Probing proton-antiproton production from QED Vacuum Excitation and Spin-Interference in Drell-Söding process in Ultra-Peripheral Au+Au Collisions at STAR

Xinbai Li, for STAR Collaboration (xinbai@mail.ustc.edu.cn)

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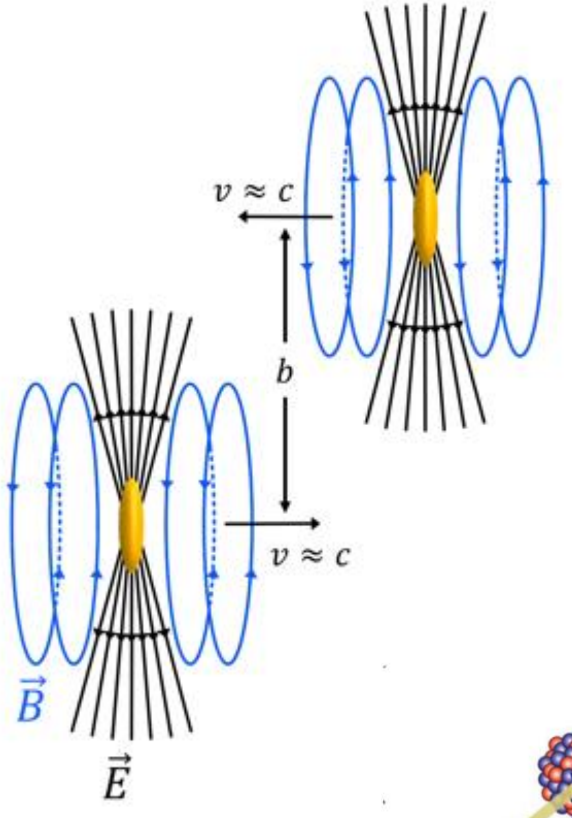
Supported in part by the U.S. DEPARTMENT OF ENERGY Office of Science

Outline

- **Equivalent photon in heavy ion collisions**
- **Vacuum pair production**
- **Observation of proton-antiproton production**

- **ρ^0 photoproduction and Drell-Söding process**
- **Spin-interference effect**
- **Observation of spin-interference in Drell-Söding process**

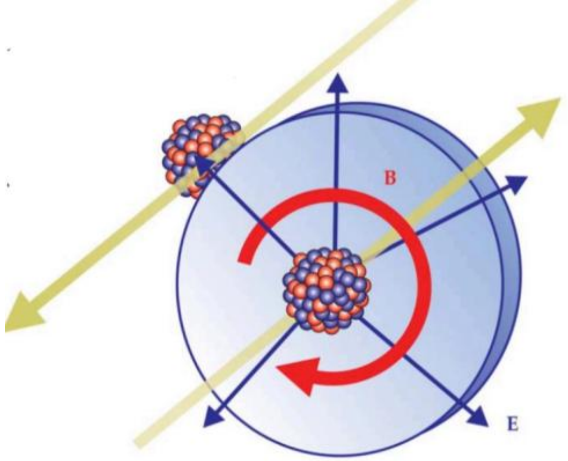
Quasi-real photons in Relativistic Heavy-Ion Collisions



In heavy-ion collisions:

$$E_{Max} = \frac{Ze\gamma}{b^2} \approx 5 \times 10^{20} - 10^{22}\ \text{V/cm};\quad B_{Max} = 10^{14} - 10^{16}\ \text{T}$$

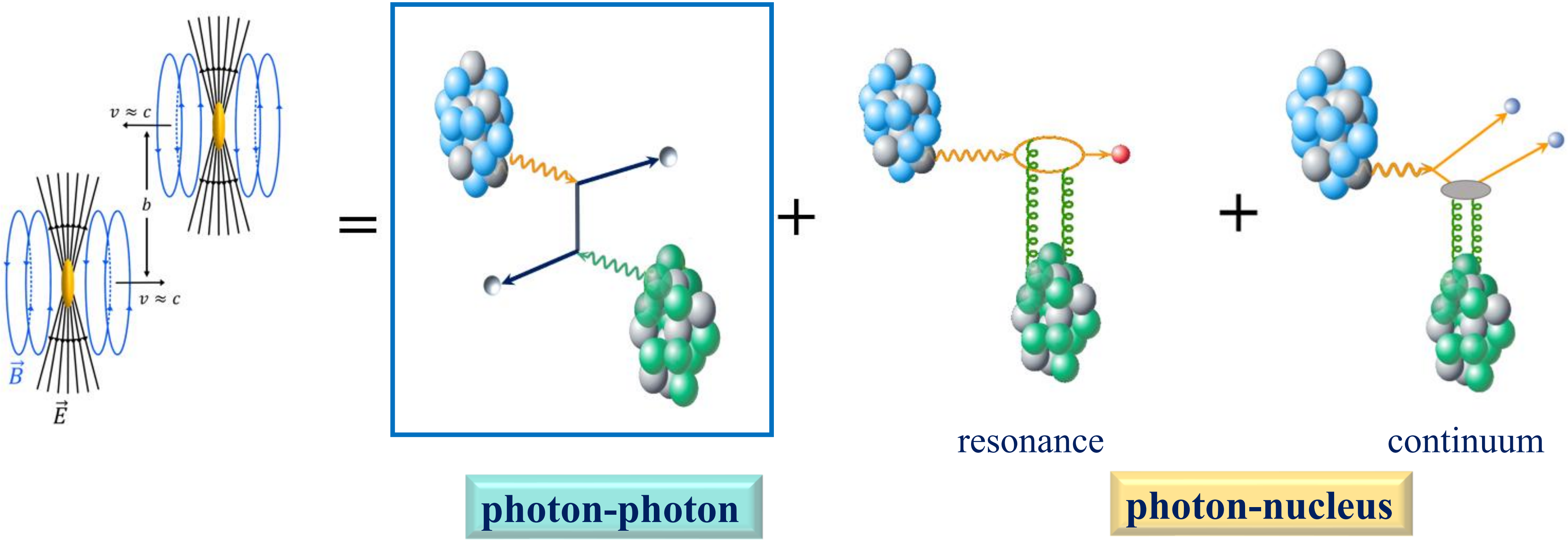
- Strongest EM fields in the Universe
- But very short lifetime – not constant
- Photons are linearly polarized



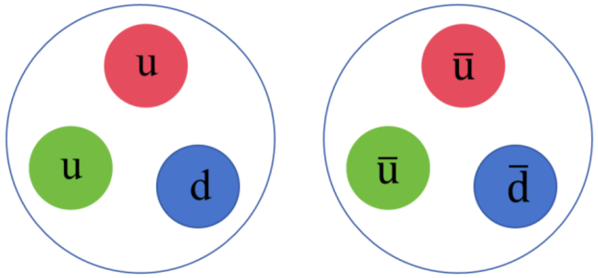
- Photon as nuclear parton
- Electromagnetic radius $R_{EM} > R_{mass}$

S. Klein, J. Nystrand Physics Today 70(10) (2017) 40

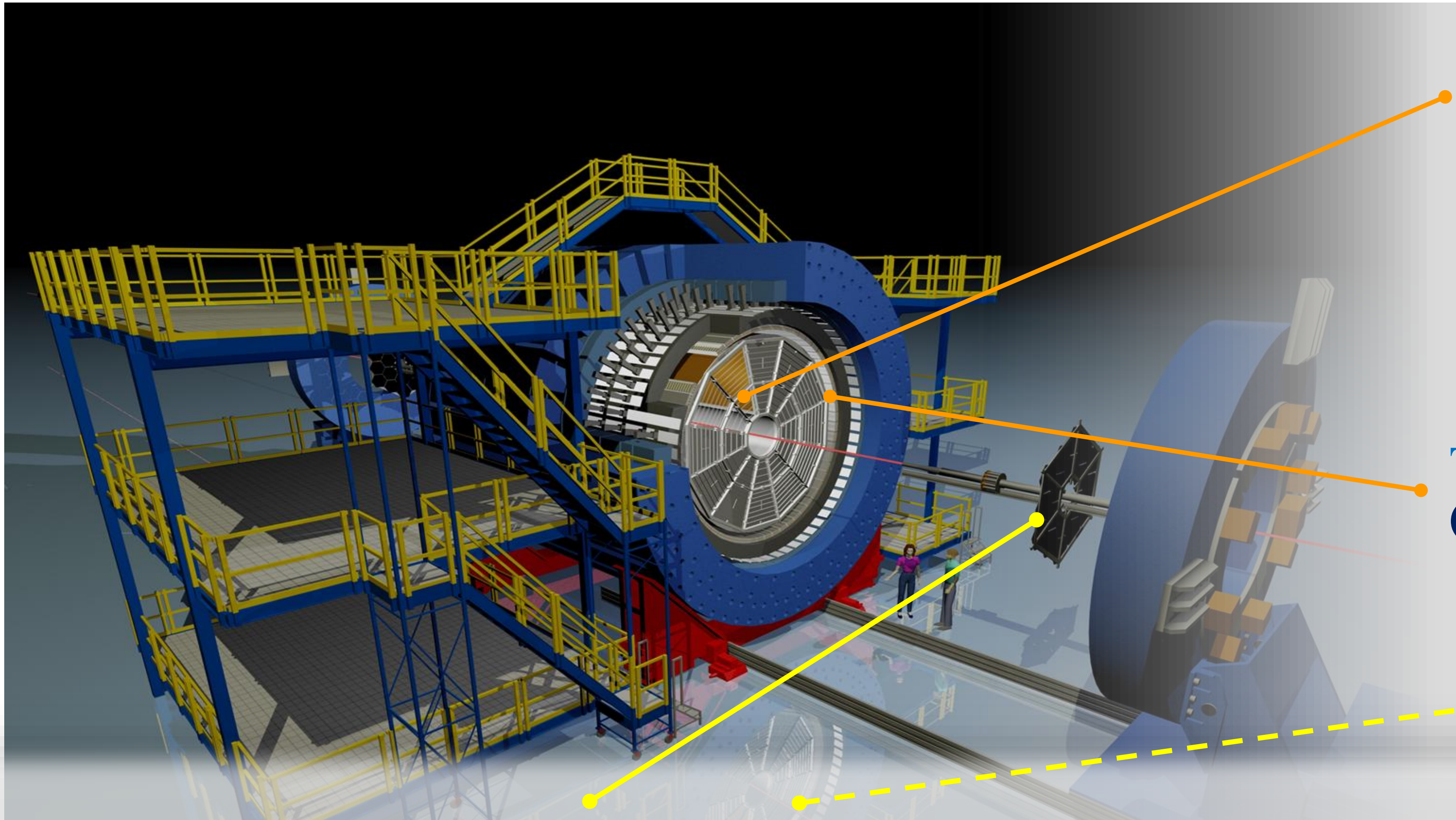
Vacuum pair production



- Explore non-linear and non-perturbative QED above the Schwinger limit
- Test for physics beyond standard model
- Breit-Wheeler process ($\gamma\gamma \to e^+e^-$) observed, what about $\gamma\gamma \to p\bar{p}$?



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 (For UPC analysis)

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

Track & pair selection

Track selection:

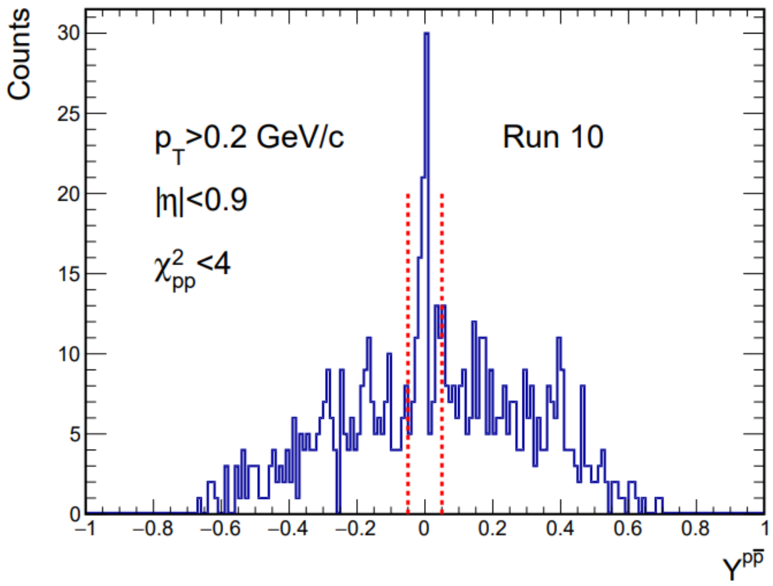
- ✓ $p_T > 0.2$ GeV/c, $|\eta| < 0.9$
- ✓ $DCA_p \leq 0.5$ cm, $DCA_{\bar{p}} \leq 1.5$ cm
- ✓ nHitsFit ≥ 20, nHitsDedx ≥ 15, nHitsFitRatio ≥ 0.52

