Precise description of medium-induced emissions

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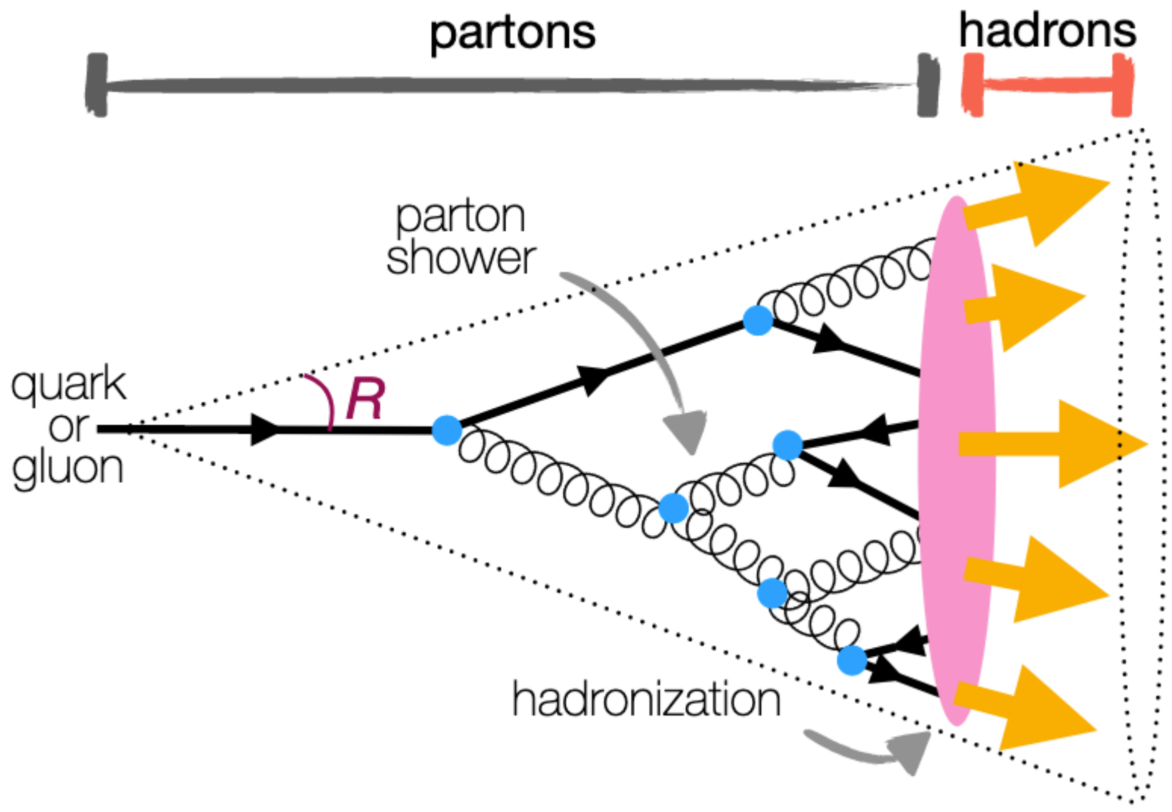
In collaboration with Konrad Tywoniuk
Based on 2107.02542 and ongoing work

Jets

In particle collider events

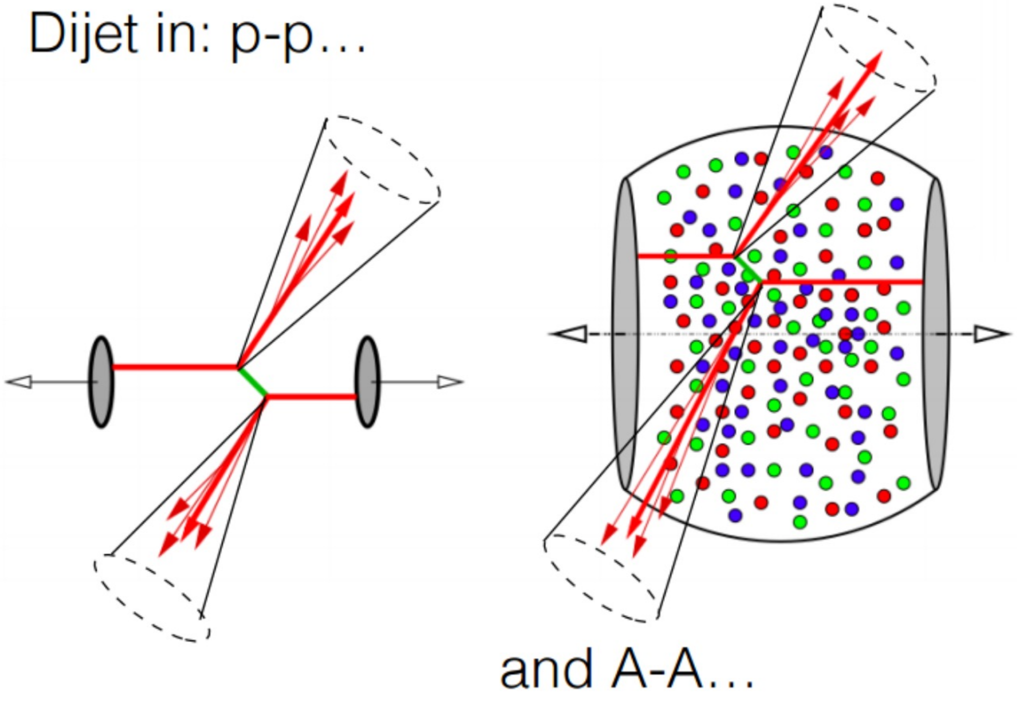
- Hard process makes highly virtual particle
- Particle radiates and creates collimated spray of hadrons
- This is called a jet
- Calculable to high precision in proton-proton collisions



[R. Cruz-Torres (2022)]

Jets in heavy-ion collisions

- Colliding two heavy nuclei creates quark-gluon plasma
- Jet must go through the medium (QGP) to reach the detector
- Medium interacts with jet and modifies it
- This is called jet quenching



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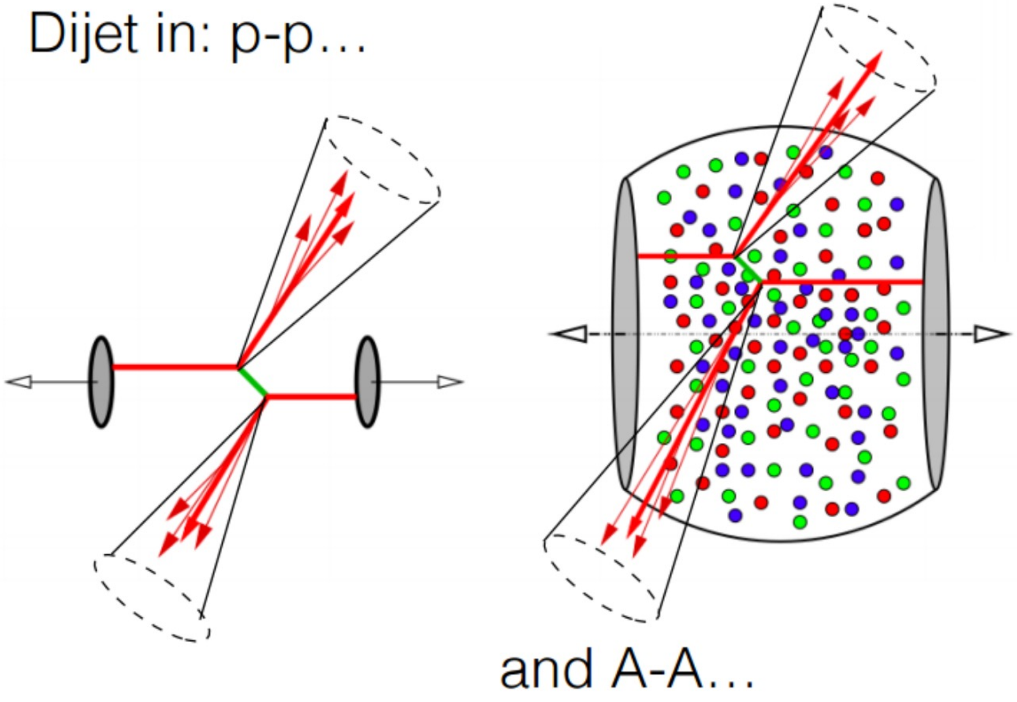
- Modified in several ways:
  - Substructure modification
  - Energy loss
  - Change of direction



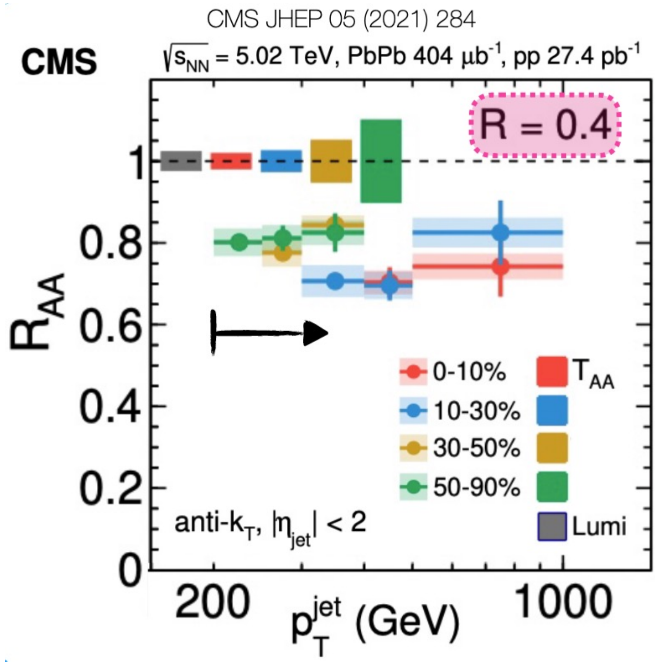
[C. Andres (2022)]

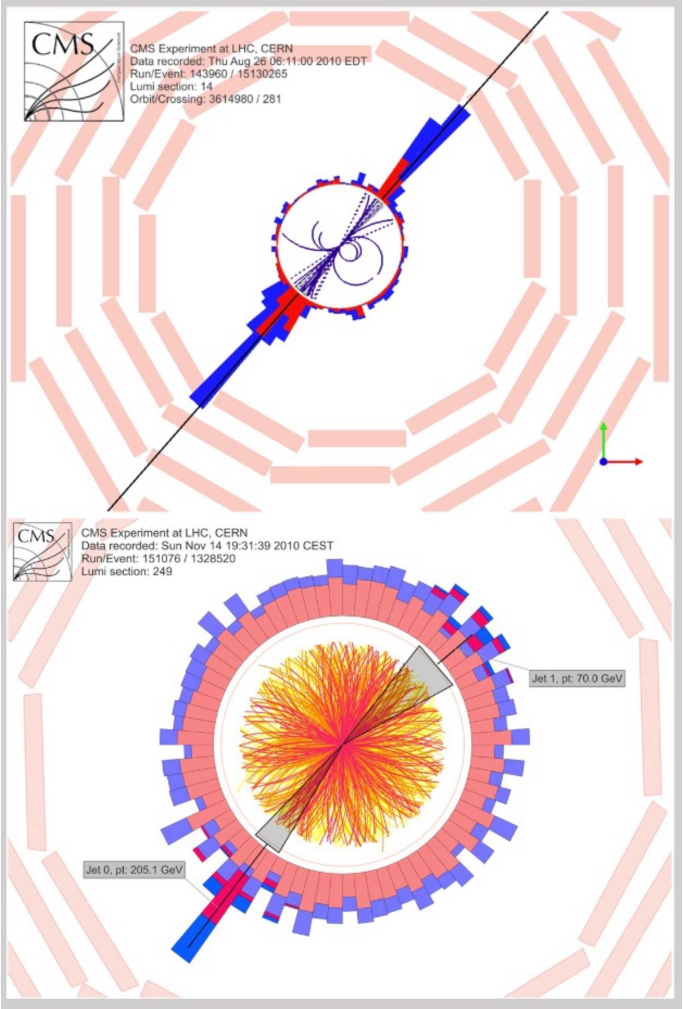
Signatures of jet quenching

- There are several experimental observables of jet quenching
- Most prominent is the nuclear modification factor

