Uncovering the microscopic structure of the quark-gluon plasma

Jaime Norman
University of Liverpool

Nuclear Physics Community Meeting Daresbury Lab
8th January 2026

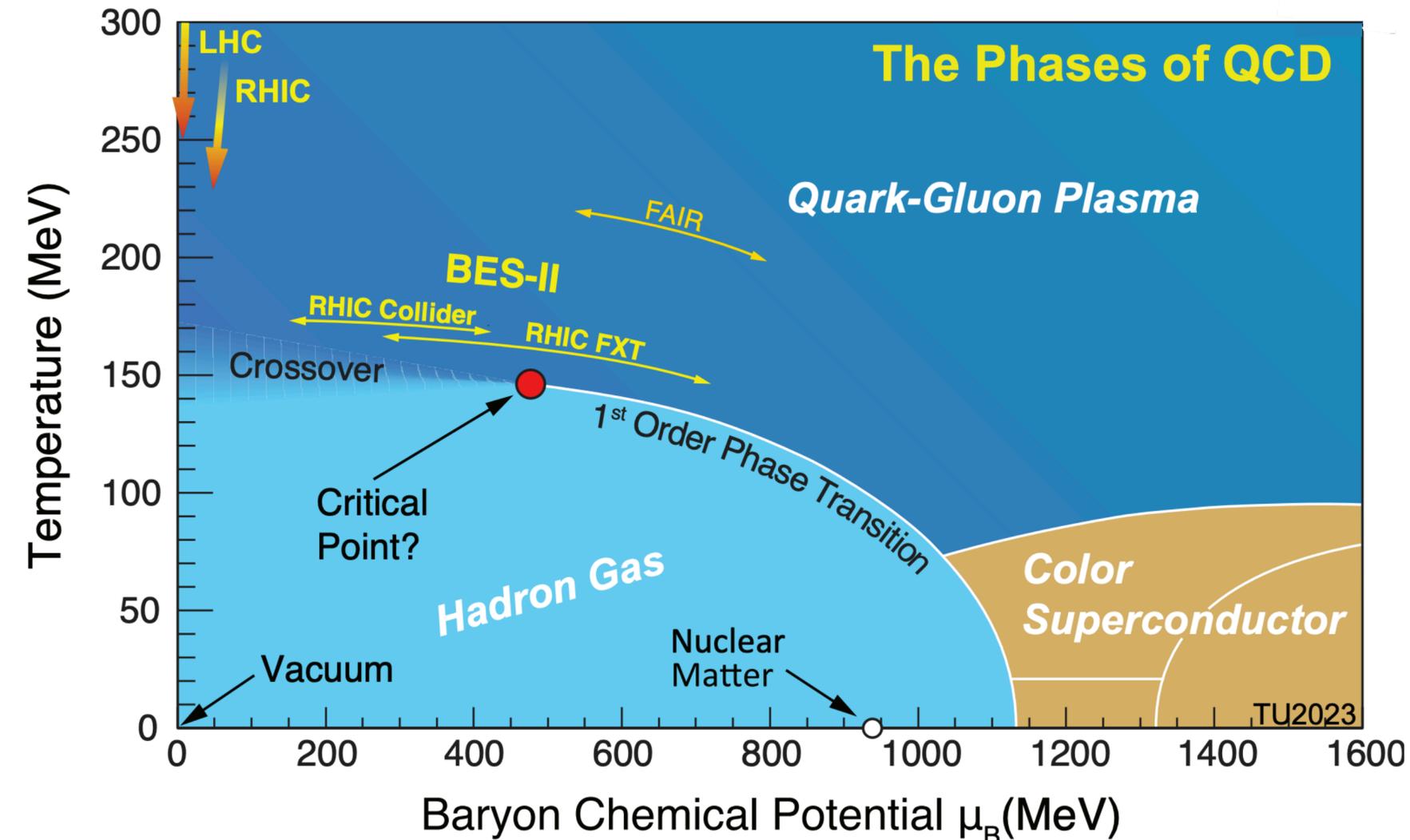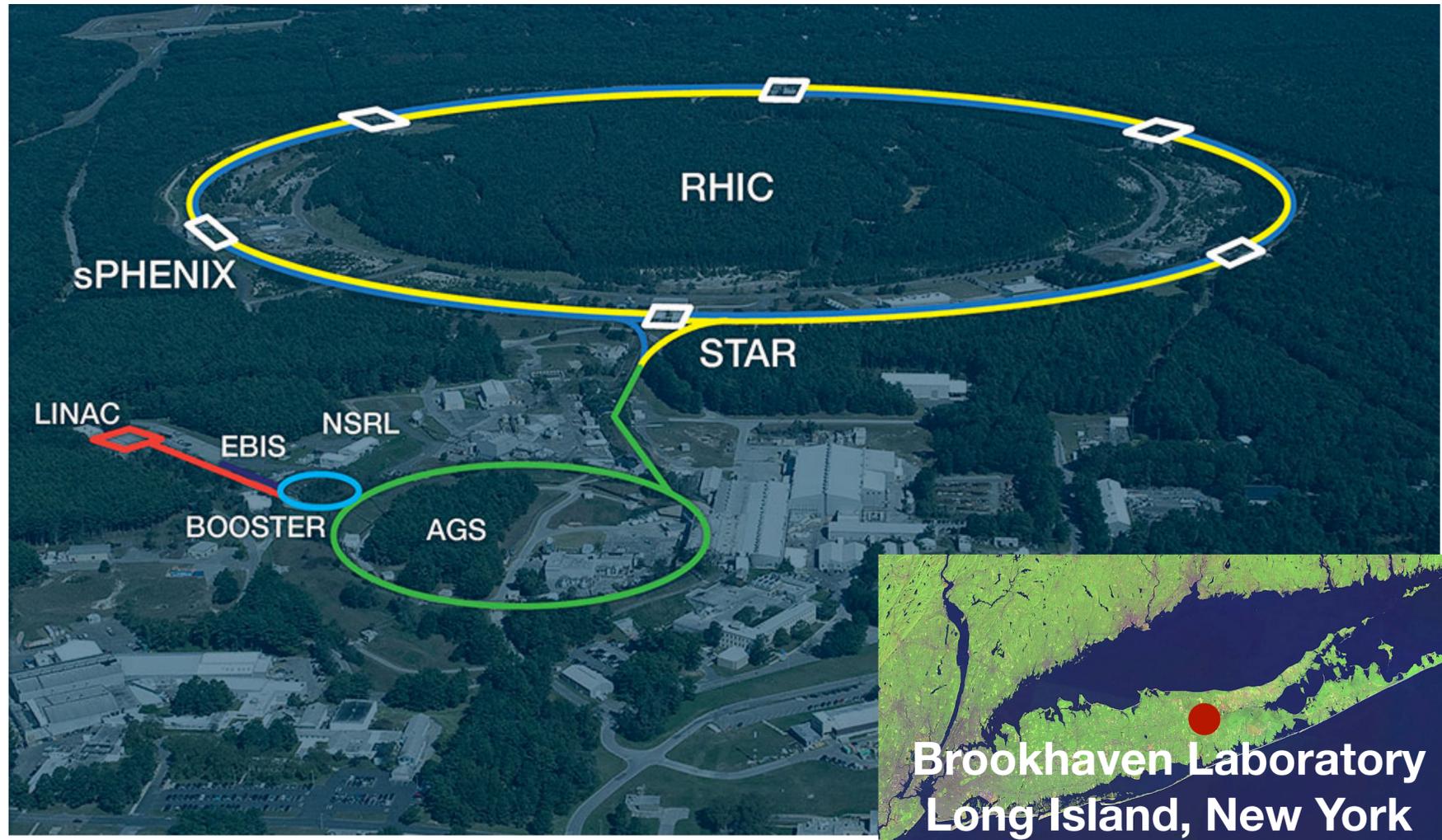# Many-body QCD and the quark-gluon plasma (QGP)

fig. H. Caines

- Phase transition at high temperature or density to deconfined state of quarks and gluons
  - **quark-gluon plasma (QGP)**

- Calculations on the lattice predicts smooth crossover at ~155 MeV at low baryon density

- Created using **ultra-relativistic heavy-ion collisions**

→ **by studying these collisions we study the bulk, high-temperature properties of QCD matter, and the emergent phenomena that may arise**

Where can we make a QGP?

RHIC

sPHENIX — STAR — LINAC — EBIS — NSRL — BOOSTER — AGS

**Brookhaven Laboratory
Long Island, New York**

Large Hadron Collider

CMS — p — LHCb — ATLAS — ALICE

**CERN
Geneva, Switzerland**

- Collisions of protons (pp), gold-ions (Au-Au), plus many other ions (Al, Cu, Zr, U…)

- Centre-of-mass energy per nucleon-nucleon collision up to $\sqrt{s_{NN}} = 200$ GeV (Au-Au)

- In addition to collisions of protons (pp), for one month a year collide lead-ions (Pb-Pb) and proton-lead (p-Pb) (plus Xe-Xe, this year O-O, Ne-Ne)

- Centre-of-mass energy per nucleon-nucleon collision up to $\sqrt{s_{NN}} = 5.36$ TeV (Pb-Pb), $\sqrt{s} = 13.6$ TeV (pp)

Heavy-ion collisions at the LHC

The ALICE detector
The dedicated heavy-ion experiment at the LHC

12.5 billion pixels

leading Liverpool/DL role in silicon tracker upgrade
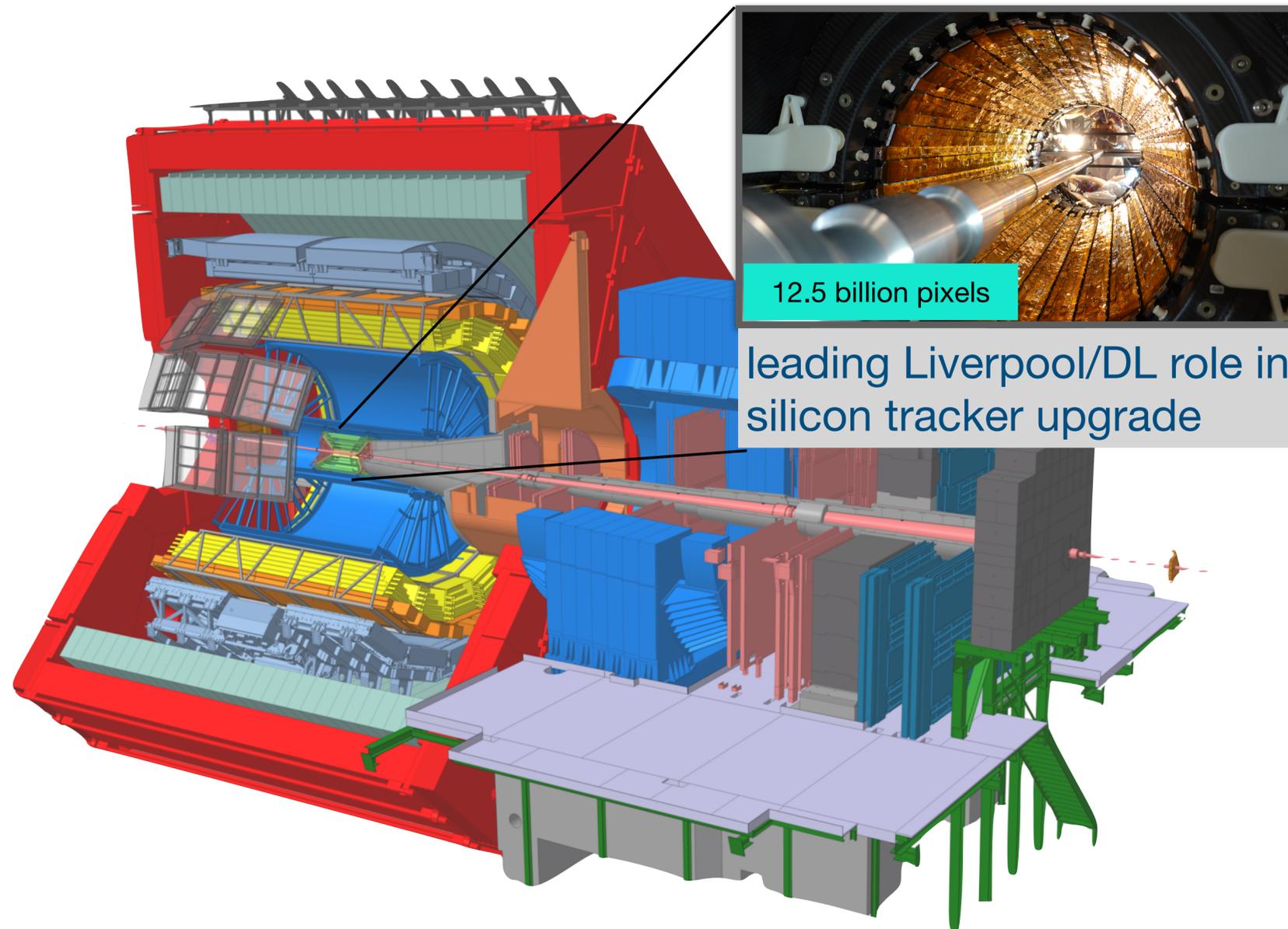
- **Charged particle tracking** performance over a wide momentum range (~0.15 - 100 GeV/c)

- **Particle identification** (TPC, TOF) and photon/neutral ID (EMCal, Photon spectrometer)

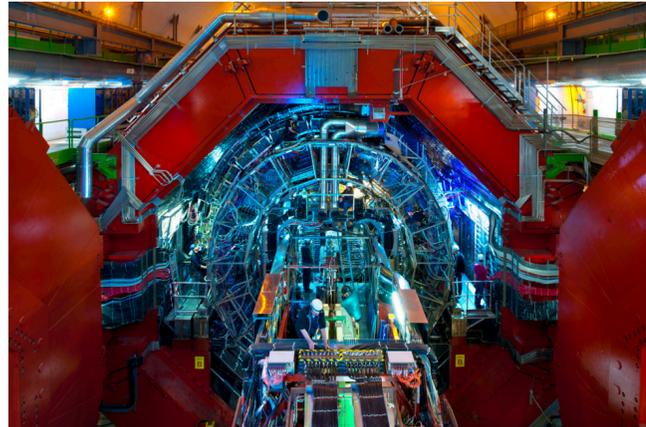- **Muon spectrometer** at forward rapidities

Major upgrade for 2022-2026 runs (LHC Run 3)

- **x2 improvement in spatial precision**

- **>x100 increase in collected collisions w.r.t Runs 1 and 2**

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QGP (in a nutshell)

Long-distance structure:

QGP is a strongly-coupled liquid (with very low viscosity)

P. Romatschke

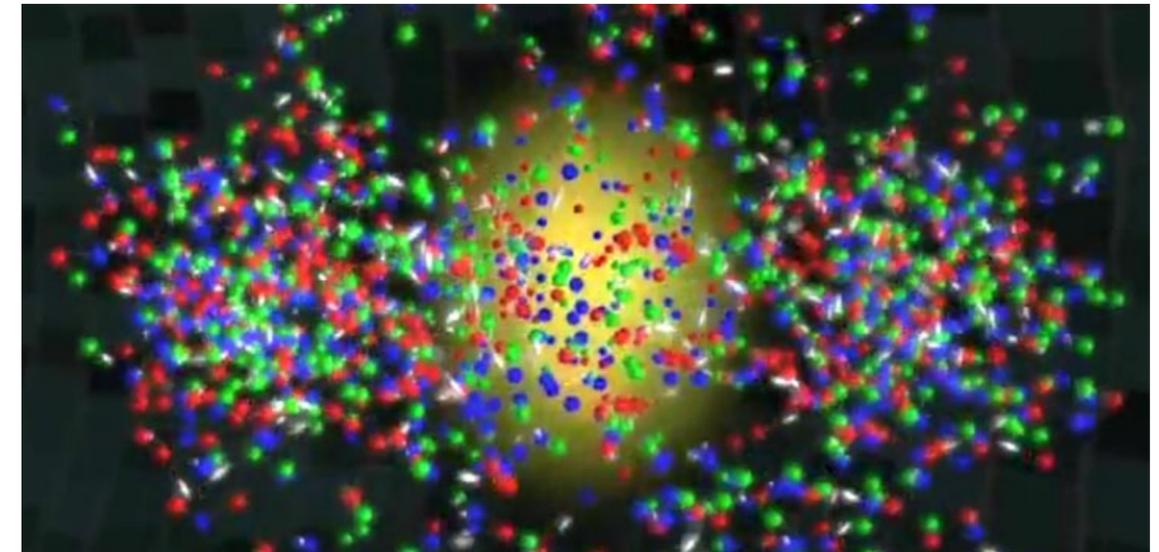$\eta/s \sim$ **280** $\eta/s \sim$ **0.12**

- Lower bound from strongly-coupled gauge theory $\sim 1/4\pi \sim 0.08$

The 'perfect liquid'!

Short distance structure:

Free quarks and gluons? Complex bound states? degrees of freedom not yet established

What is the (quasi-particle) structure of the QGP as a function of resolution scale?

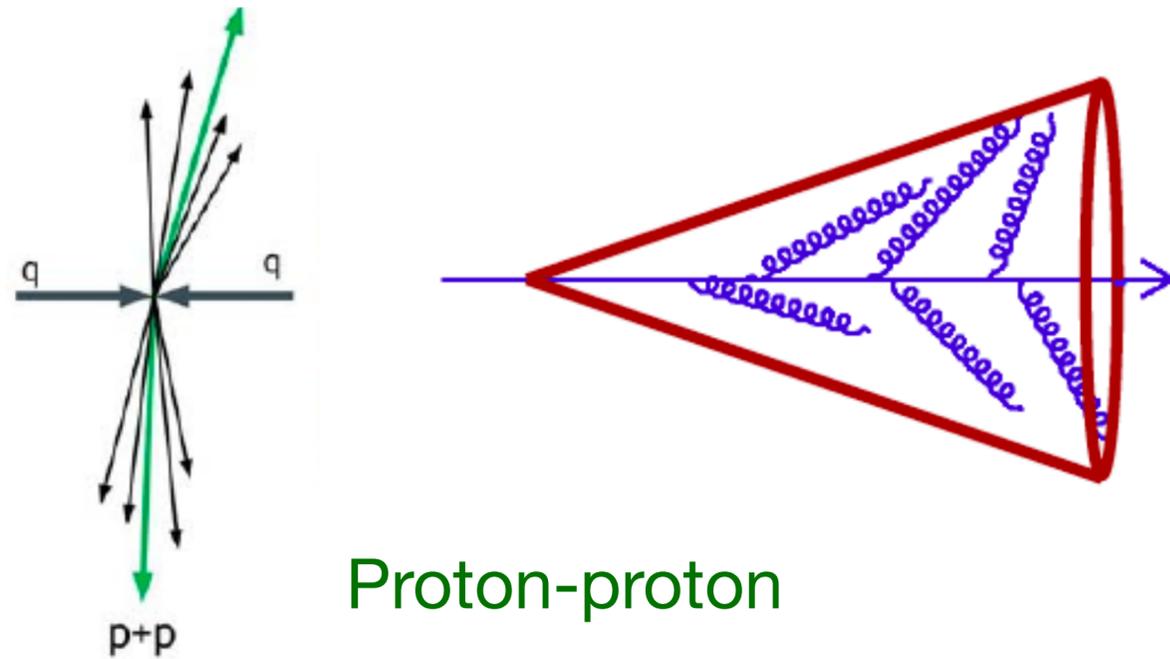# Jets: Multi-scale 'probes' of the QGP

Evolution of hard parton (quark or gluon)
→ gluon radiation

- Experimentally measured as **collimated spray of hadrons**
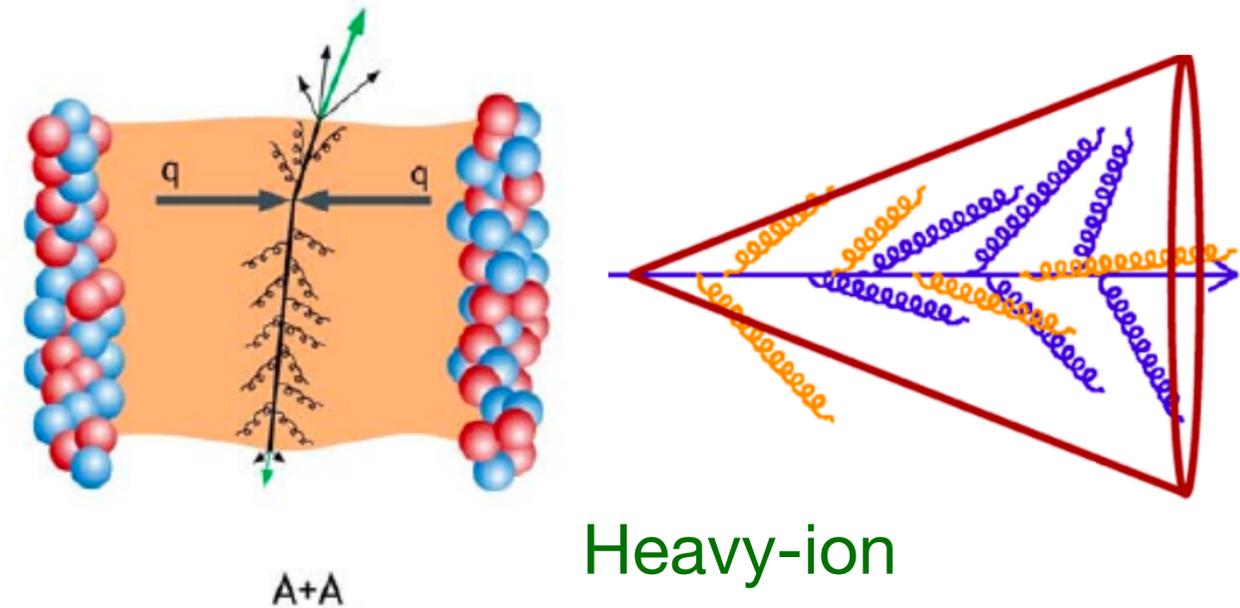
Reconstruct jets
→ measure initiating parton

Proton-proton

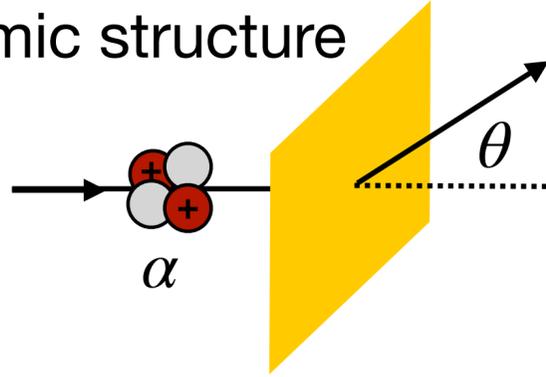'**Jet quenching' - partonic interactions in the QGP**

- inelastic (medium-induced gluon emission) and elastic (collisional) processes over full parton shower

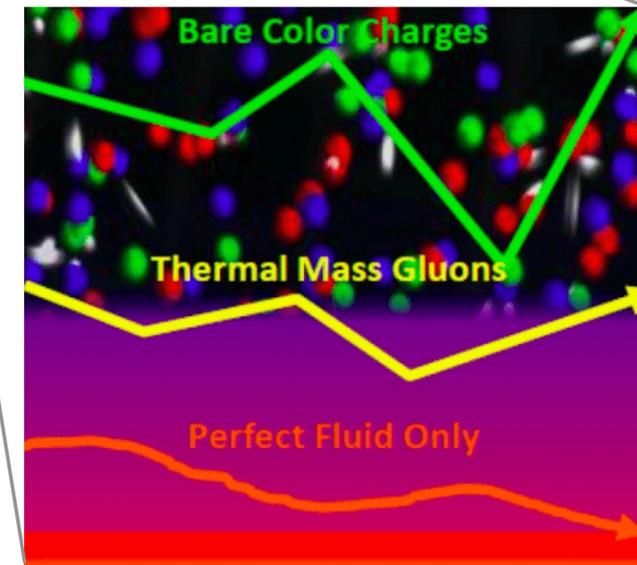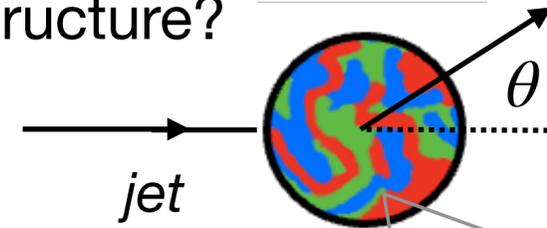**Jets provide unique probes of the QGP as a function of its resolution scale**

Heavy-ion

Designing a scattering experiment
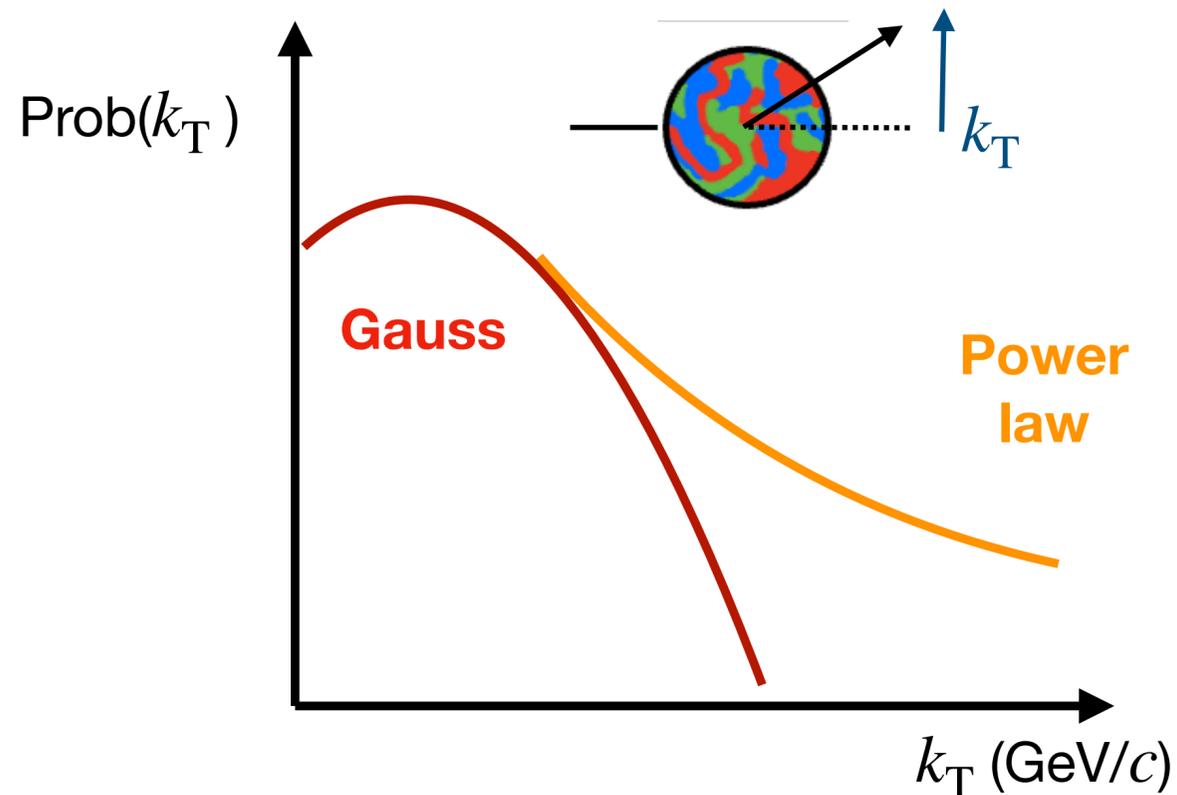
Ernest Rutherford
uncovered atomic structure

α

θ

Can we uncover
microscopic quark-gluon
plasma structure?

