Hard Probes in Ultra-Peripheral Collisions

Krista Smith

Heavy Ion Meeting, 2025-05

Pusan National University

Brief Introduction

Motivation to Study UPCs: Soft QCD Physics

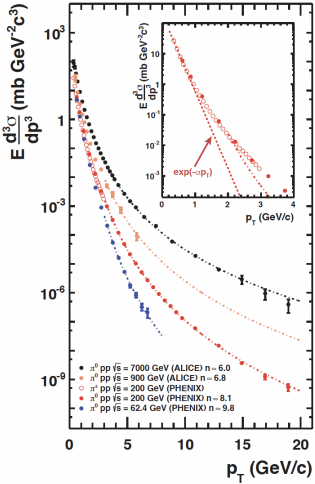
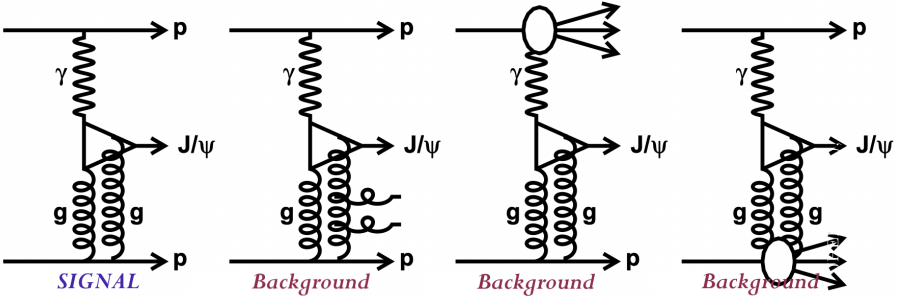


Image Credit: C. Klein-Boesing

- PHENIX π^0 cross-section in p+p collisions vs p_T
  - Fit with a power law function ($p_T > 2$ GeV/c)
  - Fit with exponential function ($p_T < 1$ GeV/c)
- Spectrum cannot be described by exponential function above ~ 2 GeV/c
- Soft QCD physics describes interactions involving small momentum transfer $Q^2 < (2\text{ GeV/c})^2$
  - Opportunities to study soft QCD physics in UPCs
- UPCs occur when distance b between two passing nuclei is more than twice their radii ($b > 2R$)
  - Involves 'long-range' photon and/or gluon interactions (no color exchanged)

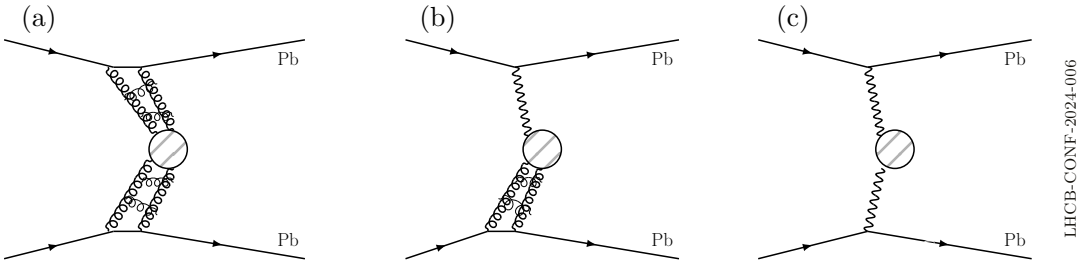
Vector Meson Photoproduction



J. Phys. G40 (2013) 045001

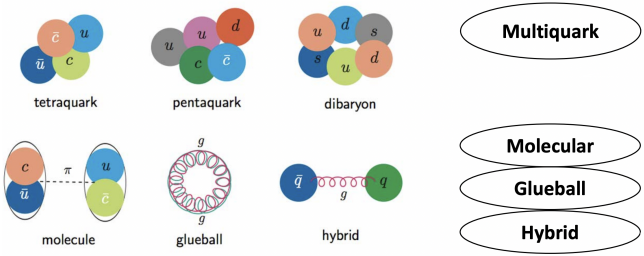
- Vector meson production in pp and AA collisions can be understood as interaction of a virtual photon $\gamma^\star$ and two gluons (or a pomeron $\mathbb{P}$)
- From left to right: Coherent interaction with no additional particles produced, inelastic interaction with gluon radiation, and the target or projectile proton dissociated by the photon-pomeron interaction $J^P = 1^-$ (γ, J/ψ, ψ(2S), ϕ(1020), Υ, ω, ρ, ...)

Additional Production Mechanisms



- Vector meson production in pp and AA collisions can be understood as interaction of a virtual photon $\gamma^\star$ and two gluons (or a pomeron $\mathbb{P}$)
- From left: Pomeron-pomeron interactions, photon-pomeron interactions (shown previously), and photon-photon interactions

Motivation to Study UPCs: Exotic Phenomena



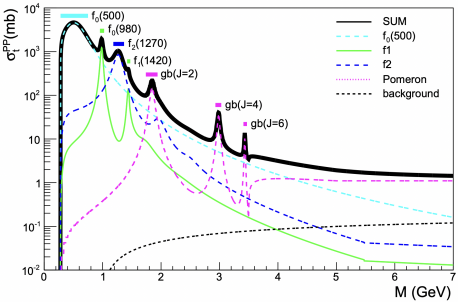


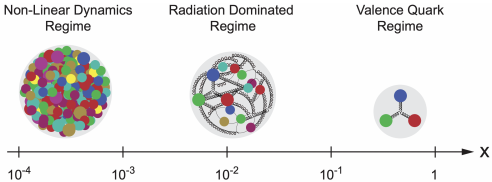
Image Credit: Hua-Xing Chen, Southeast University (CH)

