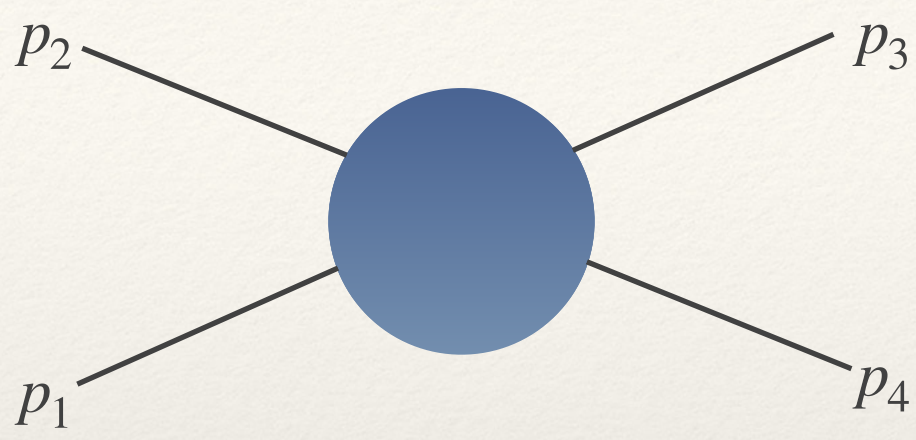
Reggeization in Color

Gregory Ridgway

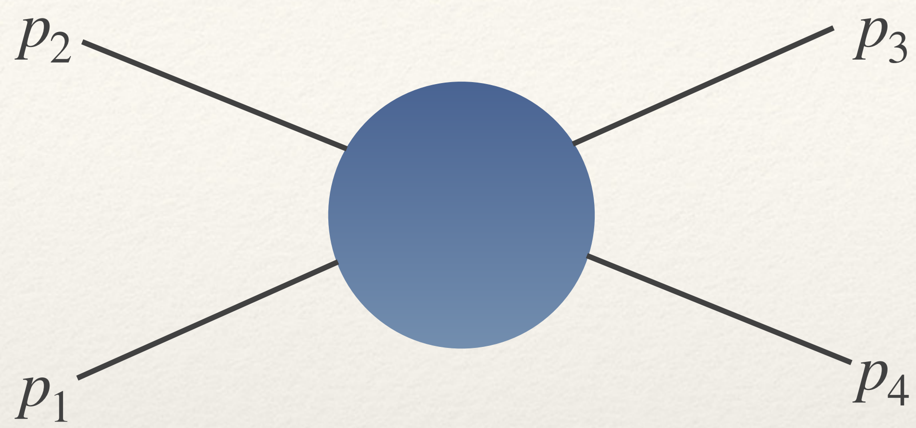
Work in progress with Ian Moult and Iain Stewart

High-Energy Limit of QCD



- Goal: Understand the form of QCD amplitudes in the "high-energy limit," $s \gg -t$

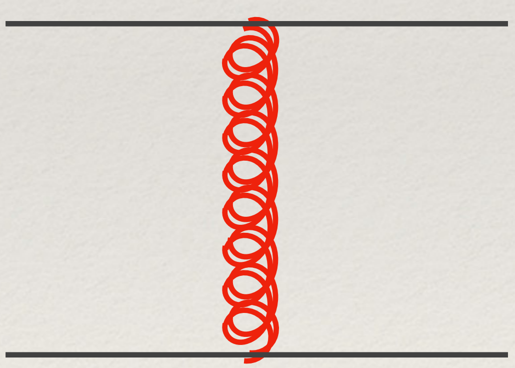
High-Energy Limit of QCD



- Goal: Understand the form of QCD amplitudes in the "high-energy limit," $s \gg -t$

The classic Regge/BFKL formula describes the leading and next to leading logarithms

$$i\mathcal{M}_{ig\to ig} \sim \frac{1}{t}\left[\left(\frac{s}{-t}\right)^{\alpha(t)} + \left(\frac{-s}{-t}\right)^{\alpha(t)}\right]$$



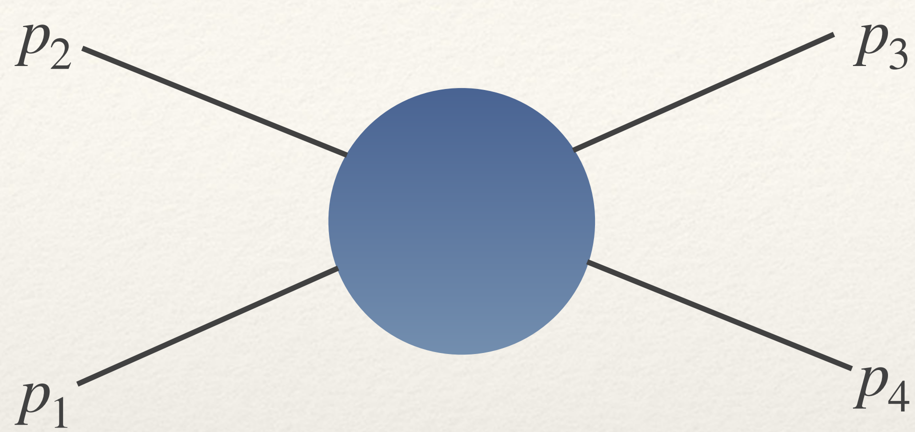
Interpreted as exchange of a "Reggeized Gluon"

Regge Trajectory

"**Regge Calculus**"

Very nice review in the talk by ***Vernazza***

High-Energy Limit of QCD



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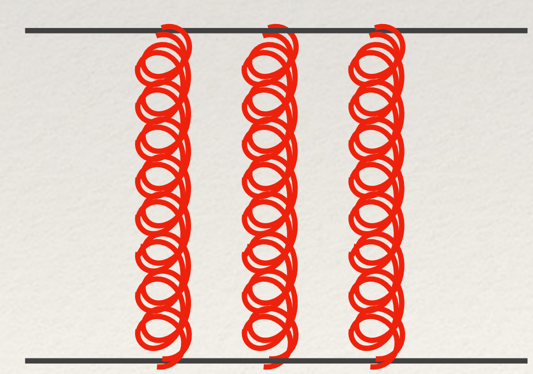
$$= \frac{1}{t}\left(\frac{s}{-t}\right)^{\alpha(t)}\left[1 + e^{-i\pi\alpha(t)}\right]$$

$$= \frac{1}{t}\left(\frac{s}{-t}\right)^{\alpha(t)}\left[\underbrace{\left(2 - i\pi\,\alpha(t)\right)}_{\text{NLL}} + \left(\underbrace{\frac{1}{2}(i\pi)^2\alpha(t)^2}_{\text{NNLL}} + \dots\right)\right]$$

See Caron-Huot, Gardi, Vernazza, 1701.05241



NLL

NNLL… want systematic framework

An SCET Framework

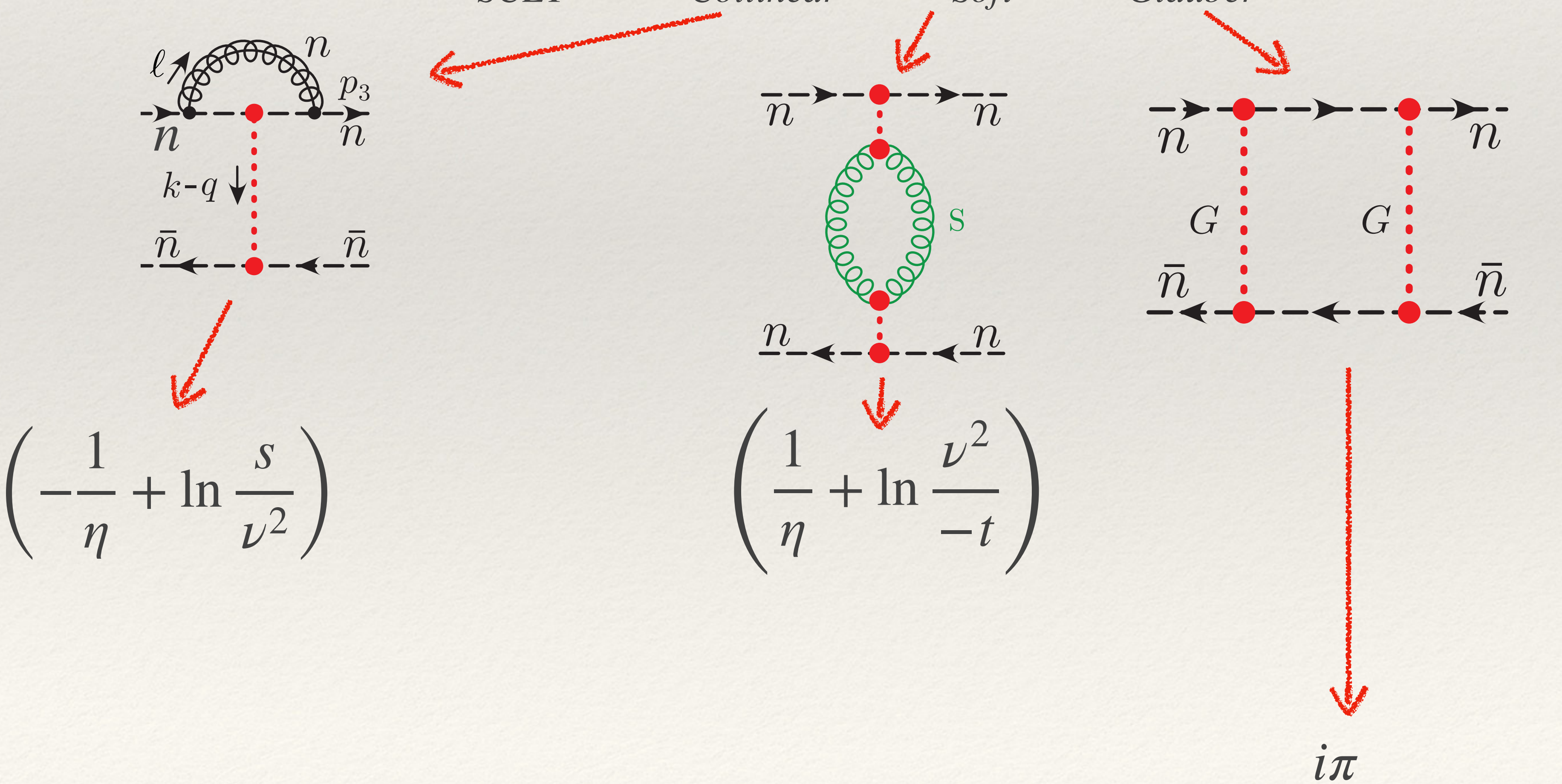
- Propose to use SCET to analyze this limit
- The pieces of the SCET Lagrangian describe dynamics of soft and collinear DoFs and Glauber interactions

$$\mathscr{L}_{SCET} = \mathscr{L}_{Collinear} + \mathscr{L}_{Soft} + \mathscr{L}_{Glauber}$$

An SCET Framework

- Propose to use SCET to analyze this limit
- The pieces of the SCET Lagrangian describe dynamics of soft and collinear DoFs and Glauber interactions (see Iain's talk)
- The loops from each sector contribute pieces to a BFKL-like form of the amplitude

$$\mathscr{L}_{SCET} = \mathscr{L}_{Collinear} + \mathscr{L}_{Soft} + \mathscr{L}_{Glauber}$$



$$\left(-\frac{1}{\eta} + \ln\frac{s}{\nu^2}\right) \qquad \left(\frac{1}{\eta} + \ln\frac{\nu^2}{-t}\right) \qquad i\pi$$

An SCET Framework

- Propose to use SCET to analyze this limit
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- The rapidity RG (RRG) re-sums logs

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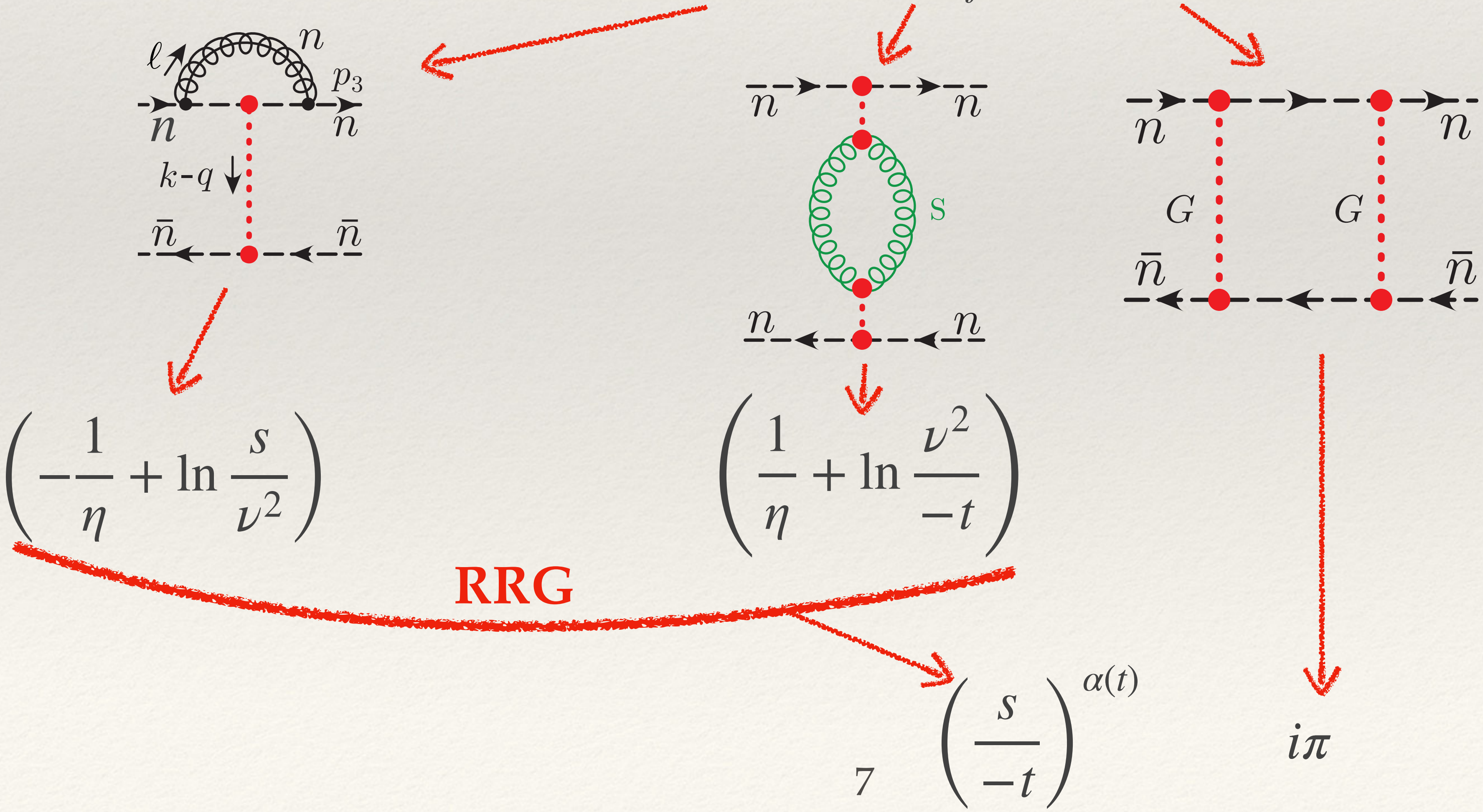

