Plan of Heavy Flavor Physics with CMS experiment

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Snowmass EF07 working meeting
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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 ~ 2024	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}
		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 ~ 2029	p-p	5.5 / 8.8 TeV	300 / 100 pb^{-1}	300 / 100 pb^{-1}
		Pb-Pb	5.5 TeV	6.8 nb^{-1}	294 pb^{-1}
		p-Pb	8.8 TeV	0.6 pb^{-1}	126 pb^{-1}

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	[illegible]	
	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 [illegible]	[illegible] pb^{-1}
Run 3	2022 ~ 2024	p-p	5.5 / 8.8 TeV	300 / [illegible]	[illegible] 00 pb^{-1}
		Pb-Pb	5.5 TeV	6.2 nb^{-1}	
		p-Pb	8.8 TeV	0.6 pb^{-1}	
		O-O / p-O	7 / [illegible]	[illegible] 5 / 0.2 nb^{-1}	
Run 4	2027 ~ 2029	p-p	5.5 [illegible]	[illegible] 00 / 100 pb^{-1}	300 / 100 pb^{-1}
		Pb-Pb	5.5 TeV	6.8 nb^{-1}	
		p-Pb	8.8 TeV	0.6 pb^{-1}	

2015 PbPb: 0.5 nb^{-1}
2018 PbPb: 1.7 nb^{-1}
pPb: 0.18 pb^{-1}

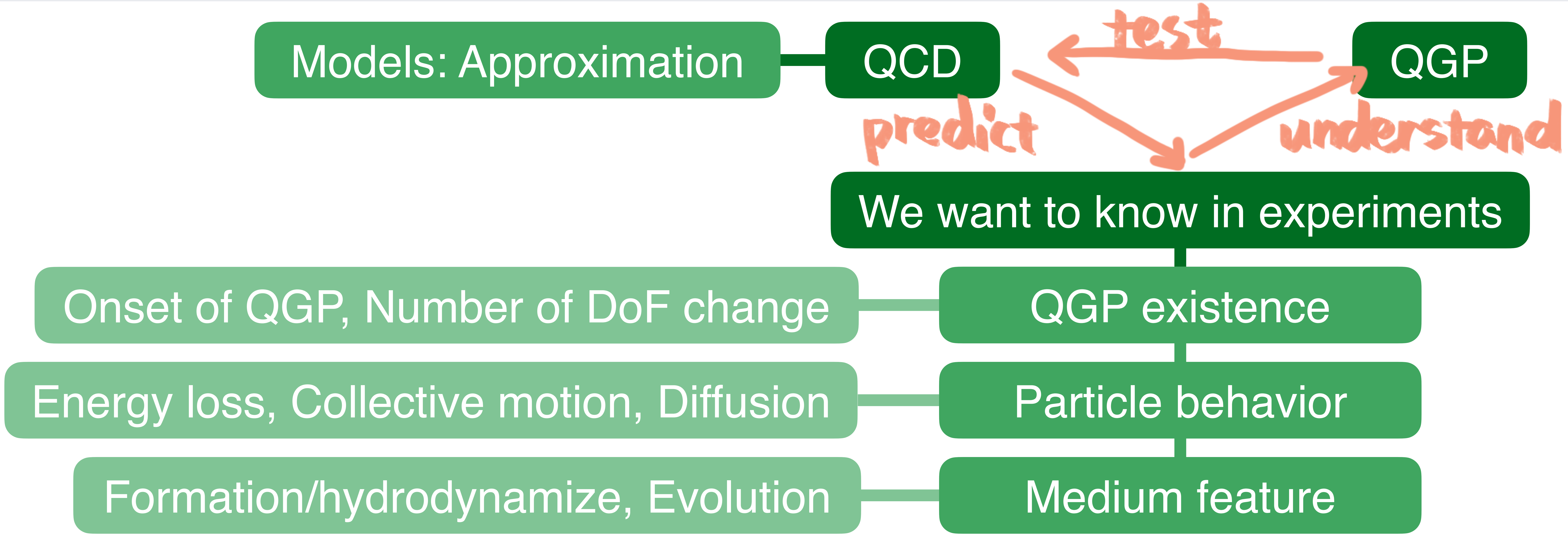
3-10x statistics

7x statistics
0.38x errors

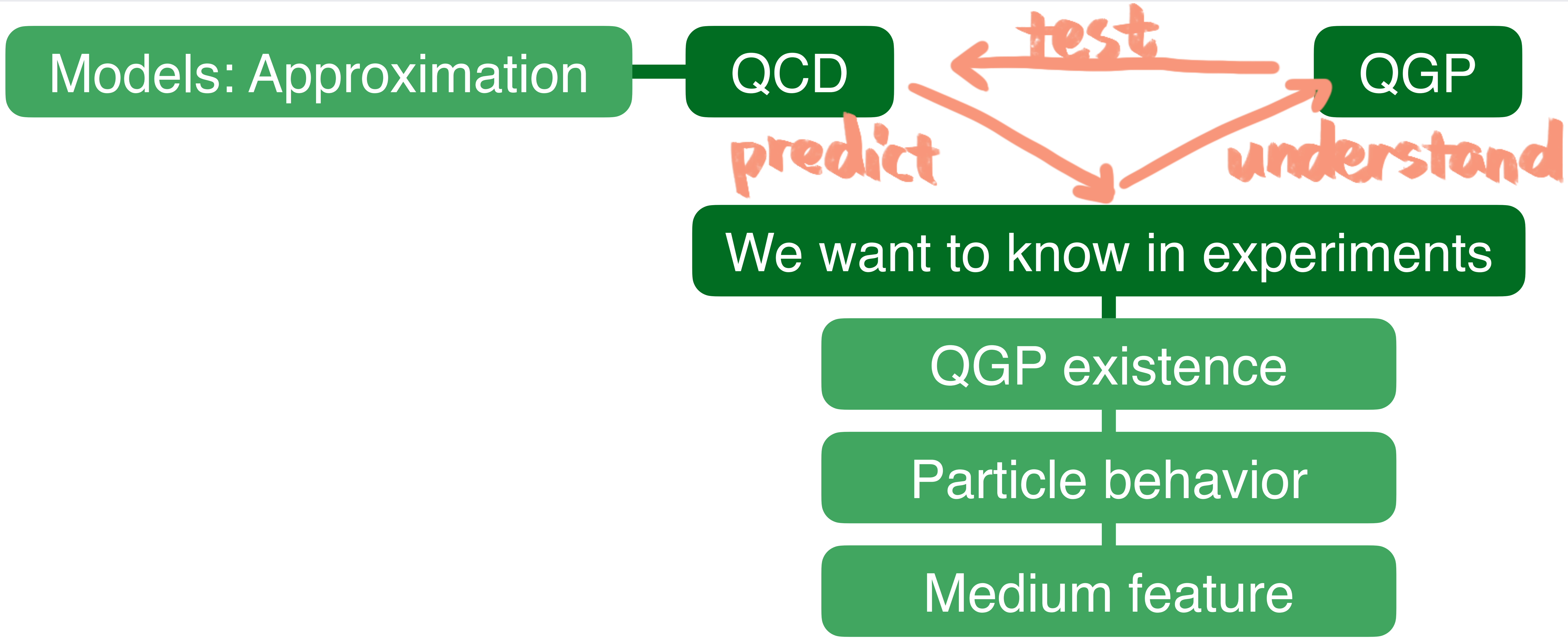
We will have
PbPb: 13 nb^{-1}
pPb: 1.2 pb^{-1}

Big Questions?

Big Questions?



Solve Big Questions?



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?

Models: Approximation — QCD —test— QGP

predict — understand

We want to know in experiments

- QGP existence
- Particle behavior
- Medium feature

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

simplify

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 pT (m_c, $m_b \gg \Lambda_{QCD}$)
- Clean: difficult produced in medium (m_c, $m_b \gg T_{QGP}$)

help guarantee

Prerequisites

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Solve Big Questions with Heavy-flavors?

Models: Approximation — QCD —(test)— QGP

predict / understand

We want to know in experiments
- QGP existence
- Particle behavior
- Medium feature

test models across flavors

isolate process

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 pT (m_c, $m_b \gg \Lambda_{QCD}$)
- Clean: difficult produced in medium (m_c, $m_b \gg T_{QGP}$)

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Interactions of Heavy quarks with Medium

Models: Approximation — QCD

QCD ← test — QGP

QCD → predict → We want to know in experiments → understand → QGP

We want to know in experiments:
- QGP existence
- Particle behavior
- Medium feature

Energy loss, Collective motion, Diffusion — Particle behavior

Prerequisites

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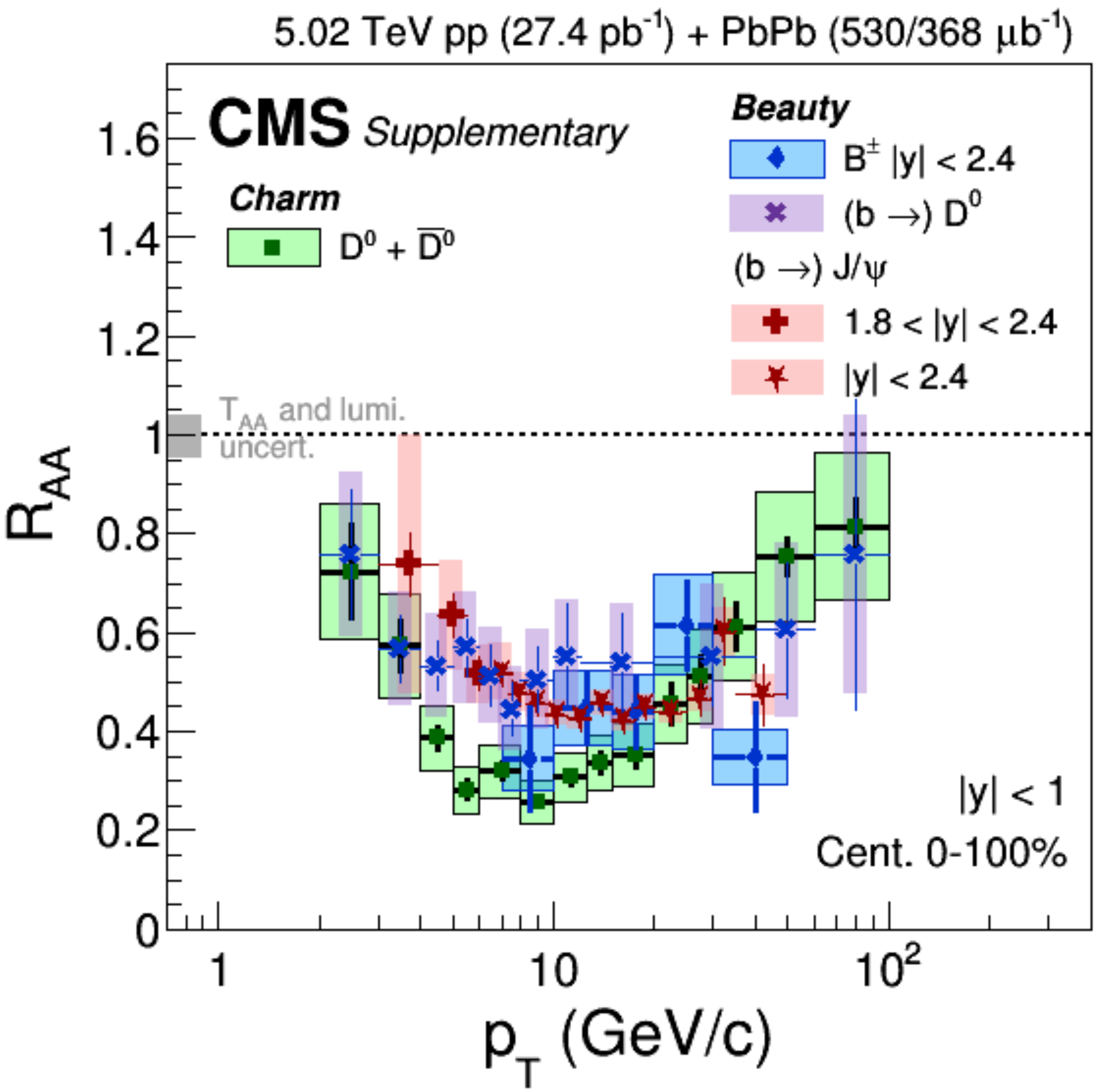
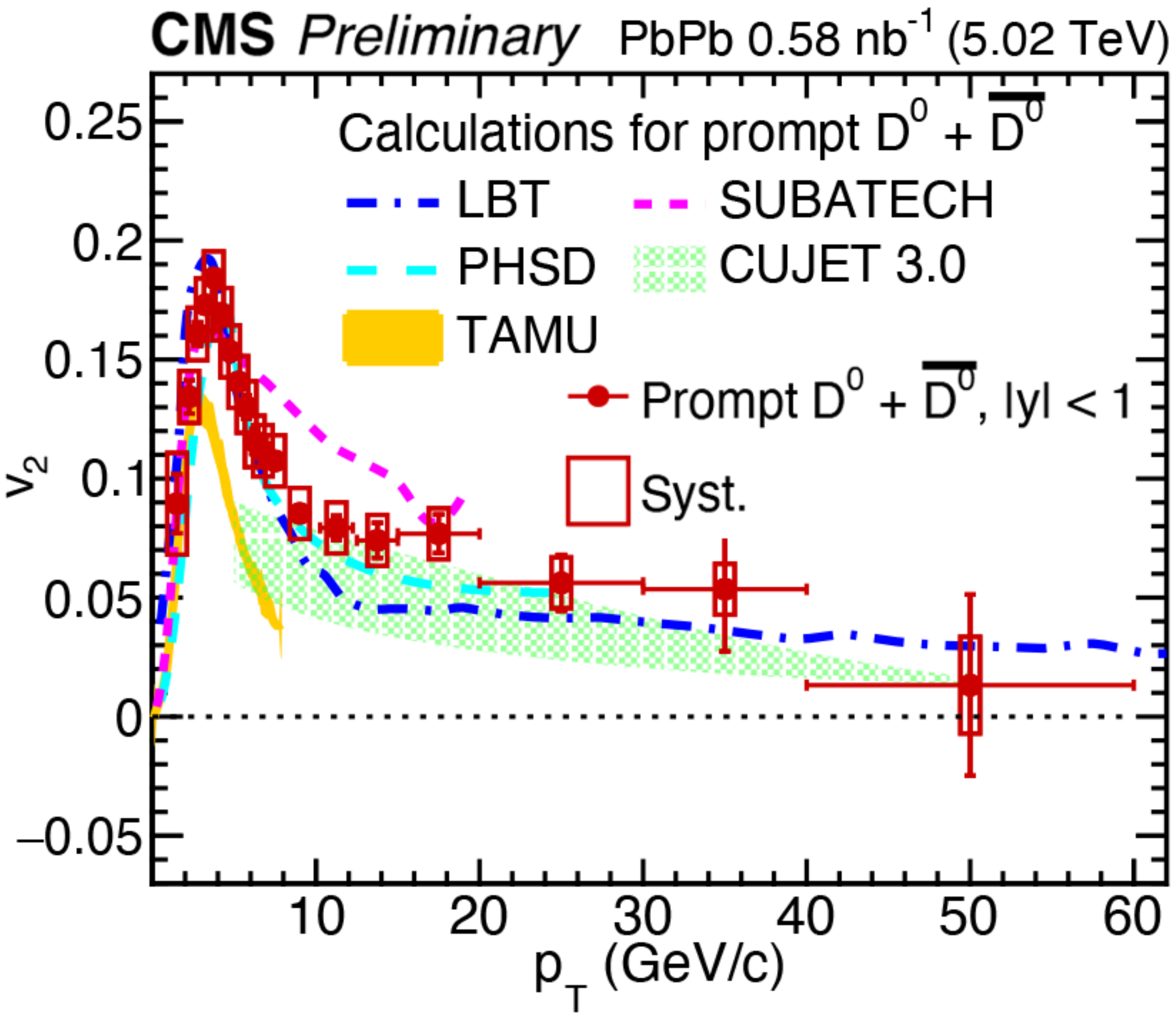
- Good understanding of baseline/ reference system
- Good knowledge of initial energy density distribution
- Good understanding of hadronization

