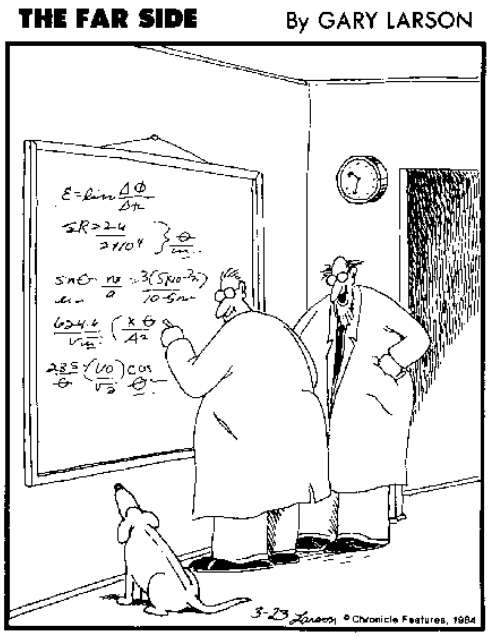
Quantum mechanics in coherent photoproduction: the limits of coherence, and multiple vector mesons

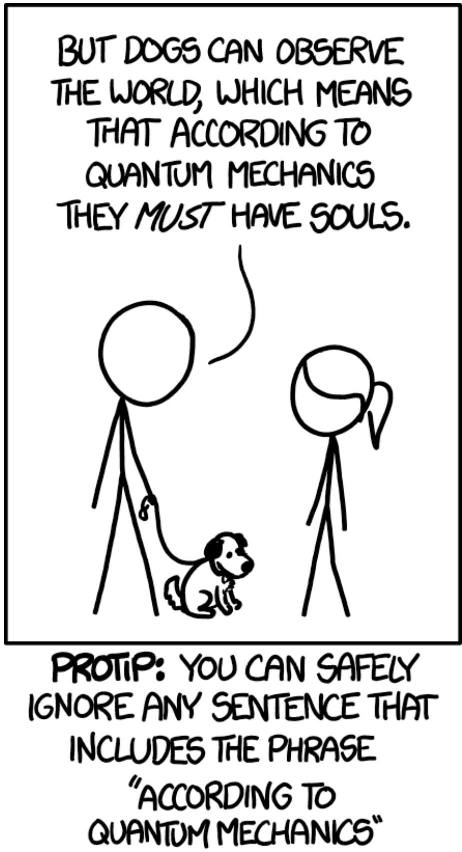
Spencer R. Klein, LBNL

Presented at UPC2023, Dec. 10-15, Playa del Carmen, Mexico

- Good-Walker paradigm
- Where GW fails
- An alternative to GW
- Beyond the Pomeron:
  - Coherence with Reggeons?
- Multiple Vector Meson emission



"Ohhhhhhh . . . Look at that, Schuster . . . Dogs are so cute when they try to comprehend quantum mechanics."



xkcd.com

Coherent and Incoherent Photoproduction: a quantum view

- The Good-Walker formalism links coherent and incoherent production to the average nuclear configuration and event-by-event fluctuations respectively
  - Configuration = position of nucleons, gluonic hot spots etc.
- Coherent: Nucleus remains in ground state, so sum the amplitudes, then square -> average over different configurations
- Incoherent = Total – coherent; total: square, then sum cross-sections for different configurations

$$\frac{d\sigma_{\rm tot}}{dt} = \frac{1}{16\pi}\left\langle \left|A(K,\Omega)\right|^2 \right\rangle$$ Average cross-sections (Ω)

$$\frac{d\sigma_{\rm coh}}{dt} = \frac{1}{16\pi}\left|\langle A(K,\Omega)\rangle\right|^2$$ Average amplitudes (Ω)

$$\frac{d\sigma_{\rm inc}}{dt} = \frac{1}{16\pi}\left(\left\langle \left|A(K,\Omega)\right|^2 \right\rangle - \left|\langle A(K,\Omega)\rangle\right|^2\right)$$ Incoherent is difference

Good and Walker, Phys. Rev. D **120**, 1857 (1960); Miettinen and Pumplin, Phys. Rev. D **18**, 1696 (1978)

Transverse interaction profiles

- The coherent cross-section gives us access to the transverse spatial distribution of individual targets within the nucleus

$$\frac{d\sigma_{coh}}{dt} = \frac{1}{16\pi} \left| \langle A(K,\Omega) \rangle \right|^2$$

Average amplitudes (Ω)

  - $t = p_T^2 + p_z^2 \sim p_T^2$
- p_T and b are conjugate. $d\sigma/dp_T$ encodes information about the transverse locations of the interactions
- The two-dimensional Fourier transform of $d\sigma/dt$ gives F(b), the transverse distribution of targets

$$F(b) \propto \frac{1}{2\pi} \int_0^\infty dp_T p_T J_0(bp_T) \sqrt{\frac{d\sigma}{dt}}$$

*flips sign after each diffractive minimum

  - Without shadowing, this is the shape of the nucleus
- Multiple serious caveats – range of integration/ windowing finding diffractive minima, subtracting out photon p_T etc.

Incoherent production and event-by-event fluctuations

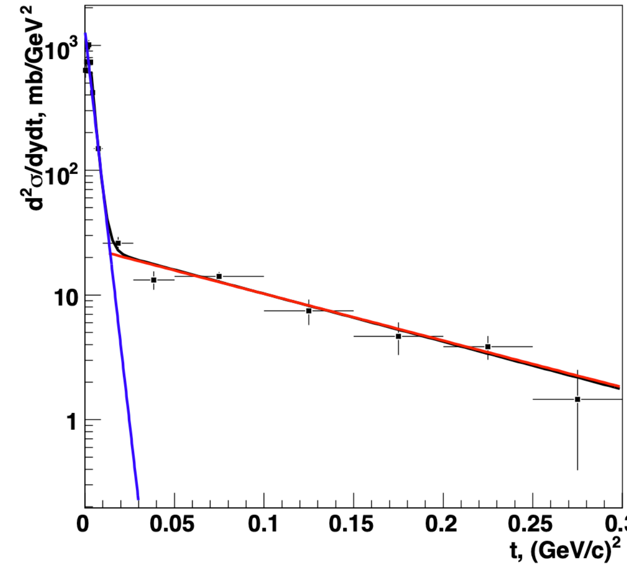
- The incoherent cross-section accesses event-by-event fluctuations in the nuclear configuration, including the positions of individual nucleons, gluonic hot spots, etc.

