Odderon in the Color Glass Condensate

Yoshitaka Hatta

(BNL)

First, a few words about Jean-Paul

In the fall of 2006, I became a postdoc at Saclay.
But unfortunately Jean-Paul wasn't there during my entire stay in France, since he was the director of ECT at that time...

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Thermalization of overpopulated systems in the 2PI formalism

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Based on the two-particle irreducible (2PI) formalism to next-to-leading order in the $1/N$ expansion, we study the thermalization of overpopulated systems in scalar $O(N)$ theories with moderate coupling. We focus in particular on the growth of soft modes, and examine whether this can lead to the formation of a transient Bose-Einstein condensate (BEC) when the initial occupancy is high enough. For the value of the coupling constant used in our simulations, we find that while the system rapidly approaches the condensation threshold, the formation of a BEC is eventually hindered by particle number changing processes.

In 2015, I invited Jean-Paul to Yukawa institute as a visiting professor for 3 months.
We published one paper on the non-formation of BEC in scalar field theory.

In 2003, I got a postdoc offer from RIKEN BNL where Larry was the theory group leader. But I was actually thinking of moving to another place.
I told this to Larry, then he said

"I really think it is better for you to stay at Brookhaven. You should work with me."

So I started to work with Larry in the spring of 2004.
My PhD thesis was on QCD phase diagram, but I switched fields to Color Glass Condensate. Our first project was Odderon.

Initially, it was difficult for me to follow what people were discussing.

Raju: "He does not understand anything."
Larry: "You have to make money."

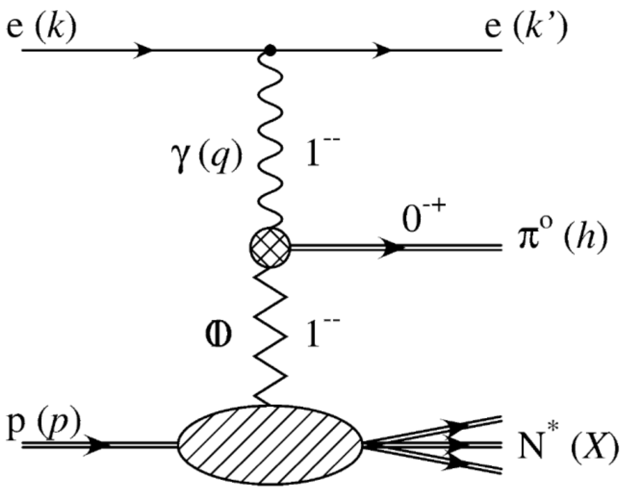
At some point I must have wondered if I made the right choice…

Odderon

C-odd counterpart of Pomeron,
definite prediction of QCD

To lowest order, it's a three-gluon exchange.

Elusive to detect. Trauma at HERA



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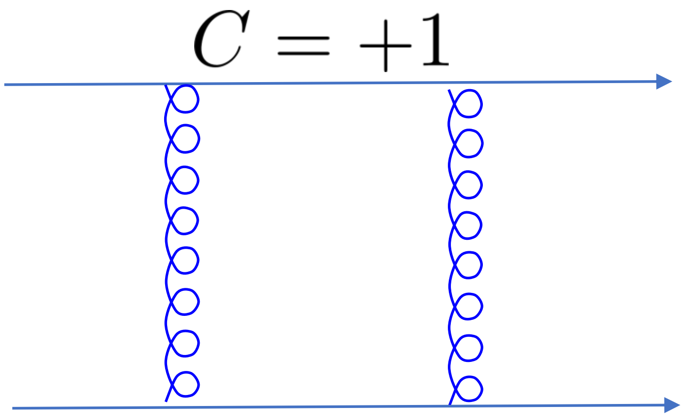
Search for odderon-induced contributions to exclusive π^0 photoproduction at HERA

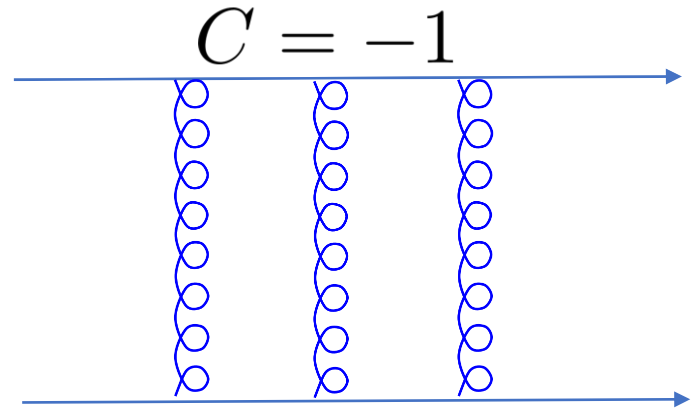
H1 Collaboration

The search for the odderon has therefore become an additional part of the QCD tests to be performed at HERA, and expectations for its discovery are high.

