



Plan of Heavy Flavor Physics with CMS experiment

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1 July 2020



Heavy-ion data in CMS



	Run	Collision	Energy	Lumi	Scale to pp
Run 1	2011	Pb-Pb	2.76 TeV	0.17 nb ⁻¹	7.5 pb ⁻¹
	2013	p-Pb	5.02 TeV	0.035 pb ⁻¹	7.4 pb ⁻¹
Run 2	2015	p-p	5.02 TeV	28 pb ⁻¹	28 pb ⁻¹
	2015	Pb-Pb	5.02 TeV	0.55 nb ⁻¹	24 pb ⁻¹
	2016	p-Pb	8.16 TeV	0.18 pb ⁻¹	38 pb ⁻¹
	2017	Xe+Xe	5.44 TeV	6.0 μb ⁻¹	0.1 pb ⁻¹
	2017	p-p	5.02 TeV	316 pb ⁻¹	316 pb ⁻¹
	2018	Pb-Pb	5.02 TeV	1.7 nb ⁻¹	74 pb ⁻¹
Run 3	2022	p-p	5.5 / 8.8 TeV	300 / 100 pb ⁻¹	300 / 100 pb ⁻¹
		Pb-Pb	5.5 TeV	6.2 nb ⁻¹	268 pb ⁻¹
	~ 2024	p-Pb	8.8 TeV	0.6 pb ⁻¹	126 pb ⁻¹
		O-O / p-O	7 / 9.9 TeV	0.5 / 0.2 nb ⁻¹	
Run 4	2027	p-p	5.5 / 8.8 TeV	300 / 100 pb ⁻¹	300 / 100 pb ⁻¹
	~ 2029	Pb-Pb	5.5 TeV	6.8 nb ⁻¹	294 pb ⁻¹
		p-Pb	8.8 TeV	0.6 pb ⁻¹	126 pb ⁻¹



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2015 PbPb: 0.5 nb⁻¹
 2018 PbPb: 1.7 nb⁻¹
 pPb: 0.18 pb⁻¹

3-10x statistics

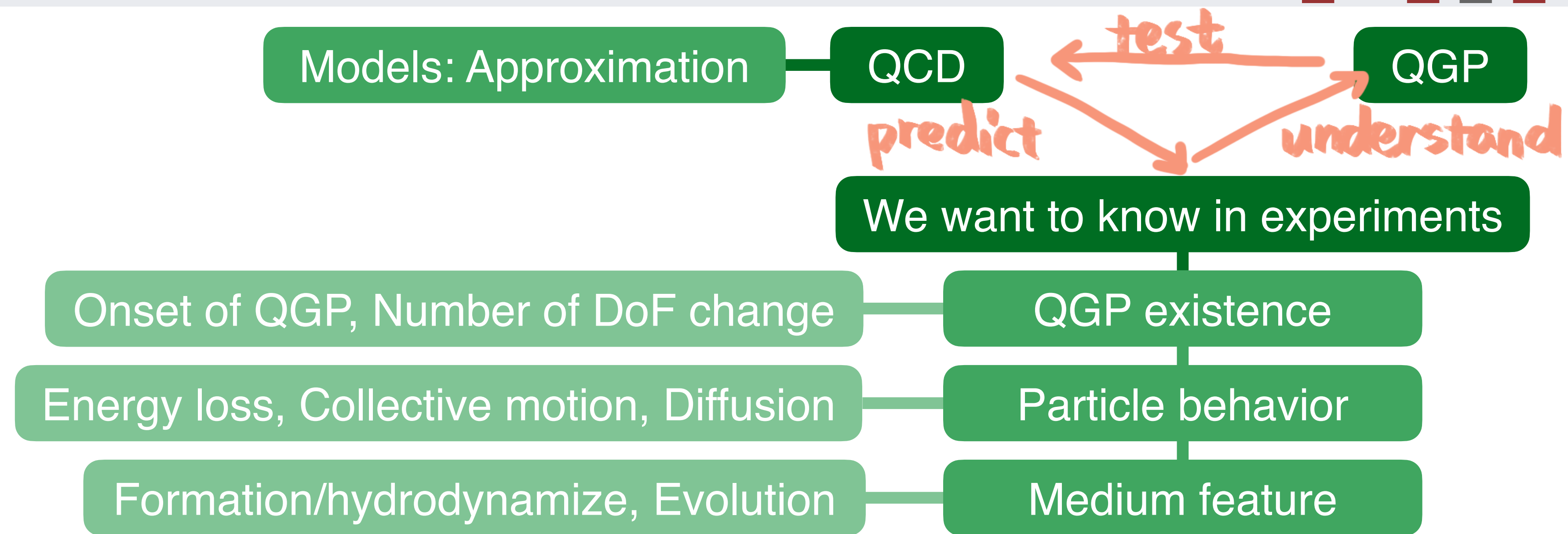
7x statistics

0.38x errors

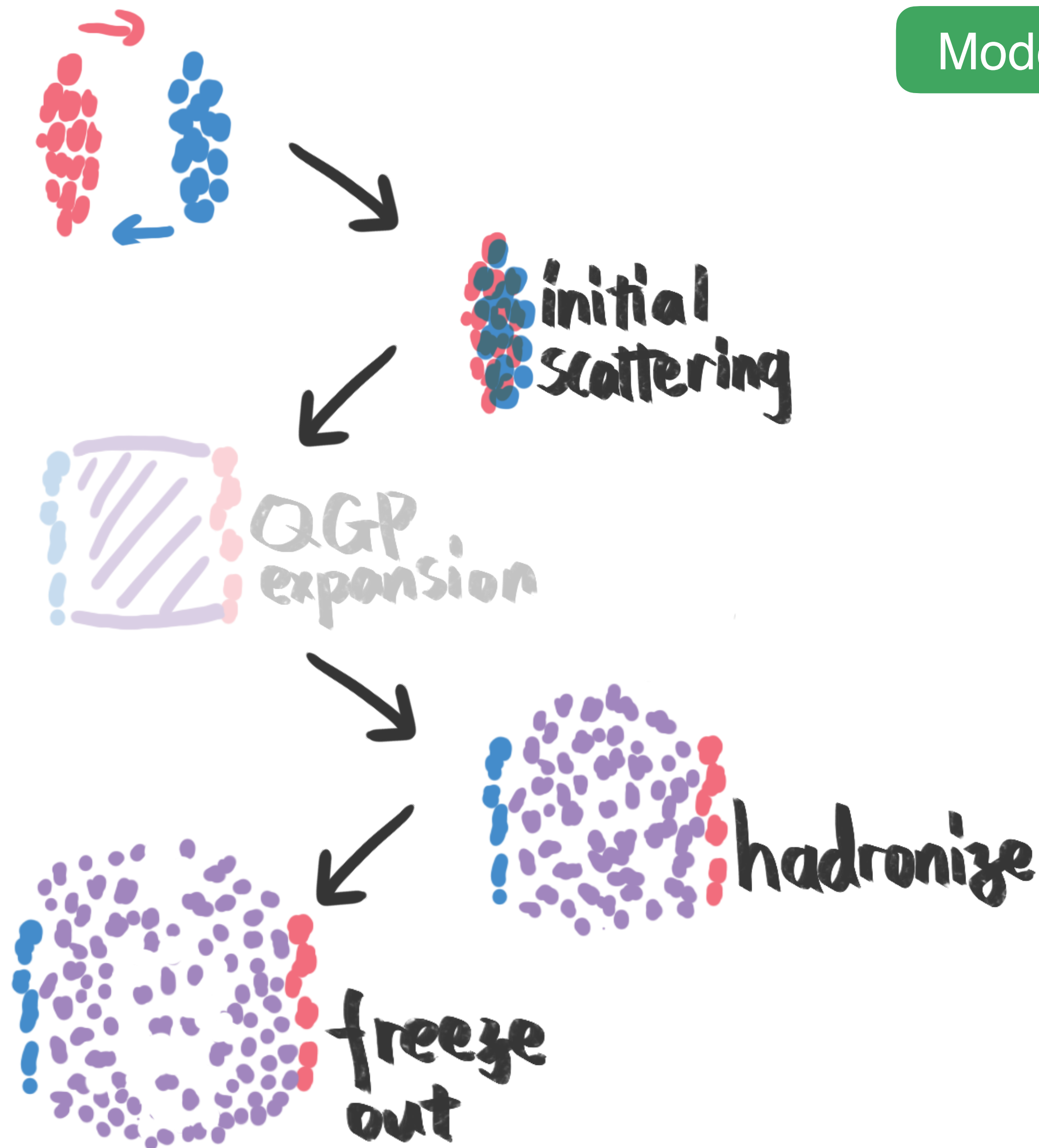
We will have
 PbPb: 13 nb⁻¹

pPb: 1.2 pb⁻¹

Big Questions?



Solve Big Questions?



Models: Approximation

QCD

QGP



We want to know in experiments

QGP existence

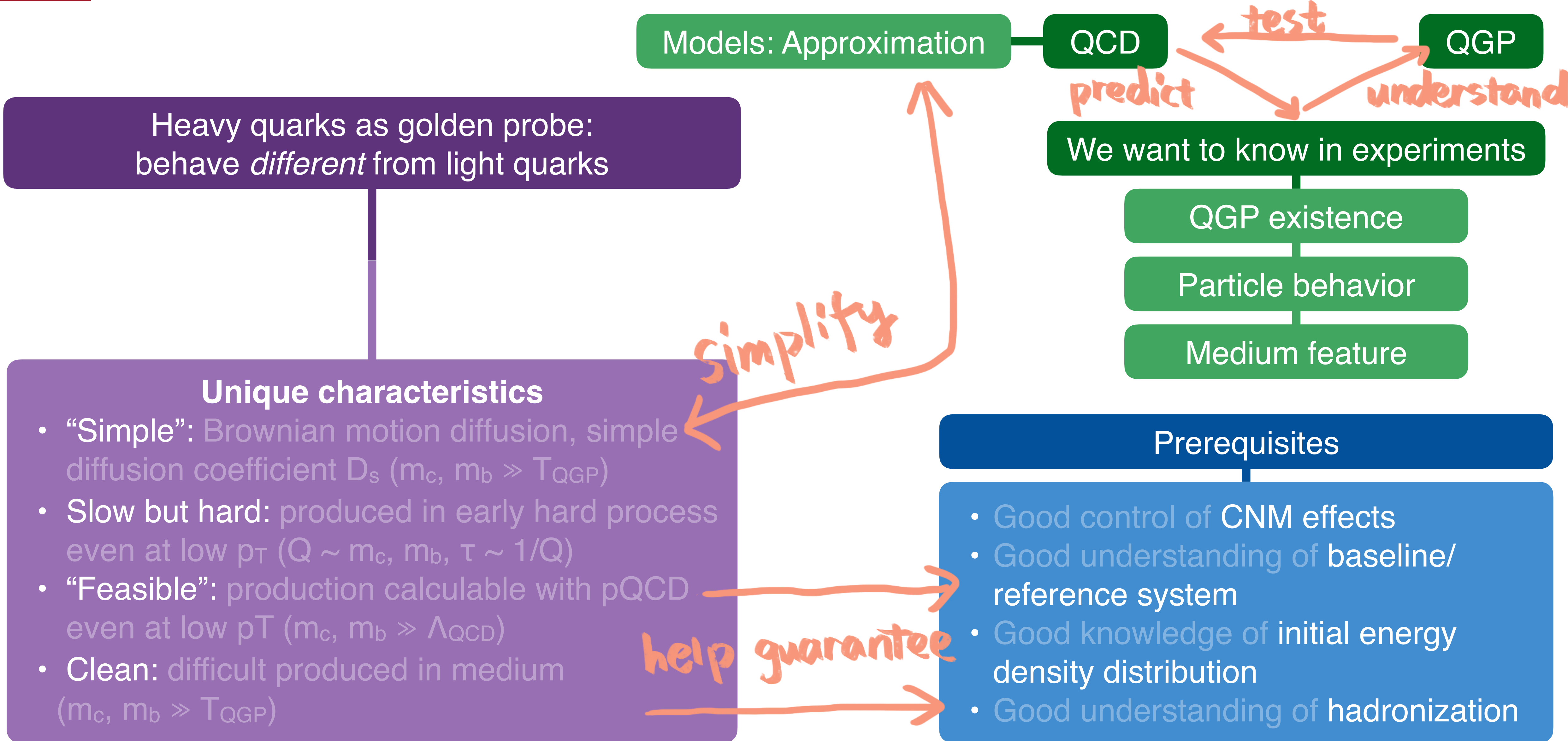
Particle behavior

Medium feature

Prerequisites

- Good control of CNM effects
- Good understanding of baseline/reference system
- Good knowledge of initial energy density distribution
- Good understanding of hadronization

Solve Big Questions with Heavy-flavors?



Solve Big Questions with Heavy-flavors?



Heavy quarks as golden probe: behave *different* from light quarks

Different response to medium

- Flavor dependence (dead cone effect)
- Harder to be dragged by medium

Unique characteristics

- “Simple”: Brownian motion diffusion, simple diffusion coefficient D_s ($m_c, m_b \gg T_{QGP}$)
- Slow but hard: produced in early hard process even at low p_T ($Q \sim m_c, m_b, \tau \sim 1/Q$)
- “Feasible”: production calculable with pQCD even at low p_T ($m_c, m_b \gg \Lambda_{QCD}$)
- Clean: difficult produced in medium ($m_c, m_b \gg T_{QGP}$)

Models: Approximation

QCD

QGP



We want to know in experiments

QGP existence

Particle behavior

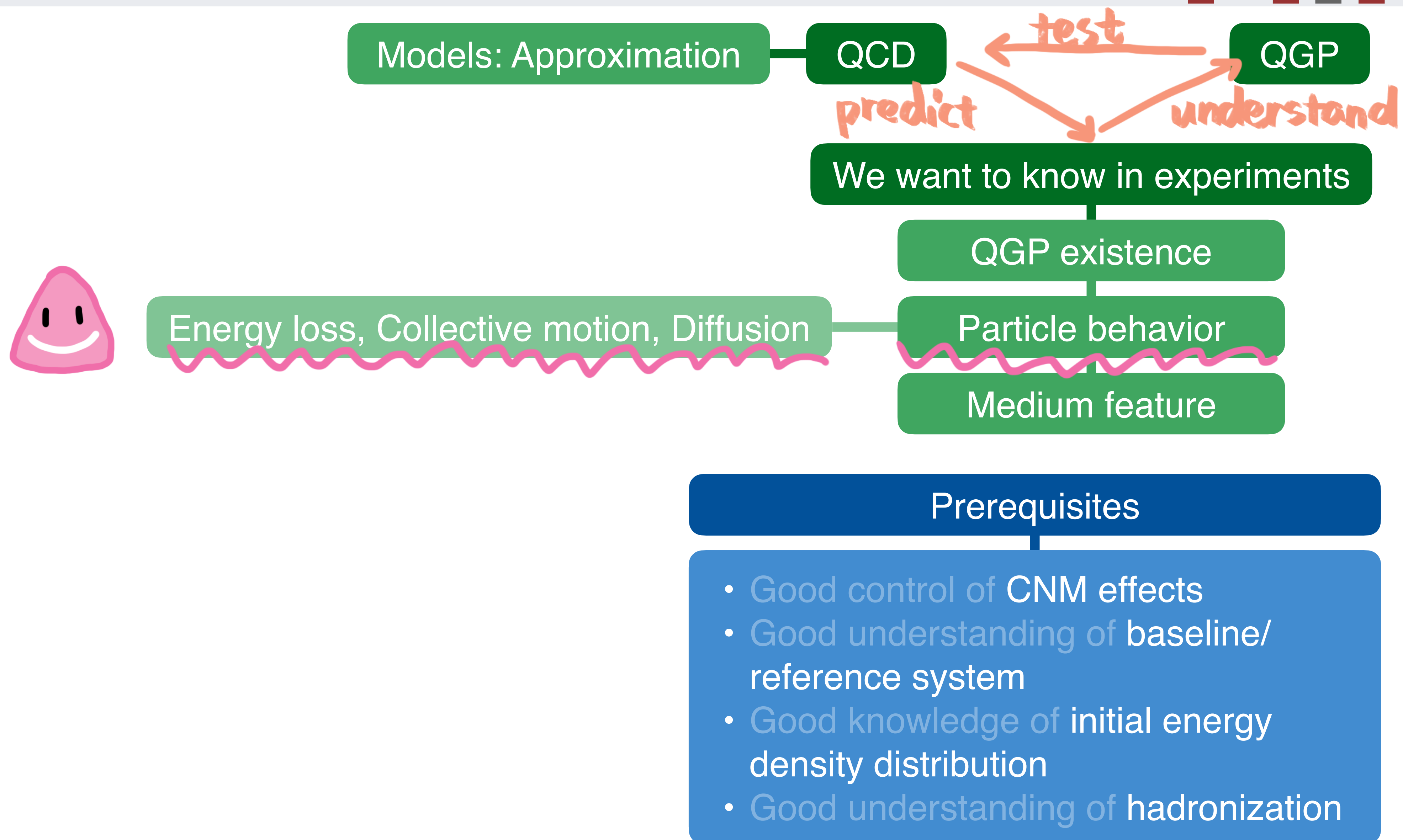
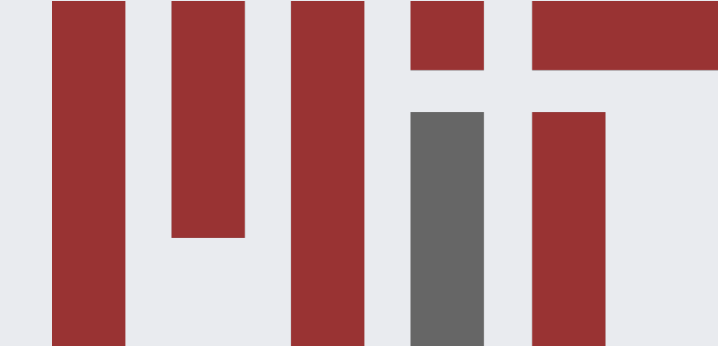
Medium feature