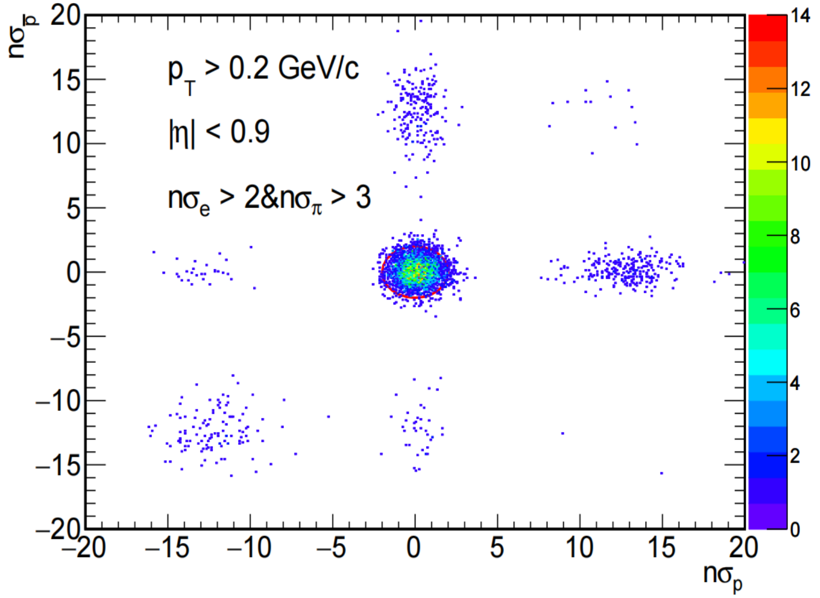
Pair selection:

- ✓ $0.05 < |y_{pair}| < 0.5$

PID:

- ✓ $\chi^2_{pp} = n\sigma^2_{p,1} + n\sigma^2_{p,2} < 4$
- ✓ $n\sigma_e > 2;\ n\sigma_\pi > 3$

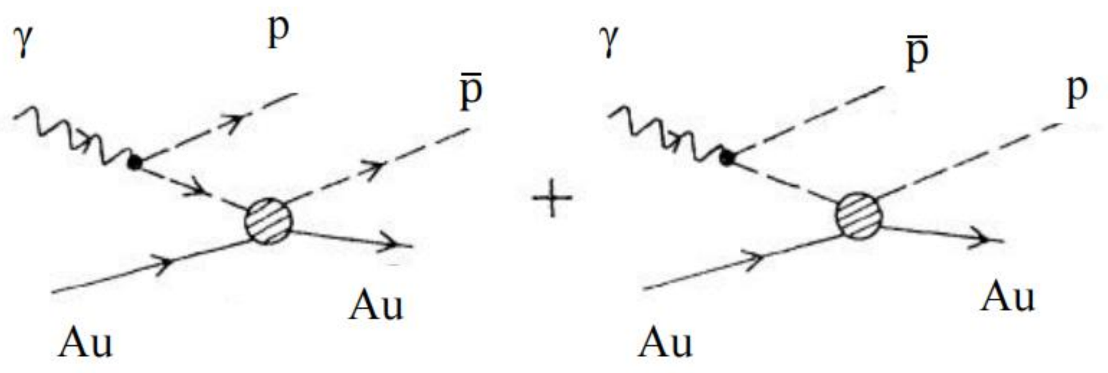




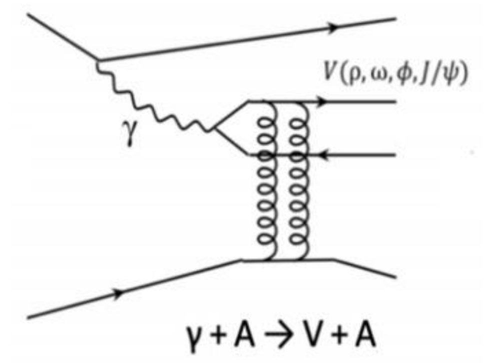
Physical background

- Photon-nuclear interaction

Non-resonance production

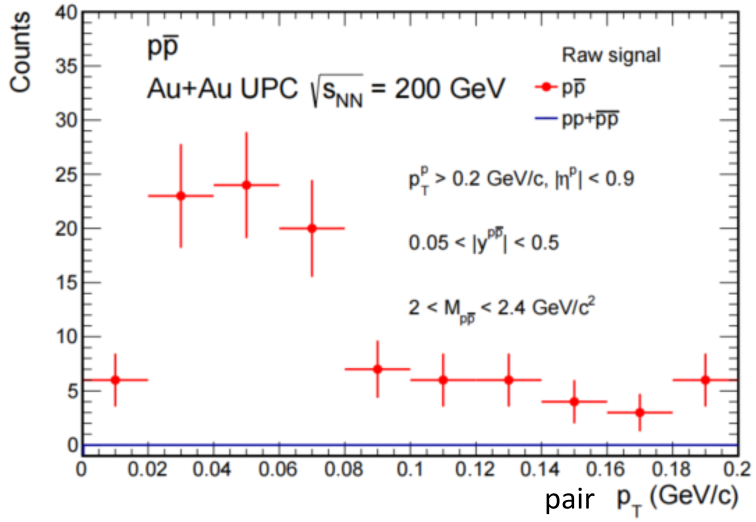


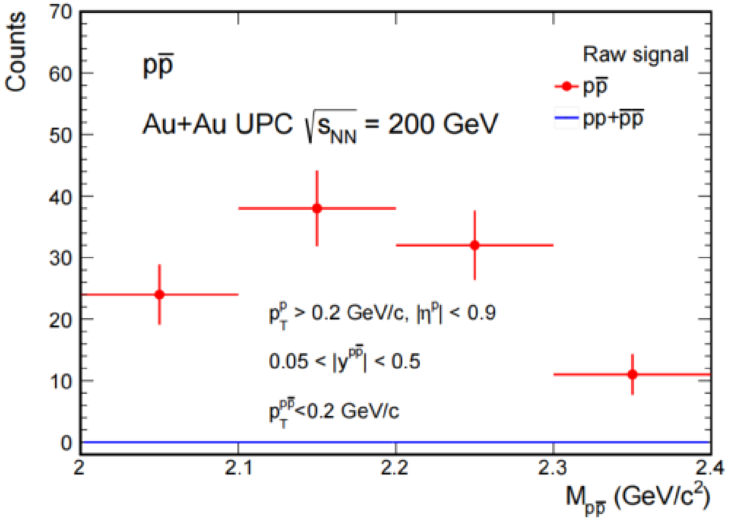
Vector meson $J/\psi \to p\bar{p}$



To enhance $\sigma_{\gamma\gamma}(M)/\sigma_{\gamma A}(M)$

- Choose $M_{p\bar{p}}$ near threshold $2m_p$
- Require a smaller pair p_T





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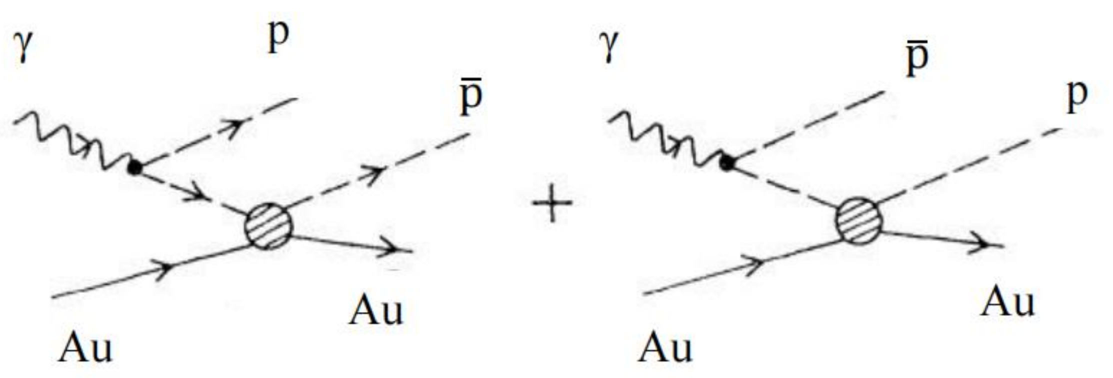
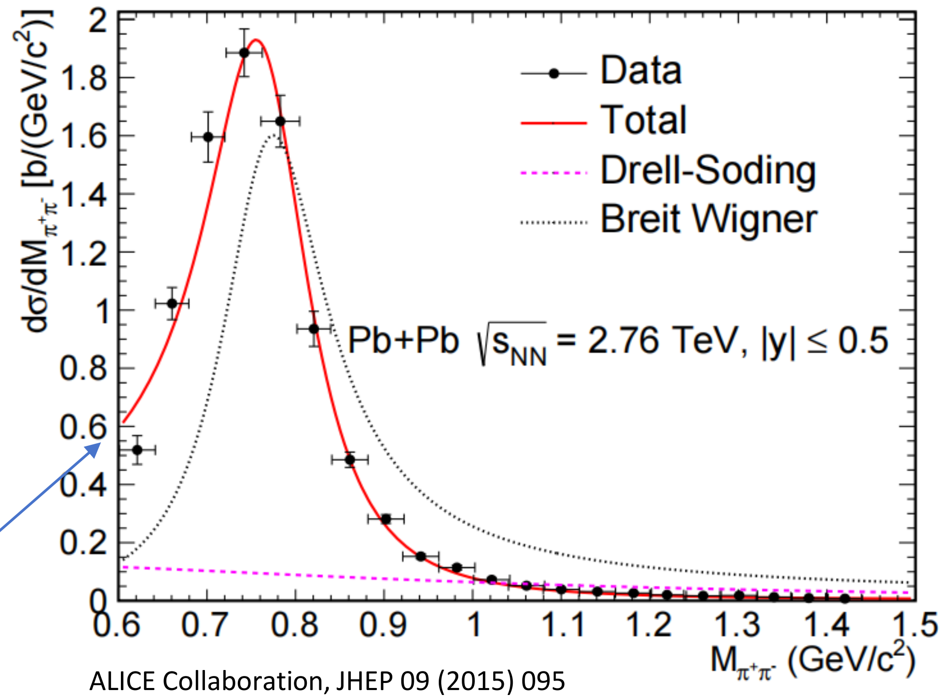




ALICE Collaboration, JHEP 09 (2015) 095

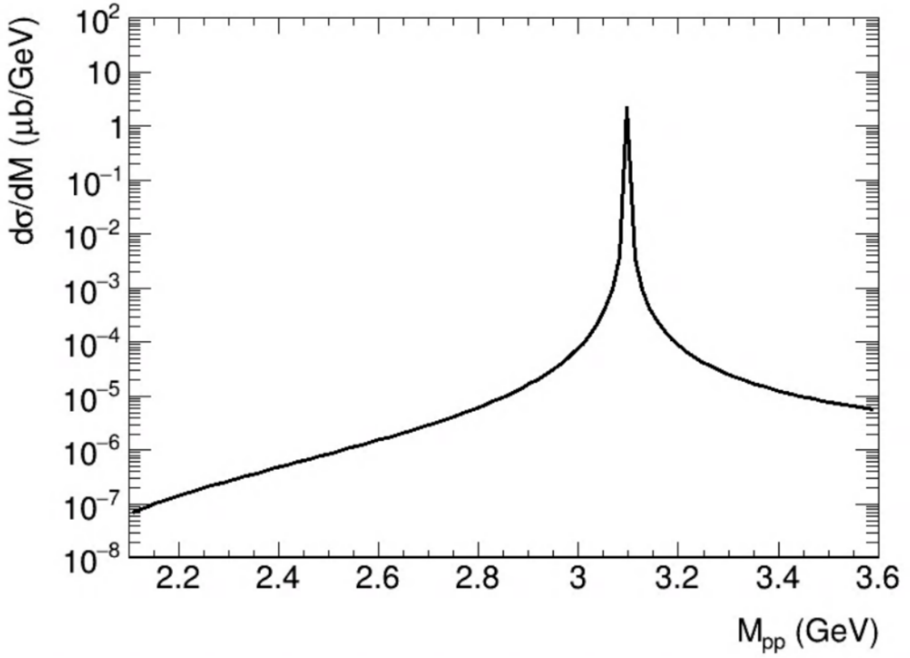
- Validated by model calculation with Drell-Söding process compared with exclusive $\pi^+\pi^-$ measurement
- Non-visible in the selected mass range $2.1 < M_{p\bar{p}} < 2.4$ GeV/c^2 (shown in P9)
- Need further consideration of the model uncertainty

