Ultra Peripheral Heavy Ion collisions in CMS Run III

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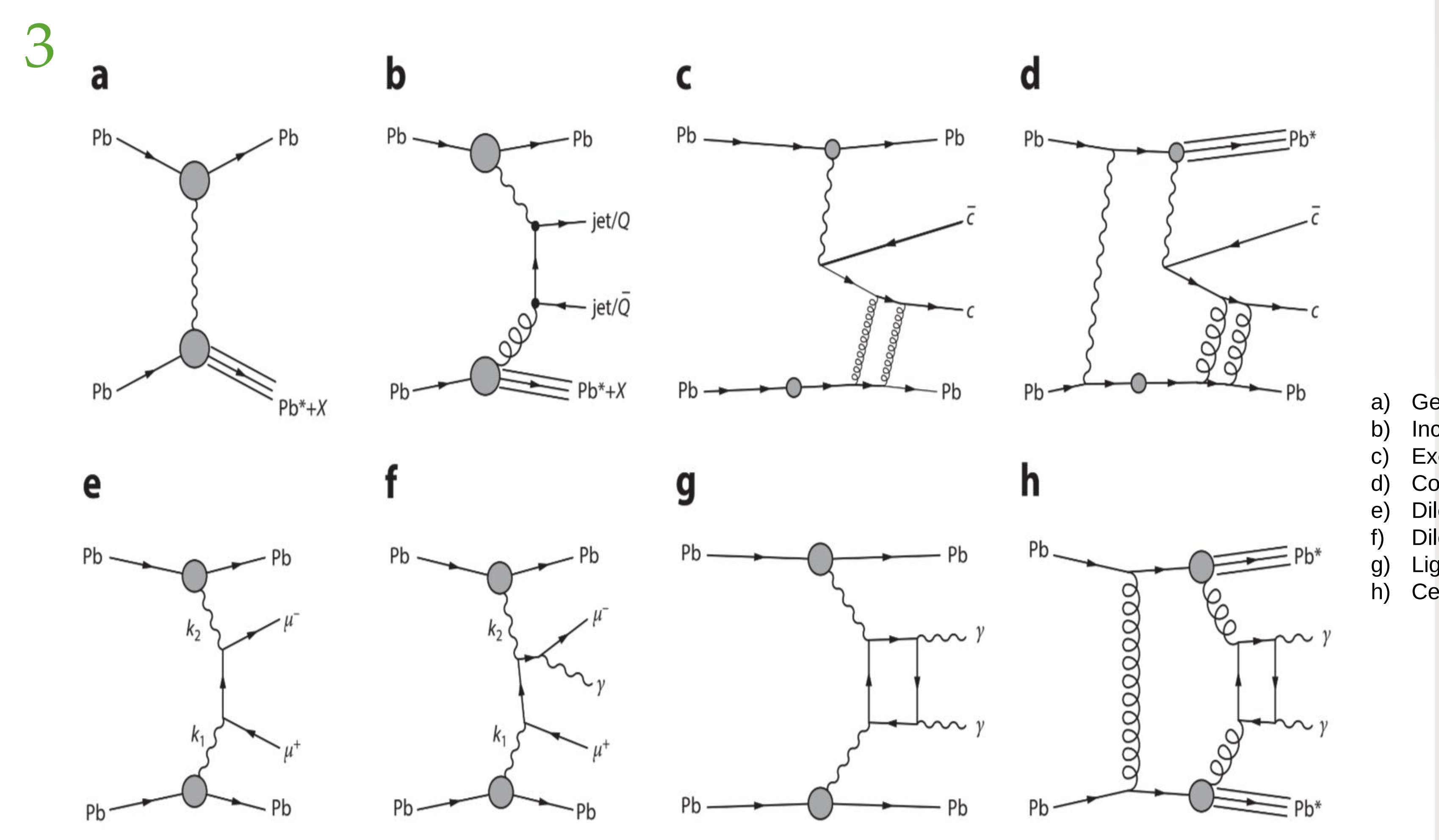
Physics of UPC

- Ultraperipheral collision (UPCs) are the ultimate energy frontier for electromagnetic interactions
  - UPC are collisions of relativistic nuclei at high ***b*** → ***no hadronic interaction***
  - Photons are nearly virtual $Q^2 < (\hbar/R_A)^2$, where R_A is the nuclear radius.
  - Valid for photonuclear and two photons interactions
  - LHC is the frontier energy for these two processes
  - UPC (heavy ions and protons) can address some interesting physics areas:
    - Nuclear shadowing, nuclear structure
    - Beyond the Standard Model and many others

S. Klein & P. Steinber – Annu. Rev. Nucl. Part. Sci. 2020. 70:323-54

Physics of UPCs

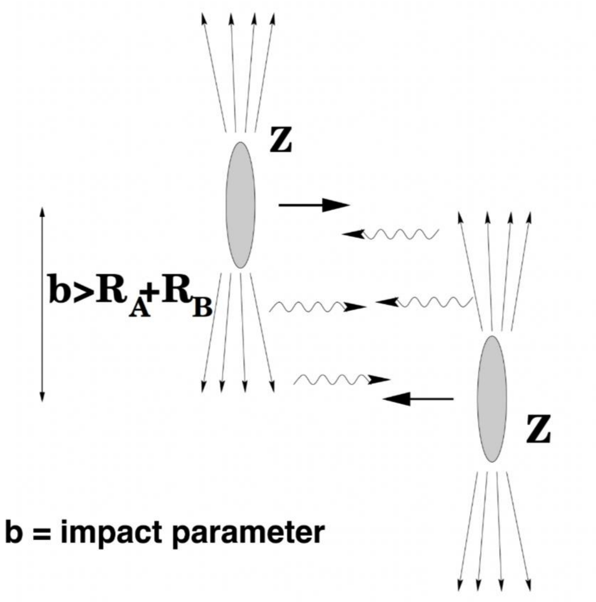
3



a) Generic photonuclear interaction with nuclear breakup target
b) Incoherent photoproduction
c) Exclusive photoproduction of a vector meson
d) Coherent photoproduction of a vector meson
e) Dilepton production
f) Dilepton production Higher Order
g) Light-by-light scattering with no nuclear breakup
h) Central exclusive diphoton production with double breakup

UPCs in CMS RUN III

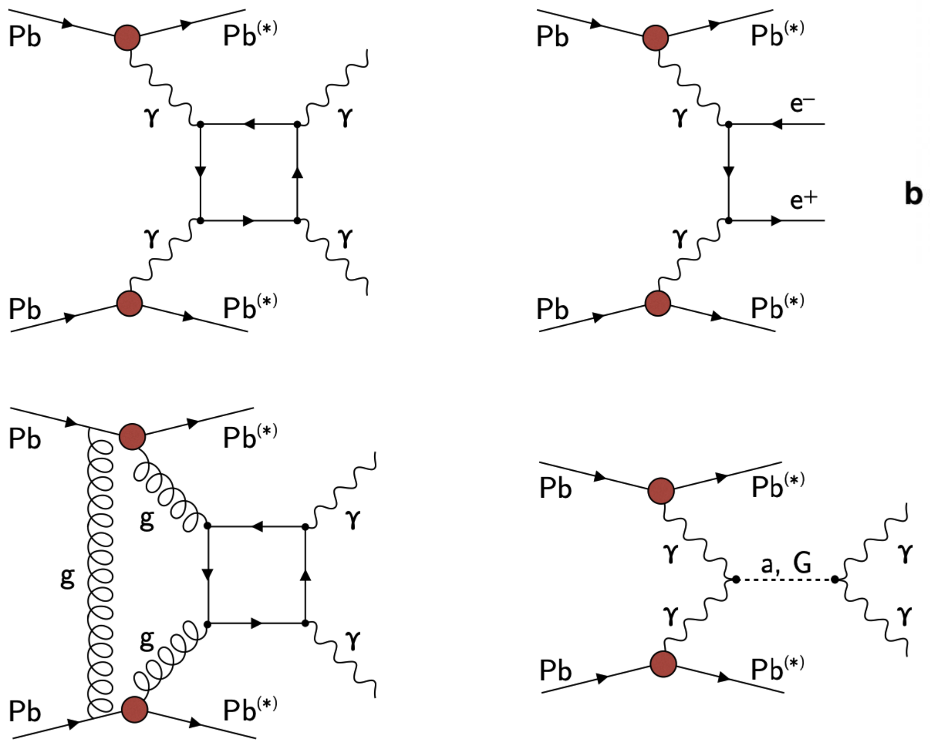
4



Ultra-peripheral collisions (impact parameter b > R_A+R_b)
- Flux of photon is proportional to Z^2

- **Photon kinematics**:
  - $p_T < \hbar/R_A \sim 30$ MeV
  - $E_{max} \sim O(100)$ GeV at LHC.

