Laboratory for Nuclear Science

HP2024 NAGASAKI

Highlights from CMS

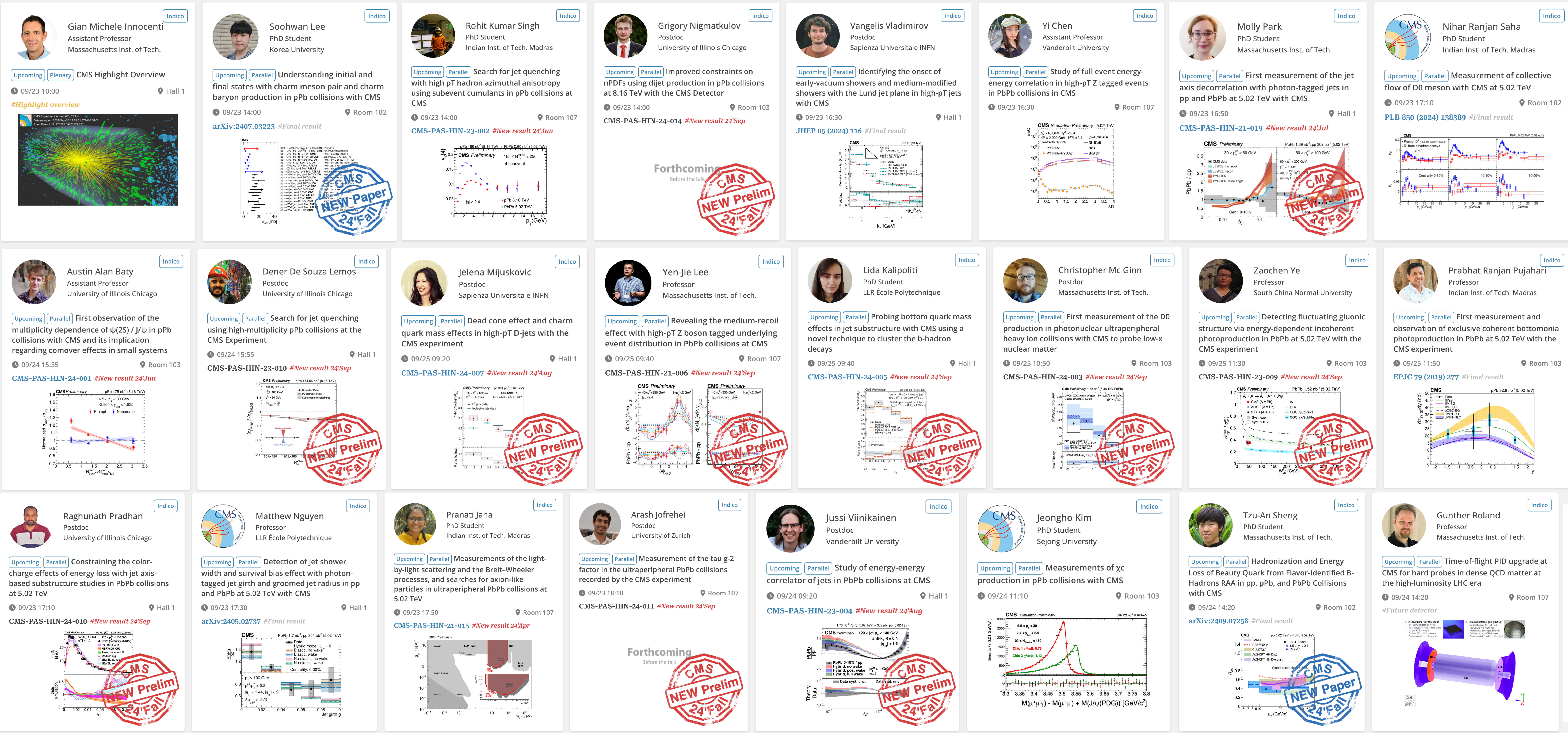
12th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions
September 22-27, 2024

Gian Michele Innocenti
Massachusetts Institute of Technology
(on behalf of the CMS collaboration)

MIT HIG group's work was supported by US DOE-NP

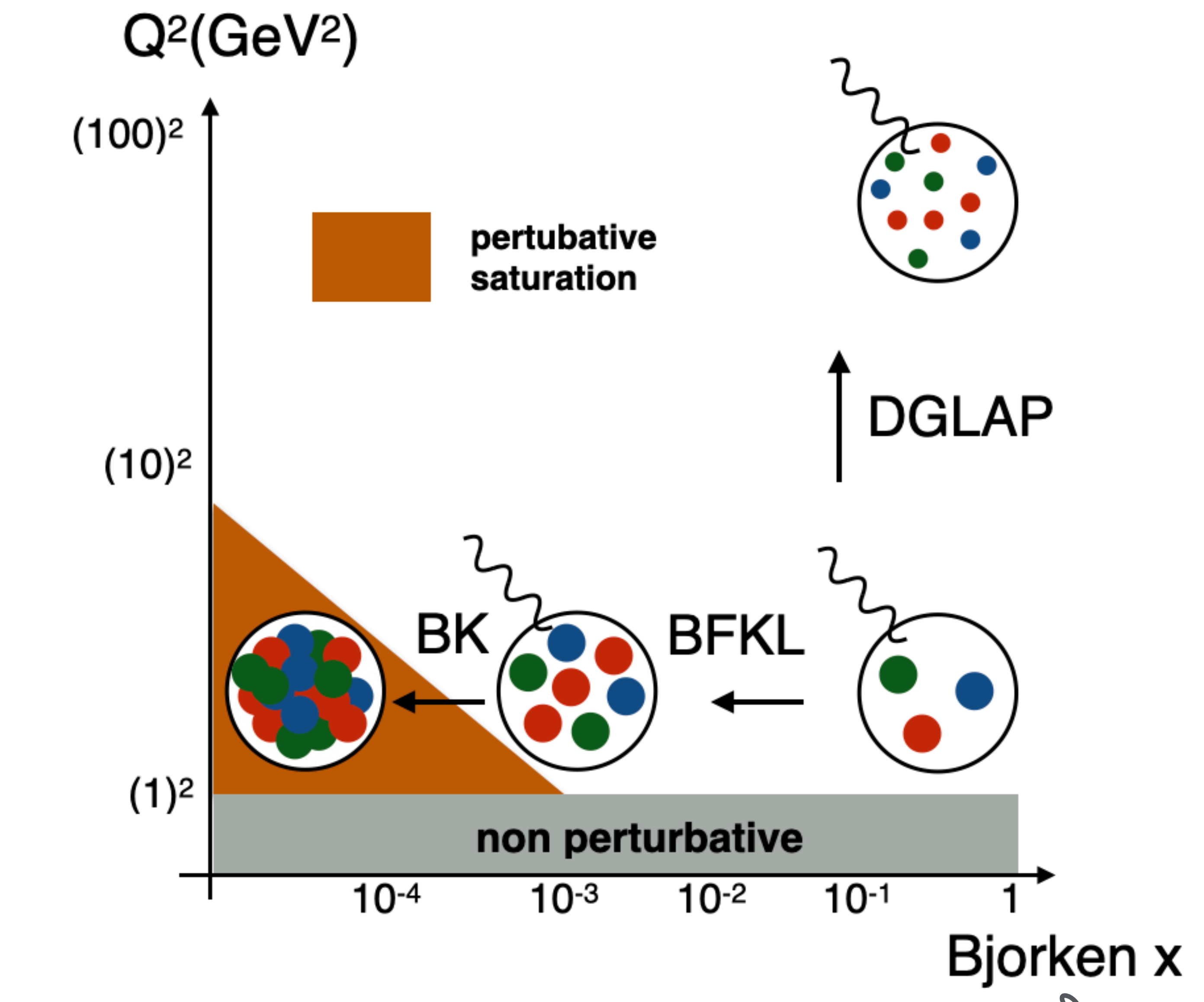
Overview of CMS contributions

In this conference → many new preliminary and final results, **presented in 23 parallel talks + 2 posters**

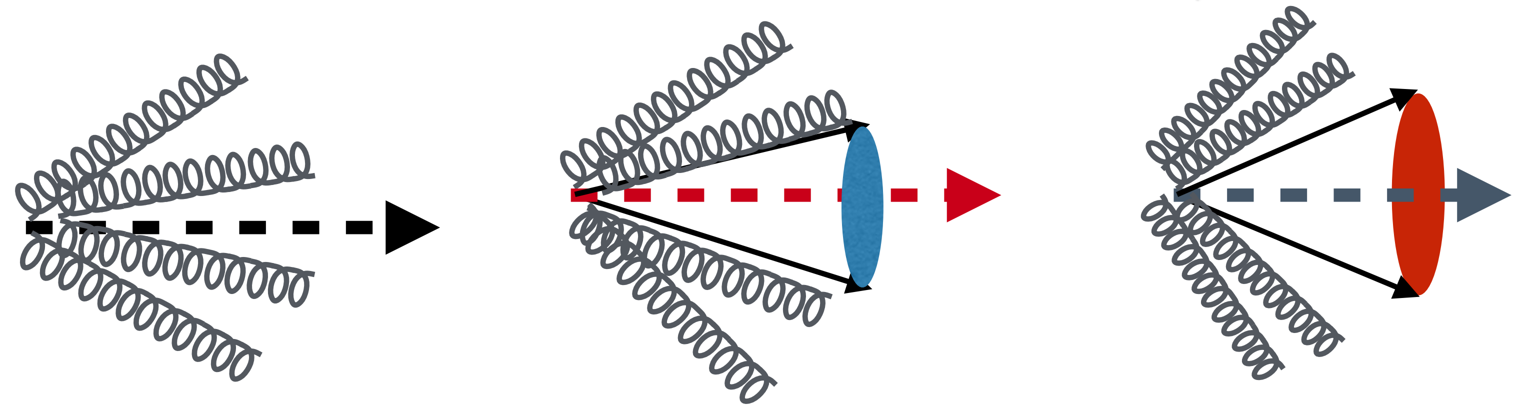


https://cms-hin-public.web.cern.ch/speakers/HP2024

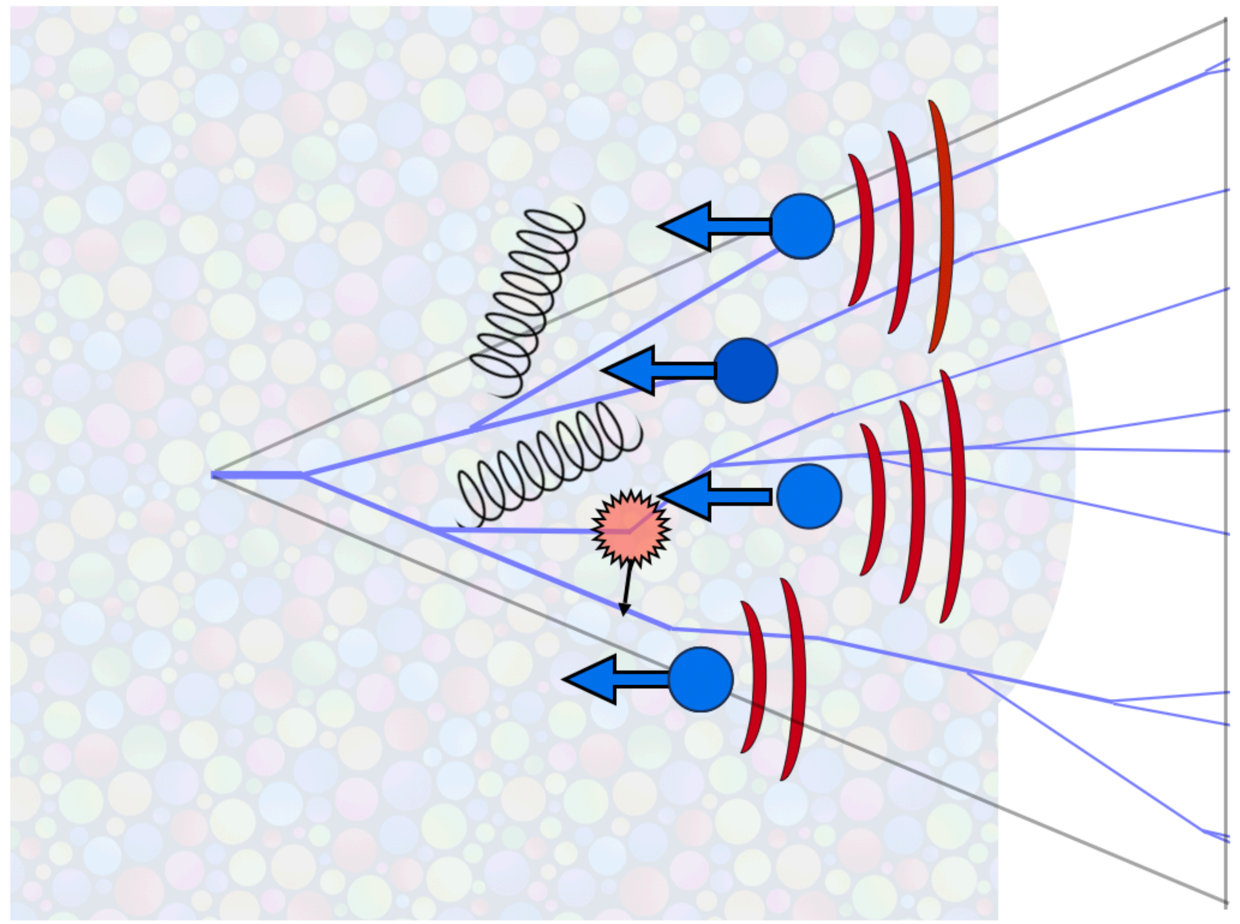
Focus of this talk



Properties of nuclear matter in nuclei

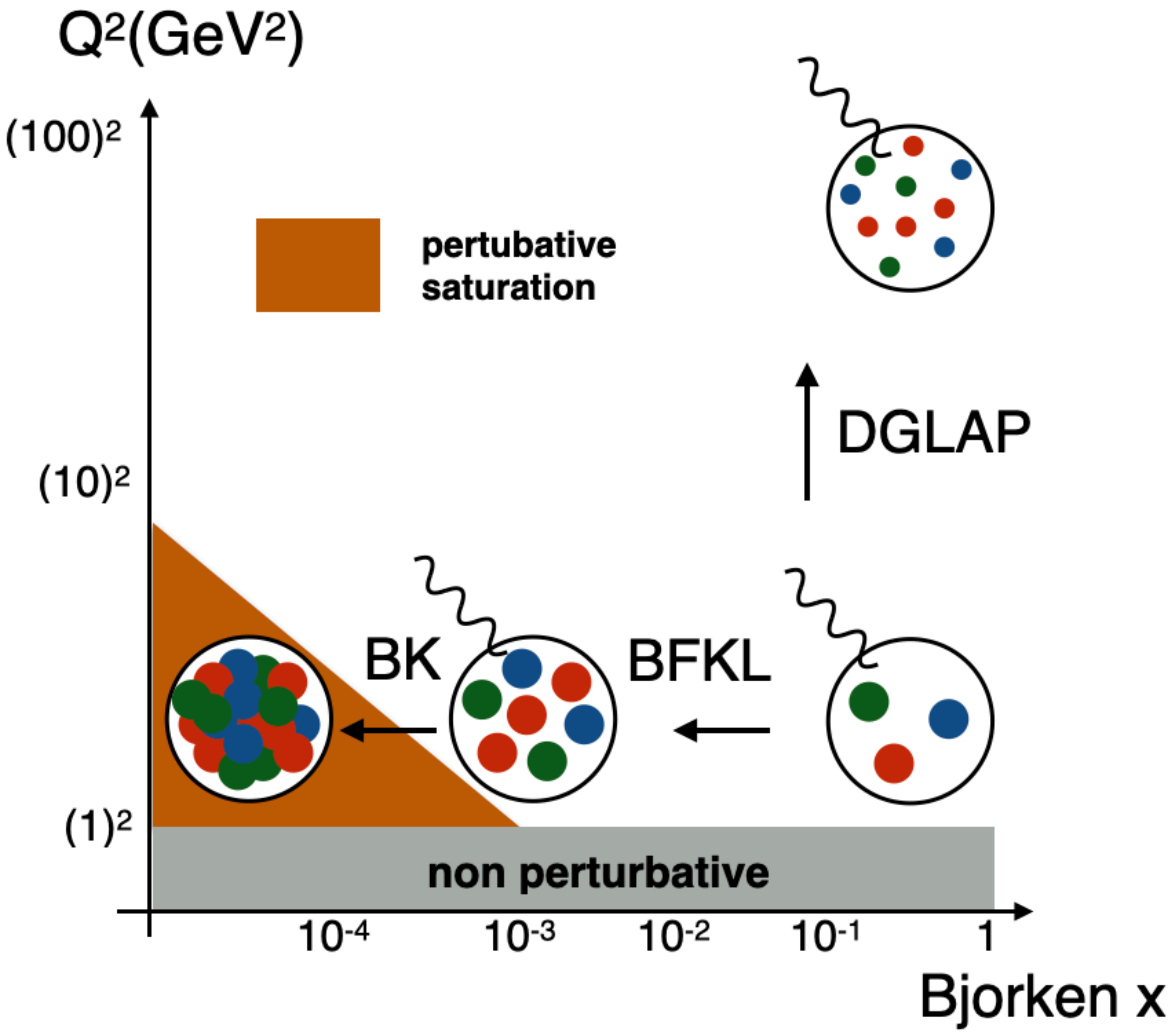


Heavy-quark parton shower in vacuum



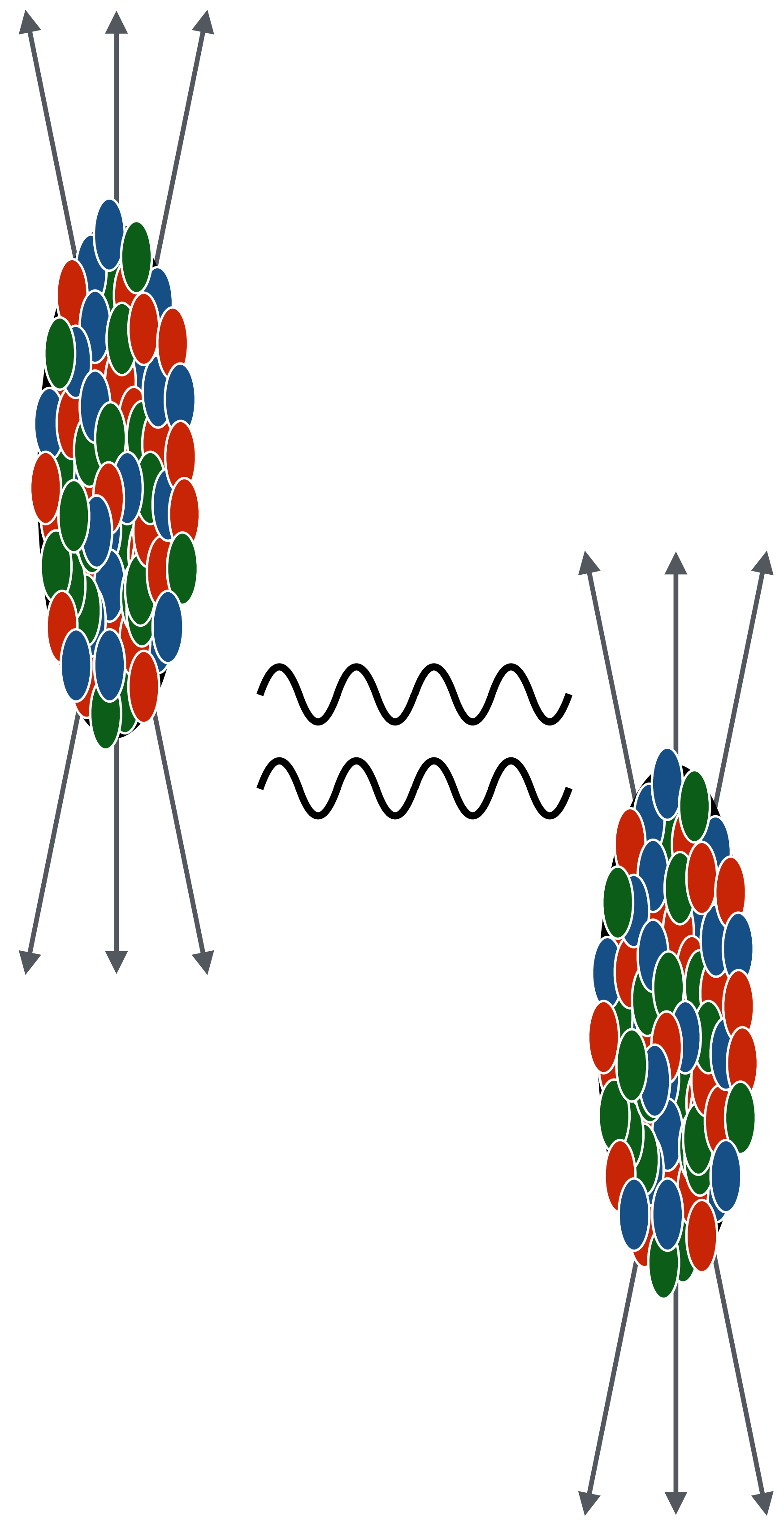
Phenomenology of jet-medium interactions

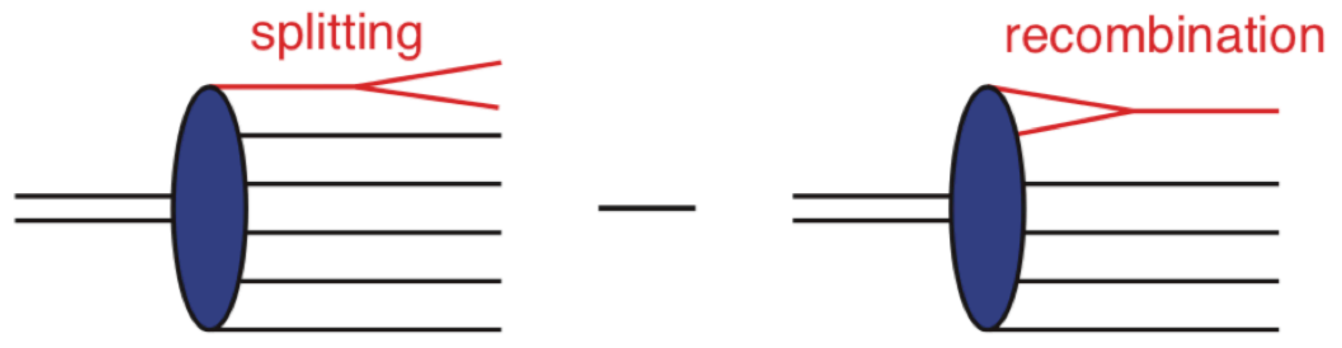
Characterizing the parton dynamics in nuclei



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)

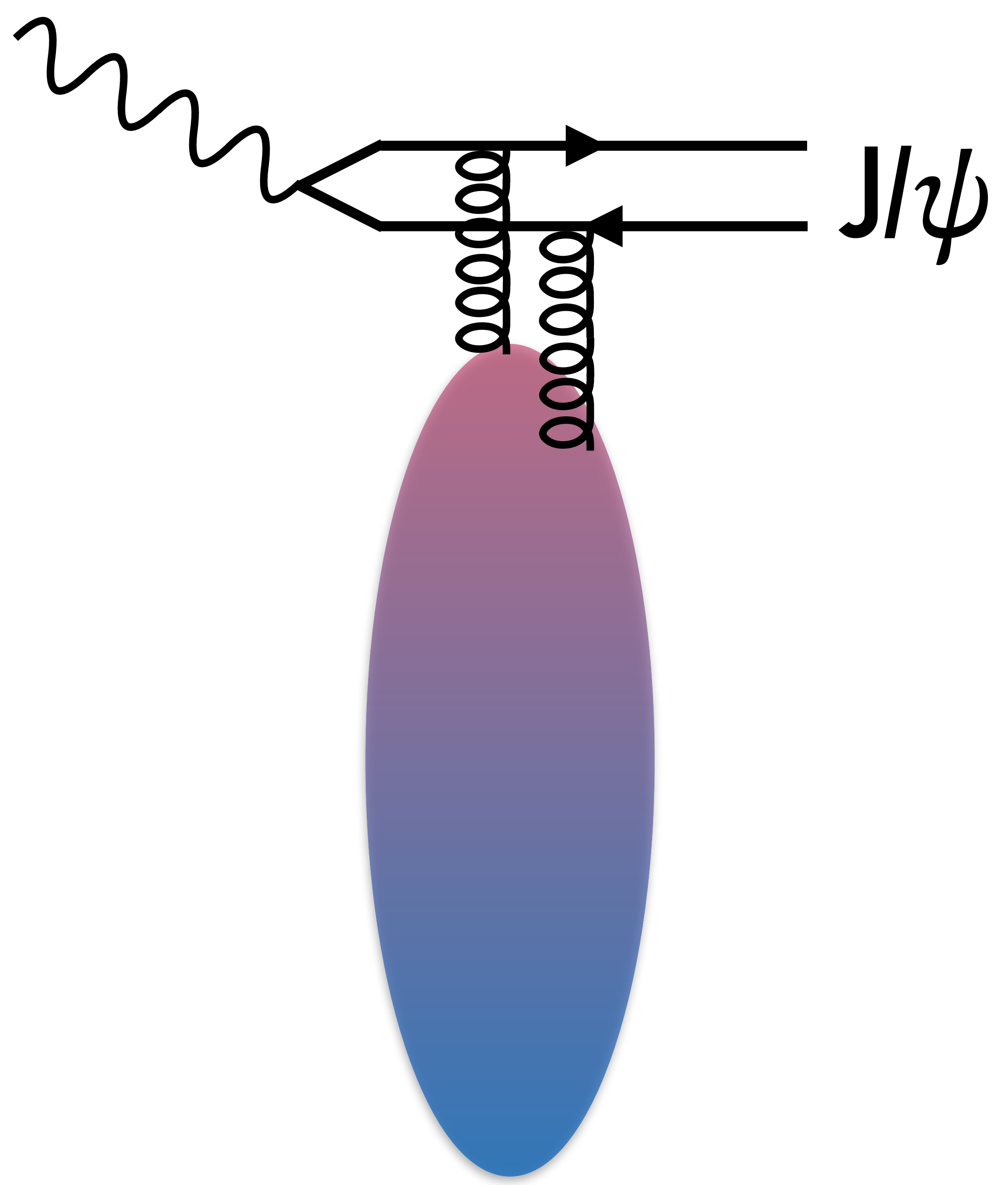
K. Hencken, M. Strikman et al.
Phys.Rept.458 1-171, 2008

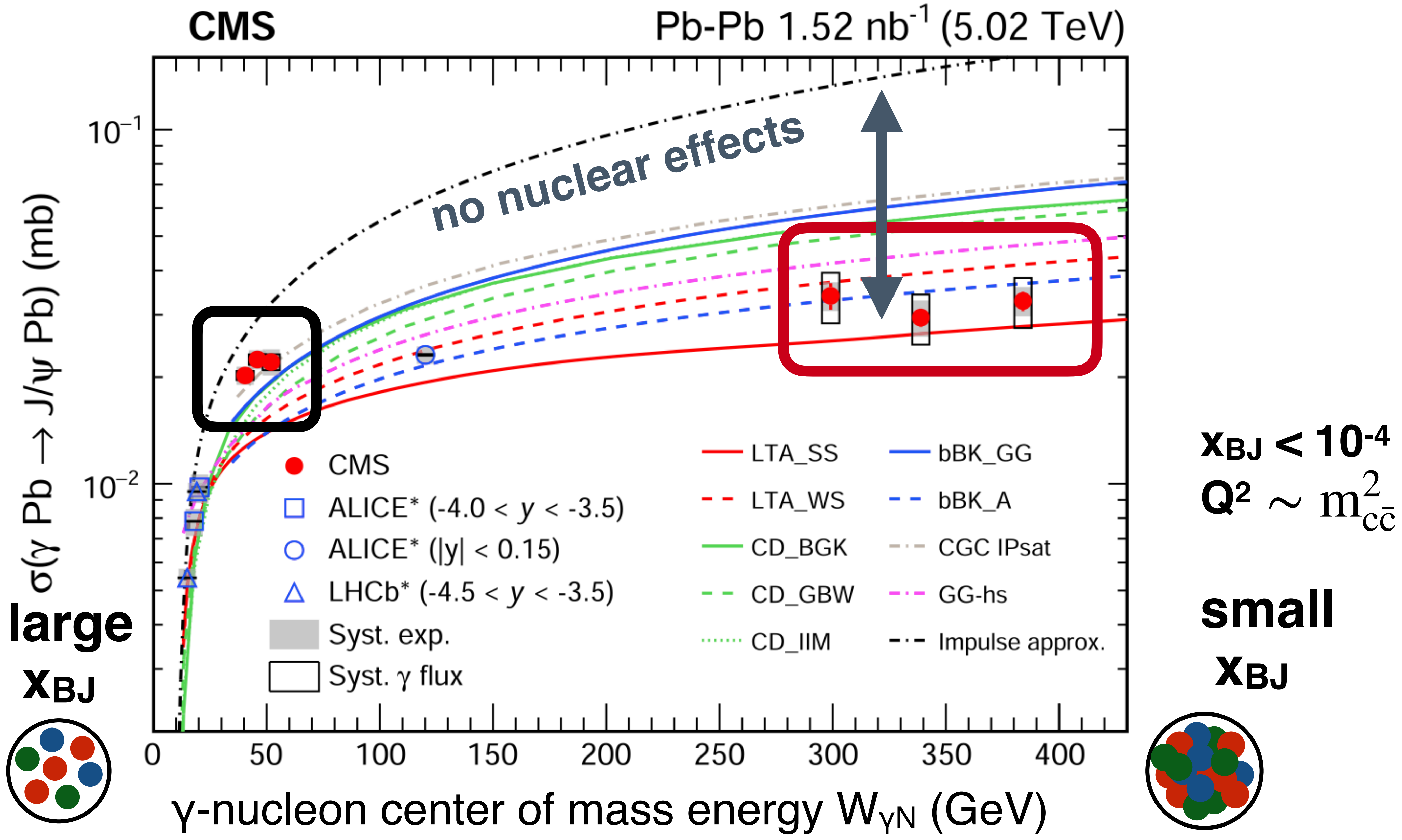
Coherent J/ψ production in PbPb UPCs

CMS, Phys. Rev. Lett. 131 (2023) 262301

Low p_T J/ψ (~50 MeV)

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





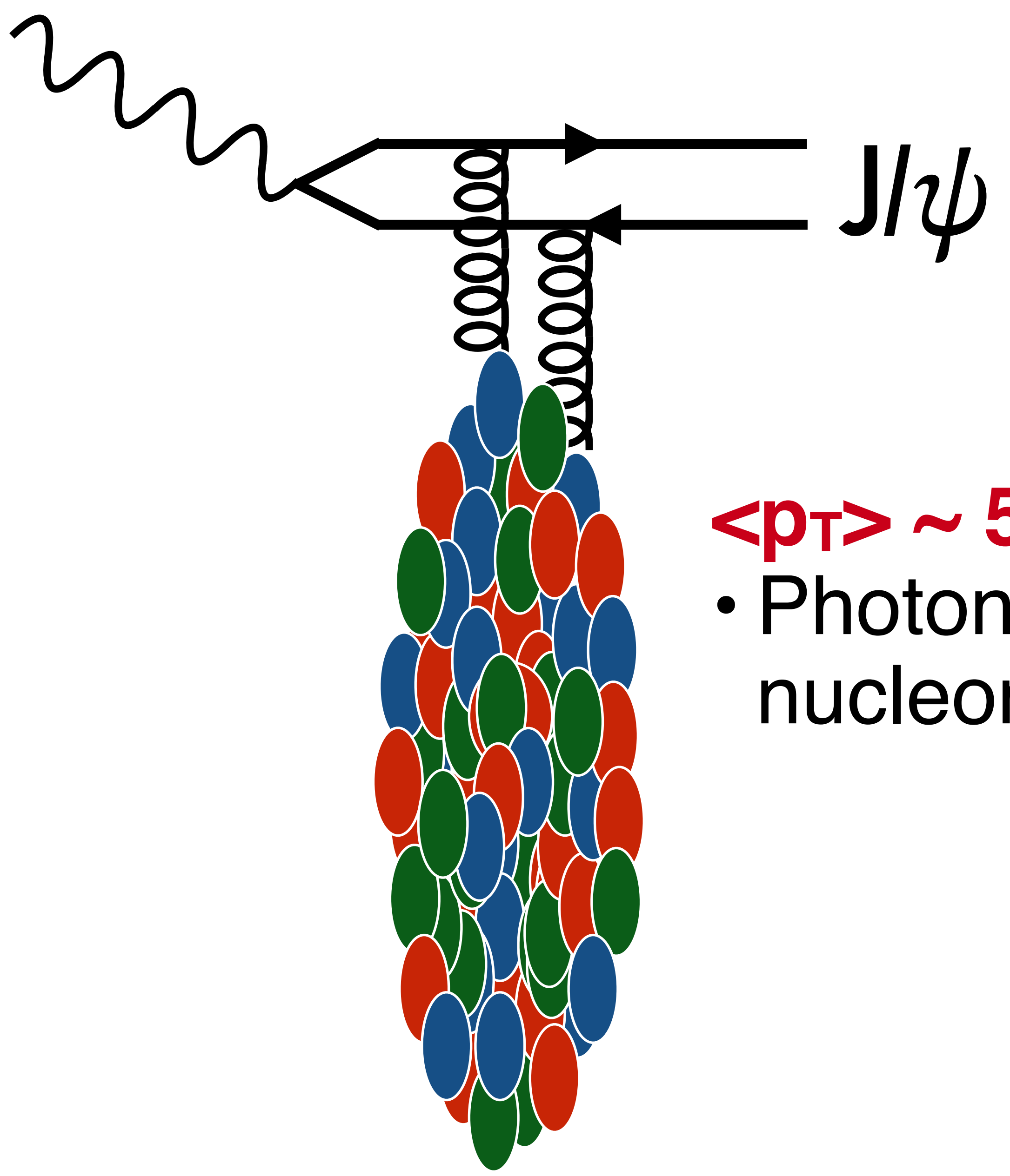
→ **strong suppression at high $W_{\gamma N}$ values (small x_{BJ})** compared to scenarios without nuclear effect (IA)

→ **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 $W_{\gamma N}$

See Zaochen Ye's talk
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 $W_{\gamma N}$

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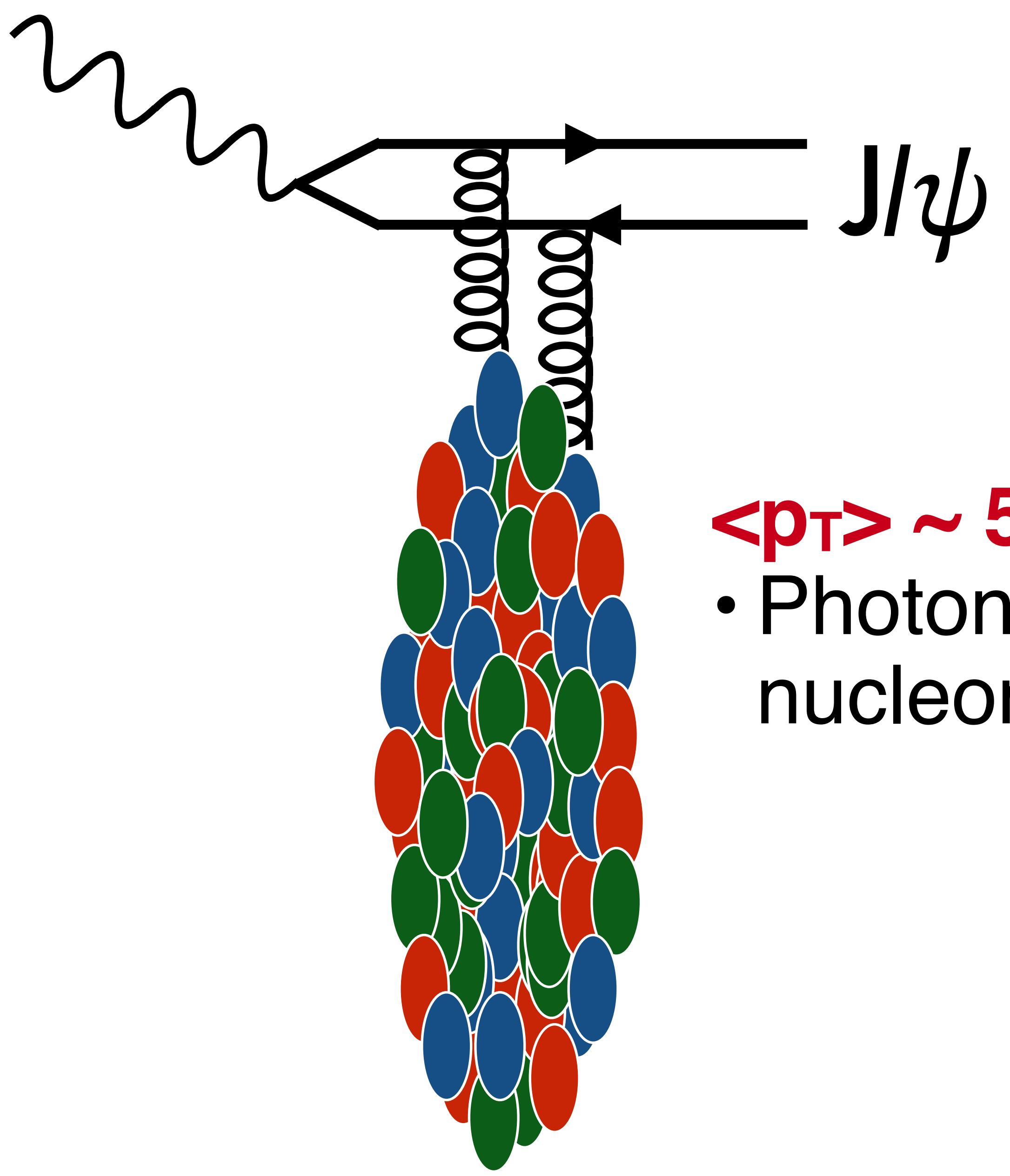

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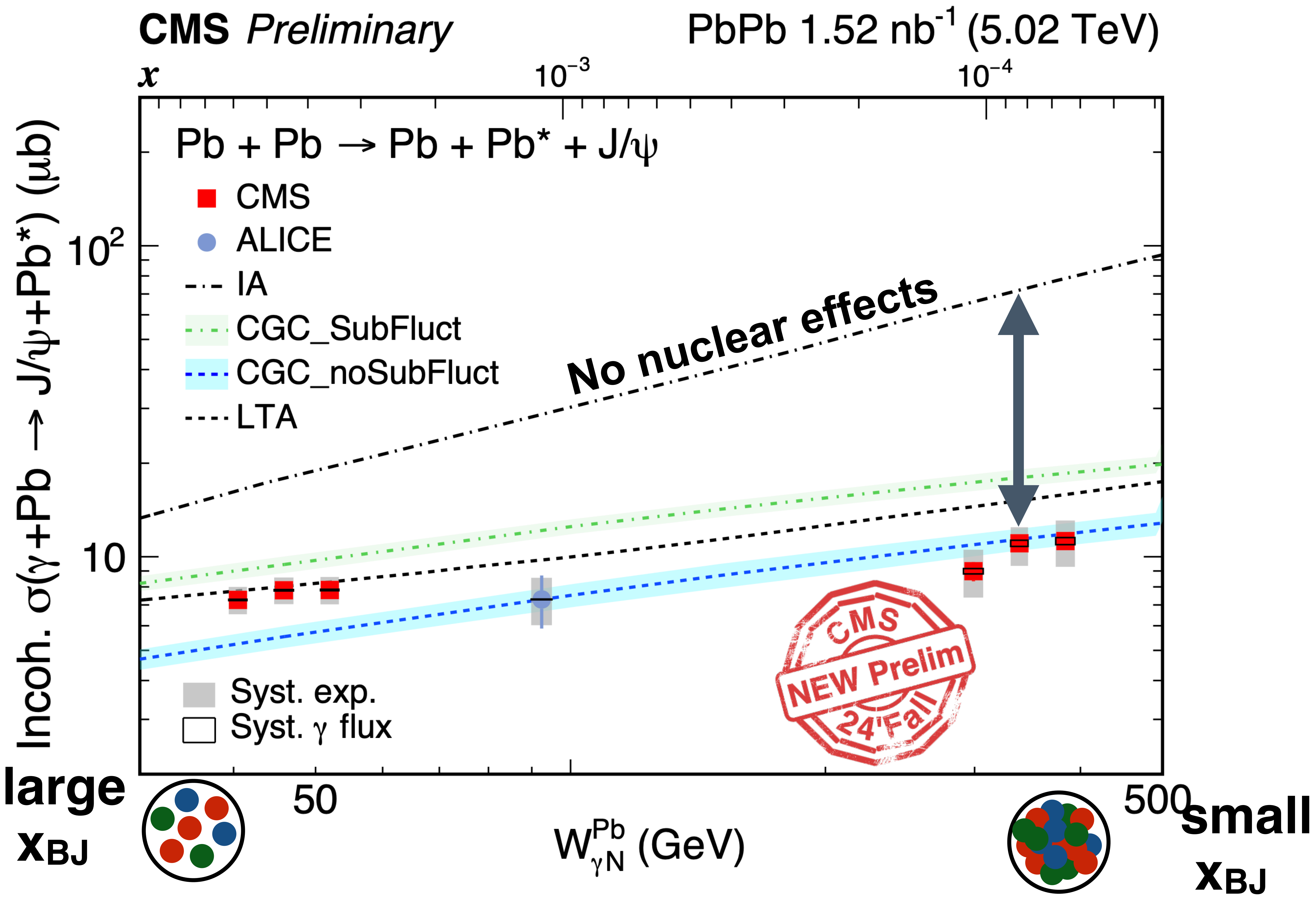

Strong suppression observed at large $W_{\gamma N}$ (small x) w.r.t. no-nuclear effects predictions
- **CMS data "challenge" both shadowing and saturation descriptions**

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

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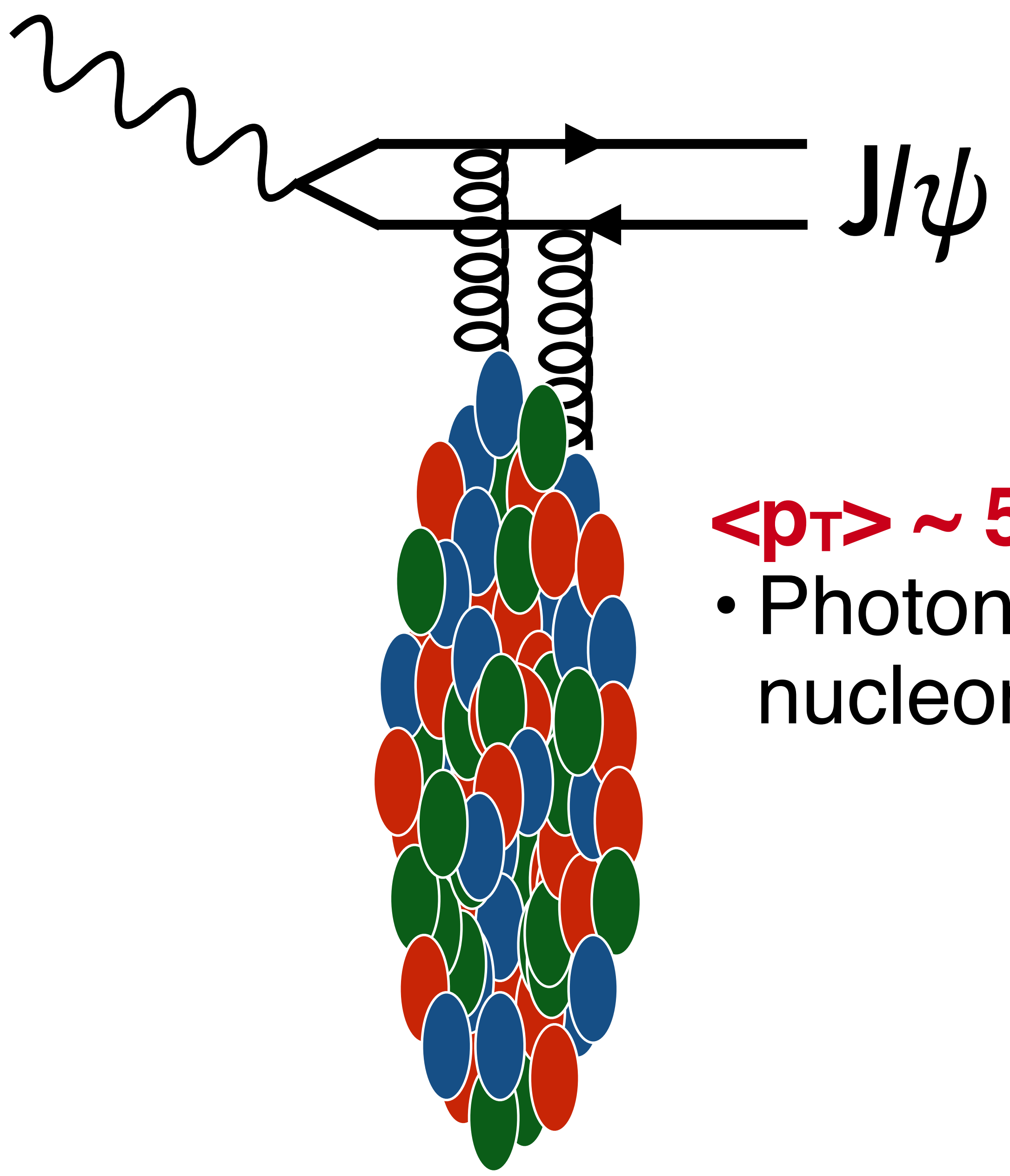
CMS-PAS-HIN-23-009



$\langle p_T \rangle$ ~ 500 MeV

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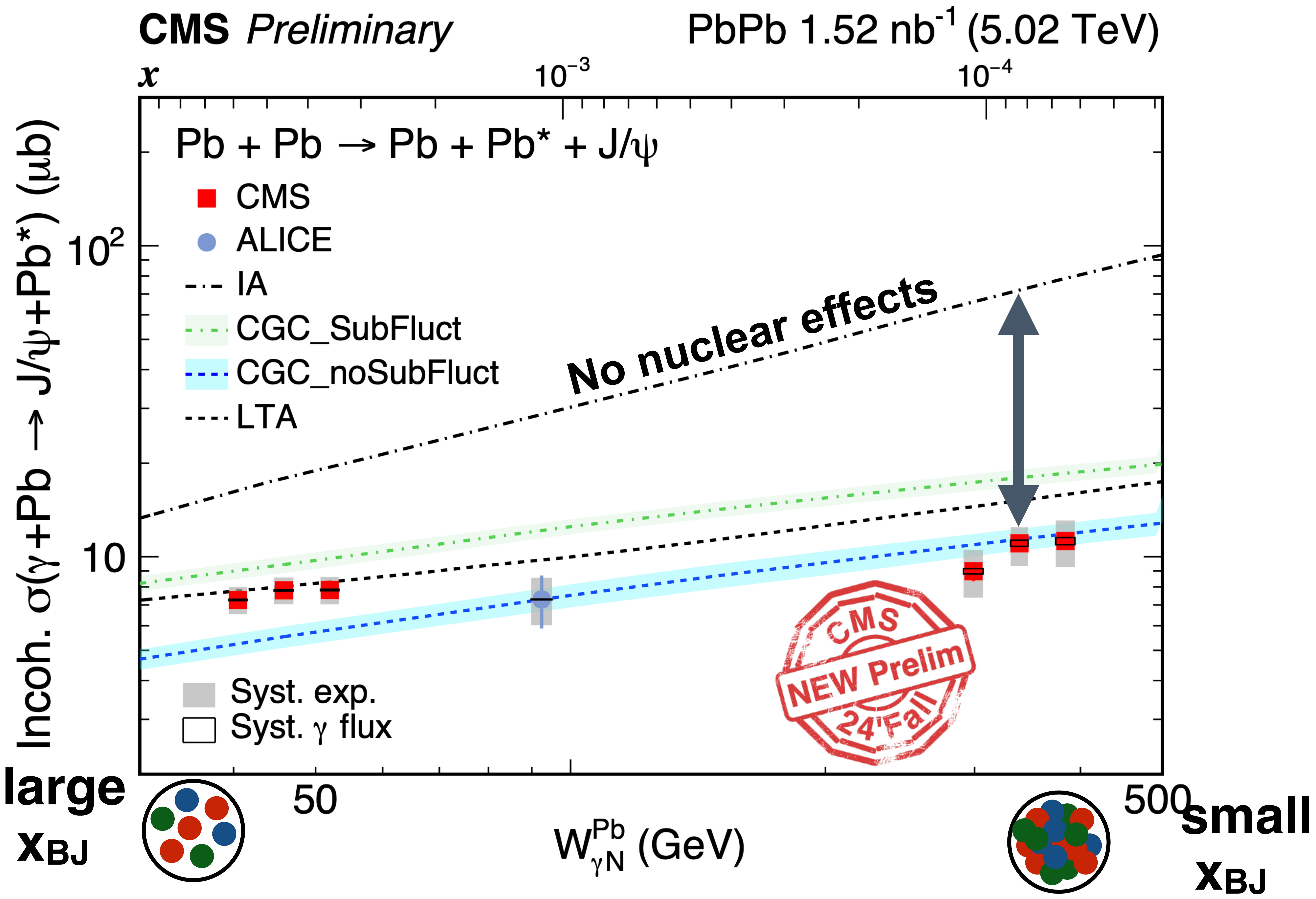
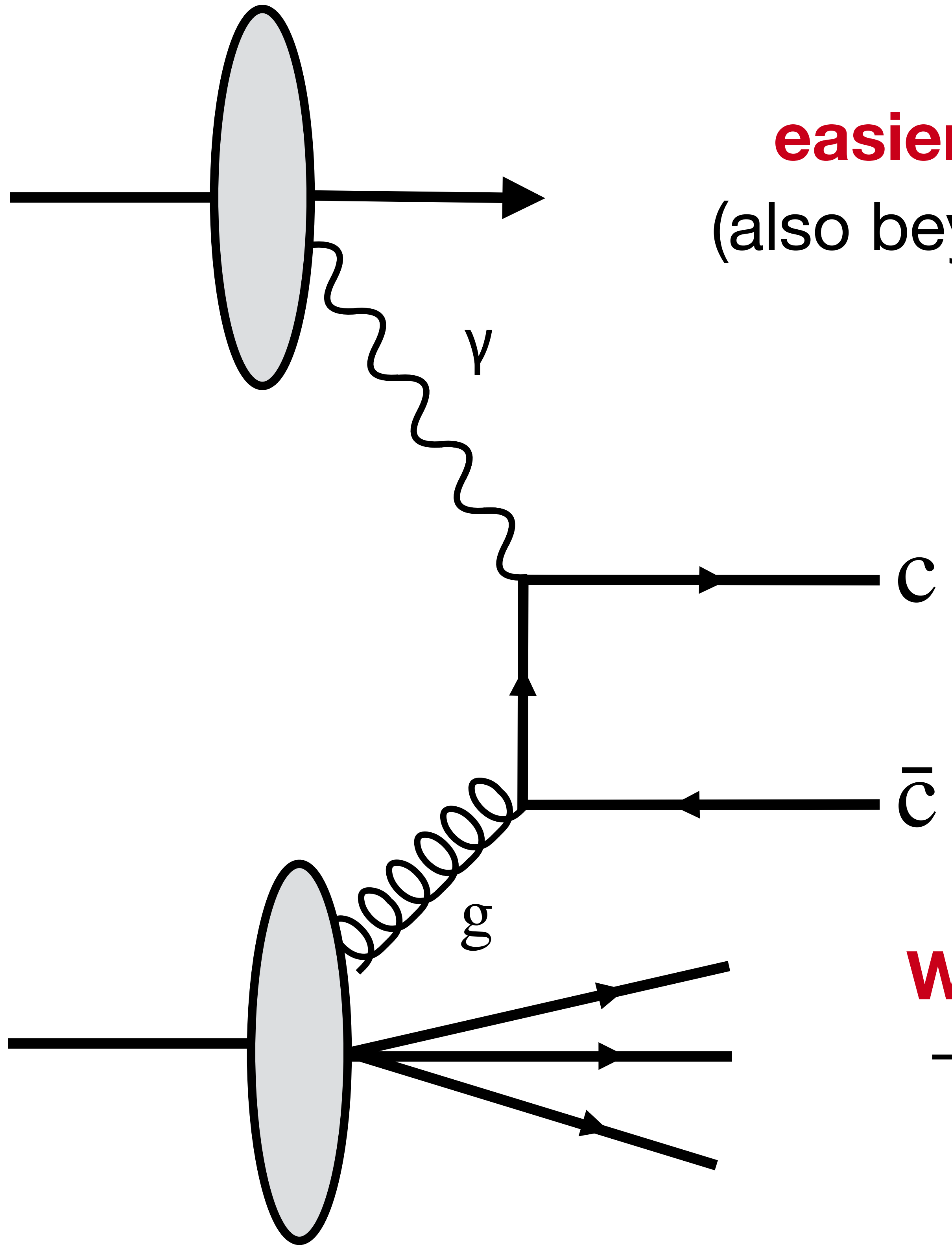


→ **Need to "overconstrain" calculations with new probes that provide additional/complementary constraints**

→ **Overcome the main limitations of current J/ψ measurements: complex theoretical description and limited Q^2 coverage**

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

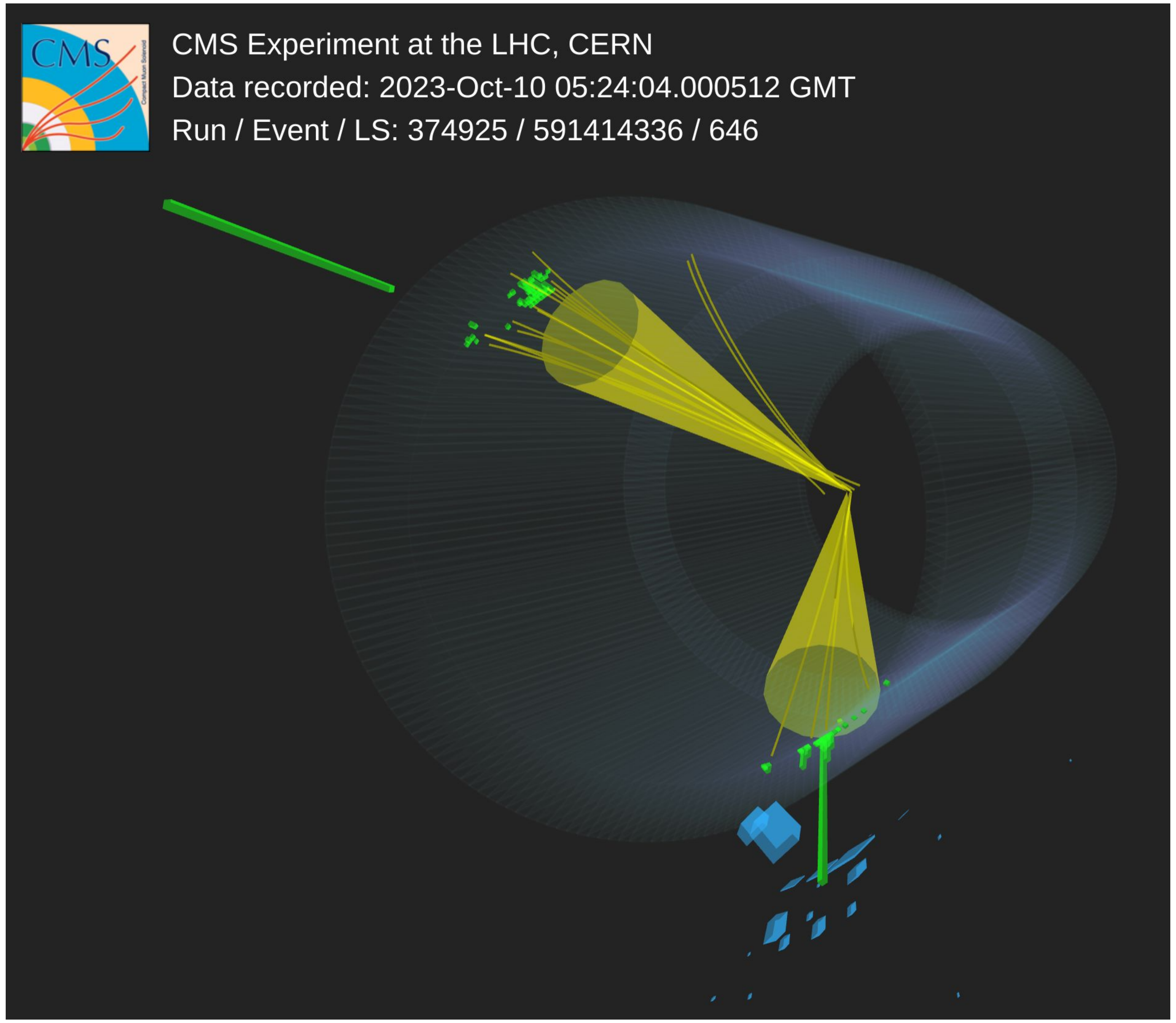
See Chris McGinn's talk
CMS-PAS-HIN-24-003



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

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

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



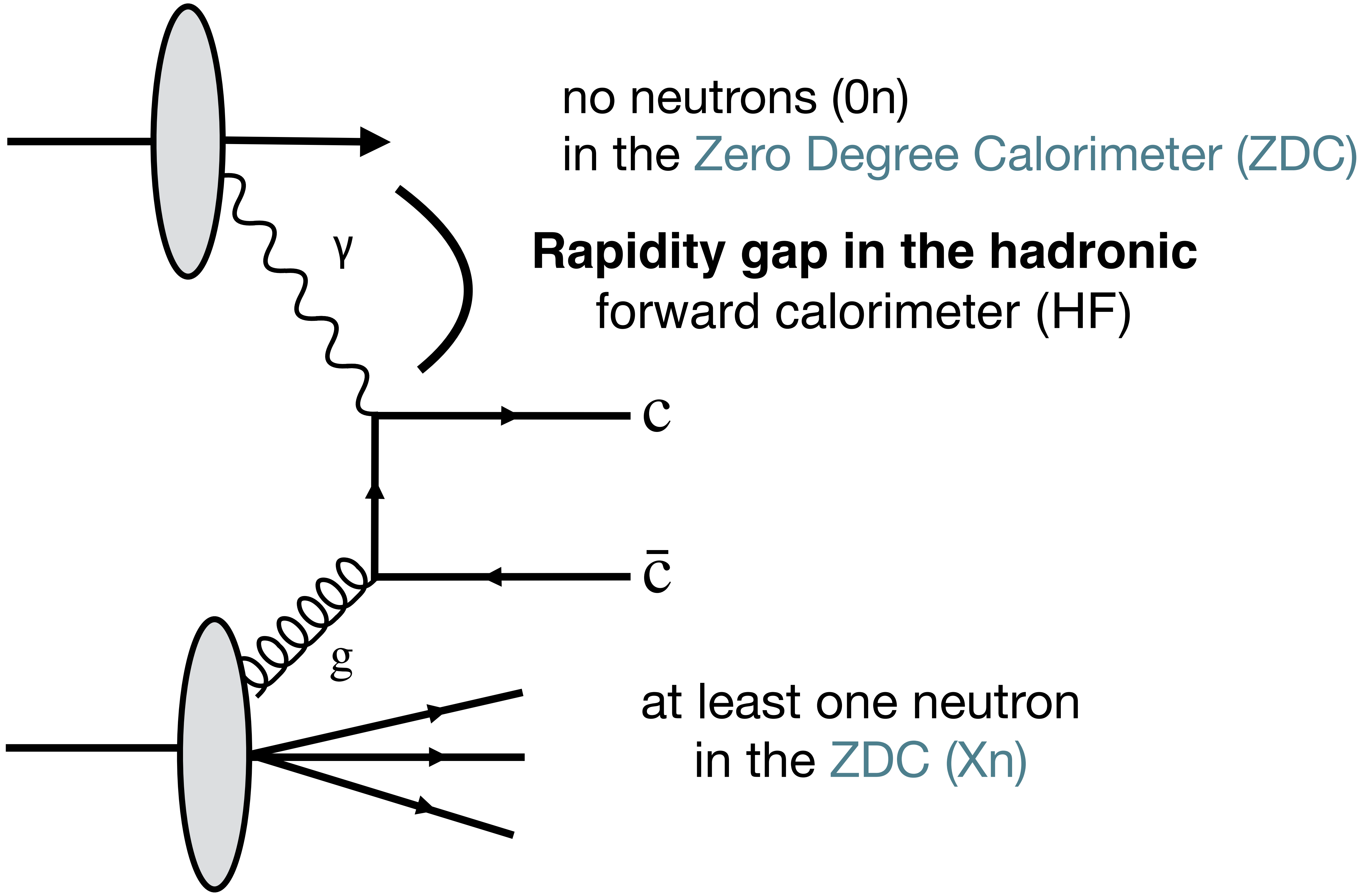
→ ideal probe to test the transition towards low-x nuclear matter in absence of sizable final state effects

