Factorization violation in Super-Weak scale Collisions

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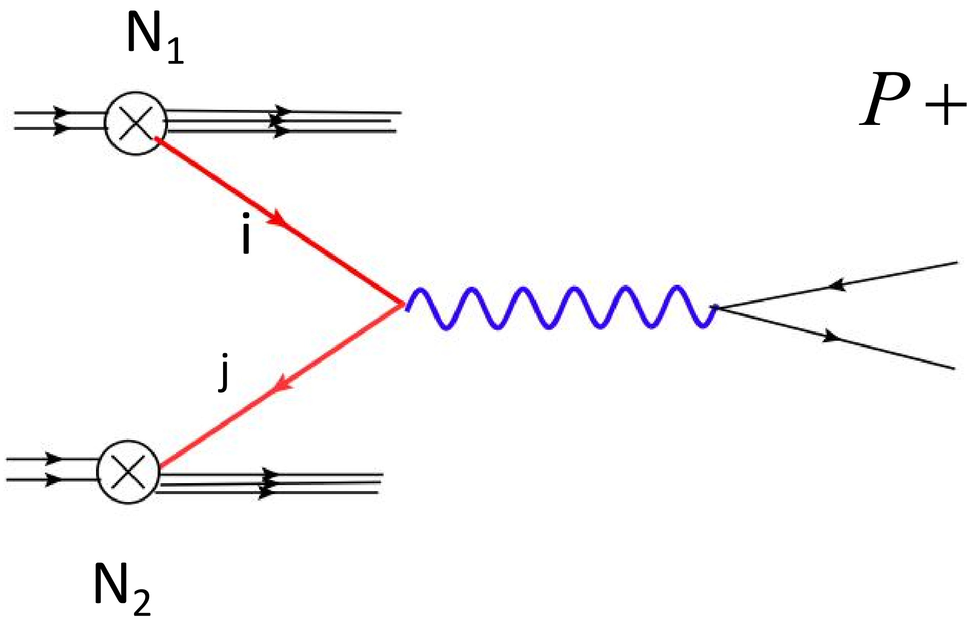
Outline

- Introduction to factorization
- Factorization violation via the glauber
- Flavor factorization violation
- Summary



$$P + P \rightarrow l^{+} + l^{-} + X$$

Lepton Pair

$$\frac{d\sigma}{dy\,dQ^2} = \int dx_1 \int dx_2\, C_{ij}(x_1, x_2, Q, s)\, f_{i/N_1}(x_1)\, f_{j/N_2}(x_2) + O\left(\frac{\Lambda_{QCD}}{Q}\right)$$

Physics at Q

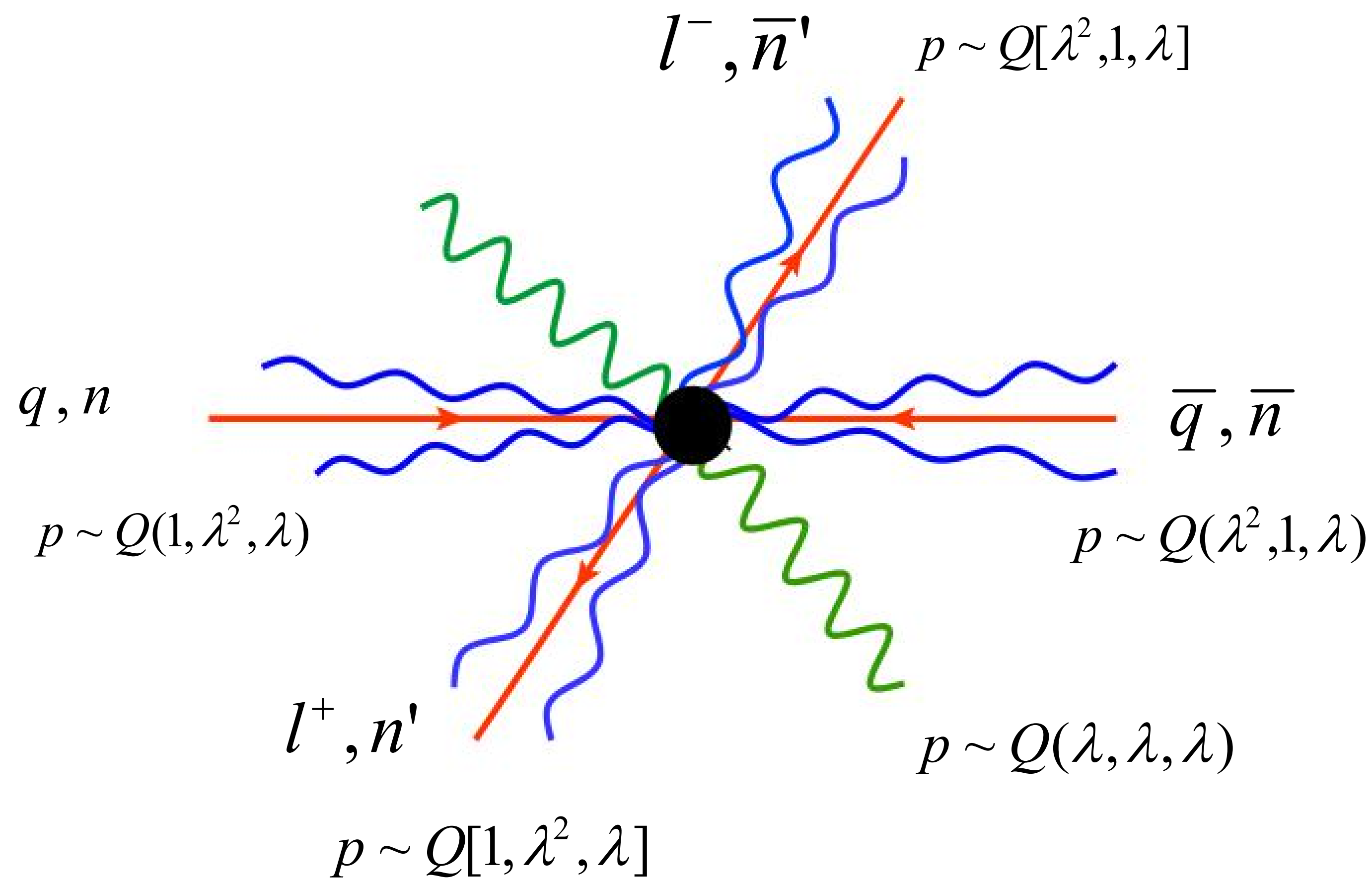
physics at Λ_{QCD} for massless particles in the z direction

