# Towards a consistent picture of in-medium parton showering

Liliana Apolinário

Universidade de Santiago de Compostela
CENTRA-Instituto Superior Tecnico

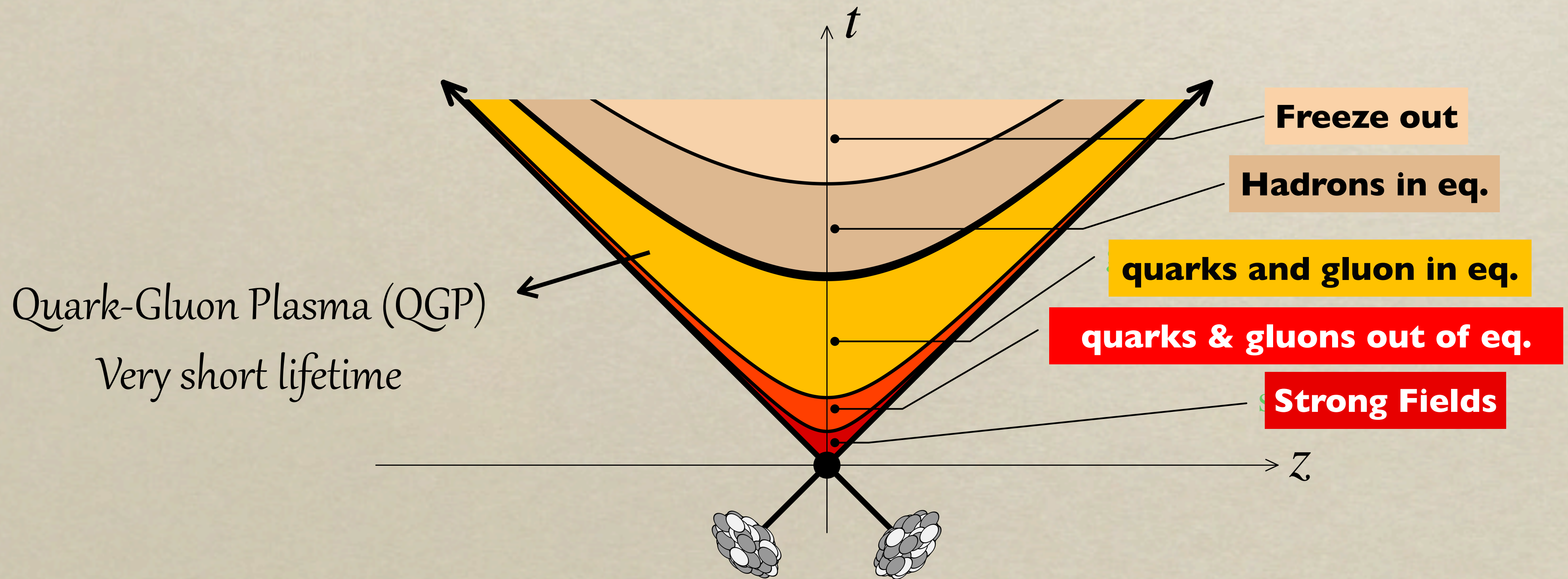
Néstor Armesto, Guilherme Milhano, Carlos Salgado

(Preprint in preparation.....)

# Introduction

- Heavy-ion collisions:
  - Production of the Quark-Gluon Plasma ➡ Opportunity to study QCD in a regime that is usually not accessible perturbatively;

    ➡ Lifetime very short ➡ Use of self generated probes!



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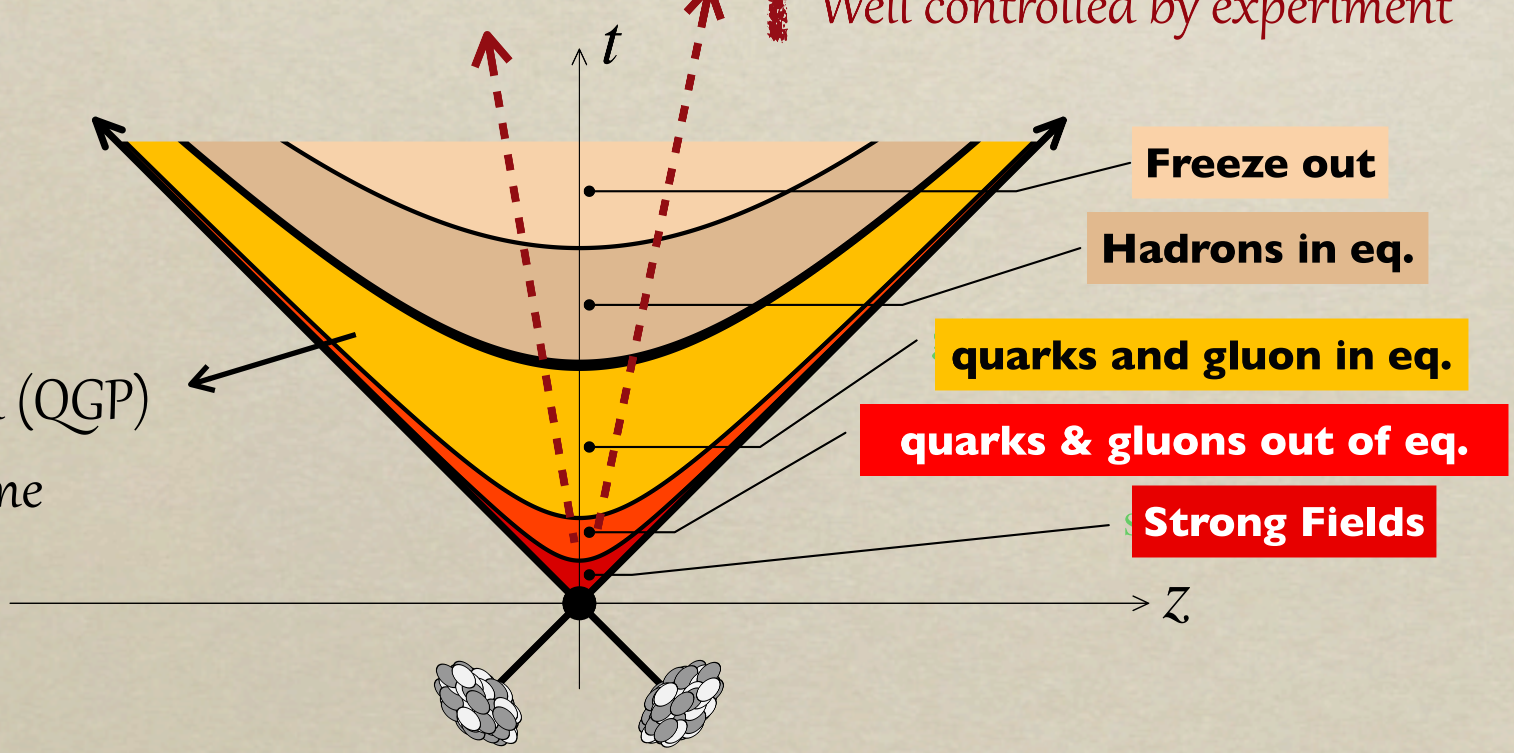
Hard Probes

- Describable by pQCD
- Initial state modifications under control
- Well controlled by experiment



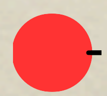

Quark-Gluon Plasma (QGP)

Very short lifetime

# Introduction

- Production of hard probes:

Hard Scattering
(matrix element)



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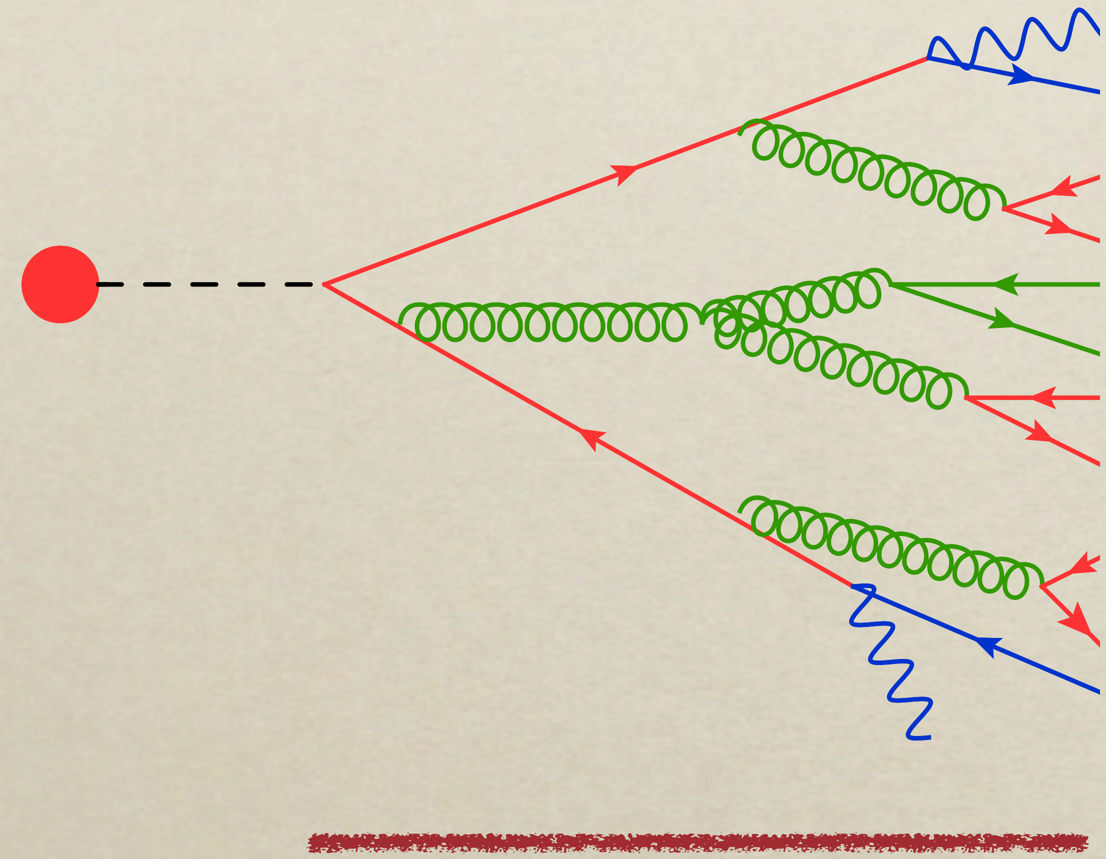

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- Calculable through pQCD
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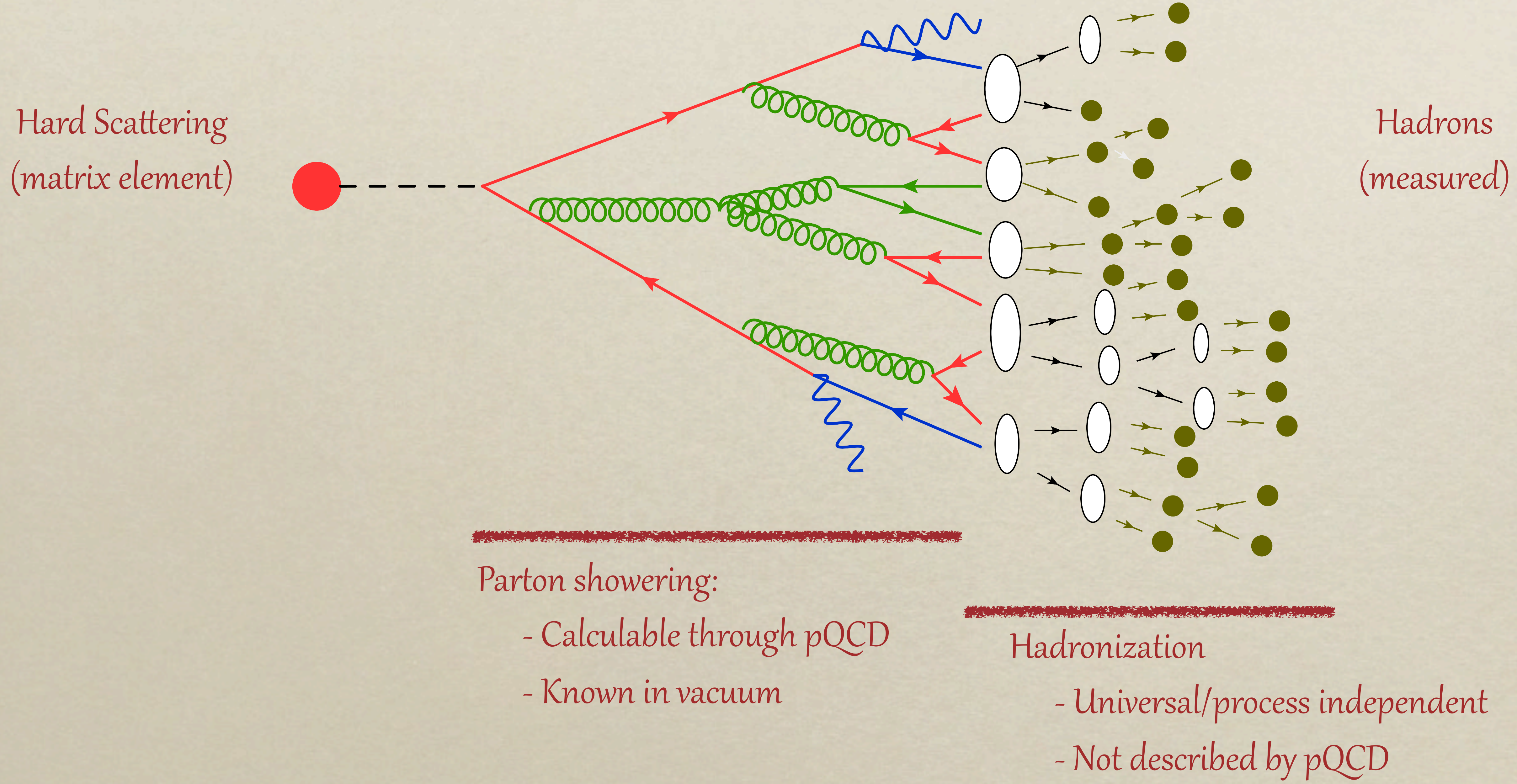

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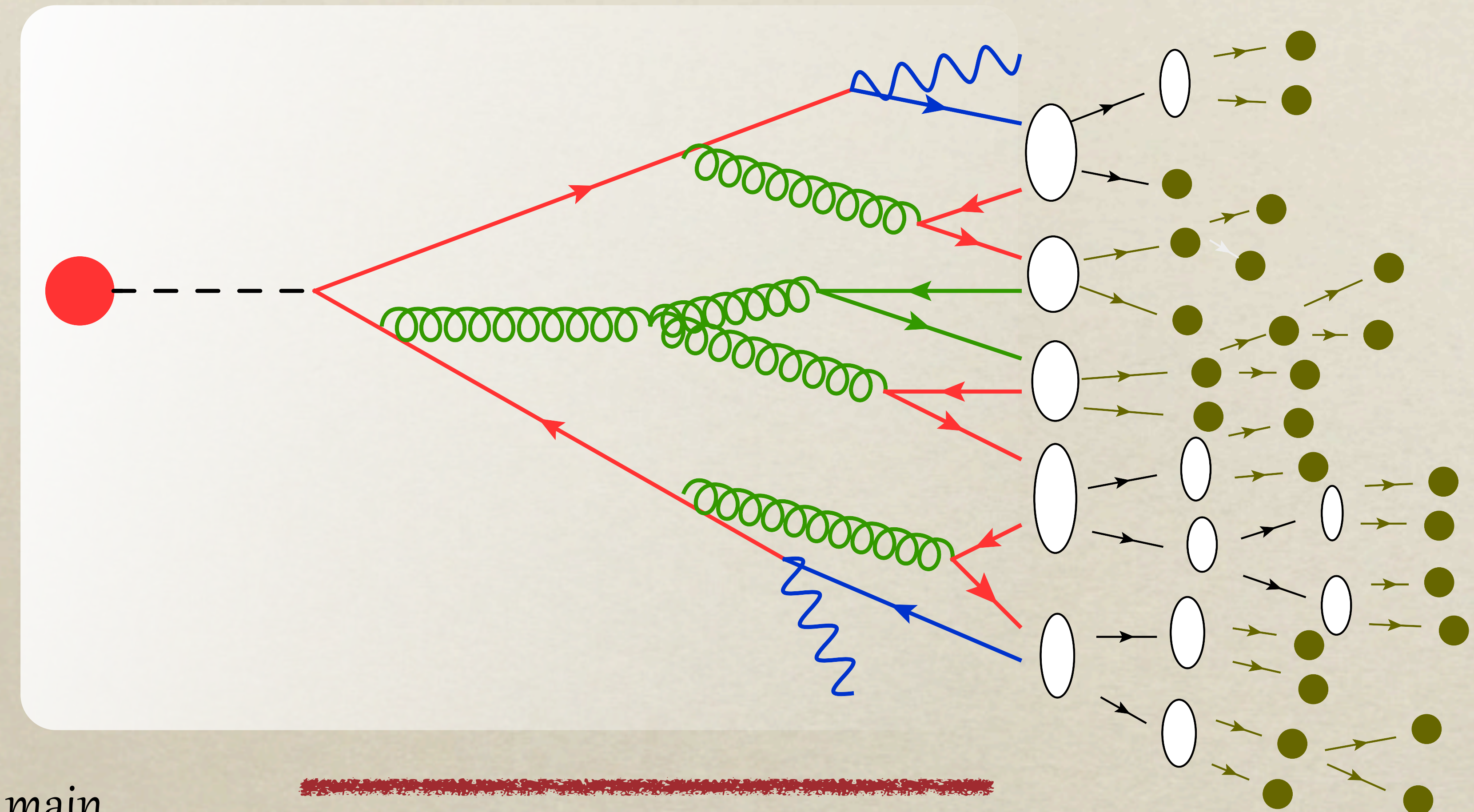

Hadrons
(measured)

Medium

What are the main mechanisms of in-medium energy loss (Jet Quenching)?

