

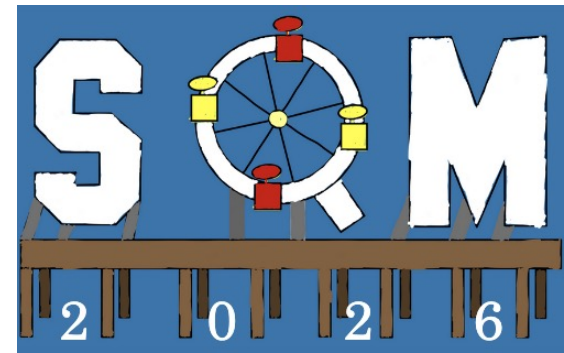


# First results from light-ion collisions at LHCb

JiaZhao Lin<sup>1</sup>

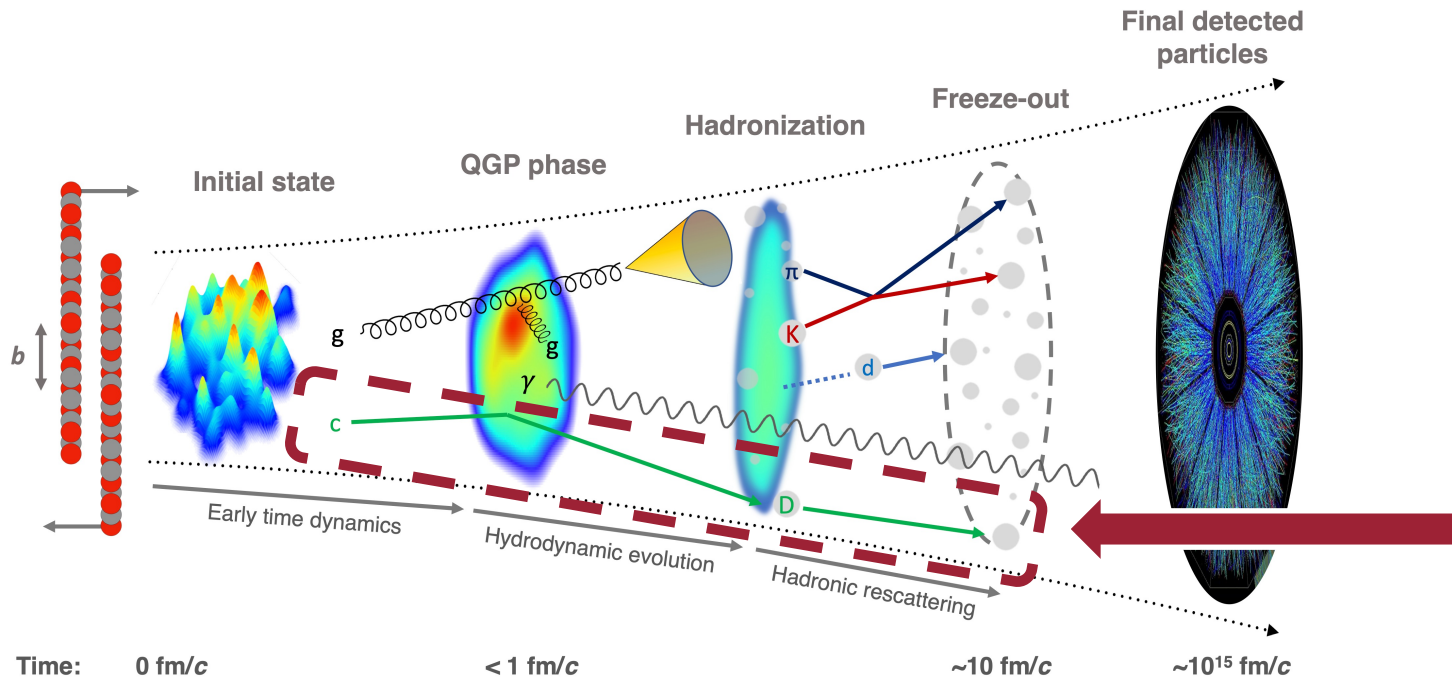
on behalf of the LHCb collaboration

*<sup>1</sup>Indiana University Bloomington*



# Motivation

- QCD predicts that at high temperature
  - nuclear matter transitions into a deconfined phase quark–gluon plasma (QGP)
  - QGP formation is well established in PbPb
- **What's the smallest nuclear systems where QGP-like effects may appear?**



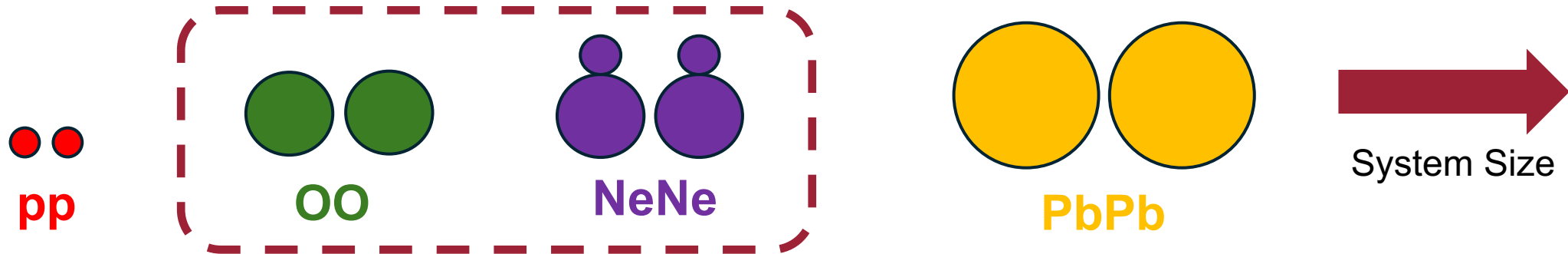
**Study final-state particles to infer properties of the early medium**

**$c$  quarks propagate the QGP phase (carry information of QGP formation)**

arXiv:2303.17254

# Charm as a QGP Probe

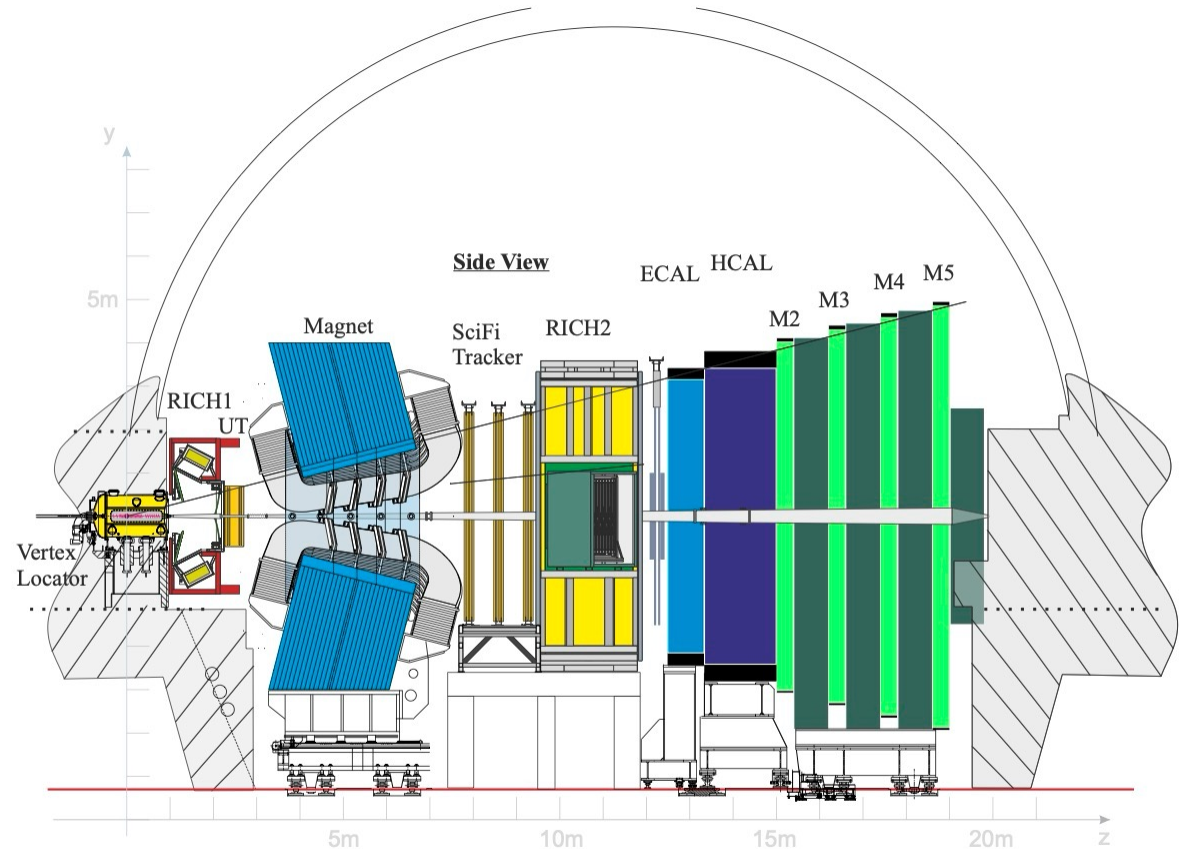
- Charm quarks are produced before the medium exists
  - experience the entire evolution
  - low  $p_T$  charm sensitive to diffusion; high  $p_T$  to energy loss
- $D^0$  in **Light ions (OO, NeNe) probe the onset of medium effects**



# LHCb Detector in Run 3

JINST 19 P05065 (2024)

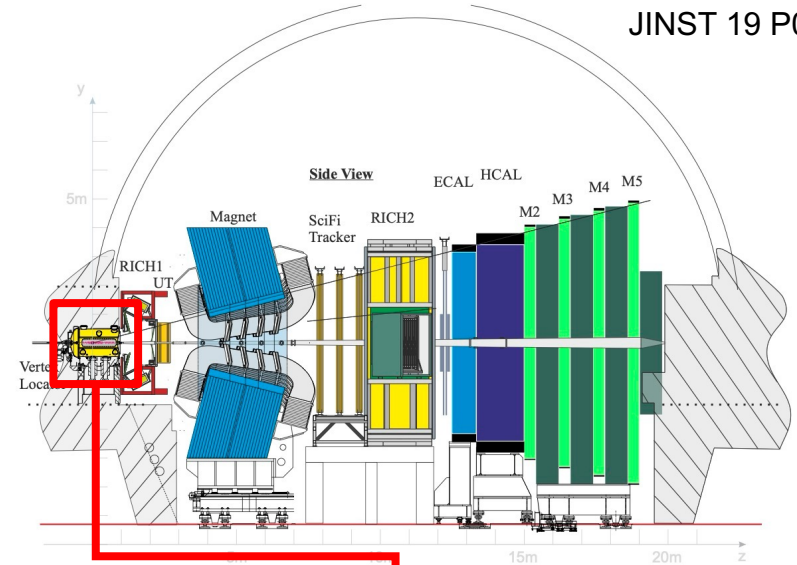
- LHCb: a single-arm forward spectrometer covering  $2 < \eta < 5$
- Optimized for heavy-flavor (c, b) physics
- Excellent tracking and particle identification capabilities
- In Run 3 the detector was upgraded
  - fully software-based trigger
  - new tracking systems



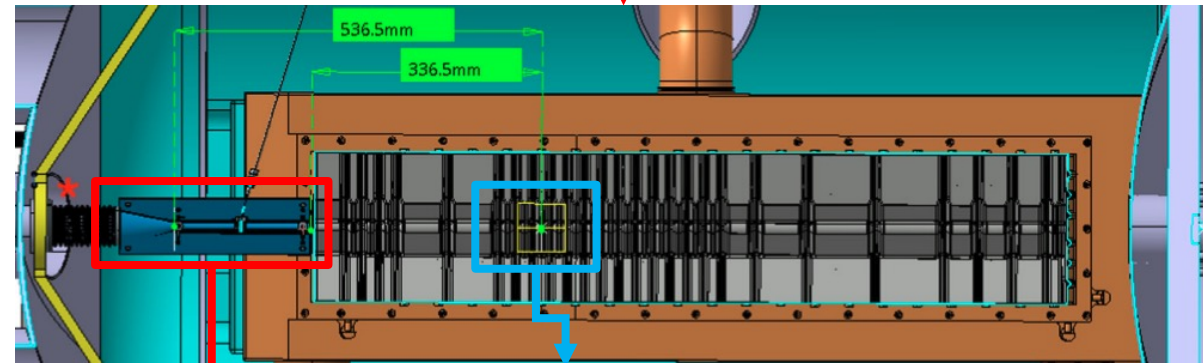
# LHCb as Fixed-Target Experiment

JINST 19 P05065 (2024)