test models across flavors

isolate process

Prerequisites

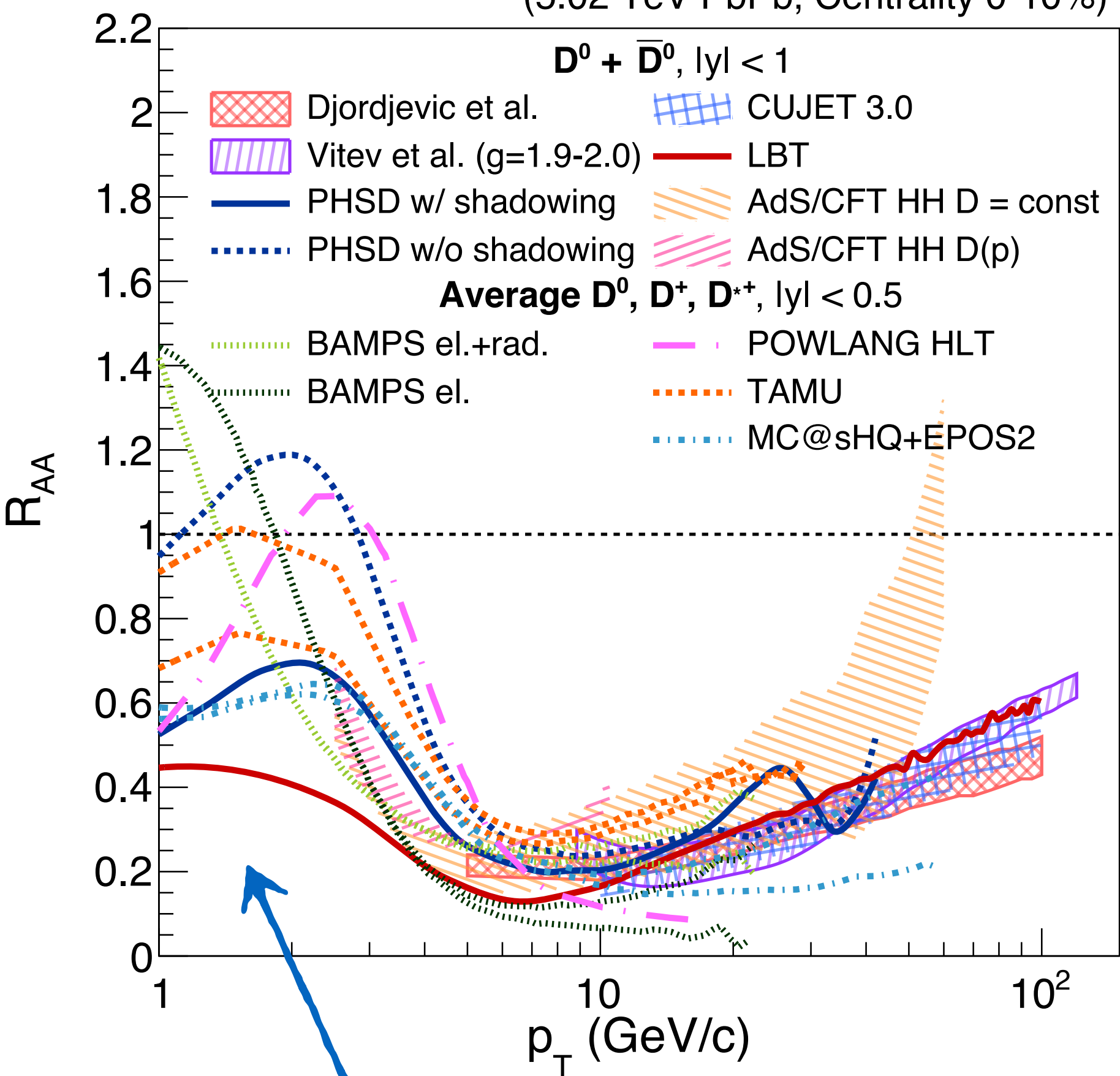
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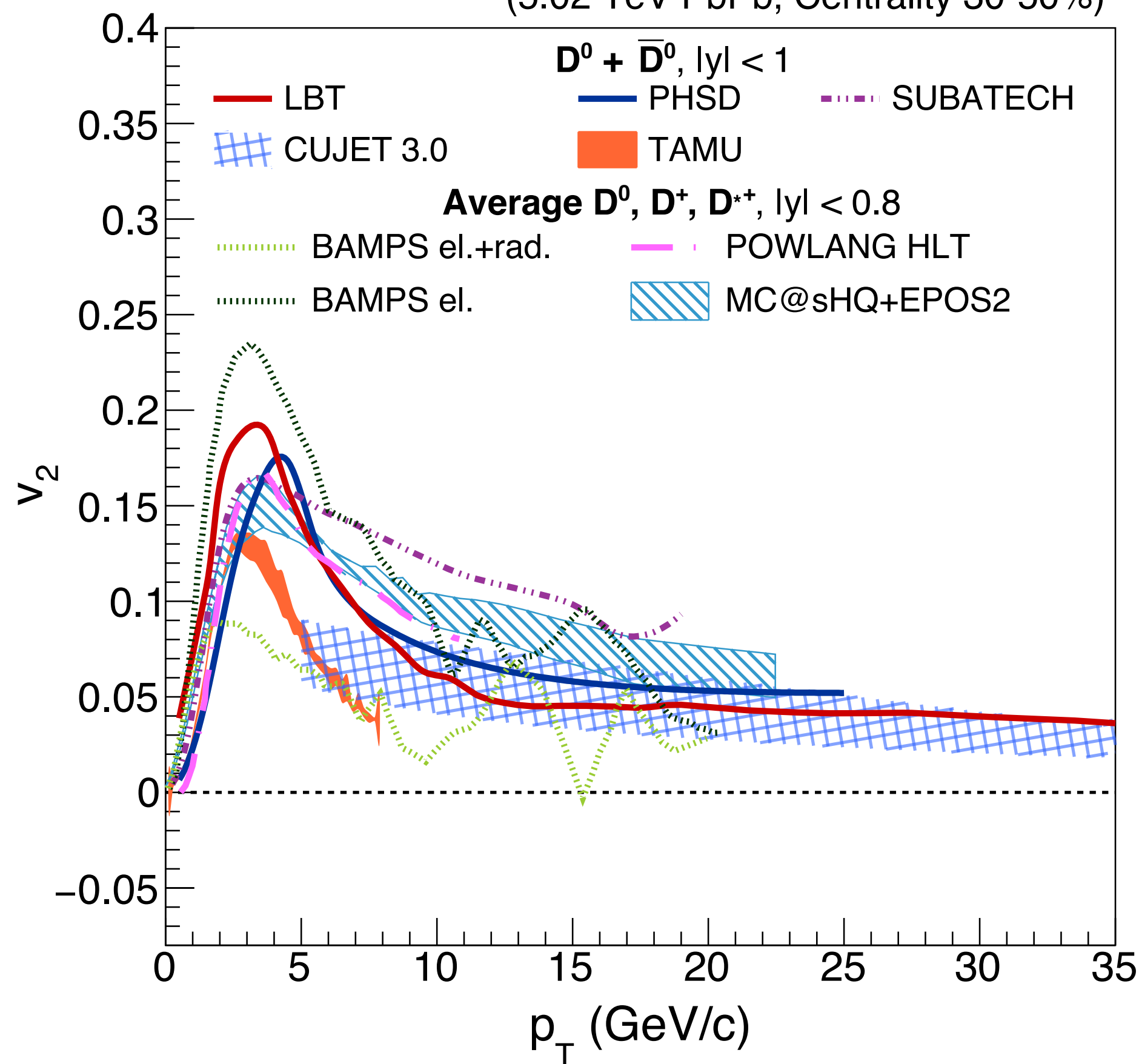
D meson R_{AA}

(5.02 TeV PbPb, Centrality 0-10%)



D meson v_2

(5.02 TeV PbPb, Centrality 30-50%)



What do we distinguish among models?

- Jet model
 - Medium modeling
 - Virtuality and branching
 - Kinematical approximation
- Transport model
 - LV vs. BM
 - Bulk evolution
 - Collisions vs. radiations
 - Initial conditions
 - Parameters (T_0 etc.)

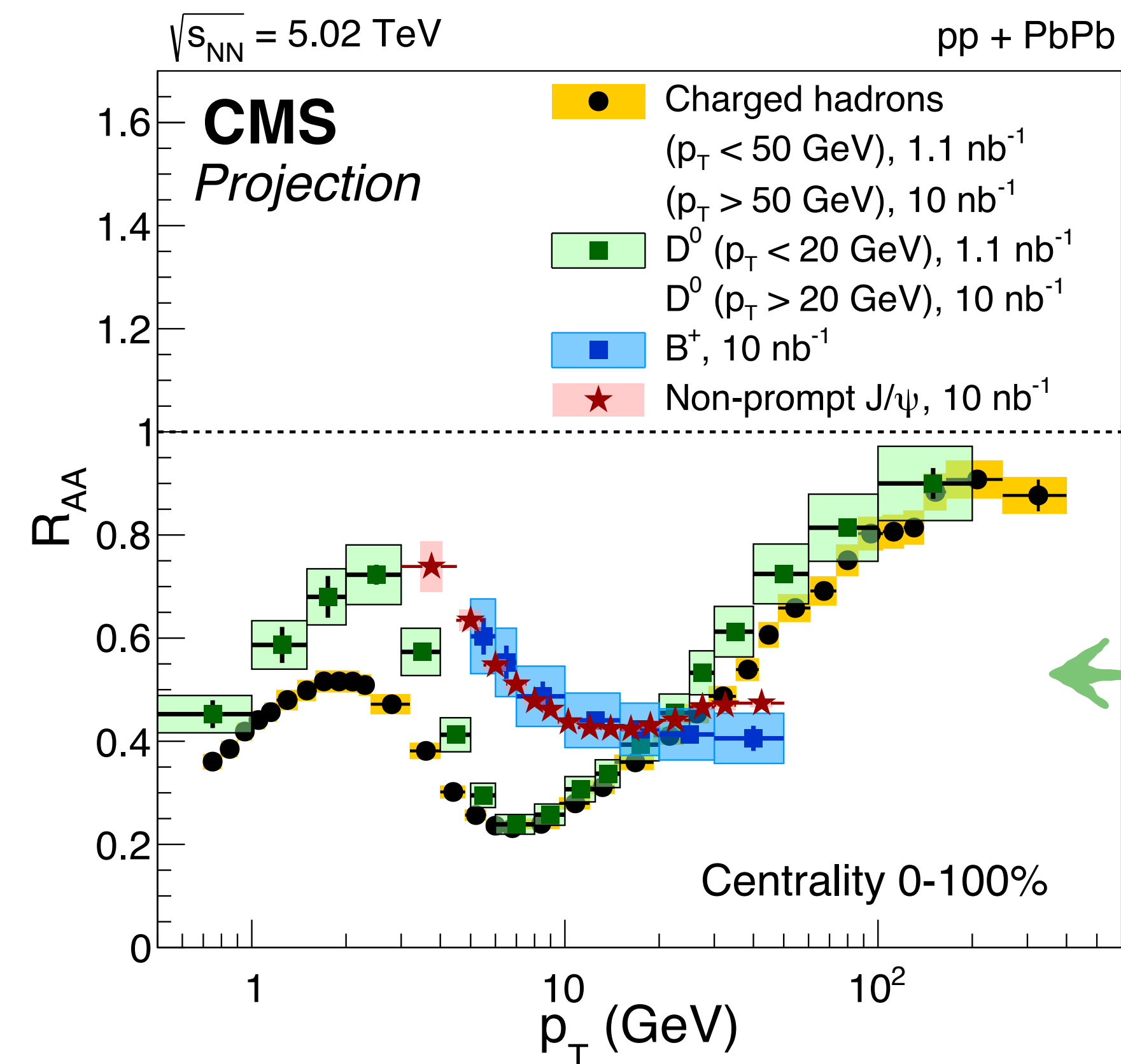
- Low p_T (convoluting multiple effects) has best distinguish power
- What will we know if we have zero-uncertainty data results?



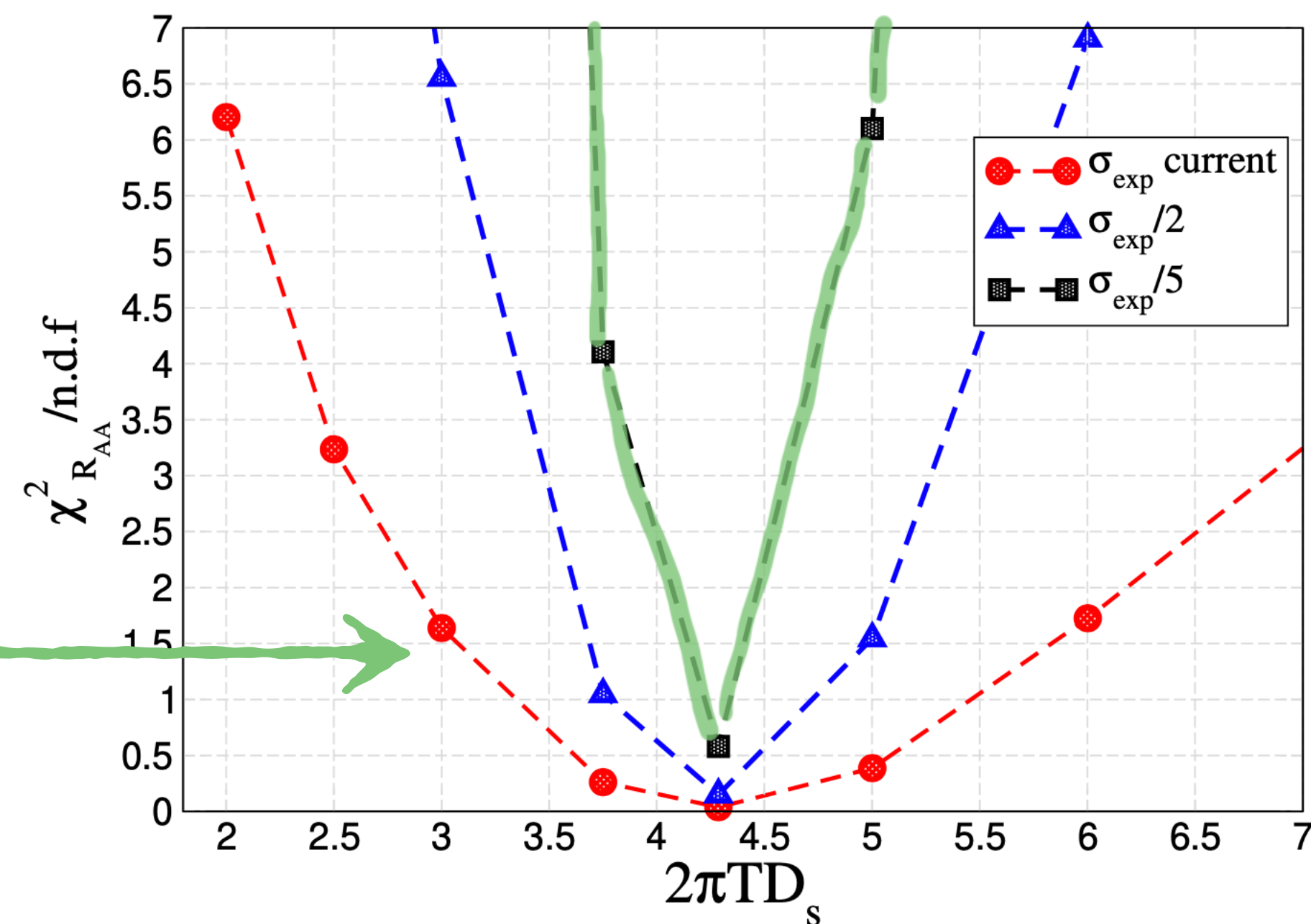
Diffusion coefficient D_s at statistics limit



