Theoretical Perspectives on Drell-Yan Production Measurements

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RBRC Workshop on "Opportunities for Drell-Yan Physics at RHIC"
May 11-13, 2011
Brookhaven National Laboratory, Upton, NY

Outline

Almost all talks so far addressed "theoretical perspectives on Drell-Yan production measurements"

- Drell-Yan production measurements:

  Drell-Yan type observables

- Theoretical perspectives:

  Opportunities and challenges

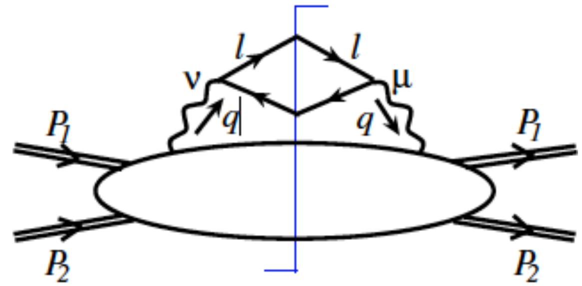
  Drell-Yan offers much more than the sign change

- Summary and outlook

Drell-Yan production measurements

❑ Process:

$$A(P_1) + B(P_2) \longrightarrow V[\to \ell^+\ell^-(q)] + X$$



❑ Observables ($V(q) \to \gamma^*(q)$):

$$\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha_{\rm em}^2}{2(2\pi)^4 S^2 Q^2}\Big[W_T(1+\cos^2\theta) + W_L(1-\cos^2\theta) + W_\Delta(\sin(2\theta)\cos\phi) + W_{\Delta\Delta}(\sin^2\theta\cos(2\phi))\Big].$$

✧ **Single-scale cross sections ($Q \gg 1/\mathrm{fm}$):**

$$q^2 \equiv Q^2 \qquad\qquad \frac{d\sigma}{dQ^2}, \quad \frac{d\sigma}{dQ^2\,dy}$$

✧ **Two-scale cross sections ($Q \gg q_T, Q \sim q_T, Q \ll q_T$):**

$$\frac{d\sigma}{dQ^2\,dq_T^2}, \quad \frac{d\sigma}{dQ^2\,dq_T^2\,dy}, \quad \frac{d\sigma}{dQ^2\,dq_T^2\,dy\,d\Omega}$$

✧ **Asymmetries $\propto$ Difference of cross sections**

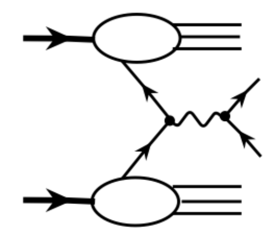
Drell-Yan mechanism in parton model

❑ Drell-Yan lepton-pair production:

$$\frac{d\sigma_{A+B\to\ell\bar{\ell}(Q^2)+X}}{dQ^2} = \sigma_0 \sum_q e_q^2 \int dx\, \phi_{q/A}(x) \int dx'\, \phi_{\bar{q}/B}(x')\, \delta(Q^2 - xx' s_{AB}) + q \leftrightarrow \bar{q}$$

$$= \frac{\sigma_0}{s_{AB}} \sum_q e_q^2\, \mathcal{F}_{q\bar{q}}(\tau = Q^2/s_{AB}),$$

$$\sigma_0 = \sigma^{\rm incl}_{q\bar{q}\to\ell\bar{\ell}(Q^2)}$$



Effective flux: $\mathcal{F}_{q\bar{q}}(\tau) = \int dx\, \phi_{q/A}(x) \int dx'\, \phi_{\bar{q}/B}(x')\, \delta(\tau - xx') + q \leftrightarrow \bar{q}$

❑ Predictions:

- ✧ No free parameter for production rate!
- ✧ Normalized Drell-Yan angular distribution

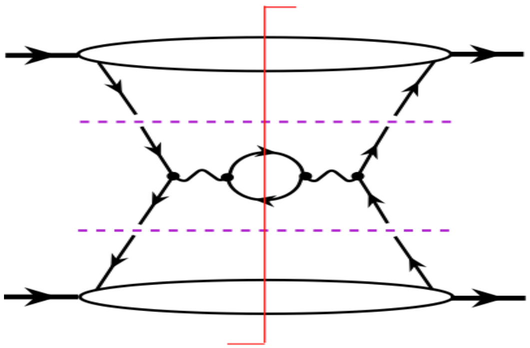
$$\frac{dN}{d\Omega} \equiv \left(\frac{d\sigma}{d^4q}\right)^{-1} \frac{d\sigma}{d^4q\,d\Omega} = \frac{3}{4\pi}\left(\frac{1}{\lambda+3}\right)\left[1 + \lambda\cos^2\theta + \mu\sin(2\theta)\cos\phi + \frac{\nu}{2}\sin^2\theta\cos(2\phi)\right]$$

- ✧ Transversely polarized virtual photon: $1 + \cos^2\theta$ distribution
- ✧ Lam-Tung relation: $1 - \lambda - 2\nu = 0$

Drell-Yan mechanism in QCD

❑ Leading order in QCD:

$$I = \frac{1}{2}\left[\gamma^+\gamma^- + \gamma^-\gamma^+\right]$$



$\Leftarrow$ all γ structure: $\gamma^\alpha,\ \gamma^\alpha\gamma^5,\ \sigma^{\alpha\beta}(\text{or } \gamma^5\sigma^{\alpha\beta}),\ I,\ \gamma^5$

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❑ Leading power distributions: $\langle P,s|\overline{\psi}_q(0)\,\mathcal{O}\,\psi_q(y^-)|P,s\rangle$

$$\mathcal{O} = \frac{\gamma\cdot n}{P\cdot n},\ \frac{\gamma\cdot n\gamma^5}{P\cdot n},\ \frac{\gamma\cdot n\gamma_\perp^\sigma}{P\cdot n} \quad \Leftrightarrow \quad q(x),\ \Delta q(x),\ \delta q(x)(\text{or } h_1(x))$$

❑ Transversity distribution:

$$h_1(x) \propto \langle P,S_\perp|\overline{\psi}(0)\,\frac{\gamma\cdot n\,\gamma_\perp^\sigma}{P\cdot n}\,\psi(yn)|P,S_\perp\rangle$$

❑ Asymmetries – collinear factorization:

$$A_{LL} \propto \sum_q e_q^2\ \Delta q(x)\Delta\bar{q}(x') \qquad A_{TT} \propto \sum_q e_q^2\,h_{1q}(x)h_{1\bar{q}}(x') \qquad A_L \propto \sum_q (c_v * c_a)\,\Delta q(x)\,\bar{q}(x')$$

$$A_N \propto \sum_q e_q^2\ T_q(x,x)\,\bar{q}(x') \qquad A_{LT} \propto \sum_q e_q^2\,\Delta q(x)\,\tilde{T}_{\bar{q}}(x')$$

From parton model to QCD

❑ Parton model – big K-factor:

$$K \equiv \frac{(d\sigma/dQ^2)_{\rm PM}}{(d\sigma/dQ^2)_{\rm exp}} \gtrsim 2$$

- ✧ Parton model = leading order QCD without DGLAP evolution
- ✧ Leading order QCD calculation has the same size K-factor

❑ QCD calculation at NLO and higher:

$$K \equiv \frac{(d\sigma/dQ^2)_{\rm NLO}}{(d\sigma/dQ^2)_{\rm exp}} = 1$$

- ✧ Normalization uncertainty in QCD global fit is limited by systematic error of individual experiment
- ✧ High order corrections are sensitive to if the virtual photon's invariant mass is space-like or time-like

$$\log(q^2_{\rm DIS}) \rightarrow \log(-q^2_{\rm DIS}) + \log(-1)$$

Factorized Drell-Yan cross section

- **TMD factorization ($q_\perp \ll Q$):**

$$\frac{d\sigma_{AB}}{d^4q} = \sigma_0 \int d^2k_{a\perp} d^2k_{b\perp} d^2k_{s\perp} \delta^2(q_\perp - k_{a\perp} - k_{b\perp} - k_{s\perp}) \mathcal{F}_{a/A}(x_A, k_{a\perp}) \mathcal{F}_{b/B}(x_B, k_{b\perp}) \mathcal{S}(k_{s\perp})$$
$$+\mathcal{O}(q_\perp/Q) \qquad x_A = \frac{Q}{\sqrt{s}} e^{y} \qquad x_B = \frac{Q}{\sqrt{s}} e^{-y}$$