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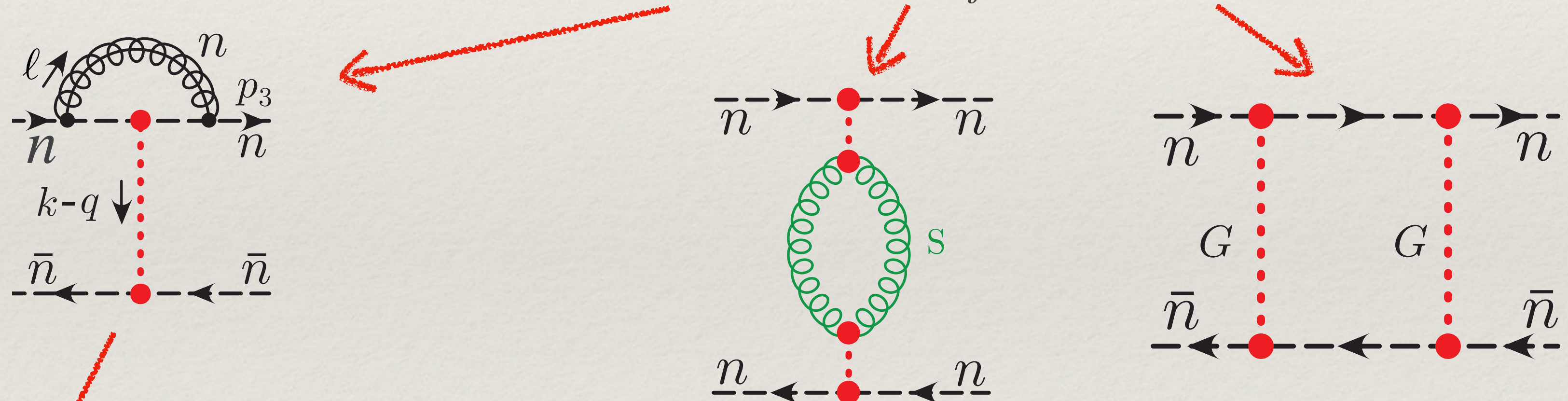

$$\left(-\frac{1}{\eta} + \ln\frac{s}{\nu^2}\right) \qquad \left(\frac{1}{\eta} + \ln\frac{\nu^2}{-t}\right) \qquad \left(\begin{matrix}\text{+ Soft/Collinear}\\ \text{loops}\end{matrix}\right)$$

RRG

RRG

$$i\mathscr{M}_{ig\to ig} = \frac{1}{t}\left(\frac{s}{-t}\right)^{\alpha(t)}\left[\left(2 - i\pi\,\alpha(t)\right)\right]$$

An SCET Framework

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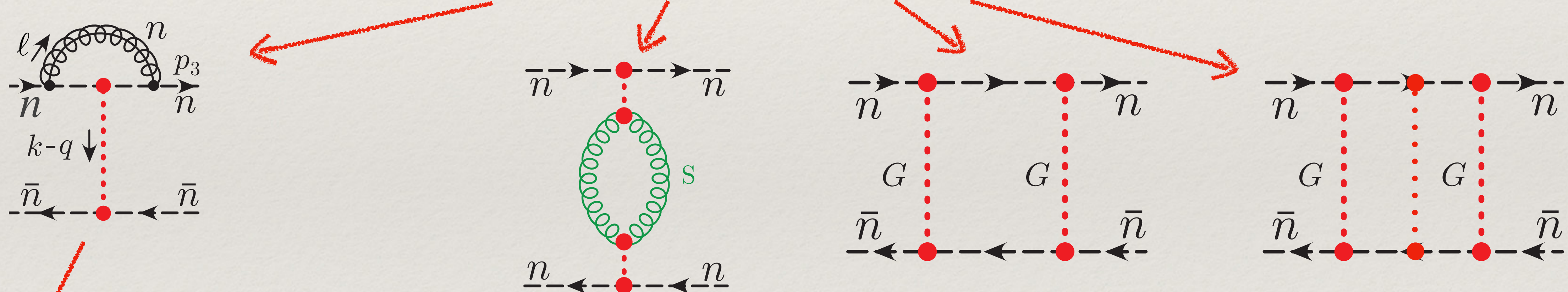


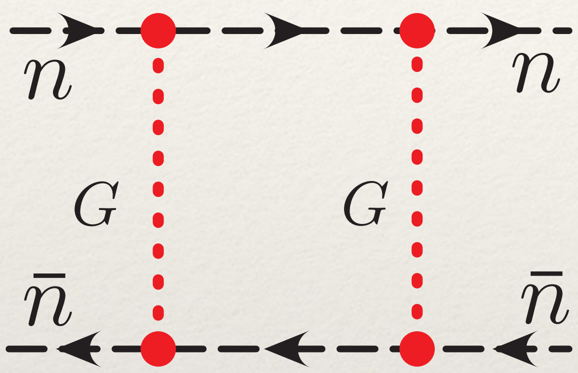
$$\left(-\frac{1}{\eta} + \ln\frac{s}{\nu^2}\right) \quad \left(\frac{1}{\eta} + \ln\frac{\nu^2}{-t}\right) \quad \left(\begin{matrix}+\text{ Soft/Collinear}\\ \text{loops}\end{matrix}\right) \left(\begin{matrix}+\text{ Soft/Collinear}\\ \text{loops}\end{matrix}\right)$$

RRG **RRG** **RRG**

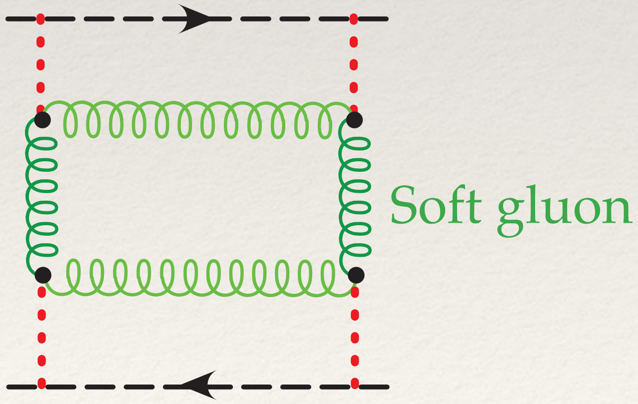
$$i\mathscr{M}_{ig\to ig} = \frac{1}{t}\left(\frac{s}{-t}\right)^{\alpha(t)}\left[\left(2 - i\pi\,\alpha(t)\right)\right] + \#(i\pi)^2 + \dots$$

Glauber Gluon $\neq$ Reggeon

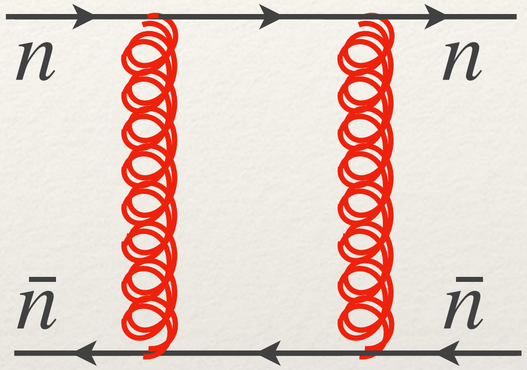
Glauber



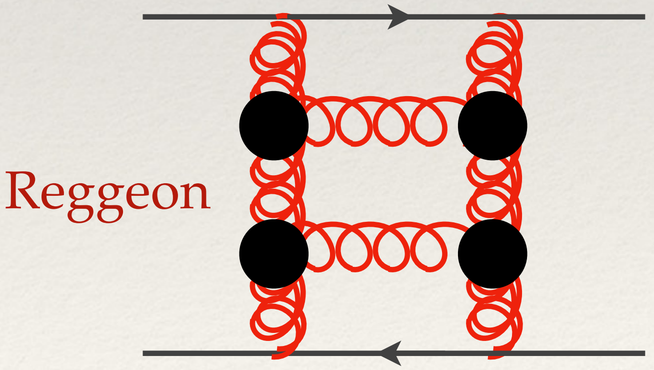
- Feynman rules from a QFT
- 4D
- Contains $(i\pi)$ in octet



Regge



- Different type of diagram
- 2D
- No octet



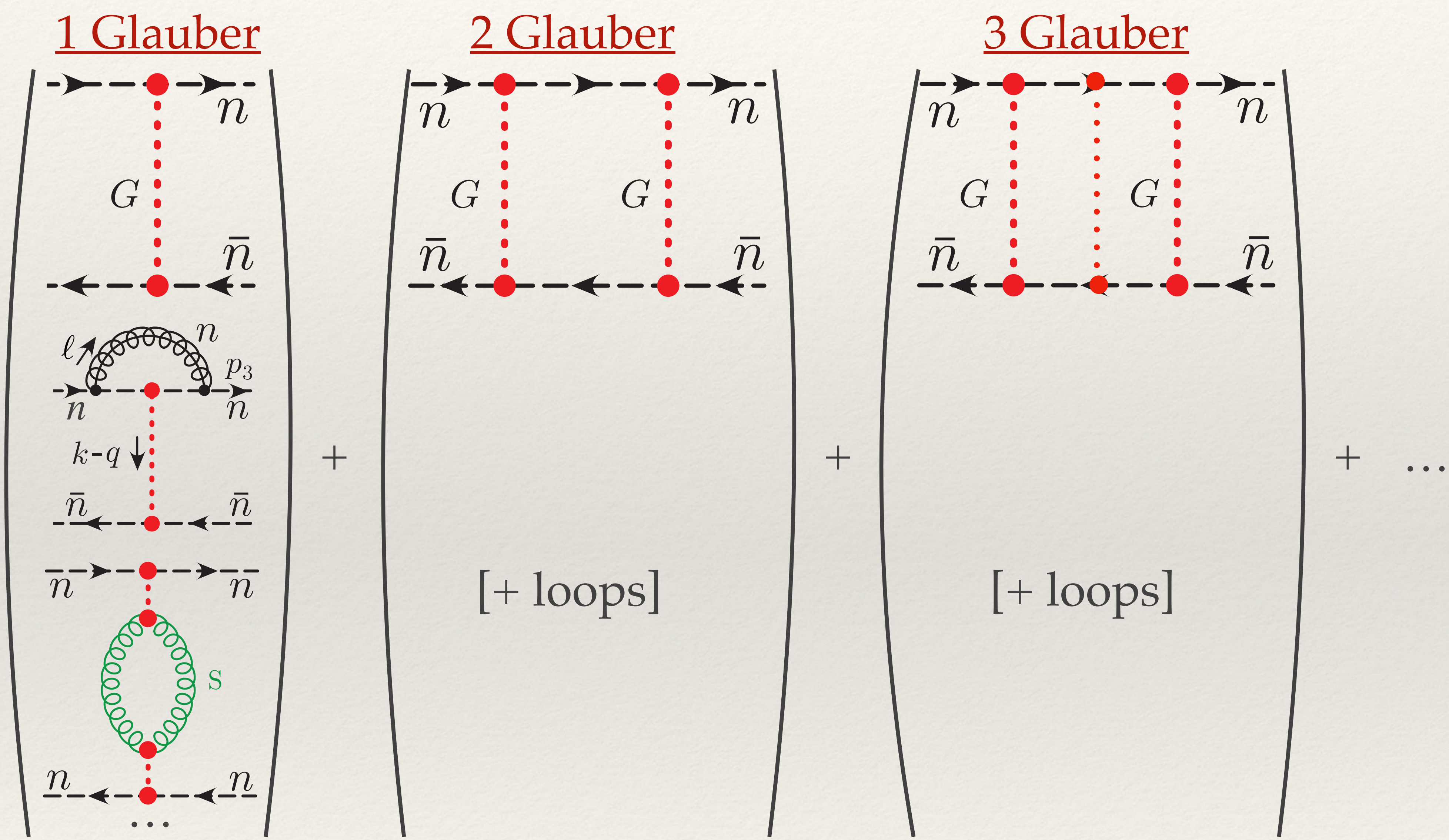
Glauber $\neq$ Regge

Glauber

Regge

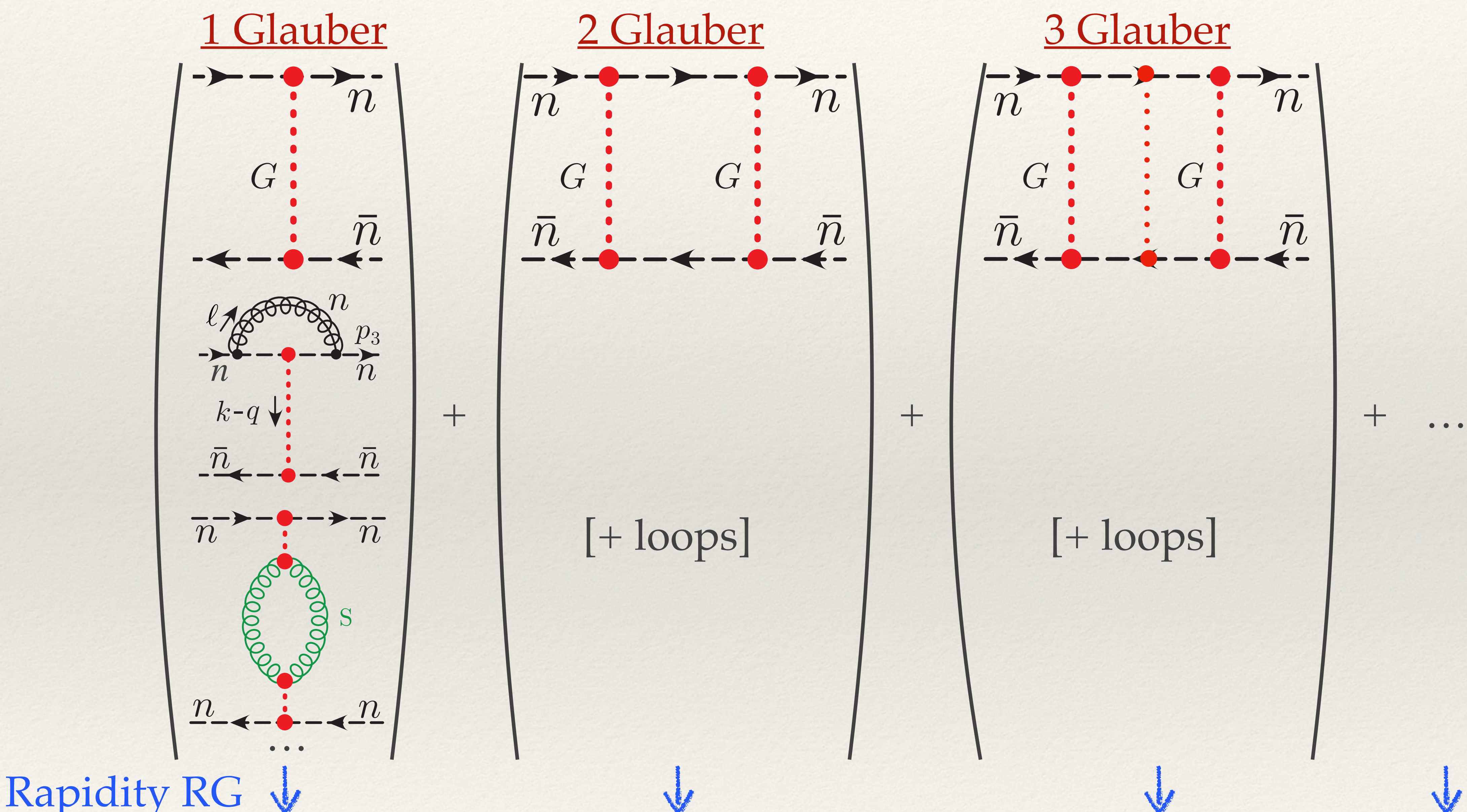
An SCET Framework

- So in general, organize into the number of Glaubers exchanged…



An SCET Framework

- So in general, organize into the number of Glaubers exchanged and rapidity renormalize



$$i\mathcal{M} = \left(\frac{s}{-t}\right)^{\alpha(t)} + (i\pi)\left(\frac{s}{-t}\right)^{\alpha(t)} + (i\pi)^2[\ldots] + \ldots$$

