Exclusive ϕ at the EIC

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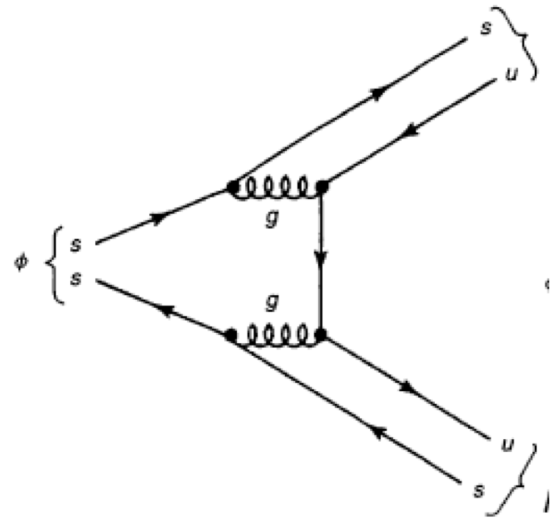
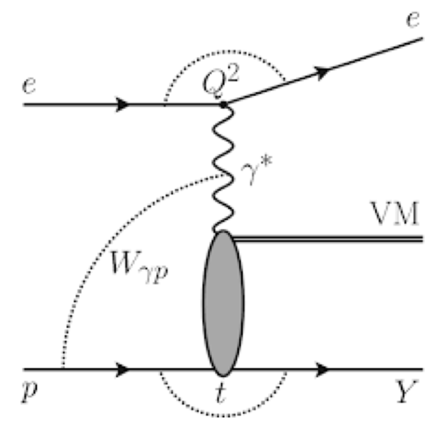
- The ϕ & limitations at the EIC
- ϕ + direct KK
  - ρ^0 + direct $\pi\pi$ as a model
  - Experimental Status
- ePIC implications



Φ production



- s-sbar vector meson with $J^{PC}=1^{--}$
  - Same quantum numbers as the photon
  - M=1020 MeV, width Γ=4.4 MeV
    - Intermediate scale – soft for pQCD, but heavier than the ρ
- Copiously produced via Pomeron exchange
  - The photon fluctuates to a s-sbar dipole which scatters elastically from the target, emerging as a real ϕ
    - To lowest order, a Pomeron is two gluons
- Elastic scattering -> $d\sigma/dt$ ($\sim d\sigma/dp_T^2$) may be Fourier transformed to give the transverse distribution of scattering centers (gluons) in the target
- Incoherent scattering is sensitive to event-by-event fluctuations in the nuclear configuration
- **Highlighted in the White Paper and Yellow Report**

ϕ decay

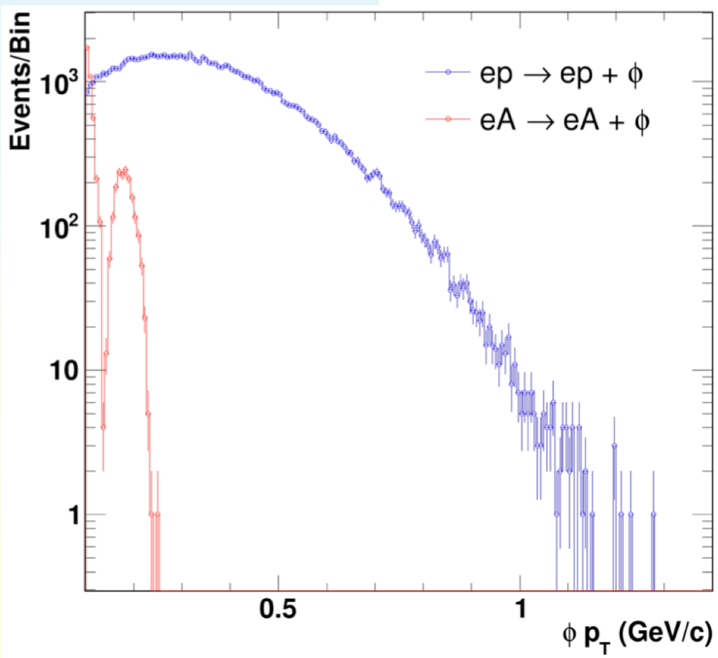
Mode		Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$K^+ K^-$	$(49.1 \pm 0.5)\%$	S=1.3	127
Γ_2	$K^0_L K^0_S$	$(33.9 \pm 0.4)\%$	S=1.2	110
Γ_3	$\rho\pi + \pi^+\pi^-\pi^0$	$(15.4 \pm 0.4)\%$	S=1.2	