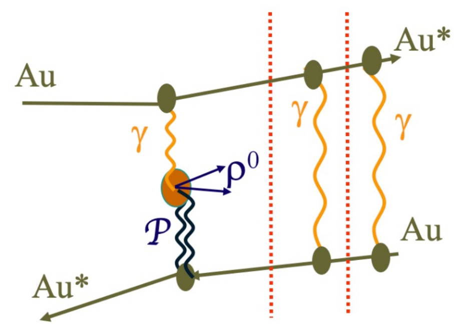
$$\frac{\mathrm{d}\sigma_{\mathrm{inc}}}{\mathrm{d}t} = \frac{1}{16\pi}\left(\left\langle \left| A(K,\Omega) \right|^2 \right\rangle - \left| \left\langle A(K,\Omega) \right\rangle \right|^2 \right)$$

- Deviations from the mean.
- The connection between t and impact parameter is weaker than for coherent production, but this can be used to test models.

Coherent photoproduction where Good-Walker predicts it should not occur

- Coherent: peak with $p_T \sim < hbar/R_A$
- AA -> A*A* V
  - Coherent photoproduction with nuclear excitation
- Most older STAR UPC analyses REQUIRE mutual Coulomb excitation in trigger
- ALICE also sees coherent photoproduction in events containing neutrons
- Explained by diagram with independent photon emission
  - Factorization!
  - But also possible with single photons, especially at larger p_T
- Good-Walker does not have an exception for mostly separable reactions

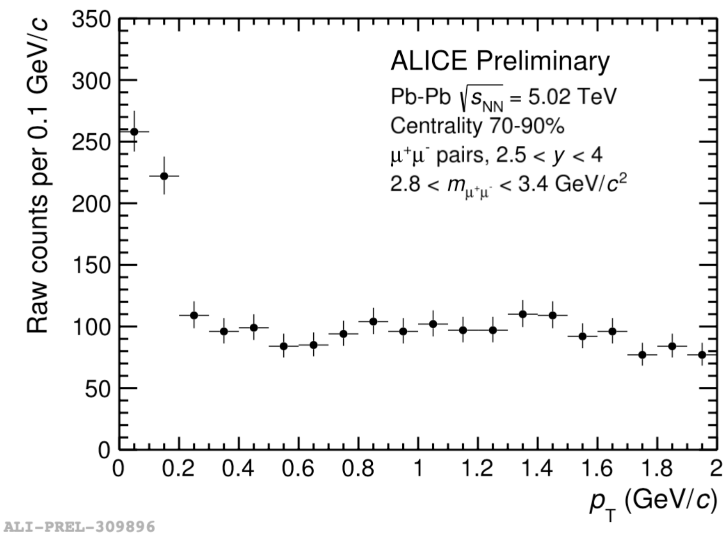




SK, Phys. Rev. C **107**, 055203 (2023)
STAR, Phys. Rev C **77**, 034910 (2008)

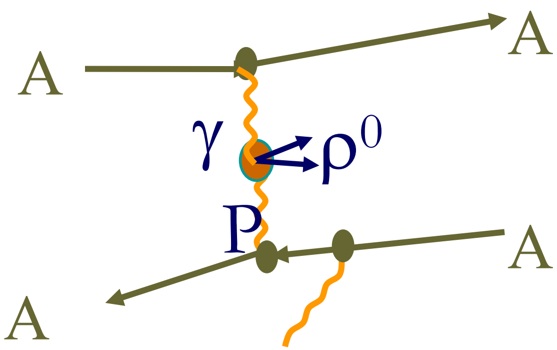
Coherent photoproduction in peripheral collisions

- Coherent J/ψ photoproduction in peripheral hadronic collisions
  - Peak at p_T < ~ hbar/R_A
- J/y photoproduction and hadronic interactions have similar time scales
- Seen by ALICE and STAR
- How large is the target region?
  - All nucleons?
  - Just spectators?

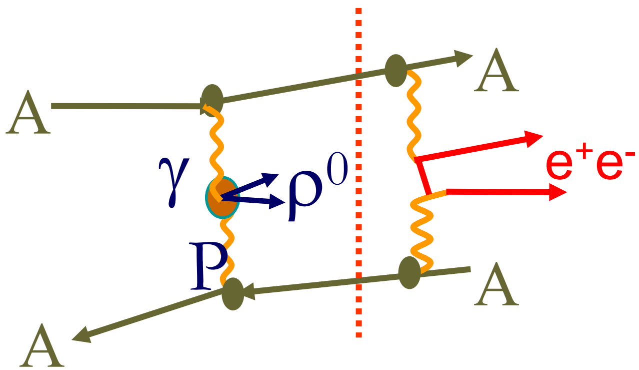


See talks by N. Brize (ALICE) & K. Shen (STAR)
L. Massacrier for ALICE, arXiv:1902.03637
W. Zha et al., PRC97, 044910 (2018)

Other possible sub-reactions



- Bremsstrahlung from the ion
  - 1/k photon energy spectrum
    - Logarithmically divergent
- Pair production
  - Electron mass keeps cross-section finite, but large
    - 200,000 barns for Pb-Pb at the LHC
    - P(pair) ~ >1 for b>= 2 R_A
    - Lepton p_T peaked at ~ few m_e
    - Leptons are at large rapidity
  - Most of these pairs are invisible



- There are many ways to have additional, unseen particles
- Small kinematic changes, but breaks exclusivity of reactions
  - Good-Walker requires exclusive reactions!

Another issue with Good-Walker

- Nuclear excitation is endothermic: energy transfer to the nucleus
- Nucleon emission requires E_T = 5-7 MeV for lead/gold
  - If the reaction proceeds by single particle excitation (as expected), $p_{struck\text{-}nucleon} > \sqrt{2 mE_T} >\sim 100$ MeV/c
    - Most of the coherent region. Incoherent cross-sections should change when crossing this threshold
- Lowest excitation energy for lead: 2.6 MeV
  - If a single nucleon is struck, $p_T > 70$ MeV
- Lowest excitation energy for gold: 77 MeV
  - If a single nucleon is struck, $p_T > 12$ MeV
- Incoherent interactions are impossible at lower energy/p_T transfer
- In contrast, in GW, high-energy incoherent photoproduction depend on low-x partonic structure of the target, which should be very similar for lead and gold.
  - This difference should be testable.