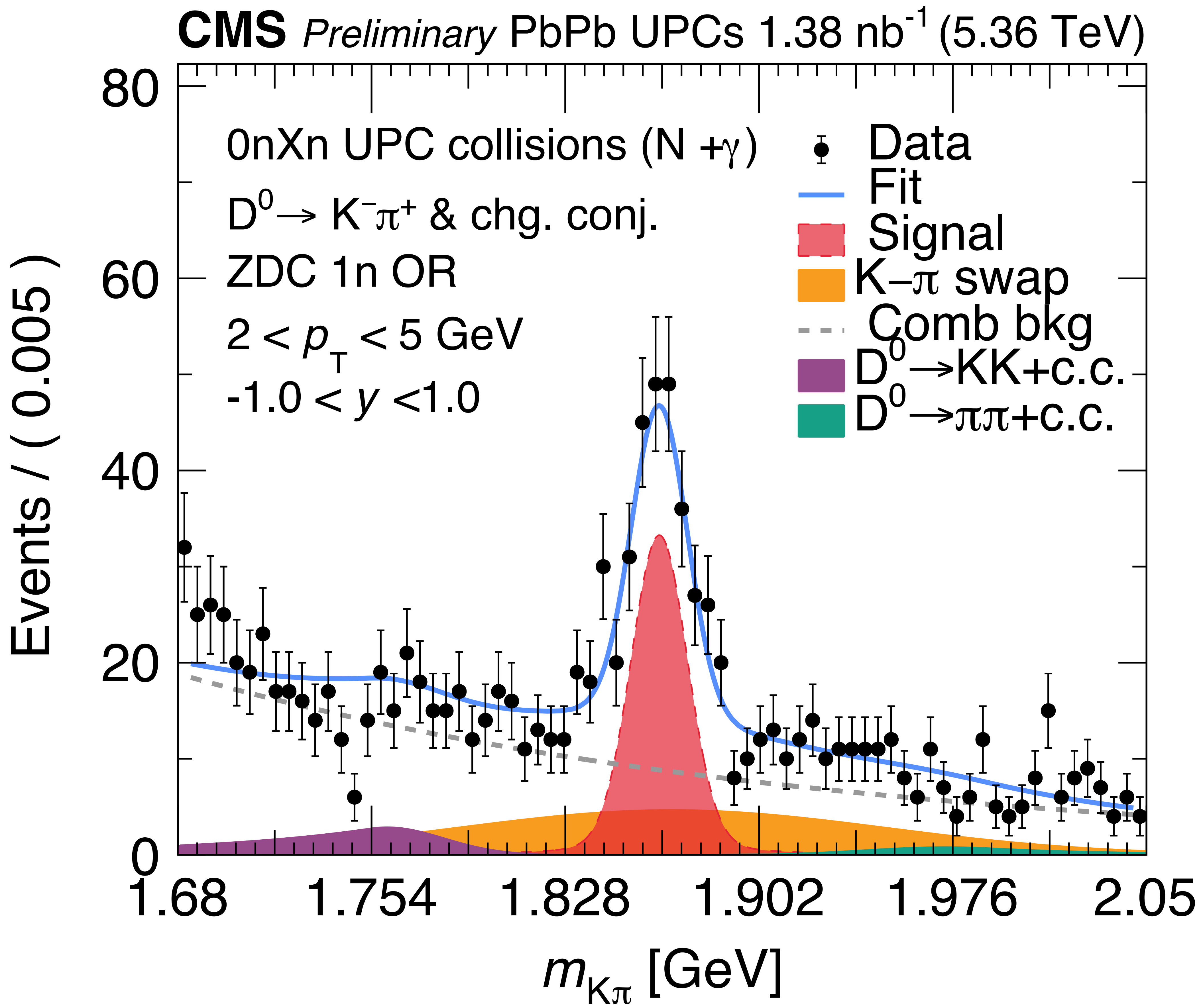
ATLAS, ATLAS-CONF-2017-011
S. Klein, R. Vogt et al: Phys. Rev. C, v66, 2002

D^0 photonuclear production in UPCs

See Chris McGinn's talk
CMS-PAS-HIN-24-003

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

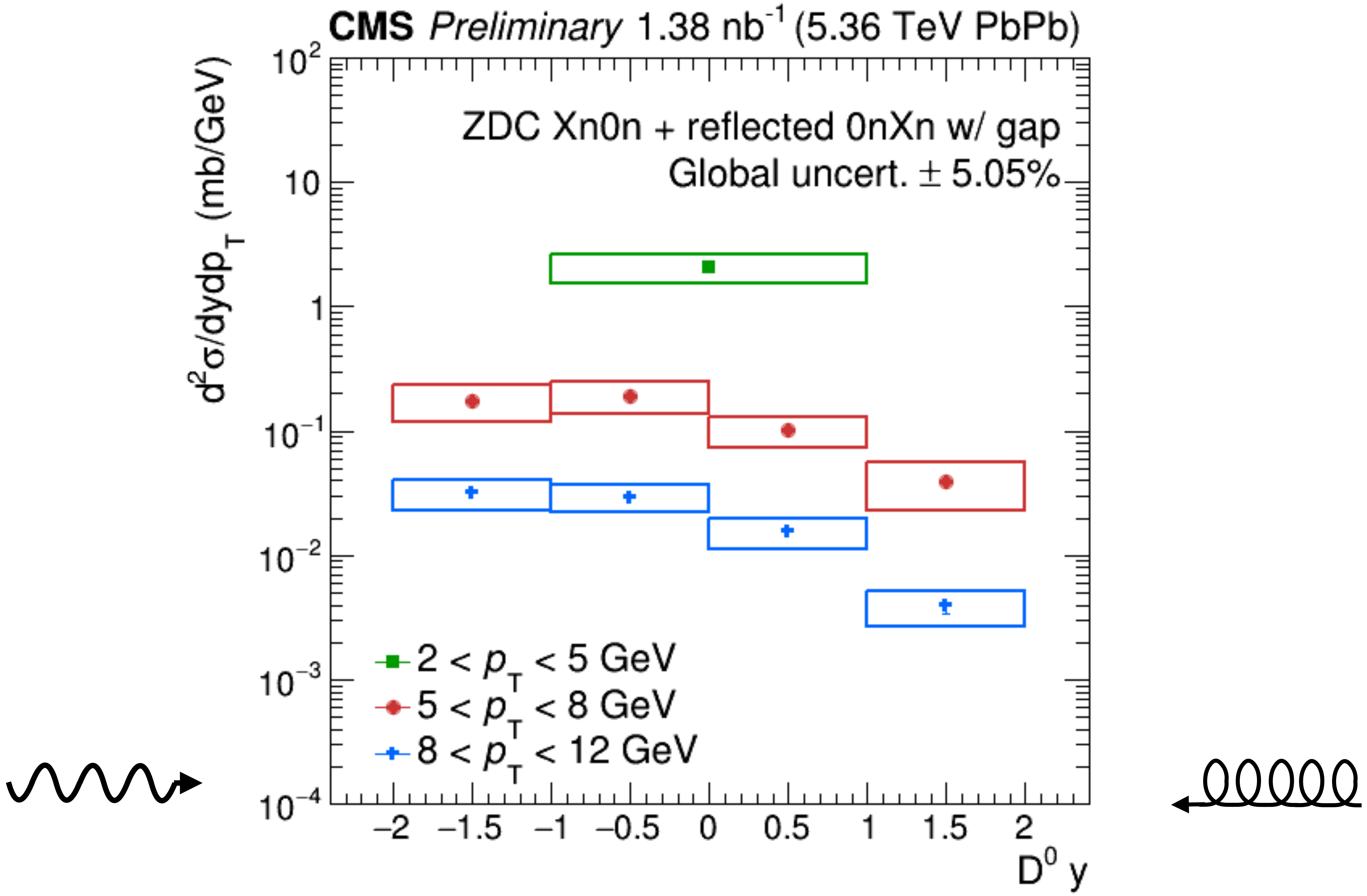




A new trigger strategy for both soft and hard photonuclear events

→ O(1000) times more photonuclear events than in Run 2

First measurement of the D^0 photonuclear production in UPCs



See Chris McGinn's talk

CMS-PAS-HIN-24-003

First measurement of the D^0 photonuclear production in UPCs

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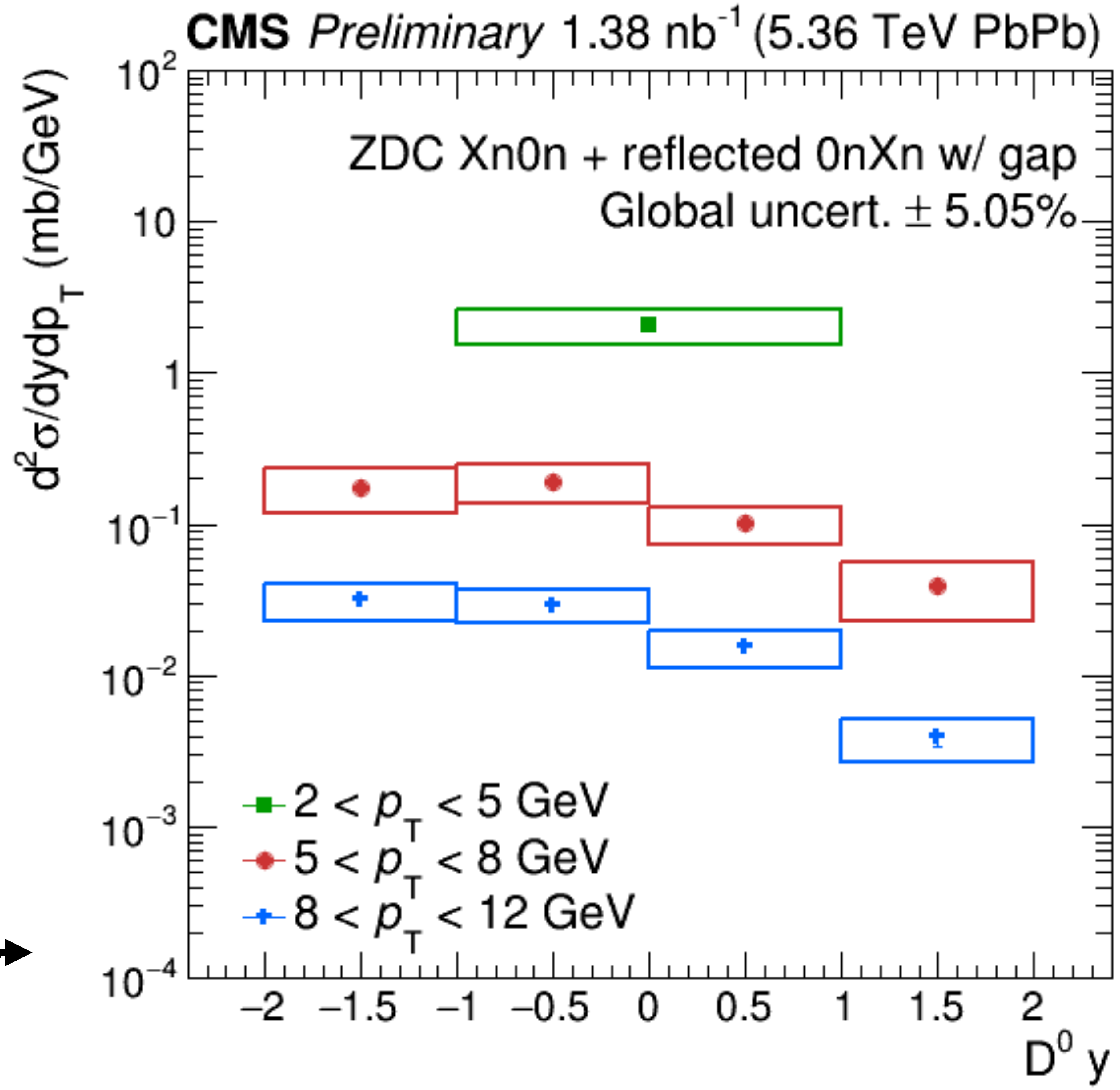
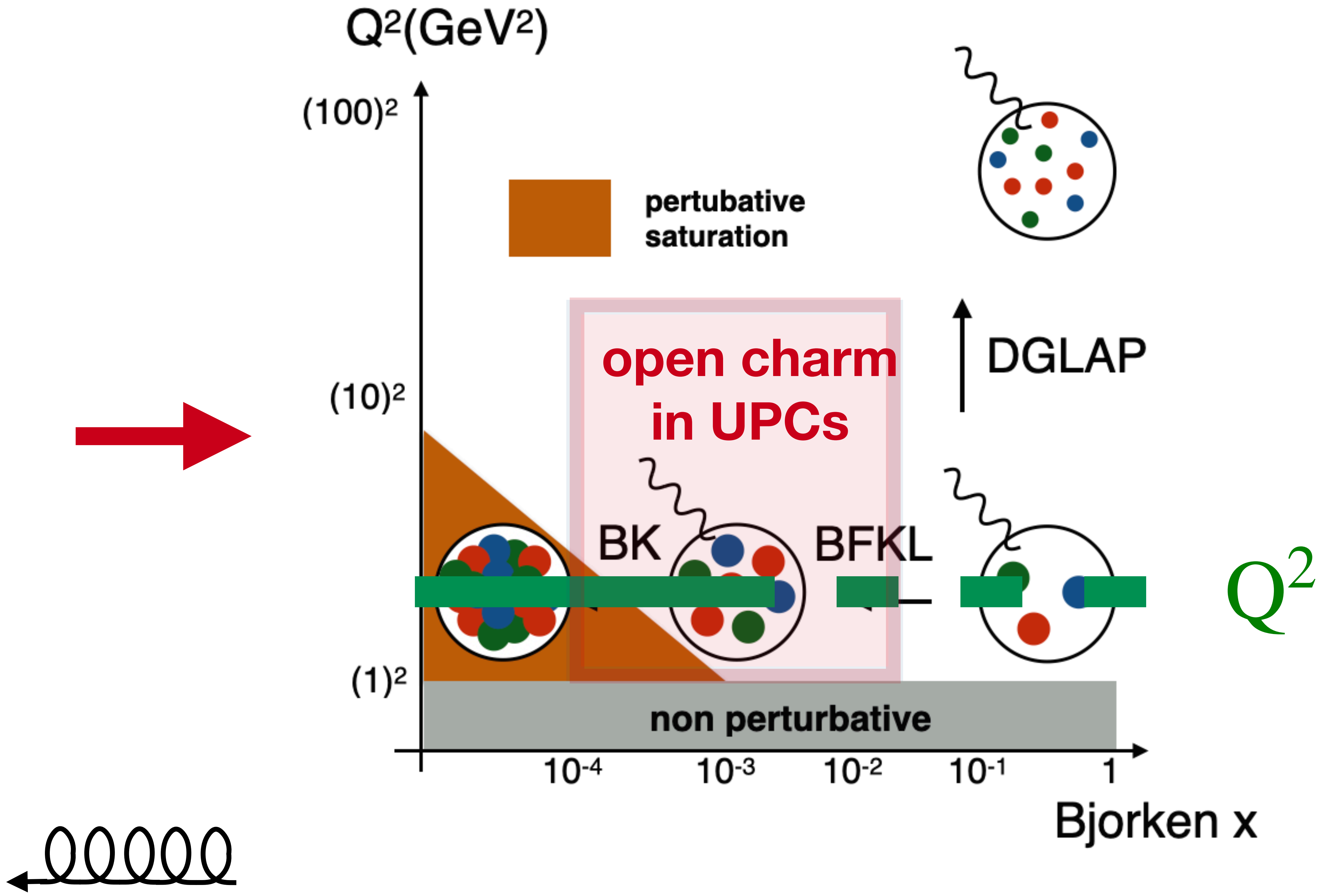




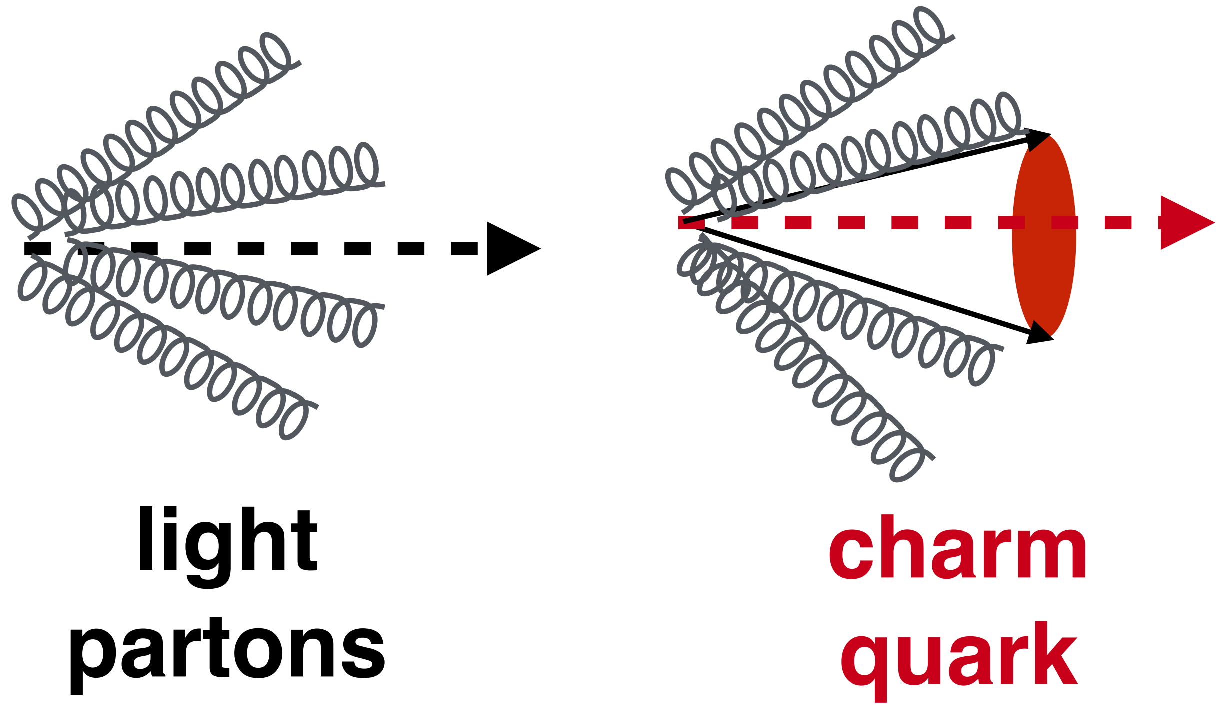
→ **First constraints on nuclear gluon PDFs <u>over a wide region of Q^2 ($\mathcal{O}$(10) < Q^2 < hundreds GeV^2)</u>**
at low-x (~ $5 \times 10^{-4} < x < 10^{-2}$) **in the absence of sizable final state effects**

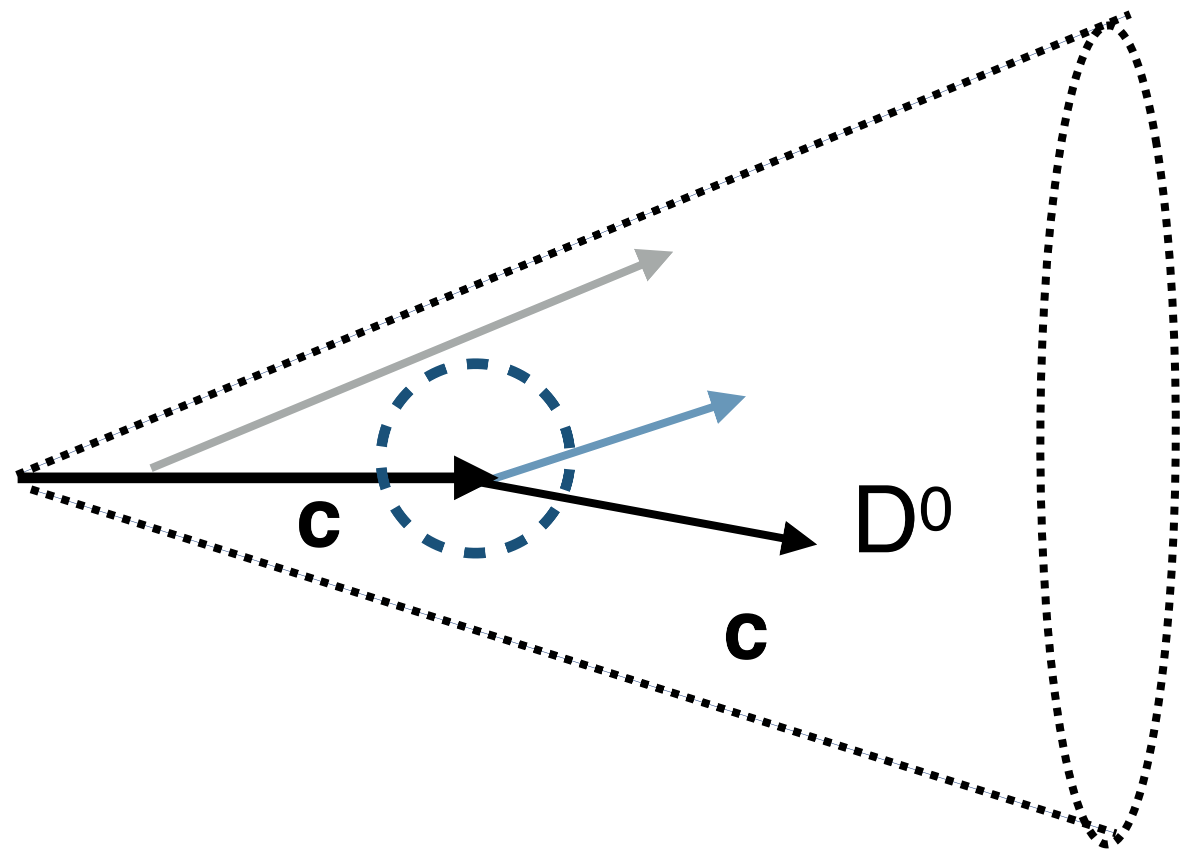
→ **opens the way for a large program of open heavy-flavor hadrons, jets and correlations in UPCs collisions at the LHC**

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

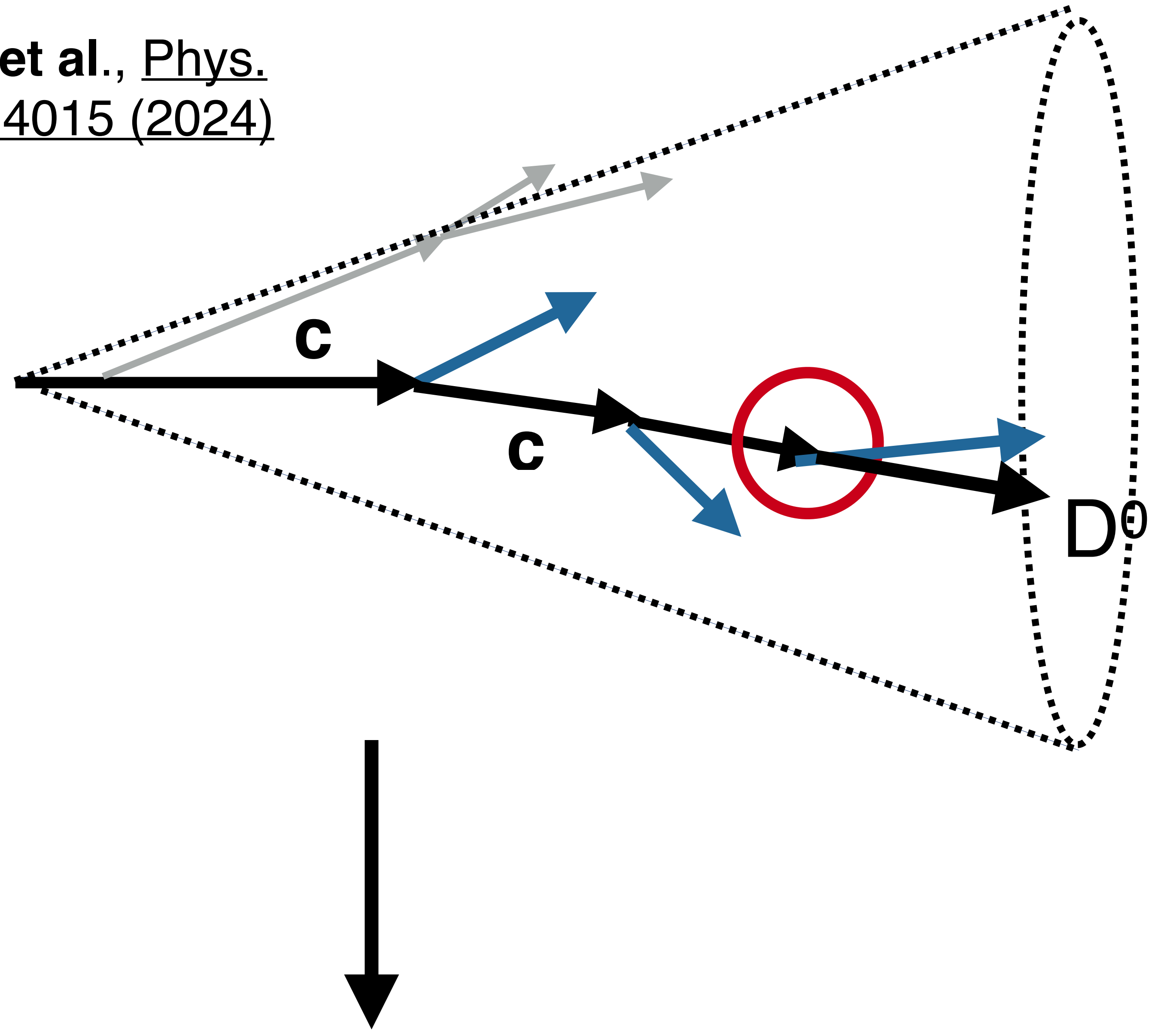
→ led to the first direct observation of the charm dead-cone
ALICE, *Nature 605 (2022) 440-446*

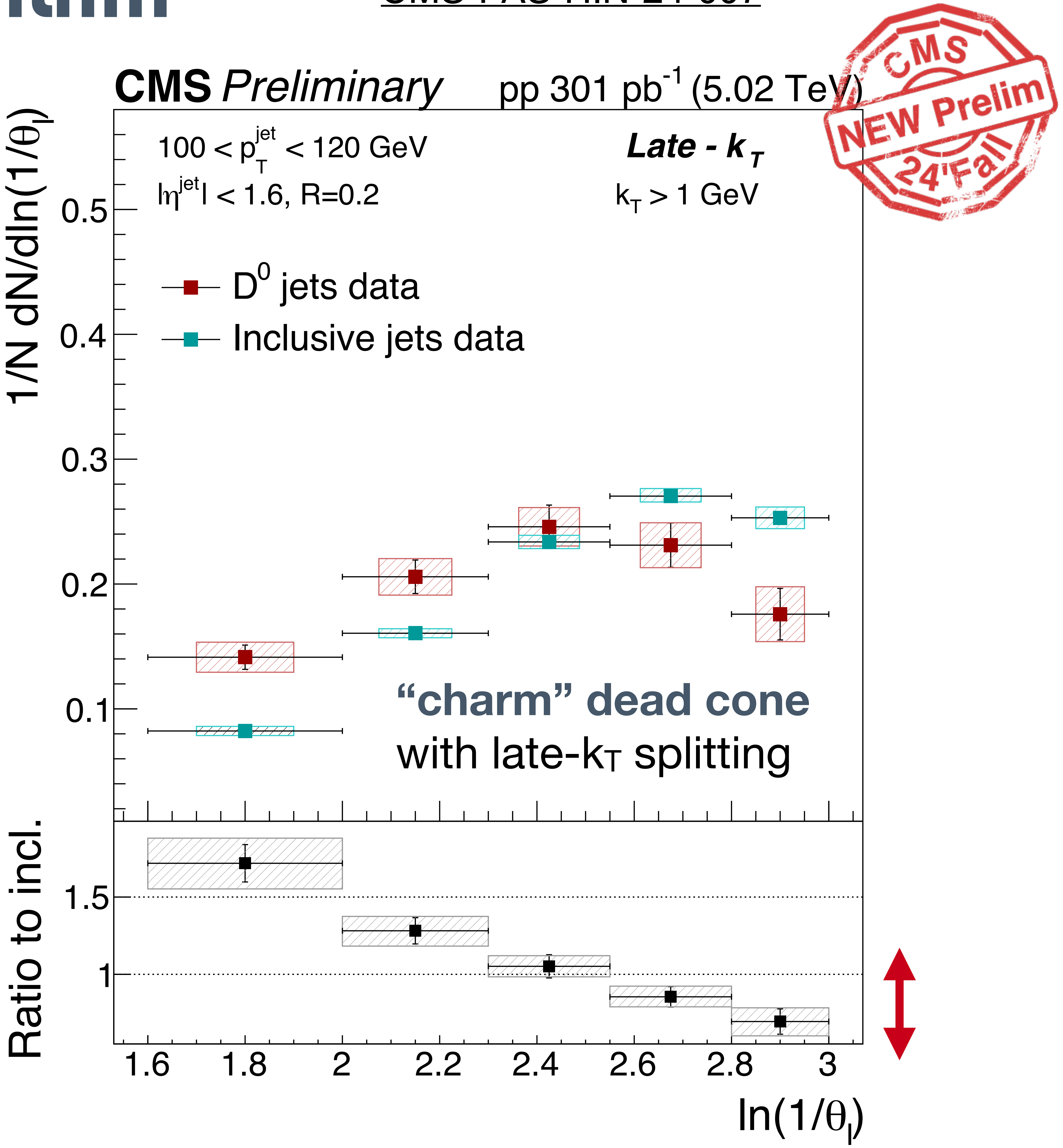
Charm dead cone with late-k_T algorithm

See Jelena Mijuskovic's talk
CMS-PAS-HIN-24-007

- PF jets $p_T > 100$ GeV
- Reclustered with **late-k_T grooming**
  → most collinear splitting with k_T>1 GeV

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



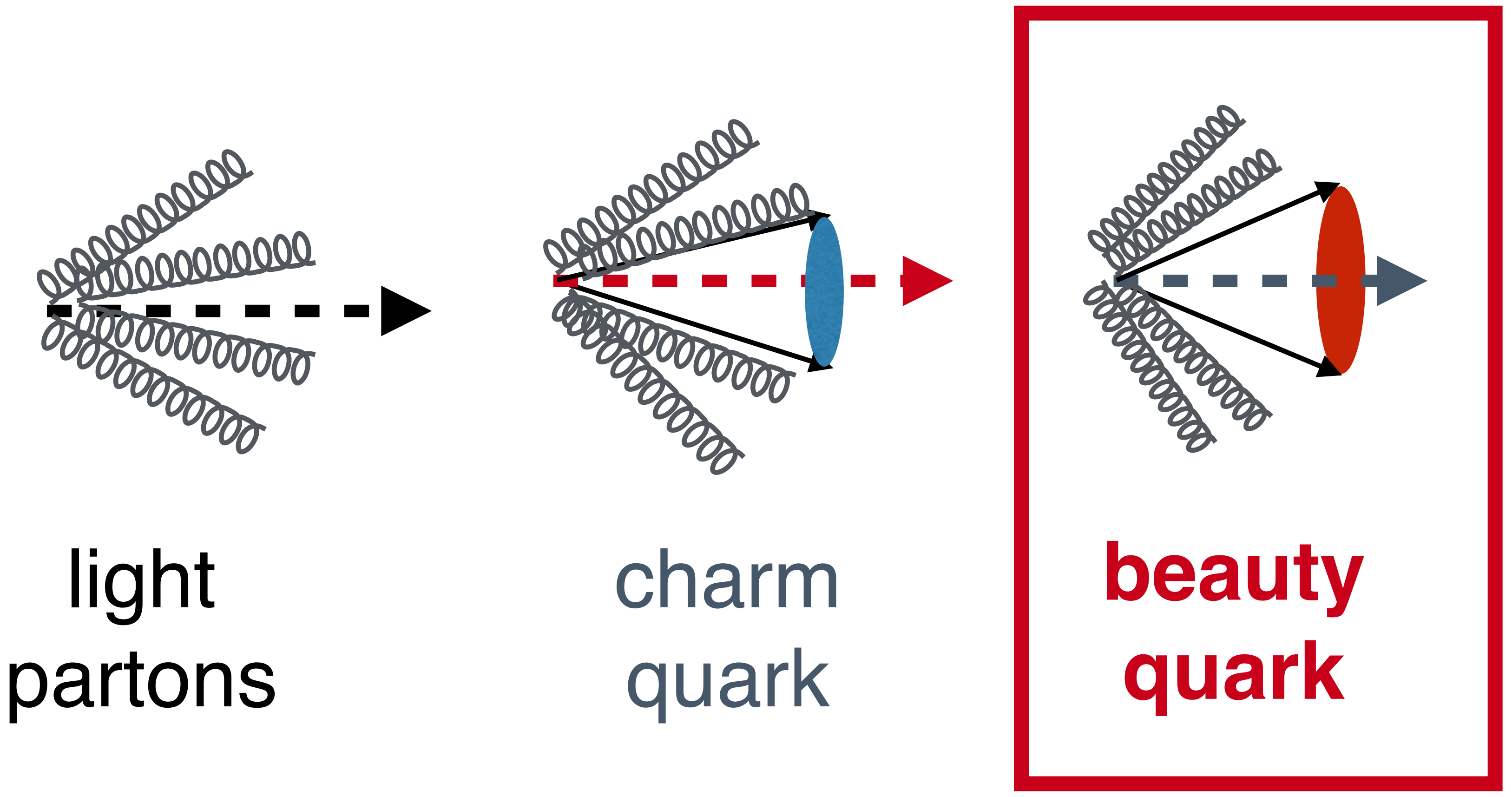


→ stronger constraints on the "perturbative" collinear radiation (where the dead-cone effect is largest)

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

First direct manifestation of the beauty dead cone

See Lida Kalipoliti's talk
CMS-PAS-HIN-24-005



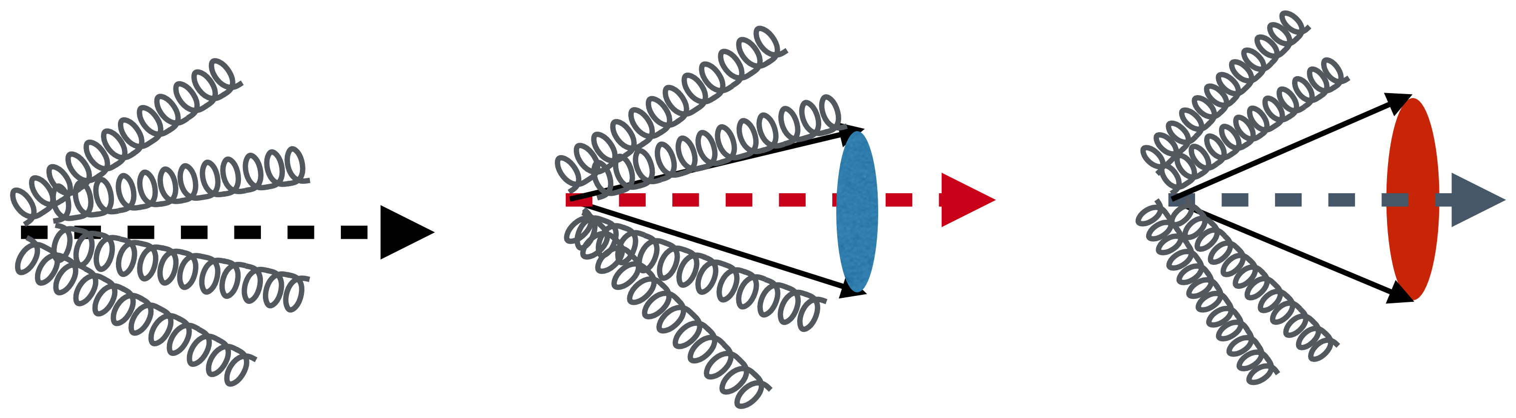
New experimental technique based on BDT

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

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

First direct manifestation of the beauty dead cone

See **Lida Kalipoliti's talk**
CMS-PAS-HIN-24-005

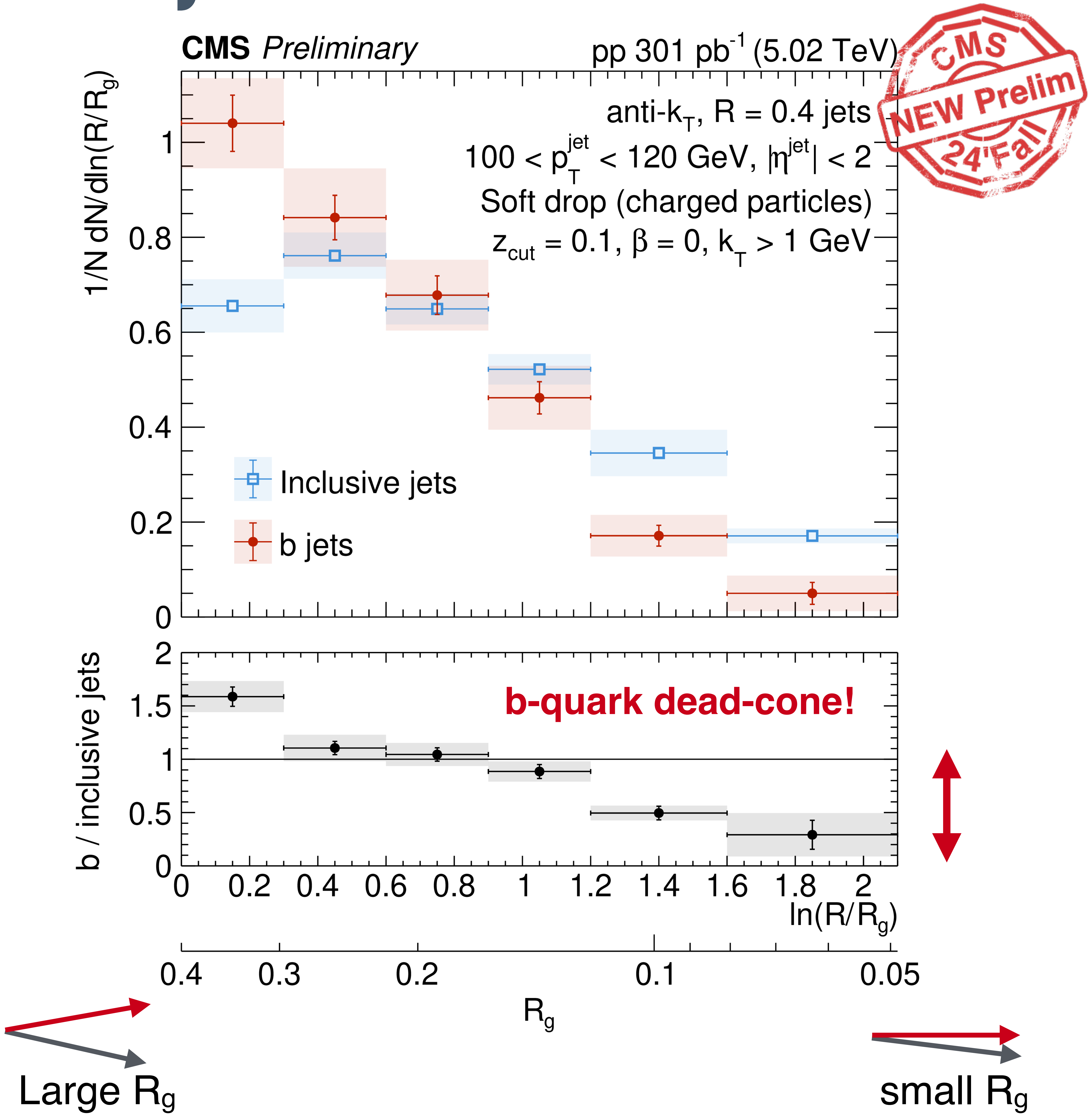


light partons | charm quark | **beauty quark**

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

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

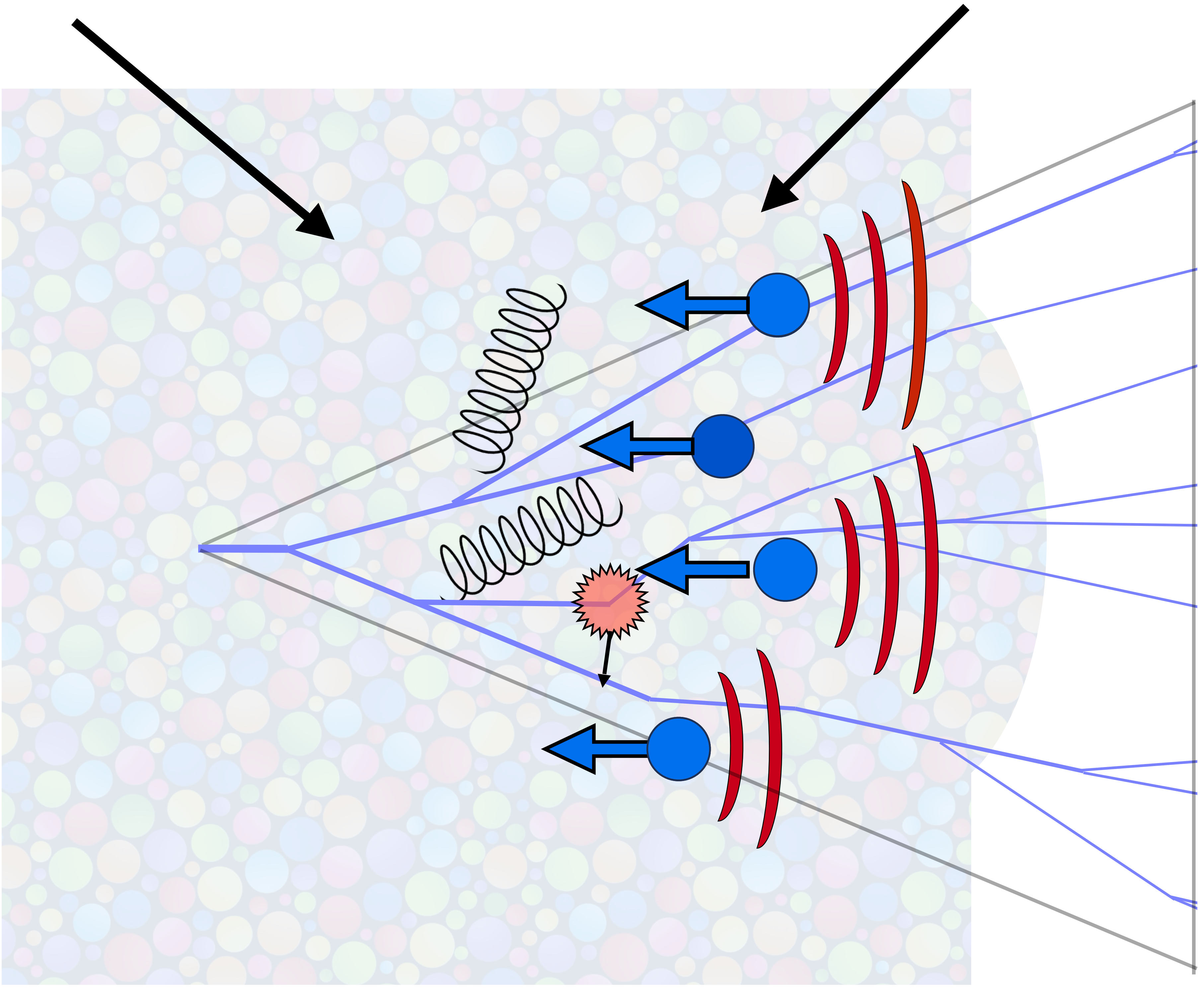


Phenomenology of jet-medium interaction

Jet-medium phenomenology: a schematic overview

Medium-induced jet modifications
e.g. medium-induced gluon radiation, elastic scatterings

Medium response
positive and negative wakes, medium recoils, QGP holes…

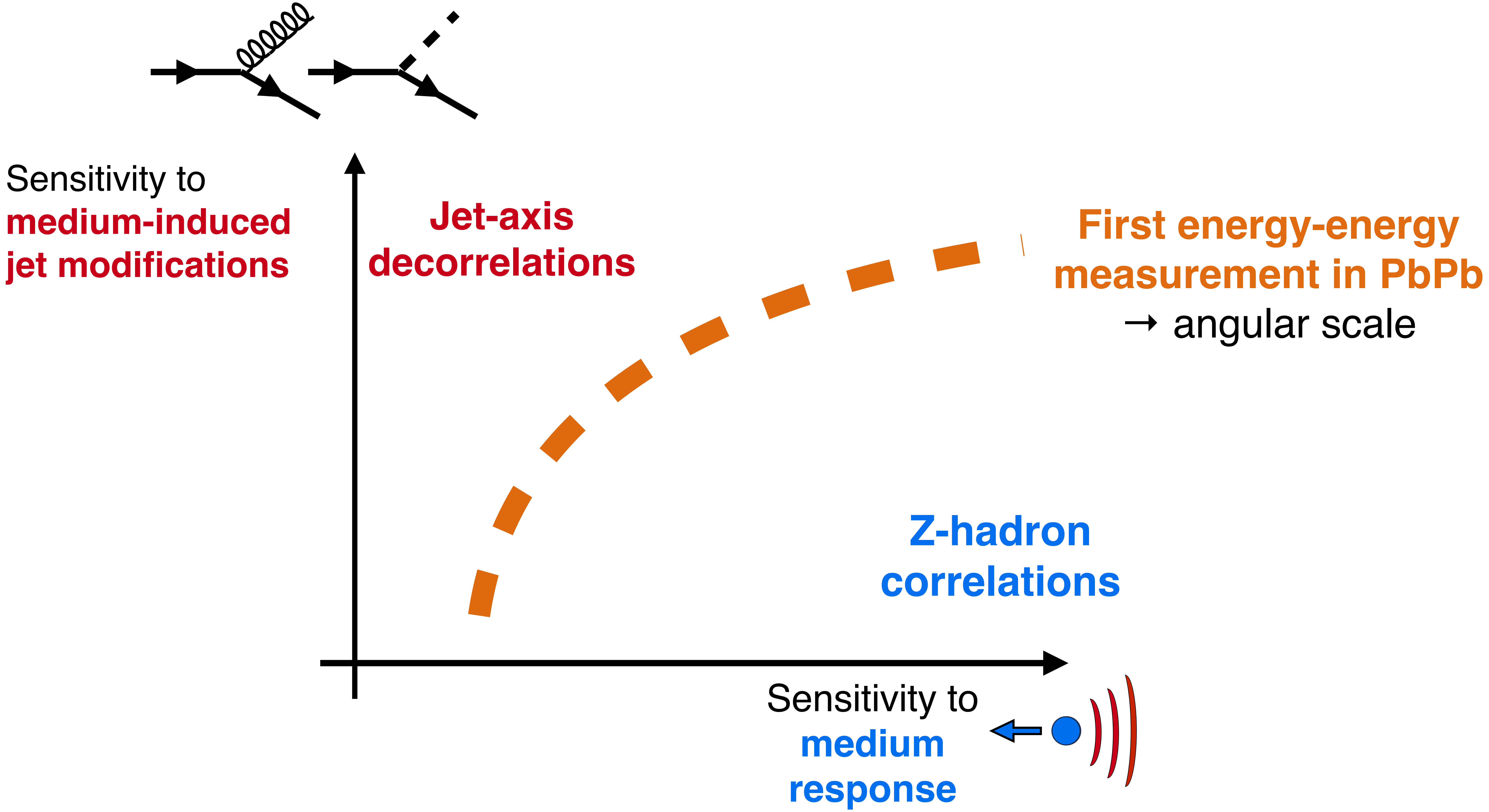


→ “entangled” in a **complex scale (space/time, ..) dependent evolution**

Two strategies:

- Option 1) **maximize the control of the underlying interaction mechanism** (e.g. medium response)
- Option 2) **maximize the control on the scale of the interaction**

New observables to constrain jet-medium interactions

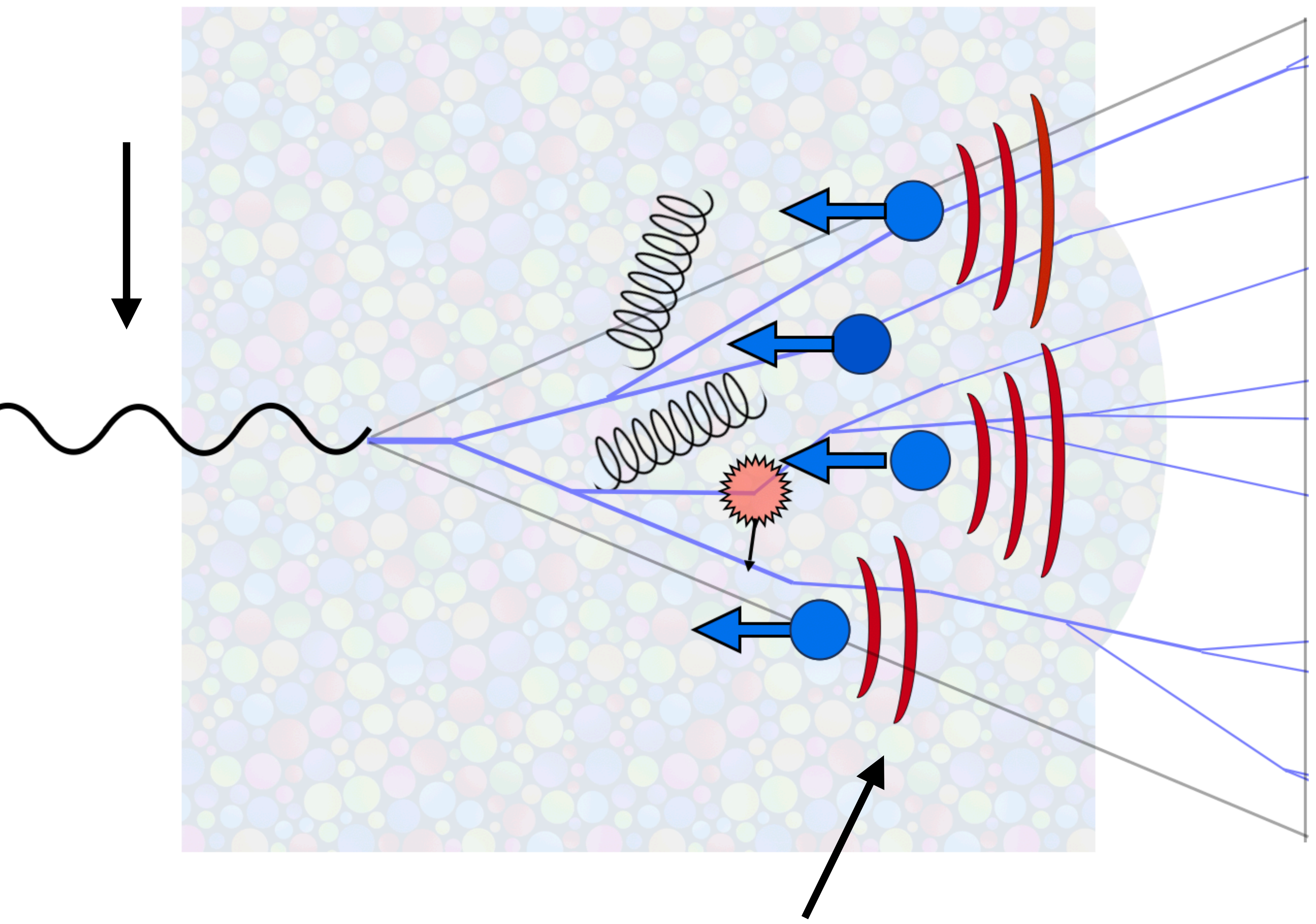


Photon-tagged jet axis decorrelation

See Molly Park's talk, 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

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

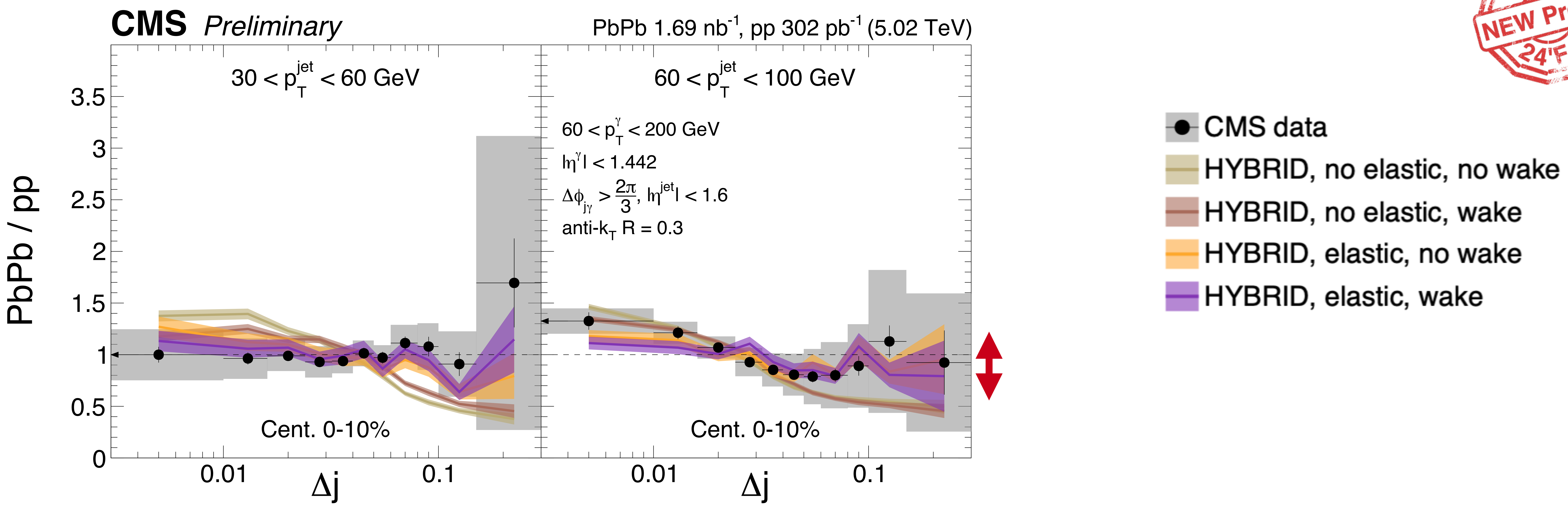
E-Scheme axis = direction of average energy flow in the jet
→ sensitive to soft radiation
WTA axis = direction of leading energy flow in jet
→ aligned with the hard-collinear core of the jet

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

See <u>Molly Park's talk</u>,
CMS-PAS-HIN-21-019



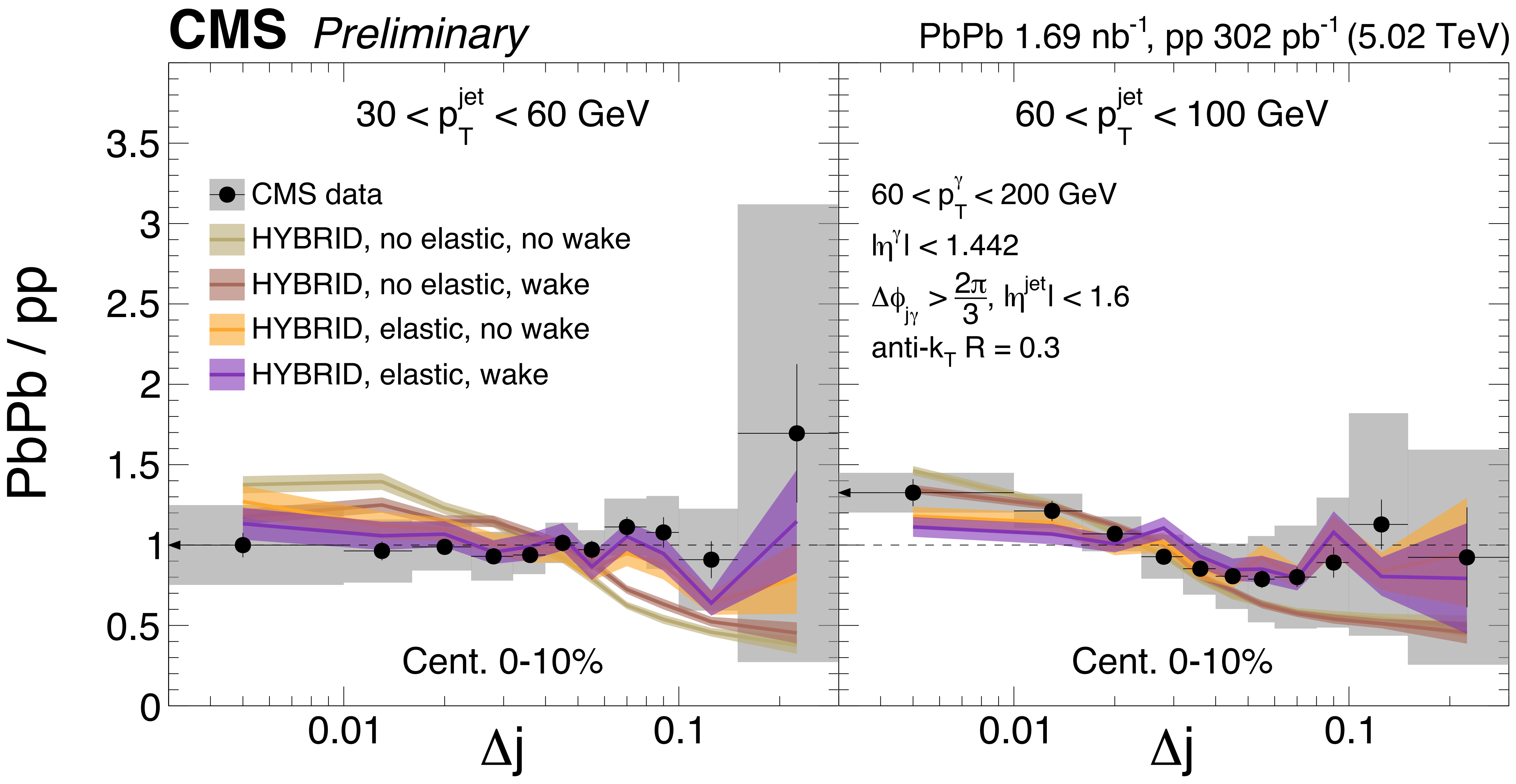
For low-p_T jet
→ similar Δj in PbPb and pp

