

# Quantum entanglement of partons in strongly coupled QFTs

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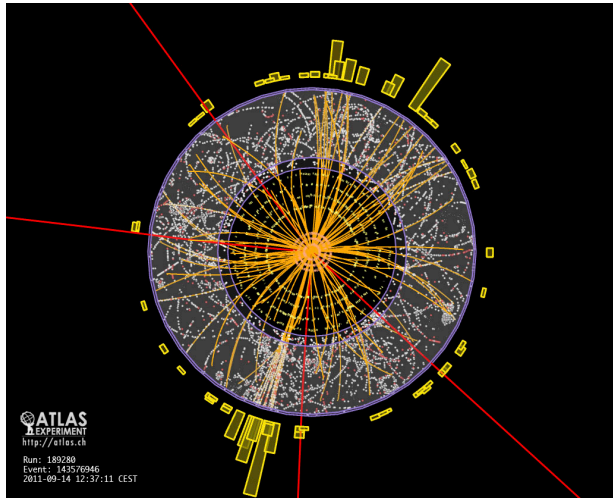
# HEP in a nutshell

$$\sigma = \sum_{a,b} \int dx_a dx_b \hat{\sigma}_{ab \rightarrow X} f_{a/A}(x_a, \mu_F) f_{b/B}(x_b, \mu_F)$$

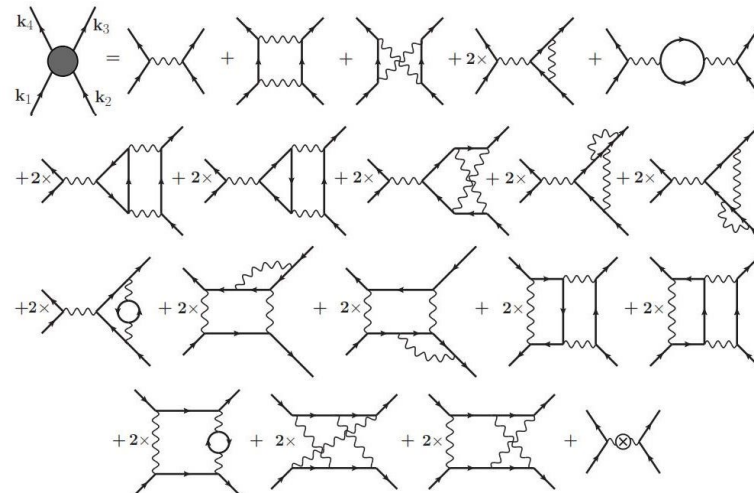
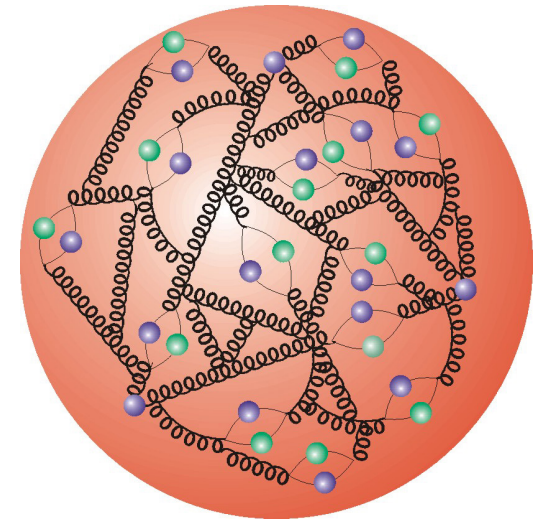
experimental  
measurements

perturbation  
theory

parton structure  
of the proton



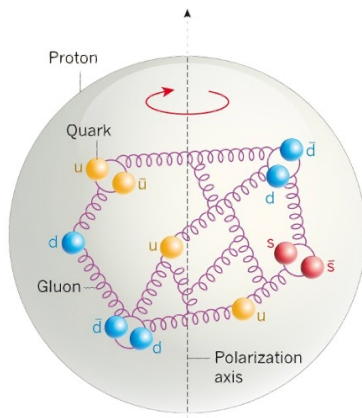
October 25, 2026



# Parton distribution function (PDF)

- PDF  $f(x)$  describes the **probability density** of finding a collinear parton of longitudinal momentum fraction  $x$
- Non-perturbative  $\rightarrow$  obtained from **global fits**

quark model, Gell-Mann 1964



$T_{\text{int}} \sim \Lambda_{QCD}^{-1} = 10^{-23} \text{s}$   
quarks are strongly coupled

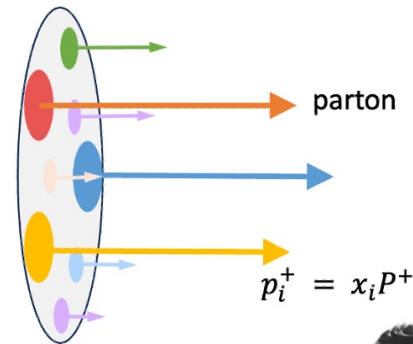


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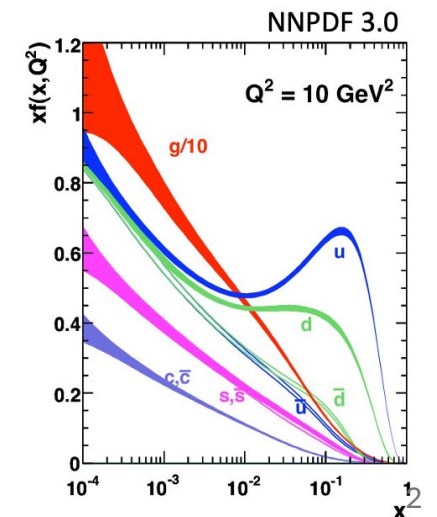
parton model, Feynman 1969



$P \rightarrow \infty$



$T_{\text{int}} \sim \gamma \Lambda_{QCD}^{-1} \gg 10^{-23} \text{s}$   
partons are free!

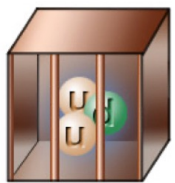


# Parton entropy paradox

Kharzeev, 2021

$$S_{\text{Shn}}(f) = \ln \Delta x^{-1} - \int_0^1 dx f(x) \ln f(x) > 0$$

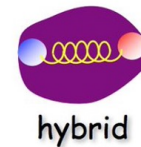
- But proton is a pure state  $\rho = |\psi\rangle\langle\psi|$  with a vanishing entropy!
- Entropy = loss of information: **some quantum information of the proton is lost in the parton picture**
- New angle to longstanding puzzles in the proton structure, e.g. confinement, origin of mass?



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dibaryon



hybrid



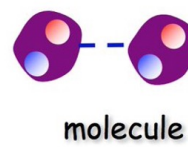
Pentaquark



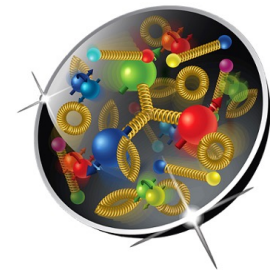
glueball



tetraquark

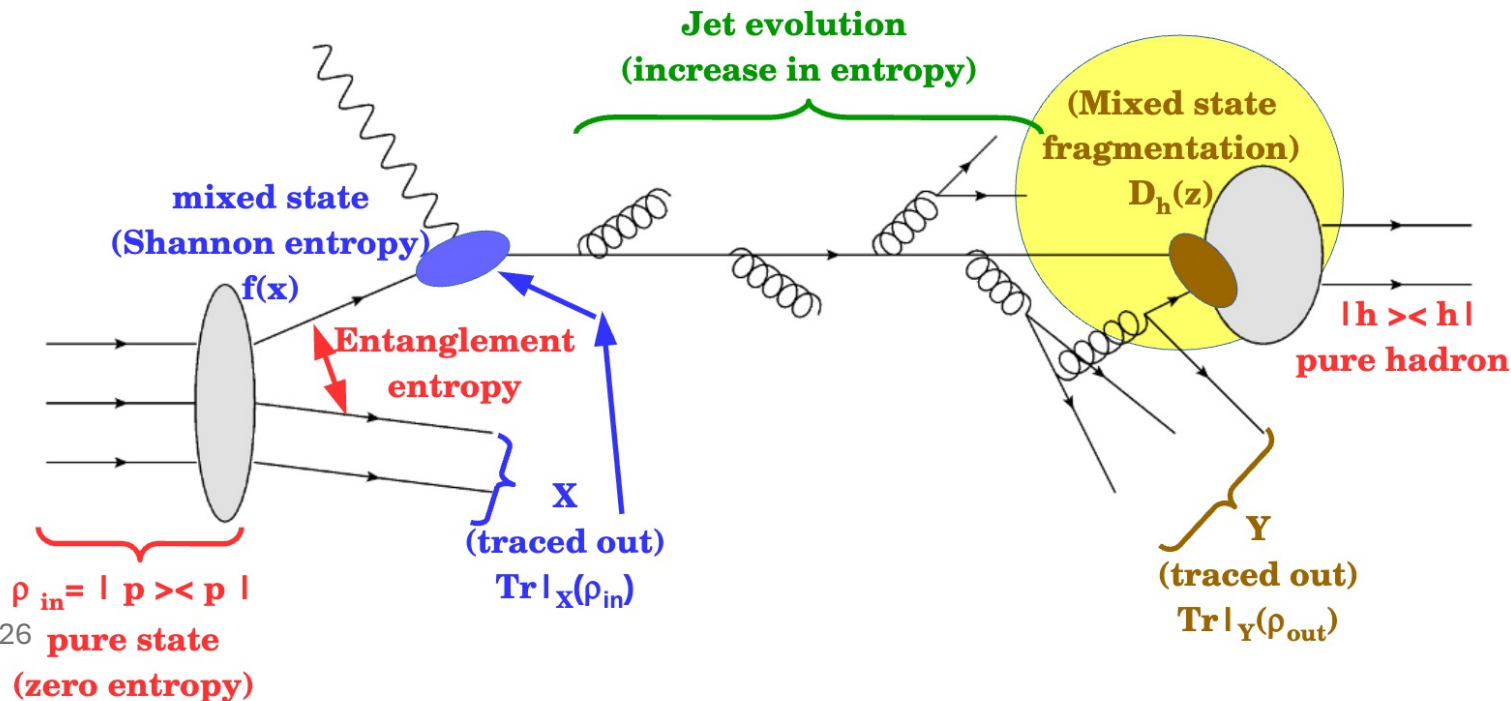


molecule



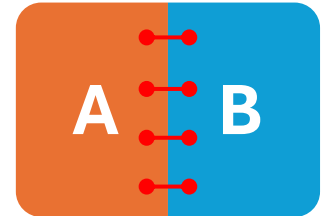
# Parton entropy as quantum entanglement

- von Neumann entropy:  $S_{\text{vN}}(\rho_A) = -\text{Tr} \rho_A \ln \rho_A$  measures the quantum entanglement between  $A$  and  $B$ , where  $\rho_A = \text{Tr}_B \rho$
- What is the relation between  $S_{\text{vN}}(\rho_A)$  and  $S_{\text{Shn}}(f)$ ?



Shannon entropy:

$$S_{\text{Shn}}(\{p_i\}) = - \sum_i p_i \log p_i$$



$$S_A = S_B$$

# Quantum entanglement

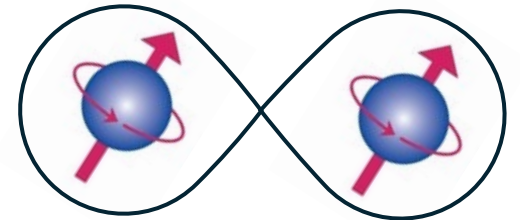
- A quantum state  $|\psi\rangle_{AB}$  is said to be unentangled (or separable) if it can be written as a product state

$$|\psi\rangle_{AB} = |\phi\rangle_A \otimes |\varphi\rangle_B$$

Otherwise it is called entangled.

- Example: the Bell state

$$\frac{1}{\sqrt{2}} (|\uparrow\rangle_A \otimes |\uparrow\rangle_B + |\downarrow\rangle_A \otimes |\downarrow\rangle_B)$$



Measuring A directly determines B – even if AB are far away!