physics at Λ_{QCD} for massless particles in the -z direction

- Does phase space IR factorization hold automatically for any observable in a scattering experiment?

- What are the general condition under which factorization is violated

A Drell Yan process



$$q + \bar{q} \rightarrow l^+ + l^- + X$$

Only Soft and Collinear momentum regions of phase space contribute at leading power in

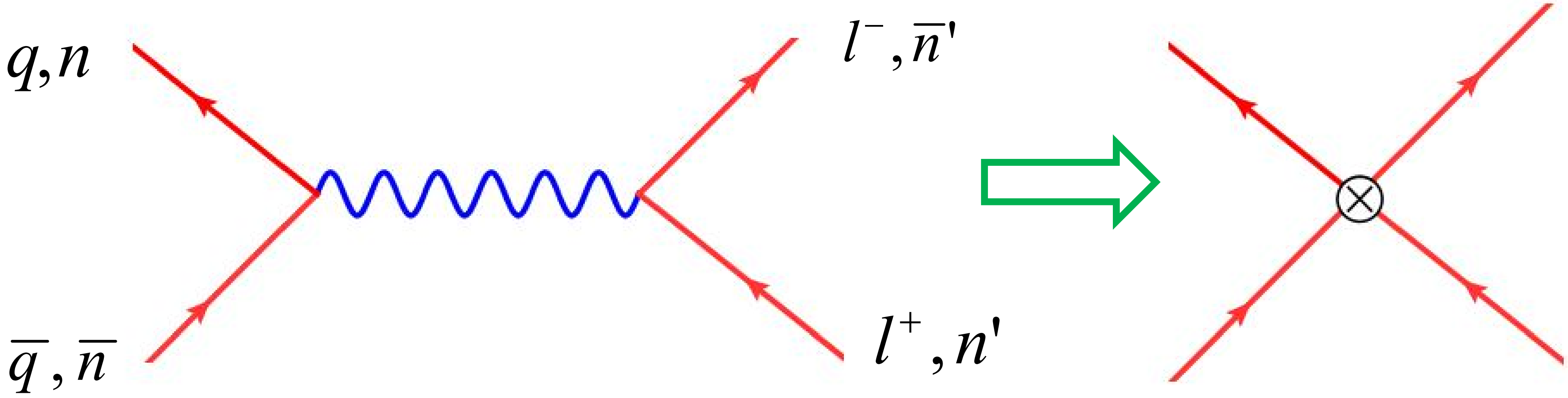
$$\lambda = \frac{m}{Q}$$

$n, \bar{n}, n', \bar{n}'$ are widely separated light-like directions

$$n \cdot n' \sim 1$$

Effective Lagrangian

$$L_{eft} = L_n + L_{\bar{n}} + L_{n'} + L_{\bar{n}'} + L_s + L_{\text{int},n\bar{n}n'\bar{n}'s} + O(\lambda)$$



$$M \propto C(Q)\left\langle l^+ + l^- + X \,|\, O \,|\, PP \right\rangle$$

$$O = \left(\bar{\psi}_{n'} \Gamma \mathrm{T}^a \psi_{\bar{n}'}\right)\left(\bar{\chi}_n \Gamma \mathrm{T}^a \chi_{\bar{n}}\right)$$

Decoupling the Soft sector

- Soft-Collinear interactions also Eikonalize

$$\psi_{\bar{n}'}^{c} \to Exp\left(-g \sum_{perm} \frac{(\bar{n}'\cdot A_s(k))}{\bar{n}'\cdot k + i0} \right)^{cc'} \psi_{\bar{n}'}^{c'} = S_{\bar{n}'}^{cc'} \psi_{\bar{n}'}^{c'}$$

$$O = \left(\overline{\psi}_{n'} W_{n'}^{+}\right)_{\mathrm{j}} \left[\mathrm{T}^{\mathrm{a}}\right]_{kl} \left(\Gamma W_{\bar{n}'} \psi_{\bar{n}'}\right)_{\mathrm{m}} \left(\overline{\chi}_{n} W_{n}^{+}\right)_{o} \left[\mathrm{T}^{\mathrm{a}}\right]_{pq} \left(\Gamma W_{\bar{n}} \chi_{\bar{n}}\right)_{r}$$
$$\left(S_{n'}^{jk} S_{\bar{n}'}^{lm} S_{n}^{op} S_{\bar{n}}^{qr}\right)$$

- Factorization !

