

# Jet vetoes and discrete symmetries

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# Outline

- 1 Jet vetoes, resummation, and Glauber gluons
- 2 Proofs of Glauber gluon cancellation
- 3 Parity and toy model for factorization violation
- 4 Discussion

## Section 1

### Jet vetoes, resummation, and Glauber gluons

## Jet vetoes and resummation

- $pp (\rightarrow H) \rightarrow W^+ W^-$  at the LHC, e.g., is subject to a **jet veto** that restricts jet  $p_T$  to be below  $\sim 25 \text{ GeV} \ll \text{hard scale } Q \implies \text{large logs}$   
 $\sim \alpha_s^n \log^{2n}(p_T^{\text{veto}}/Q)$ .
- **Resummation** relies on factorization. Factorized cross section when  $p_T^{\text{veto}} \ll Q$  Stewart, Tackmann, Waalewijn '09; Tackmann, Walsh, Zuberi '12; Becher Neubert '12; Banfi, Monni, Salam, Zanderighi '12

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

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.
- $S$  calculated in the eikonal approximation. Not applicable for **Glauber gluons** whose momenta are dominated by transverse components.

## Previous examples of factorization violation

- Dijet production with a rapidity gap [Forshaw, Kyrieles, Seymour '06, '08](#). Single logarithms turn into double logarithms.
- Dijet production with measured hadronic event shapes [Banfi, Salam, Zanderighi '10](#).
- TMD factorization breaks for hadron production. Counter-examples known [Colins, Qiu '07](#) [Rogers, Mulders '10](#).  
Affects resummation of  $t\bar{t}$  production at low pair  $p_T$  [Li, Li, Shao, Yang, Zhu '13](#), [Catani, Grazzini, Torre '14](#).
- Certain spin asymmetries, vanishing to all  $\alpha_s$  orders under TMD 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

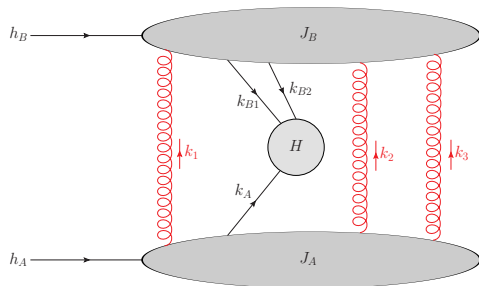
$$\int d l^+ d l^- d^2 l_\perp [I(l) - I_s(l) - I_c(l) + I_{sc}(l)]$$

has no IR divergences.

- For  $e^+e^- \rightarrow j + X$  and  $e + p \rightarrow j + X$ ,  $l^+$  or  $l^-$  contours can be deformed to large imaginary values. Only **soft** & **collinear** regions left.  $\implies$  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  $\implies$  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  $k_s^+$  and sum over "final state" cuts for soft gluons.
3. Integrate over the small momentum components  $k_A^-$ ,  $k_{B_i}^+$ .



## Section 3

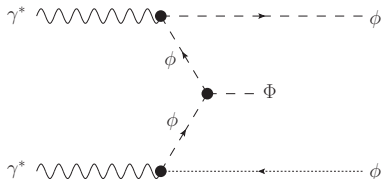
### Parity and toy model for factorization violation

## 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.
- We show that the cross section does not exhibit the **enhanced discrete symmetries** predicted by factorization. Parity used in our toy model. Charge conjugation could lead to realistic models.

## Toy model for factorization violation

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



- Observable**: double longitudinal spin asymmetry

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

in the doubly differential beam thrust distribution  $(\tau_R, \tau_L)$ , with

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

## Discrete symmetries of the toy model

- With or without factorization,  $Z_2$  spin symmetry,  $\sigma_{\uparrow\uparrow} = \sigma_{\downarrow\downarrow}$ ,  $\sigma_{\uparrow\downarrow} = \sigma_{\downarrow\uparrow}$ .  
 $\sigma_{\uparrow \text{unpol}} = \sigma_{\downarrow \text{unpol}}$ , i.e. vanishing single spin asymmetry

- With Factorization (standard or generalized),  $\sigma \sim HJ_1J_2S \implies$

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

$$\text{single spin asymmetry} \sim H \underbrace{\left( J_1^\downarrow - J_1^\uparrow \right)}_{=0} J_2^{\text{unpol}} S$$

- Double spin asymmetry also vanishes, *enhanced*  $Z_2 \times Z_2$  spin symmetry,  $\sigma_{\uparrow\downarrow} = \sigma_{\downarrow\uparrow} = \sigma_{\uparrow\uparrow} = \sigma_{\downarrow\downarrow}$ . *May not hold when Glauber region included.*
- A non-zero double spin asymmetry would disprove standard factorization and a wide class of generalizations.