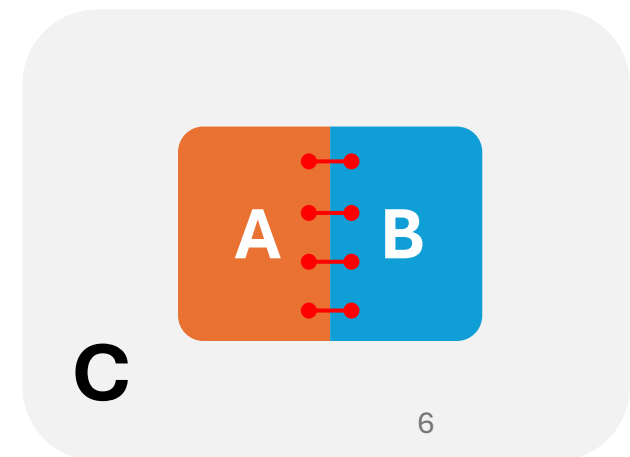
- For pure state, completely quantified by entangl. entropy  $S_{\text{vN}}(\rho_A)$

# Mixed states

- A mixed state  $\rho_{AB}$  is separable (unentangled) if it can be written as

$$\rho_{AB} = \sum_i p_i \rho_i^A \otimes \rho_i^B$$

- Entanglement entropy **fails** for mixed states
- How to detect quantum entanglement in  $\rho_{AB}$  ? an NP-hard problem
  - Mutual information
$$I(A:B) = S(\rho_A) + S(\rho_B) - S(\rho_{AB})$$
  - Bell inequality (CHSH operators)
  - Quantum negativity, related to the PPT criteria

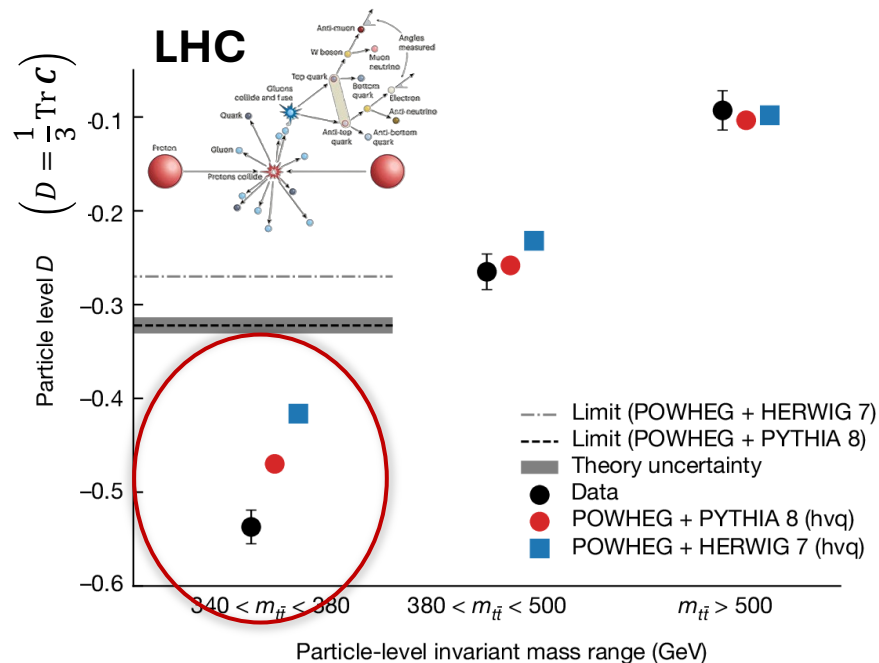
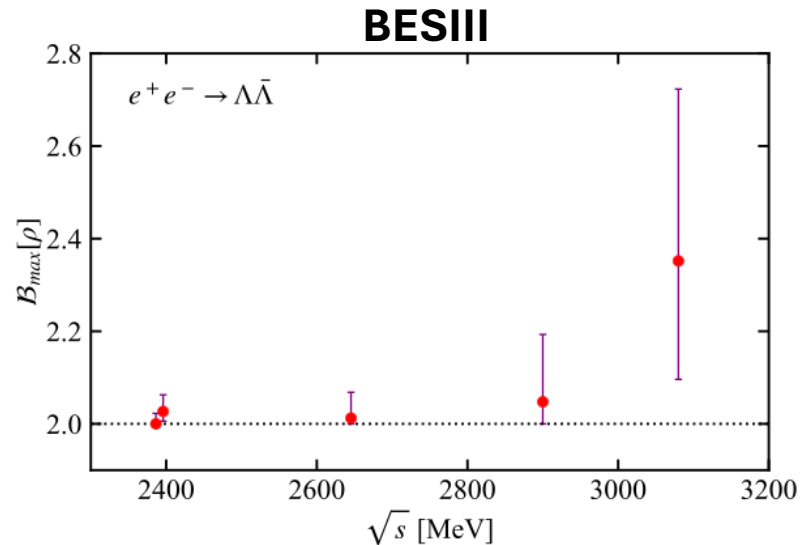
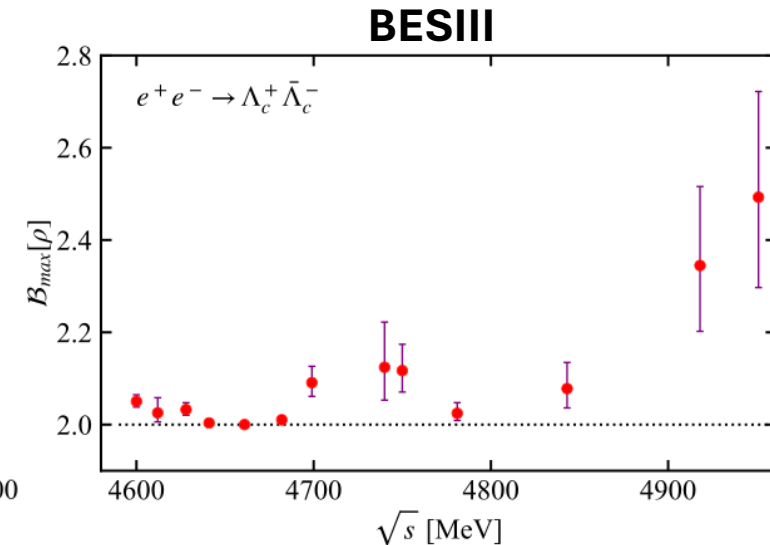


# Test of QM at subatomic level

- Spin density matrix:

$$\rho_{B\bar{B}} = \frac{1}{4} \left( 1 + \vec{P}_+ \cdot \vec{\sigma} \otimes 1 + 1 \otimes \vec{P}_- \cdot \vec{\sigma} + \mathcal{C}_{ij} \sigma_i \otimes \sigma_j \right)$$

- Loophole within HEP experiments



# Quantum entanglement as a resource

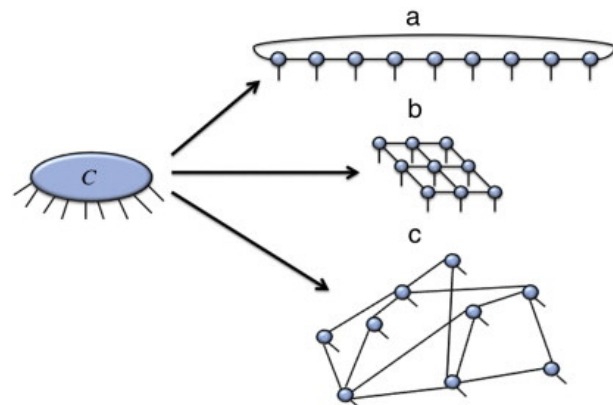
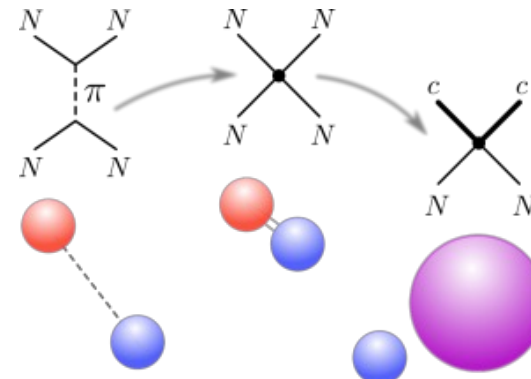
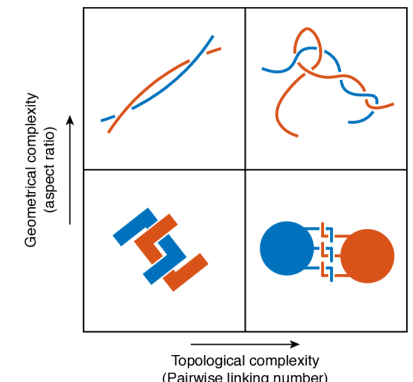
- **Quantum resource:** quantum speedup, sensing and cryptography
- classfcn. of interaction → classfcn. of **gs entanglement property**
  - Area law: gapped local Hamiltonian

$$S_A \propto |\partial A|$$

Example: 1D area law leads to matrix product state (MPS) → 2, 3D?

- Entanglement spectrum: topological order and SPT

$$\rho_A = \exp(-H_E)$$



# Entanglement entropy in QFT

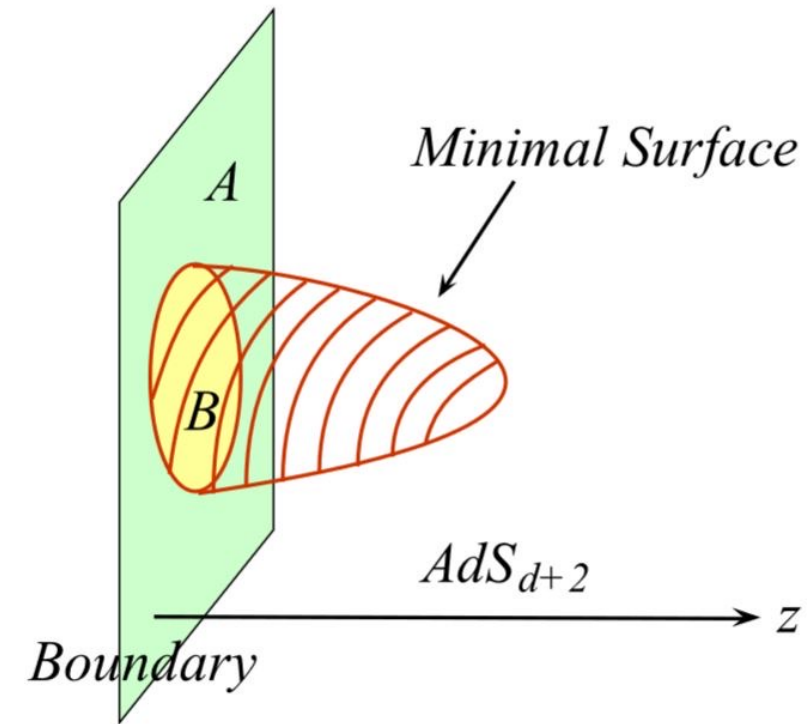
- Ryu-Takayanagi formula:

$$S_B = \min_{\partial V \sim \partial B} \frac{\mathcal{A}_V}{4G_N}$$

- Replica Trick

$$S_B = \lim_{n \rightarrow 1} \frac{\log \text{Tr } \rho_B^n}{n - 1}$$

- Not directly measurable in high-energy physics experiments:  
particles vs geometry
- How to compute the entanglement between partons?



# Density matrix

- Density matrix of the hadron:  $\rho = |\Psi\rangle\langle\Psi|$  ( $\langle\Psi|\Psi\rangle = 1$ )
- Reduced density matrix:

$$\rho_A = \text{Tr}_B |\Psi\rangle\langle\Psi|$$

- If  $\rho_A$  is diagonal:

$$\rho_A = \sum_i p_i |i\rangle\langle i|$$

$$\Rightarrow S_{\text{vN}}(\rho_A) = -\text{Tr}\rho_A \log \rho_A = -\sum_i p_i \ln p_i$$

- **Need state vector  $|\Psi\rangle$  (or wave function)**

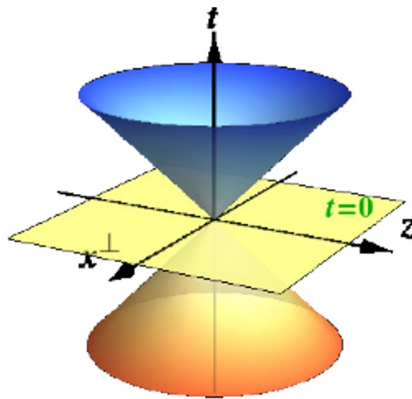
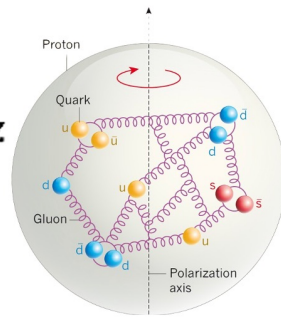
# Light-front quantization

$$i \frac{\partial}{\partial x^\mu} |\Psi\rangle = \mathcal{P}_\mu |\Psi\rangle$$

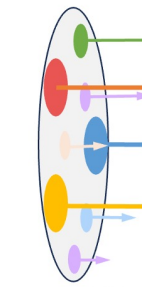
- Choice of time:  $x^0, x^+$   $\Rightarrow$  direction of dynamical evolution
- **parton field theory = light-front quantization**

Polyzou, 2021

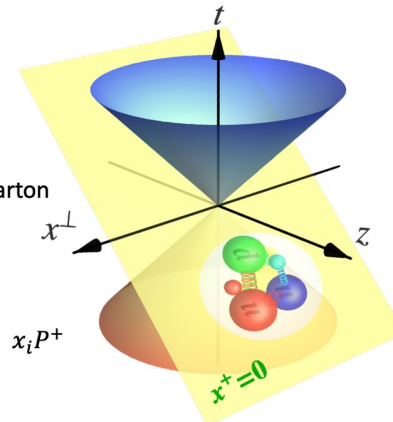
equal-time quantization  
 $t = 0$



infinite momentum  
frame  $P_z \rightarrow \infty$



light-front quantization  
 $x^+ = t + z/c = 0$



parton  
 $p_i^+ = x_i P^+$

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$$i \frac{\partial}{\partial t} |\Psi\rangle = P^0 |\Psi\rangle$$



$$i \frac{\partial}{\partial x^+} |\Psi\rangle = P_+ |\Psi\rangle$$

# Scalar Yukawa theory

$$\mathcal{L} = \partial_\mu N^\dagger \partial^\mu N - m^2 N^\dagger N + \frac{1}{2} \partial_\mu \pi \partial^\mu \pi - \frac{1}{2} \mu^2 \pi^2 + g N^\dagger N$$

- Nucleon-pion interaction – Yukawa potential

$$V(r) = -\frac{\alpha}{r} e^{-\mu r} \qquad \alpha = \frac{g^2}{16\pi m^2}$$

- Super-renormalizable: divergence only in 1-loop
- No gauge fields: no collinear divergence or gauge link
- **Non-perturbative** entanglement entropy in **3+1D** based on the state vector