The soft factor, $\mathcal{S}$, is universal, could be absorbed into the definition of TMD parton distribution

- **Collinear factorization ($q_\perp \sim Q$, $q_\perp \gg Q$):**

$$\frac{d\sigma_{AB}}{d^4q} = \int dx_a\, f_{a/A}(x_a, \mu) \int dx_b\, f_{b/B}(x_b, \mu)\, \frac{d\hat{\sigma}_{ab}}{d^4q}(x_a, x_b, \alpha_s(\mu), \mu)$$

- **Spin dependence:**

The factorization arguments are independent of the spin states of the colliding hadrons

⟶ same formula with different distributions for γ^*,W/Z, H^0…

TMD vs collinear factorization

- TMD factorization and collinear factorization cover different regions of kinematics:

Collinear: $Q_1 \ldots Q_n \gg \Lambda_{QCD}$

TMD: $Q_1 \gg Q_2 \sim \Lambda_{QCD}$

  - ✧ One complements the other, but, cannot replace the other!
  - ✧ Predictive power of both formalisms relies on the validity of their own factorization

Consistency check – overlap region – perturbative region

- "Formal" operator relation between TMD distributions and collinear factorized distributions:

spin-averaged: $$\int d^2k_\perp \, \Phi_f^{\rm SIDIS}(x,k_\perp) + {\rm UVCT}(\mu_F^2) = \phi_f(x,\mu_F^2)$$

Transverse-spin: $$\frac{1}{M_P}\int d^2k_\perp \, \vec{k}_\perp^2 \, q_T(x,k_\perp) + {\rm UVCT}(\mu_F^2) = T_F(x,x,\mu_F^2)$$

But, TMD factorization is only valid for low k_T – TMD PDFs at low k_T

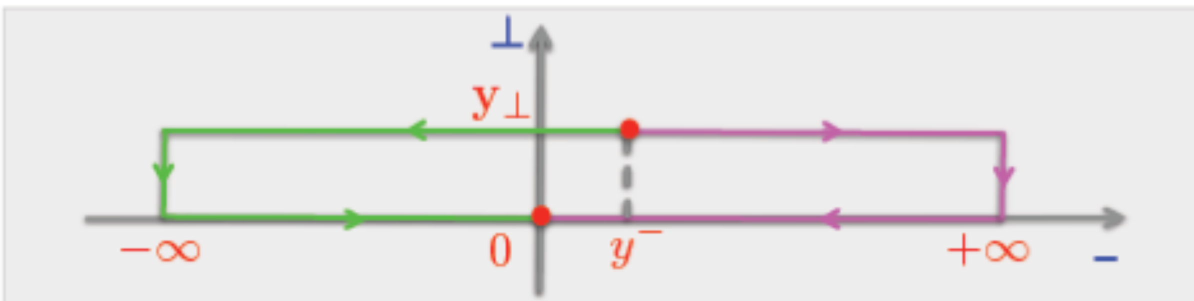
The sign change of Sivers function

❑ TMD quark distribution:

See talks by Collins, Kang, …

$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = \int \frac{dy^- d^2y_\perp}{(2\pi)^3} e^{ixp^+y^- - i\,\mathbf{k}_\perp\cdot\mathbf{y}_\perp} \langle p,\vec{S}|\overline{\psi}(0^-,\mathbf{0}_\perp)\,\boxed{\text{Gauge link}}\,\frac{\gamma^+}{2}\psi(y^-,\mathbf{y}_\perp)|p,\vec{S}\rangle$$

- SIDIS: $\Phi_n^\dagger(\{+\infty,0\},\mathbf{0}_\perp)\Phi_{\mathbf{n}_\perp}^\dagger(+\infty,\{\mathbf{y}_\perp,\mathbf{0}_\perp\})\Phi_n(\{+\infty,y^-\},\mathbf{y}_\perp)$
- DY: $\Phi_n^\dagger(\{-\infty,0\},\mathbf{0}_\perp)\Phi_{\mathbf{n}_\perp}^\dagger(-\infty,\{\mathbf{y}_\perp,\mathbf{0}_\perp\})\Phi_n(\{-\infty,y^-\},\mathbf{y}_\perp)$



- For a fixed spin state:

$$f_{q/h^\uparrow}^{\text{SIDIS}}(x,\mathbf{k}_\perp,\vec{S}) \neq f_{q/h^\uparrow}^{\text{DY}}(x,\mathbf{k}_\perp,\vec{S})$$

❑ Parity + Time-reversal invariance:

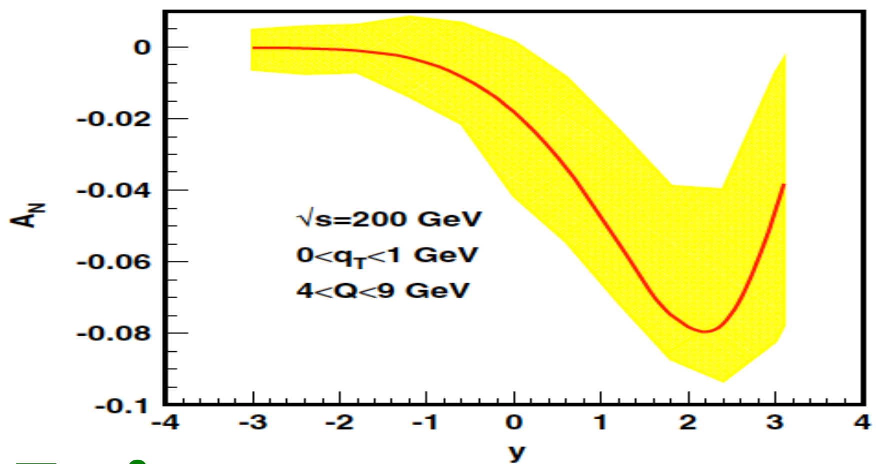
$$\Longrightarrow \quad f_{q/h^\uparrow}^{\text{Sivers}}(x,k_\perp)^{\text{SIDIS}} = -f_{q/h^\uparrow}^{\text{Sivers}}(x,k_\perp)^{\text{DY}}$$

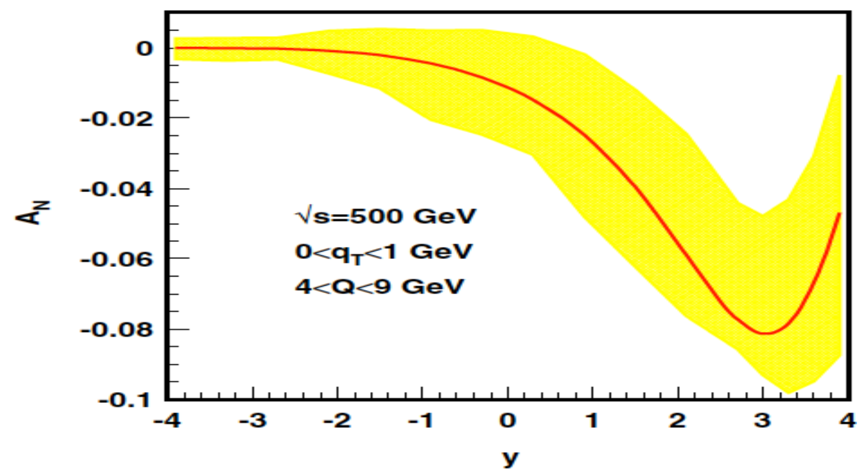
It is a critical test of TMD factorization approach

Test of the modified universality

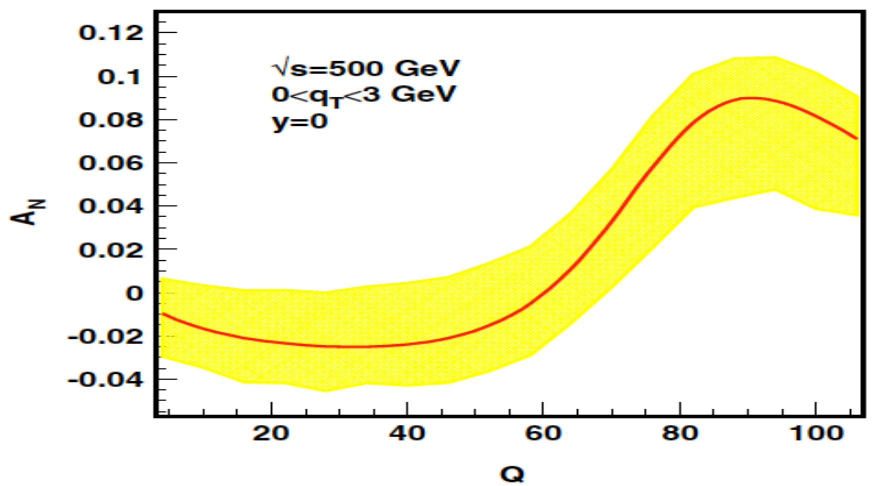
- Drell-Yan: $A_N^{\sin(\phi-\phi_s)} = -A_N$