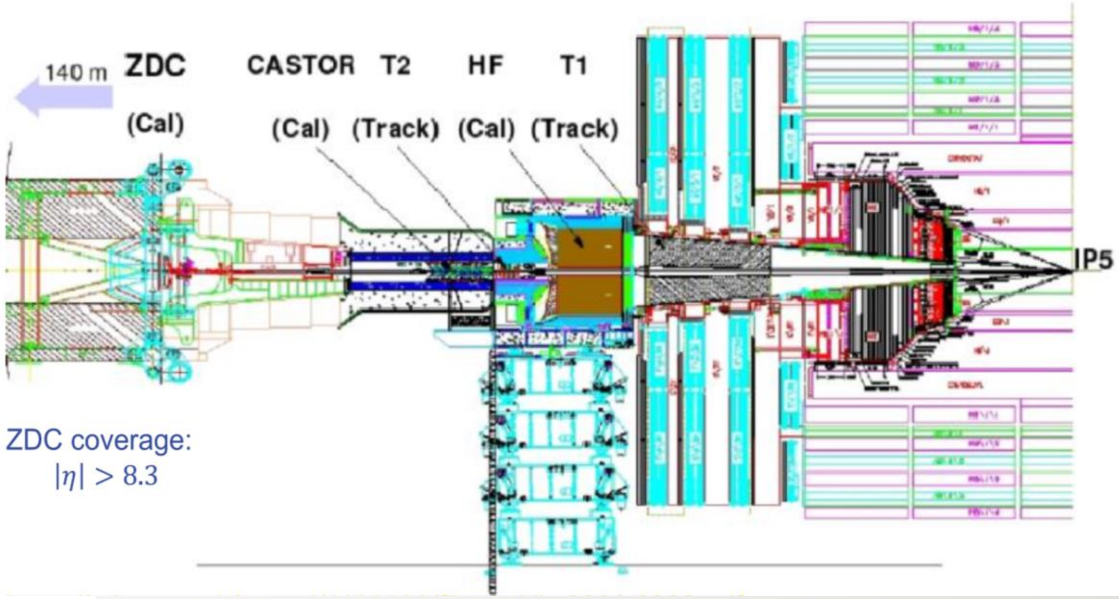
<u>**When running on PbPb, LHC is effectively a γγ and γN collider!**</u>



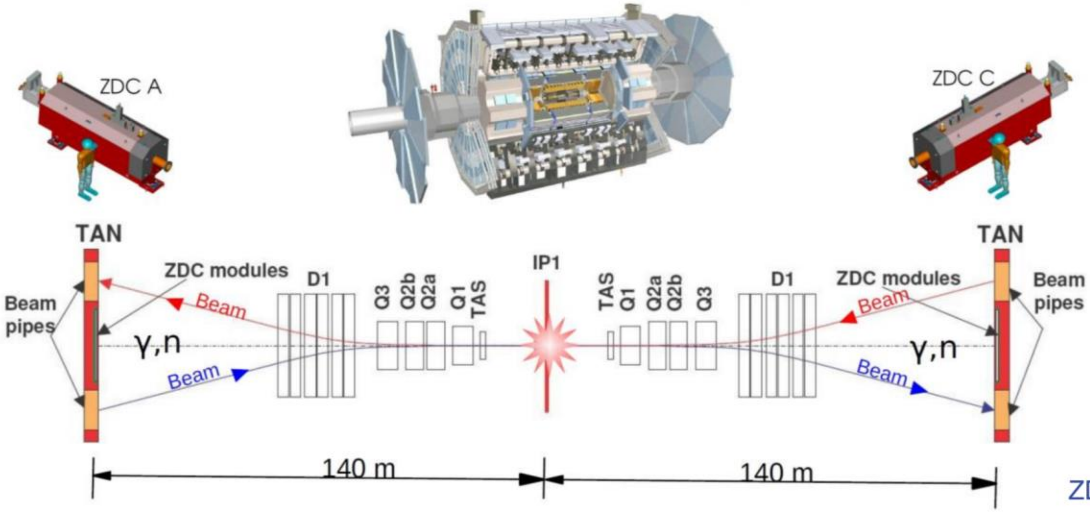
UPC in Atlas and CMS

5

CMS including ZDC



ATLAS including ZDC

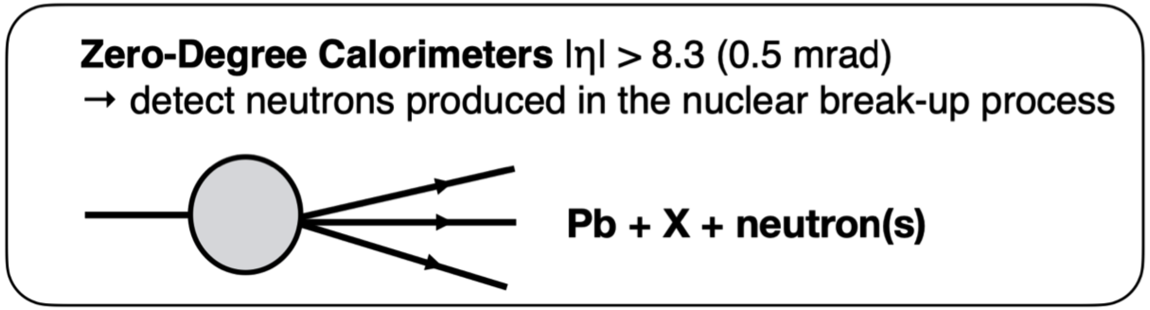


ZDC coverage:
$|\eta| > 8.3$

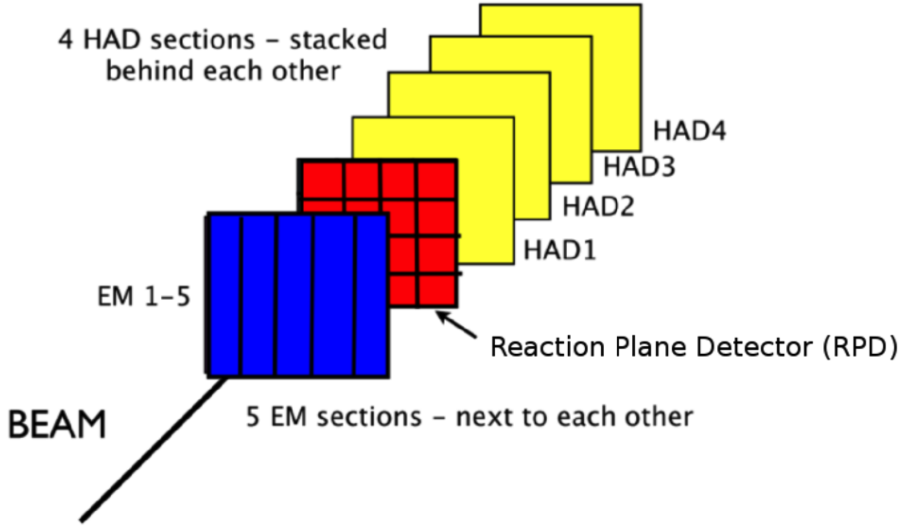
Abstract

Ultraperipheral collisions (UPCs) of heavy ions are a useful probe to study nuclear parton distribution functions (nPDFs) and, in particular, to characterize nuclear matter at Bjorken $x < 10^{-3}$ and low squared momentum transfer Q^2 (shadowing/saturation regime). In order to fully exploit these collisions, dedicated triggers on such event topologies were developed for the heavy ion data-taking period in 2023 by the CMS experiment. These triggers relied on the possibility of using the Zero Degree Calorimeter (ZDC) as a level-1 (L1) trigger detector for the first time. As a result, they allowed for an improved selection performance in addition to existing UPC triggers (as well as minimum-bias hadronic triggers), and enabled the study of hard processes (jets and heavy flavor hadrons) in photon-photon (γγ) and photon-nucleus (γN) scatterings. In this note, we present a list of selected results that highlight the performance of the L1 ZDC trigger selection as well as the performance of the L1 trigger algorithms for selecting γN dijet events.

ZDC to detect nuclear breakup

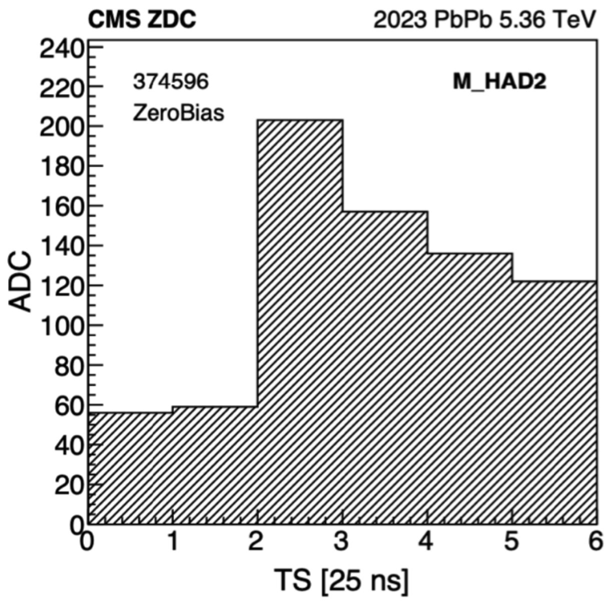


ZDC Layout



- Here the ZDC is used in order to detect nuclear breakup.
- The energy of neutrons emitted in the nucleus breaking is detected in the ZDC.
- Measure this by summing up energy in the ZDC electromagnetic (EM) and hadronic (HAD) sections. Reaction Plane Detector (RPD) not used here.