θ

jet

Bare Color Charges

Thermal Mass Gluons

Perfect Fluid Only

Designing a scattering experiment

- **Strong-coupling limit** - probability of parton to obtain momentum k_T is Gaussian (exponential) distributed

- If medium probed at short enough distance scales
  - scatter off **weakly-interacting quasiparticle**
  ~ 'Rutherford-Like' power-law distributed $\sim 1/(k_T)^4$

  F. D'eramo, M. Lekaveckas, H. Liu, K. Rajagopal, *JHEP* **05 (2013) 031**
  F. D'eramo, K. Rajagopal, Y. Yin *JHEP* **01 (2019)**

- Radiative corrections lead to harder power law $1/(k_T)^{4-2\beta}$
  - hard scatters more likely

  P. Caucal, Y. Mehtar-Tani: *Phys.Rev.D* **106 (2022) 5, L051501**
  JHEP **09 (2022) 023**
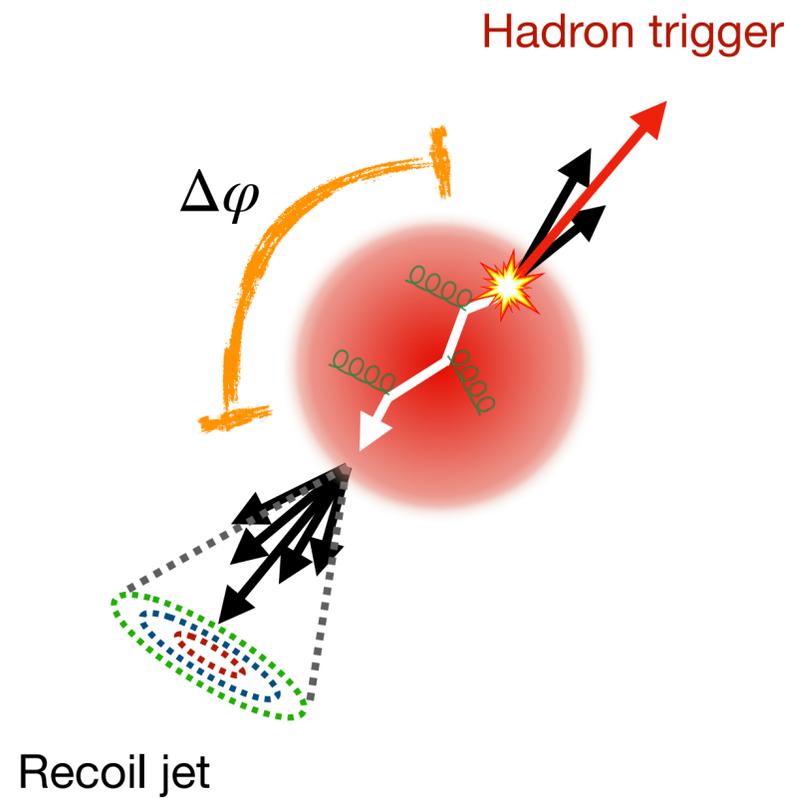 *Phys.Rev.D* **108 (2023) 1, 014008**

$\rightarrow$ search for low-energy, large-angle scatterings of jets or their constituents
'Moliére scattering'

Designing a scattering experiment

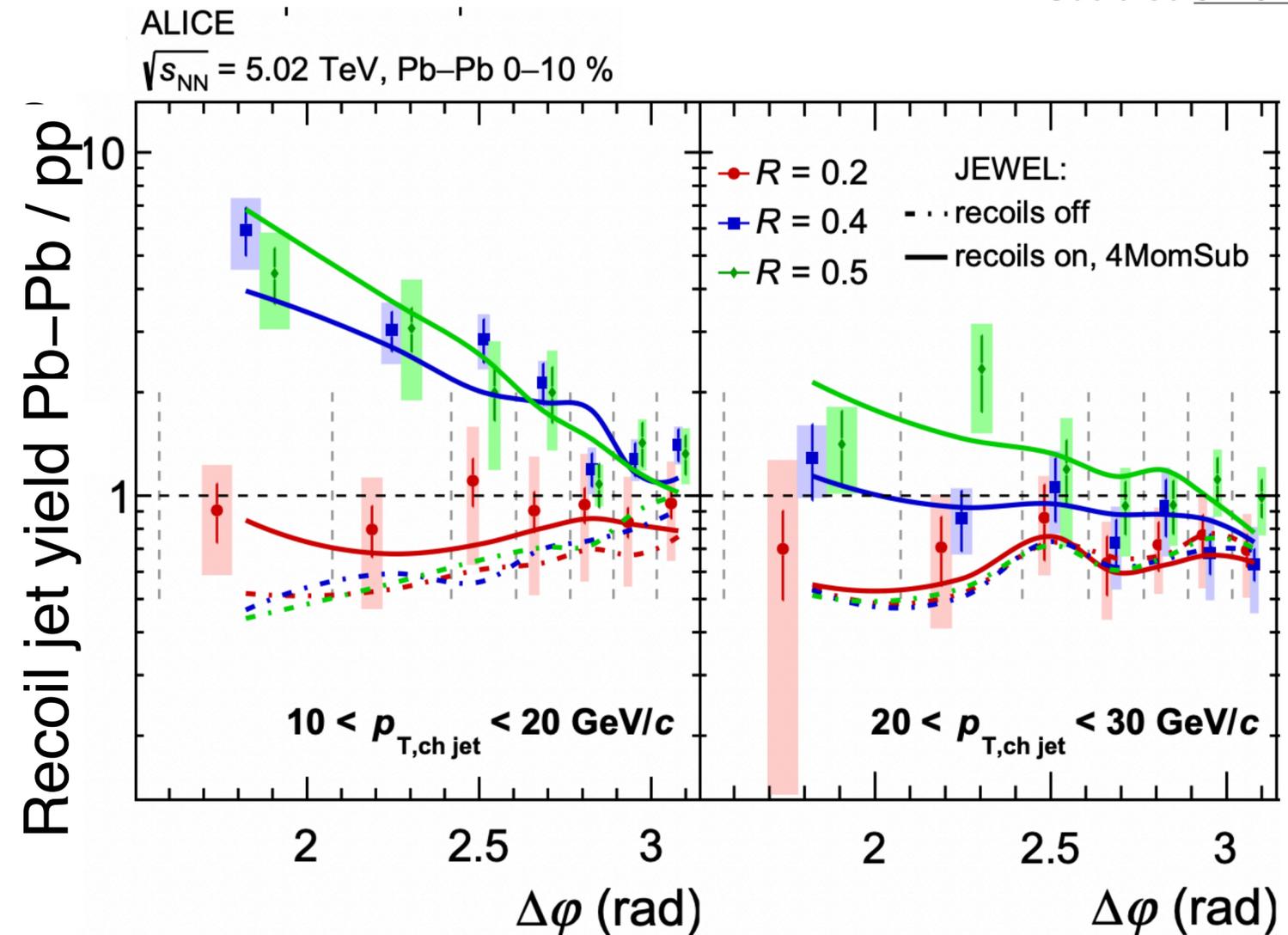Experiment state of the art: search for large-angle angular broadening of a dijet system

ALICE
$\sqrt{s_{NN}}$ = 5.02 TeV, Pb–Pb 0–10 %

- R = 0.2
- R = 0.4
- R = 0.5

JEWEL:
- - - recoils off
—— recoils on + MomSub

Recoil jet yield Pb–Pb / pp

$10 < p_{T,ch\ jet} < 20$ GeV/c

$20 < p_{T,ch\ jet} < 30$ GeV/c

$\Delta\varphi$ (rad)

- Semi-inclusive measurement of jets recoiling from high-p_T hadron

- Low energy jets (~10 GeV) accessed via background subtraction techniques

Designing a scattering experiment

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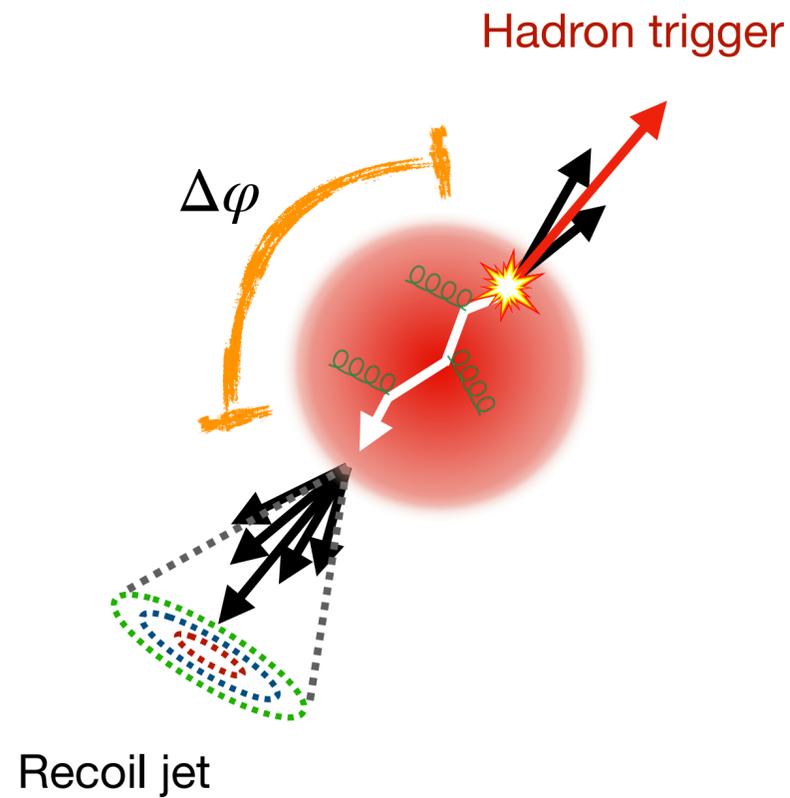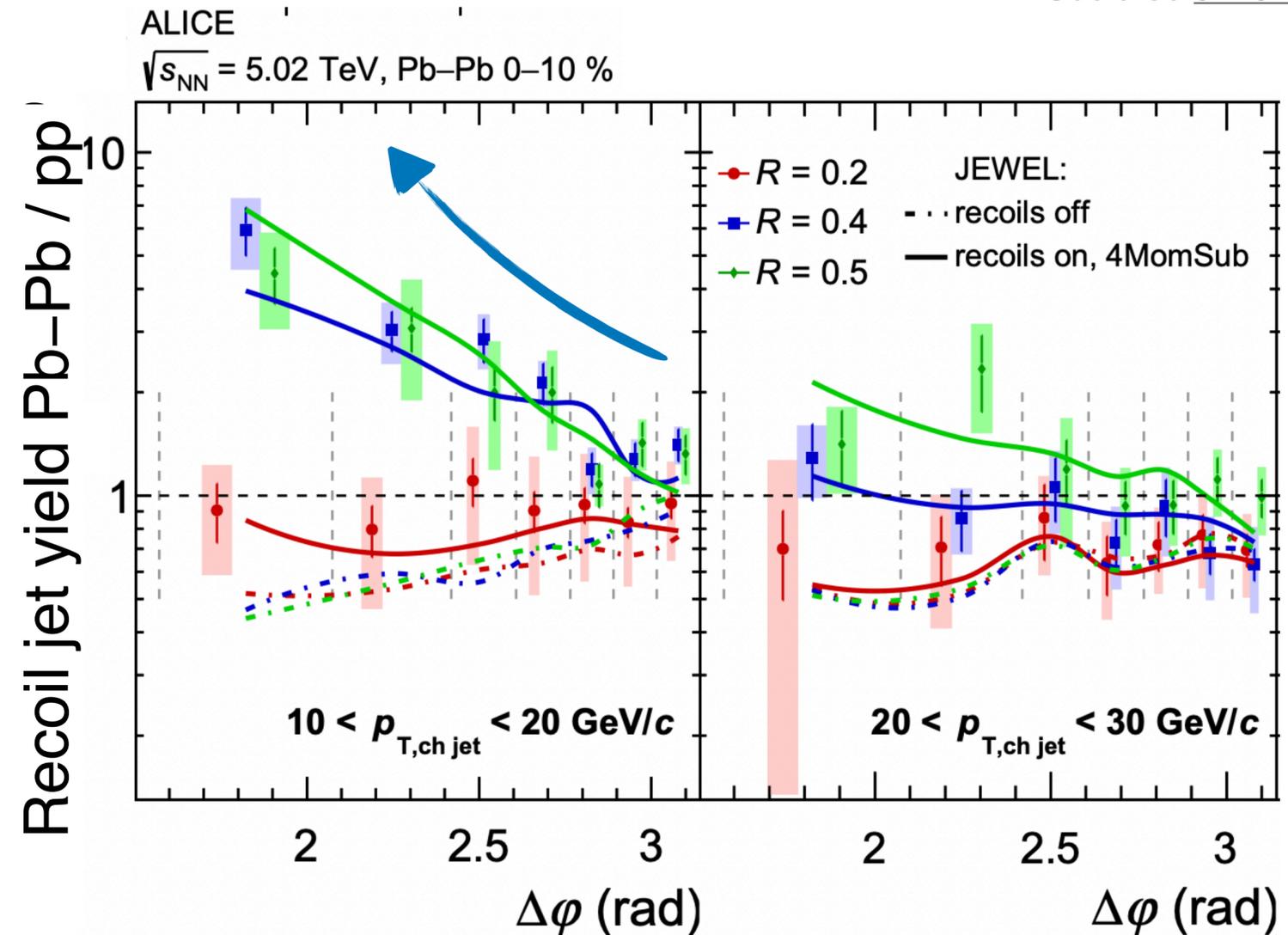- Low energy jets (~10 GeV) accessed via background subtraction techniques

→ **First observation of 'jet acoplanarity' - predicted in 80's!**

Appel, 1986
Blaizot, McLerran, 1986
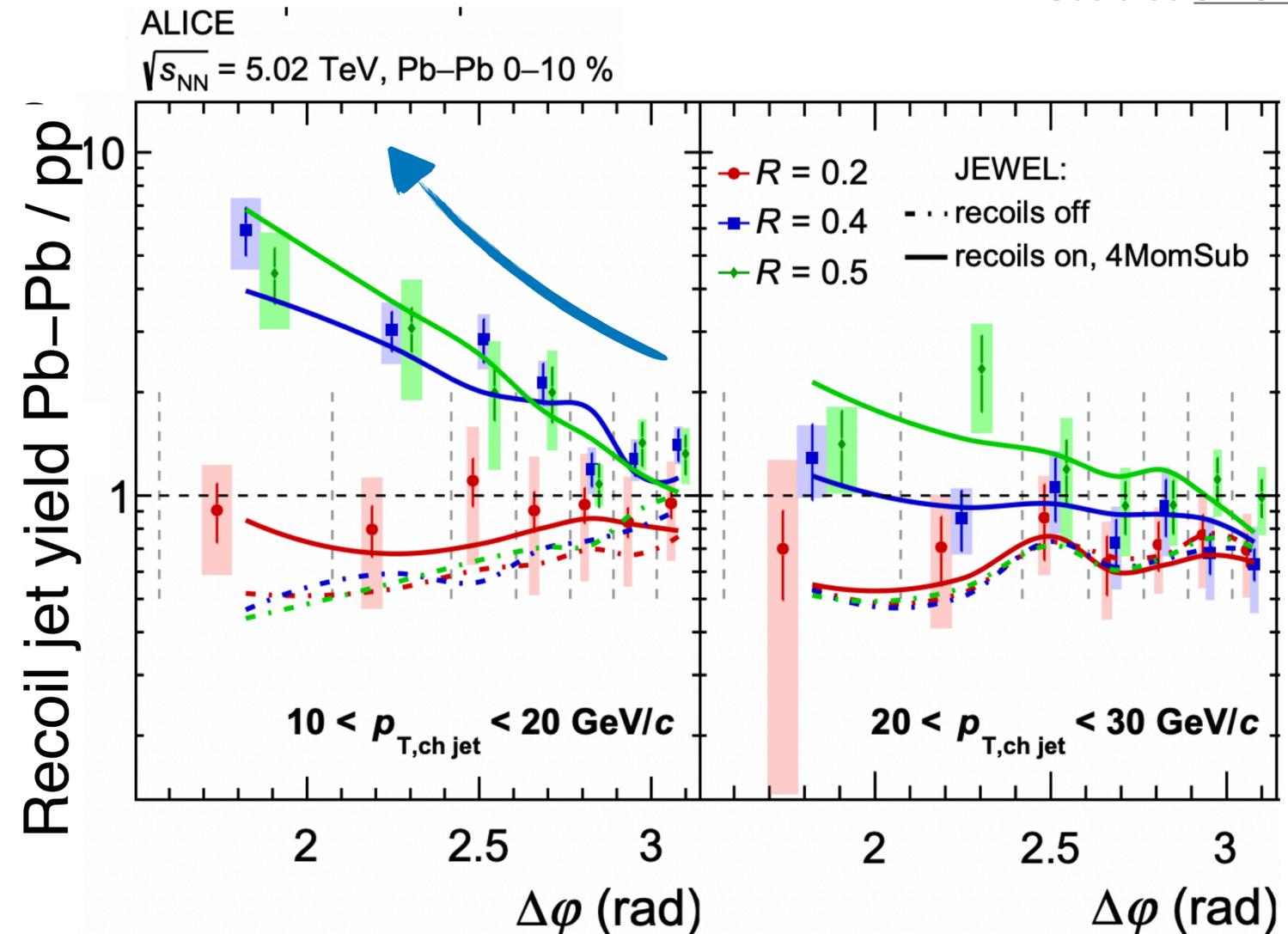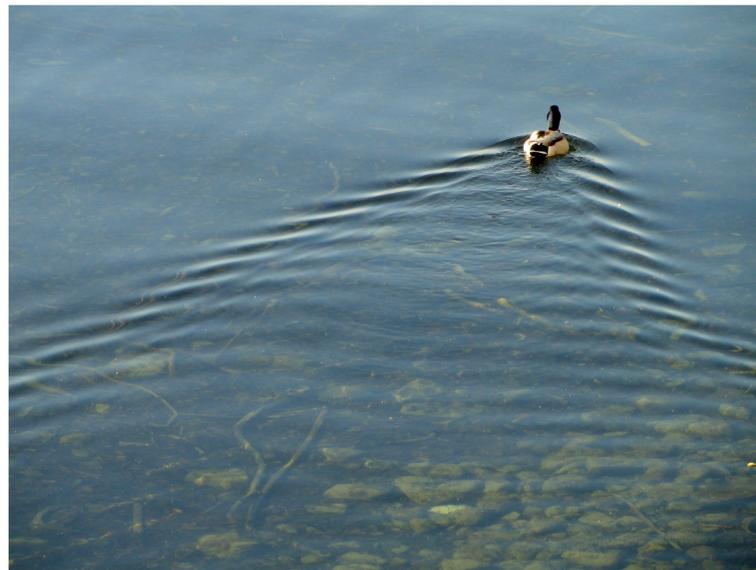
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Designing a scattering experiment

Experiment state of the art: search for large-angle angular broadening of a dijet system

Dependence on jet aperture (radius 'R') and model comparisons

→ primarily caused by '*shockwave*' (wake) in quark-gluon plasma rather than large-angle scatterings

ALICE
$\sqrt{s_{NN}}$ = 5.02 TeV, Pb–Pb 0–10 %

Recoil jet yield Pb–Pb / pp

- $R = 0.2$
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$\Delta\varphi$ (rad)

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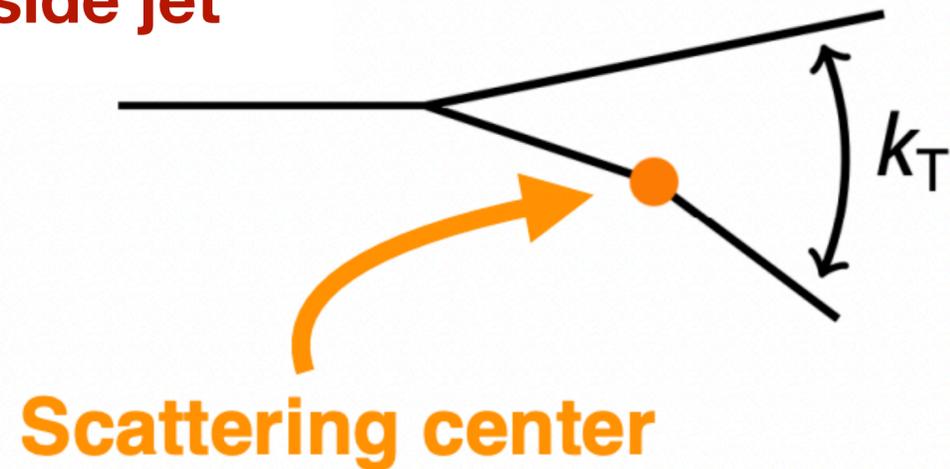
→ **First observation of 'jet acoplanarity' - predicted in 80's!**

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Designing a scattering experiment

Experiment state of the art: search for large-angle scattering of jet splittings
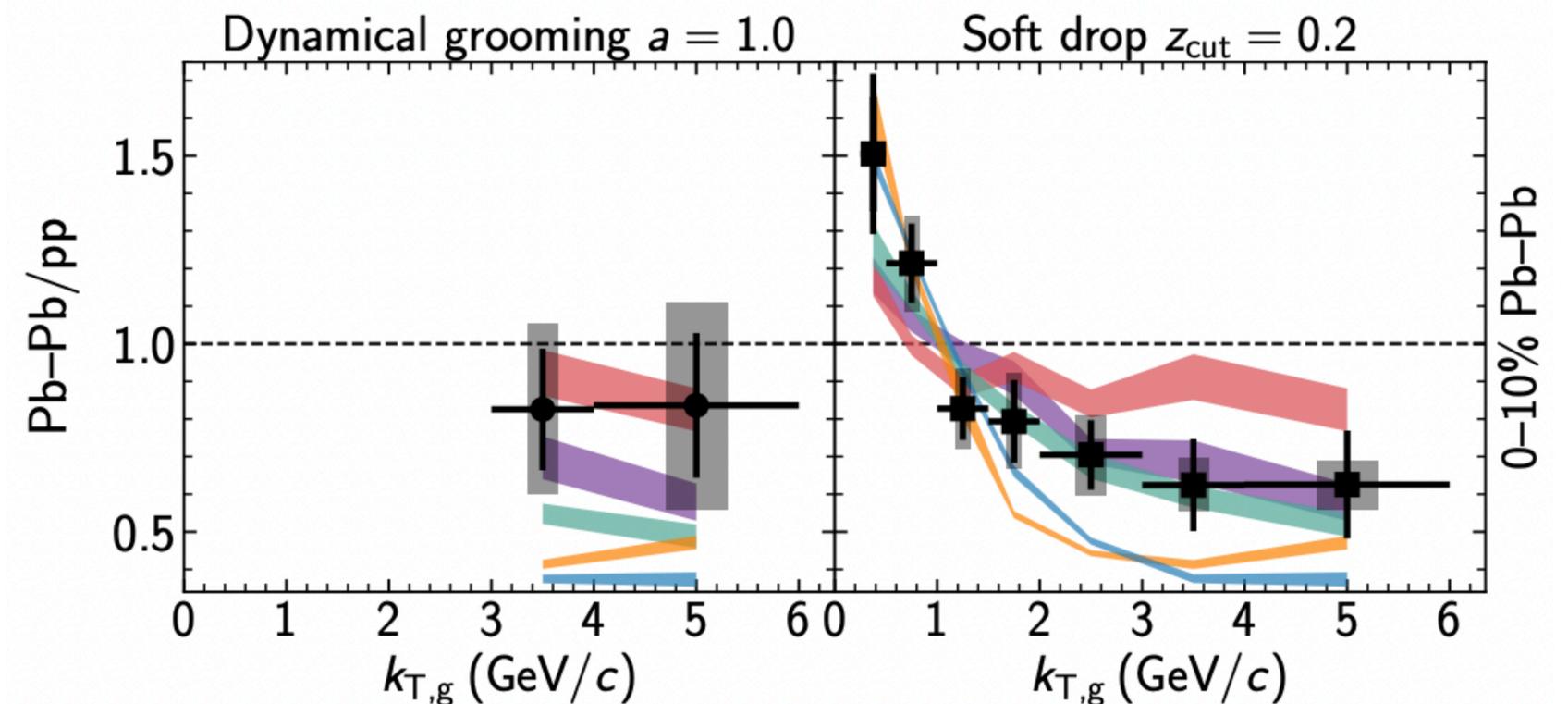
Parton inside jet

k_T

Scattering center

- Idea: Measure relative transverse momentum (k_T) of jet splittings in the parton shower
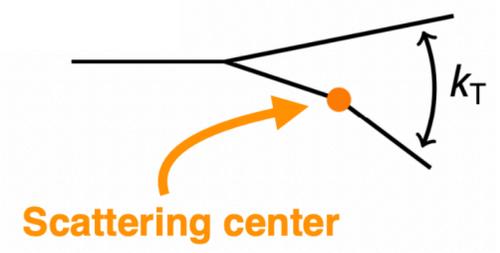
- In practice: Sequential jet clustering/declustering algorithms give access to parton shower history

