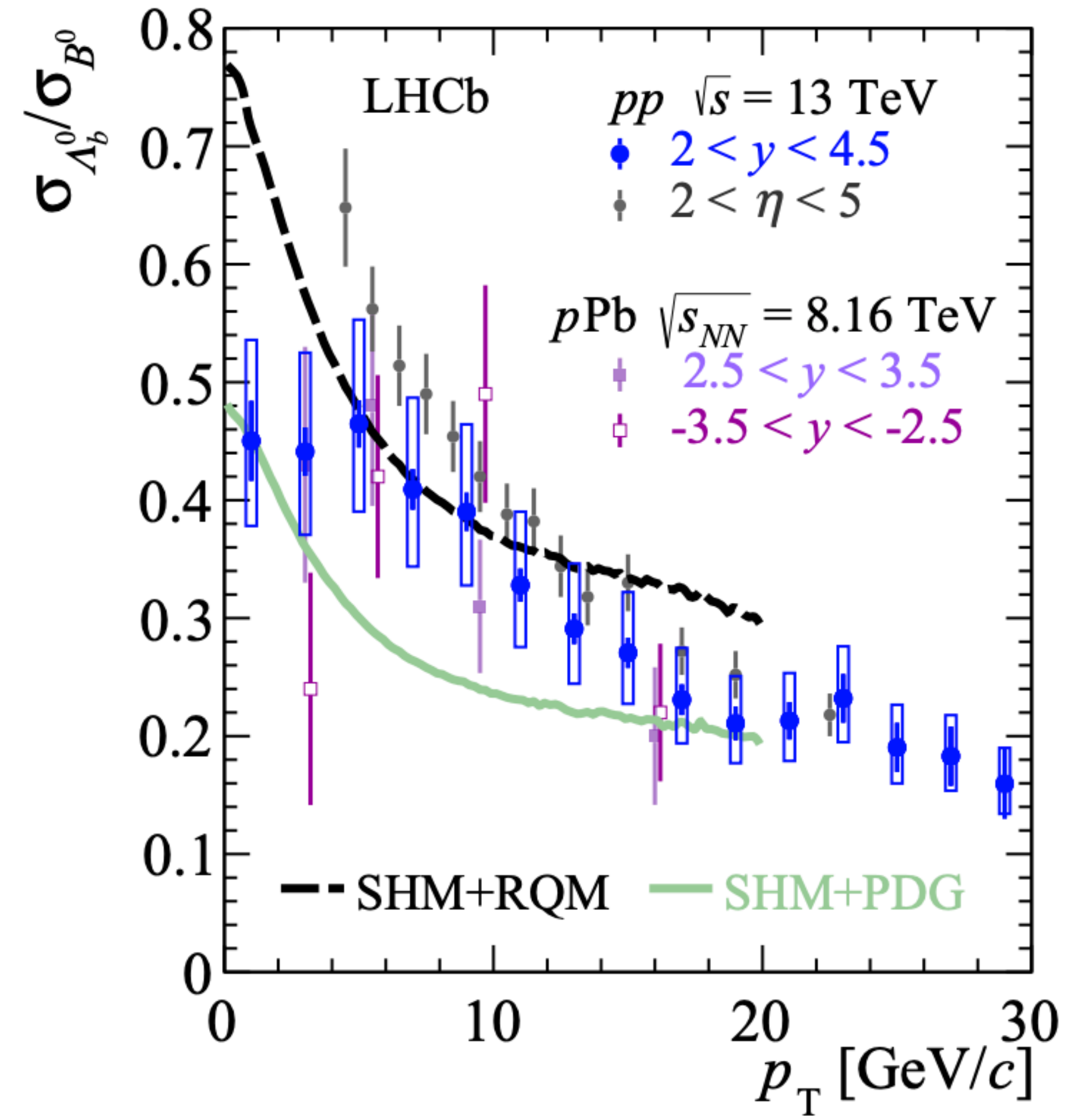
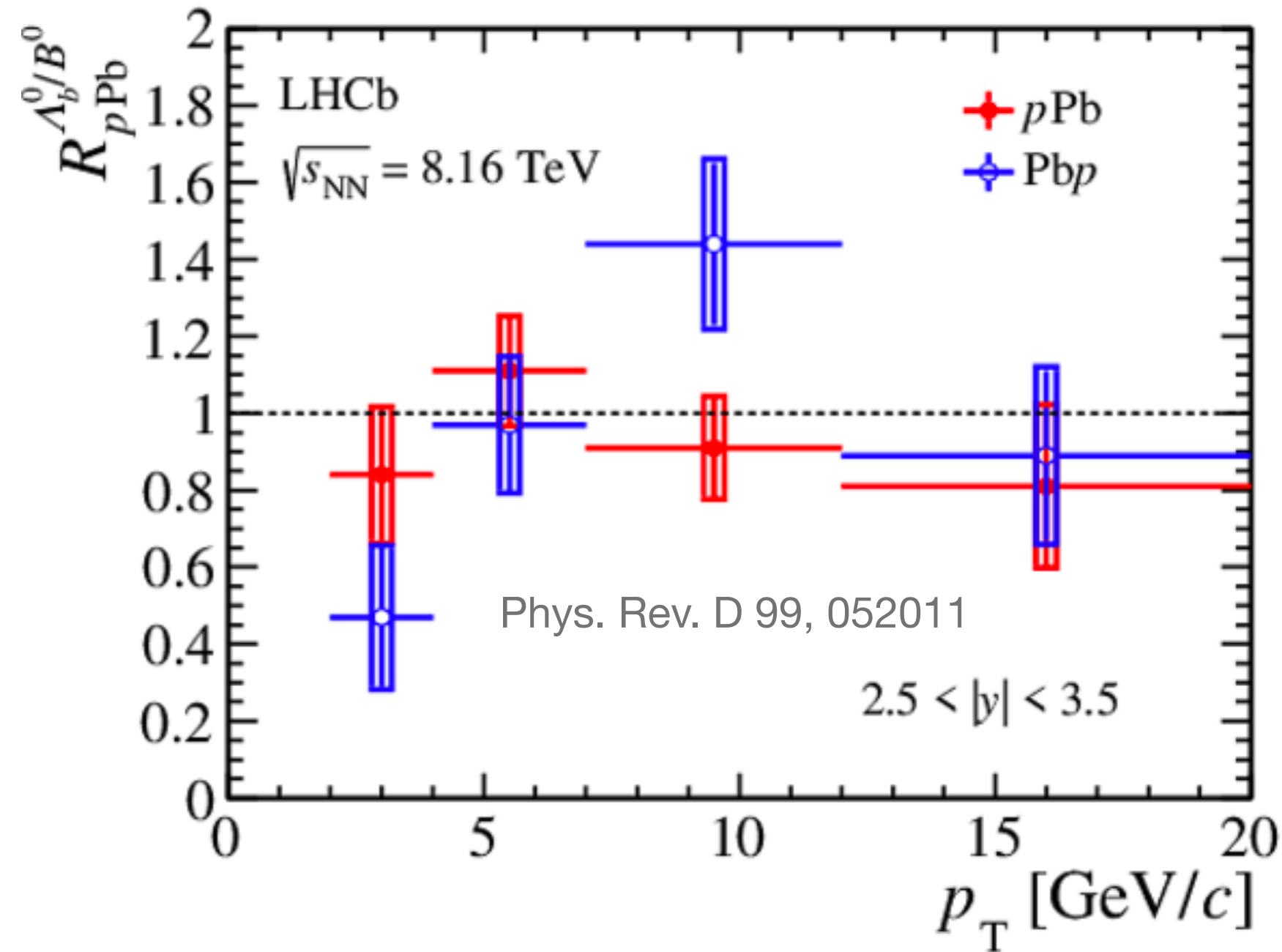




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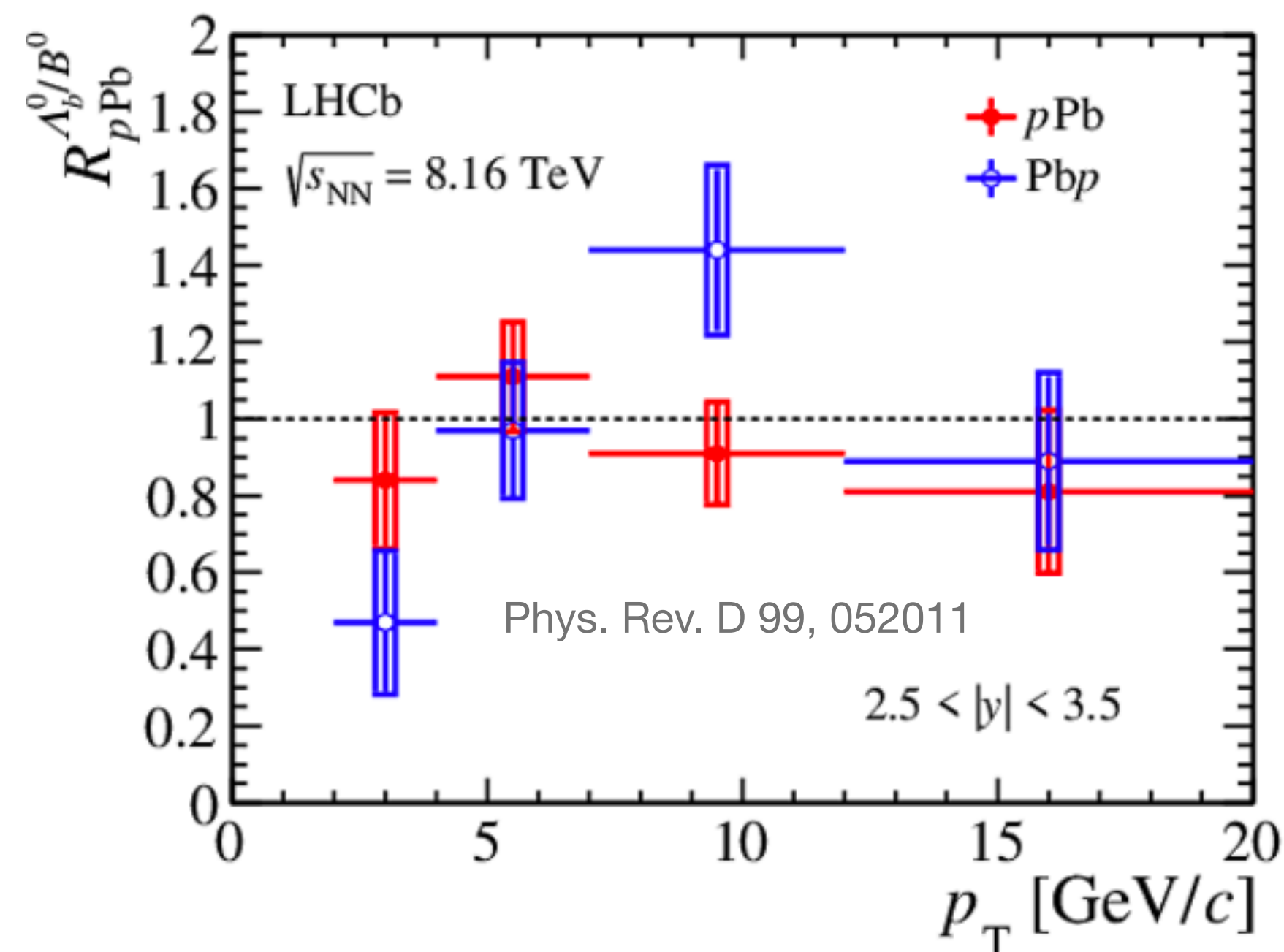


... to new results in pp



# $\Lambda_b^0/B^0$ versus multiplicity

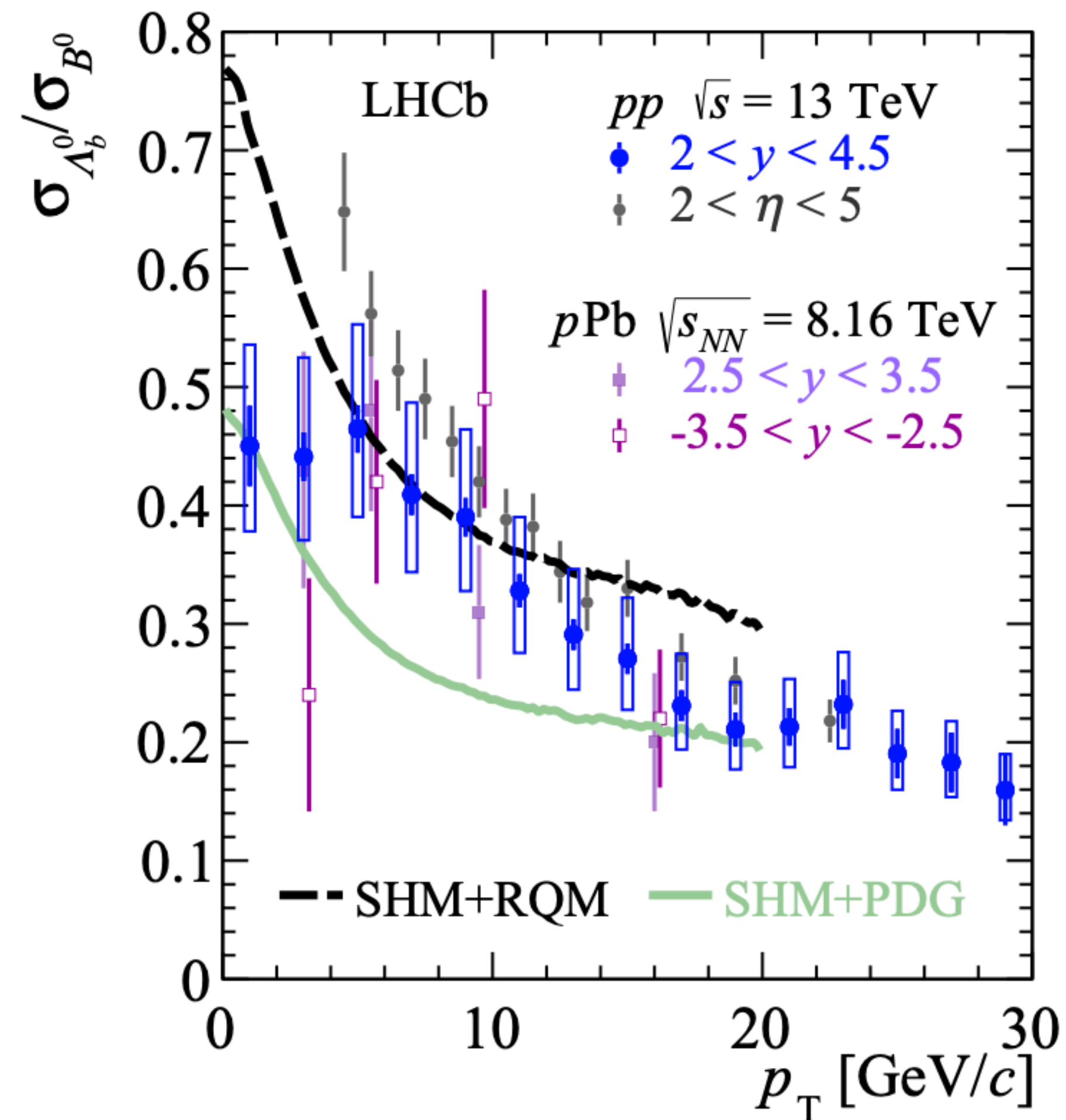
From first results in pPb and pp...