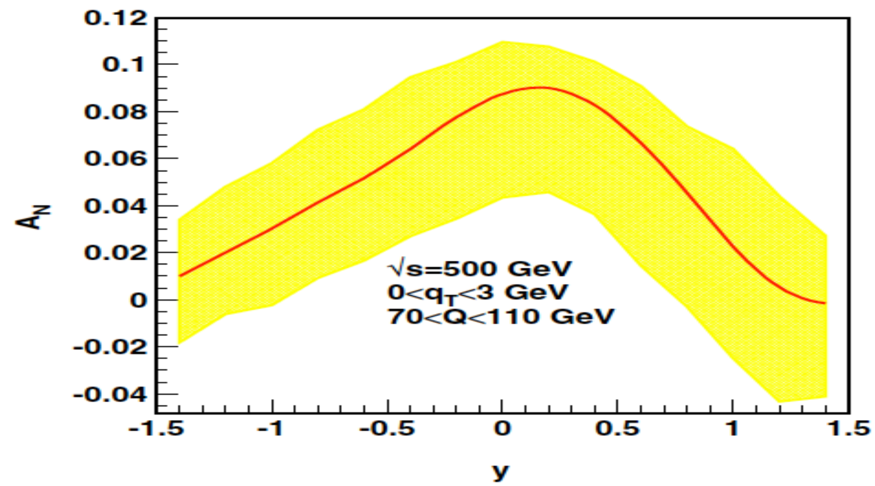
See talks by Anselmino, Rogers, …





- Z^0:





Theoretical challenge: Q-dependence of Sivers function?

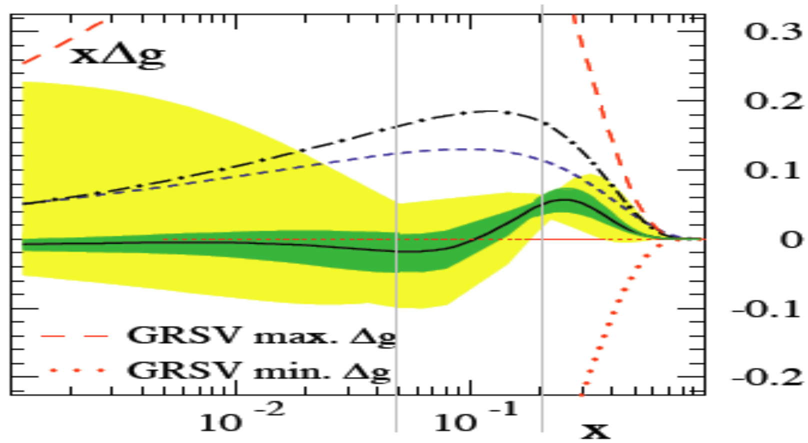
The sign "mismatch"

- Asymmetry could have a node:

See talks by Kang

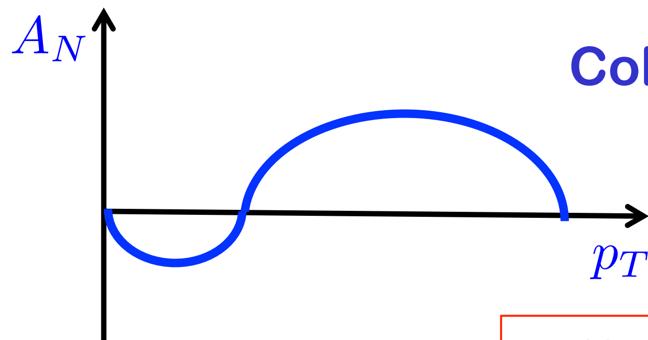
Sign change of $\Delta g(x)$:

$$A(s) \;\propto\; \sigma(s) - \sigma(-s)$$



- A_N of Drell-Yan p_T distribution:

We could have:



Collinear region ($p_T \sim Q$)

TMD region ($p_T << Q$)

Difference of two Gaussians

Important measurement for understanding A_N of hadronic pion

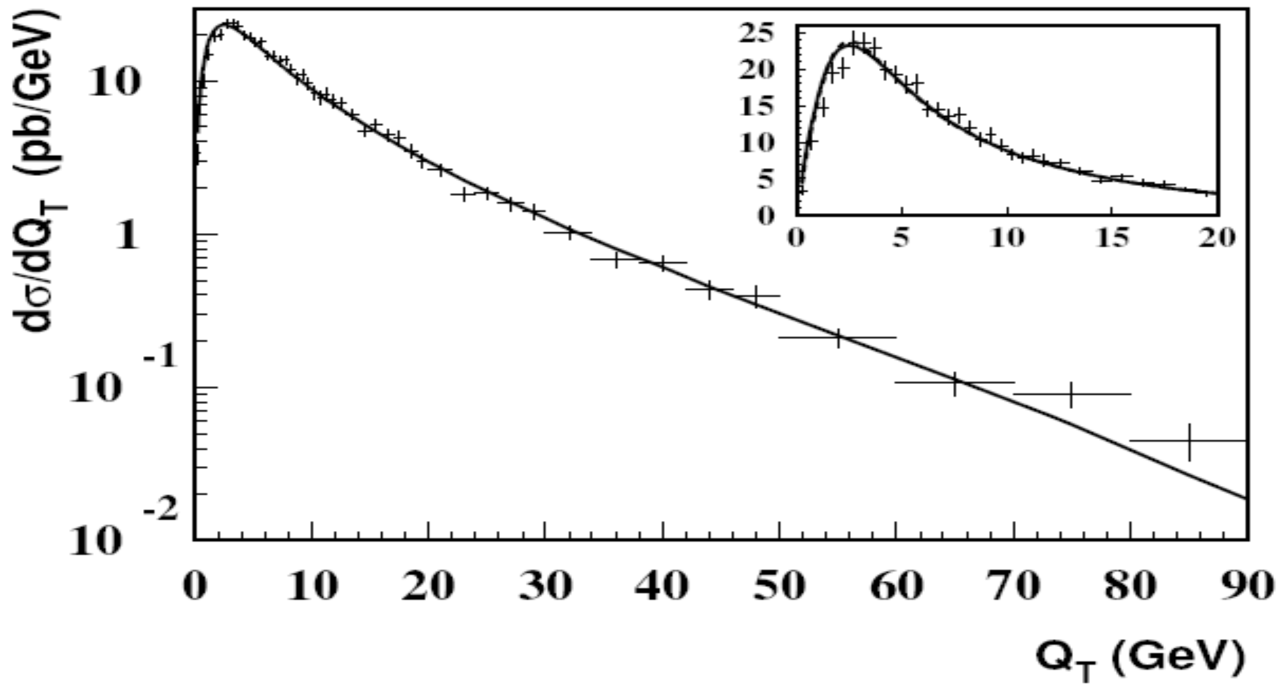
Unpolarized Drell-Yan cross section

- The denominator of the Asymmetry:

$$\frac{d\sigma}{d^4q} \qquad \frac{d\sigma}{d^4q\,d\Omega}$$

- Angular integrated Drell-Yan is under control:

  - Fermilab CDF data on Z at $\sqrt{S} = 1.8$ TeV



CSS resummation formalism – small role of nonperturbative physics

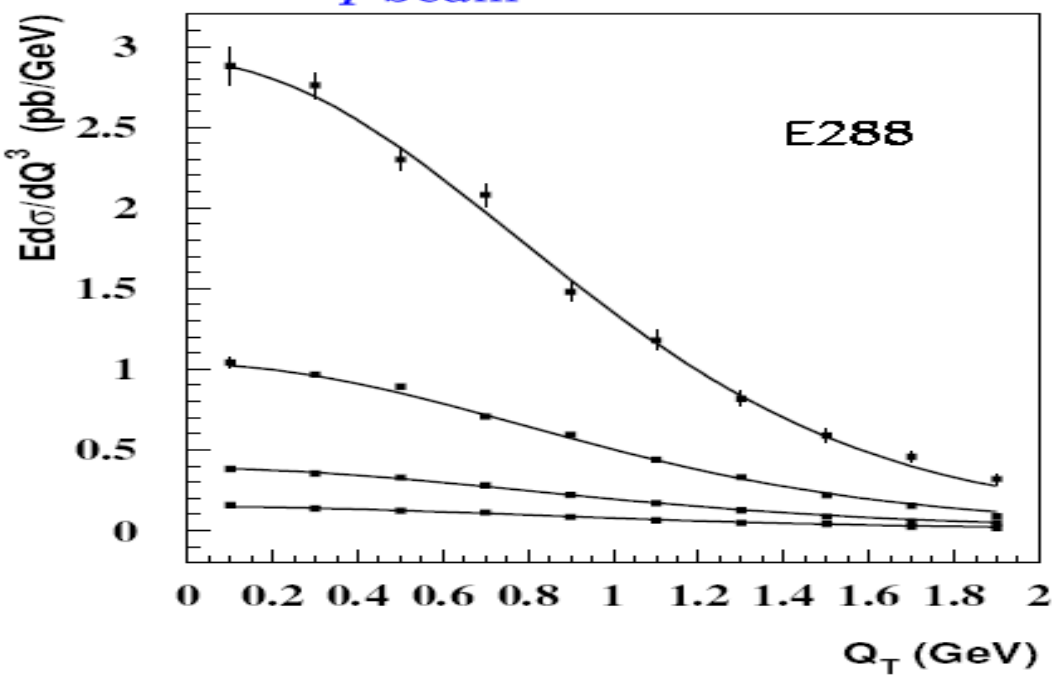
Unpolarized Drell-Yan cross section

❑ The denominator of the Asymmetry:

$$\frac{d\sigma}{d^4q} \qquad\qquad \frac{d\sigma}{d^4q d\Omega}$$

❑ Angular integrated Drell-Yan is under control:

- Fermilab E288 data at $p_{\rm beam} = 400$ GeV



Qiu and Zhang, 2001

CSS resummation formalism – importance of power corrections

Unpolarized Drell-Yan cross section

- The denominator of the Asymmetry:

$$\frac{d\sigma}{d^4q} \qquad\qquad \frac{d\sigma}{d^4q\,d\Omega}$$

- Angular integrated Drell-Yan is under control:
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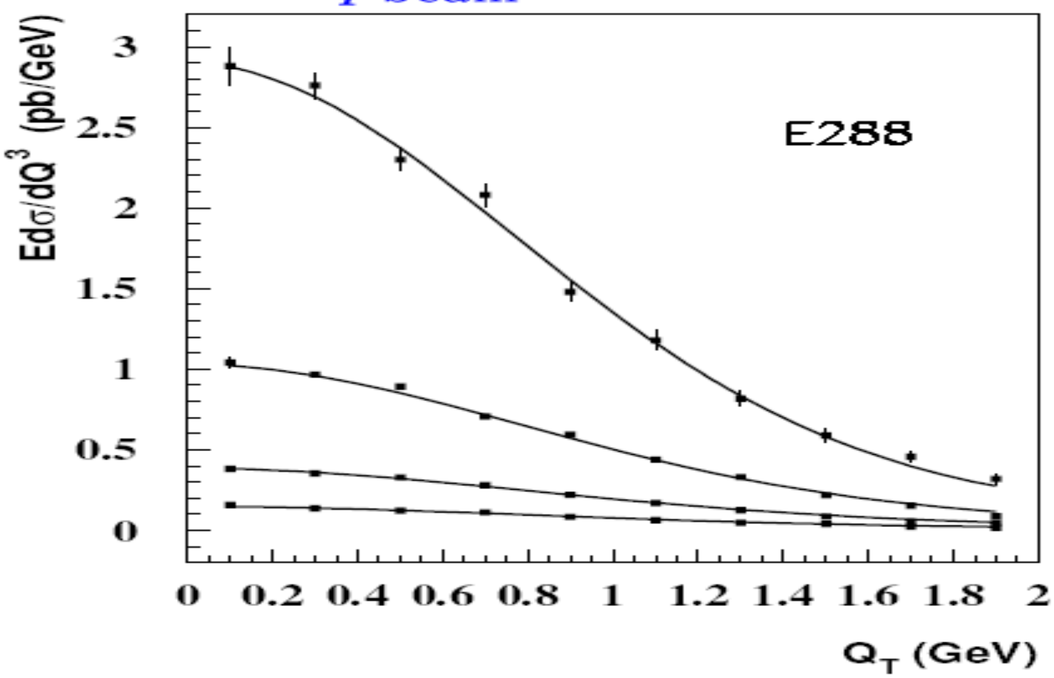


But, Drell-Yan lepton angular distribution needs work!

Lam-Tung relation

- **Normalized Drell-Yan lepton angular distribution:**

$$\frac{dN}{d\Omega} \equiv \left(\frac{d\sigma}{d^4q}\right)^{-1} \frac{d\sigma}{d^4q\,d\Omega} = \frac{3}{4\pi}\left(\frac{1}{\lambda+3}\right)\left[1 + \lambda\cos^2\theta + \mu\sin(2\theta)\cos\phi + \frac{\nu}{2}\sin^2\theta\cos(2\phi)\right]$$

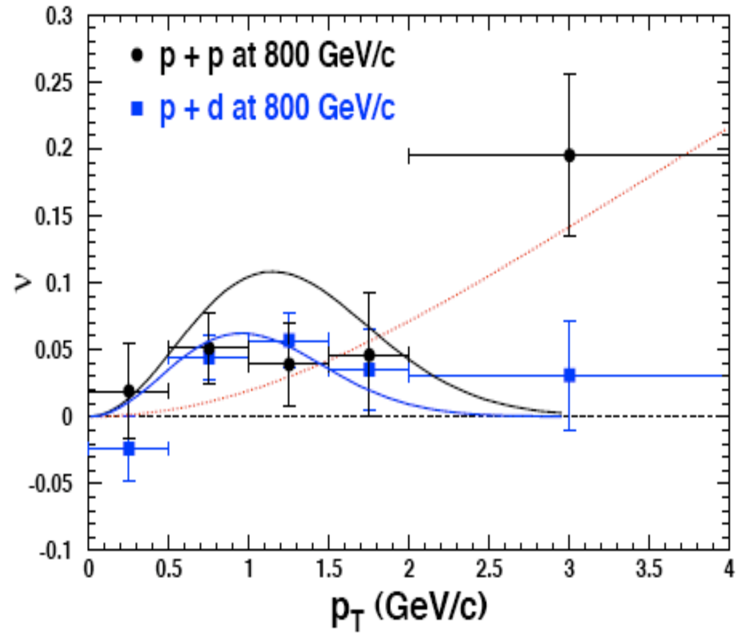
- **Lam-Tung relation:**

$$1 - \lambda - 2\nu = 0$$

- **Collinear factorization:**

$$\lambda = \frac{W_T - W_L}{W_T + W_L} \approx \frac{W_T^{\text{Resum}} - W_L^{\text{Resum}}}{W_T^{\text{Resum}} + W_L^{\text{Resum}}} = \frac{1 - \frac{1}{2}Q_\perp^2/Q^2}{1 + \frac{3}{2}Q_\perp^2/Q^2}$$

$$\nu = \frac{2W_{\Delta\Delta}}{W_T + W_L} \approx \frac{2W_{\Delta\Delta}^{\text{Resum}}}{W_T^{\text{Resum}} + W_L^{\text{Resum}}} = \frac{Q_\perp^2/Q^2}{1 + \frac{3}{2}Q_\perp^2/Q^2}$$