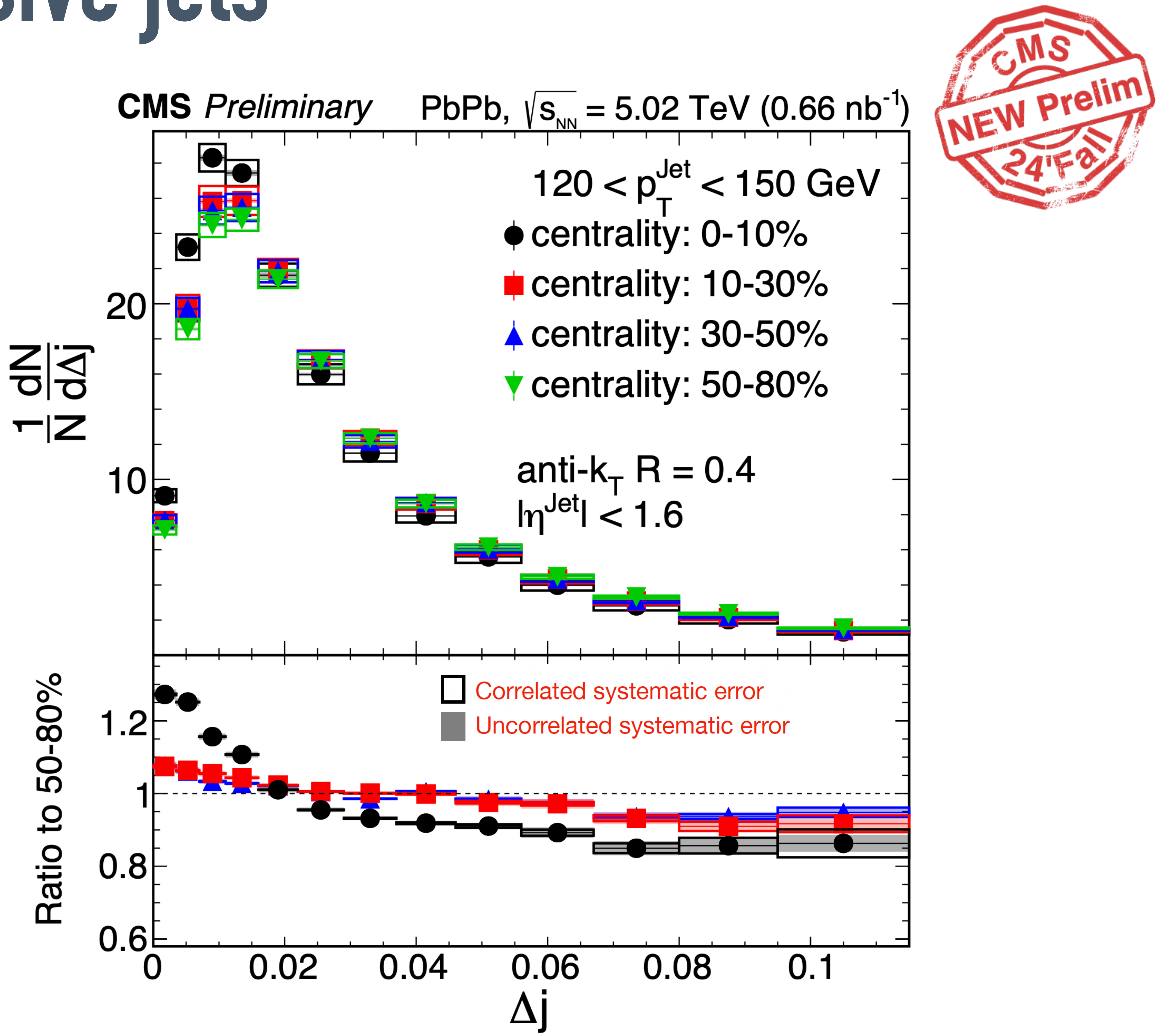
For high-p_T jet
→ suppression of large-Δj jets in PbPb

Unambiguous 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

See Raghunath Pradhan's talk
CMS-PAS-HIN-24-010





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

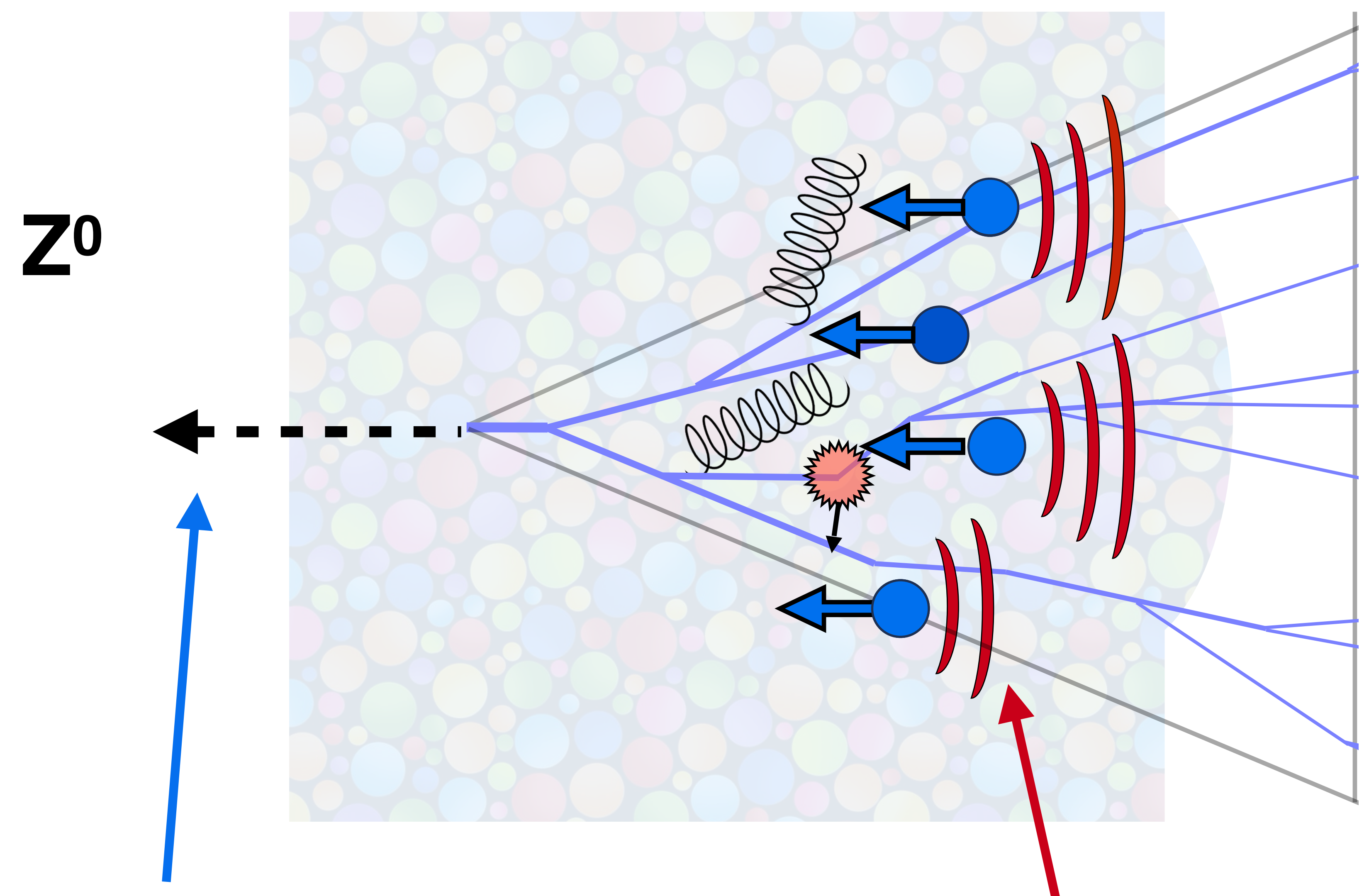
→ folding medium-induced jet medium modifications with bin-migration effects

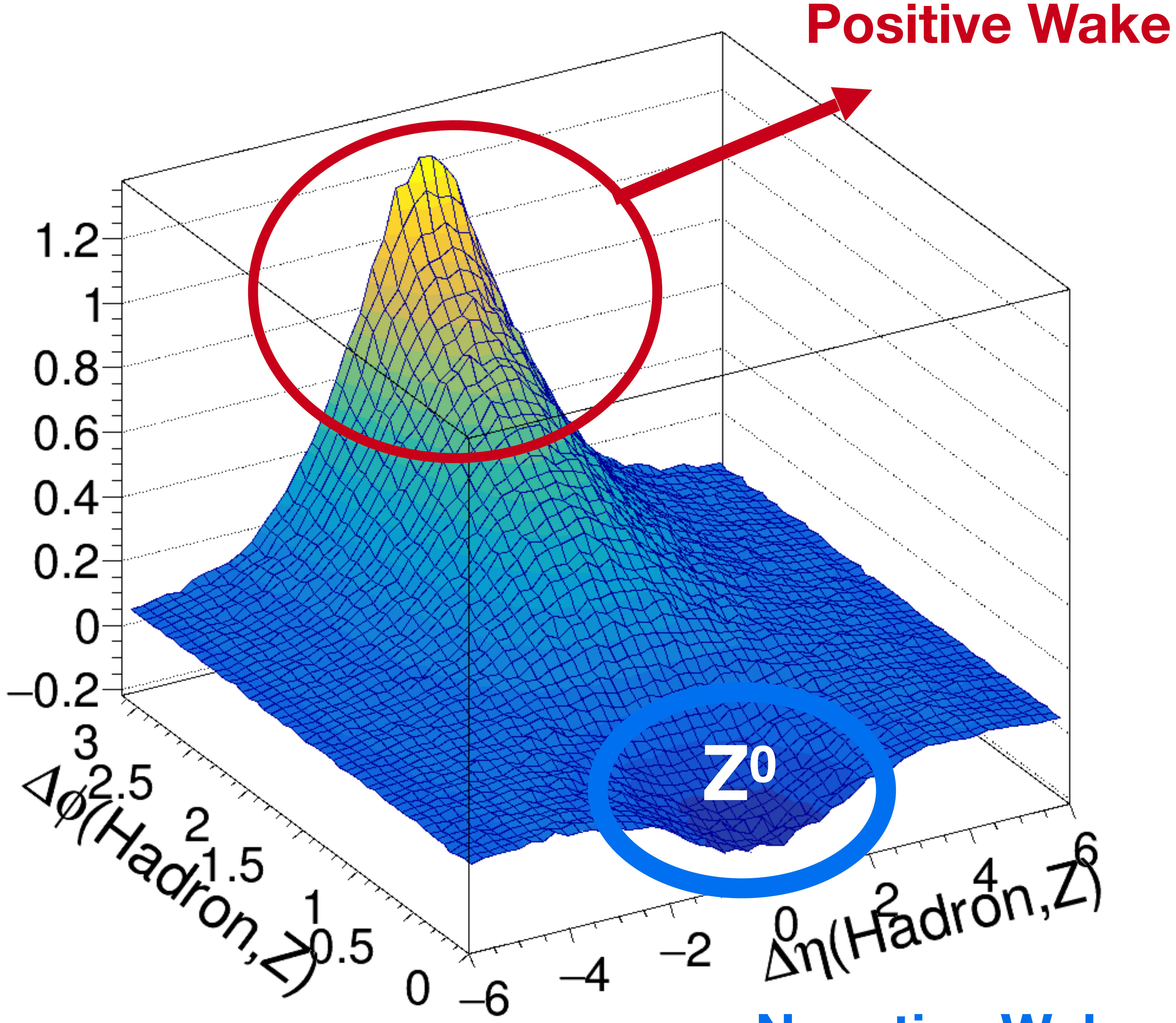
Z^0-hadron correlations in PbPb

See <u>Yen-Jie Lee's talk</u>
CMS-PAS-HIN-23-006

CMS NEW Prelim 24'Fall

→ "isolate" the effects of medium-response

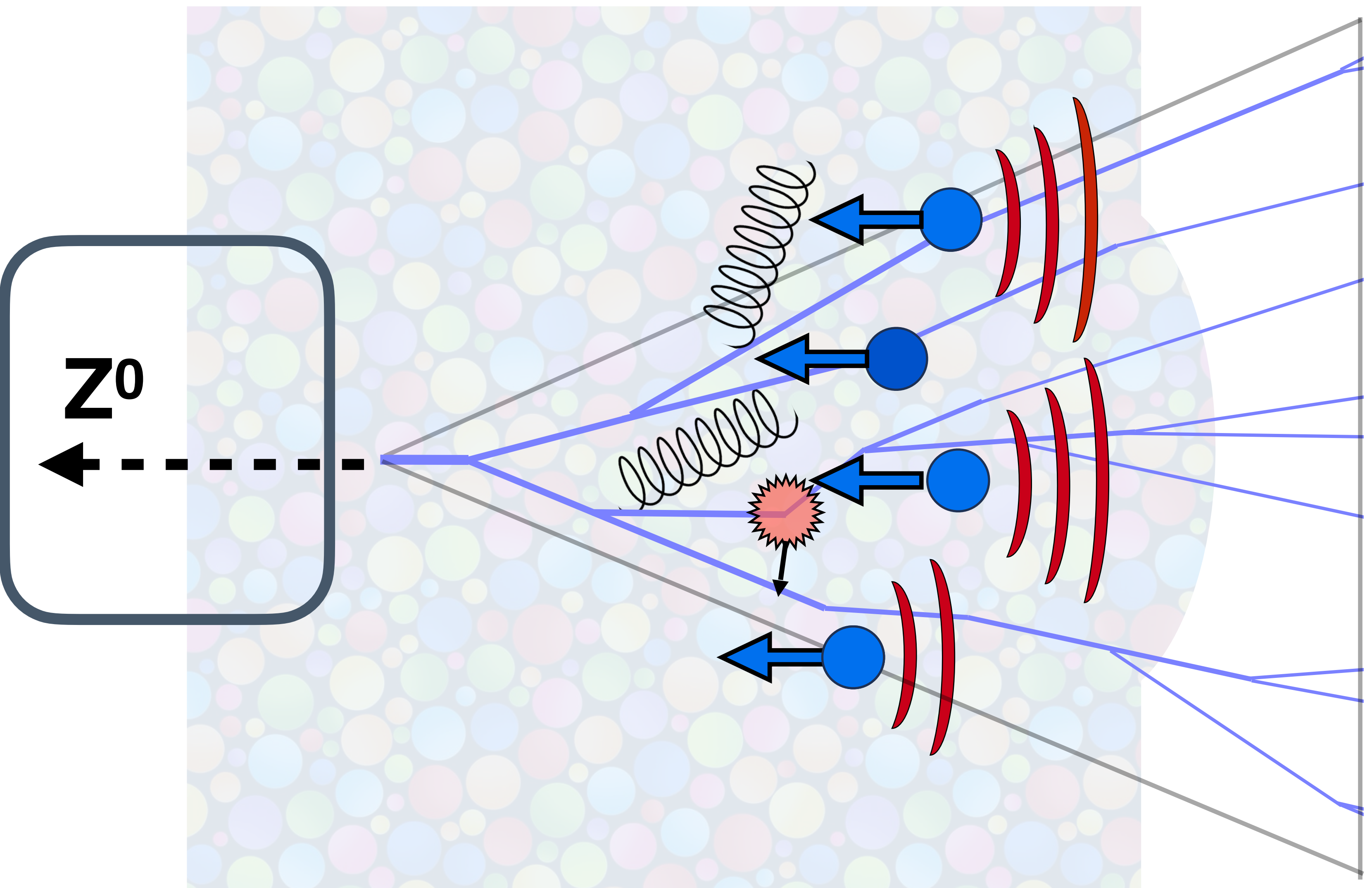


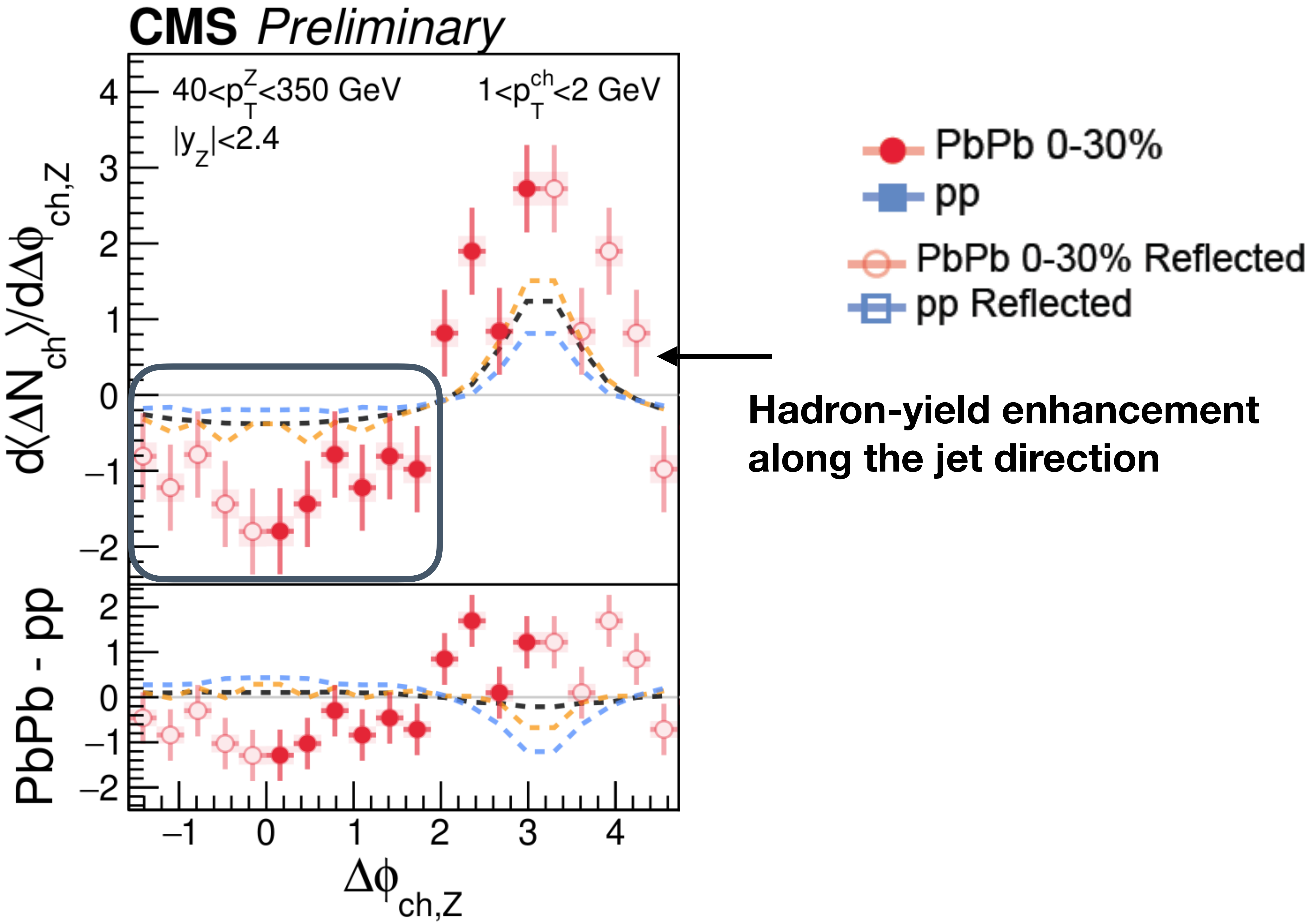


Z^0 provides an unquenched reference with high experimental accuracy
→ medium response effects without jet fragments

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

Medium response with Z^0–tagged hadrons in PbPb and pp





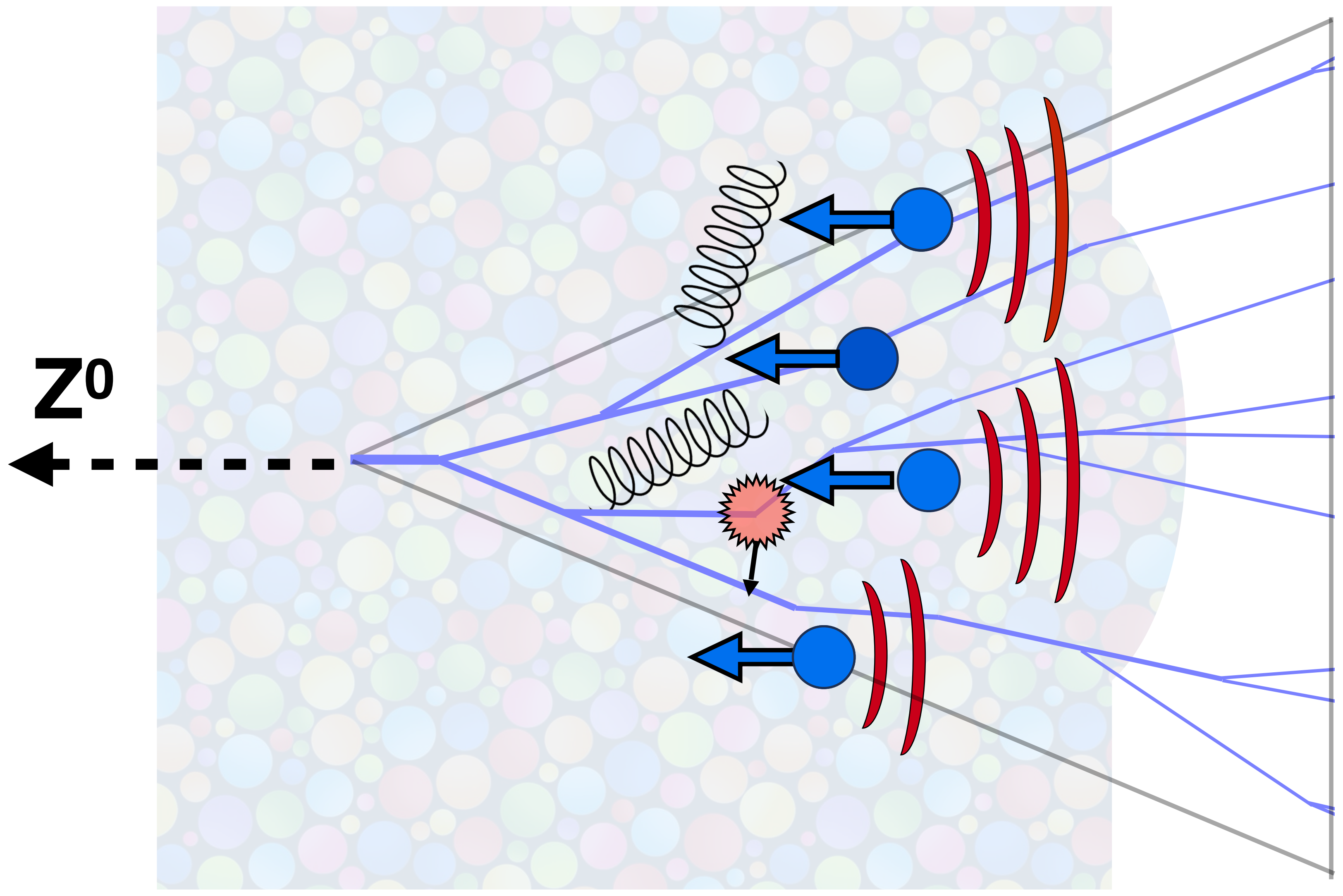
Hadron-yield enhancement along the jet direction

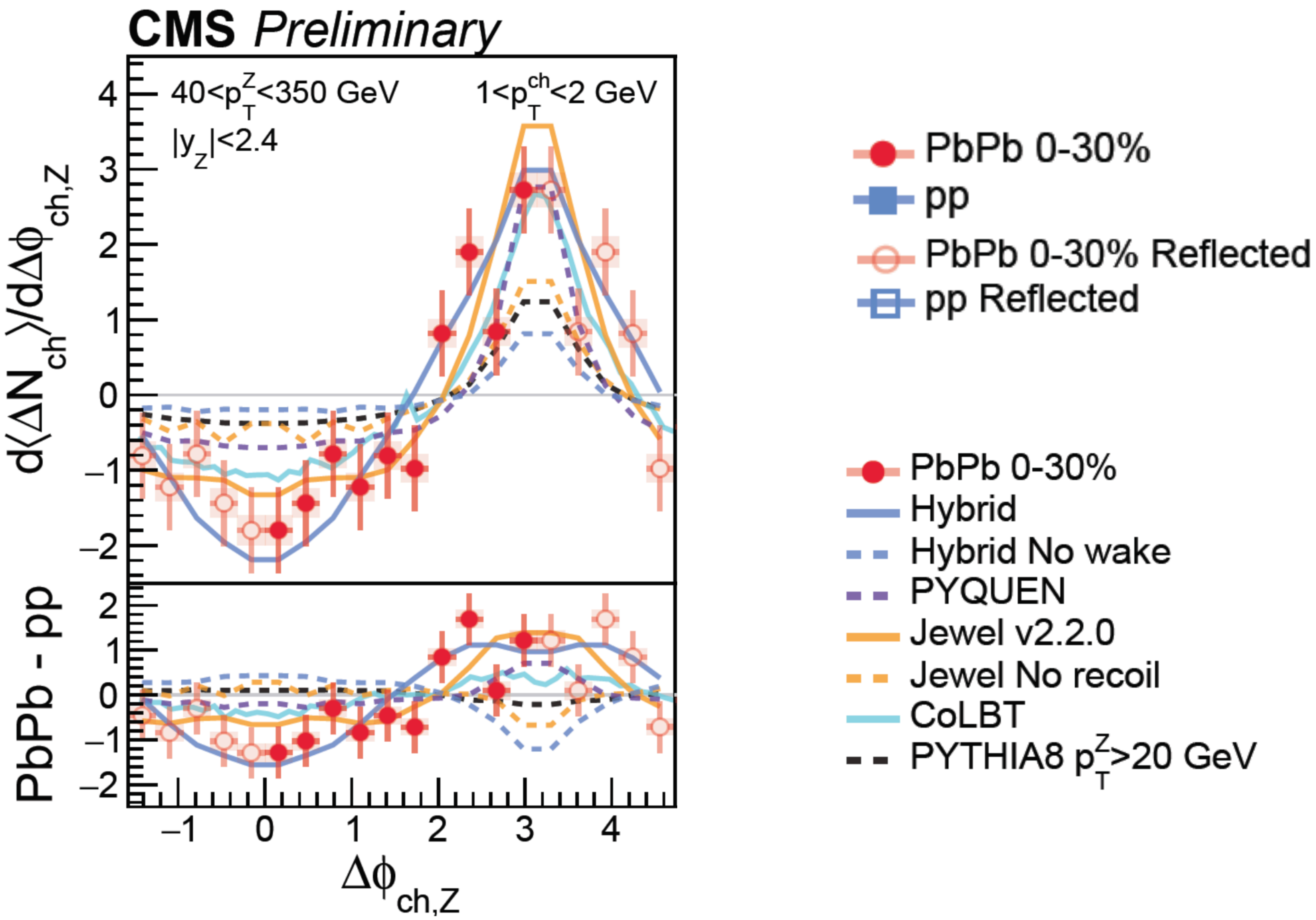
Clear depletion in PbPb on the Z side ($\Delta\phi$=0)

See Yen-Jie Lee's talk
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 and pp





See Yen-Jie Lee's talk
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 analogous study as a function of $\Delta y_{ch,Z}$)

Energy-energy correlators

→ scan the medium interaction at a fixed/tunable scale

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

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

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

Energy-energy correlators **in pp** collisions at 5.02 TeV

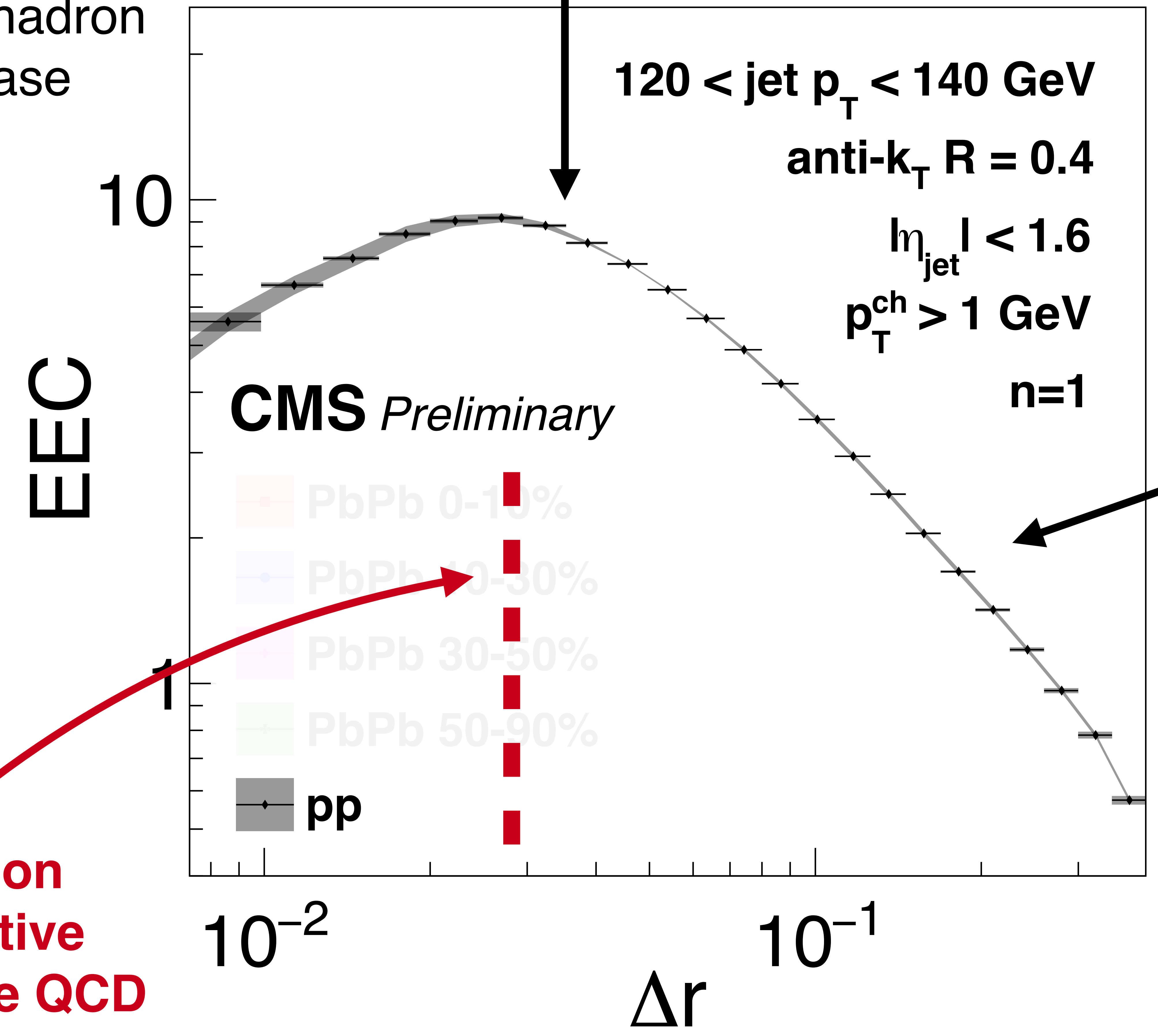
CMS NEW Prelim 24'Fall

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

See Jussi Viinikainen's talk, CMS-PAS-HIN-23-004

Intermediate Δr transition toward hadronic phase

Small Δr free hadron phase



Large angular scale Δr perturbative parton shower

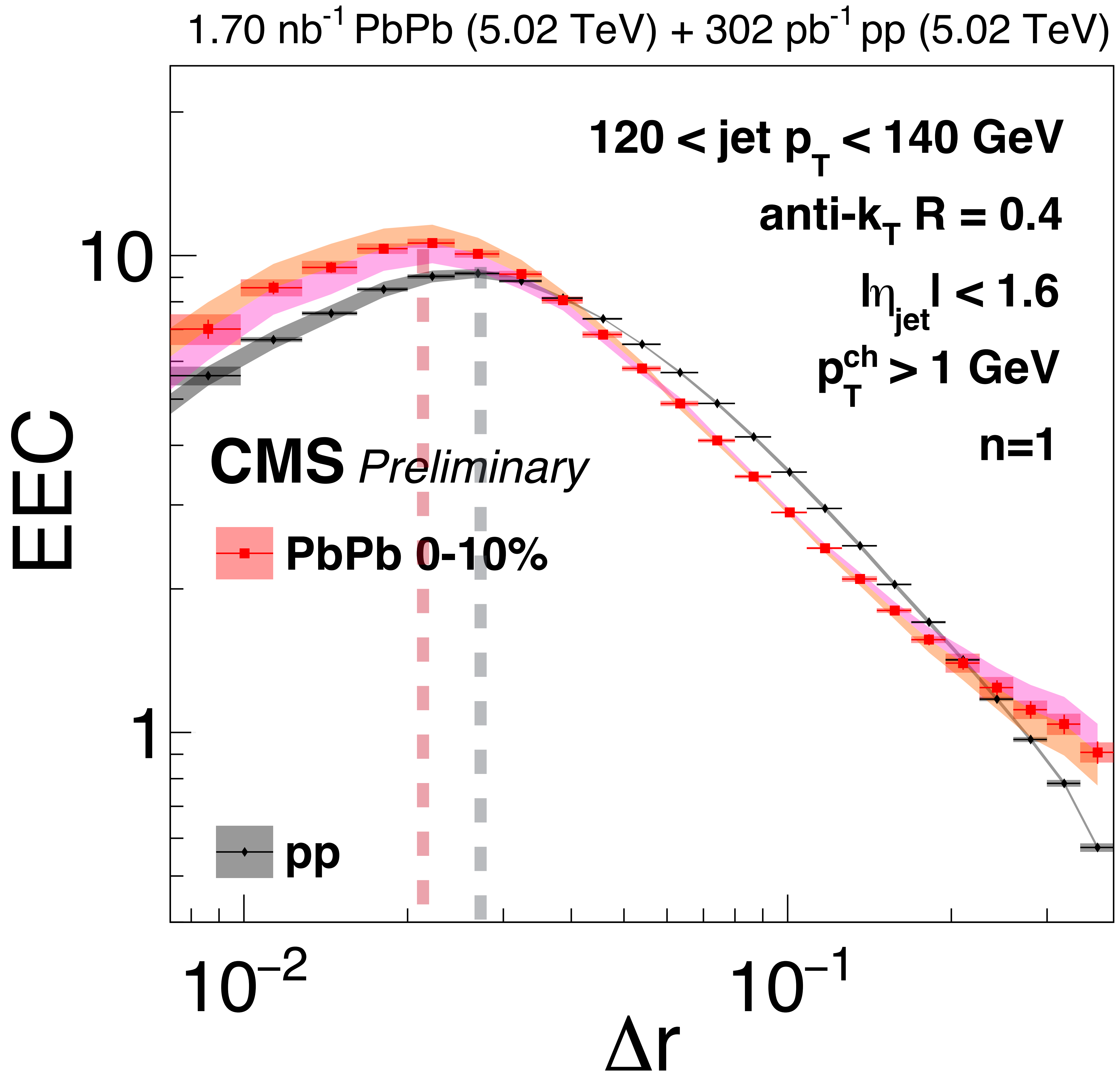
traceable transition between perturbative and non-perturbative QCD

See Jussi Viinikainen's talk, CMS-PAS-HIN-23-004

First EEC measurement in PbPb collisions at 5.02 TeV

CMS NEW Prelim 24'Fall

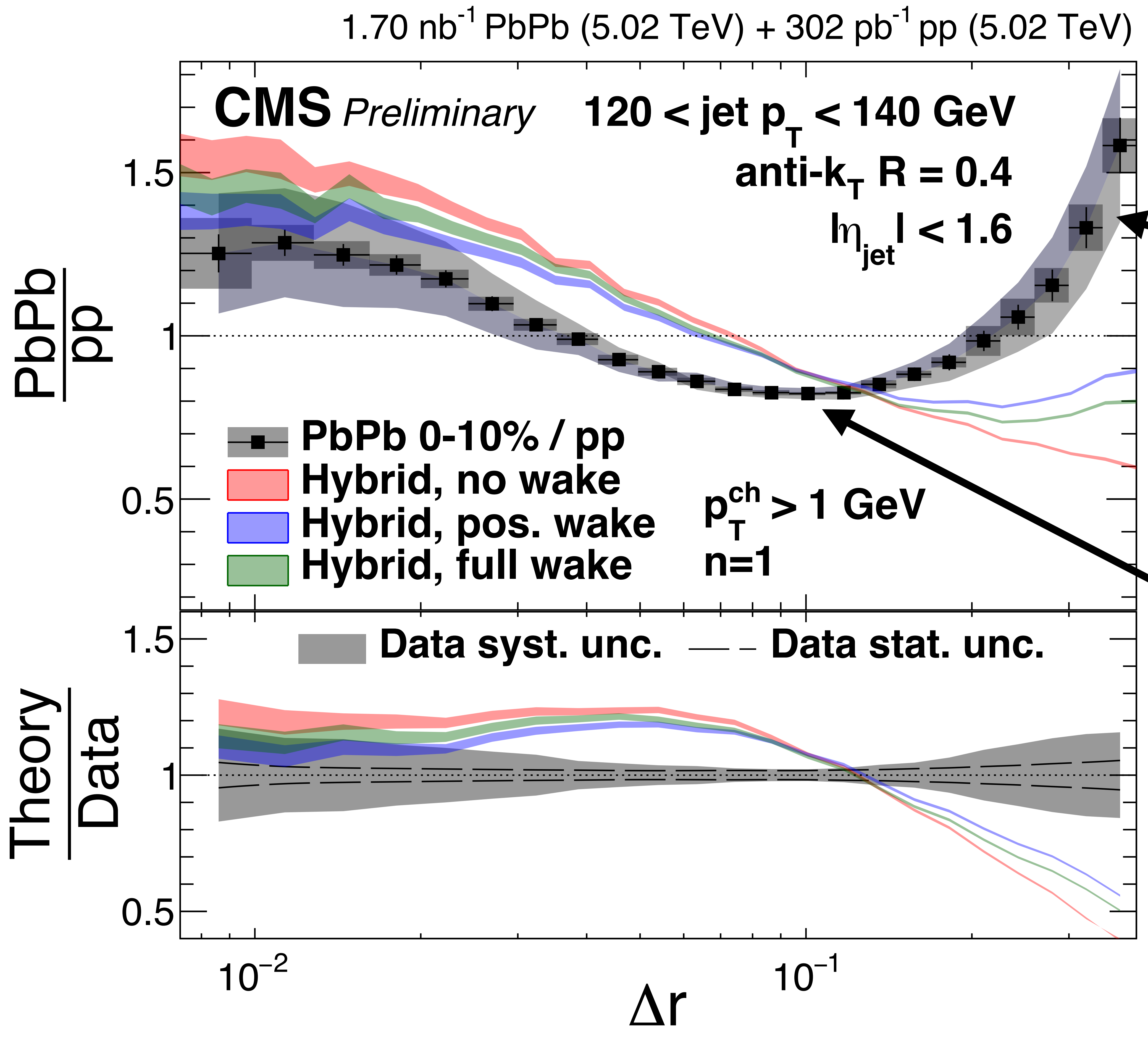
→**EEC measurements are feasible with high accuracy in PbPb collisions!**
→**PbPb results present qualitatively the same structure as in pp collisions**



See Jussi Viinikainen's talk,
CMS-PAS-HIN-23-004

EEC PbPb/pp ratio at 5.02 TeV

See Jussi Viinikainen's talk,
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 experimental constraints on nuclear matter down to small x:

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

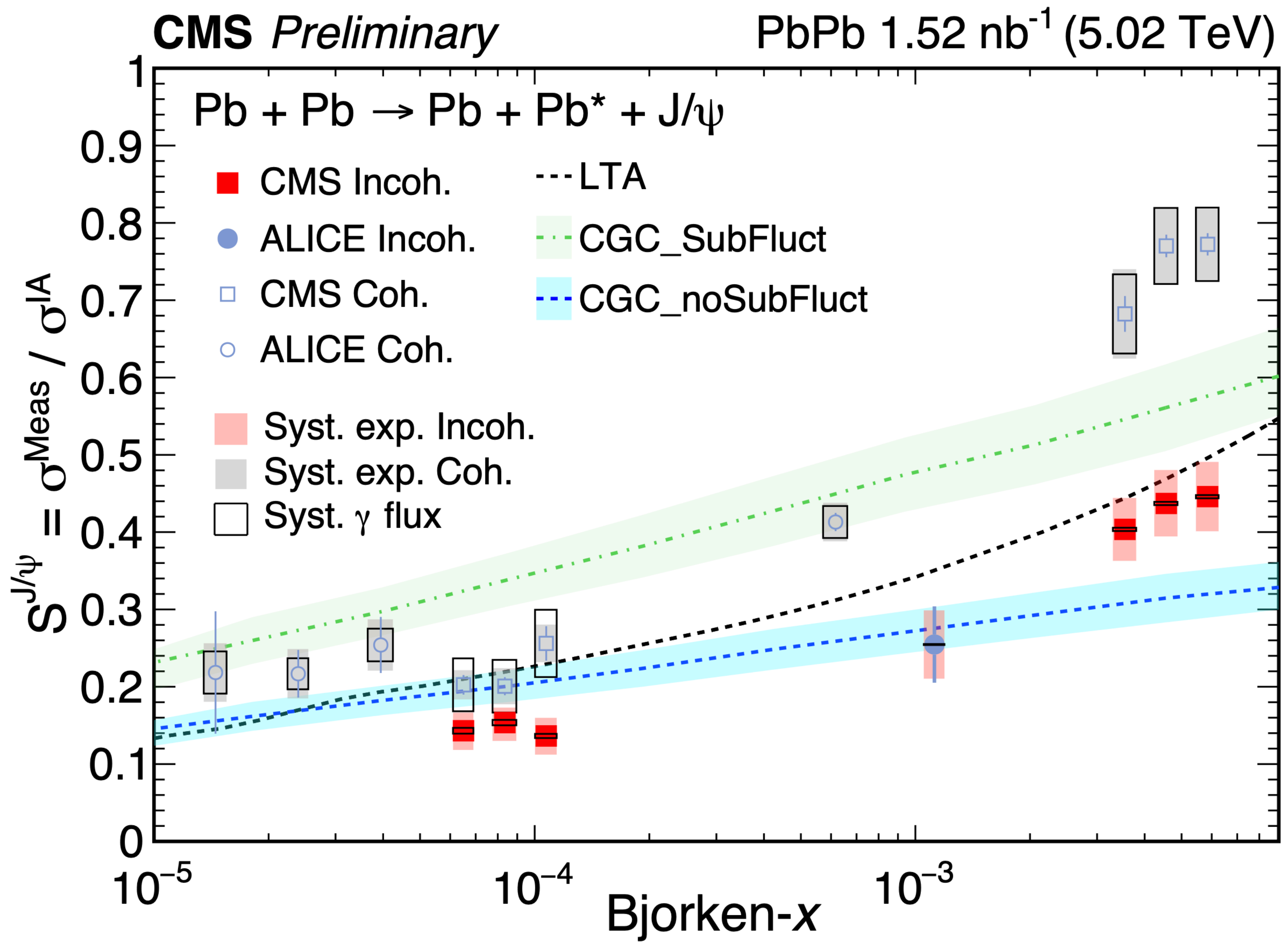
→ **first energy-dependent characterization of global and local gluon properties at small x**

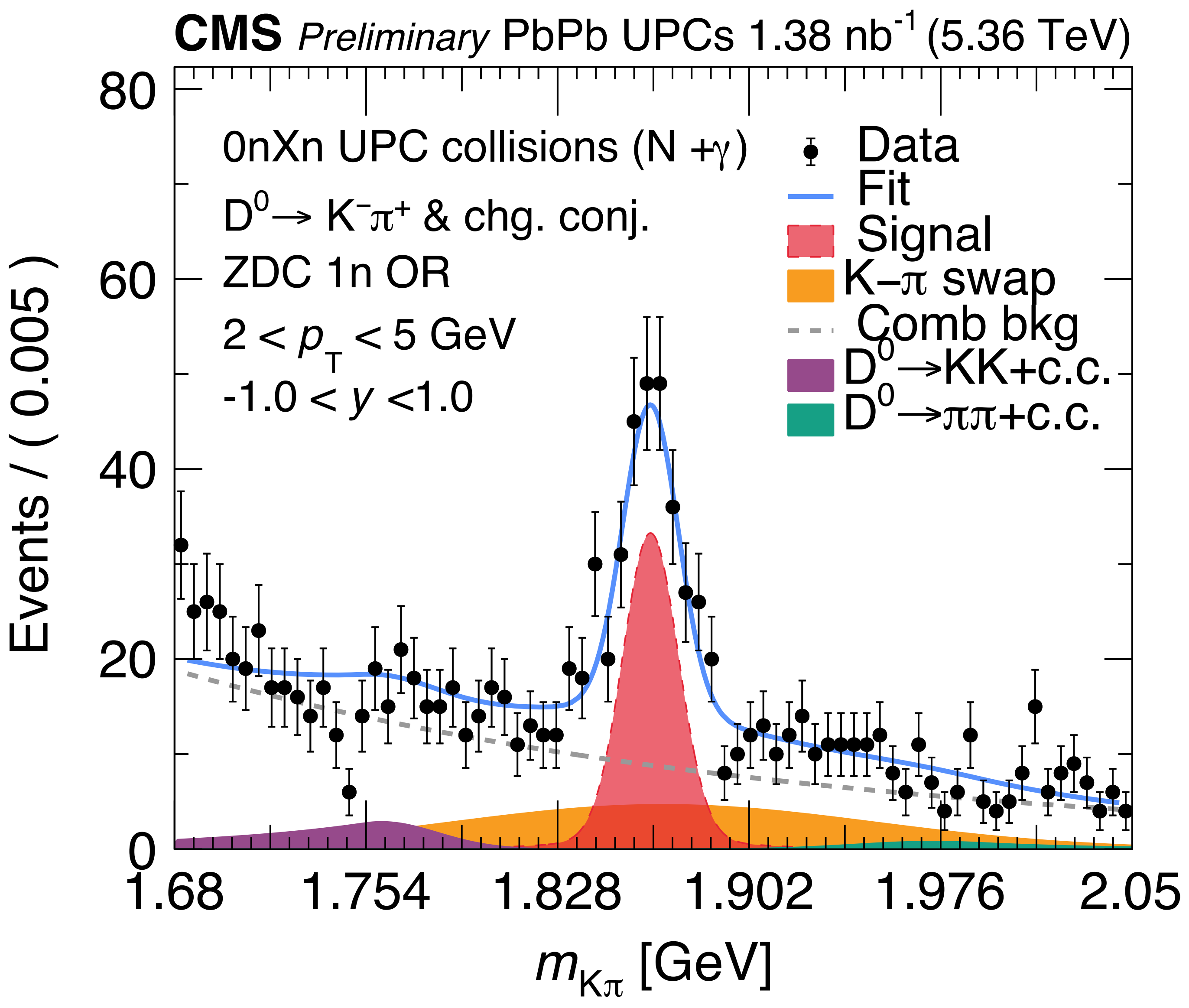
→ high-accuracy constraints at fixed Q^2 on the possible emergence of gluon saturation

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

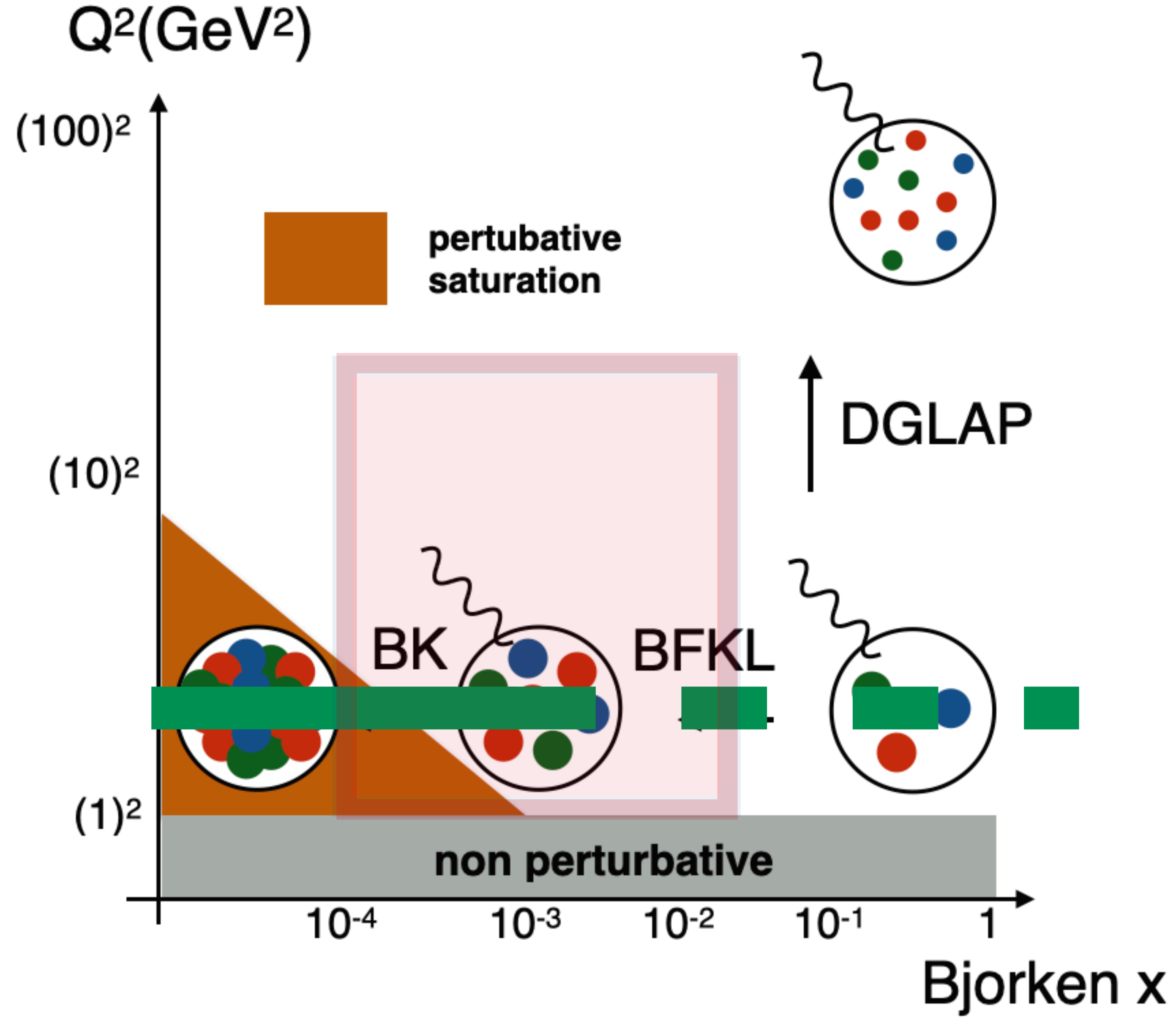
→ **First constraints on nPDFs <u>over a wide region of Q^2</u> at small-x in the absence of sizable final state effects**

→ likely the best and "simplest" observable for the transition toward saturation



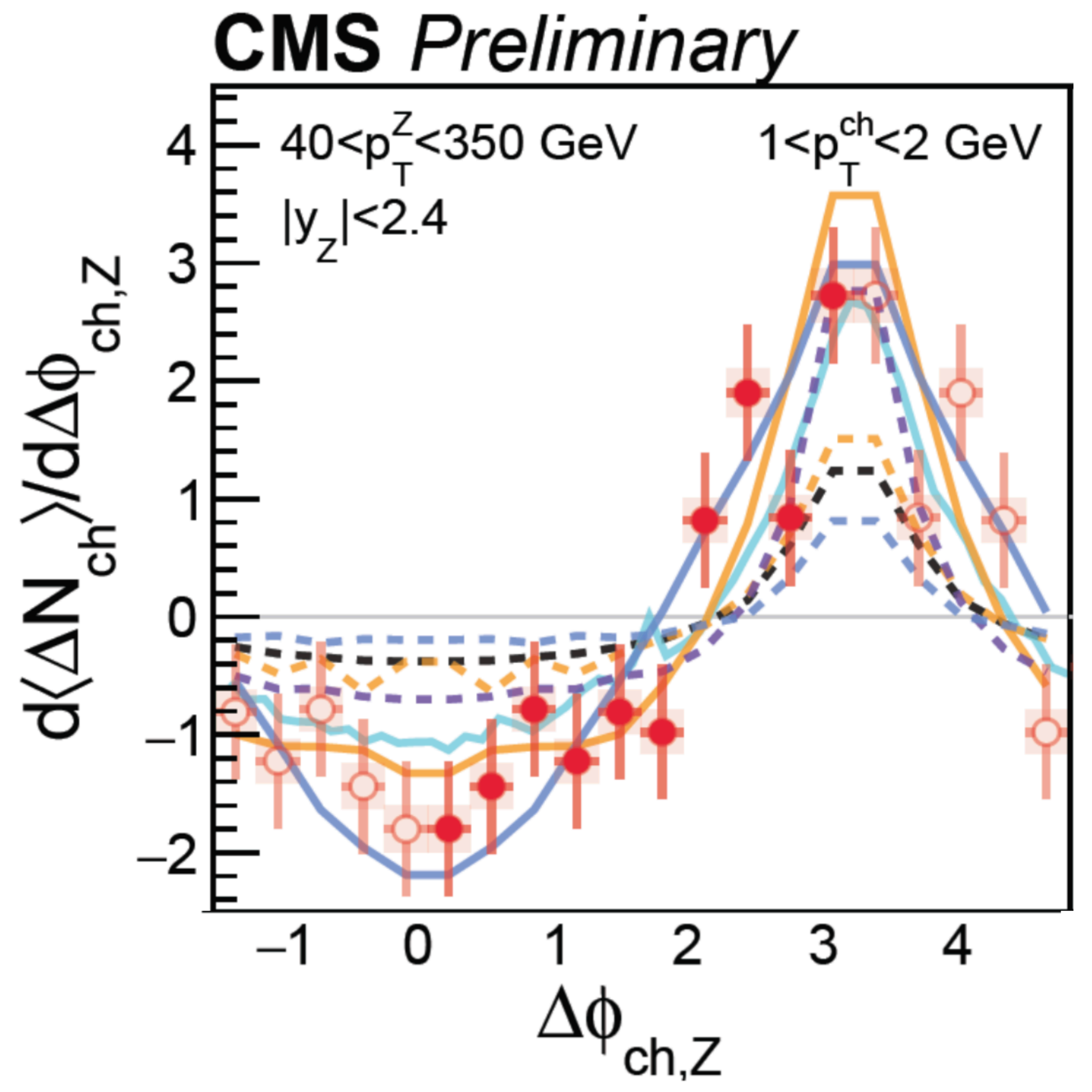


CMS RUN 3 PbPb DATA

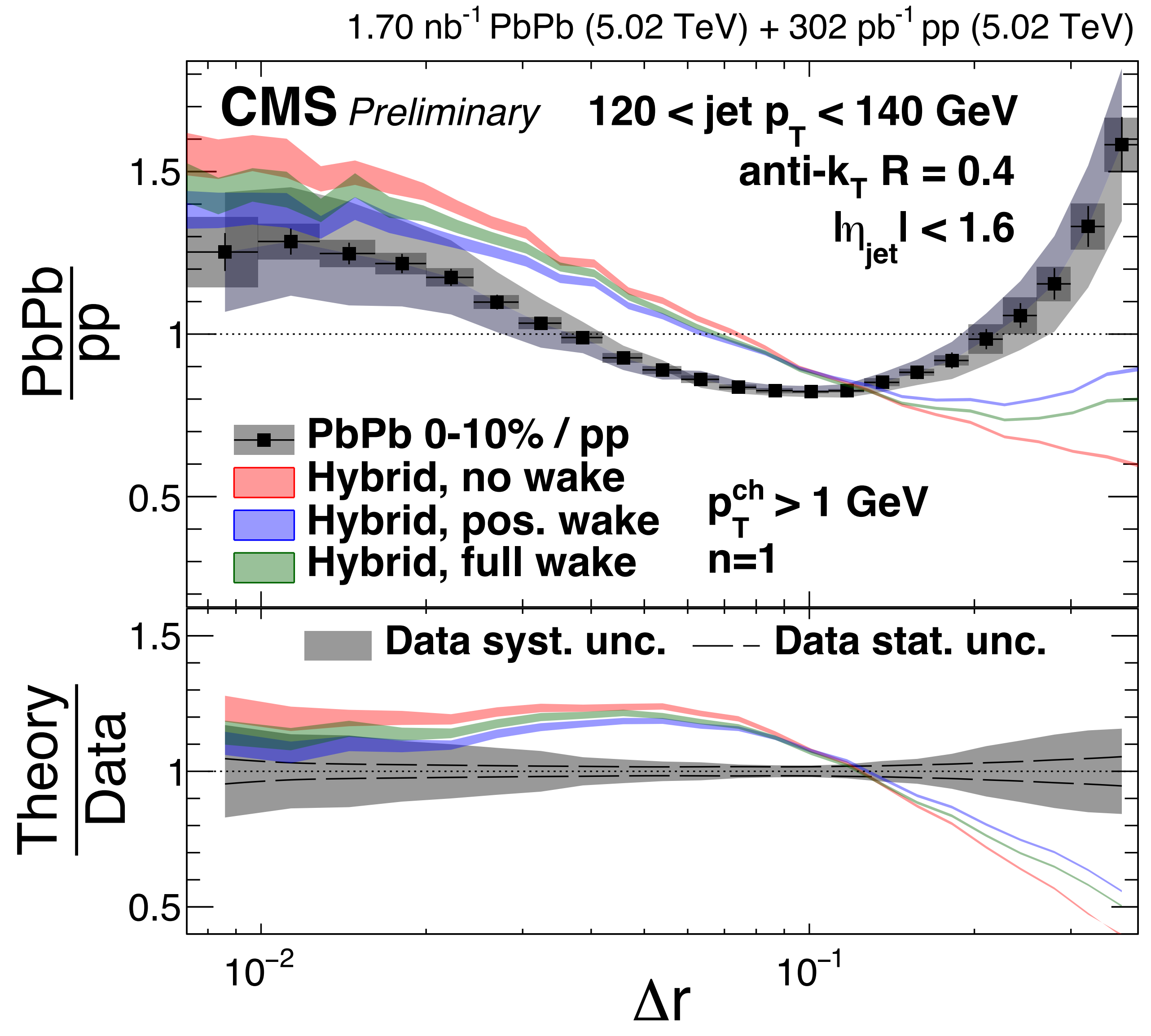


Conclusion and outlook

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 beauty quarks in vacuum**
→ open the way for the first "microscopic" observation of flavor-dependence of in-medium E_{loss} in PbPb collisions



Fundamental 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



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 beauty quarks in vacuum**
→ open the way for the first "microscopic" observation of flavor-dependence of in-medium E_{loss} in PbPb collisions

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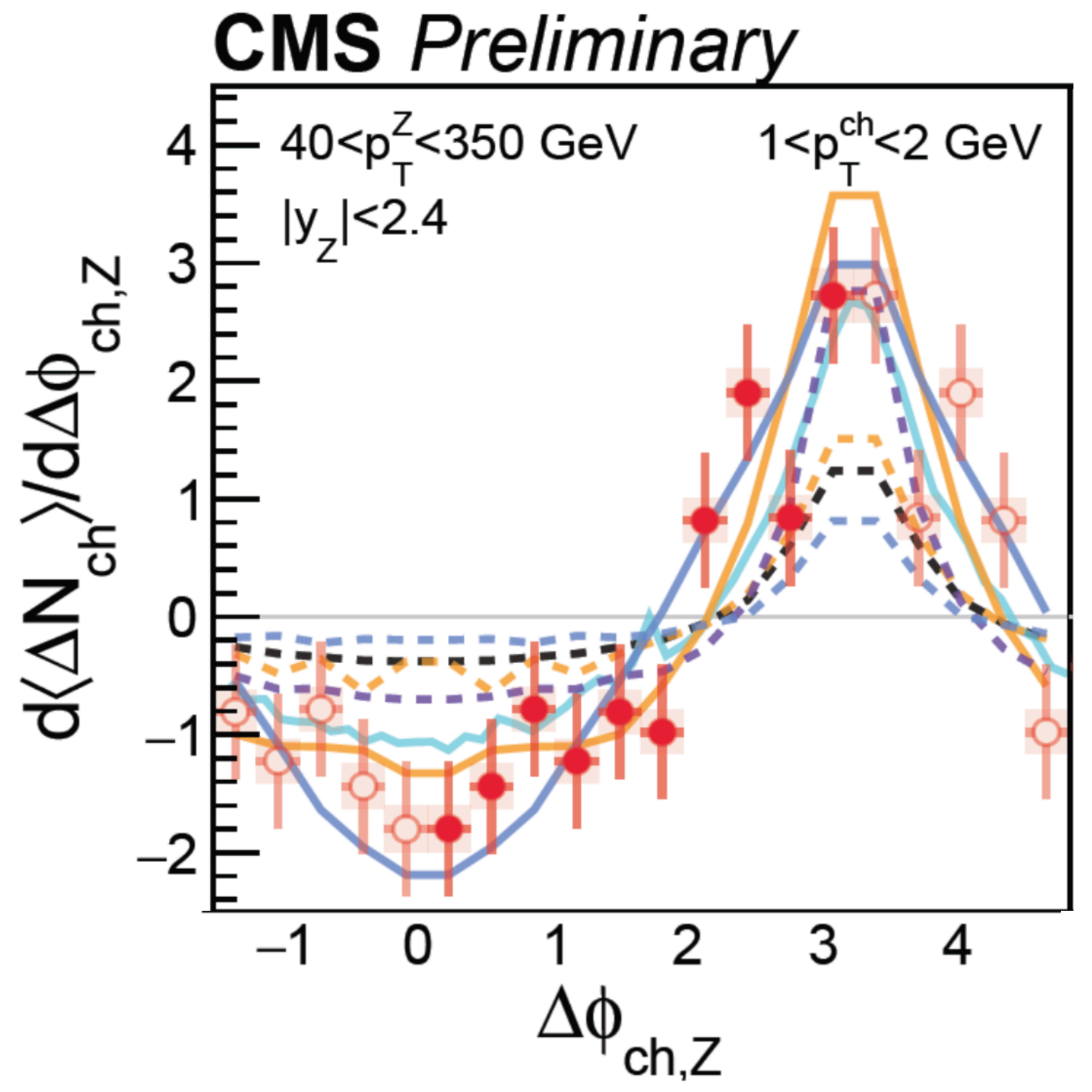
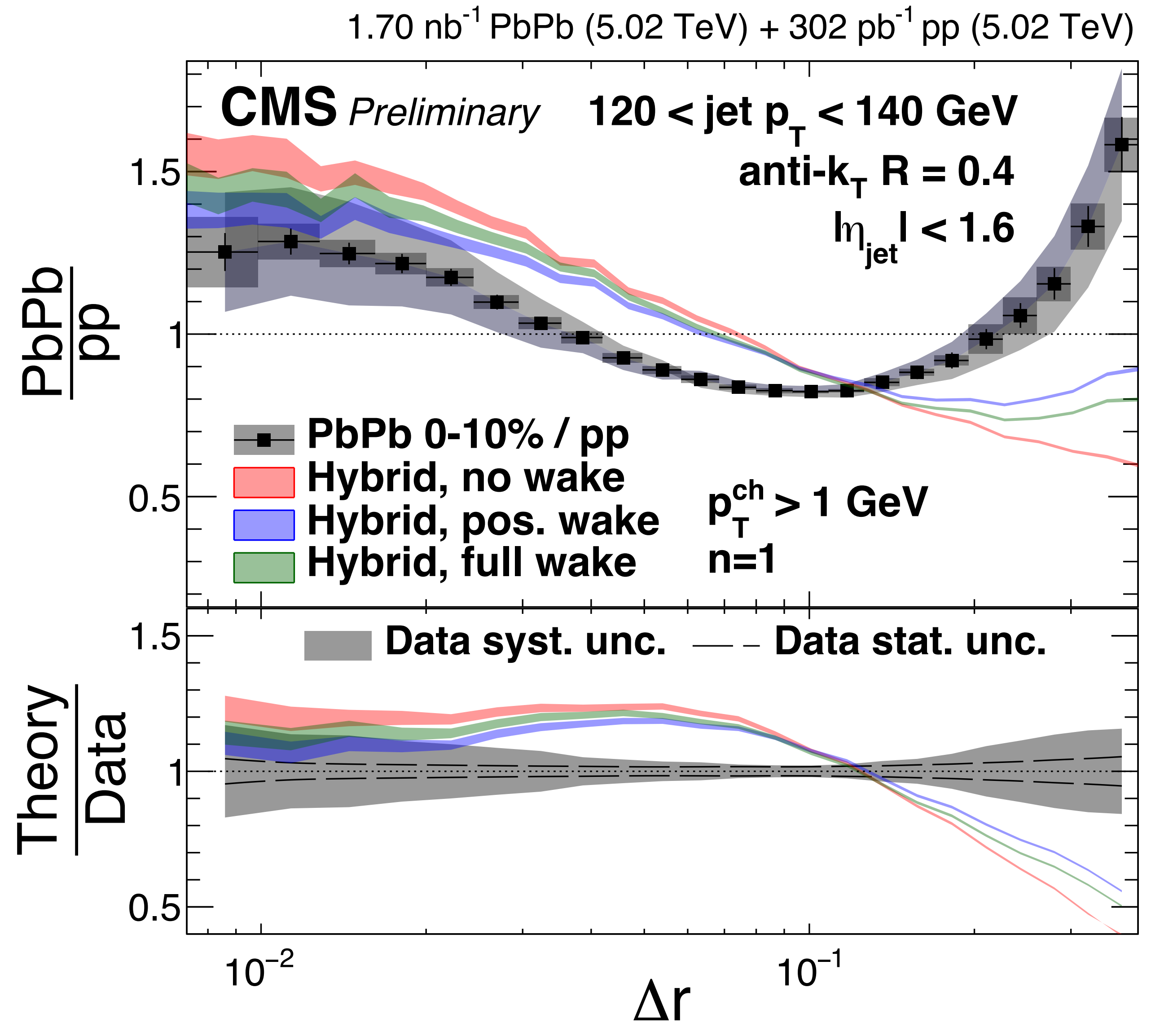


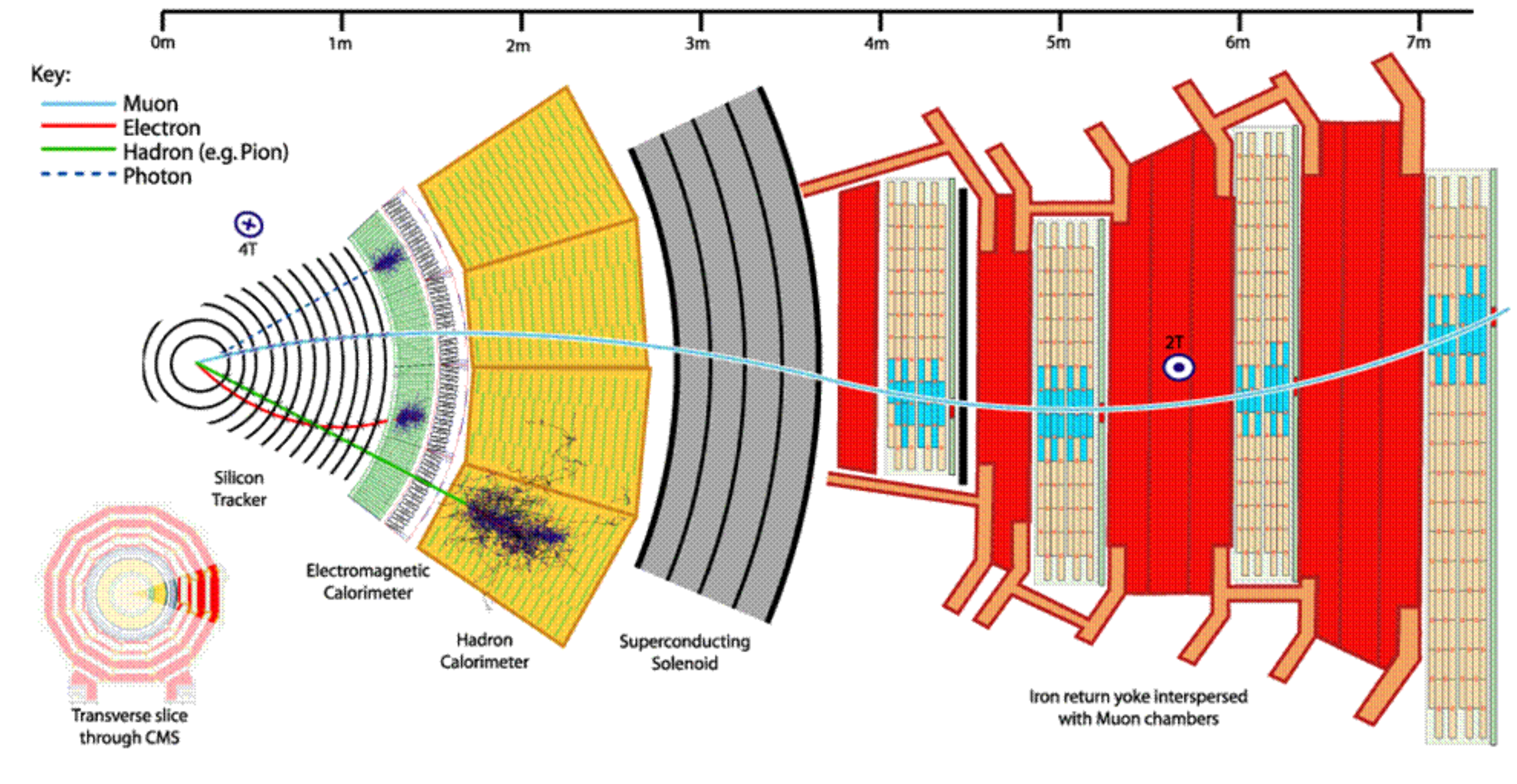


Thank you for your attention!