- \* SHM+PDG: « Small fireball » + fragmentation from PDG state.
- \* SHM+RQM: SHM+PDG + addition fragmentation from excited states.
- \* Good agreement between SHM+RQM and data → **no need of coalescence?**

SHM: Phys. Rev. Lett. 131, 012301

arXiv:2310.12278

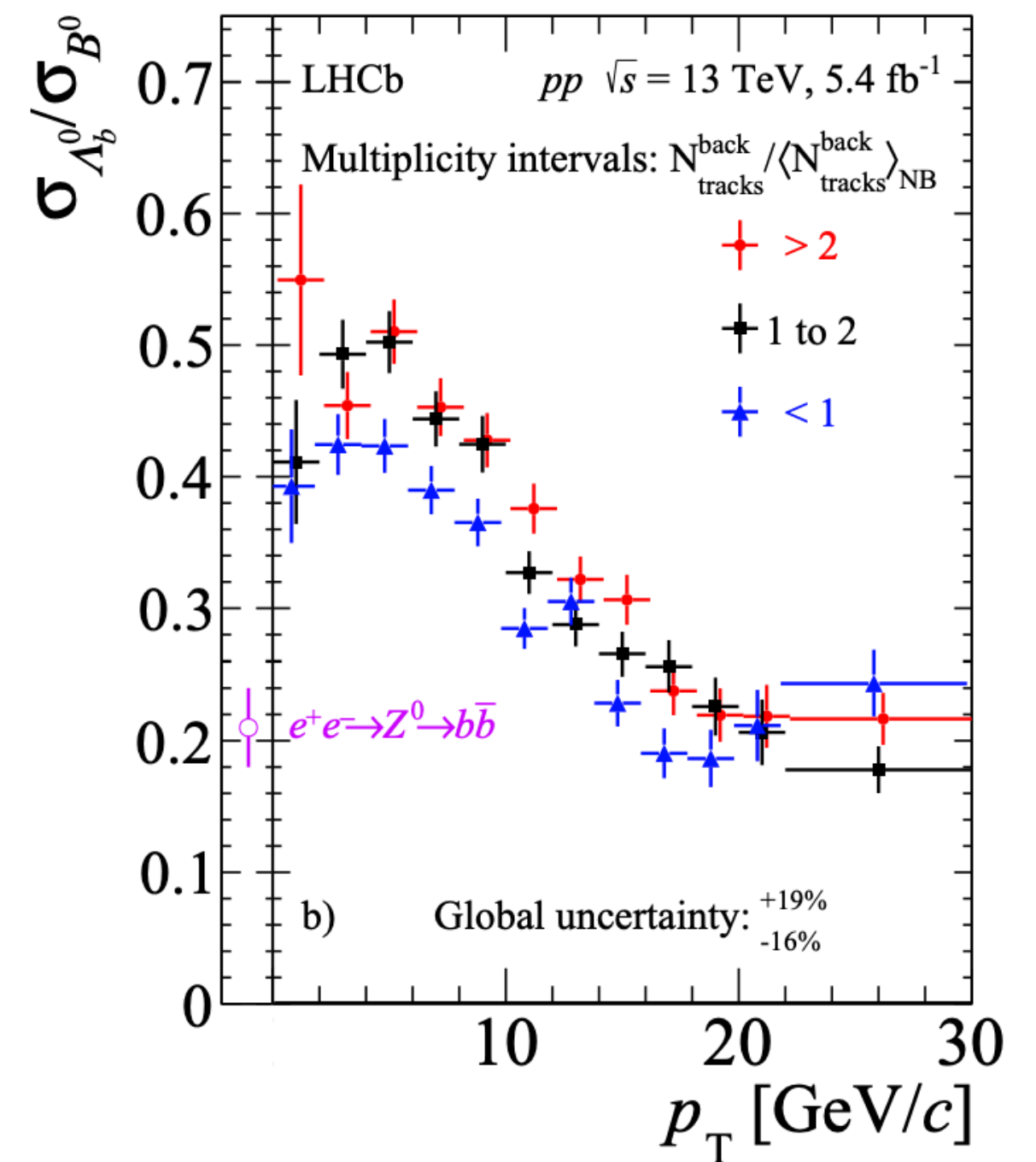
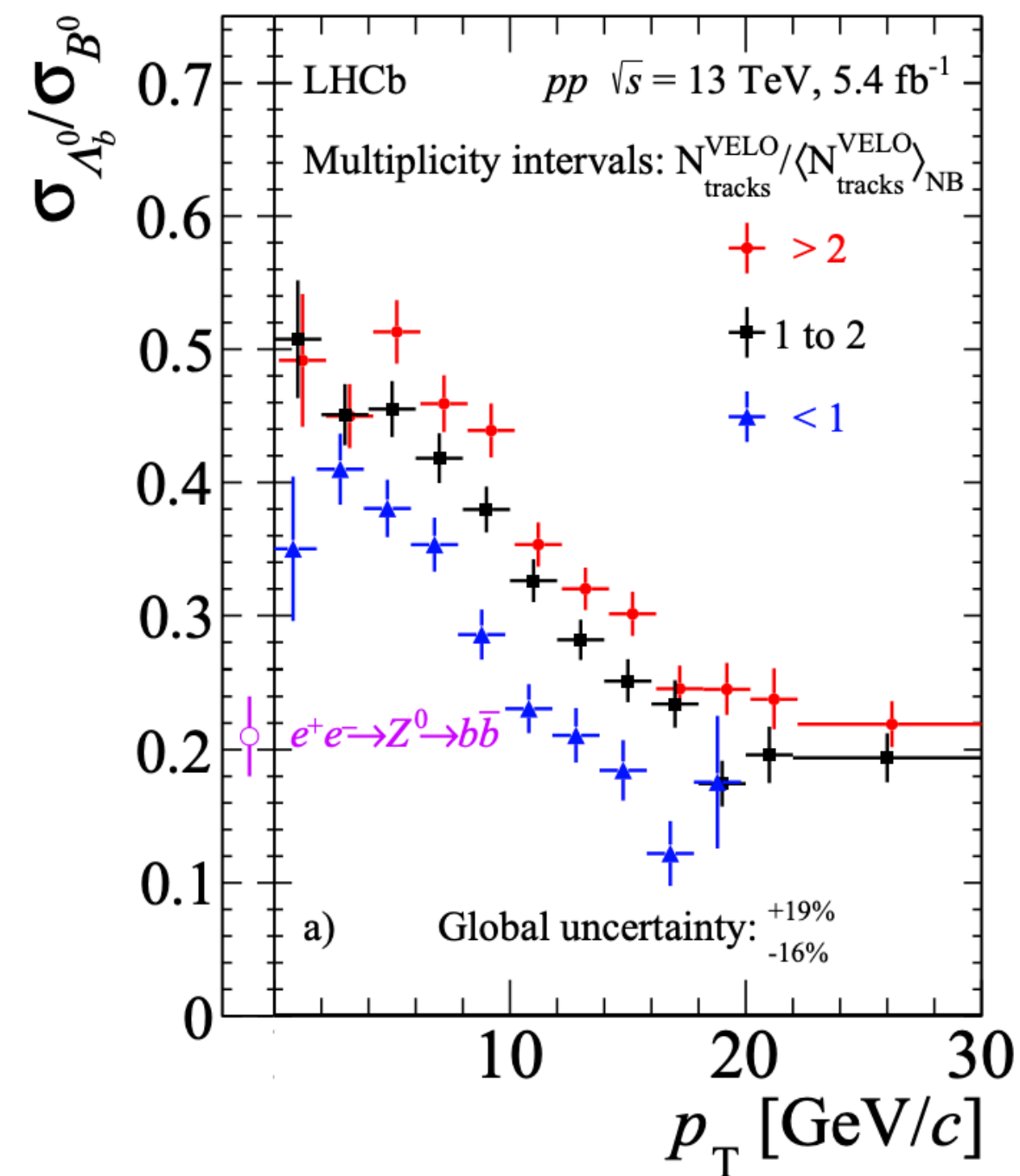
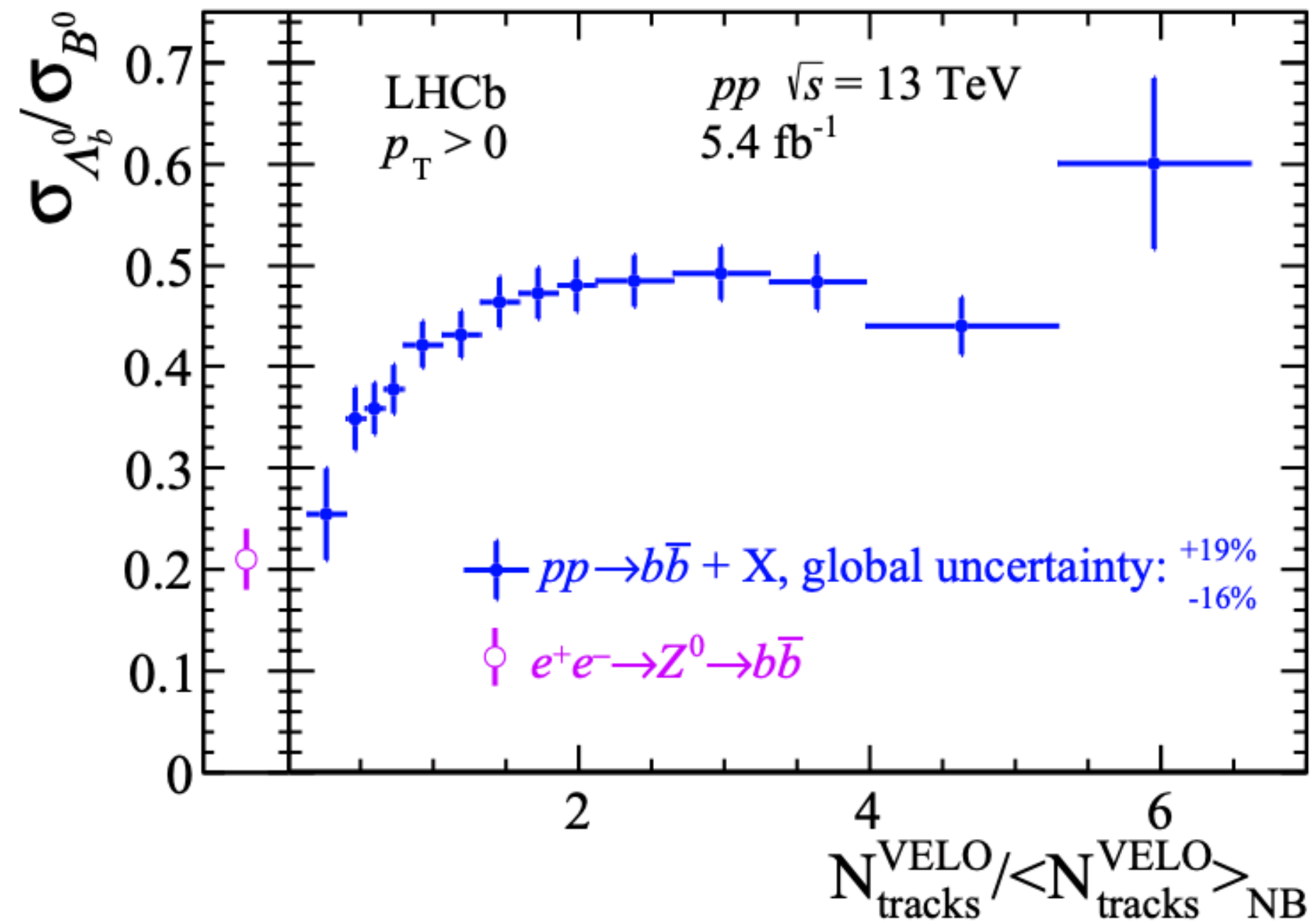


... to new results in pp



# $\Lambda_b^0/B^0$ versus multiplicity

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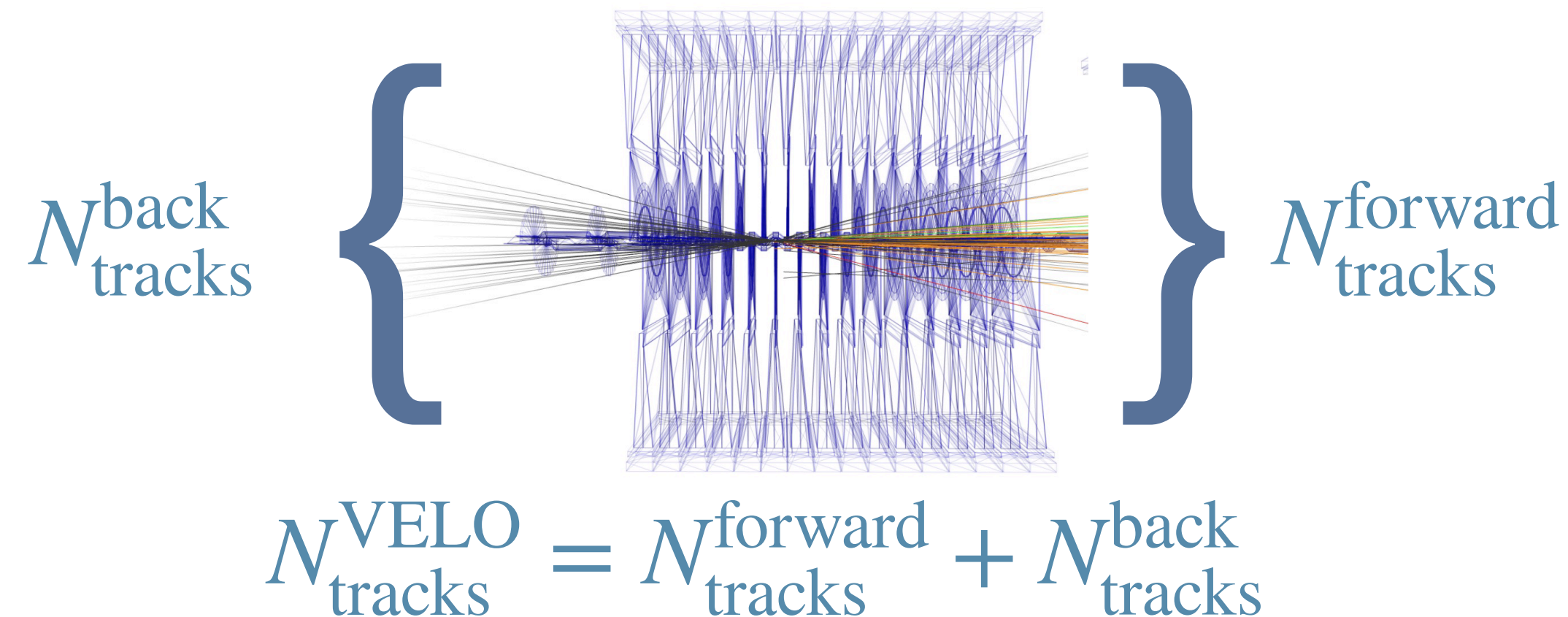


\* Clear dependance with multiplicity.

- More sensitive to  $N_{\text{tracks}}^{\text{VELO}}$ .

\* Recover  $e^+e^-$  results at low multiplicity (i.e. no activity).

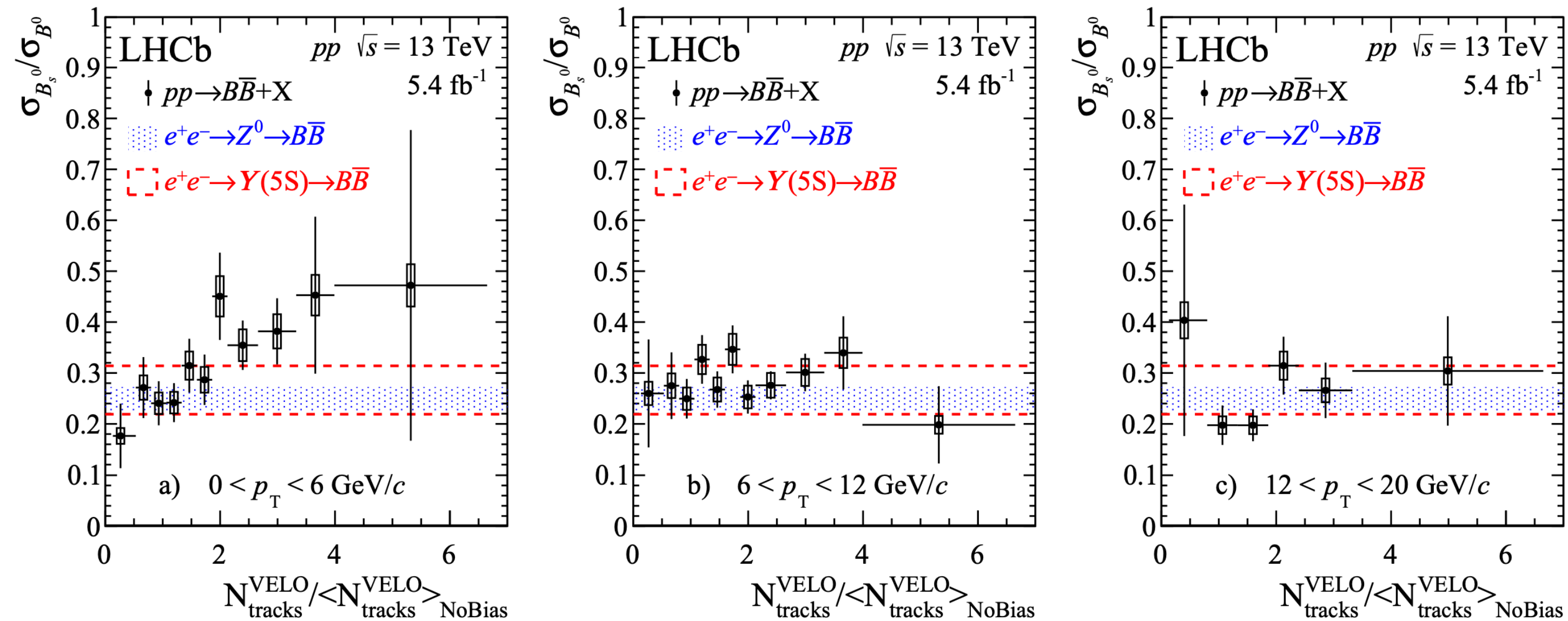
- Clear effect of the QCD medium.



