First measurement of the D^0 production in photonuclear ultraperipheral heavy ion collisions with CMS to probe low-x nuclear matter

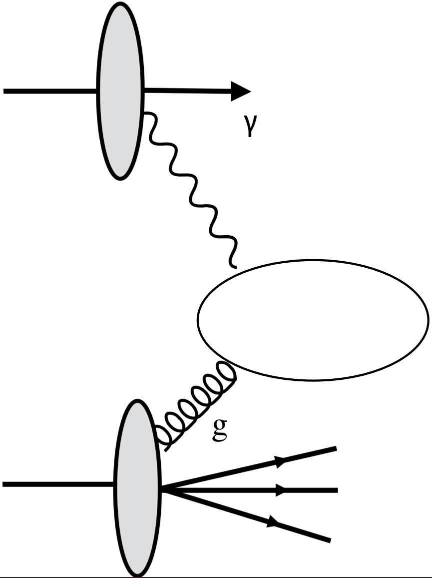
Chris McGinn on behalf of the CMS collaboration

HardProbes, Nagasaki

25 September 2024

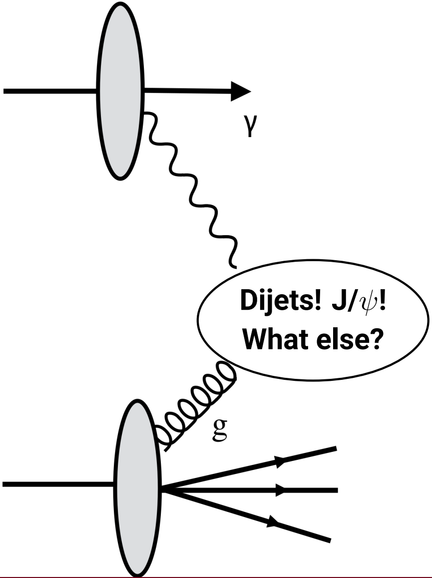
MITHIG group's work was supported by US DOE-NP

UPC at the LHC

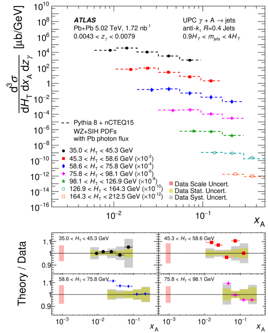


- Relativistic heavy-ions induce strong EM fields
- Ultraperipheral collisions (UPCs) occur when quasireal photons interact w/o nuclear overlap

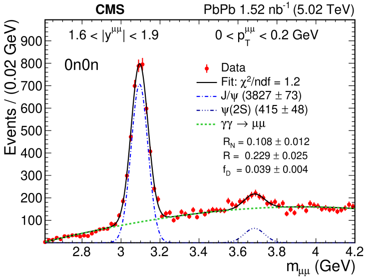
UPC at the LHC



- **Relativistic heavy-ions induce strong EM fields**
- **Ultraperipheral collisions (UPCs) occur when quasireal photons interact w/o nuclear overlap**
- **Results in UPC dijets, J/ψ, other processes**
  - **Probing partonic densities across a broad x, Q^2**

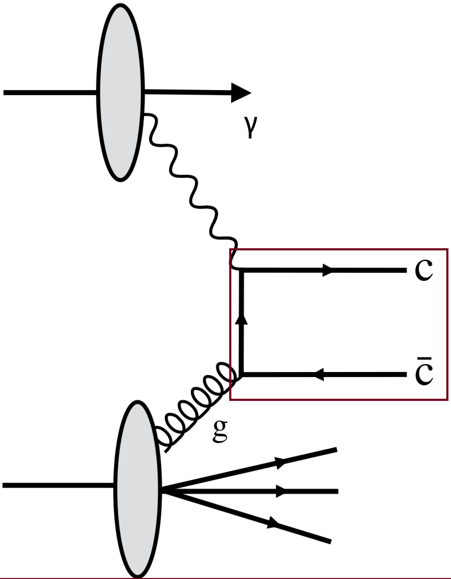


ATLAS-HION-2022-15



PRL 131 (2023)

Open Heavy Flavor in UPCs



- Mass of charm $\rightarrow$ pQCD control at p_{T} =0!
- Probes $\mathrm{Q}^2 \sim$ (charm/bottom mass)^2
- Complements higher Q^2 of dijets down to Q^2 J/ψ
- Excellent control for higher order theory corrections

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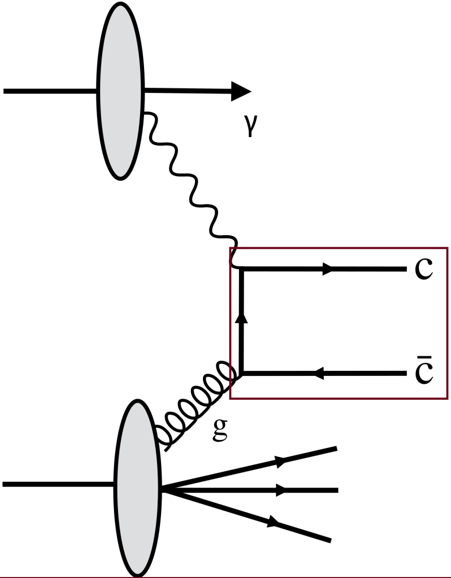