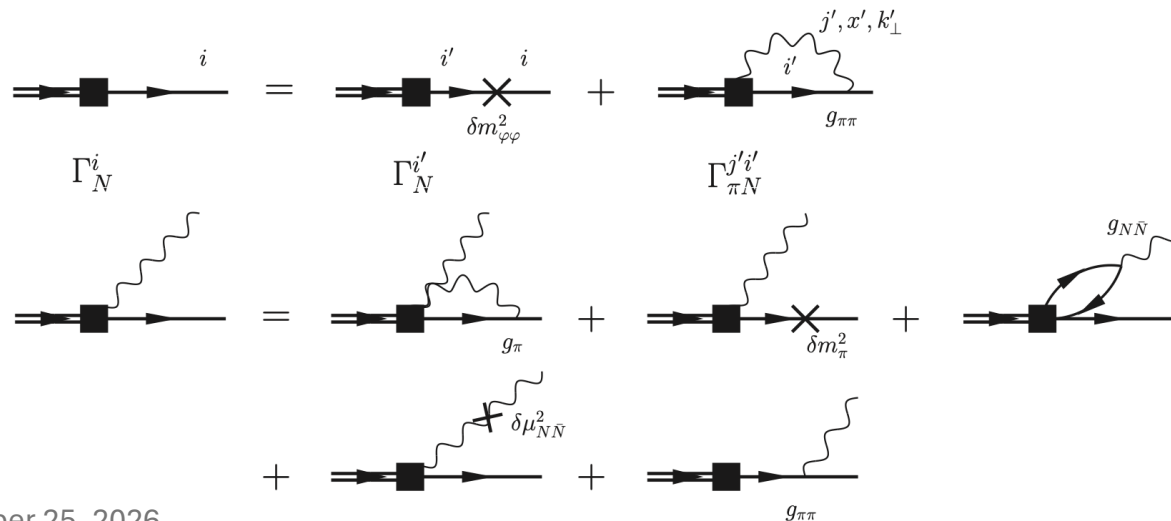
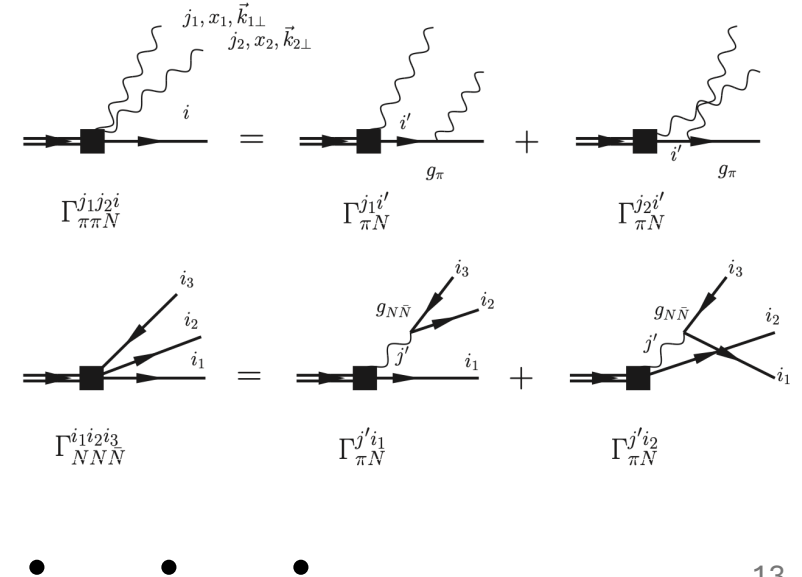
# Light-cone Hamiltonian truncation

- Fock expansion:

$$|N\rangle_{\text{ph}} = |N\rangle + |\pi N\rangle + |\pi\pi N\rangle + |NN\bar{N}\rangle + |\pi\pi\pi N\rangle + \dots$$

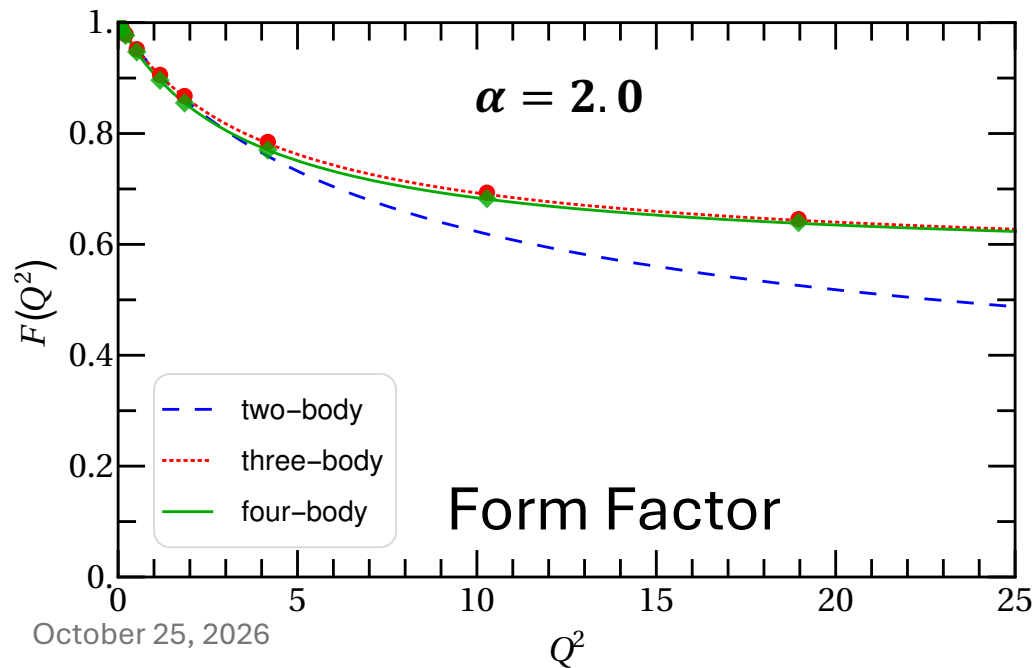
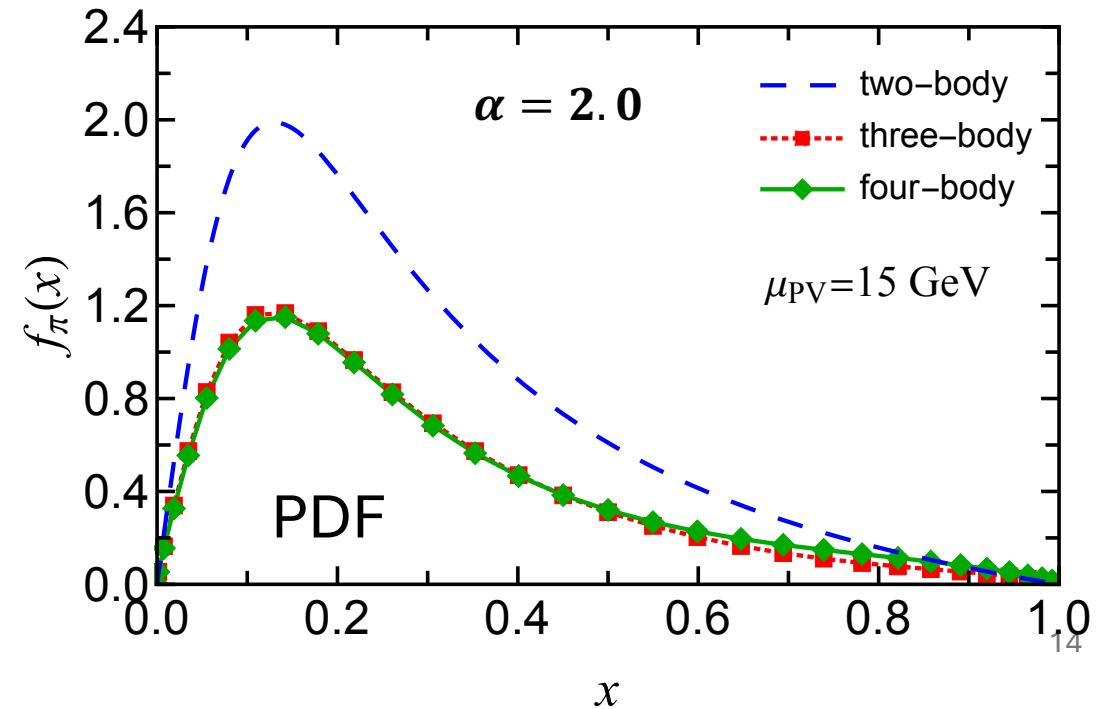
- Non-perturbative renormalization
- Numerical solution

Li 2015, Karmanov 2016,  
Zhang 2025



# Light-cone Hamiltonian truncation

- Rapid Fock sector convergence
- No zero modes



# Density matrix

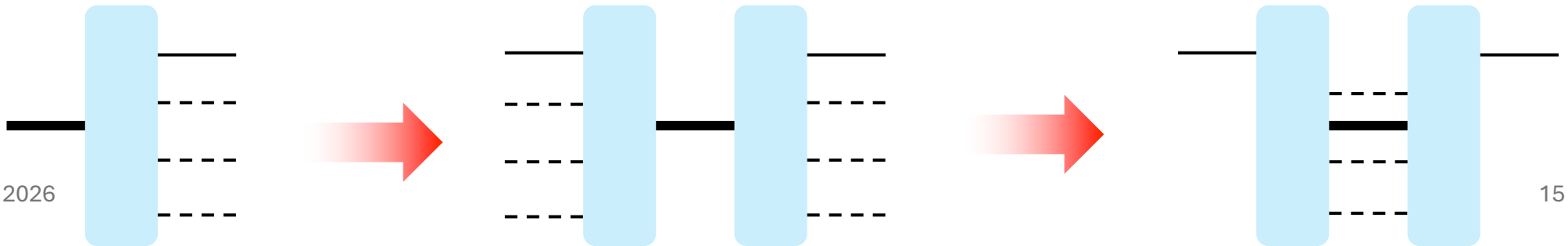
- Hadronic state vector:

$$|\Psi\rangle = \sum_F \int [d^3 p_i]_F \psi_F(\{p_1, p_2, \dots, p_n\}) |\{p_1, p_2, \dots, p_n\}\rangle$$

- Density matrix

$$\rho_N = \text{Tr}_\pi \sum_F \int [d^3 p_i]_F \int [d^3 p'_j]_F \Psi_F^*(\{p_i\}) \Psi_F(\{p'_j\}) \underbrace{|\{p_1, p_2, \dots, p_n\}\rangle}_{\text{pion d.o.f.}} \underbrace{\langle \{p_1, p_2, \dots, p'_n\}|}_{\text{pion d.o.f.}}$$

- $\rho_N$  is **NOT diagonal** in general



# Density matrix in quenched approximation

$$|N\rangle_{\text{ph}} = |N\rangle + |\pi N\rangle + |\pi\pi N\rangle + |NN\bar{N}\rangle + |\pi\pi\pi N\rangle + \dots$$

- Quenched approximation: no sea nucleons – only one nucleon
- Factorization of the **center-of-mass motion** on the light front:

$$\Psi(p_1, p_2, \dots, p_n) = \Psi(P) \psi(\{x_i, \vec{k}_i\})$$

where  $P = \sum_i p_i$ ,  $x_i = p_i^+ / P^+$ ,  $\vec{k}_{i\perp} = \vec{p}_{i\perp} - x_i \vec{P}_\perp$

- In the **narrow wavepacket limit (NWL)**, momentum conservation forces  $\rho_N$  to **become diagonal**, no need to do LF-time scrambling

$$\Psi(P) \rightarrow \delta^3(P - P_0)$$

- Not available in equal-time quantization!