A first search for events produced through odderon exchange in the process $ep \to e\pi^0 N^*$ is reported in the kinematical range $174 < W < 266$ GeV, $Q^2 < 0.01$ GeV^2 and $0.02 < |t| < 0.3$ GeV^2. No π^0 signal is observed and the number of reconstructed events

Pomeron and Odderon in CGC circa 2004



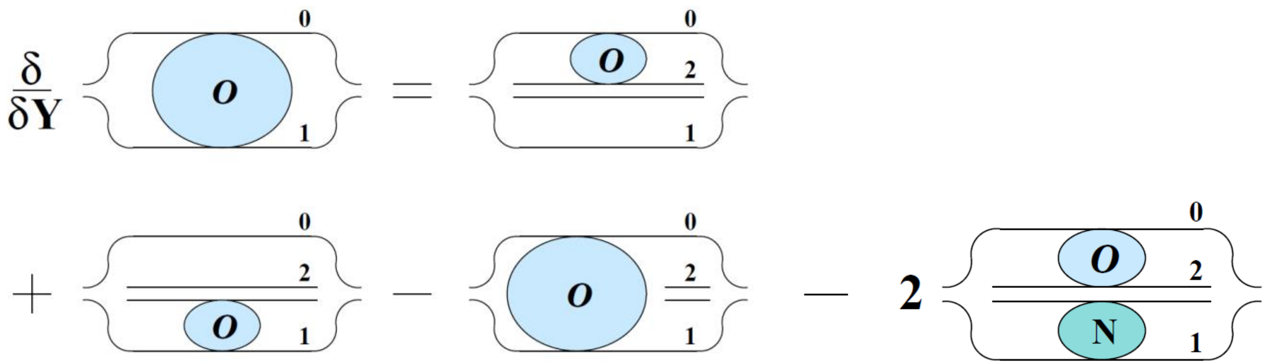


	$C = +1$	$C = -1$
Lowest order	$A^a_\mu A^a_\nu$	$d^{abc} A^a_\mu A^b_\nu A^c_\lambda$
All order	$\mathrm{tr} U_x U_y^\dagger$	?
Evolution (linear)	BFKL	BKP
Evolution (nonlinear)	JIMWLK	?

Perturbative Odderon in the Dipole Model*

arXiv:hep-ph/0309281v2

Yuri V. Kovchegov† 1, Lech Szymanowski‡ 2 and Samuel Wallon§ 3



Odderon evolution equation in coordinate space in the large-Nc approximation.

$$\frac{\partial}{\partial Y}\mathcal{O}(\underline{x}_0, \underline{x}_1, Y) = \frac{\alpha_s N_c}{2\pi^2}\int d^2x_2 \frac{x_{01}^2}{x_{02}^2 x_{12}^2}\left[\mathcal{O}(\underline{x}_0, \underline{x}_2, Y) + \mathcal{O}(\underline{x}_2, \underline{x}_1, Y) - \mathcal{O}(\underline{x}_0, \underline{x}_1, Y)\right]$$
$$- \frac{\alpha_s N_c}{2\pi^2}\int d^2x_2 \frac{x_{01}^2}{x_{02}^2 x_{12}^2}\left[\mathcal{O}(\underline{x}_0, \underline{x}_2, Y)\, N(\underline{x}_2, \underline{x}_1, Y) + N(\underline{x}_0, \underline{x}_2, Y)\, \mathcal{O}(\underline{x}_2, \underline{x}_1, Y)\right]. \qquad (26)$$

Yuri draws diagrams and immediately writes down an equation with correct coefficients. As a novice, I was very puzzled. I wanted to derive it in JIMWLK approach.

JIMWLK equation

Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner

For an operator $\mathcal{O}$ constructed from the classical field $A_a^+ \equiv \alpha^a$,

$$\frac{\partial}{\partial \tau} \langle \mathcal{O} \rangle_\tau = \left\langle \frac{1}{2} \int_{xy} \frac{\delta}{\delta \alpha_\tau^a(\boldsymbol{x})} \eta^{ab}(\boldsymbol{x}, \boldsymbol{y}) \frac{\delta}{\delta \alpha_\tau^b(\boldsymbol{y})} \mathcal{O} \right\rangle_\tau$$

$$\eta^{ab}(\boldsymbol{x}, \boldsymbol{y}) = \frac{1}{\pi} \int \frac{d^2 \boldsymbol{z}}{(2\pi)^2} \frac{(\boldsymbol{x} - \boldsymbol{z}) \cdot (\boldsymbol{y} - \boldsymbol{z})}{(\boldsymbol{x} - \boldsymbol{z})^2 (\boldsymbol{z} - \boldsymbol{y})^2} (1 - \tilde{V}_{\boldsymbol{x}}^\dagger \tilde{V}_{\boldsymbol{z}})^{fa} (1 - \tilde{V}_{\boldsymbol{z}}^\dagger \tilde{V}_{\boldsymbol{y}})^{fb},$$

$\mathcal{O} = \mathrm{Tr} U_x U_y^\dagger$ → Balitsky equation

For a more complicated operators, this form of JIMWLK is rather inconvenient.

