Heavy Flavor + Quarkonia Experiment

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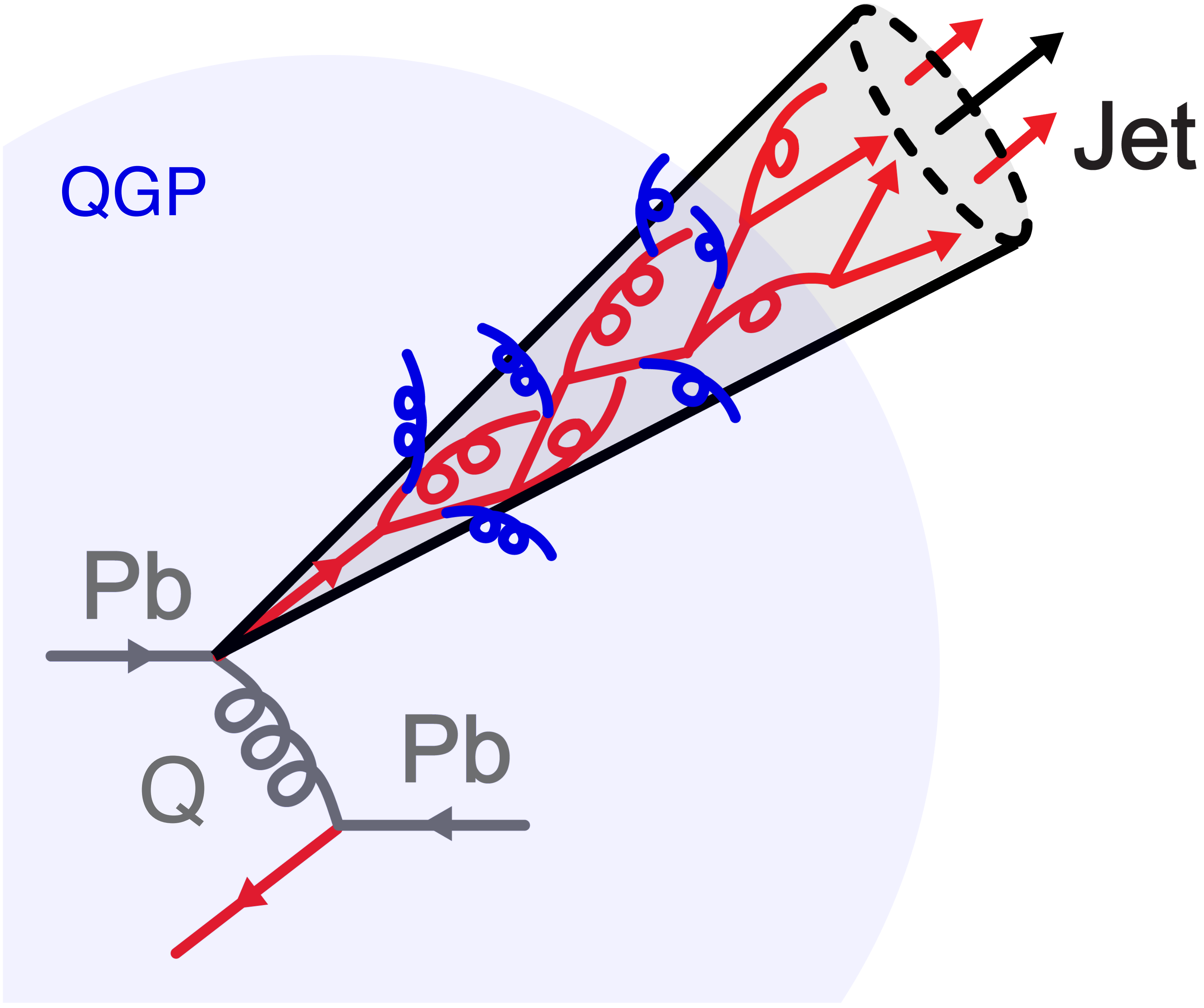
GDR-QCD: From Hadronic Structure to Heavy-ion Collisions
IJCLab, Orsay (France)
June 11, 2024

Special thanks to Gian Michele and Florian for the discussions!

After Hydrodynamics What Next?

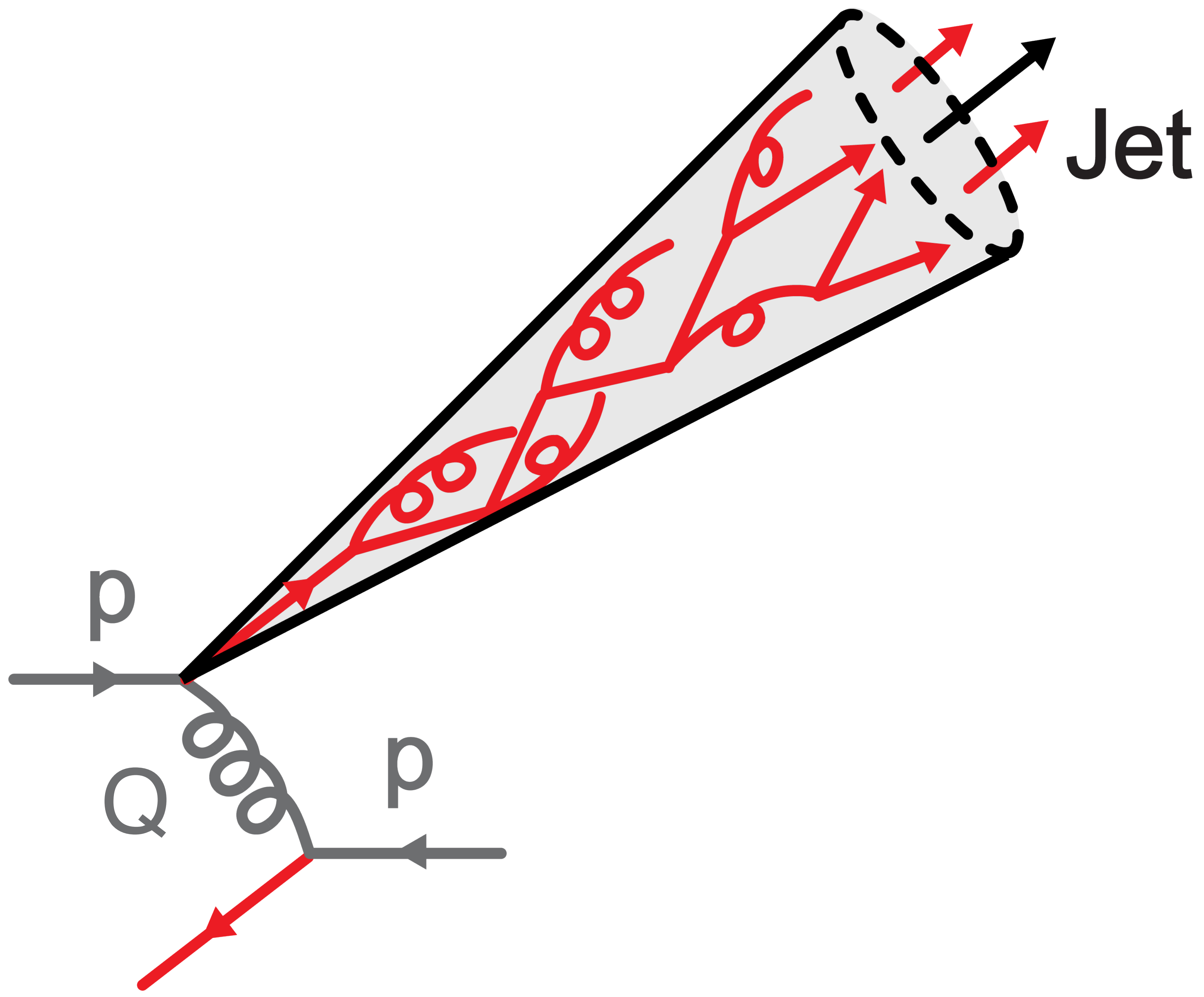
Hard Probes “Rutherford experiment”

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

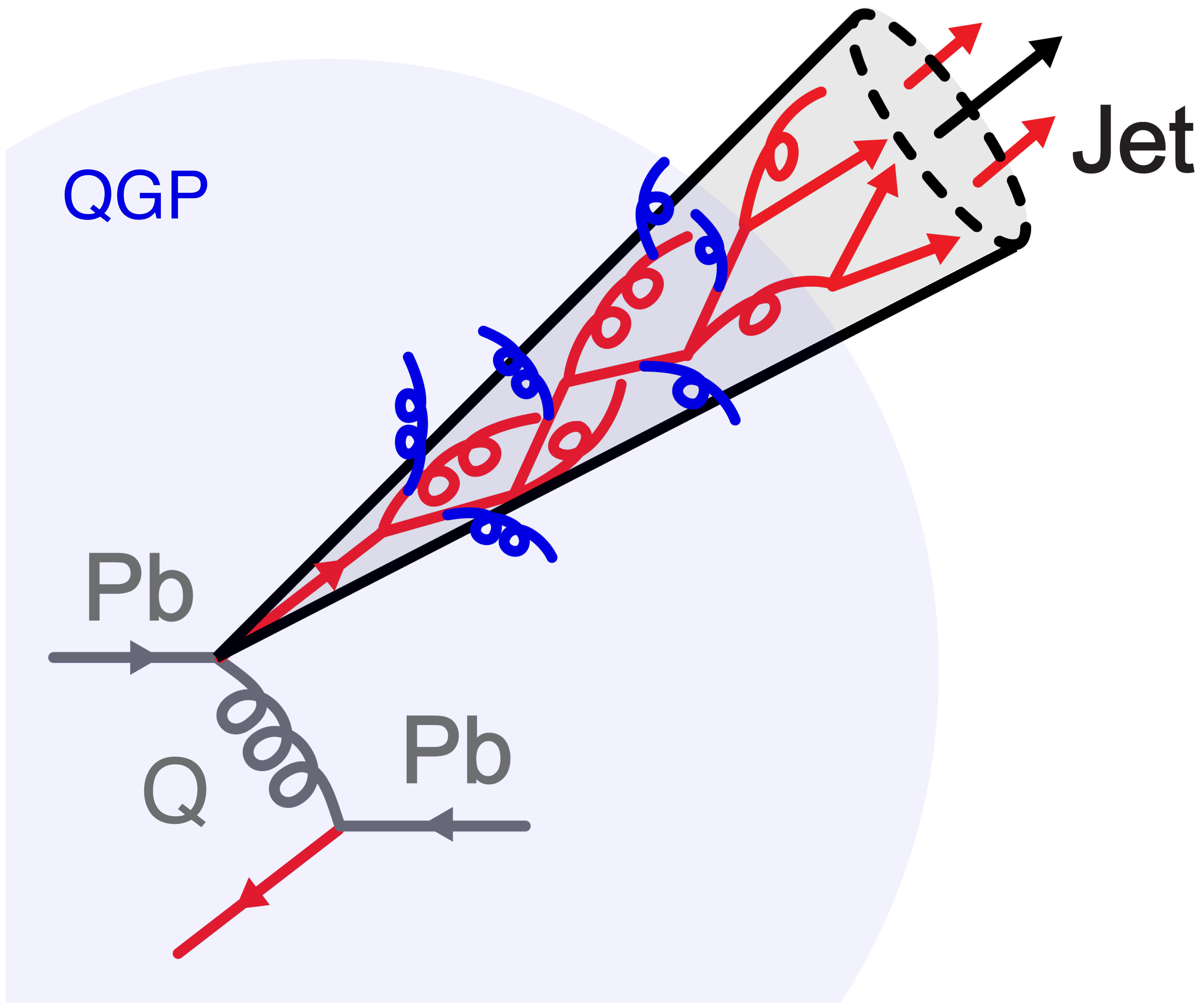


Hard Probes "Rutherford experiment"

- 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



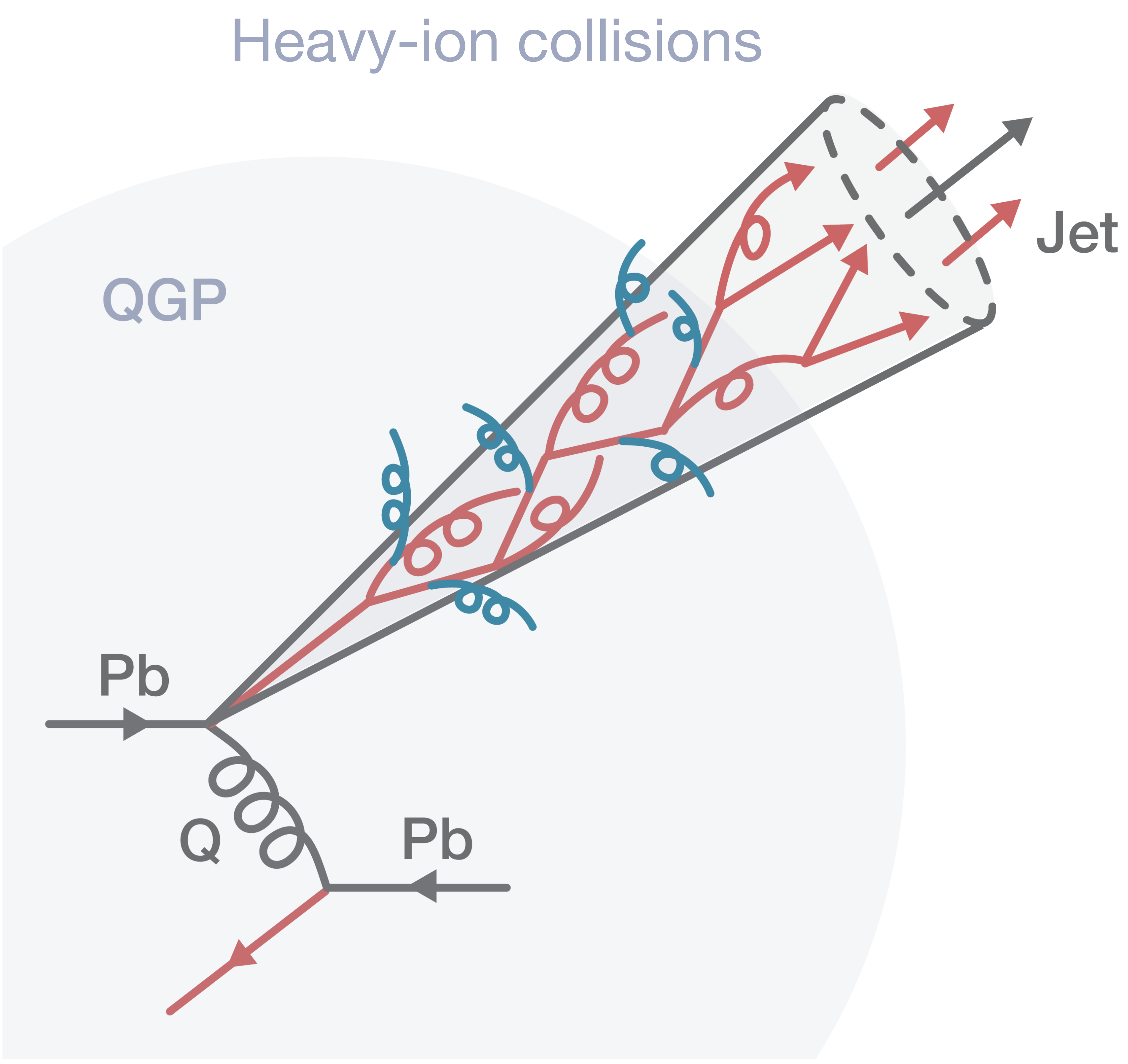
vs



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

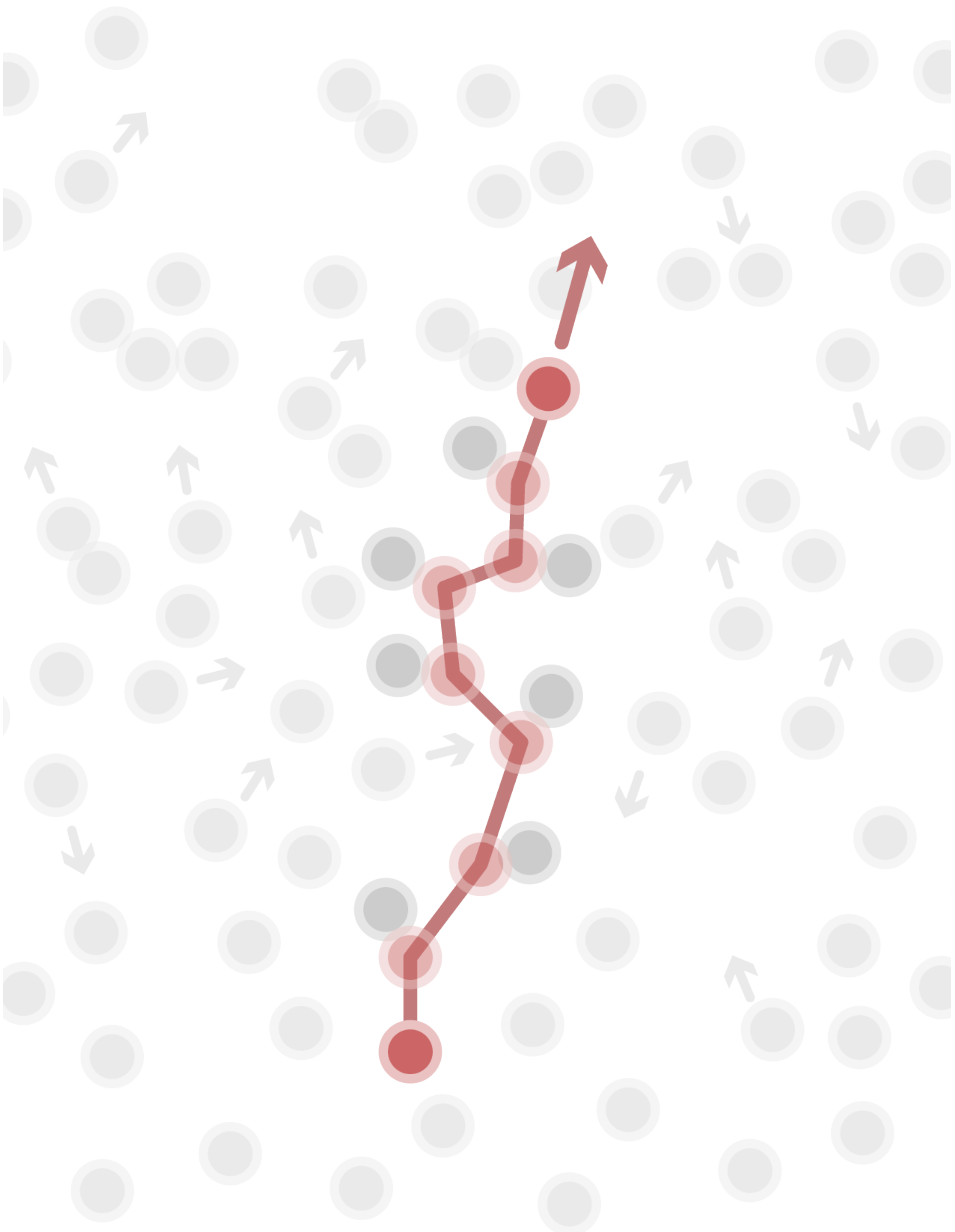


Heavy Flavors vs Other Hard Probes

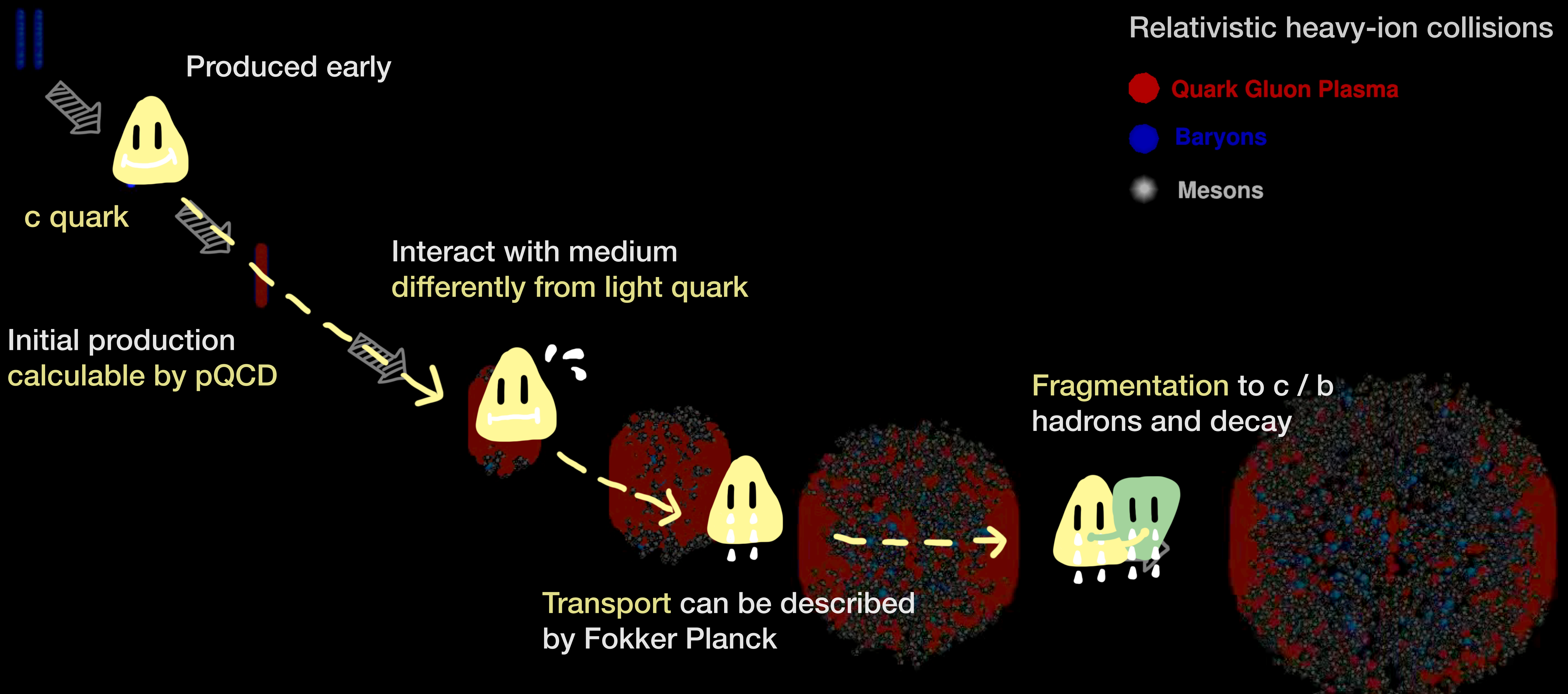
Heavy quarks (charm, beauty) → **large mass m_Q**

- $m_Q \sim 1/\tau$ 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



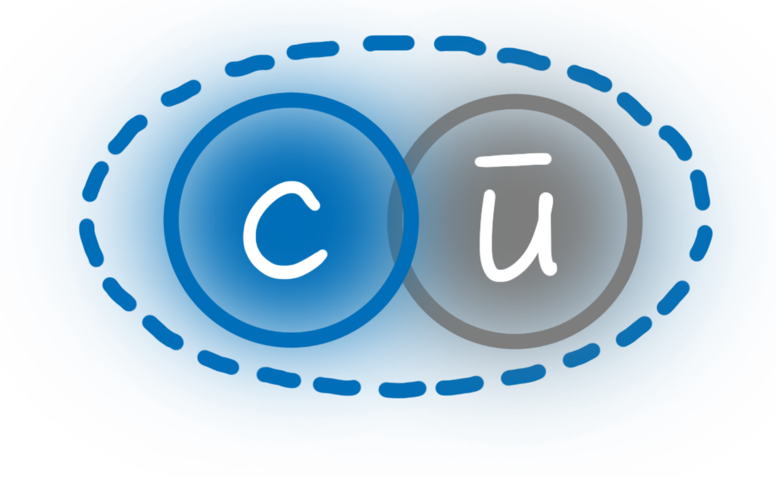
Life of a Heavy Quark in HIC



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

Connaître Representative Heavy Flavor Hadrons

Charm

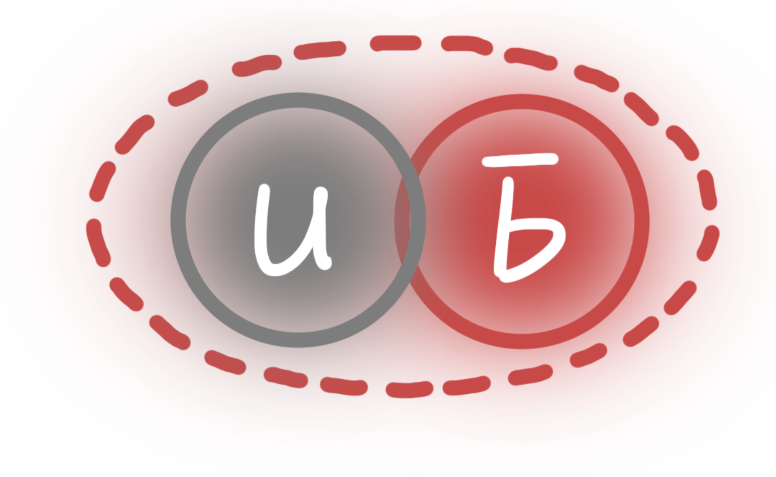


D^0 **($c \rightarrow D^0$ ~ O(50%))**

Mass 1.865 GeV

cτ ~ 120 μm

Beauty



B^+ **($b \rightarrow B^+$ ~ O(40%))**

Mass 5.279 GeV

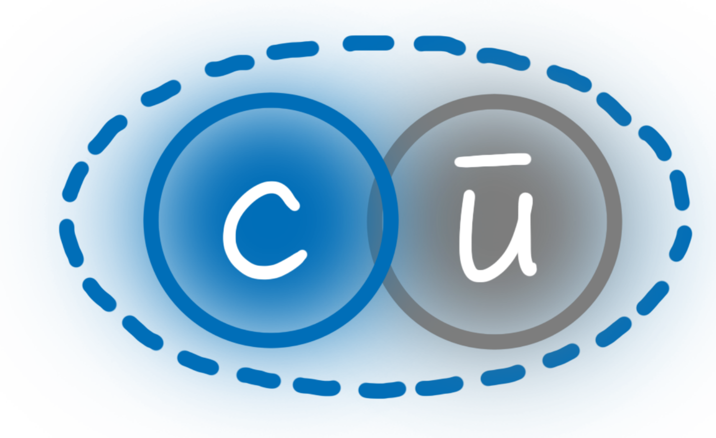
cτ ~ 490 μm

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

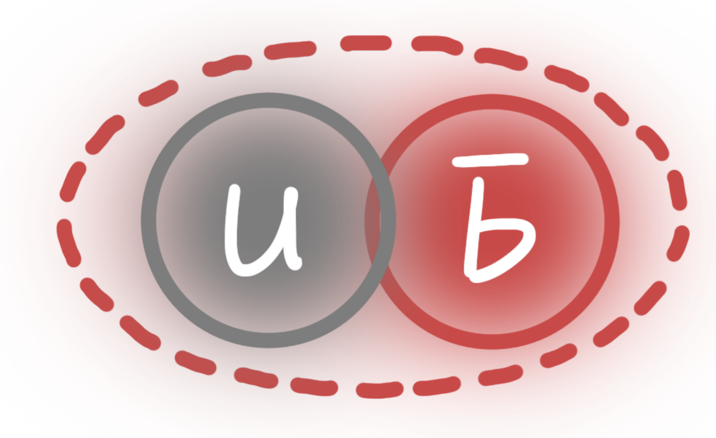


D^0 ($c \to D^0 \sim O(50\%)$)