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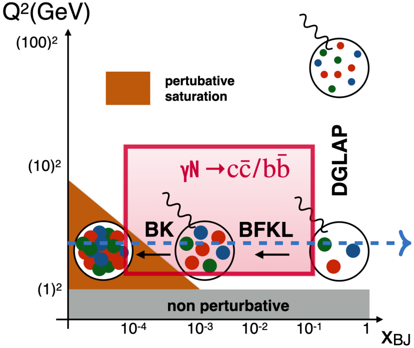
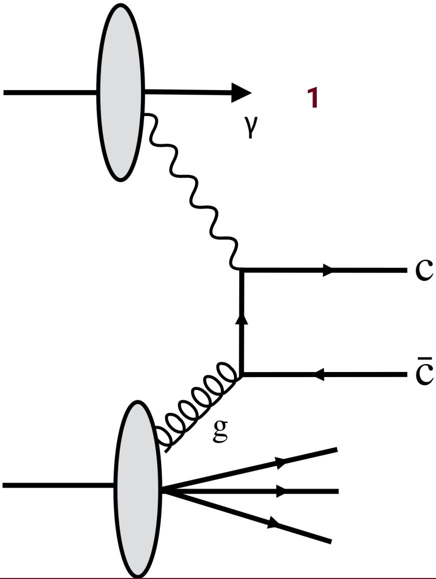


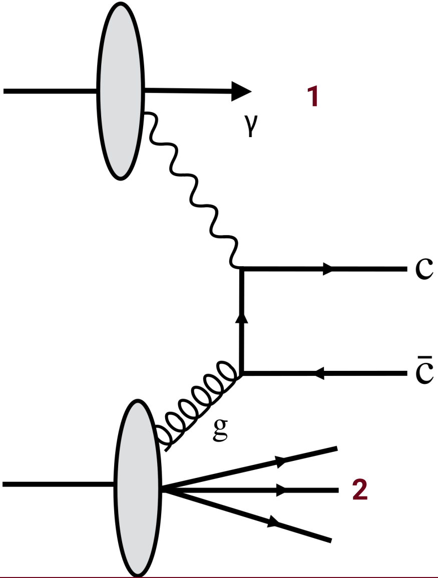
Probes x from the anti-shadowing, to shadowing, and possibly the saturation regime!

Experimental Analysis Definition



1. **Select 0n ZDC signal**
   - γ-going

Experimental Analysis Definition



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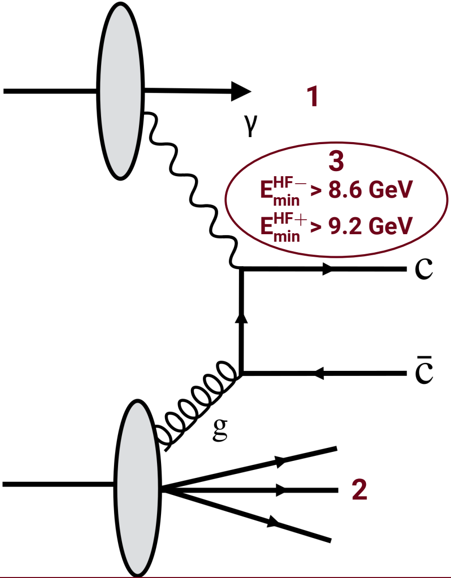
2. **Xn ZDC signal indicating nuclear breakup**
   - Pb-going

Experimental Analysis Definition



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3. Rapidity-gap in γ-going direction

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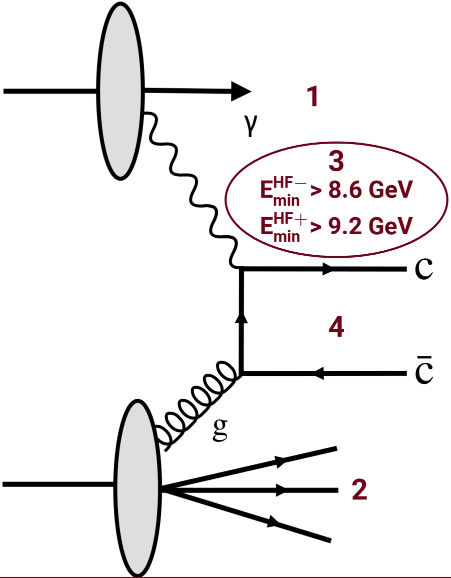

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   - Via $K^-\pi^+$ decay channel

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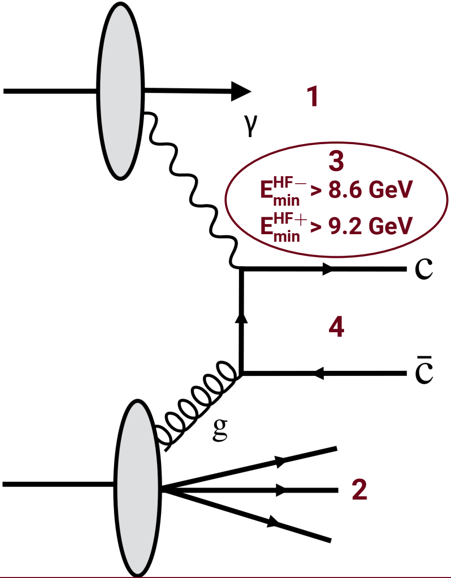

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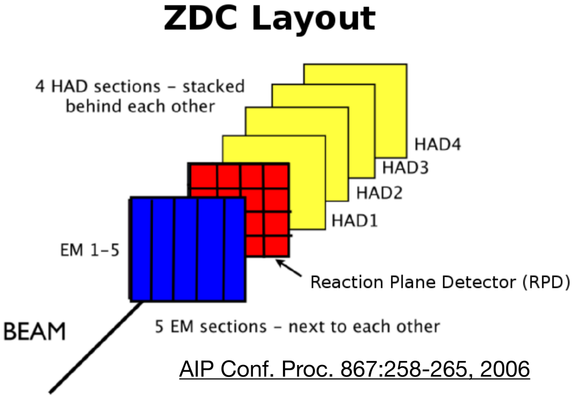
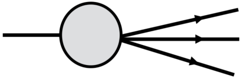
Semi-inclusive measurement by Xn0n selection
$\rightarrow$ Diffractive component reduced
$\rightarrow$ Inclusive selection for direct/resolved processes
$\rightarrow$ Inclusive selection for prompt/nonprompt

