Monte Carlo methods for parton energy loss

Liliana Apolinário

LIP

TÉCNICO LISBOA

Outline

- What is a Monte Carlo event generator?
  - How to generate a parton shower?
- What do we need to worry about when trying to describe parton showers in heavy-ion events?
  - In-medium interactions
    - Parton shower modifications?
    - Medium re-scatterings?
    - Medium evolution?
- What can we do with a Monte Carlo model for jet quenching?

What is a Monte Carlo event generator?

Monte Carlo Event Generators

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  - Quantum mechanics: amplitudes ⇒ probabilities
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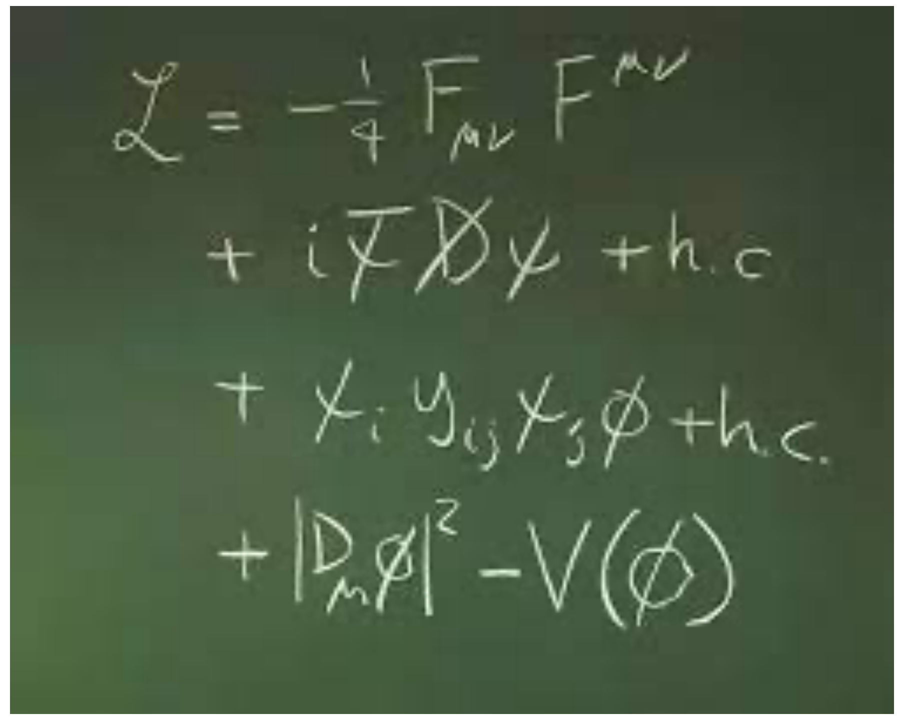
Monte Carlo Event Generators



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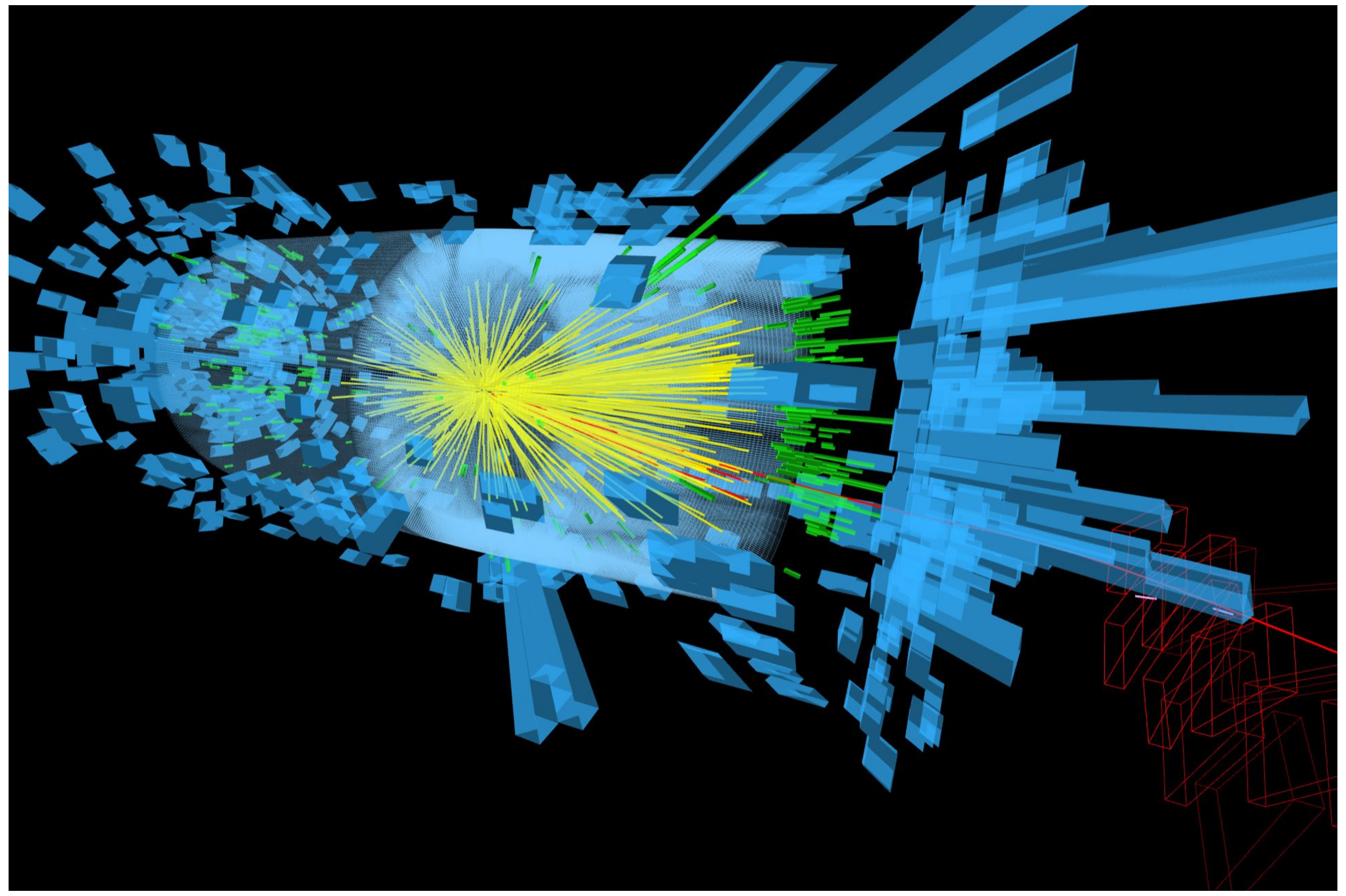
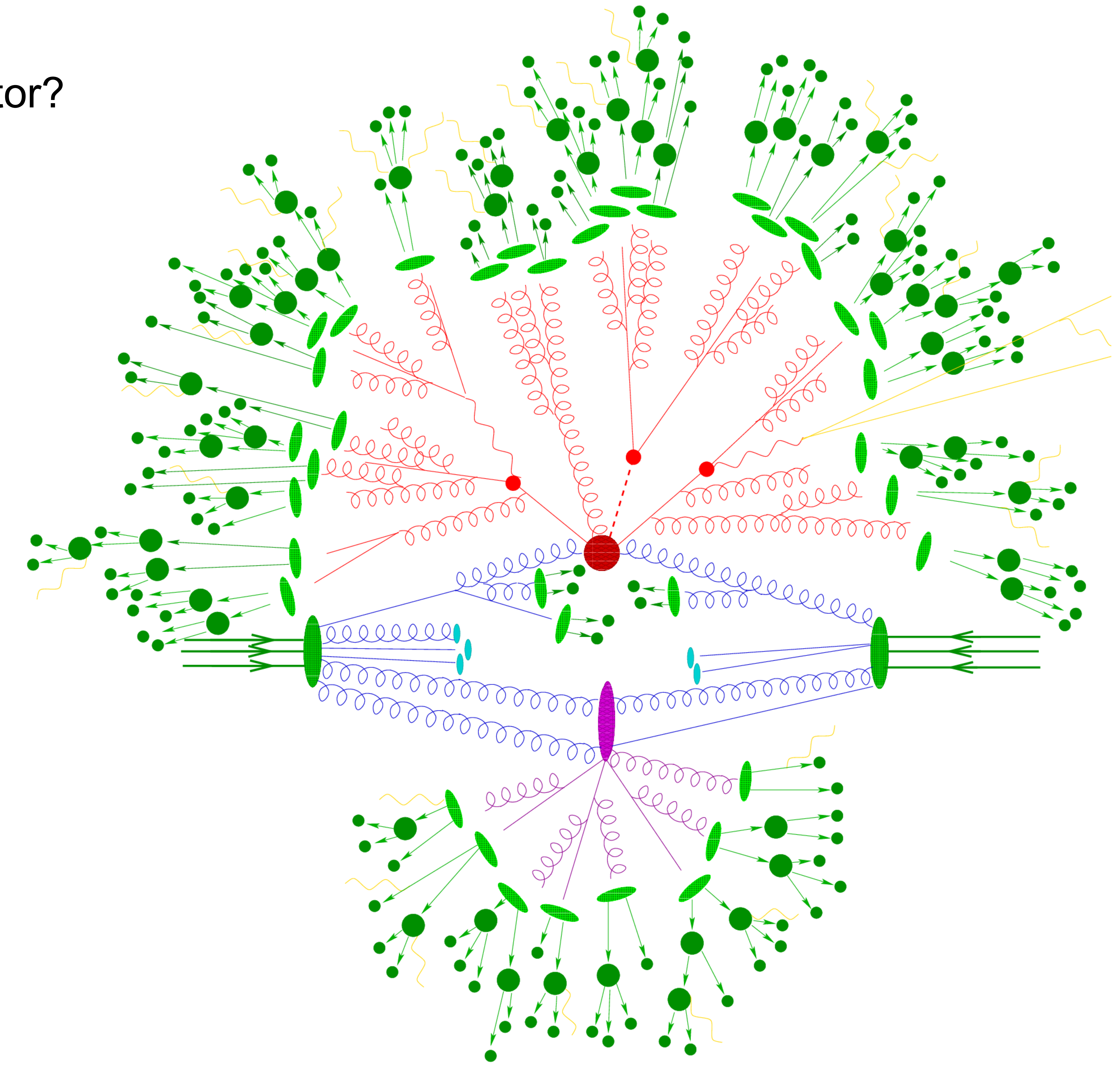


$$\mathscr{L}_{\text{int}} \longleftrightarrow \text{Final states}$$

High Energy Collision

- How to describe such a process through an event generator?



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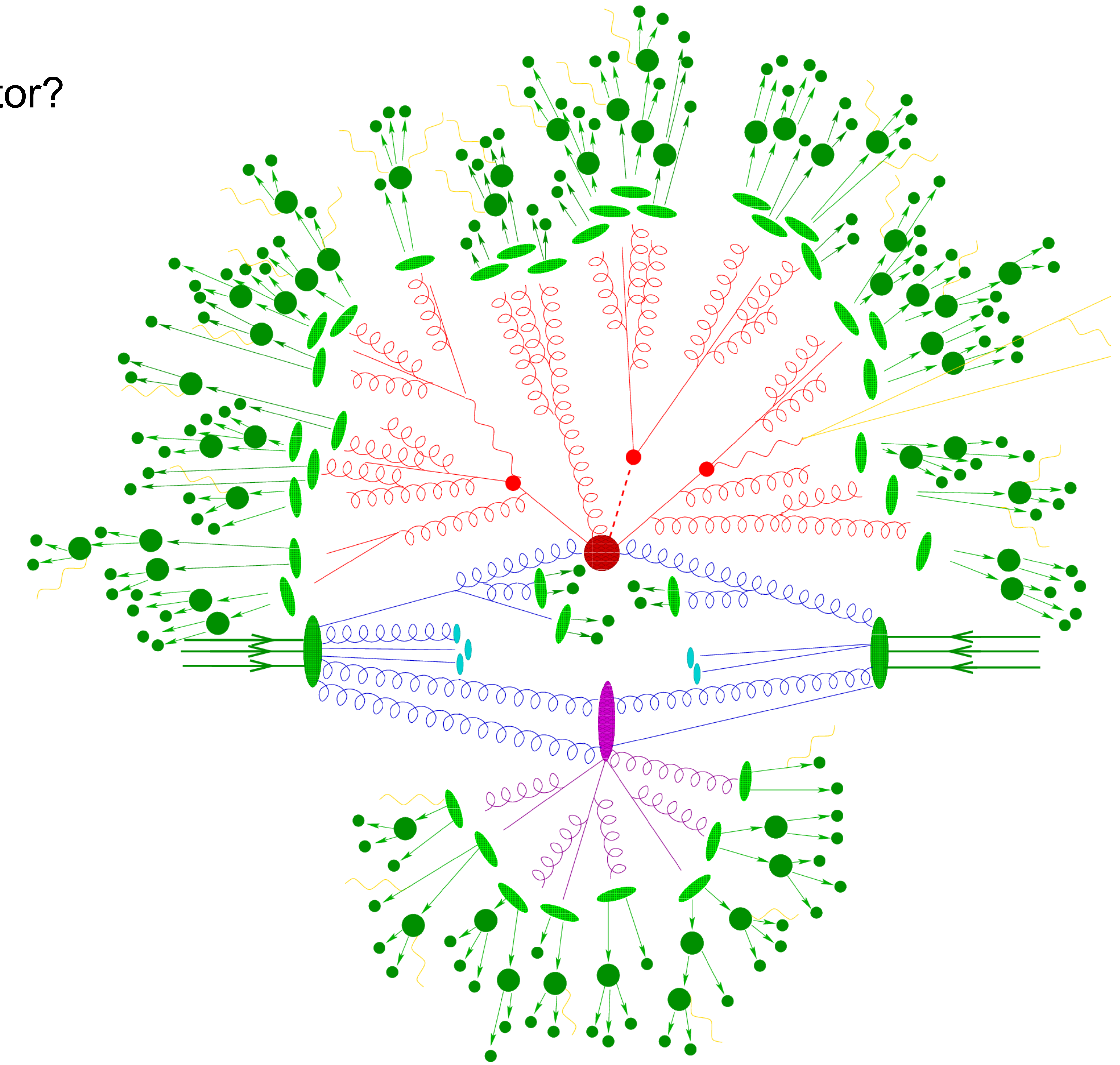

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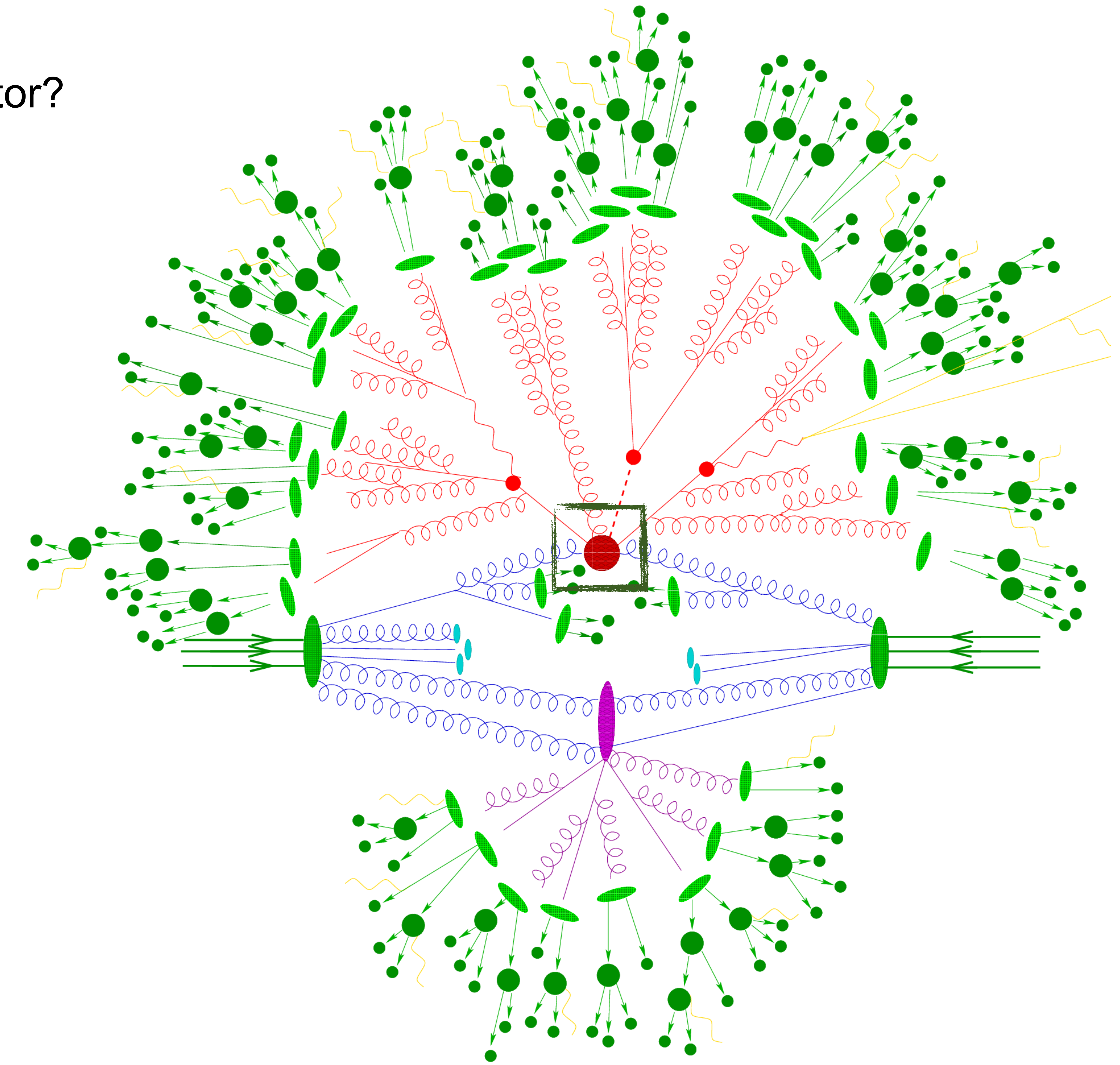

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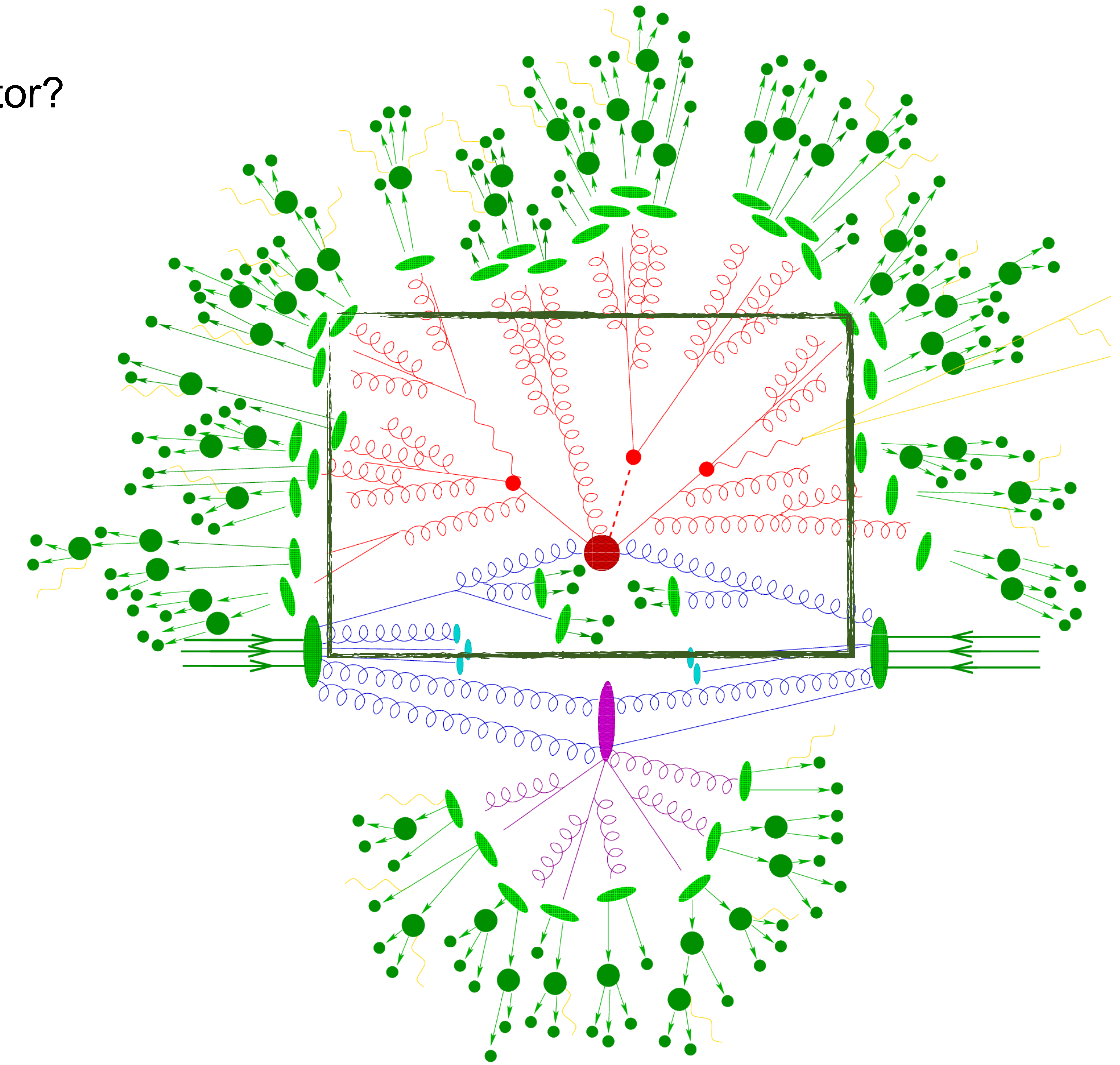

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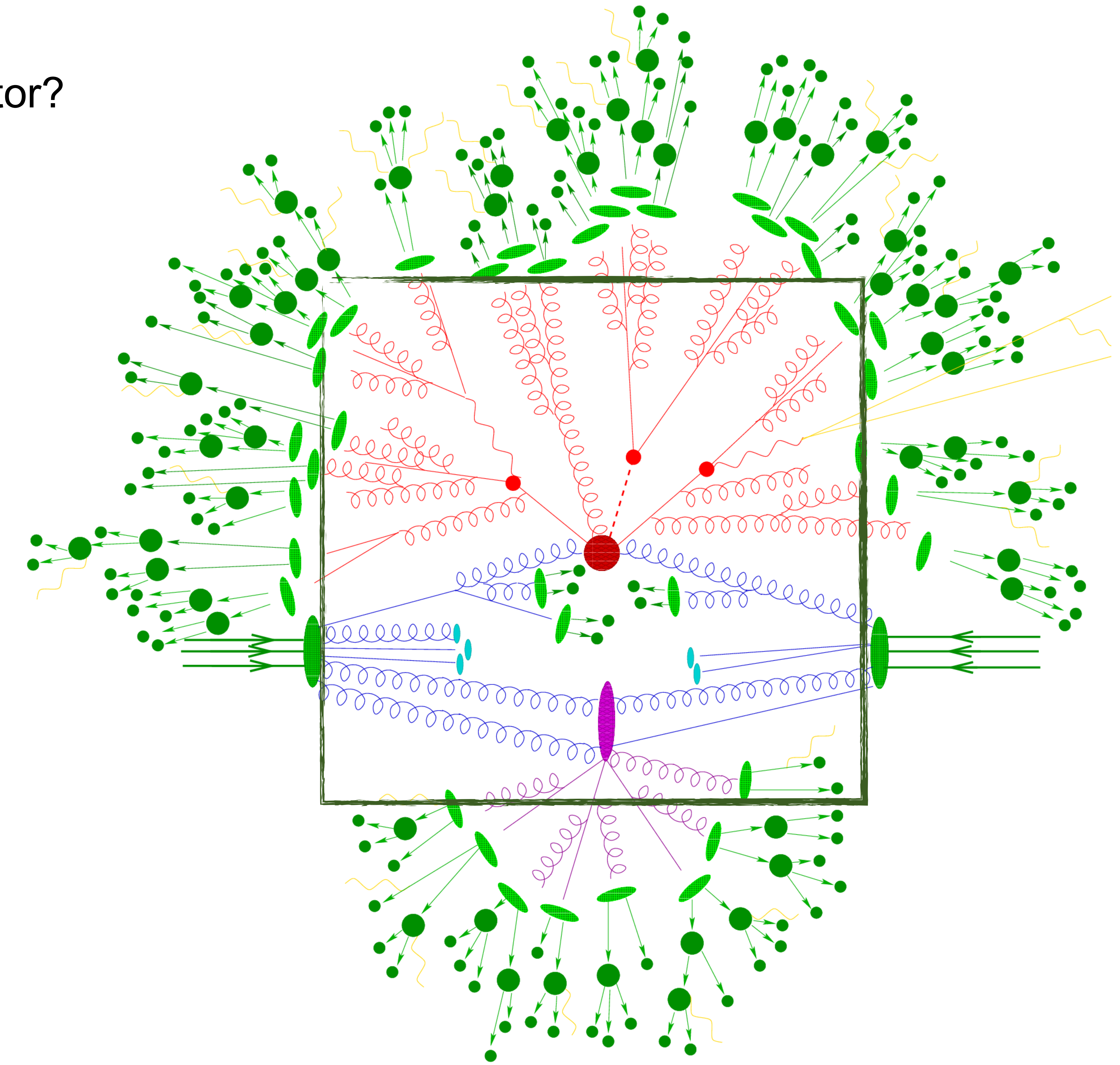

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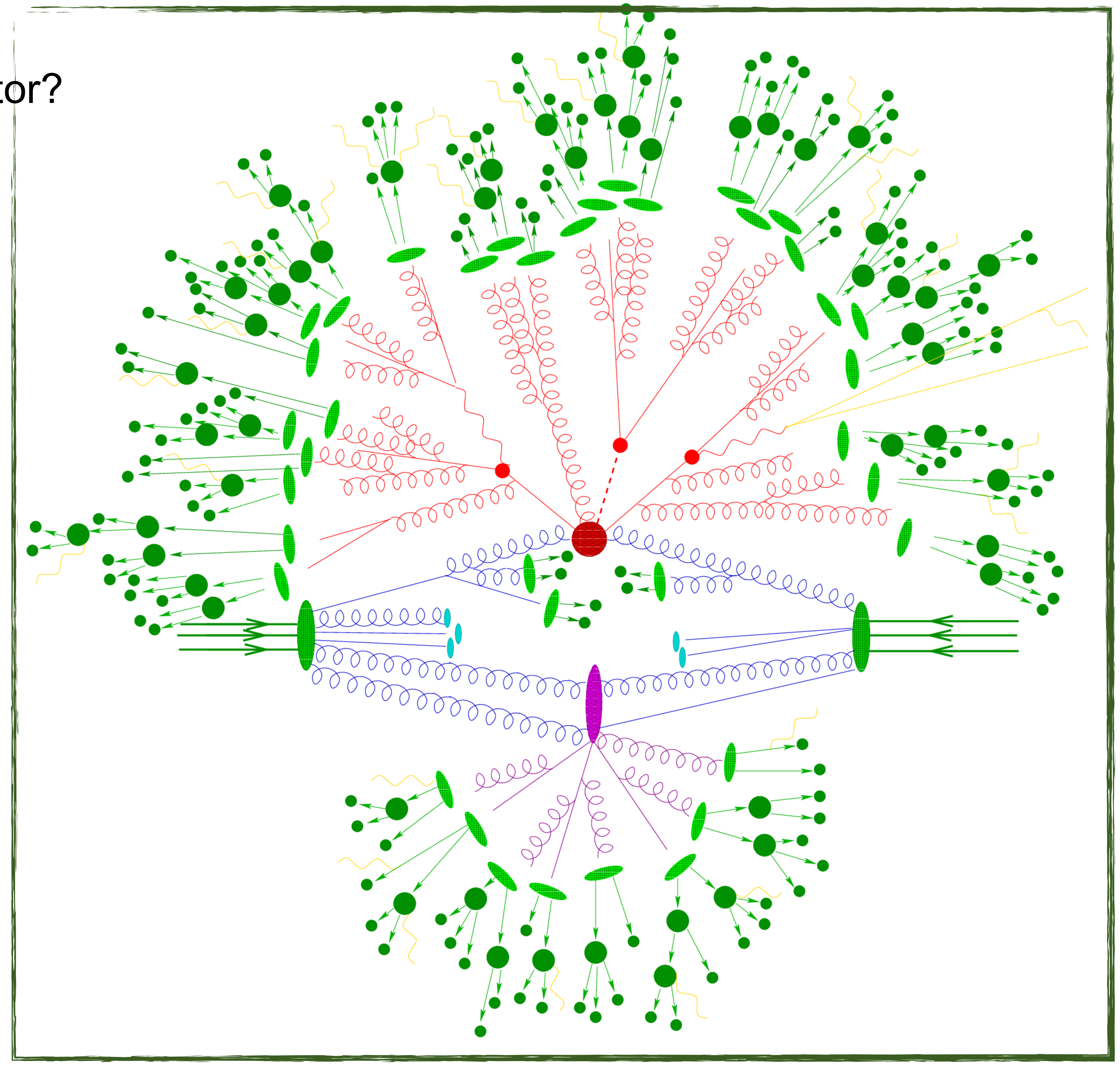

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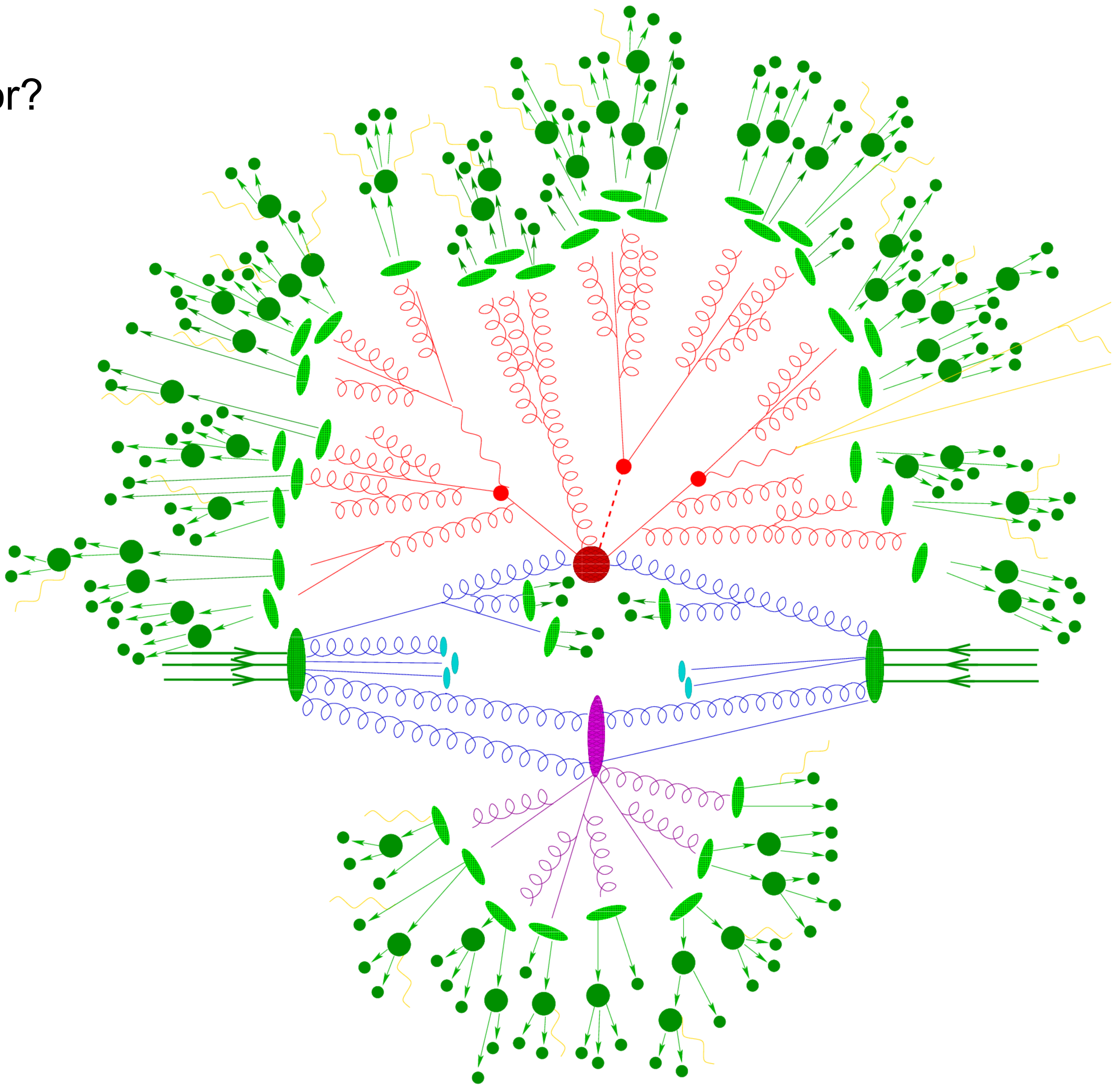
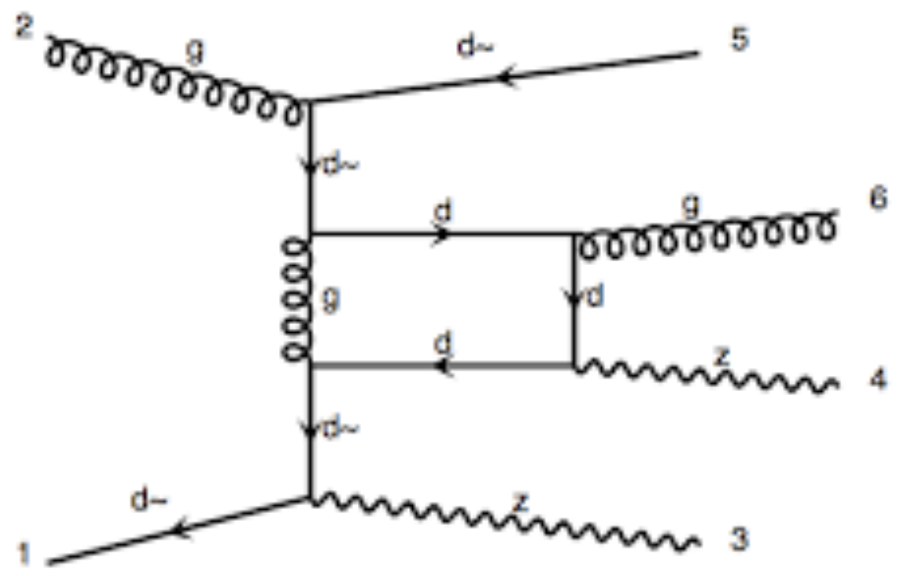
Separation in energy scale



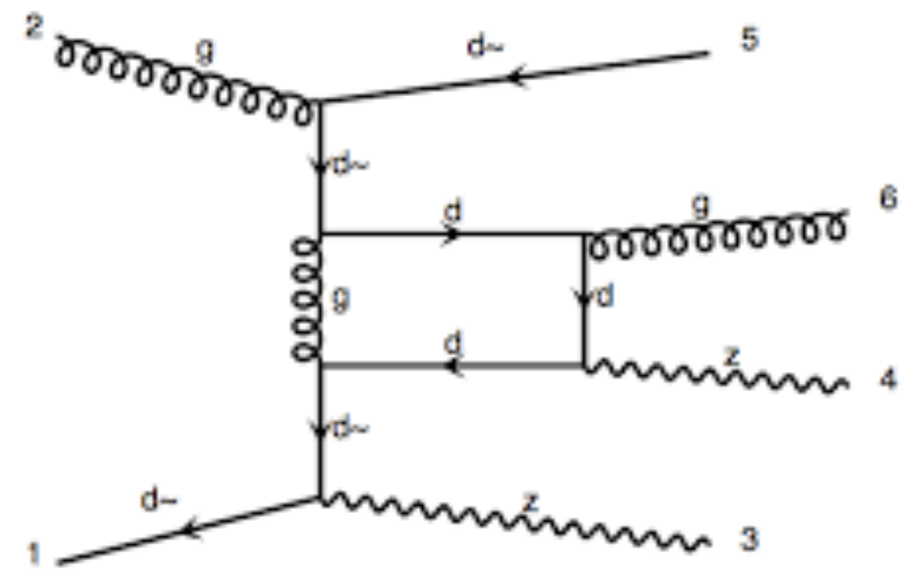
Initial- and Final-State Showers



- Two approaches to calculate additional radiation to the hard scattering:
  - Matrix elements (few particle corrections but higher order)

Initial- and Final-State Showers

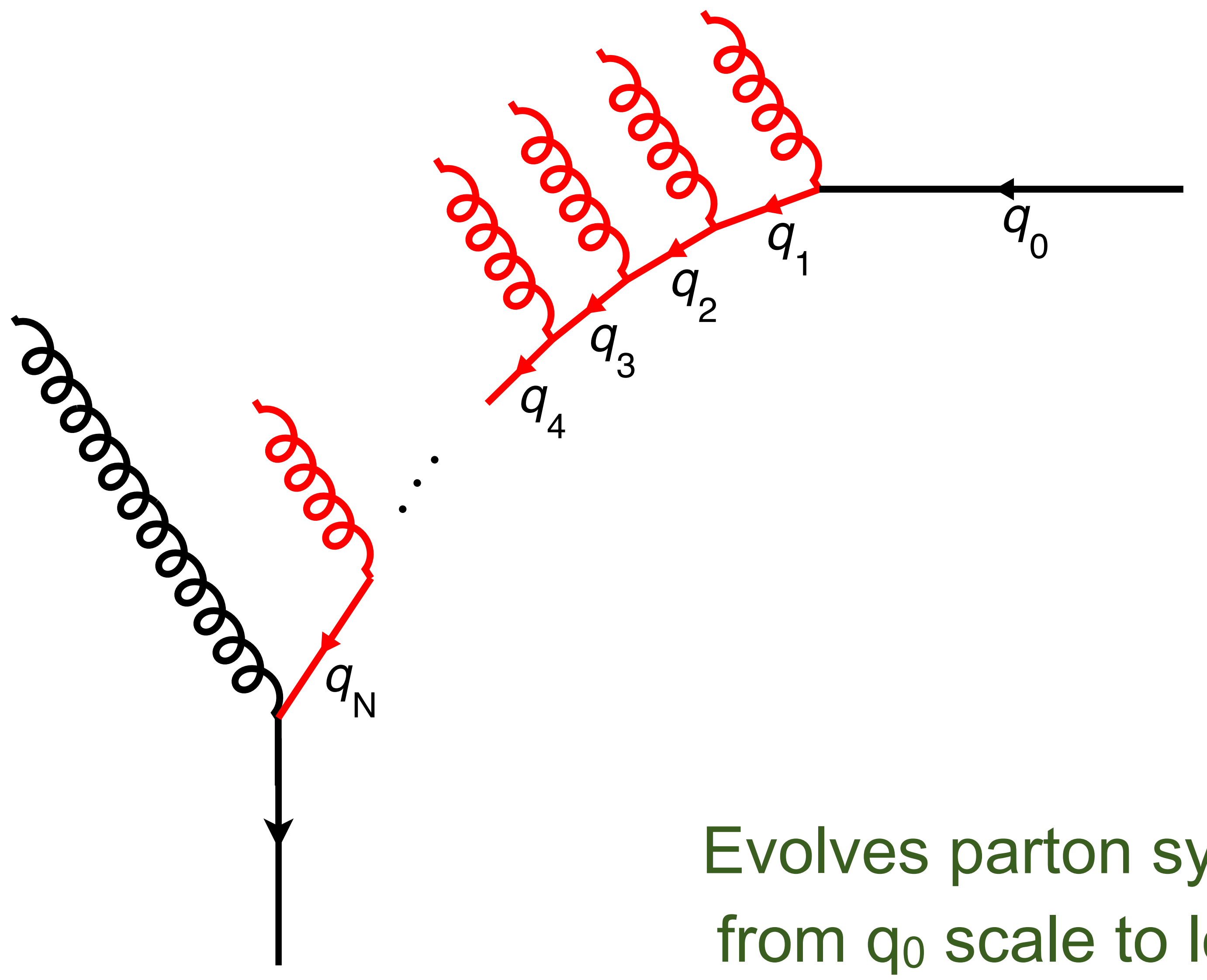
- Two approaches to calculate additional radiation to the hard scattering:
  - Matrix elements (few particle corrections but higher order)
  - Parton shower (more particle corrections but LO and NLO only)
    - Evolution equation based on splitting probabilities (SF)



$$Q^2 \frac{\partial D_a^h(x,Q^2)}{\partial Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} \sum_b \hat{P}_{b\leftarrow a}(z) D_b^h\left(\frac{x}{z}, Q^2\right) - \frac{\alpha_s(Q^2)}{2\pi} \int_0^1 dz \sum_b \hat{P}_{a\leftarrow b}(z) D_a^h(x,Q^2).$$

Splitting Function (SF)

Probability of parton 'b' splits into parton 'a' with a fraction of energy z



Evolves parton system from q_0 scale to lower scale

Monte Carlo Techniques

- Event generators = Monte Carlo techniques
  - Selection from a probability distribution function

t_0

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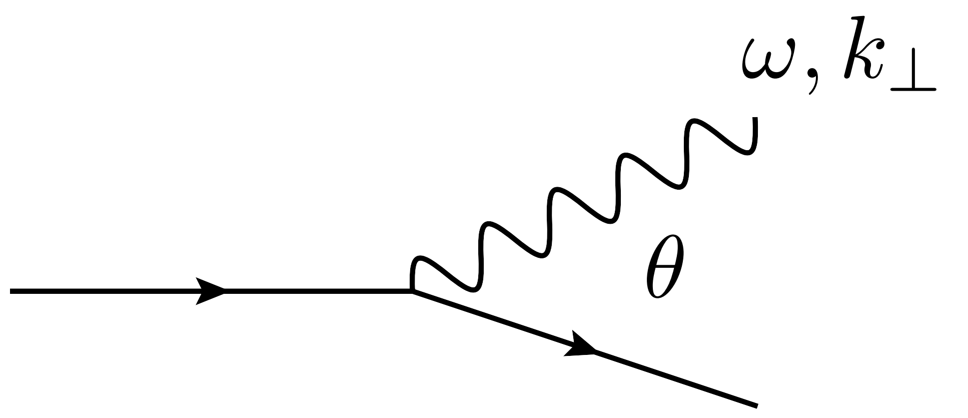

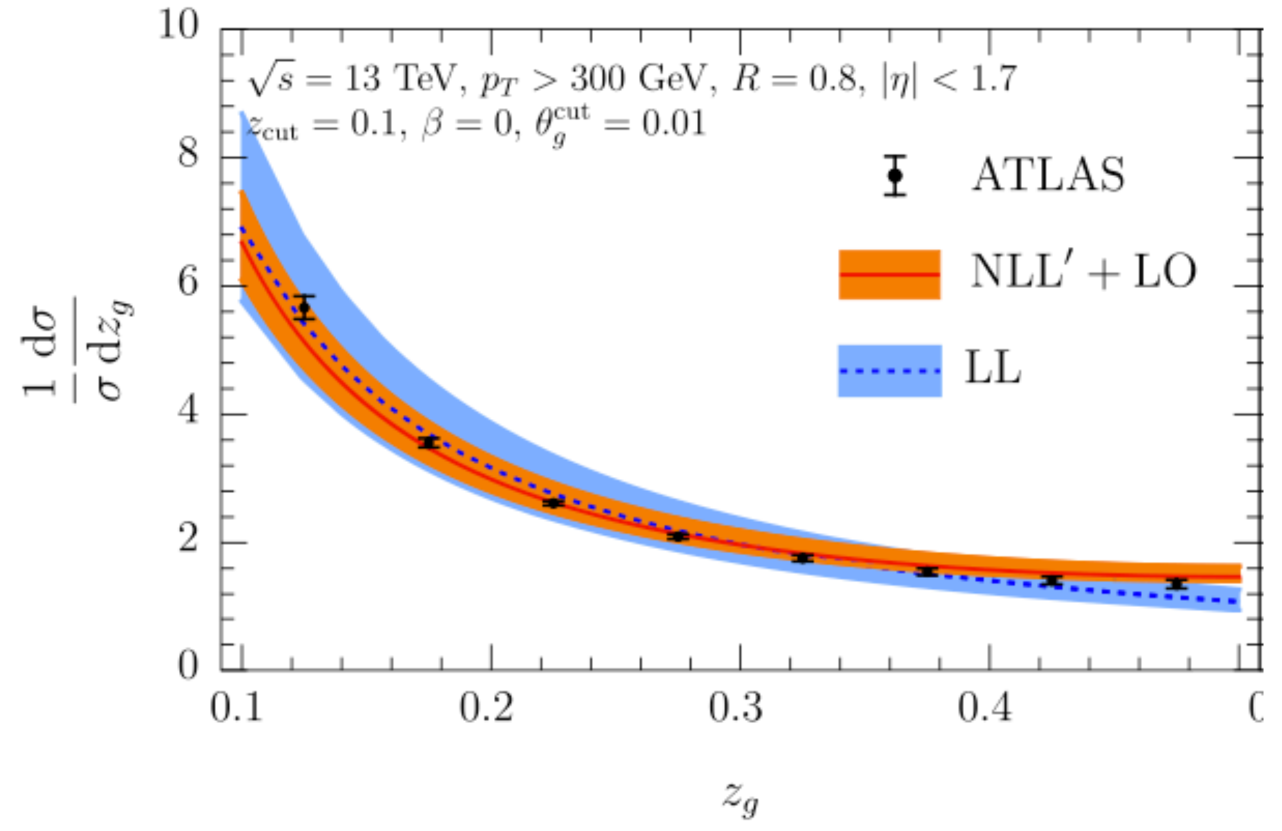

$$dP^{q\to qg} \sim \alpha_s C_R \frac{d\omega}{\omega}\frac{dk_\perp^2}{k_\perp^2}$$

t_0

Re-summation of multiple emissions

Sudakov Form factor: $$\Delta_i(t) \equiv \exp\left[-\sum_j \int_{t_0}^{t} \frac{dt'}{t'} \int dx \frac{\alpha_s}{2\pi} P_{i\leftarrow j}(x)\right]$$

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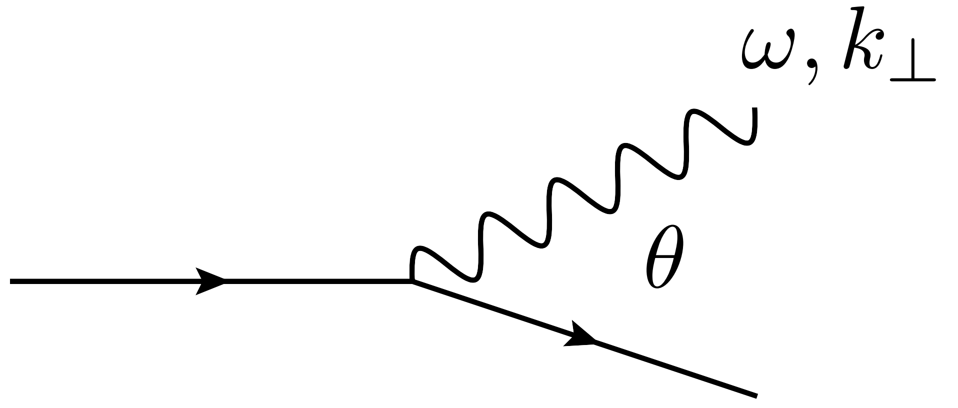

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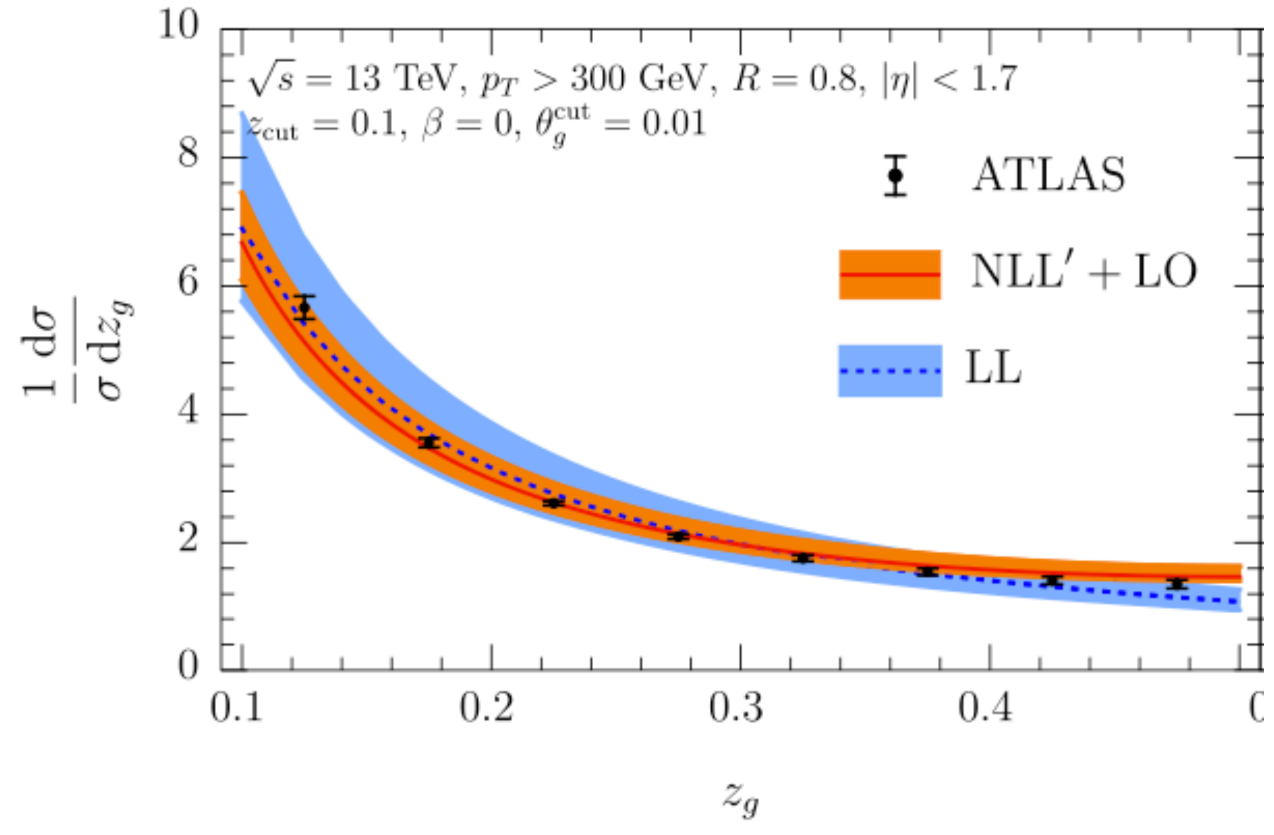

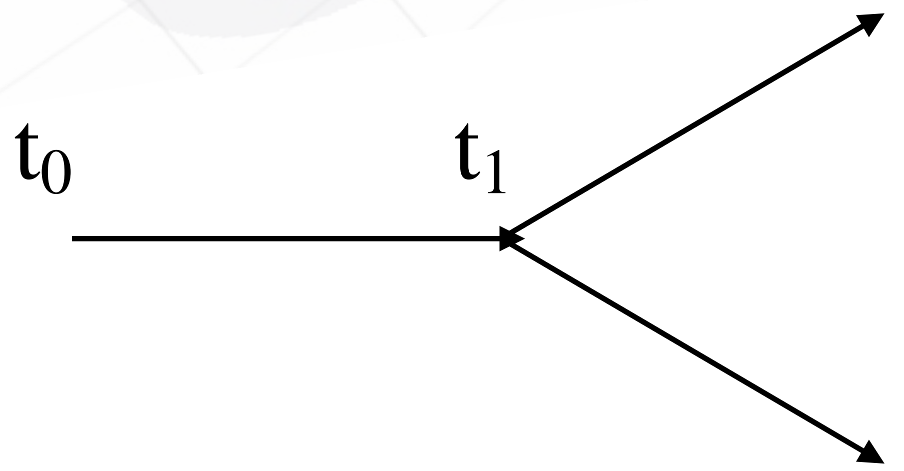

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Probability of not decay between t_0 and t_1

Given a random number, R, what is t_1?
At t_1, it decays.

