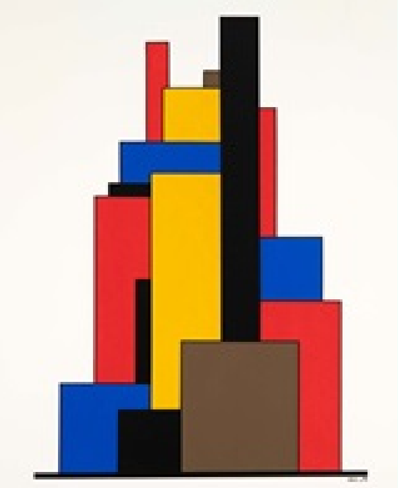
ZIMÁNYI SCHOOL 2024



L. Kassák: Image architecture

24th ZIMÁNYI SCHOOL
WINTER WORKSHOP
ON HEAVY ION PHYSICS

December 2-6, 2024
Budapest, Hungary

József Zimányi (1931 - 2006)

Overview of the CMS experimental results

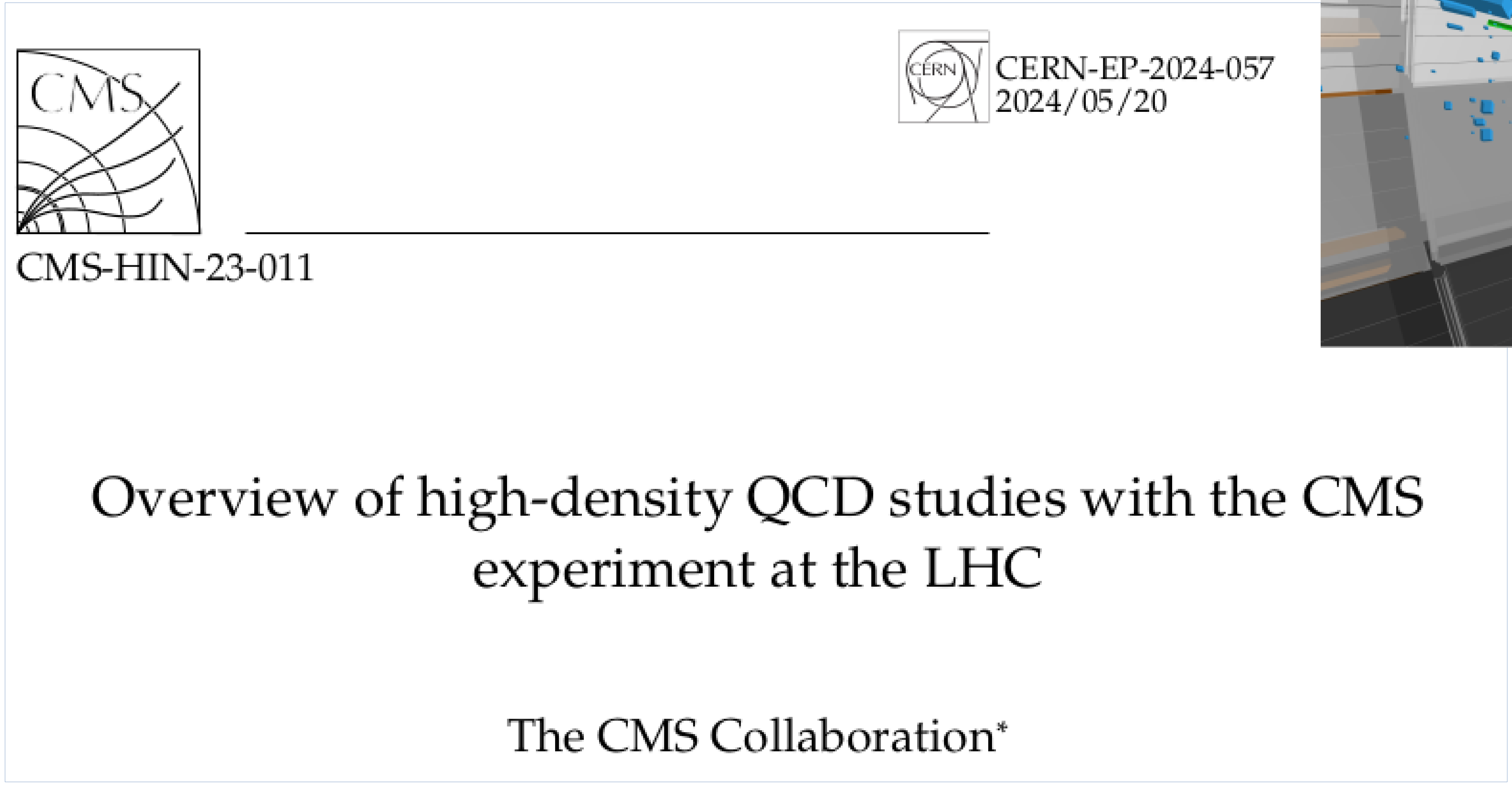
(selected topics)

24th Zimányi School
Winter workshop on heavy ion physics
2nd December, 2024

Gábor Veres
Eötvös Loránd University Budapest
(on behalf of the CMS collaboration)

Overview of CMS results from the **last decade**

Results from LHC Runs 1 (2010–2013) and 2 (2015–2018).

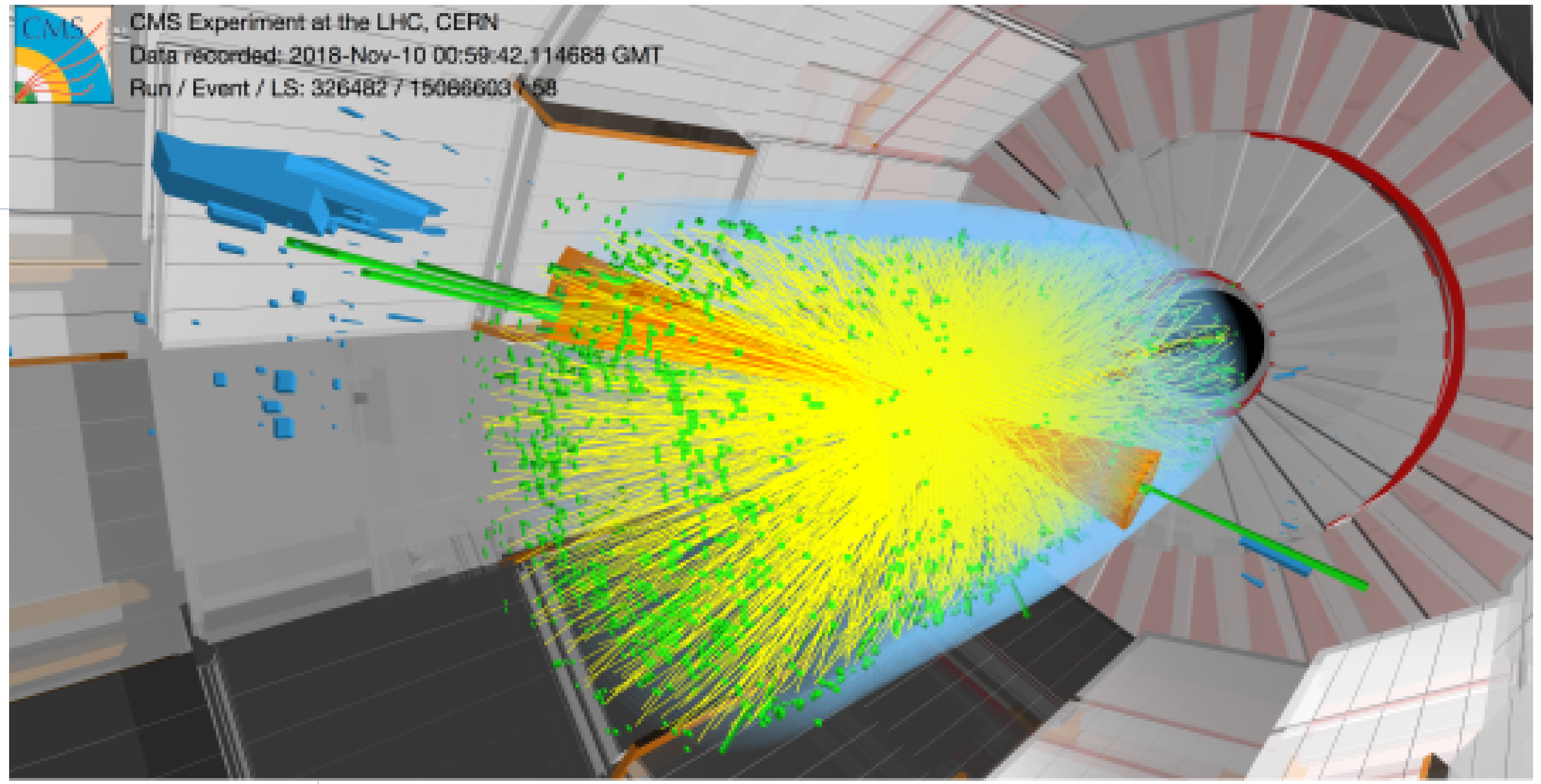


CMS-HIN-23-011

CERN-EP-2024-057
2024/05/20

Overview of high-density QCD studies with the CMS experiment at the LHC

The CMS Collaboration*



*A **textbook** for a **school**!*

Accepted by Phys. Rept.
https://arxiv.org/abs/2405.10785

Overview of CMS results from the last decade

Results from LHC Runs 1 (2010–2013) and 2 (2015–2018).

3 The initial state of the collisions . . . 33
- 3.1 Constraining nuclear parton distribution functions with hard probes . . 33
- 3.2 Tests of the Glauber model and N_{coll} scaling using electroweak bosons . . 38
- 3.3 Small-x nuclear structure . . . 42
- 3.4 Photoproduction of vector mesons . . . 46
- 3.5 Summary of results for the initial state . . . 50

4 Bulk properties and novel phenomena . . . 53
- 4.1 Initial-state entropy and energy densities . . . 53
- 4.2 The paradigm of a nearly perfect liquid . . . 55
- 4.3 System space-time evolution via femtoscopy . . . 64
- 4.4 Searches for novel phenomena: chirality and electromagnetic properties 69
- 4.5 Summary of results for bulk properties and novel phenomena . . . 75

5 Hard probes in heavy ion collisions and sensitivity to quark-gluon plasma . . . 77
- 5.1 Observations of parton quenching . . . 77
- 5.2 Strength of energy loss . . . 85
- 5.3 Medium modifications to jet substructure and fragmentation . . . 93
- 5.4 Studying wavelength behavior by varying parton flavor . . . 102
- 5.5 Studies of in-medium hadronization . . . 105
- 5.6 Quarkonium production and suppression in PbPb collisions . . . 108
- 5.7 Summary of hard probes in the QGP . . . 116

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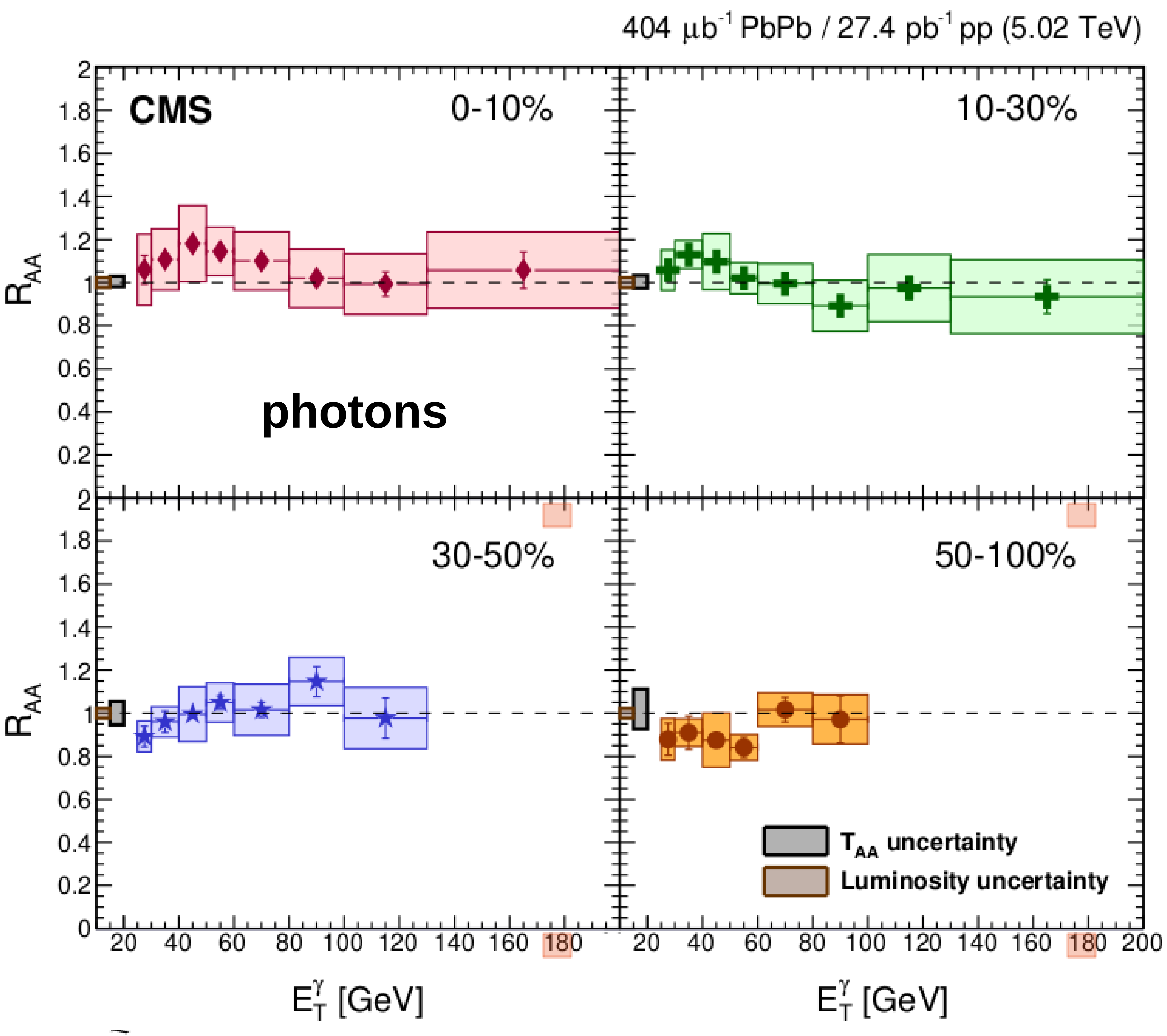

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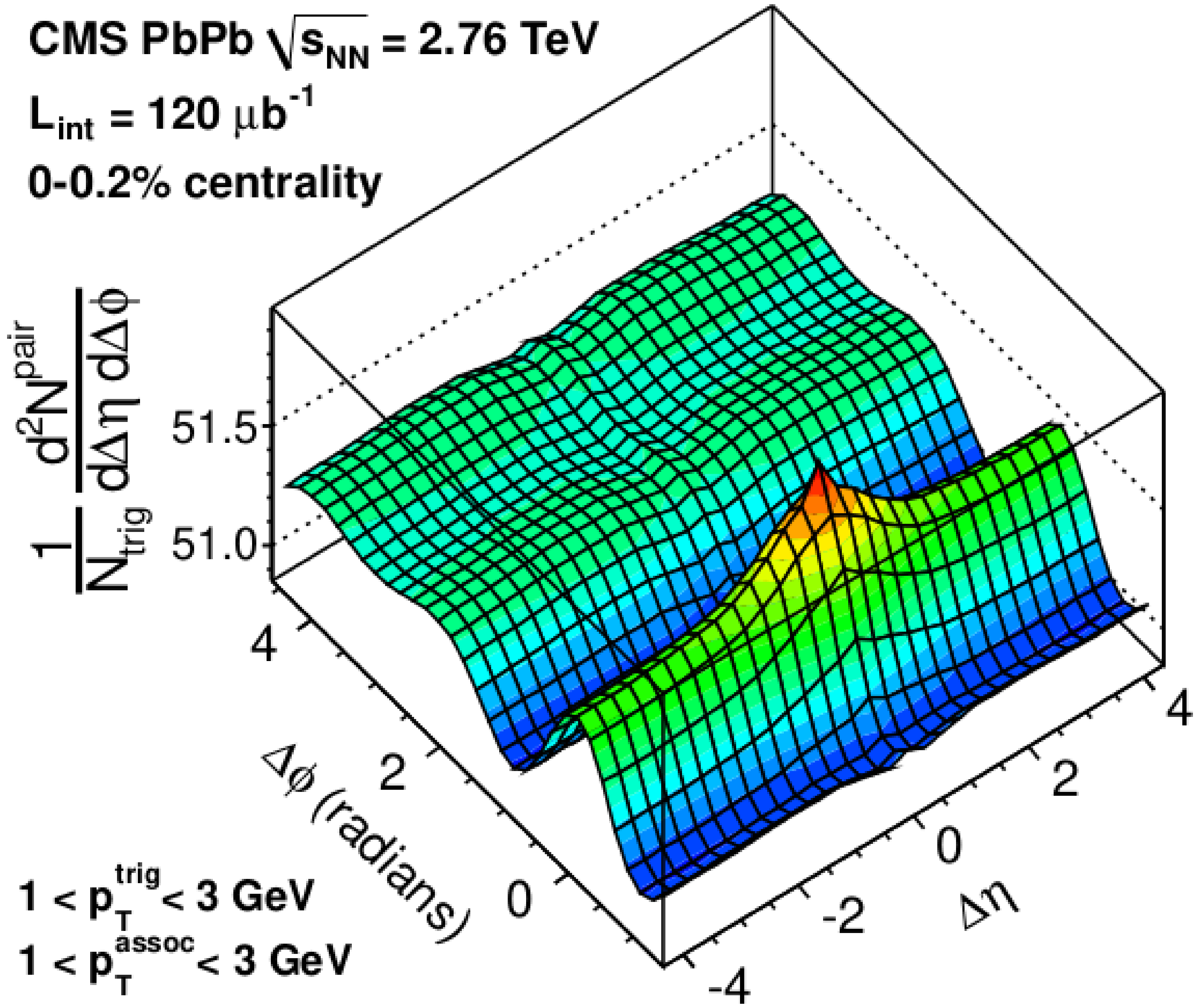

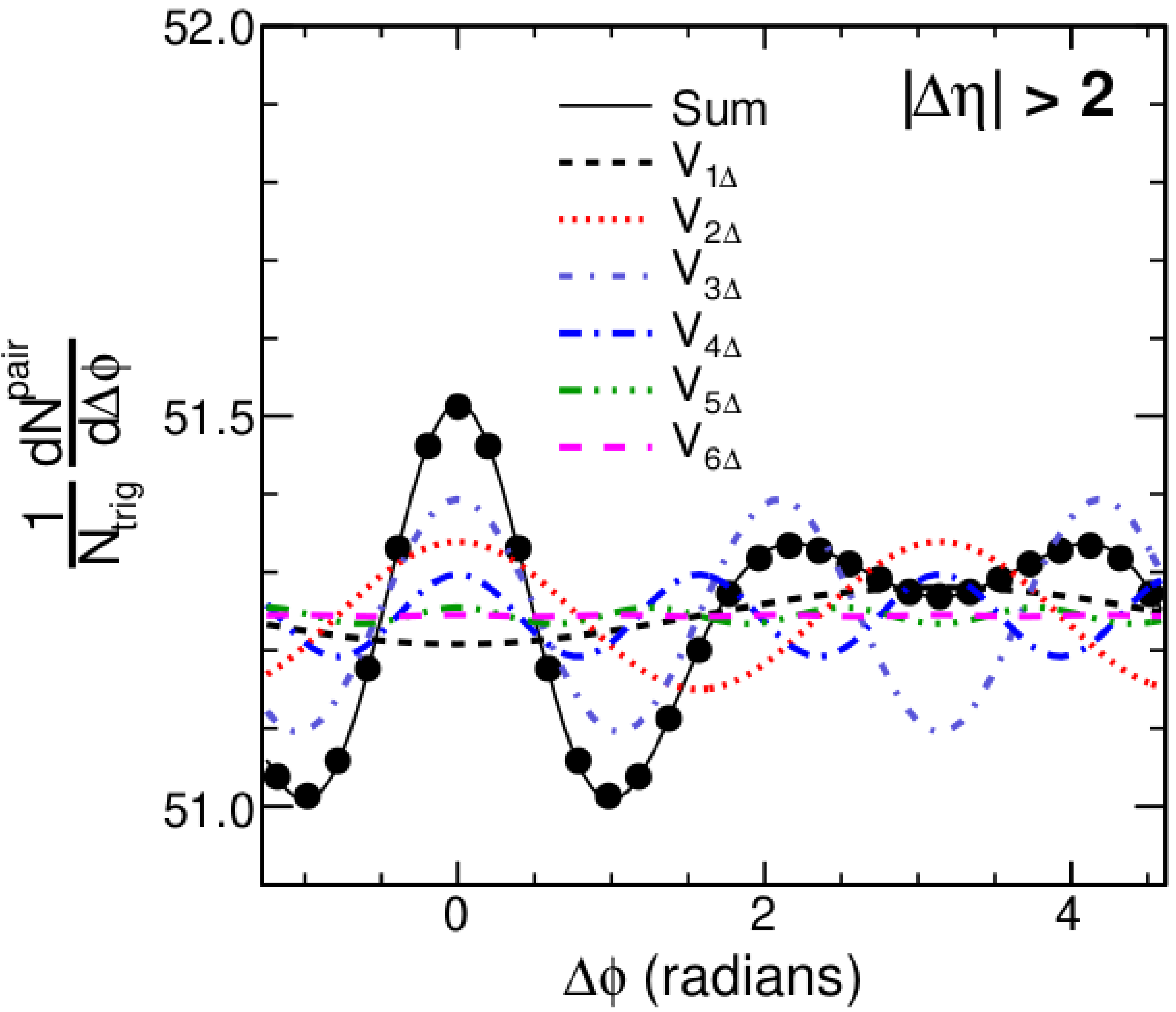

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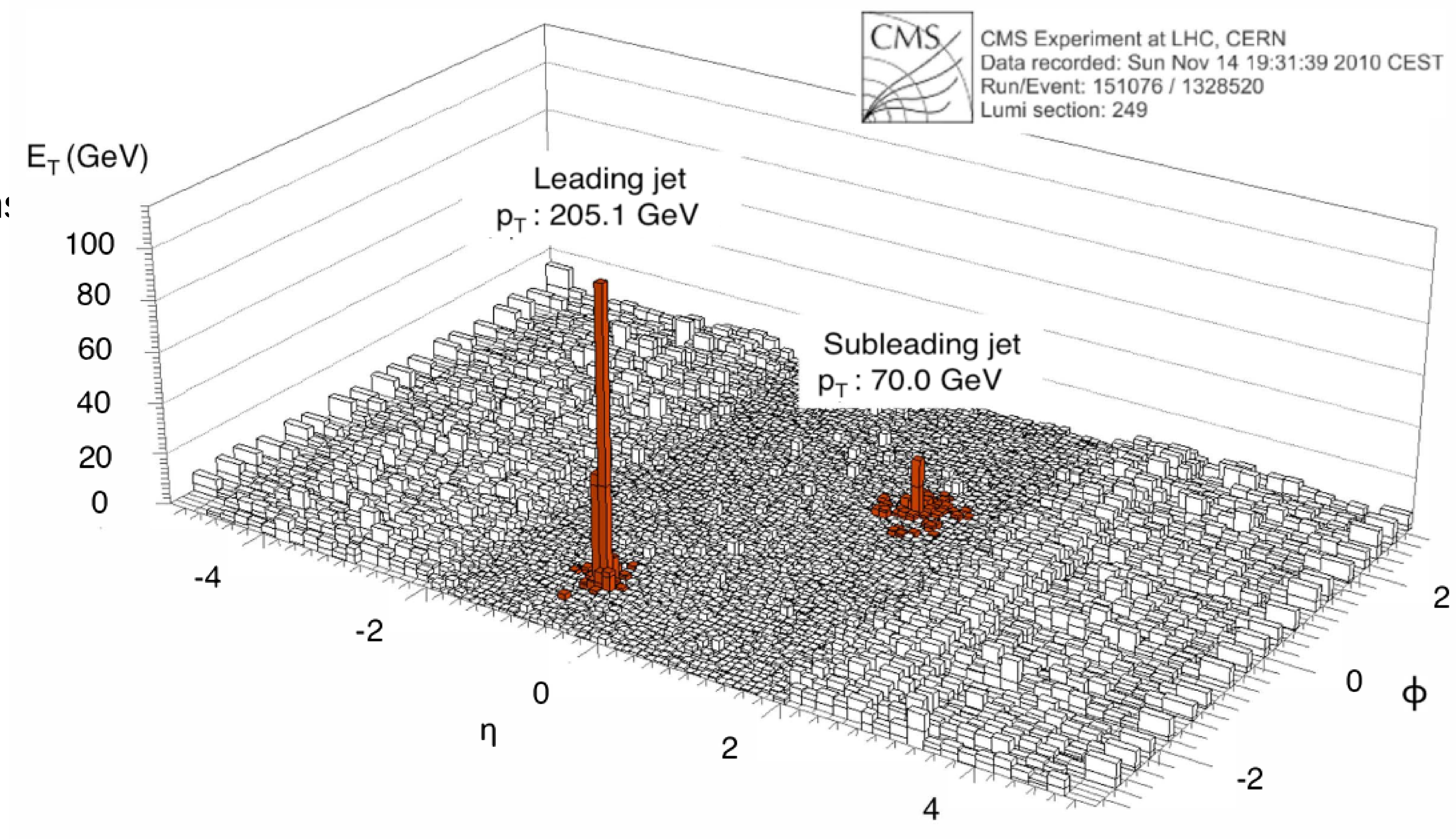
https://arxiv.org/abs/240