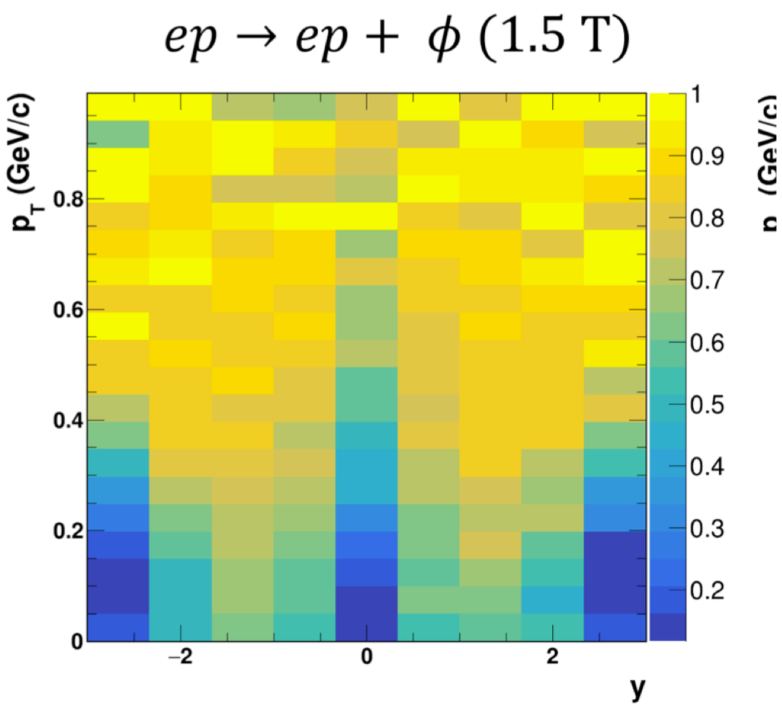
- Φ->ee and Φ-> $\mu\mu$ branching ratios too small for large signal
- $\rho\pi$ typically contains neutral particle(s)
- K_L lifetime is long enough to escape the detector
- Kaon momenta too small for easy reconstruction
- Φ->K^+K^- is the best option, but the kaons are too soft to be easily detectable

Particle Data Book, 2022

ϕ production on heavy targets

- At low Q^2, $p_T \sim hbar/R_A \sim < 100$ MeV/c
  - Need to study full Q^2 range to map out saturation
- Efficiency is poor because the kaons are so soft
  - Especially near y~0, where there is no ϕ Lorentz boost.