# Entanglement entropy in quenched theory

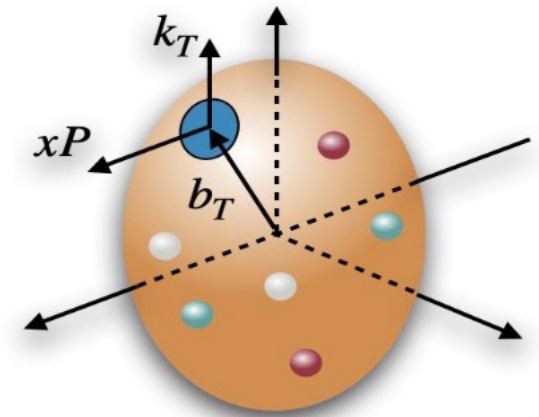
$$\rho_N = \frac{1}{P^+V} \int \frac{dx}{2x} \int \frac{d^2 k_\perp}{(2\pi)^3} f_N(x, k_\perp) |p\rangle \langle p|$$

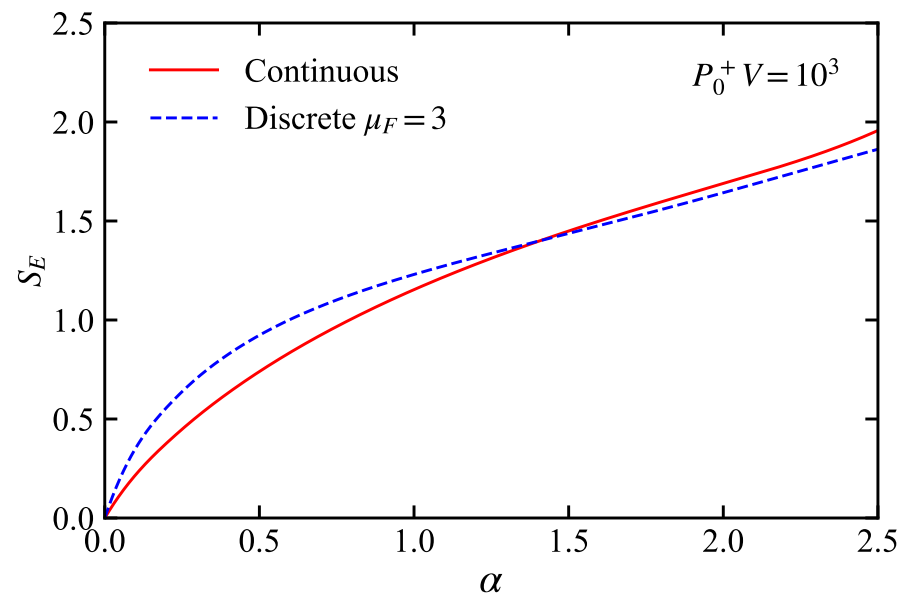
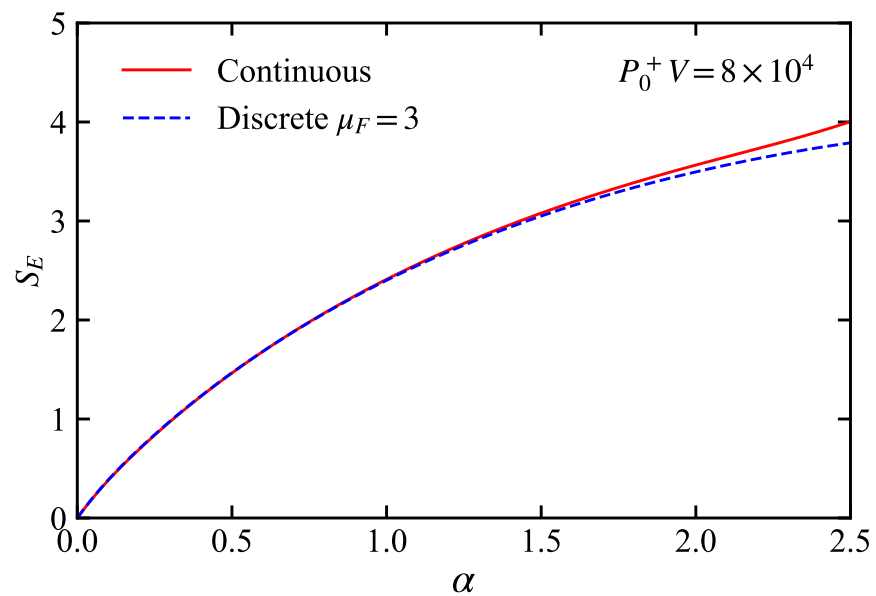
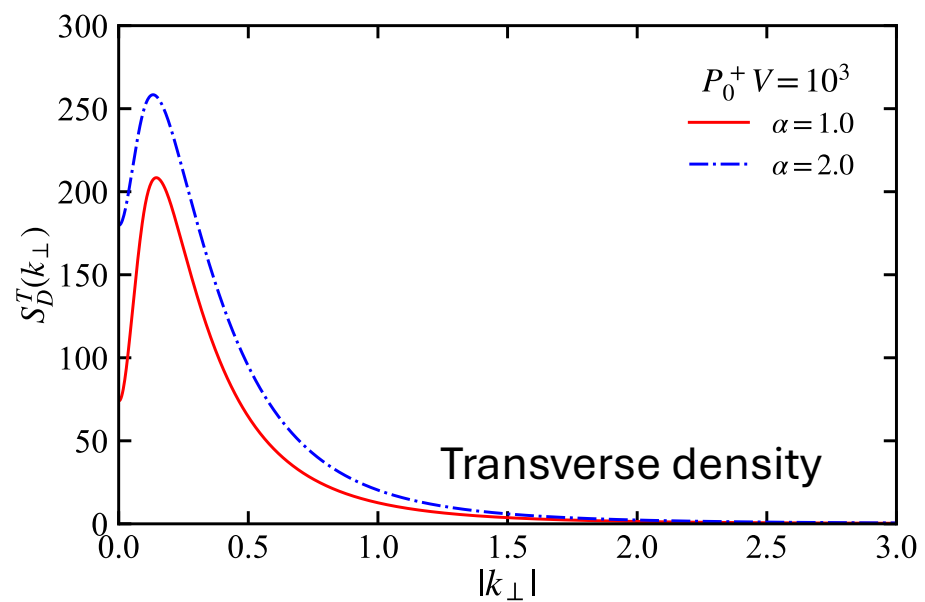
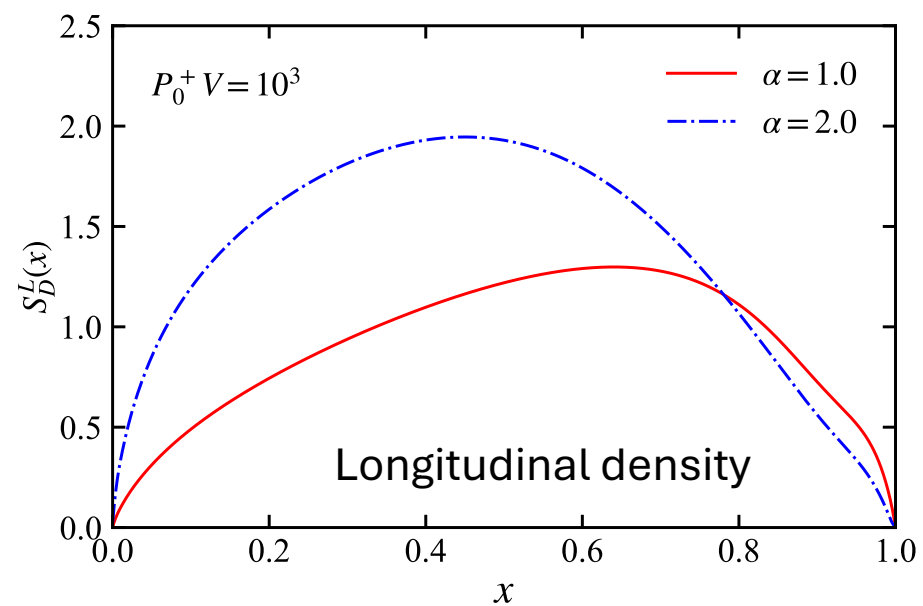
here,  $f_N(x, k_\perp)$  is the nucleon transverse momentum distribution (TMD)

- Entanglement entropy:

$$\begin{aligned} S_{\text{vN}}(\rho_N) &= \ln P^+V - \int dx \int \frac{d^2 k_\perp}{(2\pi)^3} f_N(x, k_\perp) \ln f_N(x, k_\perp) \\ &= S_{\text{Shn}}(f_N) \end{aligned}$$

- Entanglement entropy = Shannon entropy (in quenched ansatz)





# Entanglement entropy in unquenched theory

$$|N\rangle_{\text{ph}} = |N\rangle + |\pi N\rangle + |\pi\pi N\rangle + |NN\bar{N}\rangle + |\pi\pi\pi N\rangle + \dots$$

- Unquenched theory: add back **the sea**
- Problem: the reduced density matrix is no longer diagonal in the narrow wavepacket limit (NWL),

$$\rho_N = |N\rangle\langle N| + \text{Tr}_\pi |\pi N\rangle\langle \pi N| + \text{Tr}_\pi |\pi\pi N\rangle\langle \pi\pi N| \\ + \text{Tr}_{\bar{N}} |NN\bar{N}\rangle\langle NN\bar{N}|$$

- Cross terms, such as  $\text{Tr}_\pi |\pi\pi N\rangle\langle \pi N|$ , vanish
- **The sea contribution  $\text{Tr}_{\bar{N}} |NN\bar{N}\rangle\langle NN\bar{N}|$  is non-diagonal**

# Non-diagonal part

- Numerical diagonalization: is analytical expression still possible?
- Note that

$$\rho_N = \rho_N^{(1)} \oplus \rho_N^{(2)}$$

- $\rho_N^{(1)} = |N\rangle\langle N| + \text{Tr}_\pi |\pi N\rangle\langle \pi N| + \text{Tr}_\pi |\pi\pi N\rangle\langle \pi\pi N|$  is shown to be diagonal in NWL
- $\rho_N^{(2)} = \text{Tr}_{\bar{N}} |NN\bar{N}\rangle\langle NN\bar{N}|$  is non-diagonal in NWL
- Can diagonalize  $\rho_N^{(1)}, \rho_N^{(2)}$  separately:

$$\rho_N = \begin{pmatrix} \rho_N^{(1)} & \\ & \rho_N^{(2)} \end{pmatrix}$$

$$S_{\text{vN}}(\rho_N) = S_{\text{vN}}\left(\rho_N^{(1)}\right) + S_{\text{vN}}\left(\rho_N^{(2)}\right)$$

Diagonal

Non-diagonal

# Non-diagonal part

$$\begin{aligned}\varrho &\equiv |NN\bar{N}\rangle\langle NN\bar{N}| \\ \varrho_{\bar{N}} &= \text{Tr}_N |NN\bar{N}\rangle\langle NN\bar{N}| \\ \varrho_N &= \text{Tr}_{\bar{N}} |NN\bar{N}\rangle\langle NN\bar{N}|\end{aligned}$$

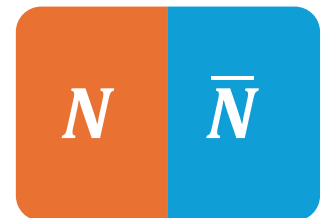
- How to diagonalize  $\rho_N^{(2)} = \text{Tr}_{\bar{N}} |NN\bar{N}\rangle\langle NN\bar{N}| \equiv \varrho_N$ ?
- Note that  $\varrho_{\bar{N}} \equiv \text{Tr}_N |NN\bar{N}\rangle\langle NN\bar{N}|$  is diagonal in the NWL

$$\varrho_{\bar{N}} = \frac{1}{P^+V} \int \frac{dx}{2x} \int \frac{d^2 k_{\perp}}{(2\pi)^3} f_{\bar{N}}(x, k_{\perp}) |p\rangle\langle p|$$

$$\Rightarrow S_{\text{vN}}(\varrho_{\bar{N}}) = Z_{NN\bar{N}} \log P^+V - \int dx \int \frac{d^2 k_{\perp}}{(2\pi)^3} f_{\bar{N}}(x, k_{\perp}) \log f_{\bar{N}}(x, k_{\perp})$$