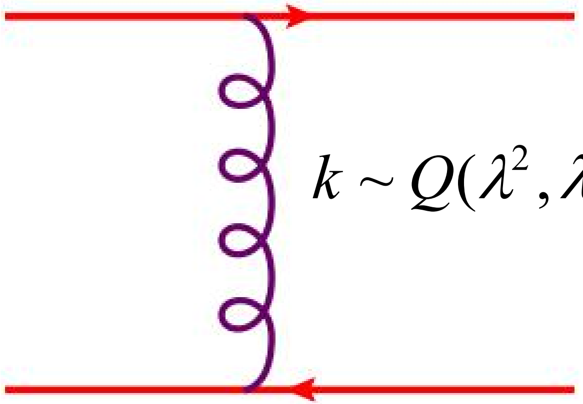
$$L_{eft} = L_n + L_{\bar{n}} + L_{n'} + L_{\bar{n}'} + L_s + O(\lambda)$$

It appears we have a complete factorization of the IR physics

But not quite ...

We have missed a region of phase space that contributes at leading power

Introducing
The collinear Glauber mode

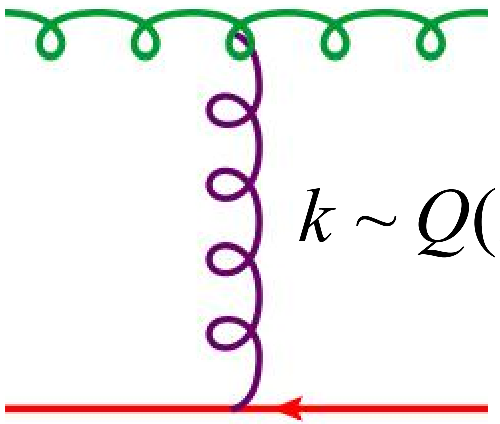


Glauber propagator

$$\frac{-i}{k^2 - m^2 + i0} \approx \frac{i}{\vec{k}_\perp^{\,2} + m^2} + O(\lambda)$$

- A momentum mode that is exchanged between two widely separated collinear sectors
- The collinear sectors maintain their scaling ⟶ Forward scattering
- Glauber acts as a potential interaction ⟶ a purely virtual contribution

The Soft-Collinear Glauber



$p_1 \sim Q(\lambda, \lambda, \lambda)$

$k \sim Q(\lambda^2, \lambda, \lambda)$

$p_2 \sim Q(\lambda^2, 1, \lambda)$

Glauber propagator

$$\frac{-i}{k^2 - m^2 + i0} \approx \frac{i}{\vec{k}_\perp^{\,2} + m^2}$$

$$L_{eft} = L_n + L_{\bar{n}} + L_{n'} + L_{\bar{n}'} + L_s + L^G{}_{\mathrm{int}, n\bar{n}n'\bar{n}'s} + O(\lambda)$$

- The glauber introduces contact interaction terms between the “factorized” sectors
- Glauber contributions do not eikonalize.

Question:
Did we forget about the Glaubers in our parton model picture?

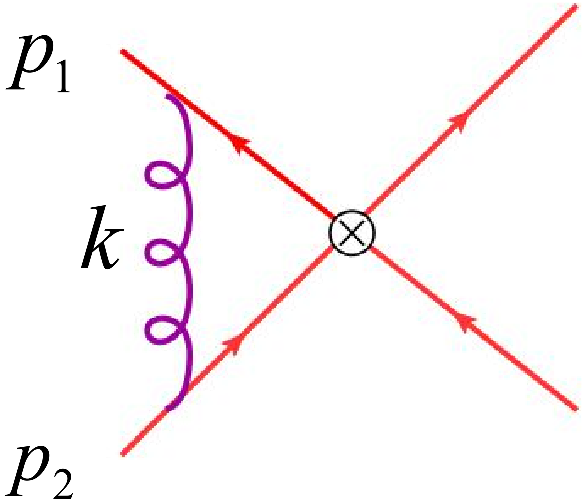
There is a way around....

- Whenever we introduce a new mode we have to be careful to check that there is no overlap with already existing regions of phase space.

- Whenever such an overlap exists, we need to do a subtraction to prevent double counting

Active-Active glauber

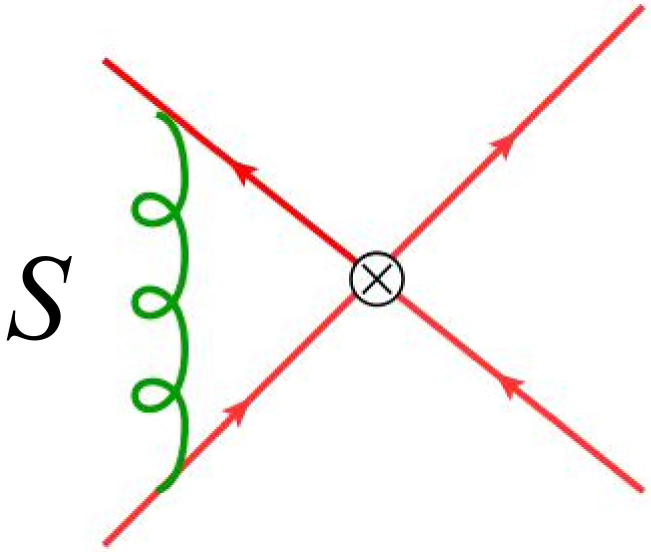
- Glauber exchange between partons participating in the hard interaction