One (partial) solution: consider higher mass K^+K^- pairs

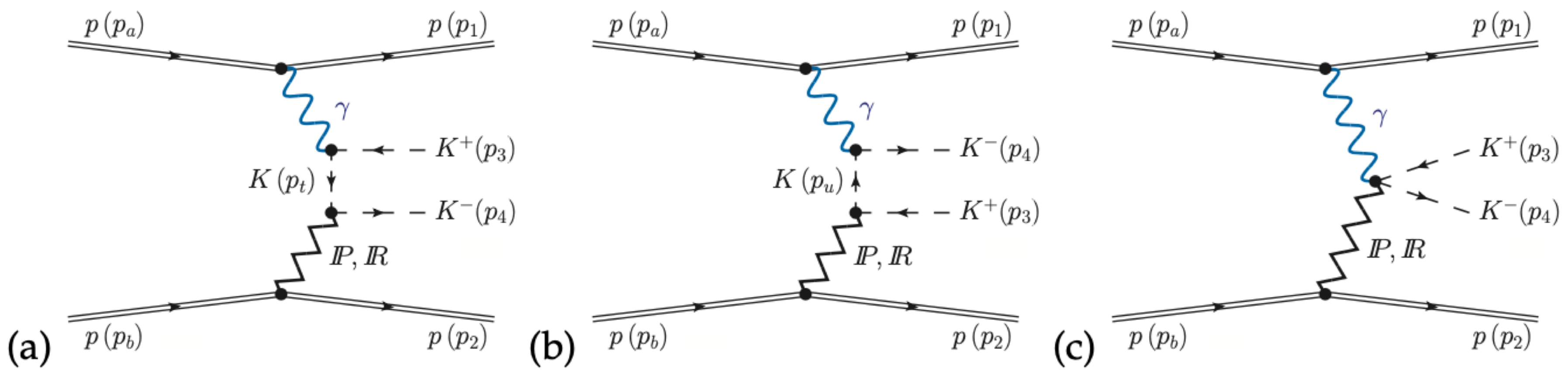
J. Arrington *et al.*, arXiv:2102.08337

Dikaons

- At least two ways to get K^+K^- pairs
  - ϕ–>K+K-
  - New: Direct production of K+K- pairs
  - Higher resonances, (e. g. the $\phi(1680)$)

Todays focus

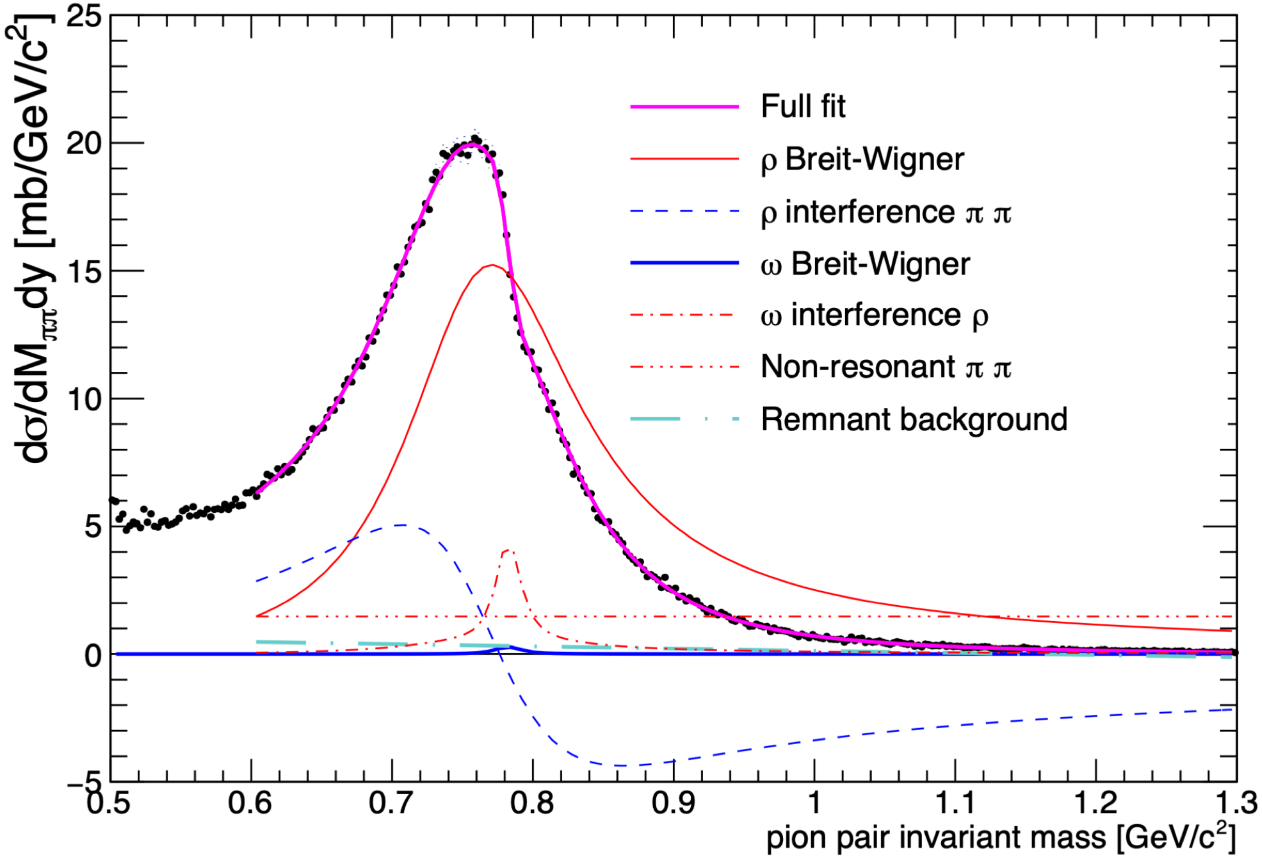
- These channels interfere with each other; the amplitudes add. Similar to the ρ^0 + direct $\pi^+\pi^-$