- On the other hand, since the subspace is **bipartite**,

$$S_{\text{vN}}(\varrho_N) = S_{\text{vN}}(\varrho_{\bar{N}})$$



$$S_N = S_{\bar{N}}$$

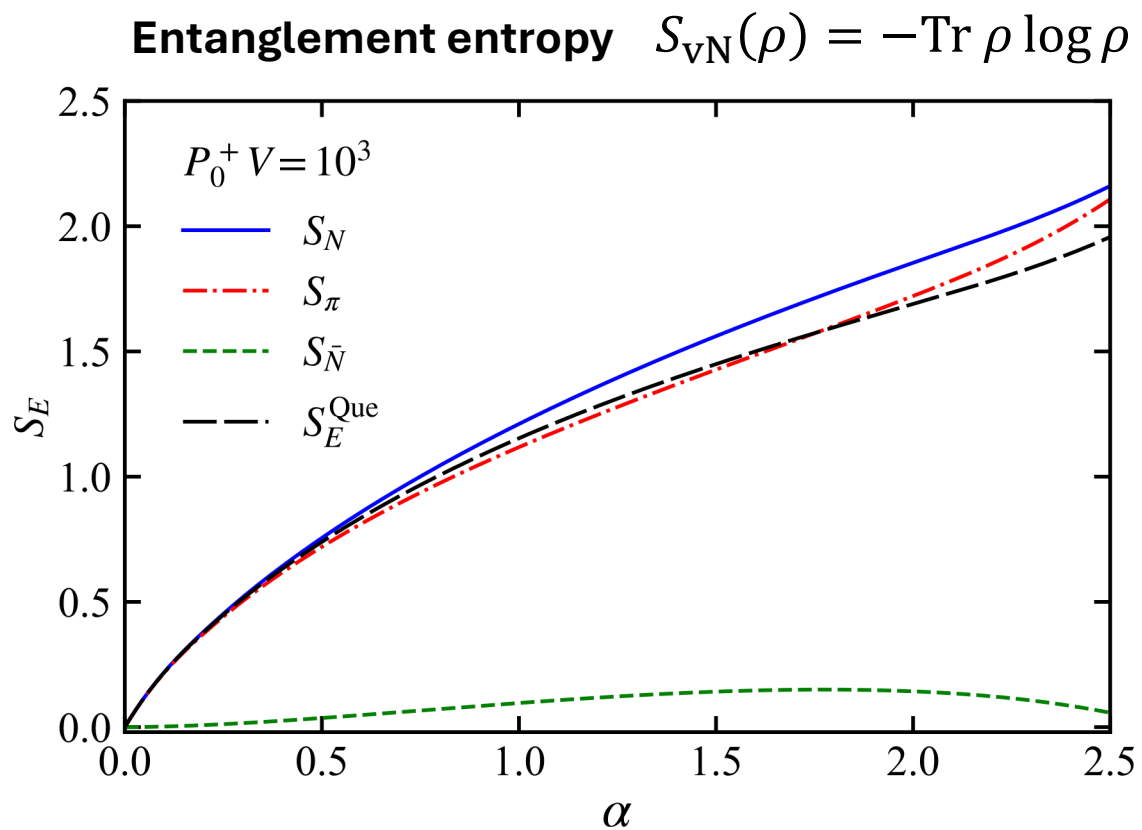
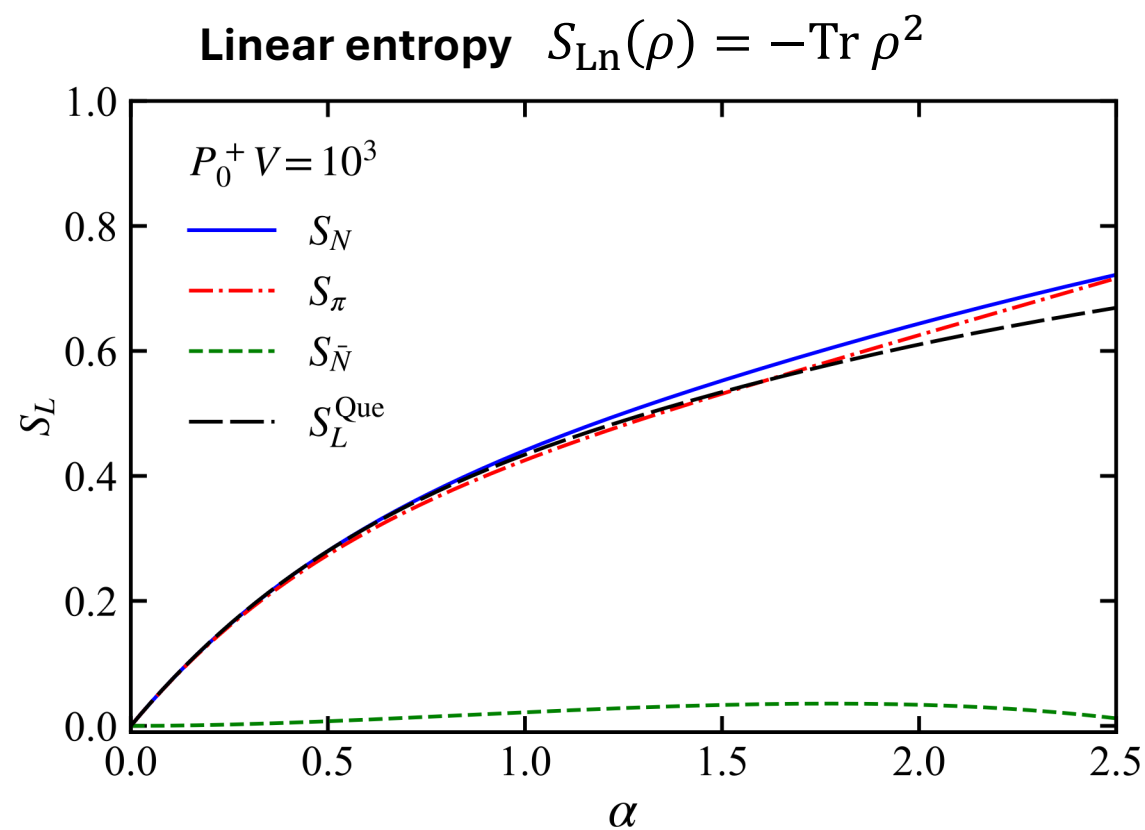
# Total entanglement entropy

$$\begin{aligned}
 S_{\text{vN}}(\rho_N) &= (1 - Z) \log P^+ V - Z \log Z \\
 &- \int dx \int \frac{d^2 k_\perp}{(2\pi)^3} f_N^{(\pi^n N)}(x, k_\perp) \log f_N^{(\pi^n N)}(x, k_\perp) \\
 &- \int dx \int \frac{d^2 k_\perp}{(2\pi)^3} f_{\bar{N}}(x, k_\perp) \log f_{\bar{N}}(x, k_\perp)
 \end{aligned}$$

where,  $Z$  is the field renormalization constant, and

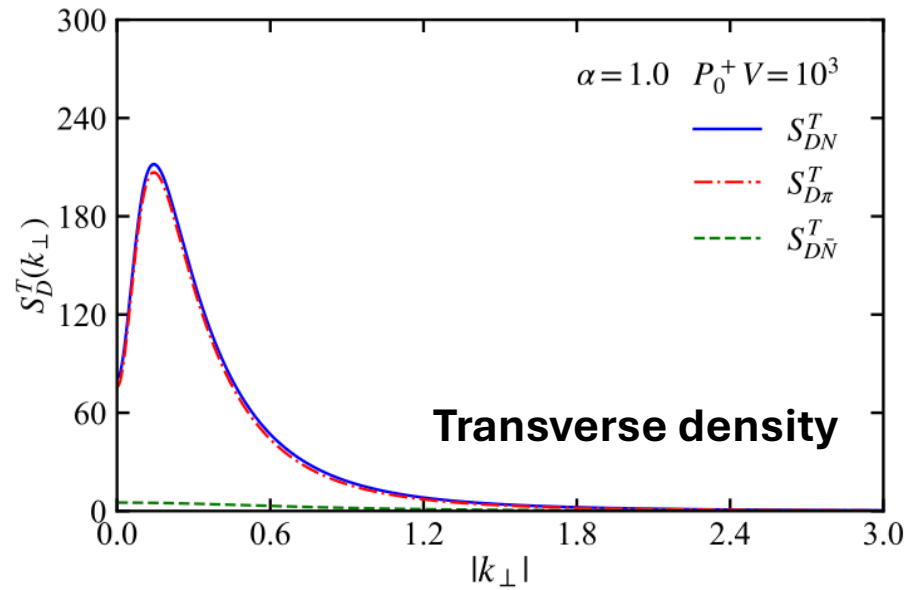
$$\begin{aligned}
 f_N^{(\pi^n N)} &\equiv f_N^{(\pi N)} + f_N^{(\pi\pi N)} + \dots \\
 &\neq f_N \equiv f_N^{(\pi N)} + f_N^{(\pi\pi N)} + \color{red}{f_N^{(NN\bar{N})}} + \dots
 \end{aligned}$$

Therefore,  $\color{red}{S_{\text{vN}}(\rho_N) \neq S_{\text{Shn}}(f_N)}$

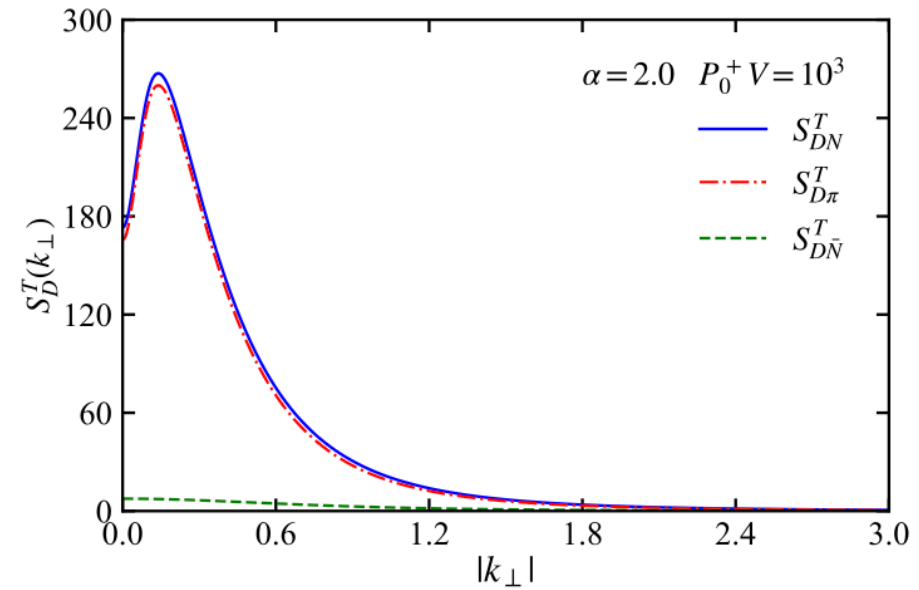
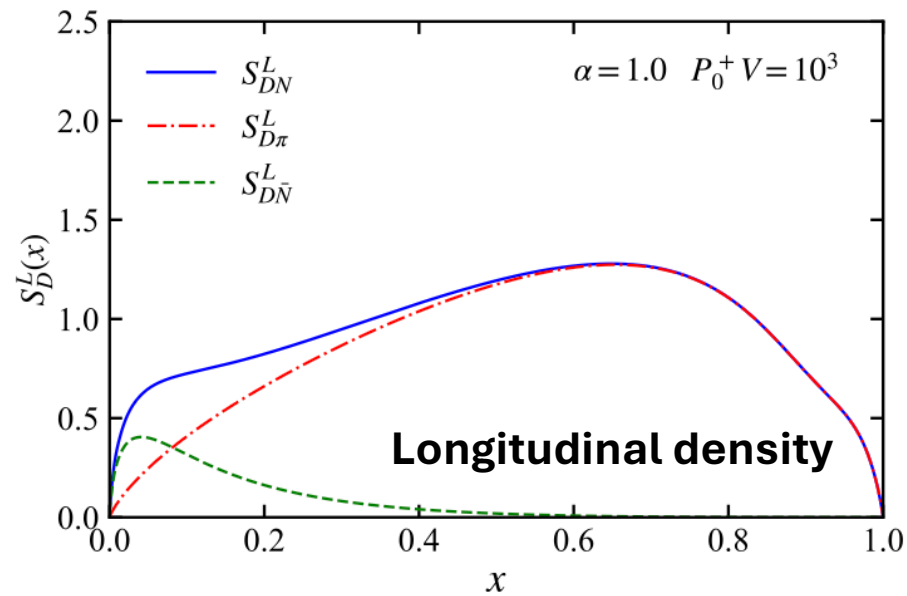
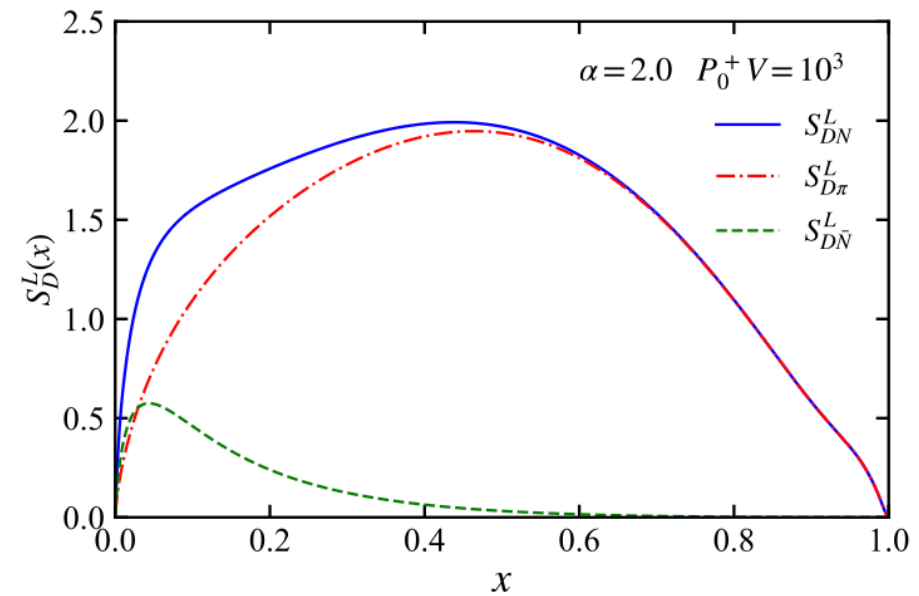


$$S_{\text{vN}}(\rho) = \frac{1}{n-1} \lim_{n \rightarrow 1} \text{Tr } \rho^n \text{ (Renyi entropy)}$$

**alpha = 1.0**

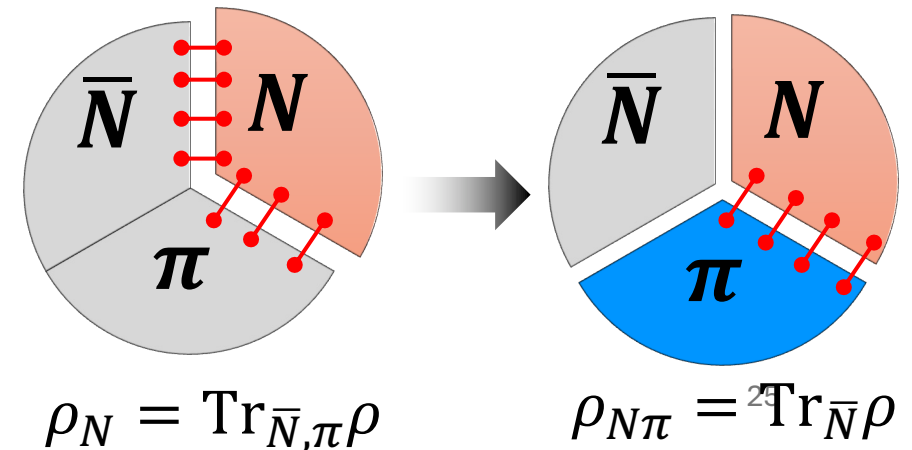


**alpha = 2.0**



# Entanglement between $N$ and $\pi$

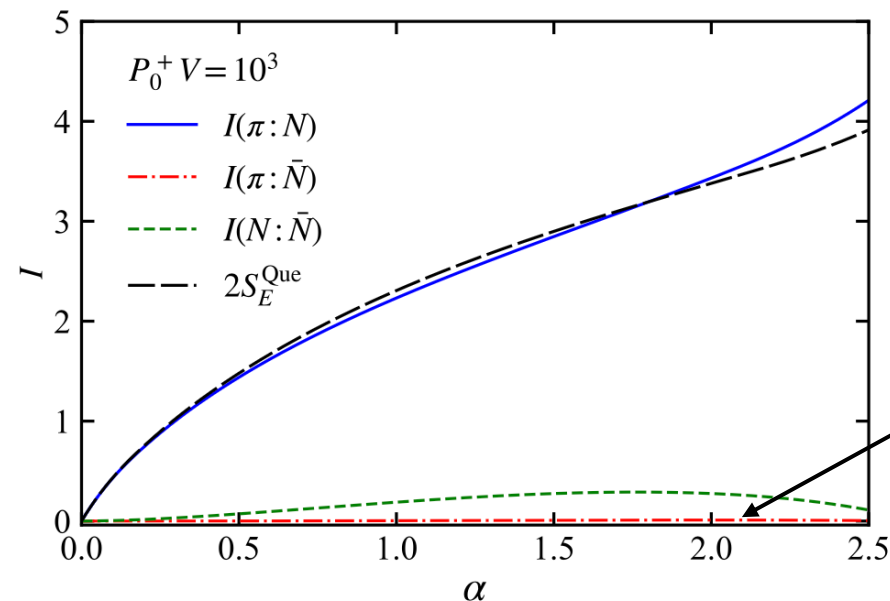
- As we trace out the anti-nucleon d.o.f., the resulting density matrix of the  $N\pi$  system  $\rho_{N\pi}$  becomes a mixed state
- Entanglement entropy contains **classical info**, only good for pure state
- There is no single criteria to detect entanglement for mixed state
  - Renyi entropy (e.g. linear entropy)
  - Mutual information
  - Quantum negativity
  - Entanglement of formation, ...