Parton showering:
- Calculable through pQCD
- Known in vacuum
- Medium?

Hadronization
- Universal/process independent
- Not described by pQCD
- Assumed to be outside the medium

# Motivation

- Energy loss processes in PbPb collisions?
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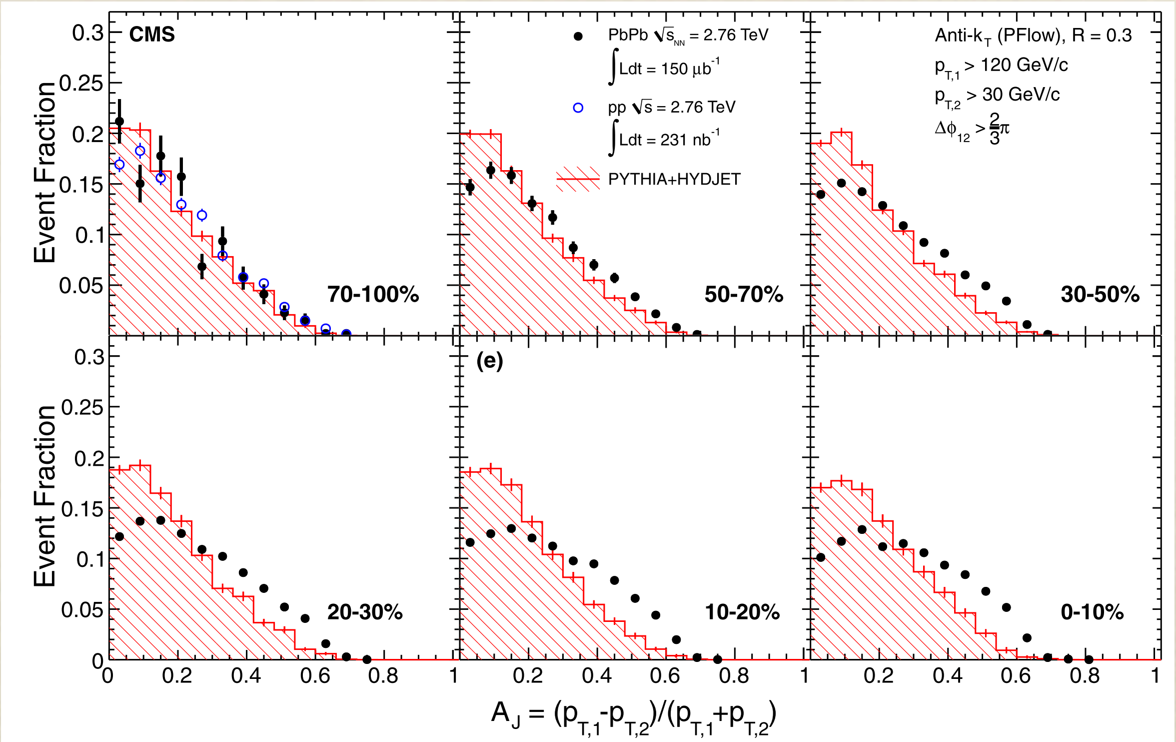
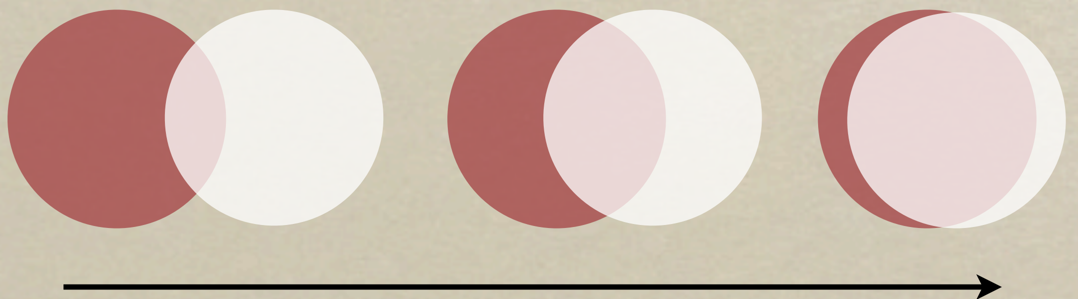
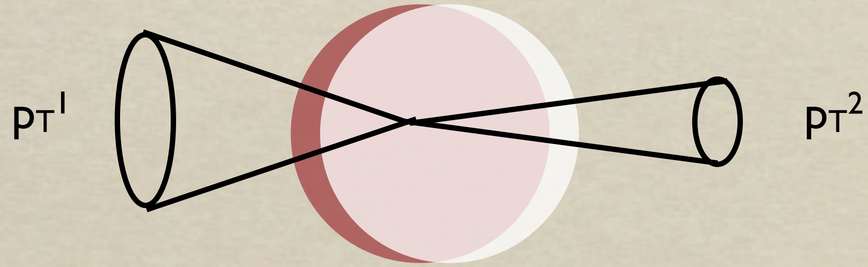



$$A_J = \frac{p_T^1 - p_T^2}{p_T^1 + p_T^2}$$



Increasing centrality




Transverse momentum of the jets

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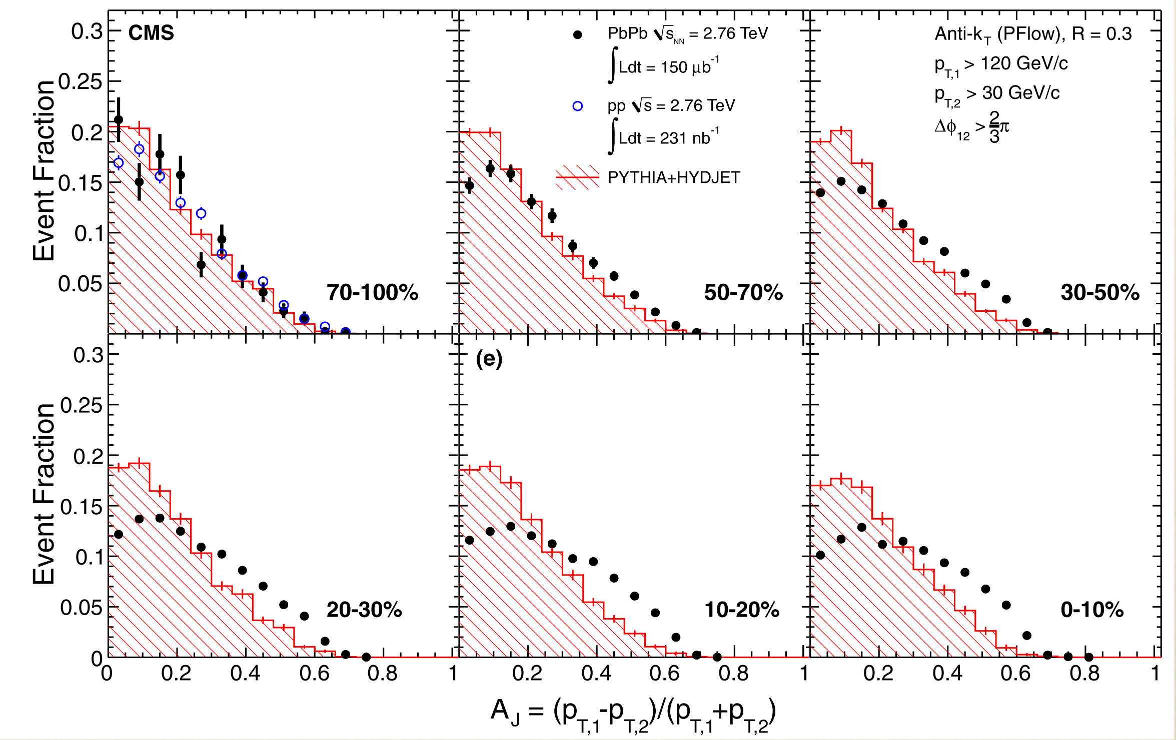


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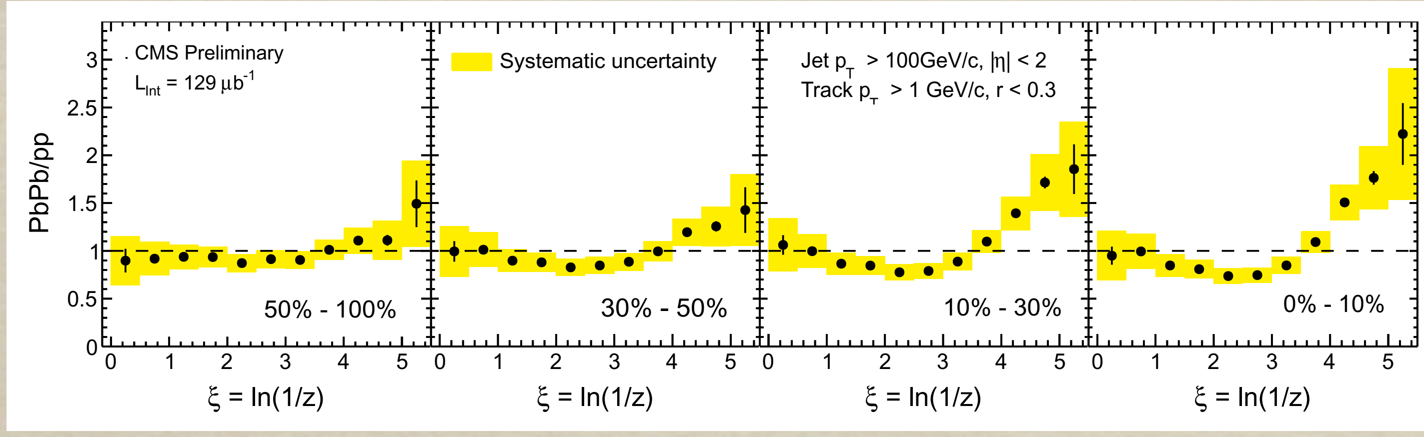
$$\xi = \ln\left(\frac{1}{z}\right) \quad , \quad z = \frac{p_{\parallel}^{tr}}{p^{jet}}$$



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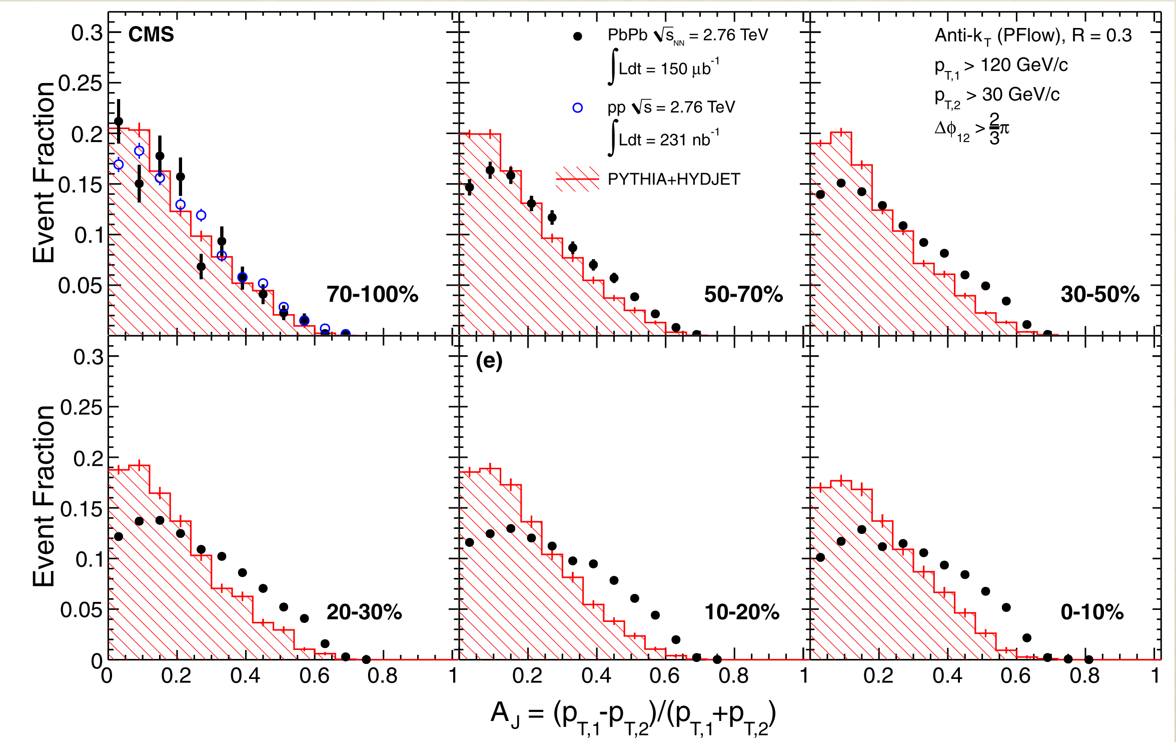


➟ Important to have a good description of energy loss mechanisms

⬇

Particularly relevant for Monte Carlo codes
(usually employ phenomenological assumptions without a firm theoretical basis)