P. Lebiedowicz et al., PRD 98, 014001 (2018)

ρ^0 + direct $\pi\pi$ data

- Highest statistics modern measurement by STAR, with UPCs
  - 294,000 pairs
- Fit to ρ^0 + direct $\pi\pi + \omega +$ interference between them
  - χ^2/DOF ~ 1



STAR: Phys. Rev. C96, 054904 (2017)

Mass spectrum

- $d\sigma/dM_{\pi\pi}$ given by a relativistic Breit-Wigner equation:

$$\frac{d\sigma}{dM_{\pi^+\pi^-}} \propto \left| A_\rho \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + iM_\rho\Gamma_\rho} + B_{\pi\pi} + C_\omega e^{i\phi_\omega} \frac{\sqrt{M_{\pi\pi} M_\omega \Gamma_{\omega\to\pi\pi}}}{M_{\pi\pi}^2 - M_\omega^2 + iM_\omega\Gamma_\omega} \right|^2 + f_p$$

- A_ρ, $B_{\pi\pi}$ and C_ω are the amplitudes for the three components
  - All can be complex (C_ω has its separate phase shown explicitly)
    - Relative phases matter
  - ρ:direct $\pi\pi$ quantified by $|B_{\pi\pi}/A_\rho|$, with units $GeV^{-1/2}$
- f_p is background (e. g. $\gamma\gamma$->ee)
- Widths depend on $M_{\pi\pi}$ (phase space)

$$\Gamma_\rho = \Gamma_0 \frac{M_\rho}{M_{\pi\pi}} \left(\frac{M_{\pi\pi}^2 - 4m_\pi^2}{M_\rho^2 - 4m_\pi^2} \right)^{3/2}$$

Jackson, 1964)

$$\Gamma_\omega = \Gamma_0 \frac{M_\omega}{M_{\pi\pi}} \left(\frac{M_{\pi\pi}^2 - 9m_\pi^2}{M_\omega^2 - 9m_\pi^2} \right)^n ,$$

K^+K^- channel

- No third (ω) component
- But, problem with low efficiency at low p_T
- An alternative: look at high(er) mass K^+K^- pairs, well above the ϕ peak
  - Need to know/assume lineshape well

$$\frac{d\sigma}{dM_{KK}} = \left| A_\phi \frac{\sqrt{M_{KK} M_\phi \Gamma_\phi}}{M_{KK}^2 - M_\phi^2 + i M_\phi \Gamma_\phi} + B_{KK} \right|^2 \quad (1)$$