Triggering with the ZDC

- **ZDC positioned $\pm$140m from IP**
  - **Signal indicates nuclear breakup**



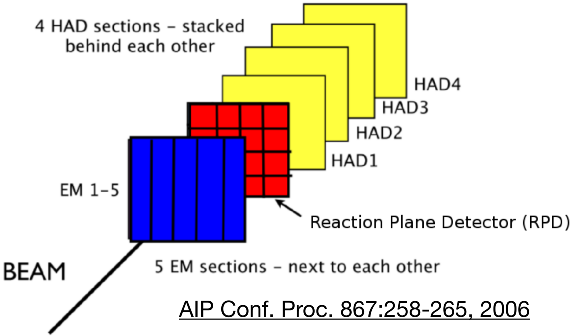
Zero-Degree Calorimeters $|\eta| > 8.3$ (0.5 mrad)
→ detect neutrons produced in the nuclear break-up process



Pb + X + neutron(s)

Triggering with the ZDC

ZDC Layout



AIP Conf. Proc. 867:258-265, 2006

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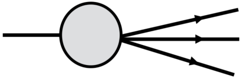
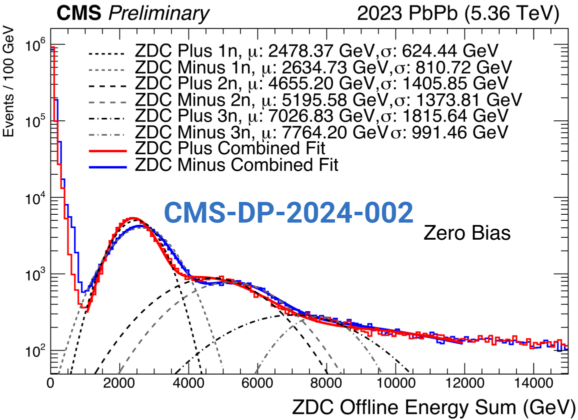
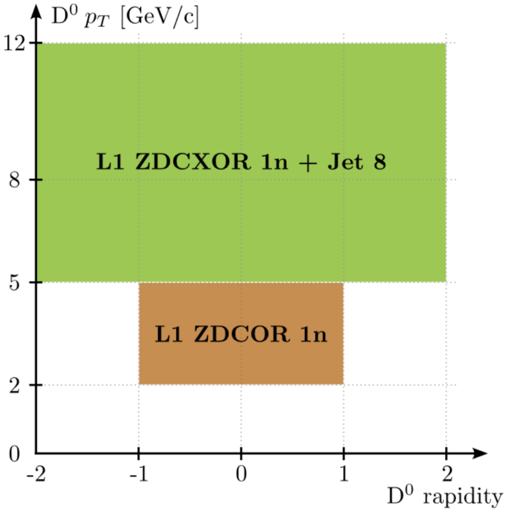


Pb + X + neutron(s)

- **ZDC positioned ±140m from IP**
  - **Signal indicates nuclear breakup**
- **ZDC incorporated into CMS trigger system for the first time in 2023**



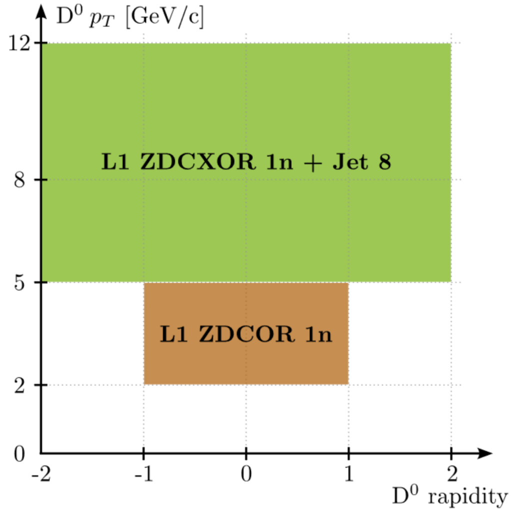
Trigger Strategy for D^0



D^0 p_T and y map

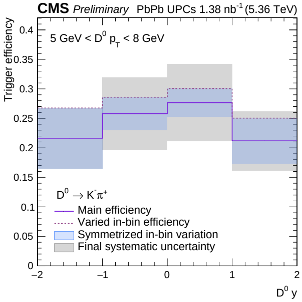
- **D^0 p_T 2-5 GeV on pure ZDC based trigger**
- **D^0 p_T > 5 GeV add hardware jet trigger**
  - **Threshold Jet p_T > 8 GeV**

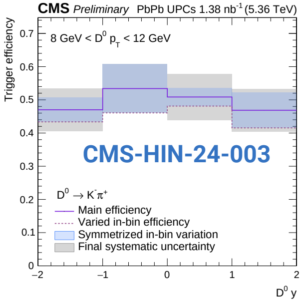
Trigger Strategy for D^0



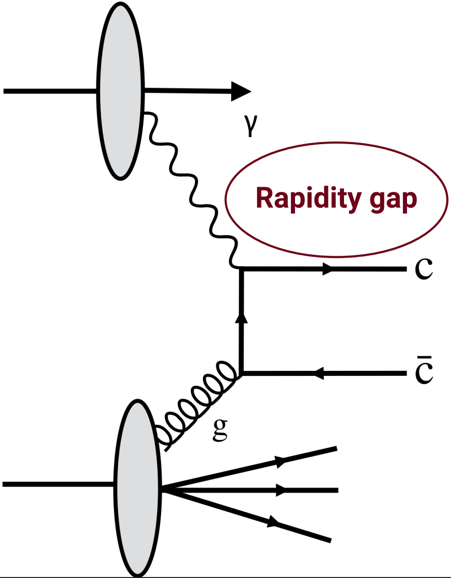
D^0 p_T and y map

- D^0 p_T 2-5 GeV on pure ZDC based trigger
- D^0 p_T > 5 GeV add hardware jet trigger
  - Threshold Jet p_T > 8 GeV
- Jet trigger substantially reduces prescale
  - Correct for efficiency in p_T, y
  - Significant source of uncertainty