LL **NLL** **NNLL**

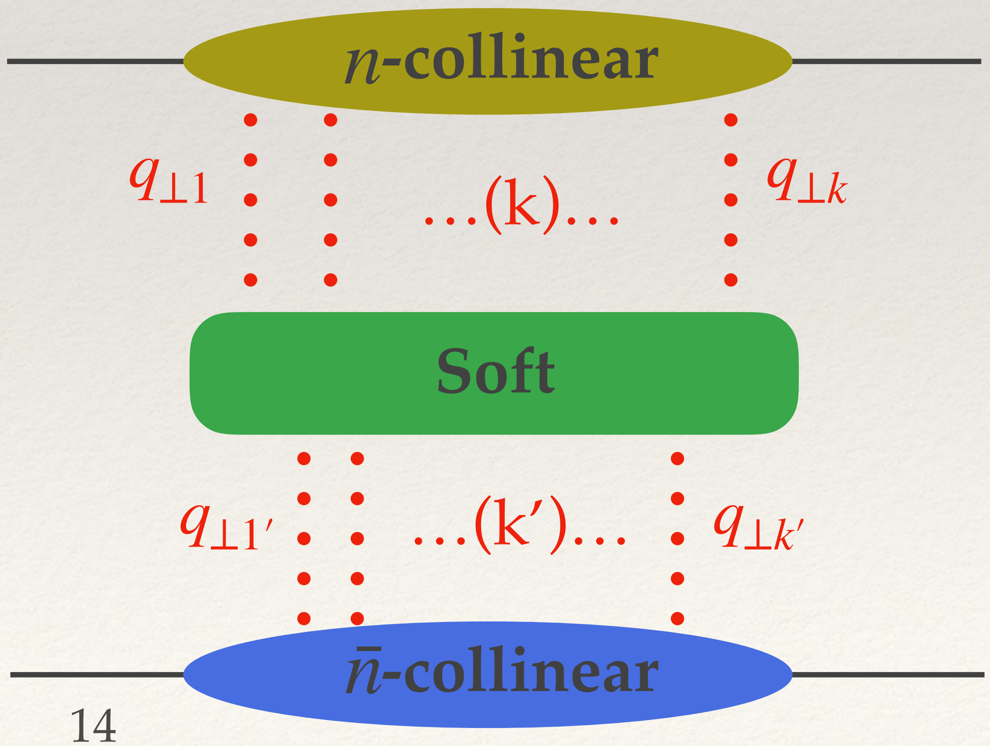
Towards Rapidity RG: Factorization

The time evolution operator: $$U(a,b;T) = \int [\mathcal{D}\phi] \exp\left[i \int_{-T}^{T} d^4x \left(\mathcal{L}_{n\bar{n}s}(x) + \mathcal{L}_{Glauber}(x) \right) \right]$$

All interactions between sectors come from: $$\mathcal{L}_{Glauber} = \mathcal{O}_n \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}_s \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}_{\bar{n}} + \mathcal{O}_n \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}_s + \mathcal{O}_s \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}_{\bar{n}}$$

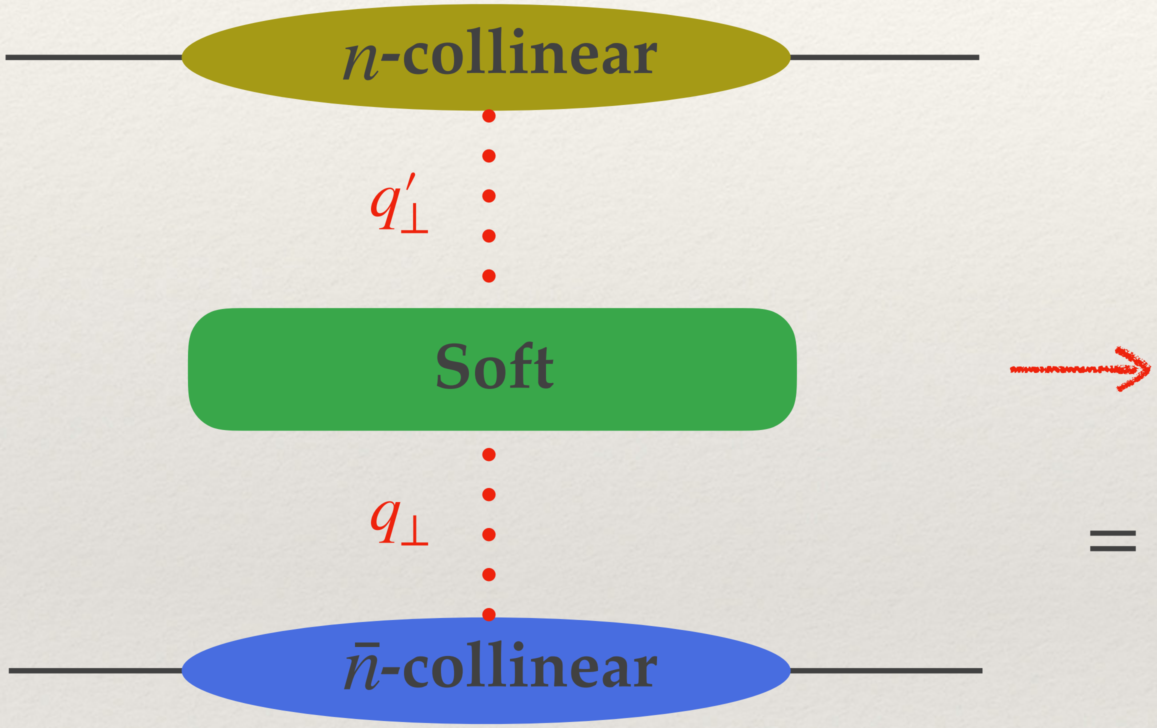
$$\mathrm{T}\exp\left(i \int d^4x \mathcal{L}_{Glauber} \right) = 1 + T \sum_{k=1}^{\infty} \sum_{k'=1}^{\infty} \left[\prod_{i=1}^{k} \int [dx_i^{\pm}] \int \frac{d^2 q_{\perp i}}{q_{\perp i}^2} \mathcal{O}_n^{A_i}(q_{\perp i})(x_i) \right] \left[\prod_{i'=1}^{k'} [dx_{i'}^{\pm}] \int \frac{d^2 q_{\perp i'}}{q_{\perp i'}^2} \mathcal{O}_{\bar{n}}^{B_{i'}}(q_{\perp i'})(x_{i'}) \right]$$
$$\times \mathcal{O}_{s(k,k')}^{A_1 \cdot A_k, B_1 \cdots B_{k'}}(q_{\perp 1}, \ldots, q_{\perp k'})(x_1, \ldots, x_{k'})$$
$$= 1 + \sum_{k}^{\infty} \sum_{k'}^{\infty} U_{(k,k')}$$

$$\langle p_3, p_4 | U_{(k,k')} | p_1, p_2 \rangle \longrightarrow$$



Rothstein and ***Stewart*** ***(2016)***

1-Glauber Exchange

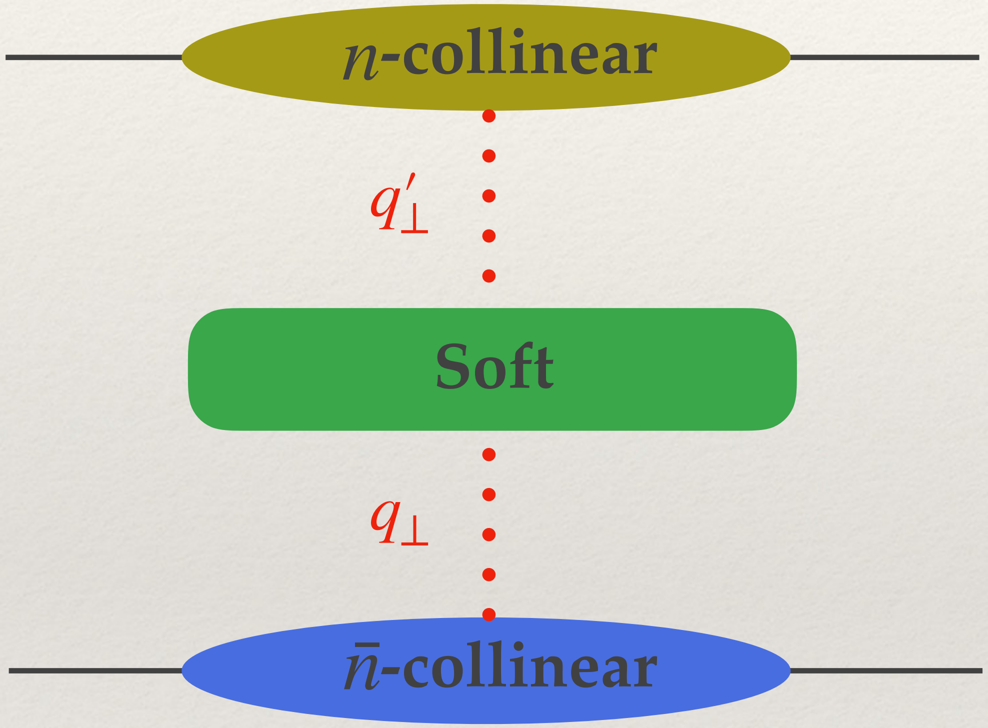


$$\langle p_3, p_4 | U_{(1,1)} | p_1, p_2 \rangle$$

$$= \int d^2 q'_\perp d^2 q_\perp C_n^{(1)}(p_3, q'_\perp) \boxed{S^{(1,1)}(q'_\perp, q_\perp)} C_{\bar{n}}^{(1)}(q_\perp, p_1)$$

1-Glauber Exchange

Demand that $\langle p_3, p_4 | U_{(1,1)} | p_1, p_2 \rangle$ be RRG invariant. The RRG equation for the soft operator leads to reggeization

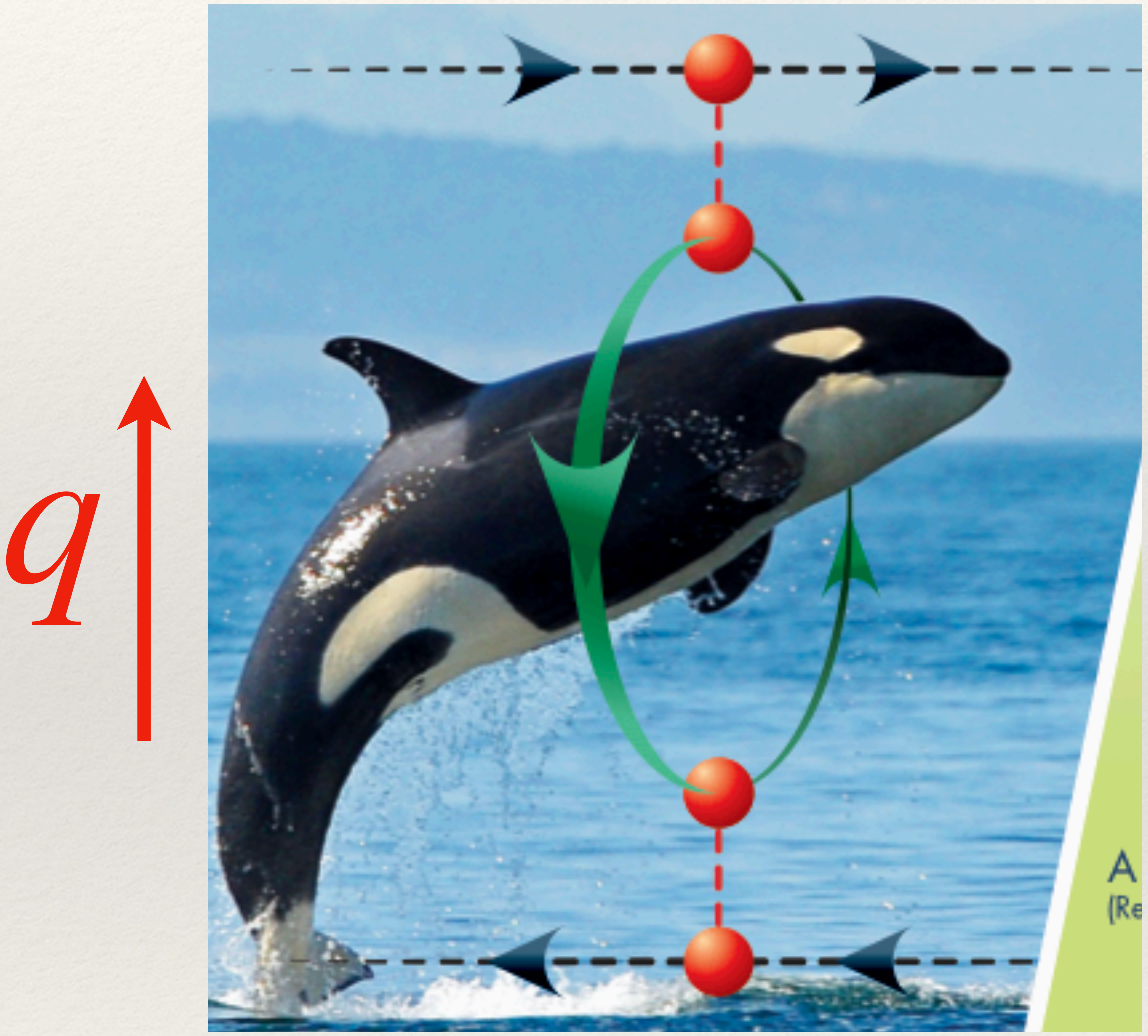


$$\longrightarrow \quad \langle p_3, p_4 | U_{(1,1)} | p_1, p_2 \rangle$$

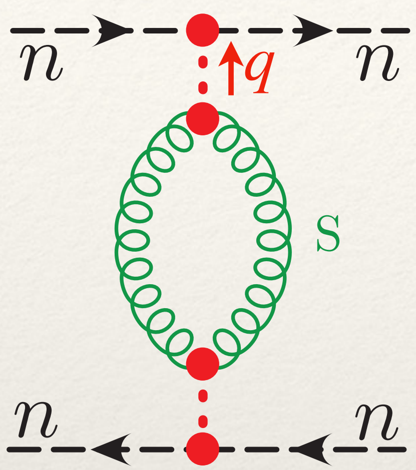
$$= \int d^2 q'_\perp d^2 q_\perp C_n^{(1)}(p_3, q'_\perp) \boxed{S^{(1,1)}(q'_\perp, q_\perp)} C_{\bar{n}}^{(1)}(q_\perp, p_1)$$