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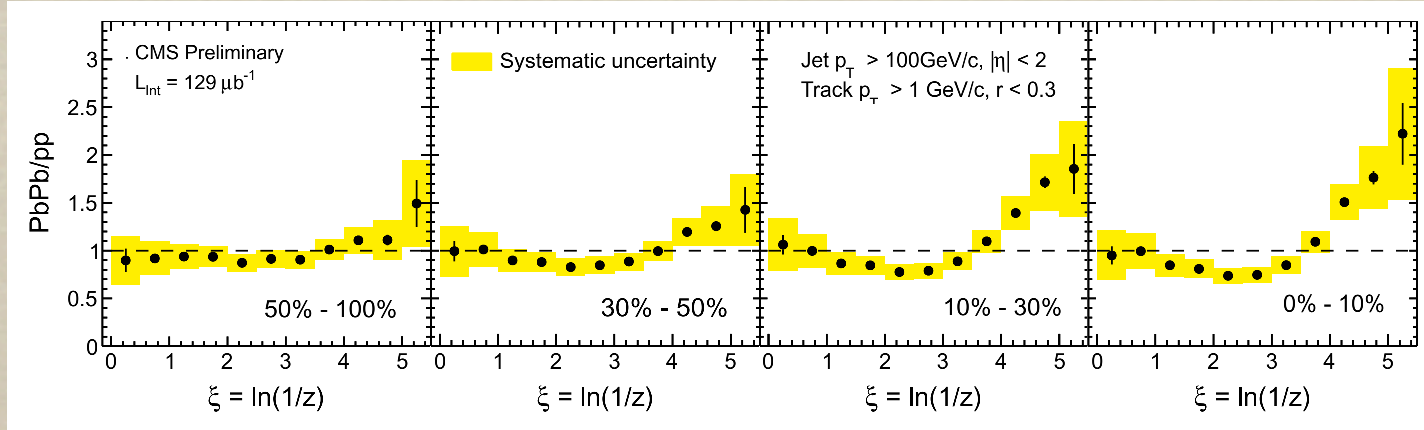


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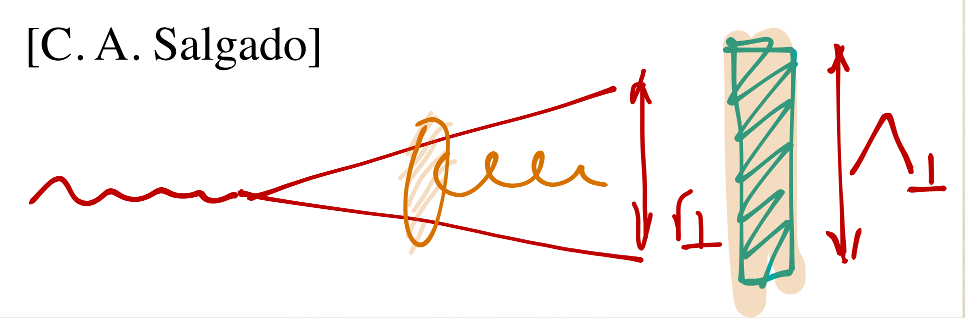

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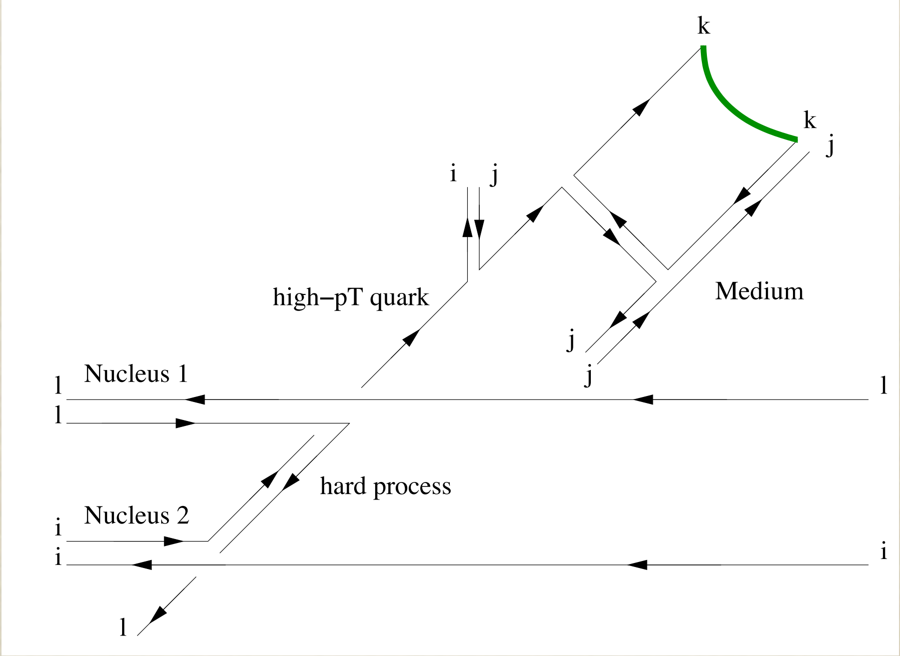

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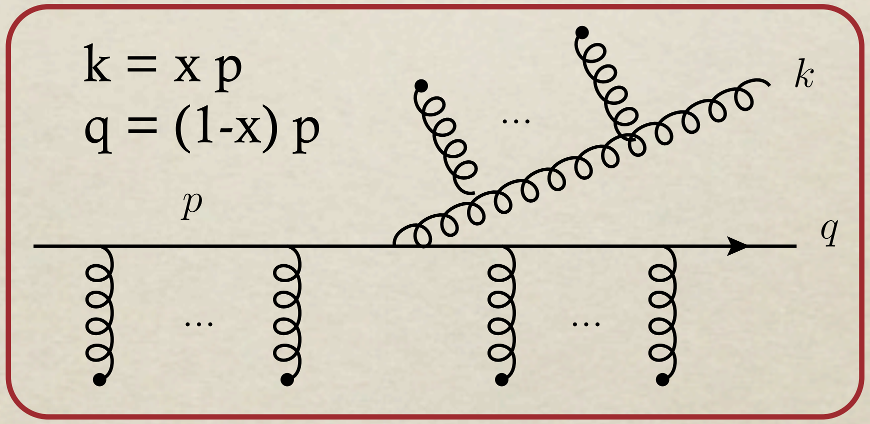

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Path-integral formalism (arXiv: 1204.2929, 1209.4585):

Interpolation function between soft and hard gluon radiation limits

Most energetic particle still constrained in the transverse plane

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Gluon branching beyond eikonal approximation but small formation times

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- This work: gluon radiation without constrains on the formation time (finite medium)

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  - Propagation timescale of energetic partons << Characteristic time of changes in the configuration of the medium;
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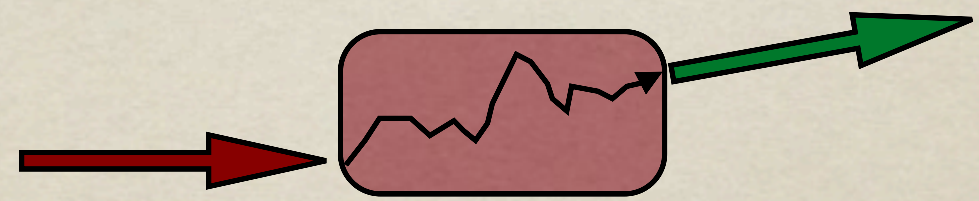

Initial/Final transverse coordinates — Path-Integral — Longitudinal particle momentum — Wilson Line

$$G(x_{0+},\mathbf{x}_0;L_+,\mathbf{x}|p_+) = \int_{\mathbf{r}(x_{0+})=\mathbf{x}_0}^{\mathbf{r}(L_+)=\mathbf{x}} \mathcal{D}\mathbf{r}(\xi)\exp\left\{\frac{ip_+}{2}\int_{x_{0+}}^{L_+} d\xi \left(\frac{d\mathbf{r}}{d\xi}\right)^2\right\} W(x_{0+},L_+;\mathbf{r}(\xi))$$

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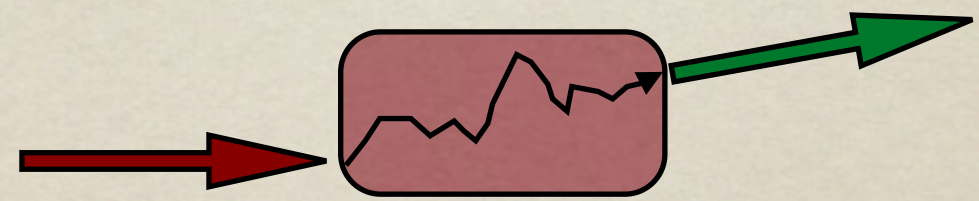

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Medium longitudinal boundaries

where $W(x_{0+}, L_+; \mathbf{x}) = \mathcal{P} \exp\left\{ ig \int_{x_{0+}}^{L_+} dx_+ A_-(x_+, \mathbf{x}) \right\}$

Path-ordering

Medium color field

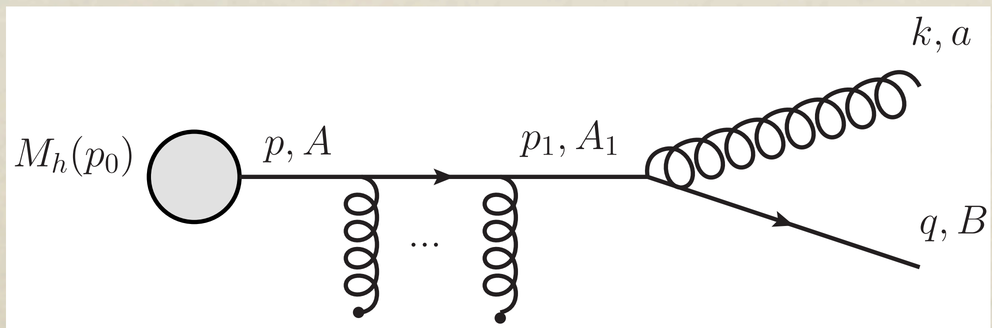
Brownian Motion

Color Rotation

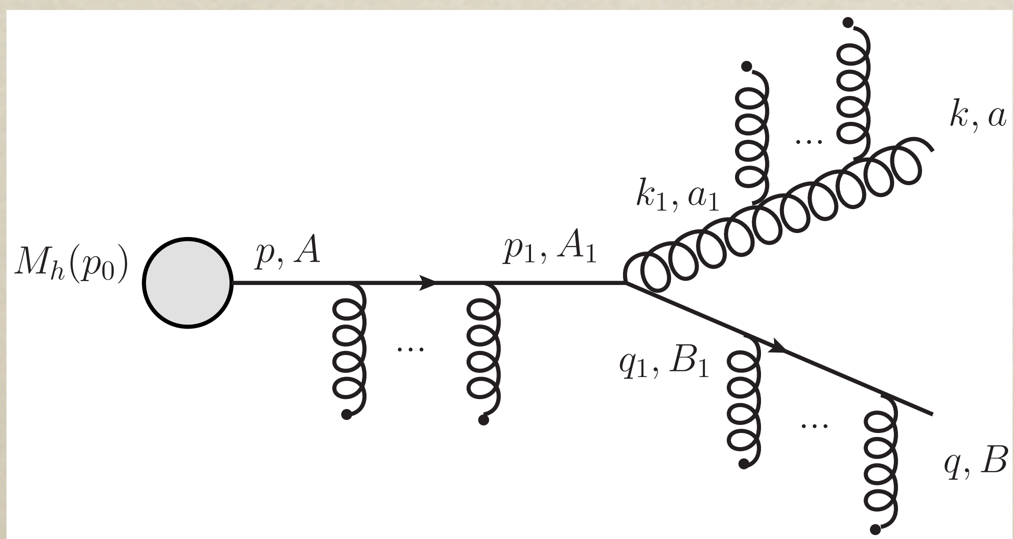
# Gluon emission spectrum

- Finite medium ➟ 2 configurations

$\mathcal{T}_{out} =$




$\mathcal{T}_{in} =$




Kinematics:

$k_+ = z\, p_+ \quad k_T = \mathbf{k}$

$q_+ = (1\text{-}z)\, p_+ \quad q_T = \mathbf{q}$

$|...| \equiv$ *Average over initial spin, color and gluon polarization*

$< ... > \equiv$ Medium averages

- Emission cross section:

$$\frac{d^2\sigma}{d\Omega_k\, d\Omega_q} = \langle |\mathcal{T}_{tot}|^2 \rangle \;, \quad \text{where} \quad |\mathcal{T}_{tot}|^2 = |\mathcal{T}_{out}|^2 + |\mathcal{T}_{in}|^2 + 2\mathrm{Re}\left\{\mathcal{T}_{in}\mathcal{T}_{out}^{\dagger}\right\}$$

$$d\Omega_k = \frac{d\mathbf{k}}{(2\pi)^3}\frac{dk_+}{2k_+}$$

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- High energy limit ➠ Medium averages can be performed locally

  ➠ Decomposition into regions where the number of Wilson lines is fixed

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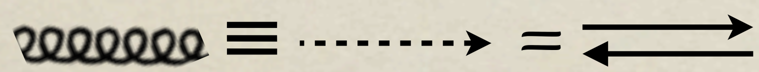
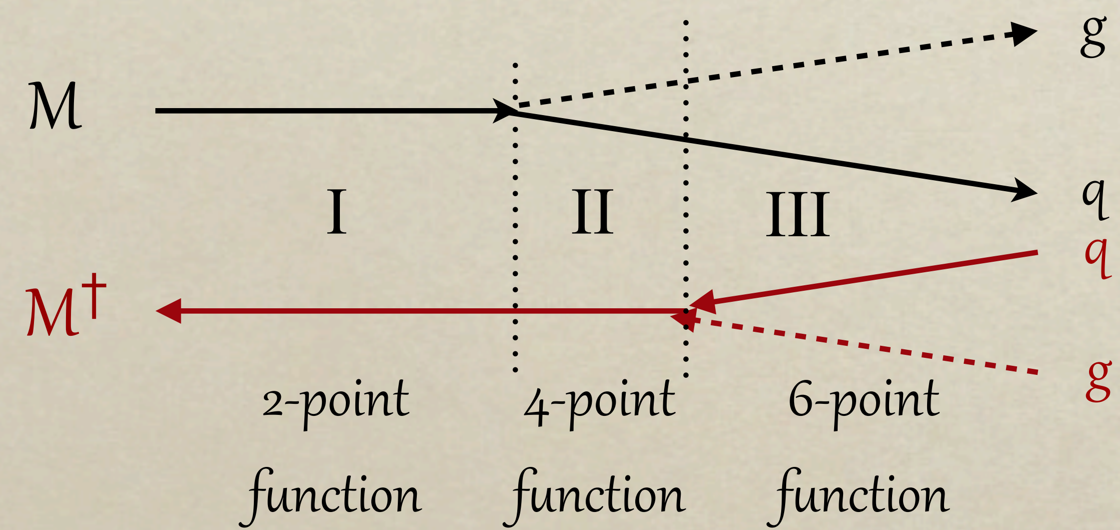
- Large $N_c$ limit ➟ 



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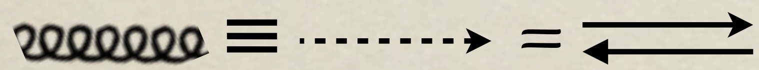
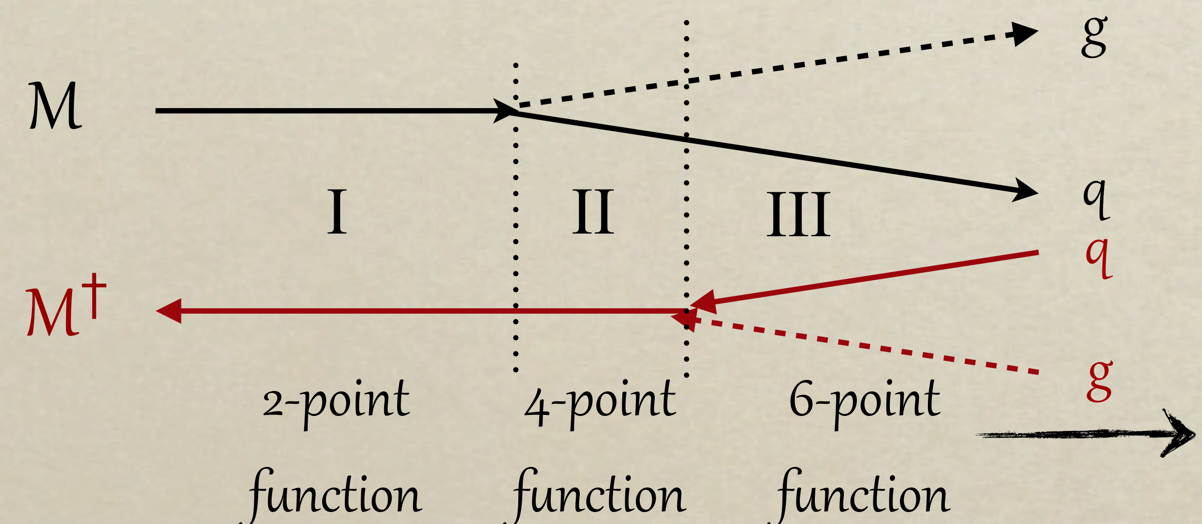
- Large $N_c$ limit ➟ 