# Mutual information

- Mutual information  $I(A: B)$  characterizes the correlation between subsystems  $A$  &  $B$
- For example:

$$I(\pi: N) = S_{vN}(\rho_\pi) + S_{vN}(\rho_N) - S_{vN}(\rho_{\bar{N}}) \xrightarrow{\text{quenched apprx.}} 2S_{vN}(\rho_N)$$



Lowest Fock sector with both  $\bar{N}$  and  $\pi$ :  $|NN\bar{N}\pi\rangle$

# Positive partial transpose (PPT)

- Detect quantum entanglement between two subsystems, e.g.  $N, \pi$ 
  - Entanglement entropy: not applicable to mixed states
  - Mutual information: contains classical correlation
- PPT criterion (Peres-Horodecki criterion): If  $\rho_{AB}$  is separable,  $\rho_{AB}^T$  must be positive semi-definite

$$\rho_{AB} = \sum_{ijkl} C_{ijkl} |i\rangle_A |j\rangle_B \langle k|_A \langle l|_B \Rightarrow \rho_{AB}^T = \sum_{ijkl} C_{ijkl} |i\rangle_A |l\rangle_B \langle k|_A \langle j|_B$$

- Existing **negative eigenvalues of  $\rho_{AB}^T$**   $\Rightarrow A, B$  are entangled
- Necessary condition for the separability of a mixed state  $\rho_{AB}$

# Quantum negativity

$$\mathcal{N}(\rho_{AB}) = - \sum_{\lambda_i < 0} \lambda_i \equiv \frac{1}{2} \left( \text{Tr} \sqrt{\rho_{AB}^{T\dagger} \rho_{AB}^T} - 1 \right)$$

where,  $\lambda_i$  are eigenvalues of  $\rho_{AB}^T$ .

- Characterizes the **quantumness** of a resource
- Measures the quantum correlation beyond local interactions
- Quenched theory:

$$E_{\mathcal{N}}(\rho_{\pi N}) = \log(2\mathcal{N} + 1) = \log P^+ V + 2 \log f_{\pi N}$$

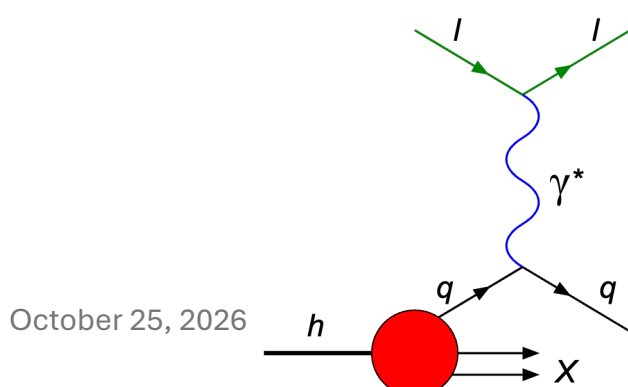
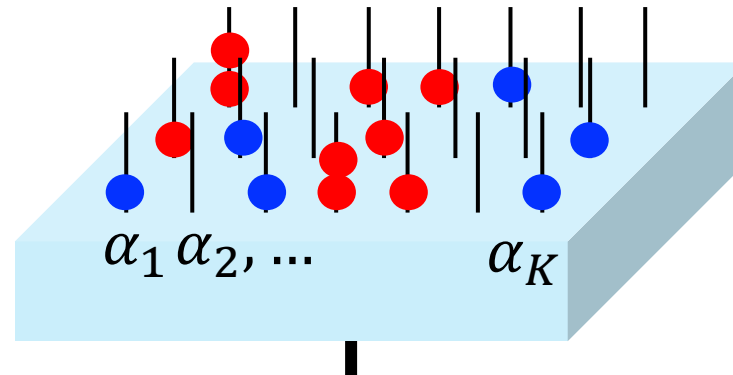
where,  $f_{\pi N}$  is the wave function at the origin, i.e. the **decay constant**

# Entanglement of struck parton

- In DIS, momentum of the struck parton is known from the leptonic probe  $(xP^+, \vec{k}_\perp + x\vec{P}_\perp)$
- What is the entanglement entropy of the struck parton?
- We adopt the occupation representation:

$$|\alpha_1, \alpha_2, \dots, \alpha_N\rangle \rightarrow |\alpha_1(n_1), \alpha_2(n_2), \dots, \alpha_K(n_K)\rangle$$

where  $\alpha = (2\pi n/L, 2\pi n_\perp/L, \lambda, c, f)$  are single-parton quanta,  $K = \frac{P^+ L}{2\pi}$ .



# Is the reduced density matrix diagonal?

$$\rho_\alpha = \sum_{n,n'} \rho_\alpha(n, n') |\alpha(n)\rangle \langle \alpha(n')|$$

- Momentum conservation:

$$np_\alpha^+ = n'p_\alpha^+, \quad n\vec{p}_{\alpha\perp} = n'\vec{p}_{\alpha\perp}$$

- Positivity of  $p_\alpha^+$  requires  $n = n'$ , then  $\rho_\alpha$  becomes diagonal:

$$\rho_\alpha = \sum_n p_n |\alpha(n)\rangle \langle \alpha(n)|$$

$p_n = \sum_{\{n\}_{j \neq i}} |\Psi(n, \{n\}_{j \neq i})|^2$  is the probability of finding  $n$  partons in mode  $\alpha$ .

# Entanglement entropy

$$S_{vN}(\rho_\alpha) = \sum_n p_n \log p_n \xrightarrow{\text{Fermion}} p_1 \log p_1$$

- Note that the average parton number is just the TMD:

$$\sum_n n p_n = \langle n_\alpha \rangle = \langle b_\alpha^\dagger b_\alpha \rangle = f(x, k_\perp)$$

- If we sum over the entropy of all modes, we obtain the Shannon entropy of the TMD – no approximation:

$$\sum_\alpha S_{vN}(\rho_\alpha) = H(f)$$

# Entanglement entropy

- But we just said the entanglement entropy is not exact the Shannon entropy of the TMD!
- Resolution: summing over the entropy of individual parton does not equal the entropy of all partons, unless they are completely independent

# Quark entanglement within hadrons

- Reduced quark density matrix in the **quenched ansatz**:

$$\rho_q^\Lambda = \sum_{s,s'} \int \frac{d^3p}{(2\pi)^3 2p^+} \rho_{ss'}^\Lambda(x, \vec{k}_\perp) \frac{1}{N_c} \sum_i |p, s', i\rangle \langle p, s, i|$$

where,

$$\rho^\Lambda = \frac{1}{2} \begin{pmatrix} \Phi_\Lambda^{[\gamma^+]} + \Phi_\Lambda^{[\gamma^+ \gamma_5]} & \Phi_\Lambda^{[i\sigma^{1+} \gamma_5]} + i\Phi_\Lambda^{[i\sigma^{2+} \gamma_5]} \\ \Phi_\Lambda^{[i\sigma^{1+} \gamma_5]} - i\Phi_\Lambda^{[i\sigma^{2+} \gamma_5]} & \Phi_\Lambda^{[\gamma^+]} - \Phi_\Lambda^{[\gamma^+ \gamma_5]} \end{pmatrix}$$

- Not diagonal due to **spin part** even in the quenched approximation
- Related to quark TMDs  $\Phi_\Lambda^{[\Gamma]}$

# Gluon entanglement within hadrons

- Reduced gluon density matrix in **one-gluon approximation**:

$$\rho_g^\Lambda = I_v |0\rangle\langle 0| + \sum_{\lambda, \lambda'} \int \frac{d^3 p}{(2\pi)^3 2p^+} \rho_{\lambda\lambda'}^g(x, \vec{k}_\perp) \frac{1}{8} \sum_c |p, \lambda', c\rangle\langle p, \lambda, c|$$

where,

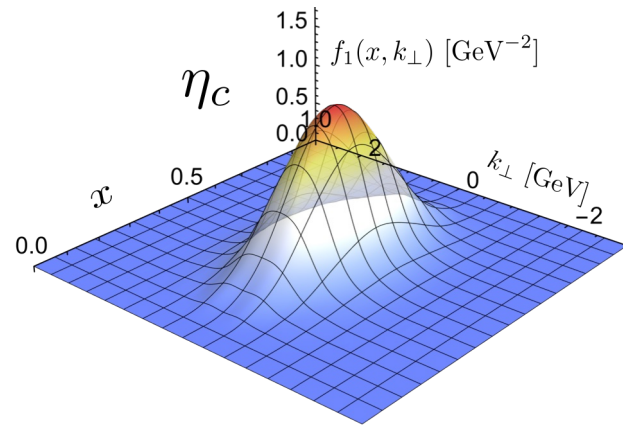
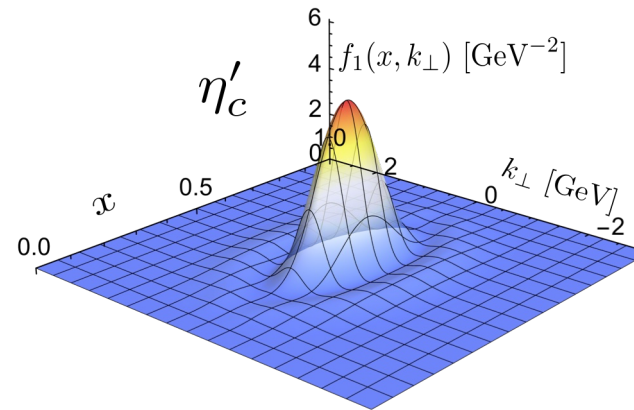
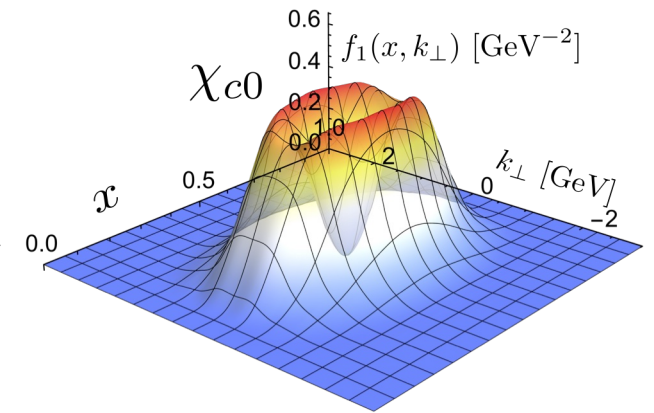
$$\rho_g = \frac{1}{2} \begin{pmatrix} \Phi_g^{[11]} + \Phi_g^{[22]} + i(\Phi_g^{[12]} - \Phi_g^{[21]}) & \Phi_g^{[22]} - \Phi_g^{[11]} + i(\Phi_g^{[12]} + \Phi_g^{[21]}) \\ \Phi_g^{[22]} - \Phi_g^{[11]} - i(\Phi_g^{[12]} + \Phi_g^{[21]}) & \Phi_g^{[11]} + \Phi_g^{[22]} - i(\Phi_g^{[12]} - \Phi_g^{[21]}) \end{pmatrix}$$