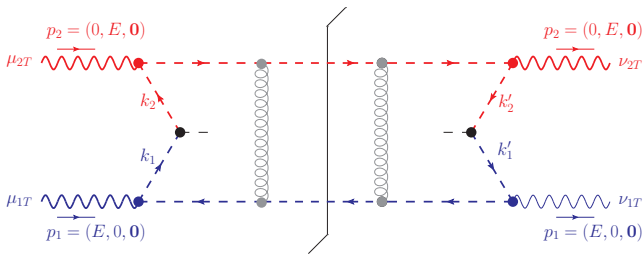
## Calculating spin asymmetry in the model

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

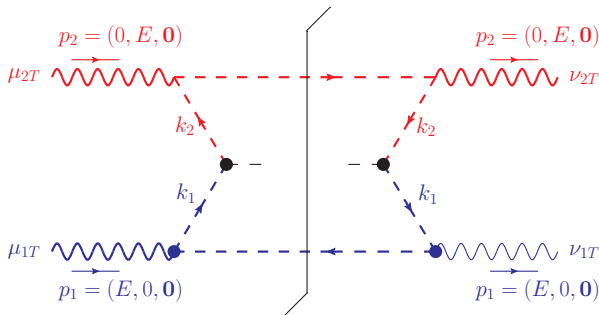
$$(\epsilon_{\downarrow}^{\mu} \epsilon_{\downarrow}^{\nu} - \epsilon_{\uparrow}^{\mu} \epsilon_{\uparrow}^{\nu})/2 = i\epsilon^{\mu T \nu T}/2$$



$$\propto \epsilon_{\mu_1 T \nu_1 T} \underbrace{k_1^{\mu_1 T} k_1^{\nu_1 T}}_{\gamma\phi\phi^* \text{ vertex}} \epsilon_{\mu_2 T \nu_2 T} k_2^{\mu_2 T} k_2^{\nu_2 T} \equiv \epsilon \left( k_1^T, k_1'^T \right) \epsilon \left( k_2^T, k_2'^T \right)$$

## Vanishing spin asymmetry at LO

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

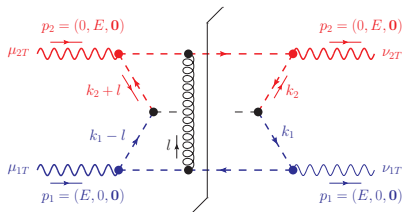


$$\propto \epsilon(k_1^T, k_1^T) \epsilon(k_2^T, k_2^T) = 0,$$

as expected.

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

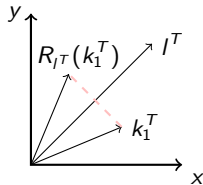
Usually, the one-Glauber cut diagram



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

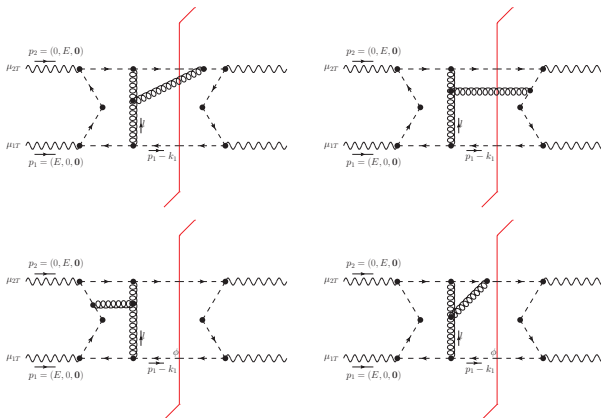
$$|\mathcal{M}^2|_{\text{asym}} \propto \int d^4 l \epsilon(k_1^T, l^T) \epsilon(k_2^T, l^T) \times \text{denominators},$$