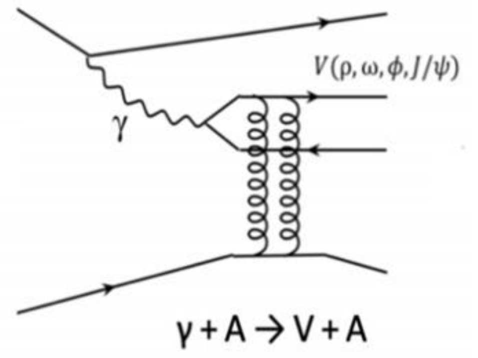
Physical background

- Photon-nuclear interaction

Vector meson $J/\psi \to p\bar{p}$

Calculate using vector meson dominance model

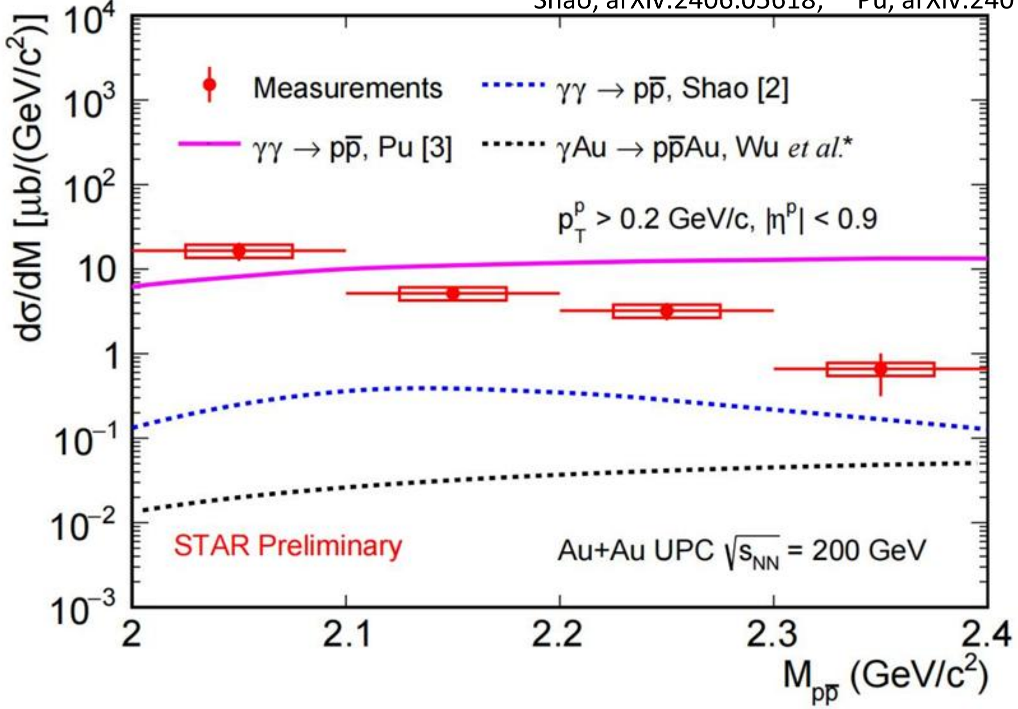


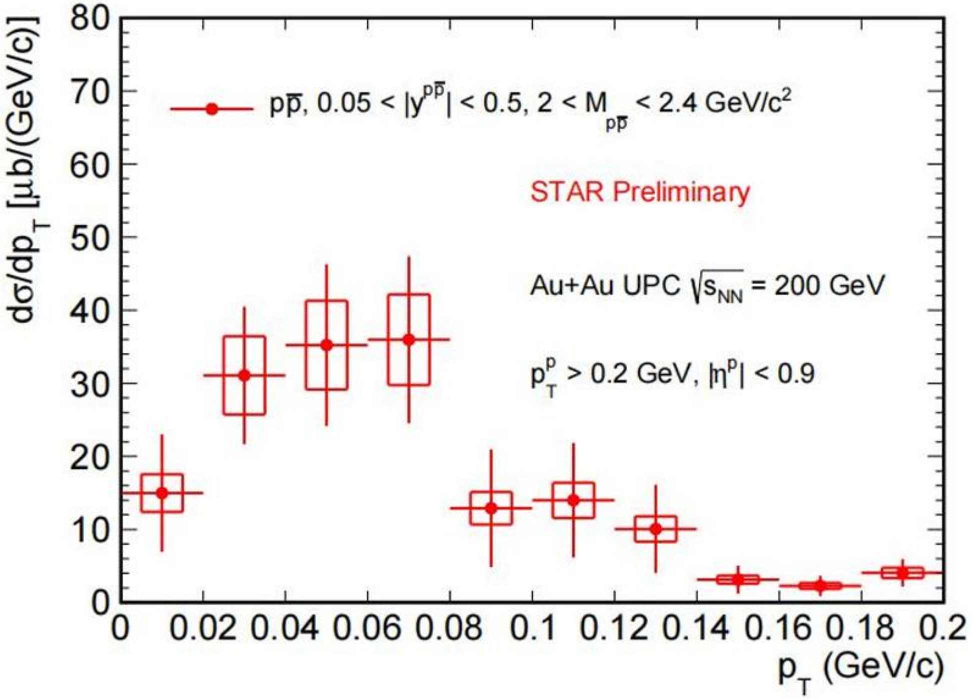


Negligible impact near threshold $2m_p$

Differential cross section

Shao, arXiv:2406.05618; Pu, arXiv:2407.06091





- Observation of $\gamma\gamma \rightarrow p\bar{p}$ (from vacuum excitation at extremely low Q^2) in Au+Au UPC collisions at $\sqrt{s_{NN}}$ = 200 GeV with $\sigma = 2.6 \pm 0.4(stat) \pm 0.5(sys)$ μb
- Current models struggle to match the data
- Future run 23-25 collected data help improve statistics for angular momentum study

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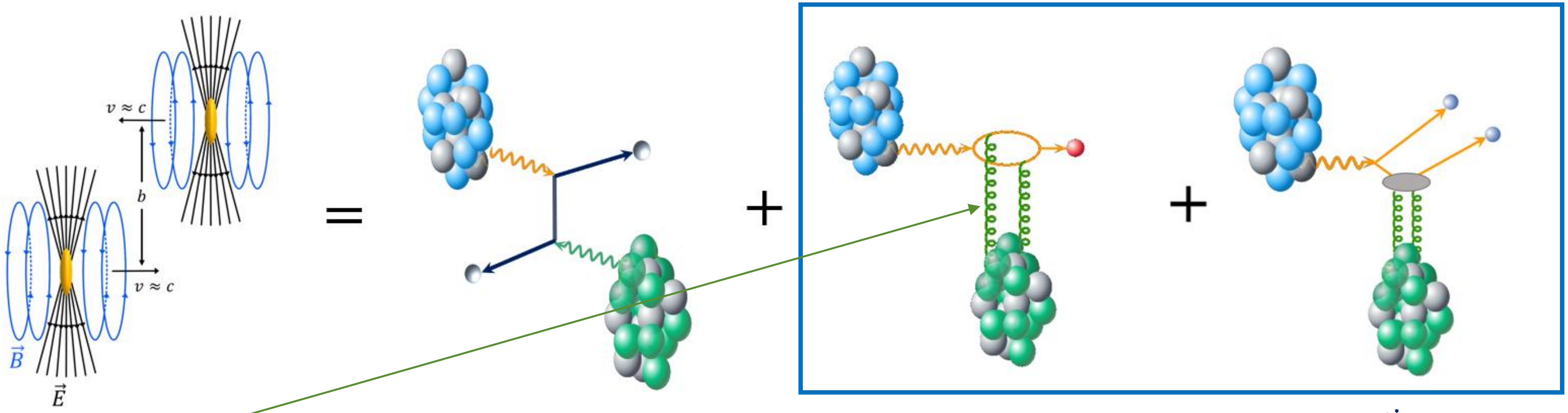
Photon induced process



resonance

continuum

Pomeron exchange: Short force range, restricted inside the nucleus.

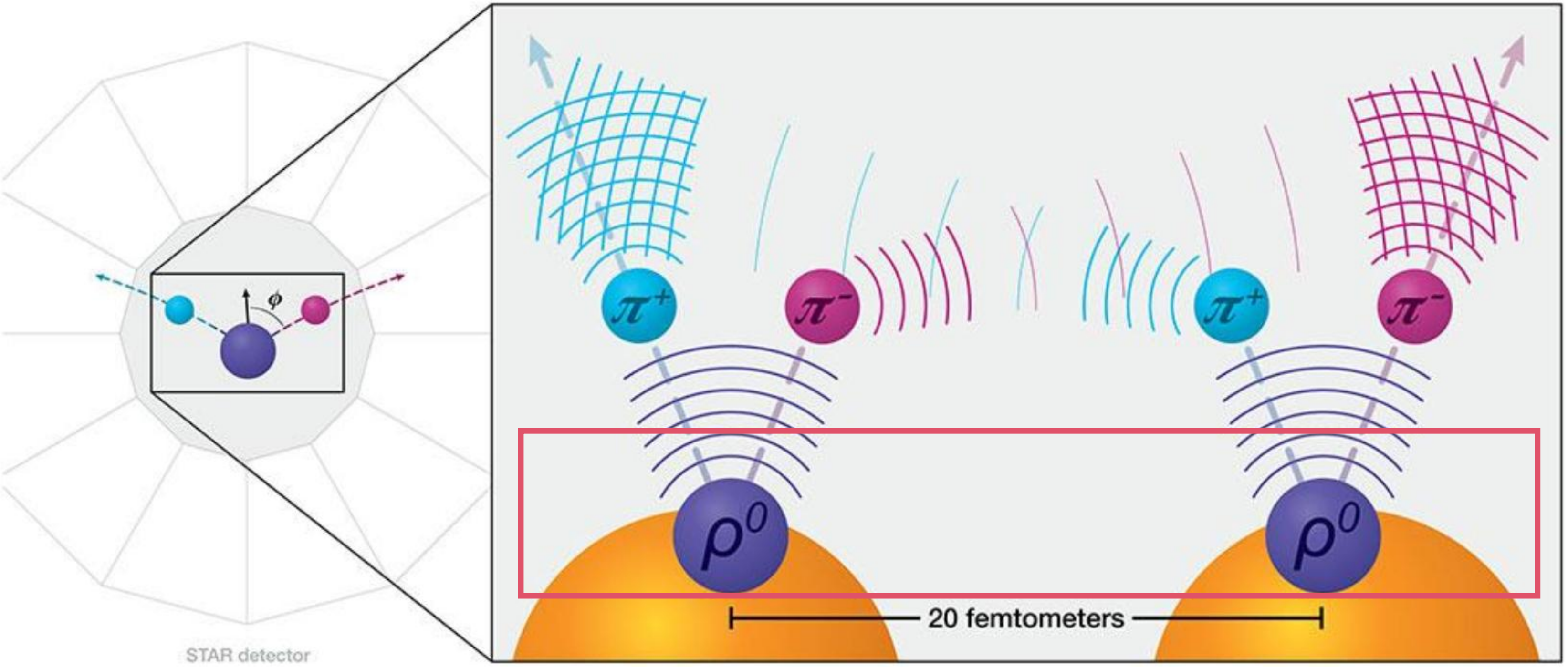
photon-photon

photon-nucleus

- For $\rho^0 \rightarrow \pi^+\pi^-$ (resonance) and Drell-Söding $\pi^+\pi^-$ (continuum)
- Söding mechanism (skewed mass shape): P. Soding Phys. Lett. 19 (1966) 702

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

Spin-Interference effect



Still coherent

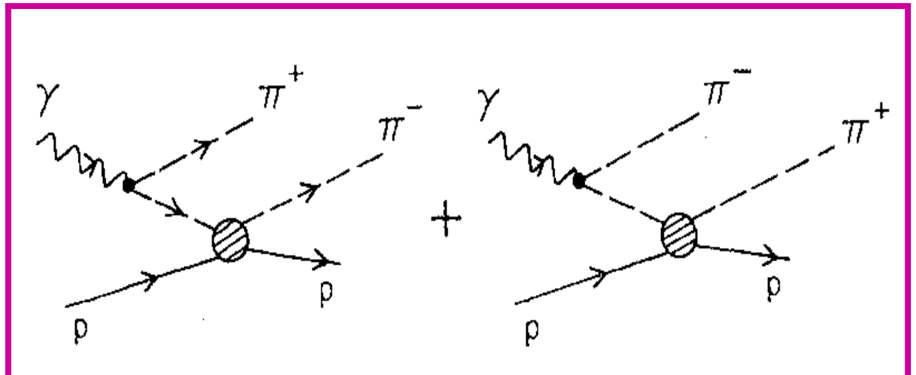
Short lifetime $\rho^0 \sim 1.3$ fm/c

"Which path issue" + different phase angle = double-slit interference

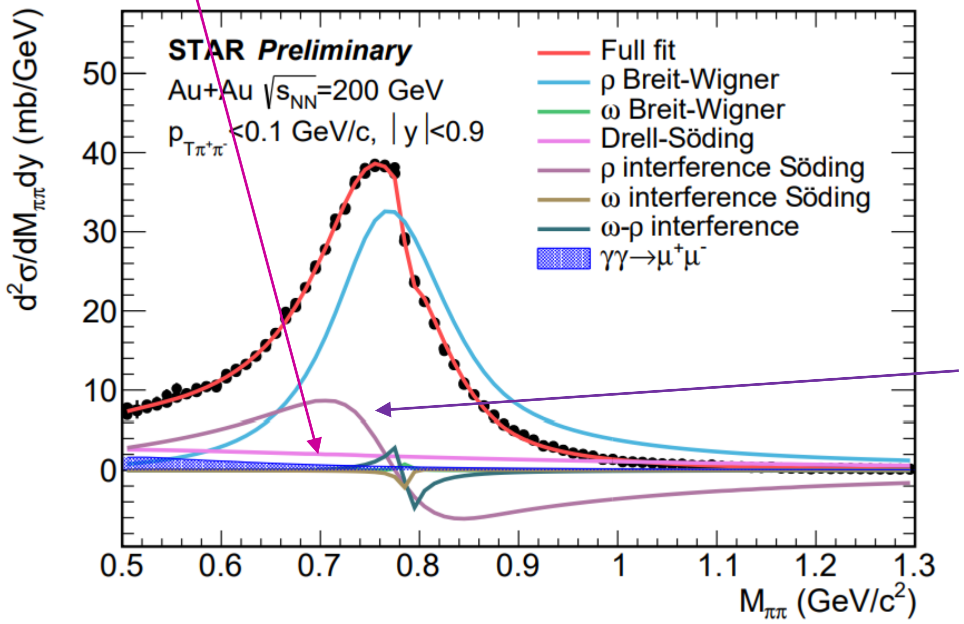
$$\frac{d^2P}{dp_x dp_y} = \frac{1}{2\pi}\left|\int d^2r\left[A_1\left(y, \mathbf{r}, -\frac{b}{2}\right) + A_2\left(y, \mathbf{r}, \frac{b}{2}\right)\right]e^{i\mathbf{p}\cdot\mathbf{r}}\right|^2$$