ZDC Out of Time Pileup Subtraction



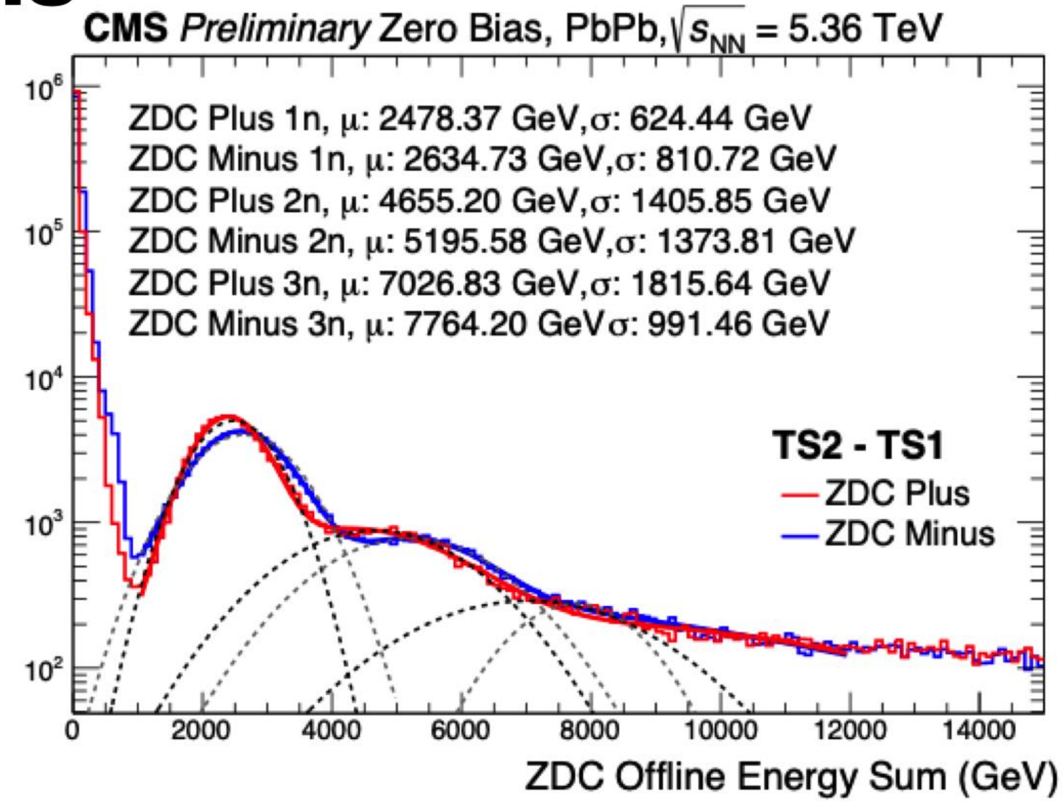
Caption: *ADC counts in the ZDC second hadronic layer on the minus side as a function of the time slice (TS) in 25 ns intervals for a zero-bias sample.*

- **Goal:** Subtract the "out-of-time" contamination from the ZDC signal. In heavy ion collisions, the probability of having two hadronic collisions in two subsequent time slices (TSs) in 25 ns intervals is negligible. Nevertheless, this subtraction can help removing noise as well as some contamination from EM pileup (e.g., from another UPC event)
- To handle this we subtract the previous time slice (TS1) from the signal (arriving in TS2) .

Two approaches
- Offline Approach: TS2 - TS1
- Online Approach: TS2 - 0.4*TS1
  - More conservative approach used in trigger mode

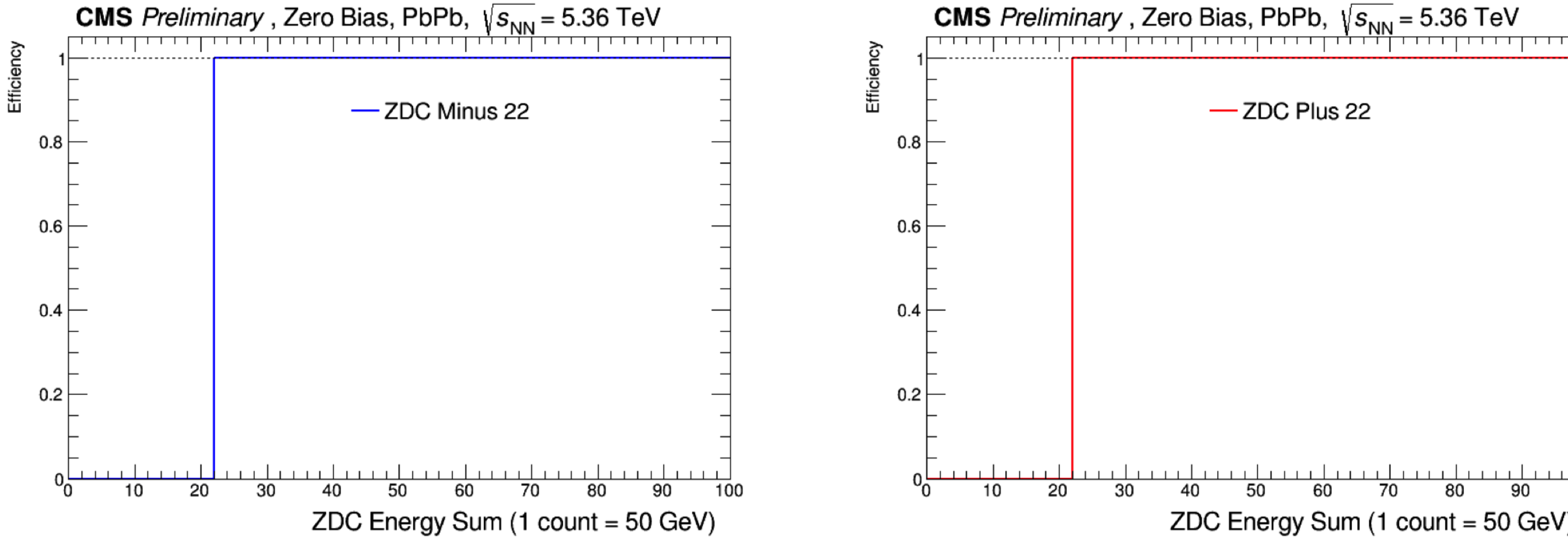
ZDC Offline Energy Sums

- ZDC offline energy sums in a sample of 3 million zero-bias events.
- No additional offline selection made.



Caption: *ZDC offline energy sums for the ZDC plus and the ZD minus in a sample of 3 million zero-bias events with fits to the 1 2n, and 3n peaks with the mean and sigma of each peak reported. For the out-of-time pileup, a TS2 - TS1 subtraction is used.*

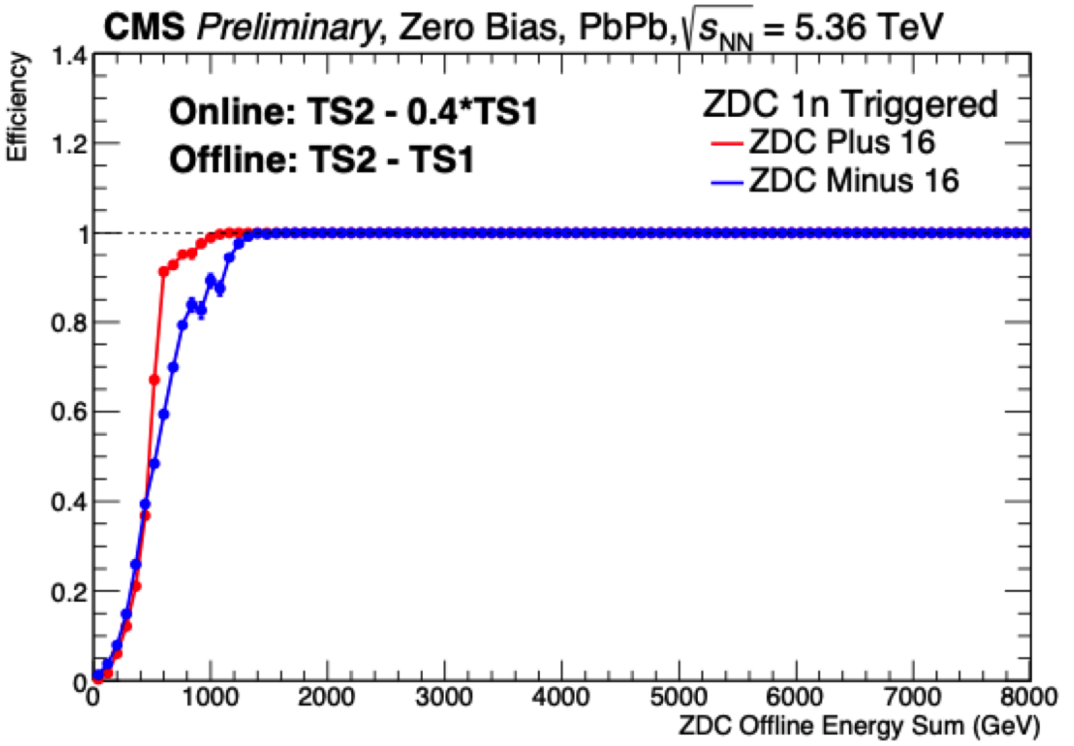
Turn-on curve as a function of online sums



Caption: *Turn-on curve for ZDC 1n triggered events as a function of the ZDC online energy s for the ZDC minus (left) and the ZDC plus (right) in a zero-bias sample with a ZDC threshold o and online sum of 22 (where 1 count = 50 GeV). The online ZDC sum is computed with an ou of time pileup subtraction of TS2 - 0.4*TS1.*

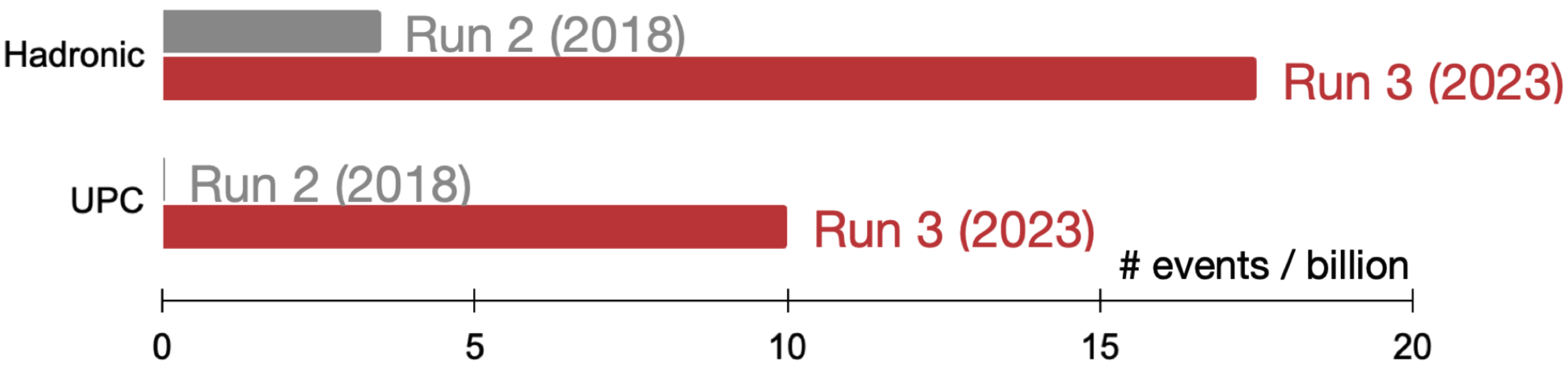
L1 ZDC 1n Trigger

- Turn on curve for ZDC 1n trigger
- Can use this plot in combination with offline energy sum plot to determine the region where fully efficient.



