Heavy Flavor + Quarkonia Experiment

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GDR-QCD: From Hadronic Structure to Heavy-ion Collisions
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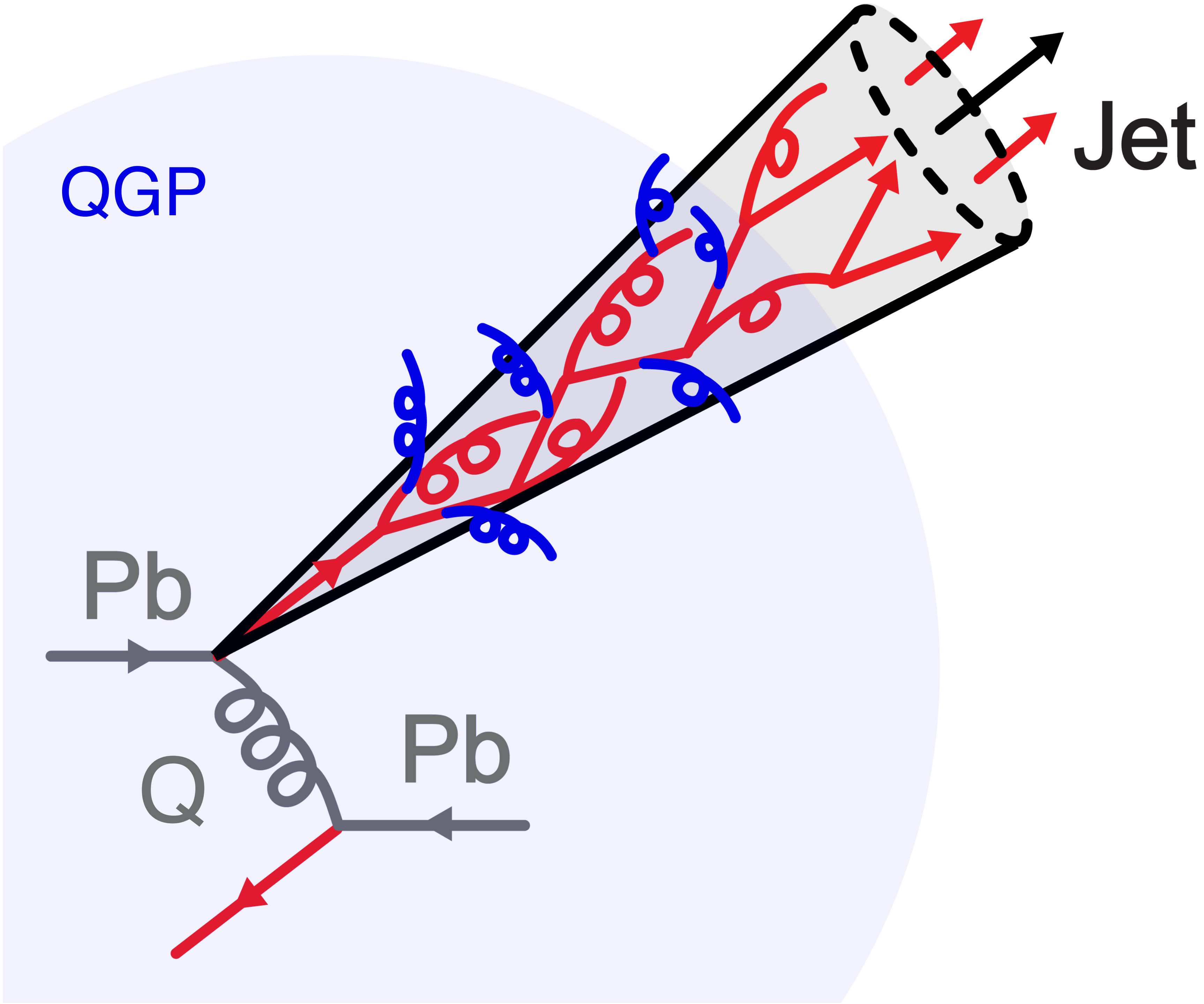
Special thanks to Gian Michele and Florian for the discussions!

After Hydrodynamics What Next?

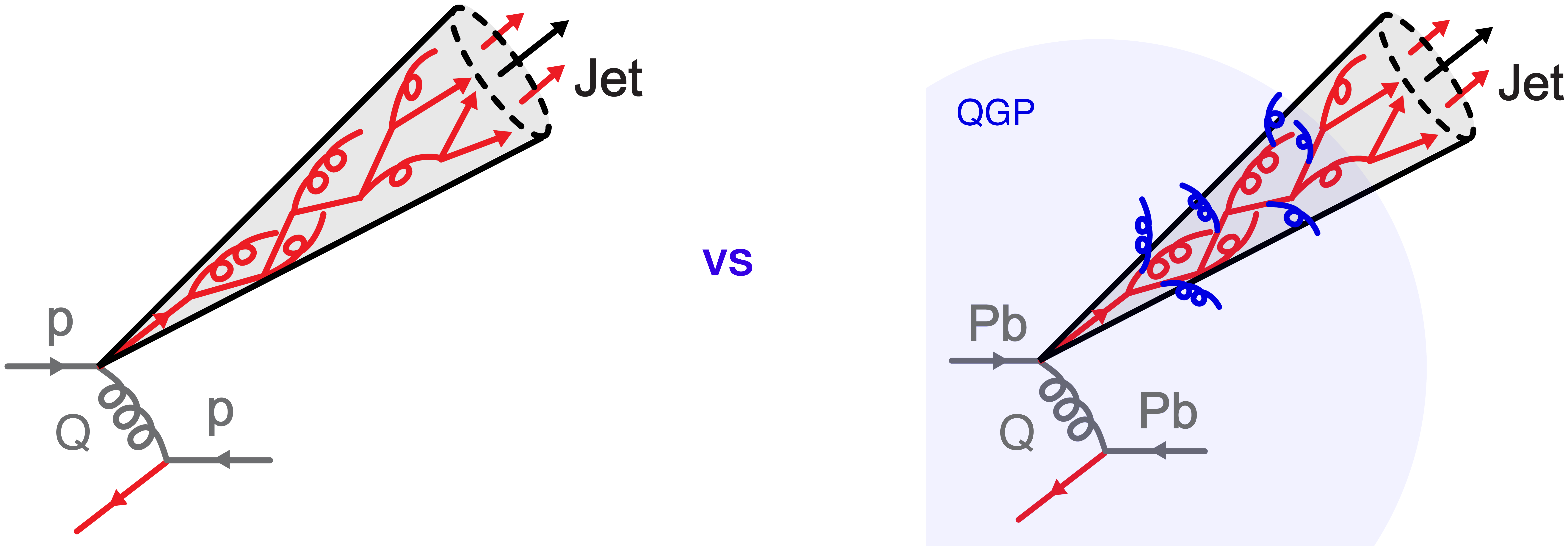
Hard Probes "Rutherford experiment"

- Hard Probes → particles created from scatterings of large momentum transfer Q



Hard Probes "Rutherford experiment"

- **Hard** Probes → particles created from scatterings of large momentum transfer Q
- Get information of medium by measuring how hard probes are modified compared to no medium → normally pp collisions as reference

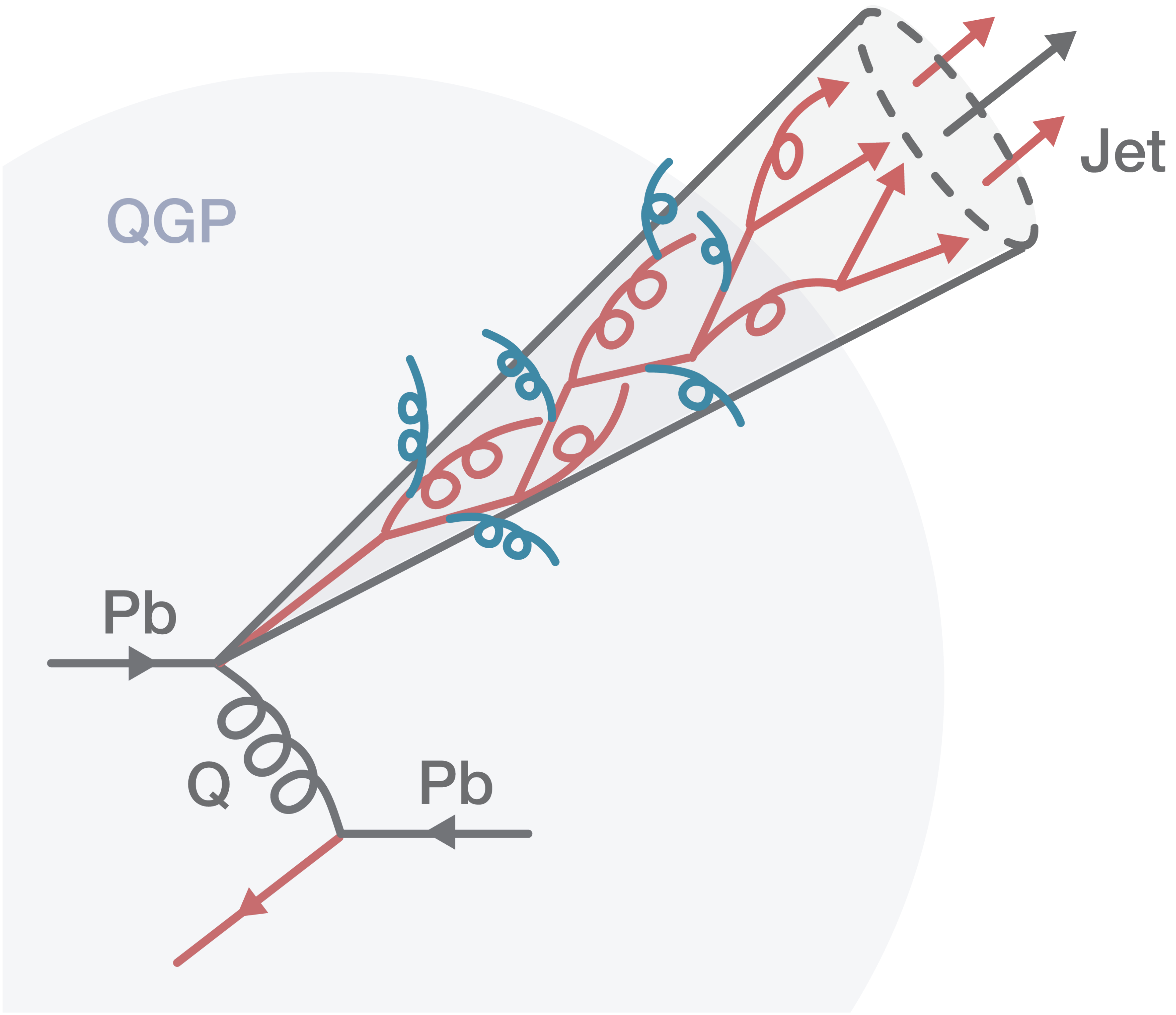


Hard Probes vs Soft Particles

Hard probes → large Q

- Q ~ 1/τ creation time
  - Produced early → experience whole evolution
  - Unique access to high temperature stage
- Q ≫ Λ_{QCD} ~200 MeV
  - Initial production calculable with pQCD
- Q ≫ T_{QGP} ~400 MeV for LHC
  - Seldom produced in QGP → Keep identity
- With color charge EM Bosons are also hard probes
  - Strong interaction with QGP

Heavy-ion collisions

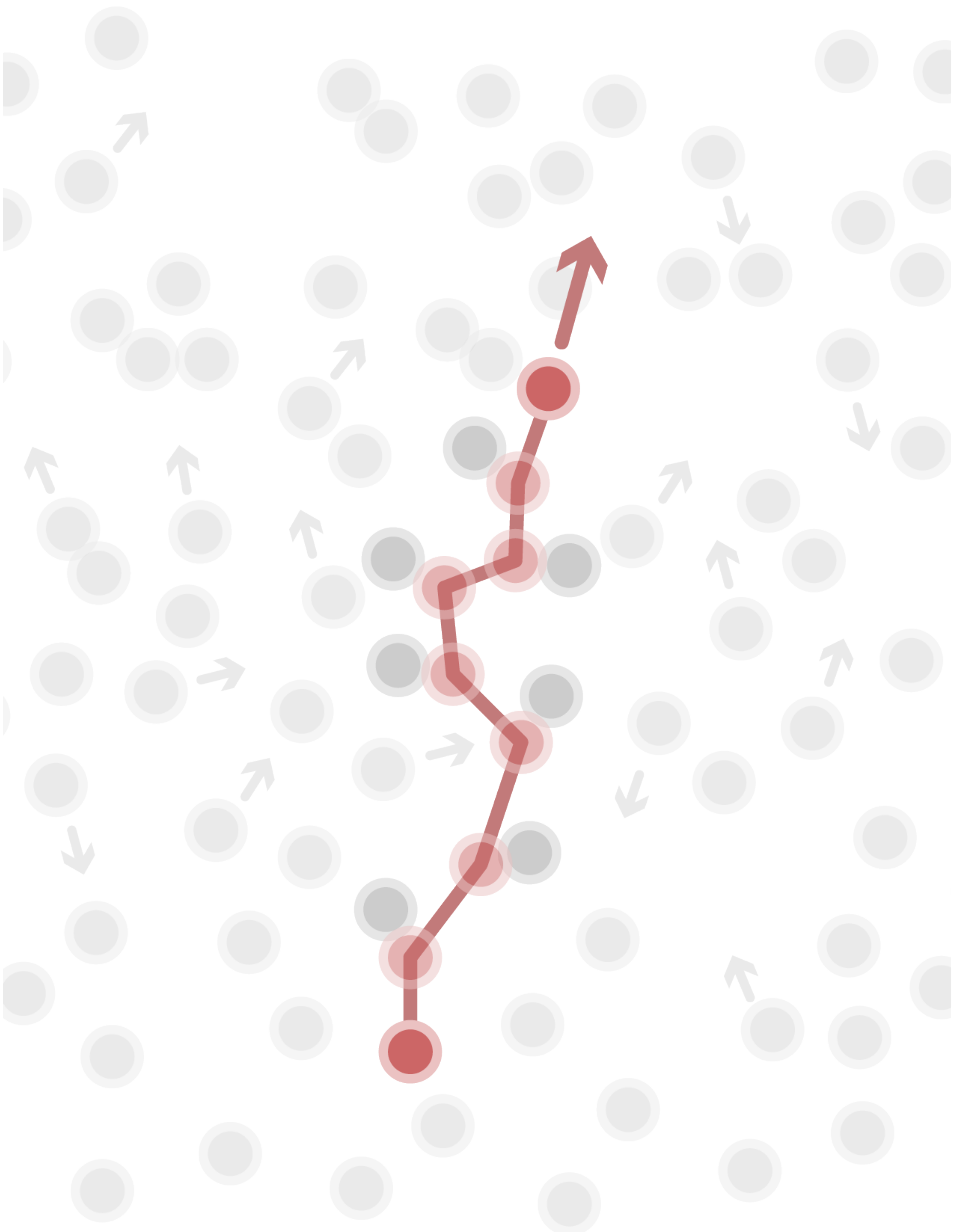


Heavy Flavors vs Other Hard Probes

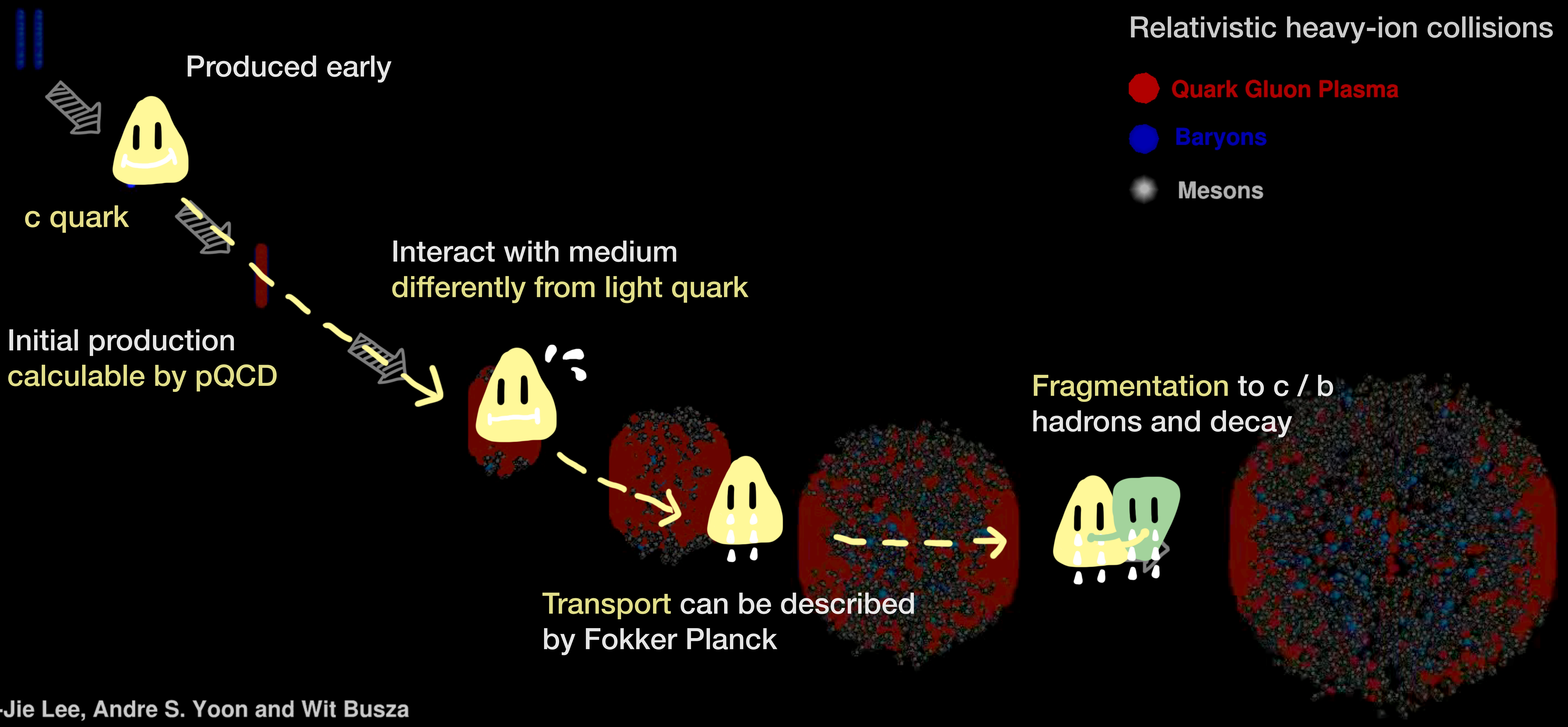
Heavy quarks (charm, beauty) → **large mass m_Q**

- $m_Q \sim 1/\tau$ creation time
  - Produced early → experience whole evolution
  - Unique access to high temperature stage
- $m_Q \gg \Lambda_{QCD}$
  - Initial production calculable with pQCD even at low p_T
  - Different length scale structure by varying p_T
- $m_Q \gg T_{QGP}$
  - Seldom produced in QGP → Keep identity
  - Brownian motion → Diffusion coeff. D_s (Fokker-Plank)
- $m_Q \gg m_q$
  - Strong interaction with QGP differently from light quark

Brownian motion of heavy quarks in medium



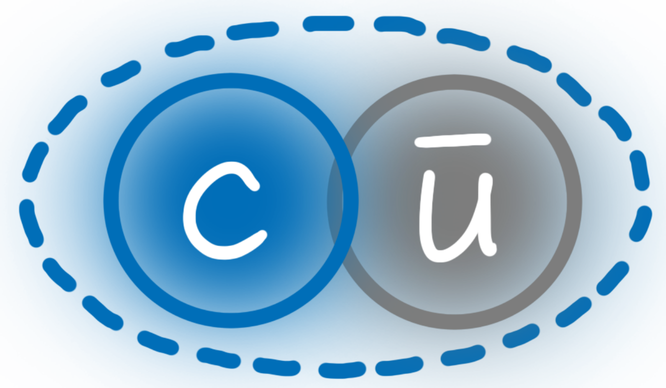
Life of a Heavy Quark in HIC



Yen-Jie Lee, Andre S. Yoon and Wit Busza

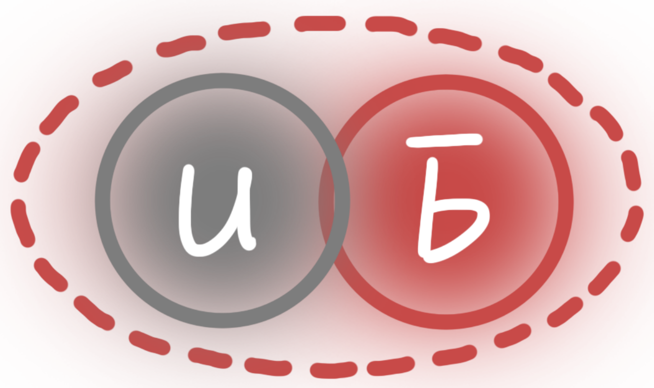
Connaître Representative Heavy Flavor Hadrons

Charm



D^0 ($c \to D^0 \sim O(50\%)$)
Mass 1.865 GeV
$c\tau \sim 120\ \mu m$

Beauty



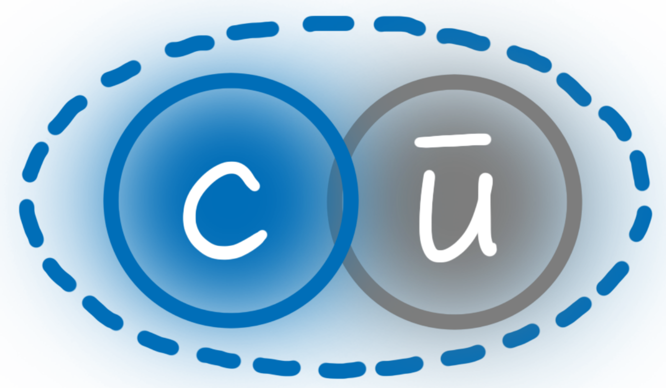
B^+ ($b \to B^+ \sim O(40\%)$)
Mass 5.279 GeV
$c\tau \sim 490\ \mu m$

Study of heavy **quarks** enabled by measurements of heavy-flavor **hadrons**

- D^0 and B^+ mesons are **go-to** proxy c- and b- hadron
  - Best fragmentation fraction
  - Relatively simple to reconstruct

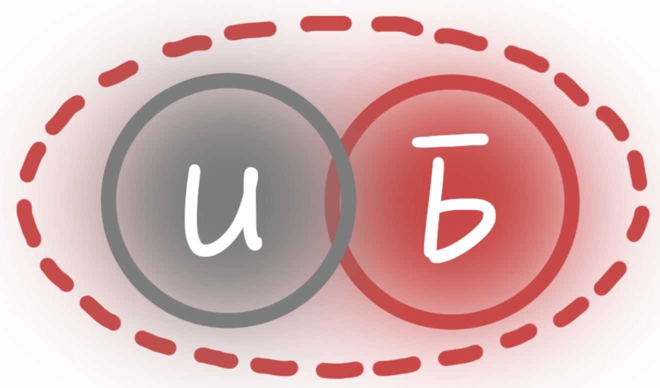
Connaître Representative Heavy Flavor Hadrons

Charm



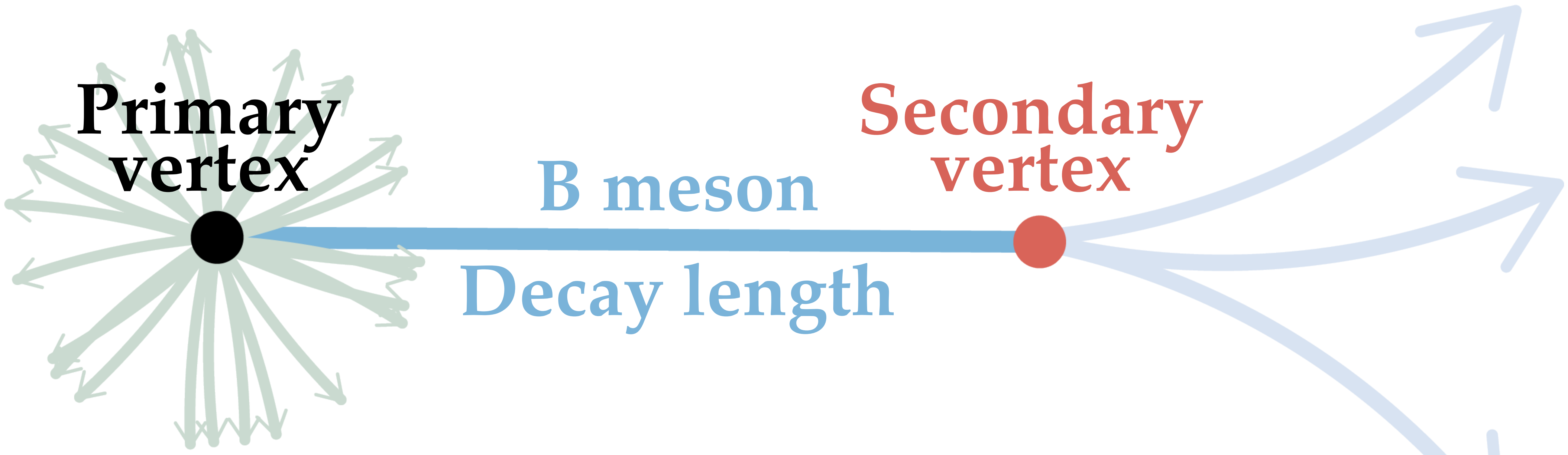
D^0 ($c \to D^0 \sim O(50\%)$)
Mass 1.865 GeV
$c\tau \sim$ 120 μm

Beauty



B^+ ($b \to B^+ \sim O(40\%)$)
Mass 5.279 GeV
$c\tau \sim$ 490 μm

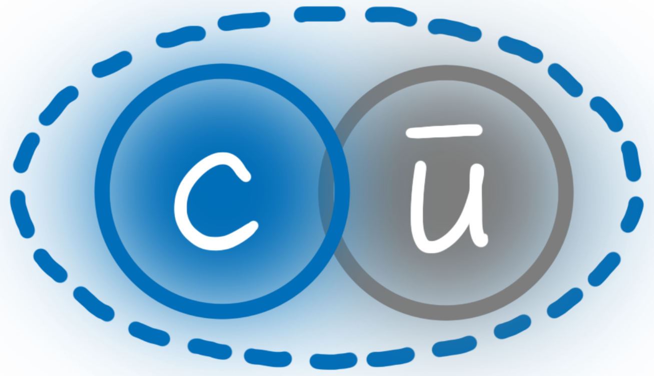
Displaced secondary vertex is an experiment signature of open HF mesons

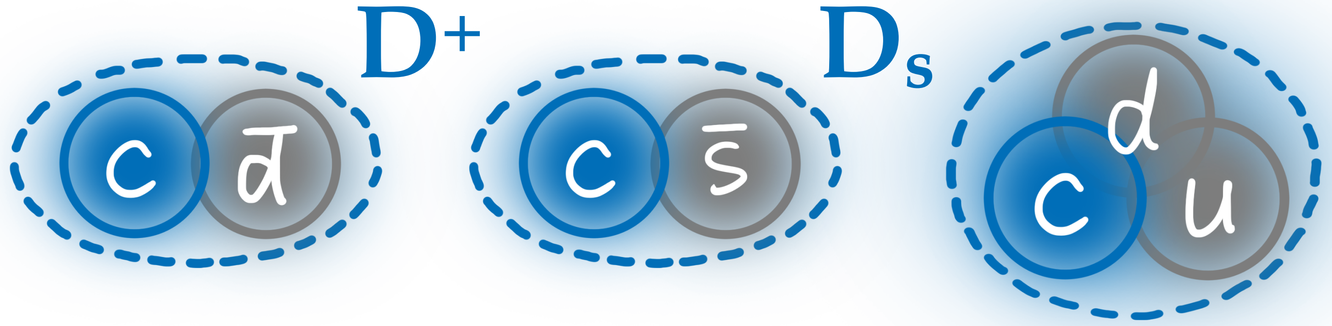


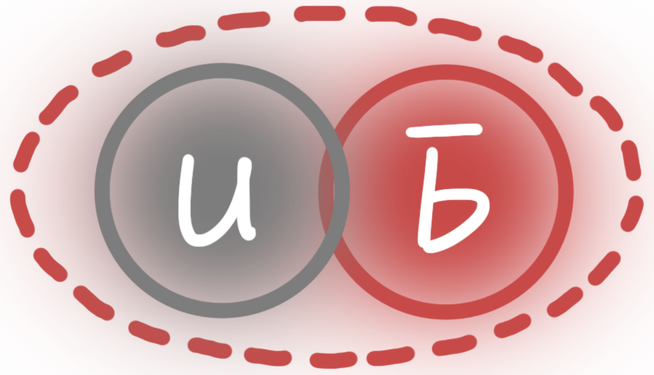
can be ~1 cm in lab frame at LHC

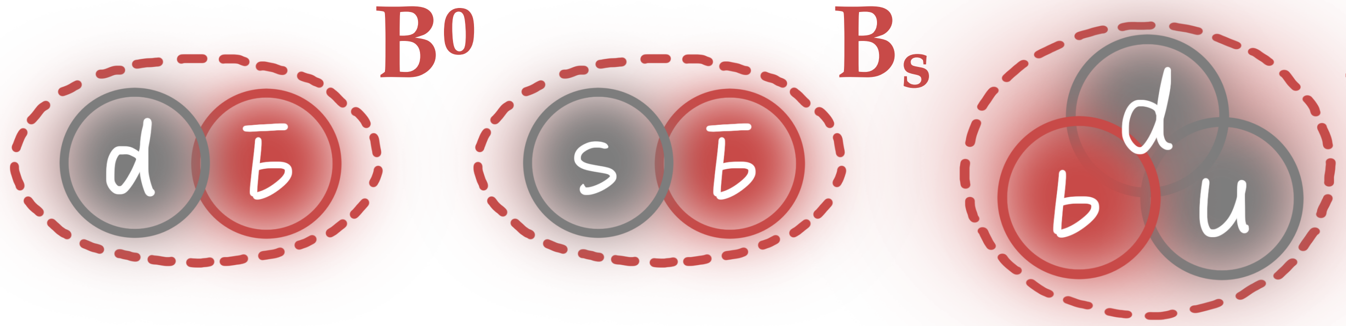
Connaître Representative Heavy Flavor Hadrons

	Charm	Beauty
Open heavy flavor	D^0 ($c \to D^0 \sim O(50\%)$) Mass 1.865 GeV $c\tau \sim$ 120 μm	B^+ ($b \to B^+ \sim O(40\%)$) Mass 5.279 GeV $c\tau \sim$ 490 μm
	D^+, D_s, Λ_c	B^0, B_s, Λ_b
Quarkonia	J/ψ $\psi(2S)$, χ_c	$\Upsilon(1S)$ $\Upsilon(2S)$, $\Upsilon(3S)$

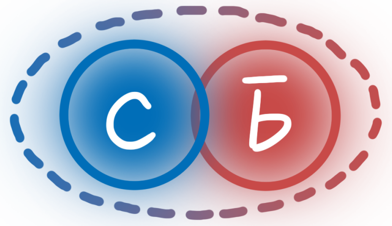


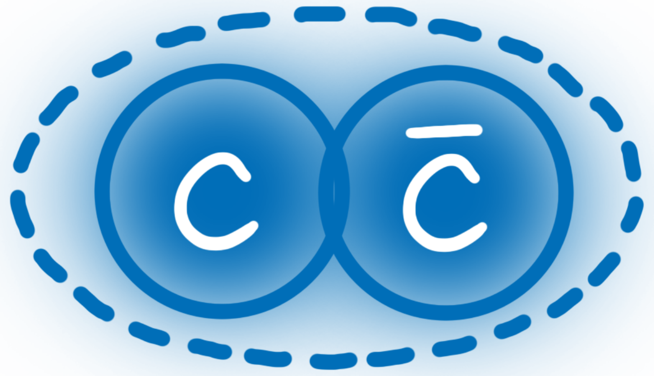


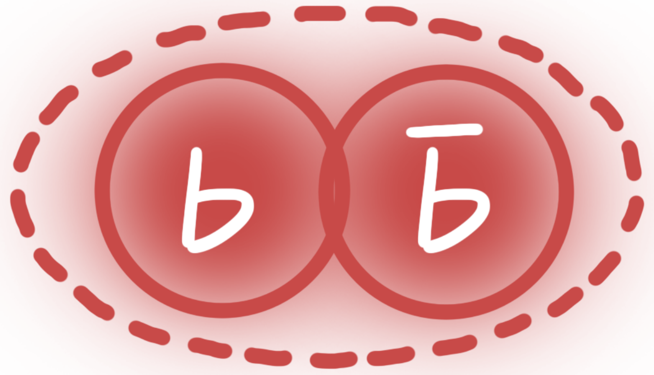




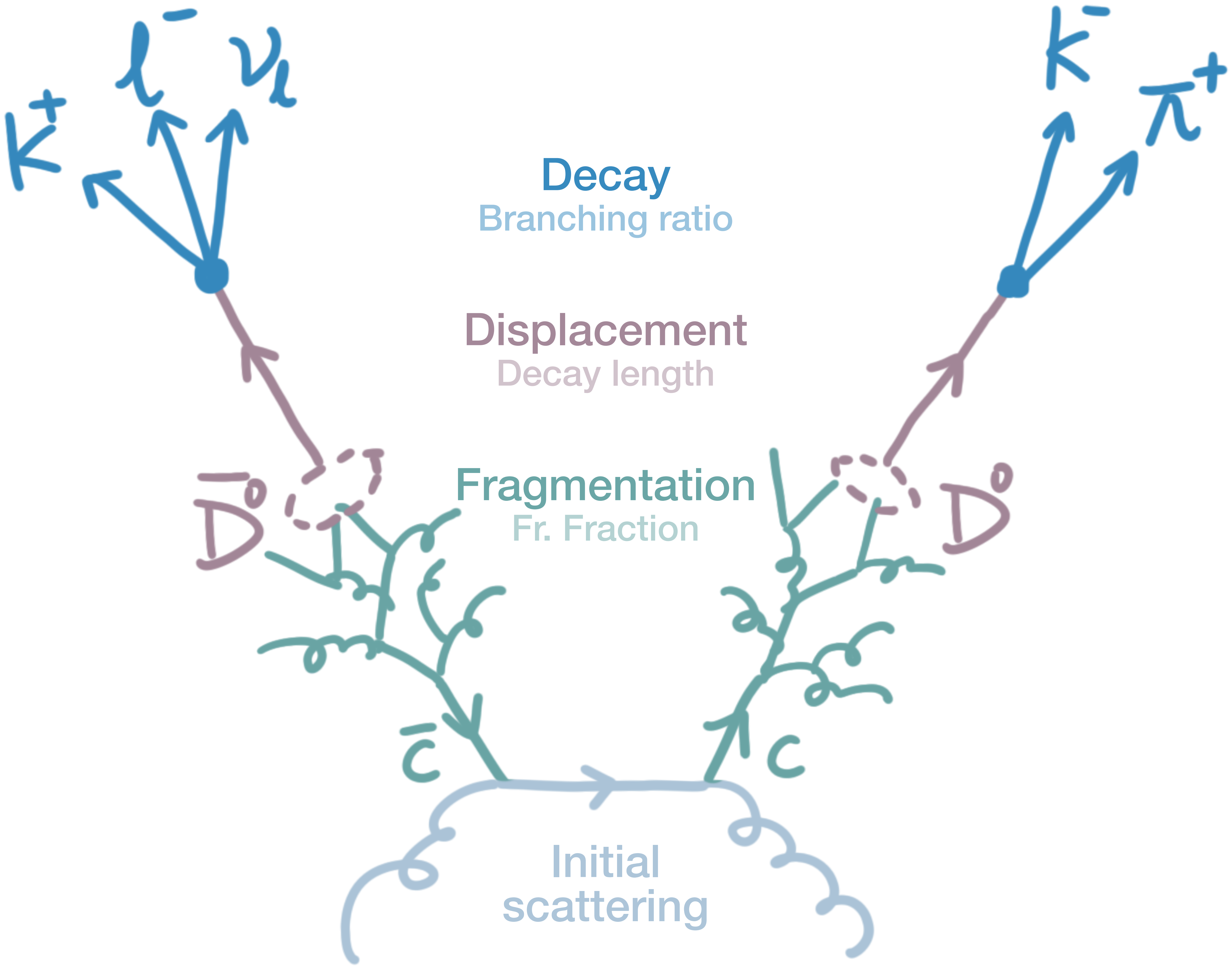
B_c^+



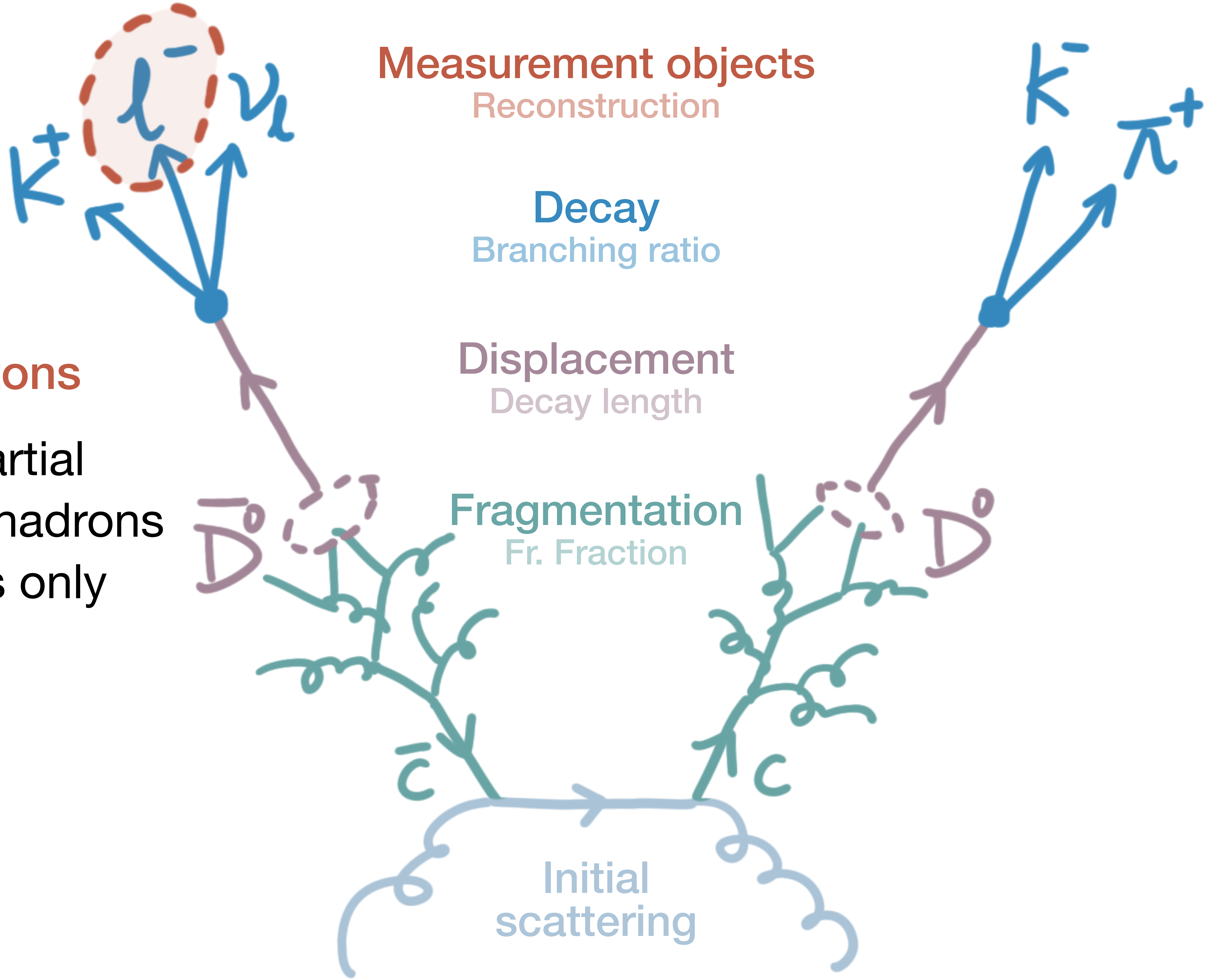




How to Measure Open Heavy Flavors



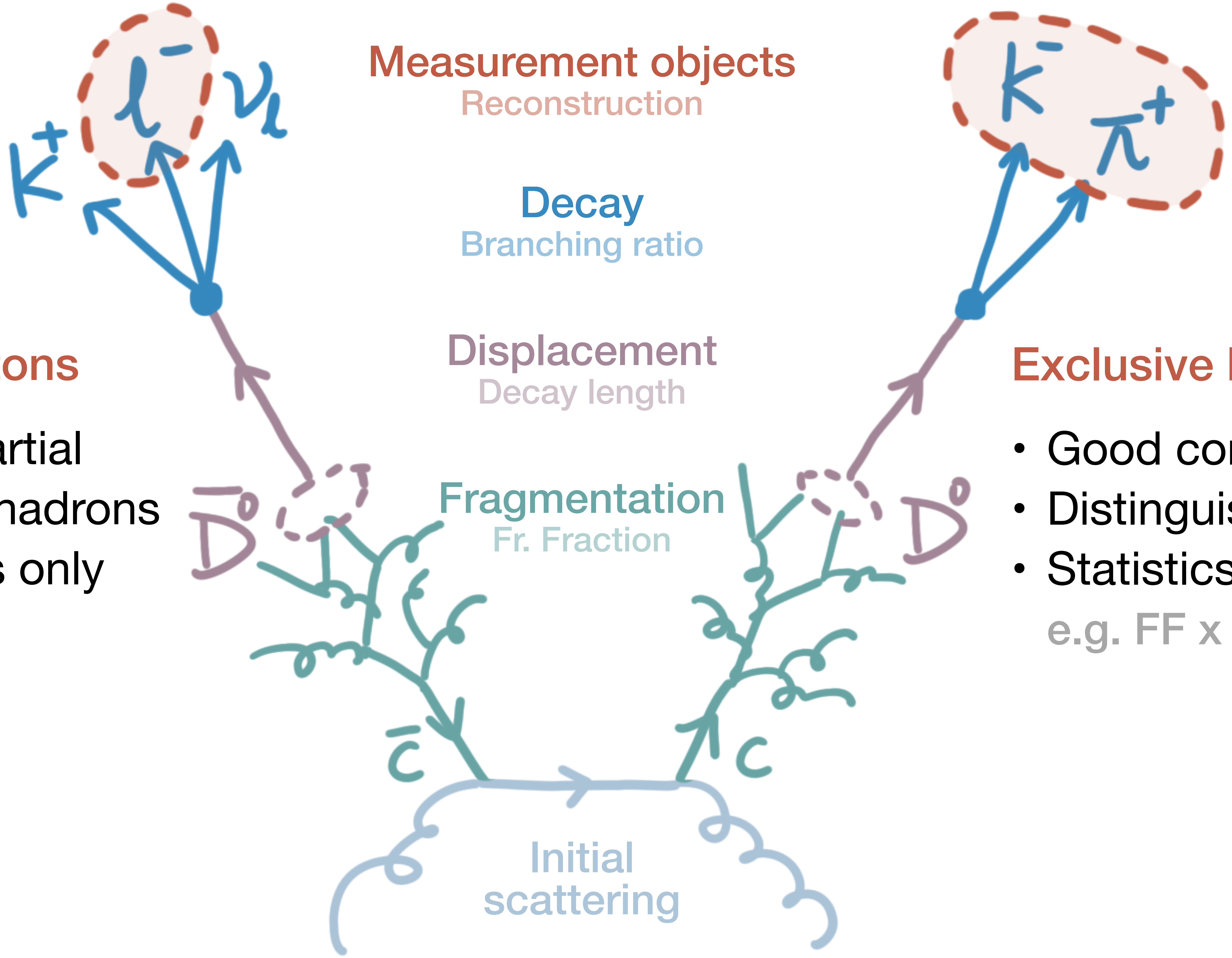
Measure Heavy Flavor HF Decayed Leptons



Inclusive decayed leptons

- Leptons only carry partial kinematics of parent hadrons
- Inclusive c/b-hadrons only

Measure Heavy Flavor Fully Reconstruction



Inclusive decayed leptons

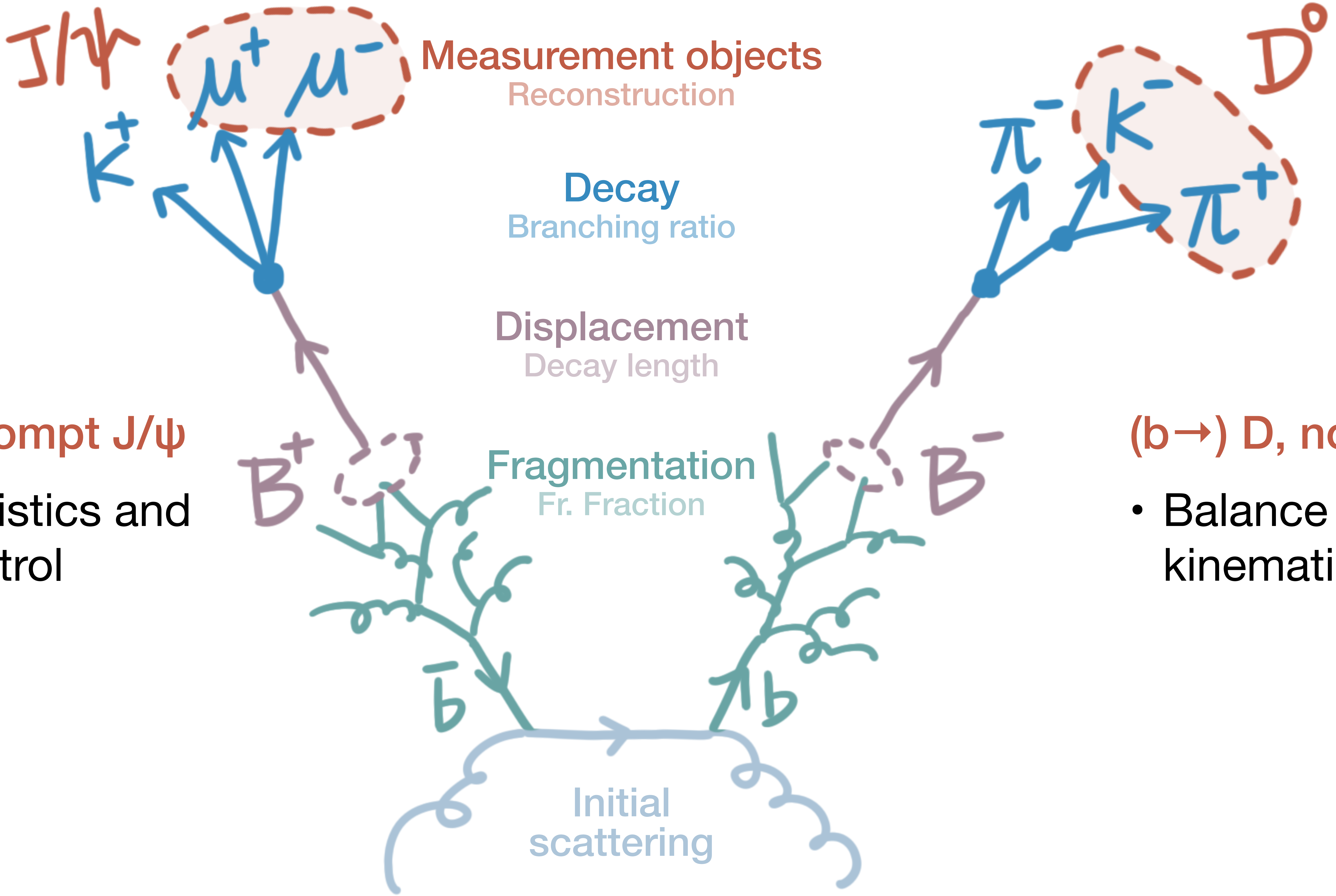
- Leptons only carry partial kinematics of parent hadrons
- Inclusive c/b-hadrons only
- Better statistics

Exclusive hadronic reconstruction

- Good control of kinematics
- Distinguish type of hadrons
- Statistics limited by FF, BR

  e.g. FF x BR ($c \rightarrow D^0 \rightarrow K\pi$) ~ 0.02

Measure Heavy Flavor Partial Reconstruction



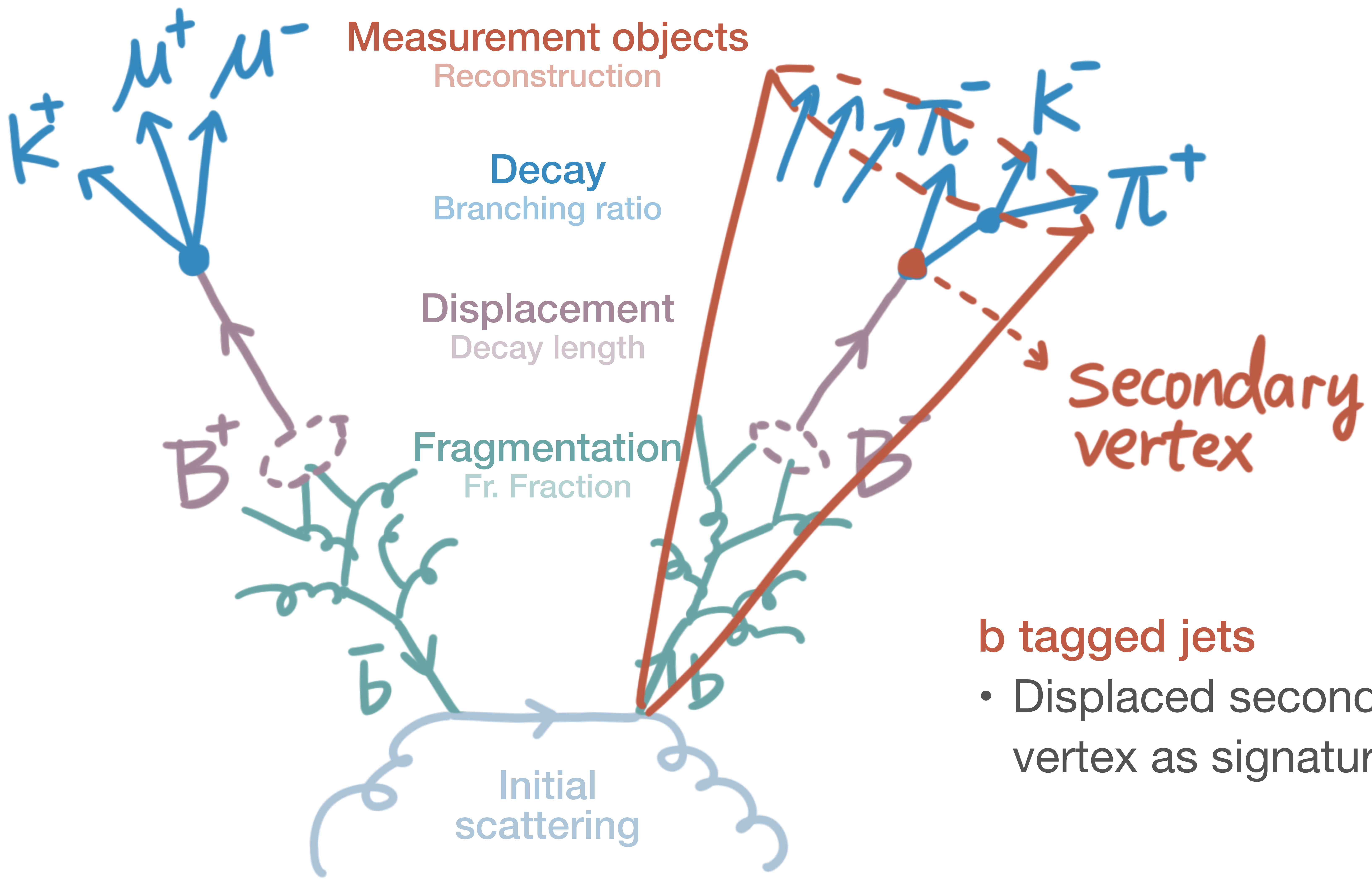
(b→) J/ψ, nonprompt J/ψ

- Balance of statistics and kinematics control

(b→) D, nonprompt D

- Balance of statistics and kinematics control

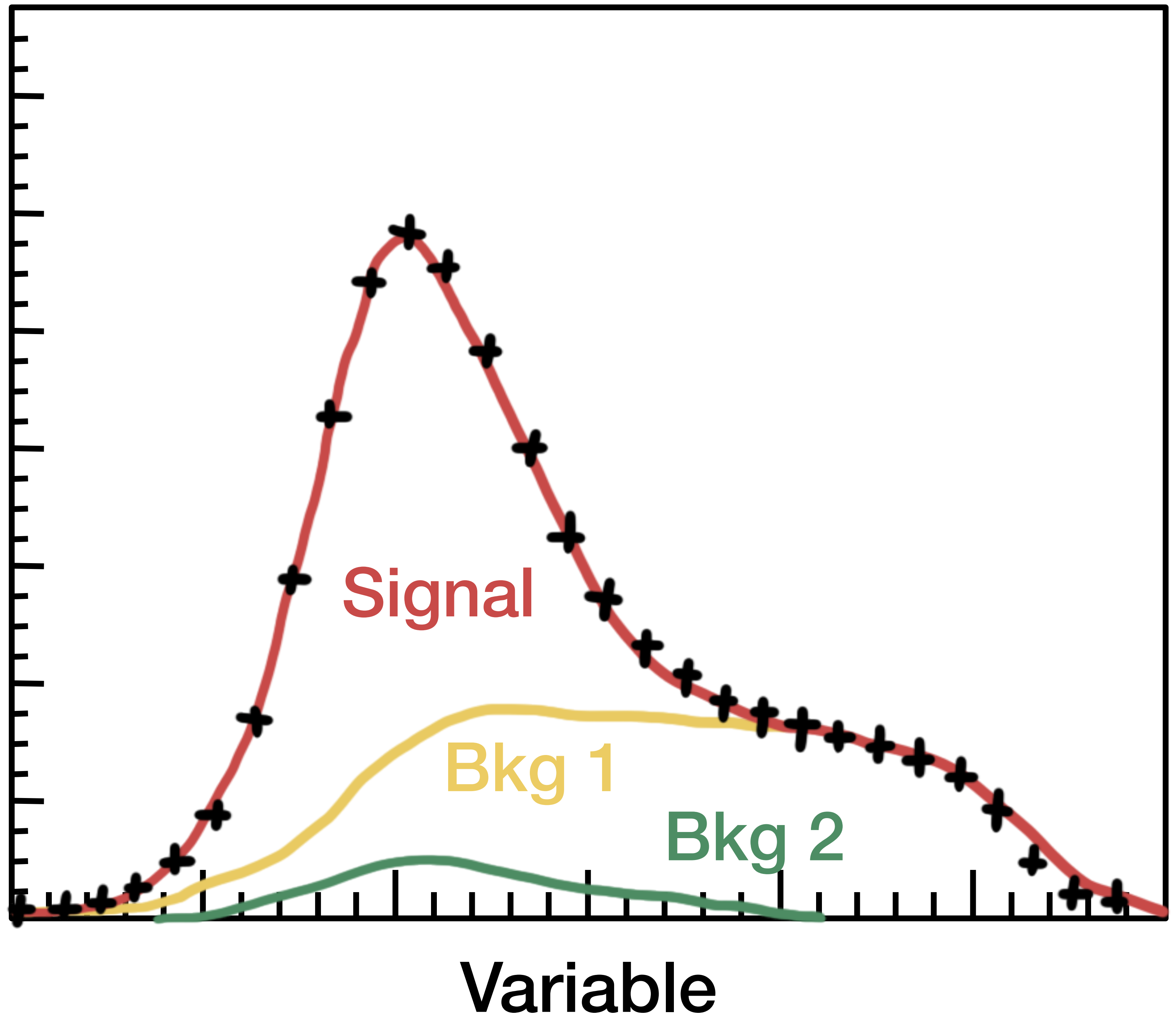
Measure Heavy Flavor HF Tagged Jets



b tagged jets

- Displaced secondary vertex as signature

Signal Extraction HF Decay Leptons



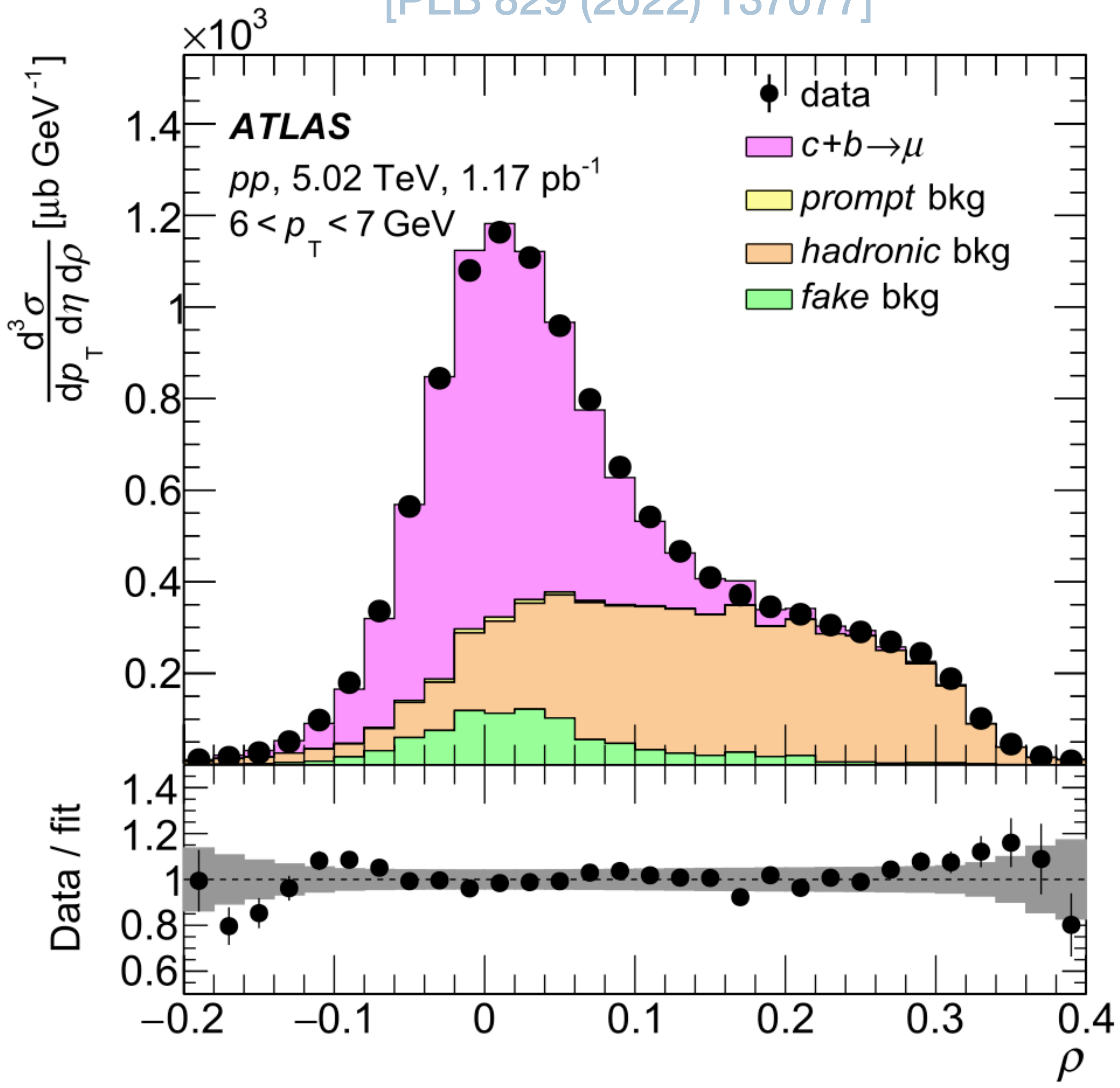
Template fit on a variable to extract the yields of signals