ALICE: Phys. Rev. Lett. 135, 031901 (2025)

0–10%, 30–50% Pb–Pb, pp $\sqrt{s_{NN}} = 5.02$ TeV
Anti-k_T ch-particle jets, $R = 0.2$, $|\eta_{jet}| < 0.7$
$60 < p_{T,ch\ jet} < 80$ GeV/c

- Hybrid w/ wake
- Hybrid w/ wake + Moliere
- JETSCAPEv3.5 AA22
- JEWEL (recoils)
- JEWEL (no recoils)

Dynamical grooming $a = 1.0$ Soft drop $z_{cut} = 0.2$

Pb–Pb/pp

0–10% Pb–Pb

$k_{T,g}$ (GeV/c) $k_{T,g}$ (GeV/c)

→ **No clear evidence of large-angle scattering**

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Next steps
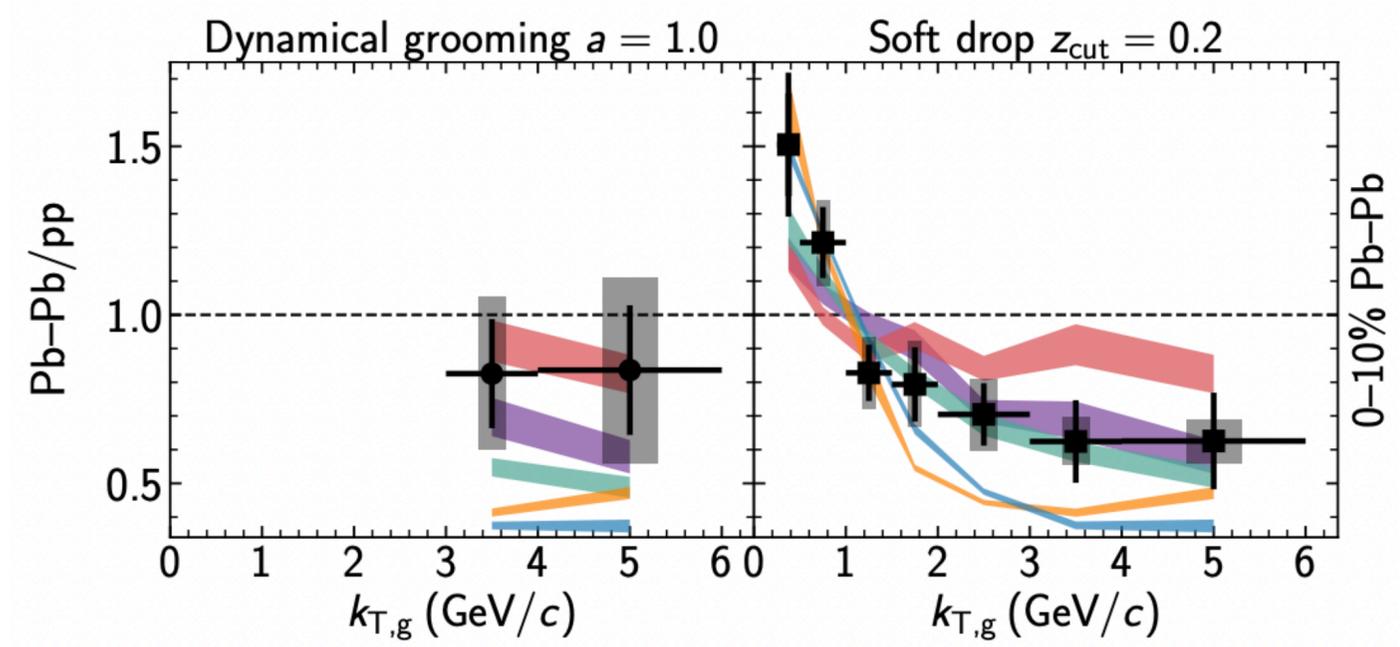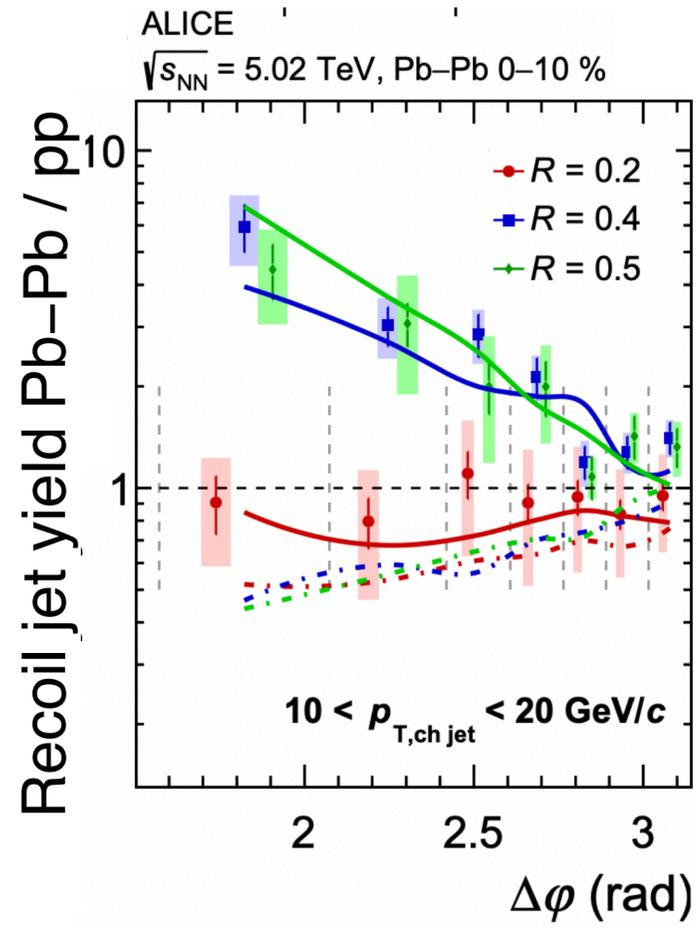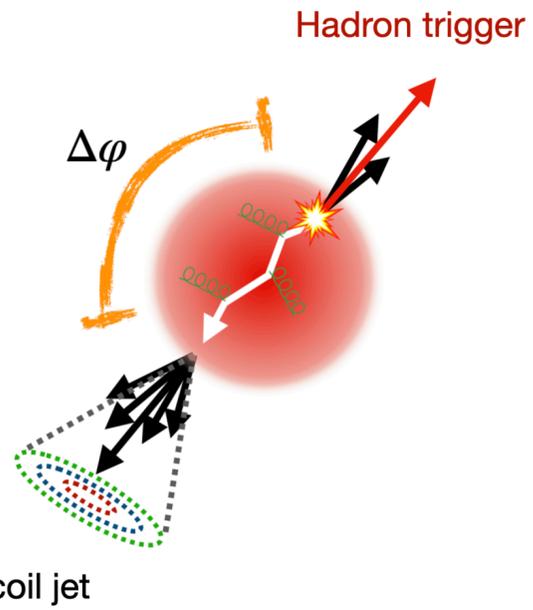
- Can we separate the jet-induced '*shockwaves*' from the '*scatters*' ?

- Can we define a precise probe sensitive to in-medium scattering?

- How can we rigorously validate models of the plasma's microscopic structure?

Constraining interplay between wake and jets

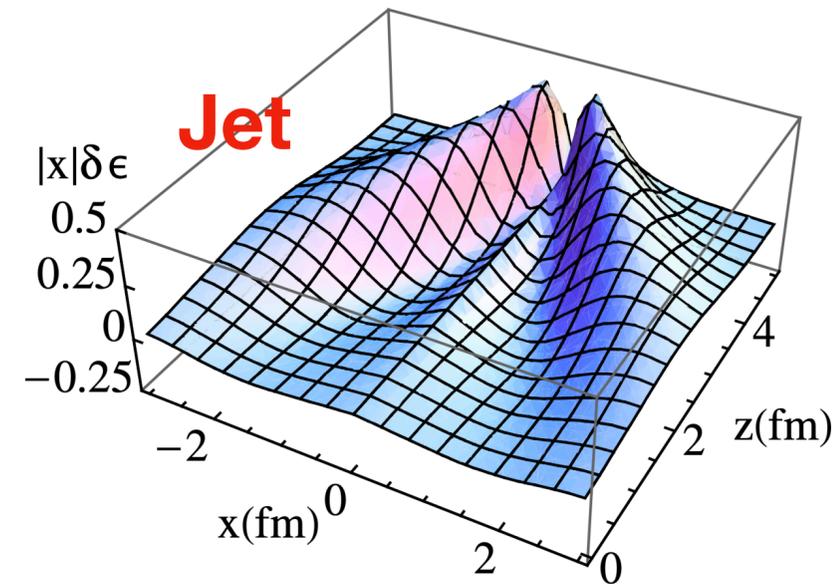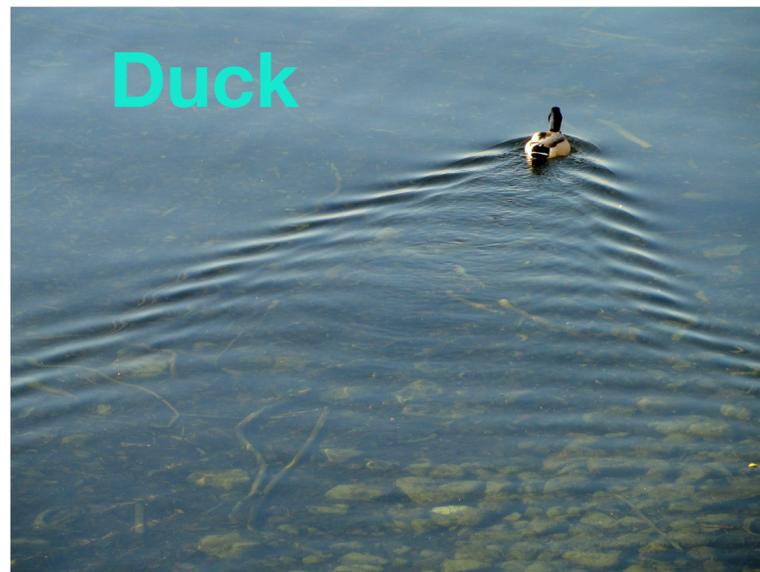Challenge: 'Wake' from jet-medium interactions
  may mask hard scatterings

Next steps: characterise wake effects
via measurement of *jet internal structure*

Duck

Jet

$|x|\delta\epsilon$

0.5
0.25
0
−0.25

−2

$x(fm)$

0

2

0

4

2 $z(fm)$

0

Qin, Majumder, Song, Heinz,
Phys. Rev. Lett. 103, 152303 (2009)

'soft' wake particles

'Hard' jet core

(Or fully-
thermalised jet?)
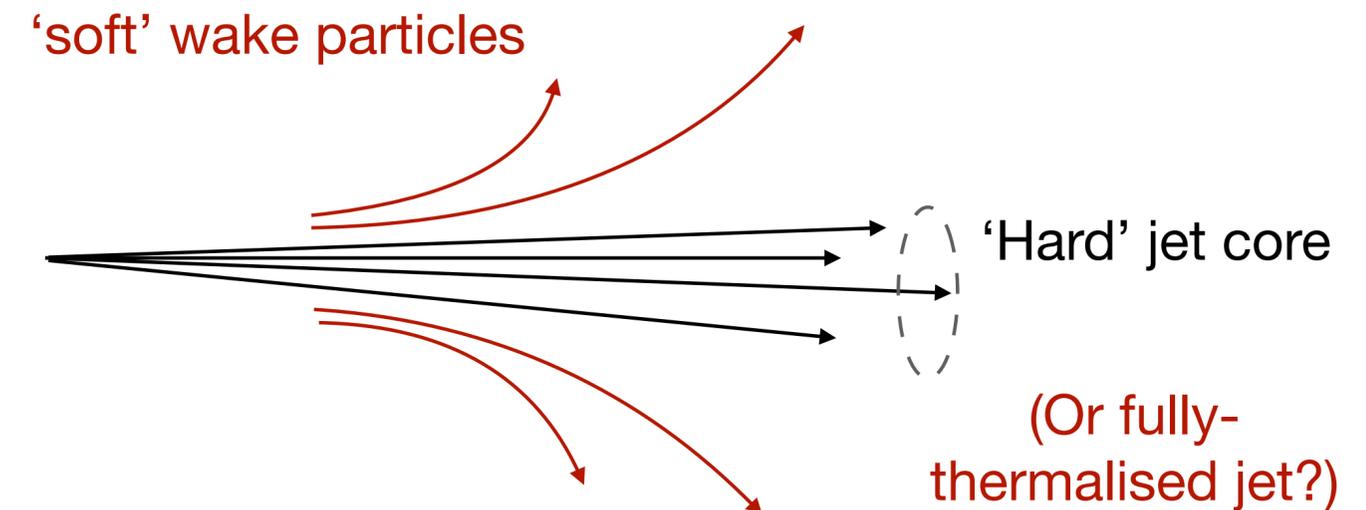
arxiv:2512.12715

Significant interest in its own right - shows how the quark-gluon
plasma responds to excitation - constrain viscocity, equation of state…
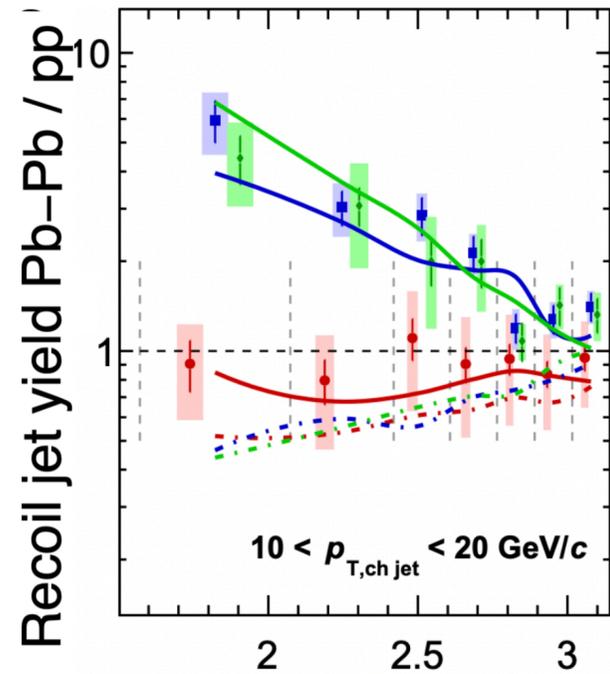
S. Cao and X.-N. Wang, Rept. Prog. Phys. 84 (2021) 024301
S. Cao and G.-Y. Qin, Ann. Rev. Nucl. Part. Sci. 73 (2023) 205

Constraining interplay between wake and jets

Recoil jet yield Pb–Pb / pp

$10 < p_{\text{T,ch jet}} < 20$ GeV/c

- Low-energy 'broadened' jets expected to have significant contribution from thermalised particles from the wake

- Studying internal structure of these jets will confirm thermal nature
  - → new window into studying the QGP and its transport properties

- Characterise thermal component
  - → more precise window into 'hard' scattering within the QGP

Constraining interplay between wake and jets
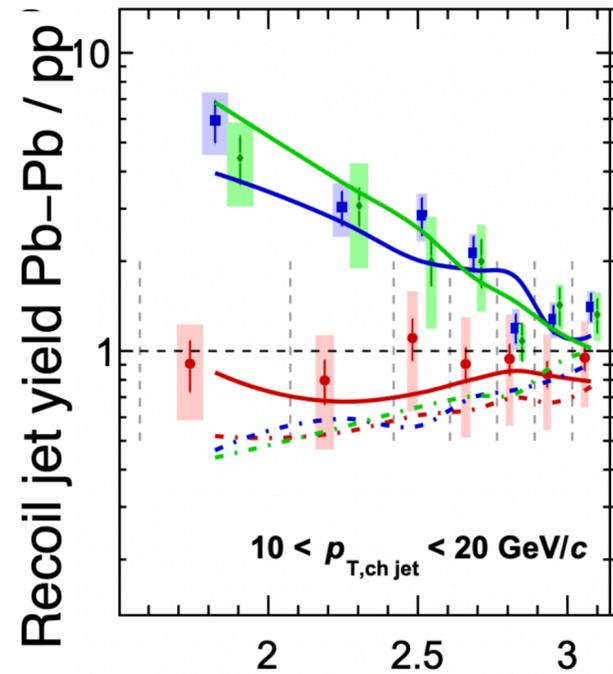
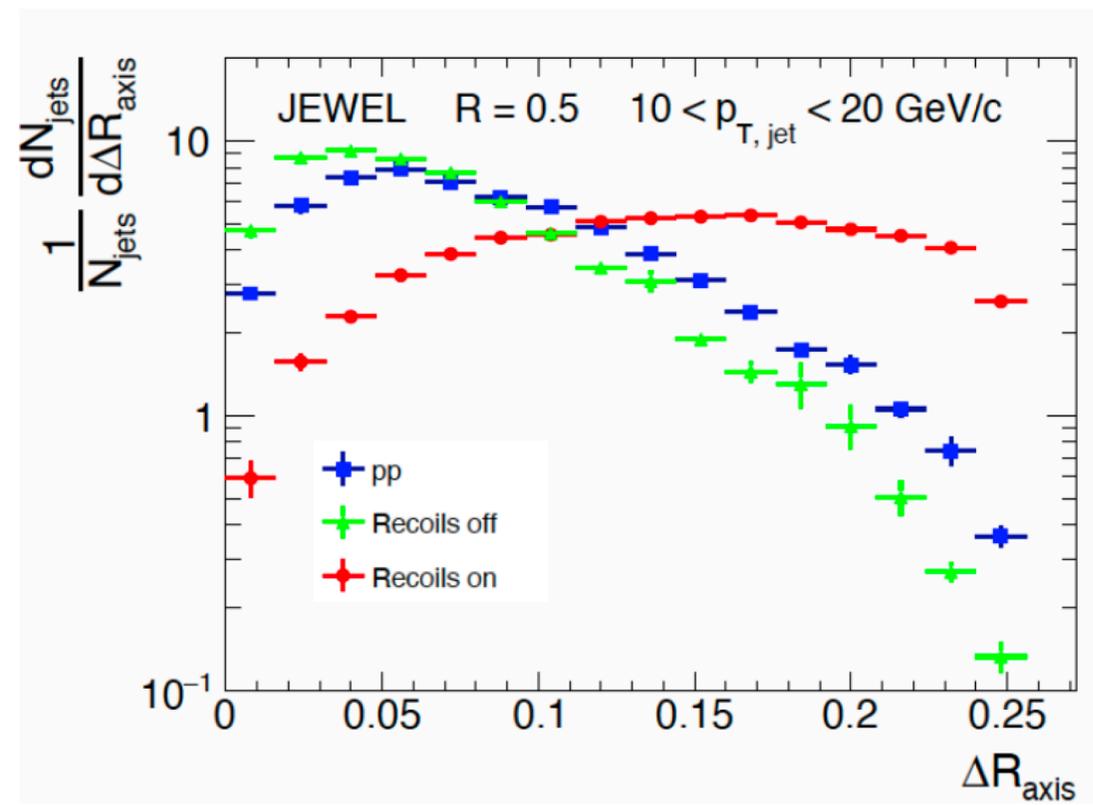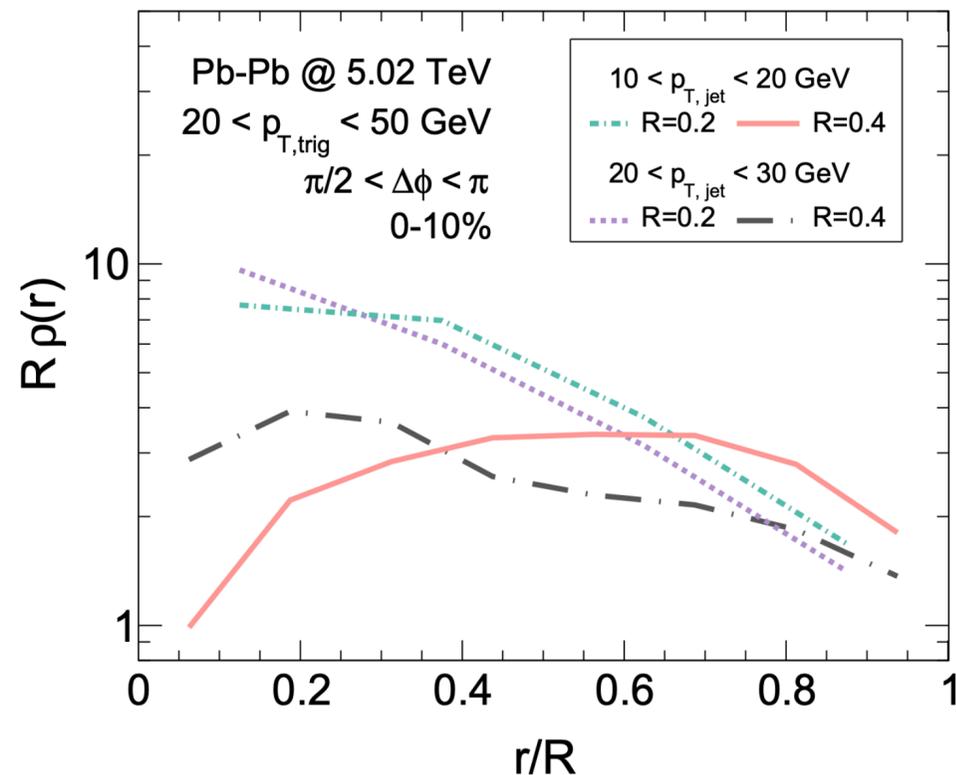$10 < p_{T,ch\ jet} < 20\ GeV/c$

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Jet transverse energy distribution

Pb-Pb @ 5.02 TeV
$20 < p_{T,trig} < 50\ GeV$
$\pi/2 < \Delta\phi < \pi$
0-10%

$10 < p_{T,jet} < 20\ GeV$	
R=0.2	R=0.4
$20 < p_{T,jet} < 30\ GeV$	
R=0.2	R=0.4

$R\ \rho(r)$

r/R

JEWEL   R = 0.5 $10 < p_{T,jet} < 20\ GeV/c$

$\frac{1}{N_{jets}}\frac{dN_{jets}}{d\Delta R_{axis}}$

- pp
- Recoils off
- Recoils on

ΔR_{axis}

Jet axes difference

STD
WTA
ΔR_{axis}
Collinear radiation

STD ~ 4-momentum sum of constituents
WTA ~ hardest constituent of hardest branch

P. Jing, W. Dang, Y. He, S. Cao, L. Yi, X.N. Wang: arxiv:2512.12715

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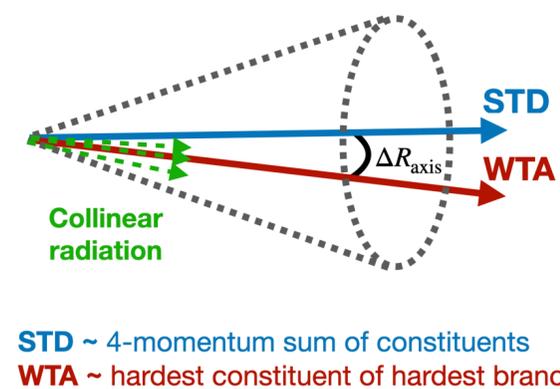# Constraining interplay between wake and jets

$10 < p_{T,ch\,jet} < 20$ GeV/c

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- Characterise thermal component
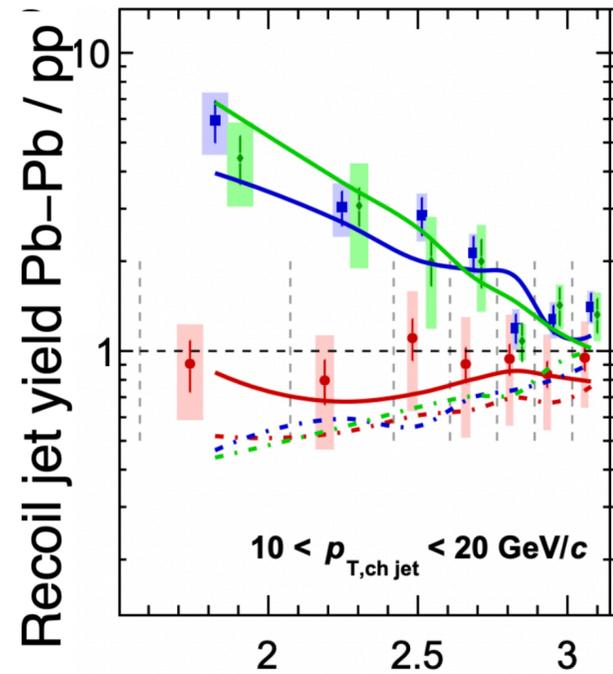 → more precise window into 'hard' scattering within the QGP