$$R_{\mathrm{AA}} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

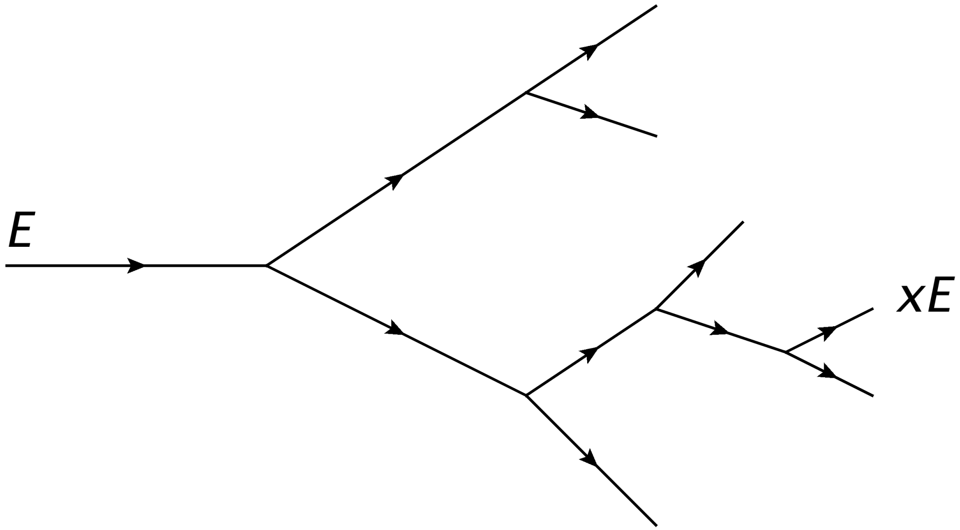
$$\begin{aligned} R_{\mathrm{AA}} > 1 &\;\rightarrow\; \text{enhancement} \\ R_{\mathrm{AA}} = 1 &\;\rightarrow\; \text{no medium modification} \\ R_{\mathrm{AA}} < 1 &\;\rightarrow\; \text{supression} \end{aligned}$$





Jets in heavy-ion collisions

- Partons going through the medium scatter with medium constituents
- Scatterings induce emissions
  - More emissions compared to vacuum jets
  - Emissions outside of the jet cone → energy loss



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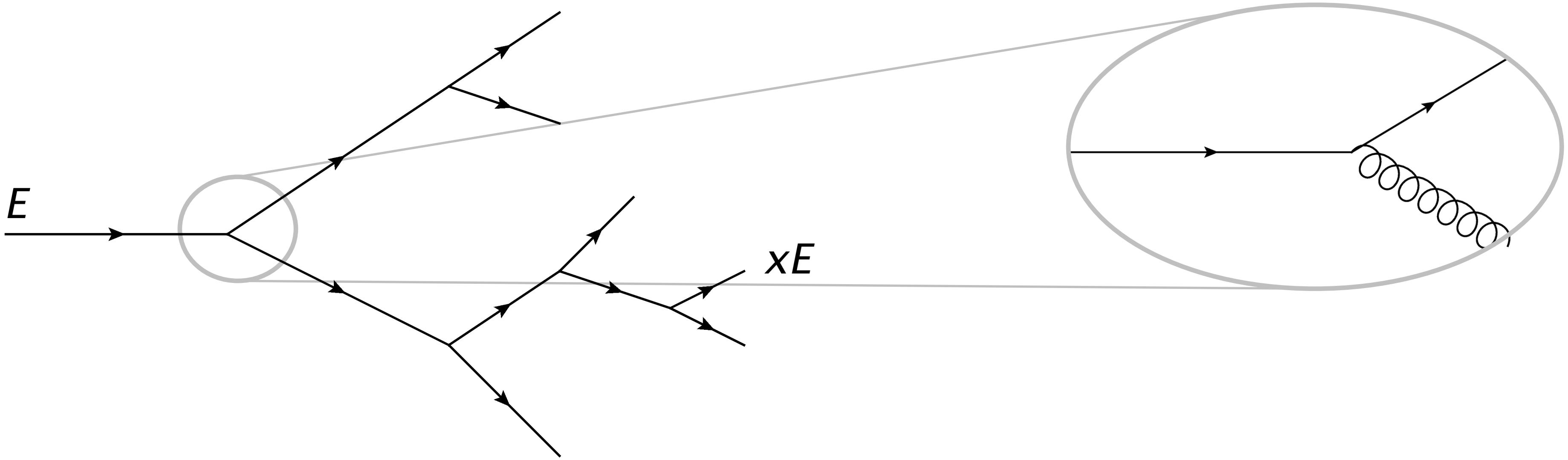

- To calculate many emissions we need to be able to calculate just one emission!

Calculating jet quenching

- To make predictions we need a theory of how partons interact with the medium
- QCD with an external field A^a
- This field represents the medium interaction
- Can make medium Feynman rules, and calculate medium Feynman diagrams

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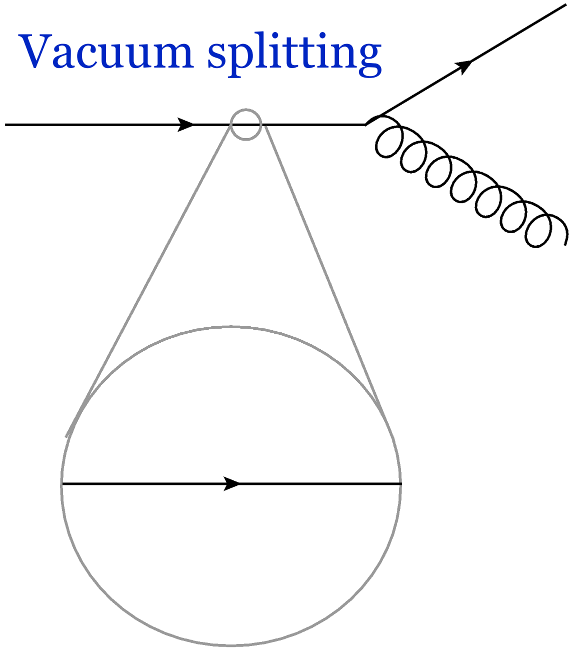
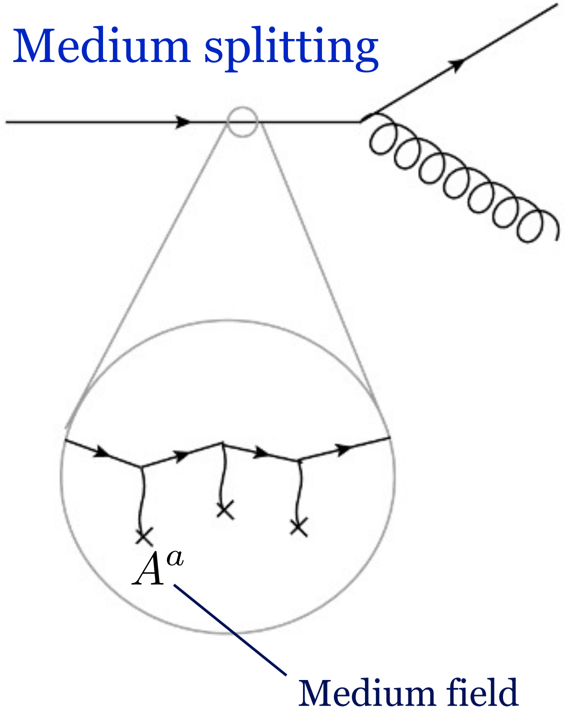
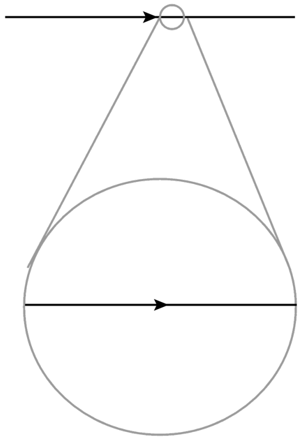




Calculating jet quenching

Vacuum propagator



$$\| $$

$$\frac{i\delta^{ij}}{\not{p} - m + i\varepsilon}$$

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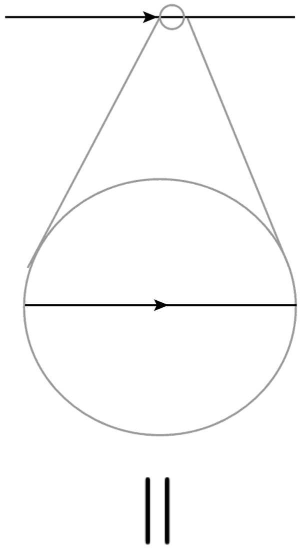

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NICE
EASY

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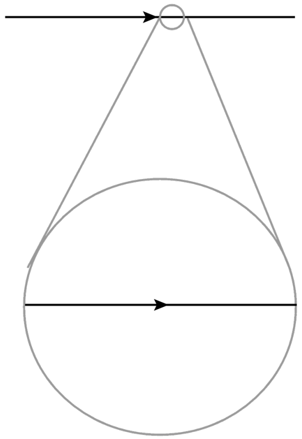

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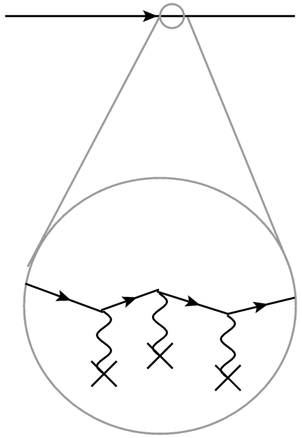
Medium propagator



$$\mathcal{G}(\boldsymbol{x}, t; \boldsymbol{x}_0, t_0) = \int_{\boldsymbol{x}_0}^{\boldsymbol{x}} \mathcal{D}\boldsymbol{r} \exp\left[i\frac{E}{2}\int_{t_0}^{t} \mathrm{d}s\dot{\boldsymbol{r}}^2(s)\right] V_R\left(t, t_0; \boldsymbol{r}(t)\right)$$

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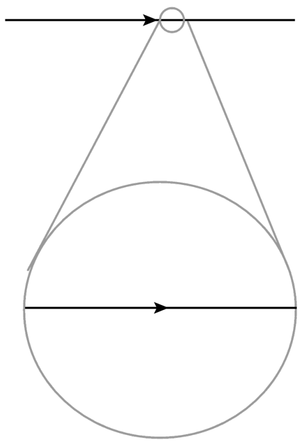

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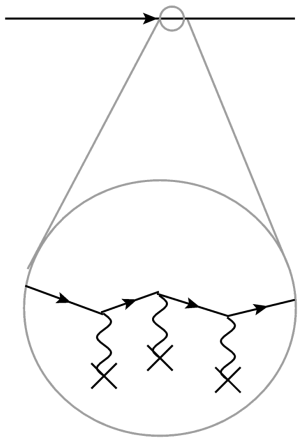

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Varying path leads to
path integral

Color rotation leads to:
Wilson line

$$V_R\left(t, t_0; \mathbf{r}(t)\right) = \mathcal{P}\exp\left[ig\int_{t_0}^{t} \mathrm{d}s\, A^a(s, \mathbf{r}(s)) T_R^a\right]$$

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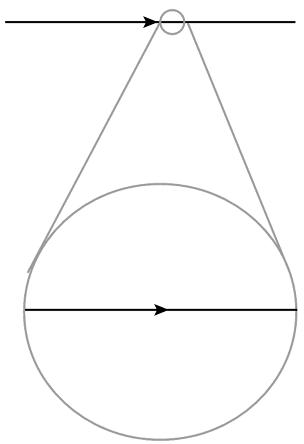

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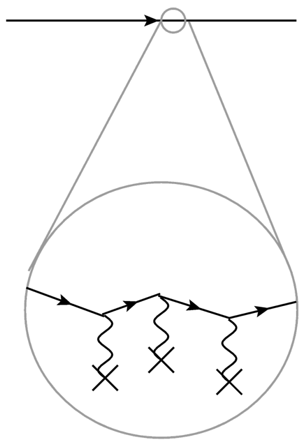

