Techniques for heavy-flavor (HF) measurements: strategies, challenges, and future directions

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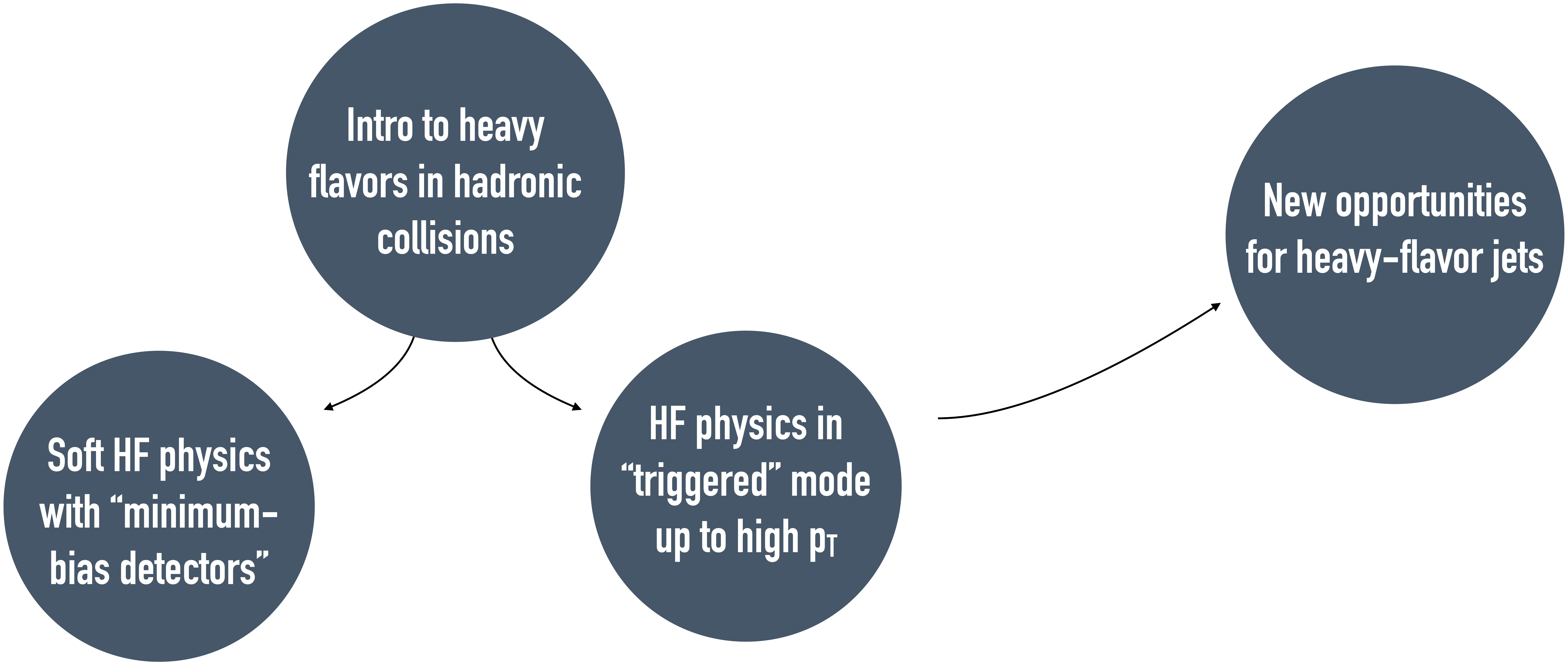
JETSCAPE online summer school 2023
24/07/2023

Overview of the talk



H-.T. Ding et al., arXiv 1504.05274
W. Busza, et al., ARNPS, Vol. 68:339-376, 2018

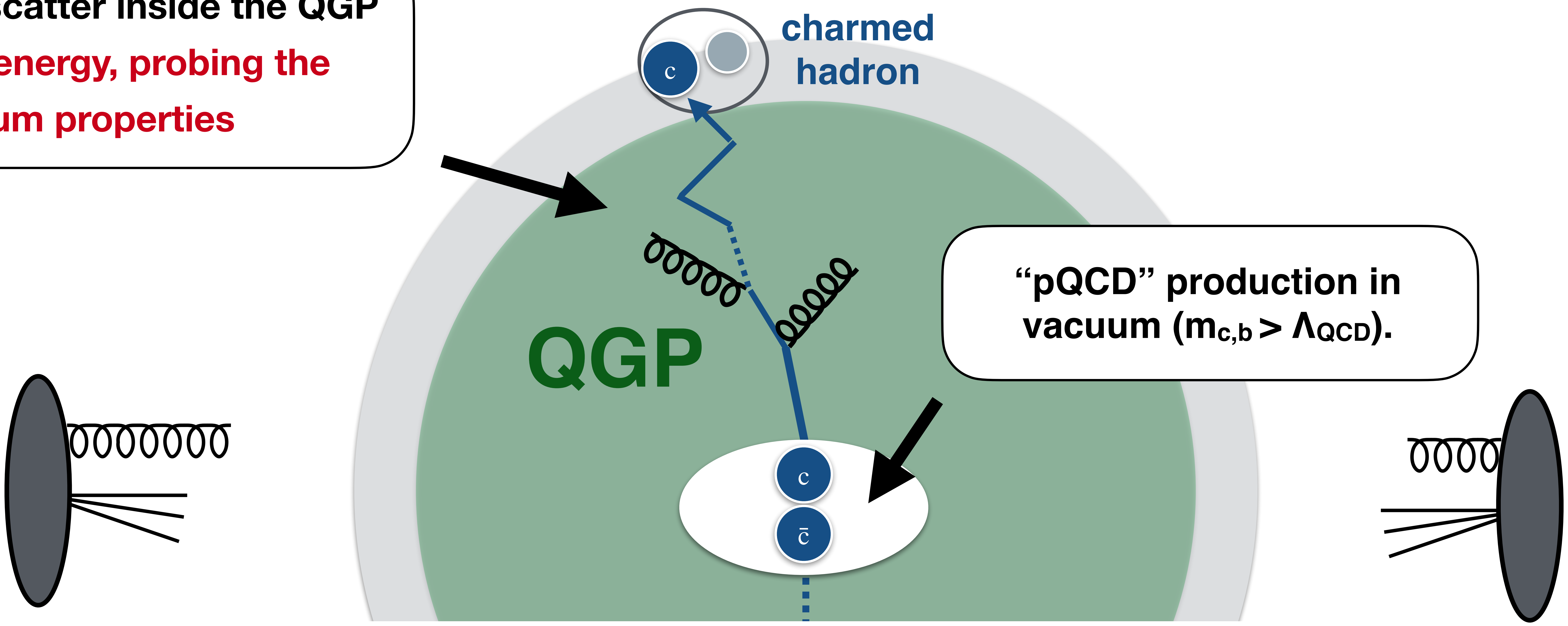
Hot QCD matter with heavy quarks

$m_c \sim$ 1.5 GeV
$\Lambda_{QCD} \sim$ 200 MeV
$T_{QGP} \sim$ 300 MeV
$m_{u,d,s} \lesssim T_{QGP}$

Hadronizes at the boundary of the QGP phase:
→probing the mechanisms of hadronization

HQs rescatter inside the QGP
→ lose energy, probing the medium properties

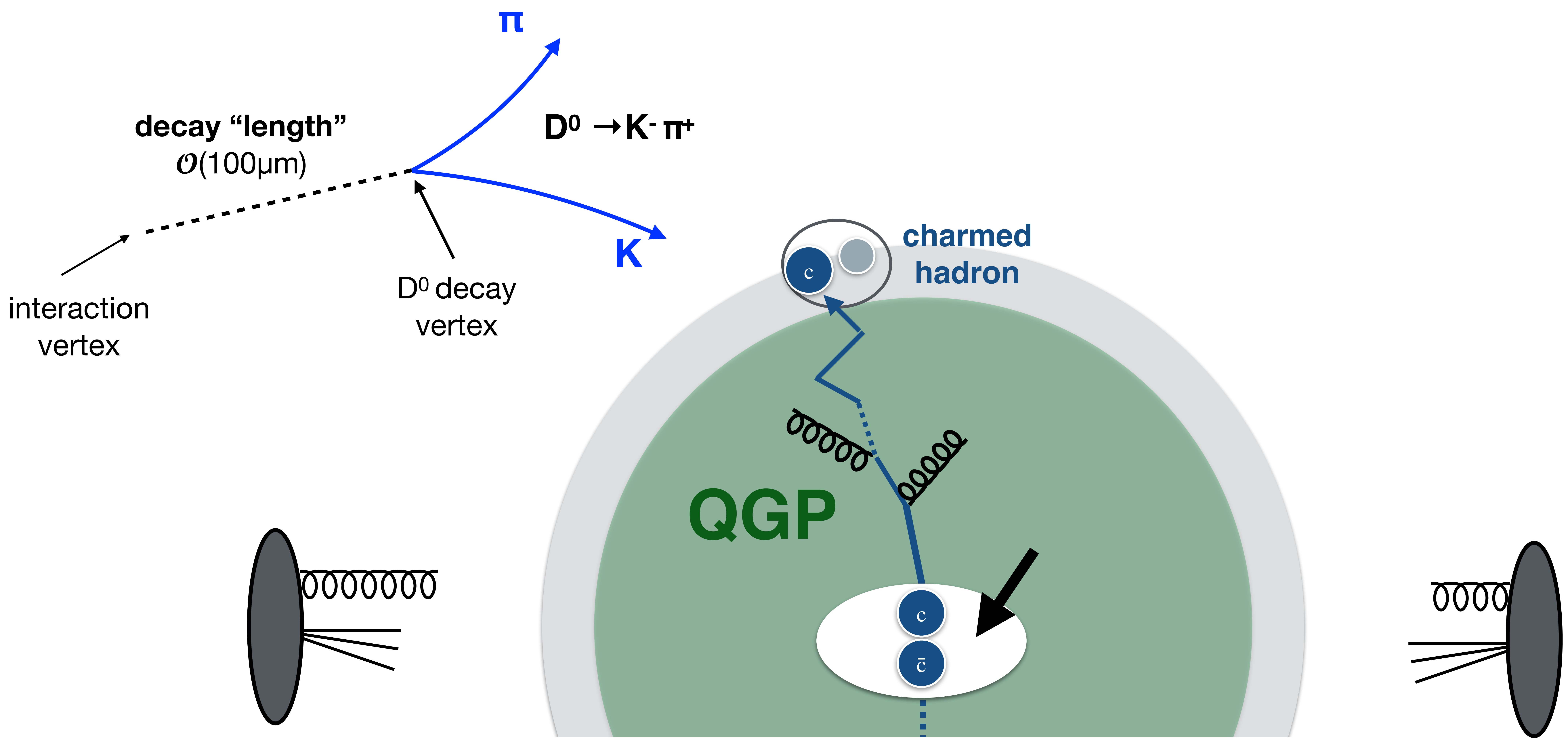
"pQCD" production in vacuum ($m_{c,b} > \Lambda_{QCD}$).



H-.T. Ding et al., arXiv 1504.05274
W. Busza, et al., ARNPS, Vol. 68:339-376, 2018

Hot QCD matter with heavy quarks

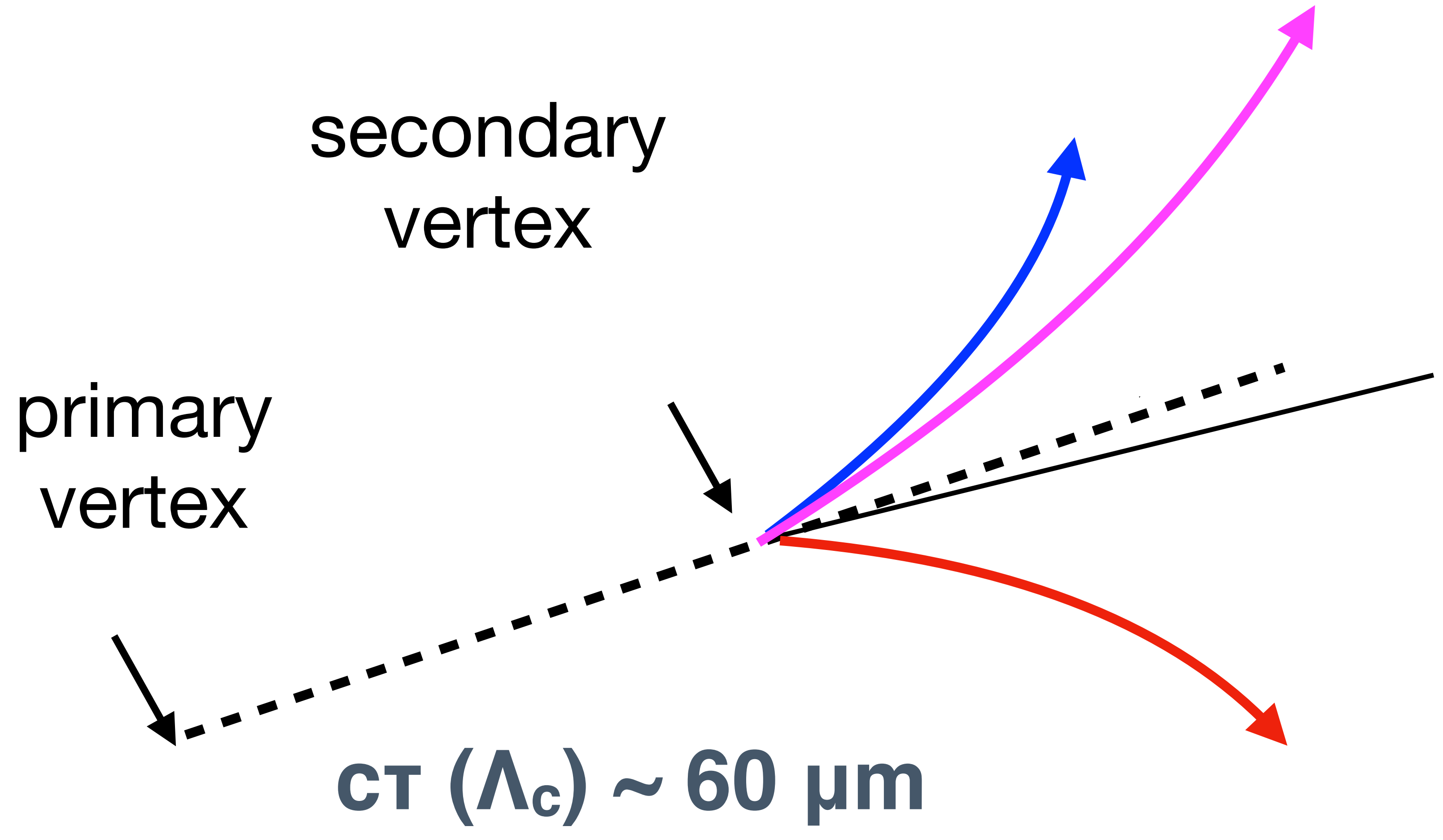
→ **Conserved and traceable witness of the QGP evolution** (no “thermal production)
→ **Experimentally accessible at any p_T via fully-reconstructed decays**

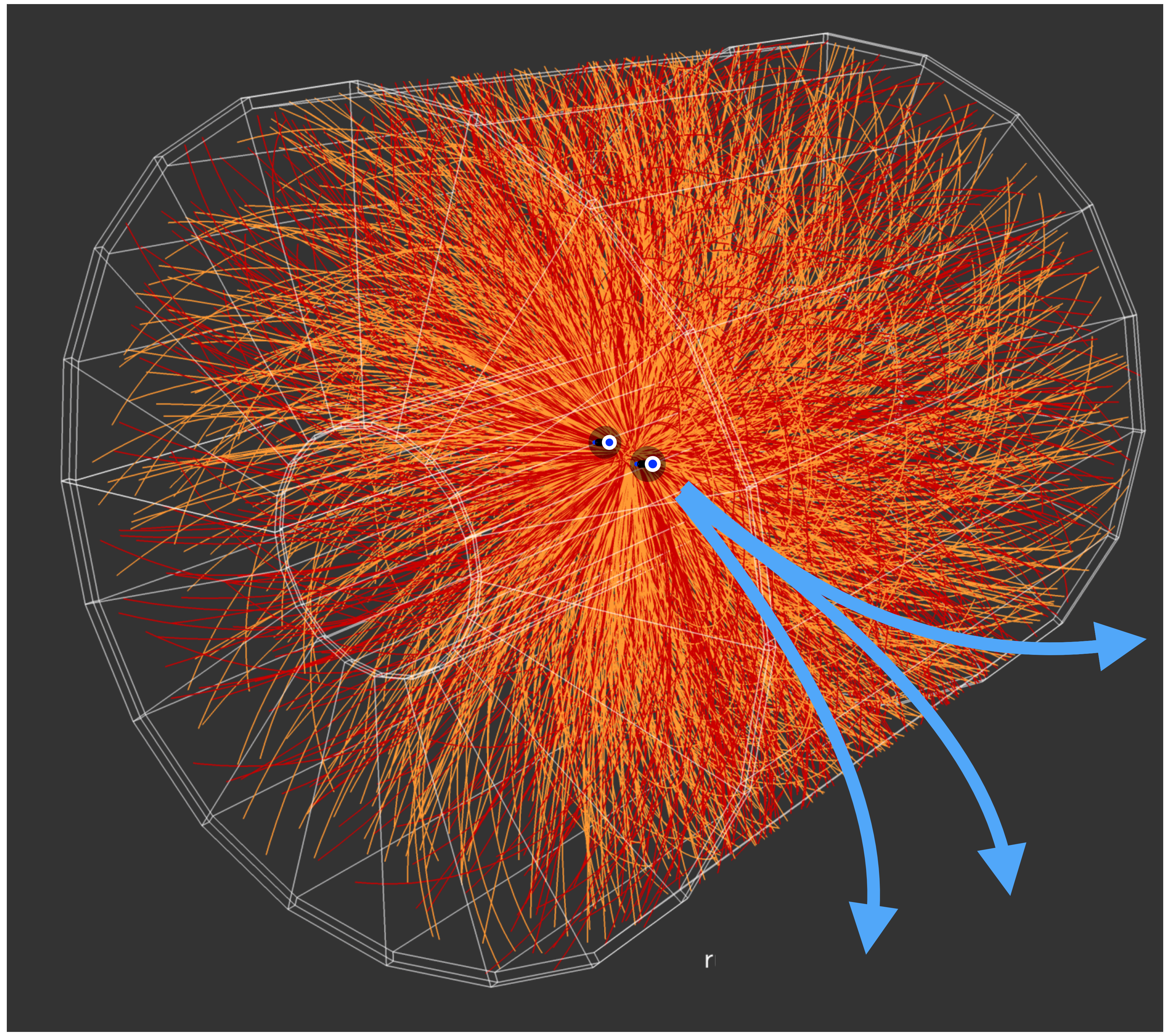


Soft HF physics with “minimum-bias detectors”

"Soft" heavy-flavor physics with minimum bias HI collisions

- low-p_T hadrons (D^0, Λ_c, Ξ_c ..) with small secondary vertex displacements
- small signal/background → **"un-triggerable" events**





Techniques:

1) Machine learning techniques + Particle Identification for improved selection performances

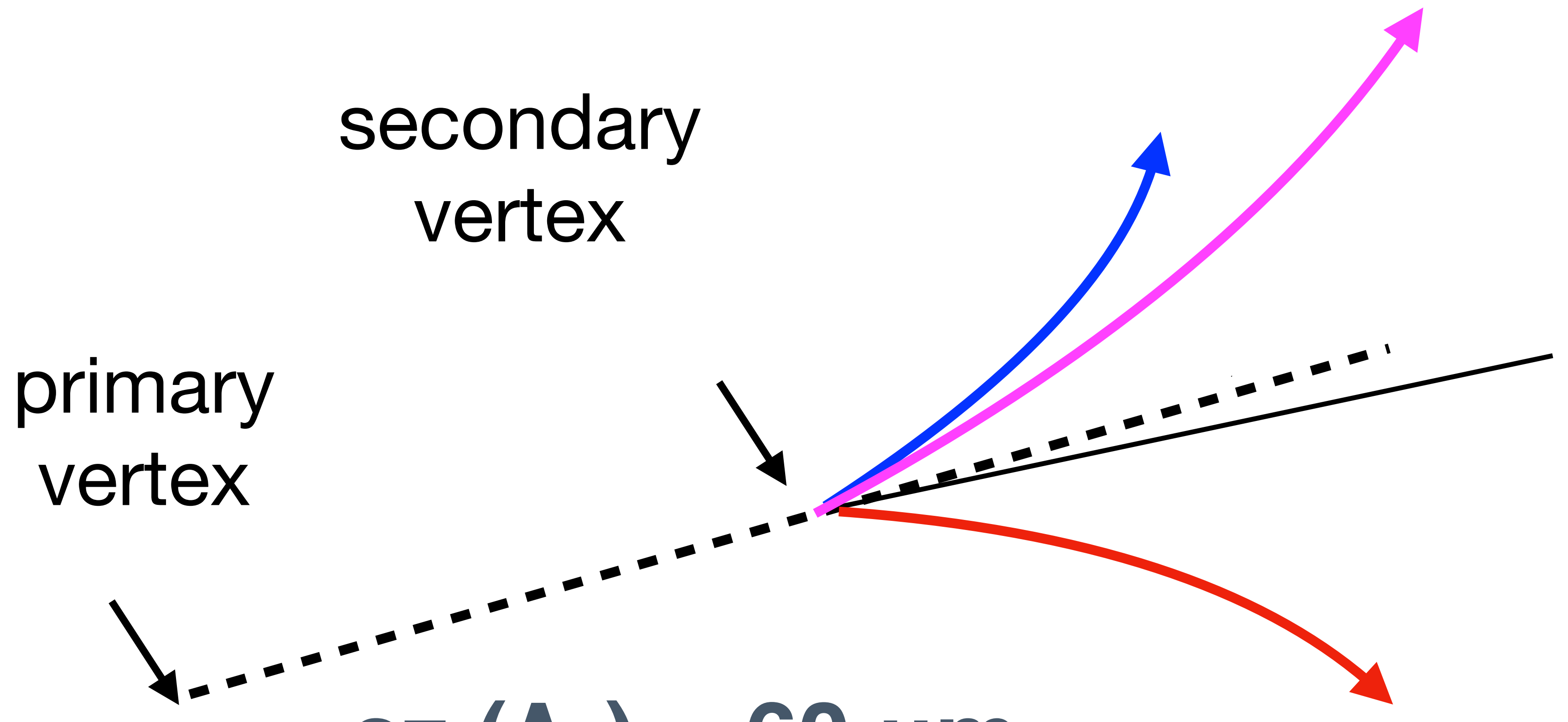
2) Large "minimum-bias" statistics and outstanding tracking/vertexing performance,

→ new analysis techniques (data processing, skimming, analysis) and detector technology

Low p_T charmed baryons: one of the biggest challenges

→ **Λ_c/D^0 ratio in PbPb and pp**: **stronge sensitivity to hadronization in a high-partonic density environment**

Secondary-vertex analysis not possible
with Run 2 ALICE DCA resolution



$c\tau$ (Λ_c) ~ 60 µm

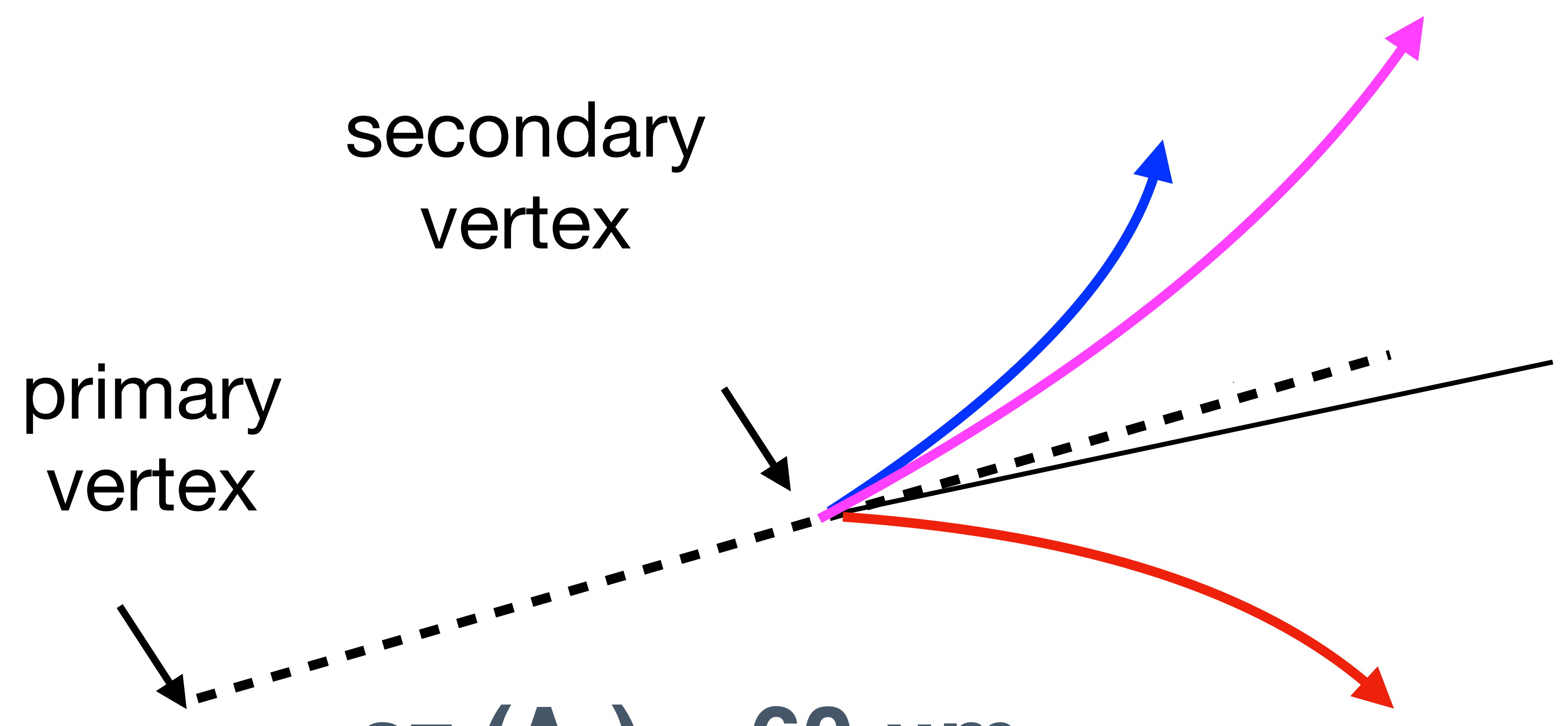
$\Lambda_c \rightarrow pK^0_s$ without secondary-vertex reconstruction

- BDT with PID and "topological" variables
- New tabular data structure + ML (link) for local processing and optimization ~ TB of data

Low p_T charmed baryons: one of the biggest challenges

→ **Λ_c/D^0 ratio in PbPb and pp**: **strongest sensitivity to hadronization in a high-partonic density environment**

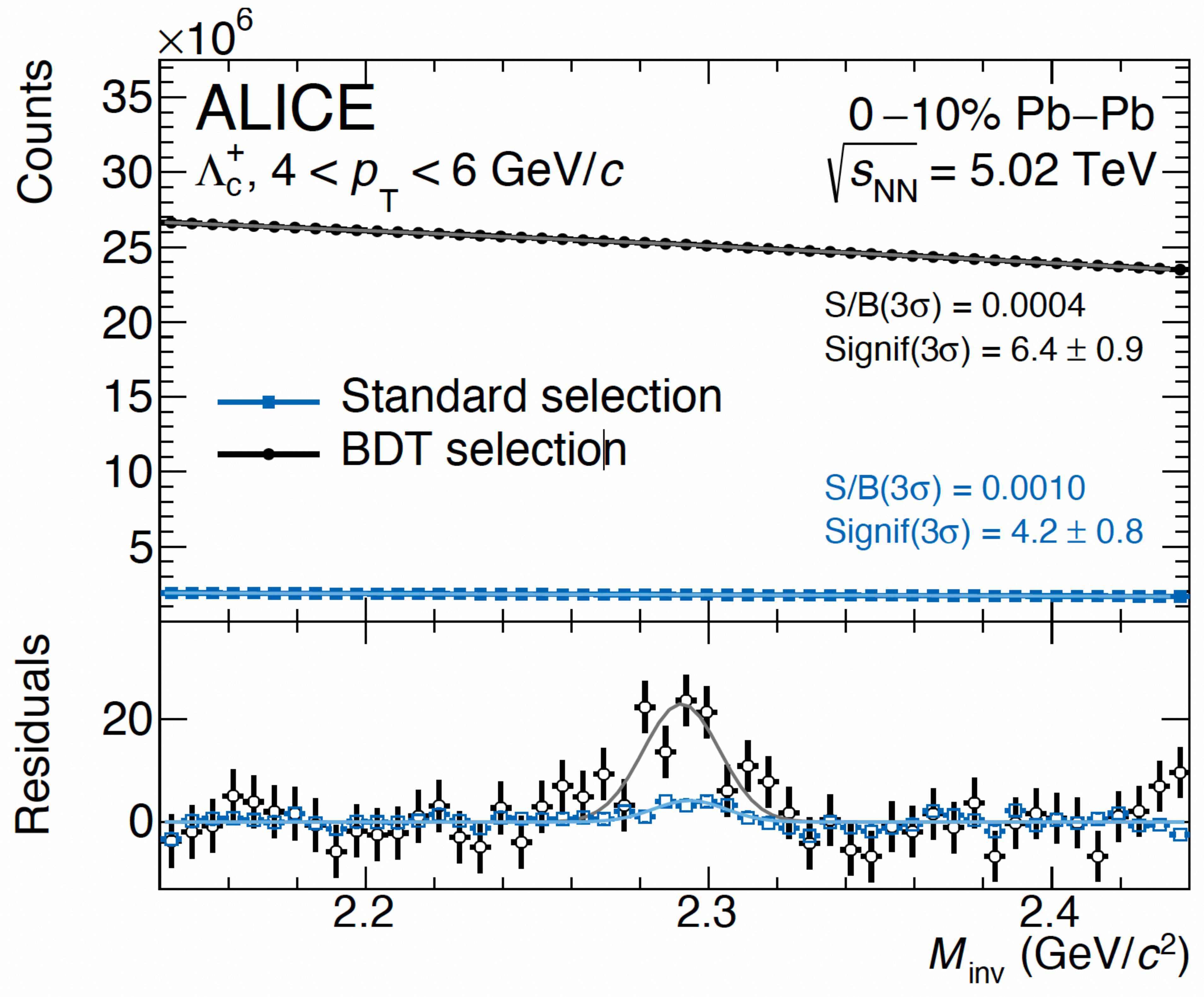
Secondary-vertex analysis not possible
with Run 2 ALICE DCA resolution