- SMOG2: System for Measuring the Overlap with Gas
  - a storage cell placed upstream of the LHC beam pipe
  - beam collides with gas nuclei at rest
- Unique physics opportunities...
  - a wide range of injectable gases:  $H_2$ ,  $D_2$ , He, Ne, Ar...
  - access to intermediate energies
- Operate simultaneously with nominal beam-beam collision



Phys.Rev.Accel.Beams 27 111001



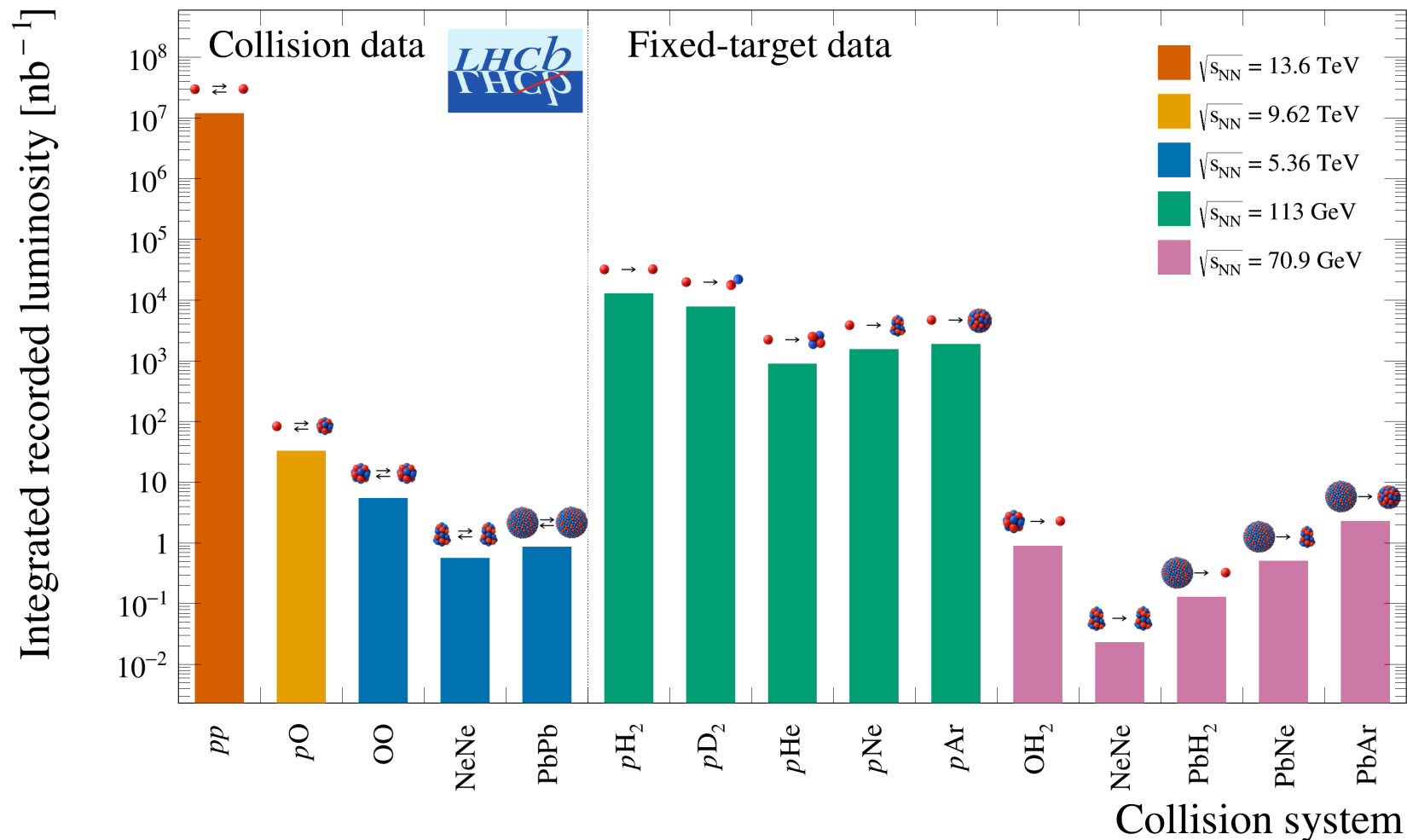
SMOG2 Storage cell  
(20cm)

Nominal beam-beam  
collision point

# LHCb's Diverse Dataset

Collect data in both colliding and fixed-target mode...

Direct comparison across systems: **Baseline** → **CNM** → **QGP**



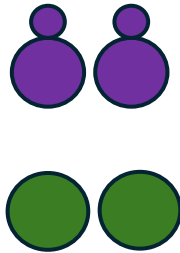
- **$D^0$  production Ratio NeNe/00**
  - Data Sample & Selections
  - Signal Extraction
  - Efficiency
  - Results
- **Highlights from fixed-target results**
  - SMOG2 PbNe and PbAr flow



# $D^0$ Production Ratio

- **Relative  $D^0$  production between NeNe/OO**

$$R(p_T) = \frac{(dN_{D^0}/dp_T)_{\text{NeNe}}}{(dN_{D^0}/dp_T)_{\text{OO}}}$$



Measure yields per  $p_T$  bin



$$\frac{n_i^{\text{NeNe}}}{n_i^{\text{OO}}} \times \frac{\epsilon_i^{\text{OO}}}{\epsilon_i^{\text{NeNe}}} \times \frac{N_{\text{Inel}}^{\text{OO}}}{N_{\text{Inel}}^{\text{NeNe}}}$$

Correct by efficiency

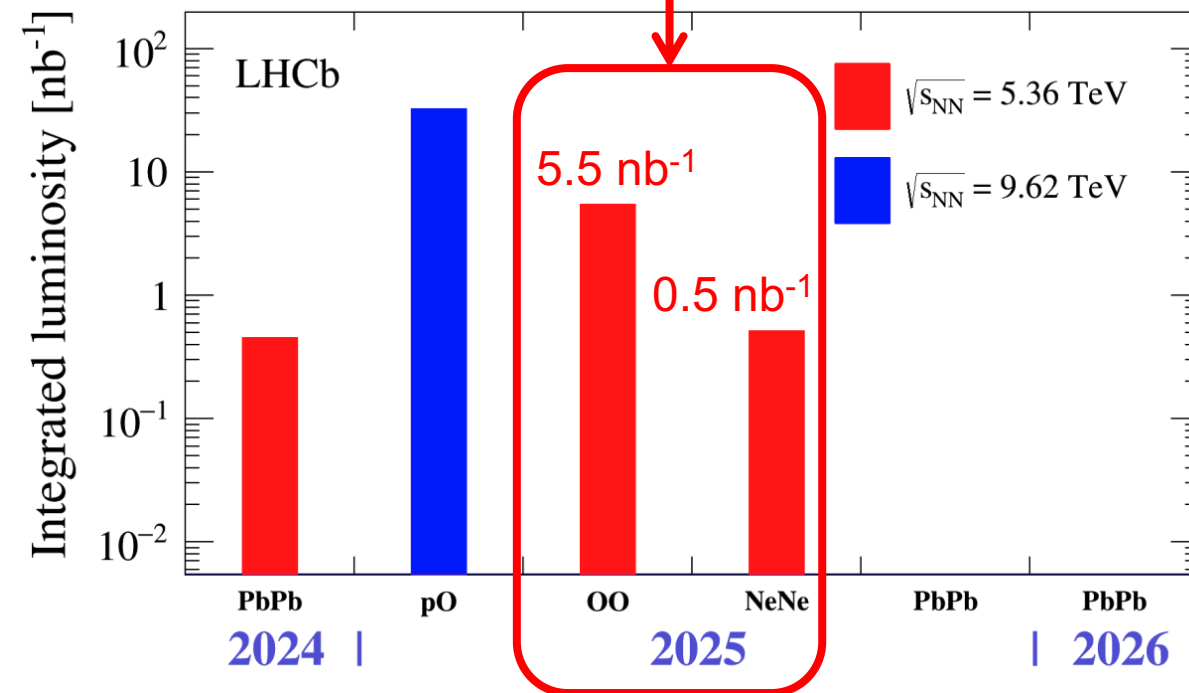
Normalize by number of inelastic collisions

- Strong cancellation of systematics
- Shape isolates nuclear effects
  - $R(p_T) \approx \text{constant} \rightarrow$  geometric scaling
  - $R(p_T) \neq \text{constant} \rightarrow$  differential nuclear modification or QGP formation onset
- **Provides first direct test of A dependence of charm production and possible modifications**

# Data Samples

## Real time analysis for $D^0 \rightarrow K^- \pi^+$

- Using data collected in
  - July 2025 during light-ion period
  - $\sqrt{s_{NN}} = 5.36$  TeV



# Data Samples

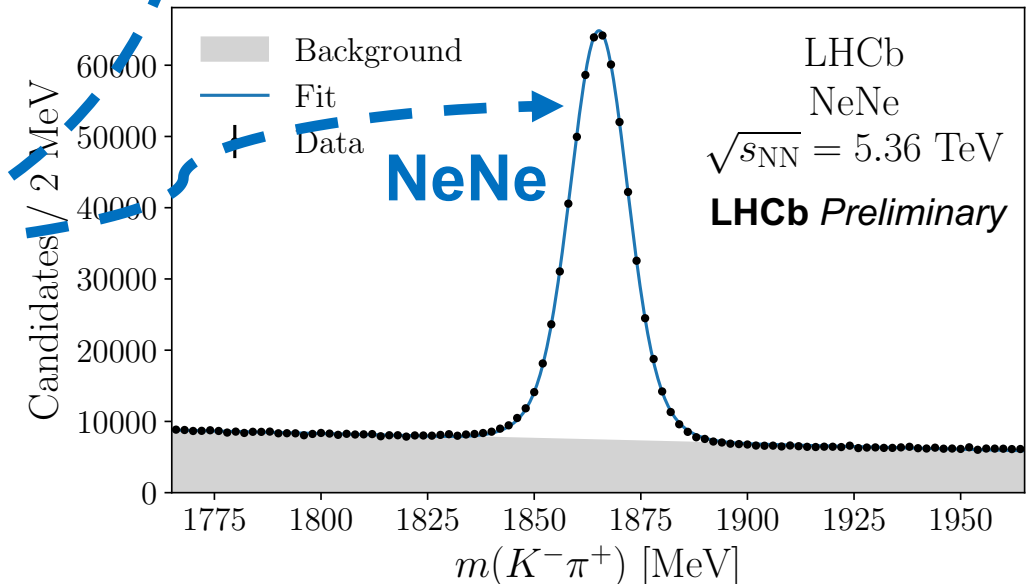
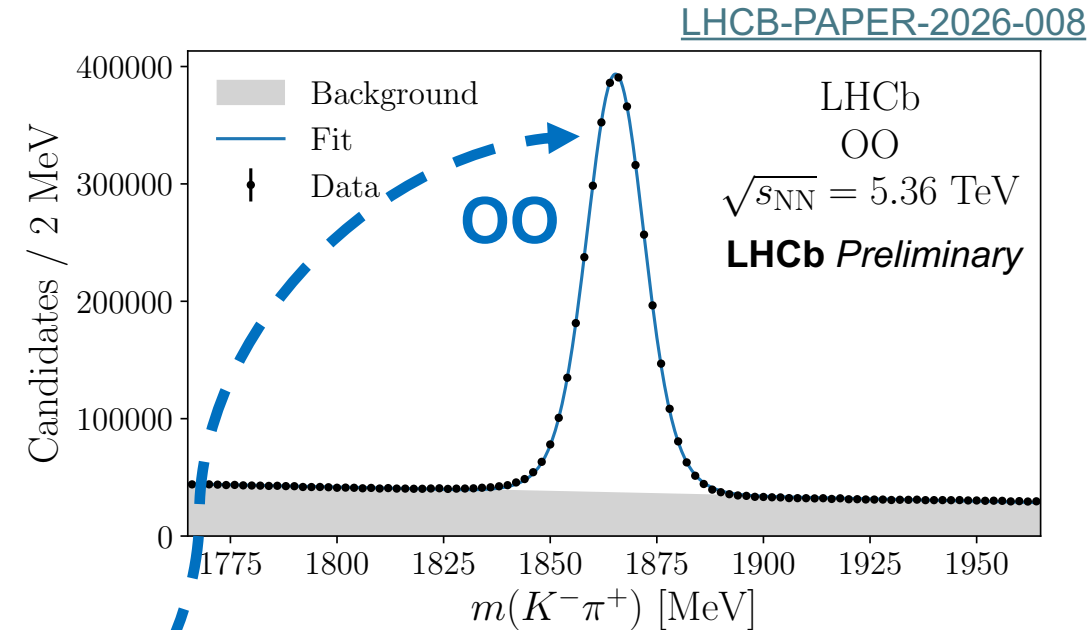
## Real time analysis for $D^0 \rightarrow K^- \pi^+$