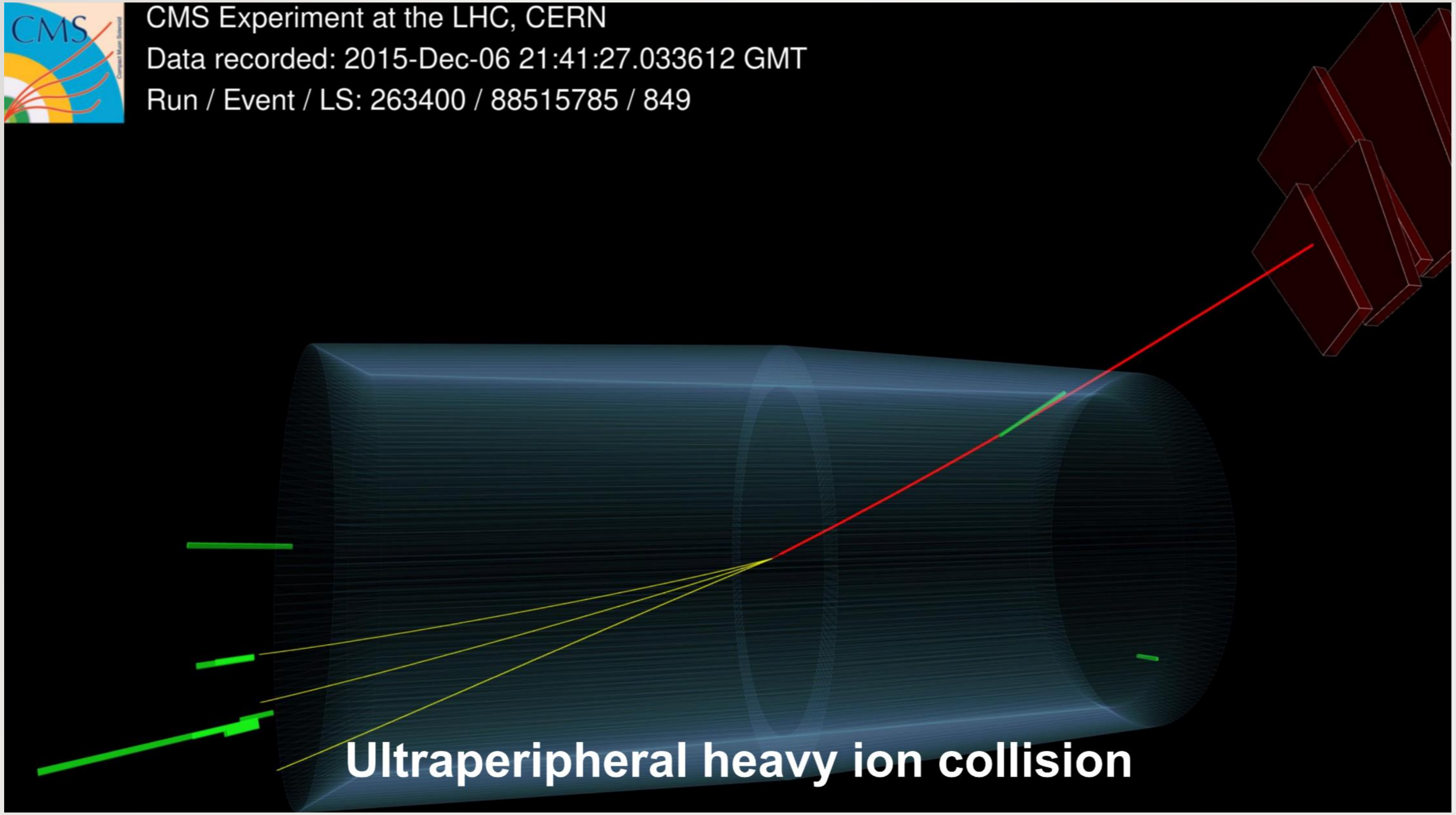
Caption: *Turn-on curve for ZDC 1n triggered events as a function of the ZDC offline energy sum for the ZDC plus and the ZDC minus in a zero-bias sample. The offline sum is computed with an out-of-time pileup subtraction of TS2-TS1 whereas the online ZDC sum is computed with an out of time pileup subtraction of TS2 - 0.4*TS1.*

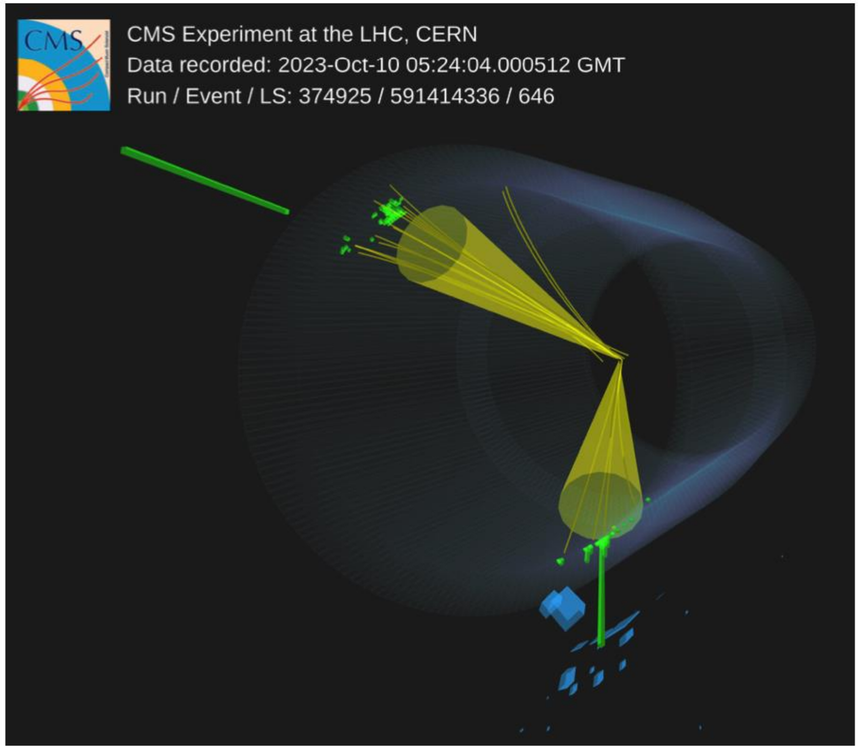
UPC dijet and heavy-flavor events: 2023 vs Run 2 (2018)

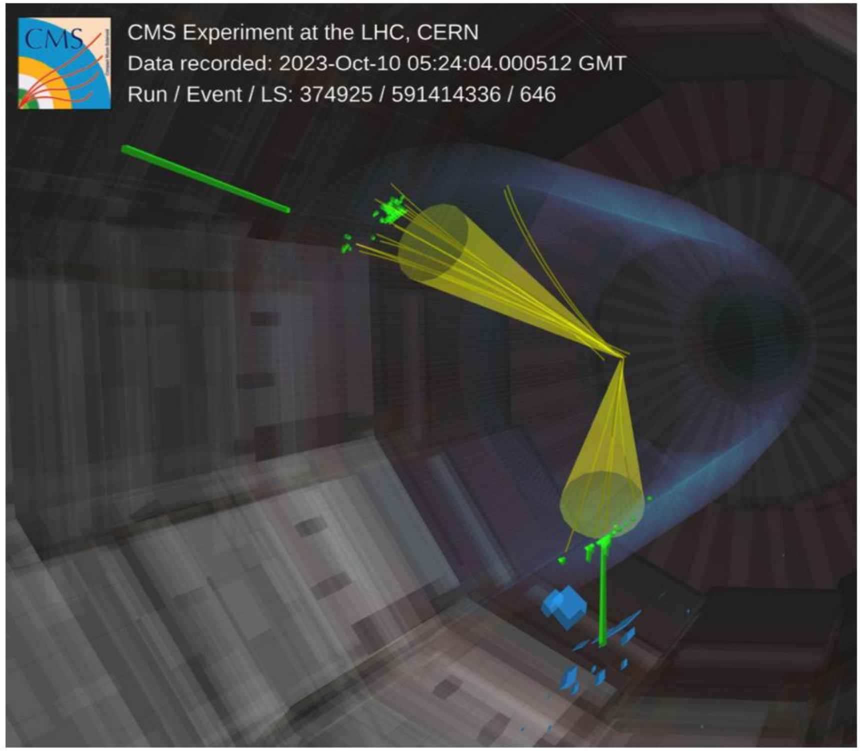


Caption: *Comparison of number of collected UPC dijet and hadronic events (reported per billion) collected in Run 2 (2018) vs. Run 3 (2023). In 2018, only a few million zero-bias (ZB) were available for the study of UPC dijets and heavy-flavors. In 2023, about 10 billions of ZDCOr and ZDCXOR+Jets events were collected, thanks to the use of the new L1 trigger strategy. There was also a large increase in the amount of hadronic events recorded in Run 3 (2023) vs. Run 2 (2018).*