$$\propto E(p_{1\perp}, p_{2\perp}) \int d^{d-2} k_\perp \frac{i}{\vec{k}_\perp^2 + m^2}$$

$$= iE(p_{1\perp}, p_{2\perp}) \ln \frac{\mu^2}{m^2} = G$$

Active-Active Soft Overlap



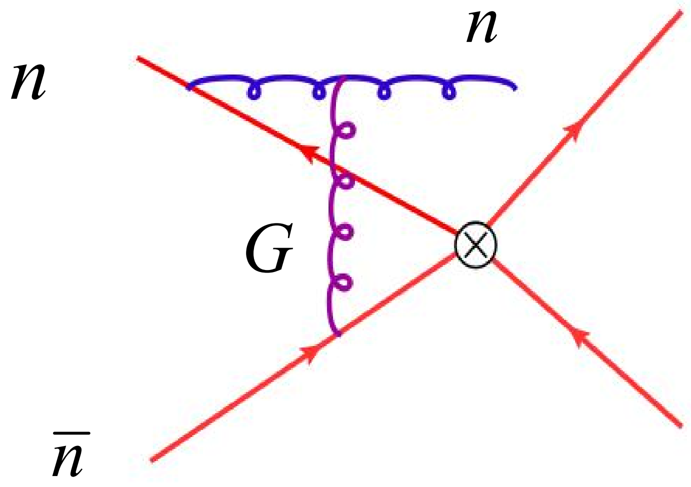
- The phase space of the soft and the glauber momenta have an overlap.

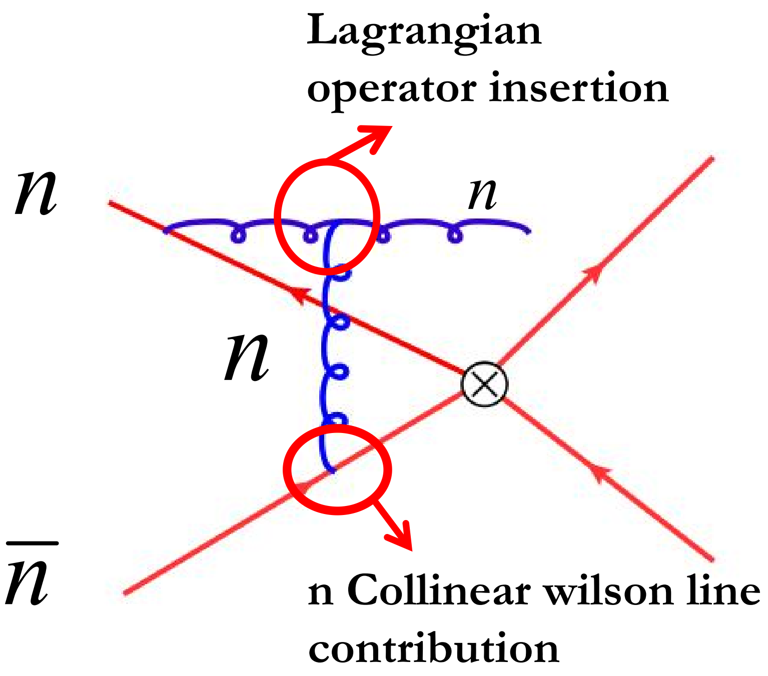
- **For an active-active exchange, the overlap is the same as the full glauber contribution**

$$S^{(G)} = G$$

Active-spectator glauber exchange

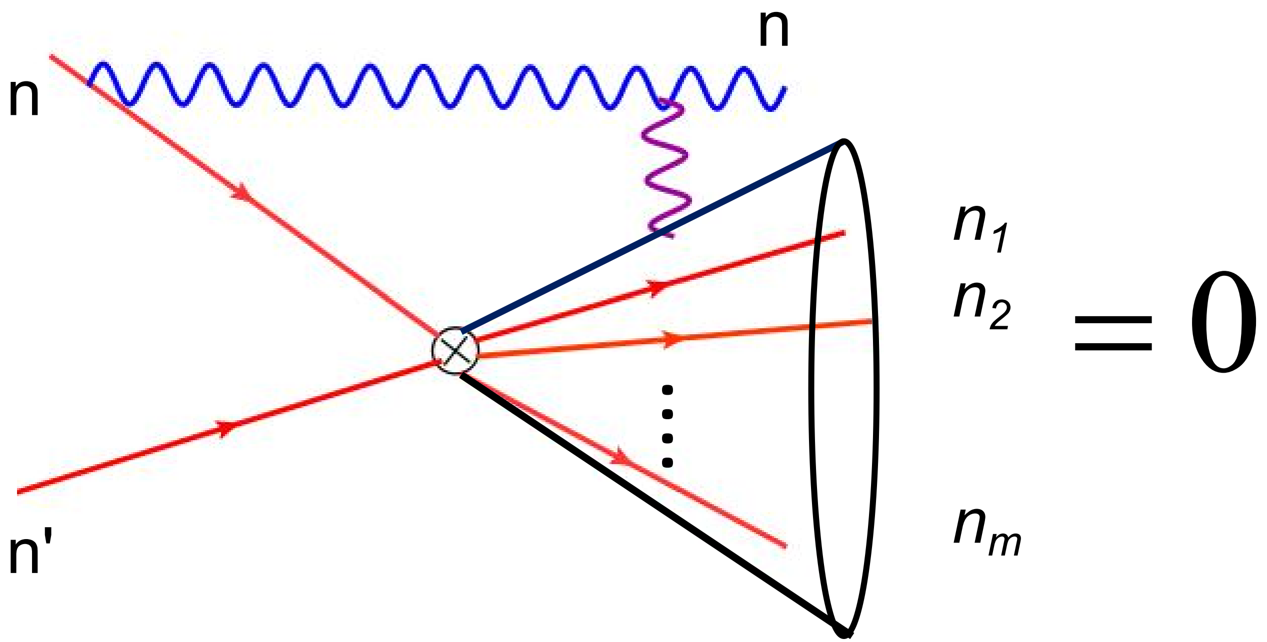
- A spectator is a parton which does not participate directly in the hard interaction.