- Using data collected in
  - July 2025 during light-ion period
  - $\sqrt{s_{NN}} = 5.36$  TeV
- The LHCb Run-3 fully software-based trigger
  - allows very loose selections
  - record almost all interactions

HLT1: requiring  
 $\geq 1$  tracks  
(fast tracking)

HLT2: full  
reconstruction

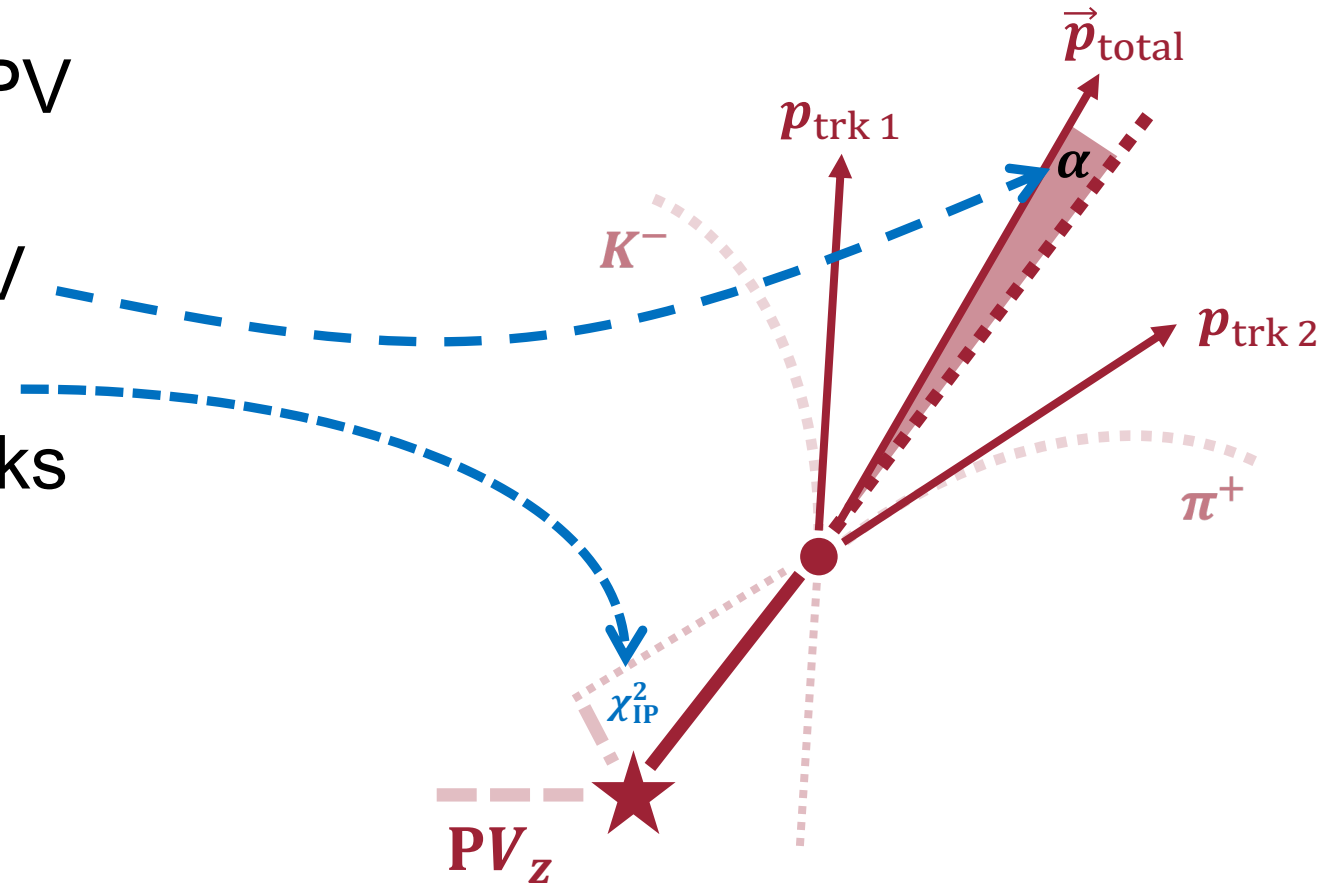
Excellent tracking and vertexing help  
us get extremely clean  $D^0$  samples



# $D^0$ Selection

## Decay geometry

- Displaced decay vertex and PV location (downstream)
- Momentum alignment with PV
- Large impact parameter significance for daughter tracks



# $D^0$ Selection

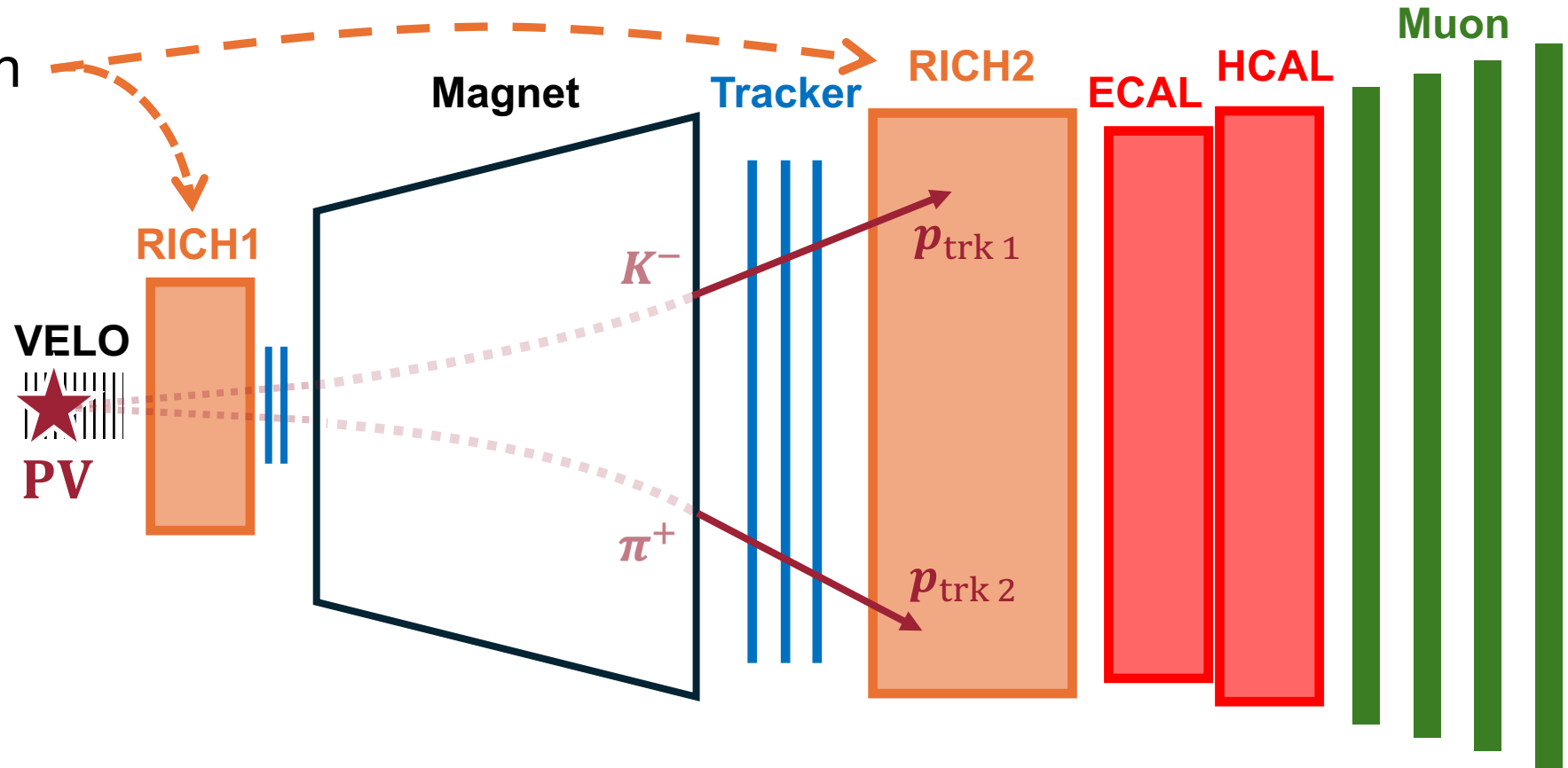
- Candidates' kinematics

- $p_T(K, \pi) > 400$  MeV
- $p(K, \pi) > 5$  GeV
- $2 < \eta(K, \pi) < 4.7$
- Particle Identification

Can construct wide range of  $D^0$ !