Hadron trigger

$\Delta\varphi$

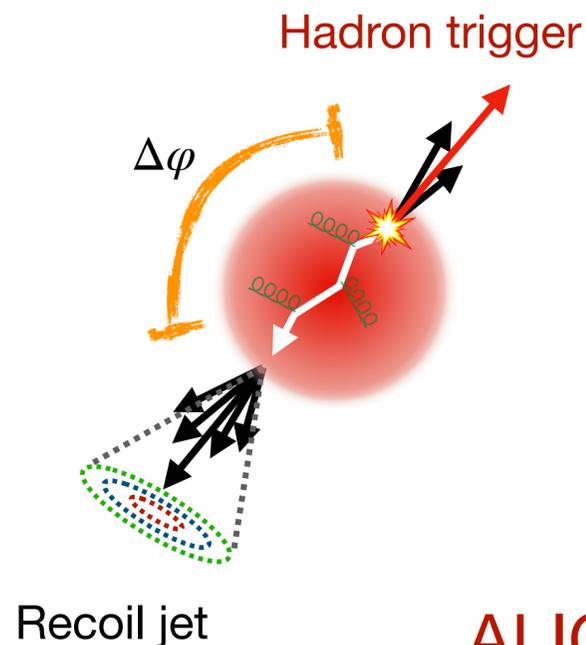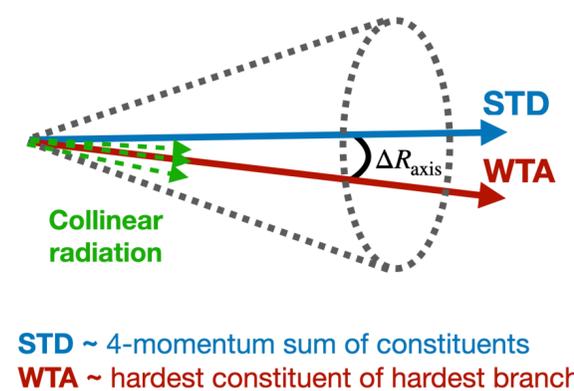Pb–Pb / pp

Recoil jet

$\Delta\varphi$ (rad)

ALICE Run 3
(uncorrected) data

$20 < p_{T,ch\,jet}^{reco} < 30$ GeV/c

ALICE Preliminary
Uncorrected
0–10% Pb–Pb, $\sqrt{s_{NN}} = 5.36$ TeV
Anti-k_T ch-particle jets, $|\eta_{jet}| < 0.5$
$|\Delta\varphi - \pi| < 0.6$, $R = 0.4$

— TT[20,50]
— TT[5,7]
— Δ_{recoil}

$\dfrac{1}{N_{trig}} \dfrac{d^3N}{dp_{T,ch\,jet}^{raw}\,d\Delta\varphi\,d\Delta R}$ (GeV/c)$^{-1}$

ΔR_{axis}

ALI-PREL-601288

Jet axes
difference

STD
WTA
ΔR_{axis}

Collinear
radiation

STD ~ 4-momentum sum of constituents
WTA ~ hardest constituent of hardest branch
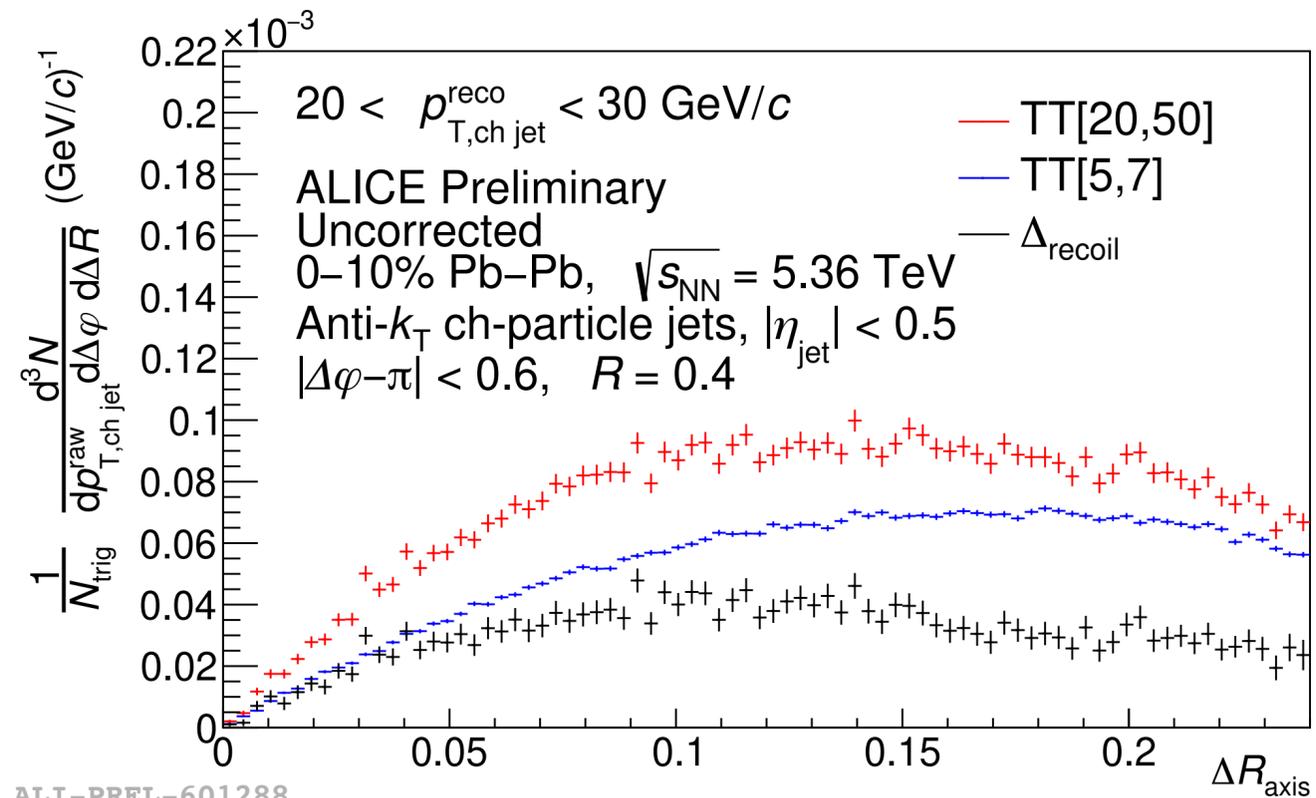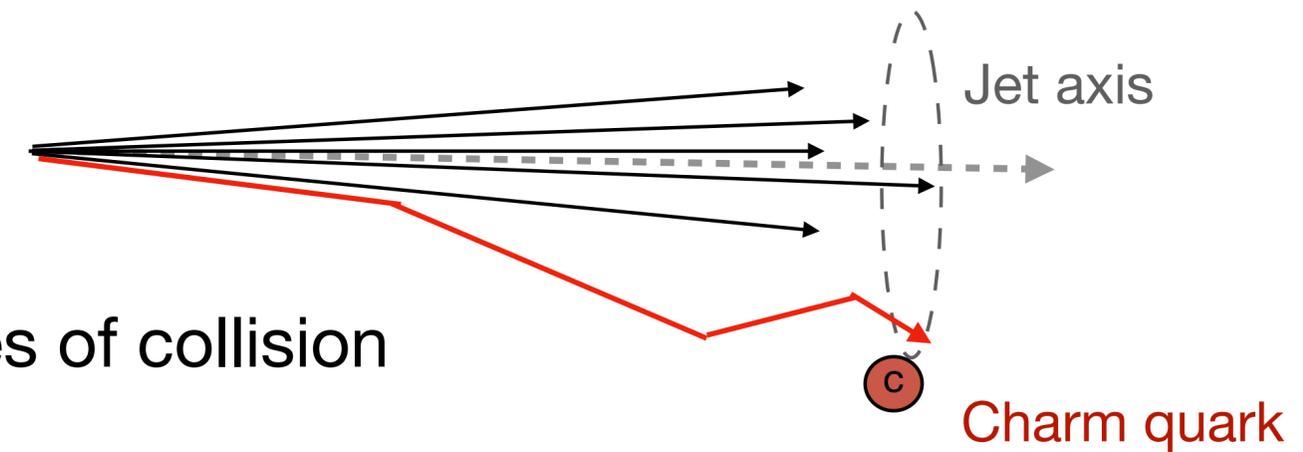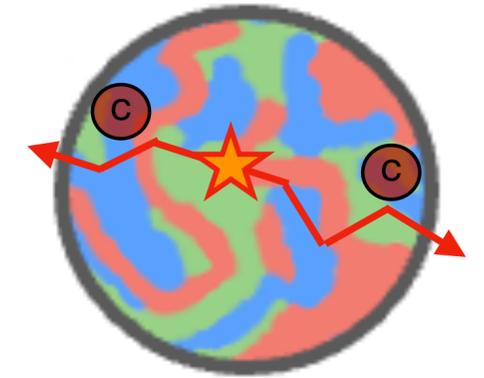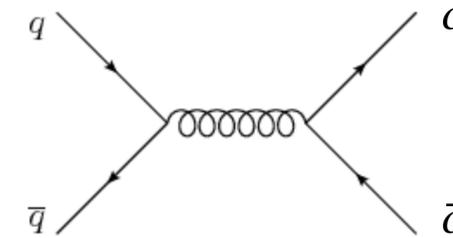
Measuring a precise scattering probe

Challenge: need precise handle on scattering probe
(time evolution, initial energy…)

Next steps: precision measurement of
charm-hadron correlations and
charm hadron-tagged jets

Jet axis

heavy quarks (charm + beauty) only produced in initial stages of collision
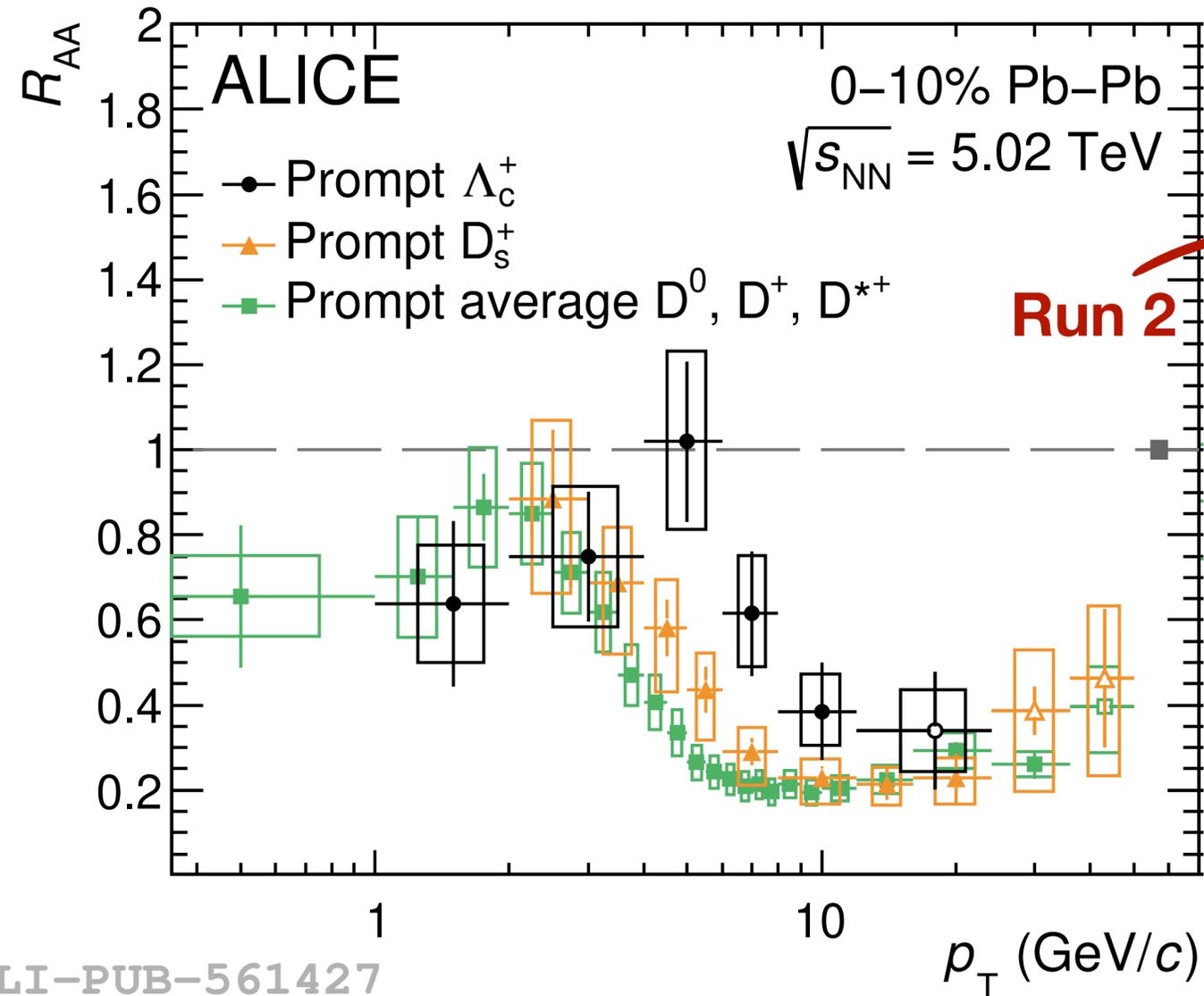→ tangible, traceable probe of scatters

Charm quark

F. Prino, R. Rapp, *J.Phys.G* **43 (2016) 9, 093002**
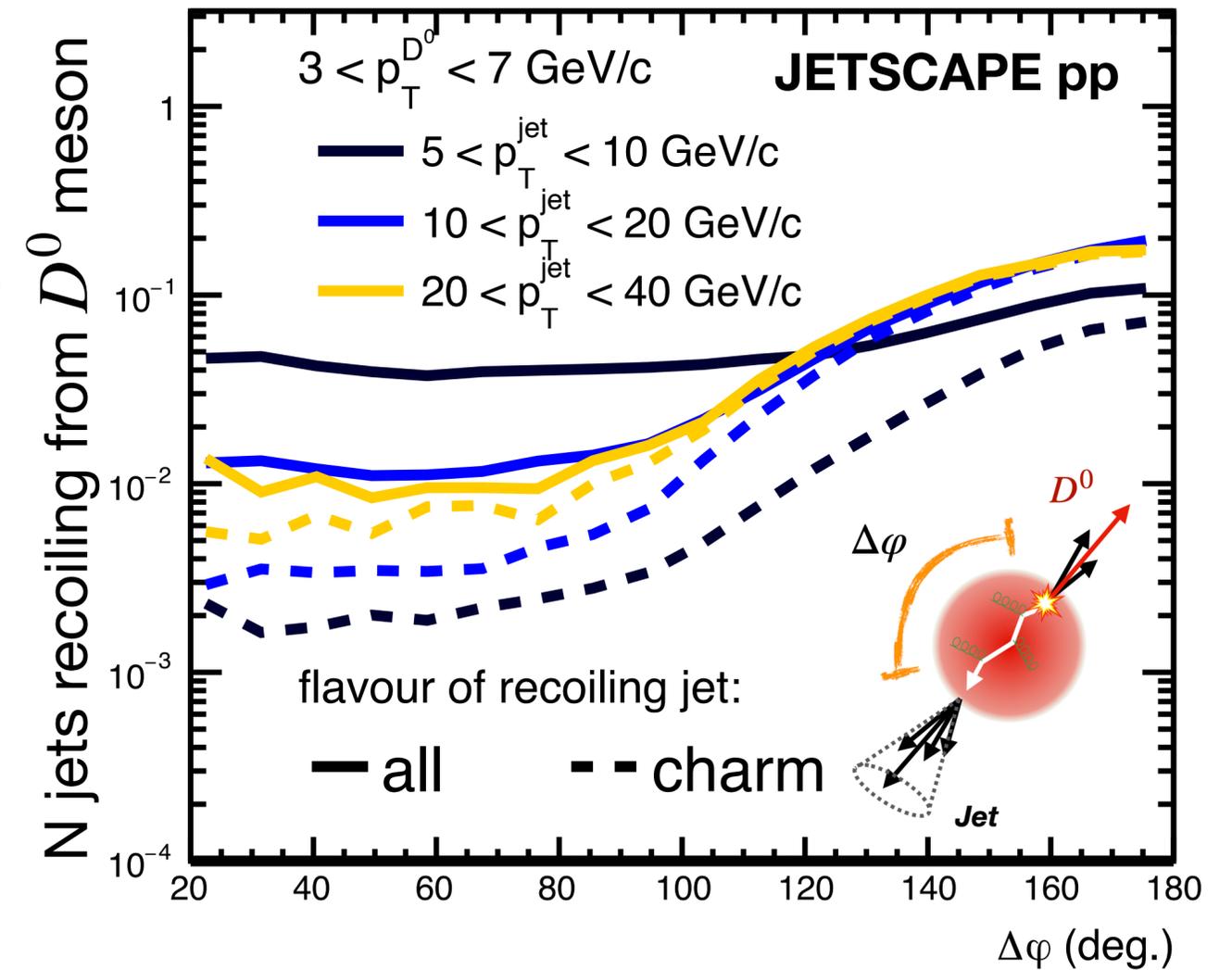L. Apolinario, Y.-J. Lee, and M. Winn, **Prog. Part. Nucl. Phys. 127 (2022) 103990**

Measuring a precise scattering probe

State of the art: inclusive charm hadron production

ALICE

Prompt Λ_c^+
Prompt D_s^+
Prompt average D^0, D^+, D^{*+}

0–10% Pb–Pb
$\sqrt{s_{NN}} = 5.02$ TeV

R_{AA}

p_T (GeV/c)

Run 2   **Run 3/4**

ALI–PUB–561427

$$R_{AA}(p_T) = \frac{1}{<N_{coll}>} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

$3 < p_T^{D^0} < 7$ GeV/c **JETSCAPE pp**

$5 < p_T^{jet} < 10$ GeV/c
$10 < p_T^{jet} < 20$ GeV/c
$20 < p_T^{jet} < 40$ GeV/c

N jets recoiling from D^0 meson

$\Delta\varphi$

D^0

flavour of recoiling jet:

━━ all   ╌╌ charm

Jet

$\Delta\varphi$ (deg.)

Exploration of *new, multi-differential methods* to measure
charm correlations, and to 'tag' charm jets ongoing

M. Nahrgrang et al, Phys. Rev. C 90, 024907 (2014)
K. Rajagopal et al, JHEP 07 (2025) 013
JETSCAPE

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Connecting data with theory

The JETSCAPE collaboration

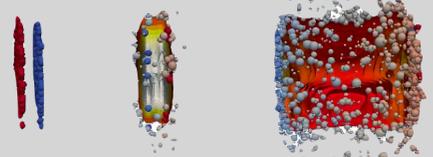*The* tool for comprehensive validation of cutting-edge models with multi-messenger data

→ does a model capture the essential physics?

Heavy-ion event generator	**Statistical toolkit**
Framework for modelling all aspects of heavy-ion collisions	Bayesian inference for data-theory comparison

$$P(\theta \,|\, \text{data}) = \frac{P(\text{data}\,|\,\theta)P(\theta)}{P(\text{data})}$$

Modular - substitute in different models

Interdisciplinary
 (experimentalists, theorists, statisticians)

Computing intensive calculations
- Requires HPC + AI/ML

Connecting data with theory

The JETSCAPE collaboration

The tool for comprehensive validation of cutting-edge models with multi-messenger data

→ does a model capture the essential physics?

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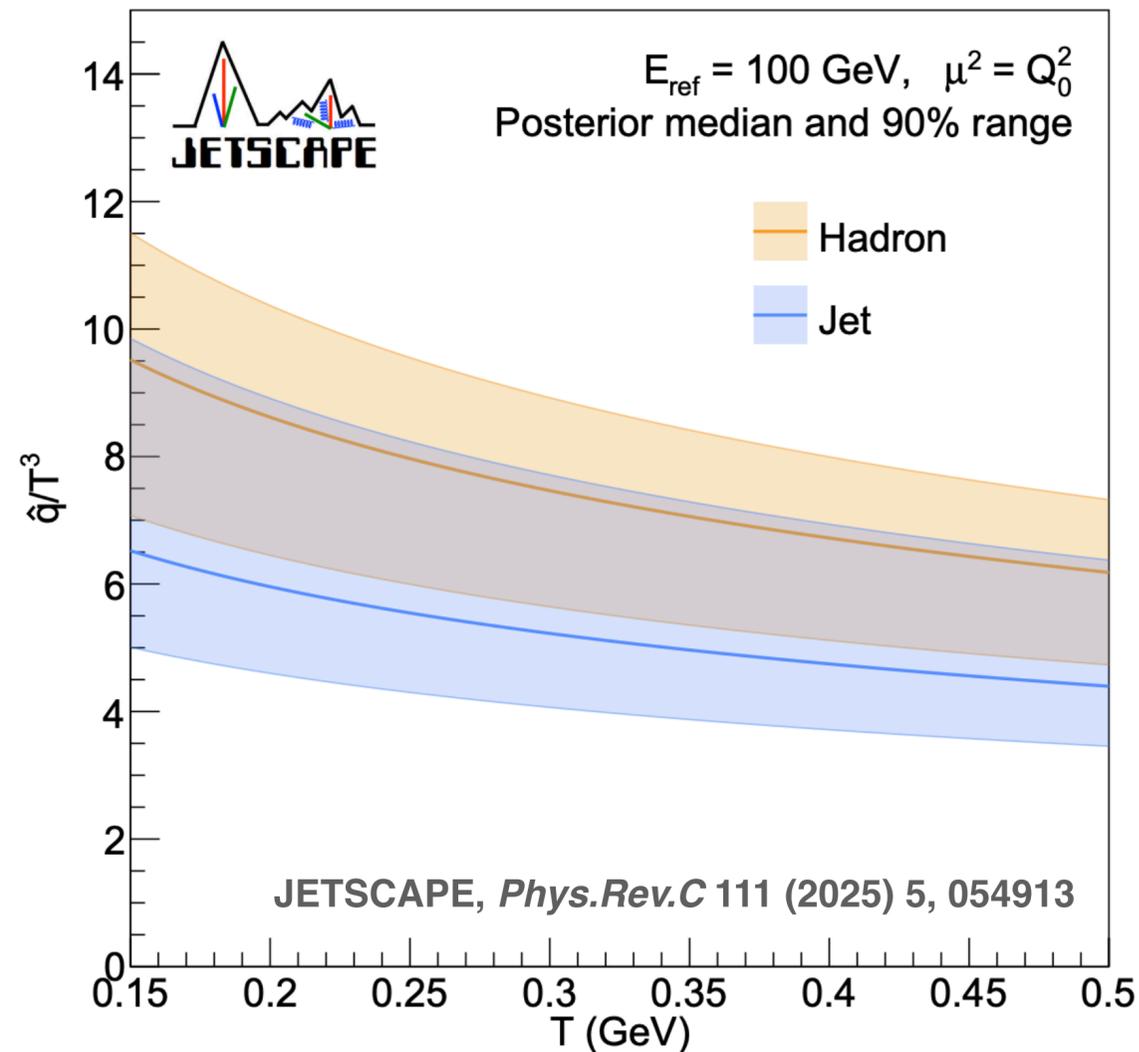Modular - substitute in different models

Interdisciplinary
(experimentalists, theorists, statisticians)

Computing intensive calculations
- Requires HPC + AI/ML

State-of-the-art:
Parameter constraints with hadron and jet spectra measurements

E_{ref} = 100 GeV, $\mu^2 = Q_0^2$
Posterior median and 90% range

Hadron
Jet

JETSCAPE, *Phys.Rev.C* 111 (2025) 5, 054913

jet transport coefficient

$$\hat{q} \sim \frac{< k_T >}{L}$$

Steps towards precise, quantitative characterisation of the QGP… but models incomplete

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Connecting data with theory

Next steps:
Next generation of Bayesian inference model constraints

- Roy Lemmon and myself joined JETSCAPE in 2023 to explore running next generation of calculations on UK facilities
- This year → obtained 11.8M CPU hours on CSD3 via IRIS

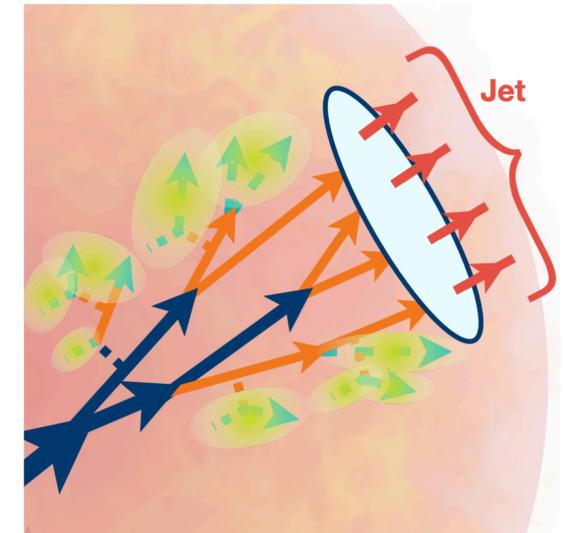→ next-gen calculations are primarily being run *here*

Calibration

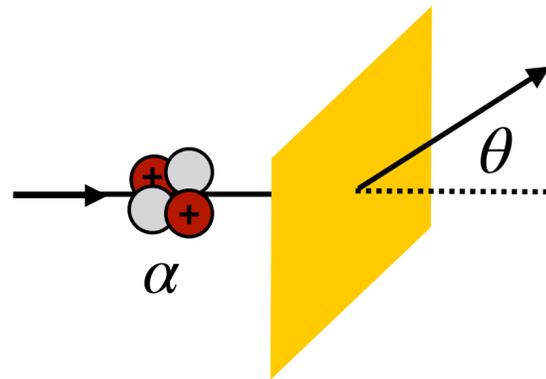Bayesian inference to constrain 'bulk' QGP properties using 3D viscous hydrodynamics

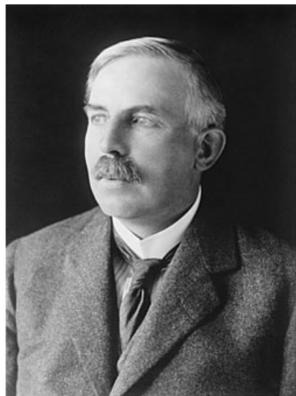Chun Shen - iEBE-MUSIC
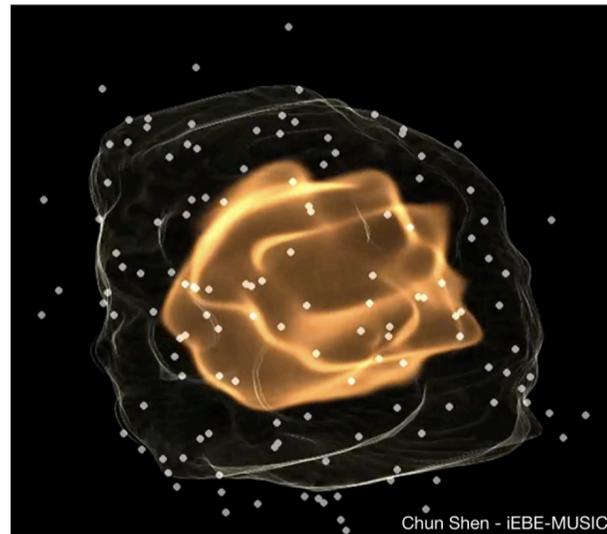
Model discrimination