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



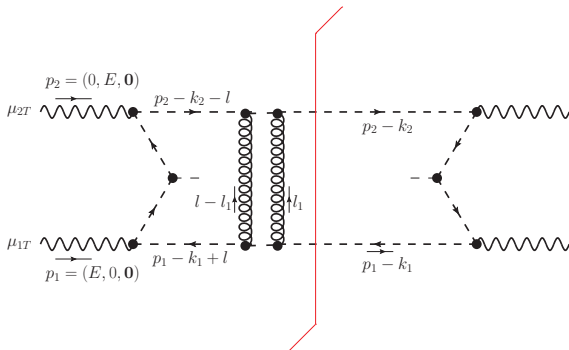
## Vanishing non-factorizable diagrams: $\mathcal{O}(\alpha_s^2)$

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





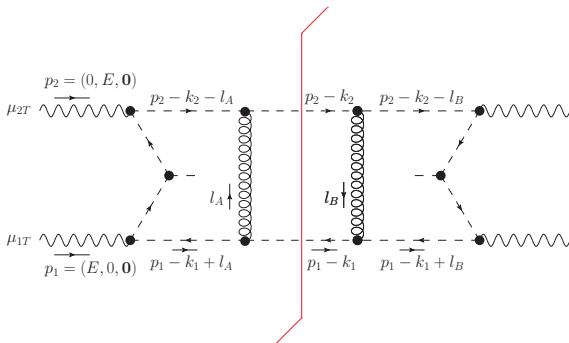
## Vanishing of same-side two-Glauber diagrams



- Total exchanged momentum,  $l$ , is Glauber-like  $\implies$  contour integration cuts two lines on the left of the gluons, giving an imaginary contribution.
- To get a real result, need another imaginary contribution from cutting the box subdiagram due to Glauber-like  $l_1$ .
- Result again  $\propto \epsilon(k_1^T, l^T)\epsilon(k_2^T, l^T)$ , vanishes after phase space integration.

## The only diagram left. . .

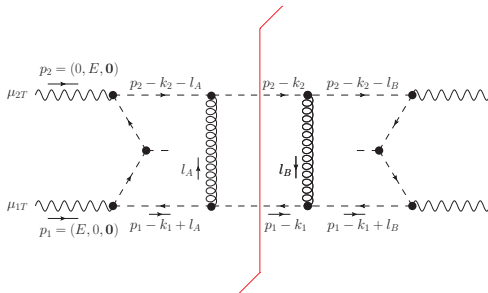
We are left with only one cut diagram at  $\mathcal{O}(\alpha_s^2)$ , from squaring the one-Glauber diagram.



If the Glauber region gives a non-zero double spin asymmetry, we obtain a contradiction to both standard and generalized factorization.

## The two-Glauber diagram

Integrating “+” and “-” loop momentum components by contours,

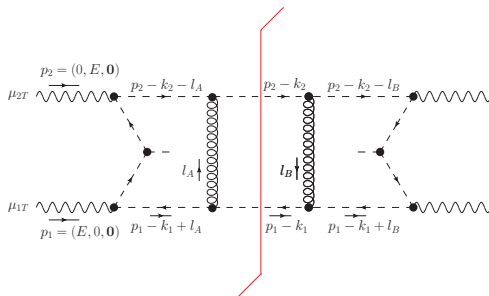


$$\propto \int d^2 l_A \int d^2 l_B \underbrace{\epsilon(k_1^T - l_A, k_1^T - l_B) \epsilon(k_2^T + l_A, k_2^T + l_B)}_{\text{denominators}}$$

→ 0 as  $l_A, l_B \rightarrow 0$ , suppresses IR divergences and lower- $p_T$  regions (ultrasoft, Glauber-II).

## 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,

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

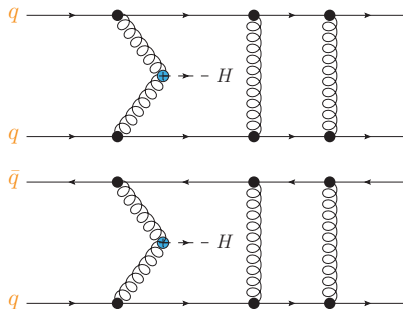
## Discussion

- Counter-example to factorization (standard or generalized), by showing the violation of  $Z_2 \times Z_2$  **enhanced spin symmetry** predicted by factorization.
- Applicable to both **Abelian** and **non-Abelian** theories.
- Due to special numerator structure, Glauber region well defined **without IR / rapidity regularization or overlap subtraction**. Not generally true!
- It has been proposed that the Glauber contribution can be minimized by using a jet algorithm with small  $R$  [[Gangal, Stahlhofen, Tackmann, '14](#)].