$\Lambda_c \rightarrow pK^0_s$ without secondary-vertex reconstruction

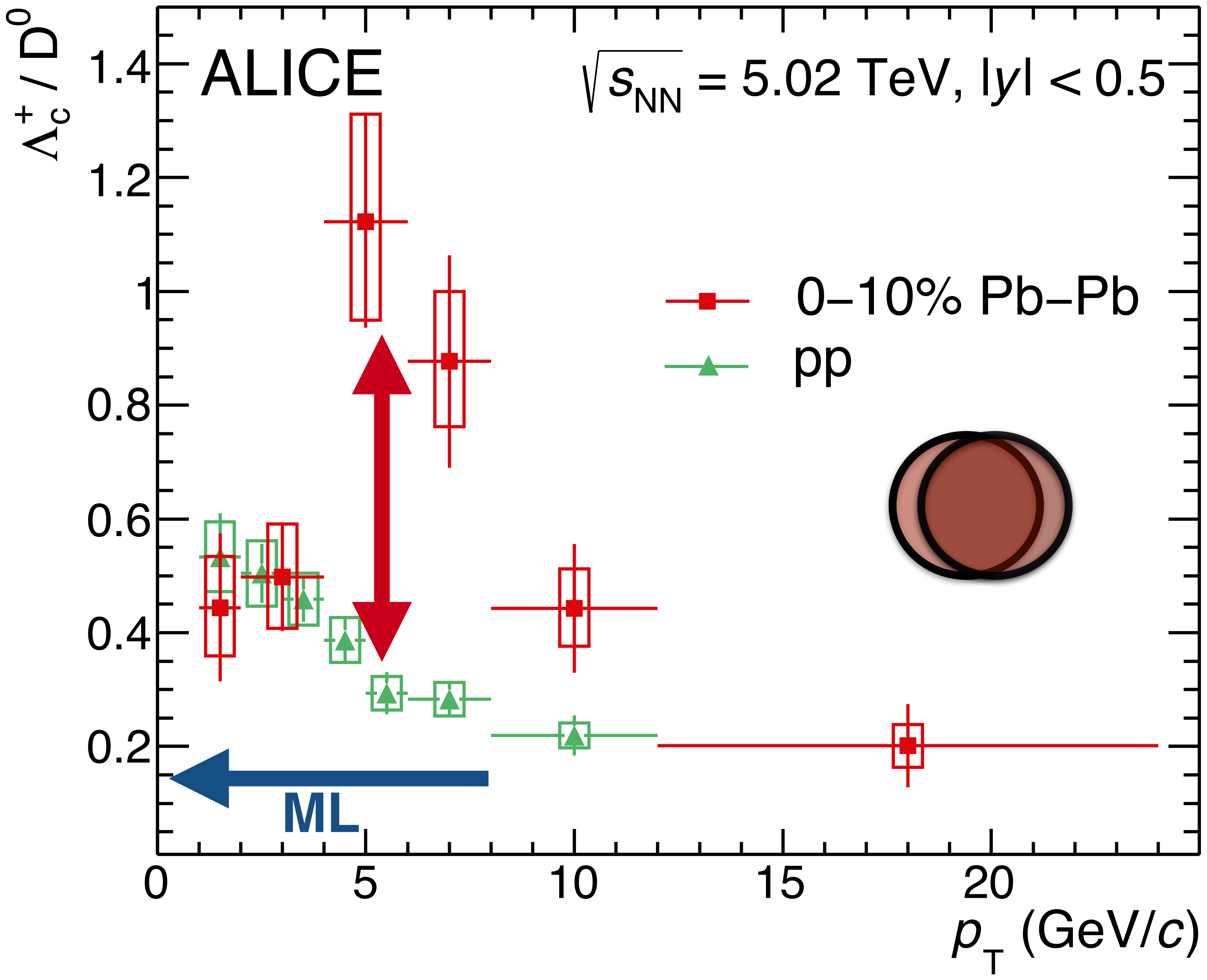
- BDT with PID and "topological" variables
- New tabular data structure + ML (link) for local processing and optimization ~ TB of data

→ **With BDT, 50% increased significance at low p_T**



ALICE, arXiv:2112.08156v1

First Λ_c/D^0 ratio in central PbPb collisions with ALICE



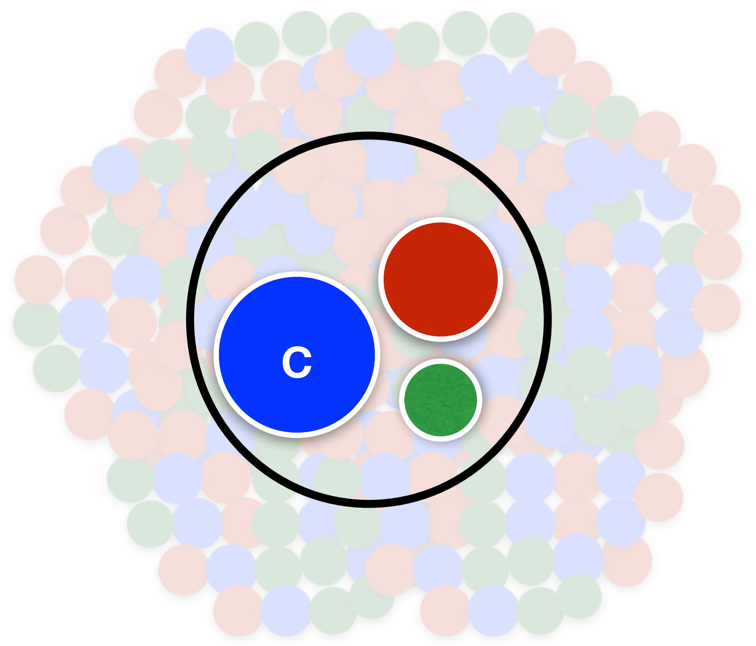
Increase of the Λ_c / D^0 ratio

in PbPb vs pp at

intermediate p_T

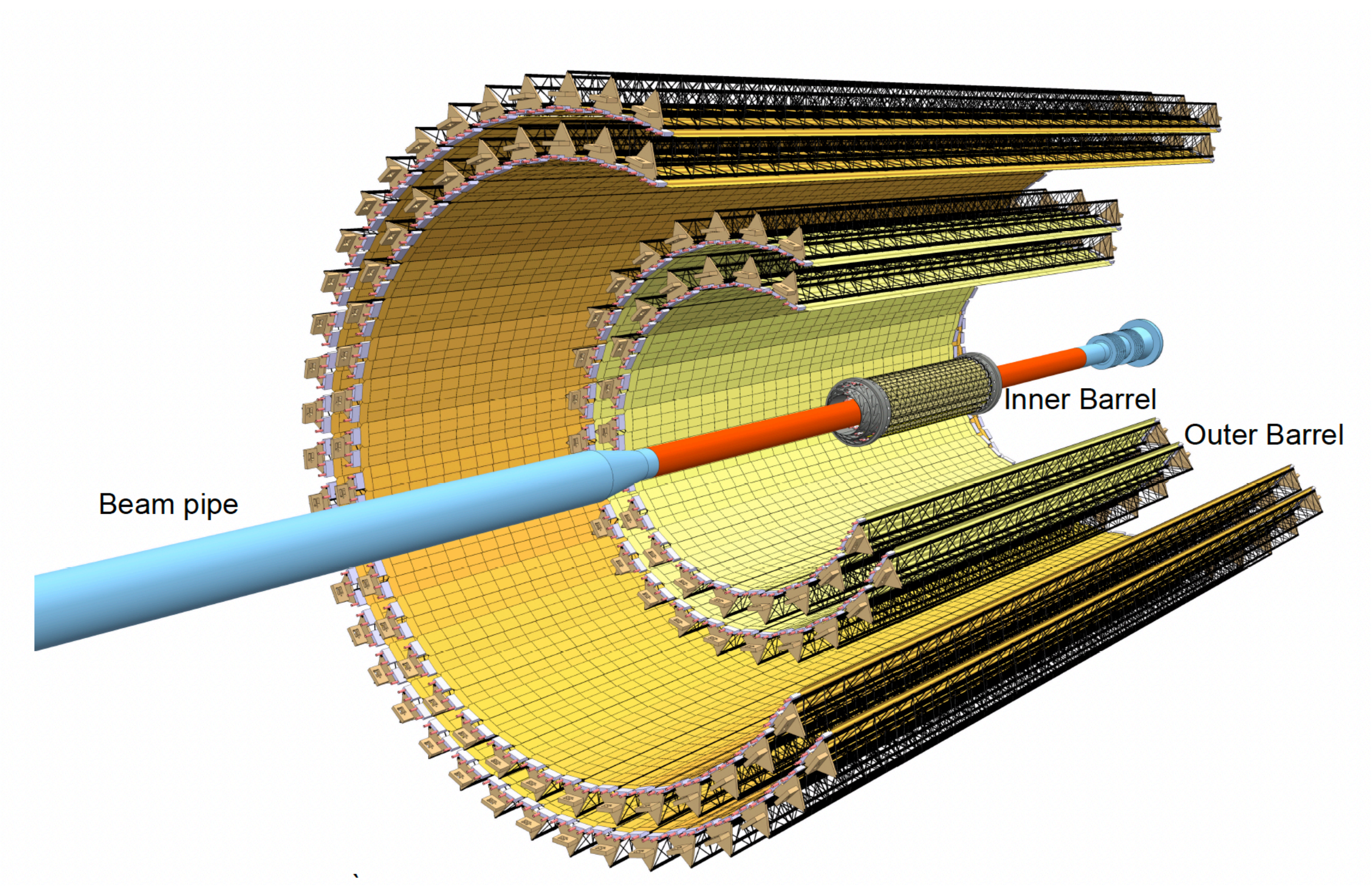
→ **constraining new hadroproduction mechanisms in PbPb**

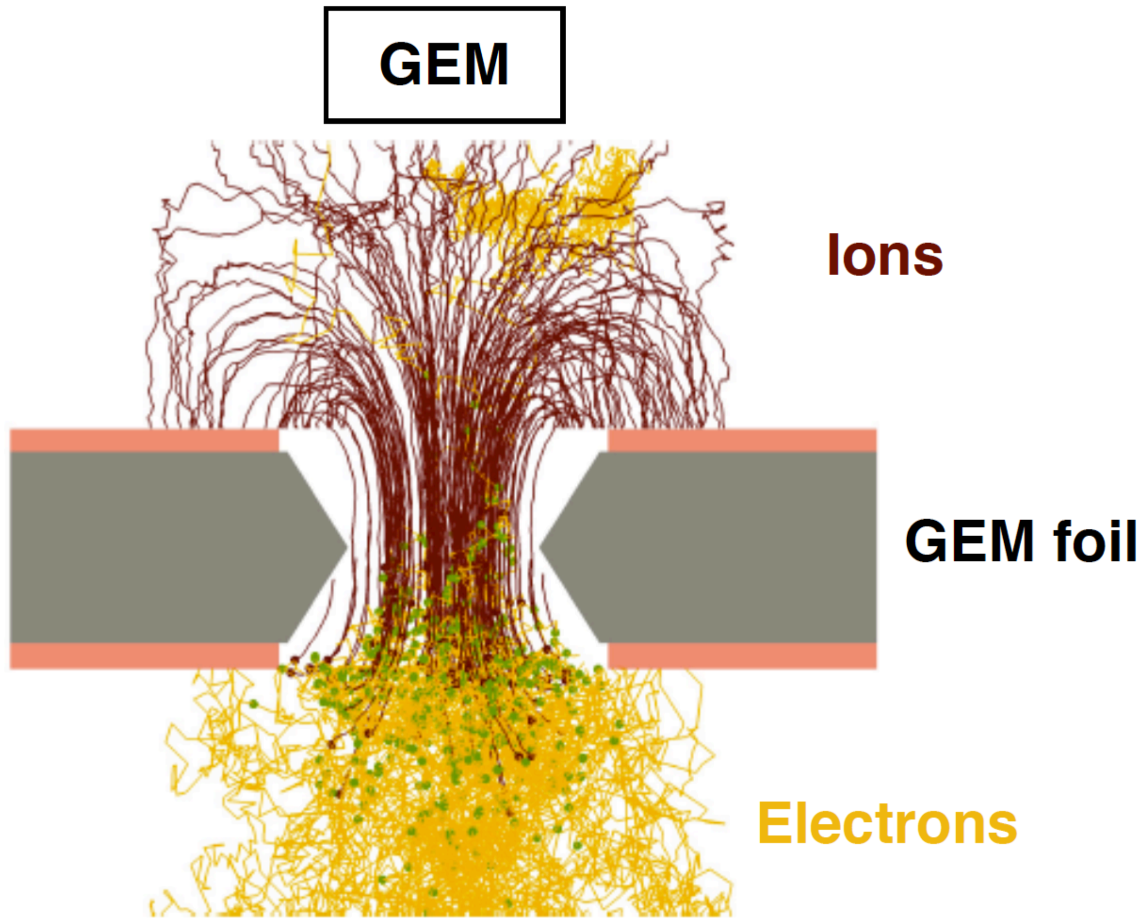
"recombination" of quarks from independent hard scatterings?



ALICE, arXiv:2112.08156v1

“heavy-flavor” upgrades: ALICE in Run3/4 and sPHENIX





Increased low p_T impact-parameter resolution:
with the new inner tracking system (ITS2 and later ITS3)

Increased rate capabilities with the new TPC readout (GEM):
~ 50-100x more PbPb statistics in **continuous-readout** mode

2022 2024 2026 2028 2030 2032 2034 2036 2038 2040

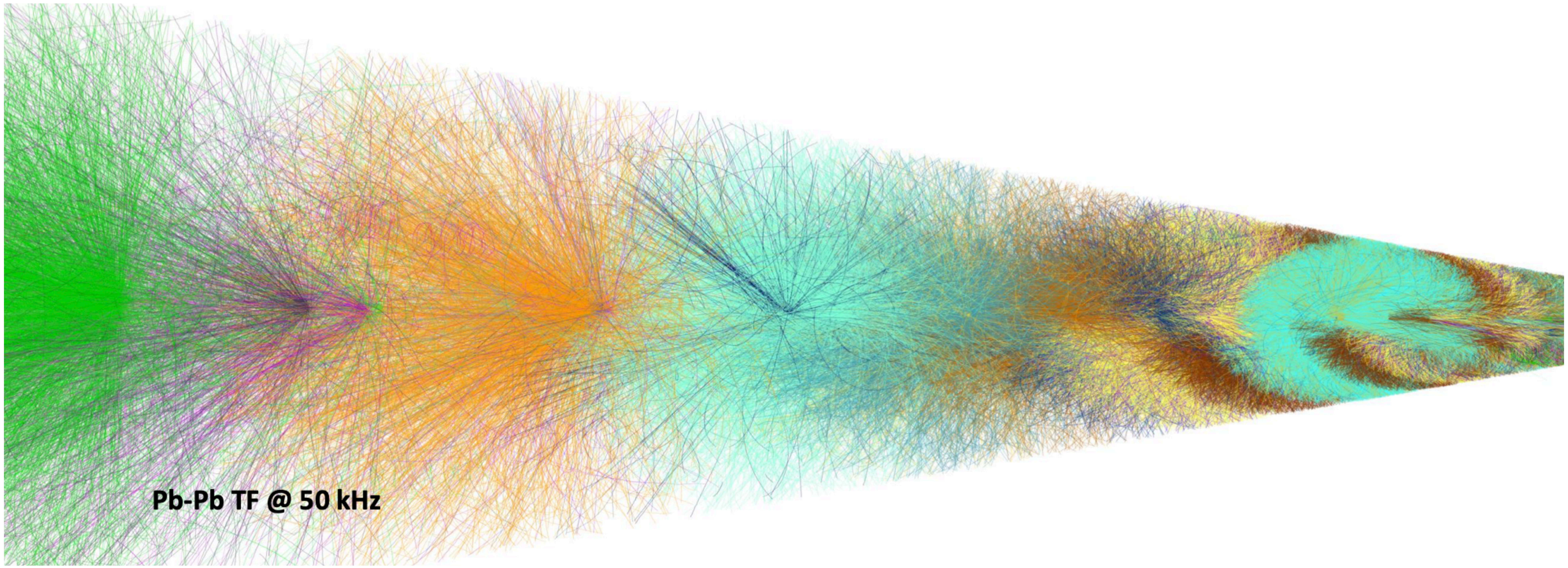
ALICE in Run 3

ALICE in Run 2

sPHENIX at RHIC

(See backup slides)

Continuous-readout mode for ALICE and sPHENIX

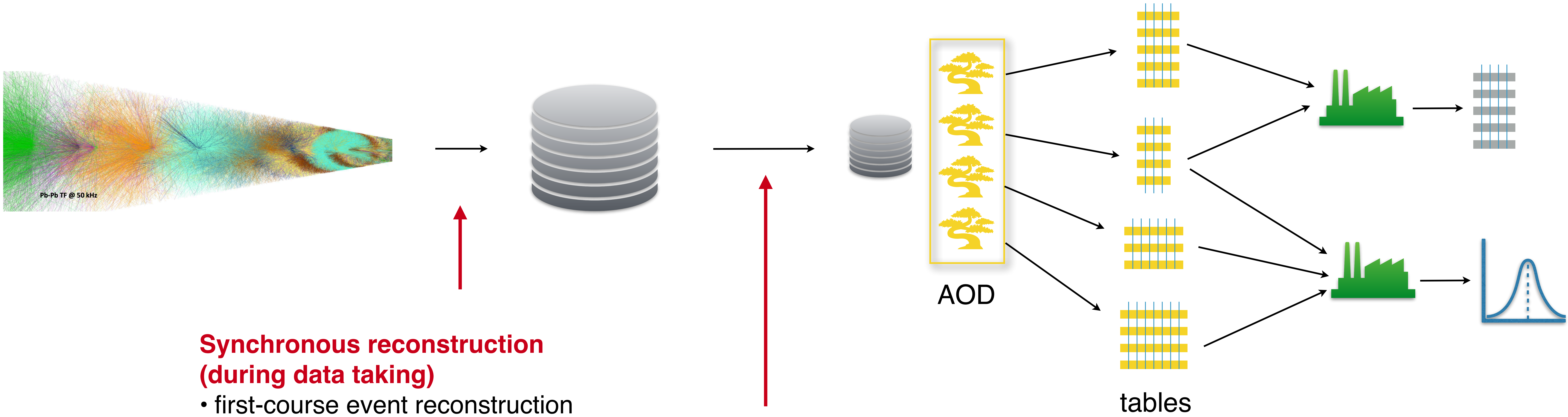


Data are <u>not</u> recorded event-by-event but → stream of data for fixed time intervals!

Challenges: event-track association, reduce storage needs, increase processing efficiency, …

ALICE offline-to-Online (O^2) data processing system

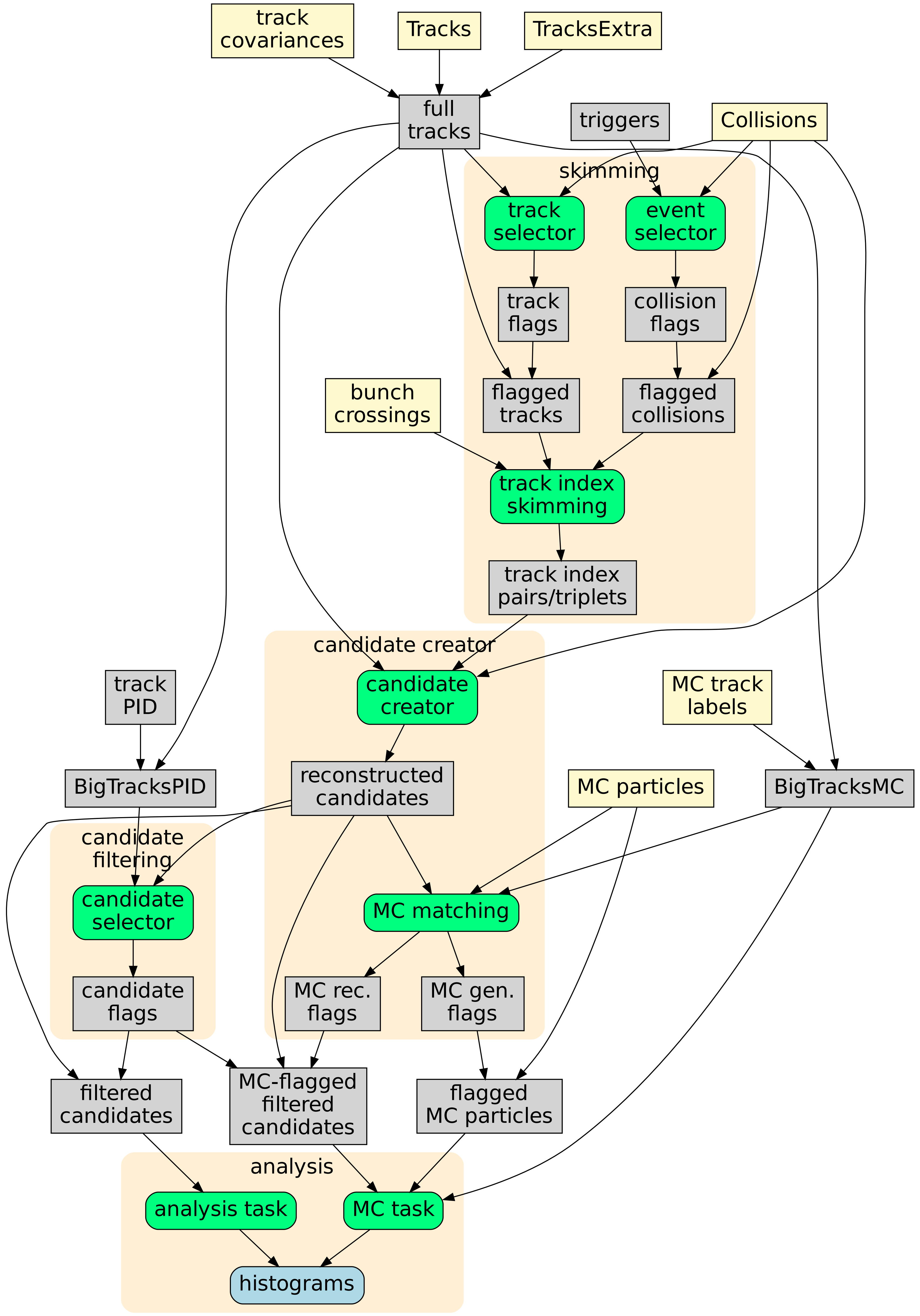
- **Tabular ("flat") data format** for both reconstruction and analysis (Apache Arrow)
- **Extreme data volume reduction** (already performed while taking data)



Synchronous reconstruction (during data taking)
- first-course event reconstruction and calibration
  → **data-size reduction!**

Asynchronous step (after data taking)
- final calibration and vertex/ track reconstruction
  → **output stored in AODs**

A new analysis framework for HF analyses



- **Flat-tables as data format**
  → efficiency and **compatibility with a continuous stream of data**
- **optimized data format for minimizing storage needs**
  → only decay tracks indices saved instead of the full HF candidate
- **Suitable for both offline and online processing**
  → designed to be used for proton-proton heavy-flavor tagging
- **Optimized/ready for ML techniques**

For more detail: V. Kucera et al. CHEP 2021 proceedings

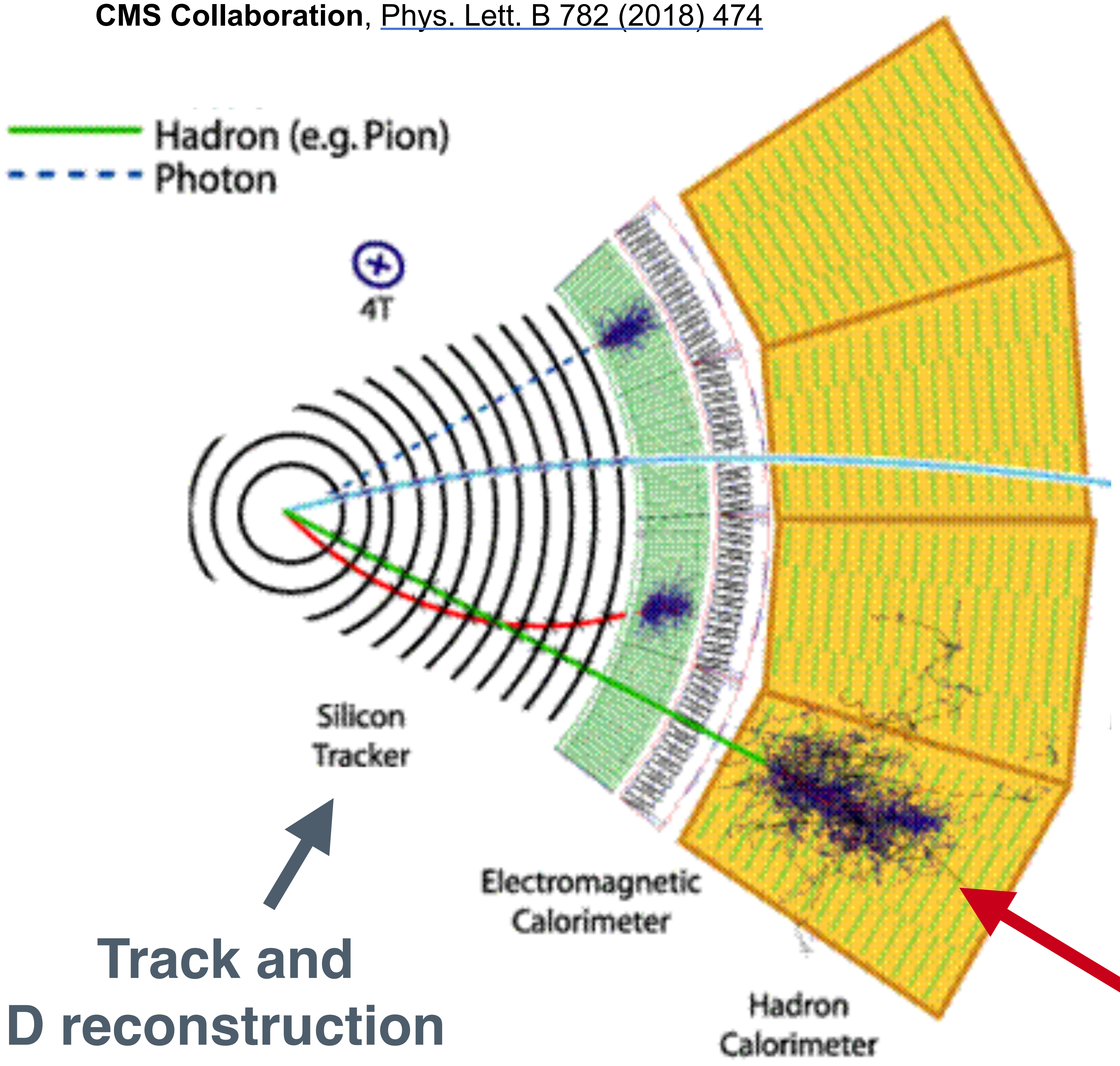
HF physics in "triggered" mode up to high p_T

Heavy-flavor physics in "triggered" mode

Challenges:

- extend high-p_T reach of HF hadrons and HF-jets
- fully reconstructed beauty hadrons

CMS Collaboration, Phys. Lett. B 782 (2018) 474



Track and D reconstruction

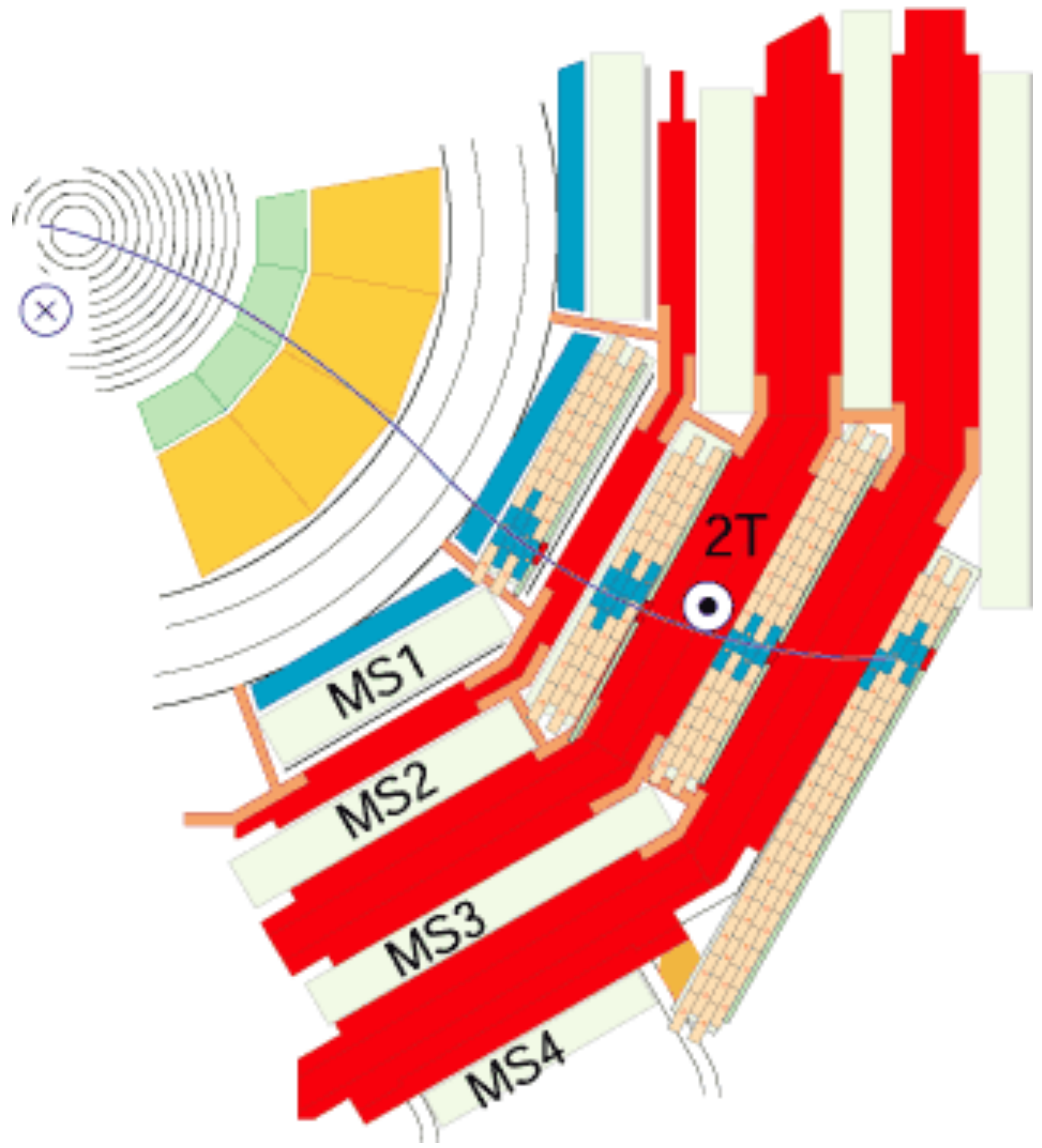
Techniques:

→exploit general-purpose HEP experiments (calorimetry)

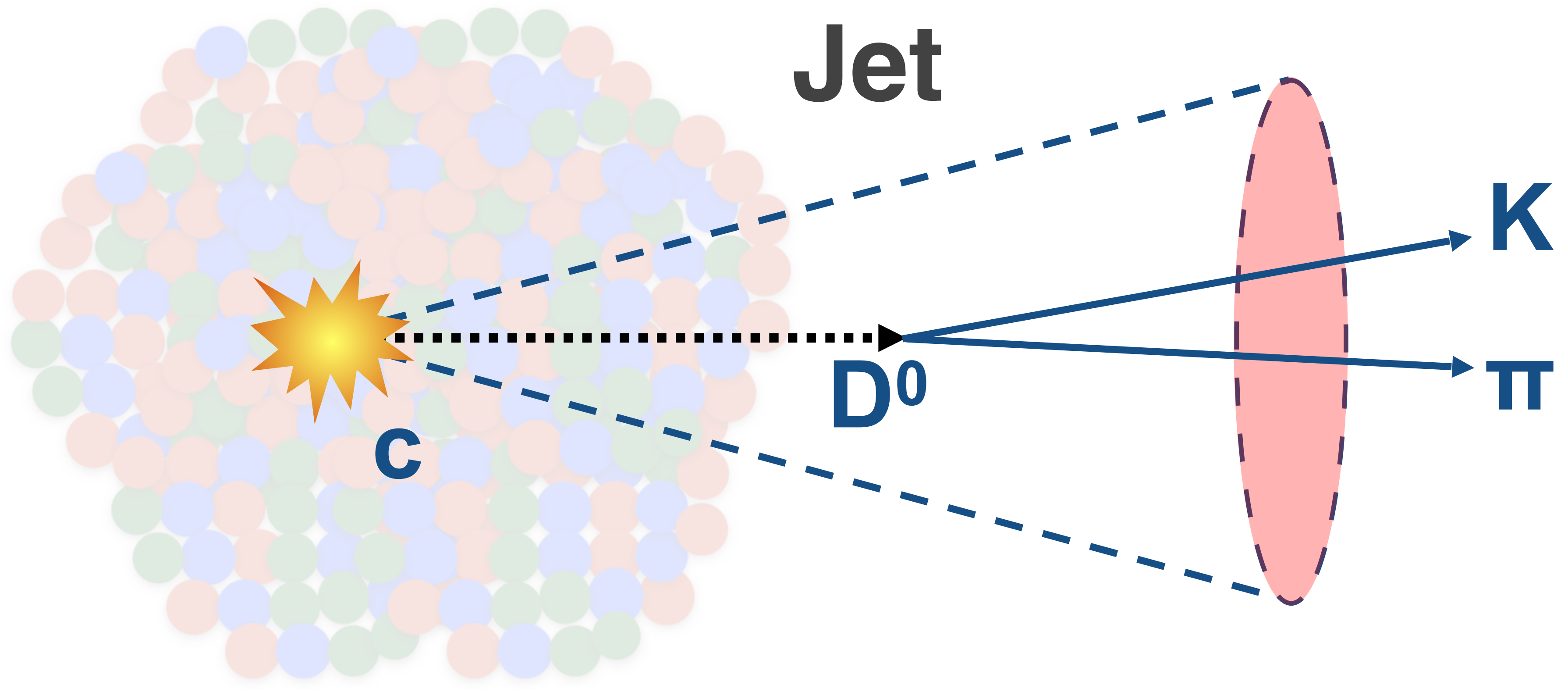
→new triggers for heavy-flavor in heavy-ion collisions