An alternate, semi-classical approach

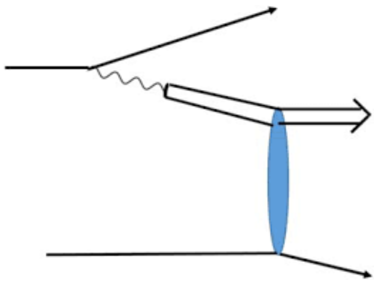
- Sum reactions where the target is indistinguishable
- $\sigma_{coherent} = |\Sigma_i A_i k \exp(ikb)|^2$
  - Usually assume A_i are identical
  - For kb < hbar exp(ikb) ~ 1, and the amplitudes add coherently
    - $d\sigma/dt |_{t=0} \sim N^2$
  - For kb > hbar exp(ikb) the exponential has a random phase
    - $d\sigma/dt |_{t=0} \sim N$
- This naturally predicts a transition between coherent and incoherent regimes as k rises
  - Could add multiple interactions (ala Glauber) to include shadowing
  - Could include nucleon excitation regime by summing over partons rather than nucleons
- Does not follow the target after the interaction
  - Insensitive to nuclear breakup
- Can accommodate gradual loss of coherence

Tests of semi-classical vs. Good-Walker

- Coherent photoproduction with nuclear excitation
- Coherent photoproduction in peripheral heavy-ion collisions
- Coherent photoproduction in Reggeon exchange
  - Reactions involving exchange of quantum numbers
  - γ + A -> a_2^+(1320) + (A-1)
    - Changes a proton into a neutron
    - Is this coherent over all protons in a target?
- Compare $d\sigma/dt$ for incoherent photoproduction in lead and gold
  - Including photoproduction accompanied by photons from nuclear excitation.
    - Possible at Jefferson Lab by adding a germanium detector to an existing spectrometer
      - For lighter (than the J/ψ) mesons

SK, 2014 CERN UPC workshop:
https://indico.cern.ch/event/216417/contributions/1515429/

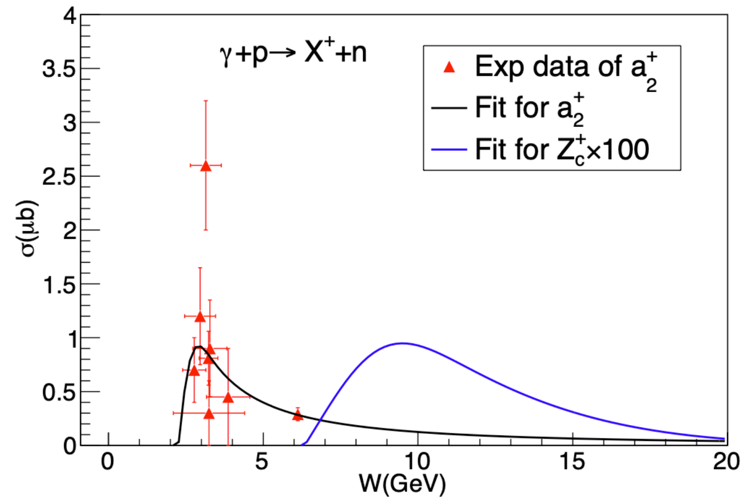
$a_2^+(1320)$ photoproduction in pA UPCs

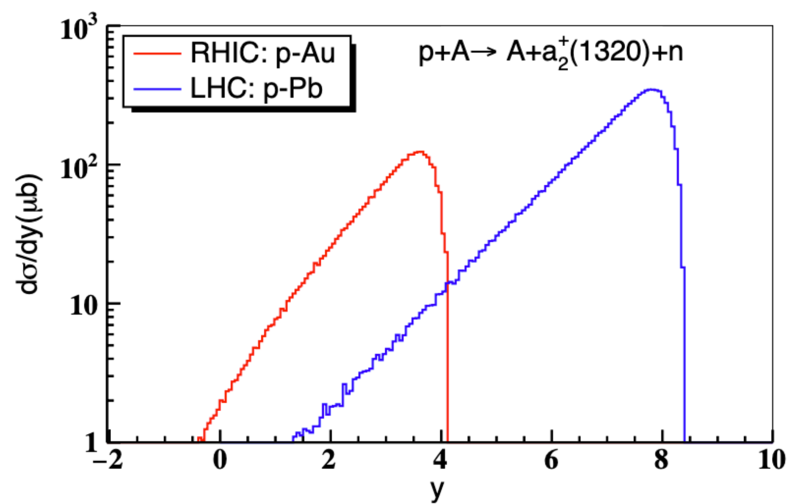


- Charged Reggeon exchange $\gamma p \to a_2(1230)^+ n$
  - Parameters based on fixed-target data
    - Limited data

$$\sigma_{\gamma p\to a_2^+(1320)n}(W) \approx 5.42(W^2 - m_p)^{-0.82}$$
$$-5.80\exp(-0.070(W^2 - m_p^2)^2),$$

- σ peaks at few*threshold
  - Favors low photon energy
- UPC signal peaks at large y
- σ=170 μb (pAu@RHIC)/560 μb (pPb@LHC)
  - Large signals
- Br($\pi^+\pi^-\pi^+$) ~ 70%
- Visible in STAR forward detector and/orLHCb & ALICE FoCal





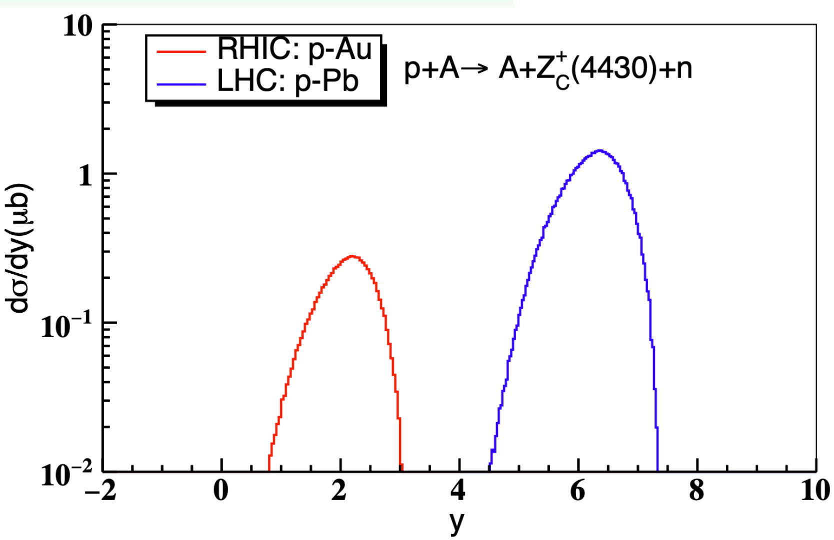
SK & Y. Xie, Phys. Rev. C **100**, 024620 (2019)