Bayesian inference to understand how these properties (+ *different models of QGP structure*) affect jet propagation
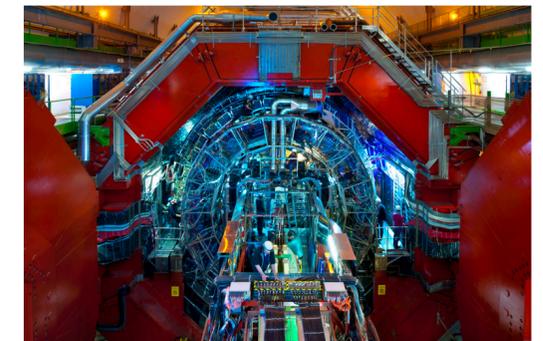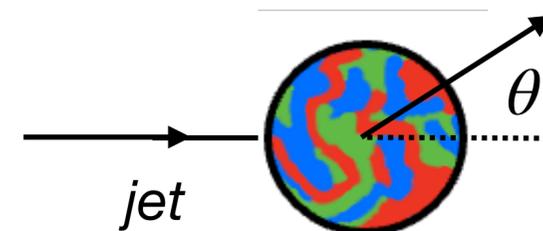

Jet

understand jet-QGP interactions → Constrain microscopic QGP structure

Summary

- With heavy-ion collisions, we study the deconfined state of QCD matter called the quark-gluon plasma - the hottest material that can be studied in a lab

- Experimental upgrades of ALICE plus theoretical developments means a *precision* understanding of its properties is on the horizon

- By measuring the *shockwaves* and *scatters* inside the quark-gluon plasma, we have a unique opportunity to uncover the microscopic dynamics of this state of matter in the near future
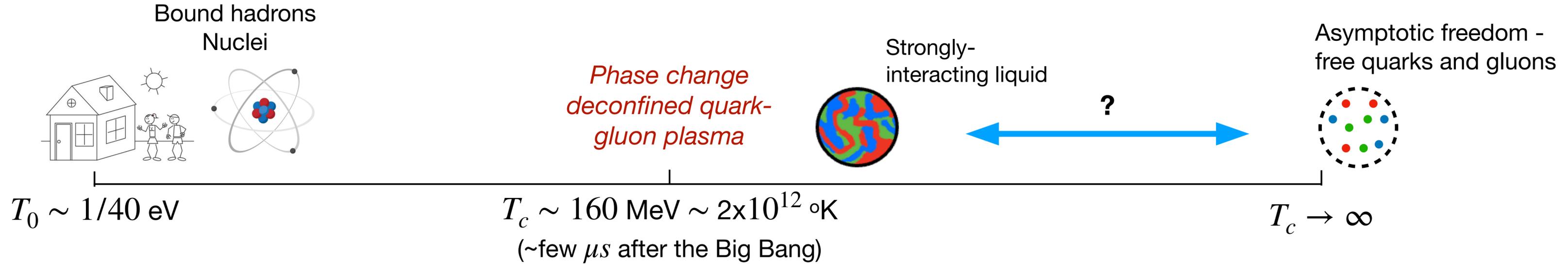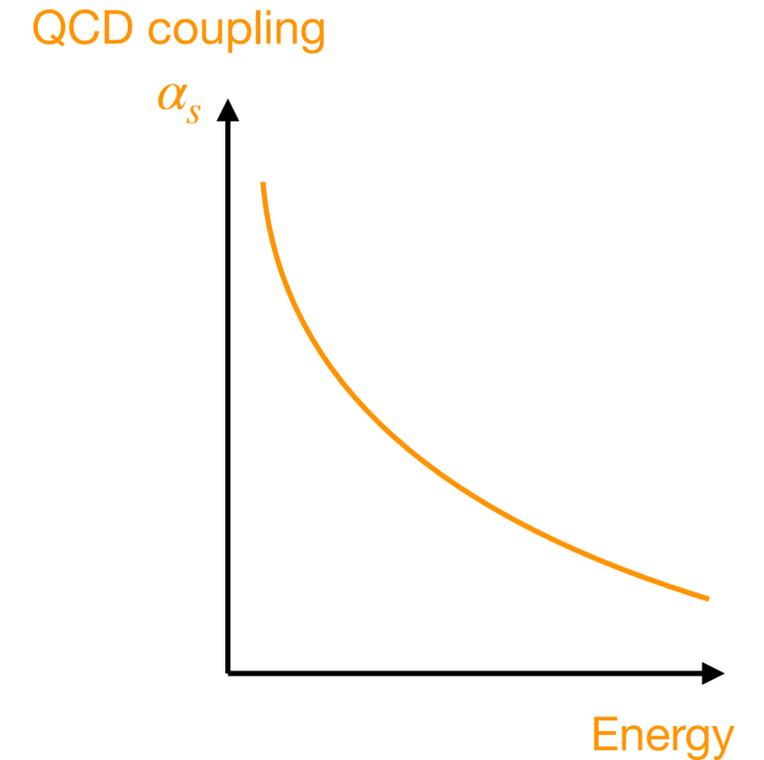

Rutherford, 1911
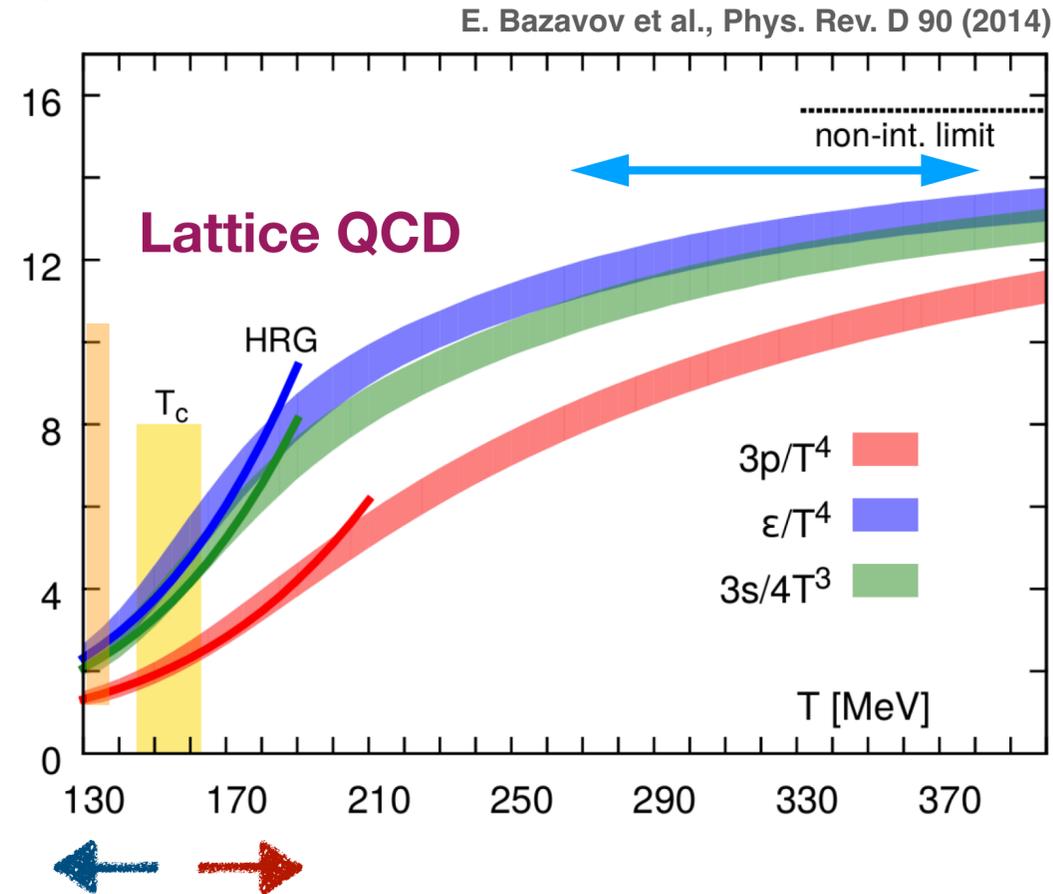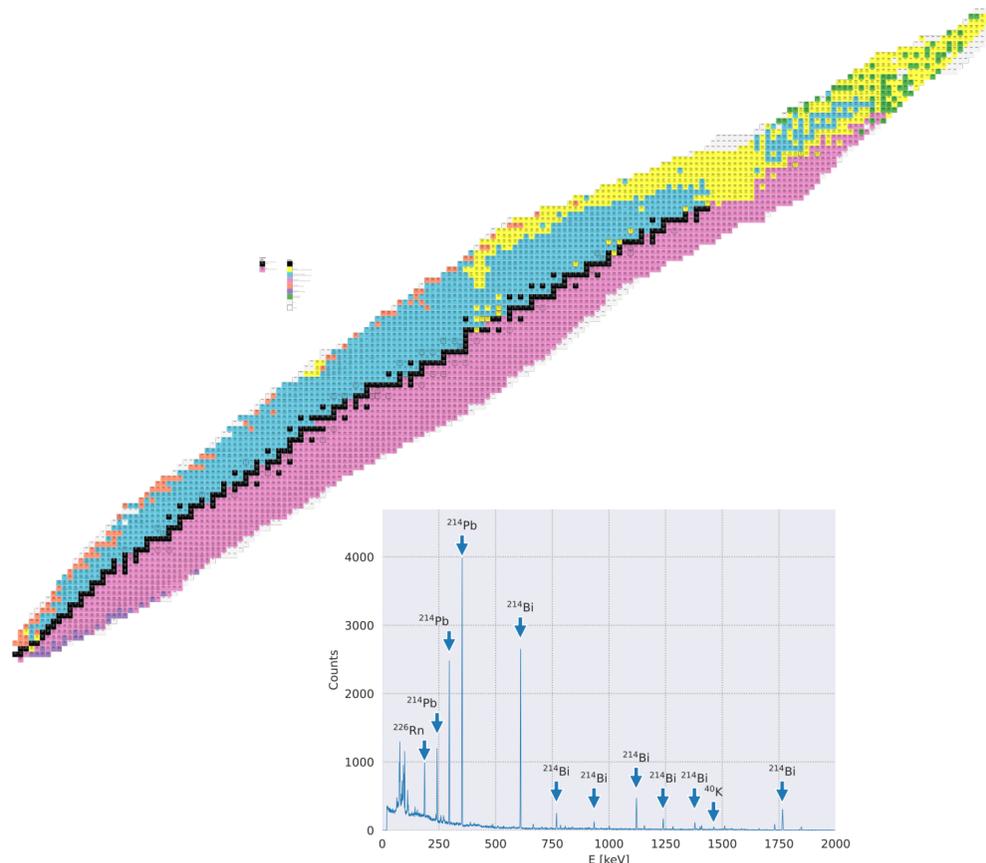

ALICE, 2020's (?)

Backup

Many-body QCD and the quark-gluon plasma (QGP)

Bound hadrons
Nuclei

Strongly-
interacting liquid

Asymptotic freedom -
free quarks and gluons

*Phase change
deconfined quark-
gluon plasma*

?

$T_0 \sim 1/40$ eV

$T_c \sim 160$ MeV $\sim 2 \times 10^{12}$ °K

(~few μs after the Big Bang)

$T_c \to \infty$

Temperature

E. Bazavov et al., Phys. Rev. D 90 (2014)

non-int. limit

Lattice QCD

HRG

T_c

$3p/T^4$

ε/T^4

$3s/4T^3$

T [MeV]

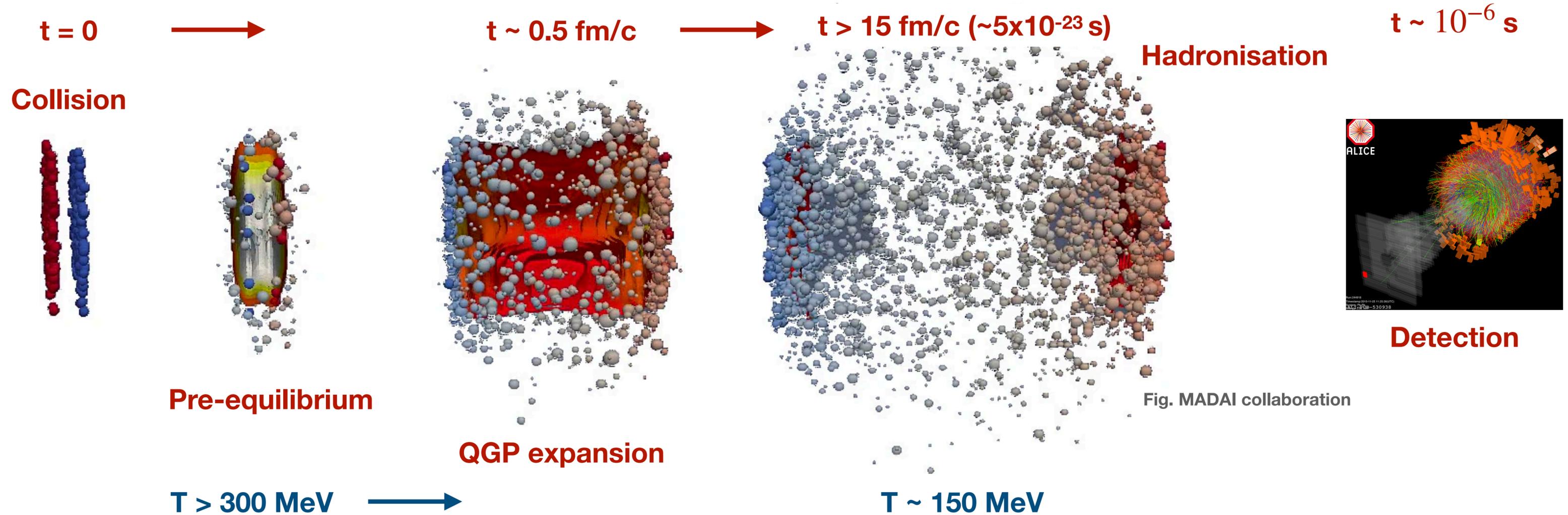QCD coupling
α_s

Energy

Confinement   **Deconfinement**

How do fundamental degrees of freedom
determine a material's emergent properties?

25

Probing many-body QCD in heavy-ion collisions

t = 0

Collision

t ~ 0.5 fm/c

t > 15 fm/c (~5x10^{-23} s)

Hadronisation

t ~ 10^{-6} s

Pre-equilibrium

QGP expansion

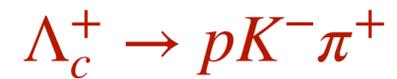Fig. MADAI collaboration

Detection

T > 300 MeV

T ~ 150 MeV

We create a QGP then measure its remnants
- How can it be investigated and its physical properties determined?

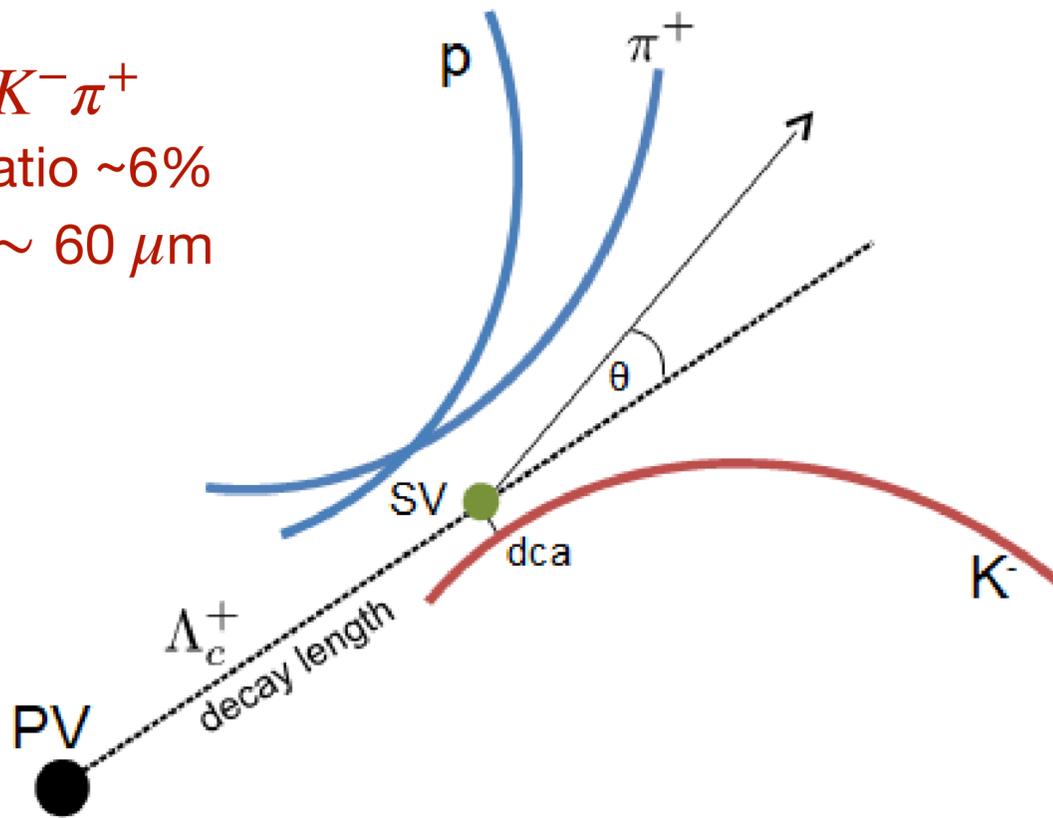# WP2: measuring a precise scattering probe

How do we reconstruct charm hadrons?

$\Lambda_c^+ \to pK^-\pi^+$

Branching ratio ~6%

Lifetime $c\tau \sim 60~\mu$m

C. Bartels thesis

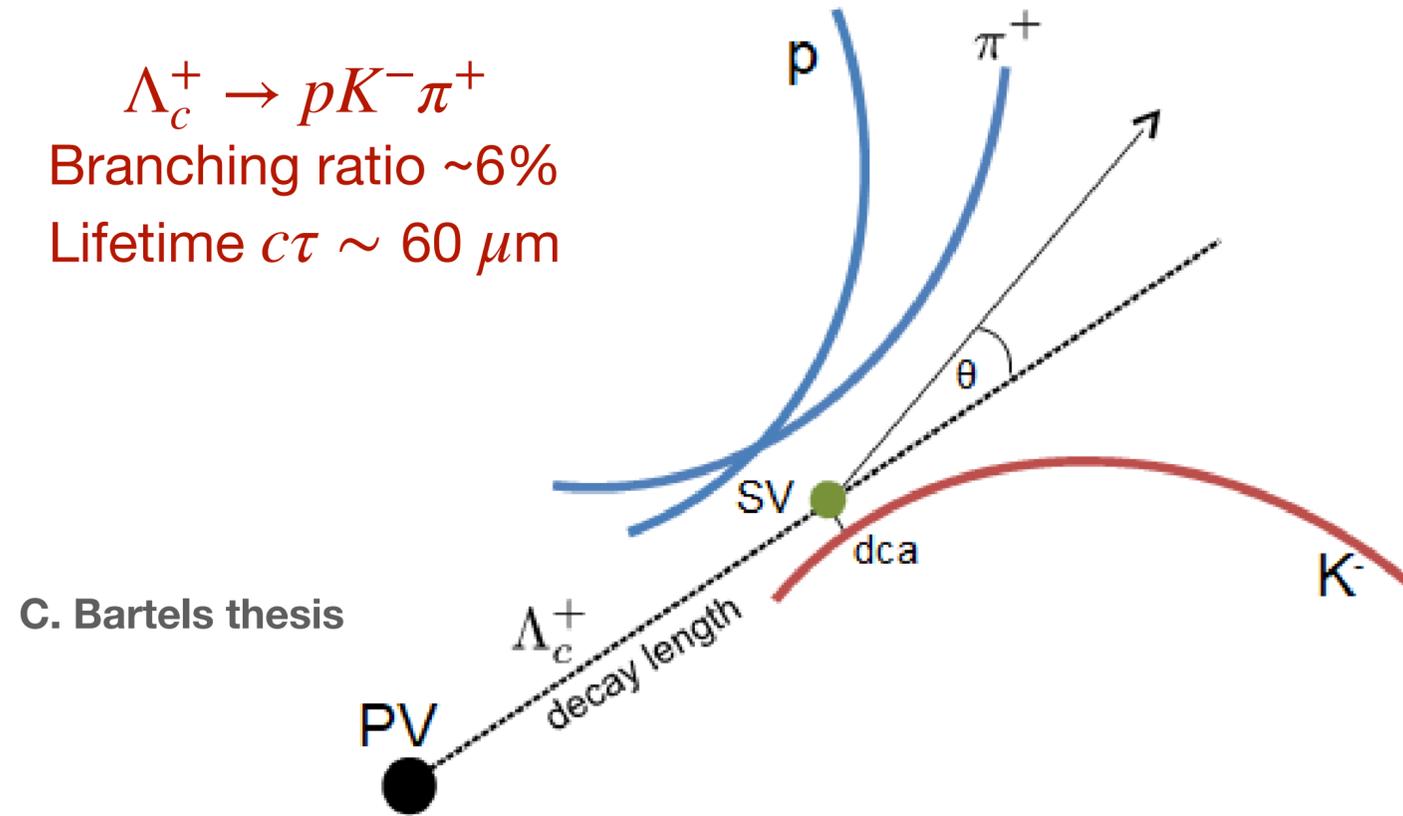→ Reconstruct charged particle tracks

→ Particle Identification

→ Charm hadron candidate reconstruction and selection

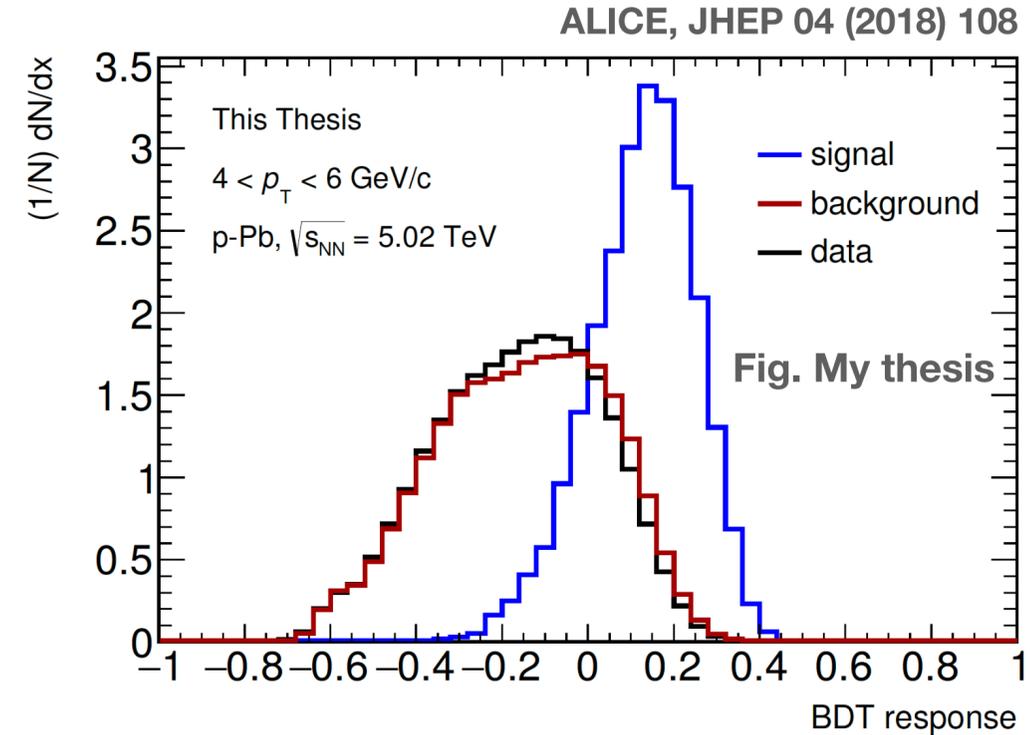# WP2: measuring a precise scattering probe

How do we reconstruct charm hadrons?

$\Lambda_c^+ \to p K^- \pi^+$
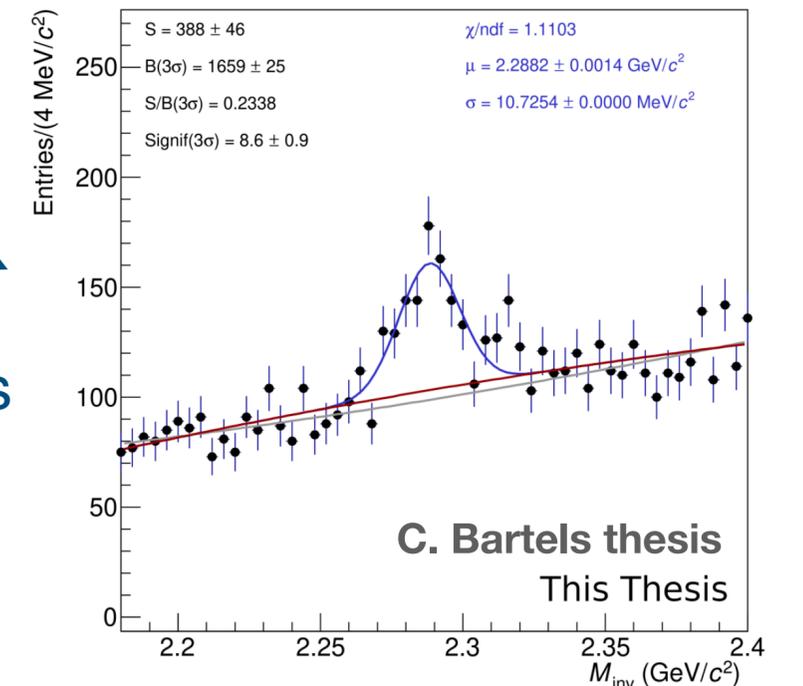Branching ratio ~6%
Lifetime $c\tau \sim 60 \ \mu$m

C. Bartels thesis

First ALICE paper to use Machine
Learning for classification task

ALICE, JHEP 04 (2018) 108

This Thesis
$4 < p_T < 6$ GeV/c
p-Pb, $\sqrt{s_{NN}} = 5.02$ TeV

— signal
— background
— data

Fig. My thesis

BDT response

→ Reconstruct charged particle tracks

→ Particle Identification

→ Charm hadron candidate reconstruction and selection

Signal extraction via
invariant mass analysis

S = 388 ± 46
B(3σ) = 1659 ± 25
S/B(3σ) = 0.2338
Signif(3σ) = 8.6 ± 0.9

χ/ndf = 1.1103
μ = 2.2882 ± 0.0014 GeV/c^2
σ = 10.7254 ± 0.0000 MeV/c^2

C. Bartels thesis
This Thesis

M_{inv} (GeV/c^2)

WP2: measuring a precise scattering probe

How do we reconstruct charm hadrons?