An example: HF measurements in heavy-ions with CMS

B-hadron analyses in heavy-ion collisions
with e.g. $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$
→ exploit **outstanding muon capabilities of** CMS
→ **direct** access to the energy loss of b quarks



HF measurement up to high-p_T



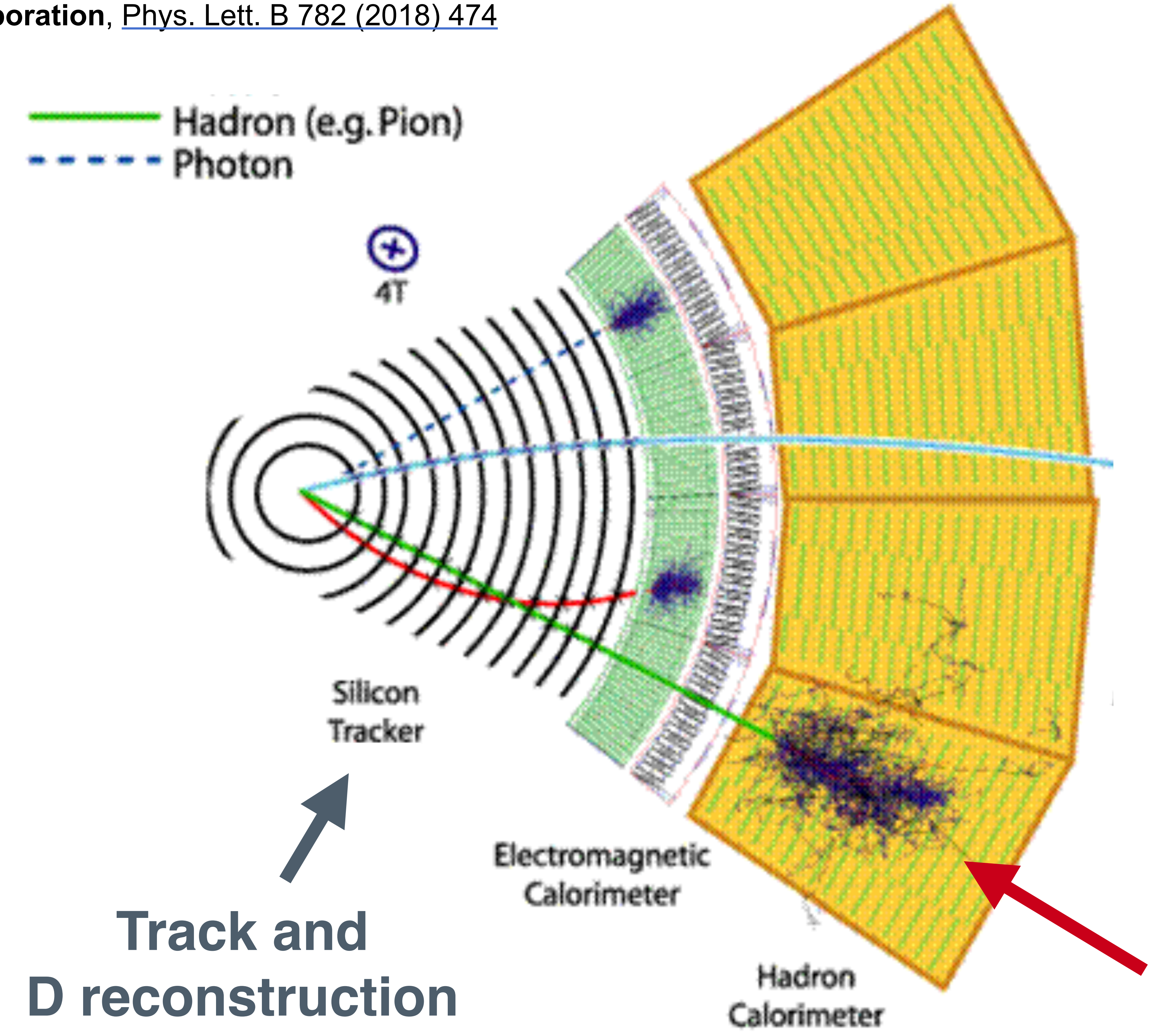
b-jet and D^0 jet-based triggers in heavy-ion collisions

- **hardware triggers with jet-background subtraction**
  → upgrade of the Level-1 trigger system
- **"Online" HQ tagging using software (High-Level) triggers**

CMS Collaboration, Phys. Lett. B 782 (2018) 474
B. Kreis, G.M. Innocenti et al., 2016 JINST 11 C01051

Online D^0–triggers in PbPb collisions

CMS Collaboration, Phys. Lett. B 782 (2018) 474



Track and D reconstruction

First "Level-1" (hardware) background-subtracted jet triggers

↓

Track reconstruction
with optimized faster algorithms

↓

D-meson reconstruction

↓

D-meson selection
optimized for poor calibrations and alignment

↓

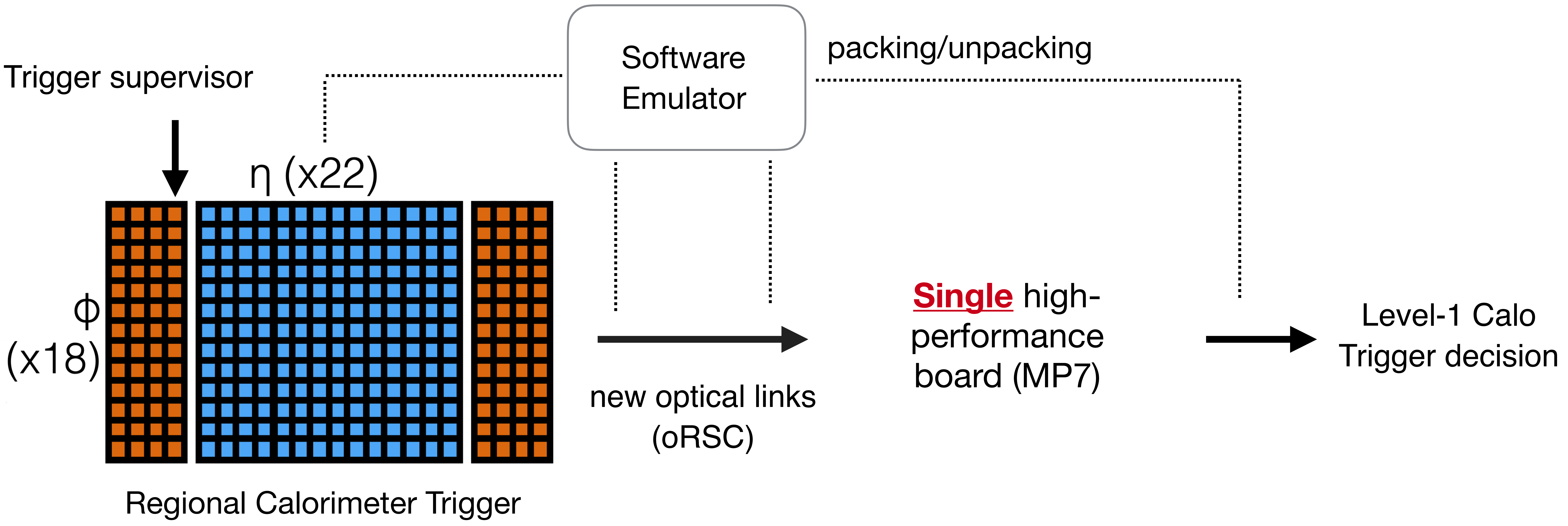
Event acquired and stored!

→ **high-p_T D^0 mesons of a factor about 100 in PbPb collisions**

CMS Collaboration, Phys. Lett. B 782 (2018) 474
B. Kreis, G.M. Innocenti et al., 2016 JINST 11 C01051

Level-1 calorimeter trigger upgrade for CMS (Stage 1)

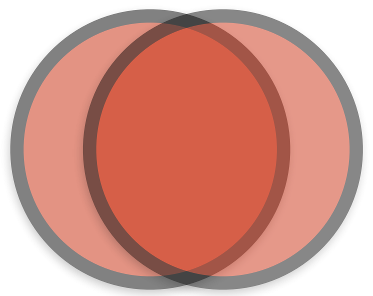
→ **A single board** to process the entire calorimeter and **allow for complex algorithms (e.g. jet subtraction) at Level-1**



B. Kreis, G.M. Innocenti et al., 2016 JINST 11 C01051

New insights into charm E_{loss}

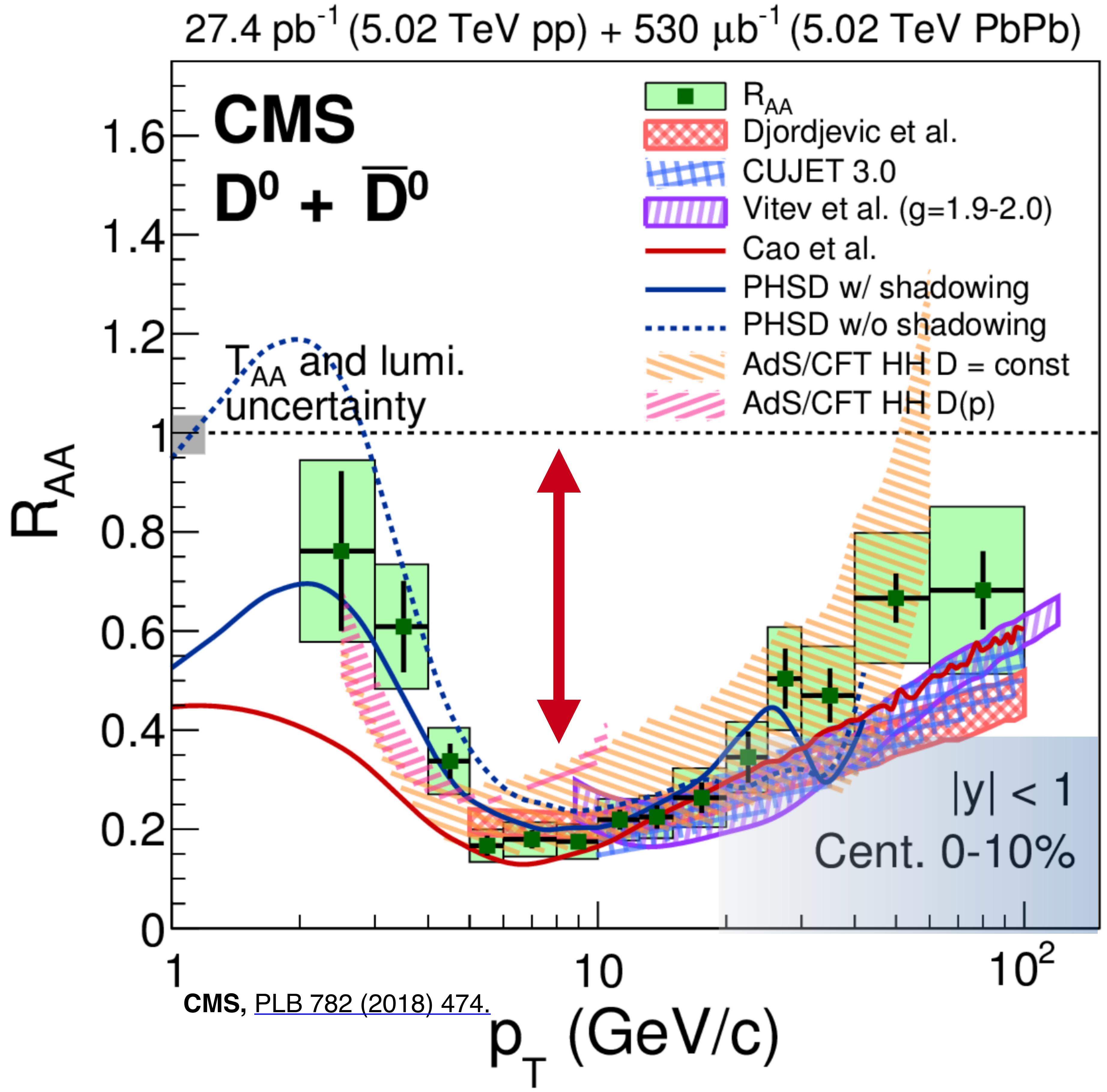
D^0 mesons



Central 0-10%

→ head-on collision!

→ larger energy density



CMS, PLB 782 (2018) 474.

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN/dp_T(AA)}{dN/dp_T(pp)}$$

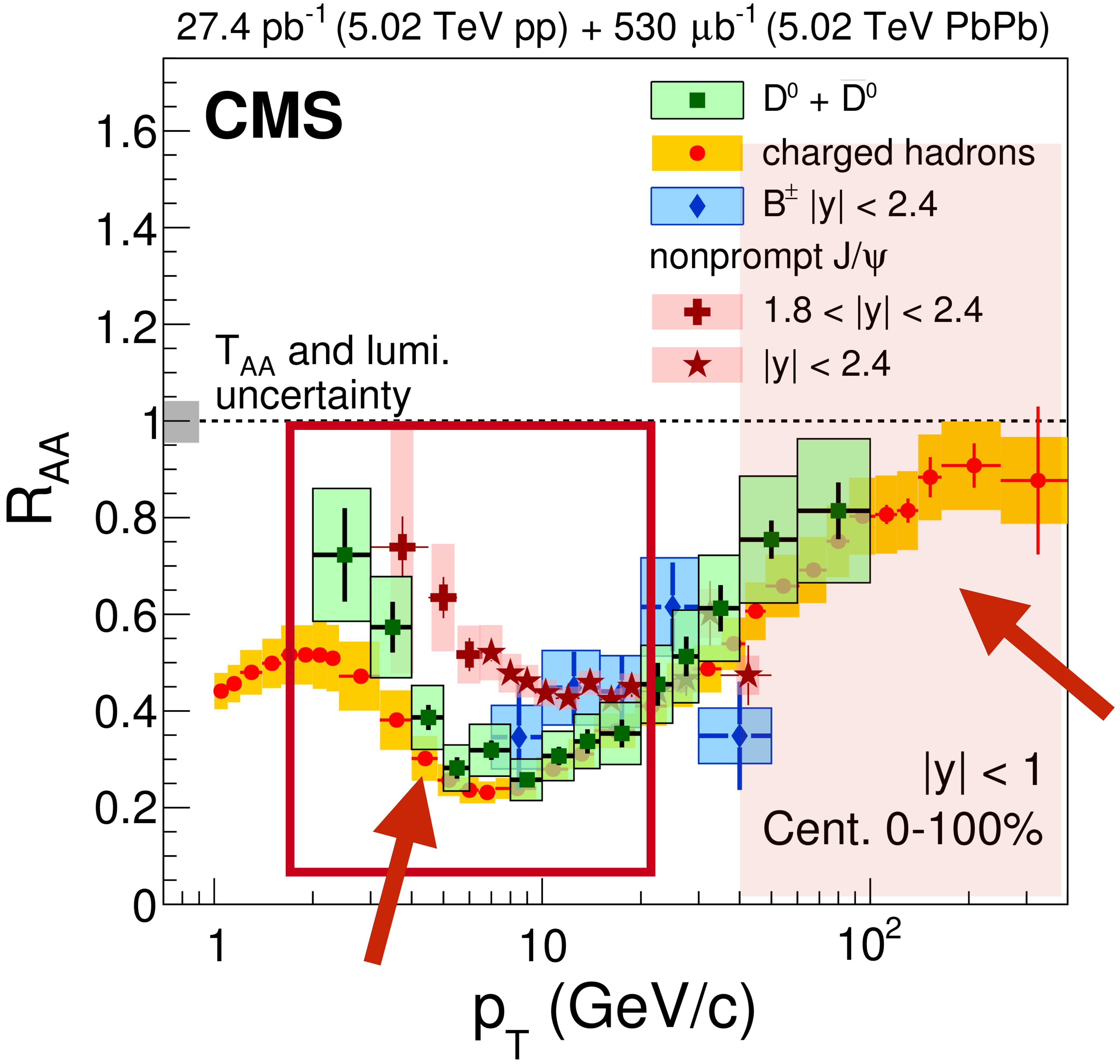
← R_{AA}=1: **no modification**

High-p_T region accessible with D^0 triggers!

R_{AA} << 1 → charm quarks strongly interact with the hot medium, and lose a sizeable amount of energy!

New constraints on flavor dependence of E_{loss}

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN/dp_T(AA)}{dN/dp_T(pp)}$$

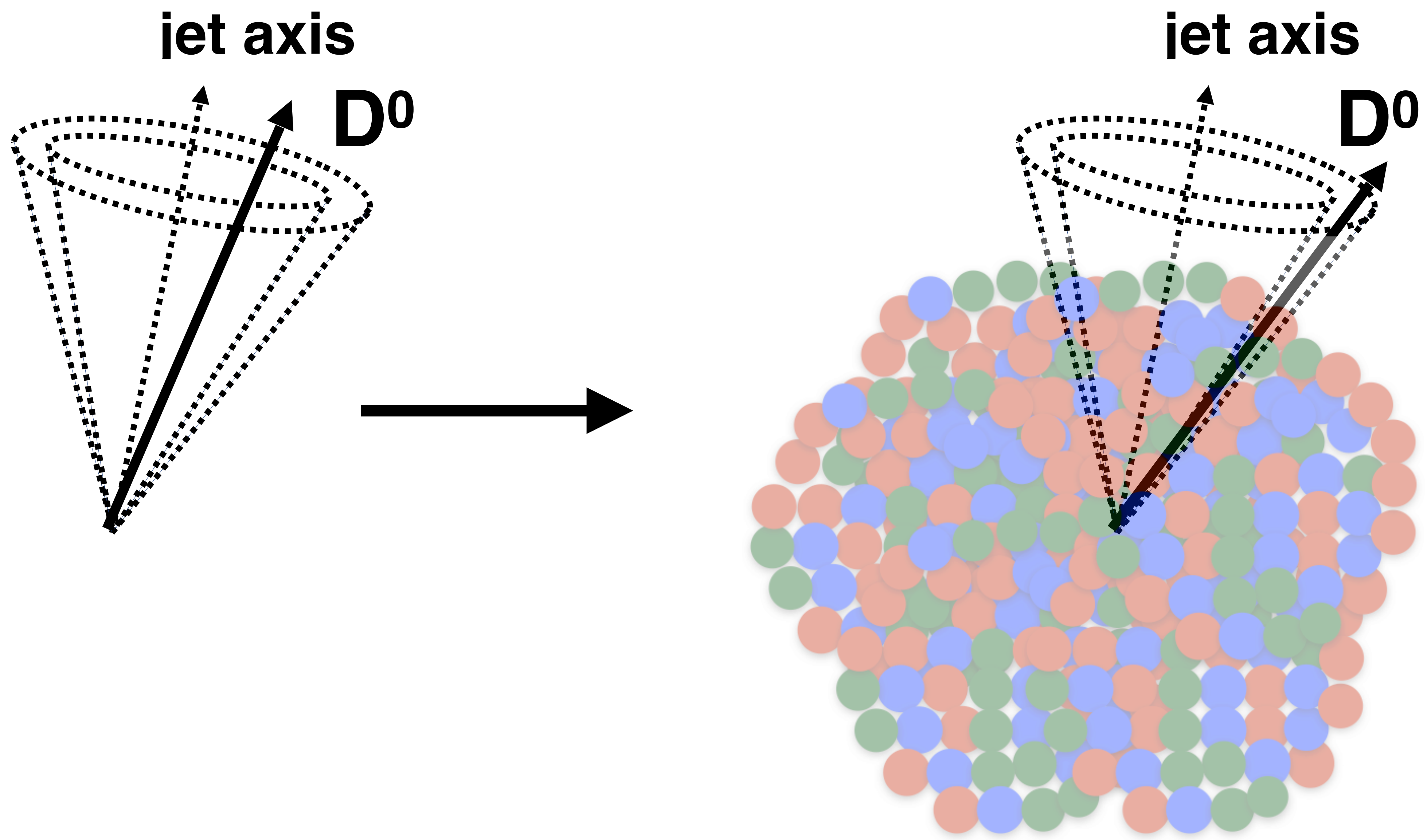


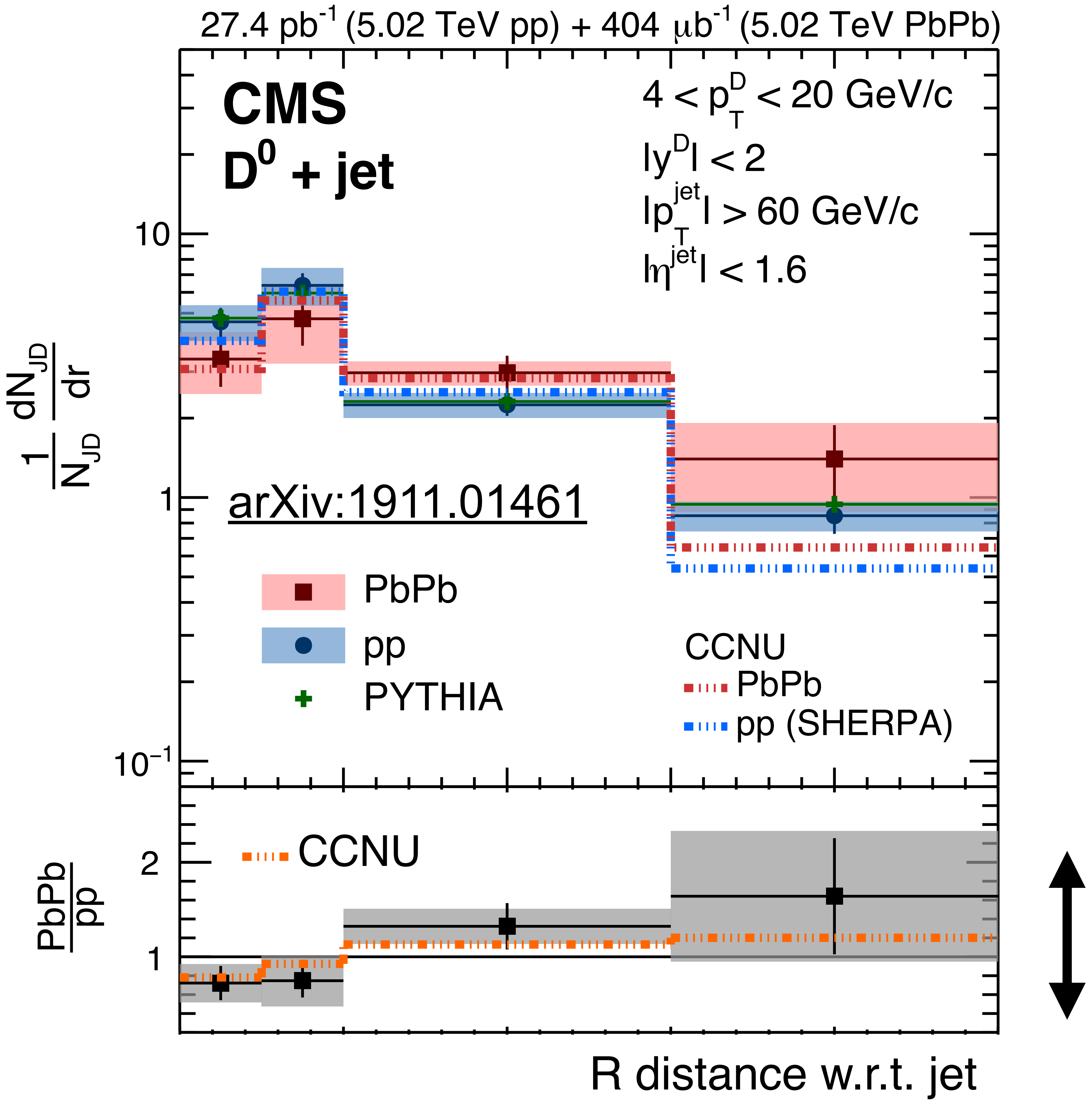
Charged hadrons
D^0 mesons
B^+ mesons
b→J/ψ

vanishing mass-dependence at high-p_T
→ only possible with D^0-triggers!

"Structure" of charm-jets in PbPb collisions

→ **Enabled studies of jets with heavy-flavour hadrons**
→ E.g. the radial distribution of D^0 inside a jet with respect to the jet axis

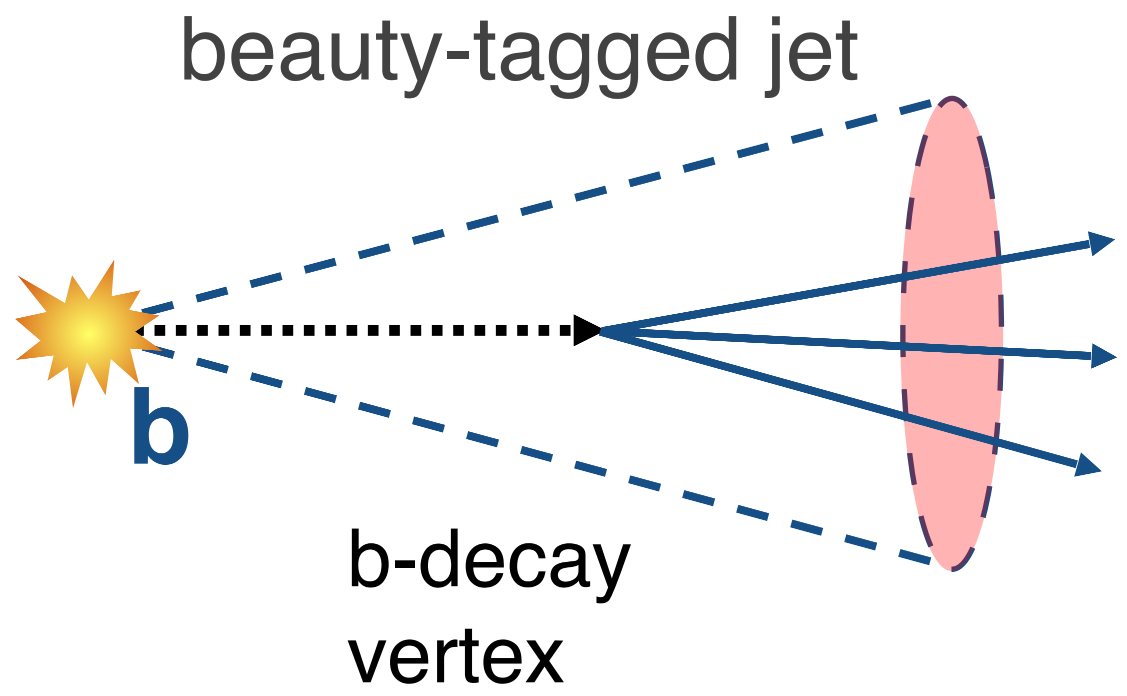


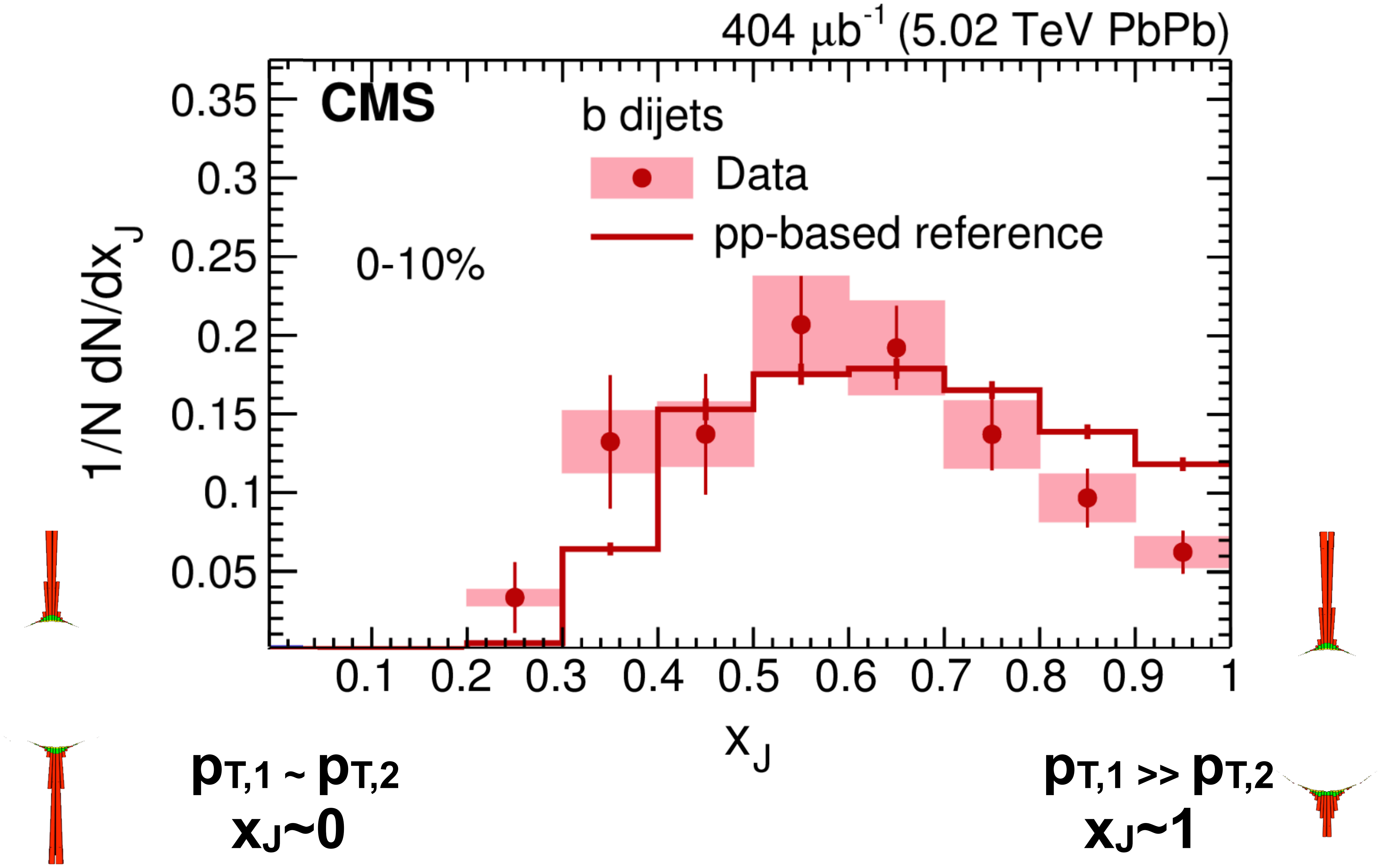


→ Sensitive to mechanism of charm diffusion inside the QGP medium
→ **First insights into the inner structure of HF jets**

- In PbPb D^0 "pushed" far from the jet cone
→to be confirmed by future measurement