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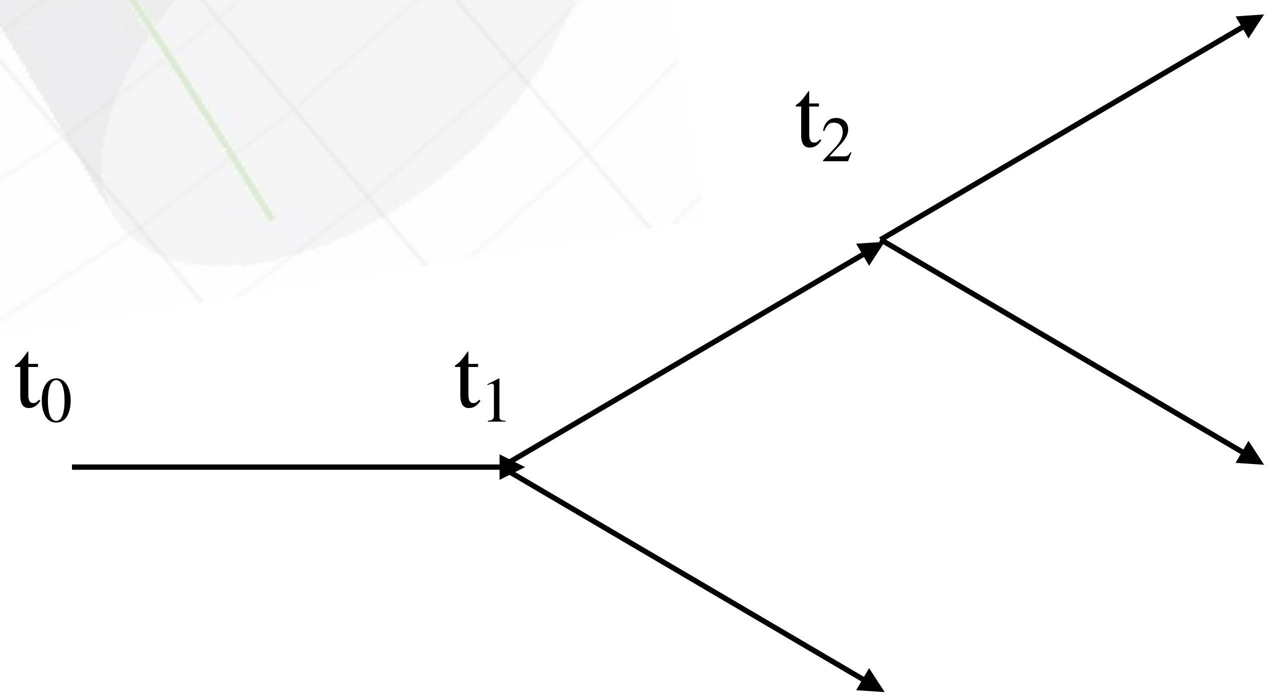

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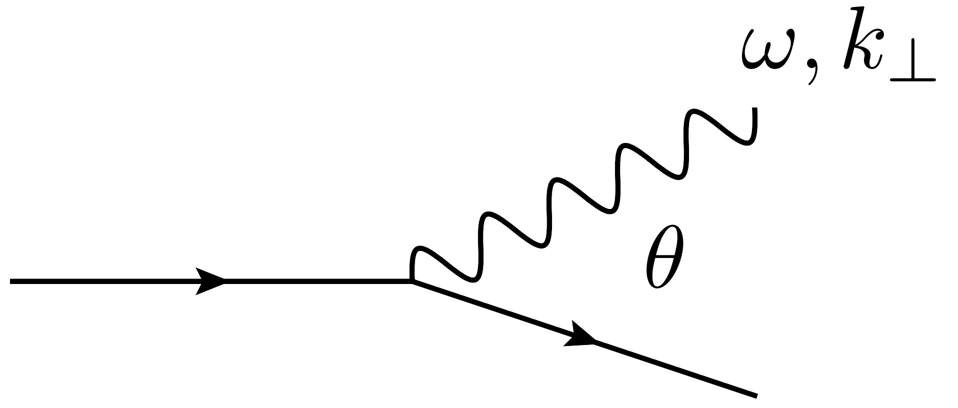

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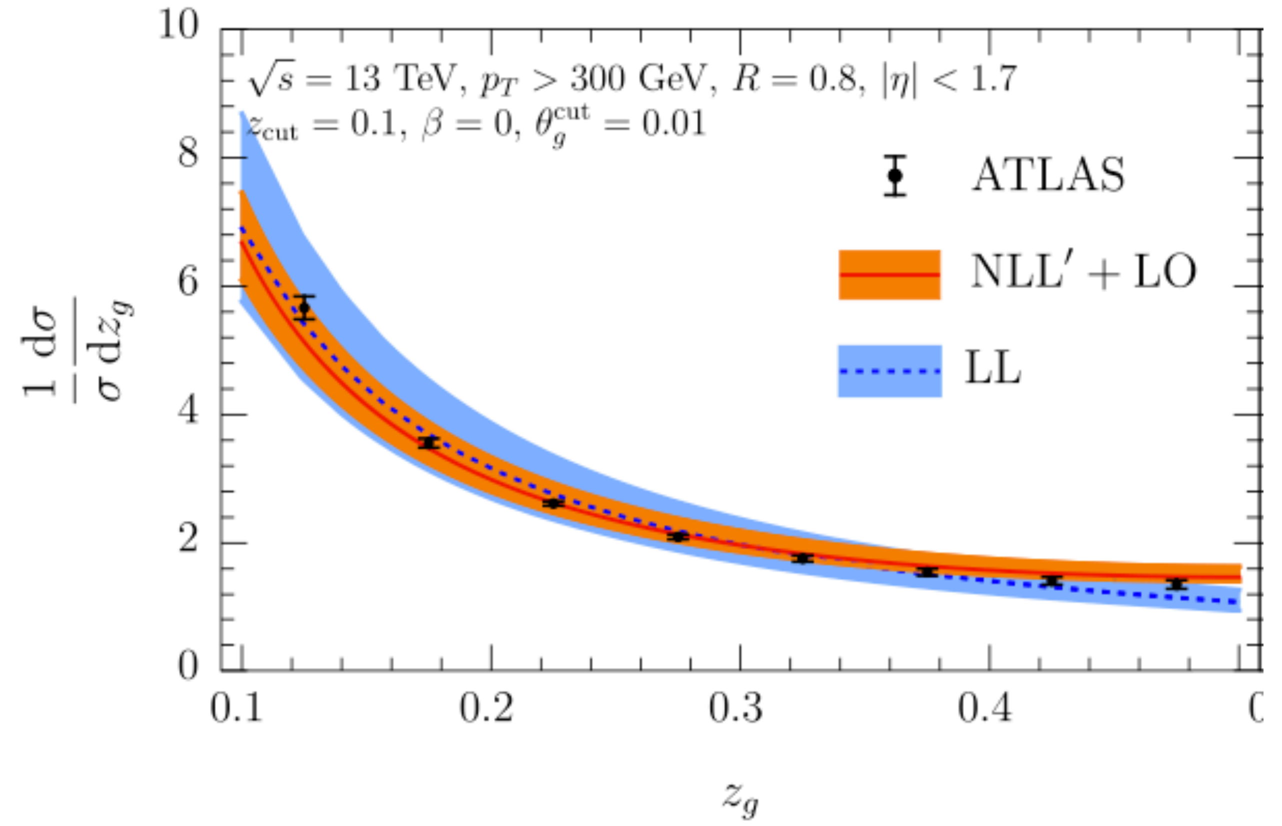

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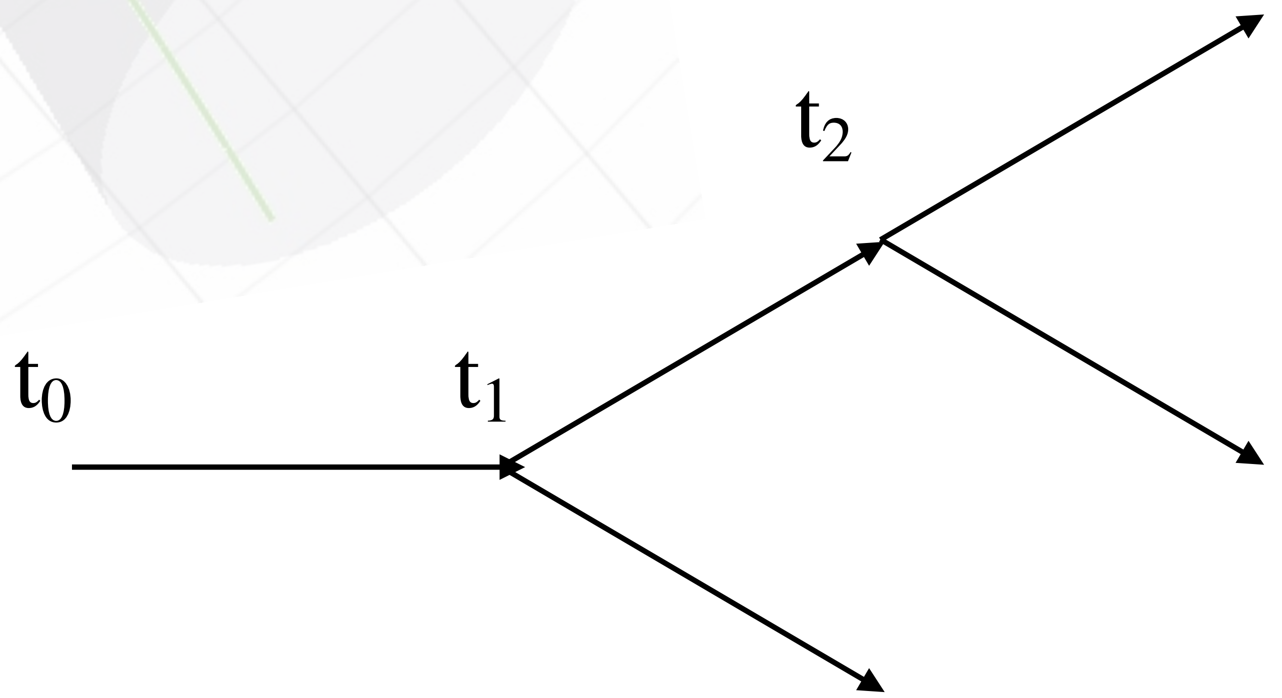

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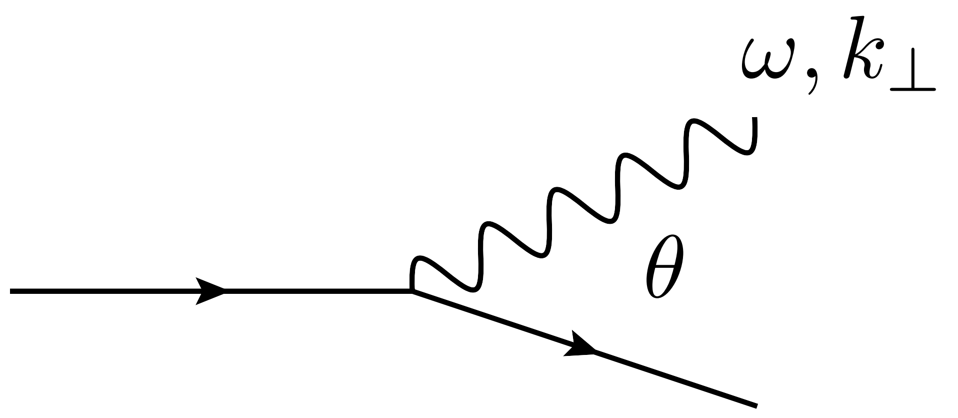

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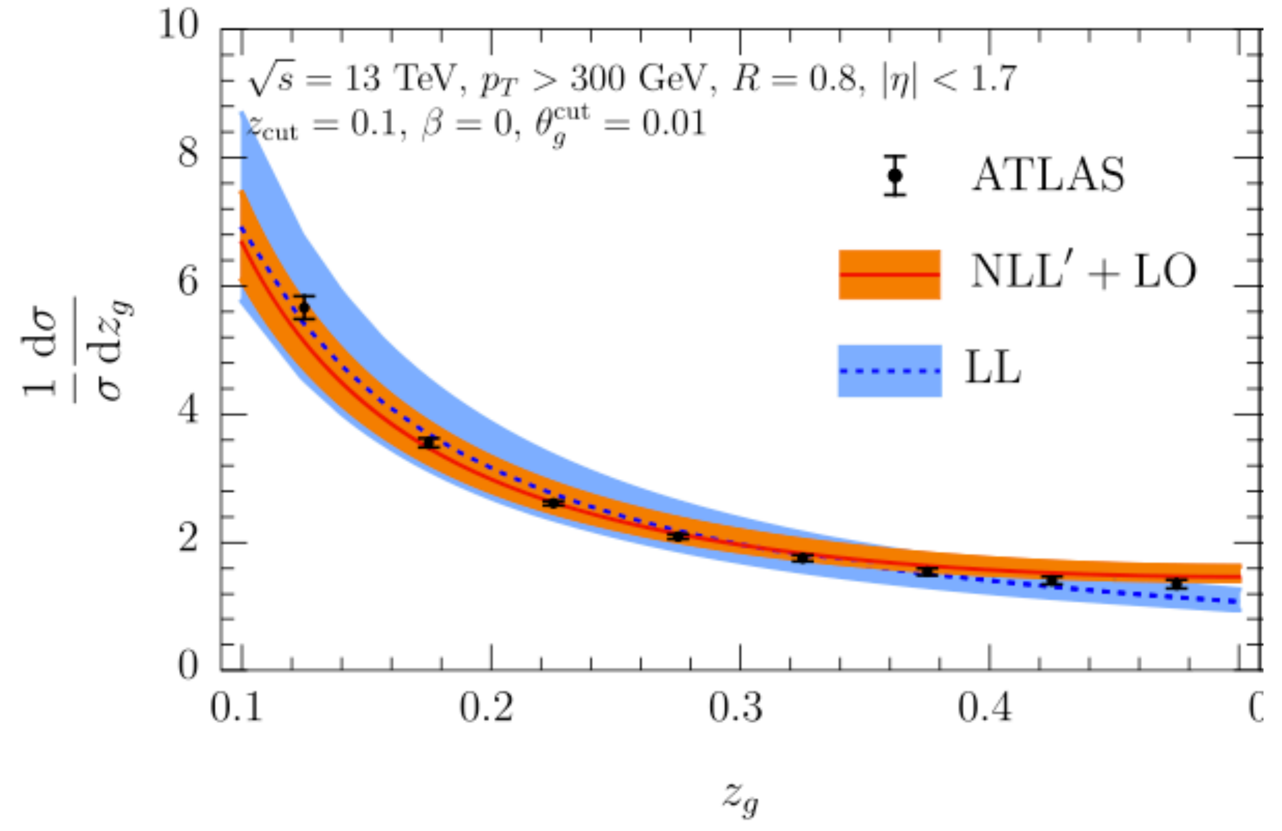

Re-summation of multiple emissions

↓

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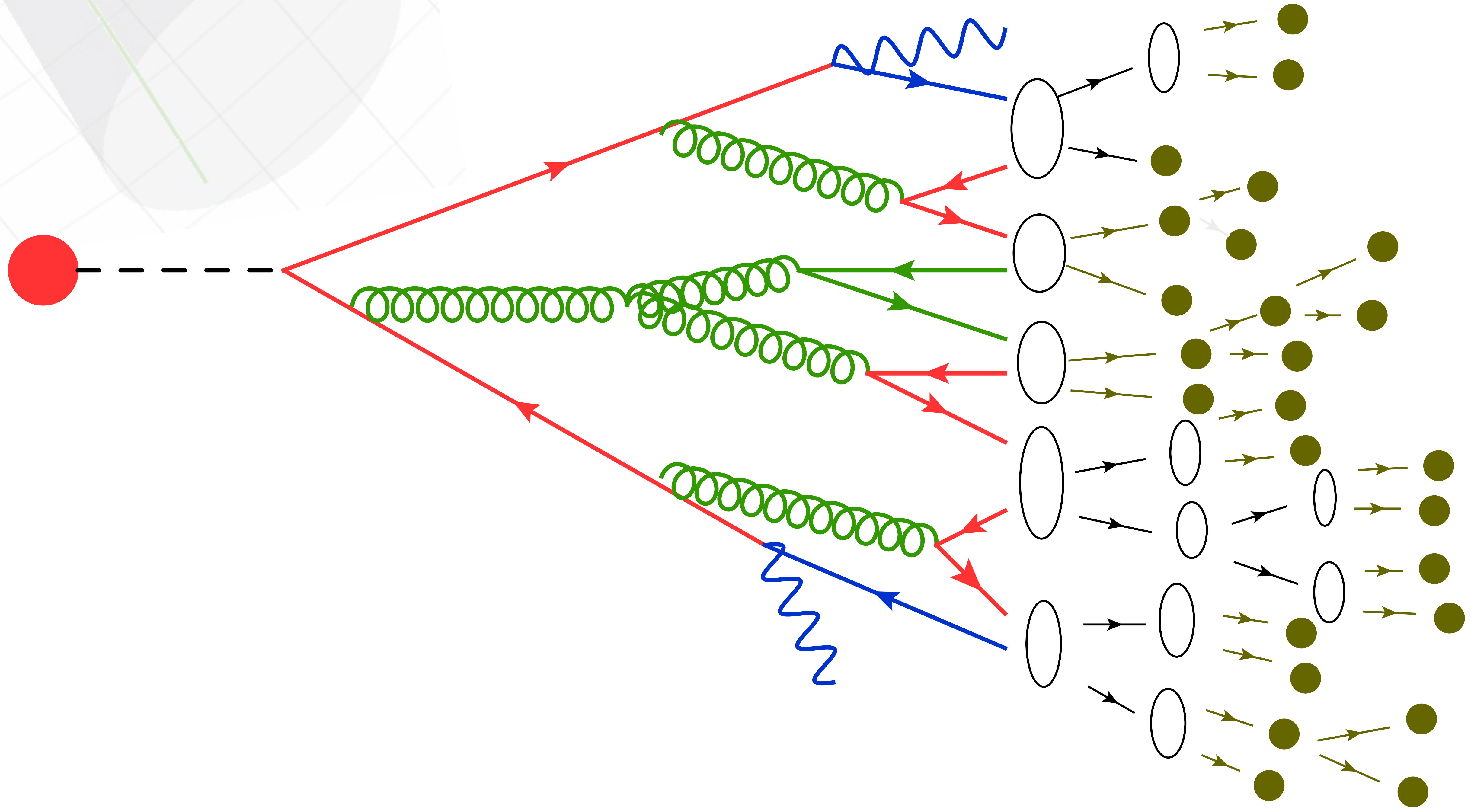
Just like a radioactive decay!

$$N(t) = \exp\left\{-\int_{t_0}^{t_1} dt f(t')dt'\right\}$$

$$\Rightarrow N(t) = N_0 e^{-\lambda t}$$

Parton Showers in pp

- Probabilistic picture allows to build subsequent parton emissions:



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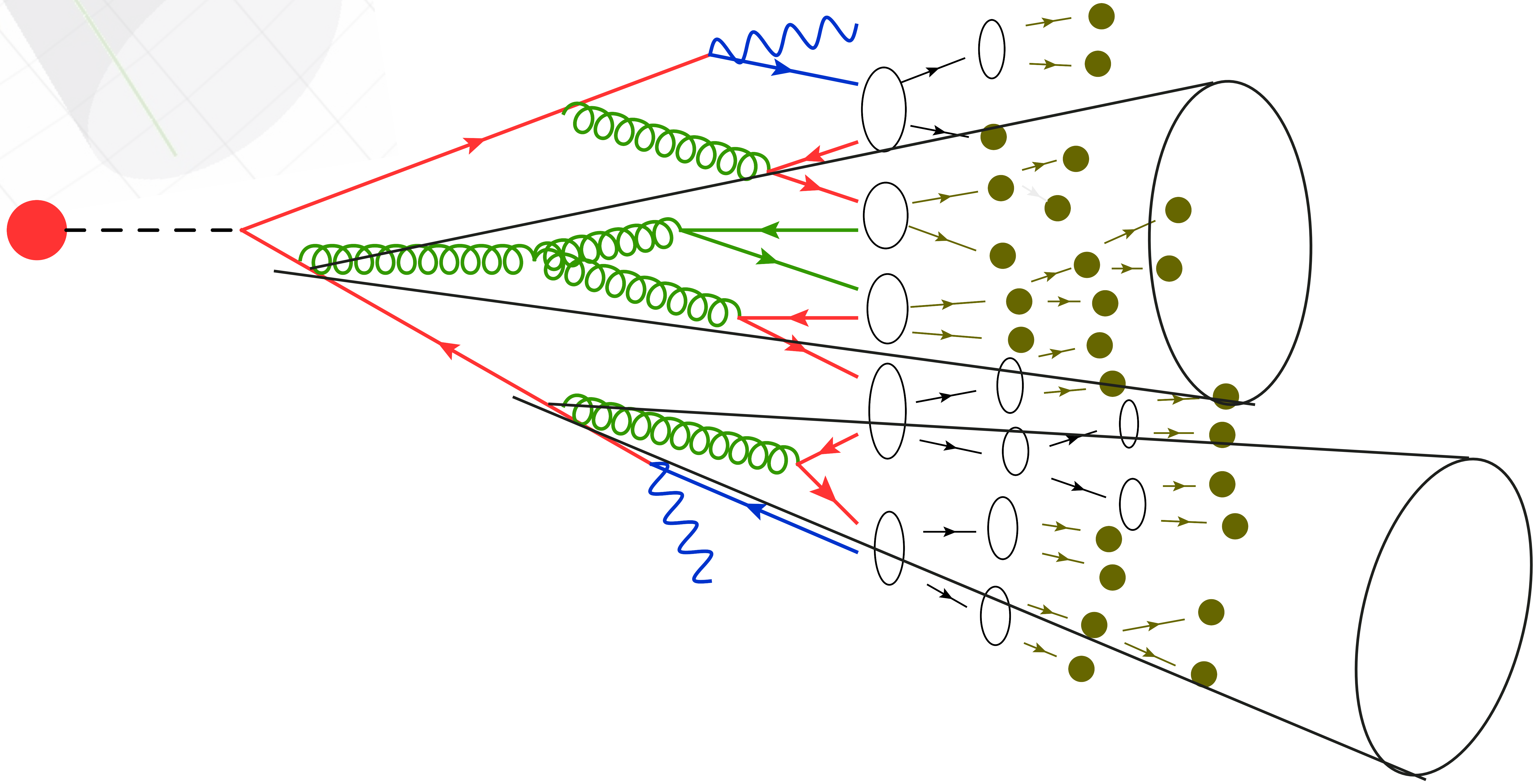


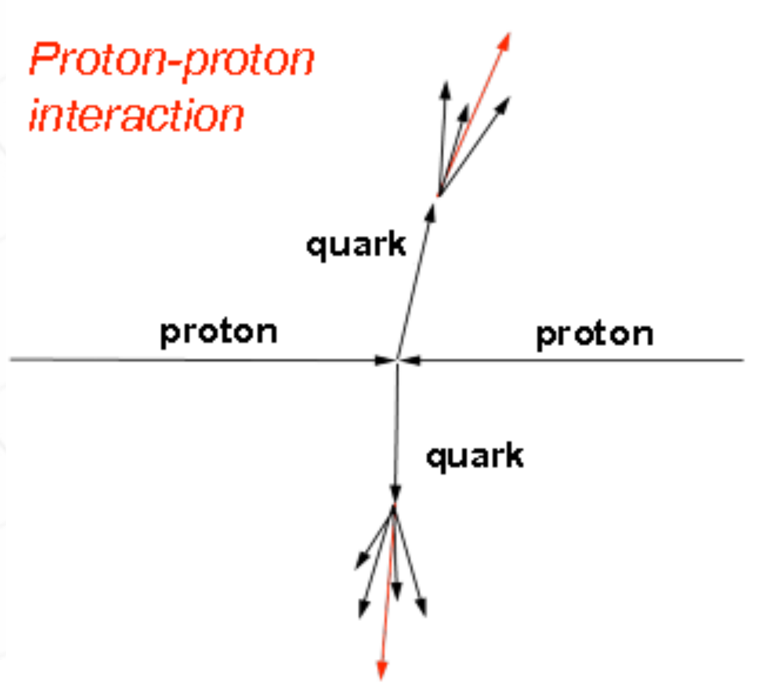
Jets in proton-proton

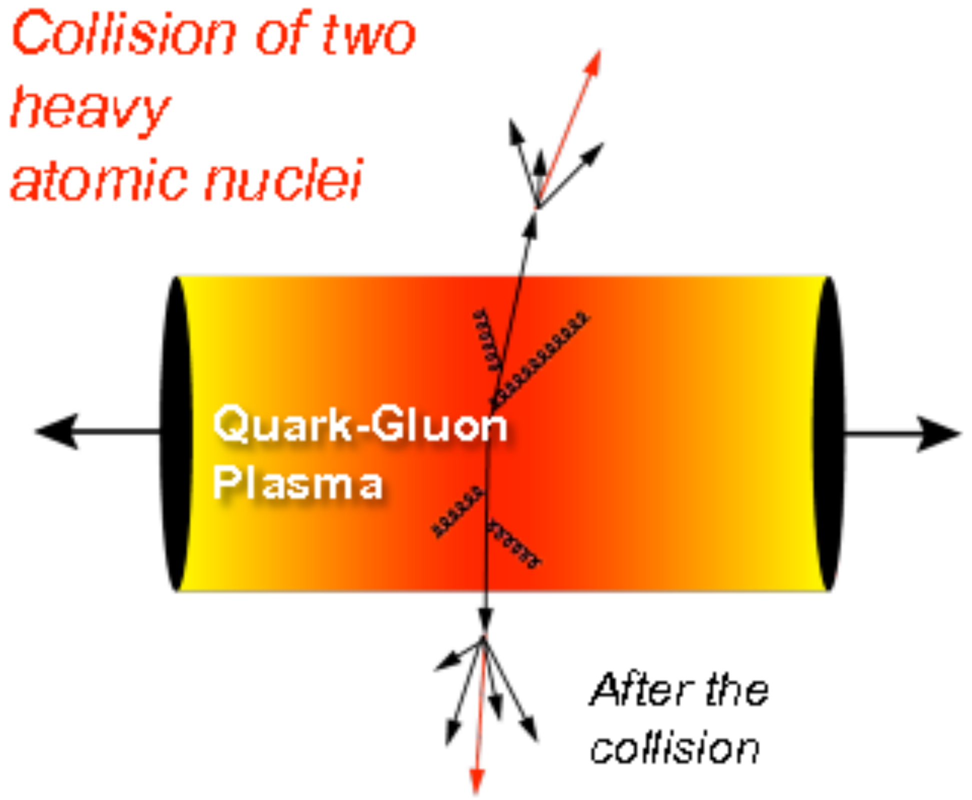
And now for something completely different…

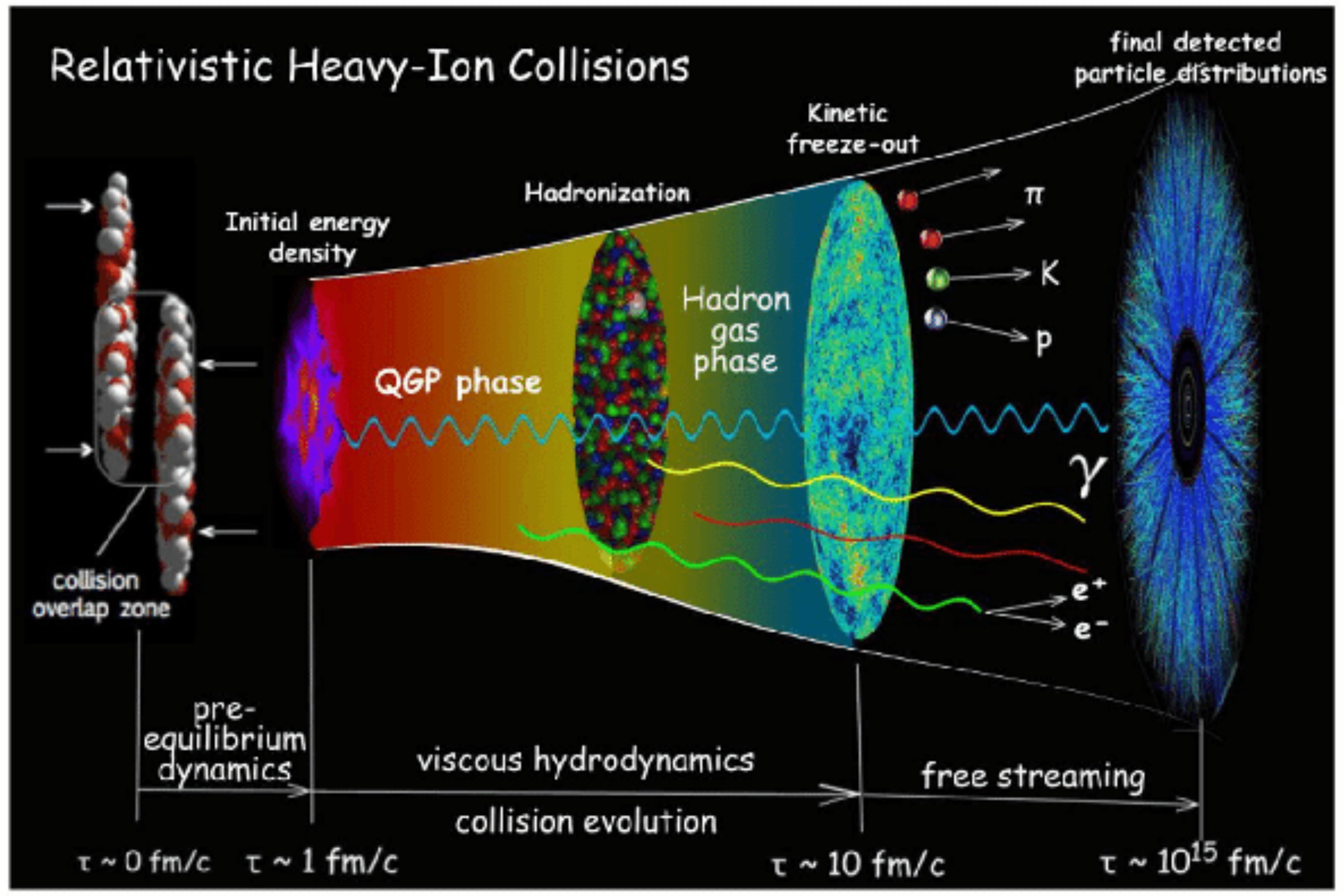
… Heavy-ions!

Heavy-Ions Collision

- PbPb collision: a complex multi-particle system



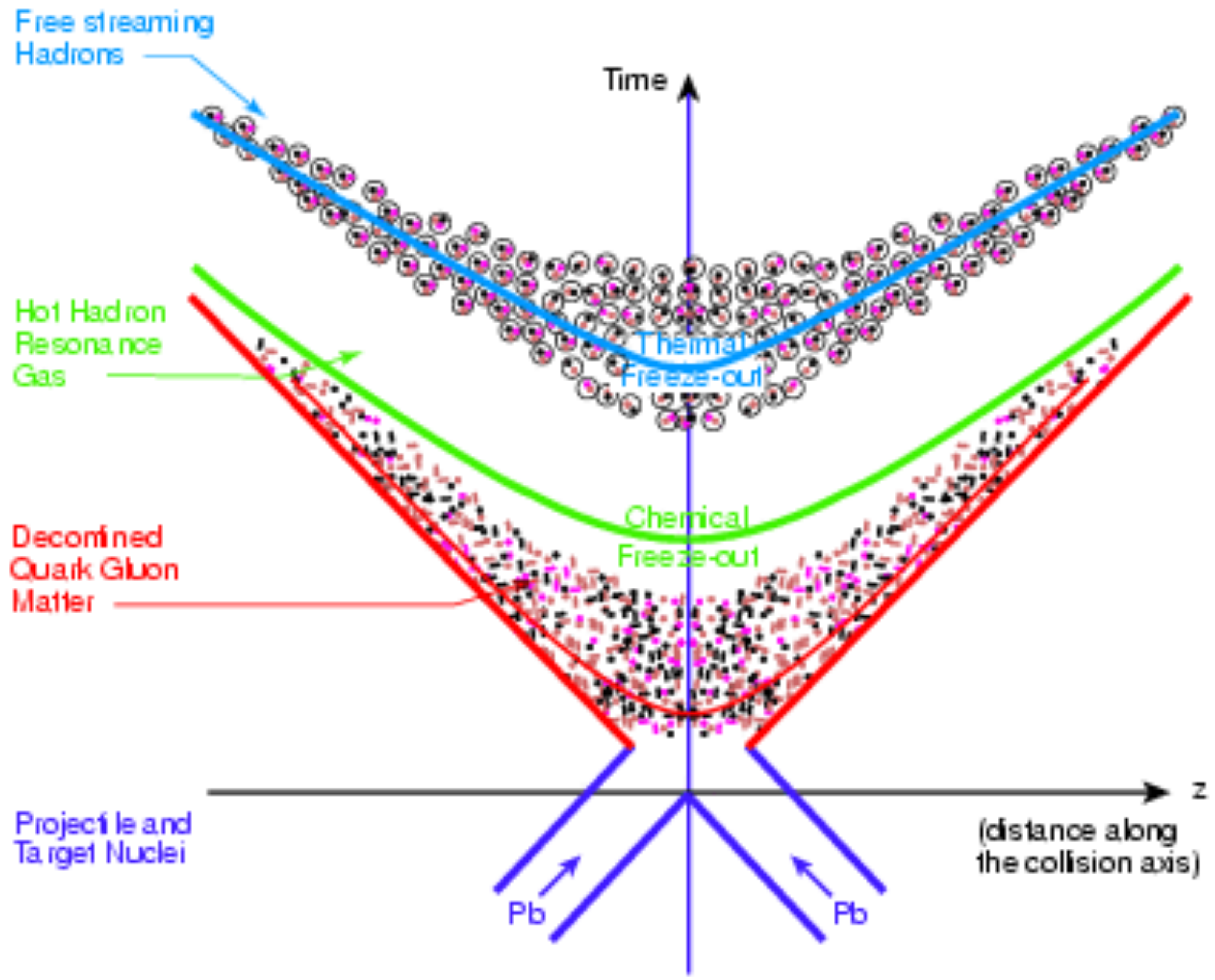




- Hot and dense medium (QGP)
  - Fluid with collectivity phenomena
  - Also QCD system, but strongly interacting!
    - How collectivity emerge from a QFT?
    - How does it evolve?
    - How is thermalised?
- Products from hard scattering:
  - Particles modified w.r.t pp:
    - Jet Quenching effects

Hard Probes

- Hard probes: Heavy-flavour, Quarkonia, jets, … See Monday lectures
  - Produced in a high momentum transfer process (hard scattering)
  - Indirect observation of the QGP effects
  - ➡ Observe the evolution of the QGP (temperature, density,…)



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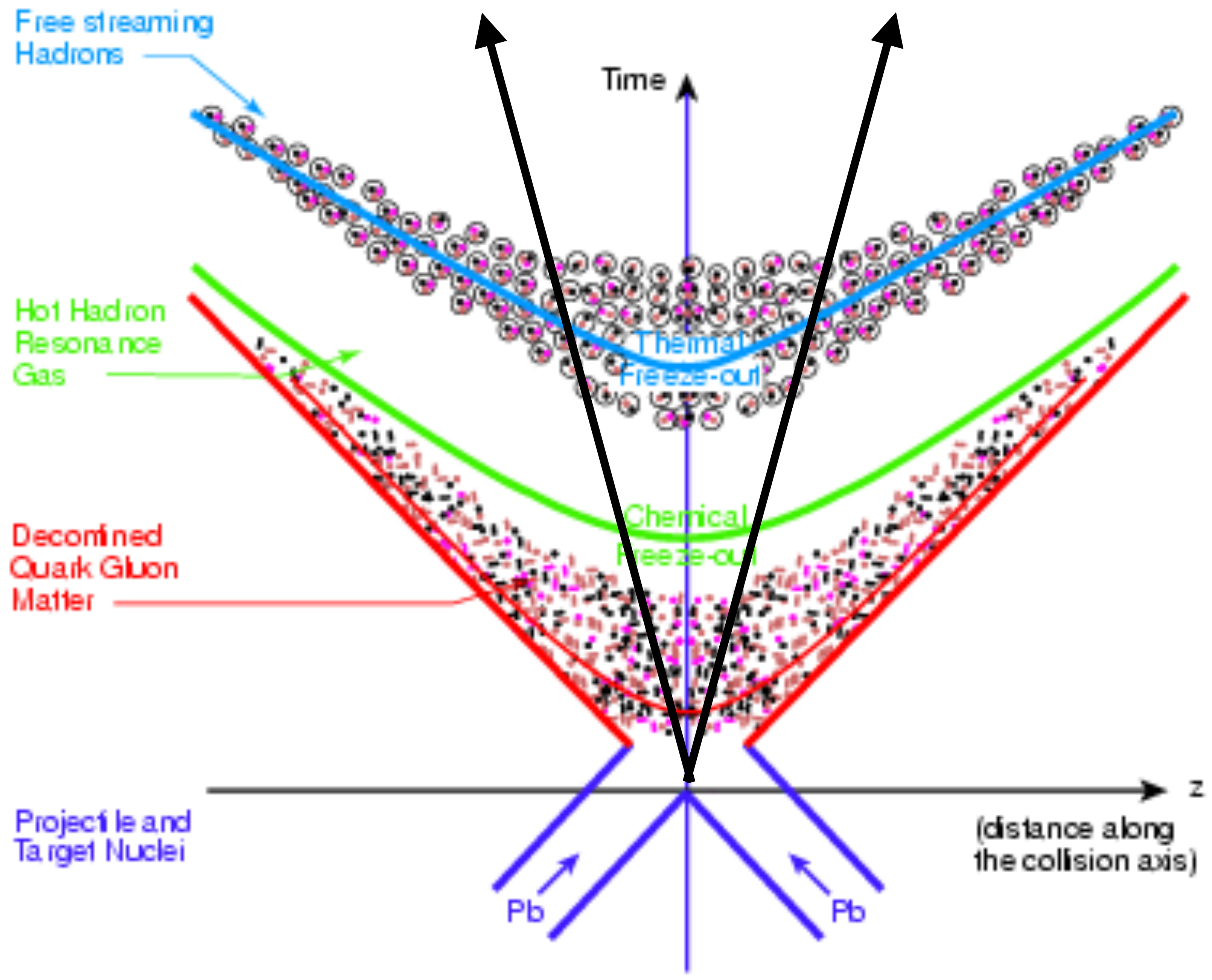
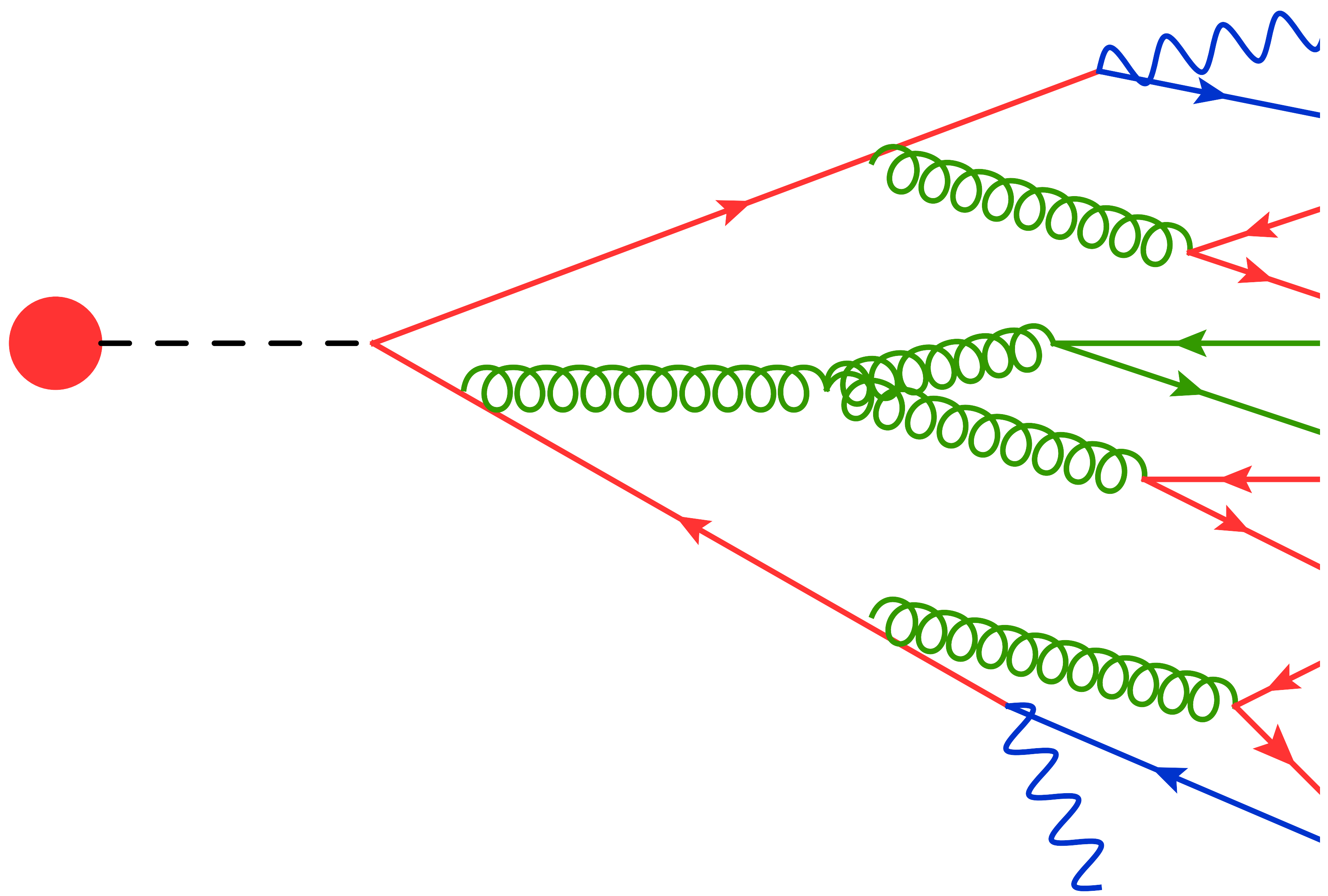


Jets in Heavy-Ion Collisions

- QGP-induced modifications on a proton-proton jet:



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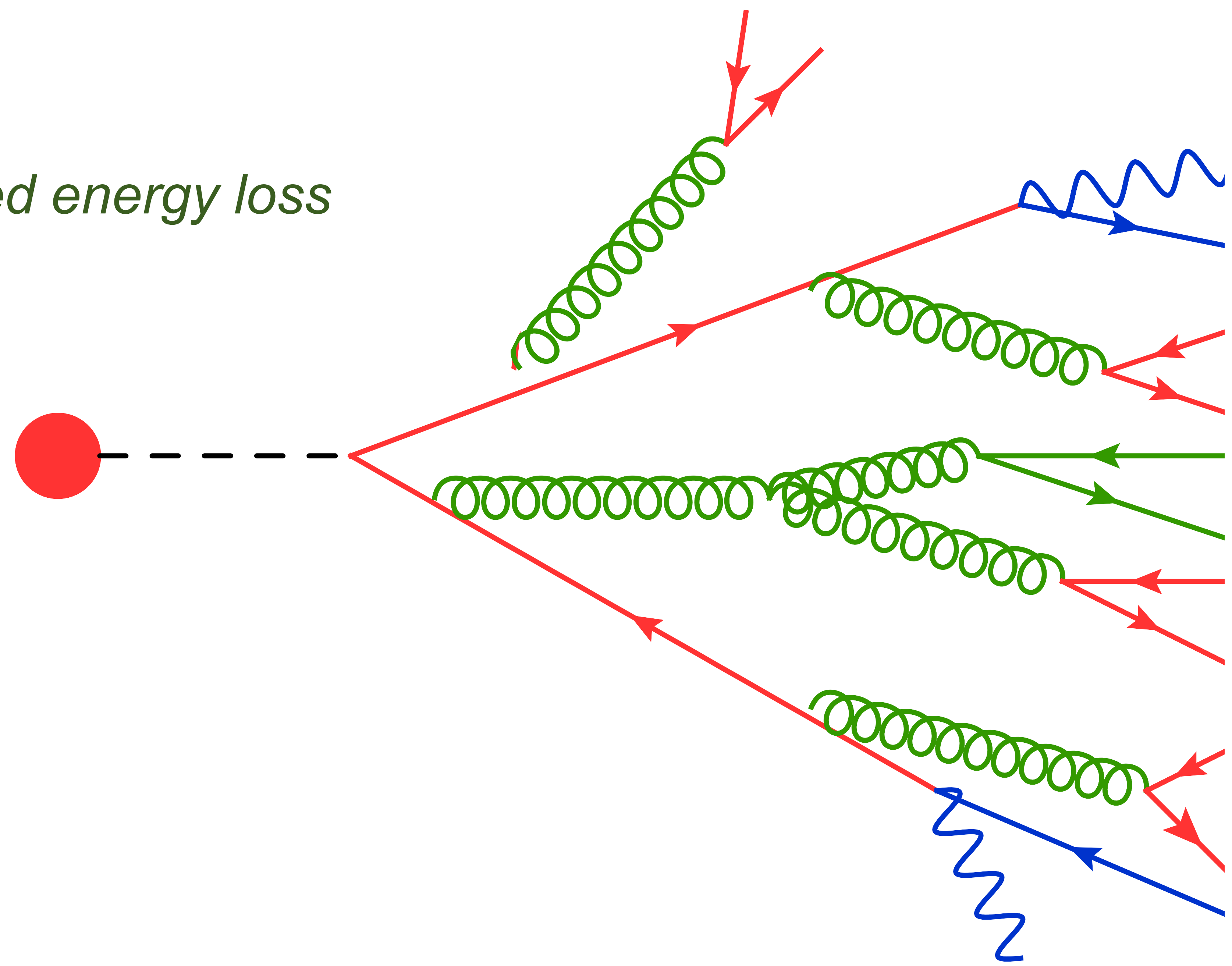
Medium-induced energy loss