JIMWLK equation with dipole kernel

Larry had an intuition that maybe one can use a much simpler kernel and get the same result

$$\frac{(\boldsymbol{x}-\boldsymbol{z})\cdot(\boldsymbol{y}-\boldsymbol{z})}{(\boldsymbol{x}-\boldsymbol{z})^2(\boldsymbol{z}-\boldsymbol{y})^2},$$

$$\frac{\partial}{\partial\tau}\langle\mathcal{O}\rangle_\tau \equiv -\frac{1}{16\pi^3}\int_{\boldsymbol{x}\boldsymbol{y}\boldsymbol{z}}\frac{(\boldsymbol{x}-\boldsymbol{y})^2}{(\boldsymbol{x}-\boldsymbol{z})^2(\boldsymbol{z}-\boldsymbol{y})^2}$$
$$\times\left\langle\left(1+\tilde{V}_{\boldsymbol{x}}^\dagger\tilde{V}_{\boldsymbol{y}}-\tilde{V}_{\boldsymbol{x}}^\dagger\tilde{V}_{\boldsymbol{z}}-\tilde{V}_{\boldsymbol{z}}^\dagger\tilde{V}_{\boldsymbol{y}}\right)^{ab}\frac{\delta}{\delta\alpha_\tau^a(\boldsymbol{x})}\frac{\delta}{\delta\alpha_\tau^b(\boldsymbol{y})}\mathcal{O}\right\rangle_\tau.$$

This turned out to be correct, provided the operator is `gauge invariant’.

Odderon operator in CGC

After many trials and errors, we understood that the odderon is just the imaginary part of the dipole operator

$$\mathrm{Tr} U_x U_y^\dagger = P(x,y) + iO(x,y)$$

Pomeron Odderon

Odd under $x \leftrightarrow y$

Three-gluon in the dilute limit

$$O(\boldsymbol{x},\boldsymbol{y}) \simeq \frac{-g^3}{24N_c} d^{abc} \{3(\alpha_{\boldsymbol{x}}^a \alpha_{\boldsymbol{y}}^b \alpha_{\boldsymbol{y}}^c - \alpha_{\boldsymbol{x}}^a \alpha_{\boldsymbol{x}}^b \alpha_{\boldsymbol{y}}^c) + (\alpha_{\boldsymbol{x}}^a \alpha_{\boldsymbol{x}}^b \alpha_{\boldsymbol{x}}^c - \alpha_{\boldsymbol{y}}^a \alpha_{\boldsymbol{y}}^b \alpha_{\boldsymbol{y}}^c)\}$$

Odderon evolution in CGC

Take the imaginary part of Balitsky equation

$$\frac{\partial}{\partial\tau}\langle O(\boldsymbol{x},\boldsymbol{y})\rangle_\tau = \frac{\bar{\alpha}_s}{2\pi}\int d^2z \frac{(\boldsymbol{x}-\boldsymbol{y})^2}{(\boldsymbol{x}-\boldsymbol{z})^2(\boldsymbol{z}-\boldsymbol{y})^2} \times \langle O(\boldsymbol{x},\boldsymbol{z}) + O(\boldsymbol{z},\boldsymbol{y}) - O(\boldsymbol{x},\boldsymbol{y}) - O(\boldsymbol{x},\boldsymbol{z})N(\boldsymbol{z},\boldsymbol{y}) - N(\boldsymbol{x},\boldsymbol{z})O(\boldsymbol{z},\boldsymbol{y})\rangle_\tau,$$

Agrees with Yuri et al. in the large-Nc approximation.
Operator definition given.
Generalized to finite Nc.

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NUCLEAR PHYSICS A

Odderon in the color glass condensate

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After completing this paper we moved on to another project.
But I returned to odderon every once in a while.