$$0.5 \text{ GeV} < p_T(D^0) < 20 \text{ GeV}$$

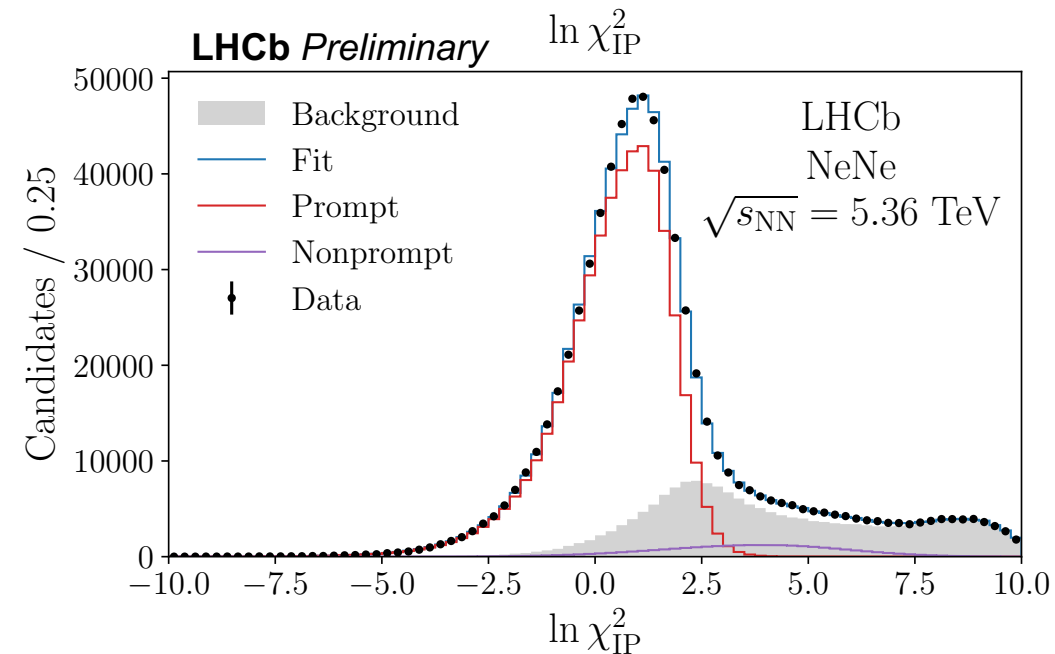
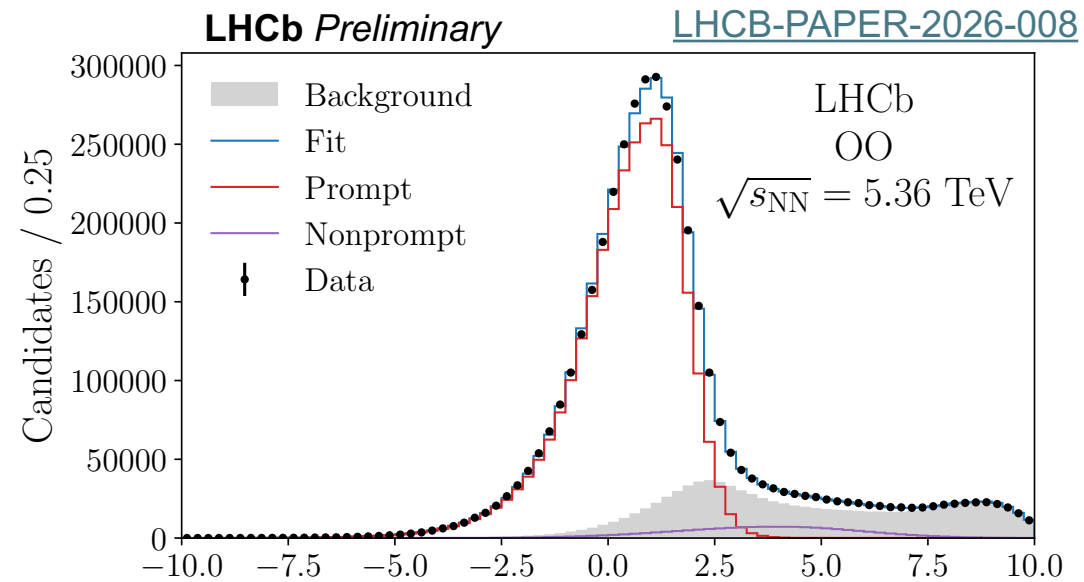
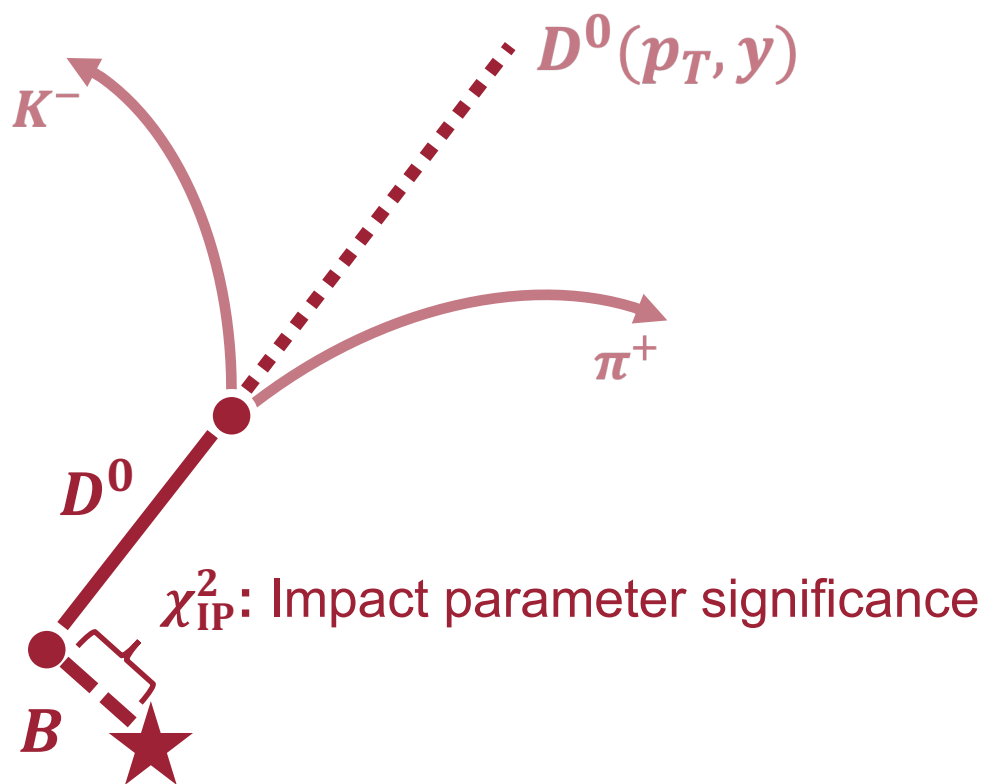
$$2.0 < y(D^0) < 4.5$$



# Yield Extraction

## $\log(\chi_{IP}^2)$ Fit

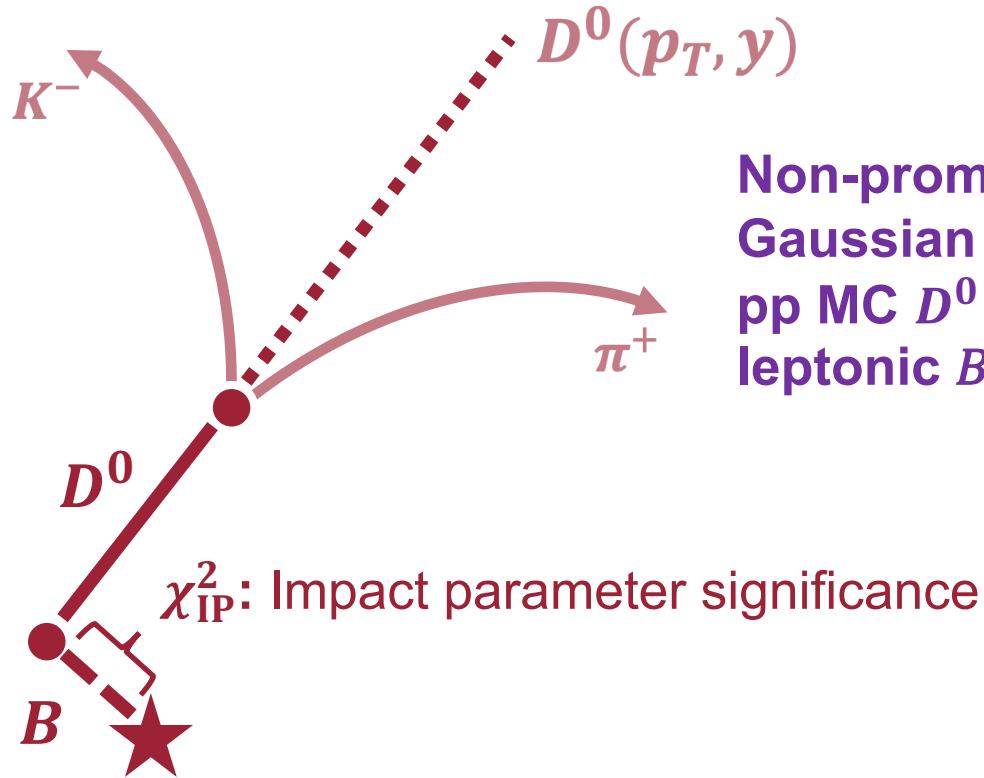
- Separates prompt and non-prompt
  - performed in  $|m_{PDG}(D^0) - m(K^-\pi^+)| < 25$  MeV



# Yield Extraction

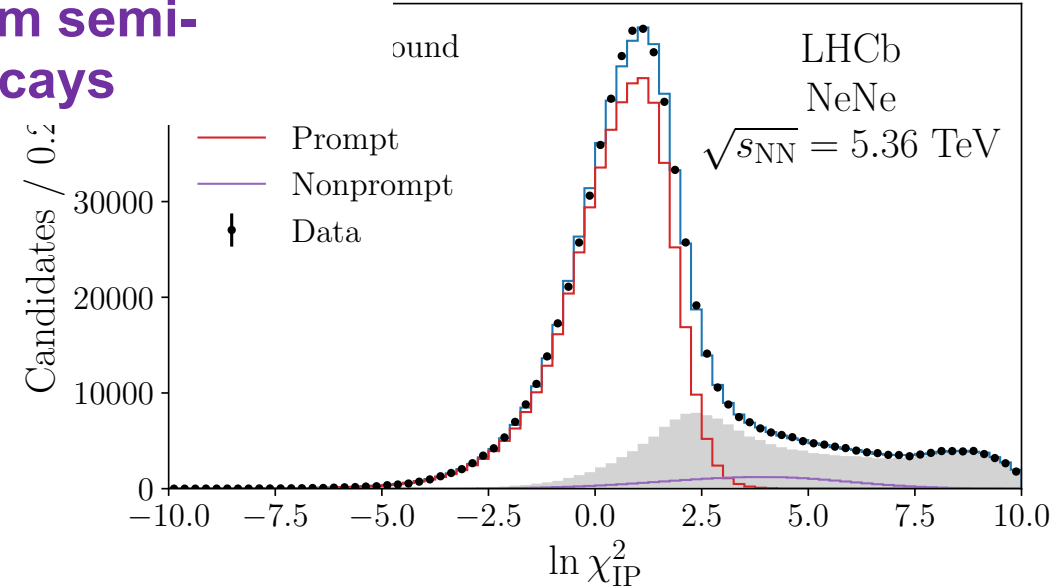
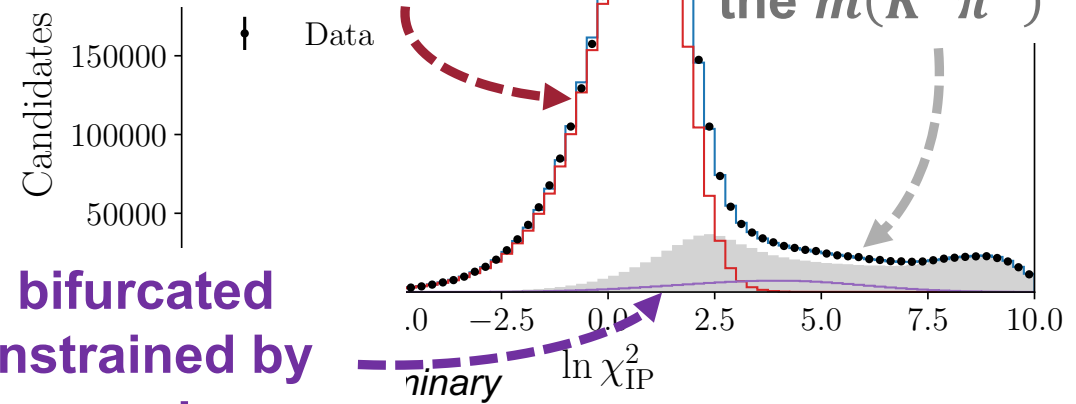
## $\log(\chi_{IP}^2)$ Fit

- Separates prompt and non-prompt
  - performed in  $|m_{PDG}(D^0) - m(K^-\pi^+)| < 25$  MeV



Non-prompt: bifurcated Gaussian constrained by pp MC  $D^0$  from semi-leptonic  $B$  decays

Prompt: parametric function (JHEP 06 (2017) 147) constrained by MC



## Efficiency factorization

- PID Calibration
  - $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$
- Tracking Calibration
  - Tag and probe with  $K_S \rightarrow \pi^+\pi^-$
- OO and NeNe differ slightly in PV resolution
  - impact is small  $<1\%$  and is fully corrected

$$\frac{\epsilon^{OO}}{\epsilon^{NeNe}} = \frac{\epsilon_{rec}^{OO}}{\epsilon_{rec}^{NeNe}} \times \frac{\epsilon_{sel}^{OO}}{\epsilon_{sel}^{NeNe}} \times \frac{\epsilon_{PID}^{OO}}{\epsilon_{PID}^{NeNe}}$$

**Final  $\frac{\epsilon^{OO}}{\epsilon^{NeNe}} \sim 1.03 - 1.04$  for all  $p_T$  bins, except for the highest-  $p_T$  and is 1.07**