R_{AA} and v_2

HF R_{AA}



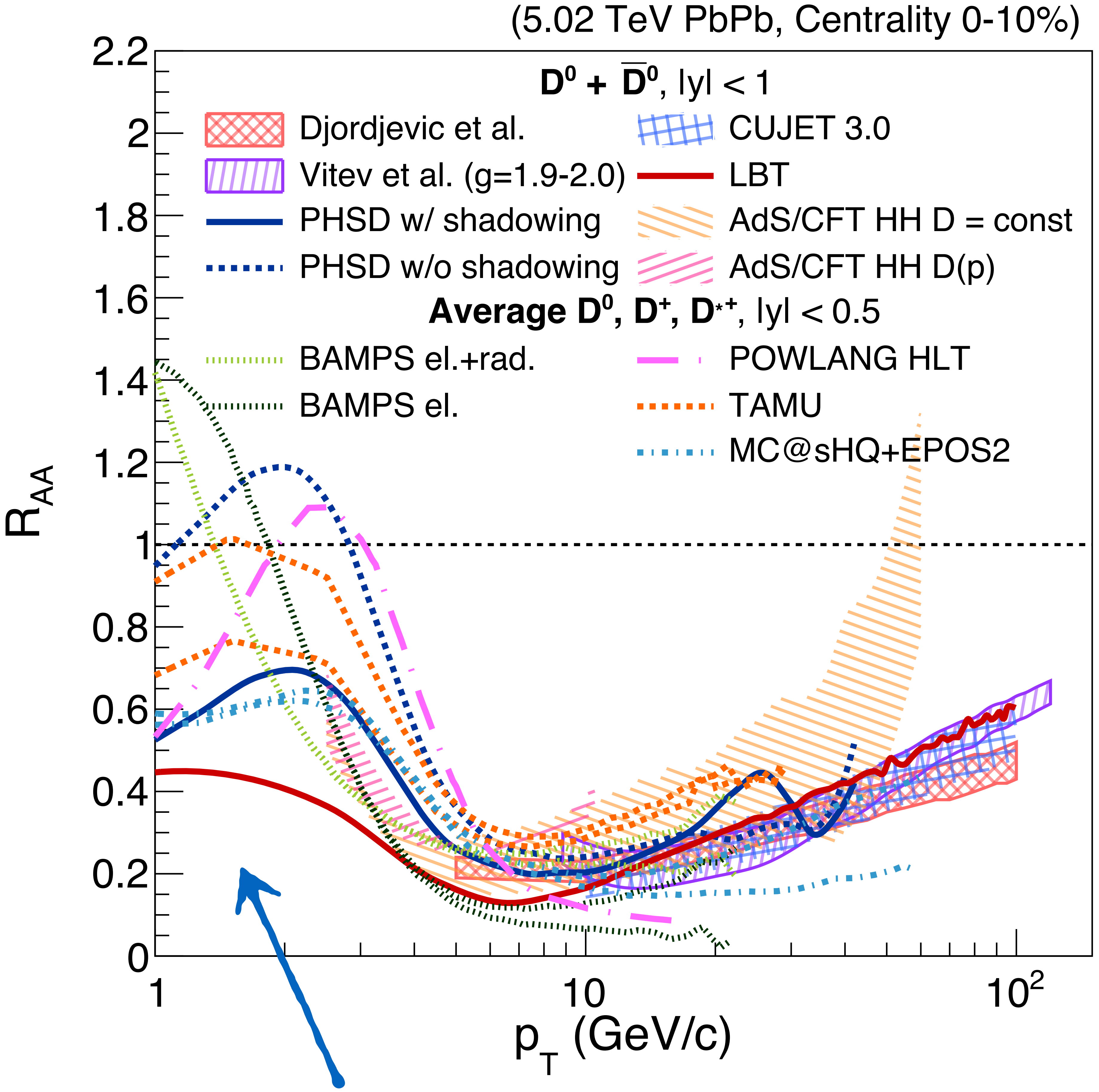
D meson v_2



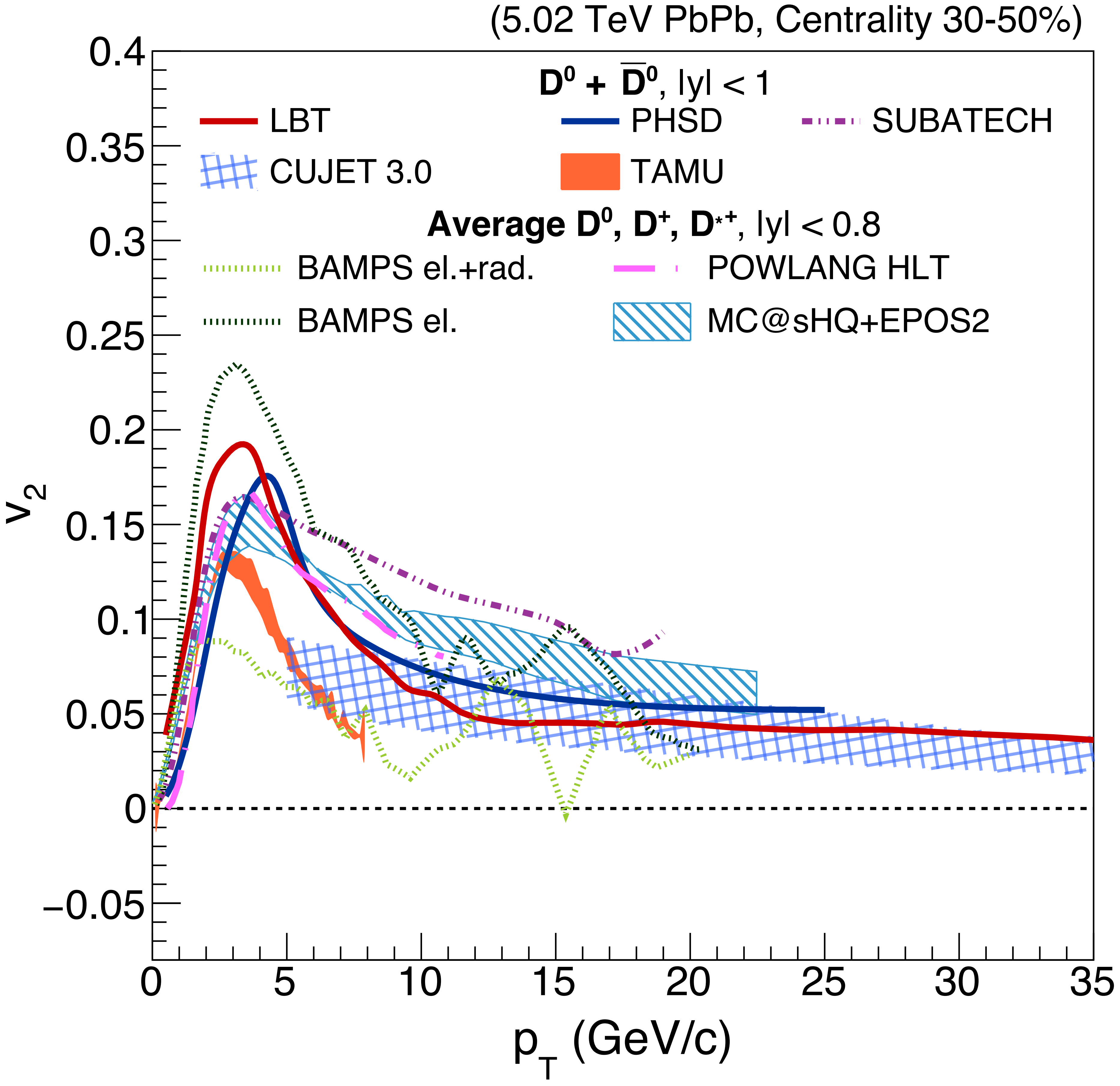
- CMS has measured R_{AA} and v_2 of various HF hadrons
- Precision expected to be improved significantly with 2018 and Run 3 data

Modeling R_{AA} and v_2

D meson R_{AA}



D meson v_2



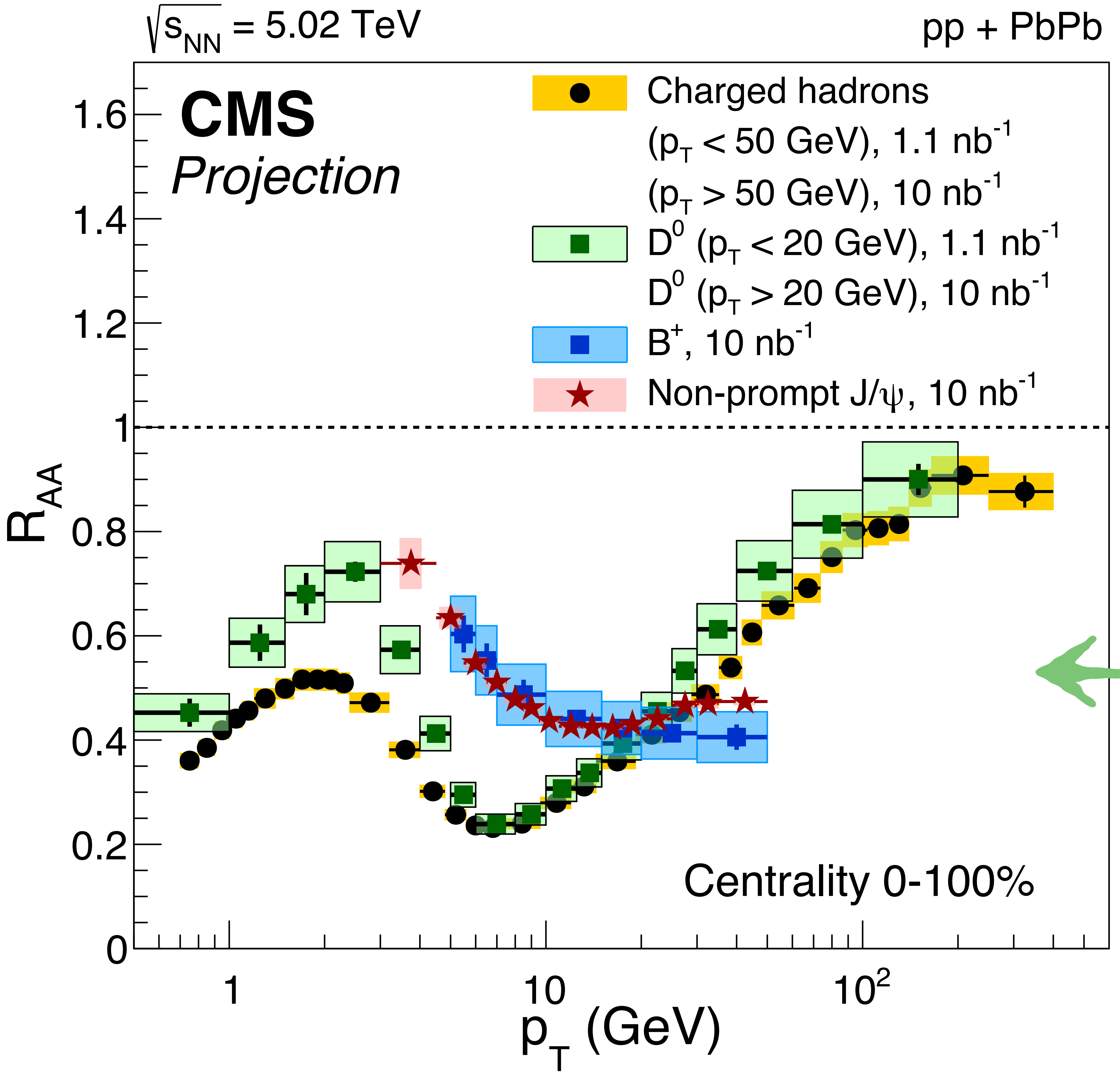
What do we distinguish among models?

- 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
- Can we get everything we want to know if we have zero-uncertainty data results?

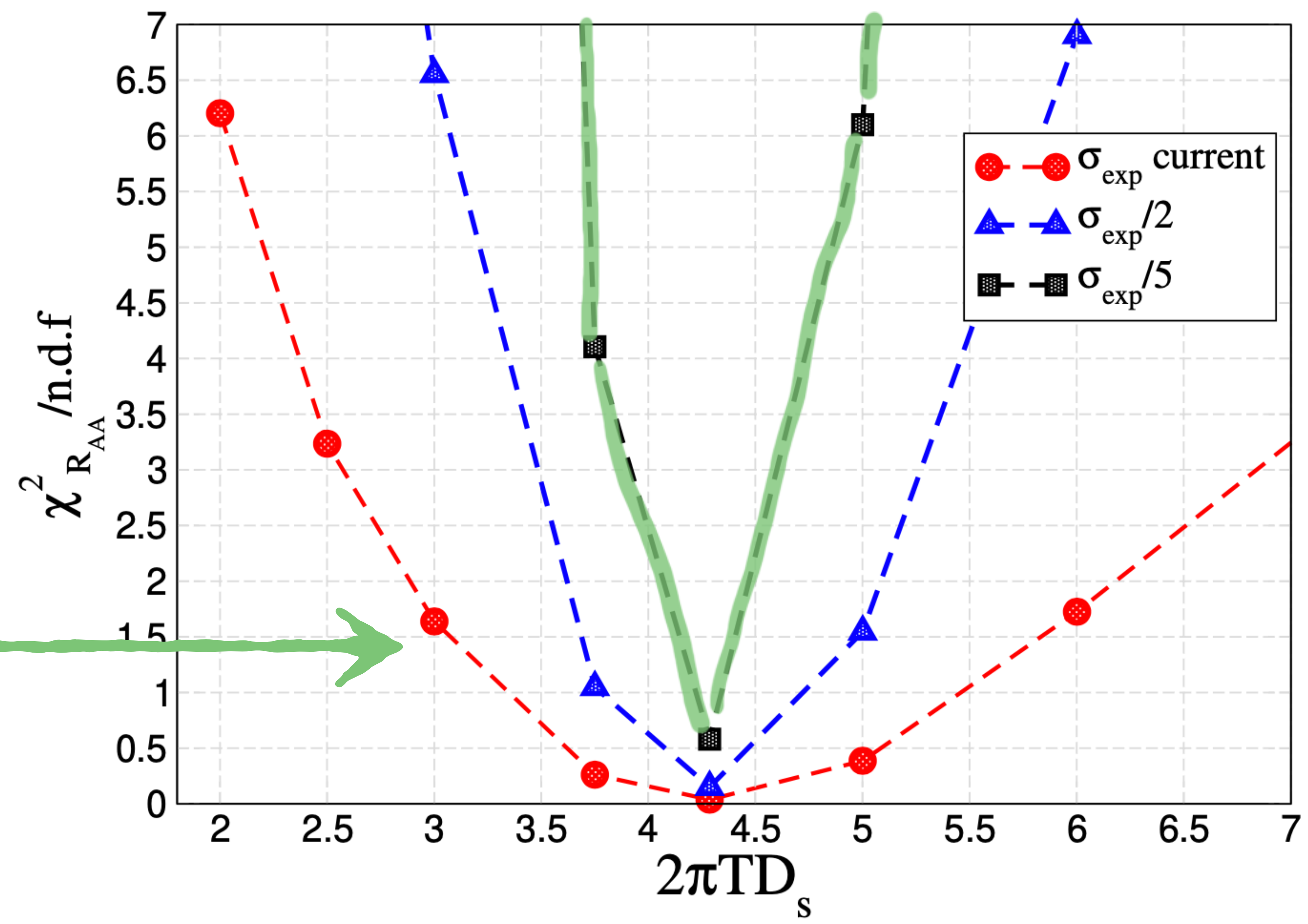
Diffusion coefficient D_s at statistics limit

Projection after Run 4

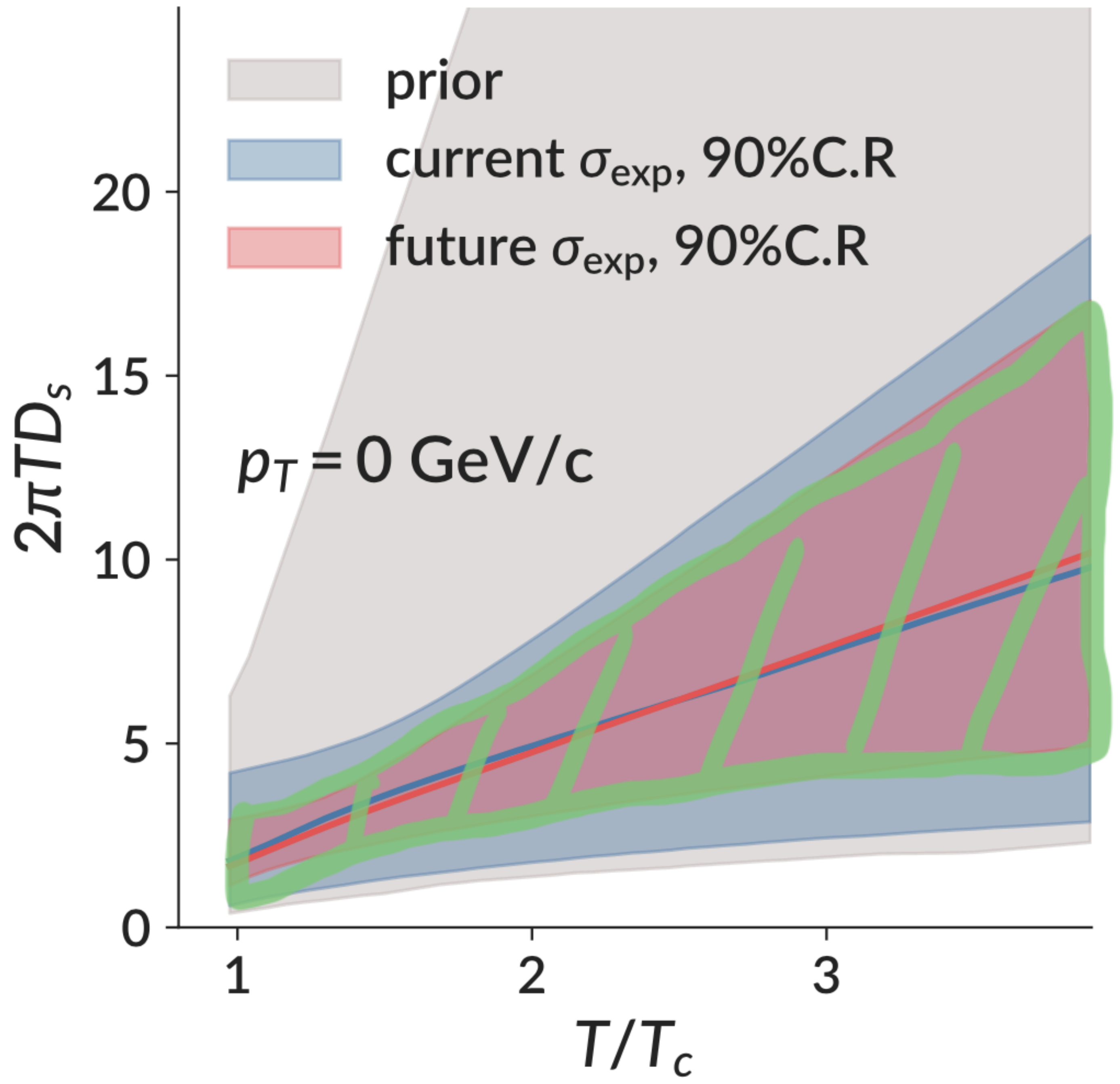


arXiv:1812.06772

D_s projection after Run 4 (Catania)



