Weaving an entangled web: synergies from UPC's to EIC

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ALICE—USA meeting, Yale, May 31, 2024

Talk outline

Interferometry: from vanilla HBT to entanglement enhanced intensity interferometry (E^2I^2)

E^2I^2 in UPC exclusive vector meson decays: insights from old wine in a new bottle*

Shadowy Pomerons and Odderons

Onwards to EIC: Weizsacker-Williams and linearly polarized gluons from di-jets at NLO

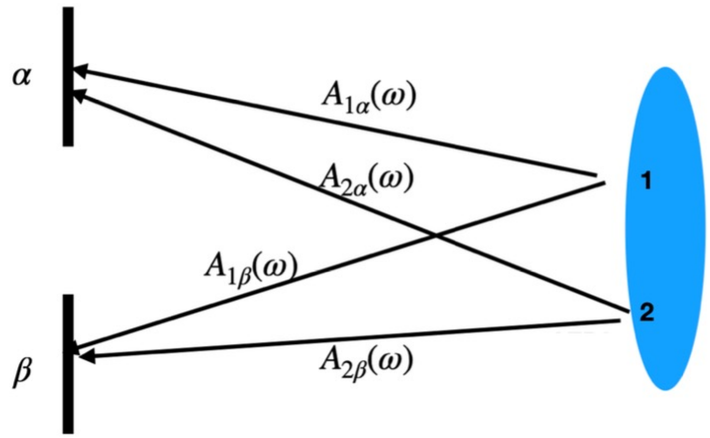
Musings in closing

* Must be 21+

Hanbury-Brown—Twiss Intensity Interferometry: rejected experiment to quantum work horse (via Roy Glauber)

A textbook example (Gordon Baym's QM book, for instance) of how quantum mechanics can provide spacetime information about distant objects

Detectors α and β



1 and 2 are random locations in stochastic source

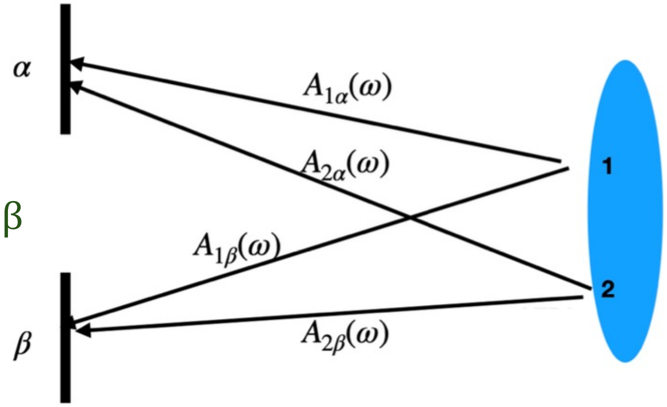
$A_{1\alpha}(\omega)$: amplitude of a photon (pion) of frequency ω from 1 captured in detector α

$$A_\alpha = A_{1\alpha} + A_{2\alpha}$$
$$A_\beta = A_{1\beta} + A_{2\beta}$$
$$\langle A_{1\alpha} \rangle \propto \int_0^{2\pi} \frac{d\theta_1}{2\pi} e^{i\theta_1} = 0$$
$$\langle A_{2\alpha} \rangle = 0 \; ; \langle A_{1\alpha} A_{2\alpha}^* \rangle = \langle A_{1\alpha} \rangle \langle A_{2\alpha}^* \rangle = 0$$

Excellent intro to field: Baym's Zakopane lectures, hep-ph/9804026

In quantum optics, see Alain Aspect, arXiv:2005.08239

A brief recap of HBT



Detectors α and β

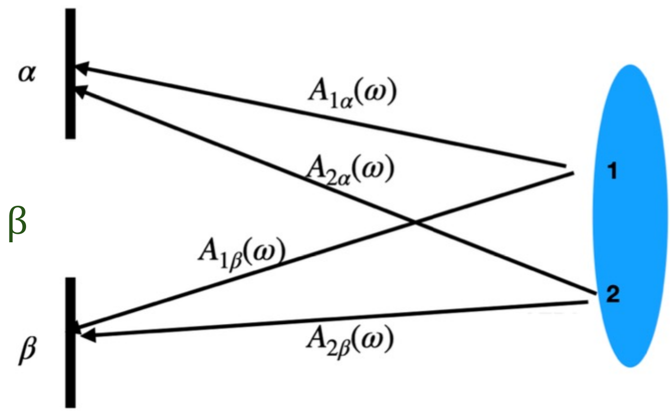
1 and 2 are random locations in stochastic source

Quantum state of Hilbert space of the two detectors $|\phi\rangle = \left(A_{1\alpha}A_{2\beta} + A_{2\alpha}A_{1\beta}\right)|\omega^{\alpha}, \omega^{\beta}\rangle$

State vectors of photons with frequency ω reaching detector α and β

A brief recap of HBT

Detectors α and β



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State vectors of photons with frequency ω reaching detector α and β

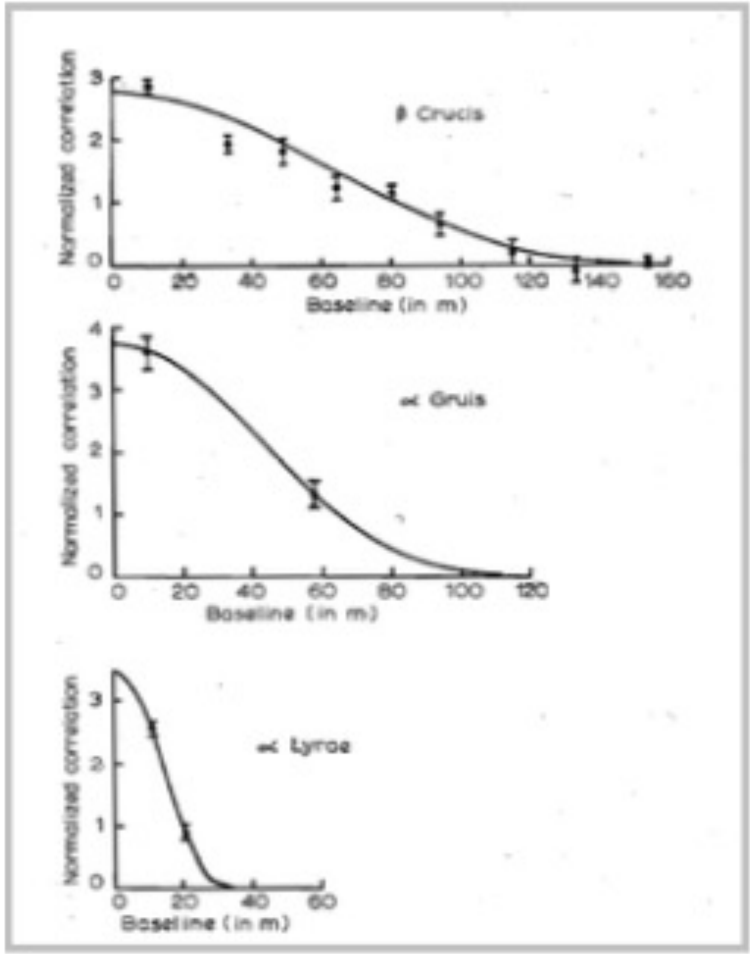
Interference pattern in HBT (excluding photons from same point)

$$\langle I_\alpha I_\beta\rangle - \langle I_\alpha\rangle\langle I_\beta\rangle = \langle\phi|\phi\rangle - |A_{1\alpha}|^2|A_{2\beta}|^2 - |A_{2\alpha}|^2|A_{1\beta}|^2 = A_{1\alpha}A_{2\beta}A^*_{2\alpha}A^*_{1\beta} + A^*_{1\alpha}A^*_{2\beta}A_{2\alpha}A_{1\beta}$$

$$\Re\langle A_{1\alpha}A^*_{2\alpha}A^*_{1\beta}A_{2\beta}\rangle = \cos(\boldsymbol{k}\cdot(\boldsymbol{r}_{1\alpha} - \boldsymbol{r}_{1\beta}) - \boldsymbol{k}\cdot(\boldsymbol{r}_{2\alpha} - \boldsymbol{r}_{2\beta})) \approx \cos[(\vec{k}_\alpha - \vec{k}_\beta)\cdot(\vec{r}_1 - \vec{r}_2)]$$

Information on size of the star !