Odderon in baryon-baryon scattering from the AdS/CFT correspondence

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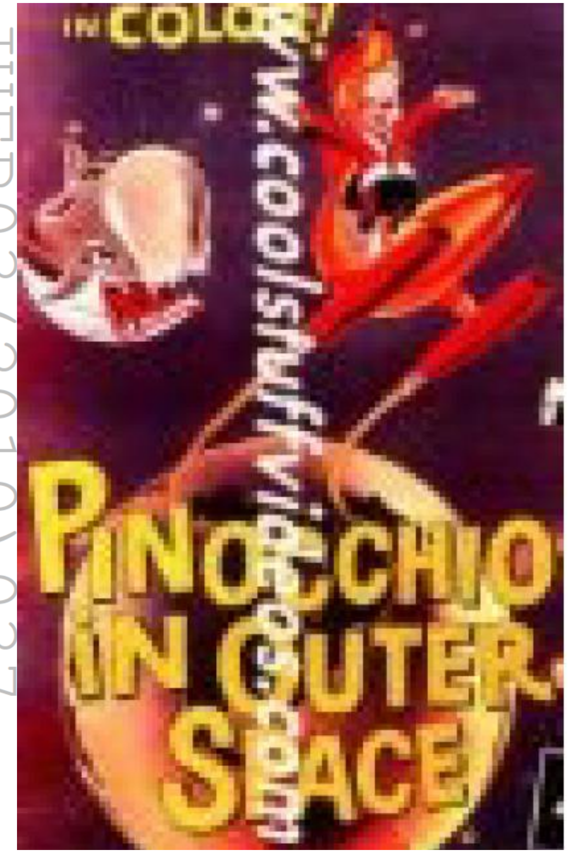
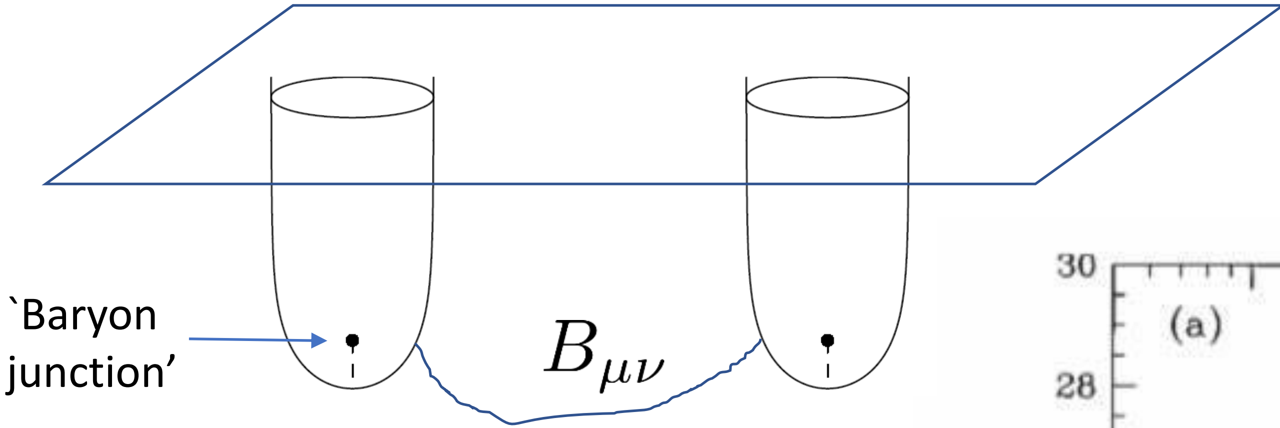
Abstract: Based on the AdS/CFT correspondence, we present a holographic description of various C-odd exchanges in high energy baryon-(anti)baryon scattering, and calculate their respective contributions to the difference in the total cross sections. We show that, due to the warp factor of AdS_5, the single Odderon exchange gives a larger total cross section in baryon-baryon collisions than in baryon-antibaryon collisions at asymptotically high energies.

JHEP03(2010)037



Sorry, Larry. I could not suppress my curiosity about AdS/CFT.
I was secretly learning string theory when I was a RBRC postdoc.
After you leave office around 4pm, I would open Polchinski's textbook...