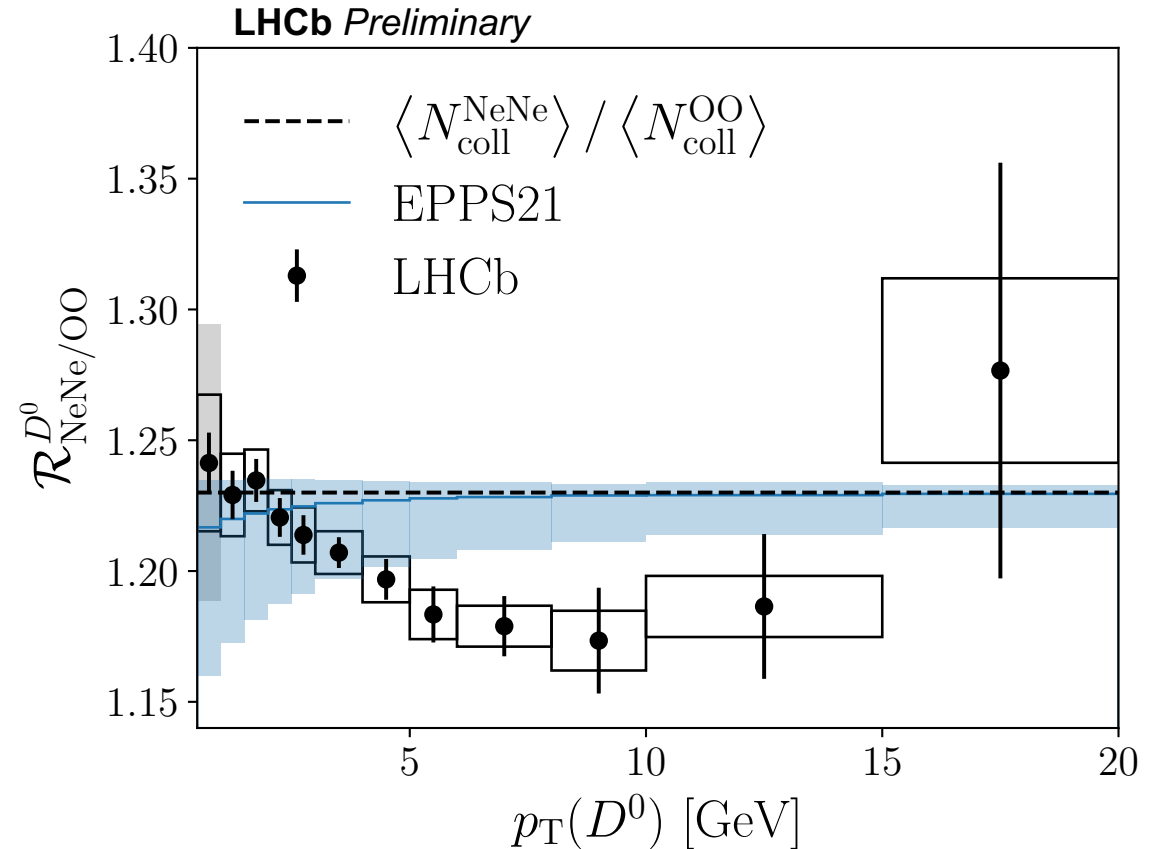
## Putting things together...

- $$R(p_T) = \frac{n_i^{\text{NeNe}}}{n_i^{\text{OO}}} \times \frac{\epsilon_i^{\text{OO}}}{\epsilon_i^{\text{NeNe}}} \times \frac{N_{\text{Inel}}^{\text{OO}}}{N_{\text{Inel}}^{\text{NeNe}}}$$

Yields

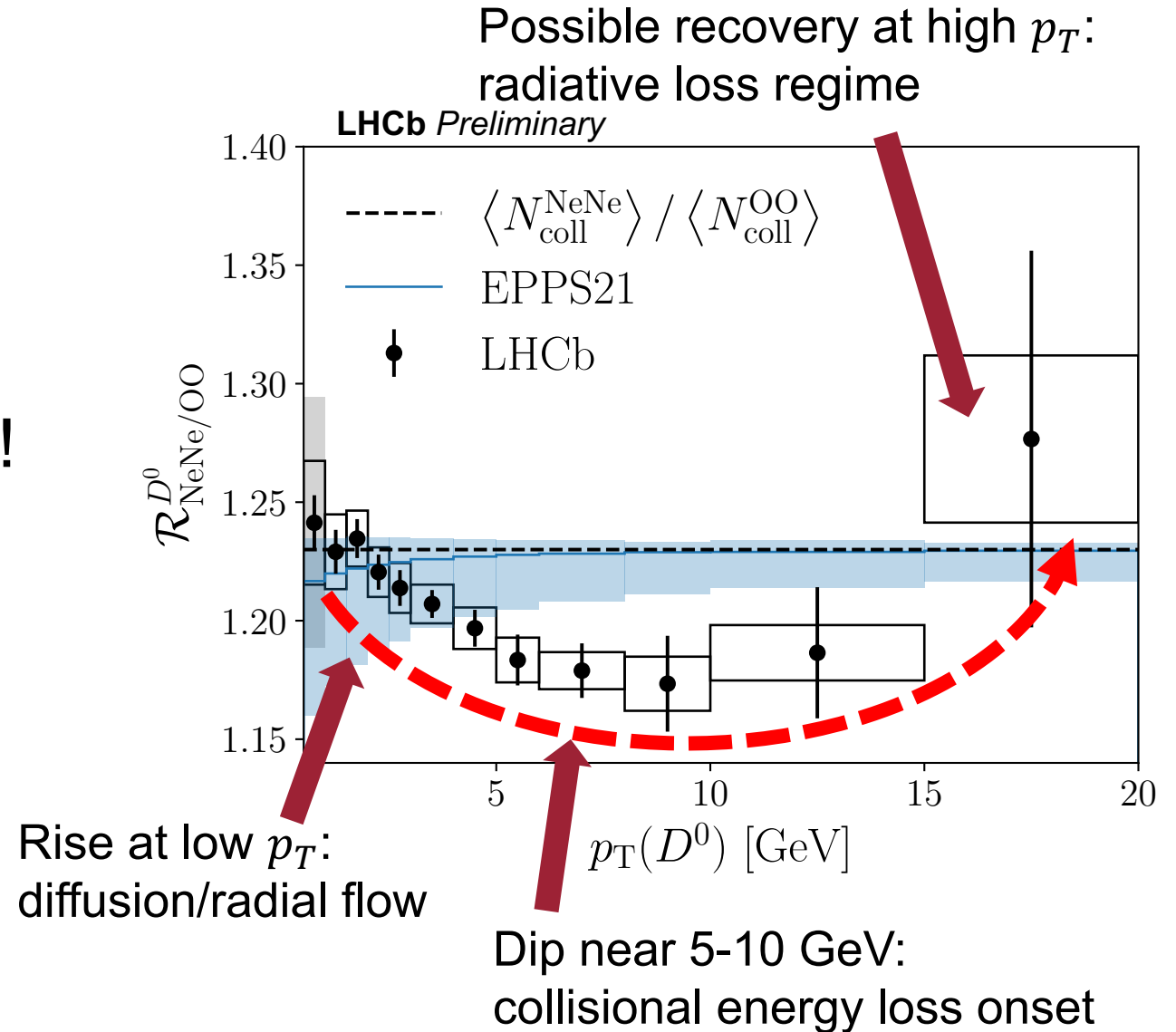
efficiency

Normalization
- First charm production measurement in light ion collision!



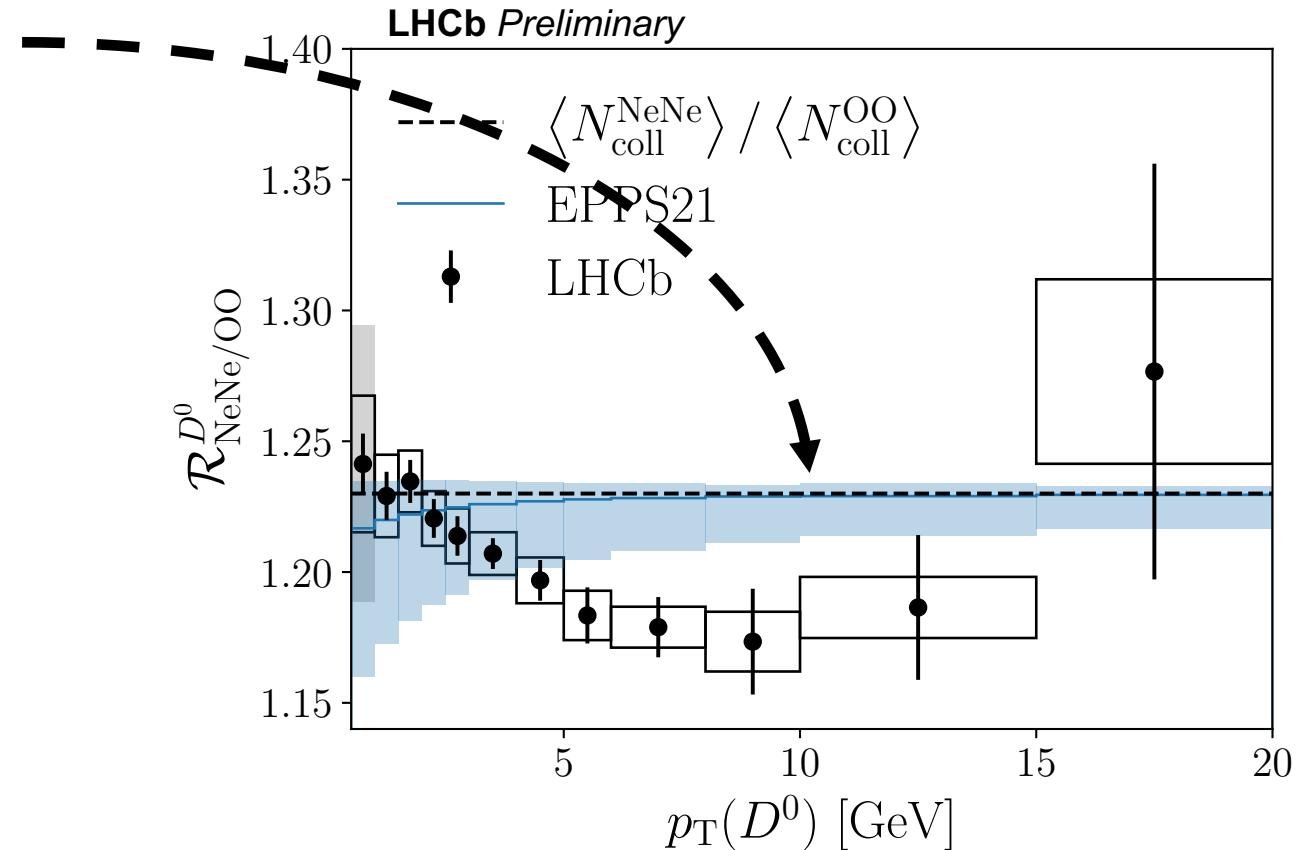
## Putting things together...