Meet CMS speakers »

BACKUP

CMS as a broad-spectrum high-density QCD experiment

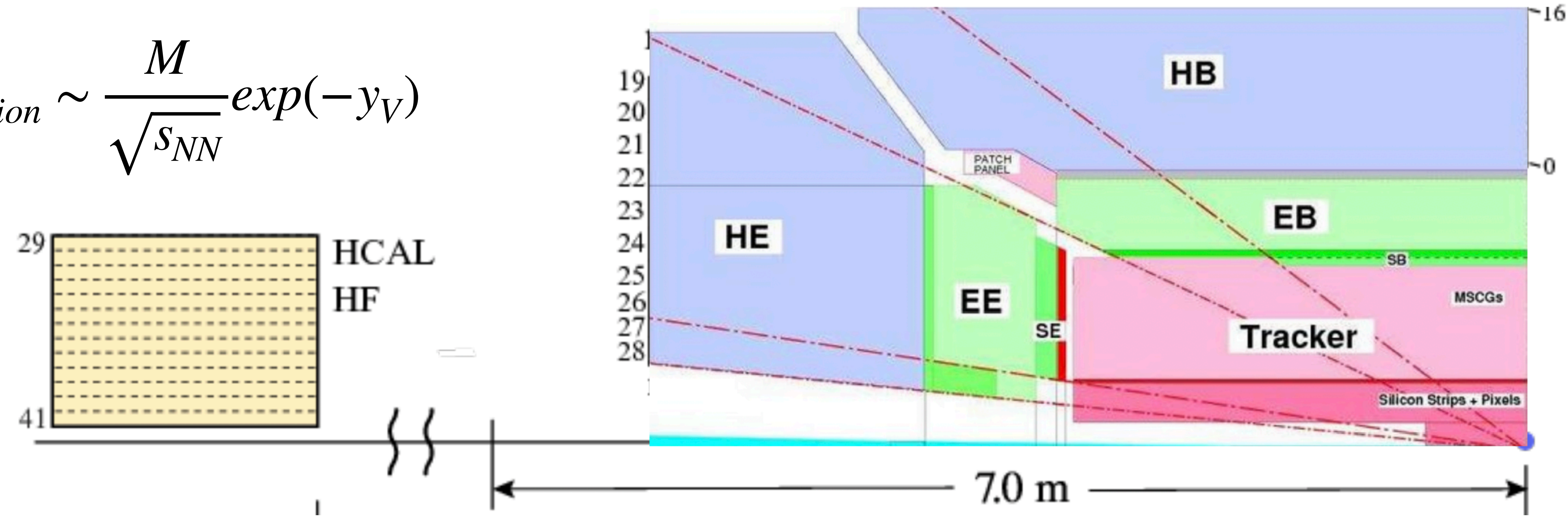


<u>Large-coverage high-rate</u> detector for hadronic and EM probes
- charged hadrons
- jets, heavy-flavour hadrons
- isolated photons, Z/W bosons

Wide pseudorapidity coverage, from high to low p_T:
- Charged tracks in $|\eta_{tracks}| \leq 3$
- Calorimetry (ECAL/HCAL) in $|\eta_{cal}| \leq 5.2$
- Muon detectors in $|\eta_{muon}| \leq 3.0$
- ZDC + PPS detectors

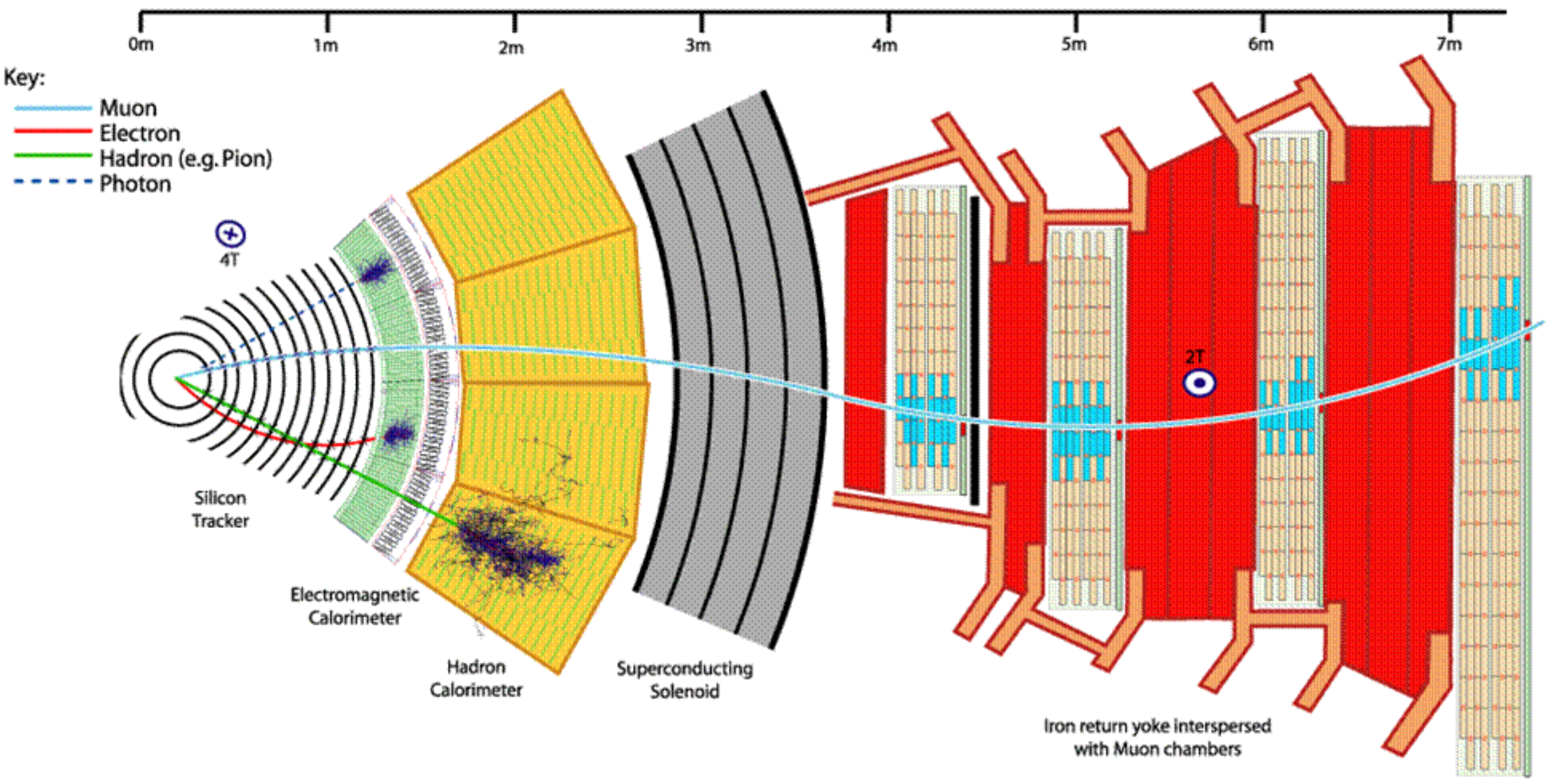
→ With even stronger capabilities after HL-LHC upgrades

$$x_{ion} \sim \frac{M}{\sqrt{s_{NN}}} exp(-y_V)$$



Hard probes for high-density QCD with CMS

→ **Multi-scale characterization of the properties of QCD matter at high temperatures and high partonic density**



Jets, heavy-flavor and exotic hadrons, Z/W over a wide p_T and η range:

→ partonic properties of the hot QCD medium
→ in-vacuum and in-medium parton propagation
→ mechanics of hadron formation
→ parton dynamics in cold nuclear matter

→ **selected CMS results from Run 2**

→ **first results with the Run 3 PbPb dataset collected in '23**

→ **Future heavy-ion measurements with the upgraded CMS for Run 4**

Run 2	Long Shutdown 2	Run 3	LS 3	Run 4	LS 4
PbPb (2.2 nb^{-1}) **pPb (0.18 pb^{-1})**		**PbPb '23 (1.7 nb^{-1})** Total PbPb (6 nb^{-1}) pO (nb), OO (nb)	CMS Phase-2 upgrades	Expected PbPb (7 nb^{-1}) pPb (0.5 pb^{-1})	

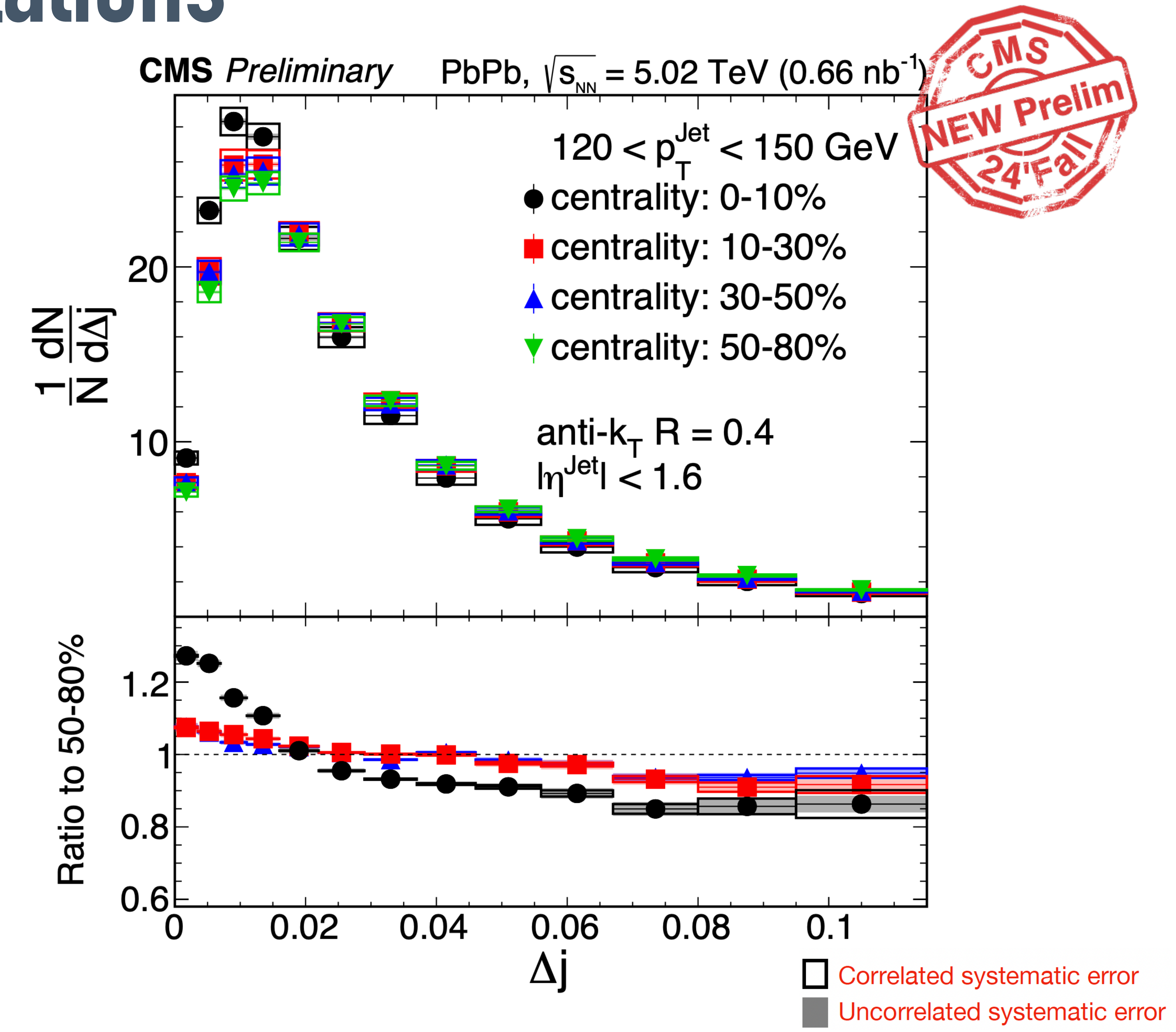
2015	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032

BACKUP: New HP results not covered

Medium-induced jet axis decorrelations

See Raghunath Pradhan's talk
CMS-PAS-HIN-24-010

→ **How does the medium modifies the structure of jets?**



More collimated jets in central than peripheral PbPb collisions:

- suppression of wide-fragmenting jets?
- "bias" bin-by-bin migration from higher-p_T jets?

Medium-induced jet axis decorrelations

See Raghunath Pradhan's talk
CMS-PAS-HIN-24-010

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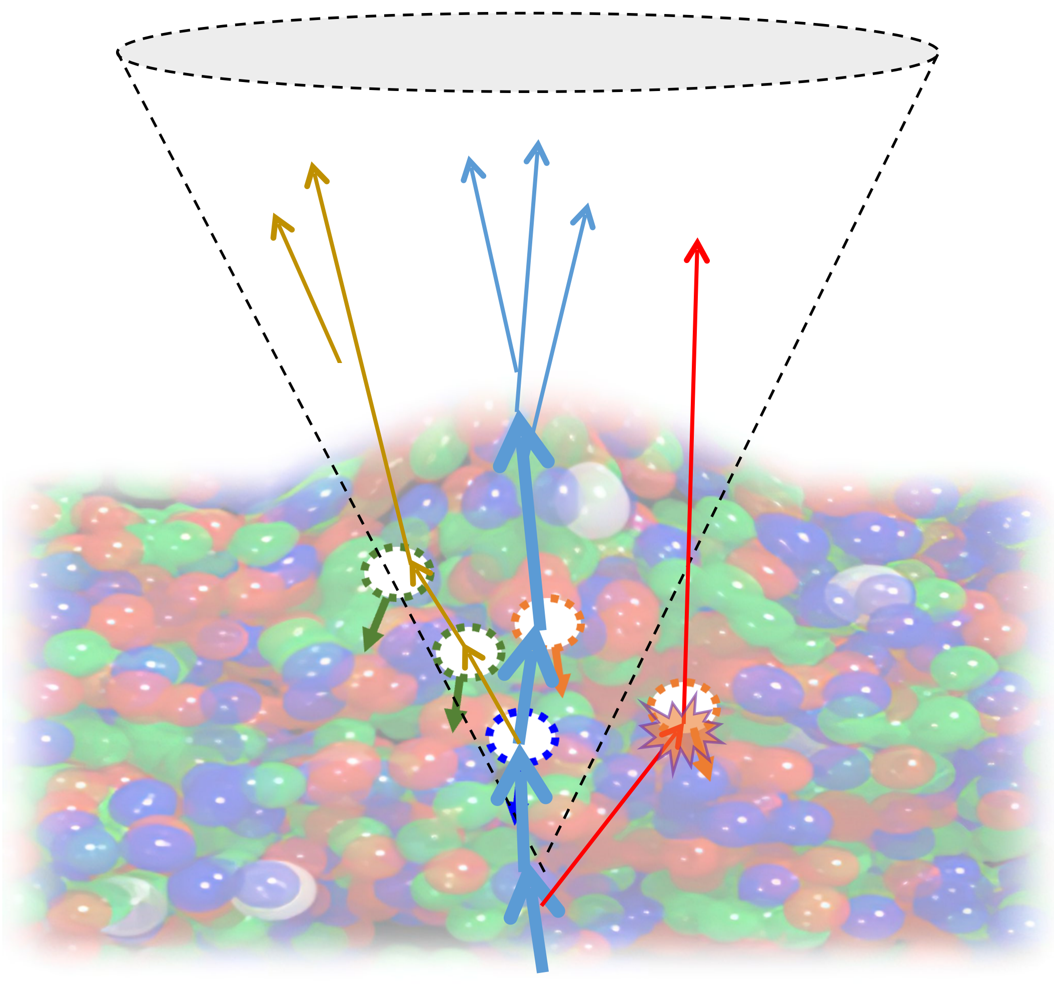
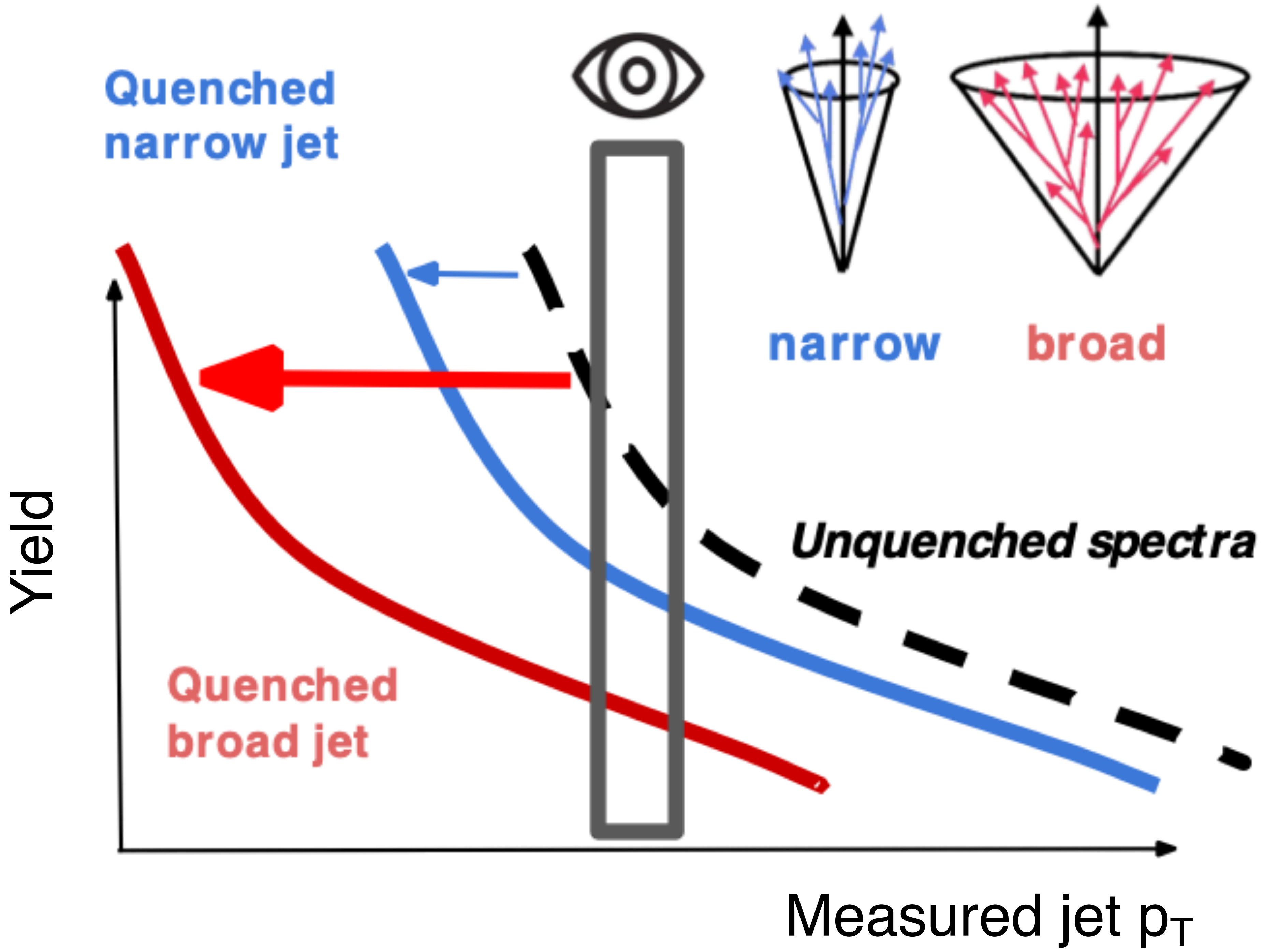


E-Scheme axis direction of average energy flow in the jet
WTA axis = direction of leading energy flow in jet

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

- **Δj = 0** → collimated "hard" jets,
- **Δj > 0** → less collimated jets, more soft radiation

Jet quenching "bias"



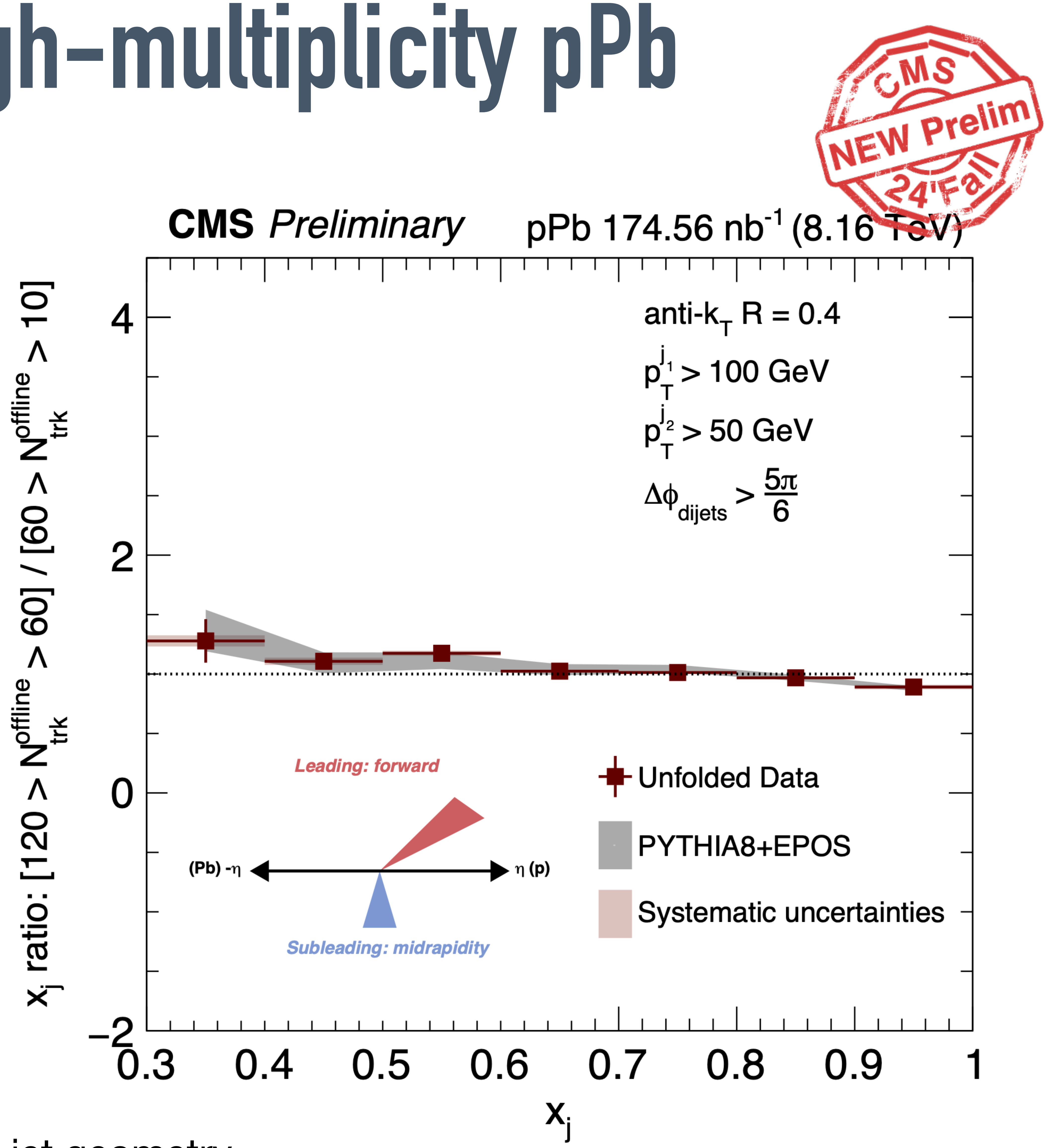
PbPb and pp jets, at the same p_T, are "different"
→ they do not correspond to the same initial parton p_T

Transverse momentum balance in high-multiplicity pPb

Study of the transverse momentum balance $\mathbf{x_J = p_{T,sub} / p_{T,\,lead}}$ for pairs of jets with different pseudorapidity:

Leading jet	Subleading jet
midrapidity	midrapidity
midrapidity	forward
midrapidity	backward
forward	midrapidity
backward	midrapidity

- **Midrapidity:** $|\eta_{CM}| < 1$
- **Forward (p direction):** $1.2 < \eta_{CM} < 2.4$
- **Backward (Pb direction):** $-3.3 < \eta_{CM} < -1.2$



High-multiplicity/low-multiplicity x_J ratio:
- no modifications were observed at high multiplicity for any configuration of jet-jet geometry
- well described by MC simulation without E_{loss}

See <u>Dener's talk</u>
CMS-PAS-HIN-23-010

Transverse momentum balance in high-multiplicity pPb

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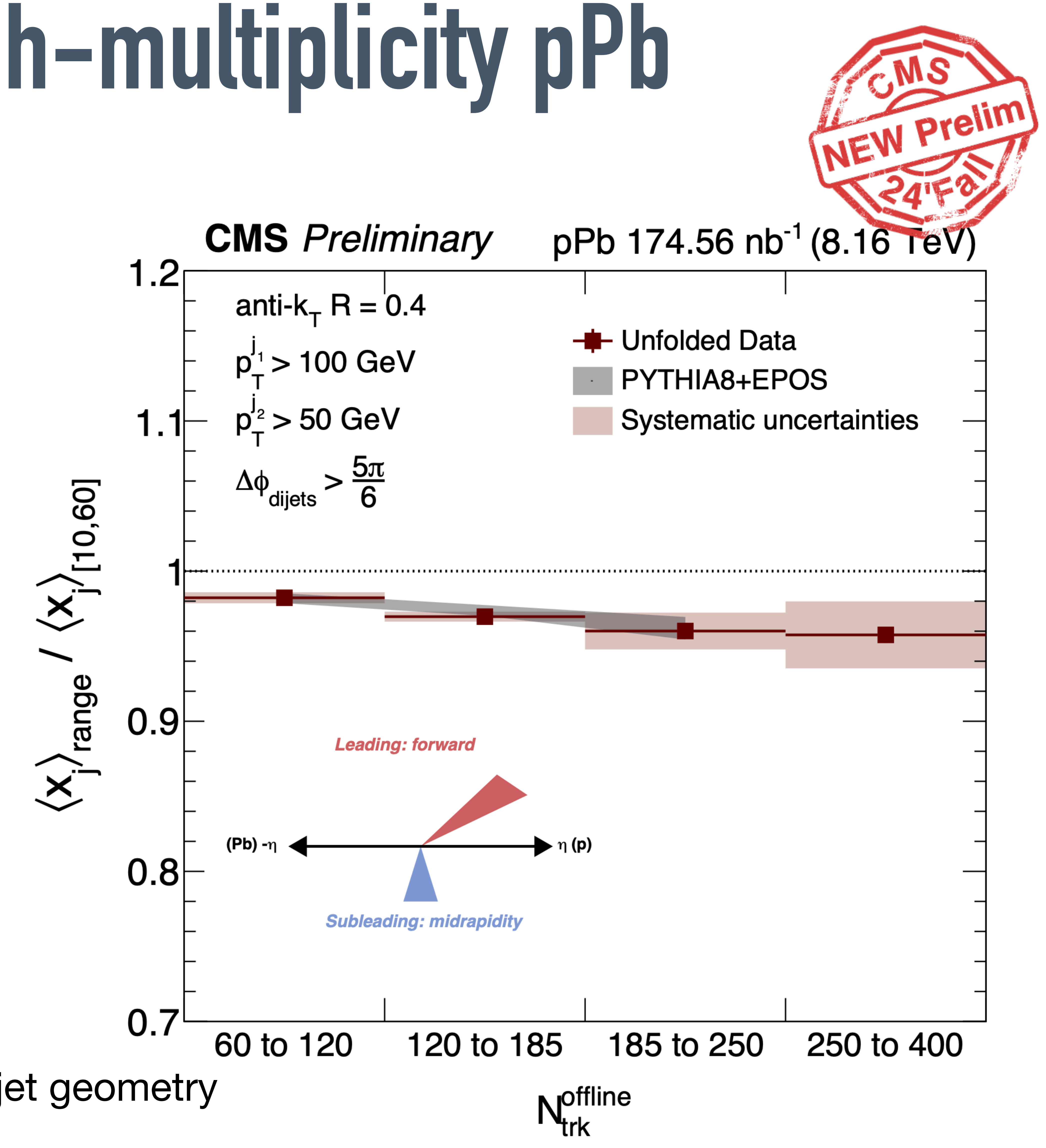

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- no modifications were observed at high multiplicity for any configuration of jet-jet geometry
- well described by MC simulation without E_{loss}

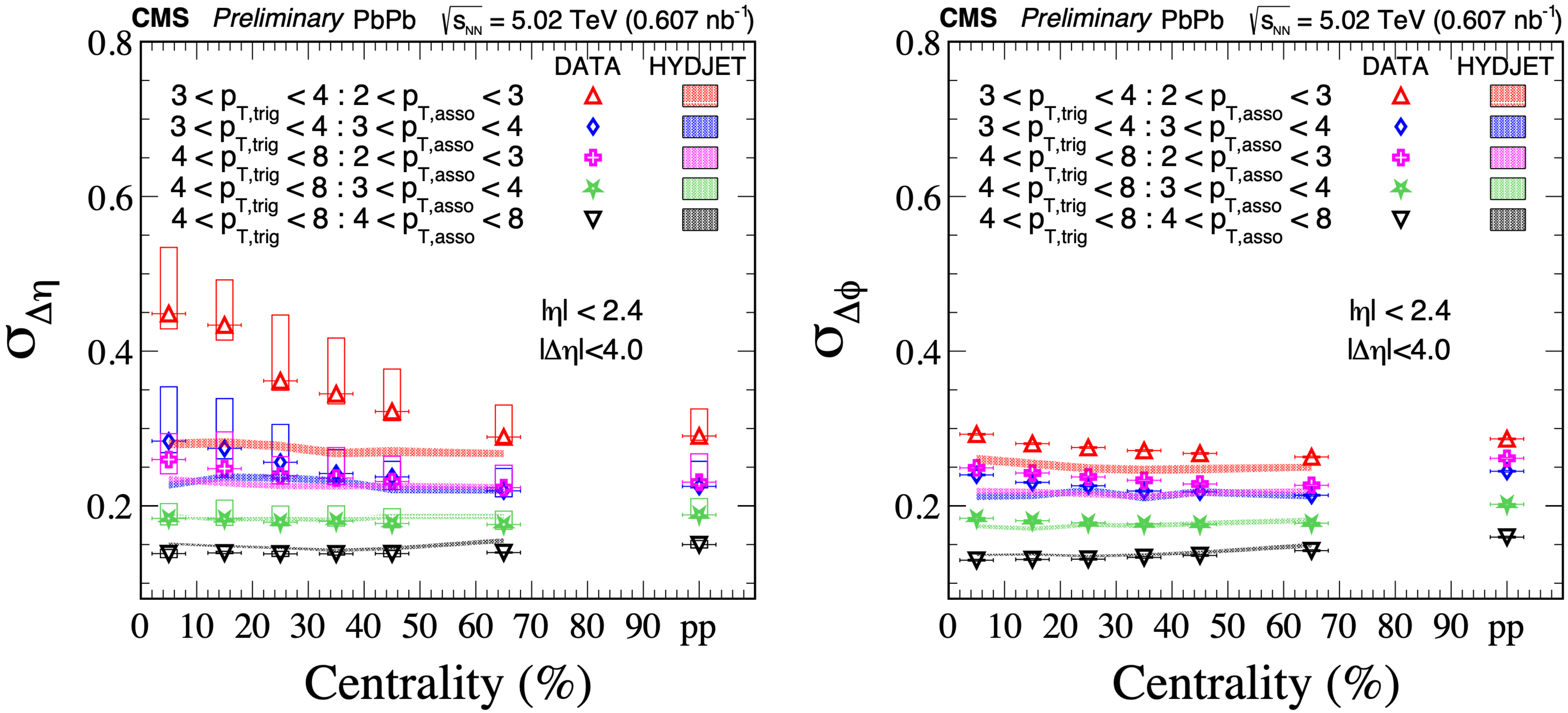
See Dener's talk
CMS-PAS-HIN-23-010

Average transverse momentum balance decreases for increasing N_{ch} :

→ Energy-momentum conservation, multi-jets

Near-side jet peak structure

CMS NEW Prelim 24'Fall



See Sayan's poster
CMS-PAS-HIN-24-008

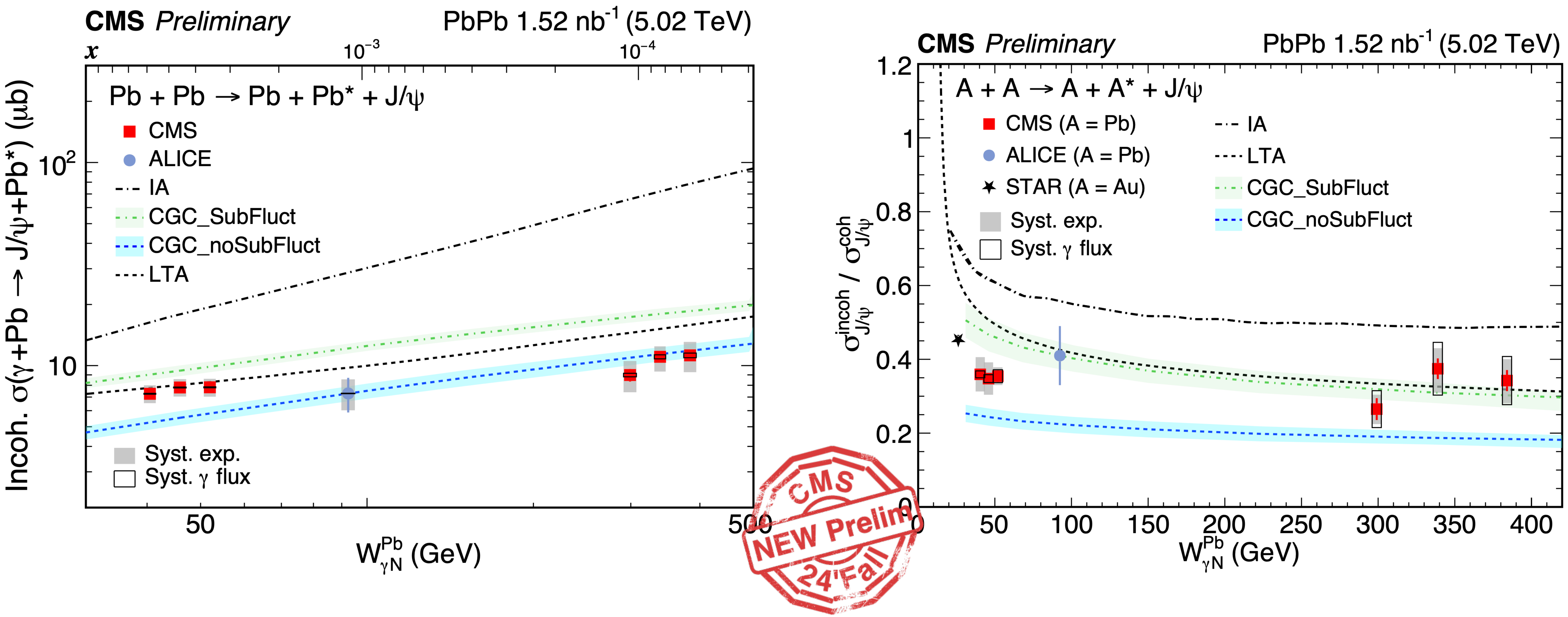
BACKUP: UPCs

First energy-dependent measurement of incoherent J/ψ in UPCs

Incoherent production (<p_T> ~ 500 MeV)

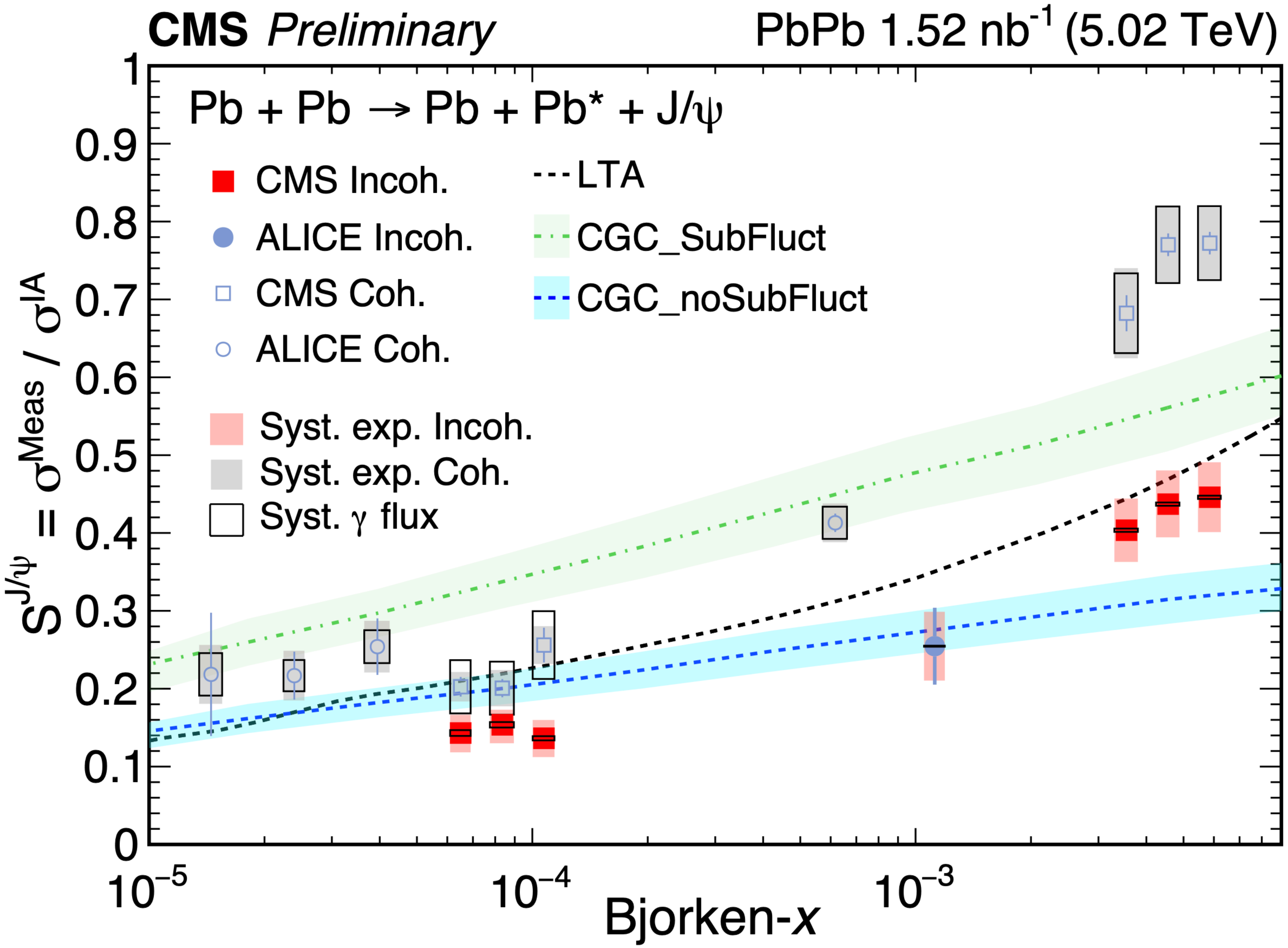
- Photon interacts with a single nucleon or sub-nucleon (→ nuclear breakup)
- Probing the local gluon density and fluctuations

See Zaochen Ye's talk
CMS-PAS-HIN-23-009

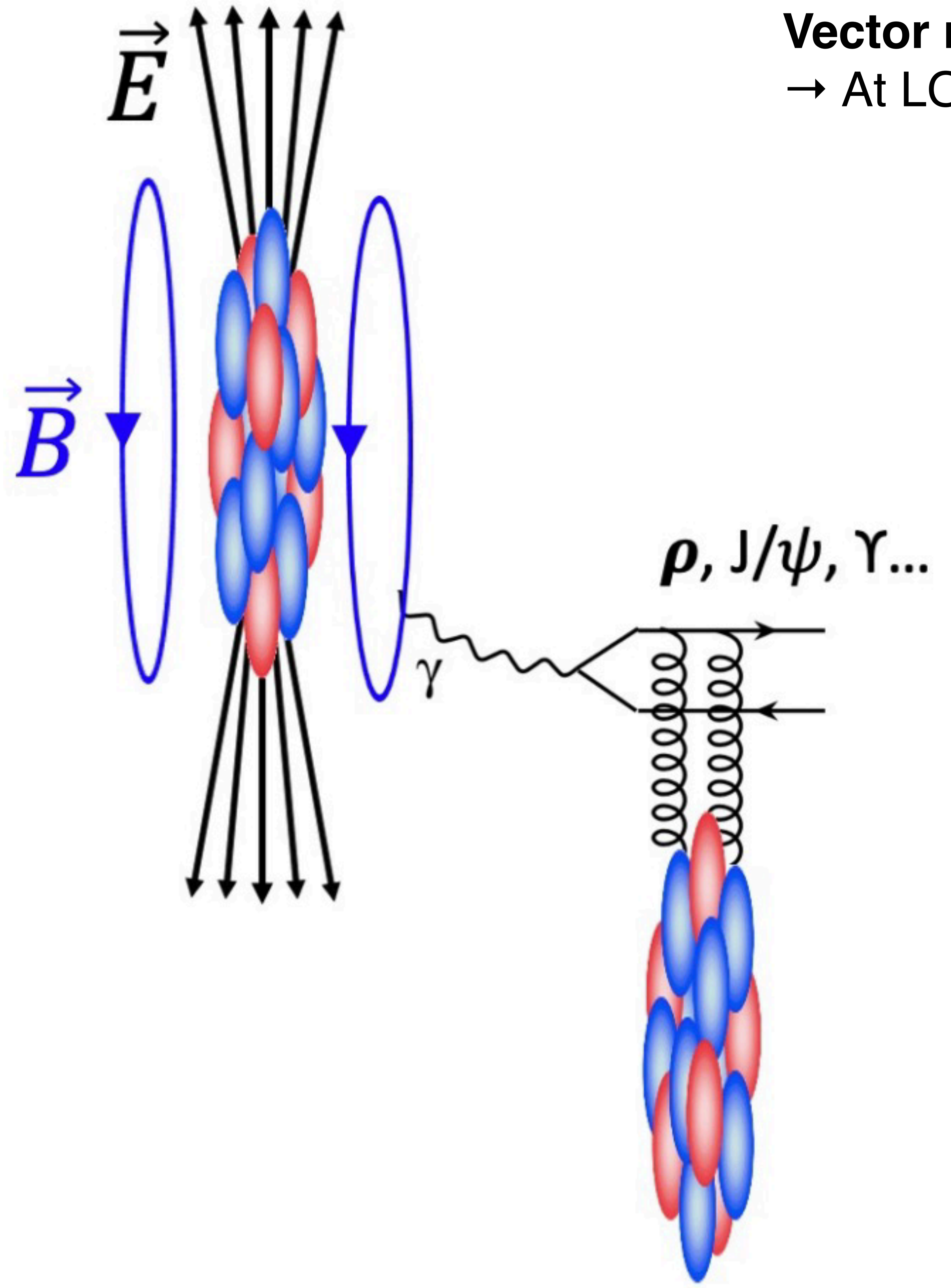


First energy-dependent measurement of incoherent J/ψ in UPCs

See Zaochen Ye's talk
CMS-PAS-HIN-23-009



Vector-meson photoproduction in UPC



Vector mesons (VM) probe gluonic structure of nucleus and nucleon.
→ At LO in pQCD, cross section ~ photon flux ⊗ [xG(x)]2

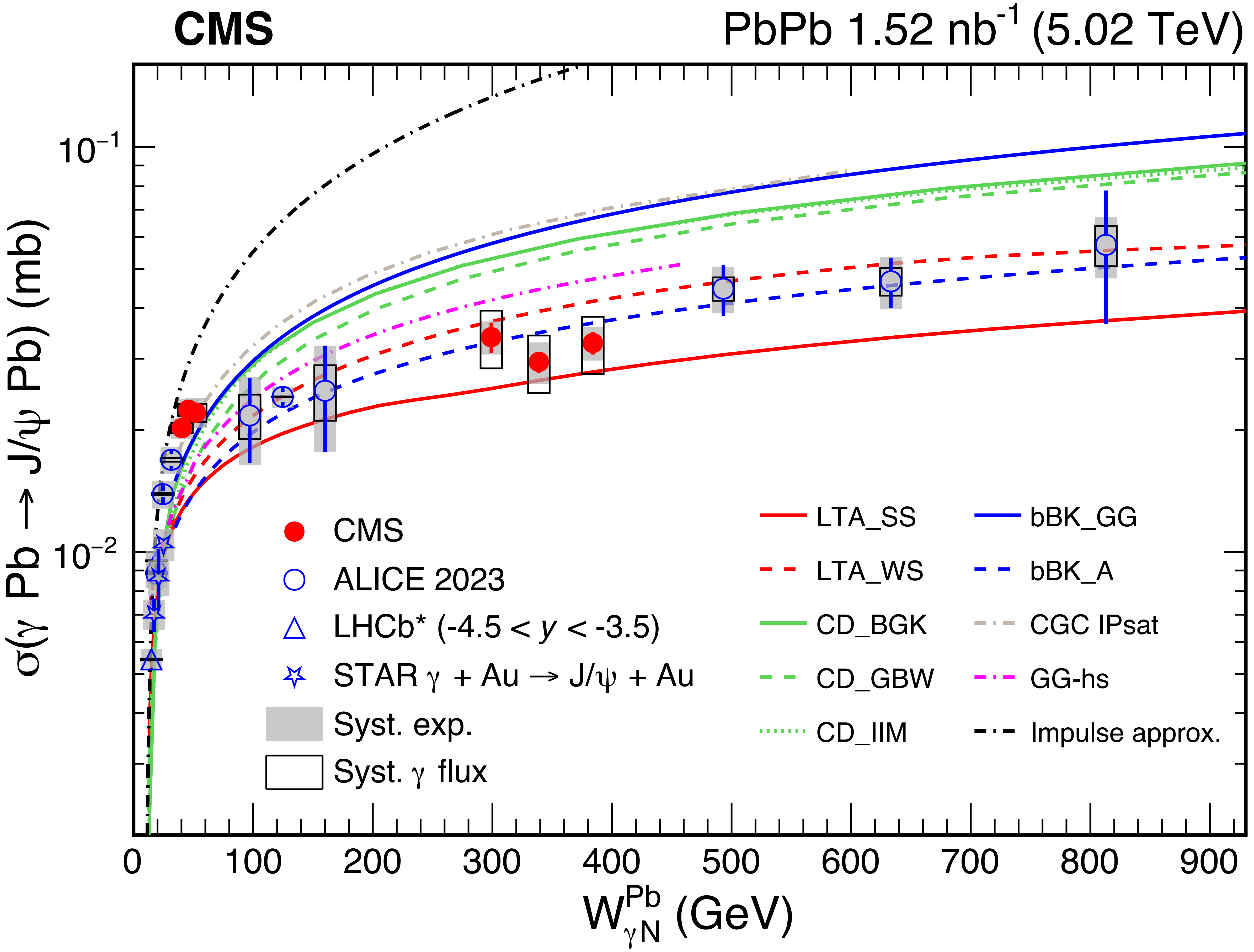
Coherent production (<p_T> ~ 50 MeV)
- Photon fluctuated dipole couples coherently to entire nucleus
- Target nucleus remains intact
- VM <p_T> ~ 50 MeV
- Probing the averaged gluon density

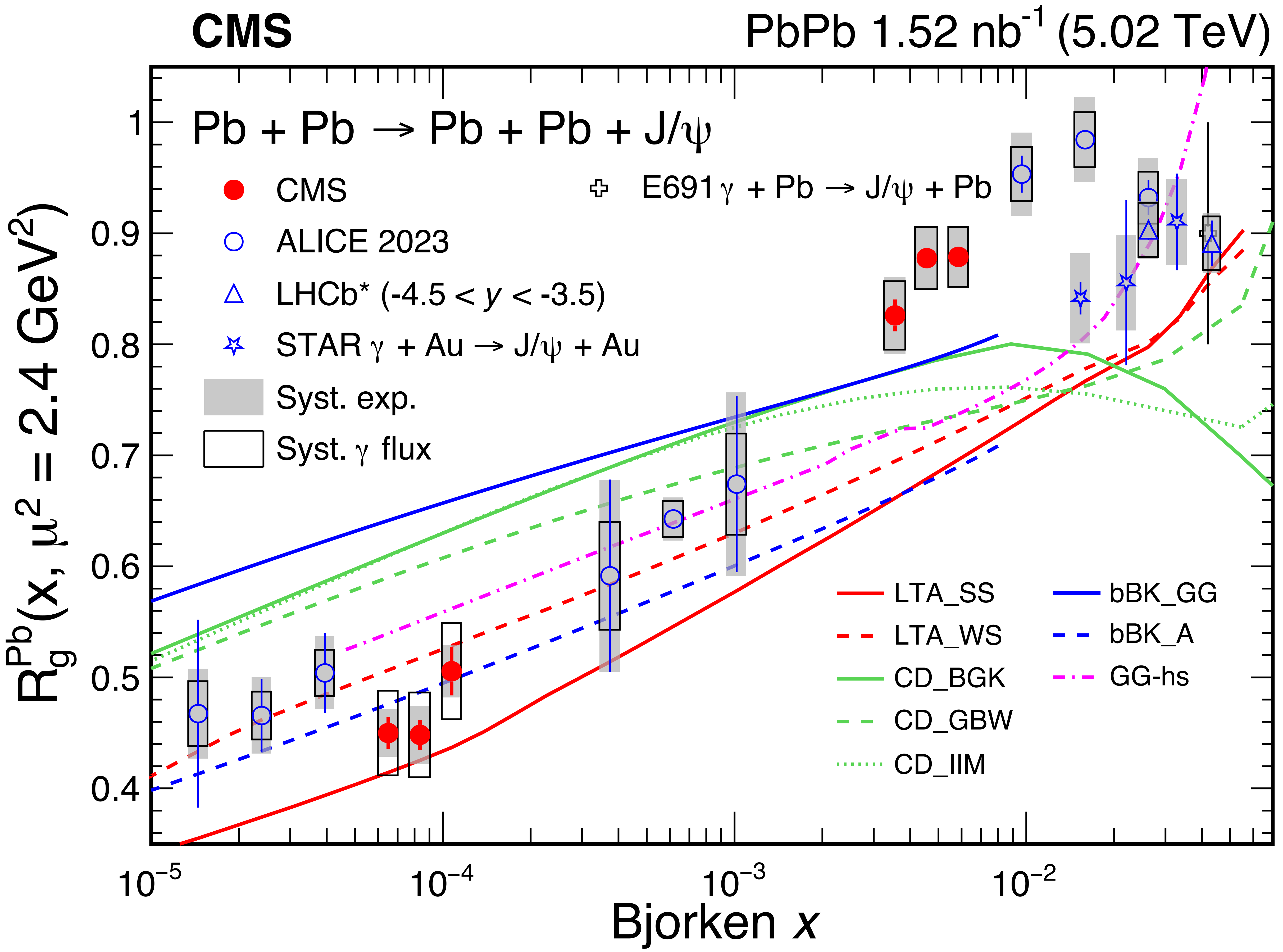
Incoherent production VM (<p_T> ~ 500 MeV)
- Photon fluctuated dipole couples to individual nucleons
- Target nucleus usually breaks
- Probing the local gluon density fluctuation