Odderon = B field in string theory



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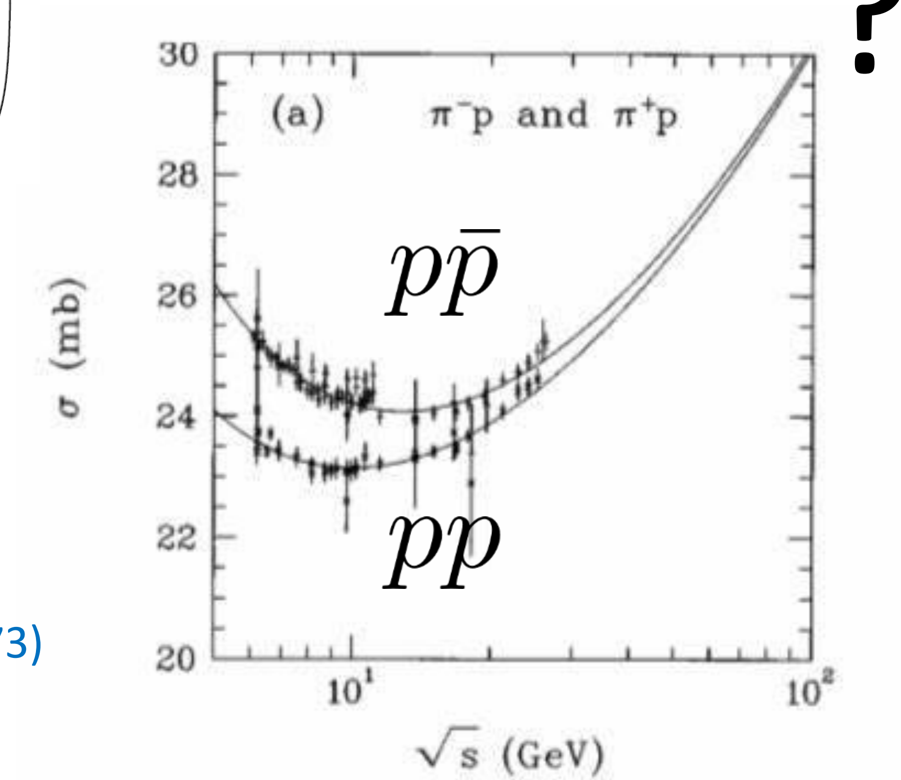
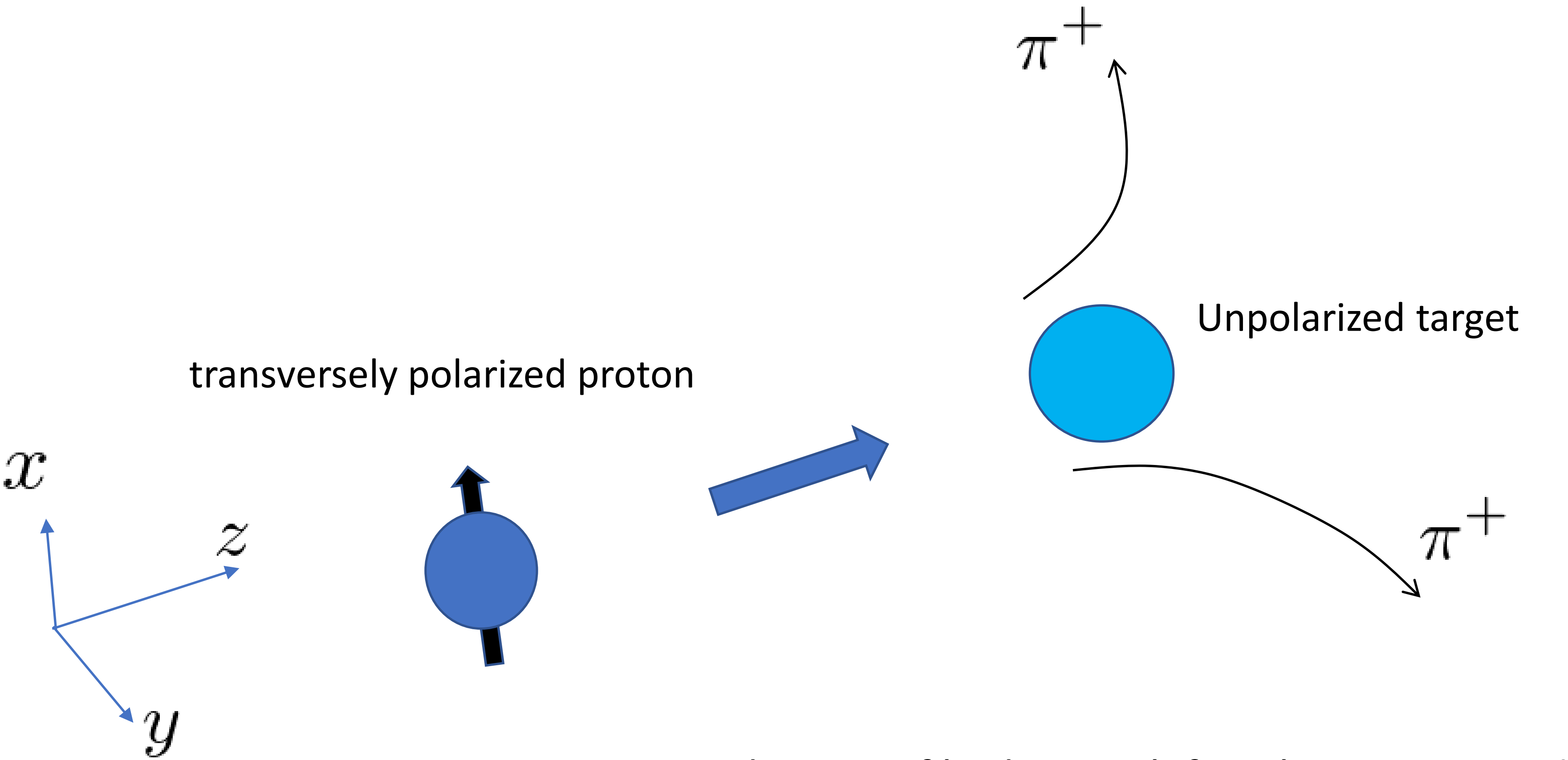


Due to the warp factor of AdS, the ordering is reversed.

$$\sigma_{tot}^{pp} > \sigma_{tot}^{p\bar{p}}$$

Same conclusion as in Lukaszuk, Nicolescu (1973)