Correlators calculated by doing an infinitesimal expansion up to 2nd order of the fields:

$$W_{ij}(L_+, x_+; \mathbf{x}) = V_{i\alpha}(L_+, \zeta; \mathbf{x}) \left[ \delta_{\alpha j} \left( 1 - \frac{C_F}{2} B(\zeta, \mathbf{0}) \right) + i T^a_{\alpha j} A^a_{\alpha j}(\zeta, \mathbf{x}) \right]$$

with $\delta^{ab} B(x_+, \mathbf{x} - \mathbf{y}) = \langle A^a(x_+, \mathbf{x}) A^b(x_+, \mathbf{y}) \rangle$

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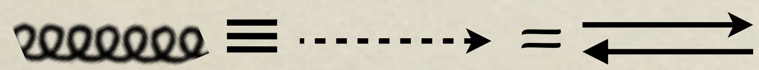
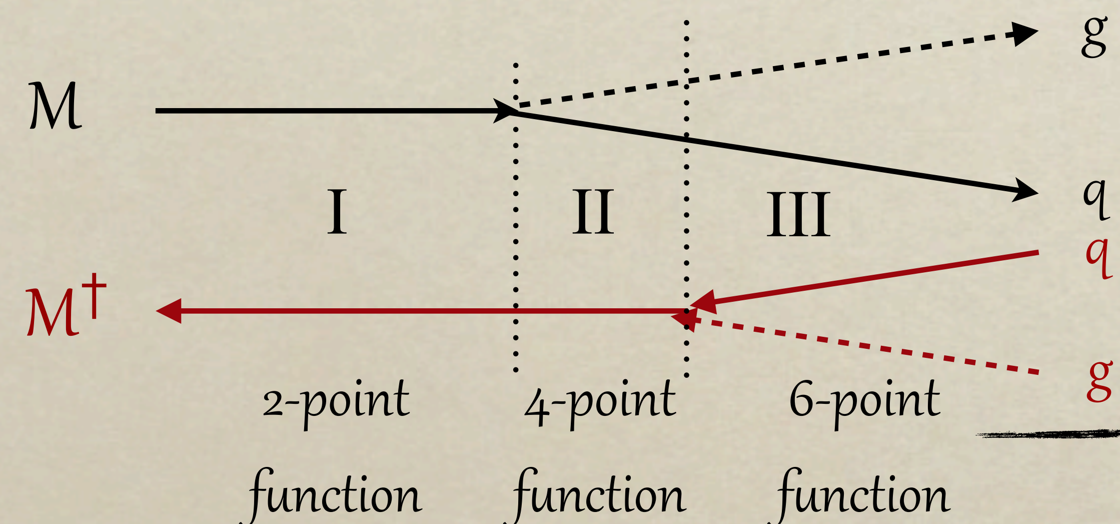
- Large $N_c$ limit ➡ 

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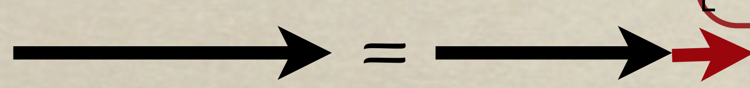

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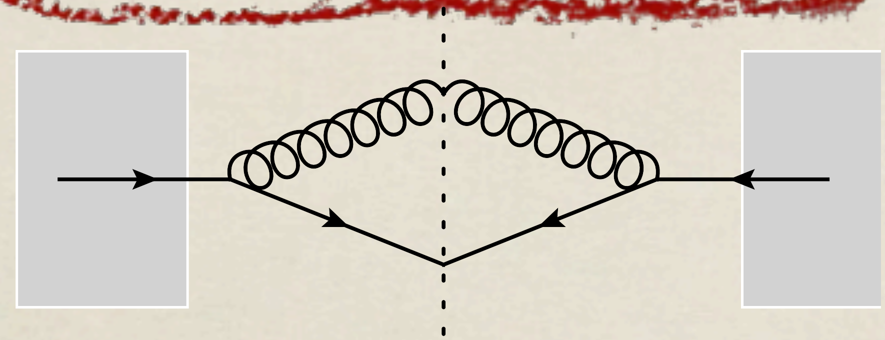
# Results

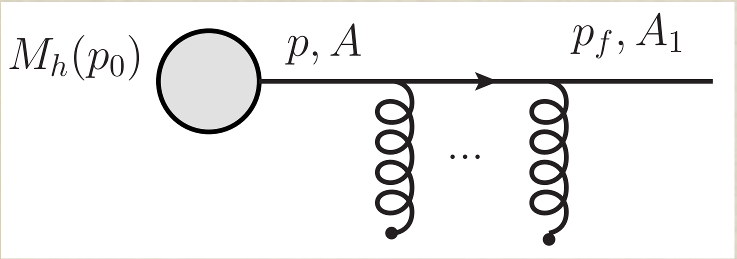
- Out-out term: $|\mathcal{T}_{out}|^2$



$$\frac{d^2 I_{out}}{d\Omega_q \Omega_k} = \frac{1}{\sigma_{el}} \frac{d^2\sigma_{out}}{d\Omega_q d\Omega_k} =$$

$$= g^2(2\pi)^3 \frac{4z(1-z)p_{0+}}{((1-z)\mathbf{k} - z\mathbf{q})^2} P_{g\leftarrow q}(z) P(\mathbf{p}_0 \to \mathbf{k}+\mathbf{q})\delta(k+q-p_0)_+$$

where $\sigma_{el} =$




Brownian motion of the initial quark

$$P(\mathbf{p}_0 \to \mathbf{p}_f) = \frac{1}{\pi(L_+ - x_{0+})\hat{q}_F} \exp\left\{ -\frac{(\mathbf{p}_f - \mathbf{p}_0)^2}{(L_+ - x_{0+})\hat{q}_F} \right\}$$

Transverse momentum broadening

Transport coefficient: $\hat{q} = \frac{\langle \mathbf{k}^2 \rangle}{\lambda}$

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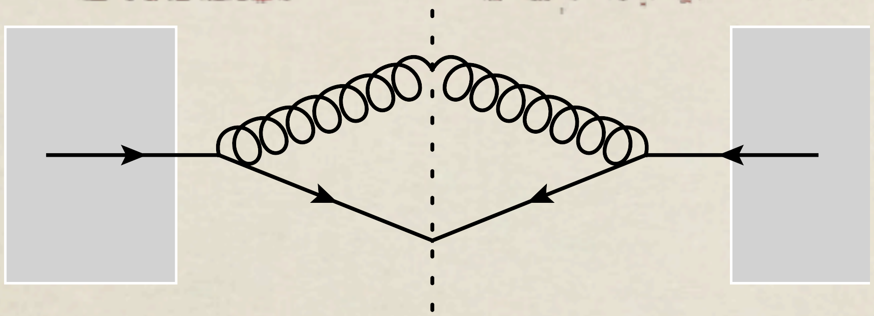

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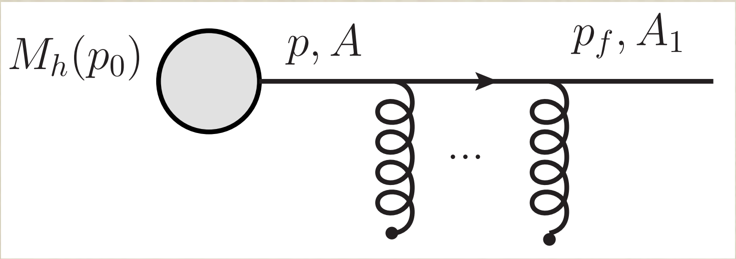
where $\sigma_{el} =$ 

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Transport coefficient: $\hat{q} = \frac{\langle \mathbf{k}^2 \rangle}{\lambda}$

- Taking the limit $\hat{q}_F L_+ \to 0$ (no medium) and integrating over $d\Omega_q$:

$$\left.\frac{d^2 I_{out}}{dz\, d\mathbf{k}}\right|_{\hat{q}_F L_+ \to 0} = \frac{d^2 I_{vac}}{dz\, d\mathbf{k}} = \frac{\alpha_s}{2\pi^2} \frac{1}{\mathbf{k}^2} P_{g\leftarrow q}(z)$$

➠ Complete vacuum radiation spectrum is recovered!

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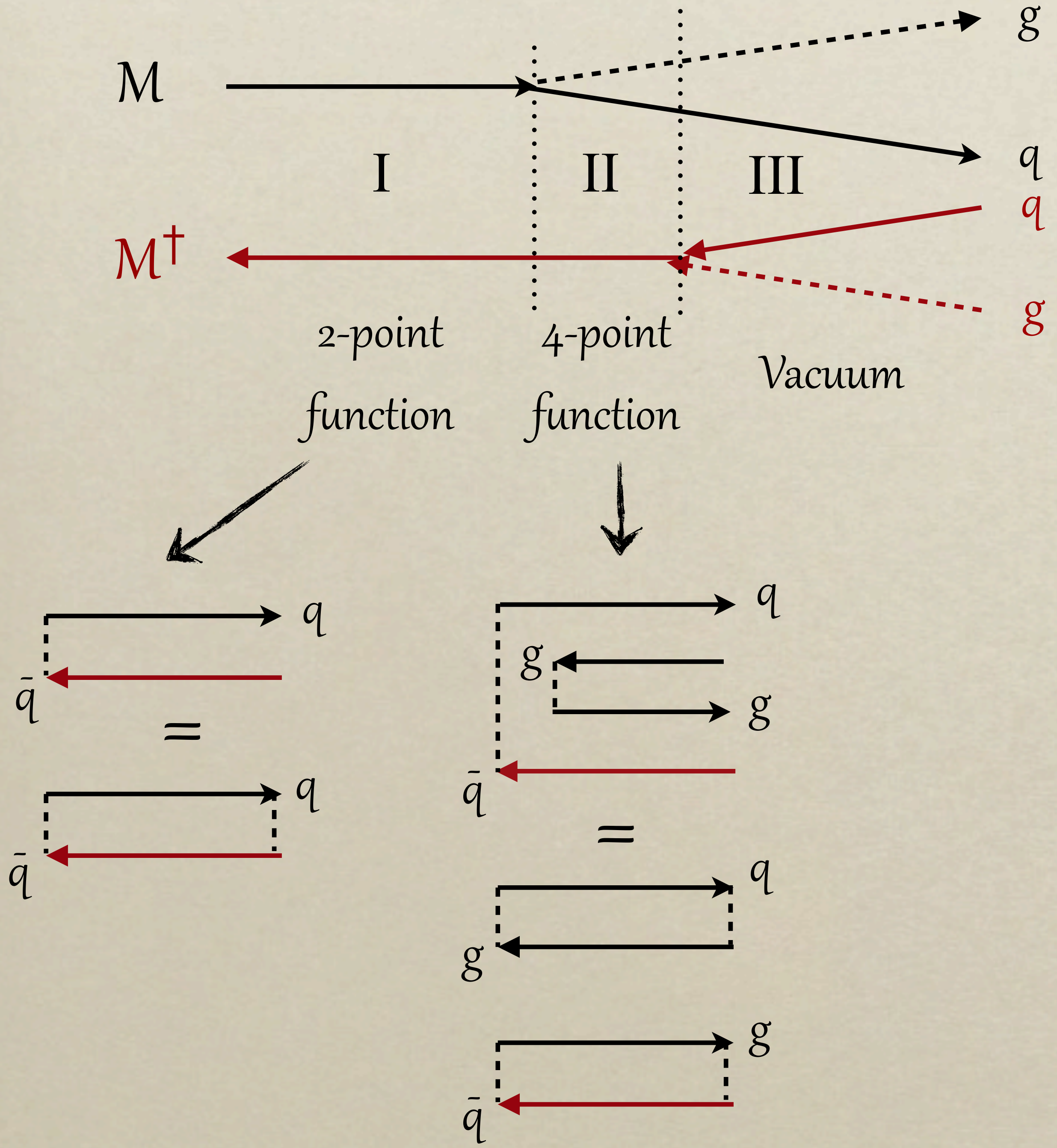
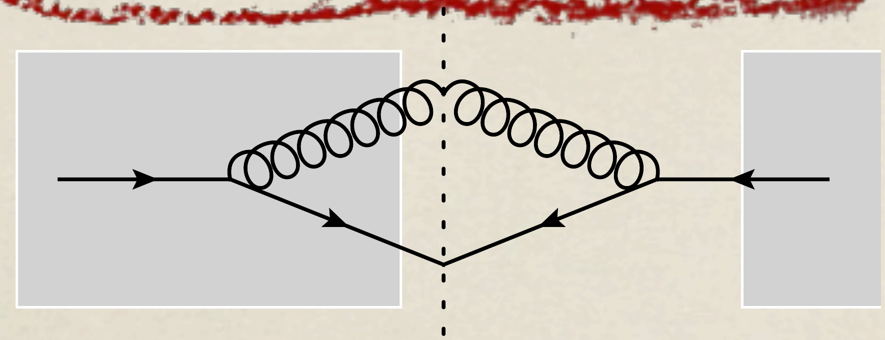
- "Medium" term: in-out contribution