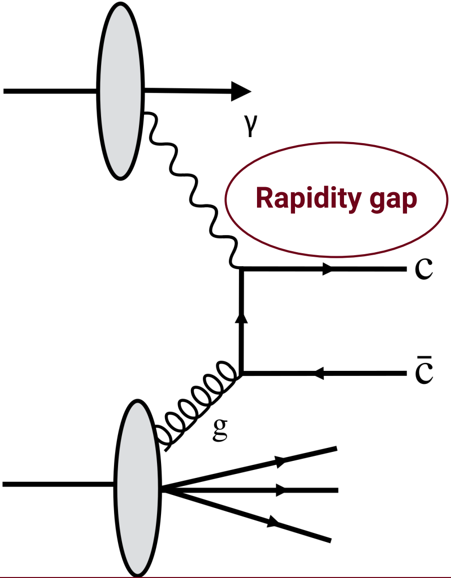


Rapidity Gap Selection

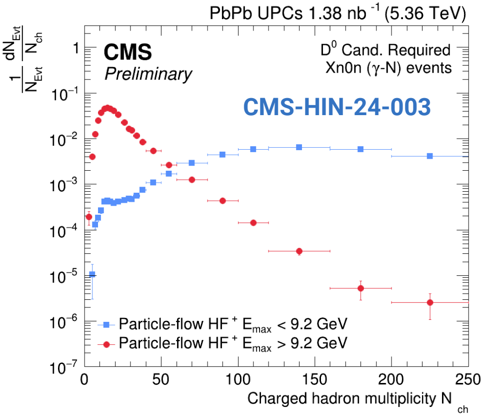


- Require also a γ-going rapidity gap
- Tuned to minimize bias to resolved events

Rapidity Gap Selection



- Require also a γ-going rapidity gap
- Tuned to minimize bias to resolved events
- No candidates in HF^{-} (HF^{+}) above 8.6 (9.2) GeV
  - Clear separation in charged track multiplicities

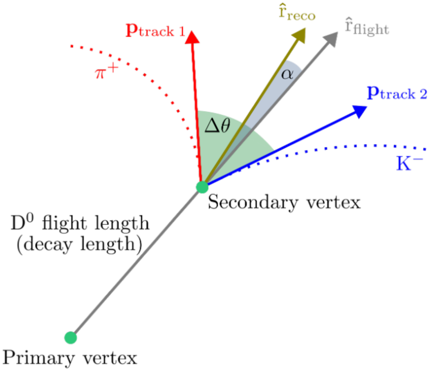


Gap removes hadronic event contamination after ZDC selection

D^0 Selection and Efficiency (I)

D^0 candidates are constructed from tracks

1. p_T > 1 GeV
2. $|\eta|$ < 2.4
3. Passing high-purity condition



D^0 kinematics

D^0 Selection and Efficiency (I)

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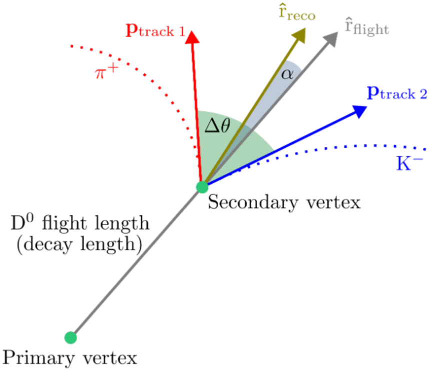
Selections on D^0 kinematics (p_T and y dependent)

1. Pointing angle (α)
2. Decay length significance
3. Secondary vertex probability
4. Opening angle between decay products ($\Delta\theta$)



D^0 kinematics

D^0 Selection and Efficiency (II)

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Selections on D^0 kinematics (p_T and y dependent)

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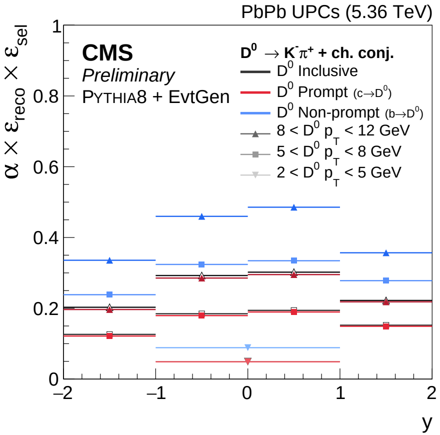
CMS-HIN-24-003

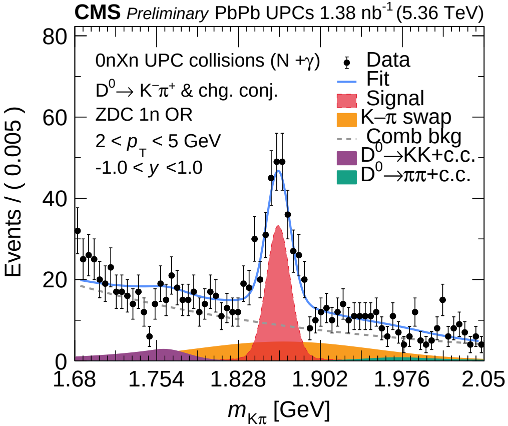


Reco. Efficiency

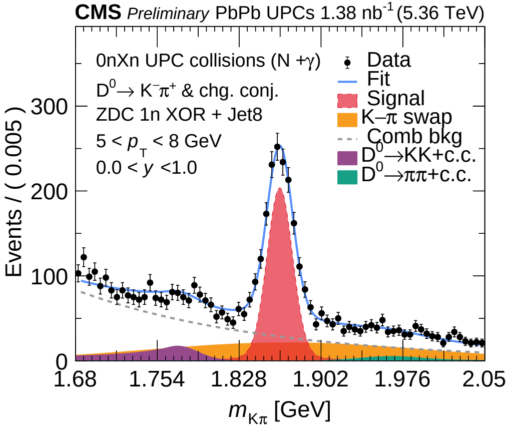
Analysis is inclusive for prompt/nonprompt D^0