Overview

Results from LHC Run

Some historical highlights



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- 6.1 Particle production and hadronization 118
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7 Tests of the electroweak sector and searches for new physics 134
- 7.1 The QED production of an exclusive muon pair 135
- 7.2 The QED production of an exclusive electron-positron pair 137
- 7.3 Light-by-light scattering and τ lepton pair production 140
- 7.4 Exclusion limits on axion-like particle production and anomalous τ lepton magnetic moment 142
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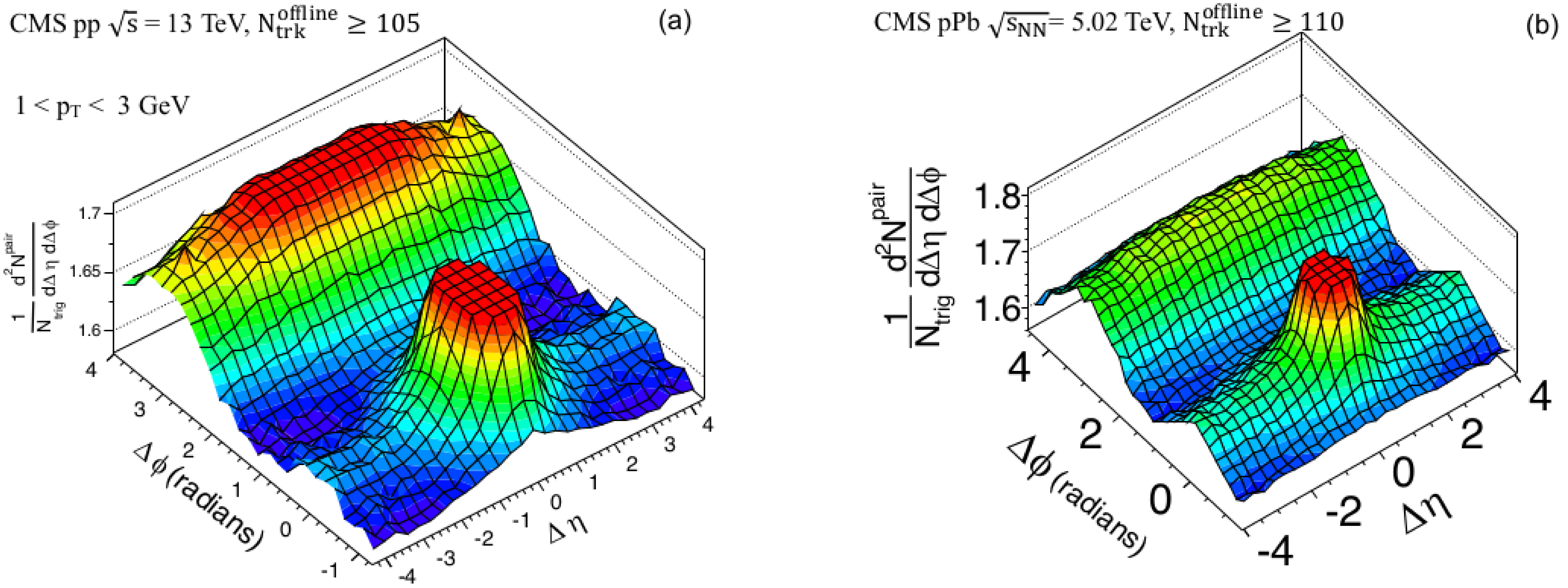
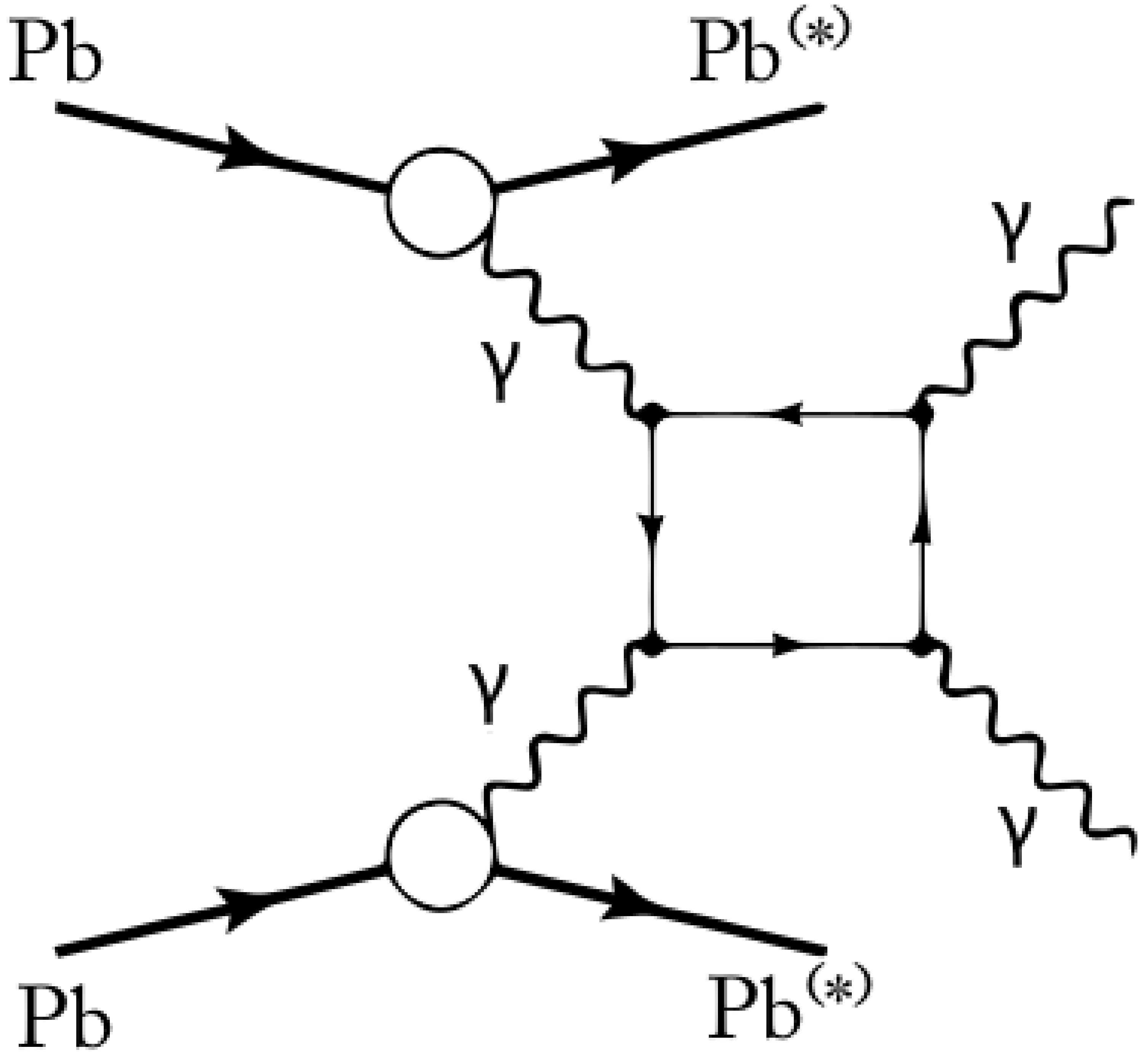
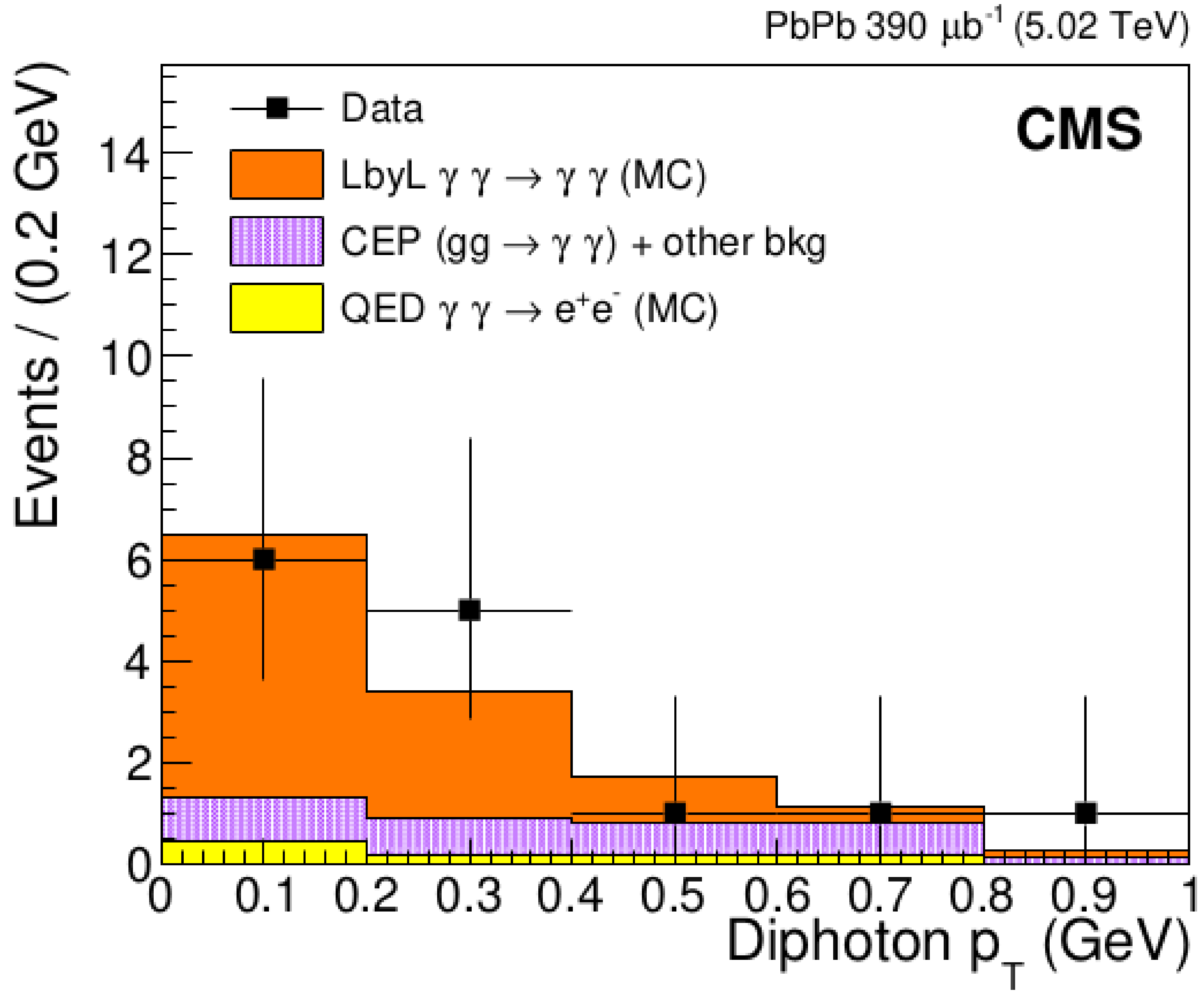


Overview

Results from LHC R

Some historical highlights





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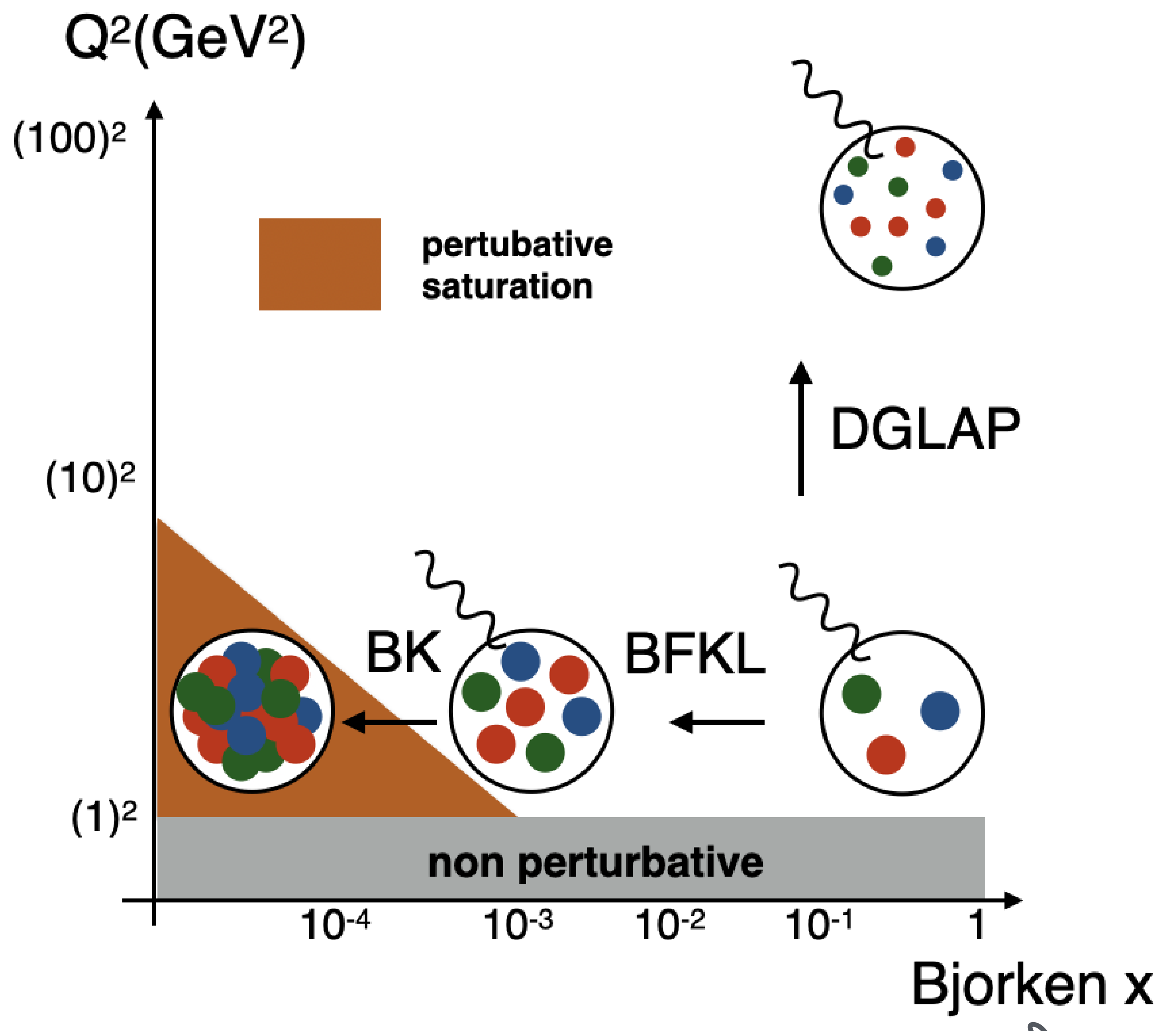
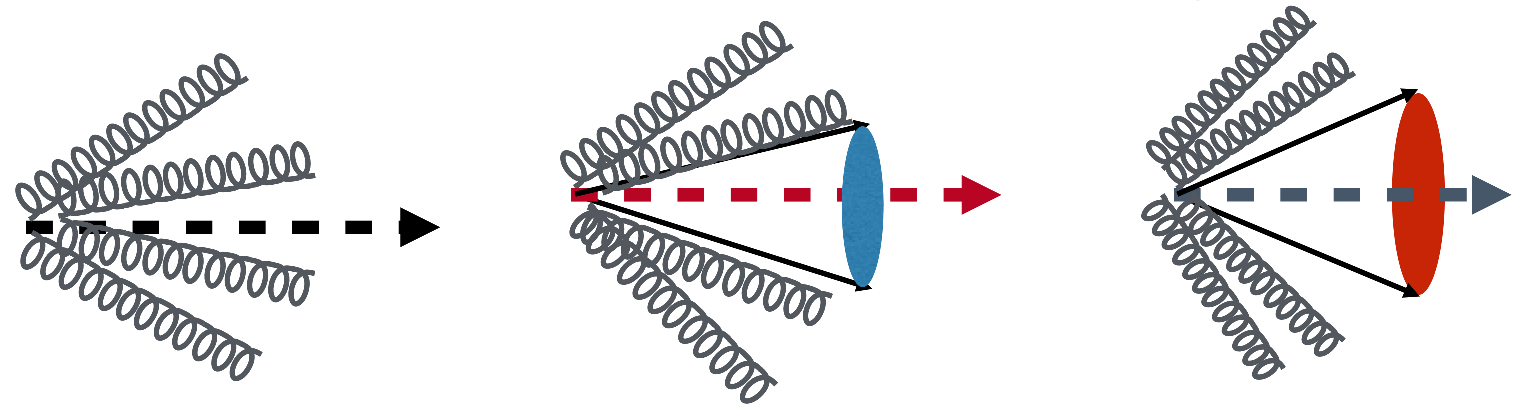
Some selected topics for today

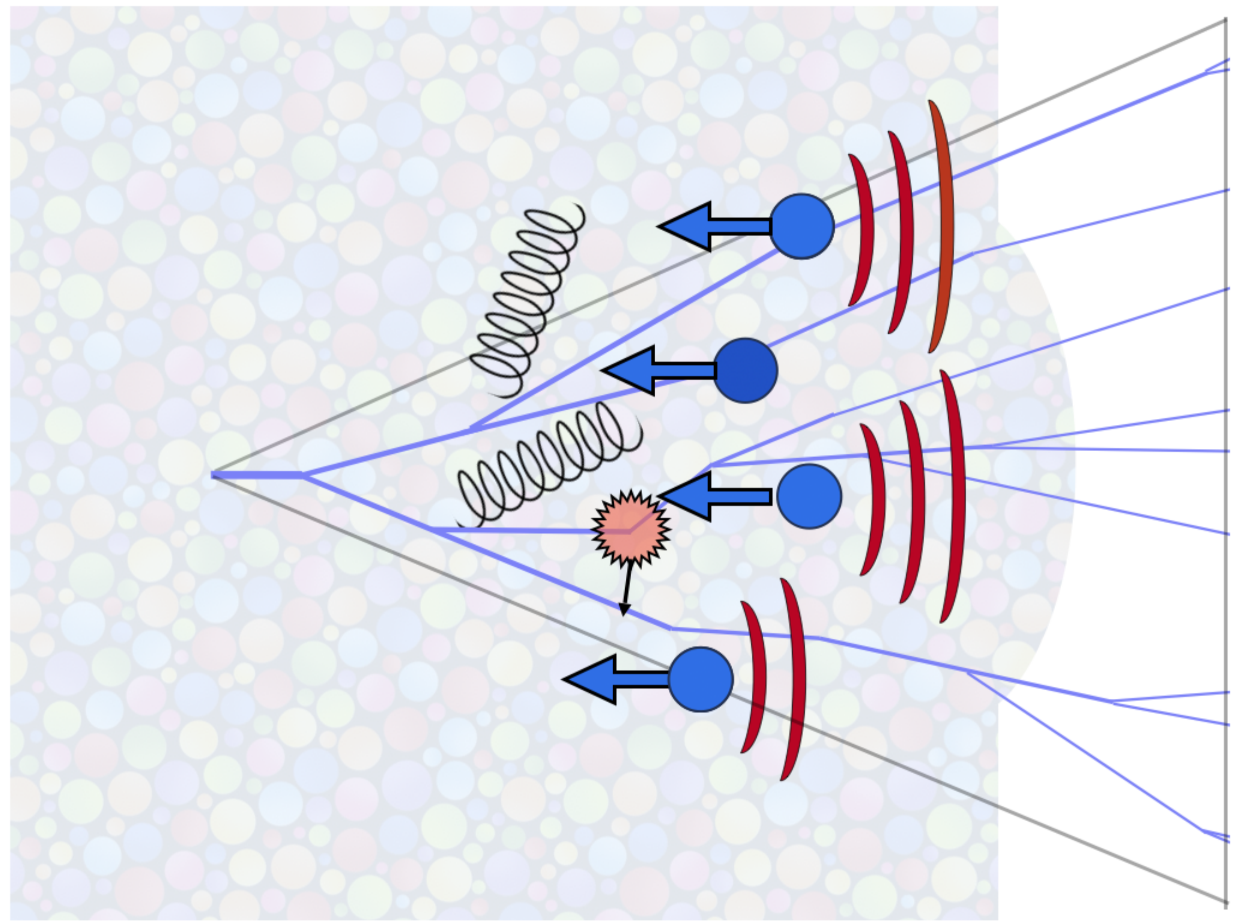


Properties of nuclear matter in nuclei

Quark content of $f_0(980)$

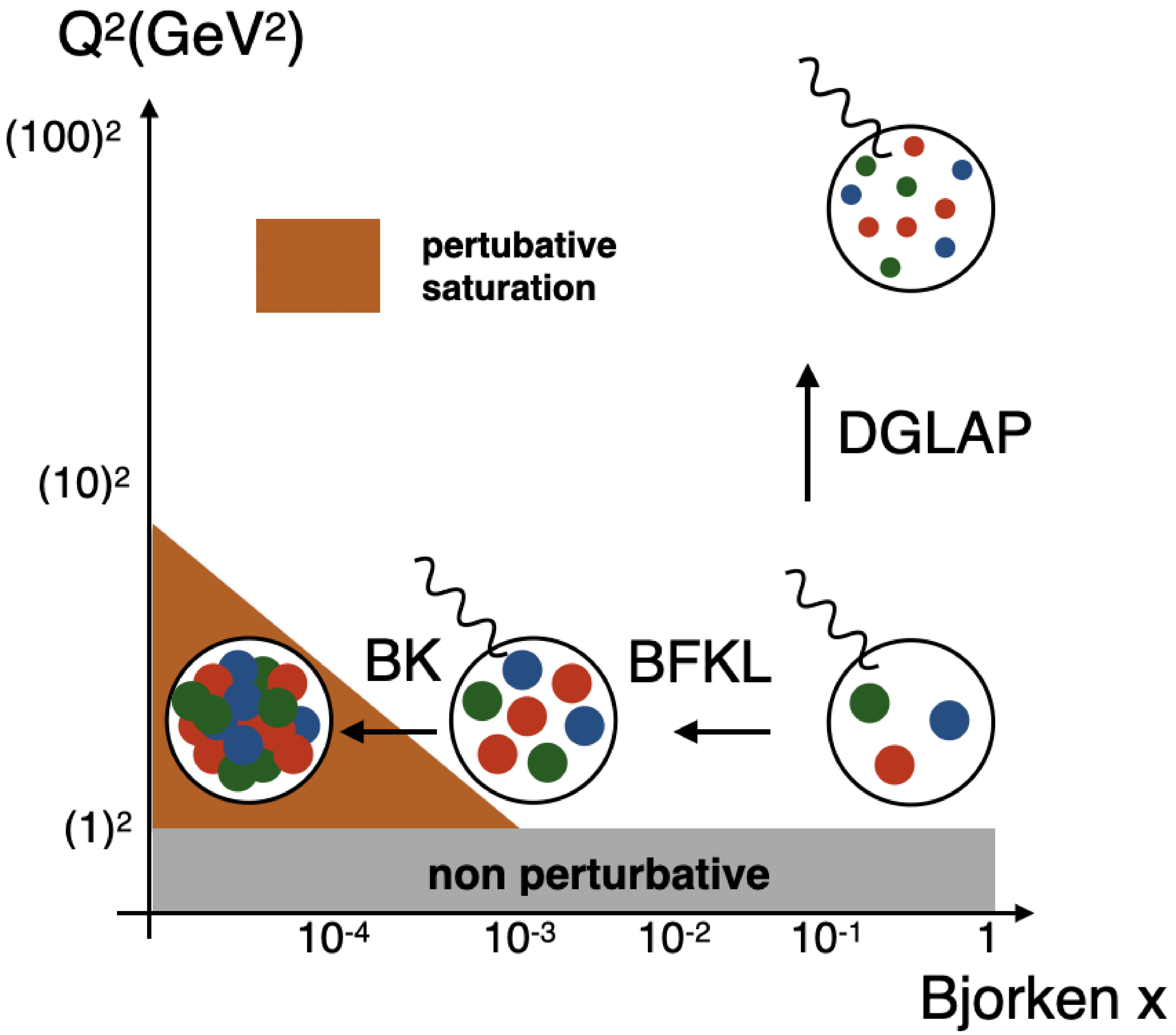


Heavy-quark parton shower in vacuum



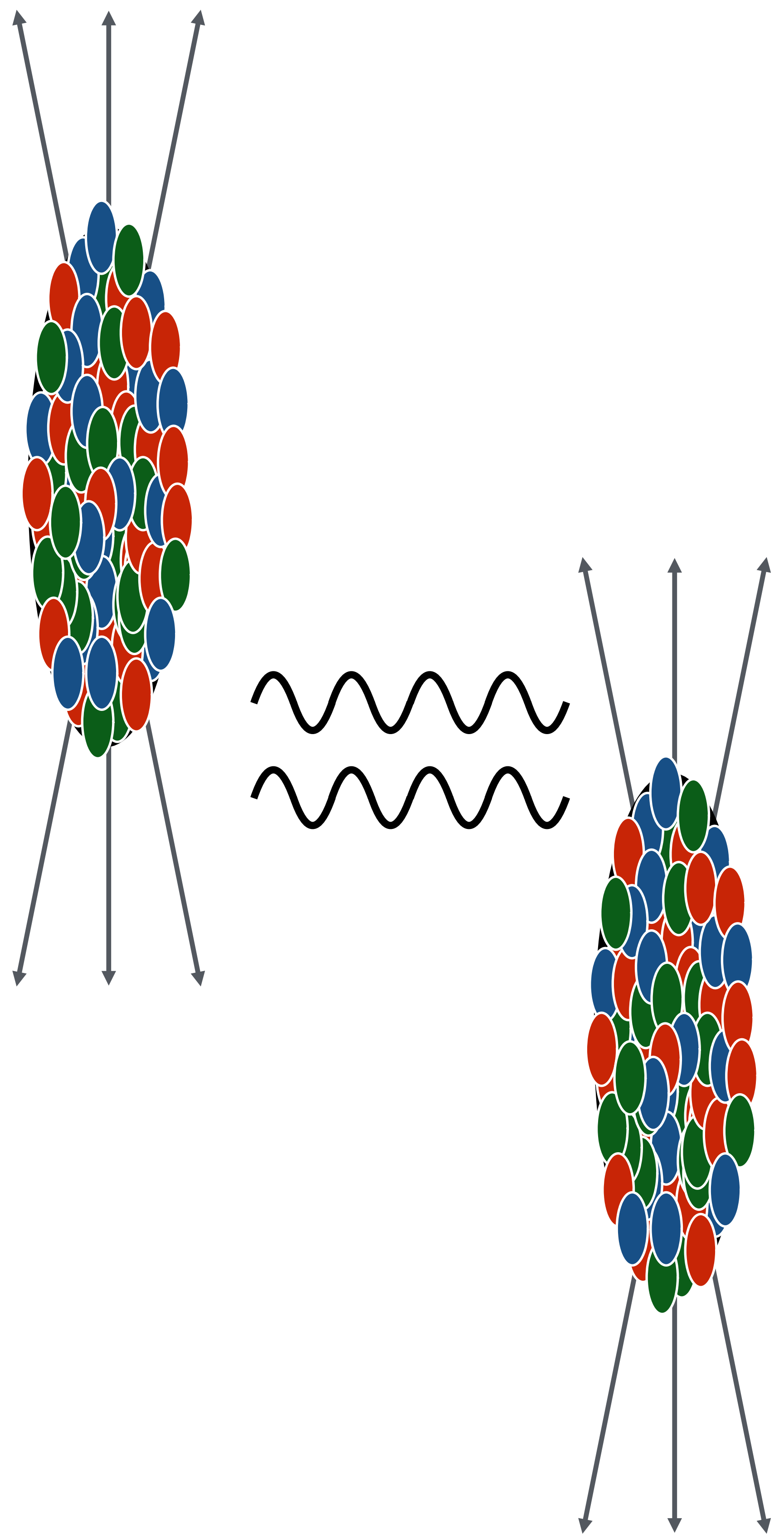
Phenomenology of jet-medium interactions

Characterizing the parton dynamics in nuclei

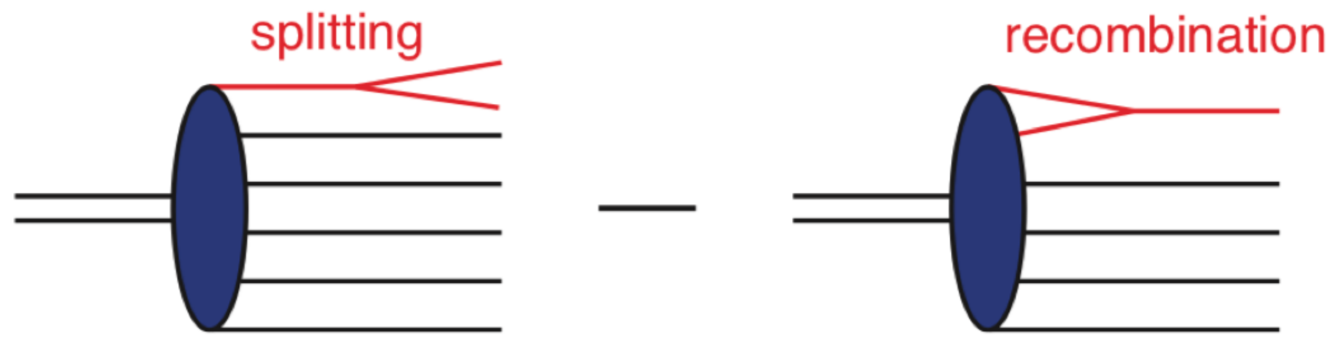


Ultraperipheral heavy-ion collisions

- highest γ-nucleon center-of-mass energy
- absence of sizable final state effects



searching for the possible emergence of **gluon saturation at small x_{BJ}**



Linear evolution
(as in DGLAP and BFKL)

Non linear evolution
(e.g. BK)

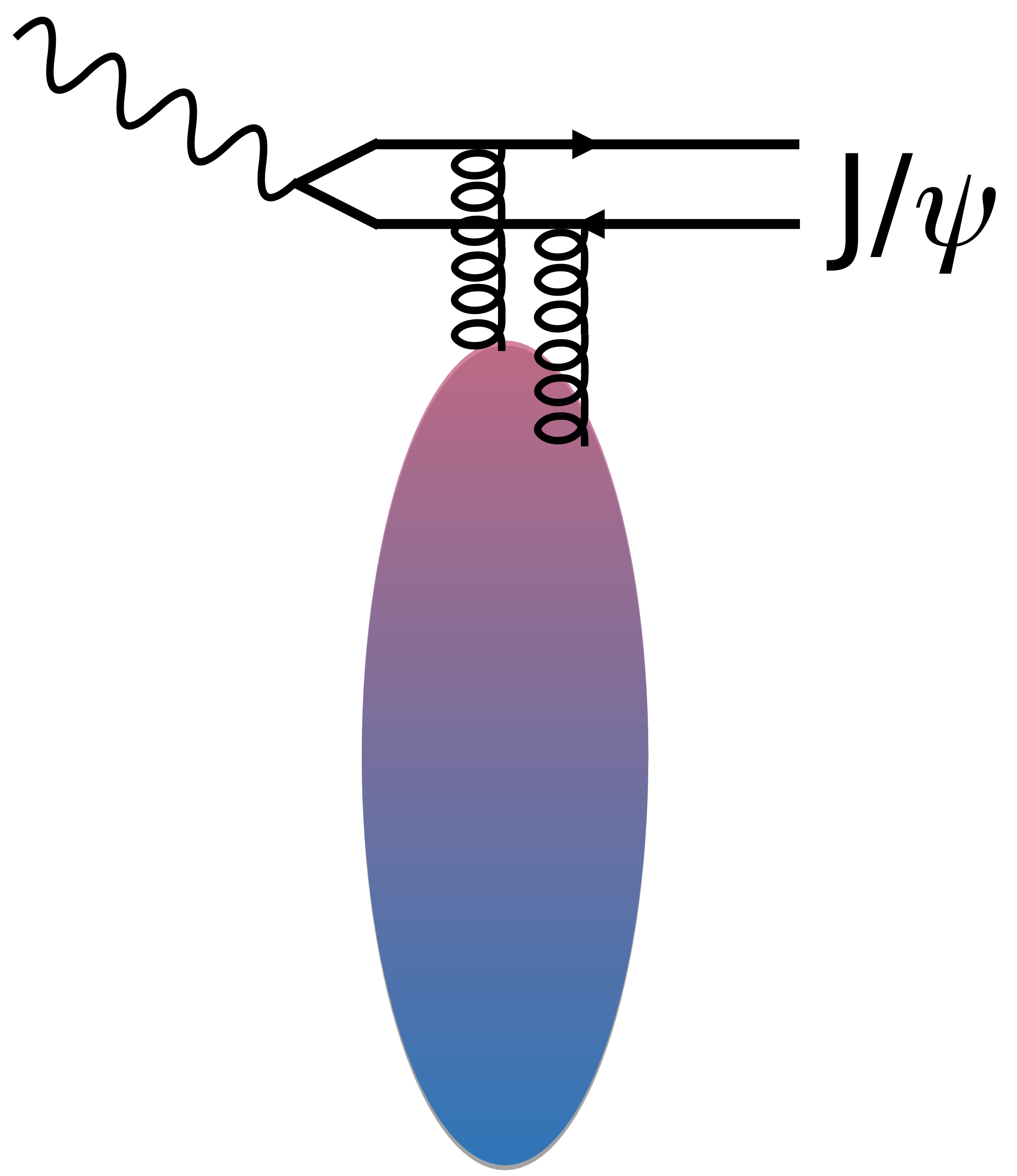
K. Hencken, M. Strikman et al. [Phys.Rept.458 1-171, 2008]