*Sketches from **Zaochen Ye's** talk at GHP2023*

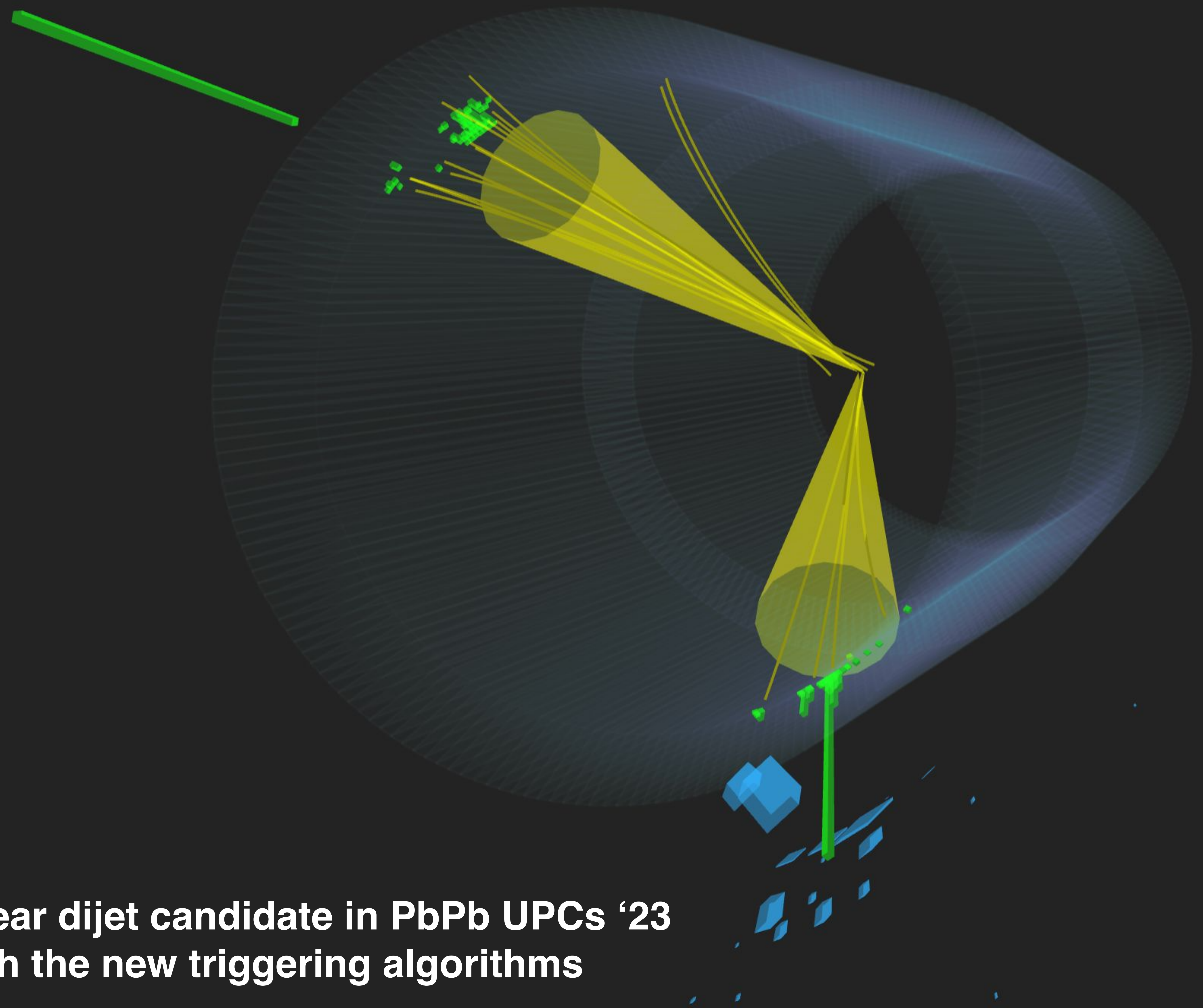
Coherent J/ψ in PbPb UPCs: CMS vs ALICE

ALICE, JHEP 10 (2023) 119
CMS, Phys. Rev. Lett. 131 (2023) 262301





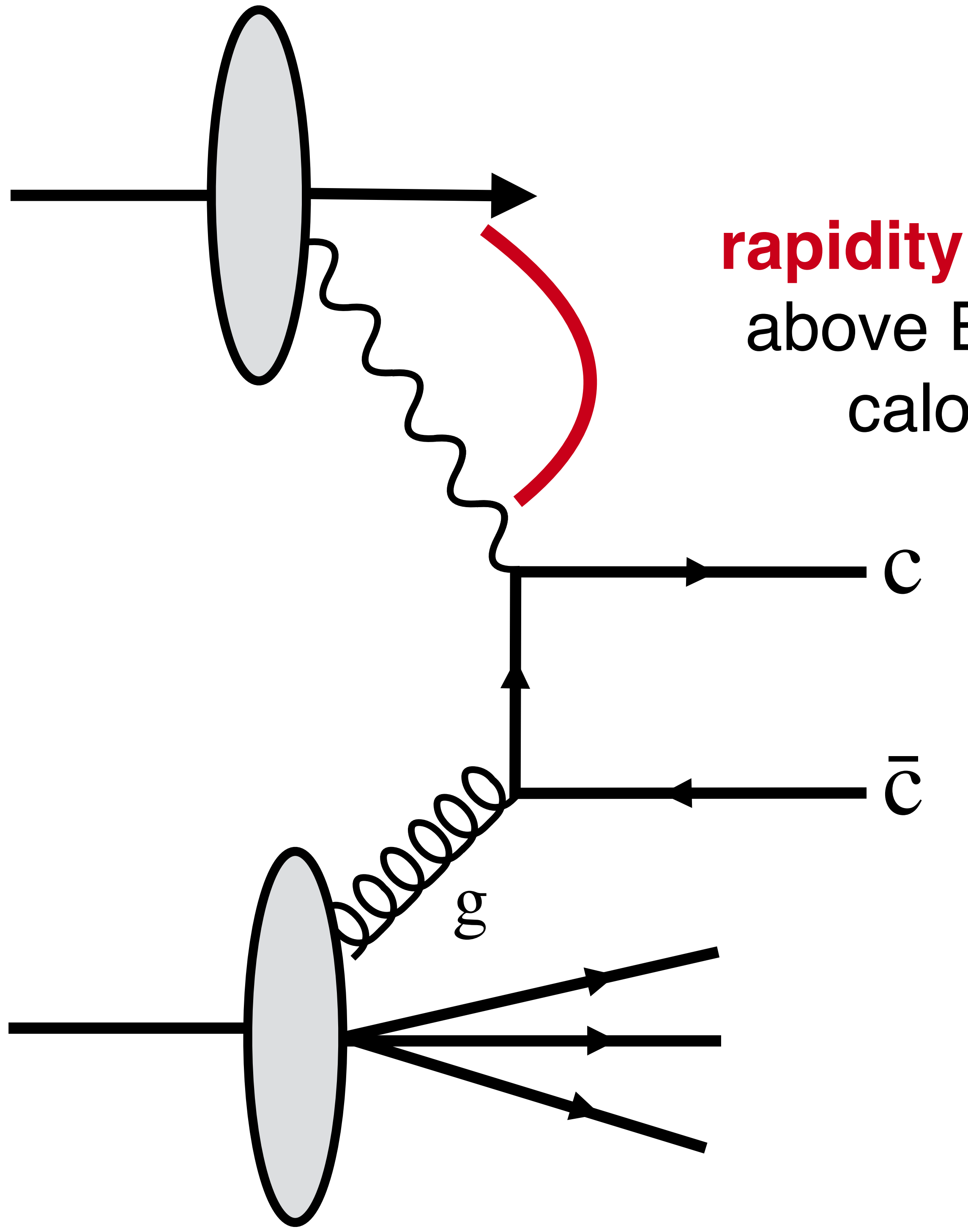
CMS Experiment at the LHC, CERN
Data recorded: 2023-Oct-10 05:24:04.000512 GMT
Run / Event / LS: 374925 / 591414336 / 646



Clean dijets events with negligible underlying QCD background

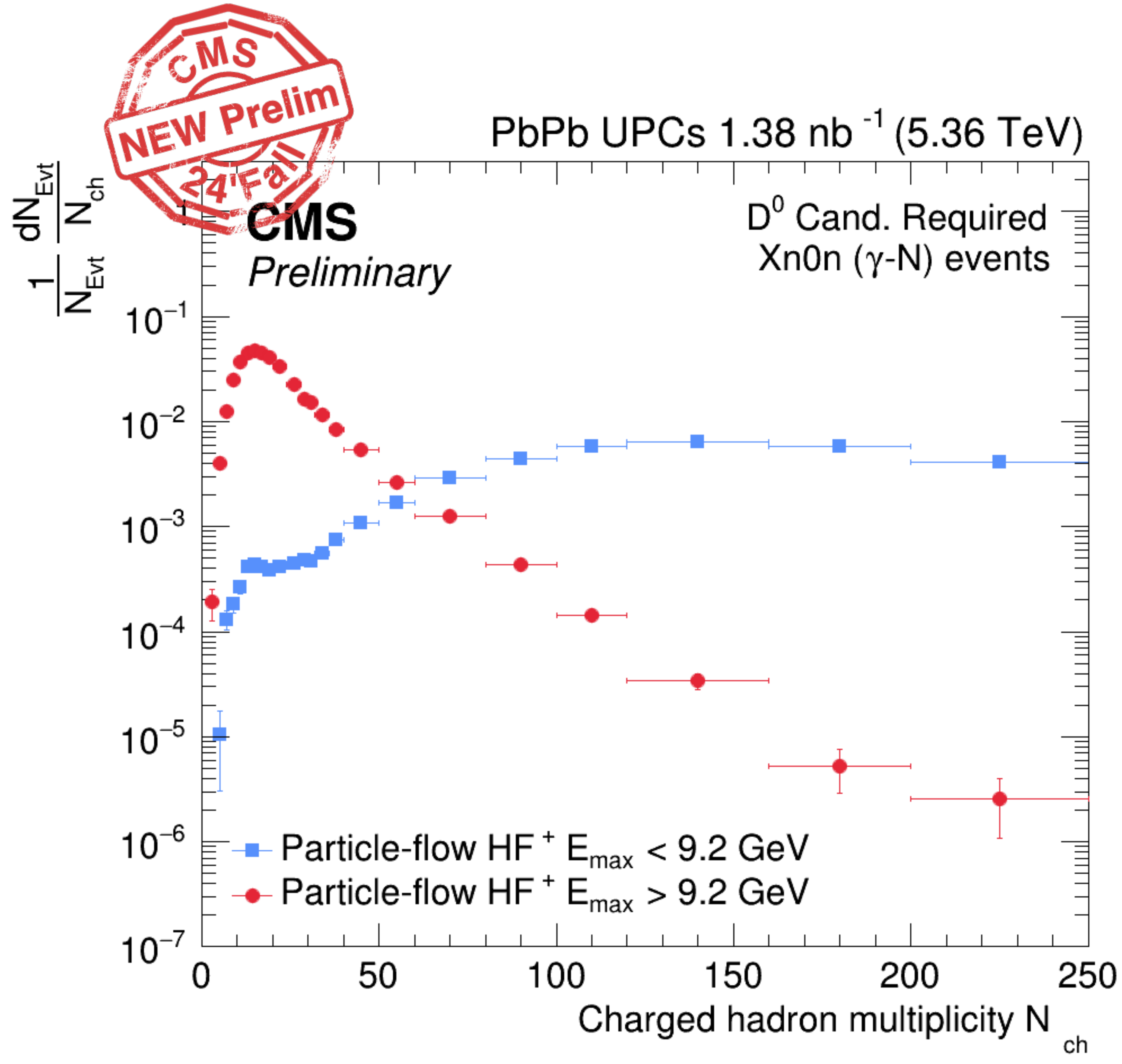
A photonuclear dijet candidate in PbPb UPCs ‘23 collected with the new triggering algorithms

Rapidity gap selection



rapidity gap condition no deposit above E^{th} in the forward hadronic calorimeter (**$3.0 < \eta < 5.2$**)

See Chris McGinn's talk
CMS-PAS-HIN-24-003



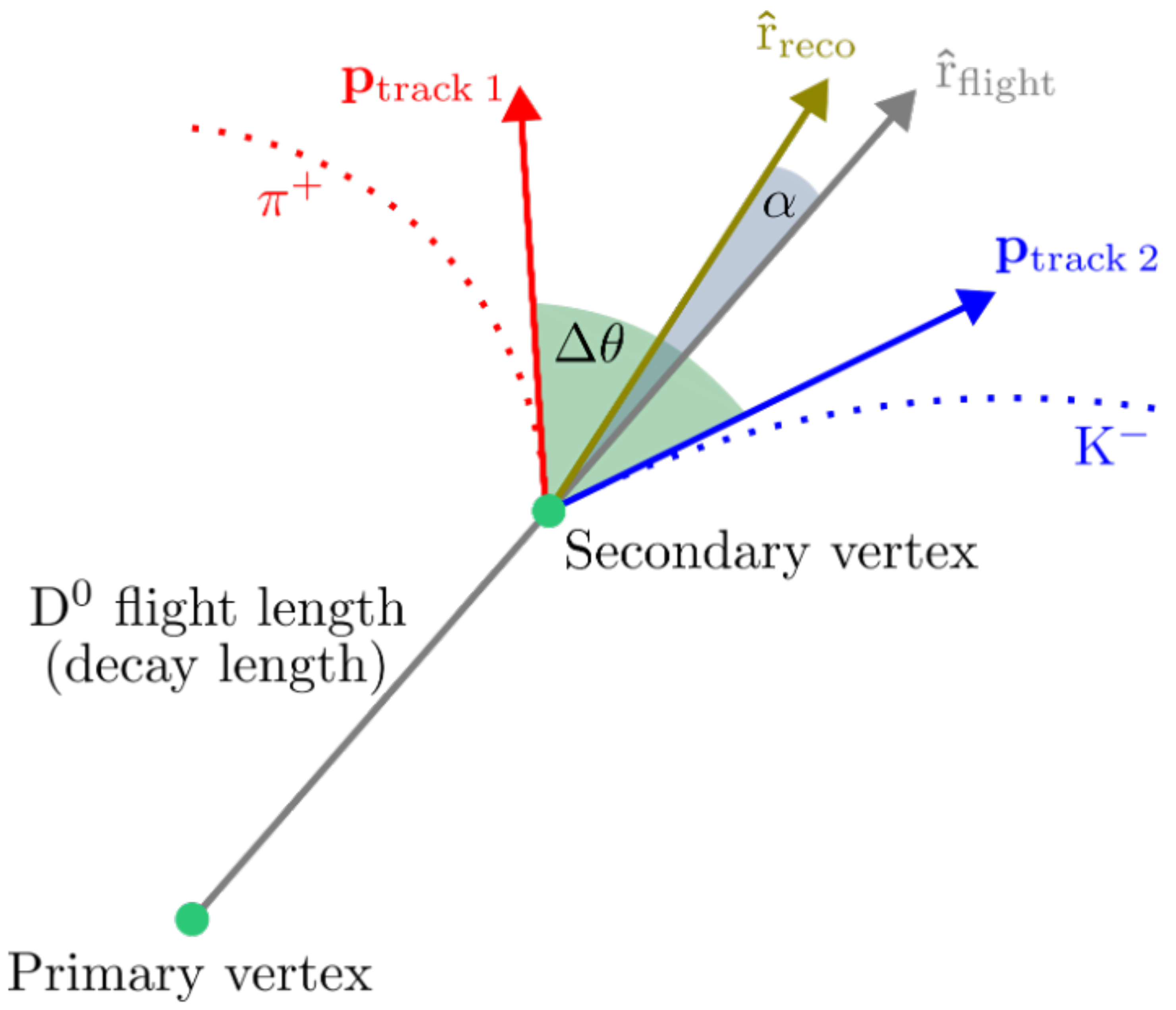
Events passing the rapidity gap condition
Events failing the rapidity gap condition (high N_{ch})
(mostly coming from "hadronic" PbPb collisions)

- **Event selection efficiency ε_{evt} > 98% for both direct-photon and resolved-photon events**
- With simultaneous requirements on ZDC Xn0n and rapidity gap
  → **negligible contamination from "hadronic" events**

D^0 reconstruction and yield-extraction

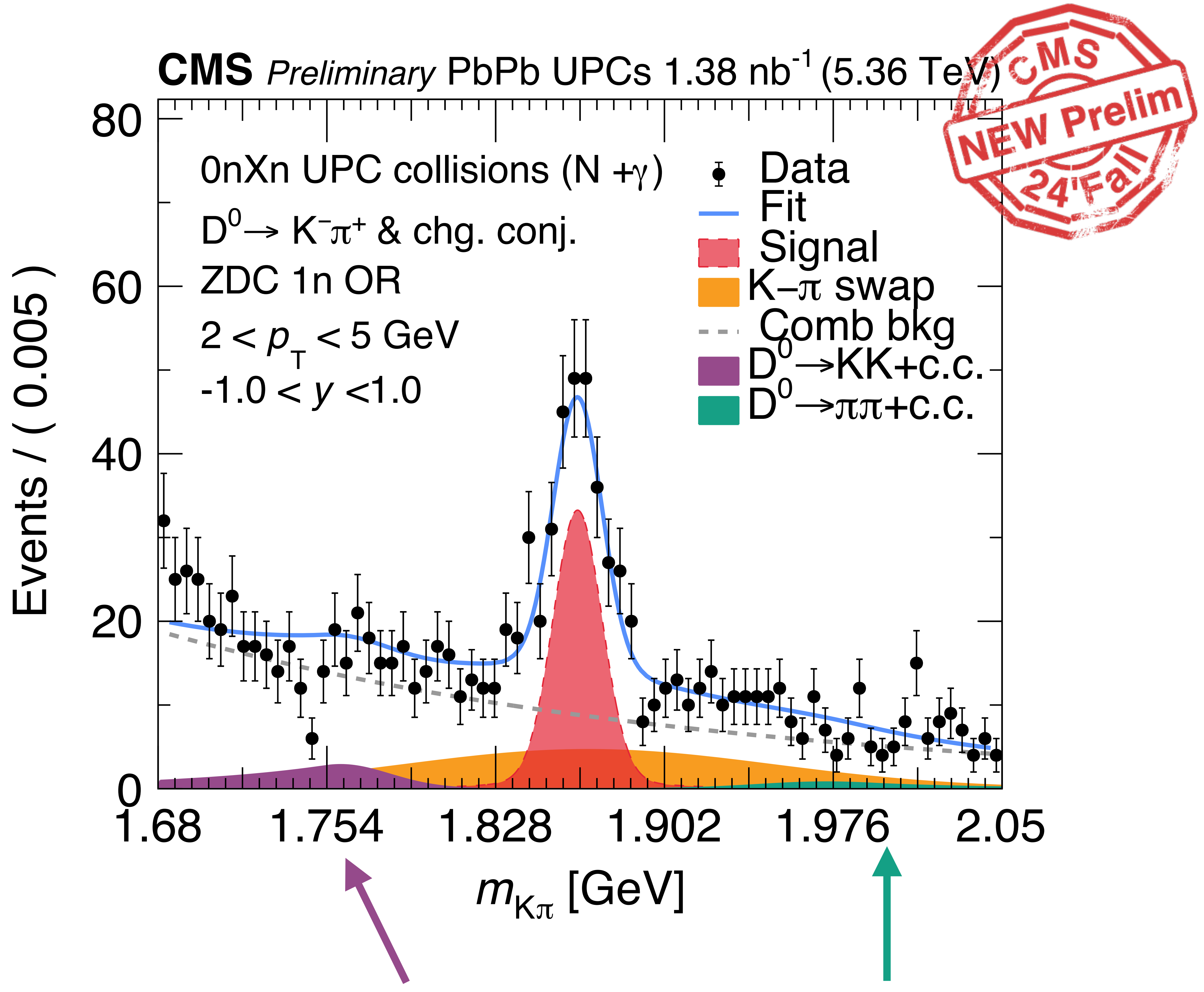
See Chris McGinn's talk
CMS-PAS-HIN-24-003

D^0 candidate reconstruction and selection:
→ topological selection optimized in bins of D^0 p_T and rapidity



- pointing angle (α)
- decay length normalized to its error (d_0)
- D^0 vertex probability
- opening angle between the D^0 daughter prongs

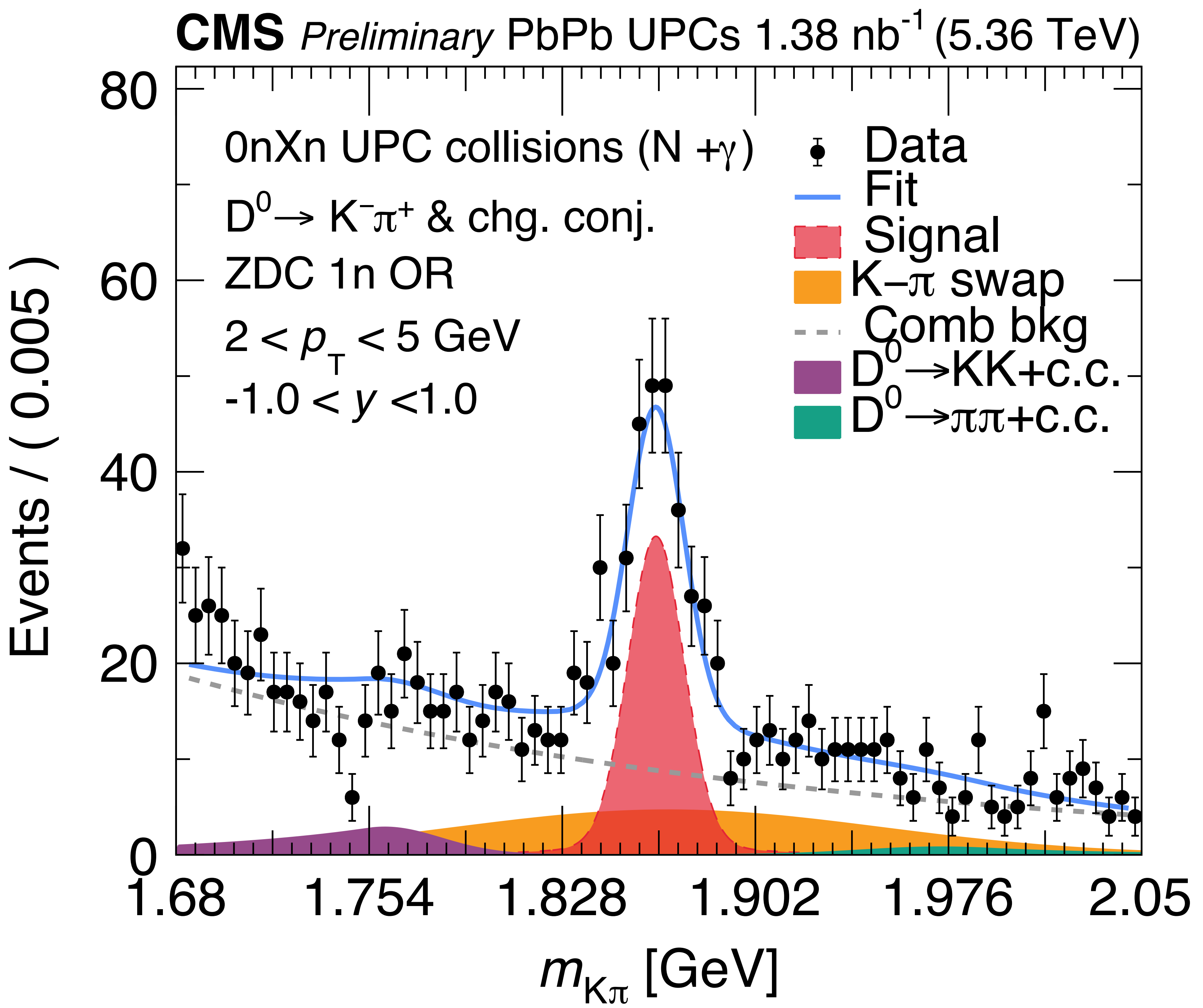
Fitting strategy:
- exponential function to model the combinatorial background
- **double Gaussian to model the signal**
- **"wide" Gaussian shape** for candidates with the "swapped" mass hypothesis

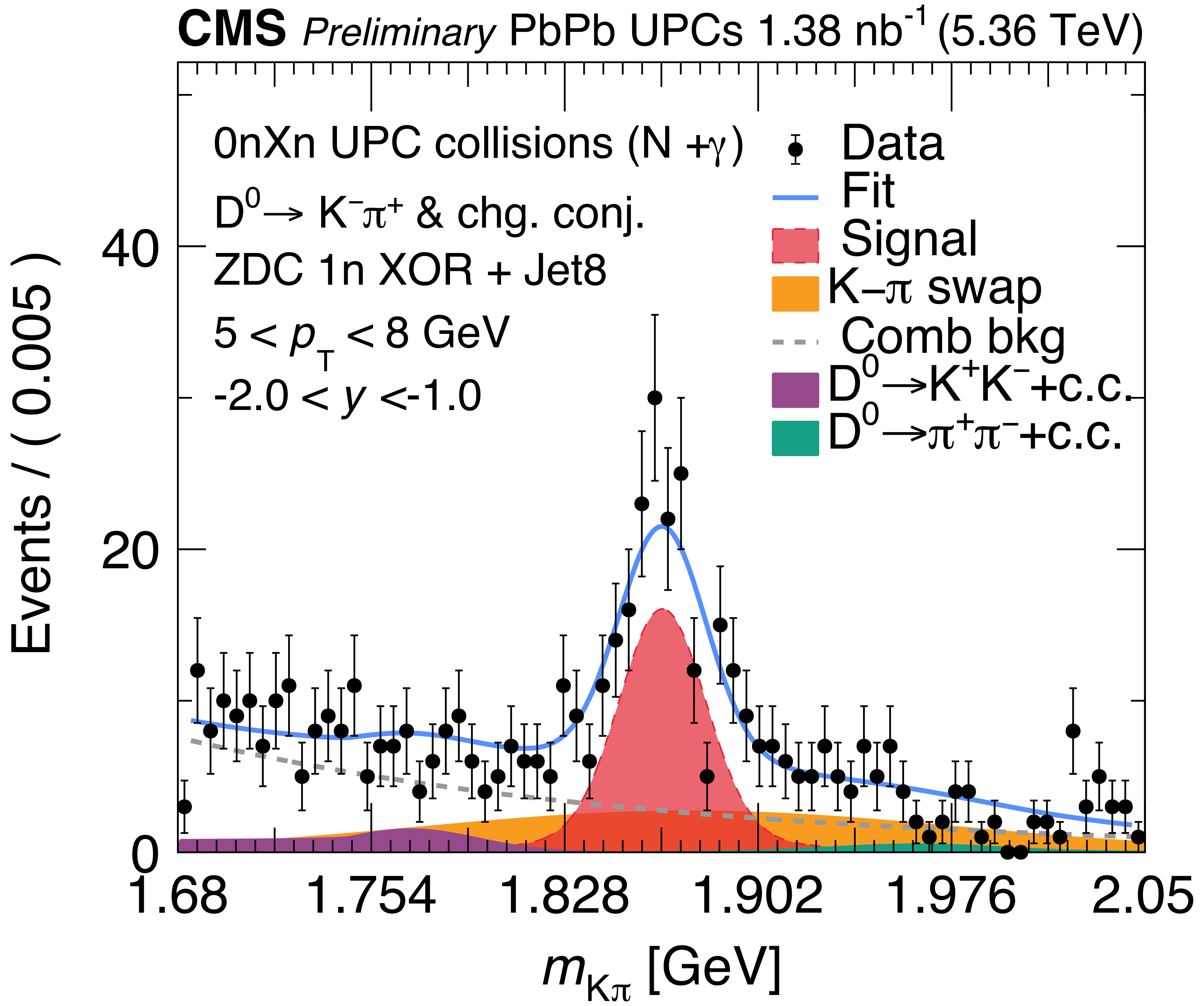


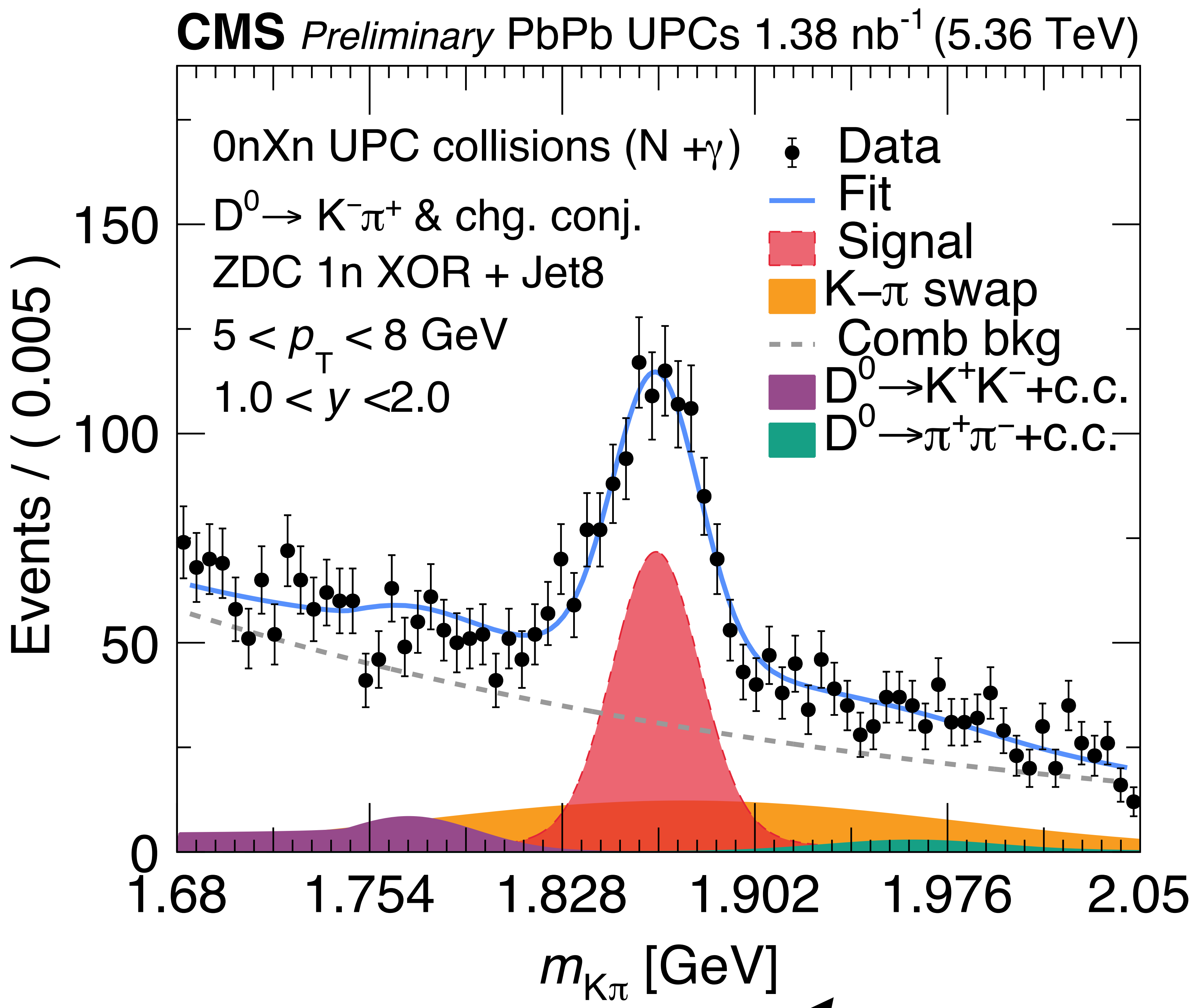
Crystal Ball functions to model the contribution from **$D^0 \rightarrow K^+K^-$** and **$D^0 \rightarrow \pi^+\pi^-$** decays

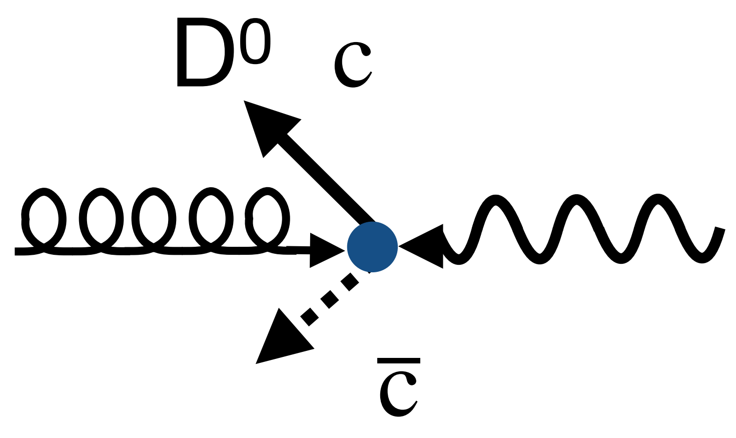
Invariant mass distributions in intervals of D^0 p_T and y

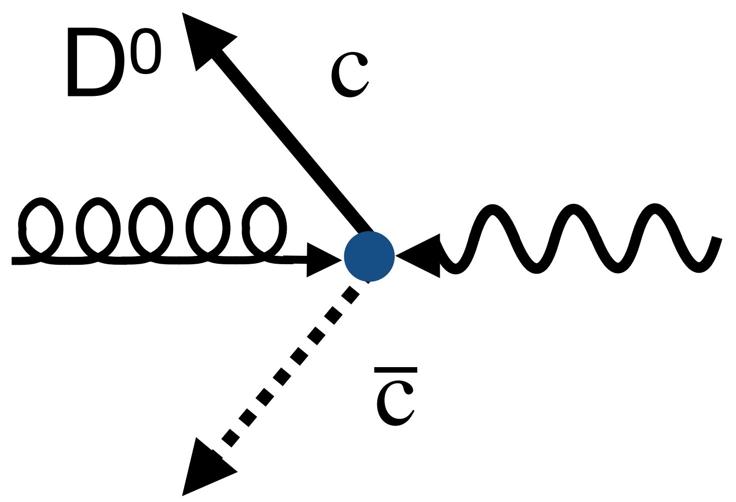
See Chris McGinn's talk
CMS-PAS-HIN-24-003

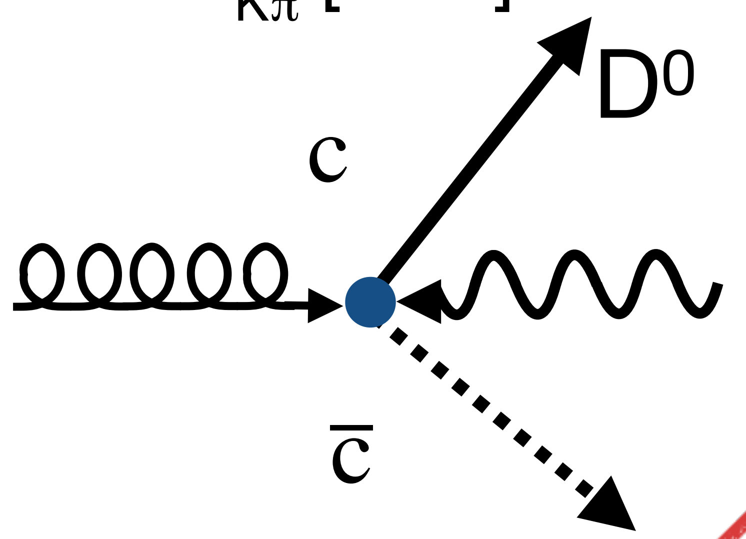












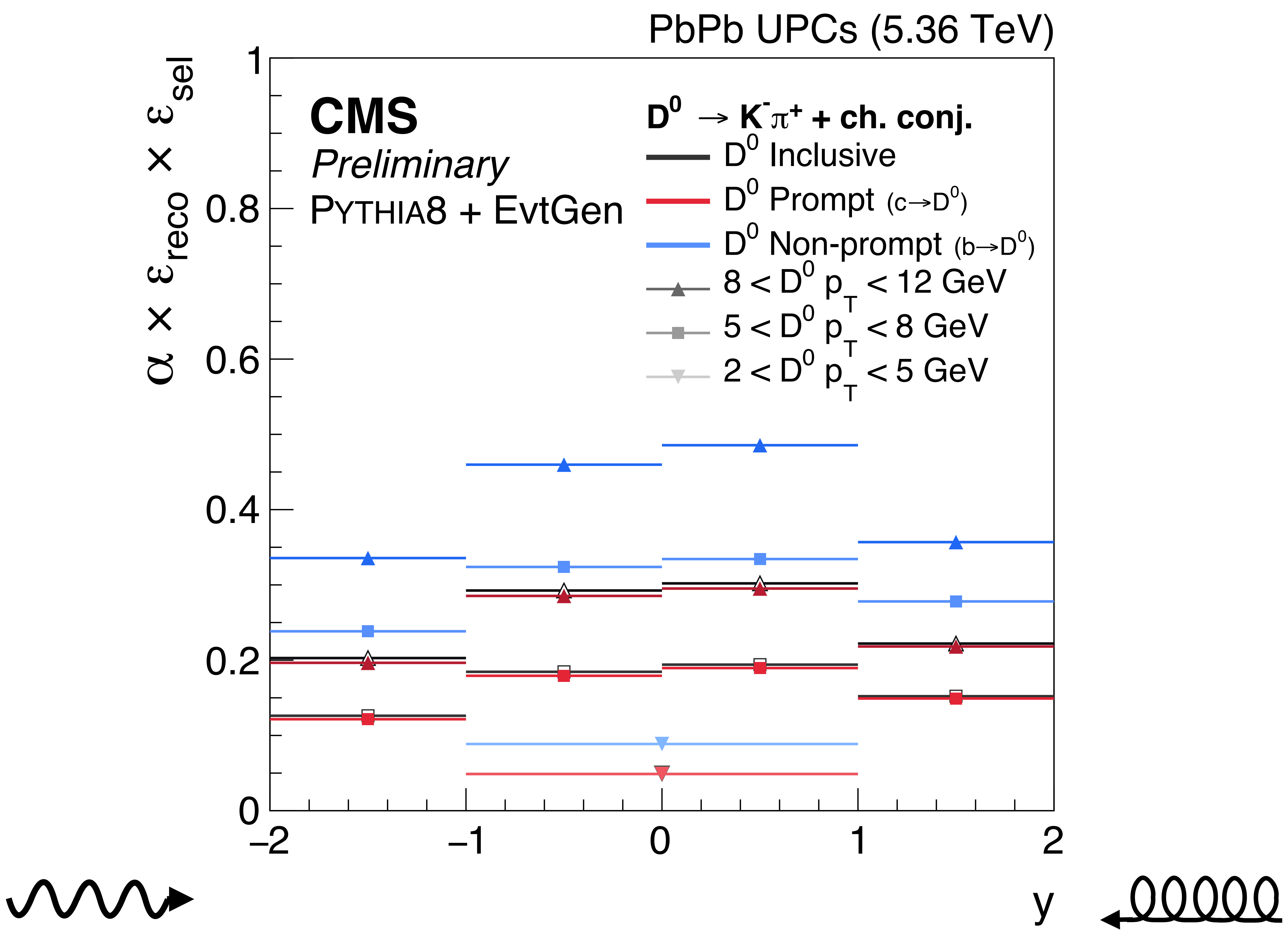
- $2 < p_T < 5$ GeV in the rapidity bin $-1 < y < 1$
- $5 < p_T < 8$ GeV with rapidity boundaries [-2, -1, 0, 1, 2]
- $8 < p_T < 12$ GeV with rapidity boundaries [-2, -1, 0, 1, 2]

CMS NEW Prelim 24'Fall

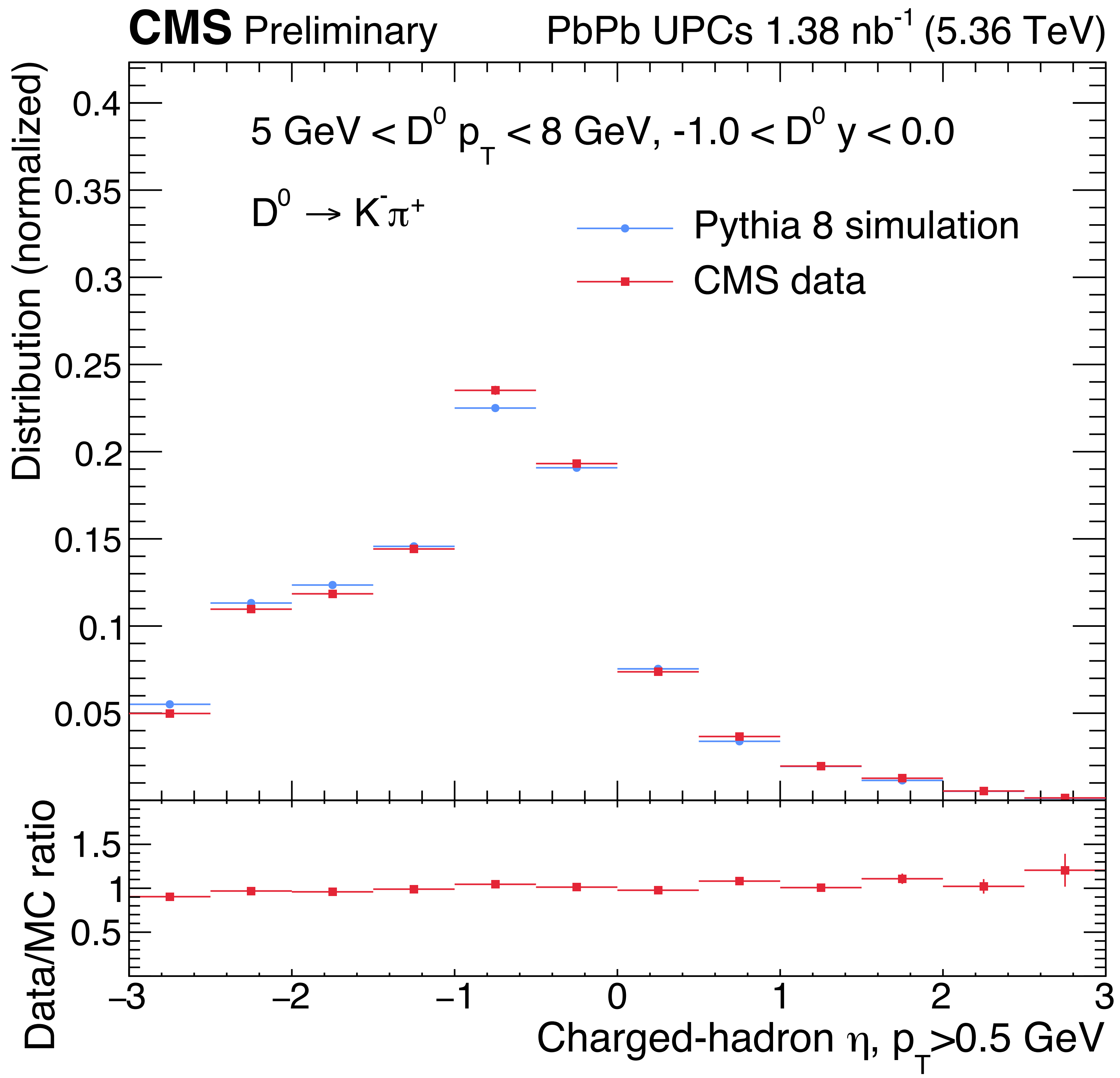
D^0 reconstruction and selection efficiencies

I. Helenius arXiv:1806.07326
K. J. Eskola et al.,, arXiv.2112.12462v2

Monte Carlo samples based on Pythia 8 + EvtGen γN events with EPPS21Pb nPDF parametrization



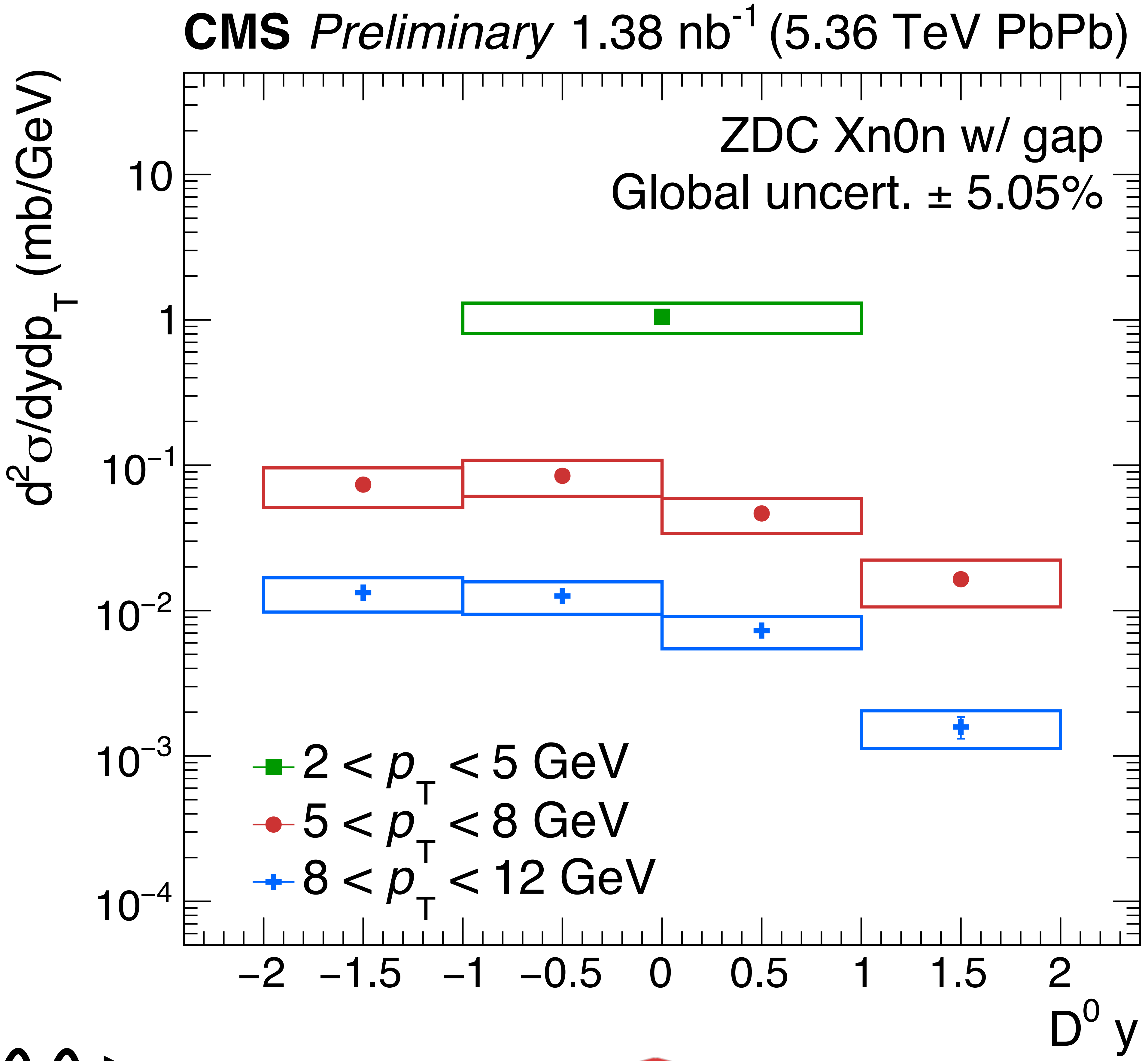
D^0 efficiencies strongly dependent on p_T and y:
due to acceptance, primary/secondary vertex resolution, topological selections



Pythia 8 γN simulations provides a very good description of the data distributions

CMS NEW Prelim 24'Fall

$d\sigma/dp_T dy$ for photonuclear D^0 production in UPC collisions



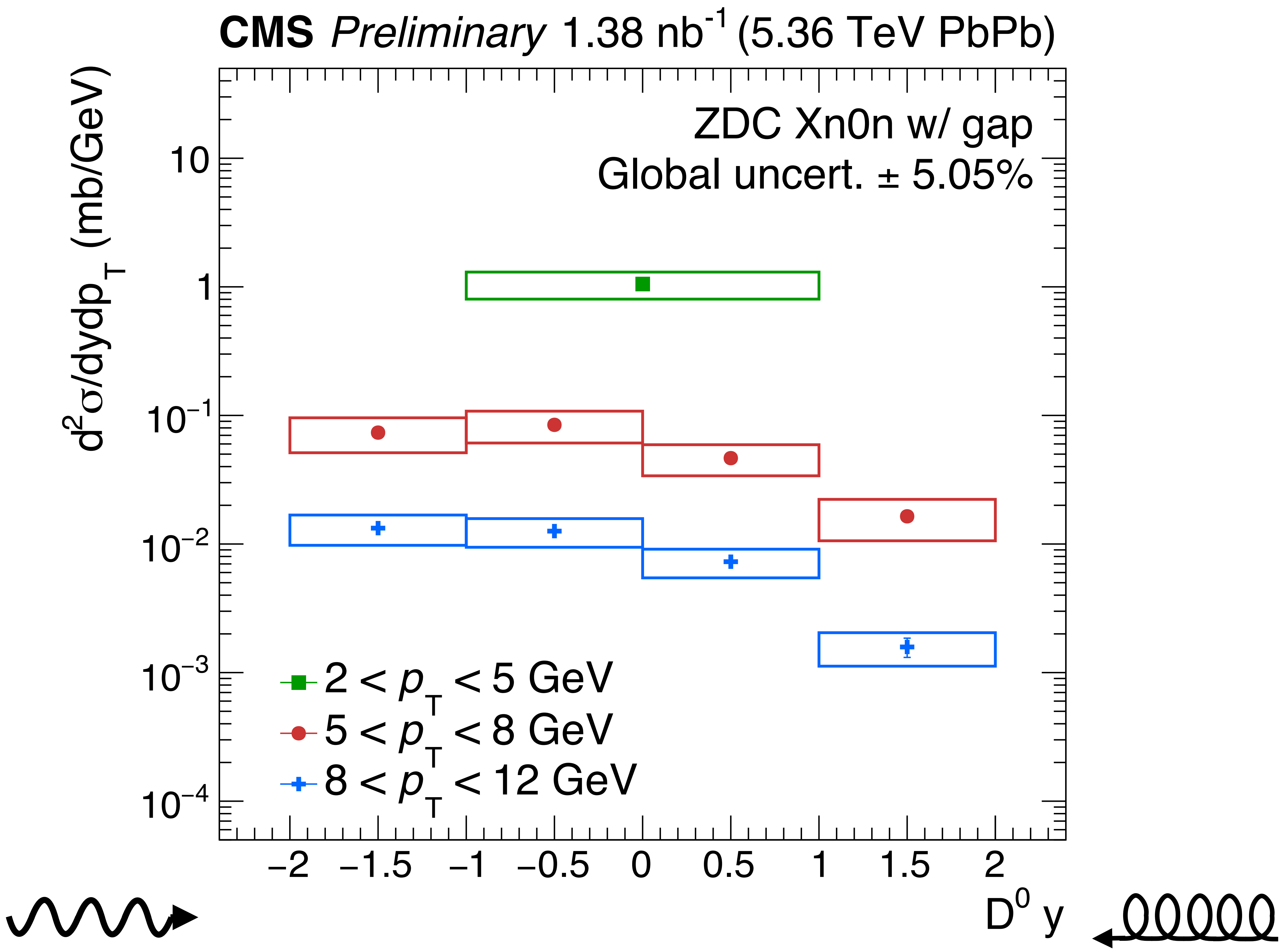
$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{2}\frac{1}{\mathscr{L}_{int}\ P_{\mathrm{trig,presc}}\ BR^{D^0\to K^-\pi^+}}\frac{N^{\mathrm{raw}}_{D^0+\bar{D}^0}}{\Delta p_T \Delta y}\frac{1}{\epsilon_{\mathrm{evt}}\ \epsilon_{\mathrm{trigger}}\ \epsilon^{tot}_{D^0}\ \epsilon_{EMpileup}}$$

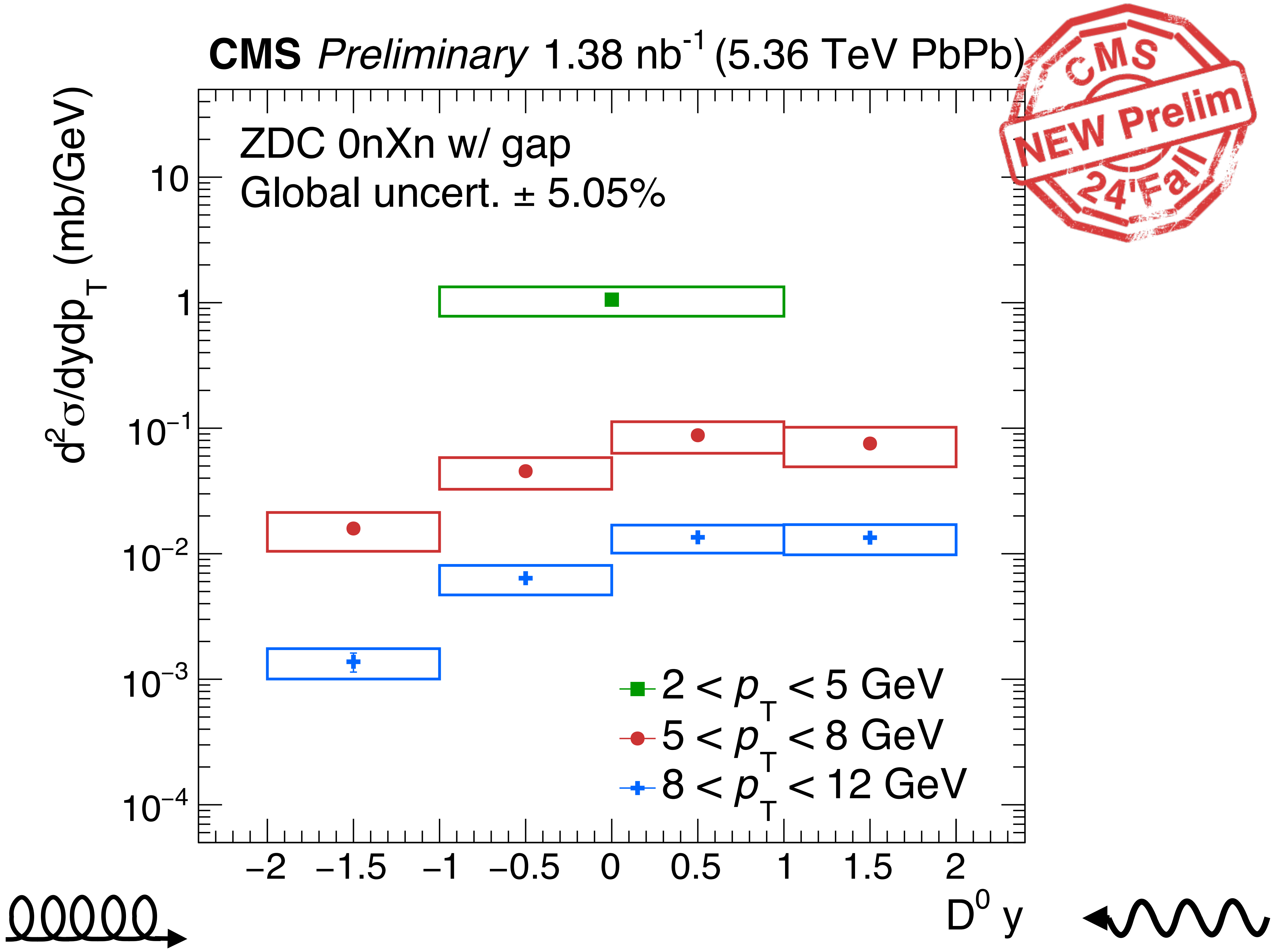
Main sources of systematic uncertainties:

- **trigger correction** (for $p_T > 5$ GeV)
- **rapidity-gap condition**
- **D^0-selection efficiency, mostly driven by MC-data differences in:**
  - distributions of selection variables
  - multiplicity, p_T/y shape,
  - fraction of prompt/non prompt D^0, resolved vs direct photon events
- **Yield-extraction and modeling of the peaking backgrounds**

See Chris McGinn's talk
CMS-PAS-HIN-24-003

$d\sigma/dp_T dy$ for photonuclear D^0 production in UPC collisions





Xn0n and 0nXn cross section are first measured separately

→ clear rapidity dependence of the D^0 cross-section with respect to the incoming photon direction

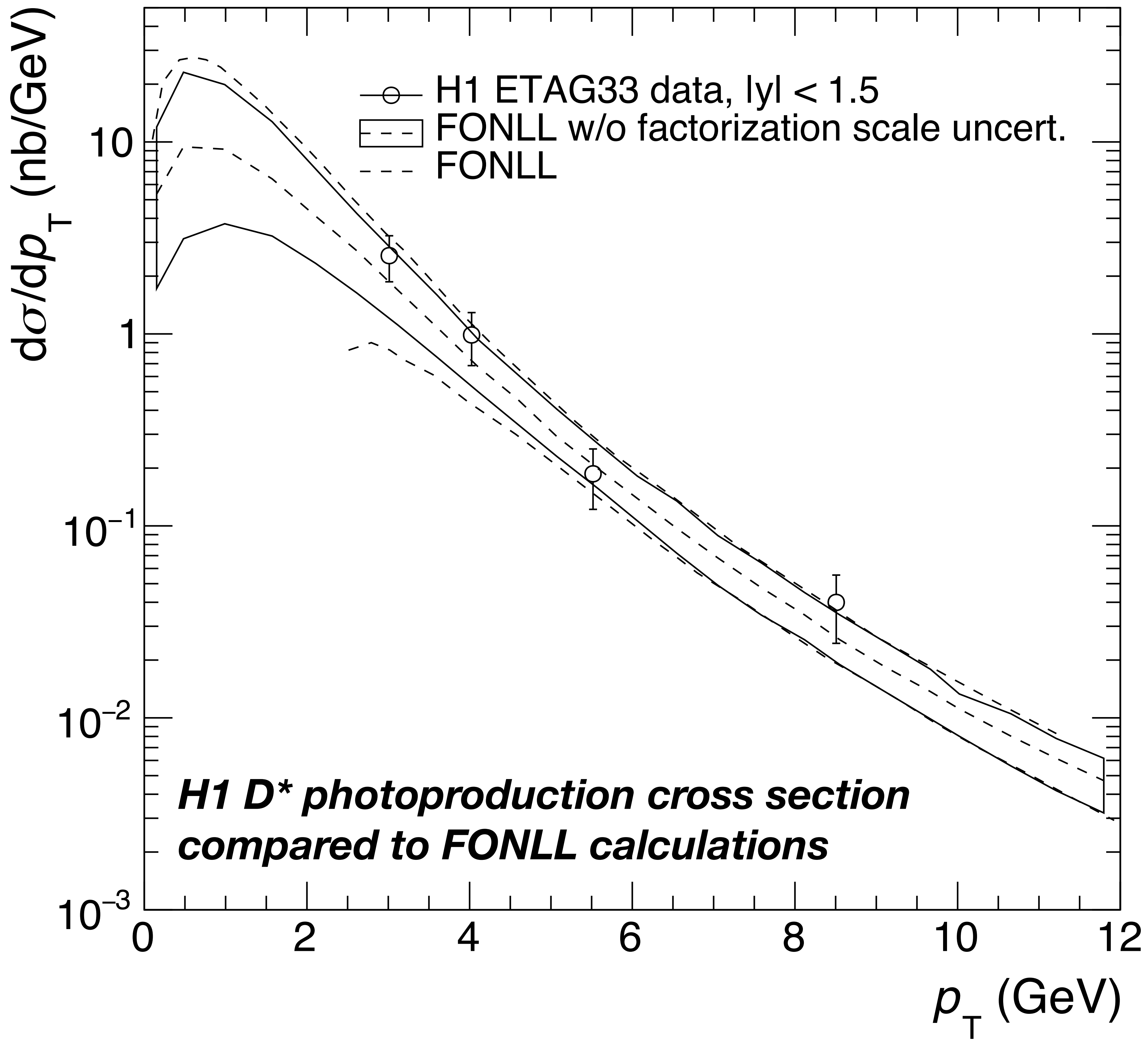
and then combined by symmetrizing the 0nXn measurement

$$\frac{d^2\sigma}{dp_T dy}_{\text{Xn0n tot}} = \frac{d^2\sigma}{dp_T dy}_{\text{Xn0n}} + \frac{d^2\sigma}{dp_T dy}_{\text{0nXn}} (y \to -y)$$

“Building” FONLL-based predictions for D^0 in UPCs at the LHC

FONLL for prompt inclusive charm photoproduction
→ *full agreement with existing predictions for ZEUS/H1*

FONLL predictions developed with ***Anna Maria Stasto****, based on the original code for photonuclear heavy-flavor production*
(paper in preparation)