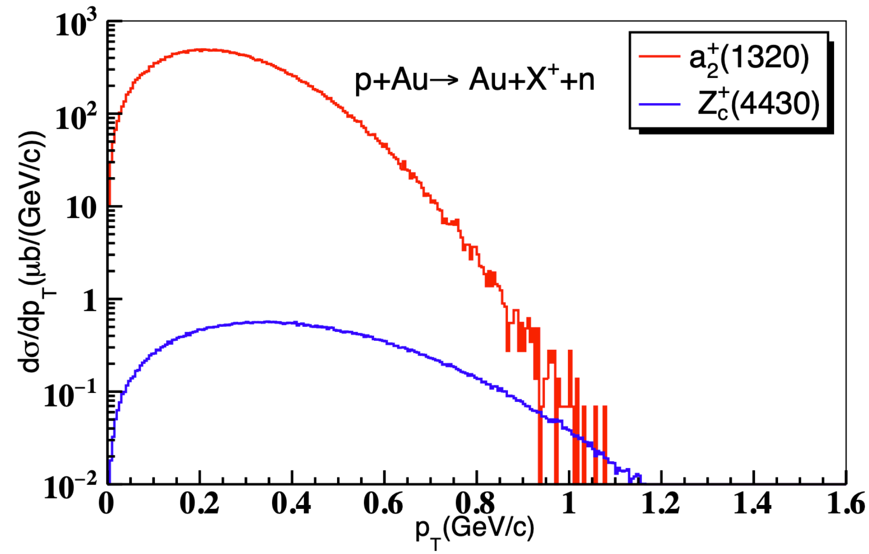
$a_2^+(1320)$ and $a_2^+(1320)$ photoproduction on ion targets

- $\gamma p \to a_2(1230)^+ n$ probes protons in target
- $\gamma n \to a_2(1230)^- p$ probes neutrons in target
- Coherent photoproduction of both can compare proton and neutron radii of heavy nuclei in a single experiment, with small systematics

Studies of exotica

- The ability to study Reggeon exchange reactions greatly expands the range of accessible final states
  - Exotica, including c cbar and lighter particles
  - Many conventional mesons
- Meson-photon couplings probe the nature of these exotica
  - Couplings depend on nature (glueball, tetraquark,meson molecule etc.) and spin of the final state
- Heavier (ccbar) mesons have smaller <y> than lighter states

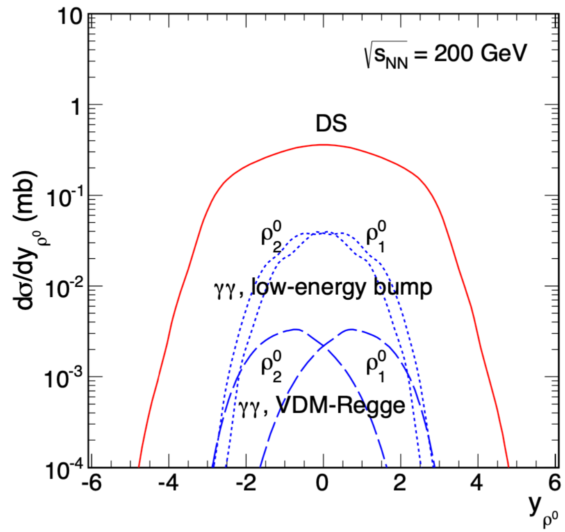




SK & Y. Xie, Phys. Rev. C **100**, 024620 (2019)

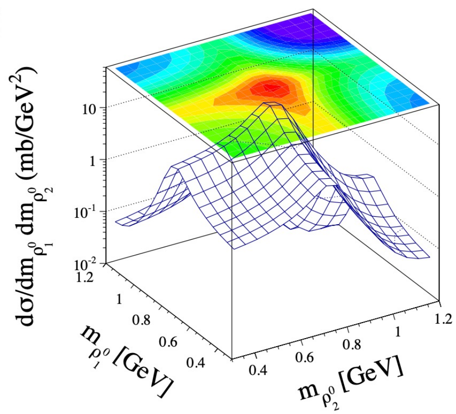
History of multiple vector meson production

- Klein & Nystrand (1999) explained via factorization:
  - $\sigma = \int d^2b\, P_1(b) P_2(b) \ldots$
  - Data on VM + mutual Coulomb excitation show factorization works



- A series of papers by Mariola Klusek-Gawenda *et al.* calculated cross-sections and kinematics

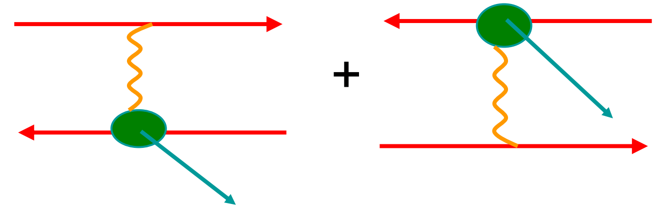
$$\sigma\left(AA \to AA\rho^0\rho^0\right) = \int \hat{\sigma}\left(\gamma\gamma \to \rho^0\rho^0; W_{\gamma\gamma}\right) S^2_{abs}\left(\mathbf{b}\right) N(\omega_1, \mathbf{b}_1) N(\omega_2, \mathbf{b}_2) \times d^2\mathbf{b}_1 d^2\mathbf{b}_2 d\omega_1 d\omega_2 \,,$$



- Other papers showed used similar approaches
- $\sigma(\rho^0\rho^0)$ ~ 20% of $\sigma(\pi^+\pi^- \pi^+\pi^-)$, so current non-observation not problematic

SK & J. Nystrand, Phys. Rev. C **60**, 014903 (1999); M. Klusek-Gawena & Szczurek, Phys. Rev. C **89**, 024912 (2014);C. Azevedo et al., Eur. Phys. J. A **59**, 193 (2023)