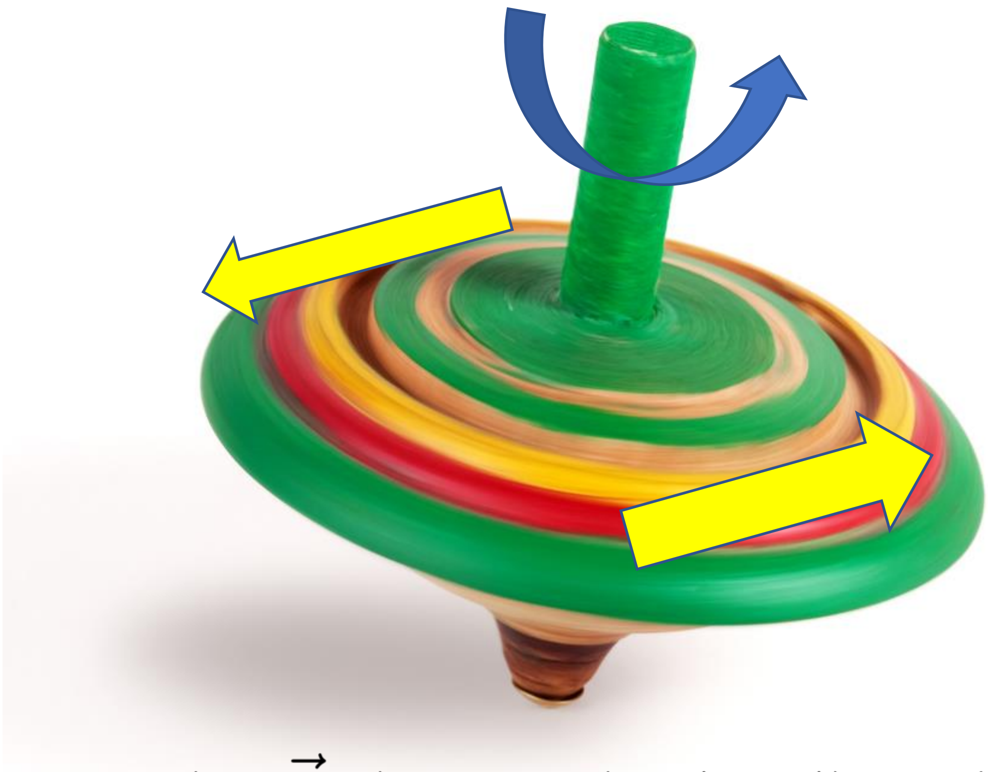
Single Spin Asymmetry (SSA)

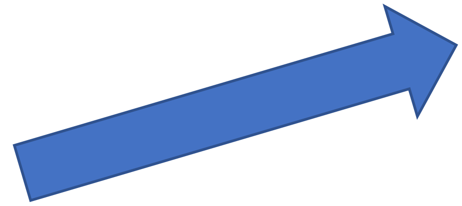


Production of hadrons is left-right asymmetric!

Sivers function

Sivers (1990)





Distribution of partons is left-right asymmetric

$$f(x, \vec{k}_\perp) = f_1(x, |k_\perp|) + (\vec{k}_\perp \times \vec{S}_\perp)^z f_{1T}^\perp(x, |k_\perp|)$$

Spin-dependent Odderon

Zhou (2013)

Consider the dipole operator in proton state with definite spin polarization

$$\langle PS|\mathrm{tr}\,U(r_\perp)U^\dagger(0_\perp)|PS\rangle$$

This cannot depend on spin S^μ if longitudinally polarized (parallel to P^μ)

However, it can depend on S^μ if transversely polarized!

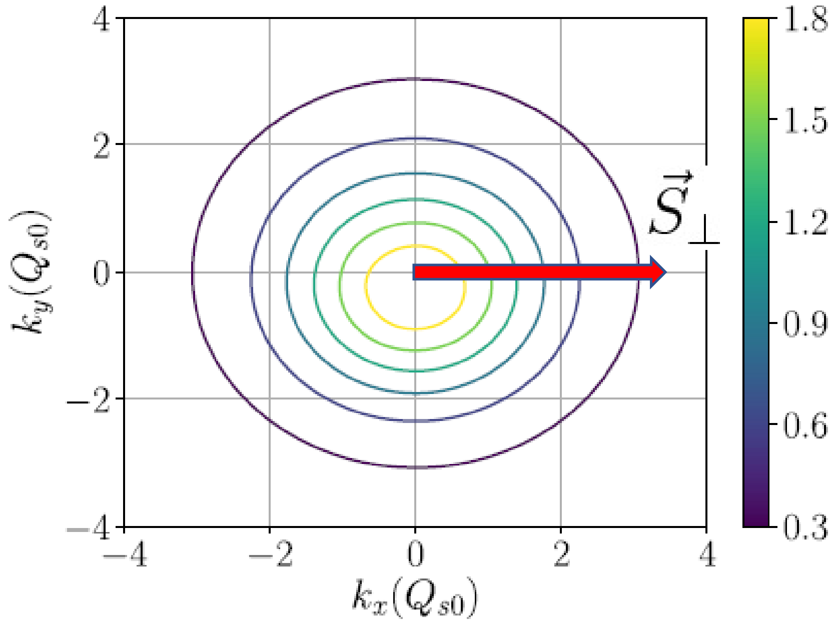
$$\langle PS|\mathrm{tr}\,U(r_\perp)U^\dagger(0_\perp)|PS\rangle = P(r_\perp) + iS_\perp \times r_\perp Q(r_\perp)$$