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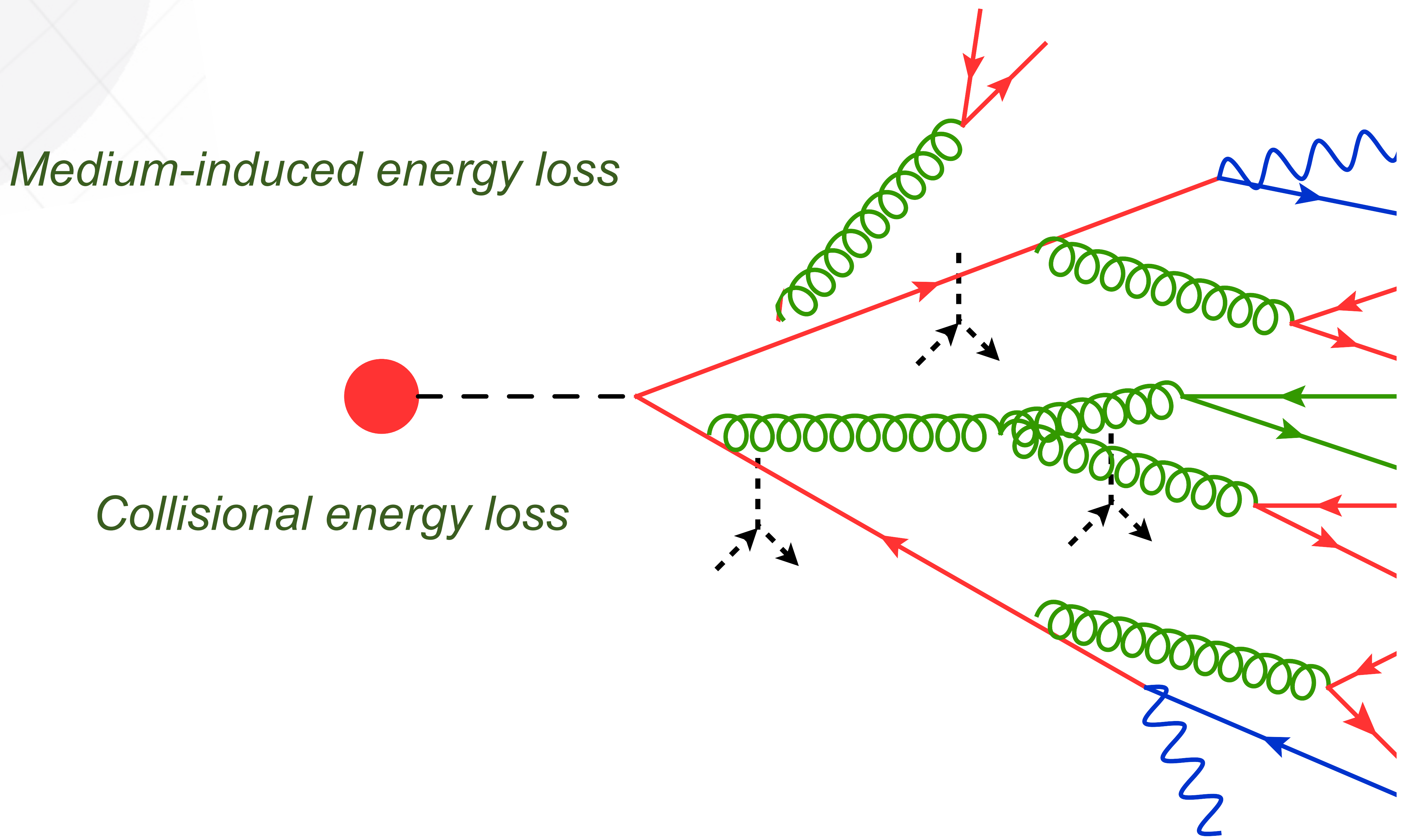

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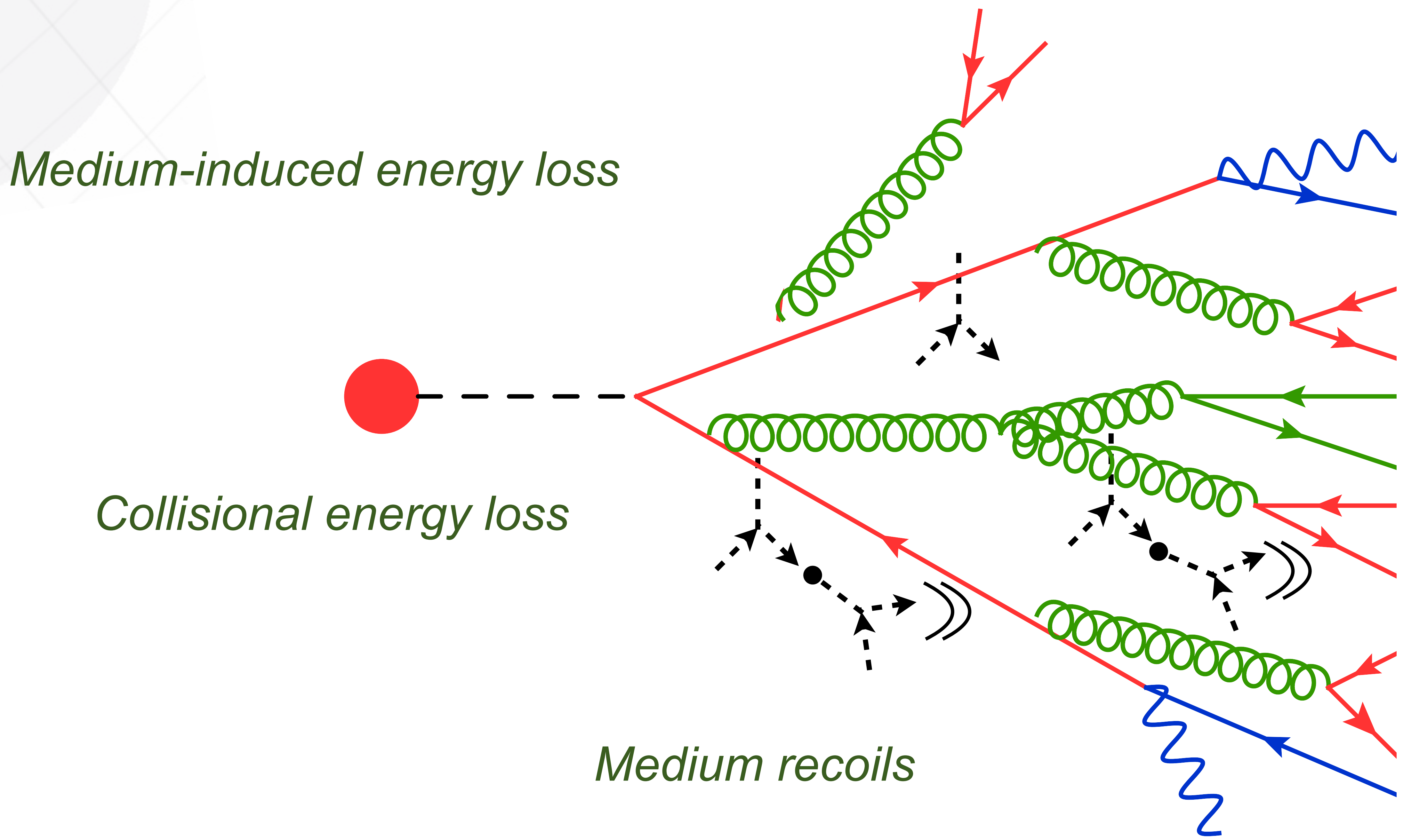

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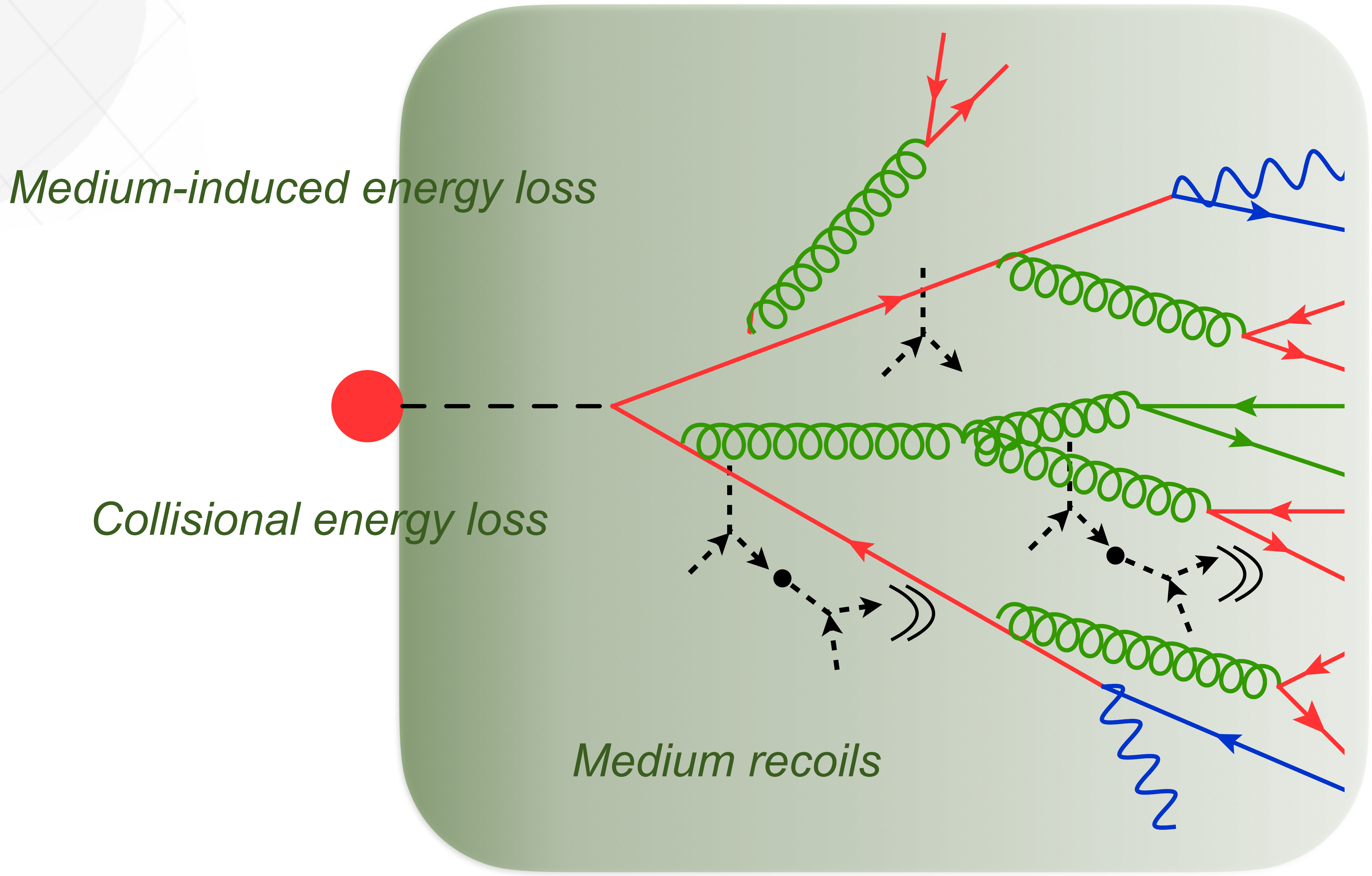

Medium: Strongly coupled fluid?

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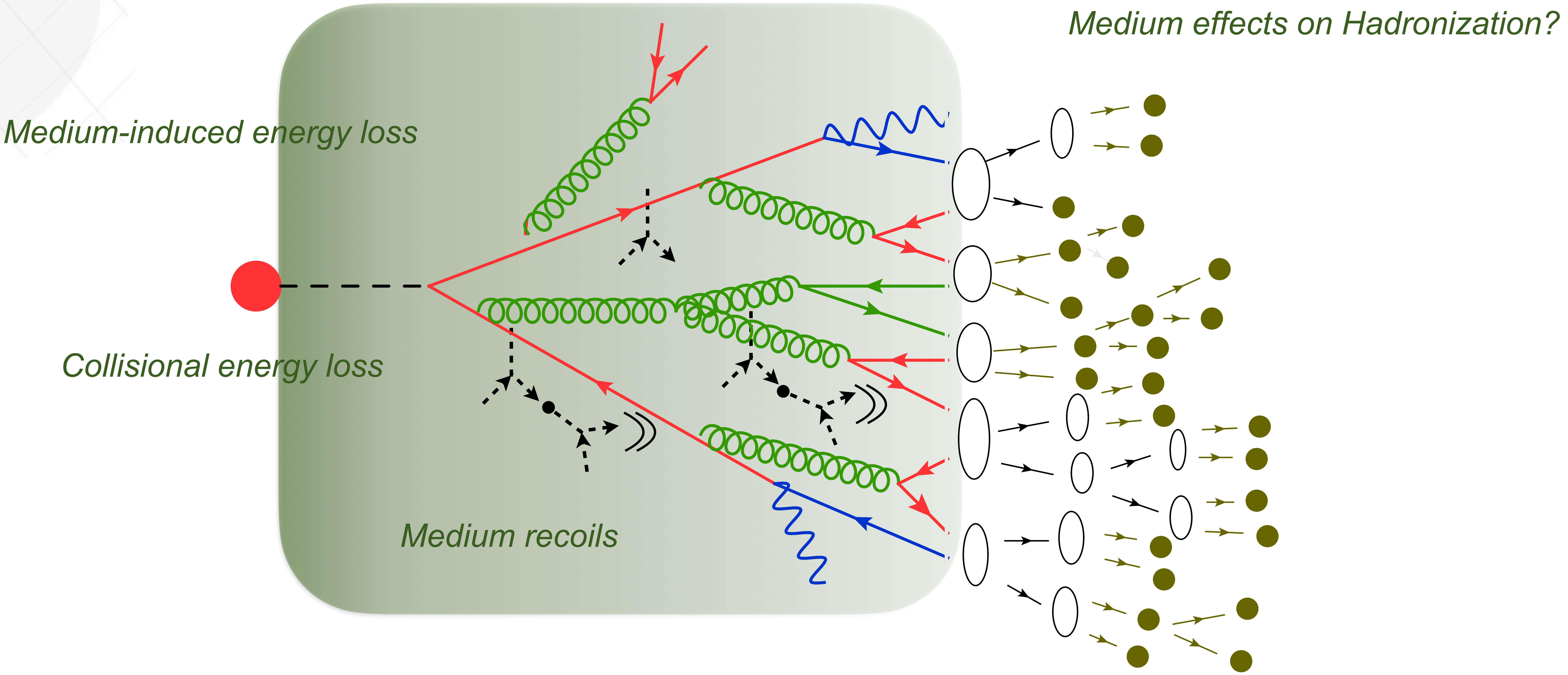


Medium: Strongly coupled fluid?

Jets in Heavy-Ion Collisions

See Ismail Soudi (Fri)

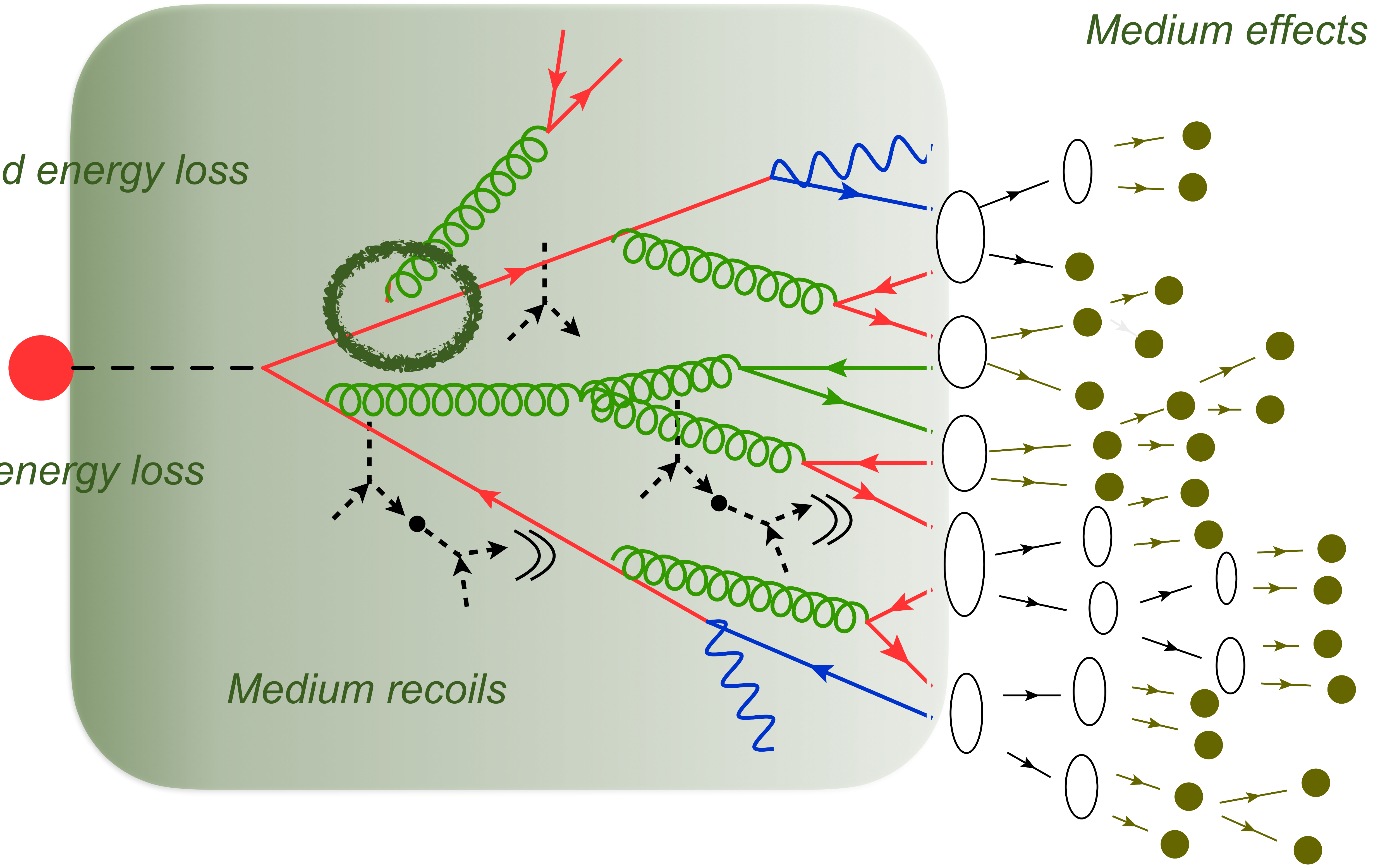
- QGP-induced modifications on a proton-proton jet:

Start with the building blocks:

Medium-induced energy loss

Medium effects on Hadronization?

Collisional energy loss



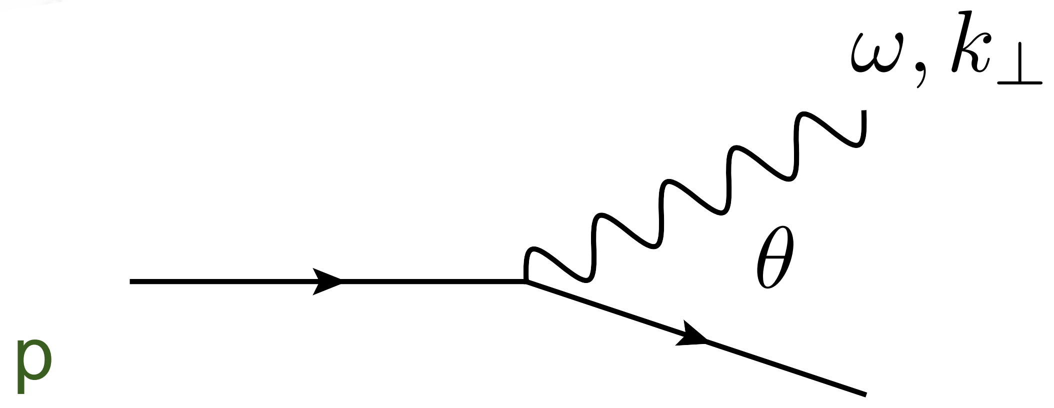
Medium recoils

Medium: Strongly coupled fluid?

Medium-induced radiation

- Within a perturbative QCD perspective, the incoming quark will undergo multiple scatterings with the medium (QGP):

Vacuum



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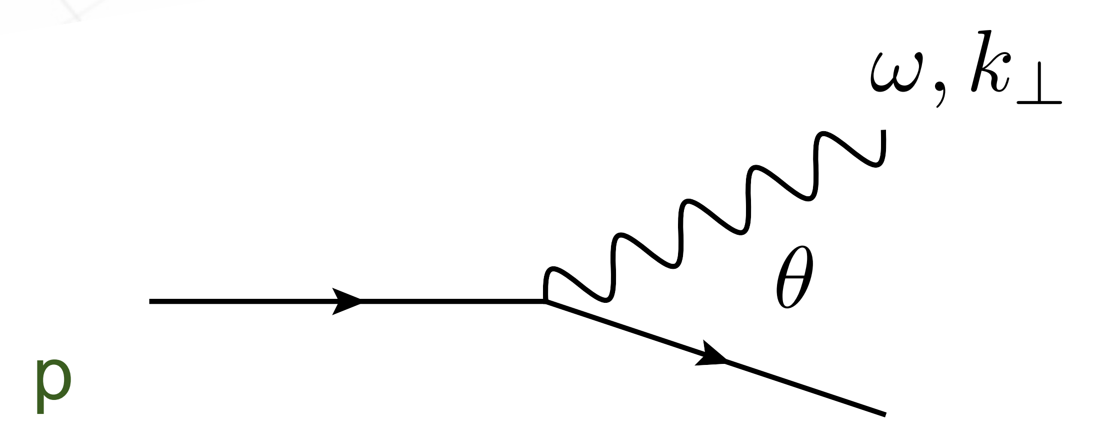
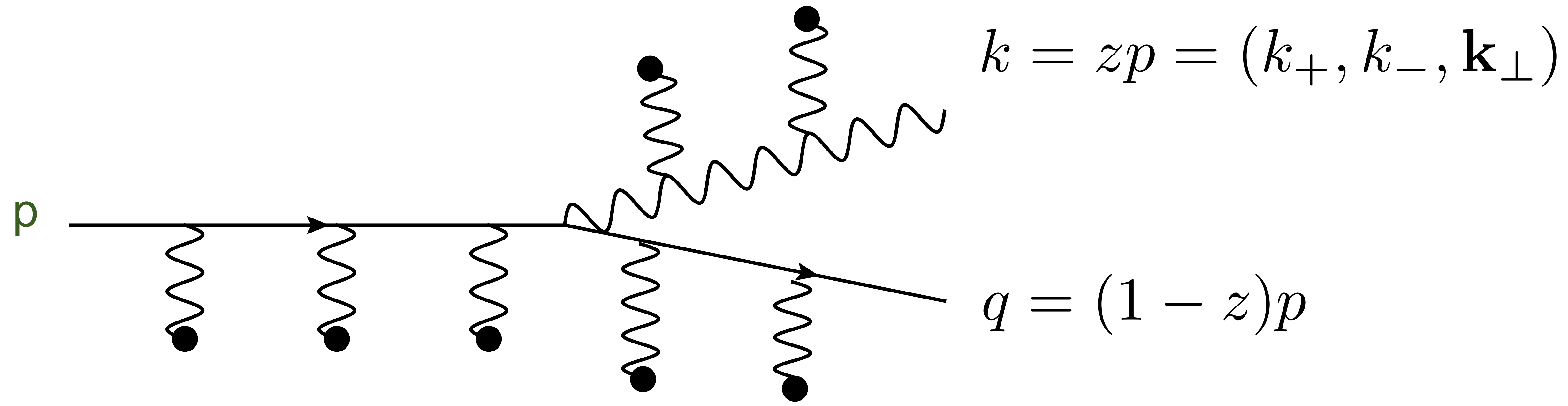


In-medium



Light-cone gauge:
(High-energy limit)

$$p_+ = \frac{p_0 + p_3}{\sqrt{2}} \simeq \sqrt{2} p_0$$

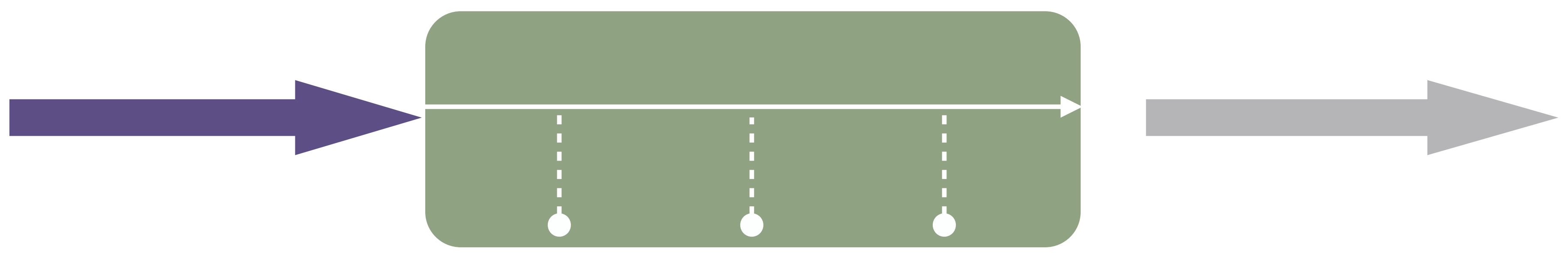
$$p_- = \frac{p_0 - p_3}{\sqrt{2}} \simeq 0$$

In-medium propagators

- Adapt Feynman rules to account for a hot and dense QCD medium:

Vacuum QCD Feynman rules $\Longrightarrow$ In-medium QCD Feynman rules

$$= i\delta^{ab}\frac{\not{p}+m}{p^2-m^2+i\varepsilon}$$



Wilson line (change in colour):

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

Gluon fields

Medium longitudinal limits from $[x_{0+}, L_+]$

Path-ordered gluon fields

Transverse coordinate of the incoming parton

In-medium propagators

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Vacuum QCD Feynman rules

$\Longrightarrow$

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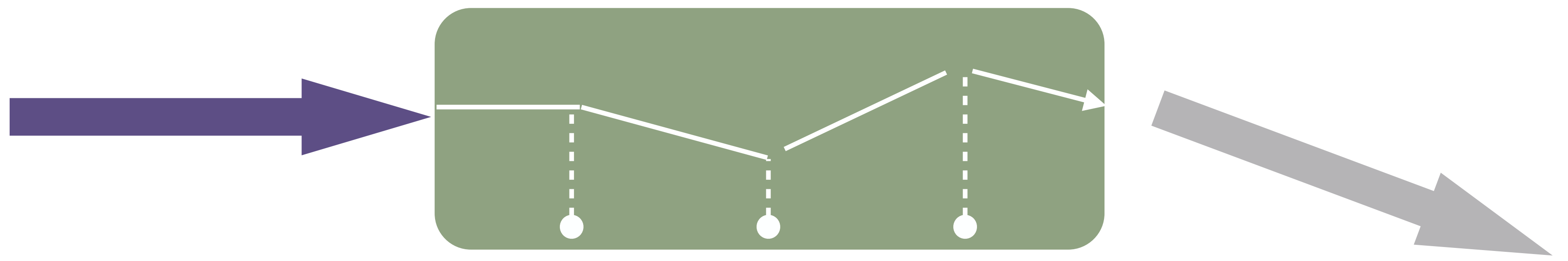

Green's function (+ change in xT):

Kinetic energy

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

Transverse positions at medium limits [x_{0+},L_+]

Incoming parton's energy

Path-integral (all possible trajectories)

In-medium propagators

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Vacuum QCD Feynman rules

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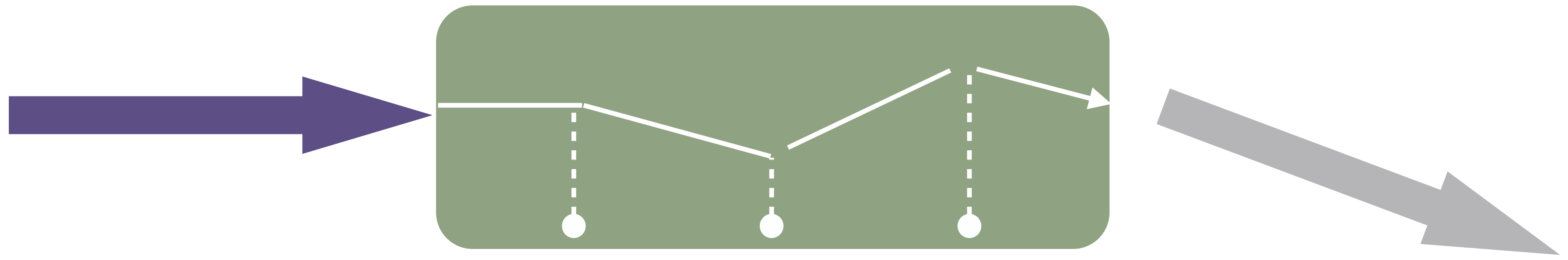
(...)



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Kinetic energy

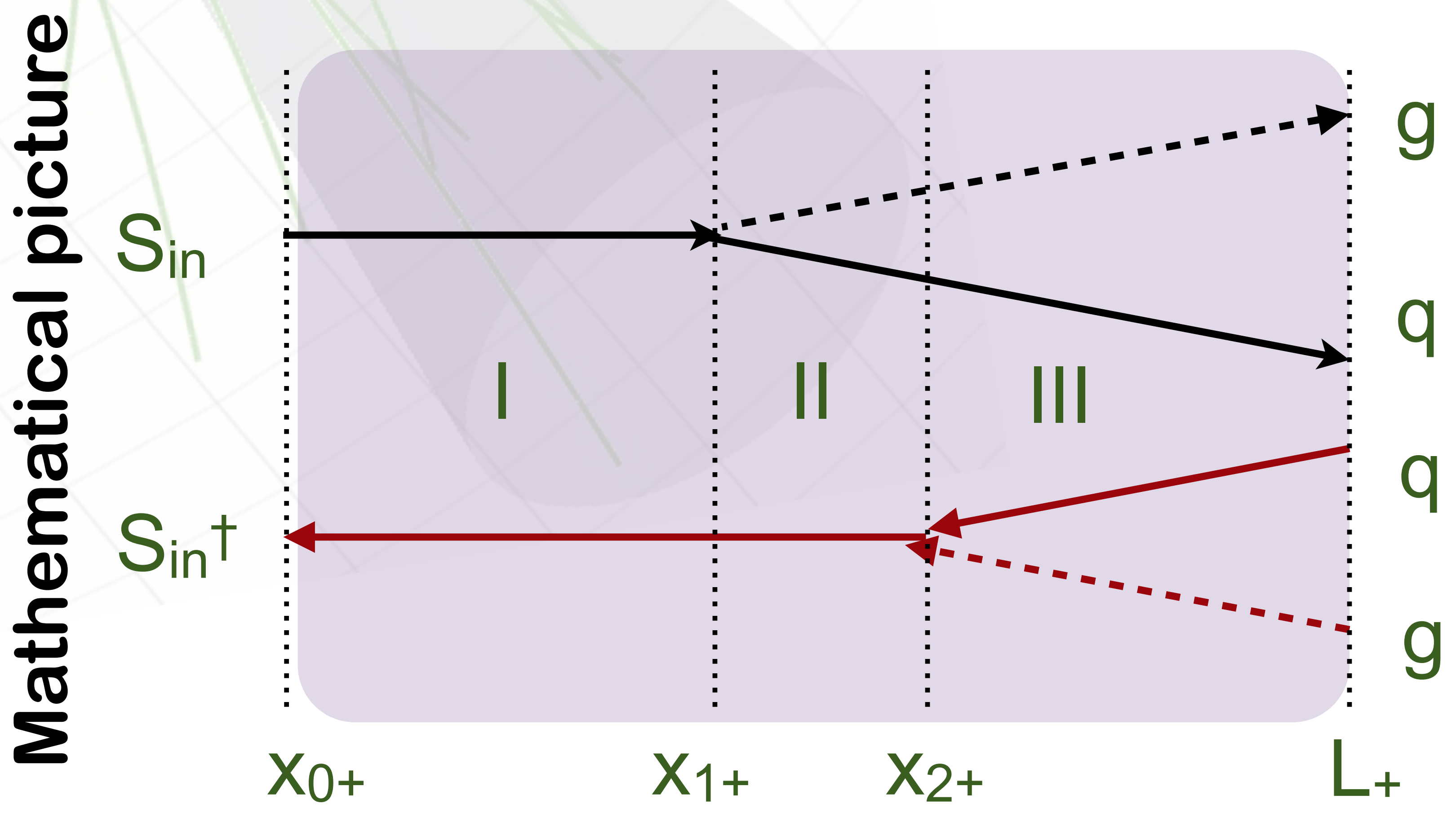
Transverse positions at medium limits [x_{0+},L_+]

Incoming parton's energy

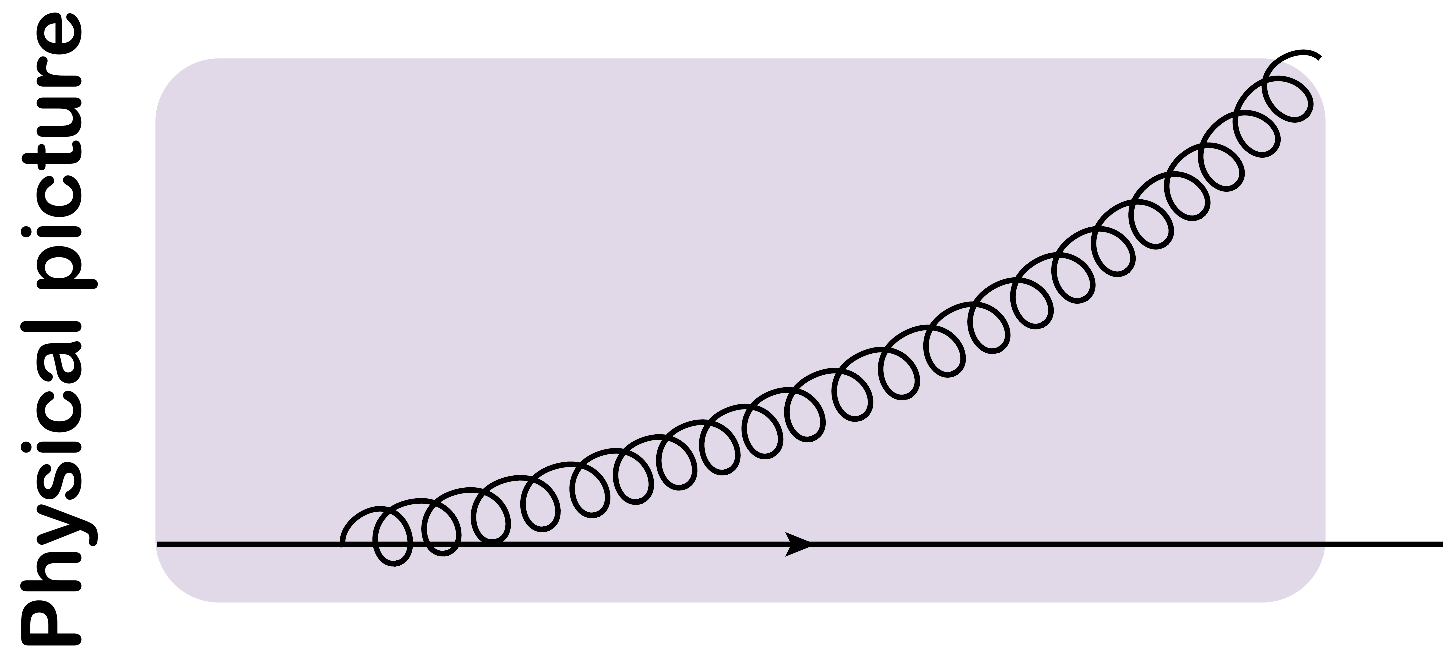
Path-integral (all possible trajectories)

Single in-medium gluon emission

- Medium-induced gluon radiation:



High energy approximation:
⇒ Decomposition with a fixed number of propagators
⇒ 3 different regions



$$k_+ \frac{dI}{dk_+ d^2\mathbf{k}_\perp} = \frac{1}{k_+} \int_{x_+}^{L_+} d\bar{x}_+ \; e^{-\frac{1}{2}\int_{x_+}^{L_+} d\xi n(\xi)\sigma(\mathbf{x})} \frac{\partial}{\partial \mathbf{y}} \cdot \frac{\partial}{\partial \mathbf{x}} \mathcal{K}(\mathbf{y}=0, x_+; \mathbf{x}, \bar{x}_+)$$

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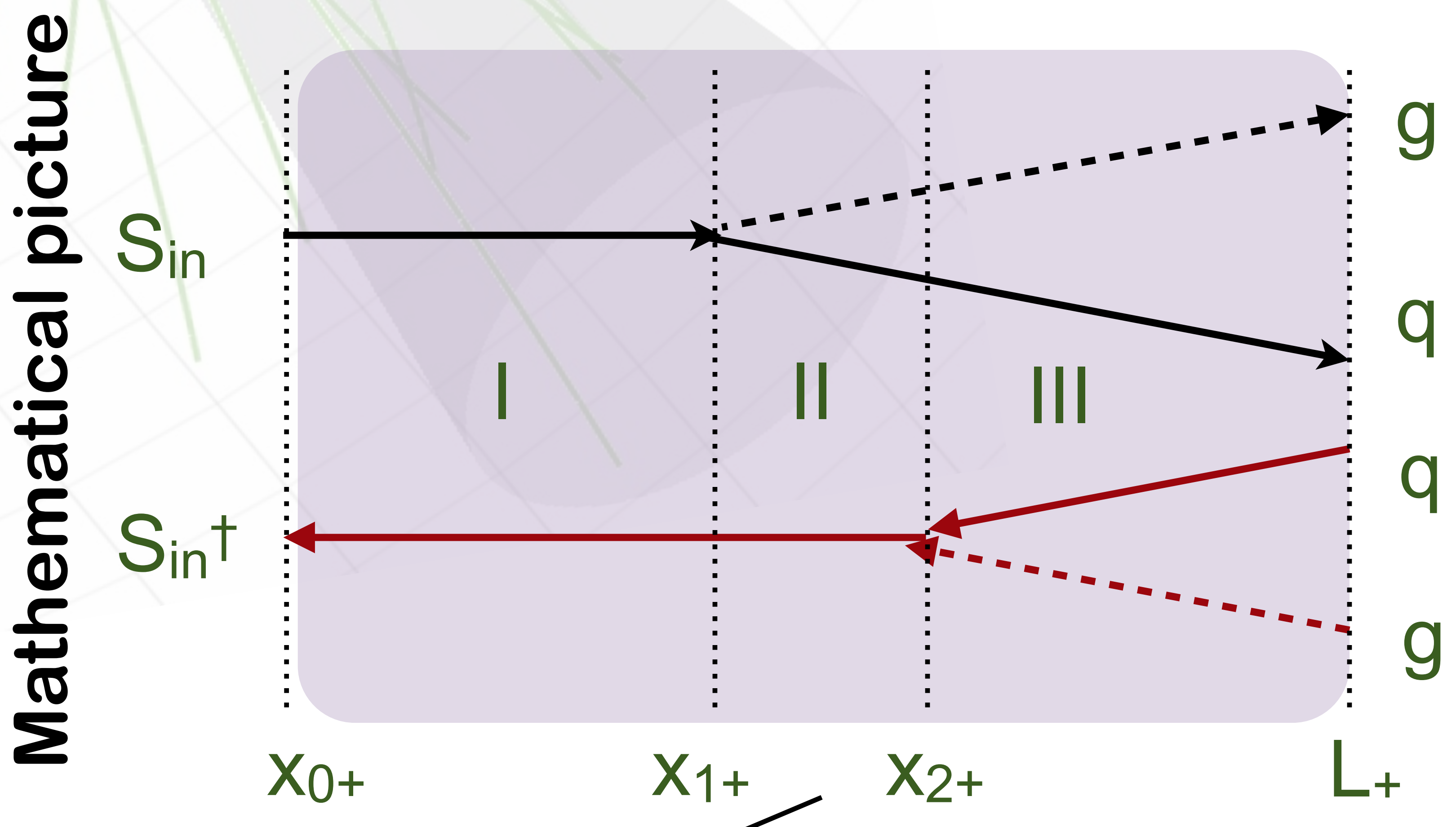
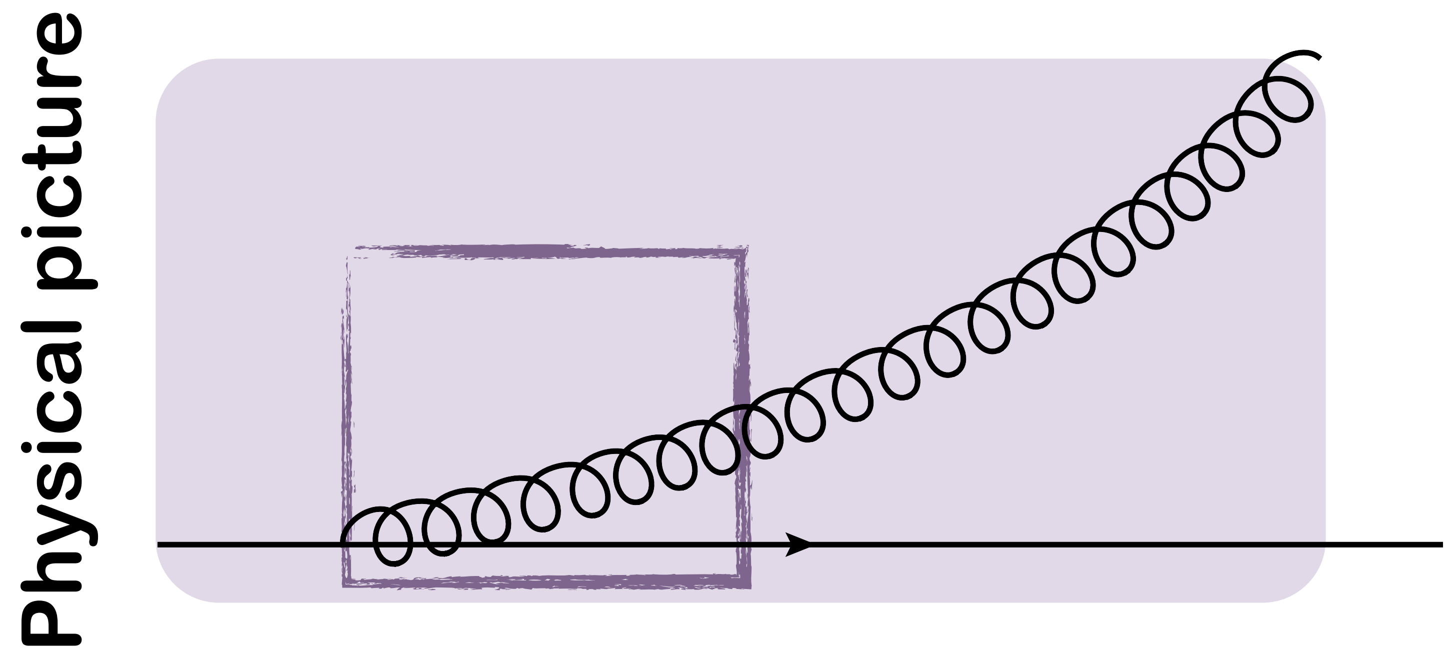


High energy approximation:
⇒ Decomposition with a fixed number of propagators
⇒ 3 different regions



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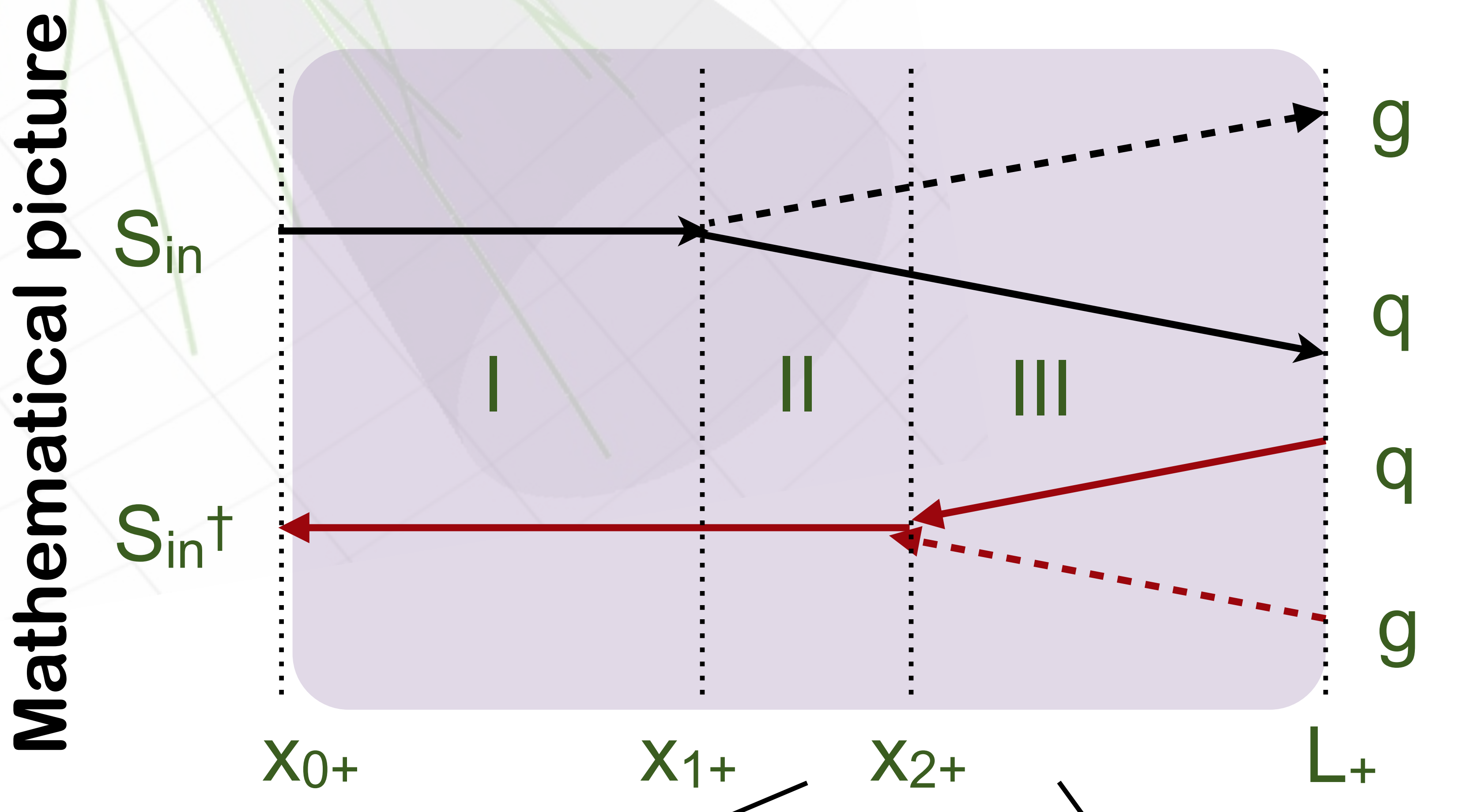