Mass 1.865 GeV

$c\tau \sim$ 120 μm

Beauty

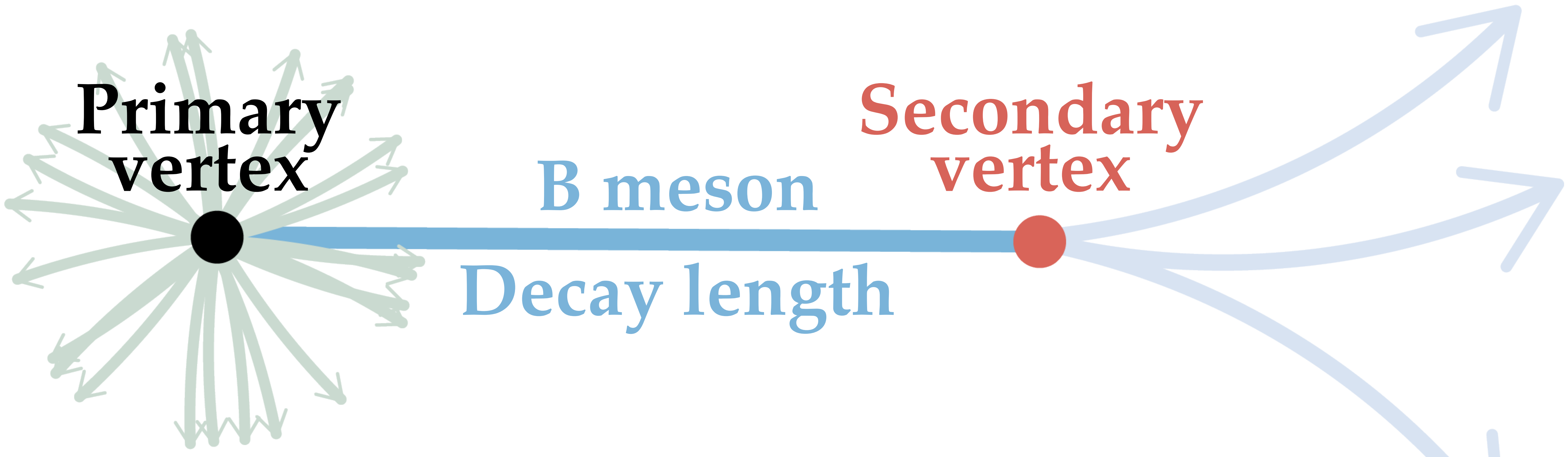


B^+ ($b \to B^+ \sim O(40\%)$)

Mass 5.279 GeV

$c\tau \sim$ 490 μm

Displaced secondary vertex is an experiment signature of open HF mesons

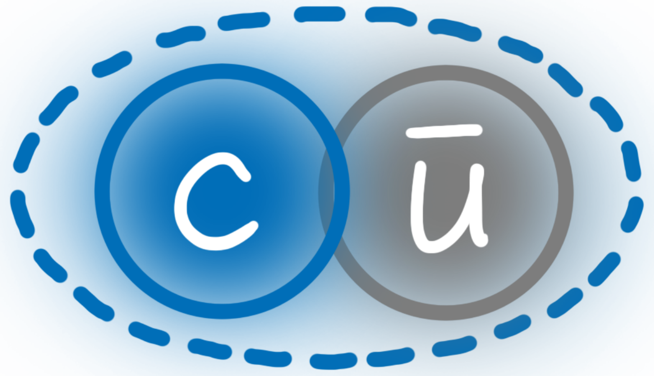


can be ~1 cm in lab frame at LHC

Connaître Representative Heavy Flavor Hadrons

Charm | **Beauty**

Open heavy flavor



D^0 ($c \to D^0 \sim O(50\%)$)

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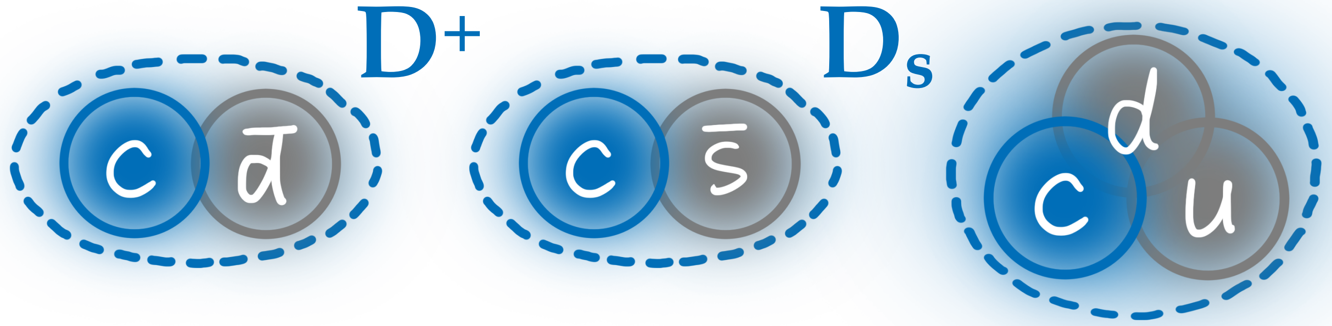
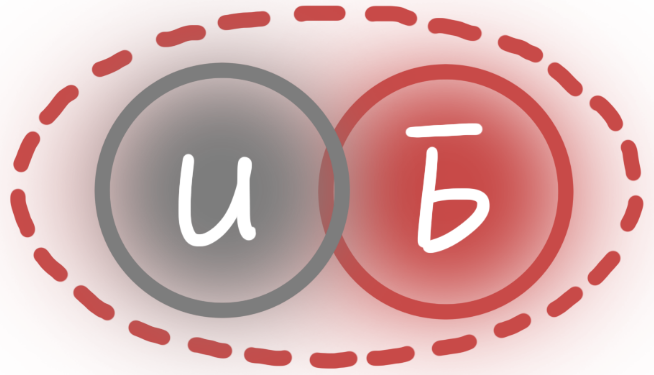


D^+ D_s Λ_c



B^+ ($b \to B^+ \sim O(40\%)$)

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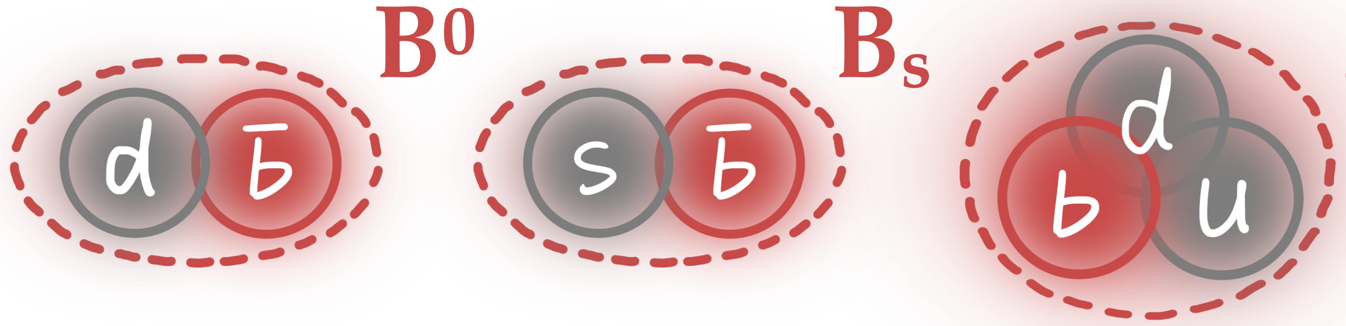
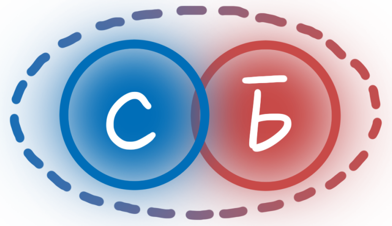


B^0 B_s Λ_b

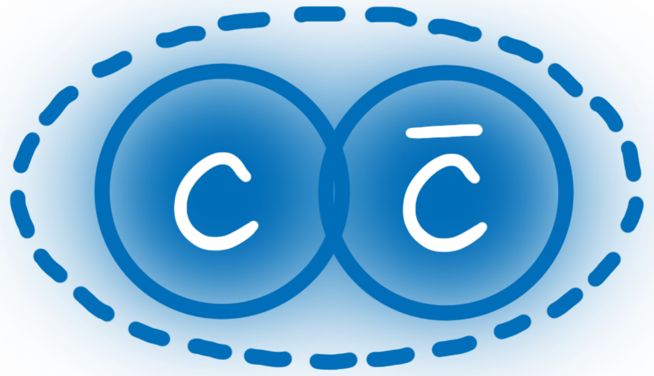
B_c^+



Quarkonia

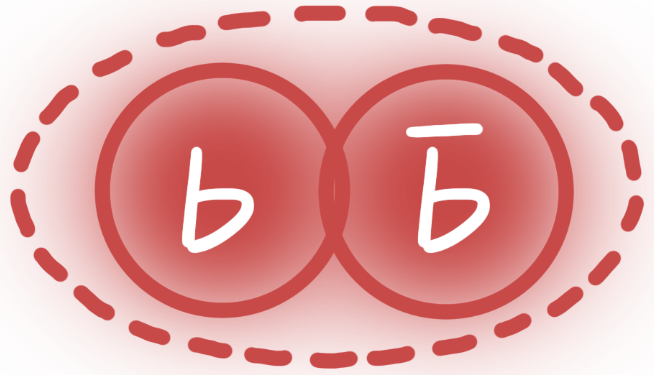
J/ψ

$\psi(2S)$, χ_c

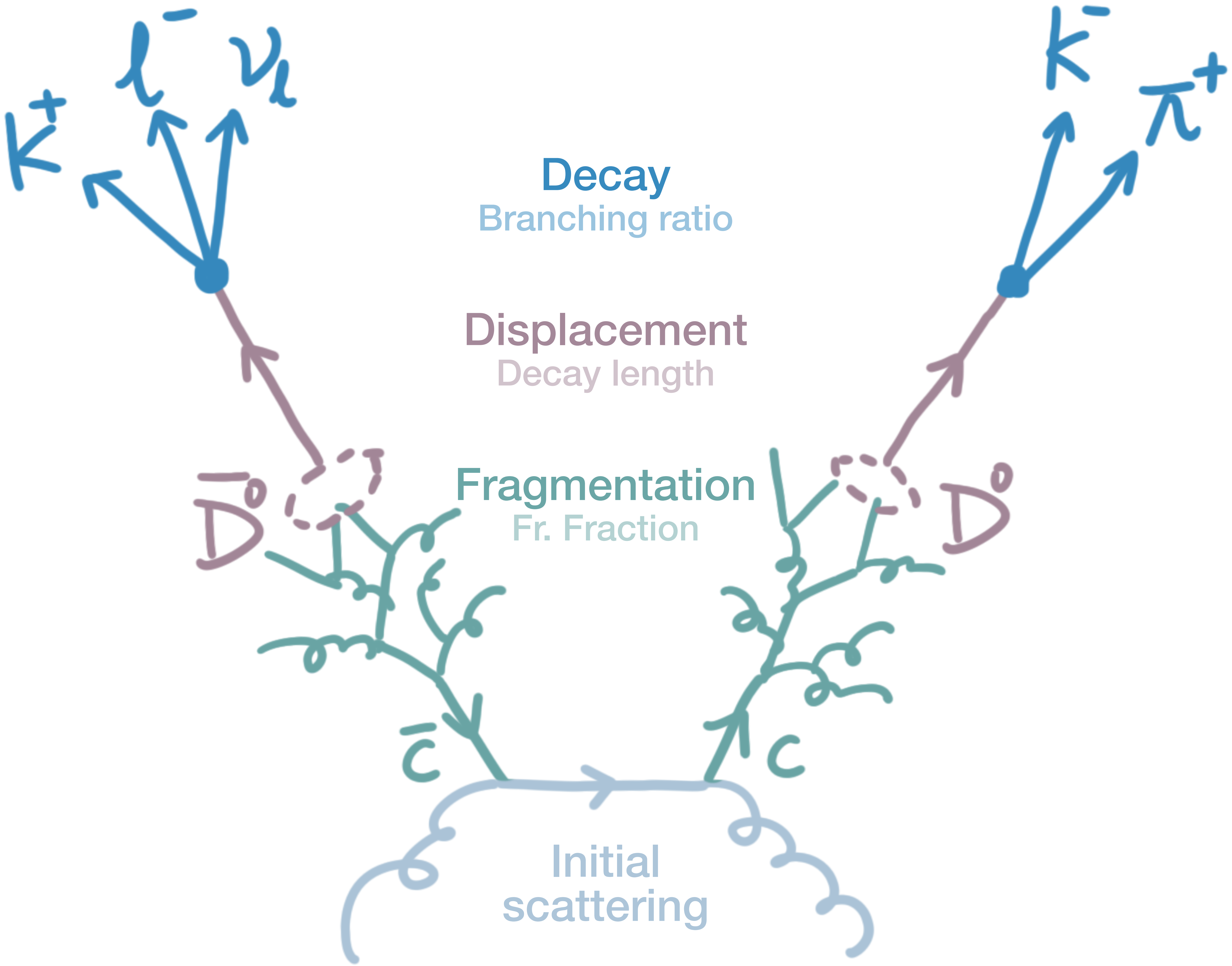


$\Upsilon(1S)$

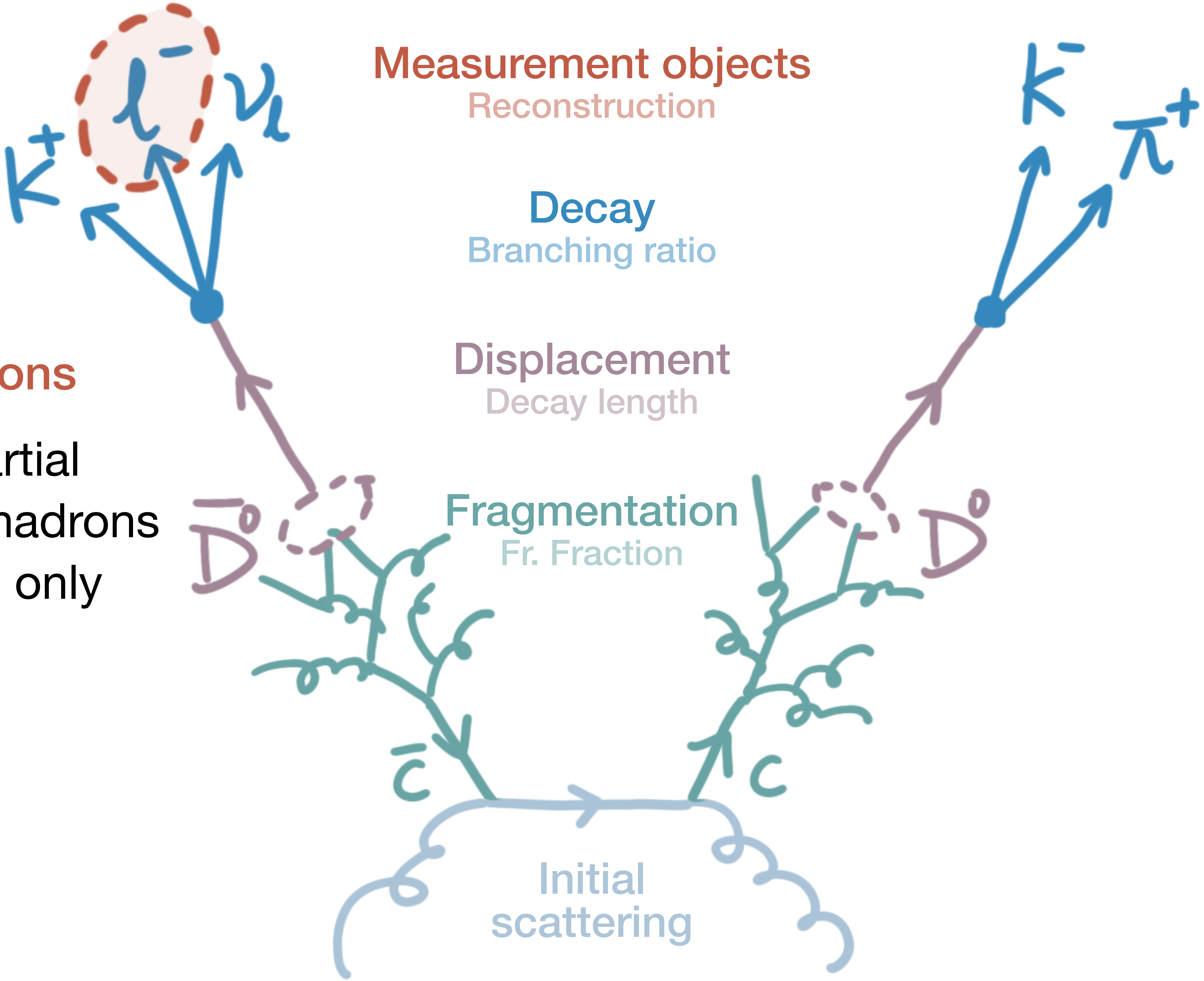
$\Upsilon(2S)$, $\Upsilon(3S)$



How to Measure Open Heavy Flavors



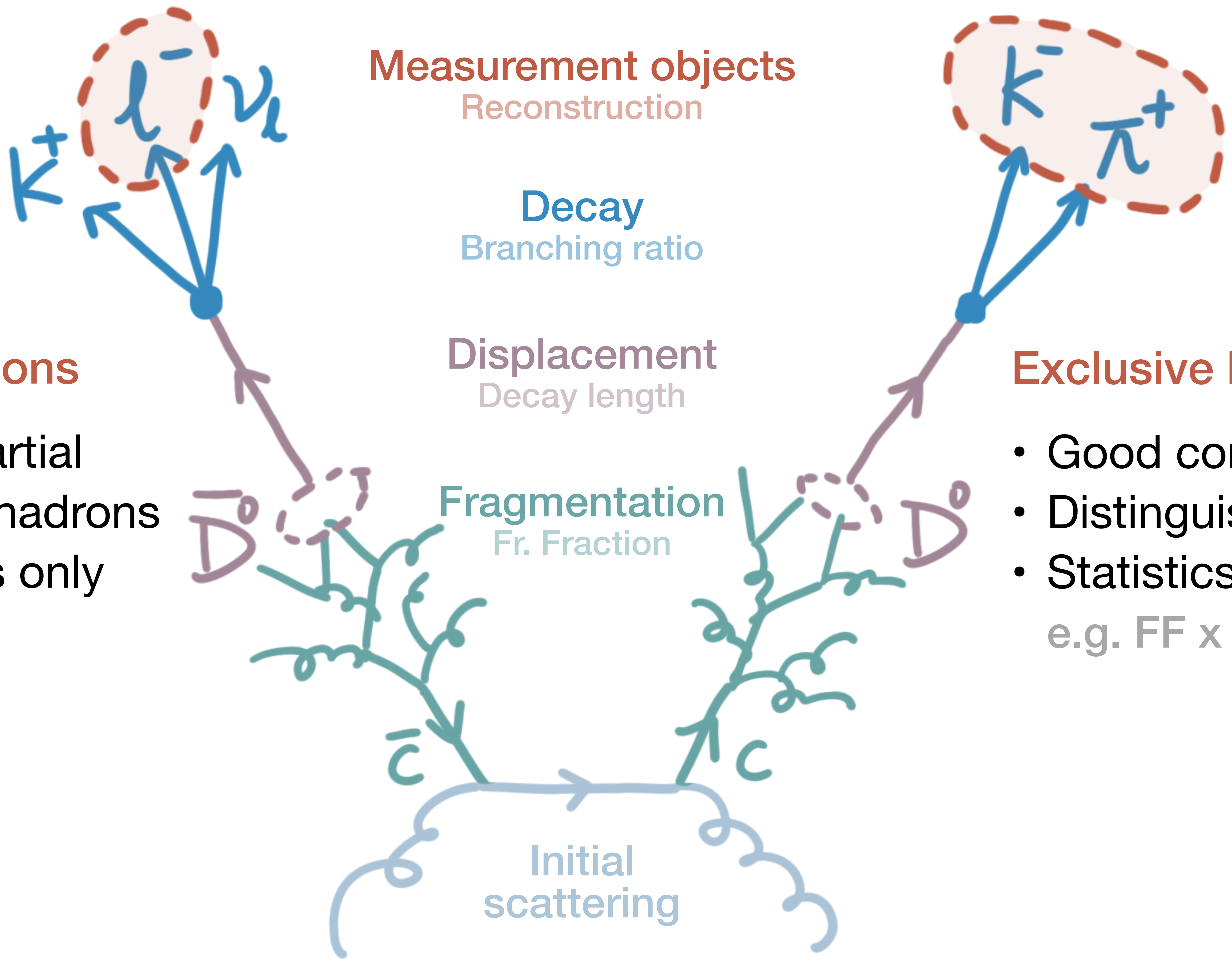
Measure Heavy Flavor HF Decayed Leptons



Inclusive decayed leptons

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

Measure Heavy Flavor Fully Reconstruction



Inclusive decayed leptons

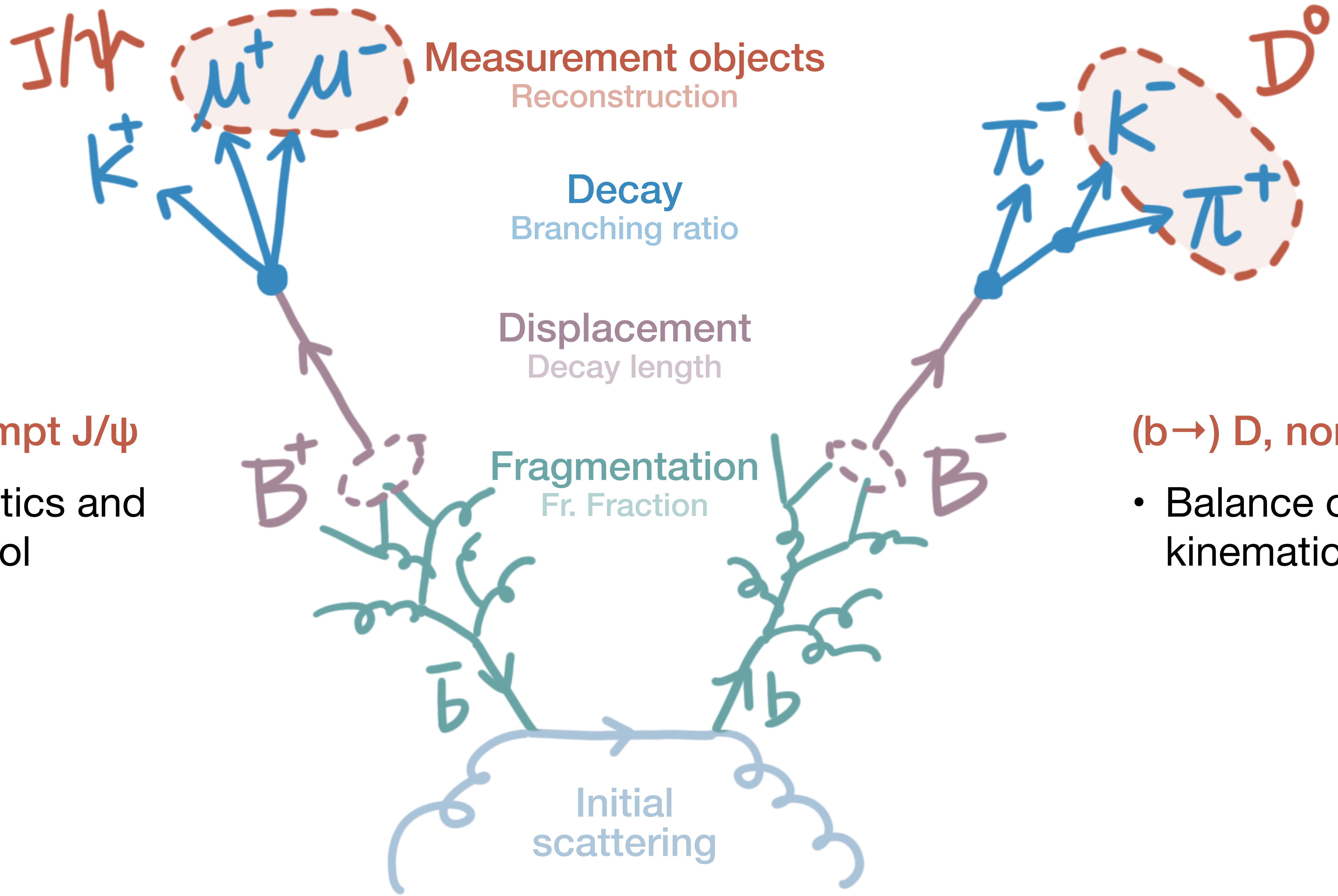
- Leptons only carry partial kinematics of parent hadrons
- Inclusive c/b-hadrons only
- Better statistics