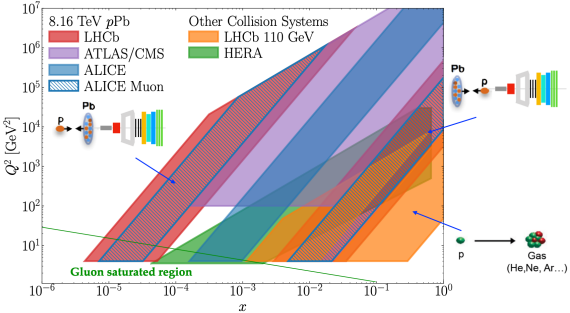
Eur.Phys.J.C 76 (2016) 1, 38

- UPCs could provide an environment to access exotic phenomena (ex: tetraquarks, glueballs)
- Some predictions look for scalar glueball decaying to pair of pseudoscalars ($\pi^+\pi^-$, K^+K^-)
  - Prediction for pomeron-pomeron production in the $\pi^+\pi^-$ spectrum shown (right)

Motivation to Study UPCs: Small Bjorken-x

- Soft processes can probe smaller Bjorken-x than hard processes (right)
- Smaller x values imply higher gluon densities
- In non-linear regime (below), gluons expected to radiate/recombine at same rate (could indicate high levels self interaction)
- Potential environment for color glass condensate





Left: Rept.Prog.Phys. 82 (2019) 2, 024301. Above: LHCb Publicity Figure

Hard Probes in Ultra-Peripheral Collisions

- Processes specific to ultra-peripheral collisions shown with corresponding Q^2 and x values
- Here, soft processes defined as $Q^2 < (1\ \mathrm{GeV}/c)^2$
- Hard probes in UPCs would include UPC dijets, open charm production, and vector meson production
- Υ and J/ψ photoproduction described as perturbative processes
- The lighter ϕ and ρ vector meson production falls within non-perturbative scale

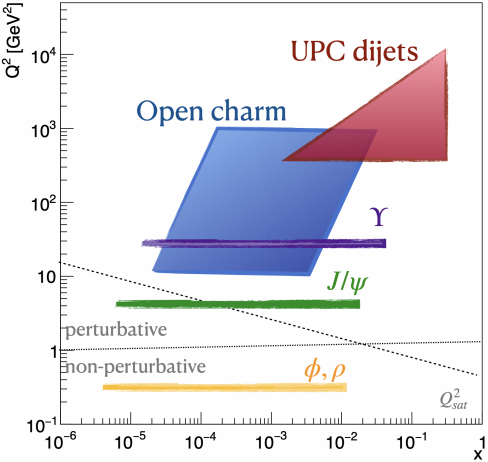


Diagram credit: A. Ogrodnik (QM 2025 talk)

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Focusing on Lower Q^2

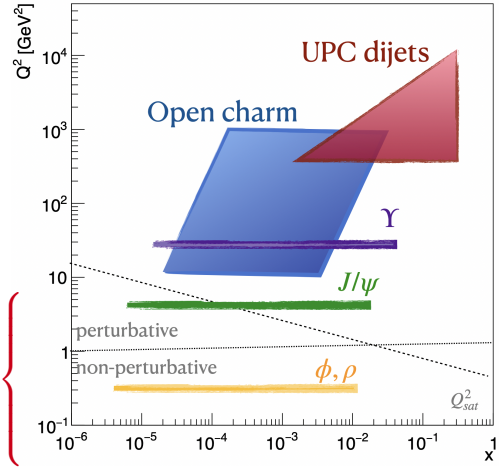
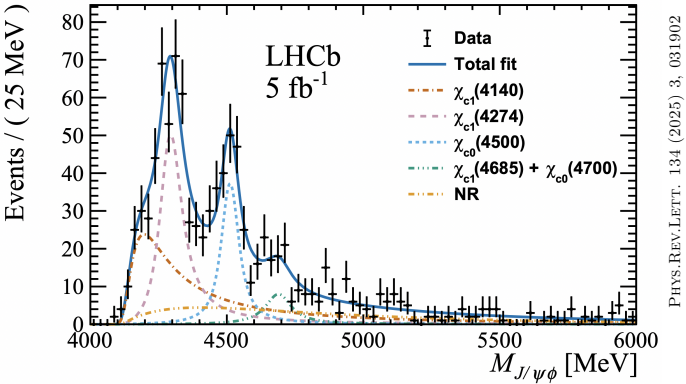


Diagram credit: A. Ogrodnik (QM 2025 talk)

Centrally Produced, Peripheral, and Ultra-Peripheral Collision Results

$J/\psi\phi$ in Central Production

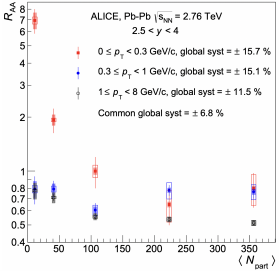


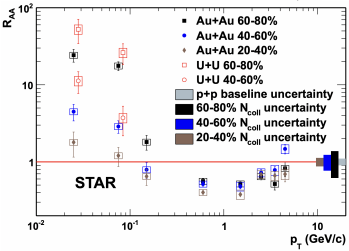
Phys.Rev.Lett. 134 (2025) 3, 031902

- Exotic states in diffractive processes: $\chi_{c0}(4500)$ and $\chi_{c1}(4272)$ observed with $> 4\sigma$ significance
  - At least 69% of candidates are produced in events where one or both protons dissociate
- Confirms previous LHCb results in hadronic collisions (Phys.Rev.Lett. 118 (2017) 2, 022003)