$\Lambda_c^+ \to pK^-\pi^+$
Branching ratio ~6%
Lifetime $c\tau \sim 60\ \mu$m

C. Bartels thesis
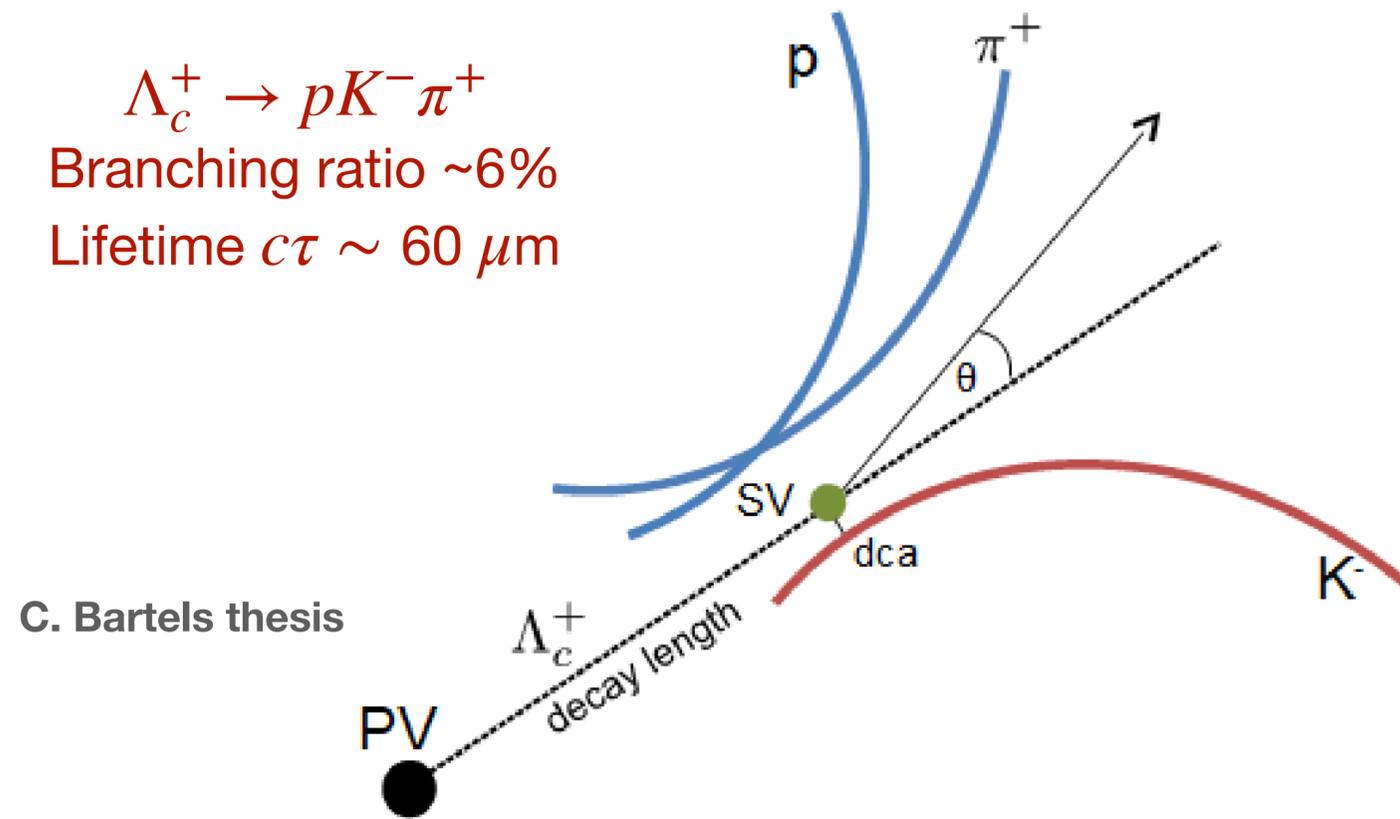
Charm baryon measurements
probe how hadrons form
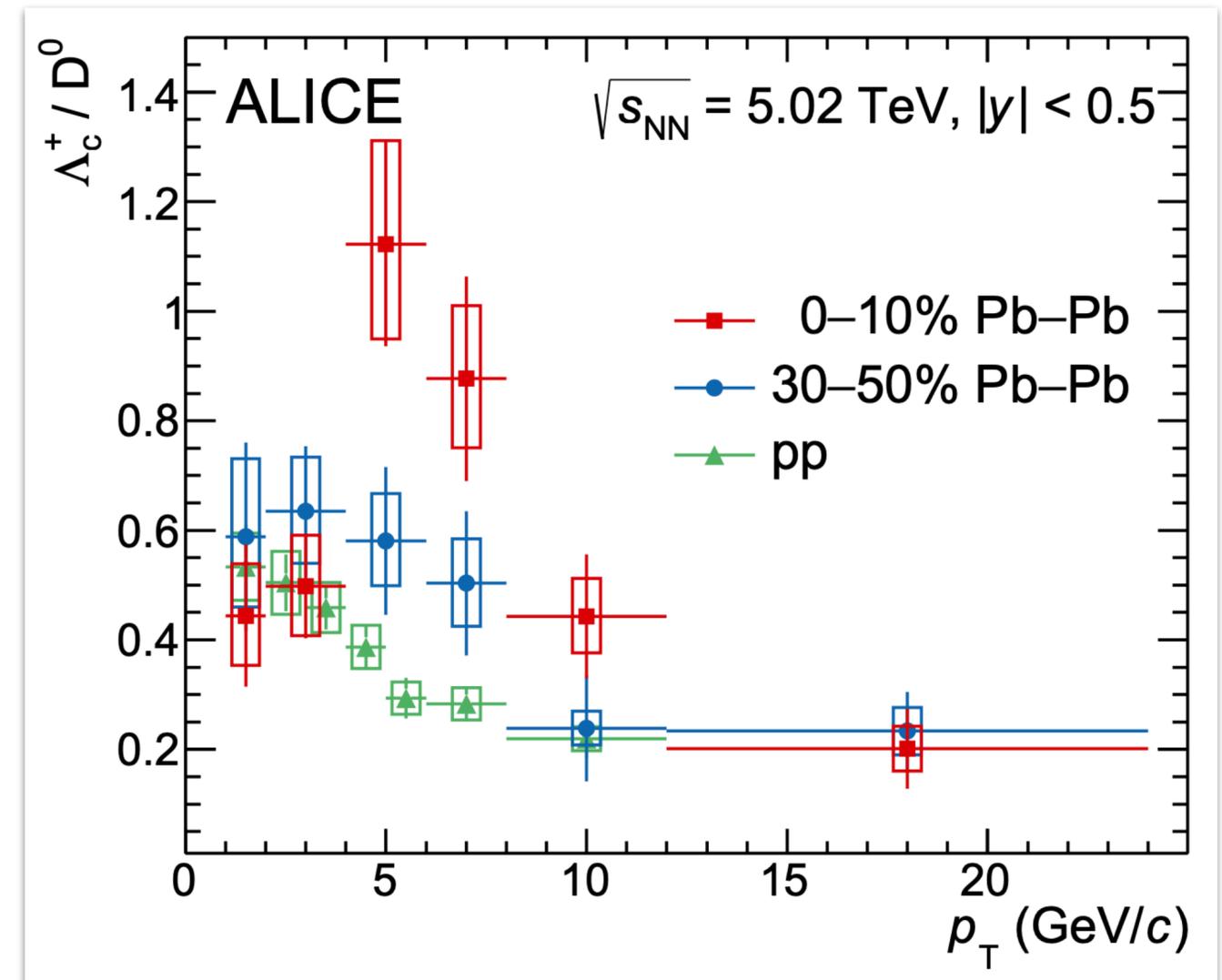
→ Reconstruct charged particle tracks

→ Particle Identification

→ Charm hadron candidate reconstruction and selection

29

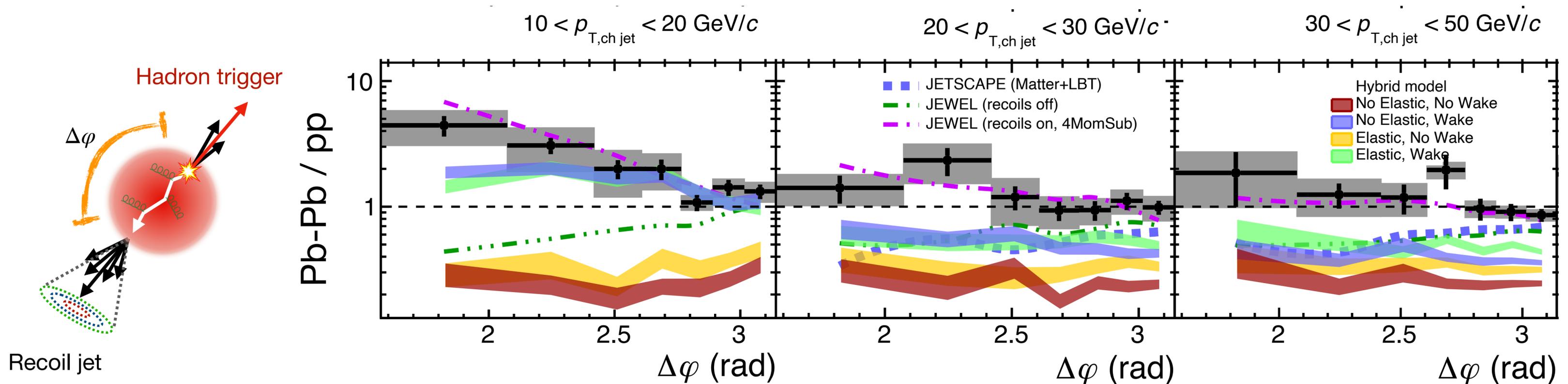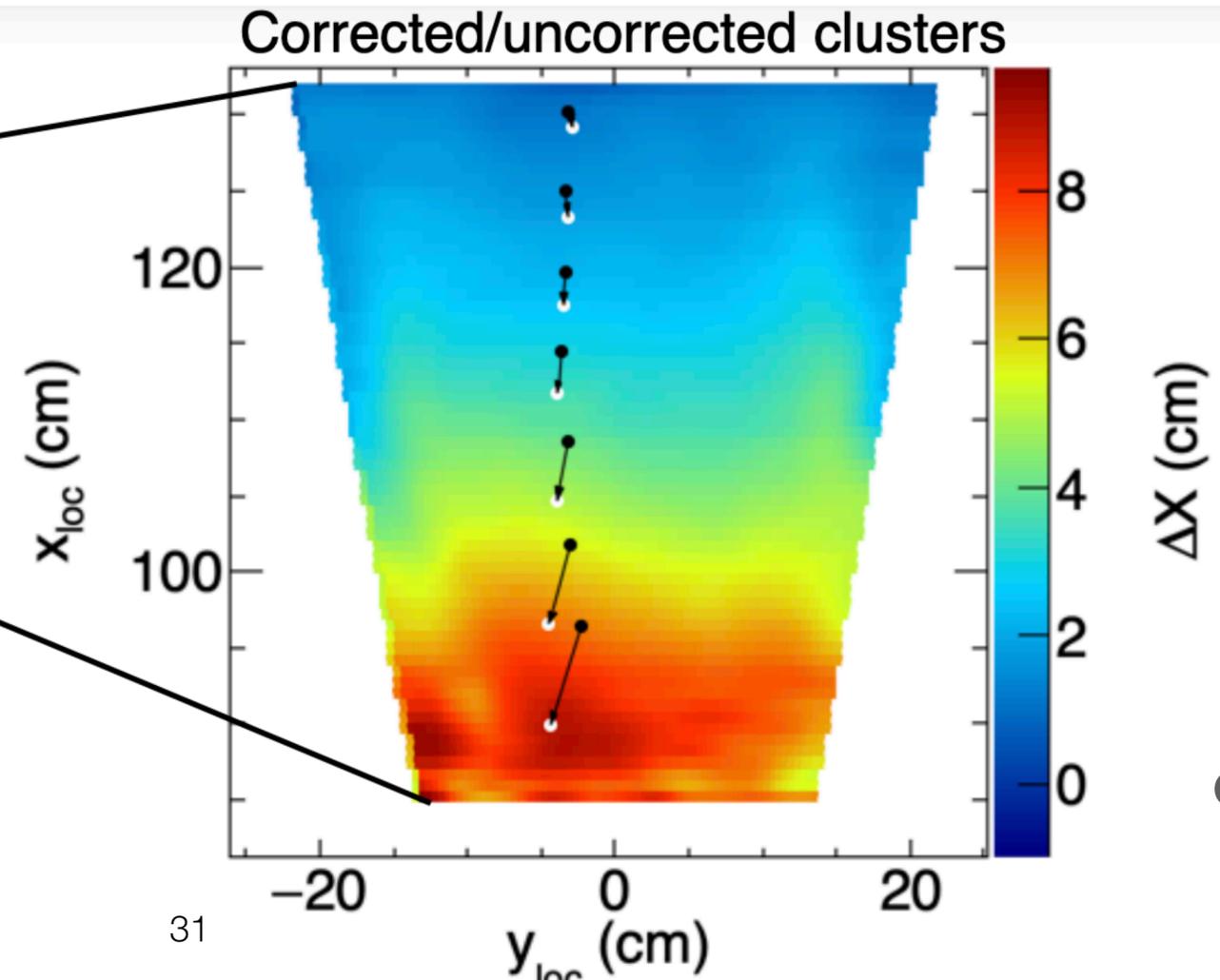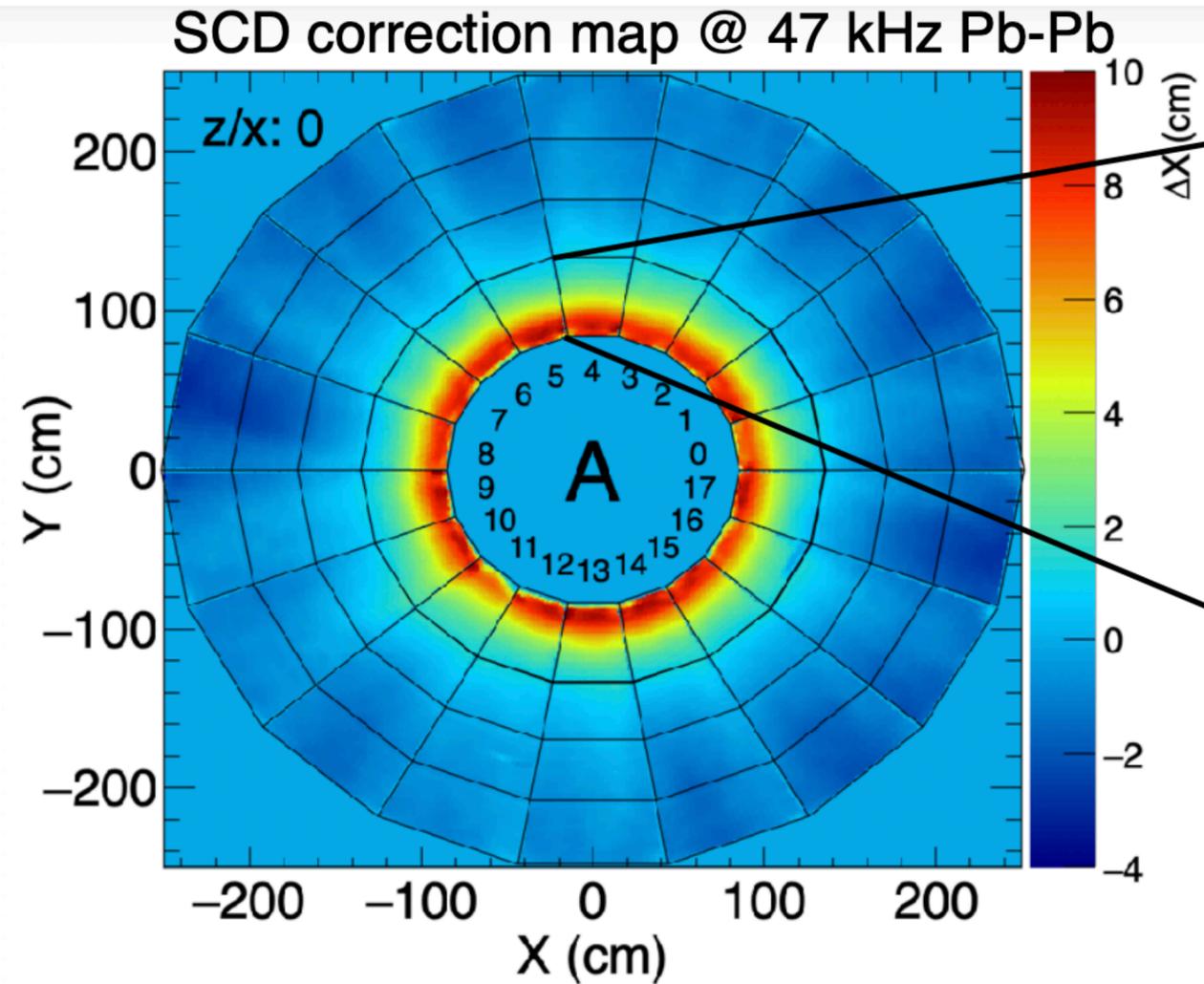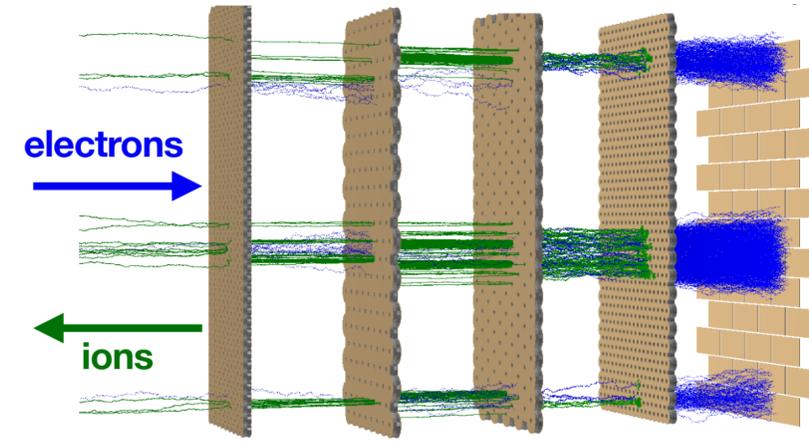# WP3: connecting data with theory

- **Multi-messenger physics** - many measurements sensitive to same underlying physics

- Eventual aim - Model discrimination via Bayesian inference taking into account complete set of data
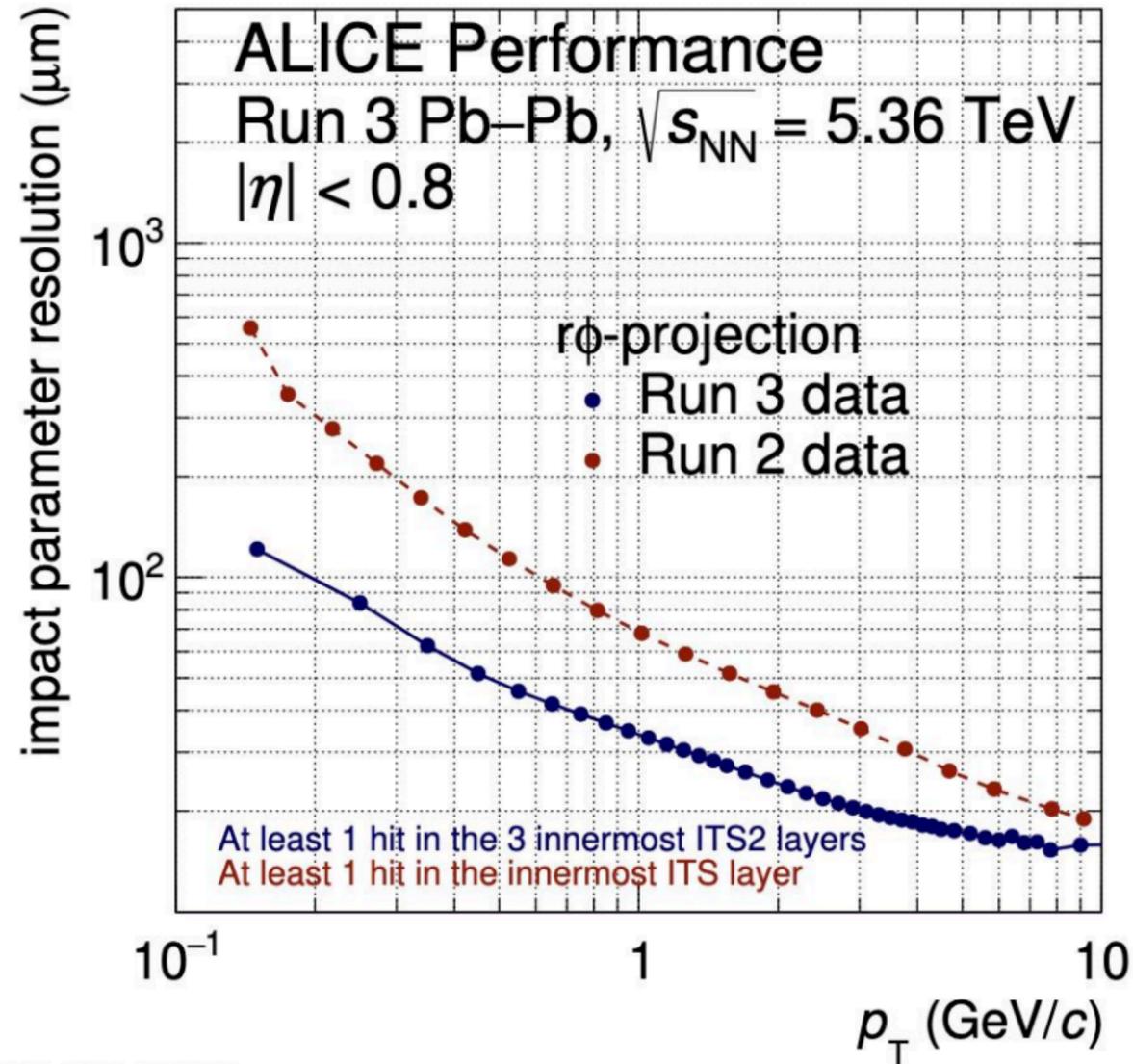
Key challenge - TPC space charge distortions

- Drifting ions cause significant local charge which distorts driving electron path in ALICE Time Projection Chamber

- Correction maps correct distortions from up to 10cm to <1mm
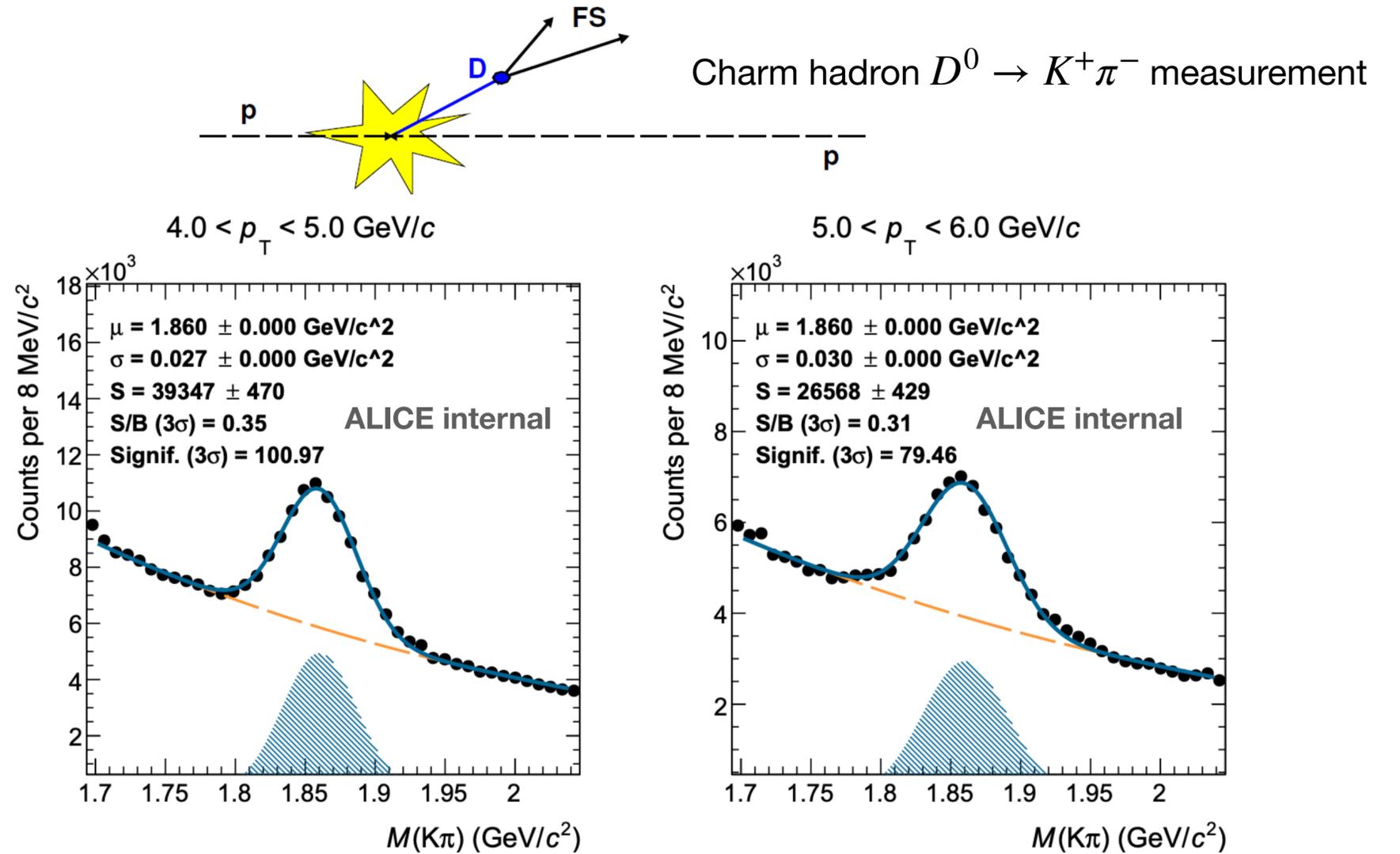
- Now close to Run 2 performance