Exclusive hadronic reconstruction

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

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

Measure Heavy Flavor Partial Reconstruction



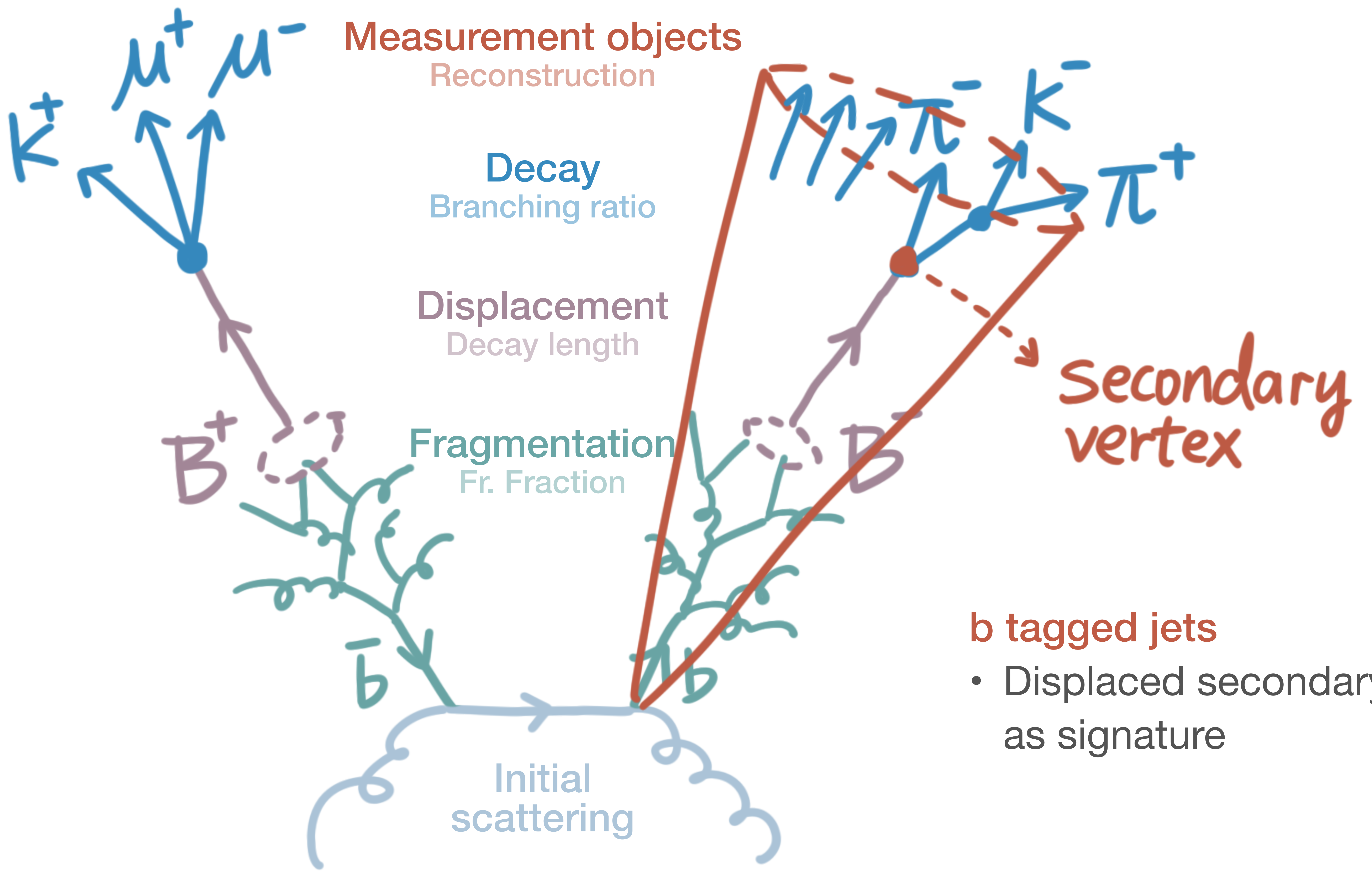
(b→) J/ψ, nonprompt J/ψ

- Balance of statistics and kinematics control

(b→) D, nonprompt D

- Balance of statistics and kinematics control

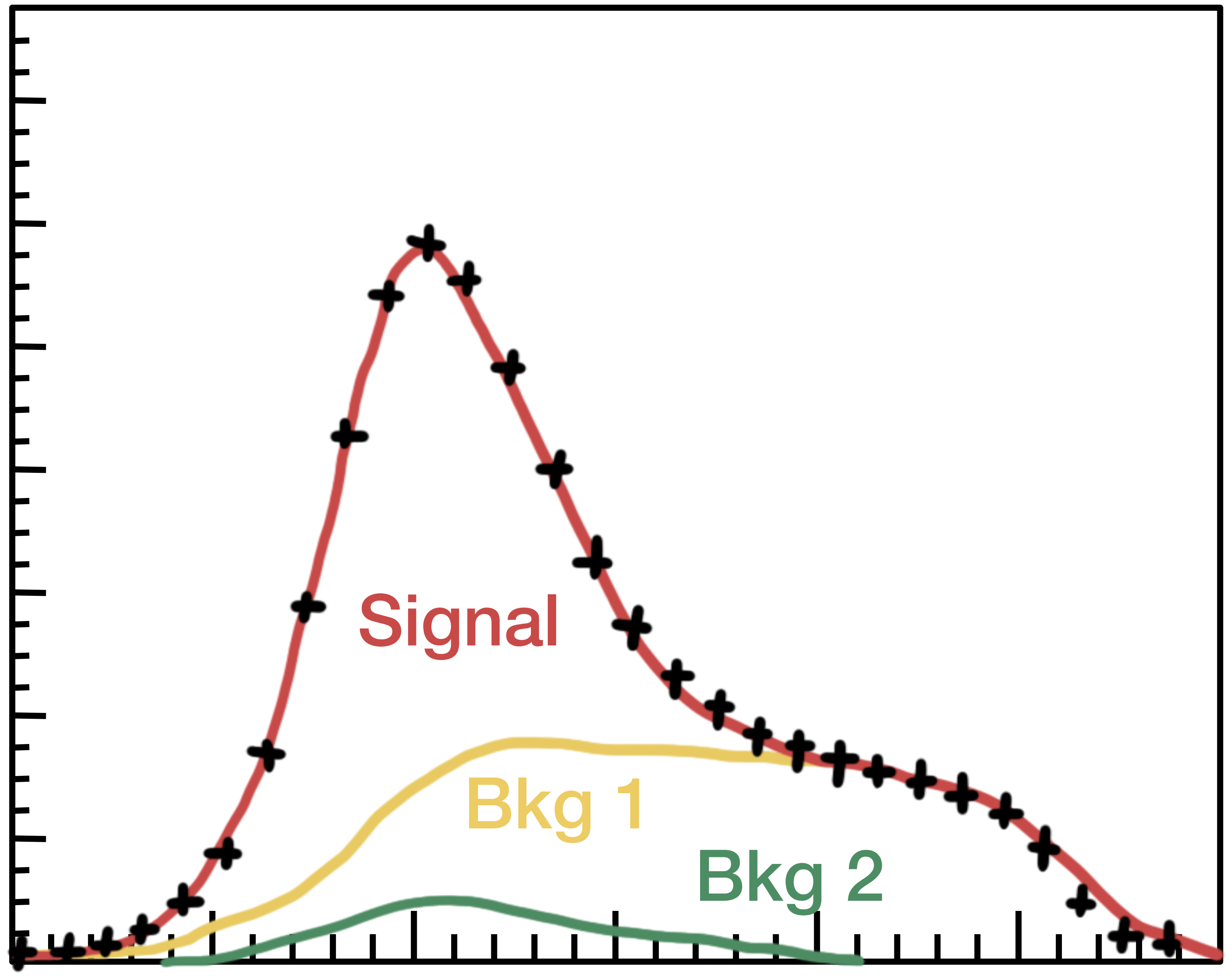
Measure Heavy Flavor HF Tagged Jets



b tagged jets

- Displaced secondary vertex as signature

Signal Extraction HF Decay Leptons



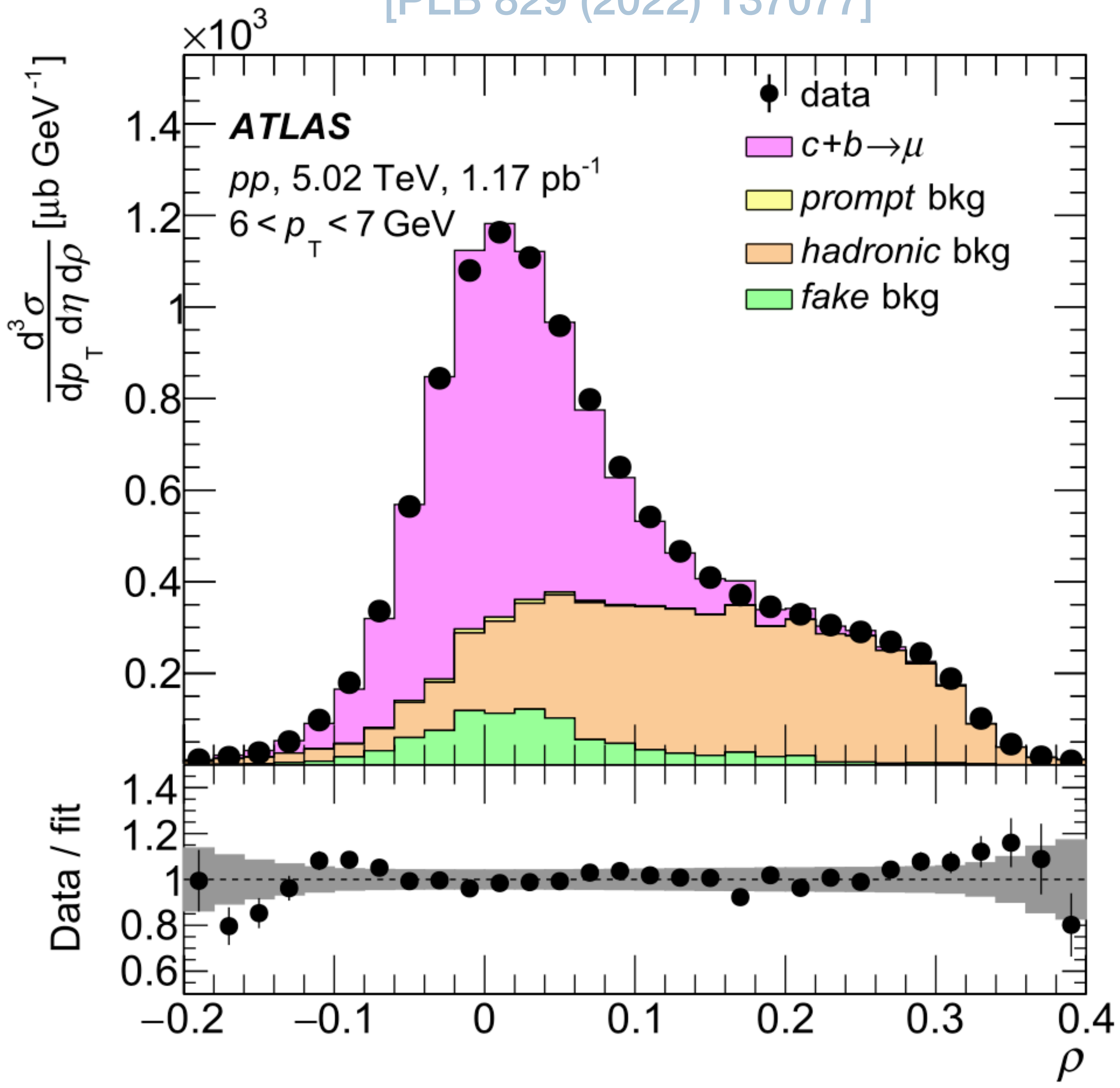
Template fit on a variable to extract the yields of signals

- 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

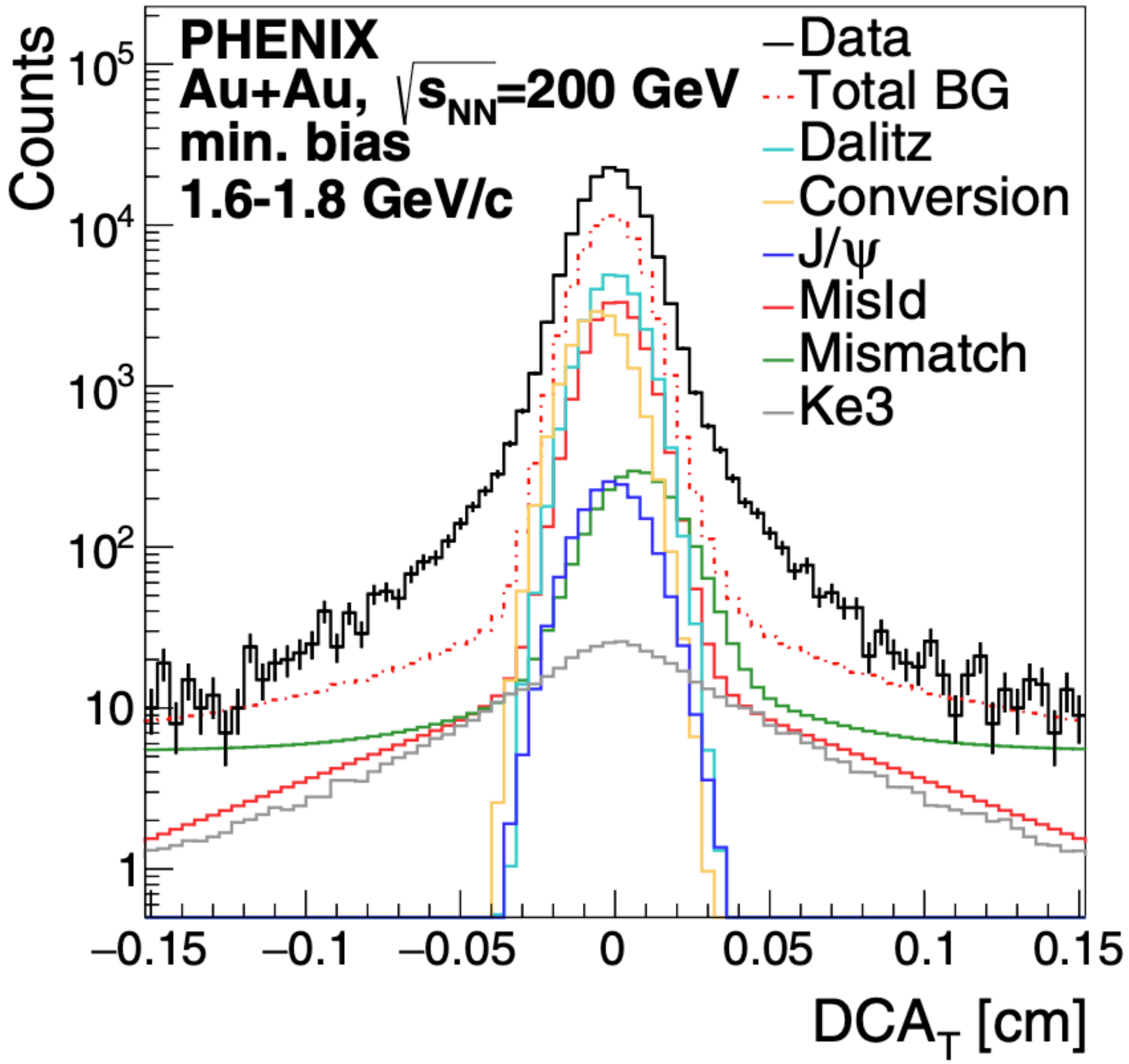
[PLB 829 (2022) 137077]



- 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]



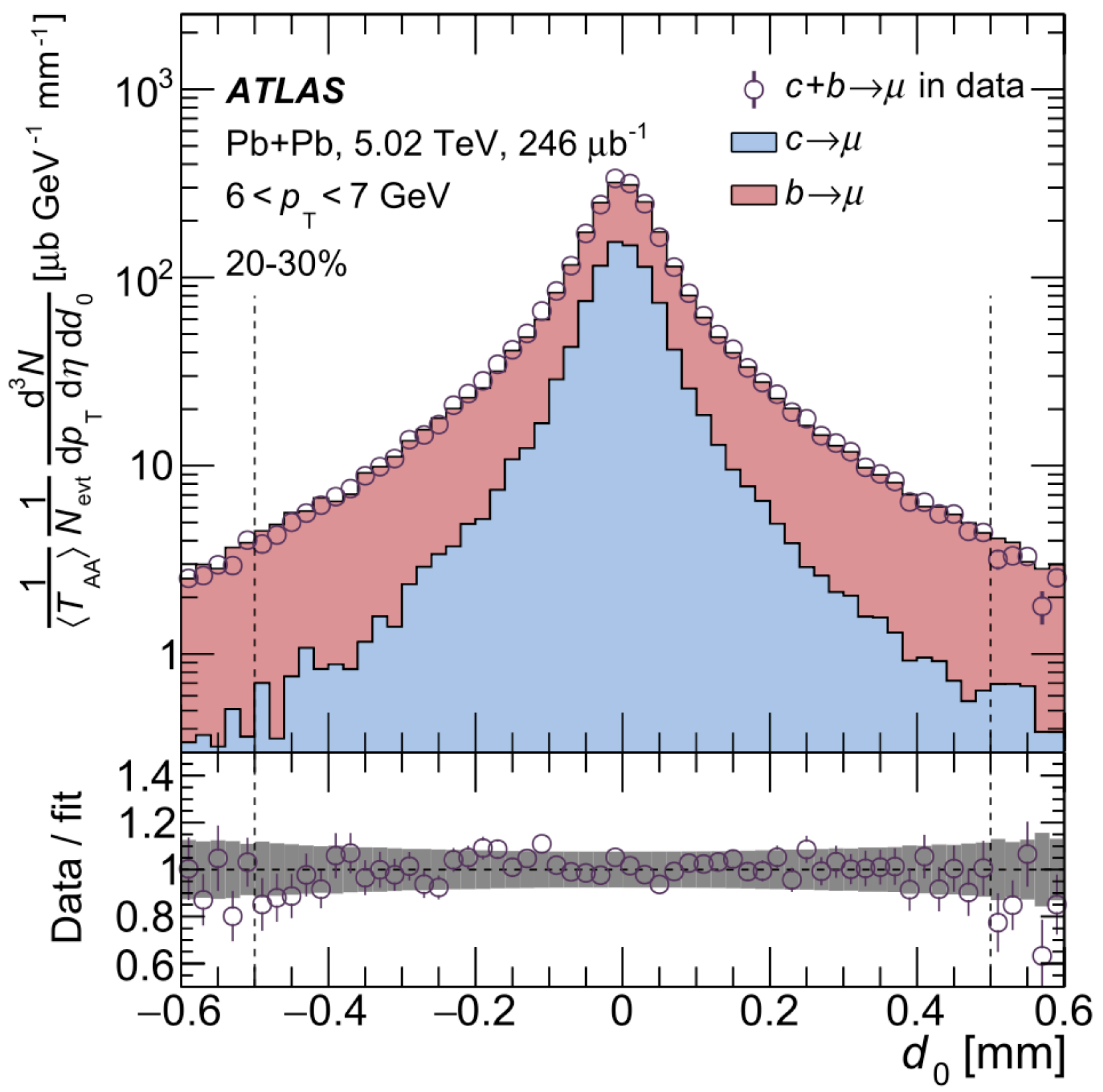
Extension for homework HF → e

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

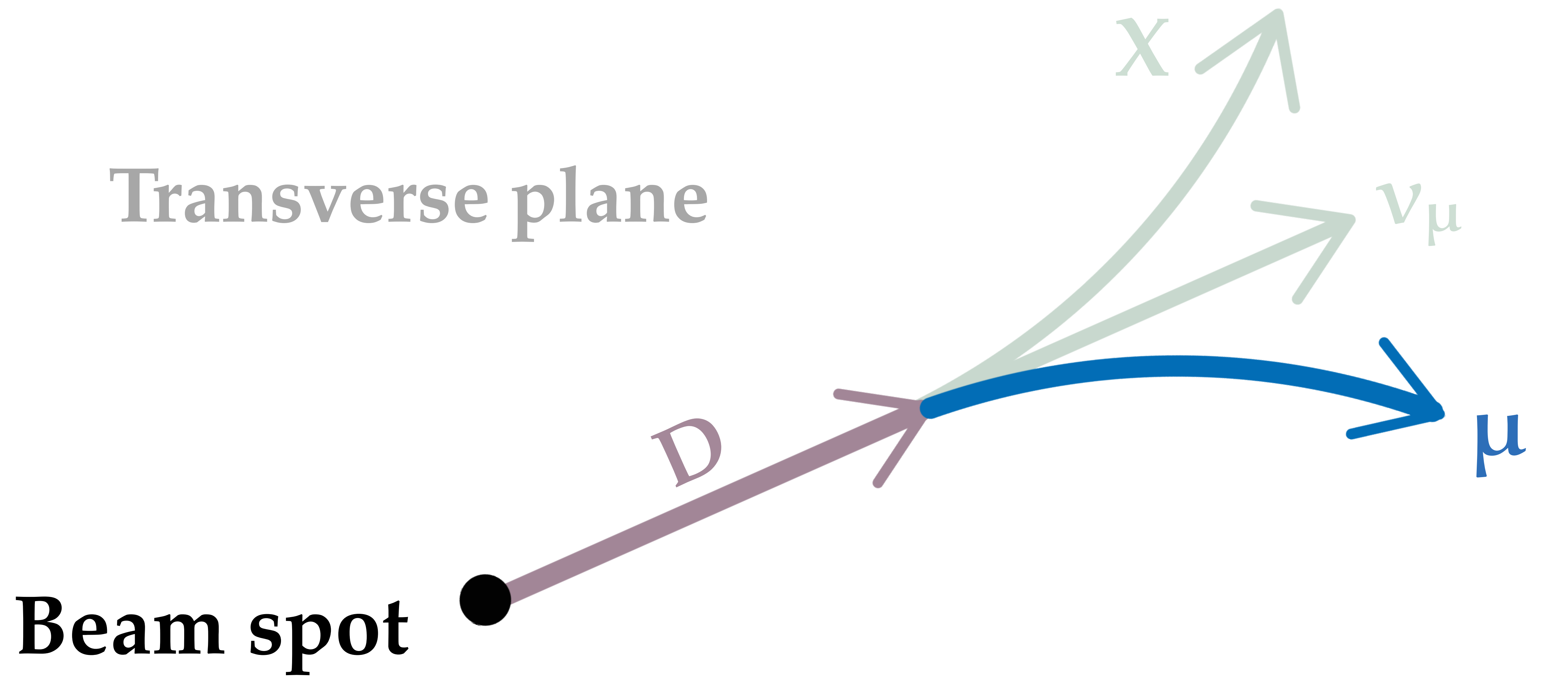
- Similar one from STAR [1]

Signal Extraction Separate c→ and b→μ

[PLB 829 (2022) 137077]

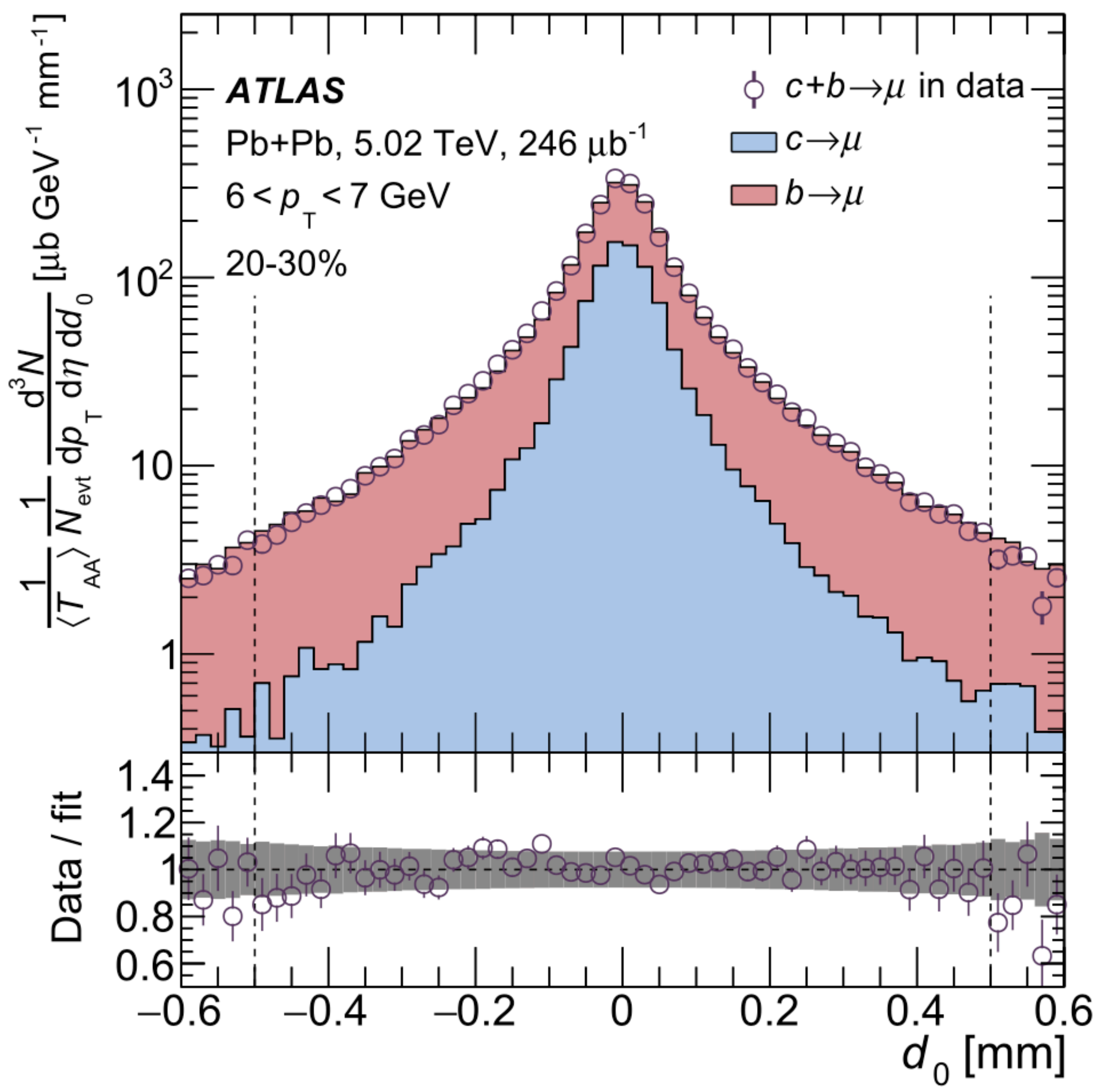


Template fit on **Variables** d_0 (Distance of Closest Approach DCA) relative to the beam spot (primary vertex sometimes)

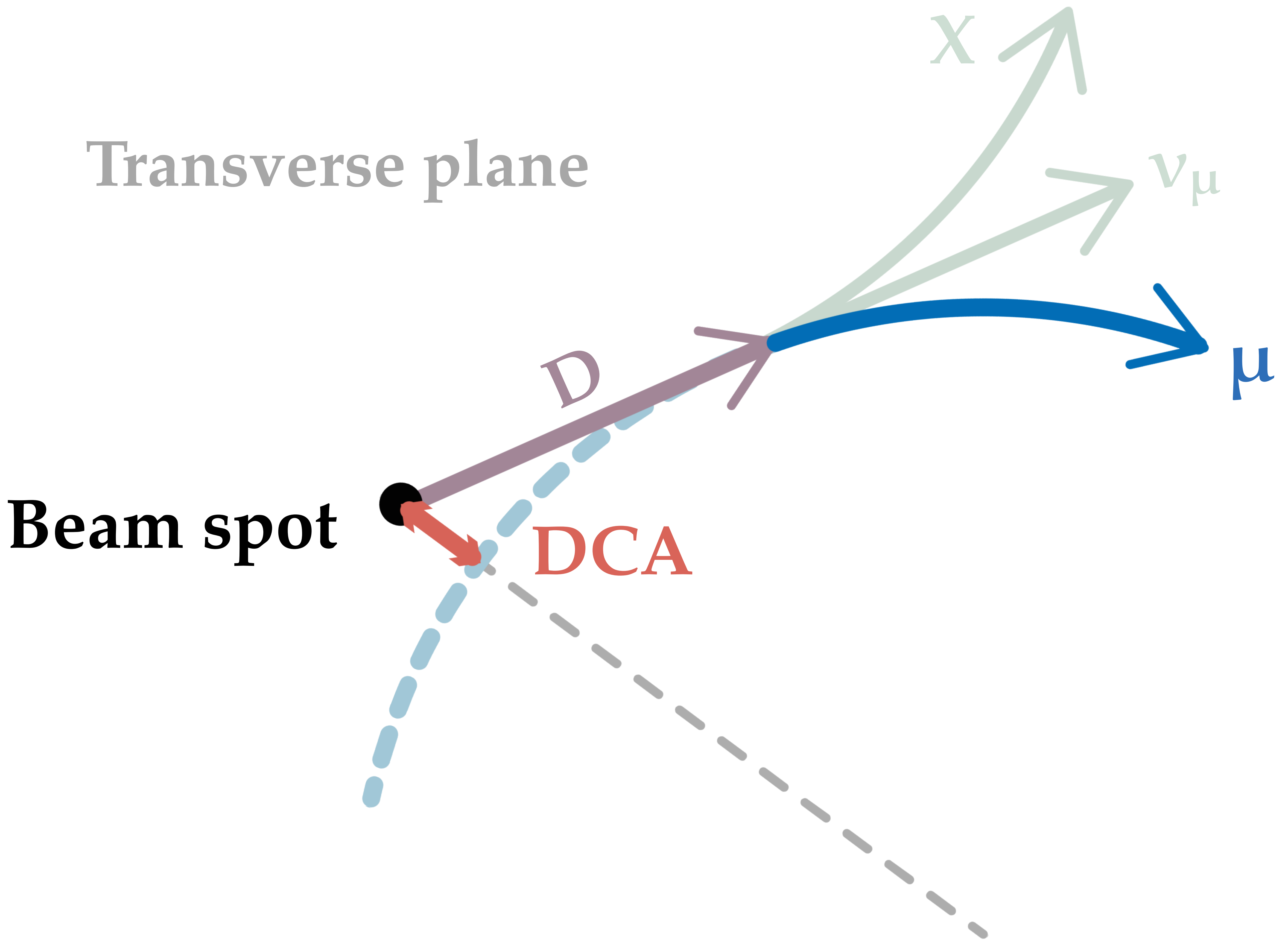


Signal Extraction Separate c→ and b→μ

[PLB 829 (2022) 137077]