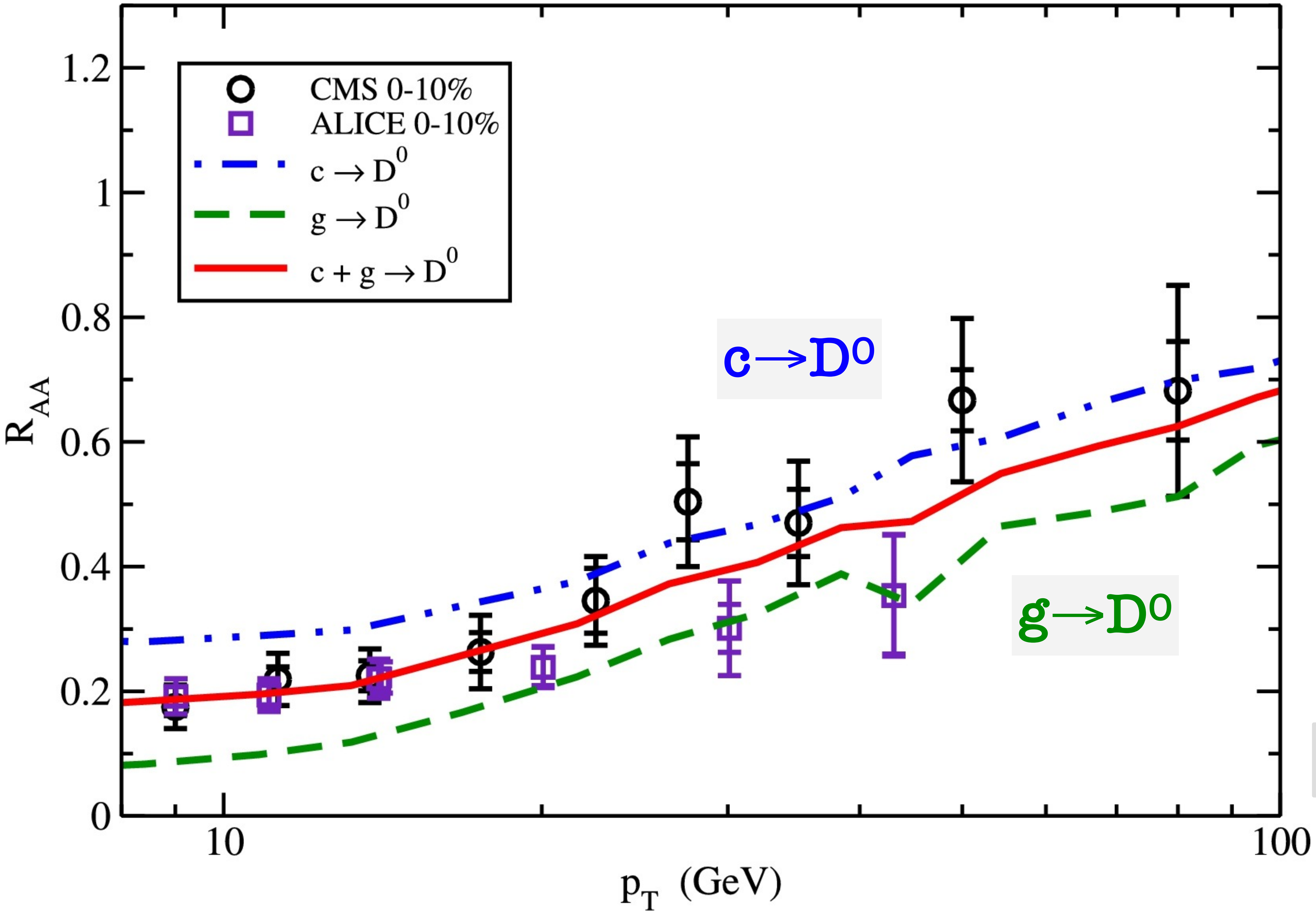
D_s projection after Run 4 (LBT)



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

More “differential”

For example:

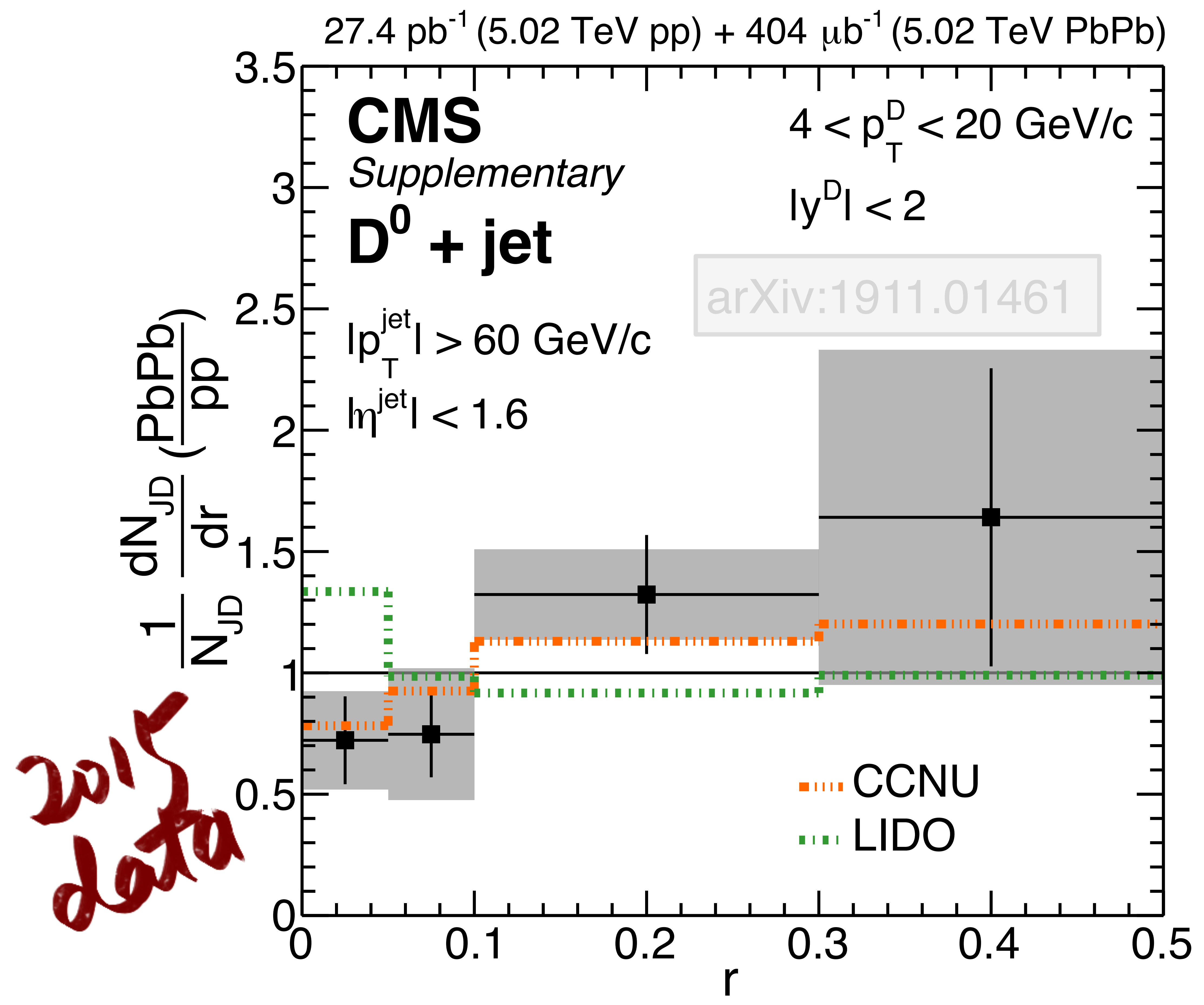


PLB 805 (2020) 135424

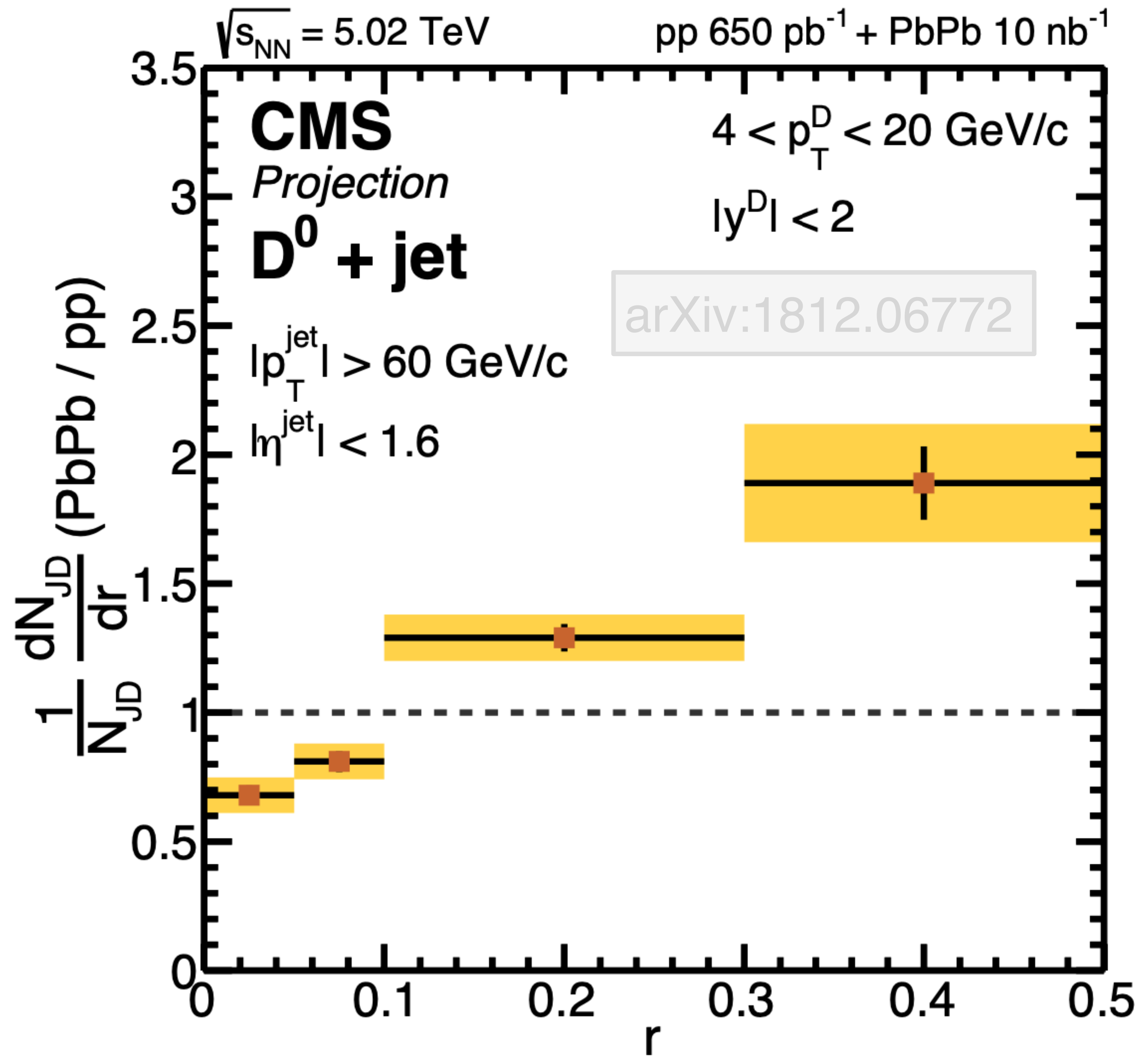
- Isolate charm quark fragmentation component?