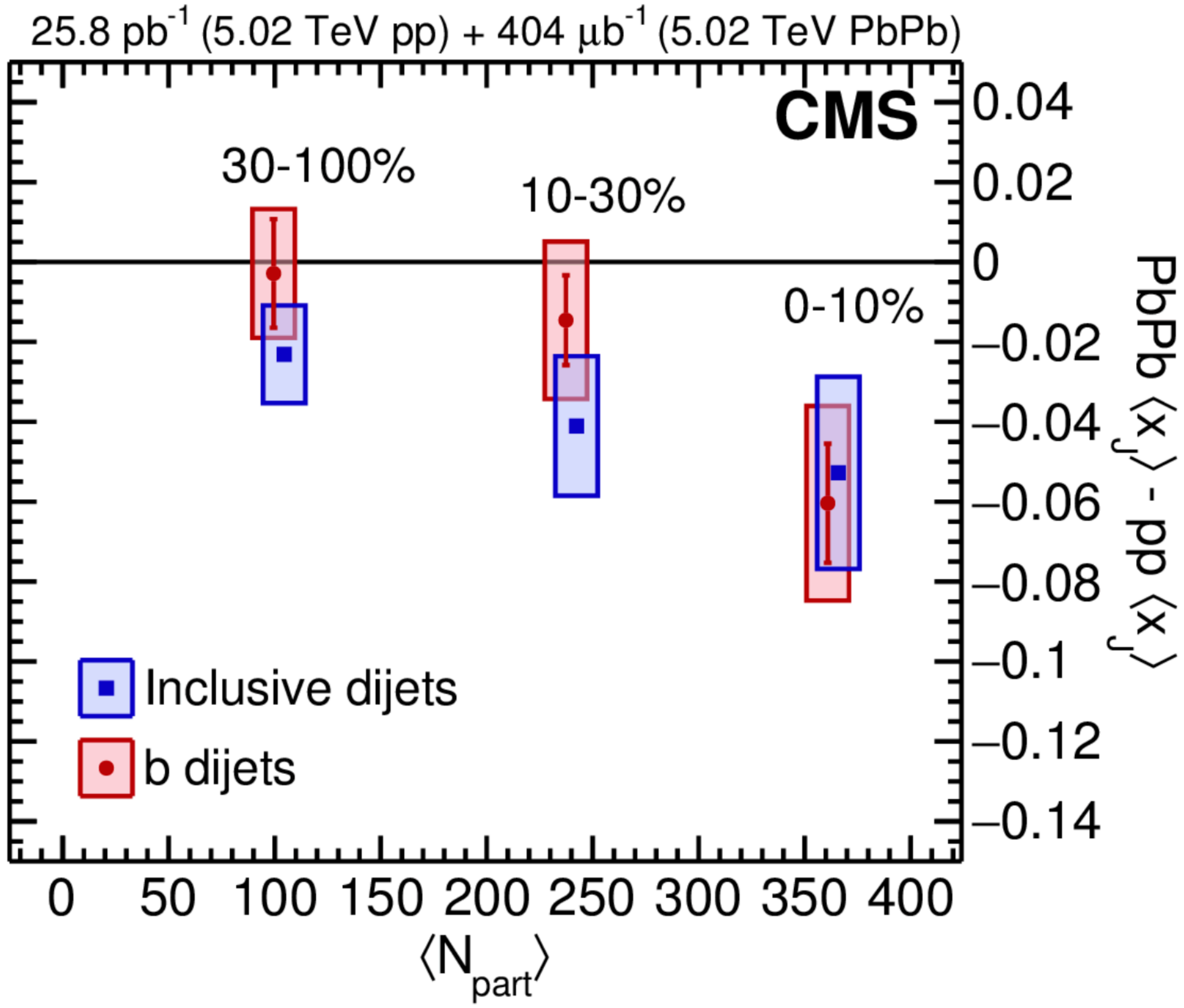
Transverse momentum balance of b jet pairs





b-jets show an increased p_T-asymmetry in PbPb

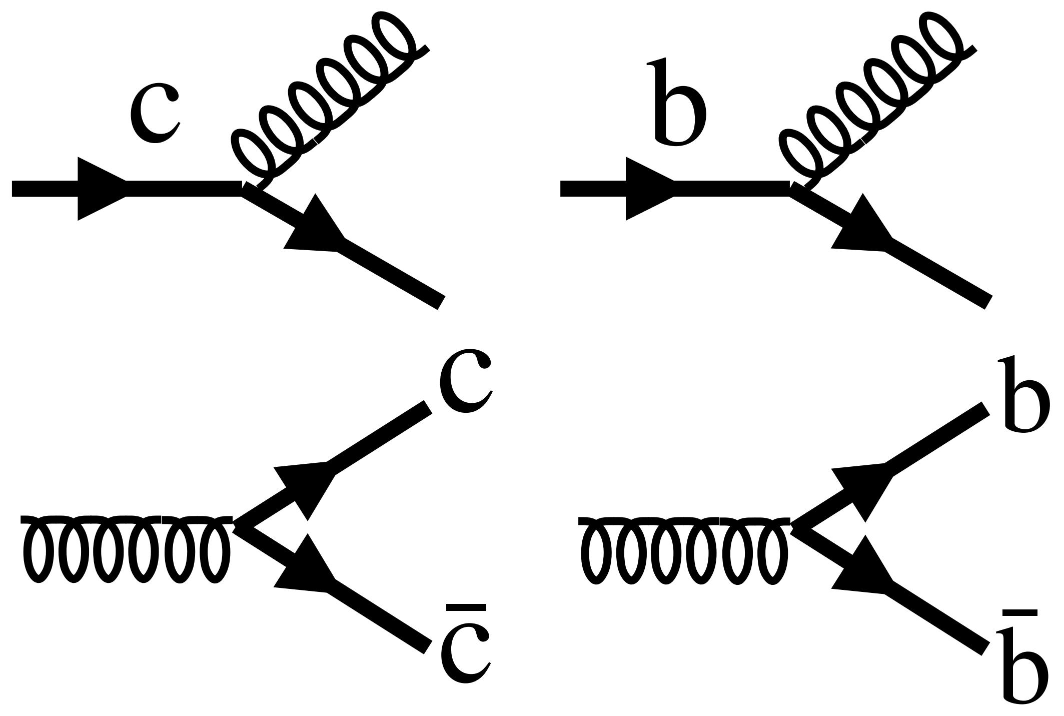
consistent with in-medium E_{loss}

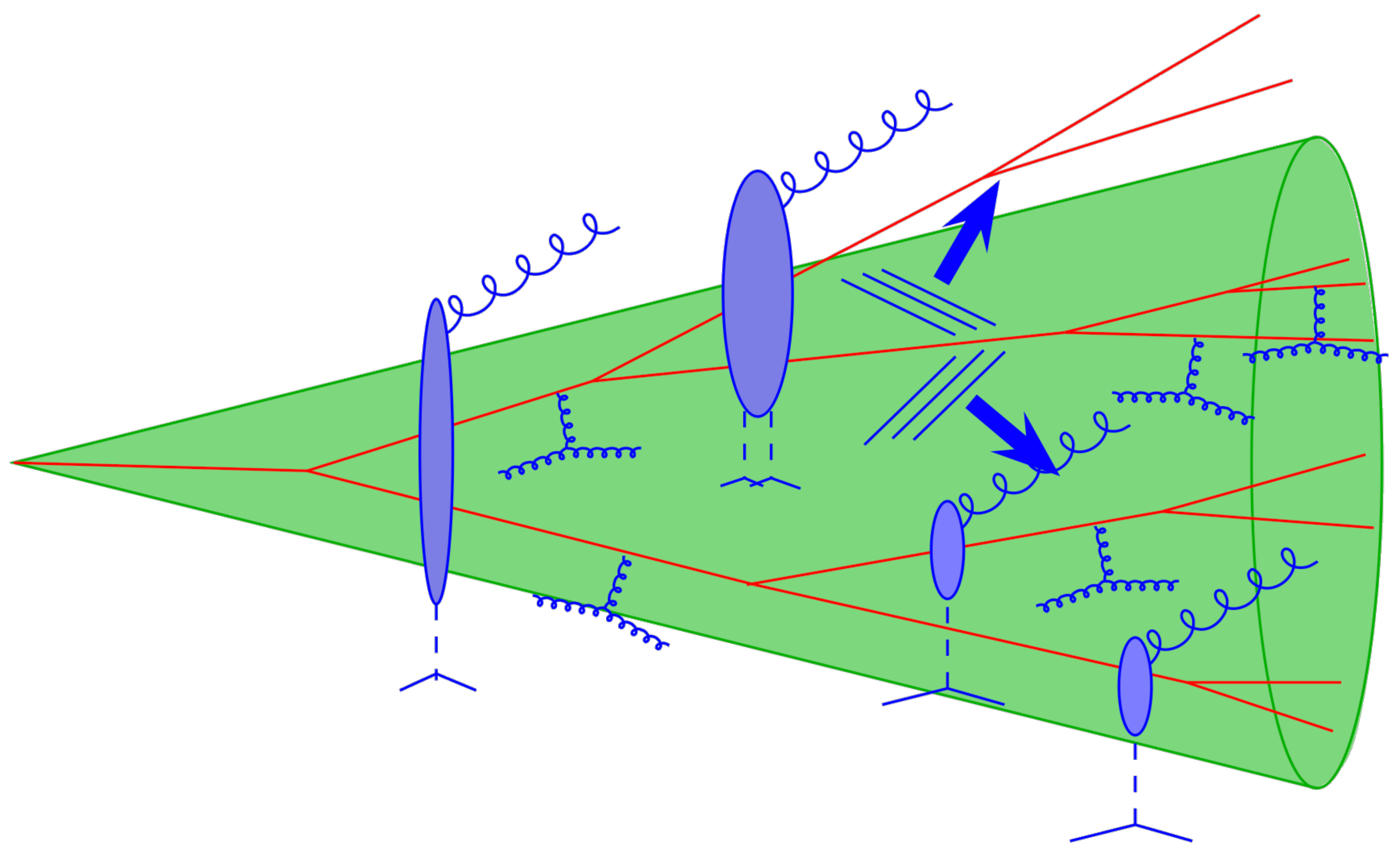


Magnitude of the effect is similar for b jets and inclusive jets

CMS, JHEP 03 (2018) 181

Heavy-flavor jets: a new territory for heavy-ion physics

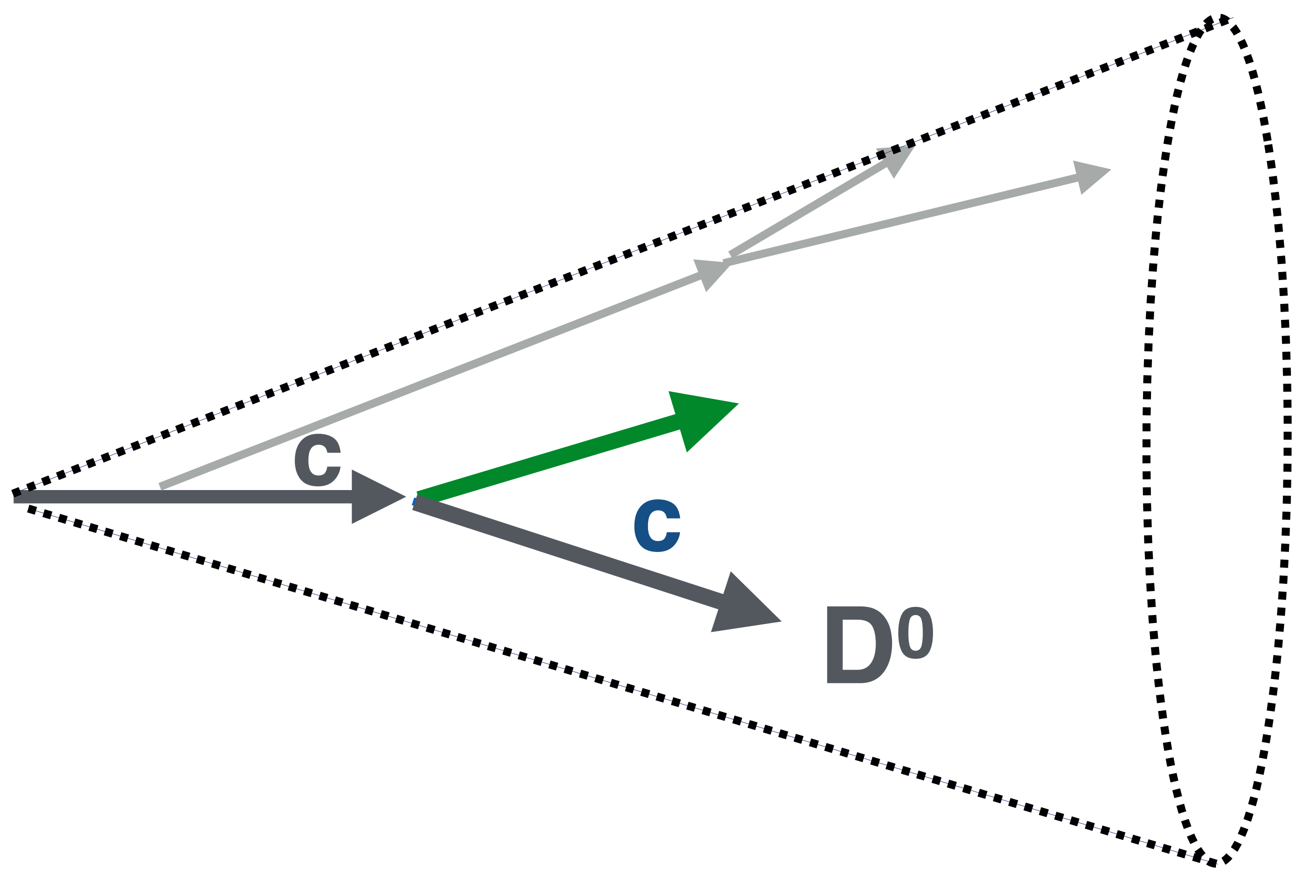




- Textbook-grade characterization of in-medium splitting functions?
- Time-space evolution of jet quenching?
- New tools for characterizing hadronization mechanisms?

Fully-reconstructed D^0 mesons as proxy for c quarks

Exploiting recent reclustering and "grooming" techniques
→ **First study of the p_T-balance (z_g) of the first splitting of the c-quark**

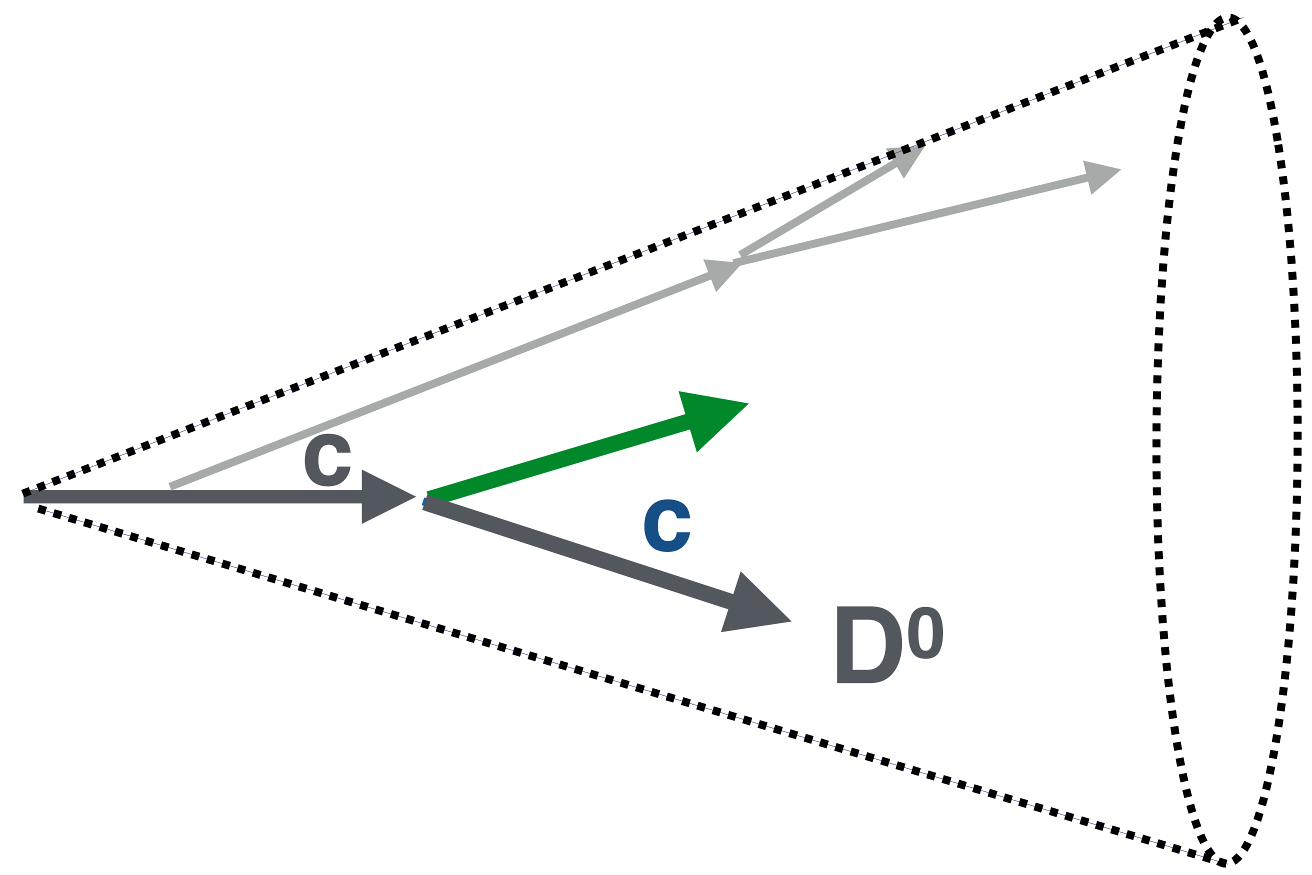


p_T balance between prongs $$z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

First measurement of the c→ cg splitting function in vacuum

Exploiting recent reclustering and "grooming" techniques

→ **First study of the p_T-balance (z_g) of the first splitting of the c-quark**

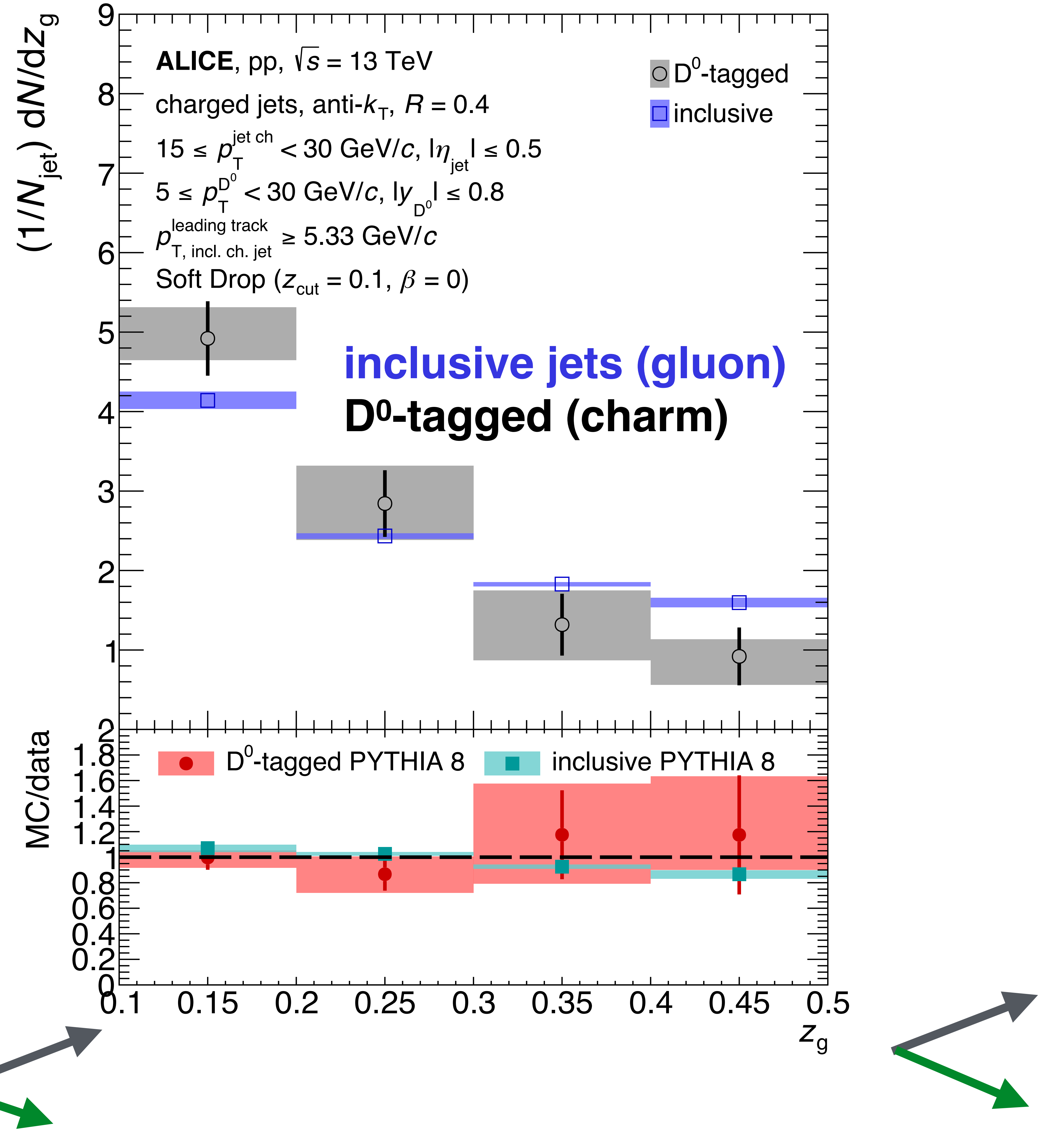


p_T balance between prongs $$z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

→ **fewer "p_T"-symmetric splittings for c-quarks than gluons** as expected in the presence of dead-cone effect

First constraints on the c→cg splitting function in pp collisions and benchmark for future heavy-ion measurements

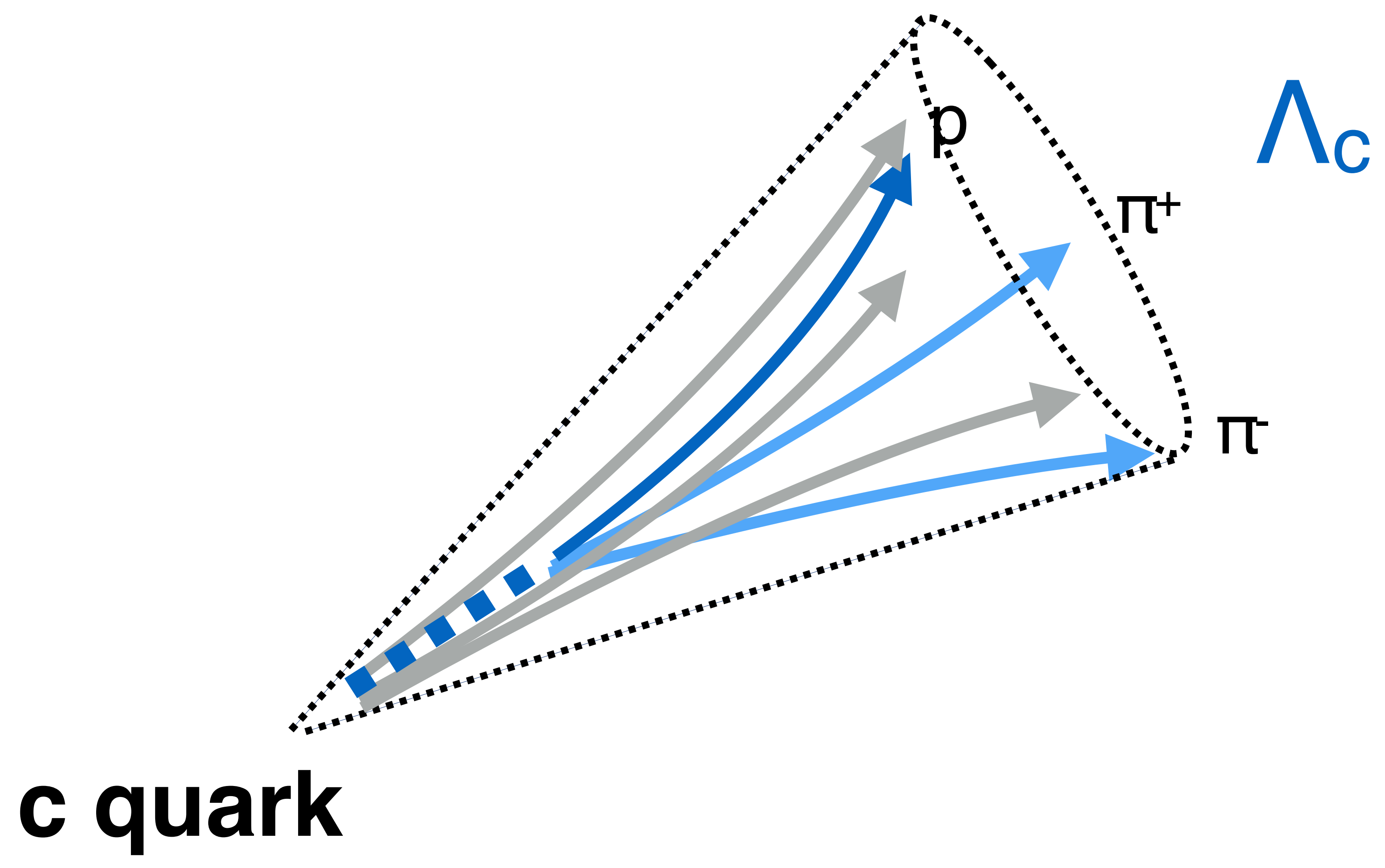
P. Ilten, N. L. Rodd, J. Thaler, M. Williams, Phys. Rev. D 96, 054019 (2017)
L. Cunqueiro, M. Ploskon, Phys. Rev. D 99, 074027 (2019)



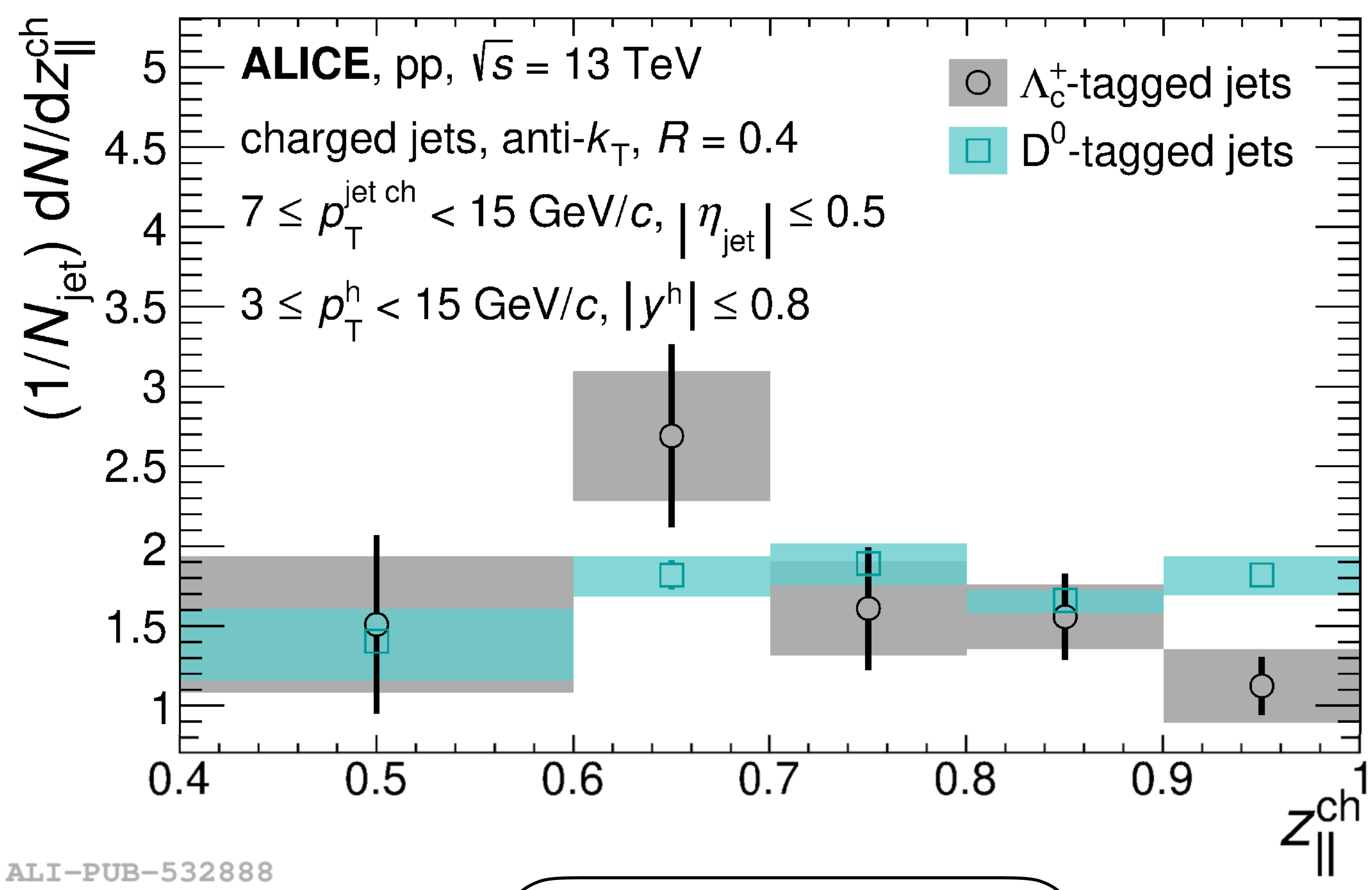
ALICE, arXiv:2208.04857, accepted by PRL

Searches for "new" hadronization in pp collisions with HF jets

Longitudinal momentum fraction carried by the Λ_c



ALICE collaboration, arXiv.2301.13798



→ Hint of softer fragmentation for **Λ_c (baryon)** w.r.t. **D^0 (meson)**

→ **Not consistent with in-vacuum fragmentation**

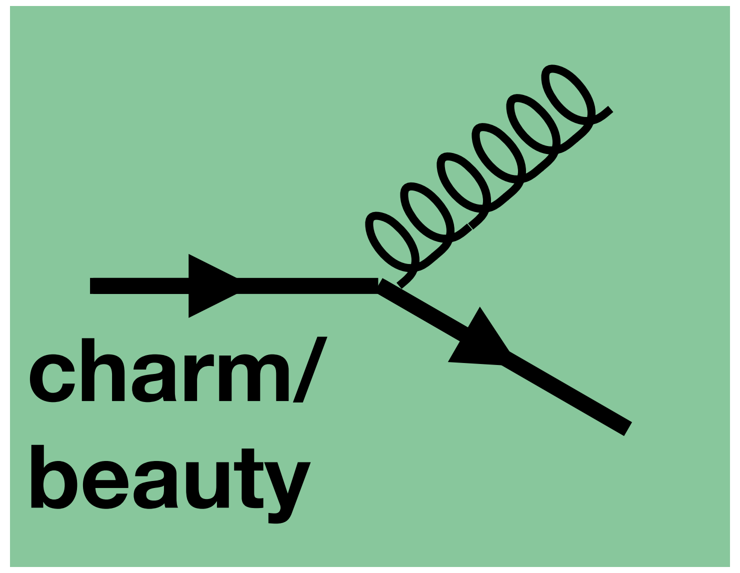
Hadronization universality is broken already in pp!