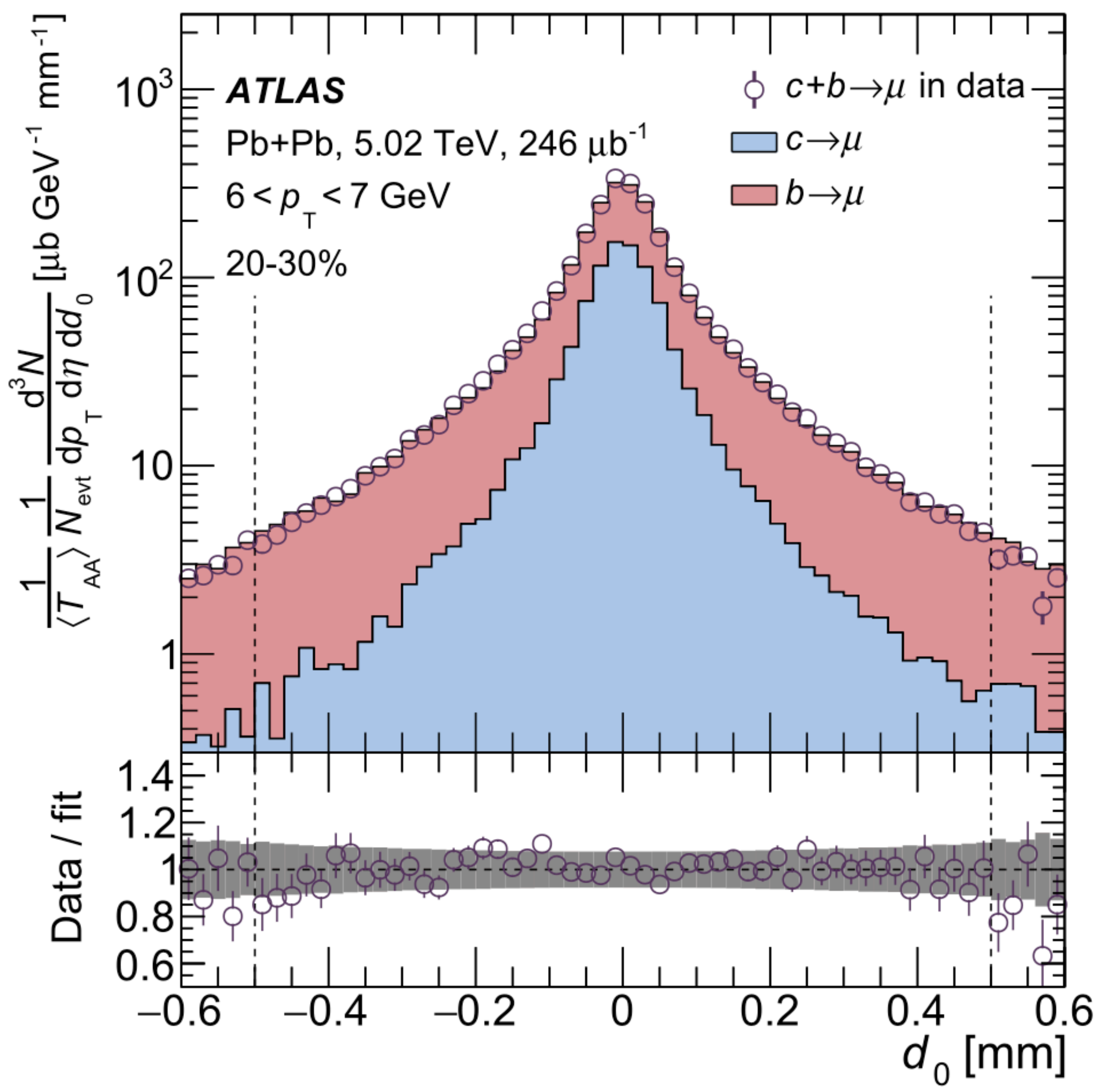


Template fit on **Variables** *d_0* (Distance of Closest Approach DCA) relative to the beam spot (primary vertex sometimes)



Signal Extraction Separate c→ and b→μ

[PLB 829 (2022) 137077]



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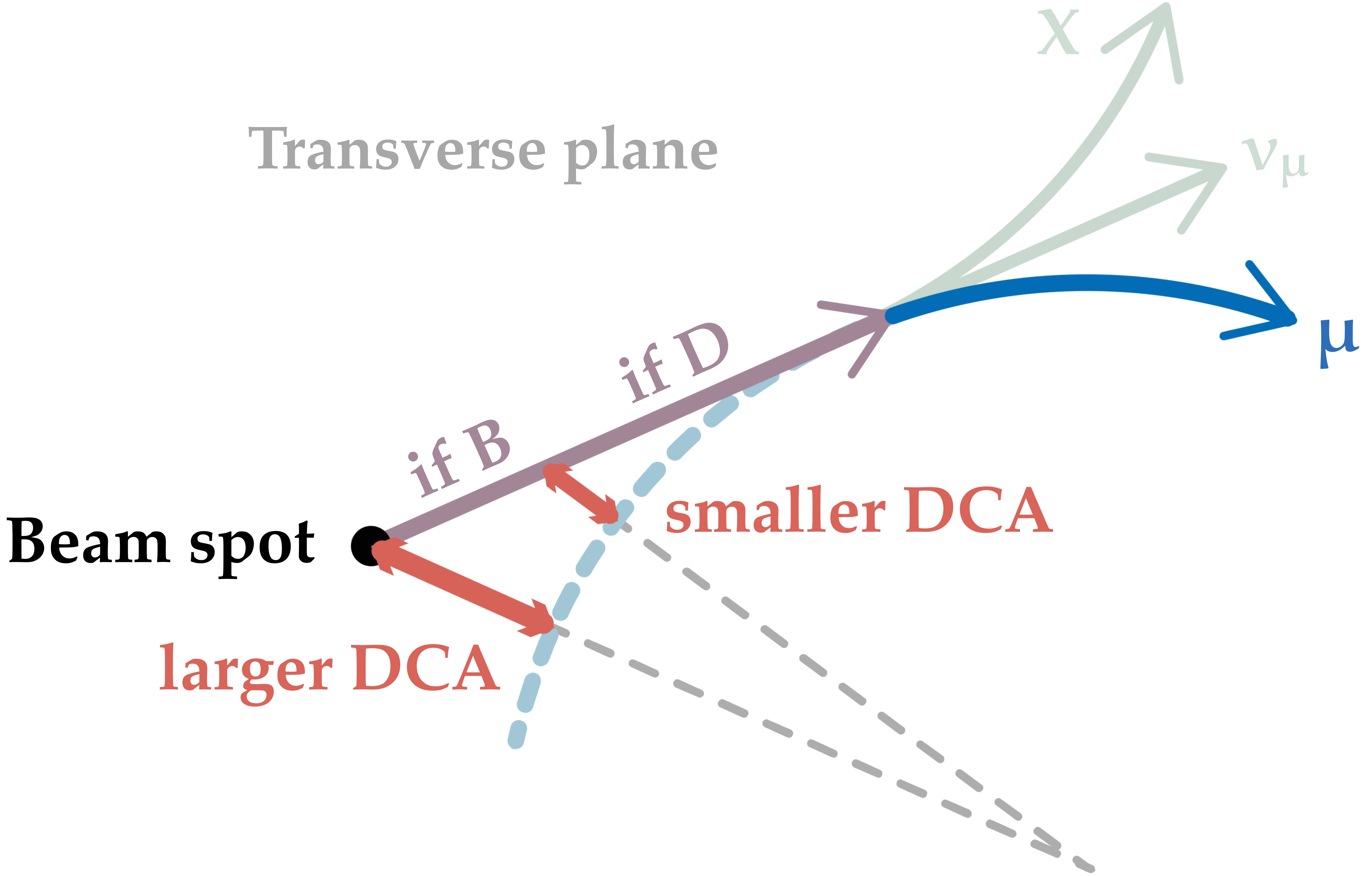
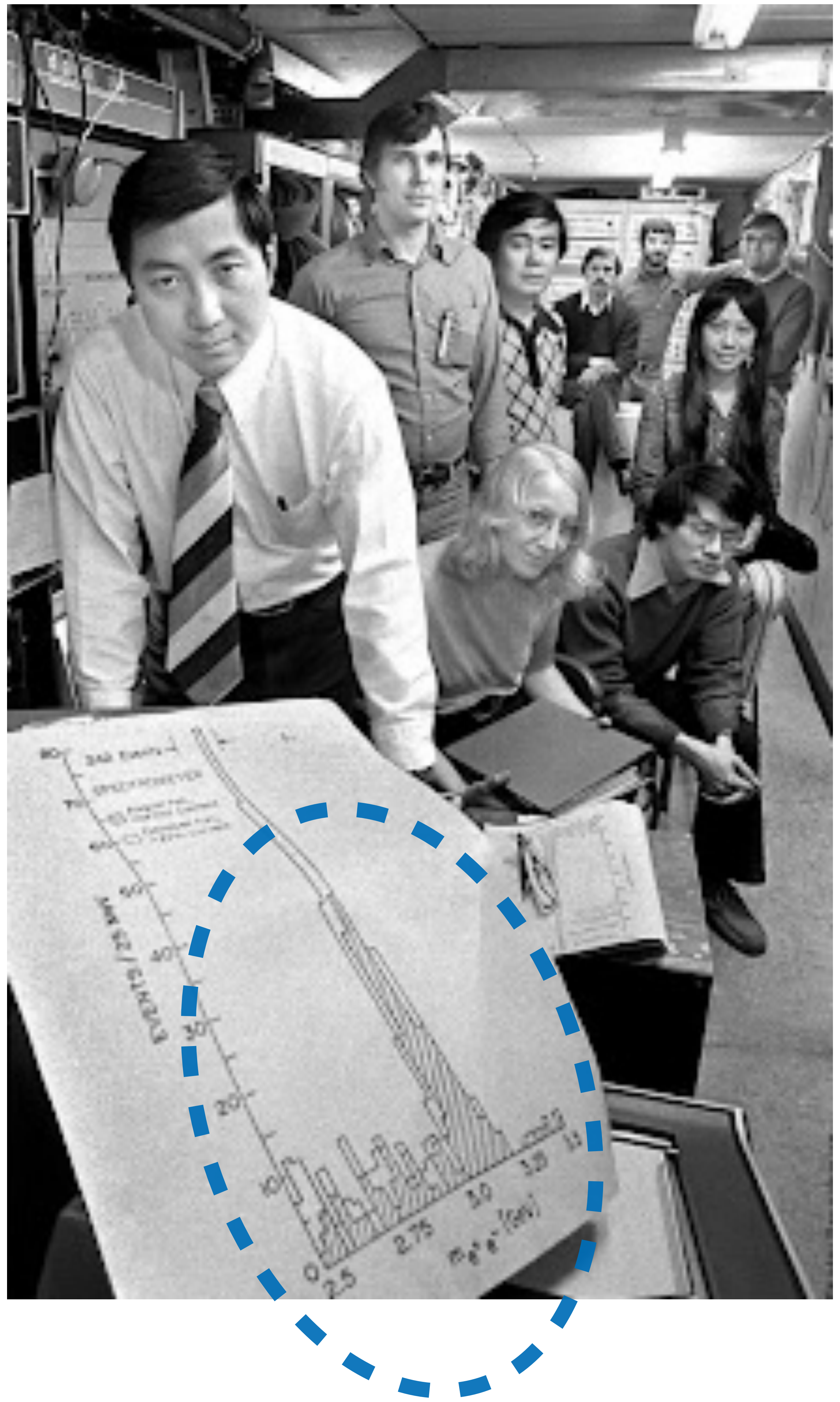


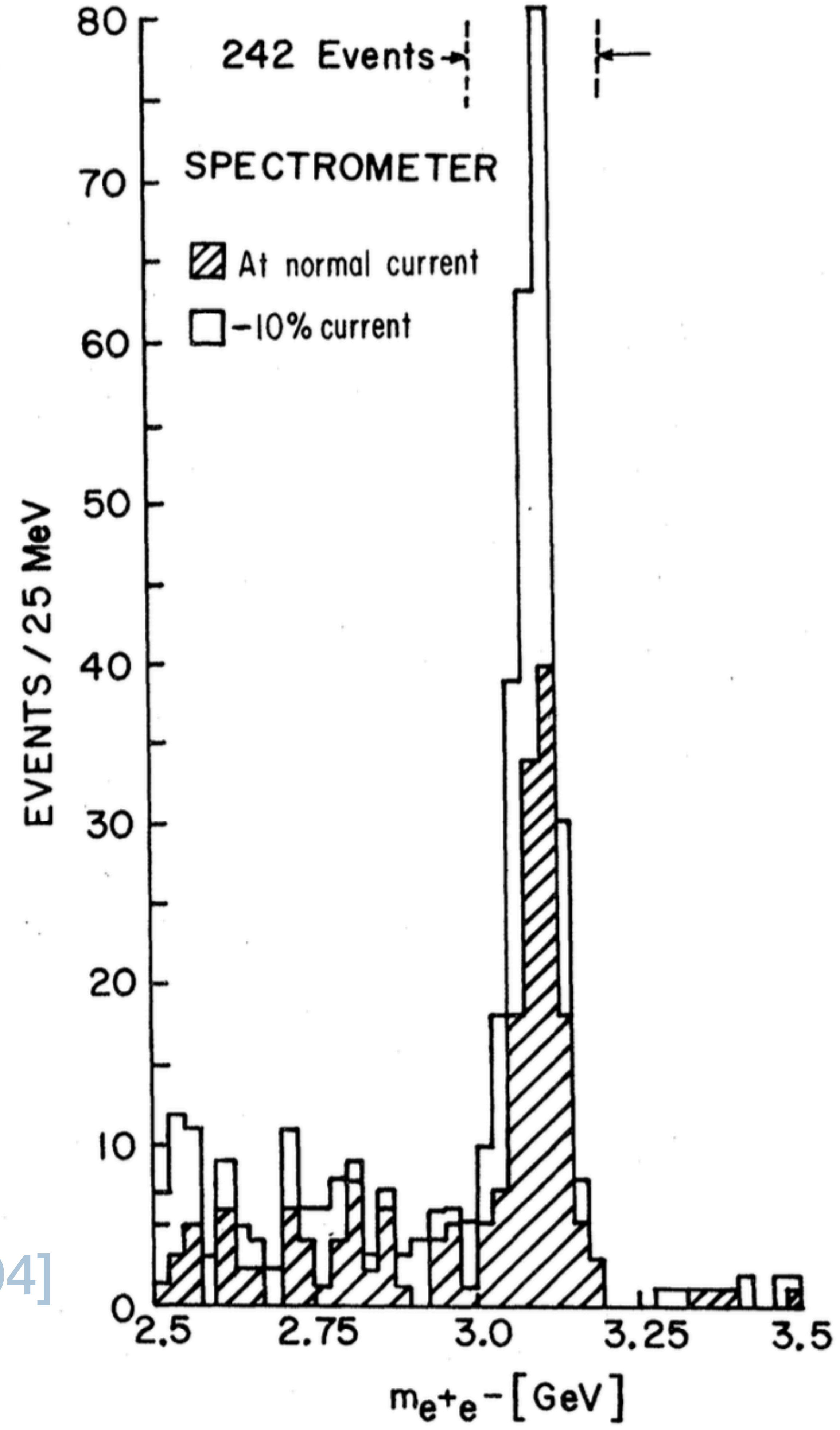
Signal Extraction Fully Reconstruction

Discovery of J/ψ



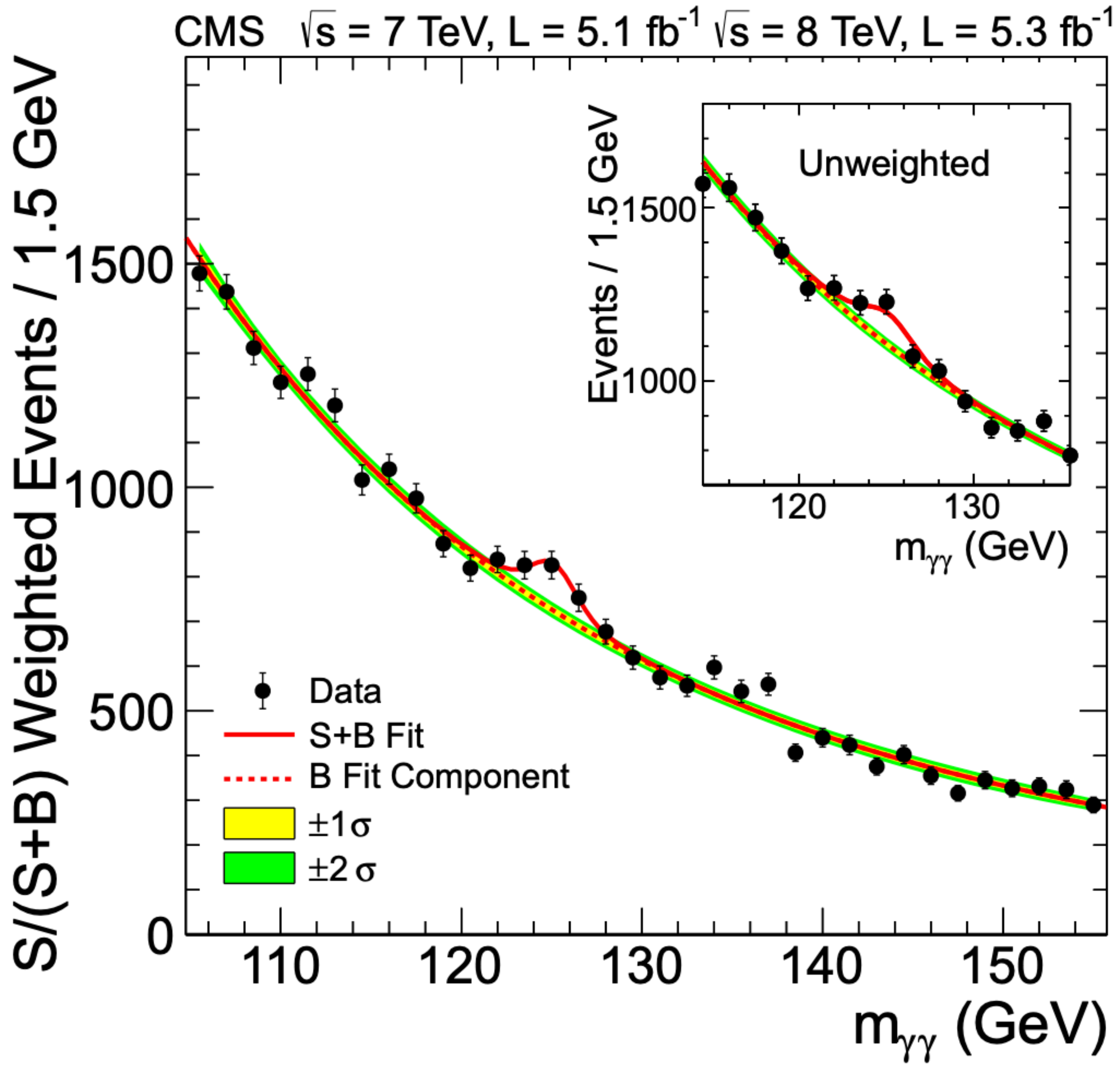
Fit on invariant mass

- 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

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

Fit on invariant mass

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

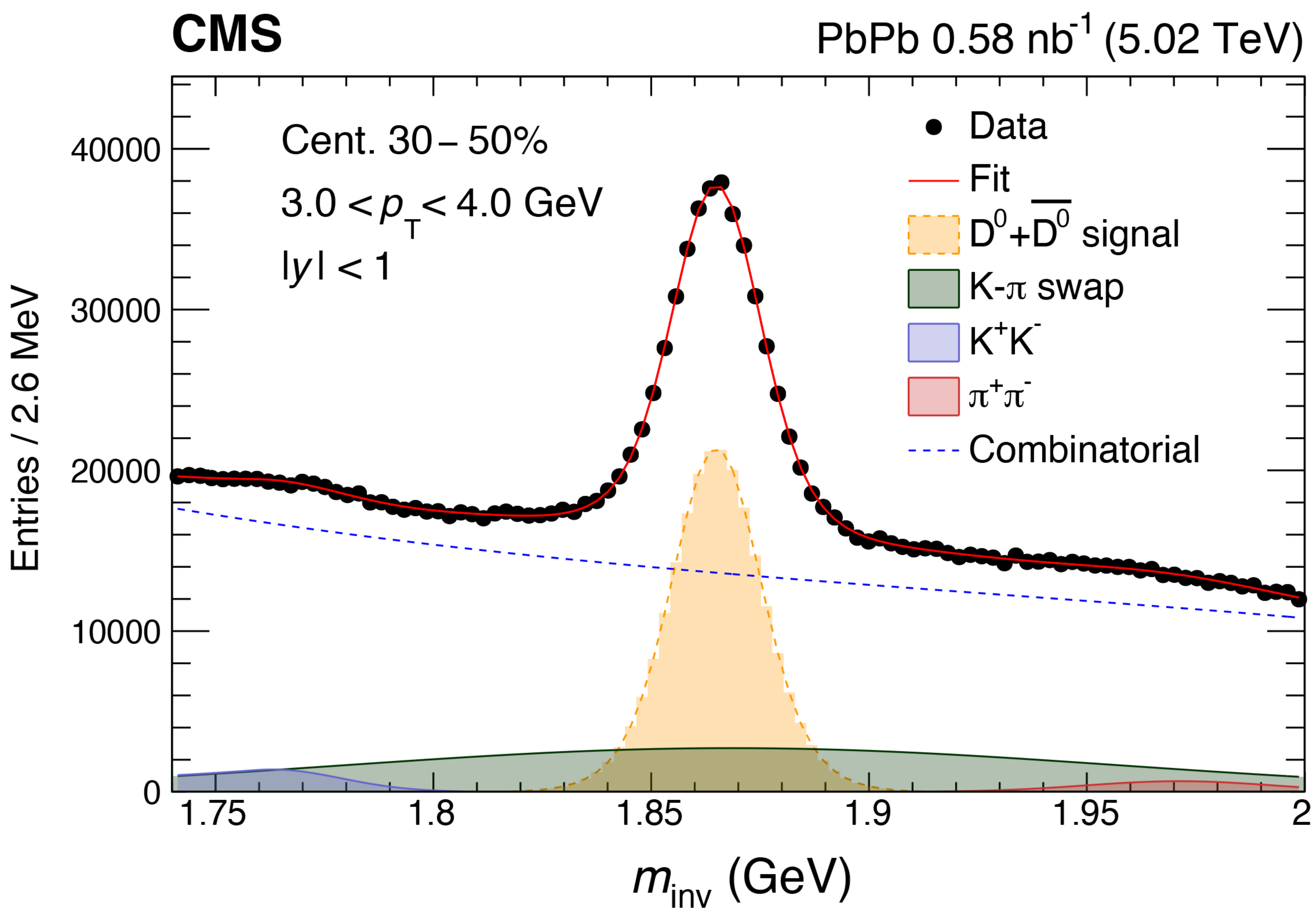
D^0	$\rightarrow$	$K^- \pi^+$
D^+	$\rightarrow$	$K^- \pi^+ \pi^+$
D_S^+	$\rightarrow$	$\phi\,(K^+ K^-)\,\pi^+$
D^{*+}	$\rightarrow$	$D^0\,(K^- \pi^+)\,\pi^+$
Λ_c^+	$\rightarrow$	$p\,K^- \pi^+$
Λ_c^+	$\rightarrow$	$p\,K_s^0\,(\pi^+ \pi^-)$
B^+	$\rightarrow$	$J/\psi\,(\mu^+\mu^-)\,K^+$
B^+	$\rightarrow$	$\bar{D}^0\,(K^+ \pi^-)\,\pi^+$
B^0	$\rightarrow$	$J/\psi\,(\mu^+\mu^-)\,K_s^0\,(\pi^+ \pi^-)$
B^0	$\rightarrow$	$D^-\,(K^+ \pi^- \pi^-)\,\pi^+$
B_S^0	$\rightarrow$	$J/\psi\,(\mu^+\mu^-)\,\phi\,(K^+ K^-)$
Λ_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]