J/ψ Photoproduction in Hadronic Collisions

- Excess J/ψ yield in peripheral PbPb collisions measured by ALICE; postulated due to photoproduction
- Confirmation of excess J/ψ yield in AA collisions by STAR for $p_T^{ee} < 100$ MeV/c
- LHCb discrimination shown between J/ψ hadronic production and J/ψ photoproduction in peripheral PbPb collisions (top)
- Differential yield as function of p_T and rapidity (right) support hypothesis of coherent photoproduction in hadronic collisions
  - $\langle p_T \rangle = 64.9 \pm 2.4$ MeV/c





ALICE: Phys.Rev.Lett. 116 (2016) 22, 222301
STAR: Phys.Rev.Lett. 123 (2019) 13, 132302

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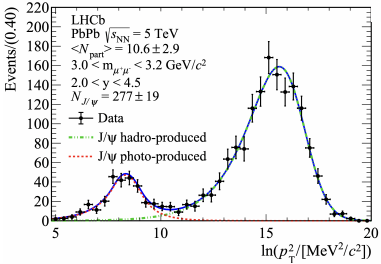
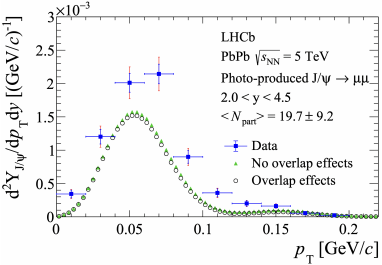
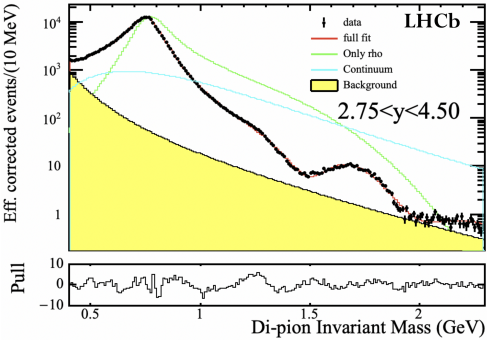




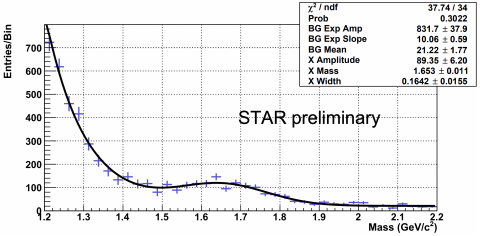
Phys. Rev. C 105 (2022) 3, L032201

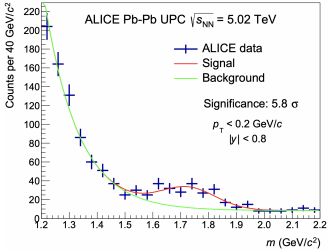
$\pi^+\pi^-$ Invariant Mass Distribution in UPC

- The dipion invariant mass spectrum shown for LHCb (below), STAR and ALICE (right)
- STAR measurement consistent with $\rho_3(1690)$
- ALICE observed structure with similar mass and width



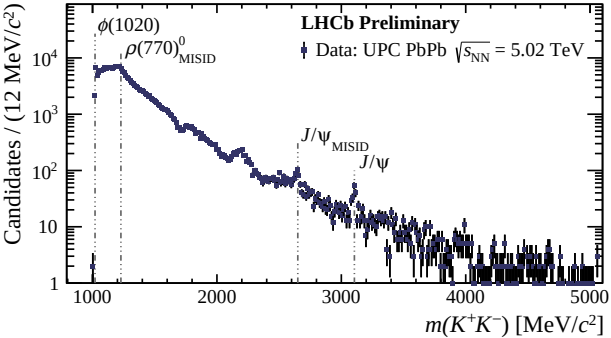
LHCb-PAPER-2024-042 (IN PREP.)



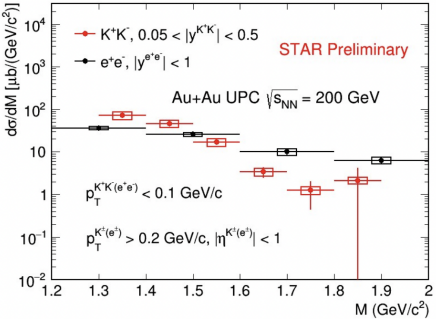


JHEP 06 (2020) 035

K^+K^- Invariant Mass Distribution in UPC

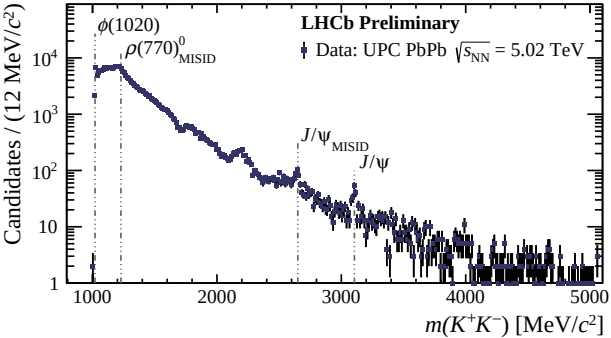


LHCB-CONF-2024-006 (IN PREP.)