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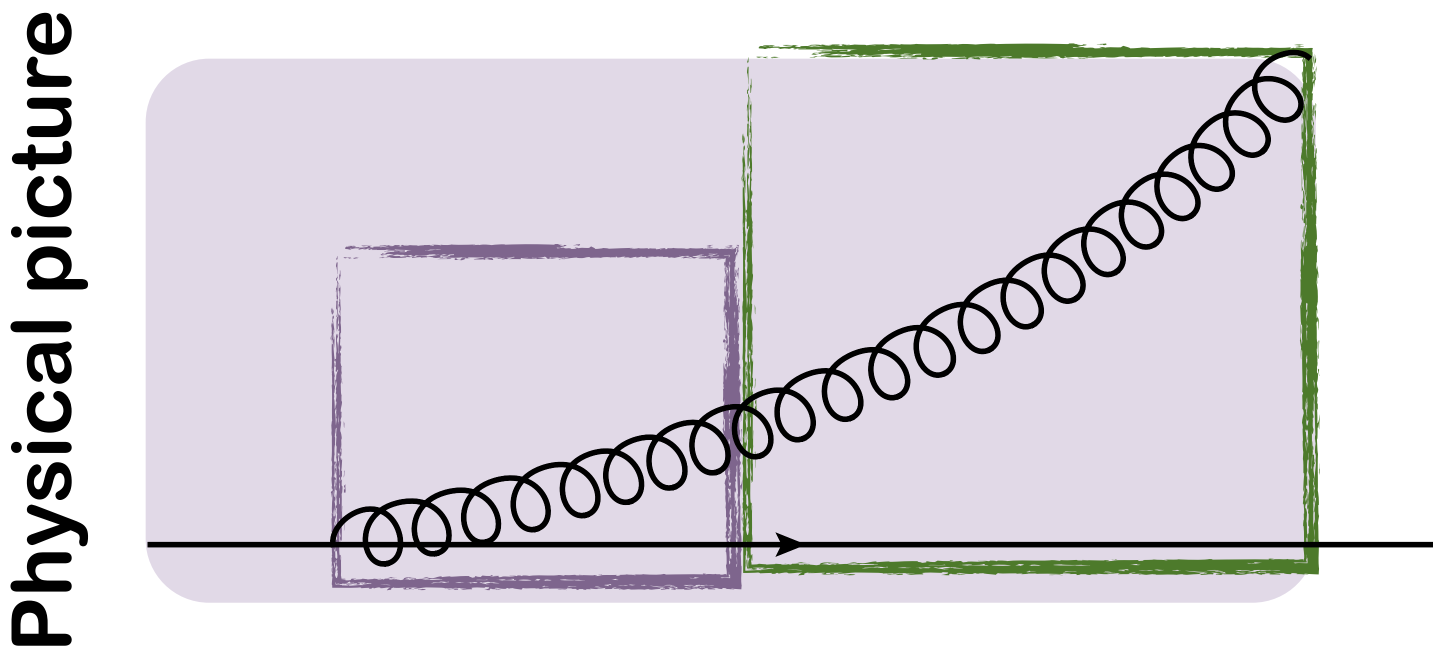

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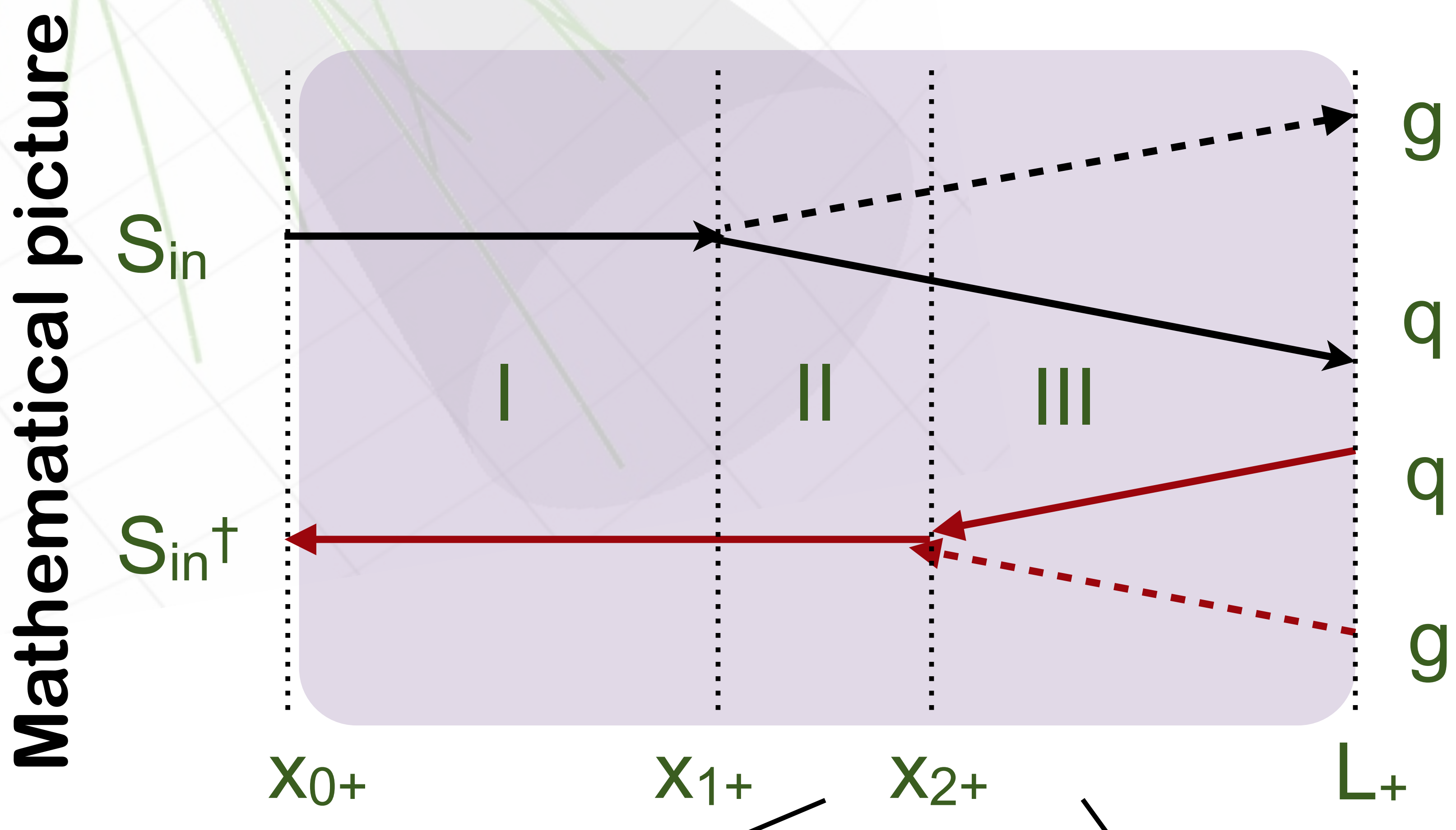

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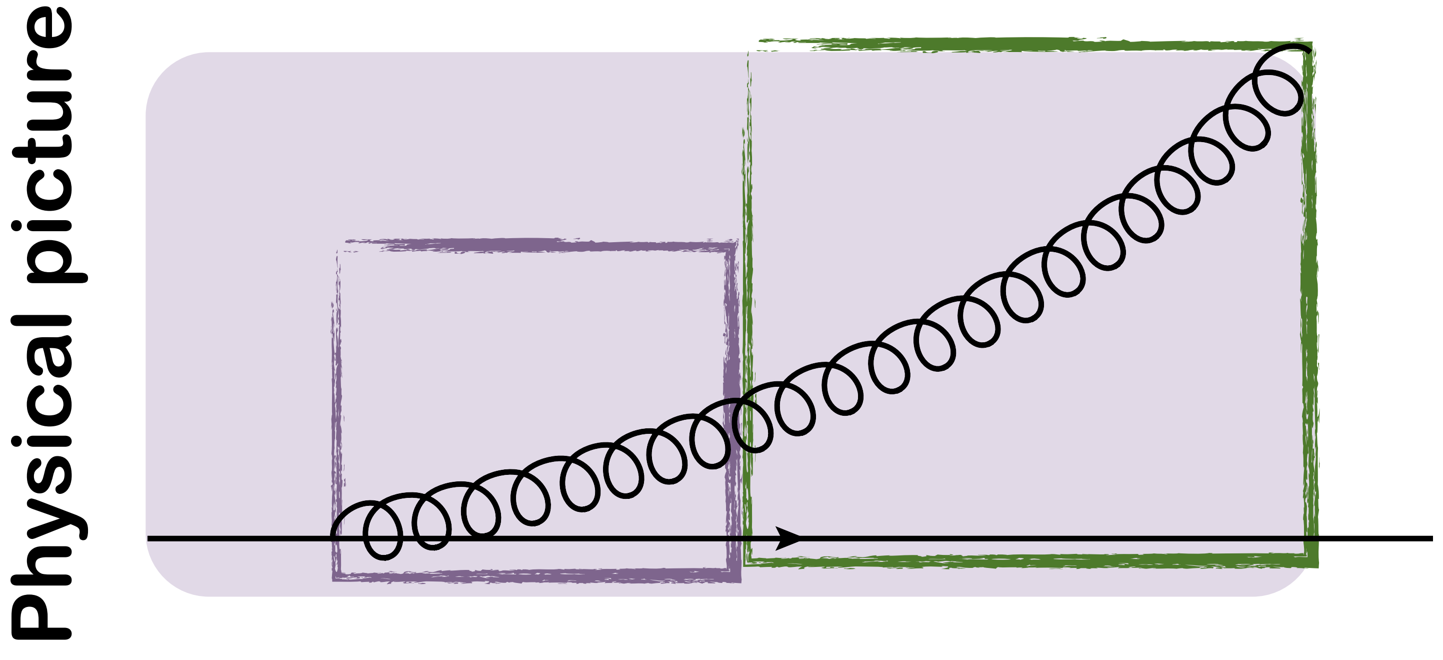

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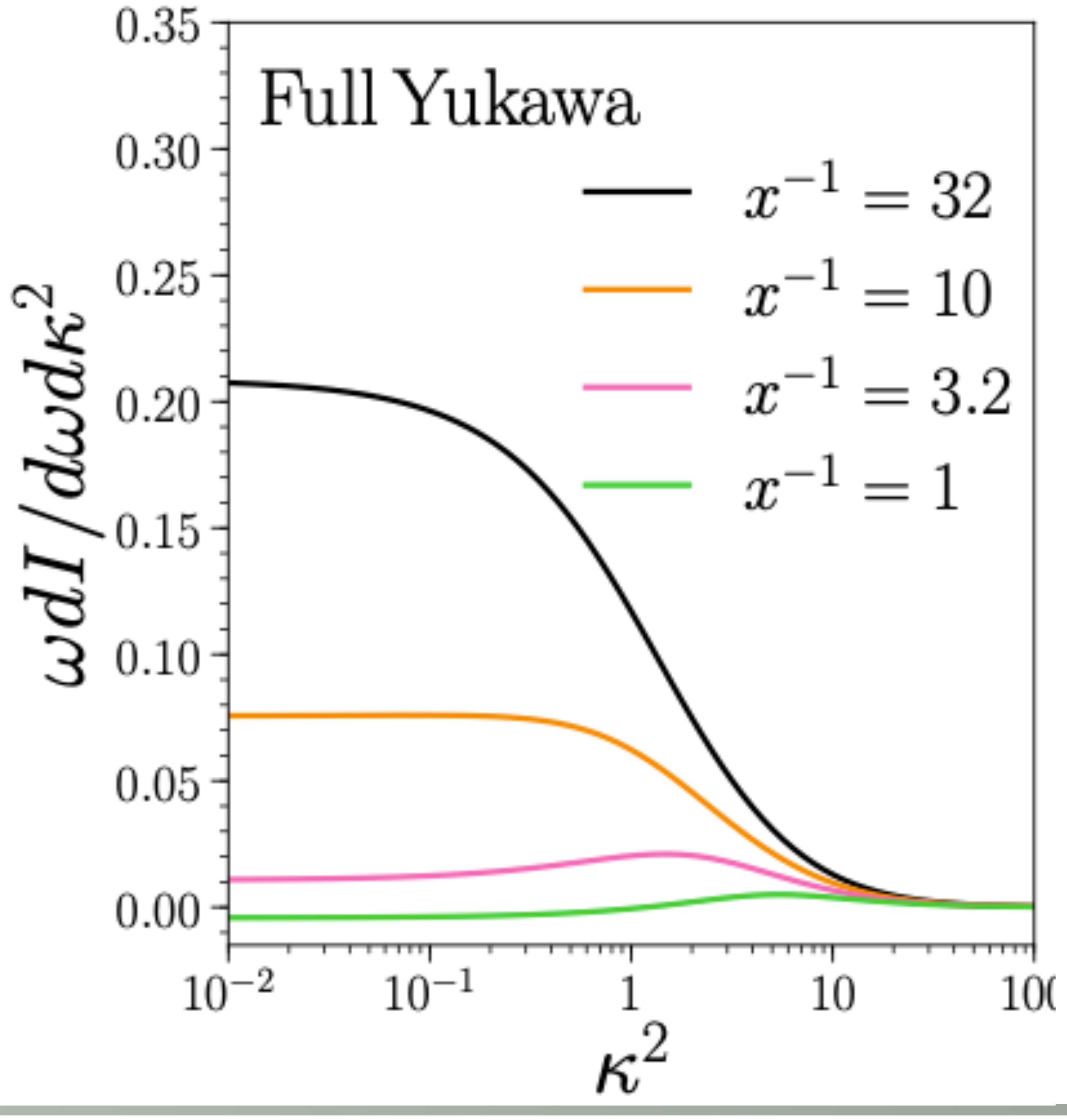
[Andrés, LA, Dominguez (2002.01517)]



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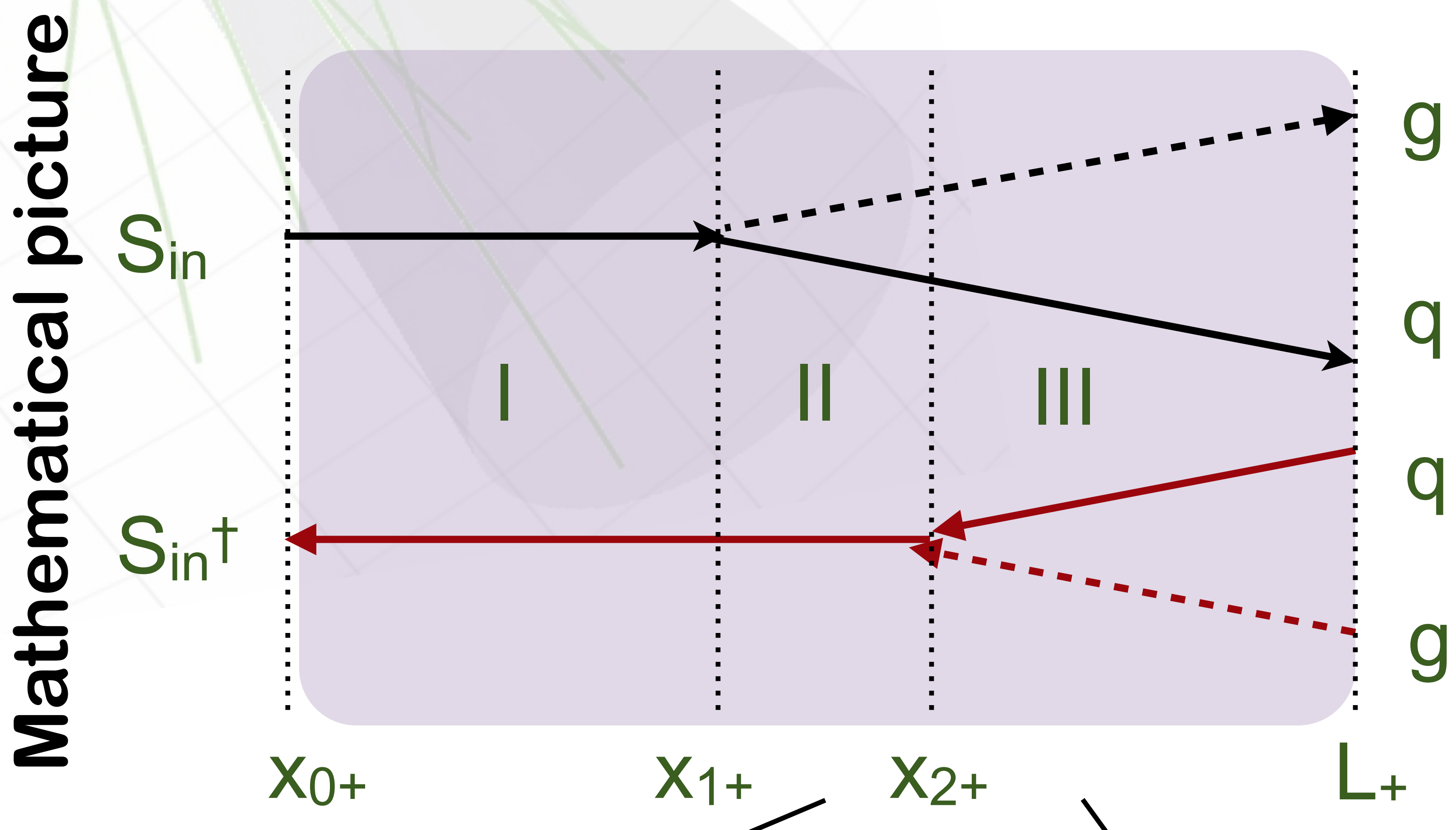

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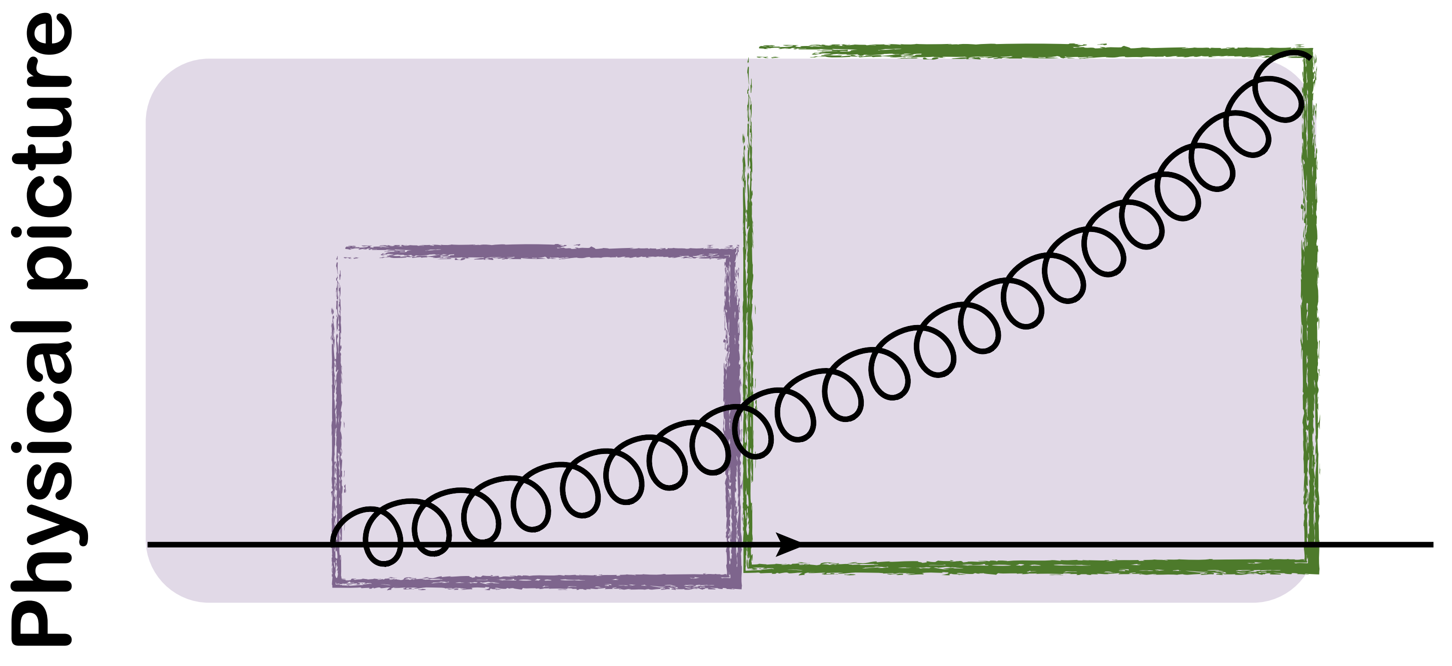

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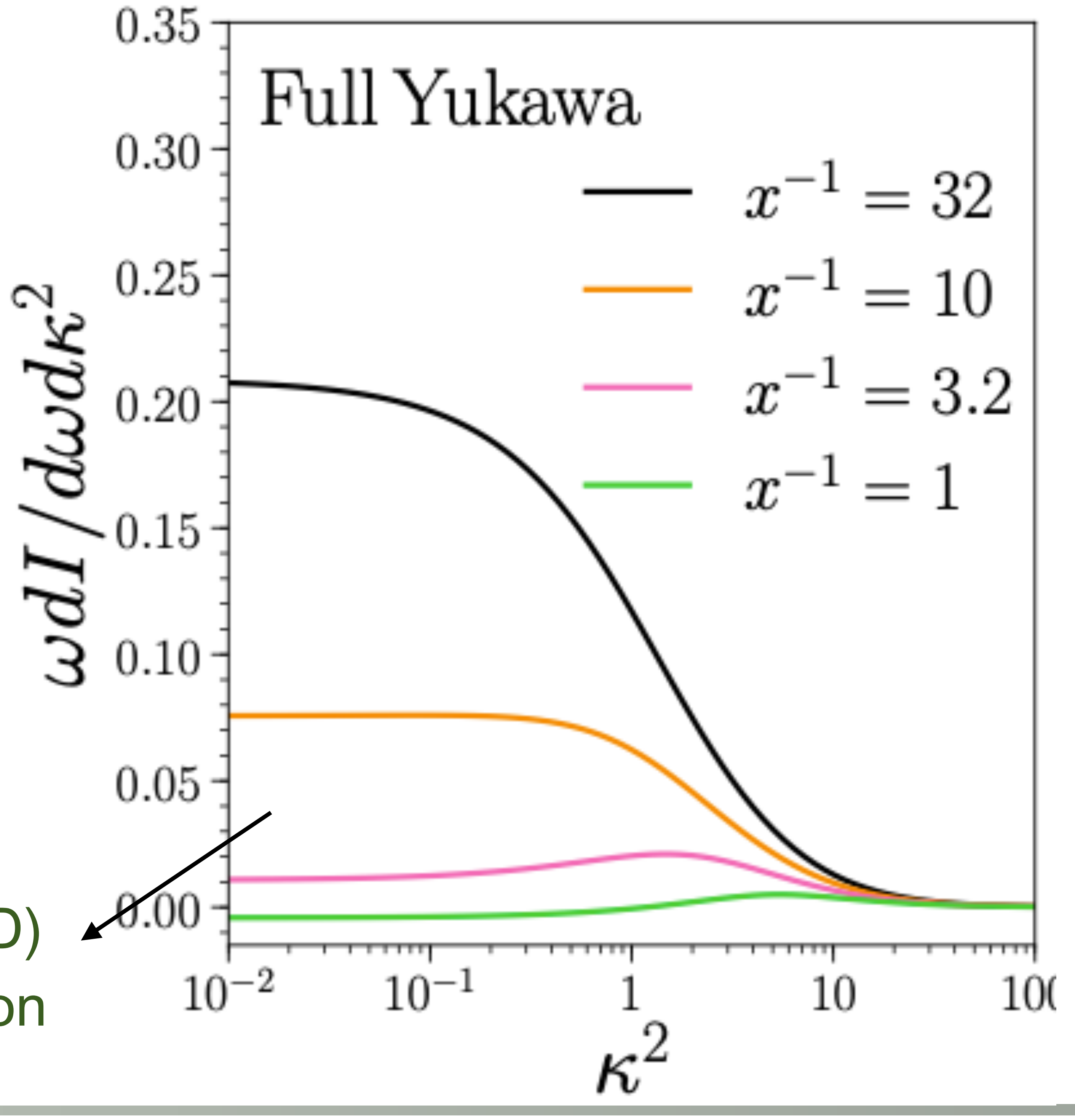


LPM (QCD) suppression

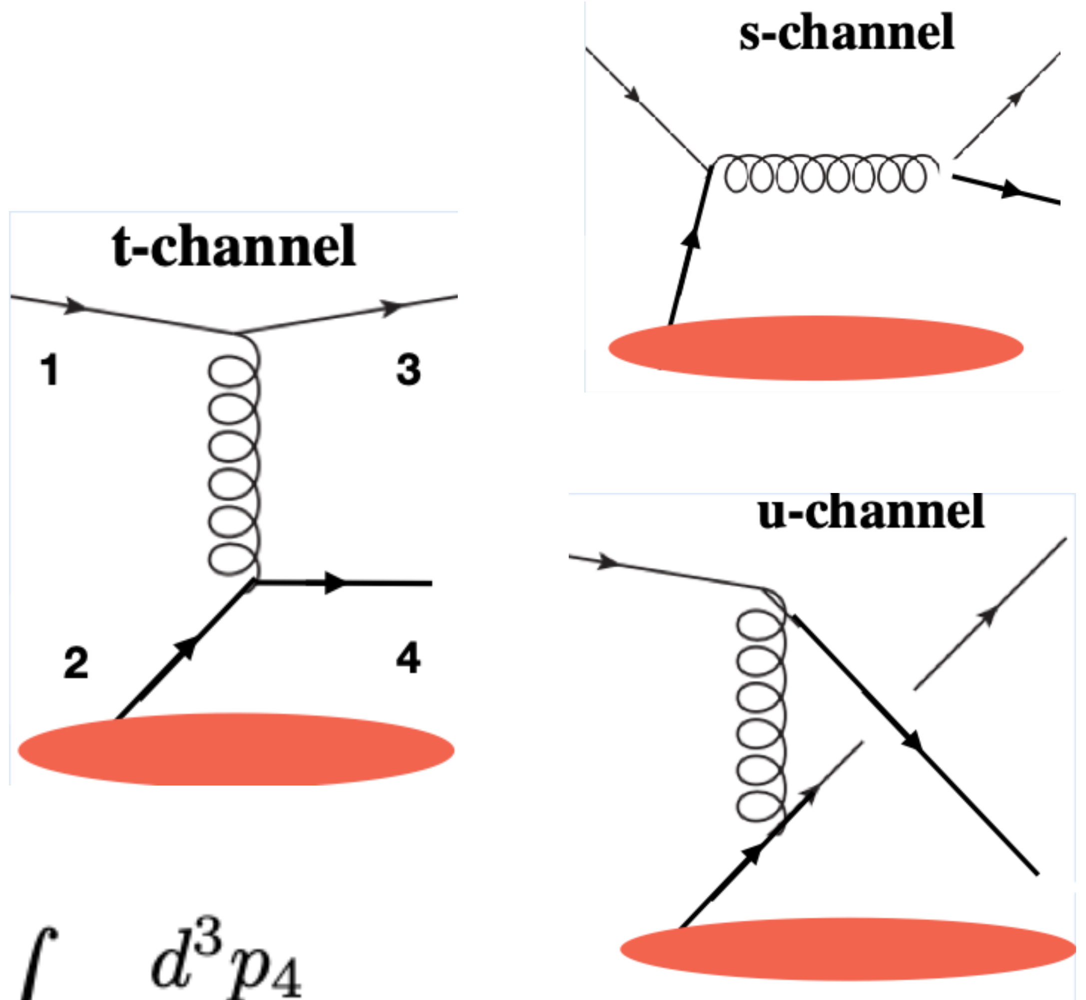
Medium response

LBT: [Cao, Luo, Qin, Wang (16) He, Luo, Wang, Zhu (17)]

MARTINI: [Schenke, Gale, Jeon (09)]

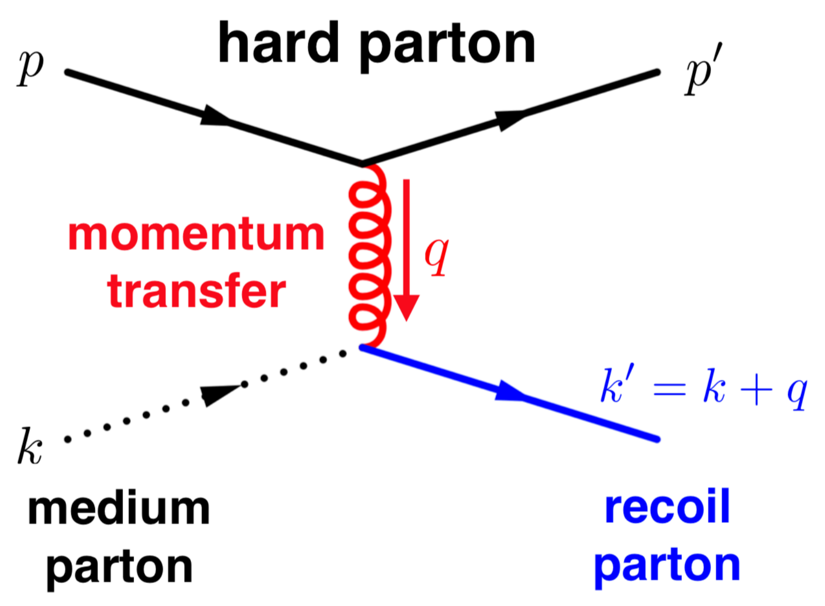
JEWEL: [Elayavalli, Zapp (17)]

- QGP part that become correlated with the jet:
  - Seen as (pQCD approach):
    - Recoils from jet-medium interactions with a QGP particle distribution
      - ➡ Dominated by small momentum transfers (close to non-perturbative region)



E.g: JEWEL

$$\frac{d\hat{\sigma}}{d\hat{t}}(\hat{s}, |\hat{t}|) \simeq \frac{C_R 2\pi\alpha_s^2}{(|\hat{t}| + \mu_D^2)^2}$$

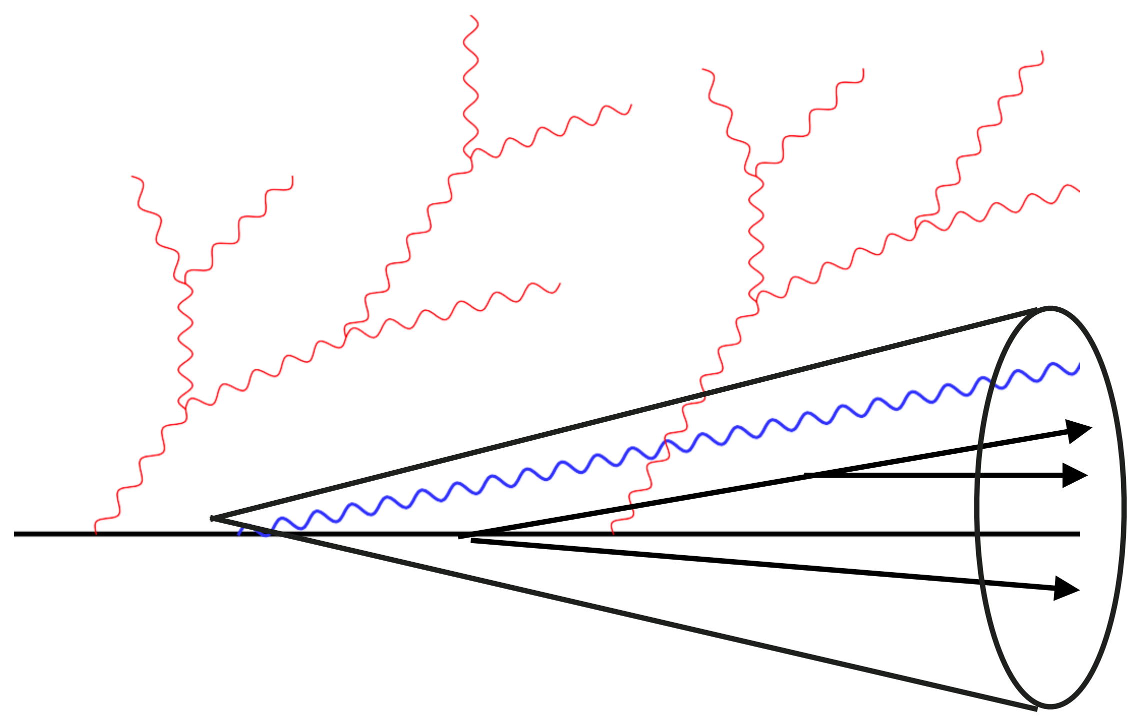


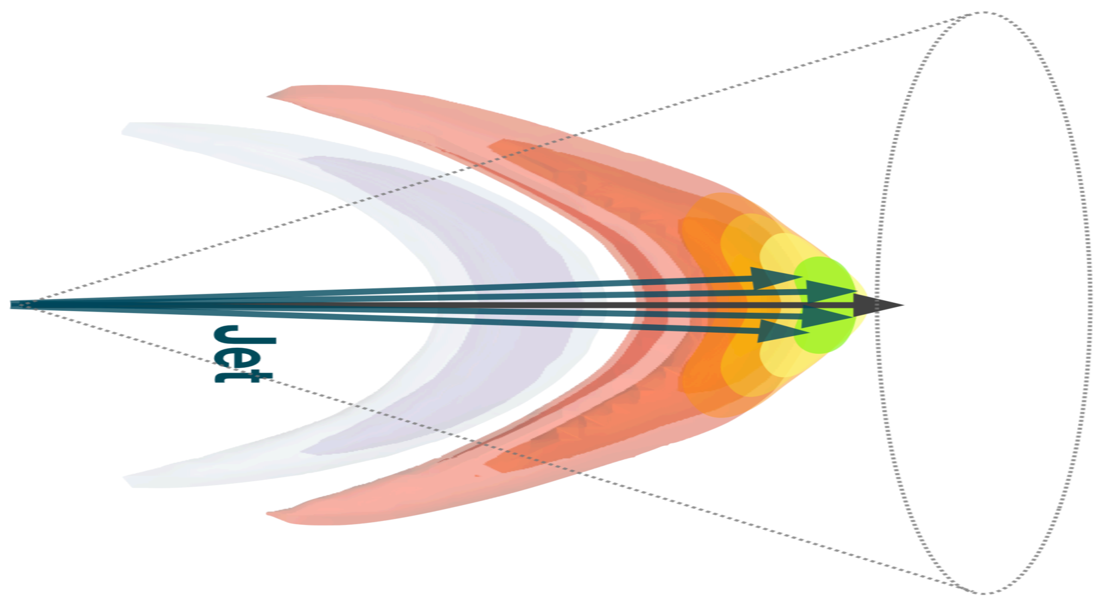
E.g: LBT

$$p_1 \cdot \partial f_a(p_1) = -\int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} \sum_{b(c,d)} \frac{g_b}{2} \left[f_a(p_1) f_b(p_2) - f_c(p_3) f_d(p_4)\right] |M_{ab\to cd}|^2 \times S_2(s,t,u)(2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4),$$

Description of a heavy-ion jet

- What is a jet in heavy-ion collisions?
  - Multi-scale process:
    - High momentum particles (typically from vacuum-like parton shower)
    - "Semi-hard" & Soft medium-induced radiation
    - Soft jet-induced medium response





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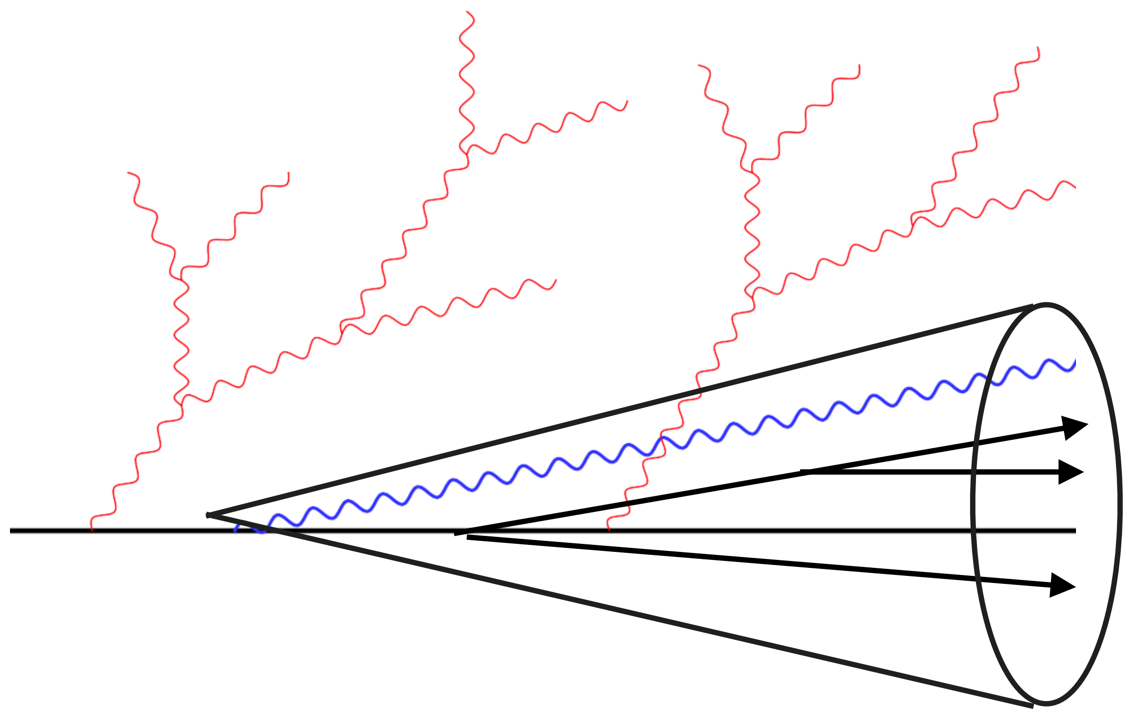

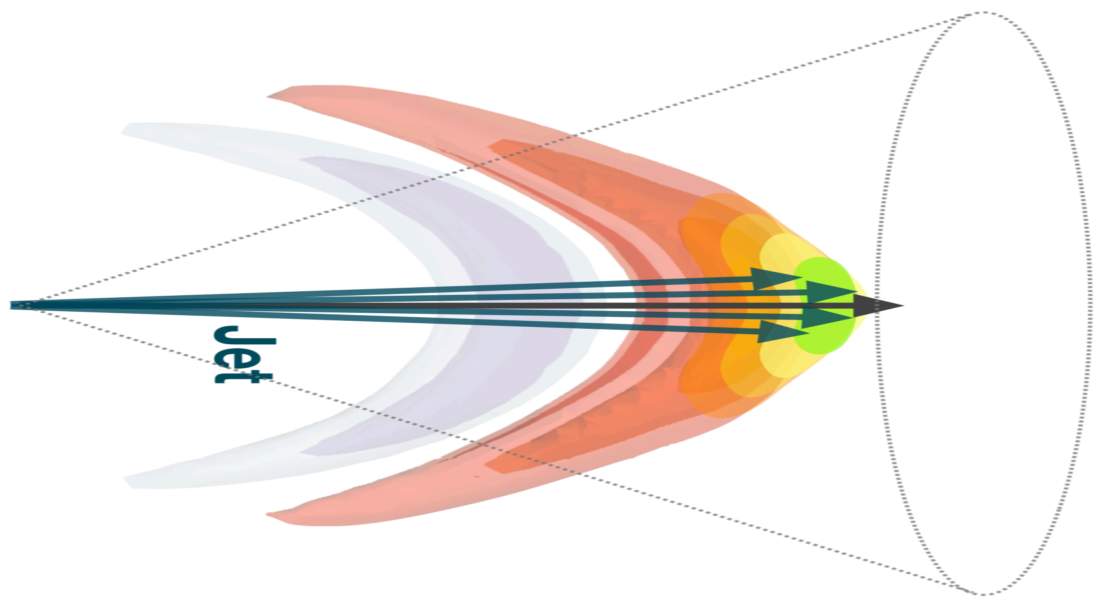

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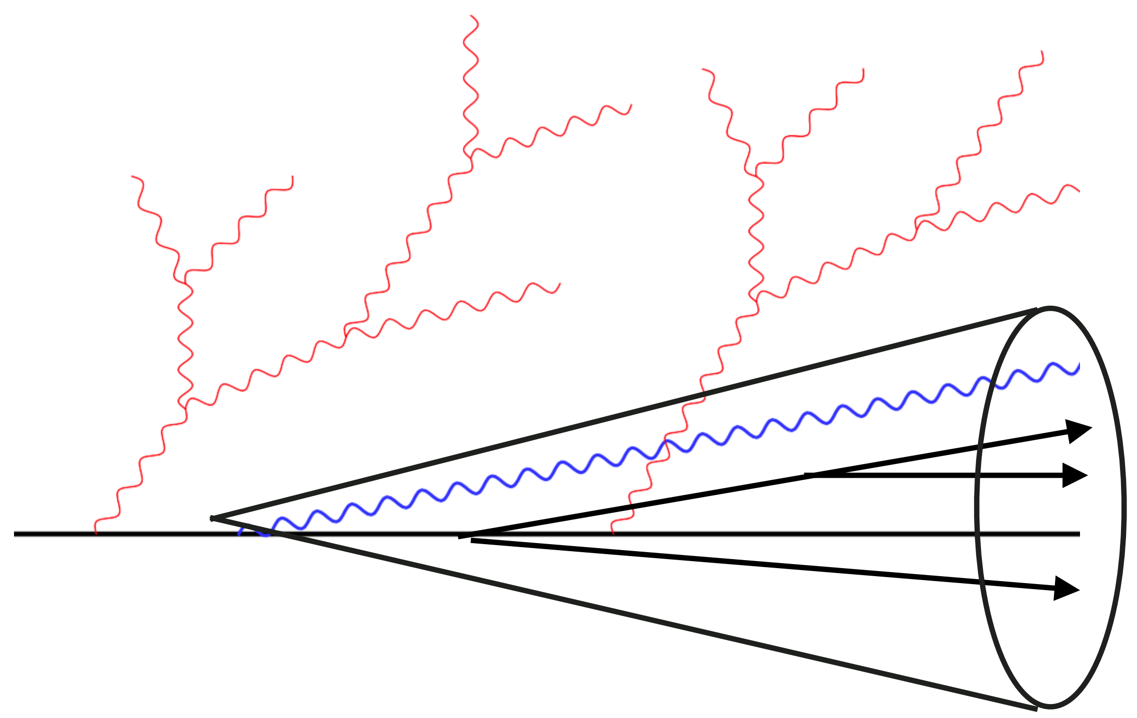
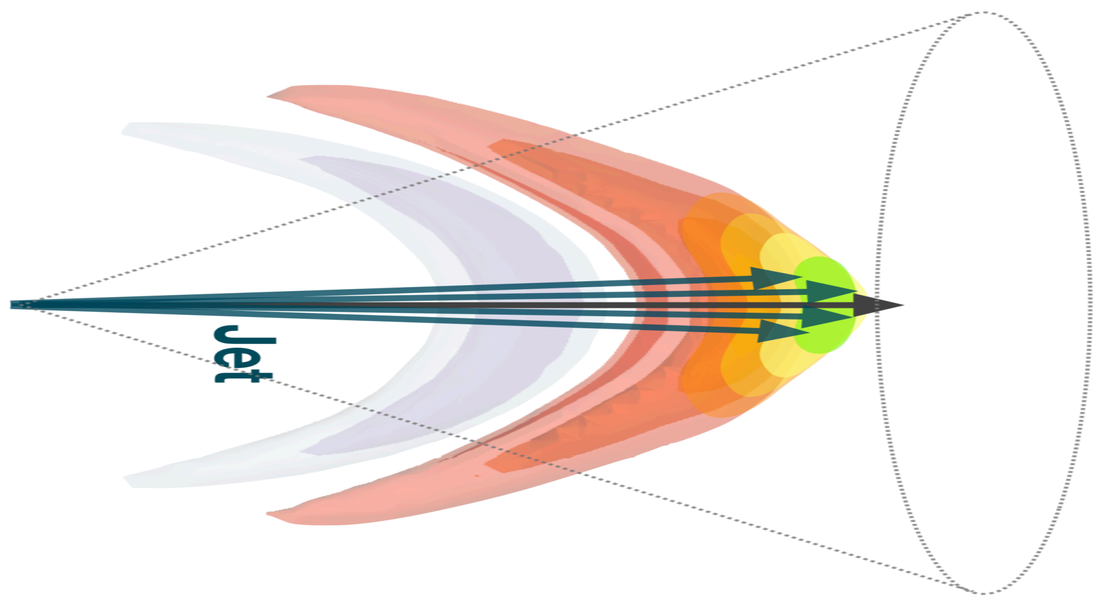


Not as “easy” as in pp…

How to describe it?



Analytic vs MC approaches

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Based on first principle calculations that address elementary jet processes

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✓ Improvements beyond:
- static medium
- limited kinematic approximations
- …

⚠ Limited understanding for:
- lower momentum scales
- interplay between "vacuum" and "medium"-induced shower

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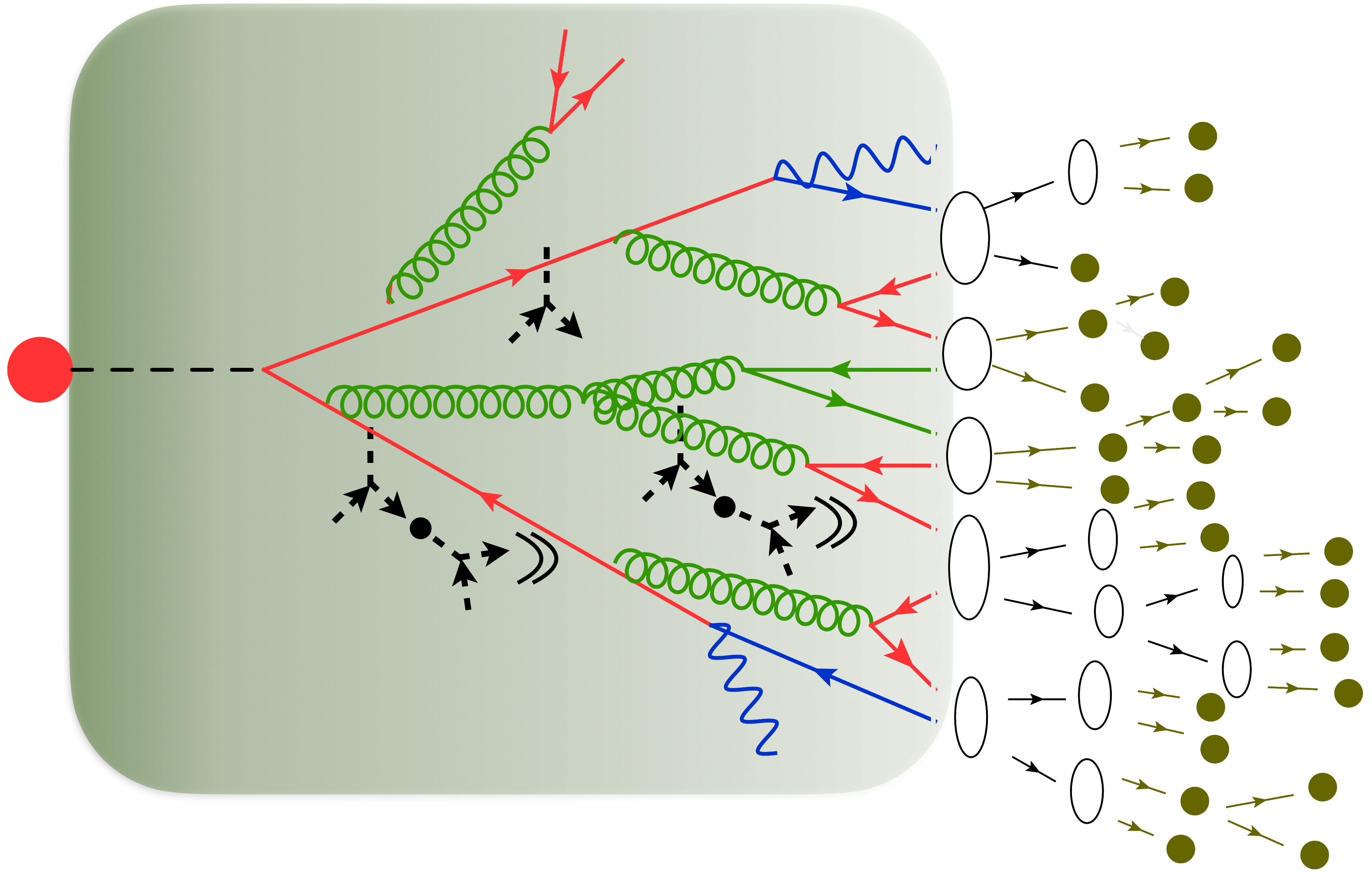
⚠✓ Require further modelling beyond analytically-controlled phase-space regions

What is a jet quenching Monte Carlo?

Jet quenching Monte Carlo models

- N-particle system originated through a parton shower
  - Vacuum radiation
  - Medium-induced effects
    - Medium-induced radiation
    - Jet-induced medium response
    - Medium response re-scattering

Hadronization



Medium-modified jet in all momentum scales?