- The overlap between the glauber exchange and the Collinear wilson line contribution is same as the full glauber contribution

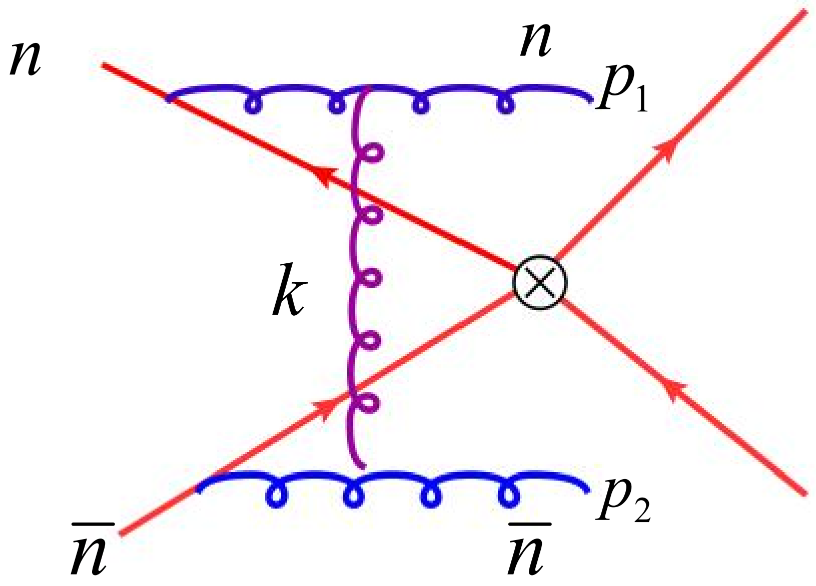
Corollary: A color singlet **active** object does not couple to an external spectator via a glauber



Color-Singlet active object T

- The contribution to the n collinear Wilson line from T is 0 .
- Hence the glauber contribution must be zero
- The glauber exchange bewteen n and n_i does not depend on these directions as long as they are widely separated.
- The exchanges between the components of T and n spectator cancel out

Spectator-Spectator glauber



$$\propto \int d^{d-2}k_\perp \times \frac{F(k_\perp + p_{1\perp}, k_\perp - p_{2\perp})}{\left[(\vec{k}_\perp + \vec{p}_{1\perp})^2 + m_\chi^2\right]\left[(\vec{k}_\perp - \vec{p}_{2\perp})^2 + m_\chi^2\right]}$$

$$= \int d^{d-2}k_\perp \boxed{\frac{i}{(\vec{k}_\perp^2 + m^2)}} \times E(k_\perp + p_{1\perp}, k_\perp - p_{2\perp})$$

phase factor

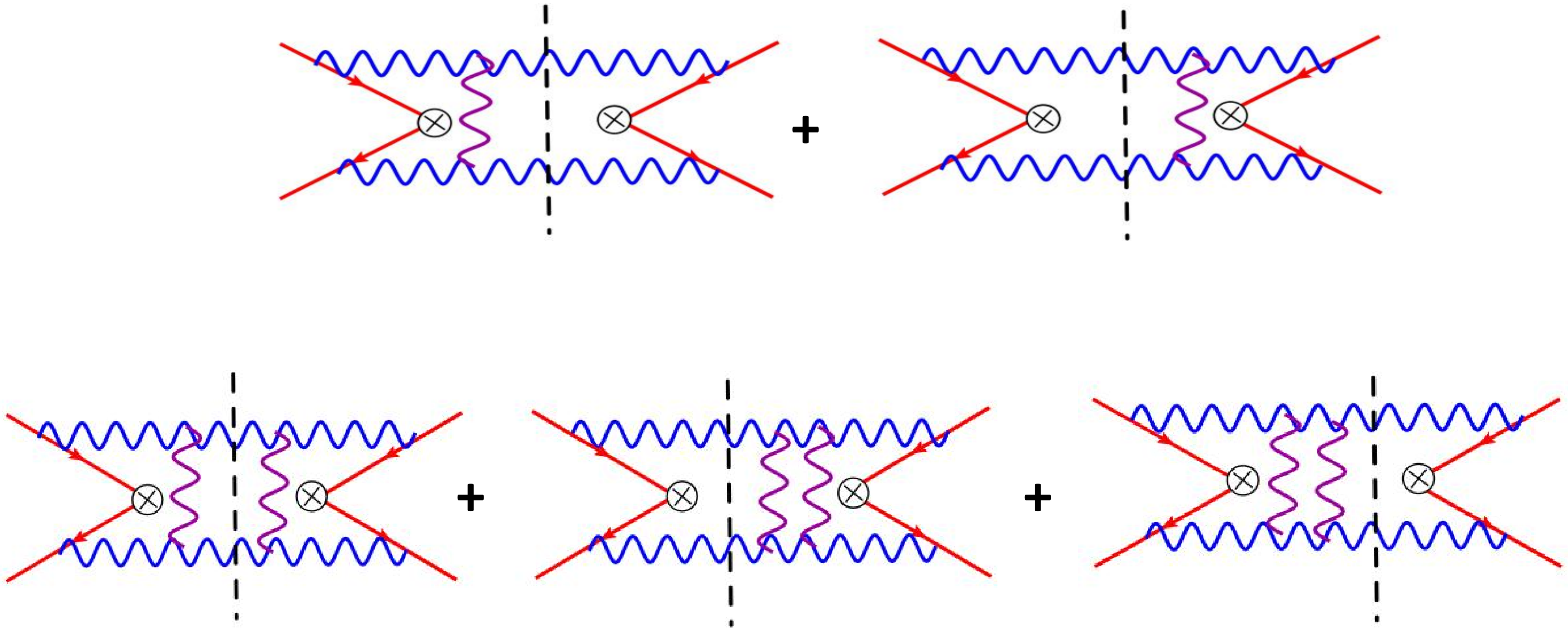
- We cannot draw any other diagram which can possibly overlap with this glauber exchange