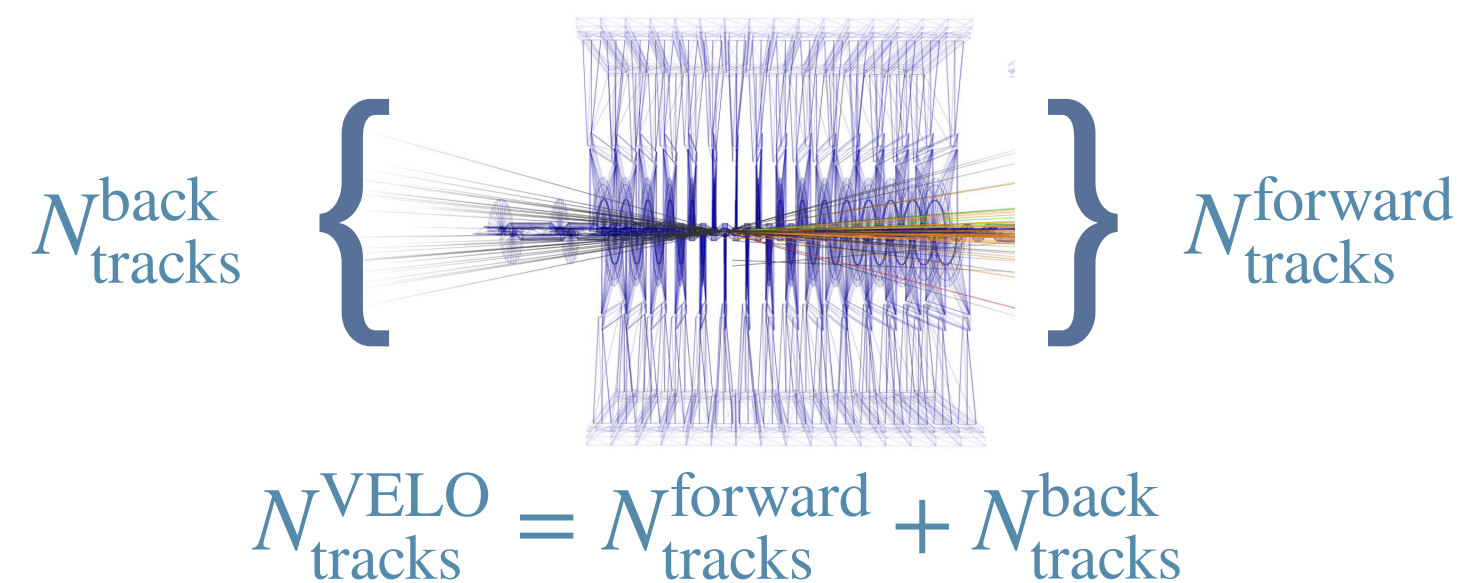


# $B_s^0/B^0$ production versus multiplicity in pp@13TeV

Phys. Rev. Lett. 131 (2023) 061901



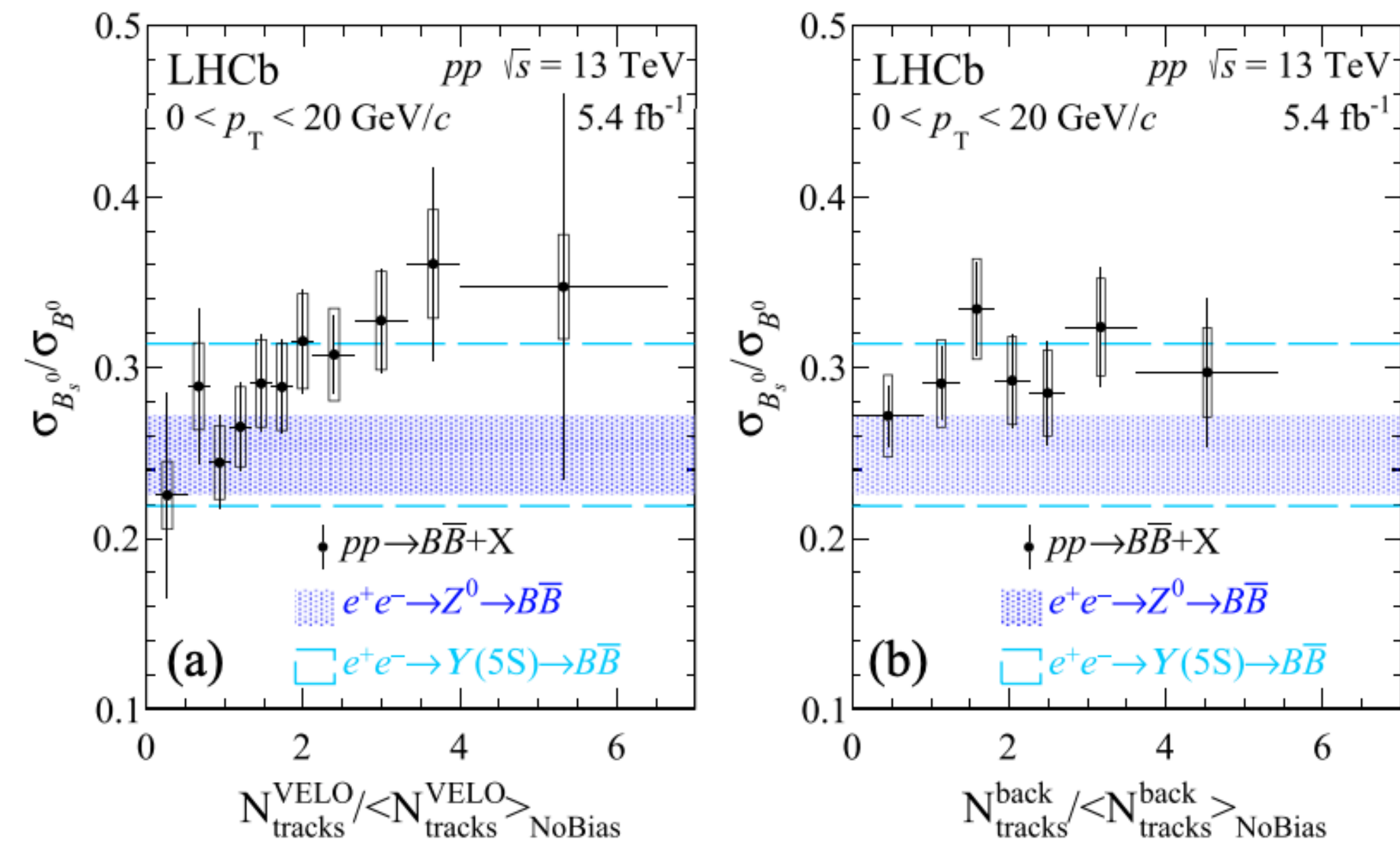
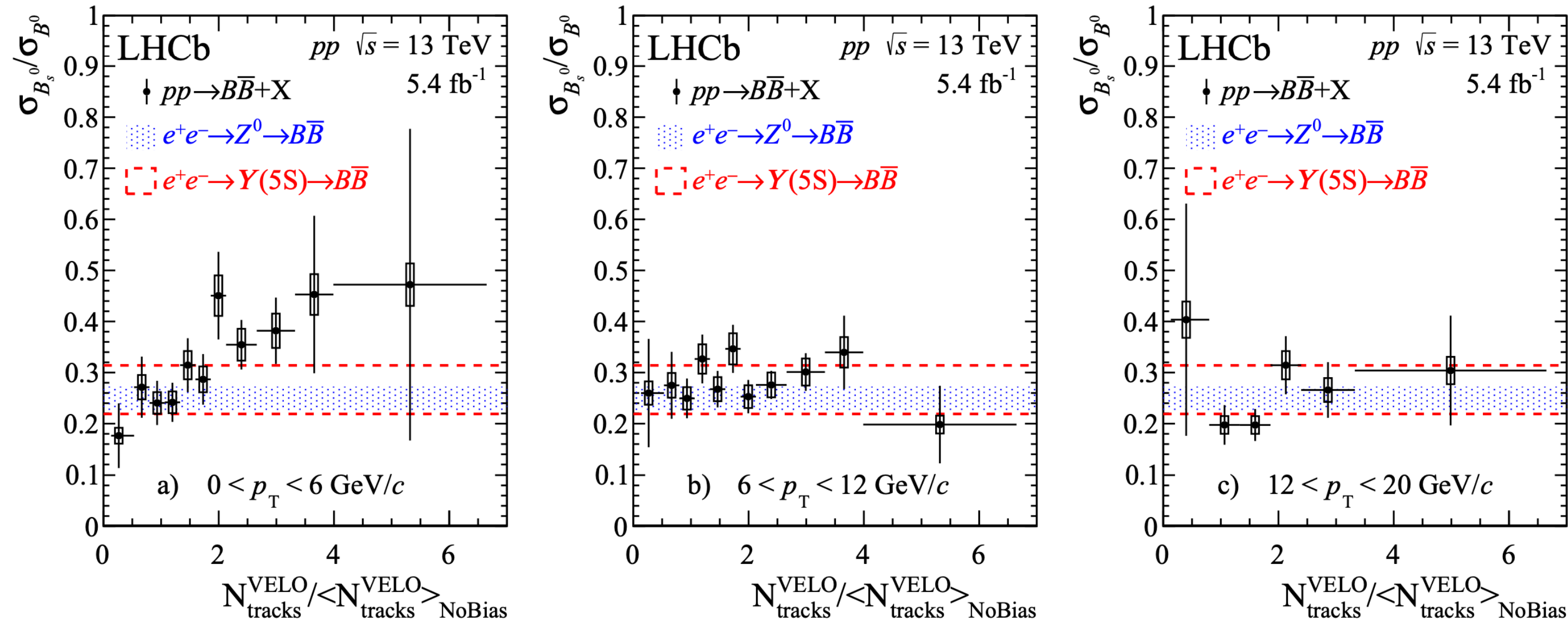
- Increase of  $B_s^0/B^0$  with multiplicity at low- $p_T$ .
  - Slope significance = 3.4 sigma.
- No significant dependence on multiplicity at high- $p_T$ , consistent with  $e^+e^-$  data.