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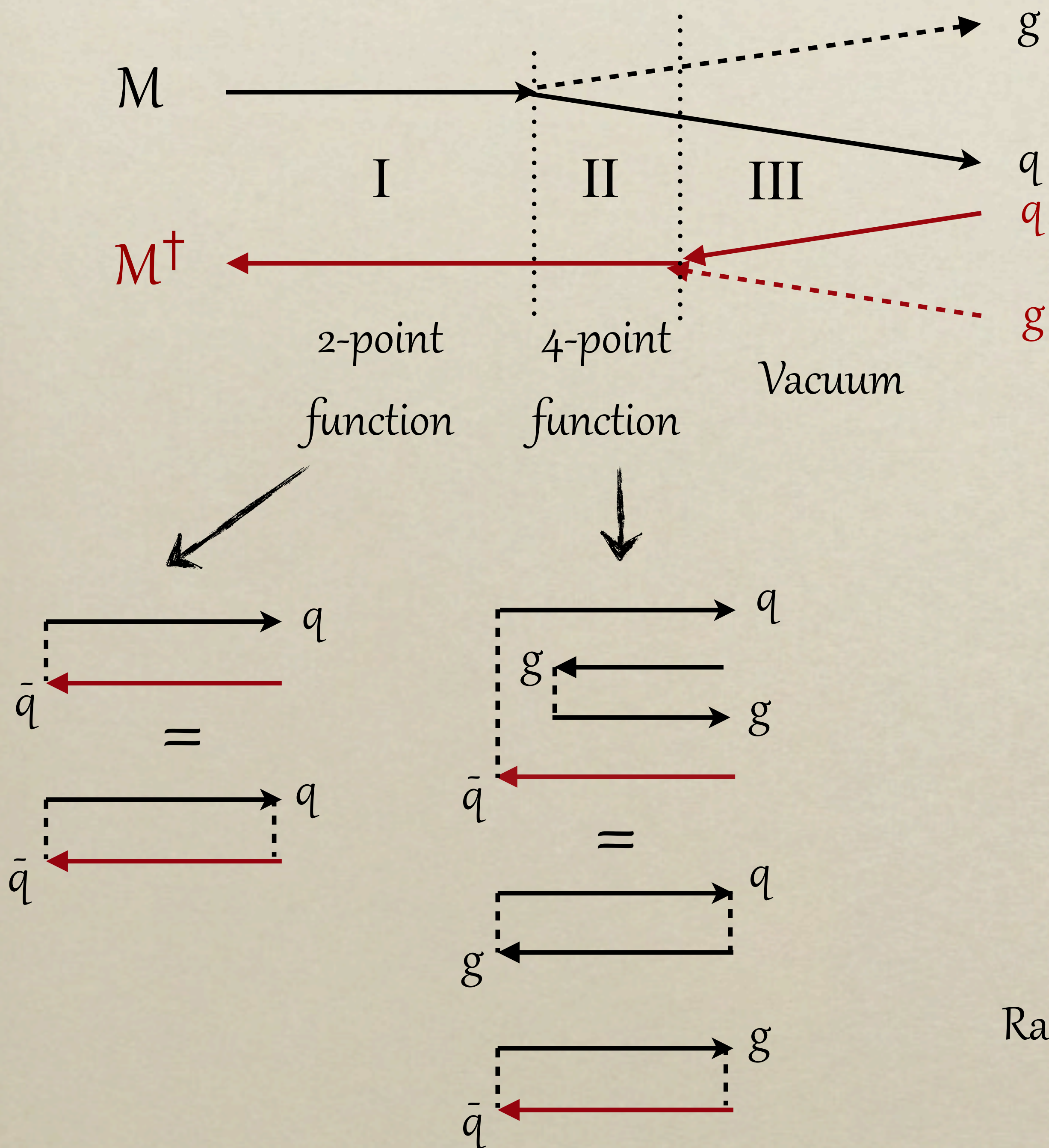
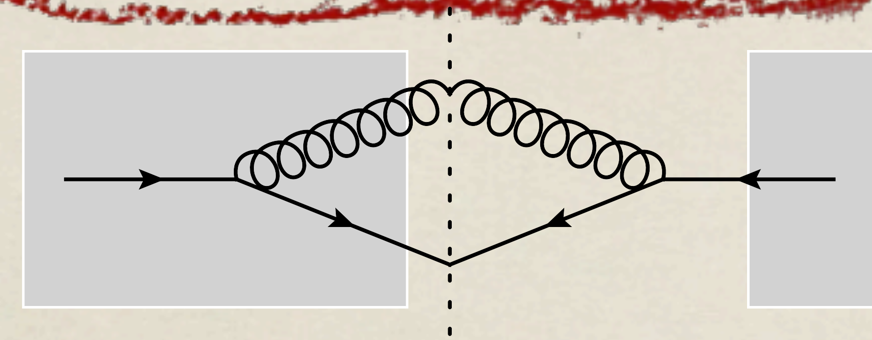
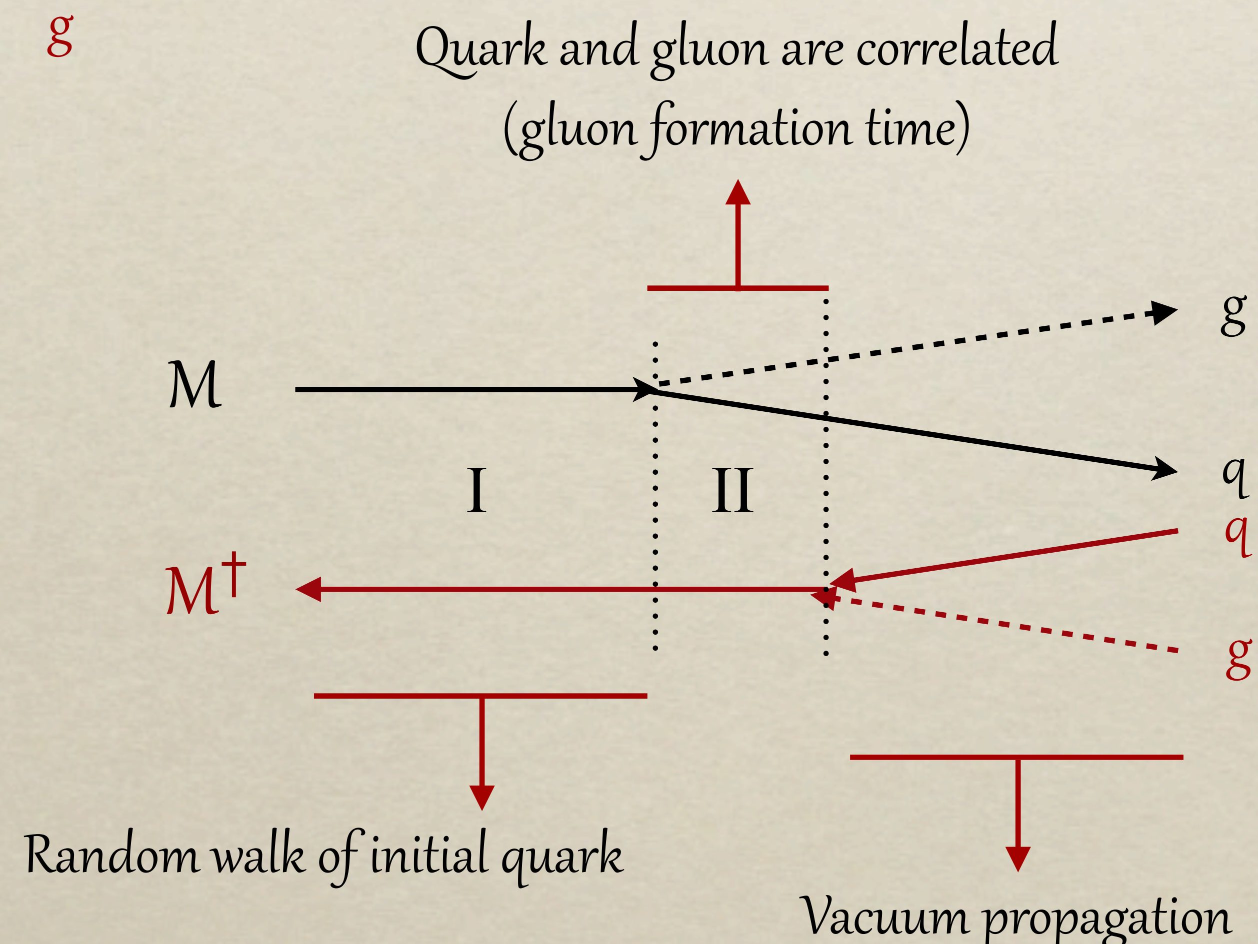
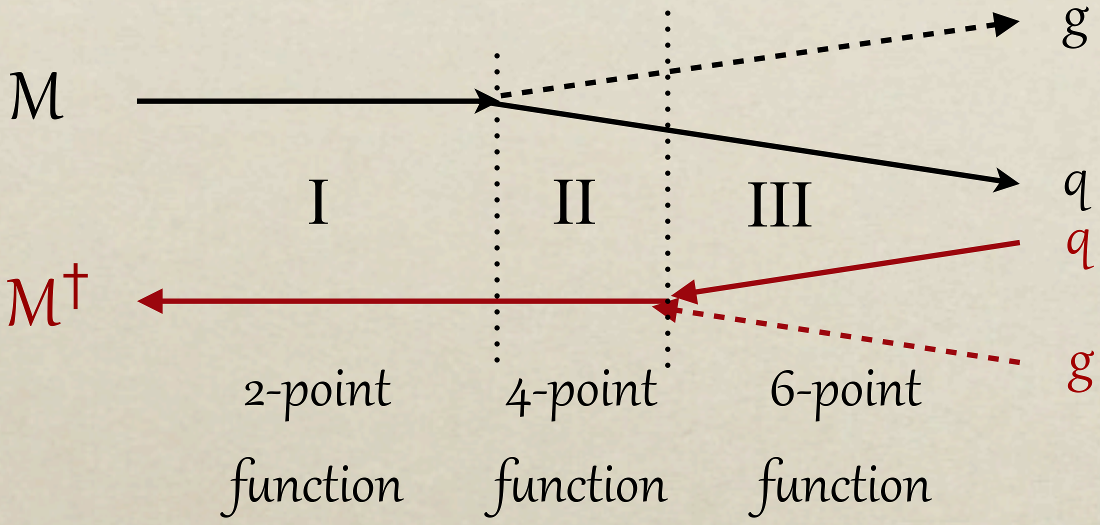


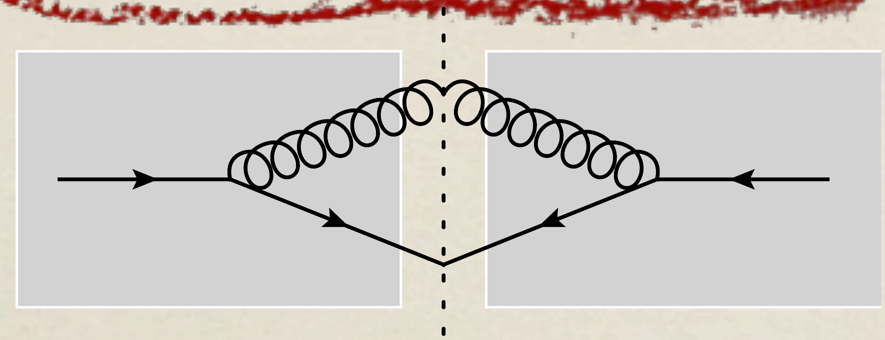



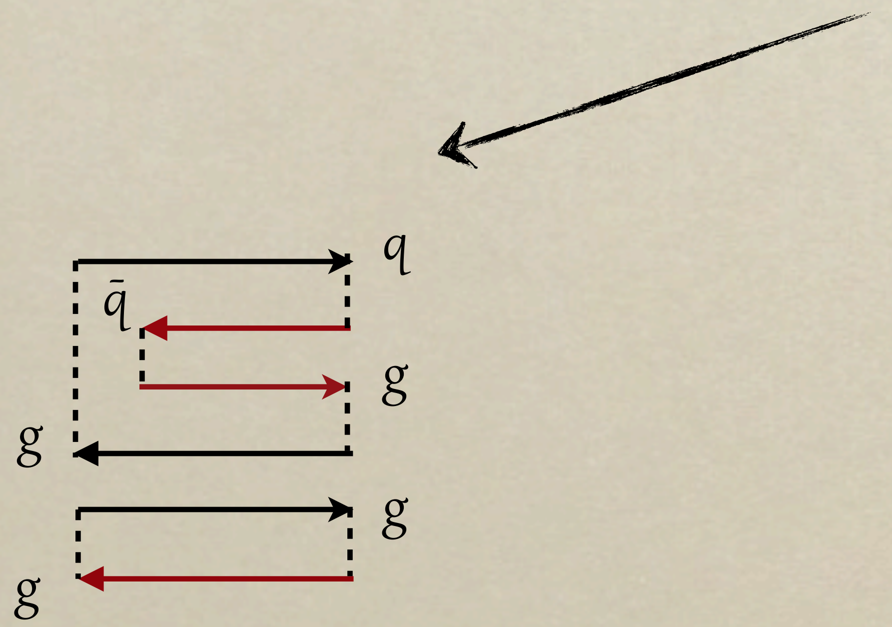


# Results

- "Medium" term: in-in contribution





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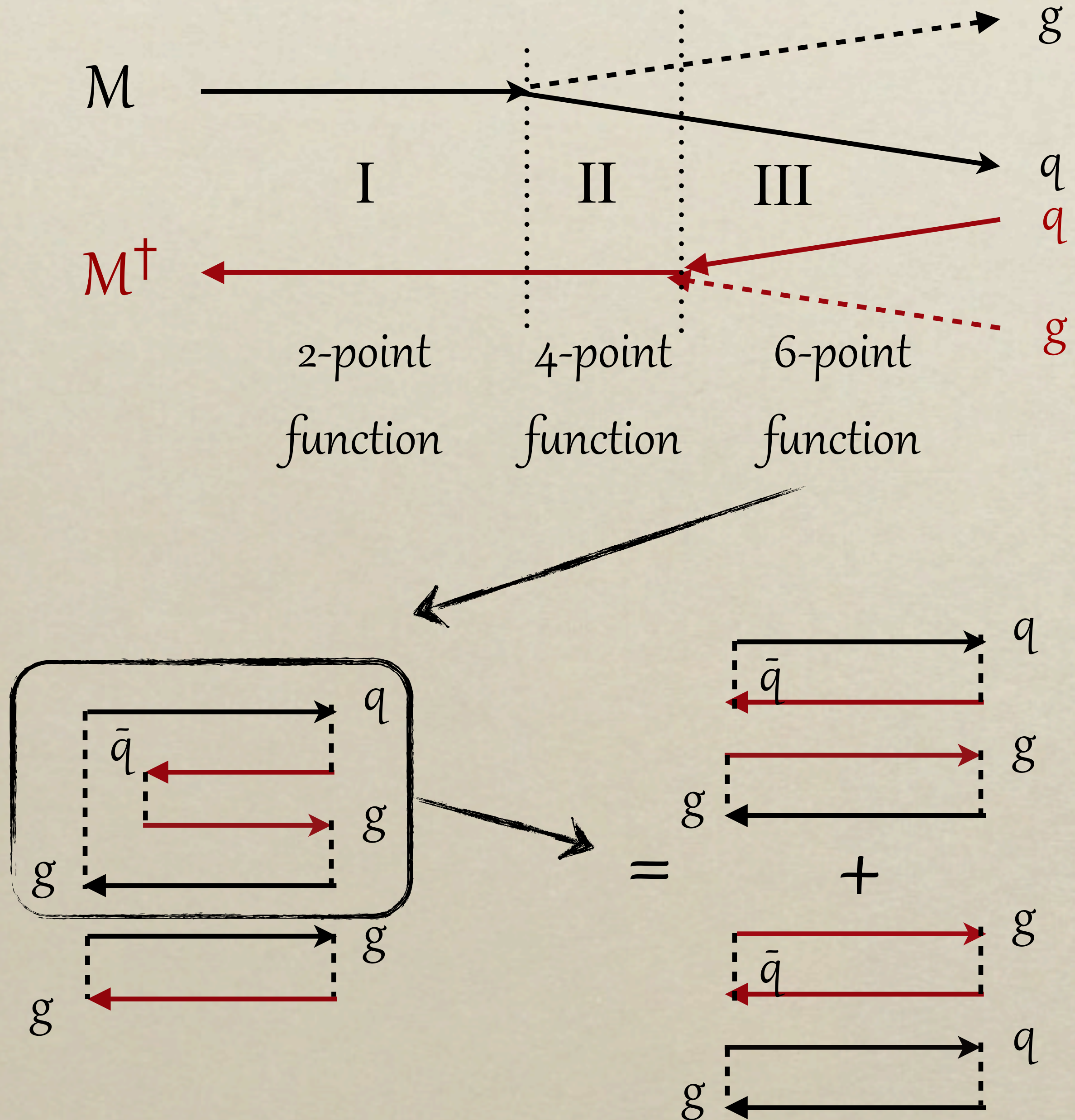