Other observables: D-jet Correlation

D-jet correlation vs. models



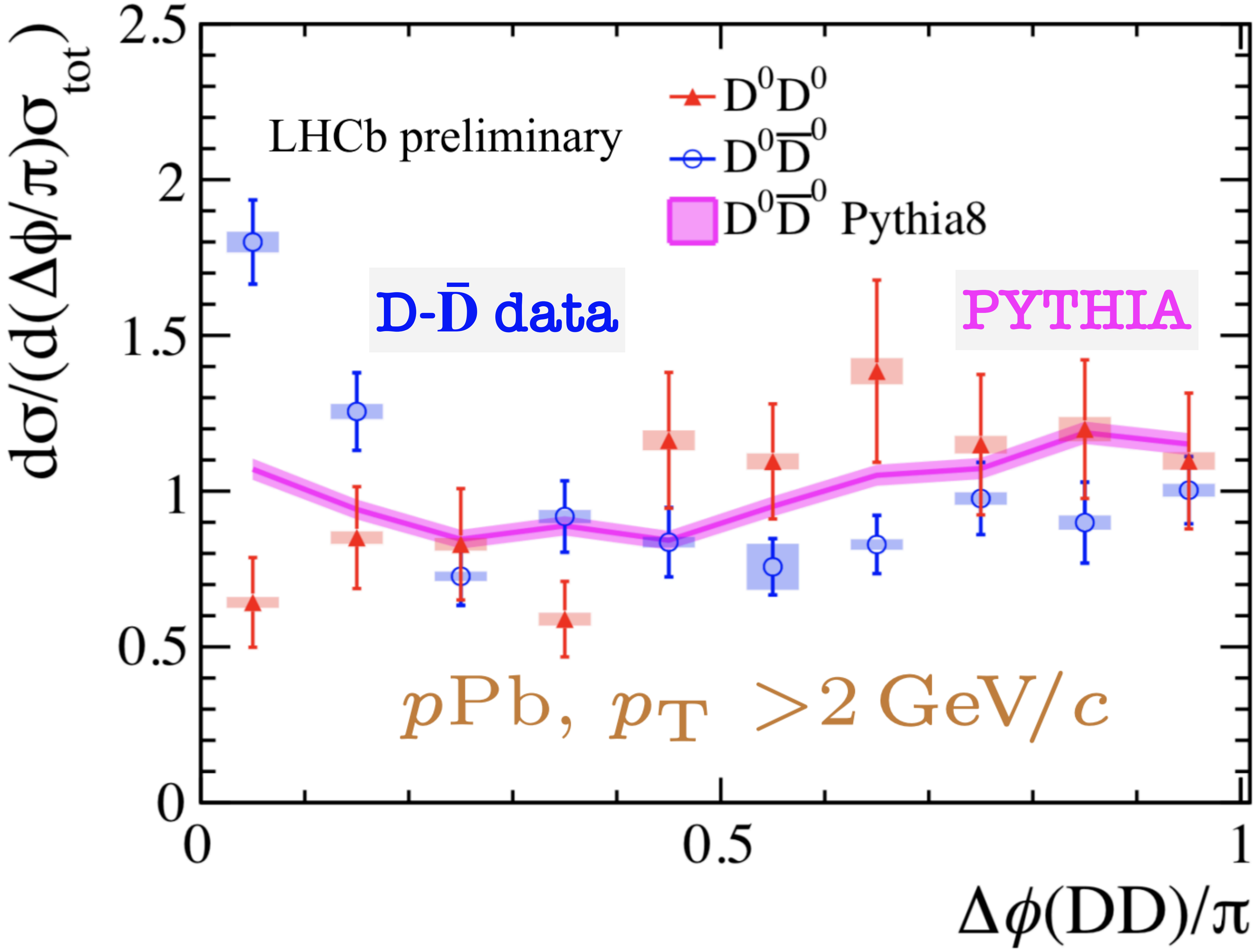
D-jet projection after Run 4



- Different trends from models

Other observables: D-D̄ Correlation

D-D̄ in pPb



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

Onset of QGP

Models: Approximation — QCD

QCD —test— QGP

predict / understand

We want to know in experiments

Onset of QGP, Number of DoF change — QGP existence

Particle behavior

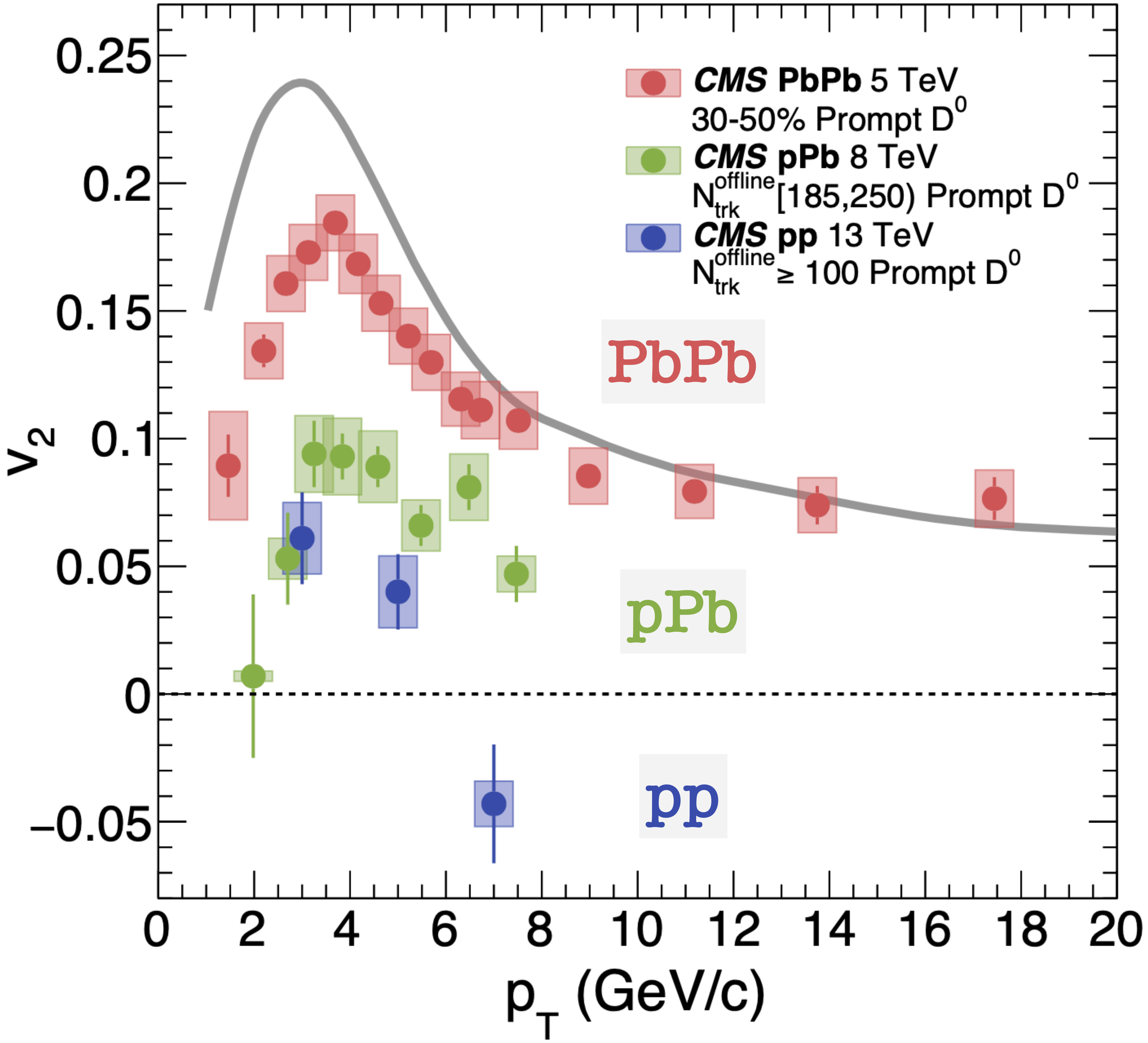
Medium feature

Prerequisites

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

Onset of QGP

Prompt D^0 v_2 in various systems

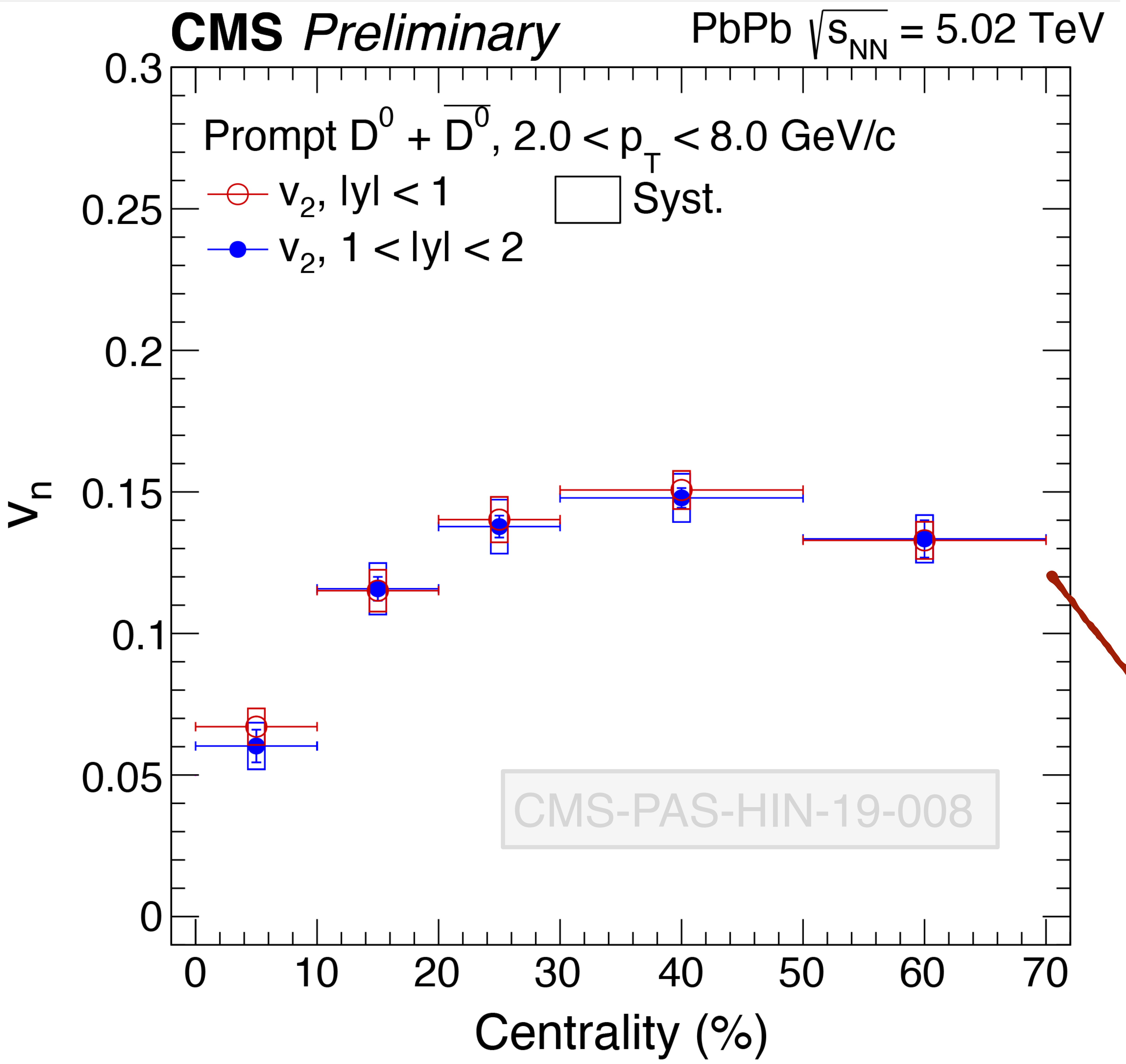


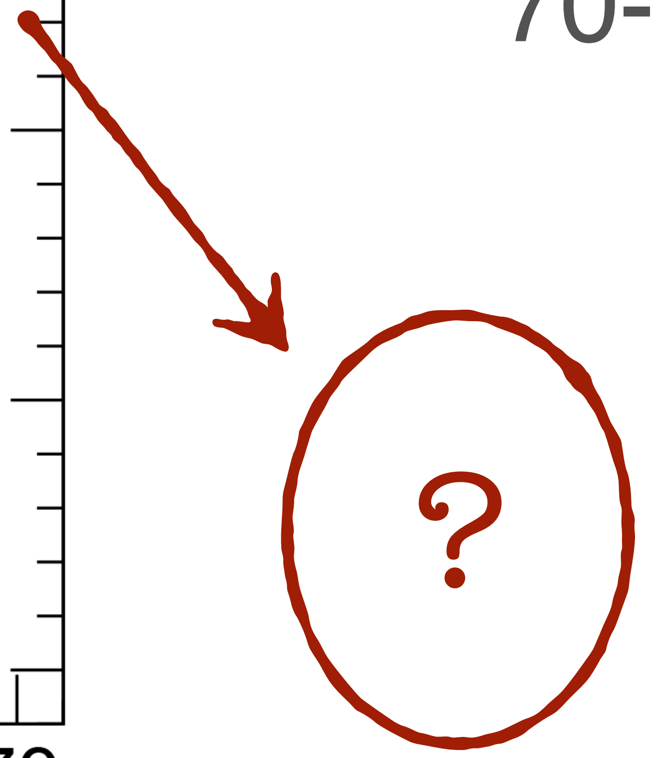
- Non-zero prompt D^0 v_2 in pp, pPb, PbPb
- When we will get QGP?
- What is the smallest droplet of QGP that behaves hydrodynamically?

Camelia's HP talk

Onset of QGP

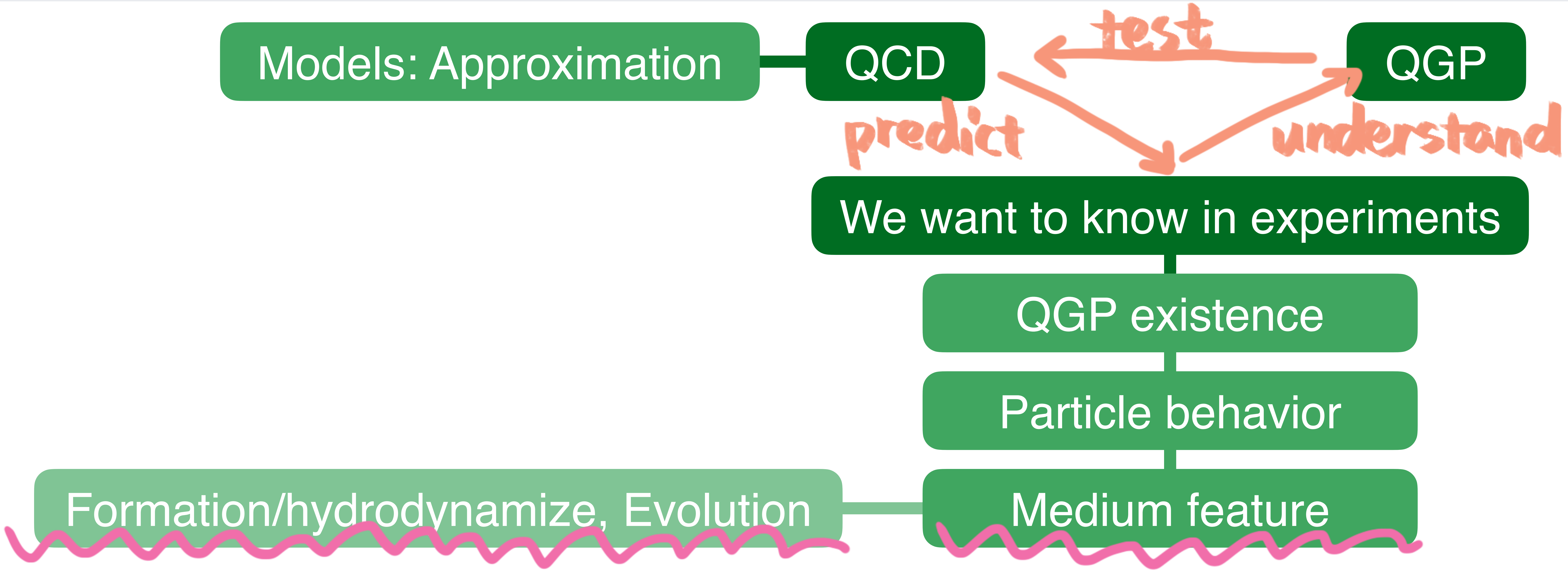
Prompt D^0 v_2 vs. centrality





- 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)

Medium evolution



Prerequisites

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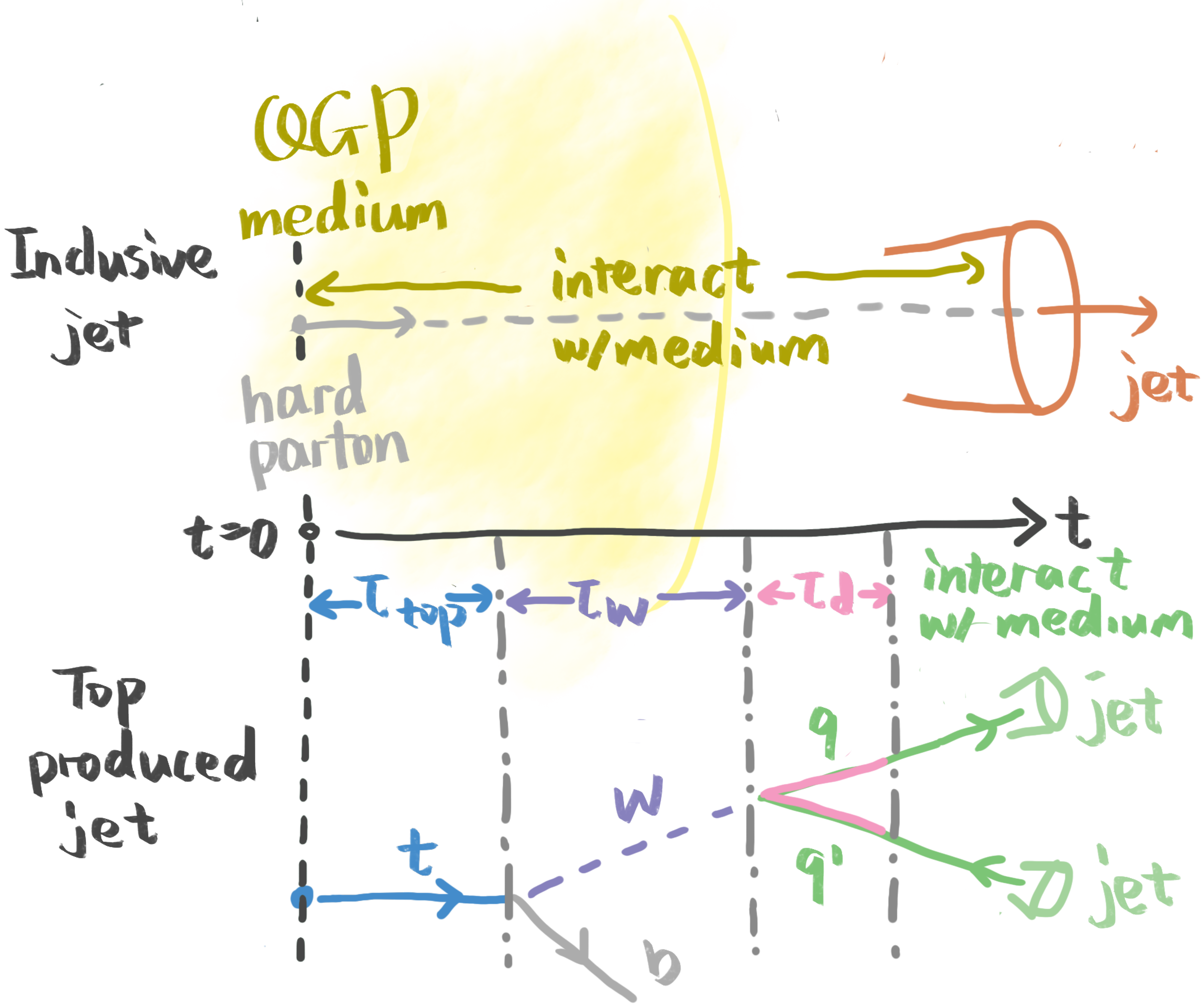
Time structure of evolution: Top quark