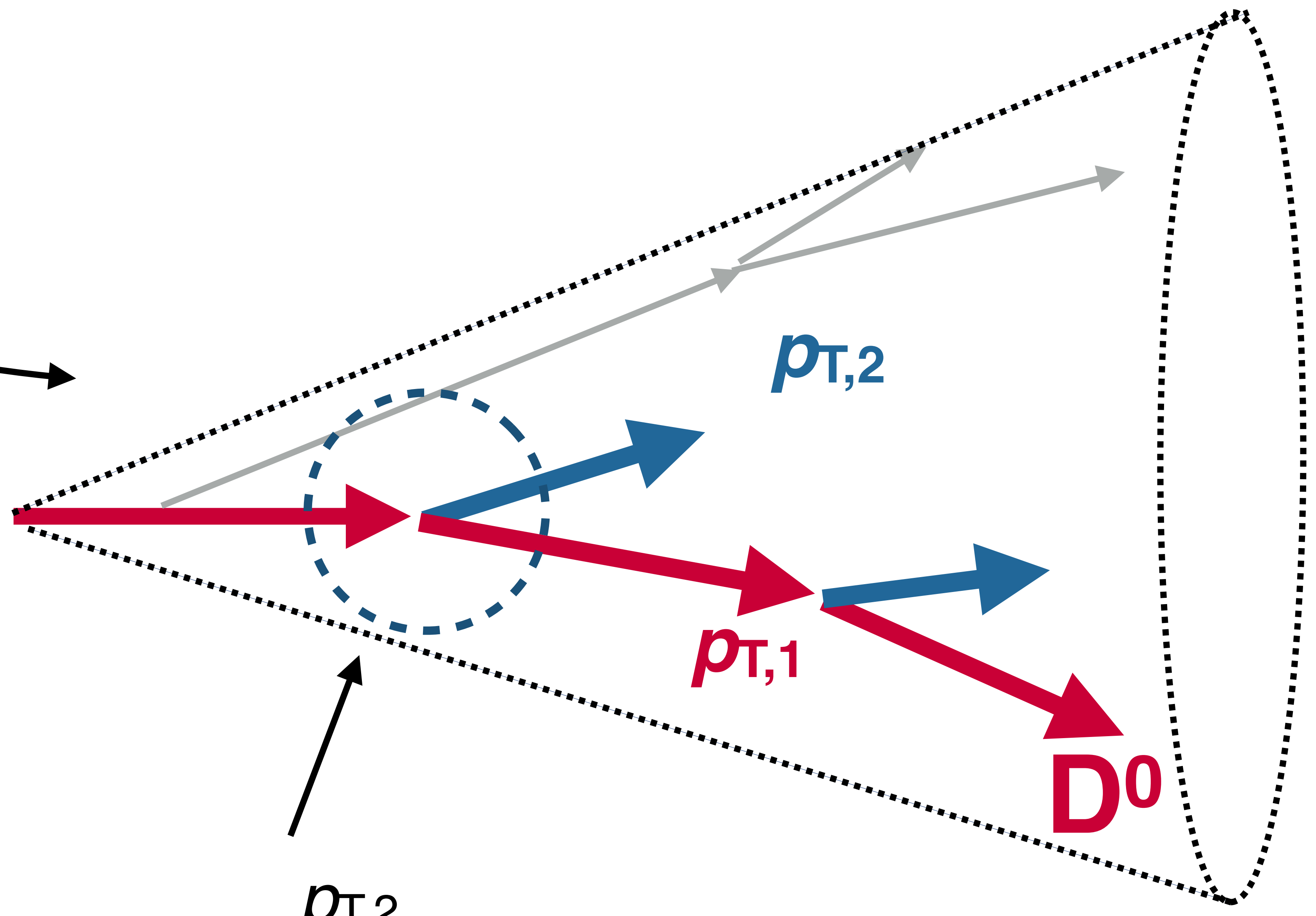
$\sigma(pp \to H_Q X) = \text{PDF} \otimes \boldsymbol{\sigma(\text{pQCD})} \otimes D^{\text{vacuum}}(z,Q^2)$

$$z_{||}^{ch} = \frac{\boldsymbol{p}^{\text{jet ch}} \cdot \boldsymbol{p}^{\text{HF}}}{\boldsymbol{p}^{\text{jet ch}} \cdot \boldsymbol{p}^{\text{jet ch}}}$$

Future: characterization of c→cg splittings in the medium

$P_{med}(c \rightarrow cg)$





$$z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

"Follow" the heavy quark by tracing the fully reconstructed heavy-hadron

→ "grooming" to suppress non-perturbative splittings

→ explored in a first pp D^0-tagged jets study (link)

Measurements of z_g (and other substructure variables) for D^0 tagged, B^+ tagged jets in pp and heavy-ions:

→ First direct constraints on $P_{med}(c \rightarrow cg)$ and $P_{med}(b \rightarrow bg)$

P. Ilten, N. L. Rodd, J. Thaler, M. Williams, Phys. Rev. D 96, 054019 (2017)
L. Cunqueiro, M. Ploskon, Phys. Rev. D 99, 074027 (2019)

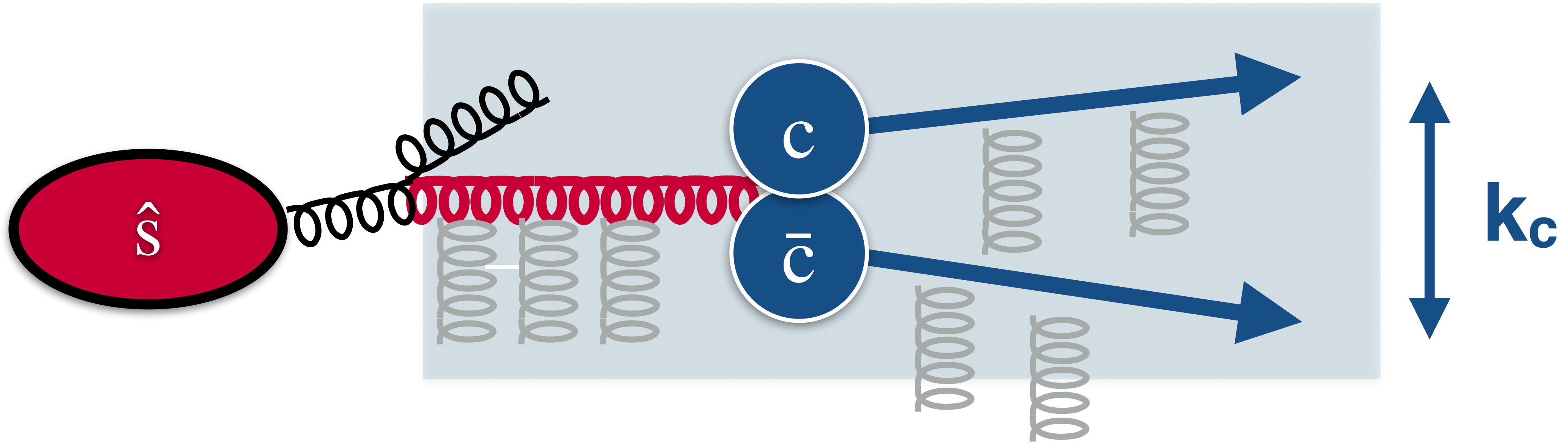
ALICE, arXiv:2208.04857, submitted to PRL

Future: "Boosted" $g \rightarrow c\bar{c}$: a new probe for quenching studies

Only heavy quarks→ **fully traceable, stronger theoretical control**

→ **Boosted** (time-delayed) → **splitting occurs in the medium**

$$\tau^{\mathrm{lab}}_{g\rightarrow c\bar{c}} \sim \frac{1}{Q}\frac{E_g}{Q} = \frac{E_g}{Q^2}$$



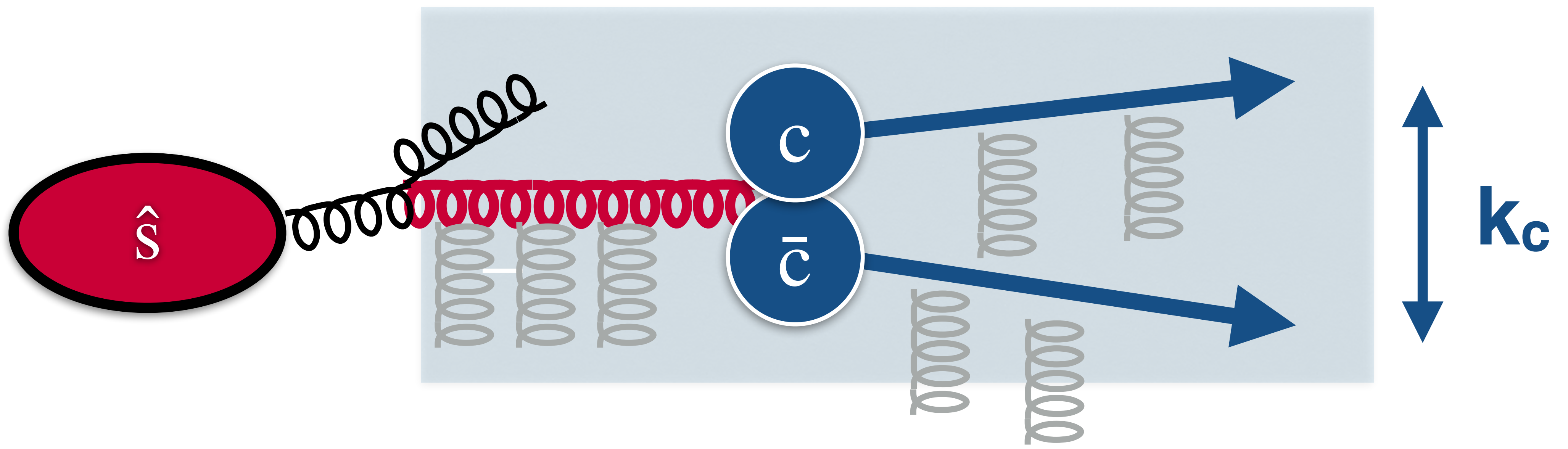
QGP with length L

→ **developed with the CERN theory group led by Dr. Urs Wiedemann**

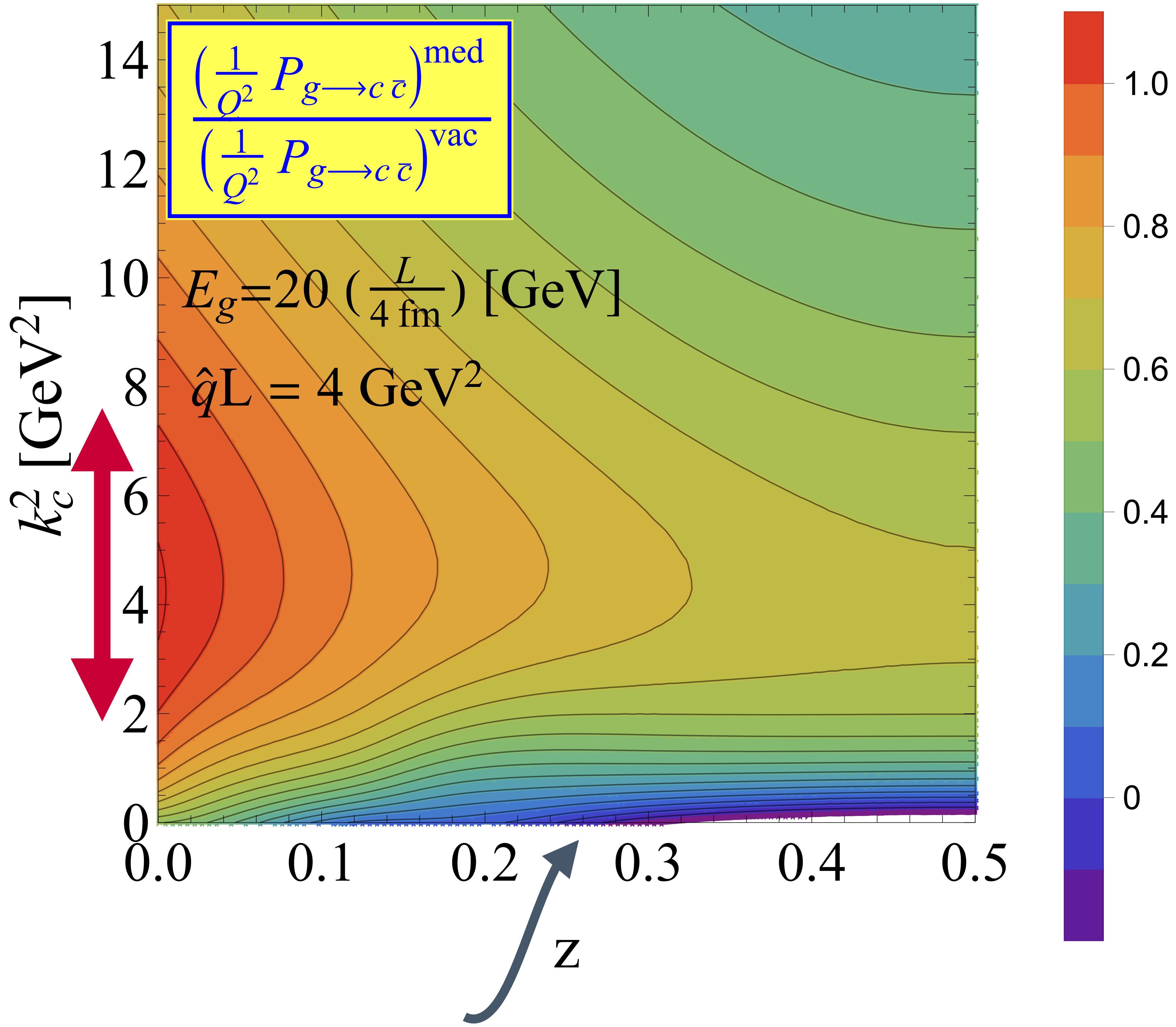
G.M. Innocenti, U. Wiedemann et al., arXiv:2209.13600, submitted to PRL
G.M. Innocenti, U. Wiedemann et al., JHEP 01 (2023) 080

"Boosted" g→c$\bar{c}$: a new probe for quenching studies

→ pQCD formalism (BDMPS-Z) to calculate $P^{med}_{g\to c\bar{c}}$



QGP with length L

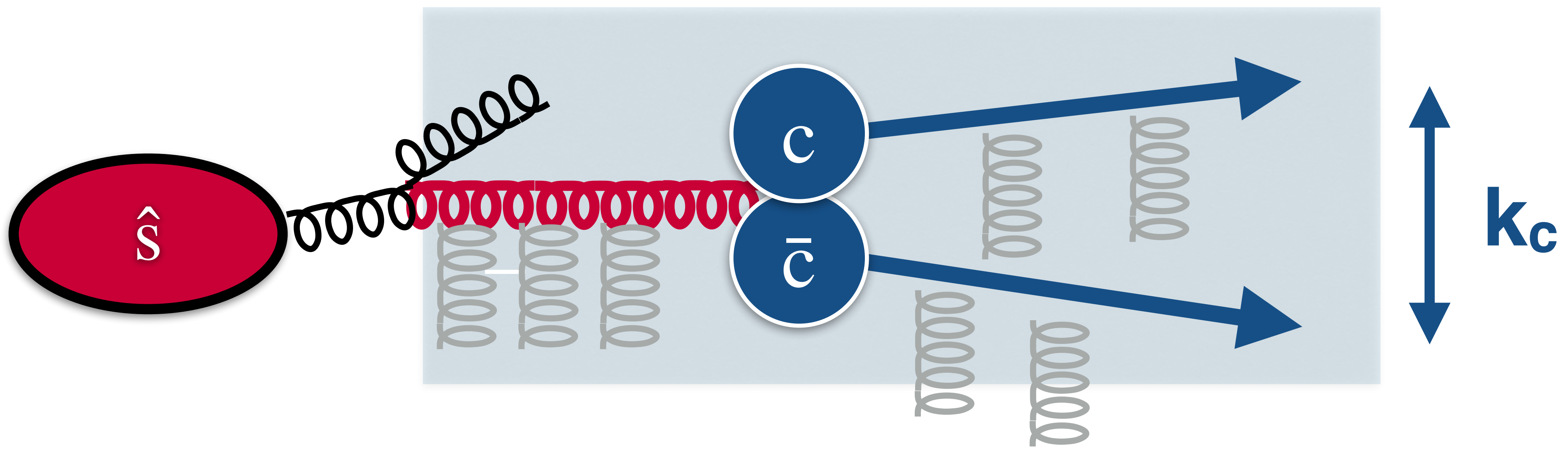


k^2_c **increases** due to transverse momentum broadening on the individual quarks

G.M. Innocenti, U. Wiedemann et al., arXiv:2209.13600, submitted to PRL
G.M. Innocenti, U. Wiedemann et al., JHEP 01 (2023) 080

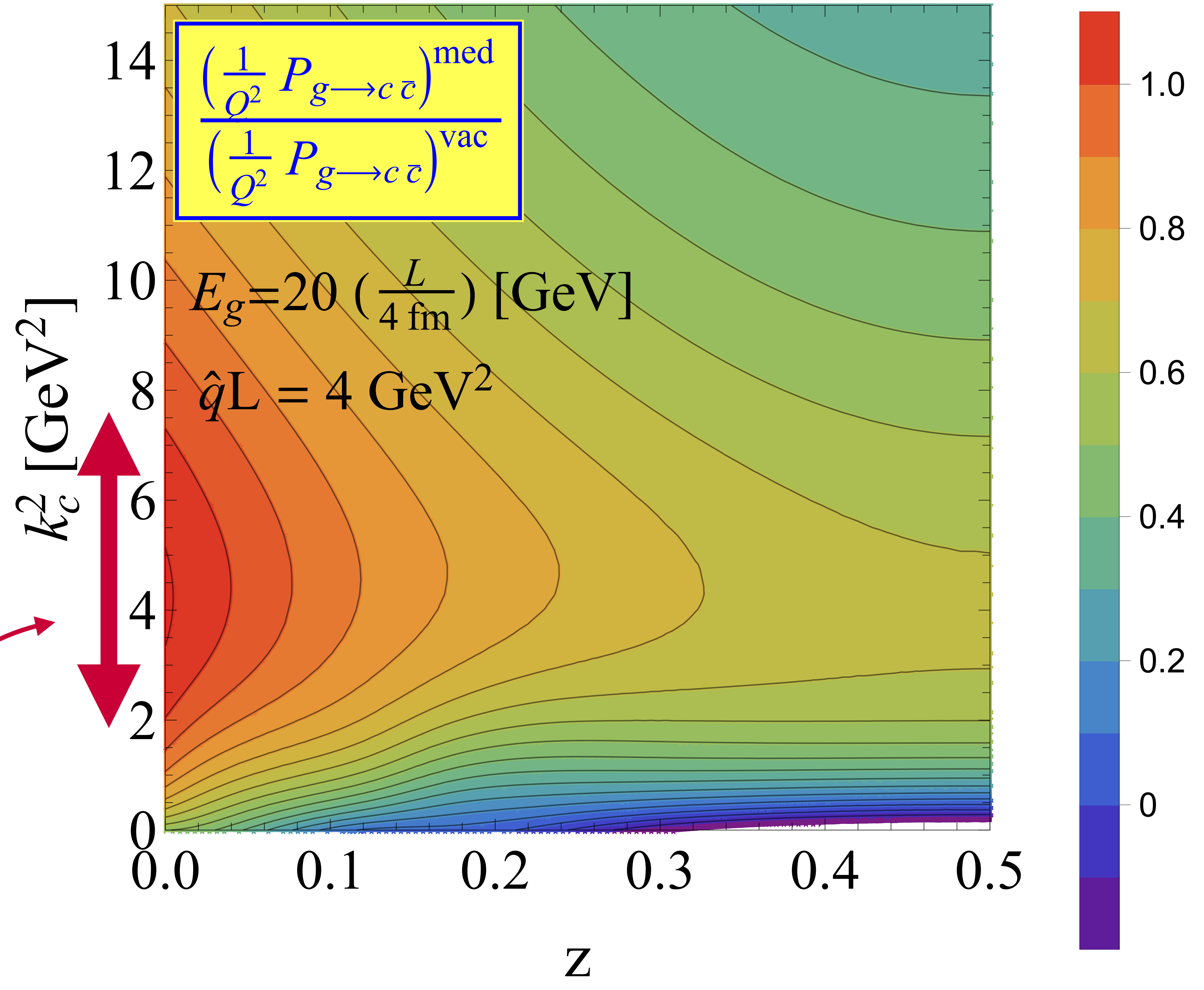
"Boosted" $g \to c\bar{c}$: a new probe for quenching studies

→ **pQCD formalism (BDMPS-Z) to calculate $P^{med}_{g \to c\bar{c}}$**



Net enhancement of g → $c\bar{c}$ splittings:

→ Gluons that would not split in the vacuum, can split due to the interaction with the QGP

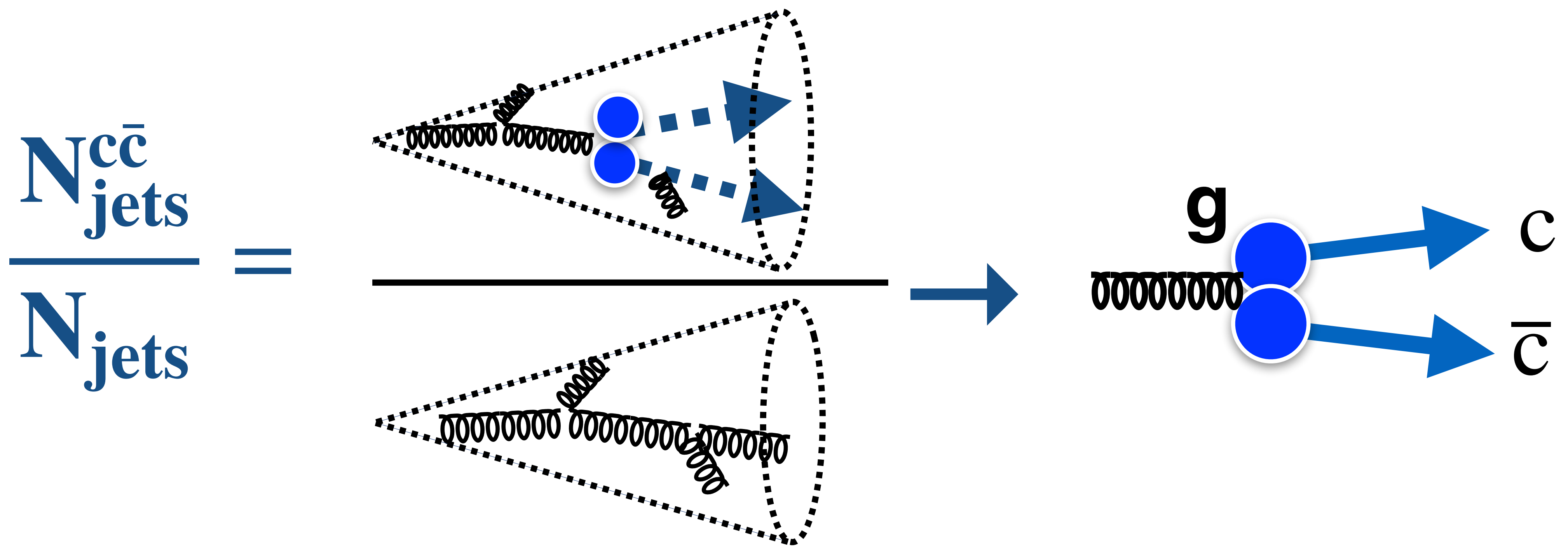


G.M. Innocenti, U. Wiedemann et al., arXiv:2209.13600, submitted to PRL
G.M. Innocenti, U. Wiedemann et al., JHEP 01 (2023) 080

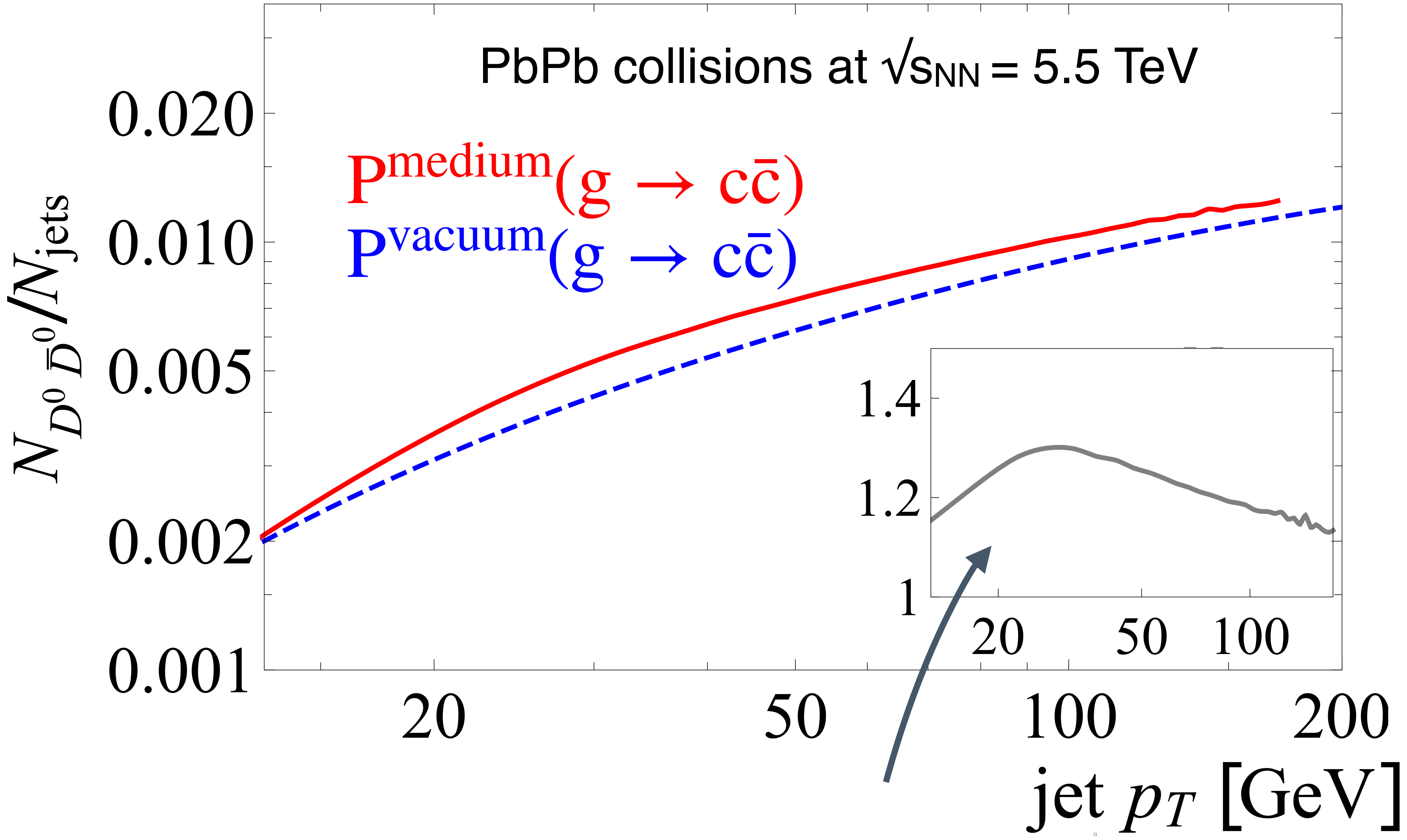
Toward measurements of $g \to c\bar{c}$ enhancement in HI collisions

Experimental strategy:

- $c\bar{c}$-tagged jets → almost pure source of $g \to c\bar{c}$
- $N^{c\bar{c}}_{jets}/N_{jets} \propto P^{med}_{g\to c\bar{c}}$



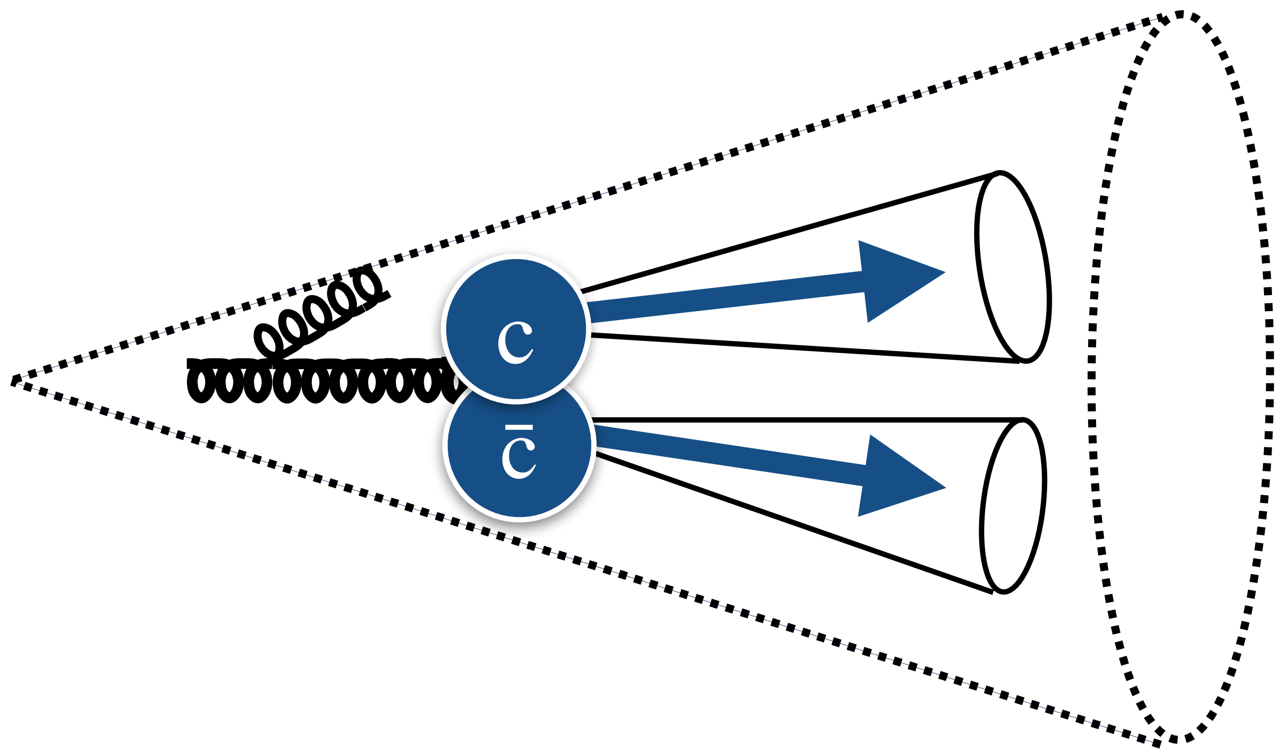
G.M. Innocenti, U. Wiedemann et al., arXiv:2209.13600, submitted to PRL



Up to ~30% increase as a consequence of modified $g \to c\bar{c}$ splitting function