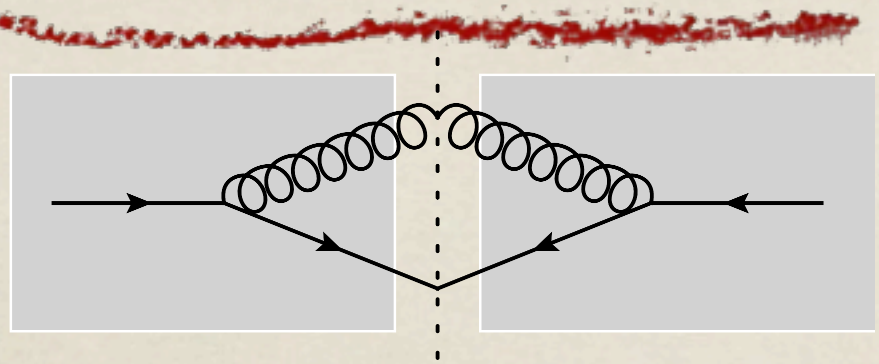

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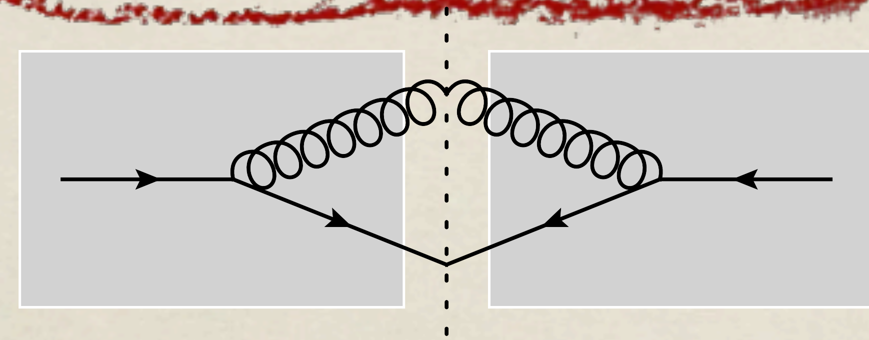

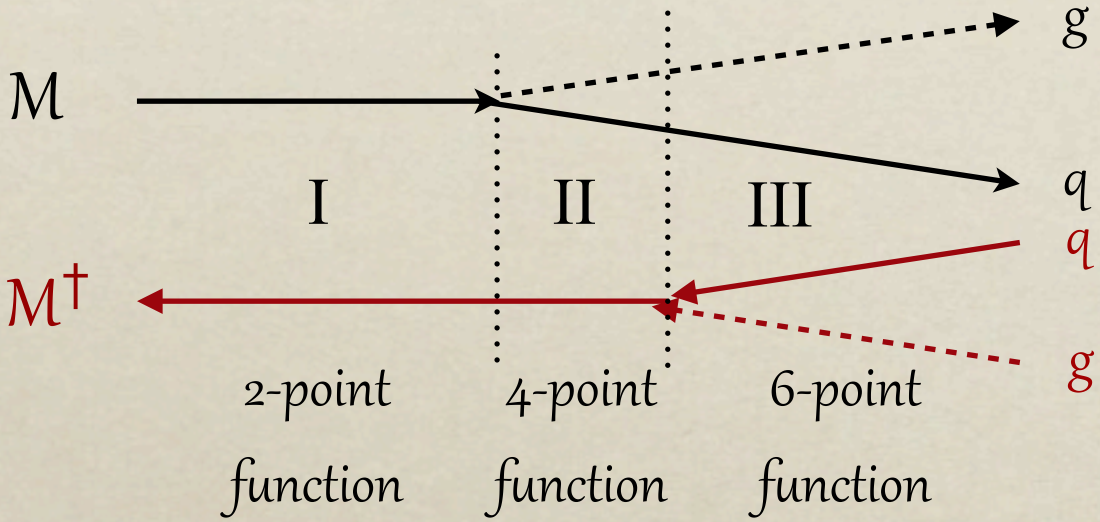


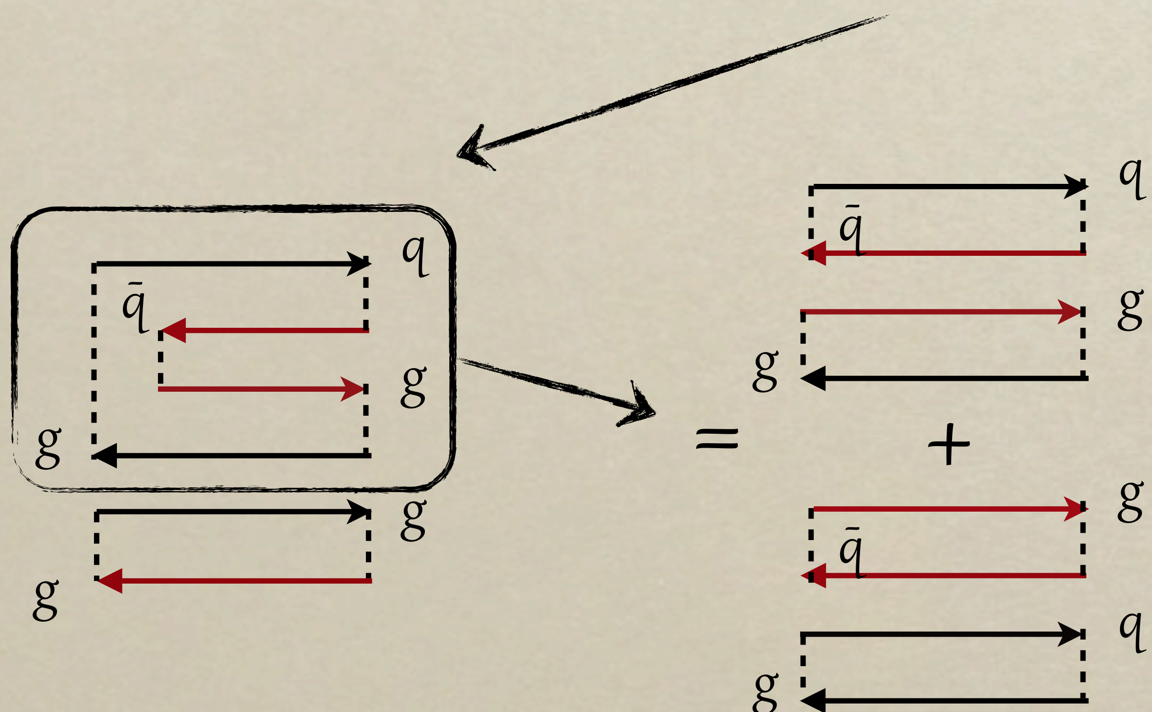


$$\left\langle \mathrm{Tr}\left(W^\dagger(\mathbf{x}_g)W(\mathbf{x}_{\bar{g}})W^\dagger(\mathbf{x}_{\bar{q}})W(\mathbf{x}_q)\right)\right\rangle$$

$$= N\exp\left\{-\frac{C_F}{4}\hat{q}(L_+ - x_{2+})\left[(\mathbf{x}_{\bar{g}}-\mathbf{x}_g)^2+(\mathbf{x}_q-\mathbf{x}_{\bar{q}})^2\right]\right\}\Delta_{med}$$

where

$$\Delta_{med} \equiv 1-\exp\left\{-\frac{C_F}{2}\hat{q}(L_+ - x_{2+})(\mathbf{x}_{\bar{q}}-\mathbf{x}_g)\cdot(\mathbf{x}_q-\mathbf{x}_{\bar{g}})\right\}$$

Transport coefficient: $\hat{q} = \dfrac{\langle \mathbf{k}^2\rangle}{\lambda}$

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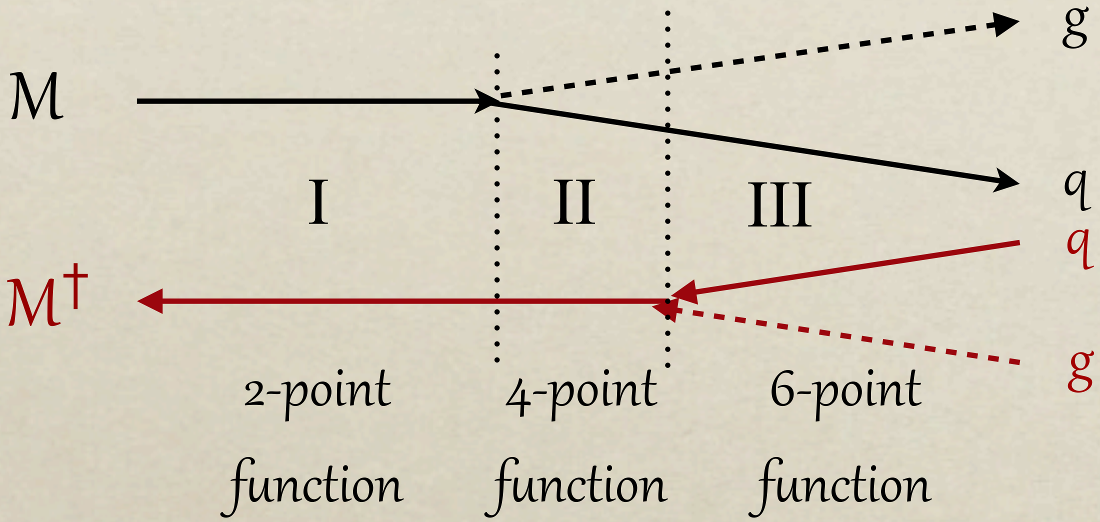
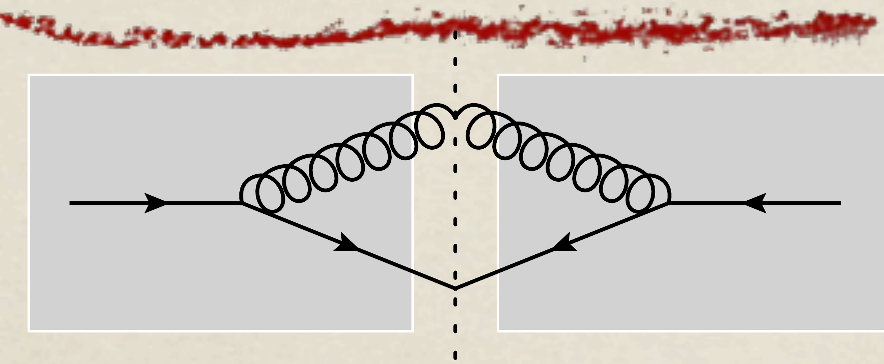
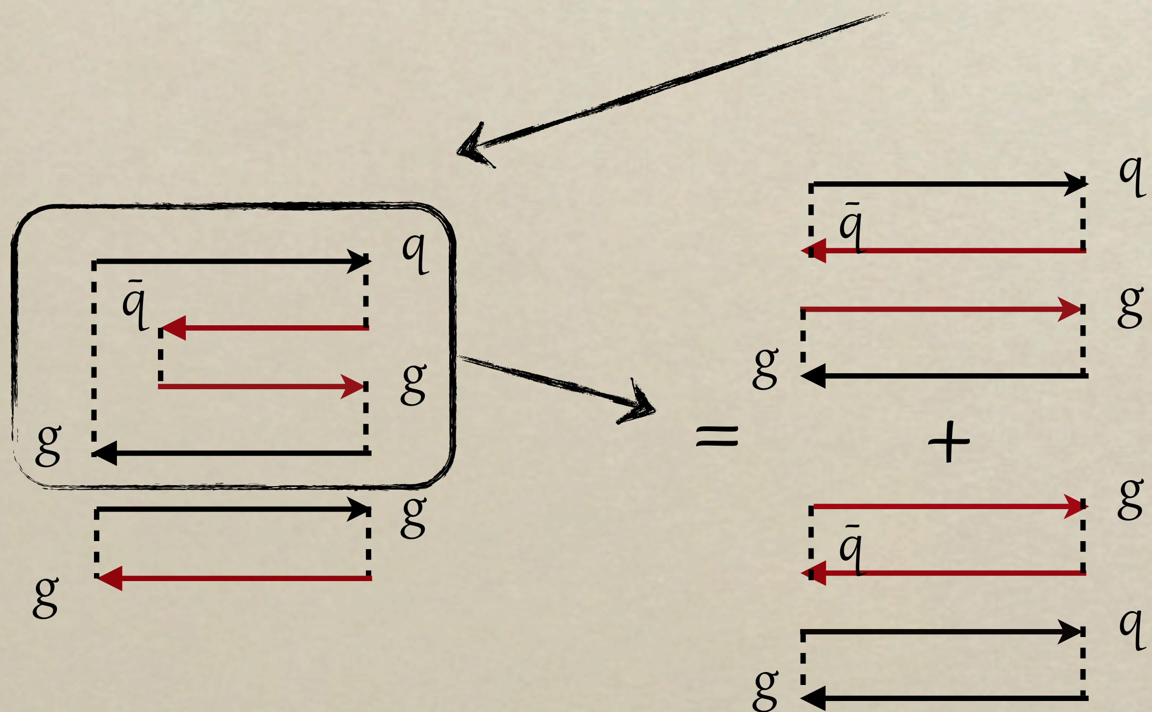


$\Delta_{med}$ controls the decoherence of color sources:

$$\hat{q}_F L_+ \to \infty \Rightarrow \Delta_{med} \to 1$$

➟ Quadrupole factorizes into two independent dipoles!

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➟ Generalized $\Delta_{med}$ parameter to account for the transverse walk of both particles

Transport coefficient: $\hat{q} = \dfrac{\langle \mathbf{k}^2 \rangle}{\lambda}$

[1109.2965, 1102.4317, 1205.5739, 1110.4343]

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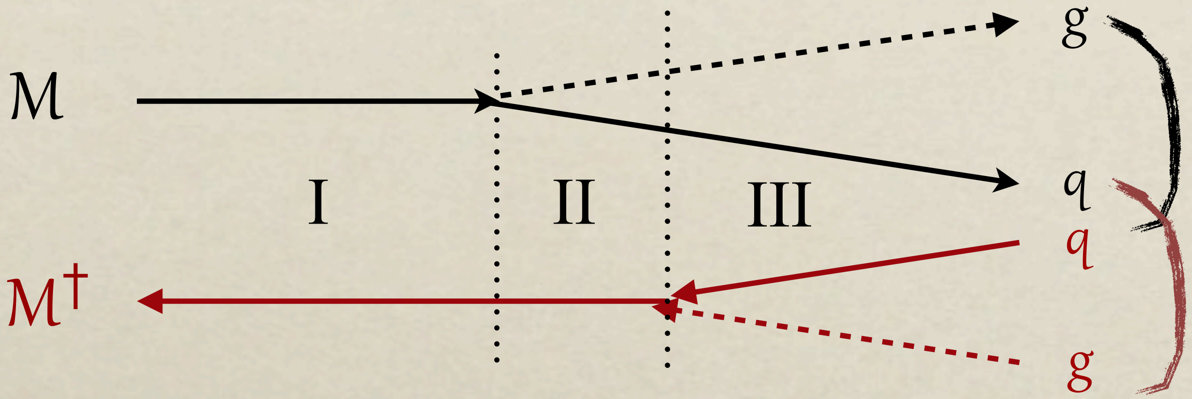


