Drell-Yan with jet vetoes: violation of generalized factorization

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Outline

Section 1

Jet vetoes, resummation, and Glauber gluons

Jet vetoes and resummation

- $pp\ (\to H) \to W^+W^-$ at the LHC, e.g., is subject to a **jet veto** that restricts jet p_T to be below ~ 25 GeV $\ll$ hard scale $Q \implies$ large logs $\sim \alpha_s^n\, log^{2n}(p_T^{\rm veto}/Q)$.

- **Resummation** relies on factorization. Factorized cross section when $p_T^{\rm veto} \ll Q$ Stewart, Tackmann, Waalewijn '09; Tackmann, Walsh, Zuberi '12; Becher Neubert '12; Banfi, Monni, Salam, Zanderighi '12

$$\sigma^{\rm veto} = H \times J_1 \times J_2 \times S + \mathcal{O}\left(p_T^{\rm veto}/Q\right).$$

  Other application: N-jettiness subtraction Gaunt, Stahlhofen, Tackmann, Walsh '15; Boughezal, Focke, Giele, Liu, Petriello '15.

- $J_i \sim$ probability of collinear splitting not producing an identified jet. $S \sim$ probability of soft radiation not producing an identified jet.

- S is the soft function calculated in the eikonal approximation. *Not justified* when soft momentum k_s is dominated by transverse components. Called **Glauber gluons** (always virtual); non-cancellation breaks factorization.

Previous examples of factorization violation

- Dijet production with a rapidity gap Forshaw, Kyrielesis, Seymour '06, '08. Naive factorization predicts single logarithms, but factorization violation leads to double logarithms.
- Dijet production with measured hadronic event shapes Banfi, Salam, Zanderighi '10.
- Naive resummation of $t\bar{t}$ production at low pair p_T Li, Li, Shao, Yang, Zhu '13, Catani, Grazzini, Torre '14 breaks down at sufficiently high log orders, due to violation of TMD factorization in hadron production.
- Counter-examples to TMD factoriation are known, contradicting standard factoriation Colins, Qiu '07 and generalized factorization Rogers, Mulders '10.
- Certain spin asymmetries, predicted to be zero to all orders by factorization, can become non-zero Rogers '13.

Section 2

Proofs of Glauber gluon cancellation

Glauber cancellation I: e^+e^- and SIDIS

- Standard factorization takes into account the soft, collinear and soft-collinear overlap regions.
- To show that no other IR regions are relevant, need to show

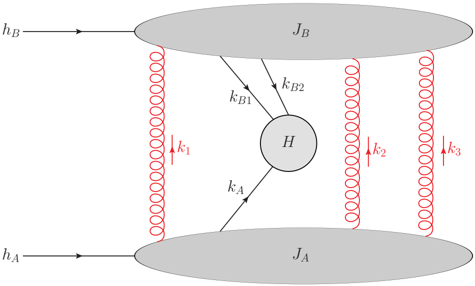
$$\int dl^+ dl^- d^2 l_T \, [I(l) - I_s(l) - I_c(l) + I_{sc}(l)]$$

has no IR divergences.

- For $e^+e^- \to j + X$ and $e + p \to j + X$, l^+ or l^- contours can be deformed to large imaginary values. Only soft & collinear regions left. $\Longrightarrow$ Subtracted integrand above has no IR divergences at any point.
- For the deformation to be successful, I, I_s, and I_c must have the same pole structure $\Longrightarrow$ strong constraints on Wilson line direction and rapidity regularization Collins, Metz '04, Collins '11.

Glauber cancellation II: Drell-Yan (inclusive or with measured pair-p_T)

For Drell-Yan, glauber gluons do not cancel at the amplitude level, but after sum over cuts. Bodwin '85, Collins, Soper, Sterman '85, '88



CSS '88 proof requirements:

1. At least one incoming hadron contributes a single massless parton.
2. Integrate over the small momentum components k_A^-, $k_{B\,i}^+$.
3. Integrate over k_s^+ and sum over "final state" cuts for soft gluons.

In the proof, a spacetime point x is part of the "final state" if either x^+ or x^- is greater than the value at hard scattering. In fact x can be at spacelike separations from the hard scattering.

Section 3

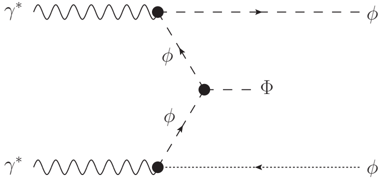
Counter-example to factorization under jet vetoes

Failure of Glauber cancellation?