- Related to gluon TMDs correlator  $\Phi_g^{[ij]}$

# Charmonium structures

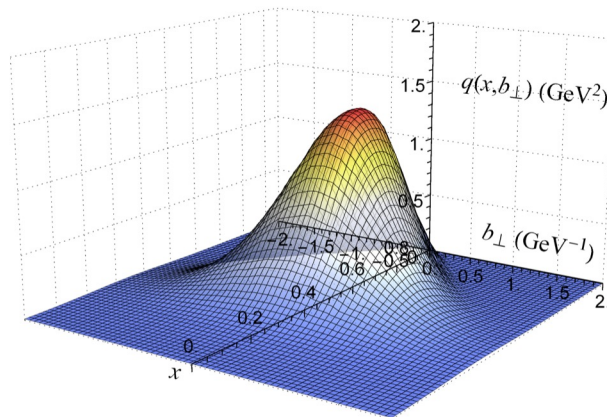
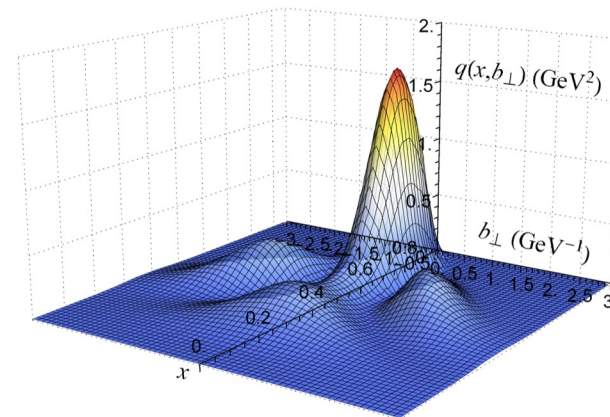
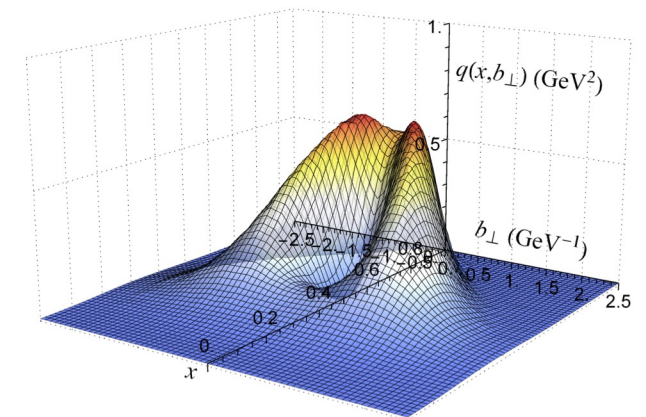
Li, 2015 & 2017

**TMDs**



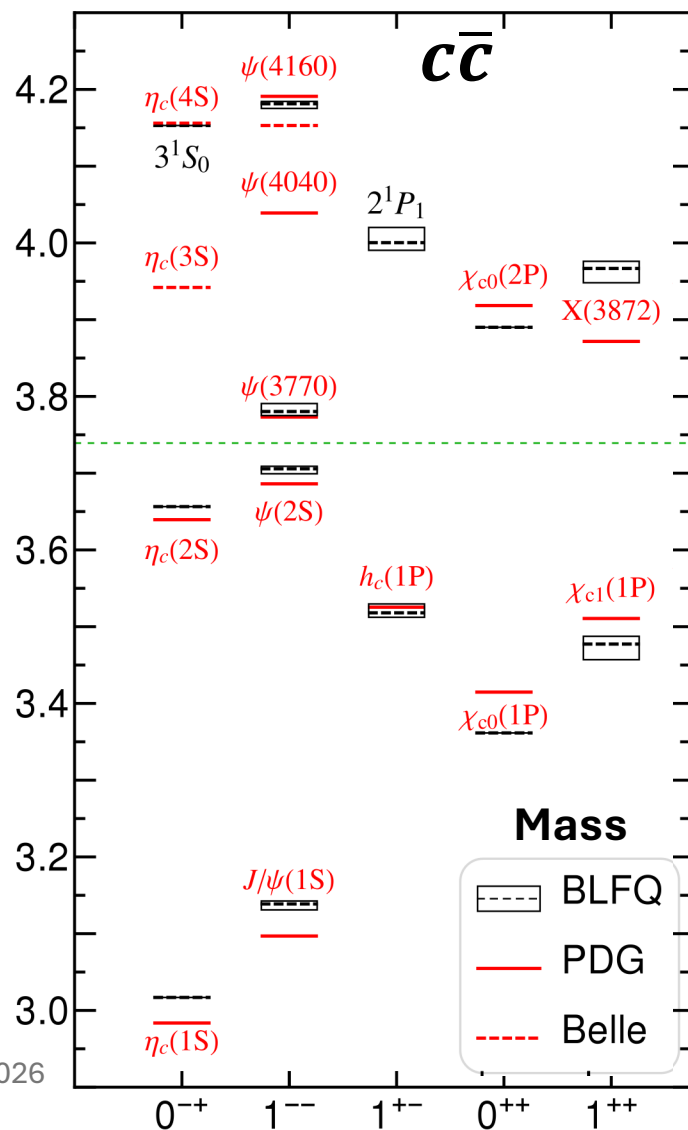
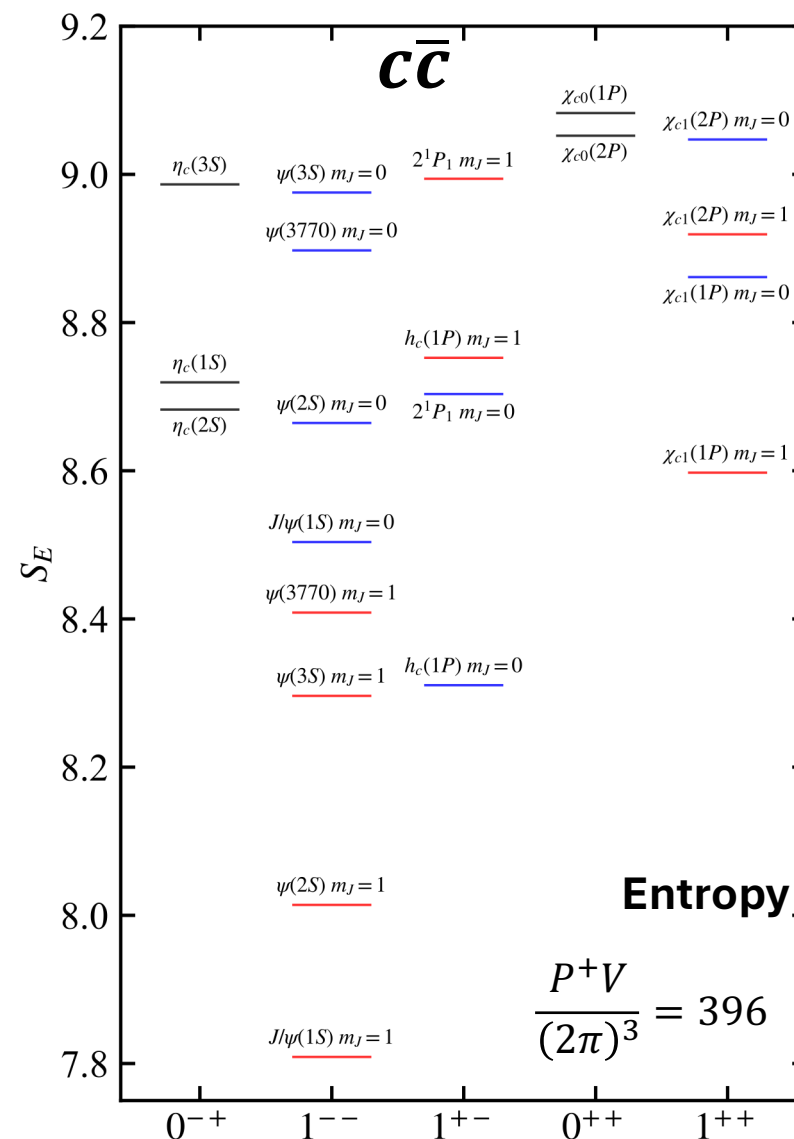
**GPDs**

(impact-parameter space)

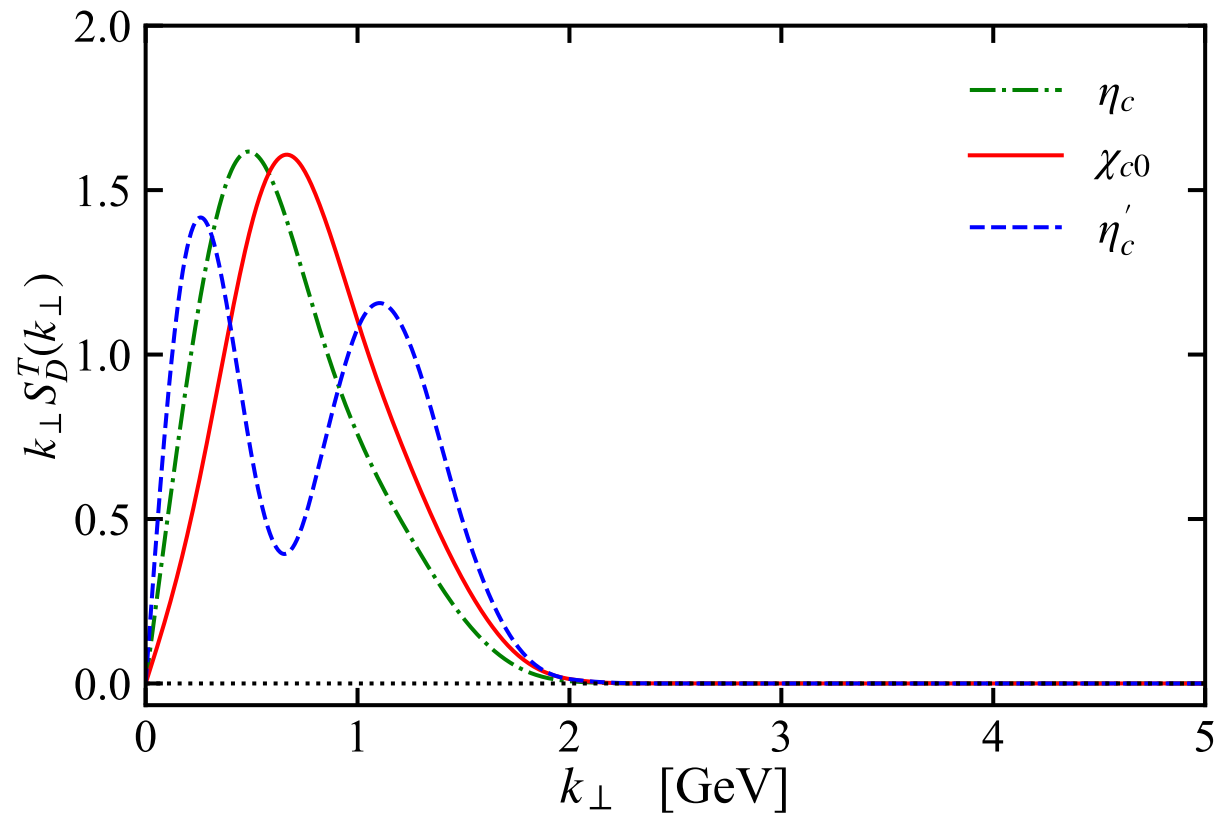
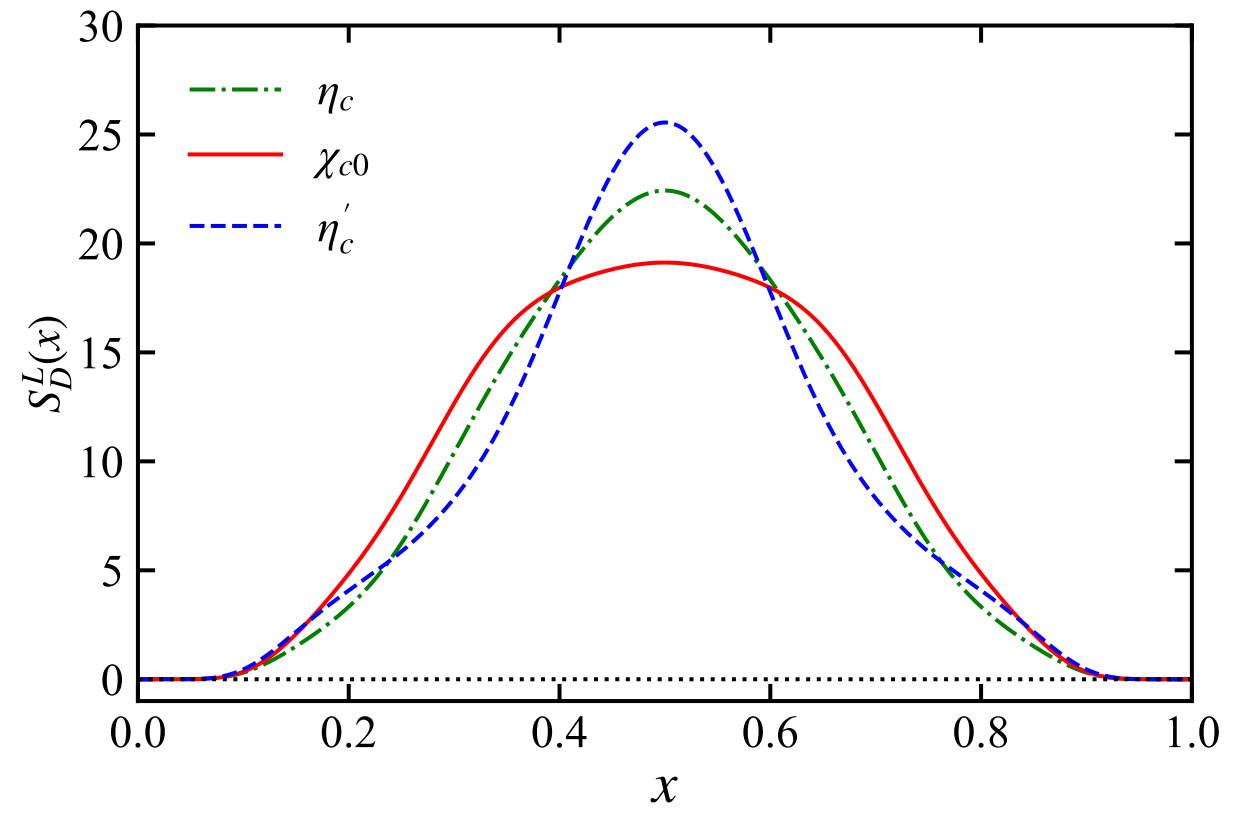