Notice, at this order the only color that can be exchanged is 8_A (i.e. we will be dressing the exchanged gluon)

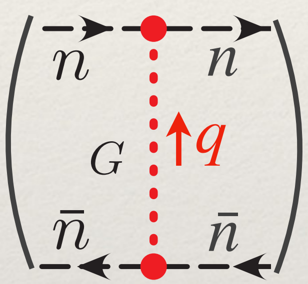
1-Glauber exchange



1-Glauber Exchange: Reggeization



$$= \frac{-8\pi i\alpha_s}{C_A \vec{q}_\perp^{\,2}} S_3^{n\bar{n}} \left(-\nu^\eta \frac{2C_A\alpha_s}{\eta} \int \frac{d^{d-2}\vec{k}_\perp}{(2\pi)^d} \frac{\vec{q}_\perp^{\,2}}{\vec{k}_\perp^{\,2}(\vec{k}-\vec{q})_\perp^2} \right)$$

$=$ 

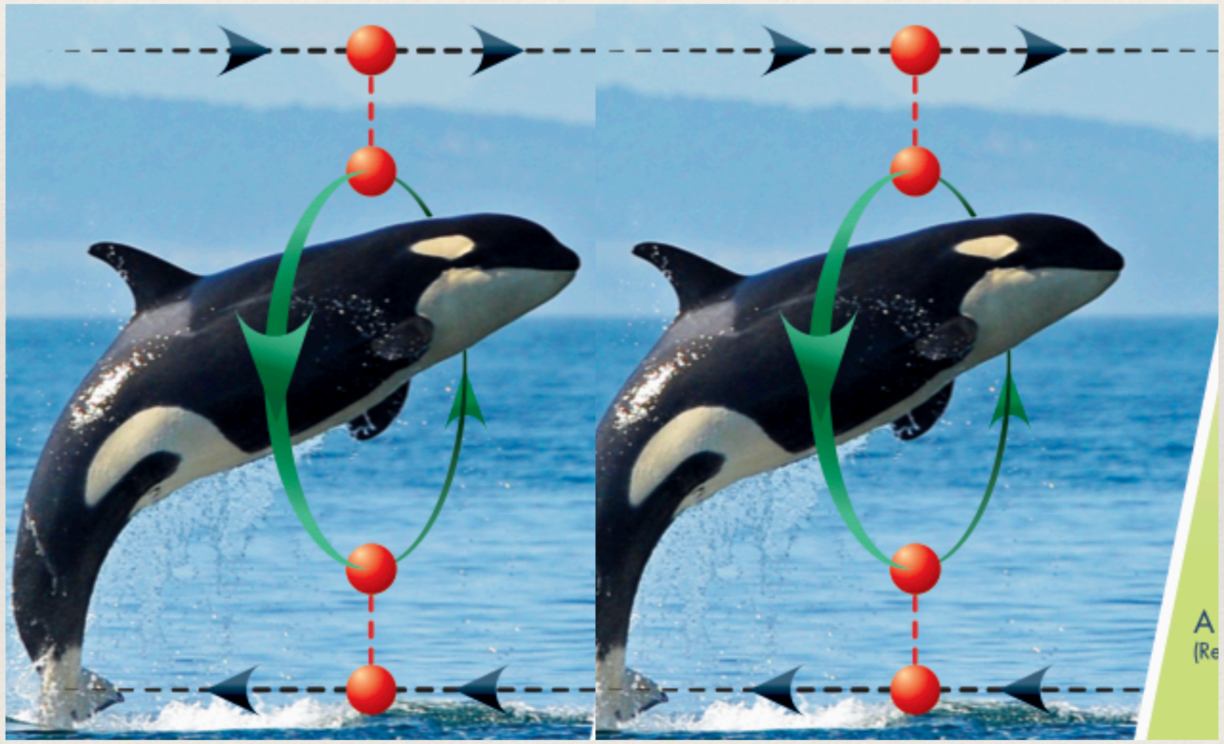
$$\times \left(2\alpha(t) \frac{\nu^\eta}{\eta} \right)$$

Leads to a simple RG equation for the soft operator in this diagram

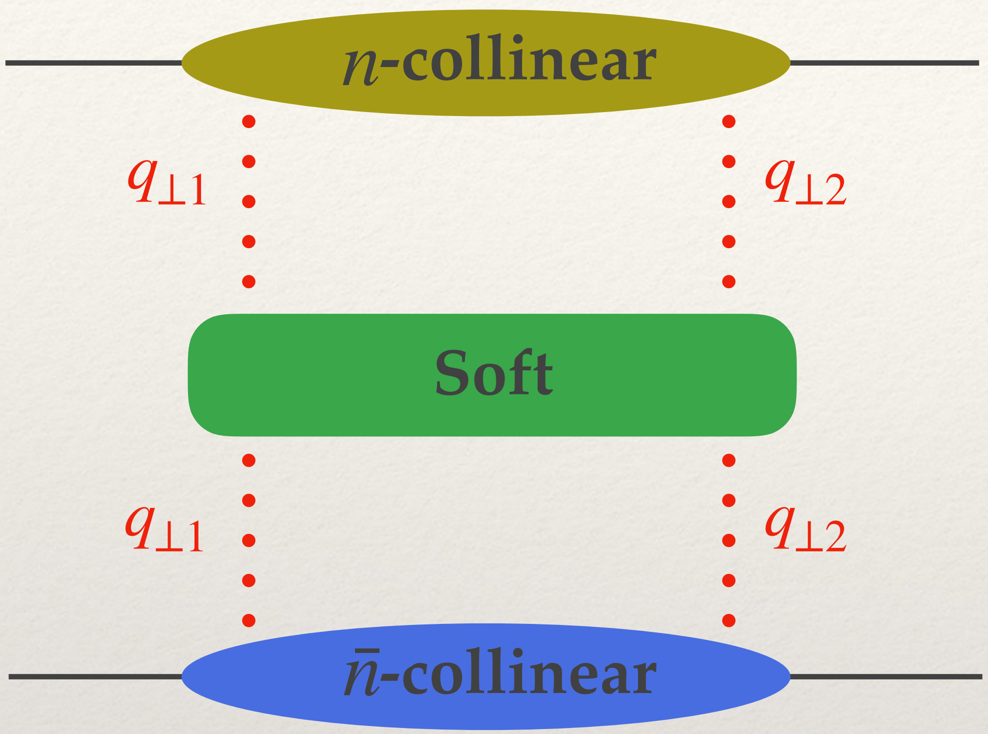
$$\nu \frac{\partial}{\partial \nu} S^{(1,1)}(\nu) = \gamma_{s\nu} S^{(1,1)}(\nu)$$

With $\gamma_{s\nu} = 2\alpha(t)$ defining the rapidity anomalous dimension of this soft operator.
When flowing from the soft to the collinear sector, we find the ***Regge Trajectory***

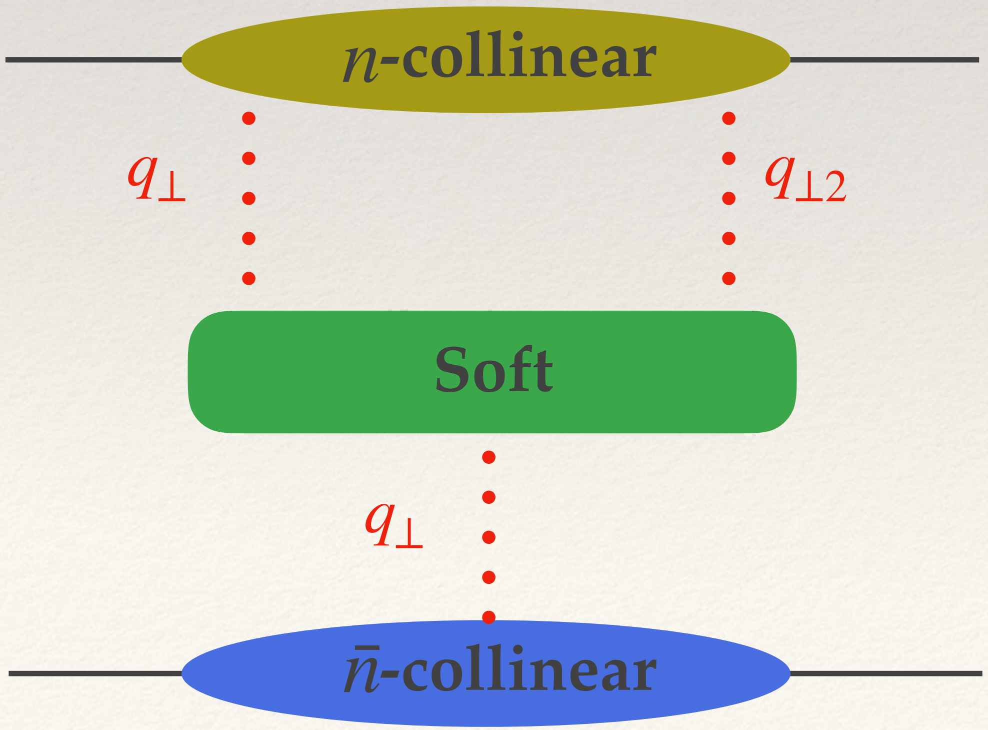
$$S^{(1,1)}(\sqrt{s}) = \left(\frac{s}{-t} \right)^{\alpha(t)} S^{(1,1)}(\sqrt{-t})$$



2-Glauber Exchange



$$\langle p_3, p_4 | U_{(2,2)} | p_1, p_2 \rangle = \int d^2q_{\perp 1} d^2q'_{\perp 1} d^2q_{\perp 2} d^2q'_{\perp 2} \Big[C_n^{(2)} S^{(2,2)} C_{\bar{n}}^{(2)} \Big]$$



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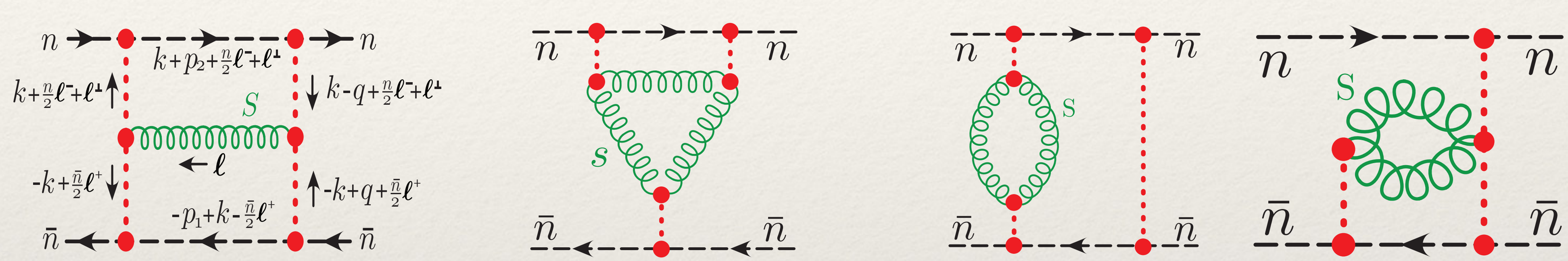
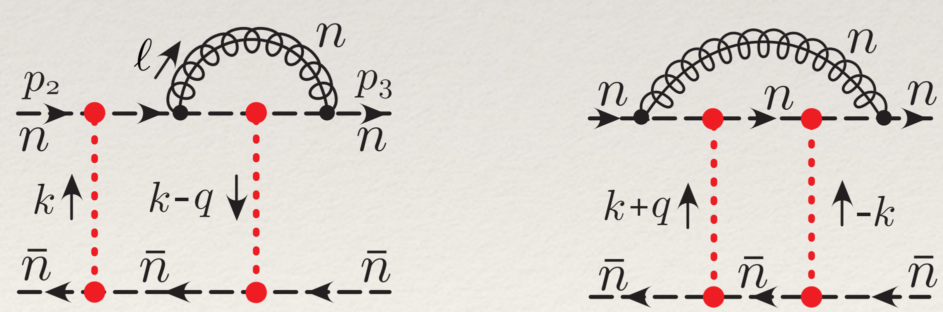
2-Glauber Graphs

Write all of the (2,2) and (2,1) graphs.

Soft Loops



Collinear Loops



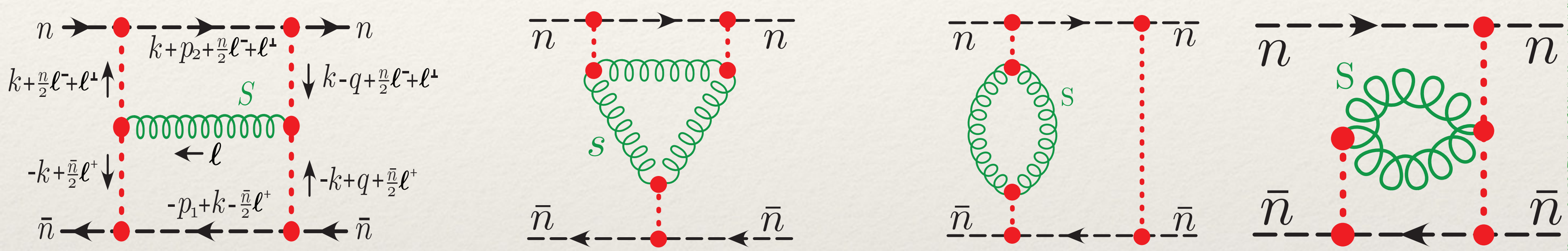
…

2-Glauber Graphs: Soft Function

Write all of the (2,2) and (2,1) graphs.

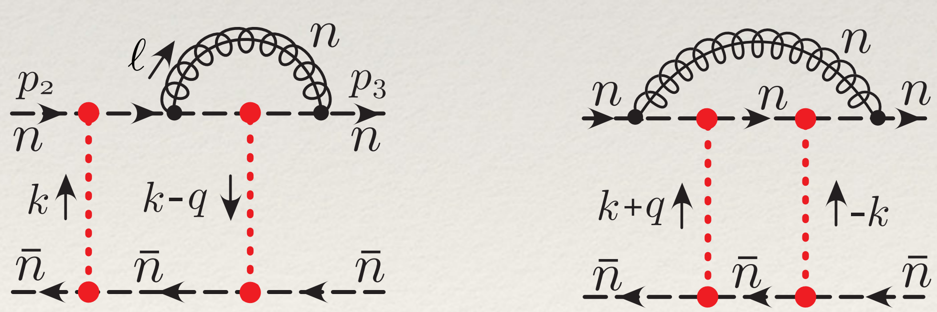
Renormalize $S^{(2,2)}(\nu)$ and $S^{(2,1)}(\nu)$

Soft Loops



Redundant Info.

~~Collinear Loops~~

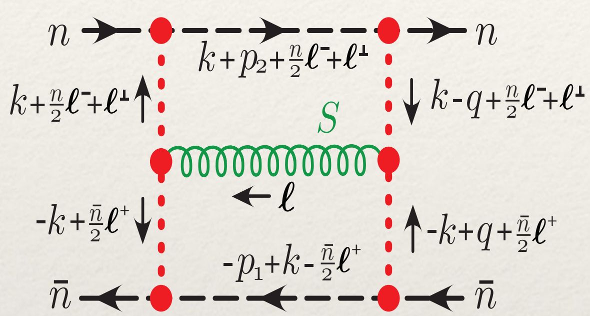


. . .