D^0 Yield Extraction

CMS-HIN-24-003



2 < p_T < 5 GeV



5 < p_T < 8 GeV

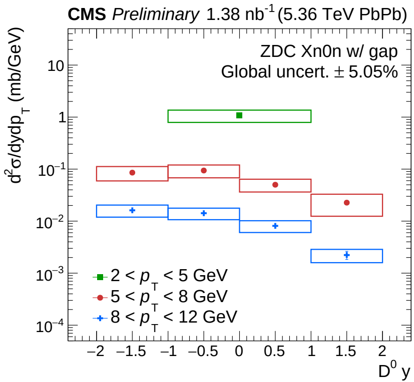
- **Model D^0 signal peak with double Gaussian; swapped mass with single Gaussian**
- **Background modeled with exponential; K^+K^-, $\pi^+\pi^-$ with Crystal Ball**

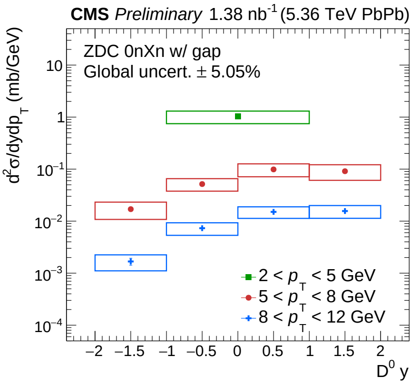
D^0 Systematic Uncertainties

- Trigger correction uncertainty
- Rapidity gap selection uncertainty by varying HF energy threshold
- Global uncertainties from luminosity and $D^0 \rightarrow K^- \pi^+$ branching ratio
- Tracking uncertainty accounting for Data/MC differences
- Prompt/non-prompt fraction Data/MC differences
- D^0 selection uncertainties; vary kinematic selections and re-extract yield/efficiency
- Uncertainties in efficiency from Data/MC
  - Differences in D^0 spectral shape
  - Differences in event multiplicities
- Fit modeling uncertainties
  - Varying background shape from exponential to 2nd order Chebyshev polynomial
  - Fixing the mean of the signal peak to MC value
  - Modeling of the K^+K^- and $\pi^+\pi^-$ peaks

Blue $\rightarrow$ a typically dominant uncertainty for p_T > 5 GeV

D^0 Differential Cross Sections in p_T, y

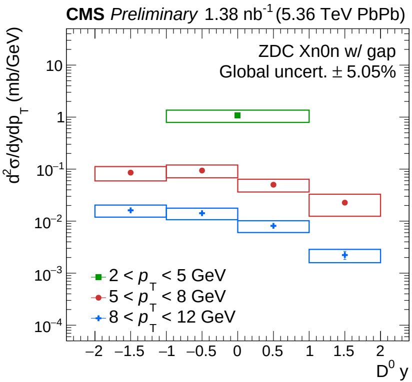


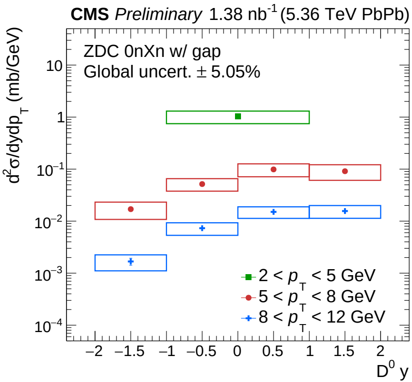


CMS-HIN-24-003

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

D^0 Differential Cross Sections in p_T, y





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- **Extracted for Xn0n (left) and 0nXn (right) conditions**
- **Result probes a broad range in x and Q^2, with p_T and rapidity coverage**
- **Statistically consistent after rapidity reflection; combine for theory comparisons**

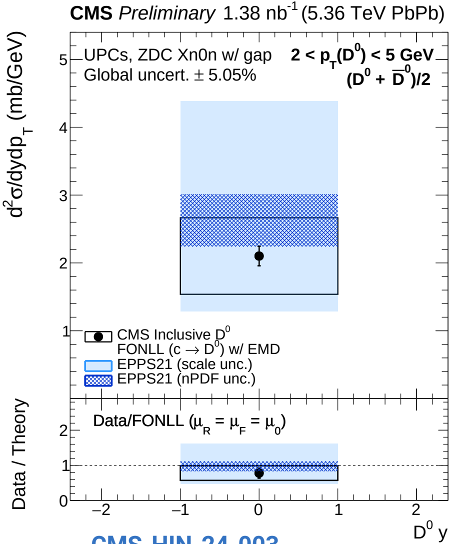
D^0 Theory Comparisons (I)

FONLL w/ EPPS21 nPDFS

- Light blue band indicates scale uncertainty
- Hatched dark blue band is nPDF uncertainty
- Via A.M. Stasto et al., paper in preparation

2 < D^0 p_T < 5 GeV

- Lowest x/Q^2 probe
- Central value slightly below FONLL
- Observe agreement within theoretical and experimental uncertainties