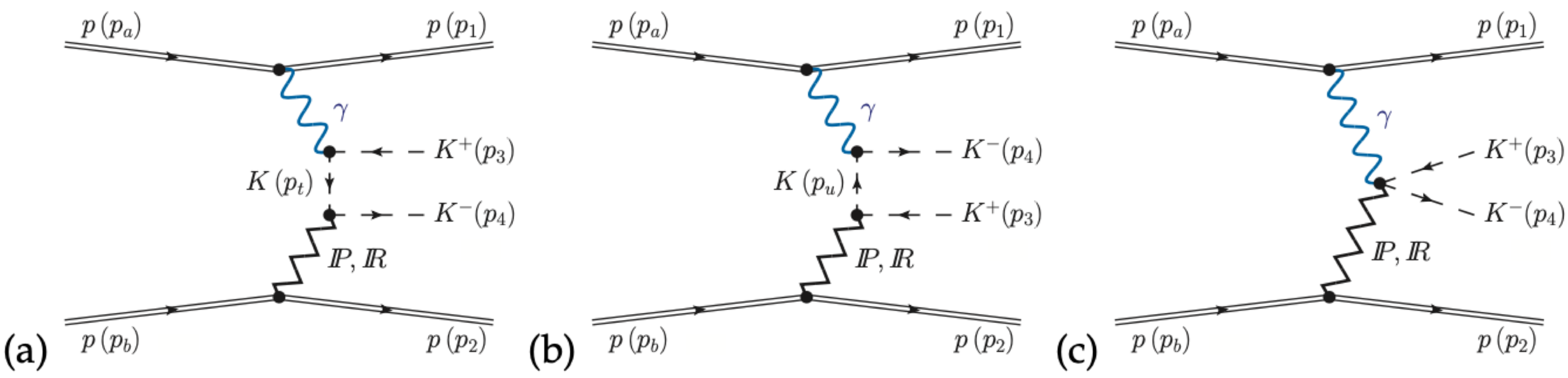
where $M_\phi = 1019.416 \pm 0.016$MeV [10] and Γ_ϕ are the ϕ mass and mass-dependent width, respectively, with

$$\Gamma_\phi = \Gamma_0 \frac{M_K}{M_{KK}} \left(\frac{M_{KK}^2 - 4M_K^2}{M_\phi^2 - 4M_K^2} \right)^{3/2}. \quad (2)$$

- Because of the mass-dependent width, drop-off is slower than it might be, even with $B_{KK}=0$

Direct KK

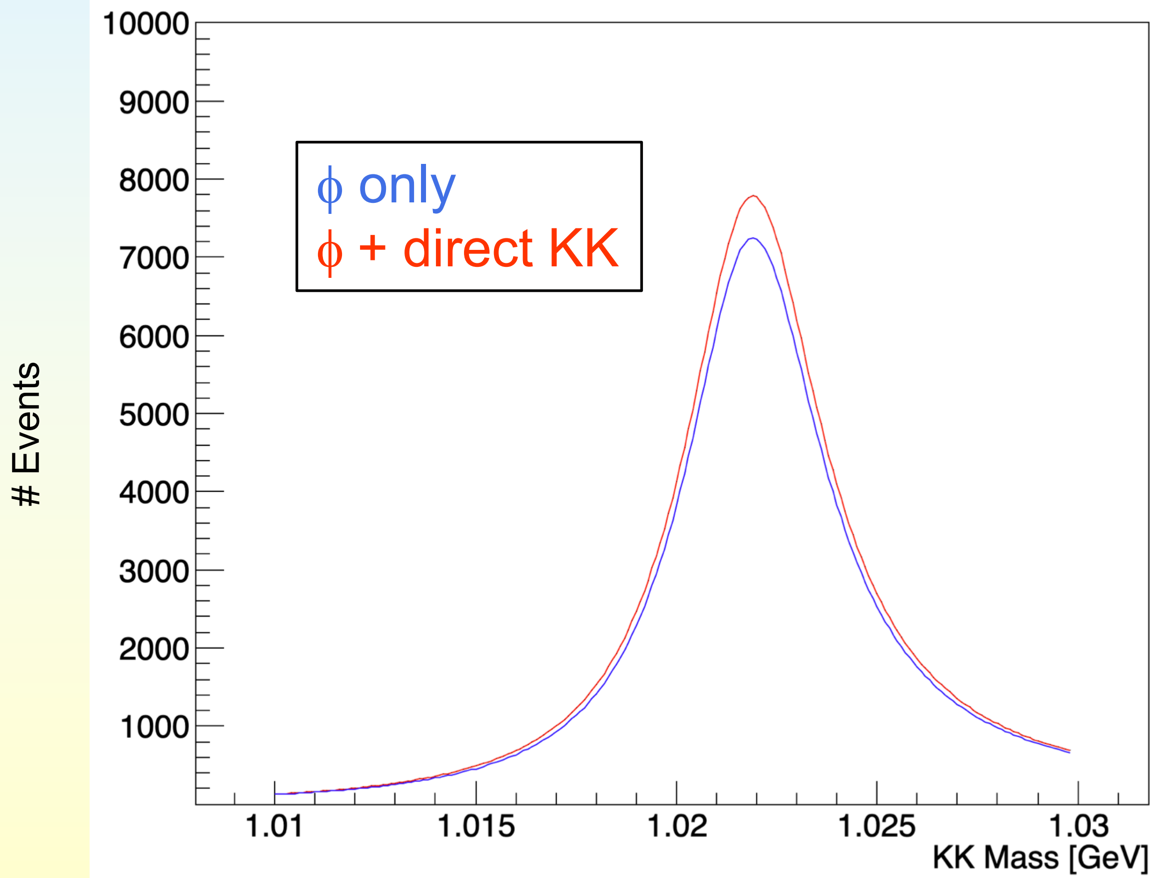
- Not yet observed (in journal articles)
- Direct KK production expected along with the ϕ, with the same mechanism - like the ρ + direct $\pi\pi$
- Roughly similar relative amplitudes and relative phase (?)
- Higher masses than the ϕ, so easier to see
- Cross-section A (target nucleus) and Q^2 dependence may differ from the ϕ