SCD correction map @ 47 kHz Pb-Pb

Corrected/uncorrected clusters

**Alex Schmah,
Quark Matter 2025**

31

Run 3 performance

Charm hadron $D^0 \to K^+\pi^-$ measurement

$4.0 < p_T < 5.0$ GeV/c

$\mu = 1.860 \pm 0.000$ GeV/c^2
$\sigma = 0.027 \pm 0.000$ GeV/c^2
S = 39347 $\pm$ 470
S/B (3σ) = 0.35
Signif. (3σ) = 100.97

ALICE internal

$5.0 < p_T < 6.0$ GeV/c

$\mu = 1.860 \pm 0.000$ GeV/c^2
$\sigma = 0.030 \pm 0.000$ GeV/c^2
S = 26568 $\pm$ 429
S/B (3σ) = 0.31
Signif. (3σ) = 79.46

ALICE internal

ALICE Performance
Run 3 Pb–Pb, $\sqrt{s_{NN}} = 5.36$ TeV
$|\eta| < 0.8$

rϕ-projection
• Run 3 data
• Run 2 data

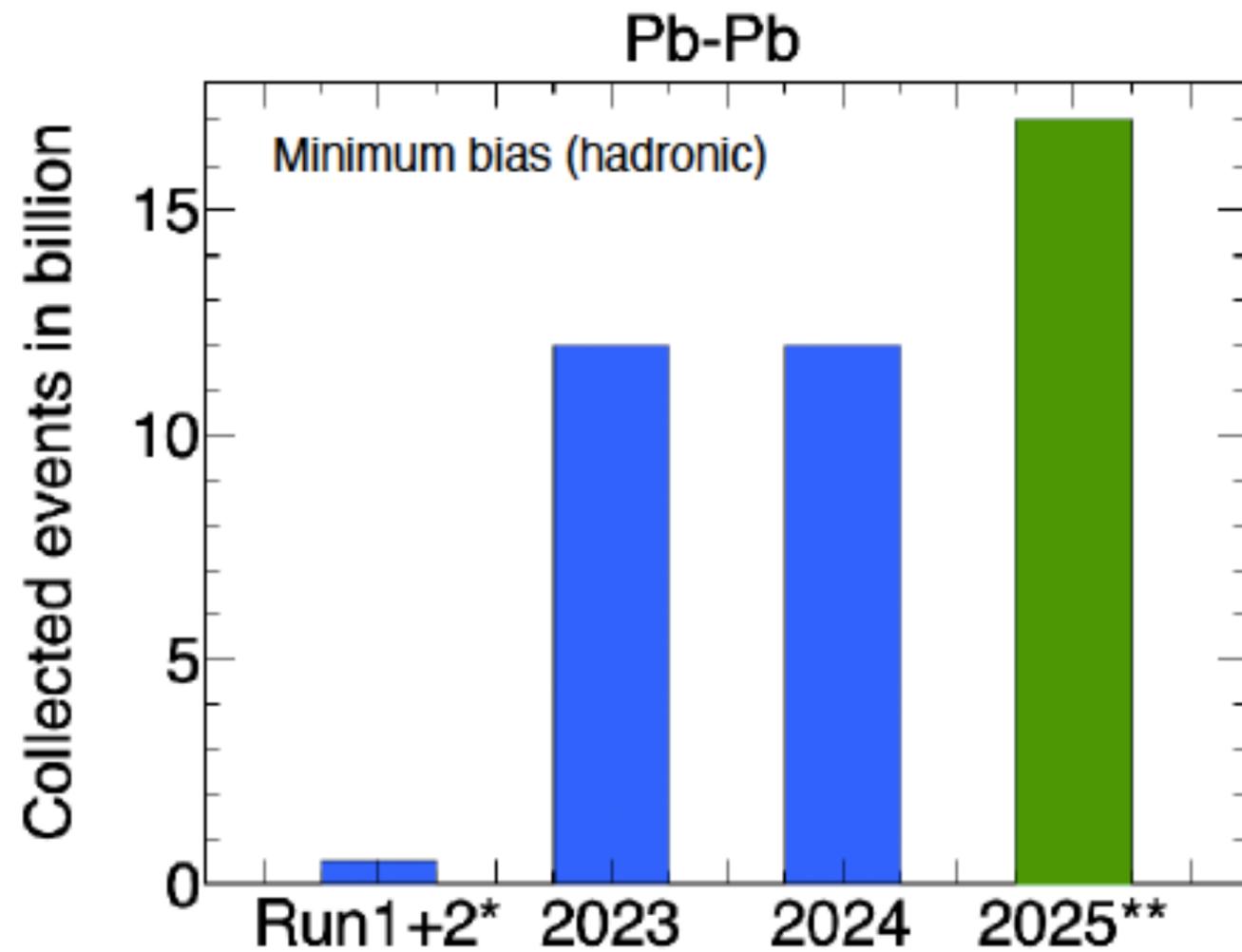At least 1 hit in the 3 innermost ITS2 layers
At least 1 hit in the innermost ITS layer

ALI–PERF–564335

- Factor ~2 improvement in track spatial (impact parameter) resolution in Run 3 w.r.t. Run 2
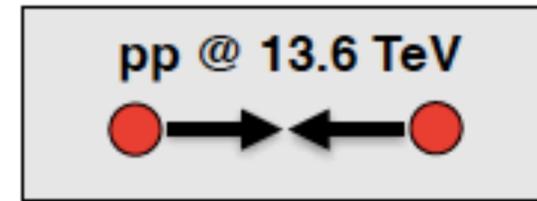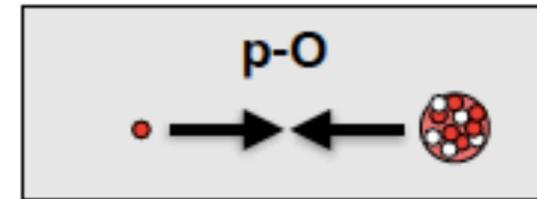
Run 3 data

Pb-Pb

Minimum bias (hadronic)

Collected events in billion

Run1+2* 2023 2024 2025**

*for central barrel only (MB)
**expected in 2025

pp:
•2 billion (Run1+2)
•5700 billion (2022-2024)

Goals for 2025-2026

pp @ 13.6 TeV

•47 pb^{-1} expected
•3 pb^{-1} low field

Pb-Pb @ 5.36 TeV

•2.6 nb^{-1} expected

p-O

•~2.5 nb^{-1} expected

O-O
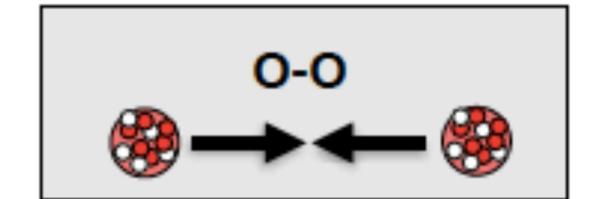
•1 day + maybe
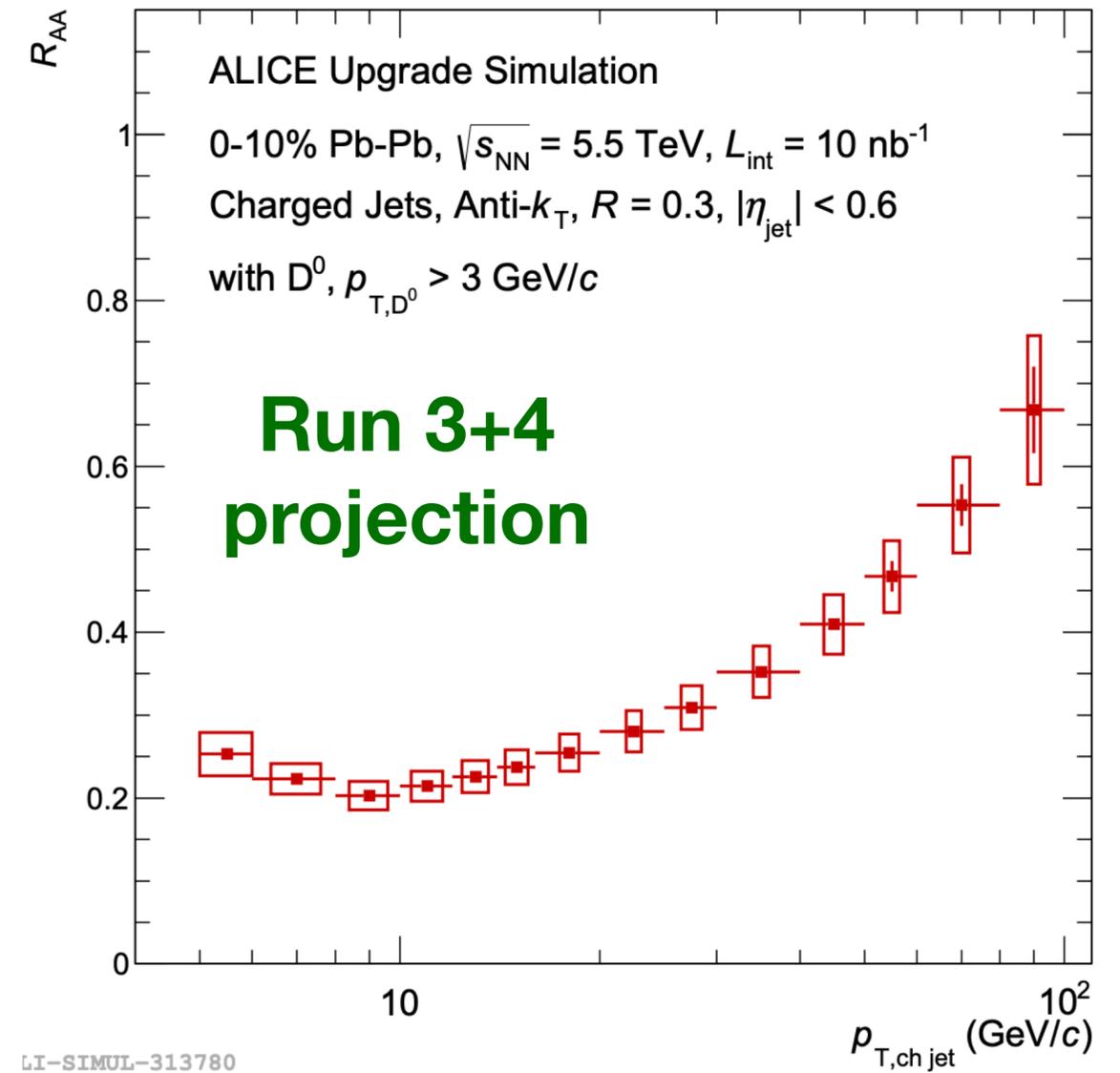one day of Ne-Ne

p-Pb/Pb-p

•~150 nb^{-1} expected

33
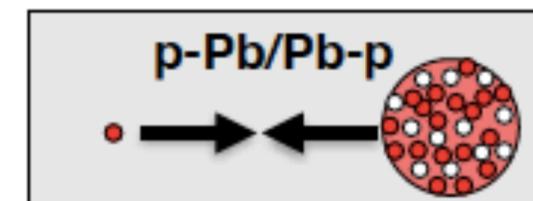
Charm-tagged jets

D^0-tagged jets

Nuclear modification factor

R_{AA}<1 - suppression

R_{AA}=1 - no suppression

$$R_{AA} = \frac{1}{<N_{coll}>} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

ALICE Preliminary

0-10% Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV

charged jets, anti-k_T

• D^0-jet, R = 0.3

3 < $p_{T,D}$ < 36 GeV/c

Run 2

p_T (GeV/c)

ALI–PREL–506526

ALICE Upgrade Simulation

0-10% Pb-Pb, $\sqrt{s_{NN}}$ = 5.5 TeV, L_{int} = 10 nb^{-1}

Charged Jets, Anti-k_T, R = 0.3, $|\eta_{jet}|$ < 0.6

with D^0, p_{T,D^0} > 3 GeV/c

Run 3+4 projection

$p_{T,ch\,jet}$ (GeV/c)

LI–SIMUL–313780

34
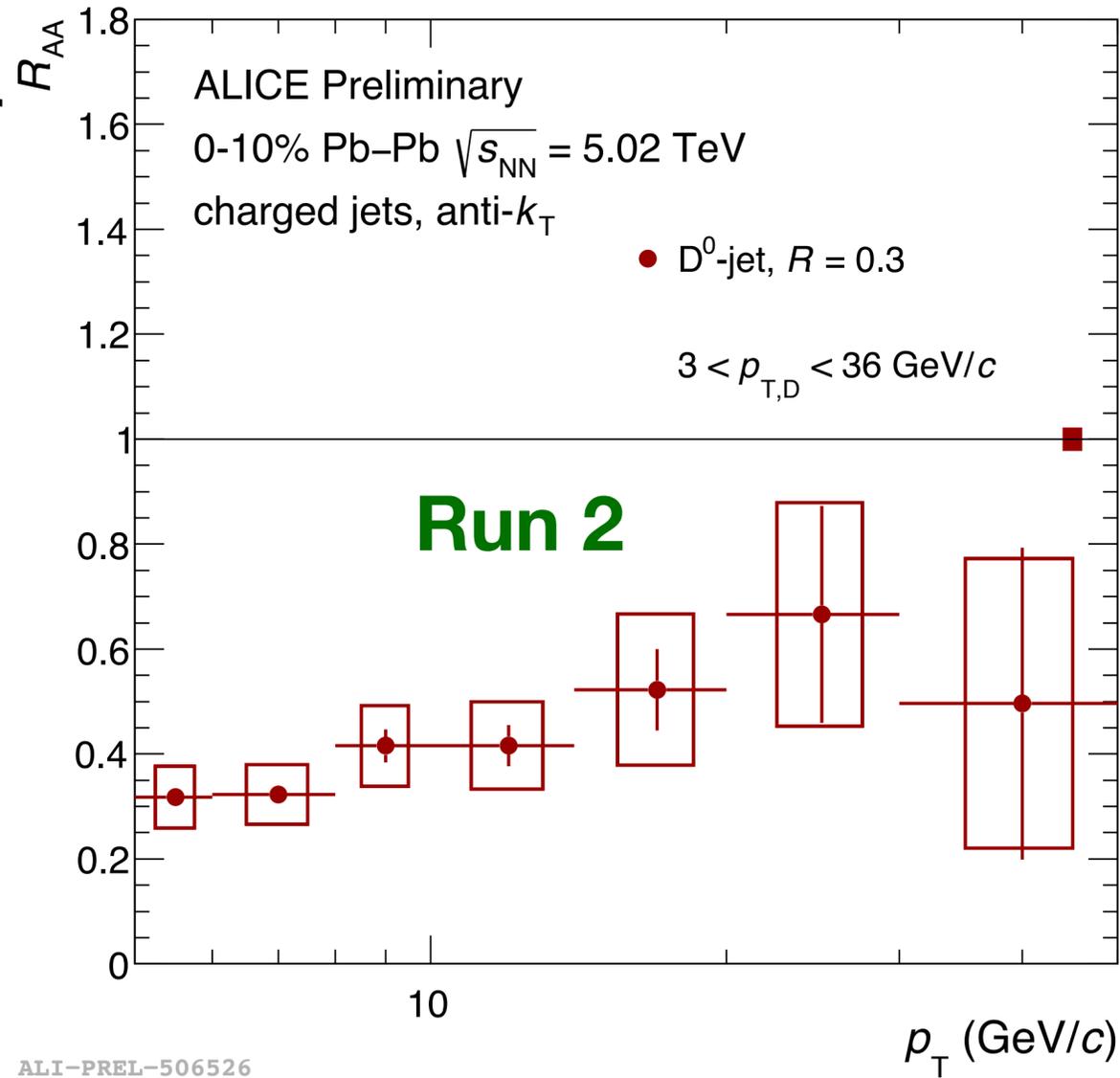
Next steps: constrain interplay between wake and jets

Jet axis difference sensitive to response of QGP to jet

Hadron trigger

$\Delta\varphi$

10

Pb–Pb / pp

STD

WTA

ΔR_{axis}

Collinear radiation

Recoil jet

2.5   3

$\Delta\varphi$ (rad)

STD ~ 4-momentum sum of constituents
WTA ~ hardest constituent of hardest branch

$20 < p_{T,ch\ jet}^{reco} < 30$ GeV/c

ALICE Preliminary
Uncorrected
0–10% Pb–Pb, $\sqrt{s_{NN}} = 5.36$ TeV
Anti-k_T ch-particle jets, $|\eta_{jet}| < 0.5$
$|\Delta\varphi - \pi| < 0.6$, $R = 0.4$

Pb-Pb data (2023)

TT[20,50]
TT[5,7]
Δ_{recoil}

$\frac{1}{N_{trig}} \frac{d^3N}{dp_{T,ch\ jet}^{raw} d\Delta\varphi\ d\Delta R}$ (GeV/c)$^{-1}$

ΔR_{axis}

ALI-PREL-601288

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Heavy-flavour correlations

- Heavy-flavour quarks produced at start of collision - provide unique way to probe the full system evolution

- 'Diffusion' as quark traverses medium, expected to partially thermalise depending on pT

- Correlation measurements one of most promising 'new' ways to constrain QGP transport properties - measuring 'kicks' to heavy-quark will allow for more precise probe of microscopic structure
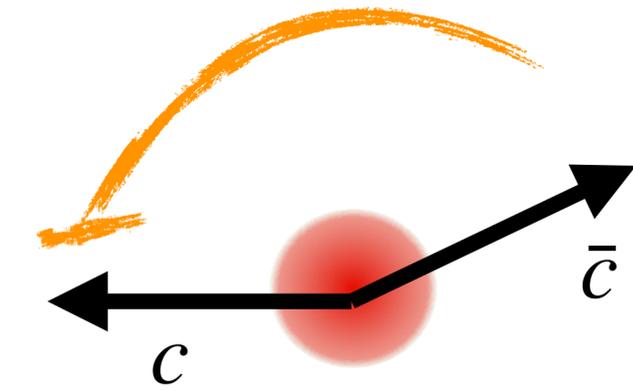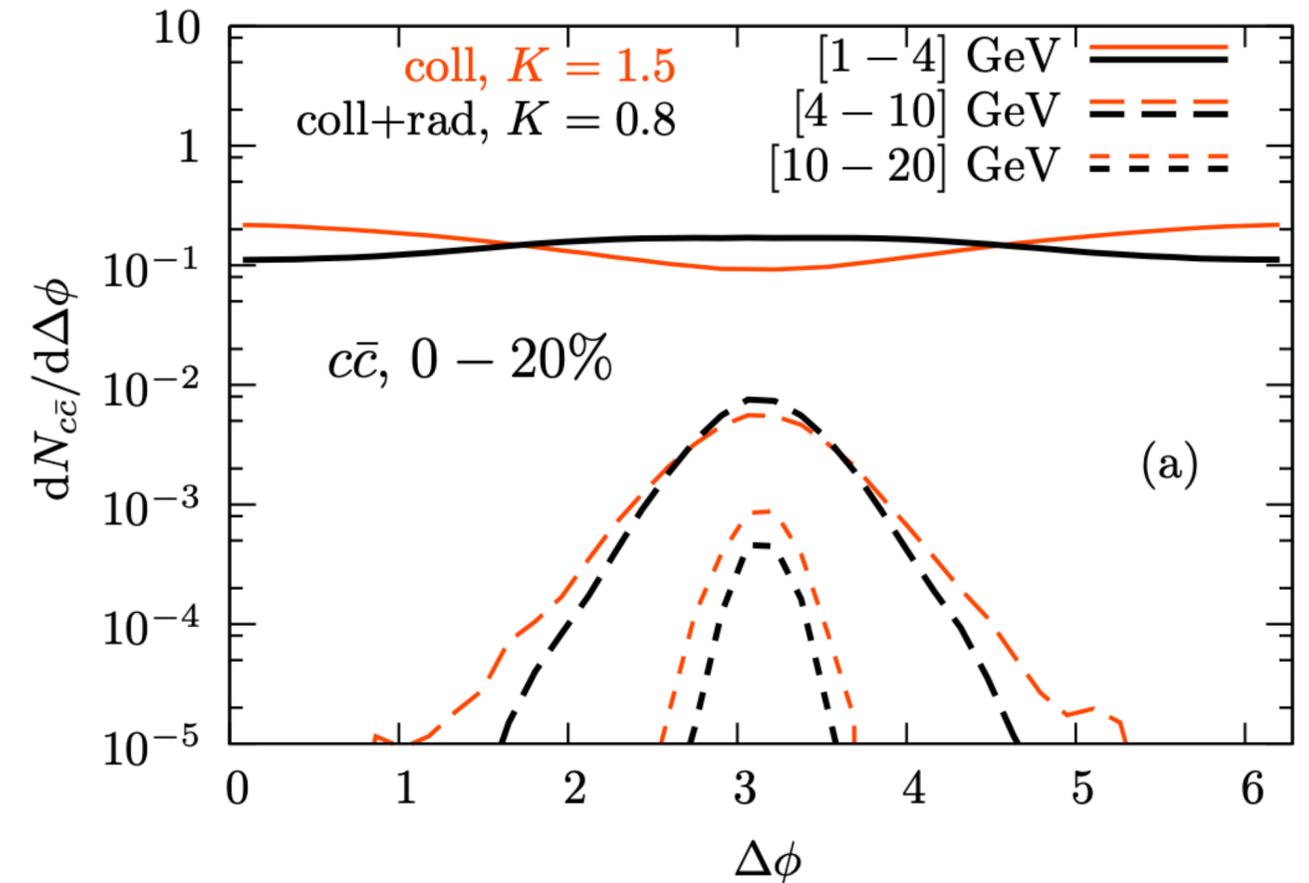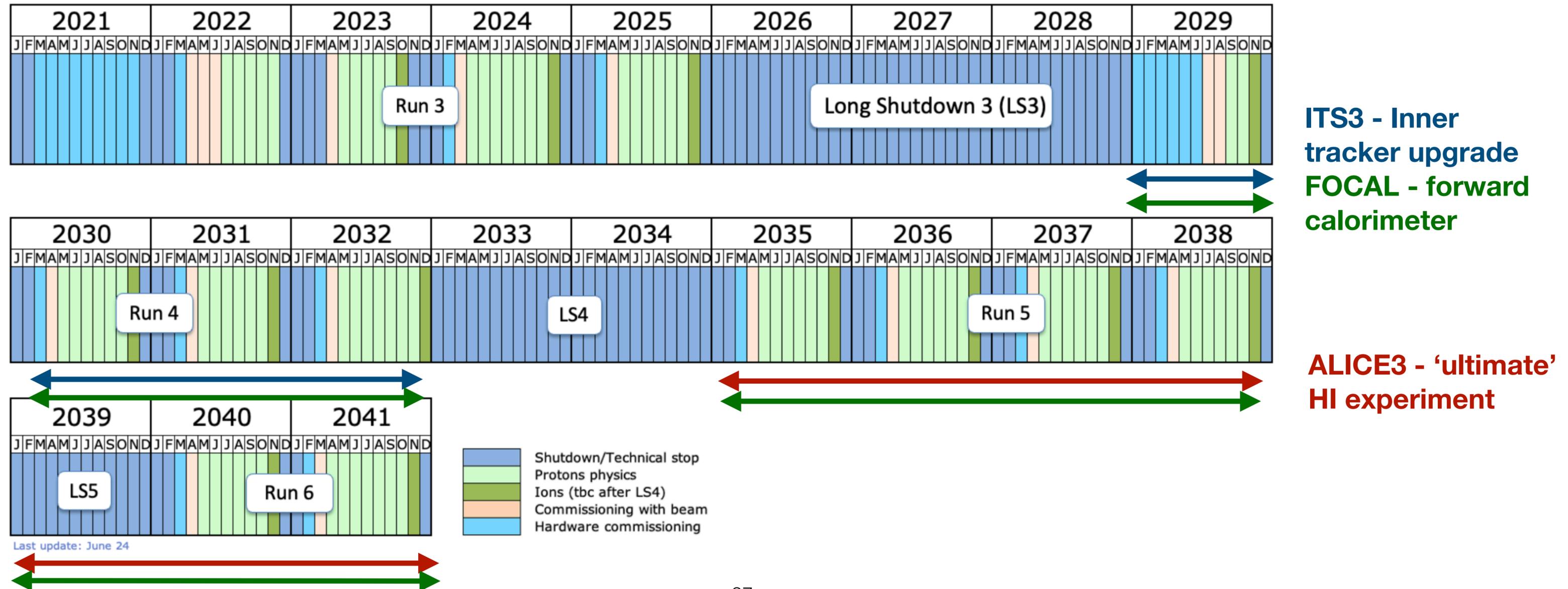
Many possibilities…

1305.3823
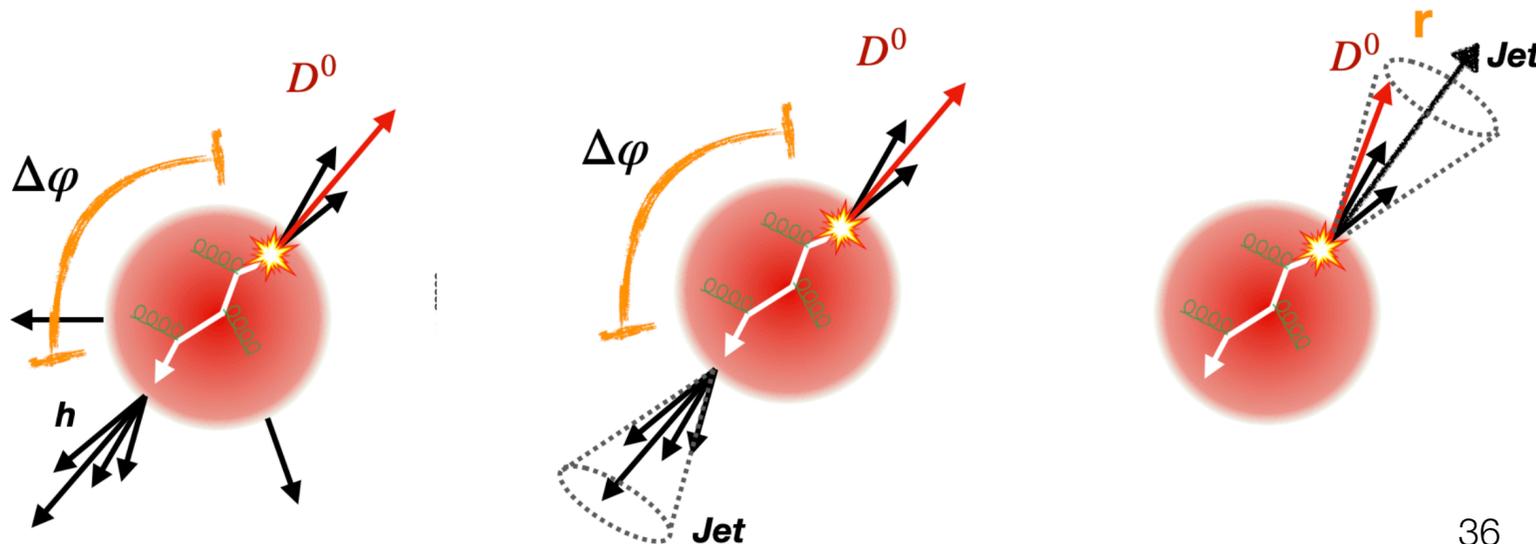
Future upgrades at the LHC

- Current ALICE setup scheduled to run until the end of Run 4 (2032), LHC scheduled to run with heavy-ions until 2041


Longer term LHC schedule

In January 2022, the schedule was updated with long shutdown 3 (LS3) to start in 2026 and to last for 3 years. HL-LHC operations now foreseen out to end 2041.