S. Frixione, P. Nason, JHEP 0203 (2002) 053
M. Cacciari, M.Greco and P. Nason, JHEP 9805:007,1998

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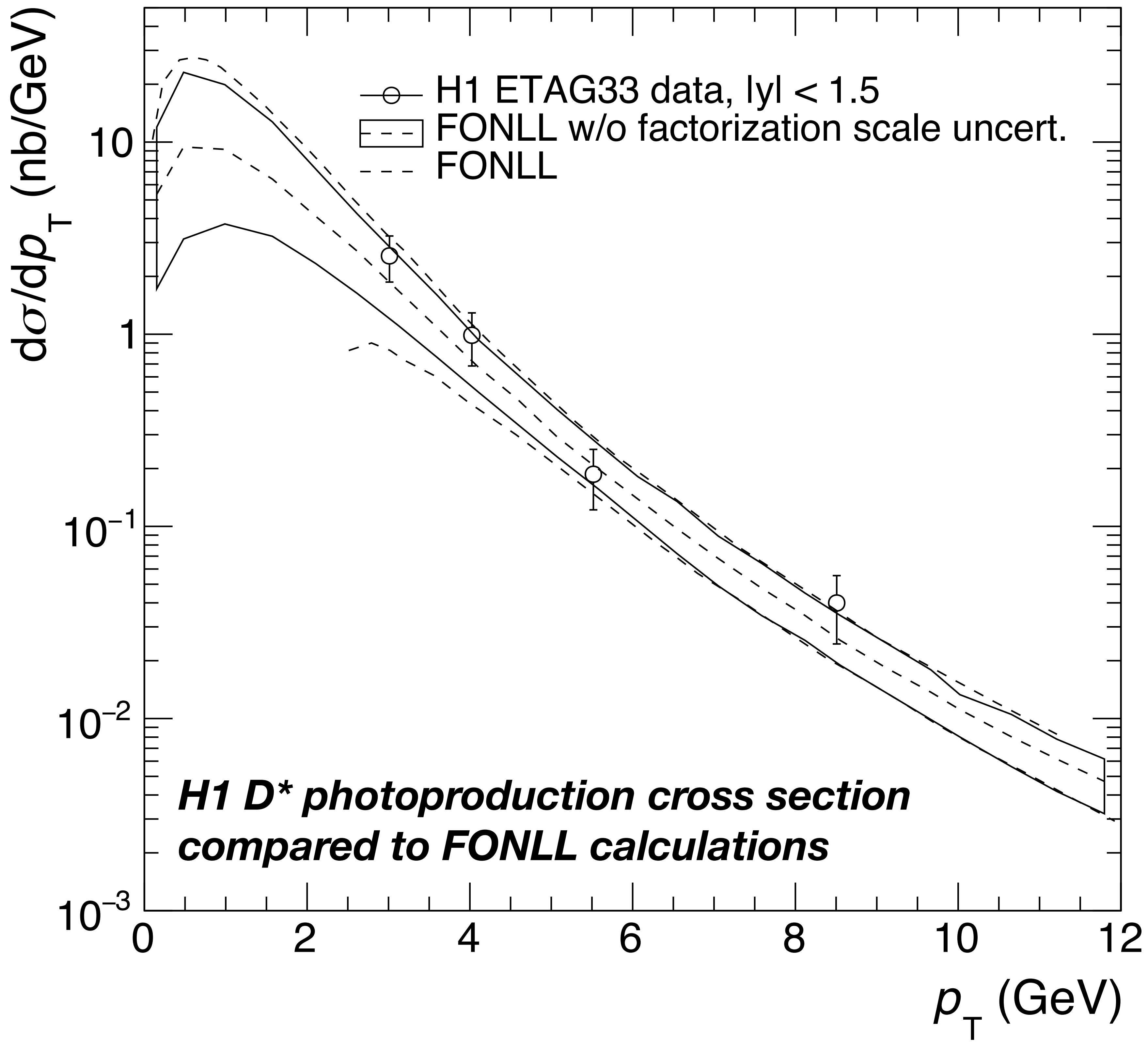
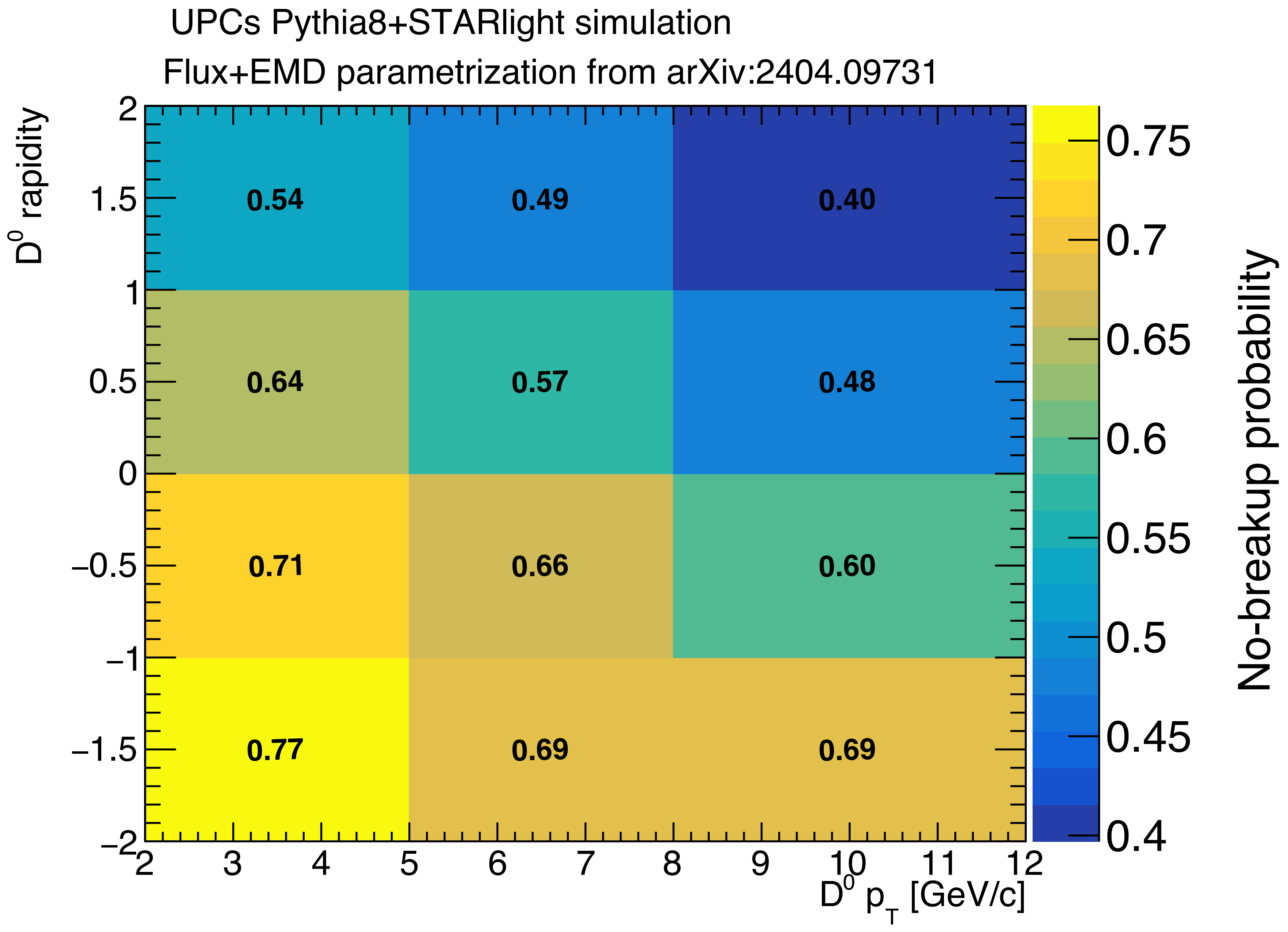


ATLAS, ATLAS-CONF-2017-011
K. J. Eskola et al., https://arxiv.org/pdf/2404.09731

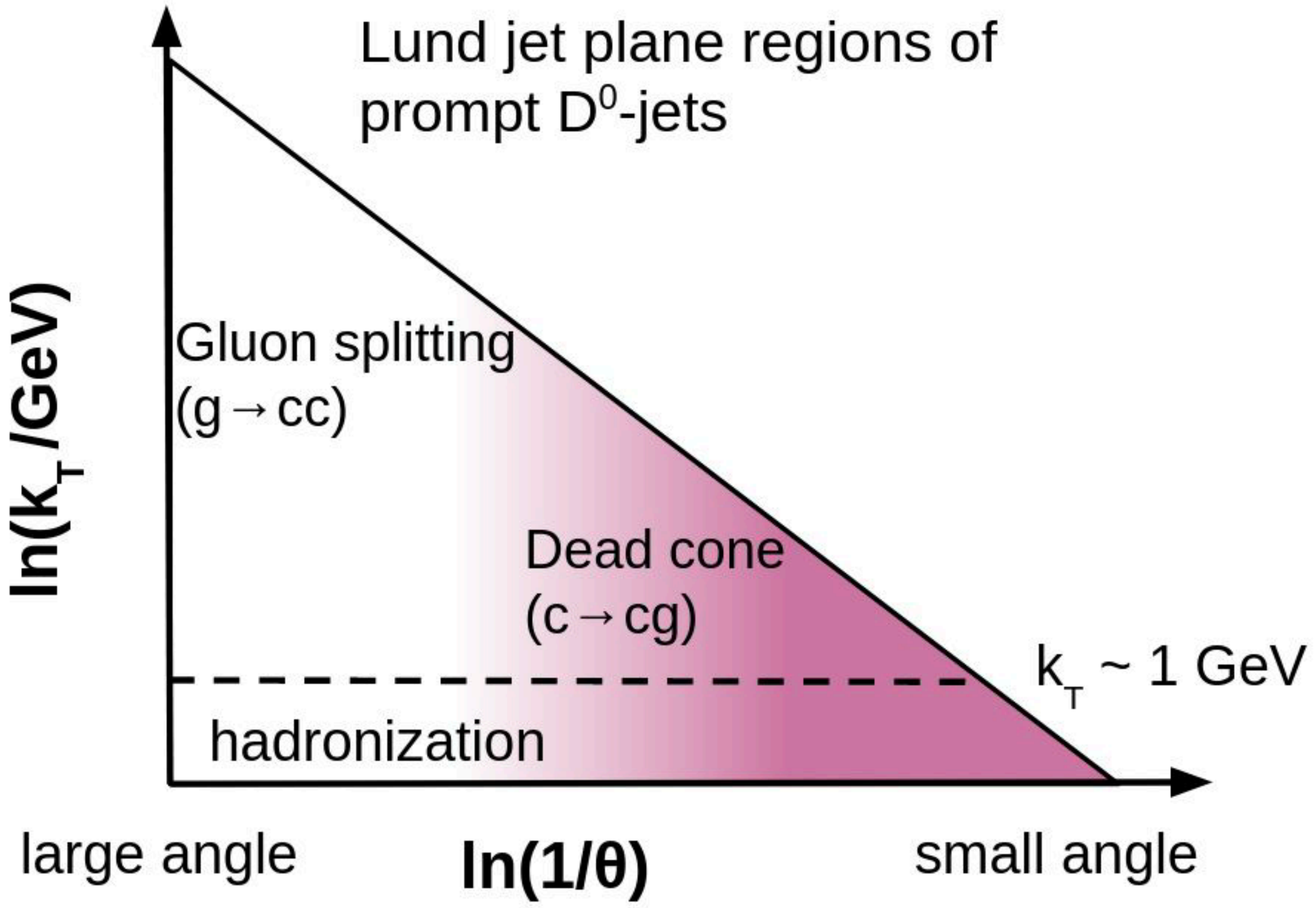
Reweight photon flux to match those expected in UPCs

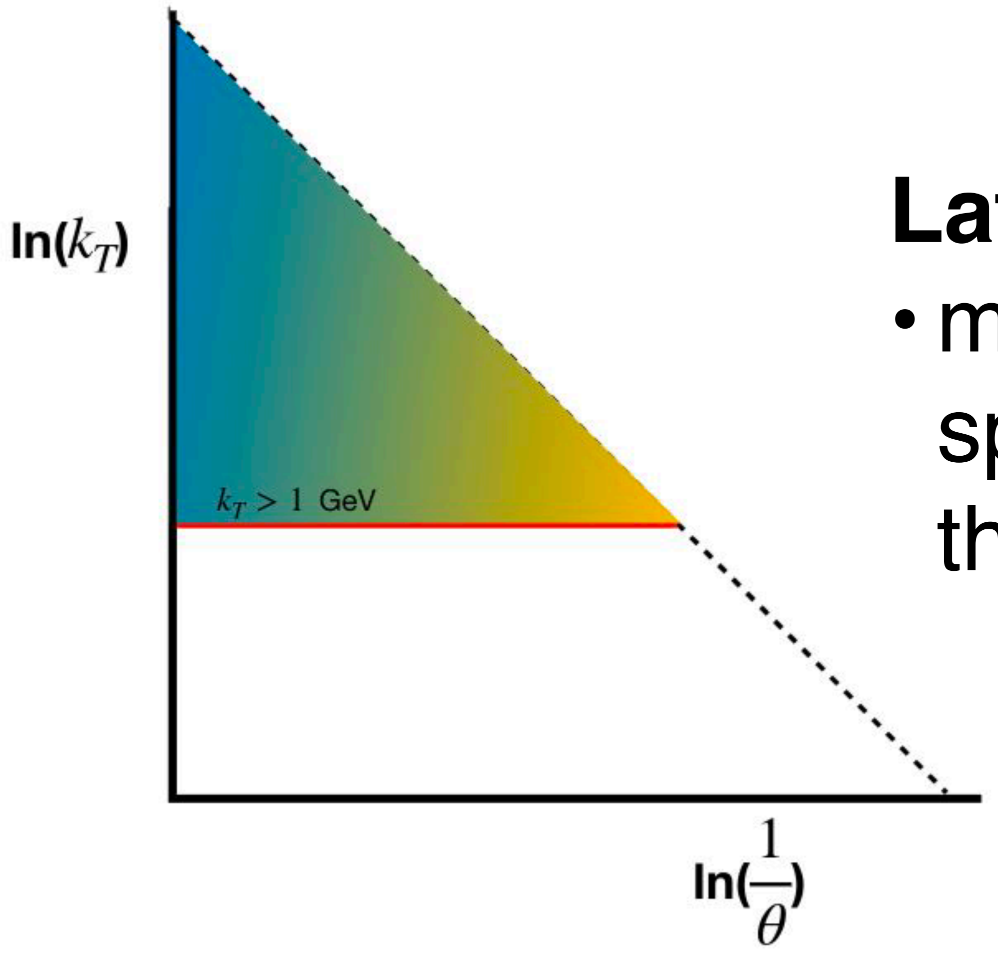


Multiply for the predicted Xn0n “survival” probability in the presence of EM dissociation (EMD)
- estimated by reweighting gen-level Pythia events by the EMD-corrected photon flux for 0nXn topologies

BACKUP: heavy-quark parton shower

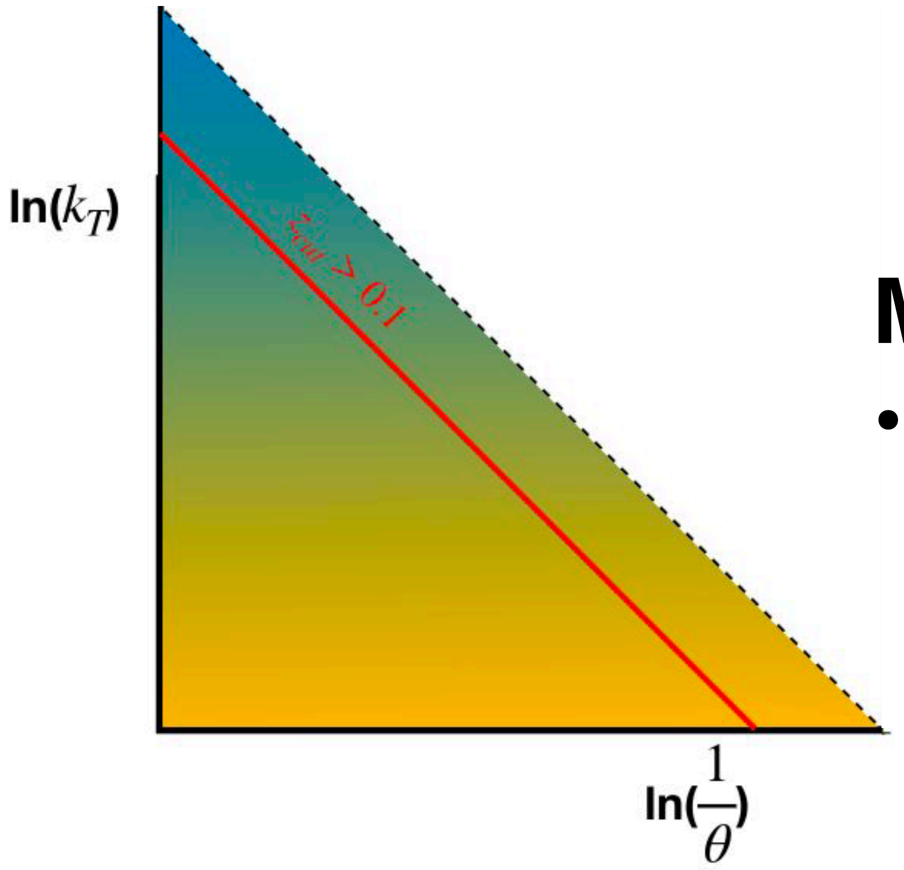
Lund plane of D-tagged jets to expose charm mass effects





Late-k_T groomer (θ_L)

- most collinear among the perturbative splittings in the jet tree the latest splitting that satisfies a hard k_T cut ($k_T > 1$ GeV)



Modified SoftDrop groomer (θ_{MSD})

- first splitting that satisfies z_{cut}=0.1, β>0, $k_T > 1$ GeV

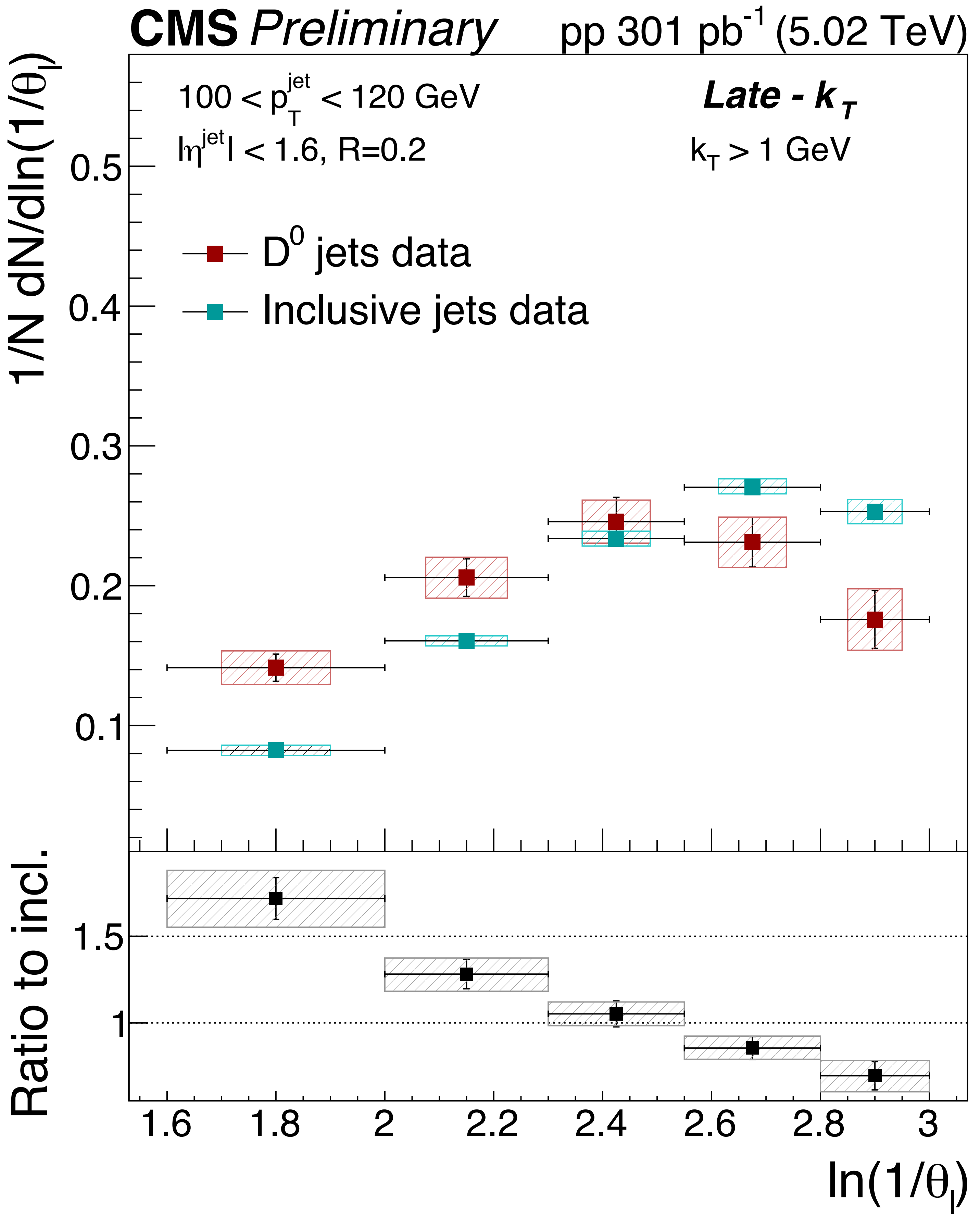
- Expose modification of the angular scale in D-jets relative to inclusive jets
- Study different regions of the Lund jet plane using different grooming algorithms

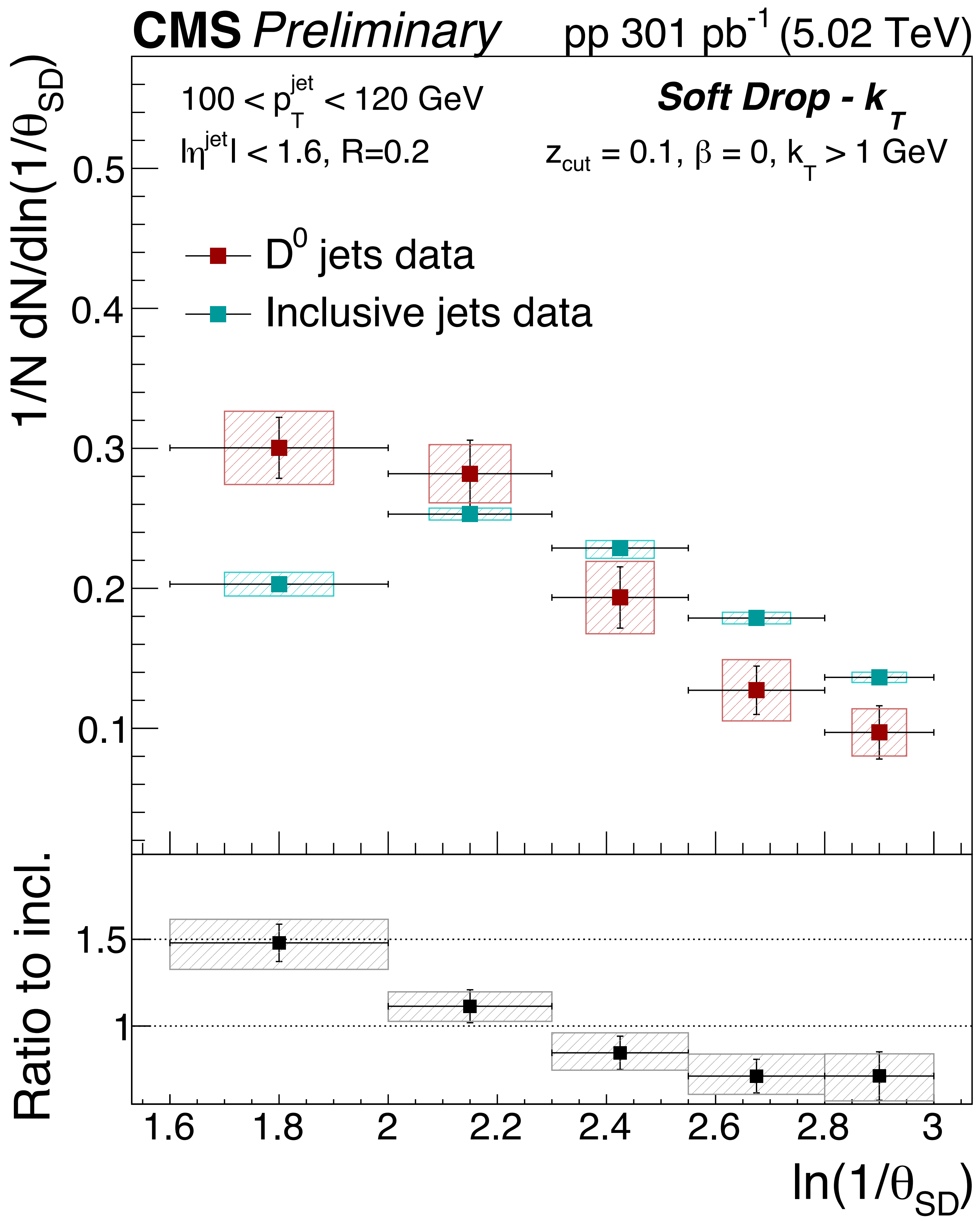
→ **sensitivity to the c mass, gluon splitting, and hadronization effects**

→ **first measurement of c jet substructure in the hard and collinear region of the jet shower**

Lund plane of D-tagged jets to expose charm mass effects

Fully corrected θ_L nd θ_{SD} distributions for D^0-tagged and inclusive jets and their ratios



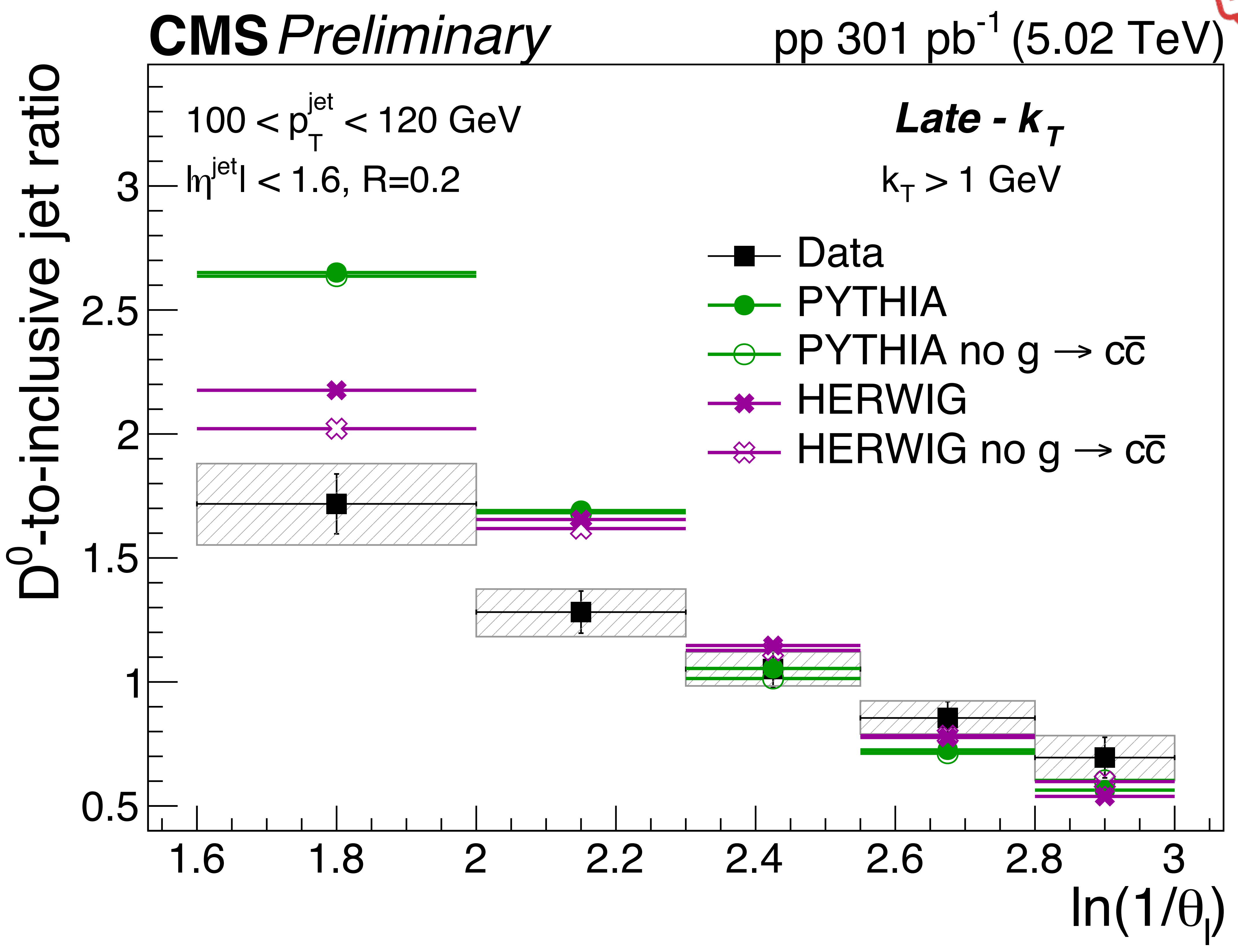


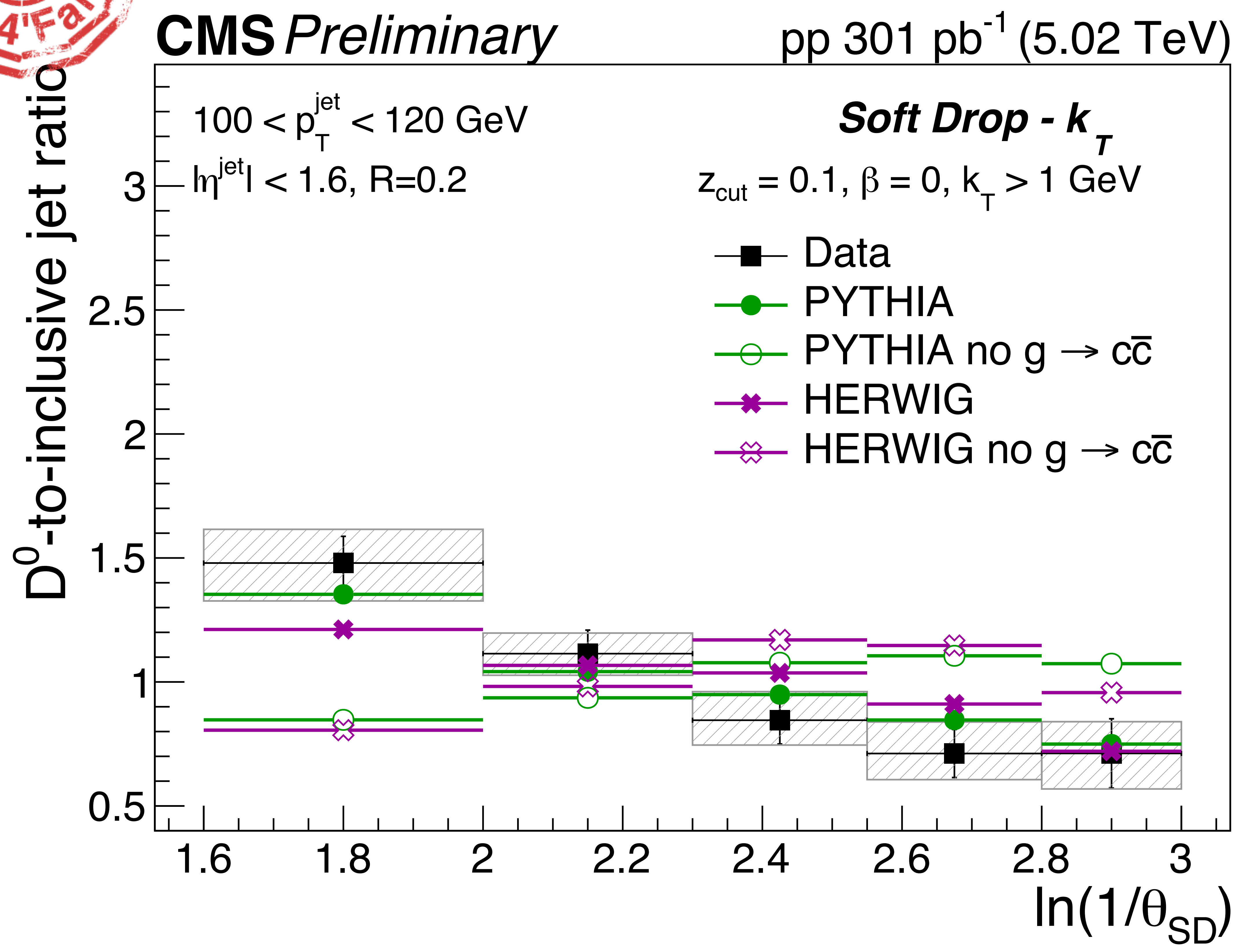
- Shift observed towards bigger angles with respect to the inclusive jets **(dead cone effect)**
- A more prominent shift is observed for the late-k_T algorithm

See Jelena Mijuskovic's talk
CMS-PAS-HIN-24-007

Lund plane of D-tagged jets to expose charm mass effects

See Jelena Mijuskovic's talk
CMS-PAS-HIN-24-007

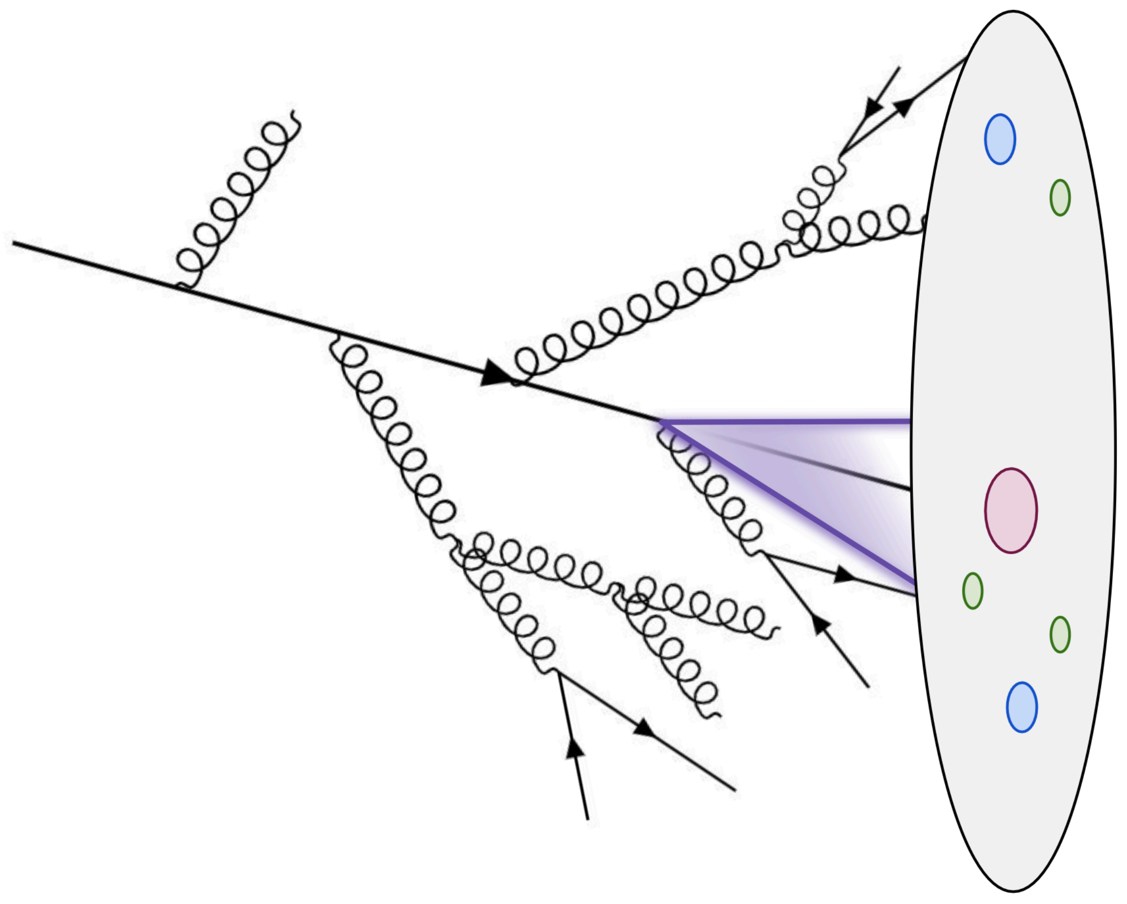


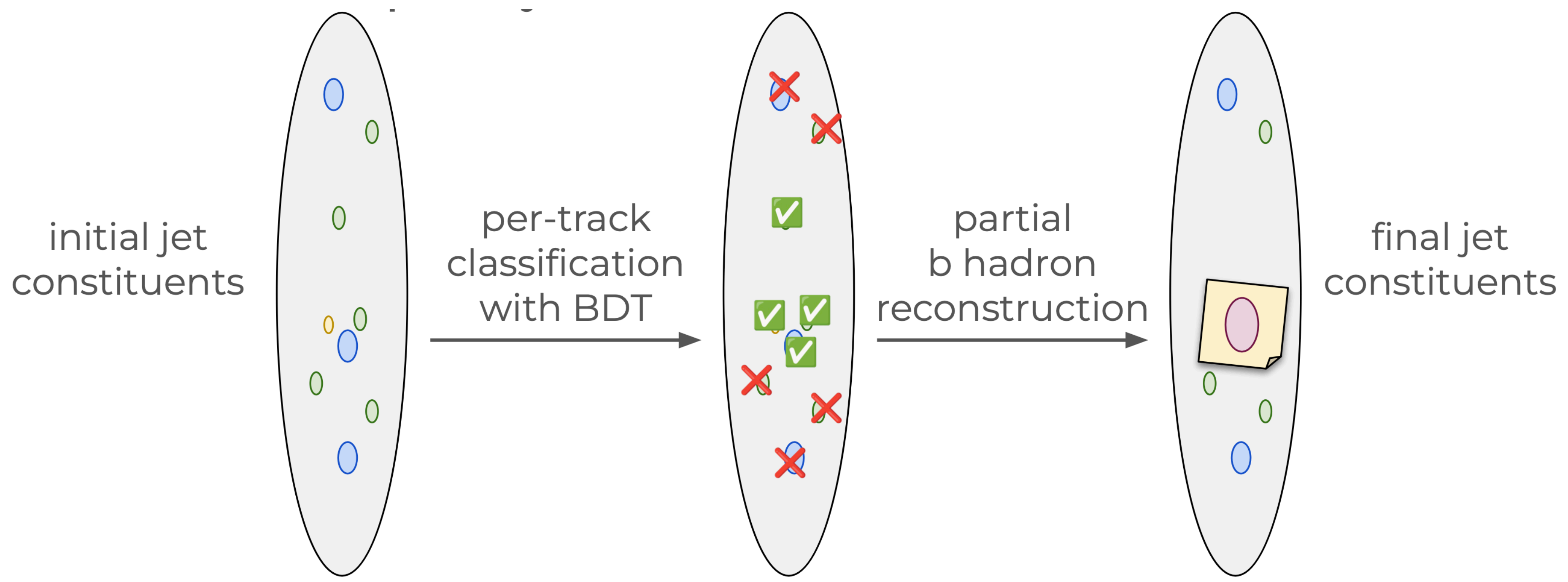


- **Late-k_T**: the gluon splitting contribution is negligible and has an effect mostly at large angles.

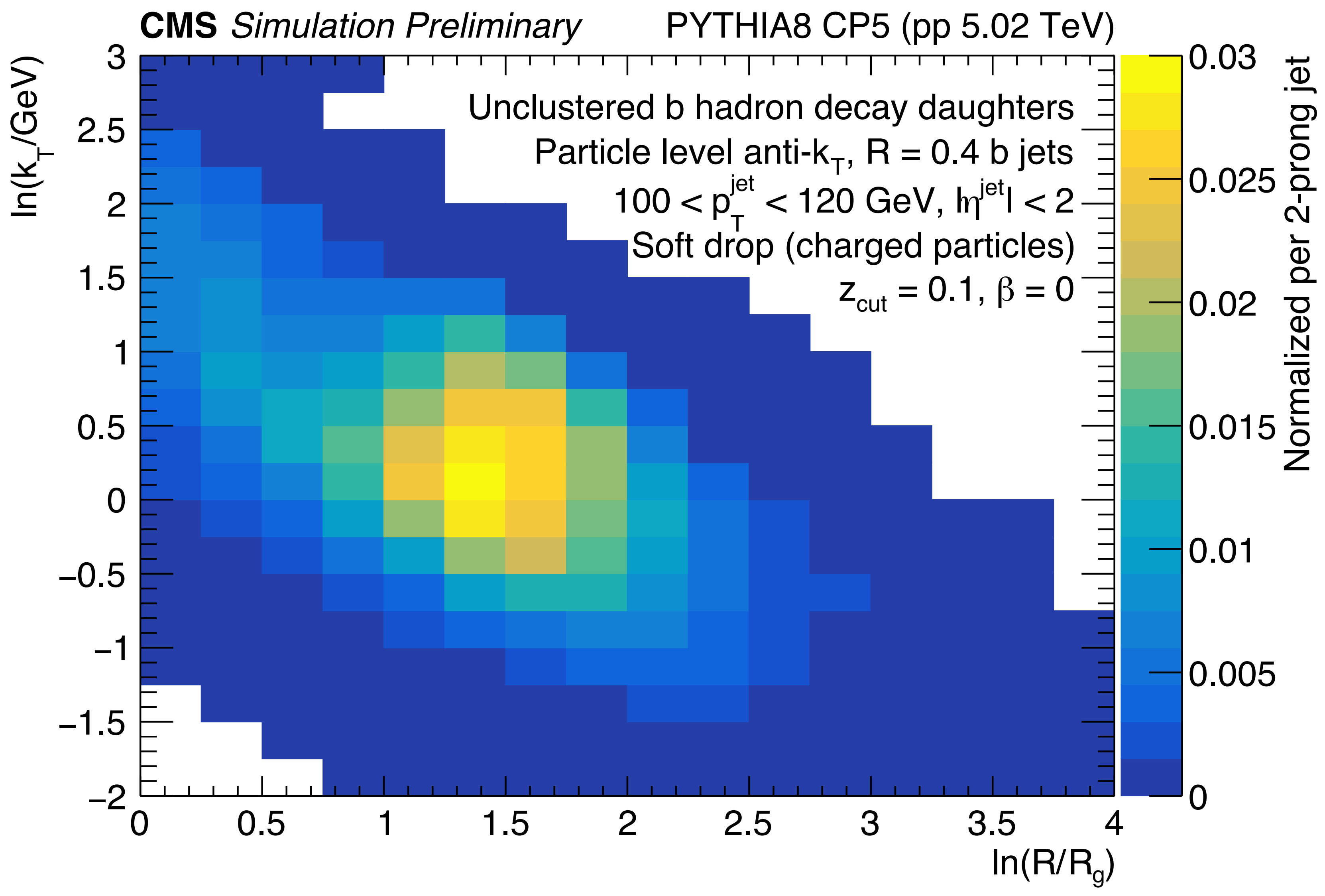
- **SD**: contribution stronger from gluon splitting
- emissions at larger angles than the ones found by late-k_T

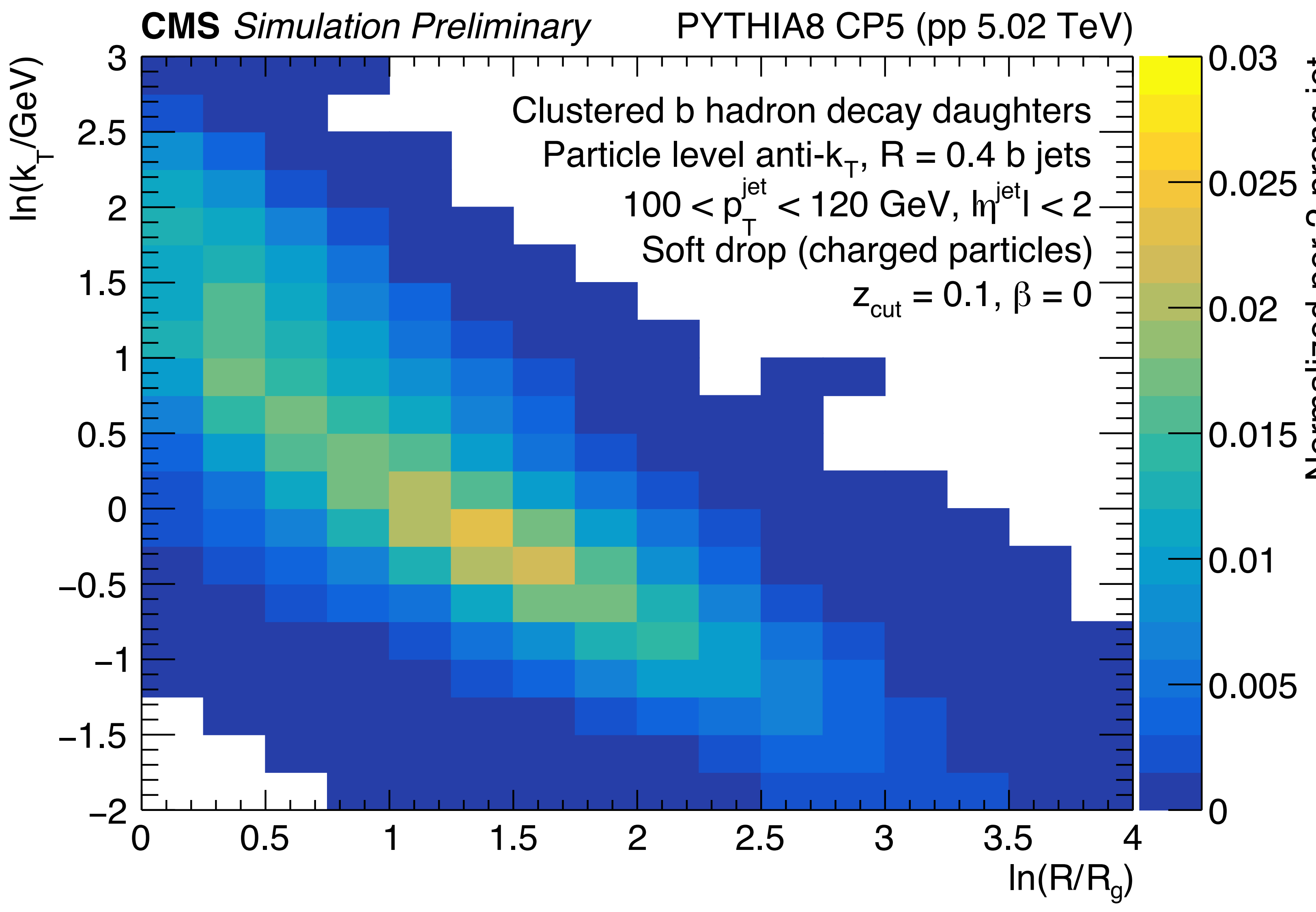
First direct observation of the b-quark dead cone





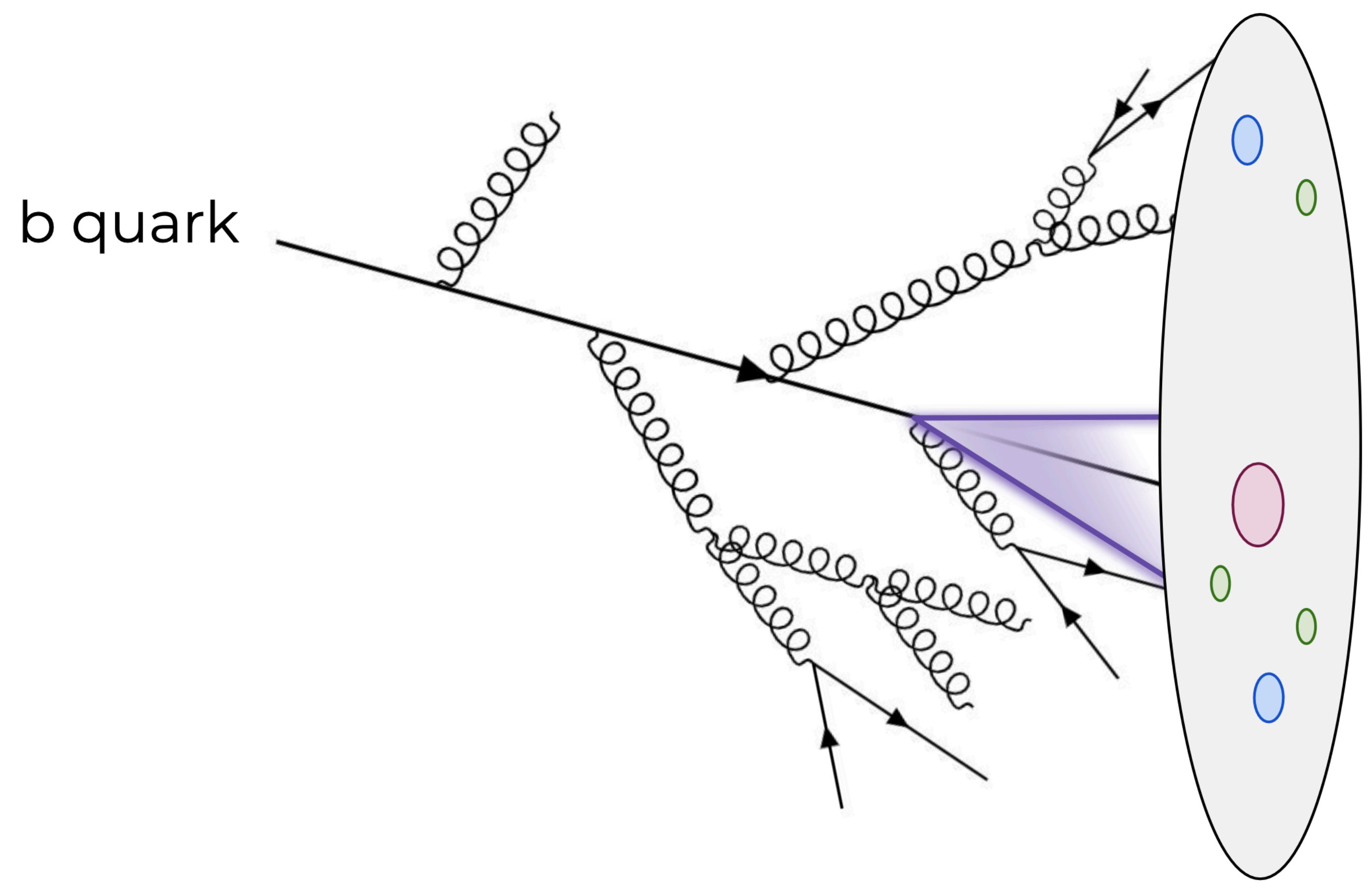
Heavy hadron decay daughters **do not** follow angular ordering





b hadron decays crucial for b jet substructure measurements ⇒ developed a tool to partially reconstruct the b hadron

b-jet substructure with aggregation of b-hadron decays



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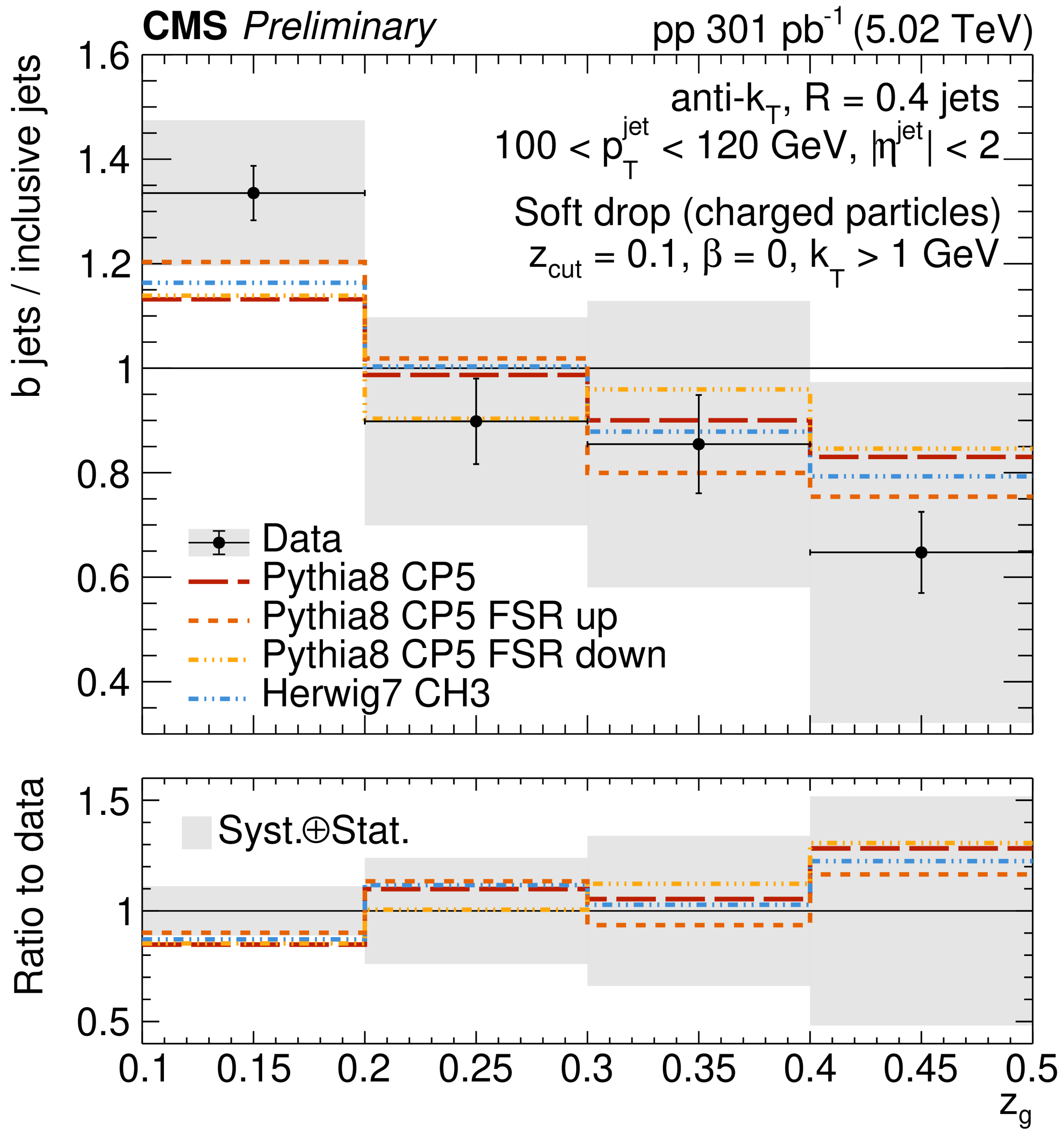
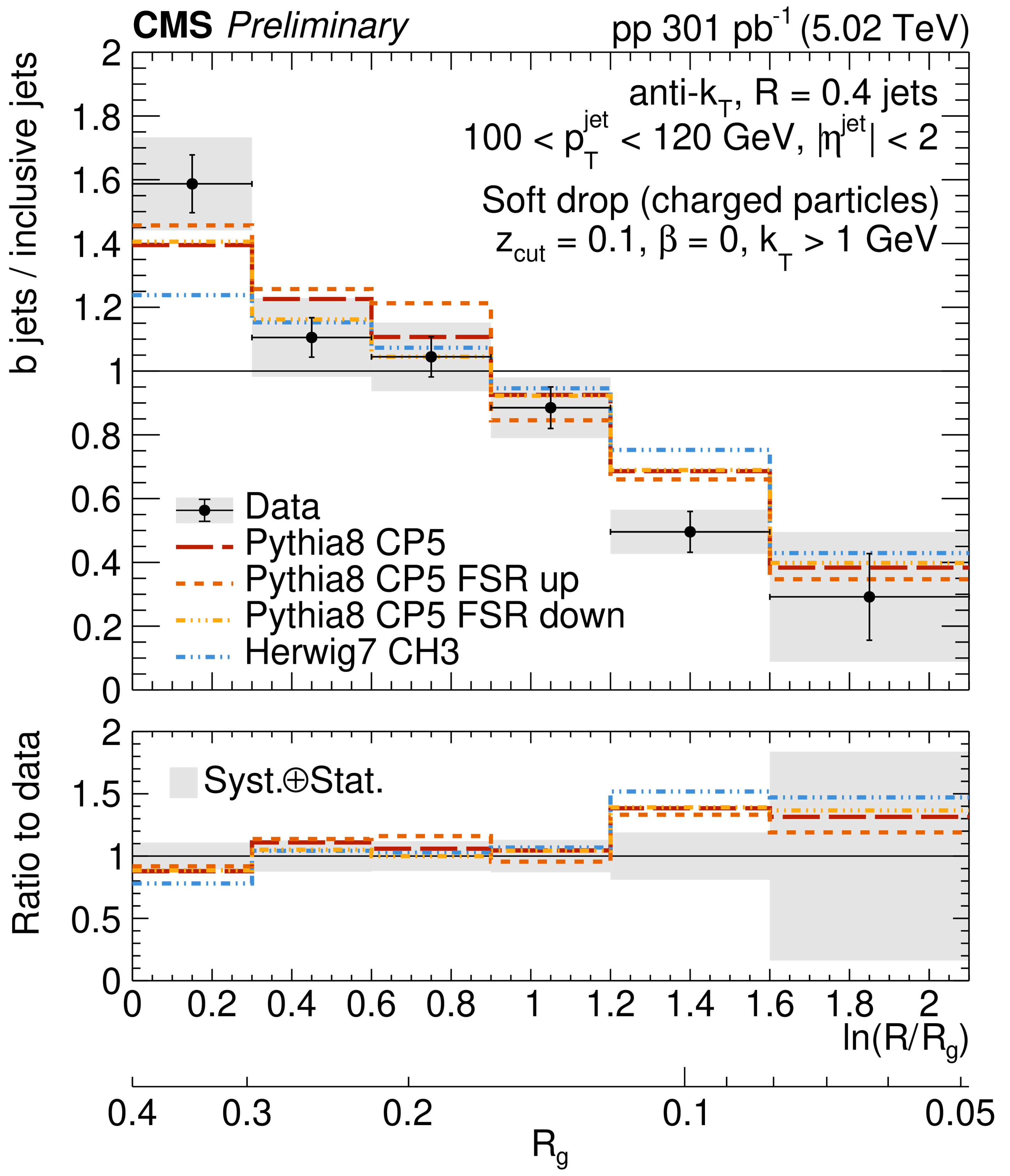




Models agree with z_g PYTHIA8 in agreement with R_g but not HERWIG7

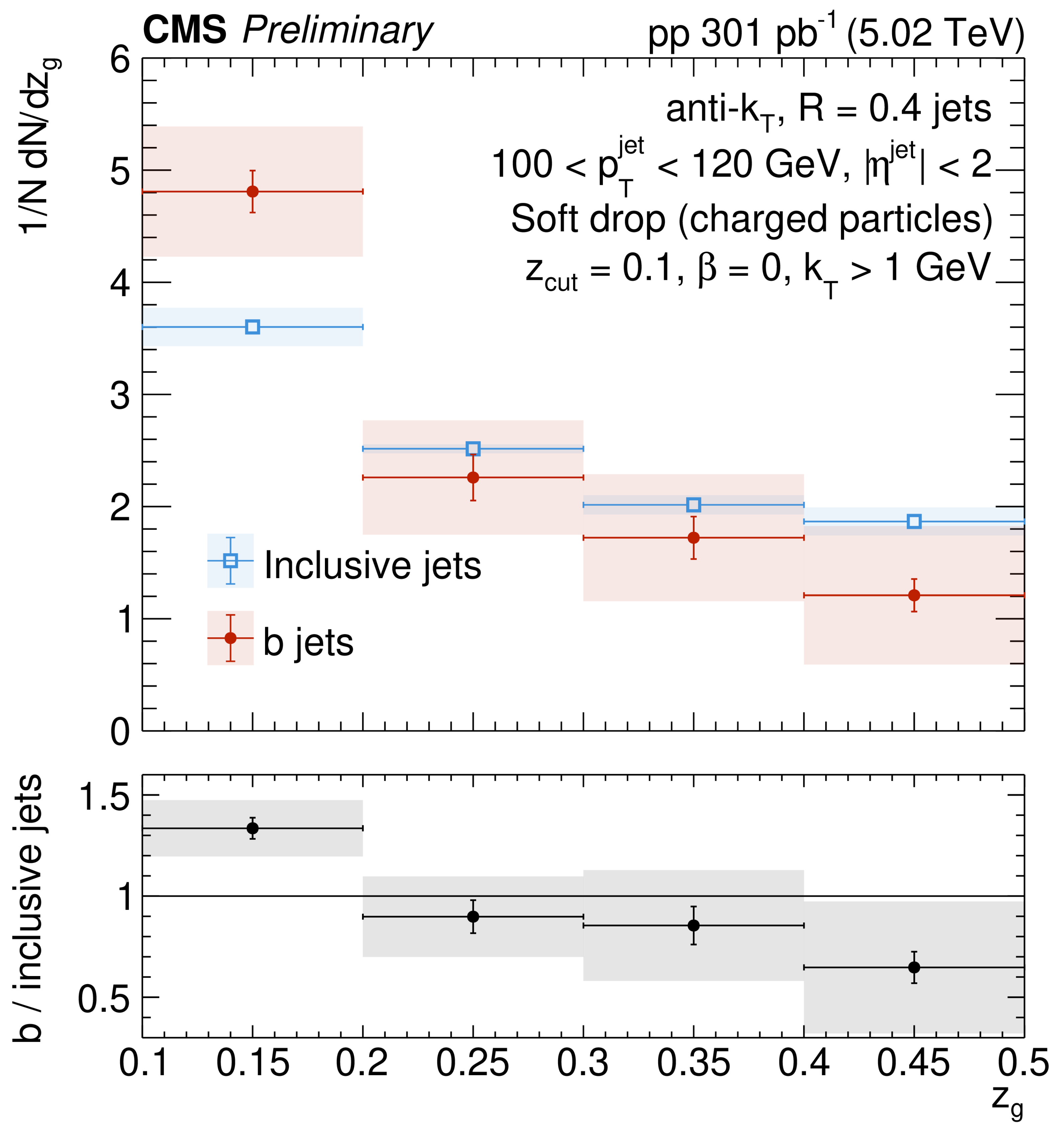
First time we observe the suppression of collinear emissions for b jets (dead cone)