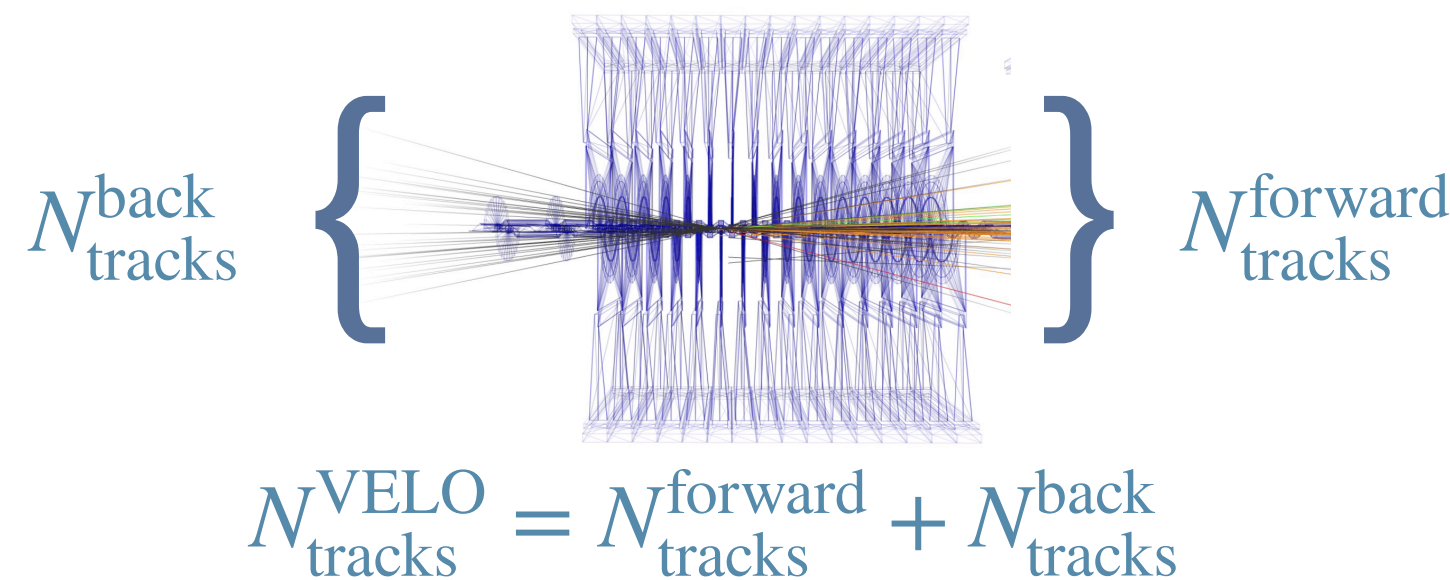


# $B_s^0/B^0$ production versus multiplicity in pp@13TeV

Phys. Rev. Lett. 131 (2023) 061901



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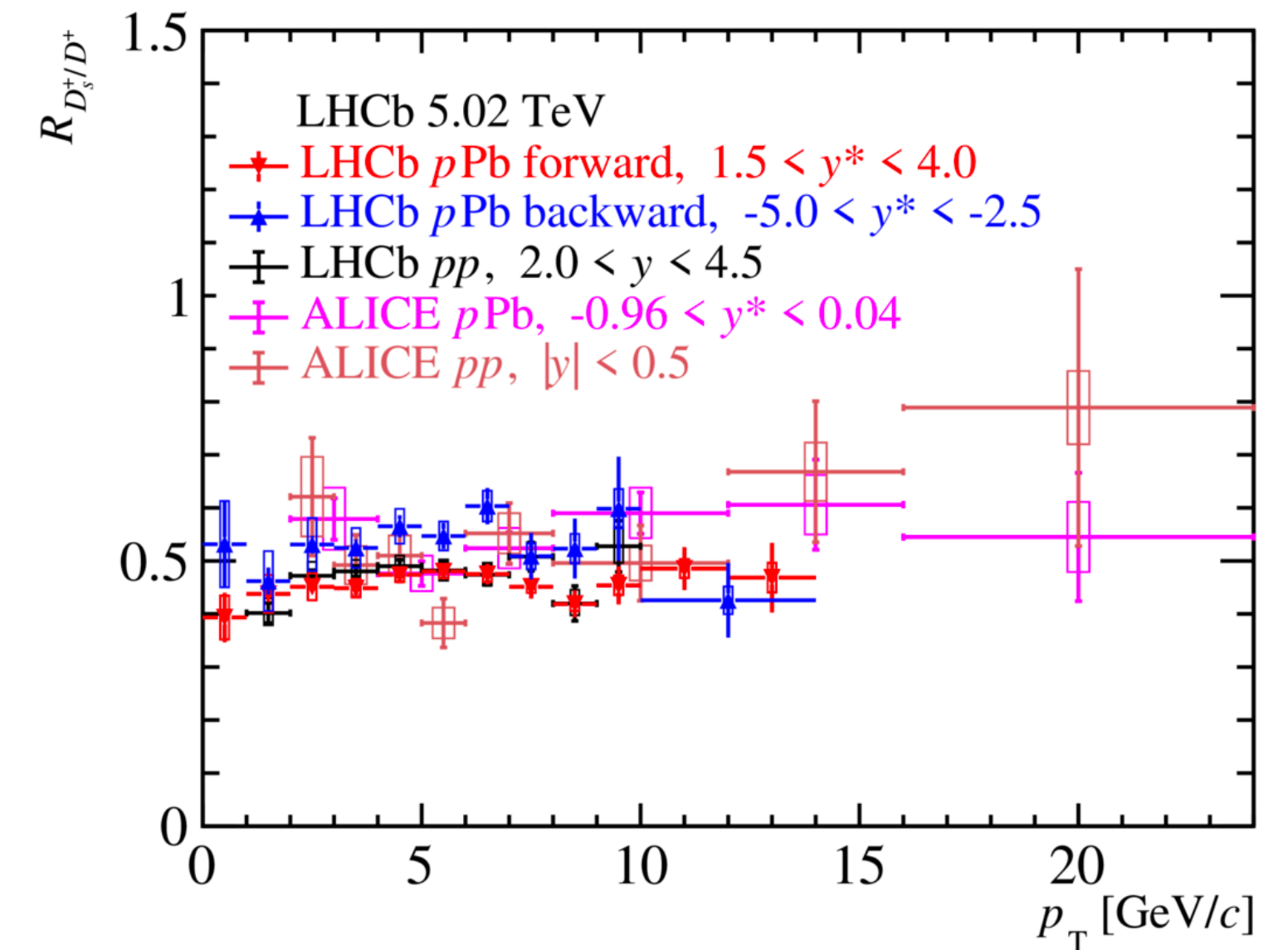
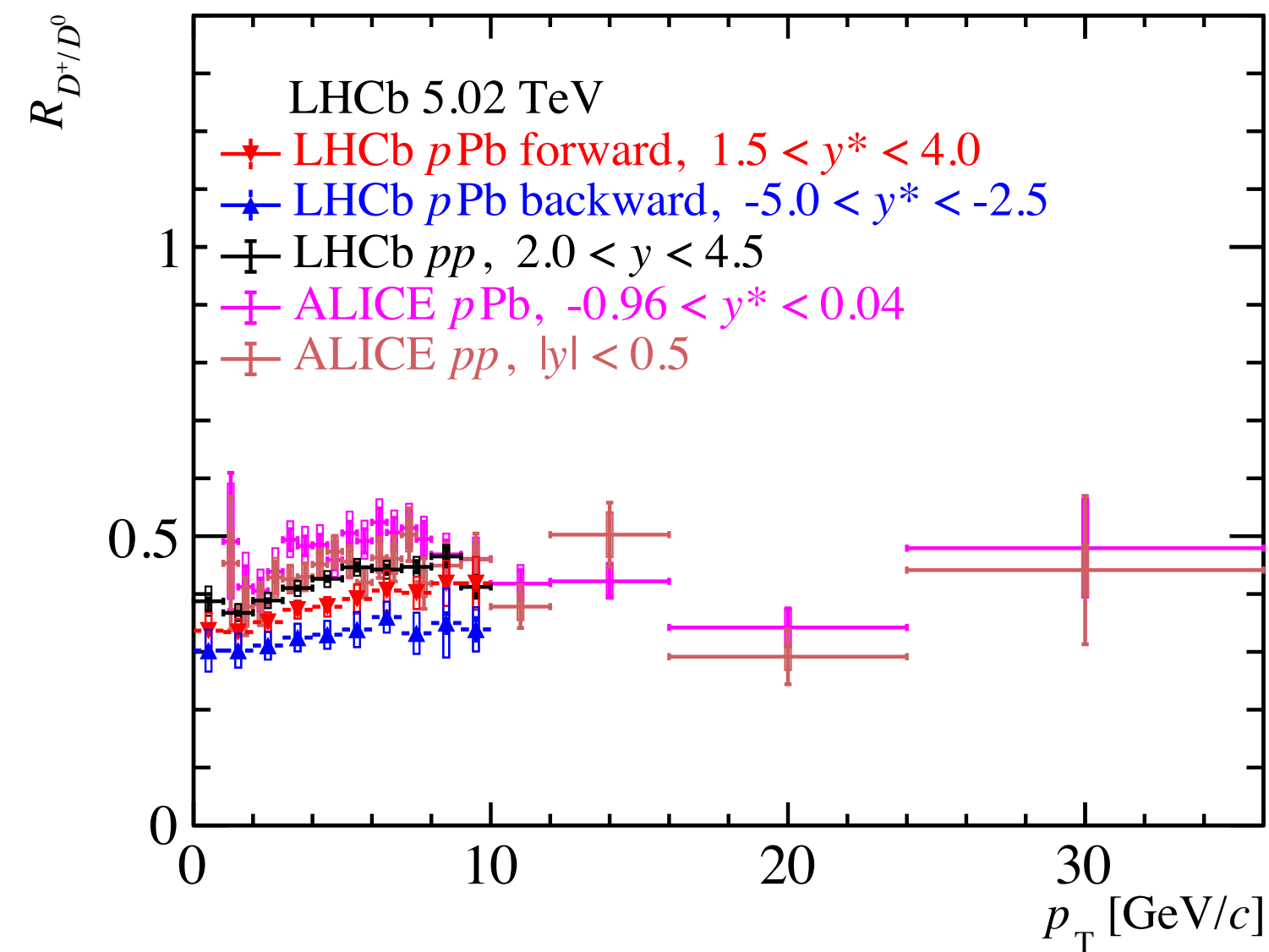
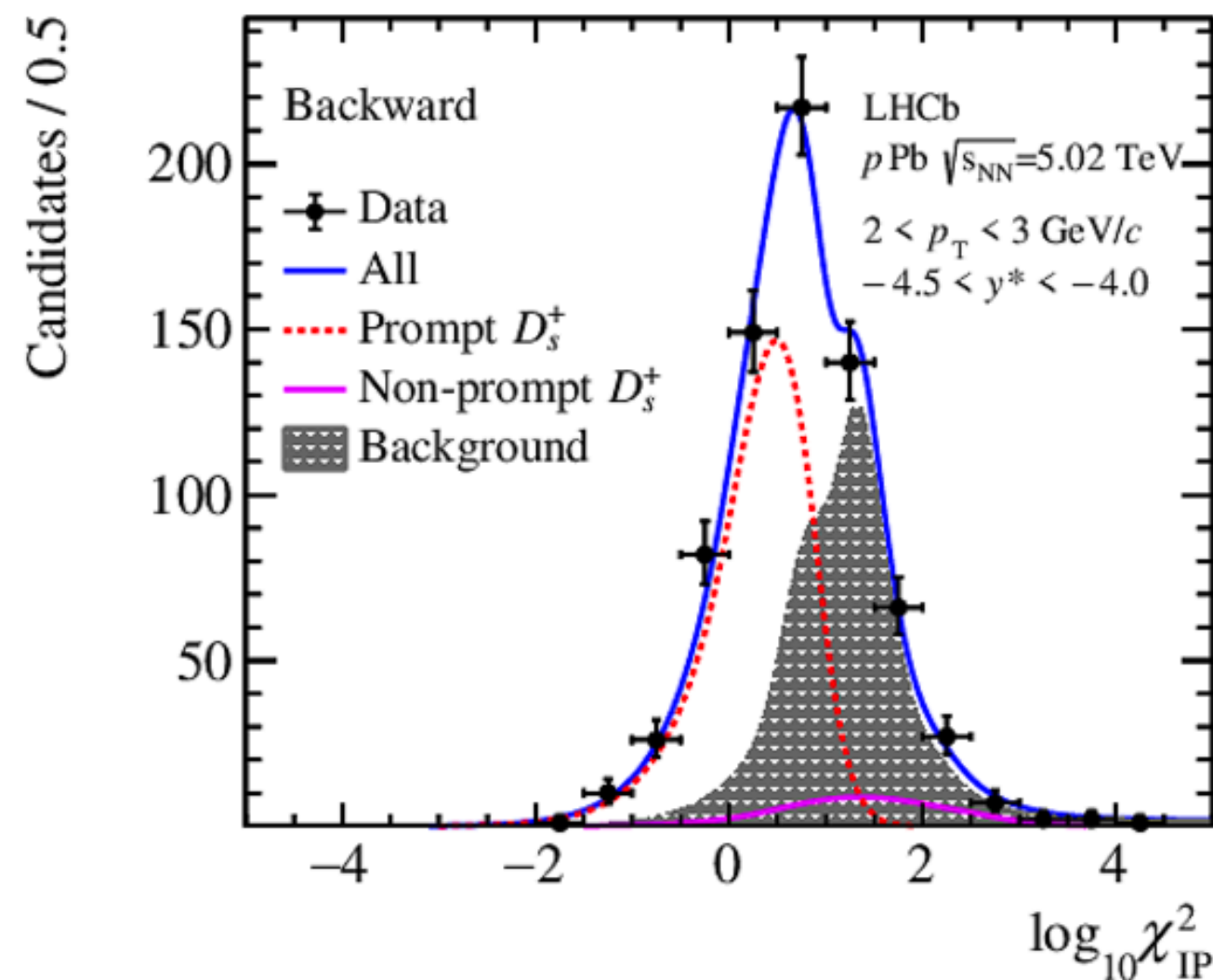
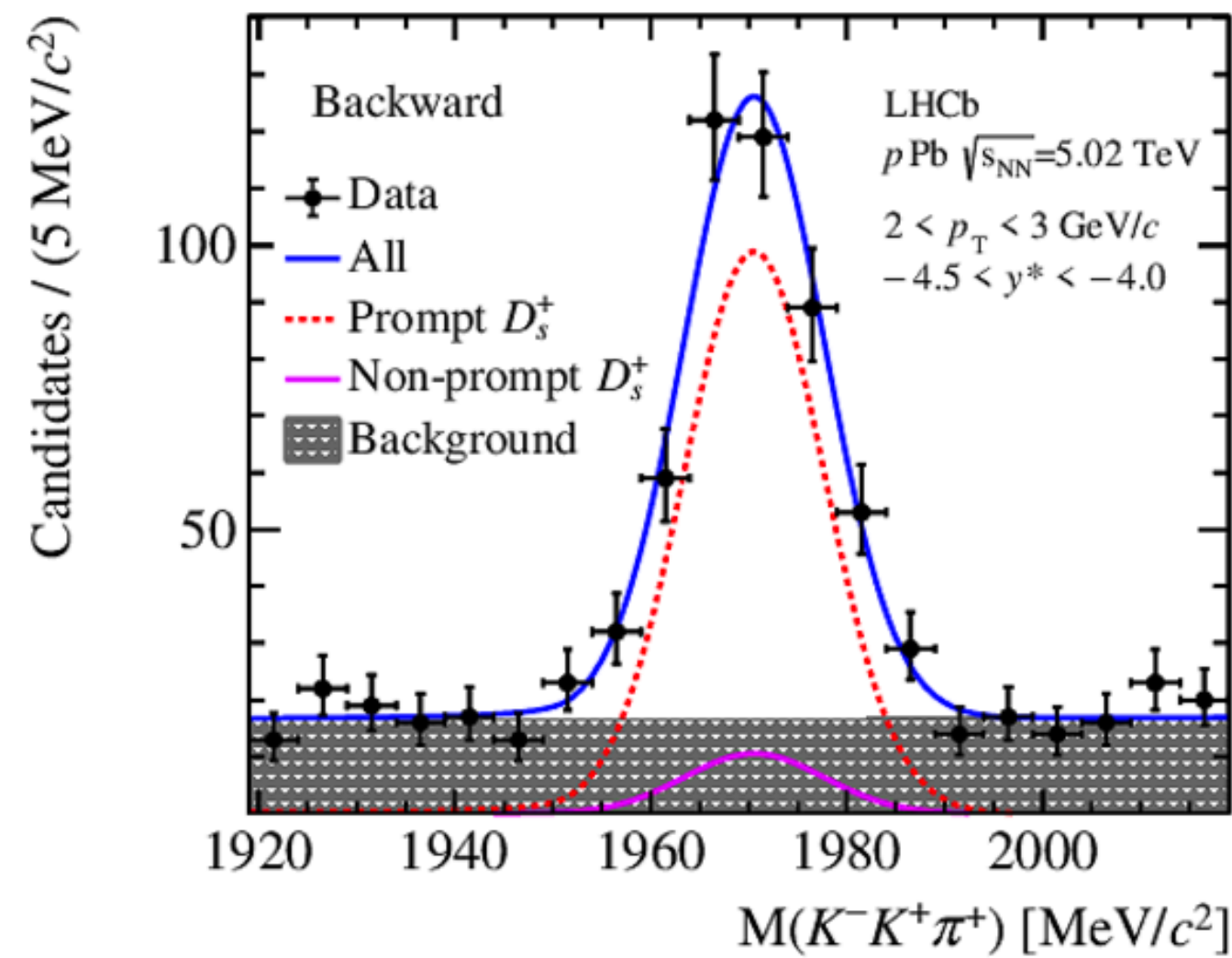
- Different dependence with  $N_{\text{tracks}}^{\text{VELO}}$  and  $N_{\text{tracks}}^{\text{back}}$ 
  - Still compatible with  $e^+e^-$  data.
  - Effect of fragmentation only or complex interplay of hadronization effects?