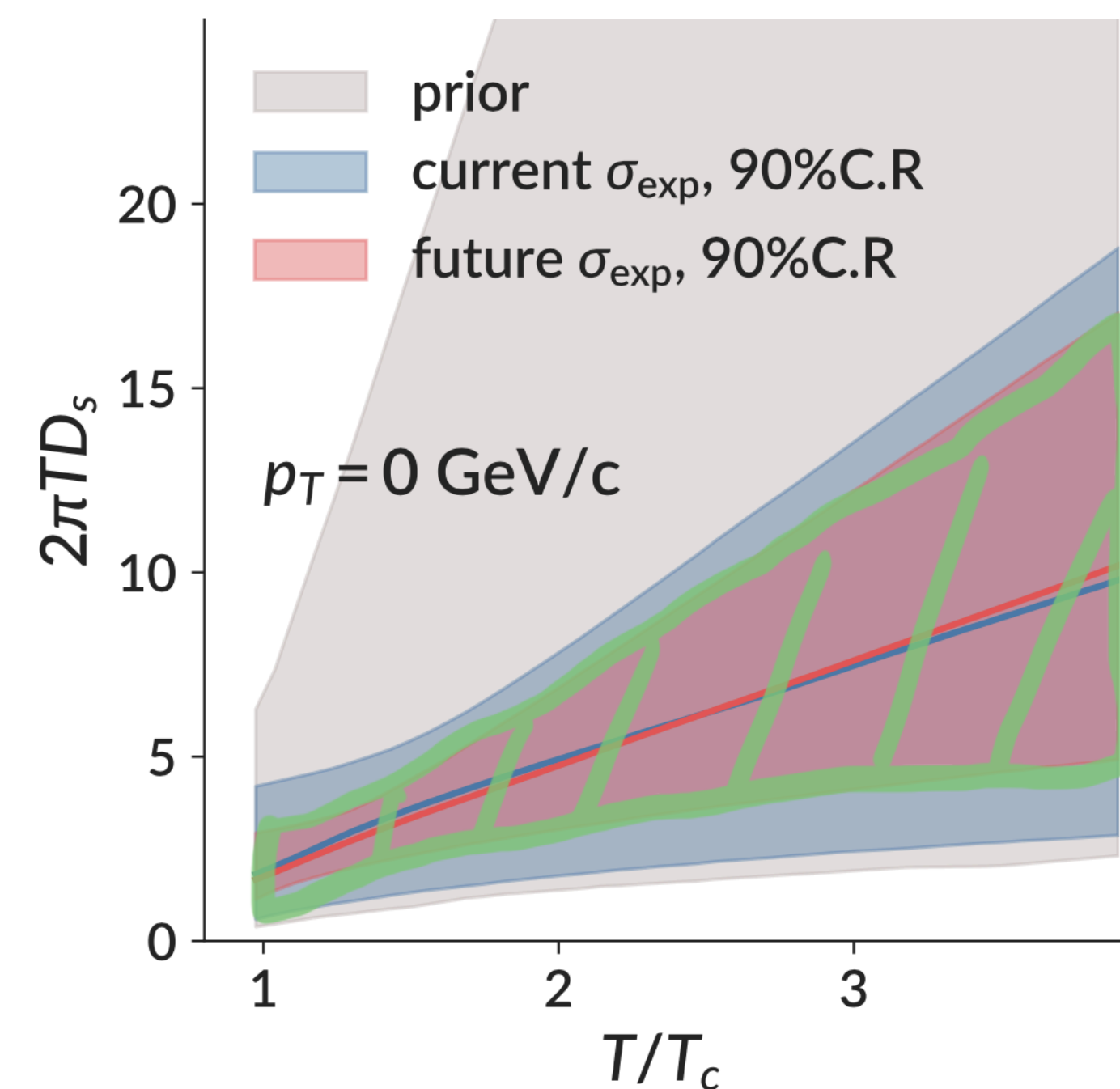
Projection after Run 4



D_s projection after Run 4 (Catania)

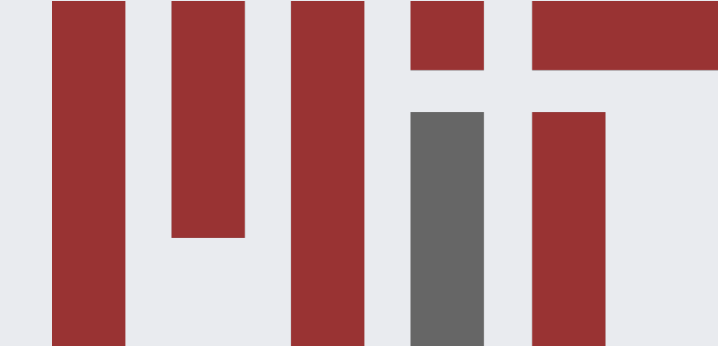


D_s projection after Run 4 (LBT)

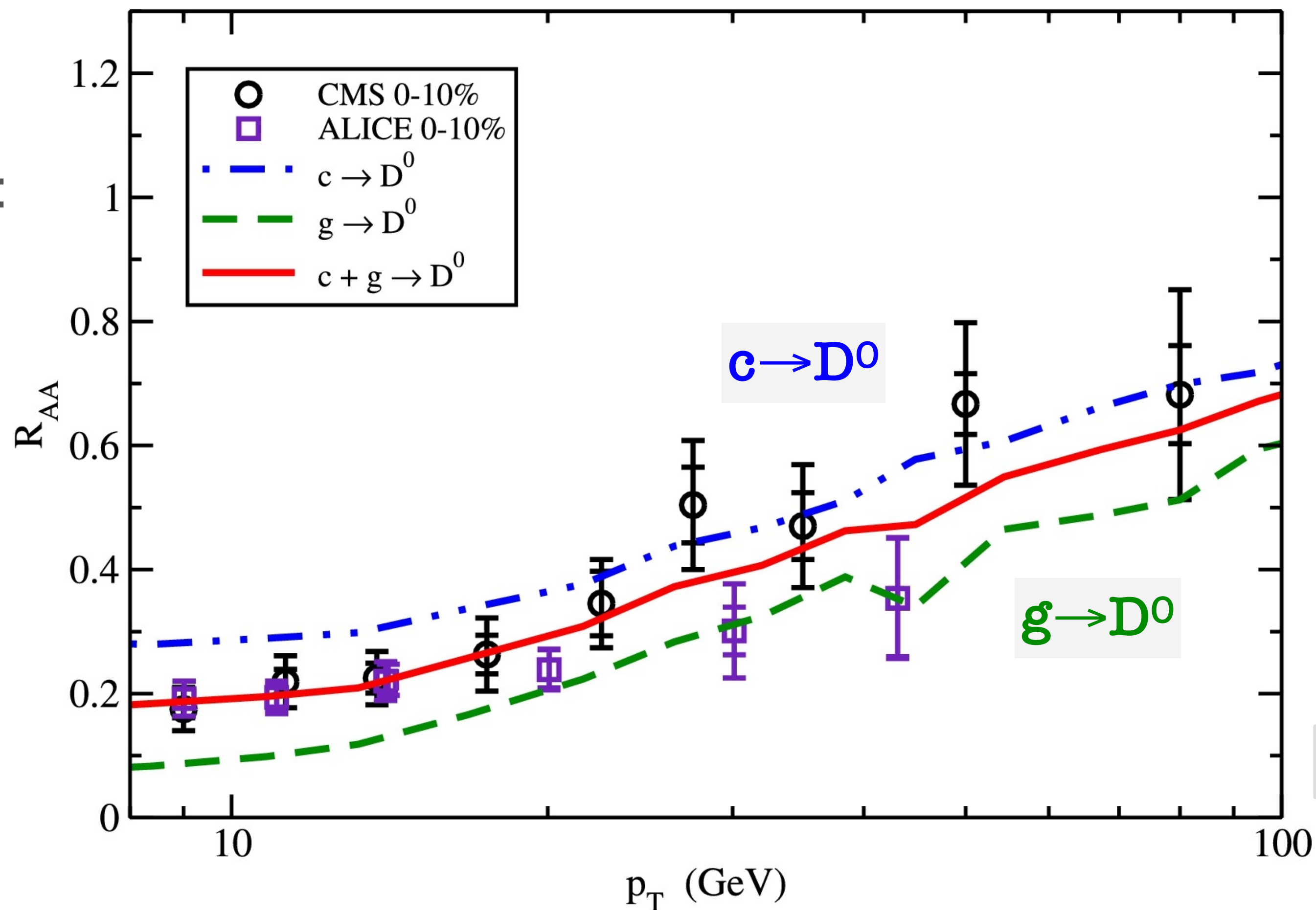


- D_s projection too optimistic: **systematics** limit
- Apart from inclusive R_{AA} and v_2
 - ➔ More **differential**
 - ➔ Other **observables**

arXiv:1812.06772



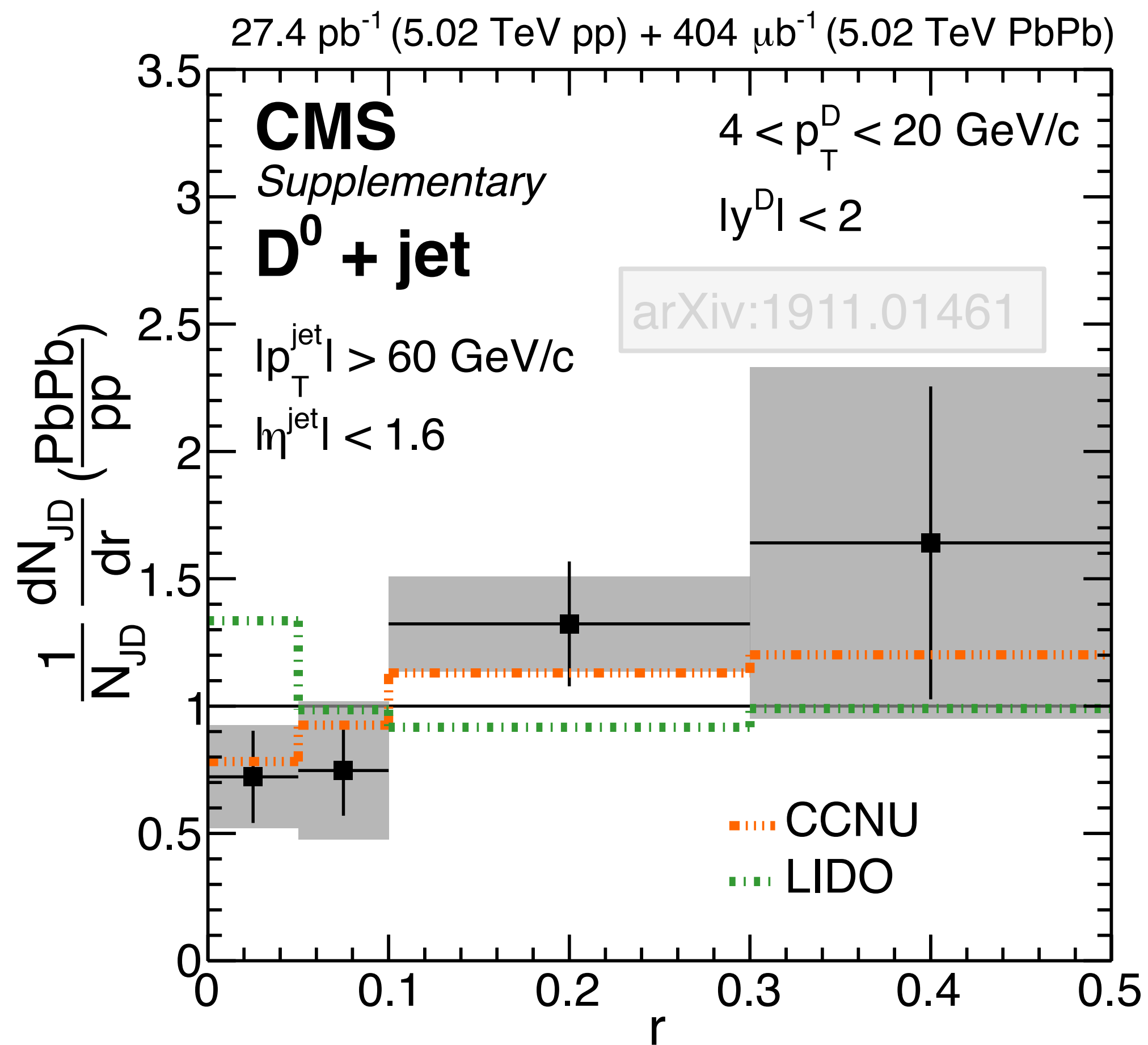
For example:



PLB 805 (2020) 135424

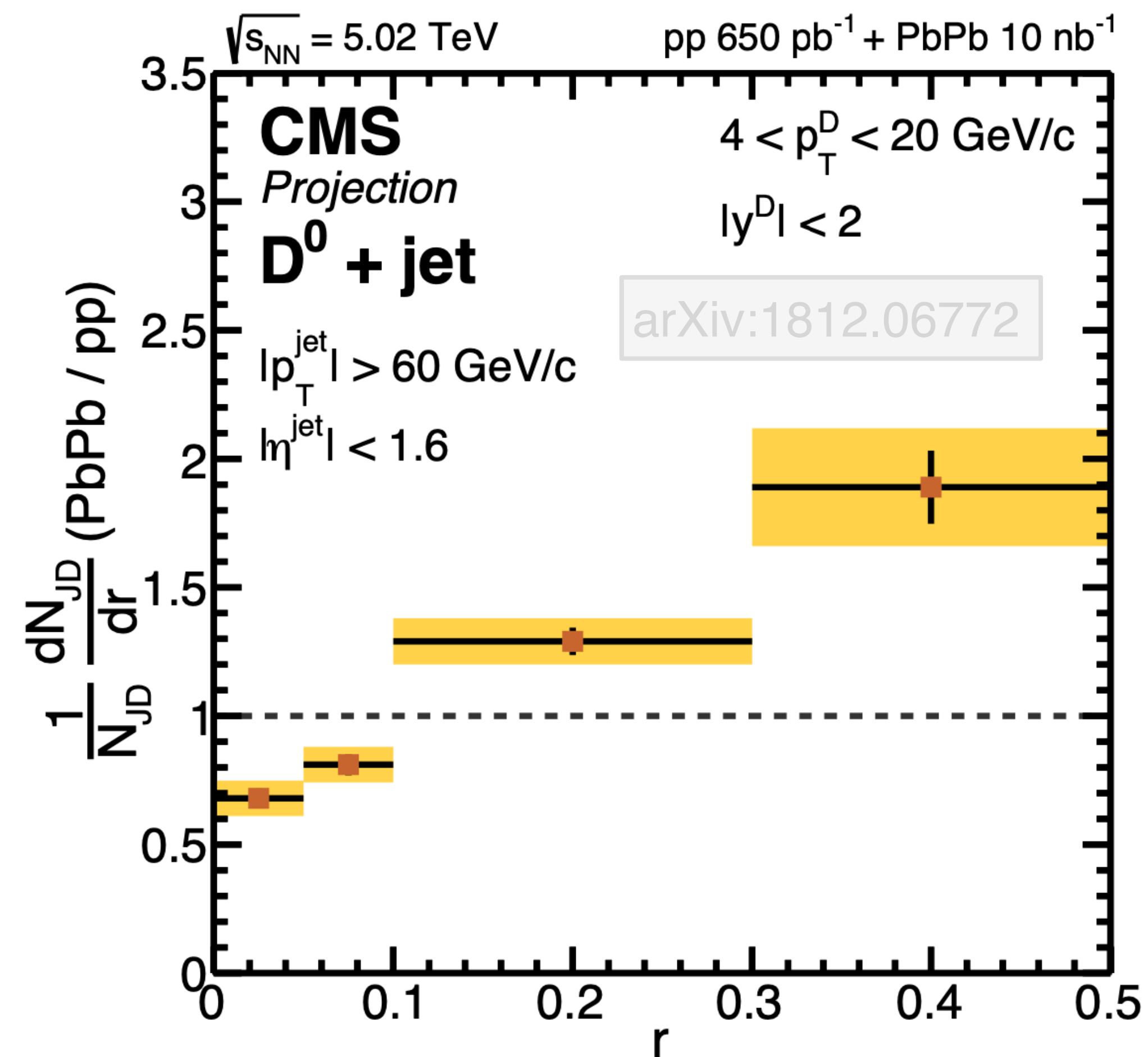
- Isolate charm quark fragmentation component?