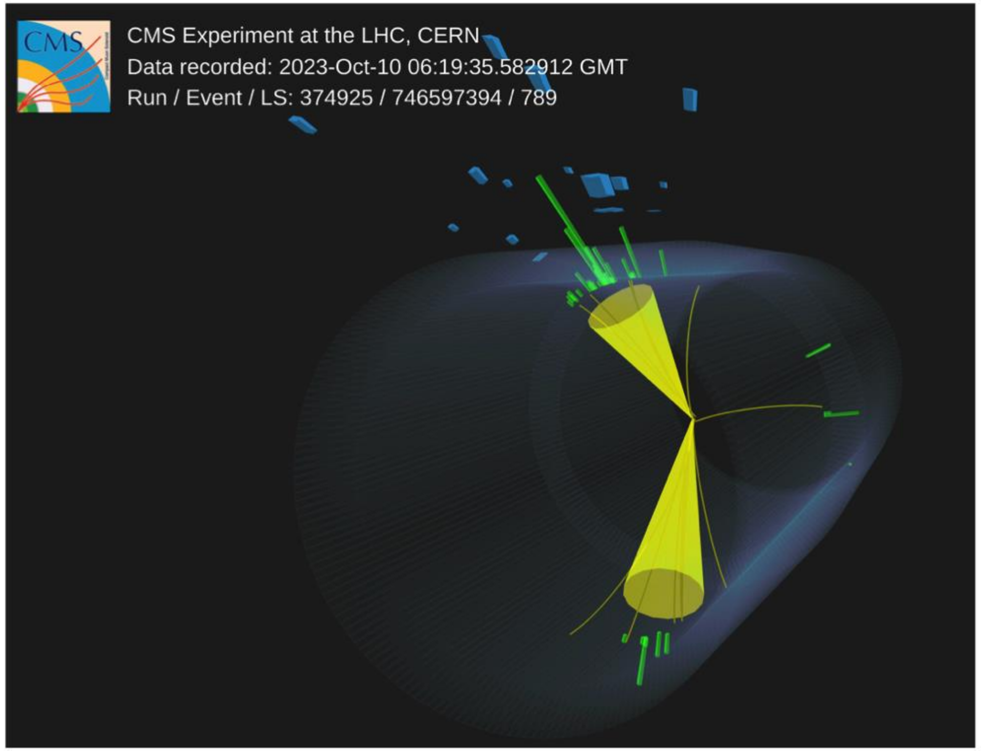
Event display for γN events in UPC

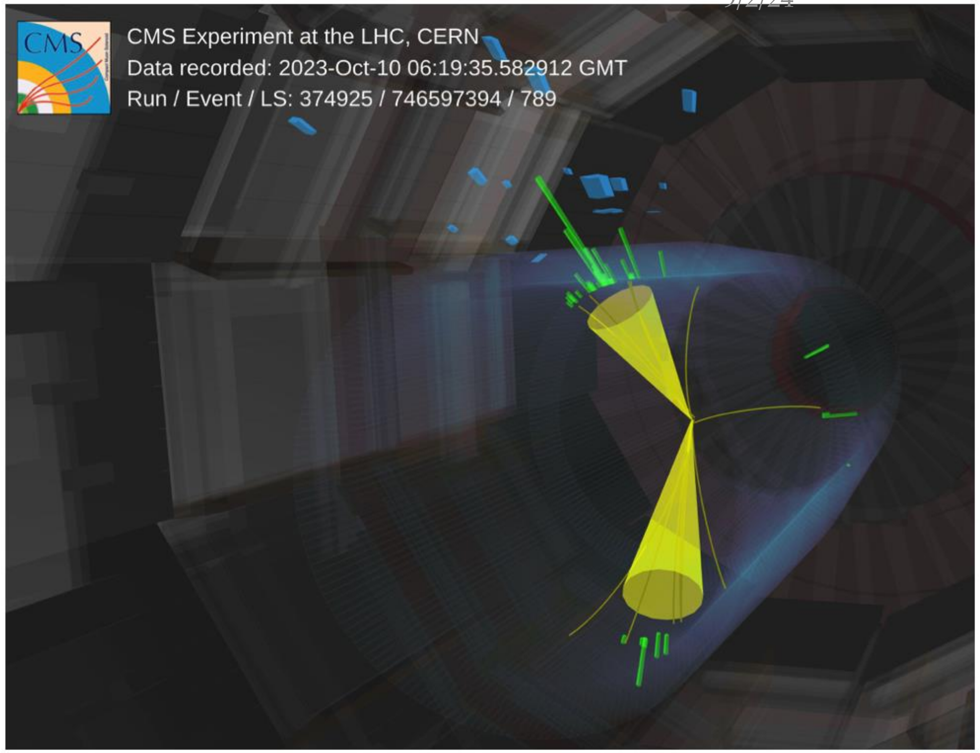




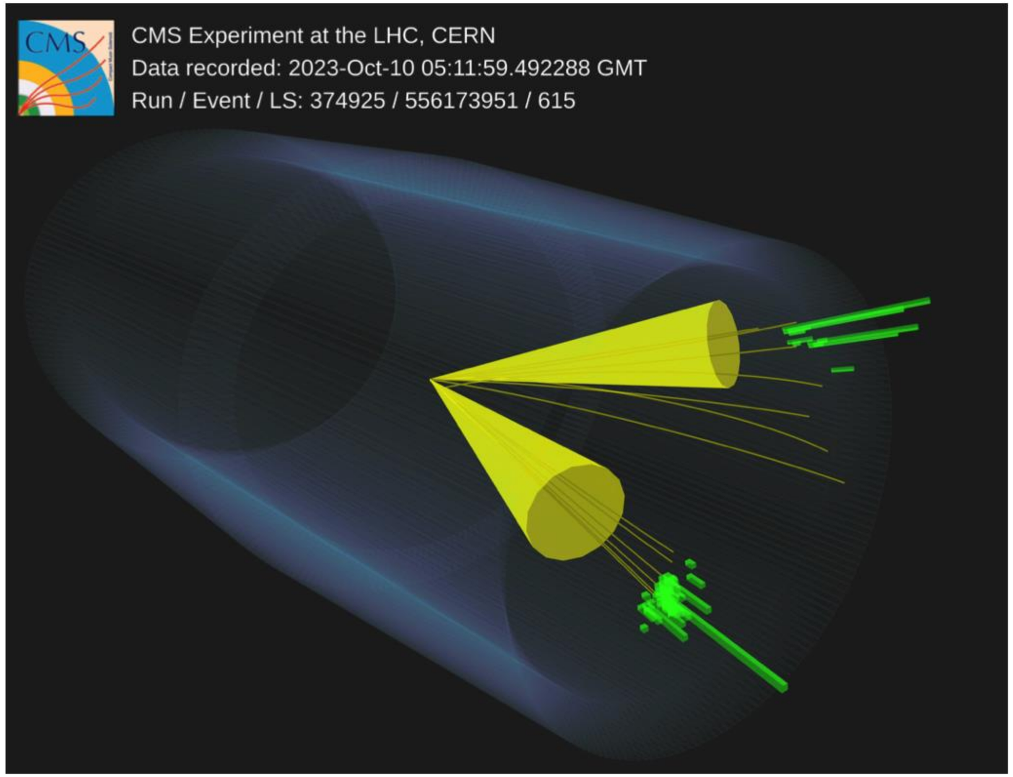


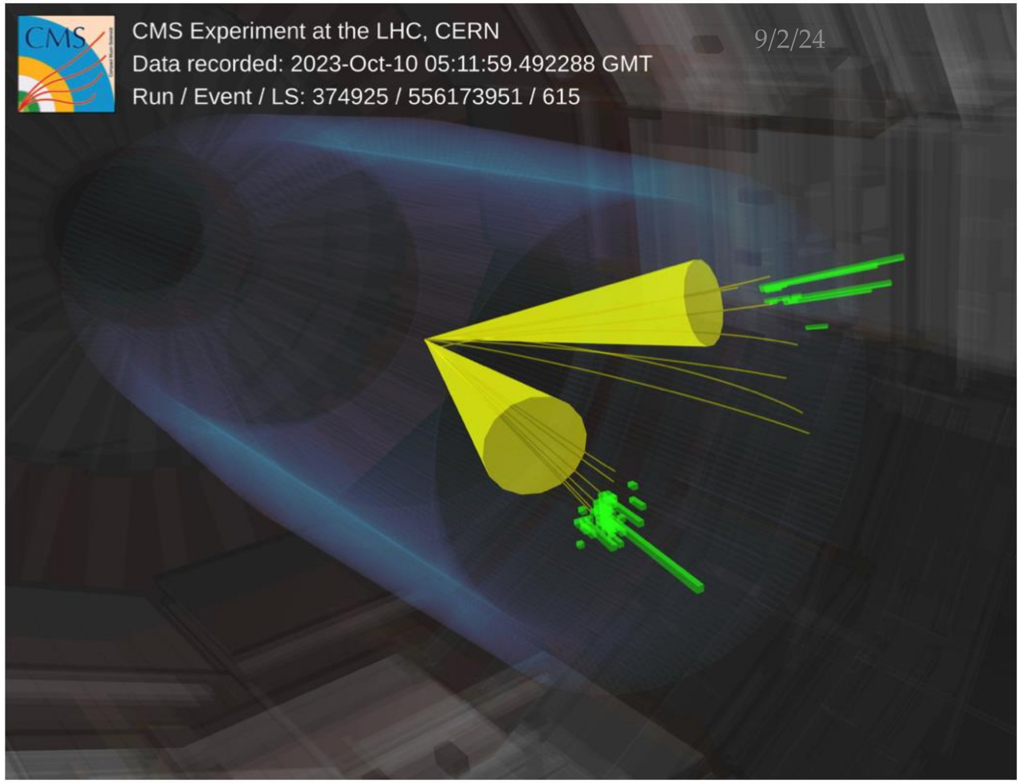
Caption: Event display of the CMS detector for an example UPC dijet event. Two configurations, both with (right) and without the support structures included are shown. This event contains three particle flow jets with a (p_T, η, ϕ) of (69.3 GeV, -1.396, -2.088), (68.7 GeV, -1.465, 1.004), and (5.8 GeV, -1.633, 1.374), ordered by index.