Parton Shower Models

- Two different approaches:

Change in the jet evolution:

Modifications on a developed shower

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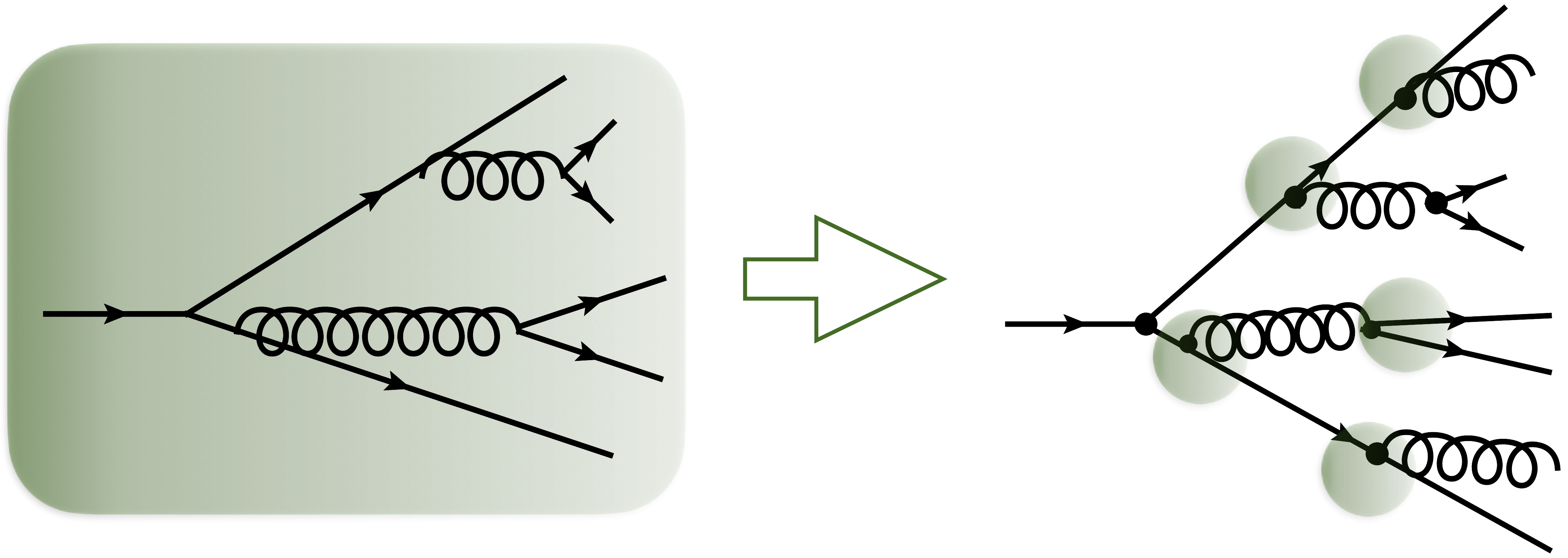

E.g: JEWEL, MATTER, Q-PYTHIA,…

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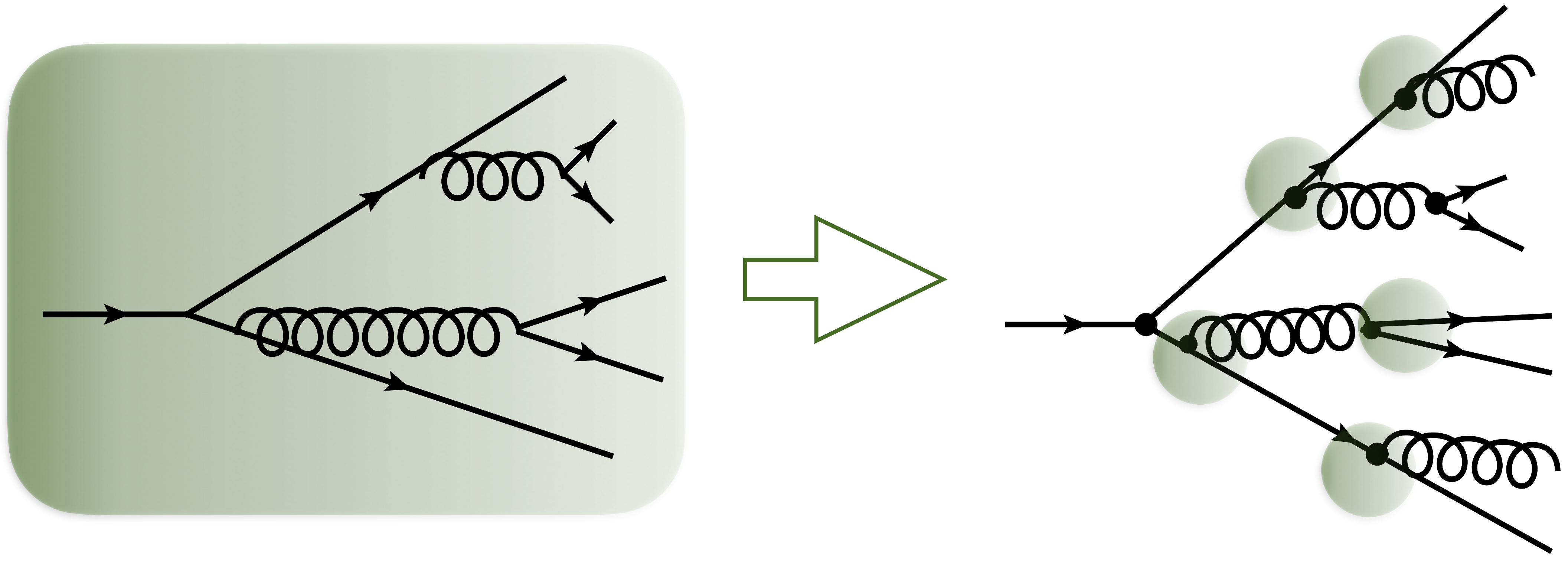

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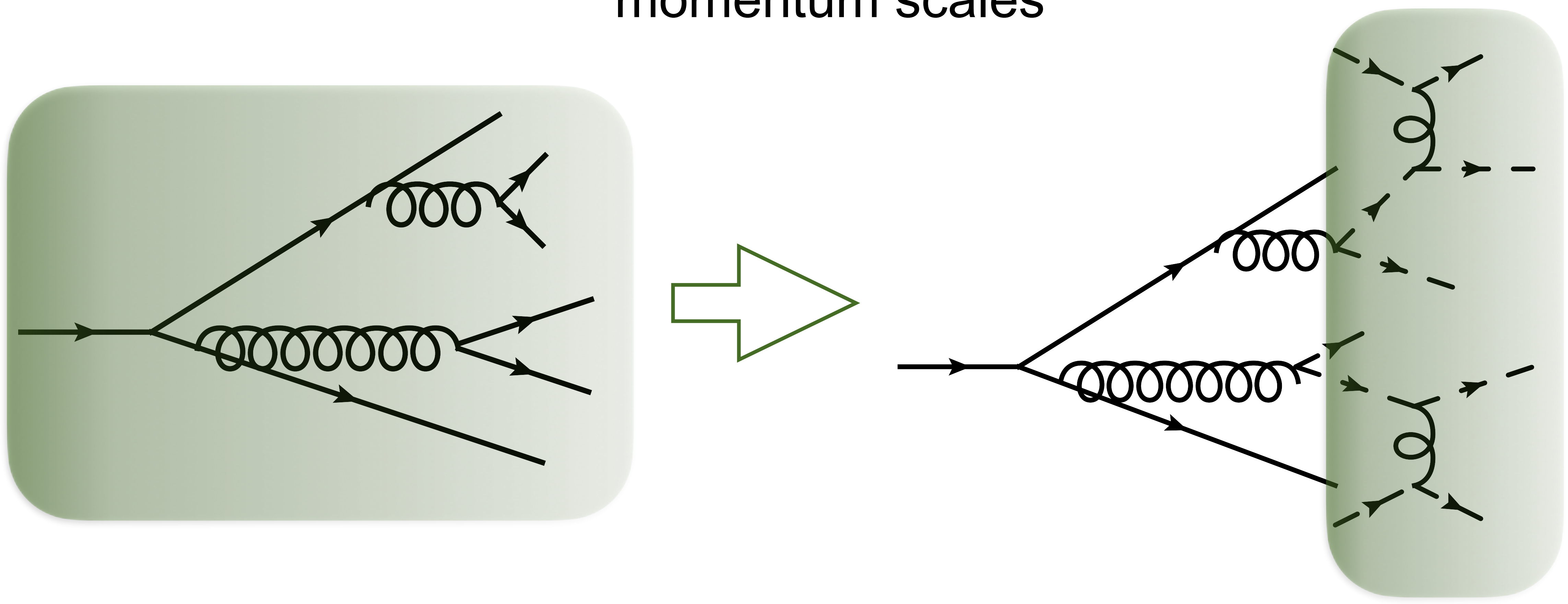
Modifications on a developed shower

Vacuum (hard and collinear) parton structure unmodified

Medium-modifications dominate low momentum scales



E.g:(Co-)LBT, Hybrid, MARTINI, JetMed..

Parton Shower Models

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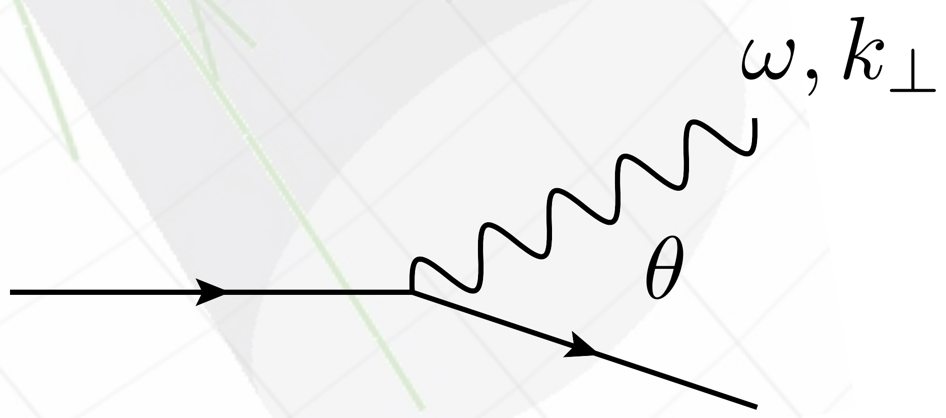

$$dP^{q\to qg} \sim \alpha_s C_R \frac{d\omega}{\omega}\frac{dk_\perp^2}{k_\perp^2}$$

Re-summation of multiple emissions

$$\Delta_i(t) \equiv \exp\left[-\sum_j \int_{t_0}^{t} \frac{dt'}{t'} \int dx \frac{\alpha_s}{2\pi} P_{i\leftarrow j}(x)\right]$$

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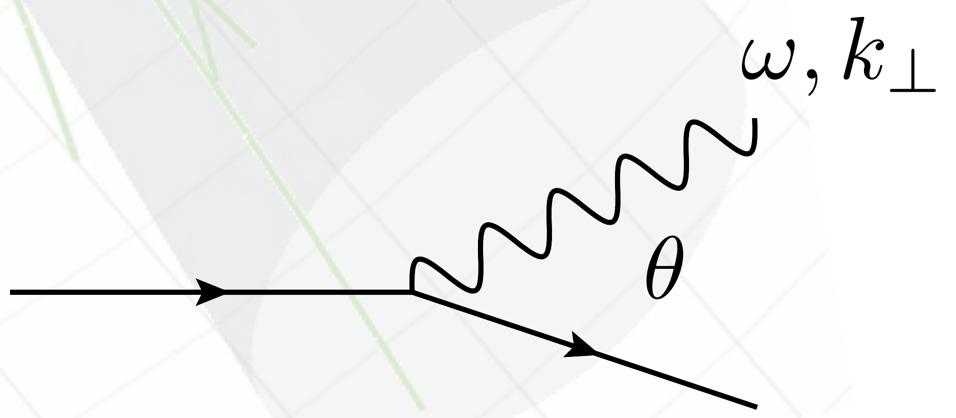

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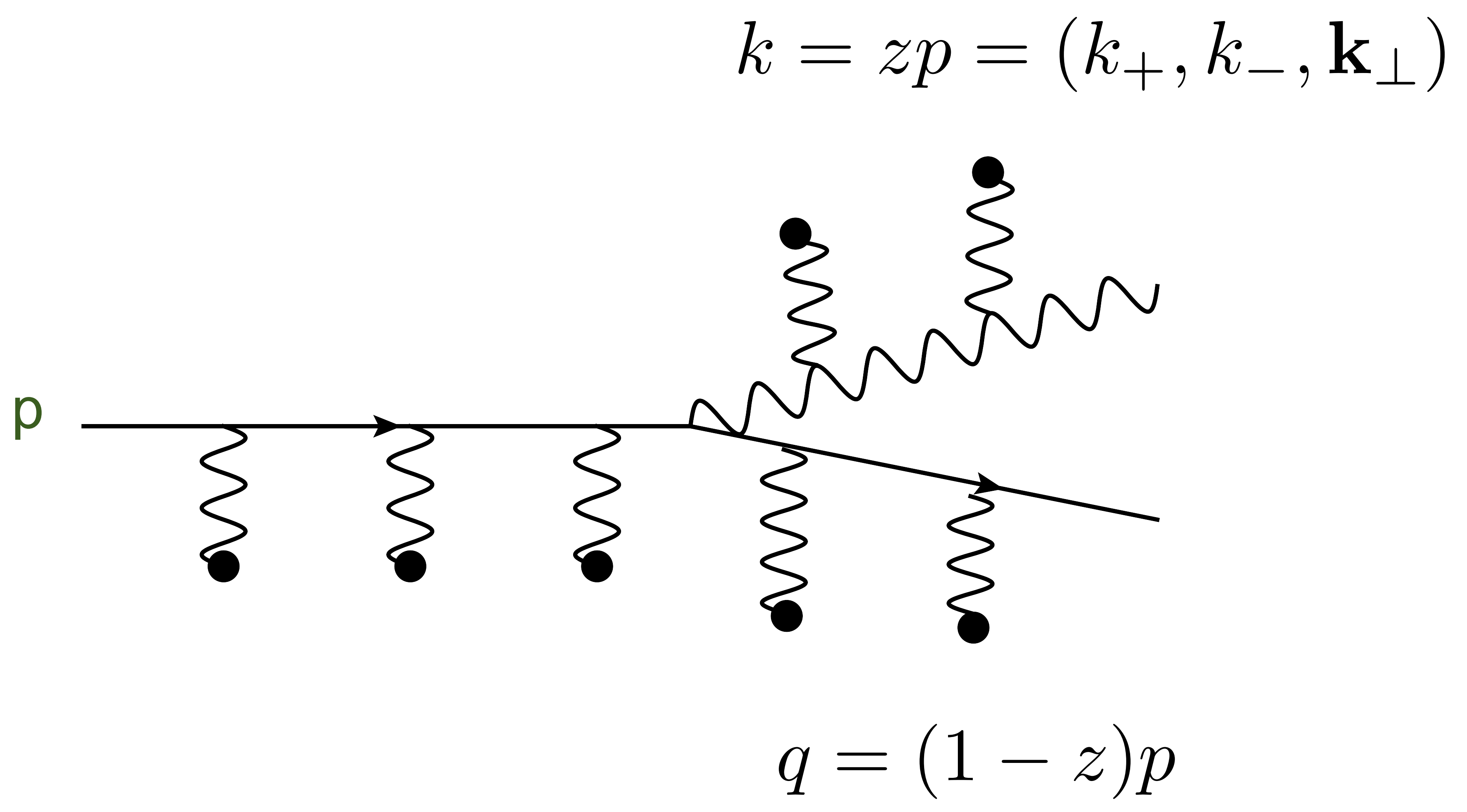

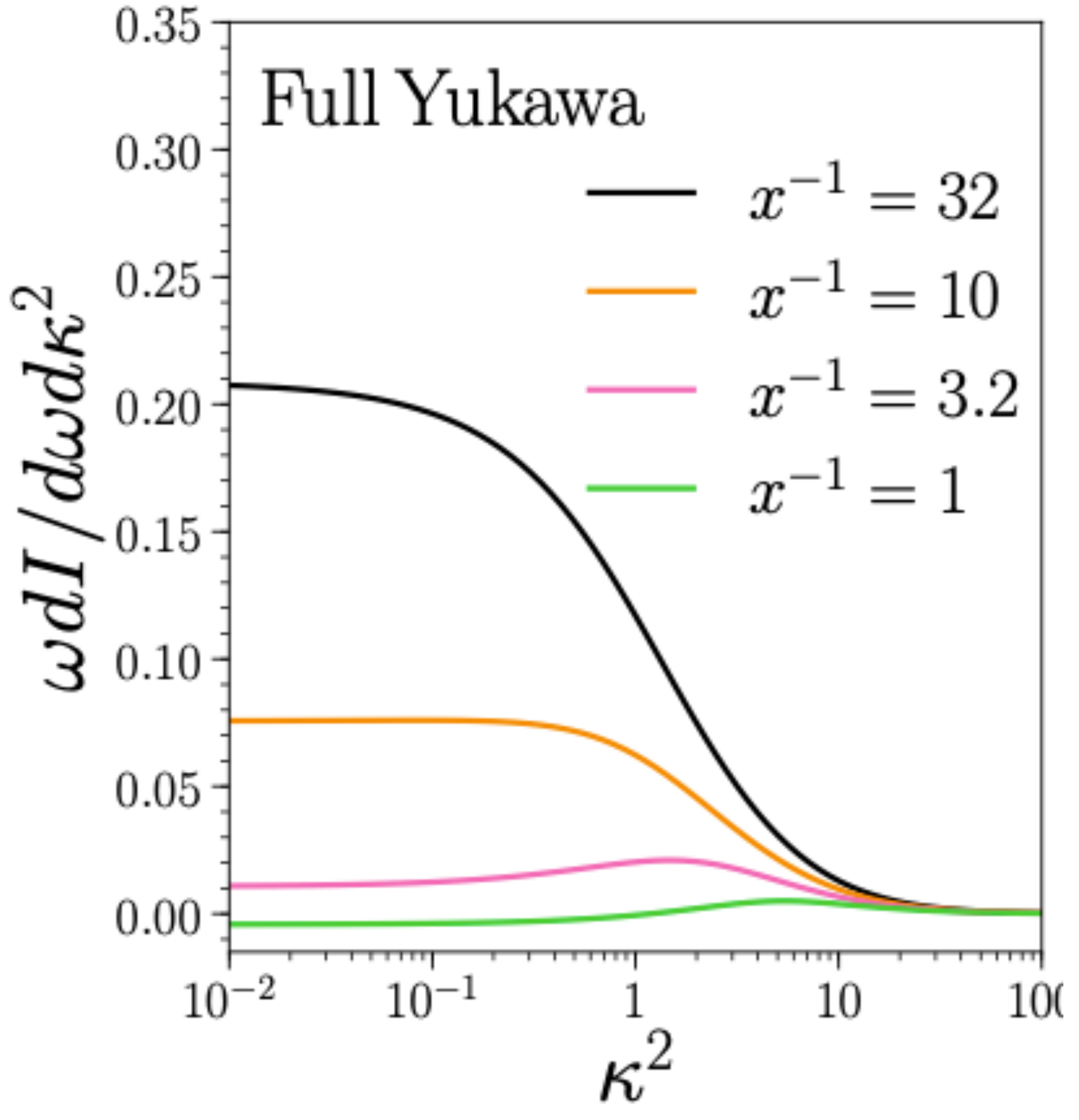

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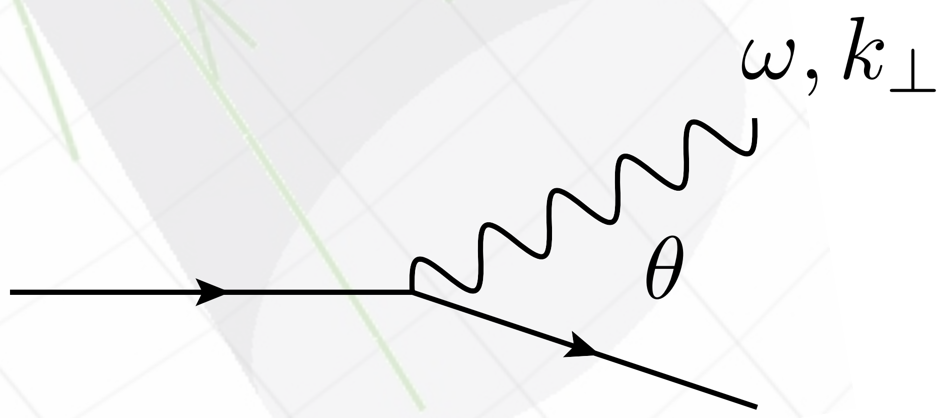

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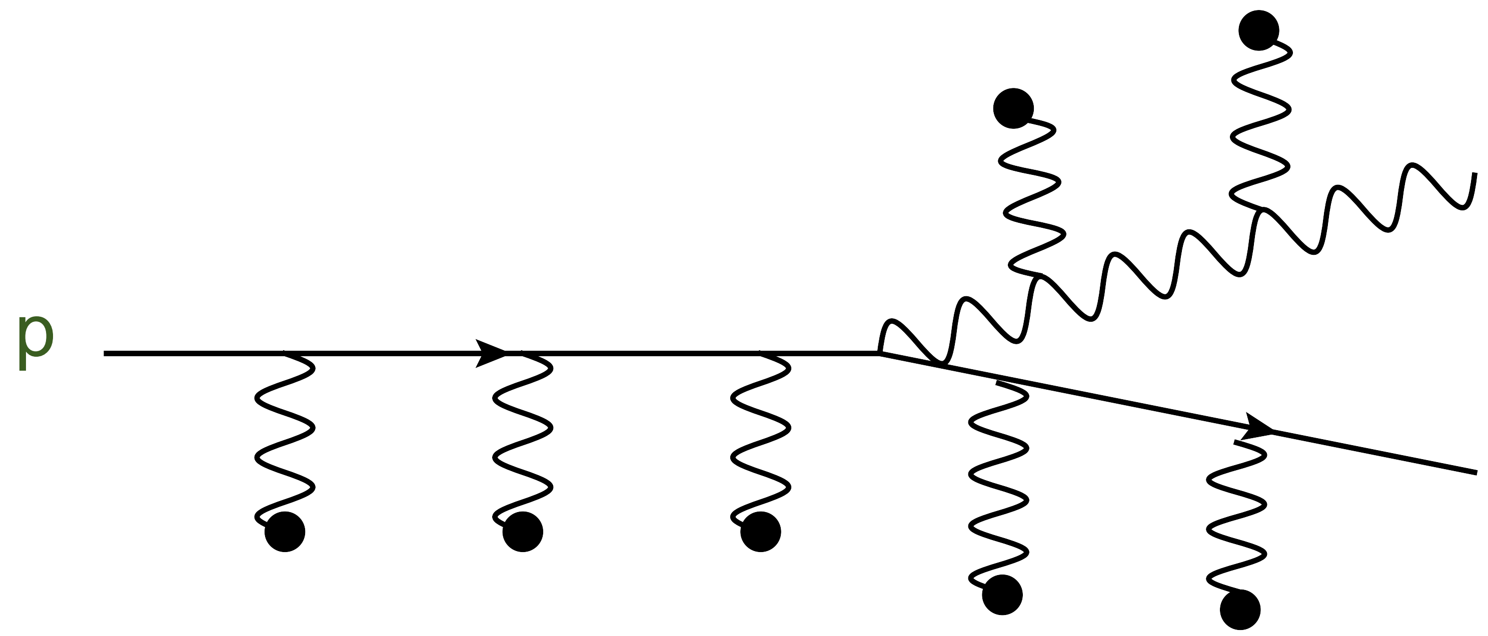
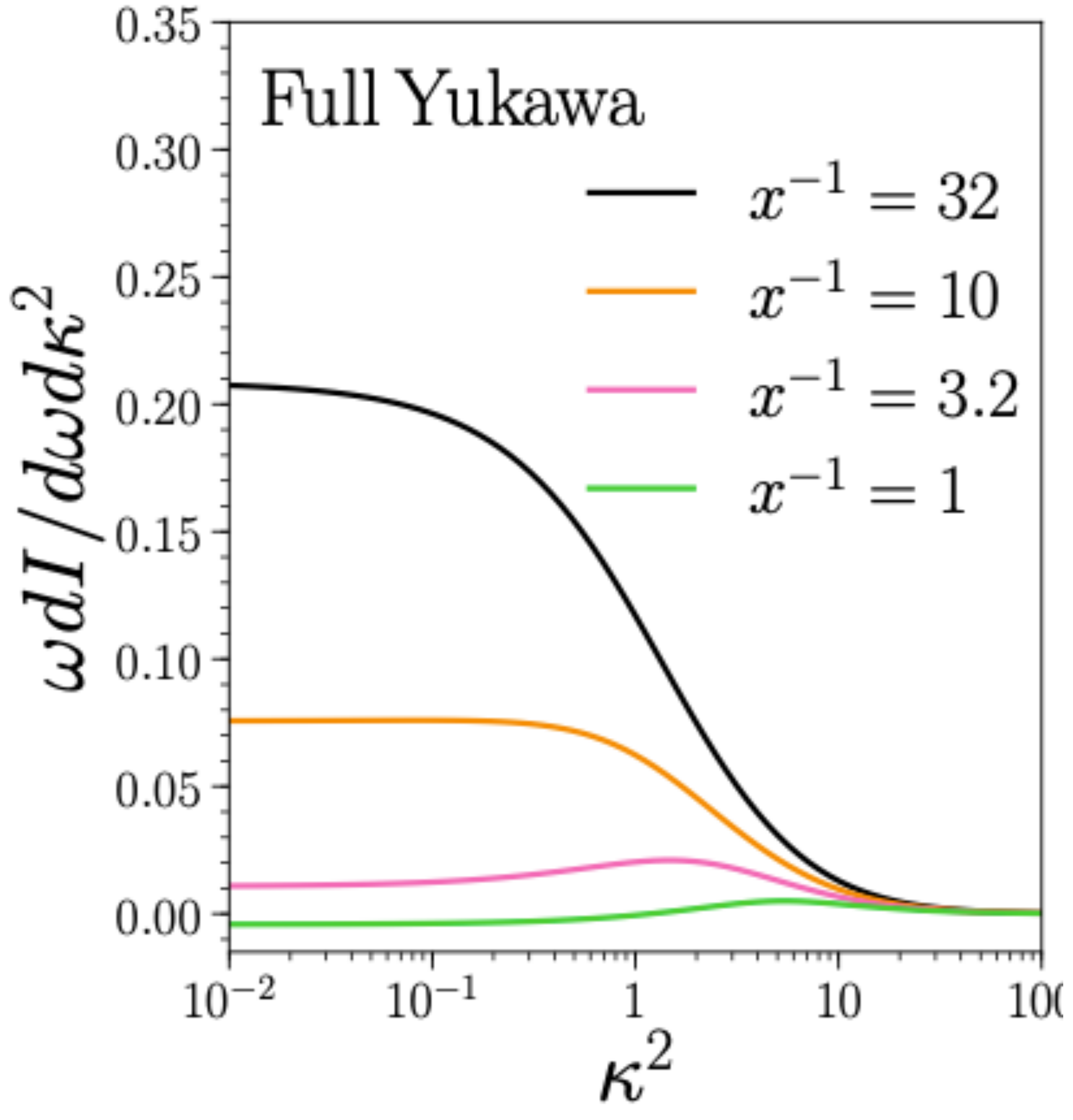


$$q = (1-z)p$$

Ansatz: $P_{\text{tot}} = P_{\text{vac}} + \Delta P$



$$\Delta P \simeq \frac{2\pi t}{\alpha_s}\frac{dI^{\text{med}}}{dzdt}$$

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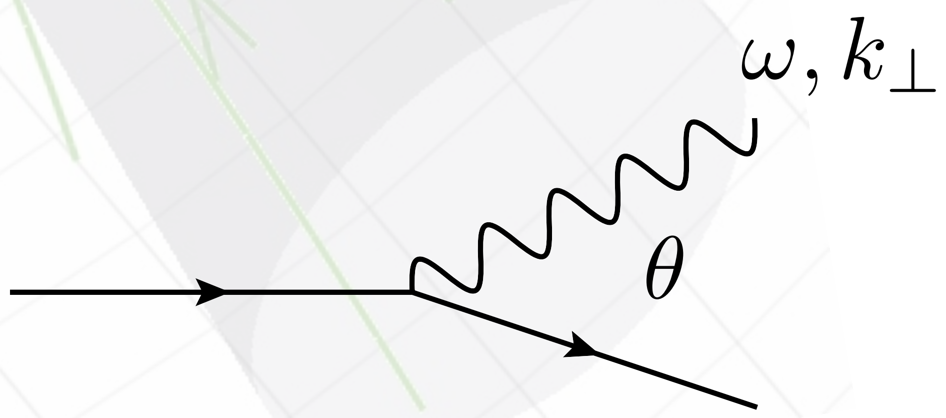

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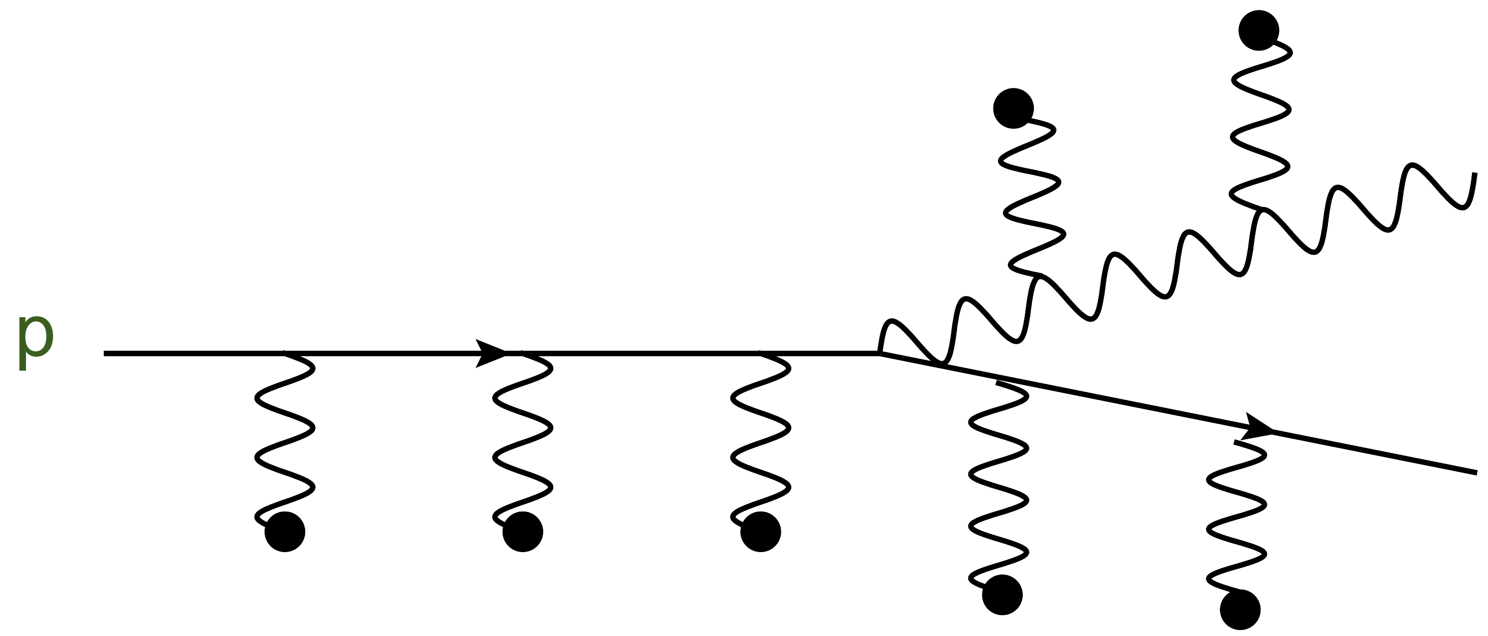

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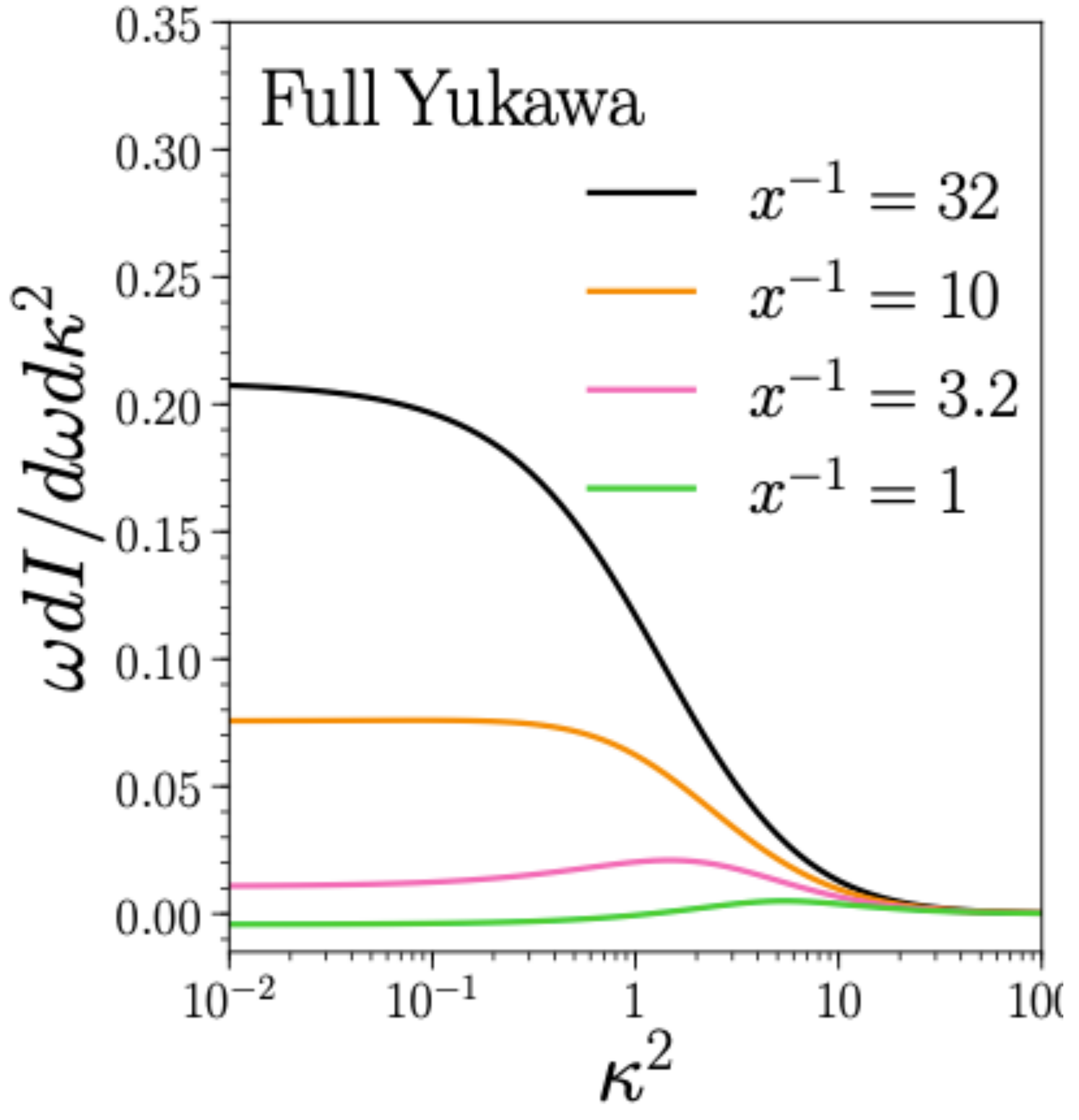

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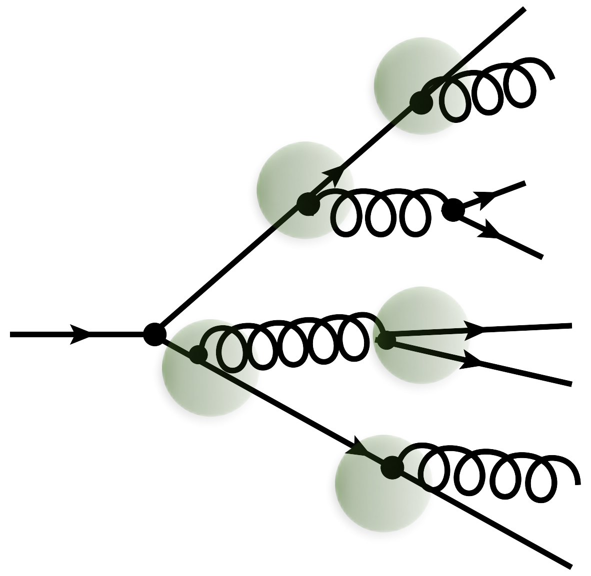

medium-induced radiations are treated as correction to vacuum kernel

Parton Shower Models

- Modifications on a developed shower

Medium-induced emissions inside them medium: $t_f \leq \sqrt{2\omega/\hat{q}}$

(But no double logarithmic enhancement)

Parton formation time: $t_f \simeq 2\omega/k_\perp^2$

Transverse momentum acquired via multiple soft scatterings: $k_f^2 = \hat{q}t_f$.

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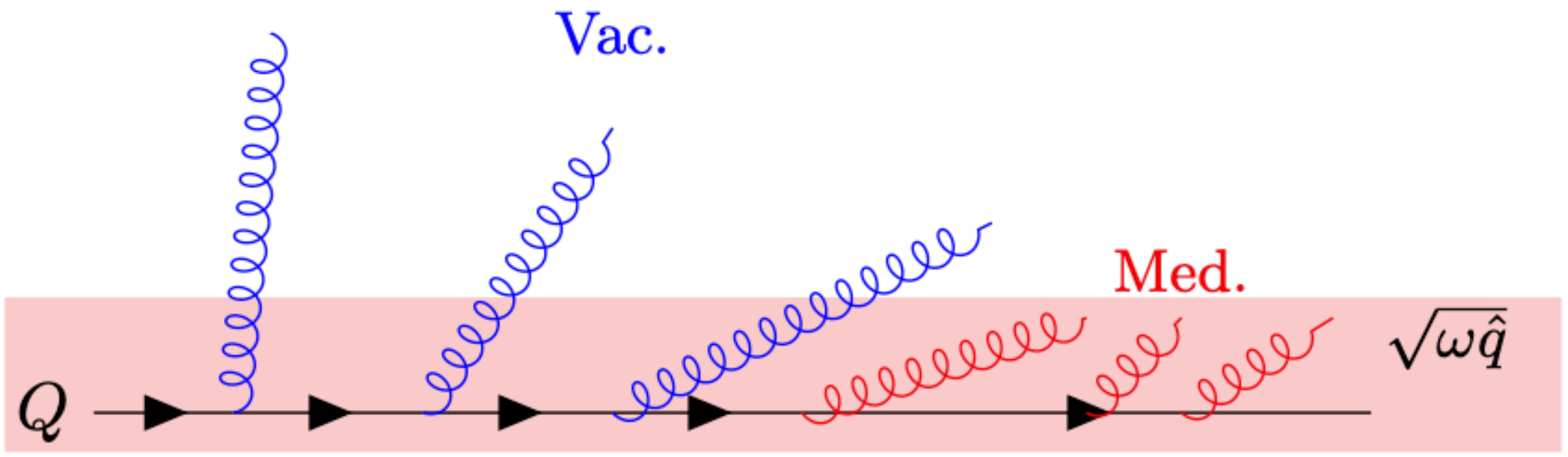

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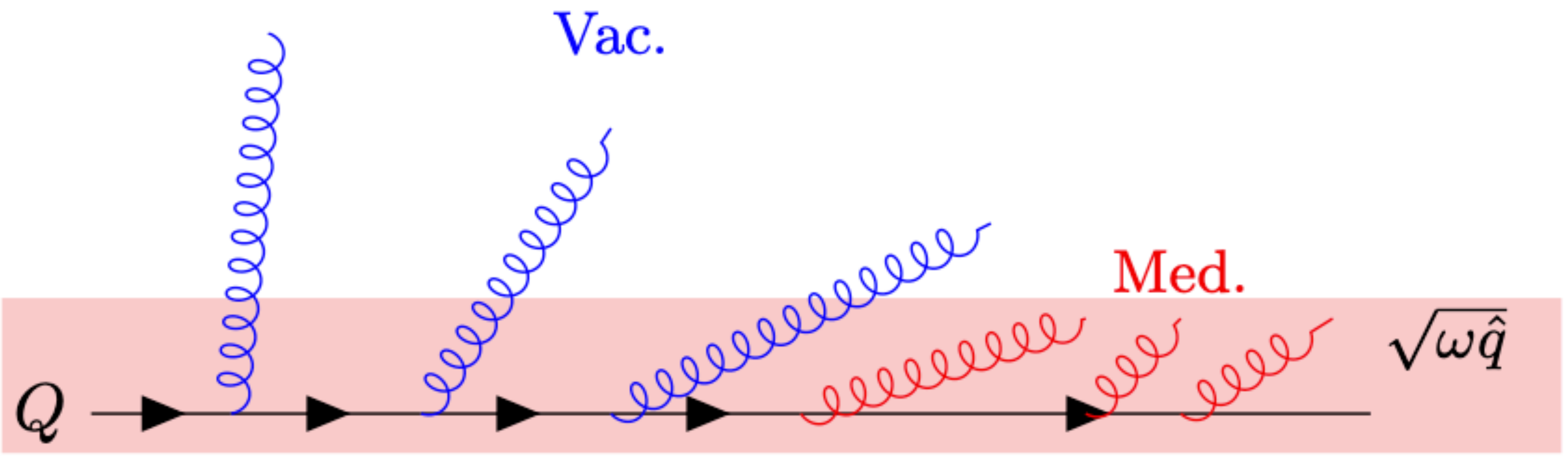

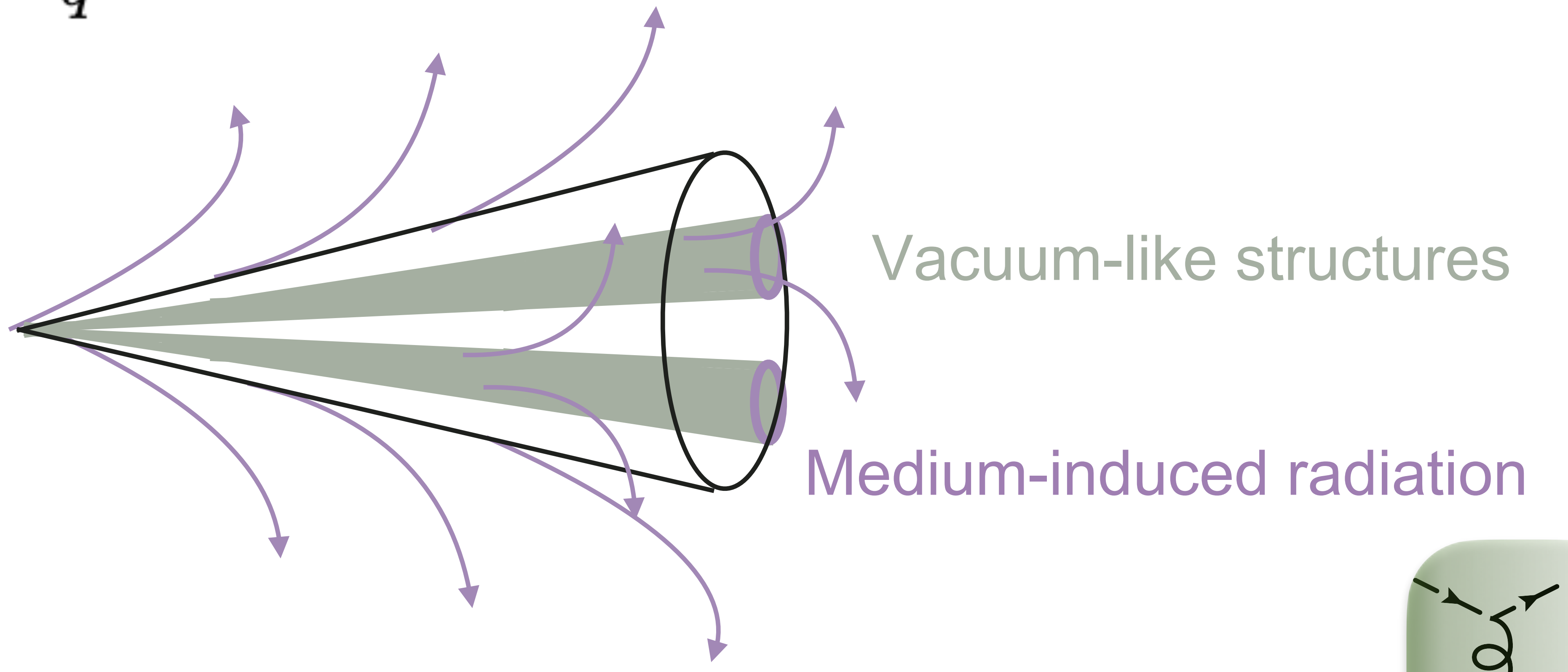

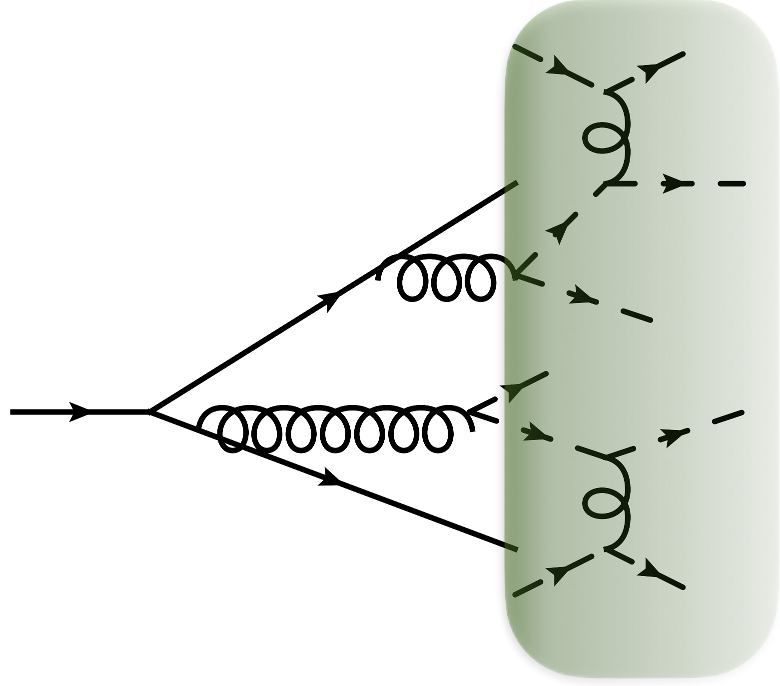

Parton Shower Models

- Comparison between the two:

Change in the jet evolution:

Choose (or develop) a given vacuum parton shower
(Fixed to the ordering variable and parton shower accuracy)

Modifications on a developed shower

Minimal changes to the vacuum parton shower
(Easier to develop alongside vacuum physics)

Parton Shower Models

- Comparison between the two:

Change in the jet evolution:	Modifications on a developed shower
Choose (or develop) a given vacuum parton shower (Fixed to the ordering variable and parton shower accuracy)	Minimal changes to the vacuum parton shower (Easier to develop alongside vacuum physics)
Medium-induced effects from in-medium radiation spectrum (inheriting kinematical restrictions)	Medium-induced effects from transport equations (inheriting kinematical restrictions)

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Modifications done in momentum scales relatively above the non-perturbative region	Modifications in the low-momentum particle distribution (close to non-perturbative region) ⚠

No “correct” answer… All with their pros and cons…

Parton Shower Models

- Comparison between the two:

Change in the jet evolution:

⚠ Choose (or develop) a given vacuum parton shower (Fixed to the ordering variable and parton shower accuracy)

Interplay between vacuum and medium shower

Modifications on a developed shower

Modifications in the low-momentum particle distribution (close to non-perturbative region) ⚠

QCD processes at lower momentum scales

Parton Shower Models

- Comparison between the two:

Change in the jet evolution:

Choose (or develop) a given vacuum parton shower (Fixed to the ordering variable and parton shower accuracy)

Interplay between vacuum and medium shower

MATTER
(High-virtuality part of the shower)

Modifications on a developed shower

Modifications in the low-momentum particle distribution (close to non-perturbative region)