- Jet vetoes break the requirements of the CSS proof. Examined in more details in the context of multi-parton scattering in Gaunt '14.
- Could an unknown new cancellation mechanism exist? Could a "generalized" factorization formula, with non-standard definitions of collinear / soft functions, correctly incorporate Glauber effects?
- We disprove both possibilities by a direct counter-example in QCD with scalar quarks.
- It sufficies to find a counter-example in any unbroken gauge theory with any matter content.

Counter-example to factorization

- **Model** (parity conserving): QCD with massless scalar quarks ϕ/ϕ^*, $SU(3)$-triplets and electrically charged, which can annihilate into a colorless real heavy scalar Φ. **Process**: $\gamma + \gamma \to \Phi + X$.



- **Observable**: double longtitudinal spin asymmetry

$$\sim \left(\sigma_{\uparrow\downarrow} + \sigma_{\downarrow\uparrow} - \sigma_{\uparrow\uparrow} - \sigma_{\downarrow\downarrow}\right)/4,$$

in the doubly differential beam thrust distribution (τ_R, τ_L), with

$$\tau_R \equiv \sum_{y_i>0} |k_{iT}| \exp(-|y_i|), \quad \tau_L \equiv \sum_{y_i<0} |k_{iT}| \exp(-|y_i|)$$

Counter-example to factorization (cont.)

- Factorization $\sigma \sim H J_1 J_2 S \implies$ double spin asymmetry

$$\sim H \left(J_1^{\downarrow} - J_1^{\uparrow}\right)\left(J_2^{\downarrow} - J_2^{\uparrow}\right) S$$

  Since the active partons are scalars carrying no spin information, and since the model conserves parity, $J_i^{\downarrow} = J_i^{\uparrow} \implies$ double spin asymmetry $= 0$, up to $\mathcal{O}(p_T^{\mathrm{veto}}/Q)$,
  i.e. factorizable contributions from soft / collinear regions give zero.

- But we find a non-zero contribution at $\mathcal{O}(\alpha_s^2)$ from the Glauber region, contradicting *standard factorization*.

- *Generalized factorization* must also satisfy $J_i^{\uparrow} = J_i^{\downarrow}$, because the single spin asymmetry vanishes due to parity (regardless of validity of factorization),

$$0 = \sigma_{\uparrow\mathrm{upol}} - \sigma_{\downarrow\mathrm{upol}} \sim H \left(J_1^{\downarrow} - J_1^{\uparrow}\right) J_2^{\mathrm{unpol}} S$$

  $\implies$ Incompatible with non-zero double spin asymmetry

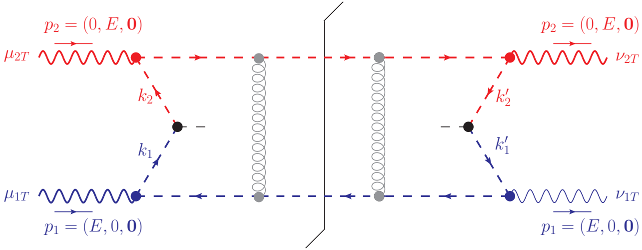
Calculating spin asymmetry in the model

With incoming photons in the $\pm z$ directions, the unpolarized spin sum is

$$(\epsilon_\downarrow^\mu \epsilon_\downarrow^\nu + \epsilon_\uparrow^\mu \epsilon_\uparrow^\nu)/2 = g^{\mu_T \nu_T}/2,$$

while the left-right spin sum asymmetry is

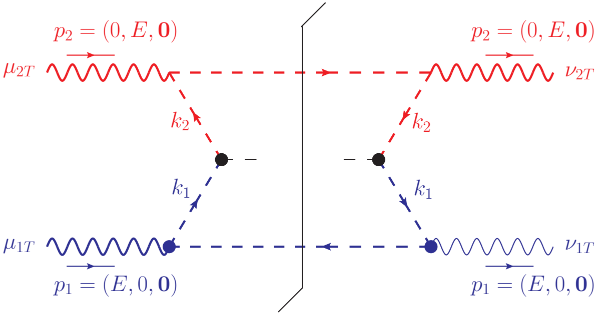
$$(\epsilon_\downarrow^\mu \epsilon_\downarrow^\nu - \epsilon_\uparrow^\mu \epsilon_\uparrow^\nu)/2 = i\epsilon^{\mu_T \nu_T}/2$$



$$\propto \epsilon_{\mu_{1T}\nu_{1T}} \underbrace{k_1^{\mu_{1T}} k_1'^{\nu_{1T}}}_{\gamma\phi\phi^* \text{ vertex}} \epsilon_{\mu_{2T}\nu_{2T}} k_2^{\mu_{2T}} k_2'^{\nu_{2T}} \equiv \epsilon\left(k_1^T, k_1'^T\right) \epsilon\left(k_2^T, k_2'^T\right)$$

Vanishing spin asymmetry at LO

Factorizable diagrams, such as the LO diagram, do not contribute.