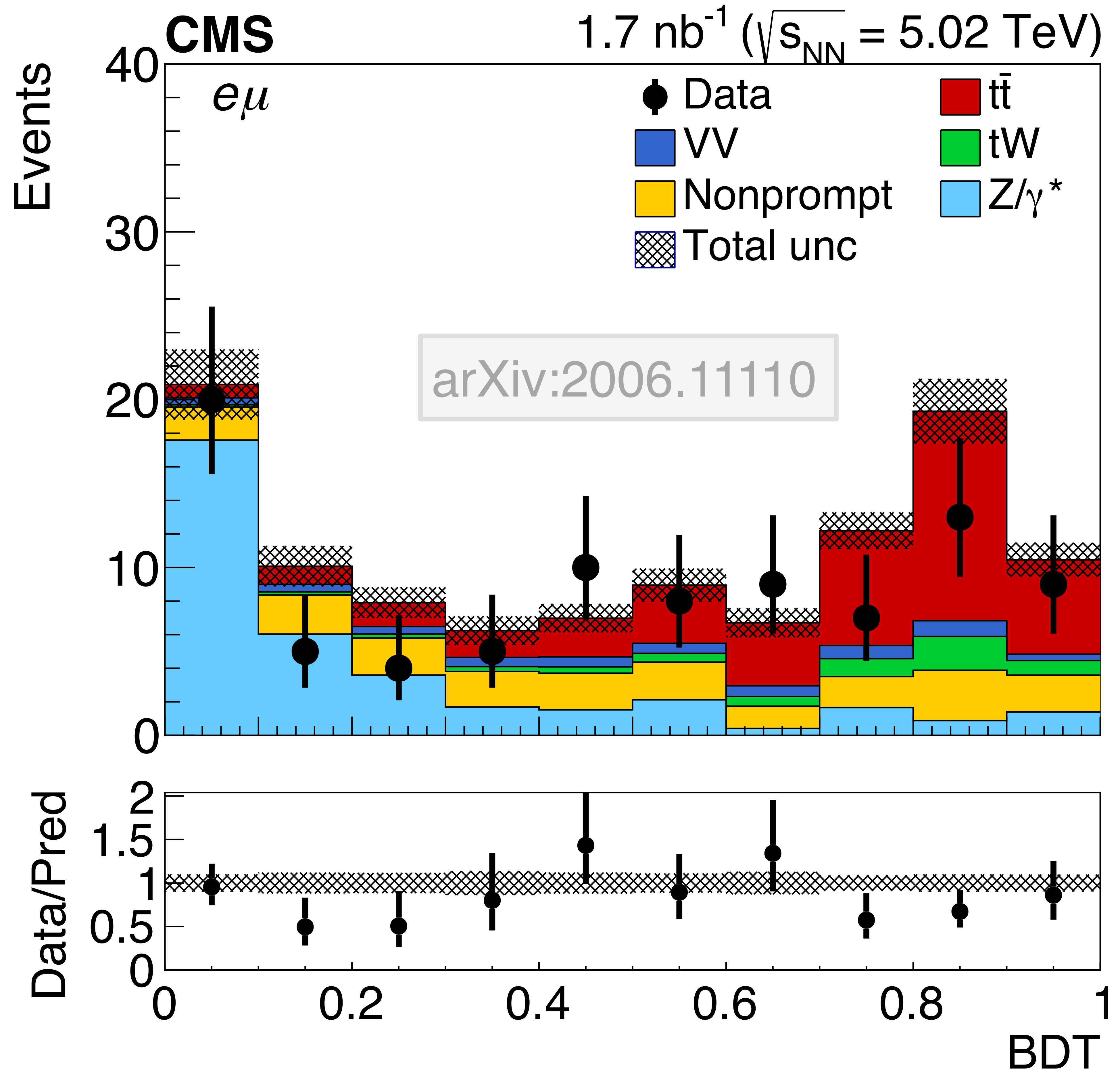


- **Hard probe R_{AA}**
  - Experience the whole evolution
  - Only see accumulated effect
  - Time dependence?

PRL 120 (2018) 23, 232301

- **Top-produced jet**
  - Interaction delayed by
    - ➡ τ_{top}: top lifetime
    - ➡ τ_{W}: W lifetime
    - ➡ τ_{d}: de-coherence time
  - Study top production helps understand evolution time structure

Time structure of evolution: Top quark



- More statistics needed to extract the info

- **Hard probe R_{AA}**
  - Experience the whole evolution
  - Only see accumulated effect
  - Time dependence?

PRL 120 (2018) 23, 232301

- **Top-produced jet**
  - Interaction delayed by
    - ➡ τ_{top}: top lifetime
    - ➡ τ_W: W lifetime
    - ➡ τ_d: de-coherence time
  - Study top production helps understand evolution time structure

Heavy flavor production in proton-proton

Models: Approximation — QCD

QCD ← test → QGP

predict · understand

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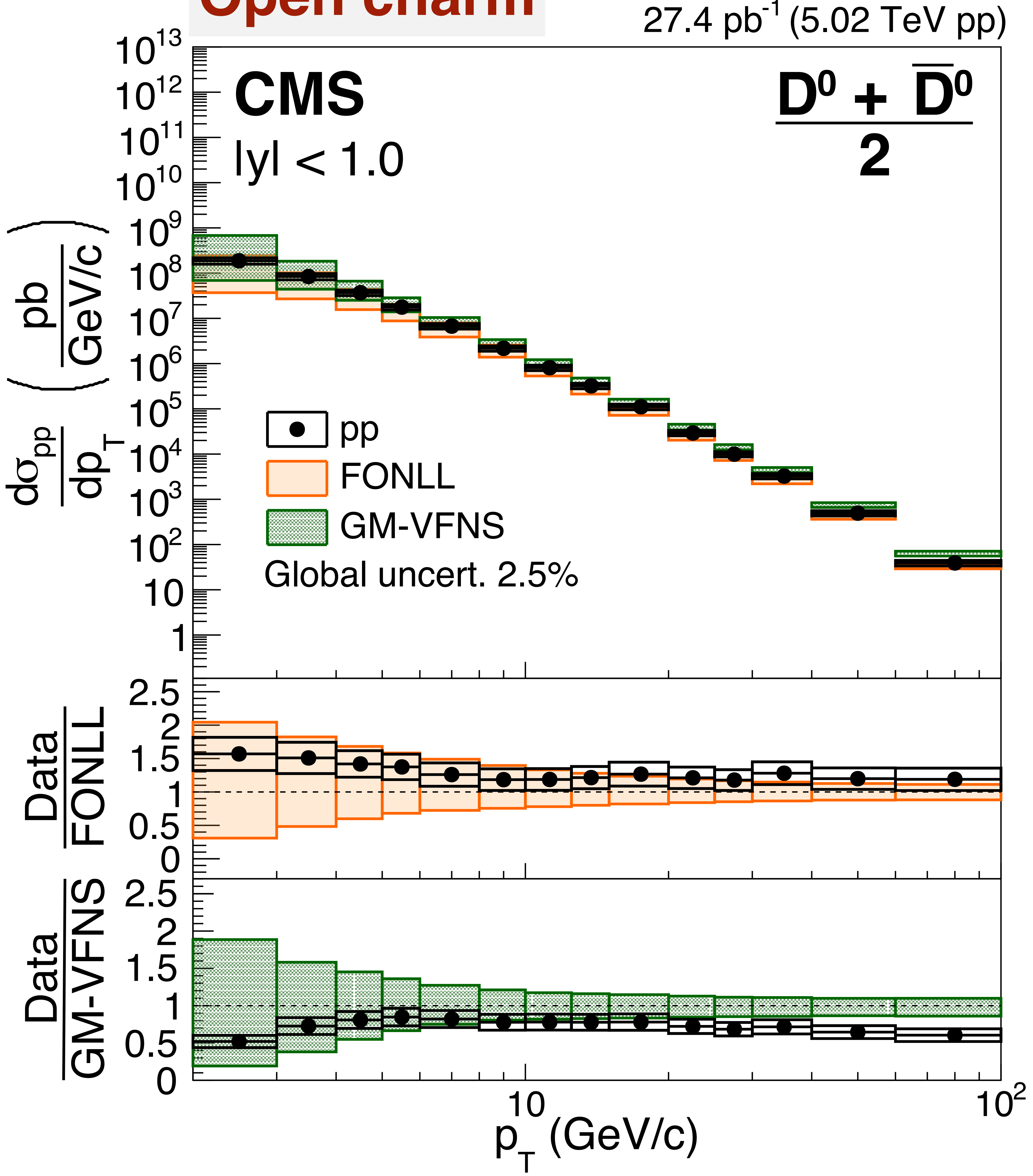
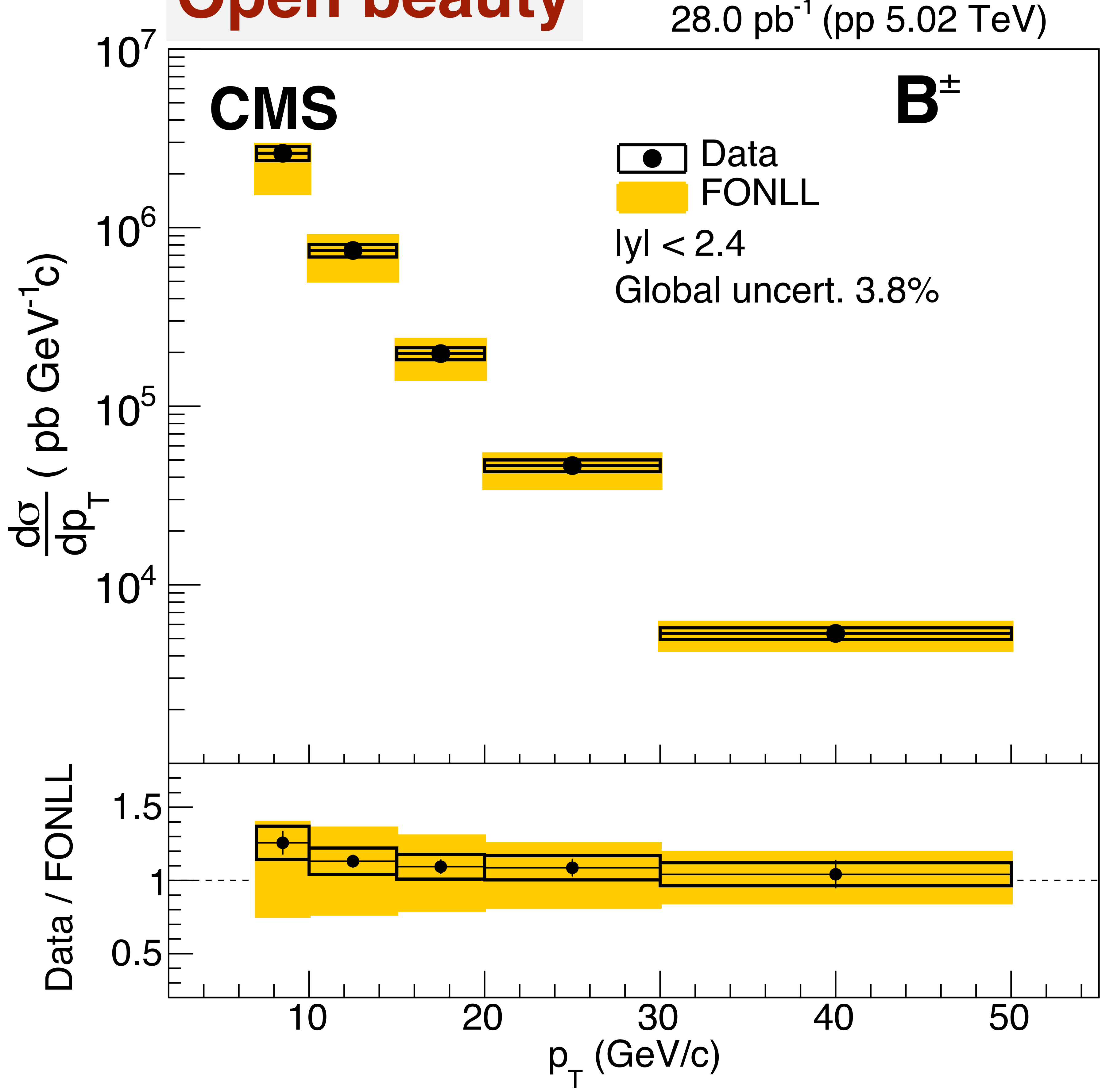
Production in pp vs. pQCD calculation