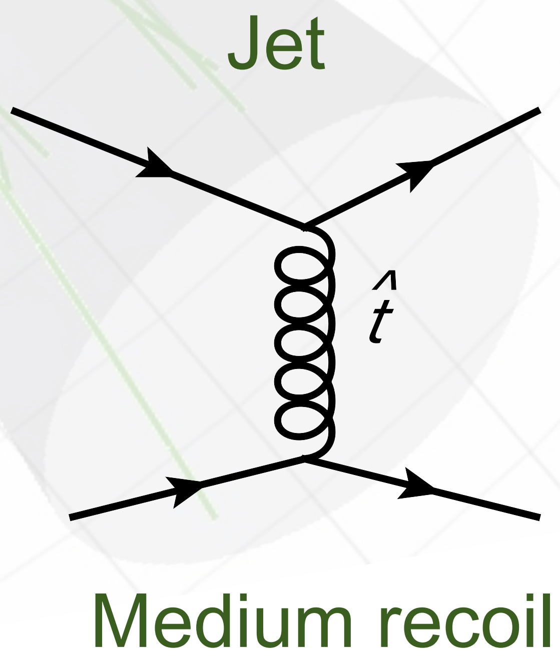
QCD processes at lower momentum scales

LBT, MARTINI,…
(Low-virtuality part of the shower)

JETSCAPE

Elastic Energy Loss

- Need phase space density of scattering centres (sampled from hydro profile or Bjorken evolution model)



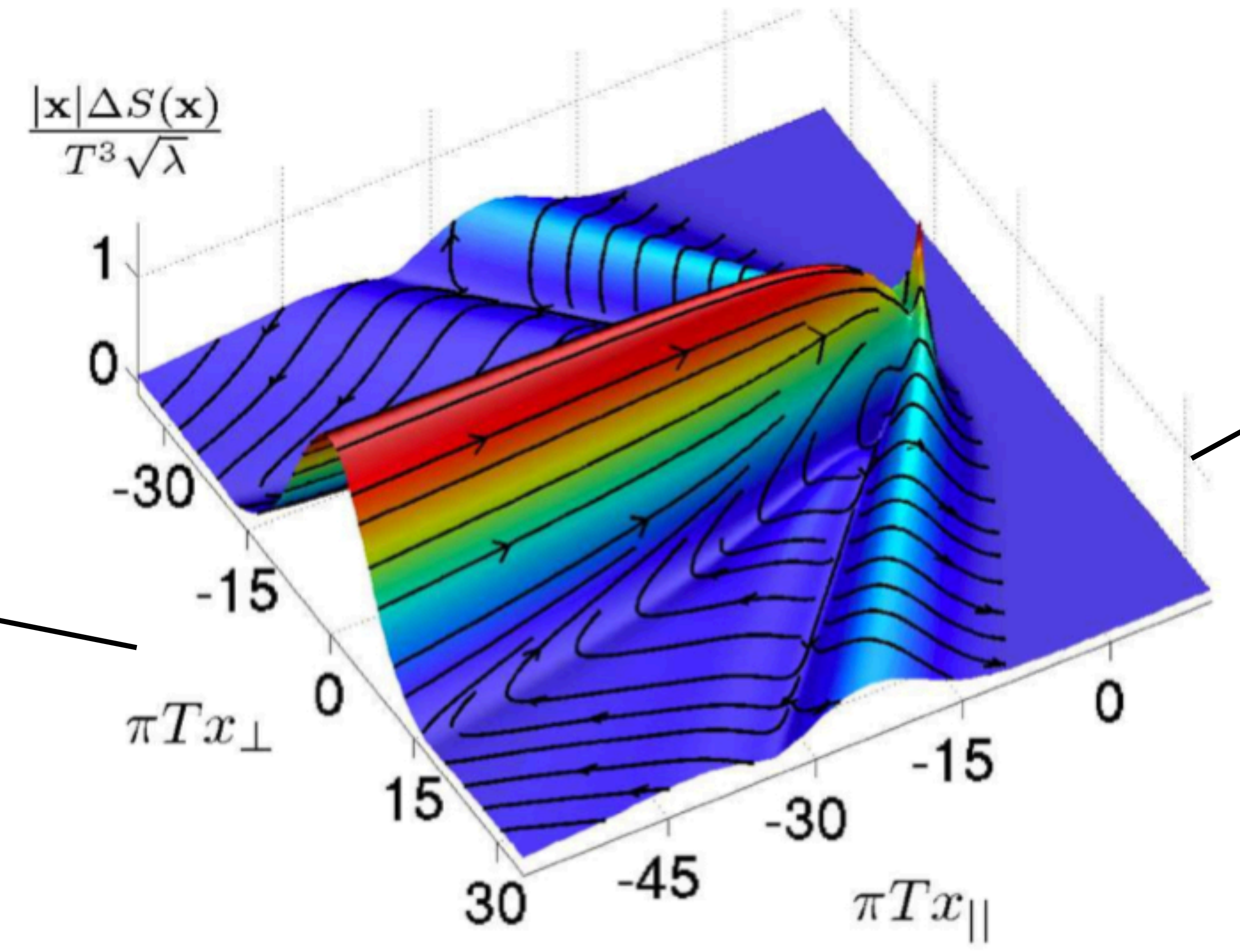
$$\frac{d\hat{\sigma}}{d\hat{t}}(\hat{s}, |\hat{t}|) \simeq \frac{C_R 2\pi\alpha_s^2}{(|\hat{t}| + \mu_D^2)^2}$$

Recoiling particles can further re-scatter

- Coupled jet-hydro evolution:

$$\partial_\mu T^{\mu\nu}_{fluid} = J^{\nu}_{jet}(x)$$

Jet



Drag effect

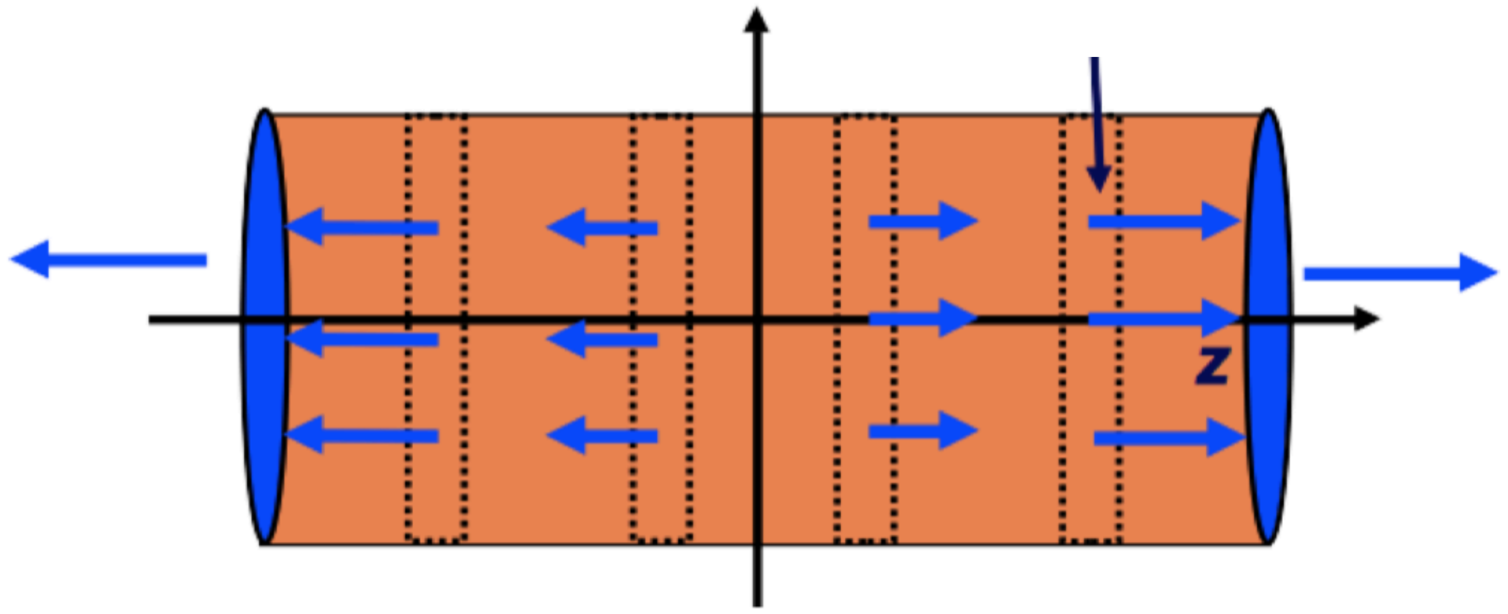
Cooper-Frye for particles from medium response

Medium Evolution modelling

- Medium evolution model

Bjorken 1D expansion

[Bjorken (1983)]



$$T = T_0 \left(\frac{\tau_0}{\tau} \right)^{v_s^2}$$

Longitudinal (1D) expansion
(Energy density characterised by a power-law evolution)

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- Medium evolution model

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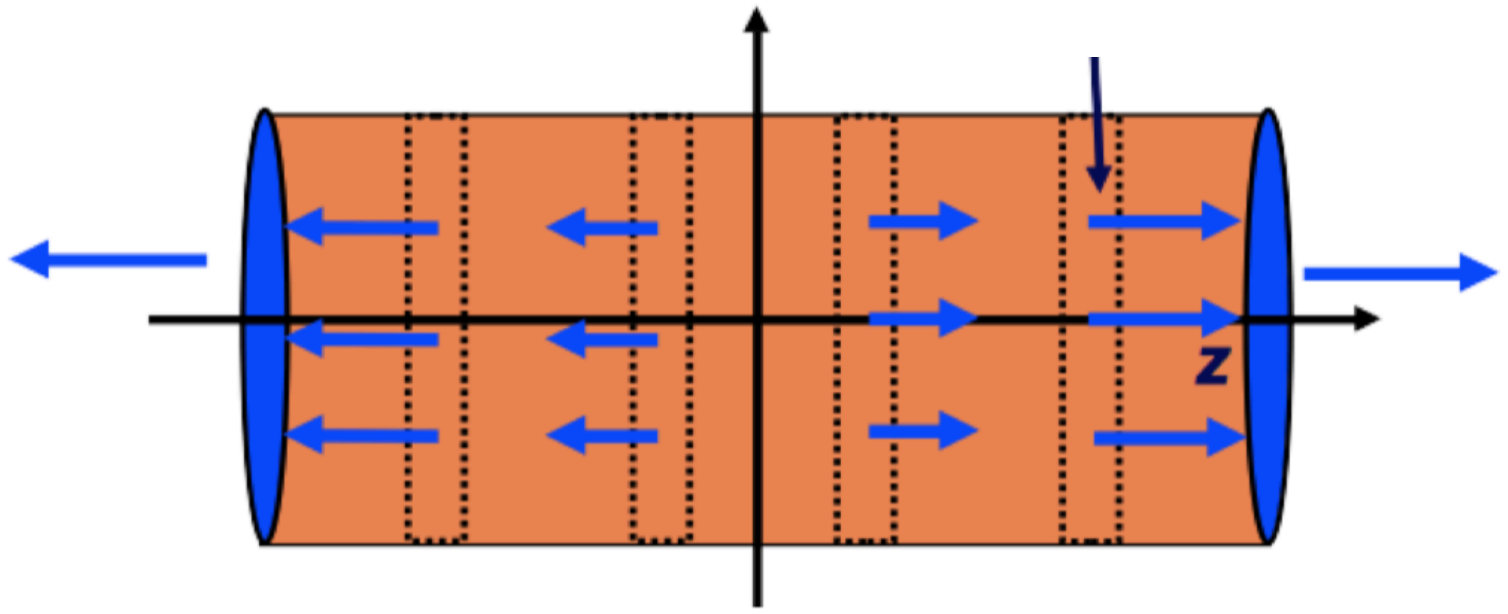

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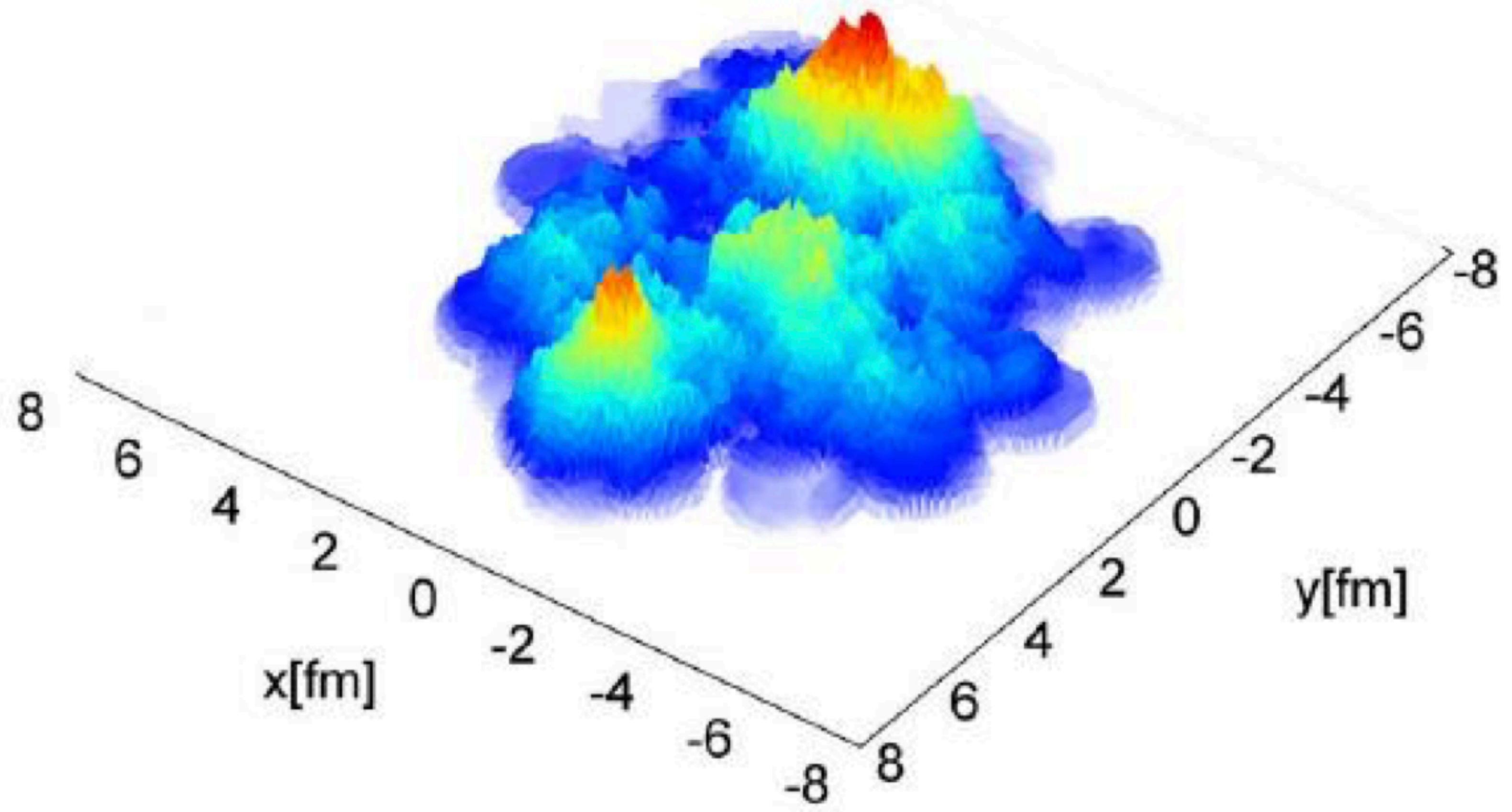
Event-by-event non-ideal hydrodynamics

[Molner et al(1407.8152), Shen et al (1409.8164),…]



$$\partial_\mu T^{\mu\nu} = j^\nu$$

3D expansion
(Energy density characterised by relativistic hydrodynamic evolution)

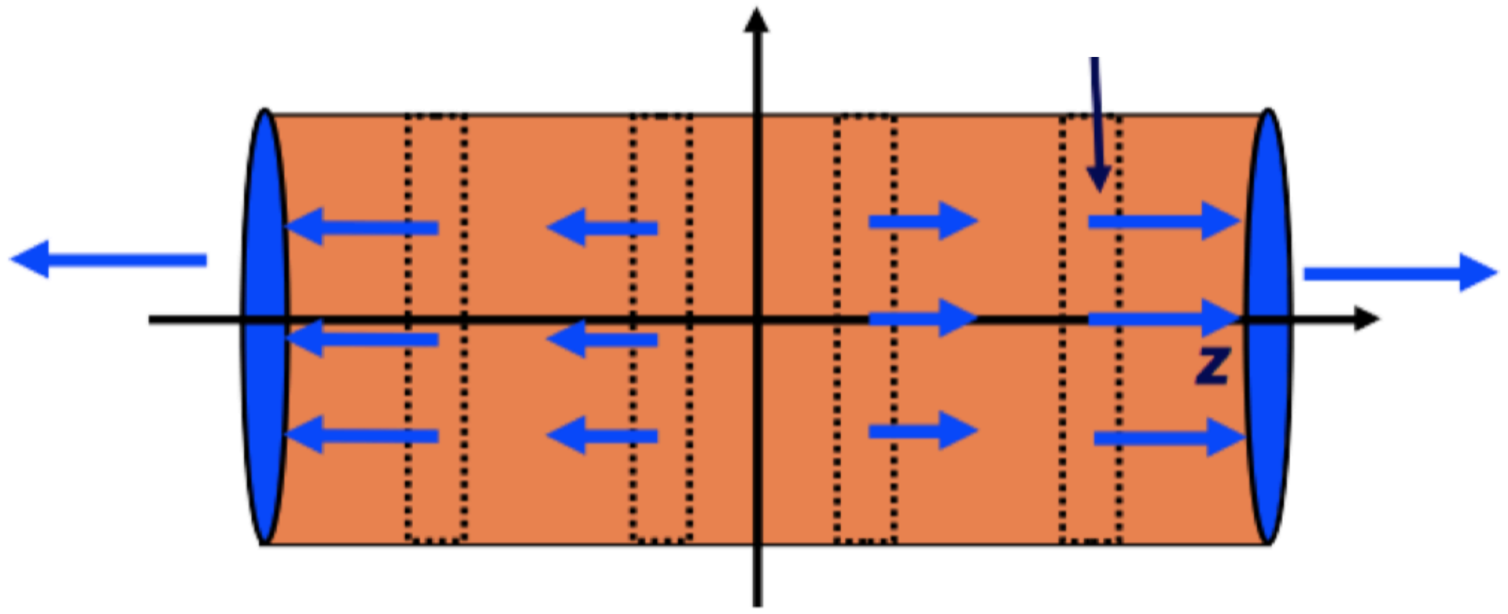
Medium Evolution modelling

- Medium evolution model

See Mayank Singh (Wed)

Bjorken 1D expansion

[Bjorken (1983)]



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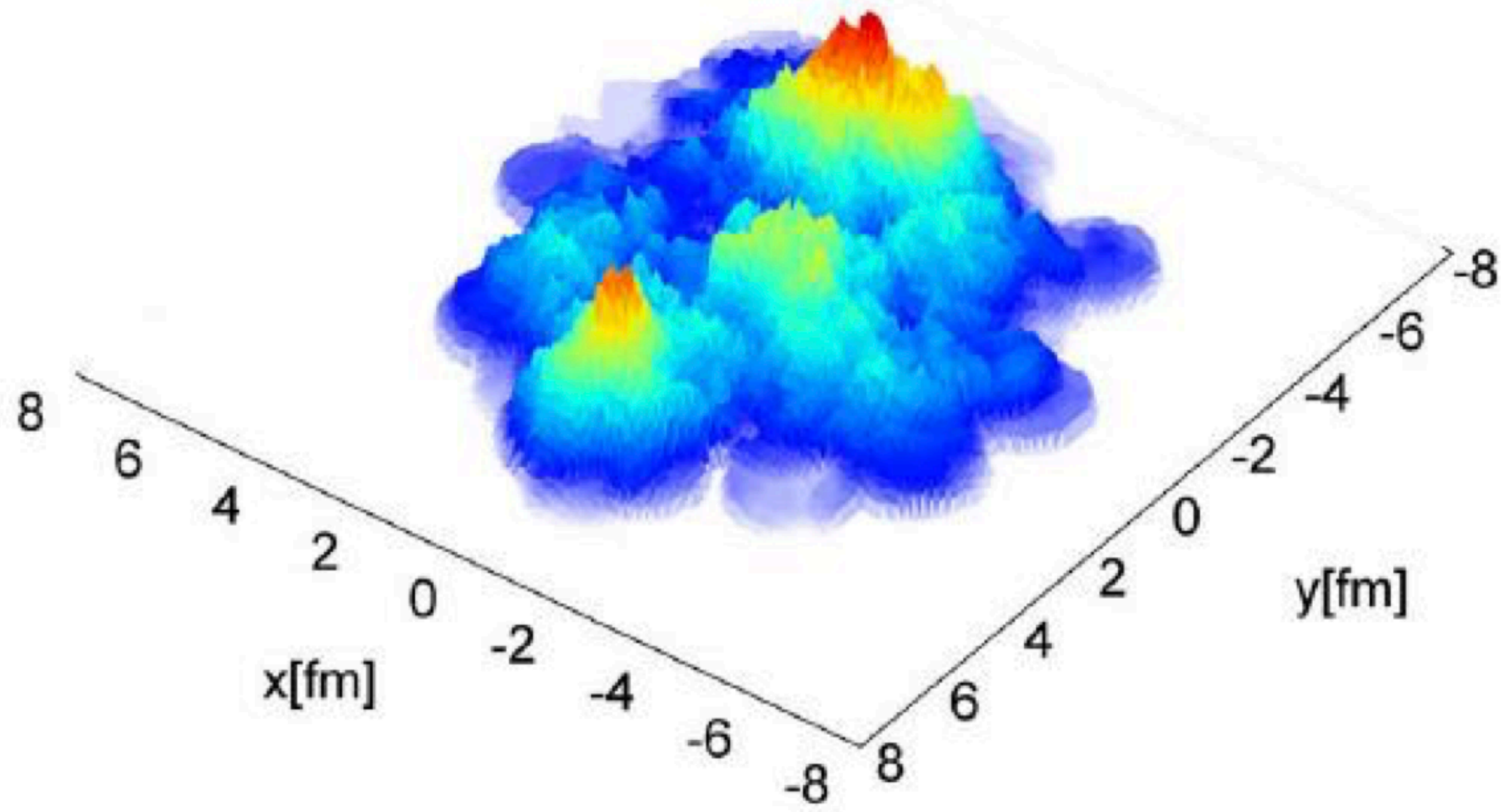

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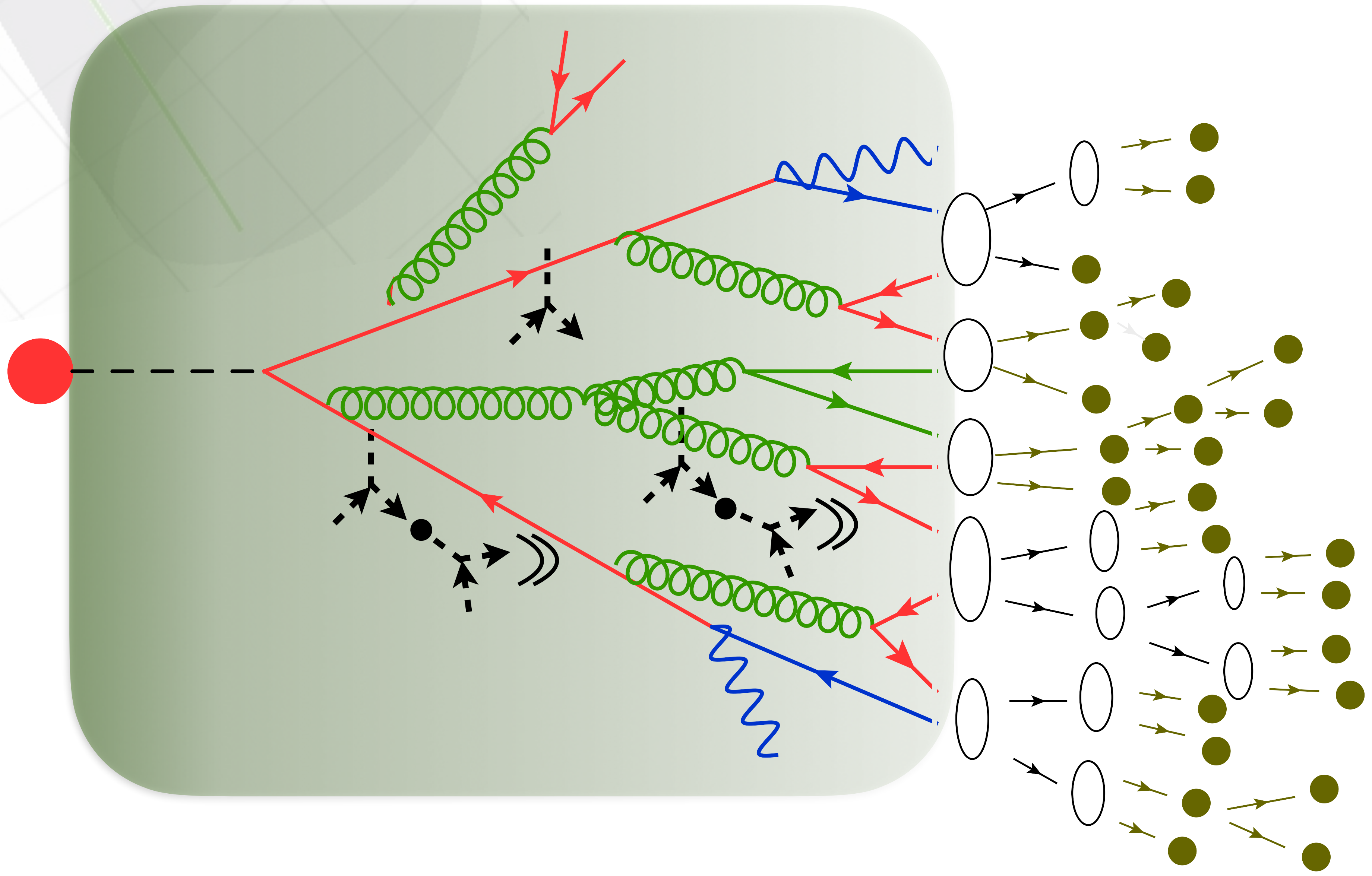
Medium Evolution modelling

[Andrés, et al (1902.03231), Stojku et al (2008.08987), JETSCAPE (2102.11337), Adhya et al (2211.15803)]

- Uncertainty driven by the onset of medium-jet interactions…



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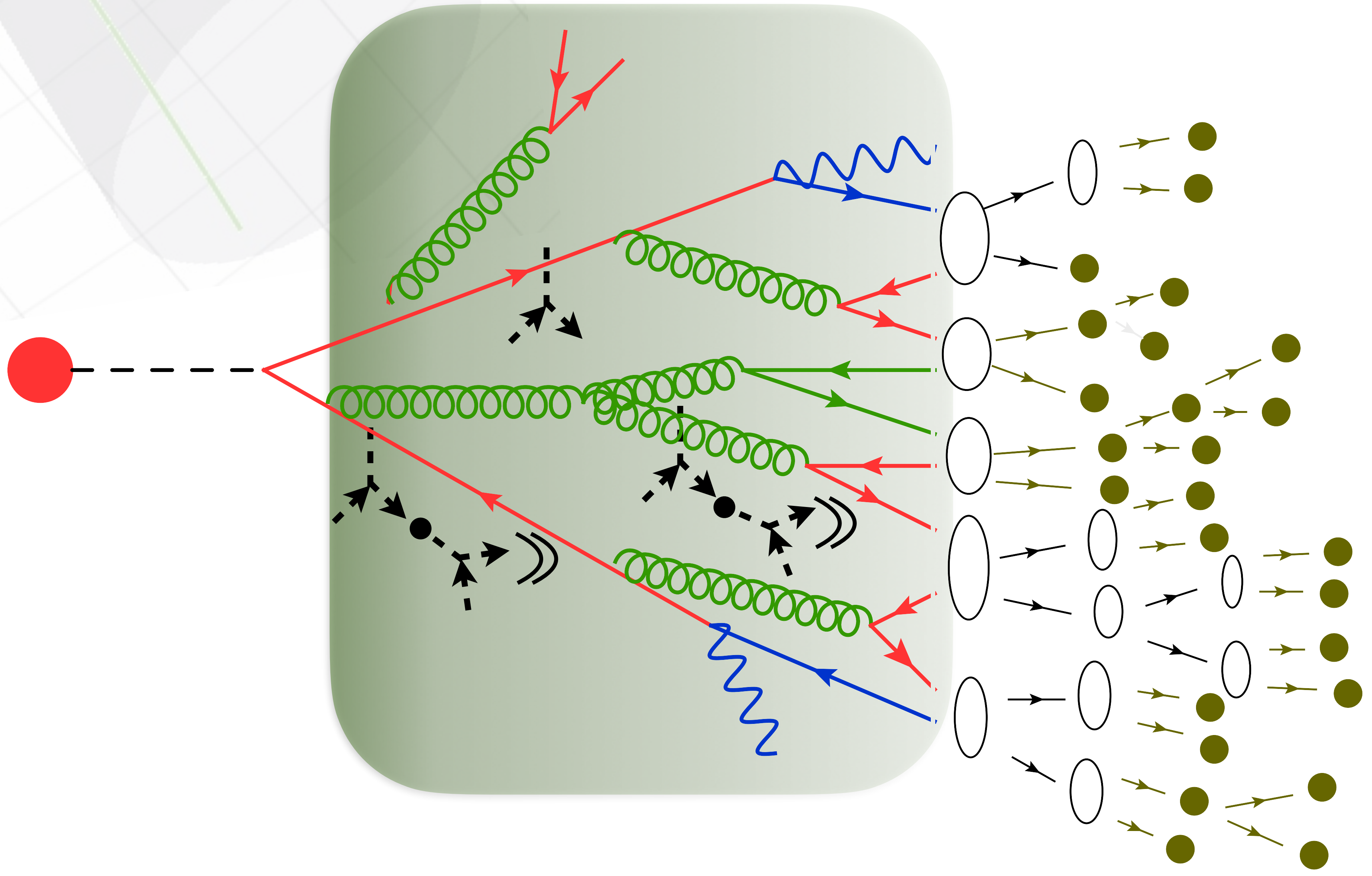
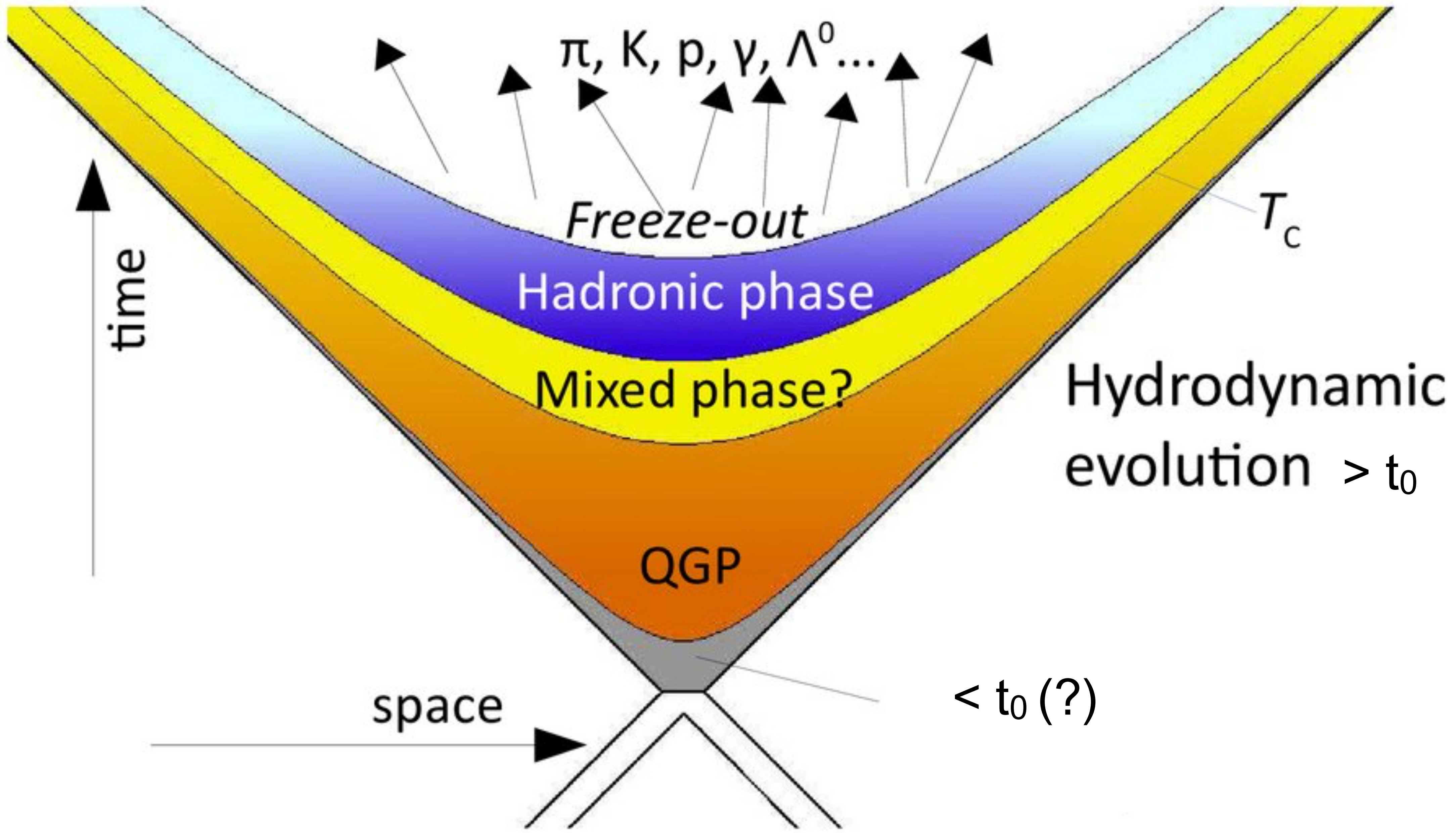
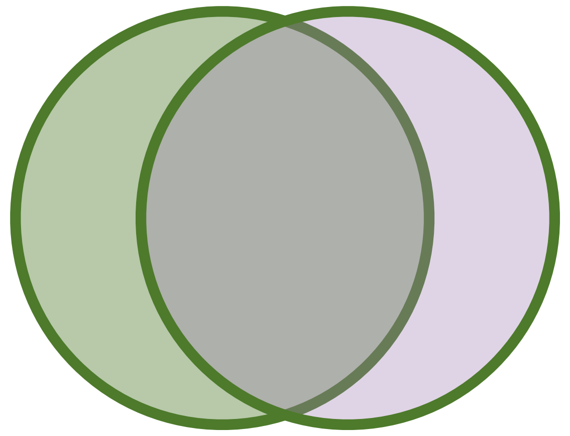
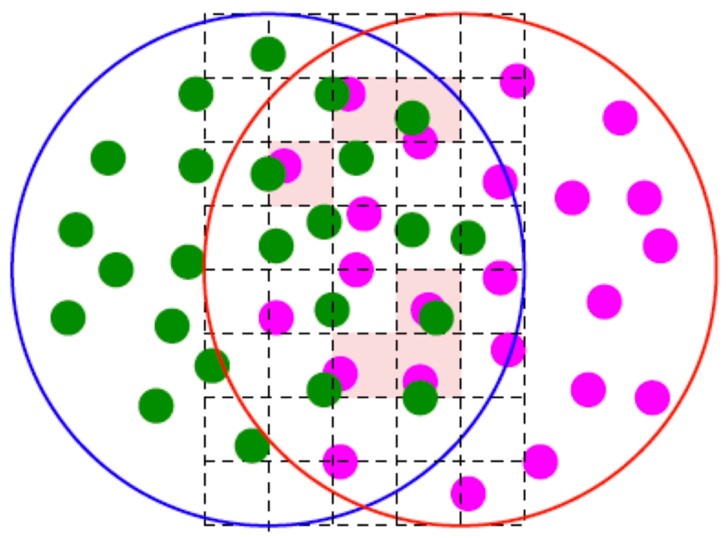




Jet-medium interactions start at t_0? What happens before?

And still more…

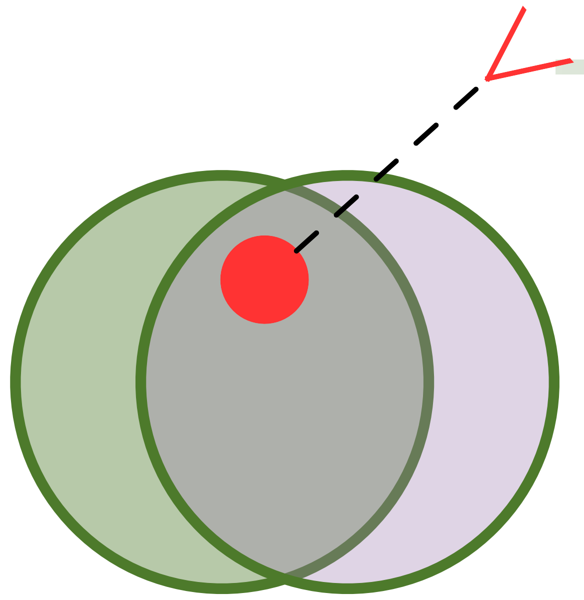


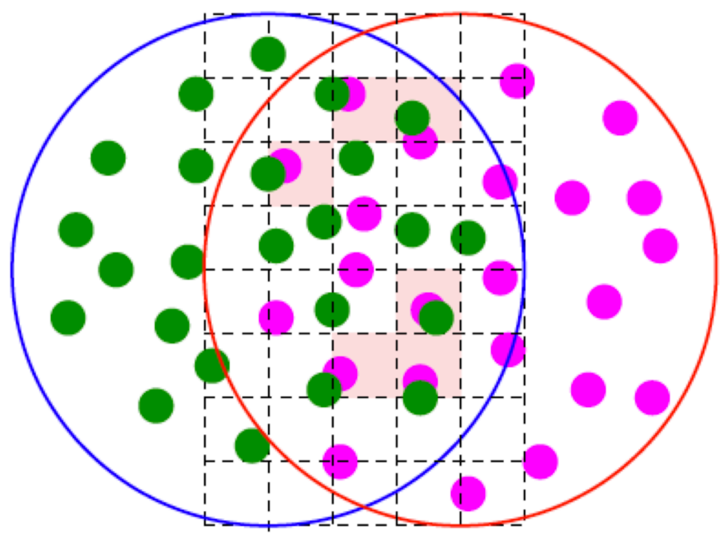


- Production point (for path-length dependence):
  - Sampled from initial nuclei overlap

And still more…

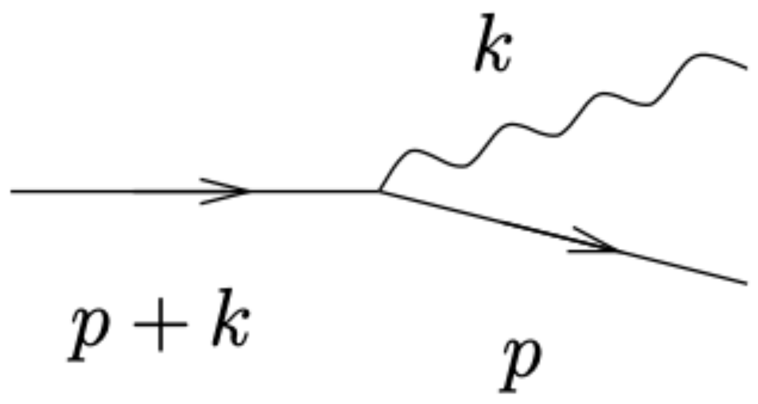
- Production point (for path-length dependence):
  - Sampled from initial nuclei overlap
  - Needs to account for space-time structure of jets
    - In vacuum parton showers?

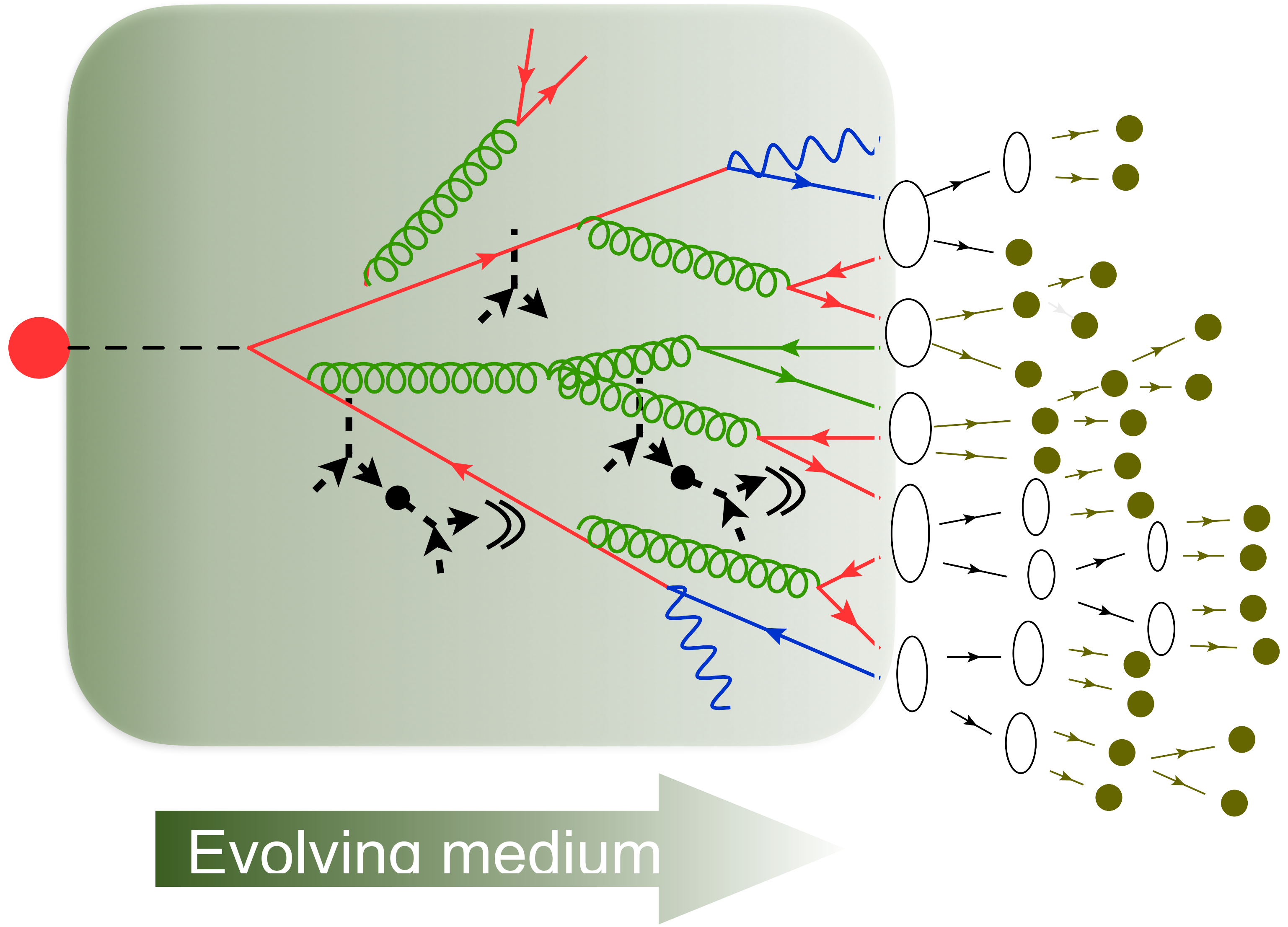




Parton formation time:

$$t_g^{form} \sim \frac{1}{M_{virt.}} \frac{E}{M_{virt.}} = \frac{E}{(p+k)^2}$$





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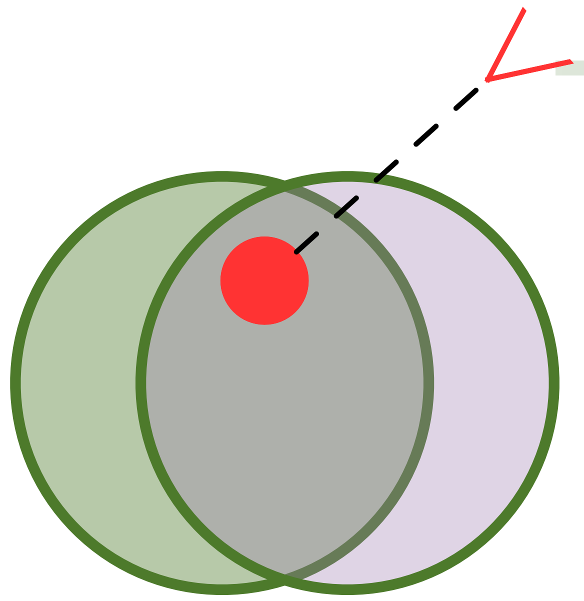

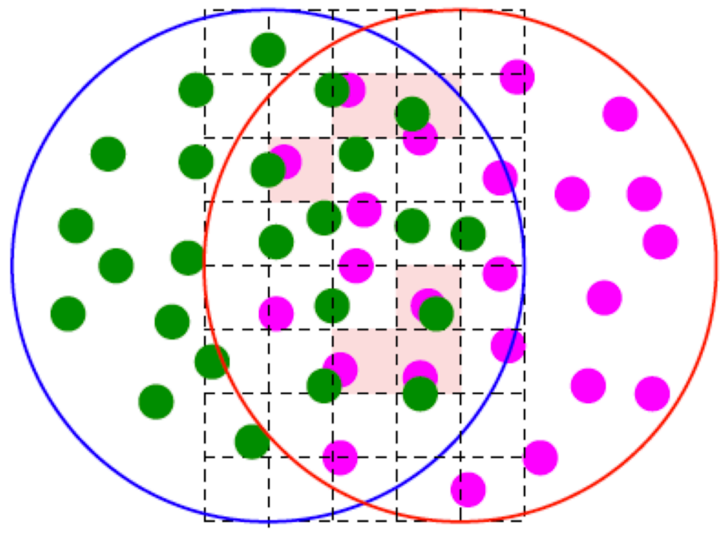

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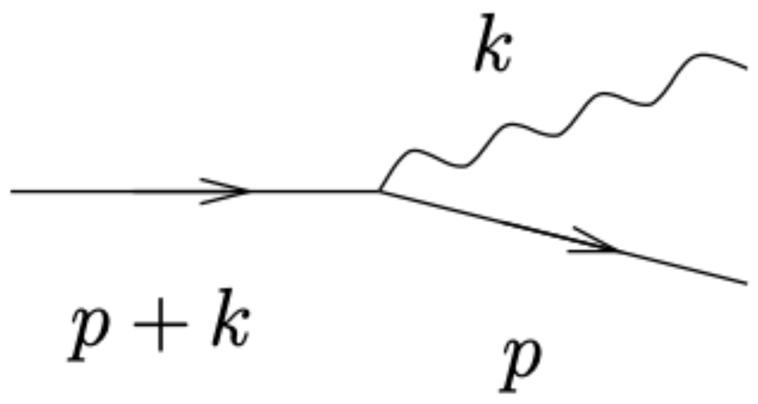
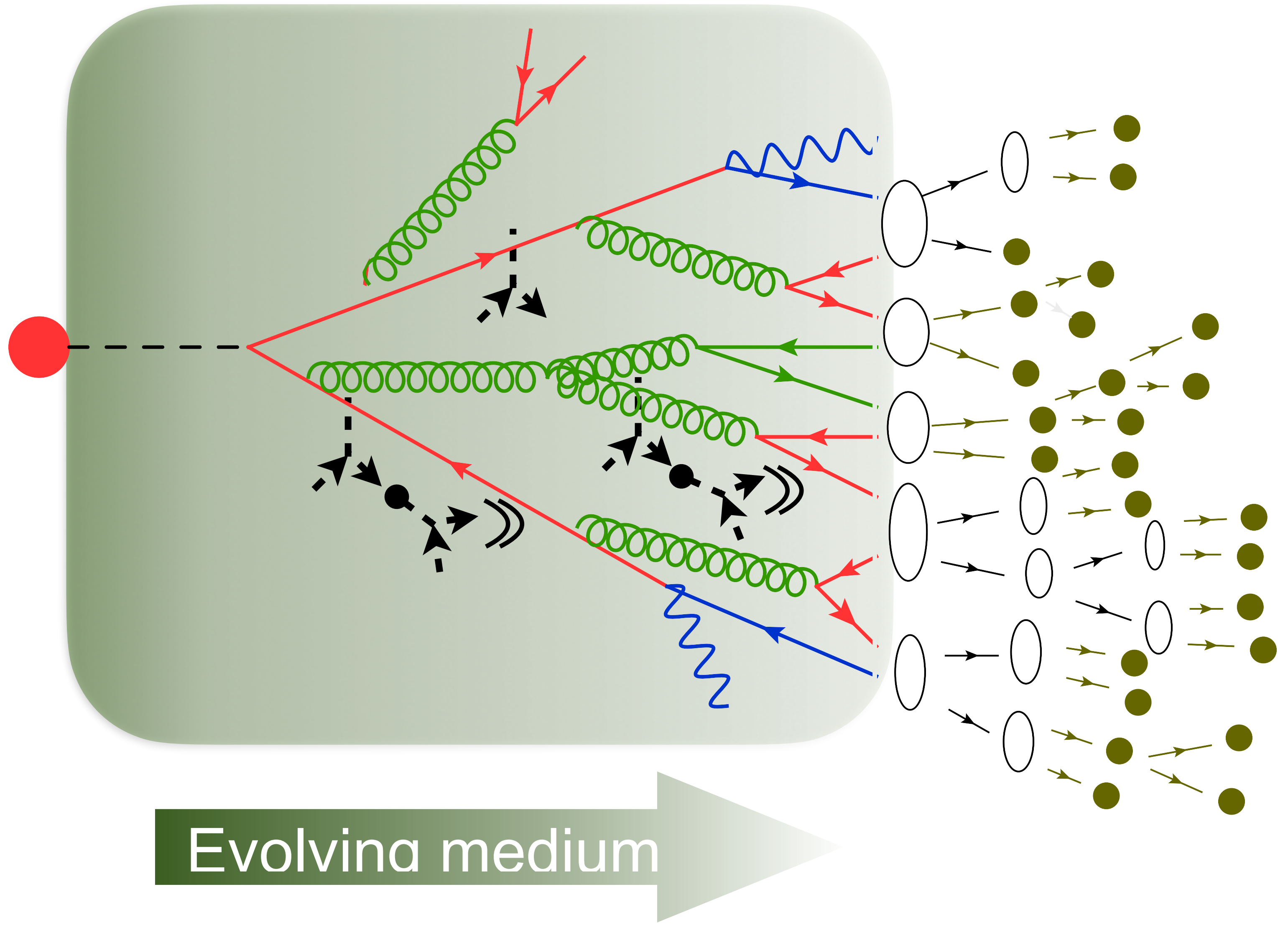




- Hadronization:
  - Usually taken from PYTHIA (might include recoiled particles)

State-of-the-art models

- Several jet quenching Monte Carlo models: See references in the backup slides

Q-PYTHIA

PYQUEN

Jetmed(Saclay)

JEWEL

JETSCAPE Co-LBT

JETSCAPE MARTINI

JETSCAPE MATTER

JETSCAPE CUJET

DREENA-A

JETSCAPE LBT

JETSCAPE Hybrid strong/weak coupling

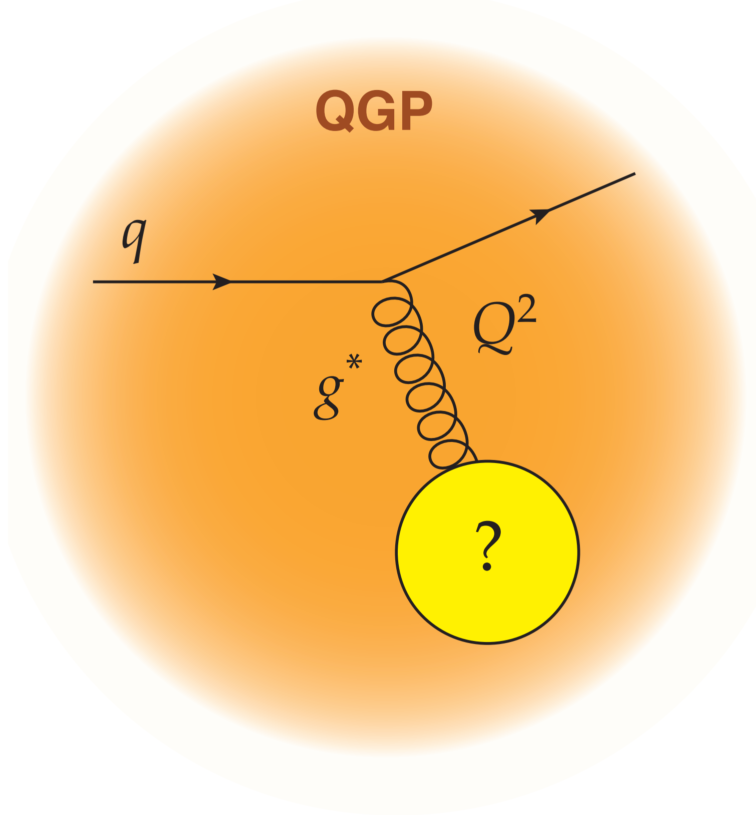
...