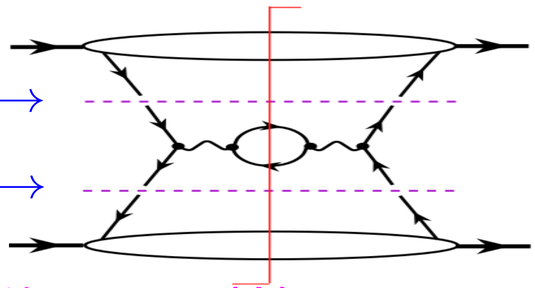


Berger, Qiu, Rodriguez, 2007

Still valid after resummation of large logs

- **TMD factorization:**
  - **Boer – Mulder function – cos(2Φ):**

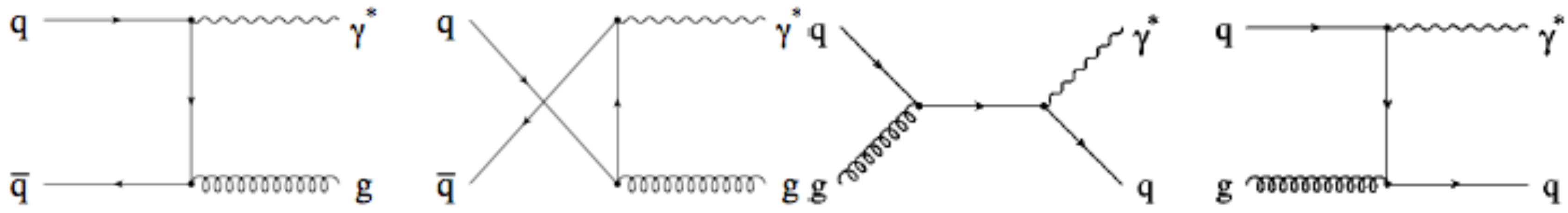
$$h_1^{\perp\text{DY}}(x) = -h_1^{\perp\text{SIDIS}}(x)$$



Theory challenge: Q-dependence of BM function, cos(Φ), …

High p_T and low mass Drell-Yan

- Clean probe of gluon without final-state interaction



(a) (b)

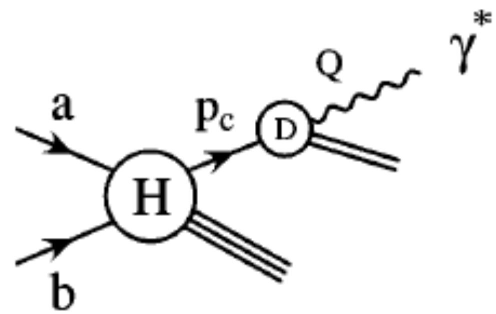
Compton subprocess dominates when q_T > Q/2

Berger, Qiu, Zhang, PRD 2002

- Complementary to prompt photon

$$\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{dQ^2\,dQ_T^2\,dy} = \left(\frac{\alpha_{em}}{3\pi Q^2}\right)\frac{d\sigma_{AB\to\gamma^*(Q)X}}{dQ_T^2\,dy}$$

$$\boxed{\frac{10^{-3}}{Q^2}}$$



- Idea: low Q^2 – increases the rate, and
  high p_T – reliable pQCD calculation

IF p_T >> Q_s, Collinear factorization is as good as that of prompt photon

Kang, Qiu, Vogelsang, PRD 2009

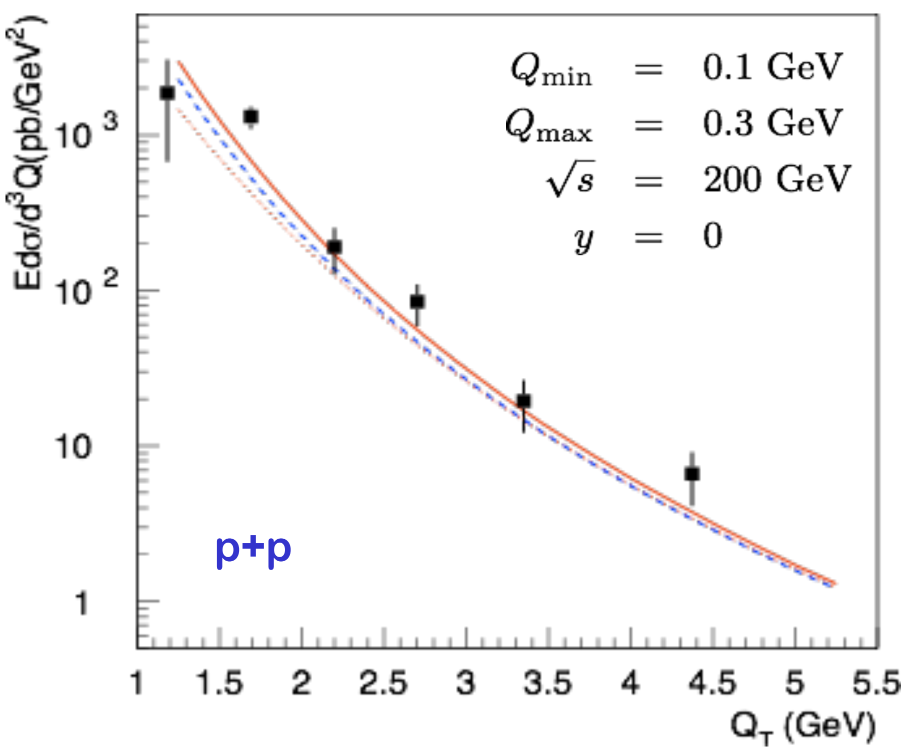
Very low mass Drell-Yan ($p_T > Q \sim 1/\text{fm}$)

Kang, Qiu, Vogelsang, PRD 2009

❑ Invariant cross section:

$$E\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{d^3Q} \equiv \int_{Q^2_{\min}}^{Q^2_{\max}} dQ^2\,\frac{1}{\pi}\,\frac{d\sigma_{AB\to\ell^+\ell^-(Q)X}}{dQ^2\,dQ_T^2\,dy}$$

❑ Role of non-perturbative fragmentation function:



Data from PHENIX: arXiv:0804.4168

✧ Input FF:

$$D(z,\mu_0) = D^{\rm QED}(z) + \kappa\, D^{\rm NP}(z)$$

✧ QED alone (dotted):

$\kappa = 0$ at $\mu_0 = 1$ GeV

✧ QED + hadronic input (solid):