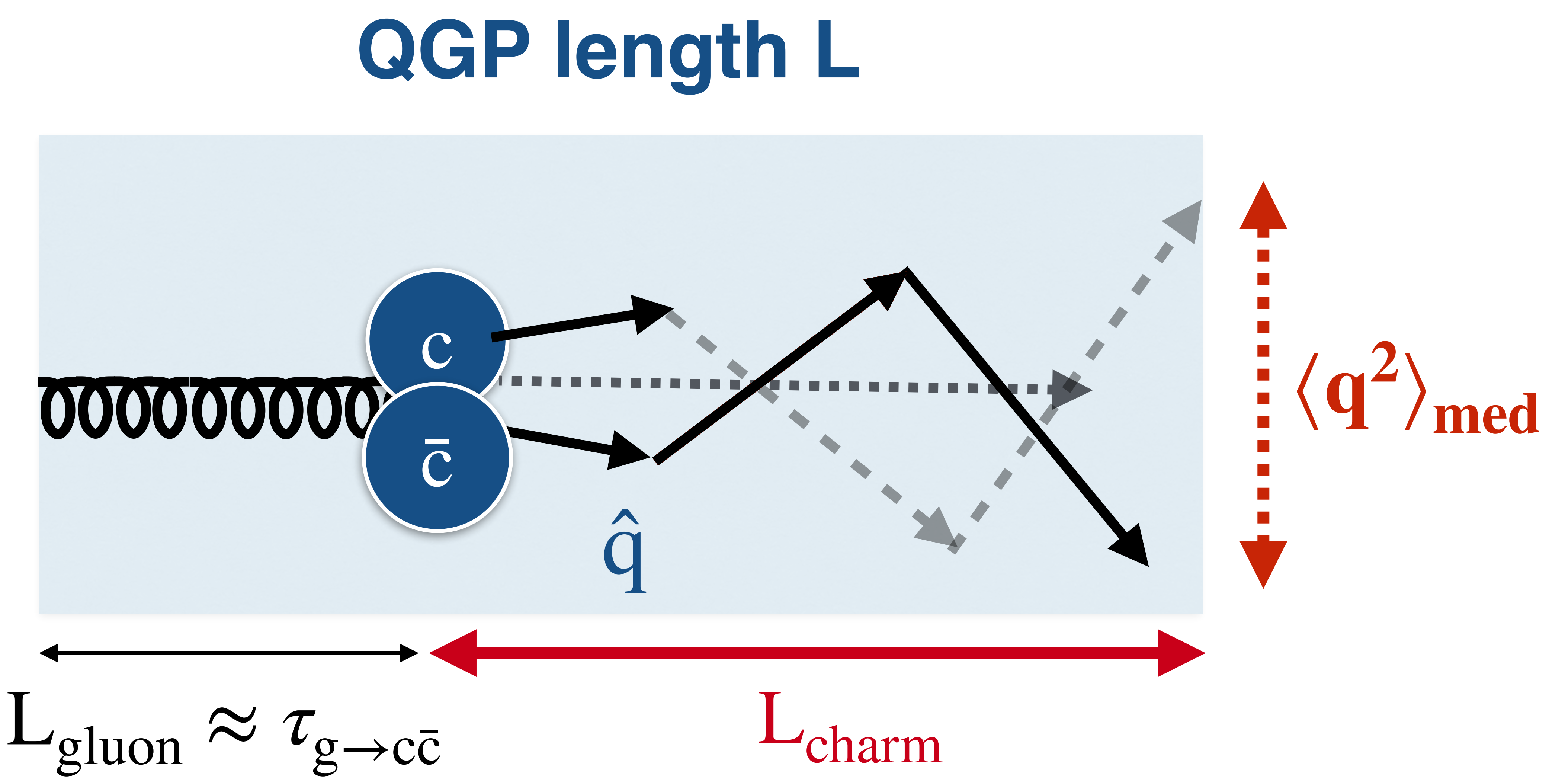
Measurements of $N^{c\bar{c}}_{jets}/N_{jets}$ in PbPb/AuAu and pp collisions:
→ by observing this new signature, **a crucial test for our theoretical understanding of jet quenching**

More differential studies of the $g \to c\bar{c}$ and $g \to b\bar{b}$ splittings



Measurements of the substructure properties of the two HQ-tagged subjets in pp, PbPb, and AuAu:

→ characterization of $P^{\text{medium}}_{g\to c\bar{c}}$ and $P^{\text{medium}}_{g\to b\bar{b}}$



Using gluon formation time as a time/space ruler:

→test the predicted $\langle k^2_T \rangle$ broadening of high-p_T partons in the hot medium

$$\langle q^2 \rangle_{\text{med}} \sim \hat{q} L_{\text{charm}}$$

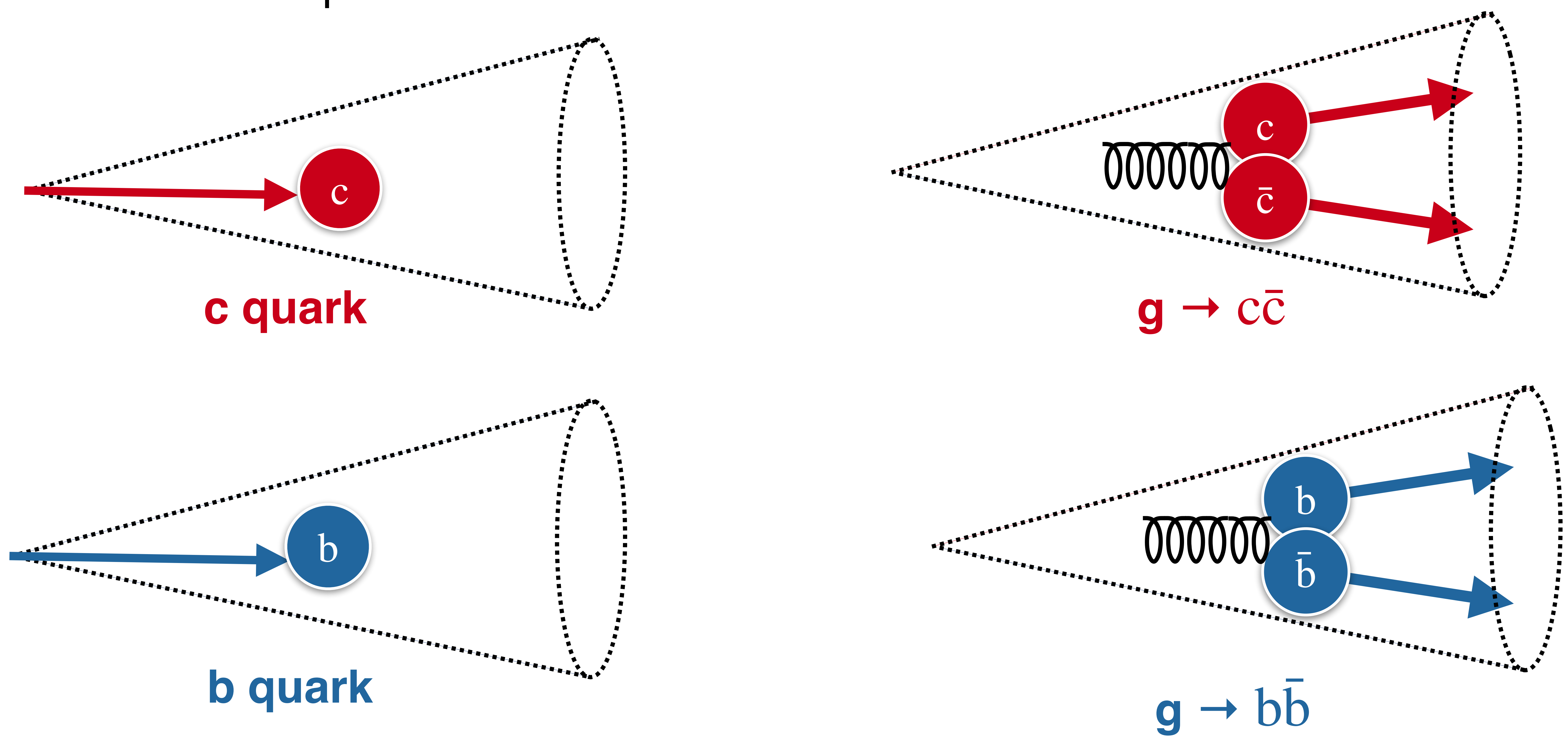
→ we need accurate simulations that can model the parton shower modifications of heavy quarks in the QGP

Future tools: DNN techniques for flavor tagging in HI

Multi-label classification algorithms for tagging of:

- c-quark, b-quark, g → $c\bar{c}$ and g → $b\bar{b}$

→ based on DNN and BDT techniques



→ O(1000) signal increase w.r.t. $D^0\overline{D}^0$-tagging technique

→ new opportunities for c-jet correlation measurements in HI

Conclusions and outlook

Over the last decade, we witnessed a revolution in the techniques of HF reconstruction and analysis:

→ HF techniques boost the theoretical and experimental control of most high-density QCD studies

→ **How can we maximize the impact of heavy-flavor observables in the future?**

One of the key elements is the availability of accurate phenomenological models and simulations:

- good description of both soft (e.g. diffusion) and hard heavy-quark interactions (in-medium splitting modifications)
- capable of producing predictions for HF jet, HF jet-substructure observables, HF-jet correlations with isolated photons…

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JETSCAPE can play a crucial role in supporting future jets and HF-jet measurements!

thank you for your attention!

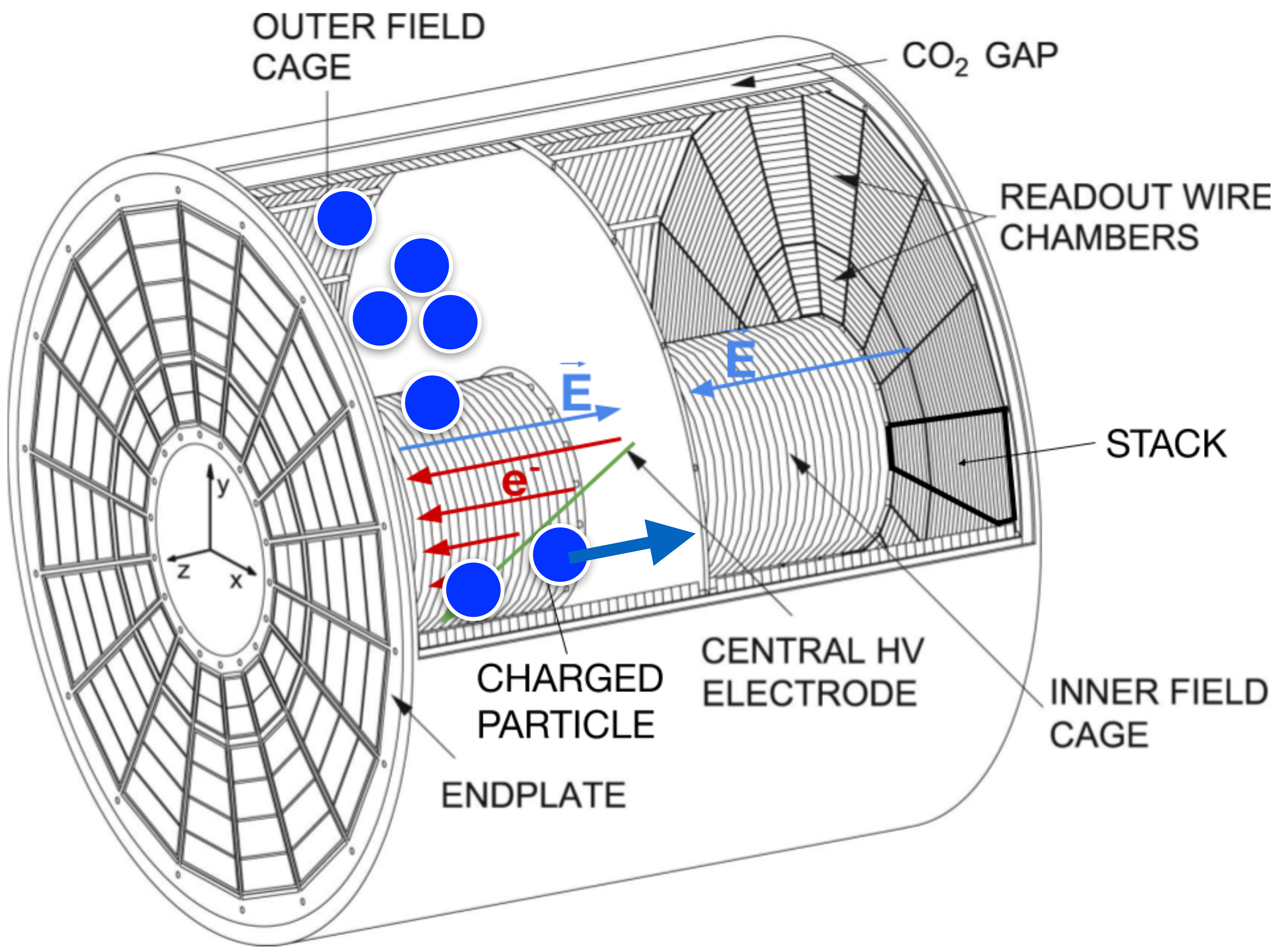
BACKUP SLIDES

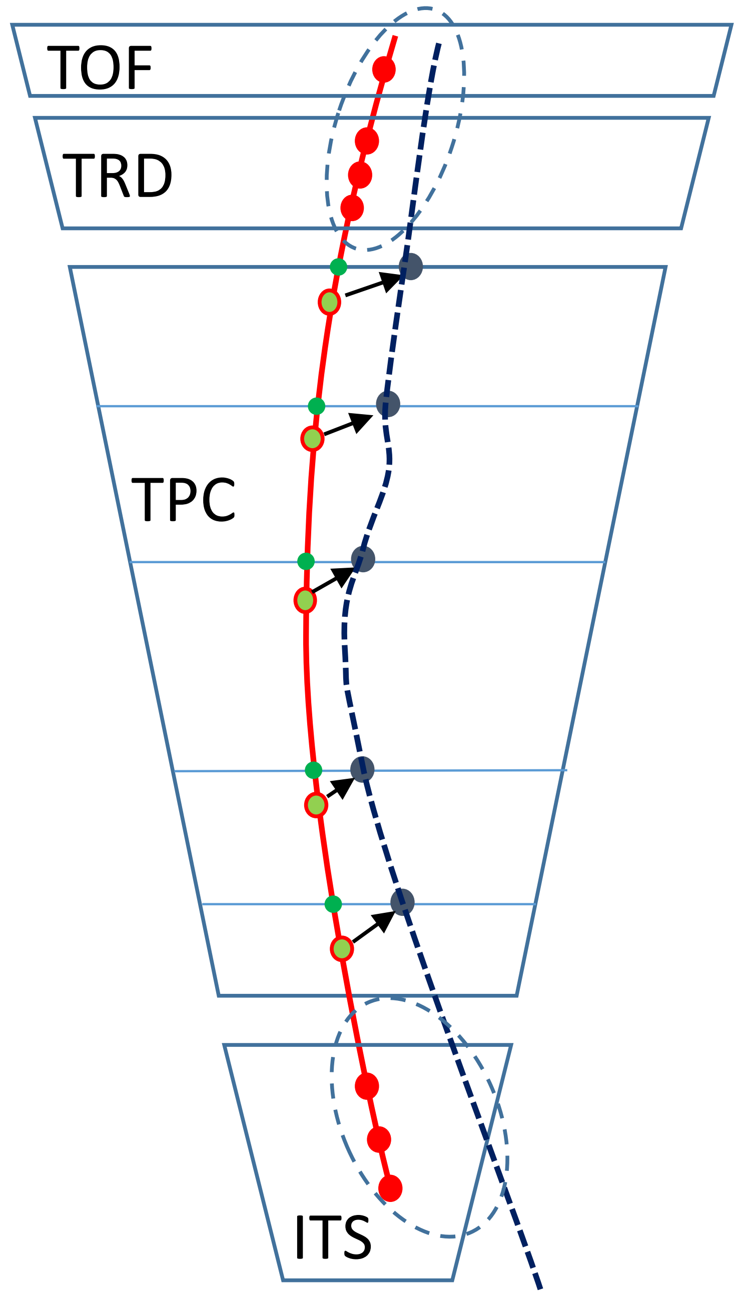
BACKUP:
ALICE Run3

Distortion fluctuations in the ALICE TPC

GEMs release <u>slow</u> ions (backflow) in the TPC:
(from up to 8000 PbPb collisions)
→ **distort the EM fields** inside the drift region

→ **time-dependent** deviations (~ mm/cm) from the ideal electron trajectories ("distortion fluctuations")





→ **A multi-dimensional time-dependent regression problem** (~video recognition) not solvable with traditional techniques

E. Hellbär, **G.M. Innocenti,** Maja Kabus et al., <u>CHEP 2021 Proceedings</u>

A big challenge: distortion fluctuations in the ALICE TPC

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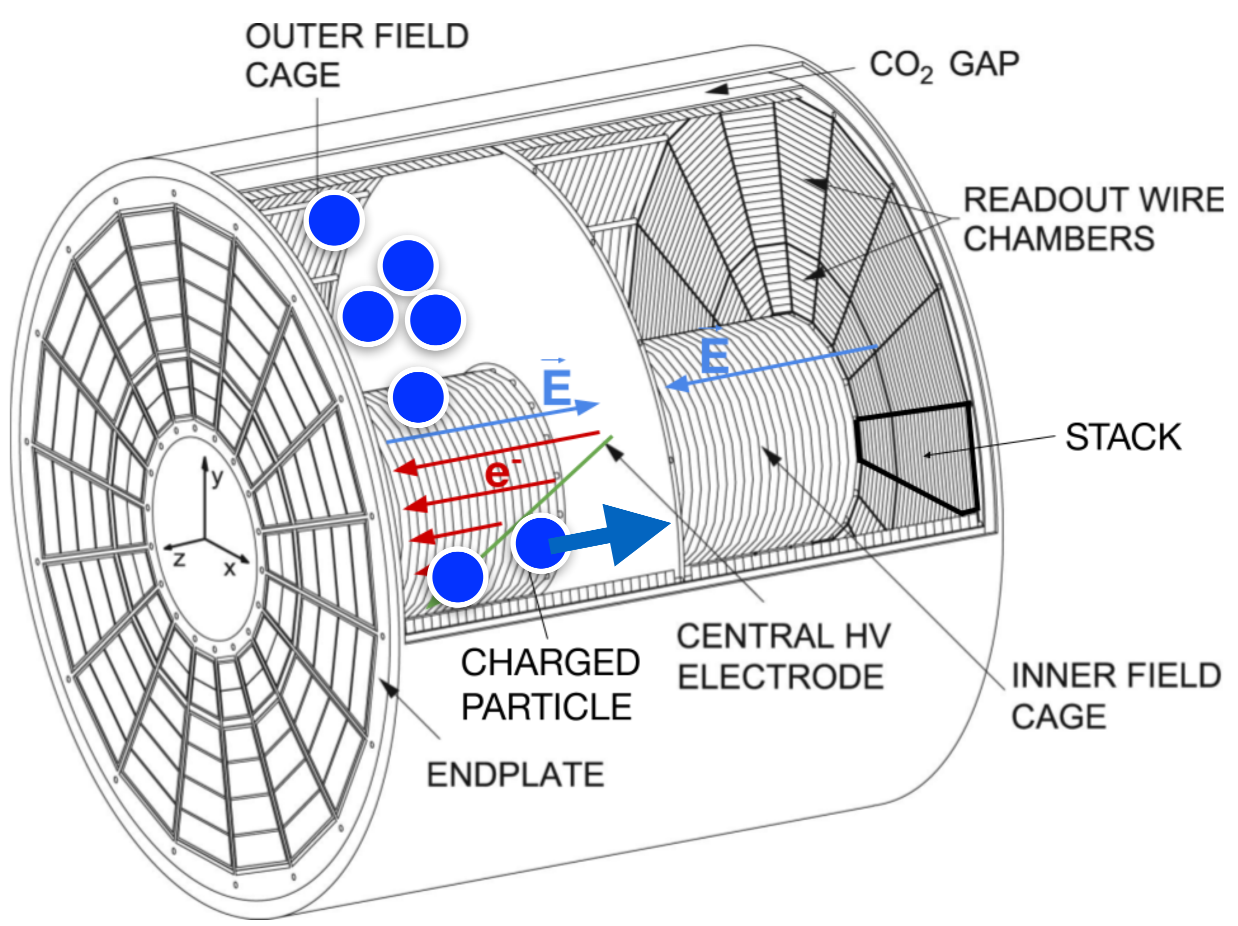
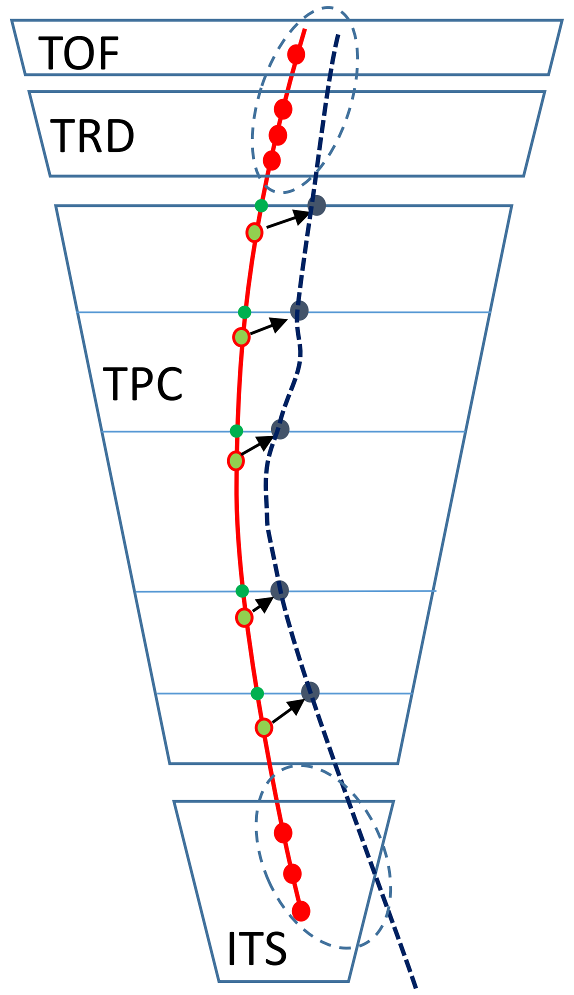
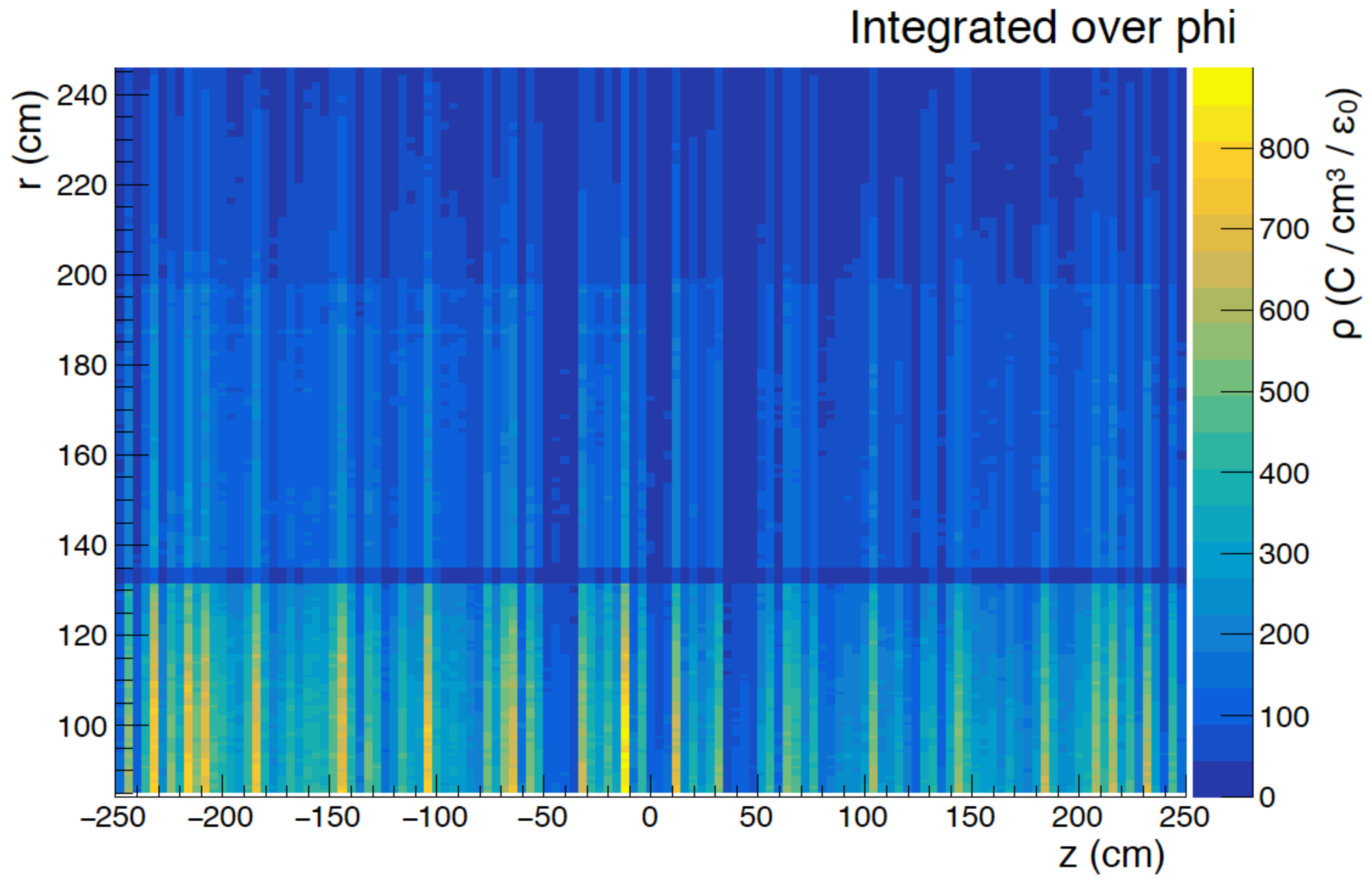




→ **~ cm deviations** from the **ideal** electron trajectories ("distortions")

Distortions are time-dependent ("fluctuations")
e.g. fluctuations in the multiplicity of PbPb events:



High-multiplicity event **(yellow)**

Low-multiplicity event **(blue)**

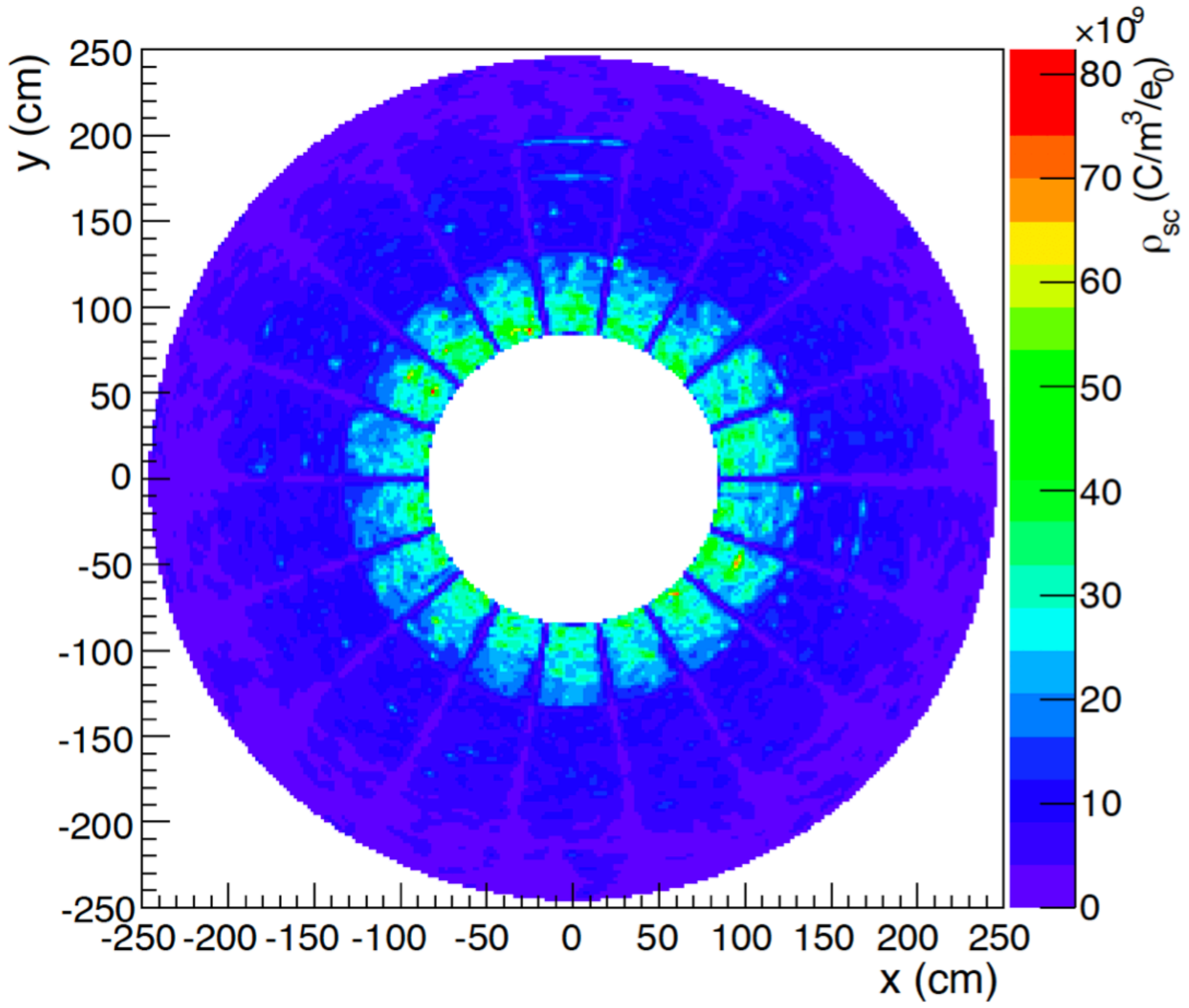
→ **A multi-dimensional time-dependent regression problem** (~video recognition) not solvable with traditional techniques

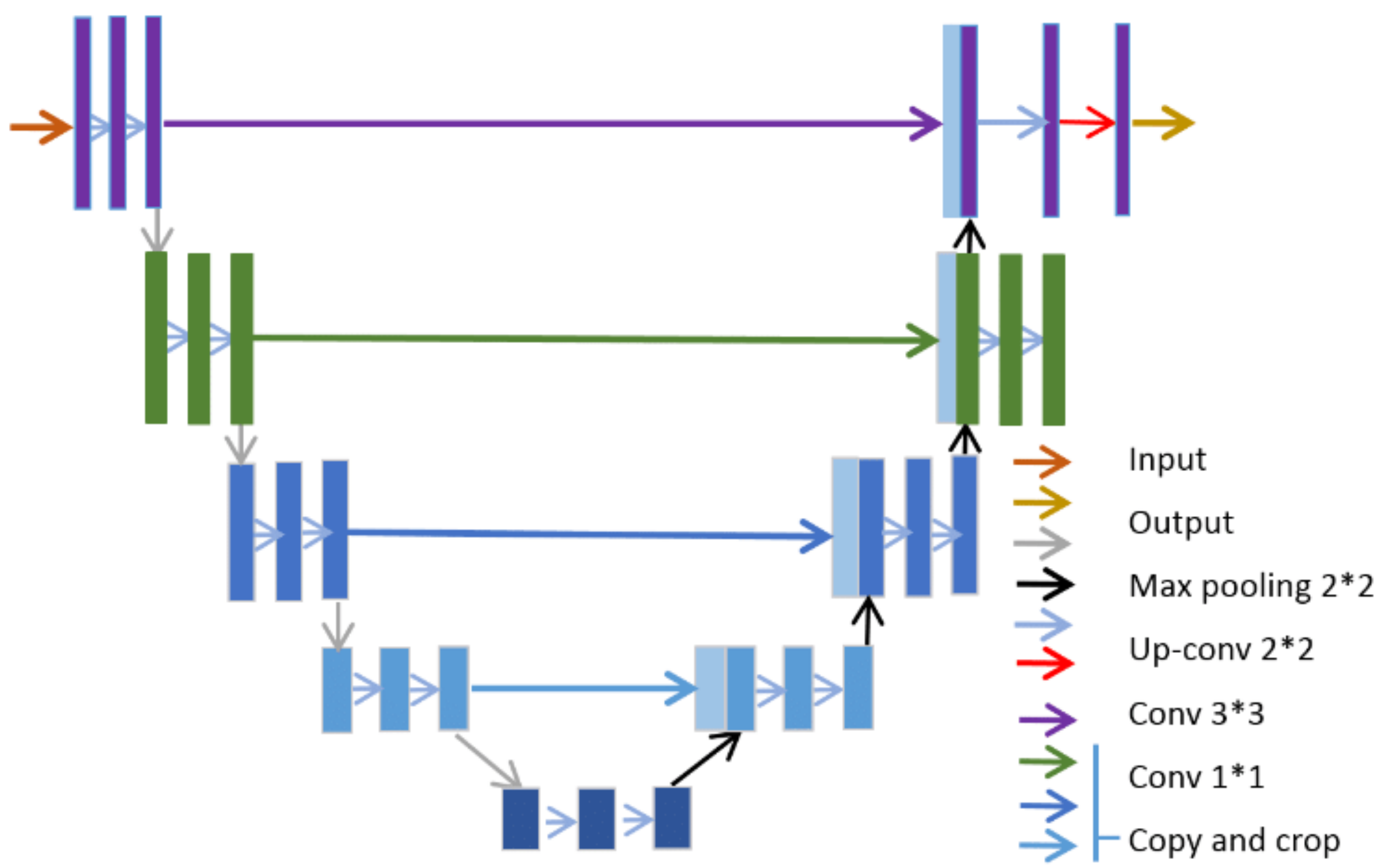
First working calibration for distortion fluctuations with DNNs

Training inputs:
4D (time+space) ion charge densities in each TPC point

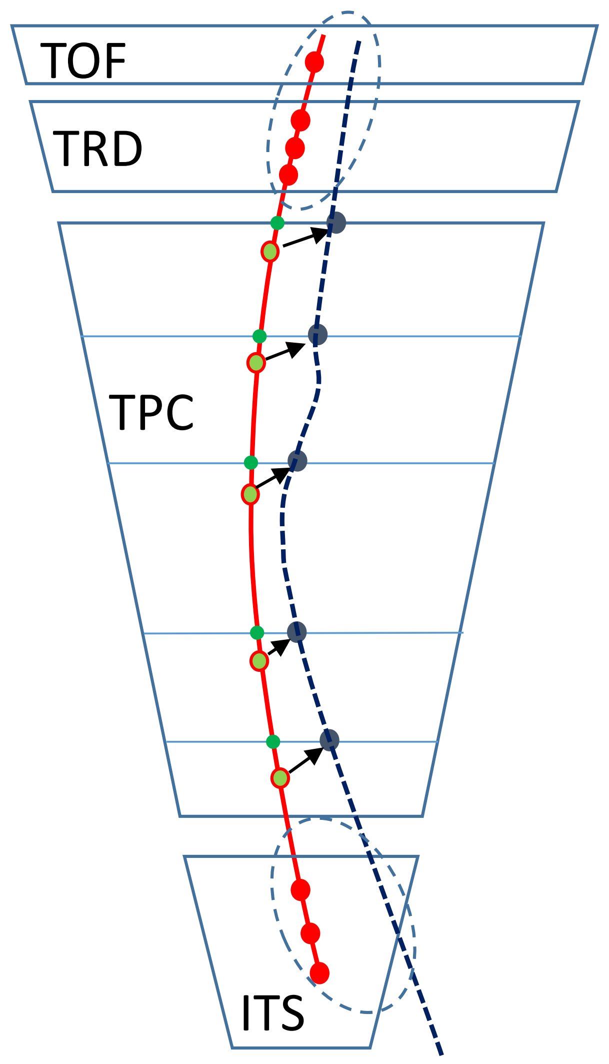
→ **UNets trained on GPUs** →

Predicted quantities:
4D (time+space) dependent distortions in each point of the TPC





E. Hellbär, **G.M. Innocenti,** Maja Kabus et al., CHEP 2021 Proceedings



Accuracy achieved ~200μm, comparable to TPC detector resolution!