Cancellation of the Glauber phase

$$\sigma \propto \int d \prod_{p1,p2} |A|^2$$

- If there are no restrictions on the limits of $\Delta \vec{p}_\perp = p_{1\perp} - p_{2\perp}$, then the phase cancels out.
- **Any observable on the final state that restricts the phase space of spectators violates factorization., e.g, Beam Thrust, Transverse thrust.**
- **These observables reduce the inclusivity of the beam**

Order by Order phase cancellation



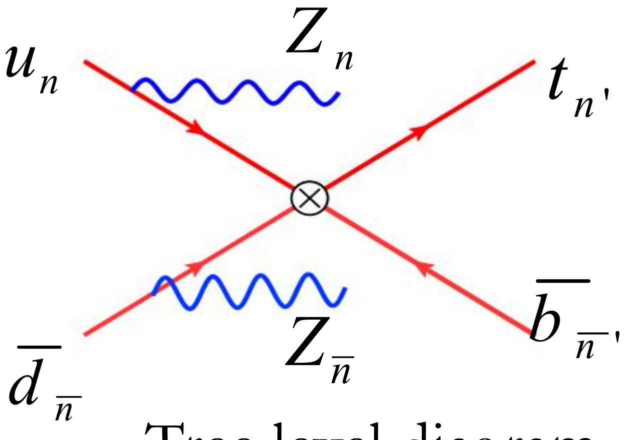
We can then make a general statement :

Any final state measurement sensitive to quantum numbers of the spectators that the glauber can influence will exibit factorization violation

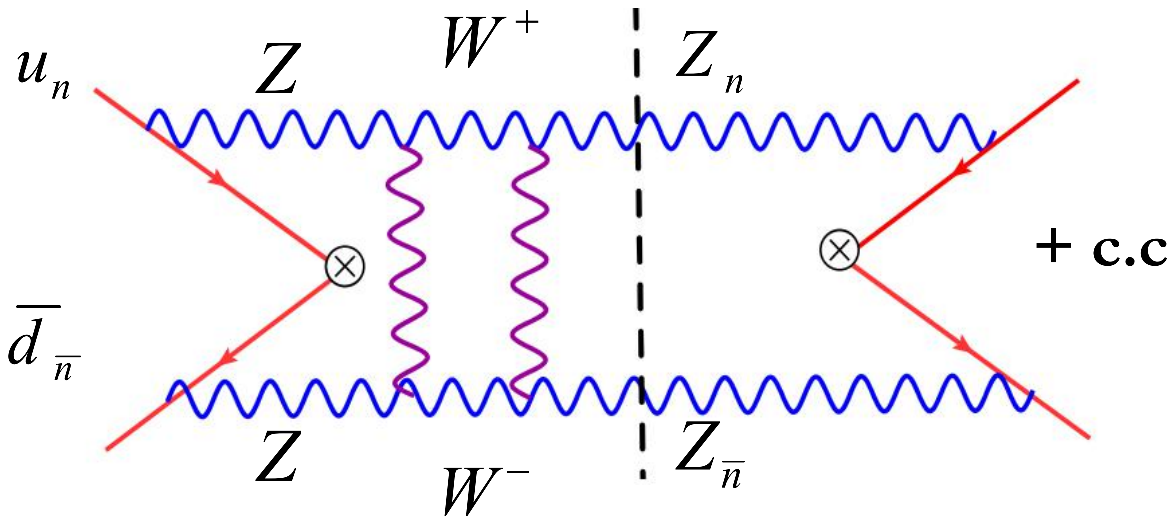
- The glauber does not influence $\Delta n \cdot p$, $\Delta \bar{n} \cdot p$ but only affects $\Delta p_{\perp}$
- The glauber obviously carries flavor and hence can influence the flavor of the spectators → Any observable sensitive to the flavor of the spectators can potentially exibit factorization violation
- Due to QCD color confinement, this is only observable for Electro-Weak charge.