$\kappa = 1$ at $\mu_0 = 1$ GeV

Hadronic component of fragmentation is very important at low Q_T

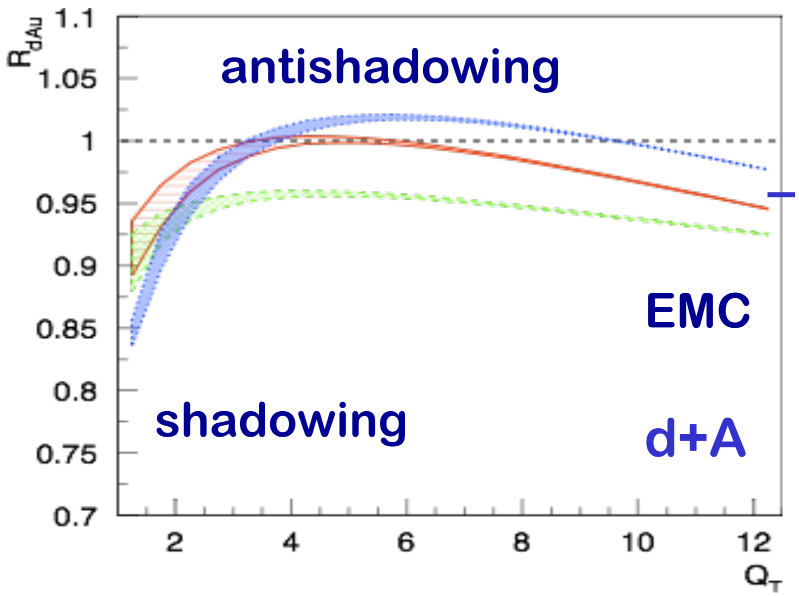
Excellent probe of gluon distribution

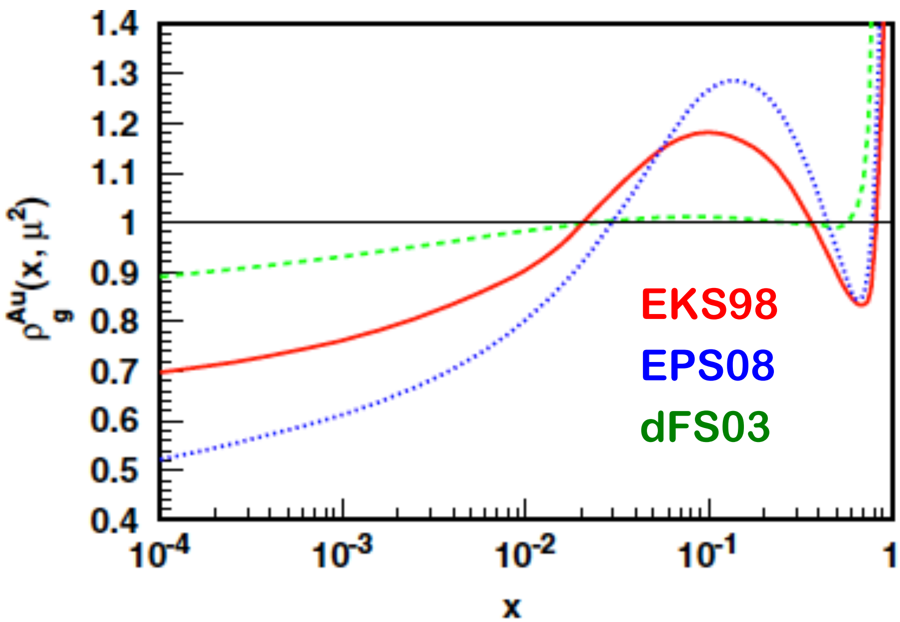
Kang, Qiu, Vogelsang, PRD 2009

- **Nuclear modification factor:**

$$R_{\rm dAu} \equiv \frac{1}{\langle N_{coll}\rangle}\,\frac{d^2N^{\rm dAu}/dQ_Tdy}{d^2N^{pp}/dQ_Tdy} \overset{\rm min.bias}{=} \frac{\frac{1}{2A}d^2\sigma^{\rm dAu}/dQ_Tdy}{d^2\sigma^{pp}/dQ_Tdy}$$

- **RHIC kinematics – if dominated by single scattering:**





– The band is given by κ=1 (top lines) and κ=0 (bottom lines)

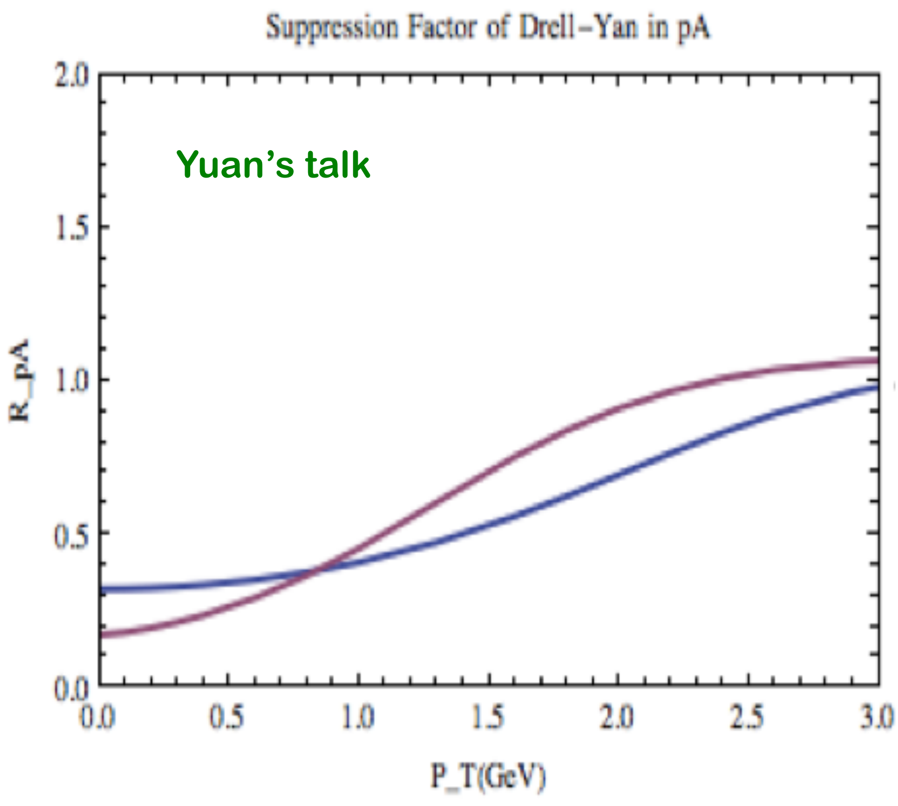
– Ratio follows the feature of gluon distribution if turns off isospin

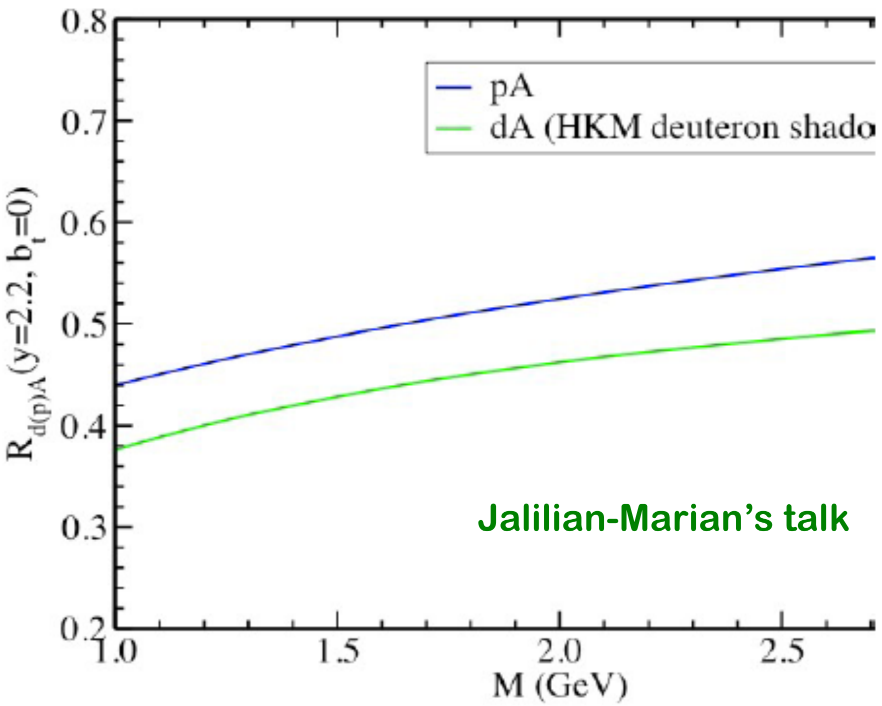
– No suppression if removing isospin effect

Saturation and CGC physics

❑ **Forward rapidity (y >> 0):**

If $Q_T \sim Q_s$, collinear factorization fails



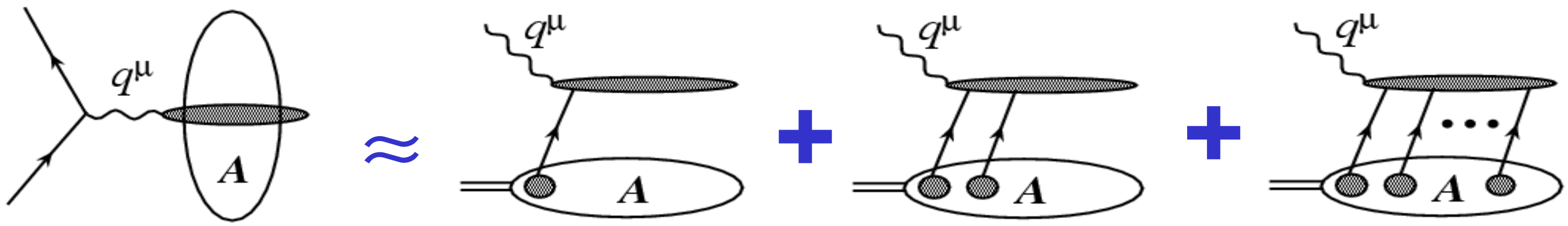


Nuclear shadowing cannot produce such suppression!

Theory challenge: Role of p_T?