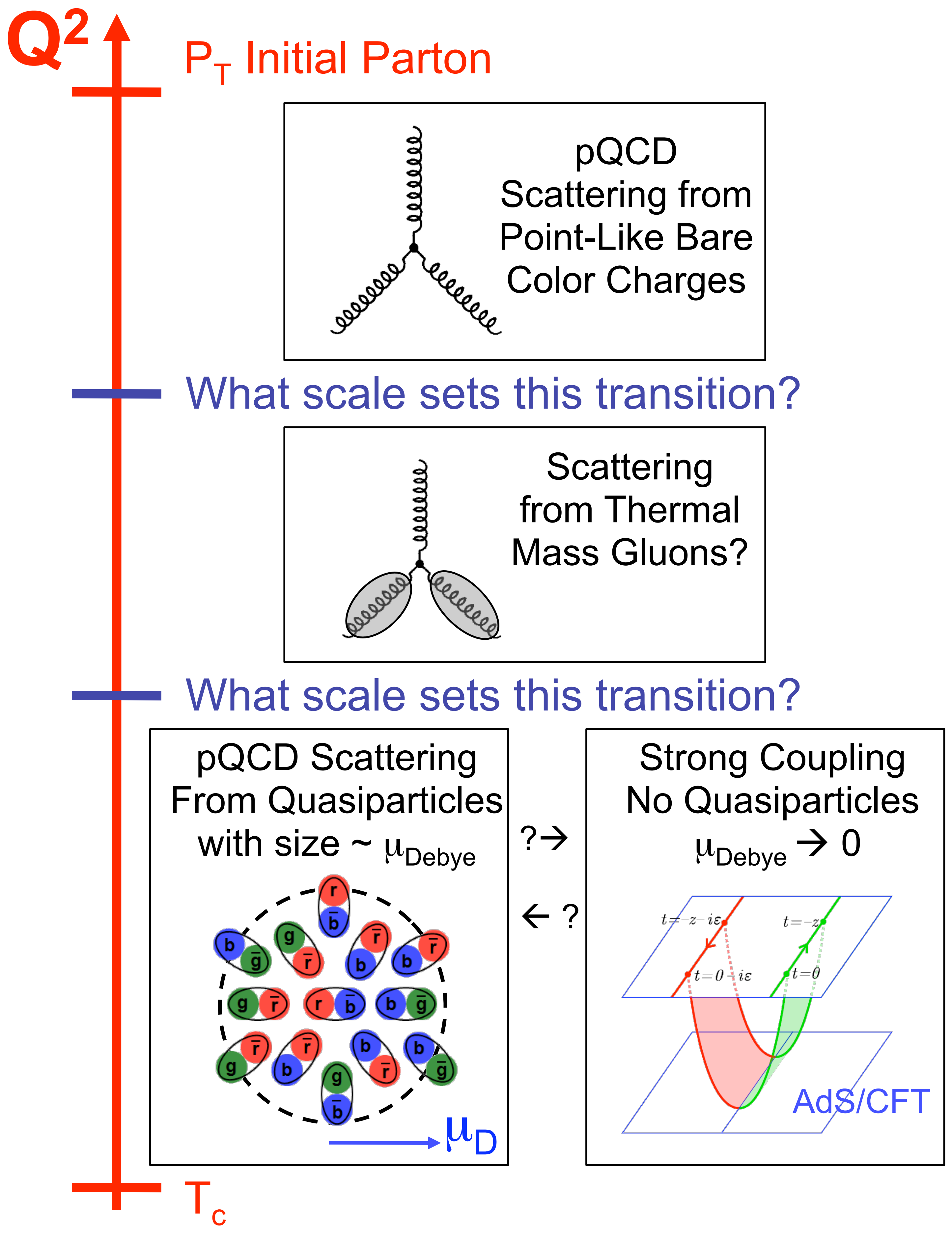
What can we do with a Monte Carlo model for jet quenching?

The successes of Monte Carlo approaches

Quantifying QGP properties

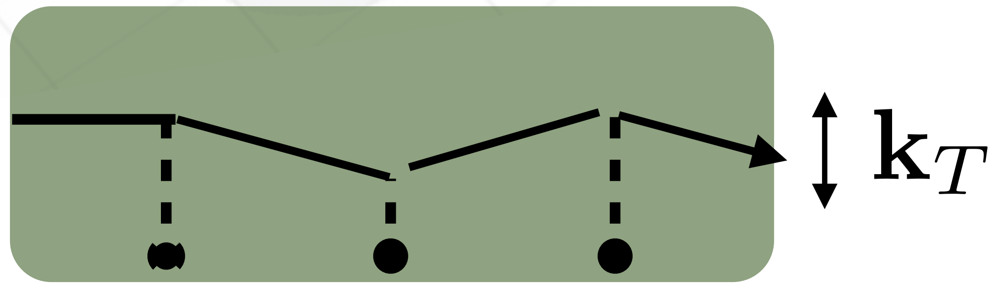
- Jets are formed in the beginning of the collision:
  - Allow detailed imaging of the QGP
    - QGP evolution (E.g: thermalisation process)
- Formed by collection of soft to hard particles
  - Allow QGP probing by different scales
    - Scale dependent quantities (Eg.: “quasi-particles”)





From the jet to the medium

- Medium-induced radiation and momentum broadening closely connected (multiple soft-scattering approximation)
  - Accumulation of momenta enhances gluon radiation and partons undergo transverse momentum broadening



Dipole cross-section (collision rate):

$$\sigma(\boldsymbol{r}) = \int_{\boldsymbol{q}} V(\boldsymbol{q}) \left(1 - e^{i\boldsymbol{q}\boldsymbol{r}}\right)$$

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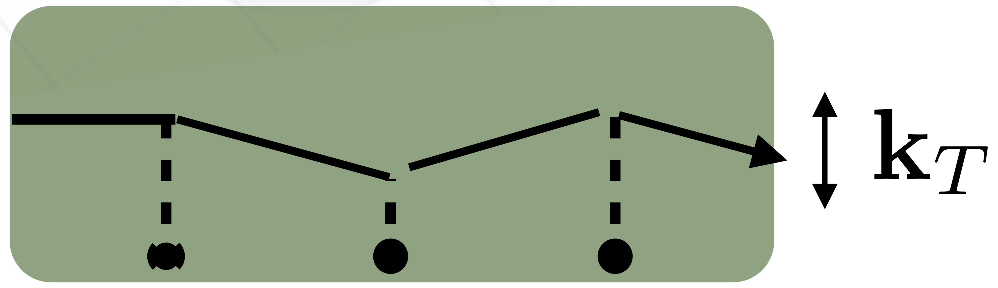

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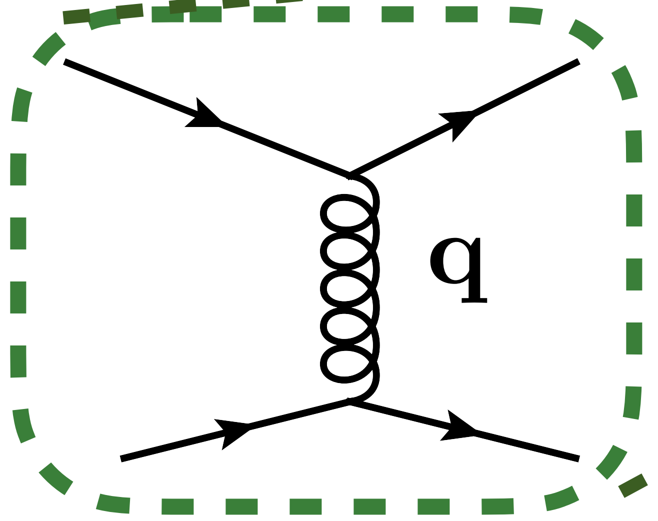

Parton-medium interaction

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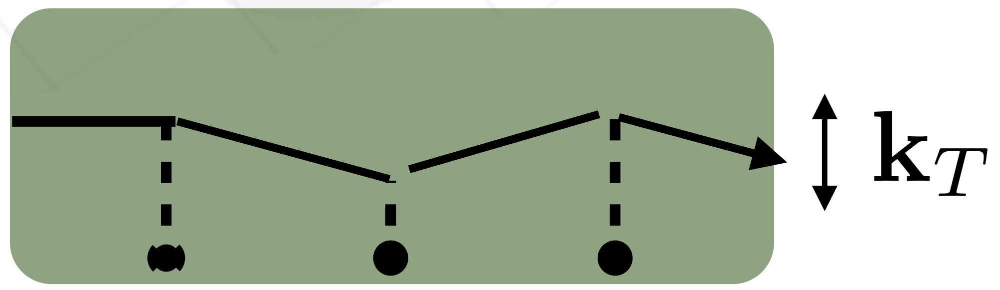

Transport coefficient:

$$\hat{q} = \frac{\langle k_T \rangle}{\lambda}$$

$$\hat{q} \propto \int d^2\mathbf{q}^2 q^2 \frac{d\sigma(\mathbf{q})}{d^2\mathbf{q}}$$

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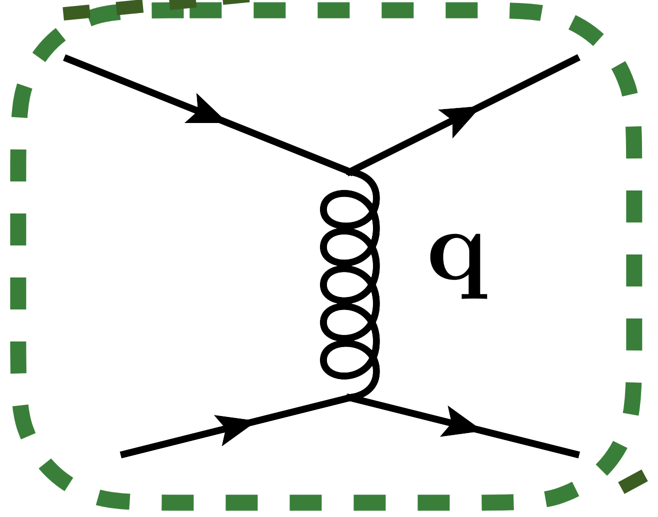


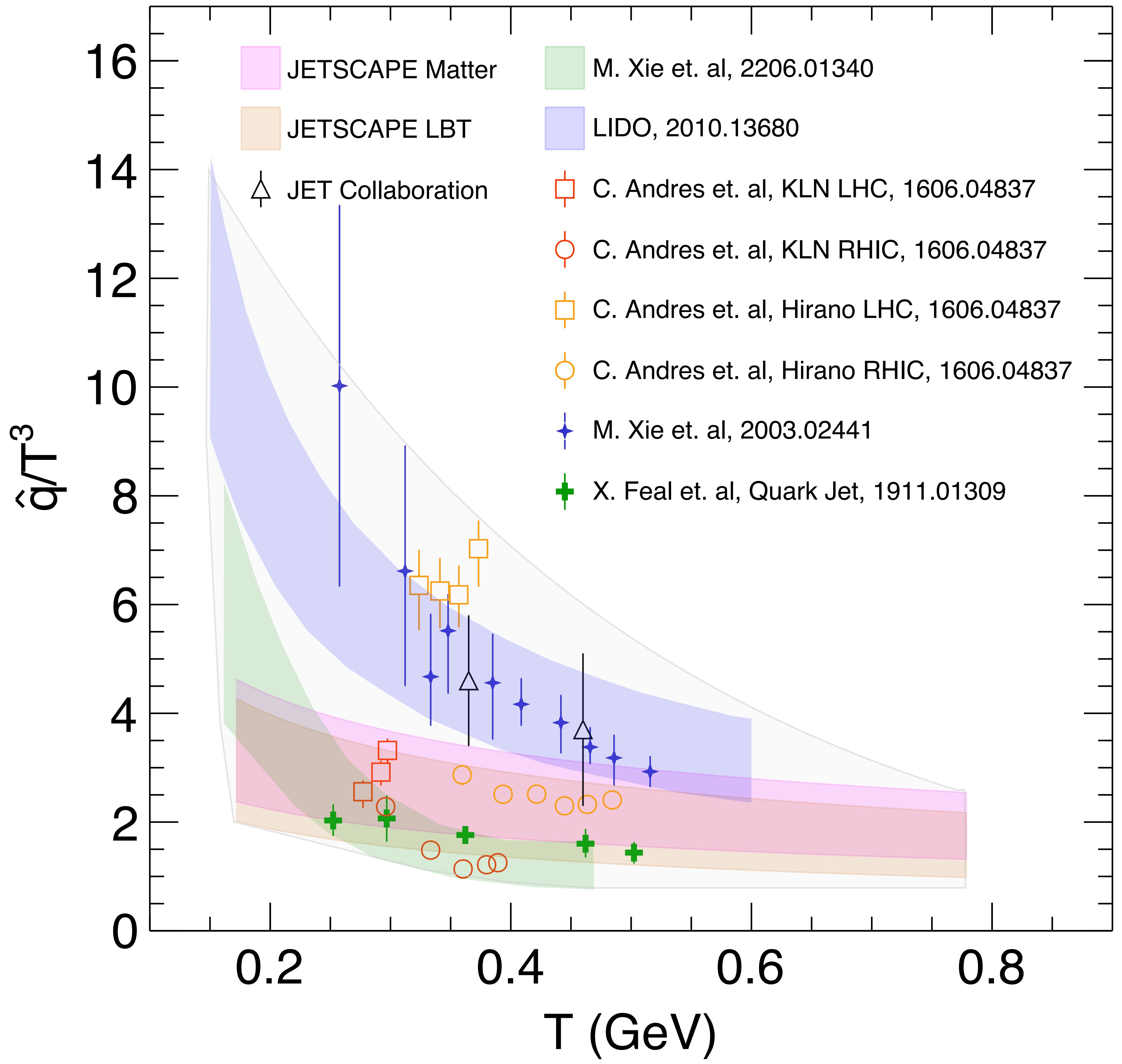
Parton-medium interaction

Medium transport coefficients

JETSCAPE

- From single-particle or jet suppression recover $\hat{q}$

[LA, Y-J Lee, M. Winn (2203.16352)]



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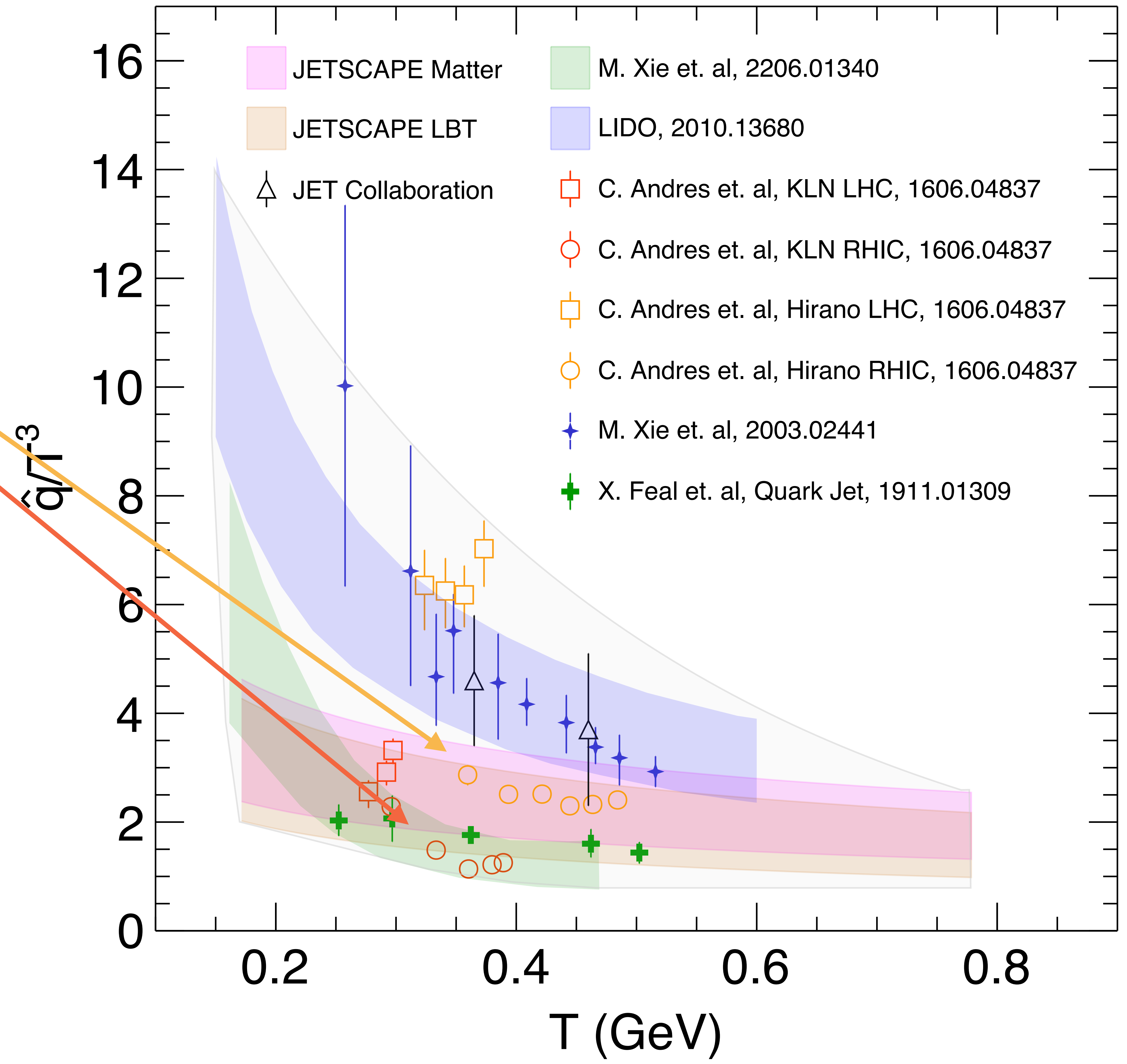

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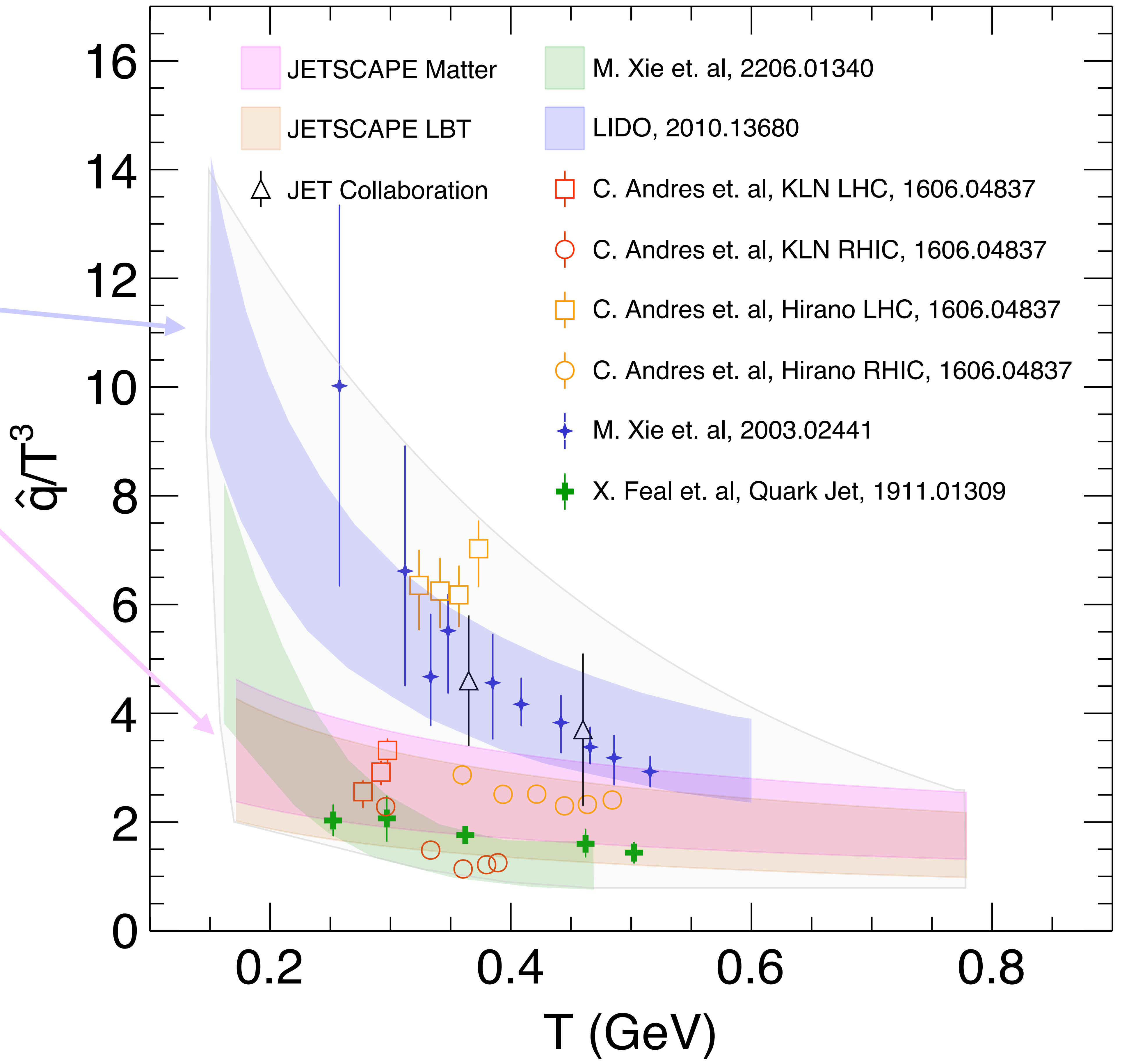
Energy loss during all parton shower evolution vs energy loss during final stage
(Compensation of effects with higher transport coefficient)



Medium transport coefficients

See John Miller (Tue 25)

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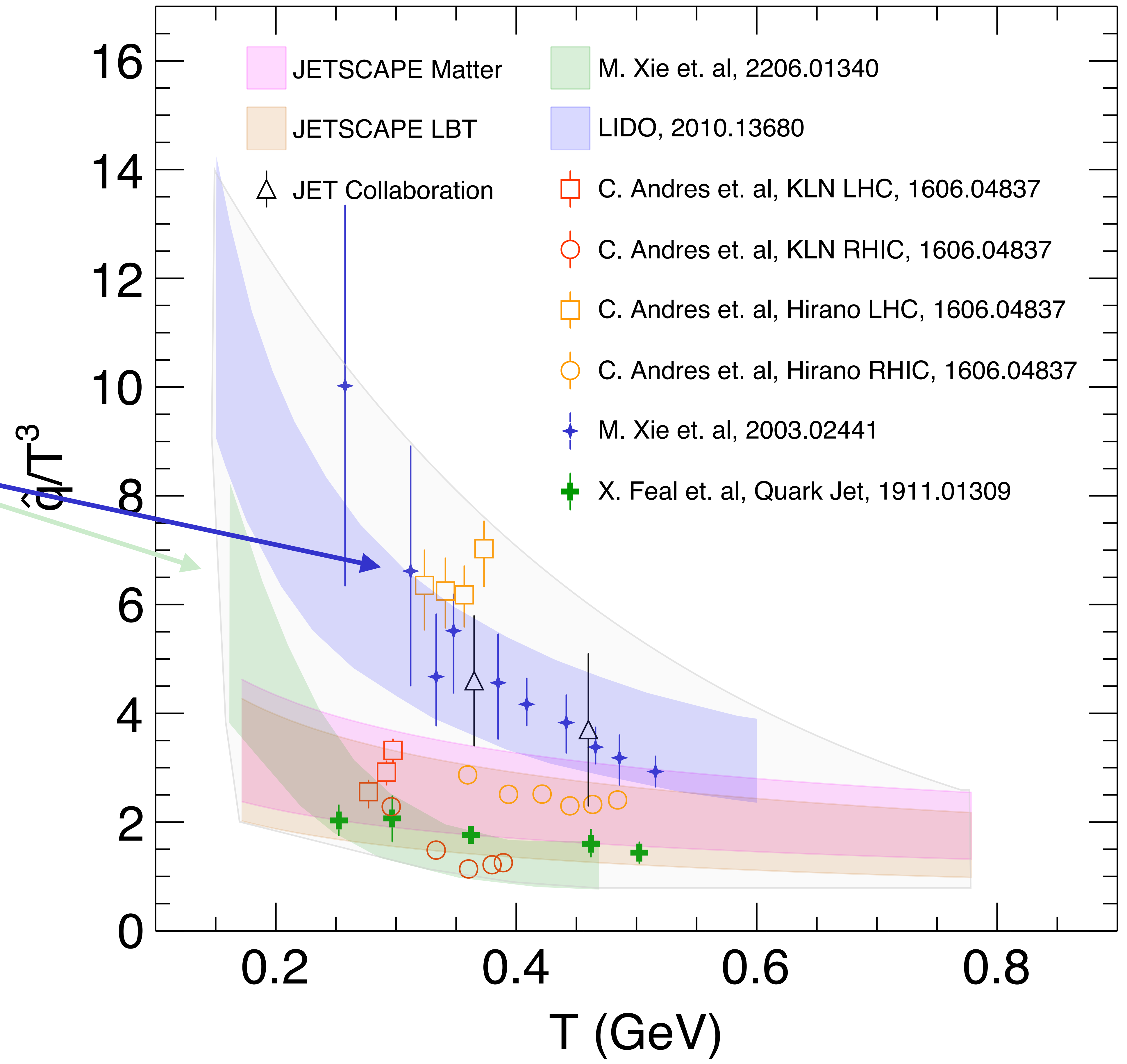

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Include different data sets
(boson-hadron correlations dominated by quark, inclusive particle spectra contains a mixture of the two)

Hadron vs Jet measurements
(model-dependent description of medium response on jets)

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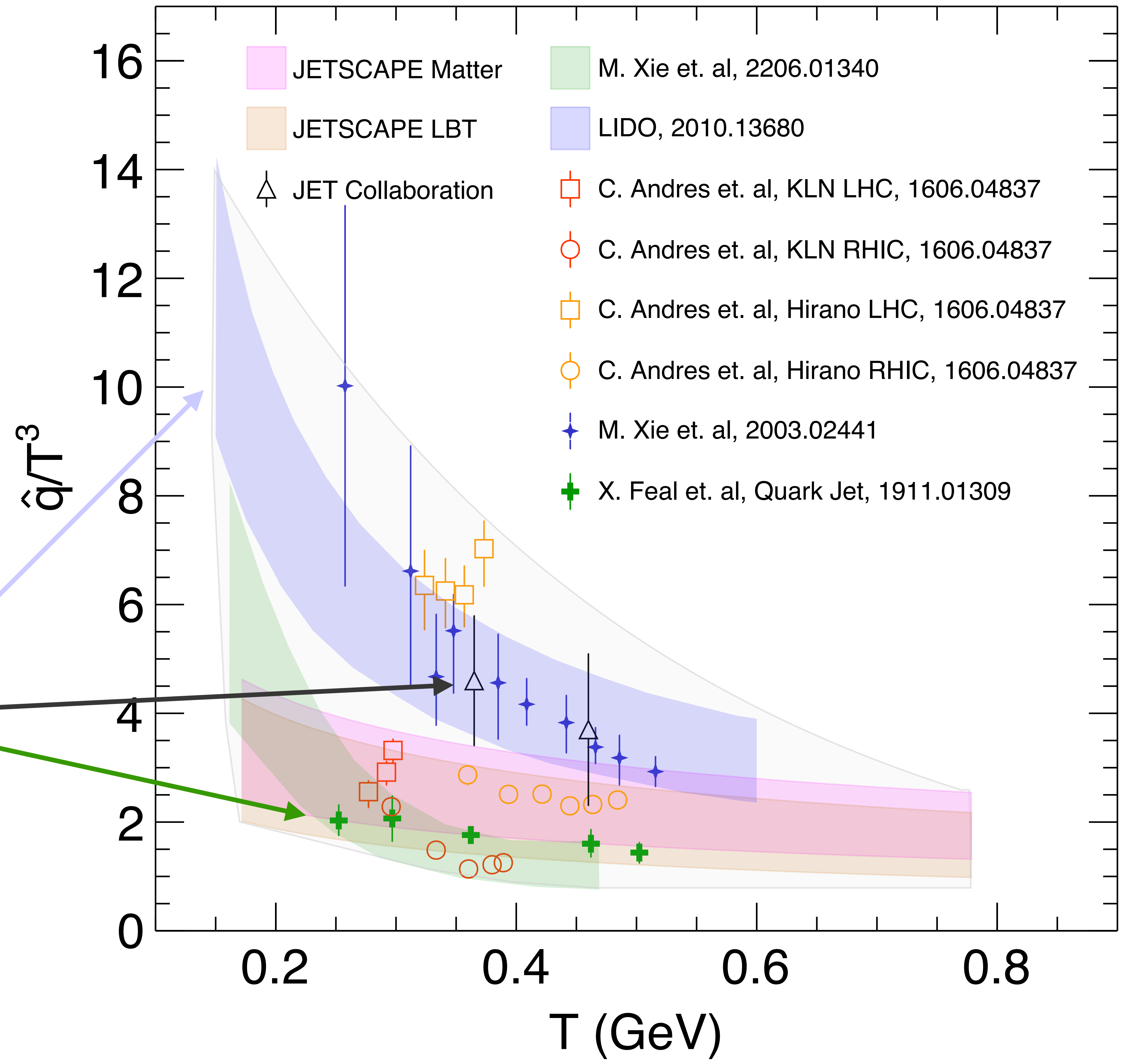

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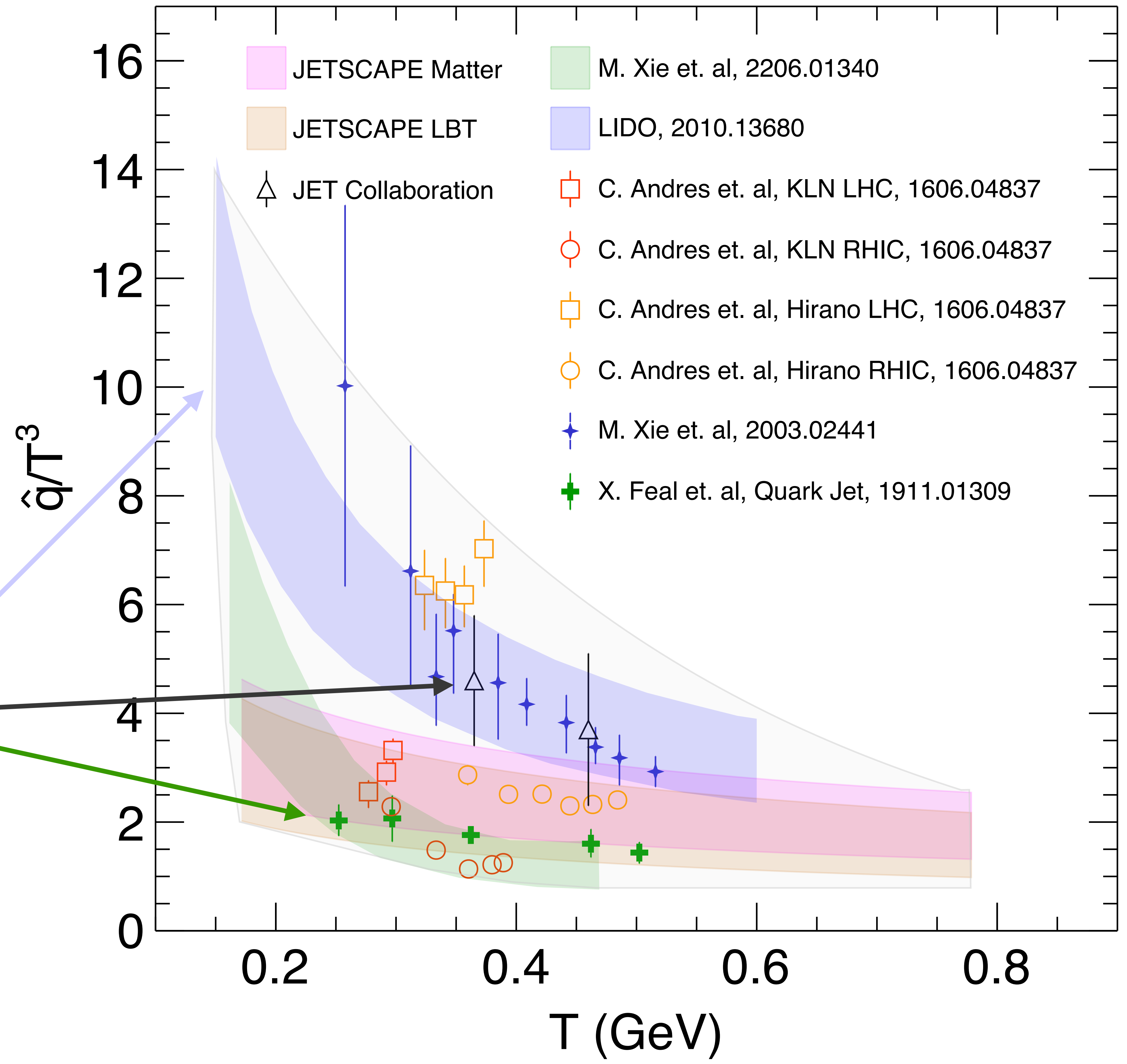
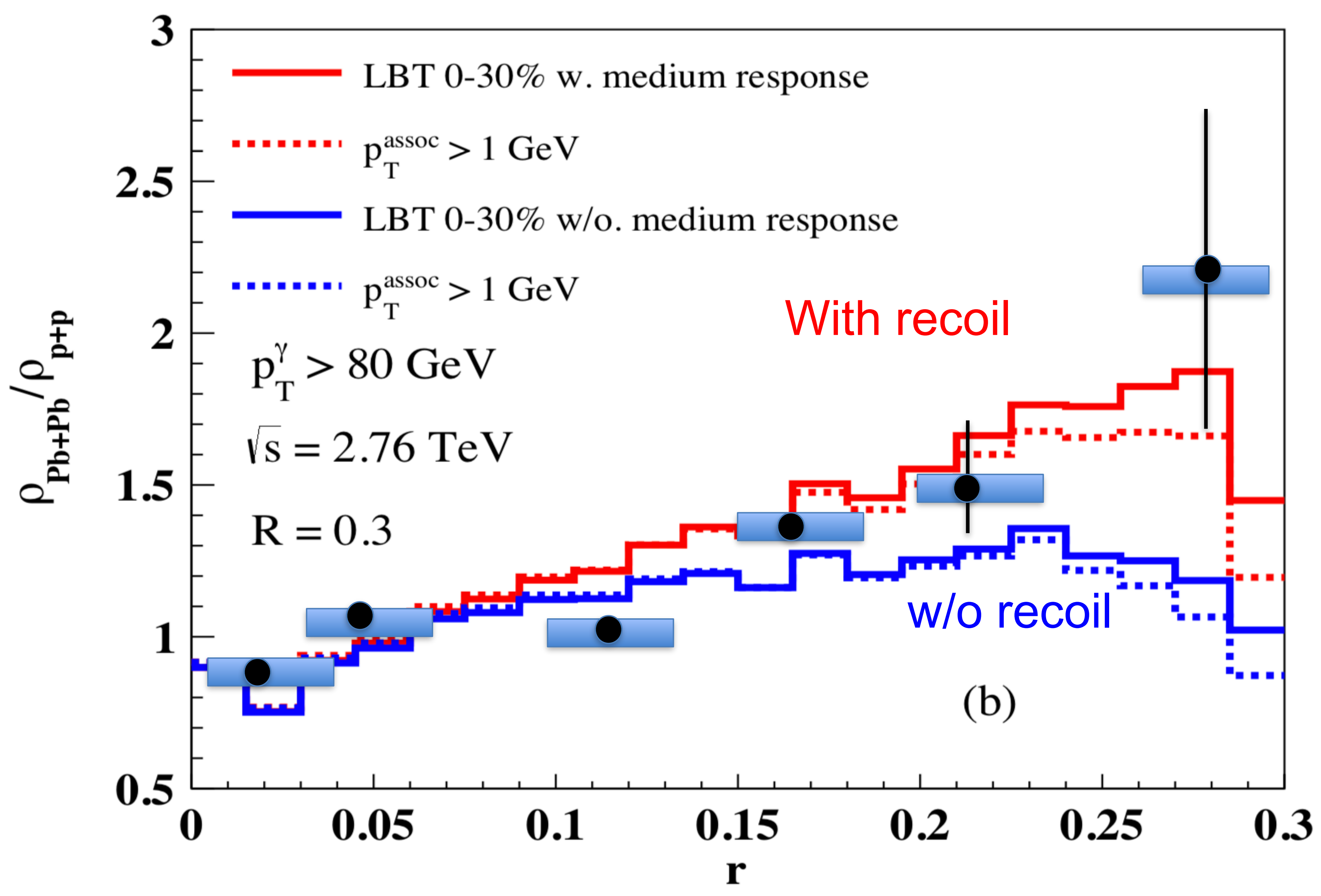


Quantitative assessment of QGP characteristics using hard probes

The elusive medium response

- Soft components seem necessary for a better description of the jet radial profile and/or jet mass:

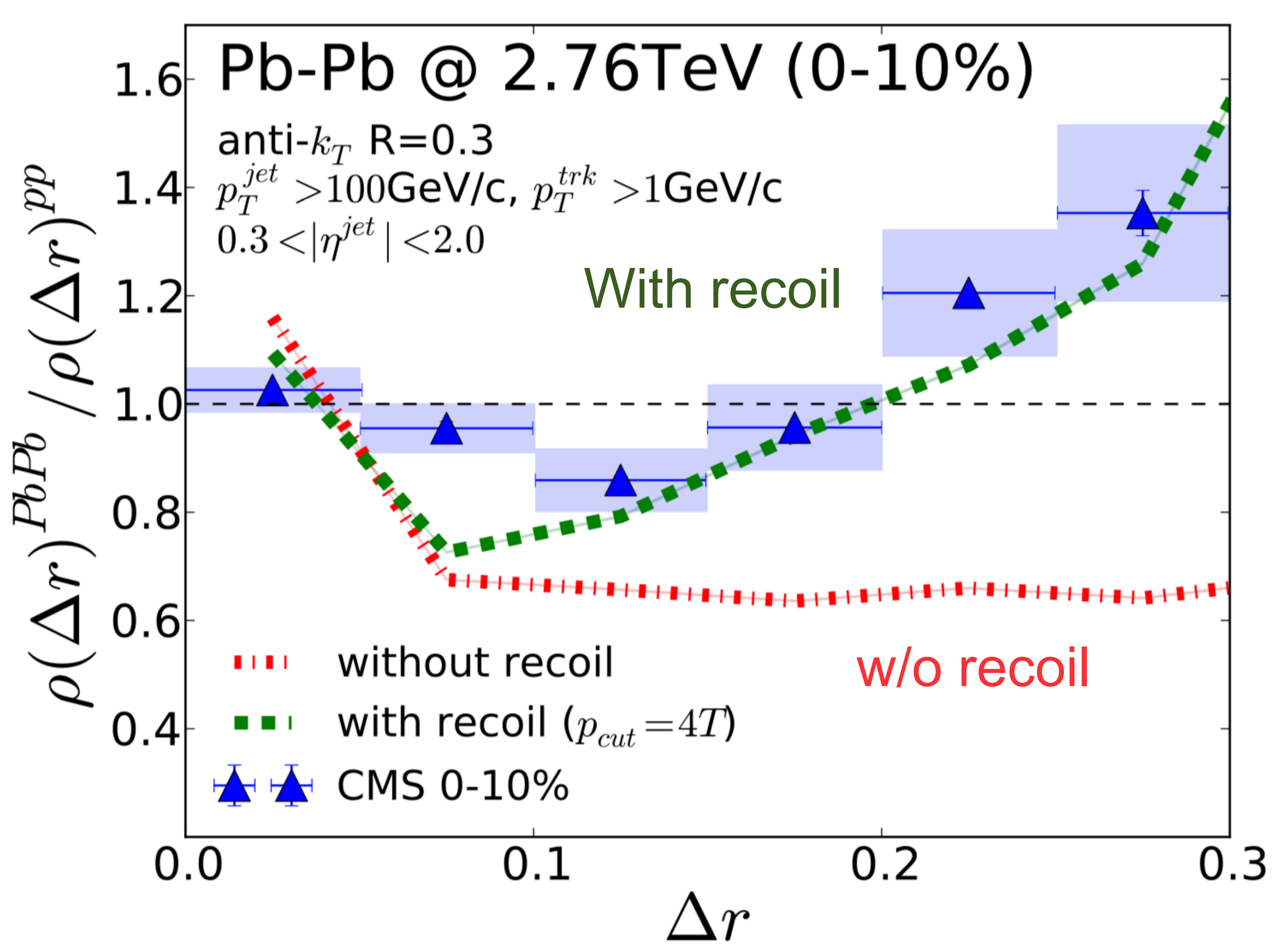
LBT



[Luo, Cao, He, Wang, (1803.06785)]

MARTINI

[Park, Jeon, Gale (1807.06550)]



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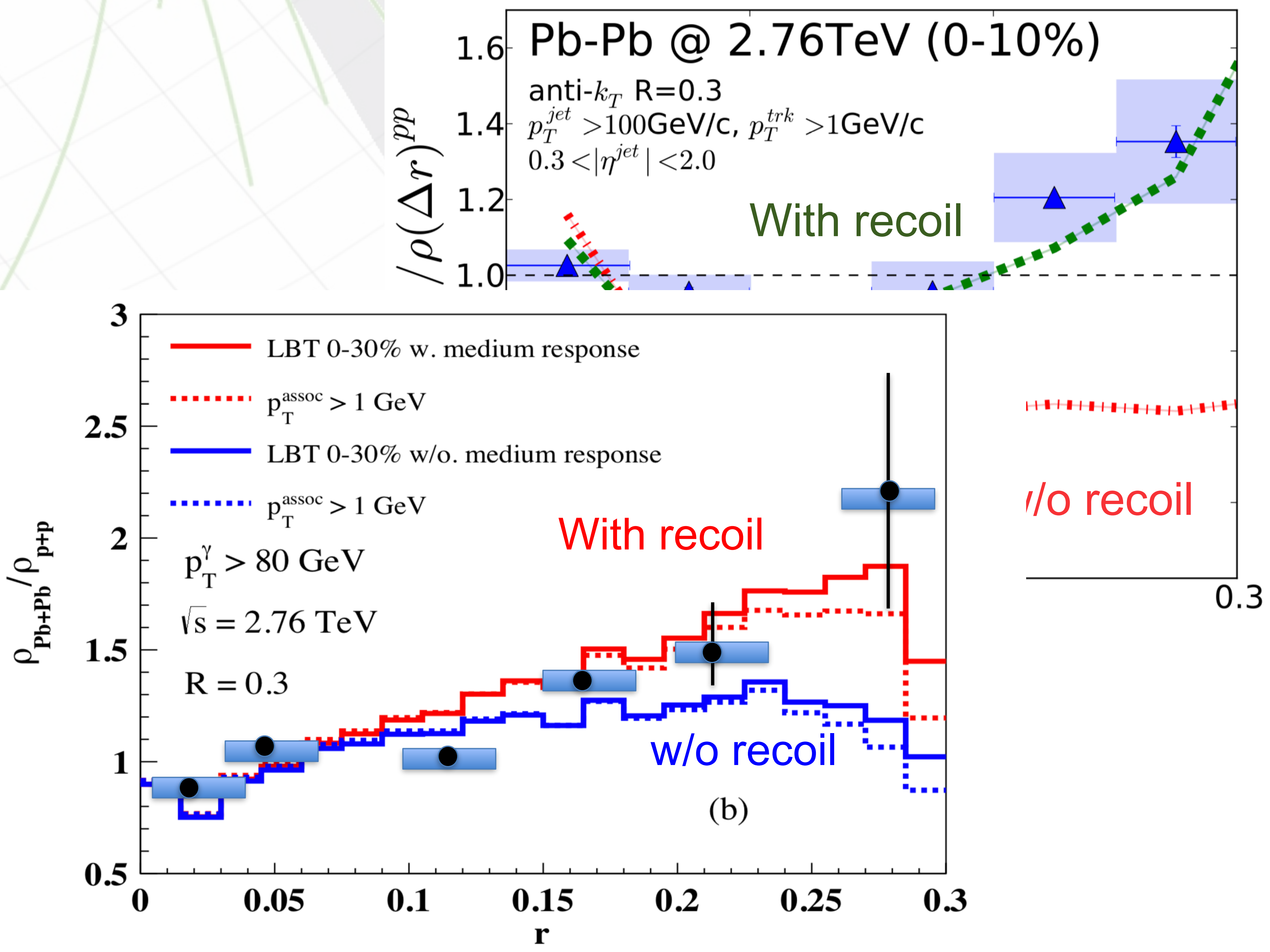
[Park, Jeon, Gale (807.06550)]