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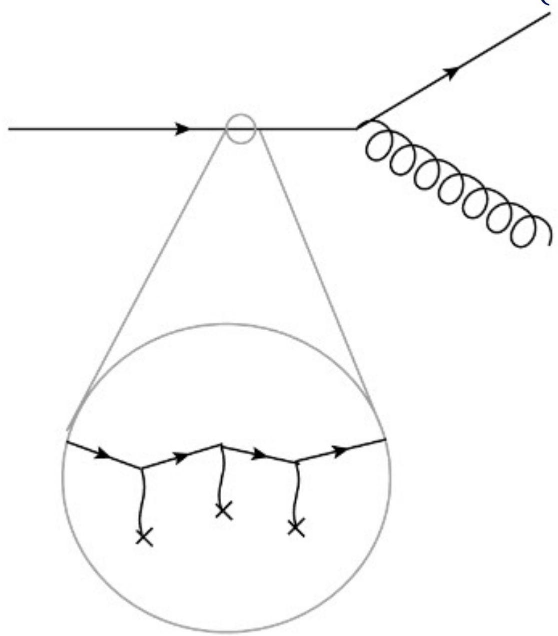
NOT NICE
NOT EASY

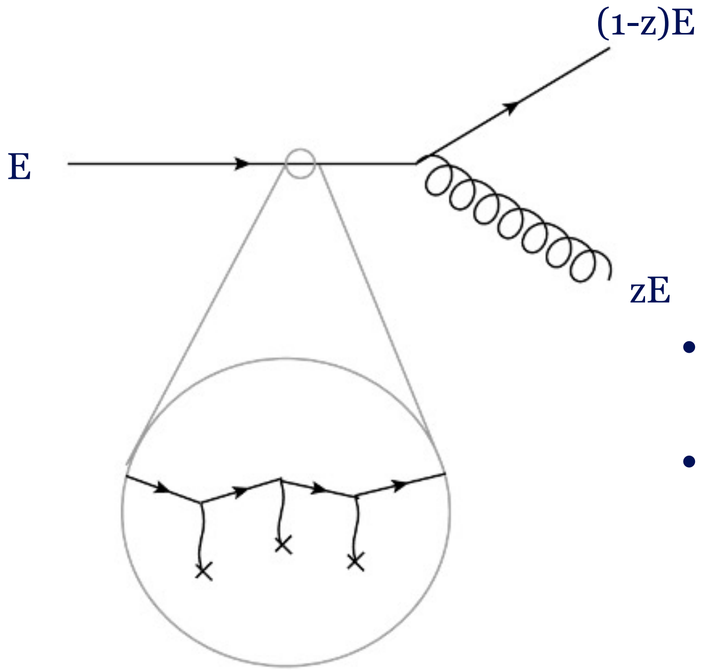
Medium-induced emissions



$$= \frac{g^2}{z(1-z)E^2} P_{a\to bc}(z) 2\mathrm{Re} \int_{t_0}^{\infty} \mathrm{d}t_1 \int_{t_1}^{\infty} \mathrm{d}t_2 \int_{\boldsymbol{p}_1 \boldsymbol{l}_1 \boldsymbol{l}_2 \bar{\boldsymbol{p}}_2 \bar{\boldsymbol{l}}_2} \boldsymbol{l}_1 \cdot \bar{\boldsymbol{l}}_2 \, \tilde{S}^4(\boldsymbol{p}, \boldsymbol{l}_2, \bar{\boldsymbol{l}}_2, \bar{\boldsymbol{p}}_2 - \boldsymbol{P} | t_\infty, t_2) \\ \times \tilde{S}^3(\boldsymbol{l}_2, \boldsymbol{l}_1, \boldsymbol{p}_1 - \bar{\boldsymbol{p}}_2 | t_2, t_1) \mathcal{P}(\boldsymbol{p}_1 - \boldsymbol{p}_0 | t_1, t_0) \, .$$

- This is not nice. Let’s break it down

Medium-induced emissions



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- $\mathcal{P}(\boldsymbol{p}_1 - \boldsymbol{p}_0 | t_1, t_0) \sim \langle \mathcal{G}\mathcal{G}^\dagger \rangle$ ✓ Can solve ☺

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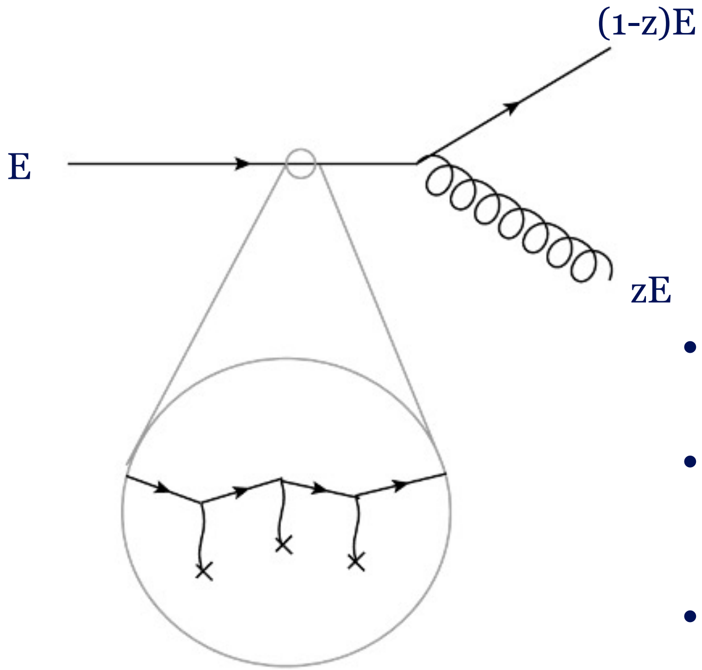

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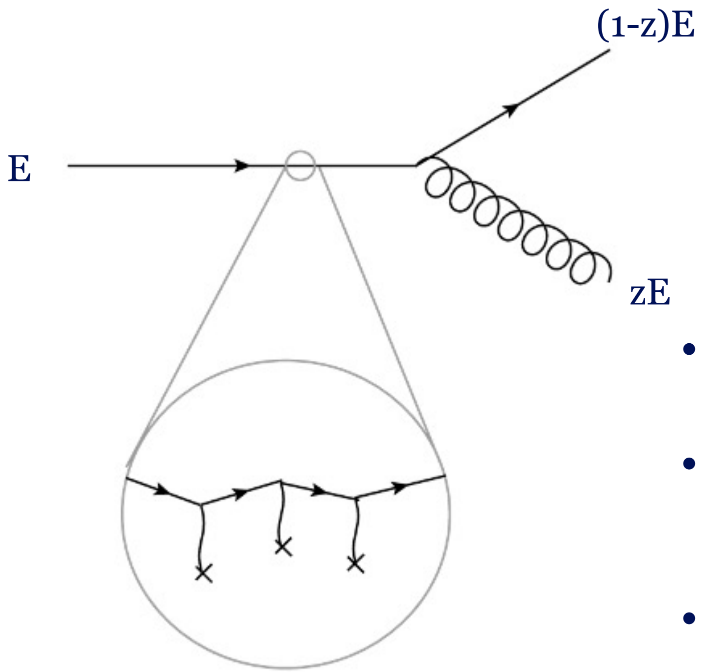

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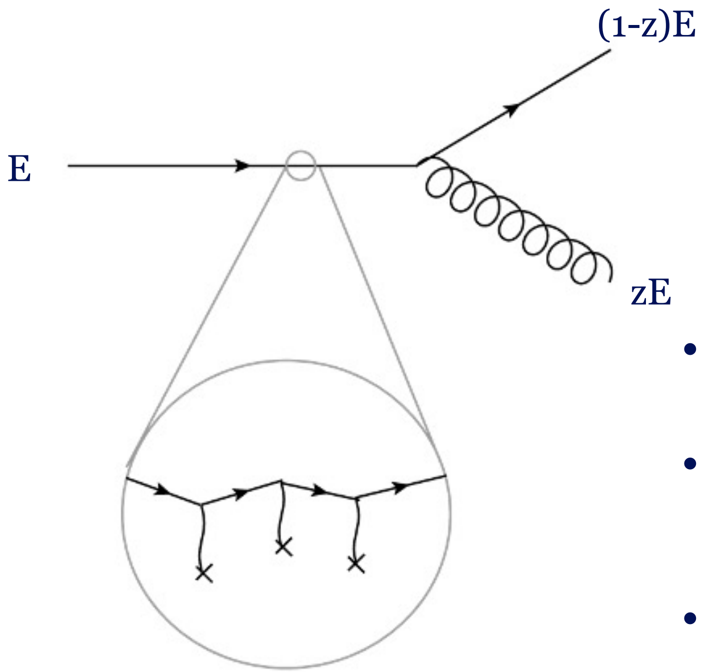

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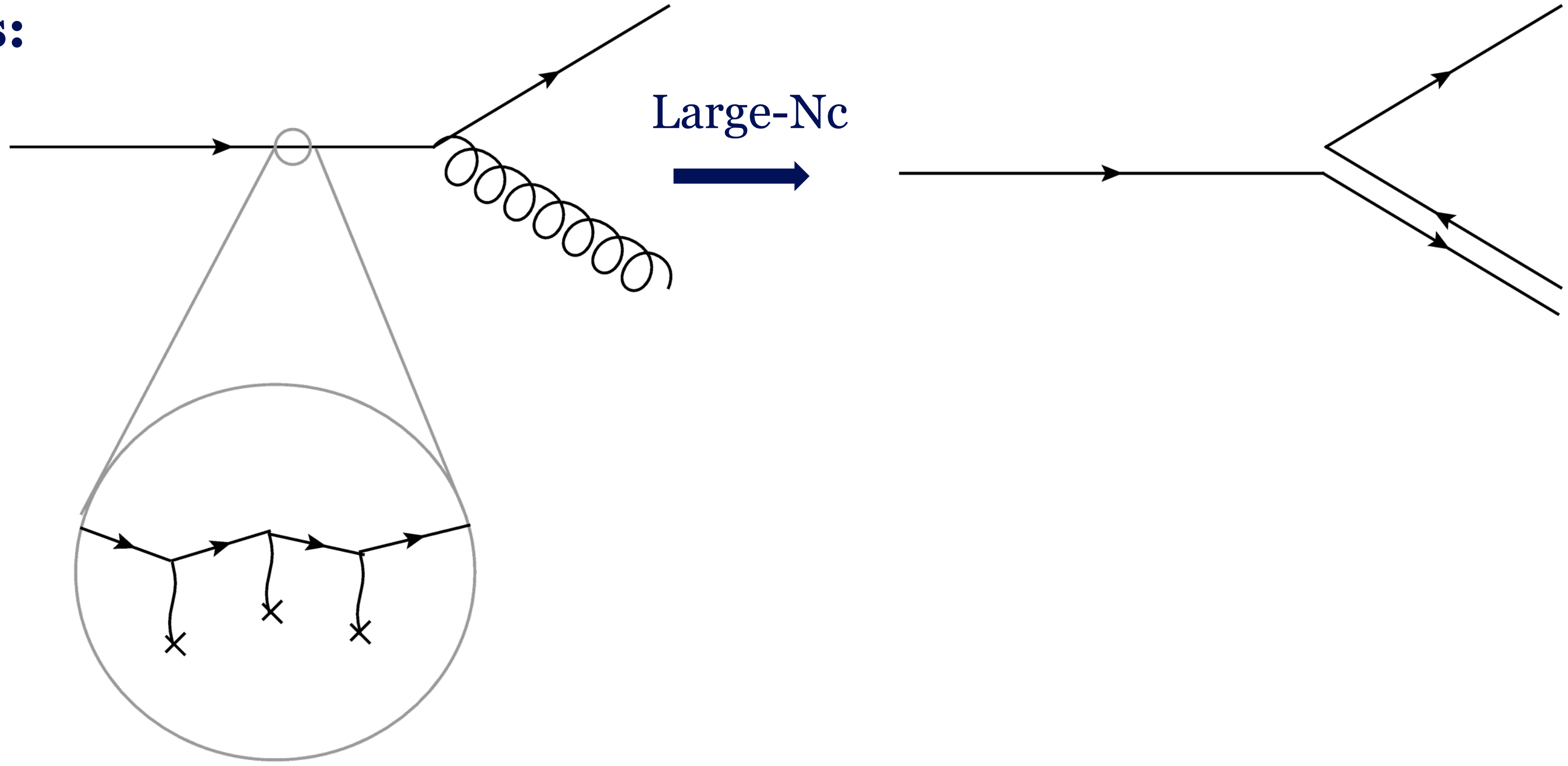
- Conventionally use two approximations to deal with this:
  - Large-Nc approximation
  - Eikonal approximation