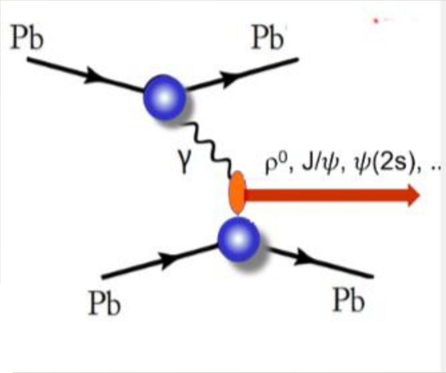
Caption: Event display of the CMS detector for an example UPC dijet event. Two configurations, both with (right) and without the support structures included are shown. This event contains three particle flow jets with a (p_T, η, ϕ) of (41.6 GeV, 0.559, 1.902), (37.5 GeV, 1.171, -1.249), and (5.8 GeV, 0.258, 0.266), ordered by index.

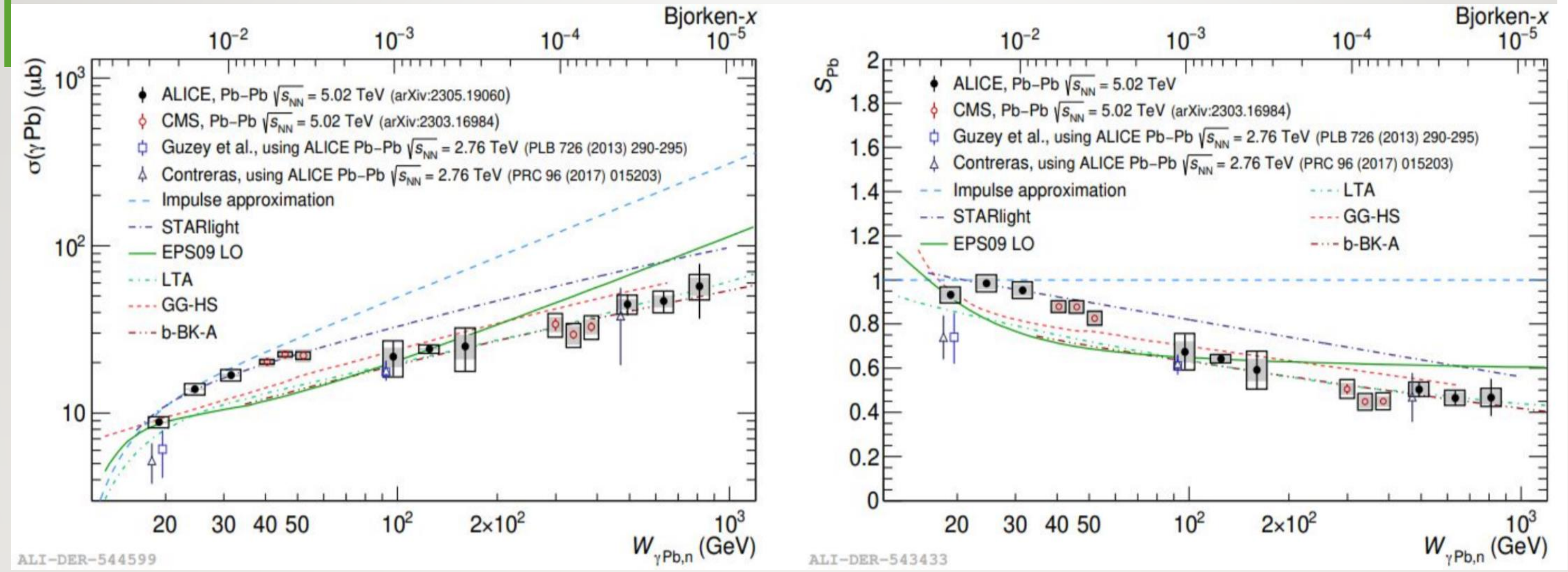




<u>Caption:</u> Event display of the CMS detector for an example UPC dijet event. Two configurations, both with (right) and without the support structures included are shown. This event contains two particle flow jets with a $(p_{\mathrm{T}}, \eta, \phi)$ of (62.2 GeV, -1.346, 2.773) and (22.3 GeV -2.236, -0.213) ordered by index.