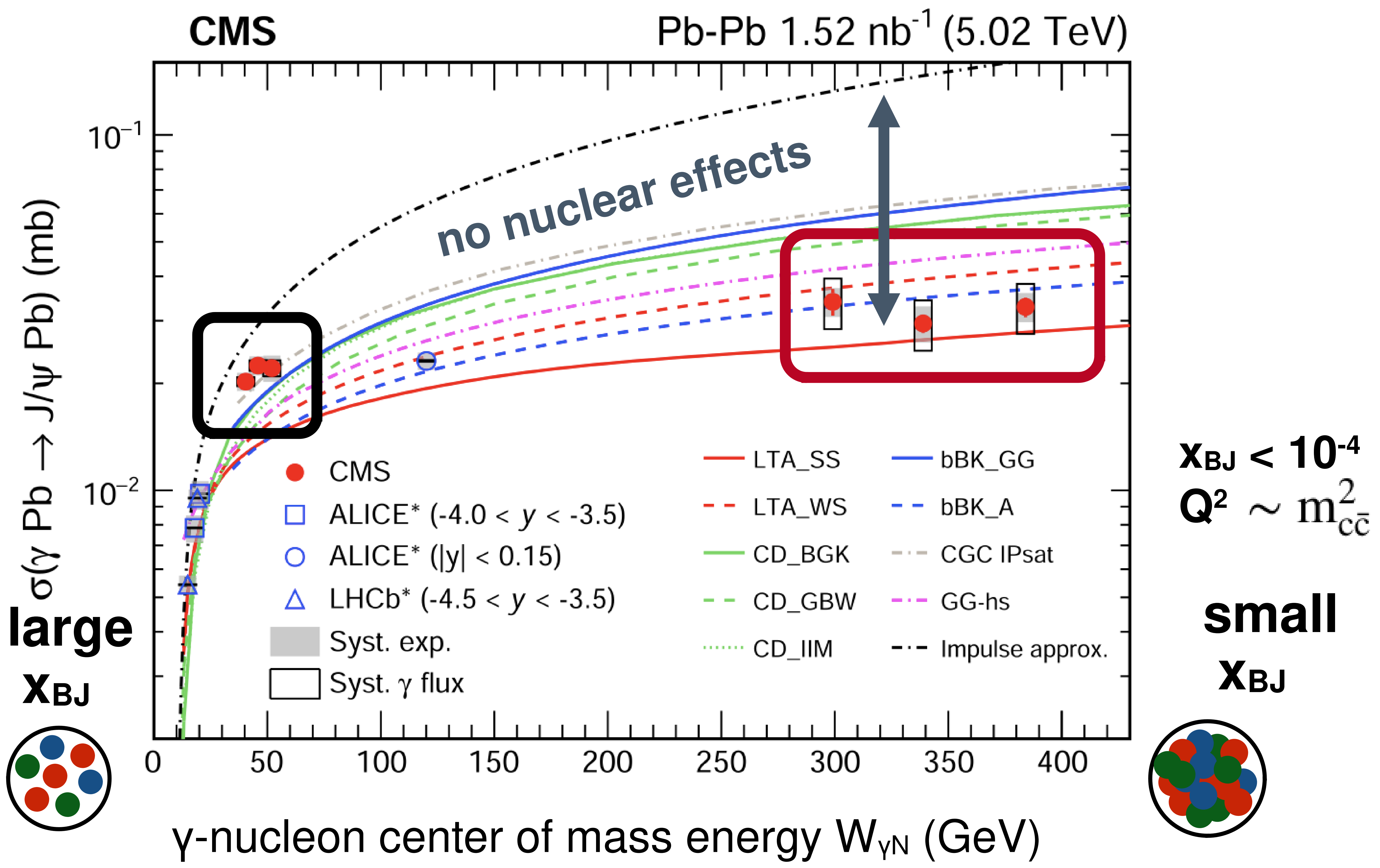
Phys. Rev. Lett. 131 (2023) 262301

Coherent J/ψ production in PbPb UPCs

Low p_T J/ψ (~50 MeV)

- Photon interacts coherently with the nucleus
  → **average gluon density at fixed Q^2**





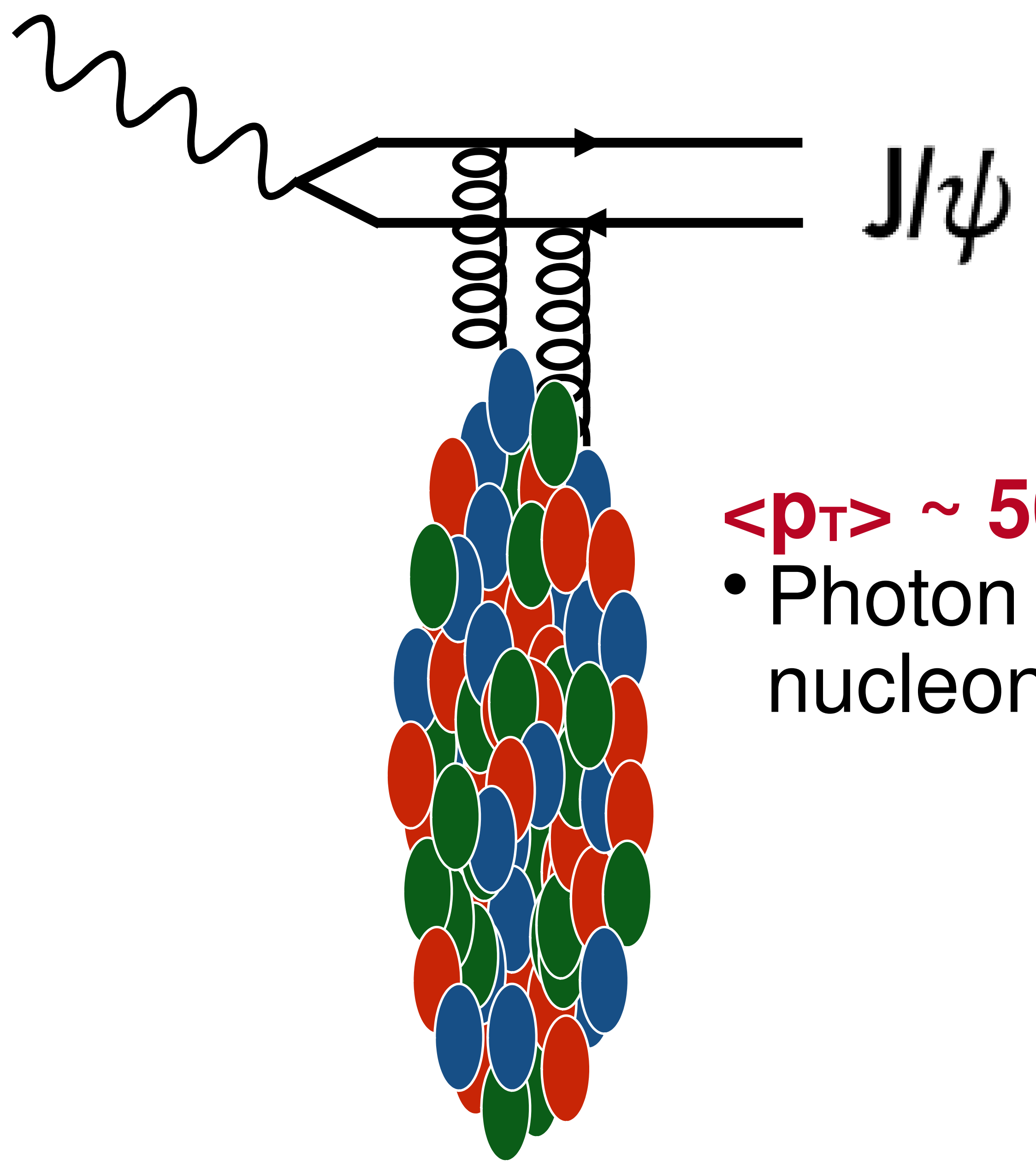
→ **strong suppression at high $W_{\gamma N}$ values (small x_{BJ})** compared to scenarios without nuclear effect (IA)

→ **both shadowing models (*linear evolution*) and saturation (non-linear) fail in describing the observed $W_{\gamma N}$ dependence**

First measurement of incoherent J/ψ in UPCs vs $W_{\gamma N}$

CMS-PAS-HIN-23-009

→ **Probing the local gluon density and fluctuations**

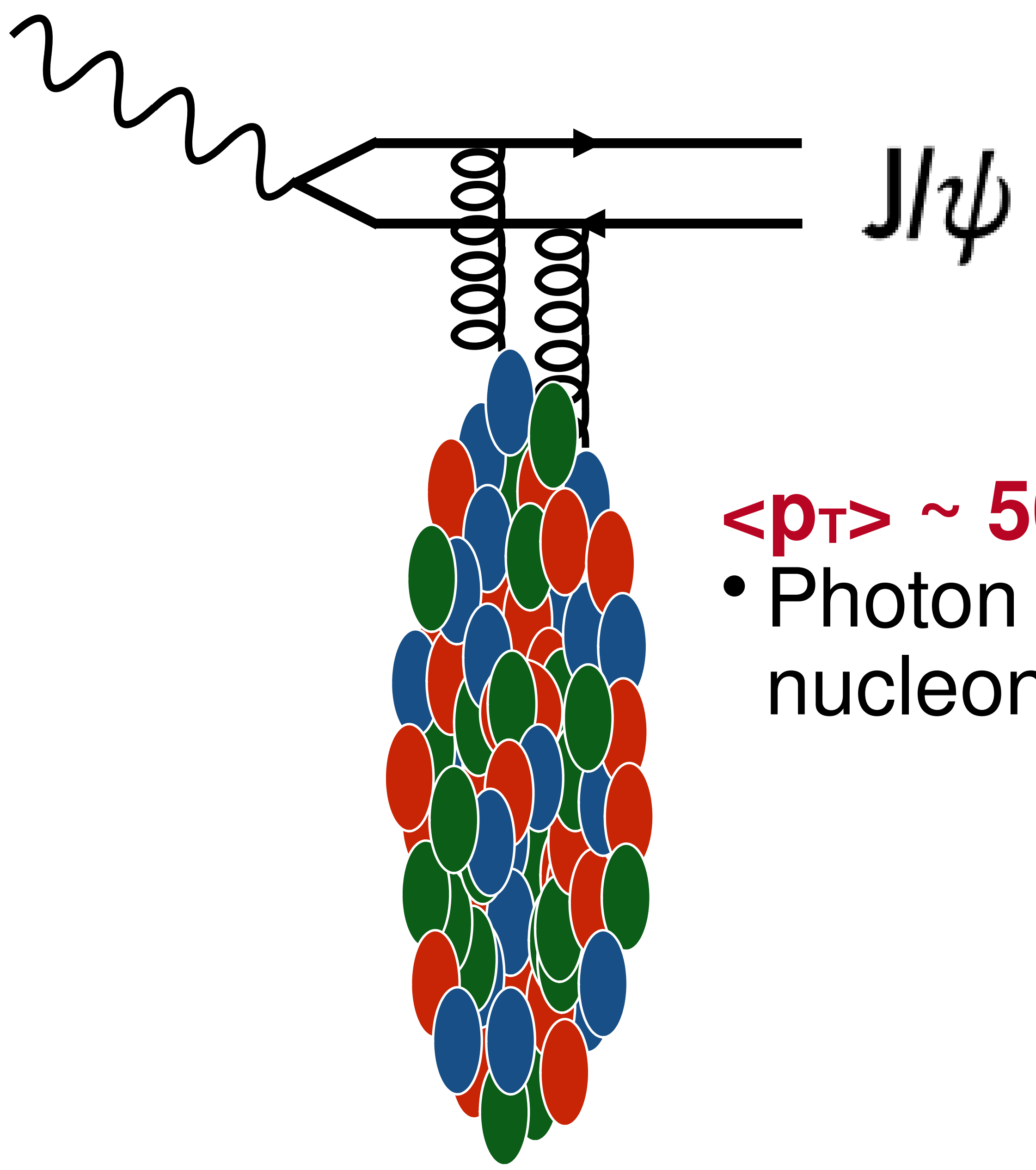


<p_T> ~ 500 MeV

- Photon interacts with a single nucleon or sub-nucleon

First measurement of incoherent J/ψ in UPCs vs $W_{\gamma N}$

CMS-PAS-HIN-23-009



$\langle p_T \rangle$ ~ 500 MeV

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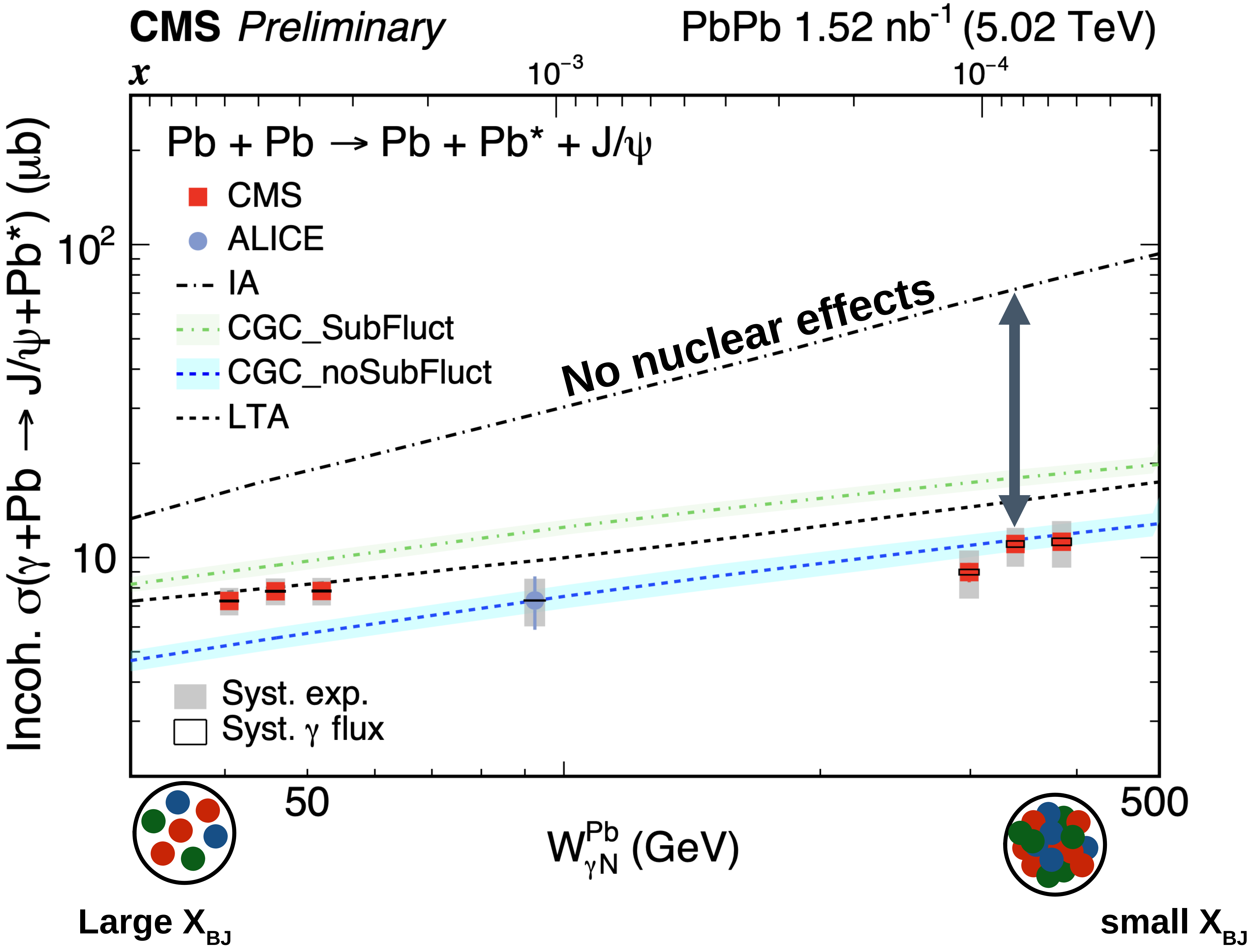
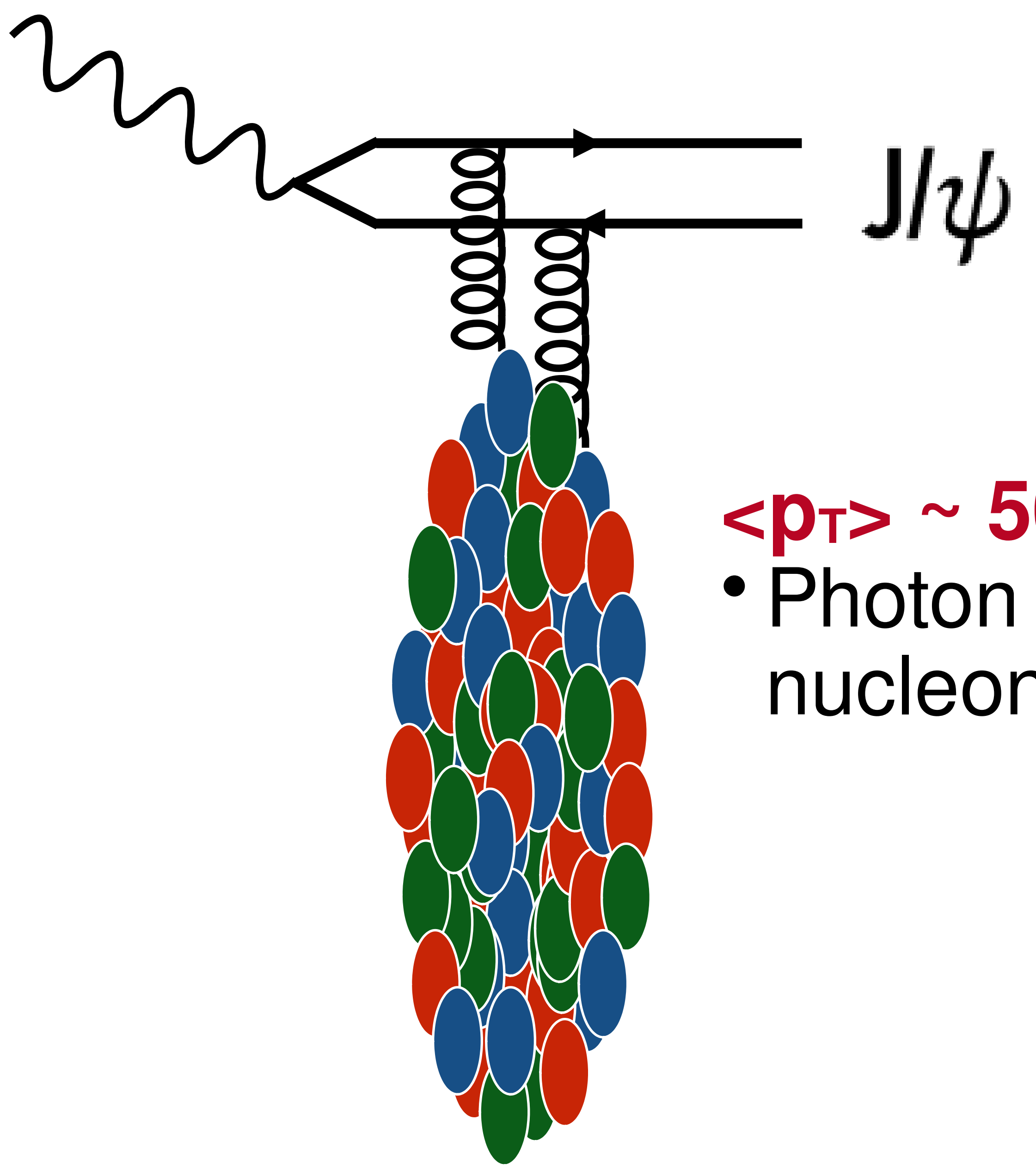


Strong suppression observed at large $W_{\gamma N}$ (small x) w.r.t. no-nuclear effects predictions

- **CMS data "challenge" both shadowing and saturation descriptions**

First measurement of incoherent J/ψ in UPCs vs $W_{\gamma N}$

CMS-PAS-HIN-23-009



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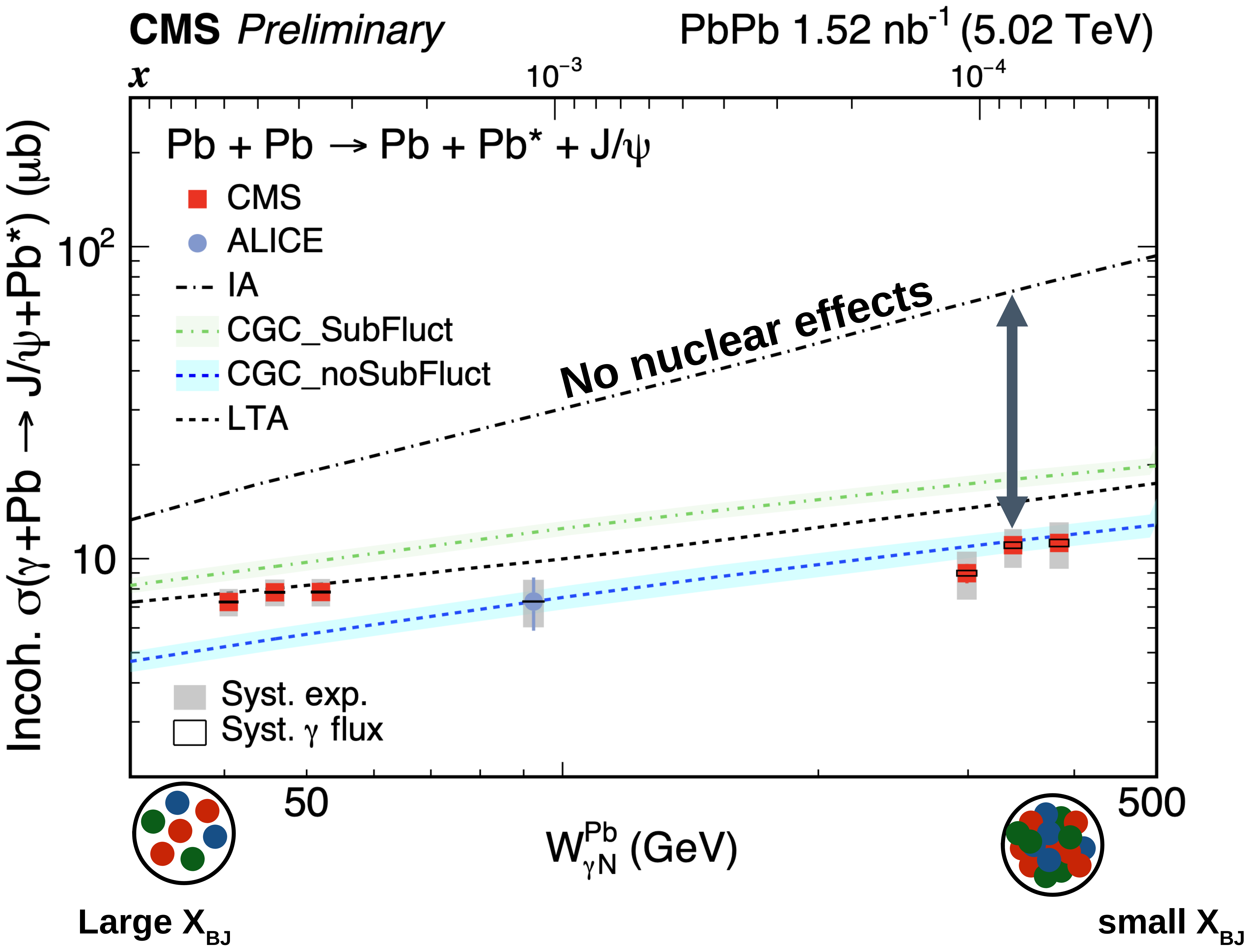
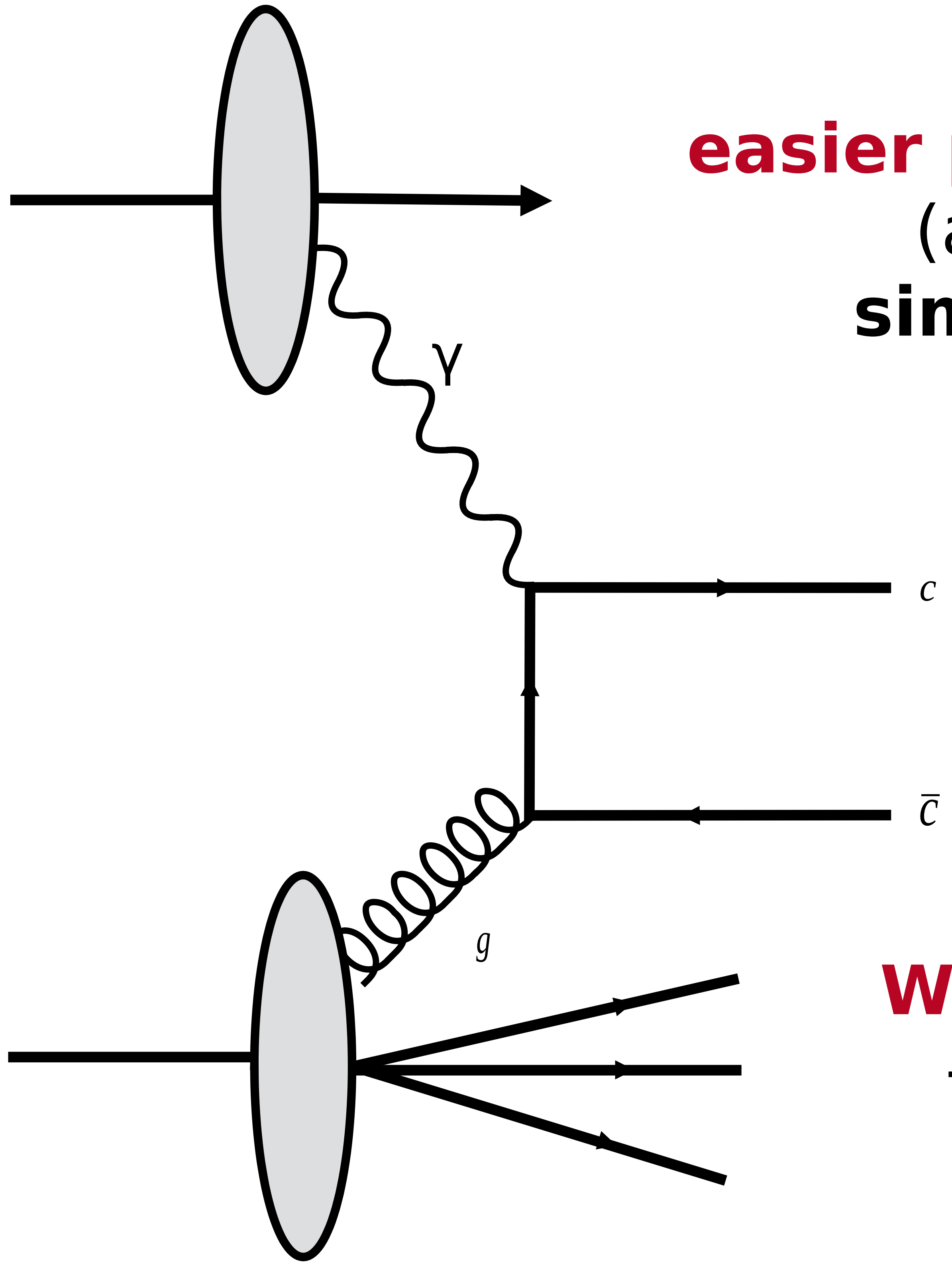


→ Need to "overconstrain" calculations with new probes

→ Current J/ψ measurements: complex theoretical description and limited Q^2 coverage

Open charm production in UPCs:
a new probe for small-x matter

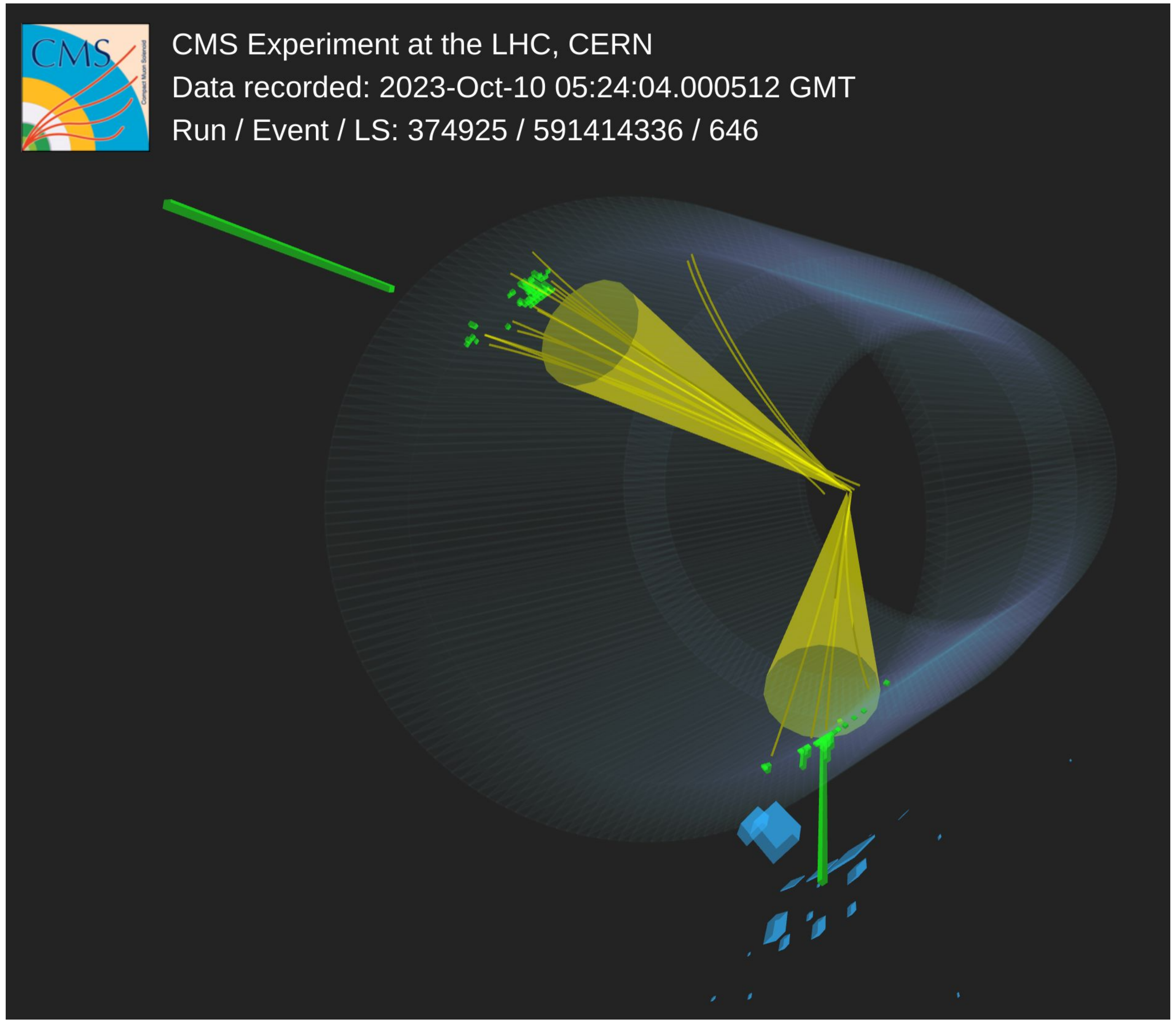
CMS-PAS-HIN-24-003



easier pQCD description at any p_T
(also beyond LO) due to
simple 1-gluon exchange