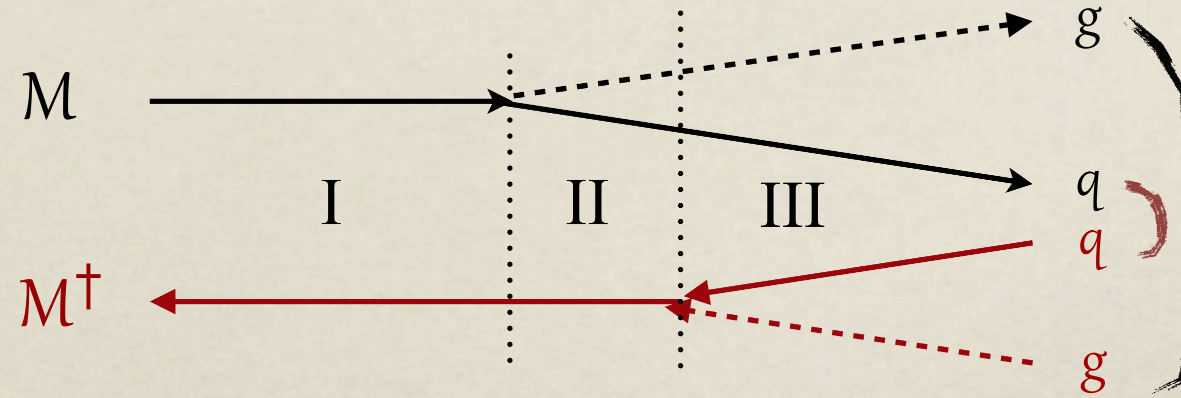

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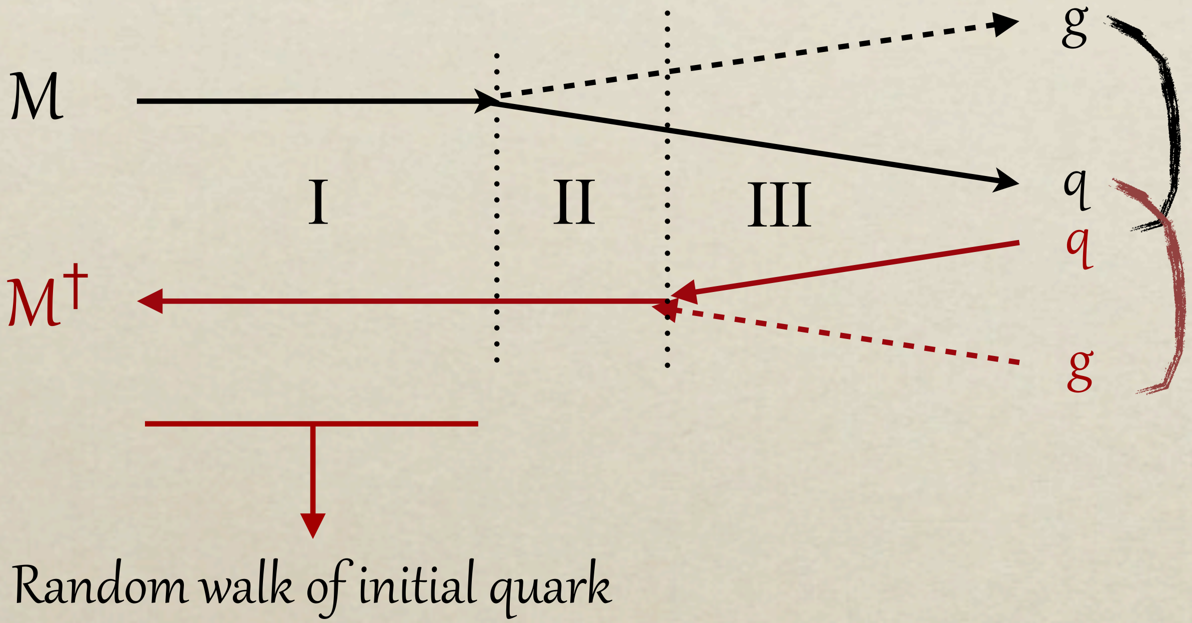


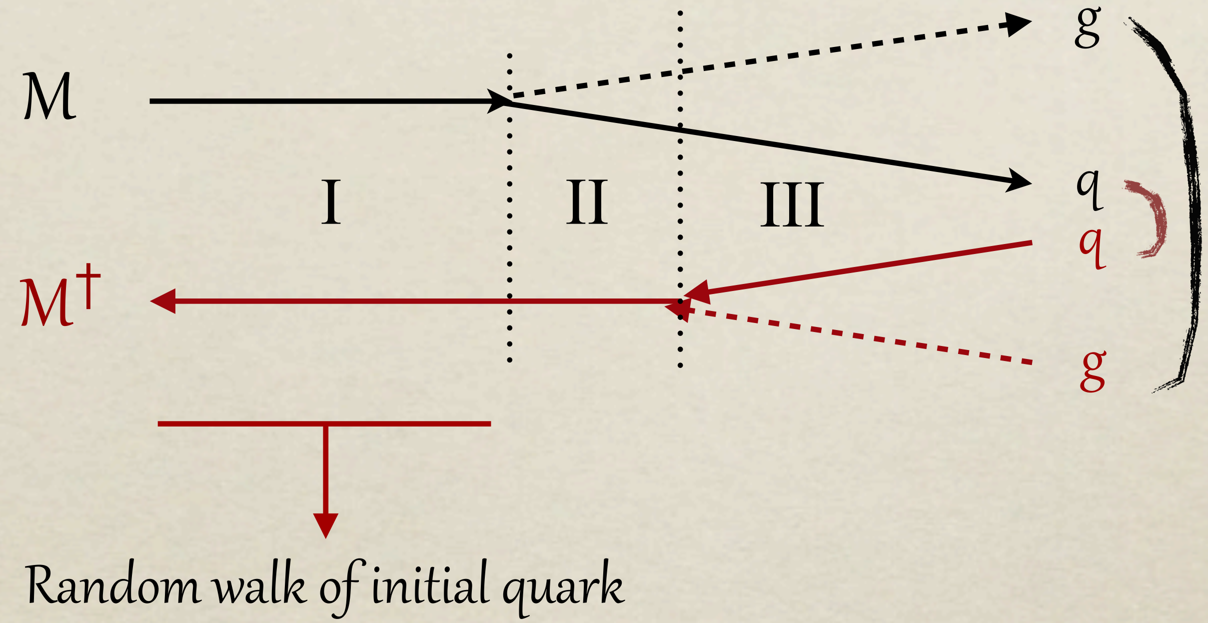

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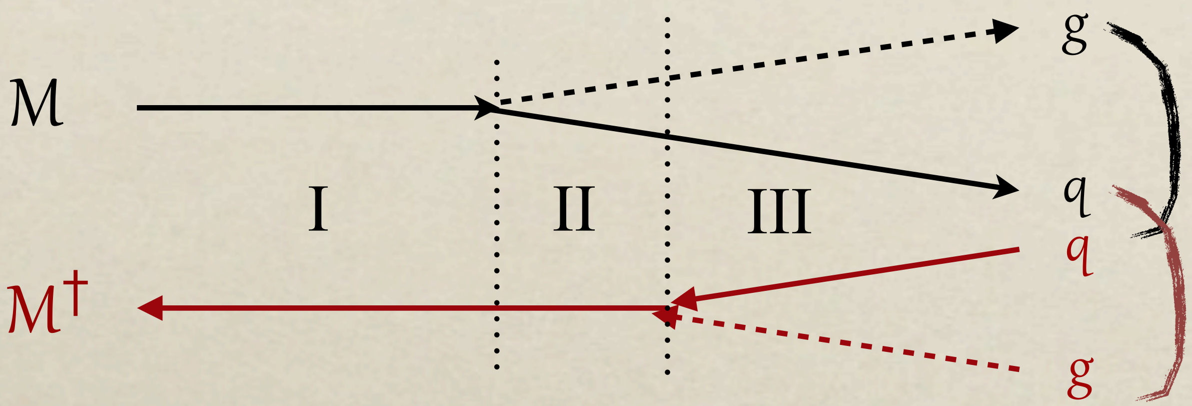
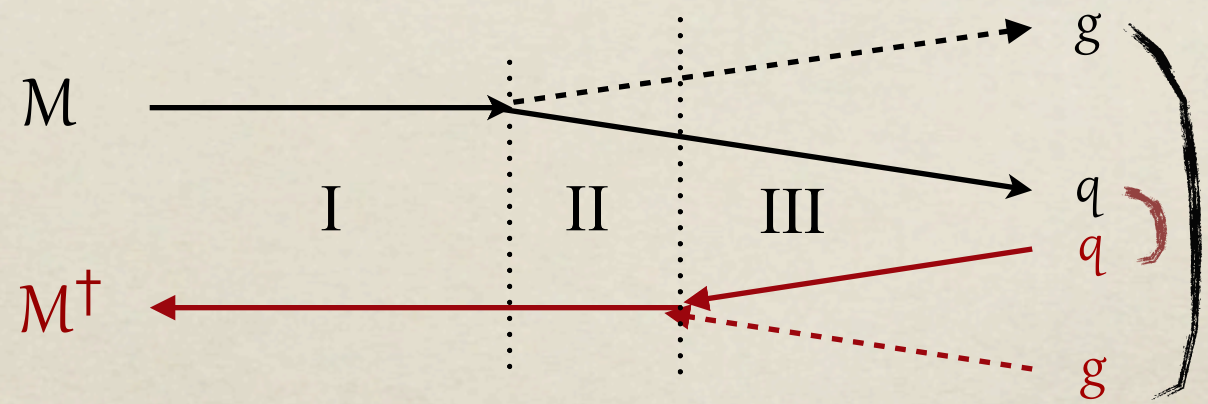



Random walk of initial quark

Quark and gluon are correlated
(gluon formation time)

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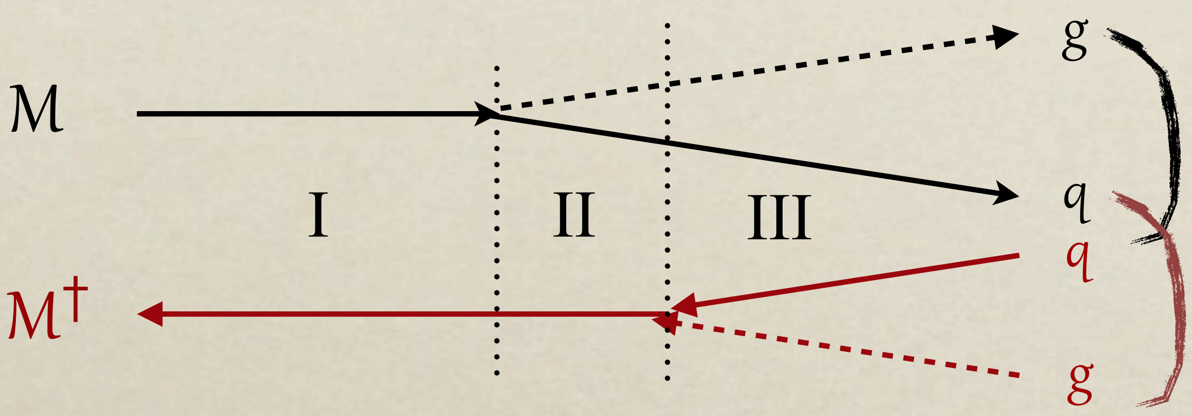


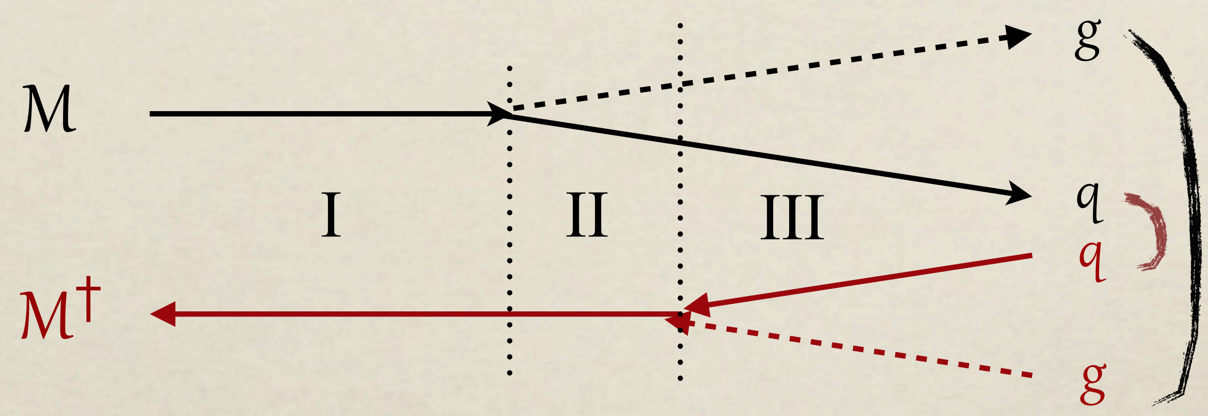


Random walk of initial quark

Quark and gluon are correlated
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Quark and gluon act coherently
(coherent propagation controlled by dipole distance)

Random walk of initial quark

Quark and gluon are correlated
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Independent broadening of final partons

# Conclusions

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  - In this work we provide a complete calculation of the medium-induced single gluon radiation spectrum off a quark in the limit of static scattering centers and small angle emissions:
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Thanks!

# Backup Slides

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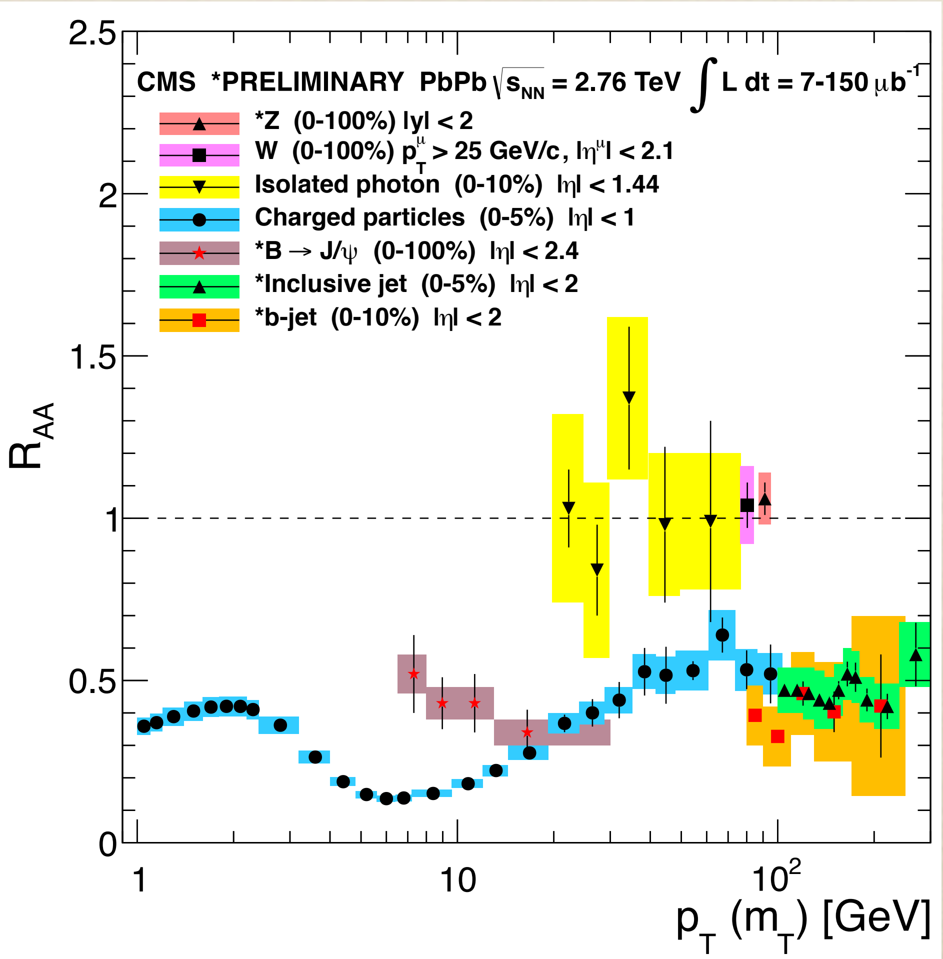


$$R_{AA}(p_T) = \frac{(1/N_{\rm evt}^{AA})d^2N^{AA}/d\eta dp_T}{< N_{\rm coll} > (1/N_{\rm evt}^{pp})d^2N^{pp}/d\eta dp_T}$$