CMS NEW Prelim 24'Fall

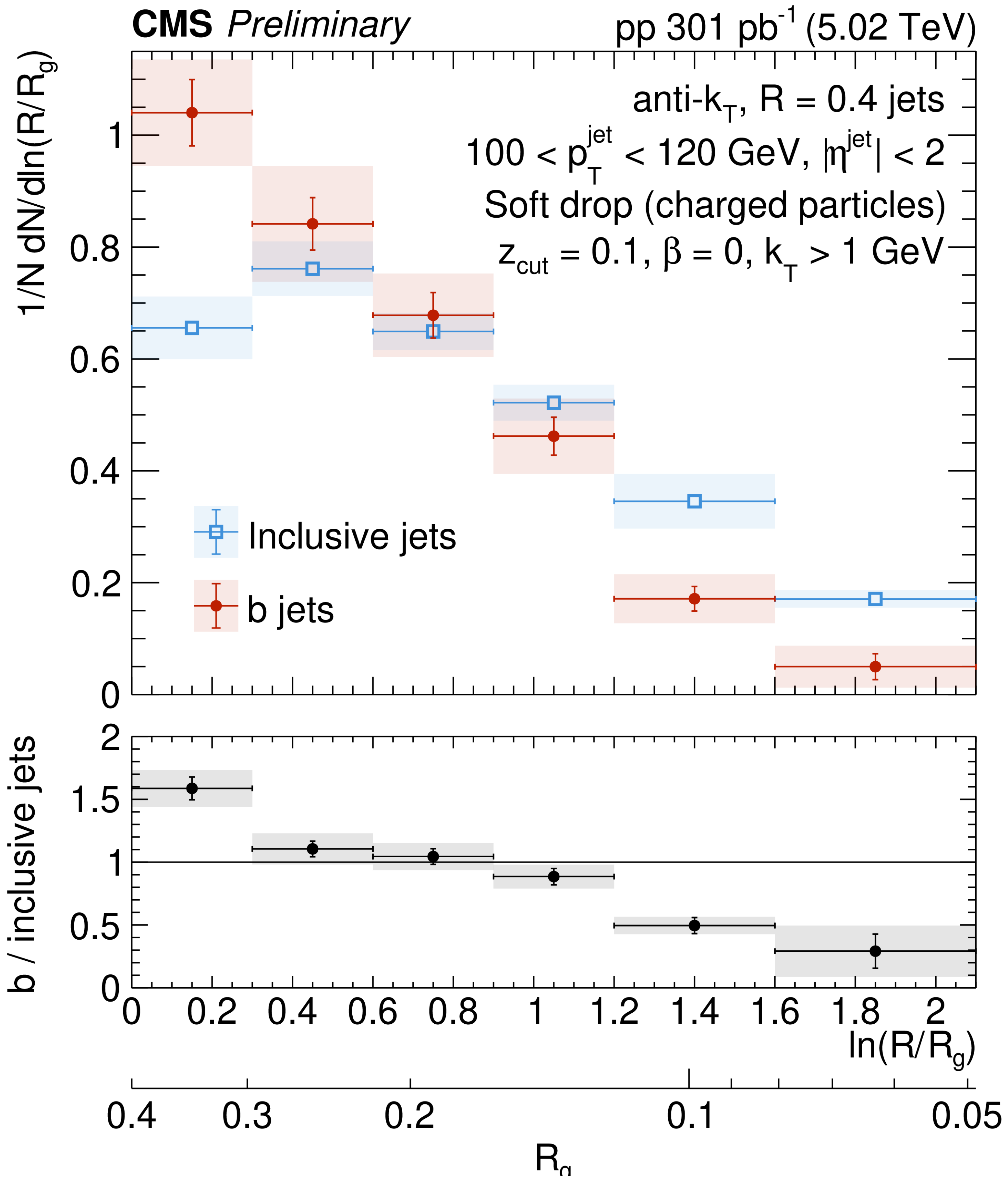
See Lida Kalipoliti's talk

CMS-PAS-HIN-24-005

b-jet substructure with aggregation of b-hadron decays



More imbalanced splittings for b jets



Suppressed small-angle radiation
dead cone manifestation

CMS NEW Prelim 24'Fall

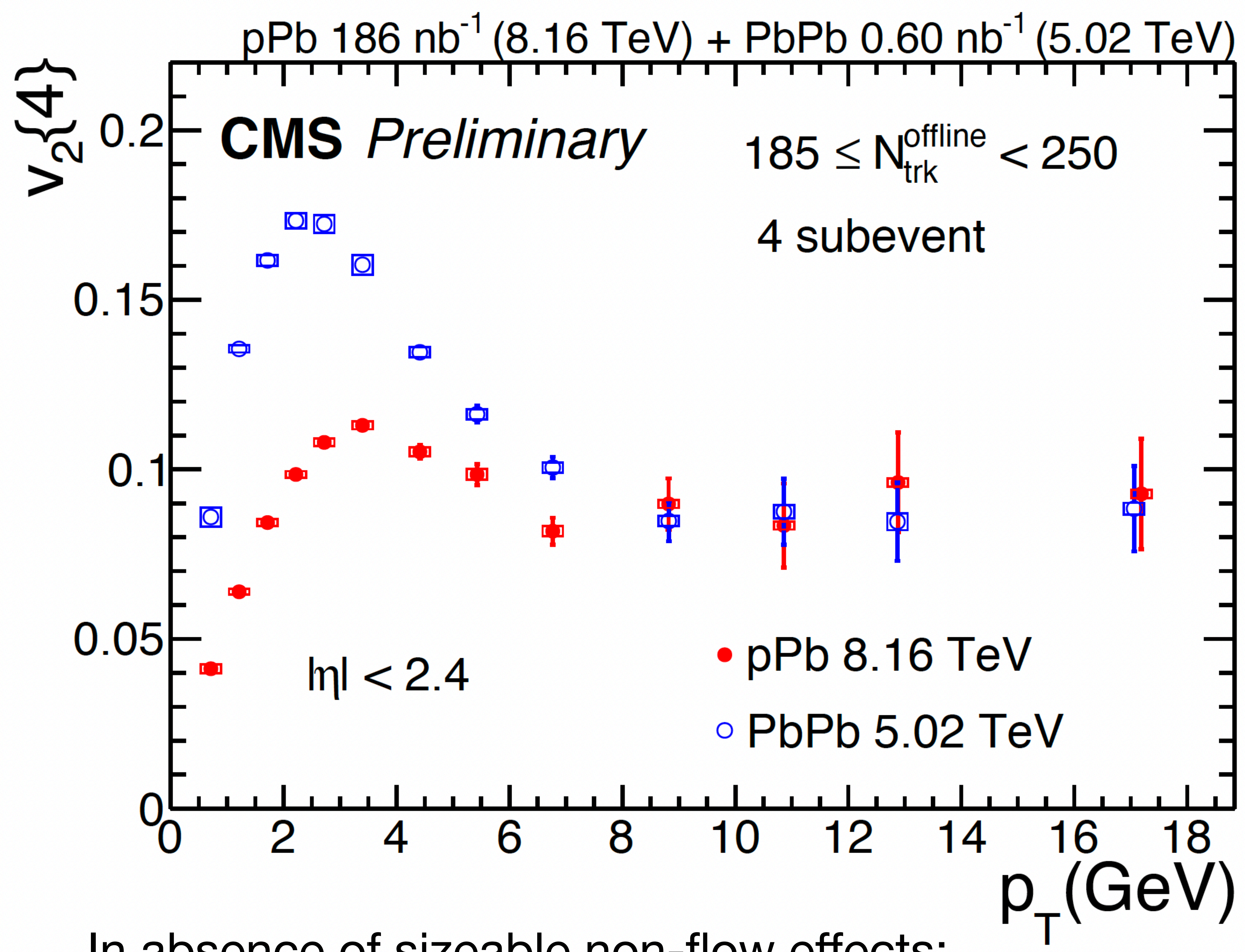
See Lida Kalipoliti's talk
CMS-PAS-HIN-24-005

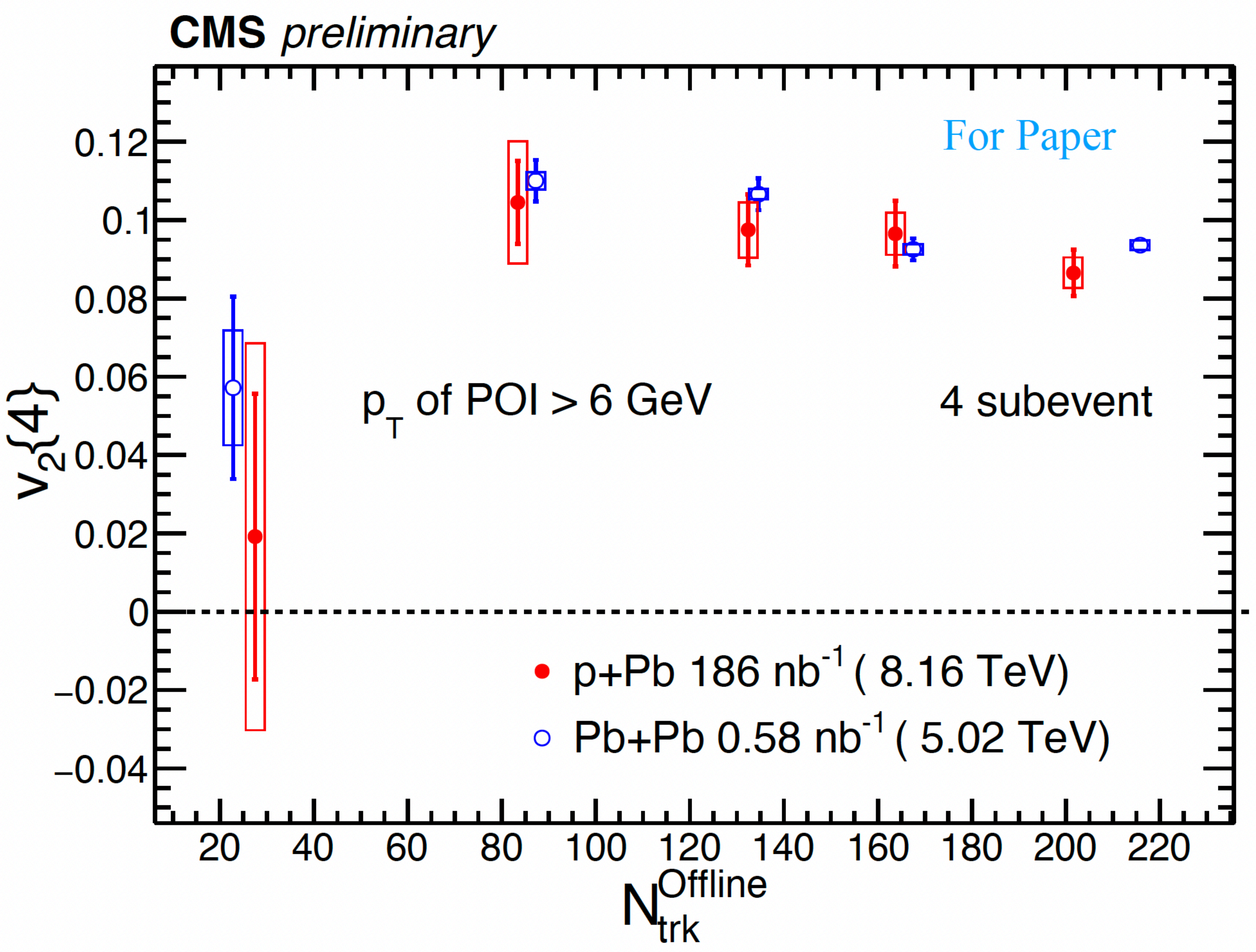
BACKUP: Jet-medium interactions

Search for energy loss in pPb collisions: high-p_T v_2

See Rohit Singh's talk
CMS-PAS-HIN-23-002

→ insights into the potential indications of high parton energy energy loss with 4-subevent cumulant method extended to high p_T





In absence of sizeable non-flow effects:
→ **positive $v_2\{4\}$ persisting up to p_T ~20 GeV**

similarity between **high-multiplicity pPb** and peripheral PbPb events in magnitude and p_T dependence

Similar magnitude and similar trend for both PbPb and pPb when POI > 6 GeV across all multiplicity bins

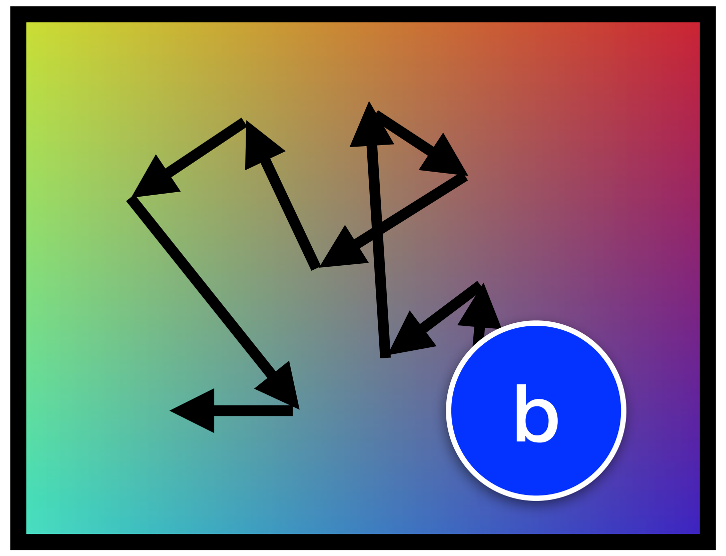
QGP diffusion properties with low p_T B hadrons

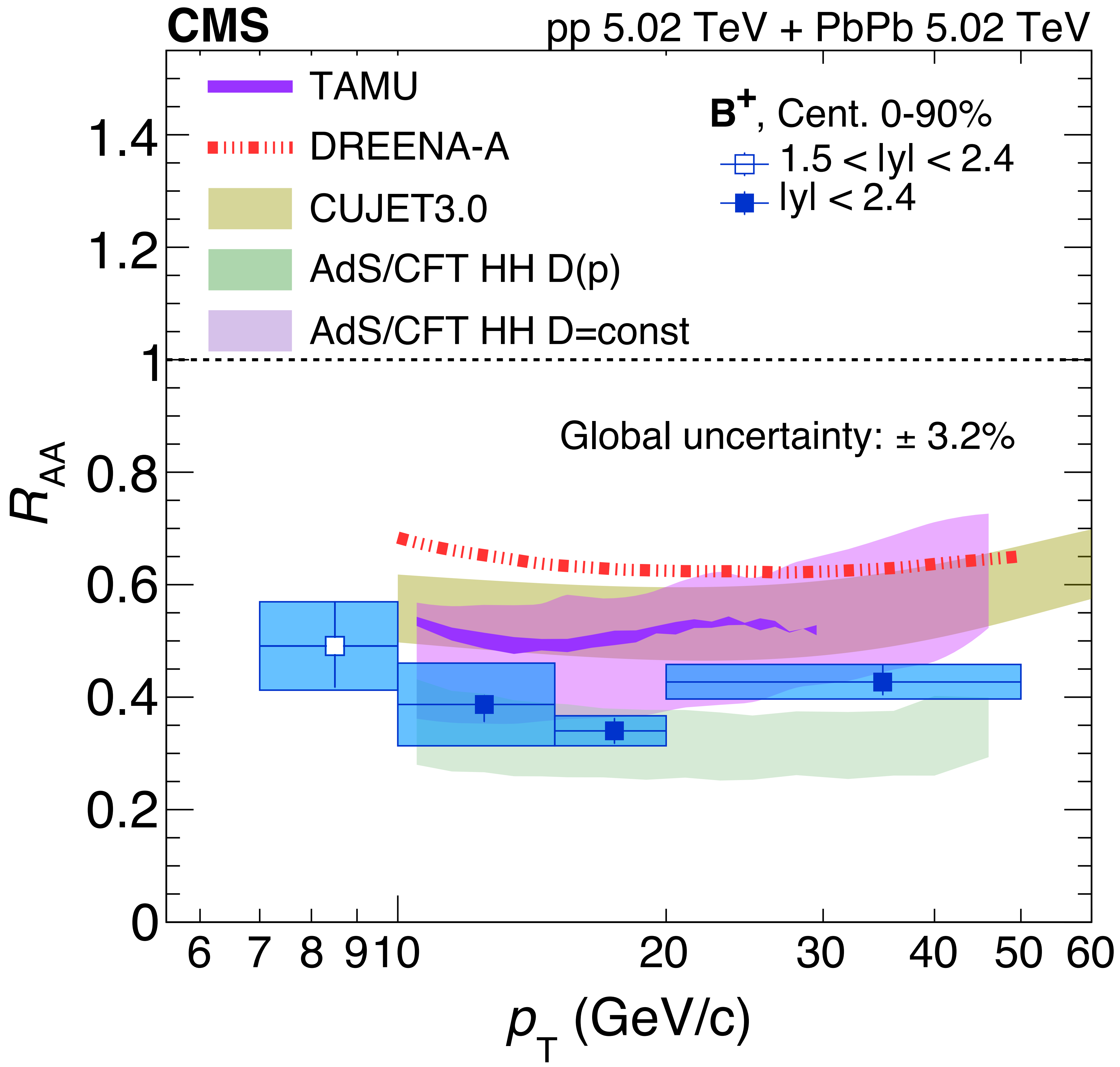
See Tzu-An's talk
arXiv:2409.07258

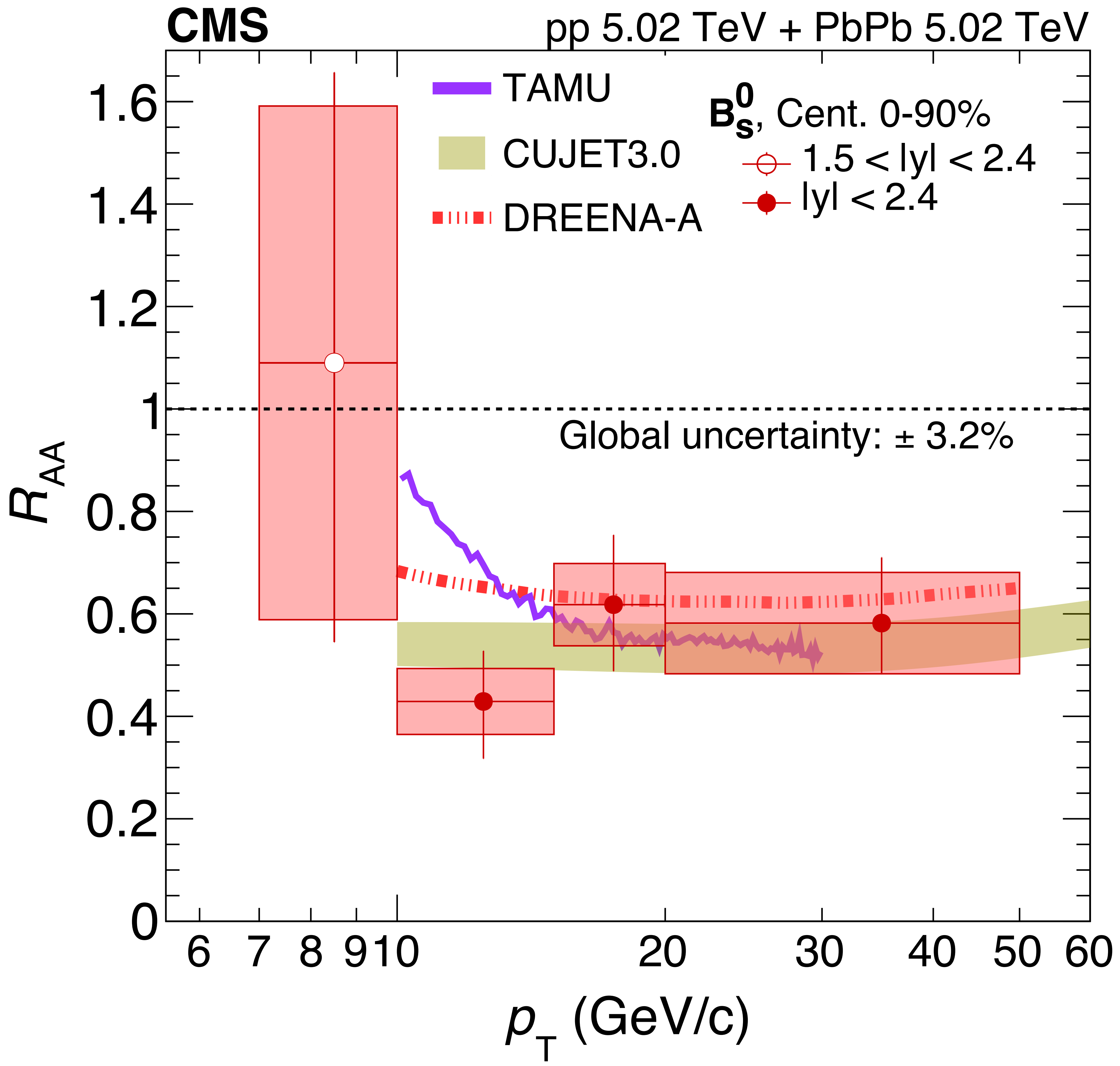
charmed and beauty mesons down to low p_T →brownian particles inside the hot medium

- **$m_{c,b}$ > $m_{u,d,s}$: "Brownian regime" in the QGP**

→ sensitive to the **QGP diffusion** and drag properties

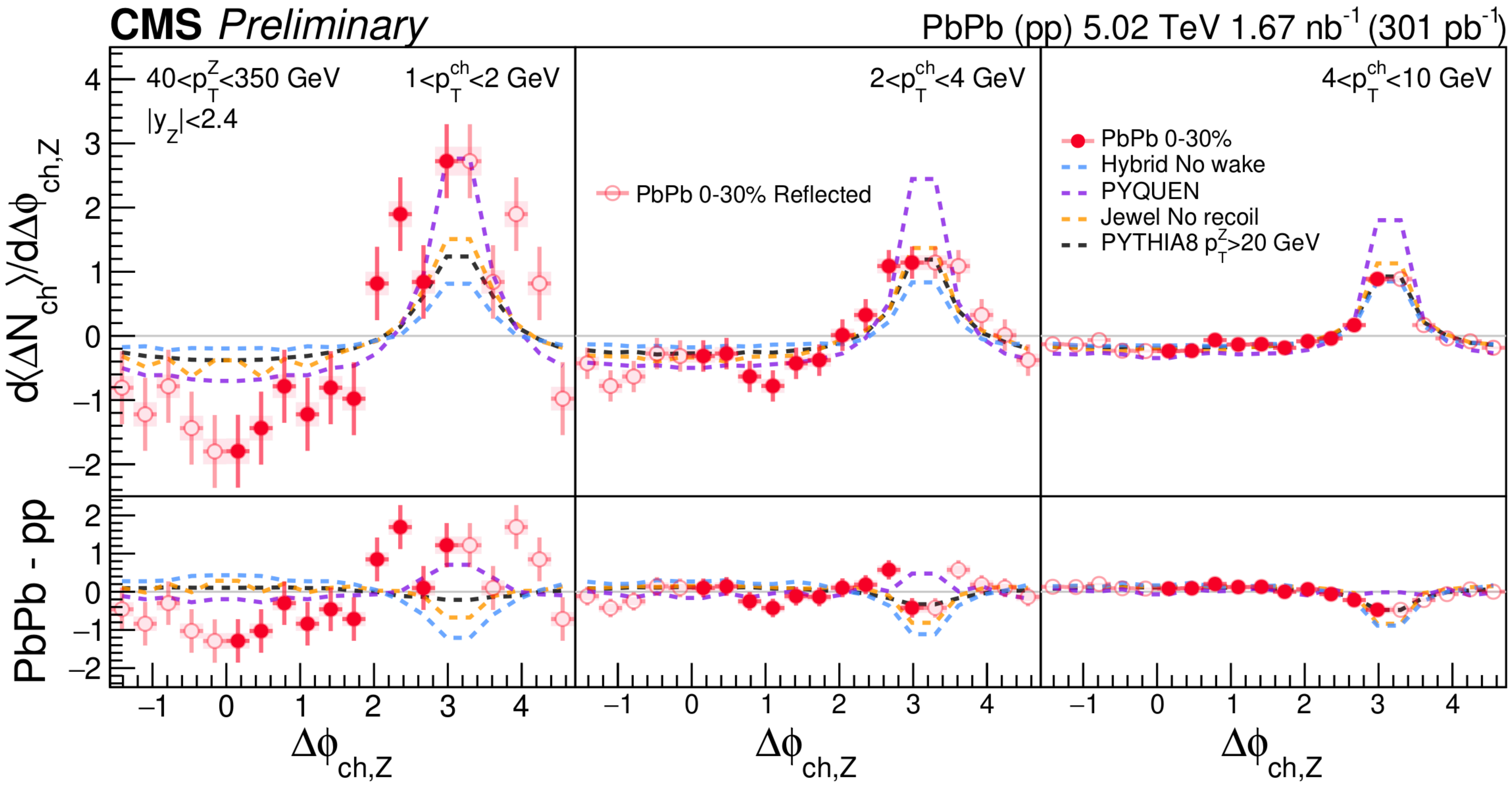






Z^0-hadrons: comparison with models w/o medium response

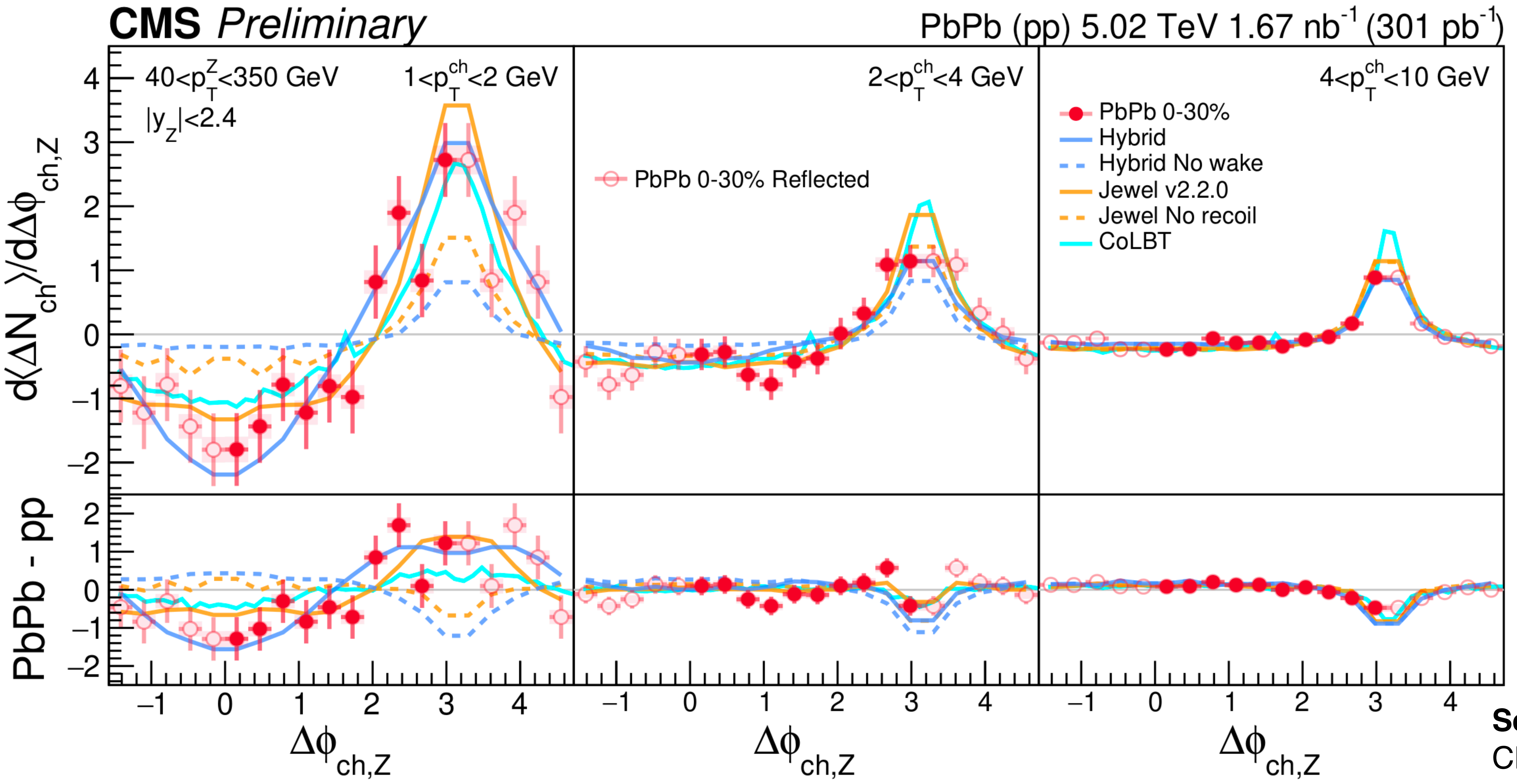
- **Hybrid without wake** and **Jewel without recoil** (dashed lines) underpredict magnitude at low hadron p_T
- **PYTHIA8 lower $p_{T,Z}$-tagged events** can describe jet quenching (similar to no-wake/recoil models with only the jet shower). It fails to describe data for hadron p_T< 4 GeV.
- **PYQUEN**, (no 4-momentum conservation), fails to describe generally the data



See Yen-Jie Lee's talk
CMS-PAS-HIN-23-006

Z⁰–hadrons: comparison with models w/ medium response

- **Hybrid without wake** and **Jewel without recoil** (dashed lines) underpredict magnitude at low hadron p_T
- **Hybrid with wake**, **Jewel with recoil** and **CoLBT with wake** **(solid lines)** agree better with the data with hadron $p_T < 4$ GeV



See Yen-Jie Lee's talk
CMS-PAS-HIN-23-006

Z0–hadrons: comparison with models w/ medium response

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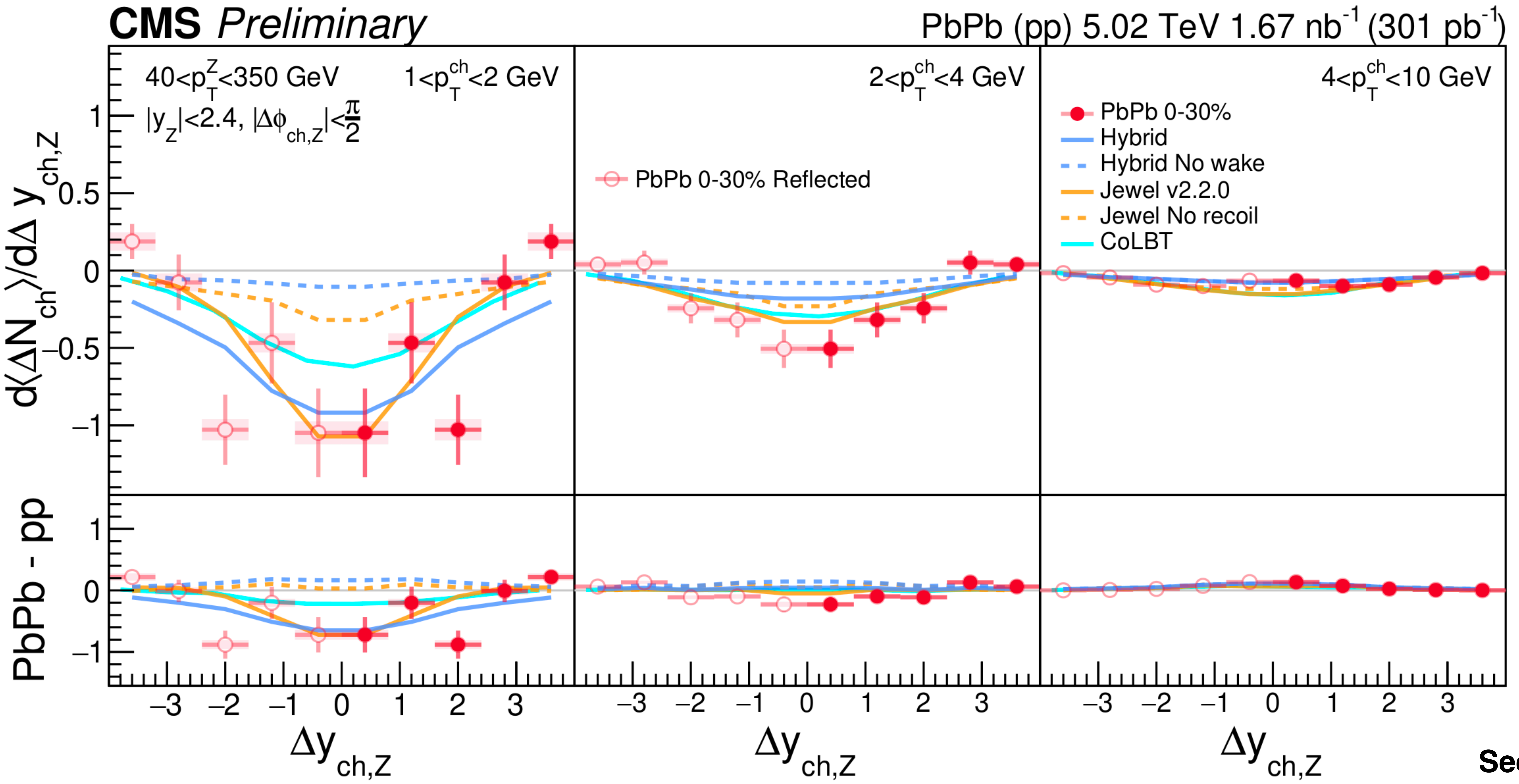
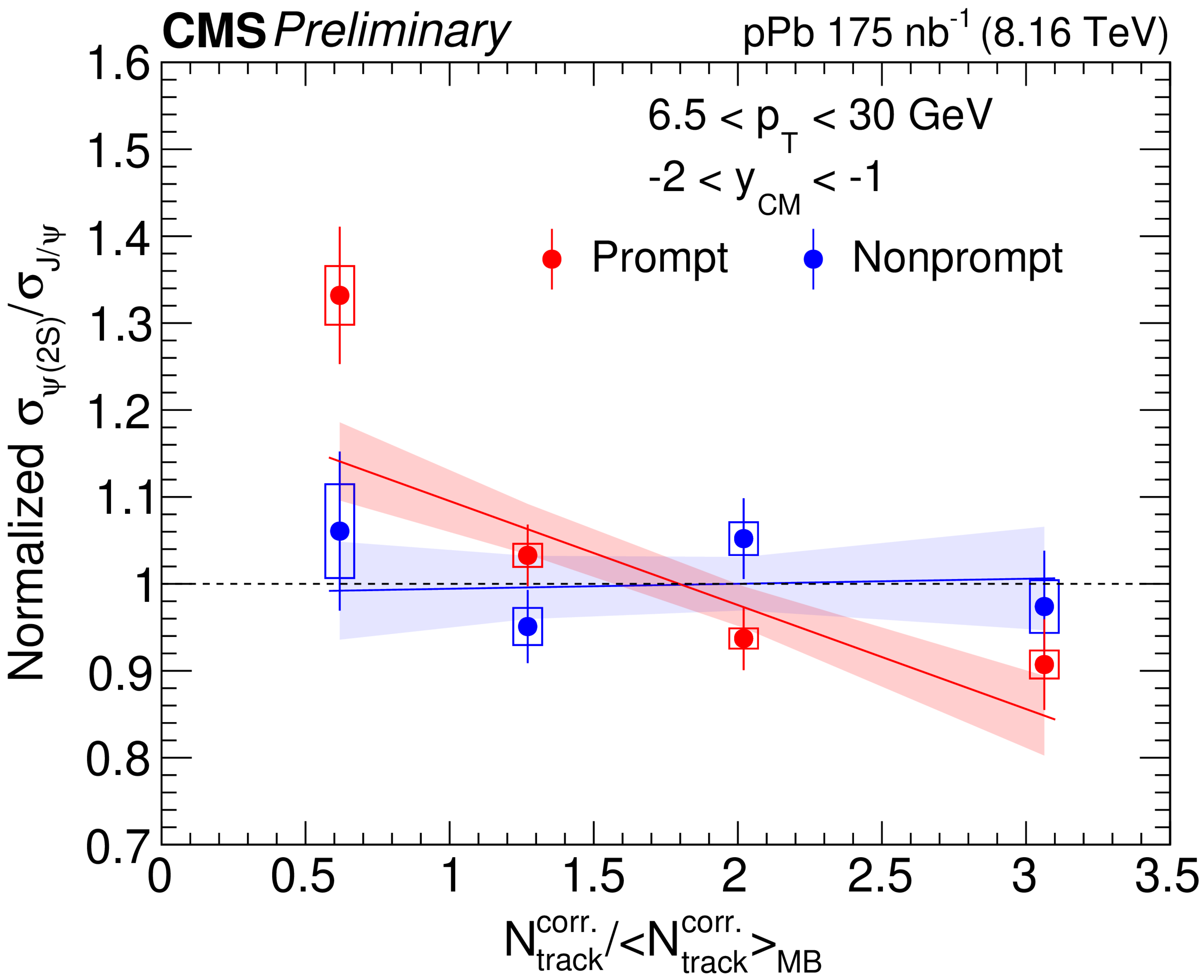


See **Yen-Jie Lee's talk**
CMS-PAS-HIN-23-006

Multiplicity dependence of Ψ(2S) / J/Ψ in pPb

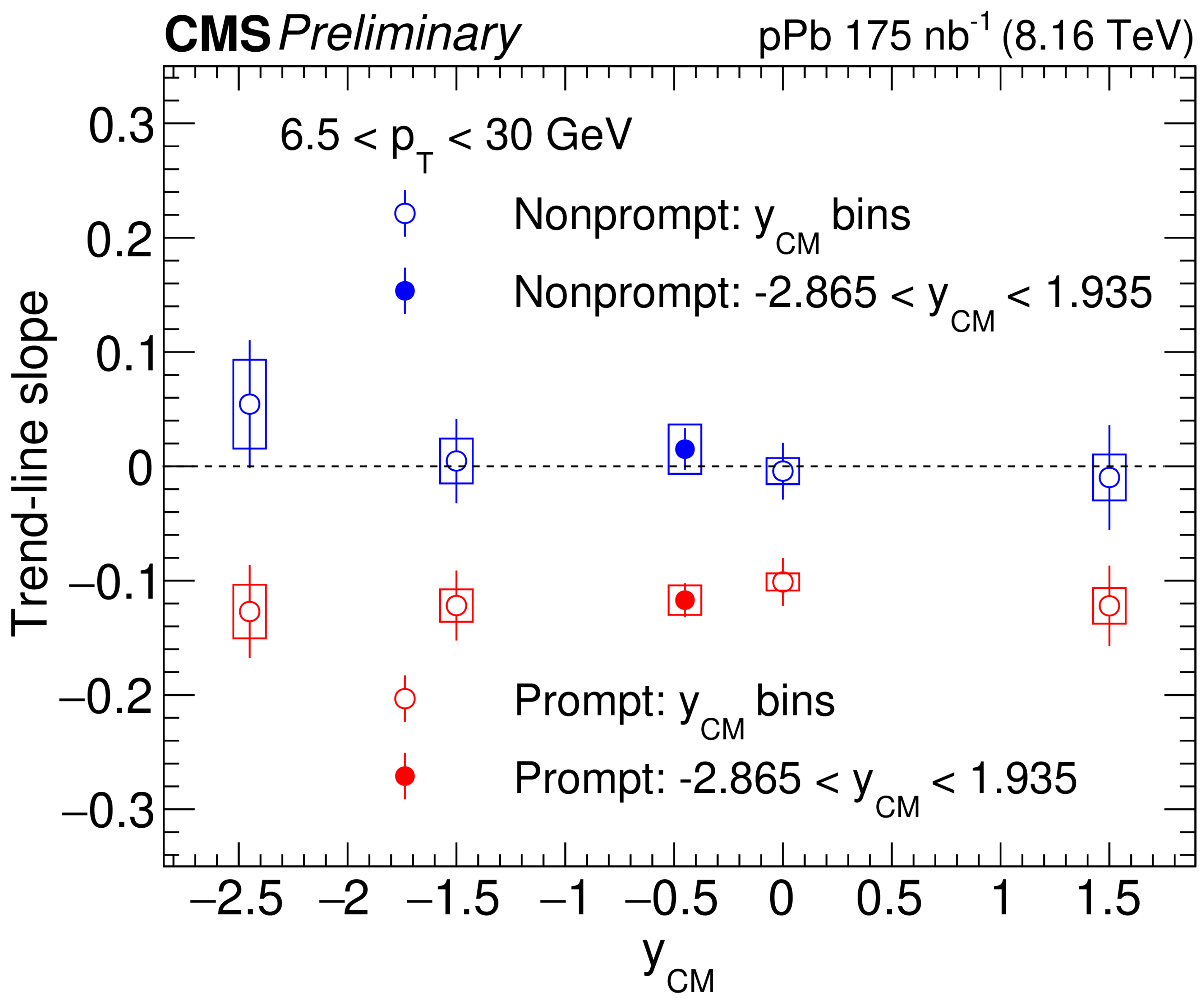
See Austin's talk
CMS-PAS-HIN-24-001



- Yield ratios to *cancel out* common modification from initial-state effects
- Decrease with increasing multiplicity for prompt while constant for b-hadron decay contributions
- relative ψ(2S) suppression from **final-state interactions** (comoving-particles picture)

Multiplicity dependence of Ψ(2S) / J/Ψ in pPb

See Austin's talk
CMS-PAS-HIN-24-001

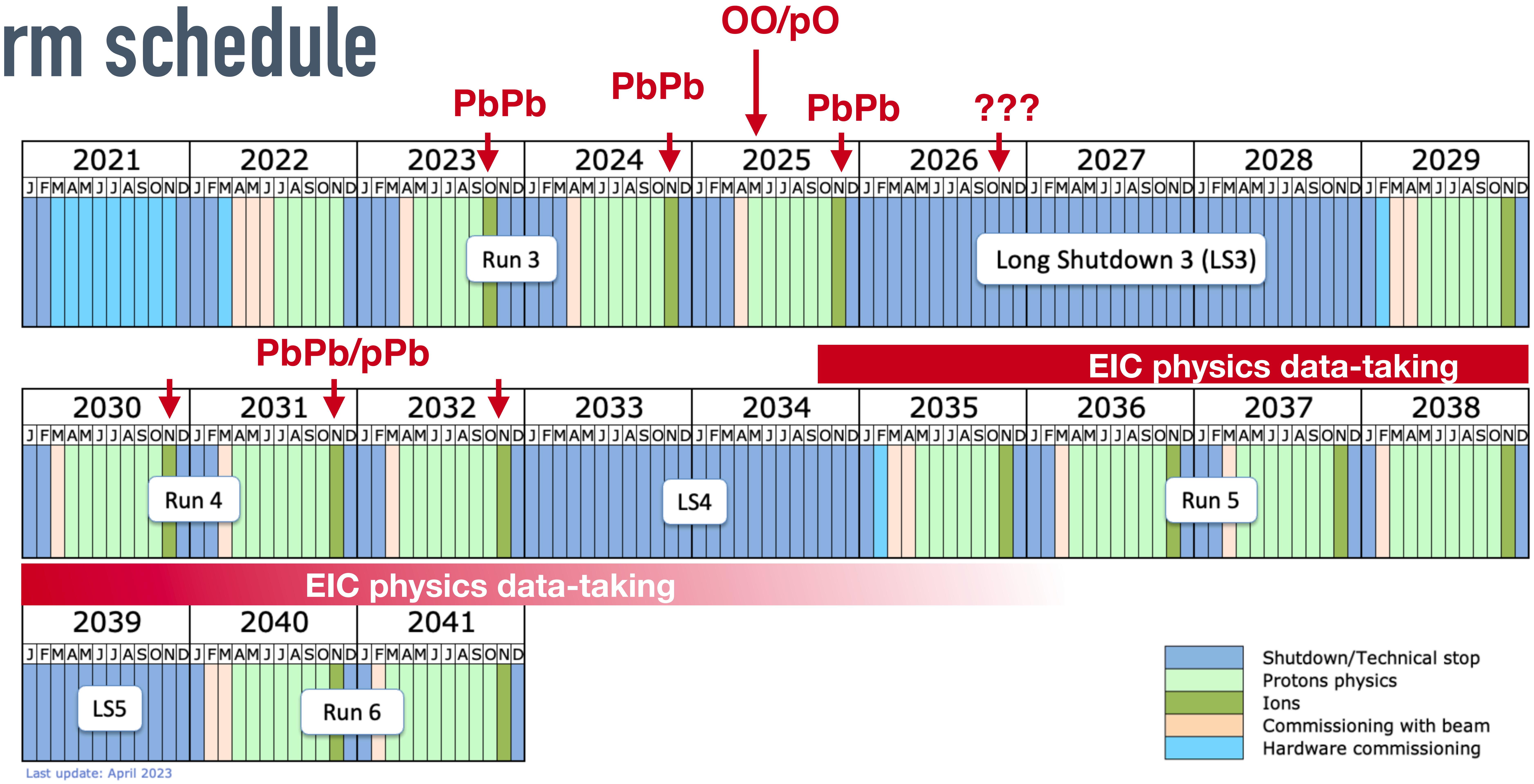


- **Slope of normalized ψ(2S) / J/ψ vs multiplicity**
- **decreasing trend observed for all ψ rapidities** without significant rapidity dependence
- **B hadron contributions not affected**
- additional constraints on the mechanisms of hadronization and suppression in pA collisions

Probed x ~ 10^{-4} – 10^{-5} in the rapidity range

BACKUP: CMS Run 4

LHC long-term schedule



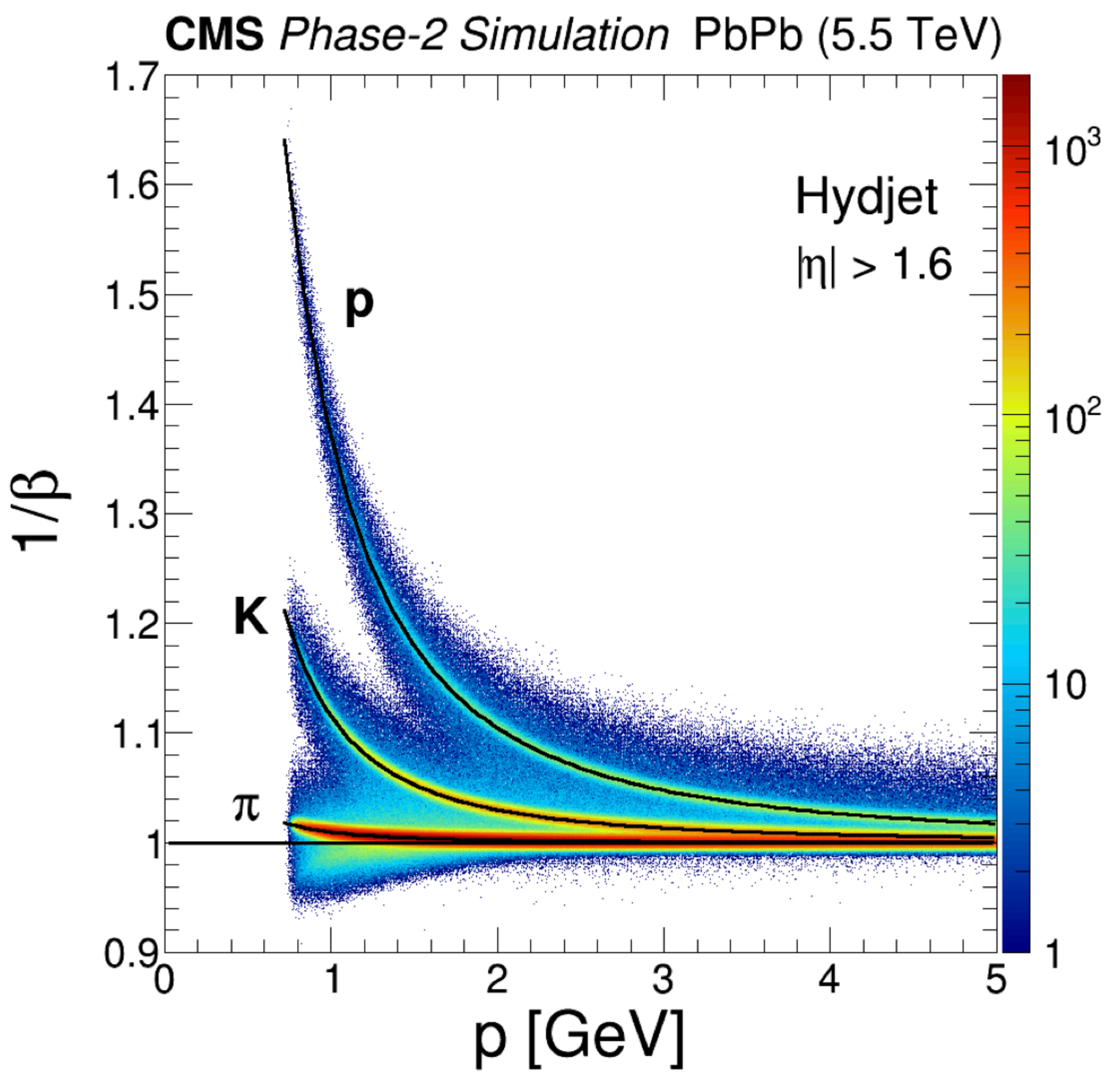
- **About a week of OO/pO in 2025:** statistics is enough for very soft-probe measurements, assessing quenching in small systems
  → we would need a few weeks of data to constrain nPDFs with EM probes or high-accuracy heavy-quark probes
- **Additional run in Run 3? pPb in Run 4?**
- **Inputs for Run 5/6 from the "parton-structure" community?**

The upgraded CMS detector for Run 4 (Phase II)

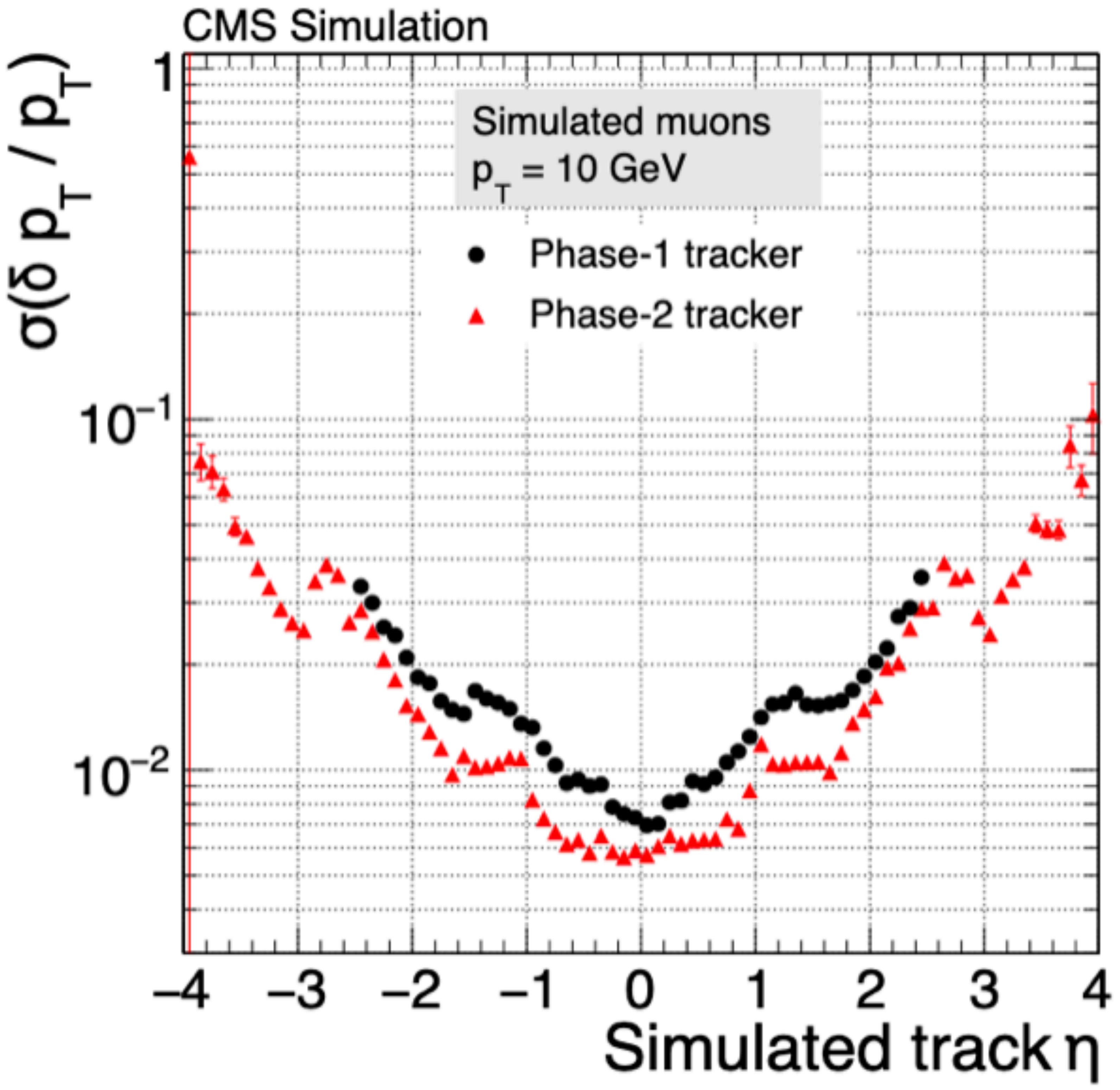
CMS, CERN-LHCC-2019-003
CMS, CMS-TDR-014

Track-based triggers at Level-1 to sample the entire cross section of photon-induced collisions in both pPb and PbPb events

Particle Identification over (MTD) in $|\eta| < 3$



New high resolution silicon tracker with ~ factor 2 larger coverage from $|\eta_{tracks}| < 2.4$ **to from** $|\eta_{tracks}| < 4.0$



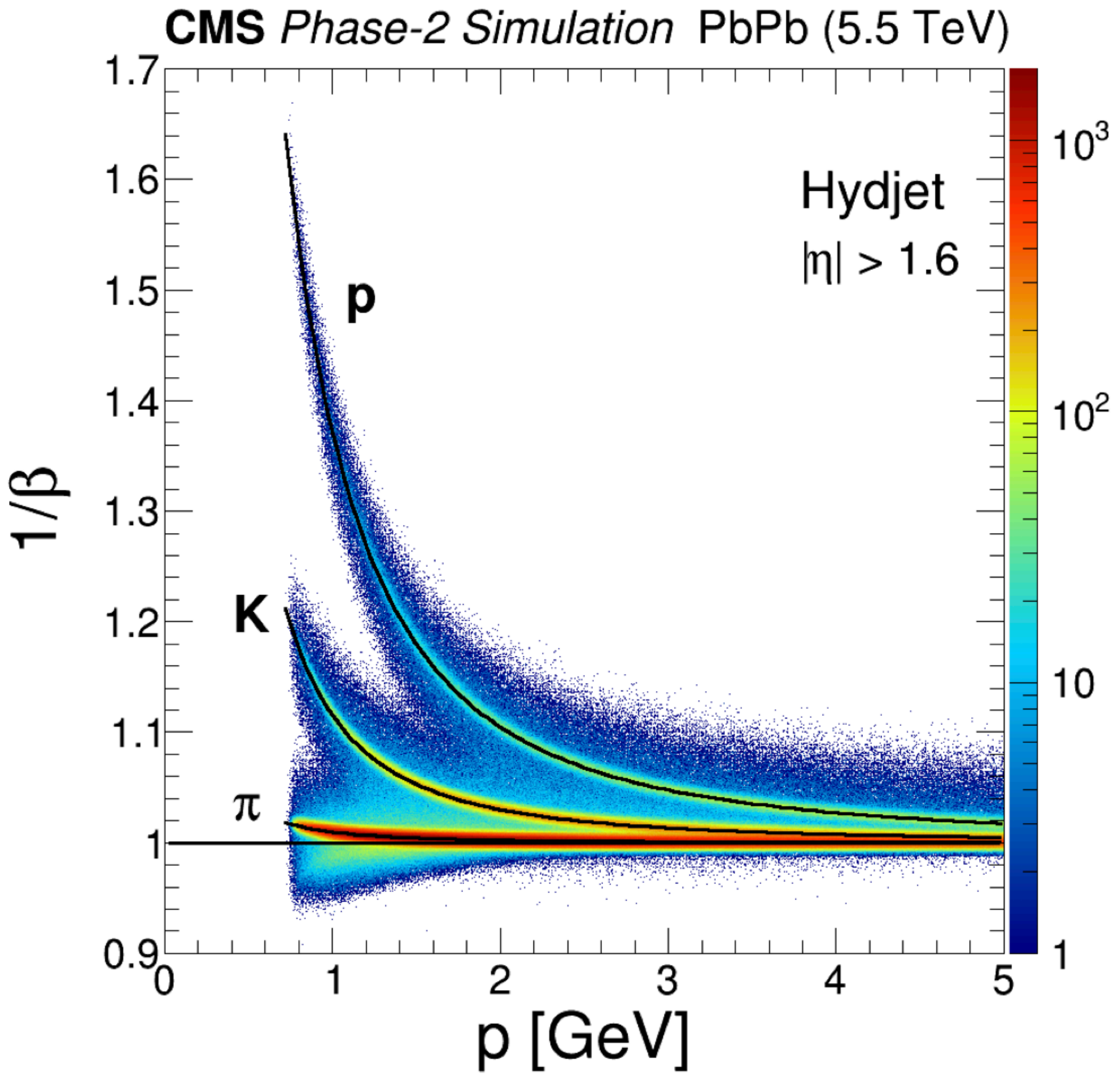
$$x_{ion} \approx \frac{M}{\sqrt{s_{NN}}} e^{-y}$$

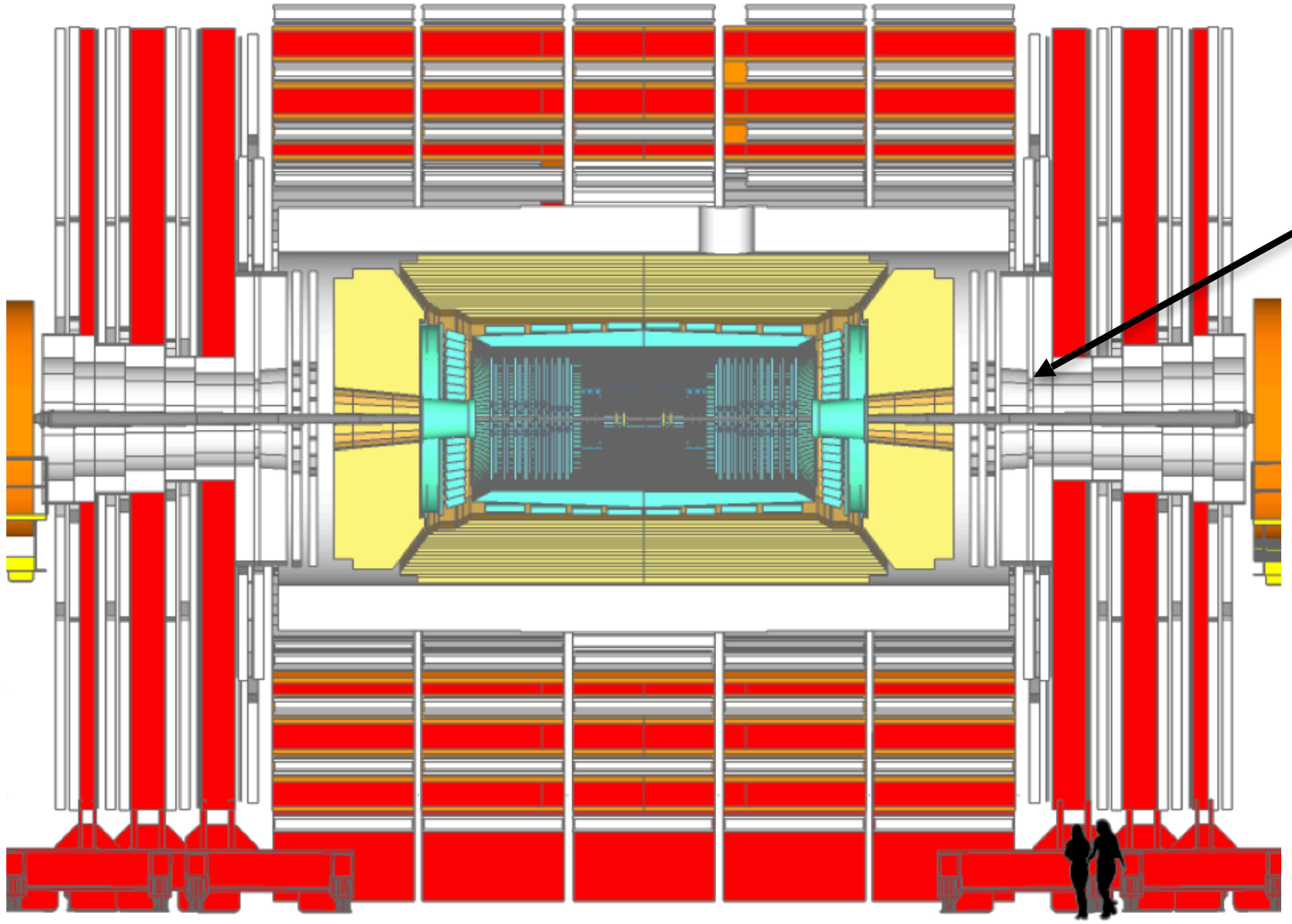
Big jump in the x_{BJ} coverage of future Run-4 analyses

The upgraded CMS detector for Run 4 (Phase II)

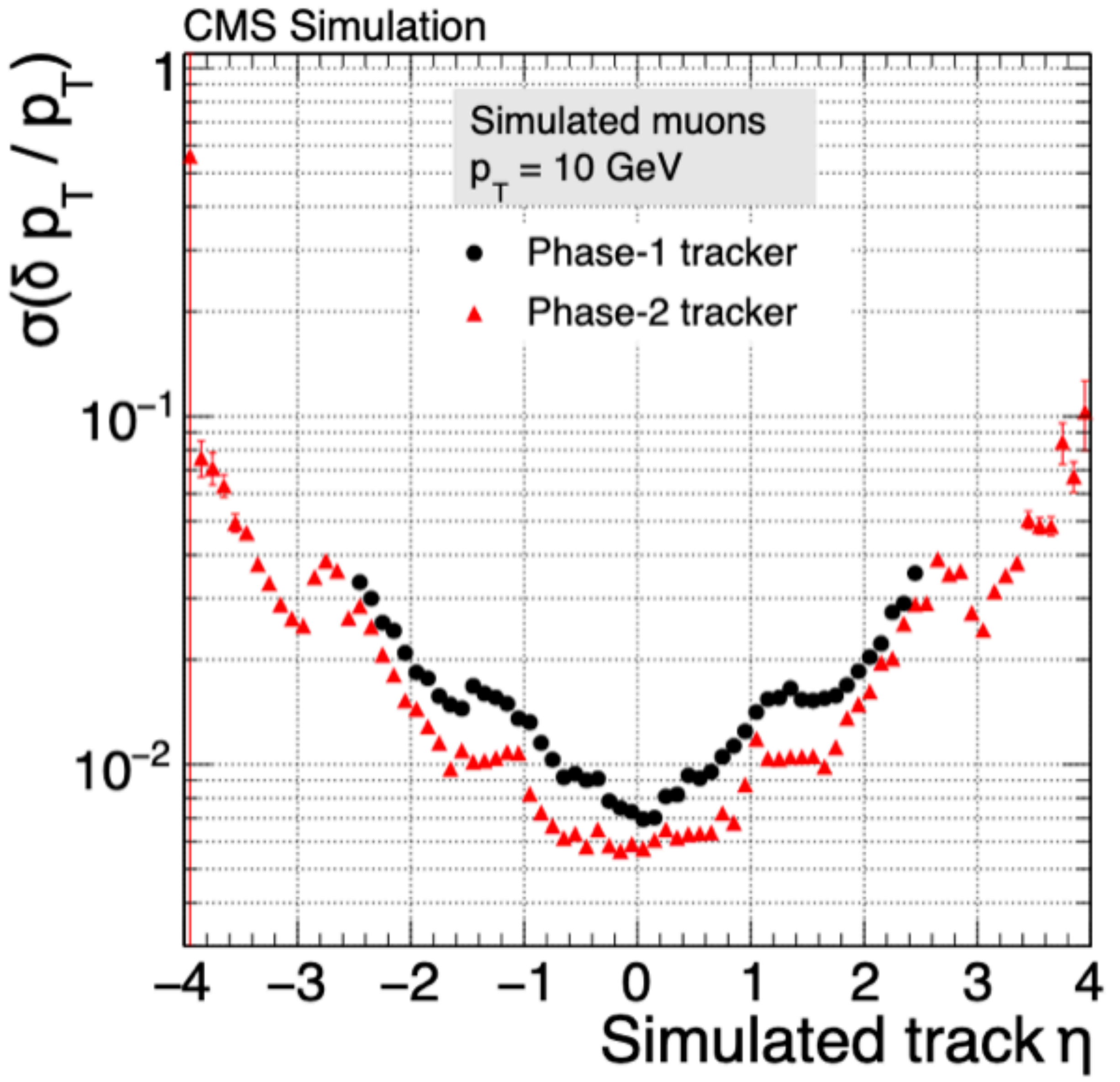
CMS, CERN-LHCC-2019-003
CMS, CMS-TDR-014

New MIP Timing Detector (MTD)
Precision timing $|\eta| < 3$
Particle Identification over several units of η!