Interference in meson production

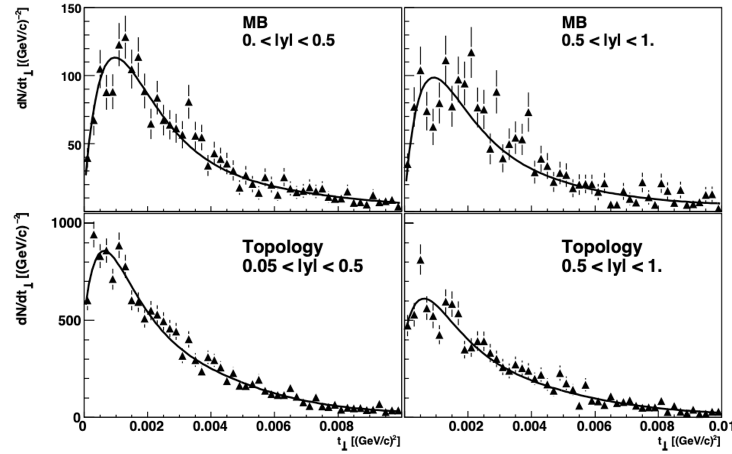


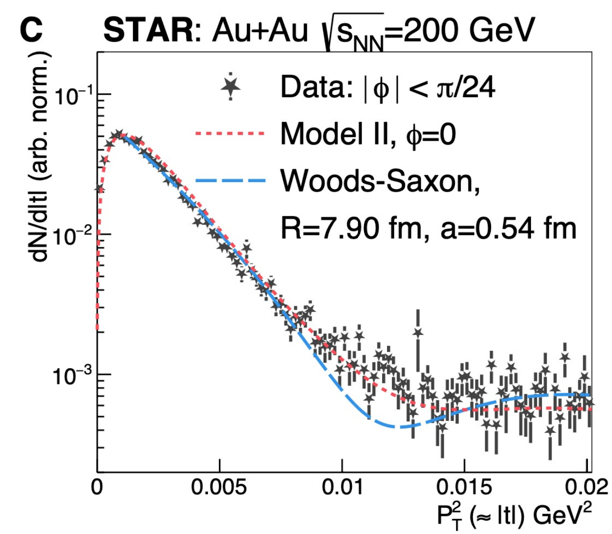
- Interference has been seen in single-meson production.
- Destructive interference

VM are negative parity

Propagator (Pomeron momentum)

  - $\sigma \sim |A_1 - A_2 e^{ik\cdot b}|^2$ for pp, AuAu…
    - A_1, A_2 are functions of photon energy
      - When $y \neq 0$ then $A_1 \neq A_2$
    - σ drop as pT -> 0
    - $\sigma \sim |A_1 + A_2 e^{ik\cdot b}|^2$ for pbarp
- Angular modulation of $d\sigma/dt$ since pair p_T follows b and $\pi^{\pm}$ p_T depends on VM polarization
  - Allows a quality fit to $d\sigma/dt$, with the reasonable nuclear radii & skin thicknesses





Talks by A. Riffero (ALICE) & K. Wang (STAR)

SK & J. Nystrand, PRL **84**, 2330 (2000); STAR PRL **102**, 112301 (2009); H. Xing et al., JHEP **10**, 064 (2020); STAR Sci. Adv. **9**, 1 eabq3903 (2023) etc.

Notation

- p – vector meson momentum
- q – photon momentum
- k – Pomeron momentum
- $A_{1,i}$ and $A_{2,l}$ – A_1 and A_2 are the two ions; the sums over indices i and l run over the individual nucleons in the ion
  - This could alternately be an integral over nuclear density, with similar results
- The nucleons have impact parameters $\overrightarrow{b_i}$ and $\overrightarrow{b_l}$. These vectors are taken from the center-of-mass of the system. For the two nuclei, $\overrightarrow{b_1}$ and $\overrightarrow{b_2}$ are the vectors from the center of the nuclei to the system COM.
  - So $\vec{b}_1$ = - $\vec{b}_2$

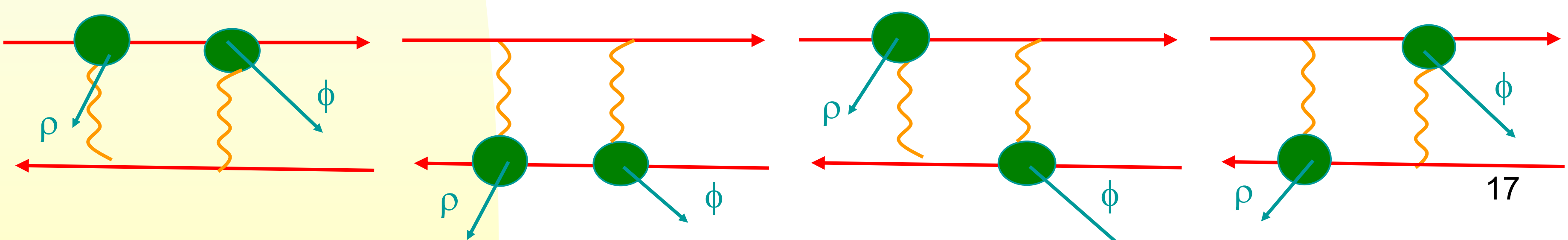
Double mesons - nonidentical (e. g. $\rho\phi$)

- Either meson can come from either nucleus -> 4 diagrams

$$P(b) = \Big| \Sigma_i A_{1,i}(b,\vec{p_j}) e^{i\vec{k_1}\cdot\vec{b_i}} \Sigma_l A_{1,l} e^{i\vec{k_2}\cdot\vec{b_l}} - \Sigma_i A_{1,i}(b,\vec{p_j}) e^{i\vec{k_1}\cdot\vec{b_i}} \Sigma_l A_{2,l} e^{i\vec{k_2}\cdot\vec{b_l}} - \Sigma_i A_{2,i}(b,\vec{p_j}) e^{i\vec{k_1}\cdot\vec{b_i}} \Sigma_l A_{1,l} e^{i\vec{k_2}\cdot\vec{b_l}} + \Sigma_i A_{2,i}(b,\vec{p_j}) e^{i\vec{k_1}\cdot\vec{b_i}} \Sigma_l A_{2,l} e^{i\vec{k_2}\cdot\vec{b_l}} \Big|^2$$

Work in progress!

  - Sum over individual nucleons; could also integrate density
    - Gives 2nd momentum scale: hbar/R_A (in addition to hbar/b)
    - Vectors b are from center of mass
- Signs come from negative parity of vector mesons
- $A_{1,i}$, $A_{2,l}$ are production amplitudes on individual nucleons
  - Slightly photon-energy dependent