Accurate final state reconstruction
(e.g. $D^0 \rightarrow K^- \pi^+$ or HF jets)

Wide x and Q^2 coverage
→ differential measurements in y and p_T of the heavy hadron



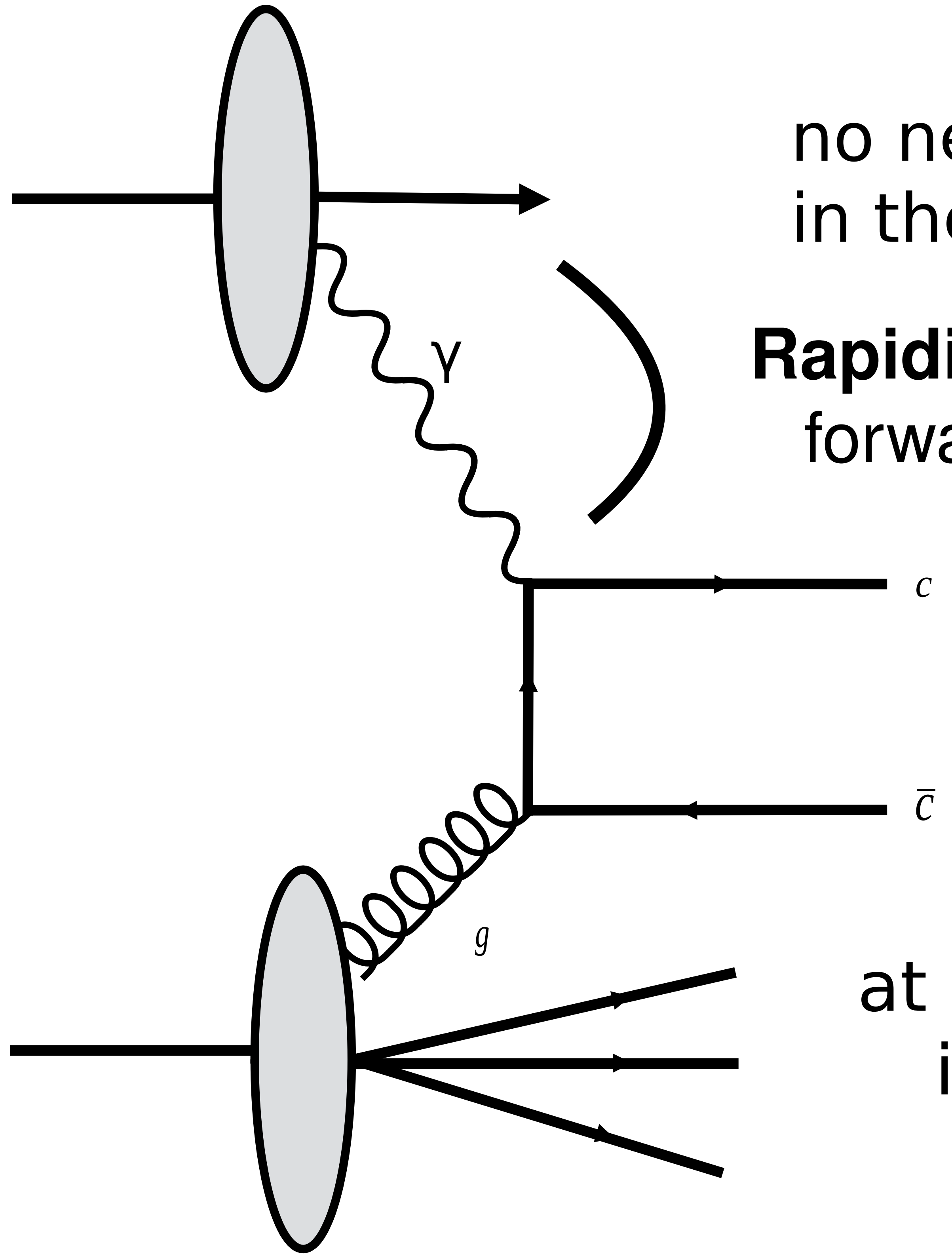
→ testing the transition towards low-x without sizeable final state effects

ATLAS, ATLAS-CONF-2017-011
S. Klein, R. Vogt et al: Phys. Rev. C, v66, 2002

D⁰ photonuclear production in UPCs

CMS-PAS-HIN-24-003

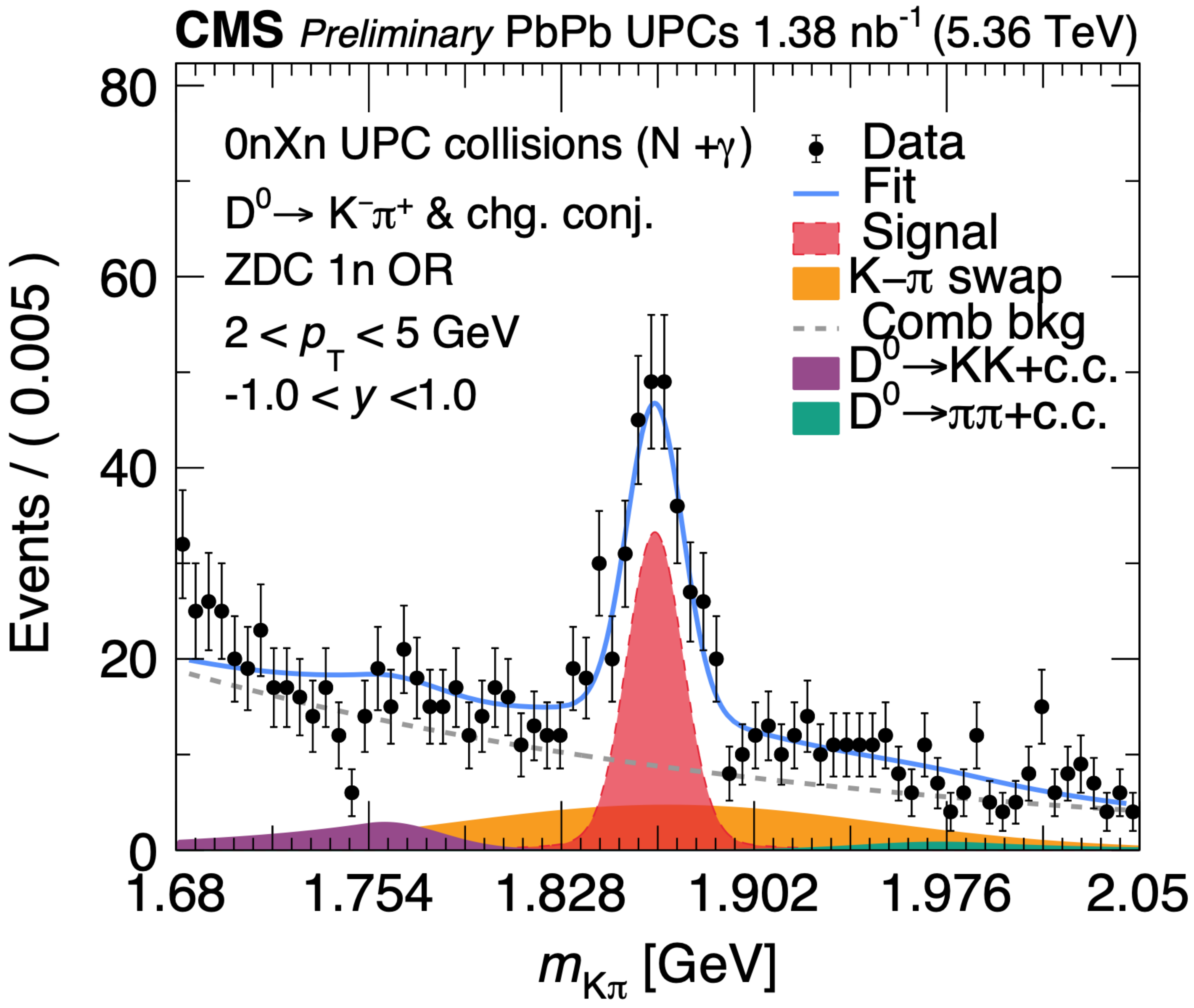
→ in **Xn0n** PbPb events with rapidity gap with **2023 PbPb data**



no neutrons (**0n**)
in the Zero Degree Calorimeter (ZDC)

Rapidity gap in the hadronic forward **calorimeter** (HF)

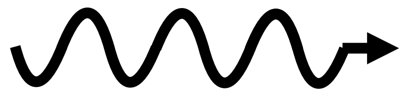
at least one neutron
in the ZDC (**Xn**)

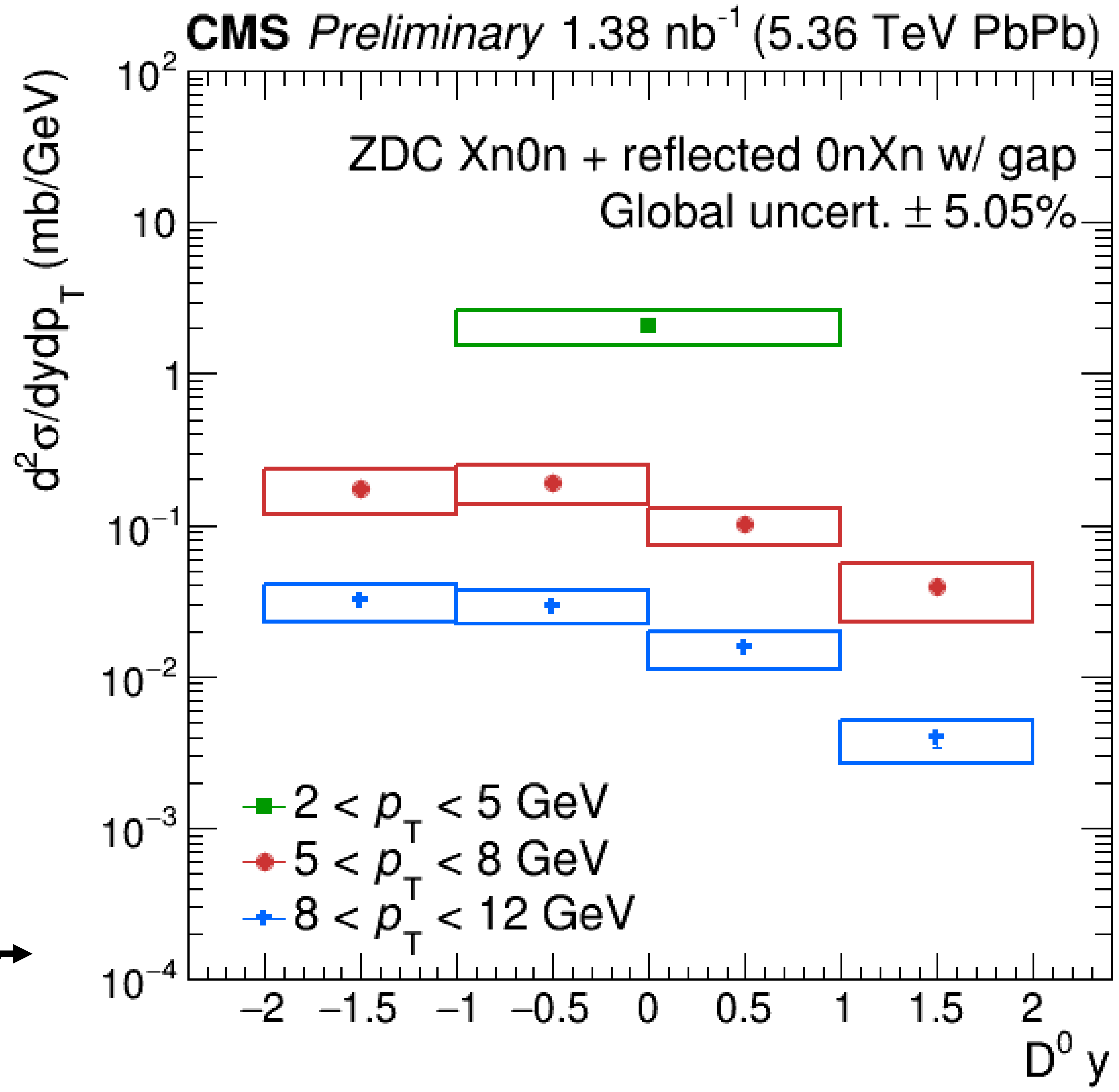


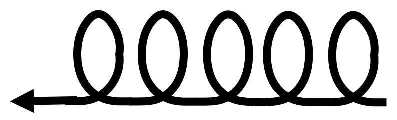
A new trigger strategy for both soft and hard photonuclear events
→ O(**1000**) times more photonuclear events than in **Run 2**

First measurement of the D^0 photonuclear production

[CMS-PAS-HIN-24-003]

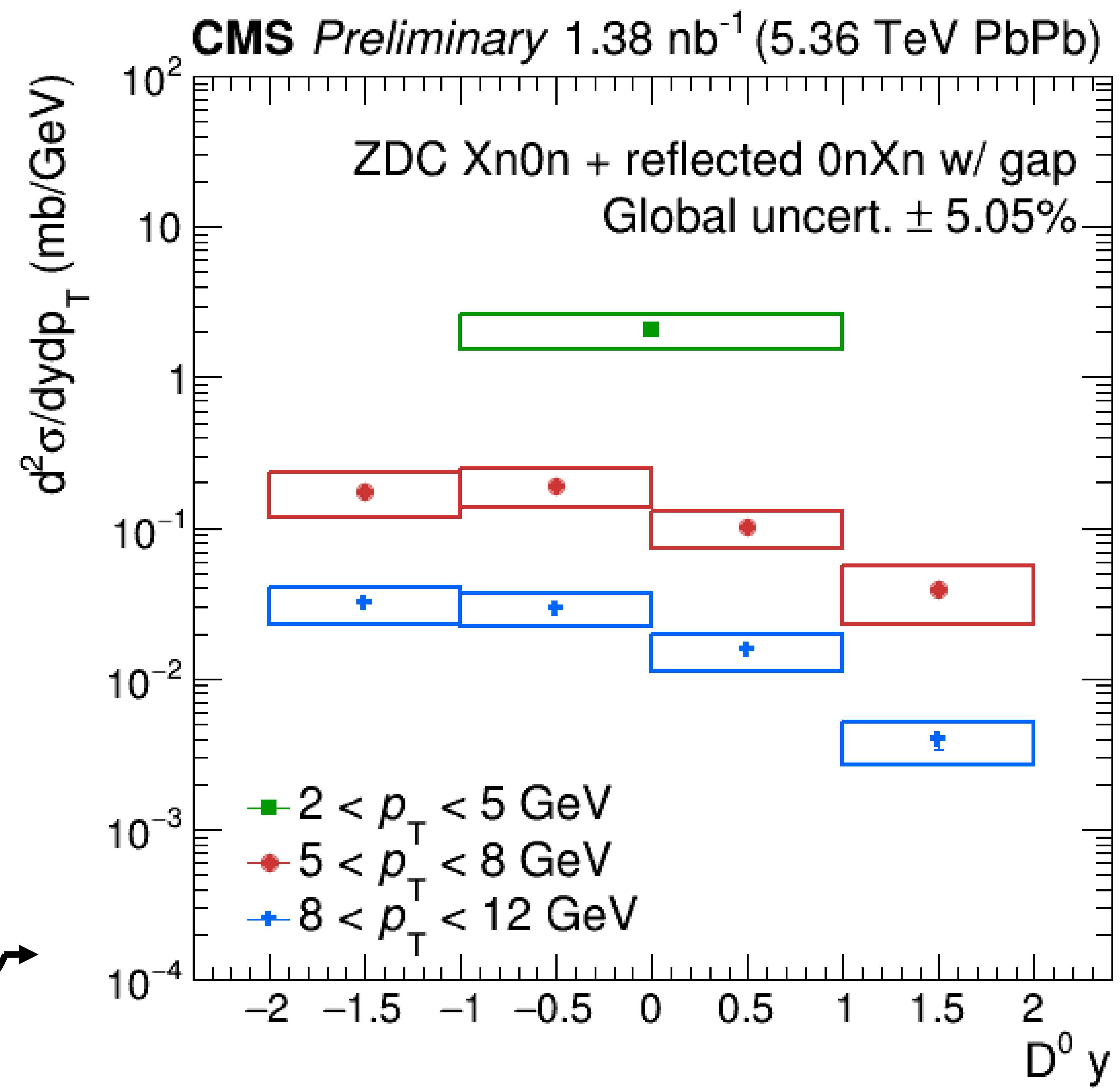


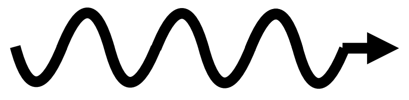


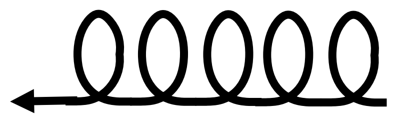


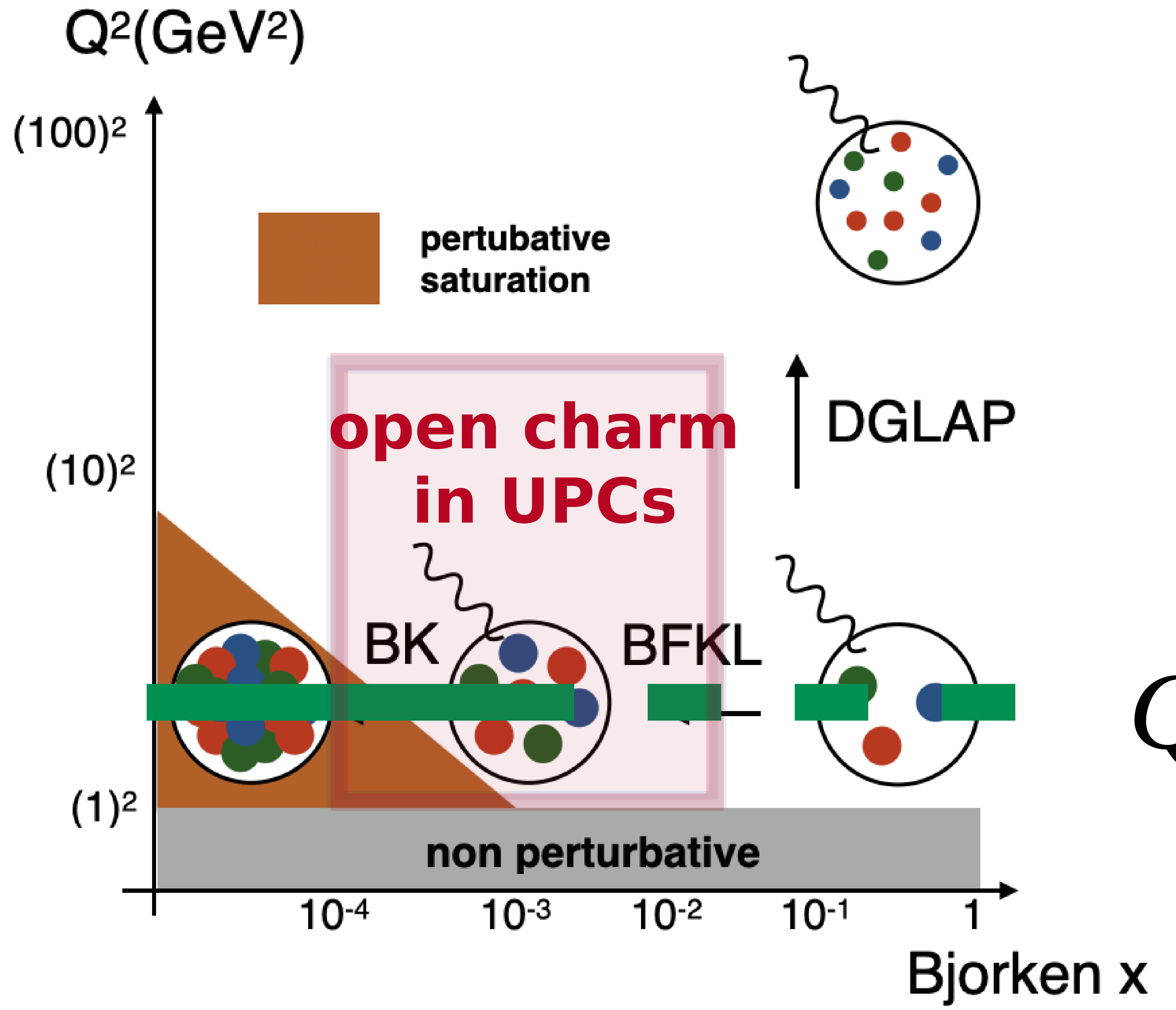
First measurement of the D⁰ photonuclear production

CMS-PAS-HIN-24-003









$$Q^2 \propto m^2_{J/\psi}$$

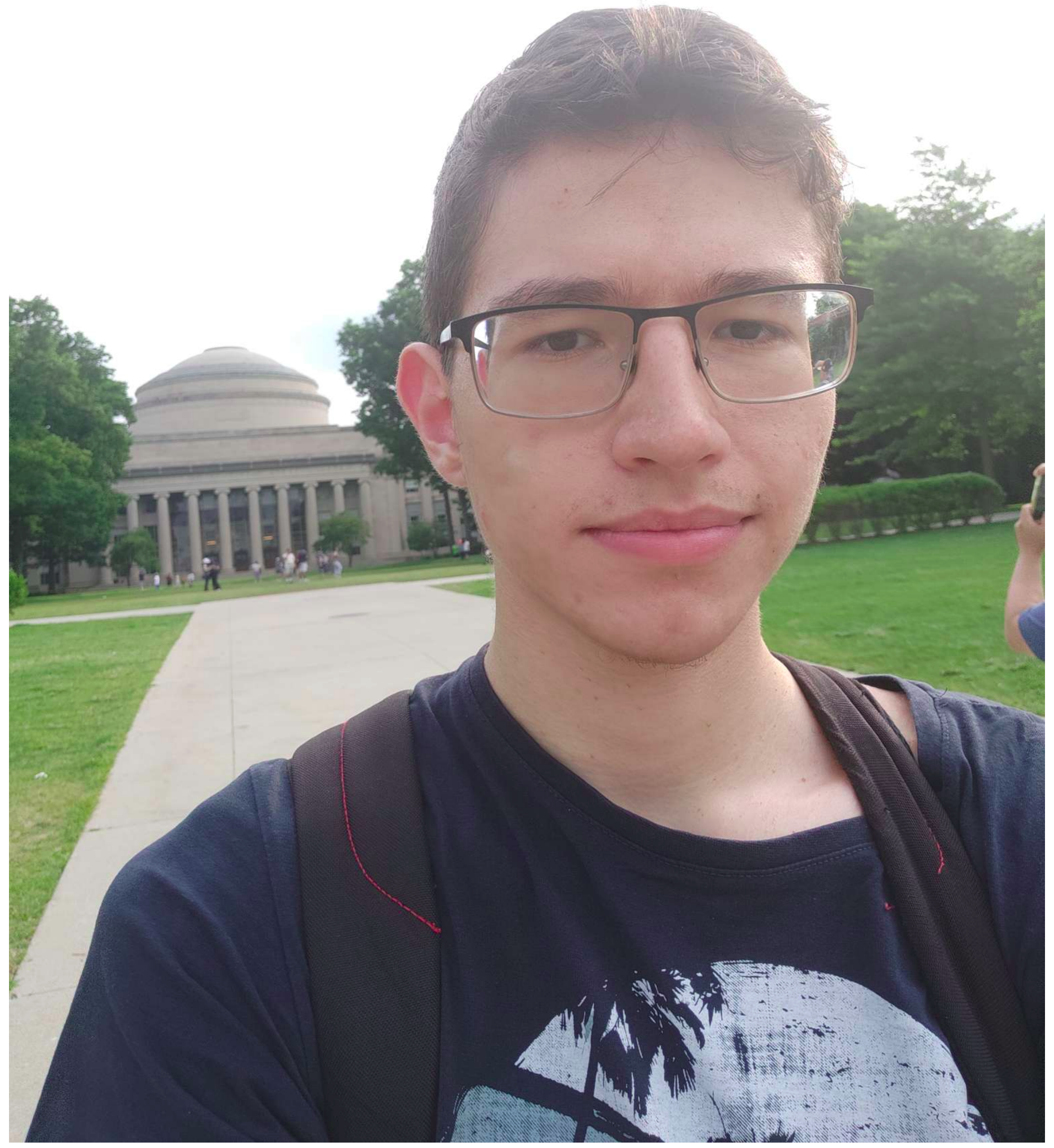
→ **First constraints on nuclear gluon PDFs <u>over a wide region of Q²</u> ($\mathcal{O}$(10) < Q² < hundreds GeV²)** at low-x (~ $5 \cdot 10^{-4} < x < 10^{-2}$) **without sizable final state effects**

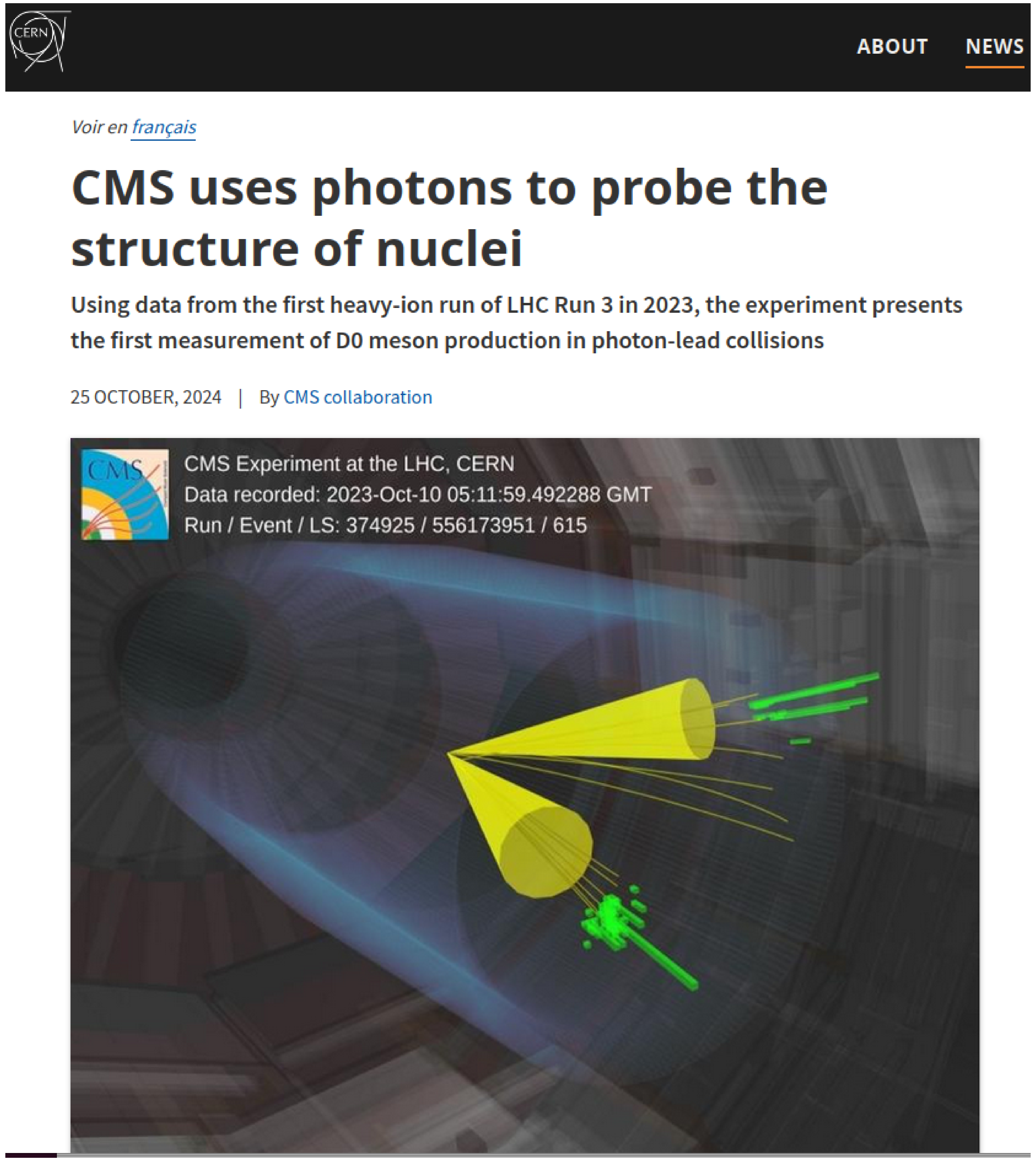
→ **opens the way for a large program of open heavy-flavor hadrons, jets and correlations in UPCs**

First measurement of the D^0 photonuclear production

CERN Press Release

See **poster and flash talk** by Balázs Kovács!