Open charm



Open beauty



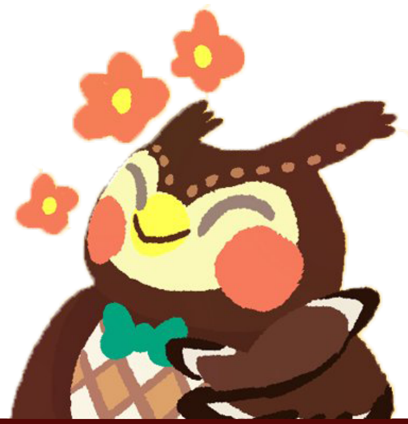
2015 data

2017: 7-10x more statistics

PLB 782 (2018) 474

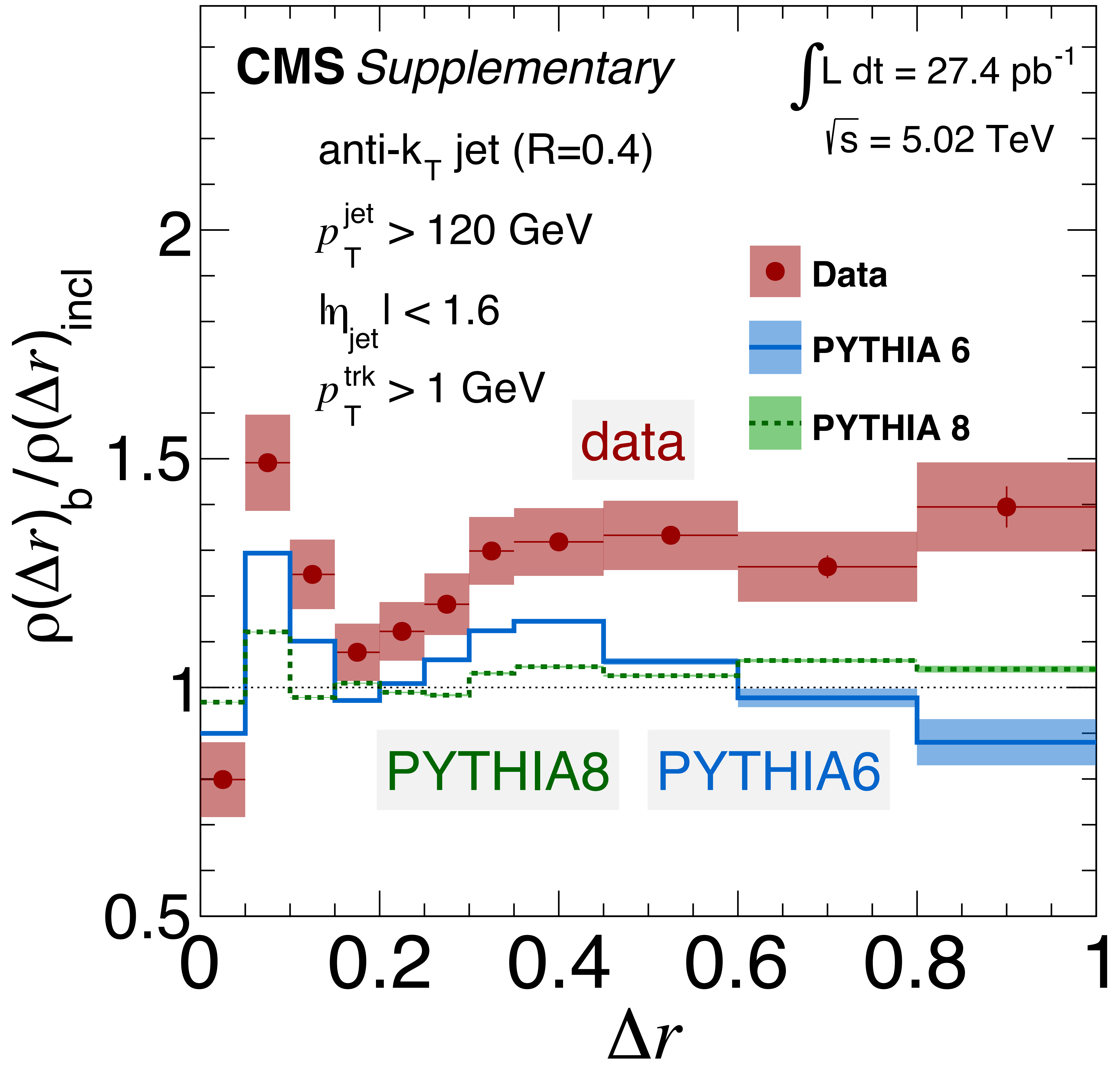
PRL 119 (2017) 152301

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



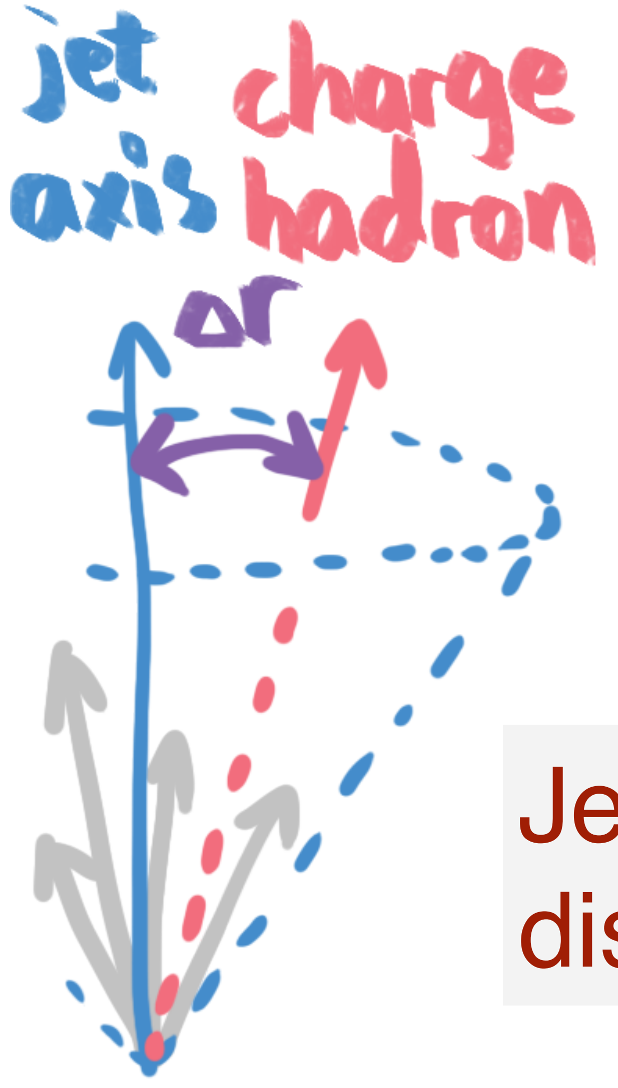
Production in pp vs. pQCD calculation

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

Models: Approximation — QCD

QCD ← test — QGP

predict

understand

We want to know in experiments

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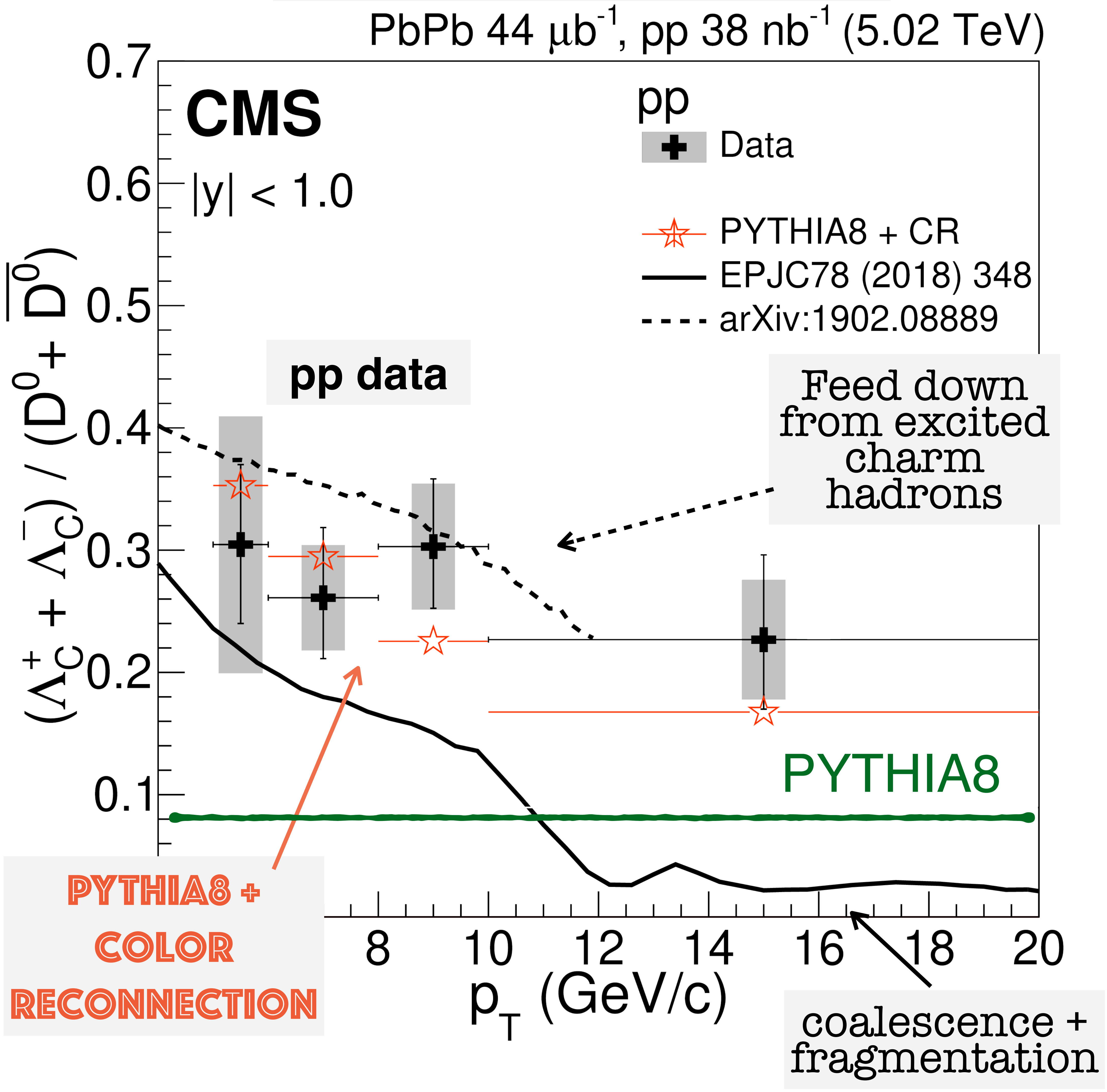
Hadronization in pp collisions

Λ_c / D^0 in pp vs. models



For the underestimation of Λ_c production by PYTHIA fragmentation only

- Is color reconnection a good solution?

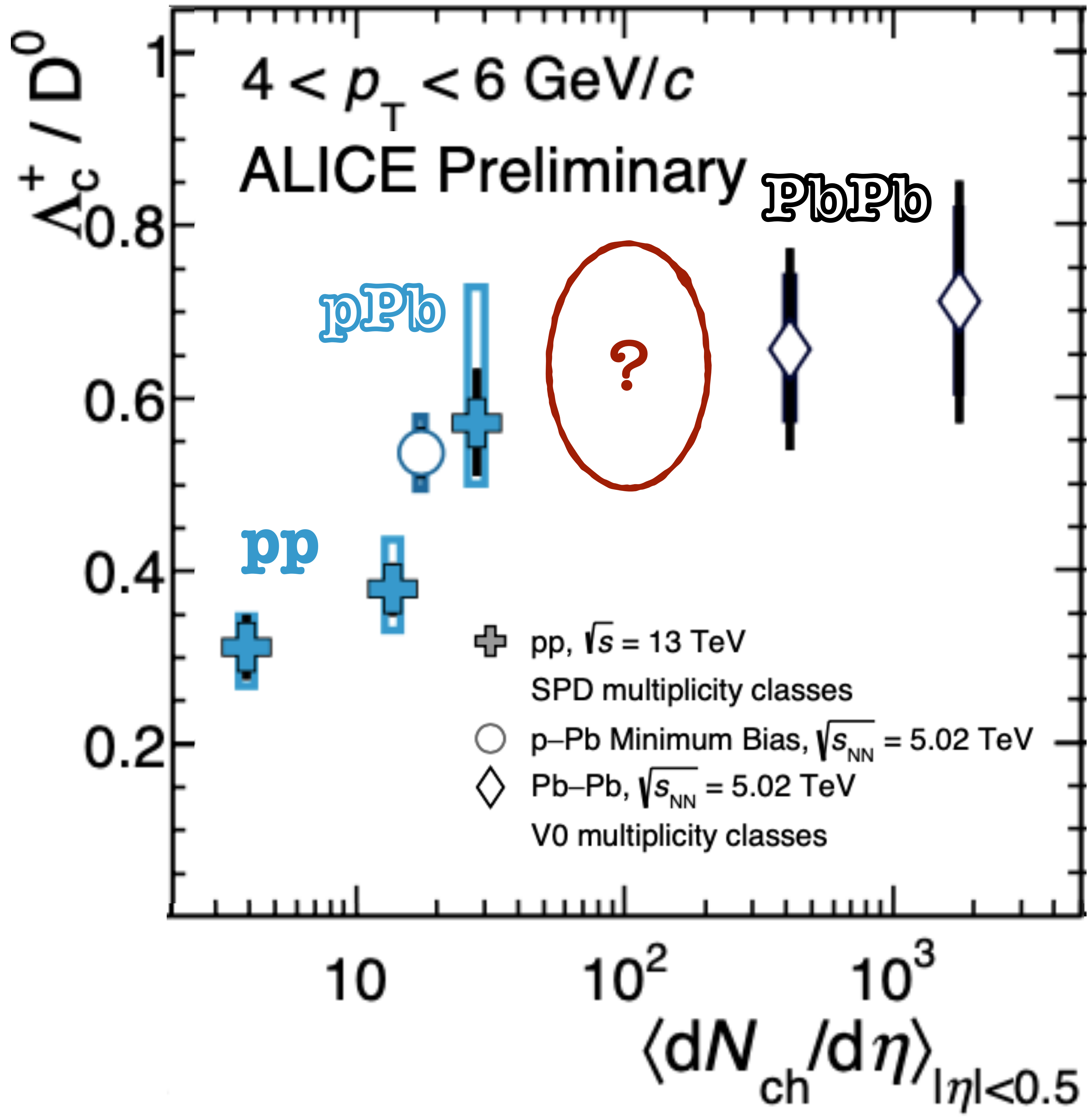
2015 data

2017: 7x more statistics

PLB 803 (2020) 135328

Hadronization across collision systems

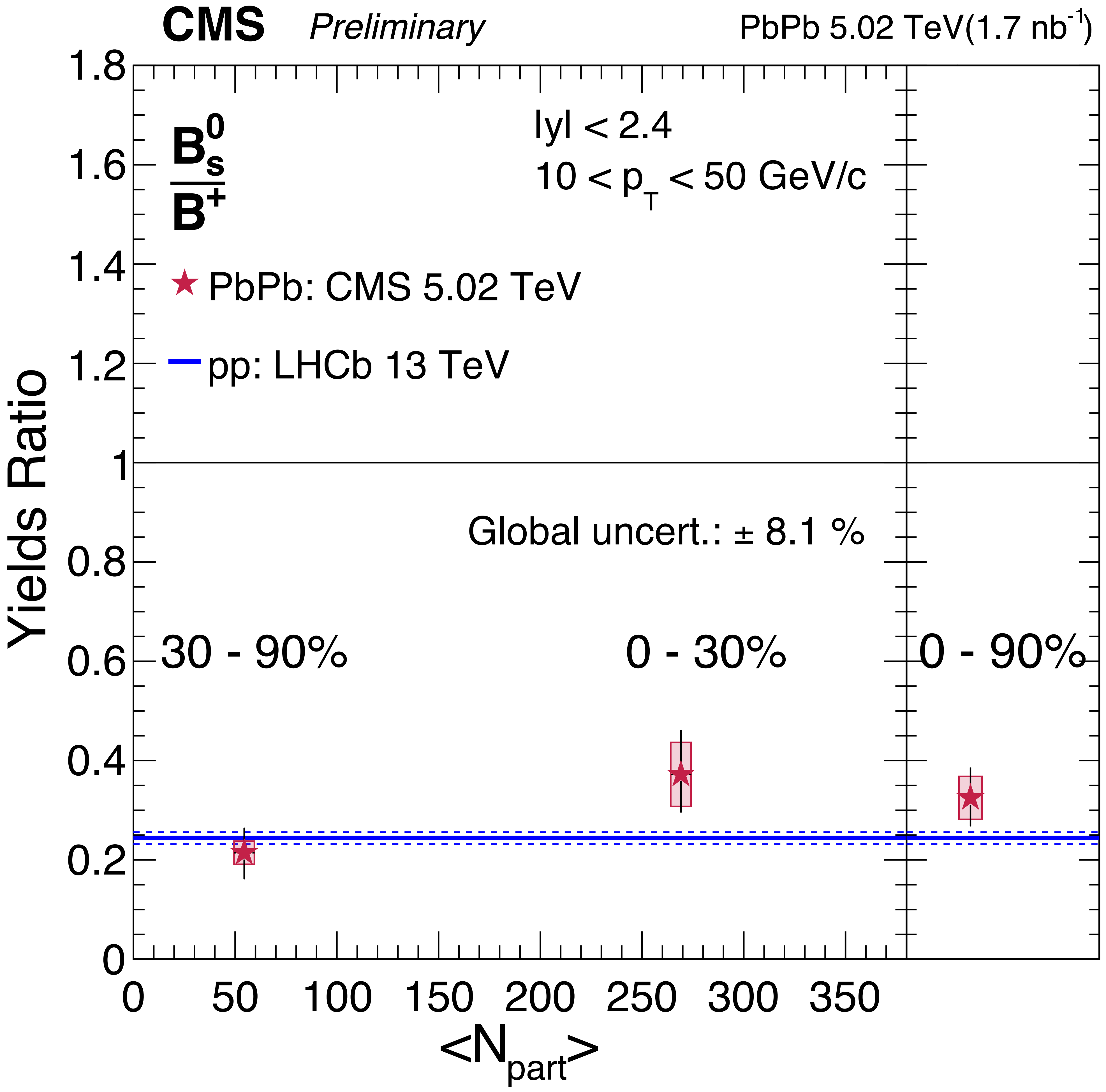
Λ_c / D^0 vs. multiplicity



- 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/dη a good scale for systems?