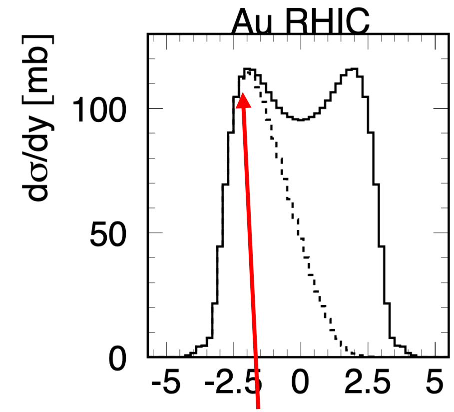


Forward production of light mesons

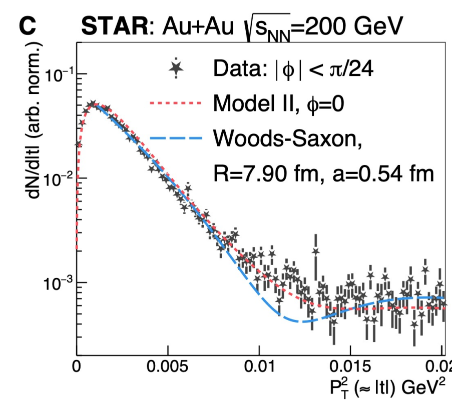
- $\sigma(\gamma A \to \rho/\phi\ A)$ varies slightly with photon energy
- Photon flux scales as 1/k
- At large |y| photons come predominantly from one nucleus
- The first two diagrams dominate at large +y and –y respectively.
  - No interference, for one direction:

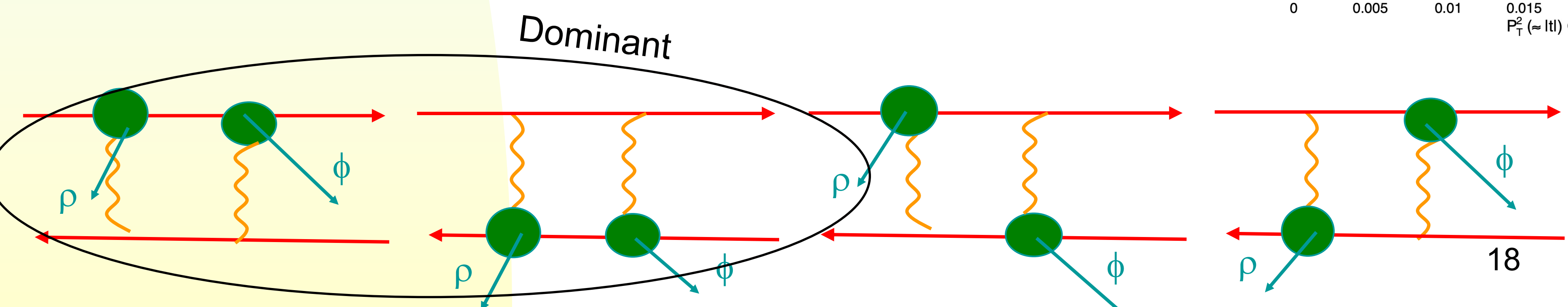
$$P(b) = \left| \Sigma_i A_{1,i}(b, \vec{p_1}) e^{i\vec{k_1}\cdot\vec{b_i}} \Sigma_l A_{1,l}(b, \vec{p_2}) e^{i\vec{k_2}\cdot\vec{b_l}} \right|^2$$

  - Same ion – p_T scale for coherence is hbar/R_A
    - As with single ions



Here



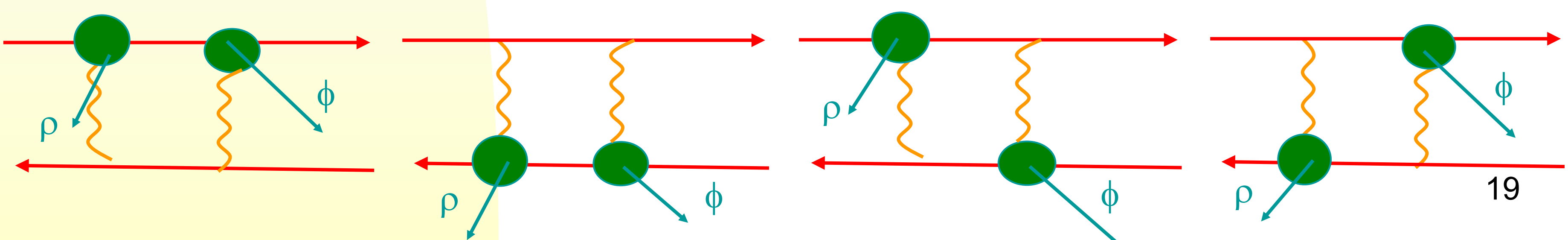


Mid-rapidity production of non-identical double mesons (e. g. ρϕ)

- All four diagrams contribute

$$P(b) = \Big| \Sigma_i A_{1,i}(b,\vec{p_j}) e^{i\vec{k_1}\cdot\vec{b_i}} \Sigma_l A_{1,l} e^{i\vec{k_2}\cdot\vec{b_l}} - \Sigma_i A_{1,i}(b,\vec{p_j}) e^{i\vec{k_1}\cdot\vec{b_i}} \Sigma_l A_{2,l} e^{i\vec{k_2}\cdot\vec{b_l}} - \Sigma_i A_{2,i}(b,\vec{p_j}) e^{i\vec{k_1}\cdot\vec{b_i}} \Sigma_l A_{1,l} e^{i\vec{k_2}\cdot\vec{b_l}} + \Sigma_i A_{2,i}(b,\vec{p_j}) e^{i\vec{k_1}\cdot\vec{b_i}} \Sigma_l A_{2,l} e^{i\vec{k_2}\cdot\vec{b_l}} \Big|^2$$

- Consider limit identical nuclei, y=0, $p_{T1}=P_{T2}=0$
  - Production disappears.
  - Some similarities to the single-ion case, but more complex patterns. Coherent enhancement for p_T<hbar/R_A, & destructive interference for p_T<hbar/<b>

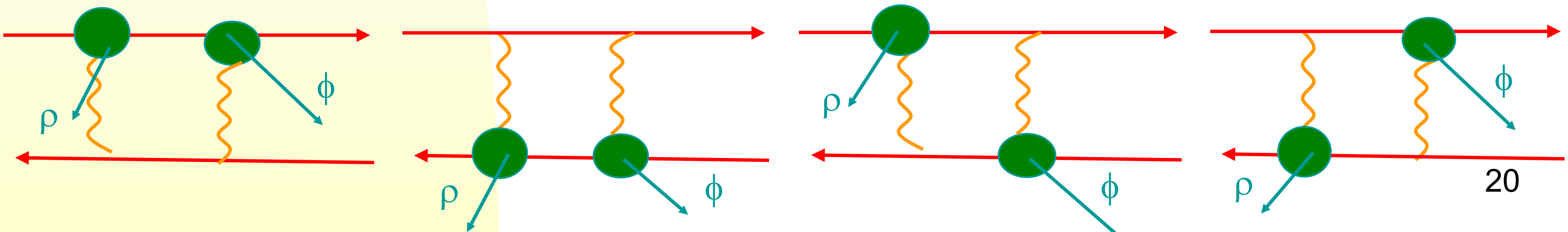


Mid-rapidity production of non-identical double mesons (e. g. ρϕ)