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

Drell-Söding process



Drell-Söding process

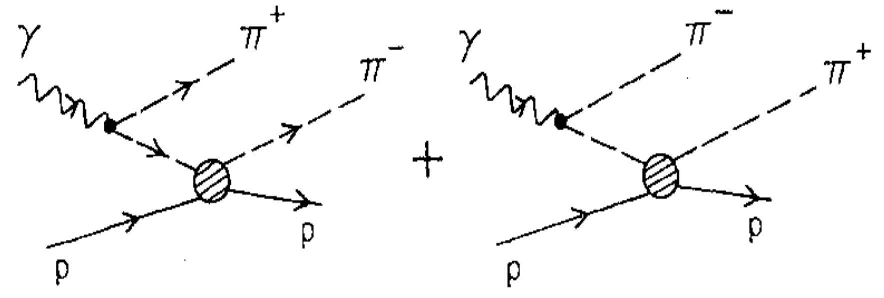


Originally proposed to

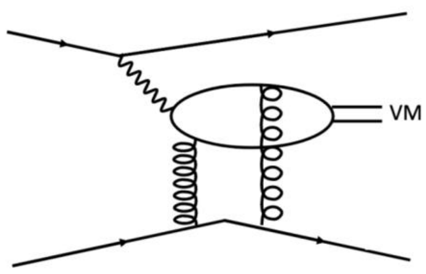
- Produce charge π/K beam
  S.D. Drell, Rev. Mod. Phys. 33 (1961) 458
- Peripheral cross section
  S.D.Drell, Phys. Rev. Letters 5 (1960} 278
- Mass shift of ρ^0
  P. Soding Phys. Lett. 19 (1966) 702
- …
- Precise measurement of Drell-Söding process

- The key to precisely measure such small contribution to the total exclusive $\pi^+\pi^-$ production

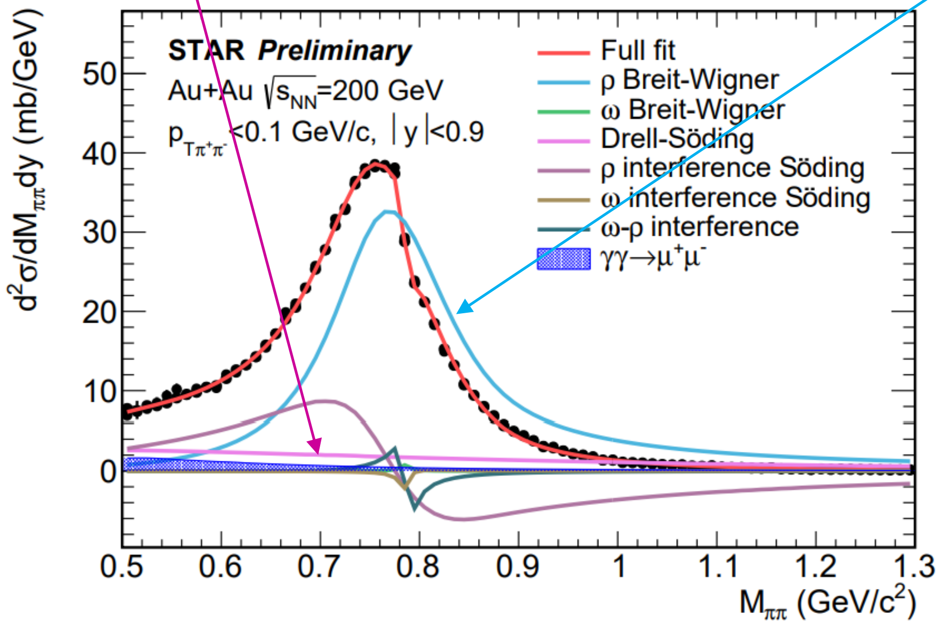
Drell-Söding process & ρ^0 photoproduction



Drell-Söding process



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!

Algorithm for signal extraction

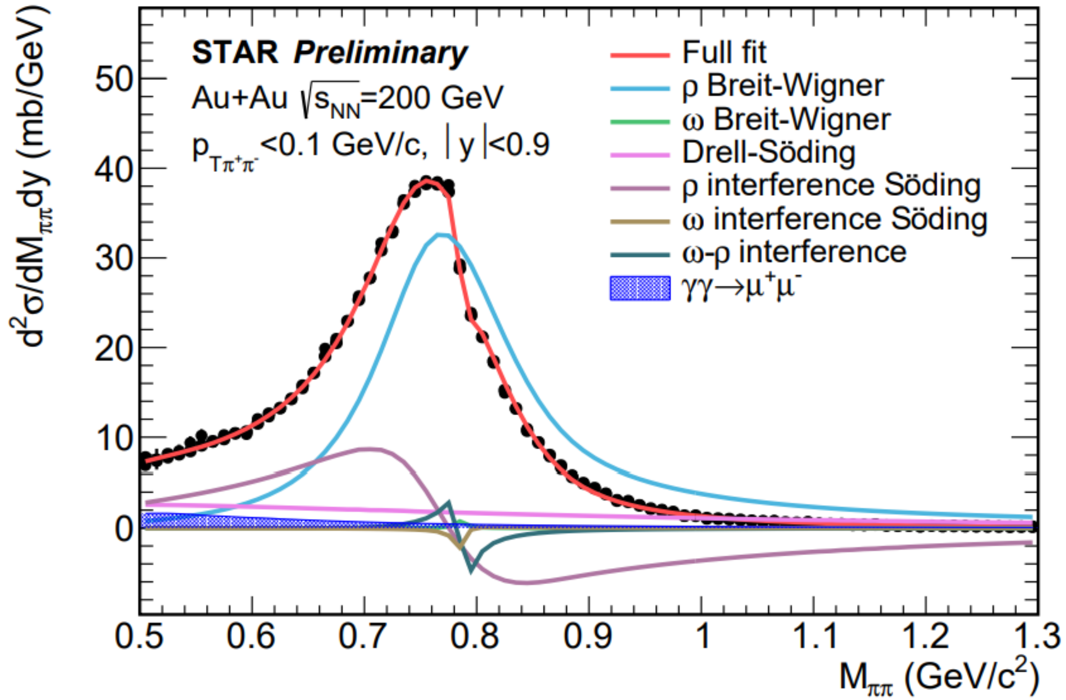
$$\frac{d\sigma}{dM_{\pi^+\pi^-}} = \left| A_\rho \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + iM_\rho\Gamma_\rho} f_{fluxcorr}(M_{\pi\pi}) + B f_{Söding}(M_{\pi\pi}) + C_\omega e^{i\phi_\omega} \frac{\sqrt{M_{\pi\pi} M_\omega \Gamma_{\omega\to\pi\pi}}}{M_{\pi\pi}^2 - M_\omega^2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

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

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

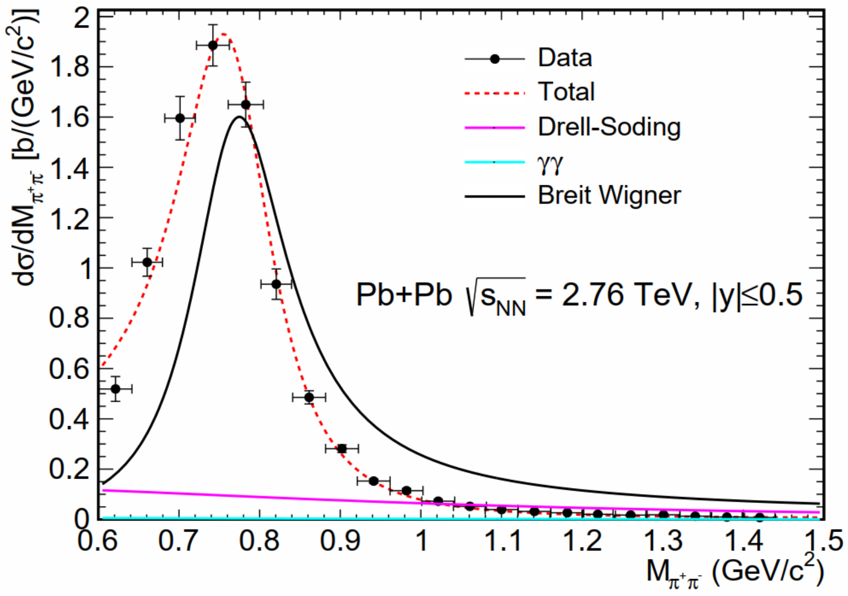


Theoretical input

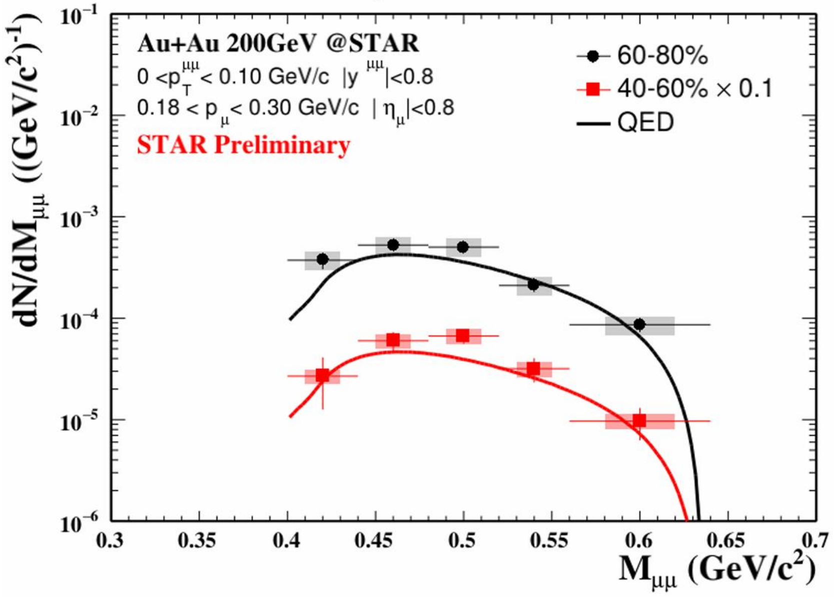
$$\frac{d\sigma}{dM_{\pi^+\pi^-}} = \left| A_\rho \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + i M_\rho \Gamma_\rho} f_{fluxcorr}(M_{\pi\pi}) + B f_{S\ddot{o}ding}(M_{\pi\pi}) + C_\omega e^{i\phi_\omega} \frac{\sqrt{M_{\pi\pi} M_\omega \Gamma_{\omega\to\pi\pi}}}{M_{\pi\pi}^2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

$f_{S\ddot{o}ding}(M_{\pi\pi})$

S.R. Klein et al., Comp. Phys. Comm. 212 (2017) 258
J. Pumplin, PRD. 2. 1859
ALICE Collaboration, JHEP 09 (2015) 095



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)

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

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

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: over 1 million exclusive $\pi^+\pi^-$ events