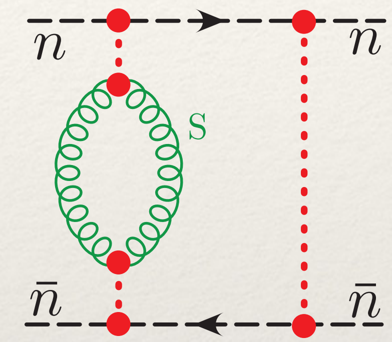
2-Glauber Graphs: Soft Function

To compute RG flows, we compute anomalous dimensions

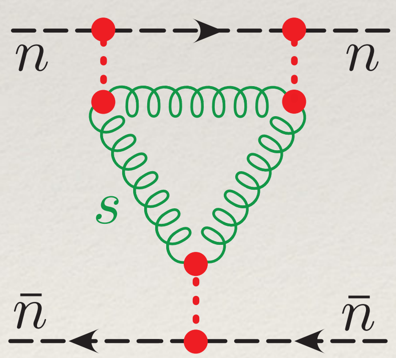
H graph



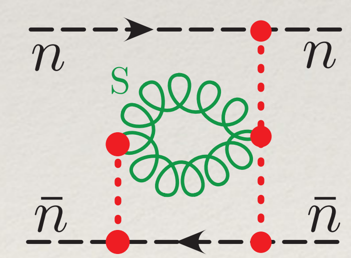
Soft-Eye Box



Triangle

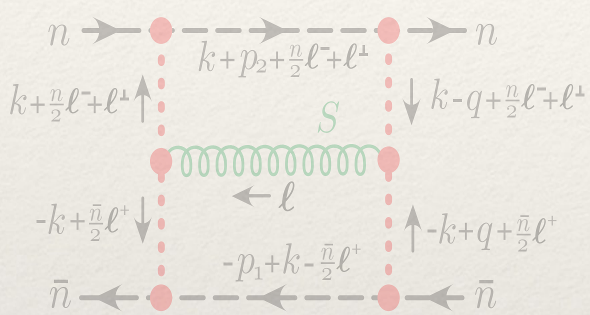


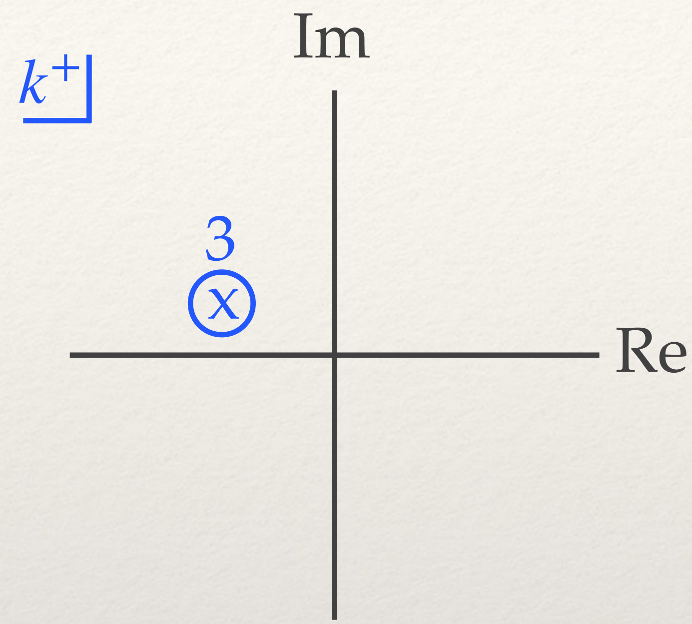
h graph



2-Glauber Graphs: Vanishing

H graph





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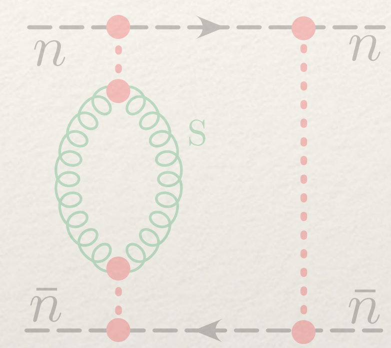

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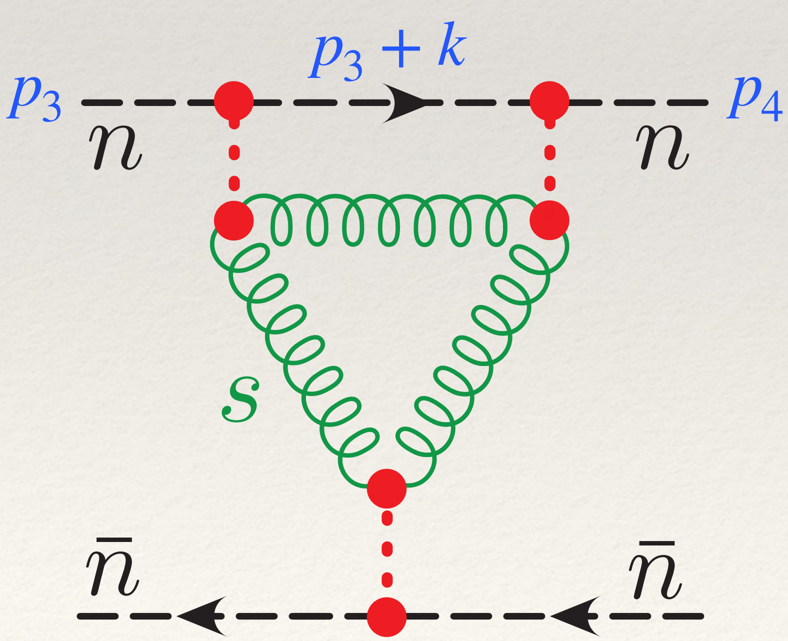
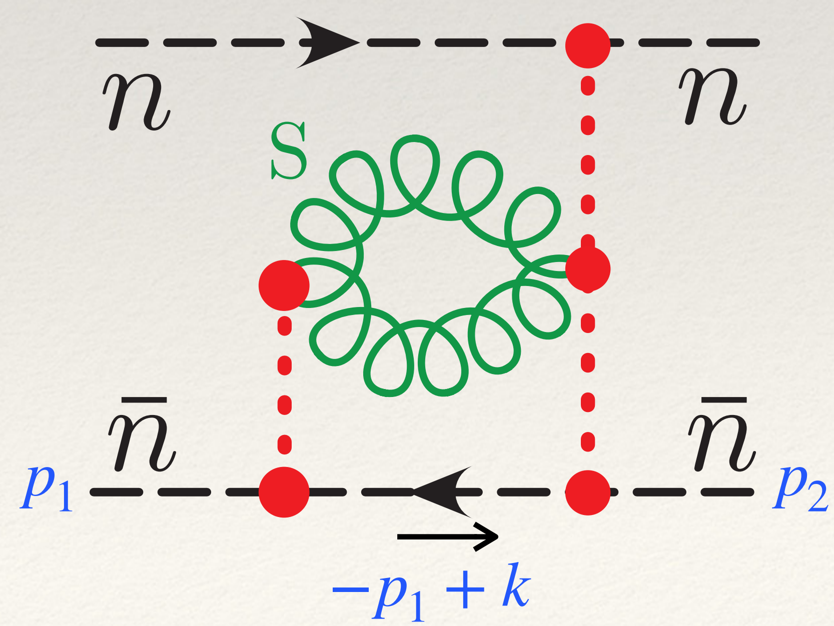


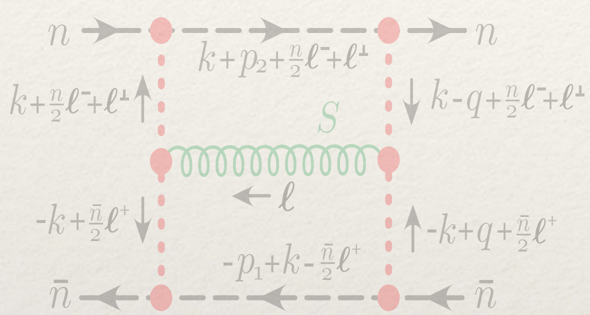
Naively forward condition arranges all poles on the same side

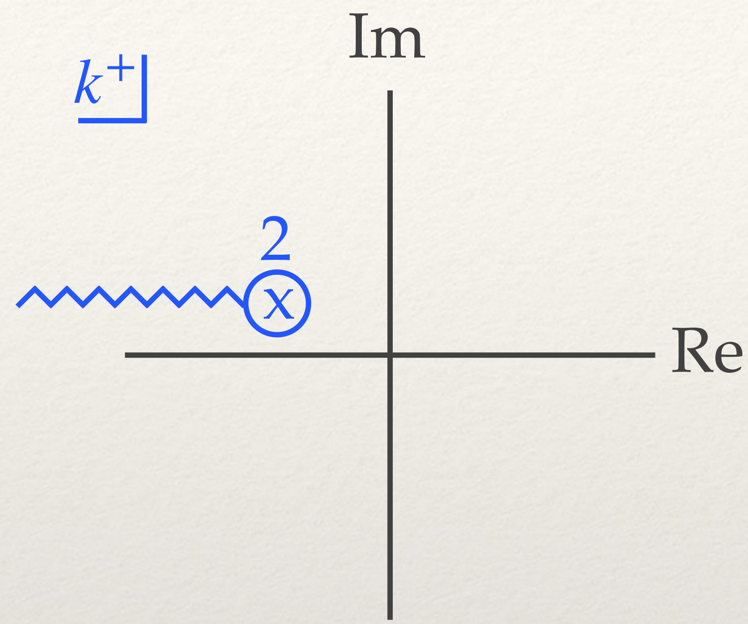
h graph



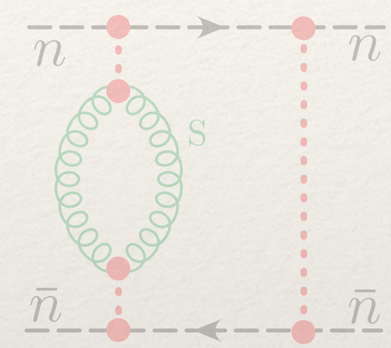
2-Glauber Graphs: Vanishing

H graph

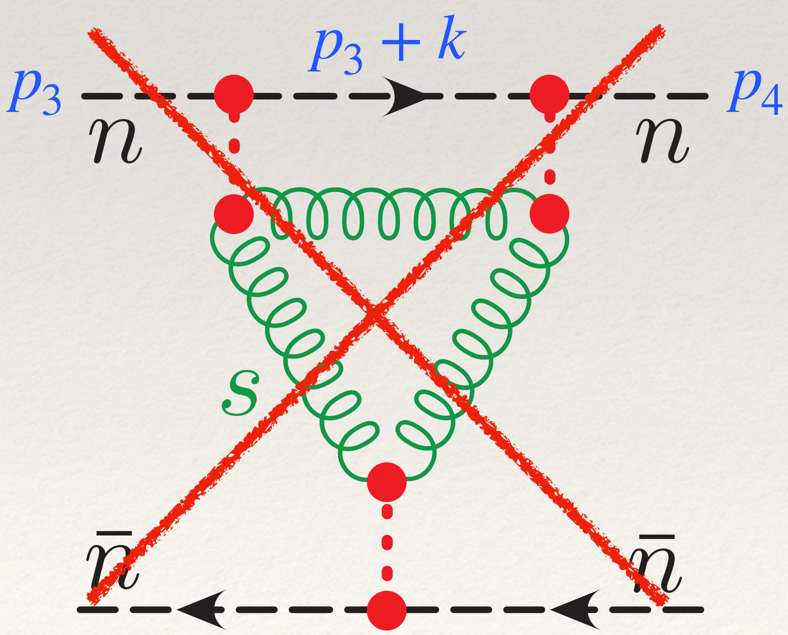




Soft-Eye Box



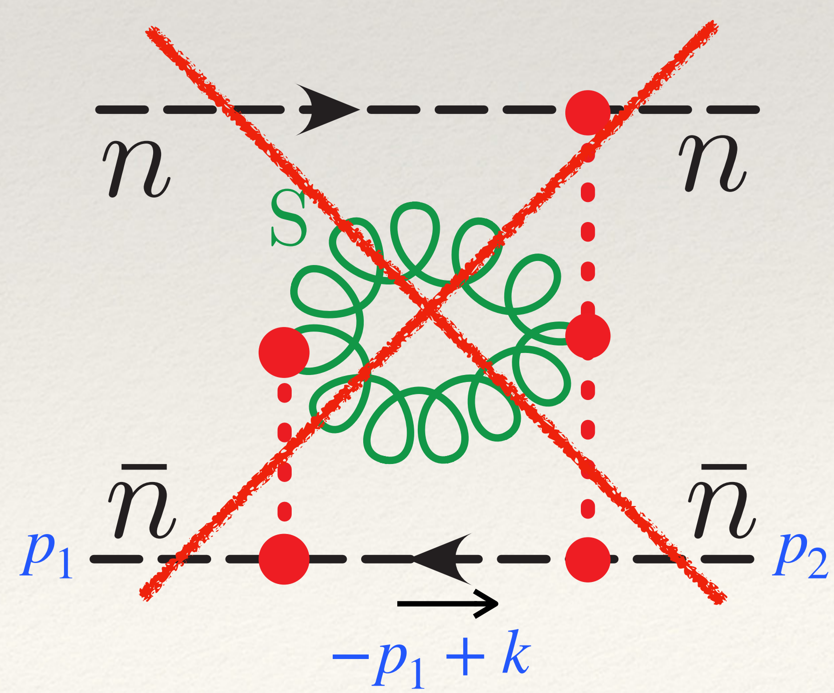
Triangle



Naively forward condition arranges all poles on the same side

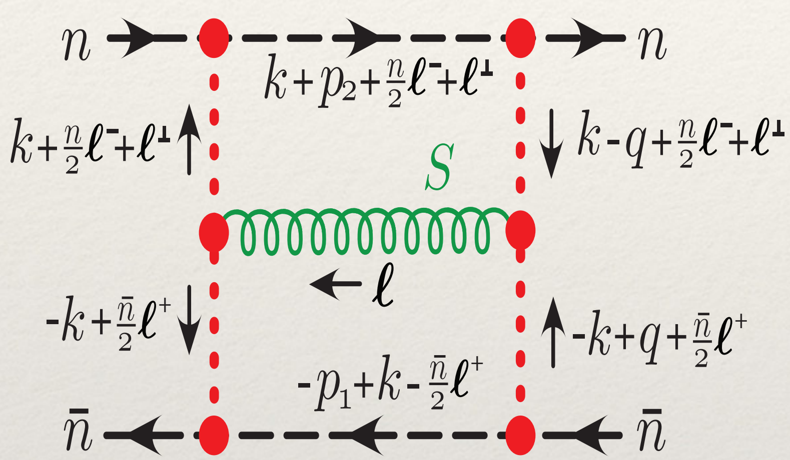
Remains zero after more careful treatment

h graph

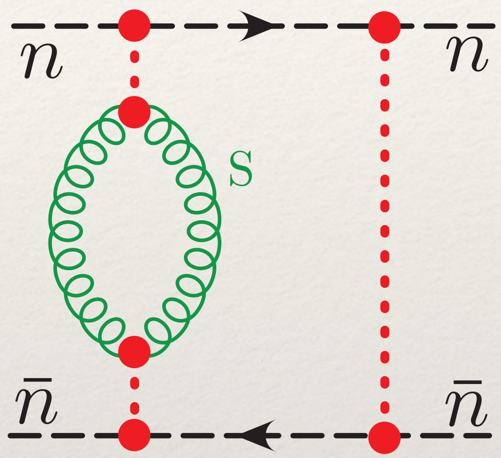


2-Glauber Graphs: Color Decomposition

H graph



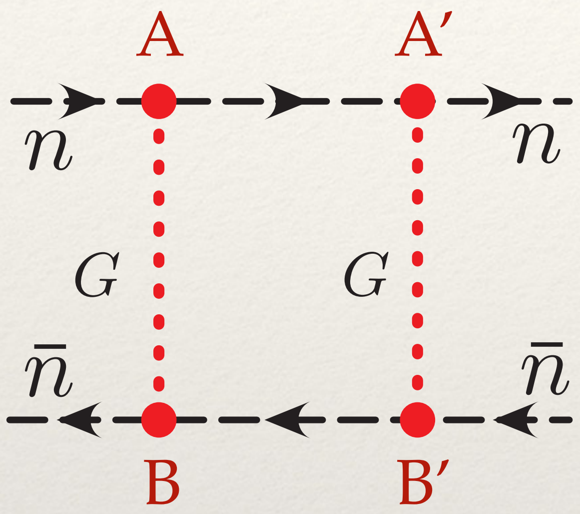
Soft-Eye Box



Now we analyze the color being passed through the t-channel of the remaining graphs.