We do not seem to confirm this, since most of the diagrams are insensitive to  $R$ , though real emission diagrams deserve further scrutiny.

## Discussion (cont.)

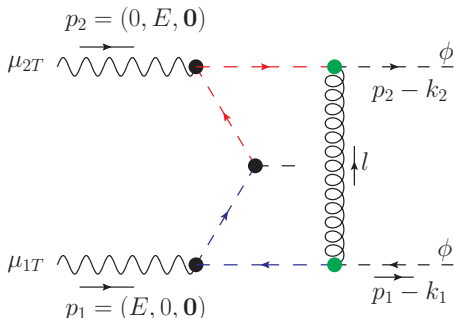
- **Charge conjugation** symmetry may be used to construct realistic examples that can be tested at colliders.
- The **gluon beam functions** from  $p$  and  $\bar{p}$  are the same, leading to the same  $gg \rightarrow H$  beam thrust distributions from  $pp$  and  $p\bar{p}$  collisions. Does  $Z_2 \times Z_2$  charge conjugation symmetry survive glauber effects?



- Worth exploring **Glauber corrections** to perturbative resummation.

Thank you!

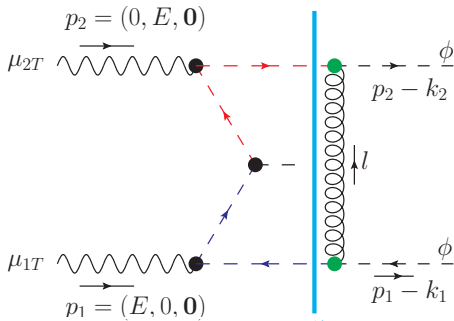
## The one-Glauber diagram at leading power



- The  $A\phi\phi^*$  vertices give  $\sim 4(p_2 - k) \cdot (p_1 - k)$ , 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  $l^-$ .



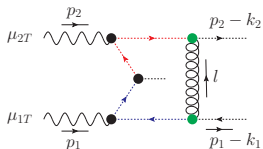
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- $l^2 \sim l_T^2$ . Only the upper fermion propagators depend on  $l^+$ . Only the lower fermion propagators depend on  $l^-$ .
- Can perform  $l^+$  and  $l^-$  integrals by contours, picking up poles from cutting two lines.

## Squaring the one-Glauber diagram

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



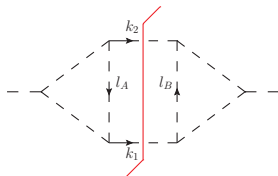
$$\propto \int \frac{d^2 l}{(2\pi)^2} \frac{1}{|l|^2} \frac{k_1^{\mu_{1T}} - l^{\mu_{1T}}}{|k_{1T} - l|^2} \frac{k_2^{\mu_{2T}} + l^{\mu_{2T}}}{|k_{2T} + l|^2}$$

Double spin asymmetry

$$\epsilon_{\mu_{1T}\nu_{1T}} \epsilon_{\mu_{2T}\nu_{2T}} \mathcal{M}_1^{\mu_{1T}\mu_{2T}} \mathcal{M}_1^{*\nu_{1T}\nu_{2T}} \propto \int d^2 l_A \int d^2 l_B$$

$$\underbrace{\epsilon(k_1^T - l_A, k_1^T - l_B) \epsilon(k_2^T + l_A, k_2^T + l_B)} \times$$

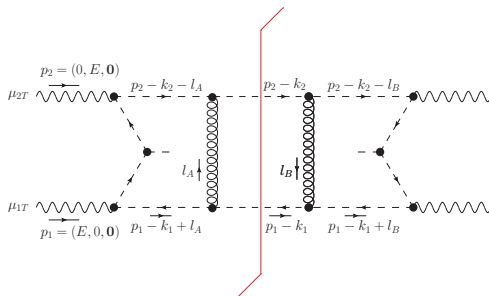
→ 0 as  $l_A, l_B \rightarrow 0$ , suppresses lower- $p_T$  regions (ultrasoft, Glauber-II) and their overlap with Glauber region.



2D  $\phi^3$  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.



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