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

Mass fits for different pair p_T

Differential cross section on p_T dependence

Mass fits for different pair $p_T - \Delta\phi$

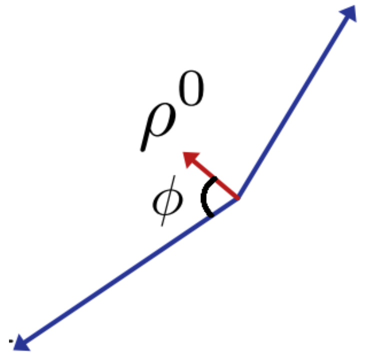
Recon $A_{2\phi}$

$A_{2\phi}$ 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

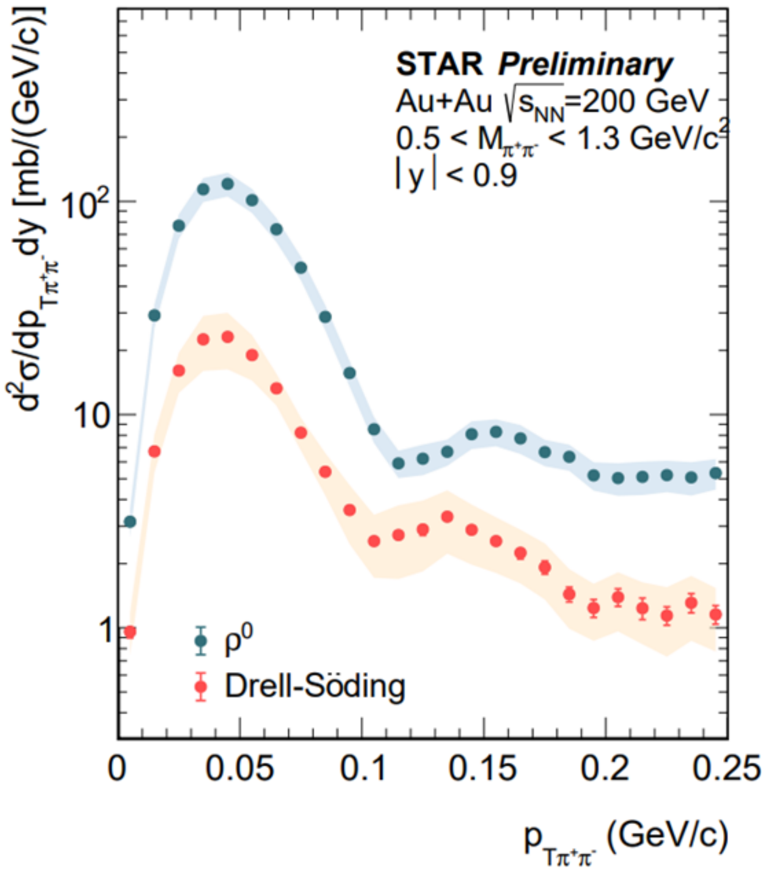


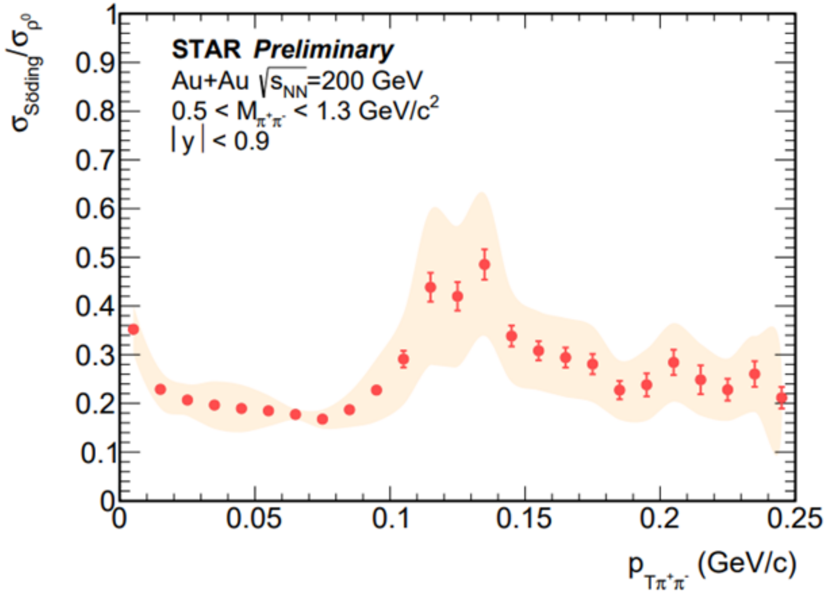
$A_{2\phi} = 2\langle\cos(2\phi)\rangle$

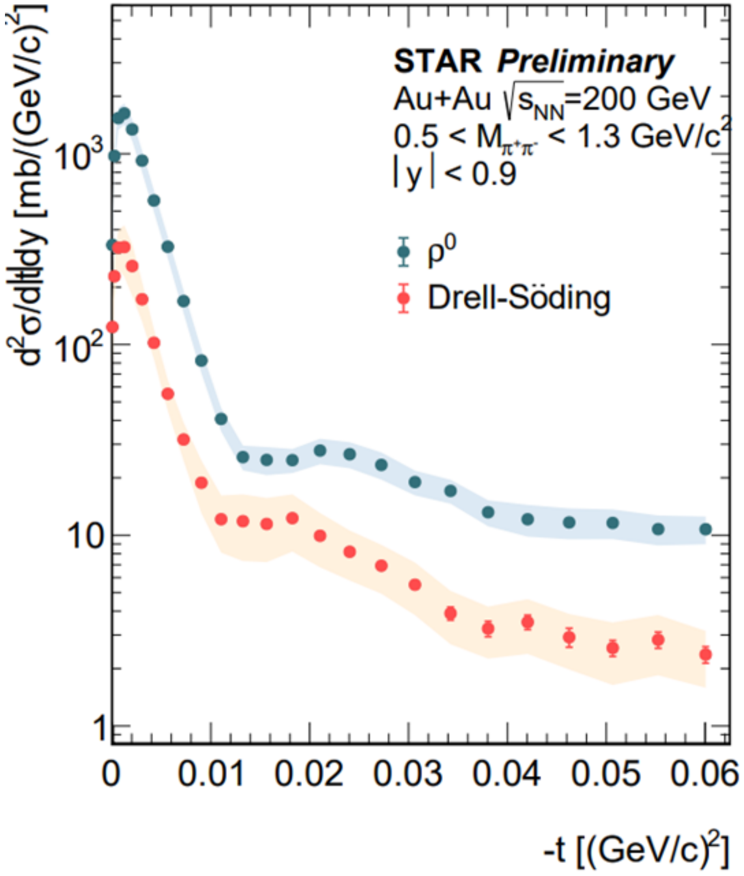
 17

Diffractive p_T spectra

- 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 ($p_T \cdot r \geq \hbar$)



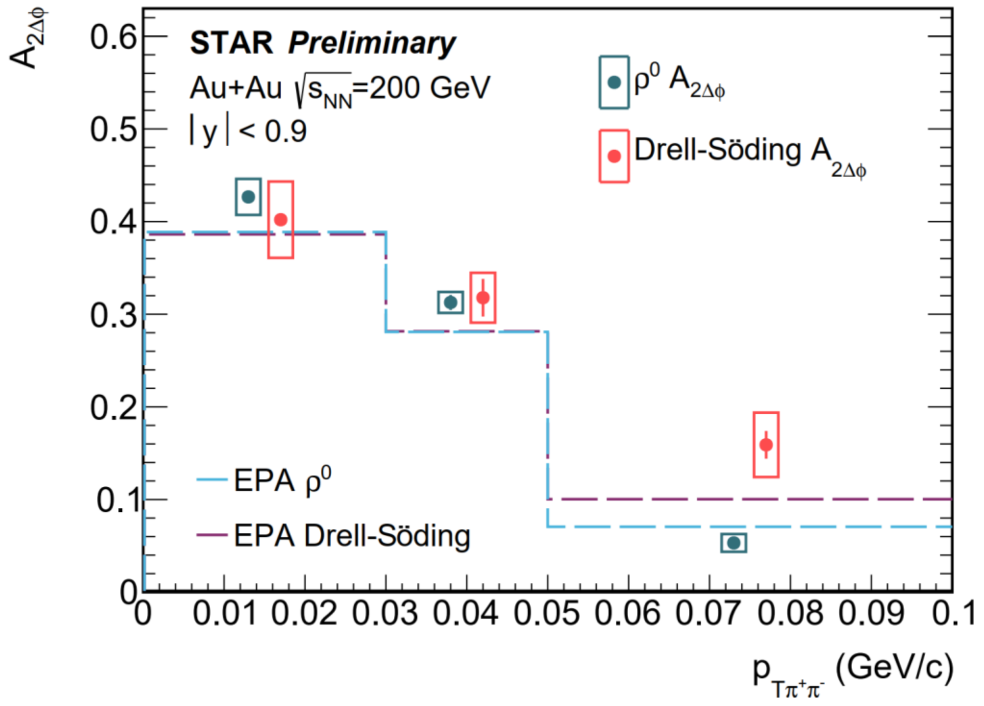


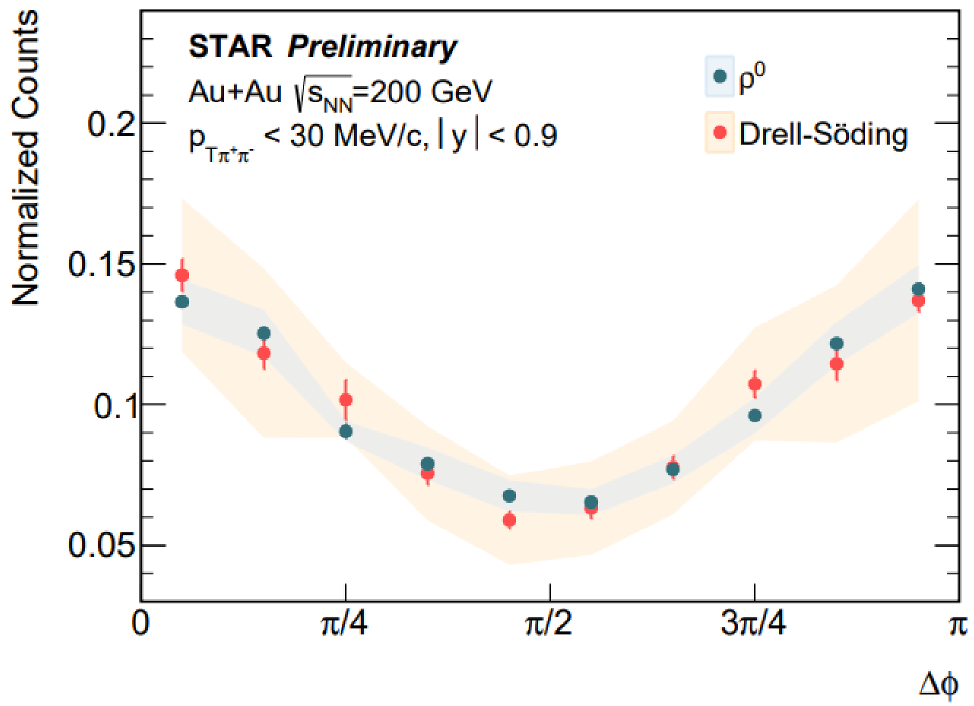


Spin-Interference

✓ Similar $A_{2\Delta\phi}$ for 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

- ✓ Observation of proton-antiproton production from vacuum excitation
- ✓ The cross section exceed the model prediction; Require further theoretical development

- ✓ First measurement of pair p_T and spin-interference of Drell-Söding process
- ✓ 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

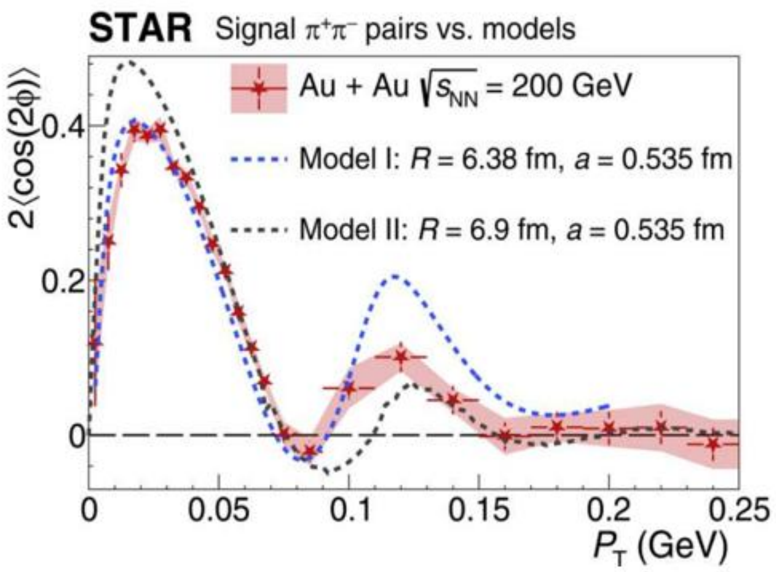
Thank you!