CMS-HIN-24-003

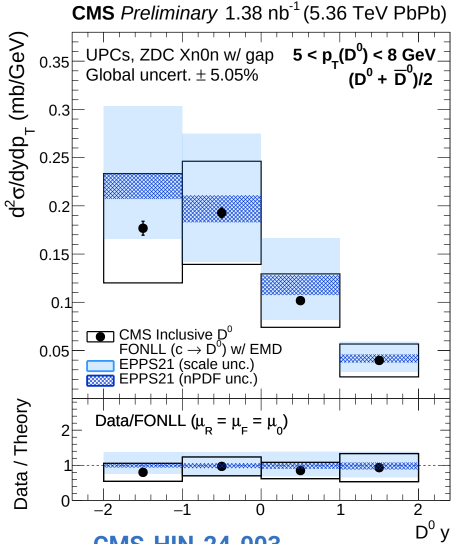
D^0 Theory Comparisons (II)

FONLL w/ EPPS21 nPDFS

- Light blue band indicates scale uncertainty
- Hatched dark blue band is nPDF uncertainty
- Via A.M. Stasto et al., paper in preparation

5 < D^0 p_T < 8 GeV

- Intermediate x/Q^2 probe; add y dependence
- Central value consistent-to-below FONLL
- Observe agreement within theoretical and experimental uncertainties



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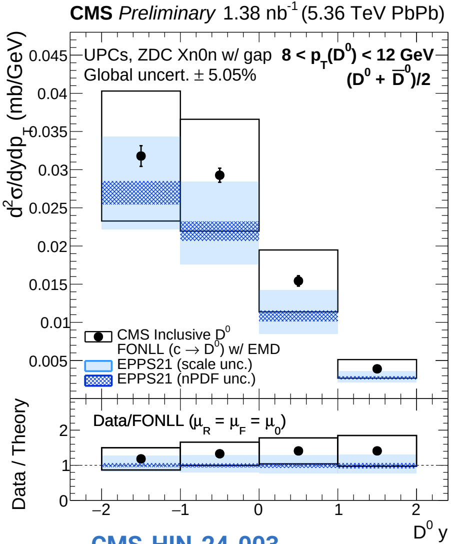
D⁰ Theory Comparisons (III)

FONLL w/ EPPS21 nPDFS

- Light blue band indicates scale uncertainty
- Hatched dark blue band is nPDF uncertainty
- Via A.M. Stasto et al., paper in preparation

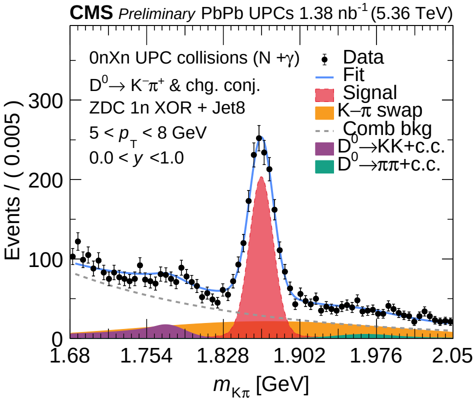
8 < D^0 p_T < 12 GeV

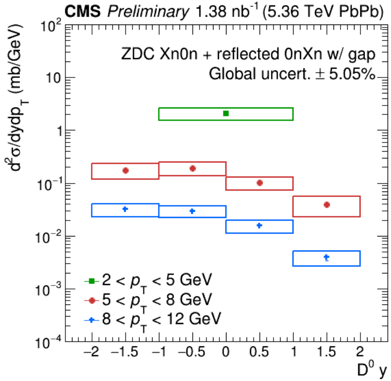
- Highest x/Q^2 probe; add y dependence
- Central value slightly above FONLL
- Observe agreement within theoretical and experimental uncertainties



CMS-HIN-24-003

Conclusions

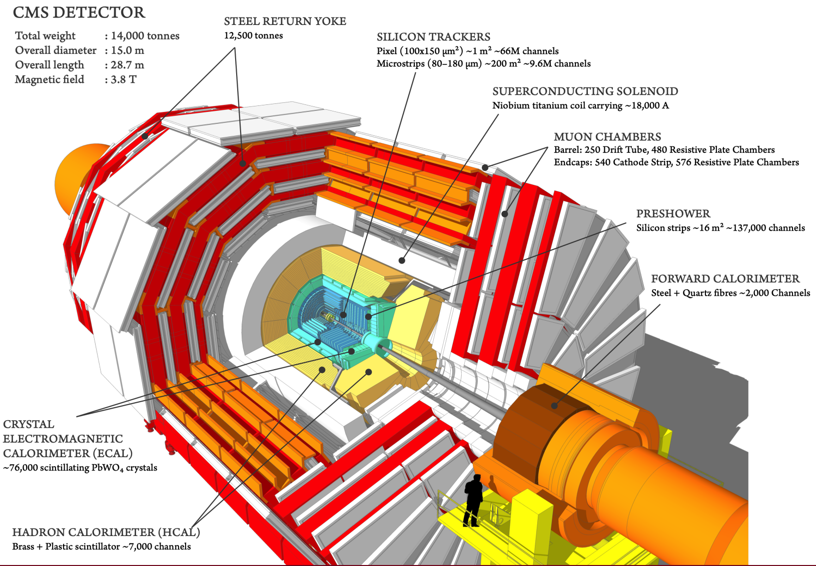




- **First measurement of UPC D^0 differential cross sections at the LHC**
- **New sensitivity to nPDFs over a broad x, Q^2 with a pQCD controlled probe**
    - **Constraints from the cleaner UPC (compared to hadronic) environment**
- **Opening a new program at CMS; stay tuned!**