Medium-induced emissions

Two simplifying approximations:

1. Large-Nc approximation
   - Take number of colors (Nc) to infinity



Medium-induced emissions

Two simplifying approximations:

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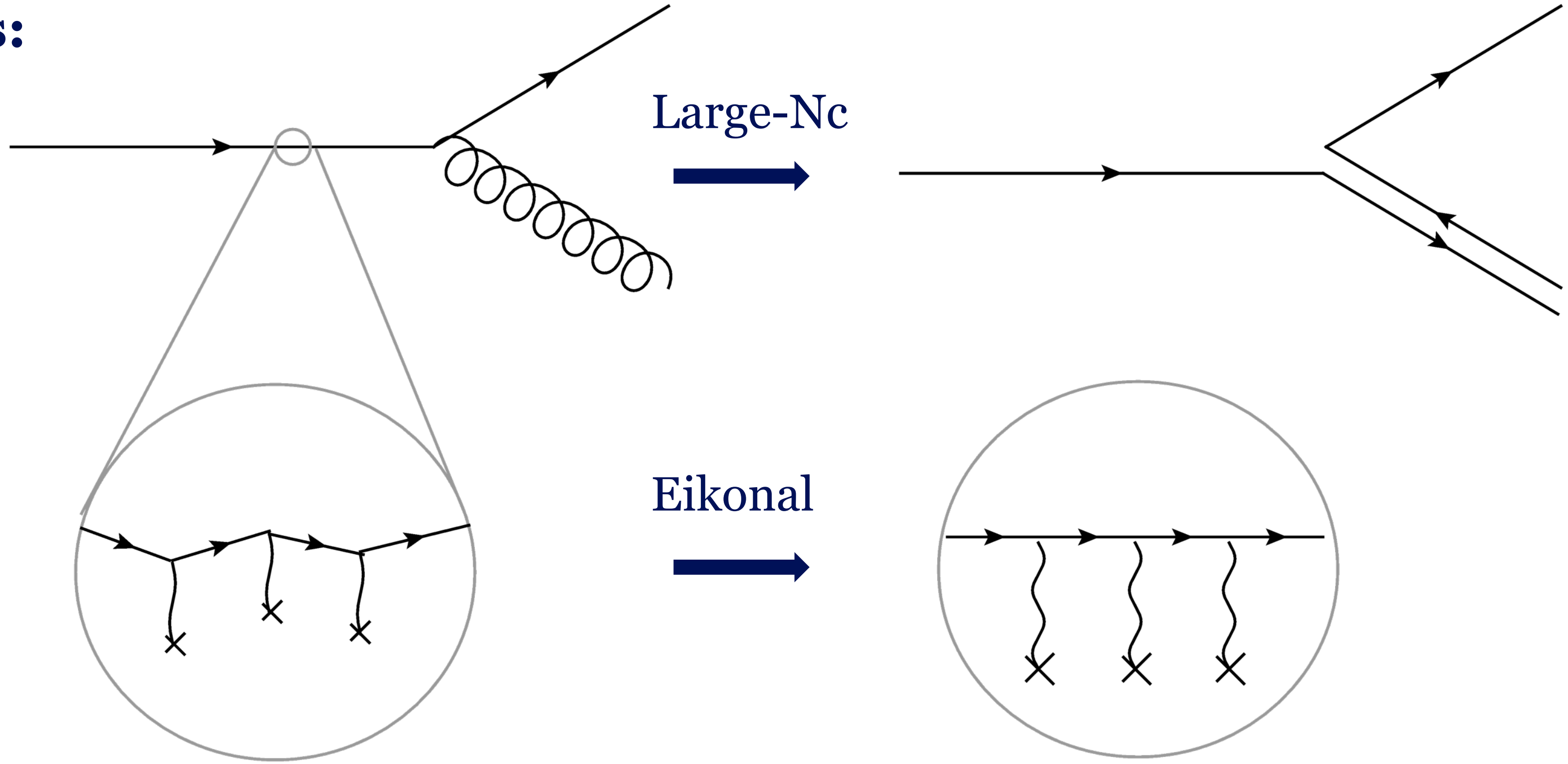
2. Eikonal approximation
   - Partons travel on straight lines
   - Good for high energy



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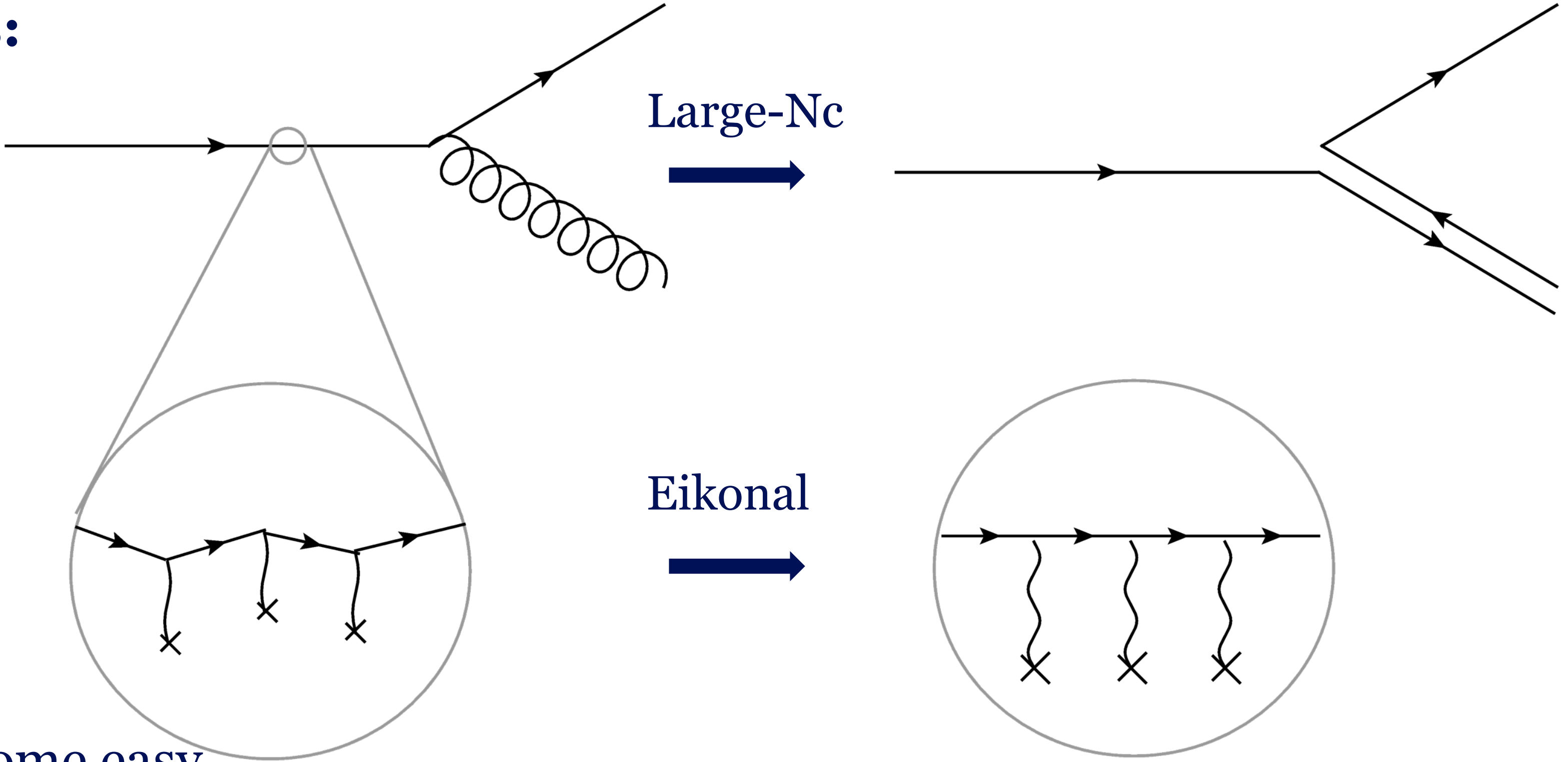

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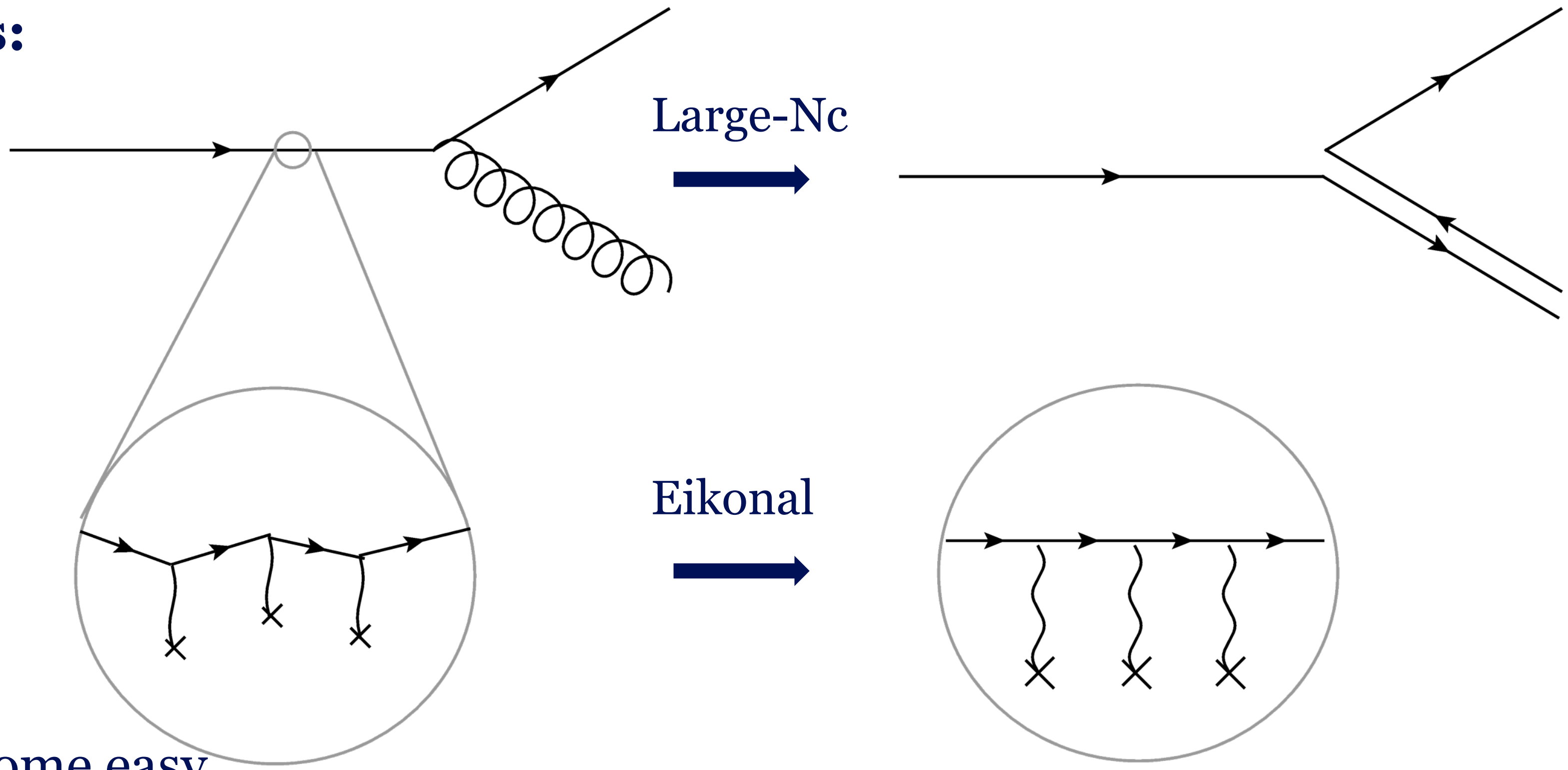

- Using this the hard calculations become easy
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  - Figure out the error
  - (Someone has to do it)