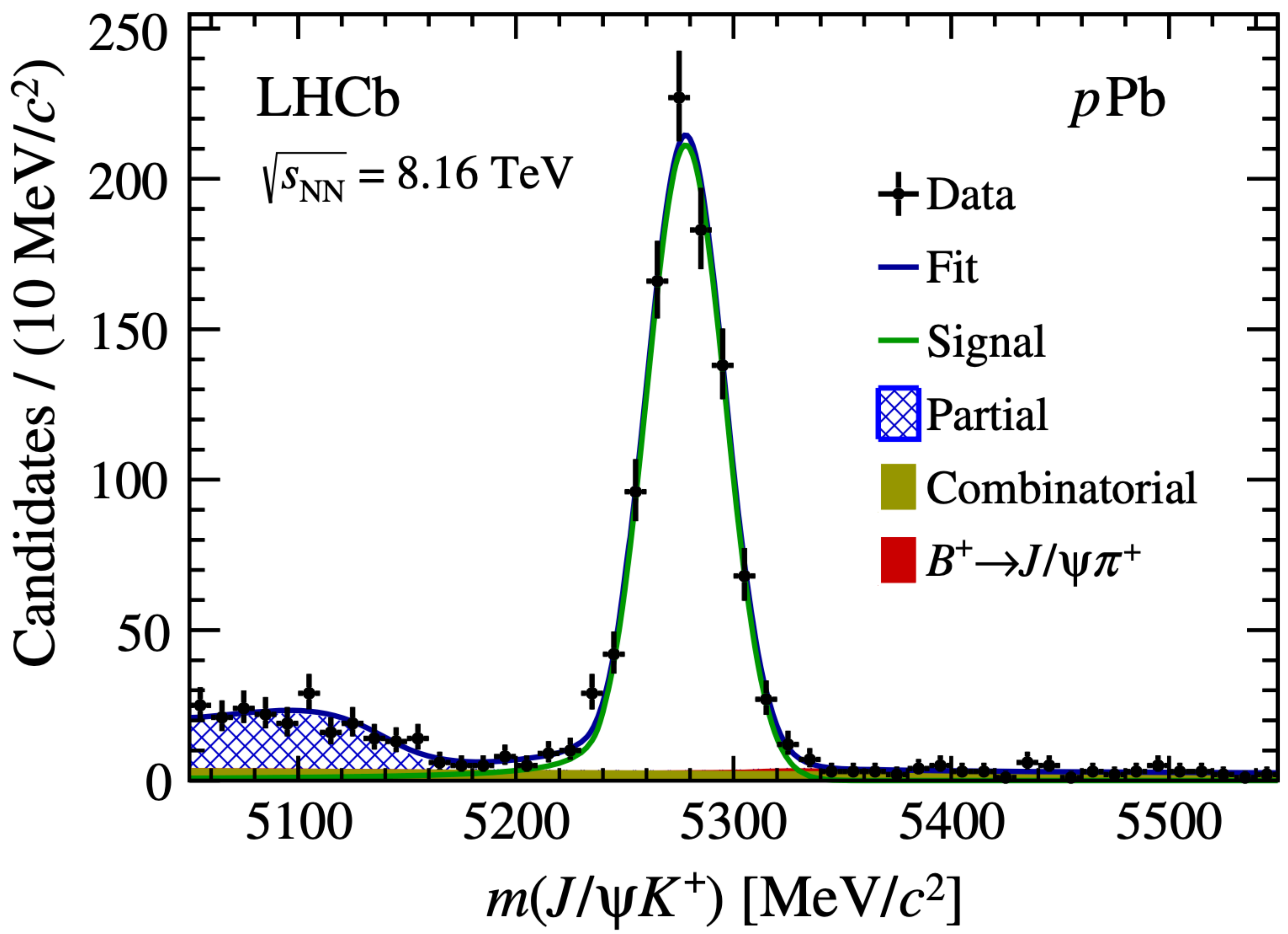
- **Signal shape** width reflects track momentum resolution
- **Combinatorial** randomly pairing two opposite-sign tracks
  - Likelihood ratio test degree of freedom needs to balance fitting performance and overfitting
- Peaky background
  - **K-π swap** $D^0 \to K\pi$ is reco-ed but the mass assignment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

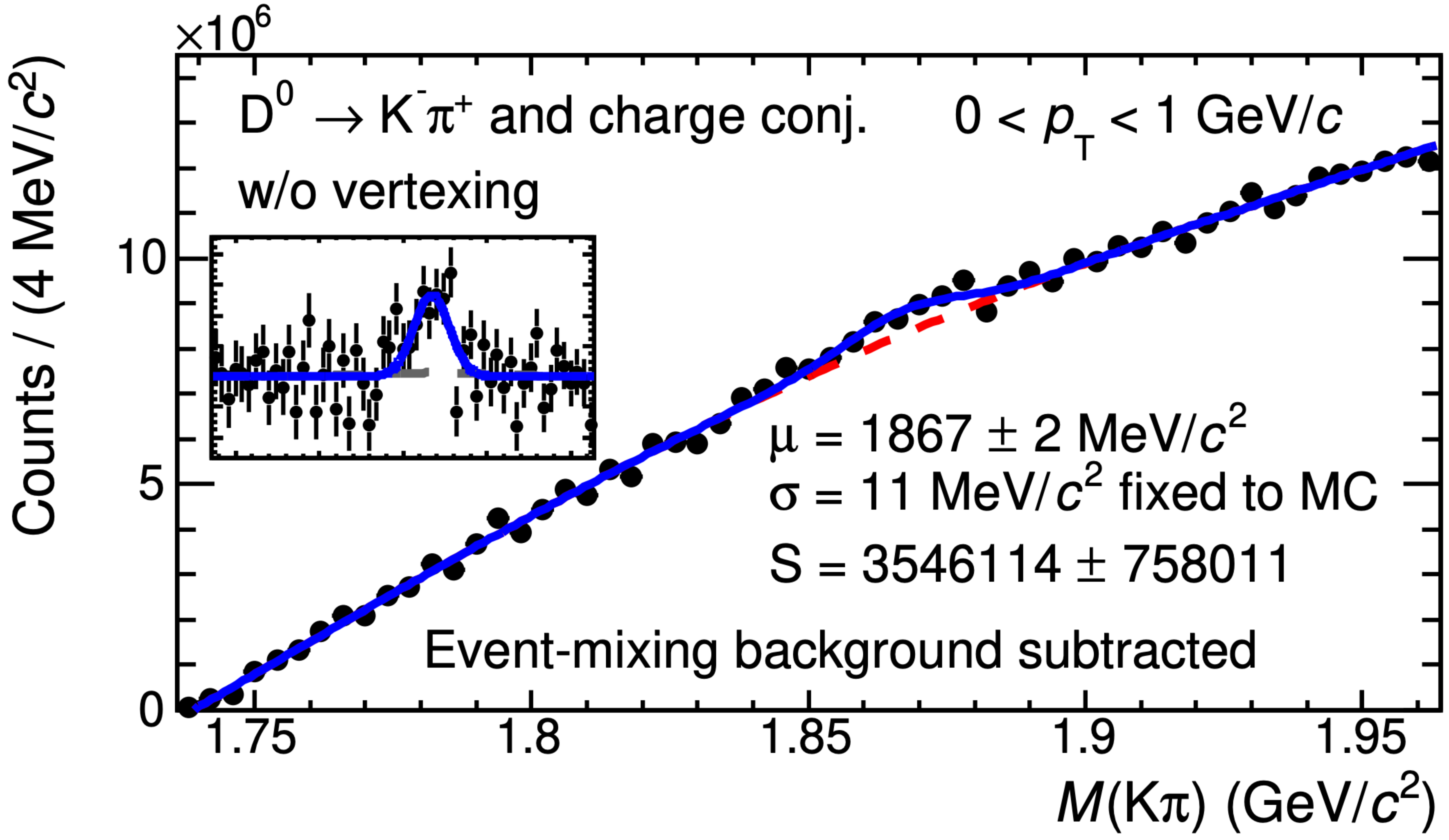
Invariant Mass Fit Extension

[PRD 99 (2019) 052011]

Extension for homework

[JHEP 01 (2022) 174]



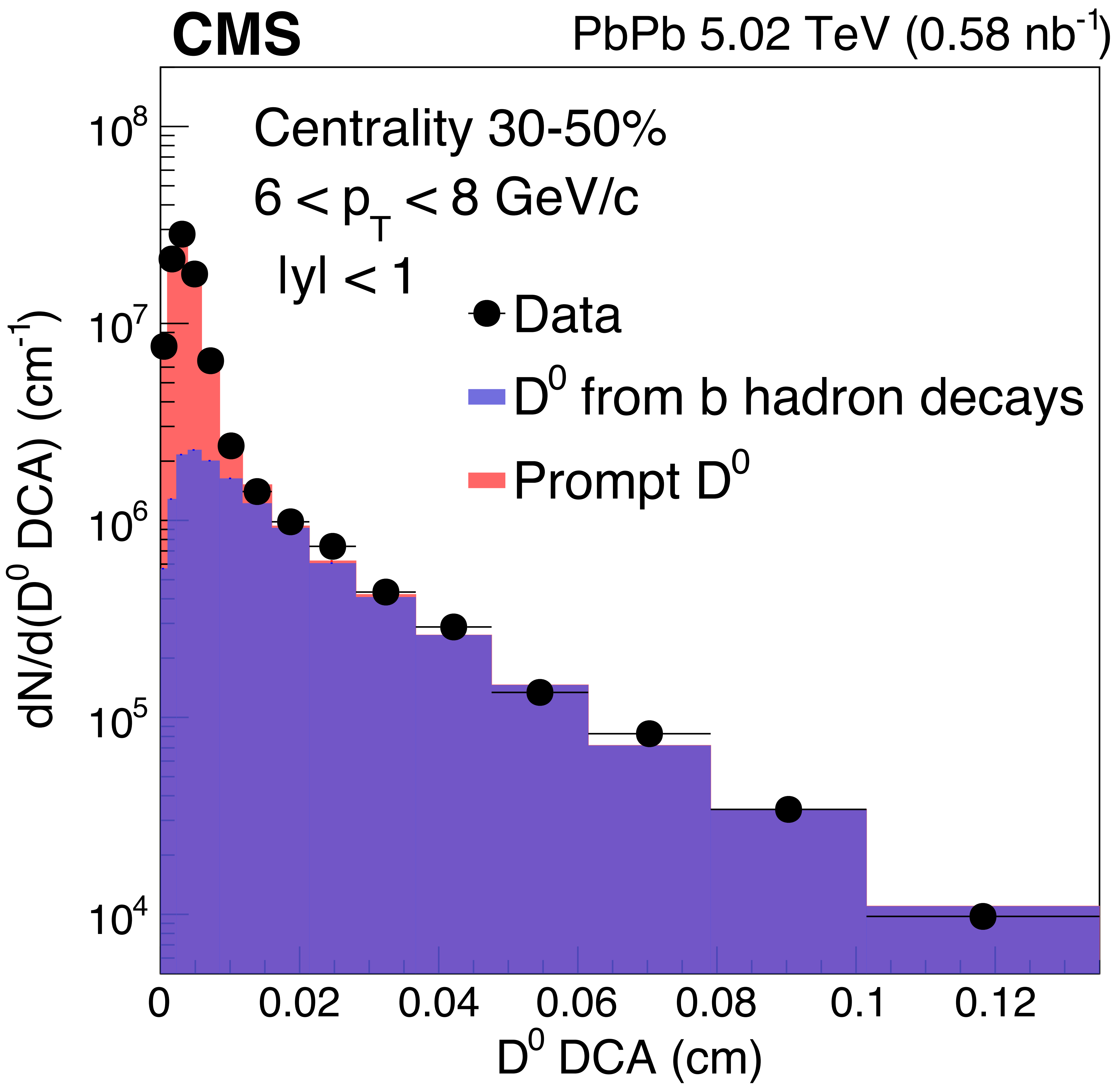


- What peaky backgrounds for $B^+ \to J/\psi K^+$?
- What functions are used to model each component?

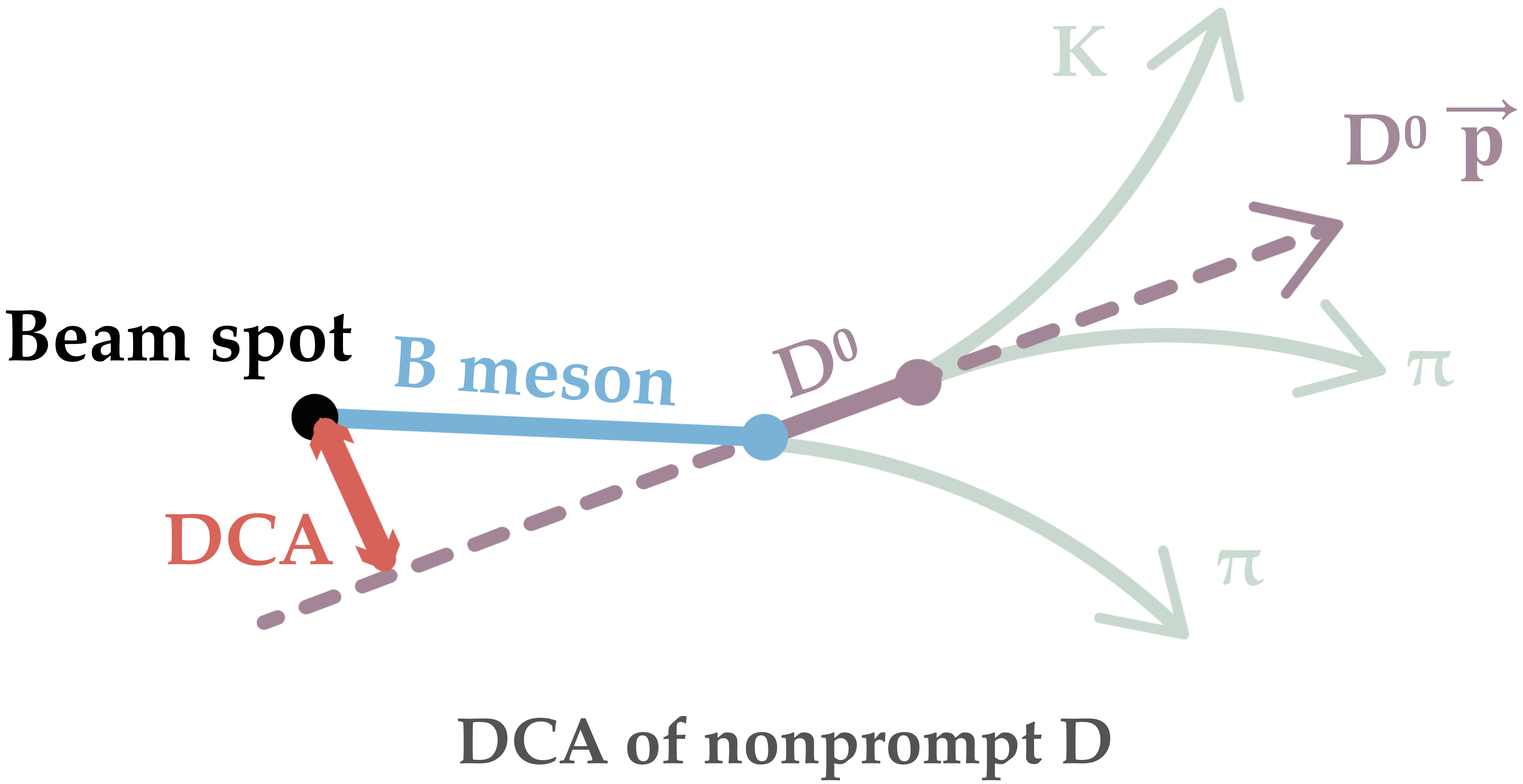
- What is the event-mixing technique used to achieve measurements down to 0 p_T by ALICE

Separate Prompt and Nonprompt D mesons

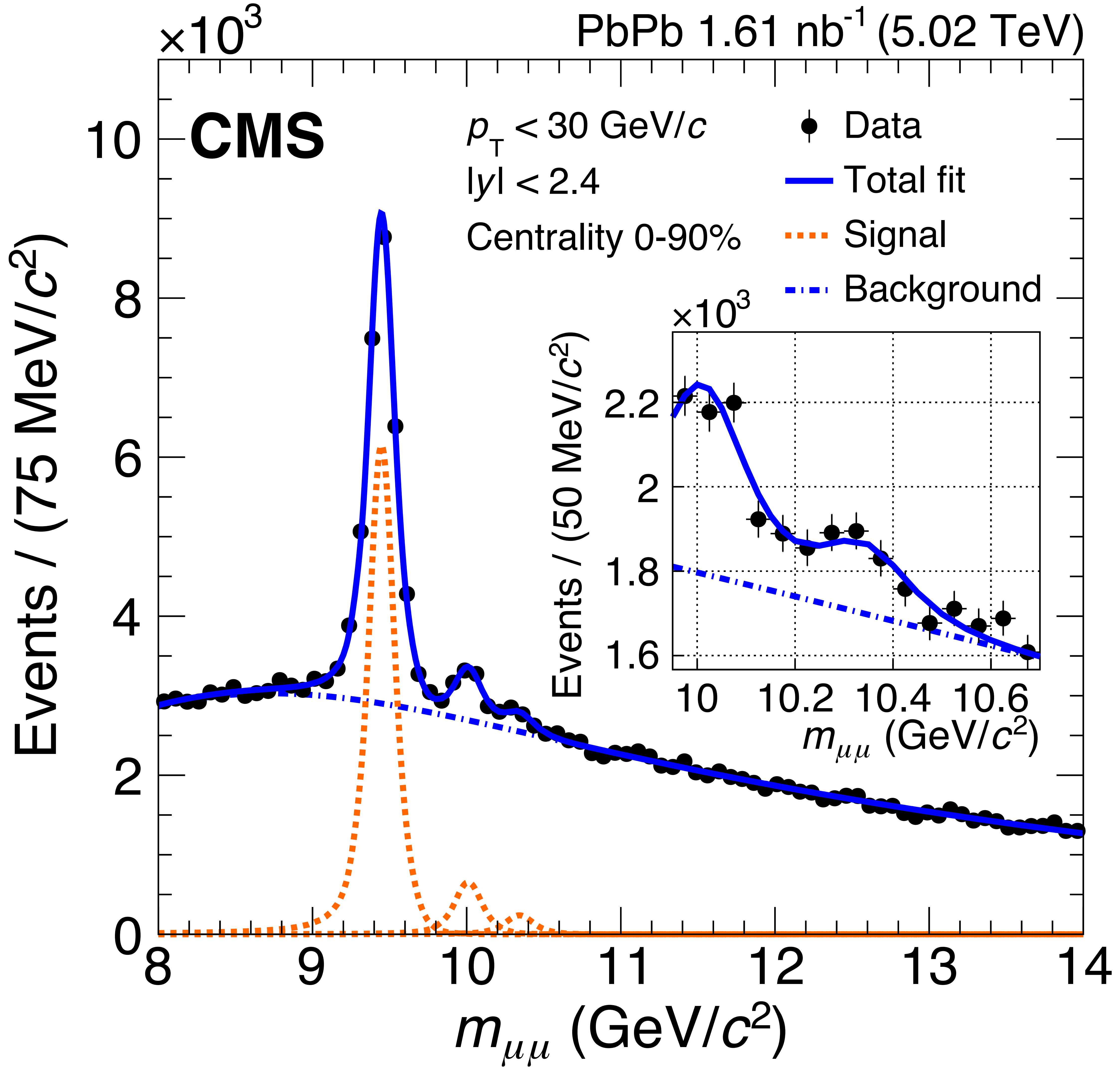
[PLB 850 (2024) 138389]



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



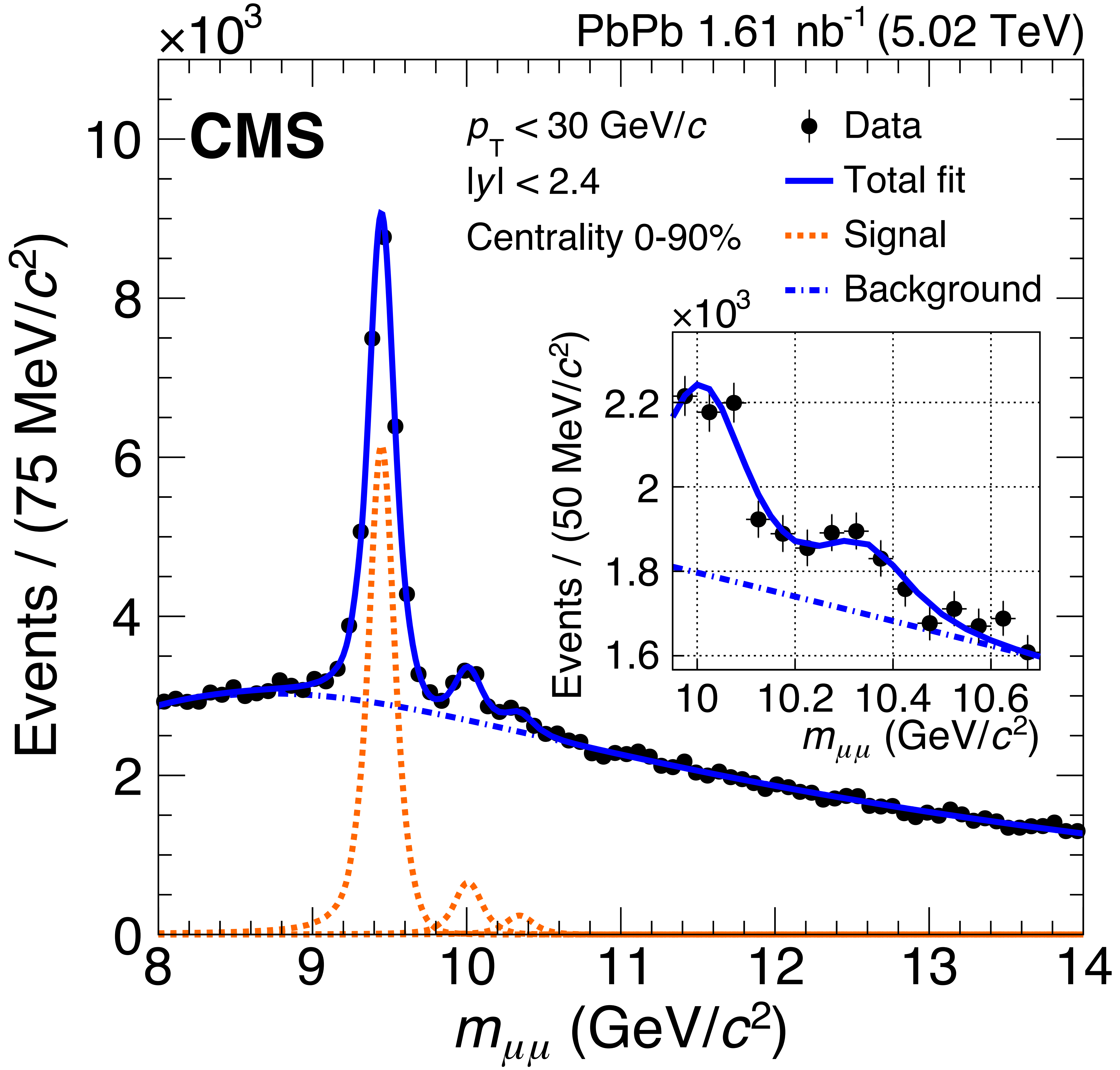
Yield Extraction Excited State Quarkonia



[2303.17026]

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

Yield Extraction Excited State Quarkonia



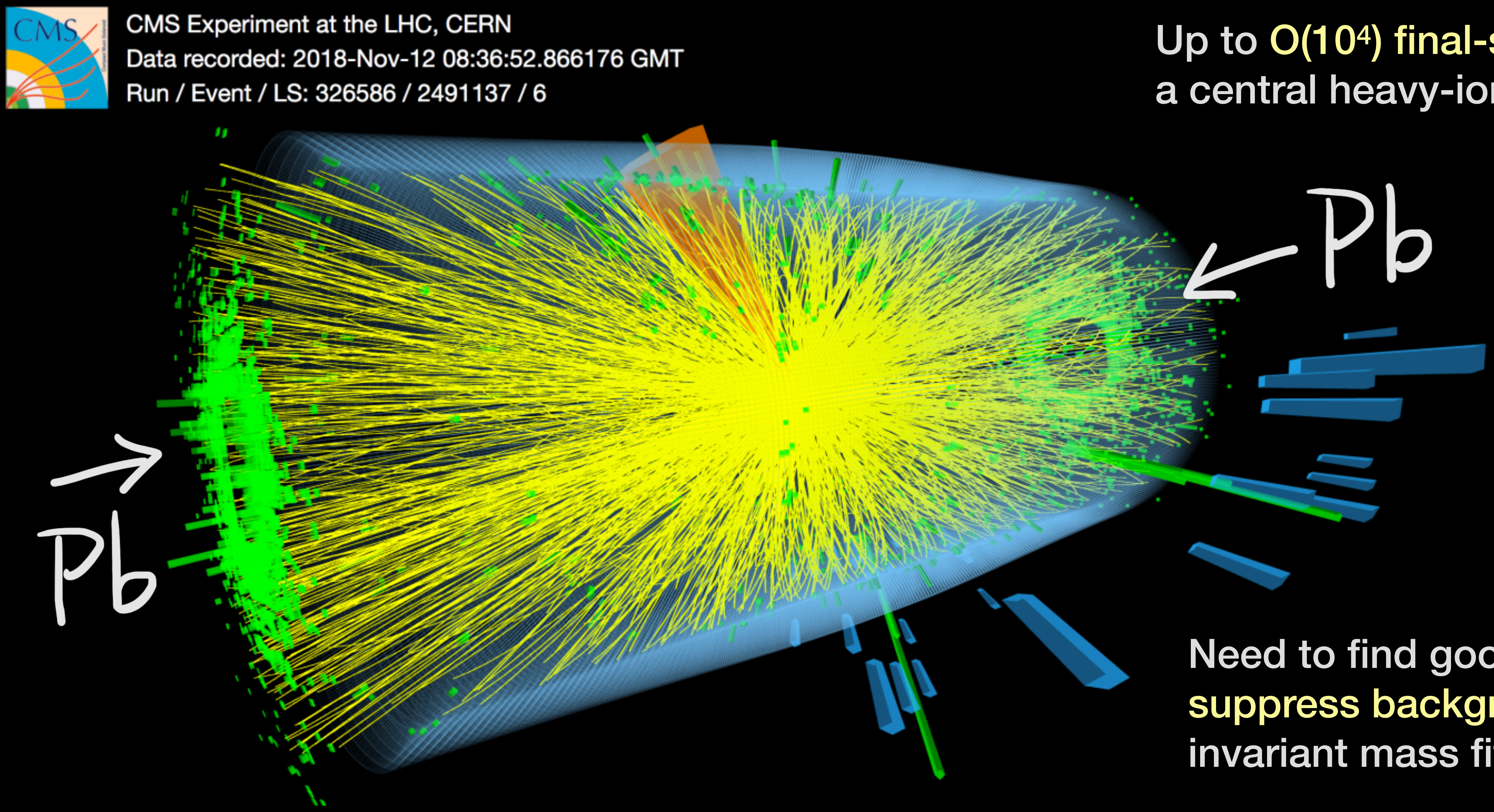
[2303.17026]