- Identify sources of backgrounds
- Determine variables, which should have *either*
  - distinct shapes between components, *or*
  - well-known yields
- Determine templates
  - Data-driven is the best
  - Simulation is commonly used
    - Need to correct or evaluate data-MC difference

This idea will be used again and again…

Signal Extraction HF Decay Muons - Example

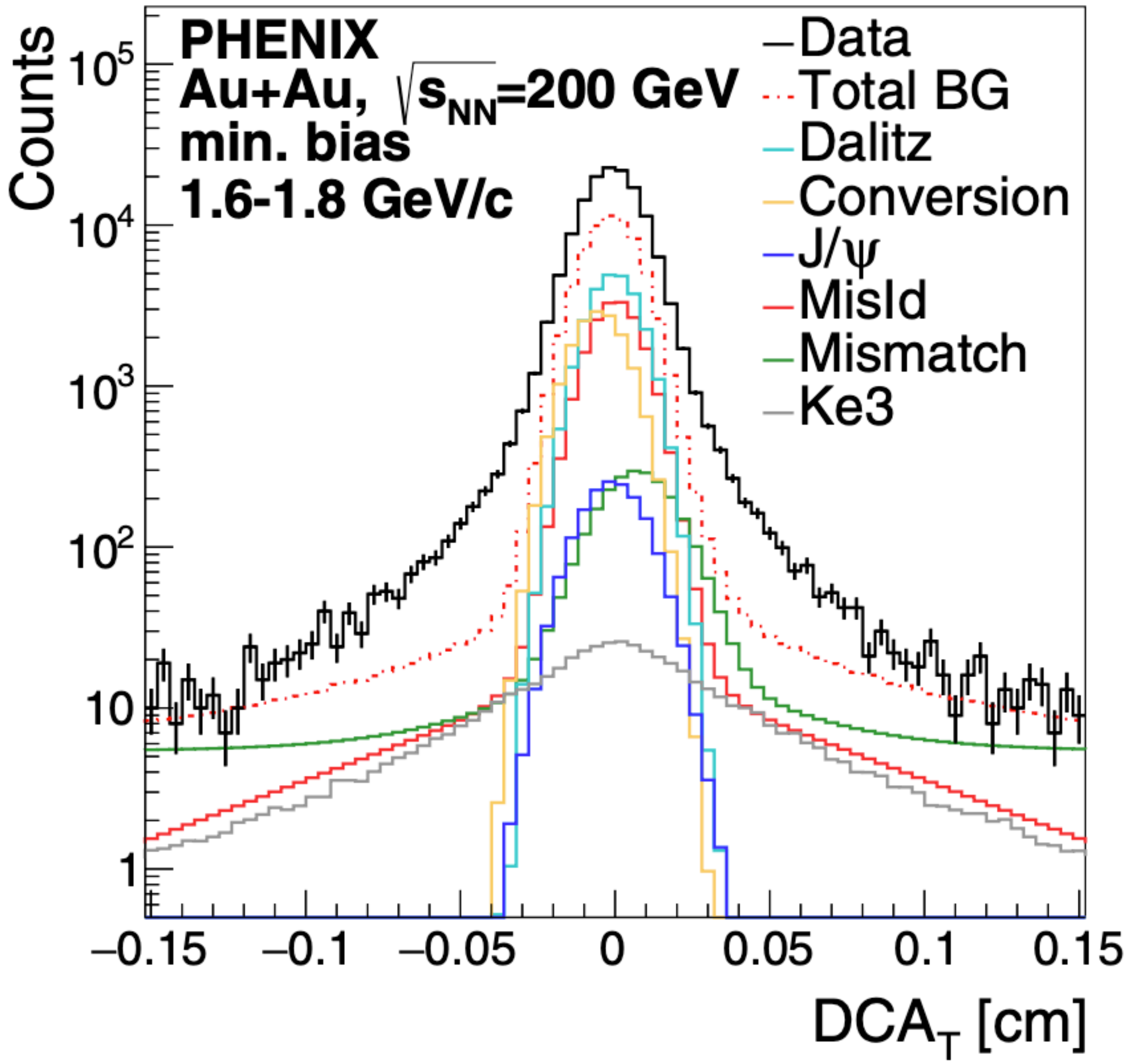
[PLB 829 (2022) 137077]



- Sources of **backgrounds**
  - *prompt* bkg muon from decay of J/ψ, ψ(2S), Υ, W/Z
  - *hadronic* bkg muon from π / K decay in inner tracker or punching through the calorimeter
  - *fake* bkg wrongly reconstructed/identified track
- **Variables**
  - ρ Difference of muon momentum determined in the inner tracker and in the muon chamber
  - *hadronic* and *fake* bkg shapes different from signals
  - *prompt* bkg yields scaled from previous measurements
- **Templates**
  - From simulations

Signal Extraction HF Decay Electrons - Practice

[PRC 109 (2024) 044907]



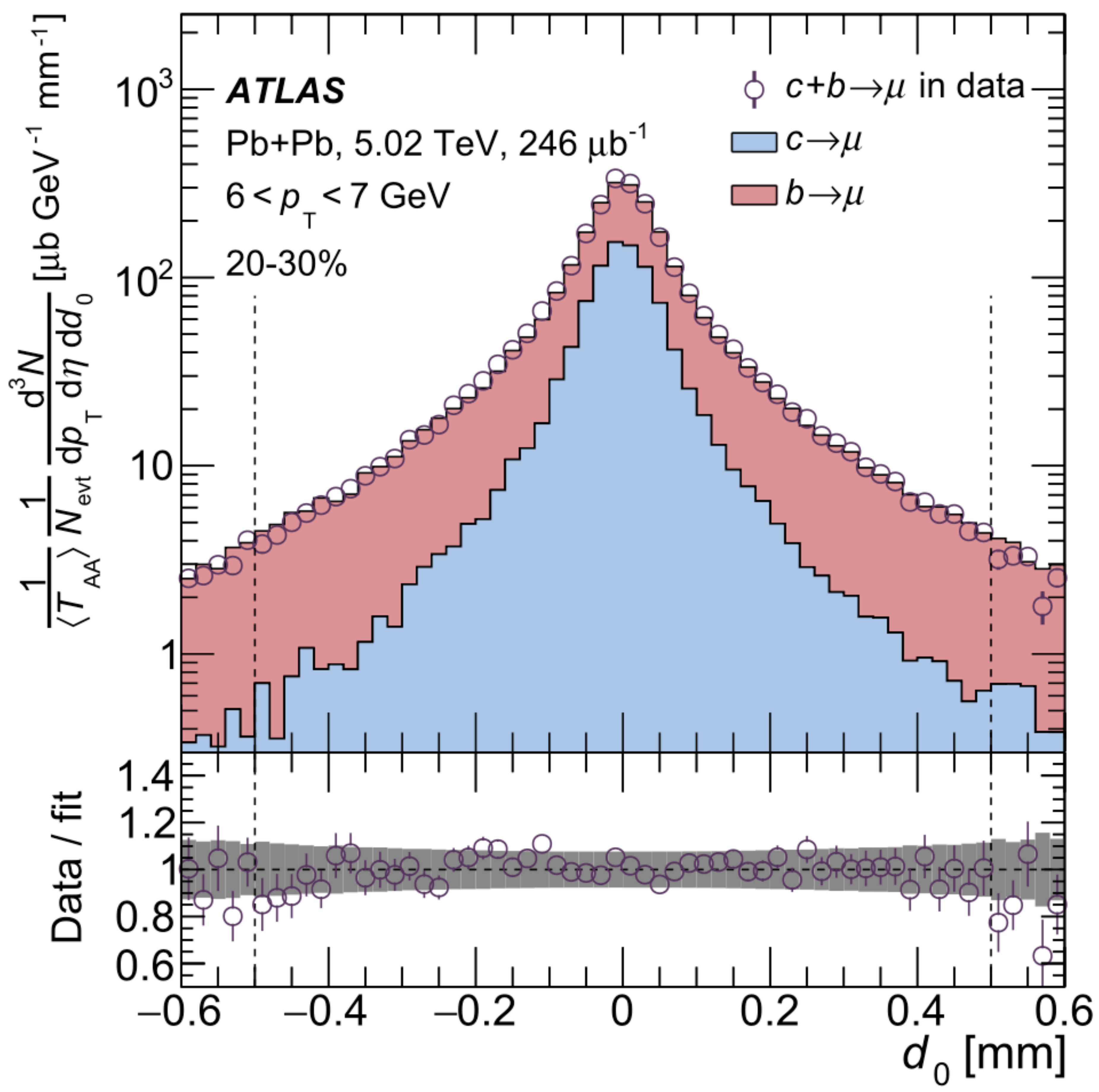
Extension for homework HF → e

- What are the background sources?
- What are the variables to separate signals and backgrounds?
- How the templates are determined?

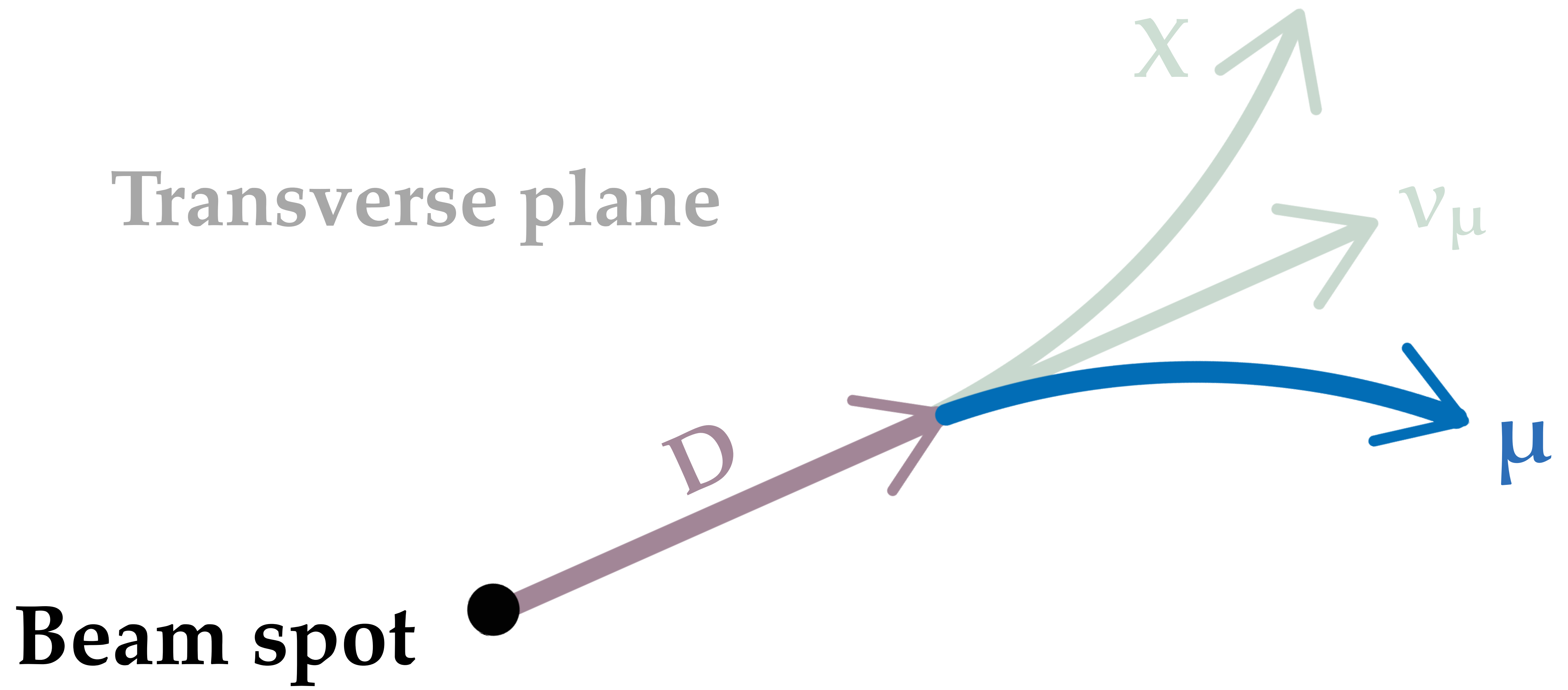
- Similar one from STAR [1]

Signal Extraction Separate c→ and b→μ

[PLB 829 (2022) 137077]

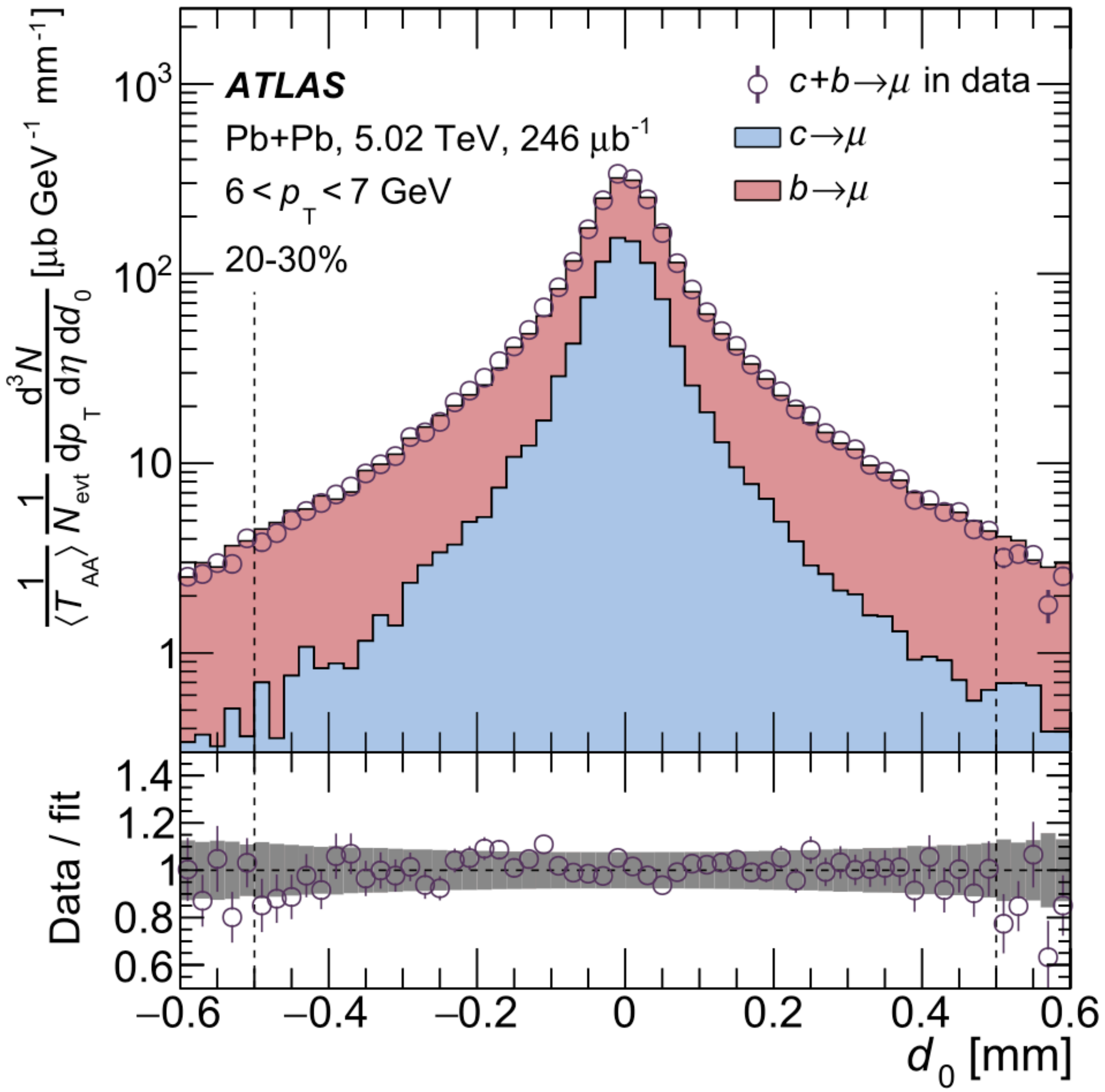


Template fit on **Variables** d_0 (Distance of Closest Approach DCA) relative to the beam spot (primary vertex sometimes)

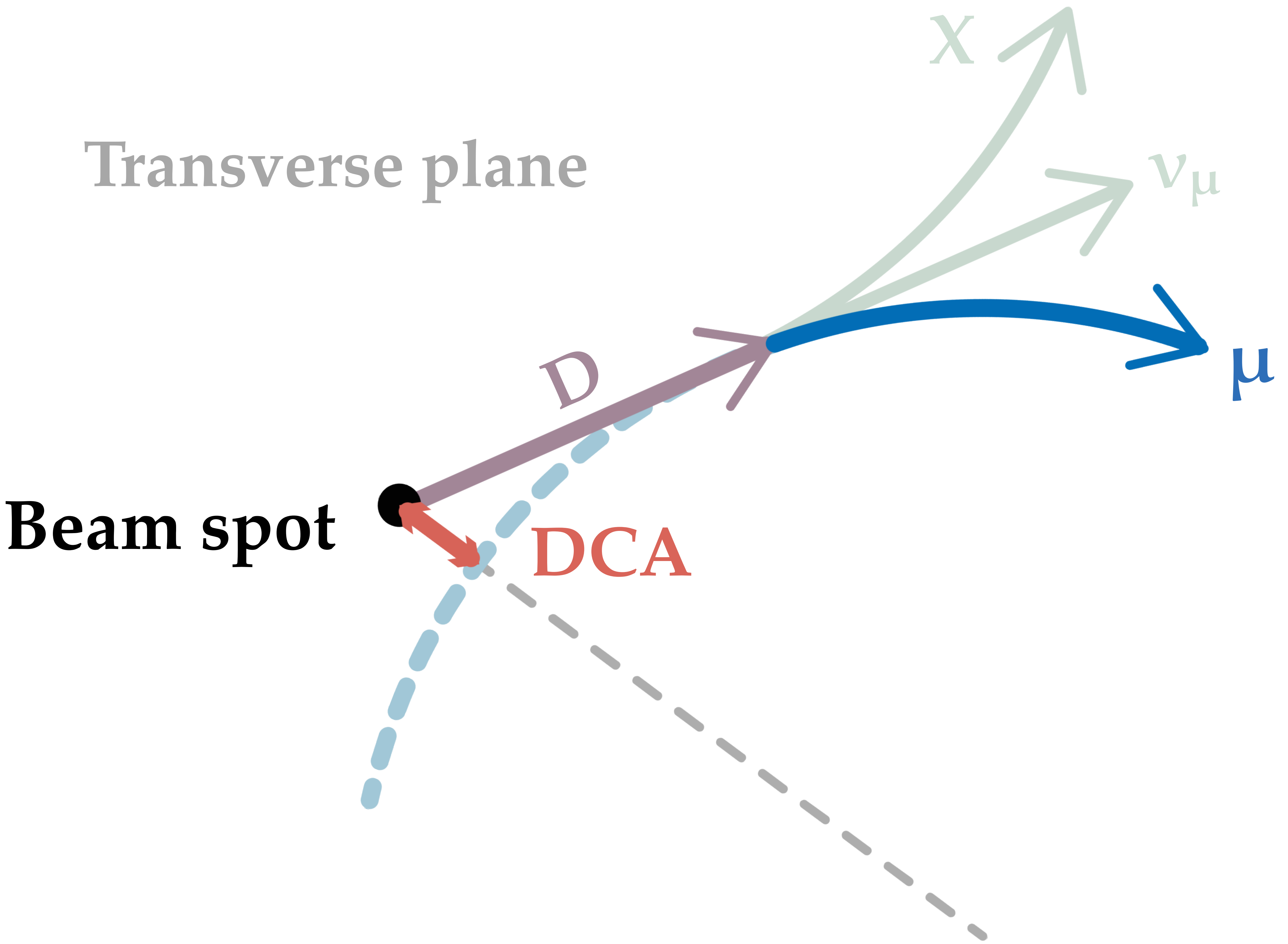


Signal Extraction Separate c→ and b→μ

[PLB 829 (2022) 137077]

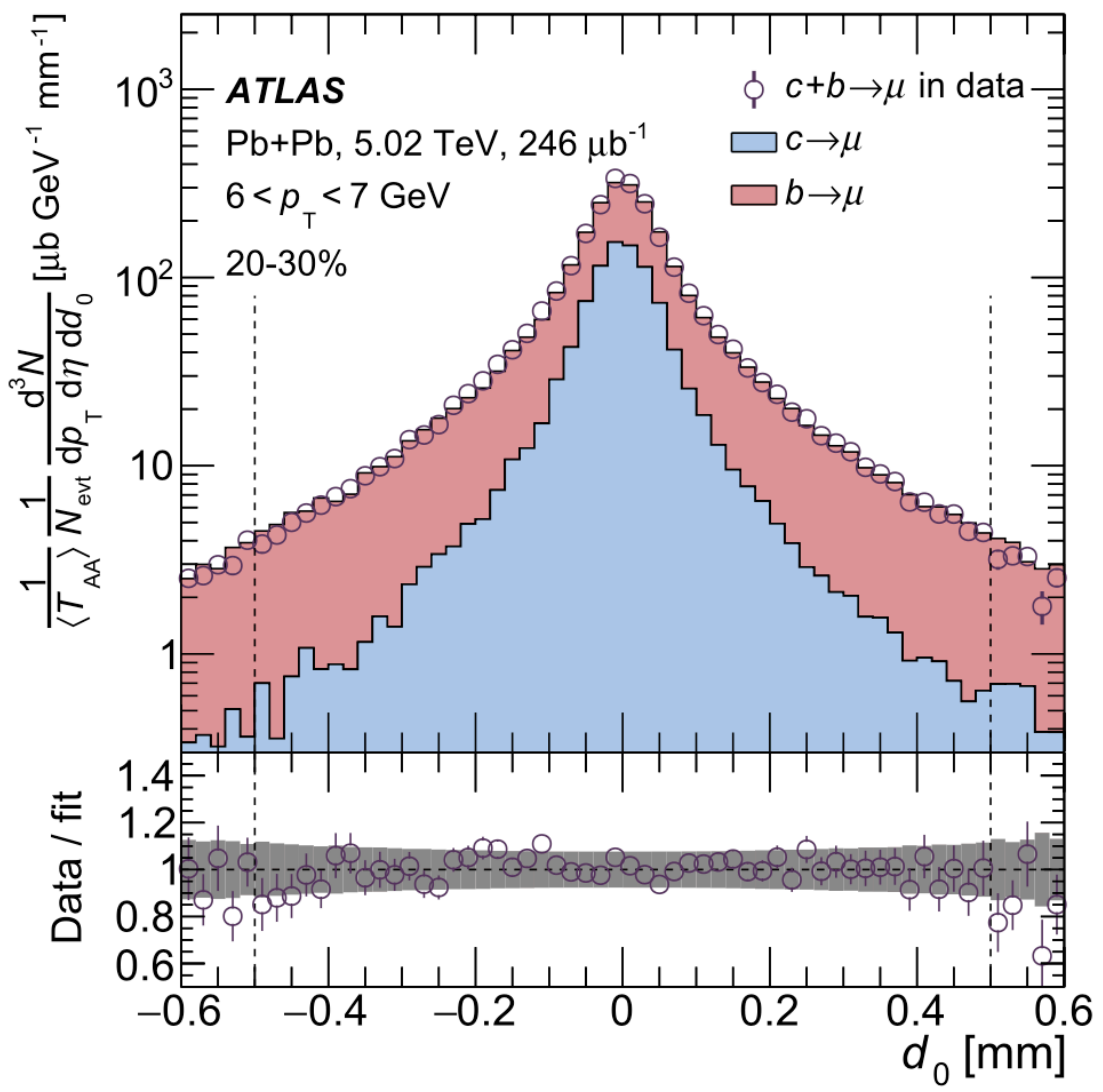


Template fit on **Variables** d_0 (Distance of Closest Approach DCA) relative to the beam spot (primary vertex sometimes)

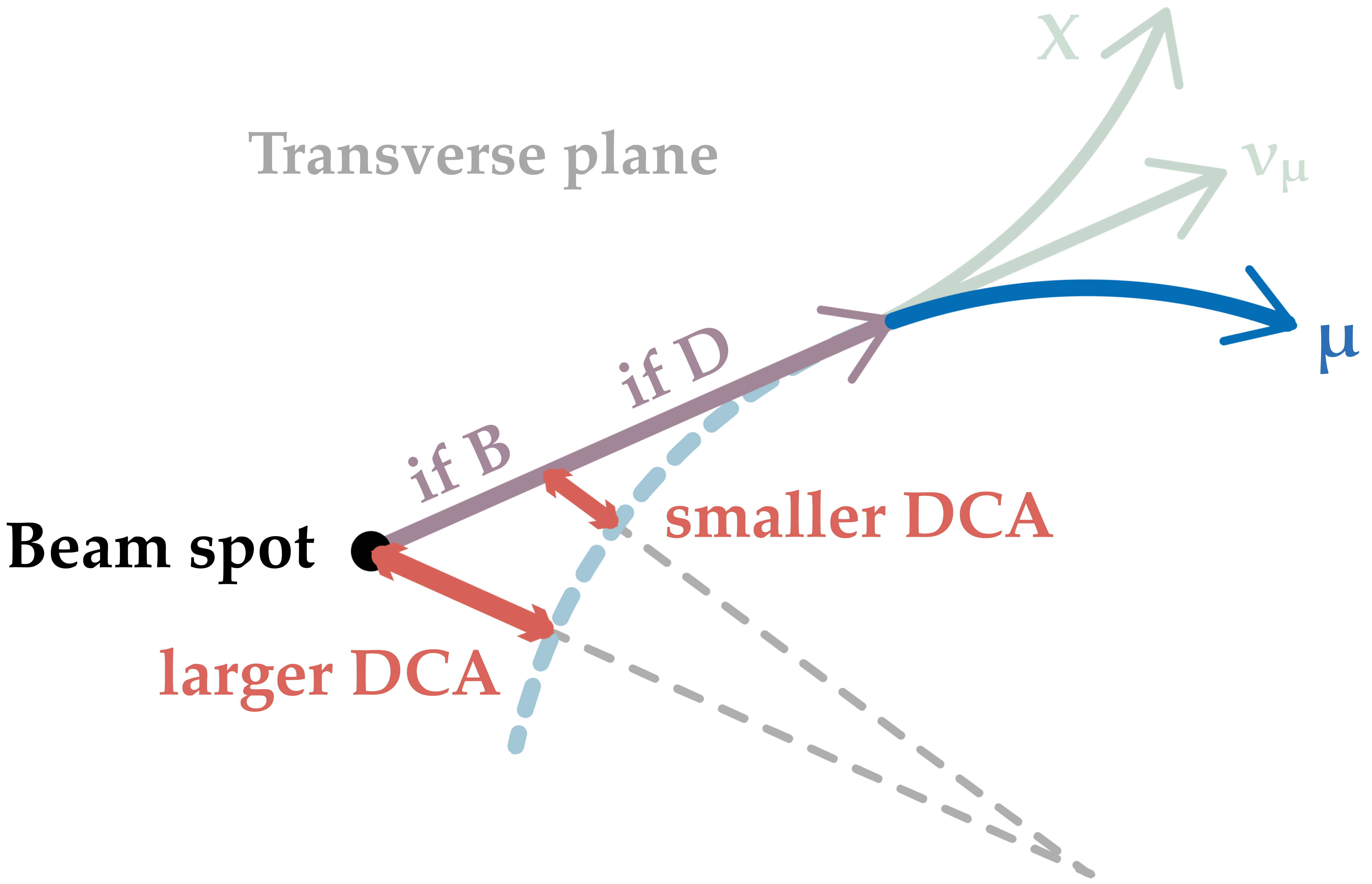


Signal Extraction Separate c→ and b→μ

[PLB 829 (2022) 137077]

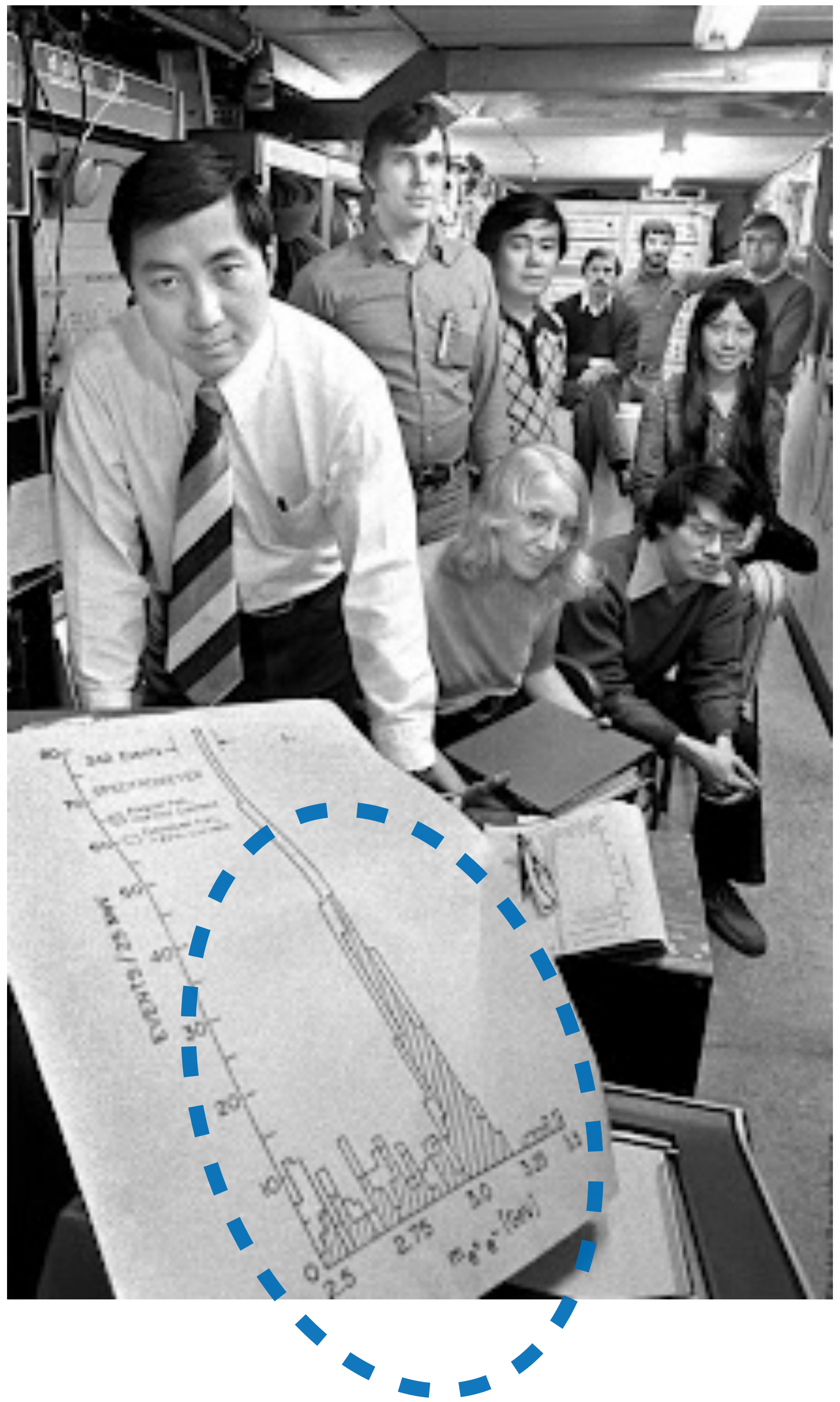


Template fit on **Variables** *d₀* (Distance of Closest Approach DCA) relative to the beam spot (primary vertex sometimes)



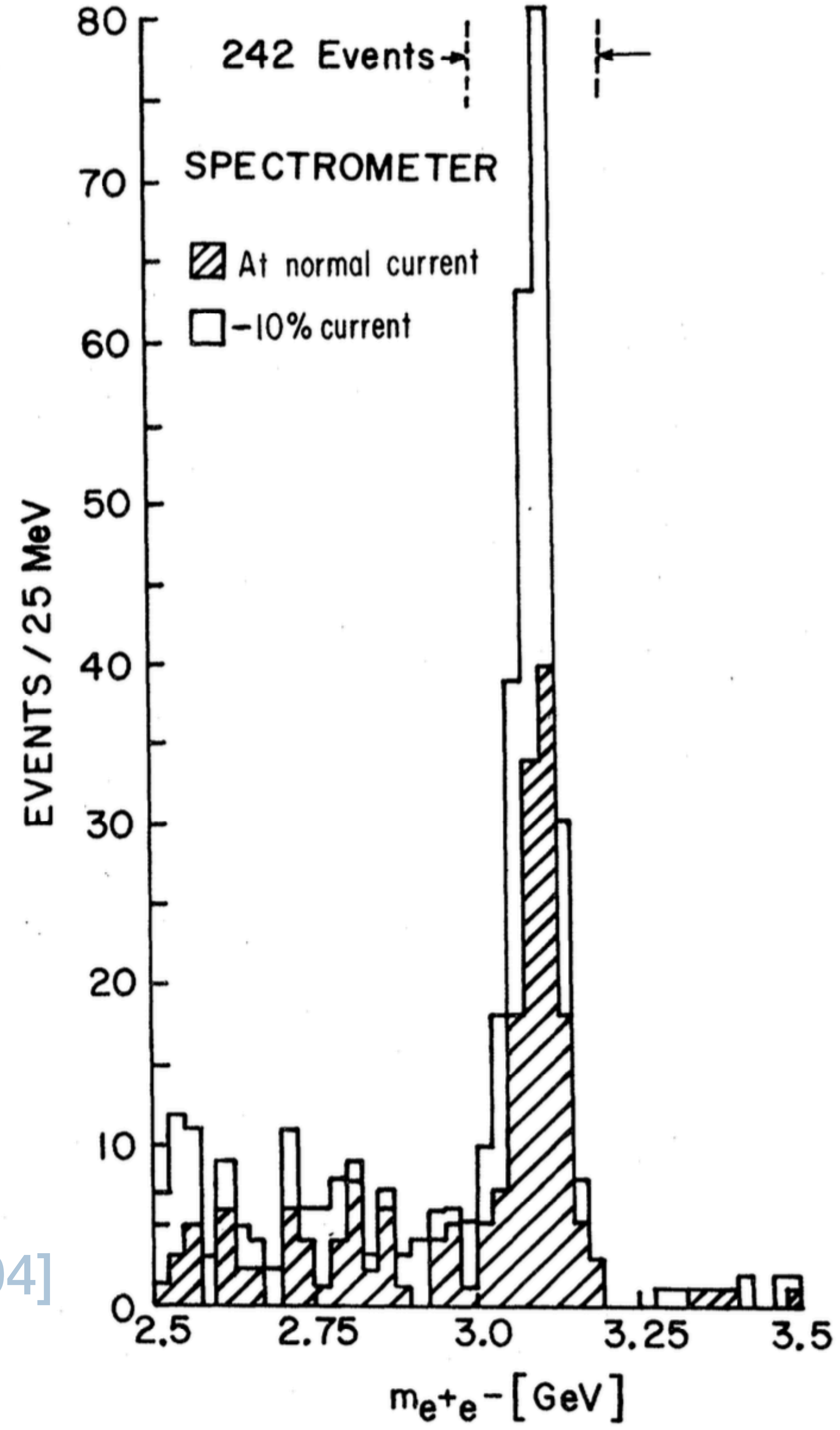
Signal Extraction Fully Reconstruction

Discovery of J/ψ



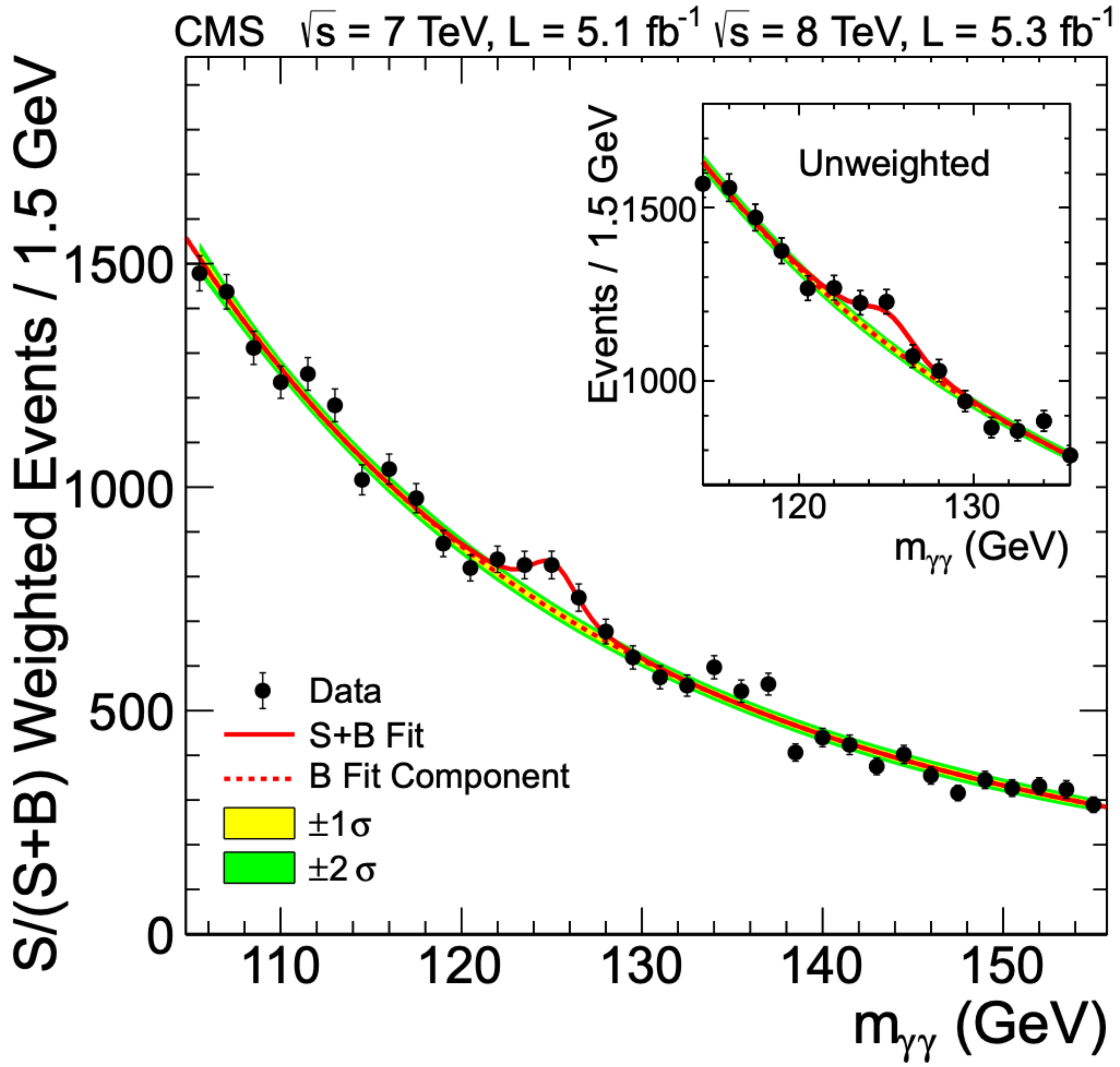
Fit on invariant mass

- Pair all the potential decay daughter particles in an event



[PRL 33 (1974) 1404]

Signal Extraction Fully Reconstruction



Discovery of Higgs boson

[PLB 716 (2012) 30]

Fit on invariant mass

- Determine decay channel, which need to balance
  - BR branching ratio
  - Purity signal to background ratio
  - Acceptance
  - Resolution

Signal Extraction Fully Reconstruction

Commonly used decay modes

$D^0 \rightarrow K^- \pi^+$	
$D^+ \rightarrow K^- \pi^+ \pi^+$	
$D_S^+ \rightarrow \phi\,(K^+ K^-)\,\pi^+$	
$D^{*+} \rightarrow D^0\,(K^- \pi^+)\,\pi^+$	
$\Lambda_c^+ \rightarrow p\,K^- \pi^+$	larger BR
$\Lambda_c^+ \rightarrow p\,K_s^0\,(\pi^+ \pi^-)$	K_s improves purity
$B^+ \rightarrow J/\psi\,(\mu^+\mu^-)\,K^+$	
$B^+ \rightarrow \bar{D}^0\,(K^+ \pi^-)\,\pi^+$	
$B^0 \rightarrow J/\psi\,(\mu^+\mu^-)\,K_s^0\,(\pi^+ \pi^-)$	
$B^0 \rightarrow D^-\,(K^+ \pi^- \pi^-)\,\pi^+$	
$B_S^0 \rightarrow J/\psi\,(\mu^+\mu^-)\,\phi\,(K^+ K^-)$	
$\Lambda_b^0 \rightarrow \Lambda_c^+\,(p\,K^- \pi^+)\,\pi^-$	

Fit on invariant mass

- Determine decay channel, which need to balance
  - BR branching ratio
  - Purity signal to background ratio
    - intermediate resonance improves purity
  - Acceptance
  - Resolution

Signal Extraction Fully Reconstruction

Commonly used decay modes

$D^0 \to K^- \pi^+$

$D^+ \to K^- \pi^+ \pi^+$

$D_S^+ \to \phi\,(K^+ K^-)\,\pi^+$

$D^{*+} \to D^0\,(K^- \pi^+)\,\pi^+$

$\Lambda_c^+ \to p\,K^- \pi^+$

$\Lambda_c^+ \to p\,K_s^0\,(\pi^+ \pi^-)$

$B^+ \to J/\psi\,(\mu^+\mu^-)\,K^+$ lower background

$B^+ \to \bar{D}^0\,(K^+ \pi^-)\,\pi^+$ better acceptance

$B^0 \to J/\psi\,(\mu^+\mu^-)\,K_s^0\,(\pi^+ \pi^-)$

$B^0 \to D^-\,(K^+ \pi^- \pi^-)\,\pi^+$

$B_S^0 \to J/\psi\,(\mu^+\mu^-)\,\phi\,(K^+ K^-)$

$\Lambda_b^0 \to \Lambda_c^+\,(p\,K^- \pi^+)\,\pi^-$

Fit on invariant mass

- Determine decay channel, which need to balance
  - BR branching ratio
  - Purity signal to background ratio
    - intermediate resonance improves purity
    - more daughters have worse purity
    - lepton channels lower combinatorial background
  - Acceptance *e.g.*
    - muons difficult to access low p_T at mid rapidity
  - Resolution

Signal Extraction Fully Reconstruction

Commonly used decay modes

$D^0 \rightarrow K^- \pi^+$	
$D^+ \rightarrow K^- \pi^+ \pi^+$	
$D_s^+ \rightarrow \phi (K^+ K^-) \pi^+$	
$D^{*+} \rightarrow D^0 (K^- \pi^+) \pi^+$	
$\Lambda_c^+ \rightarrow p K^- \pi^+$	
$\Lambda_c^+ \rightarrow p K_s^0 (\pi^+ \pi^-)$	
$B^+ \rightarrow J/\psi (\mu^+ \mu^-) K^+$	
$B^+ \rightarrow \bar{D}^0 (K^+ \pi^-) \pi^+$	
$B^0 \rightarrow J/\psi (\mu^+ \mu^-) K_s^0 (\pi^+ \pi^-)$	
$B^0 \rightarrow D^- (K^+ \pi^- \pi^-) \pi^+$	
$B_s^0 \rightarrow J/\psi (\mu^+ \mu^-) \phi (K^+ K^-)$	
$\Lambda_b^0 \rightarrow \Lambda_c^+ (p K^- \pi^+) \pi^-$	

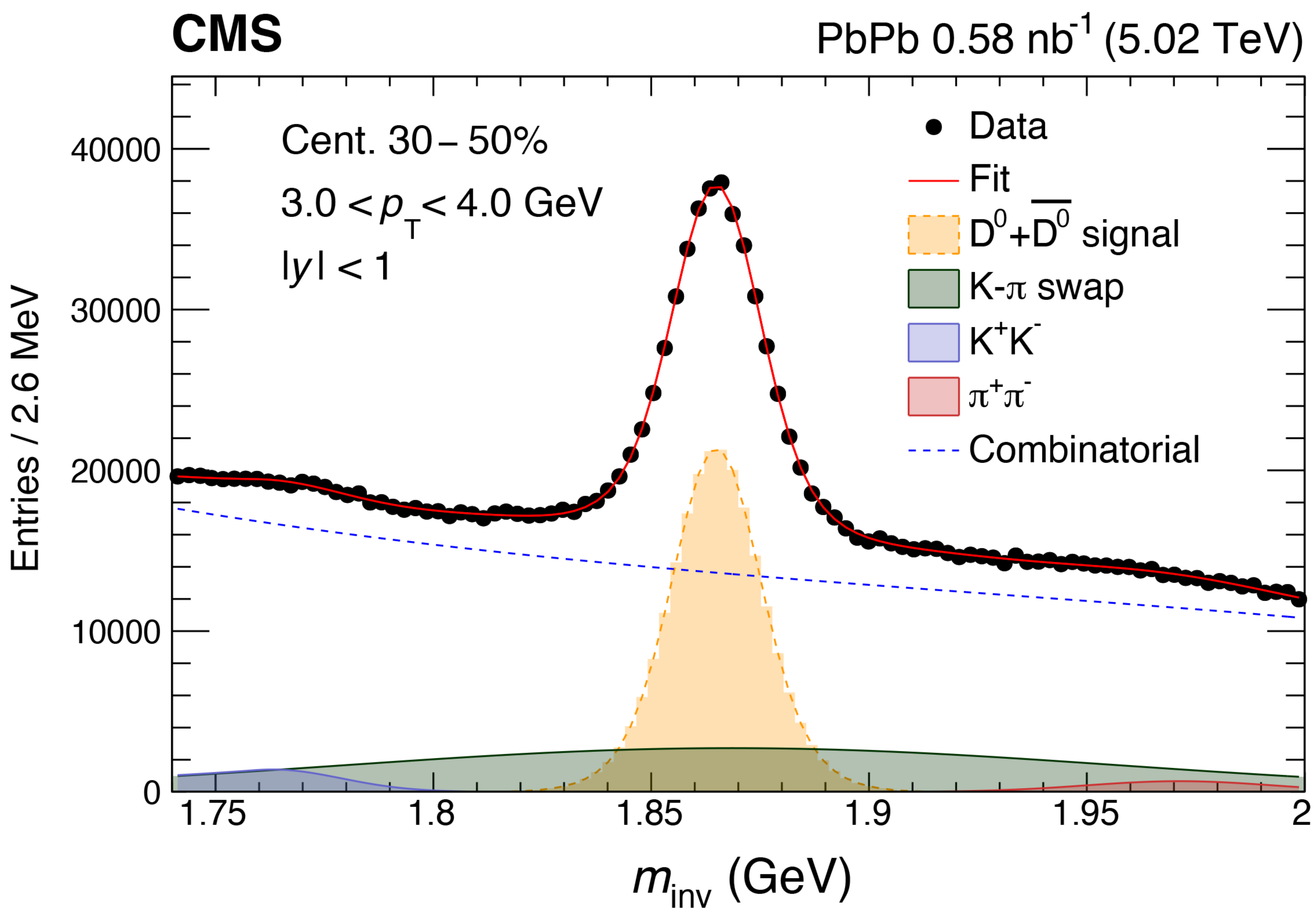
Fit on invariant mass

- Determine decay channel, which need to balance
  - BR branching ratio
  - Purity signal to background ratio
    - intermediate resonance improves purity
    - more daughters have worse purity
    - lepton channels lower combinatorial background
  - Acceptance *e.g.*
    - muons difficult to access low p_T at mid rapidity
  - Resolution

- Determine templates
  - Identify potential peaky background

Invariant Mass Fit $D^0 \to K\pi$ as Example

[PRL 129 (2022) 022001]



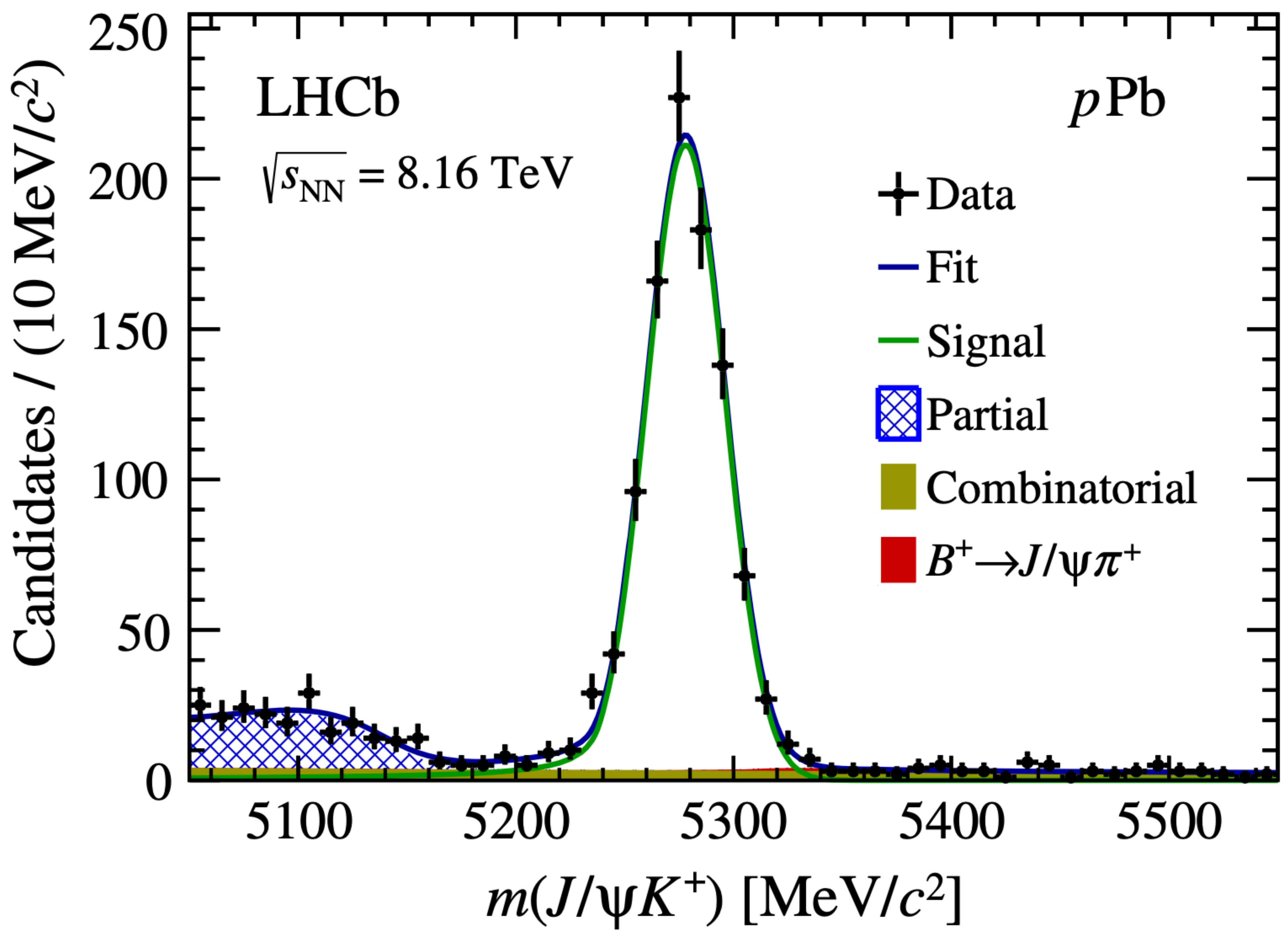
- Signal shape width reflects track momentum resolution
- Combinatorial randomly pairing two opposite-sign tracks
  - Likelihood ratio test degree of freedom needs to balance fitting performance and overfitting
- Peaky background
  - K-π swap $D^0 \to K\pi$ is reco-ed but the mass assignment is swapped
  - KK and ππ $D^0 \to KK/\pi\pi$ is reco-ed as $D^0 \to K\pi$