→ default strategy for Run 3 heavy-ion data taking

→ applicable to sPHENIX TPC

Supported by:

- Polish Ministry + CERN grant (DN-WFM.92.56.2022.SB), PI: **G.M. Innocenti**, L. K. Graczykowski
- First Cloud Broker Pilot proposal. PI: **G.M. Innocenti** et al.

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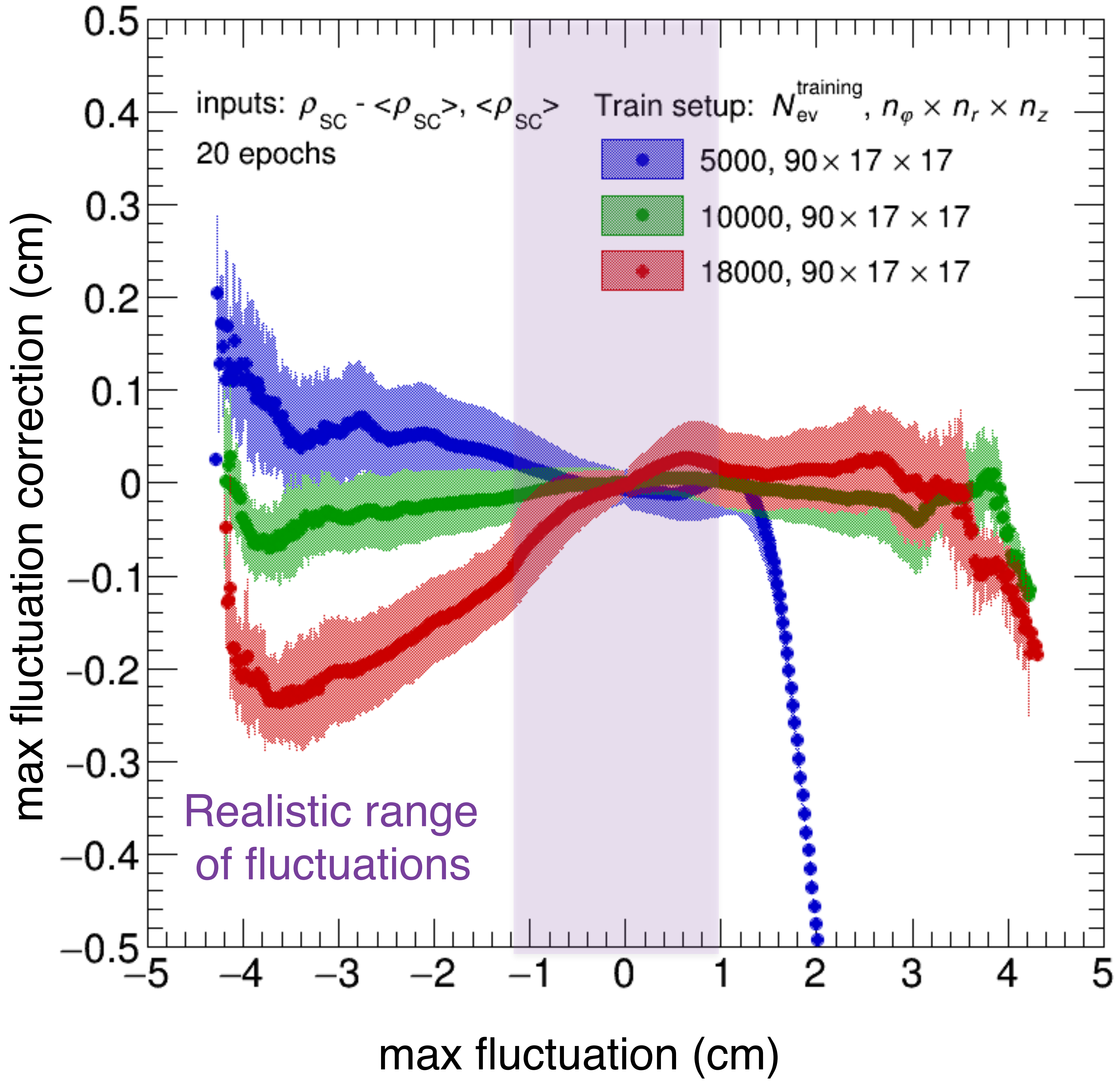
Prototype for a DNN-based correction for the TPC distortions



Correction accuracy ~ detector resolution (~200µm)

→ **DNNs can be effectively used to correct this effect!**

→ The same strategy could be applied in sPHENIX, which will also suffer from distortion fluctuations!

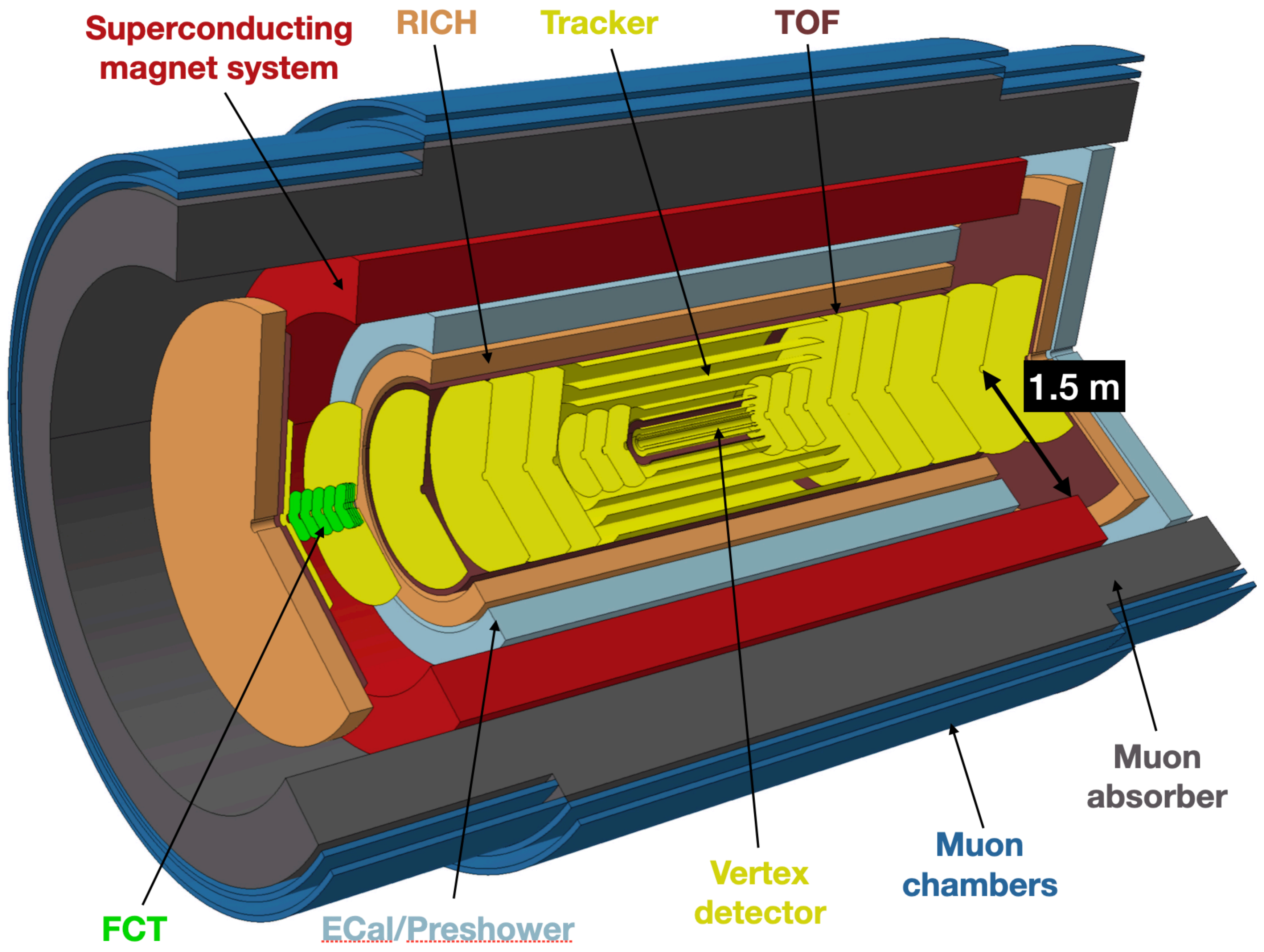
E. Hellbär, **G.M. Innocenti,** Maja Kabus et al., CHEP 2021 Proceedings

BACKUP: ALICE 3 in Run5/6

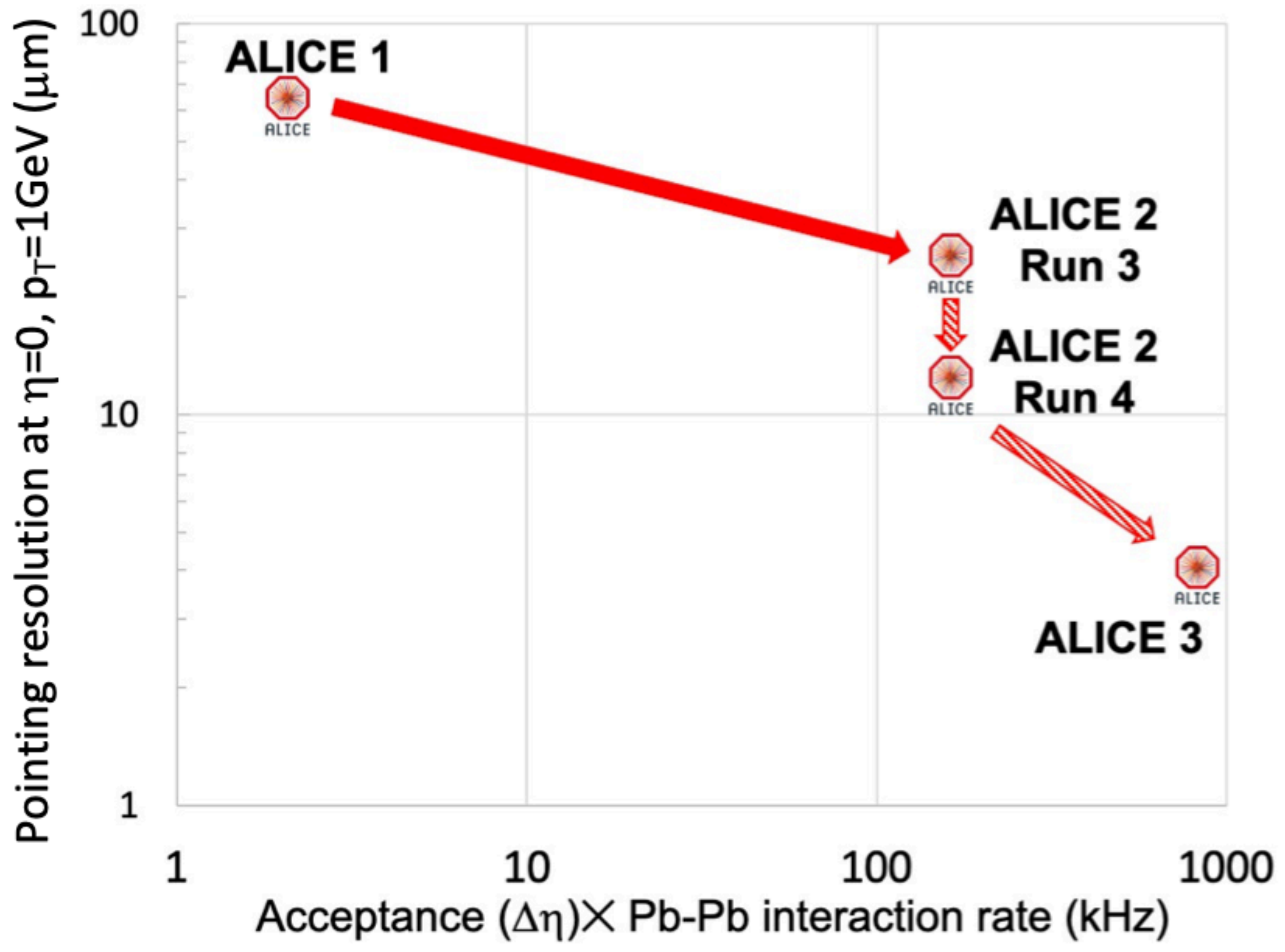
A new heavy-ion experiment for the '30

ALICE 3 Letter of Intent,
CERN-LHCC-2022-009, arXiv:2211.02491
LoI submitted in October '21
Review concluded in March '22

→ **Shaped the physics program and the detector design of ALICE 3 at the LHC**



ALICE 3: a high-rate, high-resolution experiment **|η|<4** for **rare heavy-flavor probes in light and heavy ions**



One highlight from a broad physics program

ALICE 3 Letter of Intent,
CERN-LHCC-2022-009,
arXiv:2211.02491
LoI submitted in October '21
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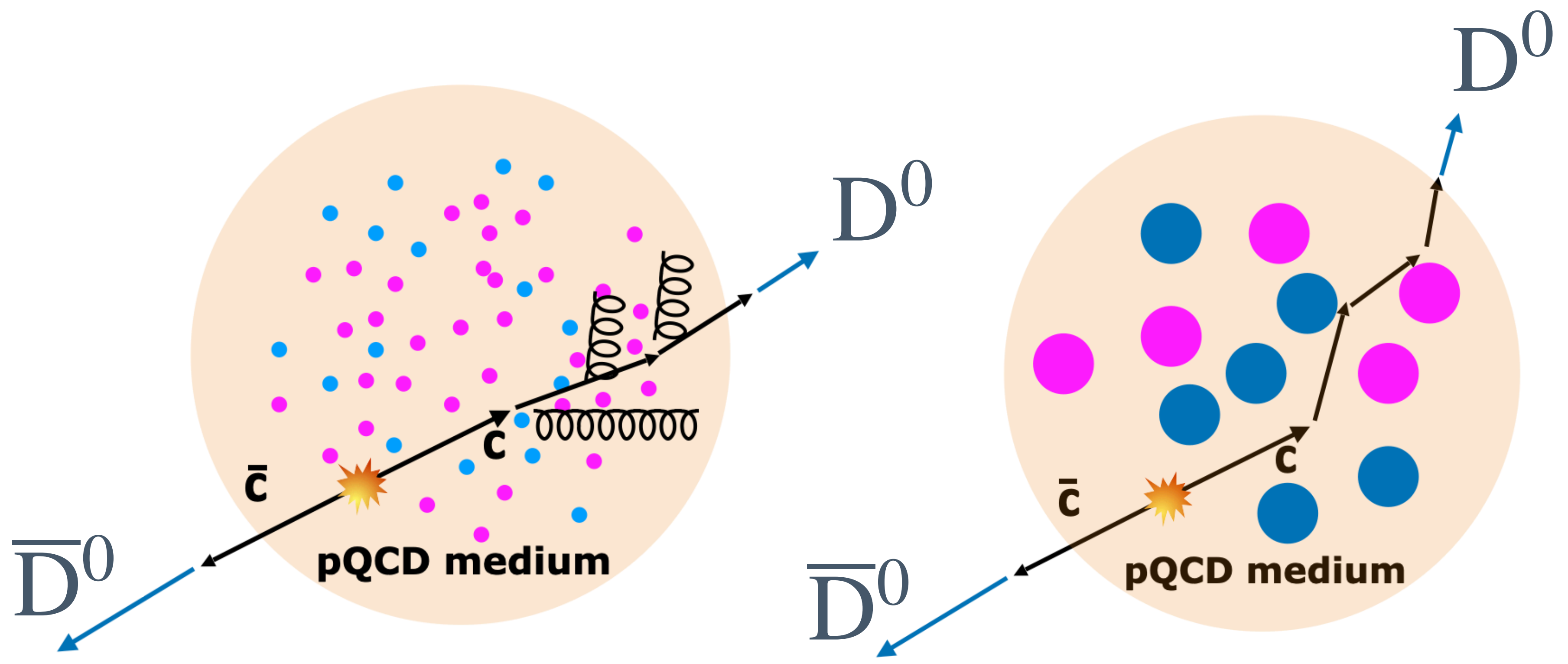
"Rutherford-like" experiment with $D^0\overline{D}^0$ correlations



→ partonic "structure" of the hot medium

→ Tracking and vertexing with µm-accuracy over |η|<4
→ superconducting magnet with forward dipoles
→ Hadron PID from low (TOF) to high p_T (Cherenkov)

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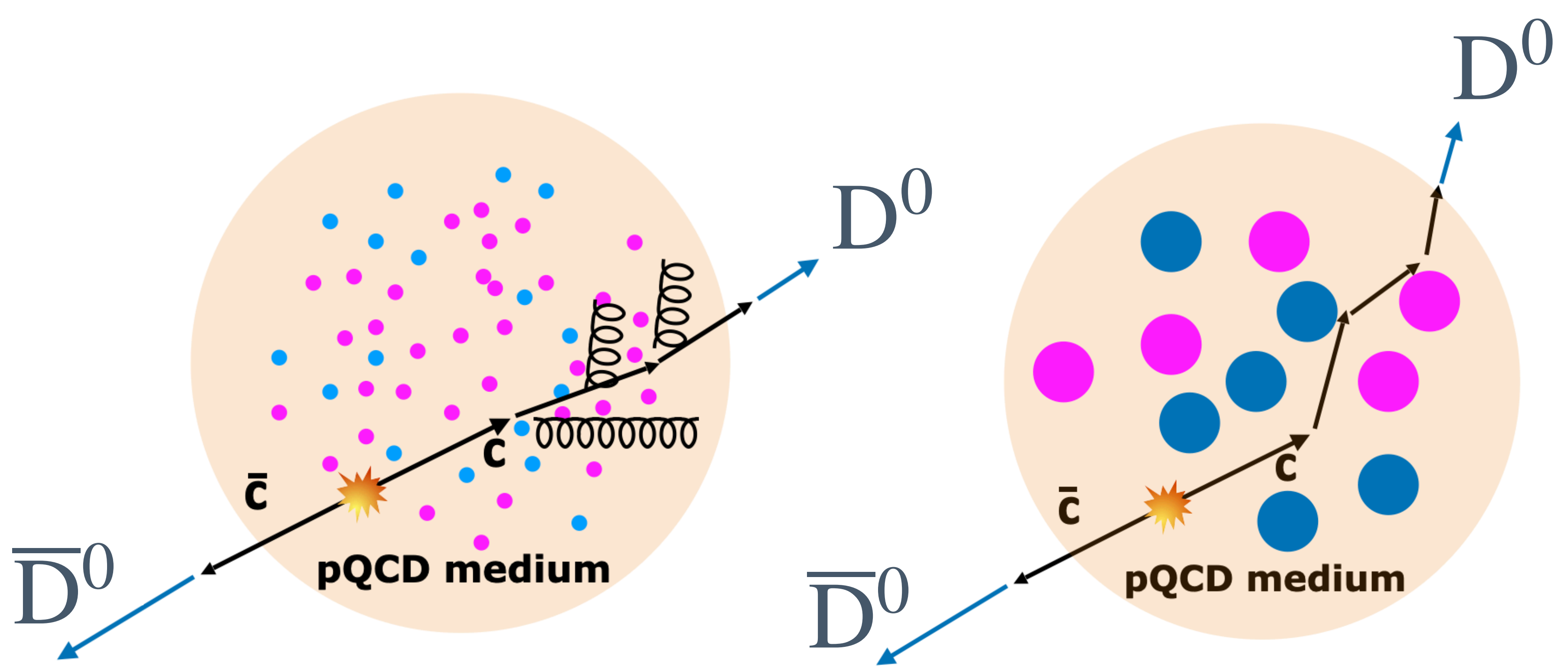

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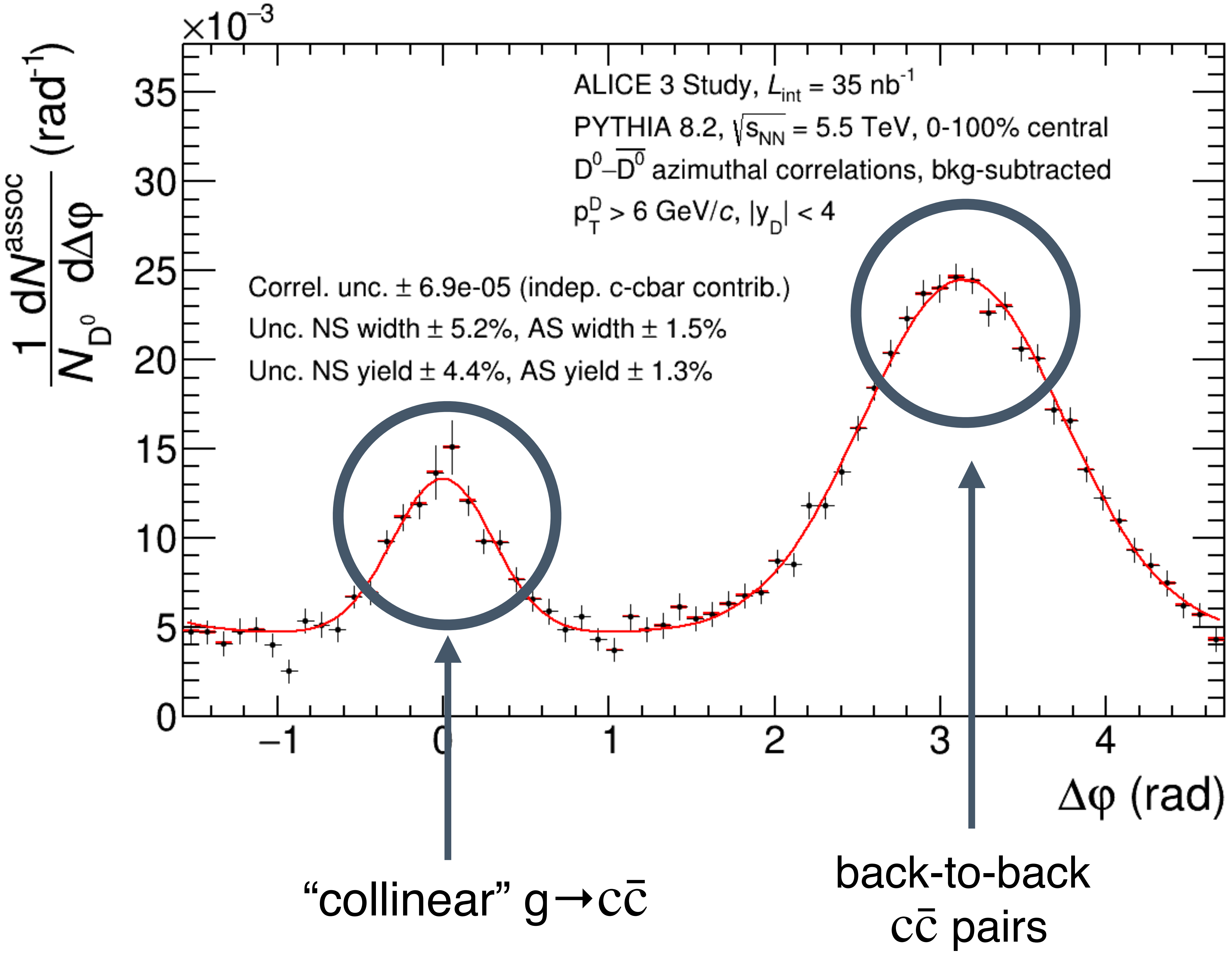

→ **Tracking and vertexing with μm-accuracy over |η|<4**
→ superconducting magnet with forward dipoles
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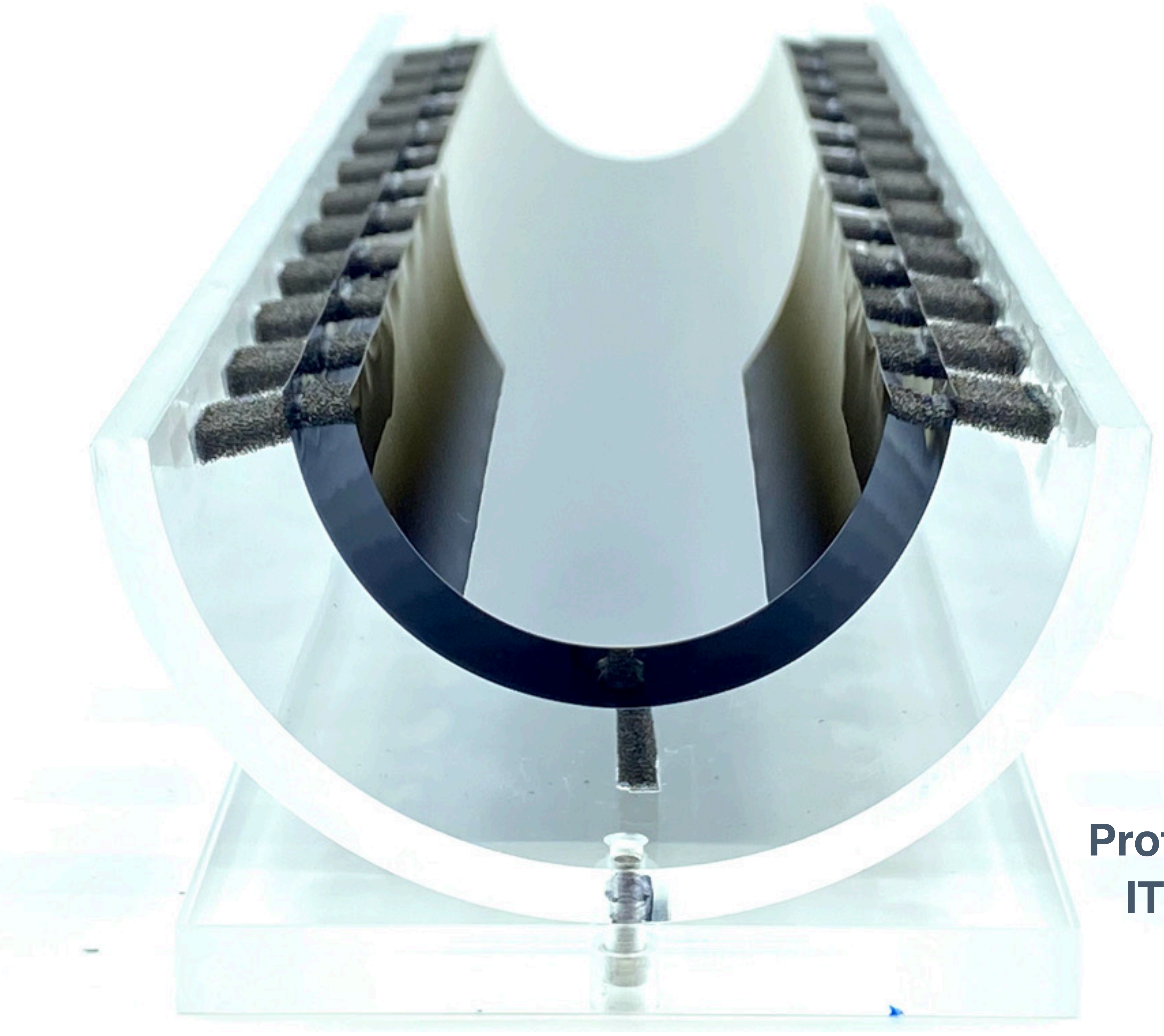
The new (bending) pixel technology at the core of ALICE 3



Prototype for the ITS3 upgrade

Ultra-light ("massless") sensors with <0.05 X_0

- large sensors **with "stitching" techniques**
- **"bendable" when thinned** below ~20-40 µm

↓

Impact parameter resolutions for tracks of about 1 GeV of a few µm!