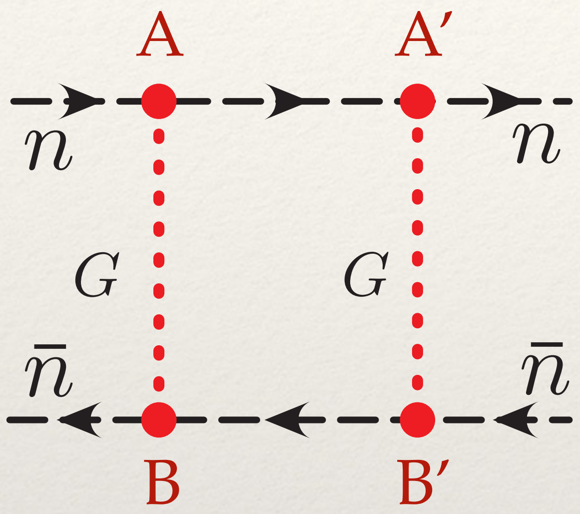
Color Decomposition

Consider the Glauber box



Color Decomposition

Consider the Glauber box

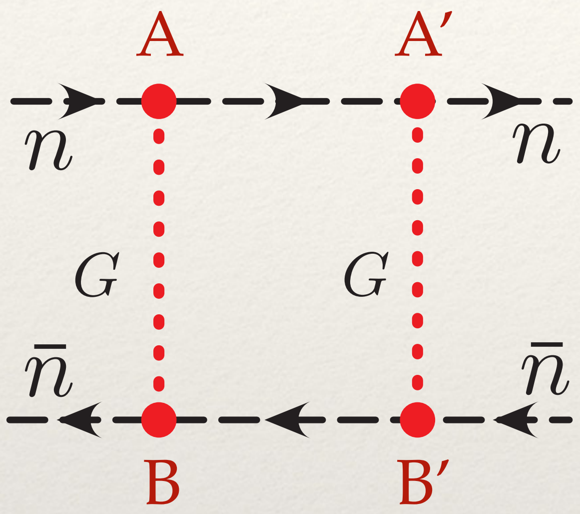


$8 \otimes 8$

- Each gluon carries octet charge in the t-channel.

Color Decomposition

Consider the Glauber box



$$8 \otimes 8 = 1 \oplus 8^A \oplus 8^S \oplus 10 \oplus \bar{10} \oplus 27$$

$$S^{(2,2)} = S_1^{(2,2)} + S_{8_A}^{(2,2)} + S_{8_S}^{(2,2)} + S_{10}^{(2,2)} + S_{\overline{10}}^{(2,2)} + S_{27}^{(2,2)}$$

- Each gluon carries octet charge in the t-channel.
- We can decompose $S^{(2,2)}$ into components within irreps that **won't mix under RRG**.

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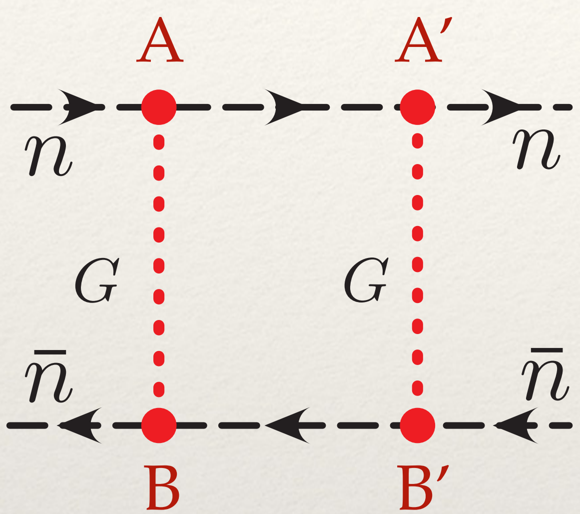

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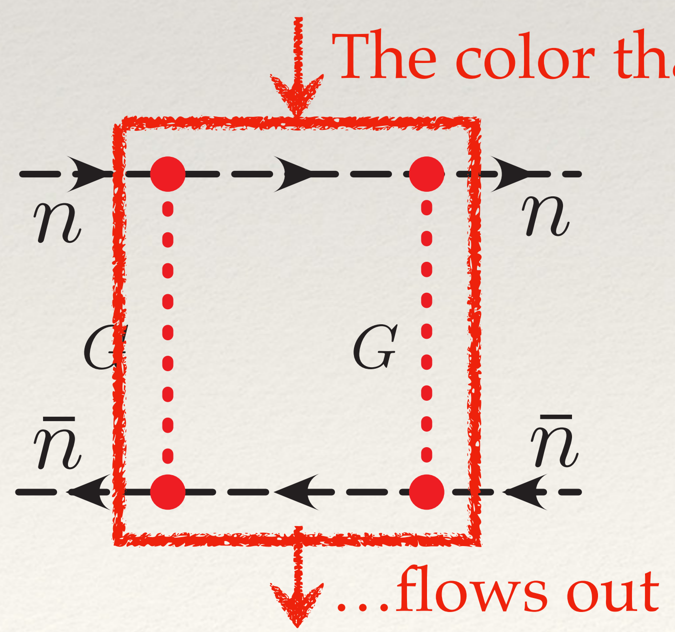
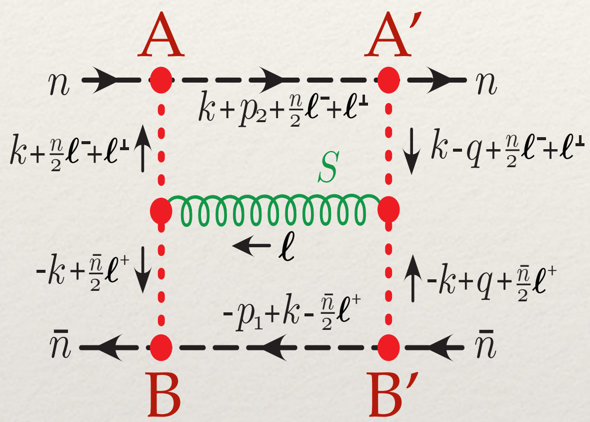
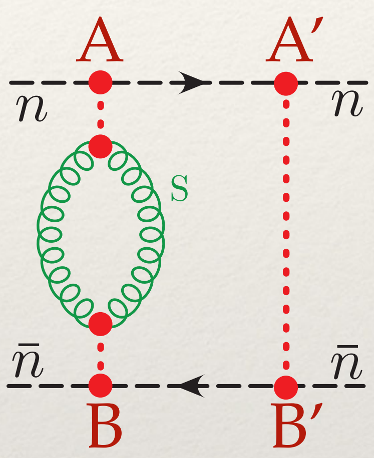


Color Decomposition

Apply color decomposition



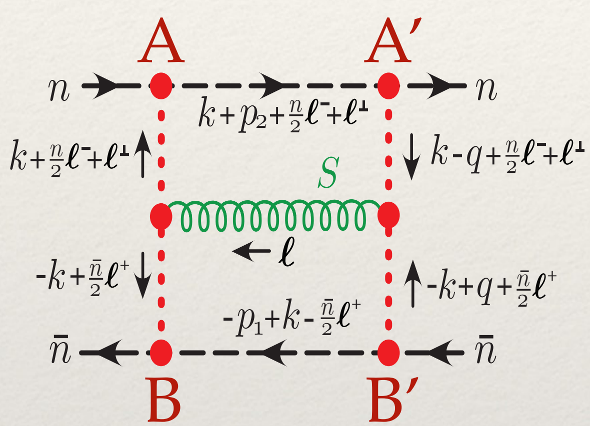
$f^{ABC} f^{A'B'C}$



$\delta^{AB}\delta^{A'B'}$

Color Decomposition

Apply color decomposition

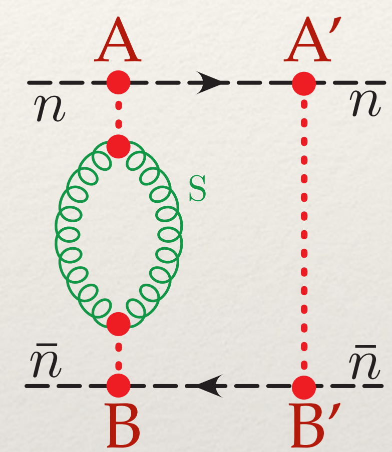


$f^{ABC} f^{A'B'C}$

$$= \sum_R c^R P^R_{AA'BB'}$$

Projectors onto irrep, R

$c^1 = 3$
$c^{8_A} = 3/2$
$c^{8_S} = 3/2$
$c^{10} = 0$
$c^{\overline{10}} = 0$
$c^{27} = -1$



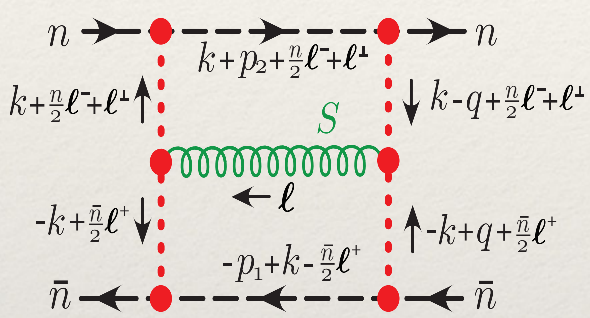
$\delta^{AB}\delta^{A'B'}$

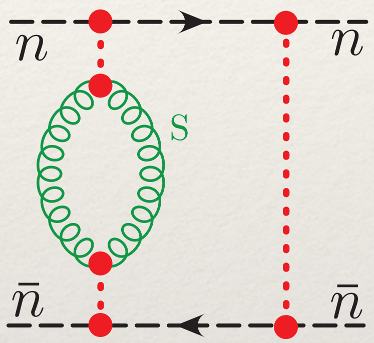
$$= \sum_R b^R P^R_{AA'BB'}$$

$b^R = 1$

Evaluation

Evaluate the rapidity divergent parts





$$\sim 2\nu^{\eta}\left(\frac{64\pi^2\alpha_s^3}{\eta}\right)\sum_R c^R P^R_{ABA'B'}(I_1 - I_2) + \mathcal{O}(\eta^0)$$

$$\sim 3\nu^{\eta}\left(\frac{64\pi^2\alpha_s^3}{\eta}\right)\sum_R P^R_{ABA'B'}(I_2) + \mathcal{O}(\eta^0)$$

Strategy:

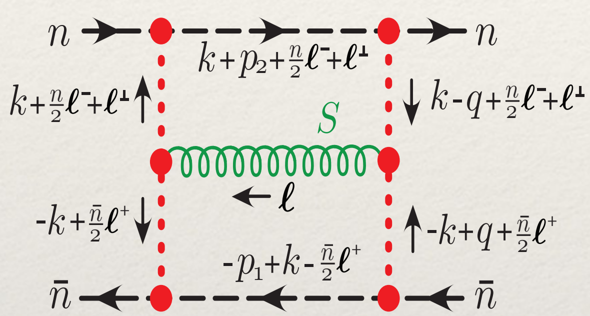
- Evaluate the $+$ and $-$ components of the loop momenta, leave the $\perp$ integrations undone.
- Identify a basis of $\perp$ integrals

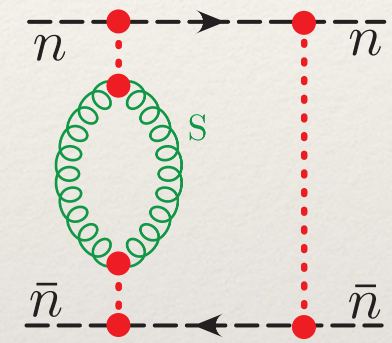
$$I_1 = \int d^{d-2}\vec{k}_\perp\, d^{d-2}\vec{l}_\perp \frac{\vec{q}_\perp^{\,2}}{\vec{k}_\perp^{\,2}\vec{l}_\perp^{\,2}(\vec{k}_\perp - \vec{q}_\perp)^2(\vec{l}_\perp - \vec{q}_\perp)^2}$$

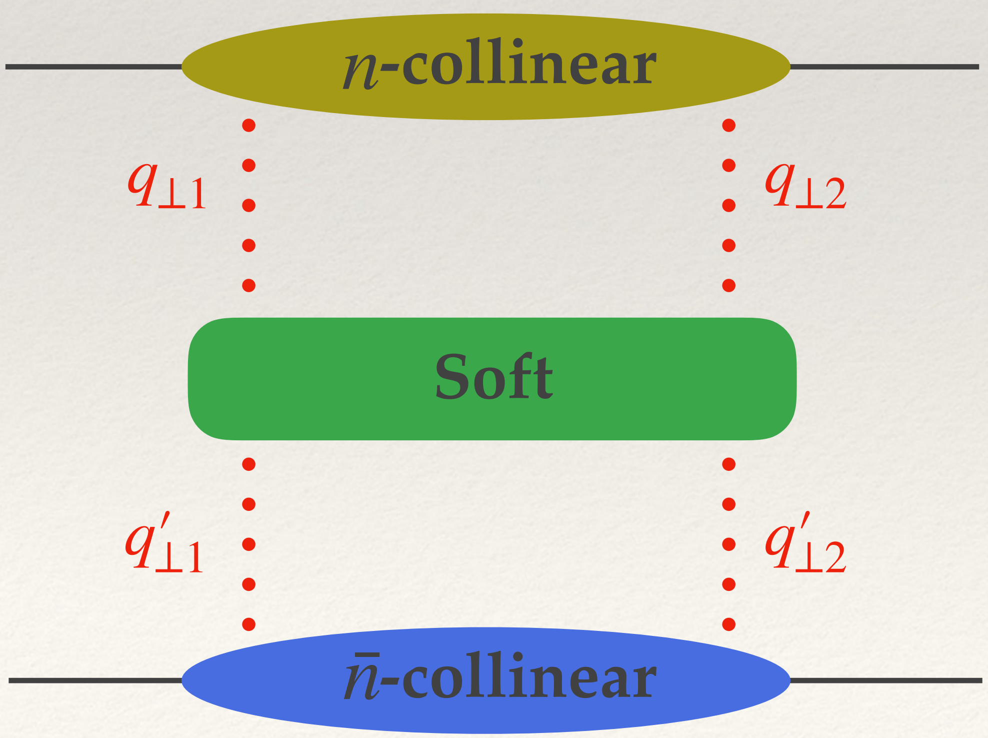
$$I_2 = \int \frac{d^{d-2}\vec{k}_\perp\, d^{d-2}\vec{l}_\perp}{\vec{k}_\perp^{\,2}(\vec{l}_\perp - \vec{q}_\perp)^2(\vec{l}_\perp - \vec{k}_\perp)^2}$$