Another sign change

- Power correction to DIS – single scale:

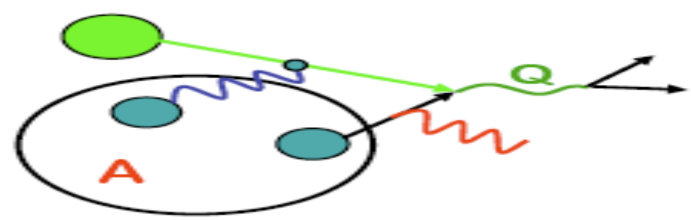


$$F_{eA}(x,Q^2) = F_{eA}^{\rm LP}(x,Q^2) + \frac{1}{Q^2} F_{eA}^{\rm NLP}(x,Q^2) + \ldots$$

Negative - suppression

- Power correction to inclusive DY – single scale:

$$\frac{d\sigma_{pA}}{dQ^2} = \frac{d\sigma_{pA}^{\rm LP}}{dQ^2} + \frac{1}{Q^2}\frac{d\sigma_{pA}^{\rm NLP}}{dQ^2} + \ldots$$

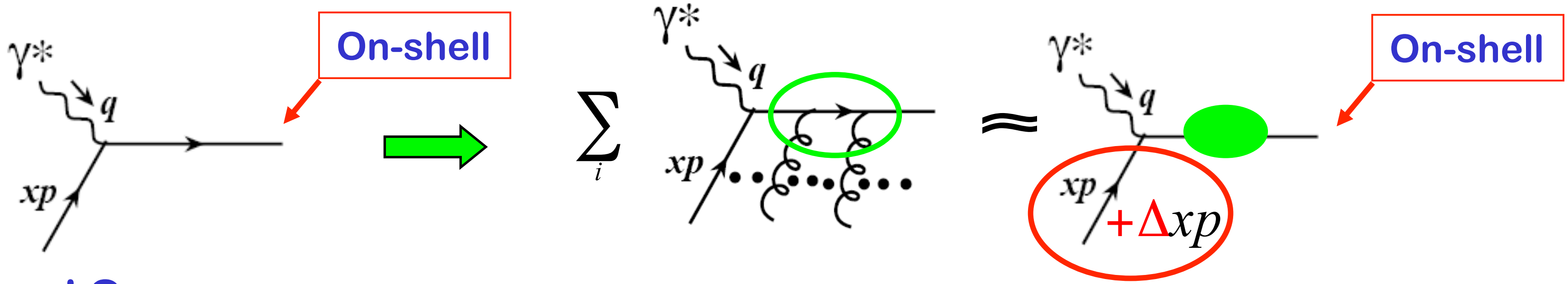


Positive - enhancement

Compton gives negative contribution in CO factorization

Another sign change

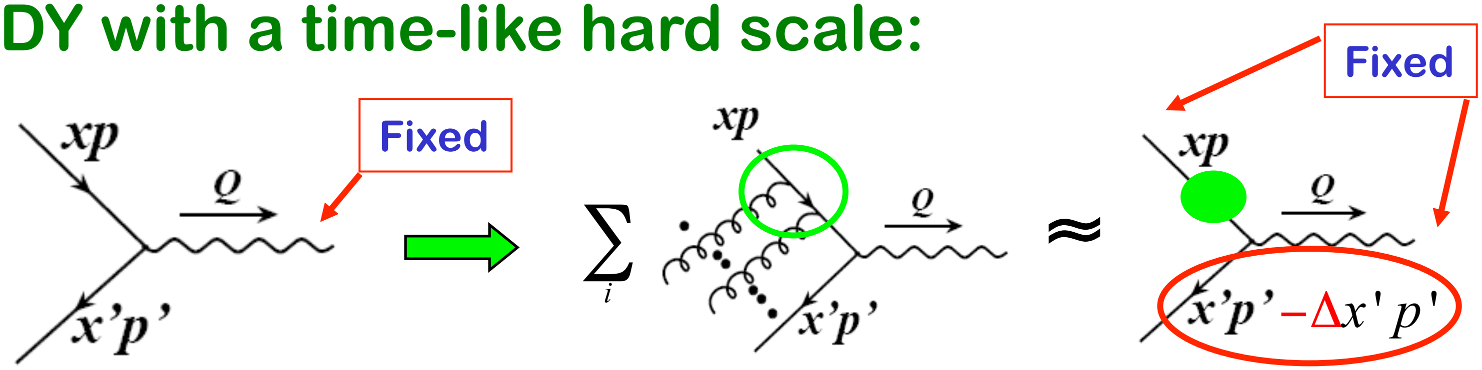
❑ DIS with a space-like hard scale:



LO

Resum all powers

❑ DY with a time-like hard scale:

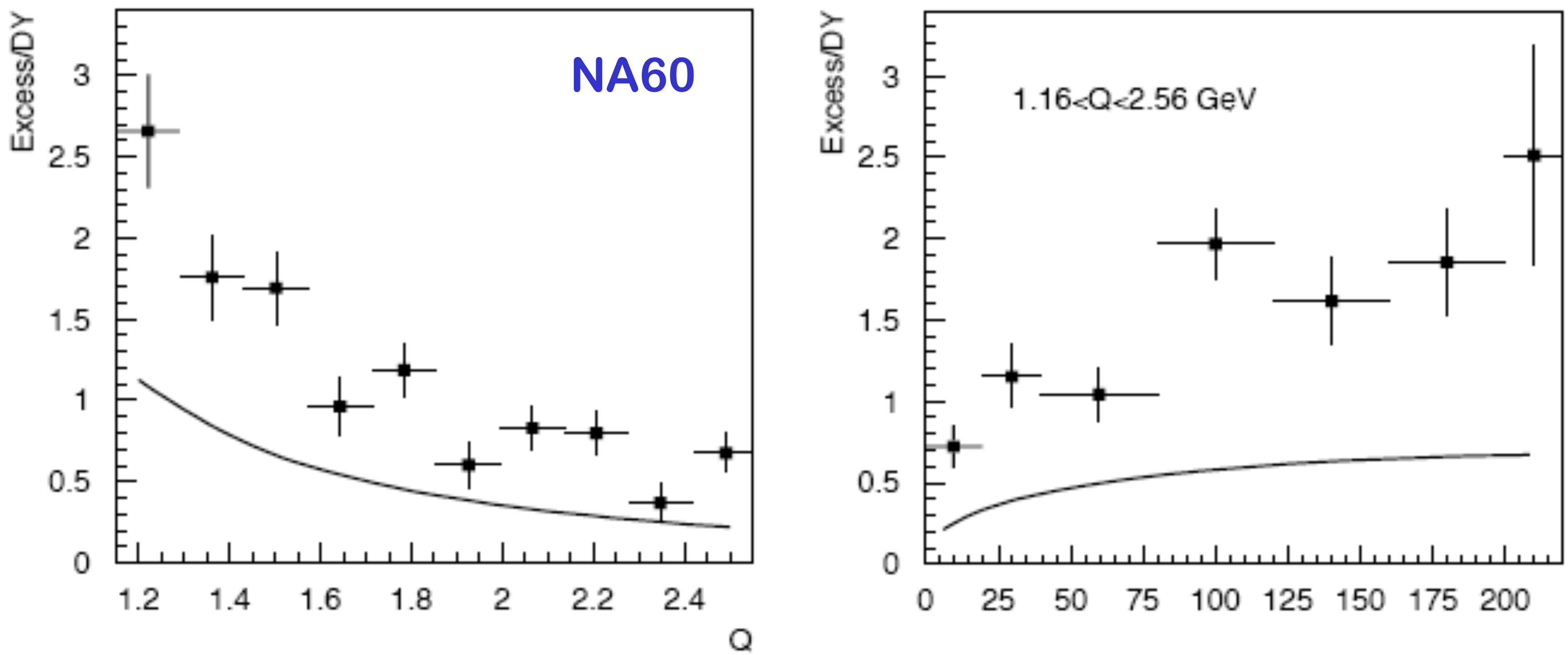


LO

Resum all powers

Inclusive low mass Drell-Yan

- ❑ **Power correction to inclusive total rate:** $d\sigma^{AA}/dQ^2$



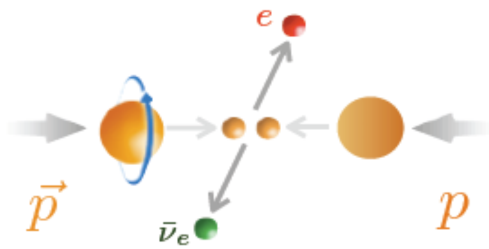
✧ **Power correction from cold nuclear matter enhances the dilepton production - consistent with NA60 data**

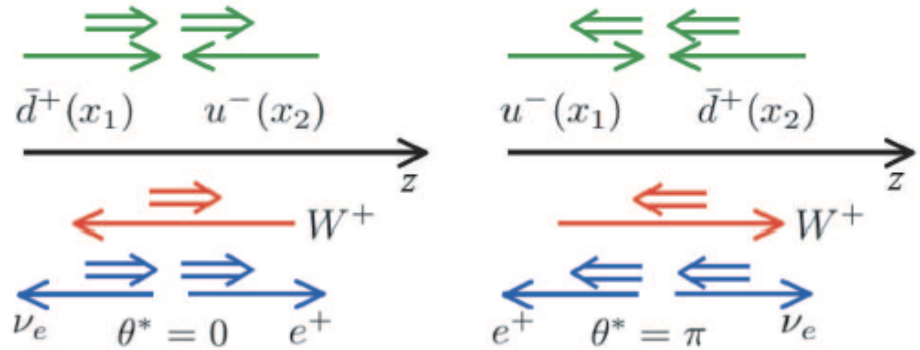
Theory challenge: A-dependence of DY's p_T and y distributions