- 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

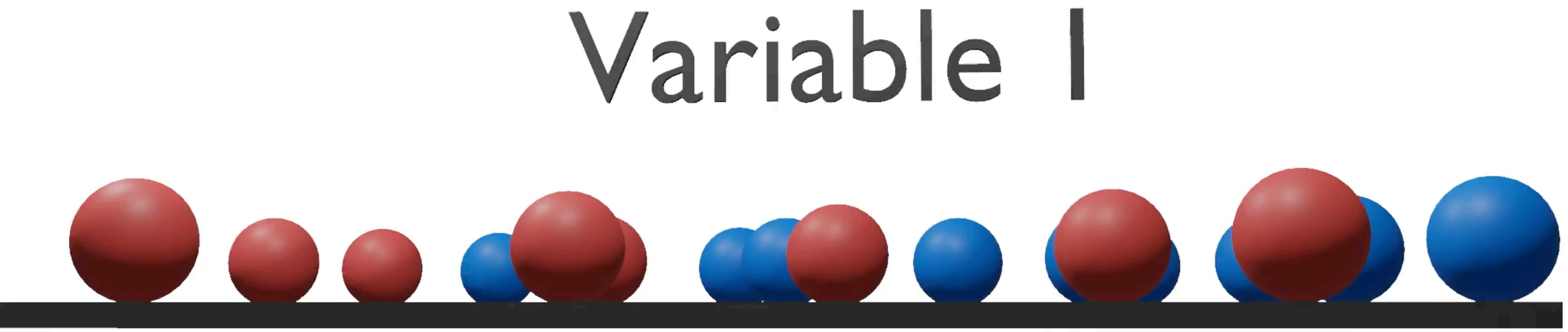


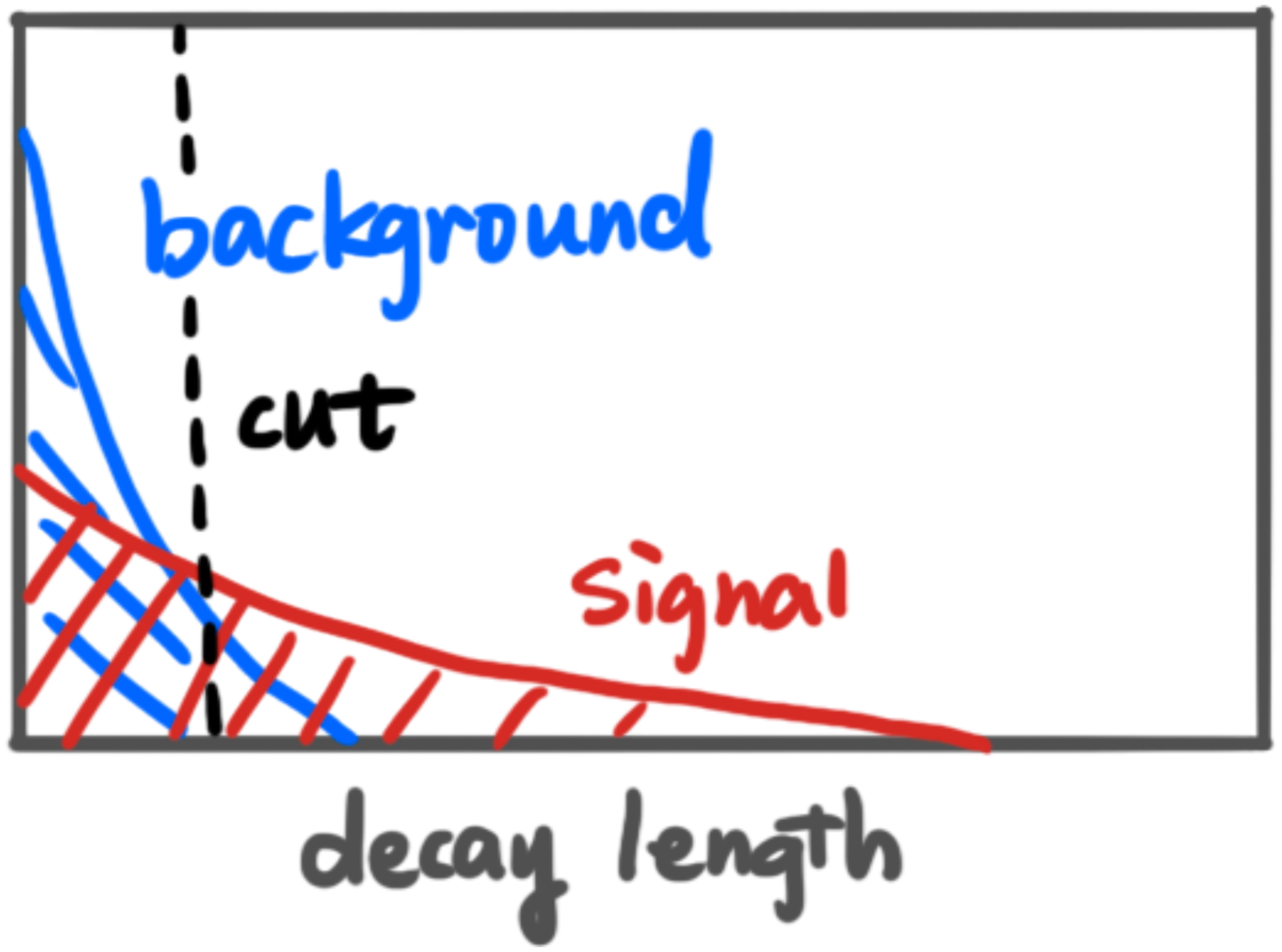
Up to O(10^4) final-state particles in a central heavy-ion event

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

Suppress Background Multivariate Classification

If want to separate red and blue balls…





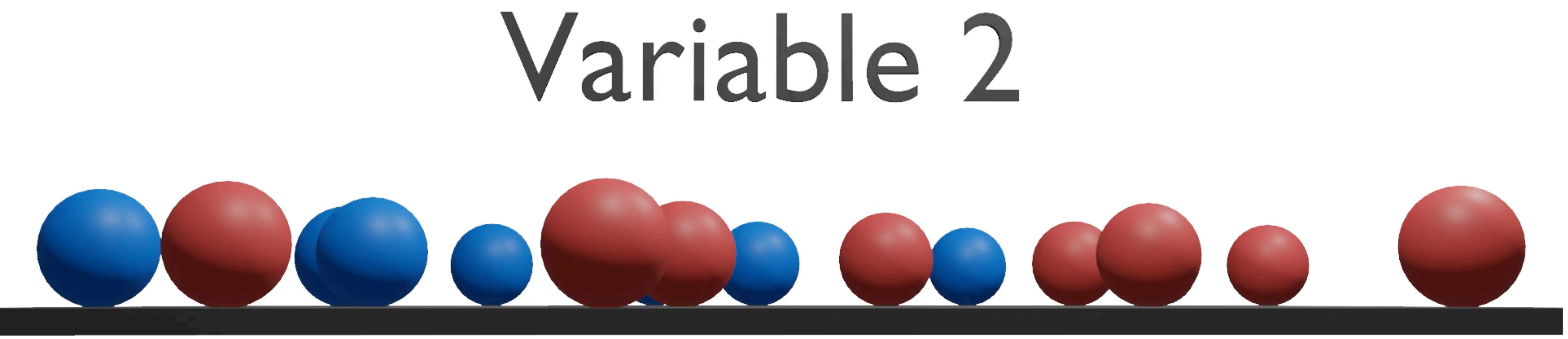
Some variables can separate signals and backgrounds to a certain extent

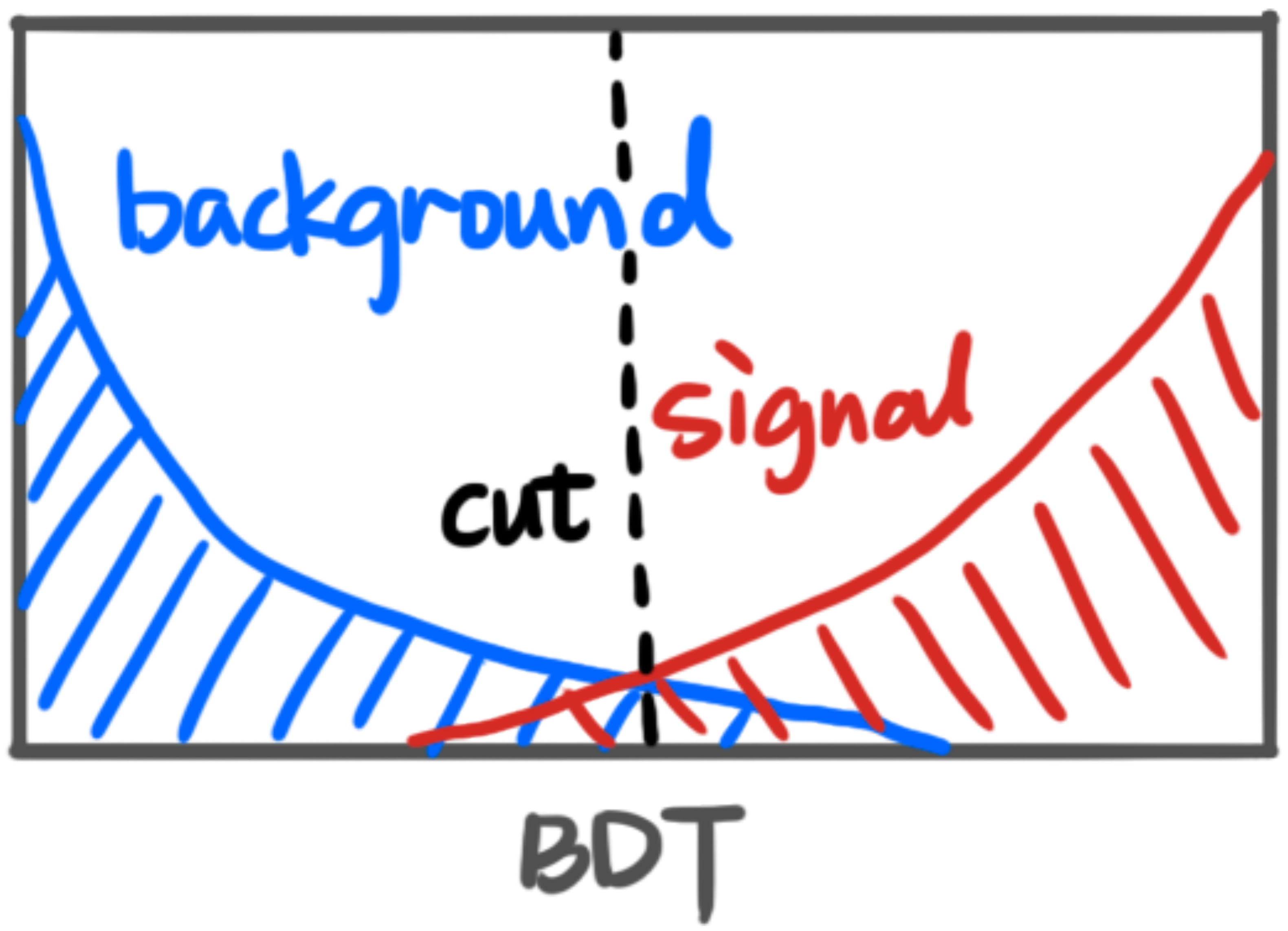
- Decay length significance
- Secondary vertex probability
- Pointing angles
- …

[Animation]

Suppress Background Multivariate Classification

If want to separate red and blue balls…

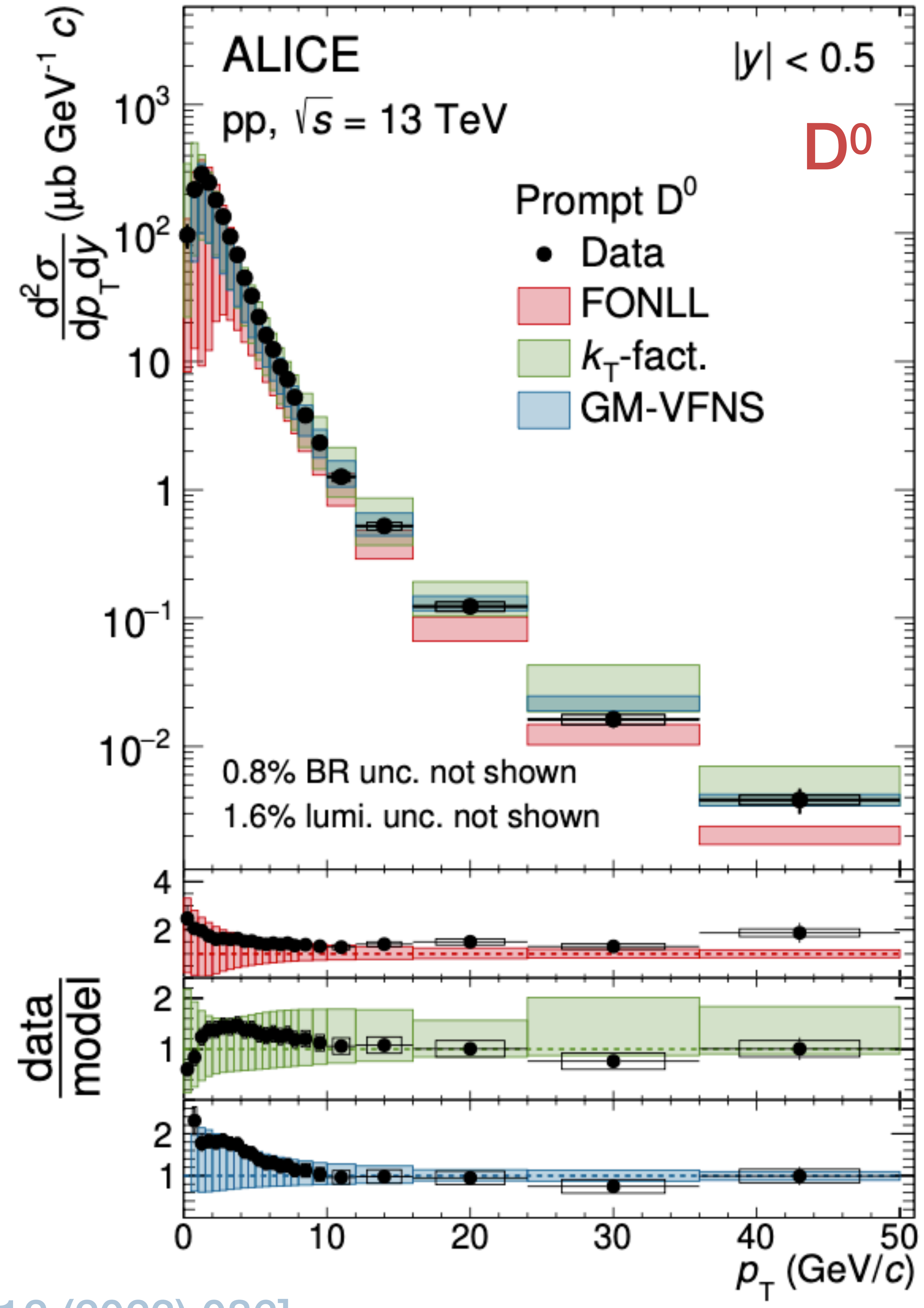




Combining multi variables in a smart way separate backgrounds and signals better → where ML can help

[Animation]

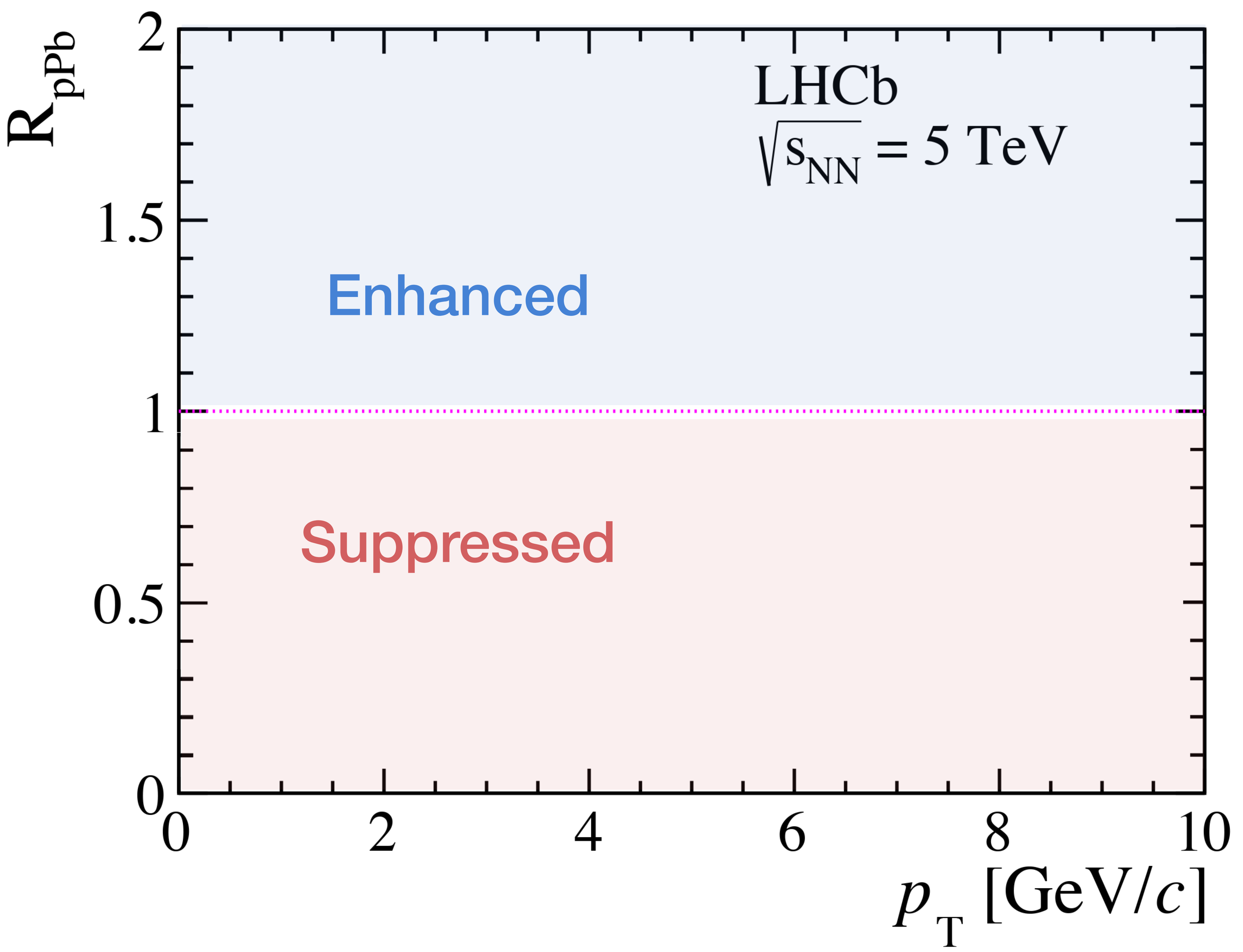
Initial Production pQCD Test



[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?

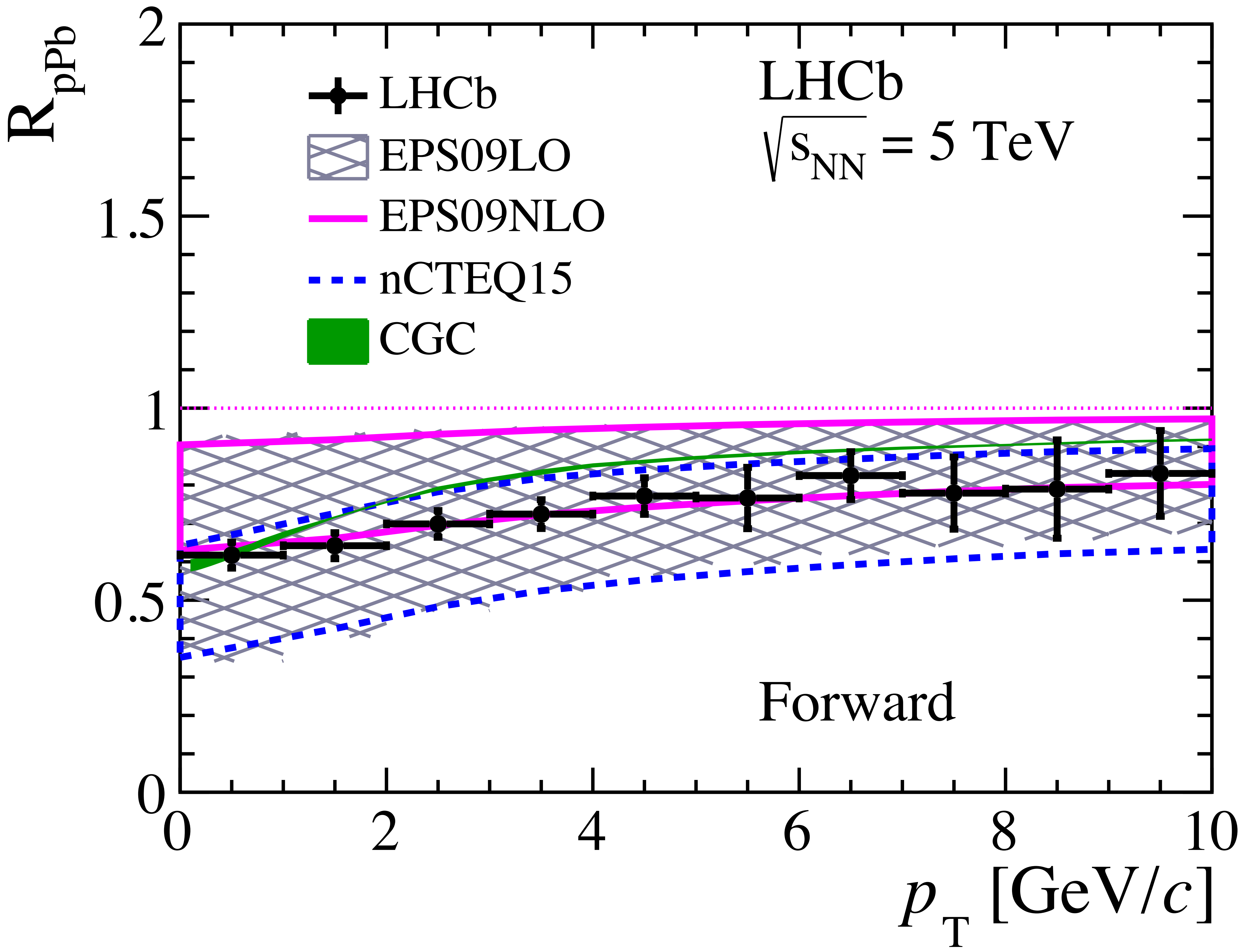
- p-A collisions to test these kind of effects
  - Ion as collision particles
  - No medium effect expected
- Observable of particle yield modification in pA collisions compared to pp

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

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

Initial Production Nuclear PDF

Forward D^0 R_{pPb}



[JHEP 10 (2017) 090]

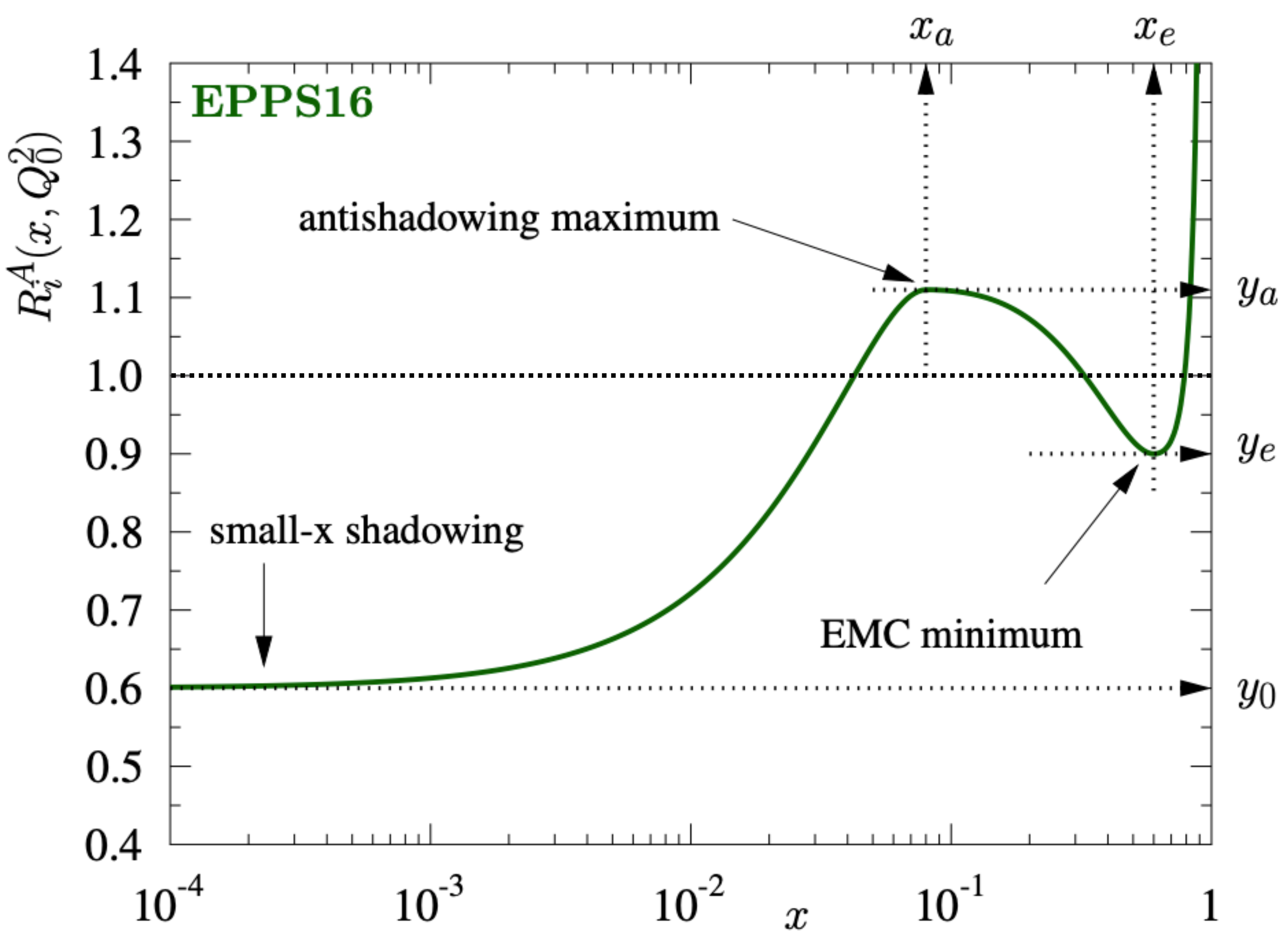
- D^0 suppressed at low p_T in forward rapidity in pA
  - Nuclear PDF model can describe it

    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]