Backup

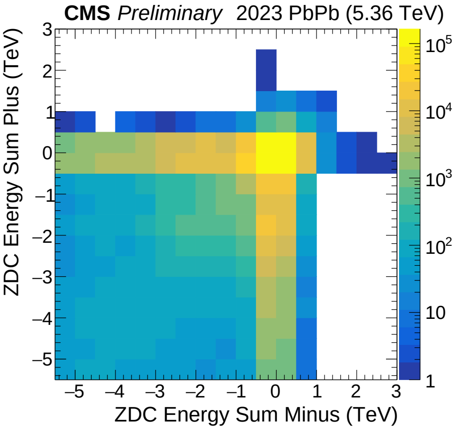
The CMS Detector

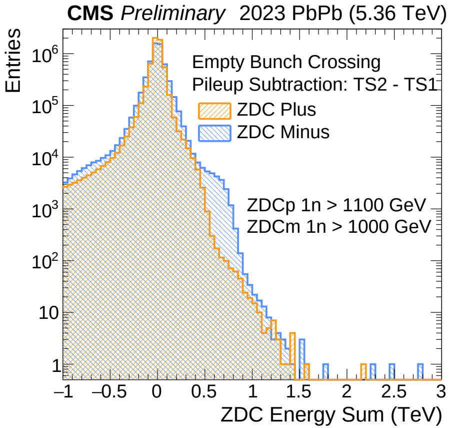


Study of HI enabled by The CMS Detector

- Silicon trackers for charged hadrons
- ECAL for photons / π^0
- HCAL for neutrals
- Forward calorimeters for event activity / centrality
- All detectors in combination produce jets

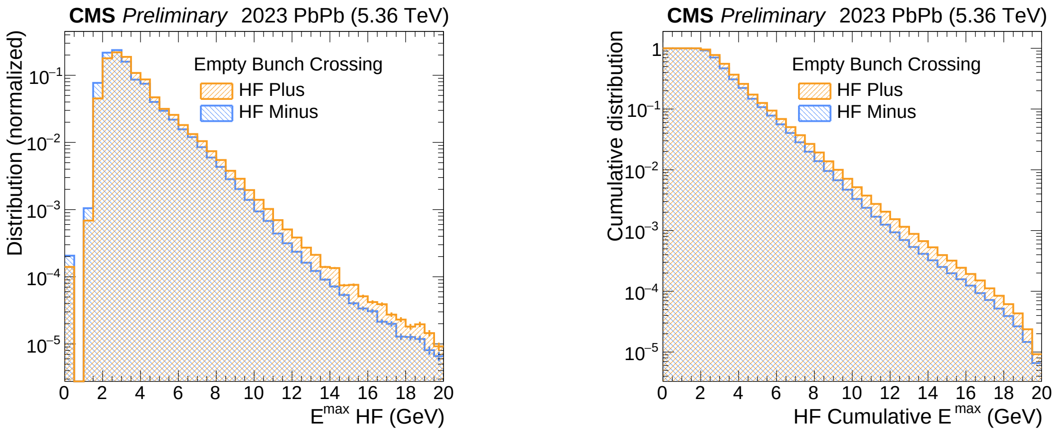
ZDC in Empty Bunches





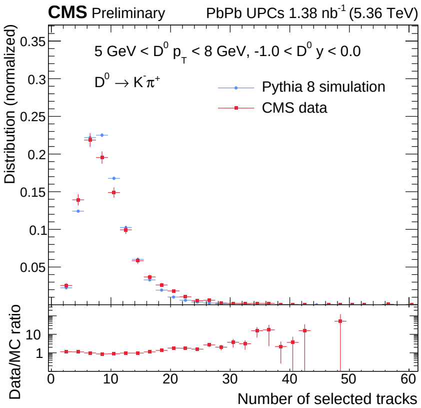
- **Empty bunches used to map noise distributions**

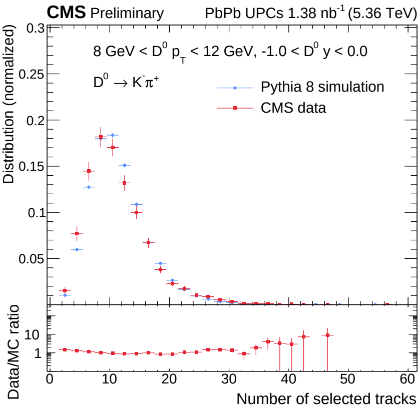
HF in Empty Bunches



- **Empty bunches used to map noise distributions**

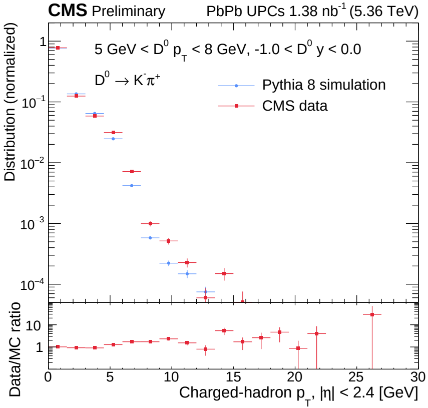
Data/MC Comparisons (I)

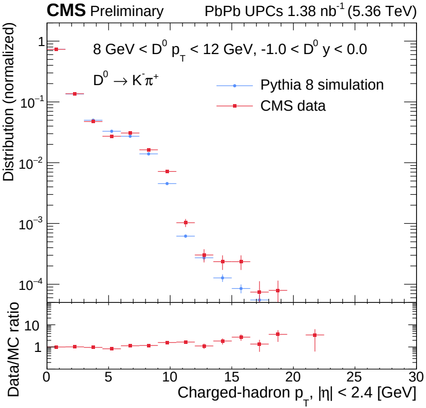




- **Track mult. distributions in data and MC**

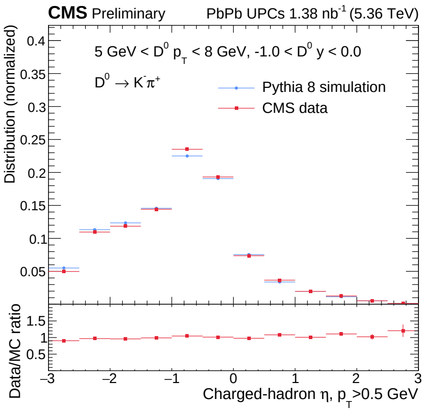
Data/MC Comparisons (II)