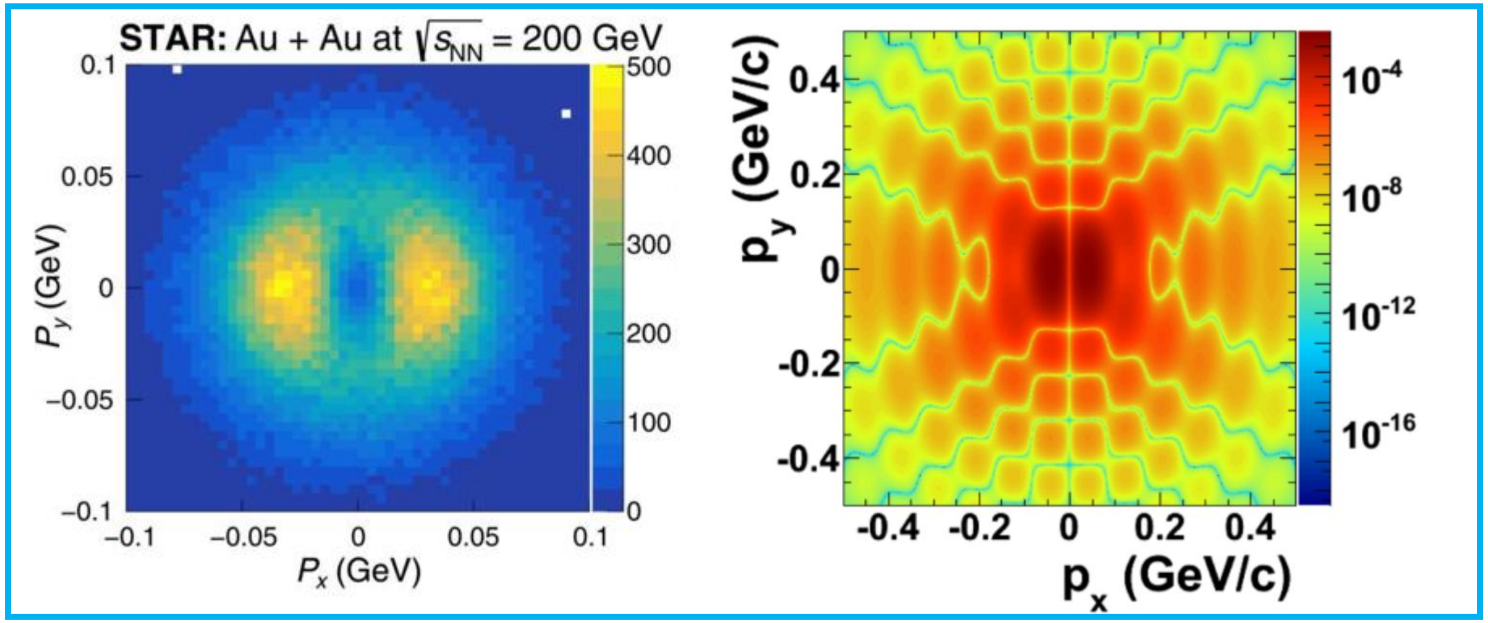
Backup

Any questions and suggestions are welcome

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

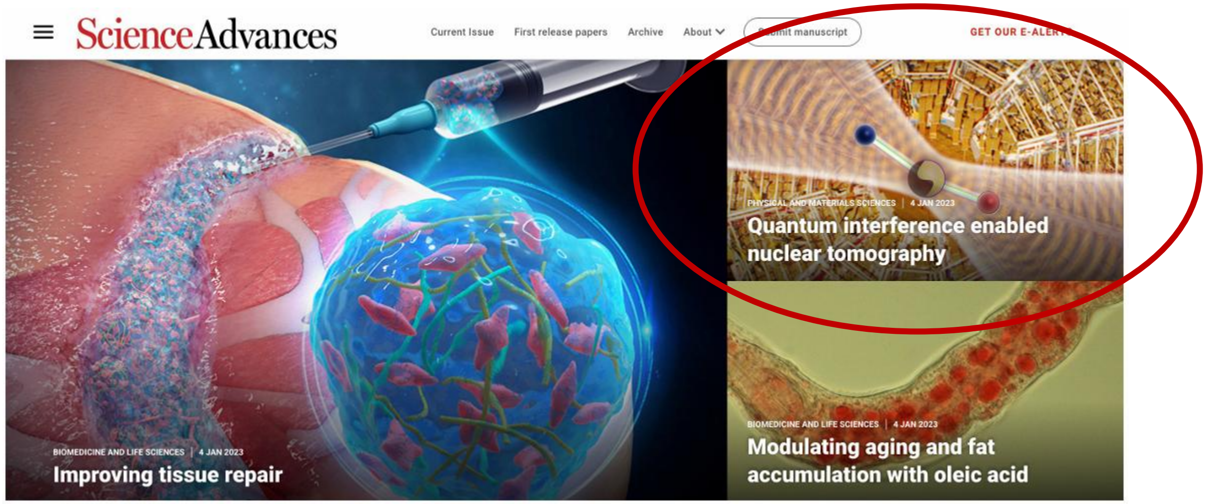
Experimental measurements

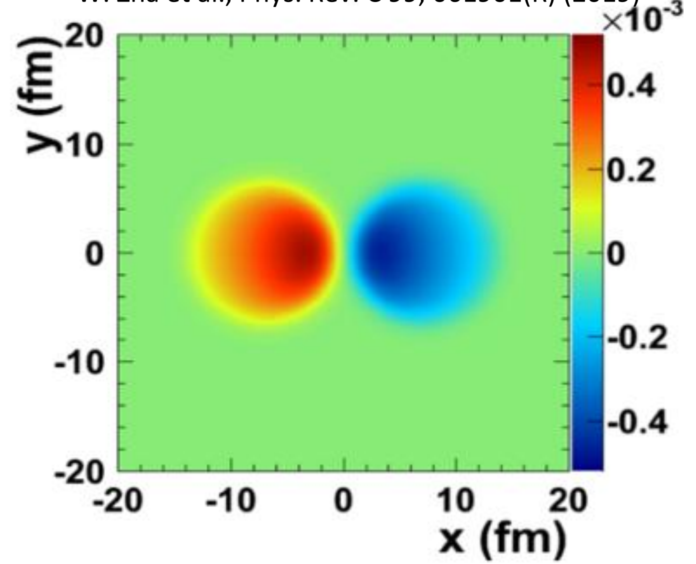




STAR collaboration, sciadv.abq3903 (2023)

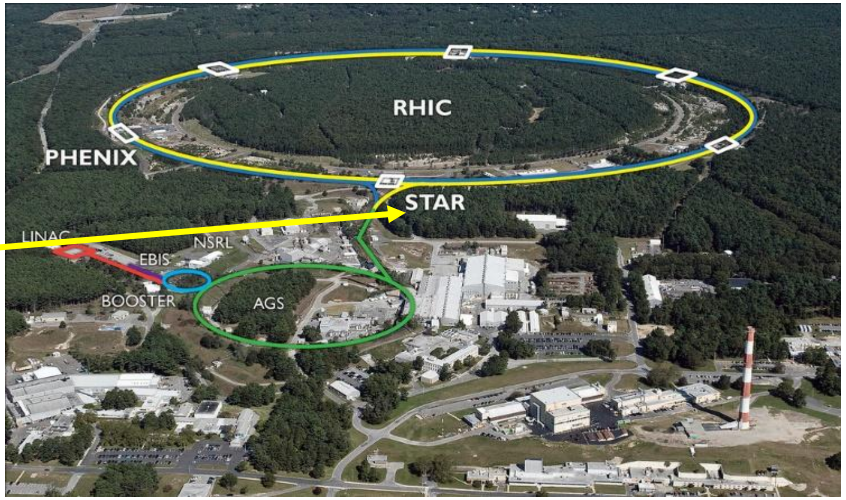
W. Zha et al., Phys. Rev. C 99, 061901(R) (2019)

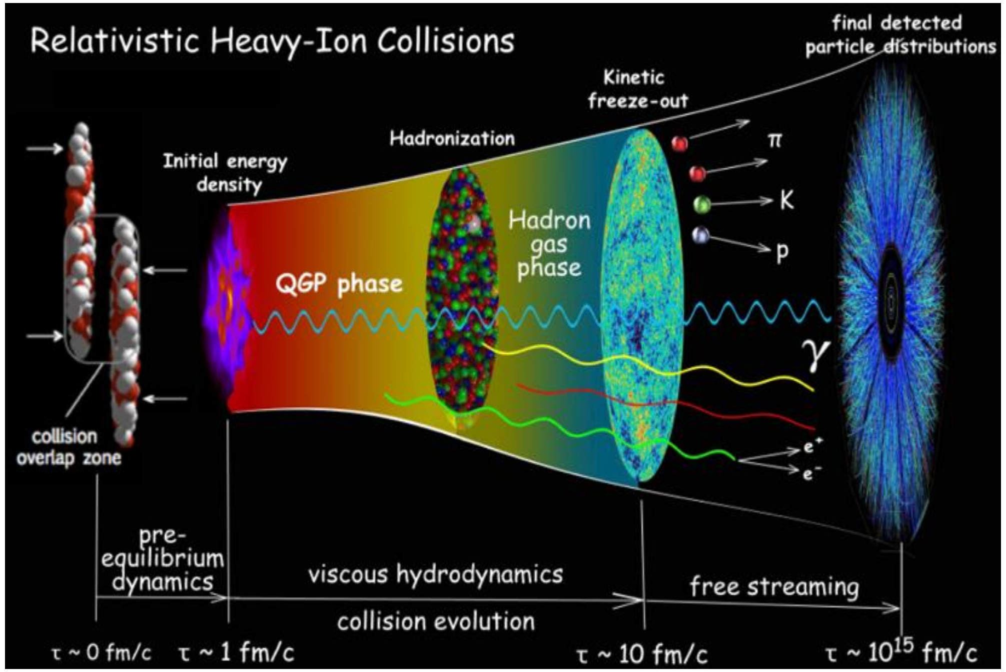




Relativistic heavy-ion collisions

- The first Relativistic Heavy-Ion Collider in the world
- 762 members from 74 institutions in 15 countries (STAR)





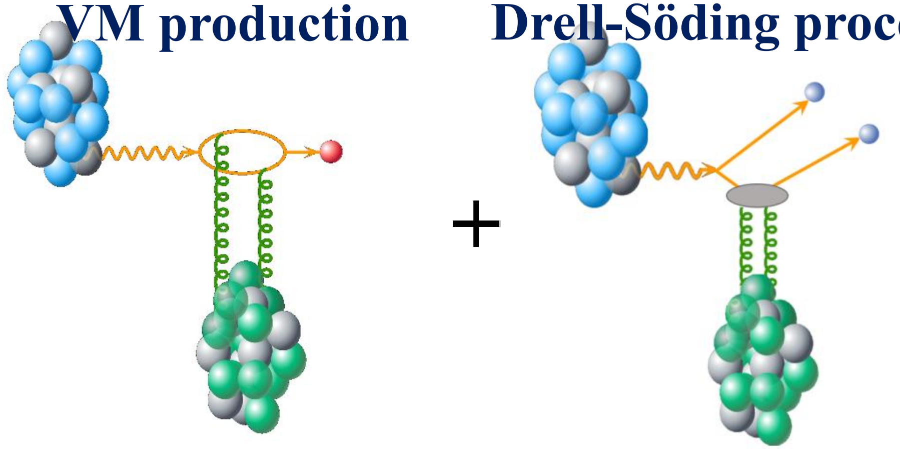
- The hottest man-made strongly coupled matter Quark-gluon plasma (QGP)
- The strongest EM fields (~10^{15} T) ever known

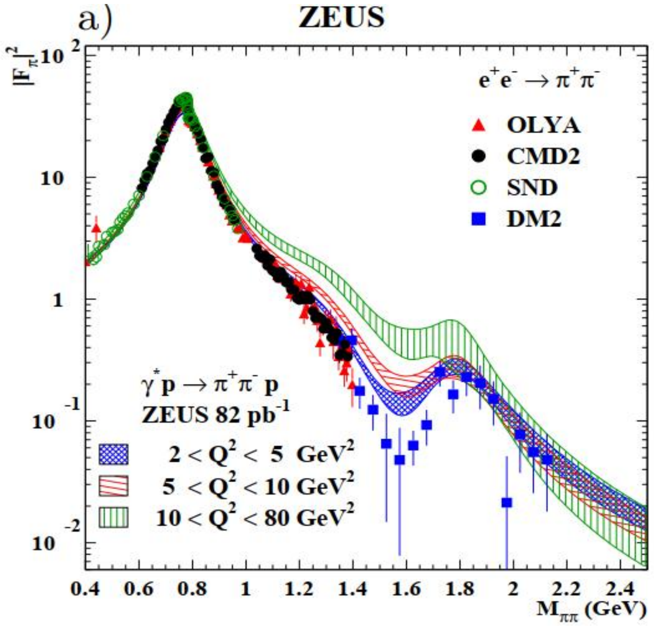
Exclusive $\pi^+\pi^-$ production

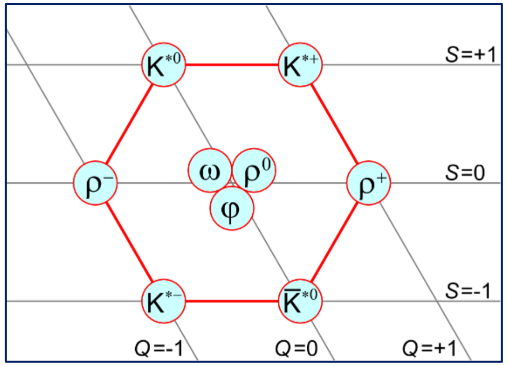
- ☐ Multiple phenomenological generators in the market:

SuperChic, gamma-UPC, STARLight, Sartre …

- ☐ However, no individual Drell-Söding channel





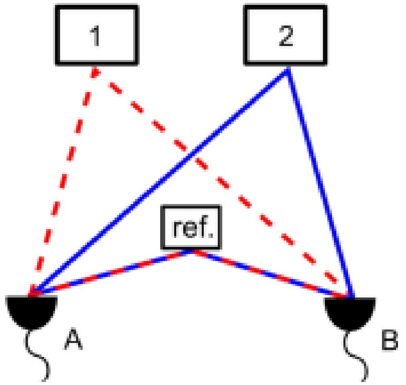


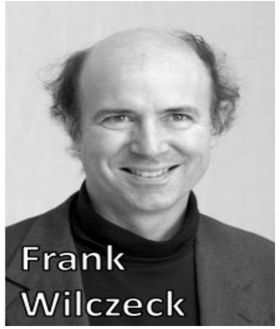
- ☐ Mass mixing of vector mesons (VMs)
- ☐ Well understood in e^-e^+ (no Söding mechanism)