# $D_s^+$ in $p$ Pb: probe for strangeness enhancement?

arXiv:2309.14206

## Simultaneous fits of D-mesons

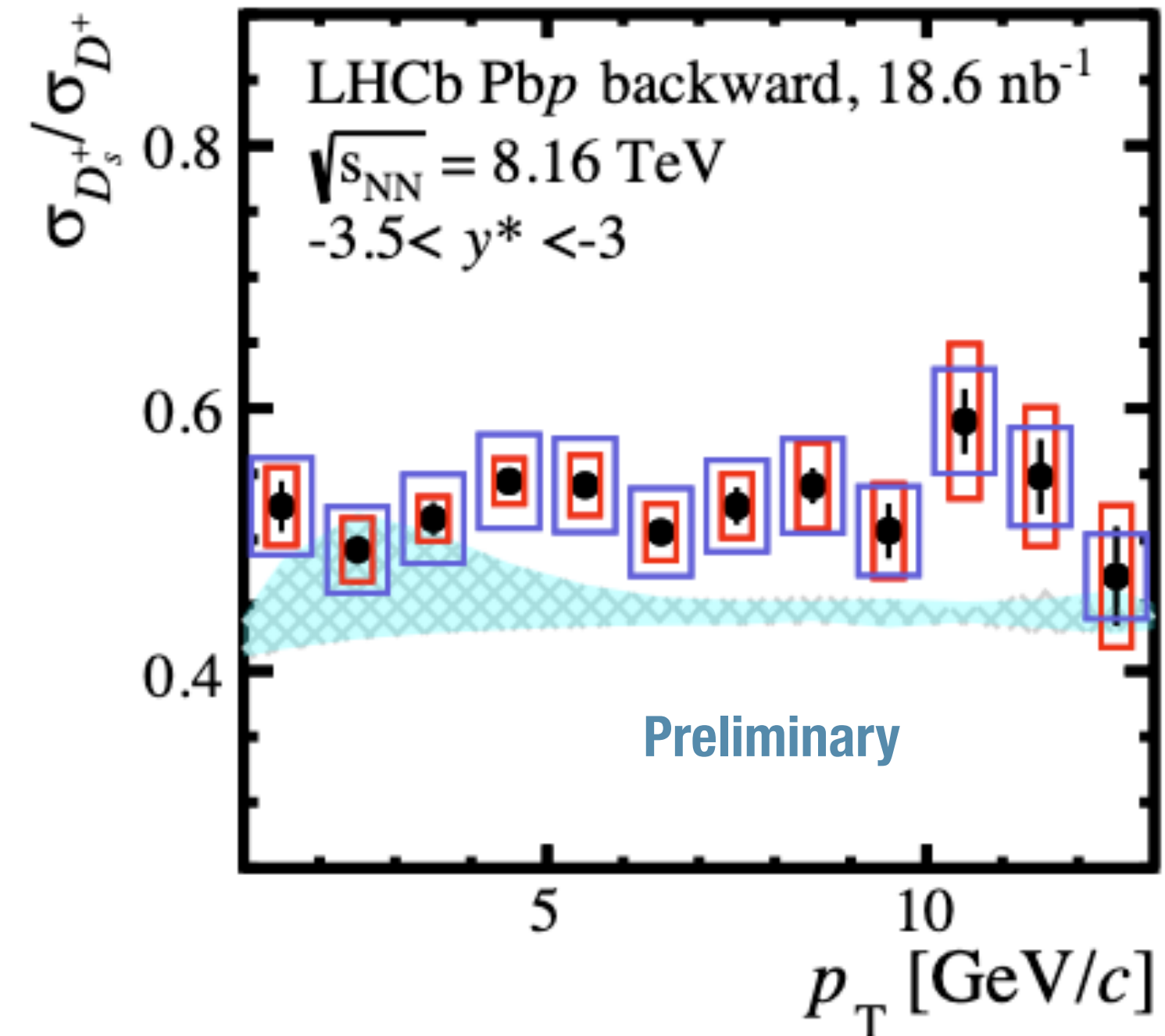
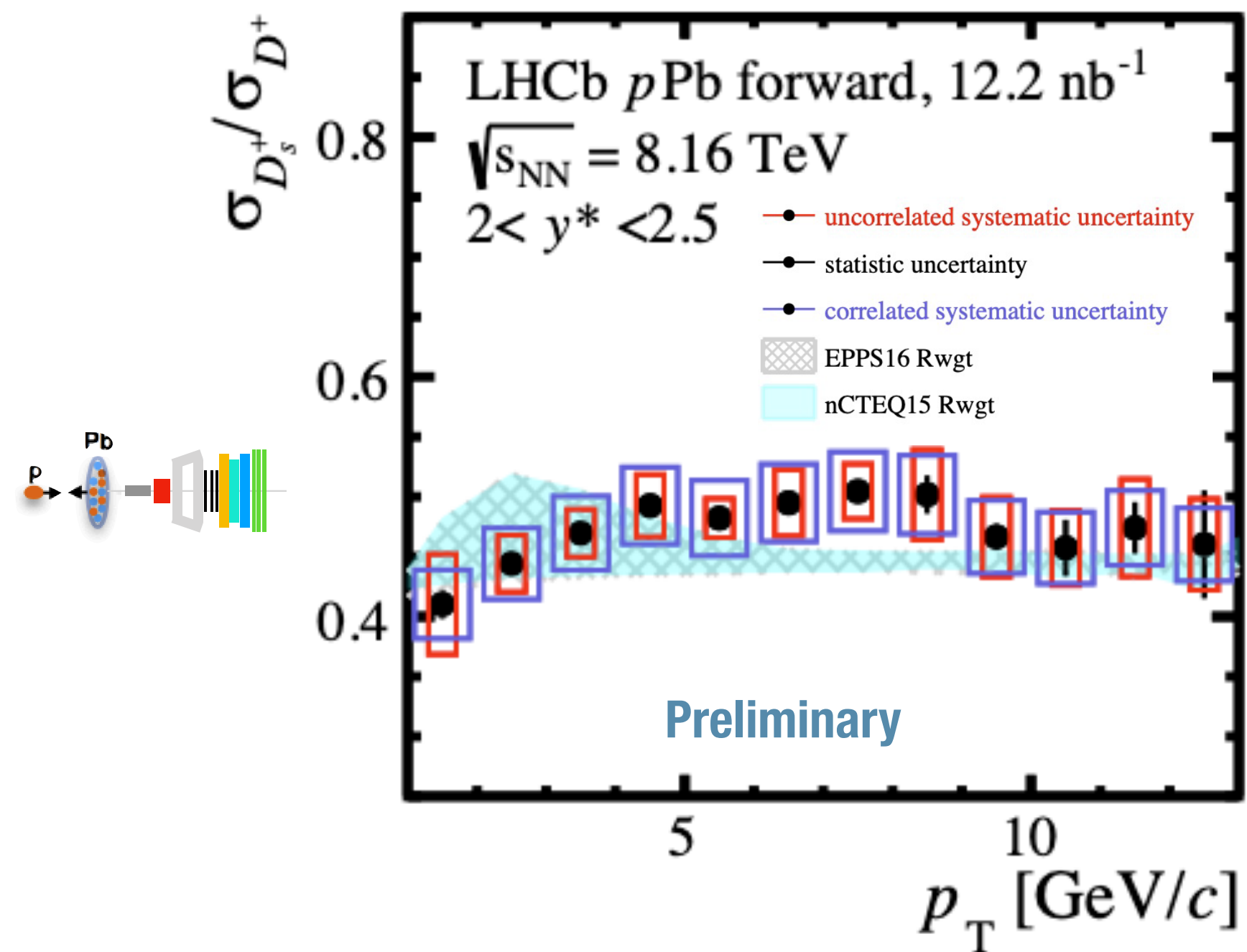


- \* **Rapidity dependence** of the  $D^+/D^0$  ratio at low to intermediate  $p_T$ .
  - Mid-rapidity (ALICE)  $>$  Forward  $>$  Backward.
- \* **Not so clear for  $D_s^+/D^+$** 
  - Backward  $>$  Forward ? Need more precise data.



# $D_s^+$ in $pPb$ : probe for strangeness enhancement?

LHCB-PAPER-2023-021



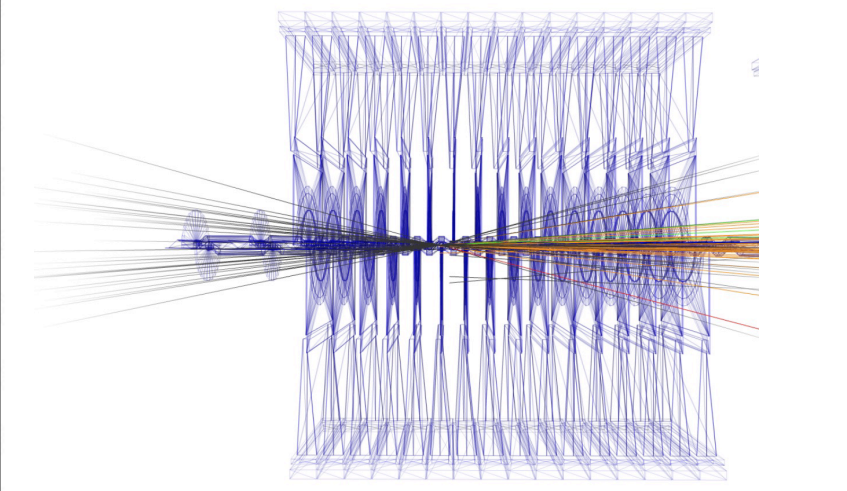
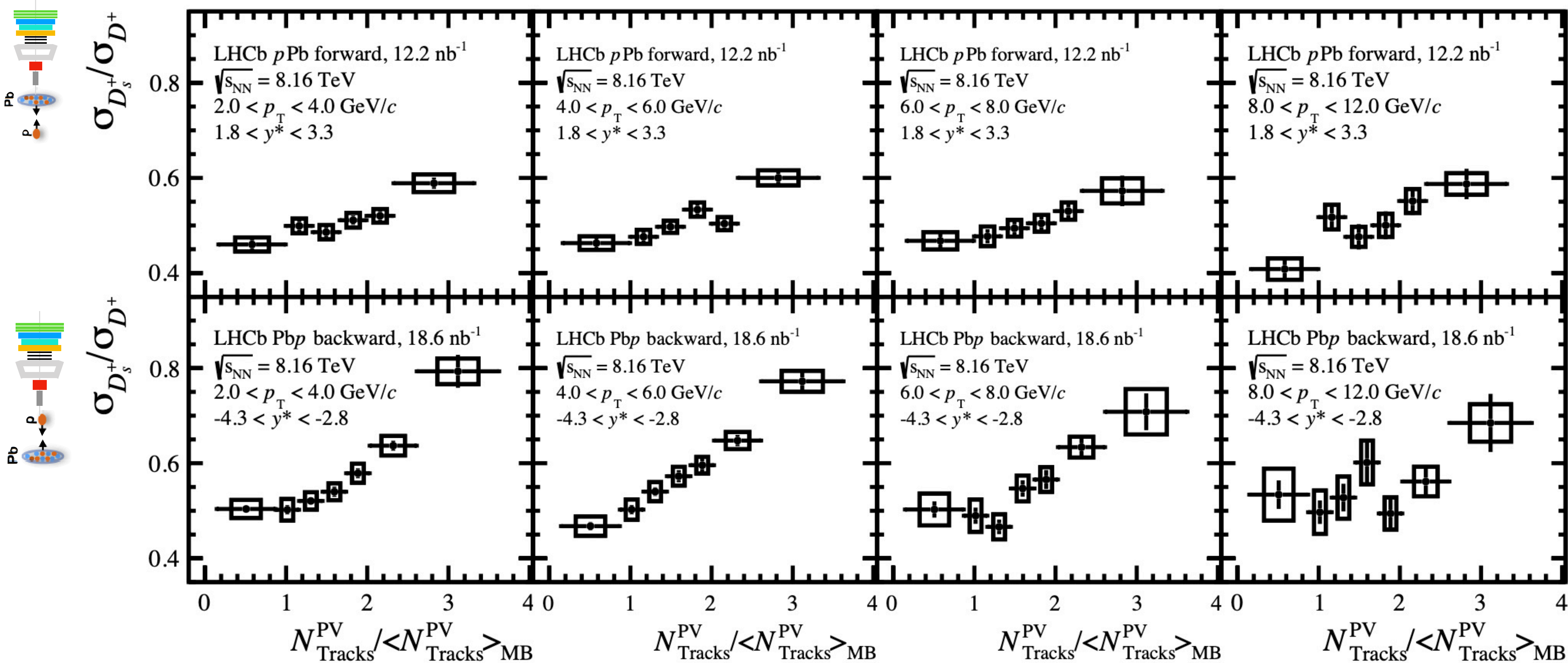
\* Preliminary  $D_s^+/D^+$  measurements in  $pPb@8.16 \text{ TeV}$ :

- Compatible with nPDFs at forward rapidity.
- Tension with theory predictions at backward rapidity.



# $D_s^+$ in $p$ Pb: probe for strangeness enhancement?

LHCB-PAPER-2023-021



$N_{Tracks}^{PV}$  = Number of tracks used to reconstruct primary vertex.

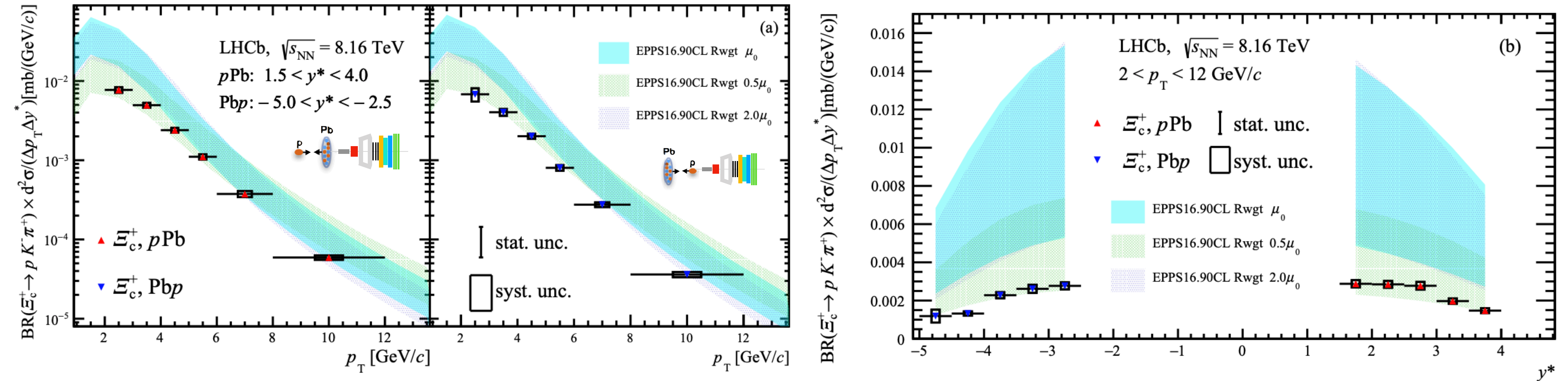
\*  $D_s^+/D^+$  enhancement vs multiplicity: strangeness enhancement or fragmentation?

- **Need theory predictions** to disentangle coalescence from jet fragmentation.