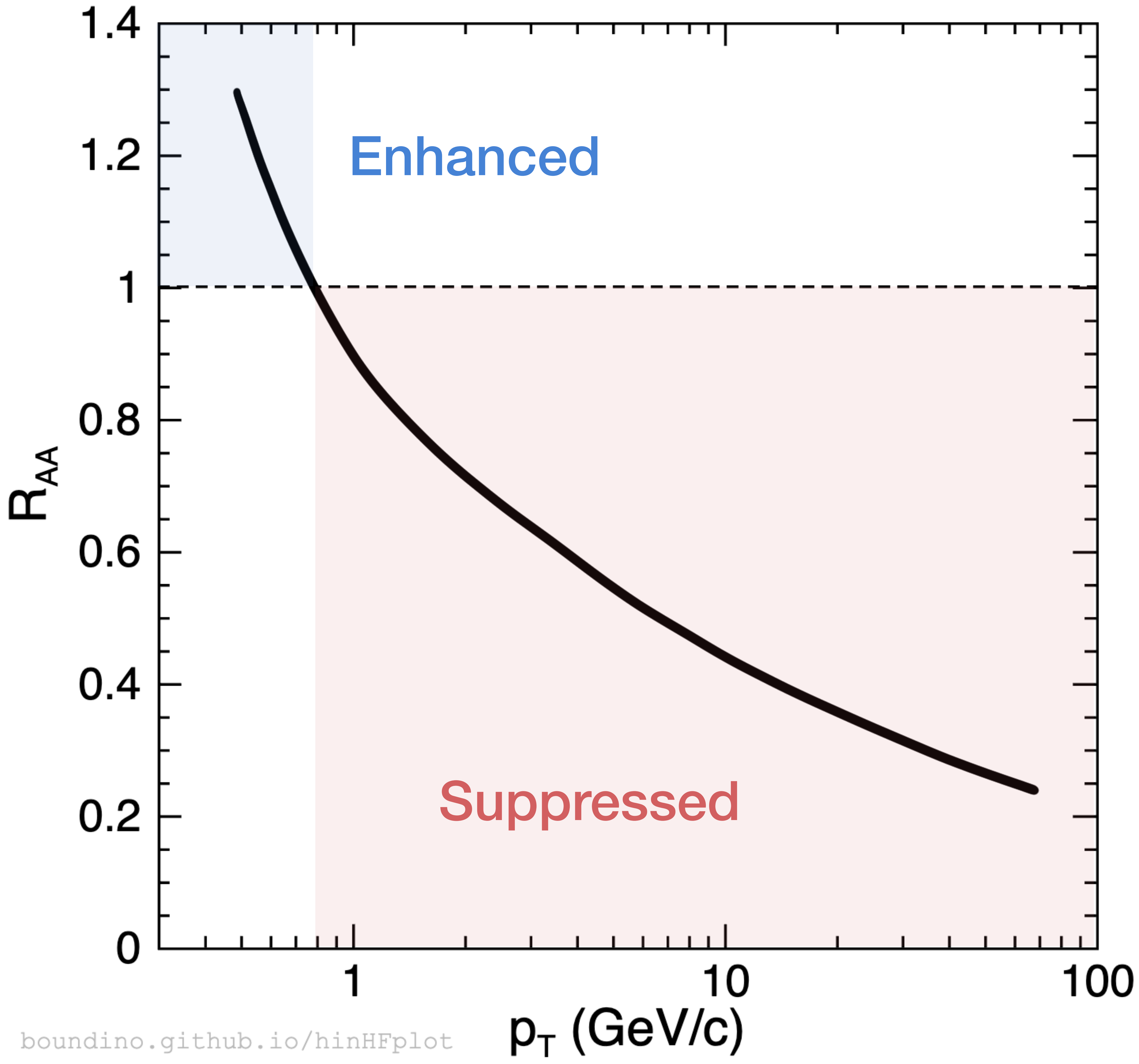
- For low-p_T D mesons in A-A collisions

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

  - $x \sim 10^{-3}$-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}

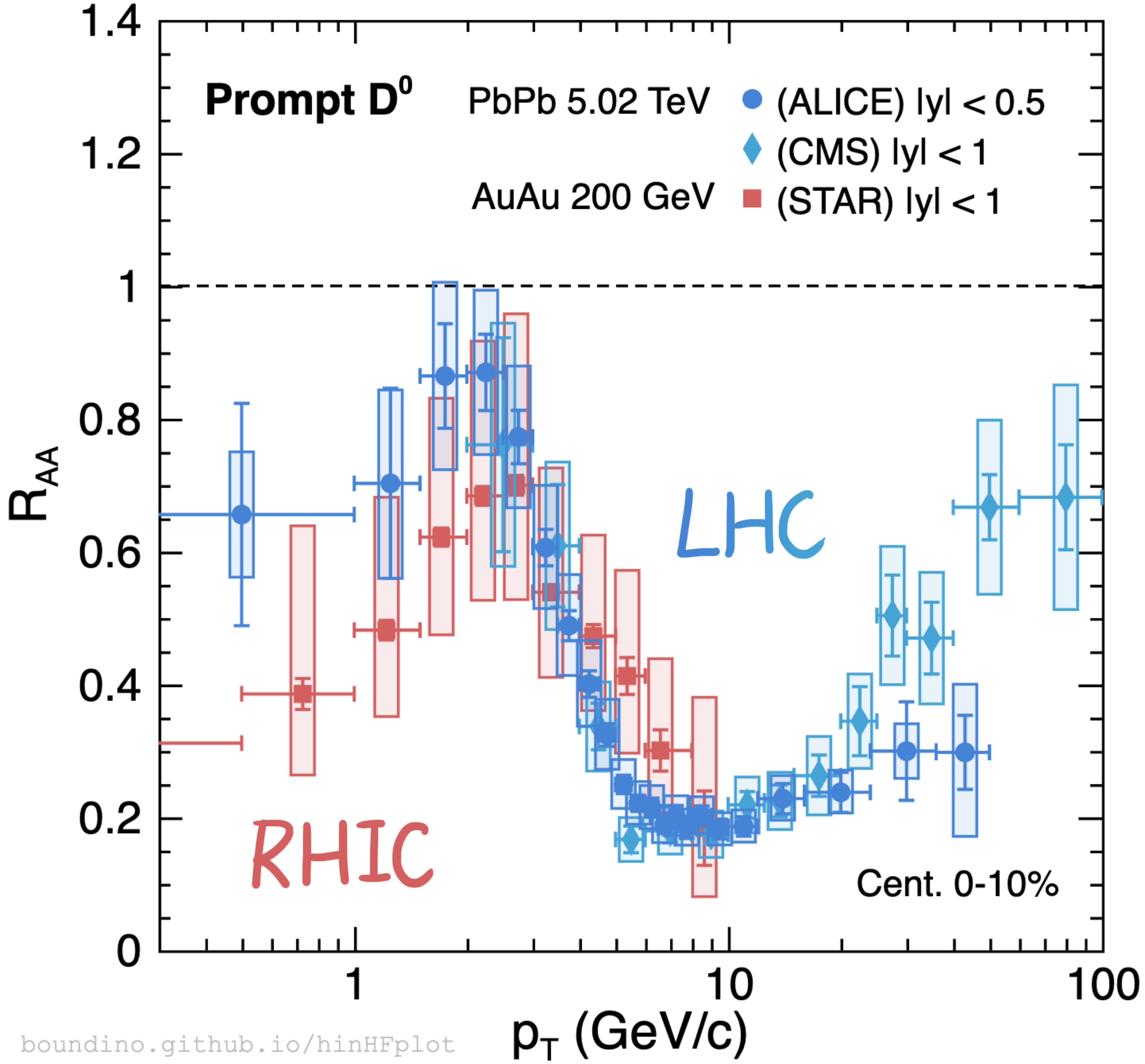
R_{AA} =1: superposition of nucleon-nucleon collisions

$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_{\mathrm{T}}}{T_{AA}\mathrm{d}\sigma_{pp}/\mathrm{d}p_{\mathrm{T}}}$$

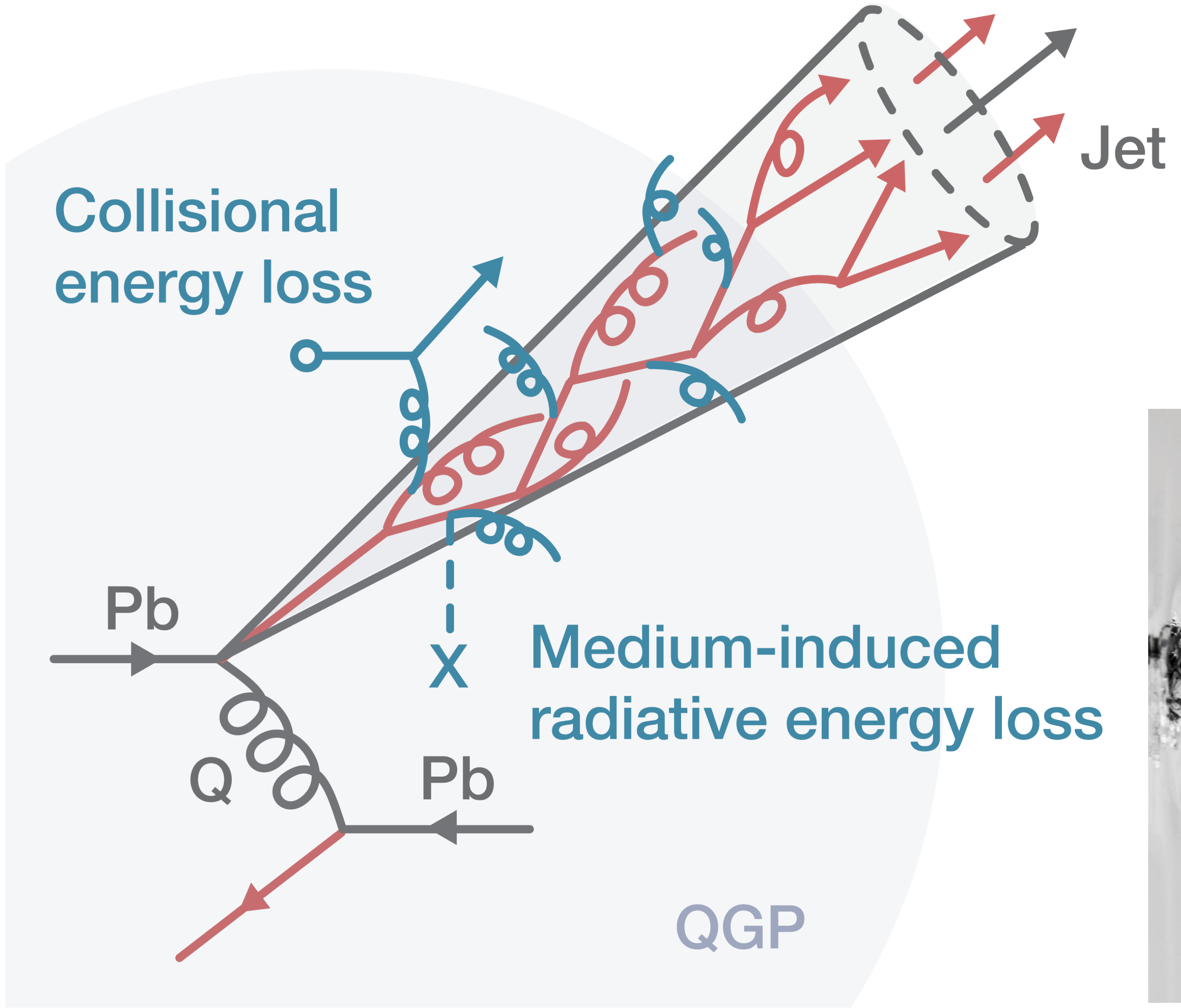
← Heavy-ion

← 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

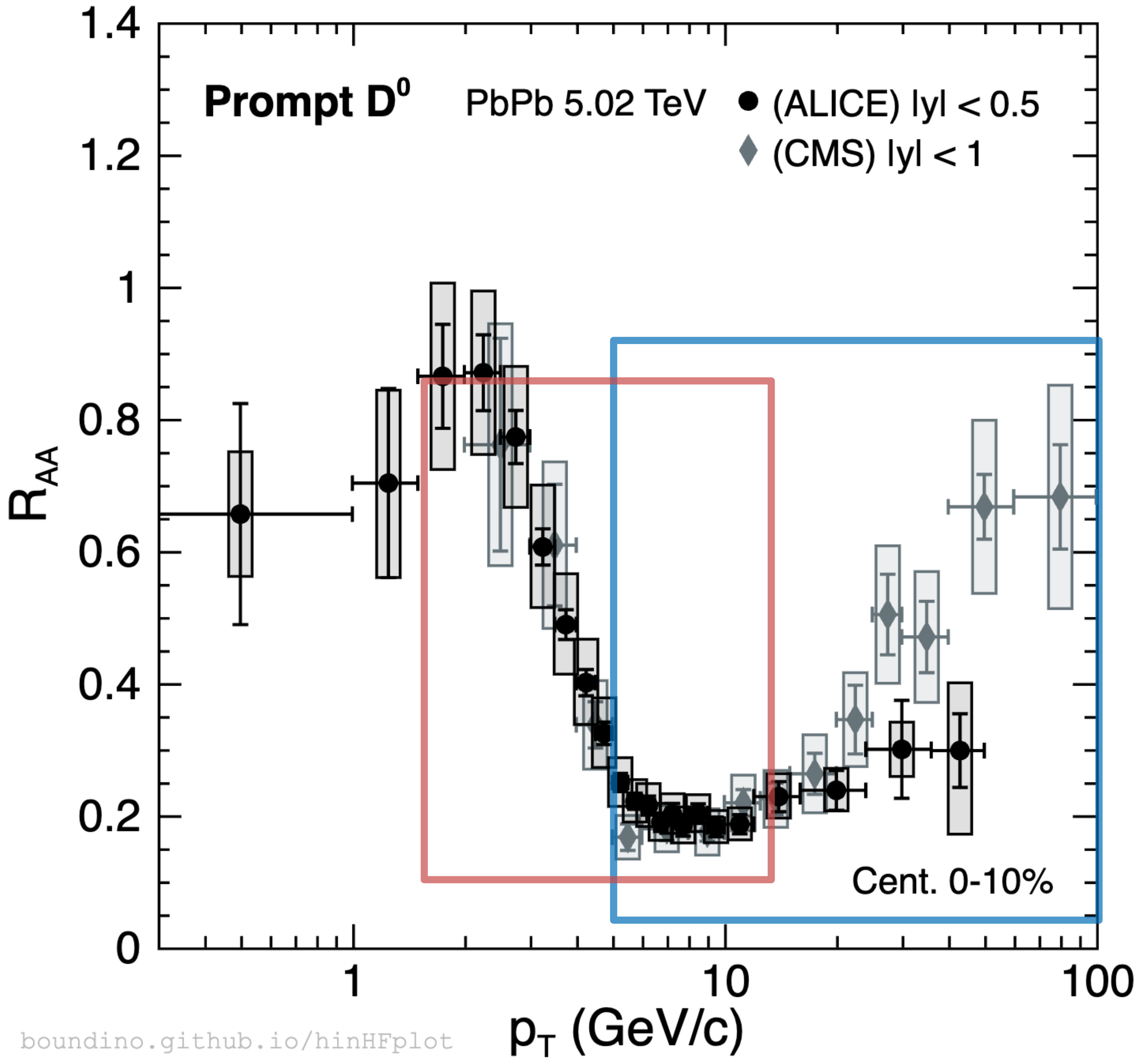


Energy loss of hard parton in QGP in pQCD picture

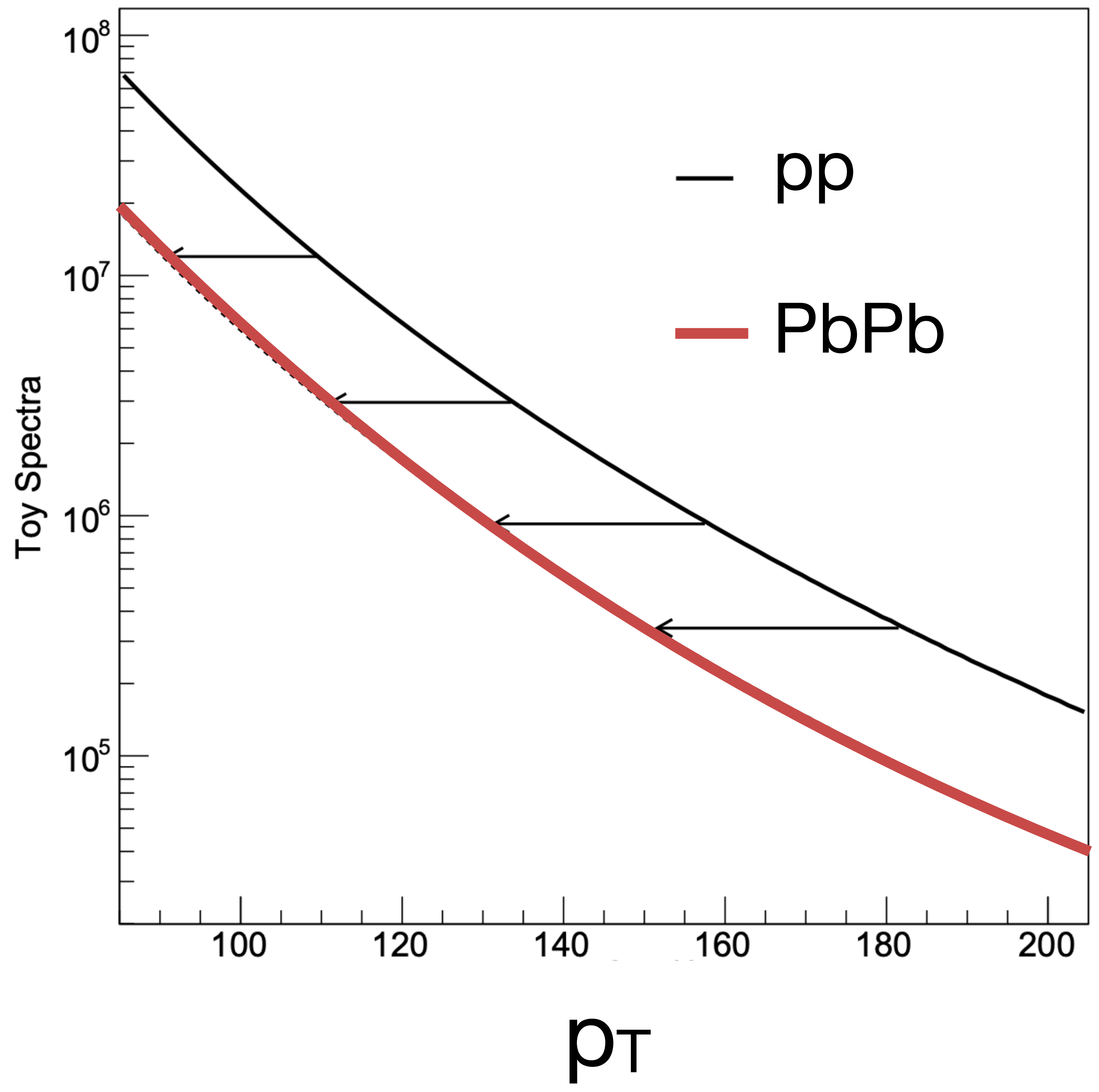
Bullet in gelatin block

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

D^0 R_{AA} Understanding the Shape

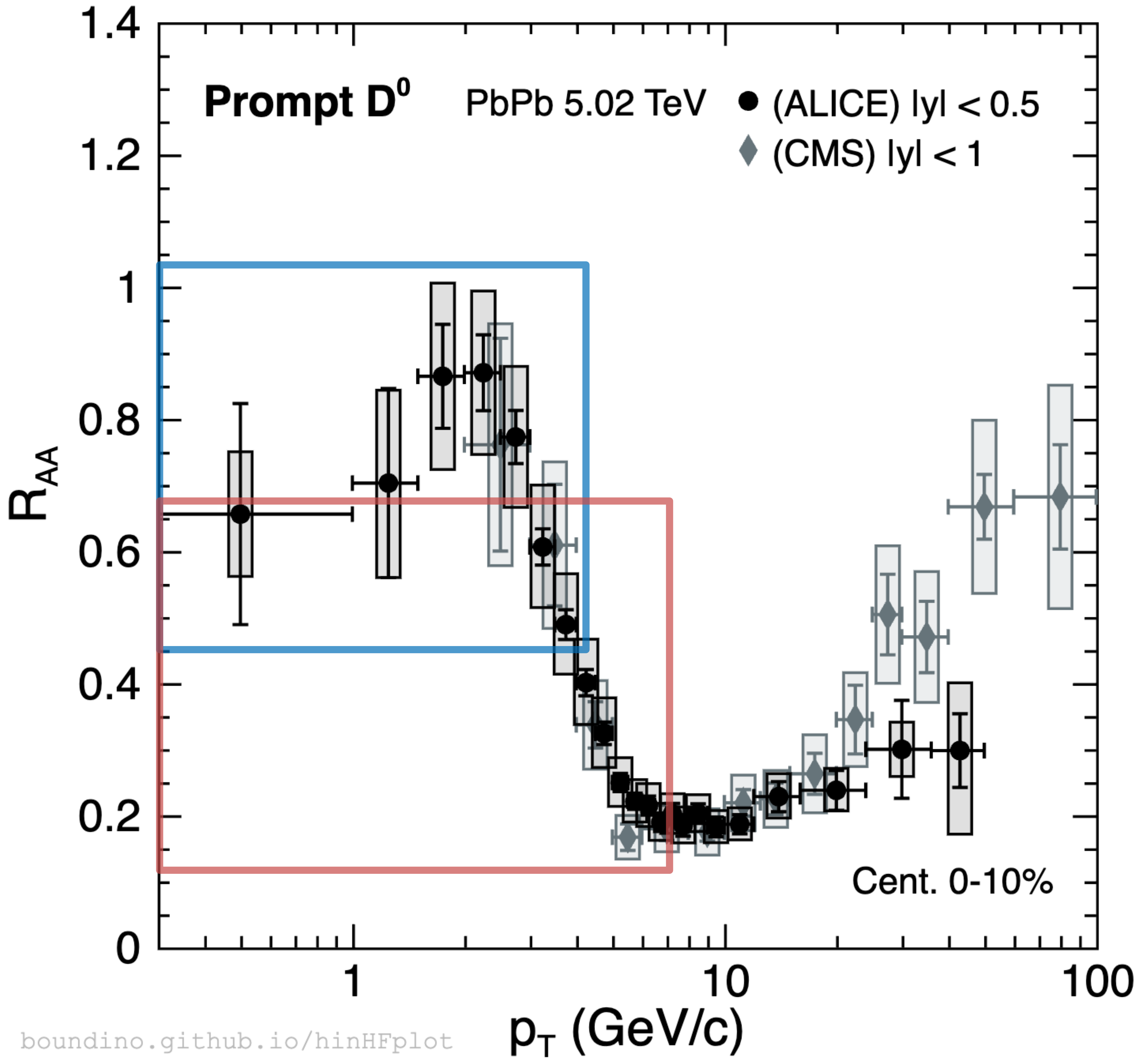


- Multiple effects interplay
  - Collisional and radiative energy loss
  - p_T shape before modification



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

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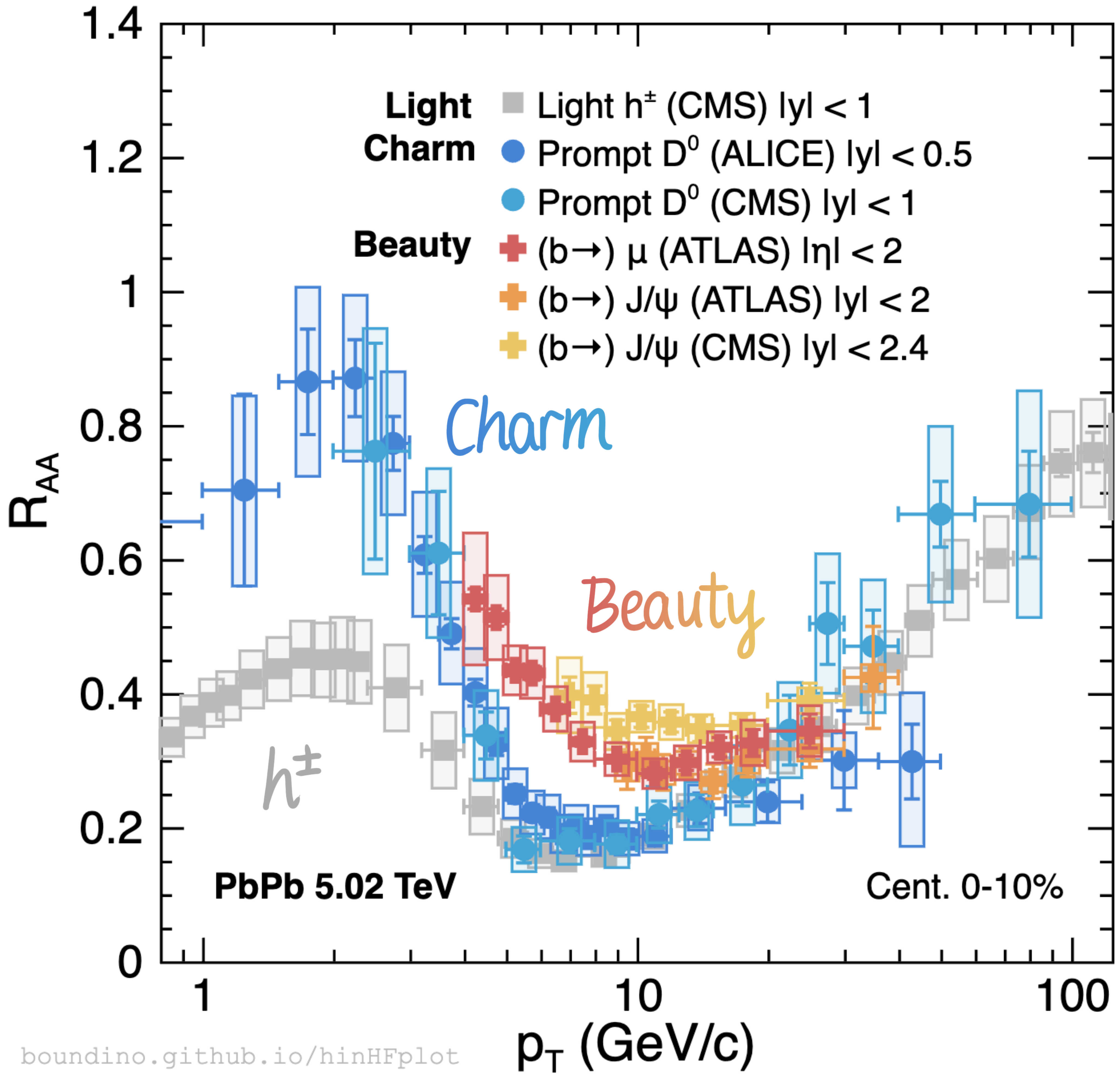
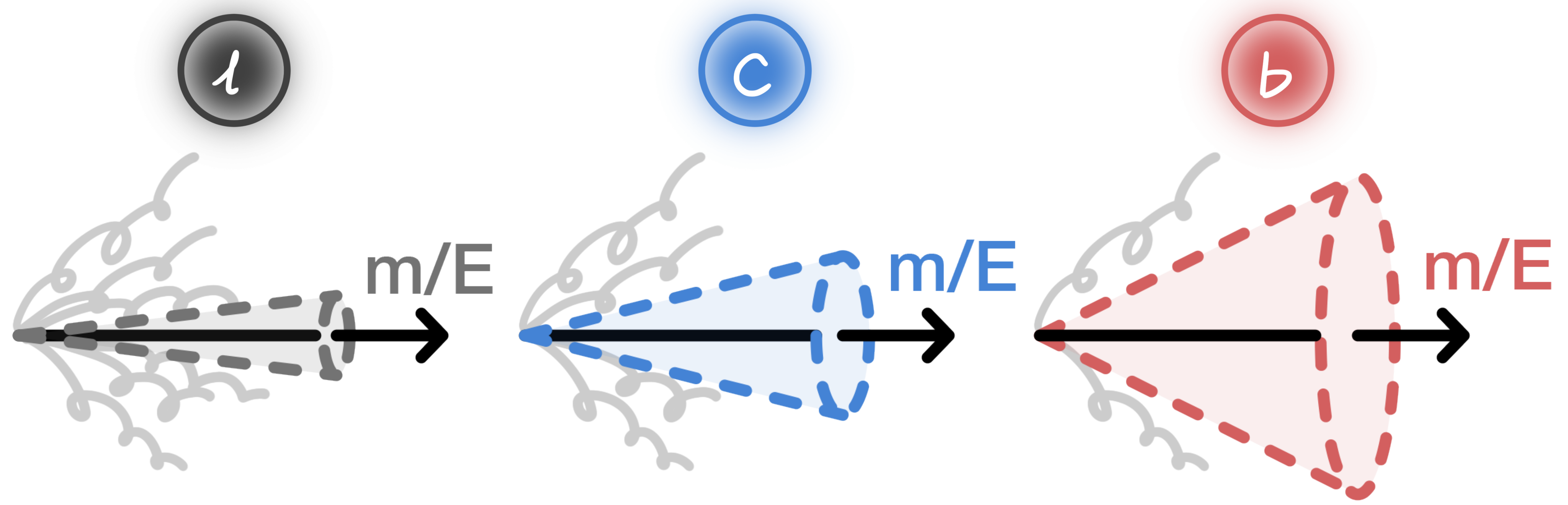
R_{AA} Mass Dependence of Energy Loss