- All four diagrams contribute
- 2 like-target terms are similar
  - Need a propagator $\exp[i(k_1-k_2)b]$ to go from one to the other by swapping targets
    - k_1-k_2 because the $\vec{b}$ go in opposite directions
  - All terms have momentum scale hbar/b
- 2 opposite-target terms:
  - $-\exp[i(k_1b_1+k_2b_2)]$ $-\exp[i(k_1b_2+k_2b_1)]$
  - $= -\exp[i((k_1-k_2)b_1)]$ $-\exp[-i((k_1-k_2)b_1)]$
  - $= -2\cos((k_1-k_2)b_1)$
    - Coherent enhancement with k_1,k_2 large as long as k_1-k_2 is small

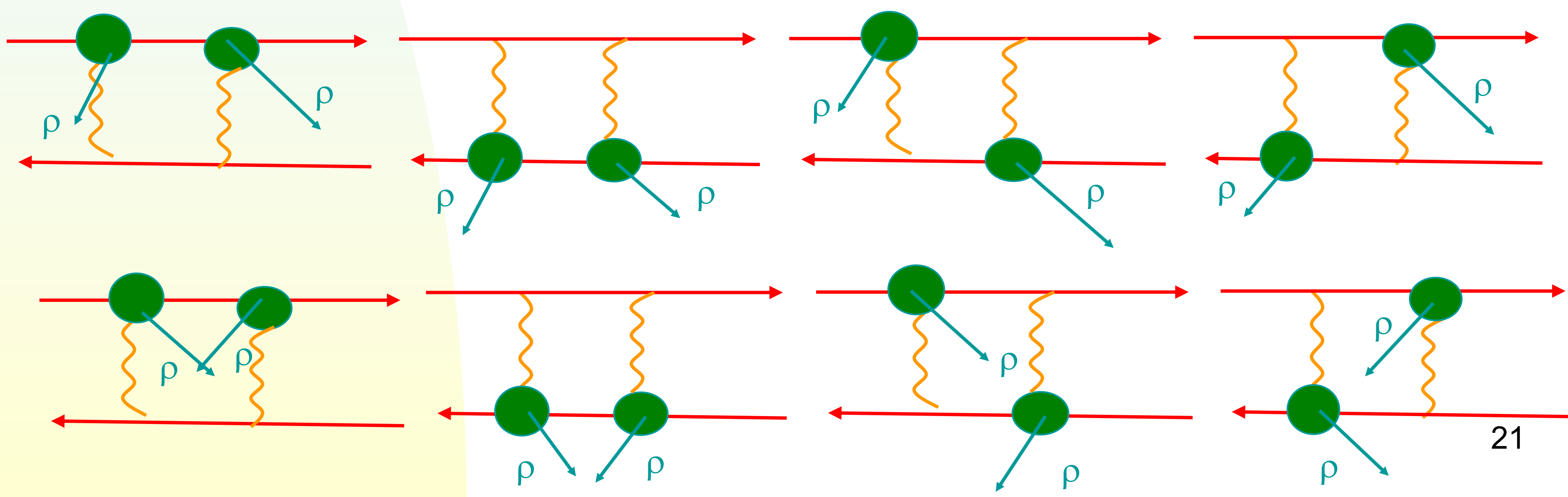
$$P(b) = \Big|\Sigma_i A_{1,i}(b,\vec{p_j})e^{i\vec{k_1}\cdot\vec{b_i}}\Sigma_l A_{1,l}e^{i\vec{k_2}\cdot\vec{b_l}} - \Sigma_i A_{1,i}(b,\vec{p_j})e^{i\vec{k_1}\cdot\vec{b_i}}\Sigma_l A_{2,l}e^{i\vec{k_2}\cdot\vec{b_l}} - \Sigma_i A_{2,i}(b,\vec{p_j})e^{i\vec{k_1}\cdot\vec{b_i}}\Sigma_l A_{1,l}e^{i\vec{k_2}\cdot\vec{b_l}} + \Sigma_i A_{2,i}(b,\vec{p_j})e^{i\vec{k_1}\cdot\vec{b_i}}\Sigma_l A_{2,l}e^{i\vec{k_2}\cdot\vec{b_l}}\Big|^2$$

Full combination
Still to come



Identical (indistinguishable) mesons

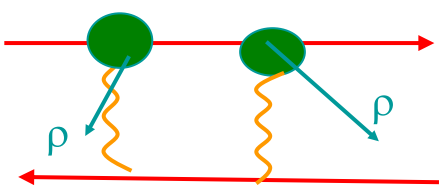
- Two possibilities
  - Photon 1 -> Meson 1 and Photon 2 -> Meson 2
  - Photon 1 -> Meson 2 and Photon 2 -> Meson 1
    - Identical routes to the same final state



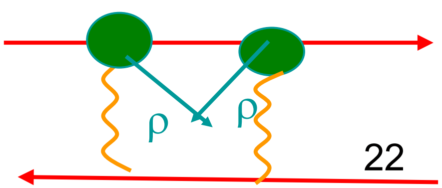
Identical (indistinguishable) mesons at forward rapidity

- Two diagrams contribute.
- $P(b) \sim |2N^2A_i^2 \exp[i(k_1+k_2)b]|^2$
  - Depends on sum of Pomeron k_T
- Coherent enhancement when $k_1 b <$ hbar
- Longitudinal coherence also required
  - $k_{z1}+k_{z2} <$ hbar$/R_A$
  - Coherence condition tightens compared to single mesons
- If coherence conditions are satisfied, the cross-section is twice the non-identical meson case.
  - Superradiance

$$P(b) = \left| \Sigma_i A_{1,i}(b,\vec{p_1}) e^{i\vec{k_1}\cdot\vec{b_i}} \Sigma_l A_{1,l}(b,\vec{p_2}) e^{i\vec{k_2}\cdot\vec{b_l}} + \Sigma_i A_{1,i}(b,\vec{p_1}) e^{i\vec{k_2}\cdot\vec{b_i}} \Sigma_l A_{1,l}(b,\vec{p_1}) e^{i\vec{k_1}\cdot\vec{b_l}} \right|^2$$