Plan

1. Calculate finite-Nc corrections
2. Calculate non-eikonal corrections **and** finite-Nc corrections

Finite Nc corrections

- First let's use the eikonal approximation, and not the large-Nc
- Path integral turns to an exponential

$$\tilde{S}^4(\boldsymbol{p}, \boldsymbol{l}_2, \bar{\boldsymbol{l}}_2, \bar{\boldsymbol{p}}_2 - \boldsymbol{P}|t_\infty, t_2) \sim \langle \mathcal{G}\mathcal{G}\mathcal{G}^\dagger\mathcal{G}^\dagger \rangle$$
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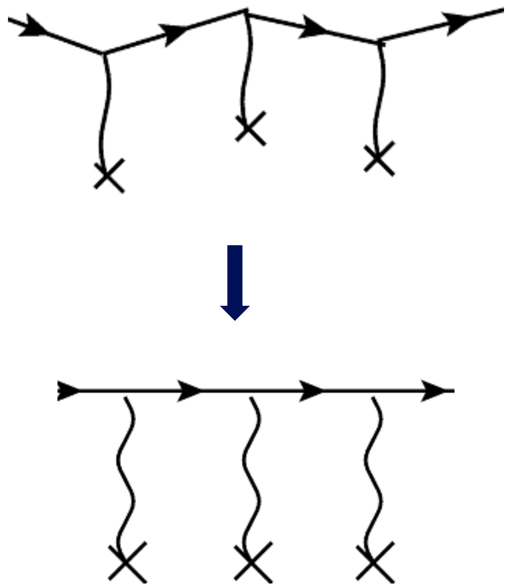

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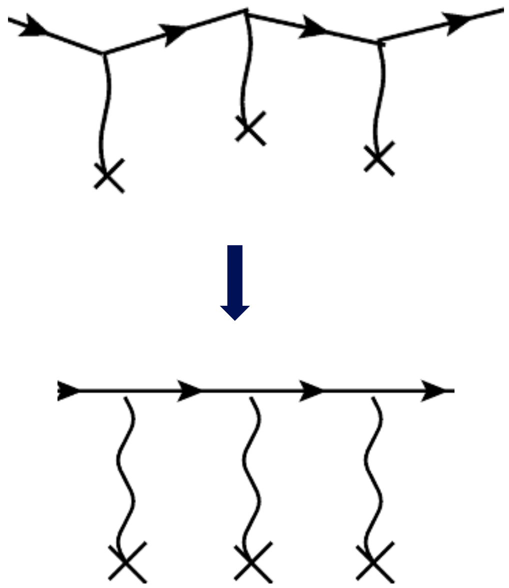


- Still have to deal with Wilson lines!
  - Wilson line correlators can be calculated through a system of differential equations!

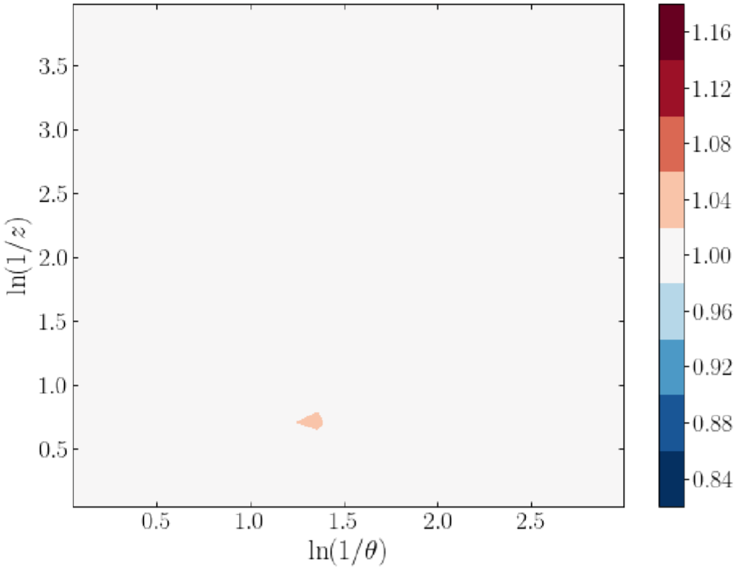
$$\frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} \langle \mathrm{tr}[VV] \, \mathrm{tr}[VV] \rangle \\ \langle \mathrm{tr}[VVVV] \rangle \end{bmatrix} = \mathbb{V}(t) \begin{bmatrix} \langle \mathrm{tr}[VV] \, \mathrm{tr}[VV] \rangle \\ \langle \mathrm{tr}[VVVV] \rangle \end{bmatrix}$$

  - The potential matrix $\mathbb{V}(t)$ simplifies greatly in the large-Nc limit
  - We solved finite Nc and large-Nc and compared the result
  - Expect correction around $\sim 1/N_c^2 \simeq 10\%$

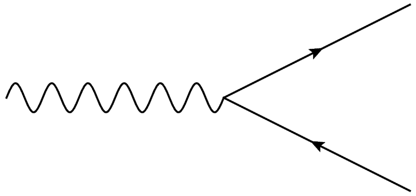
Finite Nc corrections

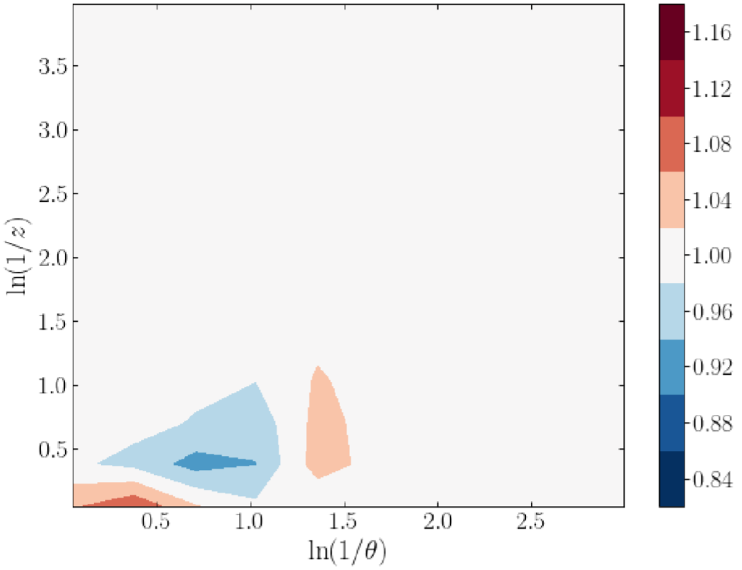
Ratio of emission spectrum for large-Nc/finite Nc

Up to 16%

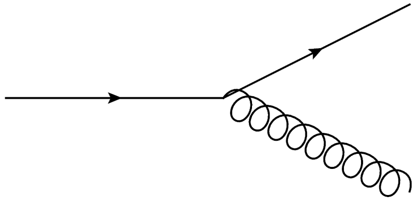


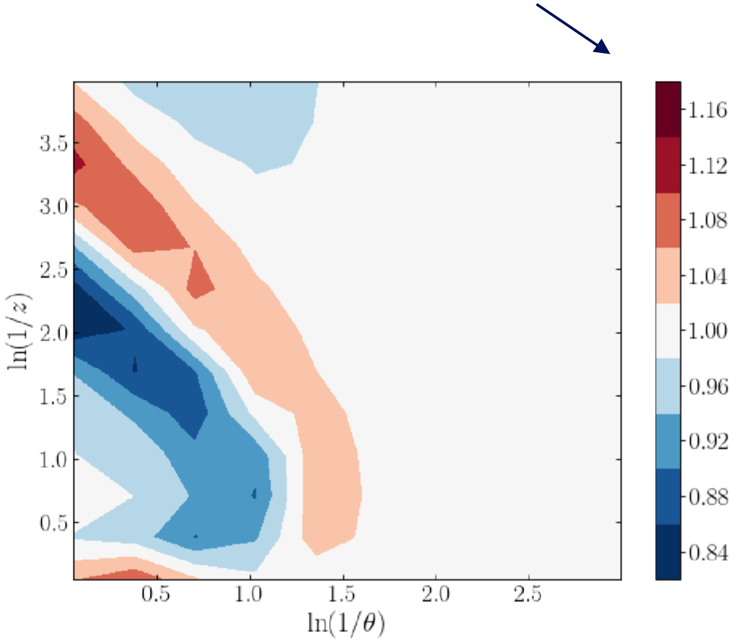
(a) Photon splitting.



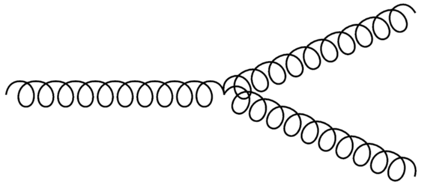


(b) Quark-gluon splitting.





(c) Gluon-gluon splitting.



Finite Nc corrections

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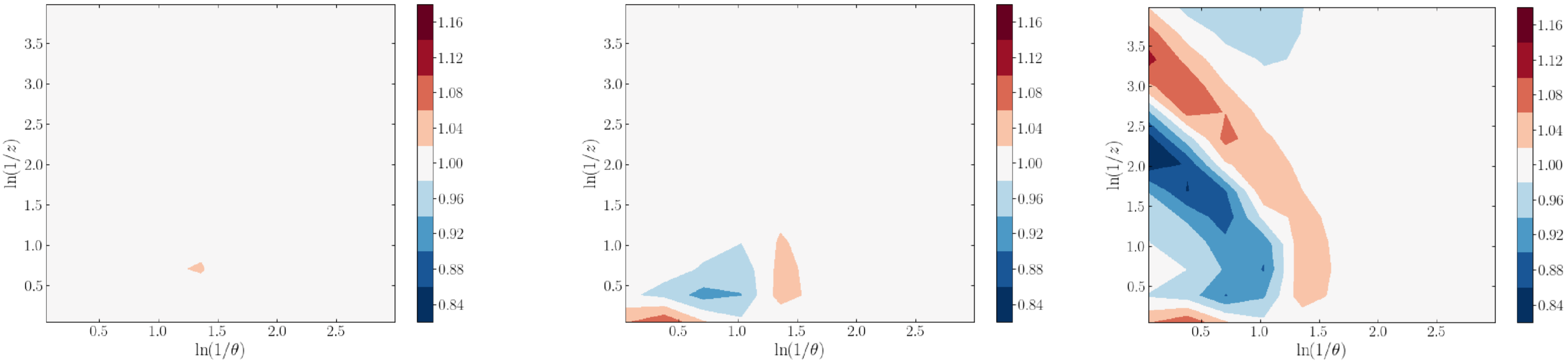
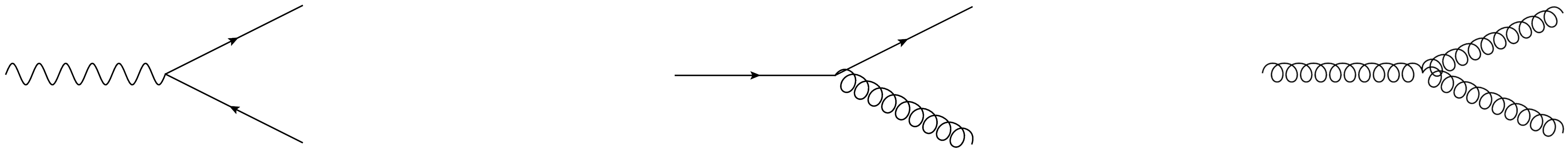


(a) Photon splitting. (b) Quark-gluon splitting. (c) Gluon-gluon splitting.



More complex color structure leads to bigger correction!