Ratio of the particle yield in AA collisions over pp collisions

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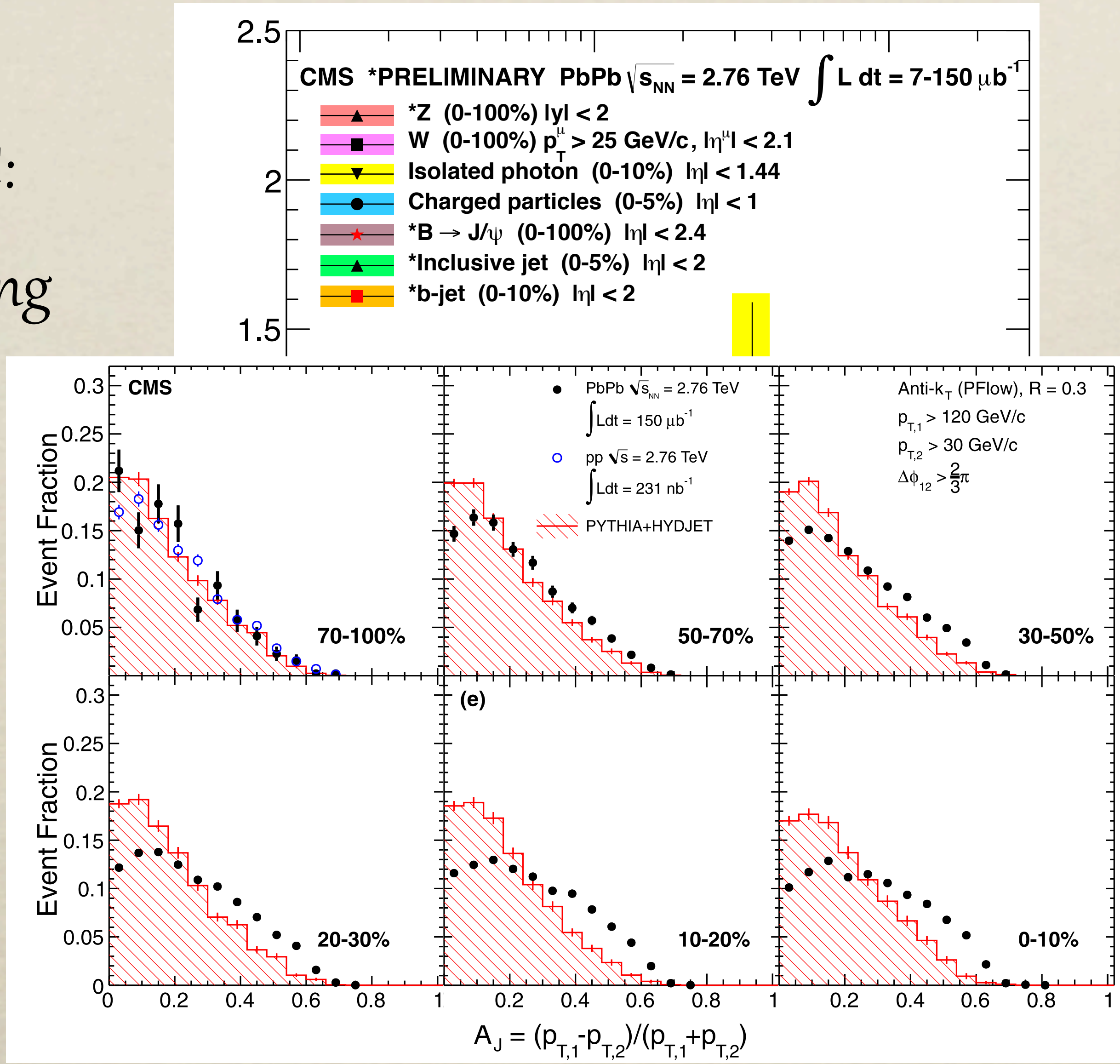


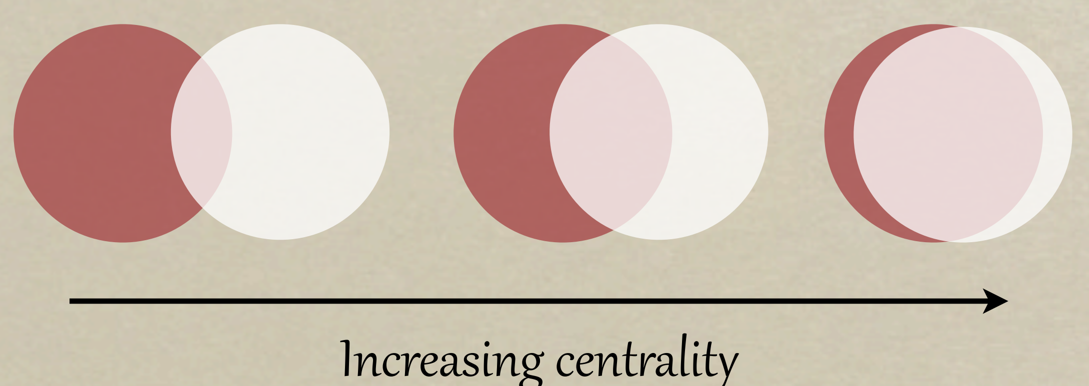


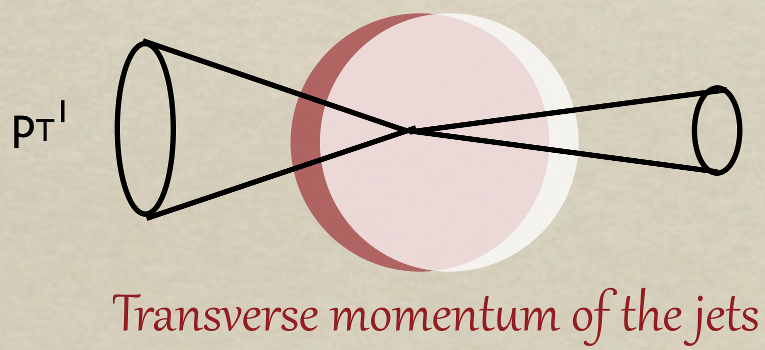


$$A_J = \frac{p_T^1 - p_T^2}{p_T^1 + p_T^2}$$

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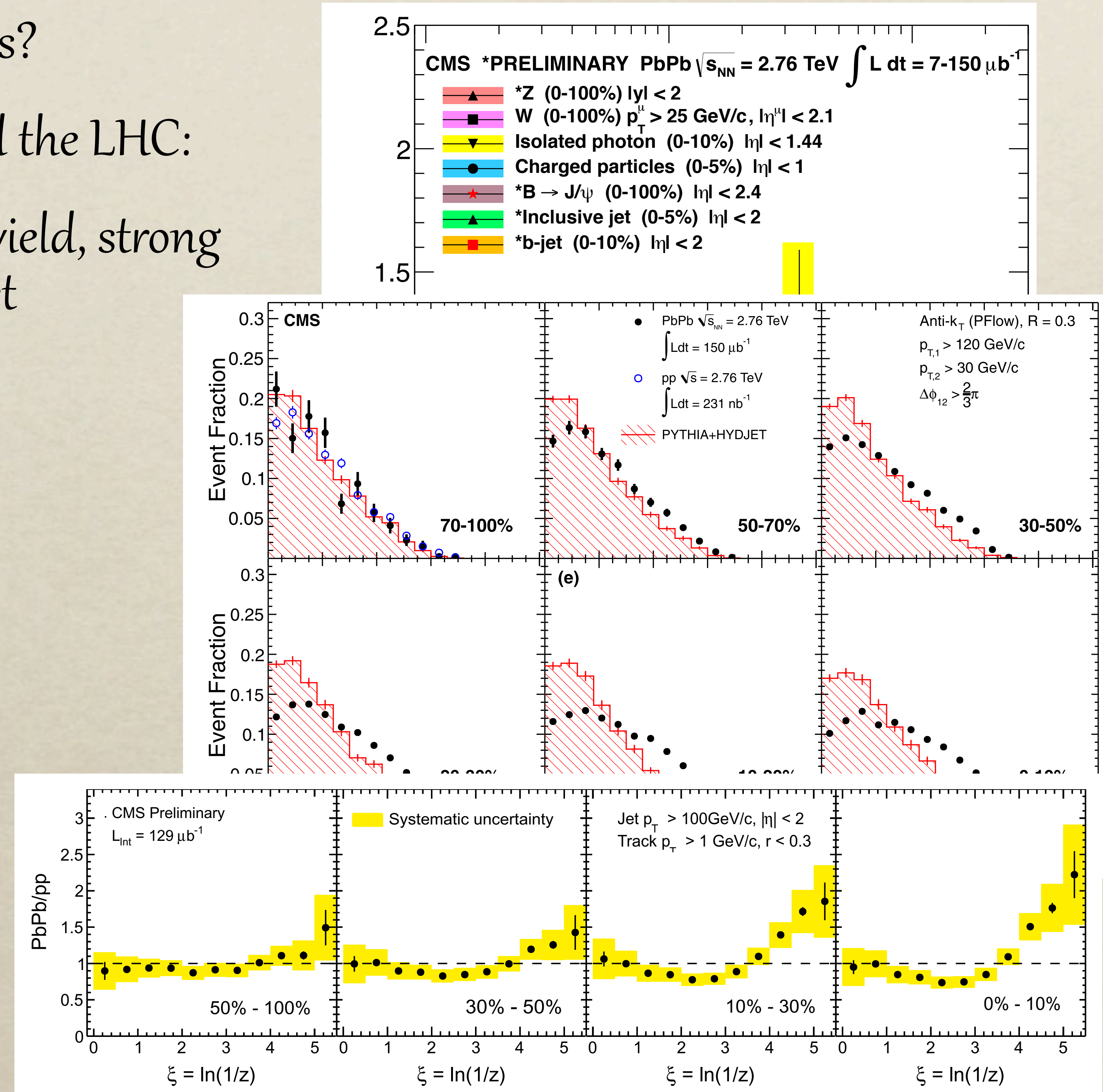


$$\xi = \ln\left(\frac{1}{z}\right) \quad , \quad z = \frac{p_{\parallel}^{tr}}{p^{jet}}$$

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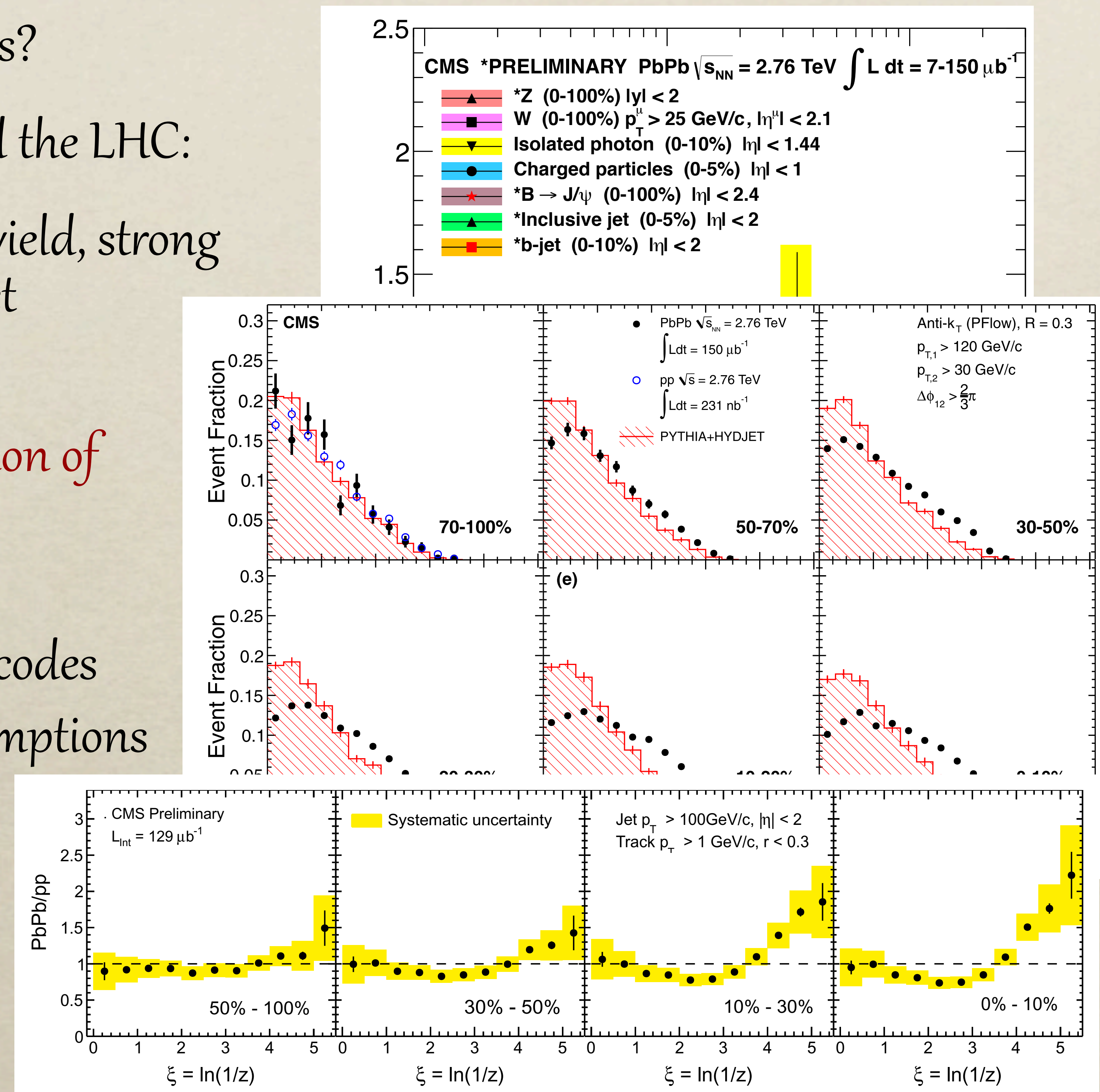
➟ Important to have a good description of energy loss mechanisms

⇓

Particularly relevant for Monte Carlo codes (usually employ phenomenological assumptions without a firm theoretical basis)

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# Medium averages

- 2-point function:
  - Result depends only on the transverse separation between the partons:

$$\frac{1}{N}\left\langle W(\mathbf{x})W^\dagger(\mathbf{y})\right\rangle = \exp\left\{-\frac{C_F}{2}\int dx_+\sigma(\mathbf{x}-\mathbf{y})n(x_+)\right\}$$

$$n(x_+)\sigma(\mathbf{x}) \simeq \frac{1}{2}\hat{q}\mathbf{r}^2 + \mathcal{O}(\mathbf{r}^2\ln\mathbf{r}^2)$$ ➟ Valid for opaque media and small r

Transport coefficient: $\hat{q} = \frac{\langle \mathbf{k}^2\rangle}{\lambda}$

- 4-point function:

$$\left\langle \left[W(\mathbf{x}_1)W^\dagger(\mathbf{x}_2)\right]_{ij}\left[W(\mathbf{x}_2)W^\dagger(\mathbf{x}_3)\right]_{kl}\right\rangle = \delta_{ij}\delta_{kl}\exp\left\{\frac{1}{2N}v(\mathbf{x}_1-\mathbf{x}_3)-\frac{N}{2}\left[v(\mathbf{x}_1-\mathbf{x}_2)+v(\mathbf{x}_2-\mathbf{x}_3)\right]\right\}$$
$$+\frac{1}{N}\delta_{il}\delta_{jk}\exp\left\{-C_F v(\mathbf{x}_1-\mathbf{x}_3)\right\} - \frac{1}{N}\delta_{il}\delta_{jk}\exp\left\{\frac{1}{2N}v(\mathbf{x}_1-\mathbf{x}_3)-\frac{N}{2}\left[v(\mathbf{x}_1-\mathbf{x}_2)+v(\mathbf{x}_2-\mathbf{x}_3)\right]\right\}$$

➟ At large Nc, factorizes into a dipoles

- 6-point function:

$$\left\langle \mathrm{Tr}\left(W^\dagger(\mathbf{x}_1)W(\mathbf{x}_2)\right)\mathrm{Tr}\left(W^\dagger(\mathbf{x}_2)W(\mathbf{x}_1)W^\dagger(\mathbf{x}_3)W(\mathbf{x}_4)\right)\right\rangle$$
$$\underset{N\to\infty}{\simeq}\left\langle \mathrm{Tr}\left(W^\dagger(\mathbf{x}_1)W(\mathbf{x}_2)\right)\right\rangle\left\langle \mathrm{Tr}\left(W^\dagger(\mathbf{x}_2)W(\mathbf{x}_1)W^\dagger(\mathbf{x}_3)W(\mathbf{x}_4)\right)\right\rangle$$

➟ At large Nc, factorization into a dipole + quadrupole