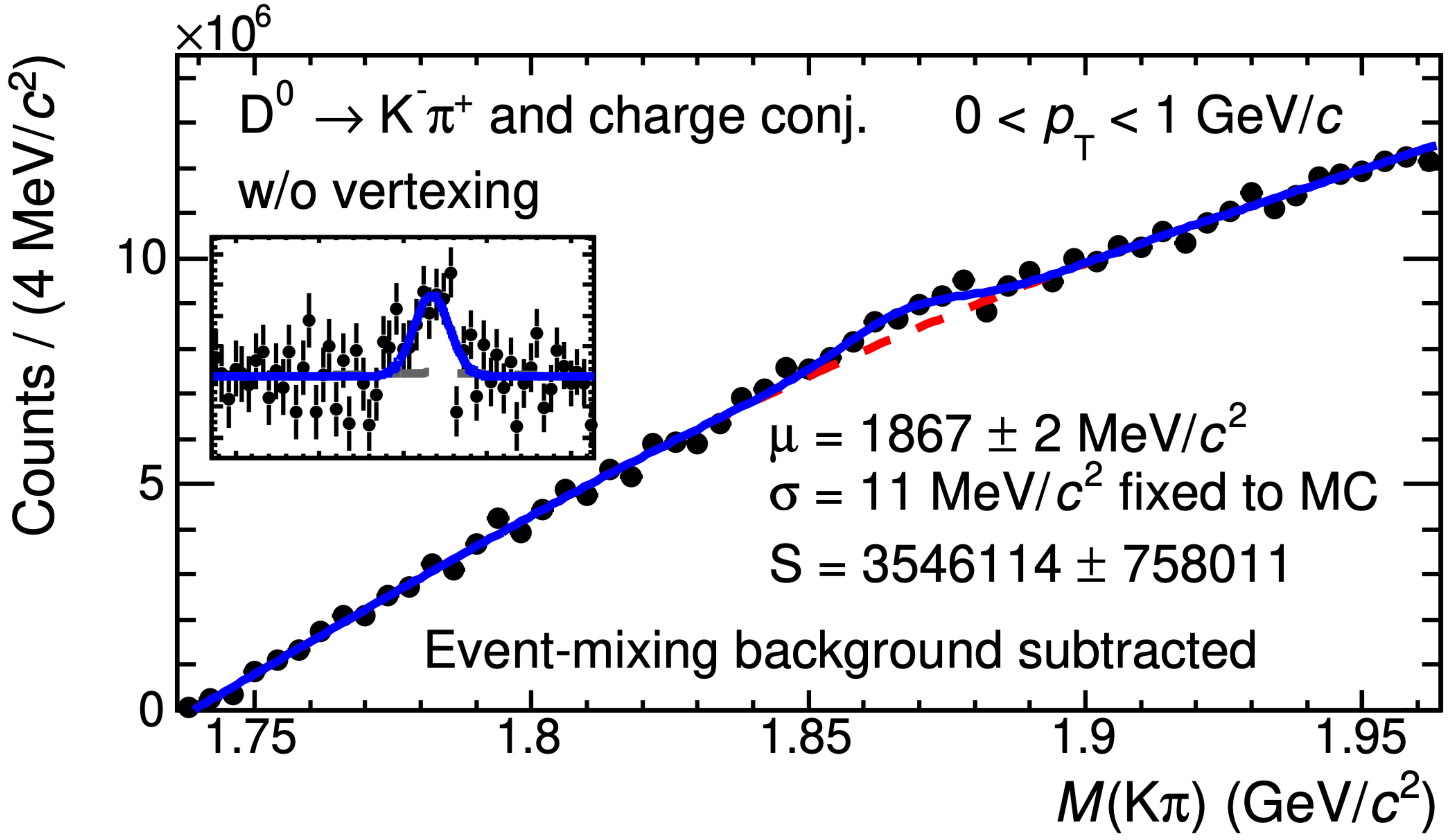
Invariant Mass Fit Extension

[PRD 99 (2019) 052011]

Extension for homework

[JHEP 01 (2022) 174]



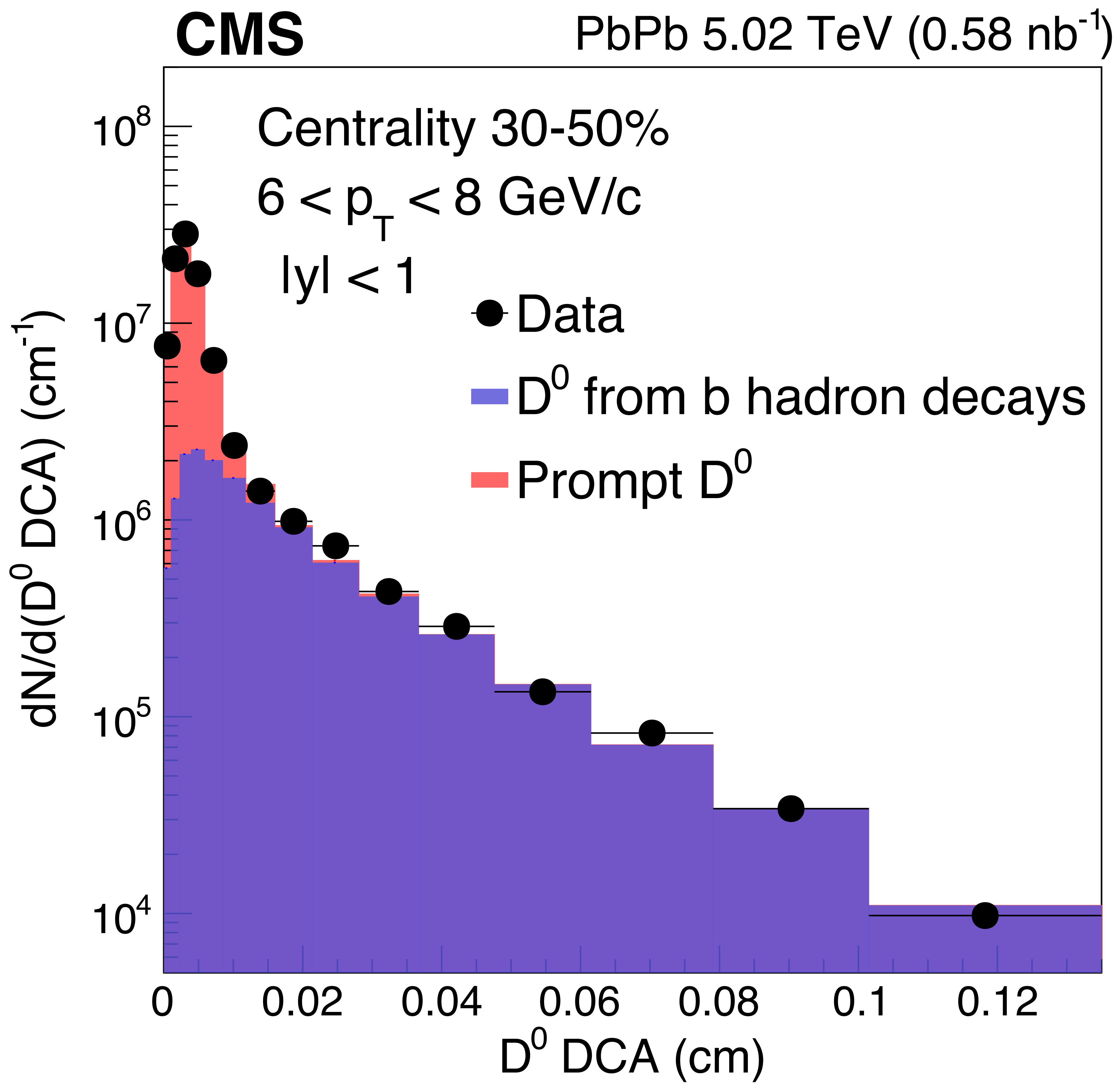


- What peaky backgrounds for $B^+ \to J/\psi K^+$?
- What functions are used to model each component?

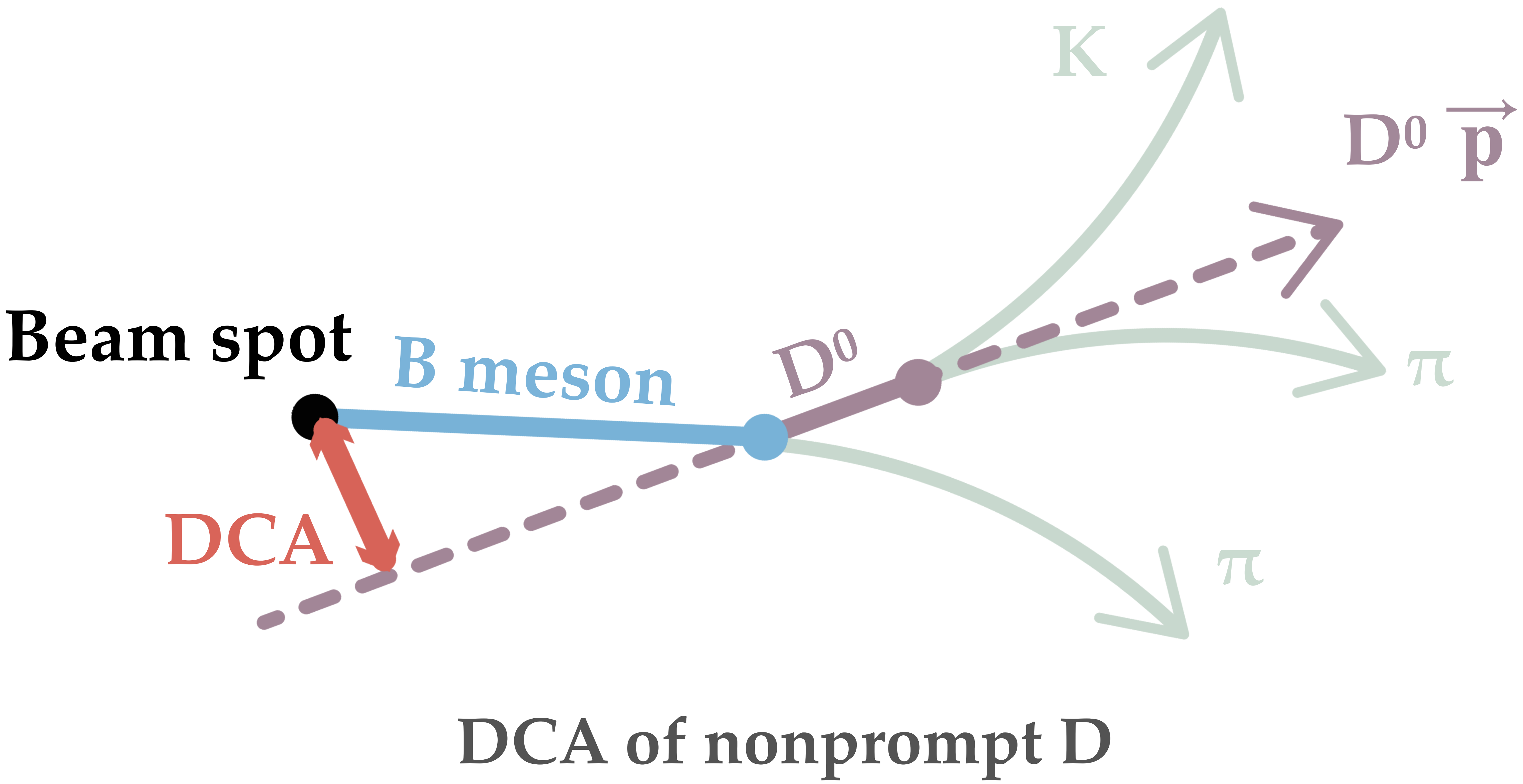
- What is the event-mixing technique used to achieve measurements down to 0 p_T by ALICE

Separate Prompt and Nonprompt D mesons

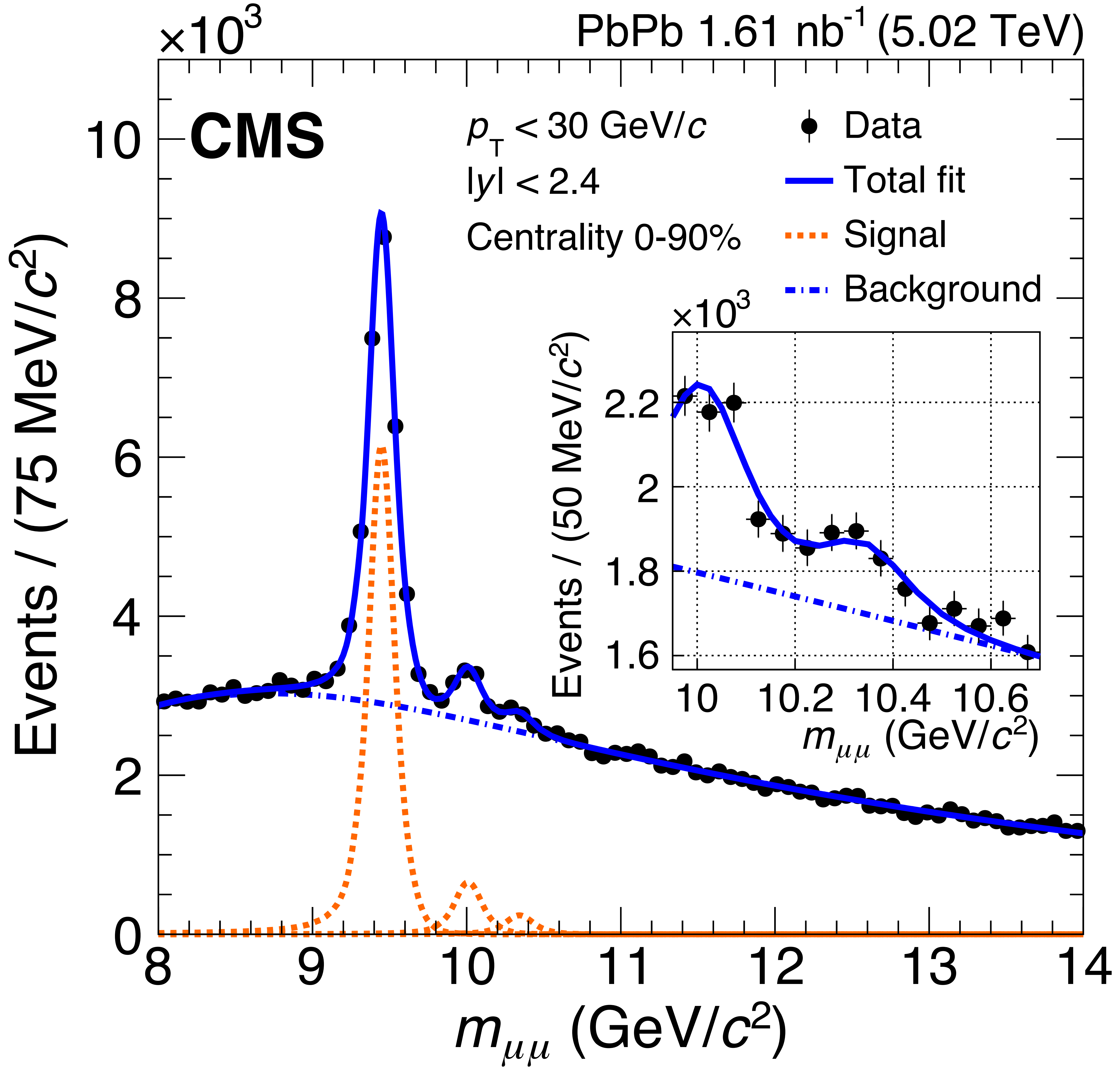
[PLB 850 (2024) 138389]



- Template fits on D meson DCA
  - DCA ~ 0 for prompt D
  - Large DCA for nonprompt D



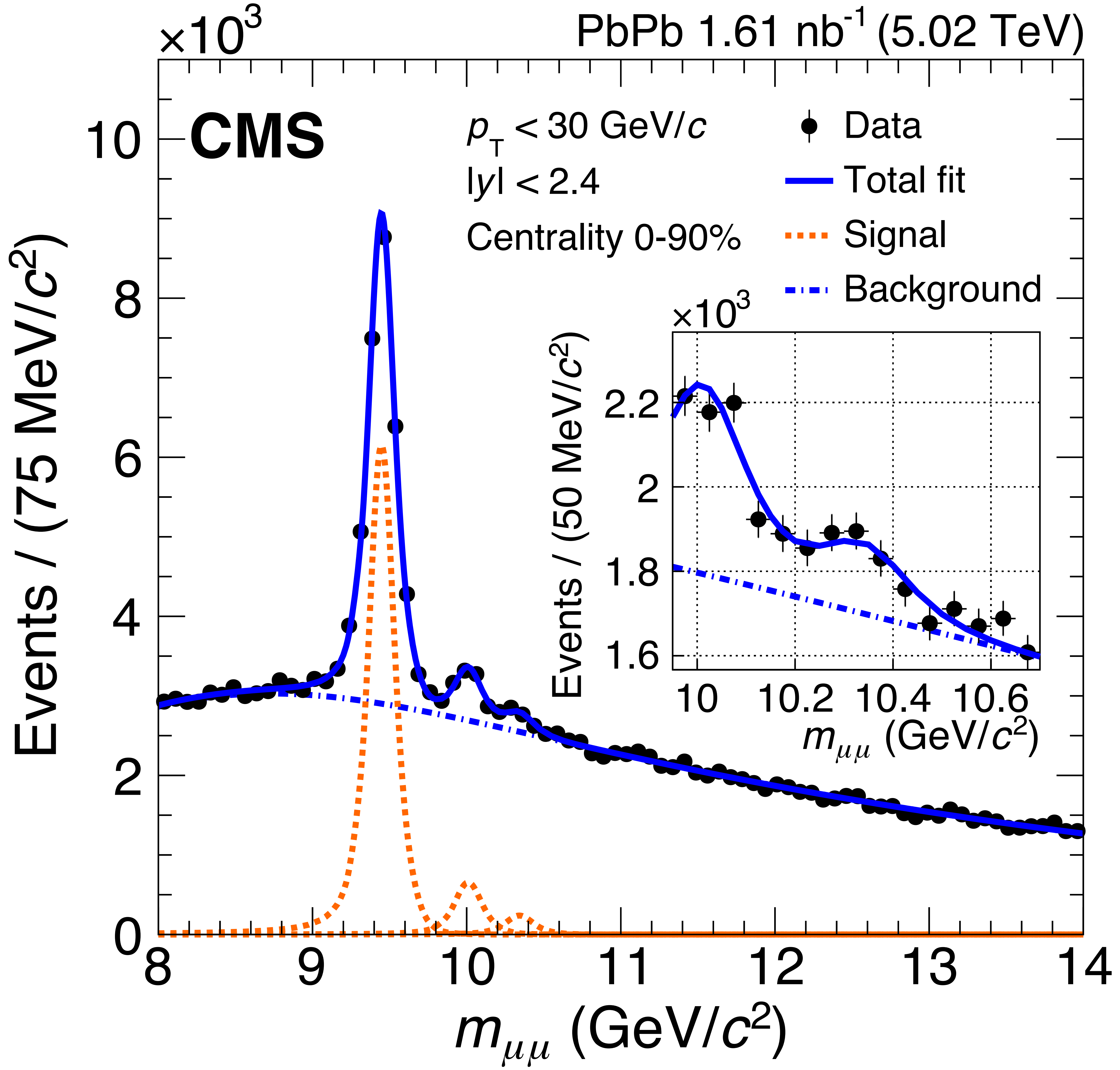
Yield Extraction Excited State Quarkonia



- Mass resolution is critical to separate excited states
  - Require ~100 MeV resolution to separate Υ(2S) and Υ(3S)

[2303.17026]

Yield Extraction Excited State Quarkonia



[2303.17026]

- For a pair of particles with same decay mode, commonly use yield ratio, e.g.

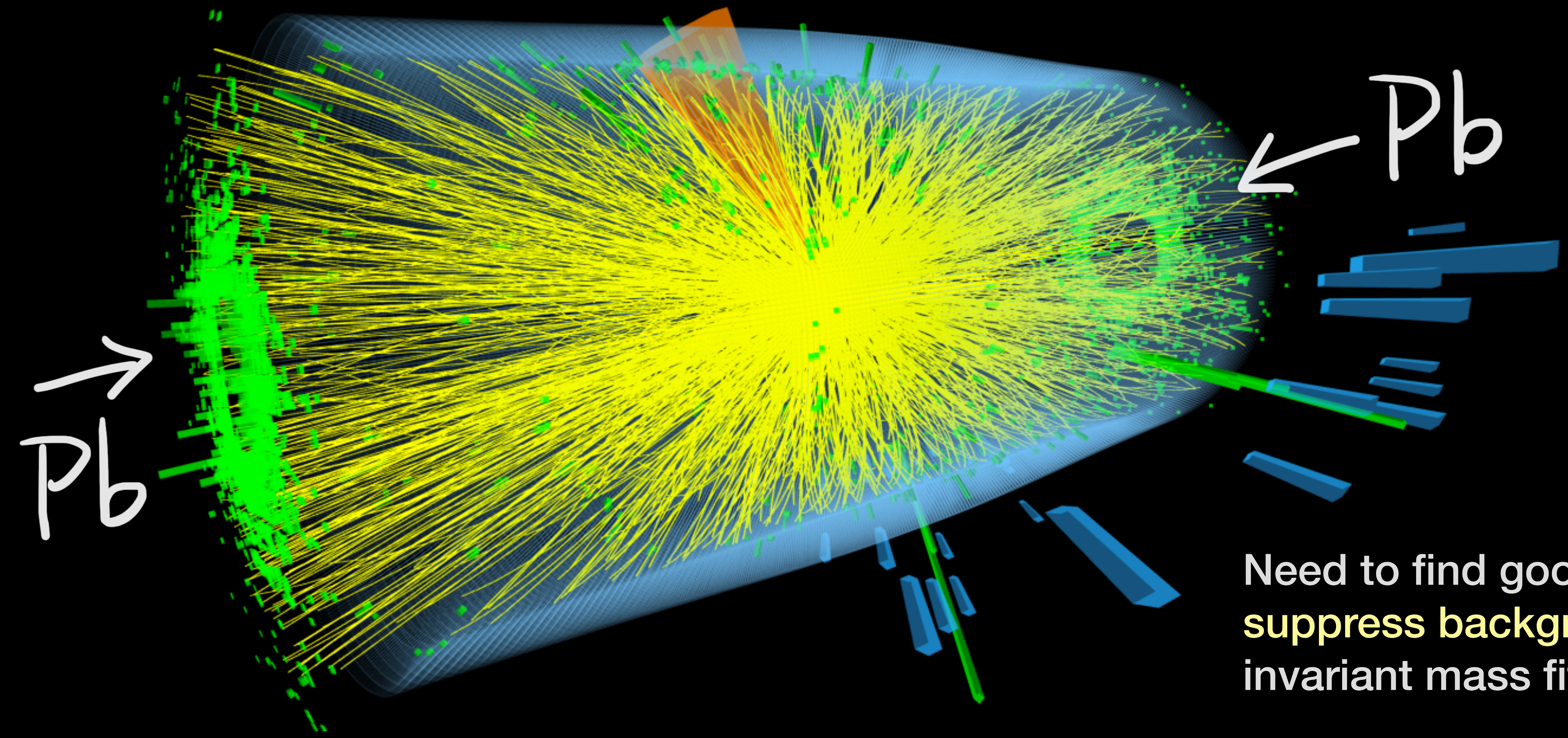
$$\sigma_{(2S)\to\mu\mu} = \left(\frac{N_{(2S)\to\mu\mu}}{N_{(1S)\to\mu\mu}}\right)\sigma_{(1S)\to\mu\mu}$$

to measure the low-stat particle

  - avoid systematics convoluted with statistics for low-stat particle if they can be canceled in ratio
    - muon efficiency & resolution for Y(nS)→μμ

Huge Combinatorial Background in HIC

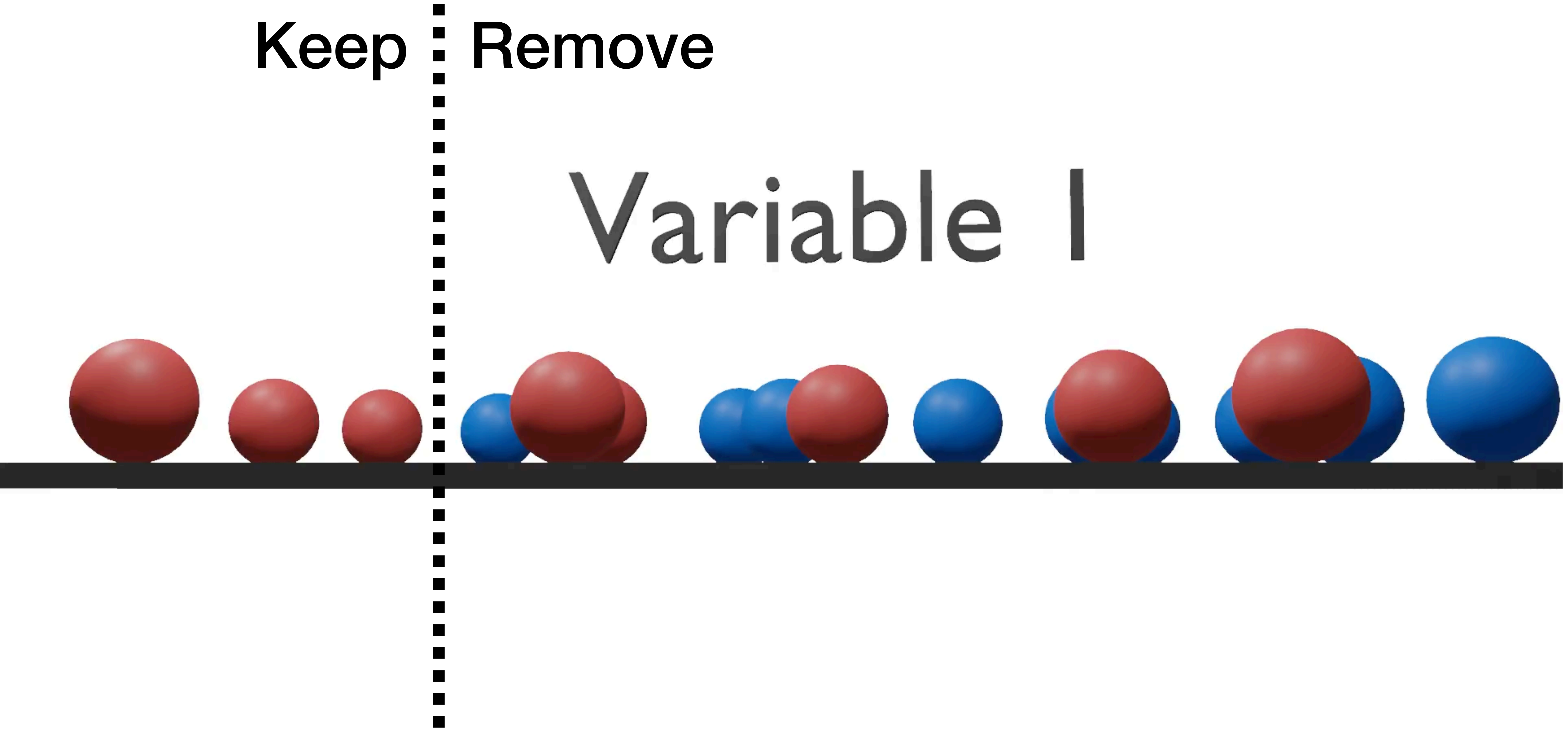
Up to O(10^4) final-state particles in a central heavy-ion event

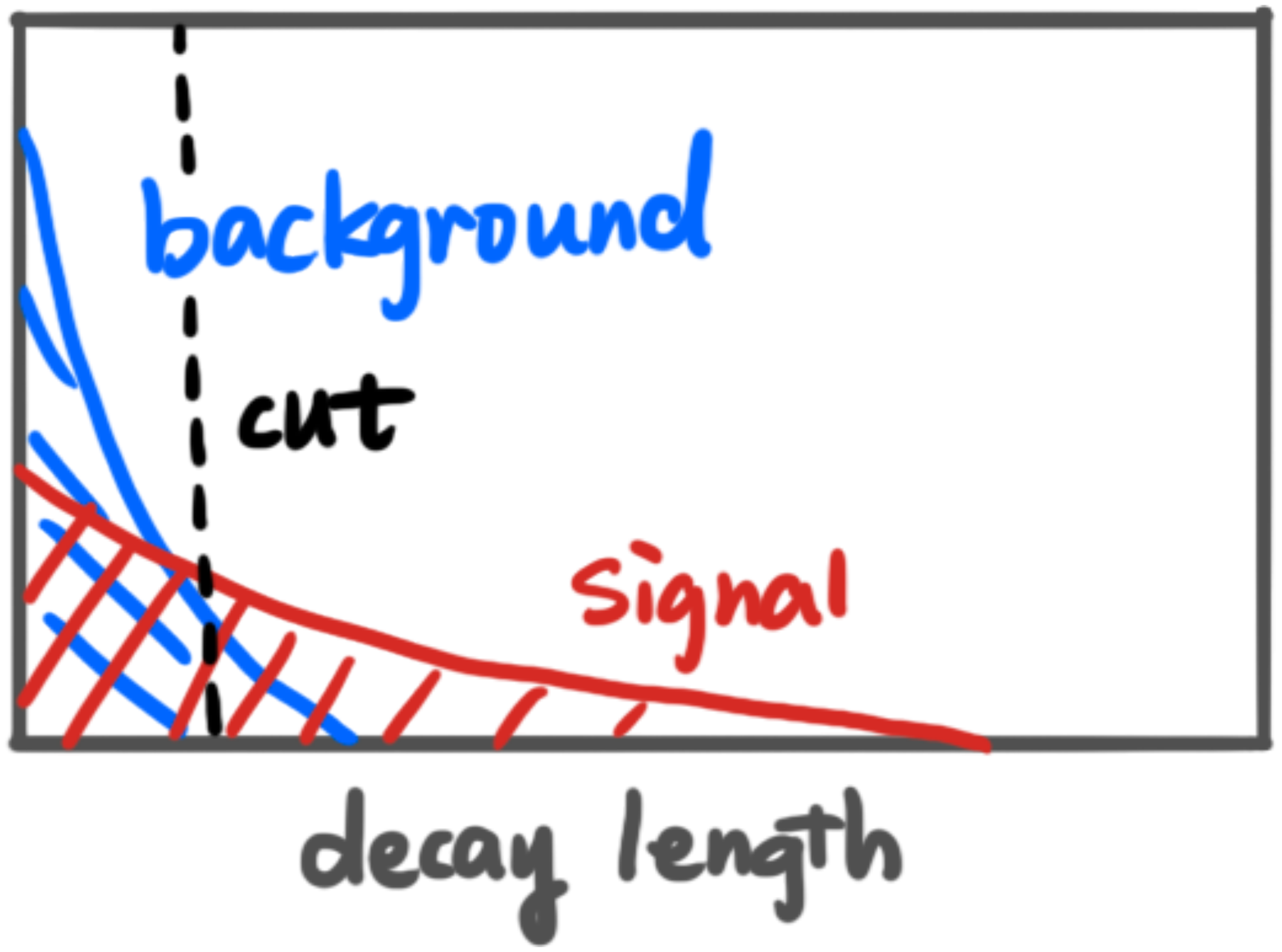


Need to find good selections to suppress backgrounds first before invariant mass fits

Suppress Background Multivariate Classification

If want to keep red and remove blue balls…





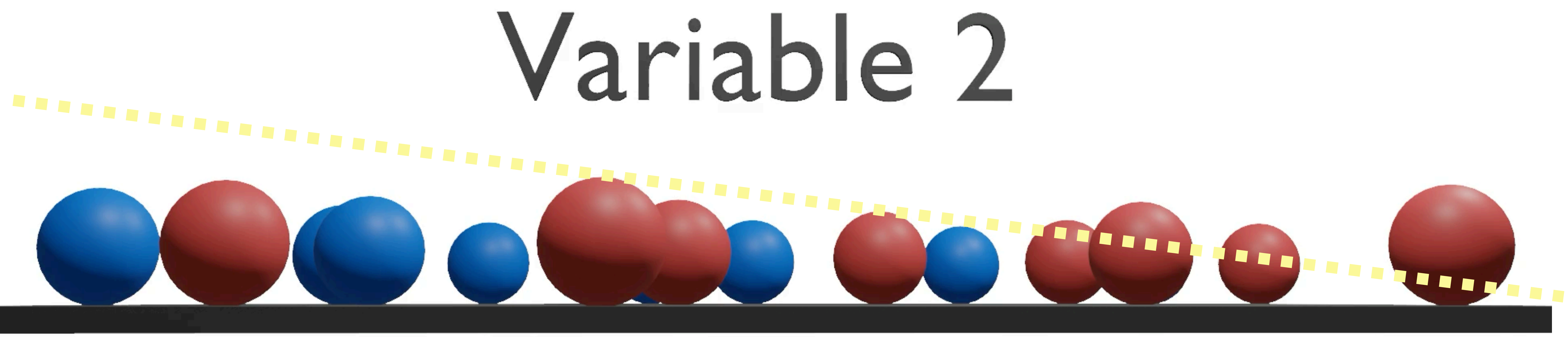
Some variables can separate signals and backgrounds to a certain extent

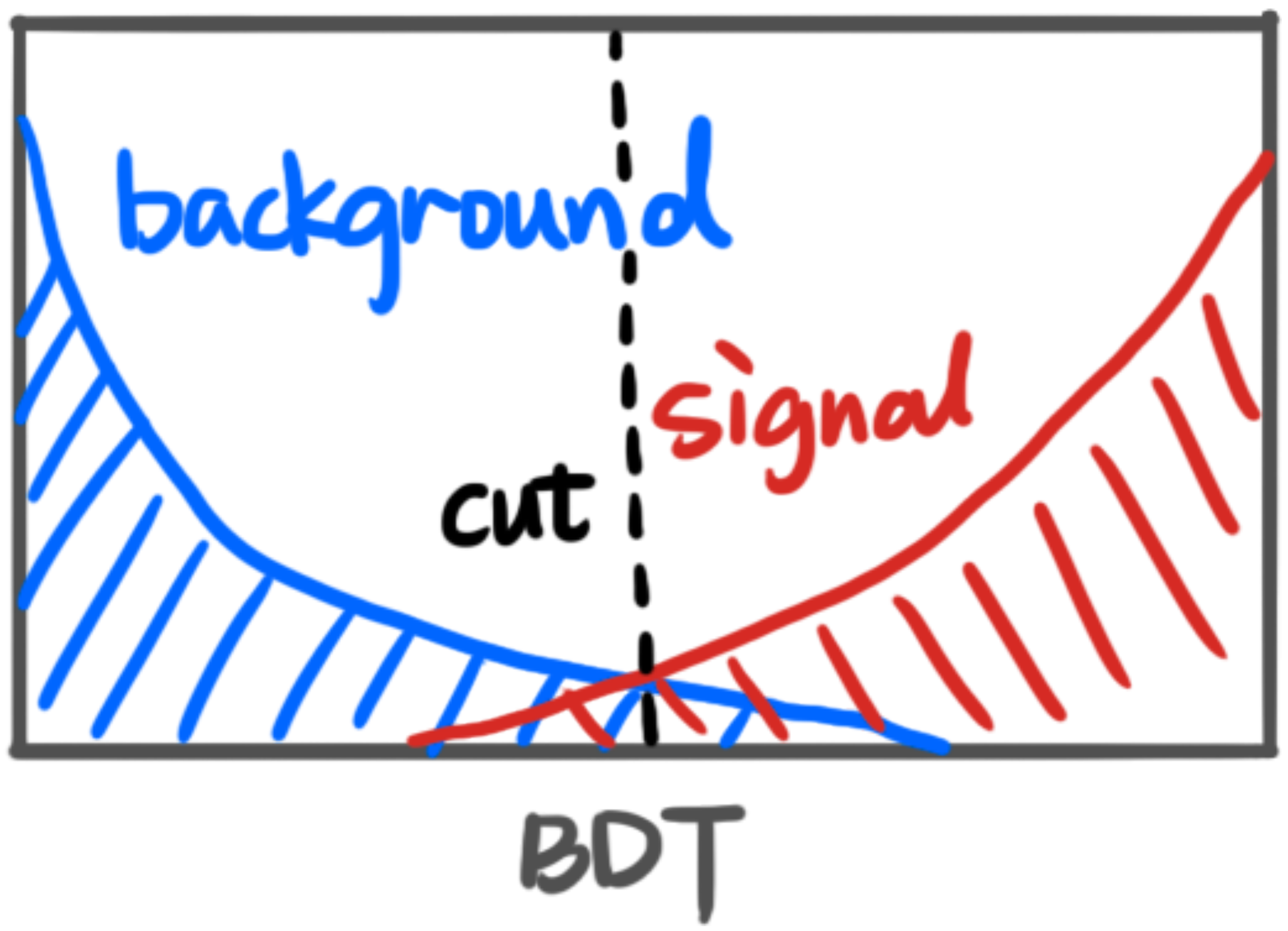
- Decay length significance
- Secondary vertex probability
- Pointing angles
- …

[Animation]

Suppress Background Multivariate Classification

If want to keep red and remove blue balls…

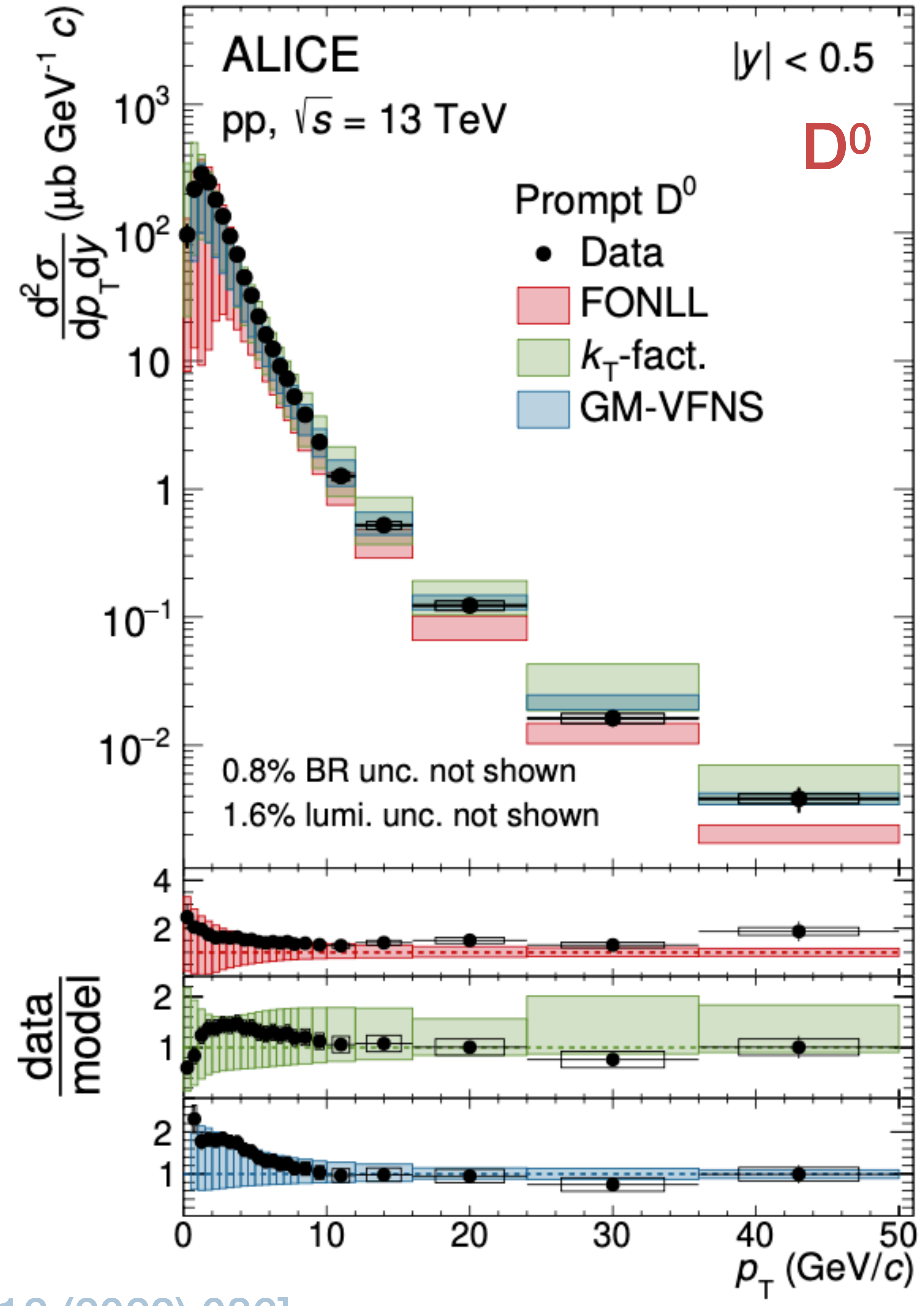




Combining multi variables in a smart way separate backgrounds and signals better → where ML can help

[Animation]

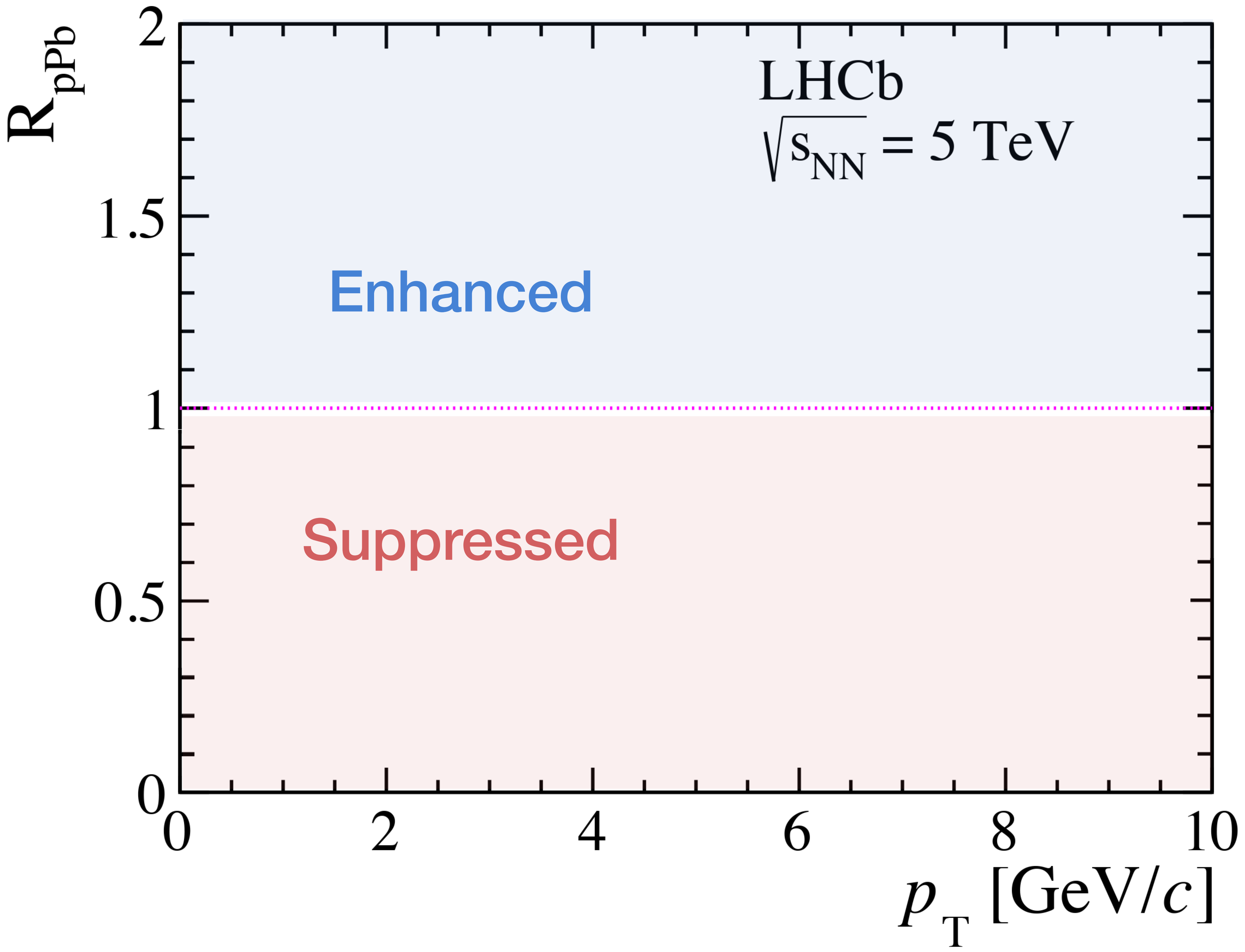
Initial Production pQCD Test



[JHEP 12 (2023) 086]

- Measurements can be described by pQCD calculations with sizable theoretical uncertainty at low p_T
- Different factorization schemes
  - FONLL Fixed-Order plus Next-to-Leading Logs [website]
- Dominant theoretical uncertainties
  - Factorization and renormalization scale, PDF
  - Can be constrained by high-precision measurements
    - Simultaneous constraints by varying collision energy and rapidity

Initial Production Nuclear Modification



Is initial production in A-A collisions just superposition of nucleon-nucleon collisions?

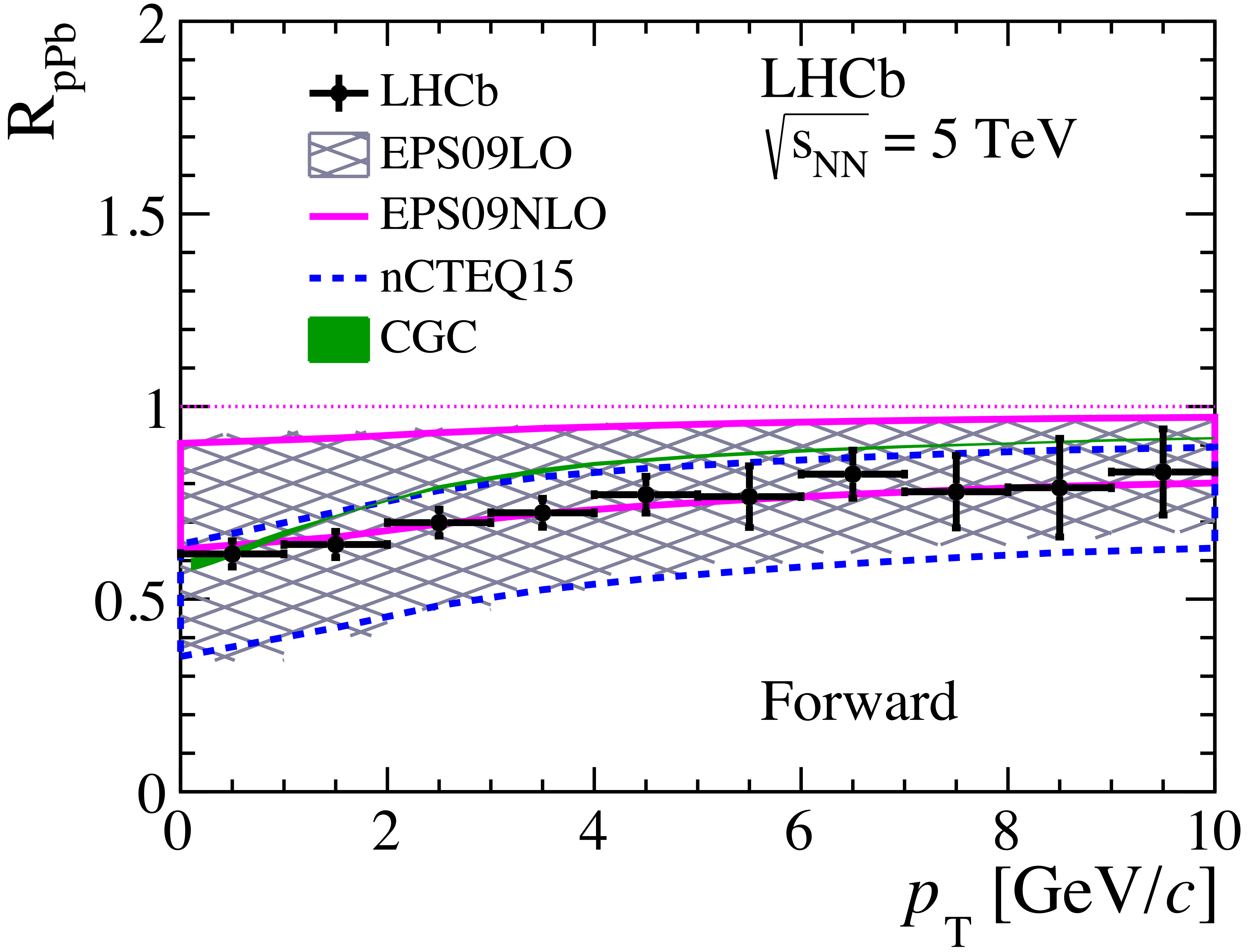
- p-A collisions to test these kind of effects
  - Ion as collision particles
  - No medium effect expected
- Observable of particle yield modification in pA collisions compared to pp

$$R_{pA} = \frac{d\sigma_{pA}/dp_T}{A\, d\sigma_{pp}/dp_T} \quad \begin{matrix} \leftarrow \text{pA} \\ \leftarrow \text{pp} \end{matrix}$$

  - R_{pA} should be 1 in the naive picture above

Initial Production Nuclear PDF

Forward D^0 R_{pPb}

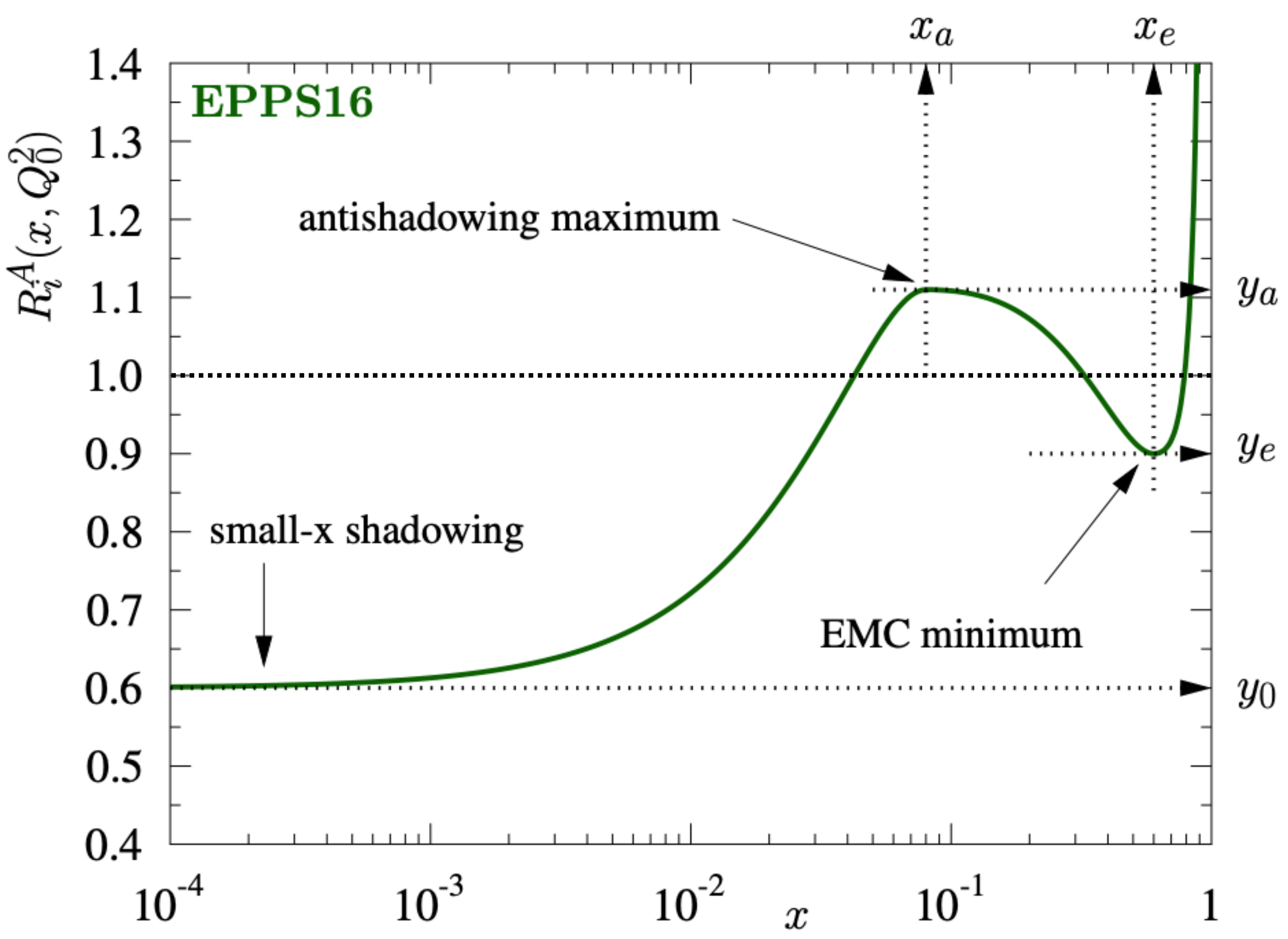


[JHEP 10 (2017) 090]

- D^0 suppressed at low p_T in forward rapidity in pA
  - Nuclear PDF model can describe it
    Nucleons in ions have different PDF from free protons
- nPDF is common input for theoretical calculations
  Not limited to heavy flavors
  - constrained by different probes, among them
  - heavy flavors are important probes for gluon nPDF
  - gluon nPDF is one of the poorest constrained

Initial Production Nuclear PDF

Illustration of nPDF / proton PDF
Parton Distribution Function



[EPJC 77 (2017) 163]