Plan

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Plan

1. Calculate finite-Nc corrections ✓
2. Calculate non-eikonal corrections **and** finite-Nc corrections

Non-eikonal corrections

Partons get kicked around by medium

- Path through the medium is not straight
- Must keep the full path integral description

$$\tilde{S}^4(\boldsymbol{u},\bar{\boldsymbol{u}},\boldsymbol{u}_2,\bar{\boldsymbol{u}}_2|t,t_2) \sim \langle \mathcal{G}\mathcal{G}\mathcal{G}^\dagger\mathcal{G}^\dagger \rangle$$

$$\sim \# \int_{\boldsymbol{u}_2}^{\boldsymbol{u}} \mathcal{D}\boldsymbol{u} \int_{\bar{\boldsymbol{u}}_2}^{\bar{\boldsymbol{u}}} \mathcal{D}\bar{\boldsymbol{u}}\, \mathrm{e}^{i\frac{\omega}{2}\int_{t_2}^{t} \mathrm{d}s\,(\dot{\boldsymbol{u}}^2-\dot{\bar{\boldsymbol{u}}}^2)} \langle VVV^\dagger V^\dagger \rangle$$

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- Again, this can be turned into a system of differential equations
- Now it is a more complicated Schrödinger equation

$$\left(i\frac{\partial}{\partial t} + \frac{\partial_{\boldsymbol{u}}^2 - \partial_{\boldsymbol{v}}^2}{2\omega} \right) \begin{bmatrix} \tilde{S}_1^4 \\ \tilde{S}_2^4 \end{bmatrix} = i\mathbb{V}(t, \boldsymbol{u}, \boldsymbol{v}) \begin{bmatrix} \tilde{S}_1^4 \\ \tilde{S}_2^4 \end{bmatrix}$$

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Eikonal limit →

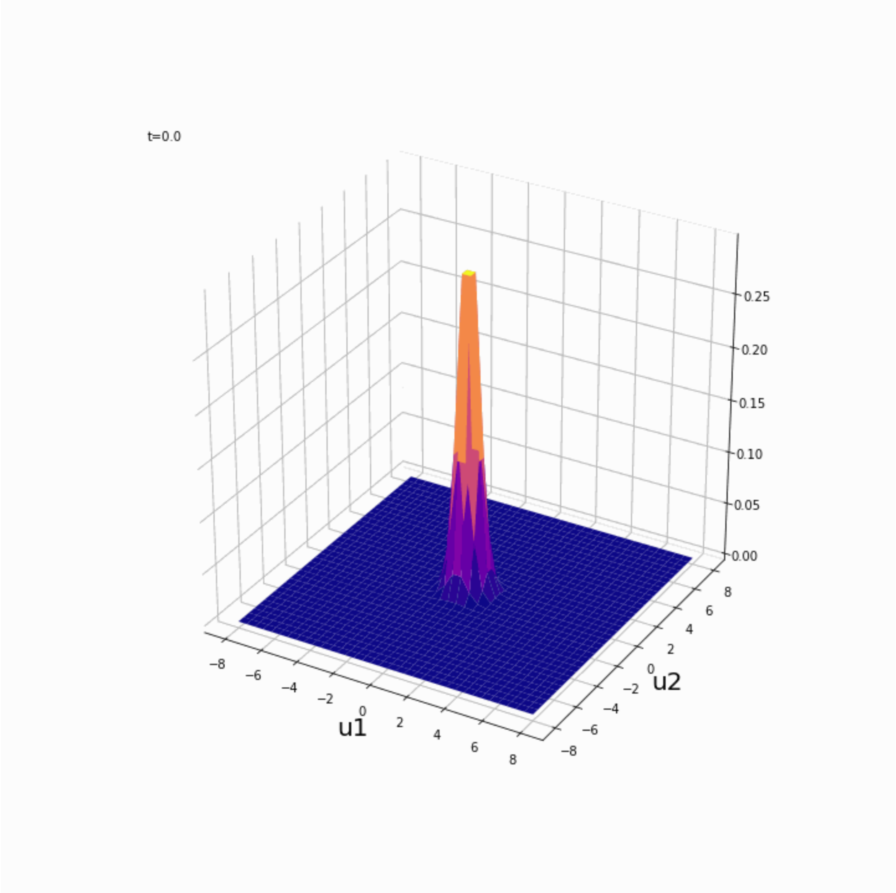
Same as before

$$\frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} \langle \mathrm{tr}[VV]\, \mathrm{tr}[VV] \rangle \\ \langle \mathrm{tr}[VVVV] \rangle \end{bmatrix} = \mathbb{V}(t) \begin{bmatrix} \langle \mathrm{tr}[VV]\, \mathrm{tr}[VV] \rangle \\ \langle \mathrm{tr}[VVVV] \rangle \end{bmatrix}$$

- This can be solved numerically

Non-eikonal corrections

- Solution of Schrödinger equation



Non-eikonal corrections

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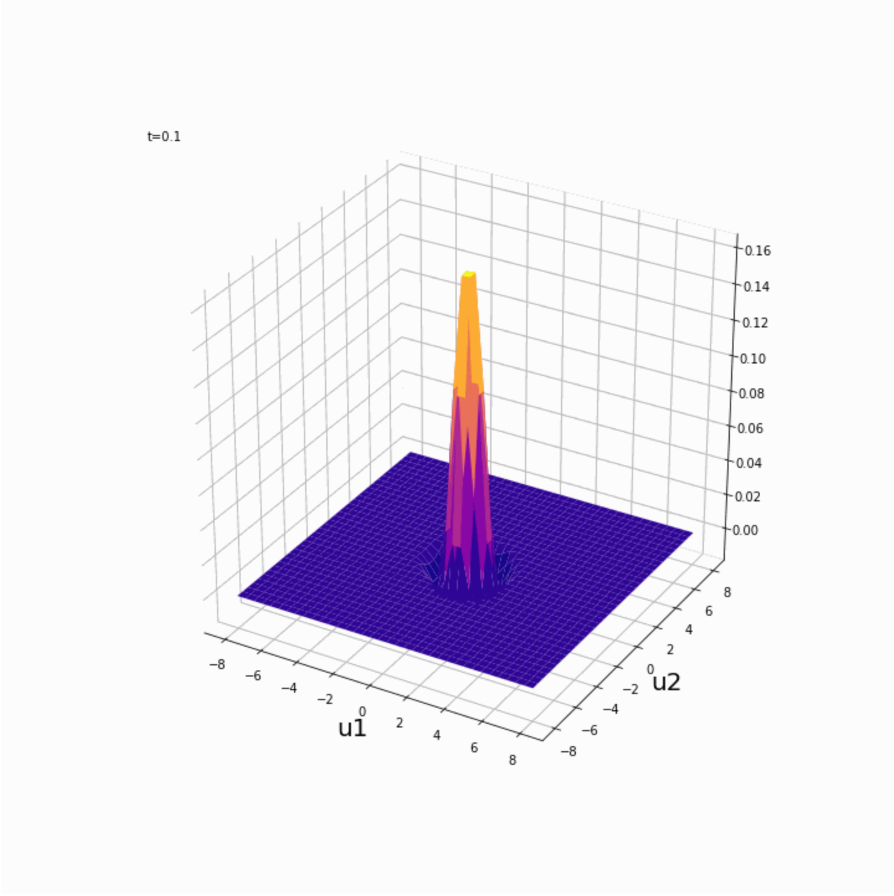

Non-eikonal corrections

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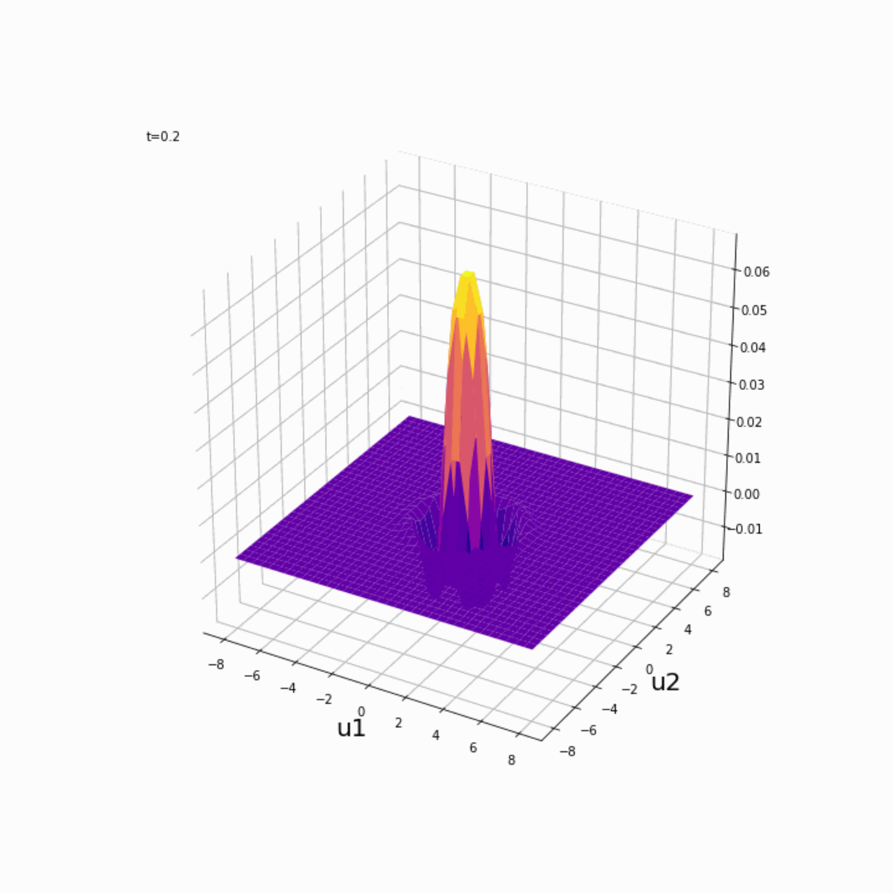

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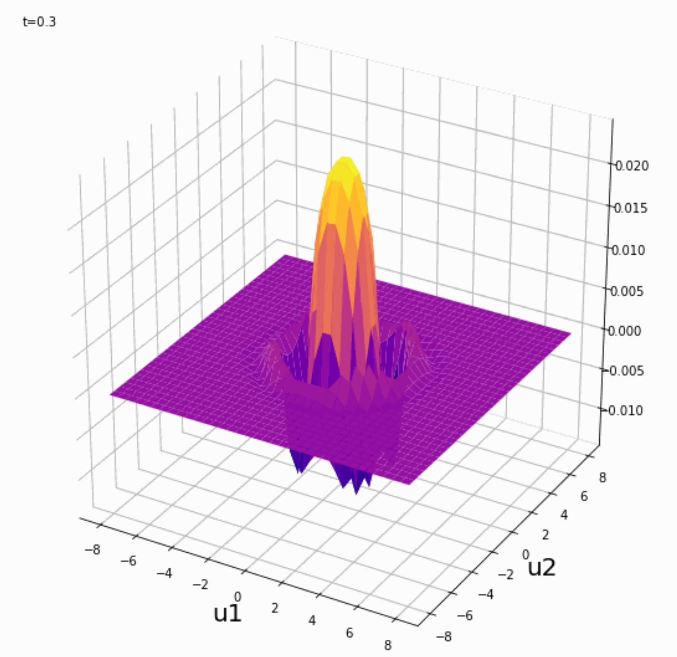

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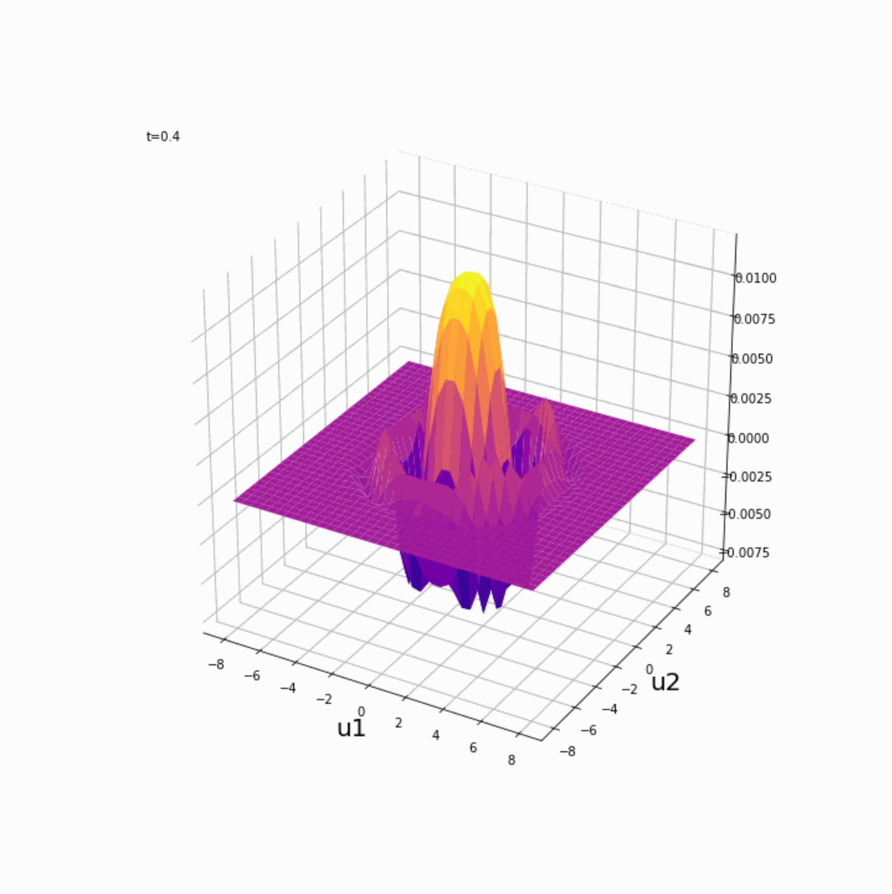