See talks by Mueller, Yuan, Jalilian-Marian, Reimer, Peng, …

Drell-Yan with parity violation

- **W's are left-handed:**





- **Flavor separation:**

Lowest order:

$$A_L^{W^+} = -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta \bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$$x_1 = \frac{M_W}{\sqrt{s}} e^{y_W}, \quad x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$$

Forward W⁺ (backward e⁺):

$$A_L^{W^+} \approx -\frac{\Delta u(x_1)}{u(x_1)} < 0$$

Backward W⁺ (forward e⁺):

$$A_L^{W^+} \approx -\frac{\Delta \bar{d}(x_2)}{\bar{d}(x_2)} < 0$$

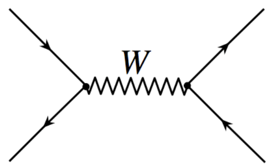
- **Complications:**

High order, W's p_T-distribution at low p_T

Challenge in predicting A_L of lepton

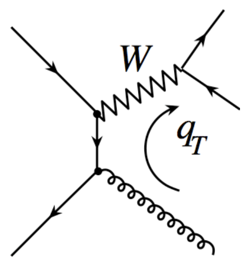
- RHIC experiments measure decay lepton not the W's:
- Fixed order pQCD calculation:

LO:



$$\propto \delta^2(q_T)$$

NLO:



$$\propto \frac{1}{q_T^2} \Rightarrow \infty \quad \text{as} \quad q_T^2 \to 0$$

Leptons not from W decay – background – hard for theorists

- All order resummation is needed:

CSS formalism – implemented in RHICBOS – only diagonal contribution

Resummation for the lepton angular distribution needed!

Scale dependence of the polarized sea

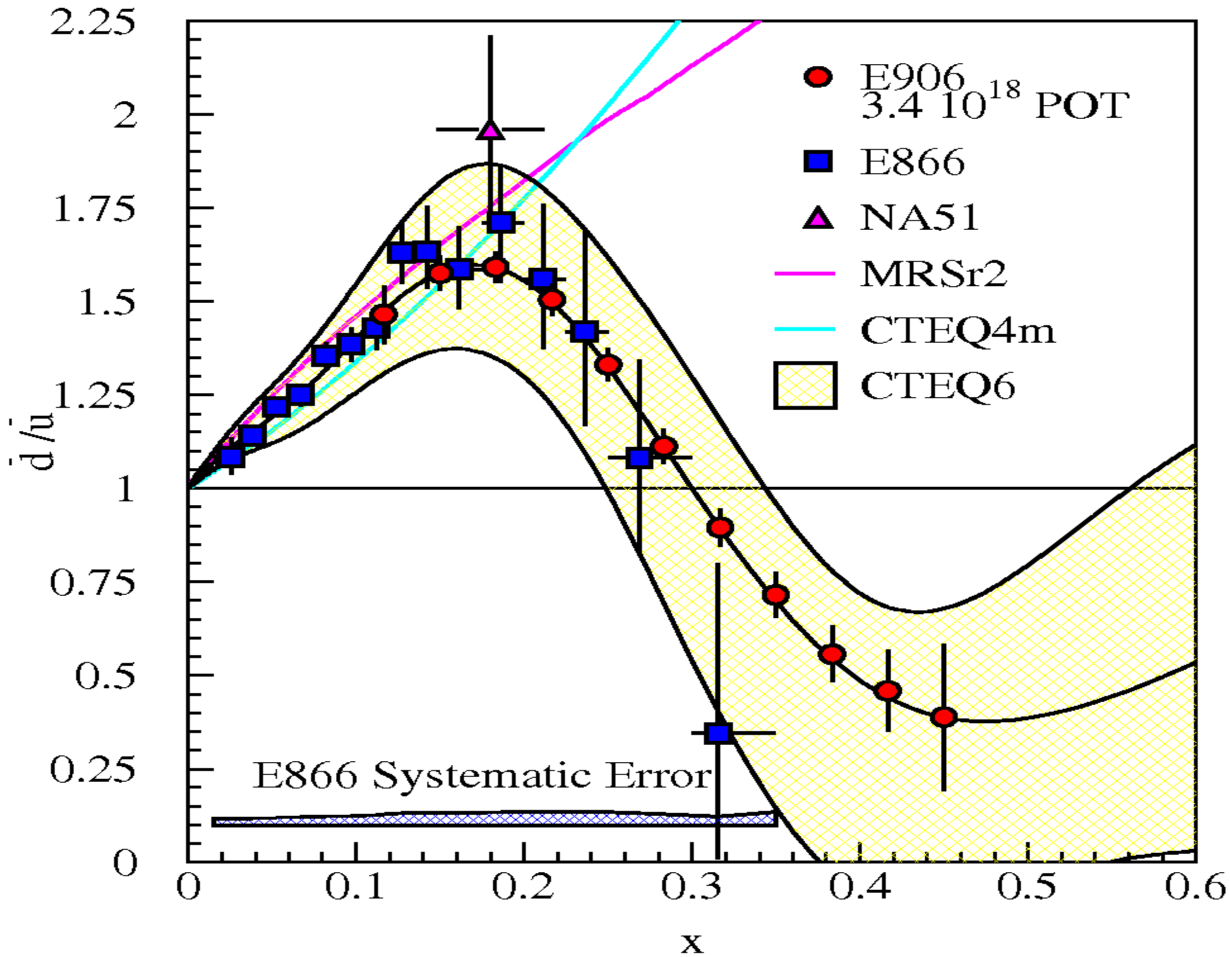
$$\Delta\bar{q}(\mu = M_W) \Longrightarrow \Delta\bar{q}(\mu = Q \sim \mathrm{GeV's})_{\mathrm{SIDIS}}$$

Sea quark asymmetry from Drell-Yan

- Flavor asymmetry of the sea:

See talks by Reimer, Peng, …

$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}\left(1+\frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right)$$



Theory challenge: Why there is a node? Role of pion cloud? …

TMD gluon distribution

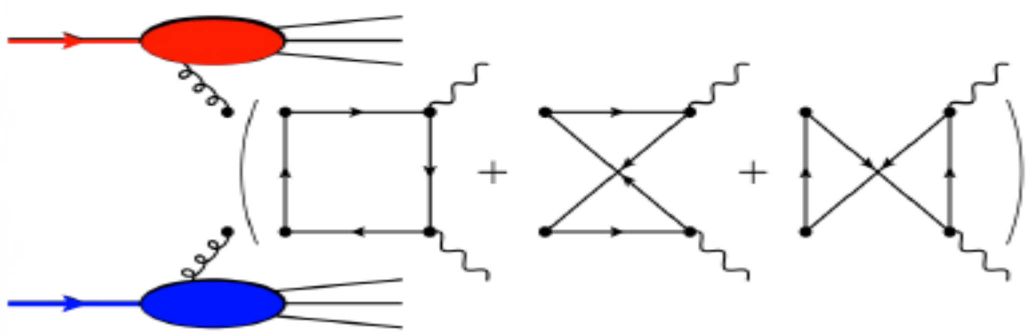
❑ **Gluon Sivers function:**

Need TMD factorizable observables!

❑ **RHIC: momentum imbalance of two isolated photons:**

$$A(P_1) + B(P_2) \longrightarrow \gamma(p1) + \gamma(p_2) + X$$

See talk by Schlegel



❑ **Future EIC:**

$$\ell(k) + B(P) \longrightarrow D(p1) + \bar{D}(p_2) + X$$

Diehl and Xiao

$$\ell(k) + B(P) \longrightarrow J/\psi(P_T) + X$$

Summary and outlook

- Drell-Yan process is one of the oldest hard process proposed to test QCD – it still a very good one!

- The proof of QCD factorization for Drell-Yan is solid (LP + NLP for collinear, LP for TMD)

- The test of the sign change of the Sivers function is a critical test of TMD factorization!

- Drell-Yan could provide much more than the sign change of Sivers function

Thank you!

Backup transparencies