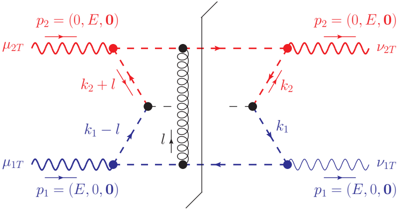


$$\propto \epsilon\left(k_1^T, k_1^T\right) \epsilon\left(k_2^T, k_2^T\right) = 0,$$

as expected.

Vanishing non-factorizable diagrams: $\mathcal{O}(\alpha_s)$

Usually, the one-Glauber cut diagram

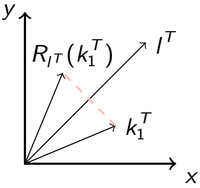


cancels with its complex conjugate cut diagram. But for our special model, the contribution by itself has zero real and imaginary parts.

$$\left|\mathcal{M}^2\right|_{\text{asym}} \propto \int d^4 l\, \epsilon\left(k_1^T, l^T\right)\, \epsilon\left(k_2^T, l^T\right)$$

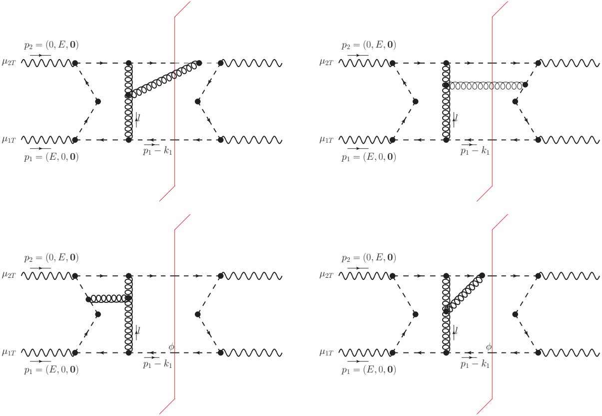
$\times$ denominators,

odd under $k_1^T \to R_{l^T}(k_1^T)$, while the measurement function (beam thrust) is even. $\implies$ zero after phase space integration.

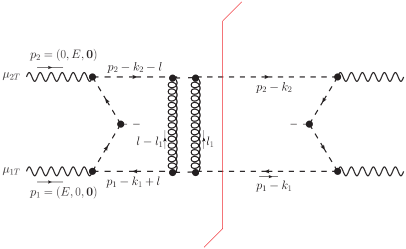


Vanishing non-factorizable diagrams: $\mathcal{O}(\alpha_s^2)$

Essentially the same argumen shows the vanishing of any diagram with at most one soft or Glauber gluon attached to the lower spectator line.



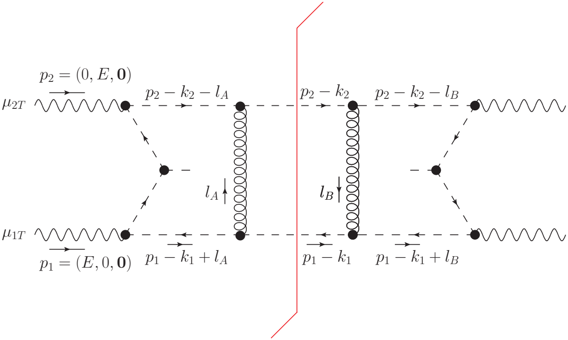
Vanishing of same-side two-Glauber diagrams



- Only l can acquire a Glauber *"pinch"* $\Longrightarrow$ contour integration cuts two lines on the left of the gluons, giving a purely imaginary contribution.
- To get a real result, need another imaginary contribution from the box subdiagram due to Glauber-like l_1.
- Result again $\propto \epsilon(k_1^T, l^T)\epsilon(k_2^T, l^T)$, and vanishes after phase space integration using the same argument.

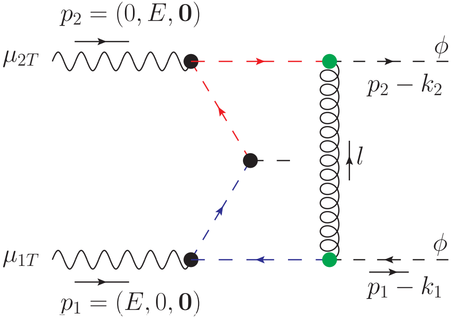
The only diagram left...

We are left with only one cut diagram at $\mathcal{O}(\alpha_s^2)$, from squaring the one-Glauber diagram.