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



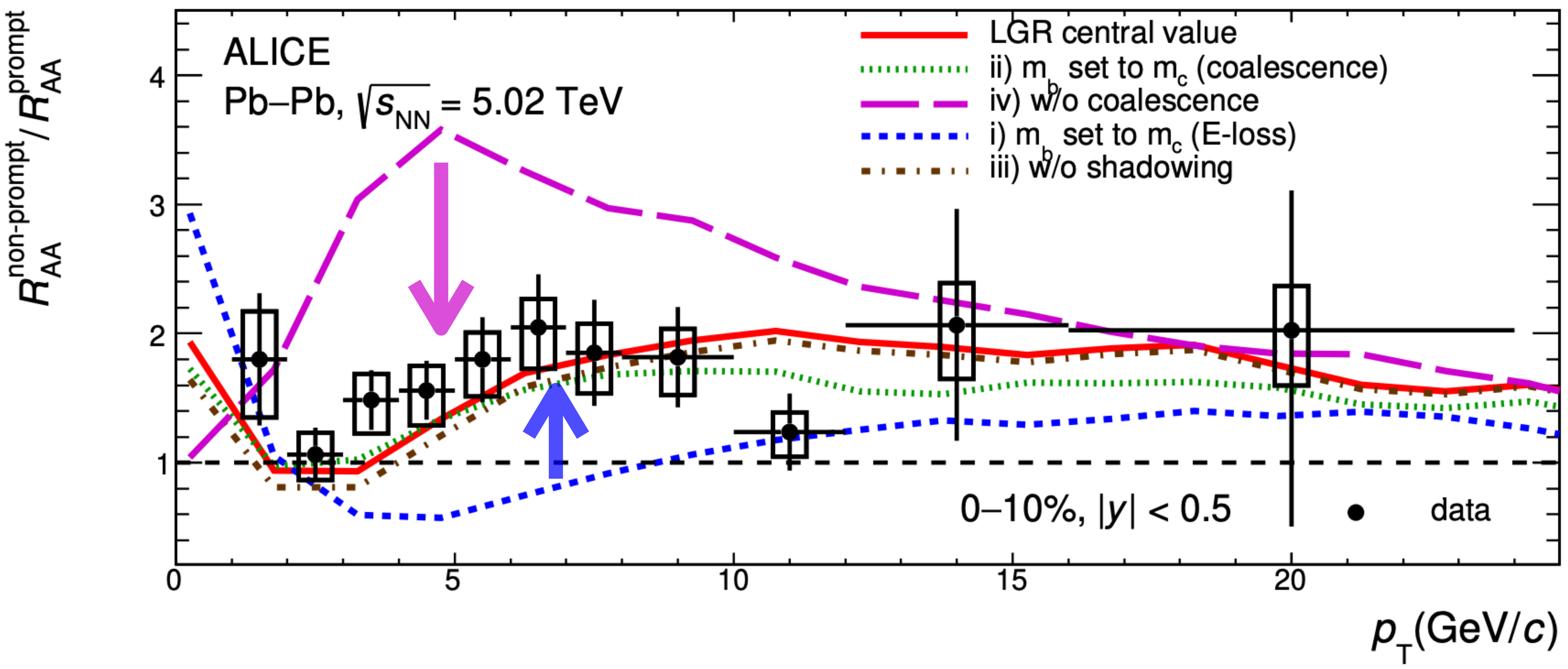
Larger energy loss ➜ Smaller energy loss

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

RAA Flavor Dependence

Non-prompt D RAA / Prompt D RAA

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

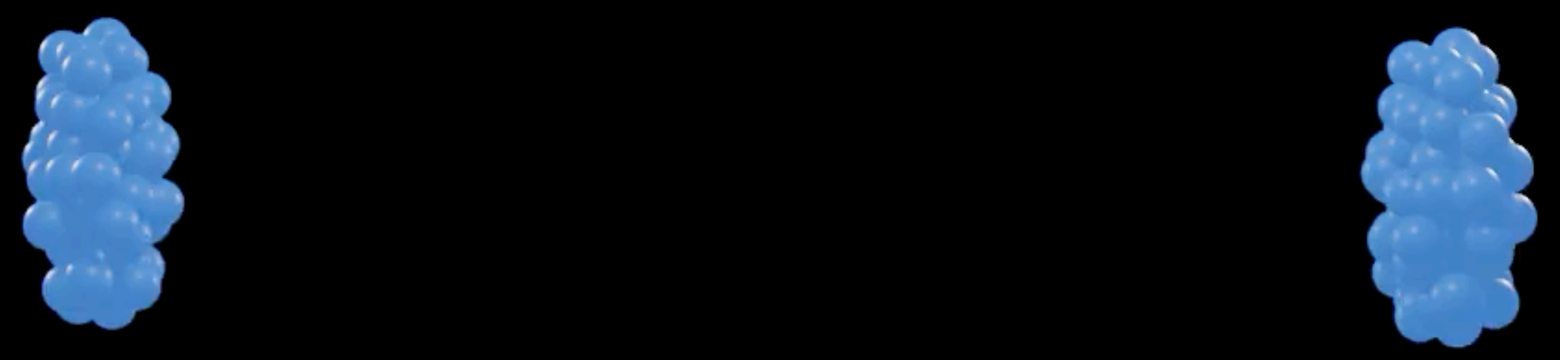
Hadronization

significant effect

- Reduce diff between c and b

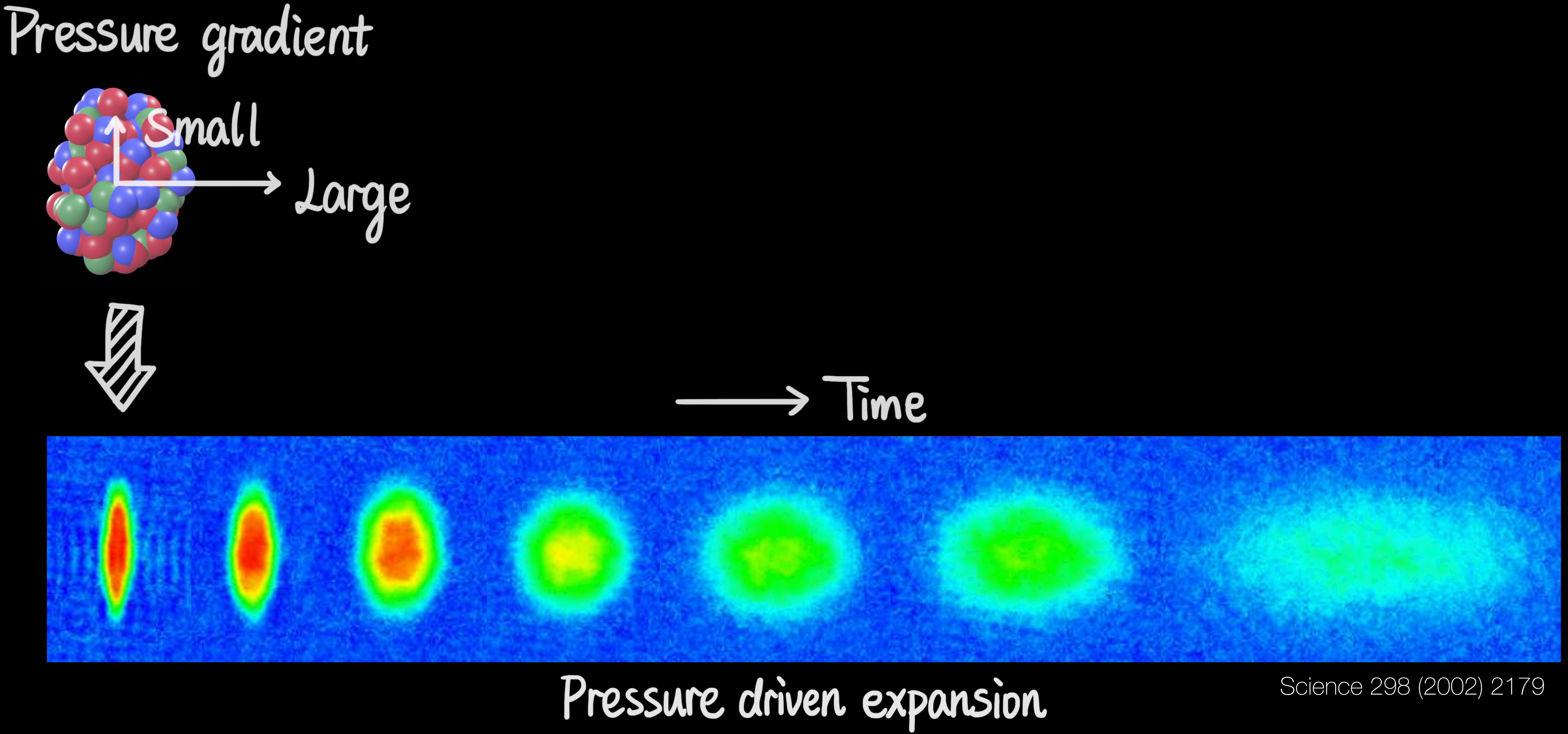
Initial Spatial Anisotropy of Medium

Azimuthal anisotropic initial shape in peripheral events



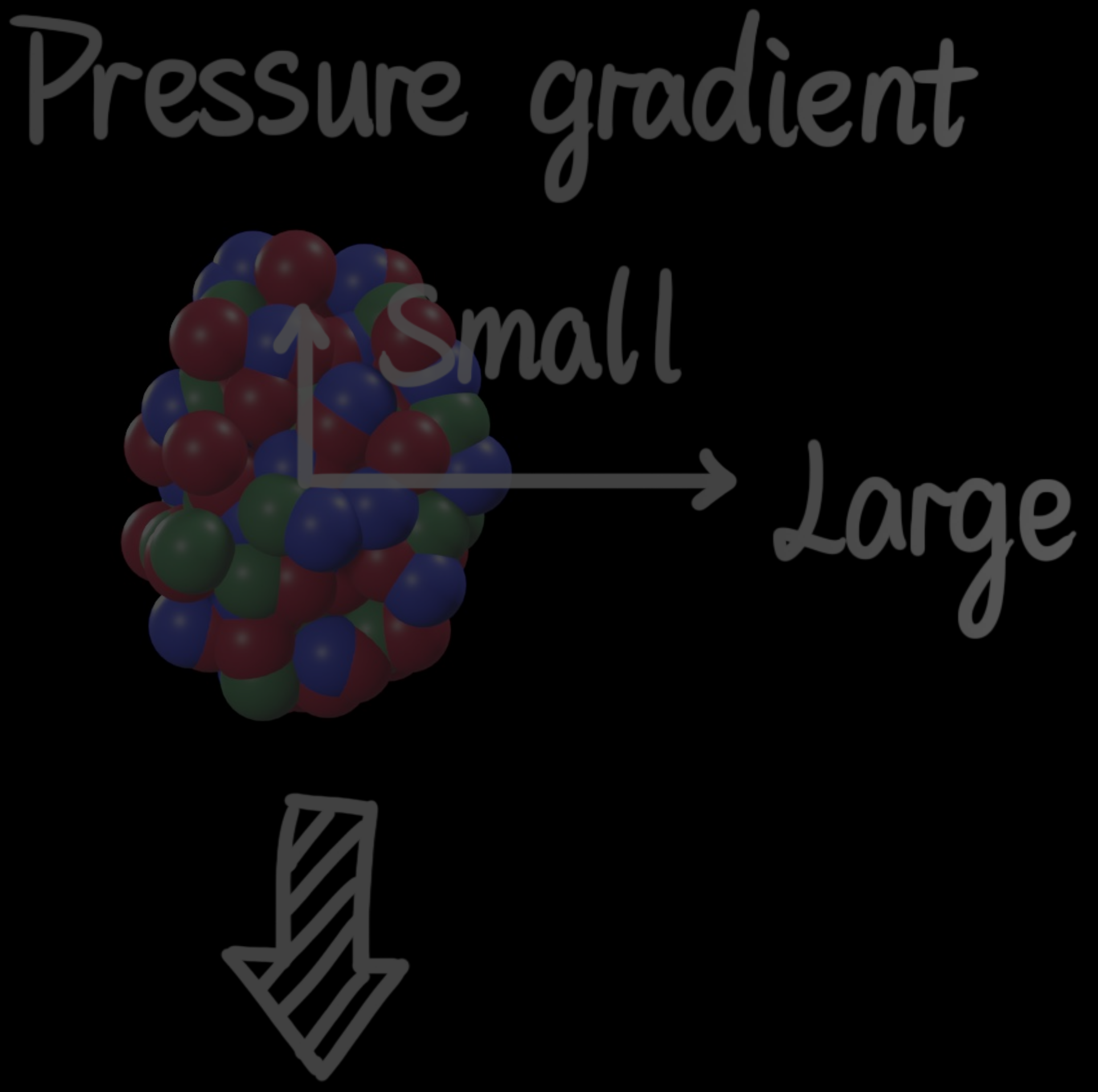
[Animation]

Collective Flow



Science 298 (2002) 2179

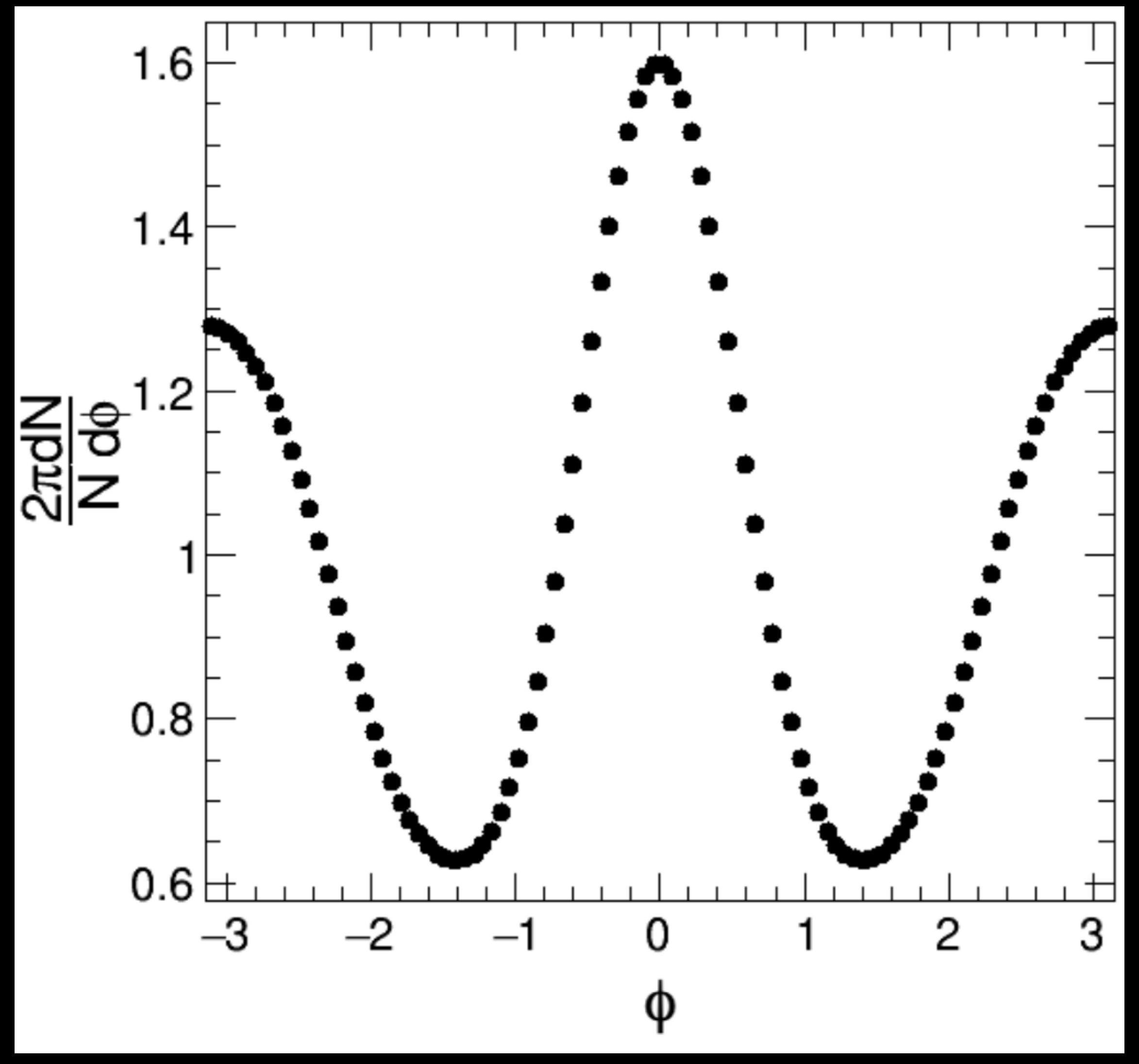
Collective Flow

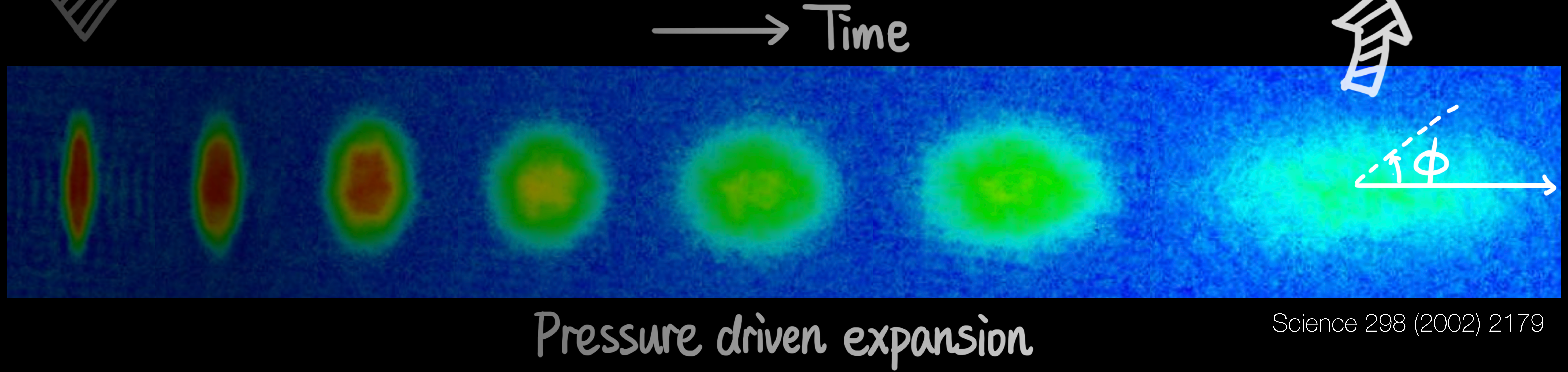


Existence of QGP ➜ Final-state particle azimuthal anisotropy

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

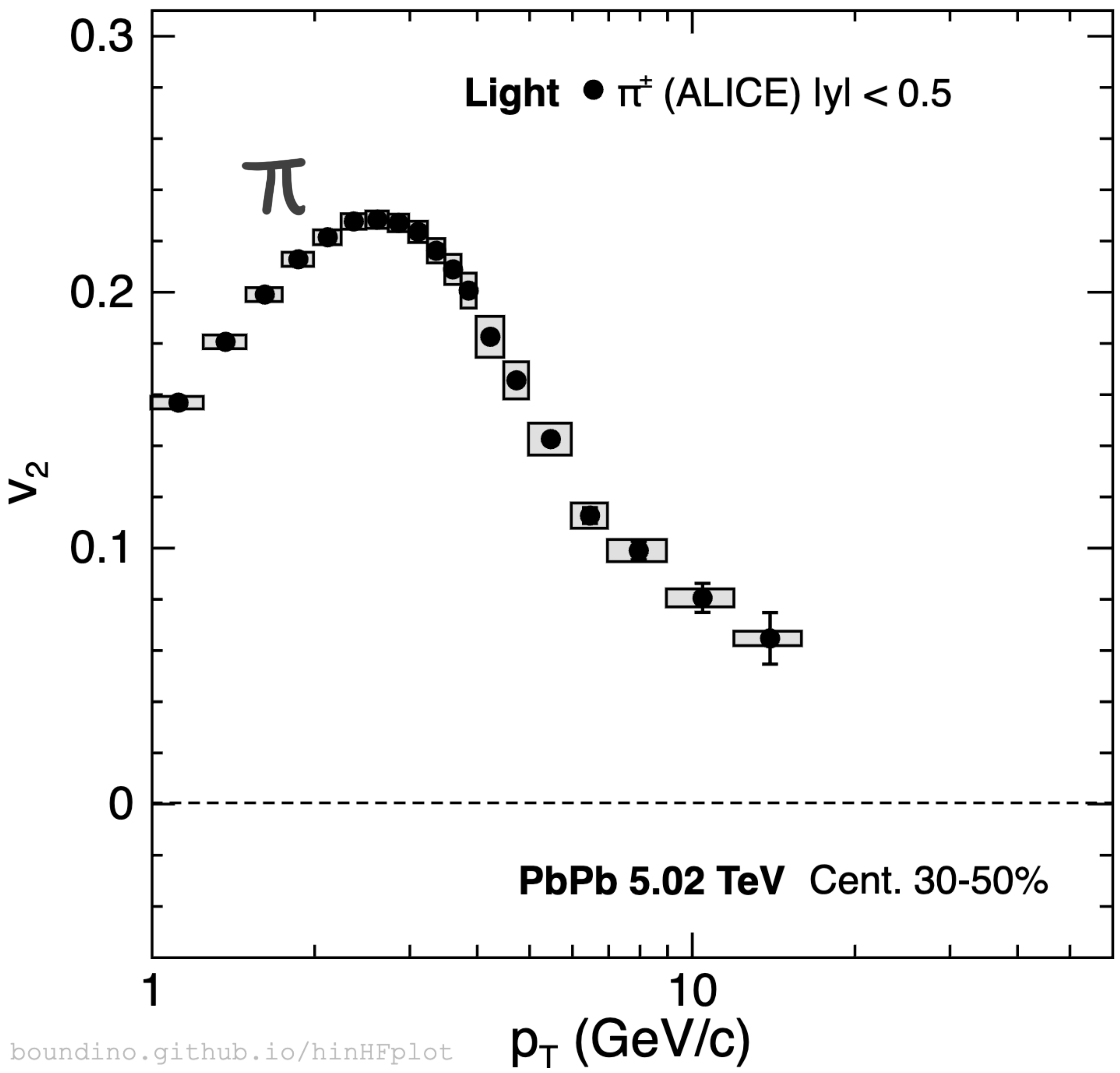
➜ Elliptic $v_2 \neq 0$



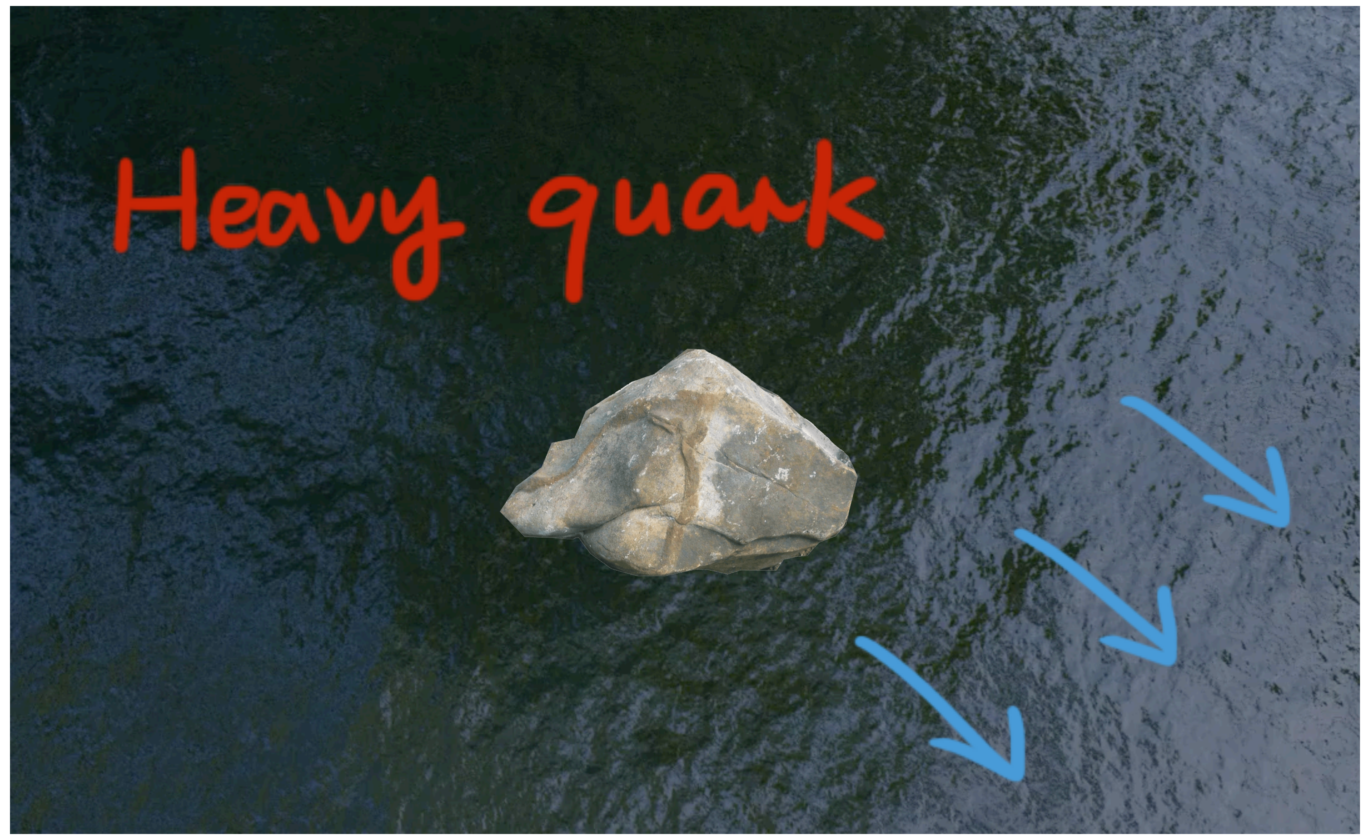


Science 298 (2002) 2179

Collective Flow Heavy Quarks



Do heavy quarks flow along with the medium?



We will see tomorrow!

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

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]