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

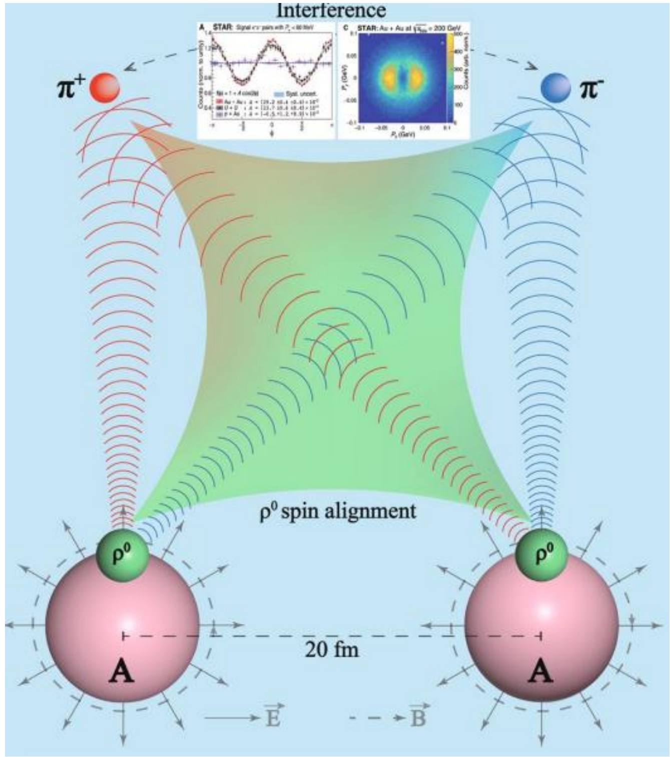
Entanglement enabled interference

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



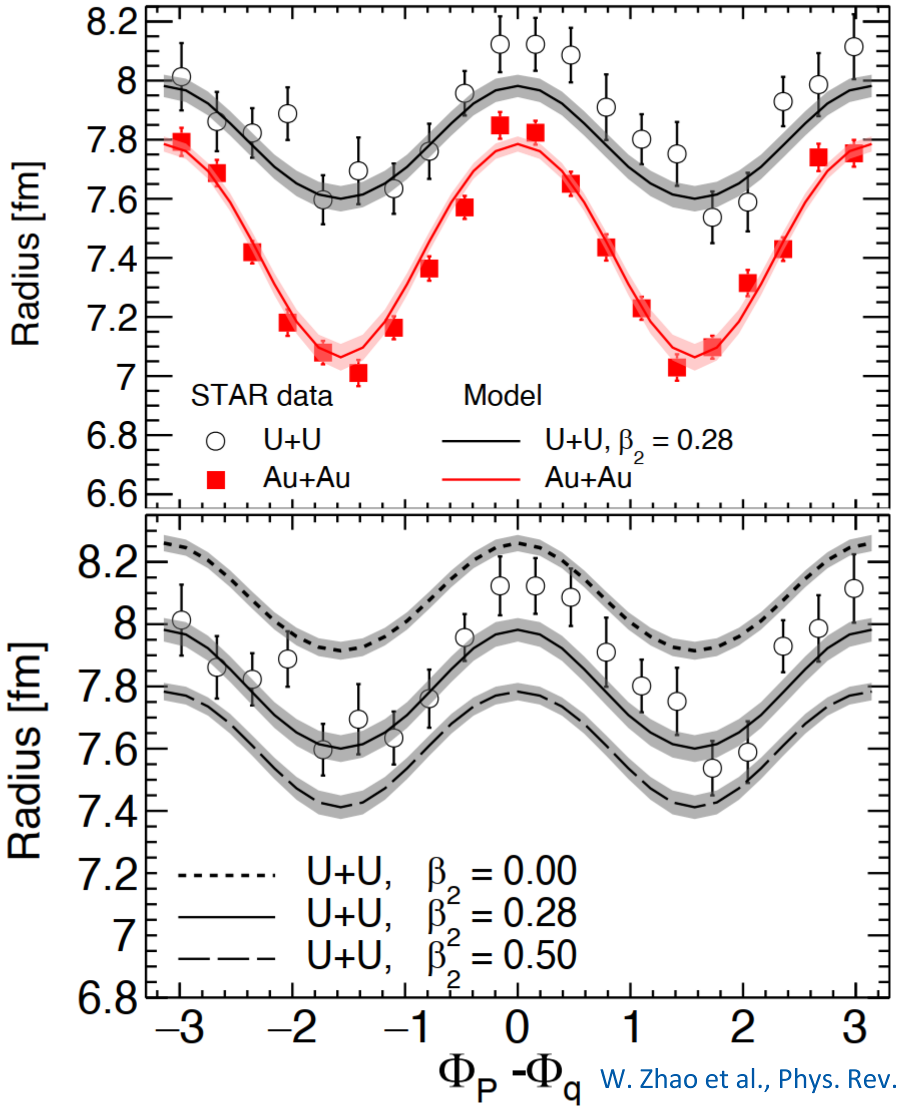


J. Cotler, F. Wilczek, V. Borish, Ann. Phys. 424 168346 (2021)



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

Image nuclei



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

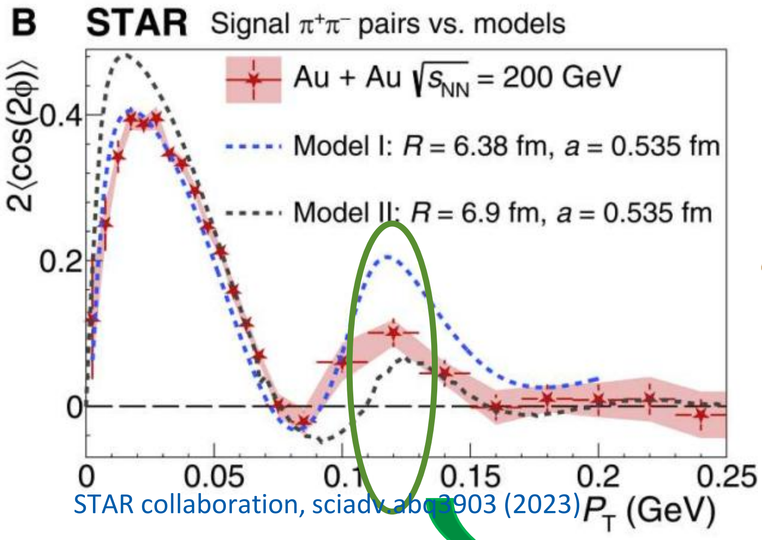
- Sensitive to **nuclear geometry**
- Indicate one solution to the **20-year puzzle** of unreasonably large nuclear radii extracted from photonuclear A+A interactions

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

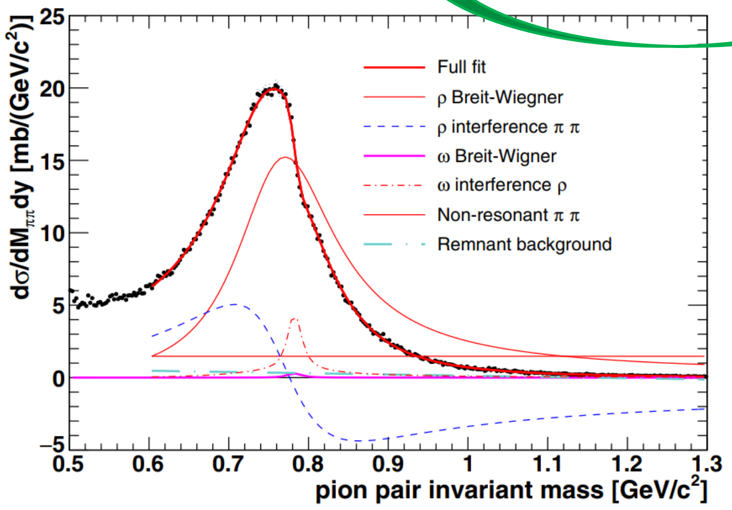
	$R_{inclusive}$ (fm)	$R(\phi = 0)$ (fm)	$R(\phi = \pm\pi/2)$ (fm)	Fitted R_0 (fm) (Eq. 4)	Fitted R_0 (fm) (Eq. 10)	Final (fm)
Au	7.47 ± 0.02	7.86 ± 0.03	7.15 ± 0.03	6.62 ± 0.03	6.72 ± 0.02	6.53 ± 0.03
U	7.98 ± 0.03	8.12 ± 0.06	7.60 ± 0.06	7.37 ± 0.07	7.37 ± 0.03	7.29 ± 0.06

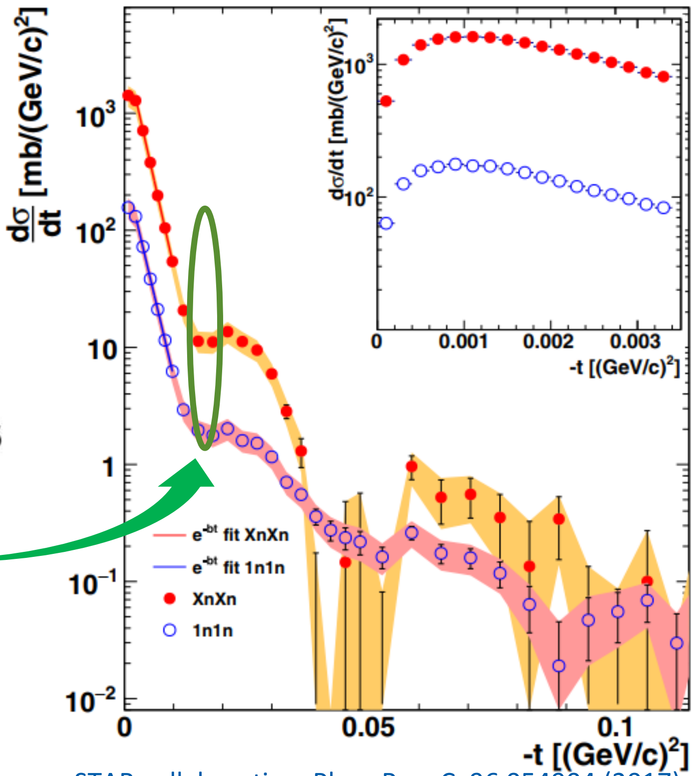
STAR collaboration, sciadv.abq3903 (2023)

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 $\gamma\gamma \to \mu^+\mu^-$

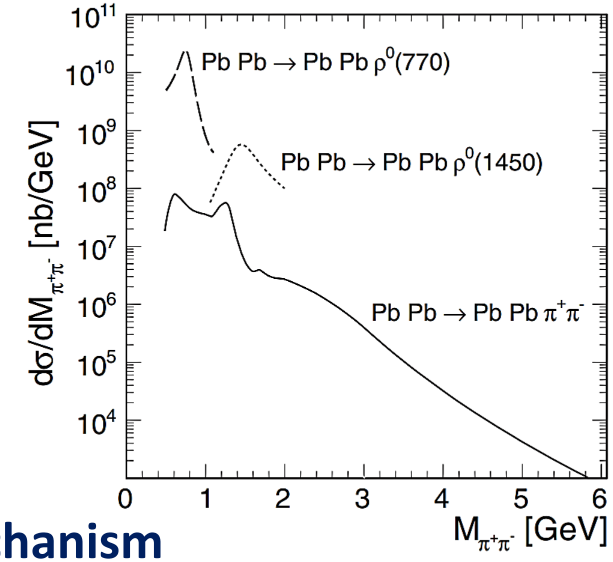
$$\hat{M} = -ie^2\int \frac{d^4q_1}{(2\pi)^4} \not{A}^{(1)}(q_1)\frac{\not{p}_- - \not{q}_1 + m}{(p_- - q_1)^2 - m^2} \not{A}^{(2)}(p_+ + p_- - q_1)$$
$$- ie^2 \int \frac{d^4q_1}{(2\pi)^4} \not{A}^{(2)}(p_+ + p_- - q_1)\frac{\not{q}_1 - \not{p}_+ + m}{(q_1-p_+)^2 - m^2} \not{A}^{(1)}(q_1)$$
$$= -i\left(\frac{Ze^2}{2\pi}\right)^2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

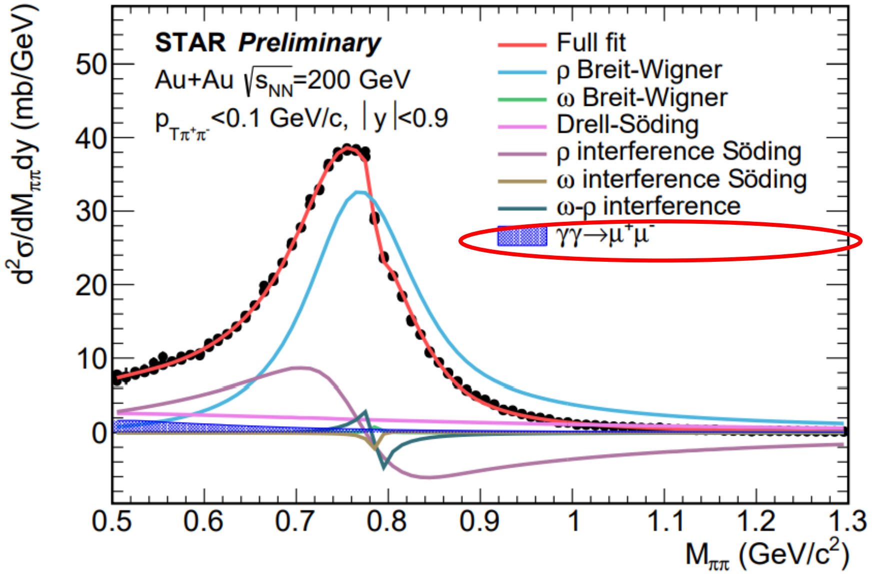
$$P(p_+, p_-, b) = \sum_s |M|^2$$

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)