Electro-Weak factorization violation

$$u_n + \bar{d}_{\bar{n}} \to t_{n'} + \bar{b}_{\bar{n}'} + Z_n + Z_{\bar{n}} + X$$



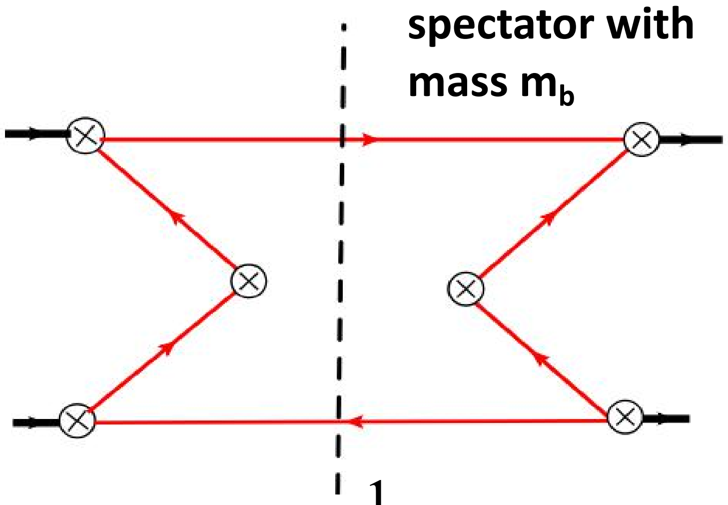
Tree level diagram



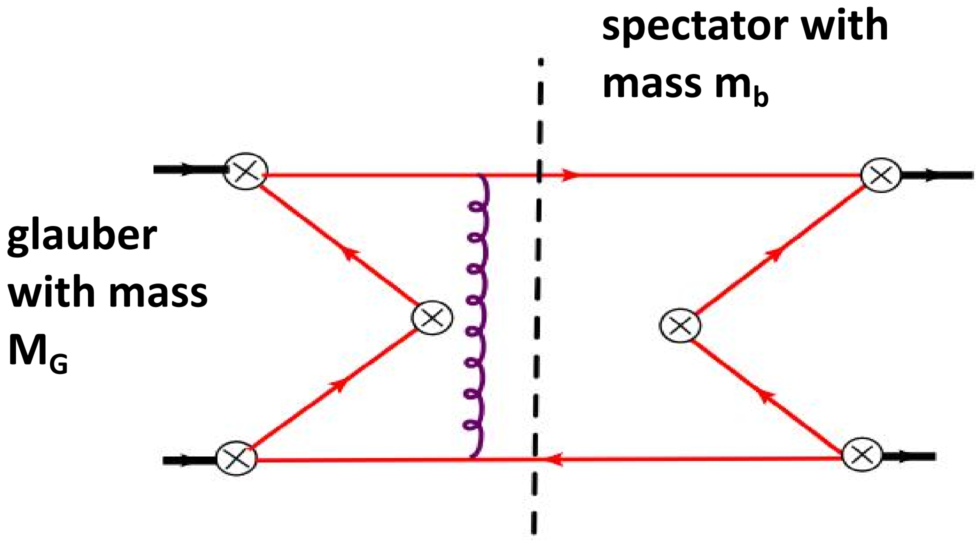
- There is no diagram possible with one glauber on each side of the cut

EW corrections to QCD

- The case of an initial bound state



$$\sigma_{tree} \propto \frac{1}{m_b^4}$$



$$\sigma_{one-glauber} \propto \frac{1}{m_b^4}\frac{m_b^2}{M_G^2}$$

- For $m_b << m_g$, the glauber contribution is power suppressed

Leading power glauber contribution

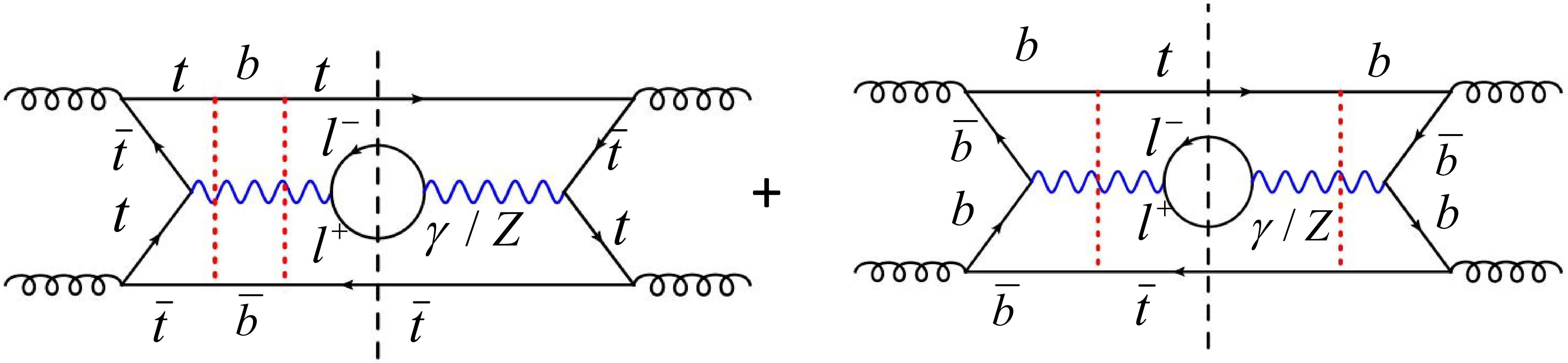
- We need a bound state at the same mass scale as the glauber.