P. Lebiedowicz et al., PRD 98, 014001 (2018)

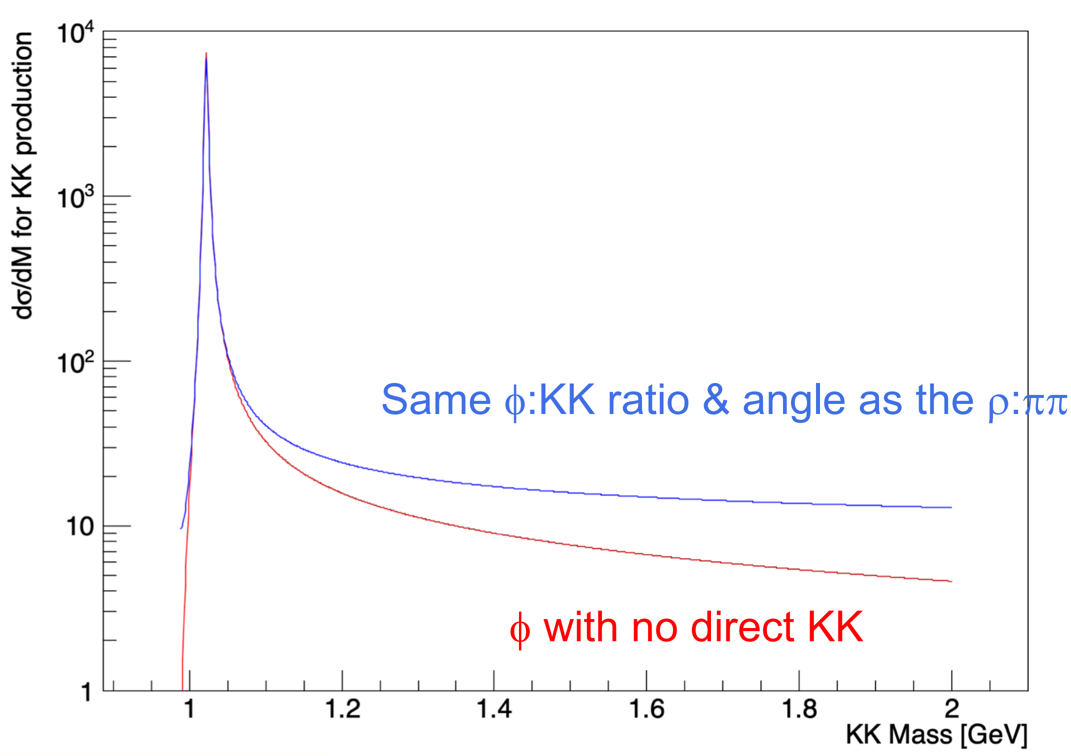
Effect on the ϕ peak

- KK mass spectrum, assuming the same ϕ:KK ratio & phase as ρ:$\pi\pi$
- Peak shift is very small (< 500 keV)
- Amplitude is about 8% higher