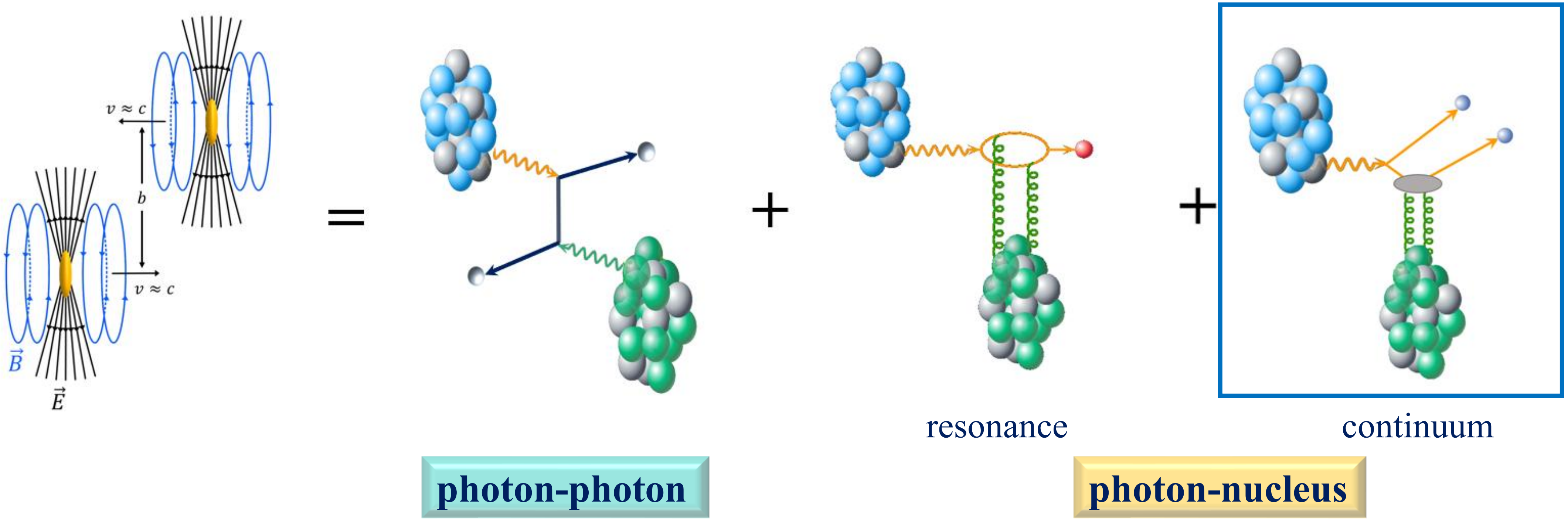




M. Kłusek-Gawenda and A. Szczurek, Phys. Rev. C 87 054908 (2013)

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

Photon induced process

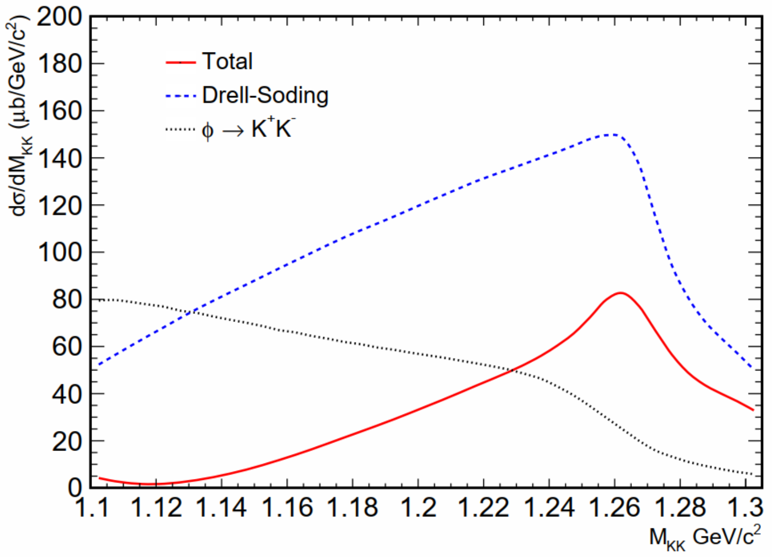


- For $\rho^0 \rightarrow \pi^+\pi^-$ (resonance) and Drell-Söding $\pi^+\pi^-$ (continuum)
- First generation quarks + same quantum number → interference of two processes
- Söding mechanism (skewed mass shape): P. Soding Phys. Lett. 19 (1966) 702

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

More related topics

> “The entanglement in each event between π^+ and π^- is essential — it ensures that the decay products share a non-factorizable quantum state, encoding the spin and angular momentum of the parent ρ. The spin interference is not entanglement *between events*, but emerges from **coherent production amplitudes** in each event, **filtered through the entangled decay products’ angular correlations**. This is aligned with the entanglement-enabled interferometry picture suggested by Cotler and Wilczek — though here, the entanglement is *intra-event*, while the observable pattern builds statistically over many events.”



(Under very specific acceptance selections)

Materials

- For different years, the results were combined using the following formula:

$$mDen = \Sigma \frac{1}{E_{stat}^2}$$

$$W_{Run} = \frac{1}{E_{stat}^2{}_{Run} \times mDen}$$

$$\sigma_{combined} = \Sigma W_{\mathrm{Run}} \times \sigma_{Run}$$

$$E_{combined}^{stat} = \sqrt{\Sigma (W_{Run} \times E_{stat})^2}$$

$$E_{combined}^{sys} = \Sigma W_{\mathrm{Run}} \times E_{sys}$$

Materials

- The cross section for $\frac{d\sigma_{\gamma p \to \pi^+\pi^- p}}{dM_{\pi^+\pi^-}}$:

$$\frac{d\sigma}{dt dM_{\pi^+\pi^-} d\Omega} = \frac{q}{256\pi^4 \left(s - m_p^2\right)^2} |M|^2$$

$$M = e\left[\left(\frac{\epsilon \cdot q_+}{k \cdot q_+}\right) T_- - \left(\frac{\epsilon \cdot q_-}{k \cdot q_-}\right) T_+ + \frac{\epsilon \cdot (p + p')}{k \cdot (p + p')} \left(T_+ - T_-\right)\right] \qquad T_\pm = 2i\sigma_{\pi p} \left[\left(q_\pm \cdot p'\right)^2 - m_\pi^2 m_p^2\right]^{1/2} e^{B_\pm t/2}$$

- The cross section in the momentum space:

$$\frac{d^3 P}{dM_{\pi^+\pi^-} dp_x dp_y} = \left|\frac{1}{2\pi} \int d^2 x_\perp \left[A_1(x_\perp) + A_2(x_\perp)\right] e^{i p_\perp \cdot x_\perp}\right|^2 \qquad \frac{d^3\sigma}{dM_{\pi^+\pi^-} dp_x dp_y} = \int \frac{d^3 P}{dM_{\pi^+\pi^-} dp_x dp_y} P(b) 2\pi b db$$

Materials

- Luminosity: Common uncertainty for each run.
- TPC efficiency: Extracted from the difference between the embedding and data.
- TOF efficiency: Extracted from the difference between the calculated from the Λ decay proton and the TPC proton.
- PID efficiency: Extracted from different centralities.
- V_z cut efficiency: Extracted from the calculated difference between UPC data and zerobias data.

	Run 10	Run 11	Run14
Luminosity	10%	10%	10%
nHitsDedx	5%	3%	2%
nHitsFit	1%	1%	2%
DCA	6%	7%	14%
TOF	10%	9%	3%
PID	7%	7%	2%
V_z	1%	2%	2%
Total	18%	17%	18%

Materials

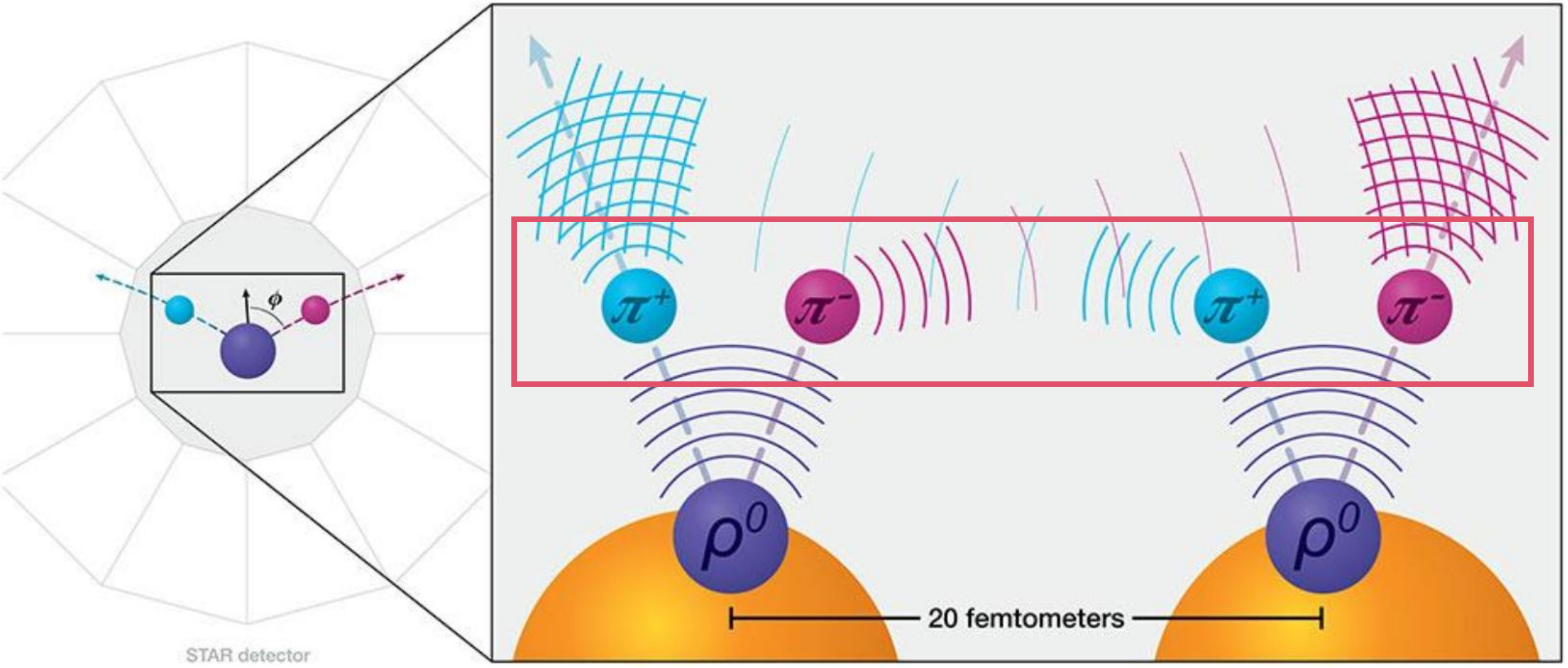
ρ^0

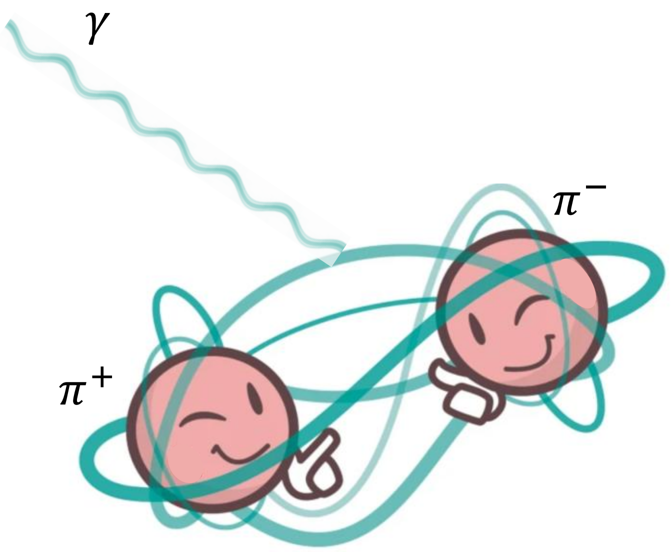
Run\sys uncert (%)	Fitting function	Fitting range	Mc model	nhitsfit	Dca	Vz	Lumi	track	Uncorr.	total
Run10	2.11	0.09	1.31	2.87	0.74	3.18	10.00	6.00	4.54	12.73
Run11	2.59	1.20	12.73	1.70	2.64	0.88	…	…	13.15	17.77
Run14high	1.24	0.02	0.06	6.63	4.12	3.56	…	…	8.67	14.78
Run14low	1.50	0.08	0.32	3.71	1.68	3.39	…	…	5.52	13.04
Run14mid	1.59	0.06	0.71	4.36	2.48	3.99	…	…	4.54	13.62

Söding

Run\sys uncert (%)	Fitting function	Fitting range	Mc model	nhitsfit	Dca	Vz	Lumi	track	Uncorr.	total
Run10	6.27	1.34	6.01	5.38	3.34	1.08	10.00	6.00	8.90	15.98
Run11	15.56	0.98	13.84	14.07	18.58	20.73	…	…	34.18	39.38
Run14high	2.53	0.16	4.93	6.51	4.47	2.27	…	…	8.60	15.52
Run14low	2.18	0.83	5.30	4.60	2.99	0.67	…	…	6.00	14.34
Run14mid	3.40	0.45	7.75	5.16	3.18	1.48	…	…	7.12	16.06

Spin-Interference effect





angular momentum conservation

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

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

Spin-Interference (EESI)!