Here, for simplicity:
Neglect longitudinal coherence



More than 2 forward mesons

- For M mesons, there are M! diagrams
- Production probability scales as

$$P_M(b) = M!N^{M*M}A_i^{M*M} = M![P_1(b)]^M$$

  - For large M, M! increases faster than $[P_1(b)]^M$
  - For PbPb at the LHC, $P\rho(b=2R_A) \sim 0.03$
- Potentially, a vector meson laser
- Significant limitations
  - The accessible phase space drops as 1/M
  - Can only access a fraction of the energy in the photon fields
  - $P\rho(b=2R_A)$ is pretty small, even for U beams at fcc
  - Open question – superradiance/lasing requires independent emitters. Photons emission is independent, but with common phase
- Clear demonstration probably requires a forward detector
  - N=2 is clearly accessible, and N=3 should also be visible with effort

Identical particles at mid-rapidity

- 8 amplitude terms
  - 4 w/ emission from same nucleus
  - 4 w/ emission from opposite nuclei
- 2 distance scales
  - hbar/R_A for emission from same nucleus
  - hbar/b for emission from different nuclei
- First, consider hbar/R_A < k < hbar/b
- 4 paired opposite nuclei terms:
  - Similar enhancement as non-identical particles
  - Coherent enhancement with k_1,k_2 large as long as k_1-k_2 is small

$$
\begin{aligned}
P(b) = \Big| & \Sigma_i A_{1,i}(b,\vec{p_j}) e^{i\vec{k_1}\cdot\vec{b_i}} \Sigma_l A_{1,l} e^{i\vec{k_2}\cdot\vec{b_l}} \\
& - \Sigma_i A_{1,i}(b,\vec{p_j}) e^{i\vec{k_1}\cdot\vec{b_i}} \Sigma_l A_{2,l} e^{i\vec{k_2}\cdot\vec{b_l}} \\
& - \Sigma_i A_{2,i}(b,\vec{p_j}) e^{i\vec{k_1}\cdot\vec{b_i}} \Sigma_l A_{1,l} e^{i\vec{k_2}\cdot\vec{b_l}} \\
& + \Sigma_i A_{2,i}(b,\vec{p_j}) e^{i\vec{k_1}\cdot\vec{b_i}} \Sigma_l A_{2,l} e^{i\vec{k_2}\cdot\vec{b_l}} \\
& + \Sigma_i A_{1,i}(b,\vec{p_j}) e^{i\vec{k_2}\cdot\vec{b_i}} \Sigma_l A_{1,l} e^{i\vec{k_1}\cdot\vec{b_l}} \\
& - \Sigma_i A_{1,i}(b,\vec{p_j}) e^{i\vec{k_2}\cdot\vec{b_i}} \Sigma_l A_{2,l} e^{i\vec{k_1}\cdot\vec{b_l}} \\
& - \Sigma_i A_{2,i}(b,\vec{p_j}) e^{i\vec{k_2}\cdot\vec{b_i}} \Sigma_l A_{1,l} e^{i\vec{k_1}\cdot\vec{b_l}} \\
& + \Sigma_i A_{2,i}(b,\vec{p_j}) e^{i\vec{k_2}\cdot\vec{b_i}} \Sigma_l A_{2,l} e^{i\vec{k_1}\cdot\vec{b_l}} \Big|^2
\end{aligned}
$$

Azimuthal asymmetries

- Multiple vector mesons are linearly polarized along the same axis
  - They should display azimuthal asymmetries
  - Sort-of like due to two-source interference, but with richer phenomenology

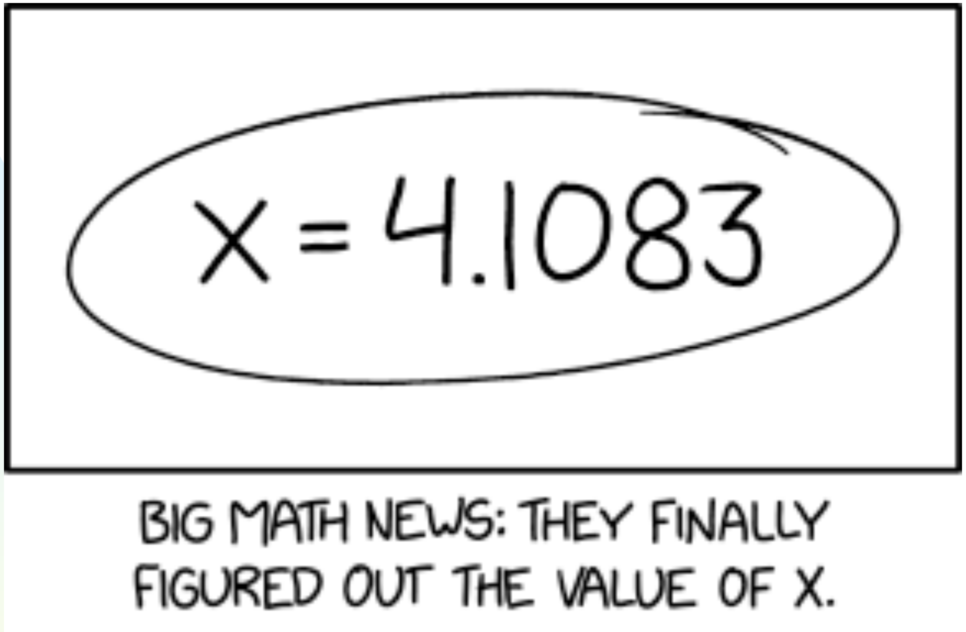
Going further – stimulated decays

- If we can produce ρ^0 (or other mesons) in the same state, then should be able to observe stimulated decays.
- Same state criteria for short-lived particles: coherence time> particle lifetime
  - Momentum close enough together
- Stimulated decays should be visible in one of two ways
  - For particles with different decays (e. g. J/ψ -> ee, $\mu\mu$) by 'tagging' one one decay, should see an excess of the same state from the other J/ψ
  - For states like $\rho^0\rho^0$, should see angular correlations between the $\pi^+\pi^+$ and $\pi^-\pi^-$

Conclusions

- Coherence is an interesting and subtle topic, with important consequences.
- The Good-Walker paradigm relates coherent and incoherent photoproduction to the average nuclear configuration and configuration fluctuations respectively. In Good-Walker coherence means that the target remains in the ground state. That disagrees with some experimental observations of coherent photoproduction
- An alternate approach to coherence – adding amplitudes, so $\sigma_{coherent} = |\Sigma_i A_i k \exp(ikb)|^2$ – can explain data where Good-Walker fails.
- 'Adding amplitudes' allows some new coherent UPCs channels, including coherent photoproduction of charged mesons.
- UPC production of multiple vector mesons exhibits many interesting aspects of interference.
  - Superradiance for identical meson emission in the forward direction.
  - Interference when k_1, k_2 > hbar/b, as long as k_1-k_2 < hbar/b.

Conclusions (II)



Gracias!

xkcd.com