# $\Xi_c^+$ : the strangely charming baryon

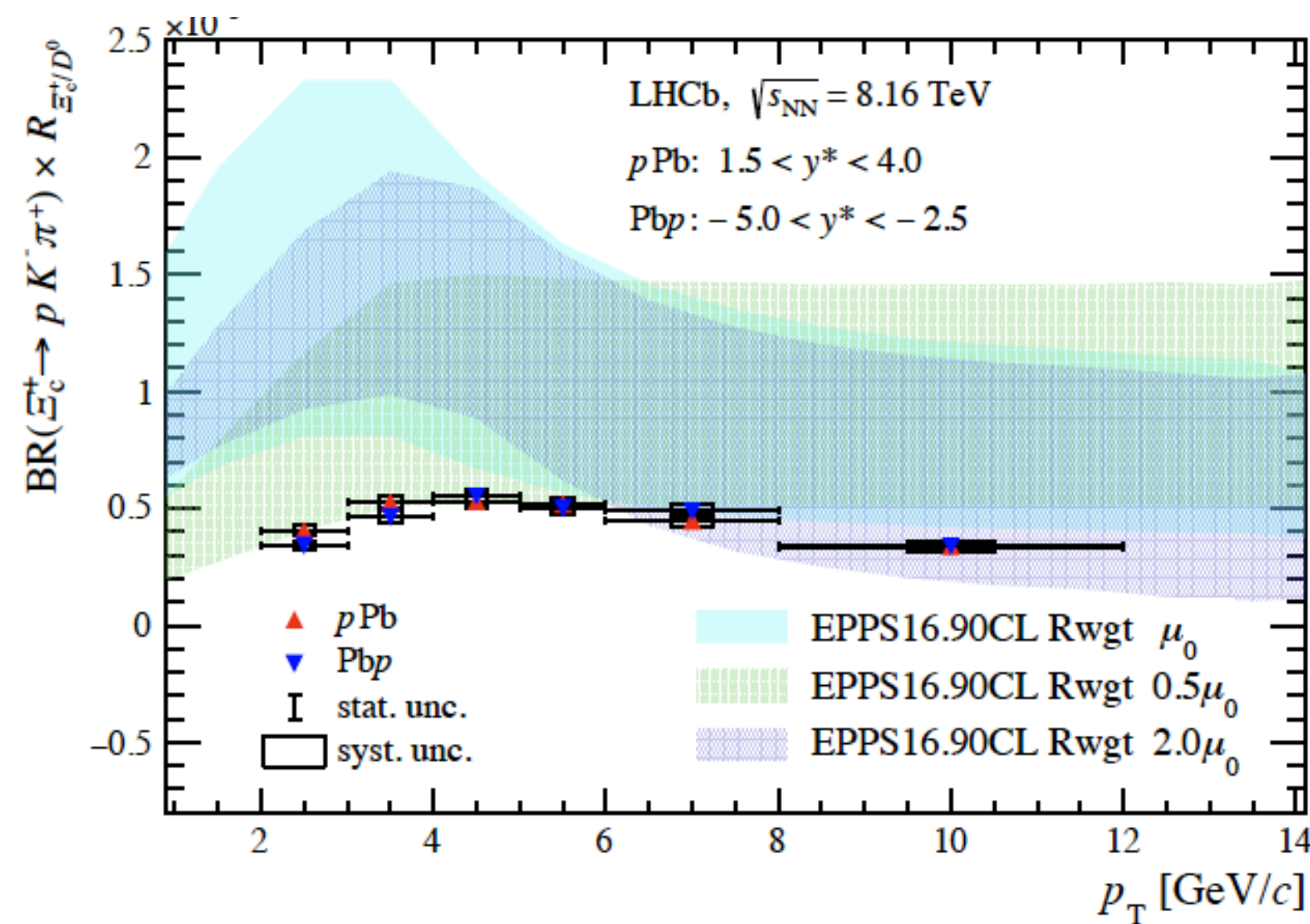
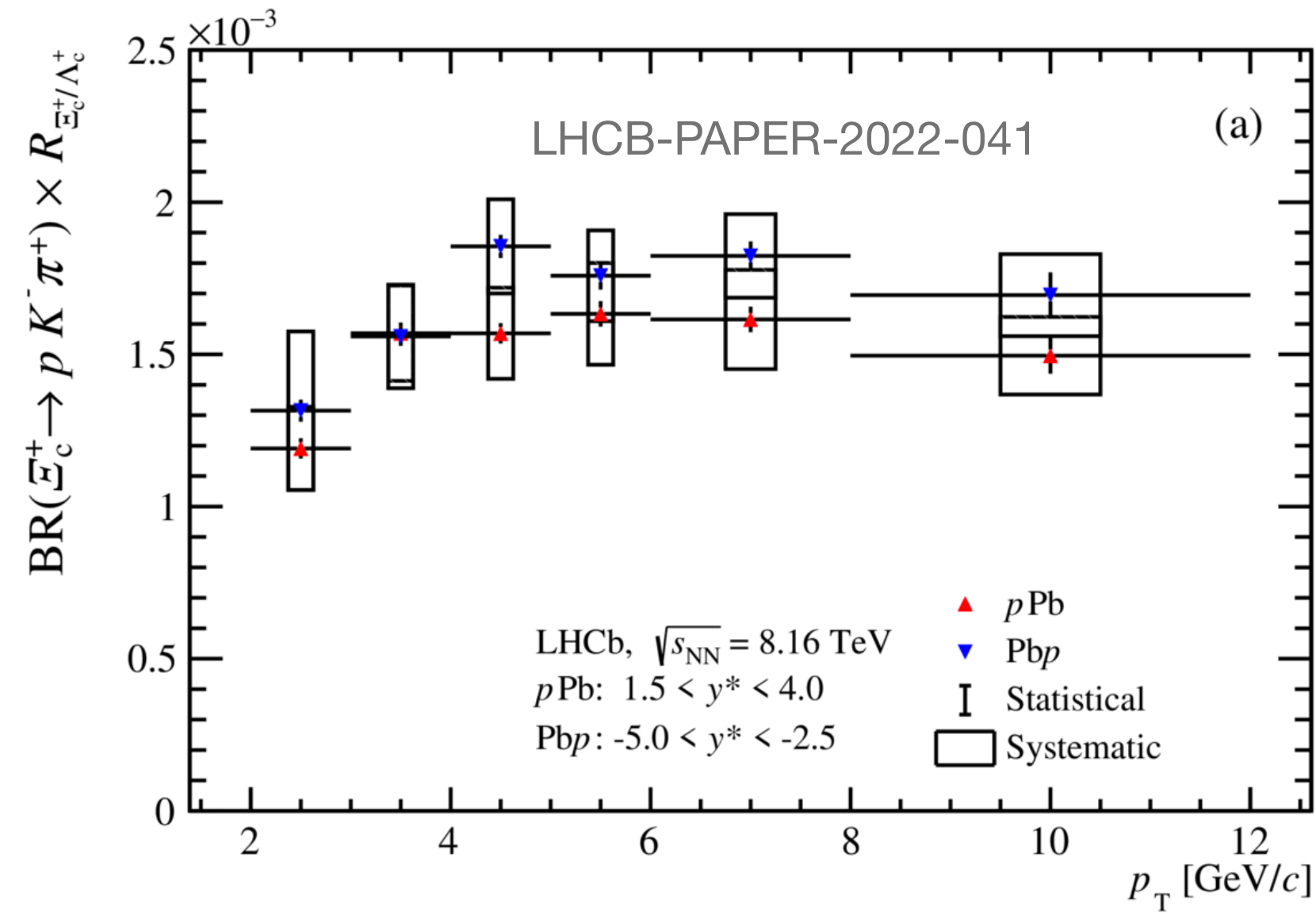
arXiv:2305.06711



- \* First measurement of  $\Xi_c^+$  in pPb collisions at forward rapidity.
- Systematics uncertainties in data dominated by branching fraction.
- \* Data are compatible with nPDFs predictions at 90% CL (lower limit).

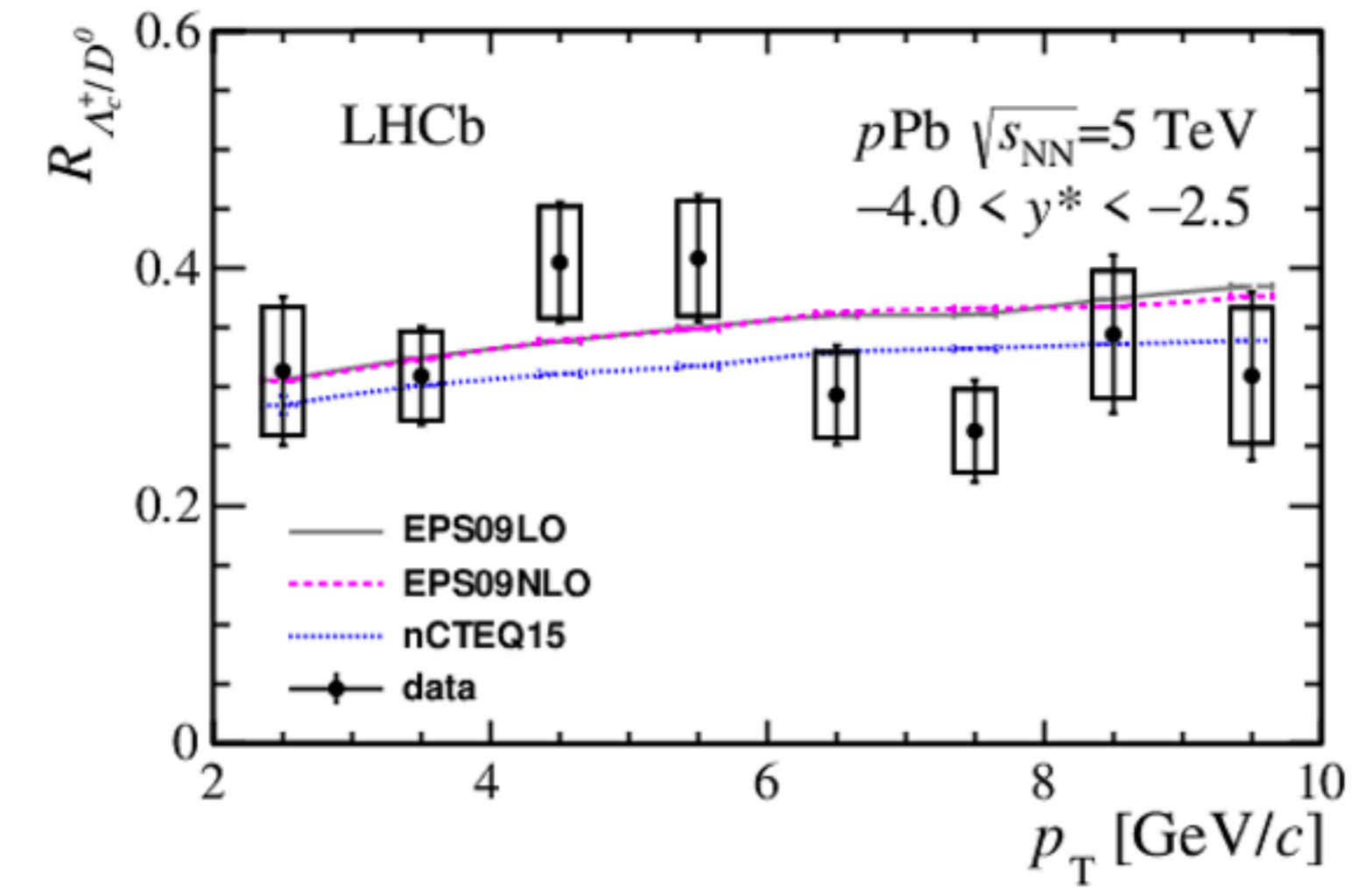
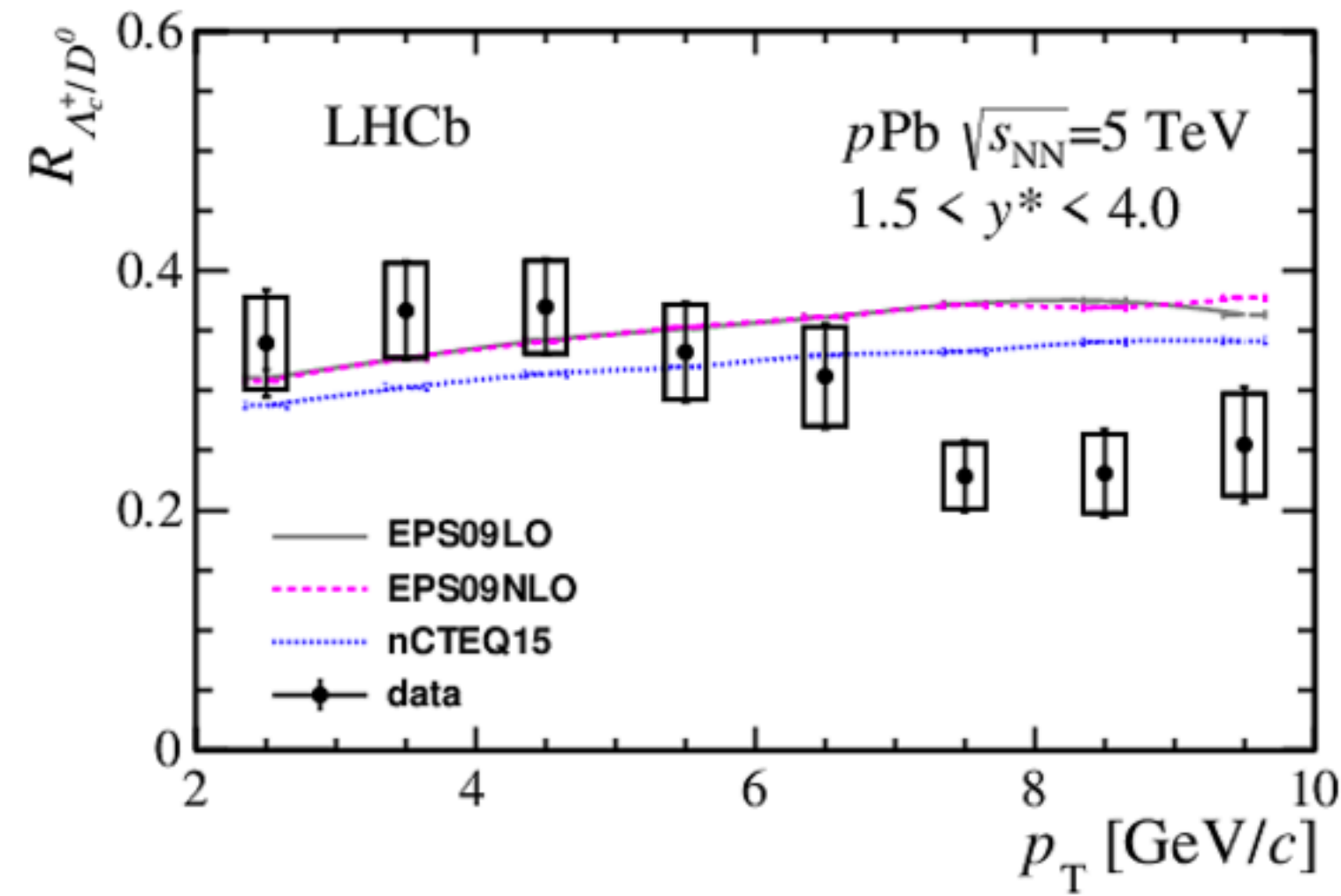
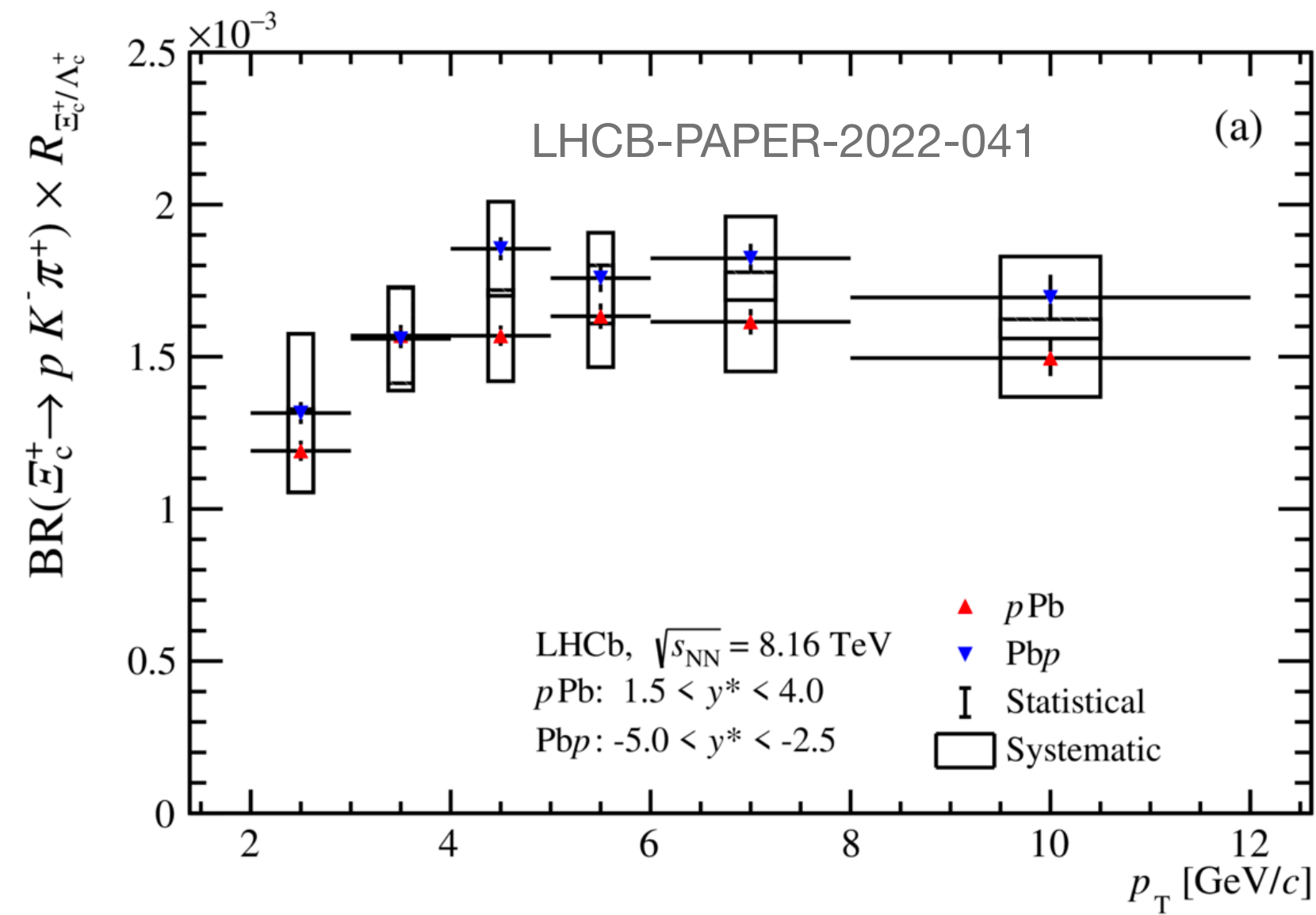