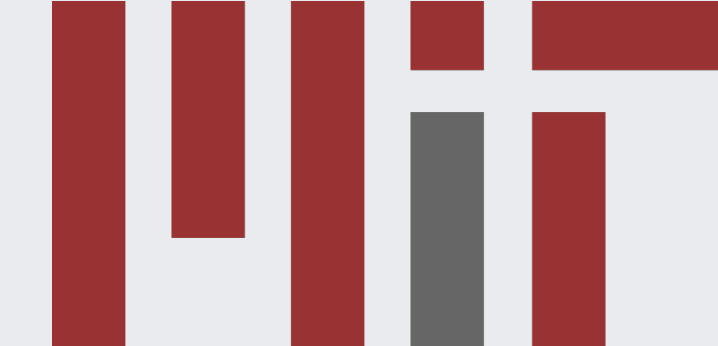
D-jet correlation vs. models



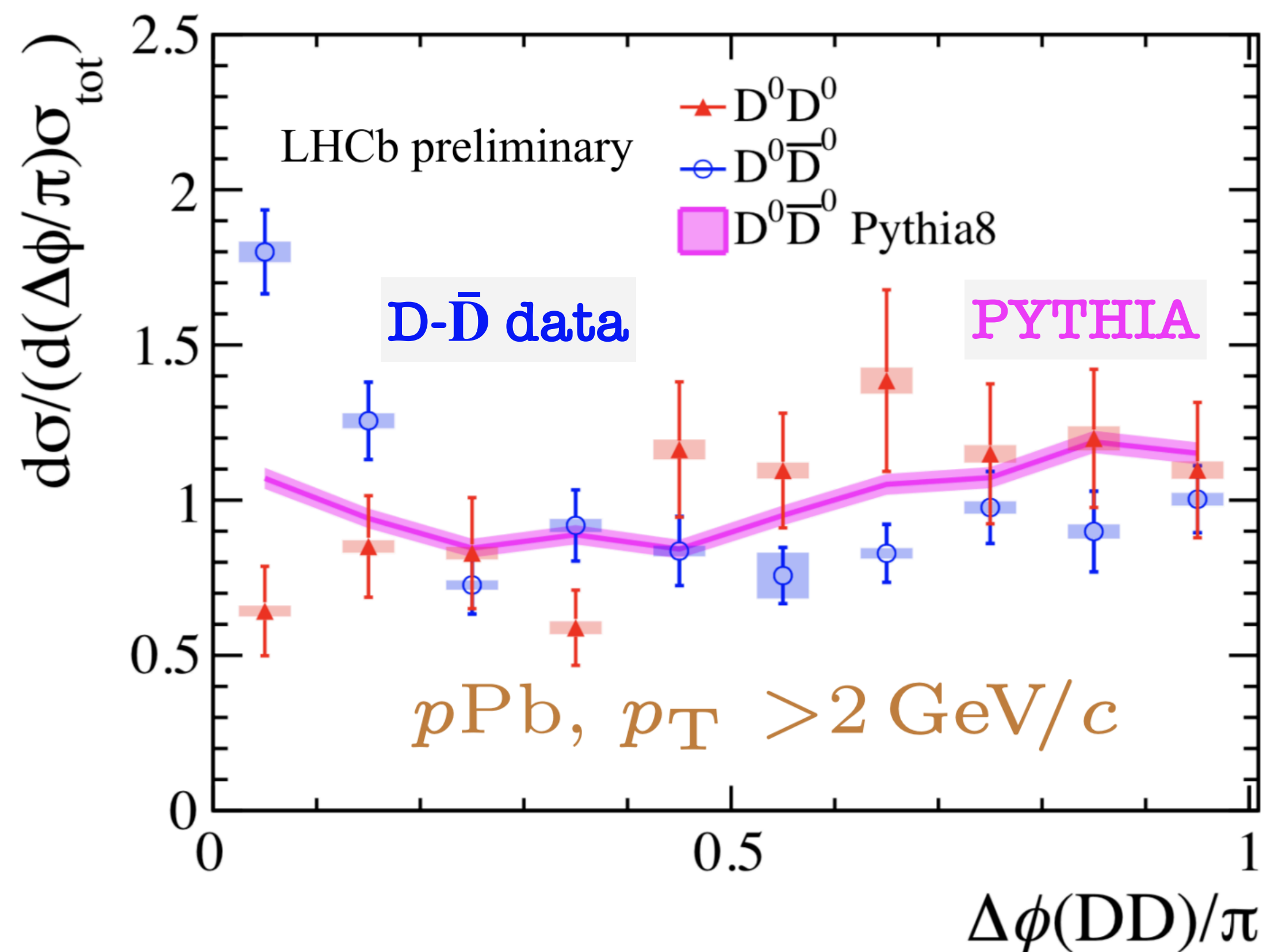
- Different trends from models

D-jet projection after Run 4



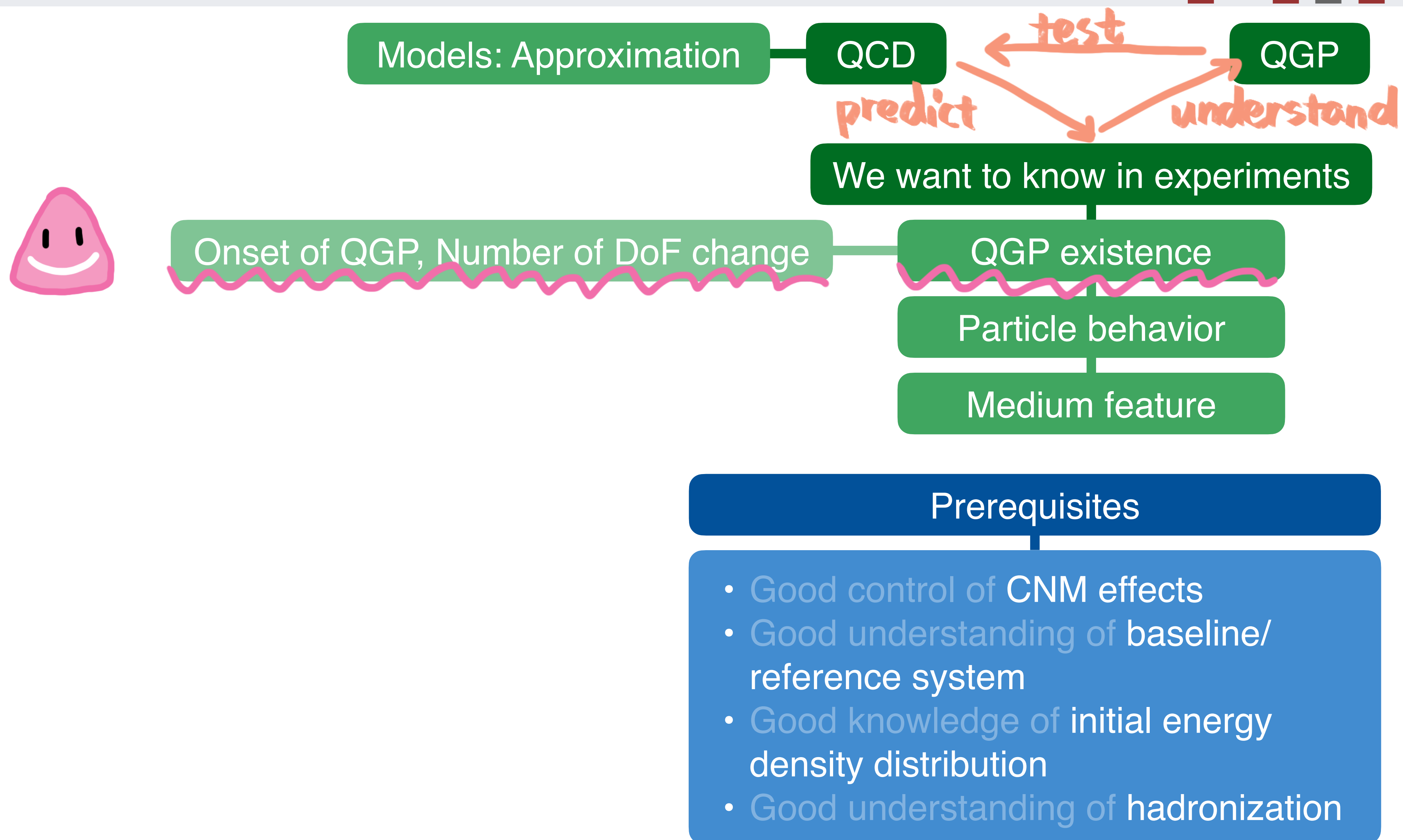


D- \bar{D} in pPb



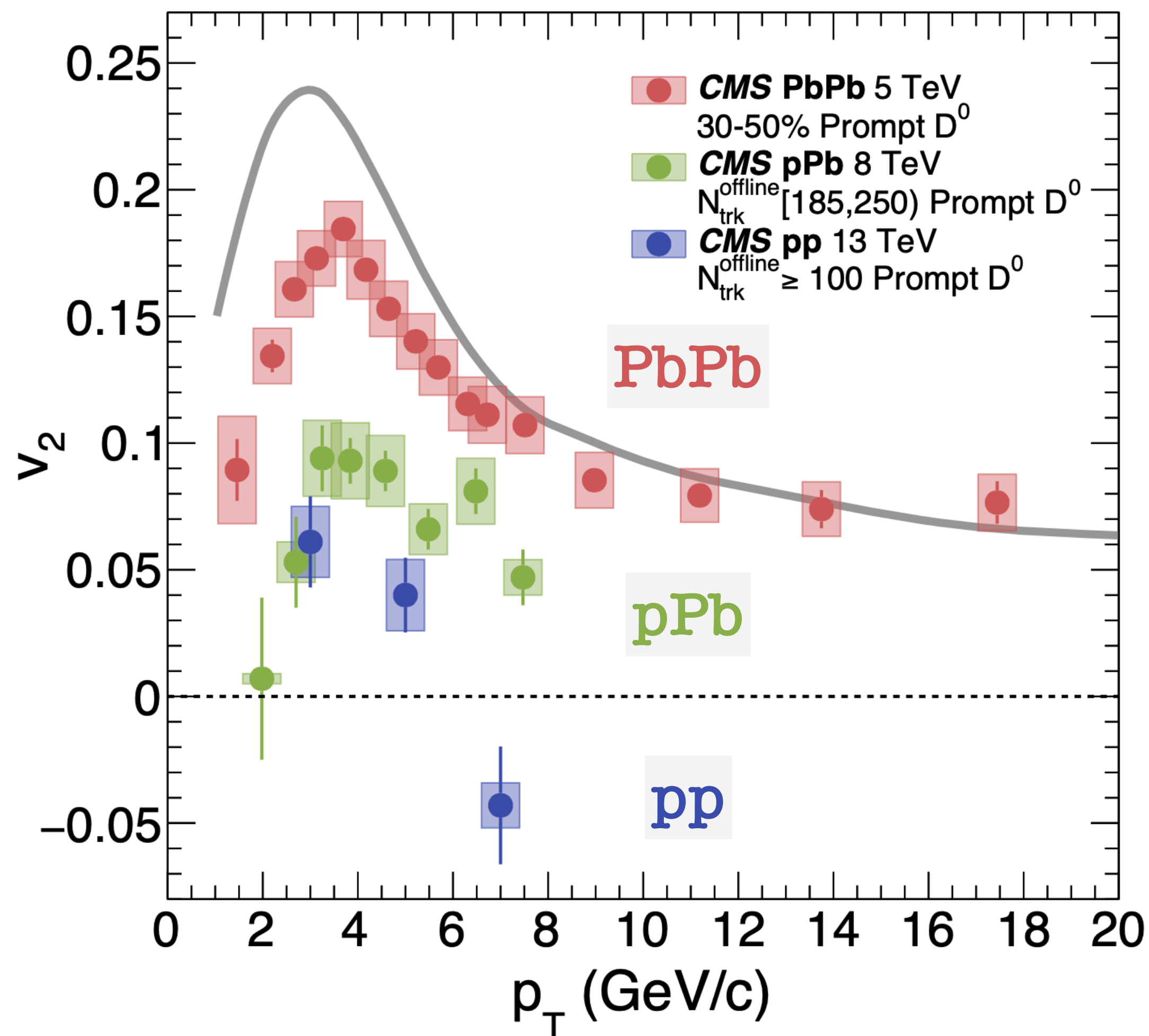
- D- \bar{D} correlation as a more sensitive observable than inclusive R_{AA} and v_2
- Relatively simpler (no jets) to calculate for theorists

Onset of QGP



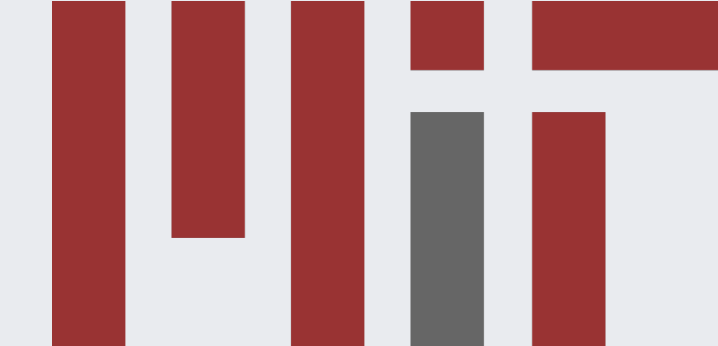


Prompt D^0 v_2 in various systems

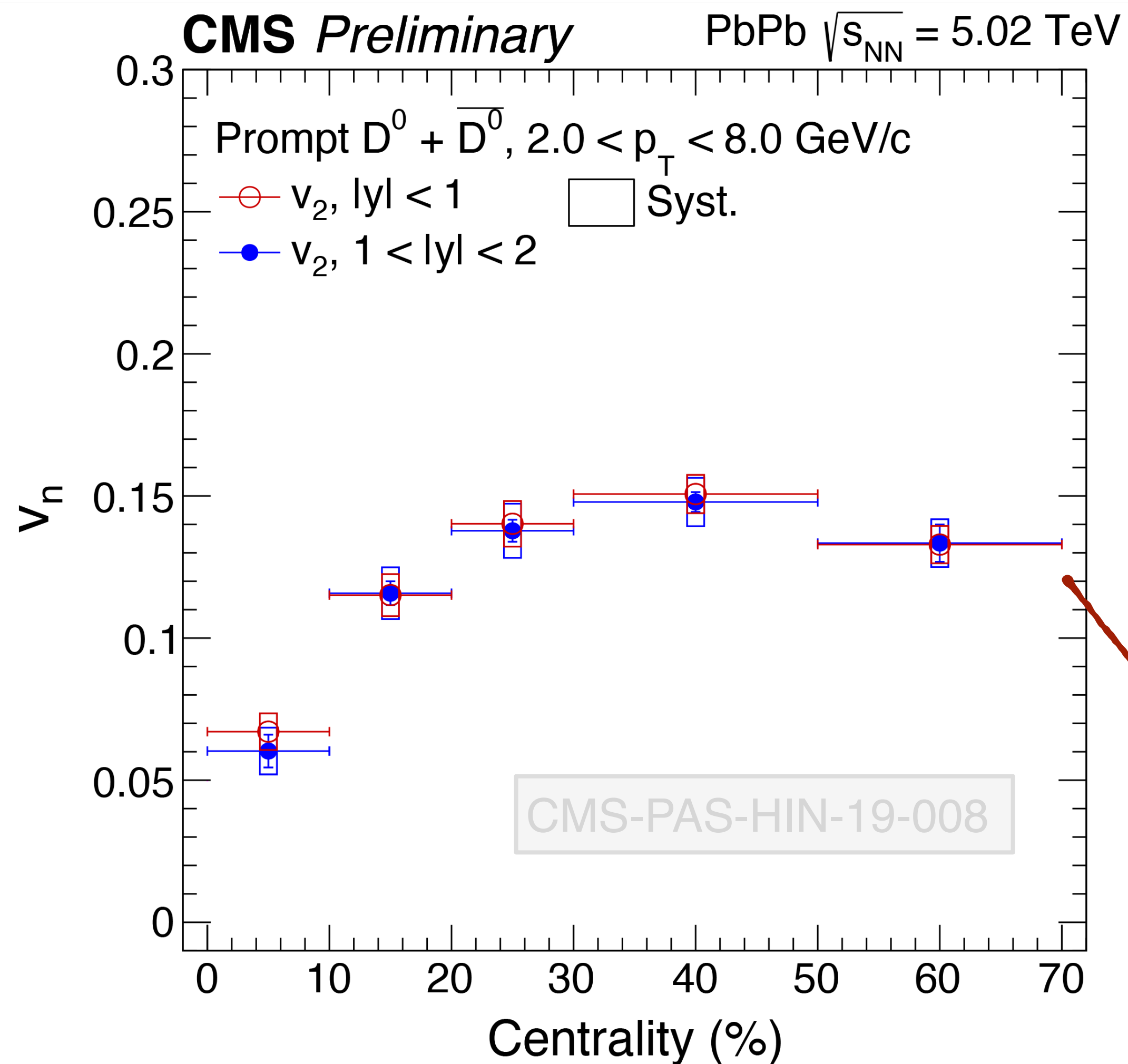


Camelia's HP talk

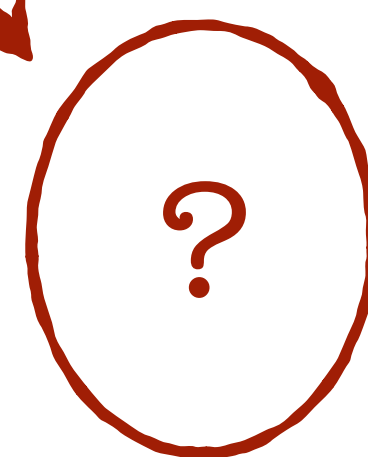
- Non-zero prompt D^0 v_2 in pp, pPb, PbPb
- When we will get QGP?
- What is the **smallest droplet** of QGP that behaves hydrodynamically?