Evaluation

Evaluate the rapidity divergent parts







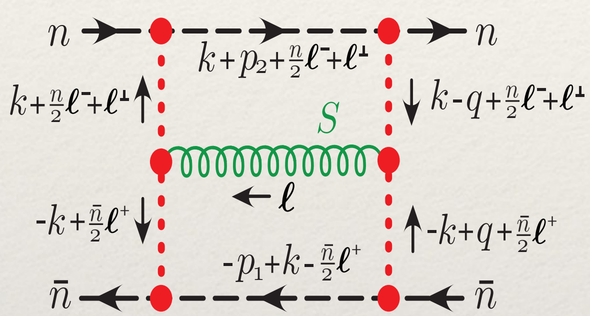
No need to evaluate the $\perp$ integrals, we wish to renormalize $S^{(2,2)}(q'_\perp, q_\perp)$

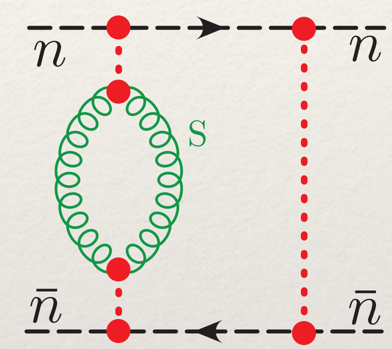
$$\longrightarrow \langle p_3, p_4 | U_{(2,2)} | p_1, p_2 \rangle$$

$$= \int d^2 q_{\perp 1} d^2 q'_{\perp 1} d^2 q_{\perp 2} d^2 q'_{\perp 2} \Big[C_n^{(2)} \boxed{S^{(2,2)}} C_{\bar{n}}^{(2)} \Big]$$

Evaluation: 8_A

Calculate the anomalous dimension of $S^{(2,2)}_{8_A}$

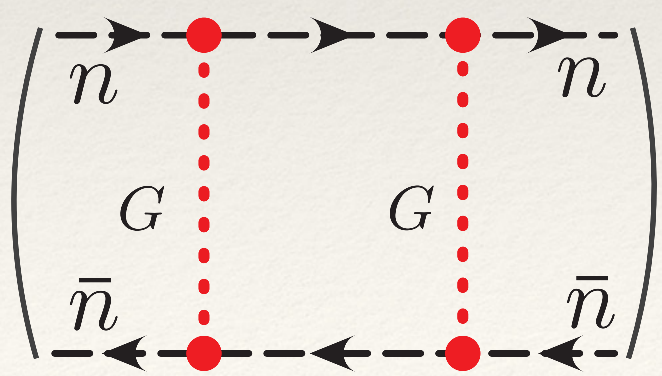




$$P^{8_A}_{CDAB}\left[2\nu^\eta\left(\frac{64\pi^2\alpha_s^3}{\eta}\right)\sum_R c^R P^R_{ABA'B'}(I_1-I_2)+\mathcal{O}(\eta^0) \quad + \quad 3\nu^\eta\left(\frac{64\pi^2\alpha_s^3}{\eta}\right)\sum_R P^R_{ABA'B'}(I_2)+\mathcal{O}(\eta^0)\right]$$

Project onto the octet (R=8) and add the two contributions.

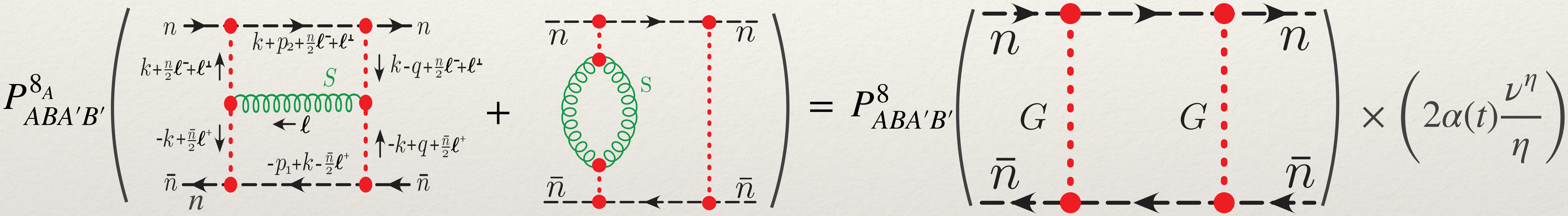
$$= 3\nu^\eta\left(\frac{64\pi^2\alpha_s^3}{\eta}\right)P^8_{CDA'B'}(I_1)+\mathcal{O}(\eta^0) \qquad =$$



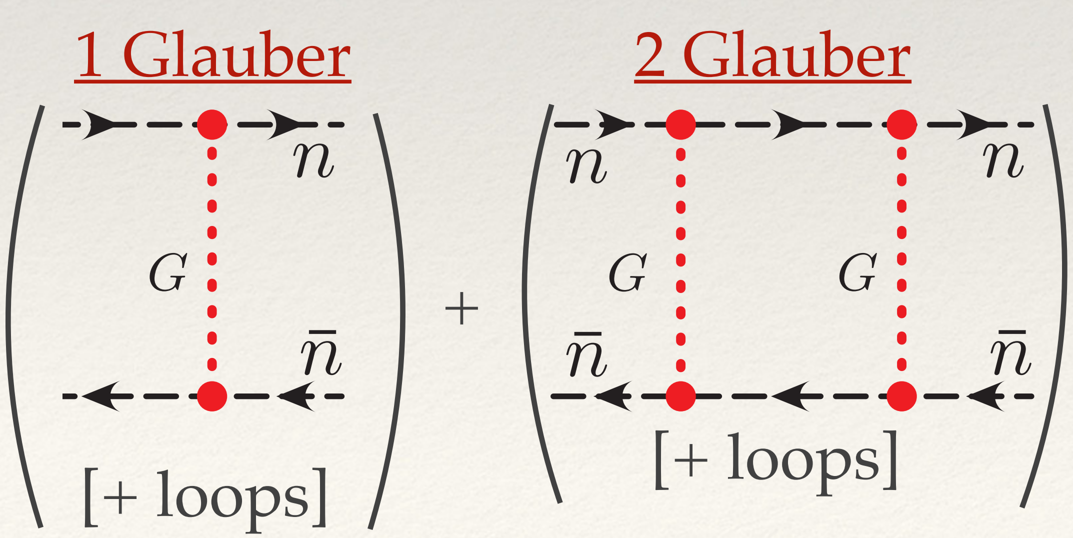
$$\times\left(2\alpha(t)\frac{\nu^\eta}{\eta}\right)$$

Evaluation: 8_A

Calculate the anomalous dimension of $S^{(2,2)}_{8_A}$



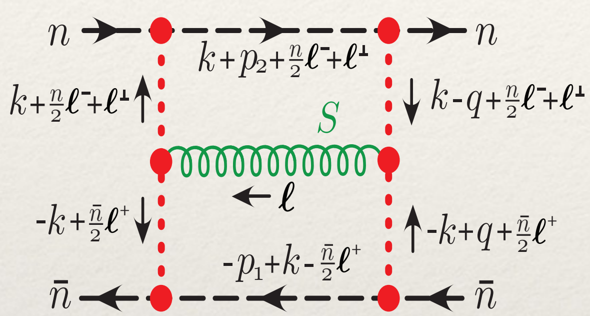
Yields the exact same anomalous dimension as $S^{(1,1)}_{8_A}$, So $S^{(2,2)}_{8_A}$ reggeizes in the exact same way.

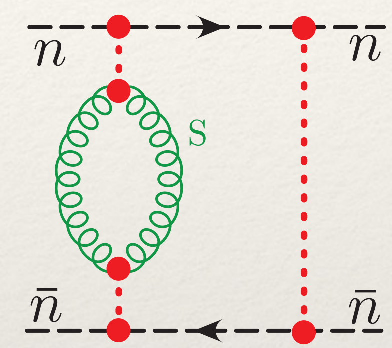


$$\underset{\text{LL}}{=} \frac{1}{t}\left(\frac{s}{-t}\right)^{\alpha(t)}\left[\left(2 - i\pi\,\alpha(t)\right)\right]$$

Evaluation: 1 (Pomeron)

Calculate the anomalous dimension of $S_1^{(2,2)}$





$$P^1_{CDAB}\left[2\nu^\eta\left(\frac{64\pi^2\alpha_s^3}{\eta}\right)\sum_R c^R P^R_{ABA'B'}(I_1 - I_2) + \mathcal{O}(\eta^0) \quad + \quad 3\nu^\eta\left(\frac{64\pi^2\alpha_s^3}{\eta}\right)\sum_R P^R_{ABA'B'}(I_2) + \mathcal{O}(\eta^0)\right]$$

Project onto the singlet (R=1) and add the two contributions. Derive the **Pomeron** BFKL Equation.

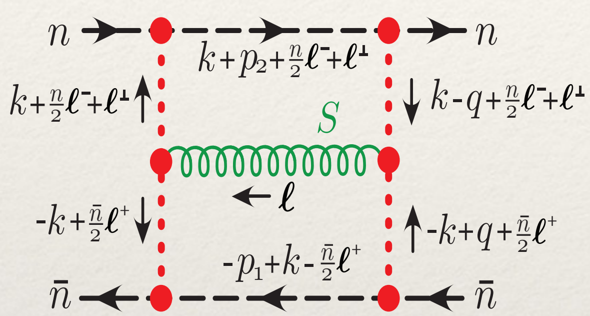
$$= 6\nu^\eta\left(\frac{64\pi^2\alpha_s^3}{\eta}\right)P^1_{CDA'B'}(I_1 - \frac{1}{2}I_2) + \mathcal{O}(\eta^0)$$

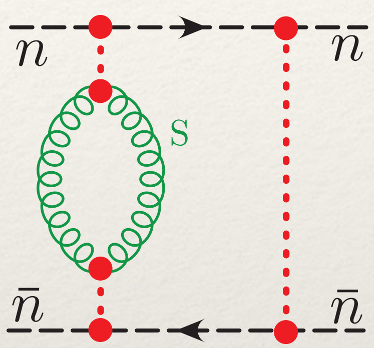
RG →

$$\nu\frac{d}{d\nu}S(q_\perp, q'_\perp, \nu) = \frac{2C_A\alpha_s(\mu)}{\pi^2}\int d^2k_\perp\left[\frac{S(k_\perp, q'_\perp, \nu)}{(\vec{k}_\perp - \vec{q}_\perp)^2} - \frac{\vec{q}_\perp^{\,2}\, S(q_\perp, q'_\perp, \nu)}{2\vec{k}_\perp^{\,2}(\vec{k}_\perp - \vec{q}_\perp)^2}\right]$$

Evaluation: Any Color Channel

Calculate the anomalous dimension of $S_R^{(2,2)}$





$$P^R_{CDAB}\left[2\nu^\eta\left(\frac{64\pi^2\alpha_s^3}{\eta}\right)\sum_R c^R P^R_{ABA'B'}(I_1-I_2)+\mathcal{O}(\eta^0) \quad + \quad 3\nu^\eta\left(\frac{64\pi^2\alpha_s^3}{\eta}\right)\sum_R P^R_{ABA'B'}(I_2)+\mathcal{O}(\eta^0)\right]$$

Project onto the representation R $\in 1, 8_A, 8_S, 10, \overline{10}, 27$

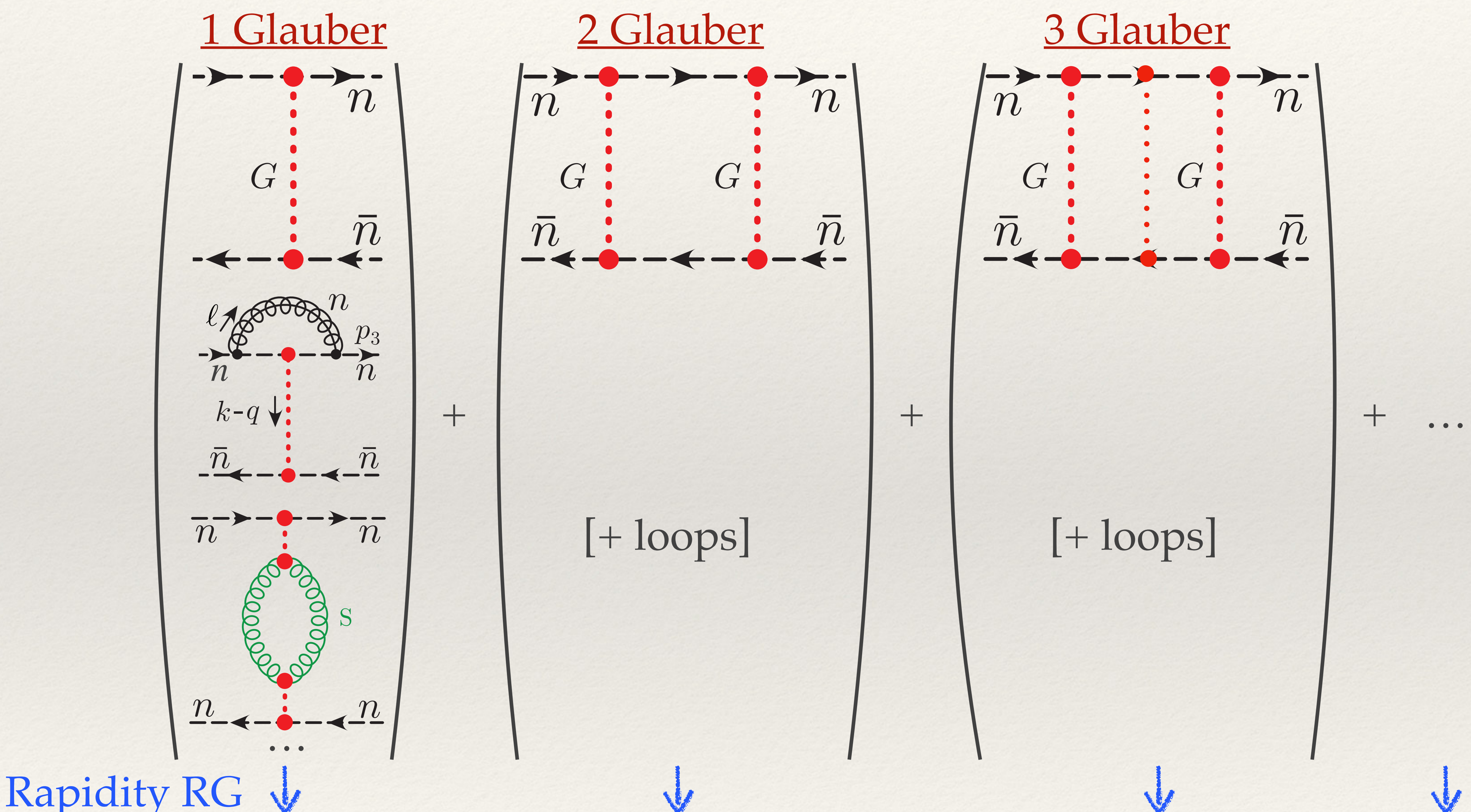
$$=\nu^\eta\left(\frac{64\pi^2\alpha_s^3}{\eta}\right)P^R_{CDA'B'}(2c^R I_1-3I_2)+\mathcal{O}(\eta^0)$$