J/psi production in PbPb in UPC

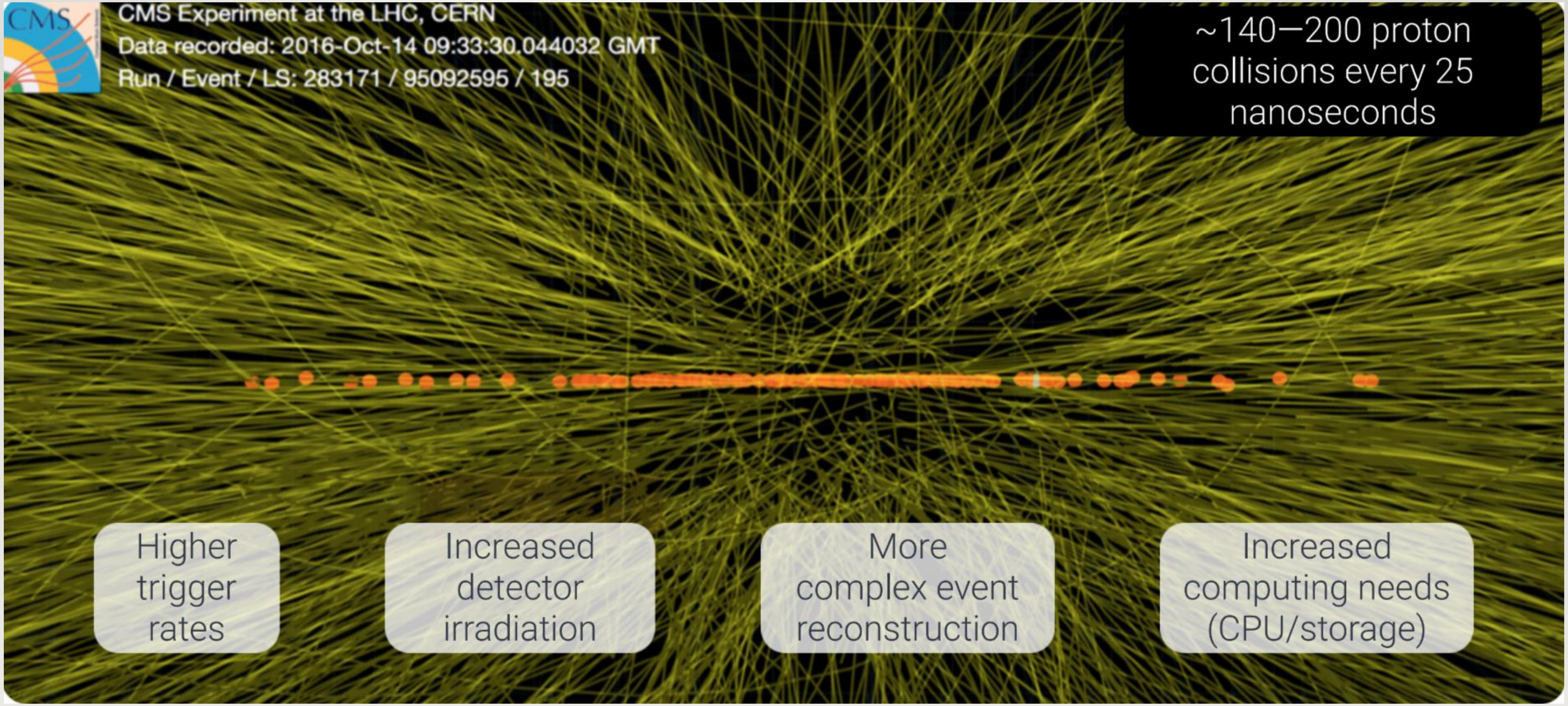




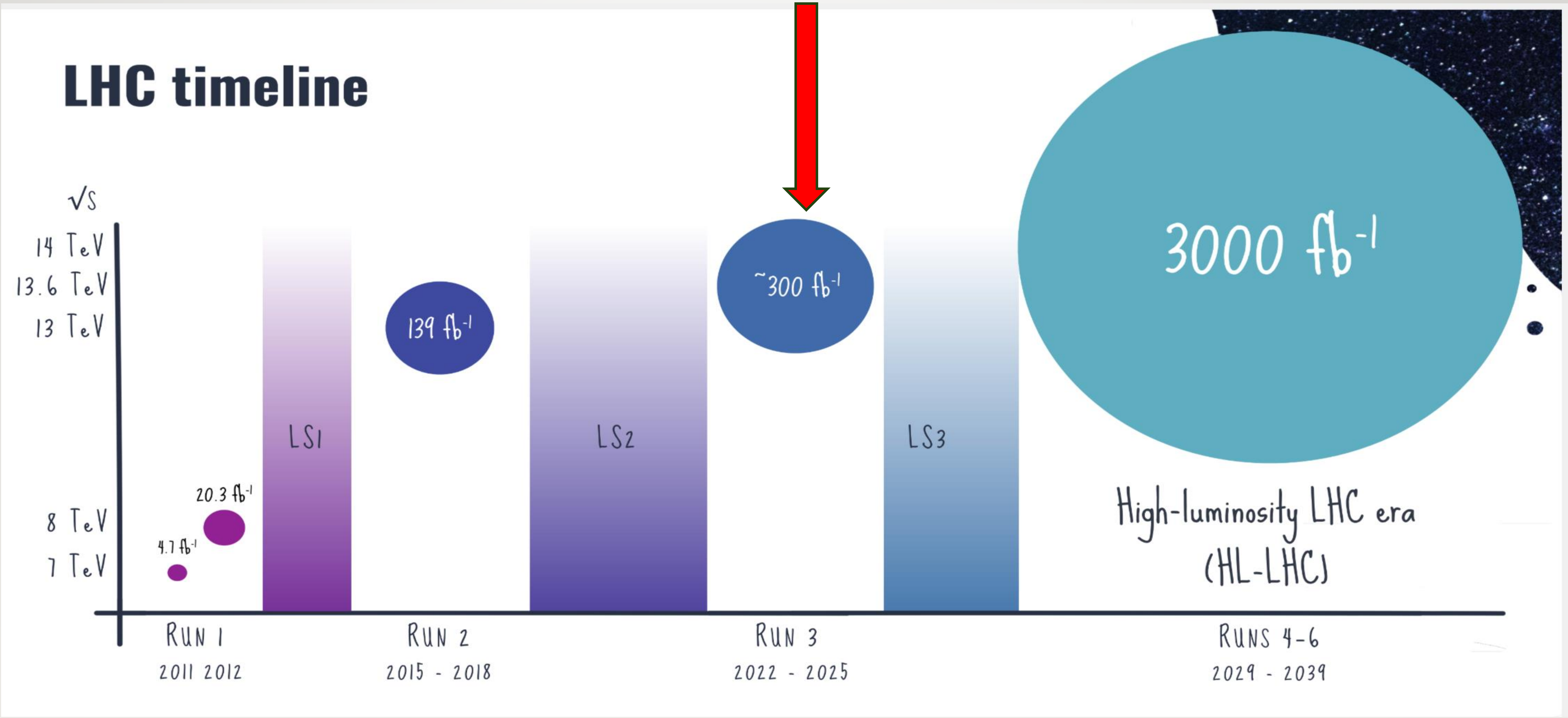
Using ZDC we can have higher energy photons extracted without increasing the energy
PRL. 131 (2023) 262301

18

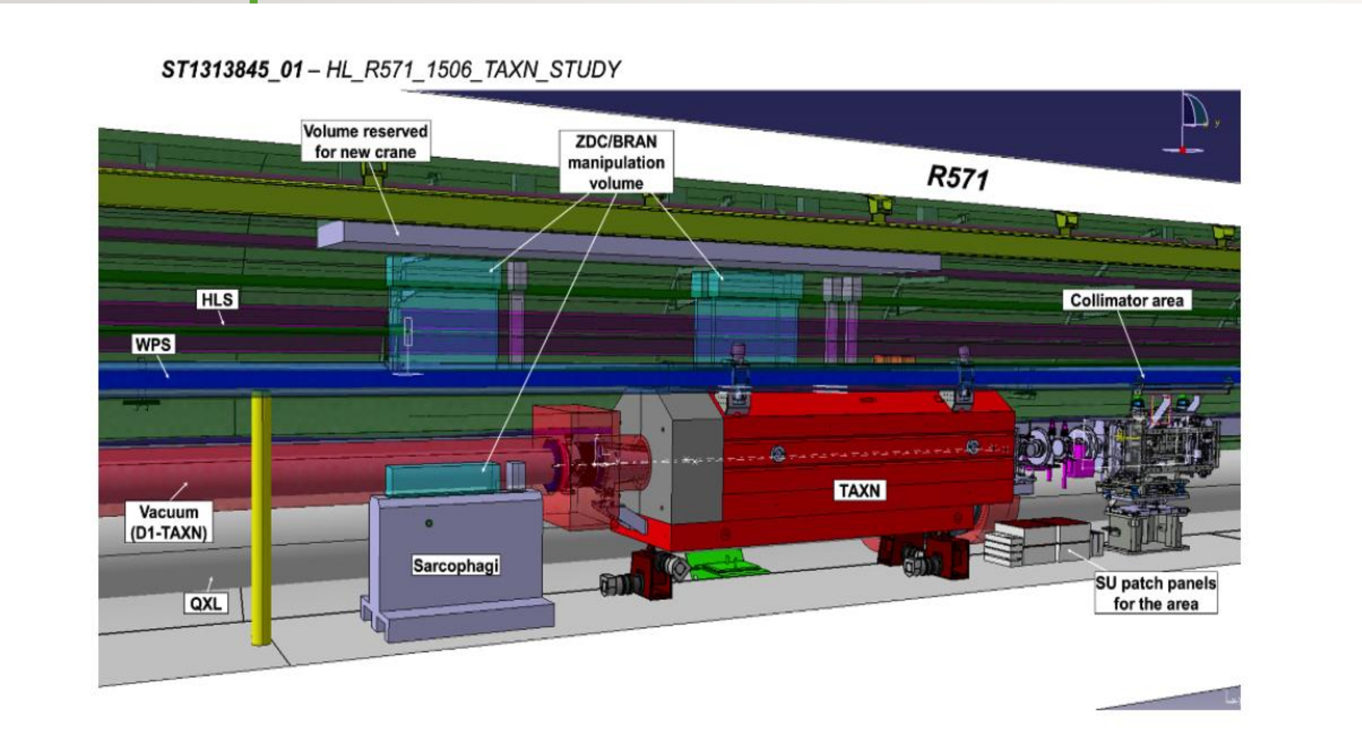
Run 3, Run 4, Run 5



Where are we today



CMS upgrades – HL-LHC

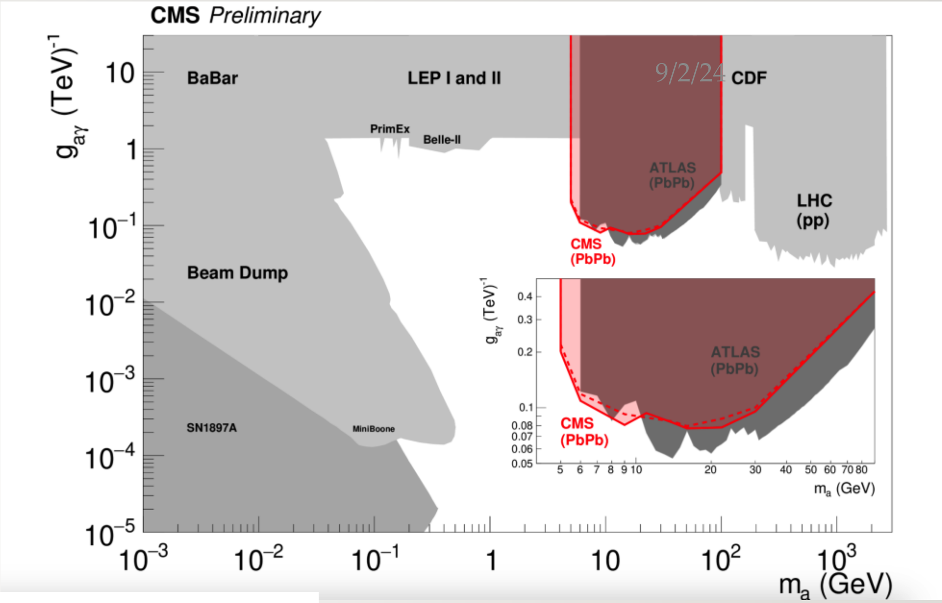


Summary

- Ultraperipheral Heavy Ion Collision (UPC) → Provides unique physcis potential
  - LHC can be used as photon-photon and photon-nucleus collider
  - Photon-induces di-lepton production
    - Study photon flux, properties of Tau-leptons
  - Photonuclear interactions
    - Charged hadron productions or Light/heavy VM production
  - Rare processes
    - Probe interaction of axion-like particles
  - Lots of trigger improvements for RUN3 (Atlas and CMS)
  - Future HL-LHC upgrades challenges and EIC -→ Stay curious ☺

Backup

ZDC in 2018



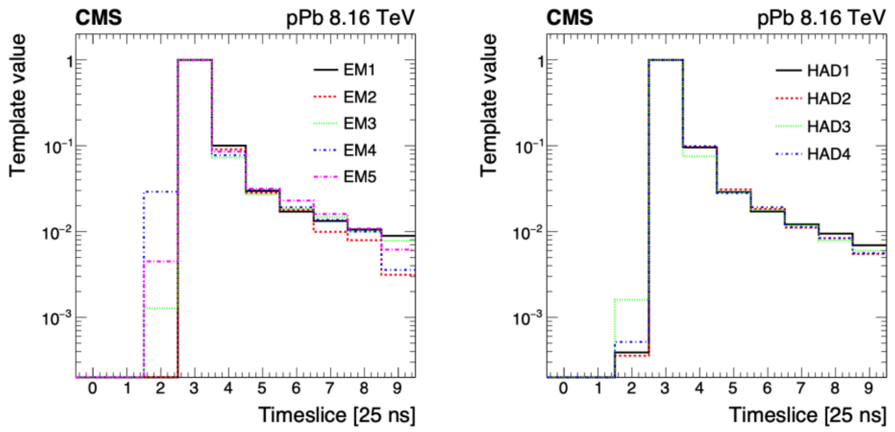


Figure 7. Average signal shapes of EM channels (left) and HAD channels (right). The first six timeslices are taken as the template of the main signal, whereas the values from TS4 to TS9 are used to construct the template of the pre-pileup signals.