ABOUT NEWS

Voir en français

CMS uses photons to probe the structure of nuclei

Using data from the first heavy-ion run of LHC Run 3 in 2023, the experiment presents the first measurement of D0 meson production in photon-lead collisions

25 OCTOBER, 2024 | By CMS collaboration

https://home.cern/news/news/physics/cms-uses-photons-probe-structure-nuclei

CMS-PAS-HIN-24-003

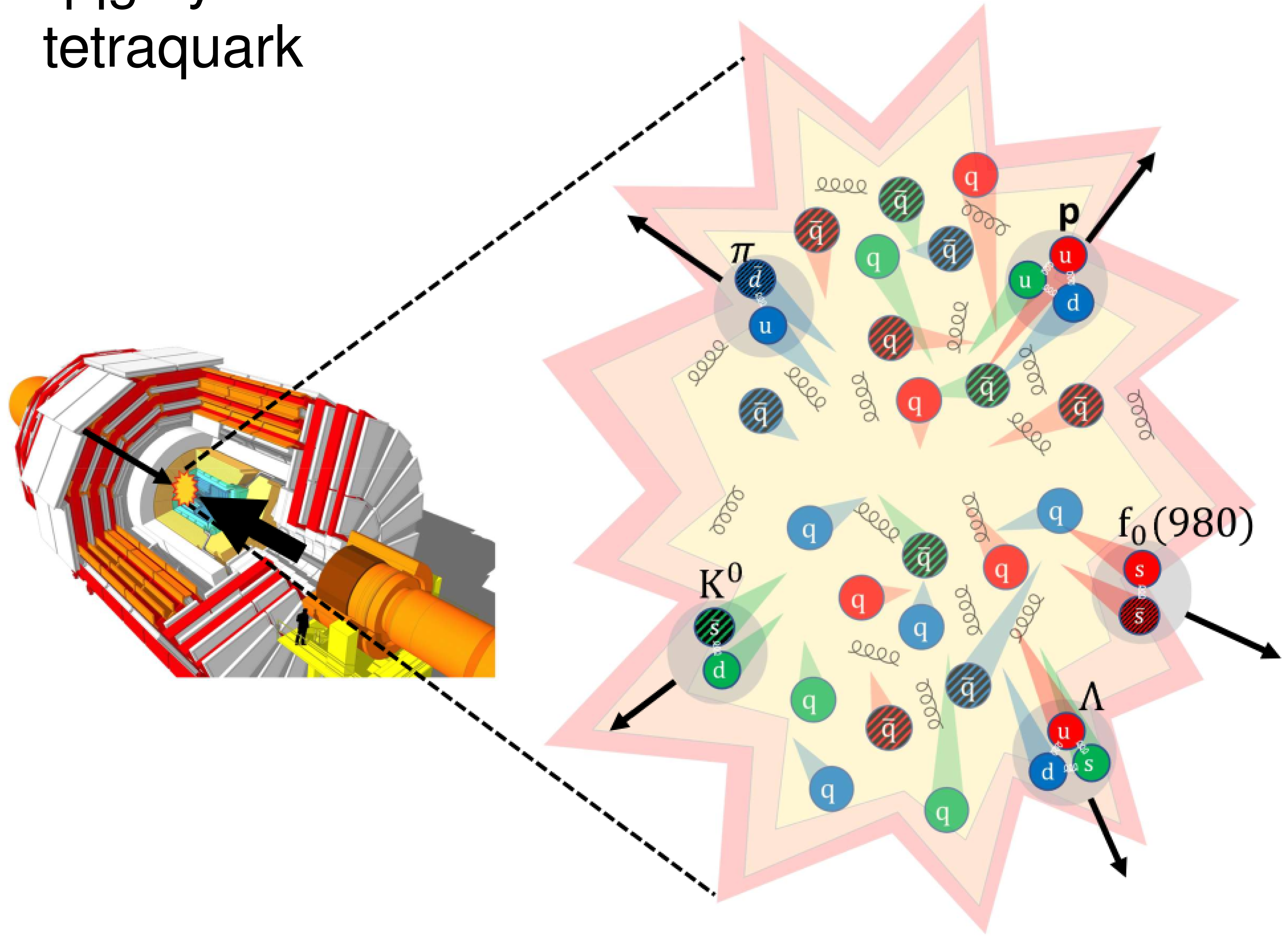
Quark content of $f_0(980)$

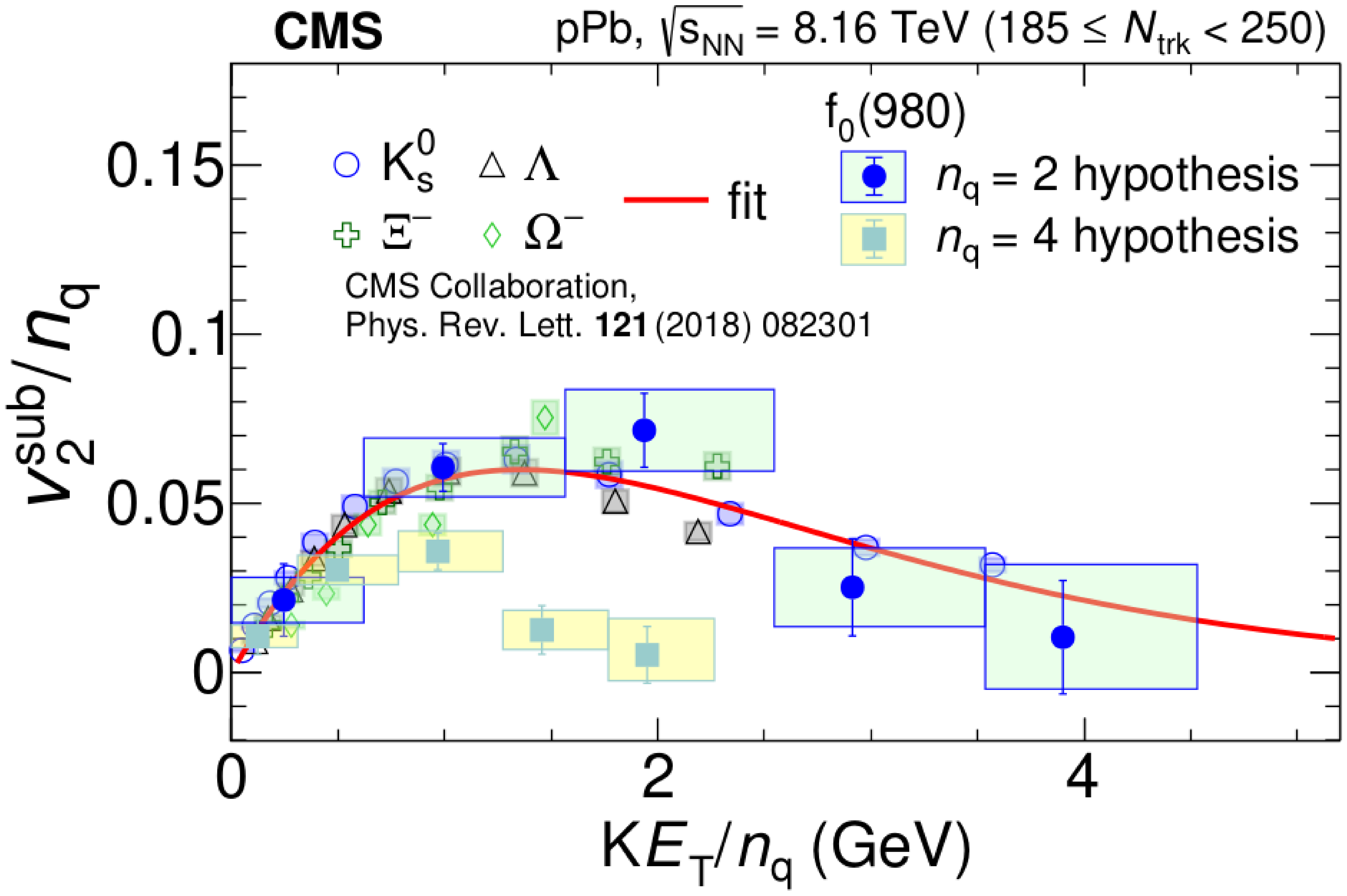
Elliptic anisotropy of $f_0(980)$

$$\frac{dN_h}{d\phi} \propto \left(\frac{dN_q}{d\phi}\right)^{n_q} \propto \left[1 + \sum_{n=1}^{\infty} 2 v_{n,q}(p_T^q)\cos(n[\phi - \psi_n])\right]^{n_q}$$

- Quark content unknown for ~50 years
- number of **constituent quark scaling** is employed
- Results compatible with $q\bar{q}$ state, and disfavor:
  - $K\bar{K}$ molecule
  - $q\bar{q}g$ hybrid
  - tetraquark

$$v_n(p_T) \approx n_q v_{n,q}(p_T/n_q)$$





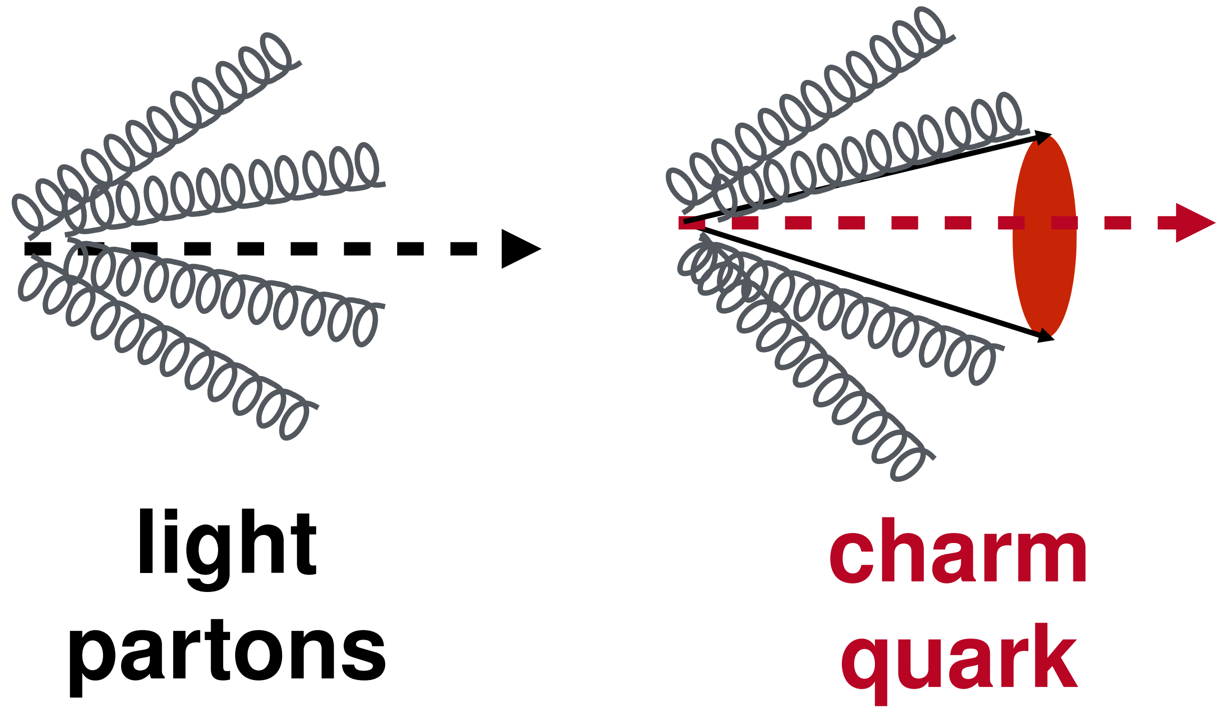
Accepted by Nature Physics Communications

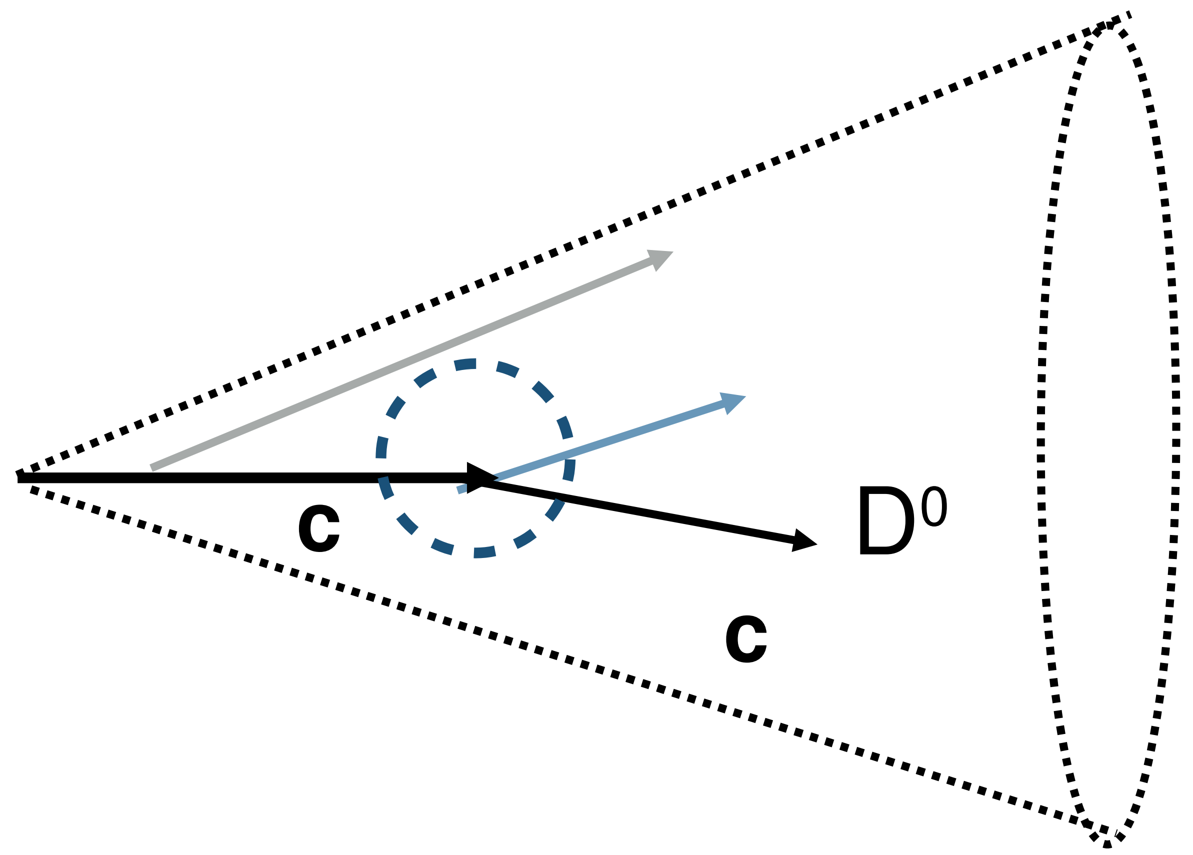
https://arxiv.org/abs/2312.17092

Heavy-quark parton shower in vacuum

New insights into the **dead**-**cone** effect in vacuum

Dead-cone effect: suppression of emissions from a radiator (quark) within $\boldsymbol{\theta_d < m_q/E_q}$





Reclustering technique: "Follow" the heavy quark using the heavy-flavor hadron as proxy for the heavy quark

→ led to the first direct observation of the charm dead-cone
ALICE, *Nature 605 (2022) 440-446*

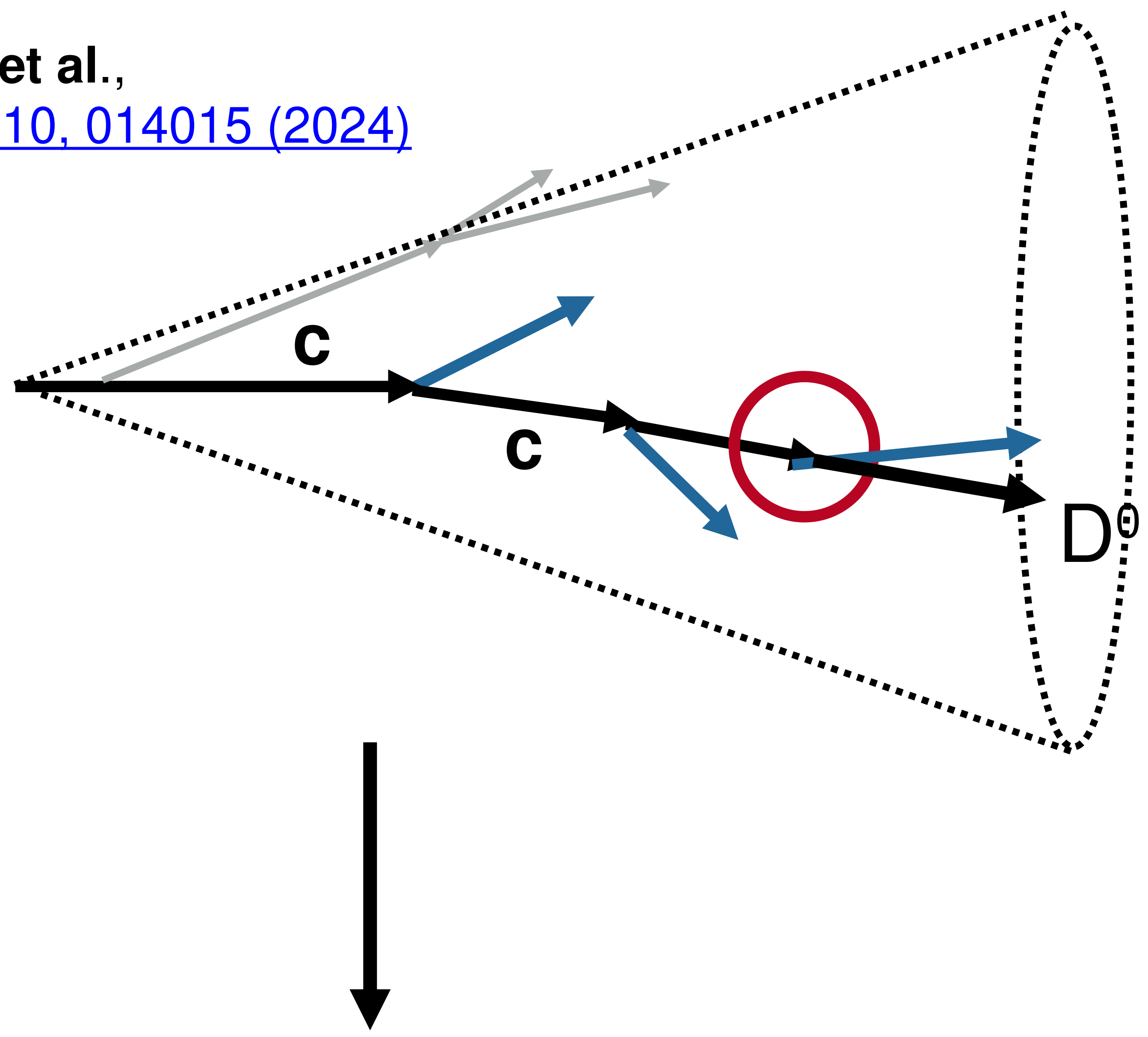
Charm dead cone with late-k_T algorithm

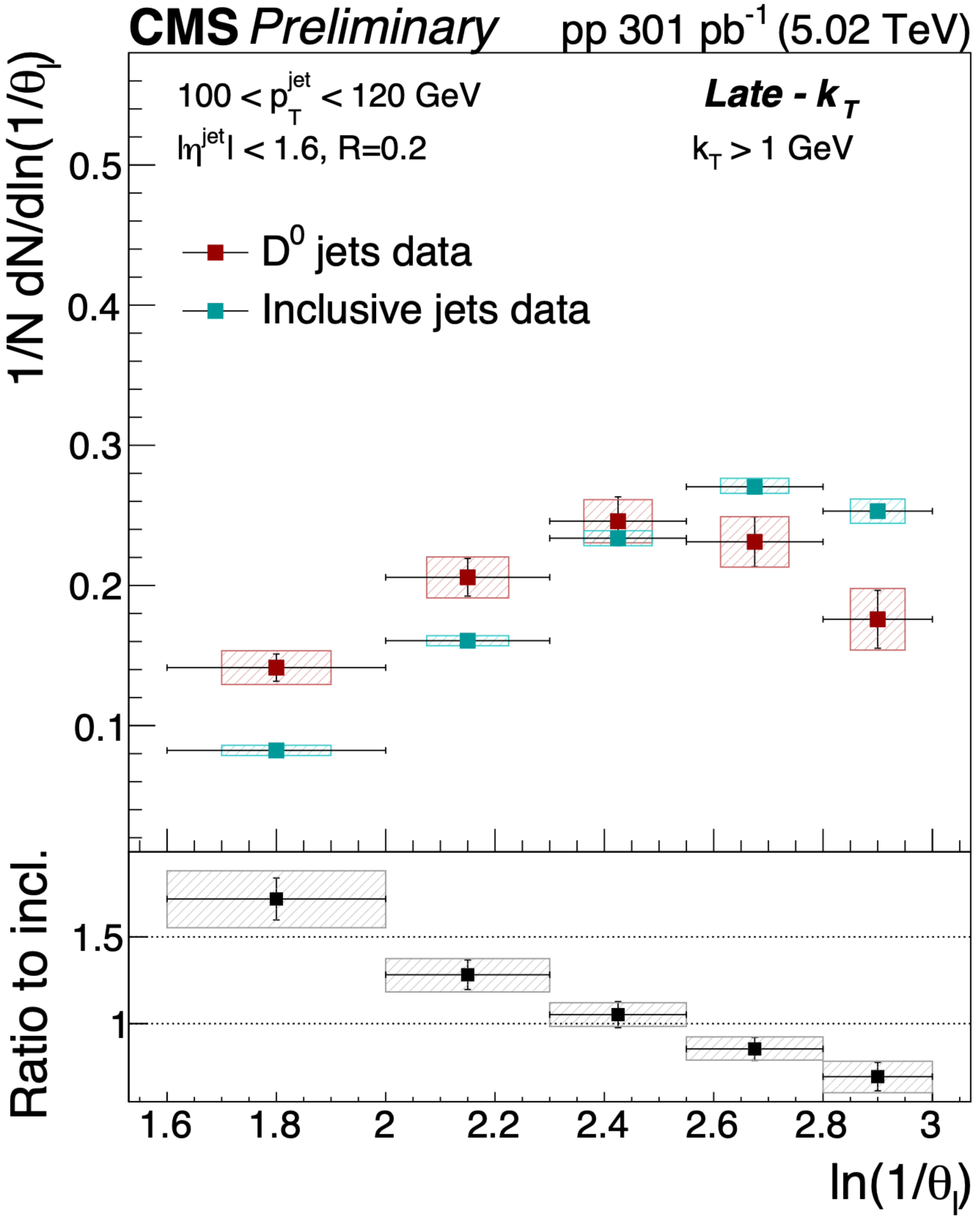
CMS-PAS-HIN-24-007

- PF jets $p_T > 100$ GeV
- Reclustered with **late-k_T grooming**

→ last collinear splitting with k_T>1 GeV

L. Cunqueiro et al., Phys. Rev. D 110, 014015 (2024)



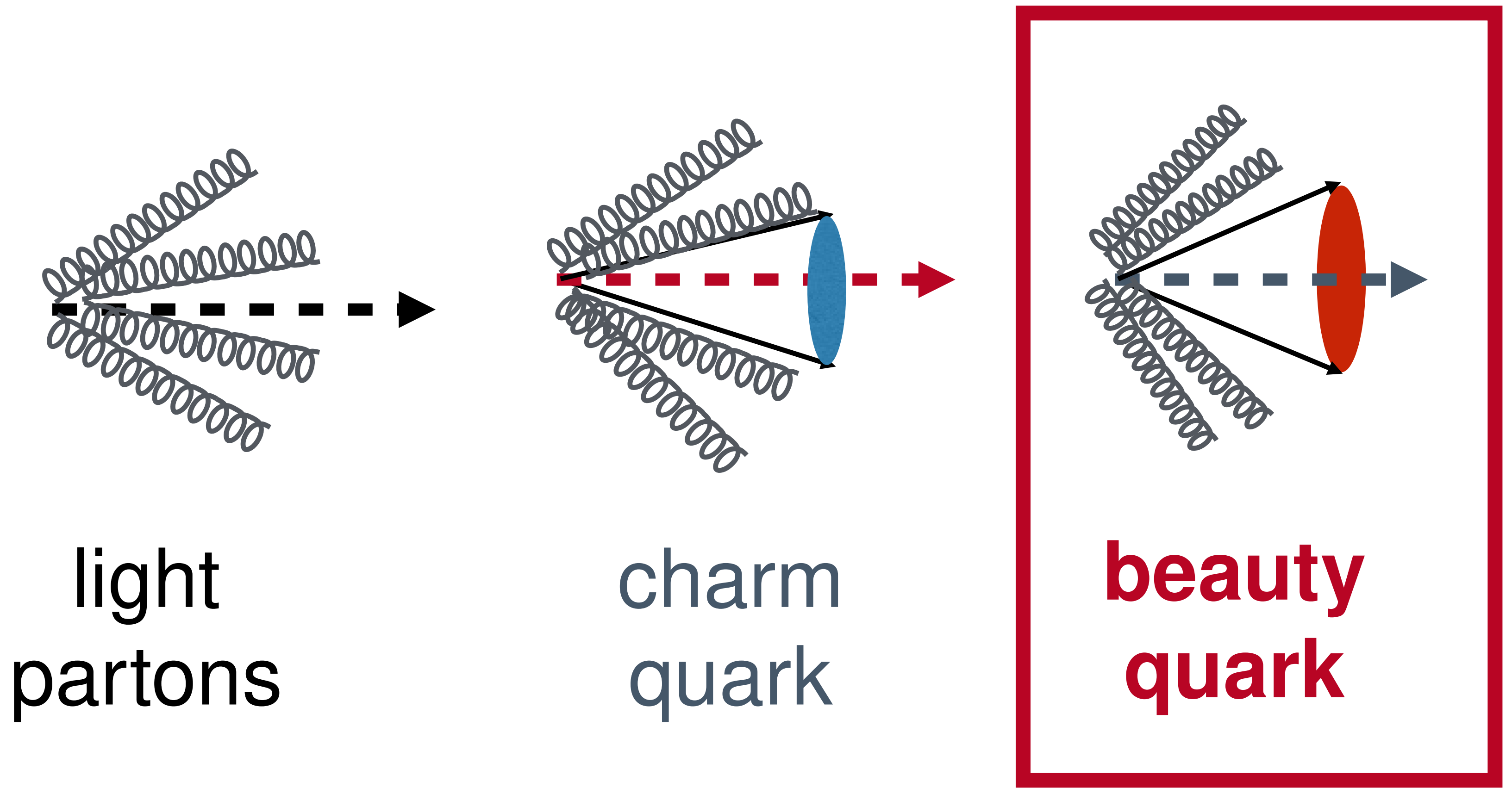


"charm" dead-cone with late-k_T splitting

→ stronger constraints on the "perturbative" collinear radiation (where the dead-cone effect is largest)

→ **more direct/unbiased comparison with pQCD calculations**

First direct manifestation of the beauty dead cone



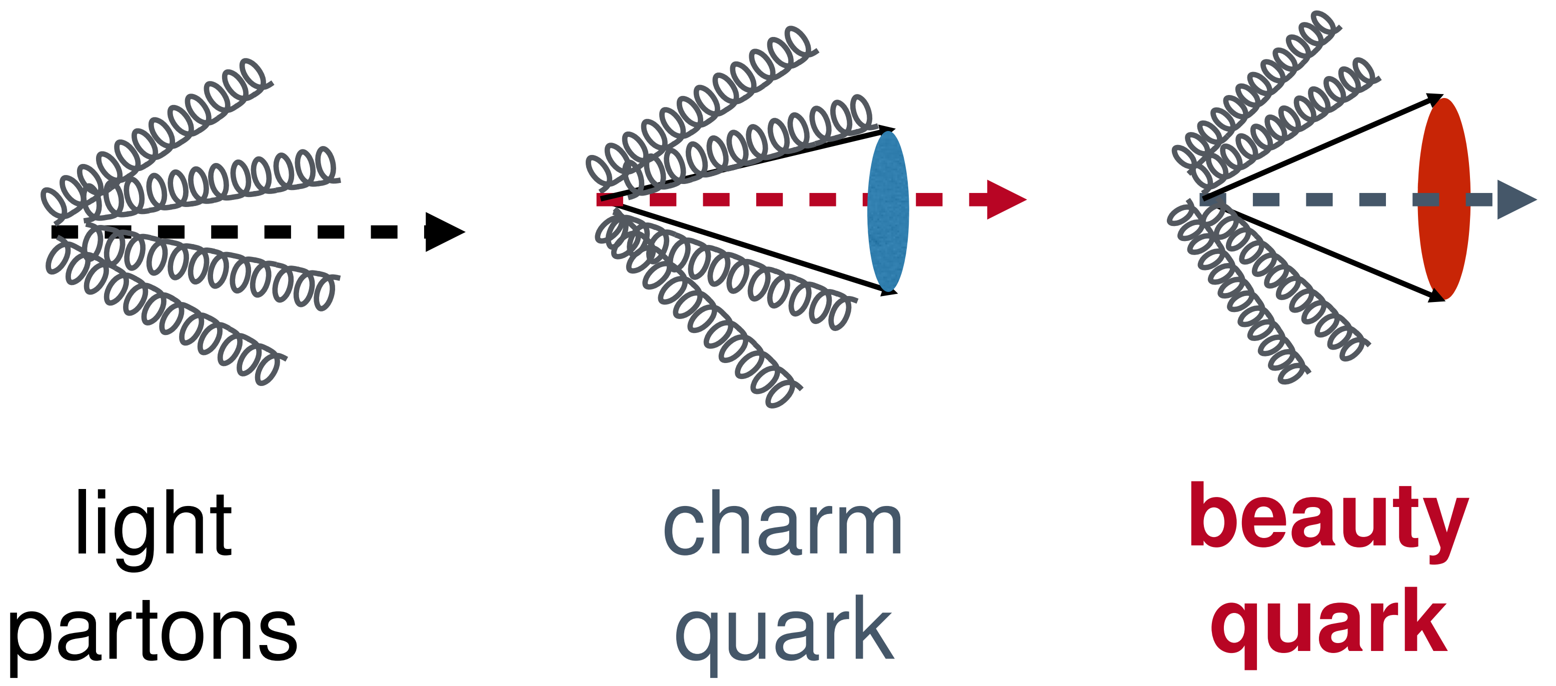
New experimental technique based on BDT

- tag hadronic and non-hadronic B-hadron decays
- **substantial increase in B-jet statistics**