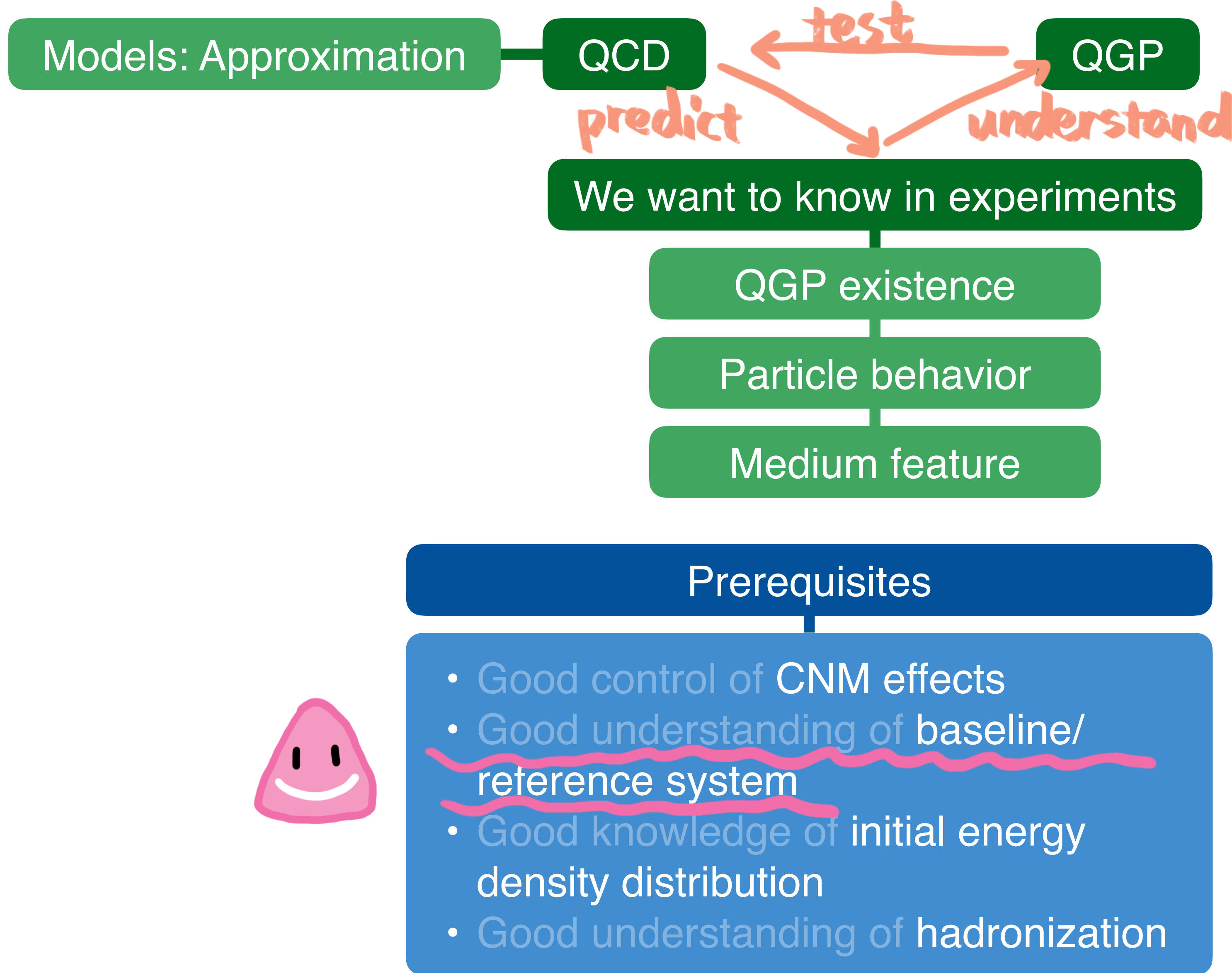


Prompt D^0 v_2 vs. centrality



- Some bridges connecting small and large system
 - **High-multiplicity pp**
 - **Intermediate** ions (O-O)
 - Very **peripheral** events (proposed record all 70-100% events in Run 3)





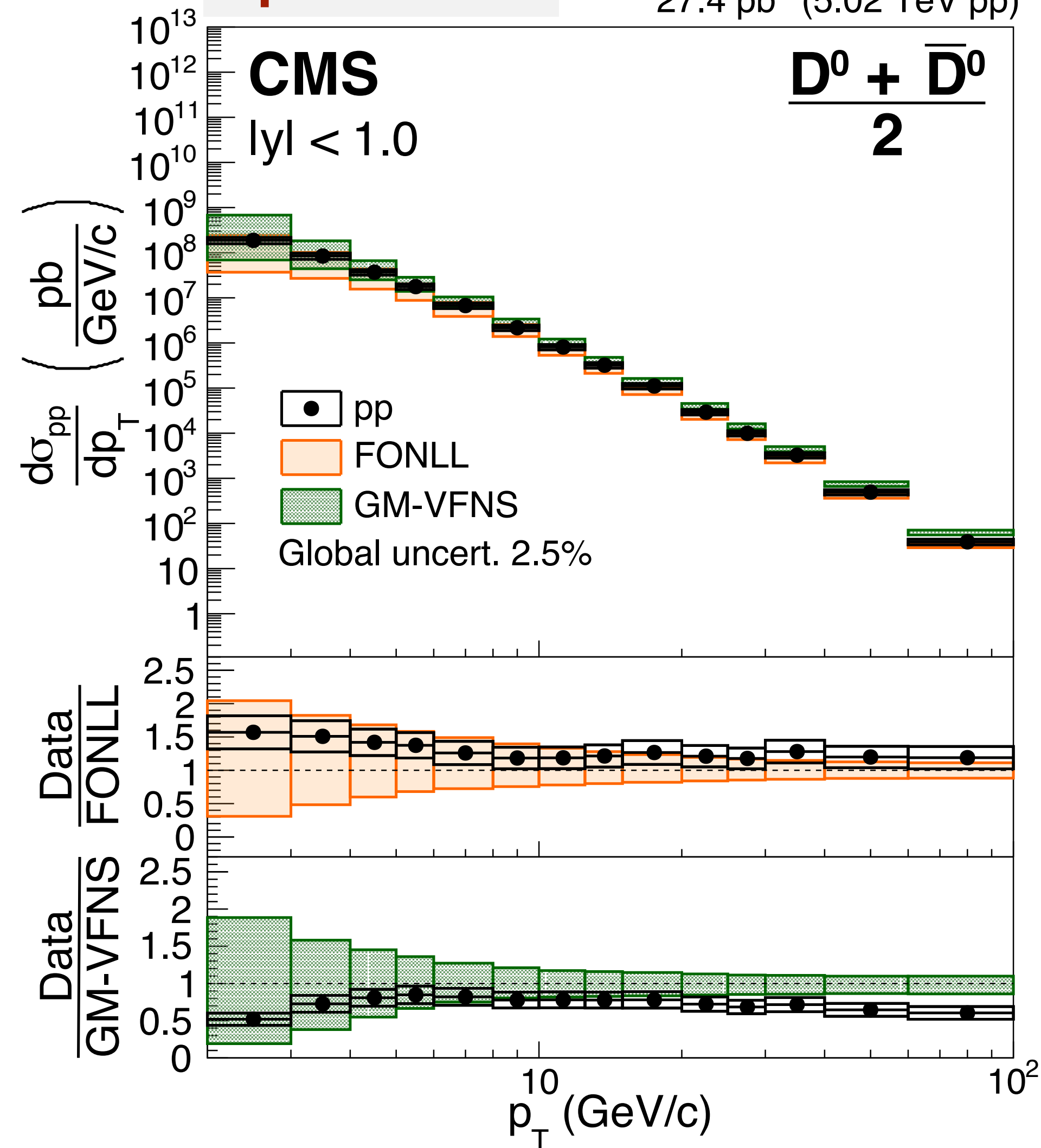


Production in pp vs. pQCD calculation



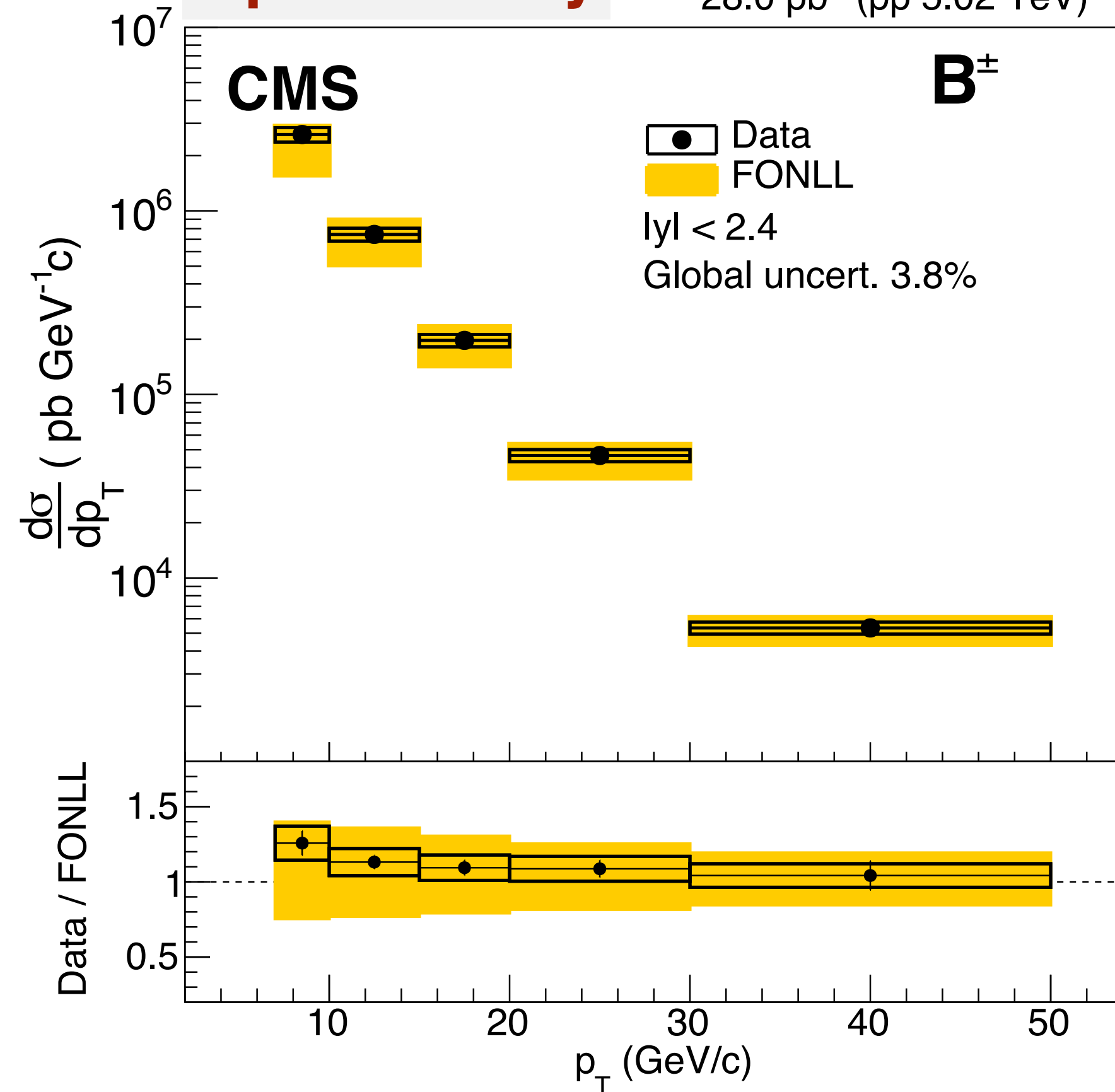
Open charm

27.4 pb⁻¹ (5.02 TeV pp)



Open beauty

28.0 pb⁻¹ (pp 5.02 TeV)



2015 data

2017: 7-10x more statistics

PLB 782 (2018) 474

PRL 119 (2017) 152301

- Decent **agreement** of pQCD calculation to data
- **Data precision** (even if 2015 statistics) much **better** than calculation → good input for theoretical models

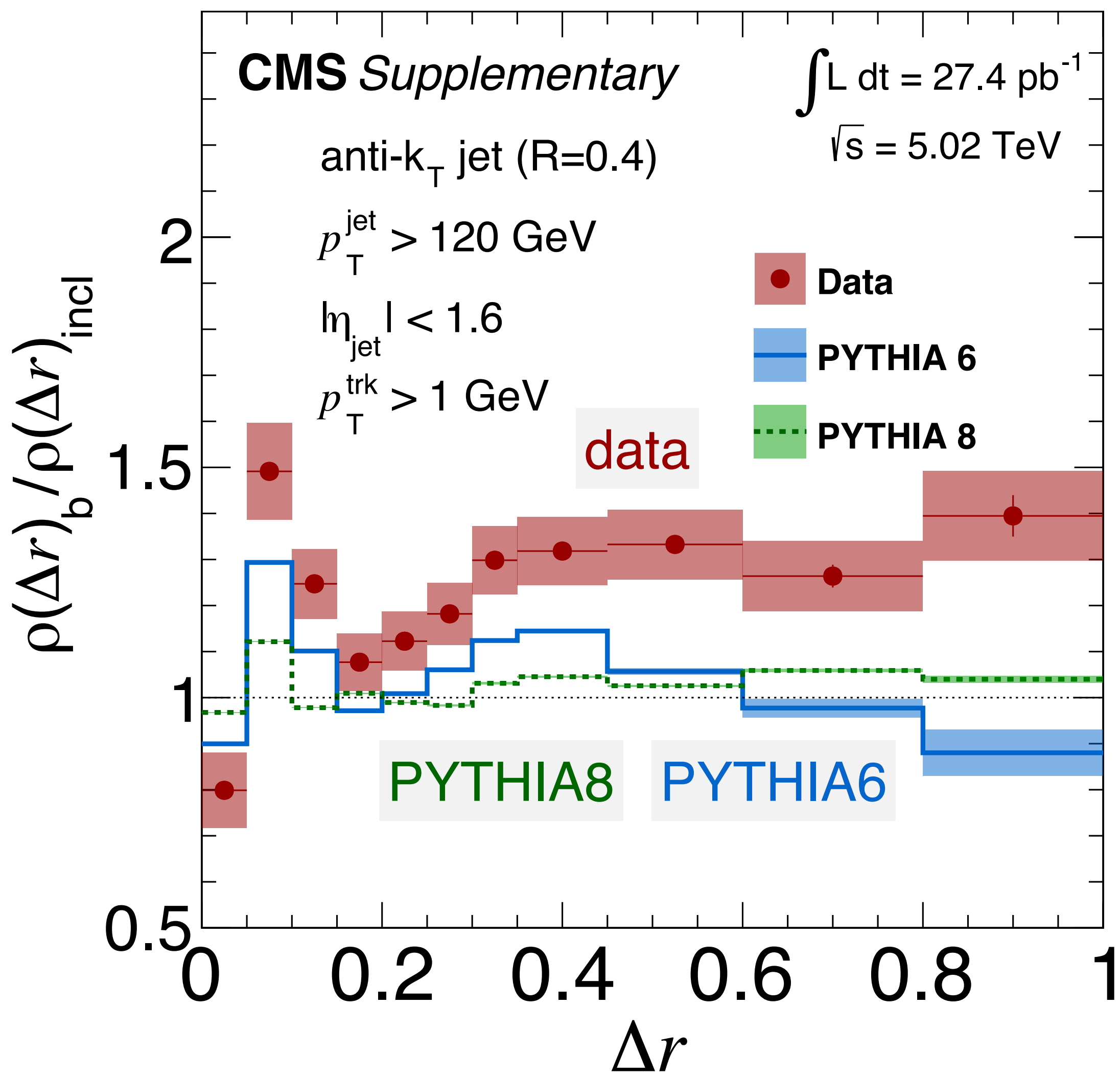




Production in pp vs. pQCD calculation

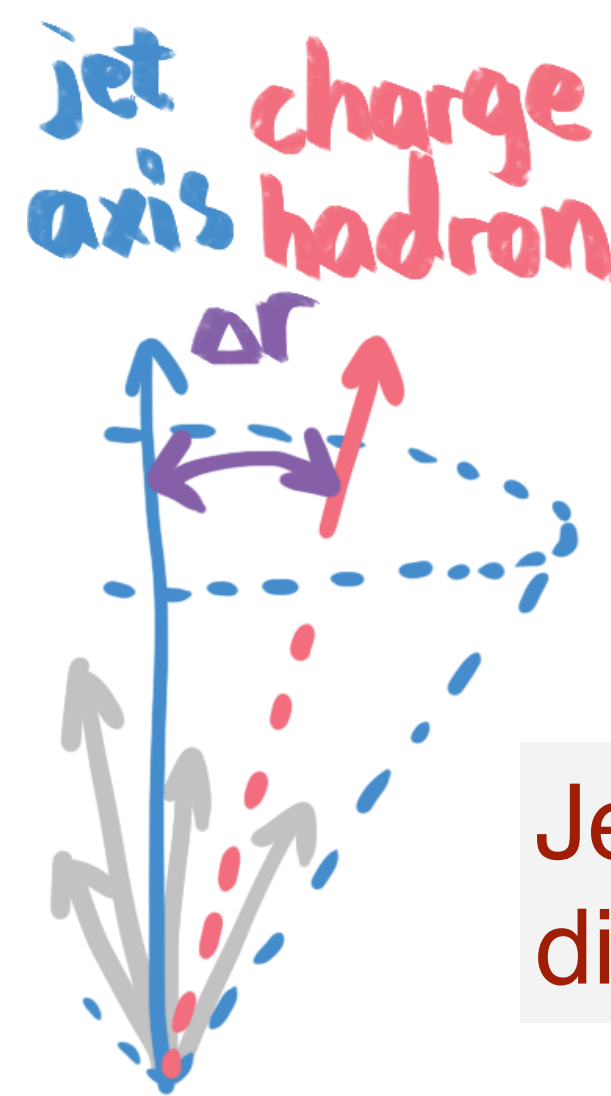


Jet shape: b jet / inclusive jet



Structure of beauty jet

- Particles shift **further** away from jet axis in b-jets
- Feature **not captured by PYTHIA** at large r