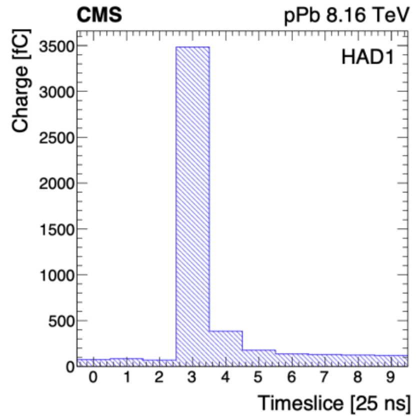


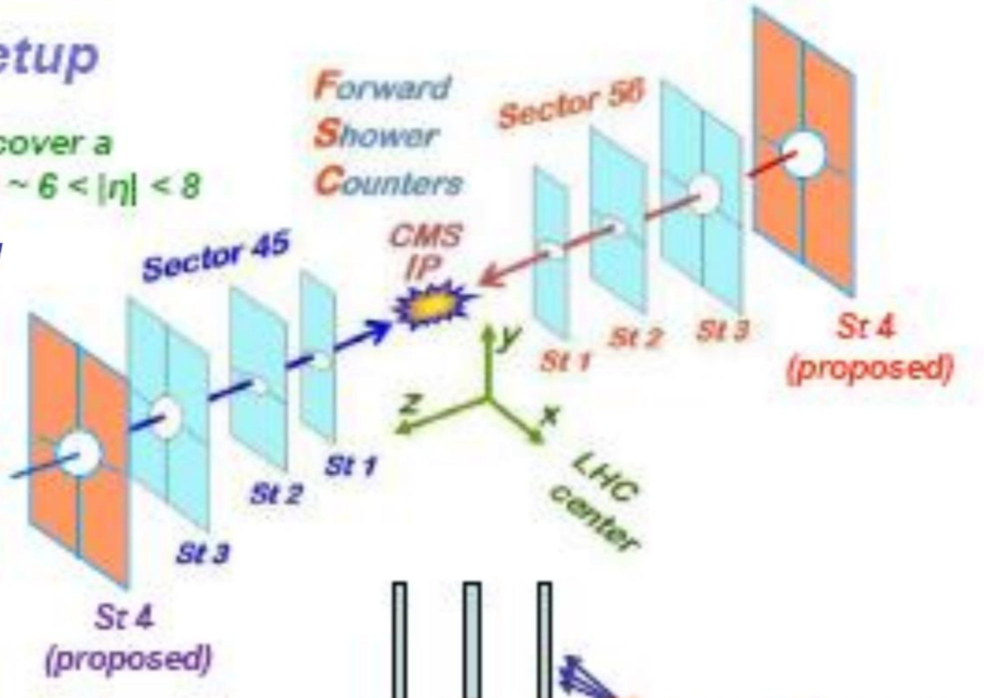
Figure 6. A typical ZDC signal shape.

Towards Full Acceptance: FSC System at Pt5

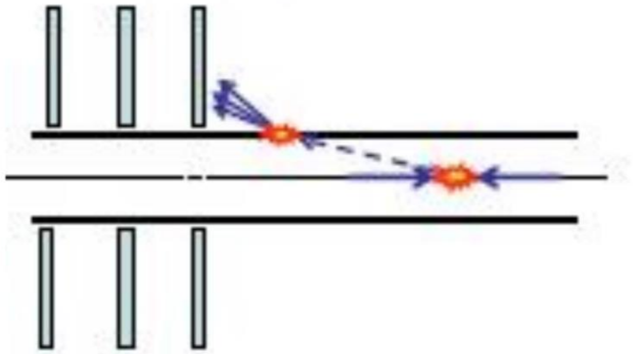
FSC Setup

FSC Counters cover a rapidity region ~ 6 < |η| < 8

[gap in η between forward (HF, CASTOR) and very forward detectors (ZDC, TOTEM RP)]

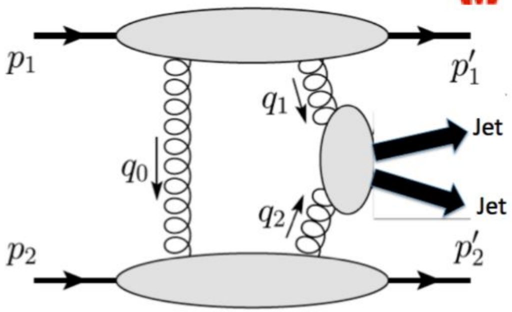


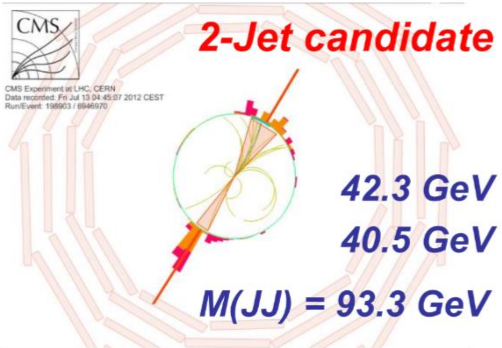
- Scintillator paddles
~25cm x 25cm with one PMT each,
- Presently 8 per side, symmetric to IP5
- Setup to be upgraded
- Extra stations - finer segmentation

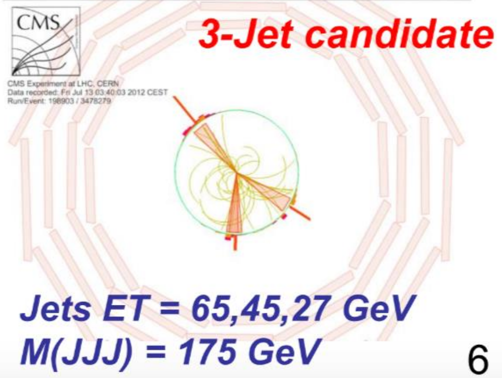


2012 CMS+TOTEM β^*=90m Run(s)

- July 2012: **low PU (β^* = 90m) pp at 8 TeV**, CMS + TOTEM **common run**(*), show events consistent with central production of high-pT jets accompanied by two leading protons.
- **FSC detectors,** covering the very forward pseudo-rapidity range 6 < | η | < 8, were **required to be empty**.
- The **leading protons** were detected in the TOTEM Roman Pots (RPs)
- Preliminary results shown in:
- **CMS DP -2013/004:** CMS-TOTEM events: high-pT jets with two leading protons
- **CMS DP -2013/006:** Central high-pT jet production during low pile-up, β^* = 90m, 8 TeV pp run



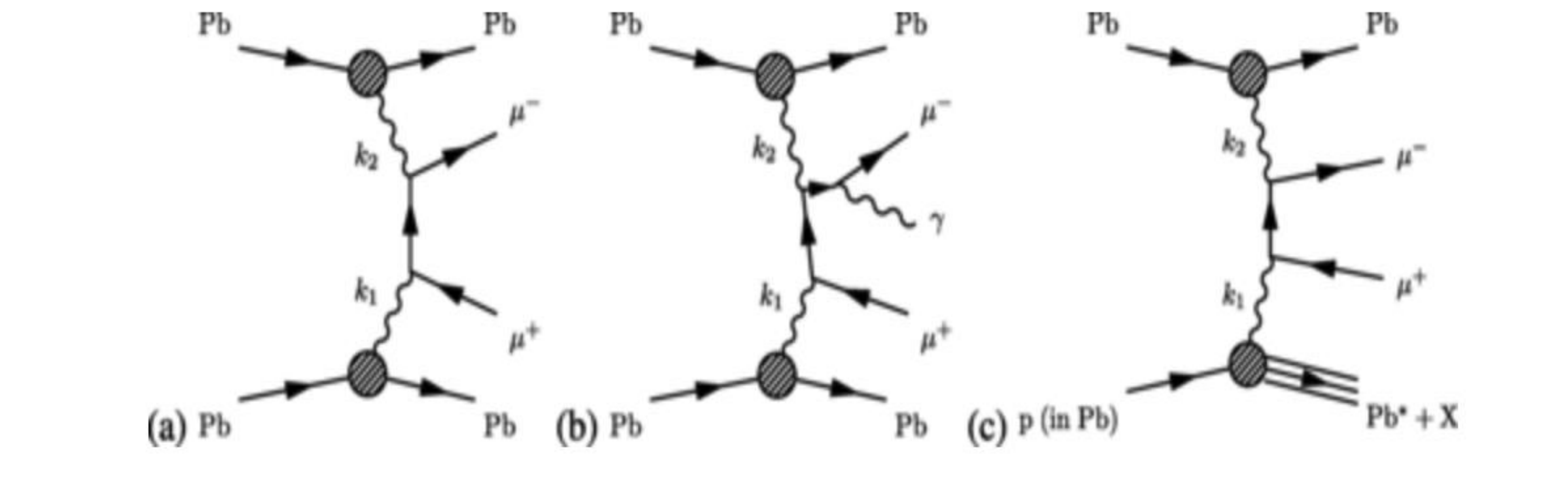




(*) Runs 198902/3 (12 hours) with β^* = 90m, low-PU (μ ~ 0.1), 112 bunches, L ~ $1.7.10^{30}$, 40 nb^{-1}

6

Back-up



-order
d (b) next-to-
$^{+}\mu^{-} + \gamma\,(\mathrm{PbPb})$
(middle) Breit-Wheeler process in Pb+Pb collisions, and (c) the dissociative $\mathrm{PbPb}\,(\gamma\gamma^{\star}) \rightarrow \mu^{+}\mu^{-} + X\,(\mathrm{Pb}^{\star}\ \mathrm{Pb})$ process where one photon is emitted from the substructure of one of the nucleons, leading to nucleon fragmentation in the far-forward direction.