- $R(p_T) = \frac{n_i^{\text{NeNe}}}{n_i^{\text{OO}}} \times \frac{\epsilon_i^{\text{OO}}}{\epsilon_i^{\text{NeNe}}} \times \frac{N_{\text{Inel}}^{\text{OO}}}{N_{\text{Inel}}^{\text{NeNe}}}$ 
  - Yields
  - efficiency
  - Normalization
- First charm production measurement in light ion collision!
- Non-constant  $R(p_T)$ 
  - low  $p_T$ : enhancement
  - mid  $p_T$ : suppression
  - high  $p_T$ : recovery
- Qualitatively consistent with presence of QGP medium



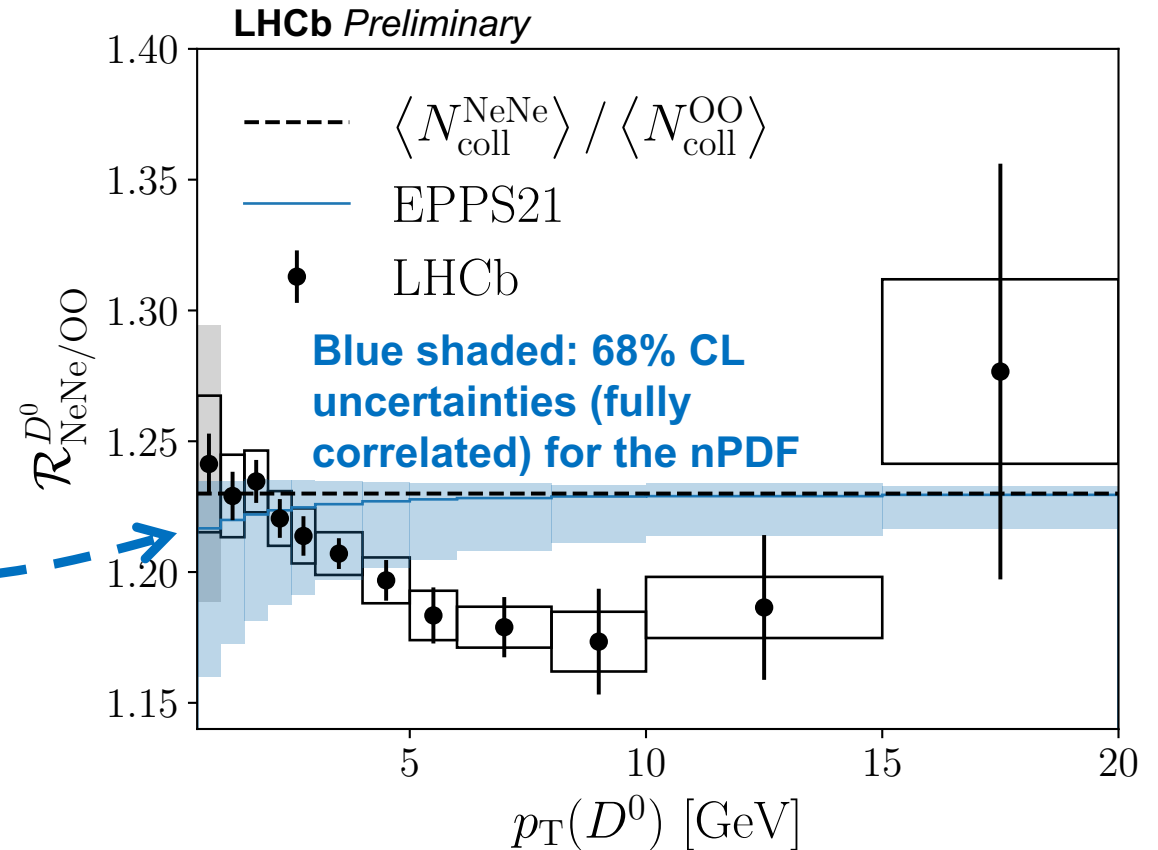
## Comparison to theoretical models...

- Glauber Model scaling  $\frac{\langle N_{\text{coll}} \rangle_{\text{NeNe}}}{\langle N_{\text{coll}} \rangle_{\text{OO}}}$ 
  - indicates that simple geometric scaling is insufficient



## Comparison to theoretical models...

- Glauber Model scaling  $\frac{\langle N_{\text{coll}} \rangle_{\text{NeNe}}}{\langle N_{\text{coll}} \rangle_{\text{OO}}}$ 
  - indicates that simple geometric scaling is insufficient
- nPDF-only EPPS21 cannot reproduce the shape
- While overall normalization is broadly consistent, the observed  $p_T$  dependence is not reproduced
  - suggests that additional effects beyond initial-state modifications



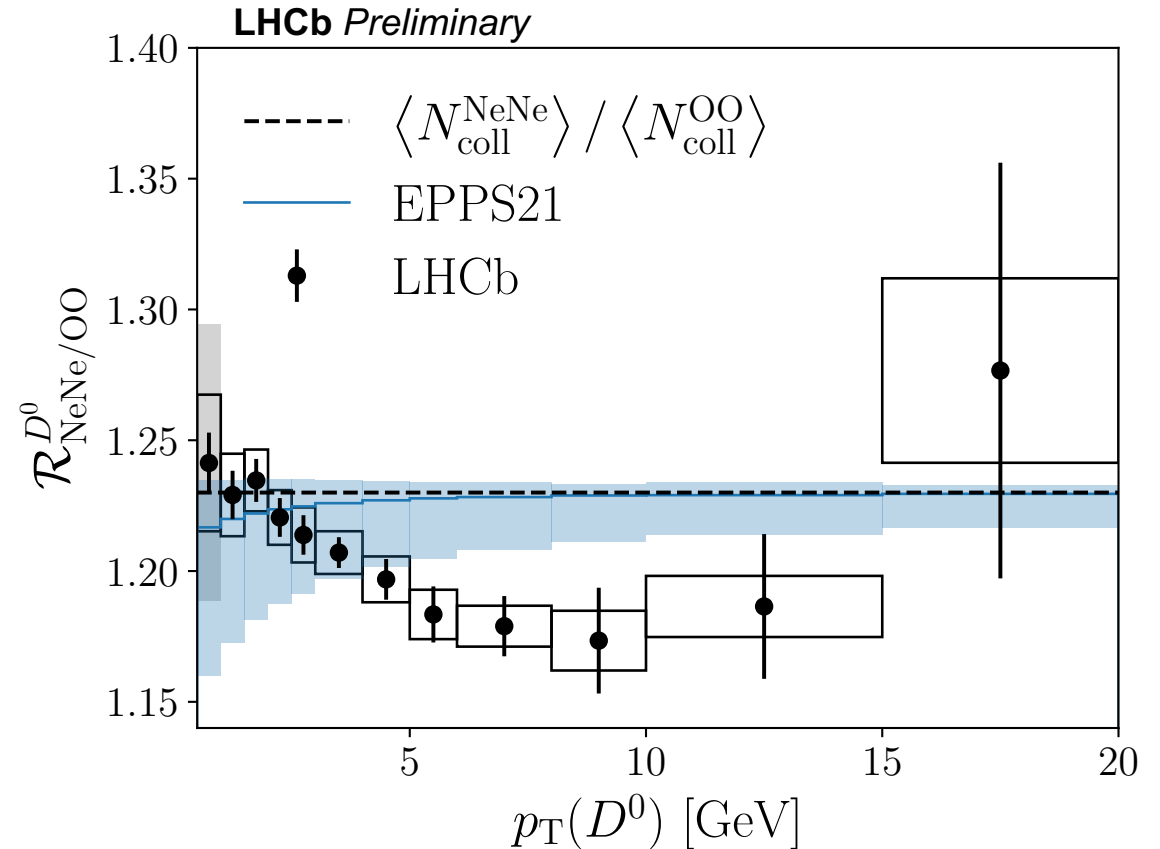
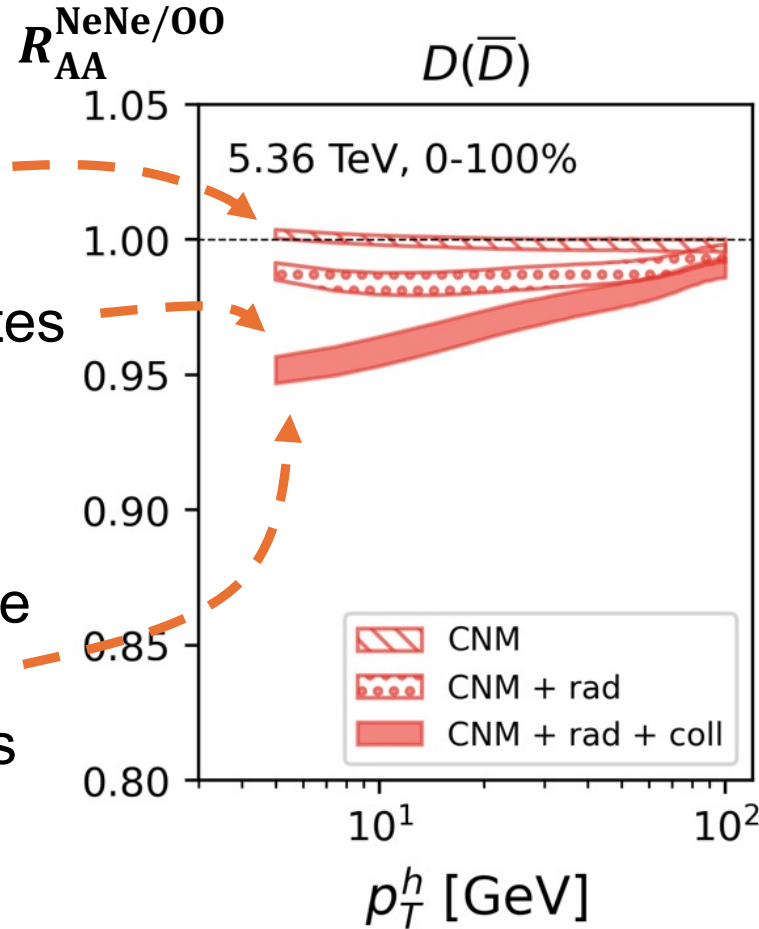
EPPS21 per-nucleon calculation is rescaled by  $N_{\text{coll}}$  for comparison ( $N_{\text{coll}}$  uncertainty not shown)

## Model including energy loss...

CNM only  $\rightarrow$  flat

Collisional contributes significantly

Dip at mid  $p_T$  can be interpreted as QGP induced energy loss

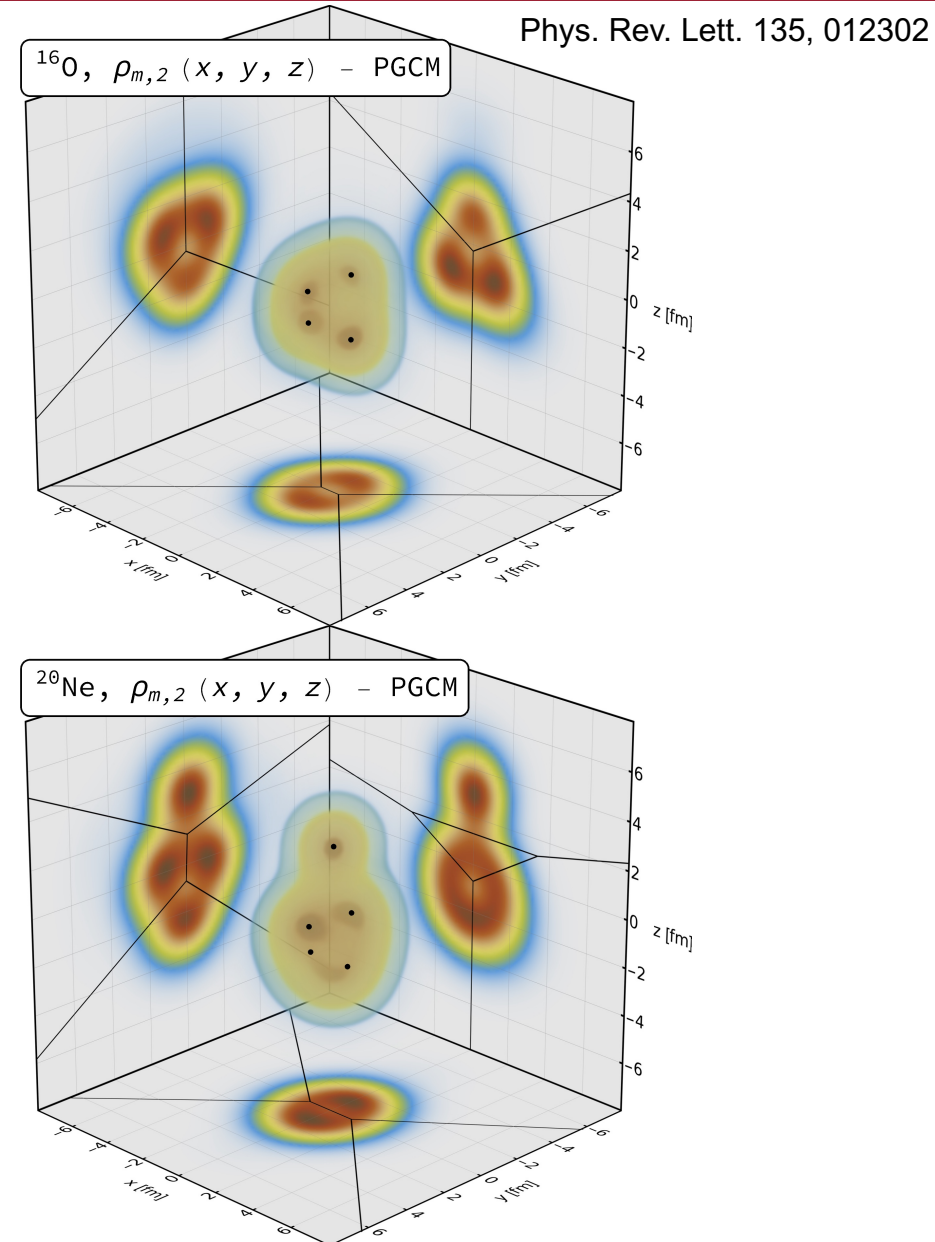
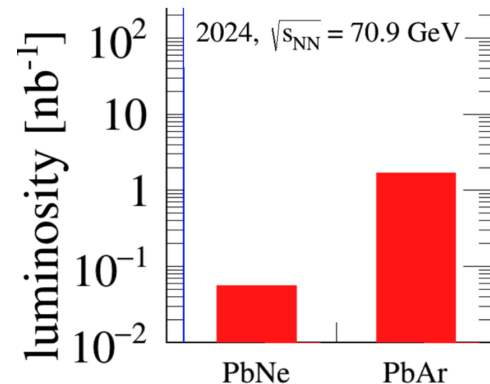
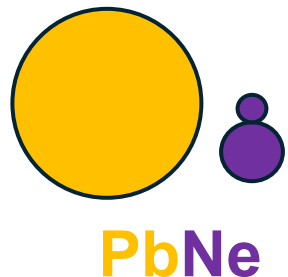