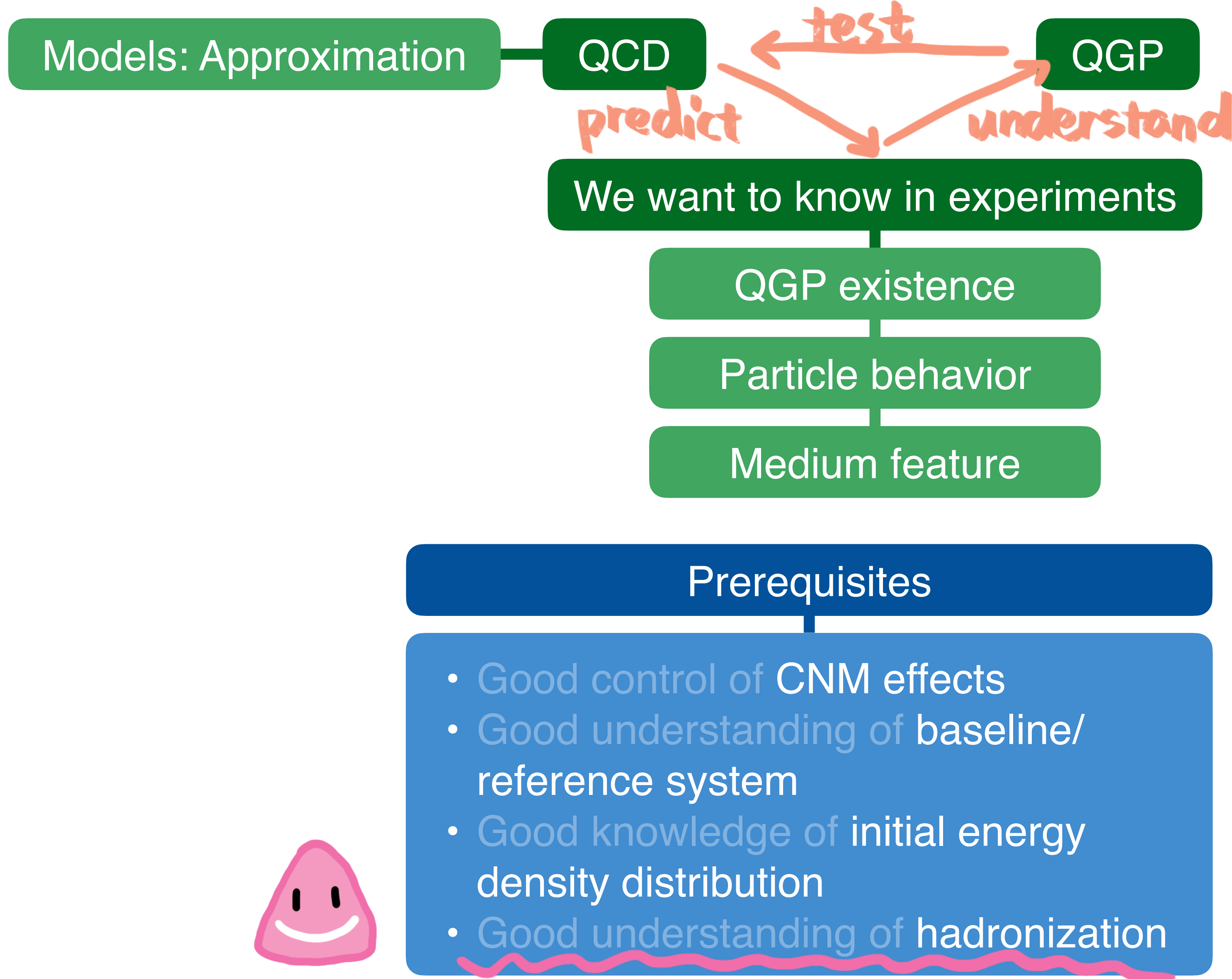


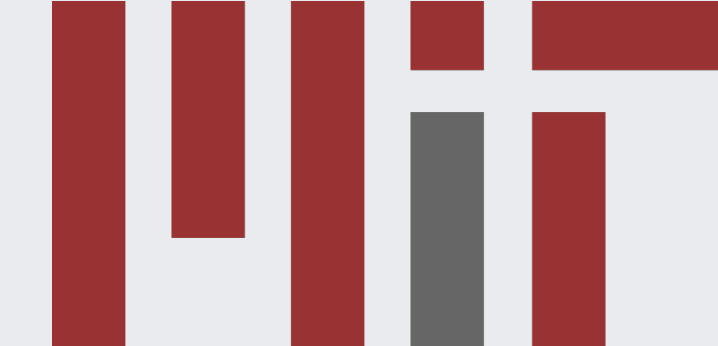
arXiv:2005.14219

Jet shape: p_T radial distribution w.r.t. jet axis



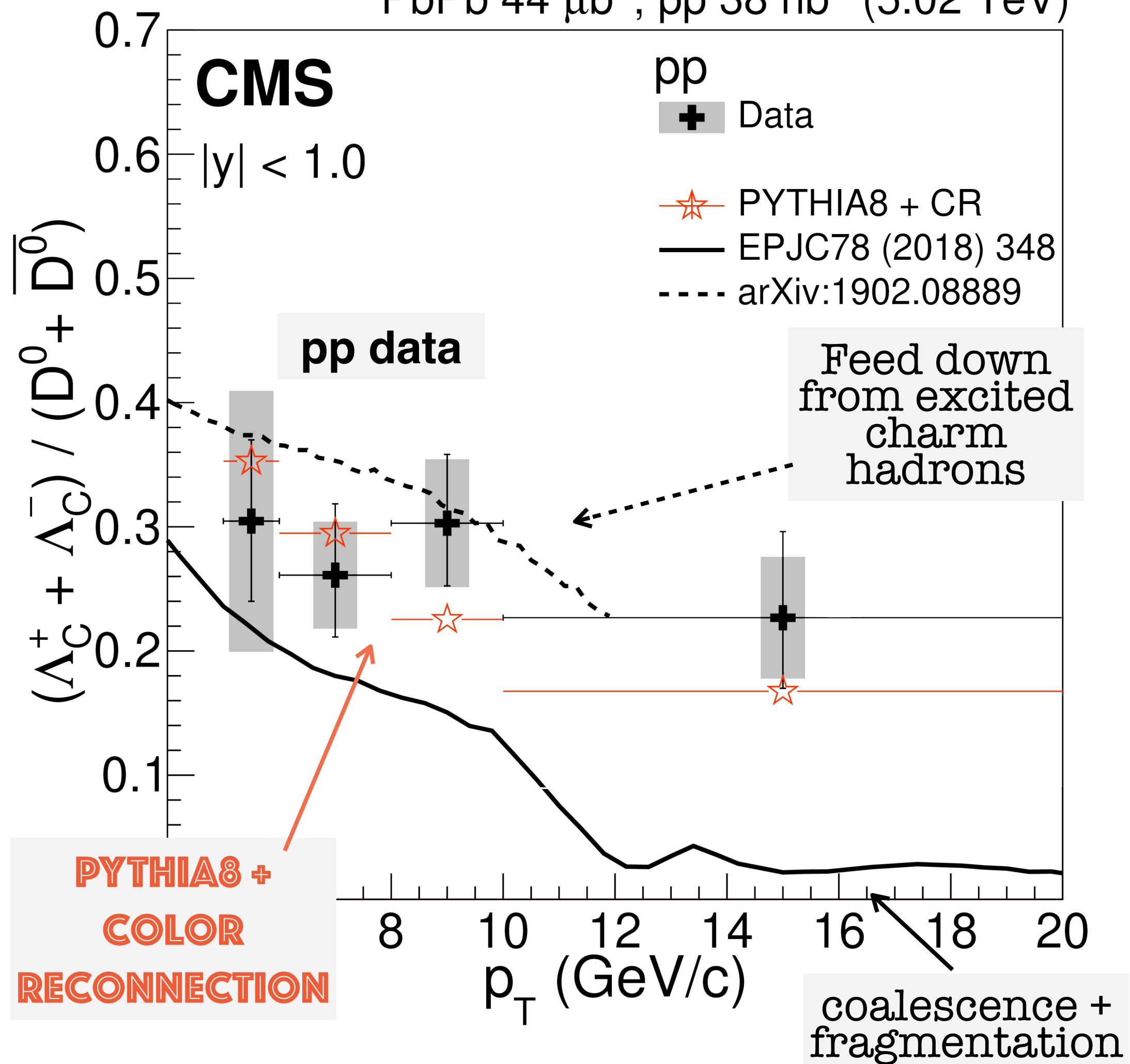
Hadronization mechanism





Λ_c / D^0 in pp vs. models

PbPb $44 \mu\text{b}^{-1}$, pp 38nb^{-1} (5.02 TeV)



For the underestimation of Λ_c production by fragmentation only

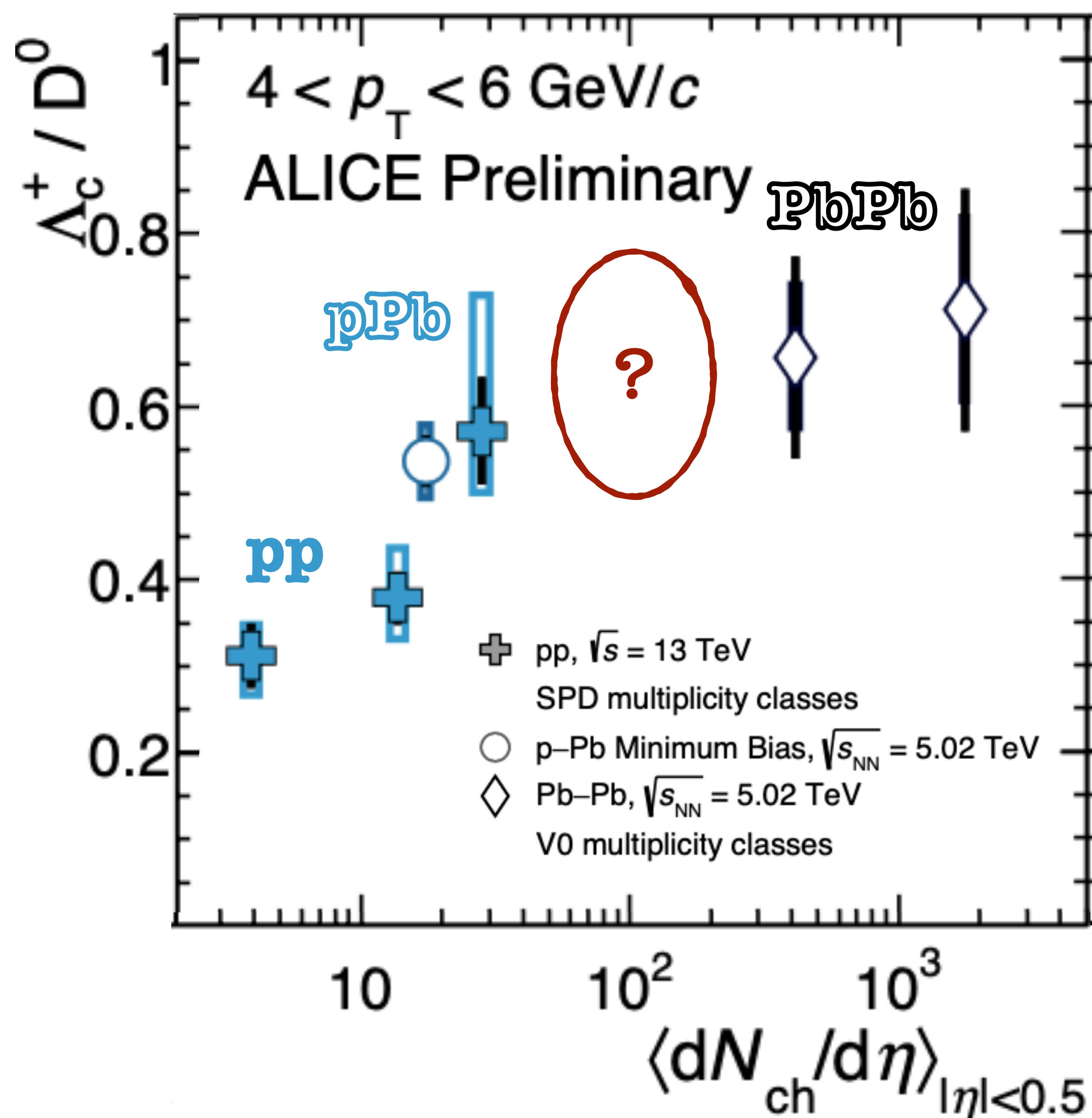
- Is **color reconnection** a good solution?

2015 data

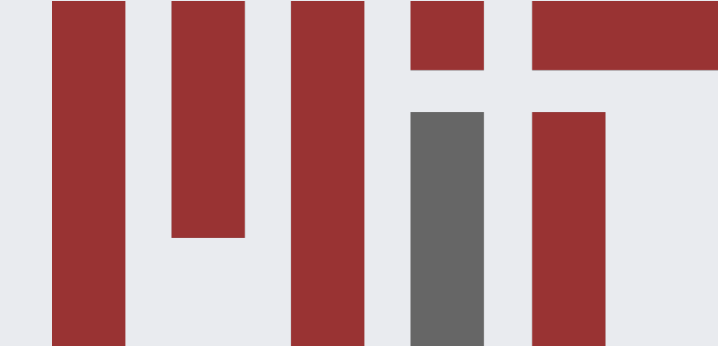
2017: 7x more statistics



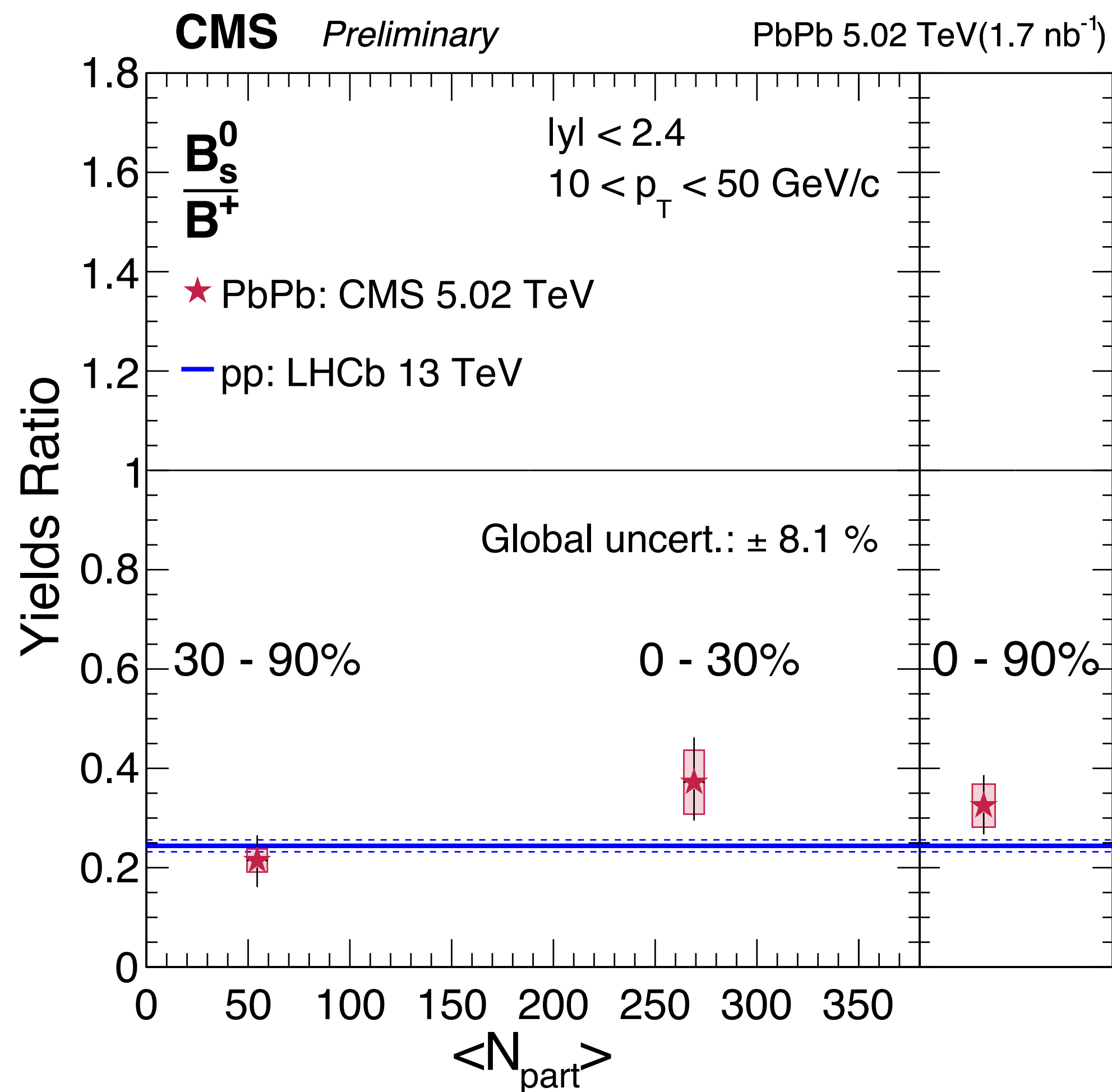
Λ_c / D^0 vs. multiplicity



- Is transition **smooth**?
 - ➔ **High-multiplicity pPb** in CMS
 - ➔ What does it mean if Λ_c/D^0 same for pp and PbPb at same multiplicity?
- Is $dN/d\eta$ a good scale for systems?