→ **enable reclustering analyses for b-hadron jets**

[CMS-PAS-HIN-24-005](CMS-PAS-HIN-24-005)

First direct manifestation of the beauty dead cone



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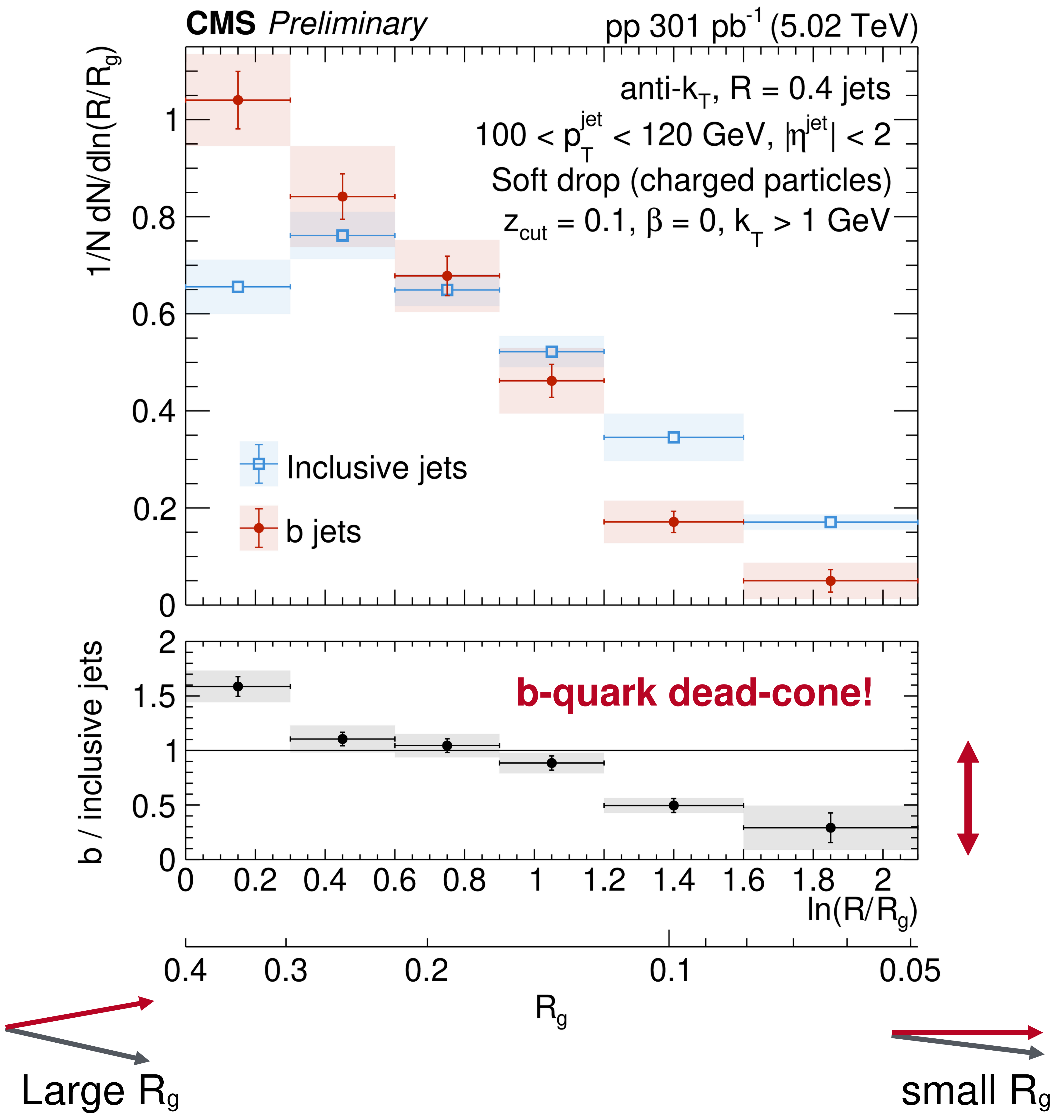
- **substantial increase in B-jet statistics**

→ **enable reclustering analyses for b-hadron jets**

First observation of a reduction of the collinear radiation for B-hadron tagged jets → **b-quark dead-cone!**



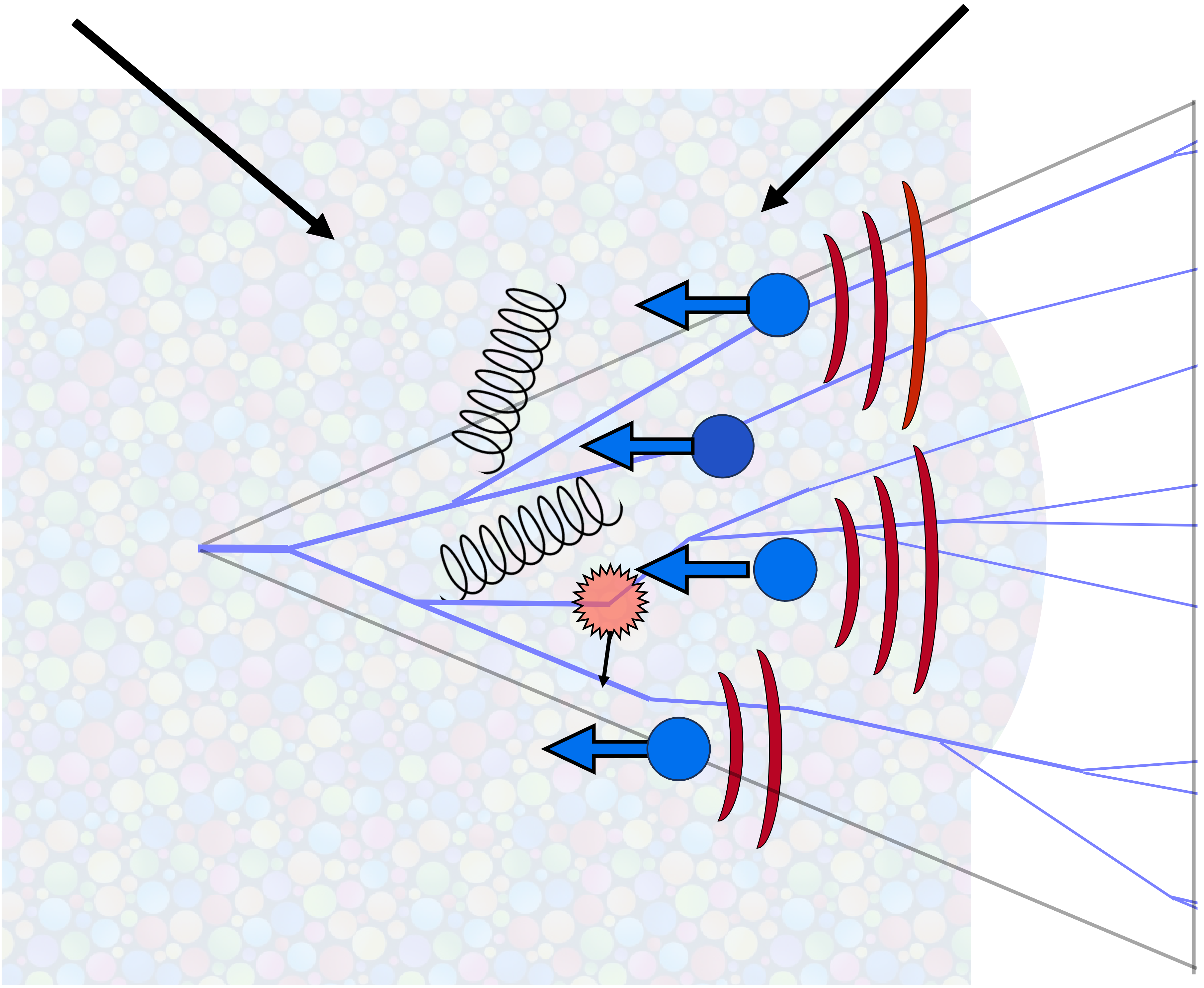
[CMS-PAS-HIN-24-005](CMS-PAS-HIN-24-005)

Phenomenology of jet-medium interaction

Jet-medium phenomenology: a schematic overview

<u>Medium-induced jet modifications</u>
e.g. medium-induced gluon radiation, elastic scatterings

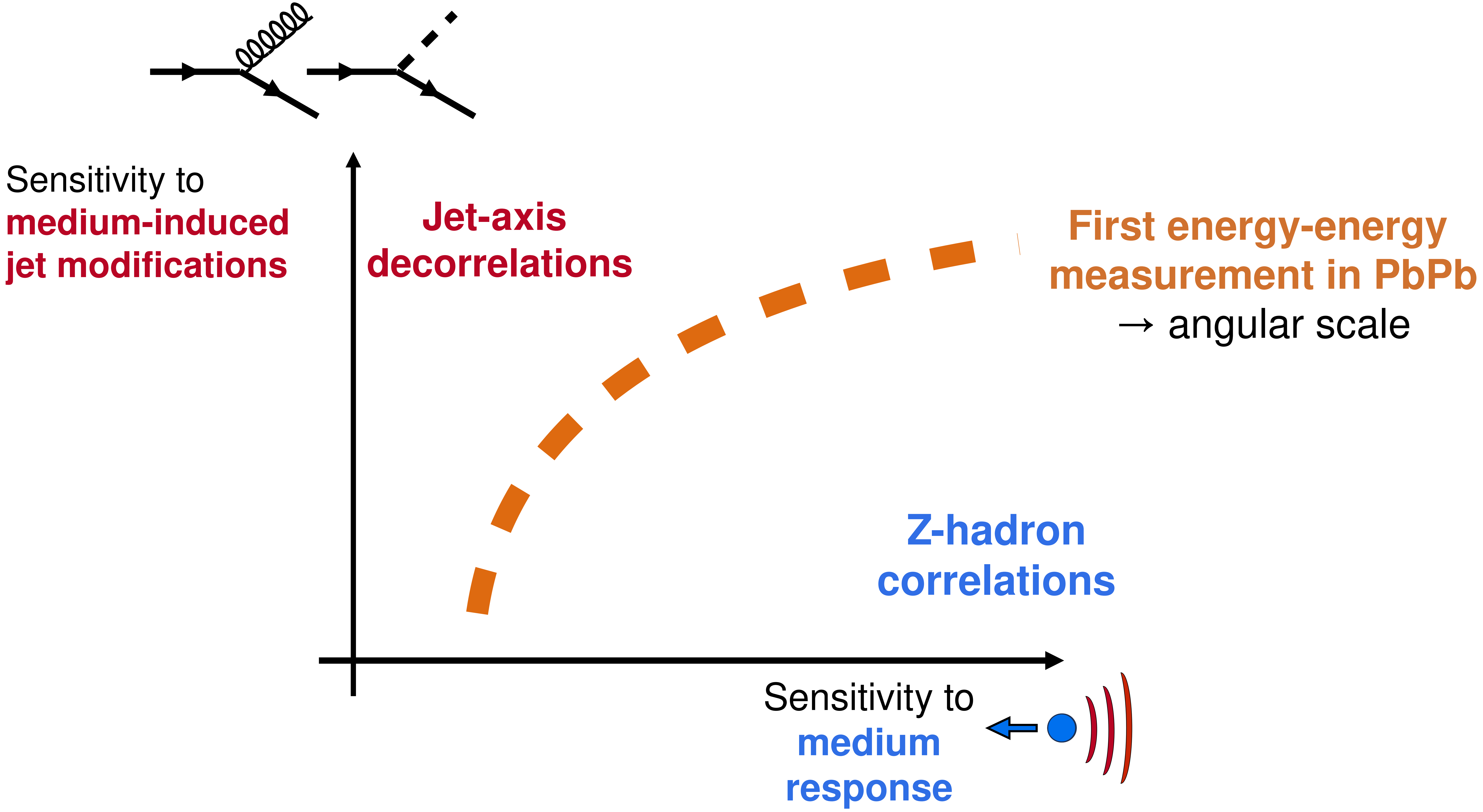
<u>Medium response</u>
positive and negative wakes, medium recoils, QGP holes…



→ "entangled" in a **complex scale (space/time, ..) dependent evolution**

Two strategies:
- Option 1) **maximize the control of the underlying interaction <u>mechanism</u>** (e.g. medium response)
- Option 2) **maximize the control on the <u>scale</u> of the interaction**

New observables to constrain jet-medium interactions

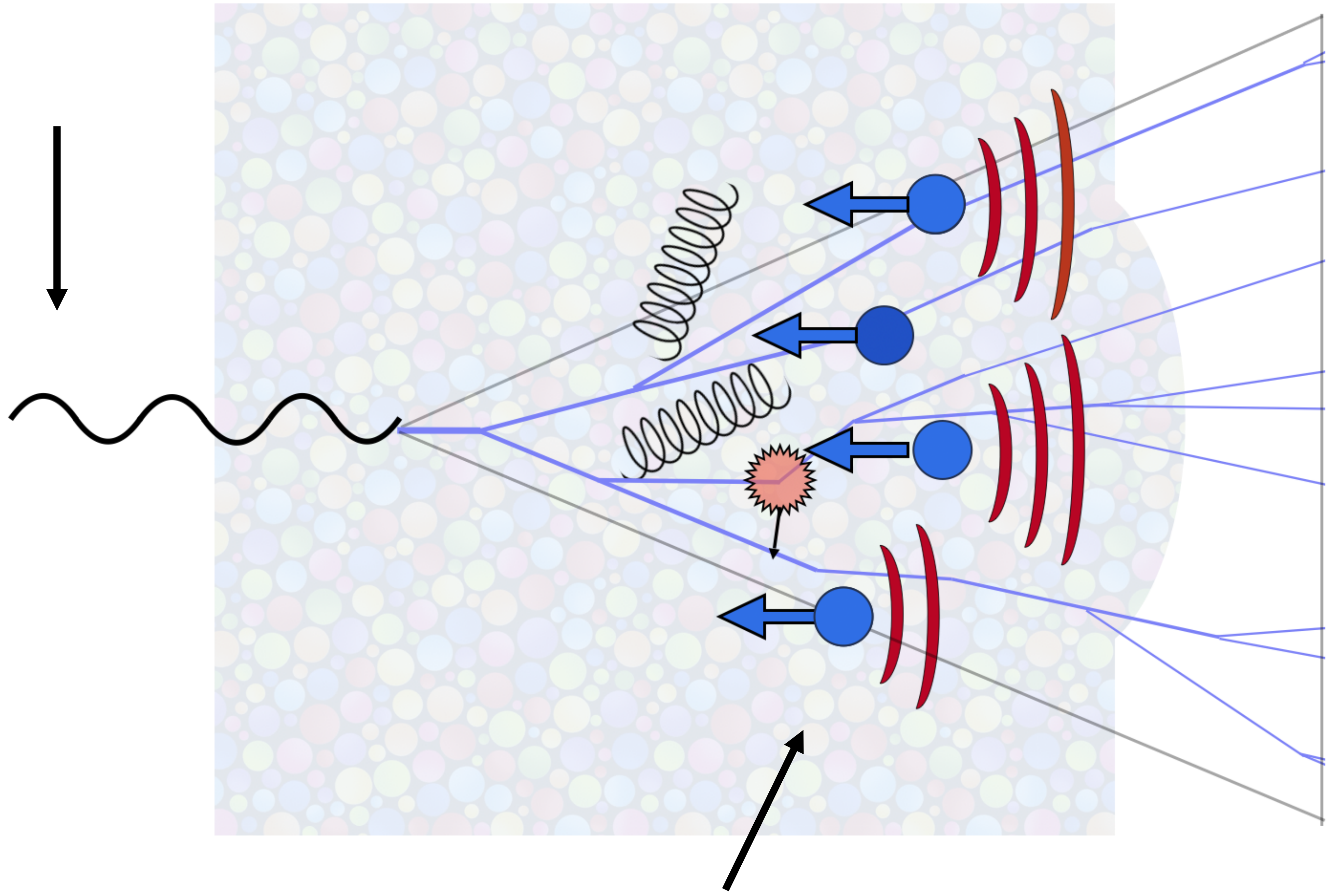


Photon-tagged jet axis decorrelation

CMS-PAS-HIN-21-019

→ **isolate the effect of jet-medium modifications** with a calibrated probe with **limited sensitivity to medium response**

Photon does not interact strongly in QGP
→ **γ tags the initial parton p_T**



Large fraction of quark-initiated jets

$$\Delta j = \sqrt{(\eta_E - \eta_{WTA})^2 + (\phi_E - \phi_{WTA})^2}$$

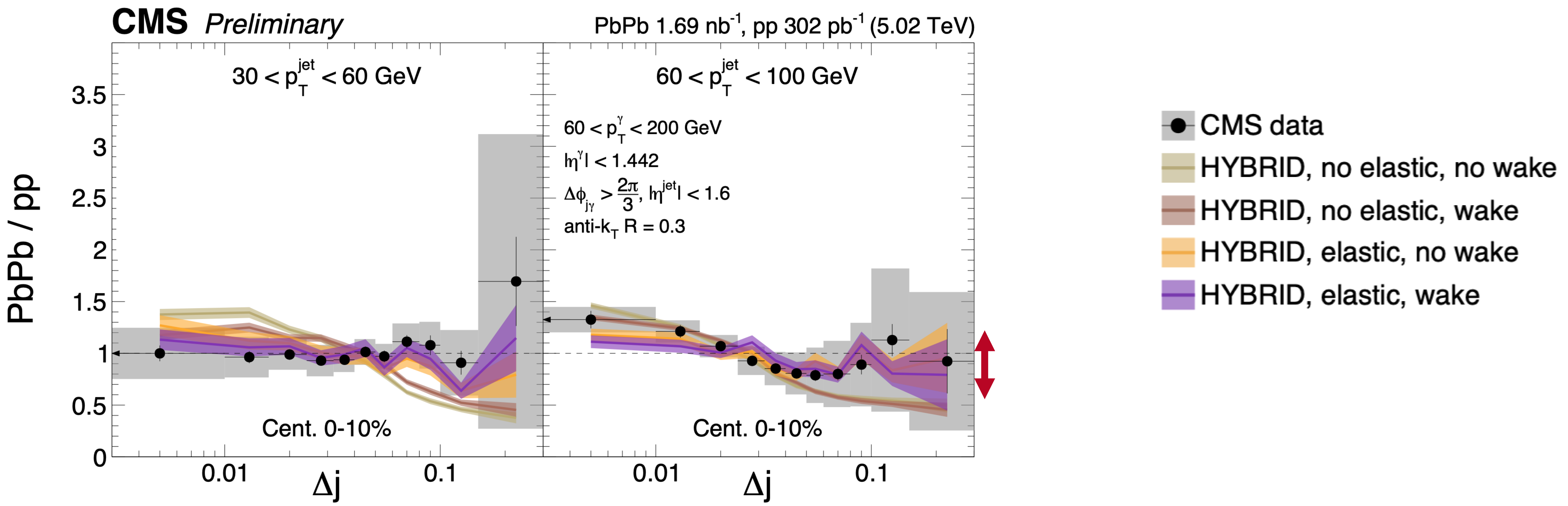
E-Scheme axis = direction of **average** energy flow in the jet
→ sensitive to soft radiation
WTA axis = direction of **leading** energy flow in jet
→ aligned with the hard-collinear core of the jet

Δj has a strong sensitivity to the jet's internal structure:

- **Δj = 0** → collimated "hard" jets
- **Δj > 0** → wider jet with more soft radiation

Photon-tagged jet axis decorrelation

CMS-PAS-HIN-21-019



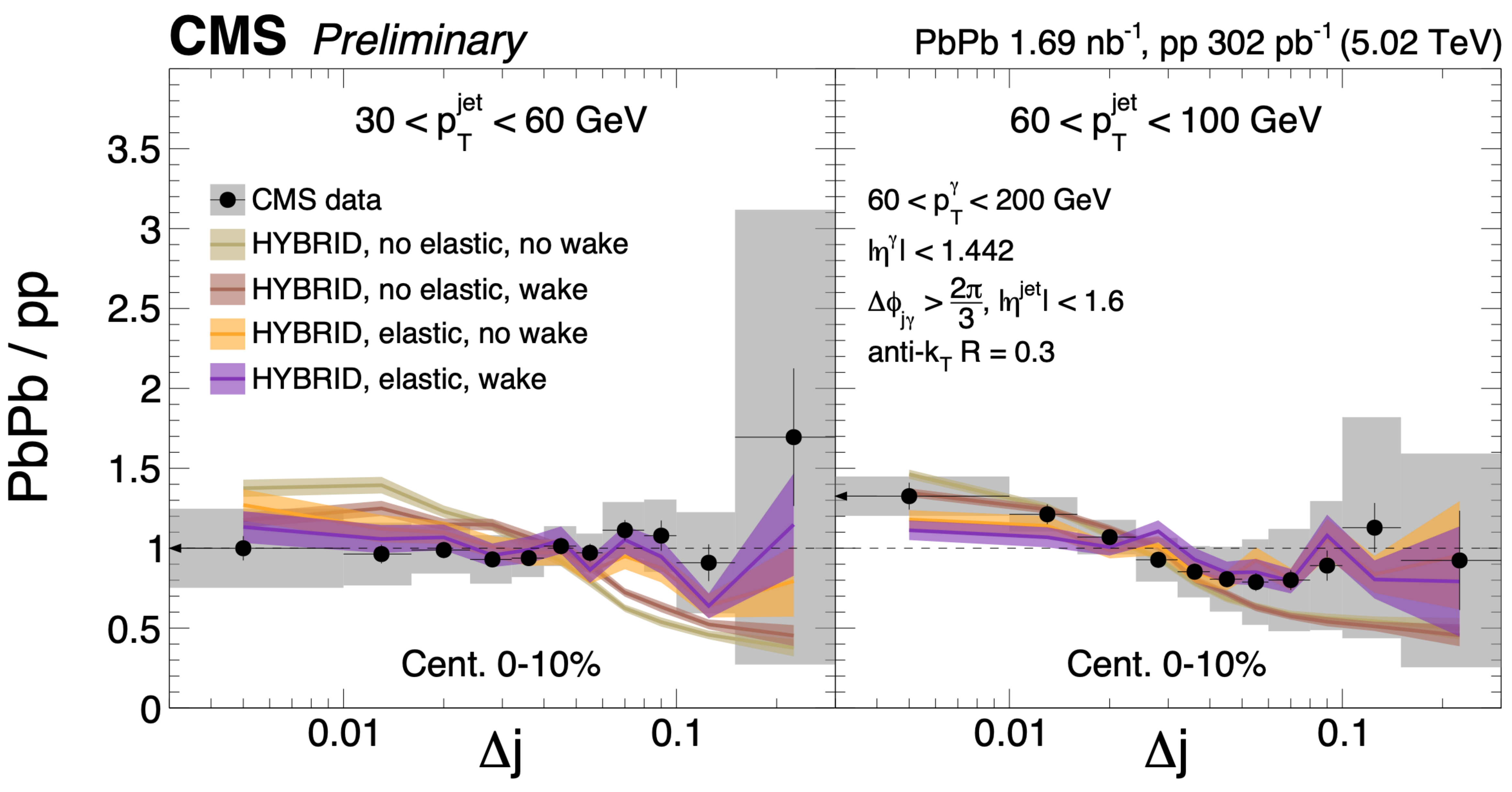
For low-p_T jet
→ similar Δj in PbPb and pp

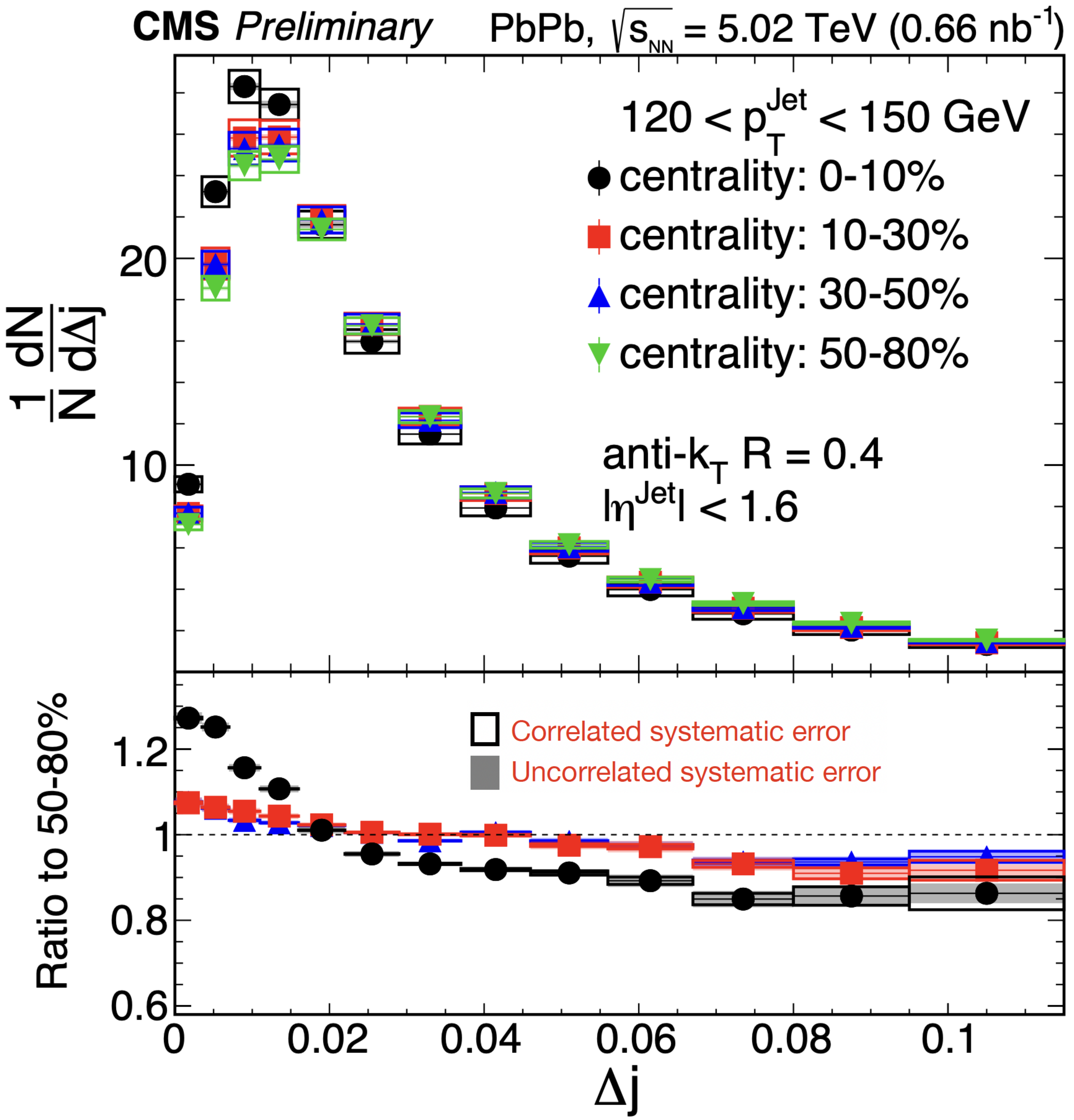
For high-p_T jet
→ suppression of large-Δj jets in PbPb

Evidence for a higher survival rate of narrow jets in PbPb collisions:
→ in the presence of an energy-calibrated probe (no bias due to jet-p_T bin migration)
→ limited dependence on the medium response