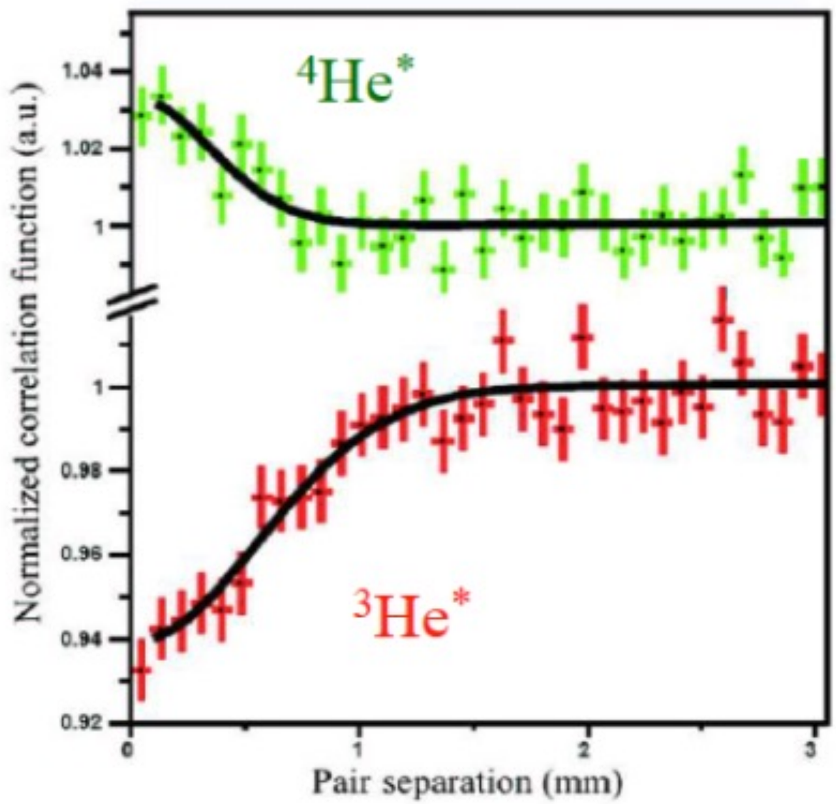
Angular diameter of stars measured by Hanbury-Brown & Twiss



Angular diameter of Sirius estimated to be 3.1 $*10^{-8}$ radians

Distance of 2.7 parsecs gives radius ~ 10^{7} Km

Boson and Fermion HBT in ultracold atomic gases



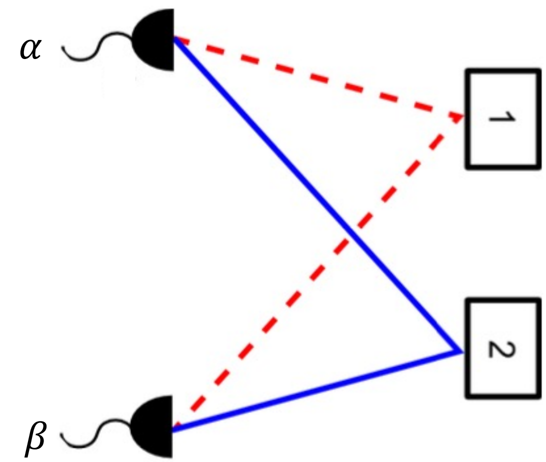
A. Ottl et al., PRL95, 9 (2005)
S. Hodgman et al., Science, vol. 331, no. 6020. (2011)

Entanglement Enhanced Intensity interferometry (E^2I^2)

If the photons have different frequencies,

$$|\psi\rangle = A_{1\alpha}A_{2\beta}|\omega_1\rangle^{\alpha} \otimes |\omega_2\rangle^{\beta} + A_{2\alpha}A_{1\beta}|\omega_2\rangle^{\alpha} \otimes |\omega_1\rangle^{\beta}$$

The two states are orthogonal – there is no HBT signal!



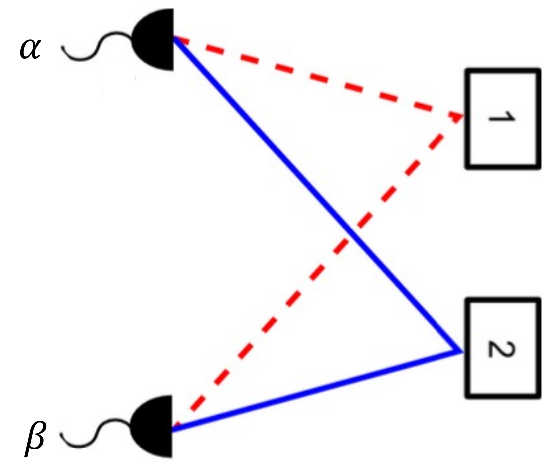
Entanglement Enhanced Intensity interferometry (E^2I^2)

Novel idea: employ quantum entanglement to recover interferometric information

I) First perform a unitary transformation on the state:

$$U|\omega_1\rangle = \cos(\theta)|\omega_1\rangle + \sin(\theta)e^{i\omega_0}|\omega_2\rangle$$

$$U|\omega_2\rangle = \sin(\theta)e^{-i\omega_0}|\omega_1\rangle + \cos(\theta)|\omega_2\rangle$$



J.Cotler, F. Wilczek, arXiv:1502.02477
J. Cotler, F. Wilczek, V. Borish, arXiv:1607.05719v2, Annals of Physics, 424 (2021) 168346

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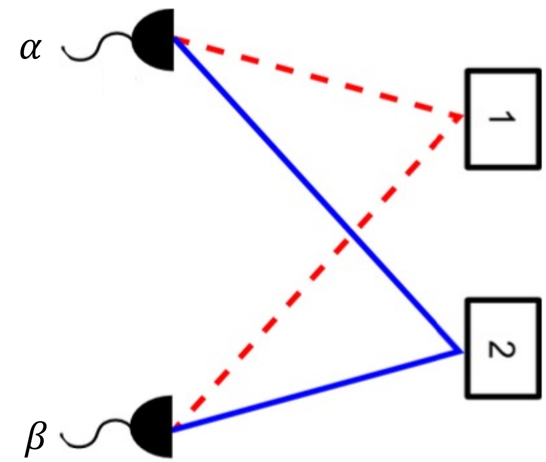

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II) Apply filter:

$$\Pi = |\omega_1\rangle^\alpha\langle\omega_1|^\alpha \otimes |\omega_1\rangle^\beta\langle\omega_1|^\beta$$
$$\Pi\, U\,|\psi> \;\rightarrow (A_{1\alpha}A_{2\beta} + A_{2\alpha}A_{1\beta})|\phi\rangle$$

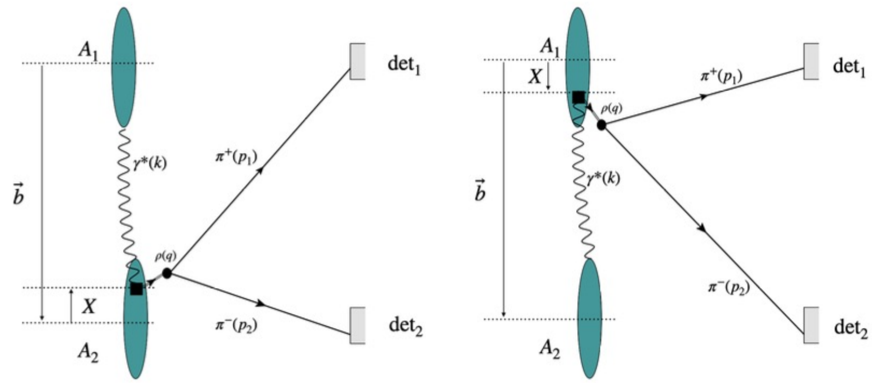
J.Cotler, F. Wilczek, arXiv:1502.02477
J. Cotler, F. Wilczek, V. Borish, arXiv:1607.05719v2, Annals of Physics, 424 (2021) 168346

III) Computing the expectation value of this state recovers the HBT signal…

E^2I^2 achievable through "quantum frequency up-conversion" erasing distinguishability of the photons

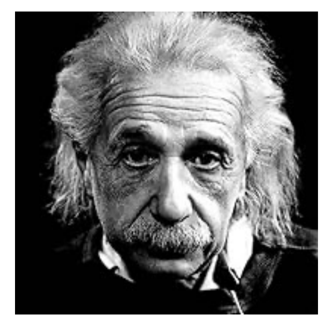
C. K. Hong et al., PRL. 59, 2044 (1987) Z. Y. Ou and L. Mandel, PRL. 61, 54 (1988)
H. Takesue, Phys. Rev. Lett. 101 (2008) 173901
L.-C. Liu, J. Cotler, F. Wilczek,J.-W. Pan et al., PRL127 (2021)103601

Entanglement Enhanced Intensity Interferometry (E^2I^2): UPC's to EIC

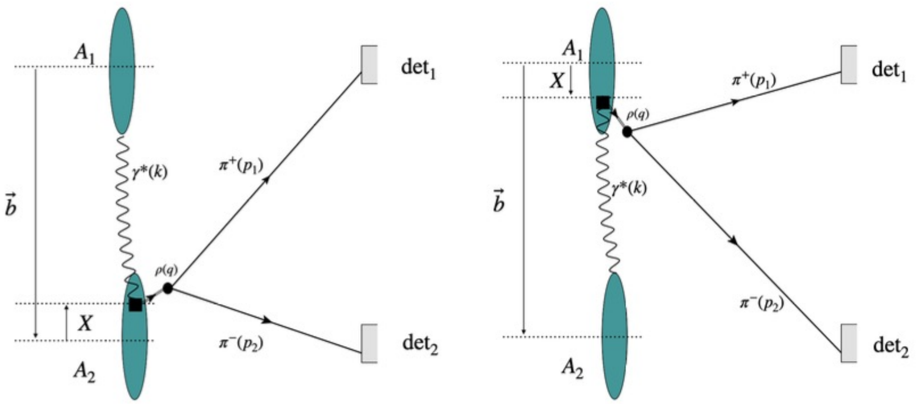


Work in preparation in collaboration* with Daniel Brandenburg, Haowu Duan, Kong Tu and Zhangbu Xu

* A theory is something nobody believes, except the person who made it.
An experiment is something everybody believes, except the person who made it.



Entanglement Enhanced Intensity Interferometry (E^2I^2) in UPCs



Exclusive two-particle decays of vector mesons, eg., $\rho \to \pi^+\pi^-$ *or* $J/\psi \to e^+e^-$ are examples of E^2I^2 where the vector meson acts to entangle the distinguishable final states

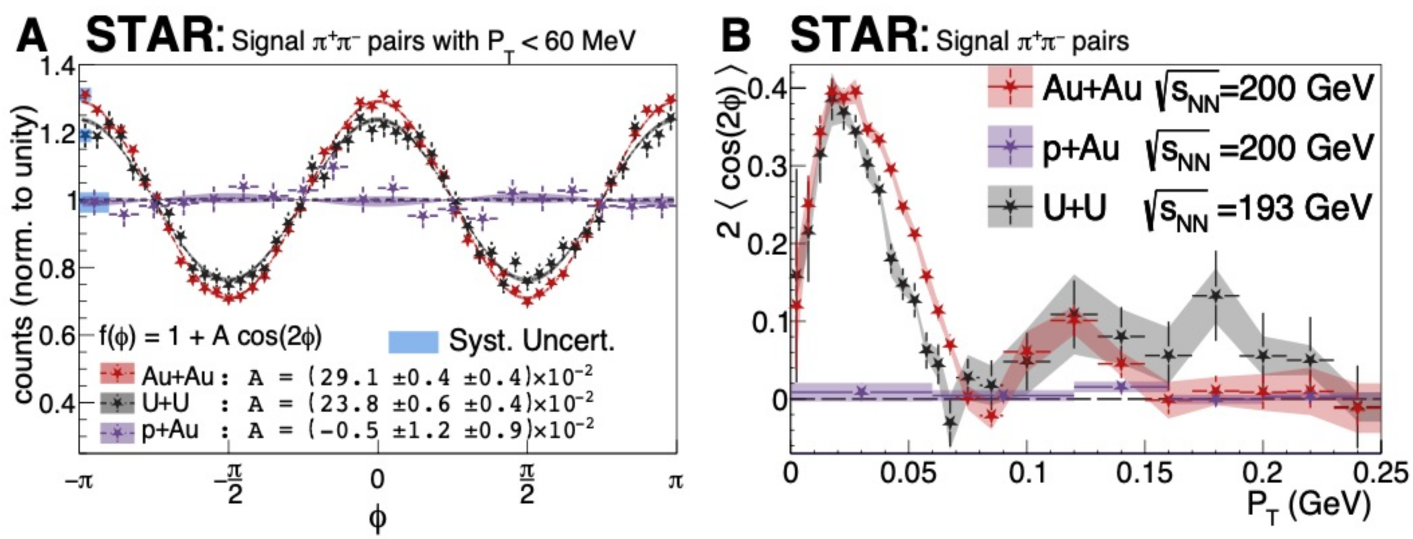
$$M_{A_1 A_2 \to \pi^+\pi^-}(\boldsymbol{p}_1, \boldsymbol{p}_2, \boldsymbol{b}) = M_{A_1 A_2 \to \rho}(\boldsymbol{q}, \boldsymbol{b})\, M_{\rho \to \pi^+\pi^-}(\boldsymbol{q}, \boldsymbol{p}_1, \boldsymbol{p}_2)$$

Two interference effects:

I) Coherent sum of the two amplitudes where the ρ-meson is produced off of one nucleus or the other

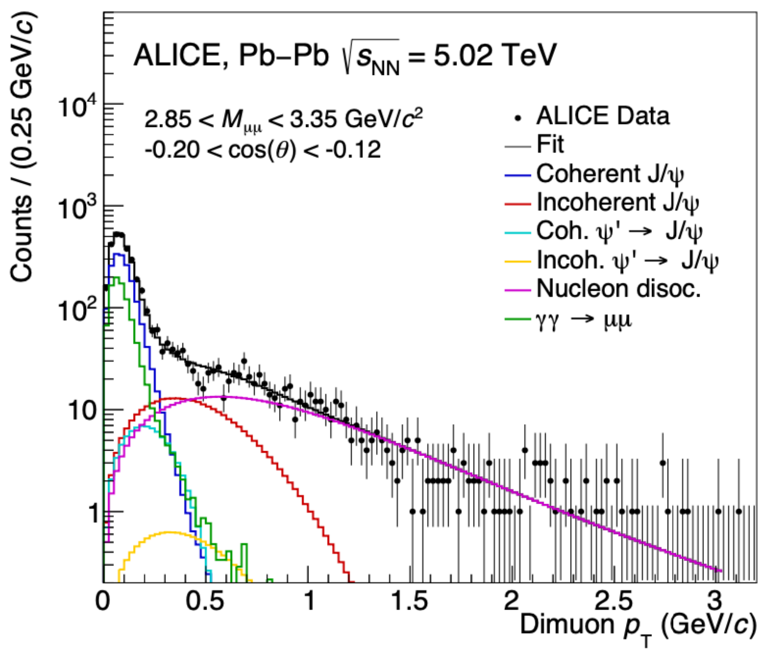
II) E^2I^2 from the exclusive decay of a spin-1 vector meson into an entangled P-wave $\pi^+\pi^-$ state

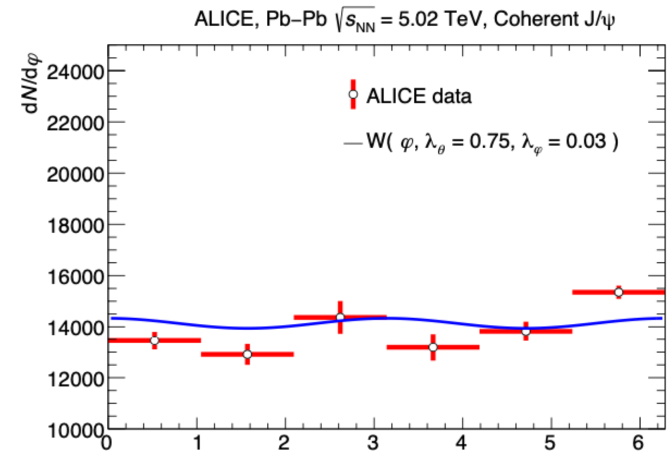
Entanglement Enhanced Intensity Interferometry (E^2I^2) in UPCs

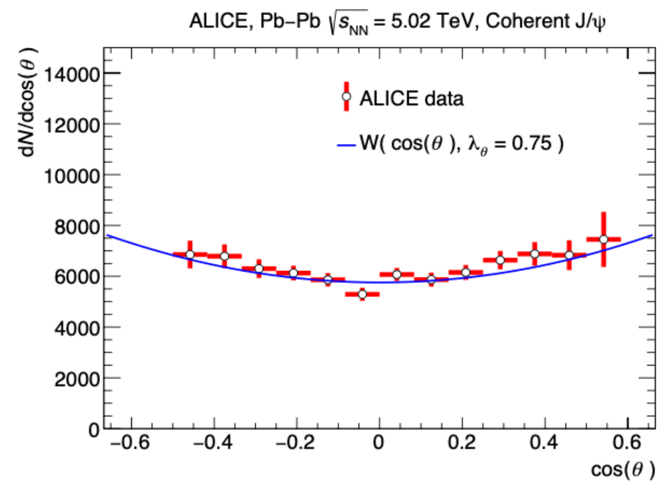


STAR Collaboration, Sci. Adv. 9, abq3903 (2023)

Entanglement Enhanced Intensity Interferometry (E^2I^2) in UPCs







Possible evidence for s-channel helicity conservation

Gillman et al. (1970)

Non-comprehensive overview of theory work

I) Pioneering study : S. Klein and J. Nystrand Phys. Rev. Lett. **84**, 2330

II) Vector-meson dominance/ (Gribov) Glauber models:

V. Guzey, E. Kryshen, and M. Zhalov, *Phys. Rev.* C93 (2016) 055206

W. Zha, J. D. Brandenburg, L. Ruan, Z. Tang, Z. Xu, PRD 103 (2021) 3, 033007

Classic review, T. Bauer, R. Spital, D. Yennie, F. Pipkin, RMP50 (1978) 261

III) CGC/dipole models

D. Bendova, J. Cepila, J. Contreras, and M. Matas, *Phys. Lett. B* 817 (2021) 136306

V. Goncalves, B. Moreira, L. Santana, PRC107 (2023)055205

H. Xing, C. Zhang, J. Zhou and Y.-J. Zhou, JHEP 10 (2020) 064

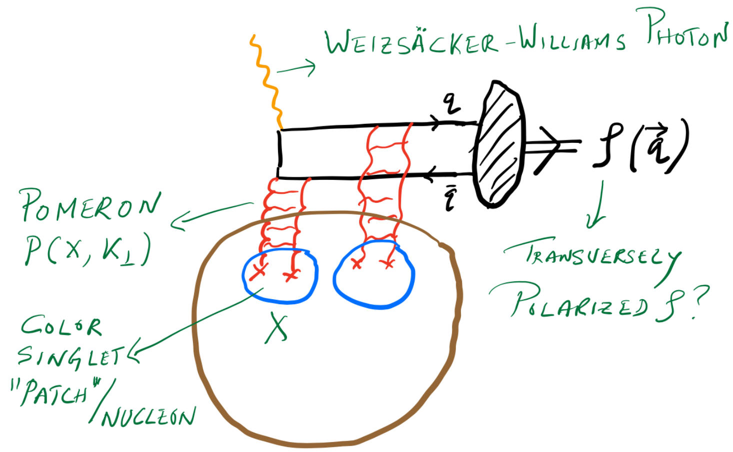
Y. Hagiwara, C. Zhang, J. Zhou and Y.-J. Zhou, Phys. Rev. D 103 (2021) no. 7 074013

H. Mäntysaari, F. Salazar and B. Schenke, Phys. Rev. D 106 (2022) no. 7 074019

H. Mäntysaari, F. Salazar, B. Schenke, C. Shen, W. Zhao, Phys. Rev. C109 (2024) 2, 024908

Our perspective: As model independent as possible, extract information on color singlet degrees of freedom in nuclei and understand this dynamics from the perspective of E^2I^2

Uncovering a shadowy pomeron and its odd partner from UPCs



Coherent amplitude:

$$M^{T\lambda_{\mathbb{P}}\lambda_\rho}_{12\to\rho}(\boldsymbol{q},\boldsymbol{b}) \;=\; \frac{\boldsymbol{b}}{|\boldsymbol{b}|}\, e^{i\boldsymbol{q}\cdot\boldsymbol{b}}\, F_{\rm QED}\Big(\boldsymbol{q}_\perp - \frac{1}{|\boldsymbol{b}-\boldsymbol{X}|}\Big) \int \frac{d^2\boldsymbol{K}_\perp}{(2\pi)^2} \int_{|\boldsymbol{X}|<R} d^2\boldsymbol{X}\, P(\boldsymbol{X},\boldsymbol{K}_\perp)$$

Photon flux times Pomeron flux

$$\times \int \frac{d^4\boldsymbol{\Delta q}}{(2\pi)^4}\, \bar{M}^{T\lambda_{\mathbb{P}}\lambda_1\lambda_2}_{\gamma\mathbb{P}\to q\bar{q}}\Big(\boldsymbol{q}_\perp - \frac{1}{|\boldsymbol{b}-\boldsymbol{X}|}, \boldsymbol{K}_\perp; \boldsymbol{q}, \boldsymbol{\Delta} q\Big)\, \mathcal{N}^{\lambda_1\lambda_2\lambda_\rho}_{q\bar{q}\to\rho}(\boldsymbol{\Delta} q;\boldsymbol{q})$$

Amplitude to produce ρ
-use your favorite model

Notes:

i) The photon is polarized in the direction of the impact parameter

ii) Clearly see one source of interference: $M^{T\lambda_{\mathbb{P}}\lambda_\rho}_{21\to\rho}(\boldsymbol{q},\boldsymbol{b}) = -\,e^{-i2\,\boldsymbol{q}\cdot\boldsymbol{b}}\, M^{T\lambda_{\mathbb{P}}\lambda_\rho}_{12\to\rho}$.

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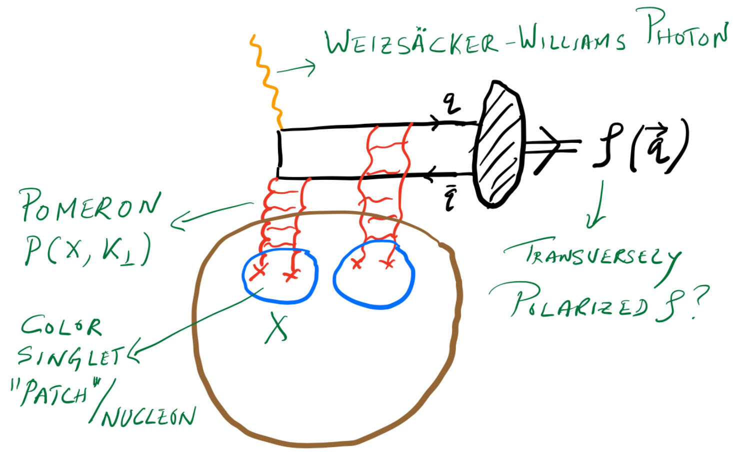

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Photon flux times Pomeron flux

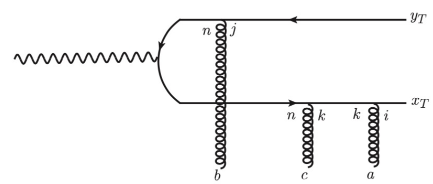
Amplitude to produce ρ
-use your favorite pert./nonpert. model

Notes:

iii) Can in principle test coupling of pomeron to hadrons: scalar, vector, tensor?

iv) For C=1 vector mesons, eg. $\chi_c \to e^+e^-\gamma$, replace $\mathrm{P} \to i\mathrm{O}$, the Odderon, pomeron's C-odd partner

Nachtmann et al. (2013- present)



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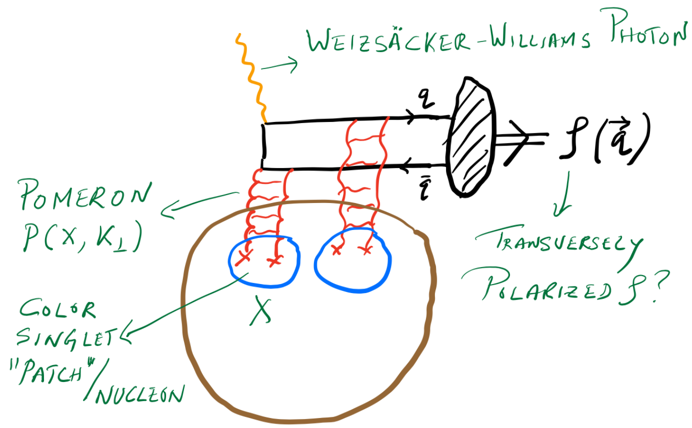


Incoherent cross-section: $<|M|^2>_N - |<M>_N|^2$ ➡ $<P^2> - <P>^2$ sensitivity to fluctuations in the pomeron distribution in the nucleus

We also see from the structure of our amplitude expression that
the phase **iq*b** is ~ cancelled by a phase **–iq*ΔK** when the momentum transfer is significant

Dominant incoherent cross section at large **q** suppresses phase fluctuations in coherent/(coherent+incoherent)

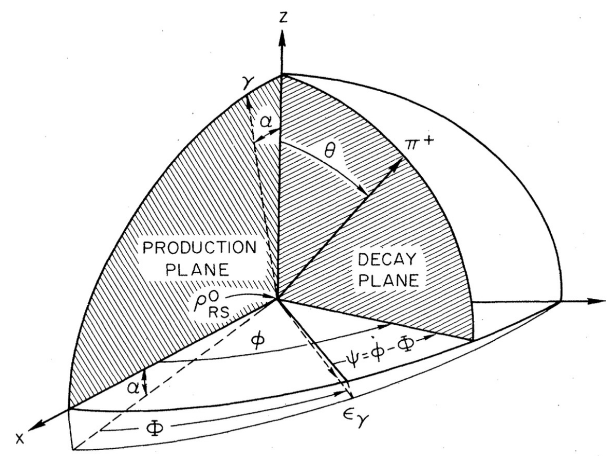
E^2I^2 in vector meson decays

The two pions one measures are a P=1 entangled state, characterized by

$$\overrightarrow{p_1} + \overrightarrow{p_2} = \vec{q} \; and \; \overrightarrow{p_1} - \overrightarrow{p_2} = \vec{P}$$

The ρ meson is produced transversely polarized along $\vec{b}$

$$|\rho_{\boldsymbol{b}}^{12}> = \cos(\phi_{pb})\cos(\theta_{pb})|\rho_{\|}> + \cos(\phi_{pb})\sin(\theta_{pb})|\rho_1^T> + \sin(\phi_{pb})\cos(\theta_{pb})|\rho_2^T>$$



Ballum et al., PRD 5, (1972), 545

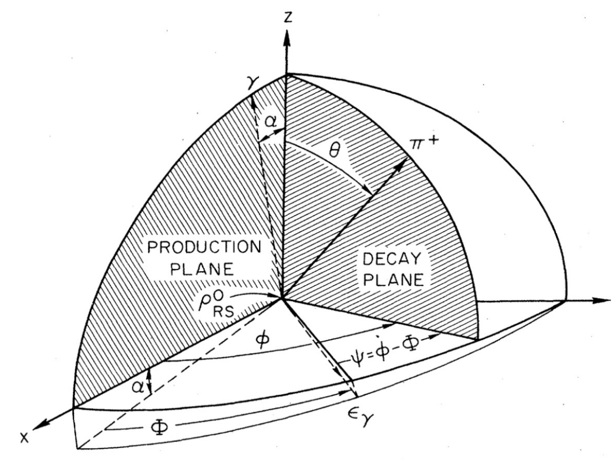
E^2I^2 in vector meson decays

Longitudinally polarized state (J=1, M=0):

$$|\rho_{\parallel}\rangle = \cos(\theta_{\boldsymbol{Pq}})\Big(|\pi^+(p_1)\pi^-(p_2)\rangle + |\pi^+(p_2)\pi^-(p_1)\rangle\Big)$$

Transversely polarized state J=1, M=$\mp$1):

$$|\rho_{\perp}\rangle = -\sin(\theta_{\boldsymbol{Pq}})\, e^{i\phi_{\boldsymbol{Pq}}}|\pi^+(p_1)\pi^-(p_2)\rangle + \sin(\theta_{\boldsymbol{Pq}})\, e^{-i\phi_{\boldsymbol{Pq}}}|\pi^+(p_2)\pi^-(p_1)\rangle$$



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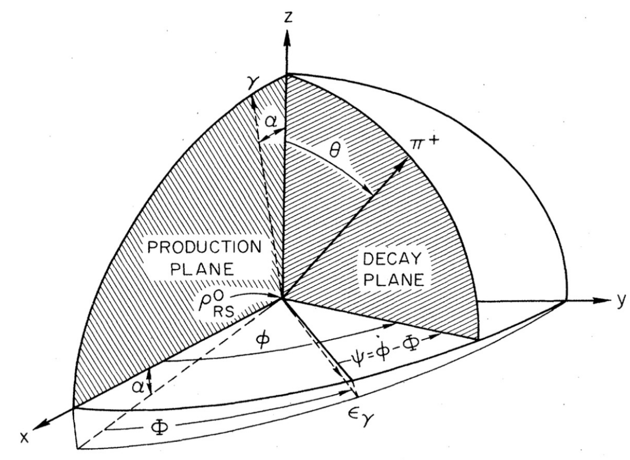


Ballum et al., PRD 5, (1972), 545

The amplitude from the decay of these entangled states:

$$M_{12}^{\rho_b \to \pi^+\pi^-} + M_{12}^{\rho_b \to \pi^-\pi^+} = A(|\boldsymbol{P}|, |\boldsymbol{q}|) * \Big(\big[\cos(\phi_{pb})\cos(\theta_{pb})\cos(\theta_{\boldsymbol{Pq}}) - \cos(\phi_{pb})\sin(\theta_{pb})\sin(\theta_{\boldsymbol{Pq}})\, e^{i\phi_{\boldsymbol{Pq}}}\big]$$

$$+ \big[\cos(\phi_{pb})\cos(\theta_{pb})\cos(\theta_{\boldsymbol{Pq}}) + \sin(\phi_{pb})\cos(\theta_{pb})\sin(\theta_{\boldsymbol{Pq}})\, e^{-i\phi_{\boldsymbol{Pq}}}\big] \Big)$$

$A(|P_T|,|q_T|)$ is the ρ decay amplitude

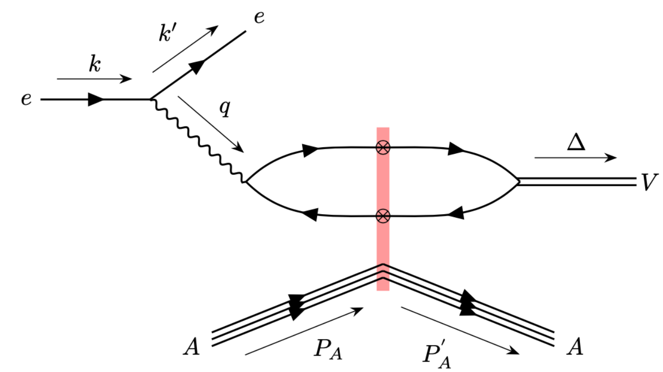
This leads to a nontrivial angular modulation $\langle\cos(2\theta_{pq})\rangle$

Old wine in a new bottle: entangled spin/angular momentum states
reveal fundamental info on the strong interaction

Onwards to the EIC

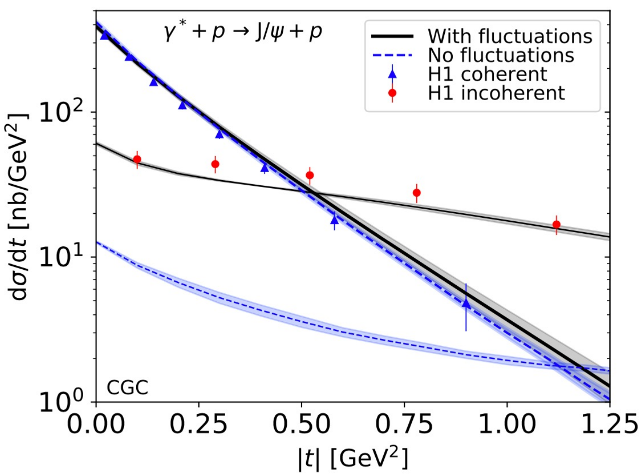
Exclusive vector meson production:

just as in UPC but control on longitudinal and transverse polarization of virtual photon

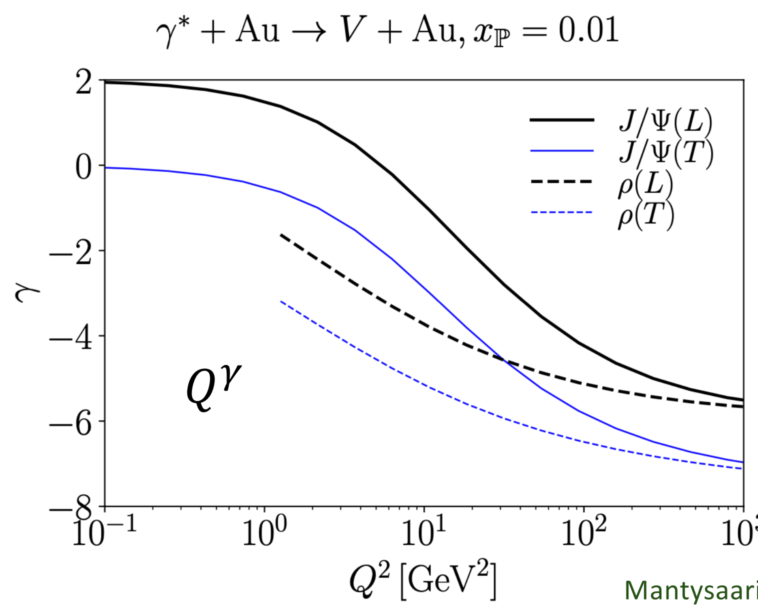


Clean sensitivity to helicity preserving, helicity flip, polarization changing, amplitudes for a variety of exclusive final states:

E^2I^2 analysis of data a powerful tool…

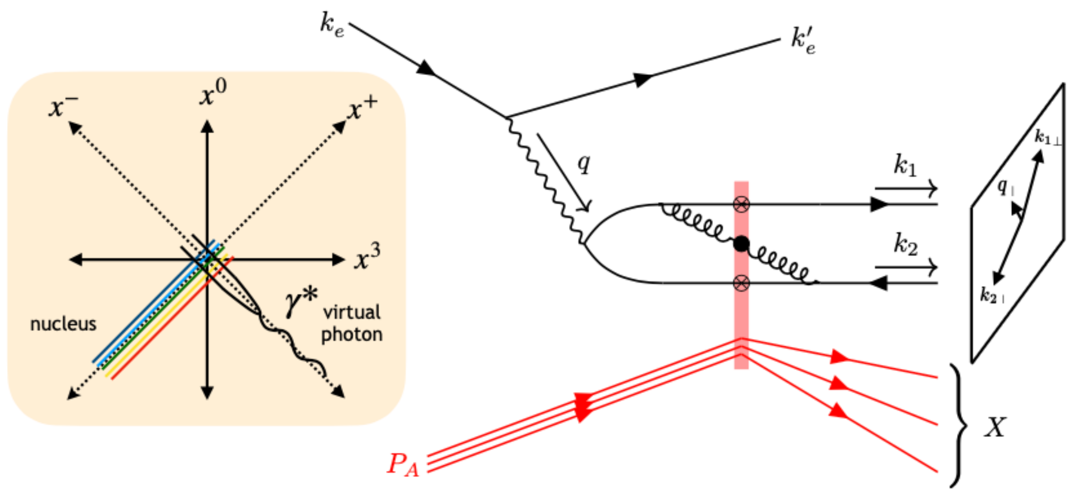


Mantysaari,Roy,Salazar,Schenke,
PRD103 (2021) 9, 094026



Mantysaari,RV, PLB781(2018)664

Extracting the gluon Weizsäcker-Williams dist. at small x



Back-to-back di-jets in DIS

First fully NLO computation in the saturation regime

Caucal,Salazar,Schenke,Stebel,RV, PRL132 (2024) 8, 081902

Extracting the gluon Weizsäcker-Williams dist. at small x

Factorization of small-x TMDs to NLO accuracy

$$
\begin{aligned}
\mathrm{d}\sigma^{(0),\lambda=\mathrm{T}} = \mathcal{H}_{\mathrm{LO}}^{0,\lambda=\mathrm{T}} \int \frac{\mathrm{d}^2 \boldsymbol{B}_\perp}{(2\pi)^2} \int \frac{\mathrm{d}^2 \boldsymbol{r}_{bb'}}{(2\pi)^2} e^{-i\boldsymbol{q}_\perp \cdot \boldsymbol{r}_{bb'}} \hat{G}^0_{\eta_c}(\boldsymbol{r}_{bb'}, \mu_0) \mathcal{S}(\boldsymbol{P}_\perp^2, \mu_0^2) \\
\times \left\{ 1 + \frac{\alpha_s(\mu_R) N_c}{2\pi} f_1^{\lambda=\mathrm{T}}(\chi, z_1, R) + \frac{\alpha_s(\mu_R)}{2\pi N_c} f_2^{\lambda=\mathrm{T}}(\chi, z_1, R) + \alpha_s(\mu_R)\beta_0 \ln\left(\frac{\mu_R^2}{P_\perp^2}\right) \right\} \\
+ \mathcal{H}_{\mathrm{LO}}^{0,\lambda=\mathrm{T}} \int \frac{\mathrm{d}^2 \boldsymbol{B}_\perp}{(2\pi)^2} \int \frac{\mathrm{d}^2 \boldsymbol{r}_{bb'}}{(2\pi)^2} e^{-i\boldsymbol{q}_\perp \cdot \boldsymbol{r}_{bb'}} \hat{h}^0_{\eta_c}(\boldsymbol{r}_{bb'}, \mu_0) \mathcal{S}(\boldsymbol{P}_\perp^2, \mu_0^2) \\
\times \frac{-2\chi^2}{1+\chi^4} \left\{ \frac{\alpha_s(\mu_R) N_c}{2\pi} \left[1 + \ln(R^2)\right] + \frac{\alpha_s(\mu_R)}{2\pi N_c} \left[-\ln(z_1 z_2 R^2)\right] \right\} + \mathcal{O}\left(\frac{q_\perp}{P_\perp}, \frac{Q_s}{P_\perp}, \alpha_s R^2, \alpha_s^2\right)
\end{aligned}
$$

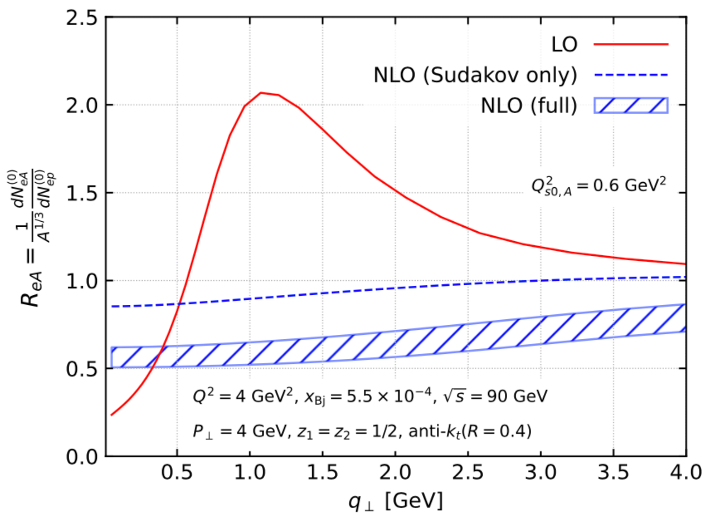
$\hat{G}^0$ and $\hat{h}^0$ respectively are unpolarized and linearly polarized WW distributions,
$\mathcal{S}$ the Sudakov soft factor resumming double+single logs in P_T/q_T

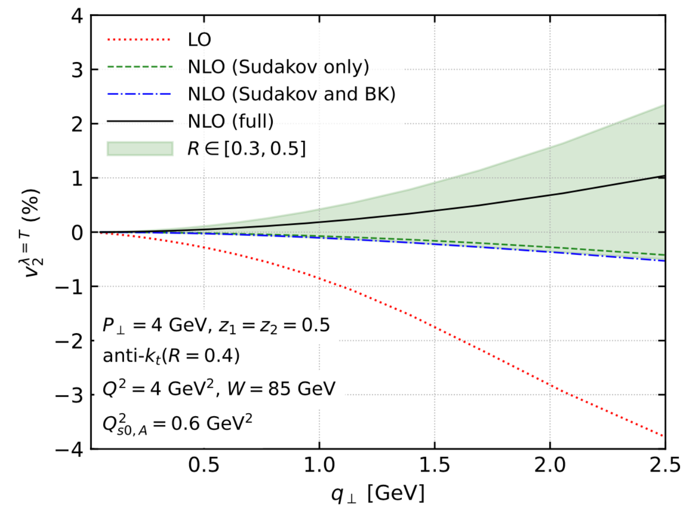
Caucal,Salazar,Schenke,Stebel,RV, PRL132 (2024)

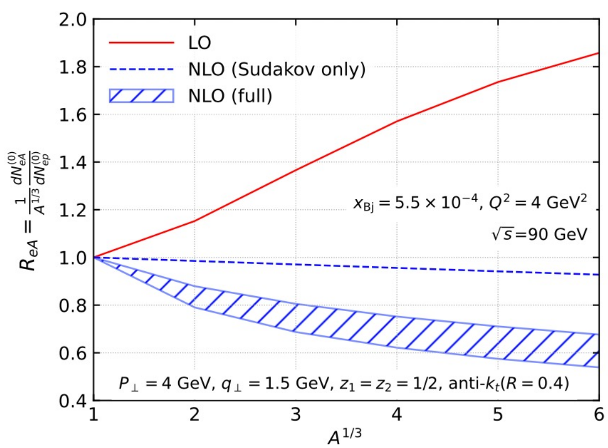
Global analyses critical to extract "universal" TMDs from p+A collisions (FoCAL @ LHC) and e+A collisions from the EIC

Large # of inclusive, semi-inclusive, exclusive and diffractive final states

Extracting the gluon Weizsäcker-Williams dist. at small x



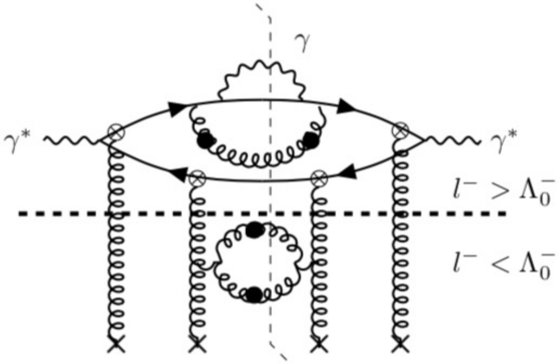




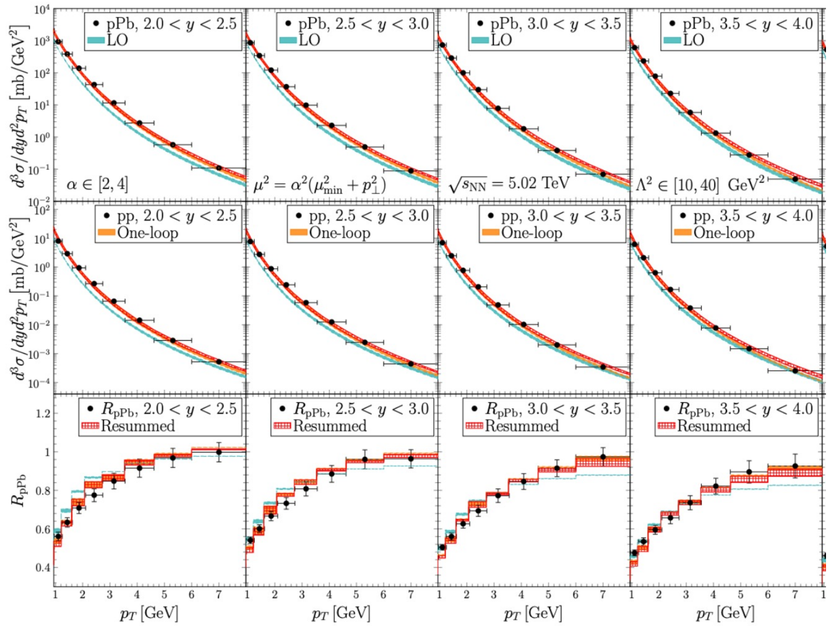
Caucal,Salazar,Schenke,Stebel,RV, PRL132 (2024)

CGC state of the art: global analysis of DIS+hadron-hadron collisions

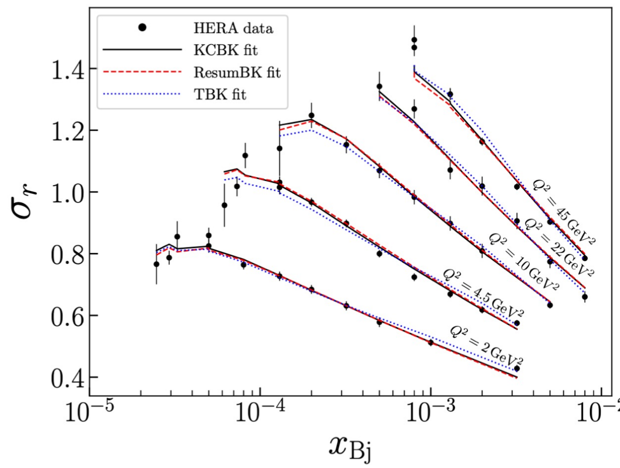
Precision CGC EFT computations



Single inclusive hadron distributions at the LHC



HERA DIS structure functions



Beuf,Hanninen,Lappi,Mantysaari, arXiv:2007.01645

Shi,Wang,Wei,Xiao, arXiv:2112.06975

SURGE DOE Topical Theory Collaboration: 22 PI’s from 16 institutions (2022-2027)

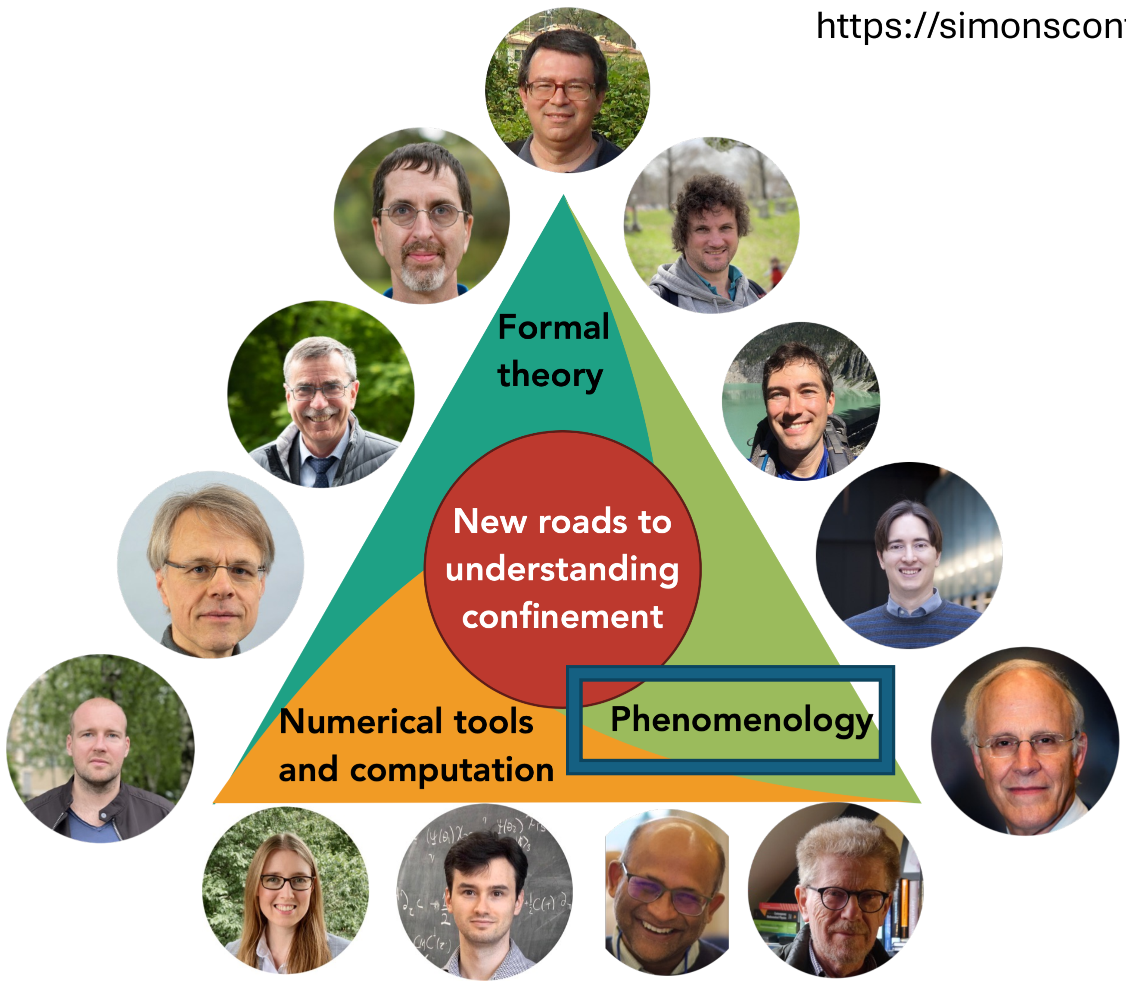
25+ published papers and 50+ on arXiv thus far

Musings in closing

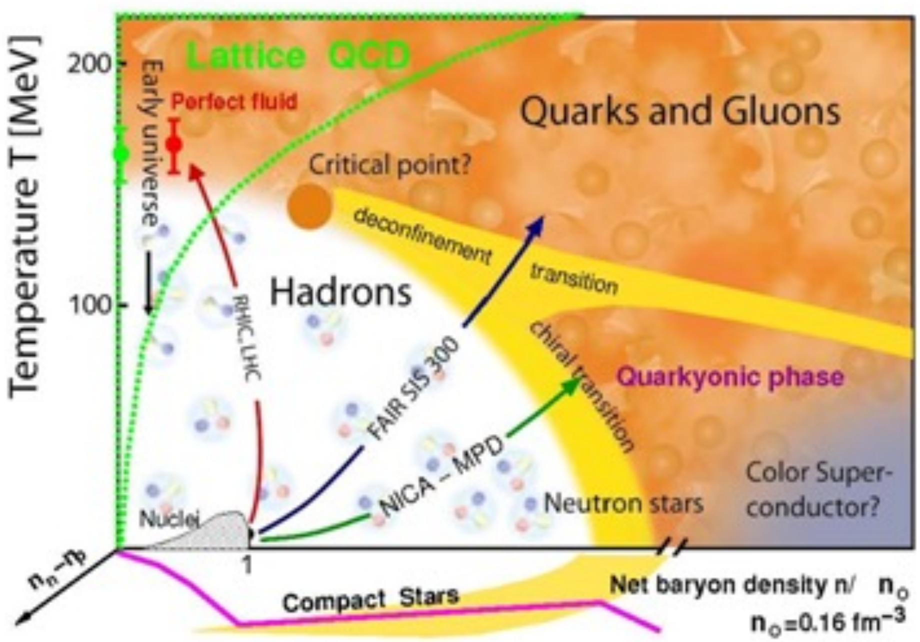
Can the buzz of wee partons provide fundamental insight into confinement?

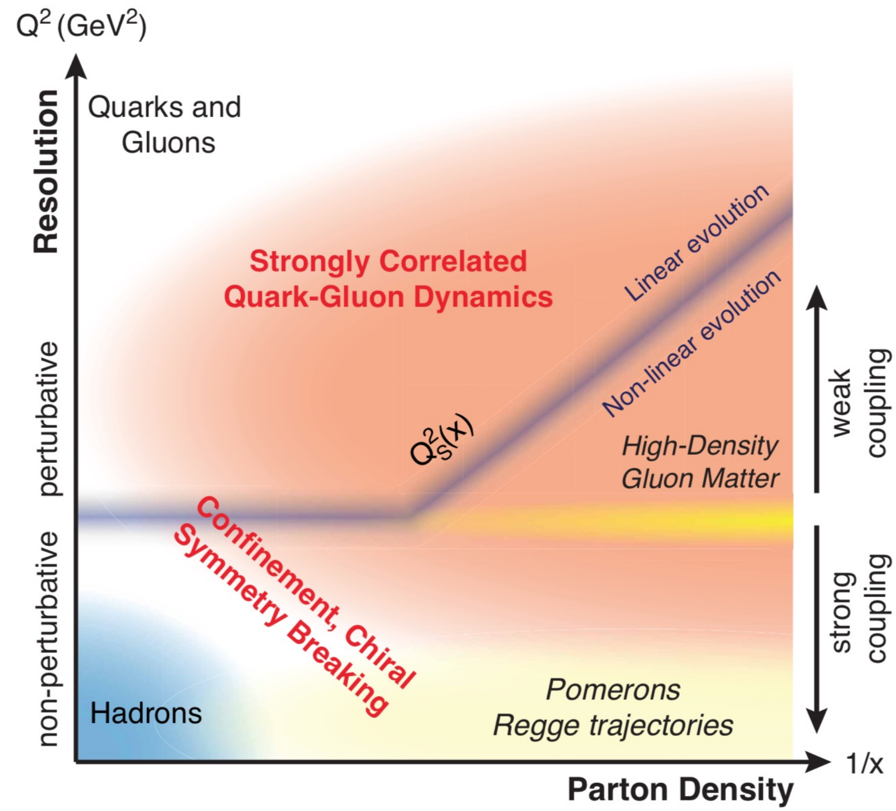
Theory effort: Simons collaboration on confinement and QCD strings

https://simonsconfinementcollaboration.org



Musings in closing





Uncovering many-body emergent phenomenon in the perfect theory is science at its finest!

Thank you for your attention!