**System-size dependence of energy-loss effects**  
 **$\rightarrow$  Qualitatively consistent with data**

# SMOG2 PbNe and PbAr Collisions

## Unique geometry: $\alpha$ -cluster

- O: 4  $\alpha$ -clusters, close to spherical
- Ne: similar, with an extra  $\alpha$ -cluster on top, bowling pin
- By injecting Ne gas in SMOG2, LHCb provide a unique opportunity to study neon nucleus structure
  - Ar: spherical for good comparison
  - PbAr as baseline

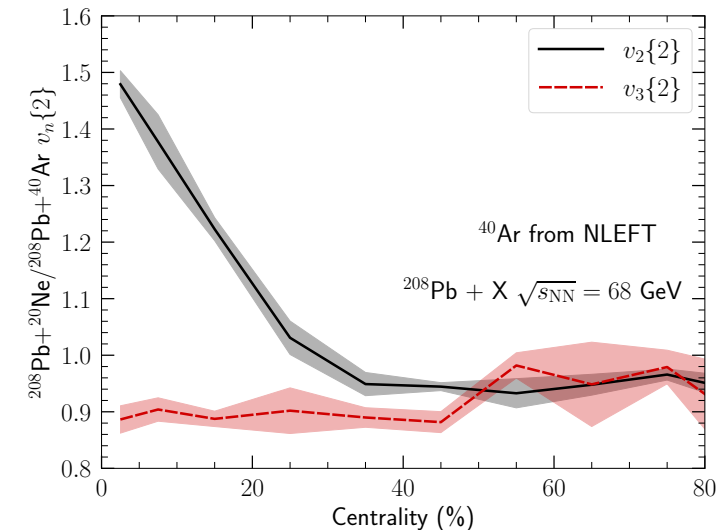
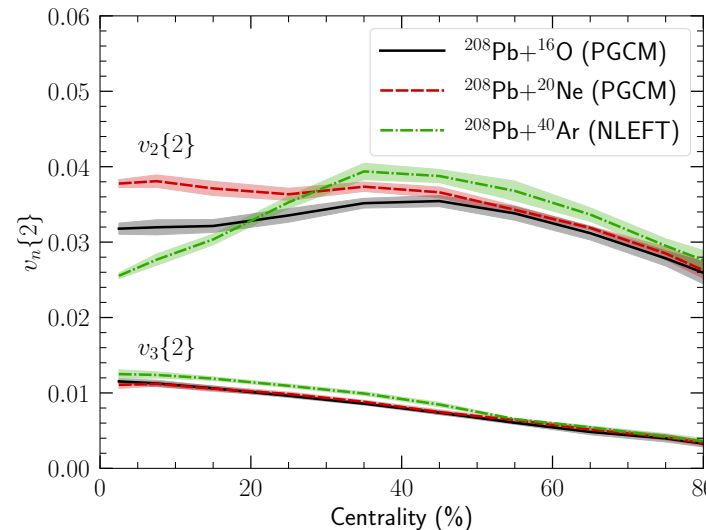
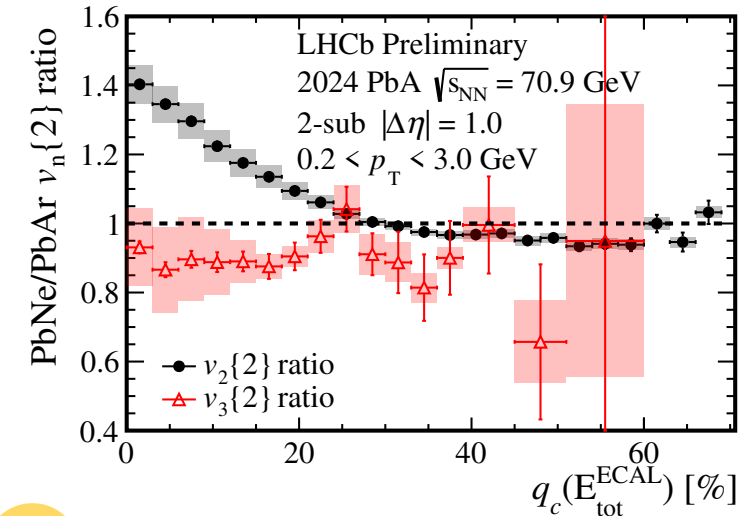
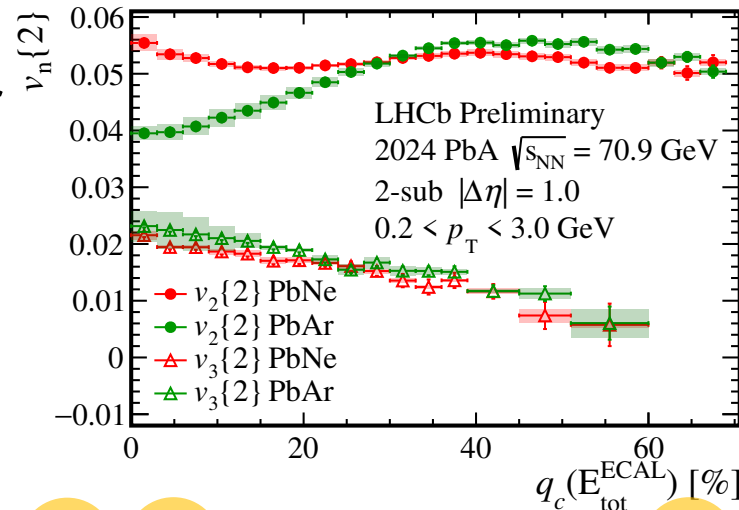


# Charged Particle Flow in PbNe and PbAr

LHCb-CONF-2025-001

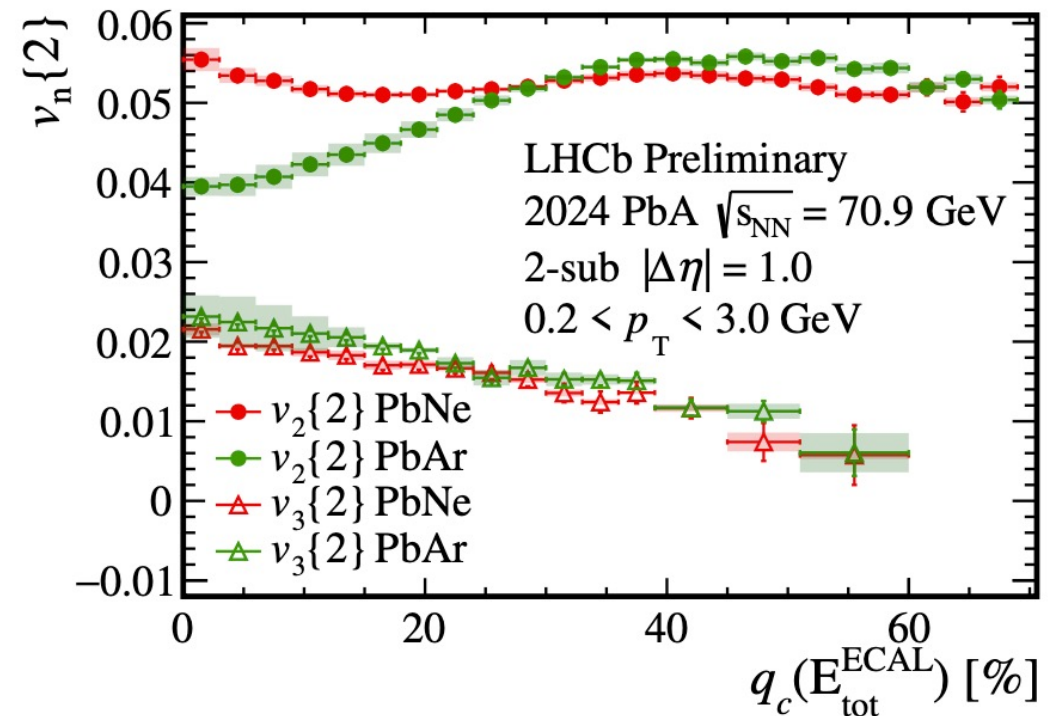
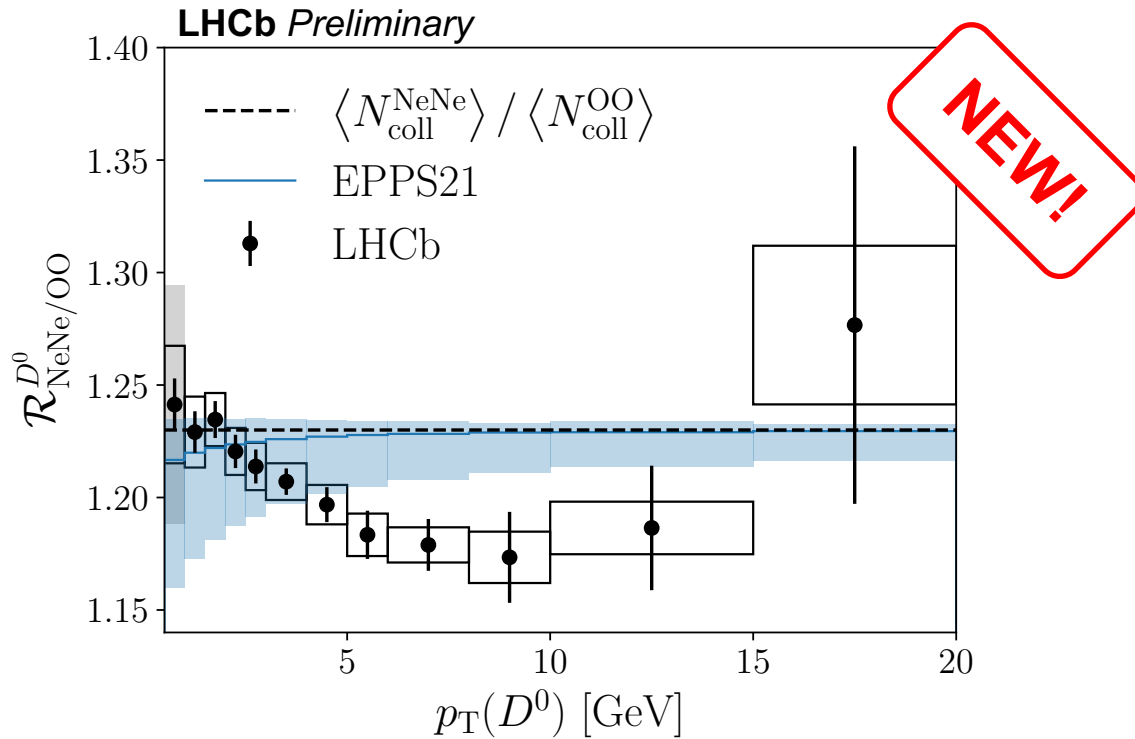
- Test both hydrodynamic and nuclear structure theories
  - using Pb as reference projector
  - overlap largely reflect shape of Ne
- $v_2\{2\}$  in central collisions
  - PbNe: flatter
  - PbAr: decreasing
- $v_2\{2\}$  ratio PbNe/PbAr in central collisions
  - significantly greater than one
  - qualitatively consistent with predictions
- Suggest the elongated nuclear shape of neon

See [Cesar Luiz Da Silva](#), Tues 3:35 PM  
[Matthew Durham](#), Wed 2:03 PM



# Summary

- **First  $D^0$  production ratio** in light-ion collisions
  - Suggests QGP-like effects may be present
- Charged particle flow in SMOG2 Pb light-ion collisions
  - Suggests an elongated nuclear shape of neon



Thanks for Attention!