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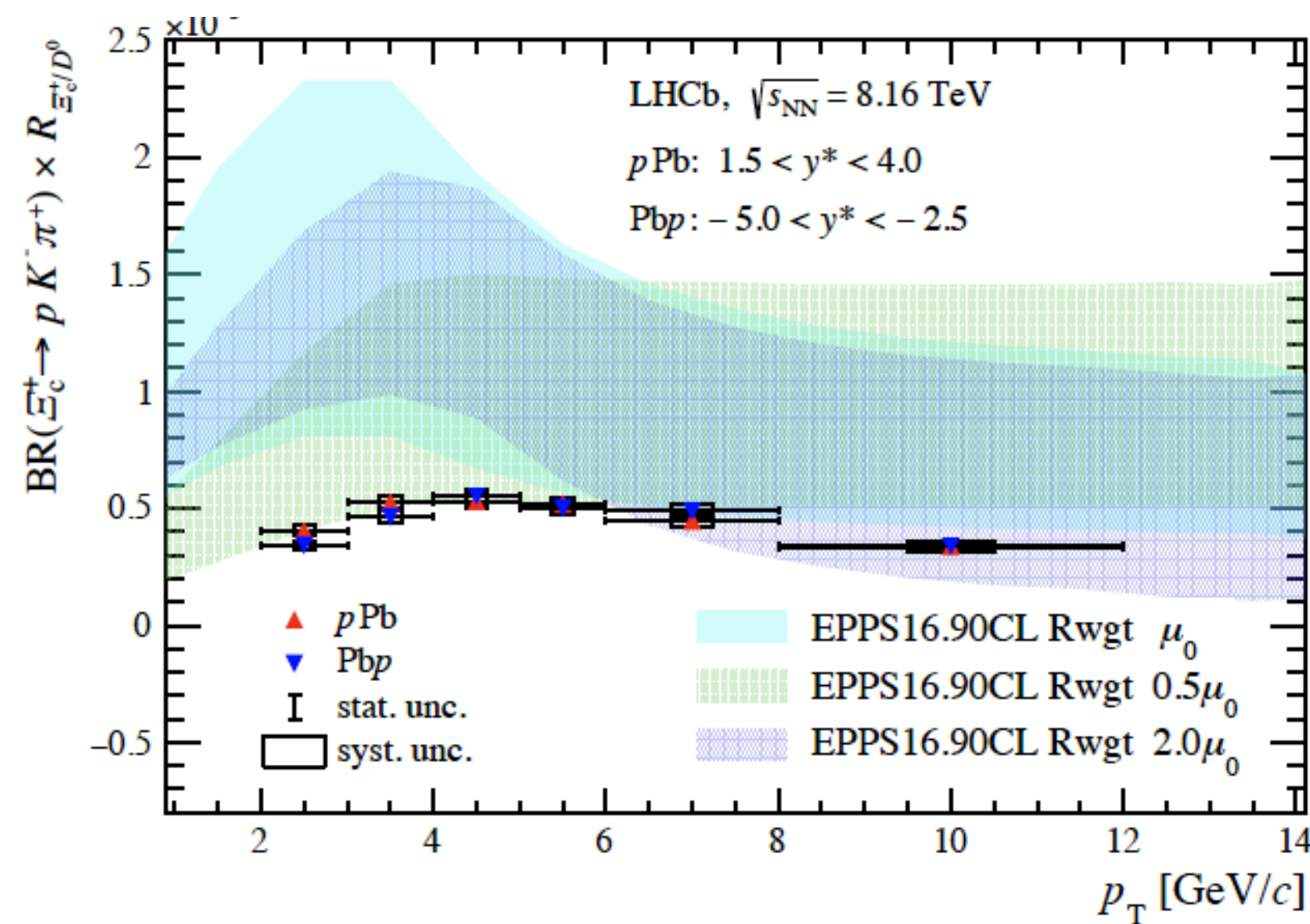




# $\Xi_c^+$ : the strangely charming baryon



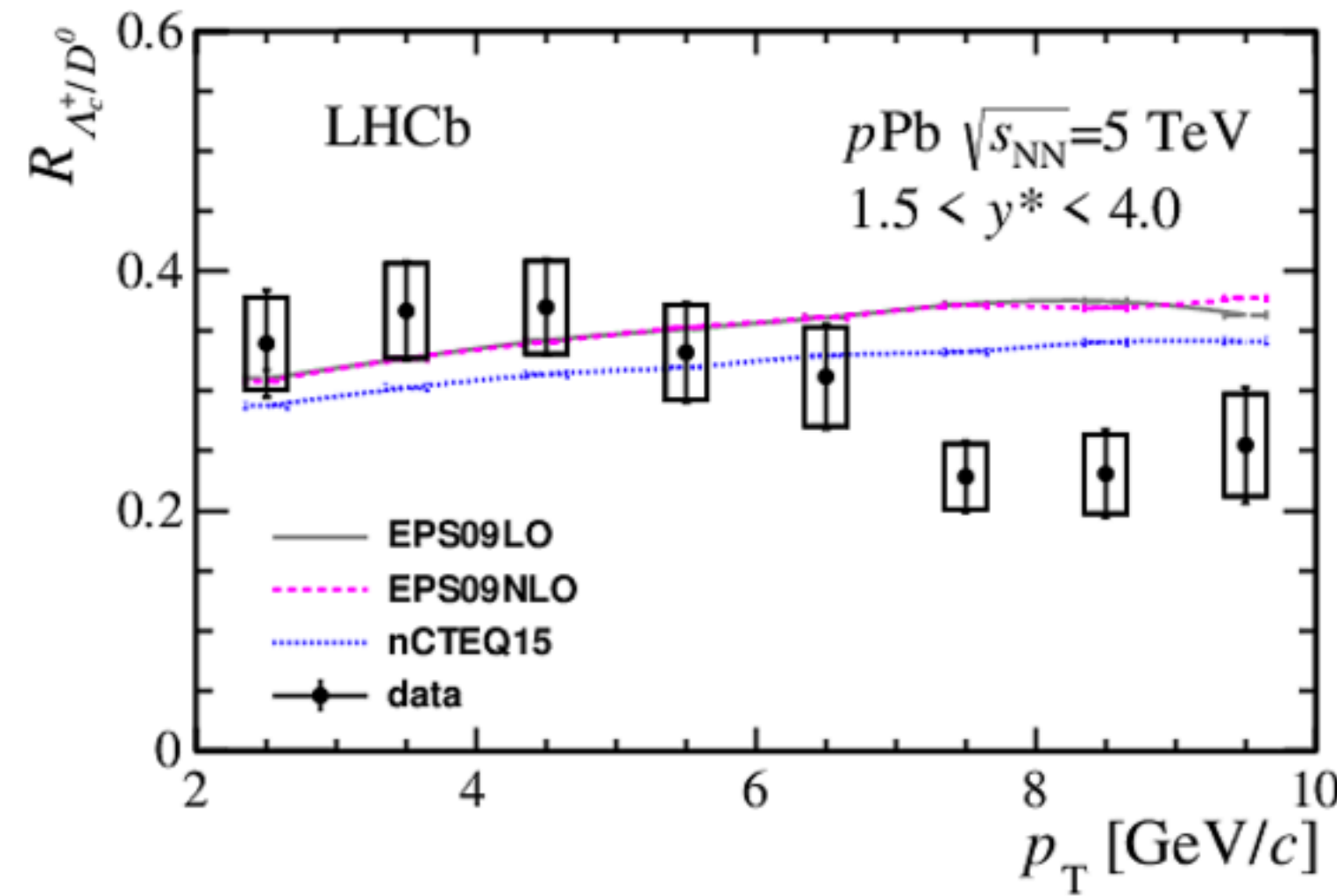
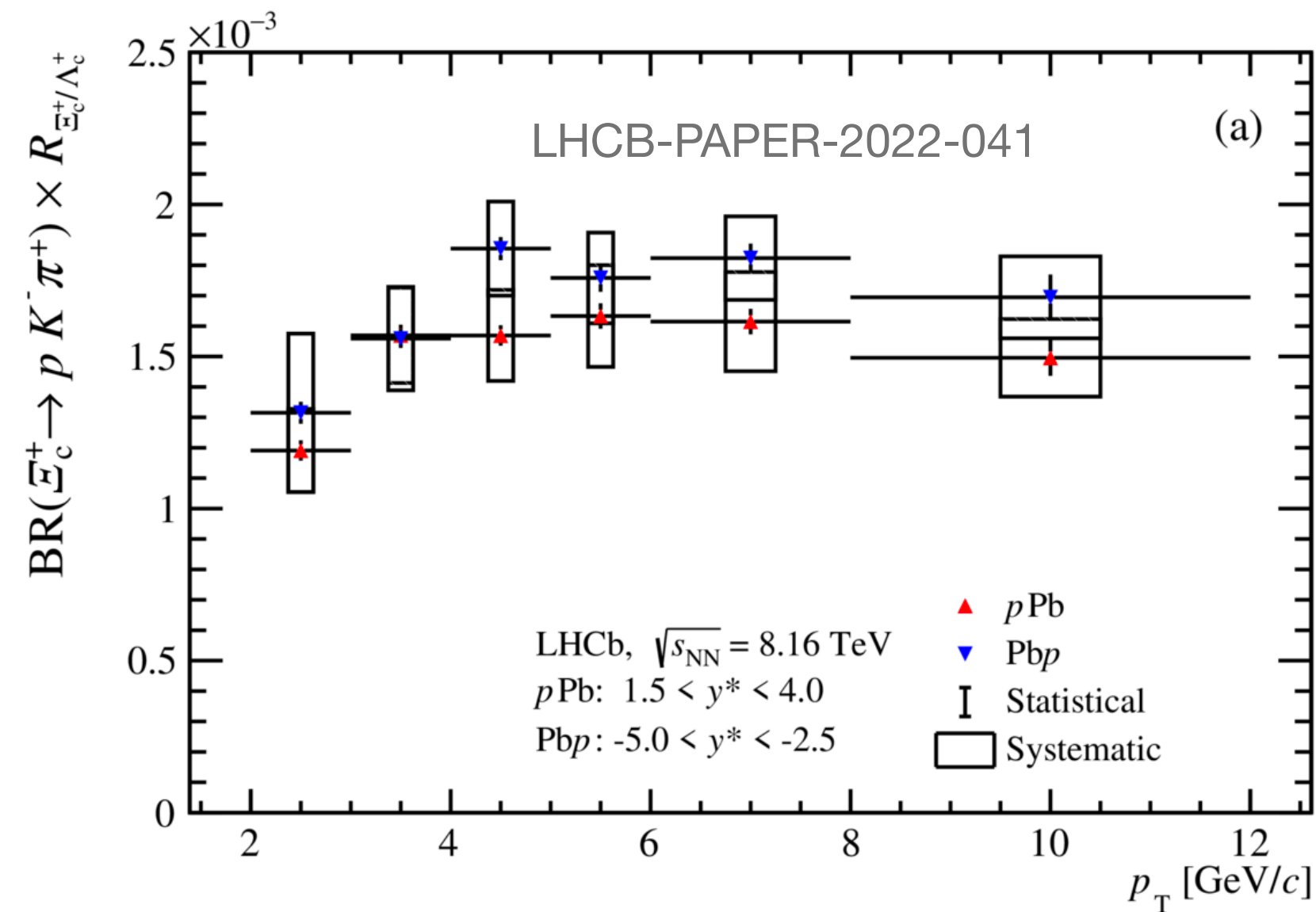
JHEP 02 (2019) 102



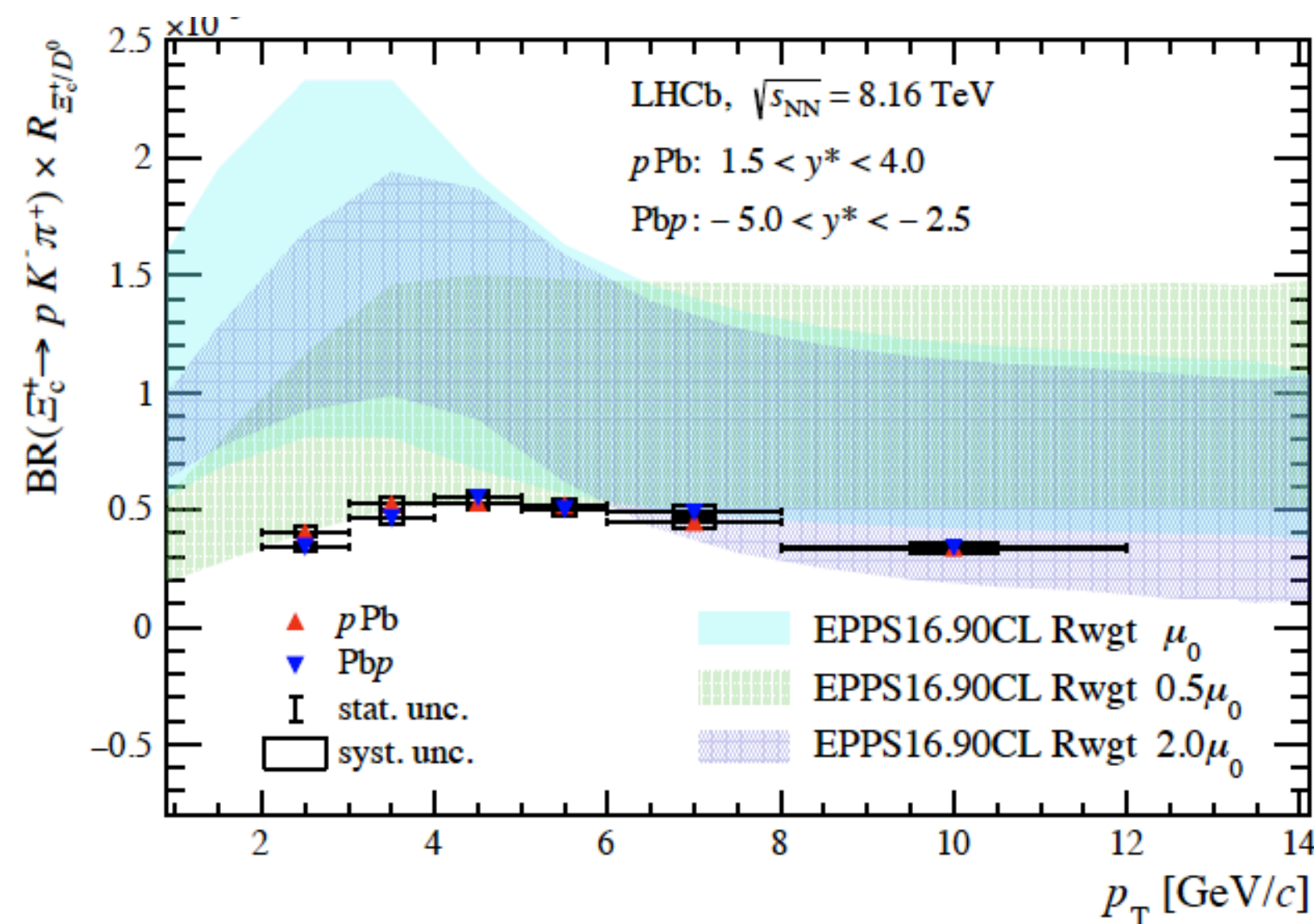
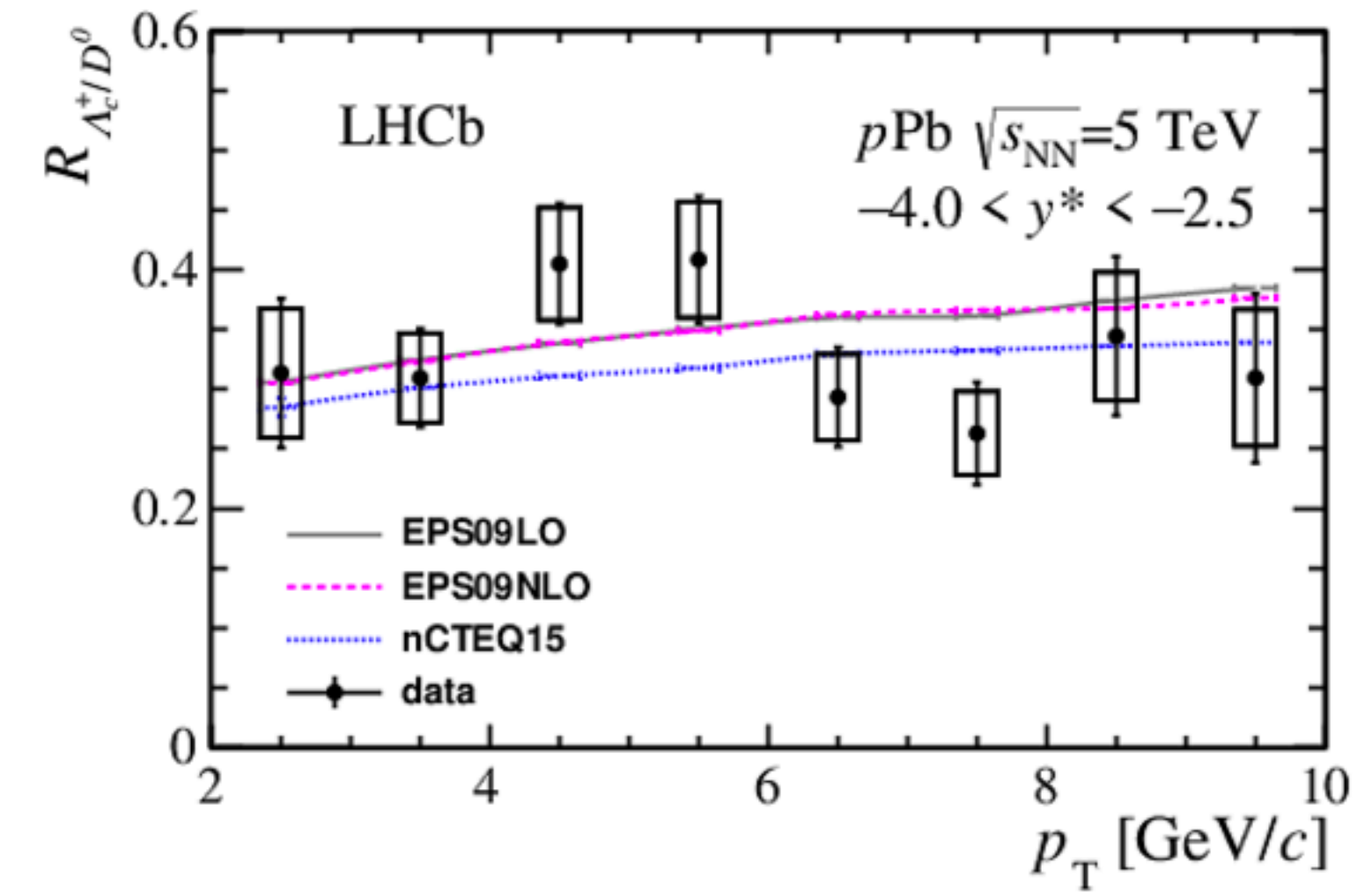
*compared to*