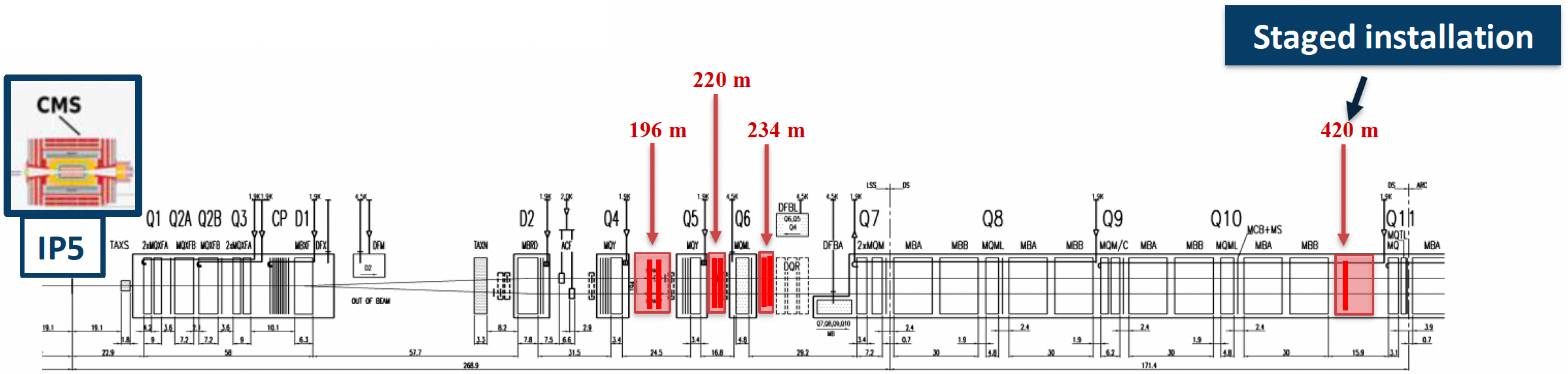


New silicon tracker
Improved granularity
Lighter material budget
$|\eta| < 2.4$ → $|\eta| < 4$



Upgraded Precision Proton Spectrometer (Run 4 and 5)

Basic working principle of the PPS: Protons which lose a fraction of momentum at the interaction point ($\xi = \Delta p/p$) are deflected away from the beam and measured by PPS → **direct measure of the $\xi = \Delta p/p$**

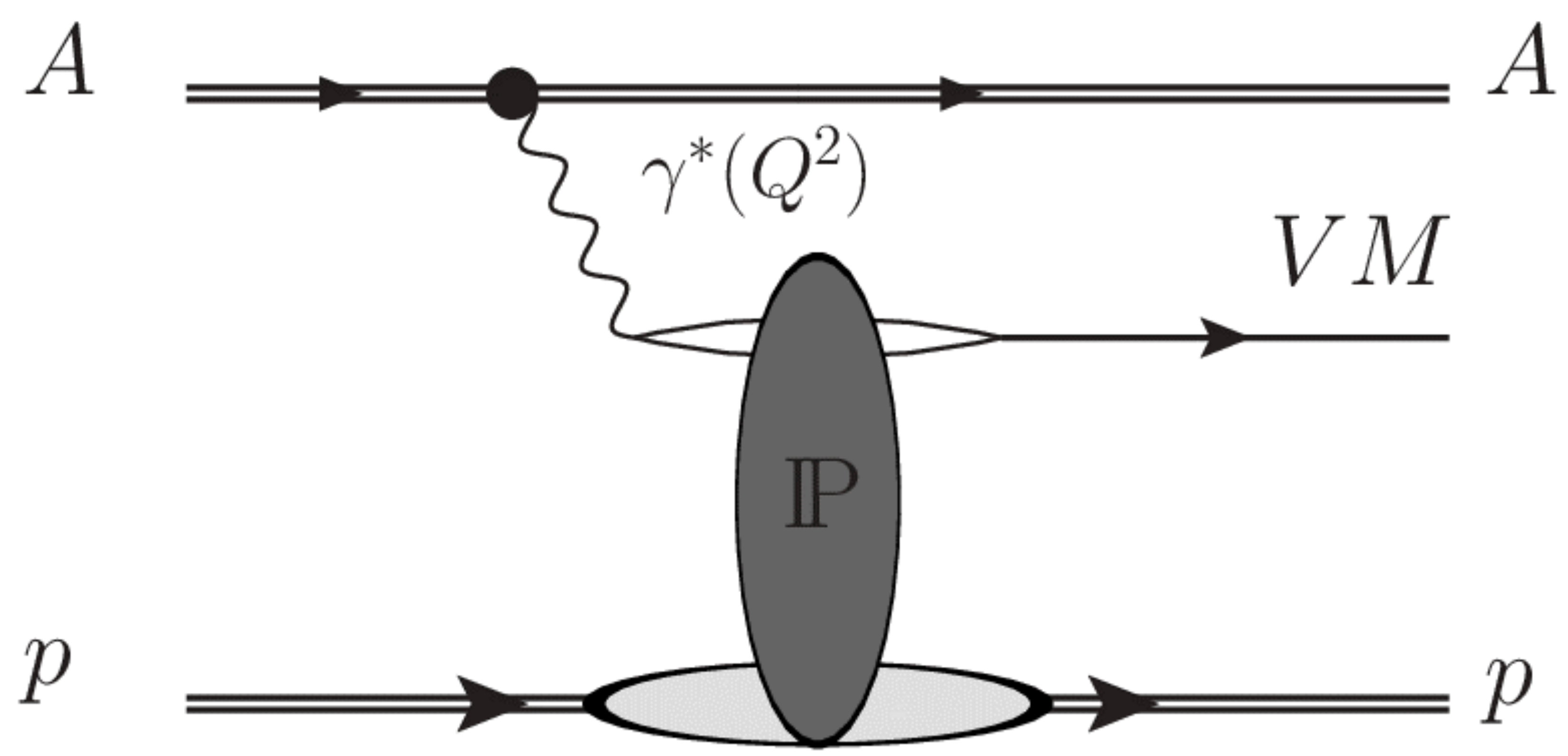


PPS upgrade will further extend the ξ acceptance of the existing PPS (already operational in Run 3)

- $1.42 < \xi < 20$ % for the first three stations (from Run 4)
- $0.33 < \xi < 20$ % for the first three stations (from Run 5)

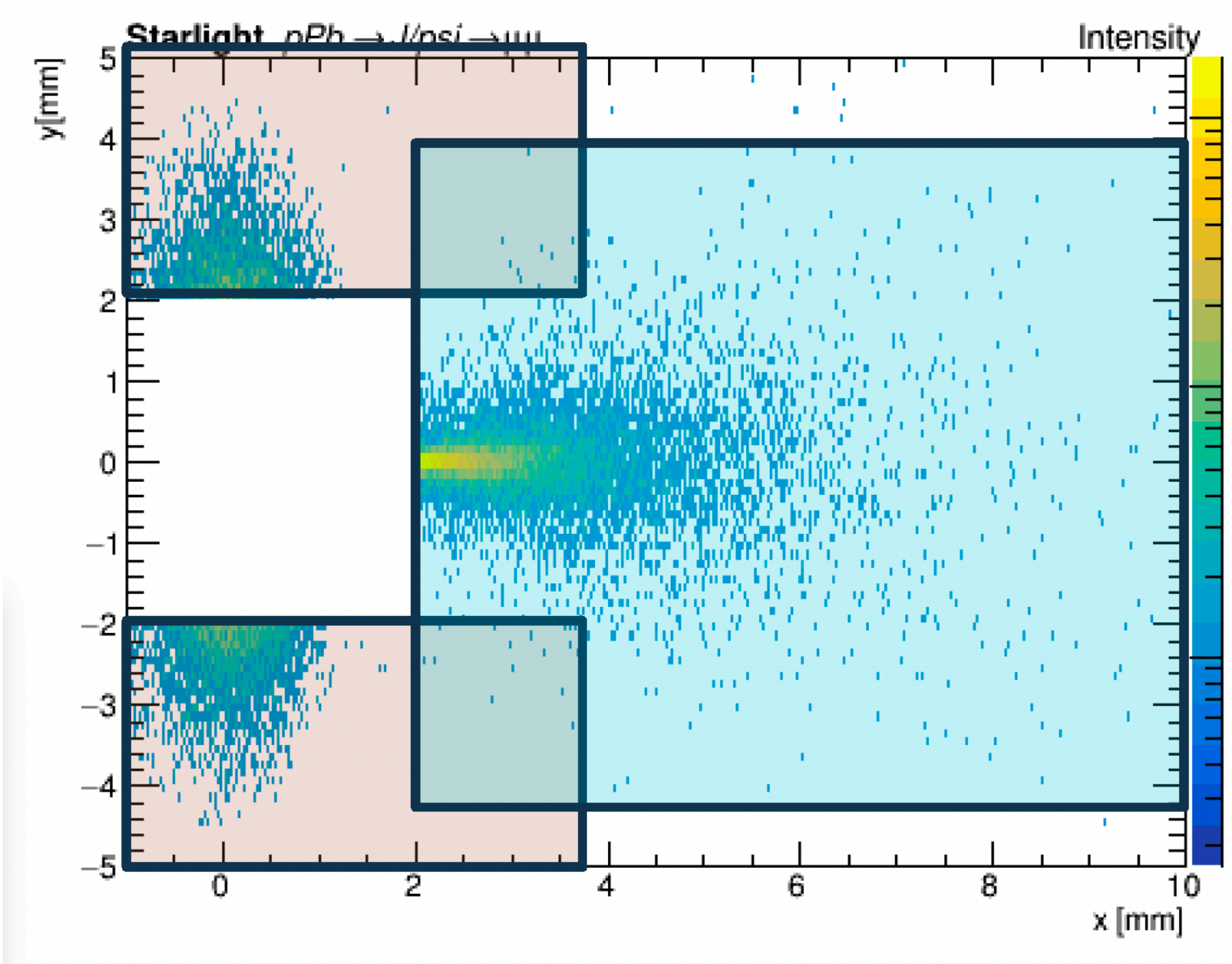
CMS NOTE -2020/008

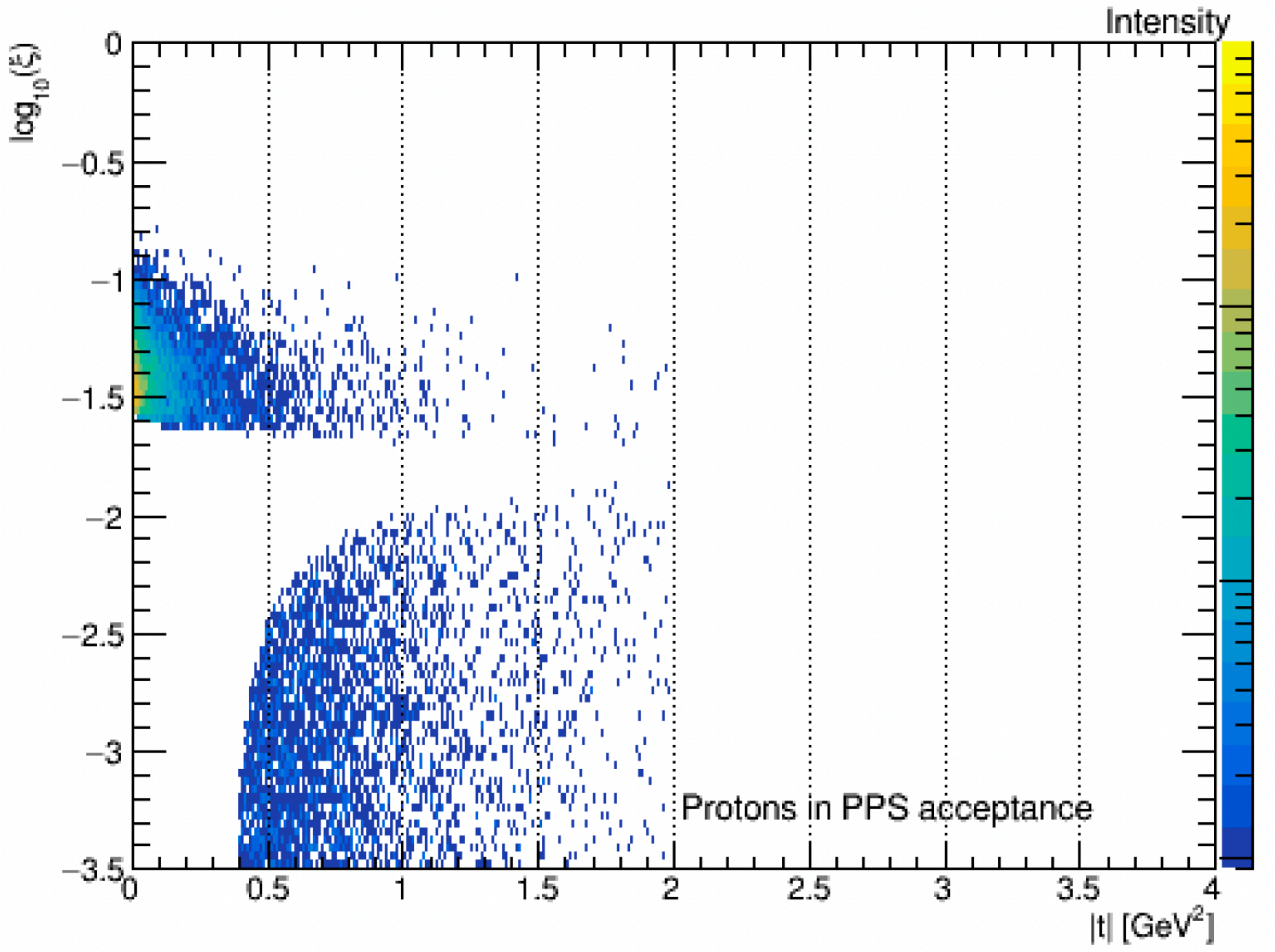
Highlight: exclusive vector-meson production in pA

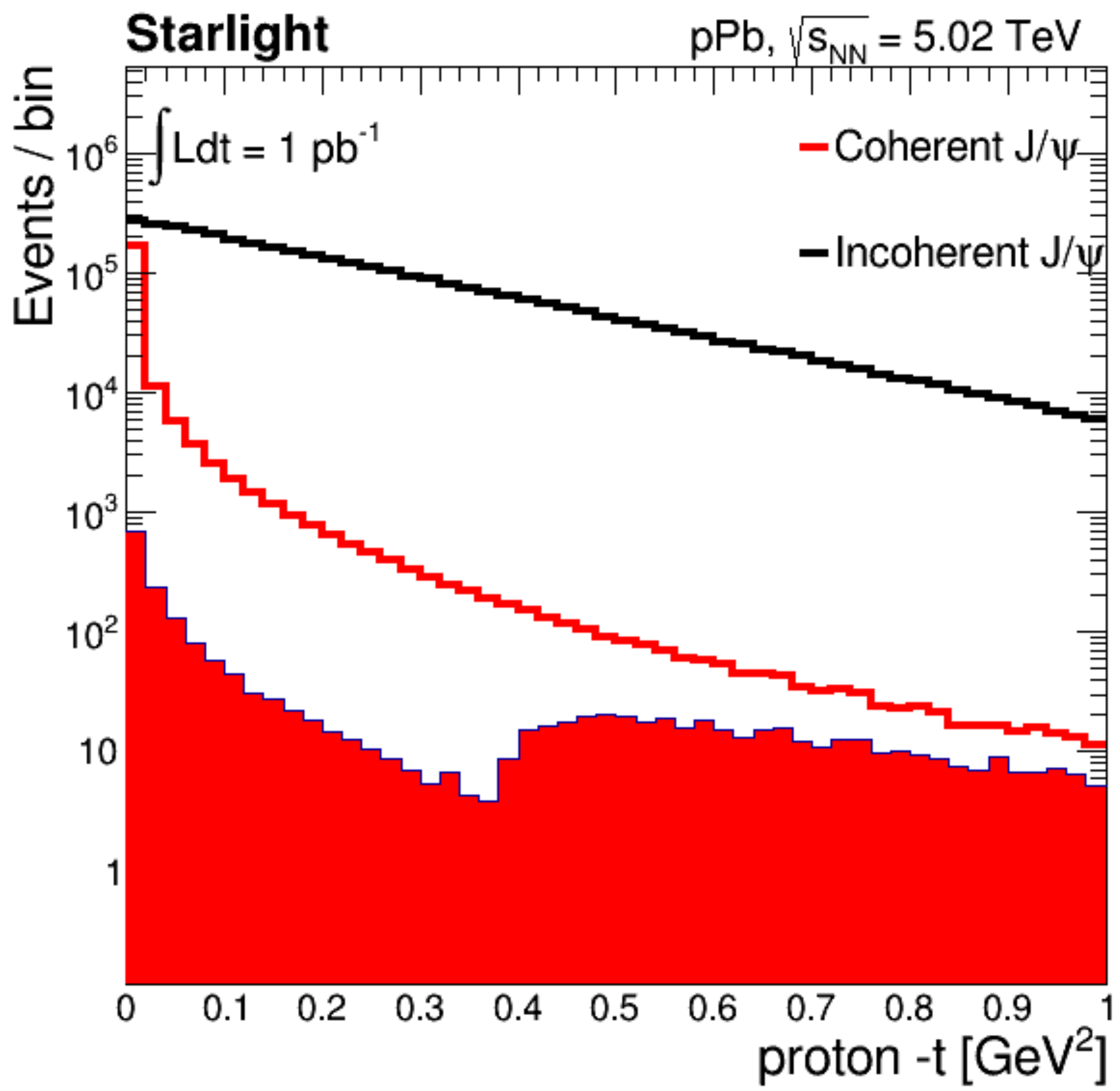


- Vector mesons (Spin 1) are produced in $\gamma - IP$ interactions
- Ions emit a photon at Q^2~0
- **In coherent production, the proton remains intact**

→ PPS would provide high-accuracy tagging of coherent processes
→ Similar technique applicable to exclusive dijet production







→ Proof of principle for proton (and ion) tagging with the upcoming pO/OO run (scheduled for 2025)

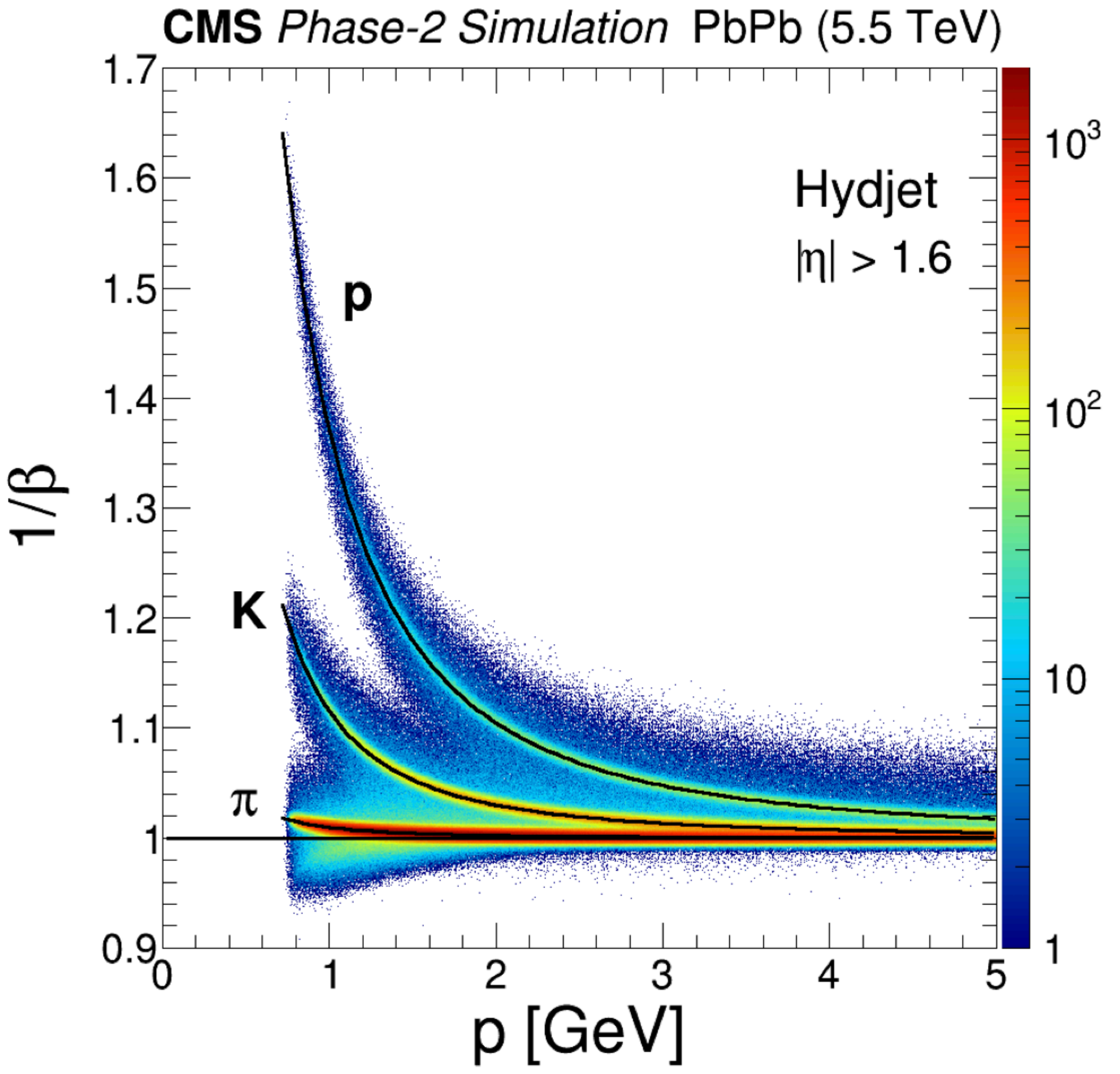
The upgraded CMS detector for Run 4 (Phase II)

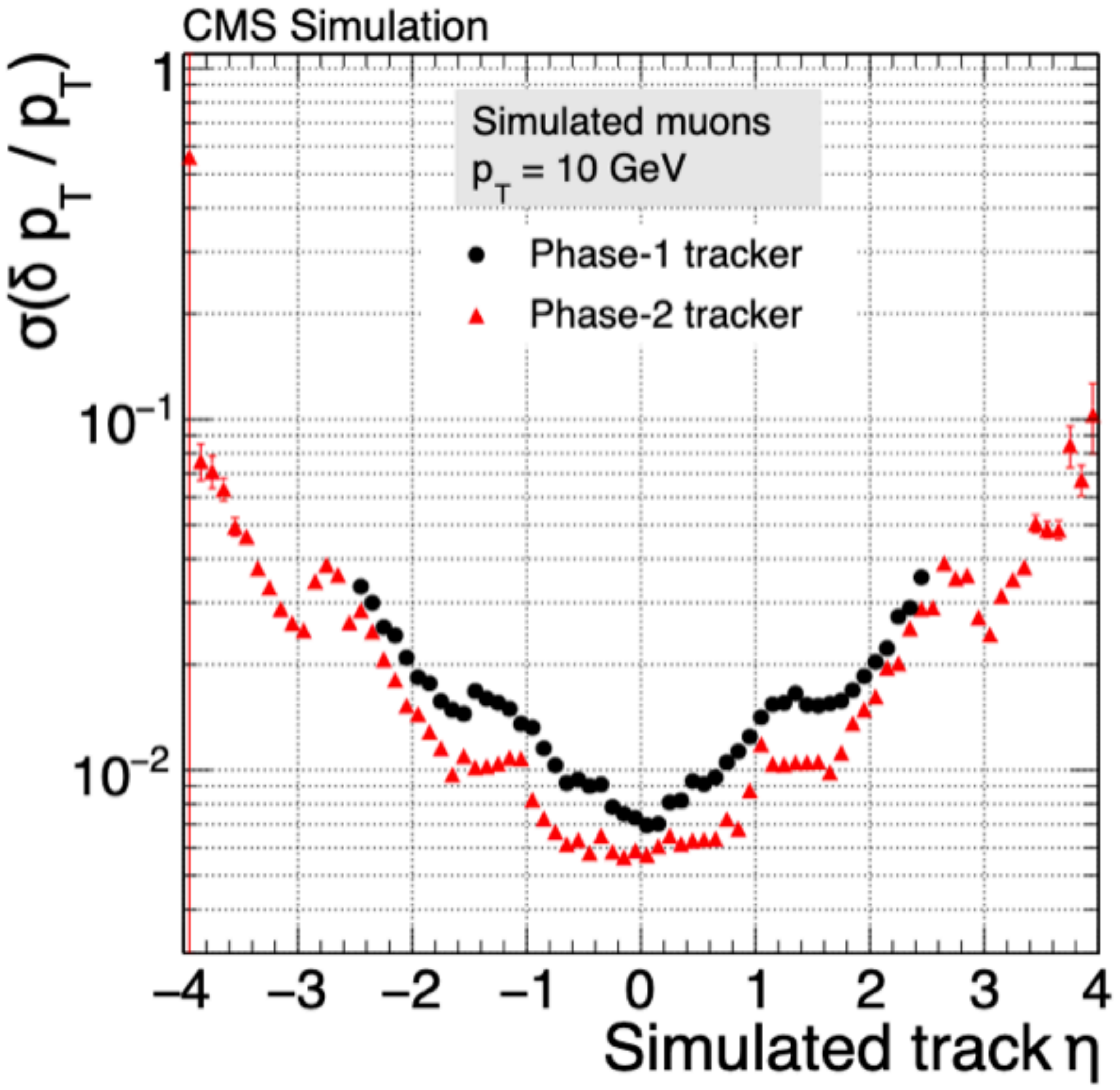
CMS, CERN-LHCC-2019-003
CMS, CMS-TDR-014

Track-based triggers at Level-1 to sample the entire cross section of photon-induced collisions in both pPb and PbPb events

New high resolution silicon tracker with ~ factor 2 larger coverage from **Iη_{tracks}I< 2.4 to** from **Iη_{tracks}I< 4.0**

Particle Identification over (MTD) in IηI < 3





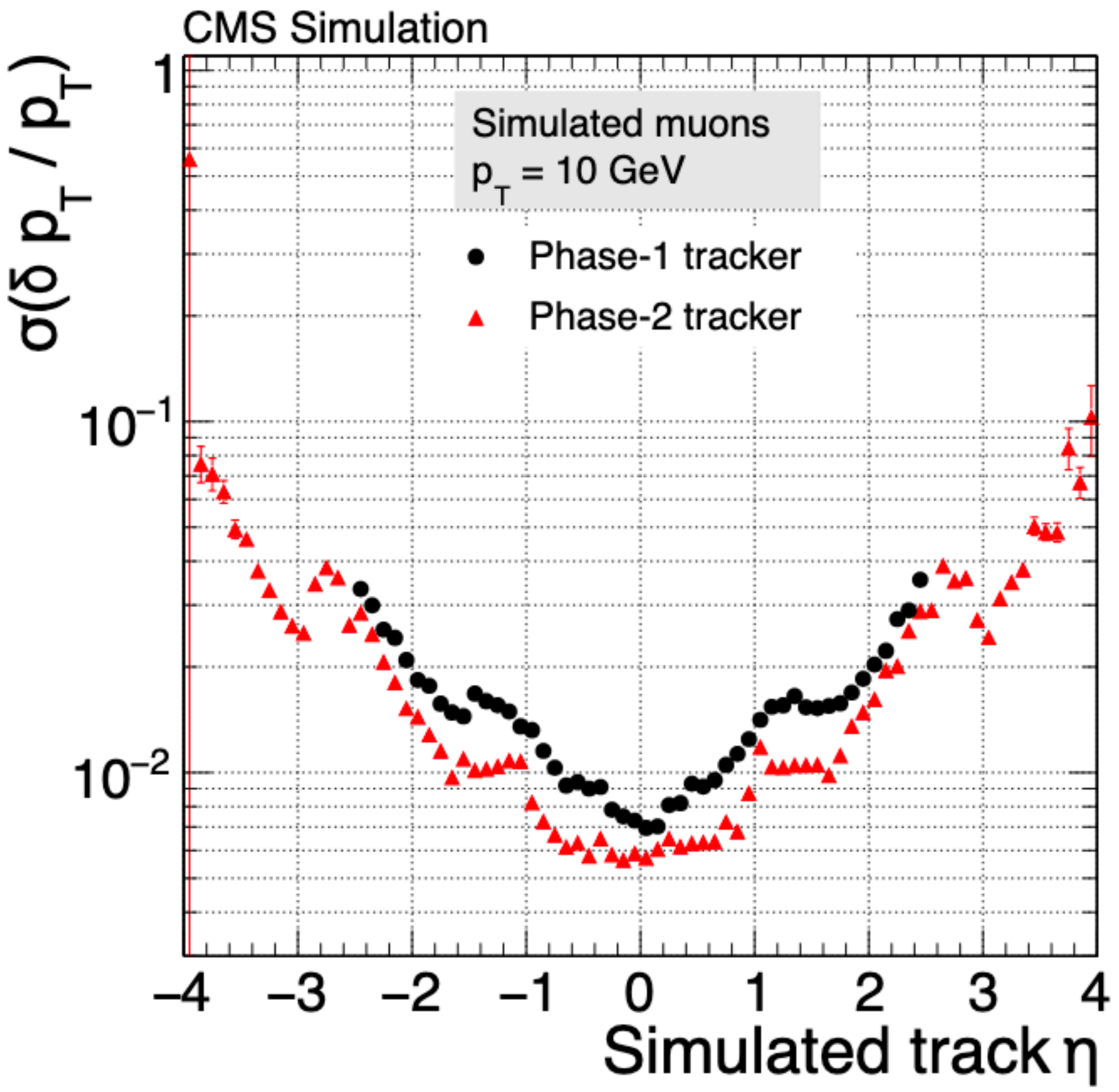
$$x_{ion} \approx \frac{M}{\sqrt{s_{NN}}} e^{-y}$$

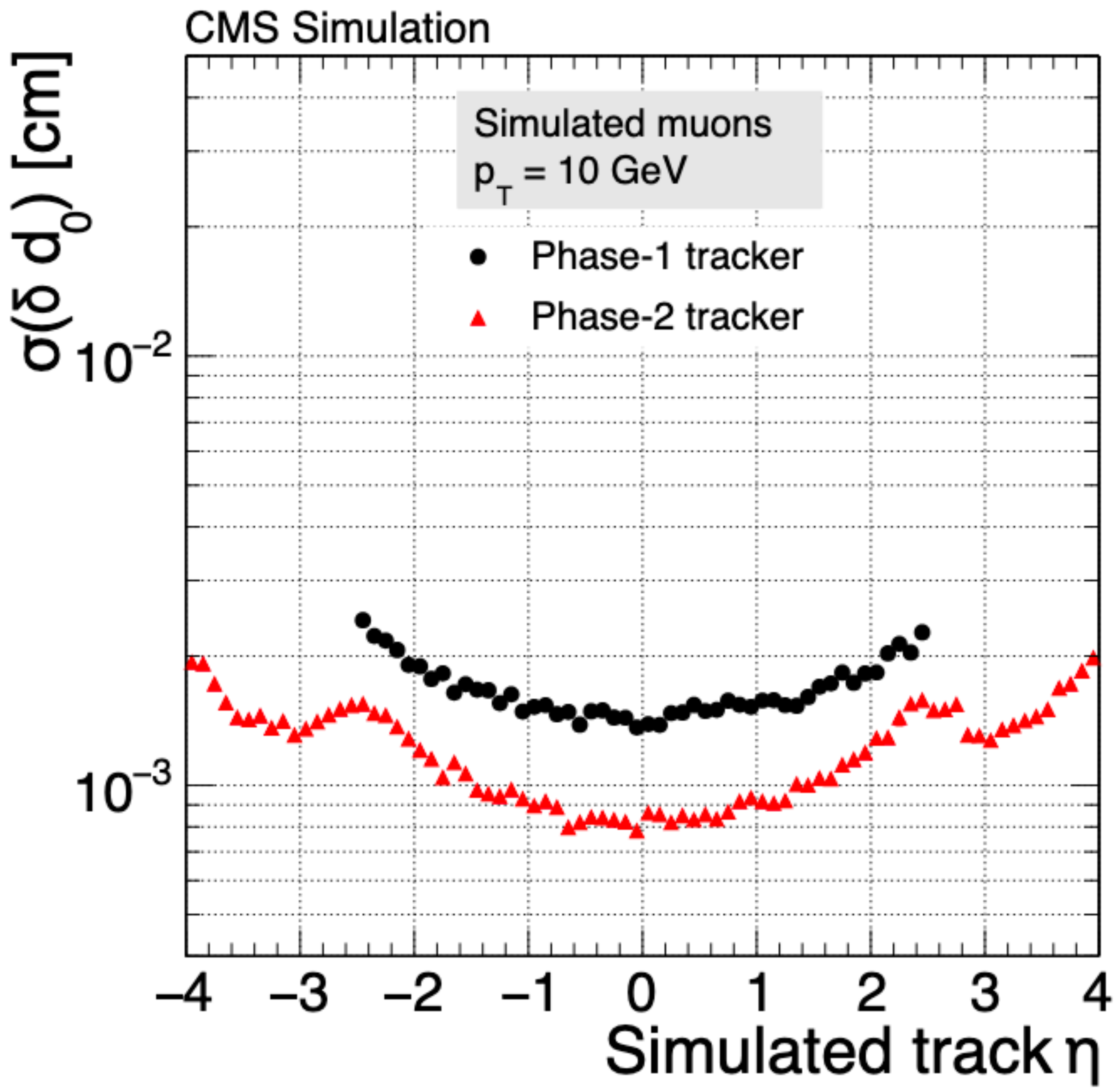
Big jump in the x_{BJ} coverage of future Run-4 analyses

High-resolution, large acceptance silicon tracker (|η| < 4)

from 100 x 150 to 50 x 50 μm^2 pixel size
Tracking out to |η| < 4 !!
Reduced material budget by up to 2x

CMS, CMS-TDR-014





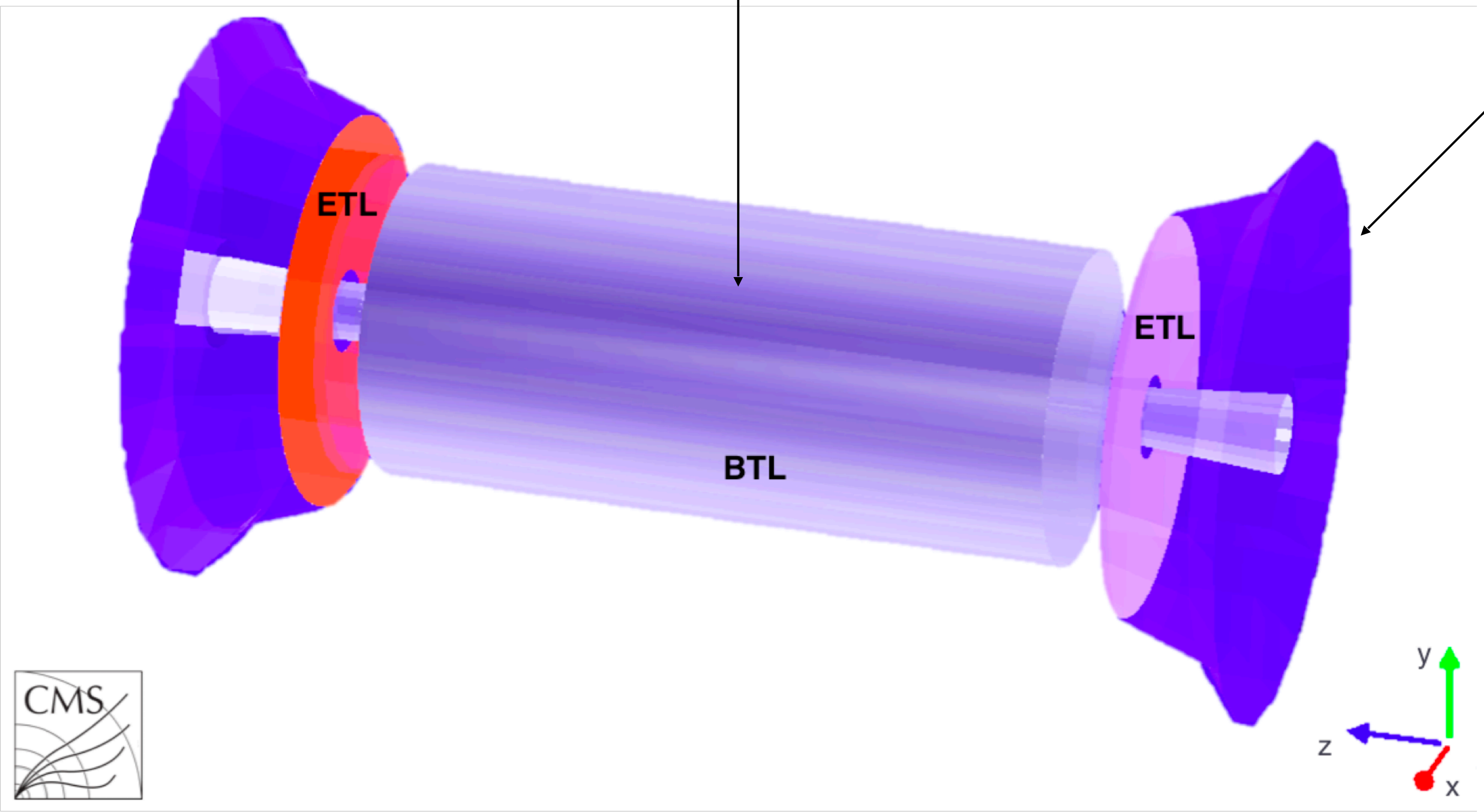
Improved p_T resolution by about 25%
- Improved mass resolution for resonances

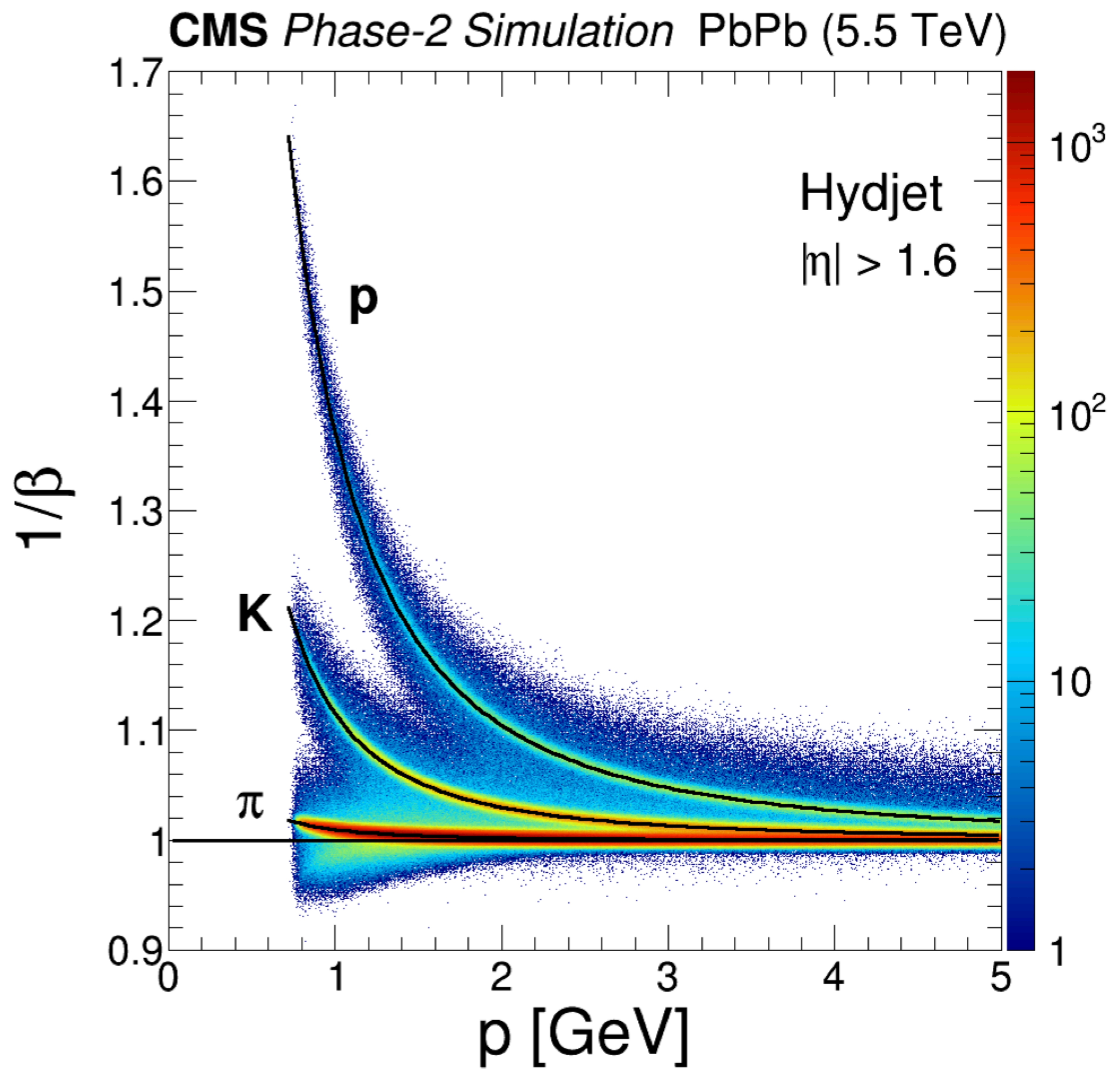
Impact parameter resolution improved by 40%
- Improved heavy flavor measurements (B/D hadrons & b/c-jet tagging)

MIP timing detector (MTD)

Barrel Timing Layer (BTL)
- Coverage: $|\eta| < 1.45$, $p_T > 0.7$ GeV
- Timing resolution: ~ 30 ps
- Tech: Scintillator + Si photo-multiplier

Endcap timing layer (ETL)
- Coverage: $1.6 < |\eta| < 3.0$, $p > 0.7$ GeV
- Timing resolution: ~ 30 – 40 ps
- Tech: Silicon w/ internal gain (LGAD)





Unlock a wide set of semi-inclusive "DIS-like" measurements with identified hadrons with CMS

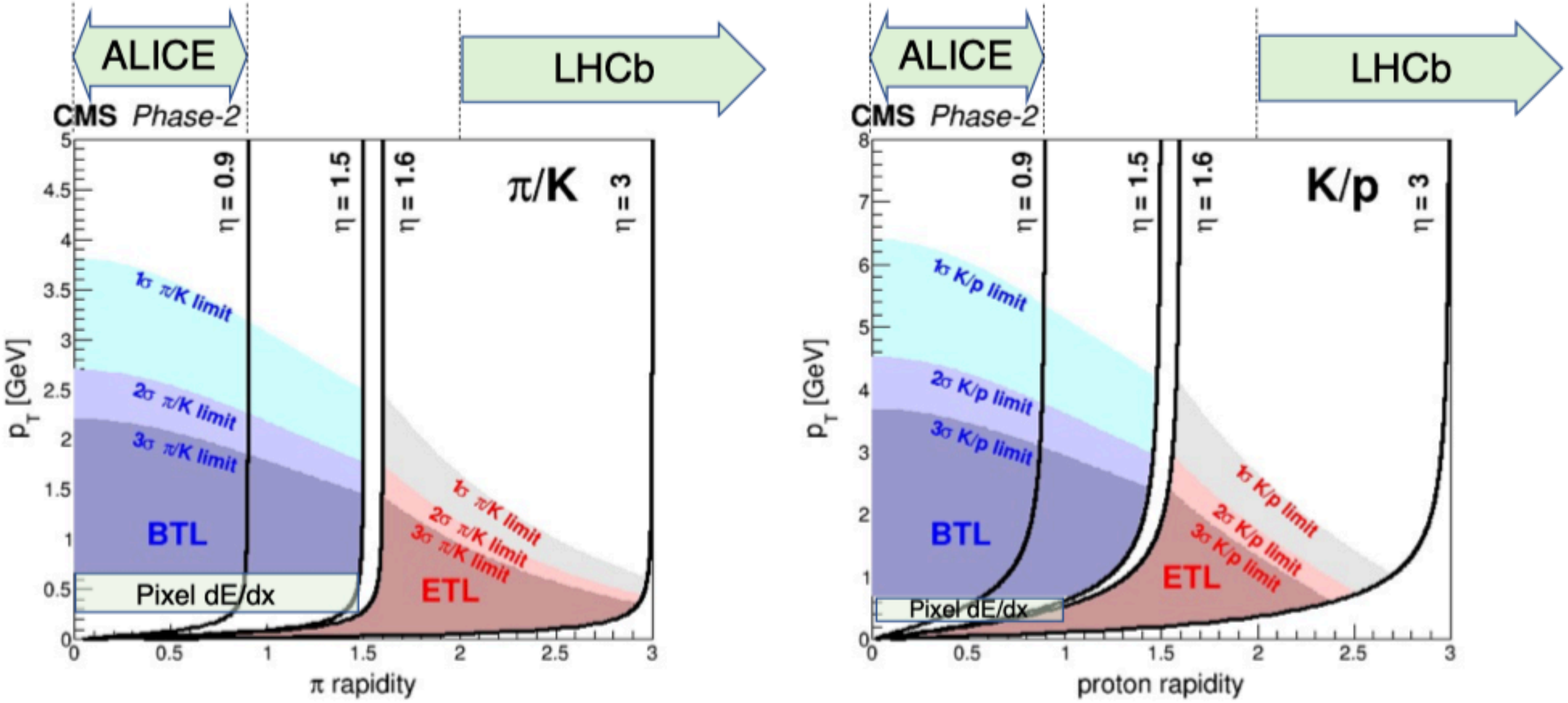
CERN-LHCC-2019-003

Future CMS PID coverage

Large acceptance PID: $|\eta| < 3$
Complementary w/ ALICE & LHCb

Experiment	η coverage	r (m)	σ_T (ps)	r/σ_T (x100)
CMS	$\|\eta\| < 3.0$	1.16	30	3.87
ALICE	$\|\eta\| < 0.9$	3.7	56	6.6
STAR	$\|\eta\| < 0.9$	2.2	80	2.75

π/K separation
up to $p \approx 2.5$ GeV

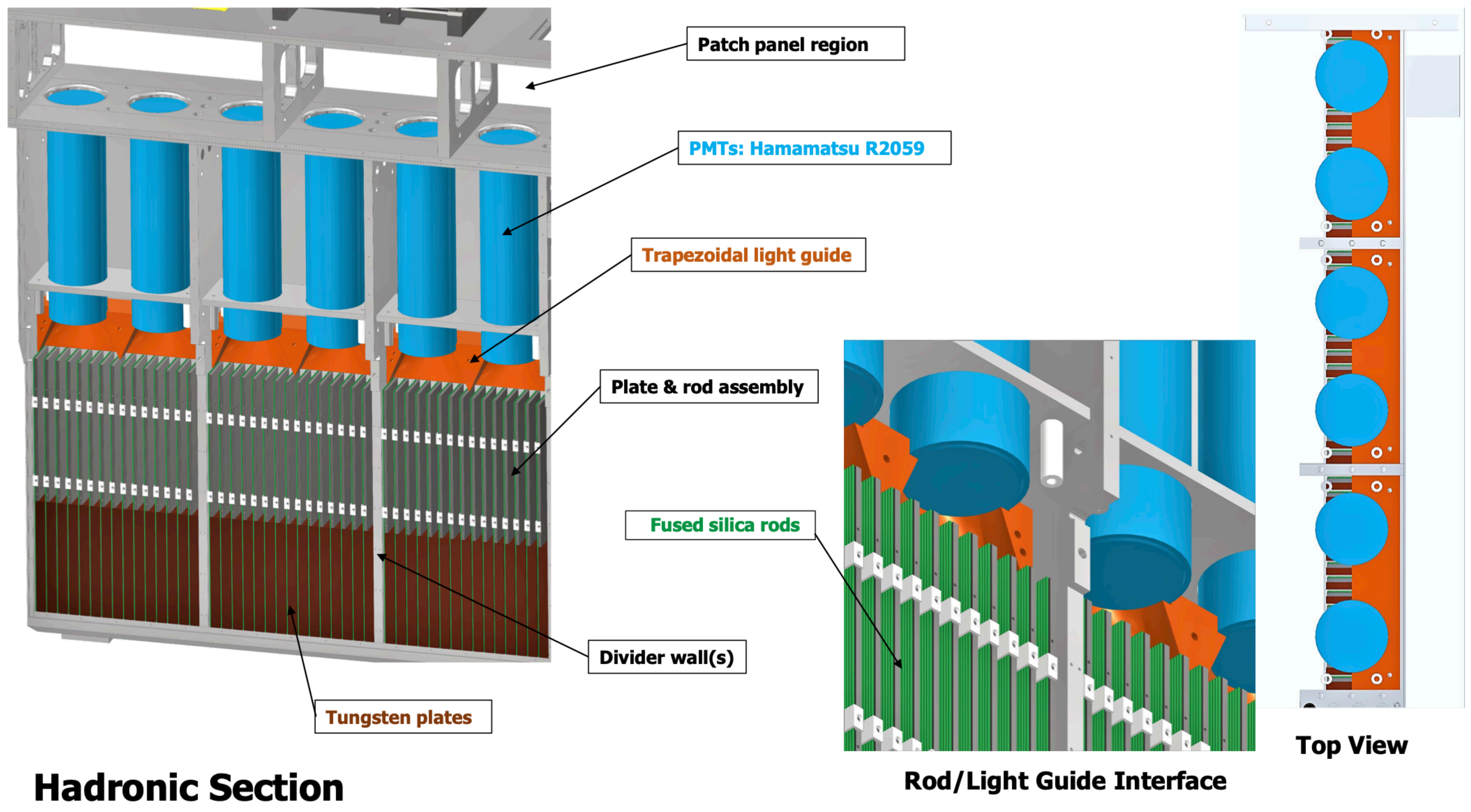


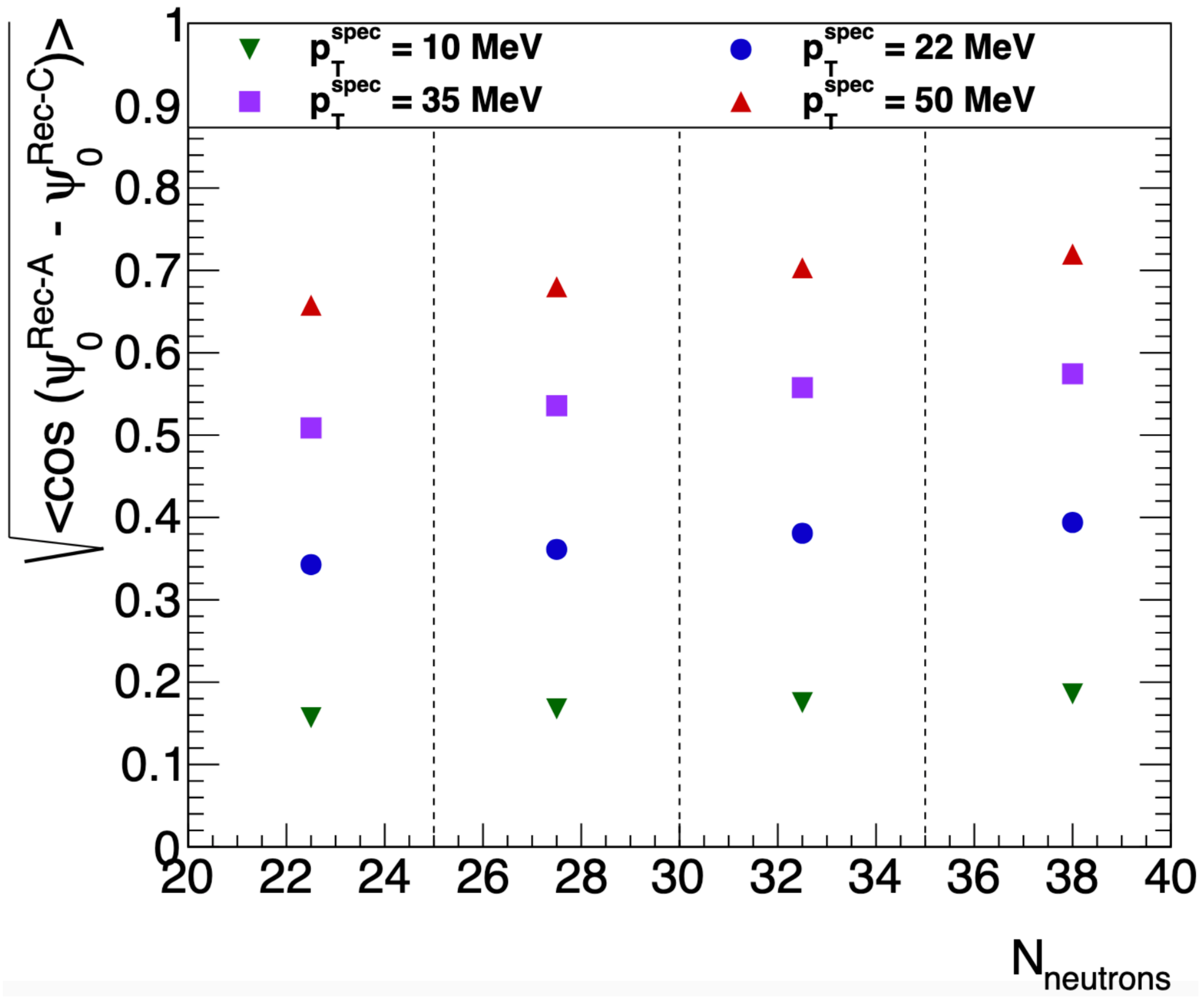
/p separation
ɔ to $p \approx 5$ GeV

-LHCC-2019-003

Combined with dE/dx from pixel detector, **π/K/p coverage down p_T = 300 MeV**!

A new ZDC CMS detector





CMS-TDR-024