B_s / B^+ vs. centrality



- What will happen to B_s in high-multiplicity pp?



“New physics”: X(3872) internal structure



- Heavy ion collisions not only for studying QGP

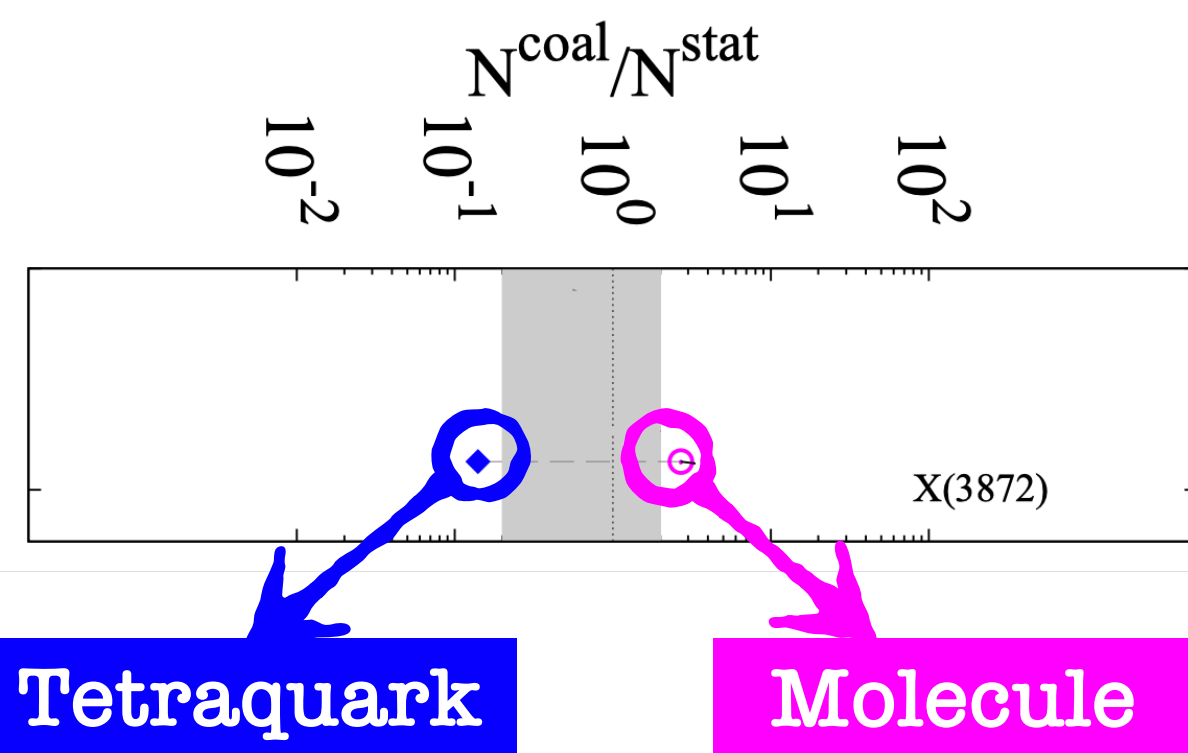
Coalescence model

AMPT transport model

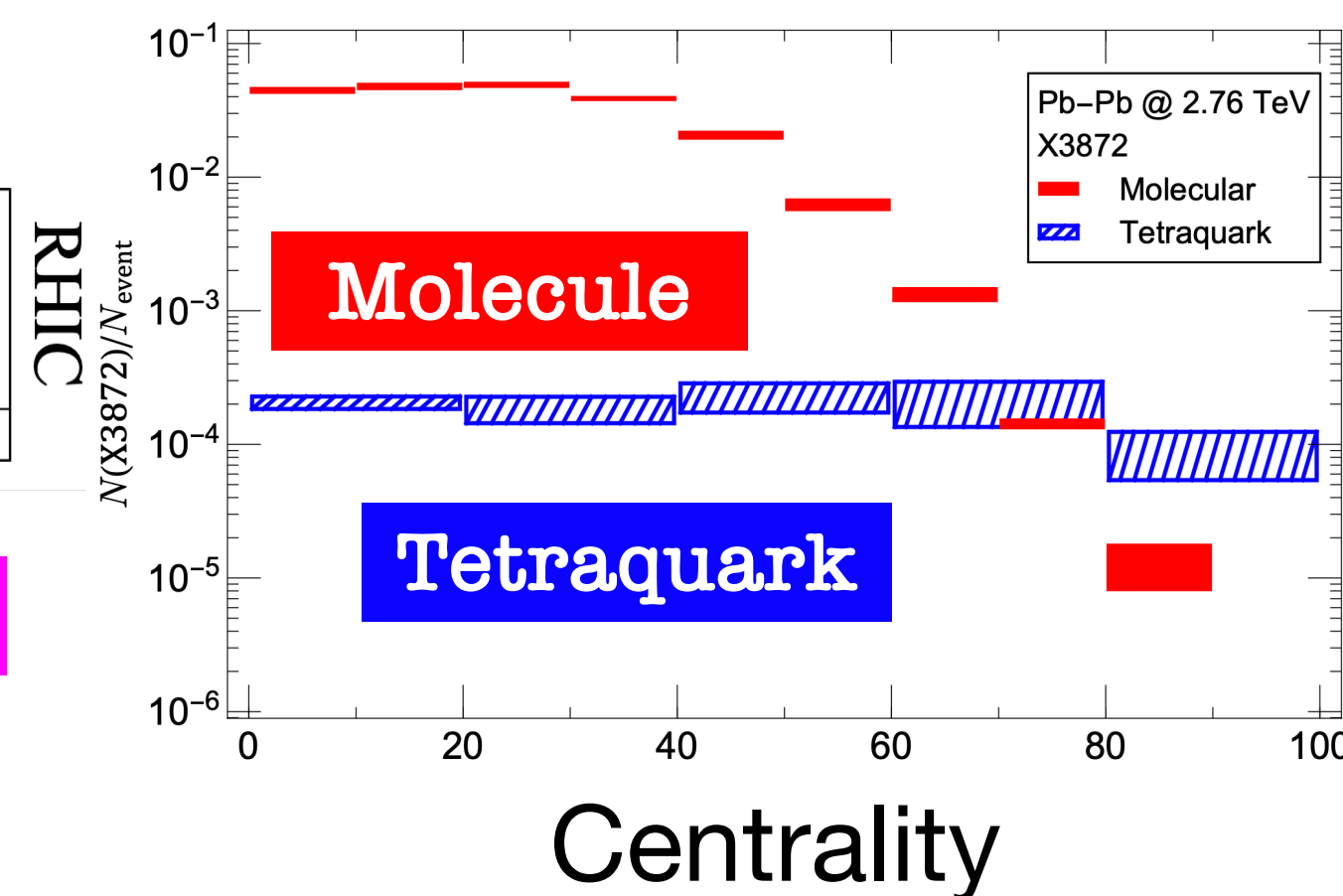
TAMU transport model

vs. multiplicity in pp

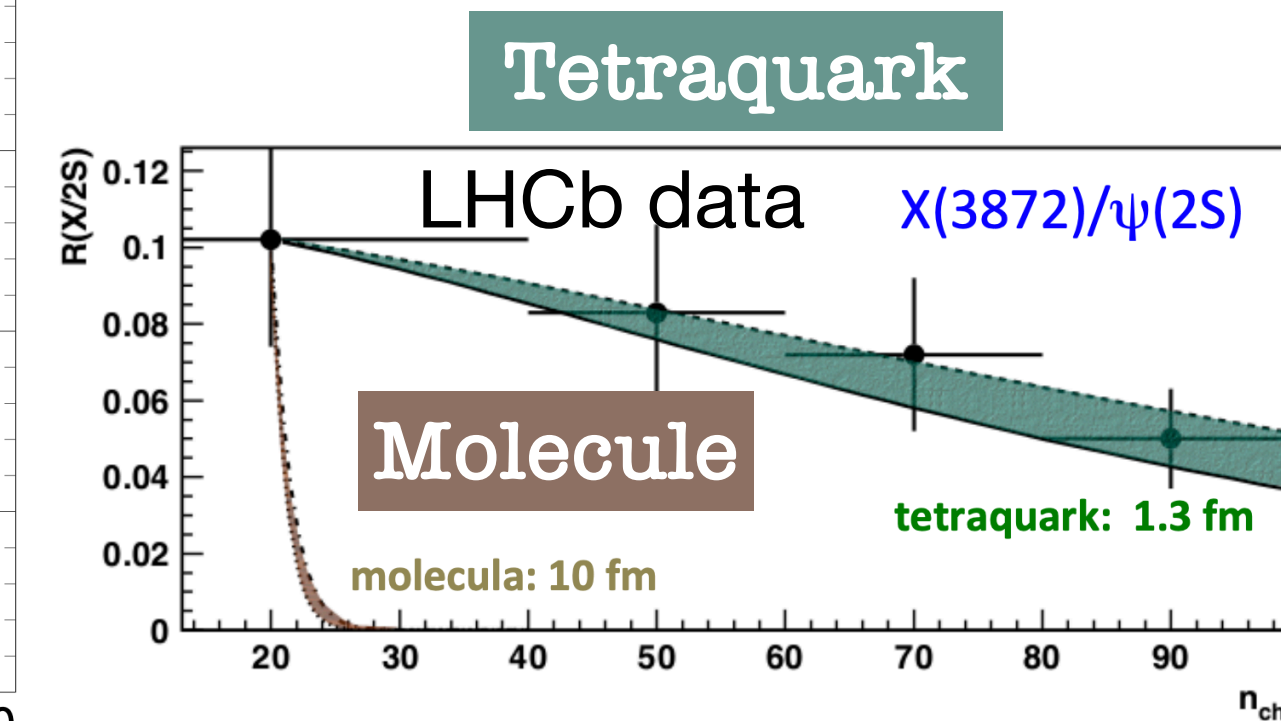
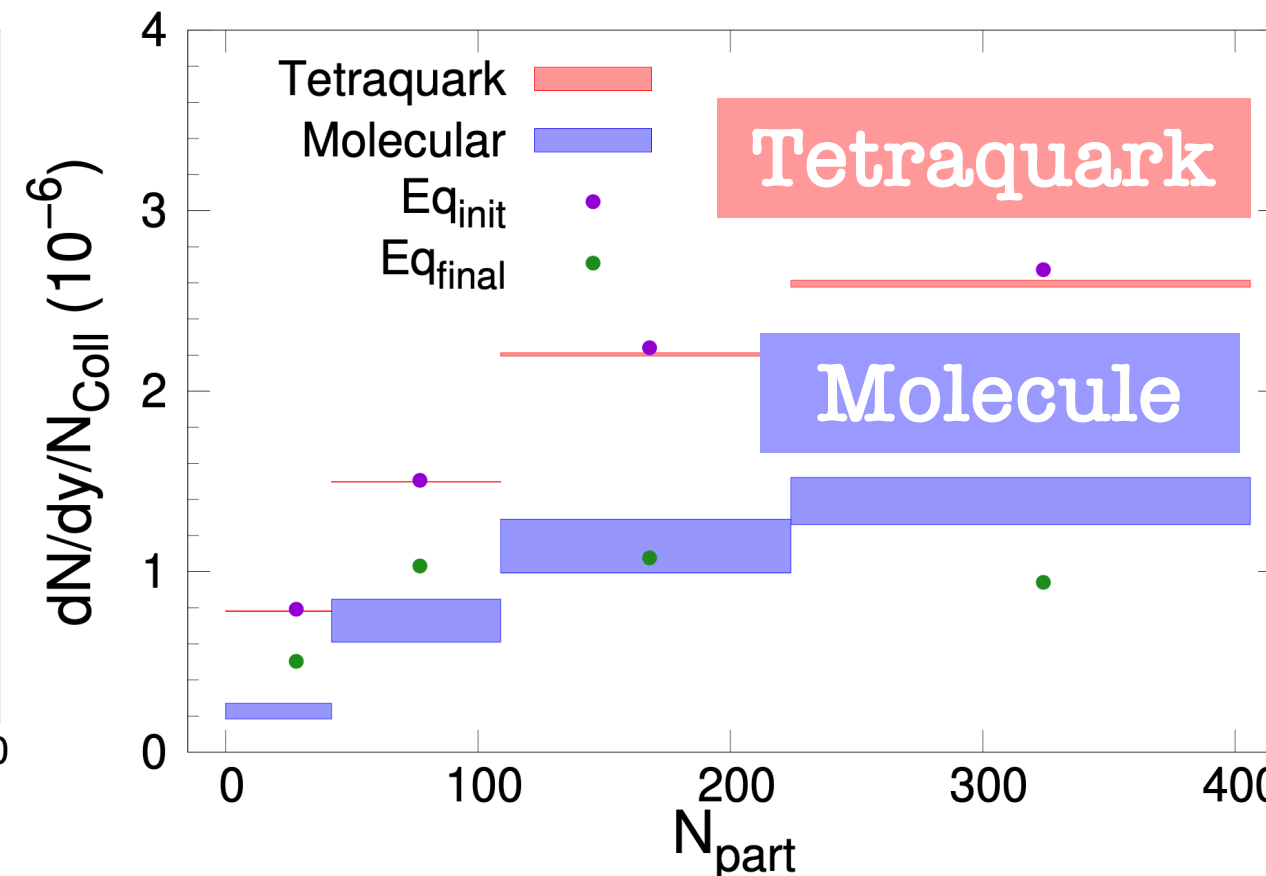
PRL 106 (2011) 212001



arXiv:2004.00024



arXiv:2006.09945



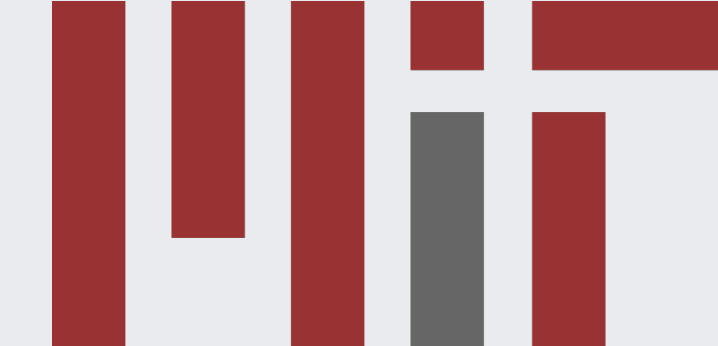
- ▶ Molecule easier to be produced w/ recombination of quarks in medium
- ▶ $N_{\text{Molecule}} > N_{\text{Tetraquark}}$

- ▶ Centrality dependence
- ▶ $N_{\text{Molecule}} > N_{\text{Tetraquark}}$

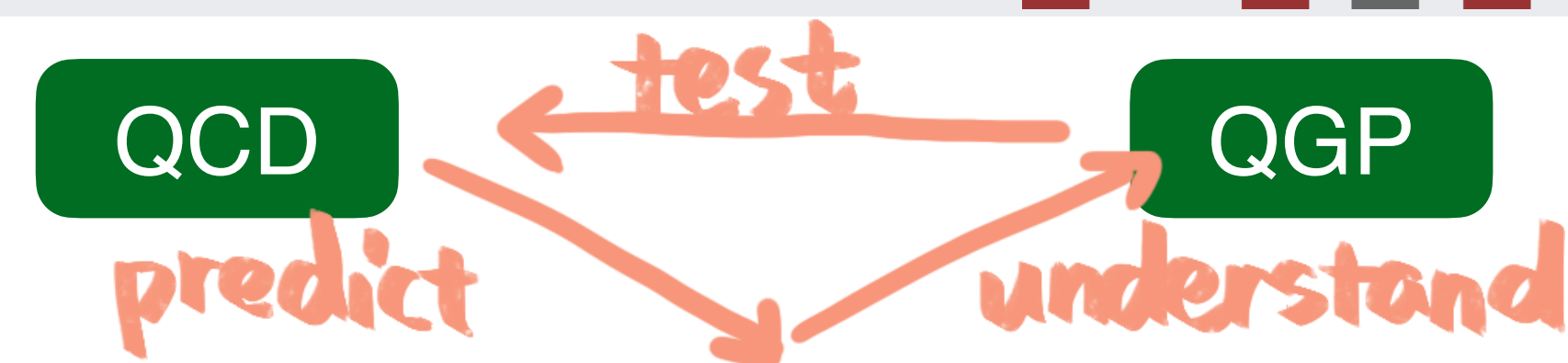
- ▶ Molecule (more loosely bound) regenerated later in the evolution compared to tetraquark
- ▶ $N_{\text{Molecule}} < N_{\text{Tetraquark}}$

- ▶ Destroyed by comover
- ▶ Recombination not included
- ▶ Including recombination gives wrong trend

Summary



- CMS has performed various HF measurements with hadrons and jets
- Expect significant improvement on precision with 2018 data
- Close to statistics limit with Run 3/4 (Systematics start to dominate)
- More differential measurements in plan
- Explore observables more sensitive to HQ diffusion
- High-multiplicity pp, intermediate ions, and ultra peripheral to study onset of QGP
- HF production in pp collisions is not perfectly understood
- Study hadronization mechanisms across system sizes
- Answer other physics questions w/ HF in Heavy-ion collisions



We want to know in experiments

- QGP existence
- Particle behavior
- Medium feature

Prerequisites

- Good control of CNM effects
- Good understanding of baseline/reference system
- Good knowledge of initial energy density distribution
- Good understanding of hadronization



Back up

Thanks for your attention!