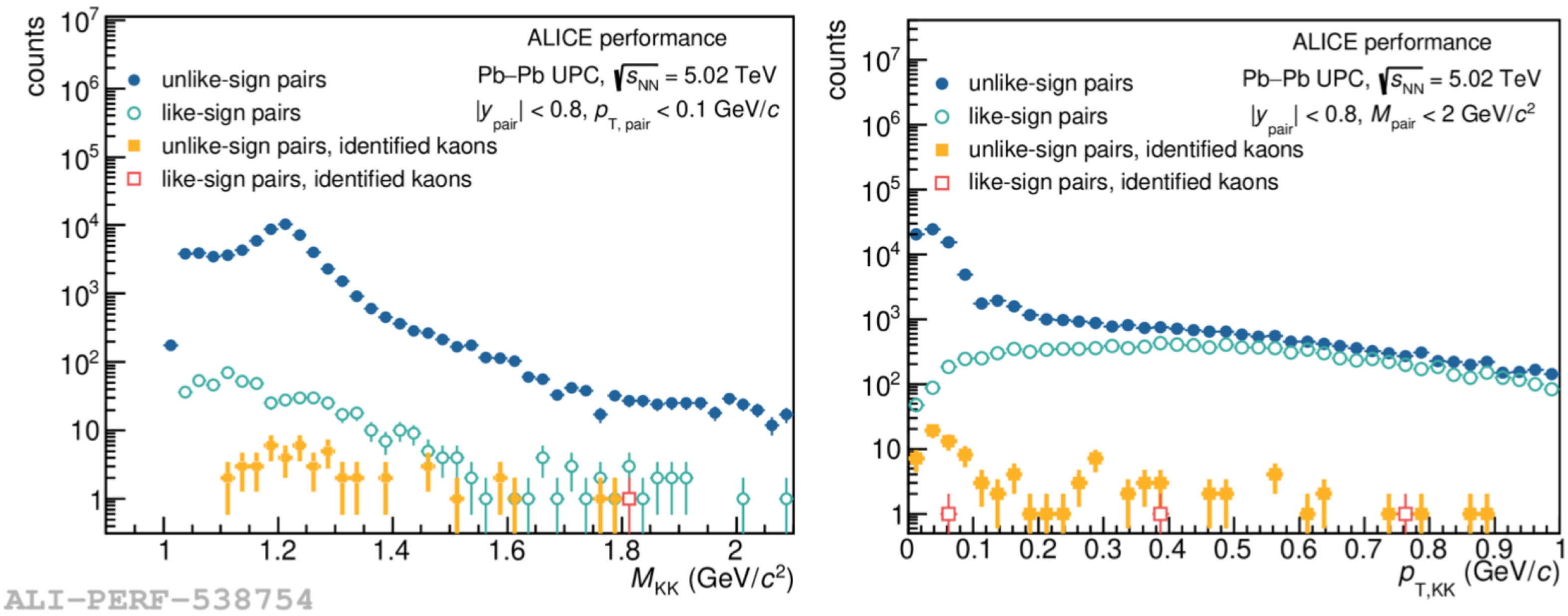
High-mass KK pairs

- Far above M_ϕ, cross-section depends on both R= $|B_{KK}/A_\phi|$ and phase
  - $|\sigma(\phi) - \sigma(KK)| < \sigma < |\sigma(\phi)+\sigma(KK)|$
    - Depending on phase