- K^+K^- invariant mass distributions measured at forward (left) and mid (right) rapidity
- Vector mesons $\phi(1020)$ and J/ψ can be seen at the lower and upper ends of the mass spectrum
- Additional structures could potentially correspond to vector, scalar, or tensor mesons
  - Quantitative interpretations of these structures is left for future studies

K^+K^- Invariant Mass Distribution in UPC



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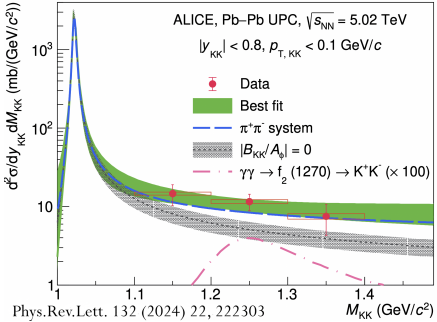
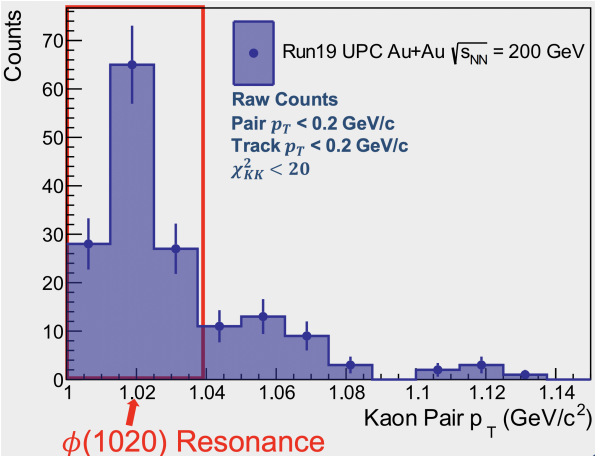


Phys.Rev.Lett. 132 (2024) 22, 222303

- K^+K^- invariant mass distributions measured at forward (left) and mid (right) rapidity
- Vector mesons $\phi(1020)$ and J/ψ can be seen at the lower and upper ends of the mass spectrum
- Additional structures could potentially correspond to vector, scalar, or tensor mesons
  - LHCb experimental results differ with respect to STAR and ALICE measurements

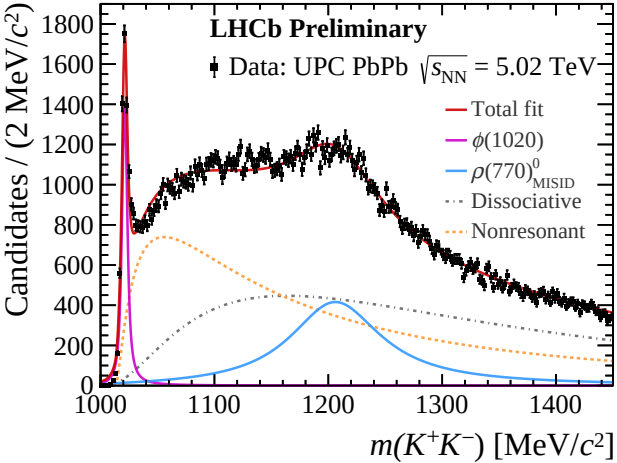
$\phi(1020)$ Photoproduction at STAR



Poster Contribution here

- Mass distribution of dikaons in UPC events for $p_T < 200$ MeV/c
- The $\phi(1020)$ resonance is observed in UPCs for the first time at RHIC energies
- Installation of new inner TPC in 2019 improved STAR acceptance from $|\eta| < 1$ to $|\eta| < 1.5$
- STAR now observes $\phi(1020) \to K^+K^-$ signal with the improved acceptance

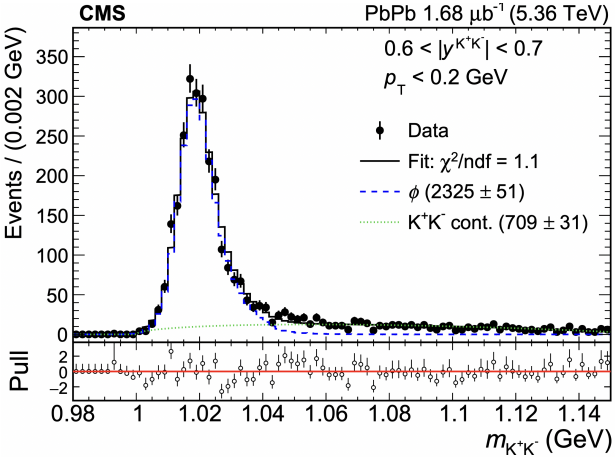
$\phi(1020)$ Photoproduction at LHCb



LHCB-CONF-2024-006

- Fit to low invariant-mass distribution of dikaons in elastic-enriched UPC events for $p_T < 100$ MeV/c
- The $\phi(1020)$ resonance is observed with a significance $> 5\sigma$
- Wider resonance at higher mass interpreted as misidentified pions from $\rho(770)^0 \to \pi^+\pi^-$ decays
- Upper limit on π/K misID $\epsilon_{MIS} < 3.19\times10^{-5}$ (95% CL)

$\phi(1020)$ Photoproduction at CMS

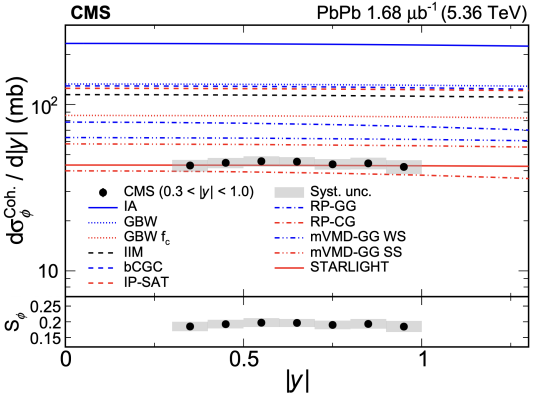


arXiv:2504.05193

- $\phi(1020) \to K^+K^-$ signal fit in the midrapidity range $0.3 < |y| < 1.0$ for $p_T < 200$ MeV/c
- An accurate description of the data was found without considering any interference effects
- Misidentified pion decays from $\rho^0(770) \to \pi^+\pi^-$ estimated to contribute less than 1%
- Fraction from dissociated contribution subtracted