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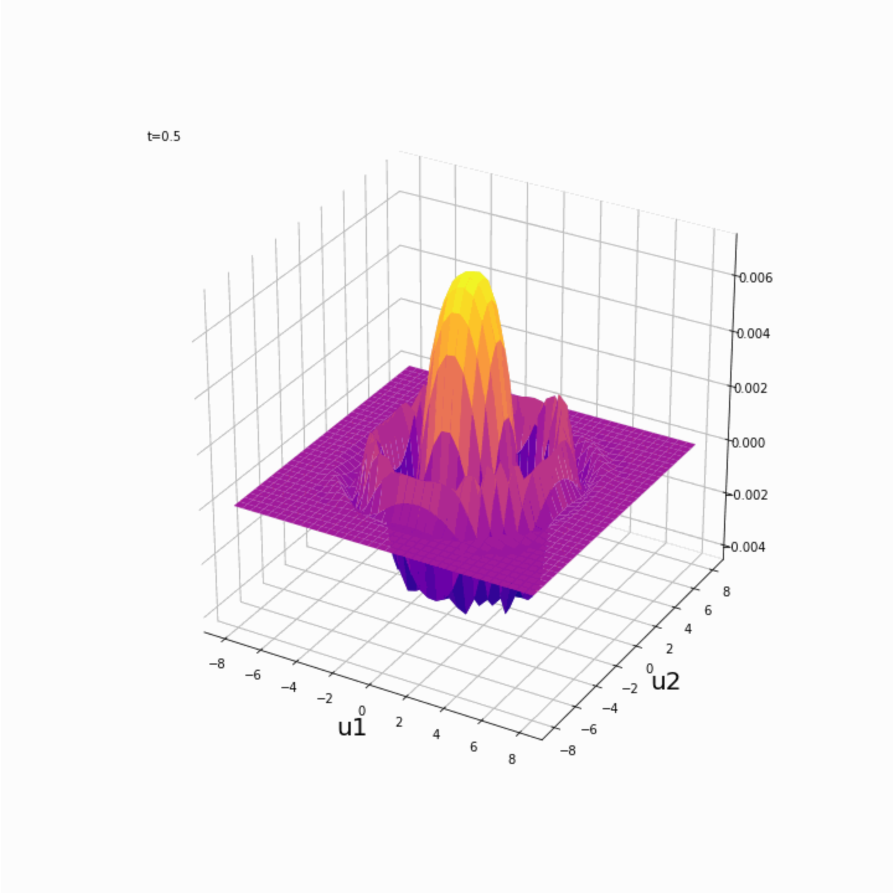

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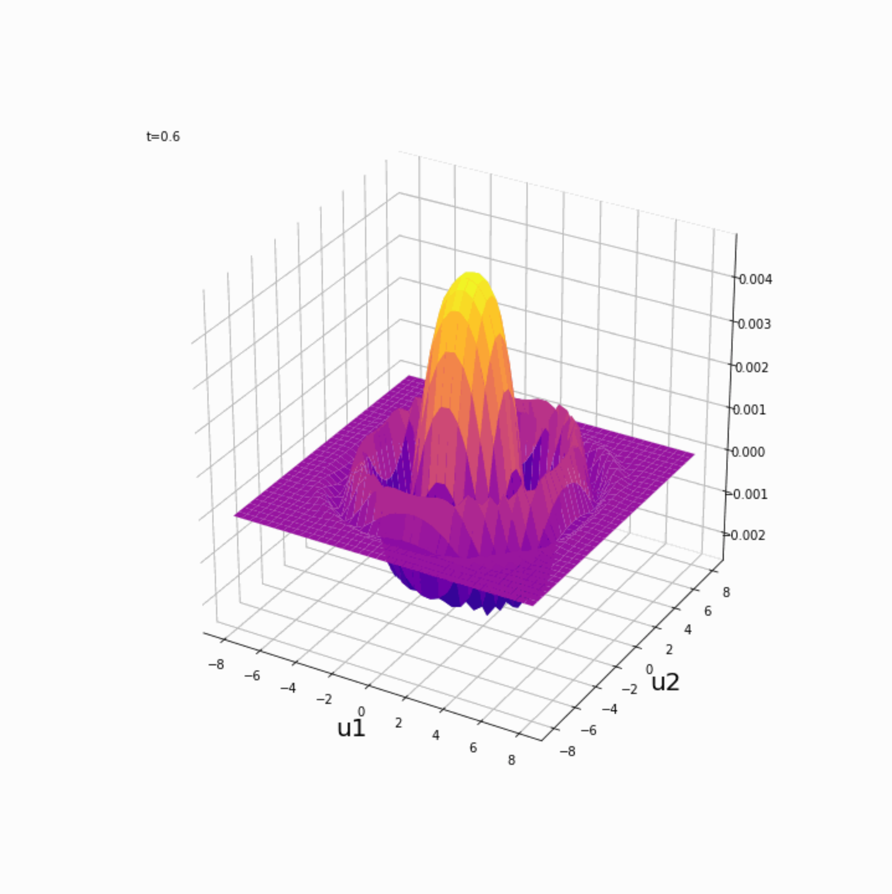

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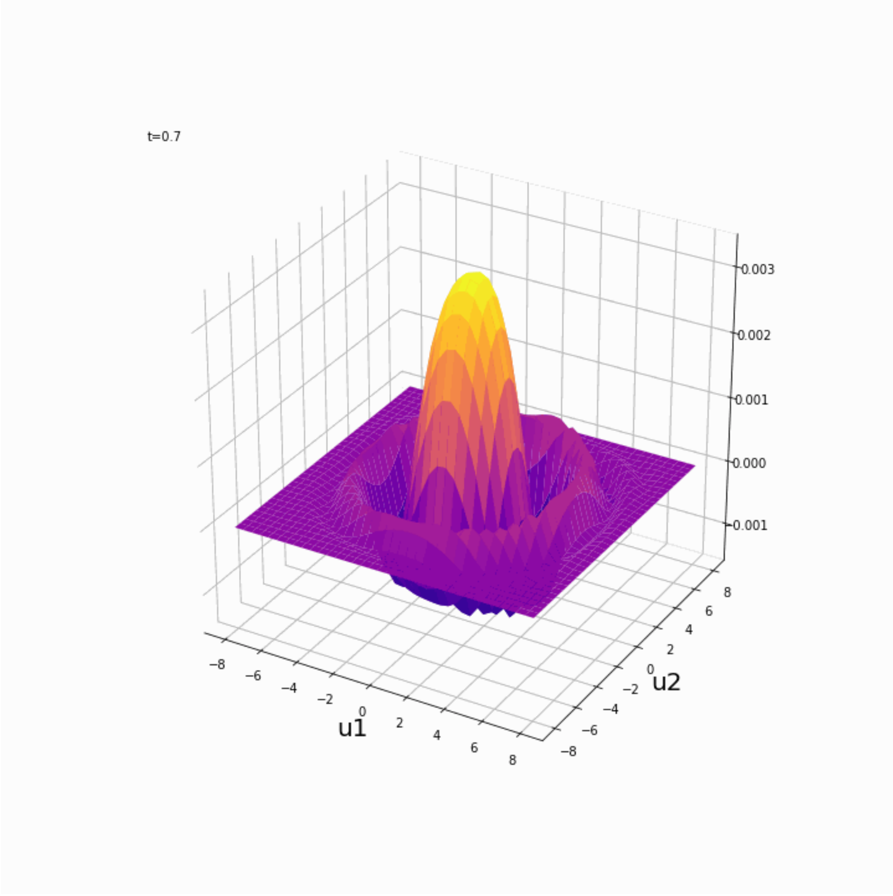

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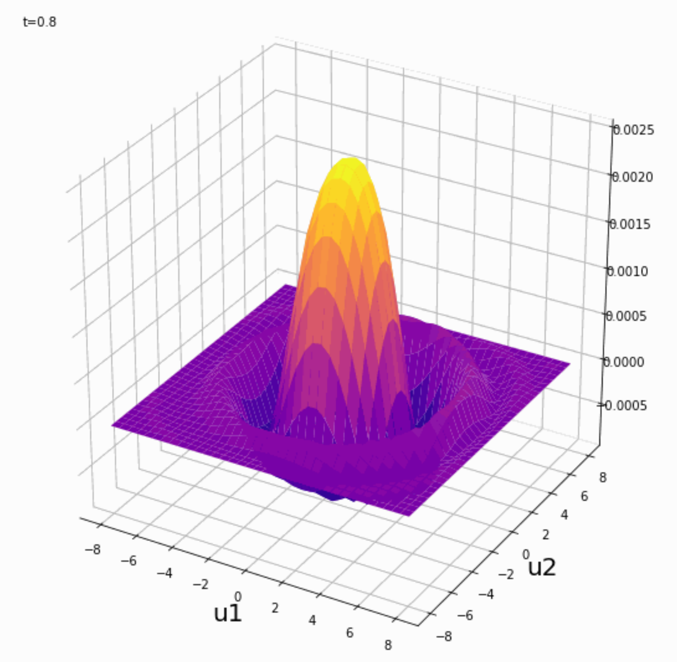

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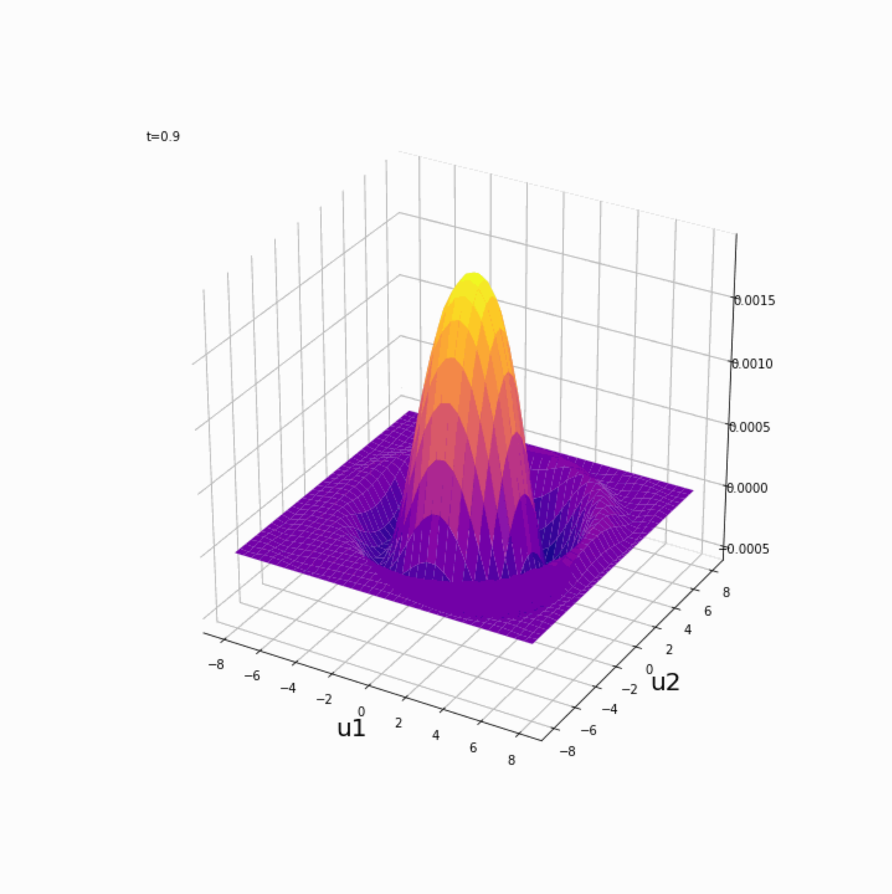