Hadronization of beauty

B_s / B^+ vs. centrality

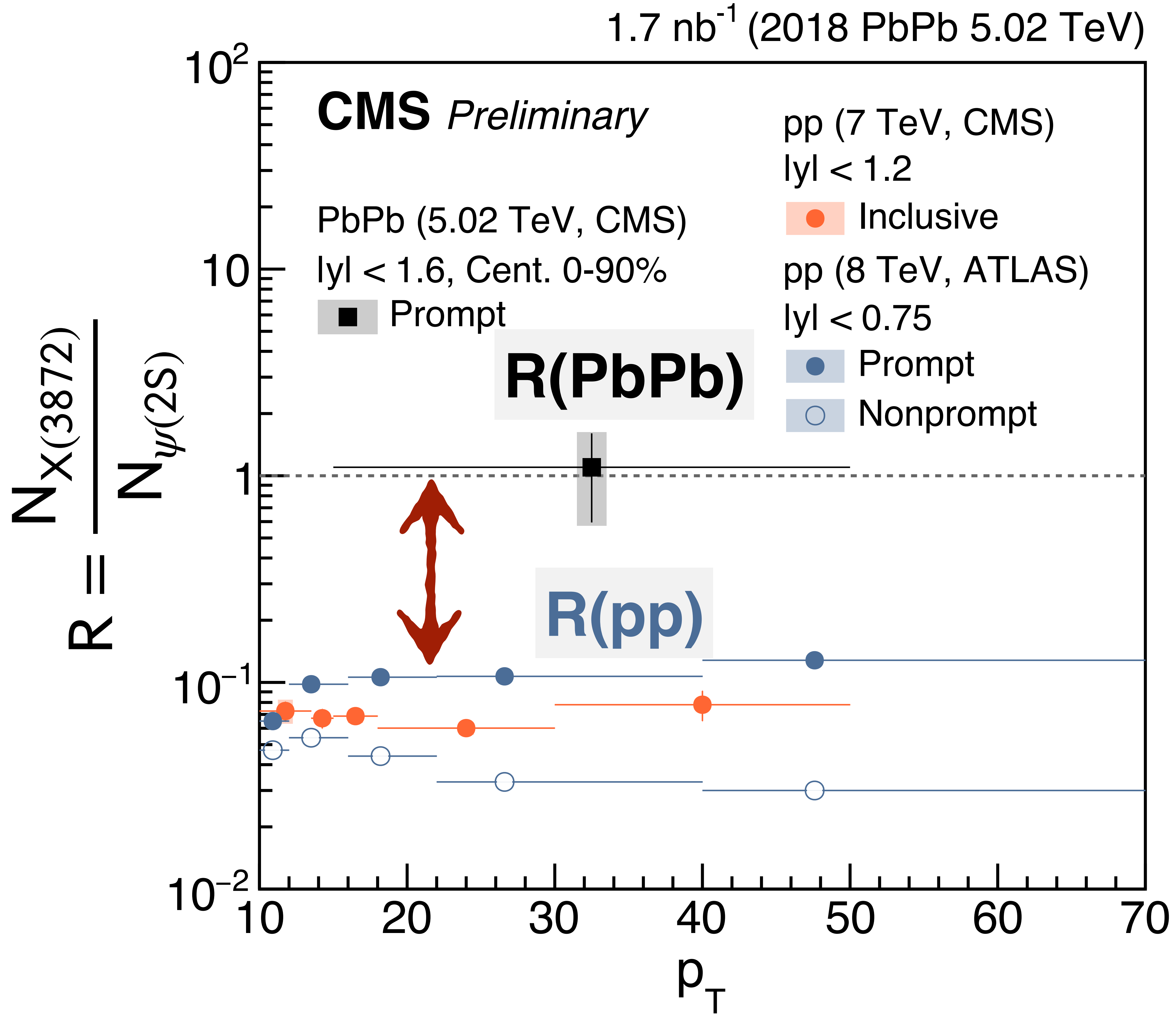


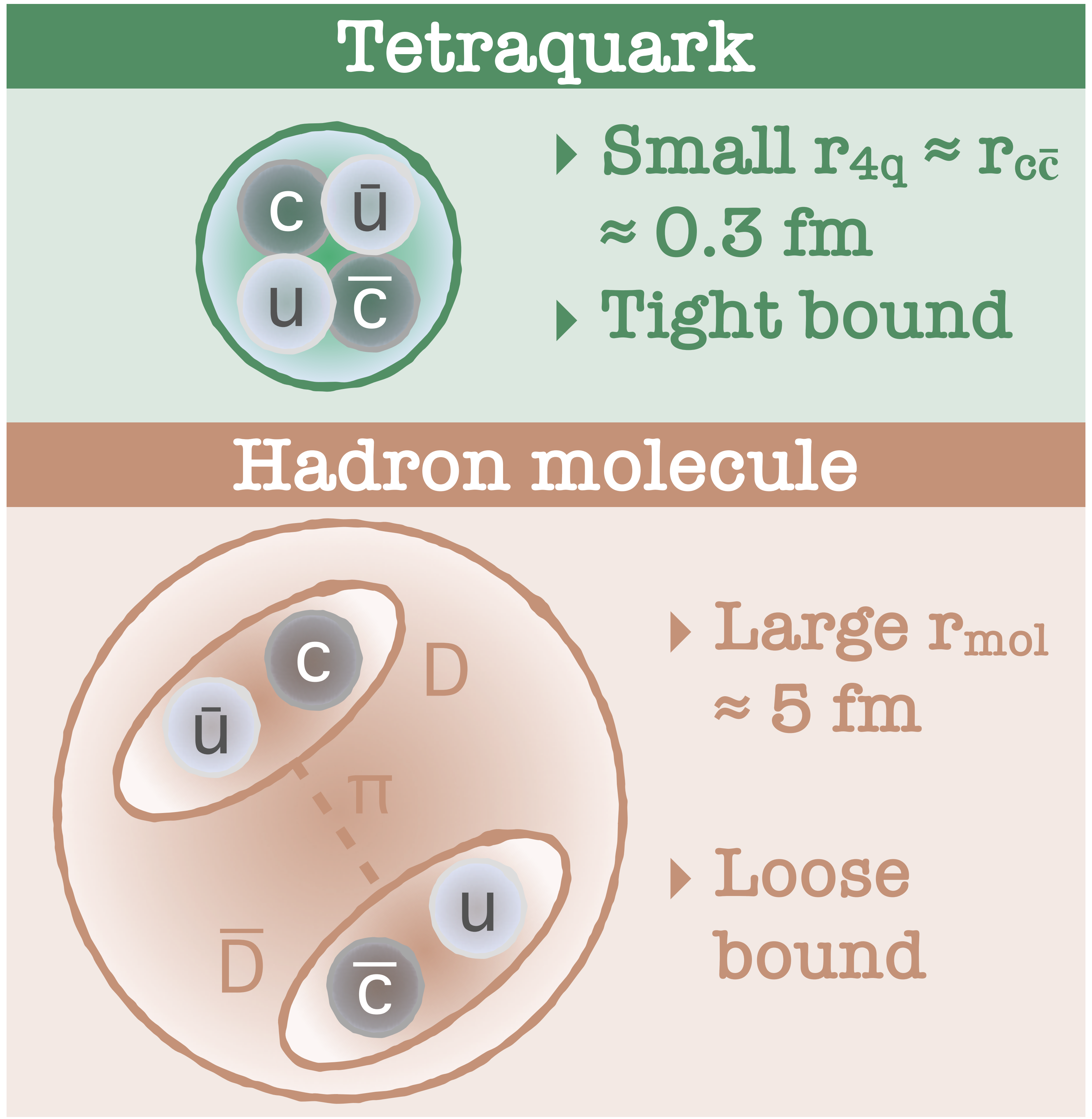
- What will happen to B_s in high-multiplicity pp?

CMS-PAS-HIN-19-011

“New physics”: X(3872) internal structure

- Heavy ion collisions not only for studying QGP

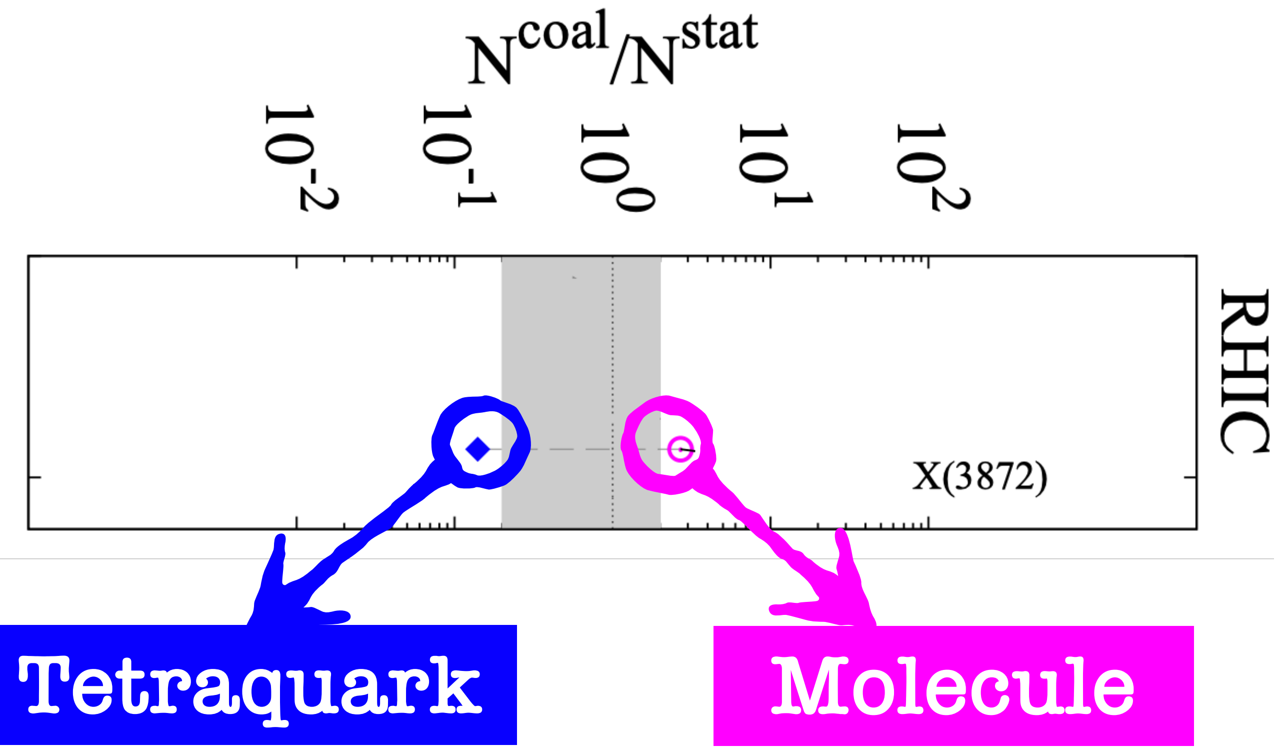


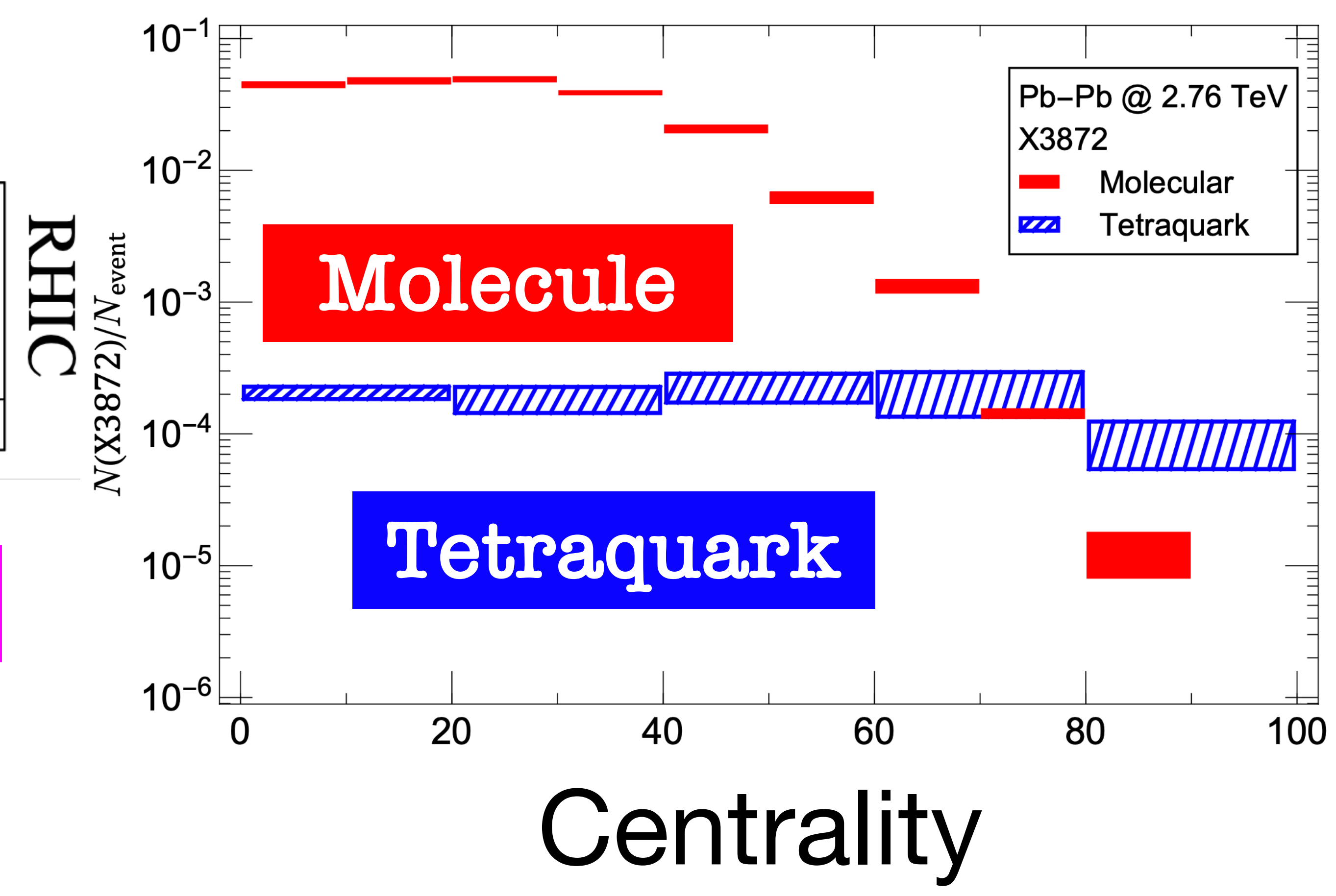


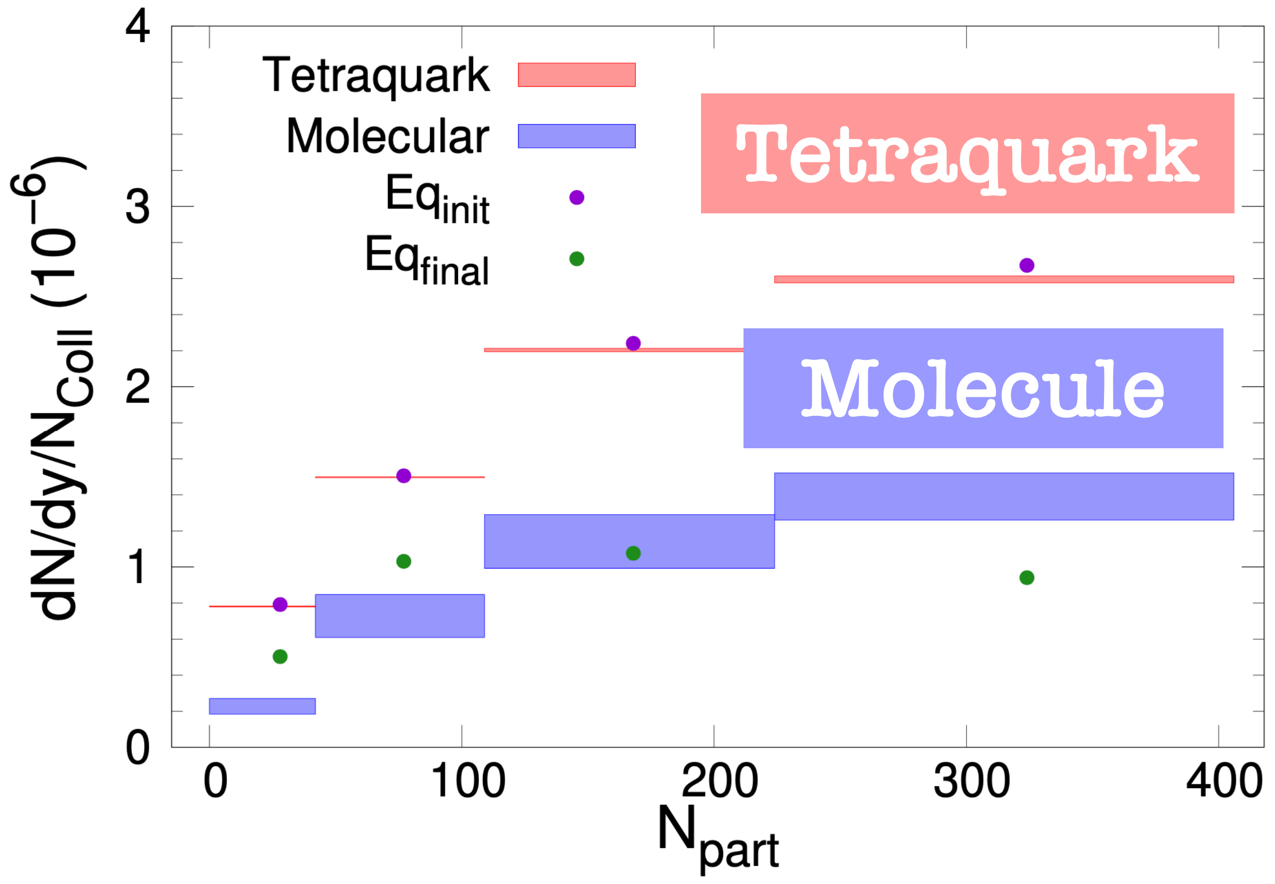
“New physics”: X(3872) internal structure

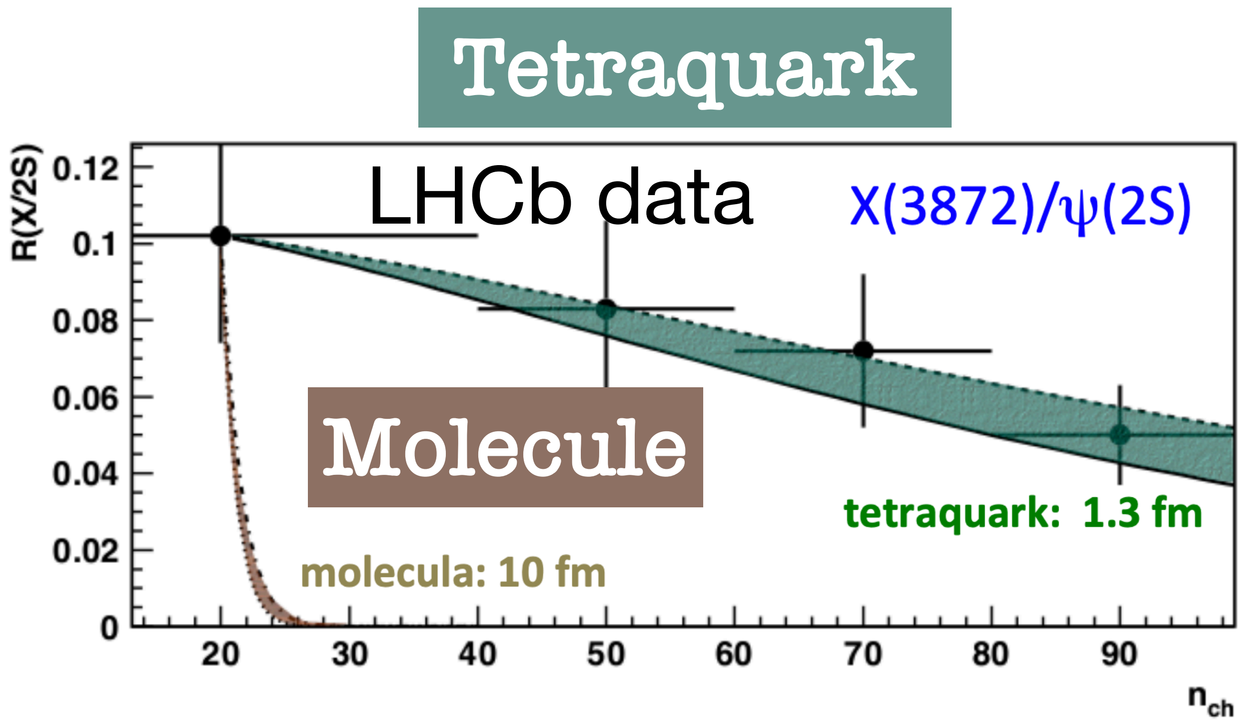
- Heavy ion collisions not only for studying QGP