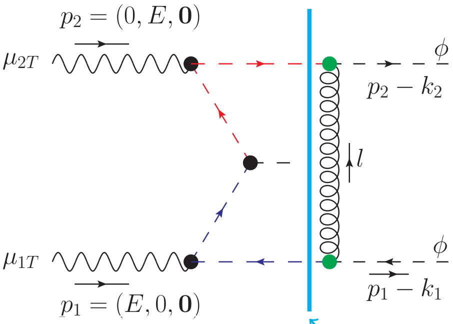
If the Glauber region contribution (minus overlap with other regions) gives a non-zero double spin asymmetry, we obtain a contradiction to both standard and generalized factorization.

The one-Glauber diagram at leading power



- The $A\phi\phi^*$ vertices give $\sim 4(p_2 - k).(p_1 - k)$, indep. of l at leading power.
- $l^2 \sim l_T^2$. Only the upper fermion propagators depend on l^+. Only the lower fermion propagators depend on l^-.

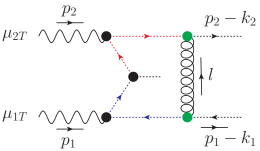
The one-Glauber diagram at leading power



- The $A\phi\phi^*$ vertices give $\sim 4(p_2 - k).(p_1 - k)$, indep. of l at leading power.
- $l^2 \sim l_T^2$. Only the upper fermion propagators depend on l^+. Only the lower fermion propagators depend on l^-.
- Can perform l^+ and l^- integrals by contours, picking up poles from cutting two lines.

Squaring the one-Glauber diagram

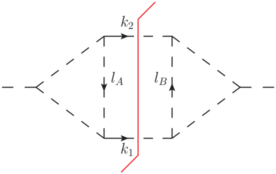
l^+ and l^- contour integrals turn 4D pentagon into 2D Euclidean triangle



$$\propto \int \frac{d^2 l}{(2\pi)^2} \frac{1}{|l|^2} \frac{k_1^{\mu_{1T}} - l^{\mu_{1T}}}{|k_{1T} - l|^2} \frac{k_2^{\mu_{2T}} + l^{\mu_{2T}}}{|k_{2T} + l|^2}$$

Double spin asymmetry

$$\epsilon_{\mu_{1T}\nu_{1T}} \epsilon_{\mu_{2T}\nu_{2T}} \mathcal{M}_1^{\mu_{1T}\mu_{2T}} \mathcal{M}_1^{*\,\nu_{1T}\nu_{2T}} \propto \int d^2 l_A \int d^2 l_B \underbrace{\epsilon\left(k_1^T - l_A, k_1^T - l_B\right) \epsilon\left(k_2^T + l_A, k_2^T + l_B\right)} \times$$

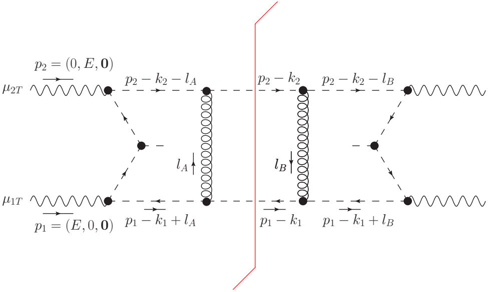


$\to 0$ as l_A, $l_B \to 0$, suppresses lower-p_T regions (ultrasoft, Glauber-II) and their overlap with Glauber region.

2D ϕ^3 diagram

Final result

The resulting loop & phase space integral in 2D Euclidean space is IR and UV finite. Can be evaluated by Monte Carlo without regularization or subtraction.



Using the Vegas algorithm in CUBA library [Hahn, hep-ph/0509016], with 4.2 million points,

$$\left(\frac{d^3\sigma_{\rm asym}}{d\tau_R d\tau_L dy} \Big/ \frac{d^3\sigma_{unpol}}{d\tau_R d\tau_L dy} \right)_{y=0, \tau_R=\tau_L=\tau_B/2 \ll 1} = (1.58 \pm 0.02) C_F^2 \alpha_s^2 \quad \neq \mathbf{0}$$

Discussion

- We constructed a counter-example to standard and generalized factorization for electroweak production with measured left- and right-hemisphere beam thrust.
- Applicable to both Abelian and non-Abelian theories (not always true for other observables).
- Our result requires entangling of two collinear sectors, but does not rule out soft factorization in some manner.
- For partonic scattering instead of $\gamma\gamma$ scattering, our diagram is at $\mathrm{N}^4 LO$, no Regge-type logarithms (yet).
- After multiplying double logs from hard function, violation of factorization starts at no later than $\alpha_s^{n+4} \ln^{2n} \tau_B$; could be worse in general situations.
- Worth exploring Glauber corrections to soft / collinear resummation for LHC processes, e.g. Drell-Yan with jet vetoes, and $t\bar{t}$ at low p_T.

Thank you!