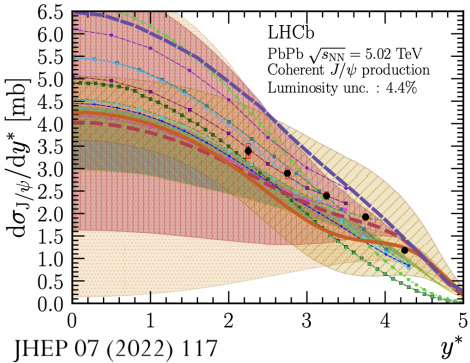
$\phi(1020)$ Photoproduction at CMS

- $\phi(1020)$ differential cross section as a function of rapidity y is shown
- Fraction of dissociative contribution to $\phi(1020)$ peak determined using STARLight MC studies
- Data compared with predictions including CGC, best described by STARLight
- S_ϕ ratio compares data to baseline Impulse Approximation (IA) model, where suppression is observed consistent with nuclear shadowing effects

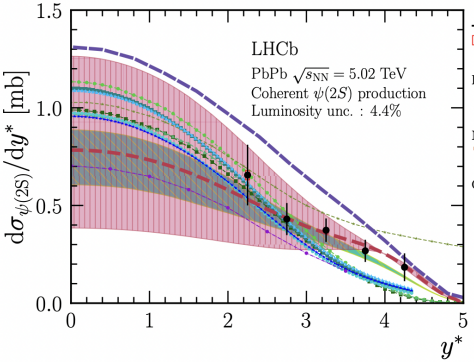


arXiv:2504.05193

J/ψ and $\psi(2S)$ Photoproduction at LHCb



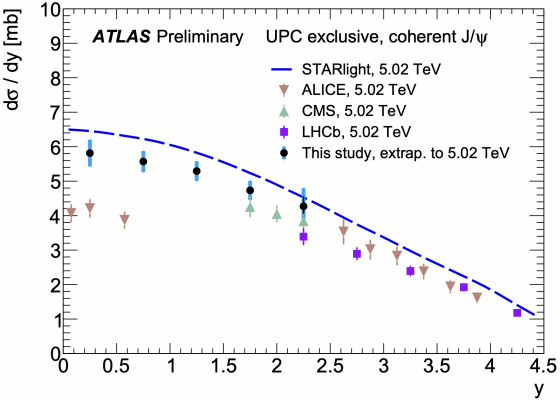
JHEP 07 (2022) 117



- First measurement at LHC for coherent $\psi(2S)$ production in UPC at forward rapidity (right)
  - pQCD calculations (red curves) best description of data at large y
- J/ψ, $\psi(2S)$ dependence similar, but smaller uncertainties (harder to discriminate models)

J/ψ Photoproduction at ATLAS

- Comparison of differential cross section vs rapidity for coherent J/ψ photoproduction at ALICE, CMS, LHCb at 5.02 TeV energy
- ATLAS measurements in Run 3 at 5.36 TeV extrapolated to Run 2 at 5.02 TeV
  - Tension with ALICE results in moving towards mid-rapidity
- Authors suggest multiple interactions occur per UPC event (ex: simultaneous J/ψ and $\rho(770)^0$ production)
  - Propose ATLAS results could include photon-photon processes while ALICE trigger might reject those events



ATLAS-CONF-2025-003

Summary

Conclusion

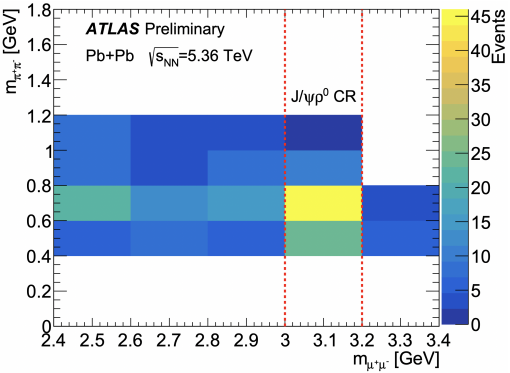
Central & Hadronic Production

- LHCb has observed the $\chi_{c0}(4500)$ and $\chi_{c1}(4272)$ states in diffractive processes
  - The above states were seen in central production events estimated to contain ~69% inelastic production
- ALICE, STAR, LHCb results all support coherent J/ψ photoproduction in hadronic A+A collisions

Ultra-Peripheral Collisions

- First observation of $\phi(1020)$ in UPCs reported by STAR, CMS, LHCb
- $\pi^+\pi^-$ spectrum similar at mid, forward rapidities and bump ~1.7 GeV
  - K^+K^- spectrum differs between rapidities with rich spectrum in forward region
- S_ϕ ratio versus y shows strong suppression inconsistent with CGC predictions
- Differences in ATLAS, ALICE J/ψ results due to simultaneous processes?

Back-Up



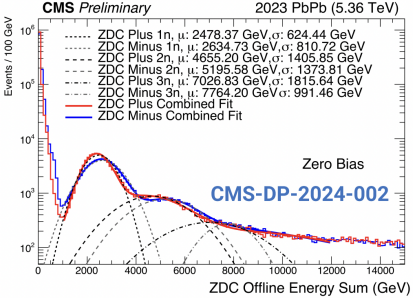
ATLAS-CONF-2025-003

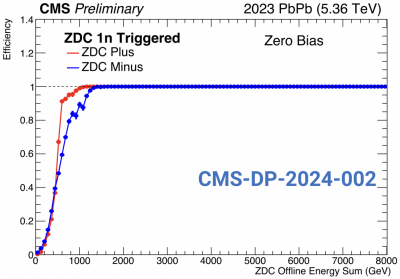
Conclusion

- The impulse approximation relies on 3 main assumptions
  - The probe interact with one degree of freedom at a time
  - The probe is not affected by the medium
  - The binding forces do not strongly depend on the nucleonic variables
- If these conditions are met, the impulse approximation is a good one, allowing to treat in a much simplified way the collision of a probe with a complex system.

Slide Credit: C. Mezrag, see talk here

ZDC Triggering in Run 3

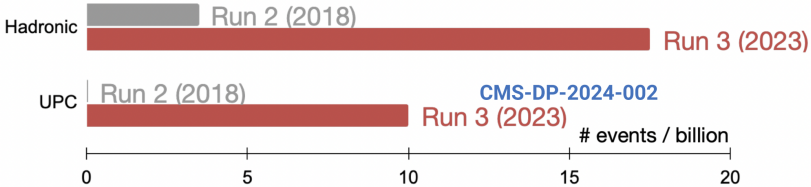


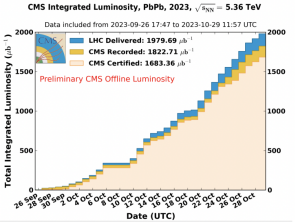


- For the first time in 2023, ZDC integrated into CMS hardware trigger
  - Important for UPC program - see talk from Gian Michele tomorrow
- For hadronic, cleans up noise of HF-based minimum bias triggering
- Possible use as unbiased centrality calibration in pPb (or triggering in pO, OO!)

Slide Credit: C. McGinn, see talk here

Run 3 Improvements Over Run 2





- Huge DAQ expansion for hadronic and UPC physics!
  - Implemented after long shutdown to great success
- All in place for OO (pO?) running in Run 3
- Run 4 plans for additional increase in capacity
  - In addition, significant upgrades to detectors

Christopher McGinn 15

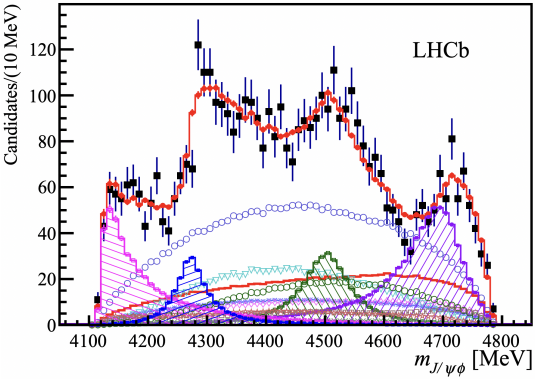
Slide Credit: C. McGinn, see talk here

Phase 2 Upgrades

- L1-Trigger CDS
  - Expanded trigger throughput and capabilities (hardware track trigger!)
- DAQ and HLT CDS
  - Expanded DAQ throughput (full hadronic PbPb at current luminosities)
- Barrel Calorimeters CDS
  - Increased ECAL readout speeds! Important bottleneck issue for HI
- Endcap Calorimeters CDS
  - High granularity + 3D cluster capabilities
- Muon Systems CDS
  - Expanded pseudorapidity coverge ($|\eta|$ from $2.4 \rightarrow 2.8$)
- Tracking Systems CDS
  - Increased pixel/strip granularity / expanded pseudorapidity coverage ($|\eta| \sim$4)
- MIP Timing Detectors (see next slides) and ZDC (backup)

Slide Credit: C. McGinn, see talk here

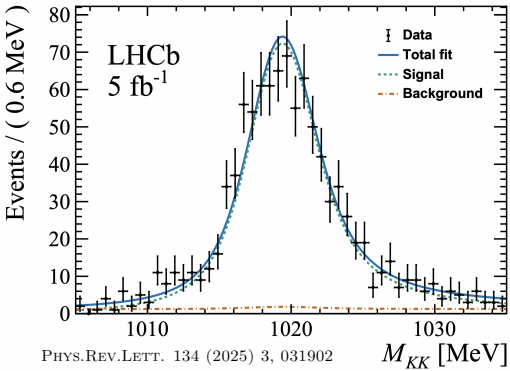
$J/\psi\phi$ in Hadronic Collisions



Phys.Rev.Lett. 118 (2017) 2, 022003

- In the original paper, an amplitude analysis was performed on the $J/\psi\phi$ spectrum
  - A search for the same resonances was performed in central-exclusive production
  - The same states were identified: $\chi_{c0}(4500)$, $\chi_{c0}(4700)$, $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$

Vector Mesons in Central Exclusive Production



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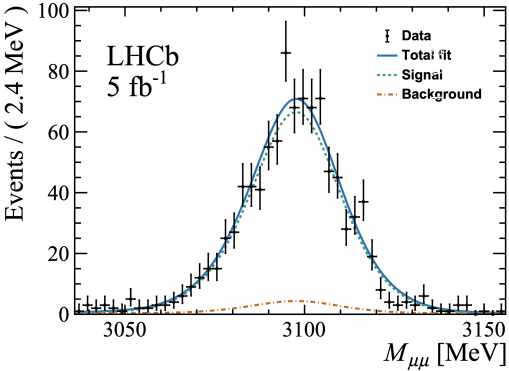
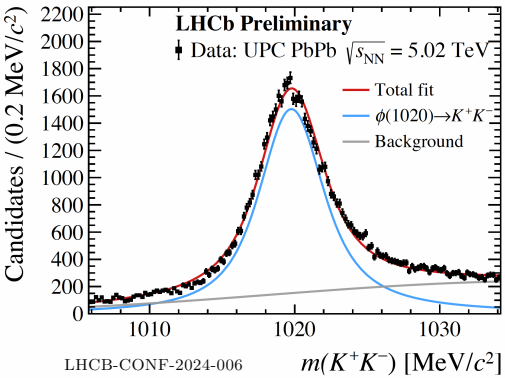


- Left: The $\phi(1020)$ mass distribution for dissociative-enriched events with $p_T > 200$ MeV/c
- Right: The J/ψ mass distribution for dissociative-enriched events with $p_T > 200$ MeV/c

Vector Mesons in Ultra-Peripheral Collisions



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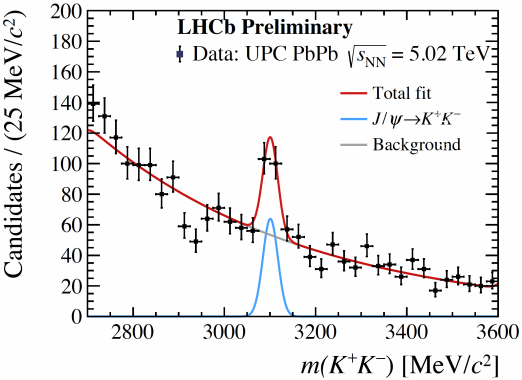
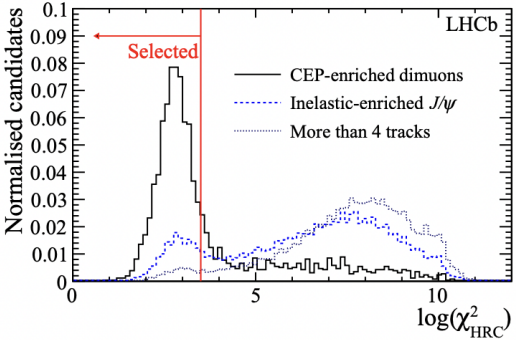
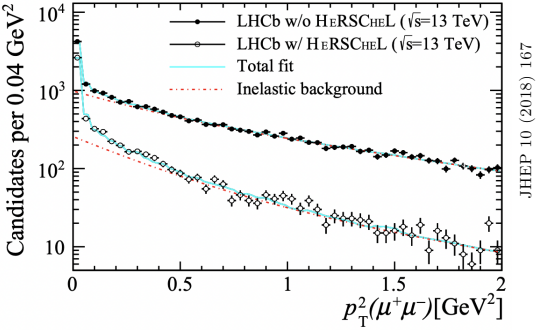


- Left: The $\phi(1020)$ mass distribution for coherent production with selection of $p_T^{KK} > 0$ MeV/c
- Right: The J/ψ mass distribution for coherent production with selection of $p_T^{KK} < 100$ MeV/c
- The extracted detector resolutions are consistent with previous LHCb measurements

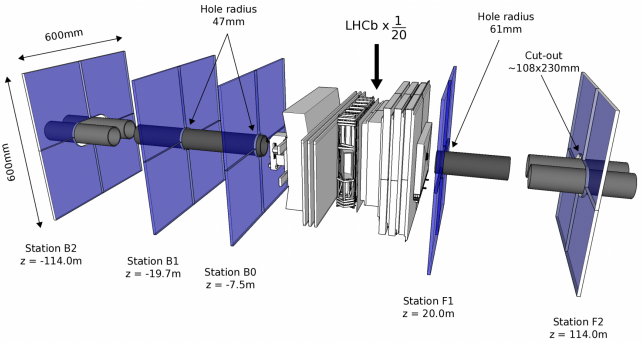
Herschel Detector Discrimination





- The Figure of Merit (left) is a χ^2 quantity that includes hits from all twenty counters and accounts for correlations among counters based on activity above the noise
  - By subtracting the background, an exclusive sample of signal events is obtained
- The p_T^2 distribution of dimuons (right) with and without the requirement on the $\log(\chi^2)$

Herschel Detector



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- HeRSCheL (High Rapidity Shower Counters for LHCb), a system of plastic scintillator planes, is located in the LHC tunnel ∼115m in $\pm z$ from LHCb interaction point
- Detects showers induced by high rapidity particles interacting with detector material
  - Installed for Run 2 of the LHC, which began in 2015, for CEP measurements

$\phi(1020) \to K^+K^-$

In the hadronic decay $\phi \to K^+K^-$, the kaons have a momentum of only 135 MeV/c in the ϕ rest frame. Since the kaon momentum is dominated by the longitudinal momentum acquired from the ϕ-meson, the kaons are produced with large pseudorapidity. Therefore, the acceptance for this channel is low at around midrapidity even without a considering a minimal kaon-p_{T}. Consequently, an observation is very difficult with the potential exception of the far forward region where the kaons are significantly Lorentz boosted. Alternately, measurements exploiting the leptonic decay channels $\phi \to \mu^+\mu^-$ore$^+$e$^-$ despite the small branching ratios. The feasibility can be conservatively estimated by scaling the $\phi \to \mathrm{K}^+\mathrm{K}^-$ rates down by Br ($\phi \to \mu^+\mu^-$)/Br($\phi \to \mathrm{K}^+\mathrm{K}^-$)$\approx 5.9 \times 10^{-4}$ neglecting the acceptance increase for leptons w.r.t. kaons.