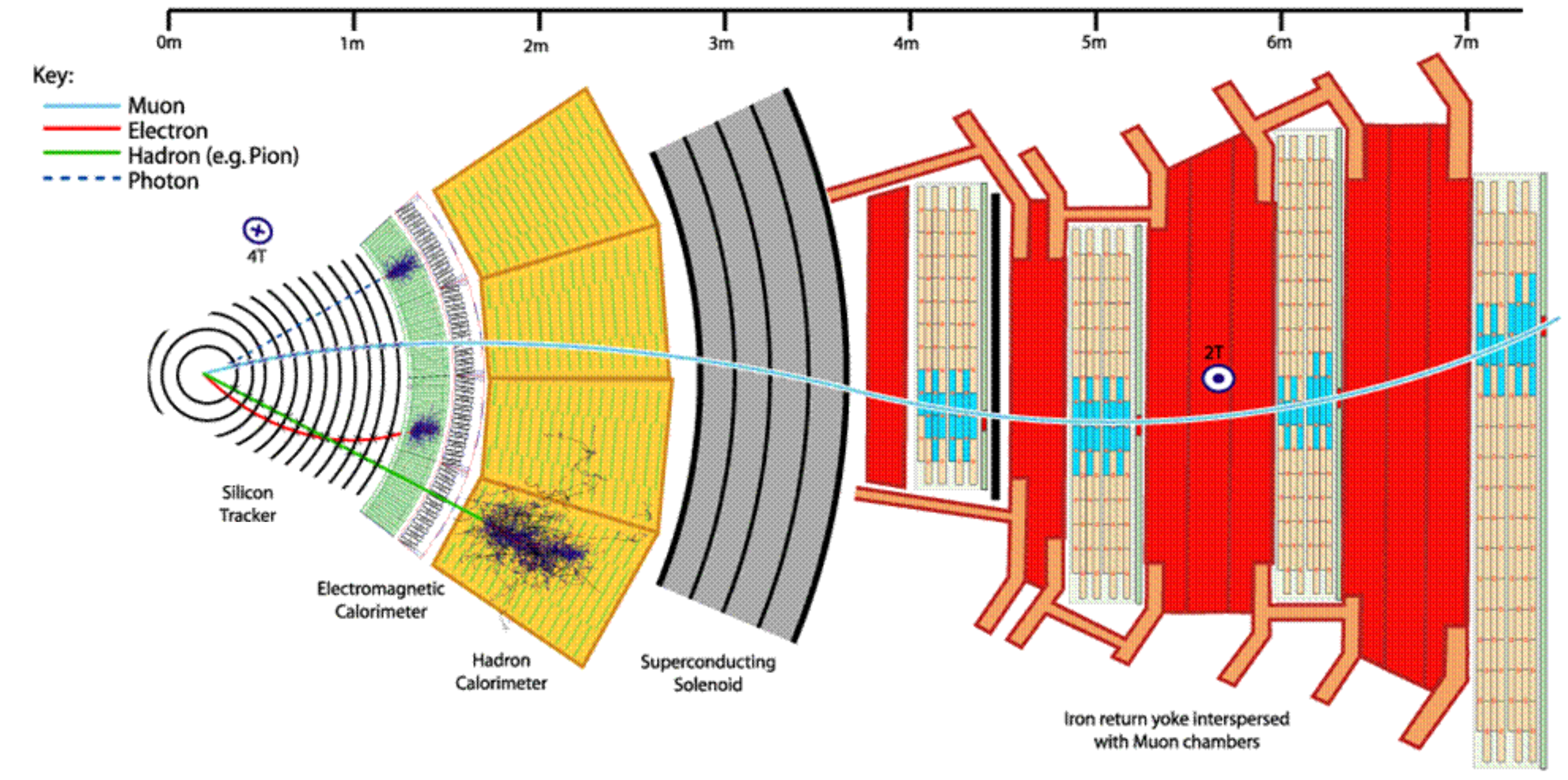
And it works! as proven by dedicated test beams after irradiation (ITS3 prototype)

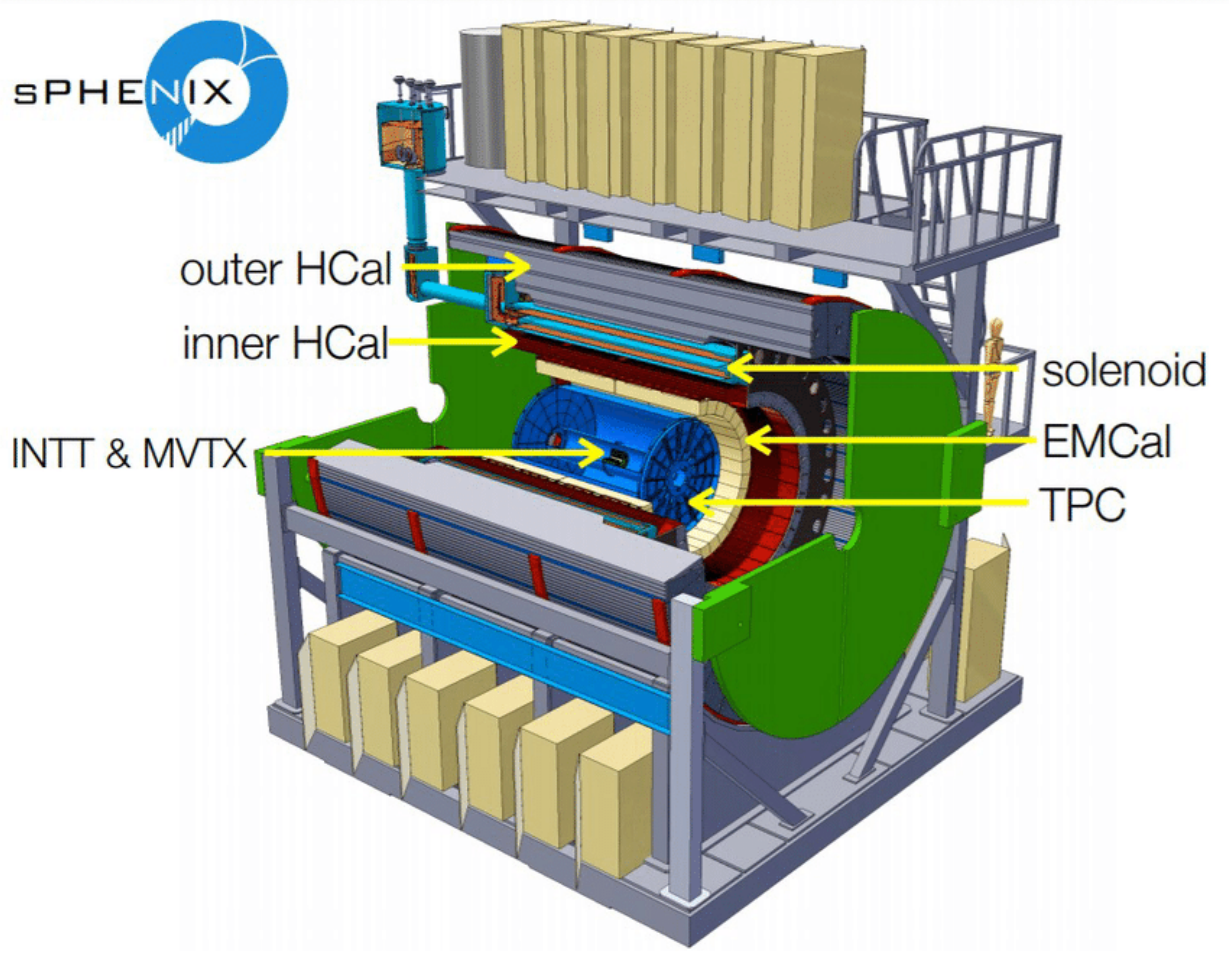
ALICE ITS3 Letter of Intent: ALICE-PUBLIC-2018-013
ALICE ITS3, arXiv.2105.13000
ALICE ITS3, arXiv.2212.08621

BACKUP:
HF analyses

CMS in Run 3 at the LHC and sPHENIX at RHIC

→ **Most complete detectors** for jets, photons, heavy-flavour hadrons
→ access to **heavy-ion collisions at very different energies** (5.5 TeV vs 200 GeV)

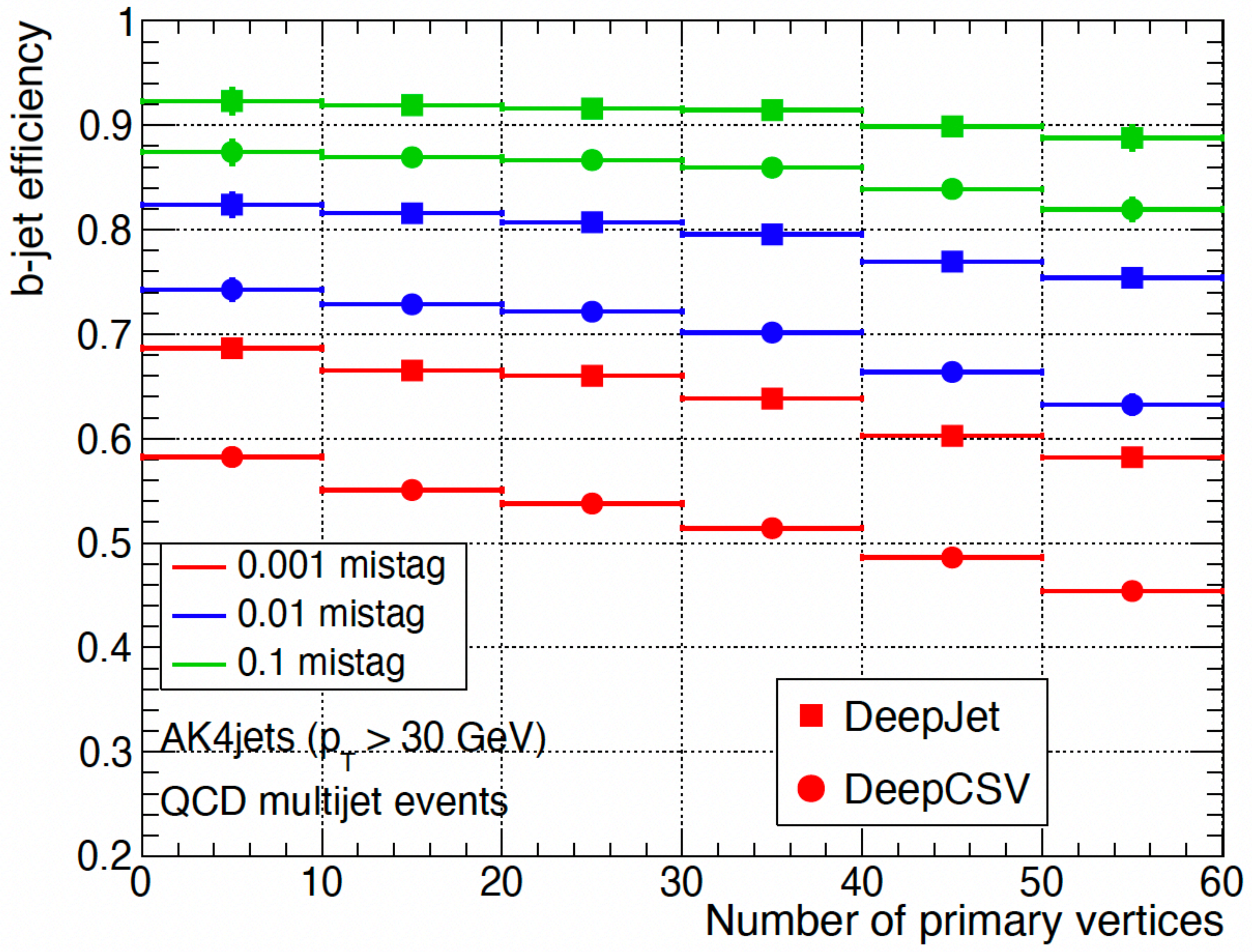


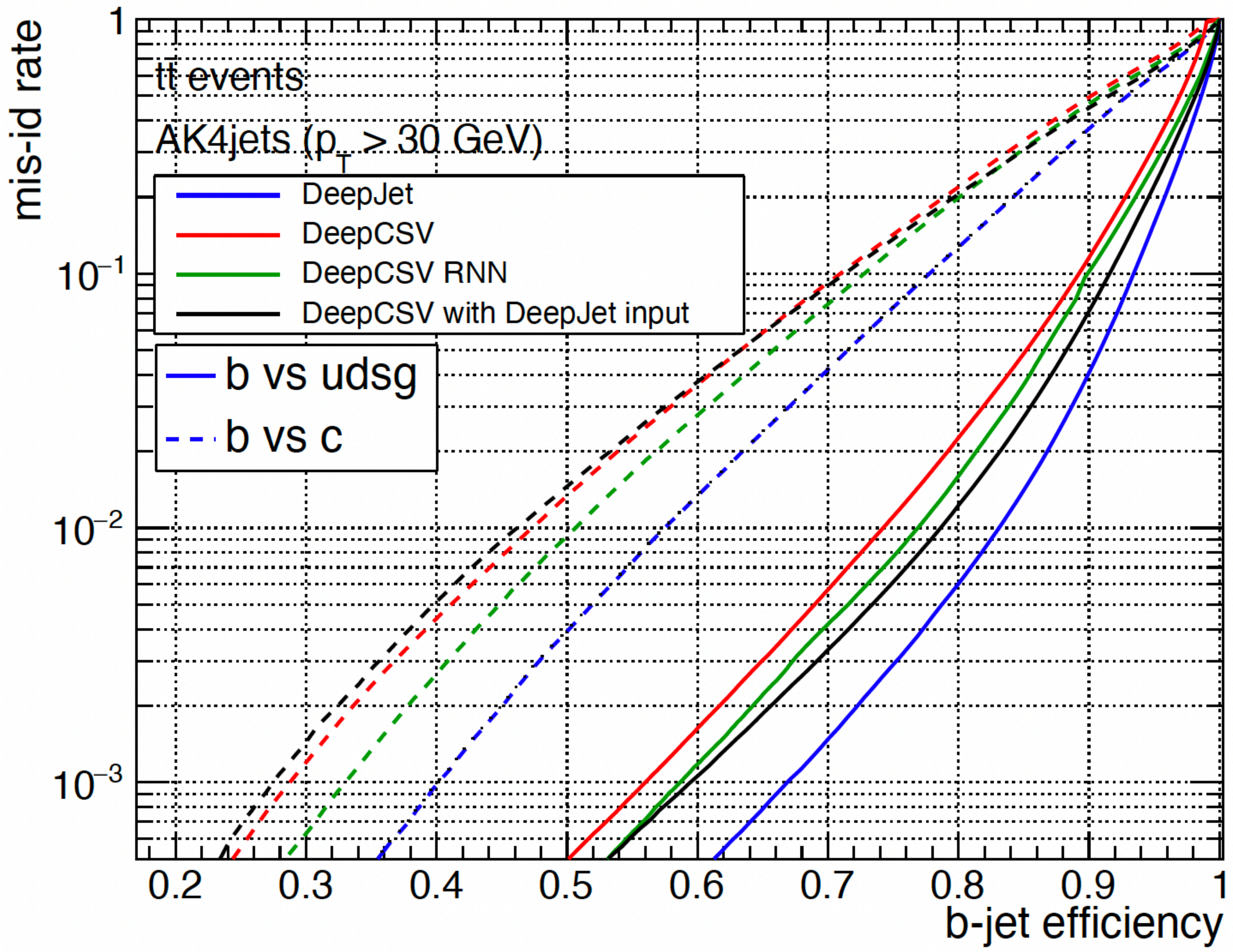


CMS at the Large Hadron Collider:
High-luminosity, full "barrel" coverage $|\eta|<2.4$
- Large acceptance tracking $|\eta|<2.4$ in Run 3
- Muon detectors, ECAL and HCAL
- Outstanding trigger system

sPHENIX at RHIC:
- **Time-Projection Chamber** (GEM readout)
→ 240 billion AuAu events in continuous readout mode
- **MVTX vertex detector** (based on ALICE ITS2 technology)
→ impact parameter resolution ~20 μm for p_T = 1 GeV/c

Flavor tagging in CMS





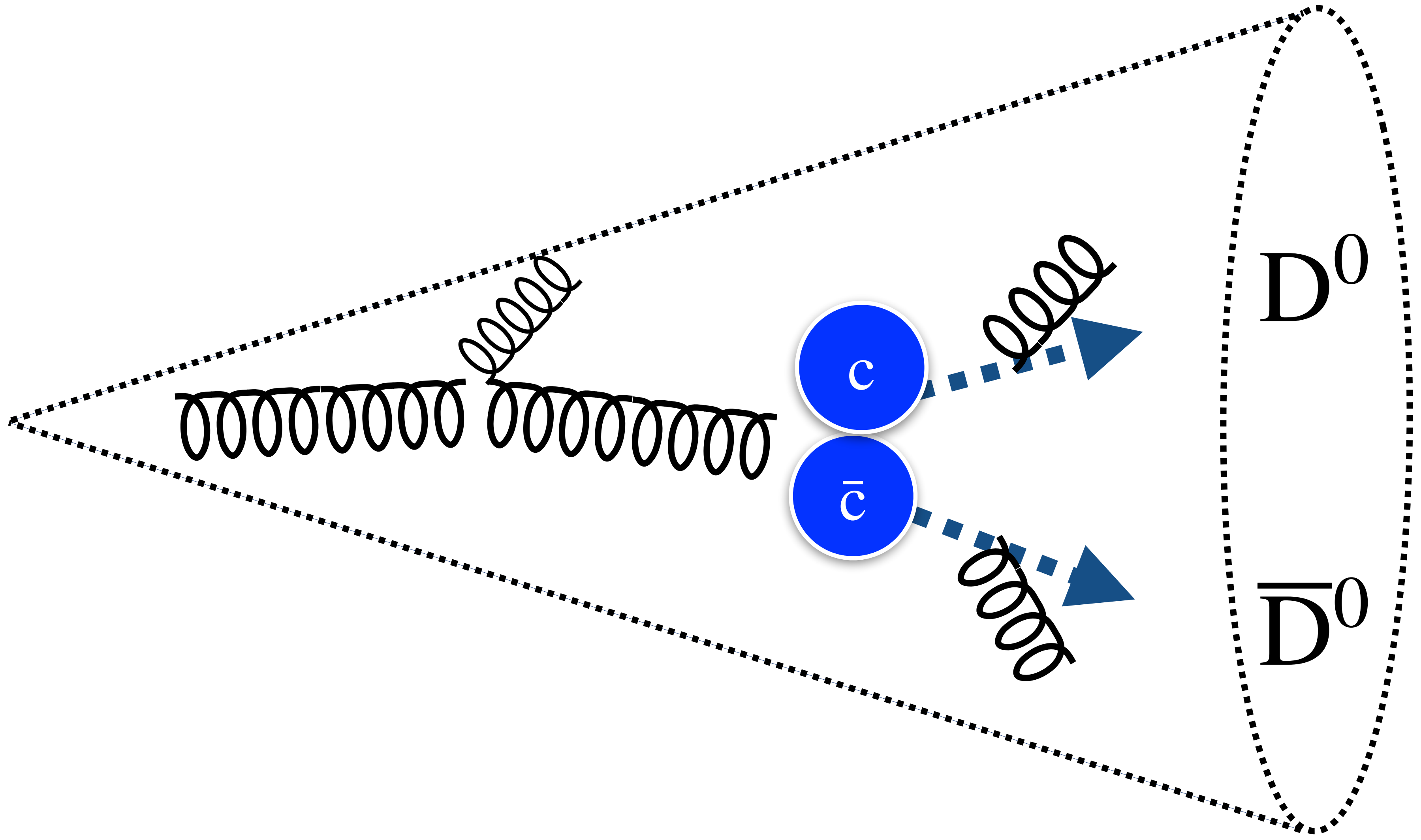
E. Hellbär, **G.M. Innocenti,** Maja Kabus et al., CHEP 2021 Proceedings

BACKUP SLIDES

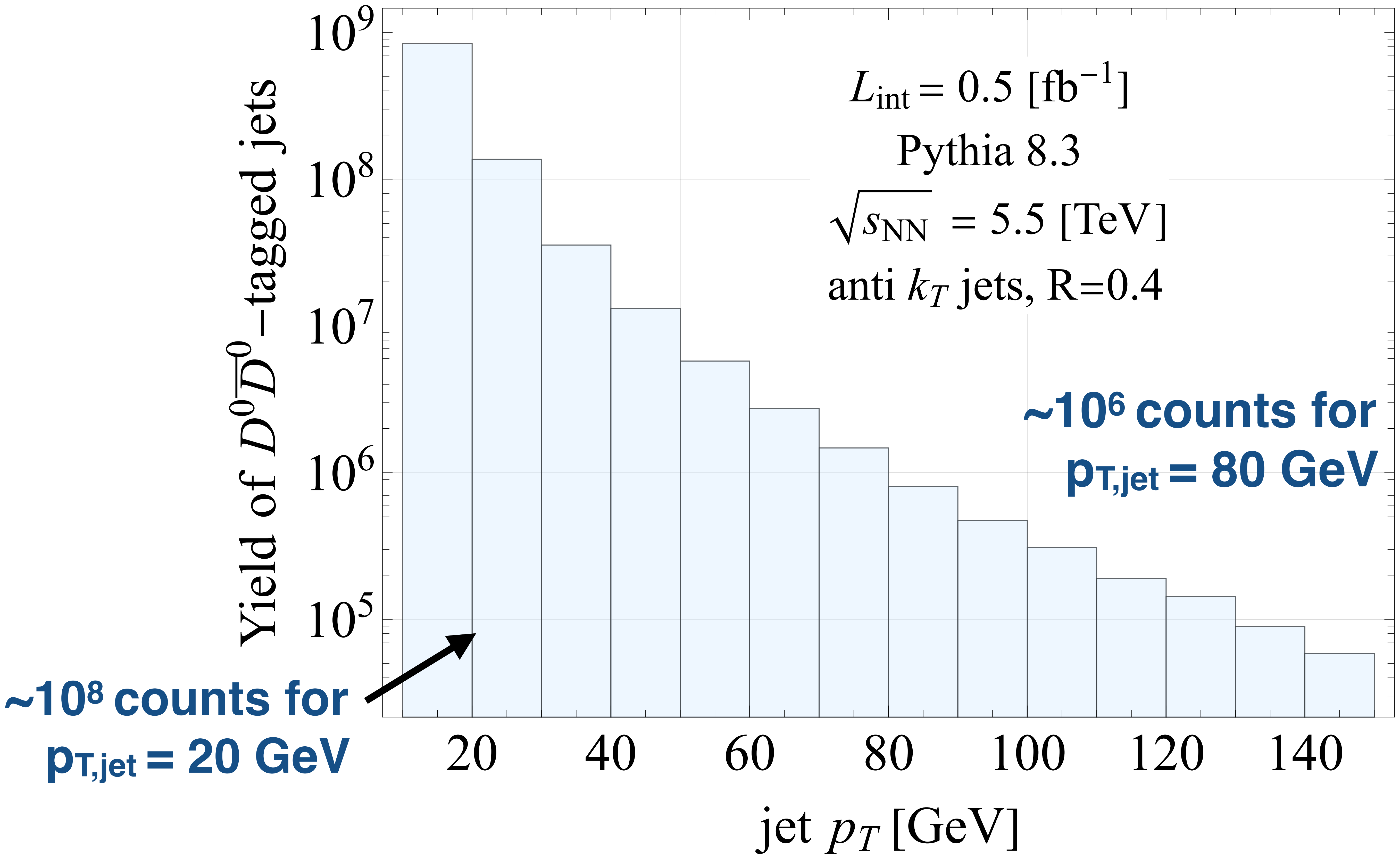
gluon splitting
and time structure

Monte Carlo studies with Pythia 8

- Anti-k_T "full" jets with FastJet (R=0.4)
- one $D^0\overline{D}^0$ per jet
- only prompt D^0 contribution considered ($c \rightarrow D^0$)



L_{int} = 0.5 fb^{-1} pp ~ 10 nb^{-1} PbPb (no quenching)



- Fully reconstructed hadronic D^0 decays
- **<u>But also</u>** $c\bar{c}$-tagging techniques high-p_T jets or tagging of semi-leptonic charm decays → **sample ~ entire $c\bar{c}$ statistics**

Challenging measurement:

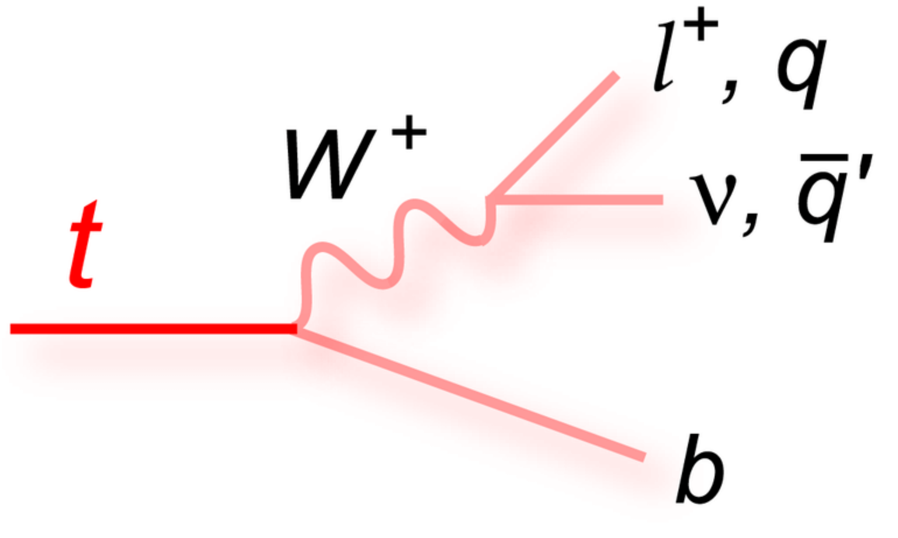
→ Based on expected yields, the measurement could be within reach with HL-LHC

Yoctosecond structure of the QGP with top quarks

→ study differentially the space-time evolution of the medium created in heavy ion collisions

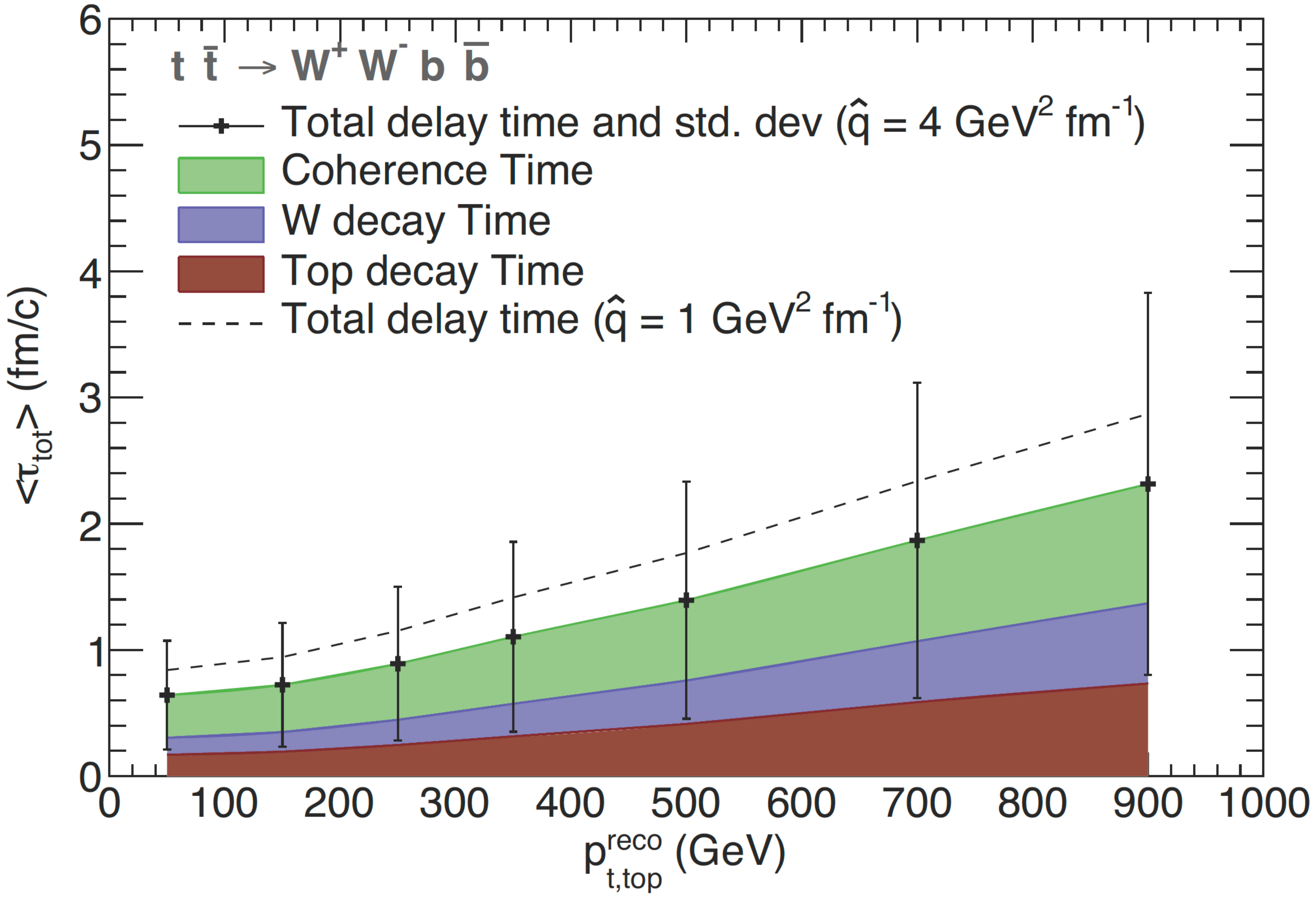
$$\langle \tau_{\rm tot} \rangle = \gamma_{t,{\rm top}} \tau_{\rm top} + \gamma_{t,W} \tau_W + \tau_d$$

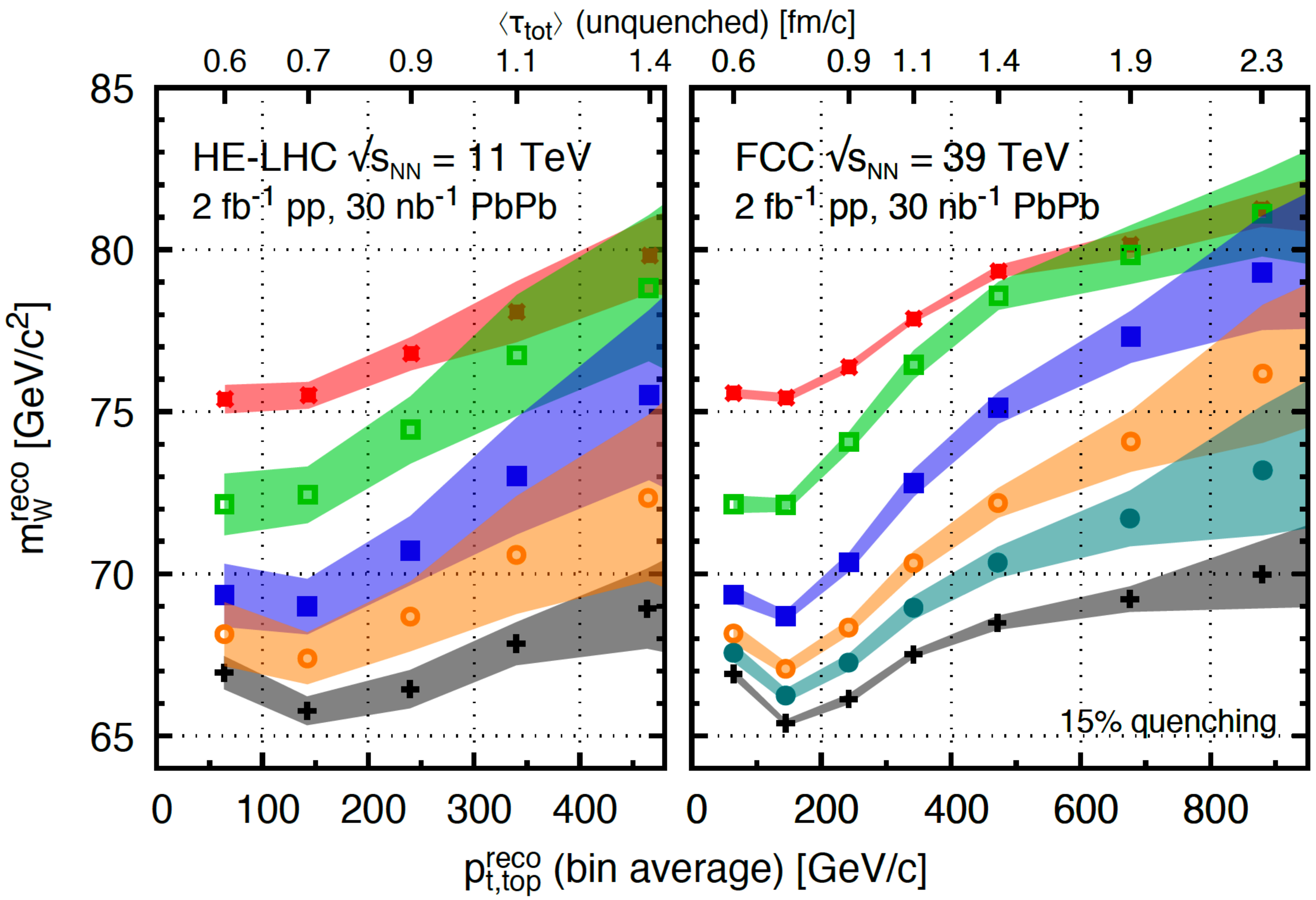
L. Apolinário, J.G. Milhano, G. P. Salam, C. A. Salgado,
Phys. Rev. Lett. 120, 232301 (2018)



$$\tau_d = \left(\frac{12}{\hat{q}\theta^2_{q\bar{q}}} \right)^{1/3}$$

decoherence time of the $q\bar{q}$ singlet





→ **effect of quenching observed via the shift in the invariant mass of the m_{jj} of the diet decays**

BACKUP SLIDES
LHC long-plan program

Longer-term LHC schedule (03/2023)

From http://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm