HOT QUARKS 2025 HEFEI, CHINA

Observation of the spin-interference in Drell-Söding process in Au+Au 200 GeV collisions

Xinbai Li (for STAR Collaboration)

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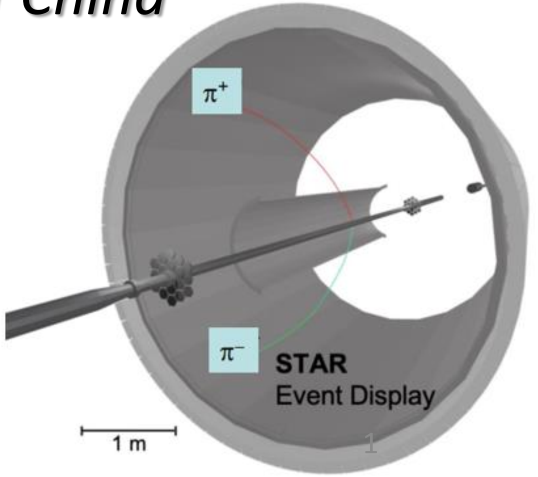
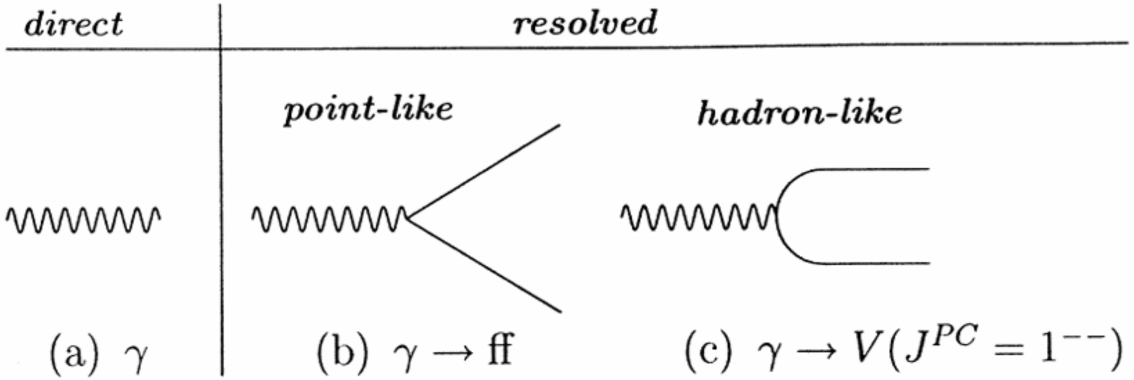
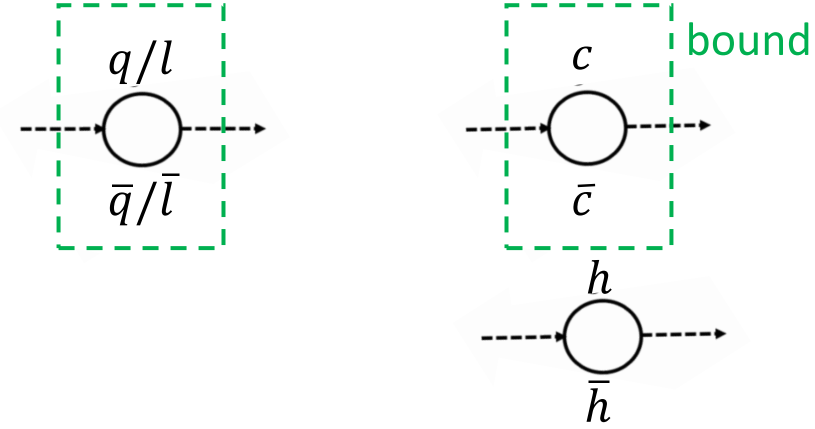
12 May 2025



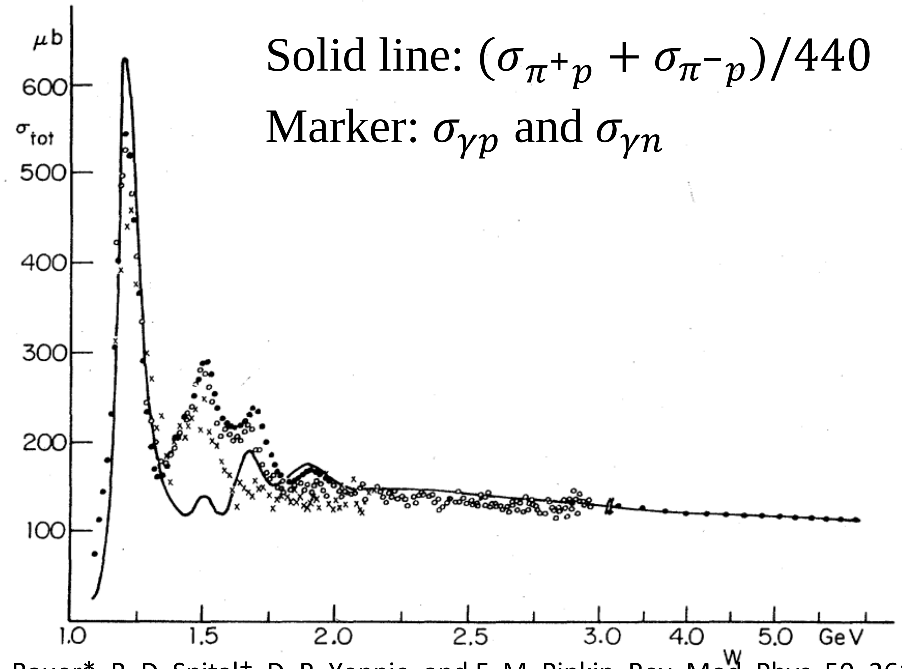
Physical Photon in HIC





Types of photon interactions in relativistic heavy-ion collisions：

- Direct photon
- Resolved photon



T. H. Bauer*, R. D. Spital†, D. R. Yennie, and F. M. Pipkin, Rev. Mod. Phys. 50, 261 (1978)

In modern physics notation, the quantum state of the electromagnetic field is written as a Fock state

$$|\gamma\rangle = C_{\text{bare}}|\gamma_{\text{bare}}\rangle + C_V|V\rangle + \ldots + C_q|q\bar{q}\rangle.$$

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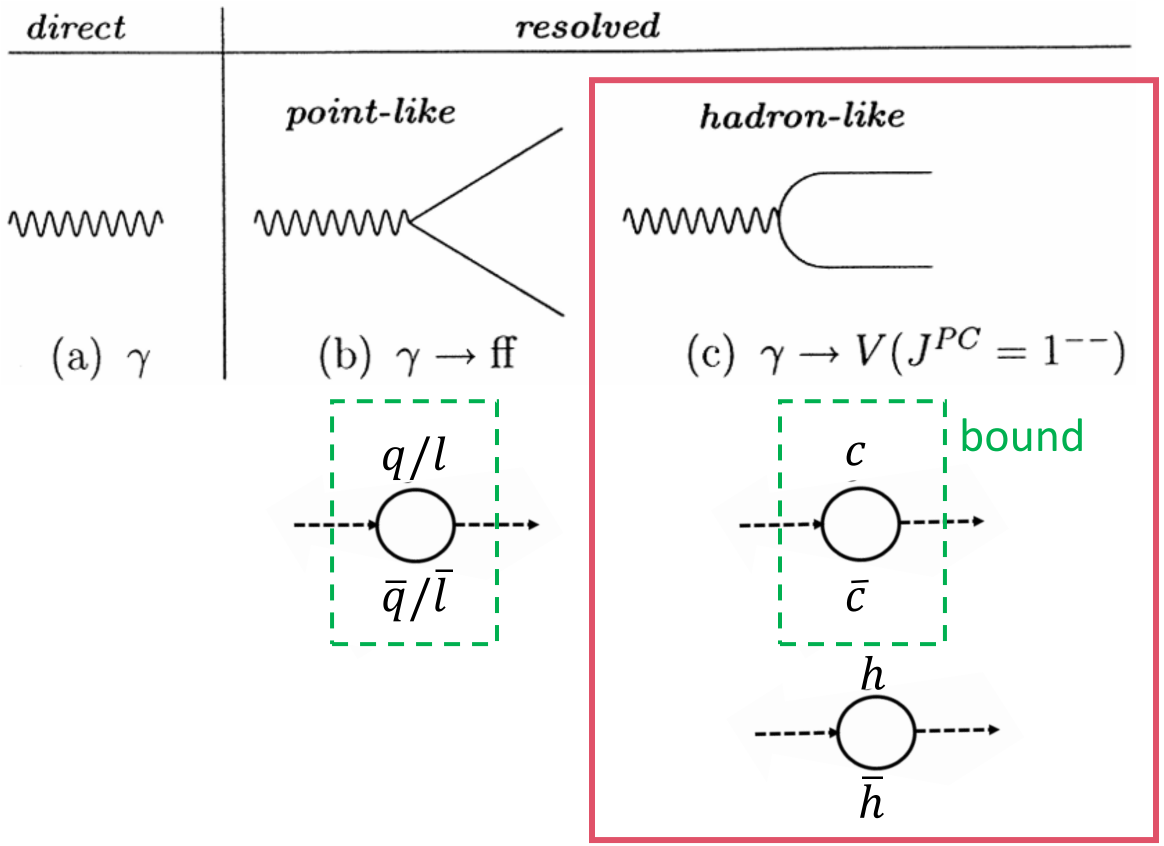

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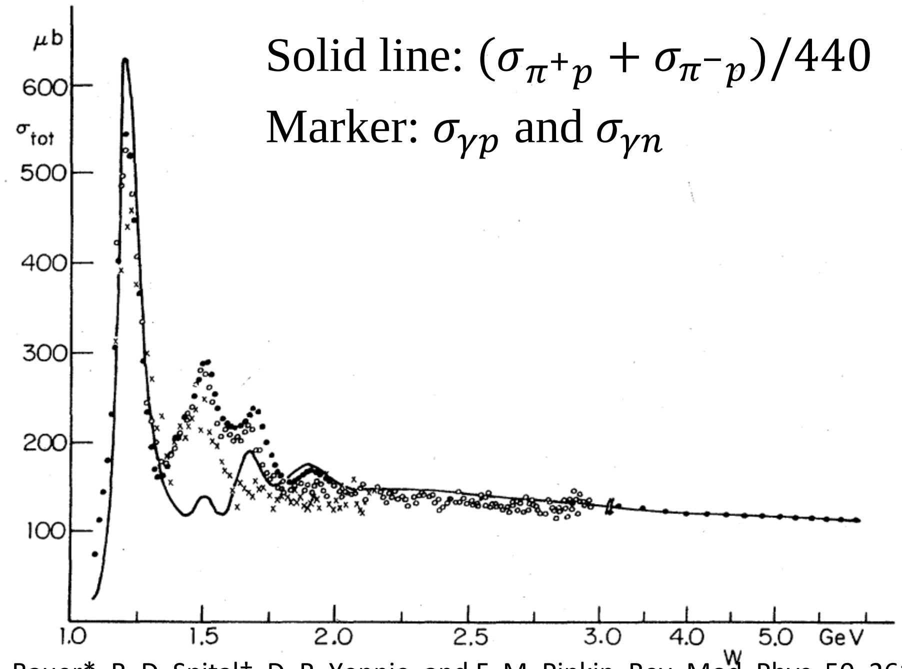

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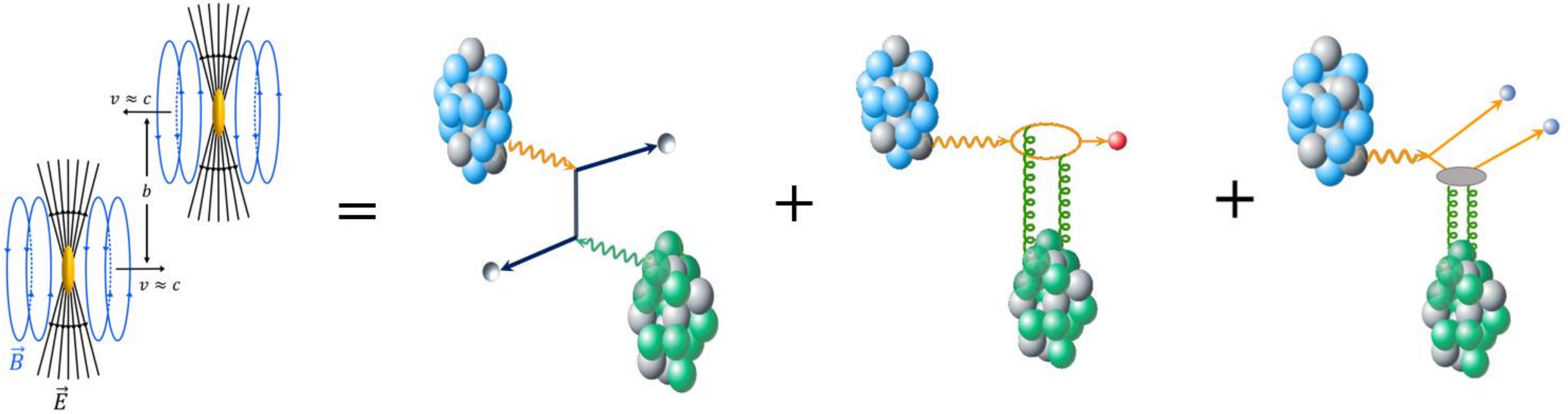
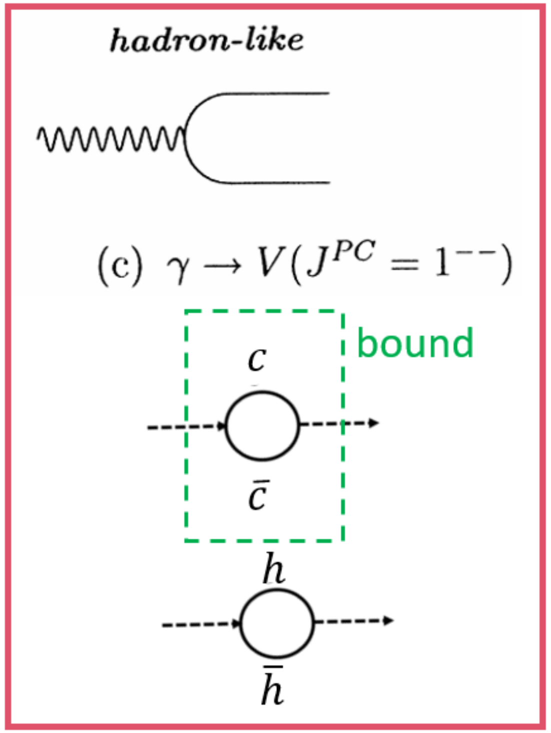
Photon induced process





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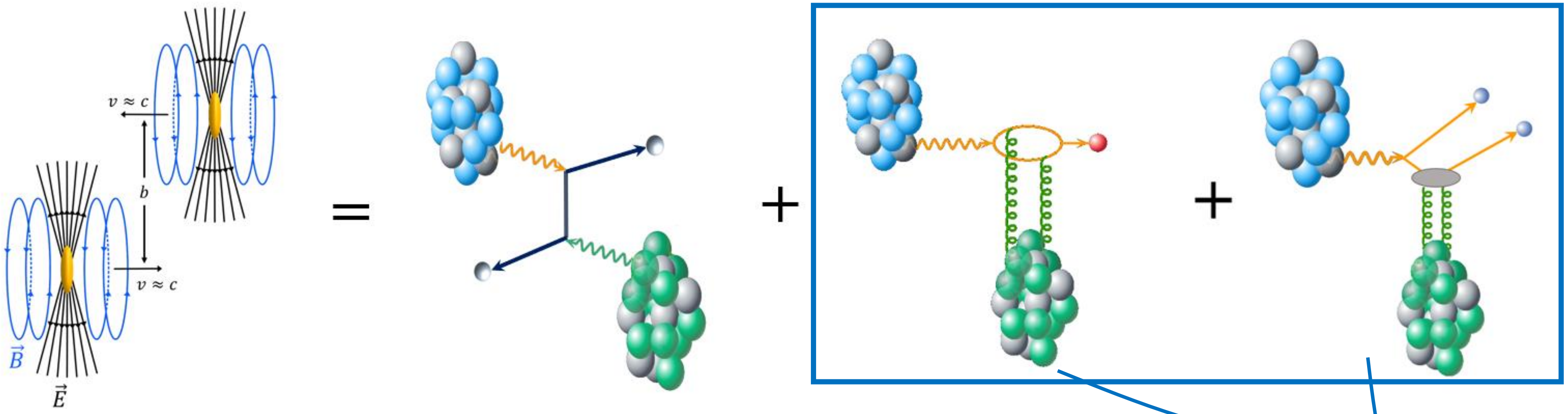
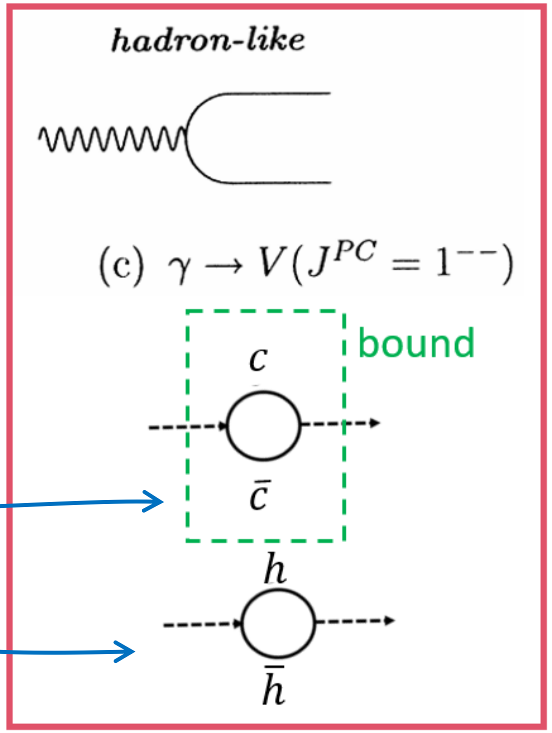




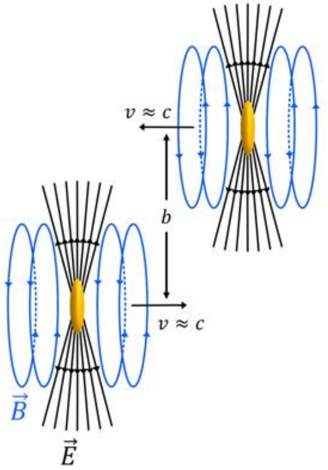
For $\rho^0 \to \pi^+\pi^-$ (resonance) and Drell-Söding $\pi^+\pi^-$ (continuum)

First generation quarks + same quantum number → interference of two processes

Söding mechanism (skewed mass shape): P. Soding Phys. Lett. 19 (1966) 702

$$\frac{d\sigma}{dM} = \left|A_{\rho^0}(M) + A_{Söding}(M)\right|^2$$

Photon induced process



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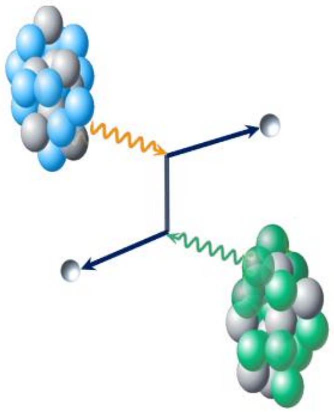

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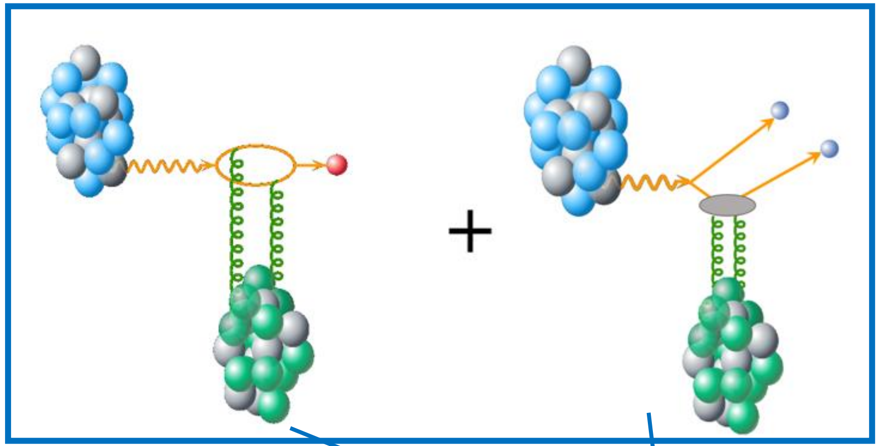

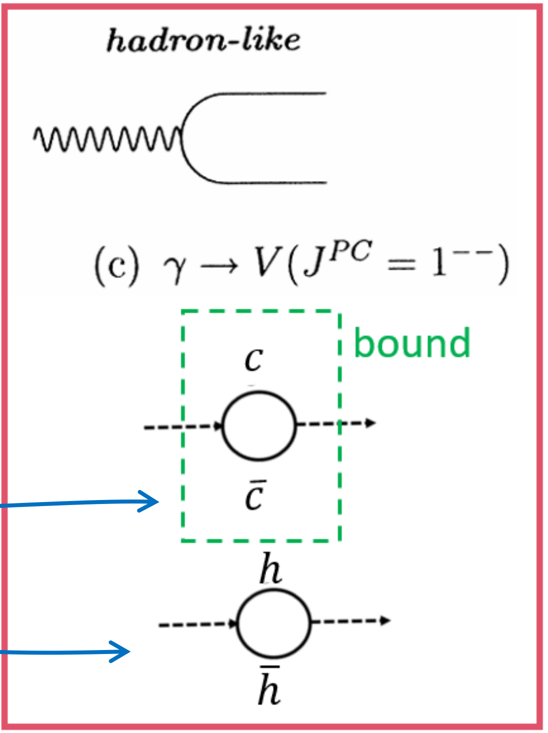

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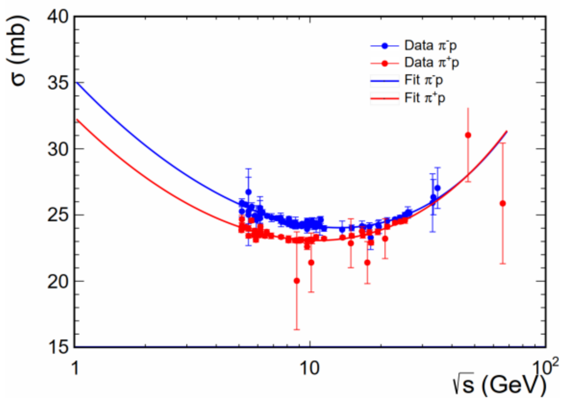
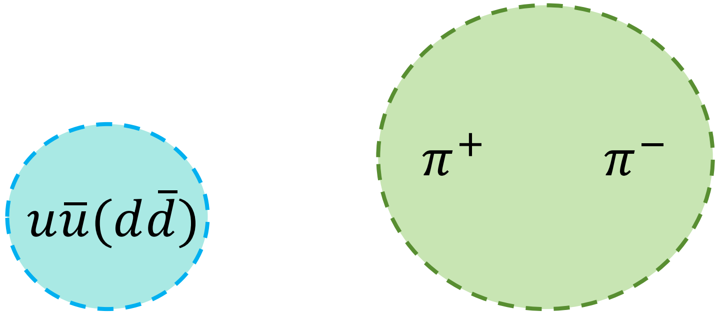
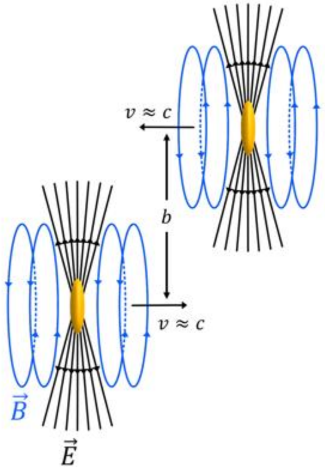
- ρ^0 has lifetime (undergo decay), S=1
- Drell-Söding $\pi^+\pi^-$ (w.o. decay), L=1, asymmetricity in $\sigma_{\pi^+p} + \sigma_{\pi^-p}$ (5%)



- Different dipole size!



Photon induced process



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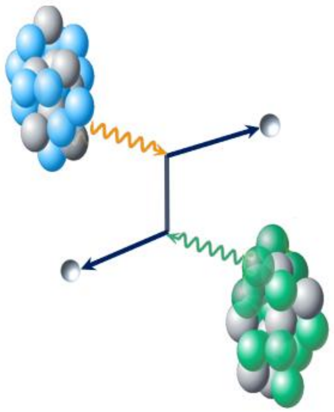

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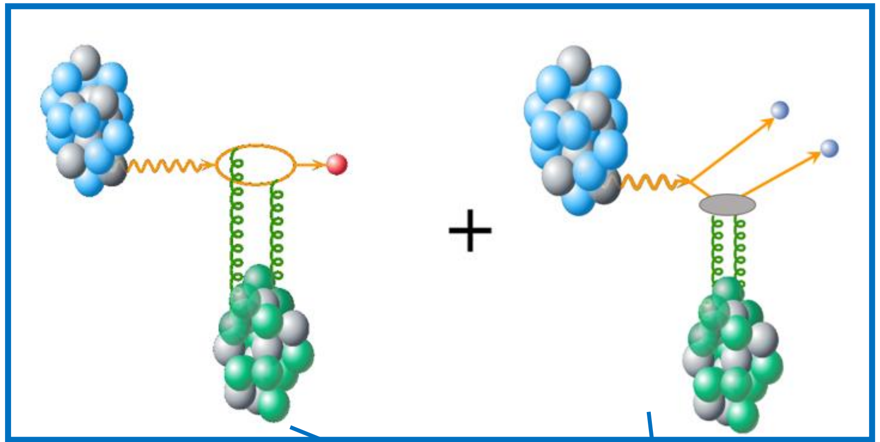

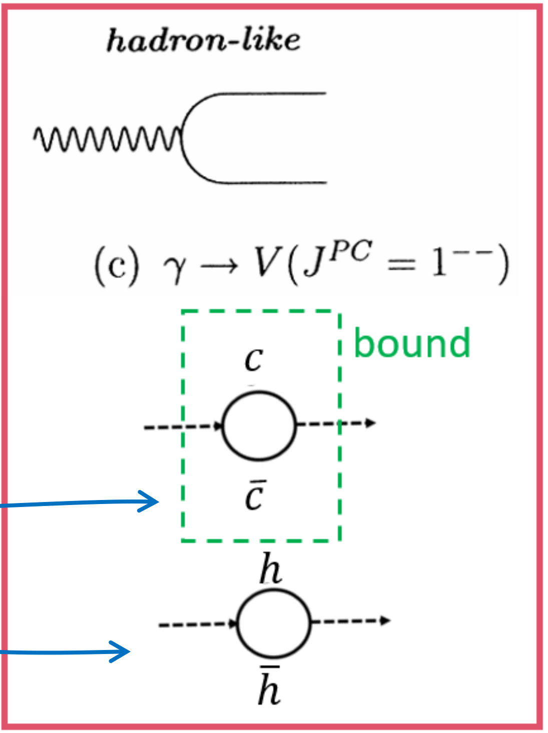

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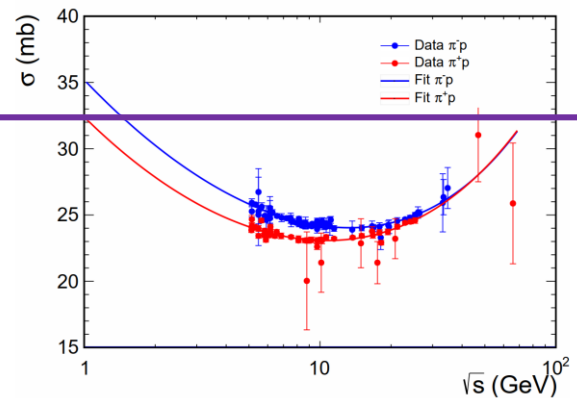

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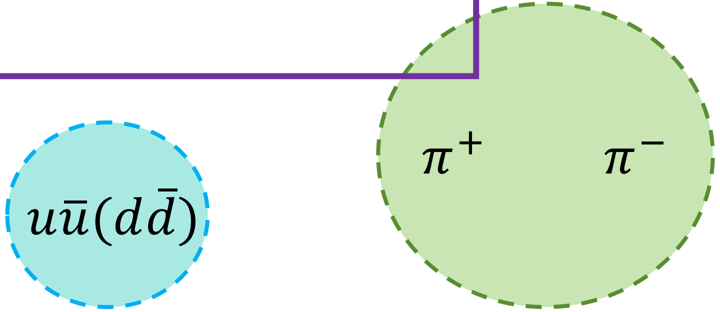
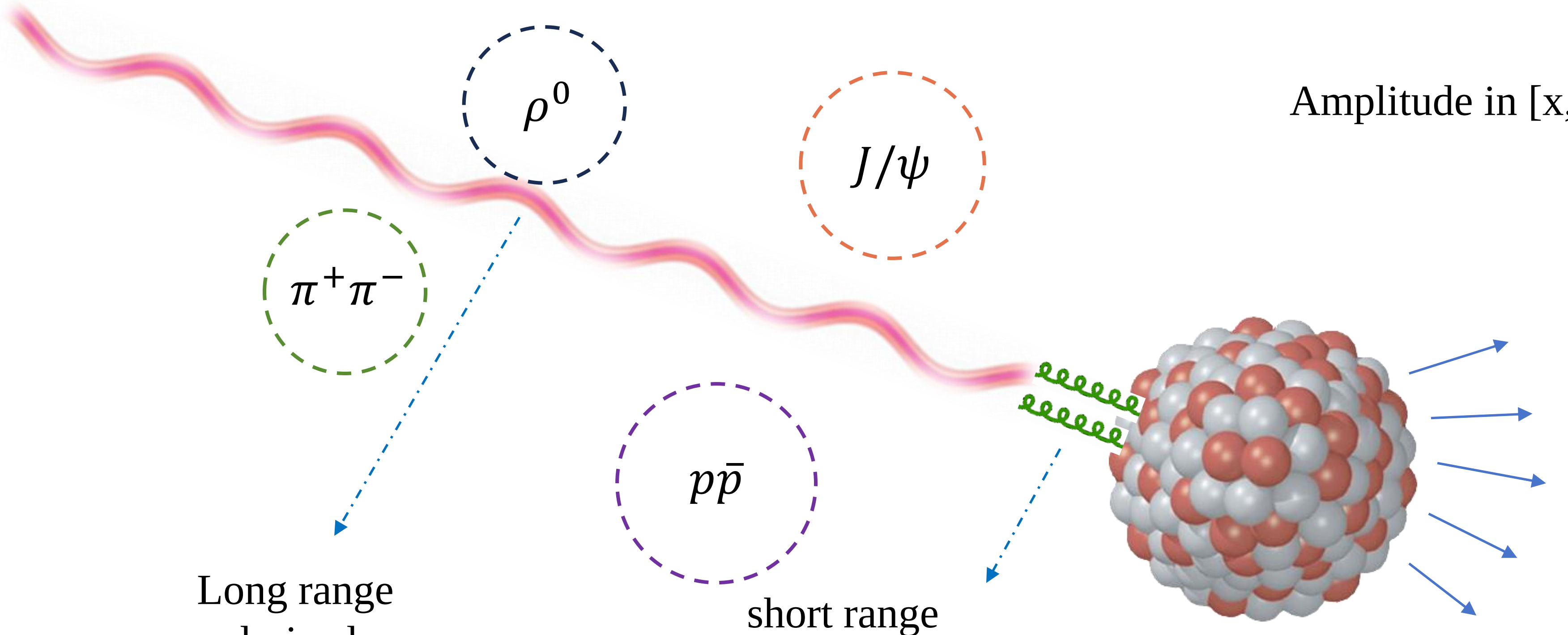


Physics opportunities

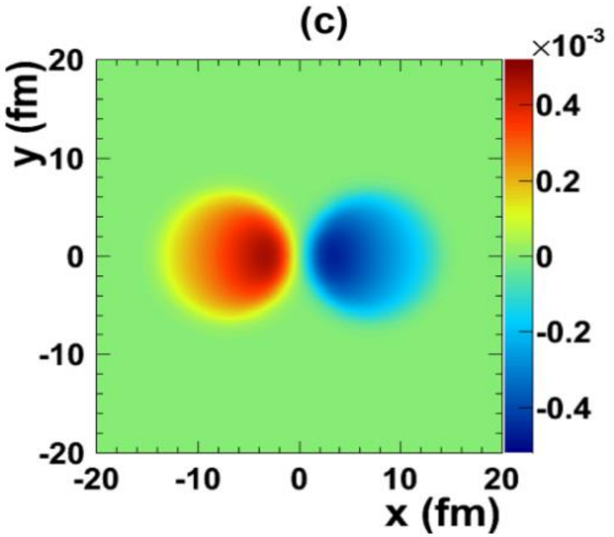
- Photon hadronic structure, gluon tomography, nuclear mass radius



Long range
polarized

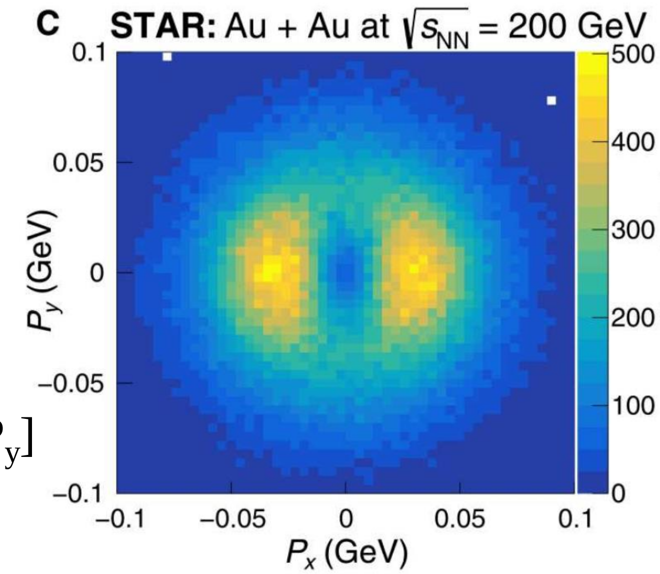
short range
(Restricted around the nucleus)

Amplitude in [x,y]



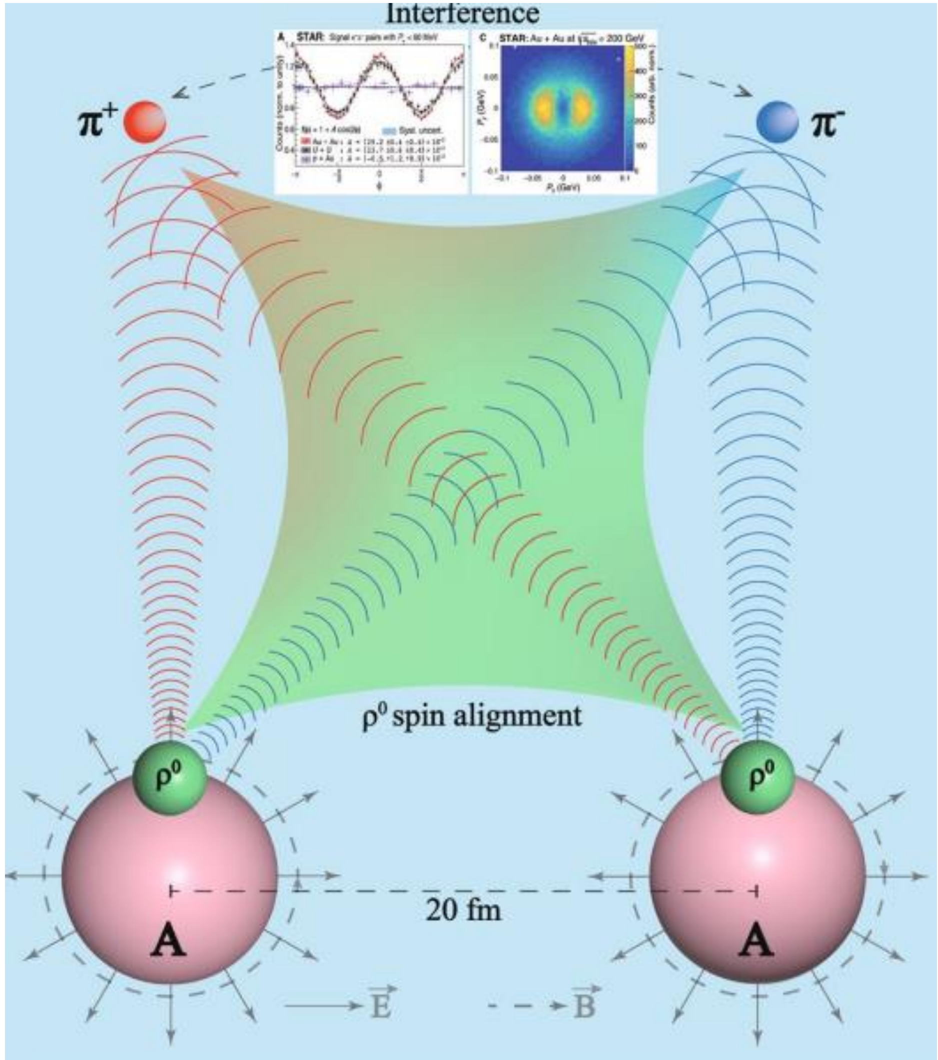
W. Zha et al., Phys. Rev. C 99, 061901(R) (2019)

Diffraction+interference in [P_x,P_y]

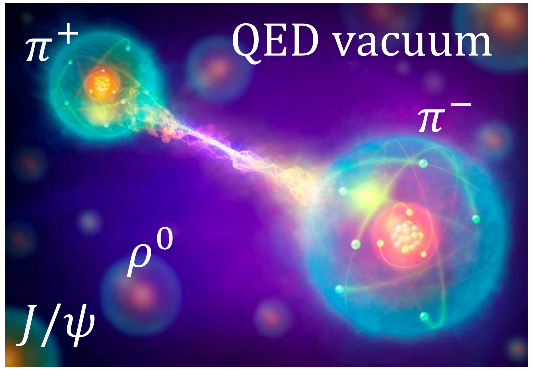


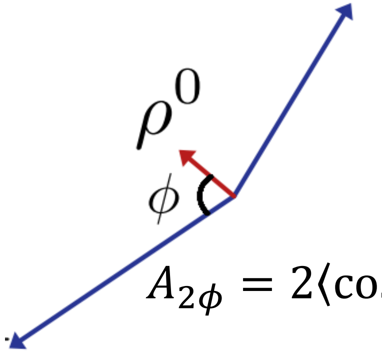
STAR collaboration, sciadv.abq3903 (2023)

Physics opportunities

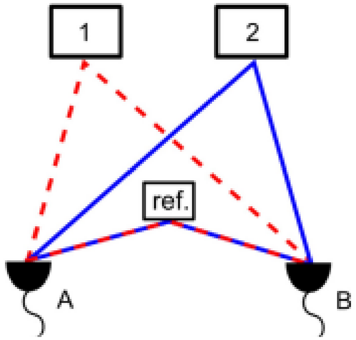


Y. Ma, Nucl. Sci. Tech. 34 (2023) 16





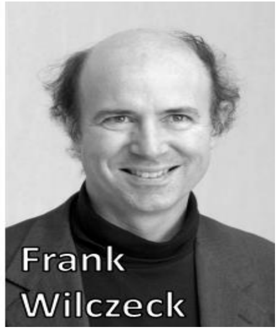
$A_{2\phi} = 2\langle\cos(2\phi)\rangle$



Entanglement Enabled Spin-Interference (EESI)

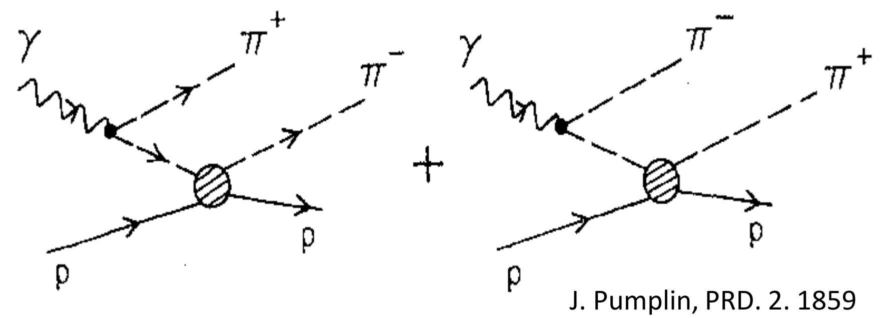
- Einstein-Podolsky-Rosen pair (angular momentum conservation)
- Nonlocal wave & not fully overlap
- Polarized decay angular distribution

$$\frac{d^2N}{d\cos\theta d\phi} = \frac{3}{8\pi}\sin^2\theta[1+\cos 2(\phi-\Phi)],$$

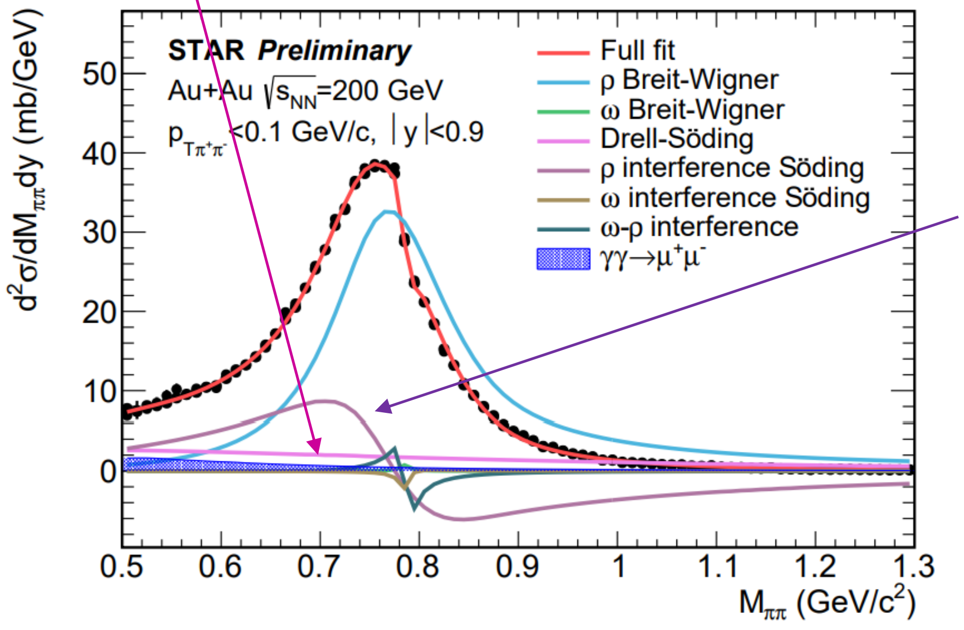


Ann. Phys. 424 (2021) 168346

Physics questions to explore



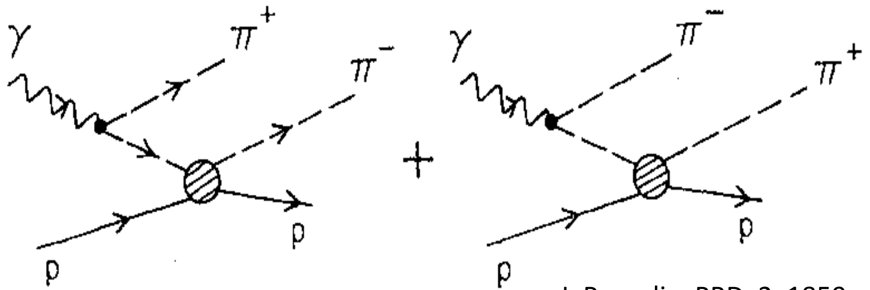
Drell-Söding process



Originally proposed to

- Produce charge π/K beam — S.D. Drell, Rev. Mod. Phys. 33 (1961) 458
- Peripheral cross section — S.D.Drell, Phys. Rev. Letters 5 (1960} 278
- Mass shift of ρ^0 — P. Soding Phys. Lett. 19 (1966) 702
- …
- Precise measurement of Drell-Söding process
- How to precisely measure such small contribution to the total exclusive $\pi^+\pi^-$ production?

Physics questions to explore



J. Pumplin, PRD. 2. 1859

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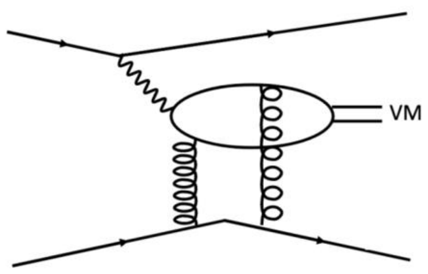
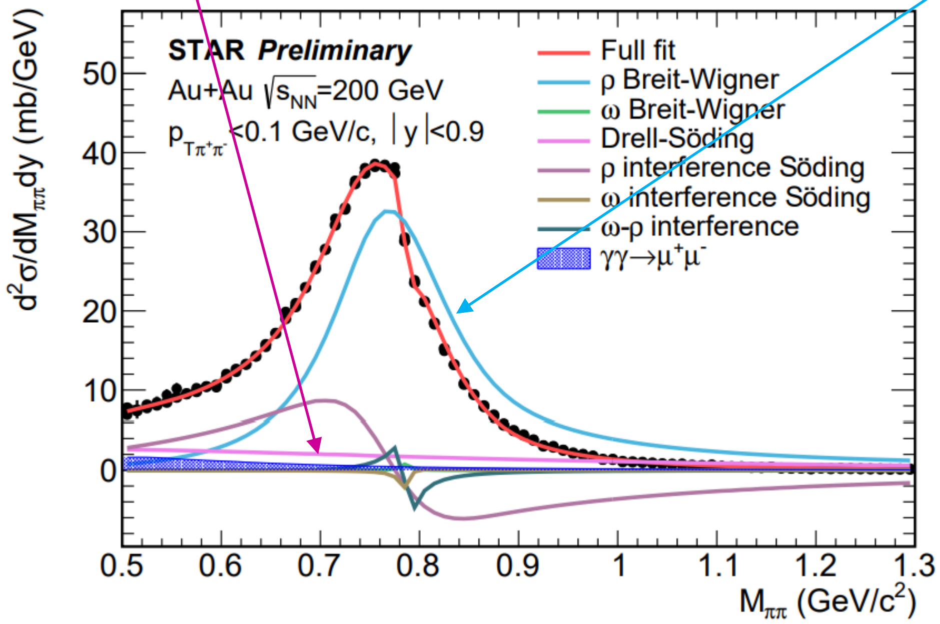


ρ^0 production



- ρ^0 finite lifetime (undergo decay), S=1
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  asymmetricity in $\sigma_{\pi^+p} + \sigma_{\pi^-p}$ (5%)

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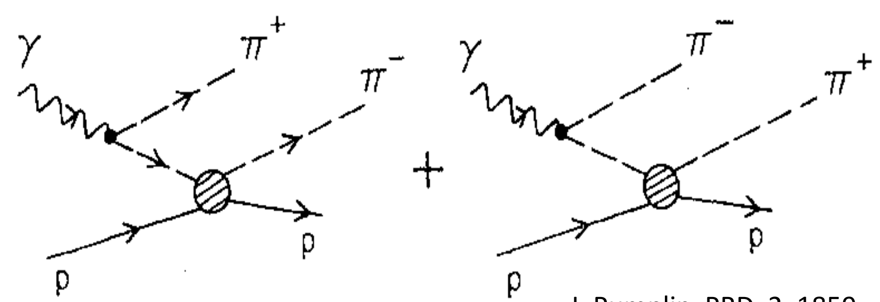

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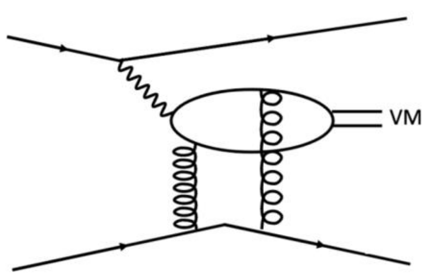
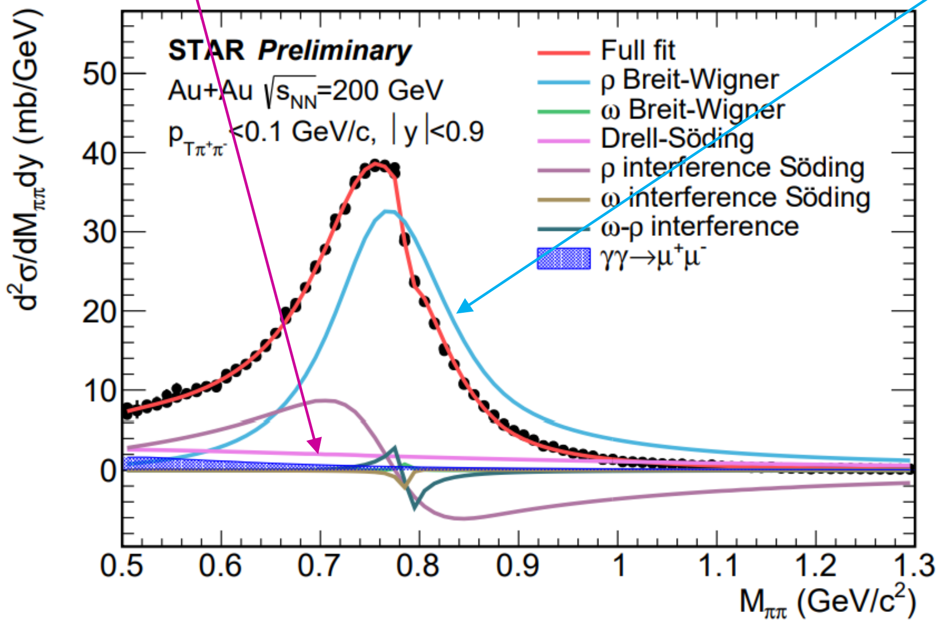


ρ^0 production



Through comparison between two processes

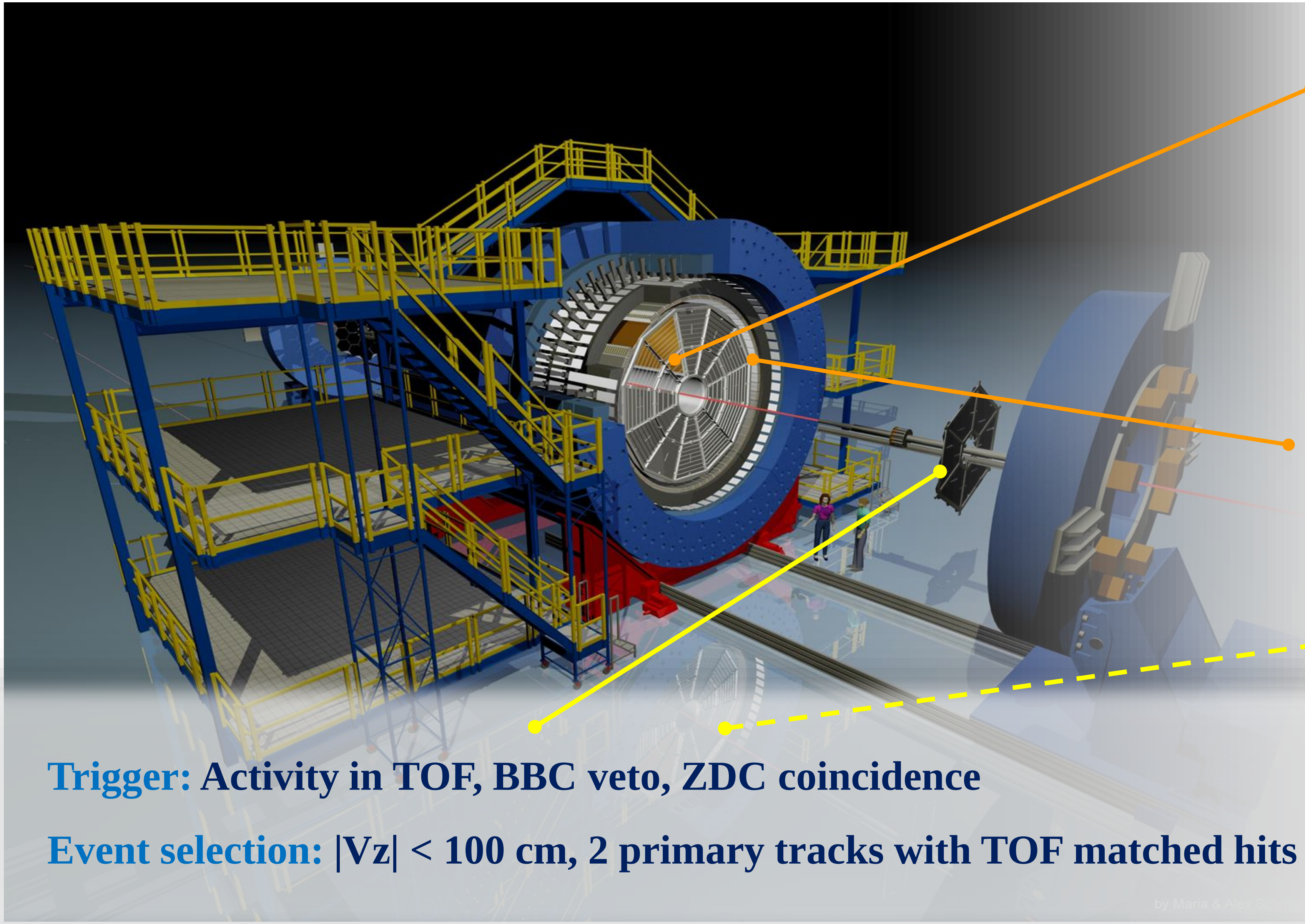
- Does ρ^0 and Drell-Söding via photon nuclear interaction have the same p_T distribution?
- Does the EESI exist in the Drell-Söding process? If yes, what's the difference (coherence loss, entanglement)?

- ρ^0 finite lifetime (undergo decay), S=1
- Drell-Söding $\pi^+\pi^-$ (w.o. decay), L=1,

asymmetricity in $\sigma_{\pi^+p} + \sigma_{\pi^-p}$ (5%)

Different dipole size!

The Solenoidal Tracker At RHIC



TPC: track and vertex reconstruction; particle identification. (full ϕ coverage, $|\eta|<1$)

TOF: fast response detector (pile-up suppression)

Trigger: Activity in TOF, BBC veto, ZDC coincidence

Event selection: $|Vz| < 100$ cm, 2 primary tracks with TOF matched hits

Algorithm for signal extraction

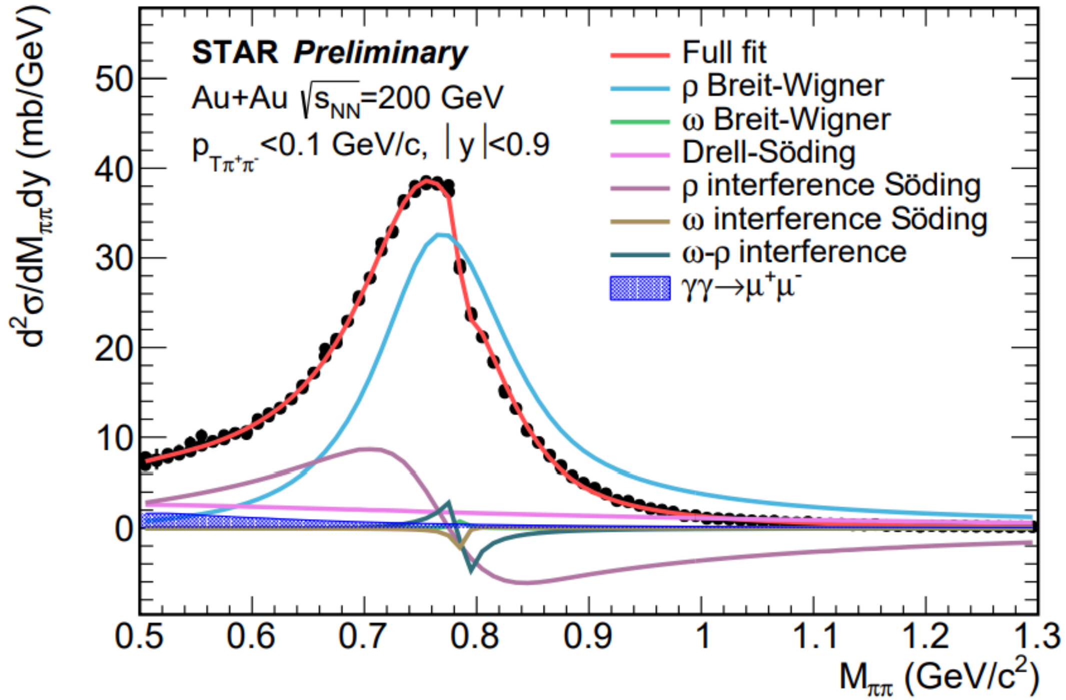
$$\frac{d\sigma}{dM_{\pi^+\pi^-}} = \left| A_\rho \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + i M_\rho \Gamma_\rho} f_{fluxcorr}(M_{\pi\pi}) + B f_{Söding}(M_{\pi\pi}) + C_\omega e^{i\phi_\omega} \frac{\sqrt{M_{\pi\pi} M_\omega \Gamma_{\omega\to\pi\pi}}}{M_{\pi\pi}^2 - M_\omega^2 + i M_\omega \Gamma_\omega} \right|^2 + f_{dimuon} + f_{background}$$

$$\Gamma_\rho = \Gamma_0 \frac{M_\rho}{M_{\pi\pi}} \left(\frac{M_{\pi\pi}^2 - 4m_\pi^2}{M_\rho^2 - 4m_\pi^2} \right)^{3/2}, \qquad \Gamma_\omega = \Gamma_0 \frac{M_\omega}{M_{\pi\pi}} \left(\frac{M_{\pi\pi}^2 - 9m_\pi^2}{M_\omega^2 - 9m_\pi^2} \right)^{3/2}, \qquad \Gamma_{\omega\to\pi\pi} = \mathrm{Br}(\omega \to \pi\pi)\Gamma_0 \frac{M_\omega}{M_{\pi\pi}} \left(\frac{M_{\pi\pi}^2 - 4m_\pi^2}{M_\omega^2 - 4m_\pi^2} \right)^{3/2}$$

Parameters:

A_ρ : amplitude for ρ
M_ρ : mass of ρ
B : scale for Söding
C_ω/A_ρ: ratio of amp.
M_ω : mass of ω
$\Gamma_{0\omega}$: mass width of ω
ϕ_ω : mixing phase angle
b_1 : polynomial $b_2(M_{\pi\pi} - b_1)$
b_2 : (remain background slope (negligible))

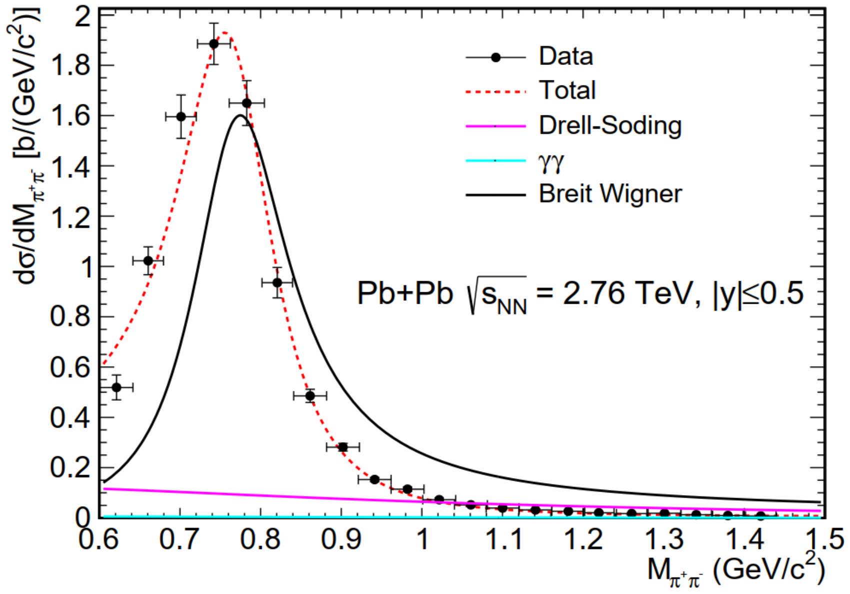
Fix to reduce the no. of free parameters



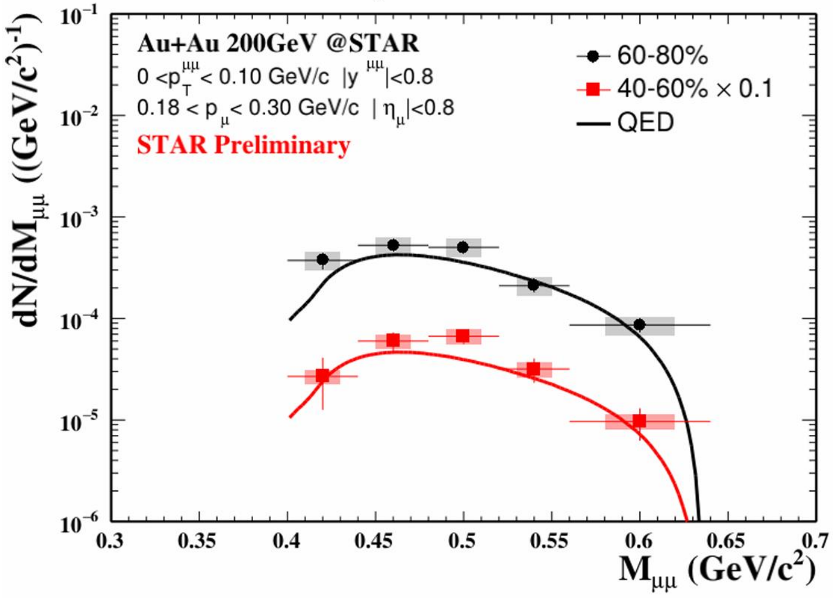
Theoretical Input

$$\frac{d\sigma}{dM_{\pi^+\pi^-}} = \left| A_\rho \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + i M_\rho \Gamma_\rho} f_{fluxcorr}(M_{\pi\pi}) + B f_{Söding}(M_{\pi\pi}) + C_\omega e^{i\phi_\omega} \frac{\sqrt{M_{\pi\pi} M_\omega \Gamma_{\omega\to\pi\pi}}}{M_{\pi\pi}^2 - M_\omega^2 + i M_\omega \Gamma_\omega} \right|^2 + f_{dimuon} + f_{background}$$

$f_{Söding}(M_{\pi\pi})$ S.R. Klein et al., Comp. Phys. Comm. 212 (2017) 258
J. Pumplin, PRD. 2. 1859



f_{dimuon} W. Zha et al., Phys. Lett. B 800 (2020) 135089



Leverage the validated theoretical input (use only the shape for Söding & consider the uncertainty due to model dependence with HERA $f_{Söding}$ parametrised function)

H1 collaboration, Eur. Phys. J. C 80 (2020) 1189

$$A_{nr} = \frac{f_{nr}}{(m_{\pi\pi}^2 - 4m_\pi^2 + \Lambda_{nr}^2)^{\delta_{nr}}}$$

(f_{nr}, Λ_{nr}, δ_{nr} are free parameters)

Analysis Flow

$$\frac{d^3\sigma}{dp_T dM d\Delta\phi} = \frac{N(p_T, M, \Delta\phi)}{\varepsilon_{\text{trig}}\,\text{corr}(p_T, M, \Delta\phi) L \Delta p_T \Delta M \Delta(\Delta\phi)}.$$

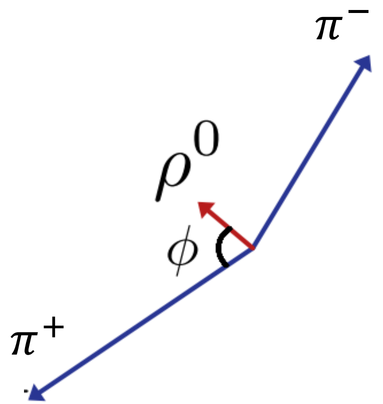
Use 3 year run data for Au+Au 200 GeV, over 1 million exclusive $\pi^+\pi^-$ events

3-d correction on pair $(p_T, M, \Delta\phi)$

Mass fits for different pair p_T → p_T differential cross section

Mass fits for different pair $p_T - \Delta\phi$ → Recon $A_{2\phi}$ → $A_{2\phi}$ as a function of pair p_T

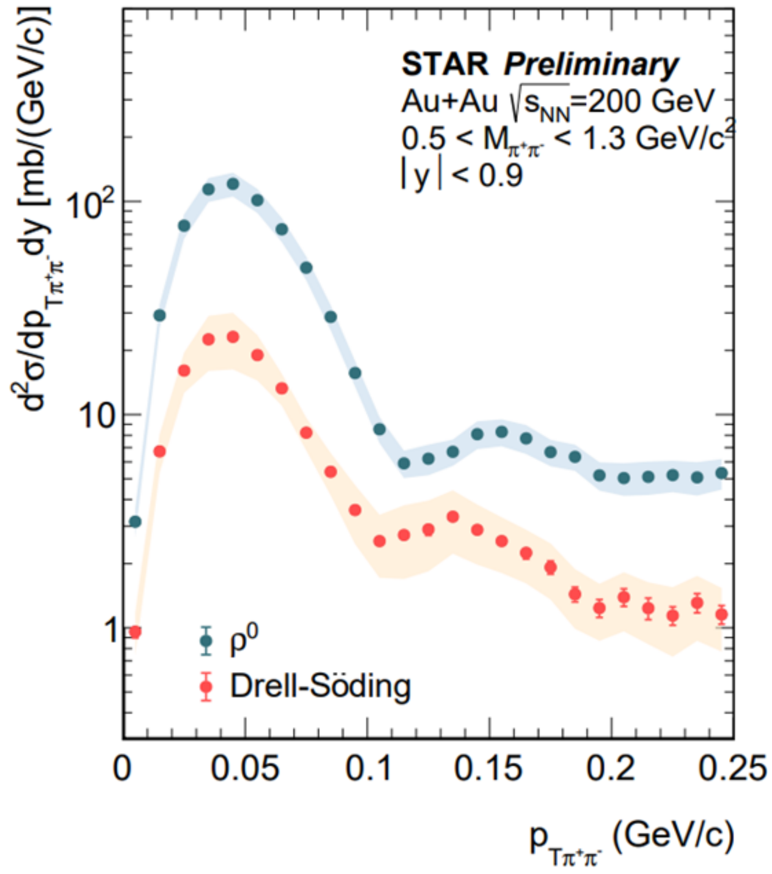
Mass fits for different pair $\Delta\phi$ → Recon $A_{2\phi}$ → $A_{2\phi}$ as a function of invariant mass

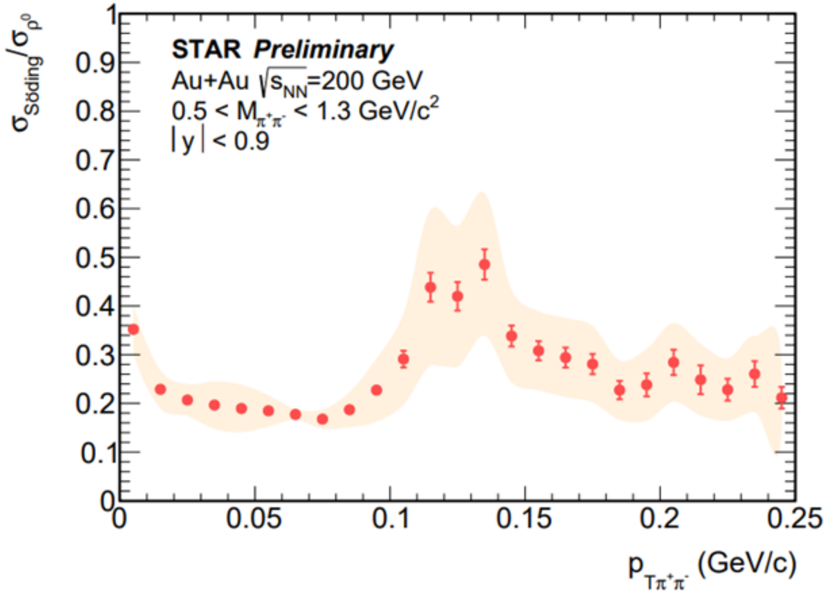


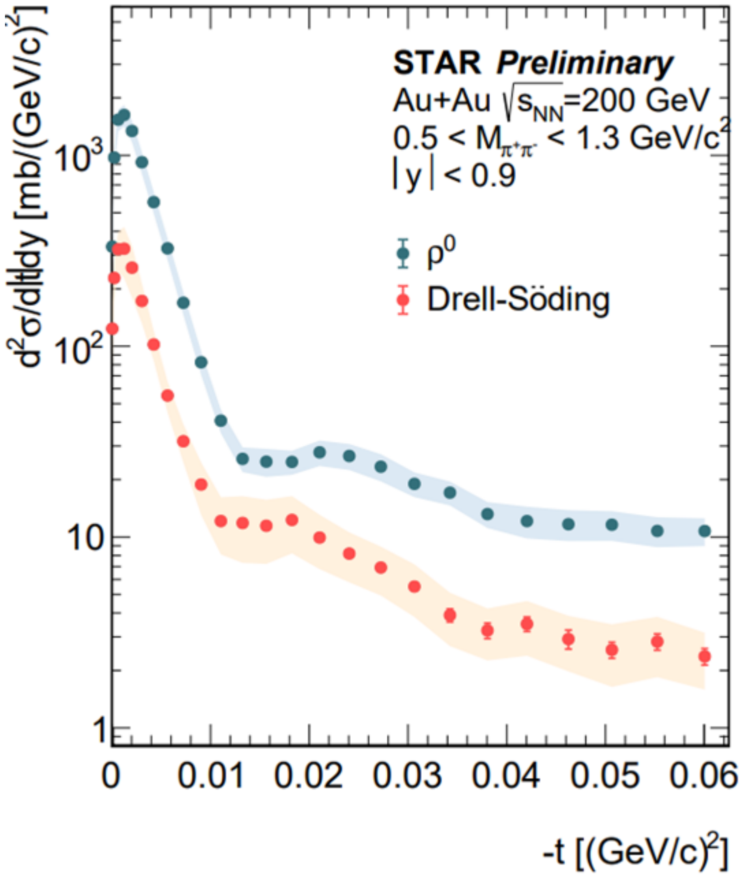
$A_{2\phi} = 2\langle\cos(2\phi)\rangle$

Differential cross section

- Drell-Söding has a softer p_T spectrum compared to ρ^0 production
- Difference from 1) different $M_{\pi\pi}$ spectrum 2) larger dipole size $(p_T \cdot r \geq \hbar)$

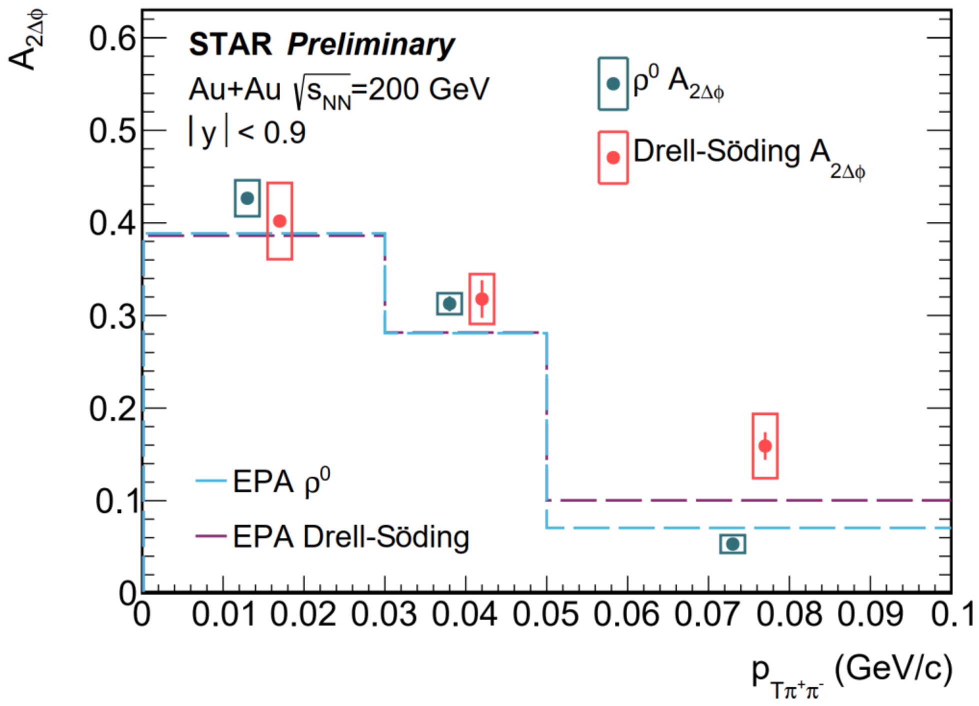


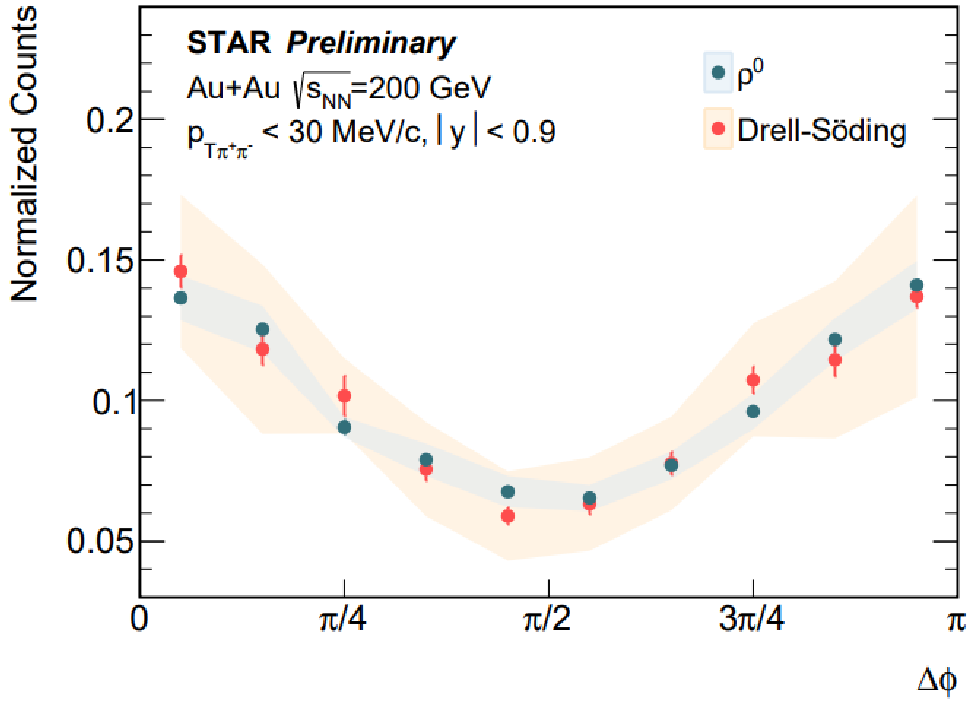




Spin-Interference

- ✓ Similar $A_{2\Delta\phi}$ for ρ^0 and Drell-Söding at low p_T $(p_T \cdot x \geq \hbar)$
- ✓ An enhancement of $A_{2\Delta\phi}$ of Drell-Söding w.r.t ρ^0 for 0.05<p_T<0.1 GeV/c





Summary

- ✓ First measurement of pair p_T and spin-interference of Drell-Söding process in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
- ✓ A softer pair p_T is observed for Drell-Söding compared to ρ^0 production
- ✓ An enhancement of $A_{2\Delta\phi}$ of Drell-Söding w.r.t ρ^0 for 0.05<p_T<0.1 GeV/c
- ✓ These results provide new insights into the interplay between spin-interference and photon-nuclear interactions in ultraperipheral heavy-ion collisions

Thank you!

Backup

Any questions and suggestions are welcome

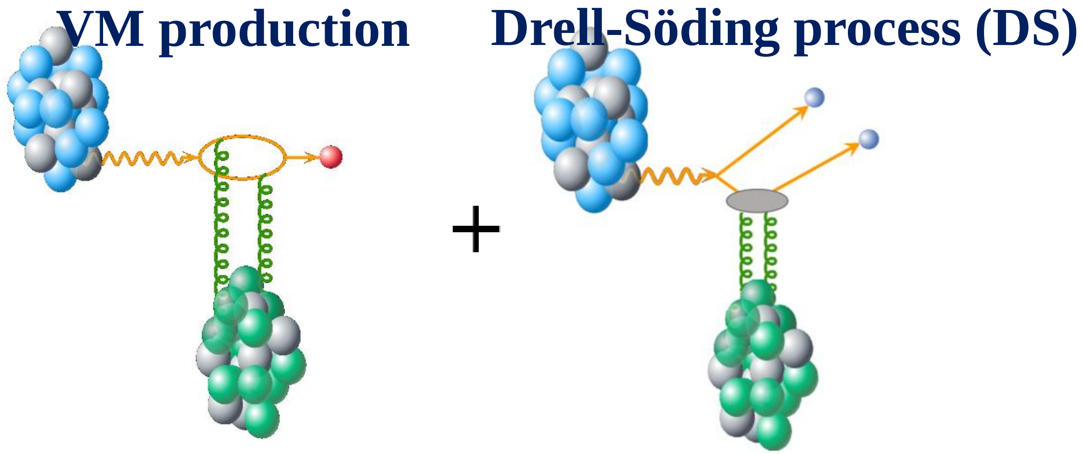
In the meeting or after
By email – xinbai@mail.ustc.edu.cn

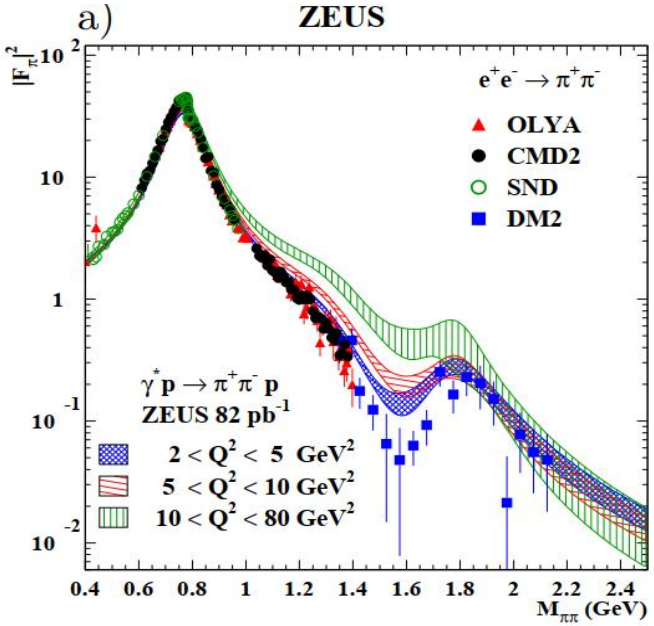
Exclusive $\pi^+\pi^-$ production

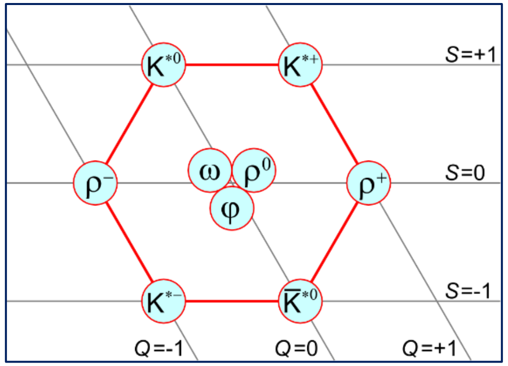
- ☐ **Multiple phenomenological generators in the market:**

SuperChic, gamma-UPC, STARLight, Sartre …

- ☐ **However, no individual Drell-Söding channel**





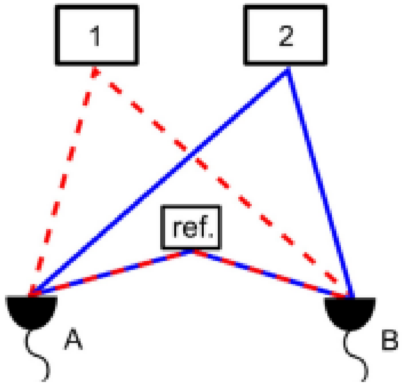


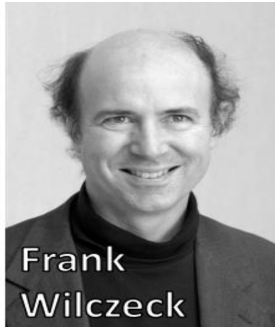
- ☐ **Mass mixing of vector mesons (VMs)**
- ☐ **Well understood in e^-e^+ (no Söding mechanism)**

$$F_\pi = \frac{BW_\rho(M_{\pi\pi}) + \beta BW_{\rho'}(M_{\pi\pi}) + \gamma BW_{\rho''}(M_{\pi\pi})}{1+\beta+\gamma}.$$

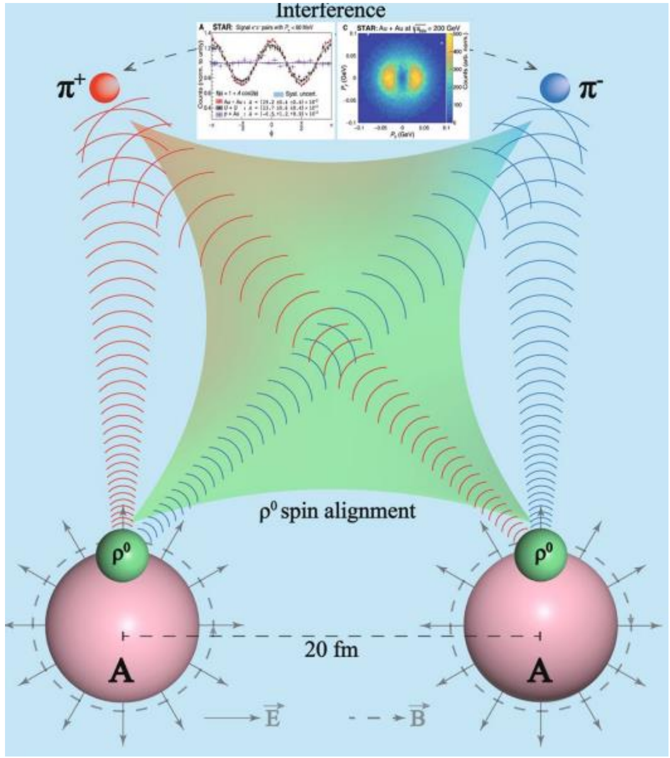
Entanglement enabled interference

- Distinguishable non-local final state $\pi^+\pi^-$
- Interference between waves with different wave frequencies —— Entanglement
- Entanglement Enabled Spin Interference (EESI)



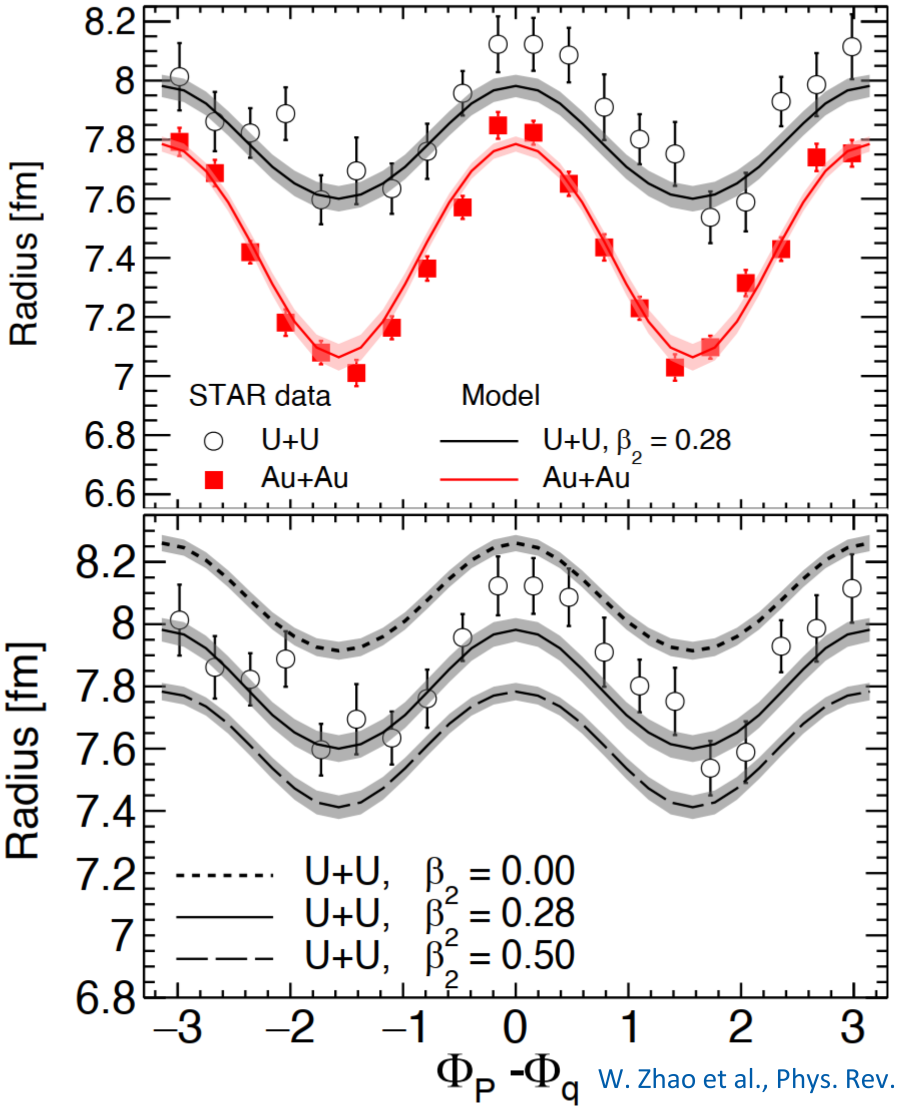


J. Cotler, F. Wilczek, V. Borish, Ann. Phys. 424 168346 (2021)



Y. Ma, Nucl. Sci. Tech. 34 16 (2023)

Image nuclei



W. Zhao et al., Phys. Rev. C. 109 024908 (2024)

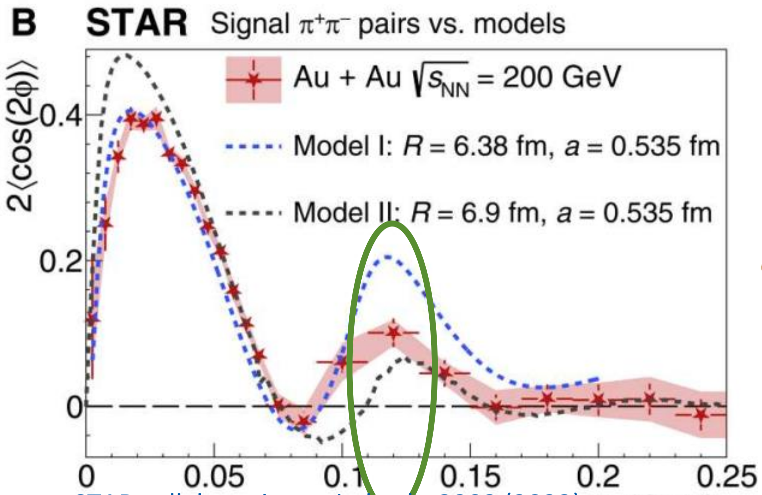
- **Sensitive to nuclear geometry**
- **Indicate one solution to the 20-year puzzle of unreasonably large nuclear radii extracted from photonuclear A+A interactions**

Table 1. Results of the extracted radii from various methods and intermediate steps.

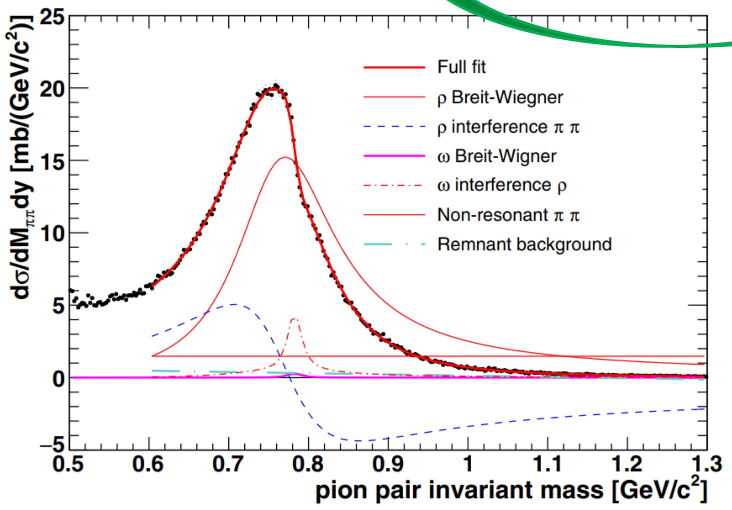
	$R_{inclusive}$ (fm)	$R(\phi = 0)$ (fm)	$R(\phi = \pm\pi/2)$ (fm)	Fitted R_0 (fm) (Eq. 4)	Fitted R_0 (fm) (Eq. 10)	Final (fm)
Au	7.47 ± 0.02	7.86 ± 0.03	7.15 ± 0.03	6.62 ± 0.03	6.72 ± 0.02	6.53 ± 0.03
U	7.98 ± 0.03	8.12 ± 0.06	7.60 ± 0.06	7.37 ± 0.07	7.37 ± 0.03	7.29 ± 0.06

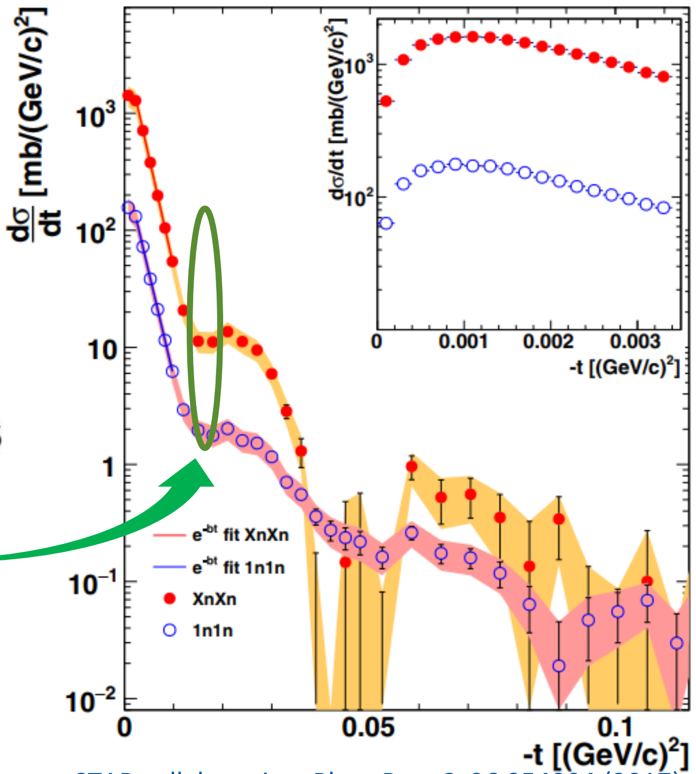
STAR collaboration, sciadv.abq3903 (2023)

What we have and where we are going



STAR collaboration, sciadv.abq3903 (2023)





STAR collaboration, Phys. Rev. C. 96 054904 (2017)

- Spin interference mostly performs in the transverse plane
- Mass dependence? (wide resonance)
- Separate the ρ^0 and Drell-Söding production
- Spin interference dynamics measurement for ρ^0 and Drell-Söding

Acceptance & efficiency correction

$$\frac{d^3\sigma}{dp_T dM d\Delta\phi} = \frac{N(p_T, M, \Delta\phi)}{\varepsilon_{BBCveto} * \varepsilon_{XnXn} * \varepsilon_{tofmult} * \varepsilon_{vzcut} * \varepsilon_{vtxalgo} * \varepsilon_{vtxloss} * Acc * \varepsilon_{TPC} * \varepsilon_{TOF} * \varepsilon_{PID} * Lumi * dphase}$$

$$= \frac{N(p_T, M, \Delta\phi)}{\varepsilon_{trigger} * \varepsilon_{vtx} * Acc * \varepsilon_{TPC} * \varepsilon_{TOF} * \varepsilon_{PID} * Lumi * dphase}$$

Same for $\frac{d^3\sigma}{dp_T dM dy}$

$\varepsilon_{trigger}$ from ZDCmonitor trigger data
ε_{vtx} from event starsim sample
ε_{vz} from ZDCdt vs TPCVz deconvolution
Acc from monte carlo simulation
ε_{TPC} from particle gun starsim sample
ε_{TOF} from mini-bias trigger data-driven
ε_{PID} from upc-main trigger data-driven

Trigger Eff	tofMult & bbc veto	ZDCmax	Vz cut
Run10	0.901	0.391	0.864
Run11	0.906	0.371	0.905
Run14high	0.797	0.571	0.833
Run14low	0.788	0.599	0.816
Run14mid	0.767	0.593	0.793

Background estimation

Contamination from $\gamma\gamma$ fusion: mainly $\gamma\gamma \to \mu^+\mu^-$

$$\hat{M} = -ie^2 \int \frac{d^4q_1}{(2\pi)^4} A^{(1)}(q_1) \frac{\not{p}_- - \not{q}_1 + m}{(p_- - q_1)^2 - m^2} A^{(2)}(p_+ + p_- - q_1)$$
$$- ie^2 \int \frac{d^4q_1}{(2\pi)^4} A^{(2)}(p_+ + p_- - q_1) \frac{\not{q}_1 - \not{p}_+ + m}{(q_1 - p_+)^2 - m^2} A^{(1)}(q_1)$$
$$= -i(\frac{Ze^2}{2\pi})^2 \frac{1}{2\beta} \int d^2 q_{1\perp} \frac{1}{q_1^2} \frac{1}{(p_+ + p_- - q_1)^2} \exp(iq_{1\perp}b)$$
$$\{\frac{\psi^{(1)}(\not{p}_- - \not{q}_1 + m)\psi^{(2)}}{[(p_- - q_1)^2 - m^2]} + \frac{\psi^{(2)}(\not{q}_1 - \not{p}_+ + m)\psi^{(1)}}{[(q_1 - p_+)^2 - m^2]}\},$$

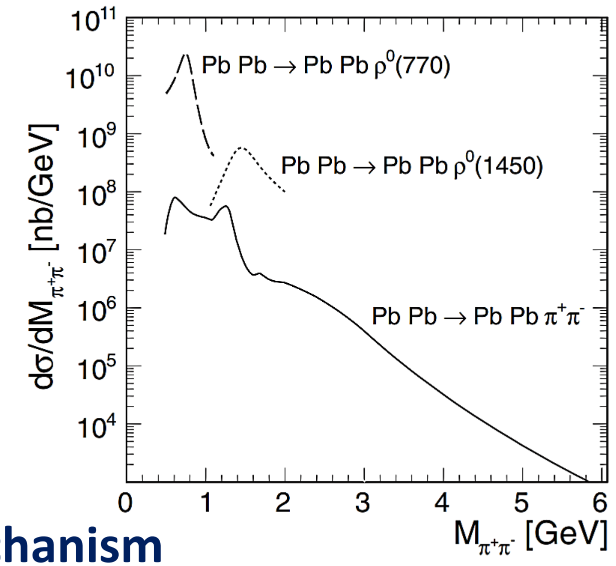
$$P(p_+, p_-, b) = \sum_s |M|^2$$

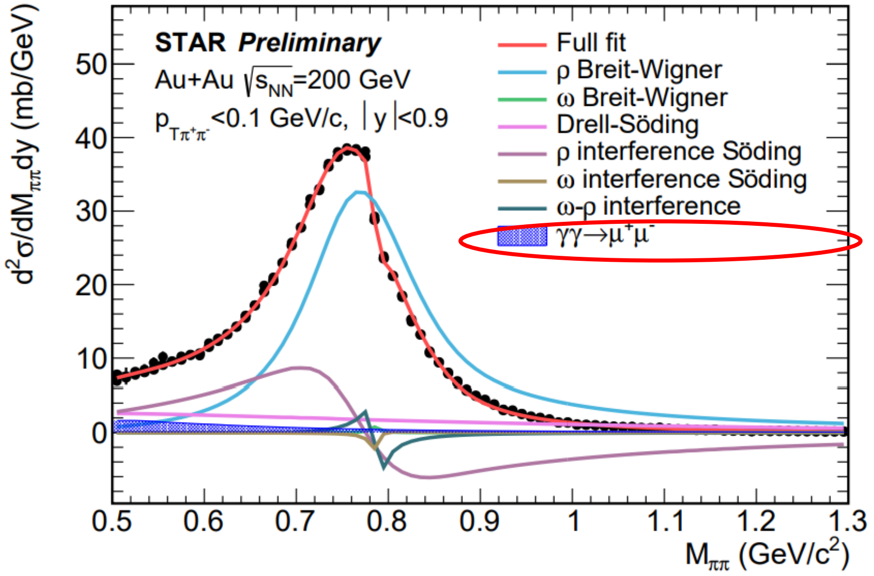
W. Zha et al., Phys. Lett. B 800 135089 (2020)

meson	mass [GeV]	$\gamma = 108$, $Z = 79$	
		σ^{tot} [μb]	σ^{red} [μb]
$\pi^\pm$	0.140	14762	12159

fermion	mass [GeV]	$\gamma = 108$, $Z = 79$	
		σ^{tot} [μb]	σ^{red} [μb]
$\mu^\pm$	0.1057	208329	177789

F. Krauss, M. Greiner and G. Soff, Prog. Parr. Nucl. Phys. 39 503 (1997)

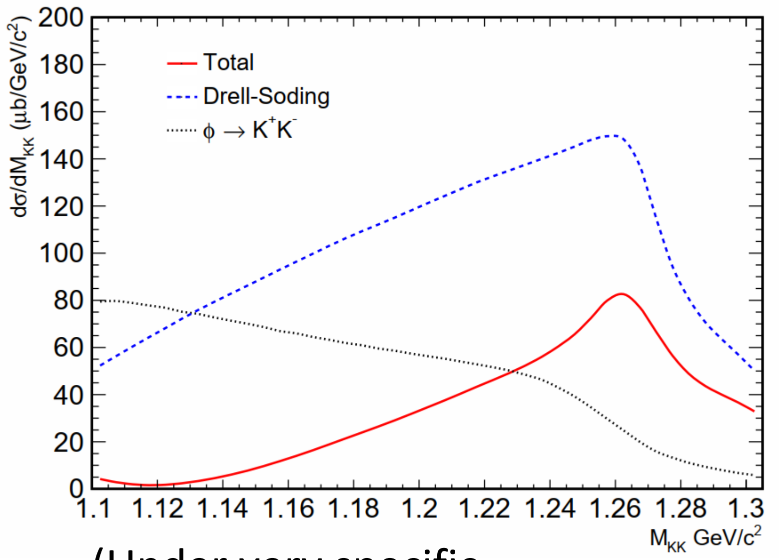




- ☐ $\gamma\gamma \to \pi^+\pi^-$ is small ~ 1/15 of Söding
- ☐ $\gamma\gamma \to \mu^+\mu^-$ is comparable to Söding mechanism

M. Kłusek-Gawenda and A. Szczurek, Phys. Rev. C 87 054908 (2013)

More related topics



(Under very specific acceptance selections)