# $\Xi_c^+$ : the strangely charming baryon



JHEP 02 (2019) 102



*compared to*

- \* Open-charm family in pPb collisions almost complete.
- Missing  $\Lambda_c$  at 8.16 TeV (work-in-progress).
- Missing new multiplicity analysis? Anything else?



# Conclusion

A lot of results available, and more incoming. Check the [IFT results webpage](#).

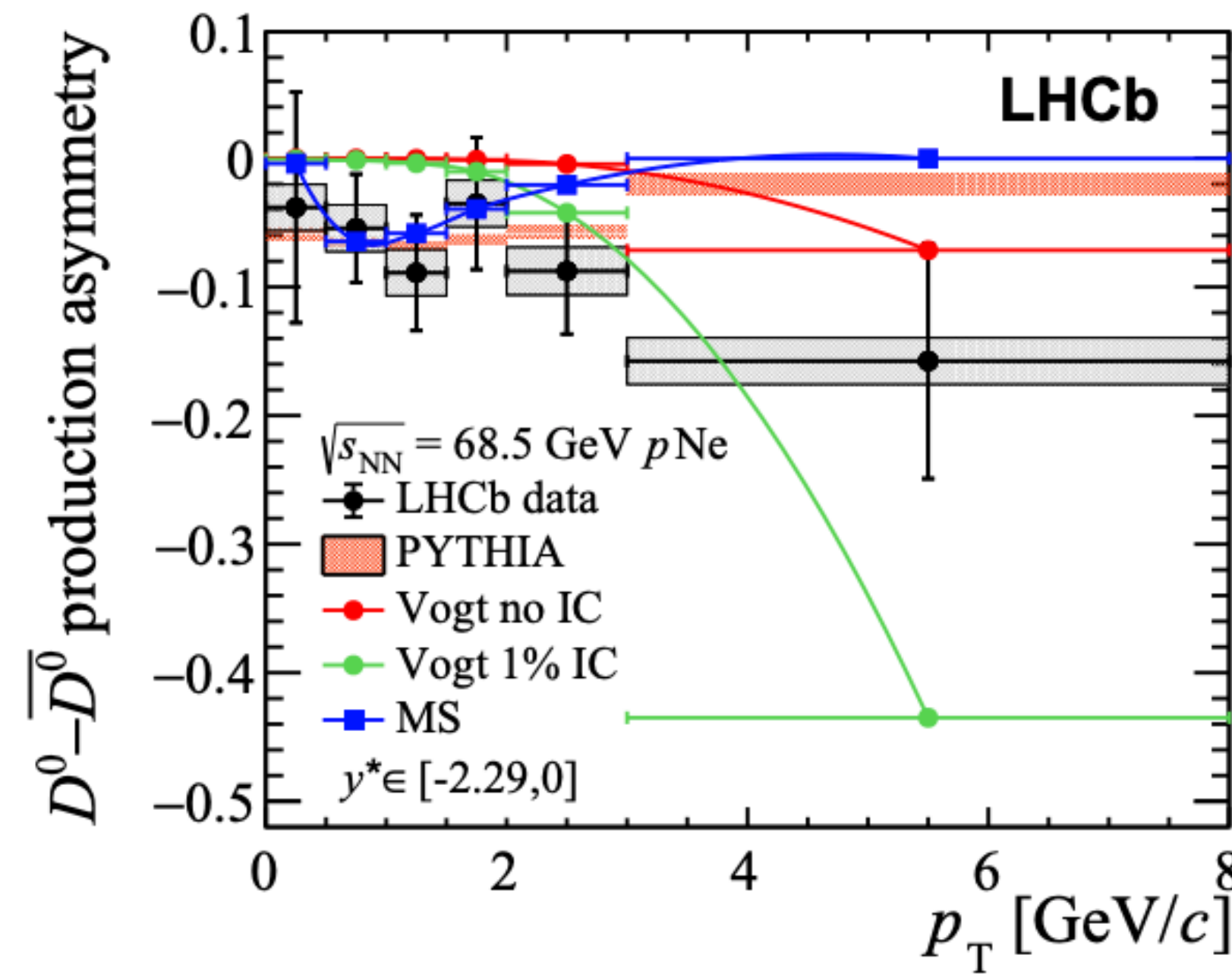
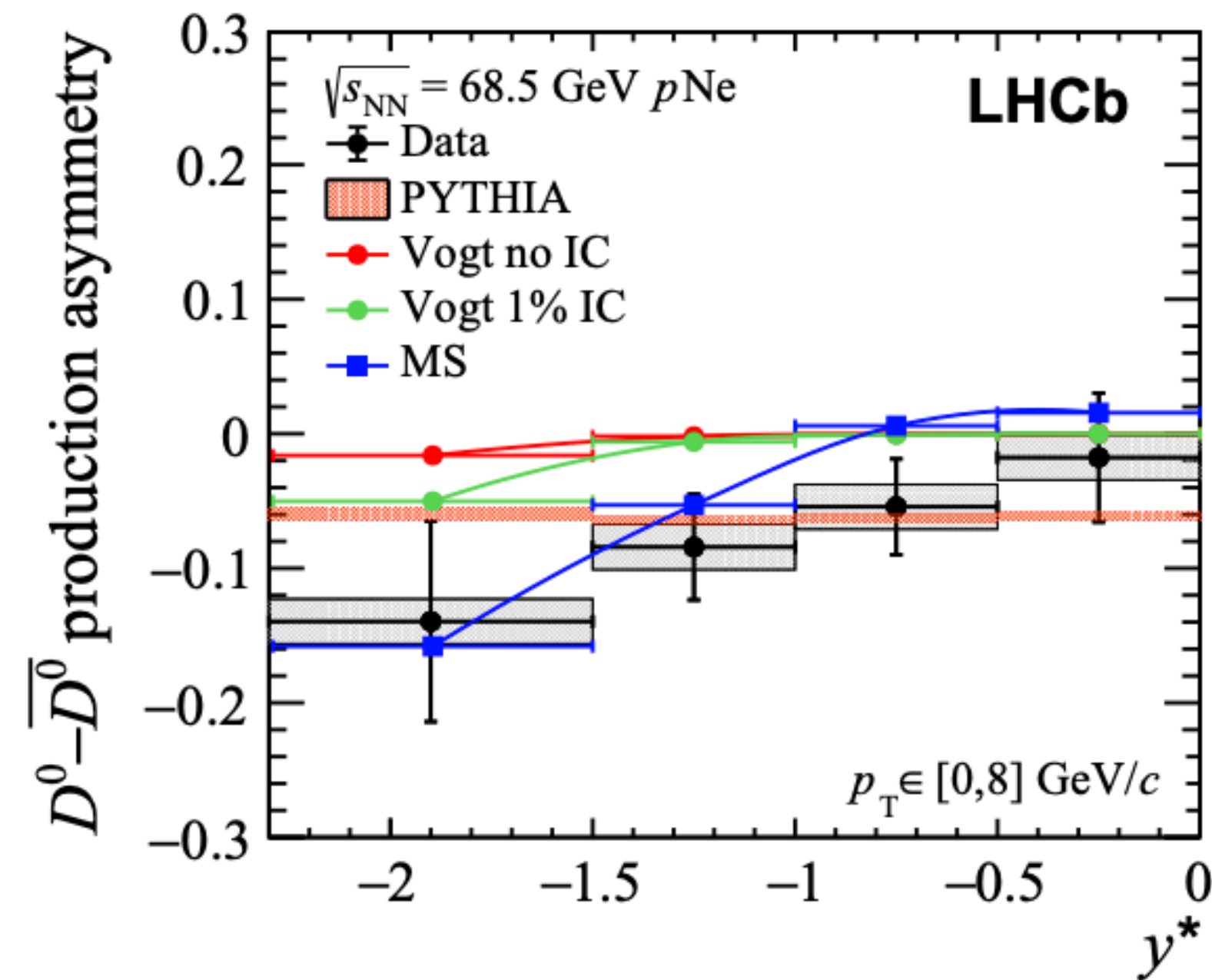
	pp@13 TeV	pPb@5TeV	pPb@8TeV	pSMOG
D <sup>0</sup>	$\sigma$	$\sigma$	$\sigma$	$\sigma$ , asymmetry
D <sup>+</sup>	$\sigma$ , ratio-to-D <sup>0</sup>	$\sigma$ , ratio-to-D <sup>0</sup> , R <sub>AA</sub>	$\sigma$ , ratio-to-D <sup>0</sup> , R <sub>AA</sub> , multiplicity	
D <sub>s</sub> <sup>+</sup>	$\sigma$	$\sigma$ , ratio-to-D <sup>0</sup> /D <sup>+</sup> , R <sub>AA</sub>	$\sigma$ , ratio-to-D <sup>0</sup> /D <sup>+</sup> , R <sub>AA</sub> , multiplicity	
$\Lambda_c^+$	$\sigma$ , ratio-to-D <sup>0</sup>	$\sigma$ , ratio-to-D <sup>0</sup> , R <sub>AA</sub>		
$\Xi_c^+$			$\sigma$ , ratio-to-D <sup>0</sup> / $\Lambda_c^+$	
B <sup>0</sup>	$\sigma$ , multiplicity		$\sigma$ , ratio-to-B <sup>0</sup> , R <sub>AA</sub>	
B <sup>+</sup>	$\sigma$ , ratio to B <sup>0</sup> , multiplicity		$\sigma$ , R <sub>AA</sub>	
B <sub>s</sub>	$\sigma$ , ratio to B <sup>0</sup> , multiplicity			
$\Lambda_b^+$	$\sigma$ , ratio to B <sup>0</sup> , multiplicity		$\sigma$ , ratio-to-B <sup>0</sup> , R <sub>AA</sub>	

Looking forward for new samples (e.g. SMOG2, PbPb, OO) to complete the picture.

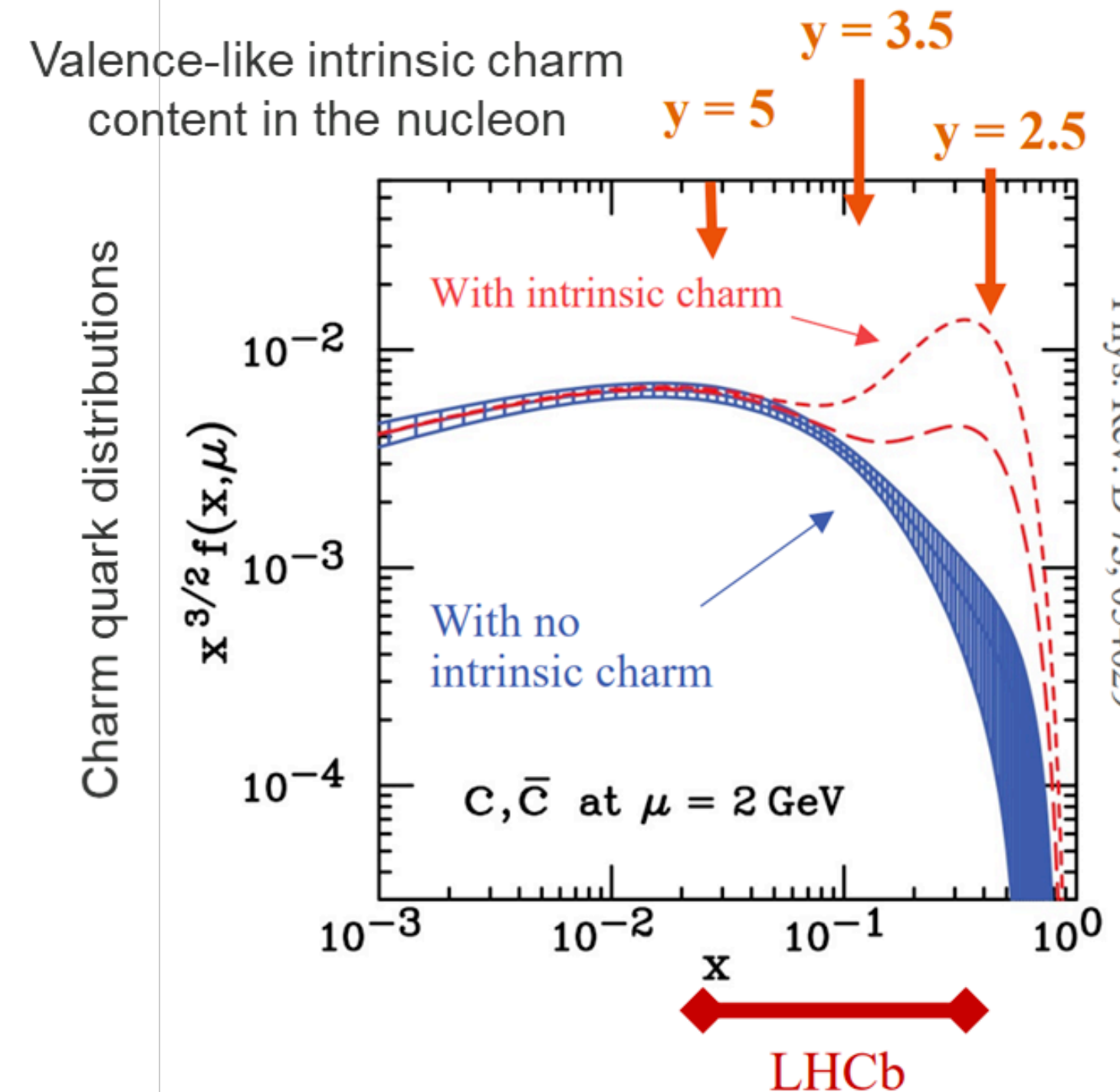


# Other opportunity: $D^0$ asymmetry in SMOG

EUR. PHYS. J. C83 (2023) 541



- Vogt = nPDFs (+ intrinsic charm)
- MS = nPDFs + IC + recombination



Phys. Rev. D 75, 054029

- \* Open charm measurements in  $p$ SMOG data:
  - Good probe for intrinsic charm production.
  - Good probe for recombination?
- \* These results ask again the question of the QCD medium:
  - Lower energy = more time in the target = more coalescence?