- We need a perturbative splitting to raise the virtuality of spectators to the glauber mass scale

An explicit calculation

- Gluon initiated process : forward top jets

$$g_n + g_{\bar{n}} \rightarrow l^+_{n'} + l^-_{\bar{n}'} + t_n + \bar{t}_{\bar{n}} + X$$



- The difference in the electro-weak charges gives a non-zero logarithmically enhanced result

$$\propto \alpha_s^2 \log^2\left(\frac{Q^2}{M_t^2}\right) \alpha_W^2 \log^2\left(\frac{Q^2}{M_W^2}\right)$$

Summary

- Factorization violation via glaubers only happens through spectator- spectator interactions, for all non-abelian gauge theories

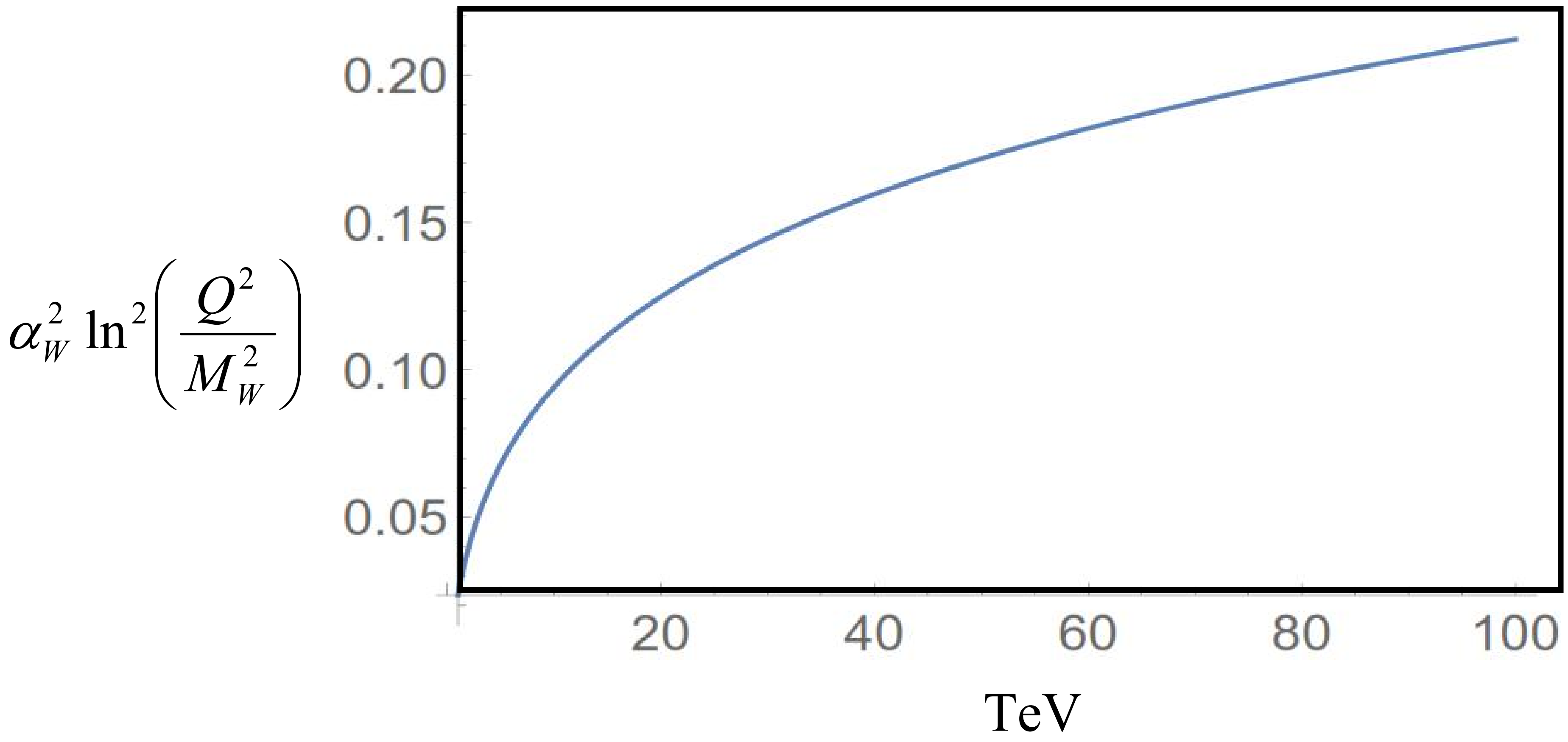
- Factorization is violated for those observables which are sensitive to the quantum numbers of the spectators that can be influenced by the glauber .

- To see EW factorization violation, a flavor measurement on the beam is required .

- A perturbative collinear splitting is needed to see leading power factorization violation.

- For such observables, new logarithms arise induced by the glauber which need to be resummed

- This is a breakdown of the parton model above the EW scale and the collinear sectors can no longer be treated separately but must be combined into a single operator for RG evolution



$\alpha_W^2 \ln^2\left(\frac{Q^2}{M_W^2}\right)$
0.20
0.15
0.10
0.05
20
40
60
80
100
TeV