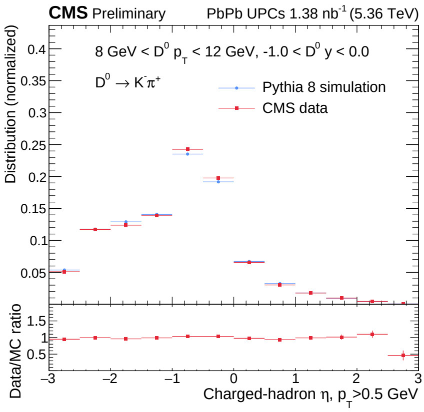




- **Track p_T distributions in data and MC**

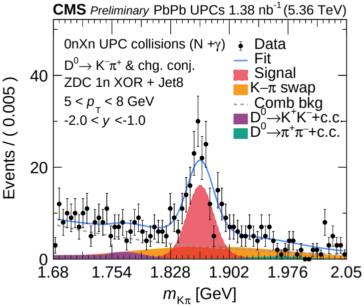
Data/MC Comparisons (III)



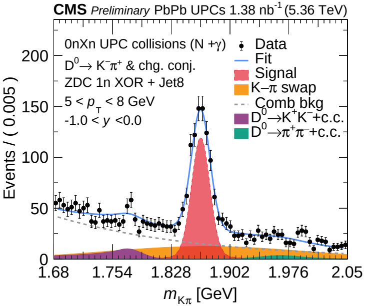


- **Track η distributions in data and MC**

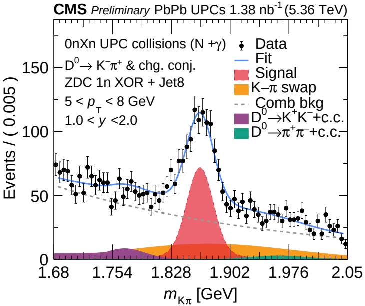
Mass Fits, 5-8 GeV in 0nXn



-2 < y < -1



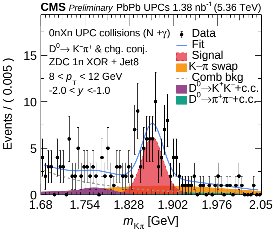
-1 < y < 0



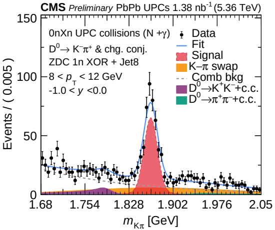
1 < y < 2

- **Remaining mass fits for all rapidity bins in 5-8 GeV, 0nXn**

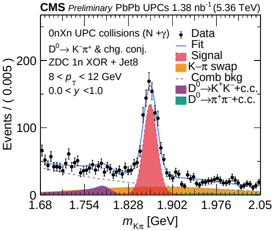
Mass Fits, 8-12 GeV in 0nXn



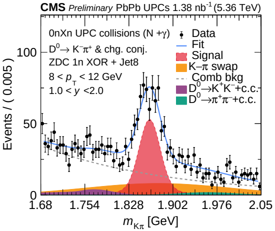
-2 < y < -1



-1 < y < 0



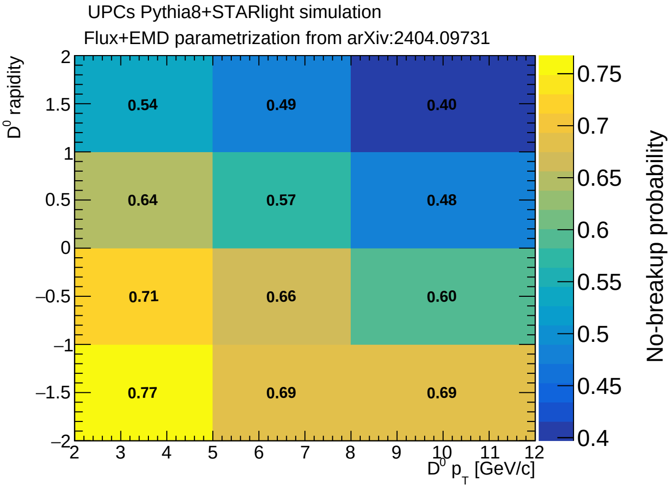
0 < y < 1



1 < y < 2

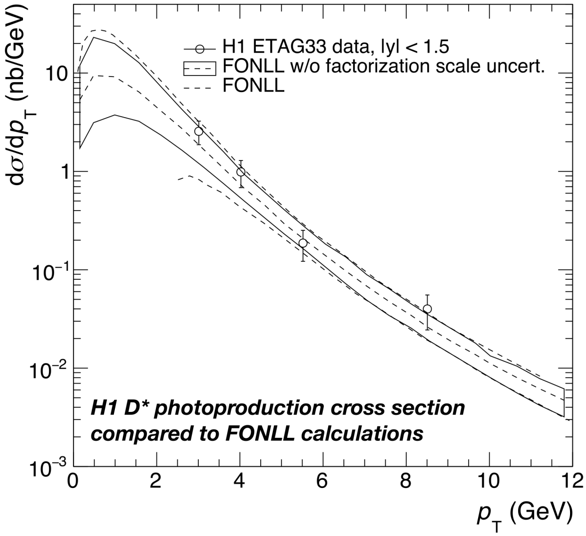
- **Remaining mass fits for all rapidity bins in 8-12 GeV, 0nXn**

Probability of No-breakup from EMD



Corrections for comparing theory-to-data

Benchmarking FONLL



FONLL compared to HERA H1 data

μ_R/μ_0 **varied from 0.5-2.0**

μ_F/μ_0 **varied from 0.5-2.0**

GRV parametrized γ PDF

Following Cacciari, Greco, Nason