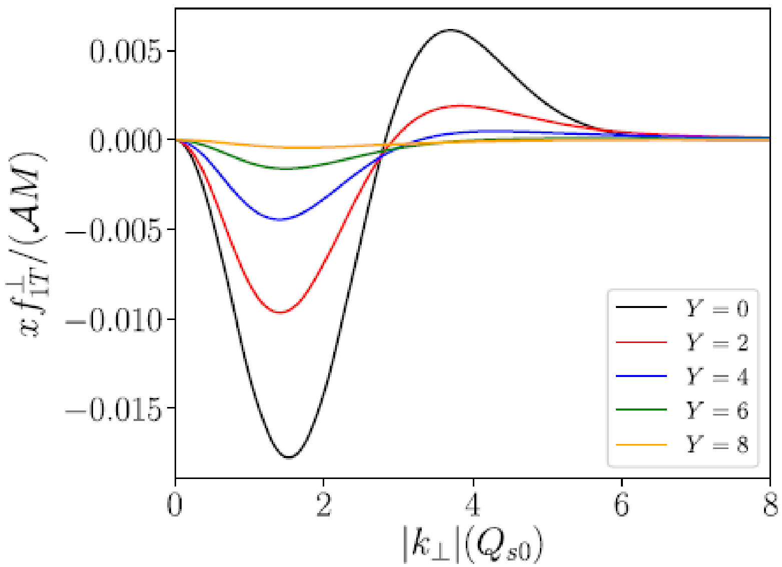
Pomeron Odderon

Gluon Sivers is proportional to Odderon!

Gluon Sivers function at small-x

Yao, YH, Hagiwara (2019)





Predict a node in transverse momentum in SSA of open charm at EIC.

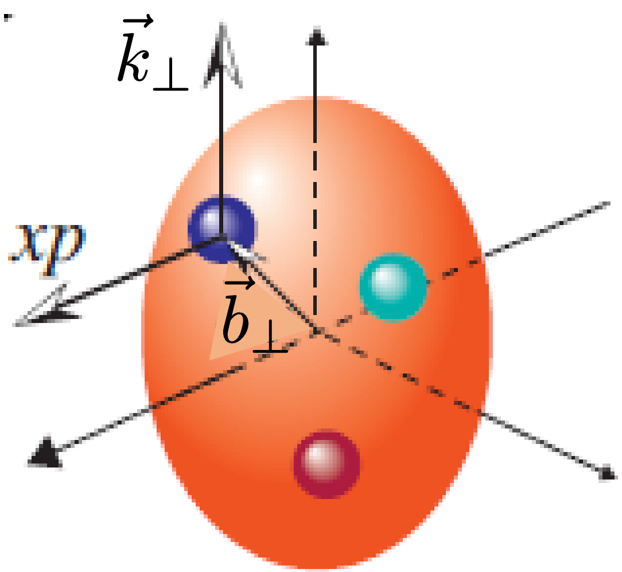
Factorization $f_{1T}^{\perp}(x,k_\perp) \approx A(x)B(k_\perp)$ holds approximately, unlike in unpolarized TMDs (Good news for phenomenology)

Gluon generalized TMD (GTMD)

$$\int d^4 v \delta(v^+) e^{ix\bar{P}^+ v^- - i(\boldsymbol{k}\cdot\boldsymbol{v})} \langle P', S' | F^{i-}(-\frac{v}{2}) \mathcal{U}^{[+]}_{\frac{v}{2},-\frac{v}{2}} F^{i-}(\frac{v}{2}) \mathcal{U}^{[-]}_{-\frac{v}{2},\frac{v}{2}} | P, S\rangle$$

$$= (2\pi)^3 \frac{\bar{P}^+}{2M} \bar{u}_{P',S'} \left[F^g_{1,1} + i\frac{\sigma^{i+}}{\bar{P}^+}(\boldsymbol{k}^i F^g_{1,2} + \boldsymbol{\Delta}^i F^g_{1,3}) + i\frac{\sigma^{ij}\boldsymbol{k}^i\boldsymbol{\Delta}^j}{M^2} F^g_{1,4} \right] u_{P,S}.$$

nucleon spinor



Fourier transform of the Wigner distribution

Odderon and GTMD

Boussarie, Grabovsky, YH, Szymanowski, Wallon, to appear

Most general coupling of the Odderon to nucleon in terms of generalized TMDs (GTMDs)

$$\frac{N_c}{g^2}\left(\boldsymbol{k}^2-\frac{\boldsymbol{\Delta}^2}{4}\right)\int d^2\boldsymbol{v}e^{-i(\boldsymbol{k}\cdot\boldsymbol{v})}\langle P'S'|\mathcal{O}(\boldsymbol{v})|PS\rangle$$