Coalescence model	AMPT transport model	TAMU transport model	vs. multiplicity in pp
PRL 106 (2011) 212001	arXiv:2004.00024	arXiv:2006.09945	









Coalescence model
- Molecule easier to be produced w/ recombination of quarks in medium
- $N_{Molecule} > N_{Tetraquark}$

AMPT transport model
- Centrality dependence
- $N_{Molecule} > N_{Tetraquark}$

TAMU transport model
- Molecule (more loosely bound) regenerated later in the evolution compared to tetraquark
- $N_{Molecule} < N_{Tetraquark}$

vs. multiplicity in pp
- Destroyed by comover
- Recomination not included
- Including recombination gives wrong trend

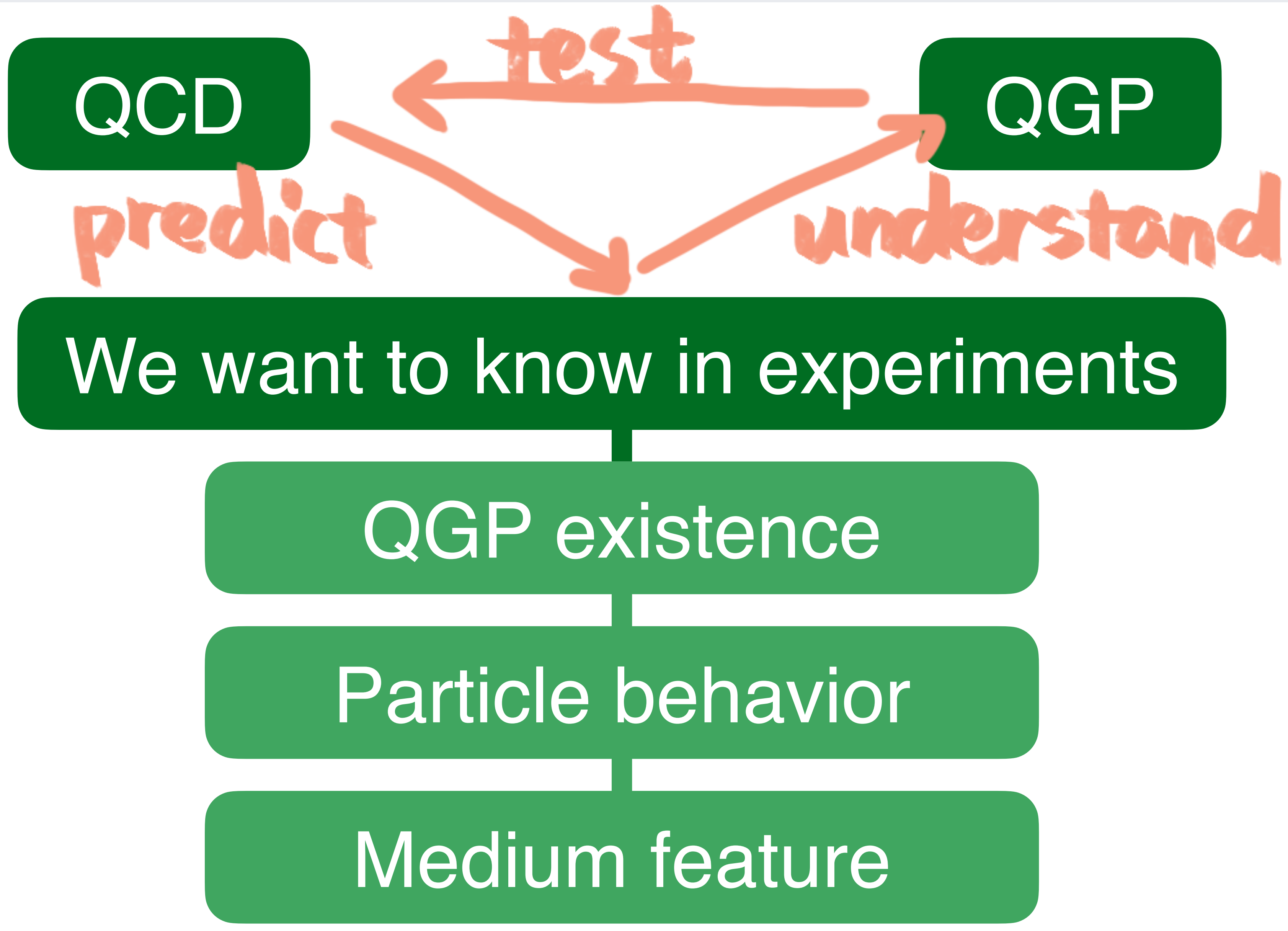
Summary

- 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



Prerequisites

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- HF production in pp collisions is not perfectly understood
- Study hadronization mechanisms across system sizes

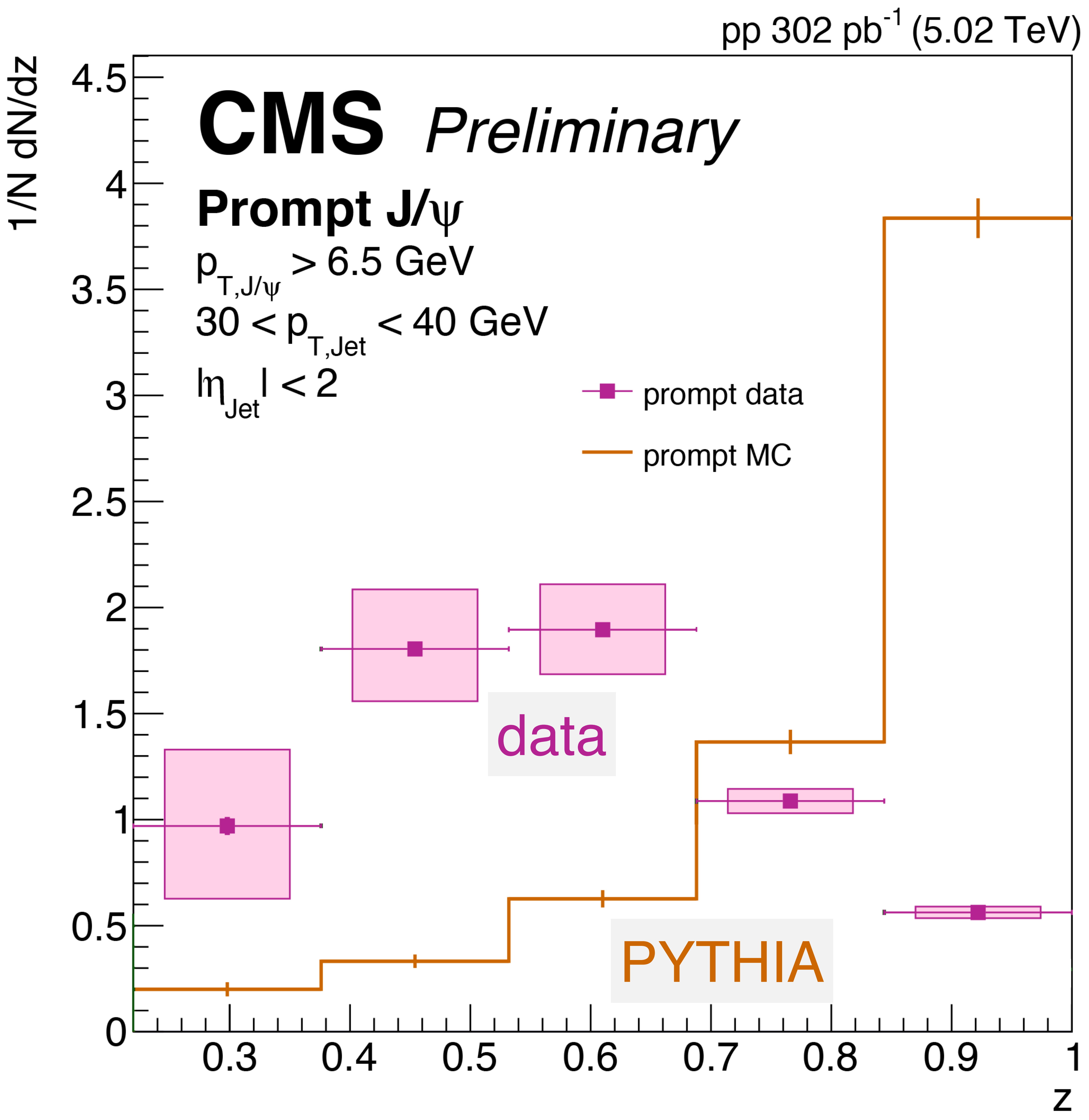
- Answer other physics questions w/ HF in Heavy-ion collisions

Back up

Thanks for your attention!


Isabelle
Thanks for your attention!

Production in pp vs. pQCD calculation



J/ψ fragmentation function in jets

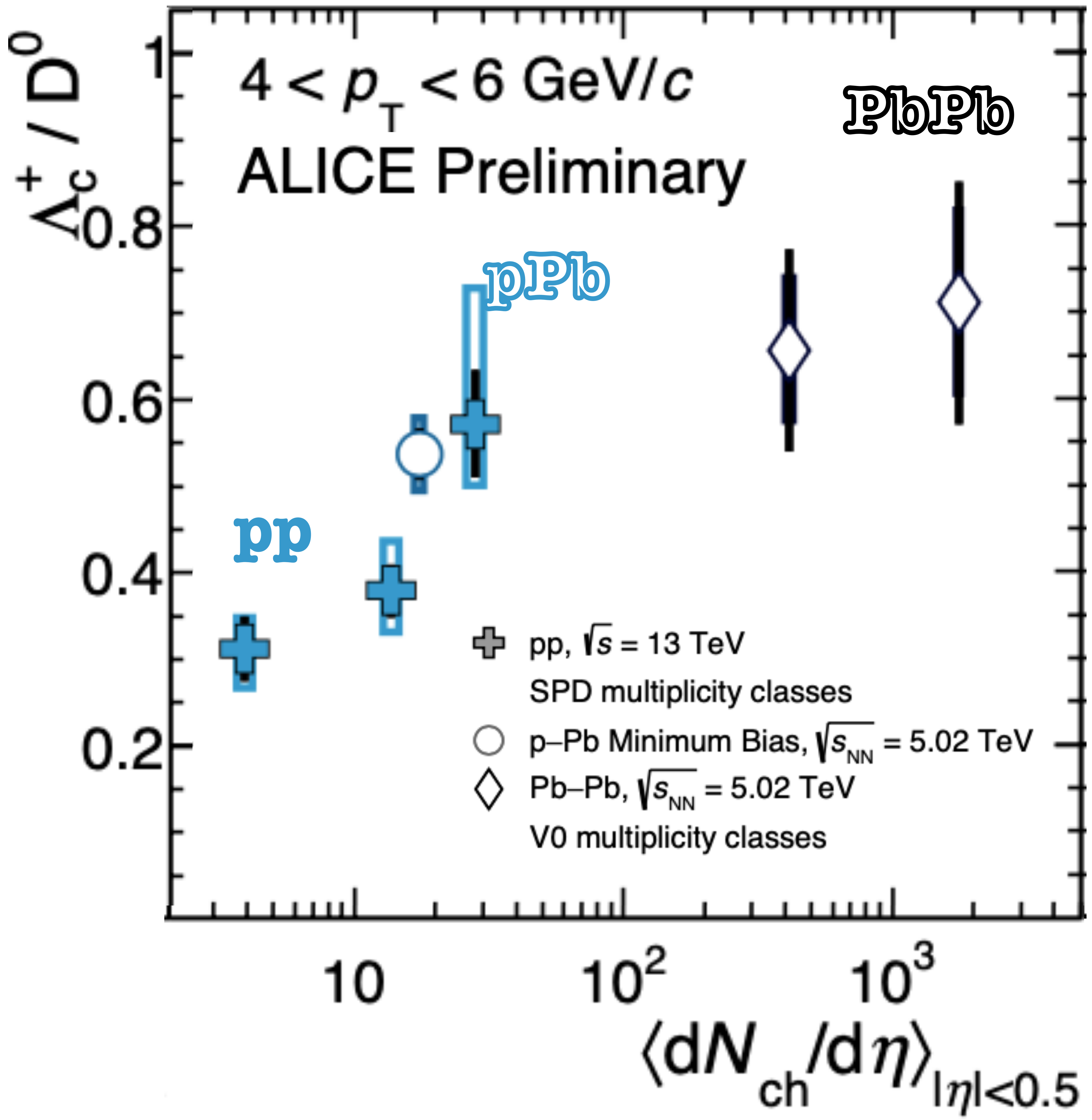
- PYTHIA8 misses the shape
- Hadron production mechanism not very well known

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

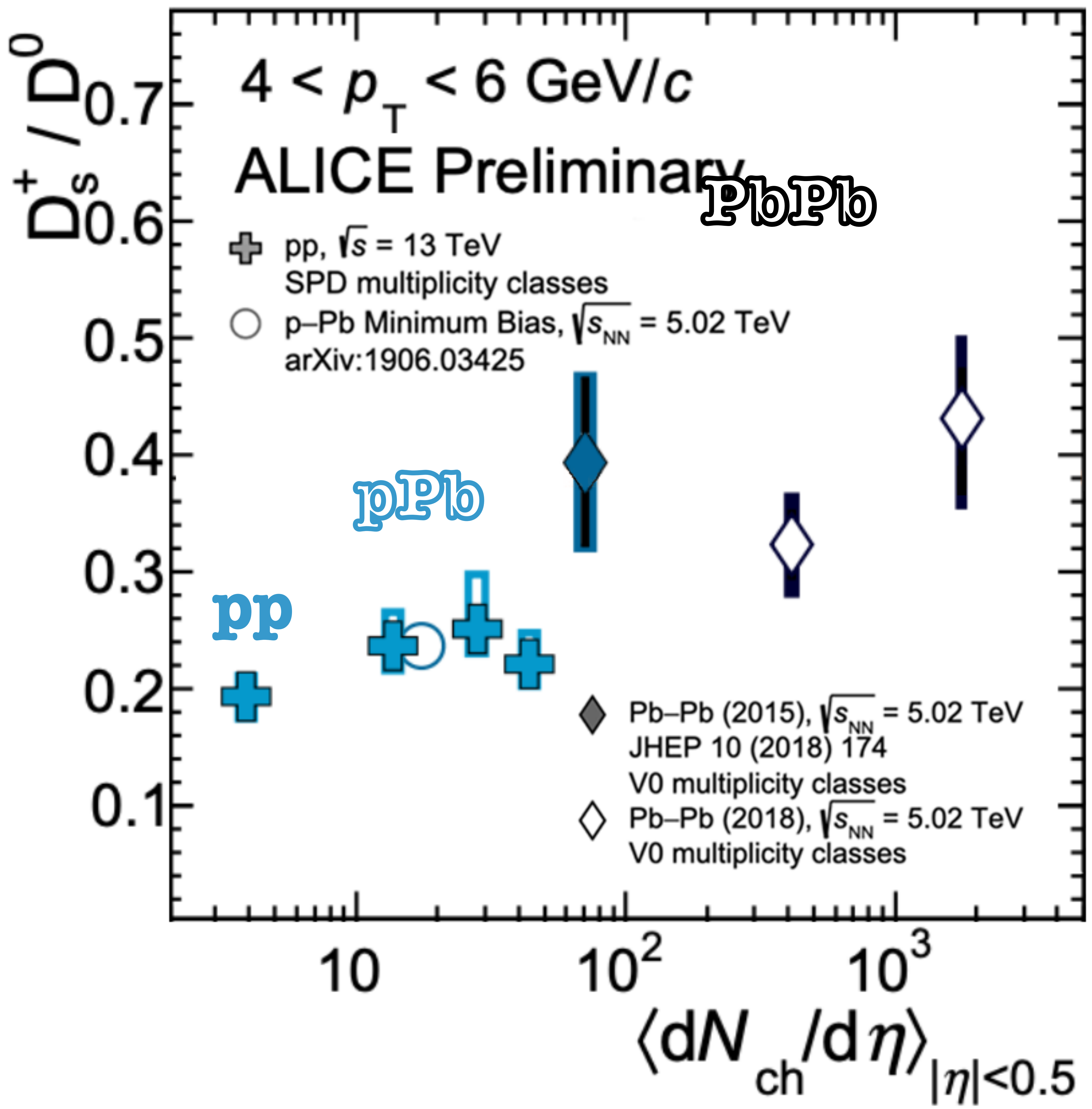
CMS-PAS-HIN-19-007

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…

nPDF
arXiv:2003.12797
PLB 800 (2020) 135048
PRL 121 (2018) 062002

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

Jet quenching
JHEP 10 (2018) 138
PLB 785 (2018) 14
PRL 119 (2017) 082301
JHEP 04 (2017) 039

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

Collective dynamics
PRC 100 (2019) 044902
PRC 98 (2018) 044902
PLB 776 (2017) 195

Small system
arXiv:1910.04812
PRC 101 (2020) 014912
PLB 791 (2019) 172
PRL 121 (2018) 082301
PRL 120 (2018) 092301

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

Quarkonion 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

Hadronization
PLB 803 (2020) 135328
PLB 796 (2019) 168

More preliminary results in queue…

➜ CMS Heavy-ion Publications

➜ CMS Heavy-ion Preliminary

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