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Söding + ω (H1) + form factor + continuum phase + ρ'

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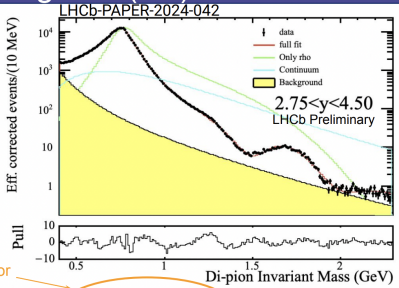


Form Factor

$$S = \frac{q^3(m_{\pi\pi})}{q^3(m_\rho)}\left|\exp\left(-\left(\frac{m_{\pi\pi}^2 - m_\rho^2}{\Delta^2}\right)^2\right)\mathcal{BW}_\rho(m_{\pi\pi})\left(1 + C\exp(i\phi_\omega)\frac{m_{\pi\pi}^2}{m_\omega^2}\mathcal{BW}_\omega(m_{\pi\pi})\right)\right.$$

Continuum Phase Shift

$$\left. + \frac{B\exp(i\phi_c)}{(m_{\pi\pi}^2 - 4m_\pi^2 + \Lambda^2)^\delta} + D\exp(i\phi_{\rho'})\mathcal{BW}_{\rho'}\right|^2 \quad (4)$$

ρ' resonance

	fit to eq. 4
M_ρ[MeV]	777.0±0.1
Γ_ρ [MeV]	152.2±0.2
ϕ_c	-0.52±0.02
$\lvert B/A\rvert$	1.1 ± 0.1
$\phi_\omega[rad]$	-0.14±.01
$\lvert C/A\rvert$	0.160 ± 0.002
Λ[MeV]	1.04 ± 0.02
δ	2.98±0.05
Δ[MeV]	1.49±0.01
$\lvert D/A\rvert$	0.0124 ± 0.0003,
$M_{\rho'}$[MeV]	1620 ± 8 }
$\Gamma_{\rho'}$[MeV]	462 ± 10 }
$\phi_{\rho'}$	-0.26 ± 0.03

} = Strongly Model Dependent

Di-Pions in Ultra-Peripheral Collisions at LHCb Amanda Donohoe 51

Slide credit: A. Donohoe, Hard Probes 2024

Phys.Lett.B 462 (1999) 462-470

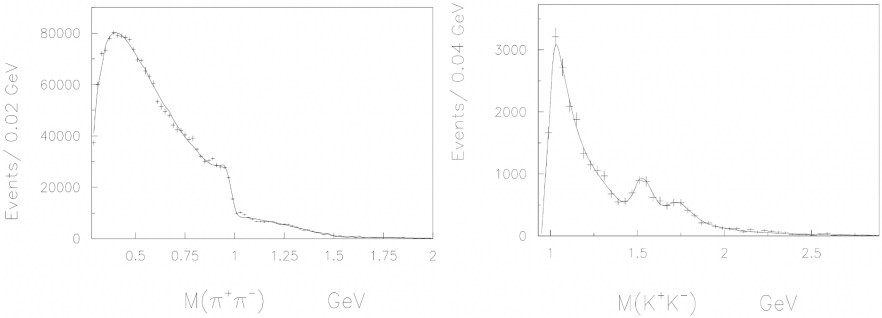


Table 4: The ratio of the cross sections at $\sqrt{s} = 29.1$ and 12.7 GeV.

	$\rho(770)$	$f_0(980)$	$f_2(1270)$	$f_0(1500)$
$\frac{\sigma(\sqrt{s}=29.1)}{\sigma(\sqrt{s}=12.7)}$	0.36 ± 0.05	1.28 ± 0.21	0.98 ± 0.13	1.07 ± 0.14

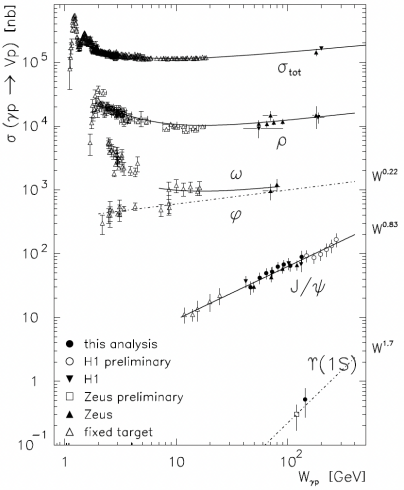
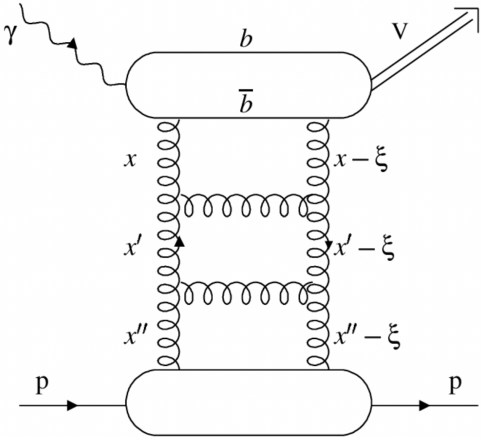


Image Credit: P. Merkel, PhD thesis (University of Hamburg)



"Because the momentum fraction x and the difference in momenta of outgoing and returning gluon are of the same order of magnitude, the two gluons couple to the partons in the proton at different x values."

P. MERKEL, PhD Thesis (1999)