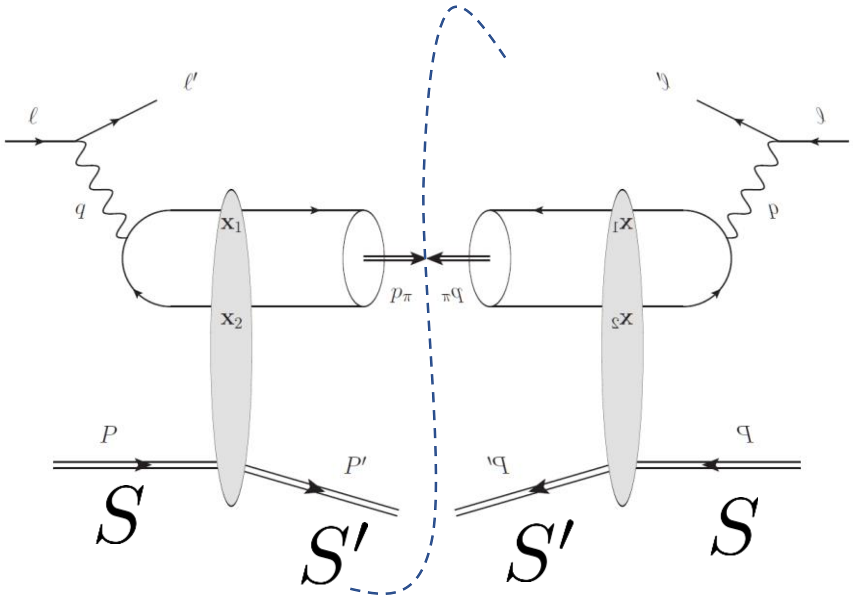
$$\sim \bar{u}_{P'S'}\left[i\frac{(\boldsymbol{k}\cdot\boldsymbol{\Delta})}{M^2}g_{1,1}+\frac{\sigma^{+i}}{\bar{P}^+}(\boldsymbol{k}^i g_{1,2}+\boldsymbol{\Delta}^i\frac{(\boldsymbol{k}\cdot\boldsymbol{\Delta})}{M^2}g_{1,3})\right]u_{PS}$$

Gluon Sivers in the forward limit

$$\bar{u}(PS)\sigma^{+i}u(PS)\sim\epsilon^{ij}S_\perp^j$$ Transverse polarization

$$\bar{u}(PS)\sigma^{+i}u(P,-S)\sim\epsilon^{ij}S_L^j$$ Longitudinal polarization, with helicity flip $\vec{S}_L=(1,ih)$

Exclusive π^0 production revisited



$$\sum_{S,S'} |\bar{u}(PS)\sigma^{+i}u(P'S')|^2$$

Non-zero contribution from $S = -S'$

In the forward region $P' \to P$, cross section is dominated by spin-dependent Odderon, or gluon Sivers

Main result

Boussarie, Grabovsky, YH, Szymanowski, Wallon, to appear

$$\frac{d\sigma}{d\xi dQ^2 d|t|} \overset{t\approx 0}{=} (2\pi)^3 \frac{\alpha_{\rm em}^2 \alpha_s^2 f_\pi^2}{8\xi N_c M^2 Q^2}\left(1 - y + \frac{y^2}{2}\right) \times \left[\int_0^1 dz \frac{\phi_\pi(z)}{z\bar{z}Q^2} \int d\boldsymbol{k}^2 \frac{\boldsymbol{k}^2}{\boldsymbol{k}^2 + z\bar{z}Q^2} f_{1T}^{\perp}(\boldsymbol{k}^2)\right]^2$$

The Sivers function appears in unpolarized cross section!

New measurements at EIC.

Dear Alice

At some point I exchanged more emails with Alice than with Larry.
She was like my counselor when I was going through a difficult time of my life.
We discussed a lot about private issues.

She was always considerate of me and my family. I miss her enormously.

My son in a blanket hand-knitted by Alice

Gmail

yoshitaka hatta <yoshitaka.hatta@gmail.com>

Another offering of advice that you may not wish to hear

3 件のメッセージ

Alice Mclerran <alicemclerran@me.com> 2014年2月27日 11:02

To: yoshitaka hatta <hatta@yukawa.kyoto-u.ac.jp>

Your unhappy situation may have improved sincee our last exchanges; I hope so. But I felt that I had already offered more advice that you could use, so I thought it best to focus on other things for a bit and let you work on the situation in your own way for a while.

Thank you Larry for your guidance, jokes, magnanimity, mentoring RIKEN postdocs. I owe you what I am now.