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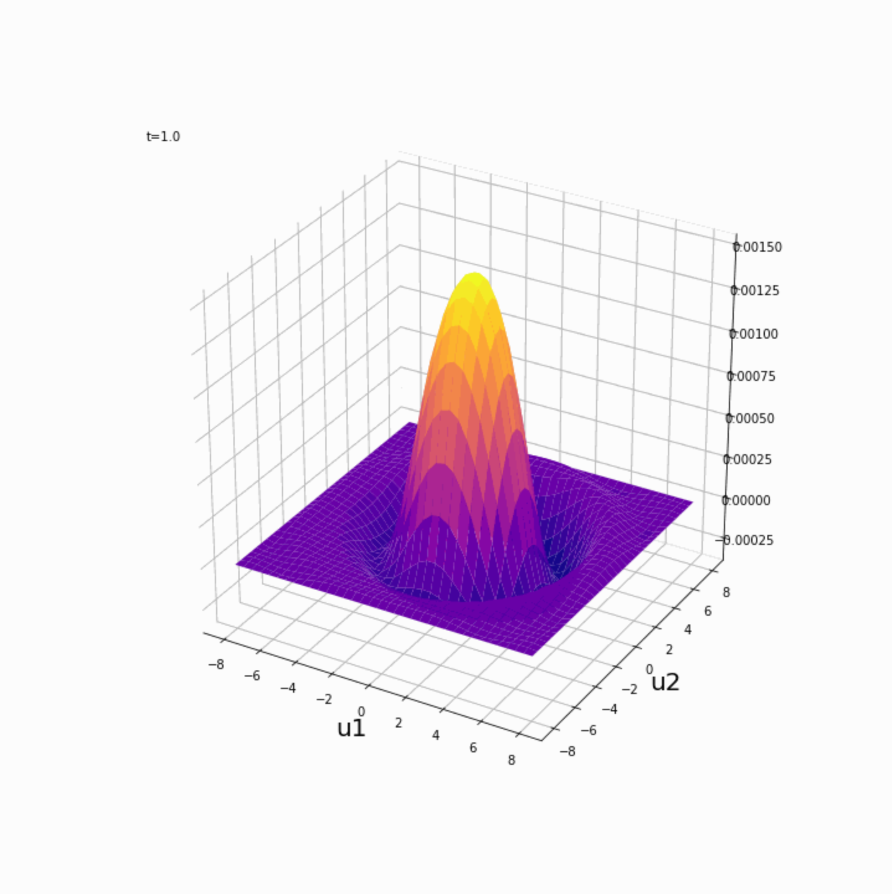

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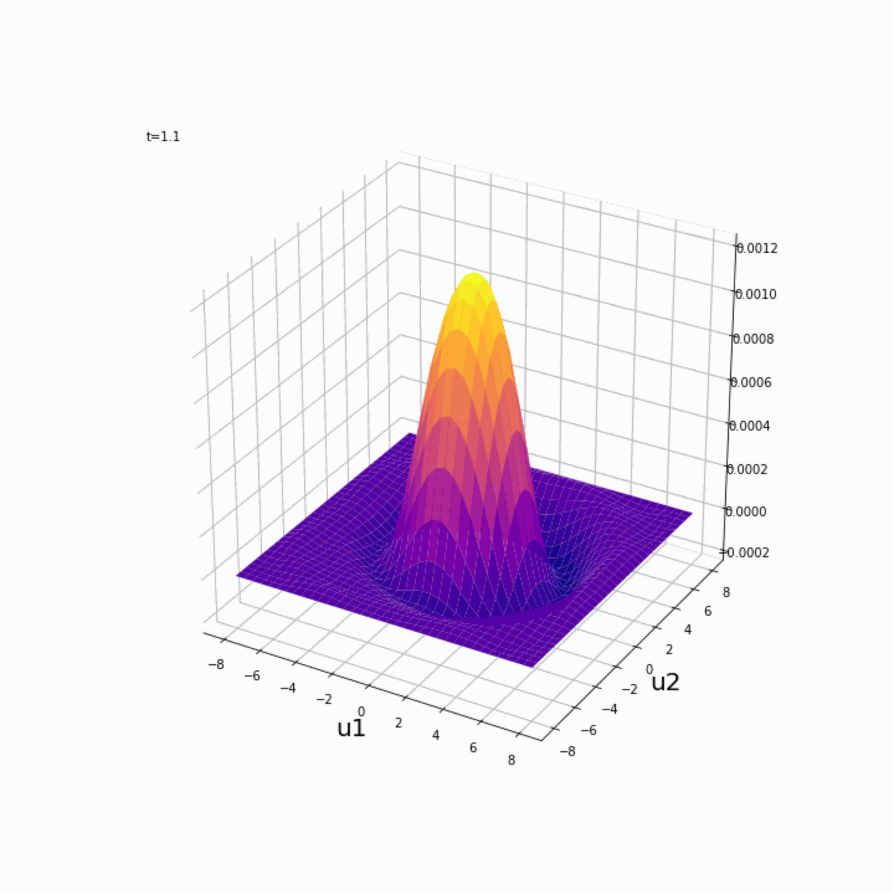

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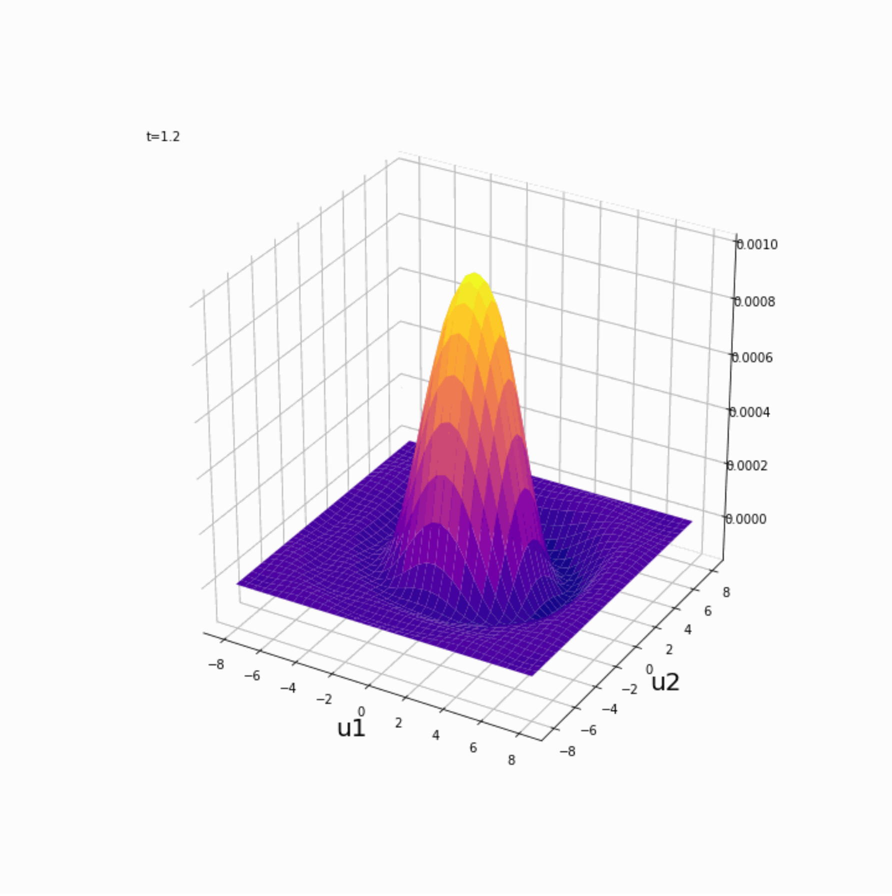

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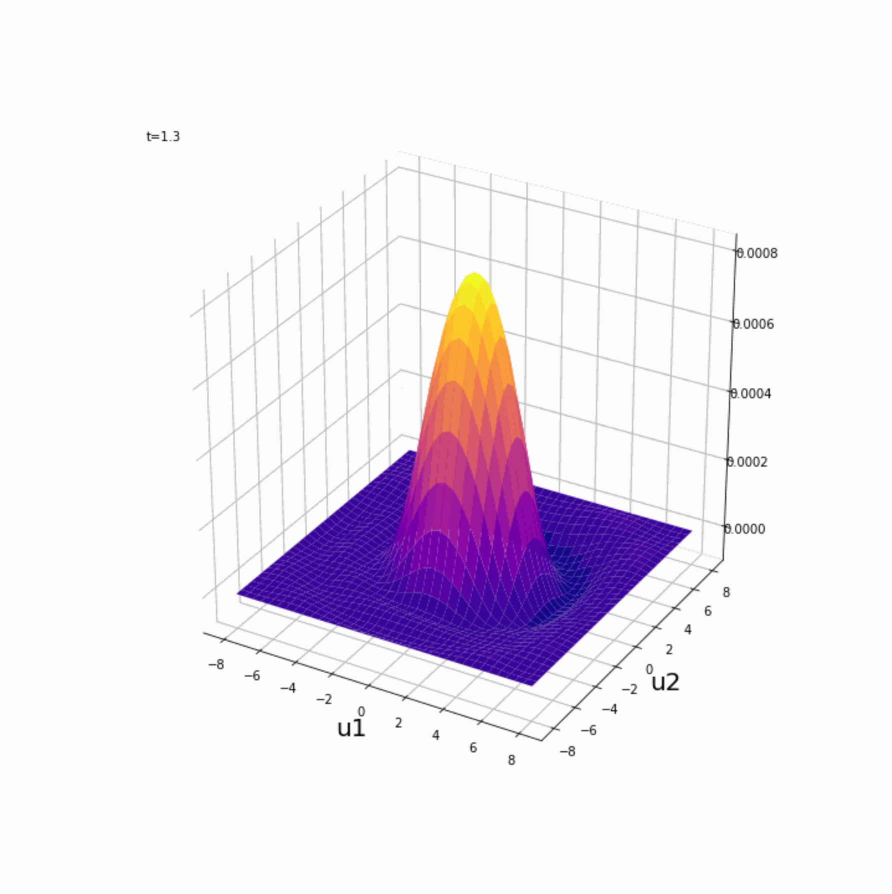

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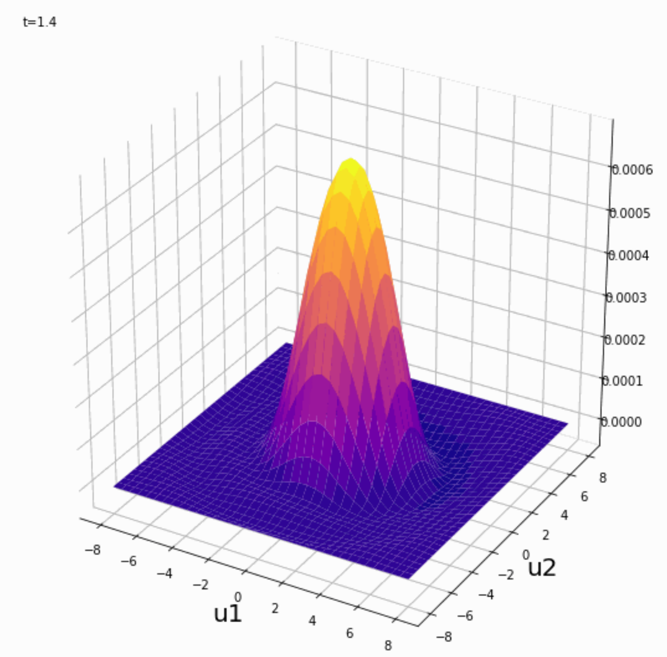

- Still some work left on numerics

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2. Calculate non-eikonal corrections **and** finite-Nc corrections
   - Theory
   - Numerics

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Conclusion and outlook

- People often use approximations to calculate medium-induced emissions
  - The large-Nc approximation
  - The Eikonal approximation
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Conclusion and outlook

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  - The large-Nc approximation
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- At finite Nc one must calculate Wilson line correlators
  - This can be transformed to a system of differential equations
  - Corrections are usually small, up to 16%

- For non-eikonal corrections one must calculate path integrals of Wilson line correlators
  - This can be transformed to a system of Schrödinger equations
  - Some numerical work remains to know the size of the corrections

Thank you for your attention!