ITS3 - Inner tracker upgrade

FOCAL - forward calorimeter

ALICE3 - 'ultimate' HI experiment

Legend:
- Shutdown/Technical stop
- Protons physics
- Ions (tbc after LS4)
- Commissioning with beam
- Hardware commissioning

Last update: June 24

Inner tracker upgrade 'ITS3'

Replacing the ITS2 inner barrel for Run 4 (2029-2032)

- **bent, wafer-scale CMOS (MAPS) sensors**

  - Extremely low material budget 0.02-0.04% X_0

  - Homogeneous material distribution

- x2 improvement in pointing resolution, large improvement in tracking efficiency at low p_T
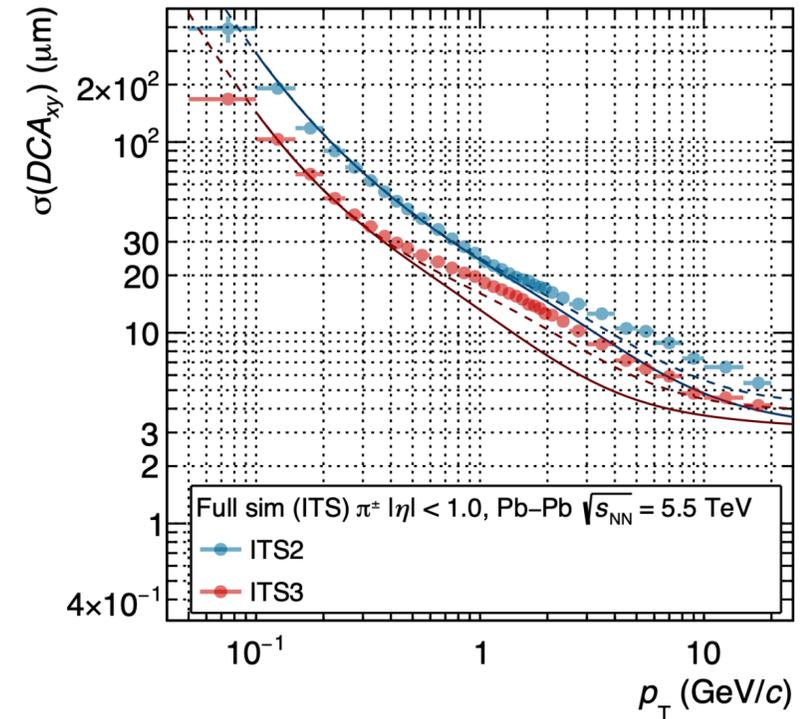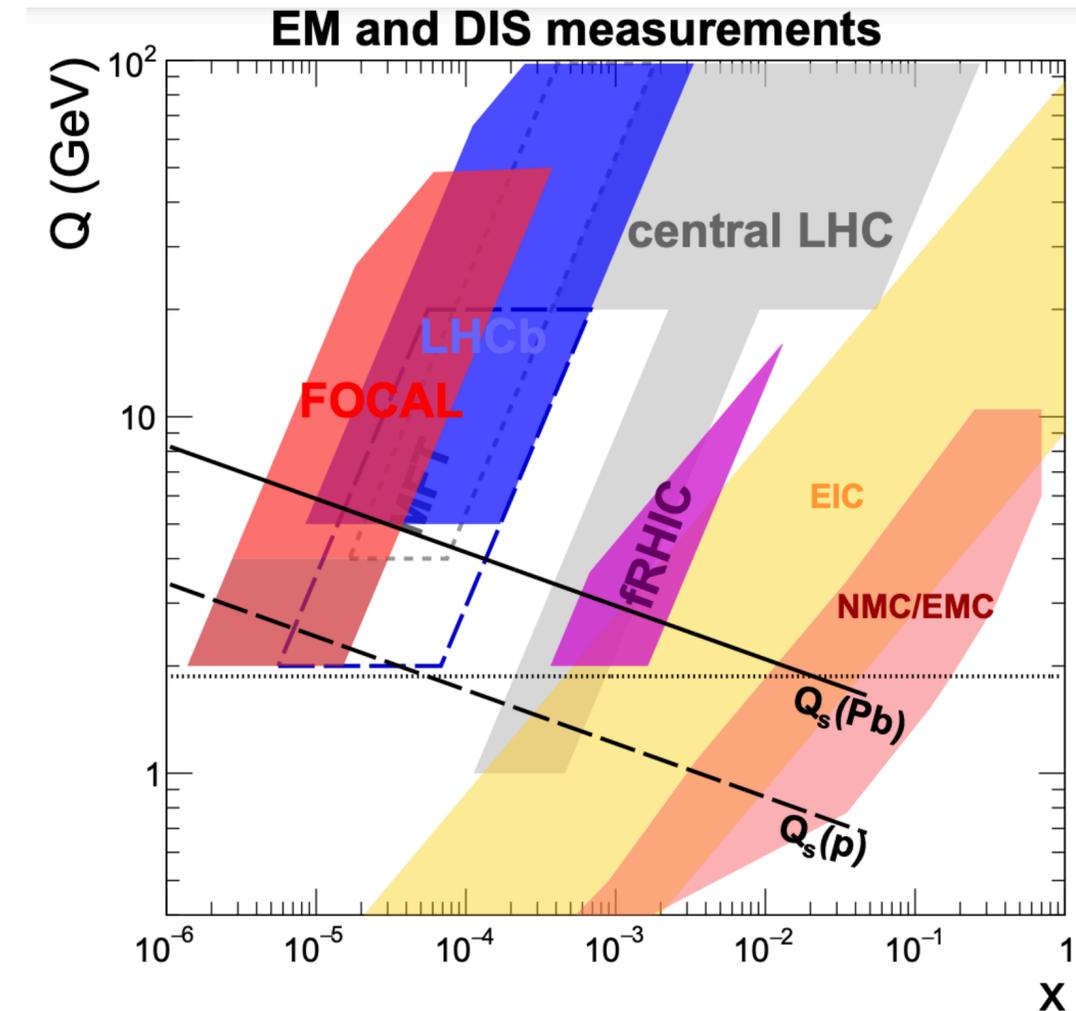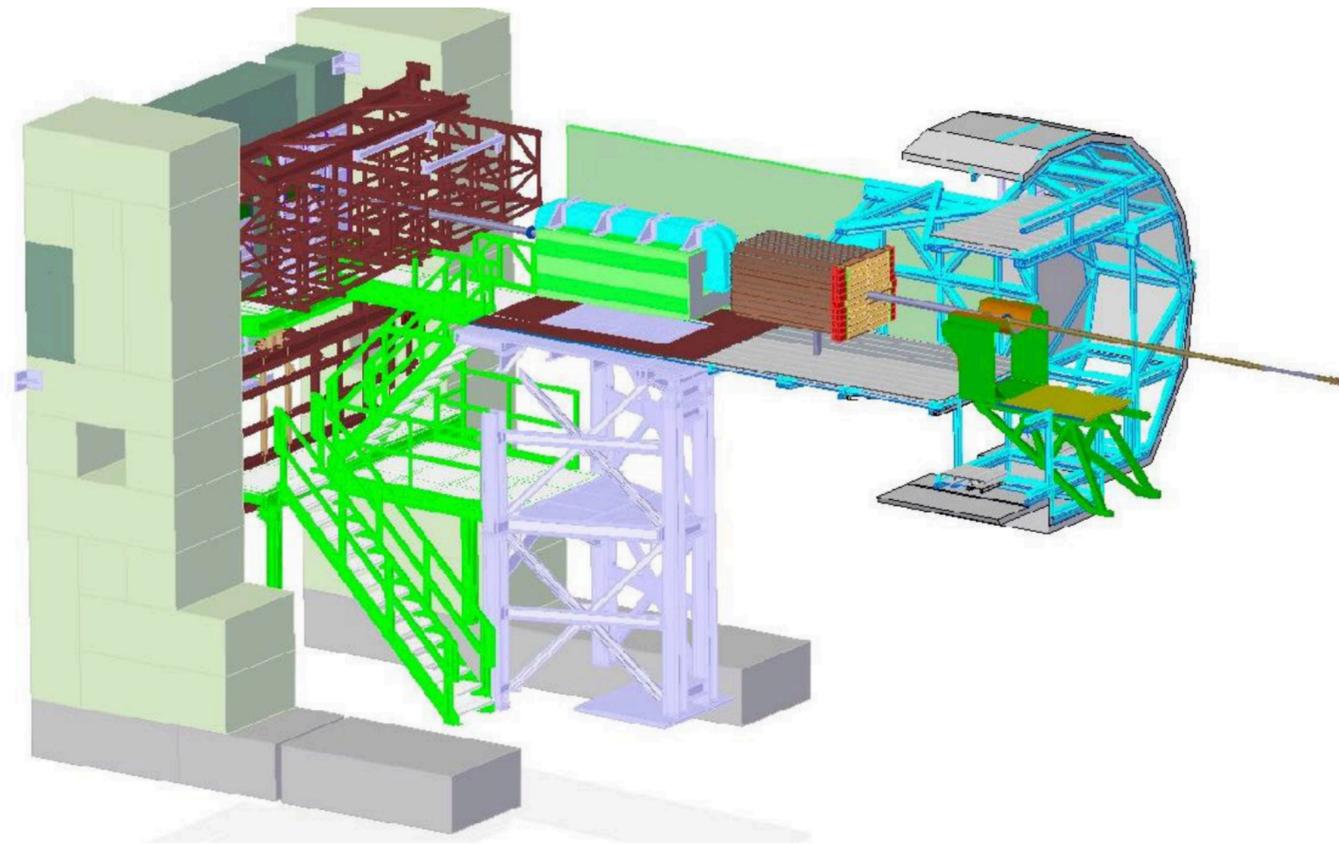

Significant improvements in measurements of charm+beauty hadrons, plus discovery potential for exotic nuclei
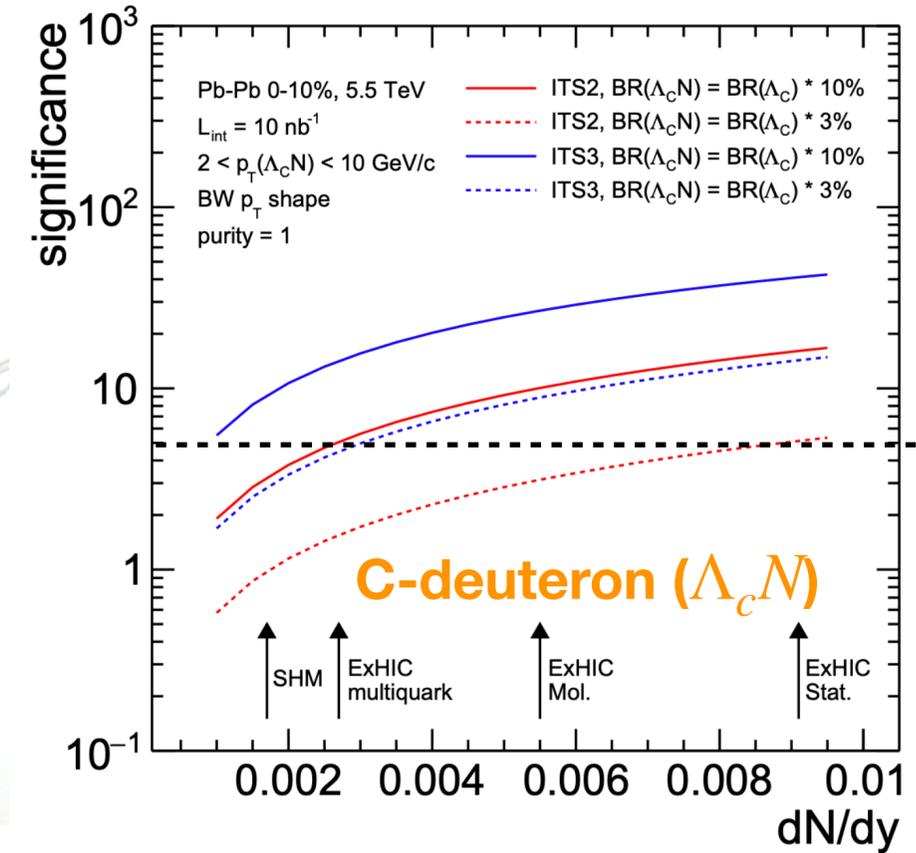
Forward Calorimeter 'FOCAL'

- **Forward (3.4<η<5.8) EM calorimeter + hadronic calorimeter to be installed for Run 4**

- Exciting low-x hadron physics program, complimentary to EIC

**TDR:** CERN-LHCC-2024-004
**Physics:** ALICE-PUBLIC-2023-001

The ultimate heavy-ion experiment - ALICE3

The next-generation heavy-ion experiment for LHC Run 5 and 6 (2035 onwards)

- Novel and innovative detector concept
  - Compact and lightweight all-silicon tracker
  - Retractable vertex detector
  - Extensive particle identification
  - Large acceptance
  - Superconducting magnet system
  - Continuous read-out and online processing
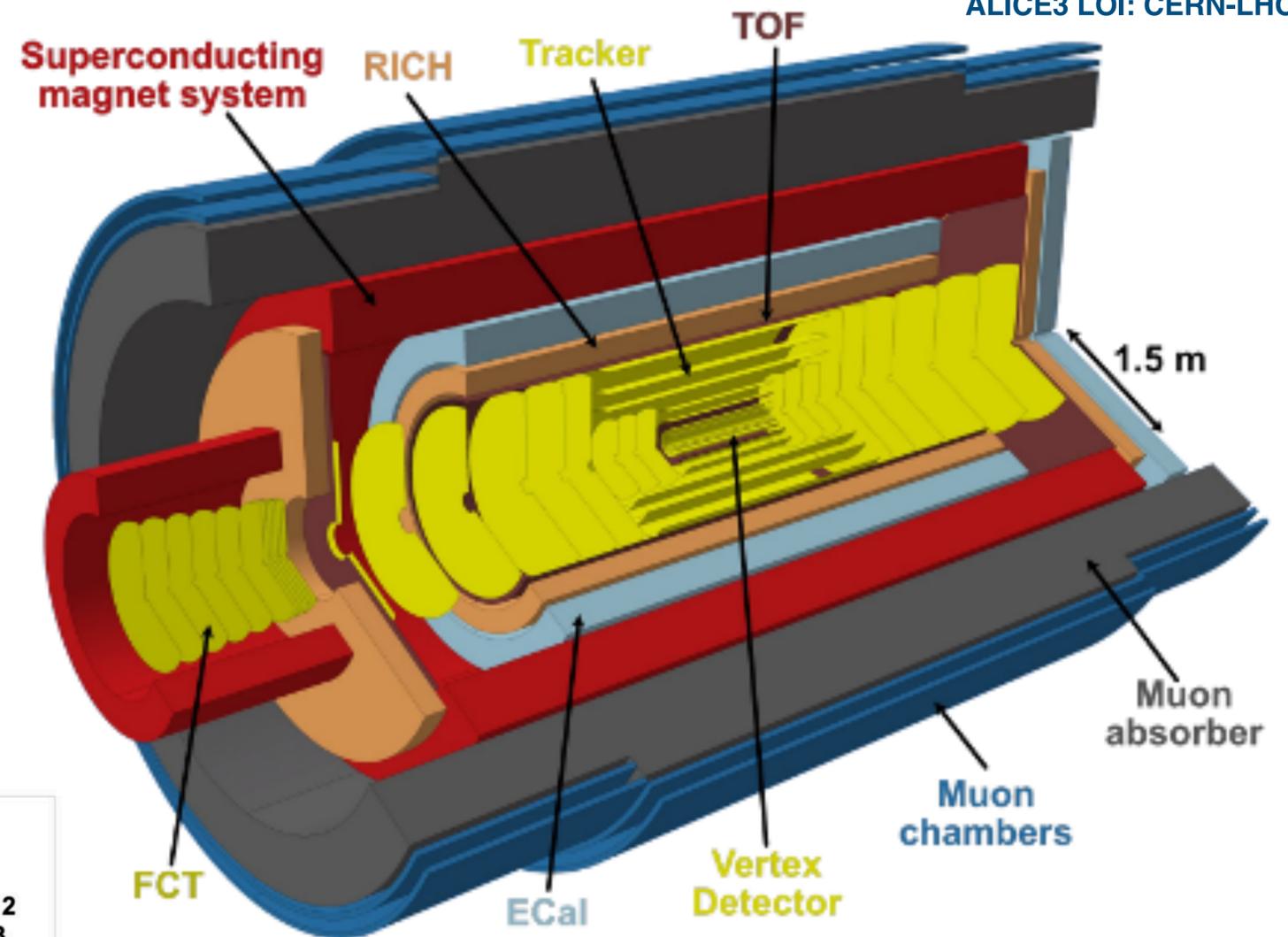
Ultimate performance in terms of acceptance, interaction rate and tracking precision
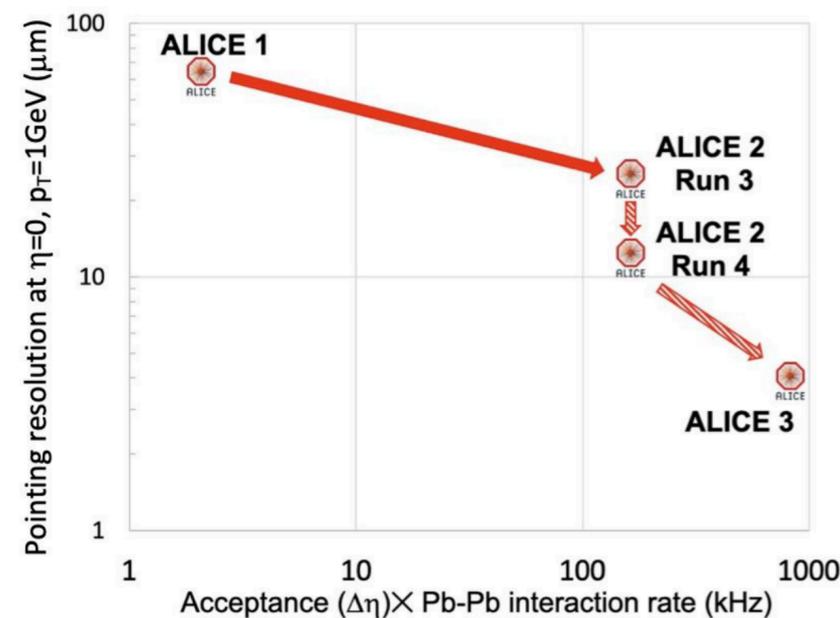
Precision beauty, charm correlations, exotic charm states and nuclei, dileptons, collectivity…

Background subtraction methods for jet analyses

- **Low-p_T measurements** are where ALICE is unique with respect to other LHC experiments

  - Broadening effects expected (and seen!) to be largest at low p_T

- **ALICE developed tools for background at the level of *ensemble-averaged distributions***

  - Data-driven

  - No fragmentation bias

  - Remove ALL background allowing to push down to low p_T

See QM23:
N Gruenwald *EPJ Web Conf.* **296** (2024) 11005
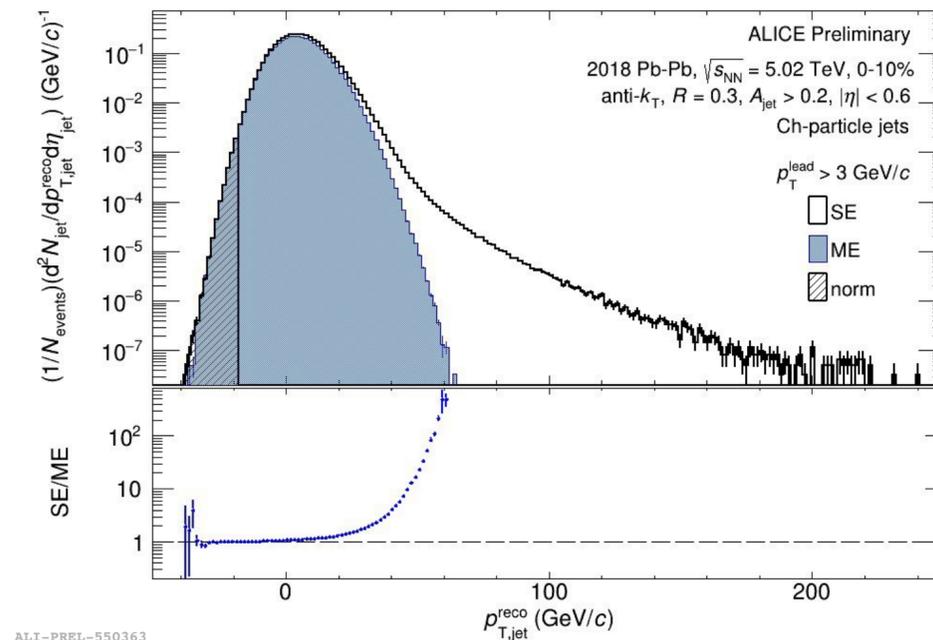J. Norman *EPJ Web Conf.* **296** (2024) 11006

- **Also ML approaches to background estimation**   ALICE: arXiv:2303.00592
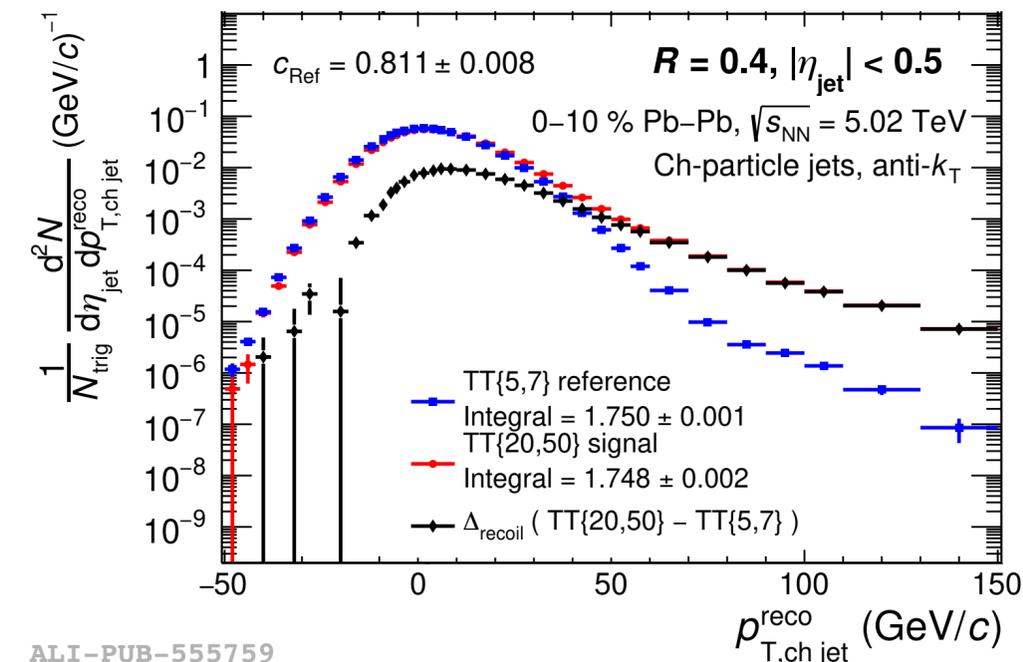 H. Bossi, CERN-EP seminar

STAR: Phys. Rev. C 96, 024905 (2017)
+ ALICE preliminary QM23

Mixed event

ALICE: JHEP 09 (2015) 170

Hadron-trigger

Important to build on in Run 3 and beyond!

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