RG →

$$\nu\frac{d}{d\nu}S(q_\perp,q'_\perp,\nu)=\frac{2C_A\alpha_s(\mu)}{\pi^2}\int d^2k_\perp\left[(2c^R-3)\frac{S(k_\perp,q'_\perp,\nu)}{(\vec{k}_\perp-\vec{q}_\perp)^2}-2c^R\frac{\vec{q}_\perp^{\,2}\,S(q_\perp,q'_\perp,\nu)}{2\vec{k}_\perp^{\,2}(\vec{k}_\perp-\vec{q}_\perp)^2}\right]$$

Current/Future Directions

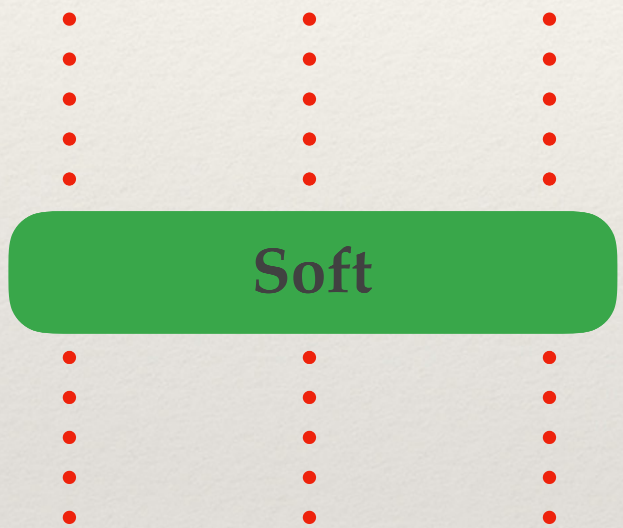
3-Glauber Exchange



$$i\mathcal{M} = \left(\frac{s}{-t}\right)^{\alpha_1(t)} + (i\pi)\left(\frac{s}{-t}\right)^{\alpha_2(t)} + \ ? \ + \ \ldots$$

LL **NLL** **NNLL**

3-Glauber exchange



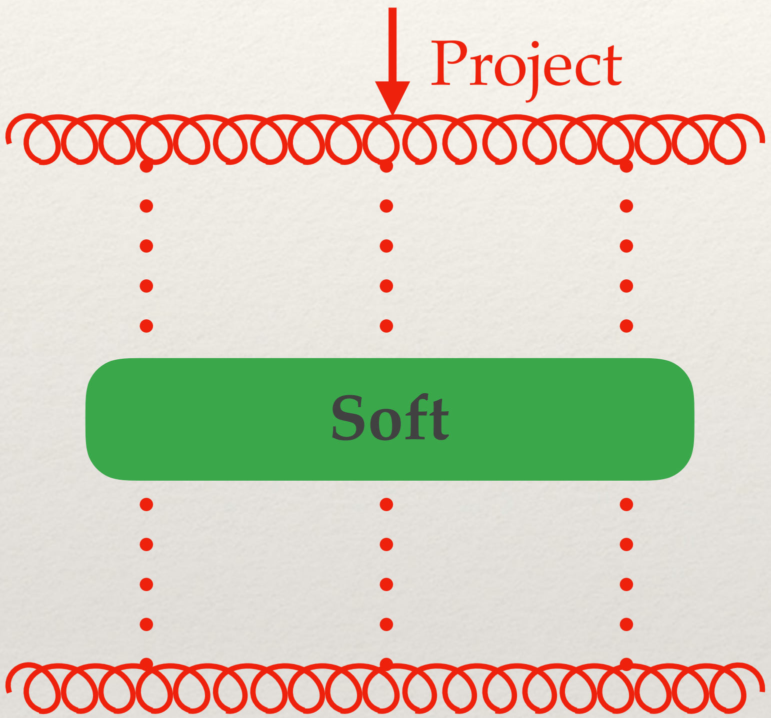
$$8 \otimes 8 \otimes 8 = 2(1) \oplus 8(8) \oplus 4(10) \oplus 4(\overline{10}) \oplus 6(27) \oplus 2(35) \oplus 2(\overline{35}) \oplus 64$$

- The soft functions are the objects of interest

$$\nu \frac{d}{d\nu} S_R^{(3,3)}(\ldots, \nu) = \ldots$$

3-Glauber exchange

$$8 \otimes 8 = 1 \oplus 8_A \oplus 8_S \oplus 10 \oplus \overline{10} \oplus 27$$



$$\longrightarrow \langle p_3, p_4 | U_{(3,3)} | p_1, p_2 \rangle$$

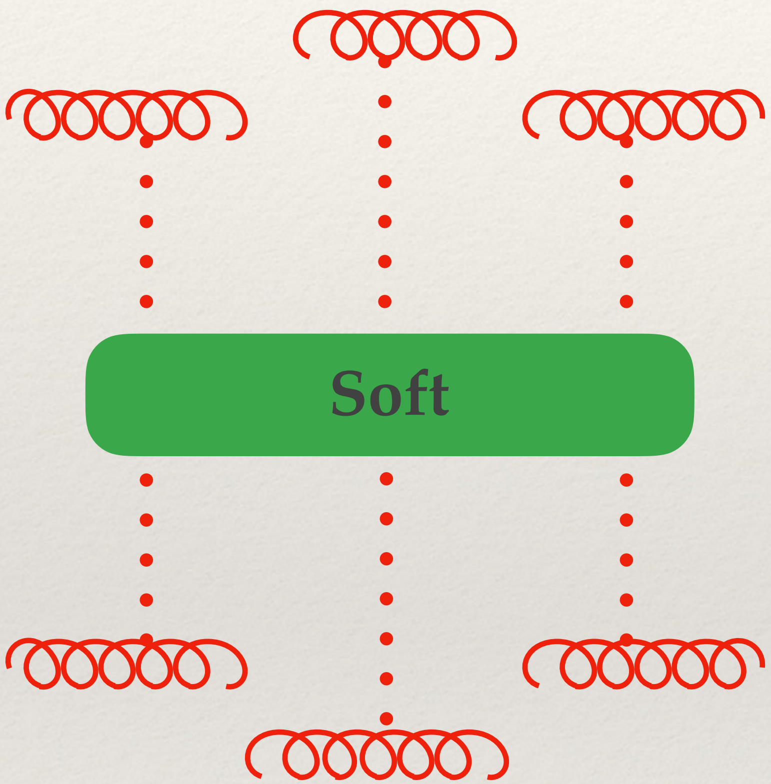
$$8 \otimes 8 \otimes 8 = 2(1) \oplus 8(8) \oplus 4(10) \oplus 4(\overline{10}) \oplus 6(27) \oplus 2(\cancel{35}) \oplus 2(\cancel{\overline{35}}) \oplus \cancel{64}$$

- The soft functions are the objects of interest
- Fixing external states projects on to irreps

$$\nu \frac{d}{d\nu} S_R^{(3,3)}(\ldots, \nu) = \ldots$$

3-Glauber exchange

Has access to higher colors



$$\longrightarrow \quad \langle p_1' \ldots | U_{(3,3)} | p_1, \ldots \rangle$$

$$8 \otimes 8 \otimes 8 = 2(1) \oplus 8(8) \oplus 4(10) \oplus 4(\overline{10}) \oplus 6(27) \oplus 2(35) \oplus 2(\overline{35}) \oplus 64$$

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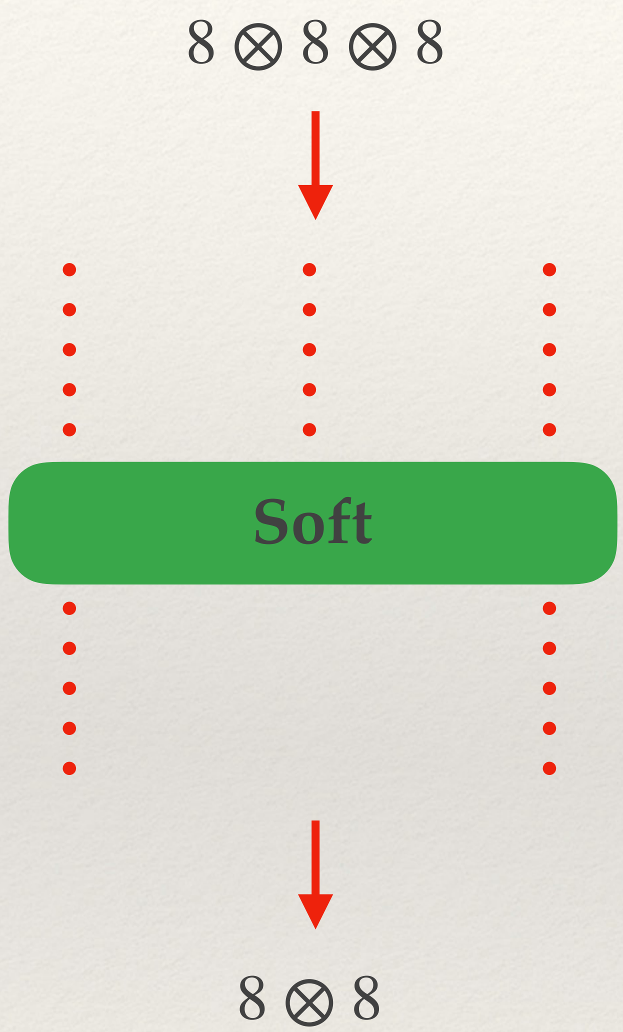
$$\nu \frac{d}{d\nu} S_R^{(3,3)}(\ldots, \nu) = \ldots$$

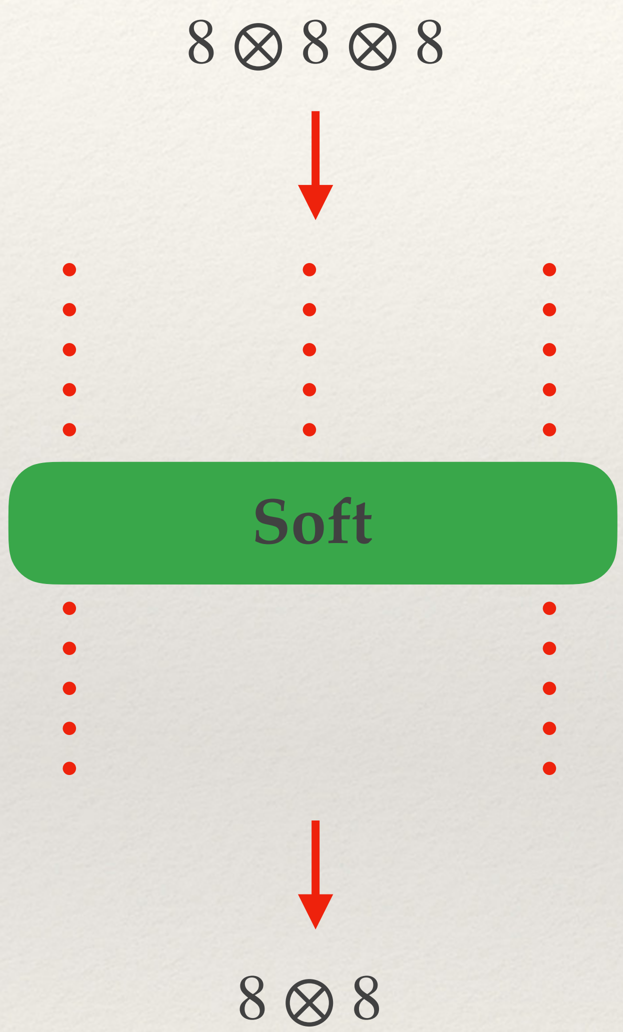
3-Glauber exchange



How do 3 to 2 transitions modify the story?

Such mixings exist in the Regge calculus formulation

3-Glauber exchange



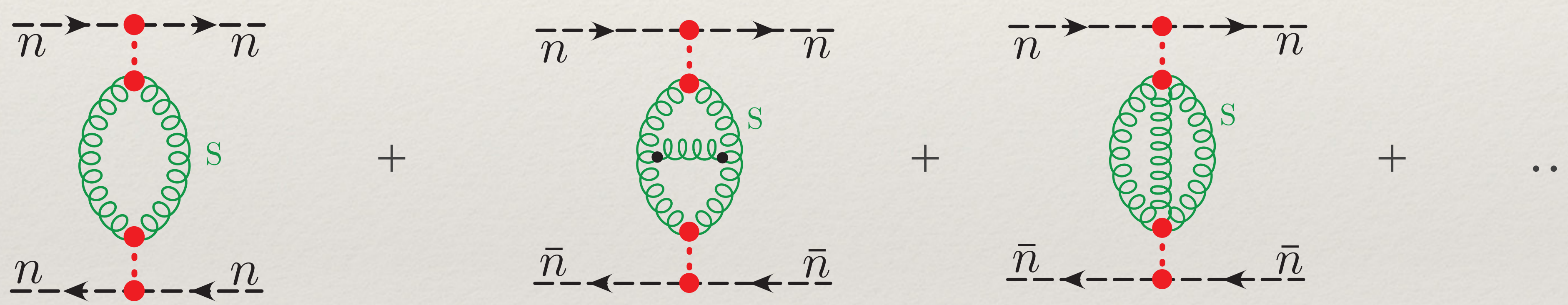
How do 3 to 2 transitions modify the story?

Such mixings exist in the Regge calculus formulation

But remember one of our main equations,  $\neq$ 

SCET Definition of the Regge Trajectory

- The SCET definition of the gluon Regge Trajectory is the anomalous dimension of the soft function for one-Glauber exchange, $S^{(1,1)}$
  - Gauge invariant from the structure of the SCET operators
  - All-orders operator definition
  - Reproduces single-Regge pole in the planar limit (close to proving this)



$$\nu \frac{d}{d\nu} S^{(1,1)}(\nu) = \gamma_{s\nu} S^{(1,1)}(\nu) \equiv 2\alpha(t) S^{(1,1)}(\nu)$$

Conclusion

- The EFT provides a natural organization of amplitudes in the Regge limit
  - Only beginning to explore its structure
- Showed how to factorize an amplitude in the Regge limit into a sum over gauge invariant (n,m) Glauber operators in color irreps, $S_R^{(n,m)}$
  - These are the fundamental objects for summation of large logs (RRGE)
- In this talk we evaluated (2,1) and (2,2) and set up the higher order structures
  - Standard Pomeron and $i\pi$ in the gluon regge trajectory reproduced as well as other color structures
  - Gave an all orders definition of the gluon regge trajectory
- Would be very useful to make a dictionary between our SCET formulation and the more standard Regge treatment

Thank You