# Entropy spectrum of charmonia

$$\frac{P+V}{(2\pi)^3} = 6L_{max}N_{max}\kappa^{-2}$$

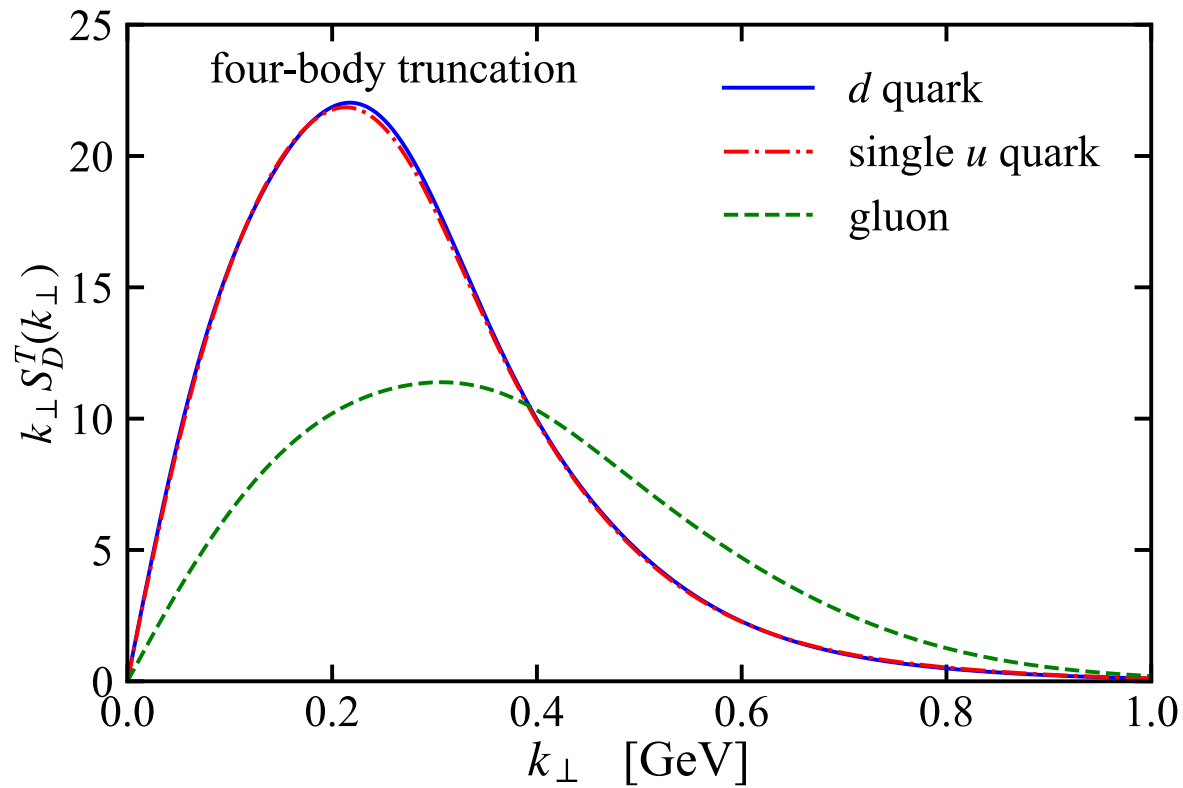
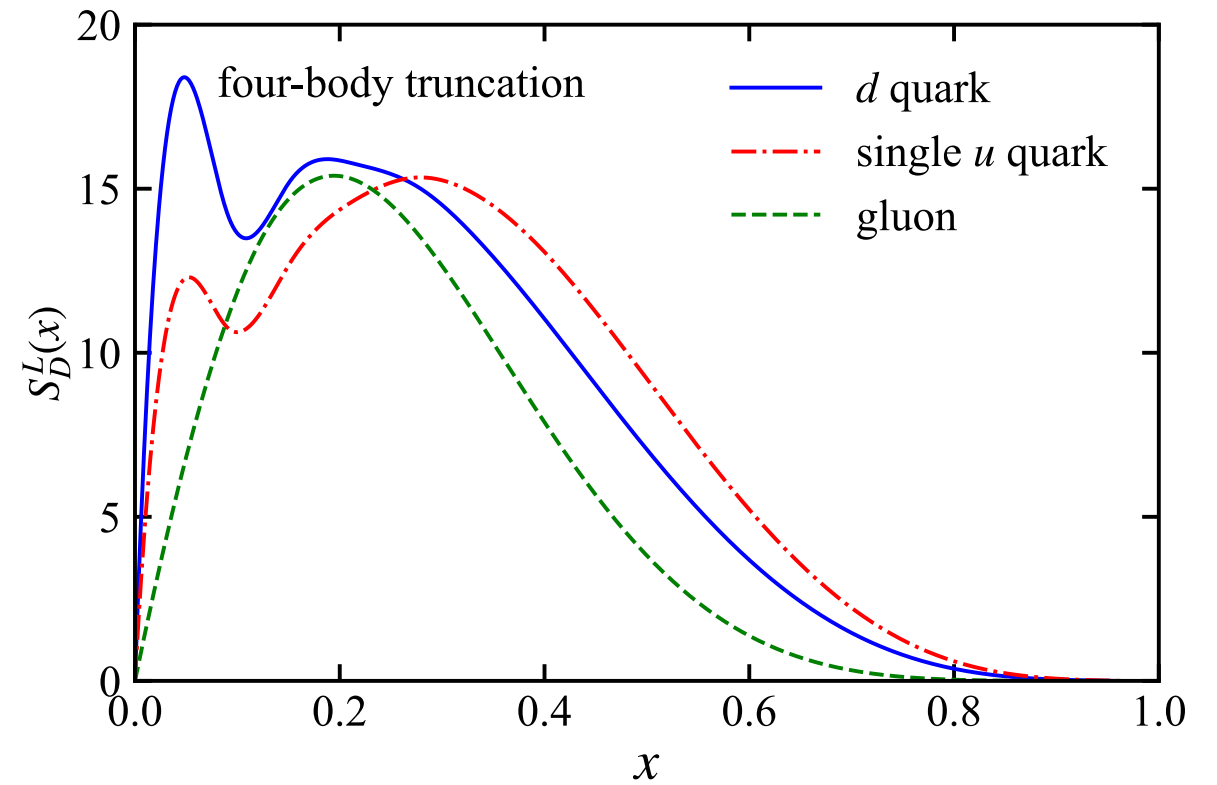


# Entropy distribution of charmonia



# Entropy distribution of the proton

BLFQ Coll. 2022, 2024, 2024;



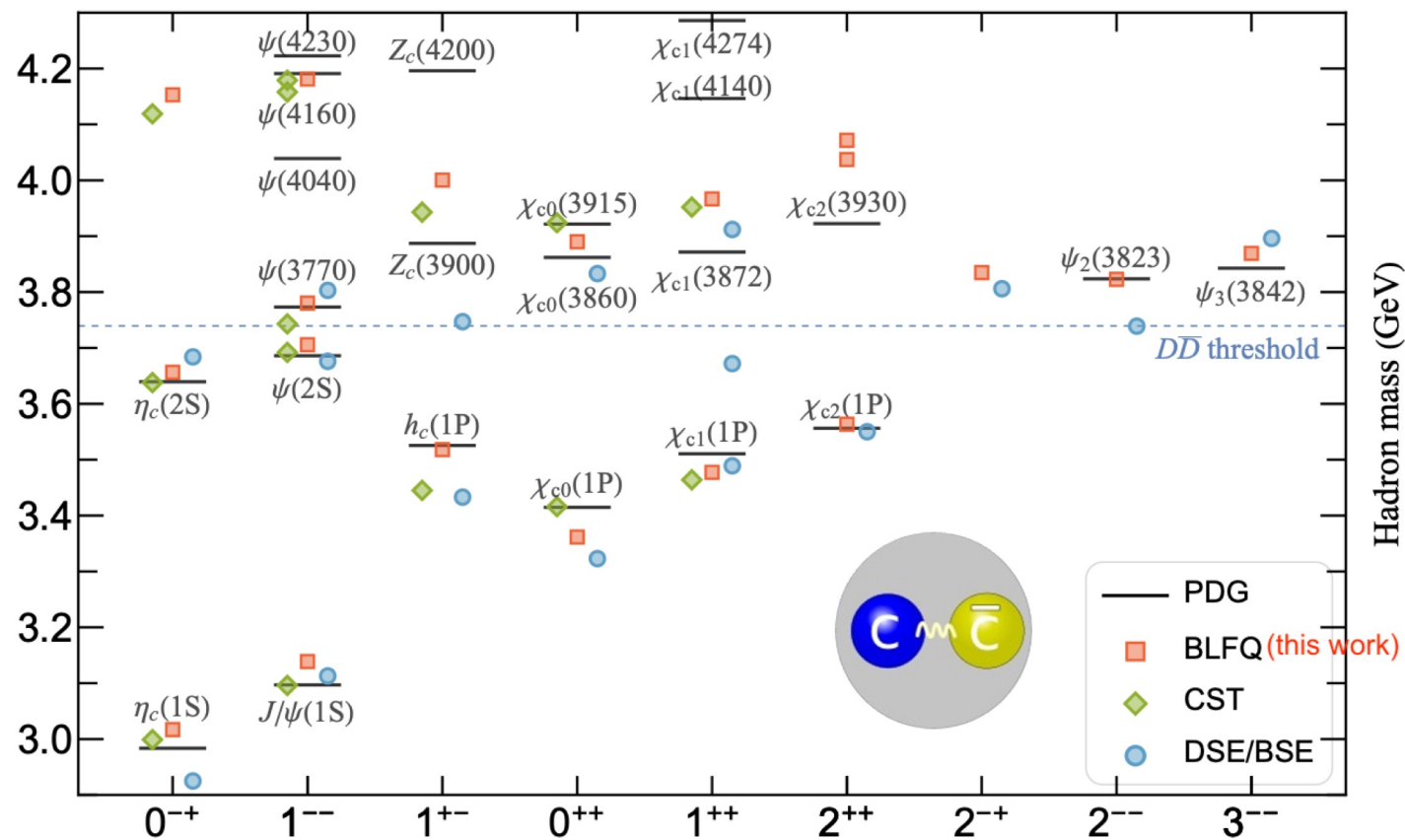
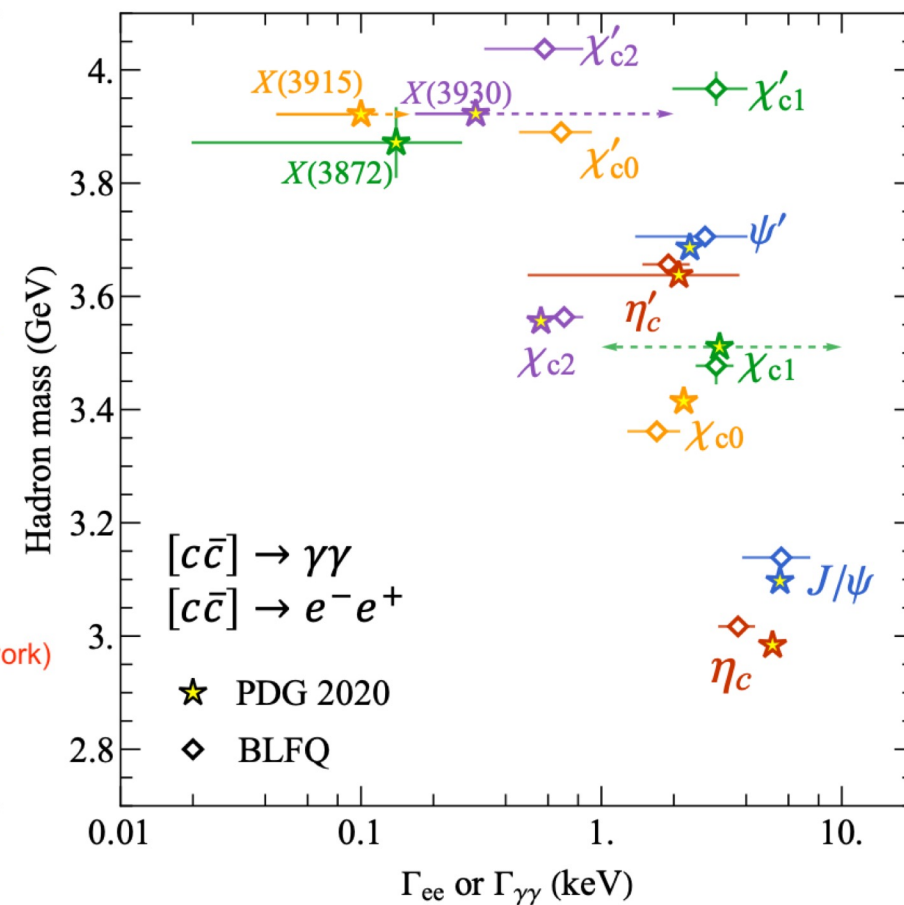
# Summary

- Using light-cone Hamiltonian formalism, we found
$$S_{\text{vN}}(\rho_i) = S_{\text{Shn}}(f_i) + \text{quantum corrections}$$
- Other entanglement observables: mutual info., quantum negativity etc reveal various quantum aspects of hadrons
- Application to QCD: quarkonium & the proton
- Challenges: UV & IR divergences, collinear div. & factorization, gauge invariance, ...

# Thank you!

# Charmonium: hydrogen atom of QCD

Li, 2015 & 2017



■ Two free parameters ( $m_c, \kappa$ ), rms deviation: 30 MeV

■ Good agreement with the PDG data for both the masses and the widths

[Gross:2022hyw]

[LFWFs published on Mendeley Data, doi: 10.17632/cjs4ykv8cv.2]