Jet axis decorrelations for inclusive jets

CMS-PAS-HIN-24-010





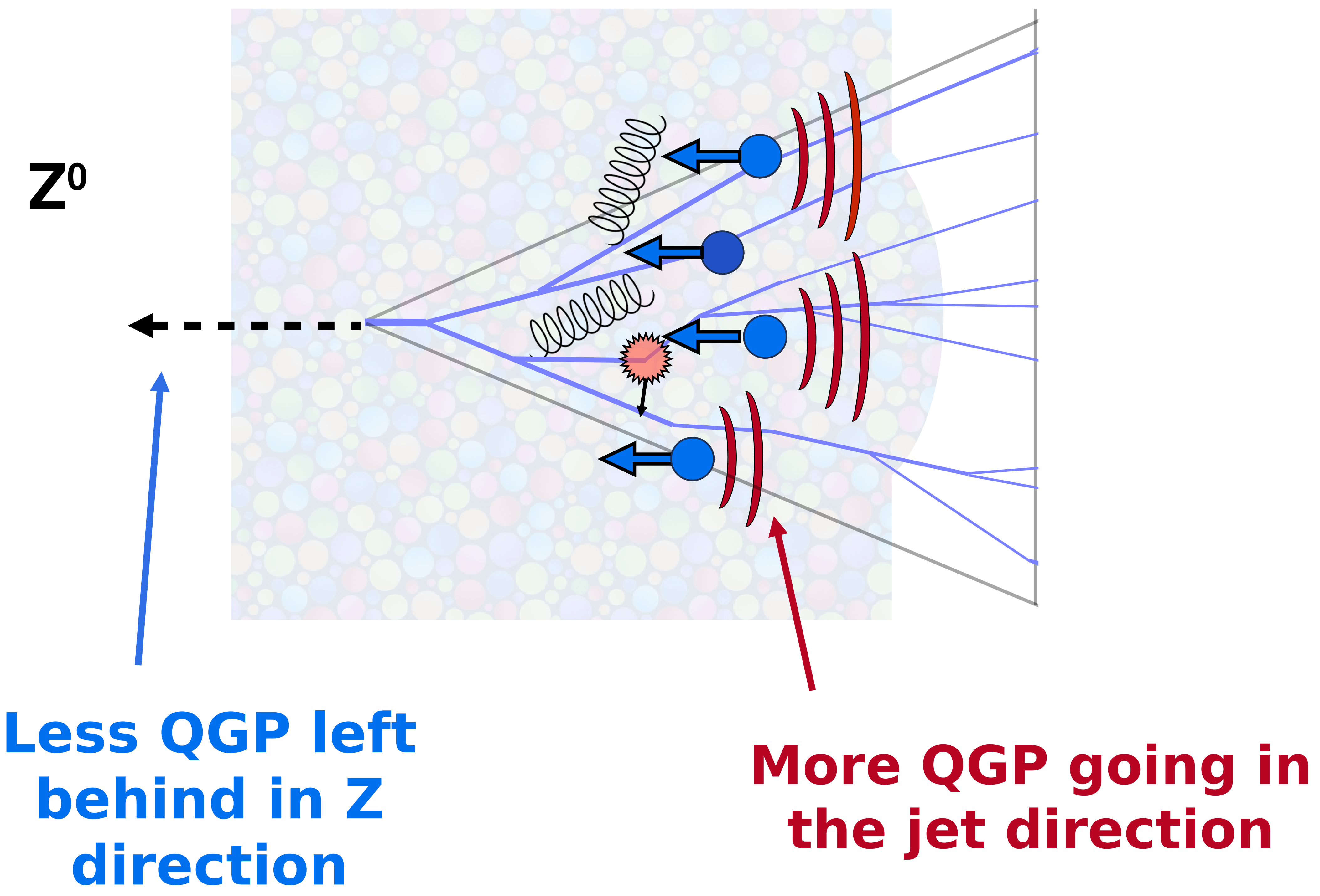
Complementary (highly-differential) constraints from jet axis decorrelations with inclusive-jet measurements:

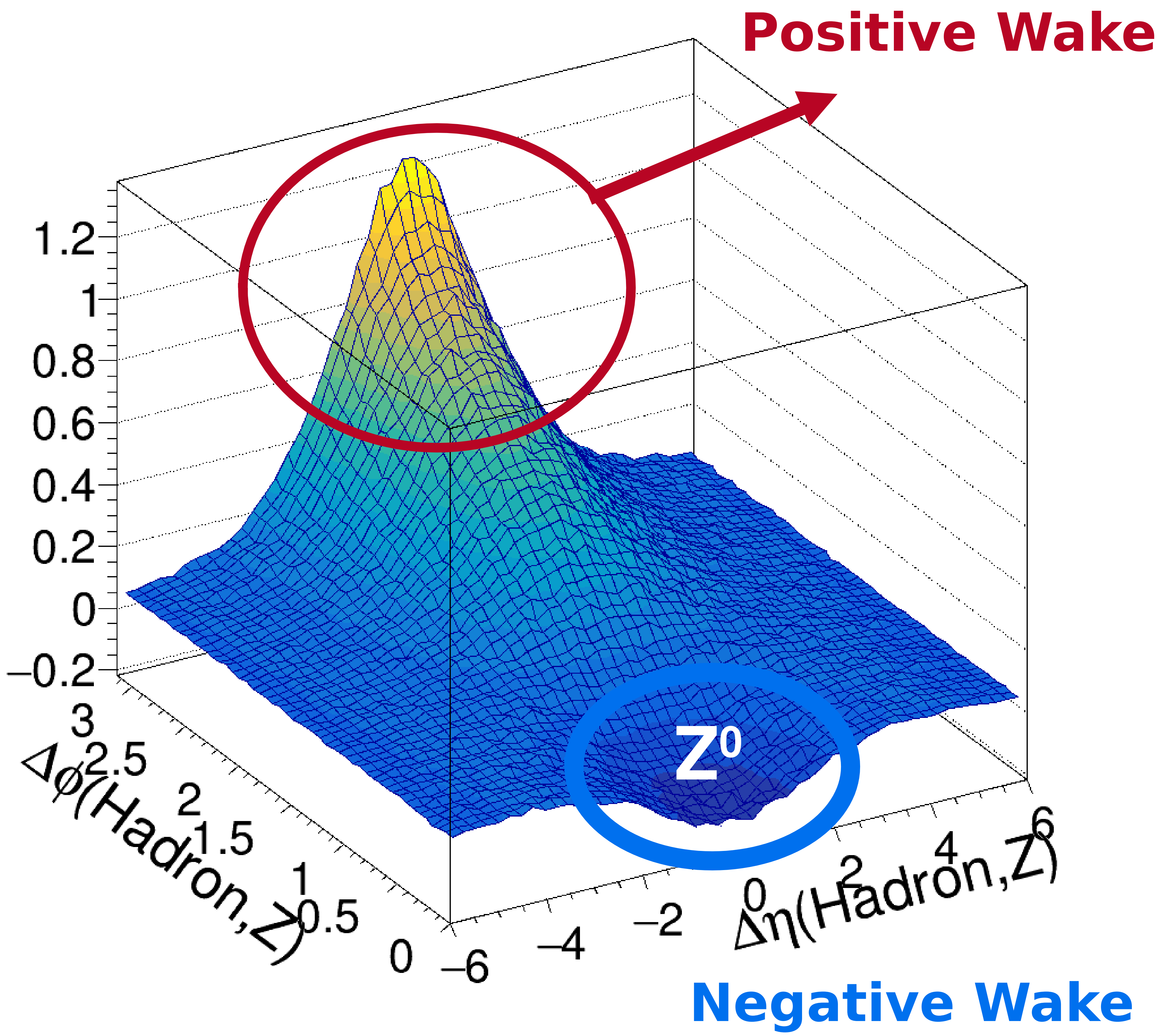
→ folding medium-induced jet modifications with bin-migration effects

Z^0-hadron correlations in PbPb

CMS-PAS-HIN-23-006

→ **"isolate" the effects of medium-response**

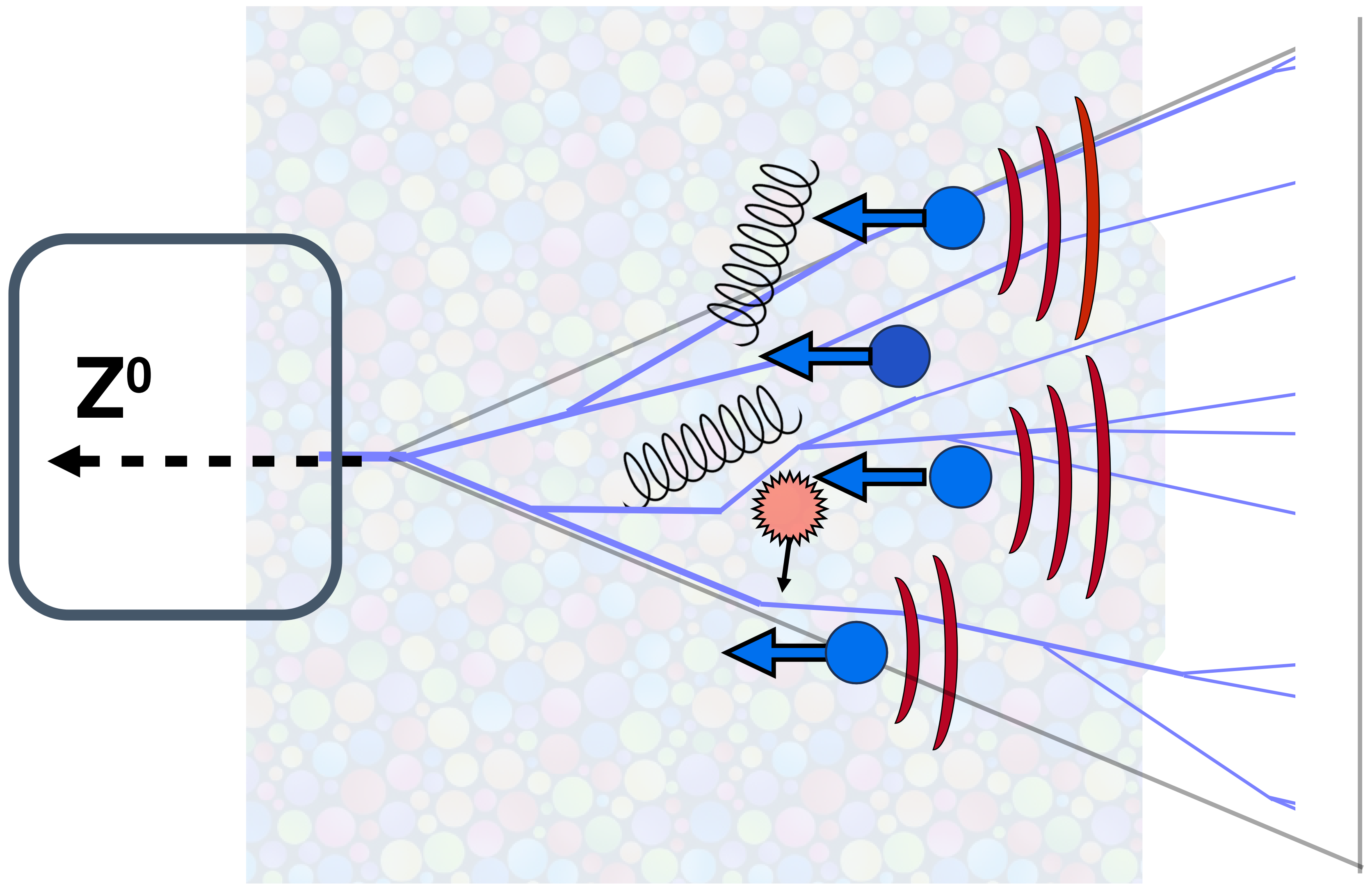


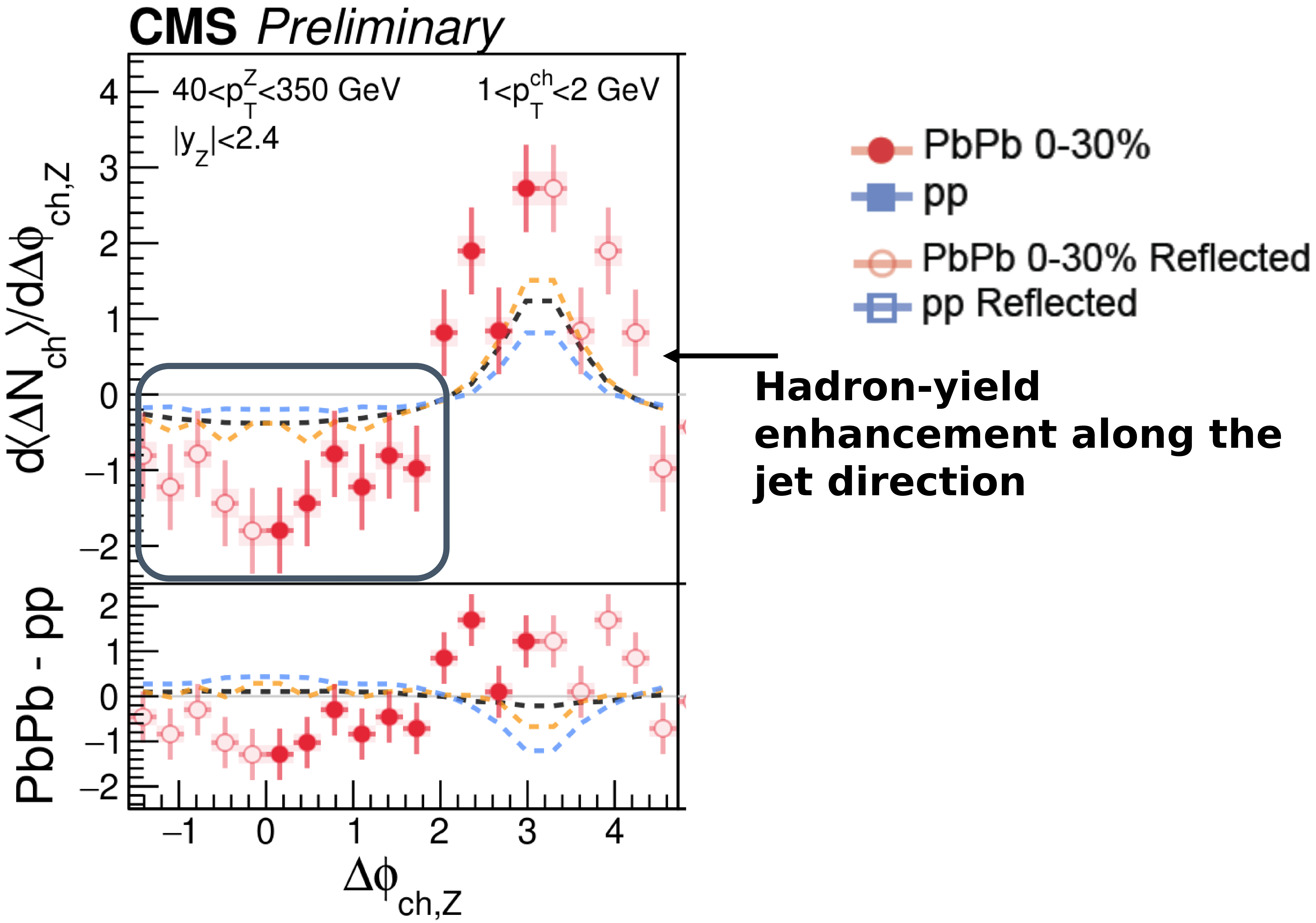


Z^0 provides an unquenched reference with high experimental accuracy
→ medium response effects without jet fragments

Z^0 and Wake Hadron correlation in Hybrid model
D. Pablos, K. Rajagopal, YJ Lee

Medium response with Z^0-tagged hadrons in PbPb, pp





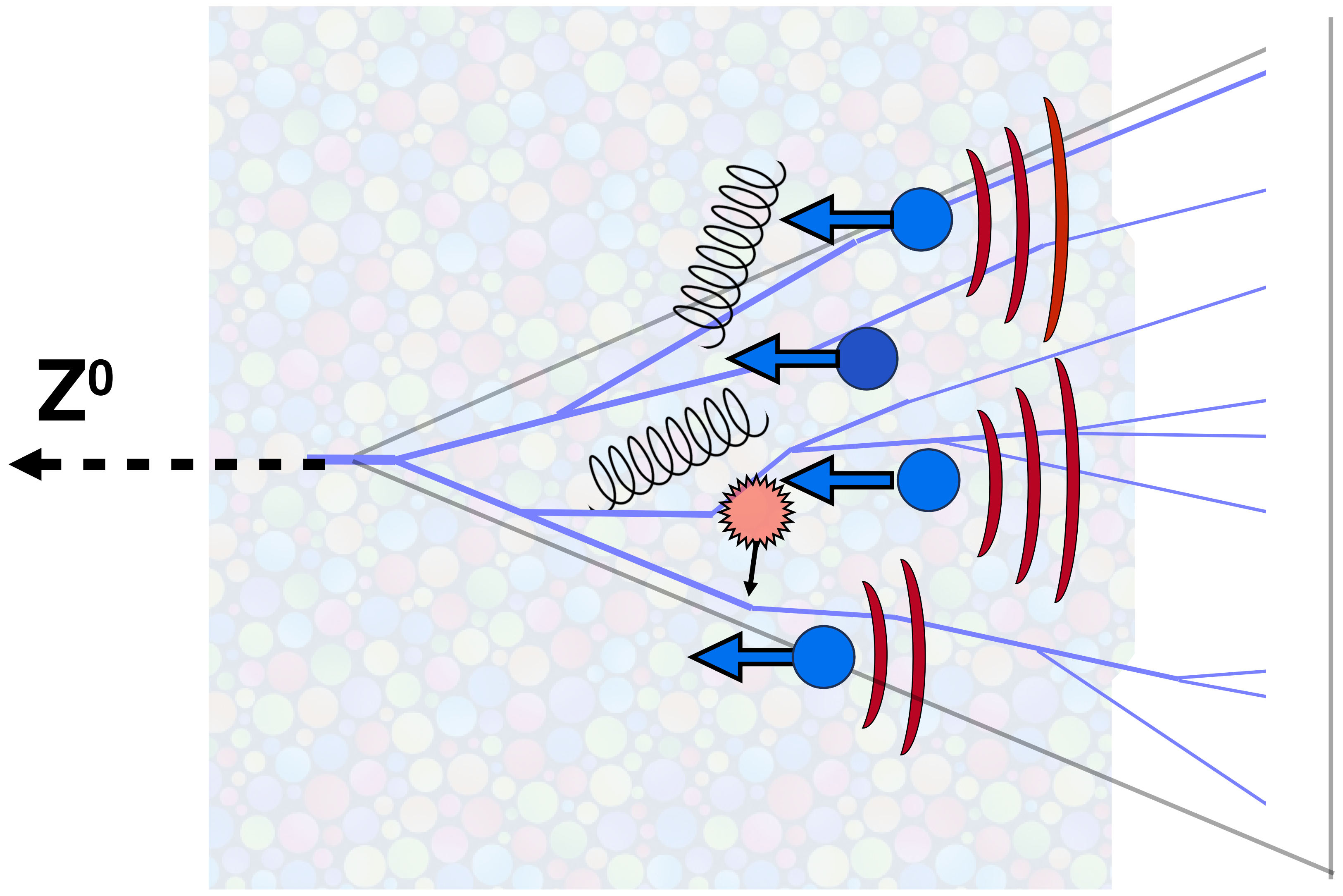
Hadron-yield enhancement along the jet direction

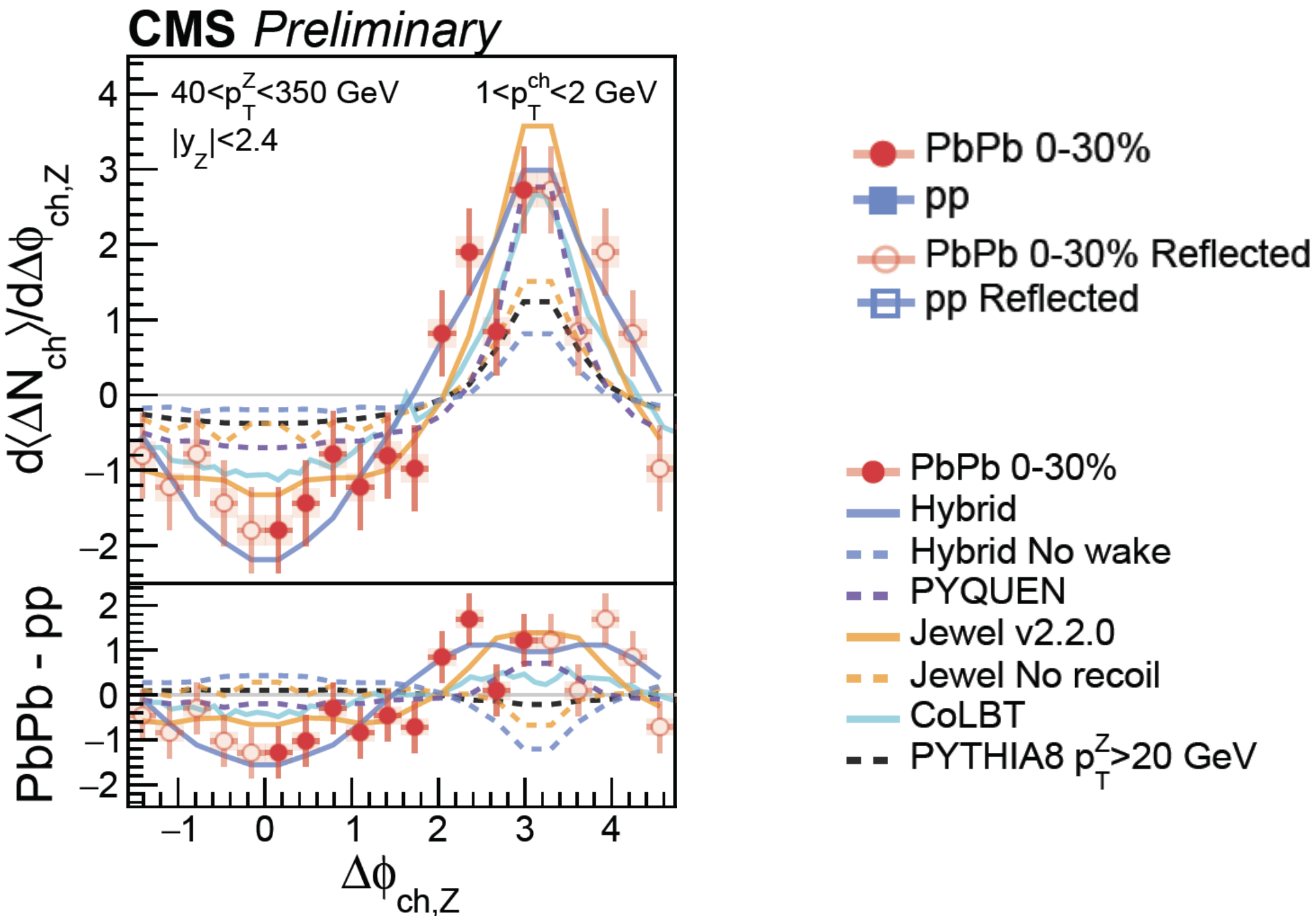
Clear depletion in PbPb on the Z side (Δϕ=0)

CMS-PAS-HIN-23-006

→ **Without wake/recoil effect models (dashed lines) under-predict the depletion in PbPb on the Z side**

Medium response with Z^0-tagged hadrons in PbPb, pp





CMS-PAS-HIN-23-006

→ **Good agreement when including medium response (e.g. recoil, wake, ...)**

→ **direct evidence of medium-response with the Z+jet event** (confirmed by similar study in $\Delta y_{ch,Z}$)

Energy-energy correlators

→ **scan the medium interaction at a fixed/tunable scale**

$$EEC(\Delta r) = \frac{1}{W_{pairs}} \frac{1}{\delta r} \sum_{jets \in [p_{T,1}, p_{T,2}]} \sum_{jets \in [\Delta r_a \Delta r_a]} \left(p_{T,i} p_{T,j}\right)^n$$

Angular distance pairs of particles within the jet,
weighted by the product of their momenta

Carlota Andres et al., Phys. Rev. Lett. 130, no.26, 262301 (2023)

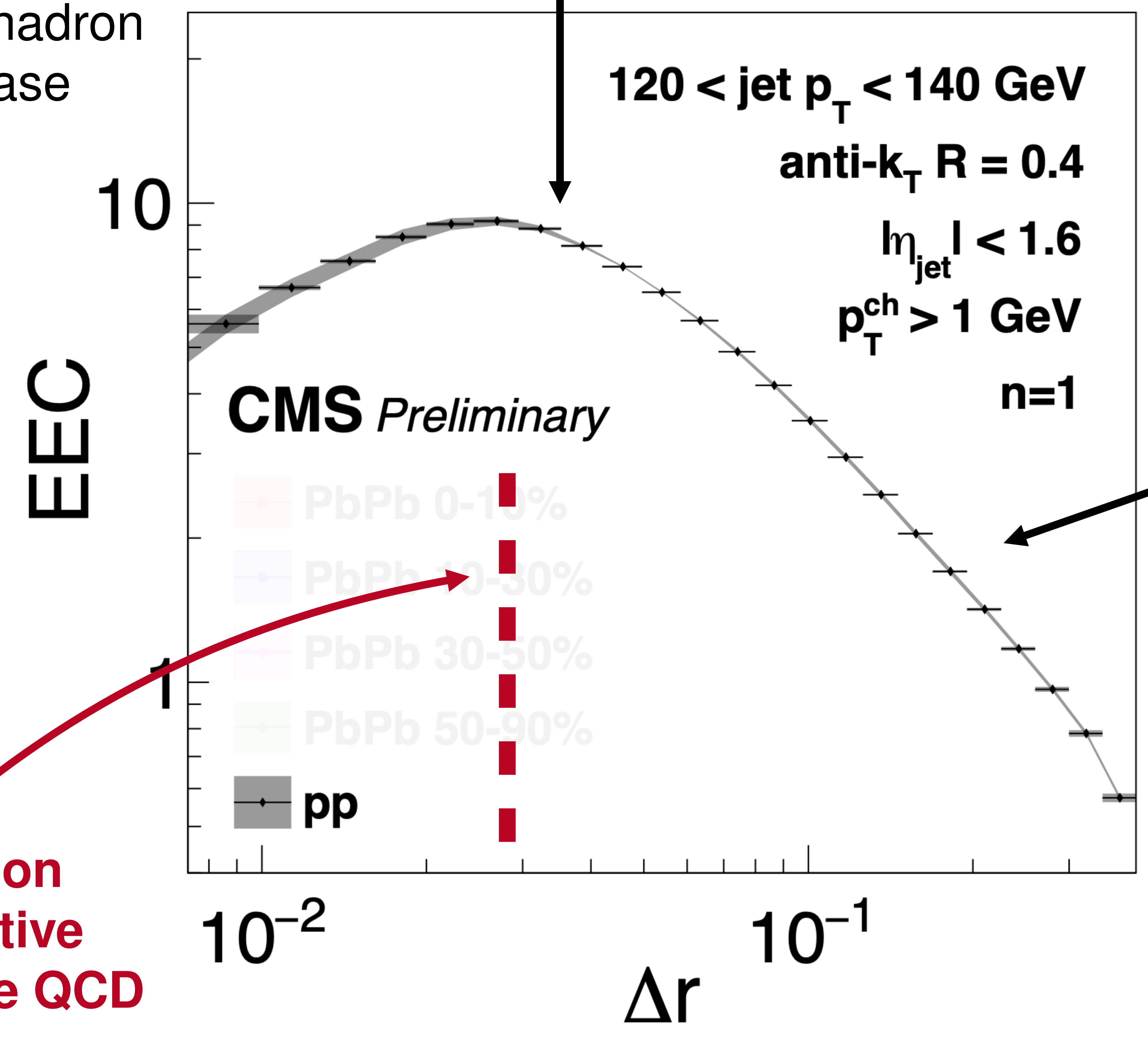
Energy-energy correlators in pp collisions at 5.02 TeV

$$EEC(\Delta r) = \frac{1}{W_{pairs}} \frac{1}{\delta r} \sum_{jets \in [p_{T,1}, p_{T,2}]} \sum_{jets \in [\Delta r_a \Delta r_a]} (p_{T,i} p_{T,j})^n$$

CMS-PAS-HIN-23-004

Intermediate Δr
transition toward
hadronic phase

Small Δr
free hadron
phase

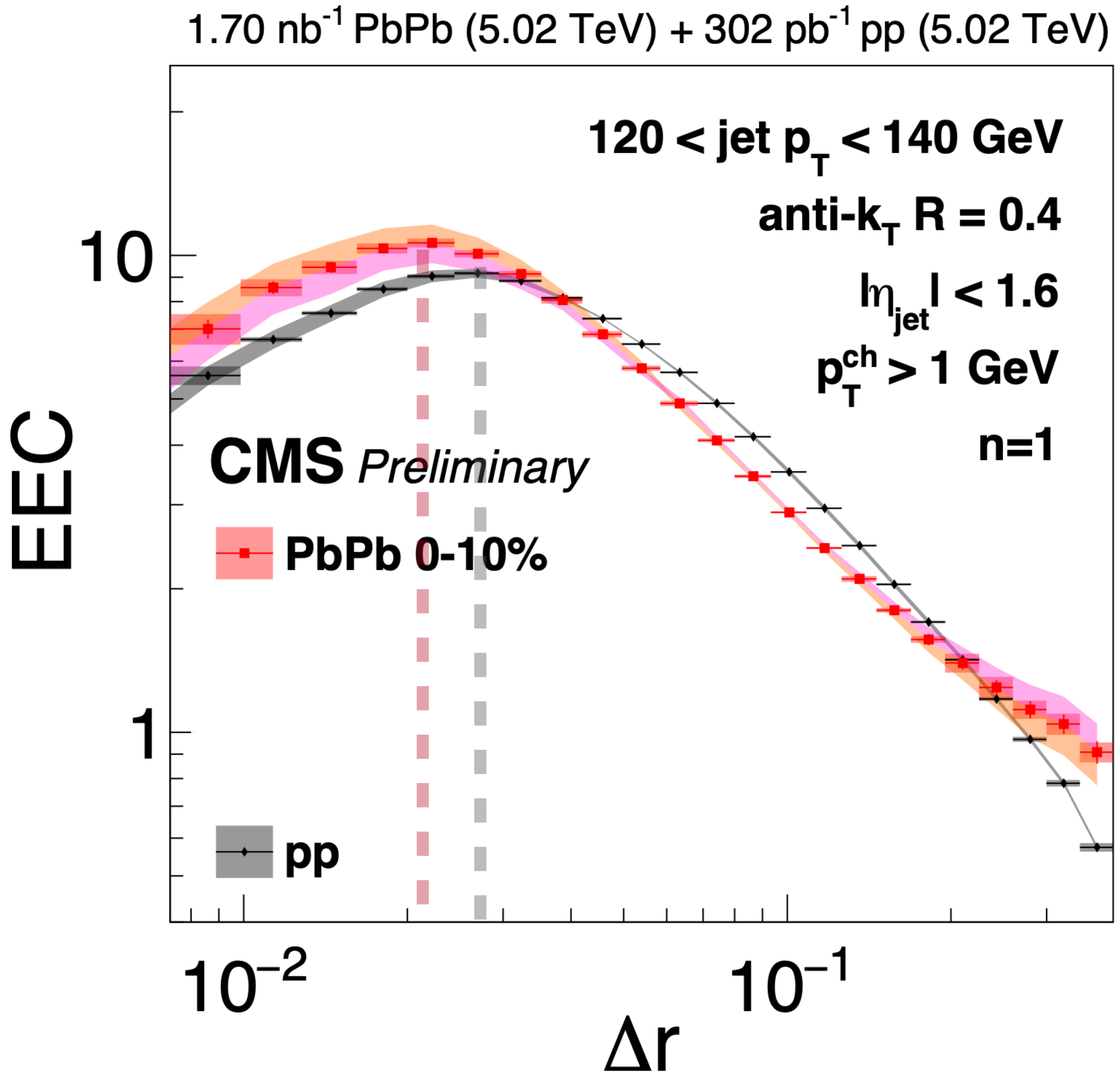


Large angular scale Δr
perturbative parton shower

traceable transition
between perturbative
and non-perturbative QCD

First EEC measurement in PbPb collisions at 5.02 TeV

→EEC measurements are feasible with high accuracy in PbPb collisions!
→PbPb results present qualitatively the same structure as in pp collisions