ALICE studies

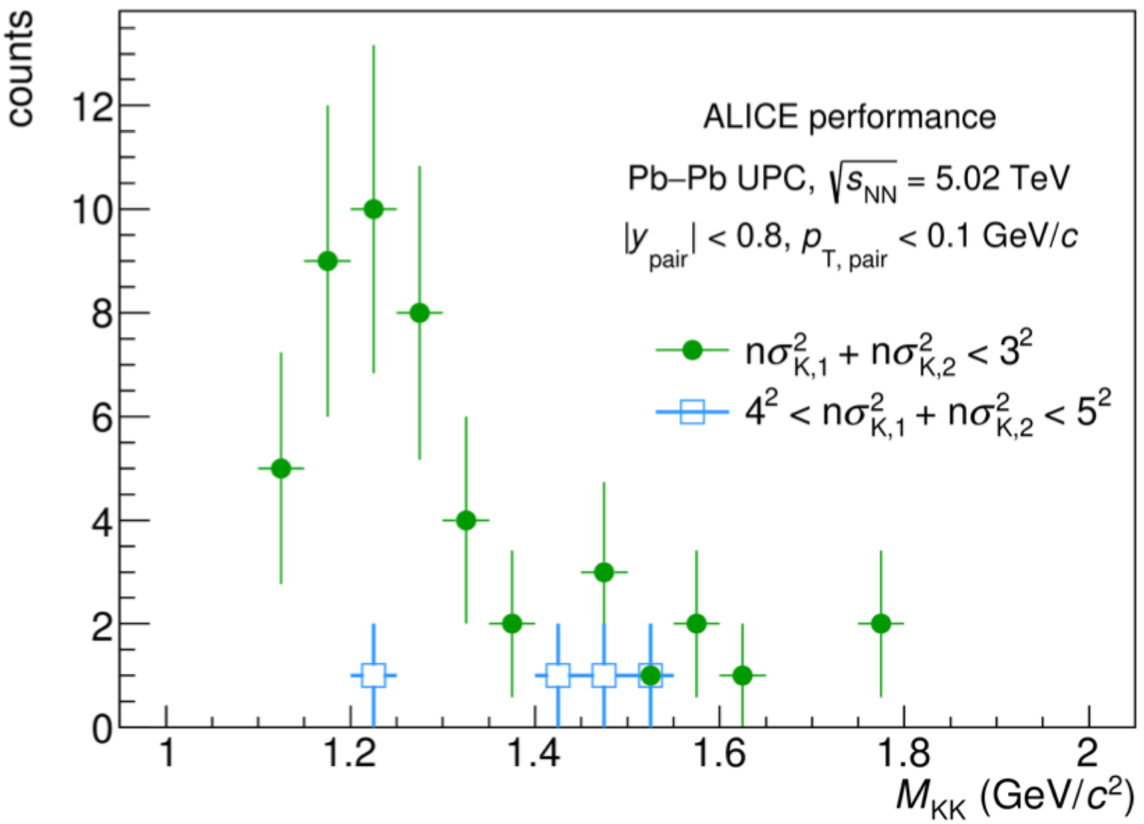
- Parallels UPC ρ+direct $\pi\pi$ photoproduction analysis, but with tight PID cuts to select a clean KK sample (above the ϕ)
  - N(KK) ~ 1/1000 N($\pi\pi$)
- 1.1 GeV < M_{KK} < 1.4 GeV
  - Sweet spot with OK acceptance and good PID $\pi\pi$ rejection



Minjung Kim at Hot Quarks 2023 and Nacer Hamdi at DIS 2023.

ALICE mass spectrum

- Clean sample in chosen mass range



Minjung Kim at Hot Quarks 2023 and Nacer Hamdi at DIS 2023.

Some implications for ePIC

- ϕ reconstruction is difficult at small p_T since the kaons are so soft.
- ϕ production is 'contaminated' by direct KK production
  - Direct KK production is a new phenomena!
- With high enough rates (i. e. ePIC), high mass KK pairs can be a proxy for the ϕ
- For measurements at $M_{KK} >> M_{\phi}$, the amplitude ratio $|B_{KK}/A_{\phi}|$ and iphase angle are correlated
  - ePIC can study the ϕ peak at higher Q^2, and then assume that the phase angle does not change much as Q^2 decreases.
    - Theoretical justification is needed.
- Any ϕ measurement will include a direct KK component. The fraction might vary slightly with Q^2 and A. This complicates measurements of the ϕ cross-section.
- Direct KK have a different wave function from the ϕ, so will complicate efforts to interpret ϕ data in terms of dipole-model parton densities.