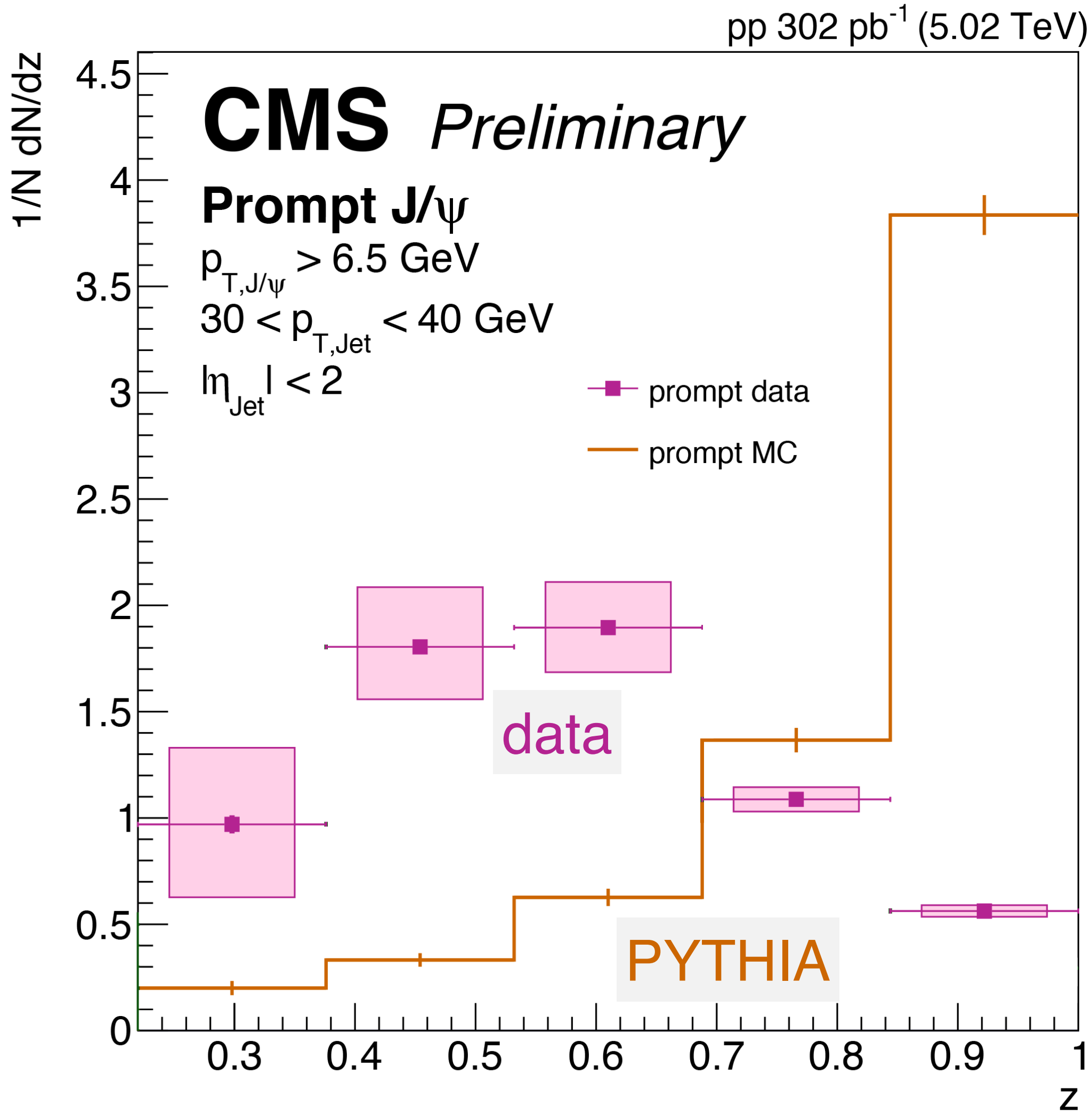


Isabelle

Thanks for your attention!

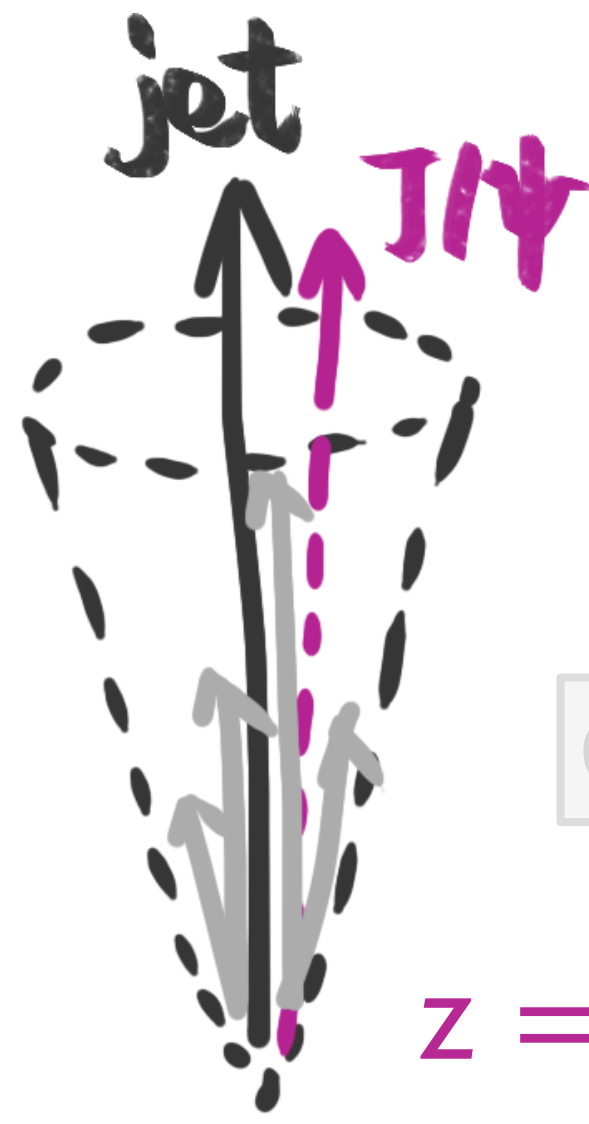


Production in pp vs. pQCD calculation



J/ψ fragmentation function in jets

- PYTHIA8 misses the shape
- **Hadron production mechanism** not very well known



CMS-PAS-HIN-19-007

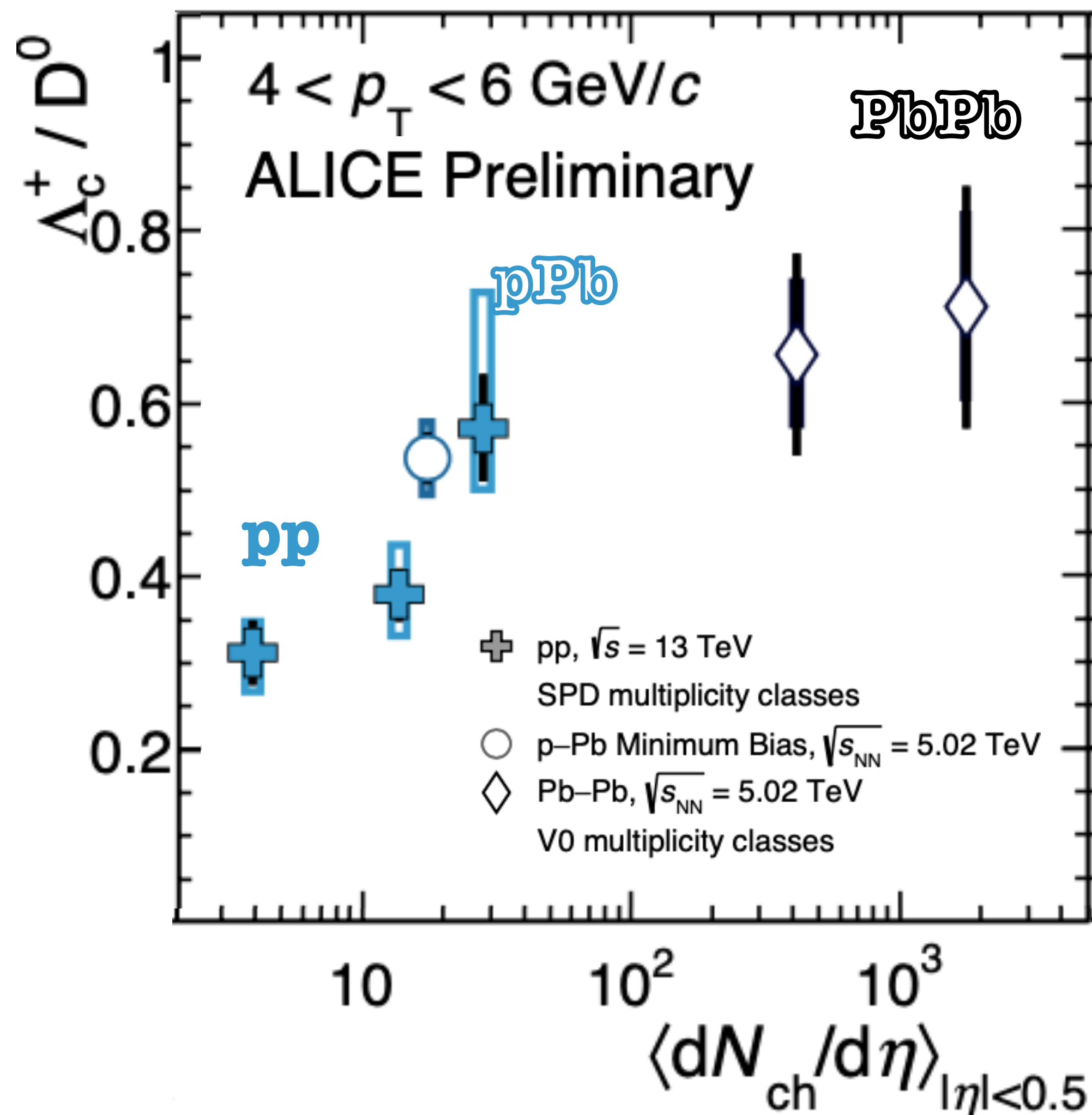
$$z = p_T^{J/\psi} / p_T^{jet}$$



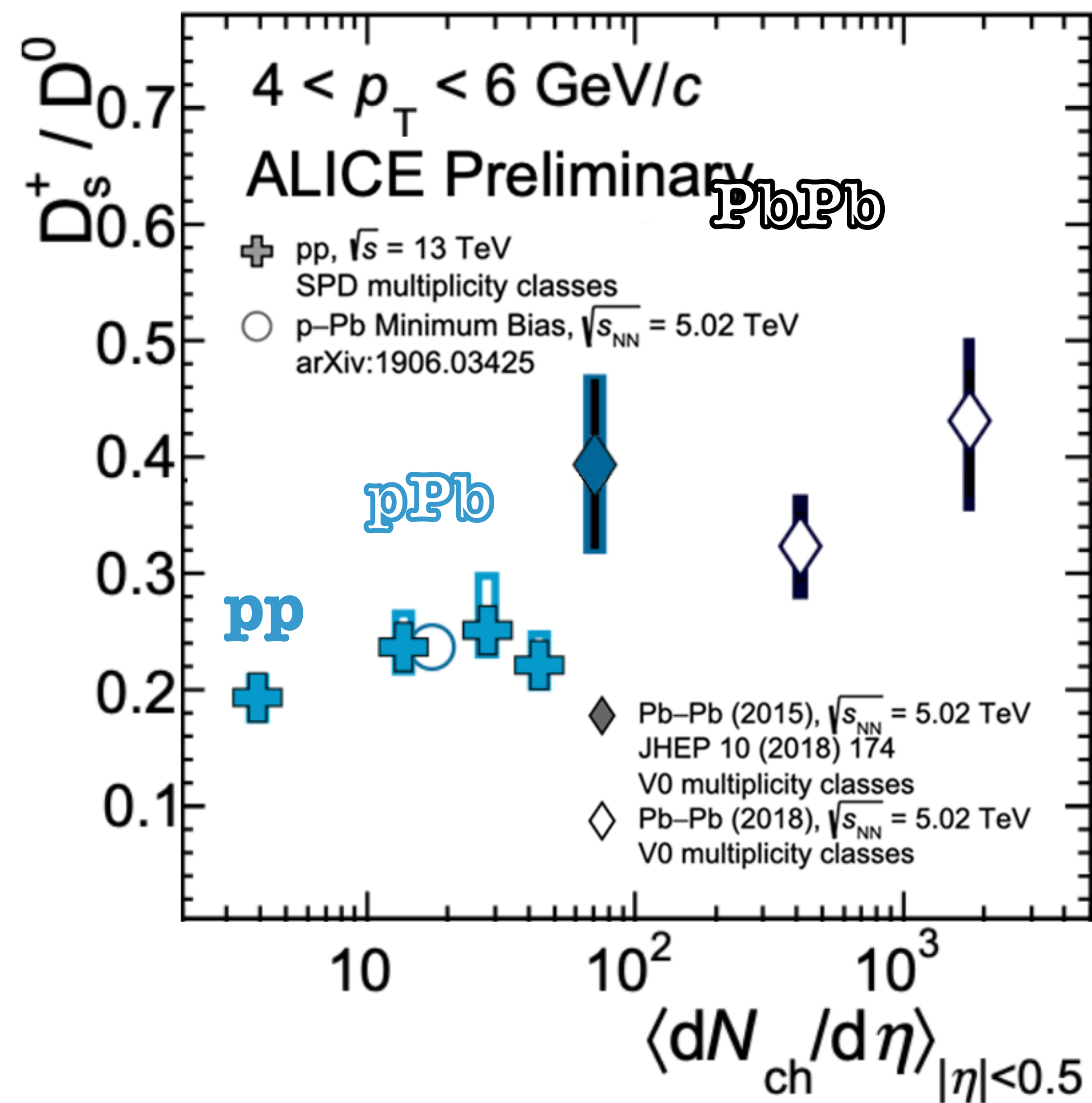
Hadronization



Λ_c / D^0 vs. multiplicity



D_s / D^0 vs. multiplicity





Summary (I): We have learnt a lot before



Only from publications w/ Run II data...

<p>nPDF arXiv:2003.12797 PLB 800 (2020) 135048 PRL 121 (2018) 062002</p>	<p>Initial stage arXiv:1910.08789 PRC 100 (2019) 064908 PLB 799 (2019) 135049 PLB 789 (2019) 643 PRC 97 (2018) 044912 JHEP 01 (2018) 045 PRL 119 (2017) 242001</p>	<p>Jet quenching JHEP 10 (2018) 138 PLB 785 (2018) 14 PRL 119 (2017) 082301 JHEP 04 (2017) 039</p>	<p>Jet substructure arXiv:2005.14219 arXiv:2004.00602 PRL 122 (2019) 152001 JHEP 10 (2018) 161 JHEP 05 (2018) 006 PRL 121 (2018) 242301 PRL 120 (2018) 142302</p>	<p>Collective dynamics PRC 100 (2019) 044902 PRC 98 (2018) 044902 PLB 776 (2017) 195</p>
<p>Small system arXiv:1910.04812 PRC 101 (2020) 014912 PLB 791 (2019) 172 PRL 121 (2018) 082301 PRL 120 (2018) 092301</p>	<p>Heavy flavors arXiv:1911.01461 PRL 123 (2019) 022001 JHEP 03 (2018) 181 PLB 782 (2018) 474 PRL 120 (2018) 202301 PRL 119 (2017) 152301</p>	<p>Quarkonium prod. PLB 790 (2019) 270 PLB 790 (2019) 509 EPJC 78 (2018) 509 PRL 120 (2018) 142301 EPJC 77 (2017) 269 PRL 118 (2017) 162301</p>	<p>Hadronization PLB 803 (2020) 135328 PLB 796 (2019) 168</p>	<p>More preliminary results in queue...</p>

[→ CMS Heavy-ion Publications](#)

[→ CMS Heavy-ion Preliminary](#)

Look into what you are interested in!