BACKUP

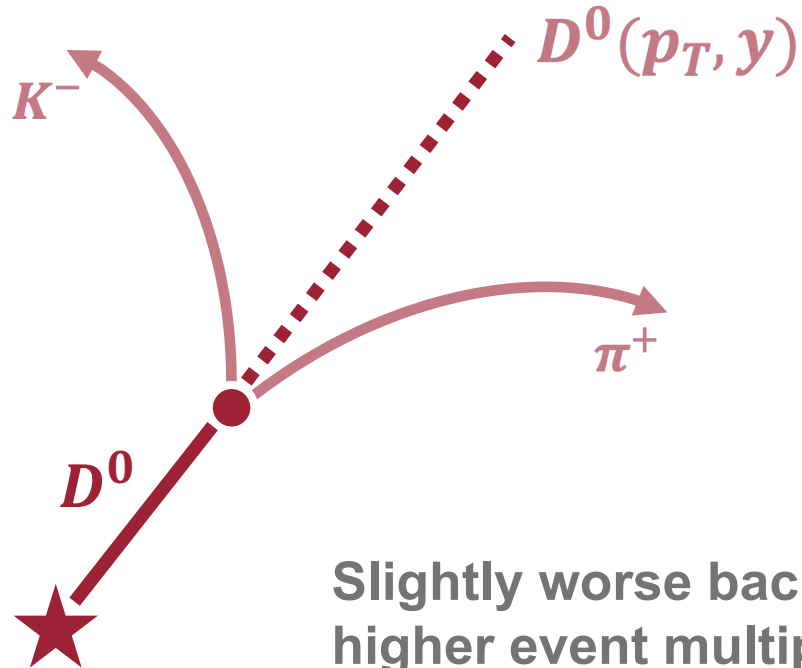
# Why the $D^0$ Ratio (NeNe / OO)

- Directly probes  $A$ -dependence of charm-quark quenching.
  - Isolates geometric scaling from dynamical effects.
  - Binary-collision baseline
  - Glauber:  $R_{\text{NeNe/OO}} = \langle N_{\text{coll}} \rangle_{\text{NeNe}} / \langle N_{\text{coll}} \rangle_{\text{OO}} = 15.8 \text{ (NeNe)} / 12.8 \text{ (OO)} \rightarrow 1.23 \times$  factor.
  - Any deviation from 1.23  $\Rightarrow$  real medium or path-length effect.
- Quantifies charm-quark energy-loss onset in the smallest QGP-capable systems.
- Tests path-length scaling  $\propto A^{1/3}$  predicted by light-ion  $R_{AA}$  studies.
- Constrains transport coefficients in a new regime
- Benchmarks theoretical models
- Completes the system-size picture:  $pp \rightarrow \text{OO} \rightarrow \text{NeNe} \rightarrow \text{XeXe} \rightarrow \text{PbPb}$ .

# Yield Extraction

## Mass Fit

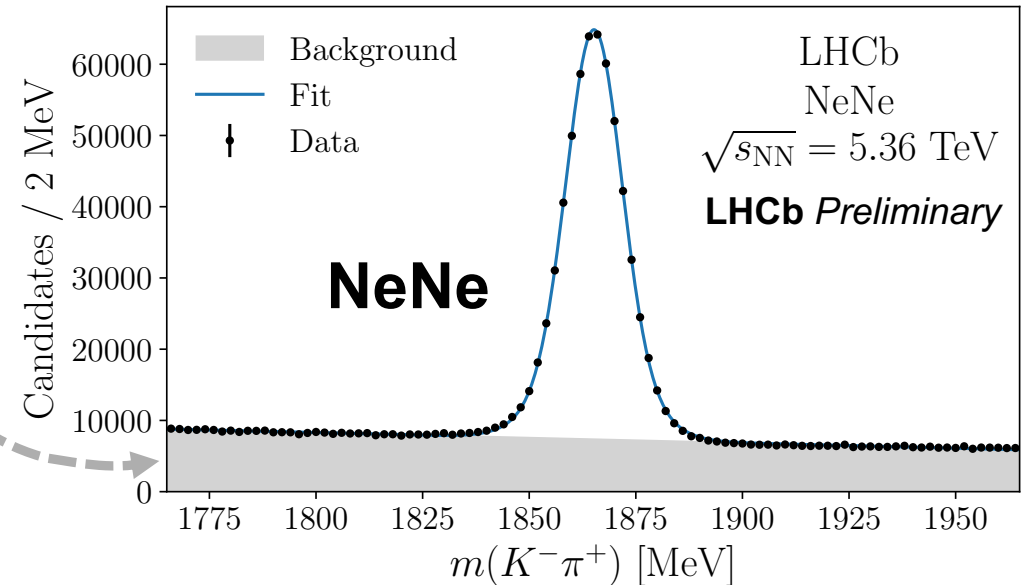
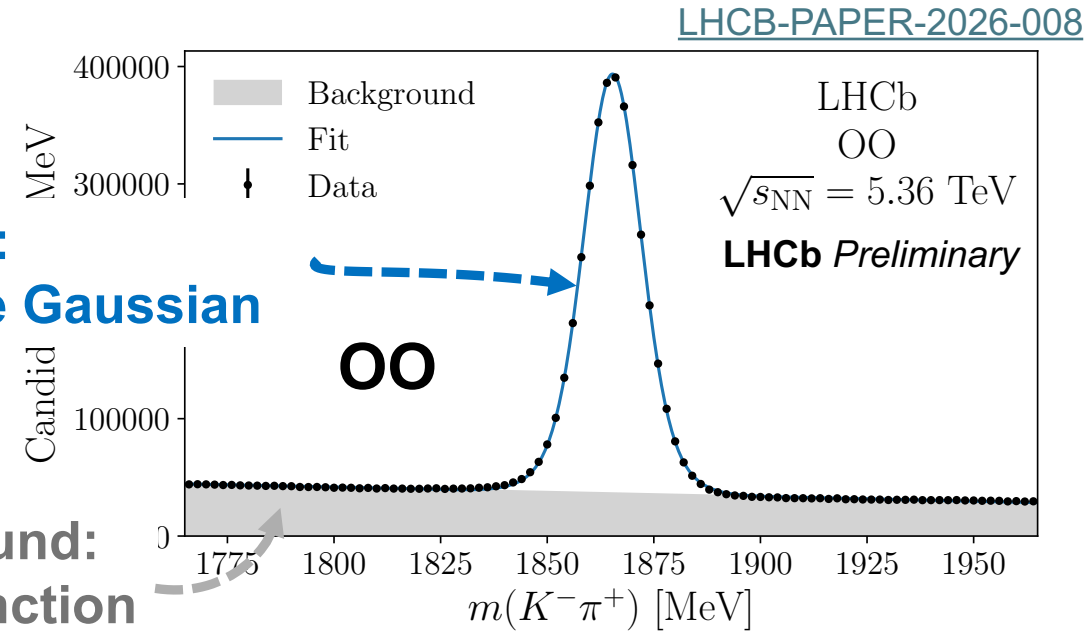
- Determines combinatorial background



Slightly worse background:  
higher event multiplicity

Signal:  
double Gaussian

Background:  
linear function



# Efficiency Calibration

## Efficiency factorization

$$\epsilon^{AA} = \cancel{\epsilon_{\text{acc}}} \times \epsilon_{\text{rec}} \times \cancel{\epsilon_{\text{trig}}} \times \epsilon_{\text{sel}} \times \epsilon_{\text{PID}}$$

Canceled = 1

**Only ratios of  $\epsilon^{AA}$  are relevant**

$\epsilon_{\text{acc}}$ : canceled; same kinematic regions

$\epsilon_{\text{trig}} = 1$ ; all reconstructed candidates must produce tracks



$$\frac{\epsilon^{00}}{\epsilon^{\text{NeNe}}} = \frac{\epsilon_{\text{rec}}^{00}}{\epsilon_{\text{rec}}^{\text{NeNe}}} \times \frac{\epsilon_{\text{sel}}^{00}}{\epsilon_{\text{sel}}^{\text{NeNe}}} \times \frac{\epsilon_{\text{PID}}^{00}}{\epsilon_{\text{PID}}^{\text{NeNe}}}$$

# Normalization

- To compare production rates across collision systems we need to normalize the observed signal yield
- Glauber model:  $R_{\text{NeNe}/\text{OO}} = \frac{\langle N_{\text{coll}} \rangle_{\text{NeNe}}}{\langle N_{\text{coll}} \rangle_{\text{OO}}}$ 
  - has large uncertainty  $\sim 10\%$ , significantly larger than in PbPb
- Instead, we use the **number of inelastic interactions** as the normalization
  - Visible interaction rate studied using two luminosity counters

$$\frac{N_{\text{Inel}}^{\text{OO}}}{N_{\text{Inel}}^{\text{NeNe}}} = 7.27 \pm 0.31$$

**4.2 % global normalization uncertainty**

- $R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$ 
  - scales with  $\langle N_{\text{coll}} \rangle$
- $R_{\text{NeNe}/\text{OO}} = \langle N_{\text{coll}} \rangle_{\text{NeNe}} / \langle N_{\text{coll}} \rangle_{\text{OO}}$
- Glauber model has large uncertainty
  - Centrality precision is limited by the small participant number ( $\sim 32/40$  for NeNe/OO) and large event-by-event fluctuations
  - Systematic uncertainties of order 10%, significantly larger than in PbPb.

	$\langle N_{\text{part}} \rangle$	$\langle N_{\text{coll}} \rangle$
NeNe	12.7	15.7
OO	10.8	12.8
NeNe/OO	1.18	<b>1.23</b>

# Systematic Uncertainties

- Uncorrelated: vary independently between bins
- Correlated: shape or model effects that vary smoothly
- Global: single normalization term common to all bins

Source	Type	Comment
Statistical fit error	Uncorrelated	Includes template & MC-shape constraints
PID finite sample	Correlated	Bootstrapped calibration maps
PID binning choice	Correlated	Alternative binning check
Tracking finite sample	Correlated	Random Gaussian variations
Selection (IP, DIRA)	Mixed	IP correlated, DIRA uncorrelated
Fit model (mass/IP shape)	Correlated	Alternative signal/background functions
Data–MC kinematics	Correlated	Checked with SWeighted data average
Normalization	Global	4.2 % from PV / track counter difference

# Hypothesis Testing with Wilks' Theorem

- Null hypothesis:  $H_0: \mathcal{R}(p_T) = c$
- Alternative hypothesis:  $H_1: \mathcal{R}(p_T) = c + s \cdot p_T$
- $\chi^2 = r^T C^{-1} r$ 
  - $r$ : residual vector between data and model
  - $C$ : full covariance matrix
  - Wilks + full covariance is the correct statistical treatment
- $\Delta\chi^2 = \chi^2(H_0) - \chi^2(H_1)$ 
  - $Z = \sqrt{\Delta\chi^2}$  (1 d.o.f.)
- Wilks + full covariance give correct statistical treatment when systematic uncertainties are correlated
- poly-1 directly interpretable as a slope and is the simplest deviation from flatness
  - Answer the question is the NeNe/OO ratio consistent with being constant in or does it exhibit a systematic trend