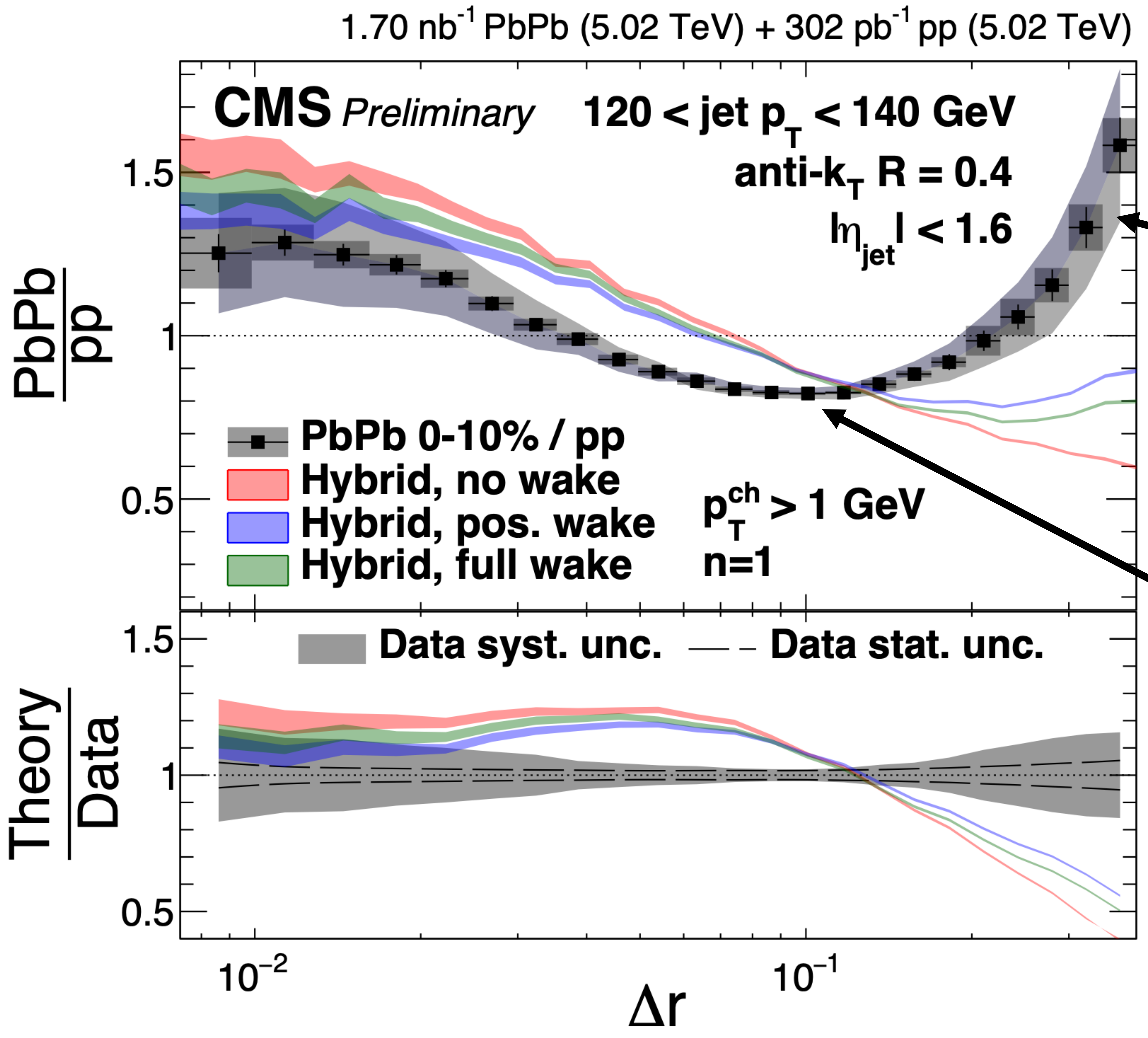


CMS-PAS-HIN-23-004

EEC PbPb/pp ratio at 5.02 TeV

CMS-PAS-HIN-23-004

Shift in the position of the "transition" peak



Large angular scale Δr
→ **sensitivity to medium response**

Intermediate angular scale Δr
→ **modification of the parton shower**
(e.g. coherence scale)

First PbPb measurement shows the potential of this new observable:
→ **Map the angular properties of jet-medium interaction with a "self-analyzing" observable**
with well-defined boundaries between perturbative and non-perturbative physics

Carlota Andres et al., Phys. Rev. Lett. 130, no.26, 262301 (2023)

Conclusion and outlook

New constraints on nuclear matter down to small x:

- incoherent + coherent charmonium photoproduction in UPCs vs $W_{\gamma N}$

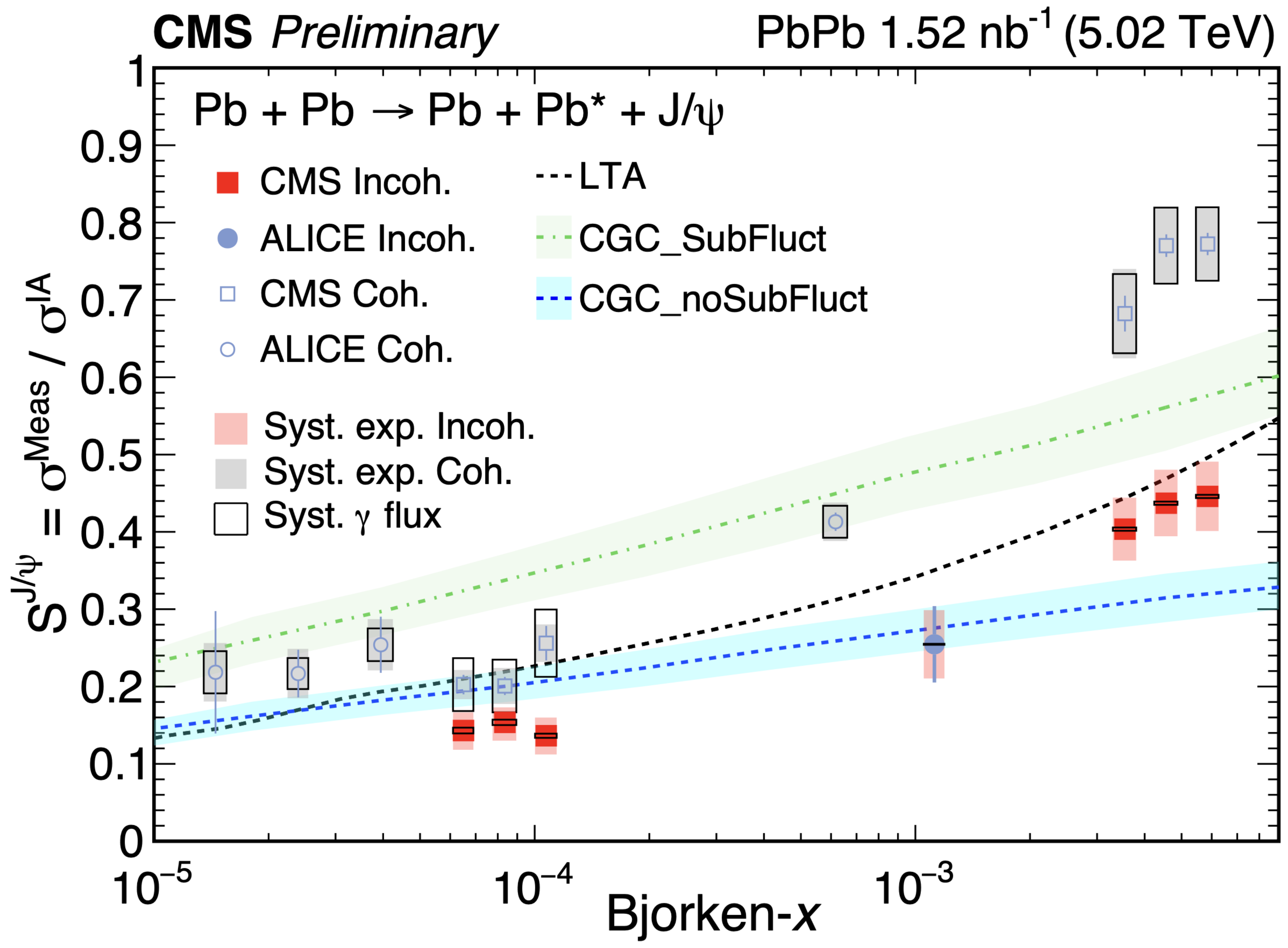
→ **first energy-dependent characterization of global and local gluon properties at small x**

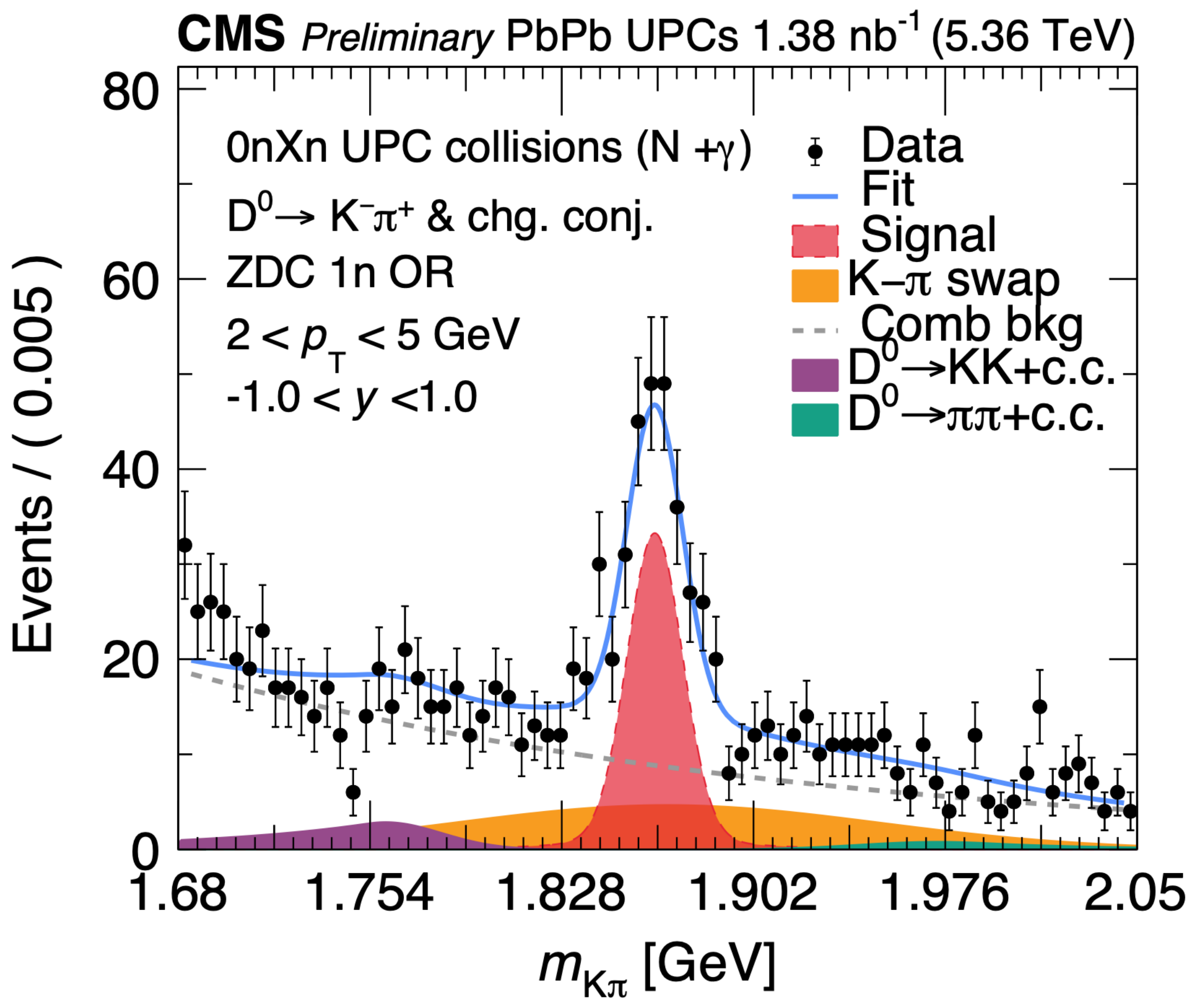
→ constraints at fixed Q^2 on the possible emergence of gluon saturation

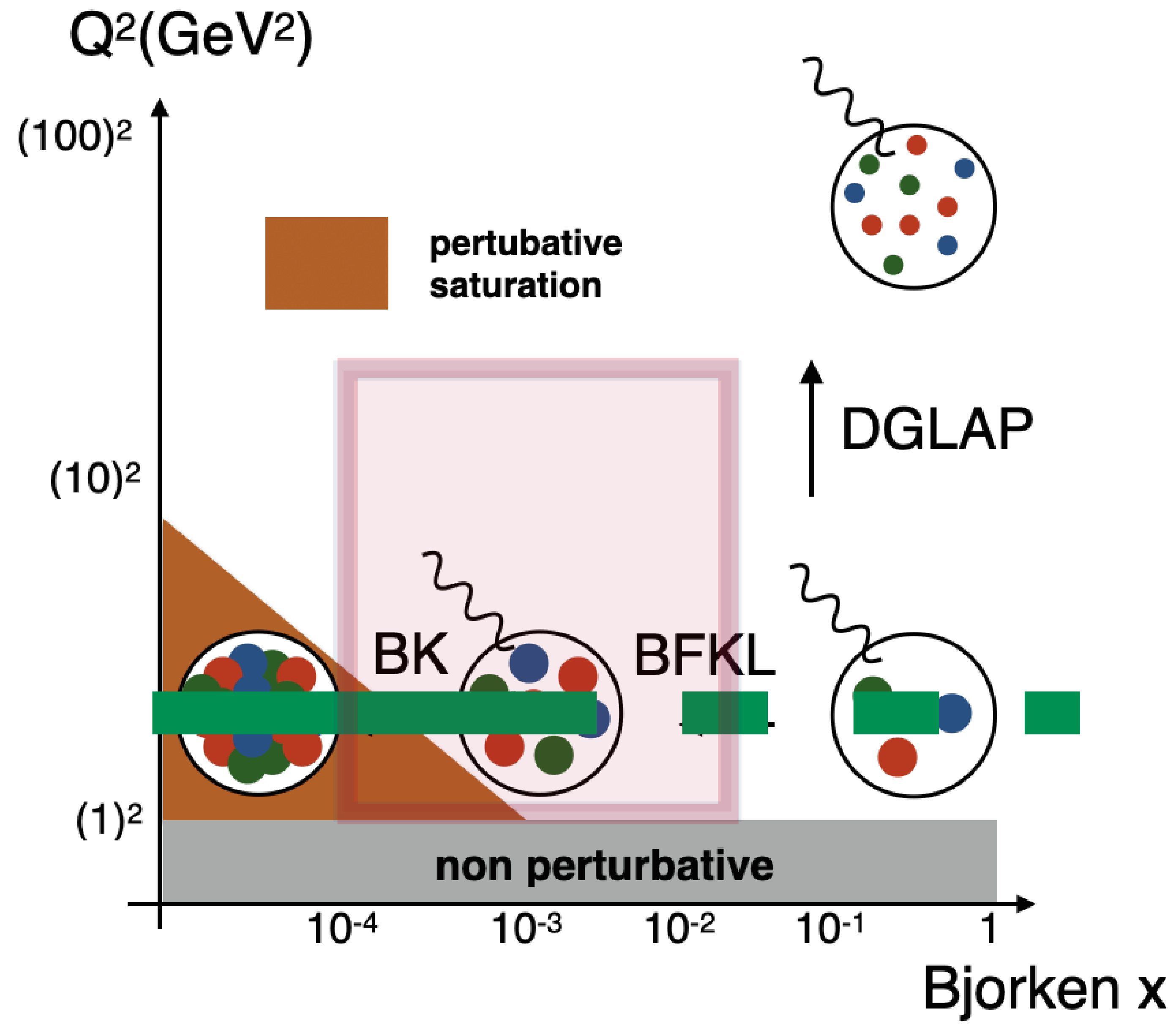
- **first measurement of open-heavy flavor production in UPCs:**

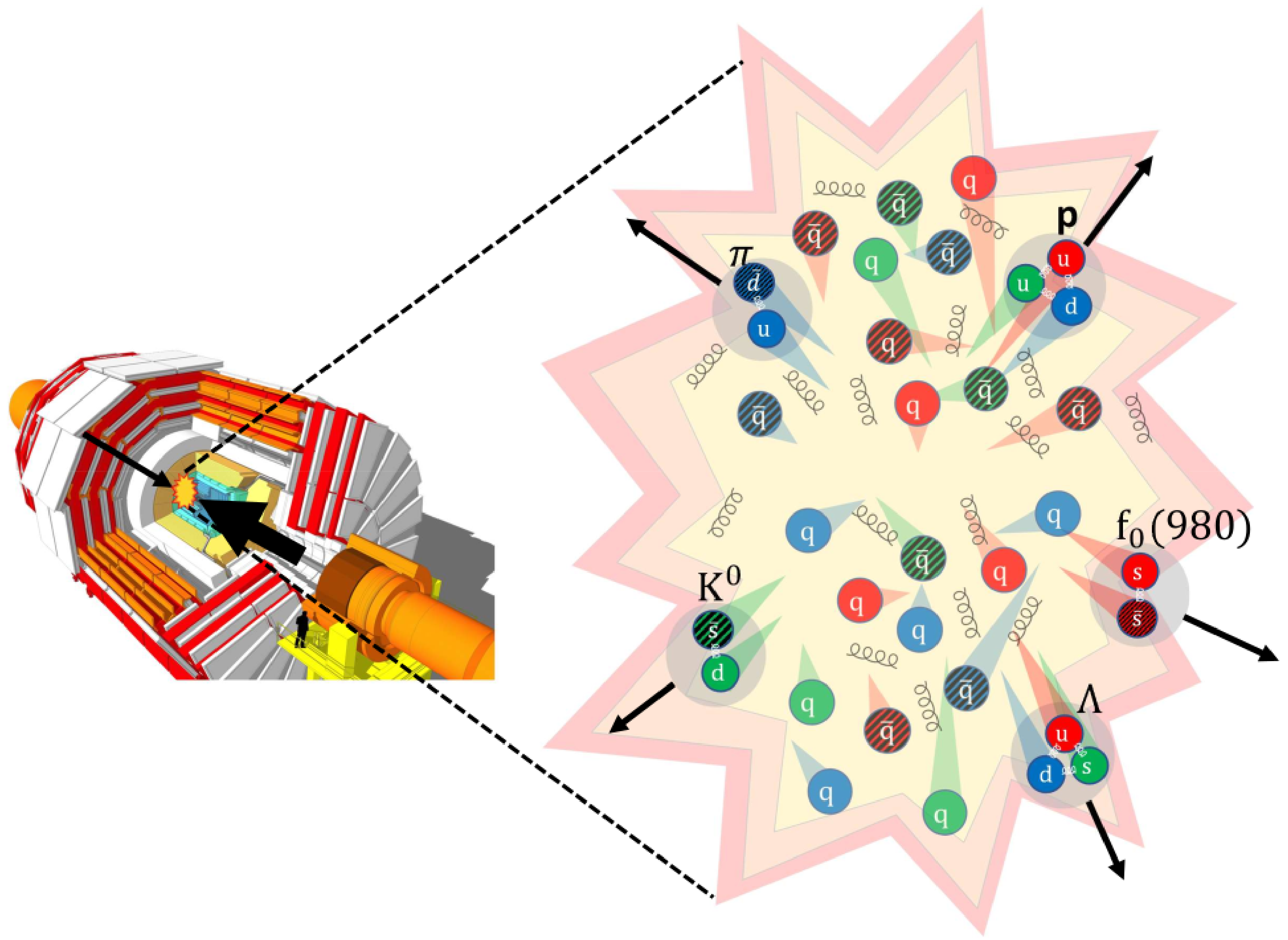
→ **First constraints on nPDFs <u>over a wide region of Q^2</u> at small-x**

- **Quark content of a hadron revealed - using heavy-ion physics concepts!**



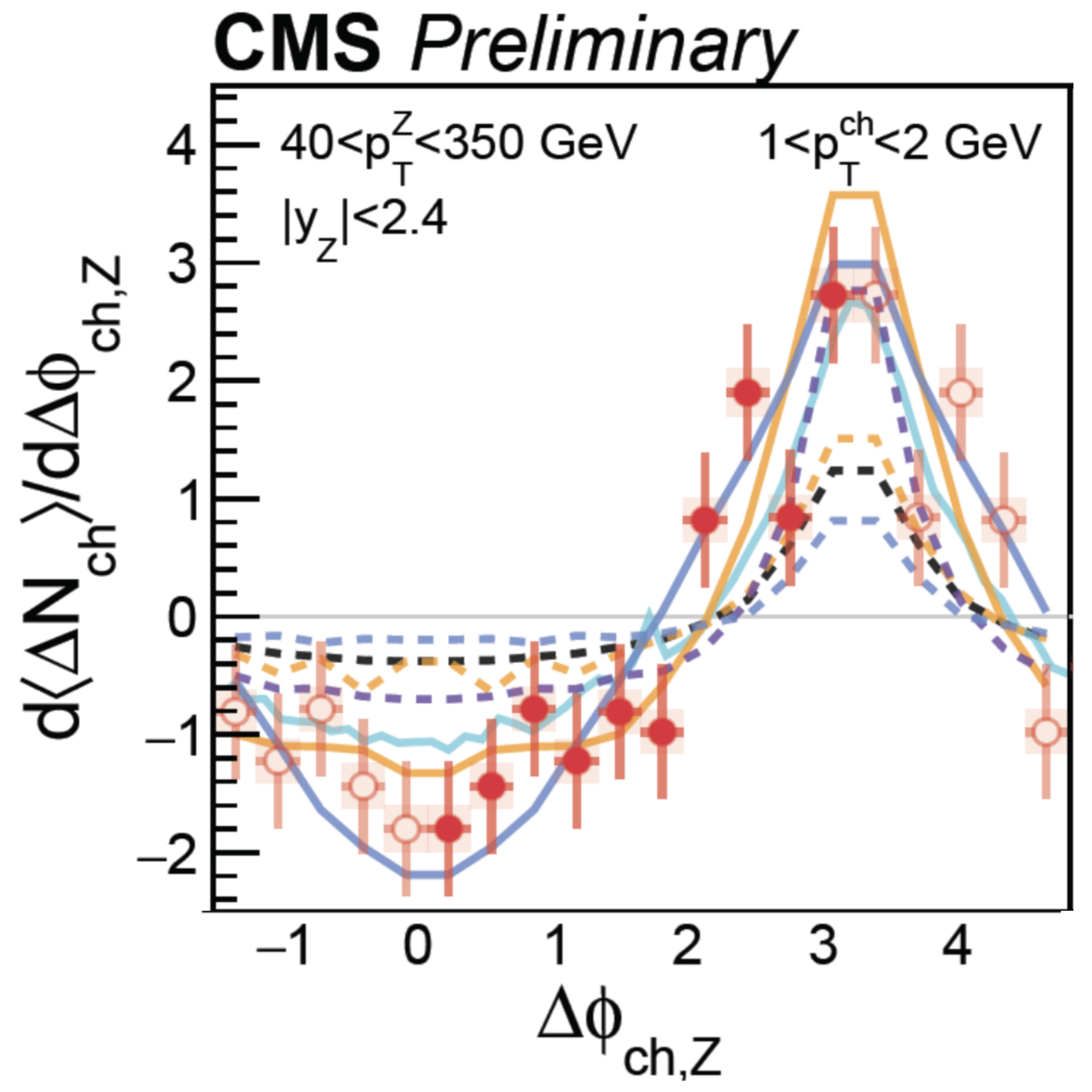






Conclusion and outlook

Substantial advancement in the characterization of in-vacuum parton shower:
with new experimental techniques and grooming algorithms
→ **first manifestation of the dead-cone effect for b quarks in vacuum**
→ open the way for the first “microscopic” observation of flavor-dependence of in-medium E_{loss} in PbPb collisions



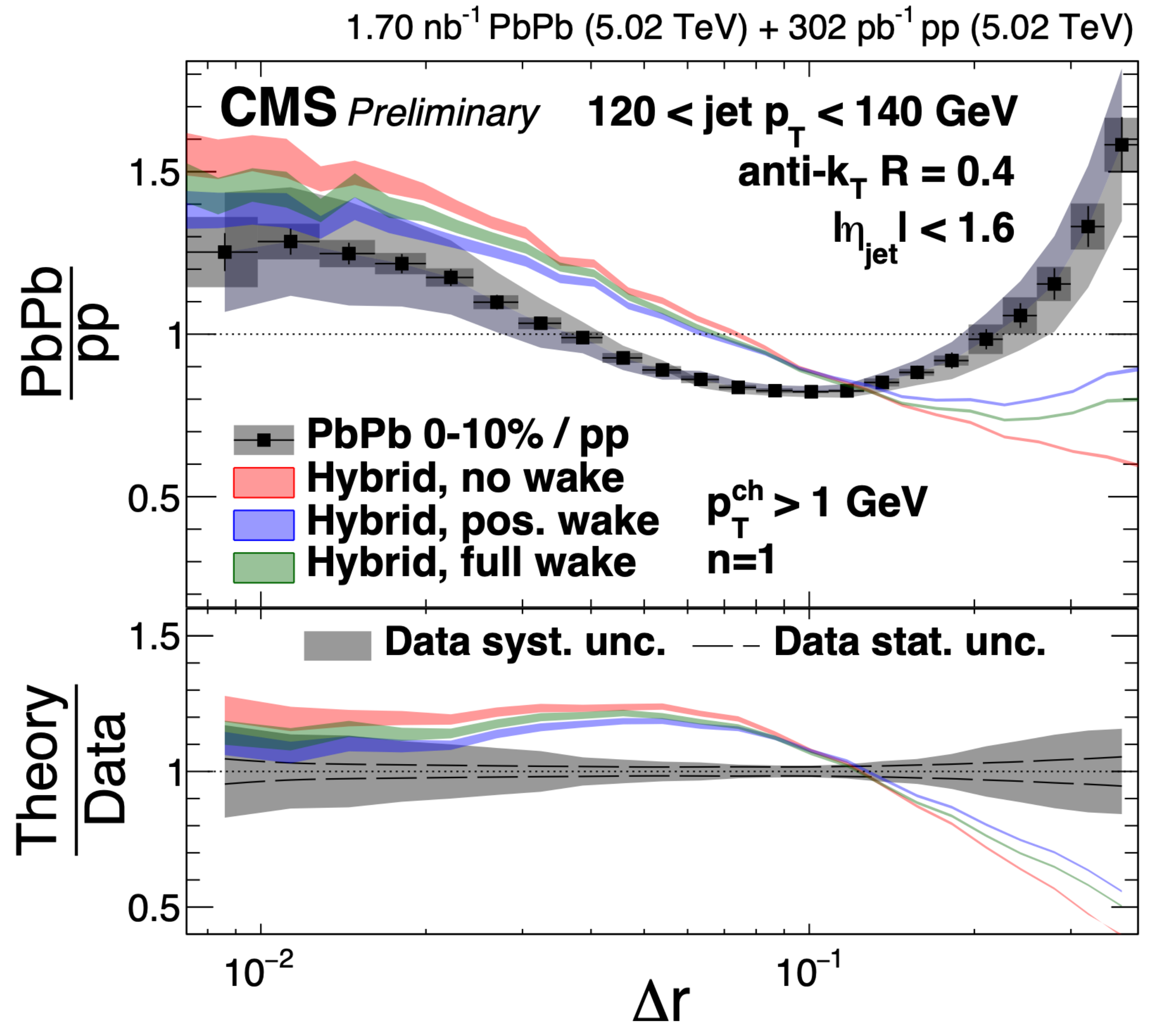
Progress in the characterization of jet-medium interactions:

- measurements of the jet-axis decorrelation in γ-jet

→ **evidence for a higher survival rate of narrow jets in PbPb** without “known” biases
Z-hadron correlations
→ **direct observation of medium-response in Z^0-hadron correlations**

- first EEC measurement in PbPb

→ **angular properties of jet-medium interaction with a “self-analyzing” observable**
with a traceable separation between perturbative and non-perturbative effects



Thank you for your attention!