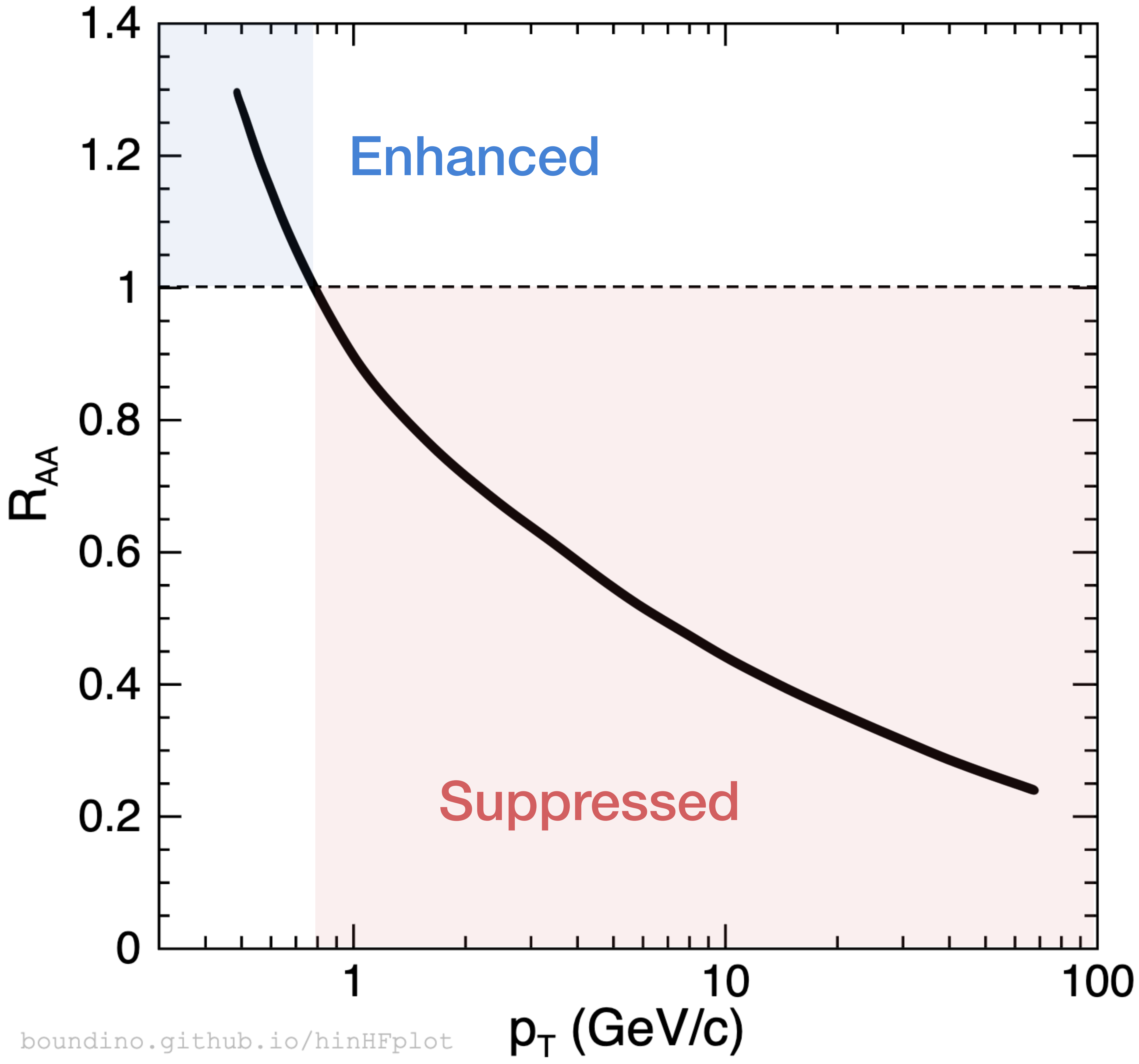
- For low-p_T D mesons in A-A collisions

$$x \sim 2\frac{\sqrt{(m_D^2 + p_T^2)}}{\sqrt{s_{NN}}}e^{-y}$$

  - $x \sim 10^{-3}$-10^{-2} for mid-rapidity
  - mix of $x \sim 10^{-5}$-10^{-4} and $x \sim 10^{-2}$-10^{-1} for LHCb rapidity

- In most cases for HF hadrons, nPDF leads to
  - suppression at low p_T shadowing
  - mild enhancement at very high p_T anti-shadowing

Nuclear Modification Factor R_{AA} in AA Collisions



Recall

Nuclear modification factor R_{AA}

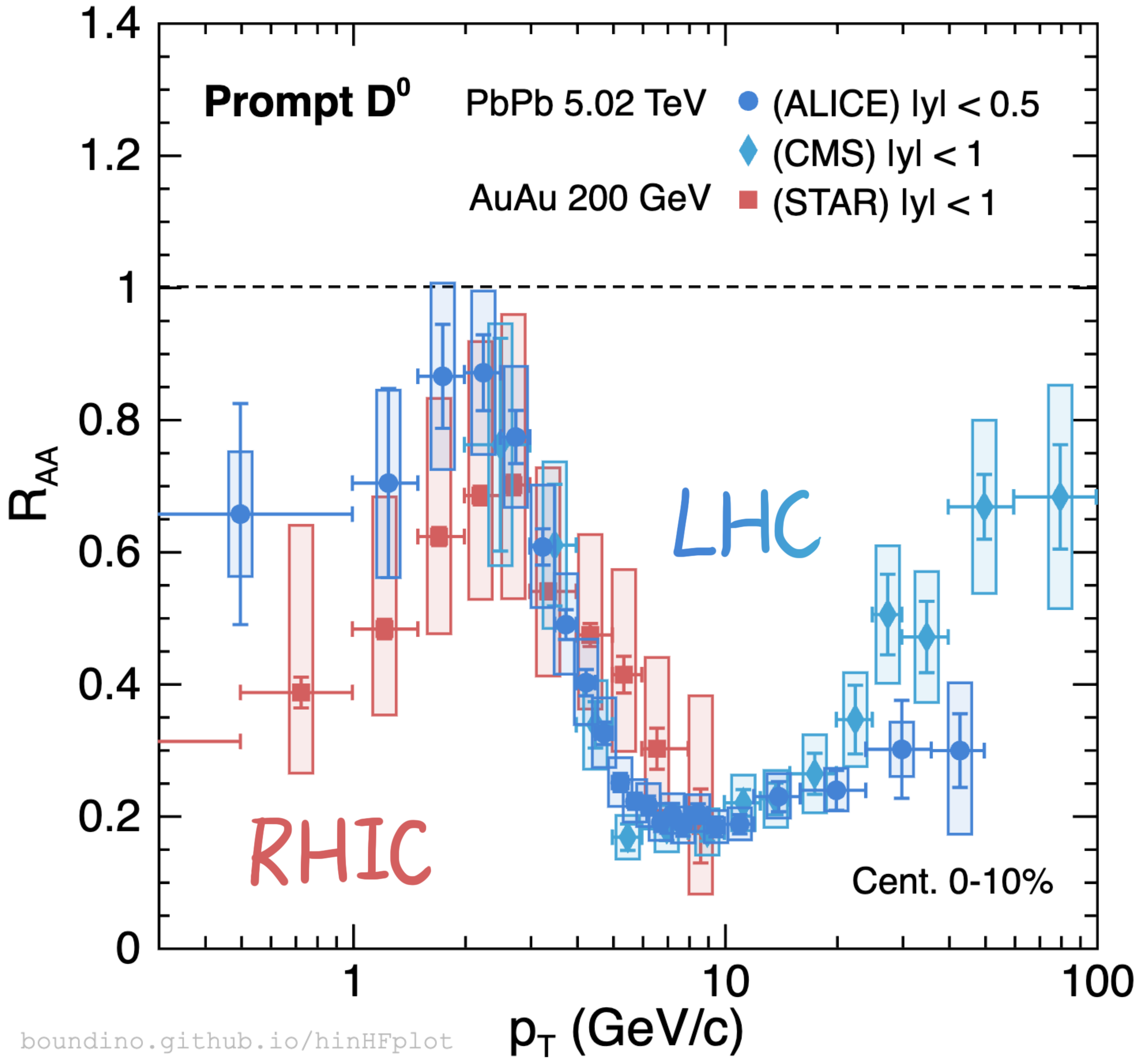
R_{AA} =1: superposition of nucleon-nucleon collisions

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

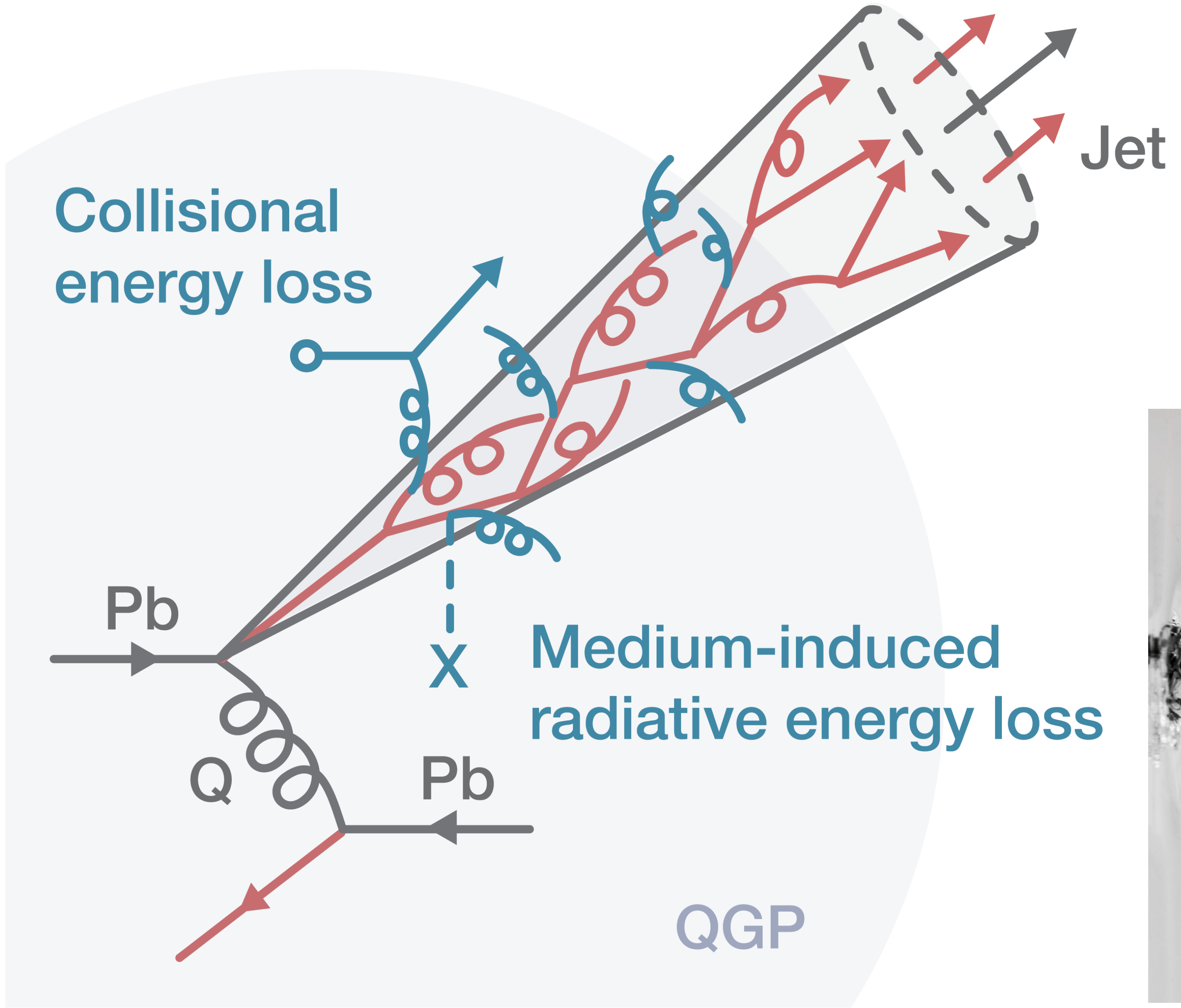
← Heavy-ion

← pp

Nuclear Modification R_{AA} D^0 Mesons



- Prompt D^0 suppression in wide kinematics
  - Charm quark lose energy in QGP via collisions low p_T and radiations high p_T

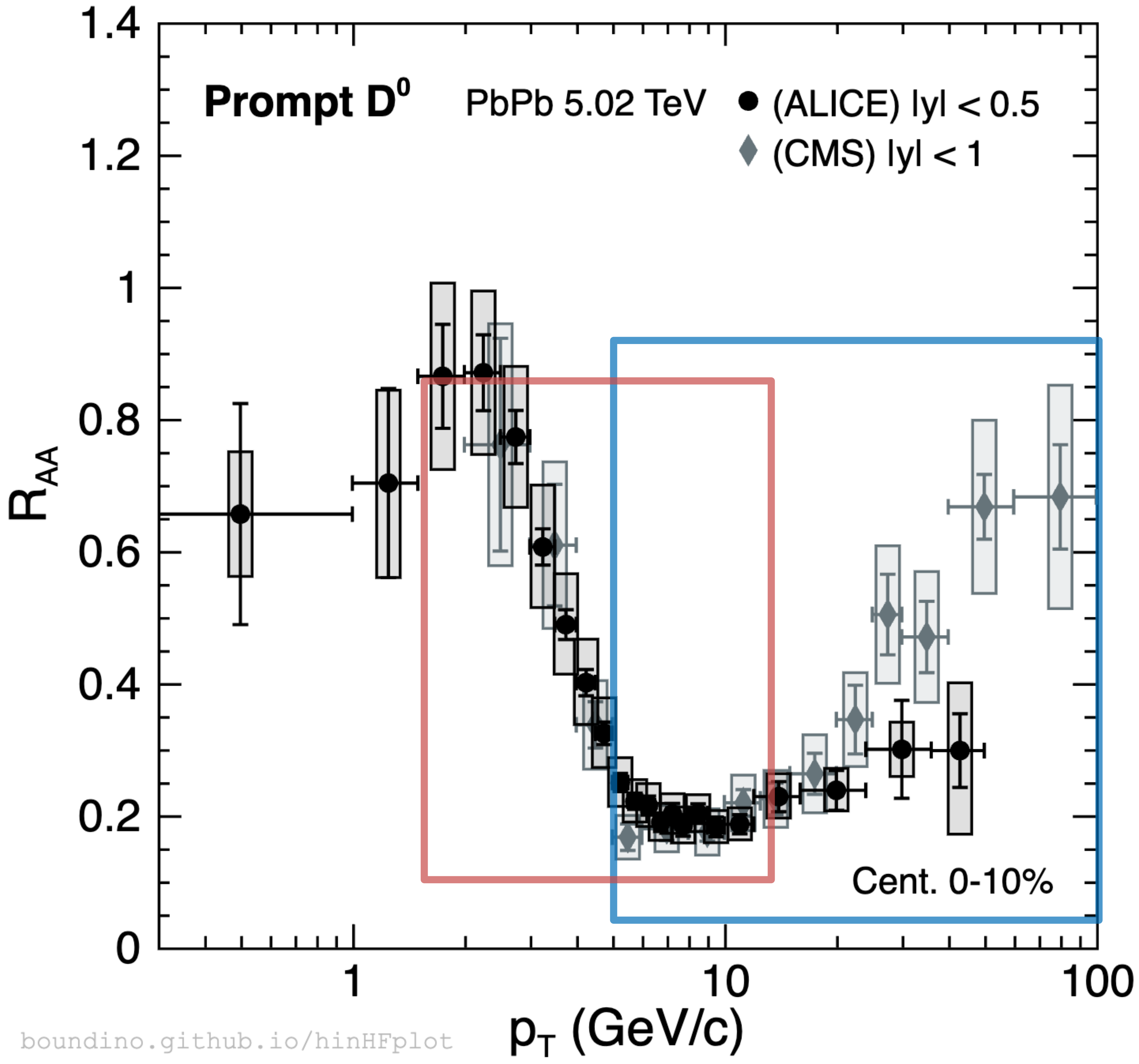


Energy loss of hard parton in QGP in pQCD picture

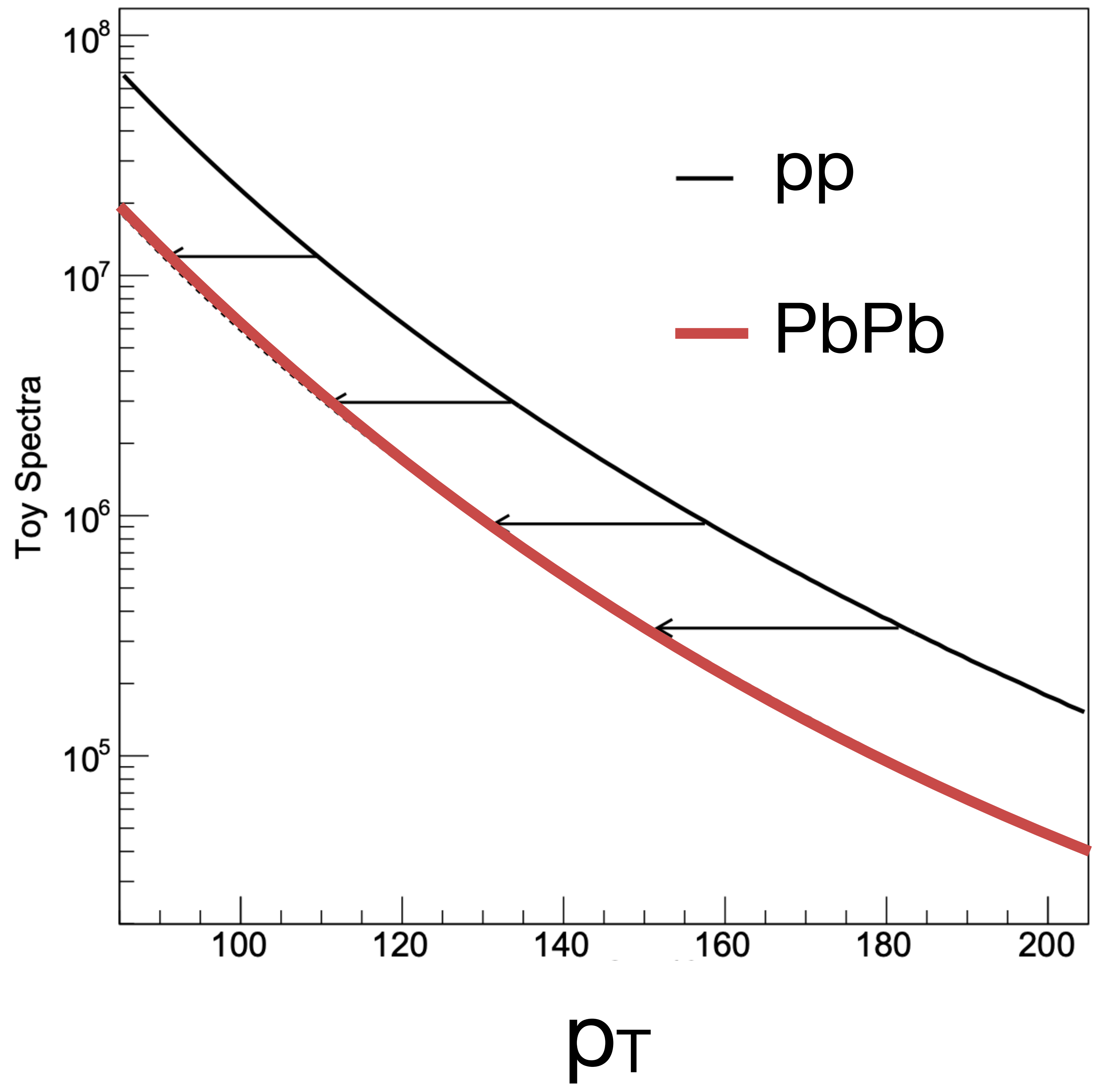
Bullet in gelatin block

PRC 99 (2019) 034908 JHEP 01 (2022) 174 PLB 782 (2018) 474

D^0 R_{AA} Understanding the Shape

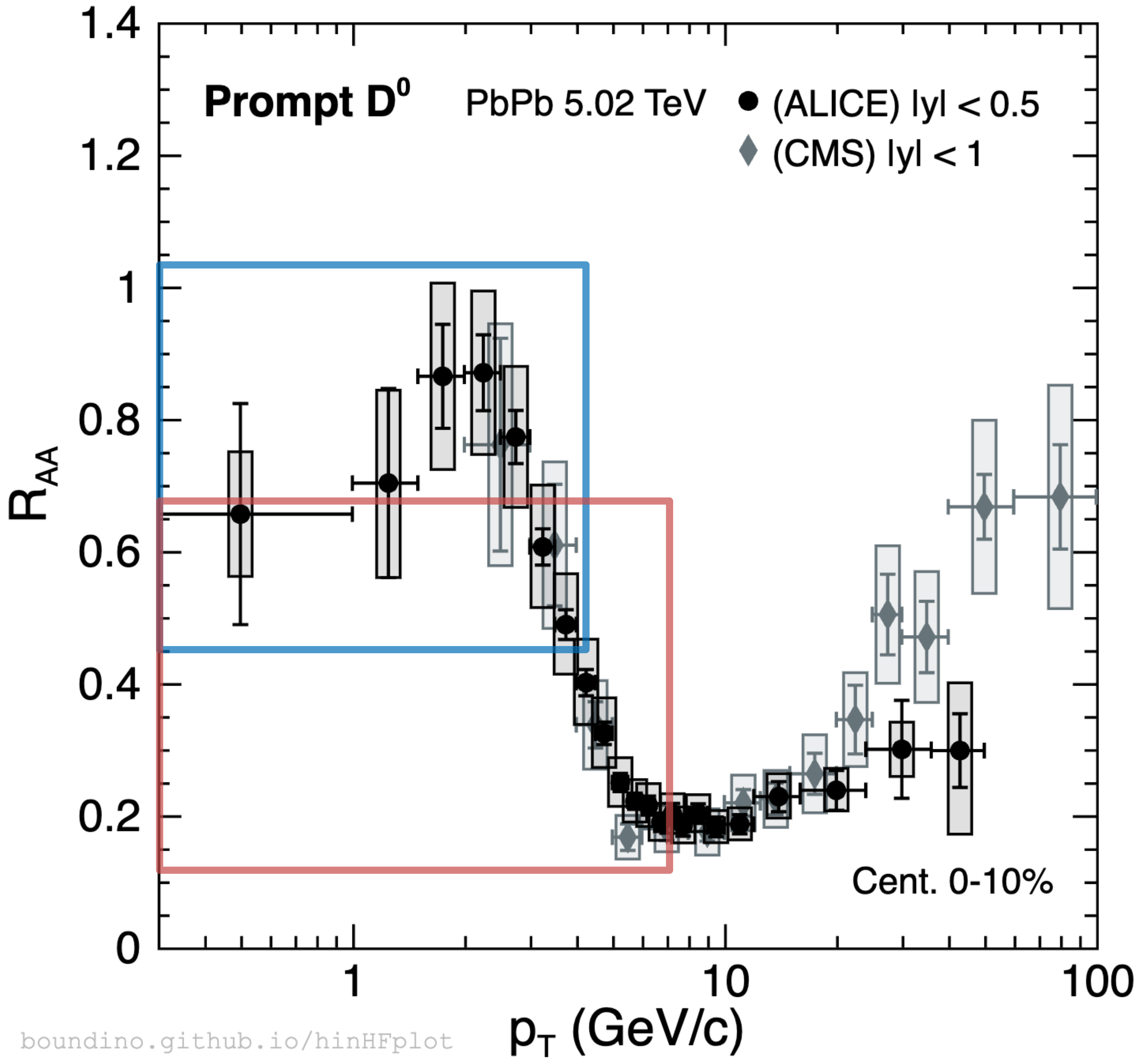


- Multiple effects interplay
  - Collisional and radiative energy loss
  - p_T shape before modification



JHEP 01 (2022) 174 PLB 782 (2018) 474

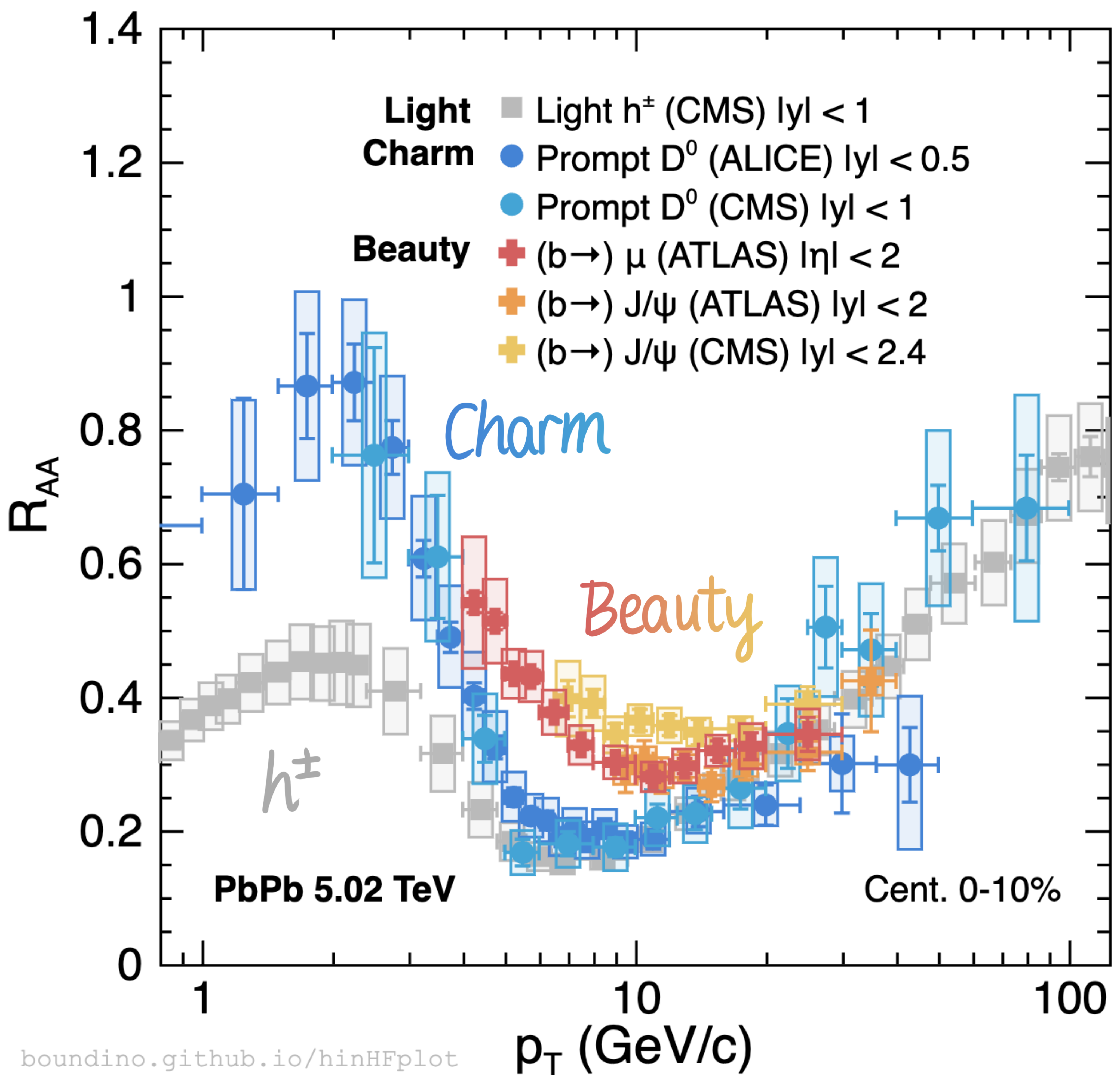
D^0 R_{AA} Understanding the Shape



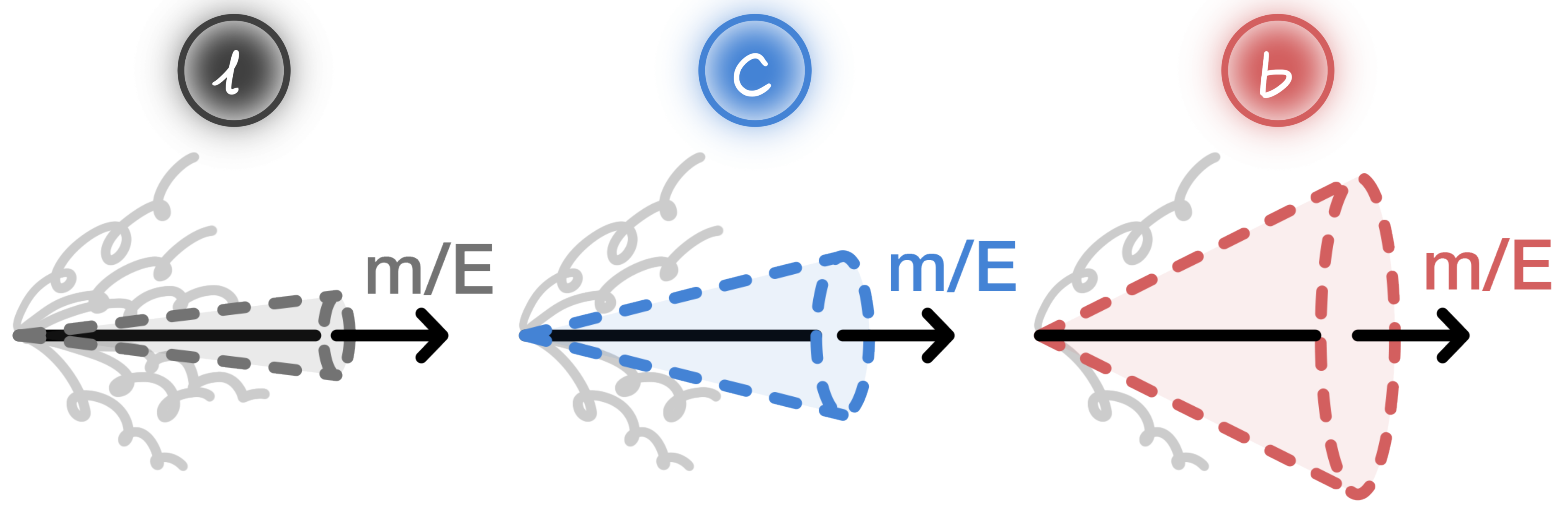
- Multiple effects interplay
  - Collisional and radiative energy loss
  - p_T shape before modification
    - lower slope at high p_T
  - Collective flow + coalescence
    - medium pushes very low-p_T partons to higher p_T
  - nPDF shadowing
    - suppress low p_T

JHEP 01 (2022) 174 PLB 782 (2018) 474

R_{AA} Mass Dependence of Energy Loss



- Flavor dependent energy loss
  Dead cone effect
  - Radiation is suppressed inside $\theta < m/E$
  - Energy loss $\Delta E_l > \Delta E_c > \Delta E_b$

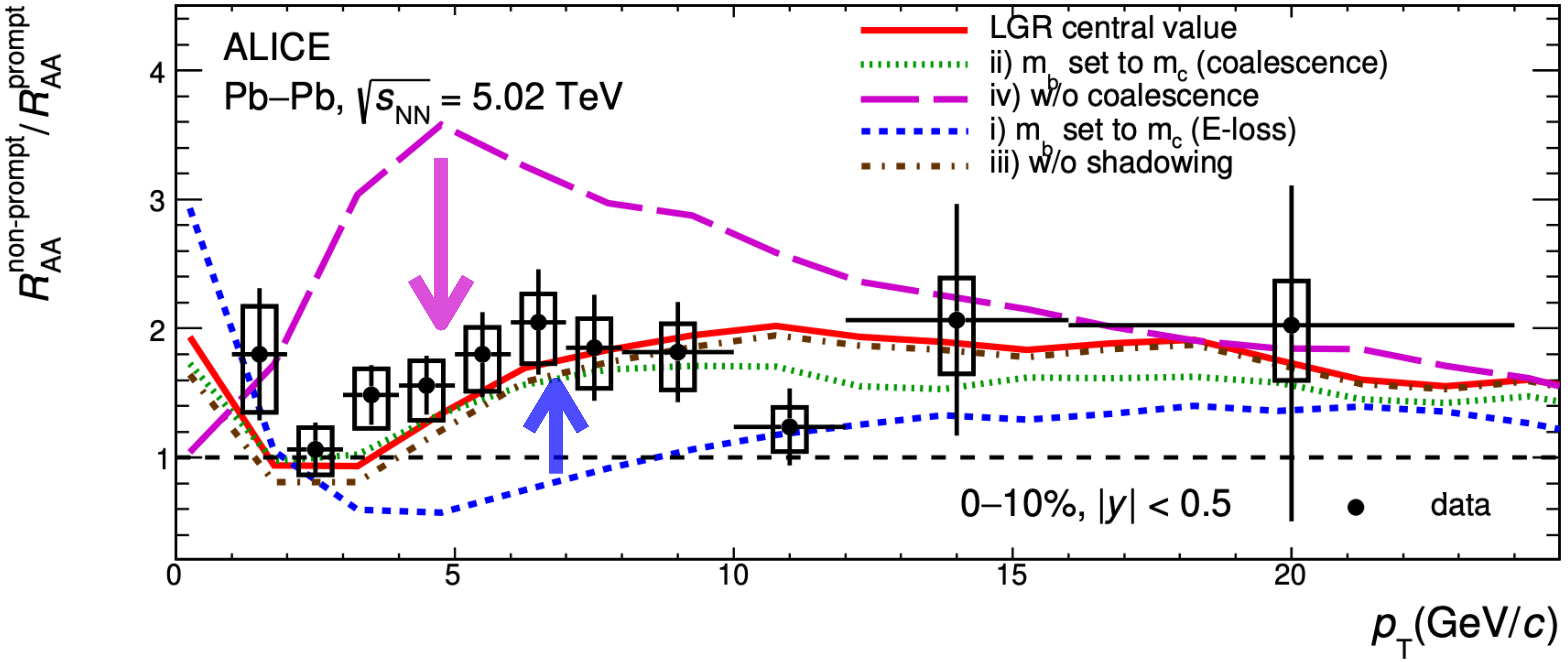


PLB 829 (2022) 137077 EPJC 78 (2018) 762 EPJC 78 (2018) 509

R_{AA} Flavor Dependence

Non-prompt D R_{AA} / Prompt D R_{AA}

Beauty / charm



[JHEP 12 (2022) 126]

nPDF *small effect*

- Simultaneous effect on charm and beauty

Mass dependent energy loss

significant effect

- Enhance difference between c and b

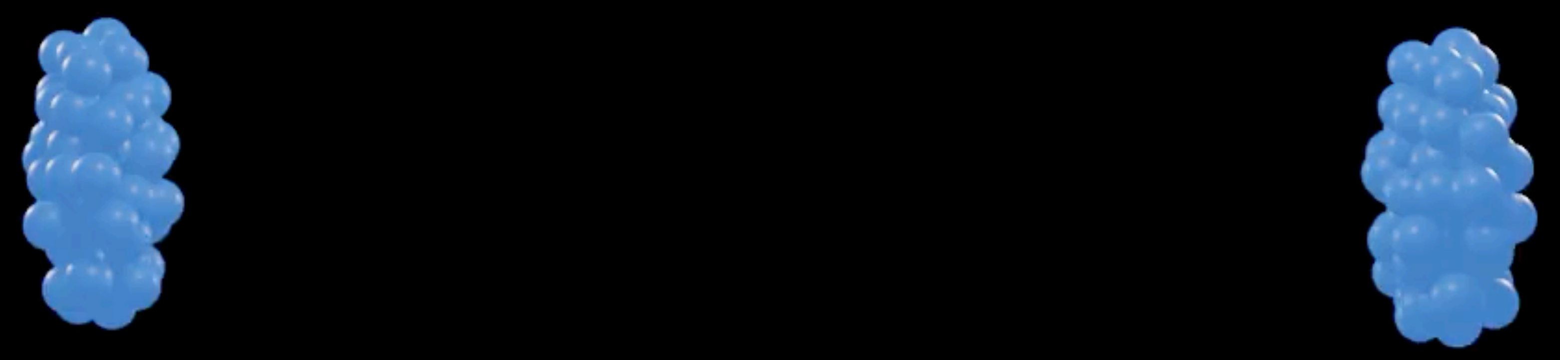
Hadronization

significant effect

- Reduce diff between c and b

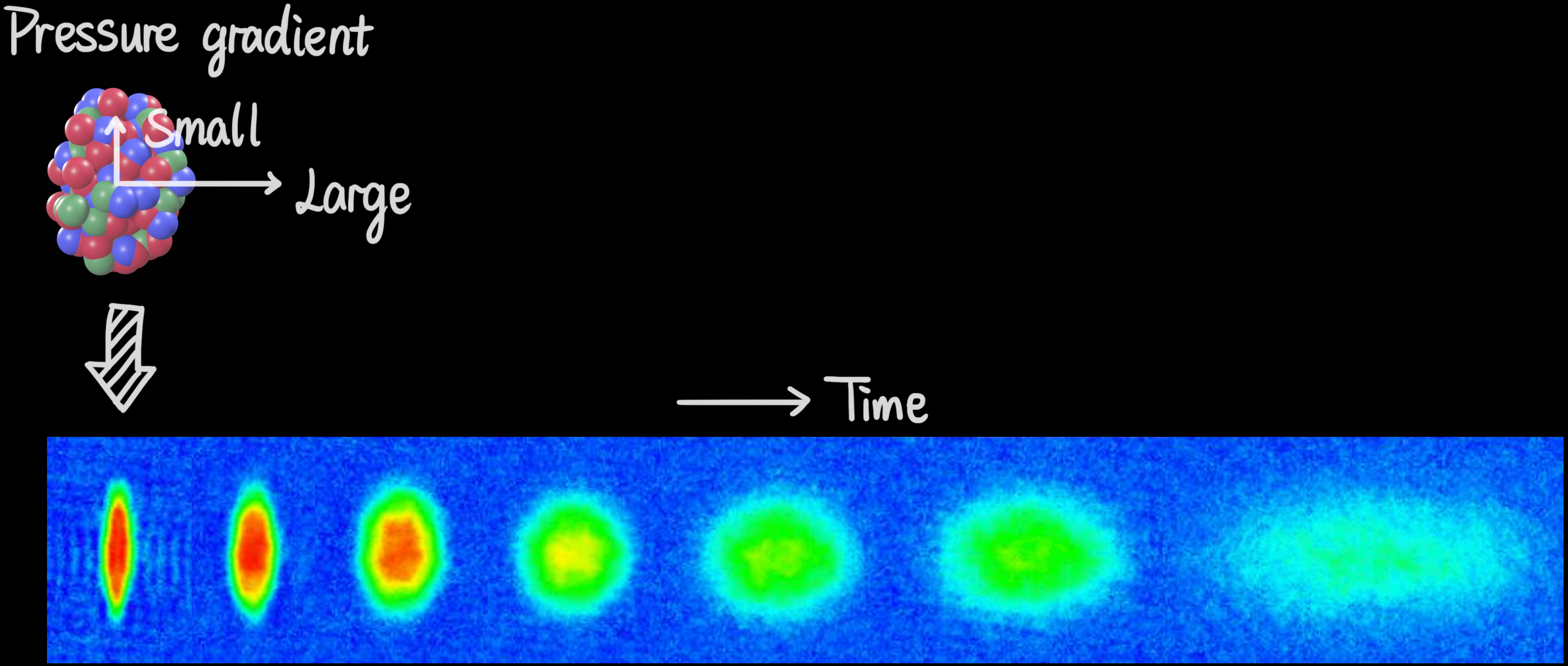
Initial Spatial Anisotropy of Medium

Azimuthal anisotropic initial shape in peripheral events



[Animation]

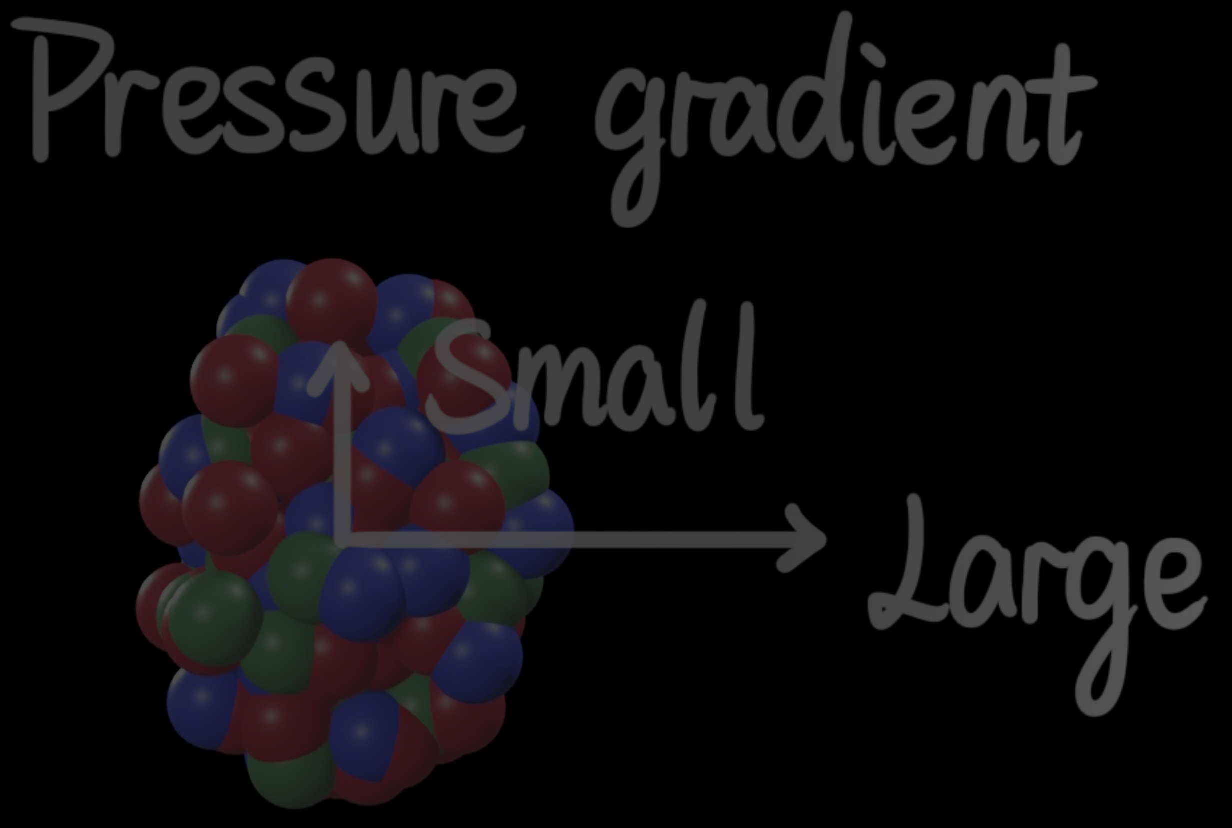
Collective Flow



Pressure driven expansion

Science 298 (2002) 2179

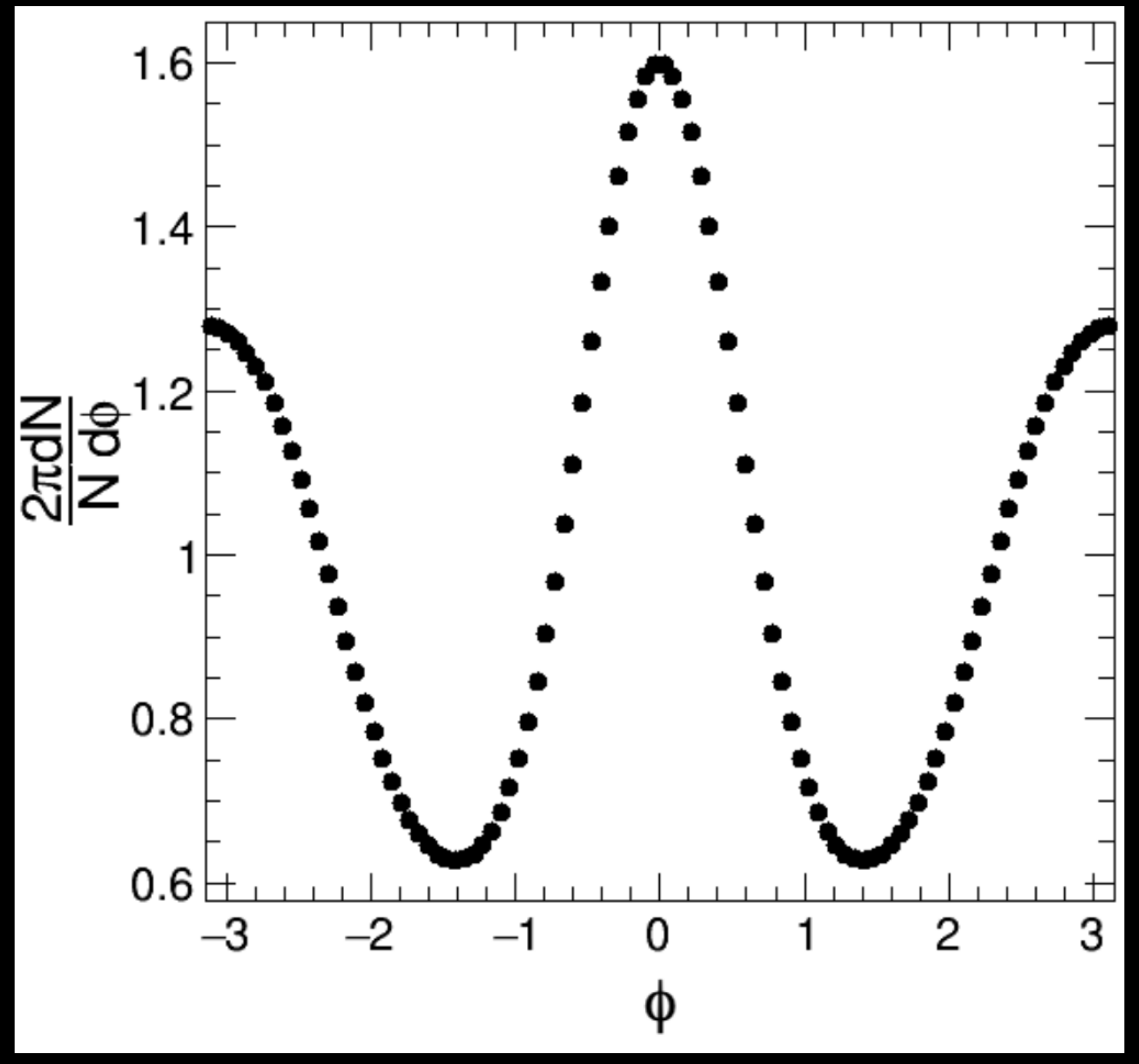
Collective Flow



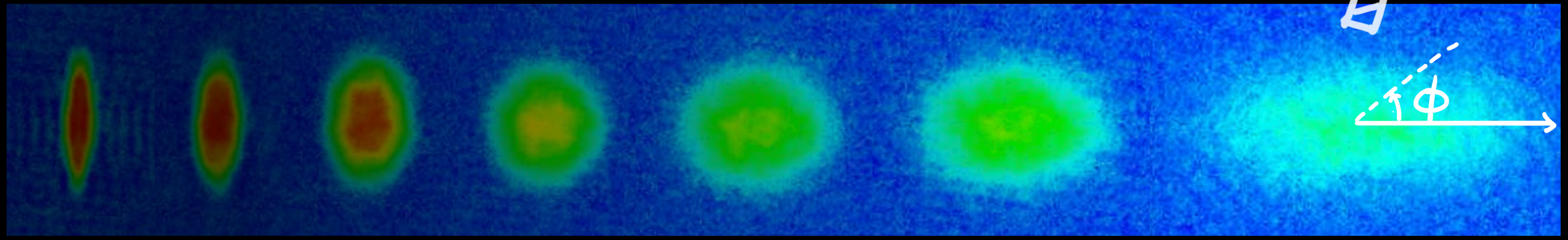
Existence of QGP ➜ Final-state particle azimuthal anisotropy

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]$$

➜ Elliptic $v_2 \neq 0$



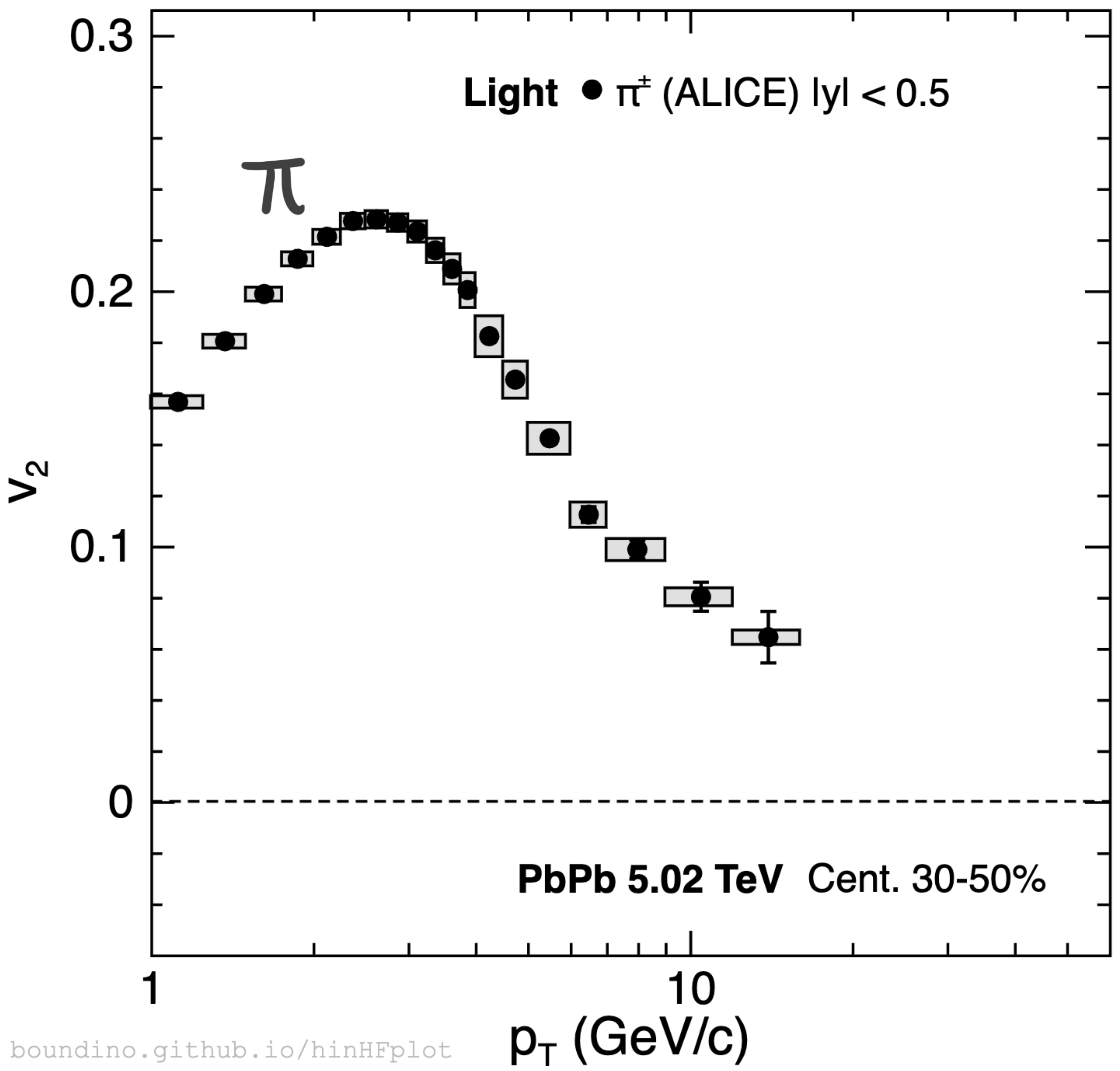
Time



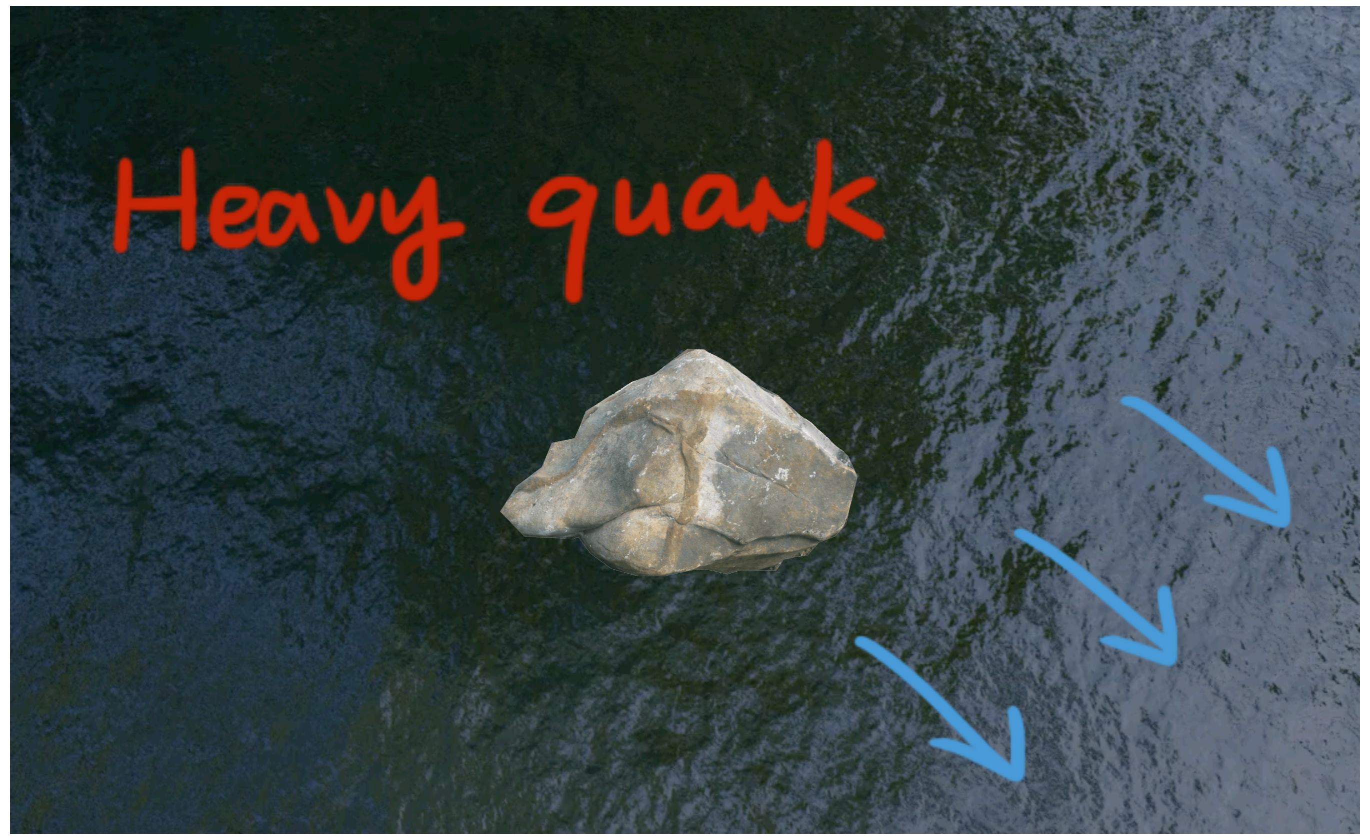
Pressure driven expansion

Science 298 (2002) 2179

Collective Flow Heavy Quarks

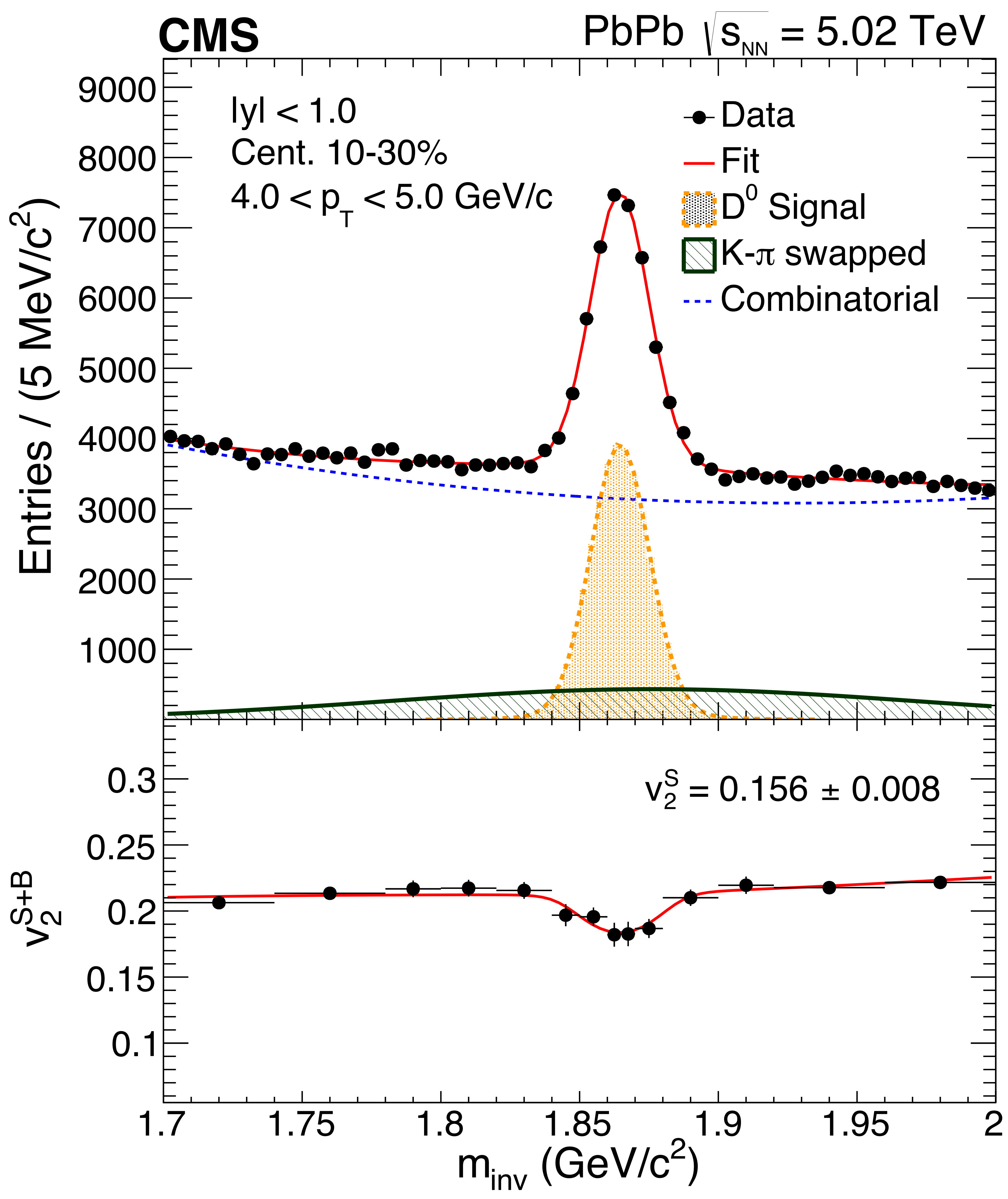


Do heavy quarks flow along with the medium?



PLB 816 (2021) 136253 PLB 813 (2021) 136054 PLB 807 (2020) 135595

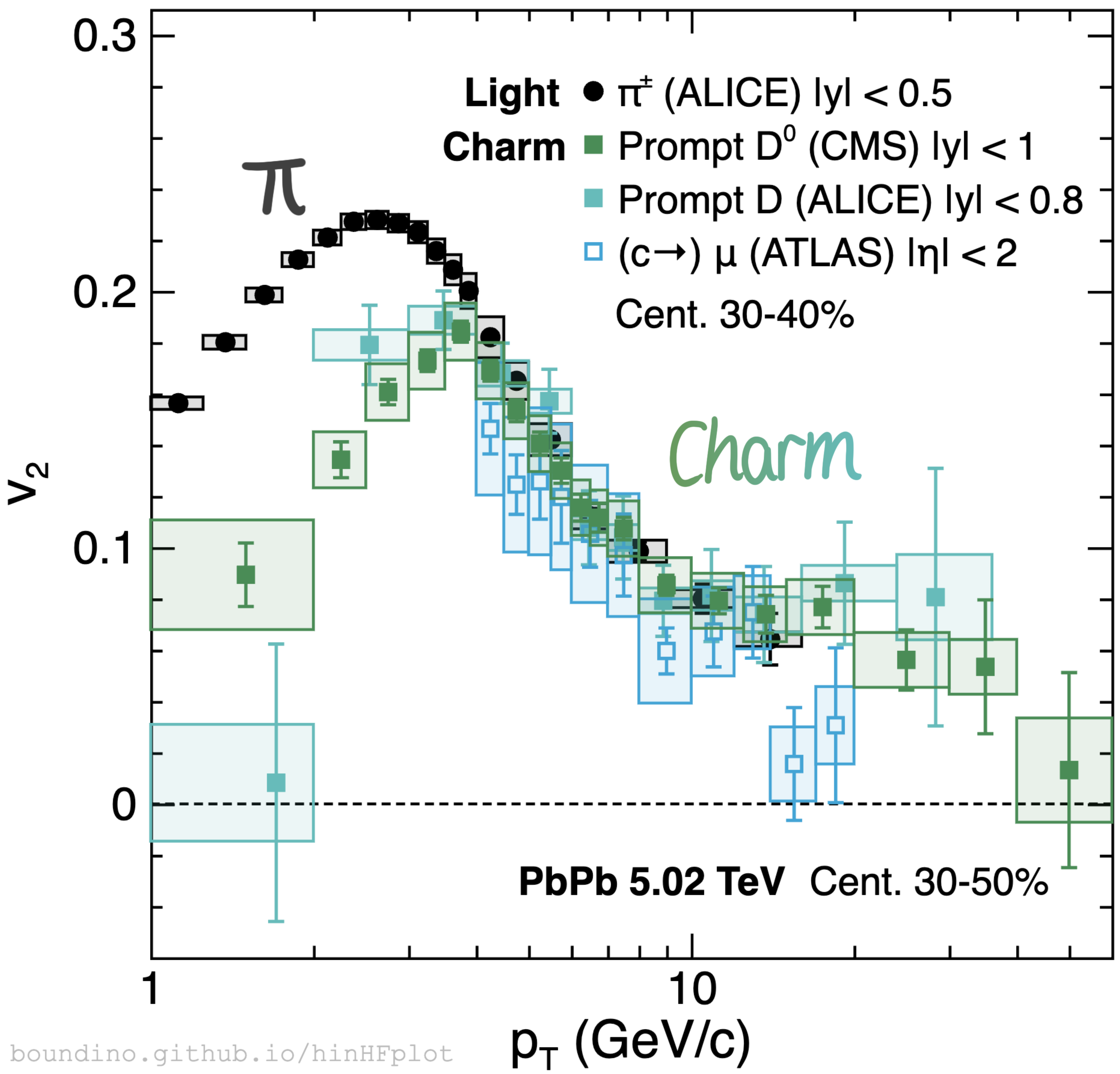
Analysis Technique Flow Coefficient



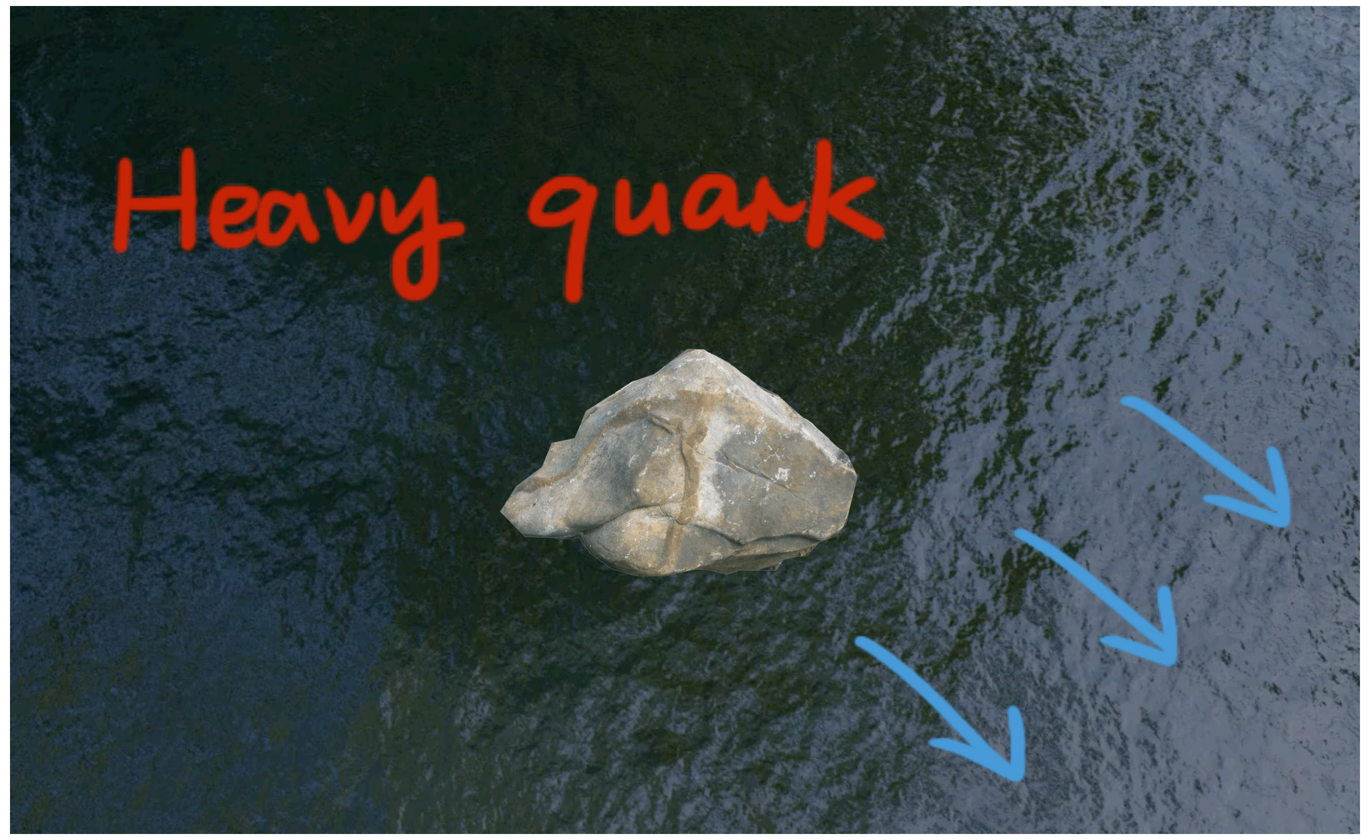
- Simultaneously fit invariant mass distribution and average v_2 Scalar Product → get signal v_2
- One of common methods for property measurements of resonances, if
  - signal and backgrounds have distinct magnitudes of the observables

[PRL 120 (2018) 202301]

Collective Flow Open Charm



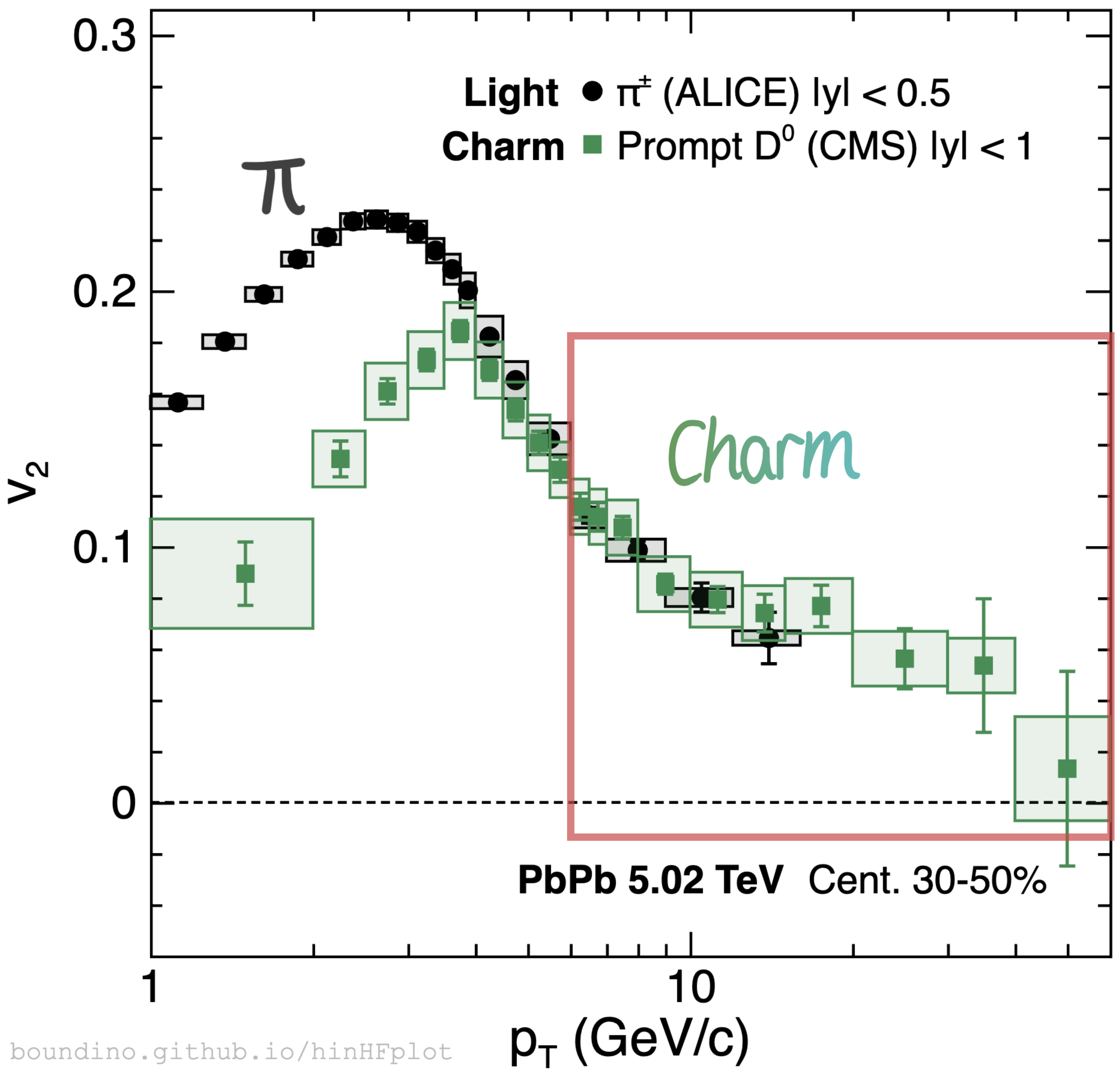
- Significant non-zero open charm flow signal
  - Smaller v_2 than light hadrons at low p_T
  - Magnitude reflects thermalization degree



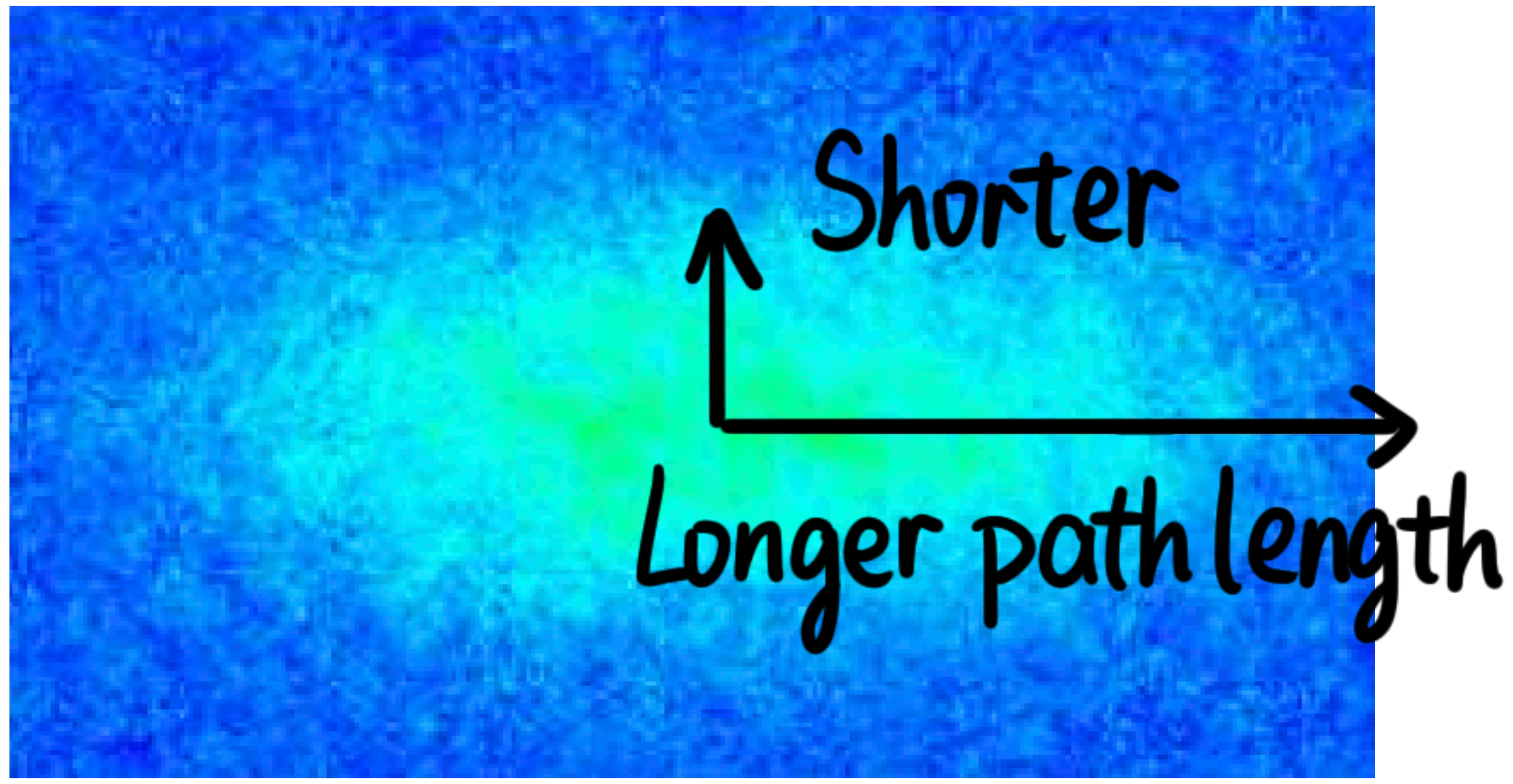
- Consistent between LHC results
  - (c→) μ seems to shift to lower p_T

PLB 816 (2021) 136253 PLB 813 (2021) 136054 PLB 807 (2020) 135595

Collective Flow Open Charm

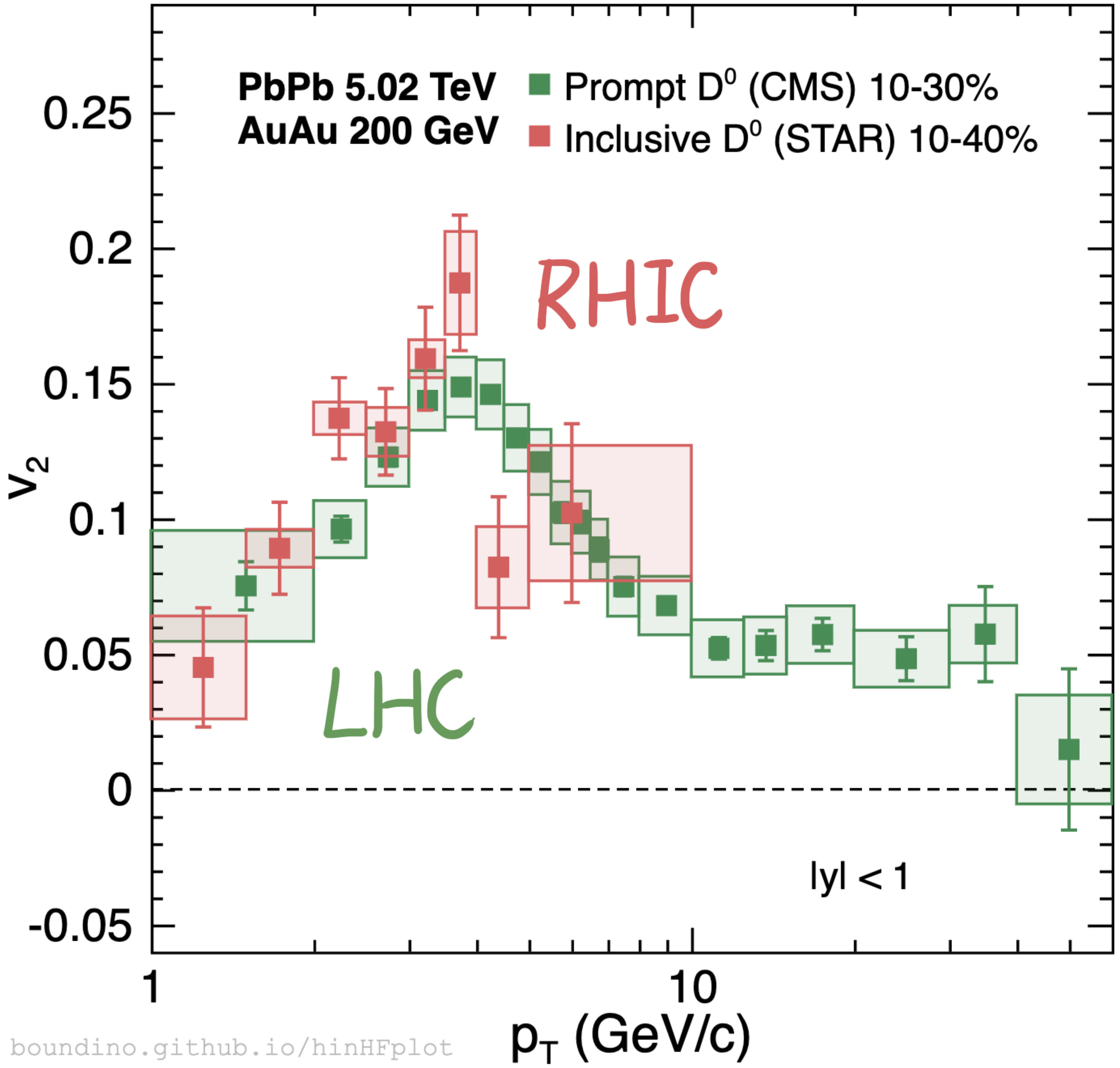


- Non-zero D meson v_2 up to high p_T
  - Same magnitude with light hadrons
  - Path-length dependence of energy loss



PLB 816 (2021) 136253 PLB 813 (2021) 136054 PLB 807 (2020) 135595

Open Charm Flow LHC vs RHIC

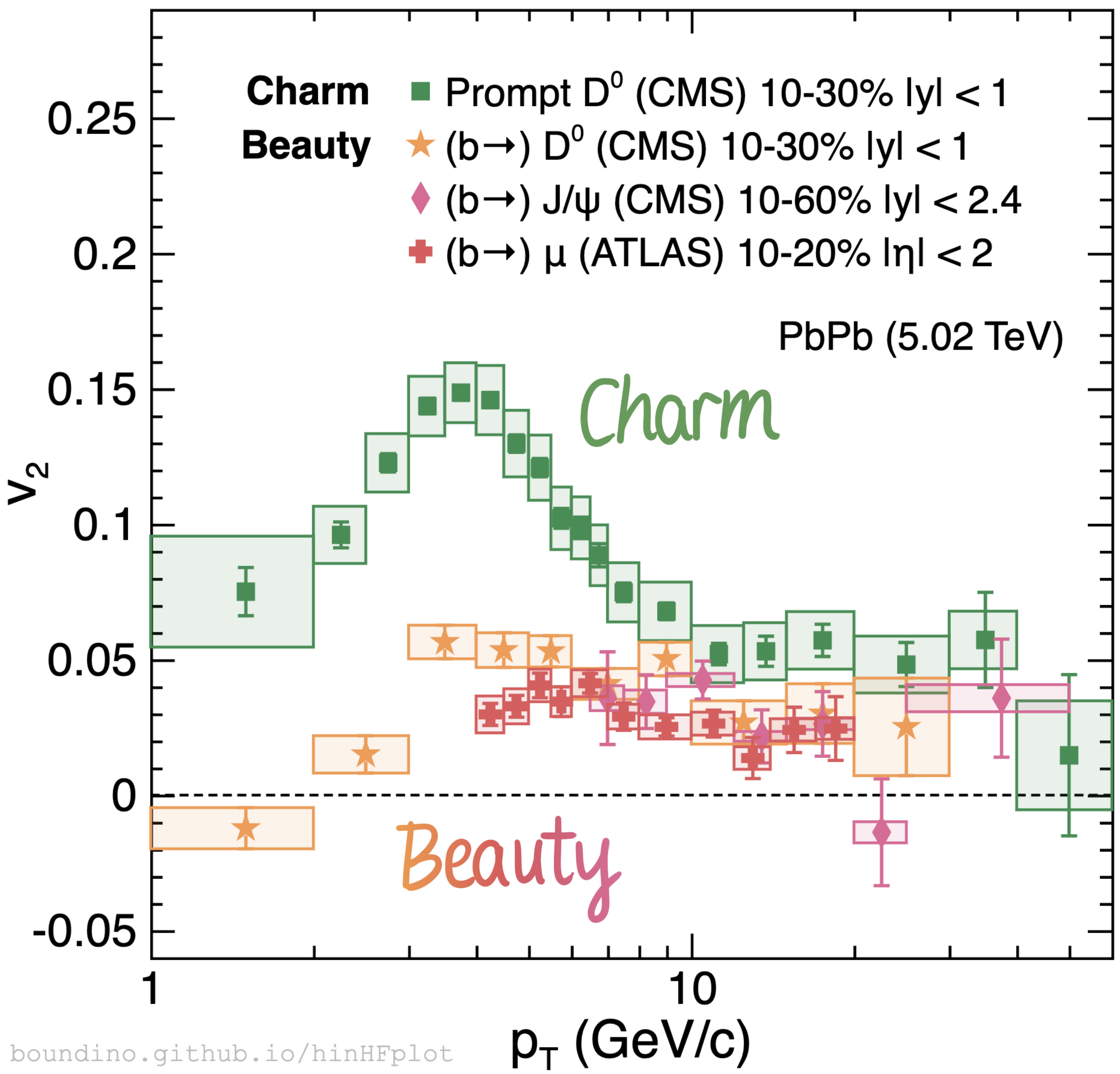


boundino.github.io/hinHFplot

- Similar D v_2 between LHC PbPb 5 TeV and RHIC AuAu 200 GeV
  - despite different temperature & size?
  - decisive precision at sPHENIX

PLB 816 (2021) 136253 PRL 118 (2017) 212301

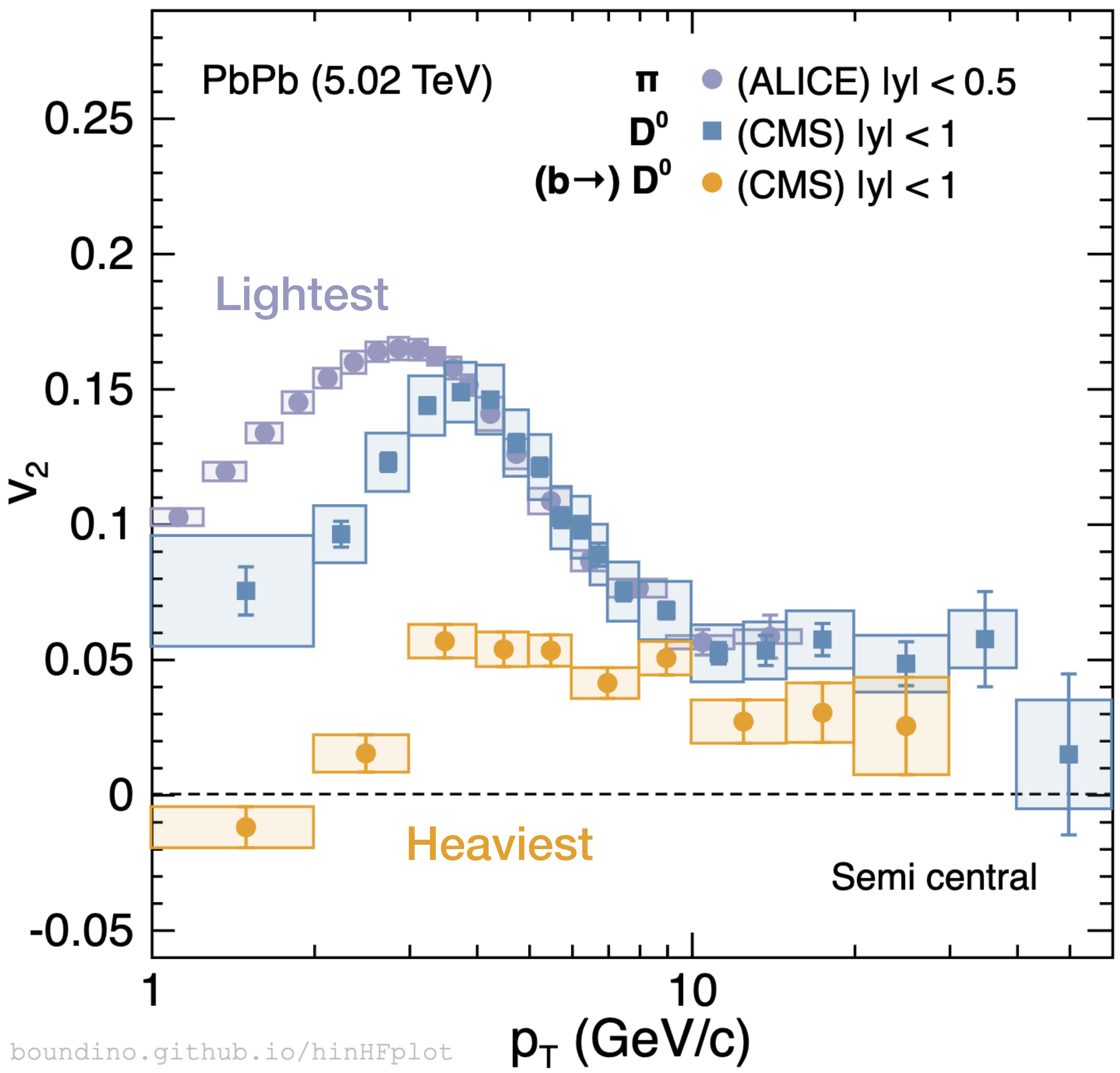
Collective Flow Open Beauty



- Significant non-zero open beauty flow signal
  - Smaller v_2 than charm hadrons at low p_T
    - Weaker collective flow behavior
  - Similar v_2 with open charm at high p_T
    - Path length dependence of energy loss

PLB 850 (2024) 138389 JHEP 10 (2023) 115 PLB 807 (2020) 135595

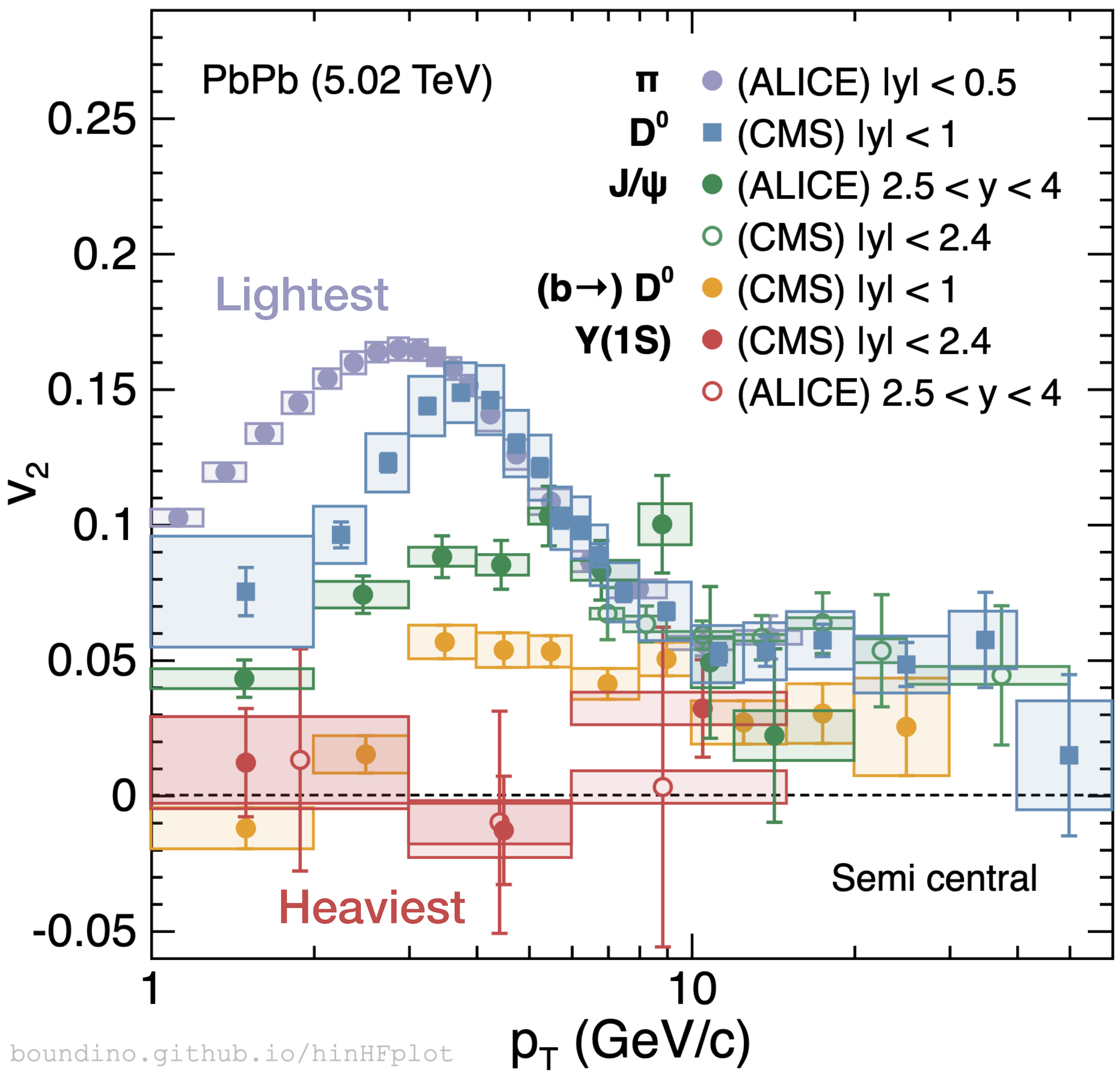
Collective Flow Mass Hierarchy



- v_2 hierarchy from lightest to heaviest hadrons

Guess whether the order still stands if adding quarkonia?

Collective Flow Mass Hierarchy Including Quarkonia

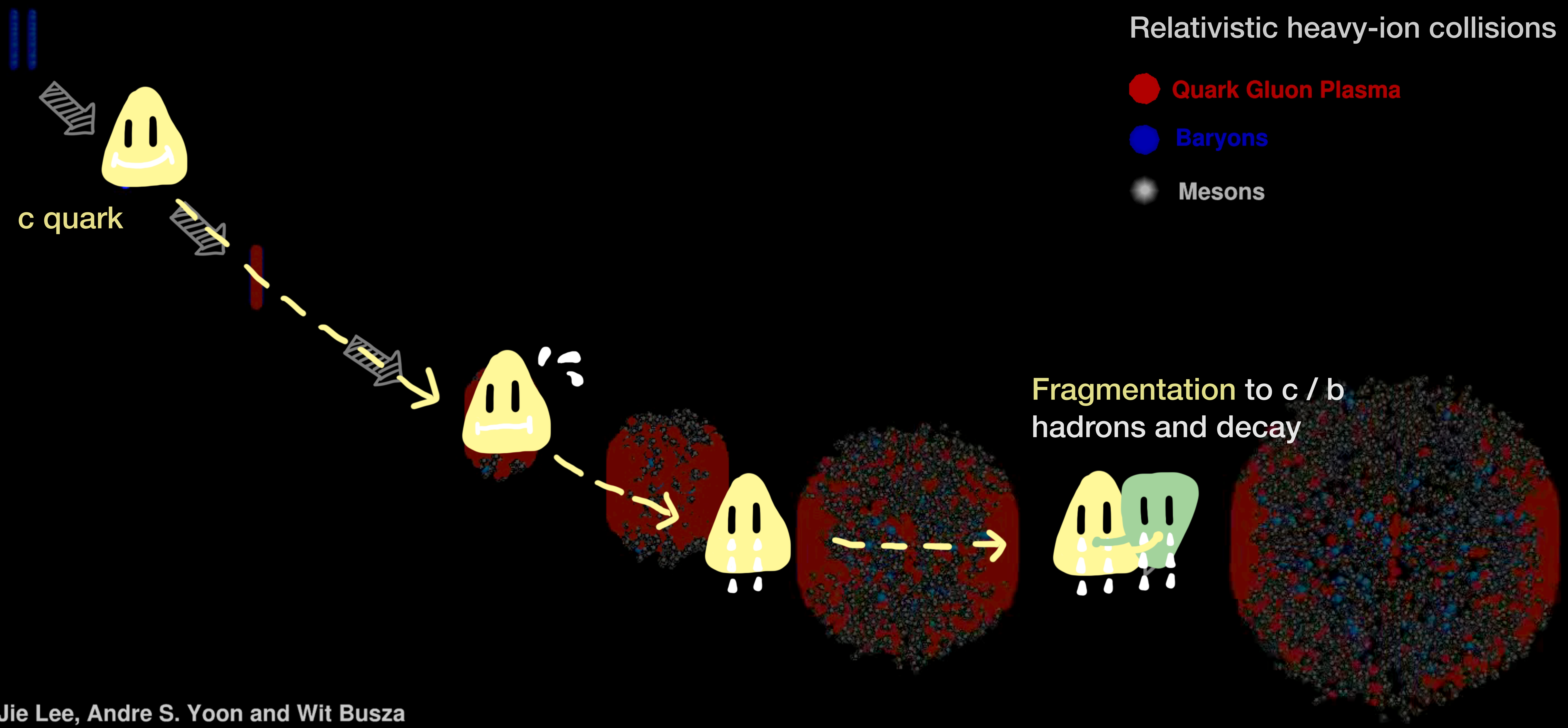


- v_2 hierarchy from lightest to heaviest hadrons

Happy with the flow picture?
Sorry…
Quarkonia actually have different stories

JHEP 10 (2020) 141 JHEP 10 (2023) 115 PLB 819 (2021) 136385 PRL 123 (2019) 192301

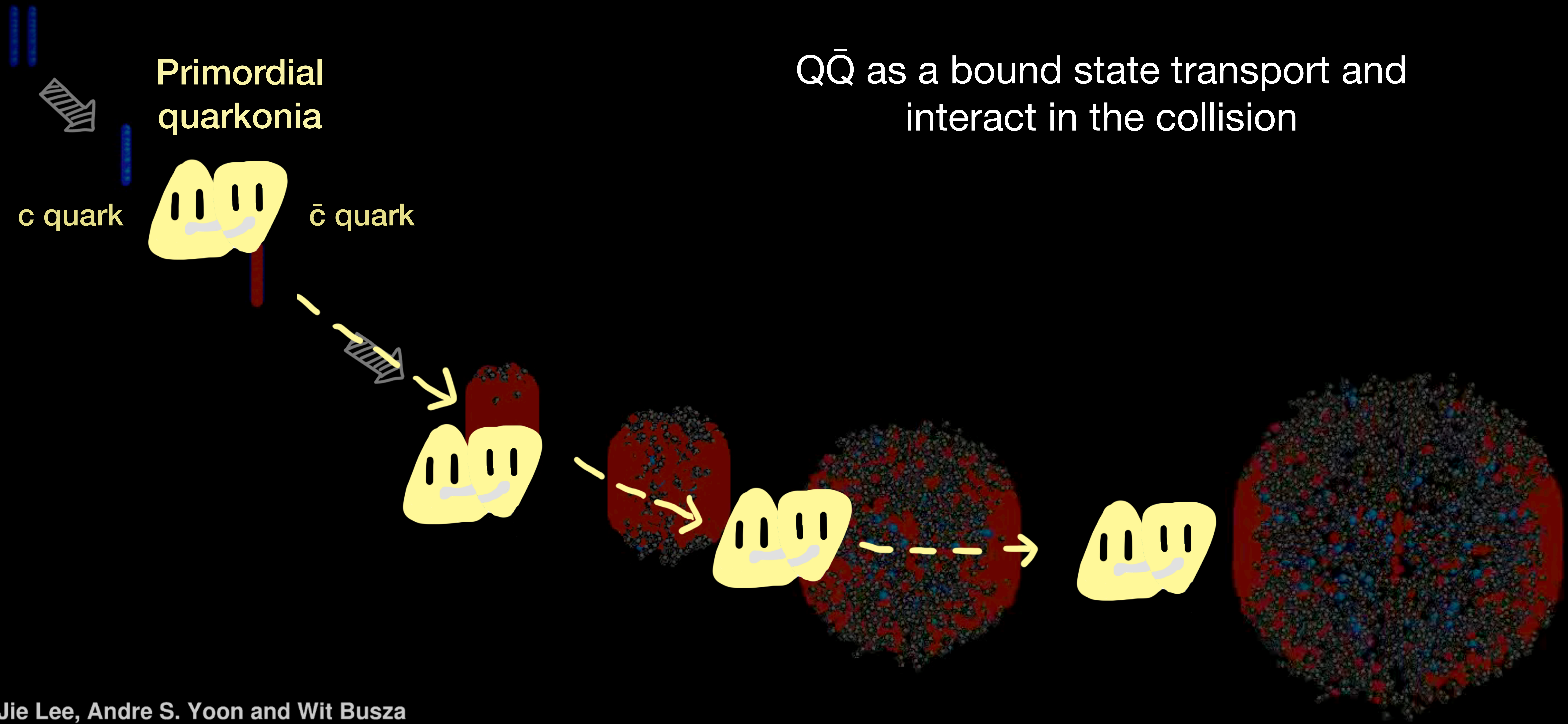
Recall Open HF hadron in HIC



Yen-Jie Lee, Andre S. Yoon and Wit Busza

Life of a Lucky Heavy Quarkonium in HIC

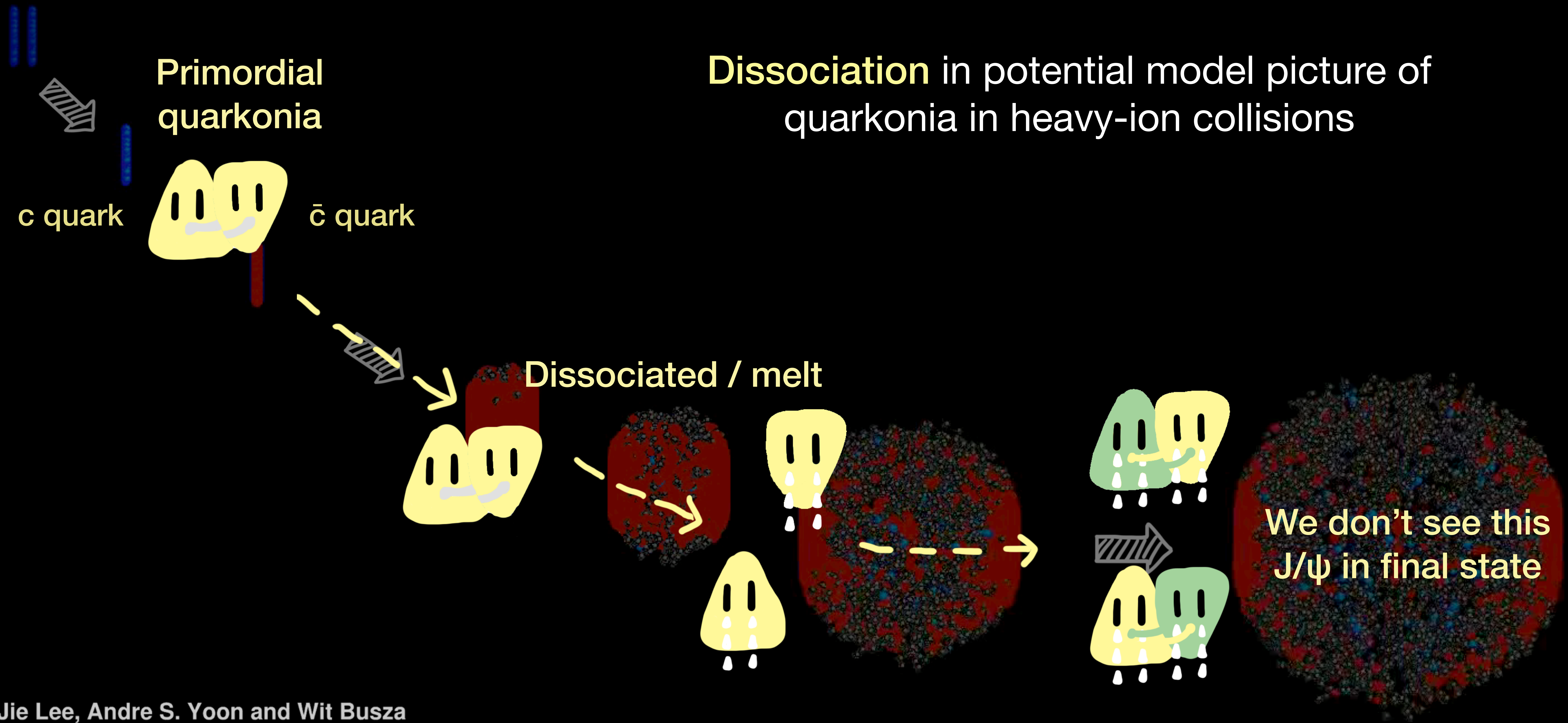
$Q\bar{Q}$ as a bound state transport and interact in the collision



Yen-Jie Lee, Andre S. Yoon and Wit Busza

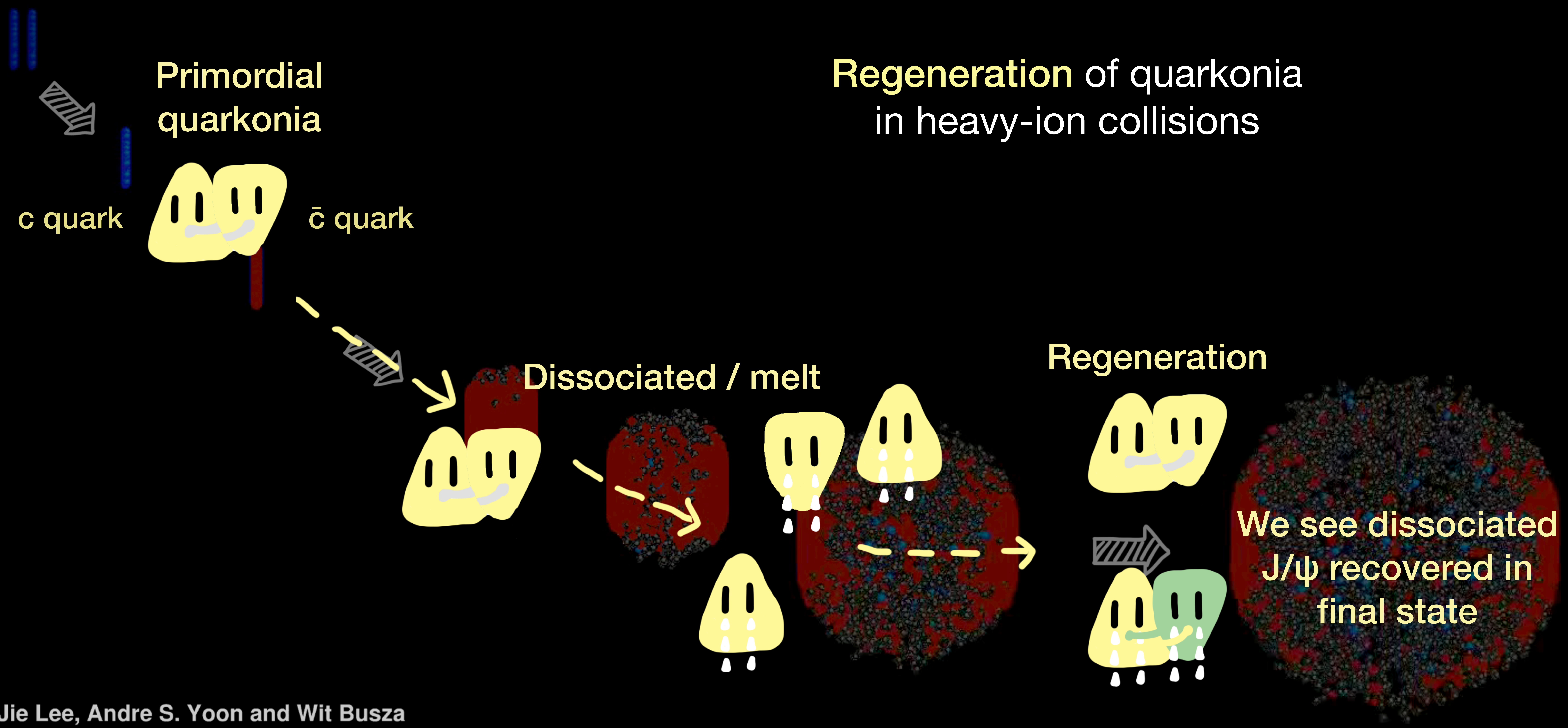
Life of a Weak Unlucky Quarkonium in HIC

Dissociation in potential model picture of quarkonia in heavy-ion collisions



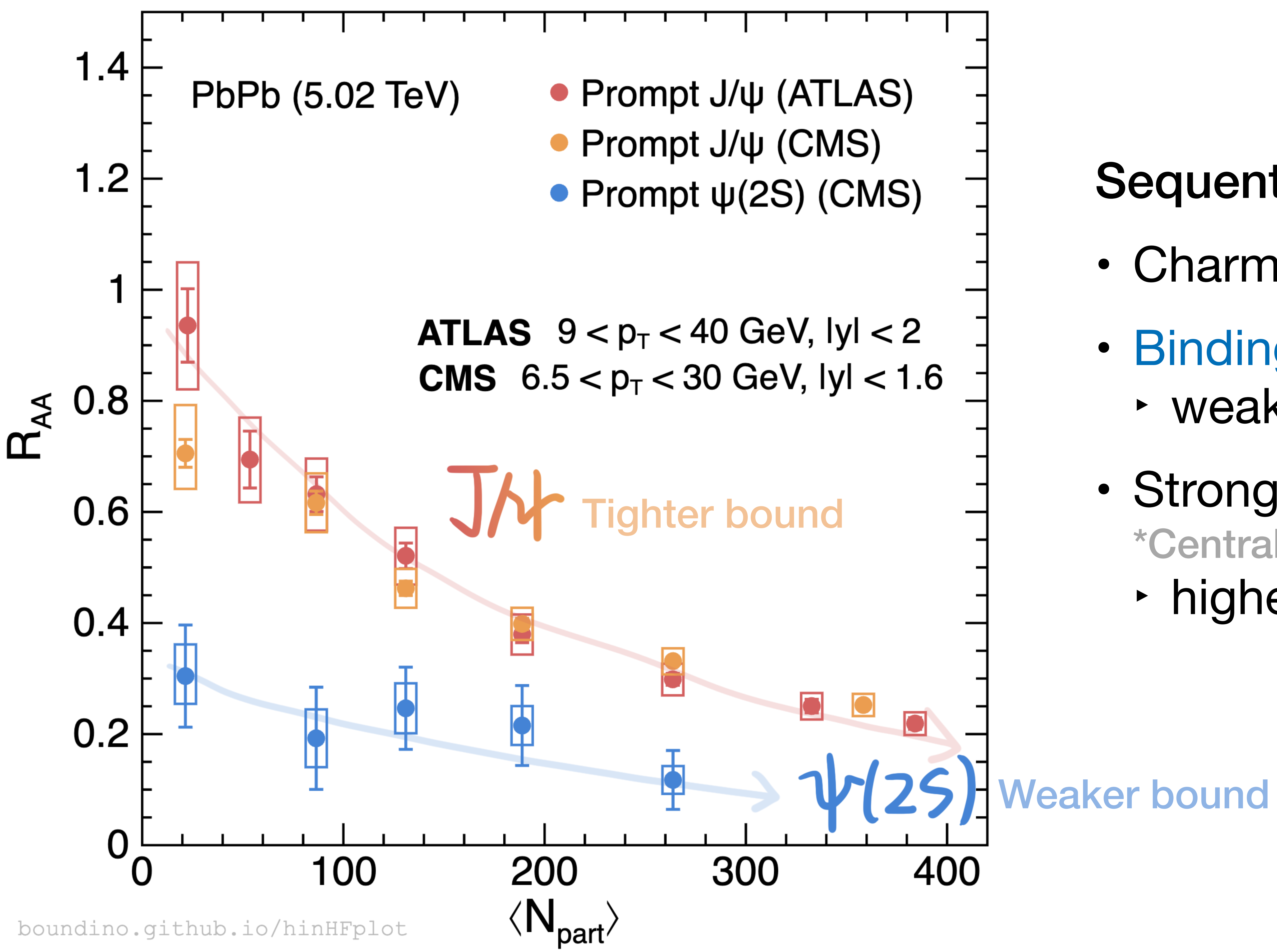
Yen-Jie Lee, Andre S. Yoon and Wit Busza

Life of a Weak Lucky Quarkonium in HIC



Yen-Jie Lee, Andre S. Yoon and Wit Busza

Charmonia in QGP Sequential Melting

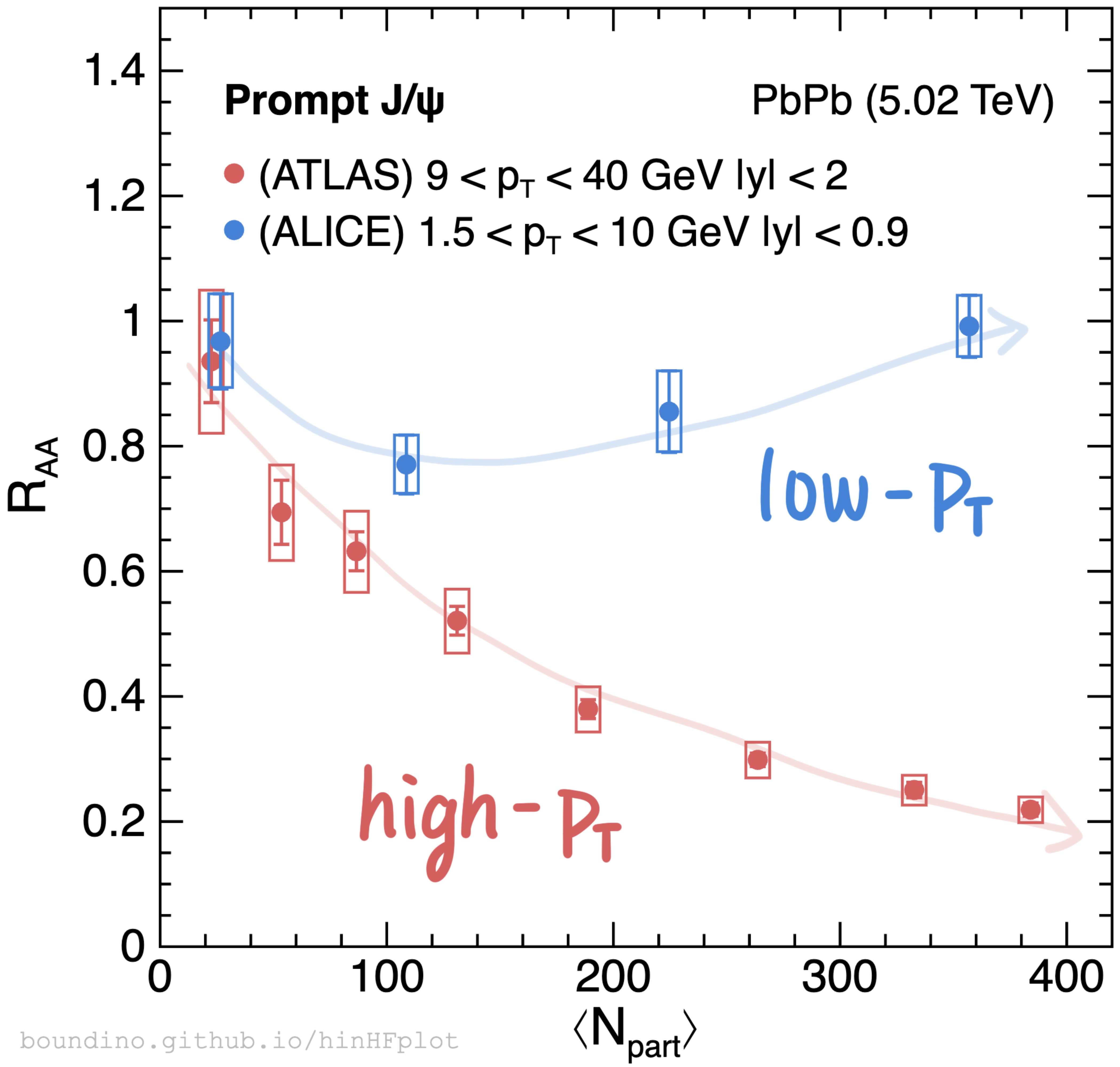


EPJC 78 (2018) 762 EPJC 78 (2018) 509 EPJC 78 (2018) 509

Sequential melting

- Charmonia strongly suppressed in PbPb collisions
- Binding energy hierarchy
  - weaker bound state easier to be dissociated
- Stronger suppression in central events
  *Central: large N_{part}
  - higher temperature and larger size

Charmonia in QGP Regeneration

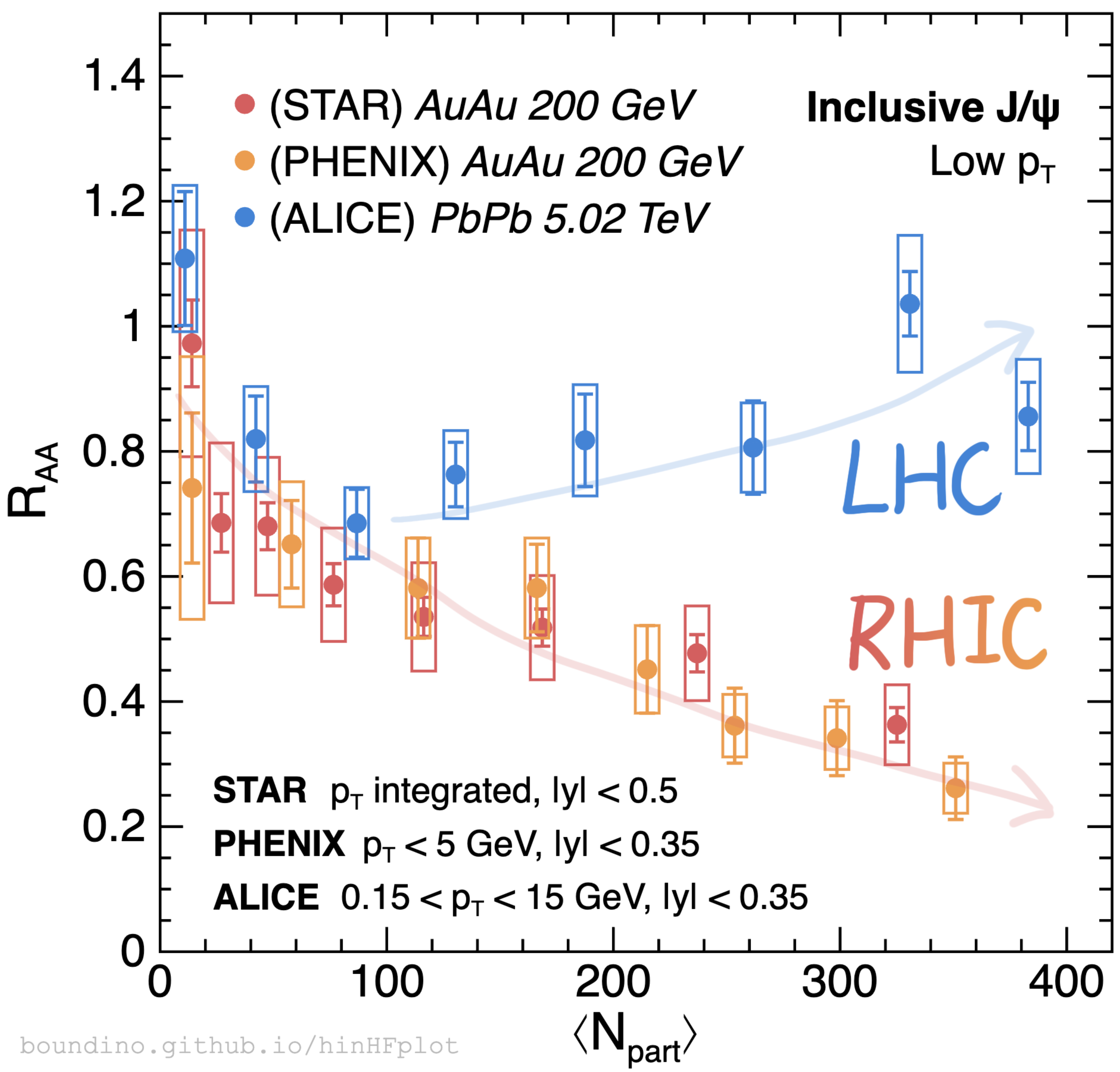


EPJC 78 (2018) 762 JHEP 02 (2024) 066

Regeneration

- Uncorrelated $Q\bar{Q}$ in QGP regenerate quarkonia
- Increasing R_{AA} at low p_T towards central events
  - central events have larger $\sigma_{c\bar{c}}$

Charmonia in QGP Regeneration

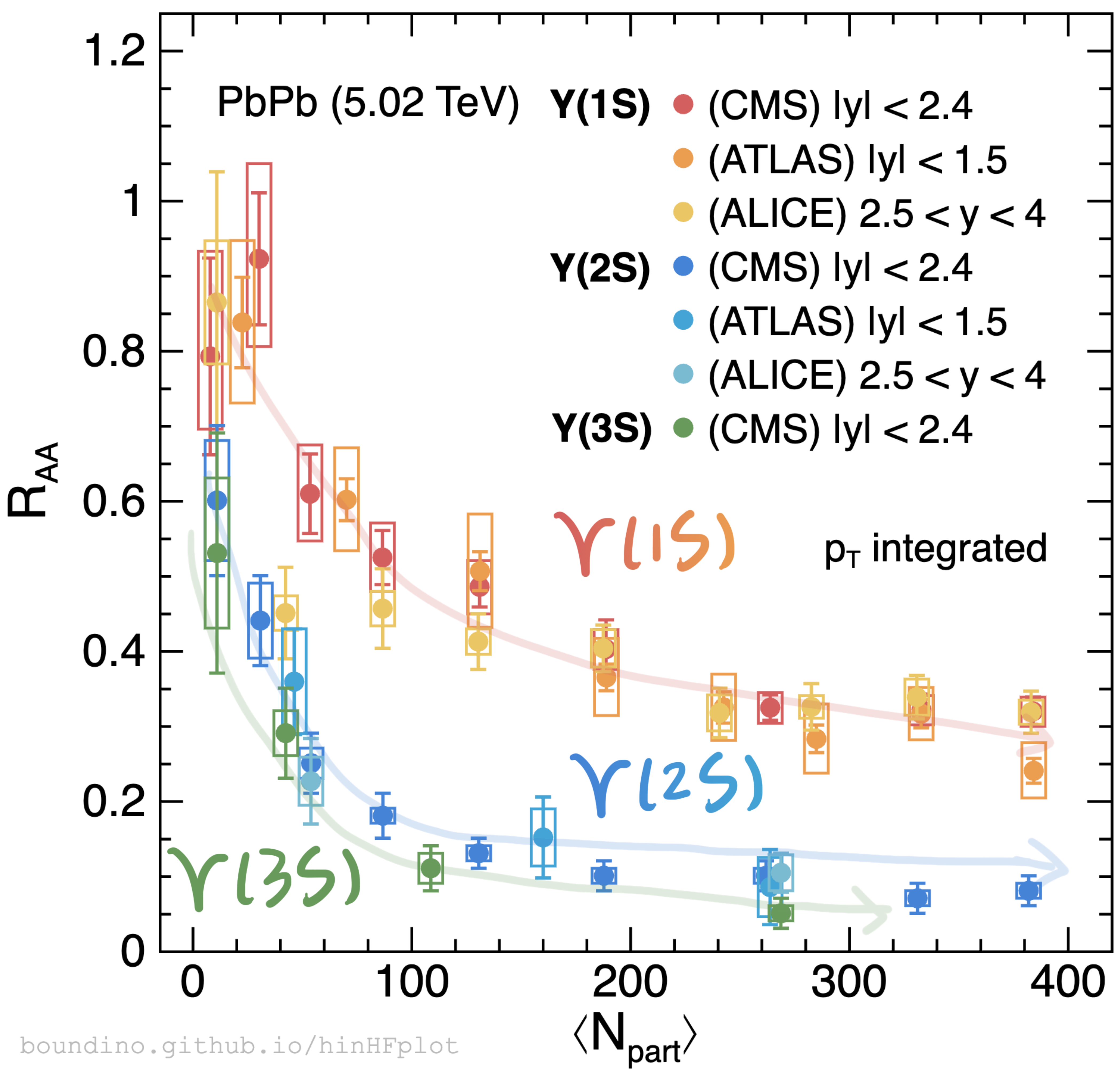


Regeneration

- Uncorrelated $Q\bar{Q}$ in QGP regenerate quarkonia
- Increasing R_{AA} at low p_T towards central events
  - central events have larger $\sigma_{c\bar{c}}$
- Significant in LHC but not in RHIC
  - higher collision energy has larger $\sigma_{c\bar{c}}$

PLB 797 (2019) 134917 PRL 98 (2007) 232301 PLB 849 (2024) 138451

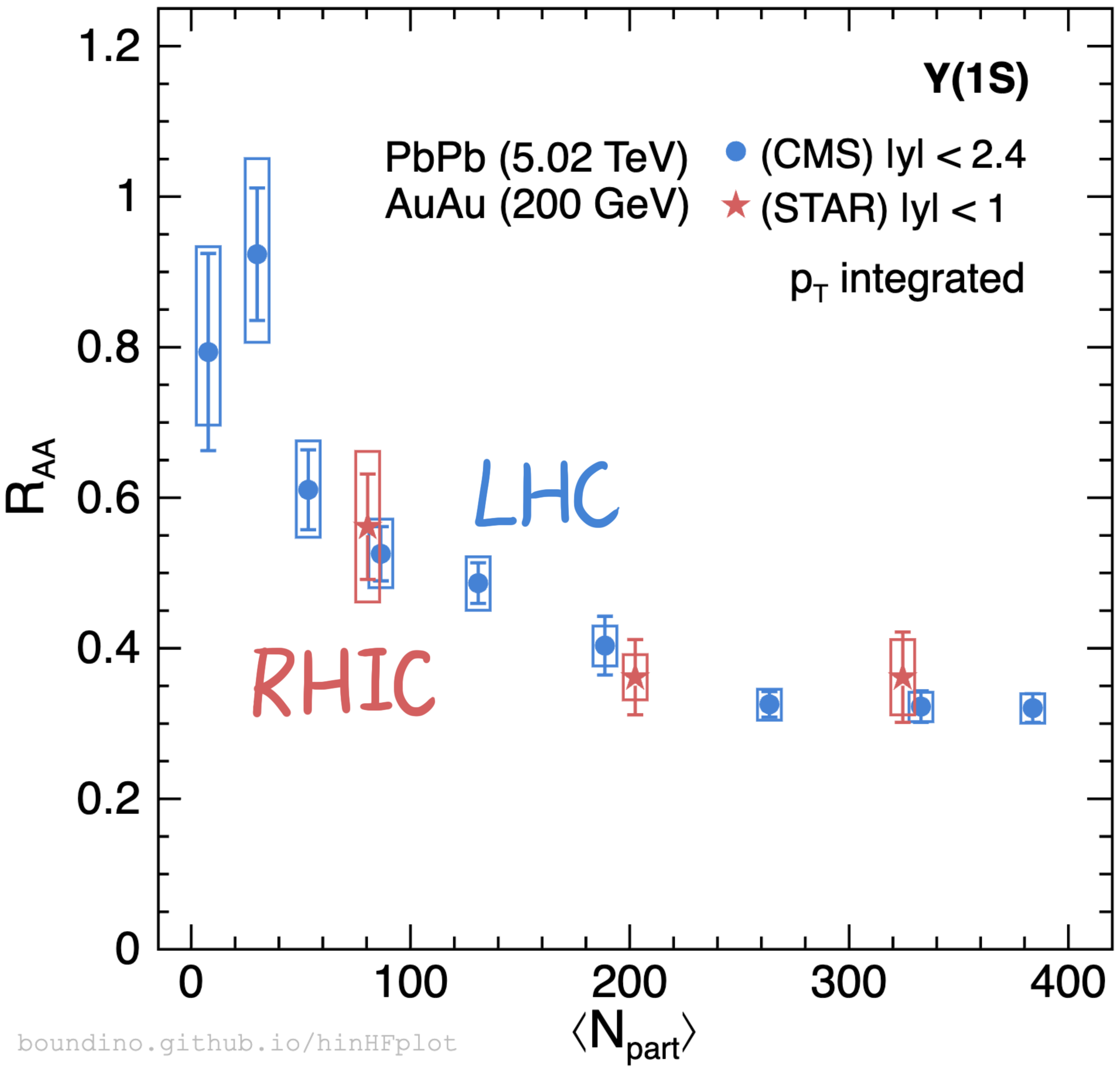
Bottomonia in QGP



Sequential melting

- Bottomonia strongly suppressed in PbPb collisions
- Binding energy hierarchy
  - weaker bound state easier to be dissociated
- Weak (if any) uncorrelated recombination expected for Υ(nS)
  - smaller $\sigma_{b\bar{b}}$ than $\sigma_{c\bar{c}}$

Dissociation + Regeneration Picture Challenge

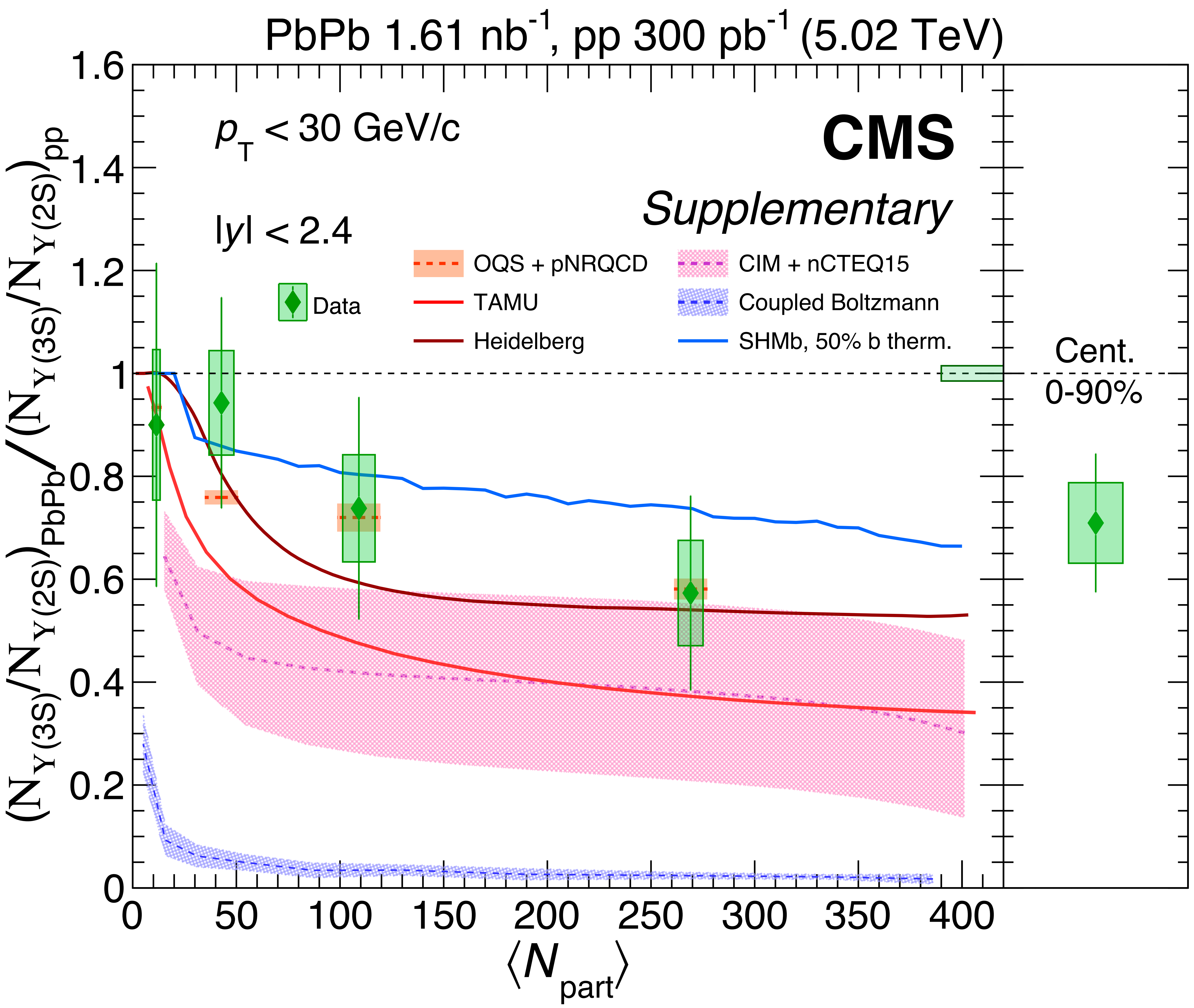


PLB 790 (2019) 270 PRL 130 (2023) 112301

Happy with dissociation + regeneration picture?

- Why is Υ(1S) suppression degree so similar in LHC and RHIC?
  - even if they have different initial temperatures
- Why does Υ(1S) not continue decreasing in most central events?
  - models with regeneration still don't describe it
- Feed-down contribution not well constrained

Dissociation + Regeneration Picture Challenge

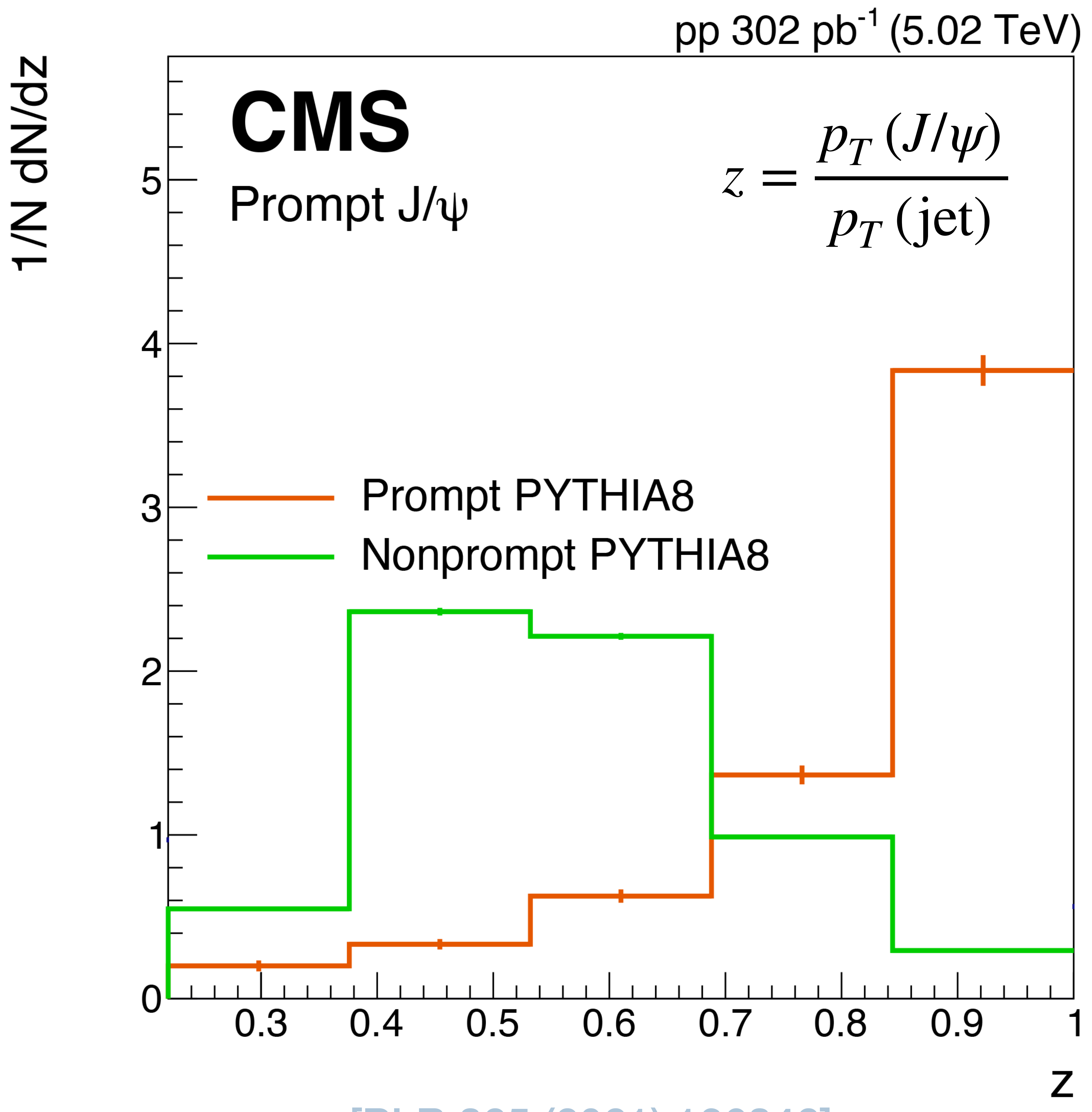


[2303.17026]

More excited states Y(3S) observation

- Challenging for theoretical models
  - Particle ratio cancels nPDF effect
- Crucial to constrain feed-down contribution

Revisit J/ψ Really Primordial?



[PLB 825 (2021) 136842]

Early bound state picture

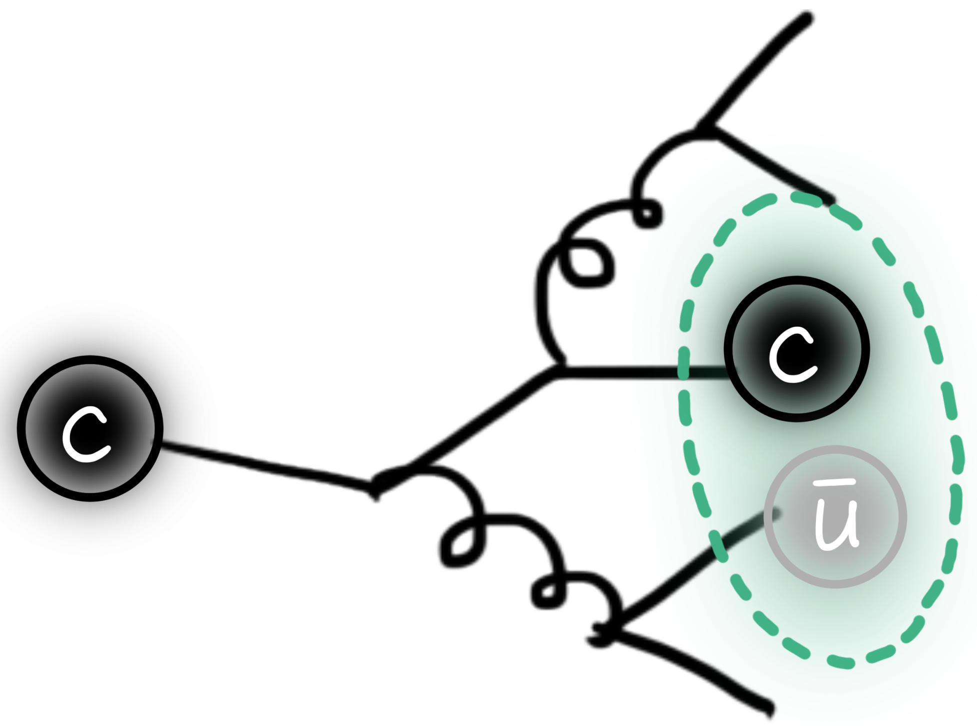
What we expect so far

- Few surrounding jet activities

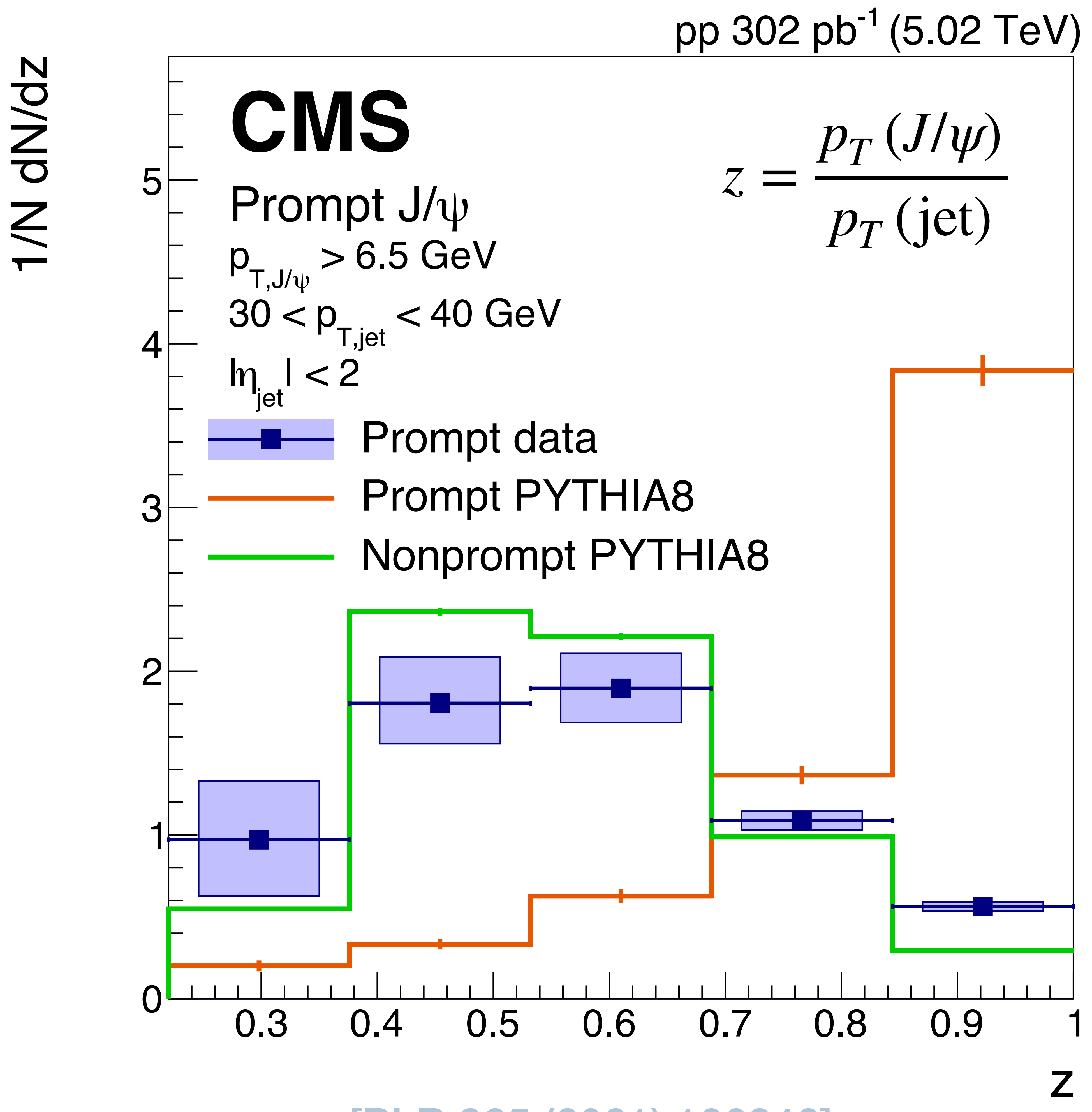
Late jet fragmentation picture

How open heavy flavors are formed

- J/ψ only carries partial transverse momentum in the jet shower



J/ψ Production Potential Jet Fragmentation

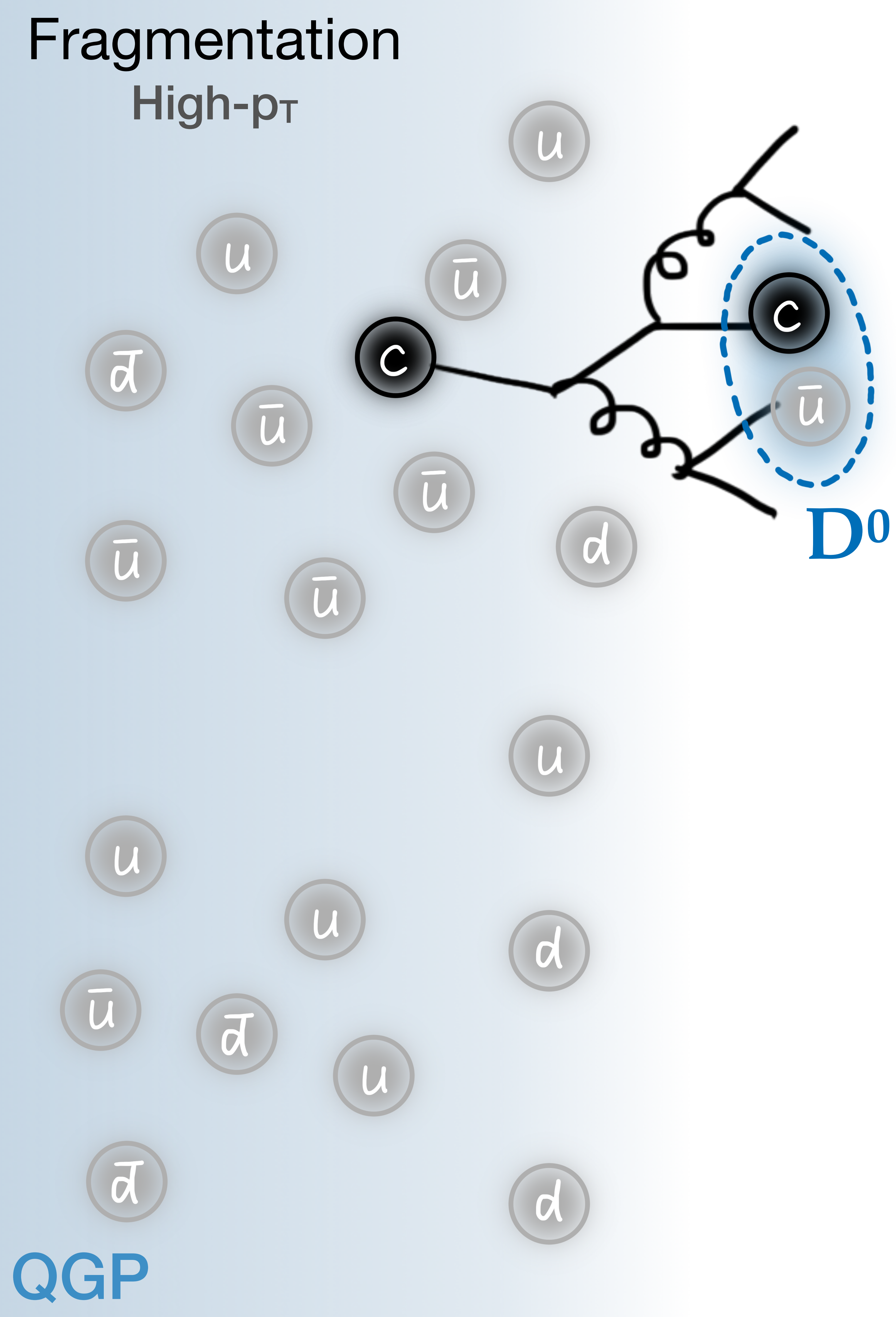


[PLB 825 (2021) 136842]

Early bound state picture
Late jet fragmentation picture

- J/ψ have more surrounding jet activities than (model) expected in pp
  - Similar to open heavy flavors
  - Parton energy loss may also play an important role in J/ψ suppression in HIC

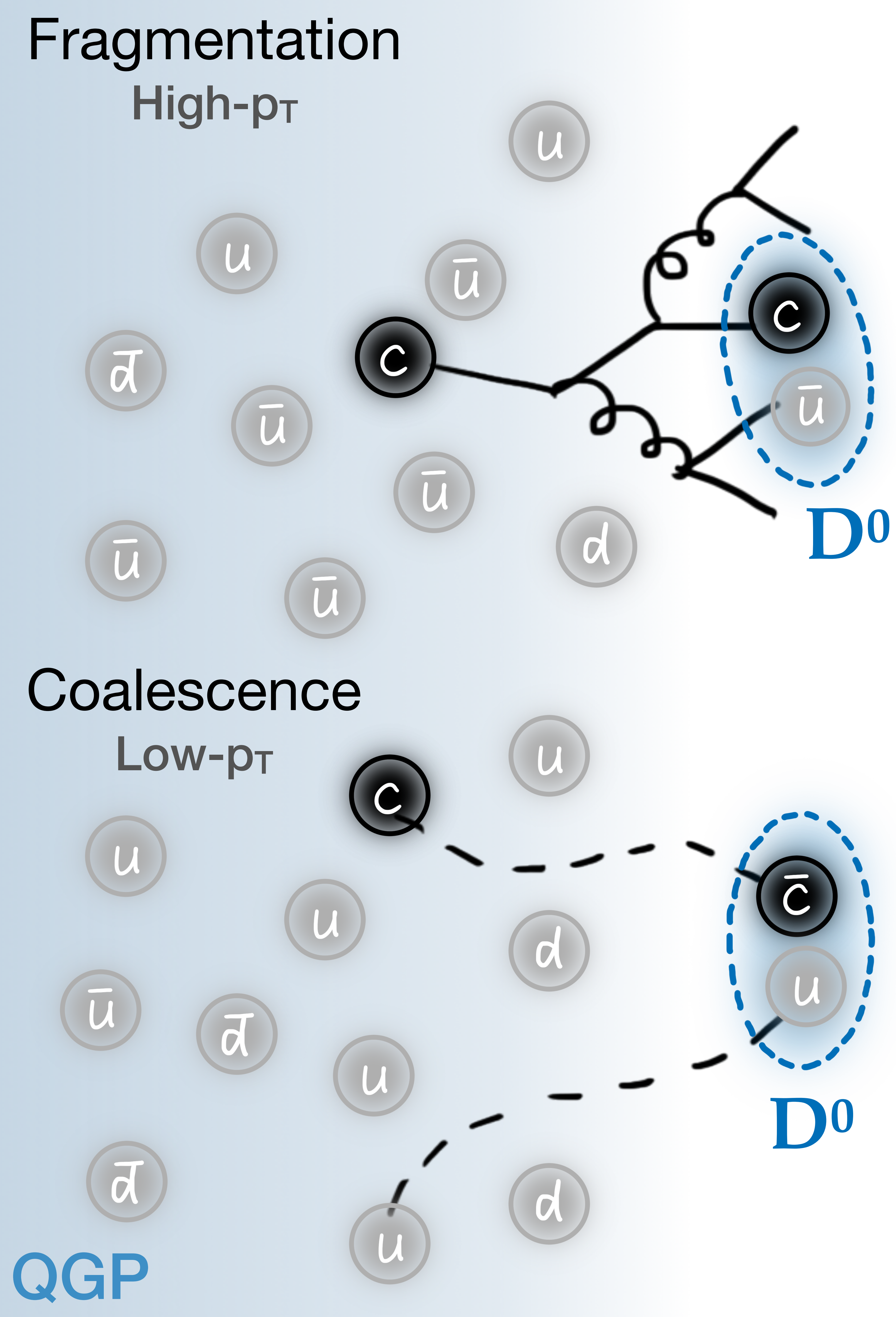
Open HF Hadrons Really from Fragmentation?



Hadronization Non-perturbative problem

- Fragmentation universality assumed across collision systems
  - Default scheme in generators, constrained by measurements in e^+e^- and ep collisions
  - Successful in HF meson production in pp

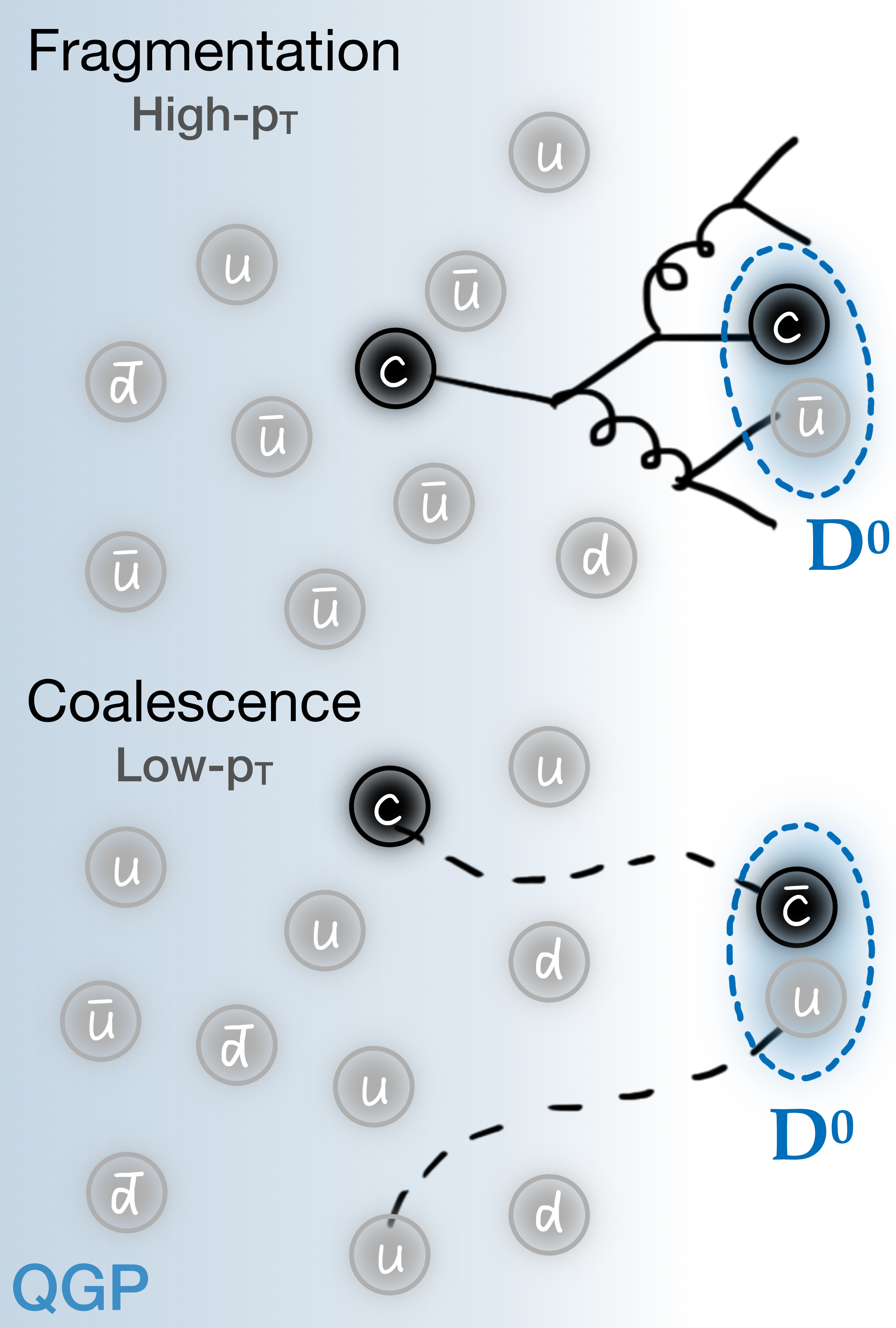
Open HF Hadrons Really from Fragmentation?



Hadronization Non-perturbative problem

- Fragmentation universality assumed across collision systems
  - Default scheme in generators, constrained by measurements in e^+e^- and ep collisions
  - Successful in HF meson production in pp
- Modification of hadronization expected in medium
  - Fragmentation + coalescence (combination with partons from medium)

Hadronization Study In Experiments



Hadronization Can only measure hadrons in experiments

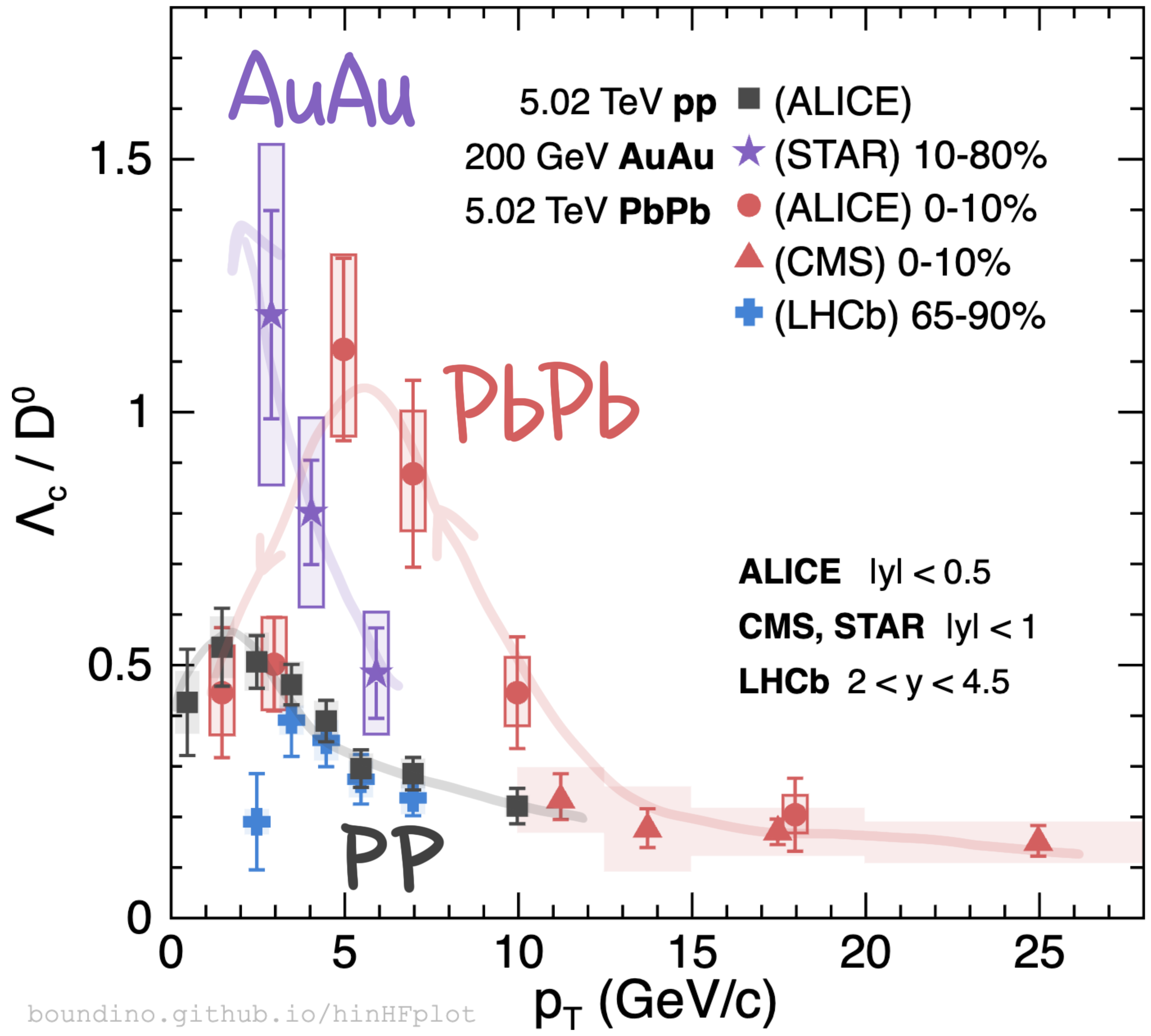
- Fragmentation universality and parameters of hadronization models need to be tested and constraint by data
  - Hadrons with different quark content as experimental proxy

If there is coalescence

Higher D_s / D^0 expected
strangeness enhancement

Higher Λ_c / D^0 expected
more valence quarks

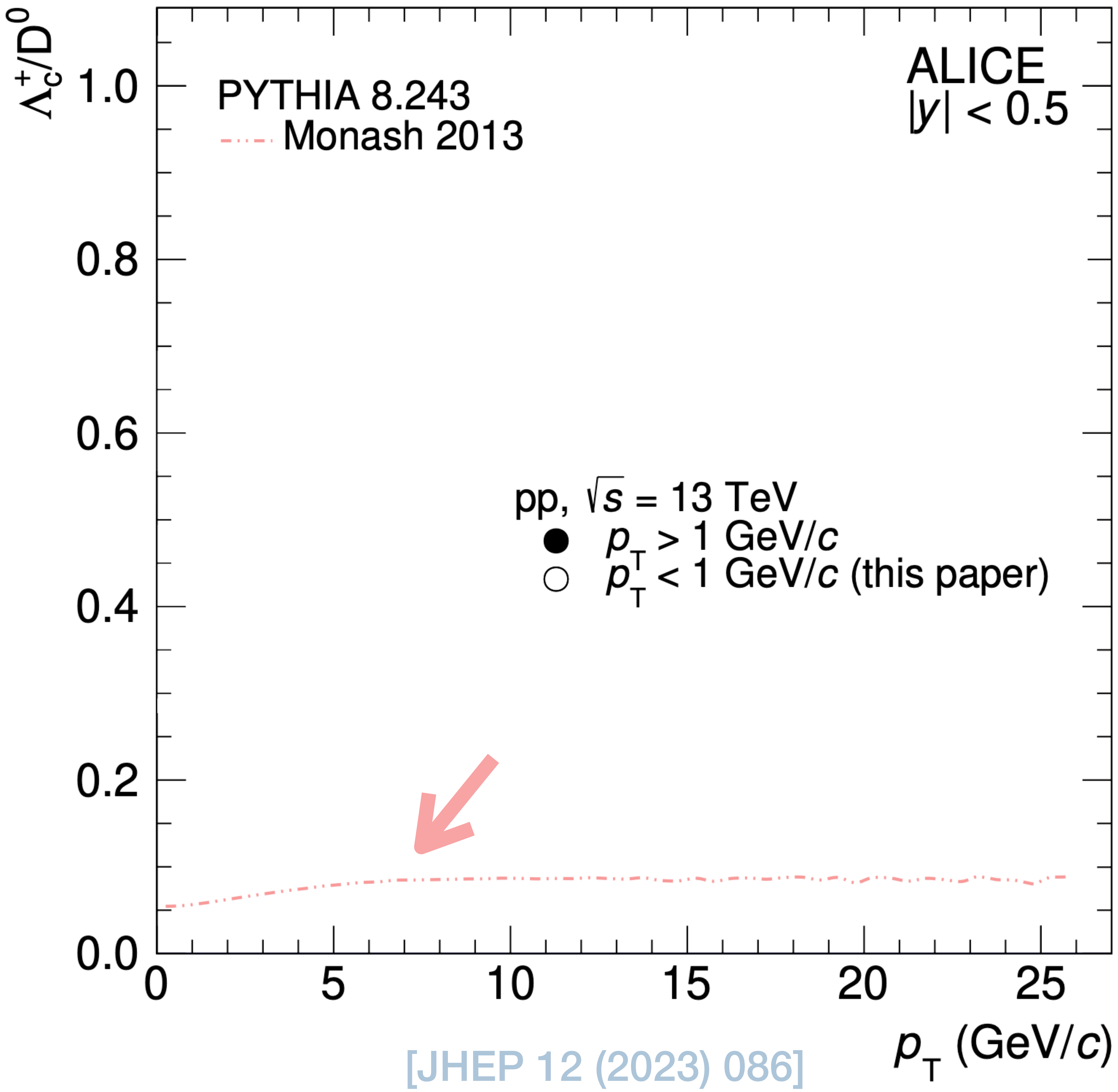
Coalescence Charm Bayron Λ_c in AA Collisions



- Significant larger Λ_c / D^0 in AA compared to pp at intermediate p_T
  - Consistent with coalescence picture

EPJC 78 (2018) 762 JHEP 02 (2024) 066

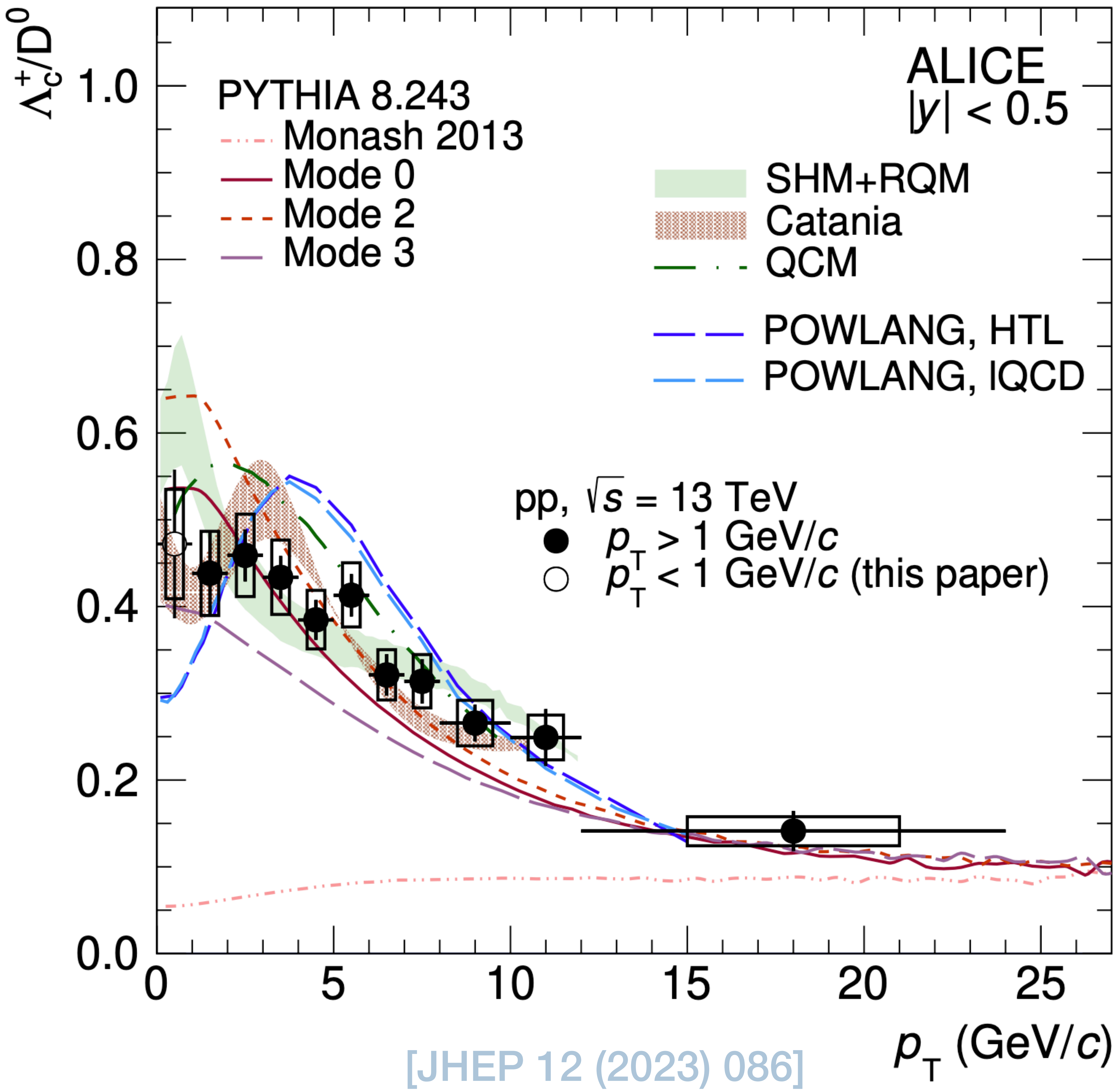
Hadronization in pp Charm Bayron Λ_c



[JHEP 12 (2023) 086]

- Fragmentation function constrained by e^+e^- predicts Λ_c / D^0 to be 0.05 - 0.1 in pp
  - Weak p_T dependence

Hadronization in pp Charm Bayron Λ_c



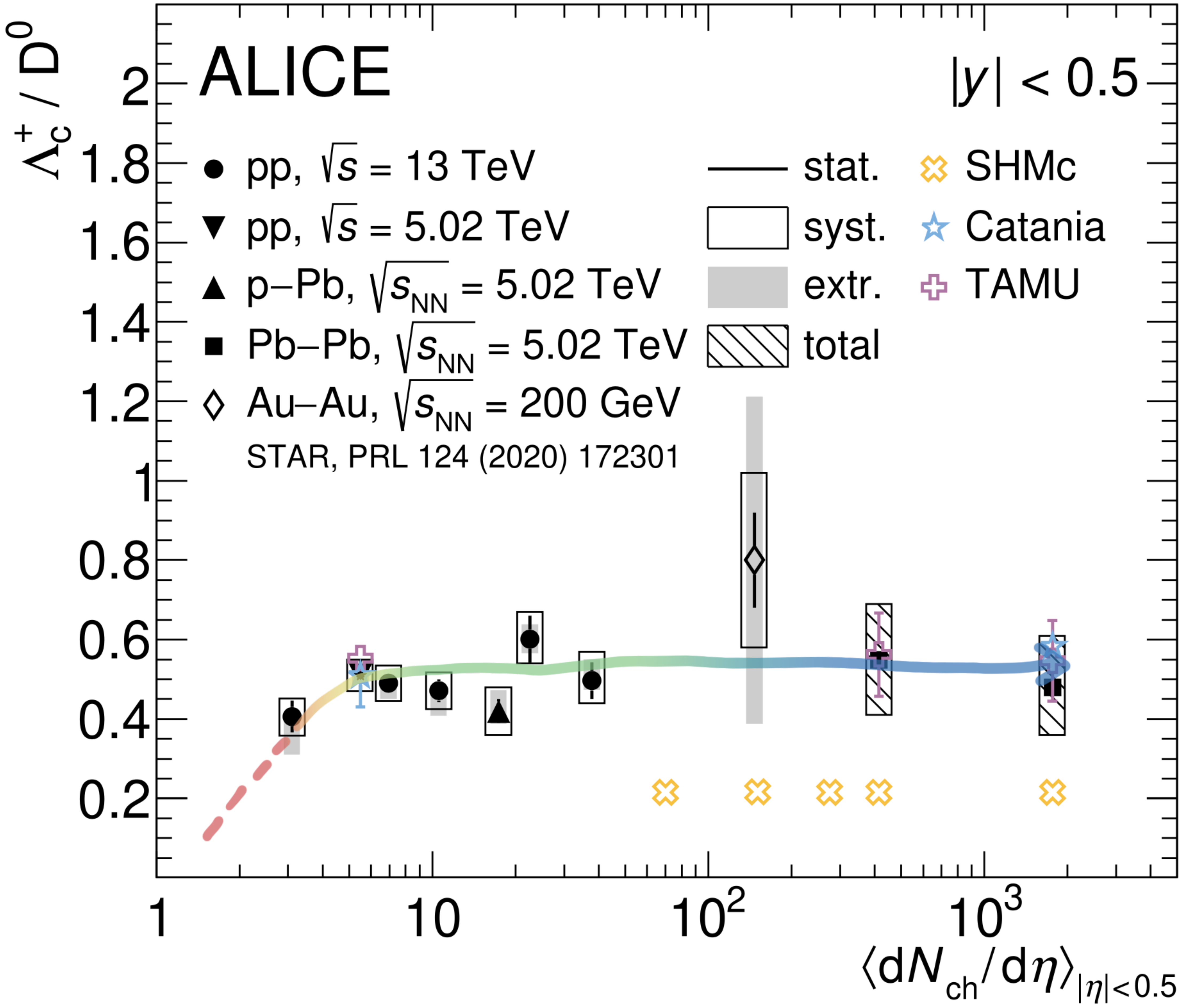
[JHEP 12 (2023) 086]

- Significant larger Λ_c / D^0 observed in pp
  - Stronger enhancement at low p_T
- Theoretical efforts to describe it
  - More excited baryons
  - Color reconnection
  - Coalescence also in pp

↑ Details see theoretical lectures

In experiments, multiplicity is a way to vary final state effects and connect different collision systems

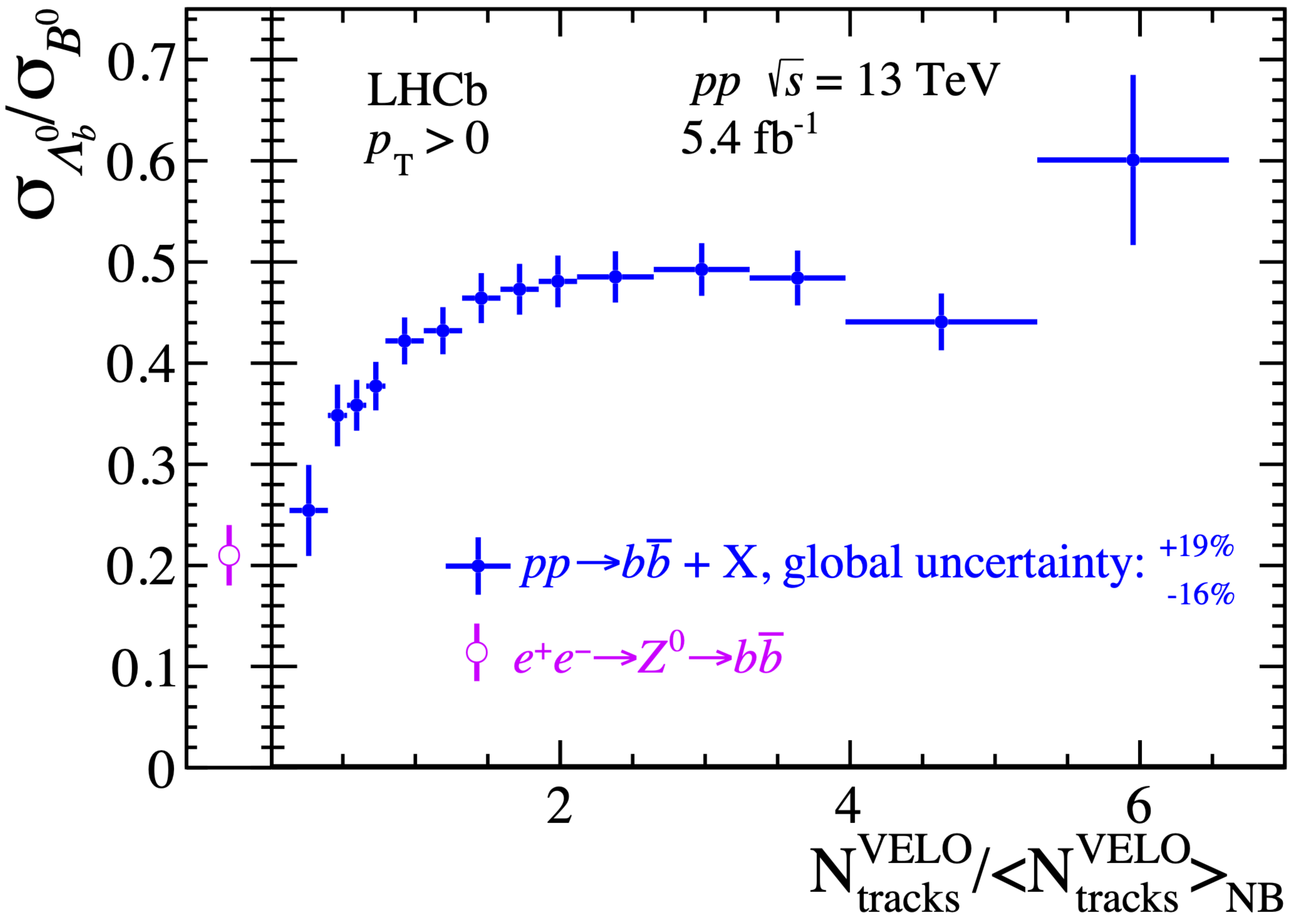
Hadronization in One Picture Λ_c/D^0 vs Multiplicity



[PLB 839 (2023) 137796]

- p_T-Integrated Λ_c / D^0 increases dramatically at small multiplicity from e^+e^- to low-multiplicity pp
  - but no data there
- Λ_c / D^0 keeps same for a wide range of multiplicity from pp to peripheral AA
- p_T-Integrated Λ_c / D^0 keeps same but p_T redistributed from peripheral to central AA

Hadronization in One Picture Λ_b/B^0 vs Multiplicity



- Similar observations for beauty sector
  - No results in AA collisions though

[PRL 132 (2024) 081901]

Hadronization Strangeness Mesons

Extension for Homework

- Using the same way we read Λ_c and Λ_b results, understand what is the current picture from the measurements of strangeness hadrons

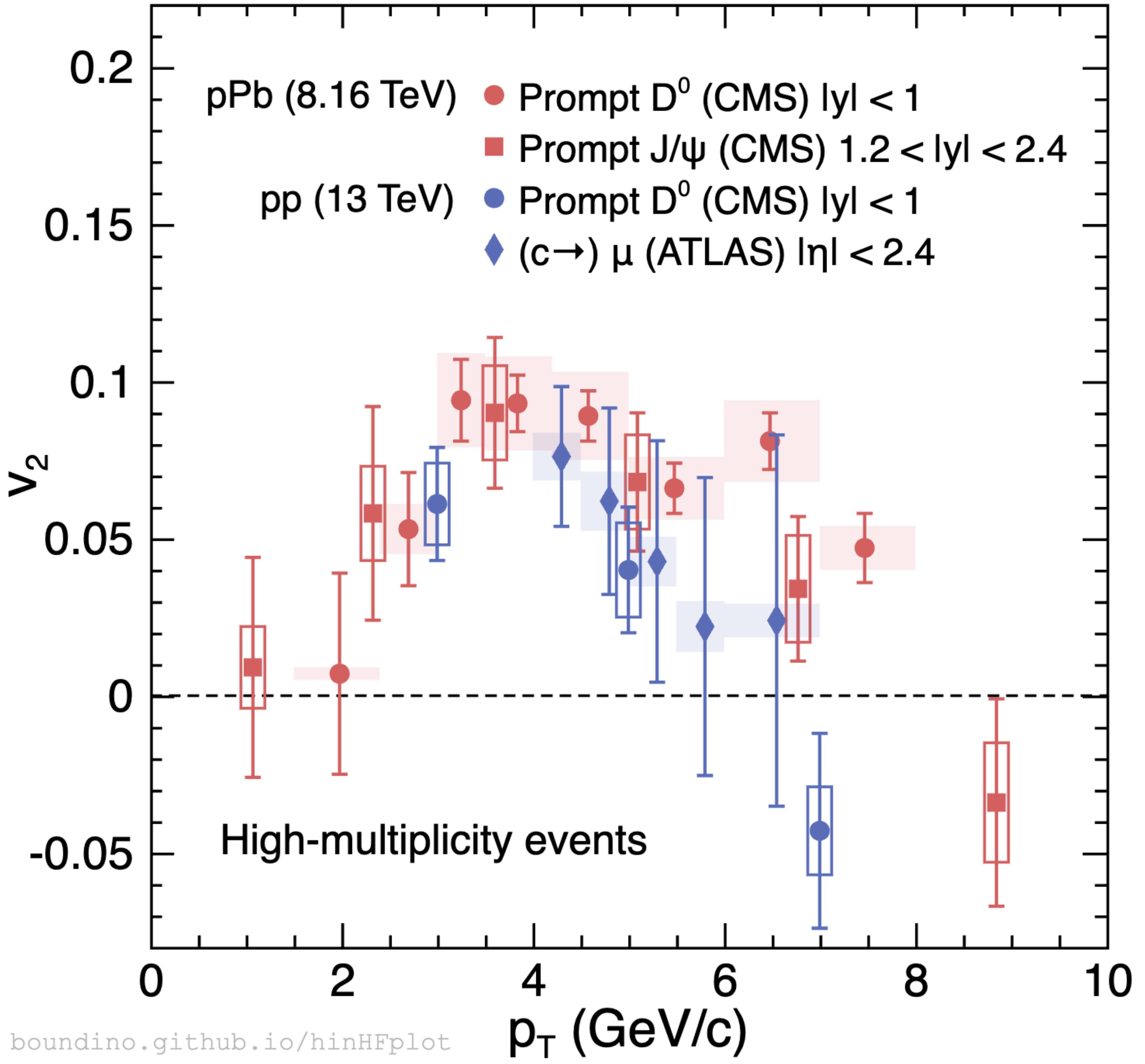
- D_s/D^+ in PbPb PLB 827 (2022) 136986 ALICE
- B_s/B^+ in PbPb PLB 829 (2022) 137062 CMS
- D_s/D^+ vs multiplicity in pPb 2311.08490 LHCb
- B_s/B^0 vs multiplicity in pPb PRL 131 (2023) 061901 LHCb
- D_s/D^+ vs multiplicity in pp PLB 829 (2022) 137065 ALICE

Small Systems Being Hot Really Matters?

Can be (kinda) understood in QGP | **Small systems where no QGP is expected**

Observations in AA collisions		Observations in pp/pA collisions
Strong suppression	Jet quenching	No energy loss observed yet
Enhancement of baryon production	Coalescence	Hadronization modification in pp/pA
Collective flow	Pressure driven medium expansion	?
$Q\bar{Q}$ sequential suppression	Dissociation as per binding energy	?

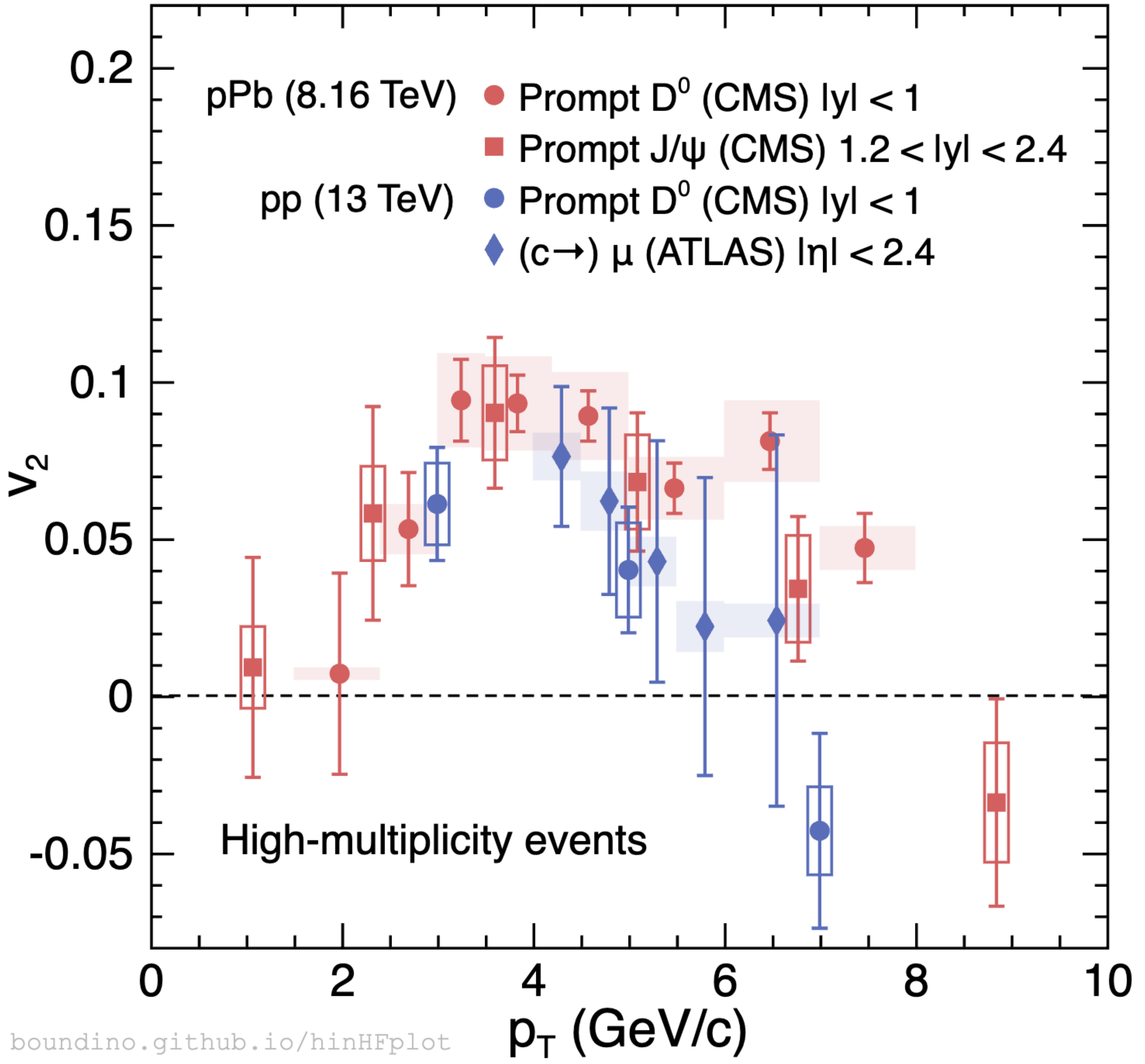
Small Systems Collective Behaviors



- Non-zero v_2 of charm hadrons in high-multiplicity pp and pPb collisions
- Source of flow signals not decisive
  - Maybe initial transverse momentum correlation in CGC framework
  - Maybe small QGP medium in final states

PRL 121 (2018) 082301 PLB 813 (2021) 136036 PLB 791 (2019) 172 PRL 124 (2020) 082301

Small Systems Non-Flow Subtraction

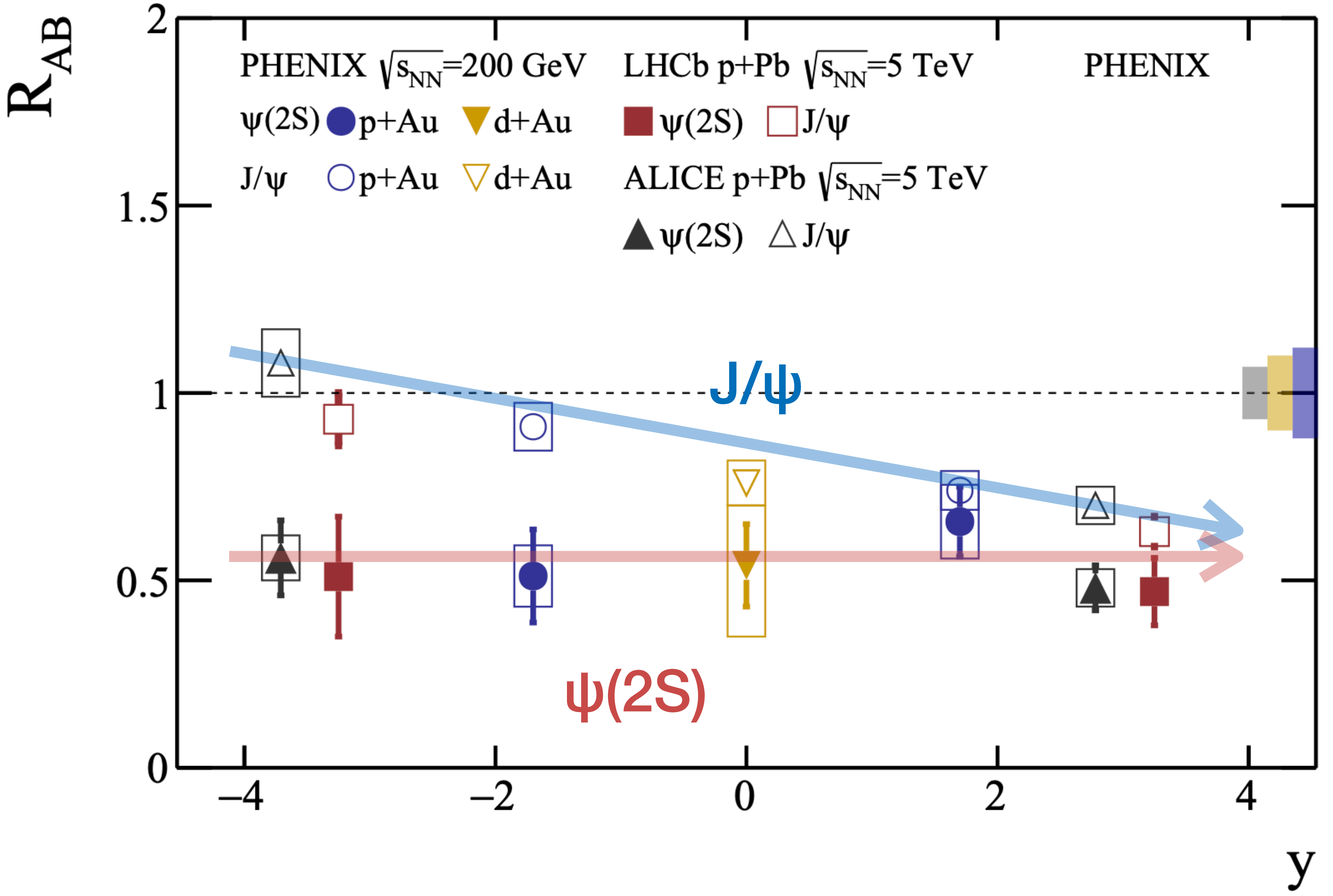


- Non-flow contribution needs to be subtracted
  - Major sources
    - Back-to-back dijets / multi-jets
    - Resonance decay
  - Subtraction method differs between experiments, commonly assuming nonflow
    - independent of multiplicity
    - dominates in low-multiplicity events

PRL 121 (2018) 082301 PLB 813 (2021) 136036 PLB 791 (2019) 172 PRL 124 (2020) 082301

Small Systems Quarkonia Sequential Suppression

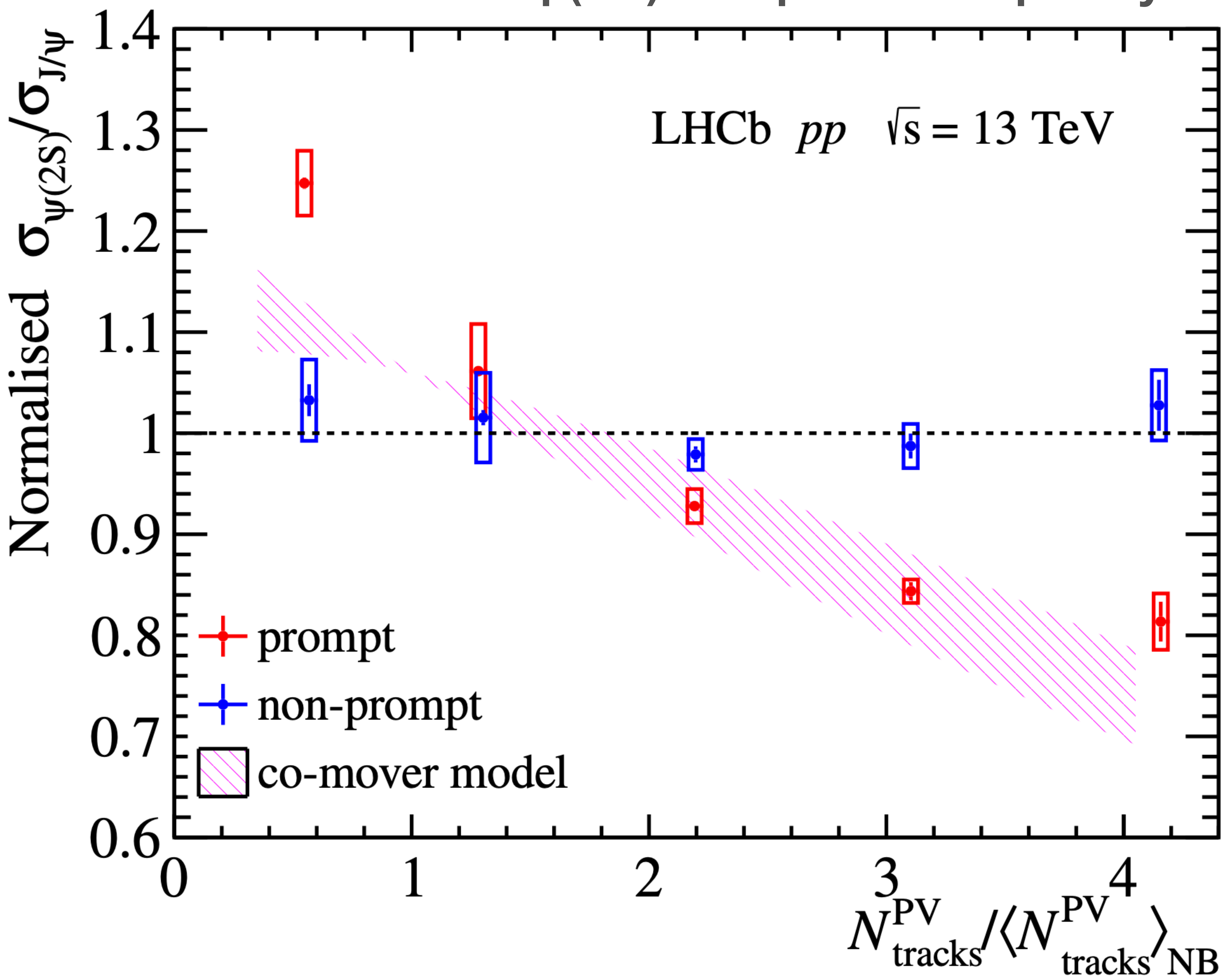
J/ψ or ψ(2S) R_{pA} vs y



- Not surprising J/ψ R_{pA} is not unity
  - Nuclear PDF
  - Initial coherent energy loss
- These initial state effects cannot explain different R_{pA} of J/ψ and ψ(2S)

Small Systems Quarkonia Sequential Suppression

Normalized ψ(2S) / J/ψ vs multiplicity

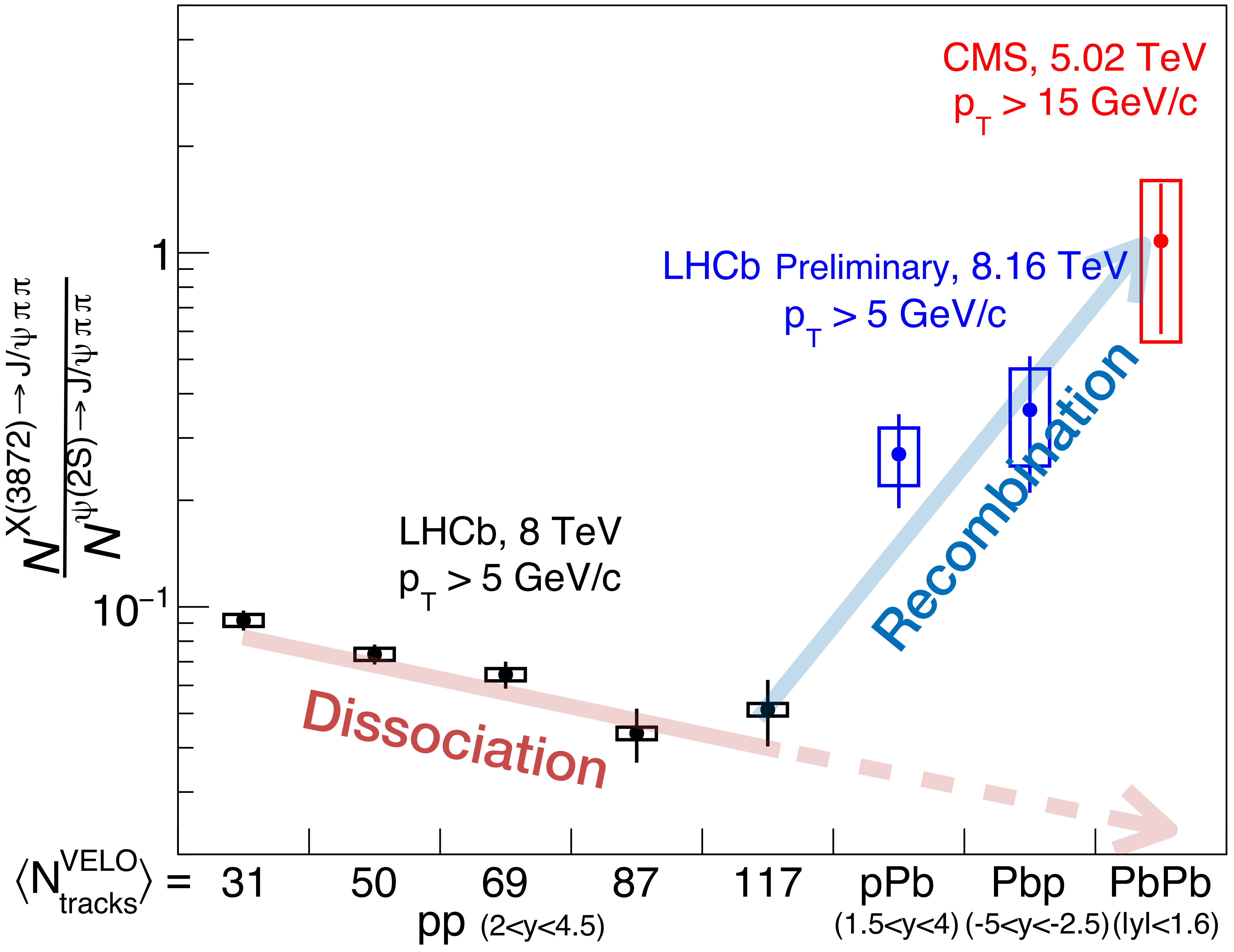


[JHEP 05 (2024) 243]

- Double ratio of ψ(2S) to J/ψ
  - Cancel initial state effects
- Vary multiplicities
  - Examine potential final state effects
    - comover dissociation
    - small medium droplet created

Apply Production Mechanism Probe Exotica Structure

X(3872) / ψ(2S) across collision systems

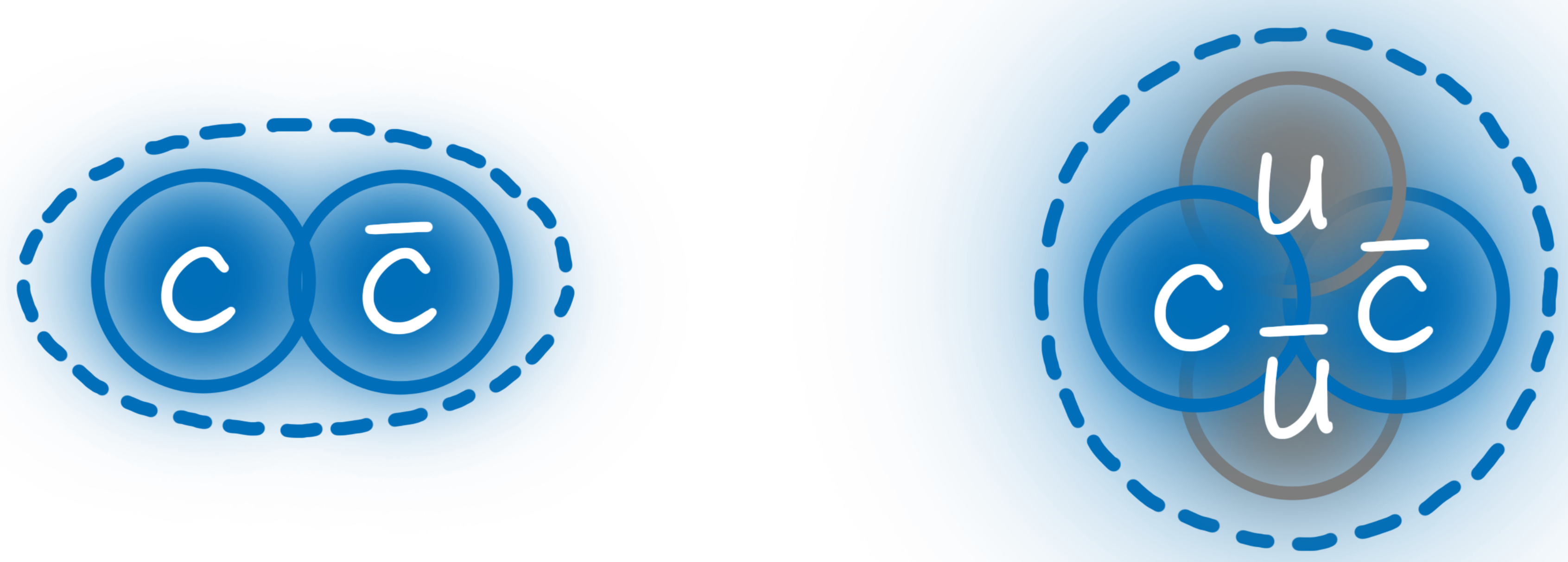


Low multiplicity **High multiplicity**

[2402.14975]

X(3872) to ψ(2S) yield ratio across collision systems

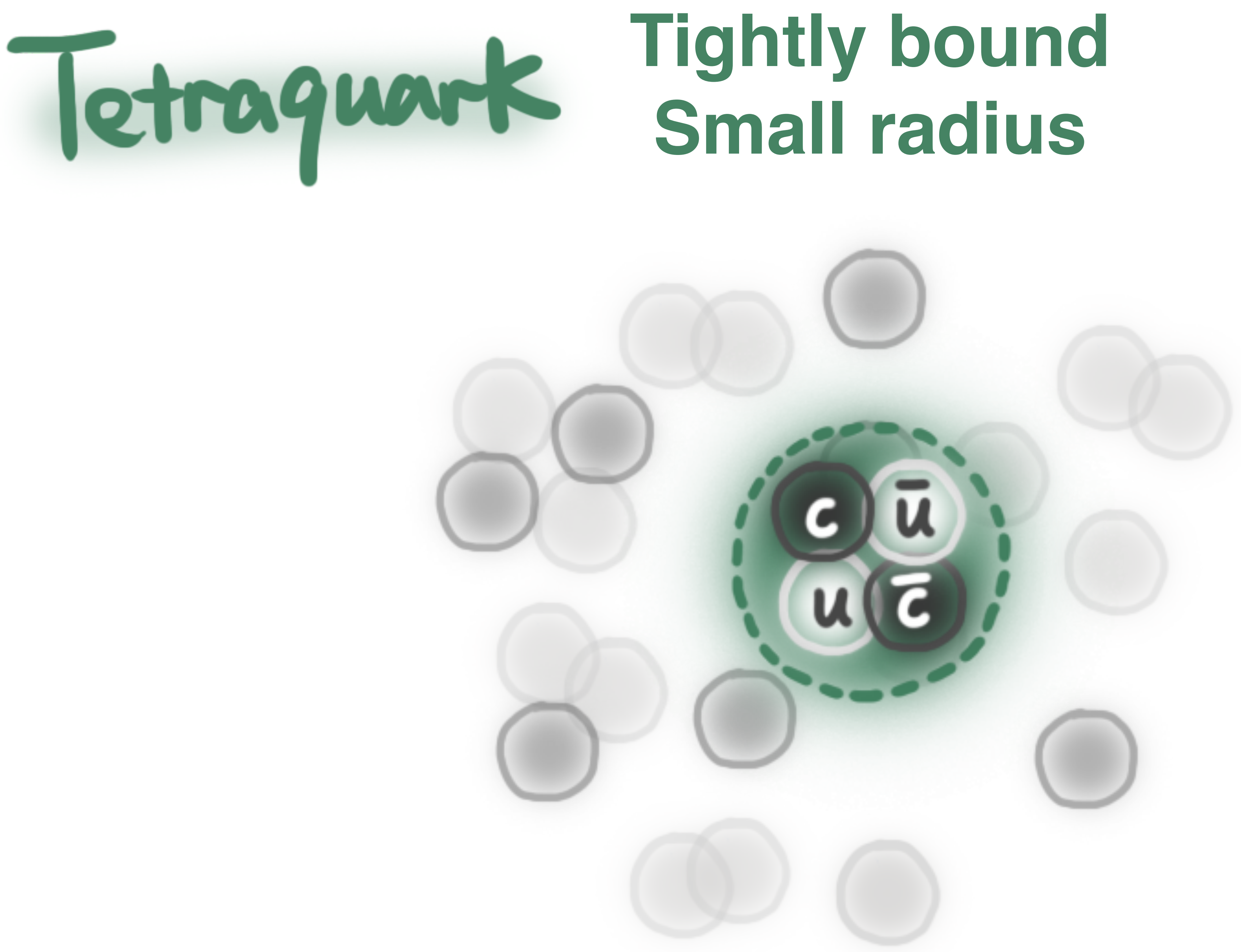
- Dissociated by interactions with comovers (pp/pPb) or medium (PbPb)
  - Different binding energy
- Enhanced via recombination



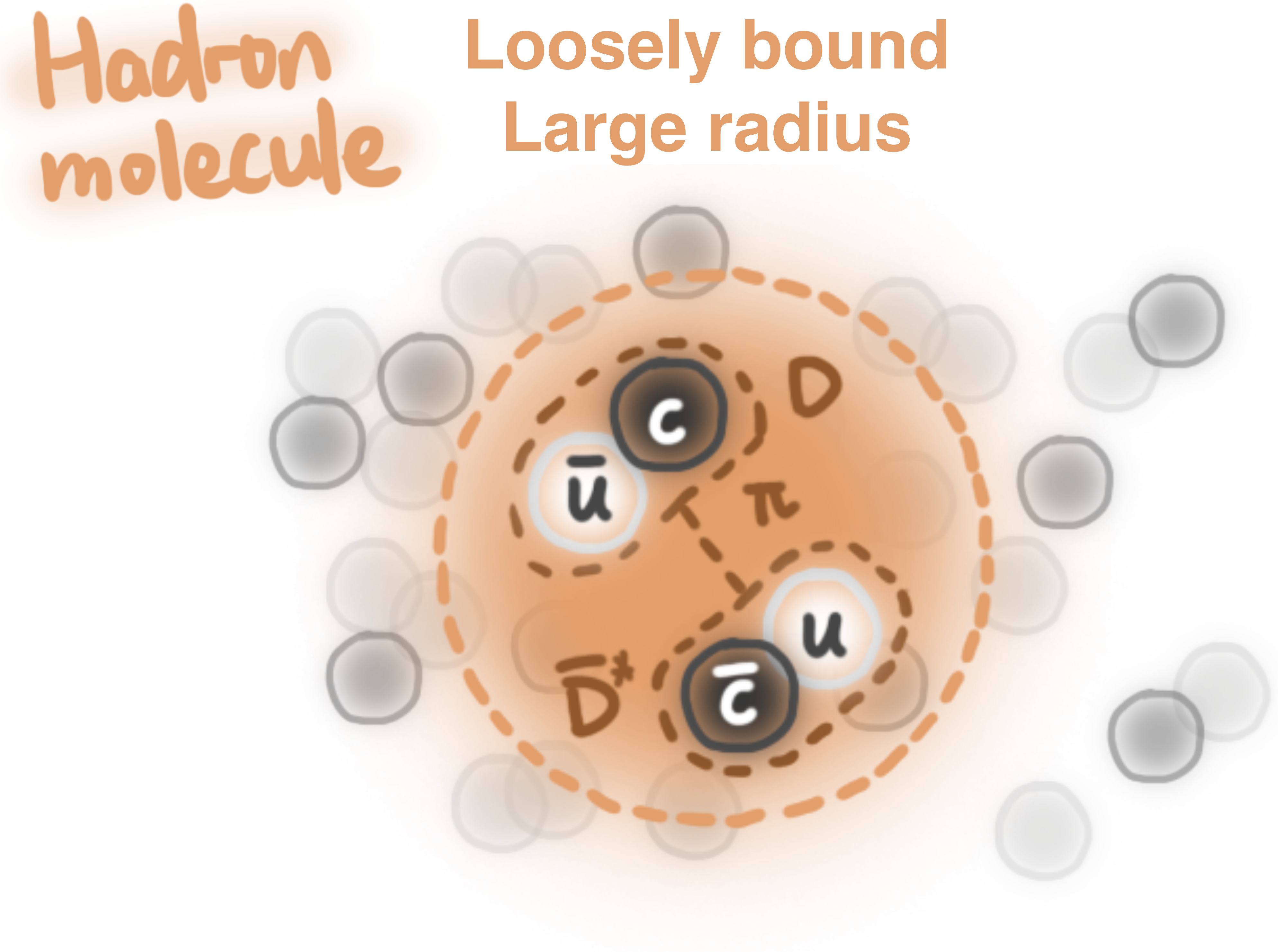
ψ(2S) X(3872)

Apply Production Mechanism Probe Exotica Structure

- Both effects depend on inner structure differently
  - Discriminate nature of exotica - Independent input in addition to quantum number



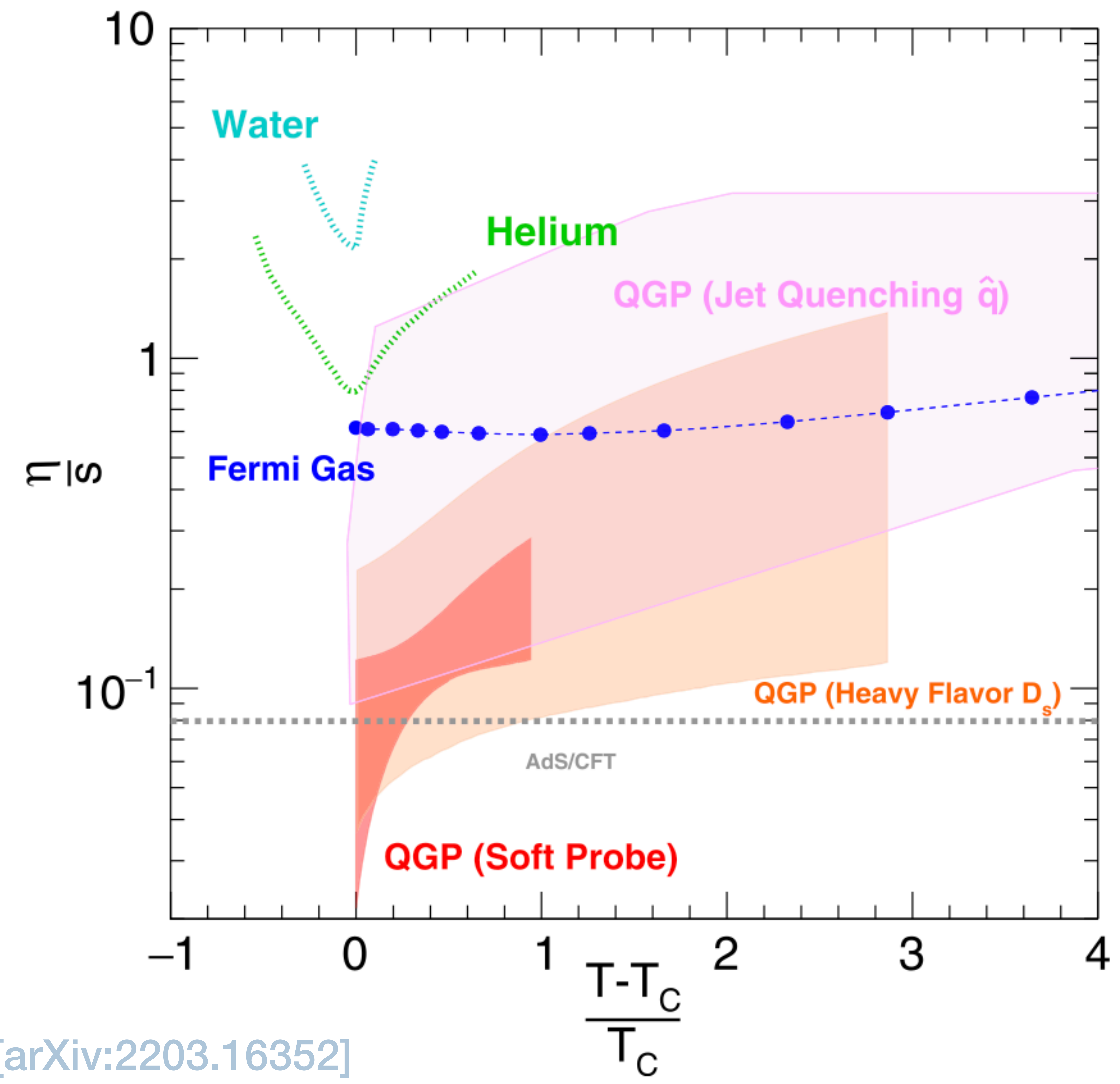
Tightly bound
Small radius



Loosely bound
Large radius

20-year debate of X(3872) nature

Let Probes Be Probes



[arXiv:2203.16352]

- Specific shear viscosity η/s derived by HF D_s
  - Consistent with soft probe
    - Sizable uncertainty though
  - Hard probes → unique high temperature
- Need substantial efforts to achieve
  - Observables › properties
  - Phenomenology › microscopic structure

Goal of This Lecture

Help you understand what people are talking about in next SQM

Enjoy Play Time!

🔗 Quiz Game

🔗 Heavy flavor result playground

Win a particle magnet by answering 3 questions correctly
Unlimited try…

Get to know the fruitful heavy flavor measurements by different experiments

I'll be around all the way to Friday to redeem the prize

[jing.wang@cern.ch]

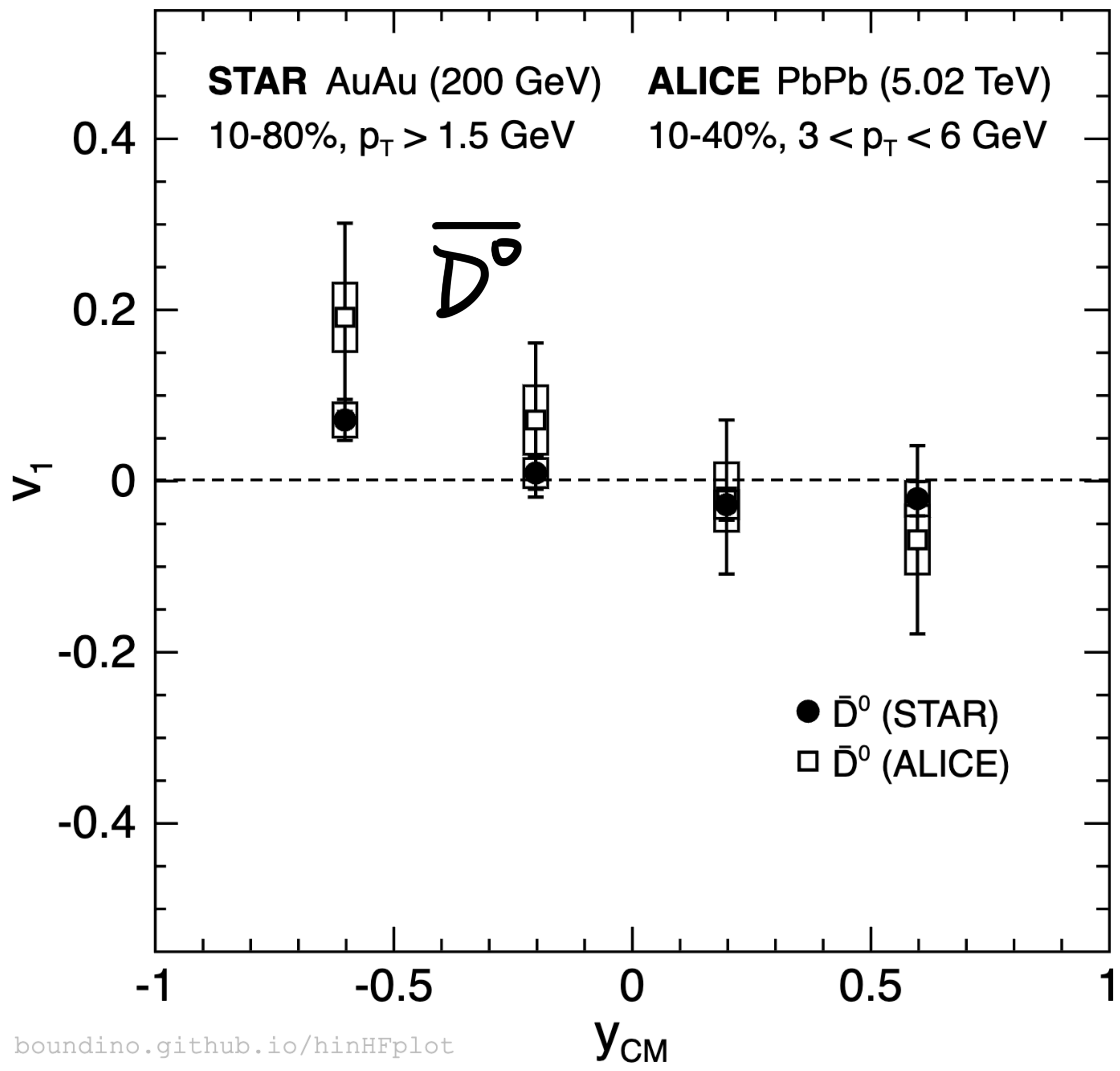

Isabelle
Thanks for your attention!

If there's more time

Let's have more fun!

HF Probe Initial Condition Tilt of Medium

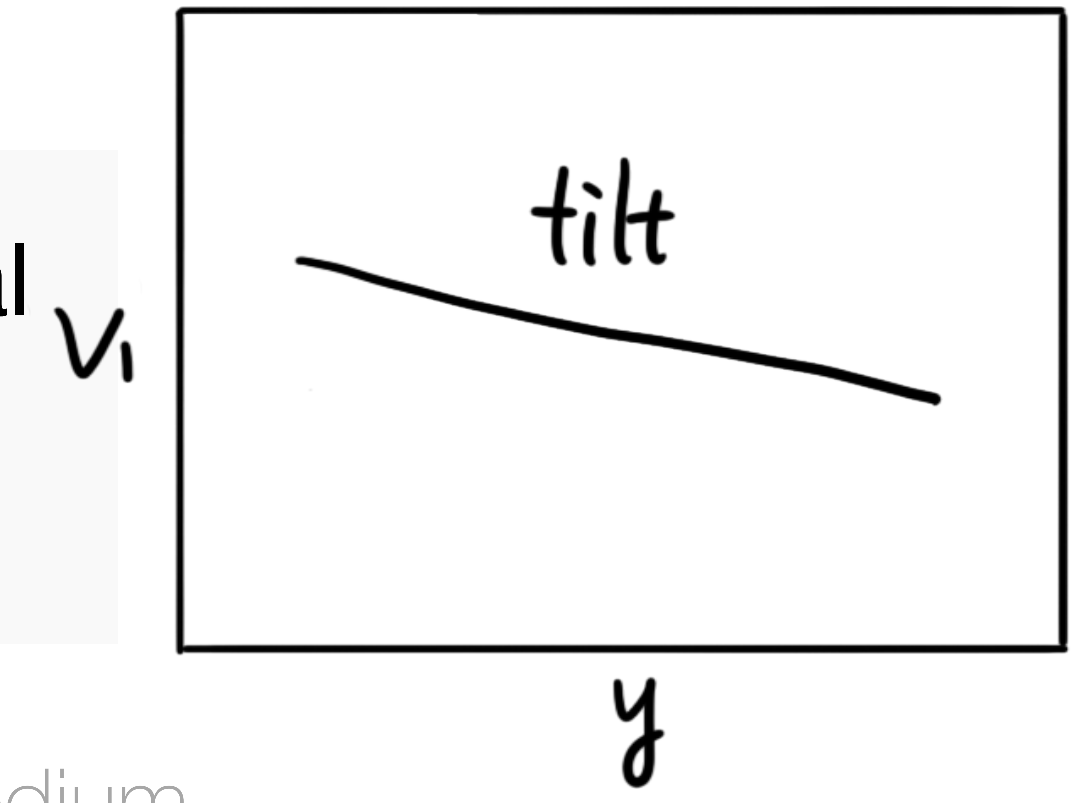
v_1 vs. y in PbPb, AuAu



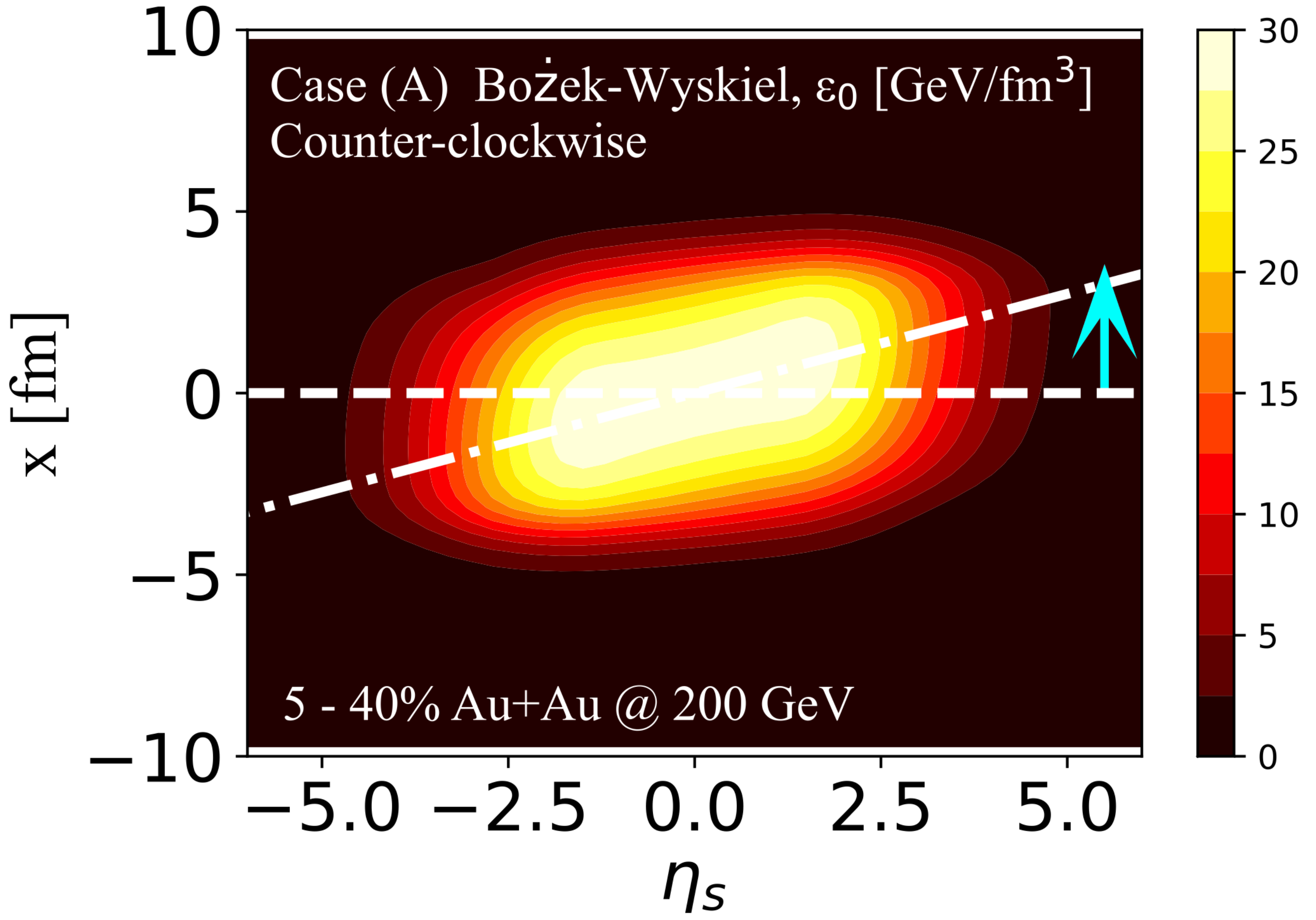
PRL 125 (2020) 022301

PRL 123 (2019) 162301

- Tilt → Longitudinal structure of initial energy density distribution
  ➡ Non-zero (rapidity-dependent) v_1



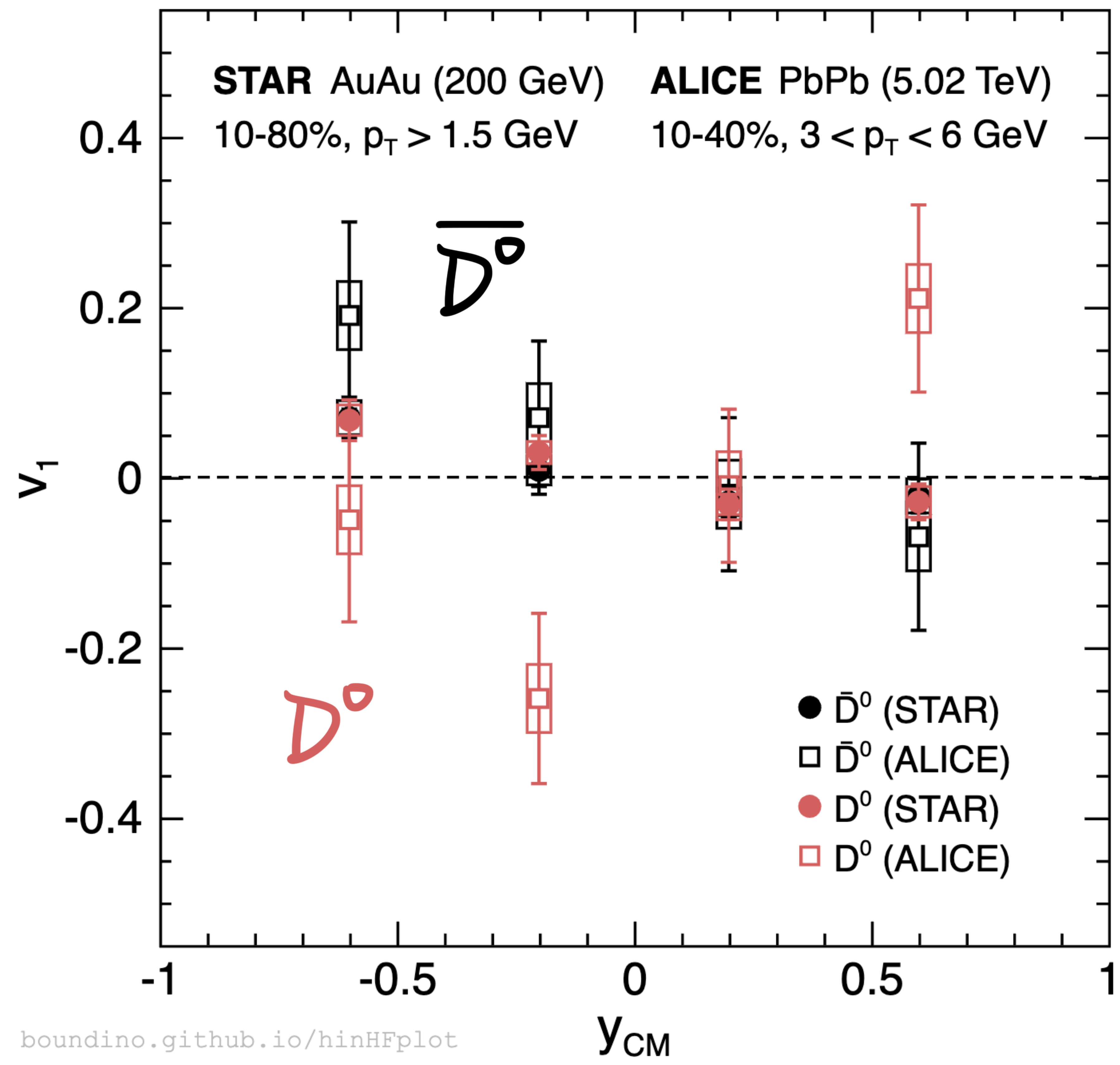
Counter clockwise tilt of the medium



PRC 105 (2022) 034901

HF Probe Initial Condition Strong EM Field

v_1 vs. y in PbPb, AuAu

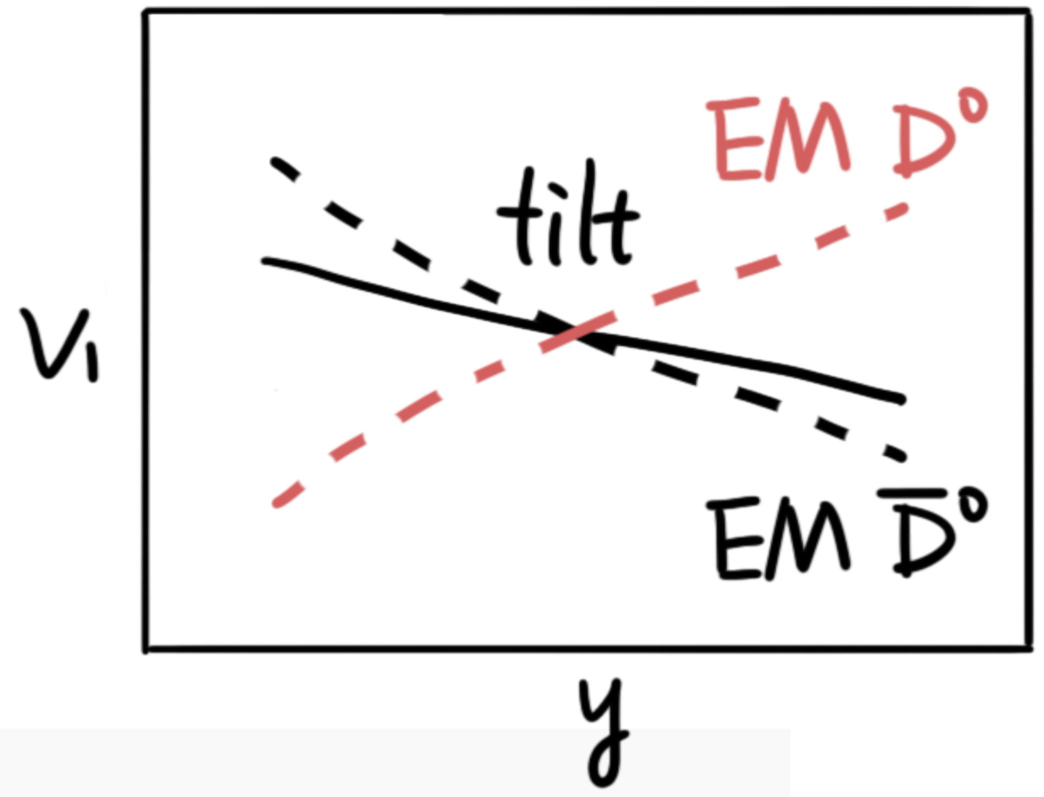


boundino.github.io/hinHFplot

PRL 125 (2020) 022301

PRL 123 (2019) 162301

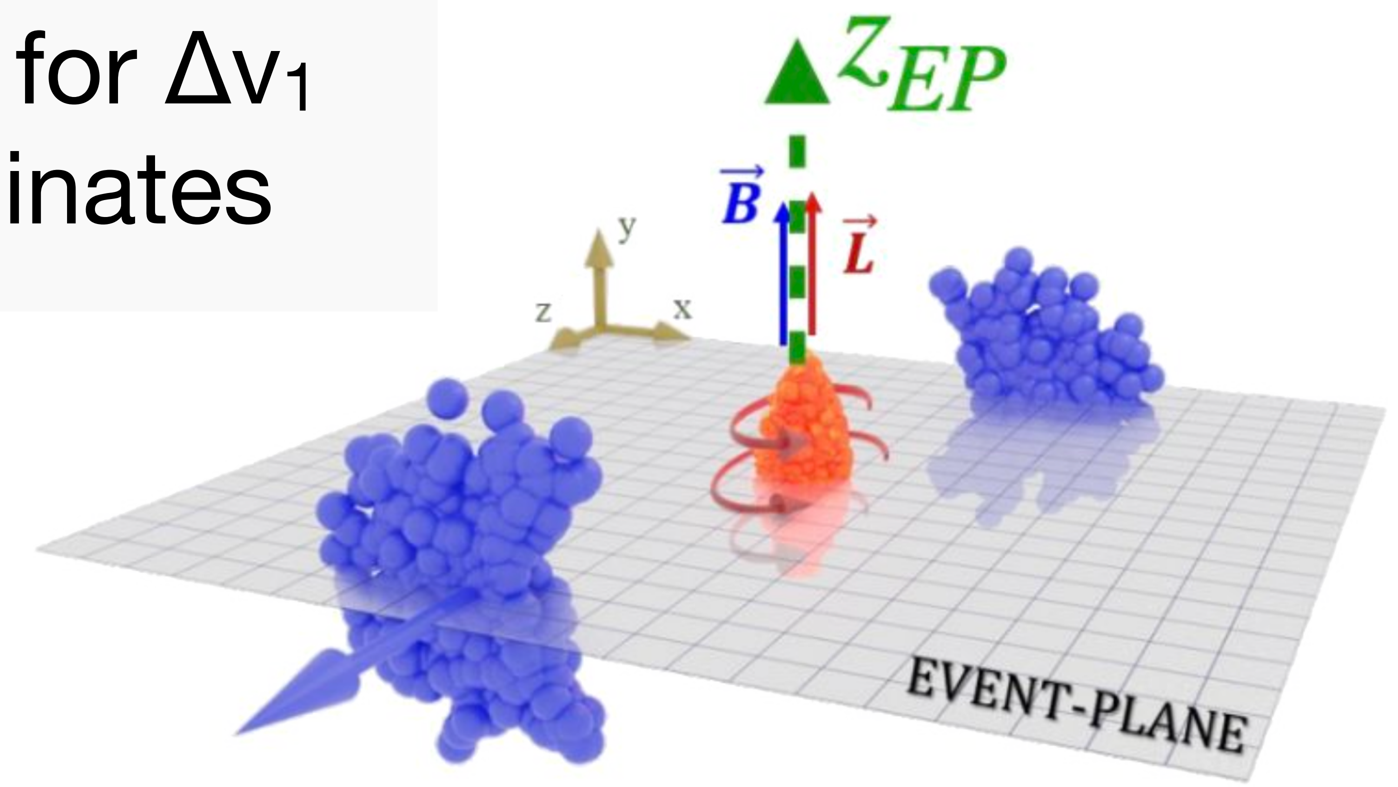
- Tilt → Longitudinal structure of initial energy density distribution
  ➡ Non-zero (rapidity-dependent) v_1



- Strong EM field emerges at early stage
  - Decays quickly → unique chance for heavy flavors

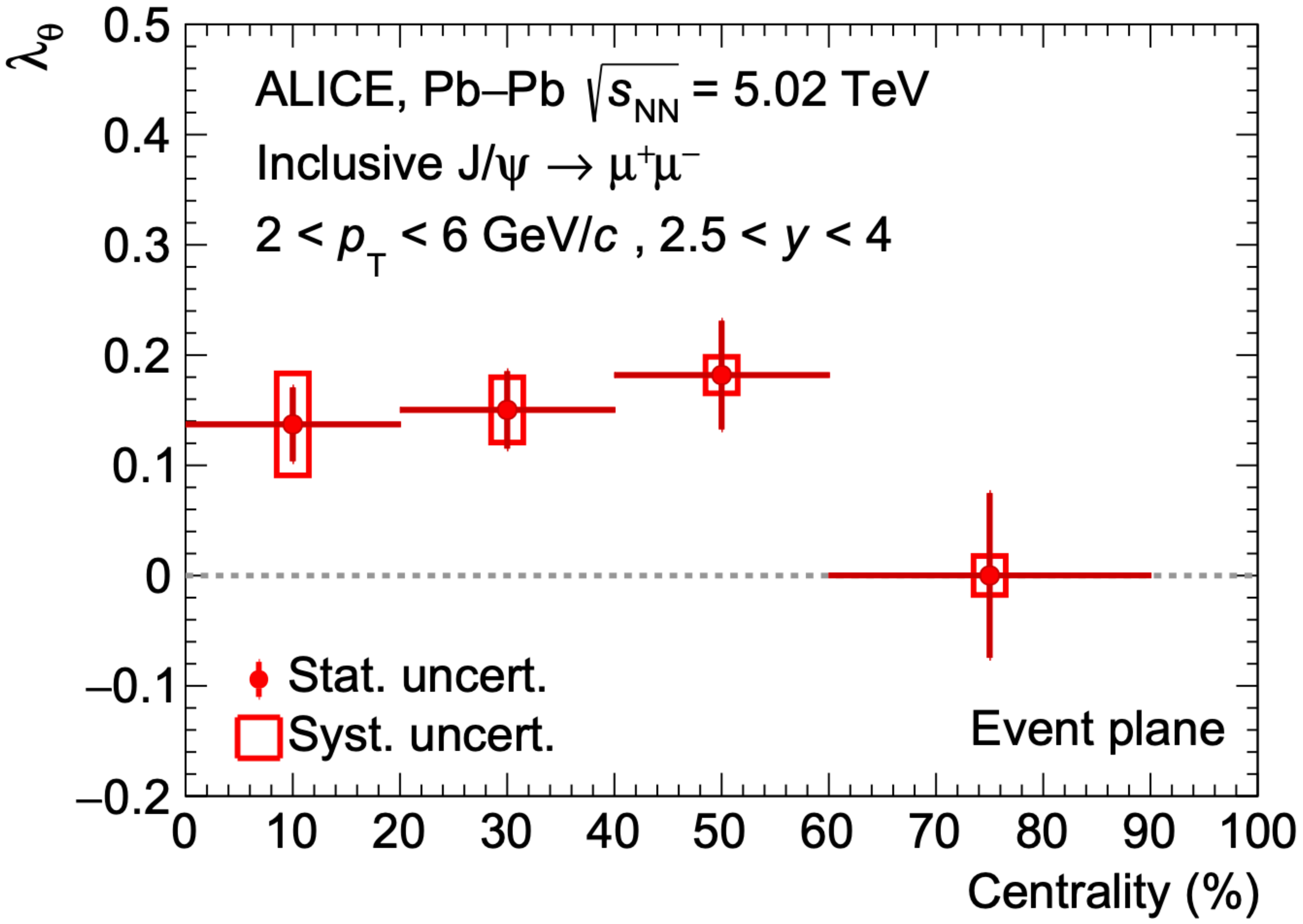
  ➡ Split v_1 of c and c̄ → non-zero (rapidity-dep) Δv_1

- Difference b/w LHC and RHIC for Δv_1
  - Possibly different effect dominates



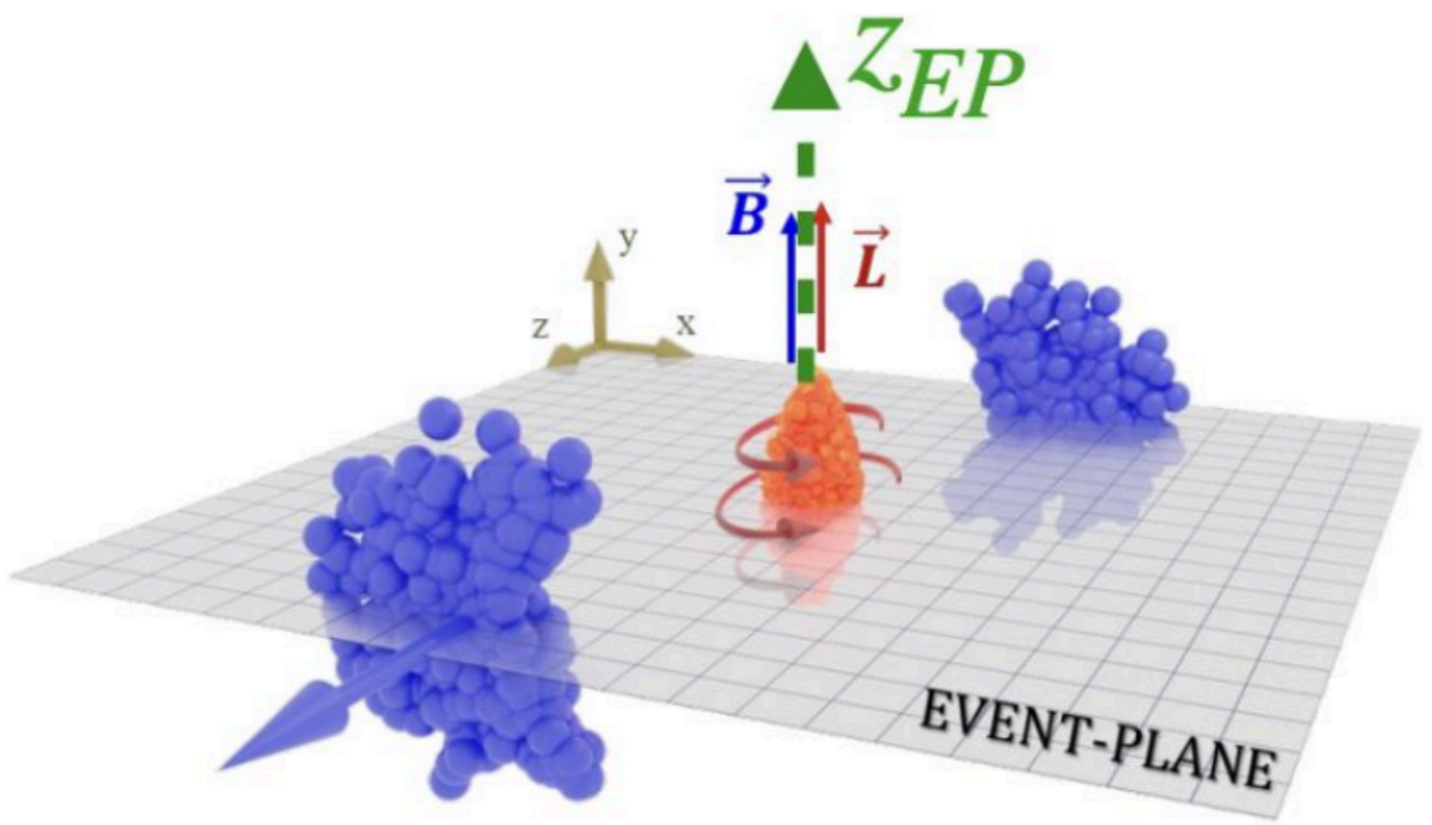
J/ψ Polarization Initial B Field, Vorticity

J/ψ Polarization

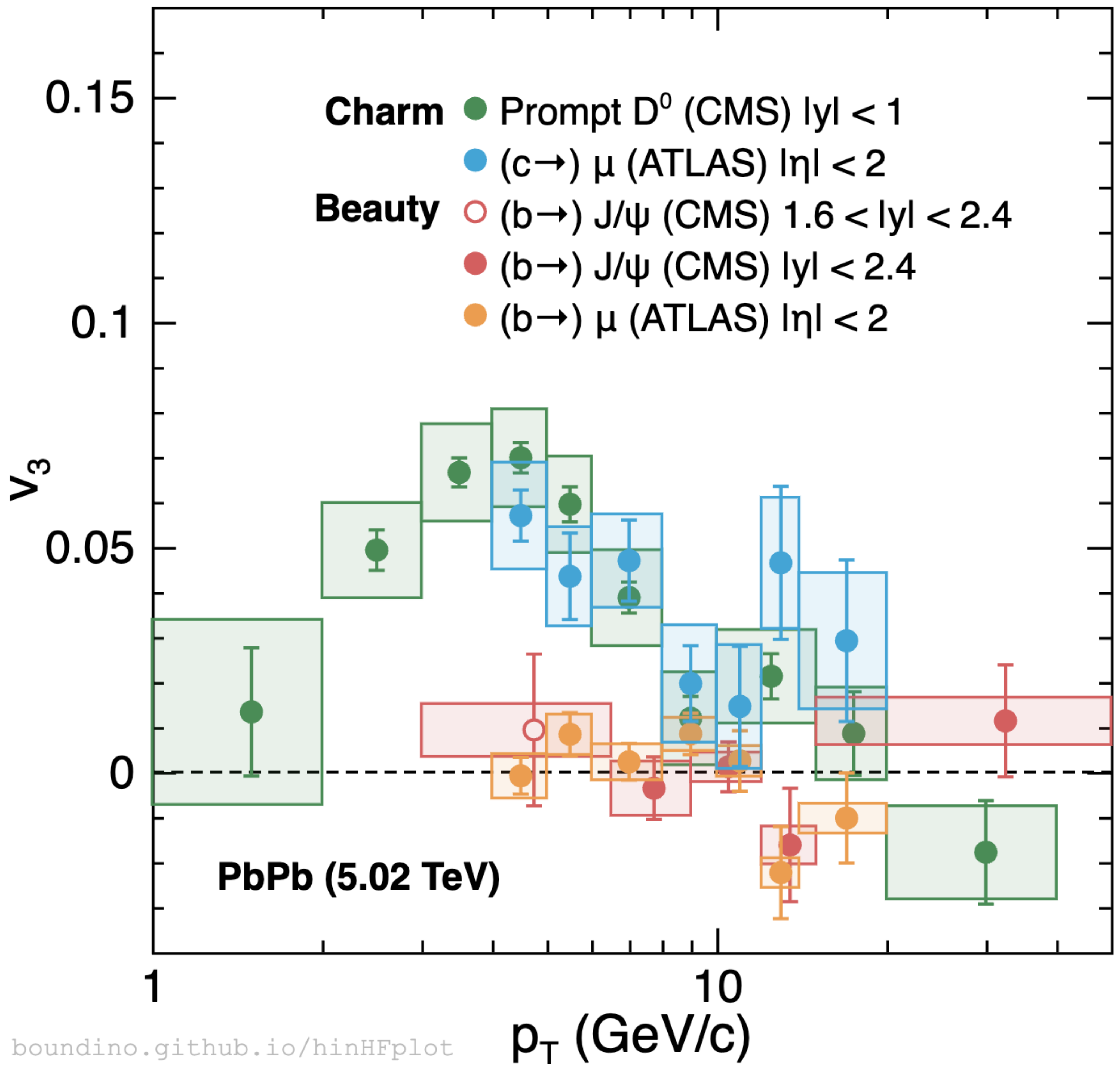


arXiv:2204.10171

- $\lambda_\theta > 0$ → Transverse polarization in the direction perpendicular to the reaction plane
  ➜ connected with
  - Strong magnetic field
  - Rotation at early stage via spin-orbit coupling



HF Probe Fluctuations Initial Geometry

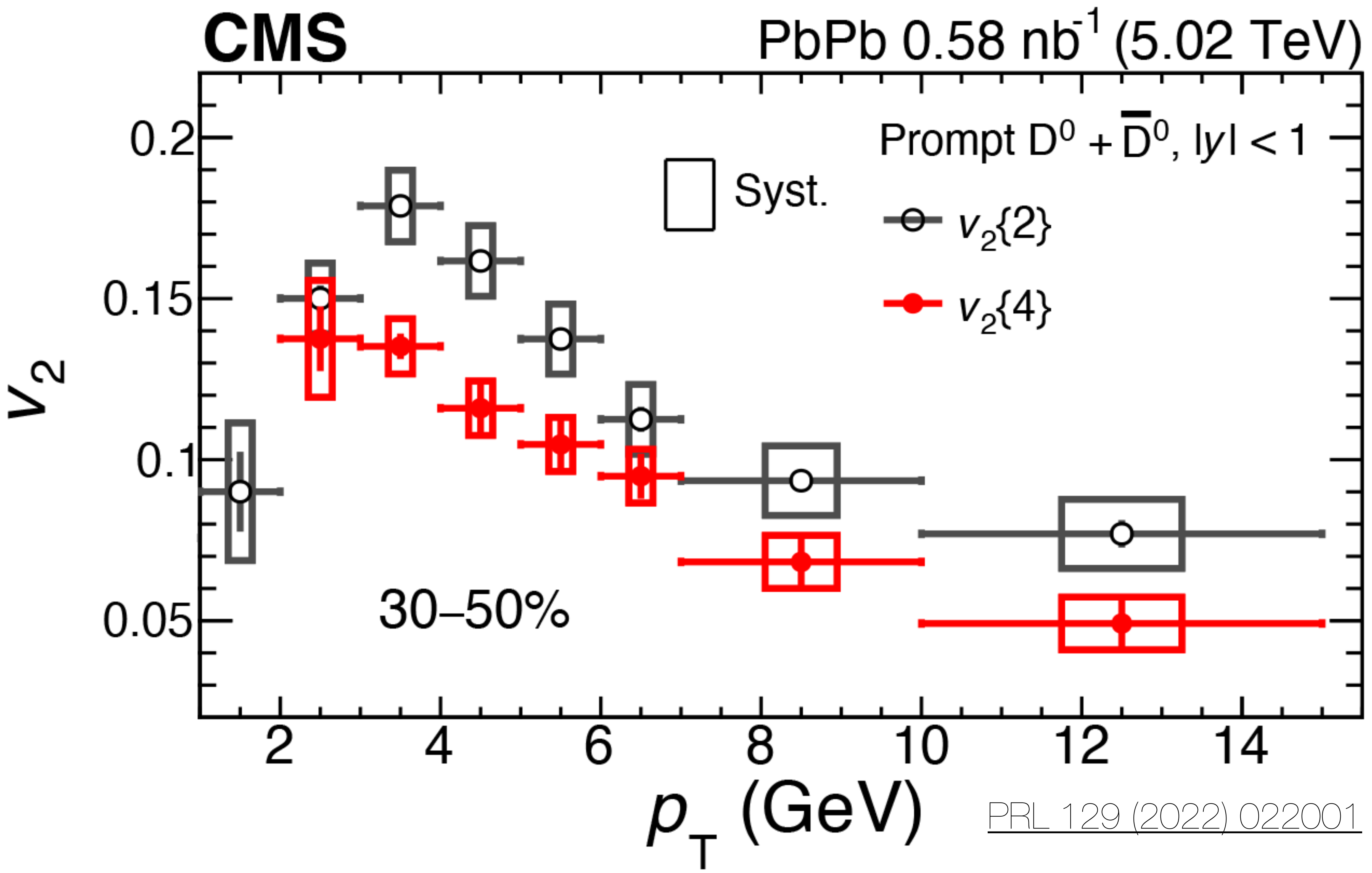


- High-order vn probes event-by-event fluctuation of initial geometry
  - Similar to soft probes but different length-wave probes

PLB 816 (2021) 136253 CMS-PAS-HIN-21-008
PLB 807 (2020) 135595 PLB 807 (2020) 135595

HF Probe Fluctuations Energy Loss

D^0 4-particle correlation $v_2\{4\}$



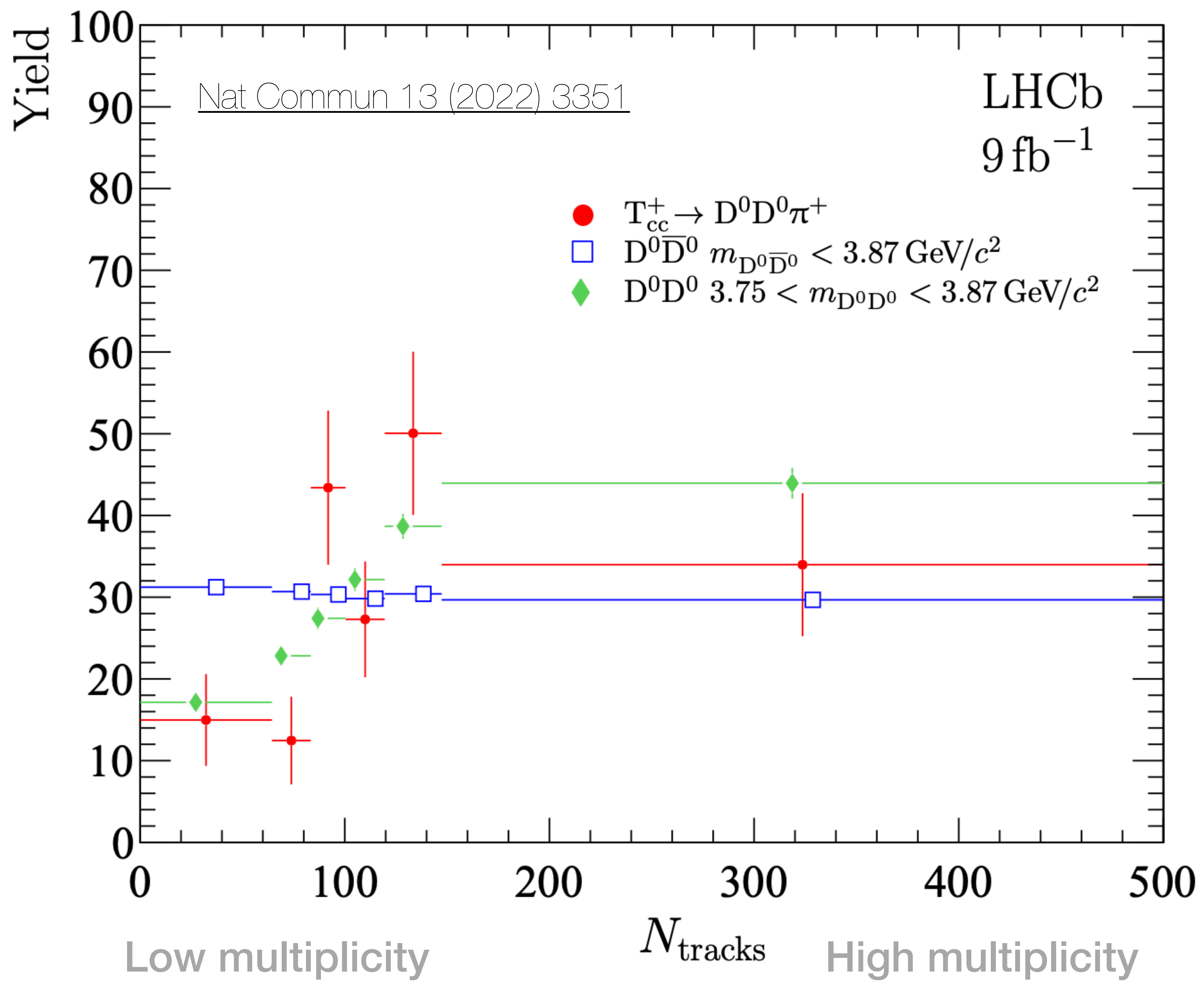
PRL 129 (2022) 022001

- Probe event-by-event fluctuation
  - $v_2\{2\}^2 \approx \langle v \rangle^2 + \sigma^2$
  - $v_2\{4\}^2 \approx \langle v \rangle^2 - \sigma^2$

  flow fluctuation
- Indeed $v_2\{4\} < v_2\{2\}$ for D^0
  - Provide additional constraints
- v_2 fluctuations from both initial geometry (soft) and energy loss (hard)

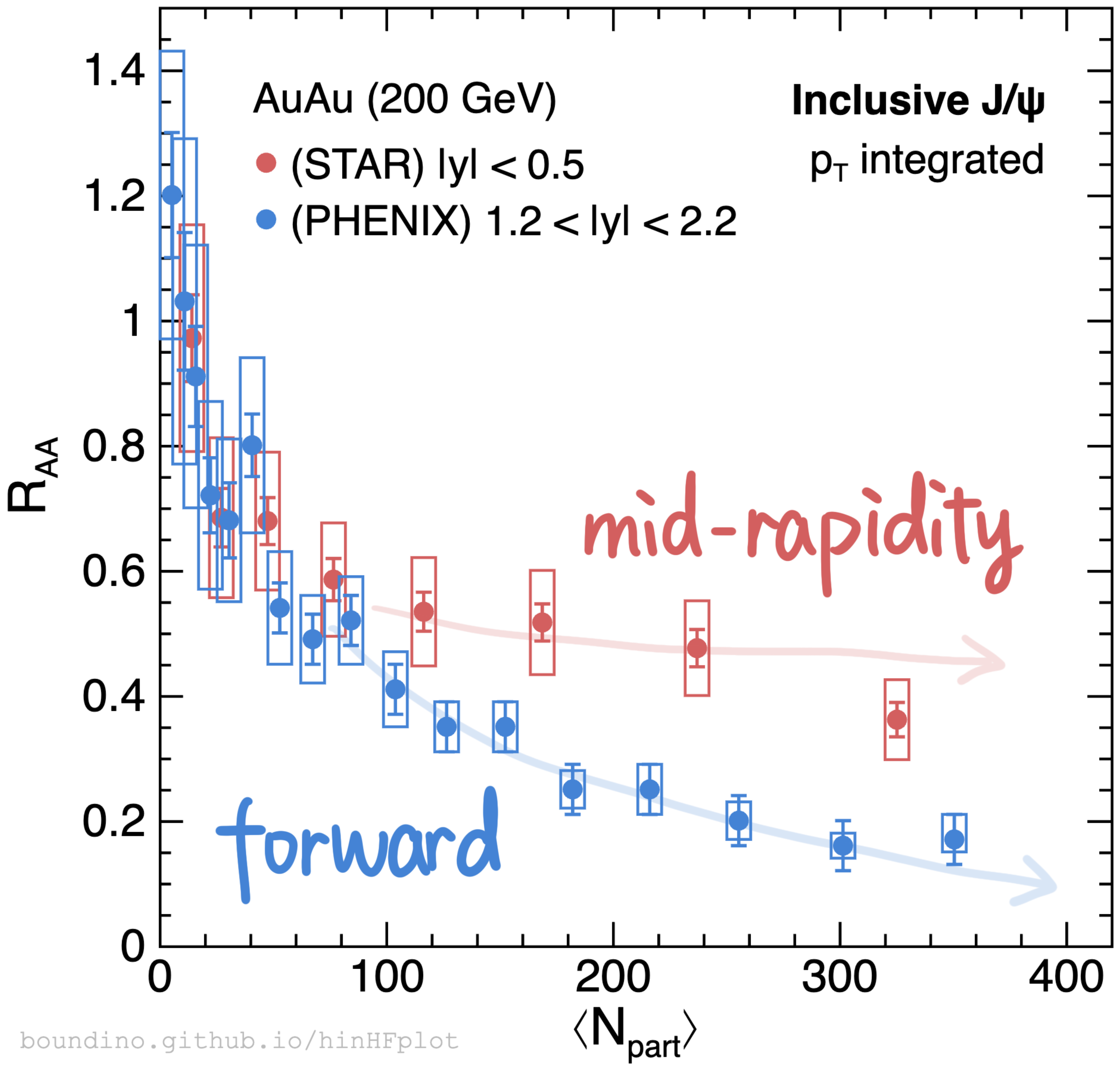
Exotica T_{cc} in High Color Density Environment

Tcc yield vs. multiplicity in pp



- Similar idea applied on another exotic T_{cc}
- No suppression in high multiplicity
  - Different response as X(3872) to the color dense environment

Charmonia in QGP Other Effects



- Stronger suppression at forward rapidity than mid-rapidity
  - similar observable in both LHC and RHIC

Cold nuclear matter effects

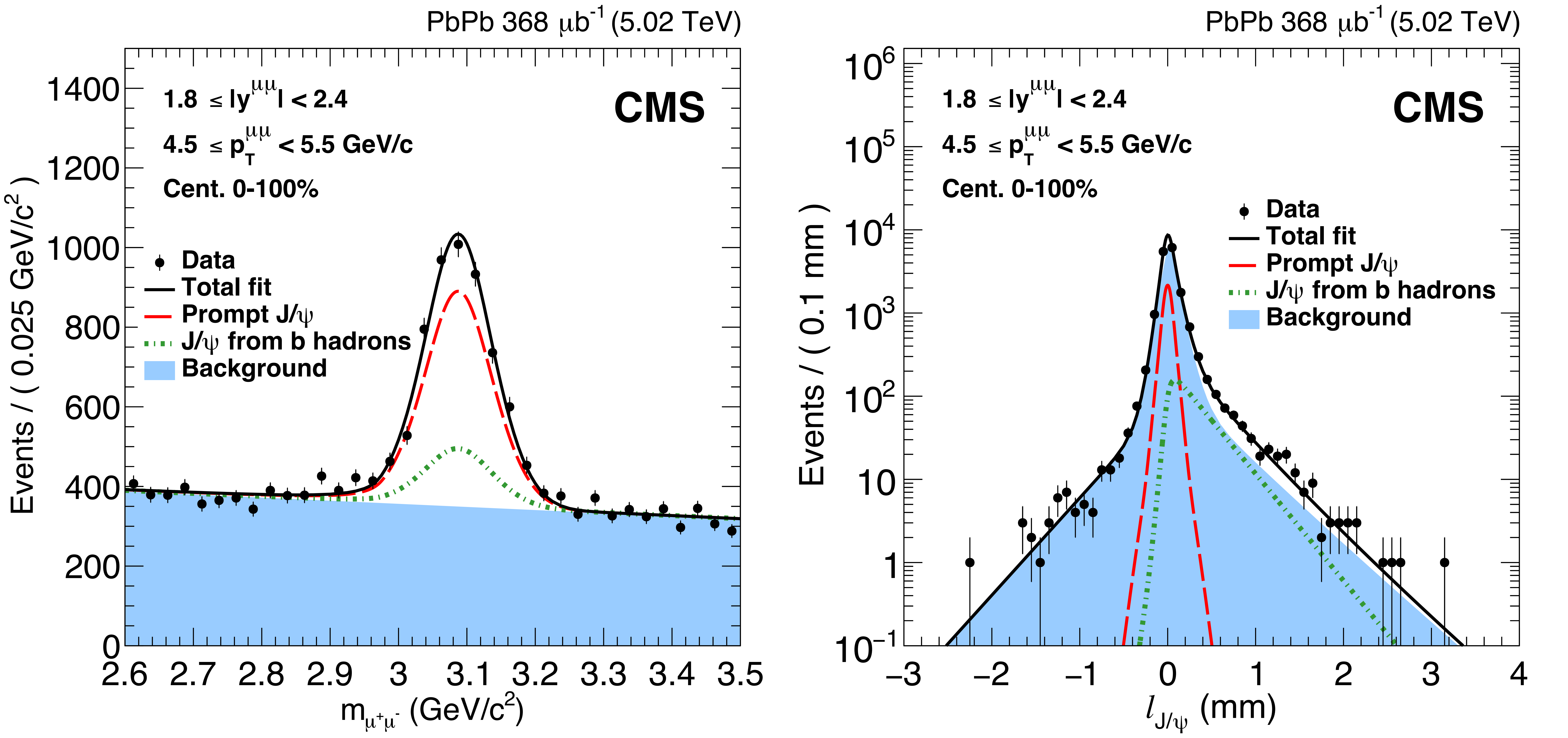
*Not saying rapidity dependence is due to CNM

- Comover breakup, nuclear absorption
- Nuclear PDF
- Initial coherent energy loss

Dead Cone Effect Direct Observation in pp

Yield Extraction Heavy Quarkonia

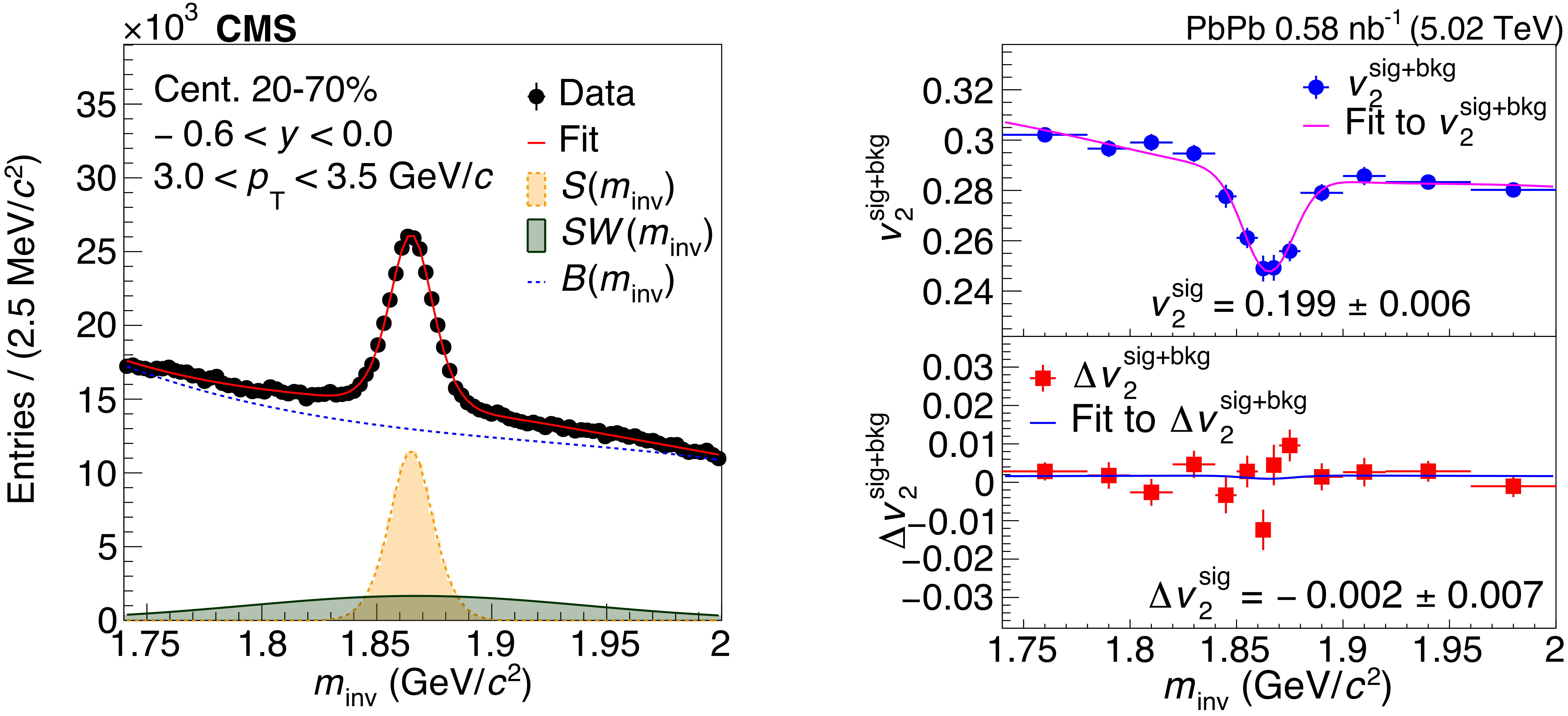
[EPJC 78 (2018) 509]



- Simultaneously fit invariant mass and pseudo-proper decay length → Similar as open HF

Relativistic Heavy-Ion Collisions

Analysis Technique Flow Coefficient



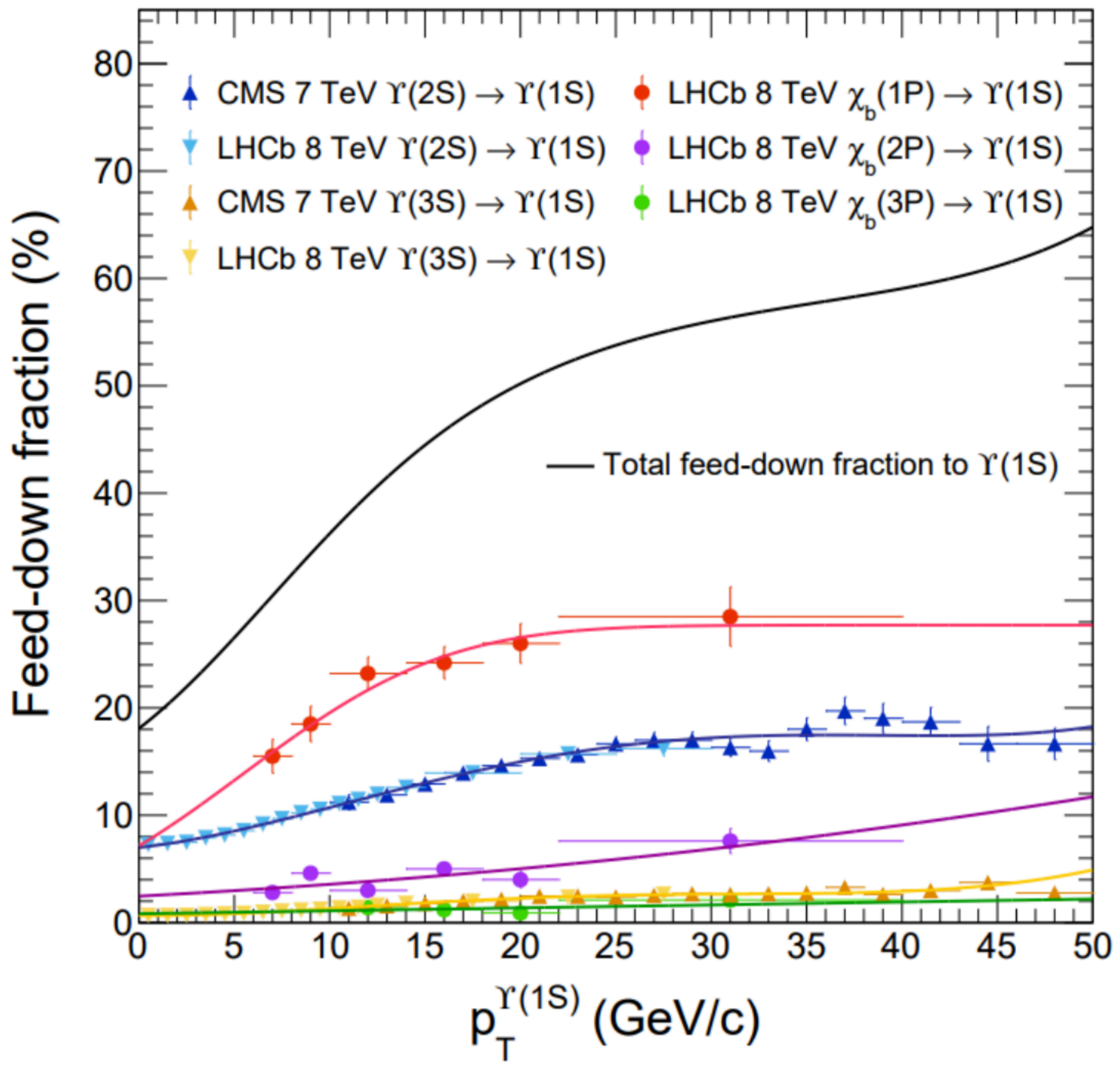
- Simultaneously fit invariant mass distribution and v_2 vs invariant mass → get signal v_2
- Common method for property measurements of resonances, if
  - signal and backgrounds have distinct magnitudes of the observables
  - the observable does not have strong dependence of invariant mass

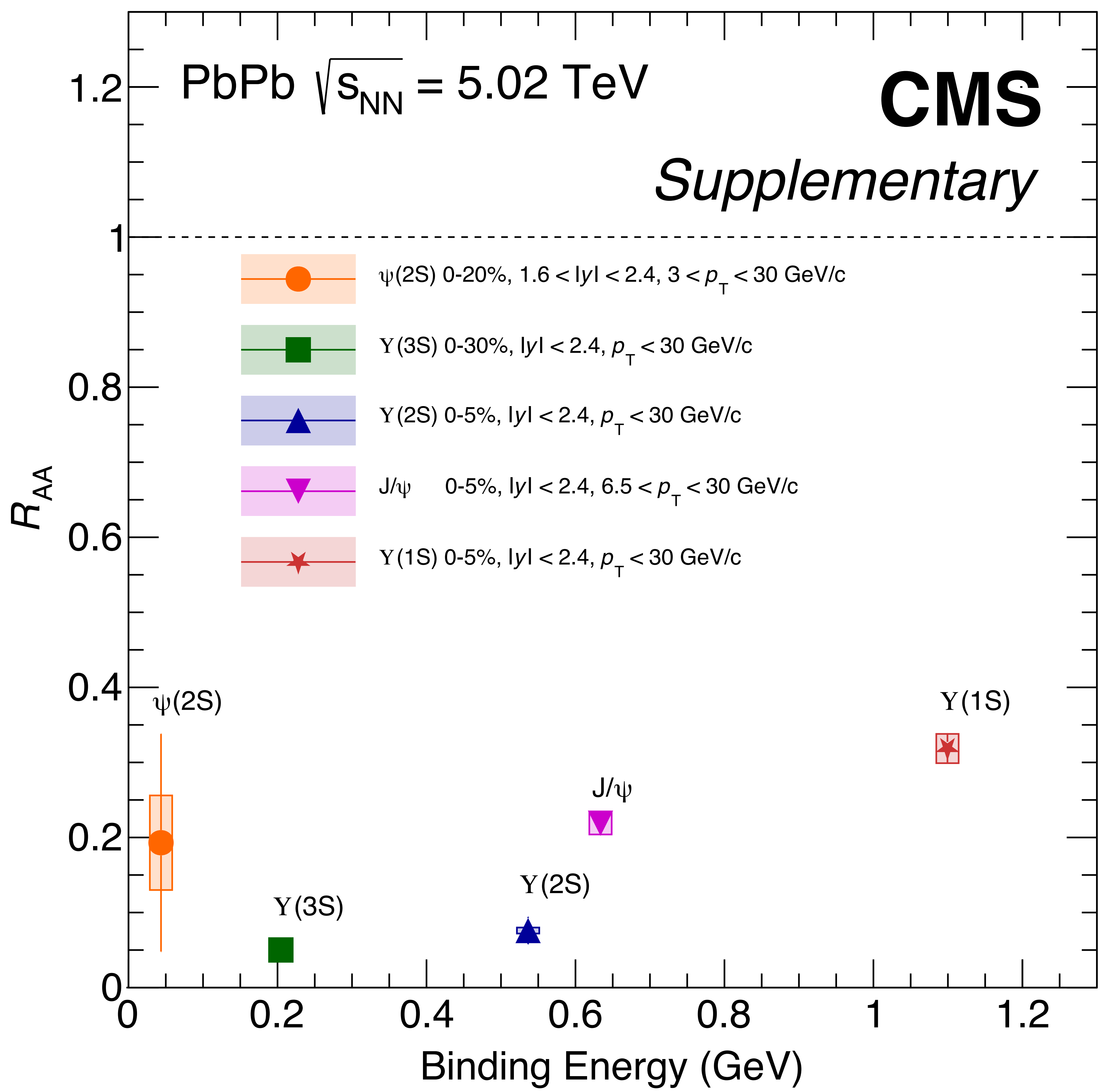
Luminosity Projection Conservative

Quantity	pp	O–O	Ar–Ar	Ca–Ca	Kr–Kr	In–In	Xe–Xe	Pb–Pb
$\sqrt{s_{NN}}$ (TeV)	14.00	7.00	6.30	7.00	6.46	5.97	5.86	5.52
L_{AA} ($cm^{-2}s^{-1}$)	3.0×10^{32}	1.5×10^{30}	3.2×10^{29}	2.8×10^{29}	8.5×10^{28}	5.0×10^{28}	3.3×10^{28}	1.2×10^{28}
$\langle L_{AA} \rangle$ ($cm^{-2}s^{-1}$)	3.0×10^{32}	9.5×10^{29}	2.0×10^{29}	1.9×10^{29}	5.0×10^{28}	2.3×10^{28}	1.6×10^{28}	3.3×10^{27}
$\mathscr{L}_{AA}^{month}$ (nb^{-1})	5.1×10^{5}	1.6×10^{3}	3.4×10^{2}	3.1×10^{2}	8.4×10^{1}	3.9×10^{1}	2.6×10^{1}	5.6
$\mathscr{L}_{NN}^{month}$ (pb^{-1})	505	409	550	500	510	512	434	242
R_{max} (kHz)	24 000	2169	821	734	344	260	187	93
μ	1.2	0.21	0.08	0.07	0.03	0.03	0.02	0.01
$dN_{ch}/d\eta$ (MB)	7	70	151	152	275	400	434	682
	at $R = 0.5$ cm							
R_{hit} (MHz/cm^2)	94	85	69	62	53	58	46	35
NIEL (1 MeV n_{eq}/cm^2)	1.8×10^{14}	1.0×10^{14}	8.6×10^{13}	7.9×10^{13}	6.0×10^{13}	3.3×10^{13}	4.1×10^{13}	1.9×10^{13}
TID (Rad)	5.8×10^{6}	3.2×10^{6}	2.8×10^{6}	2.5×10^{6}	1.9×10^{6}	1.1×10^{6}	1.3×10^{6}	6.1×10^{5}
	at $R = 100$ cm							
R_{hit} (kHz/cm^2)	2.4	2.1	1.7	1.6	1.3	1.0	1.1	0.9
NIEL (1 MeV n_{eq}/cm^2)	4.9×10^{9}	2.5×10^{9}	2.1×10^{9}	2.0×10^{9}	1.5×10^{9}	8.3×10^{8}	1.0×10^{9}	4.7×10^{8}
TID (Rad)	1.4×10^{2}	8.0×10^{1}	6.9×10^{1}	6.3×10^{1}	4.8×10^{1}	2.7×10^{1}	3.3×10^{1}	1.5×10^{1}

Table 1: Projected LHC performance: For various collision systems, we list the peak luminosity L_{AA}, the average luminosity $\langle L_{AA} \rangle$, the luminosity integrated per month of operation $\mathscr{L}_{AA}^{month}$, also rescaled to the nucleon–nucleon luminosity $\mathscr{L}_{NN}^{month}$ (multiplying by A^2). Furthermore, we list the maximum interaction rate R_{max}, the minimum bias (MB) charged particle pseudorapidity density $dN/d\eta$, and the interaction probability μ per bunch crossing. For the radii 0.5 cm and 1 m, we also list the particle fluence, the non-ionising energy loss, and the total ionising dose per operational month (assuming a running efficiency of 65%).

Feed-Down, Binding Energy





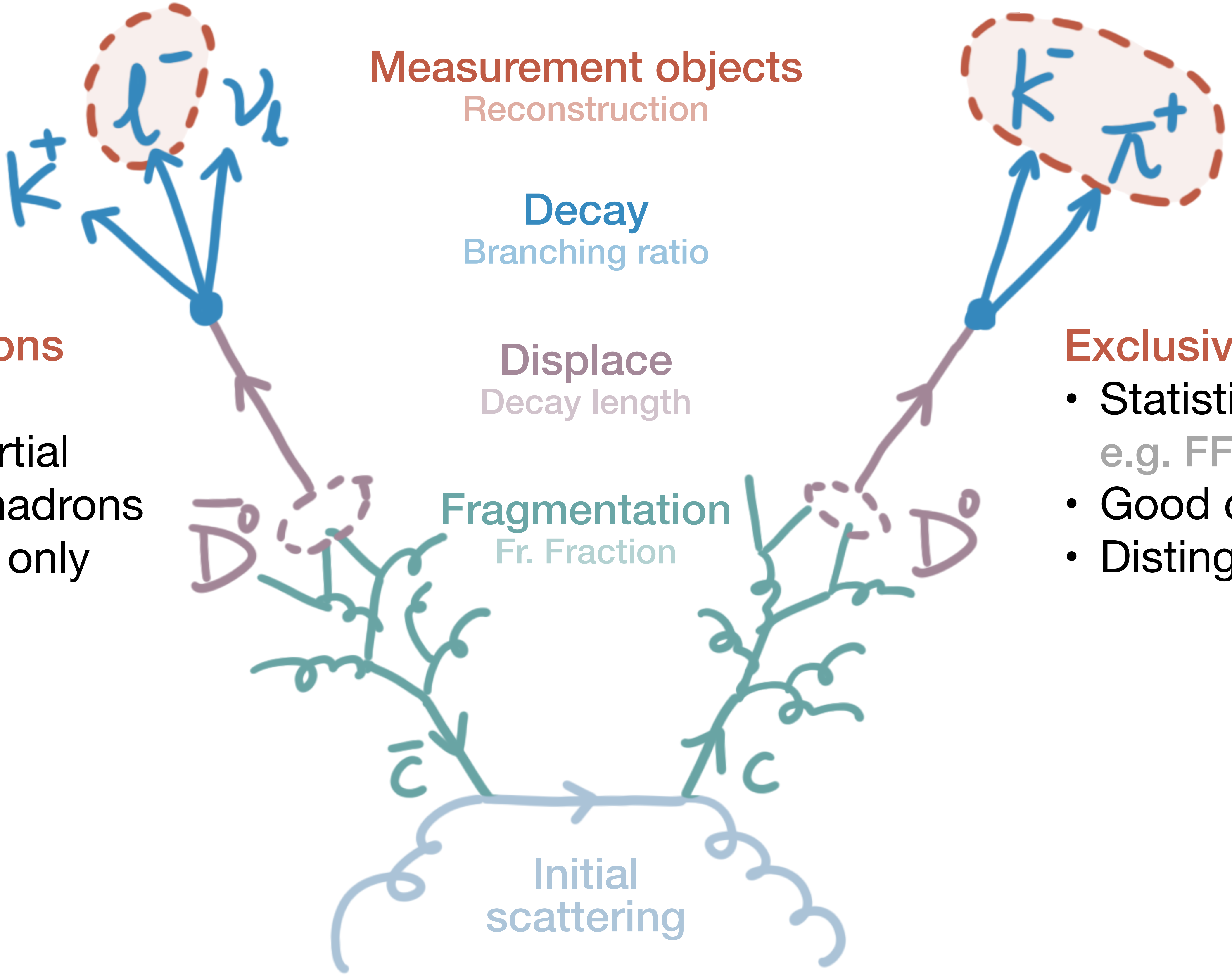
Beam Schedule Long Term

Last update: April 2023

How to Measure Heavy Flavors

Inclusive decayed leptons

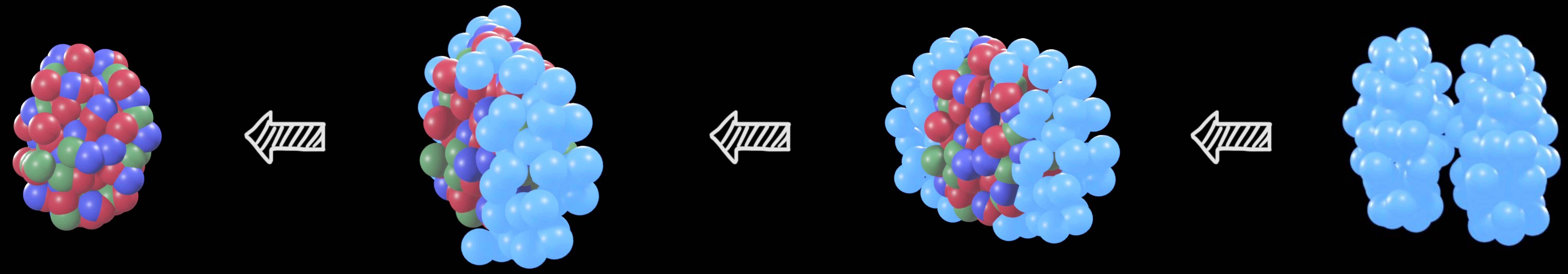
- Better statistics
- Leptons only carry partial kinematics of parent hadrons
- Inclusive c/b-hadrons only



Exclusive hadronic reconstruction

- Statistics limited by FF, BR
  e.g. FF x BR ($c \to D^0 \to K\pi$) ~ 0.02
- Good control of kinematics
- Distinguish type of hadrons

Initial Spatial Anisotropy of Medium



Azimuthal anisotropic initial shape in peripheral events

[Animation]