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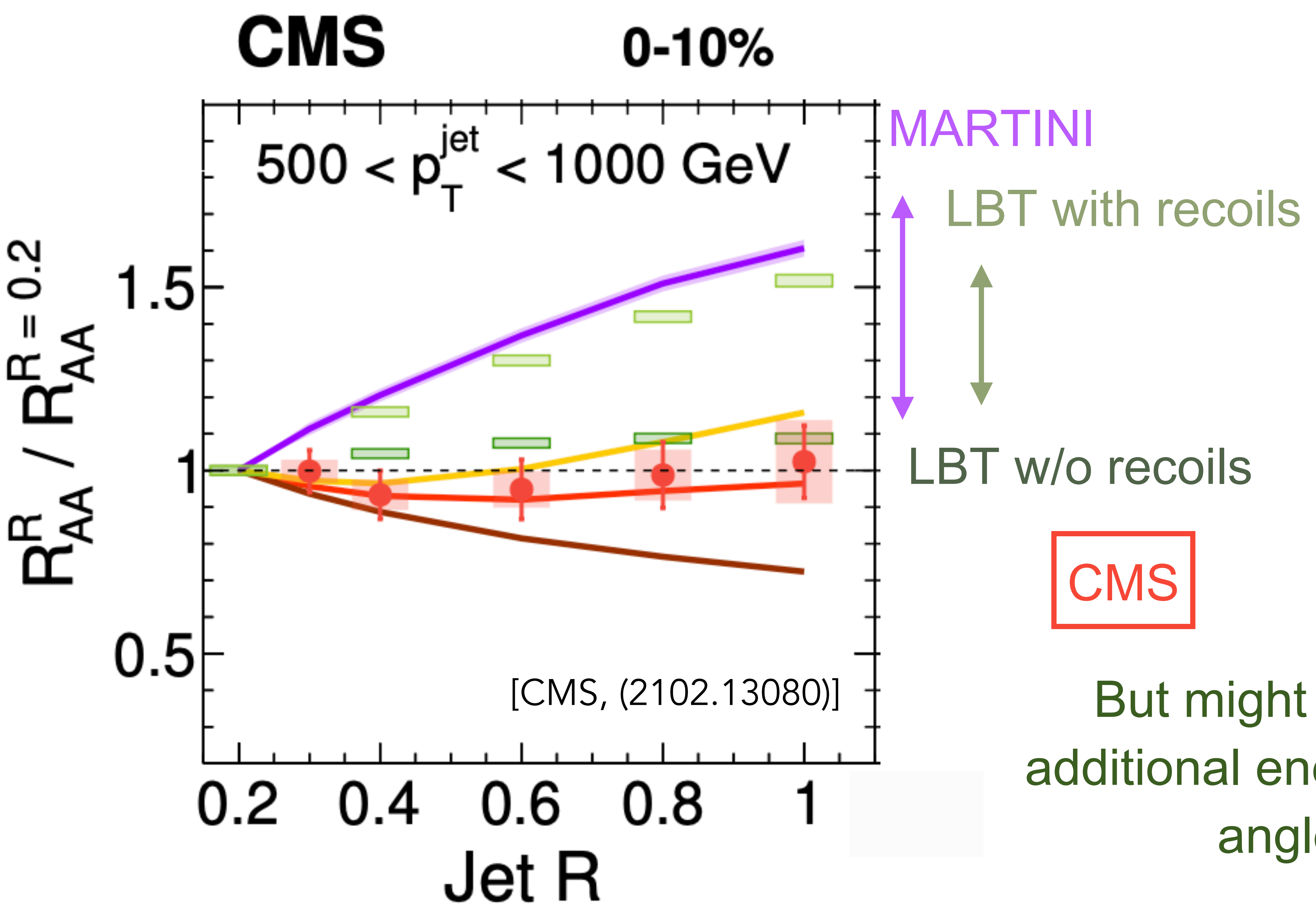


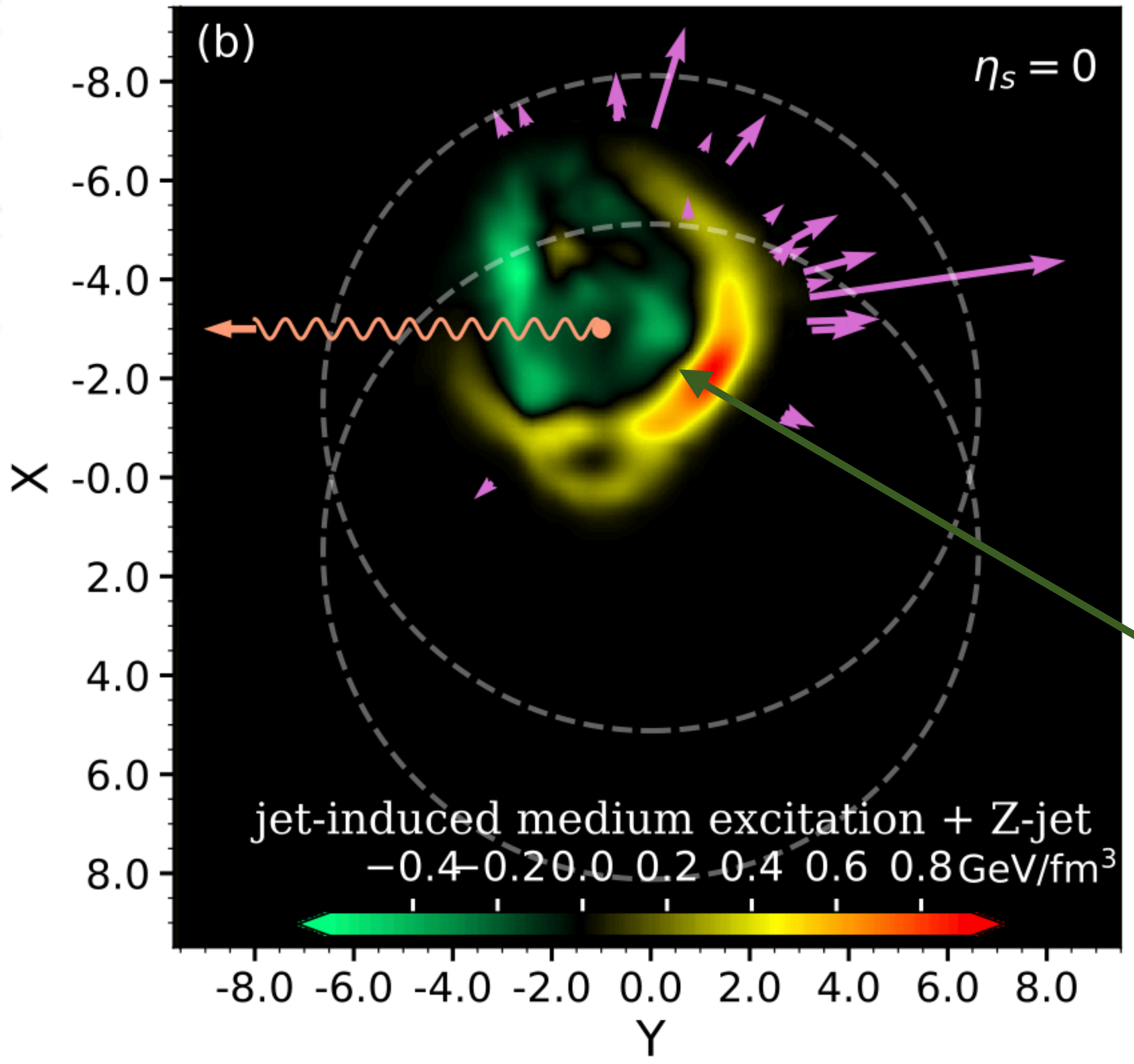
But might result into additional energy at larger angles…

Is the enhancement due to medium-response or to poorly known non-perturbative physics?

QGP-wake signal

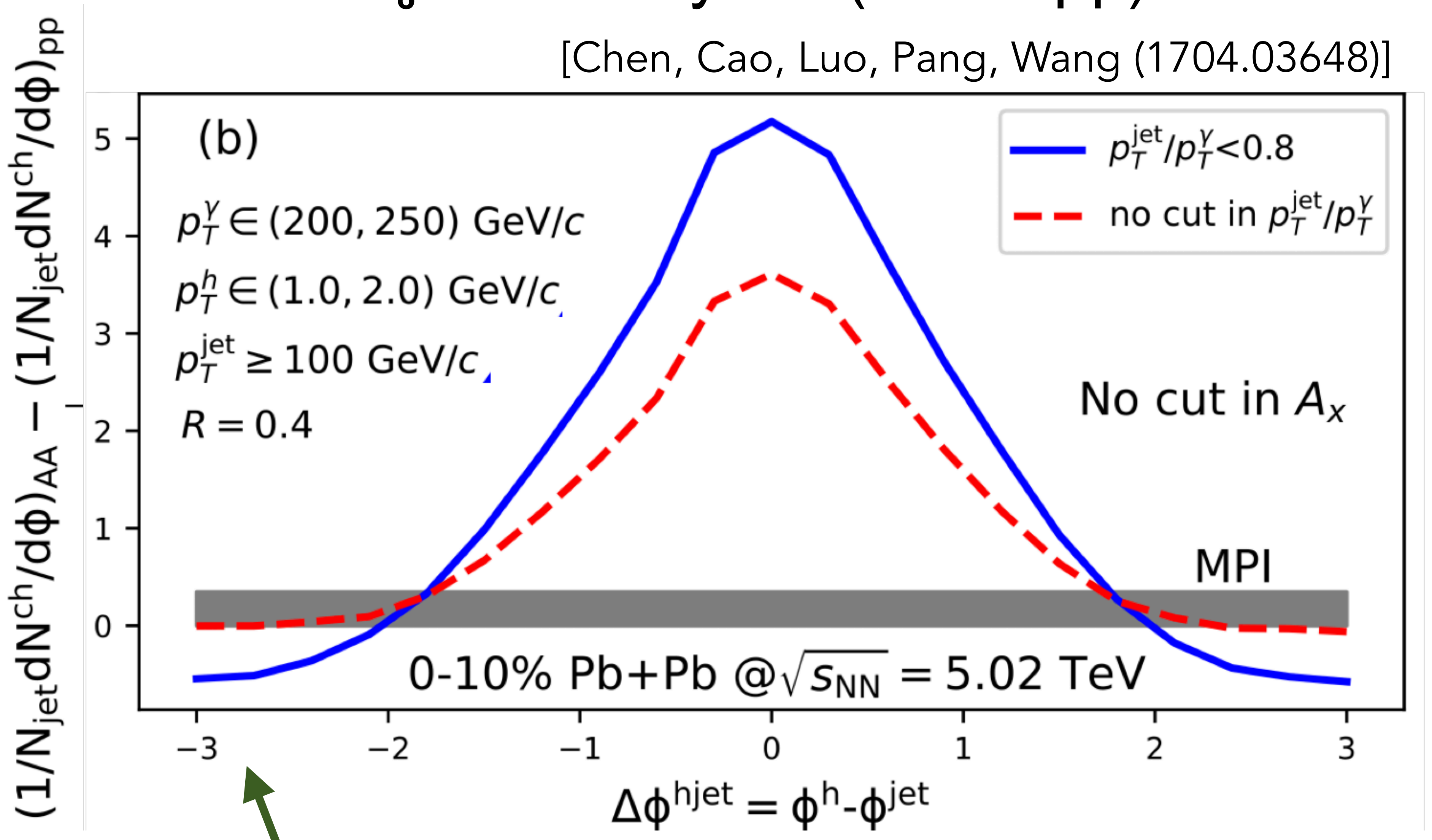
- Jet-induced medium exceptions in Z+jet events:

Co-LBT



ɣ+hadron yield (PbPb-pp)

[Chen, Cao, Luo, Pang, Wang (1704.03648)]



Soft-hadron depletion in ɣ direction

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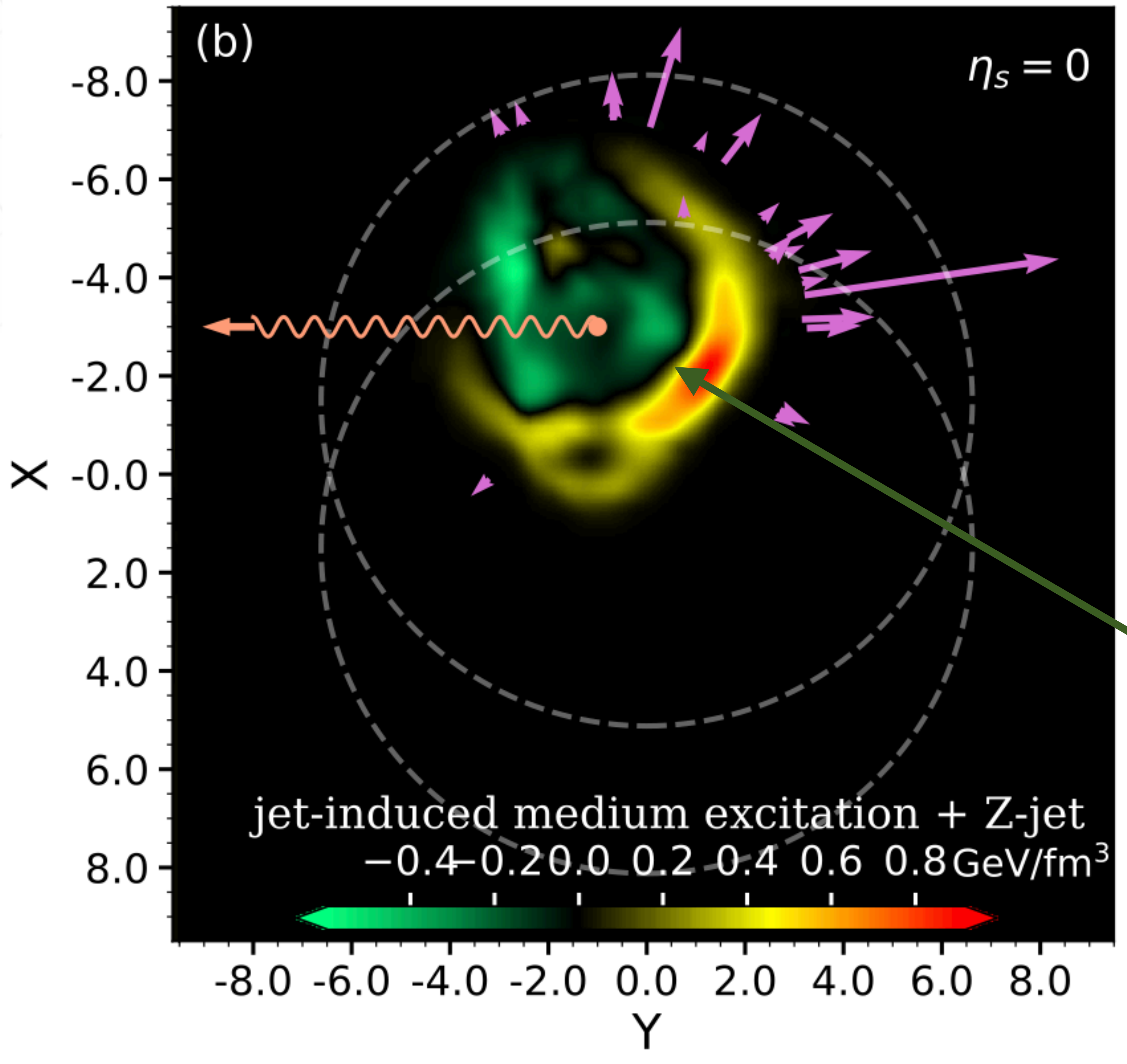
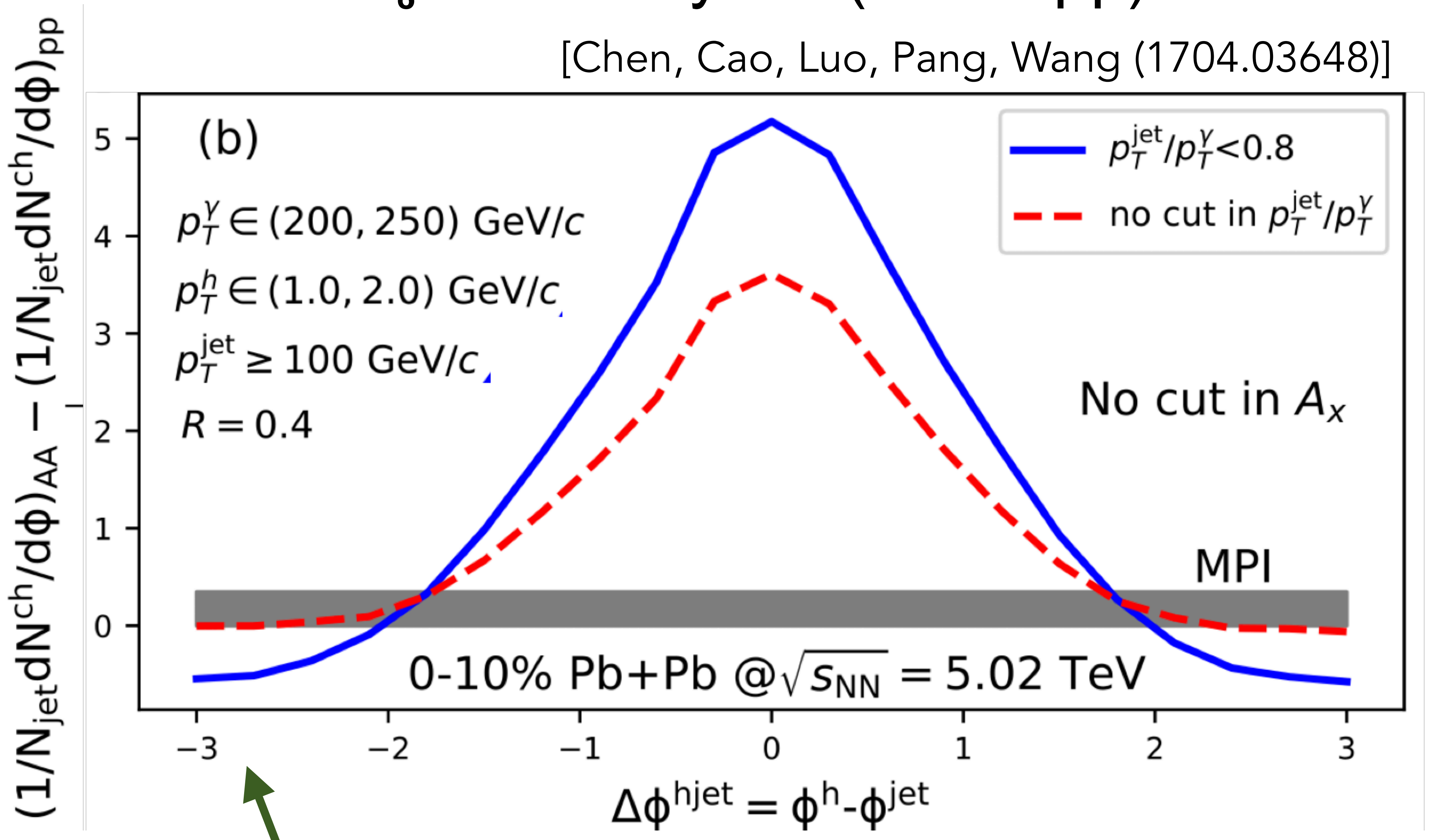


γ+hadron yield (PbPb-pp)

[Chen, Cao, Luo, Pang, Wang (1704.03648)]

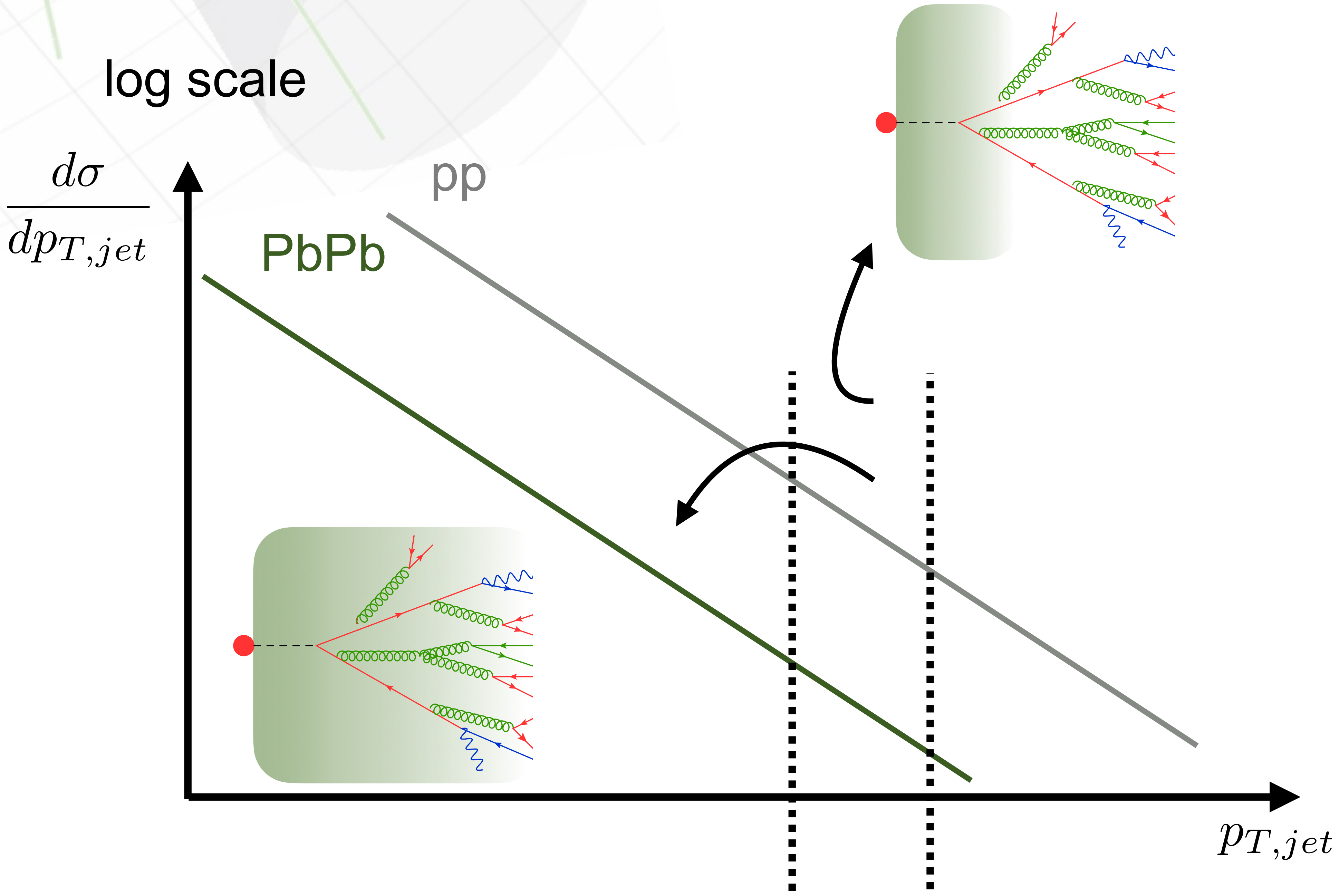


Soft-hadron depletion in γ direction

Introduction of viscous hydro in MC ⇒ 3D Wake that depend on EoS

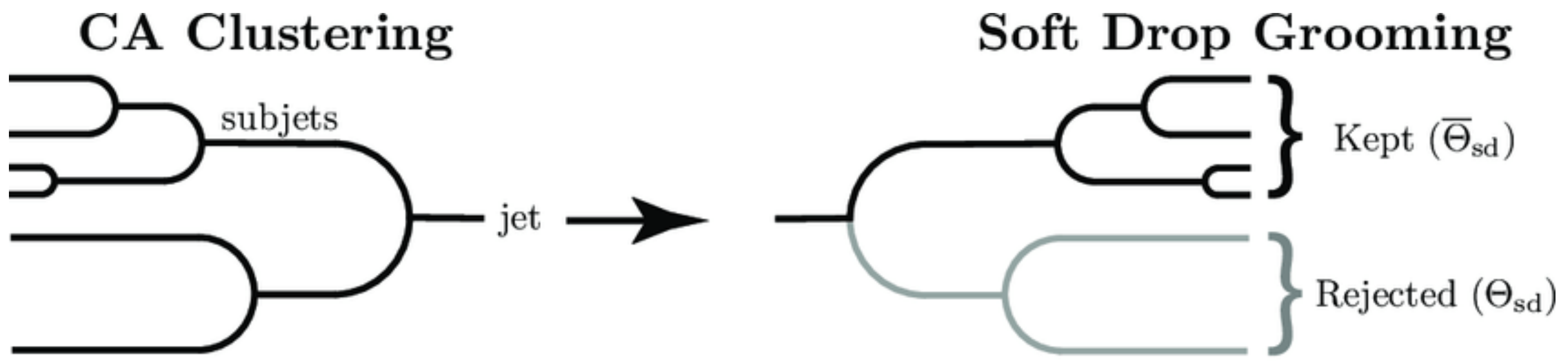
Understanding biases

- Comparison between quenched and unquenched made through some jet selection:
    - Impact of jet selection biases on jet substructure observables?



How to compare unmodified with modified jets?

Which jet selection results from applying grooming?



$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

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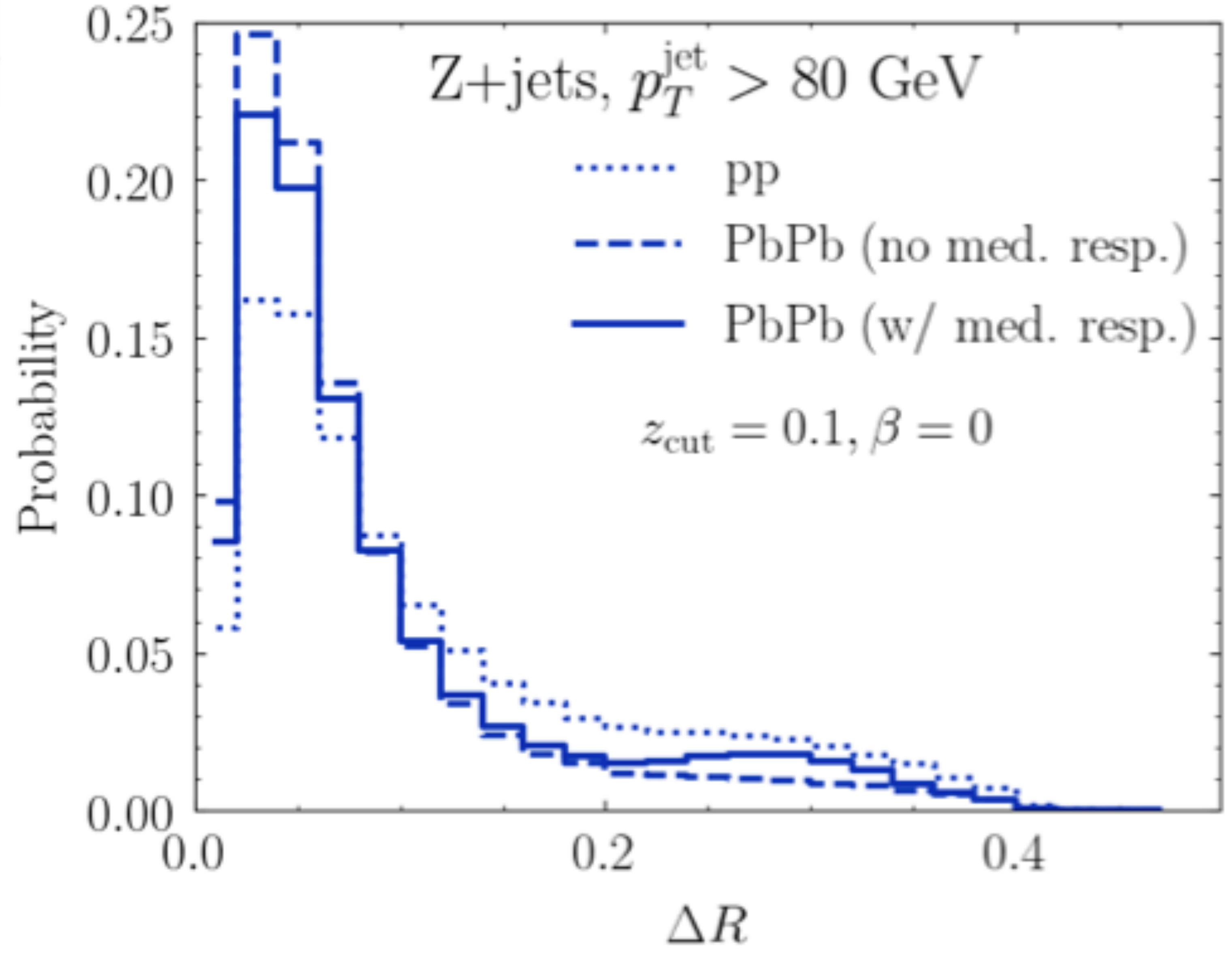
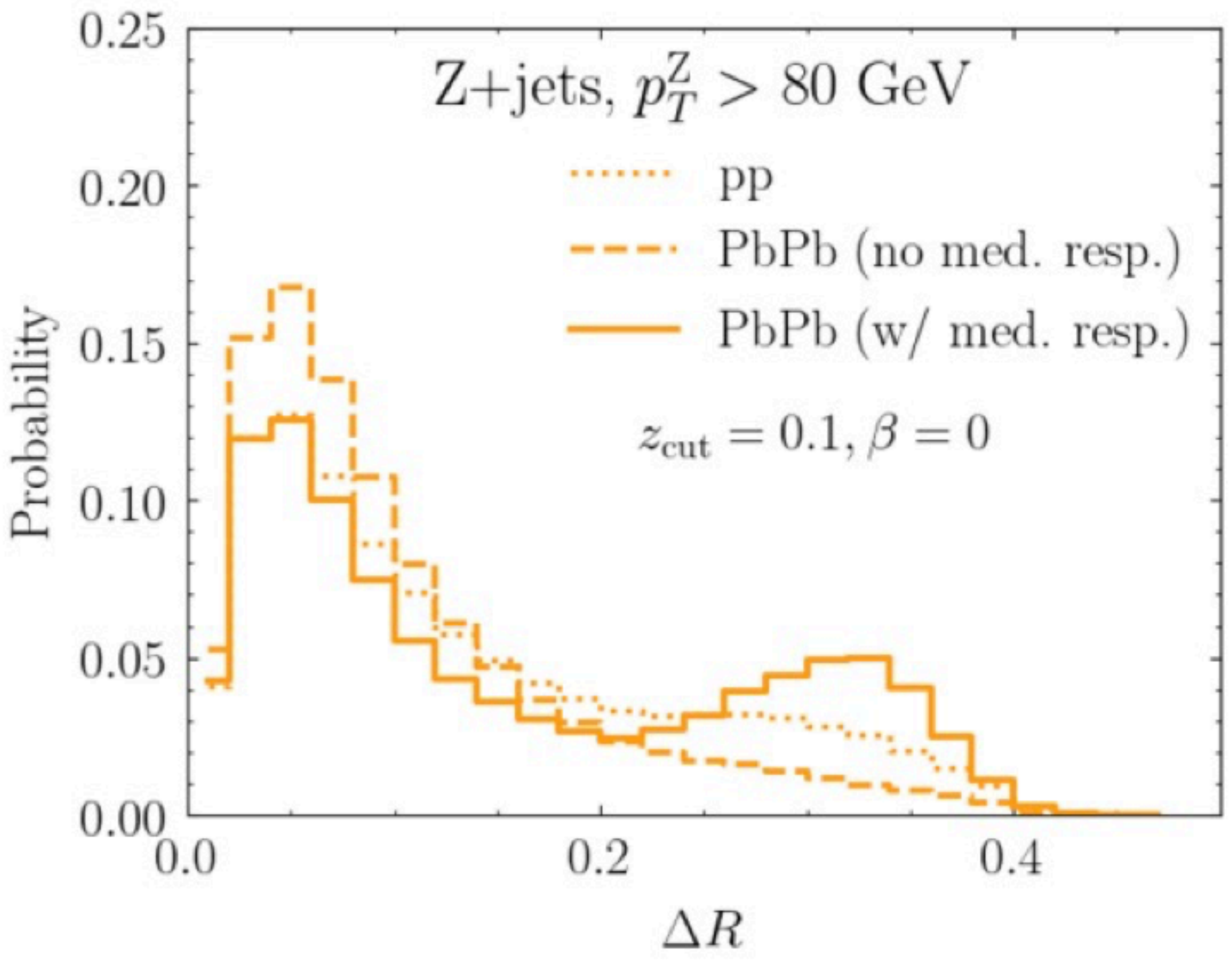
Hybrid



[Brewer, Brodsky, Rajagopal (2110.13159)]

Hybrid



[Brewer, Brodsky, Rajagopal (2110.13159)]

Jets passing the Soft Drop condition are more likely to have medium-induced/recoil effects

Understanding biases

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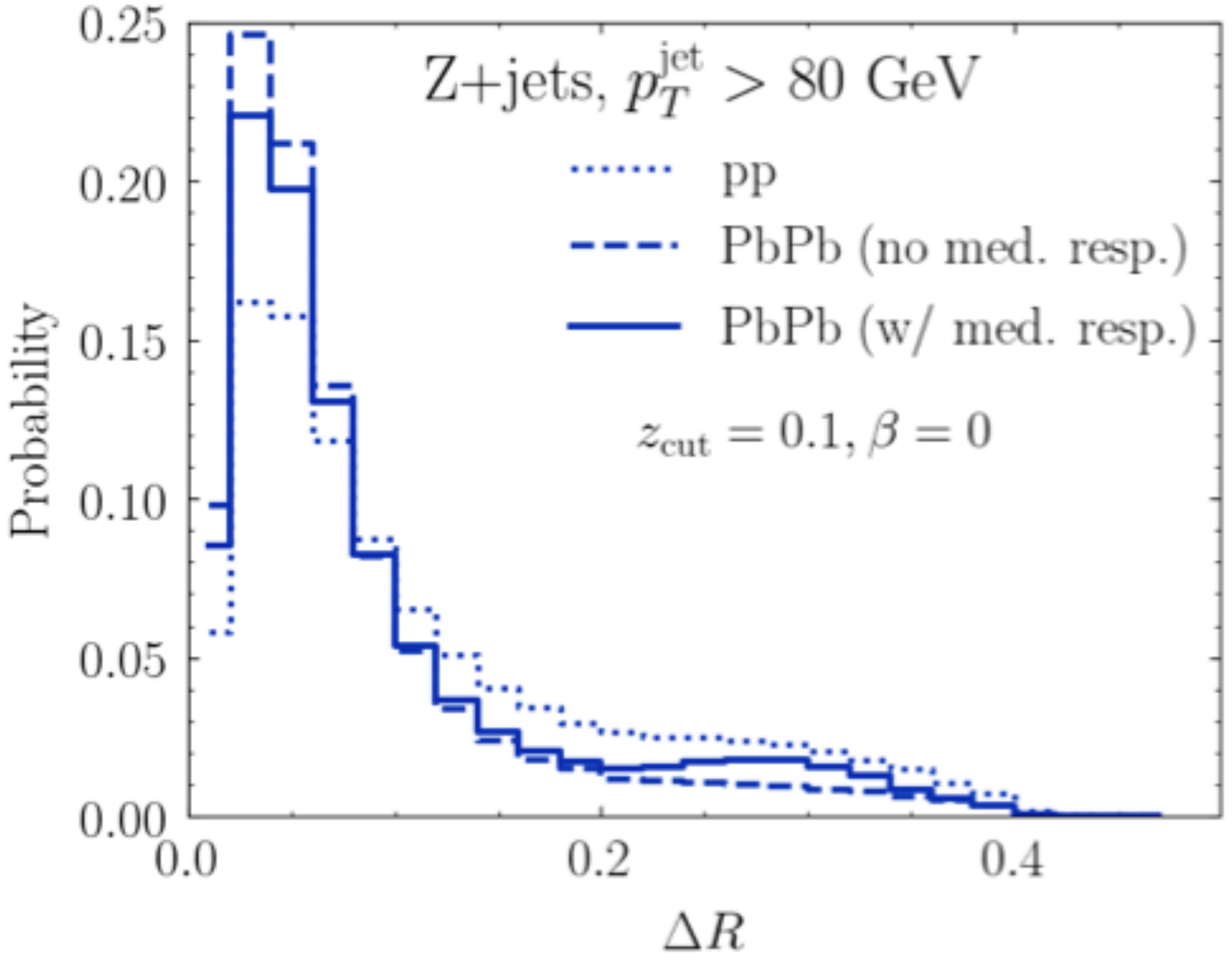
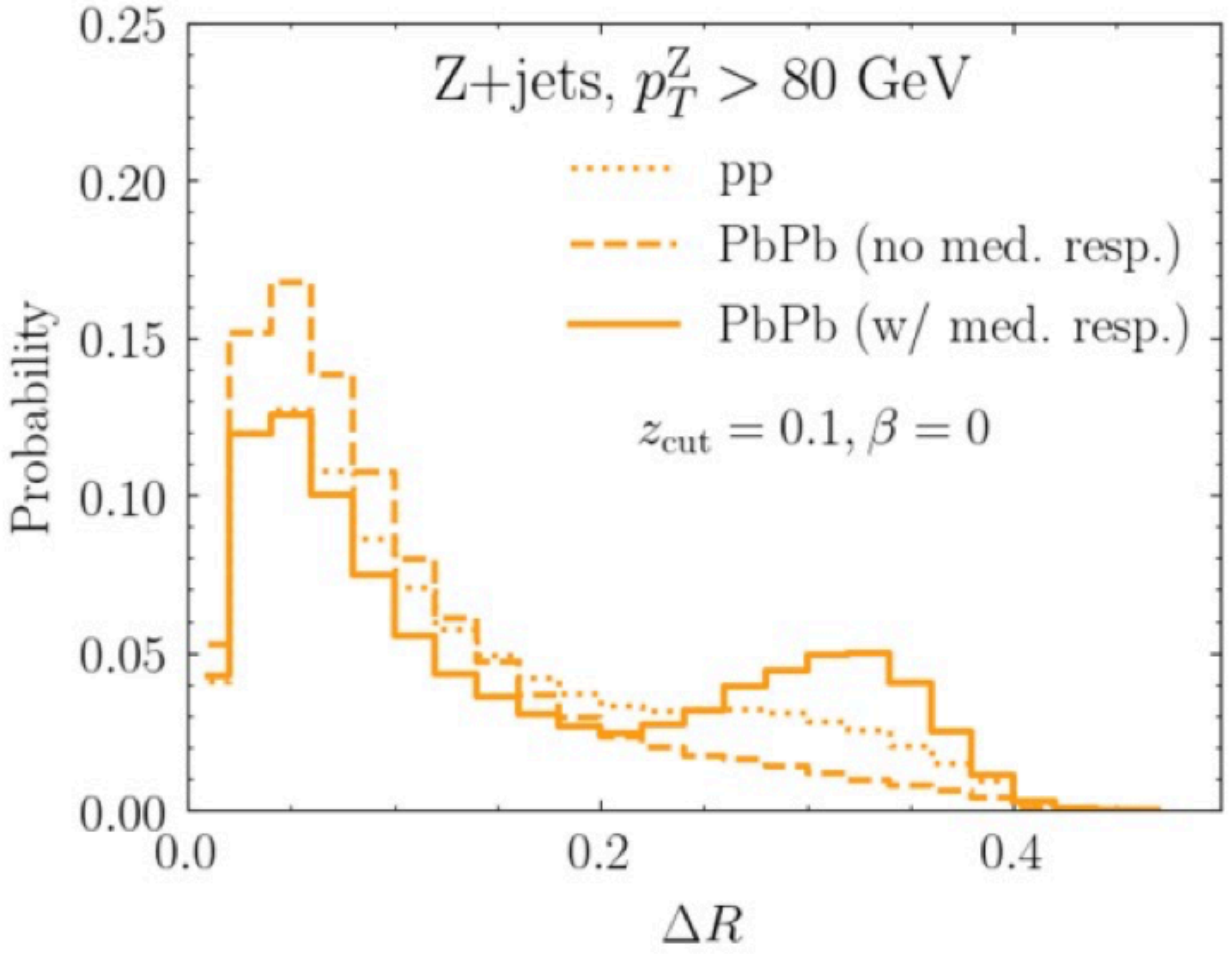
  - Impact of jet selection biases on jet substructure observables?

Hybrid



[Brewer, Brodsky, Rajagopal (2110.13159)]

Hybrid



[Brewer, Brodsky, Rajagopal (2110.13159)]

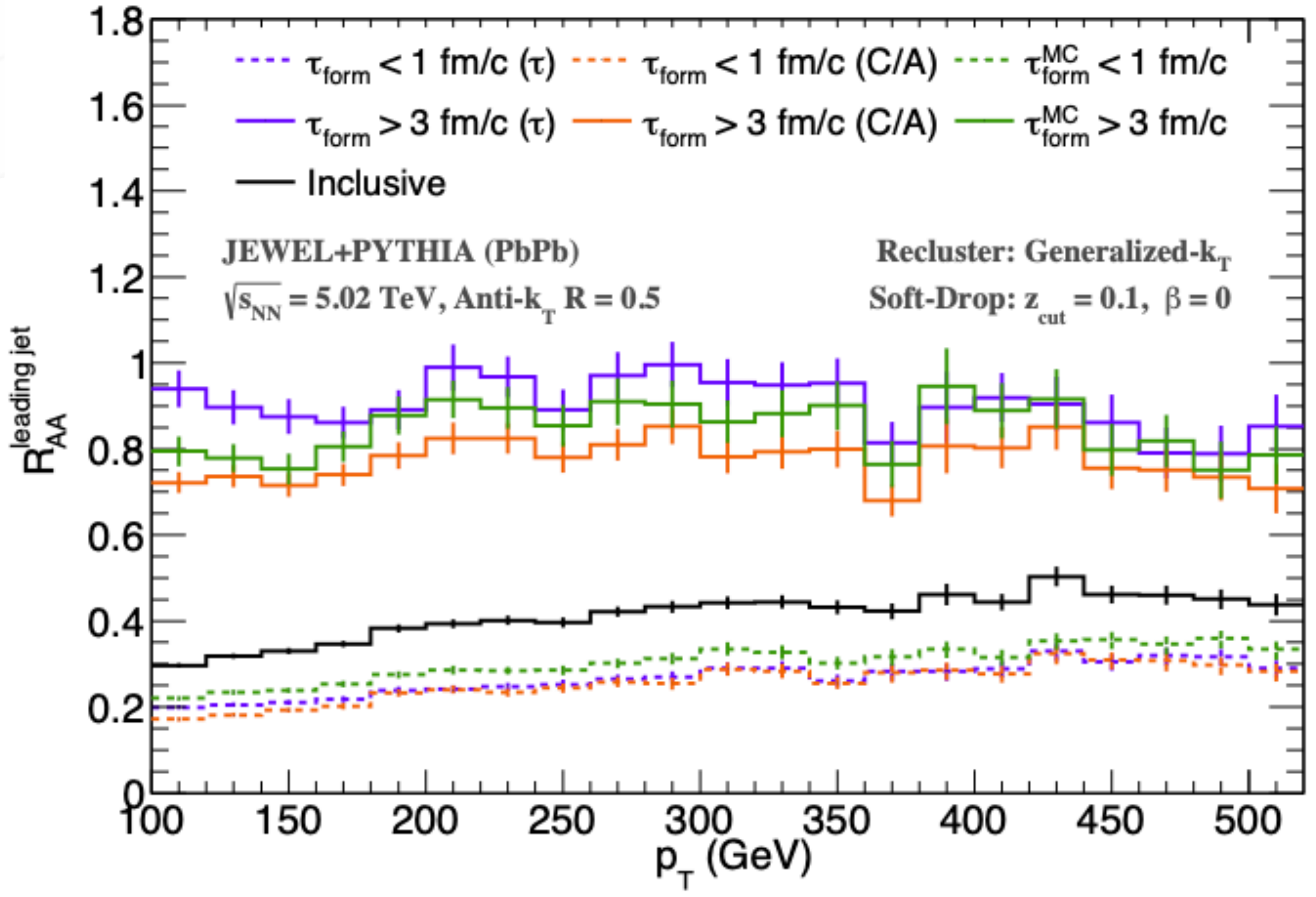
Jets passing the Soft Drop condition are more likely to have medium-induced/recoil effects

Grooming can be used to select different contributions of medium response

Understanding biases

- Comparison between quenched and unquenched made through some jet selection:
  - Impact of jet selection biases on jet substructure observables?

JEWEL



[LA, Cordeiro, Zapp (2012.02199)]

"Formation time" can also select jets with different degrees of quenching

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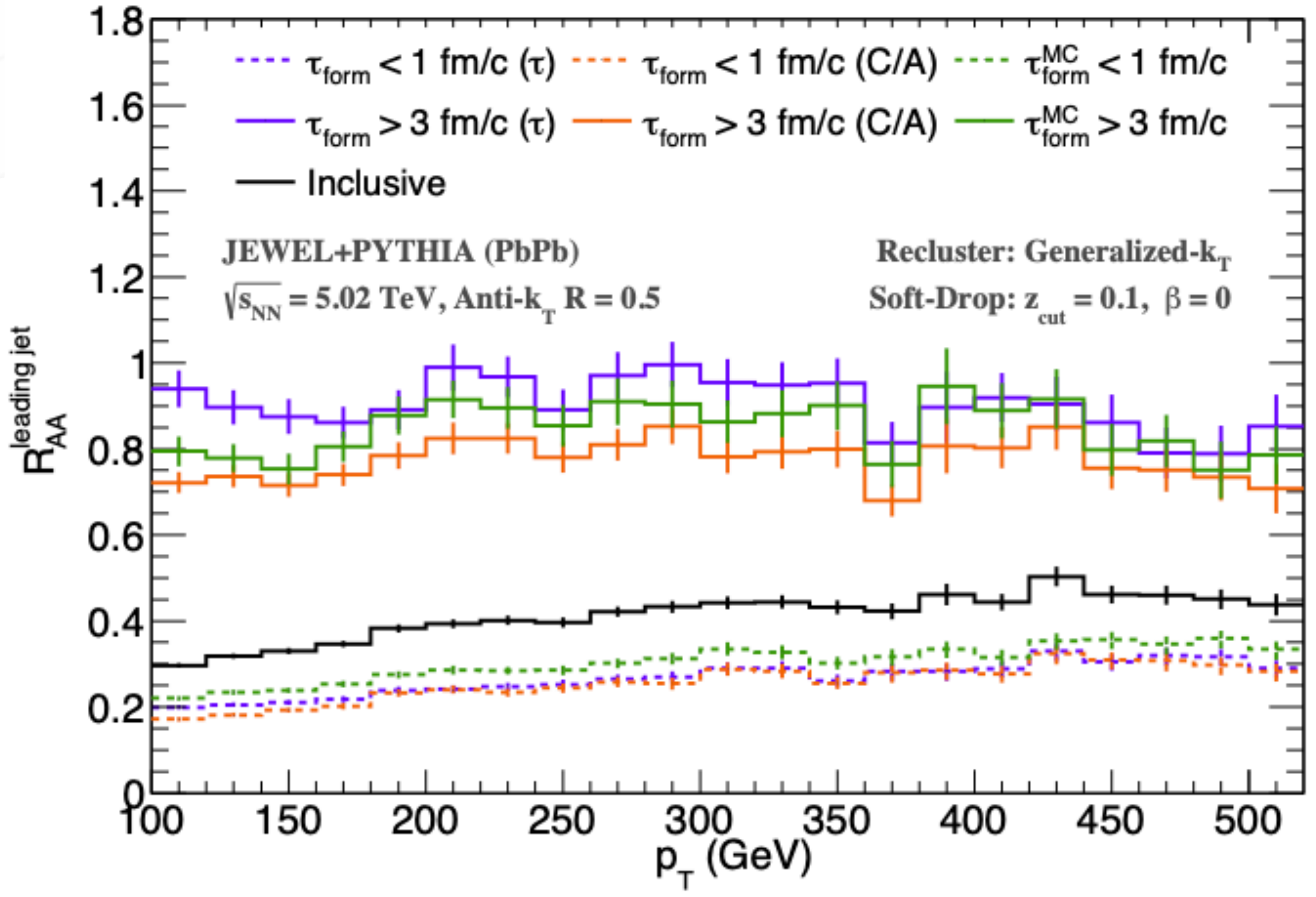

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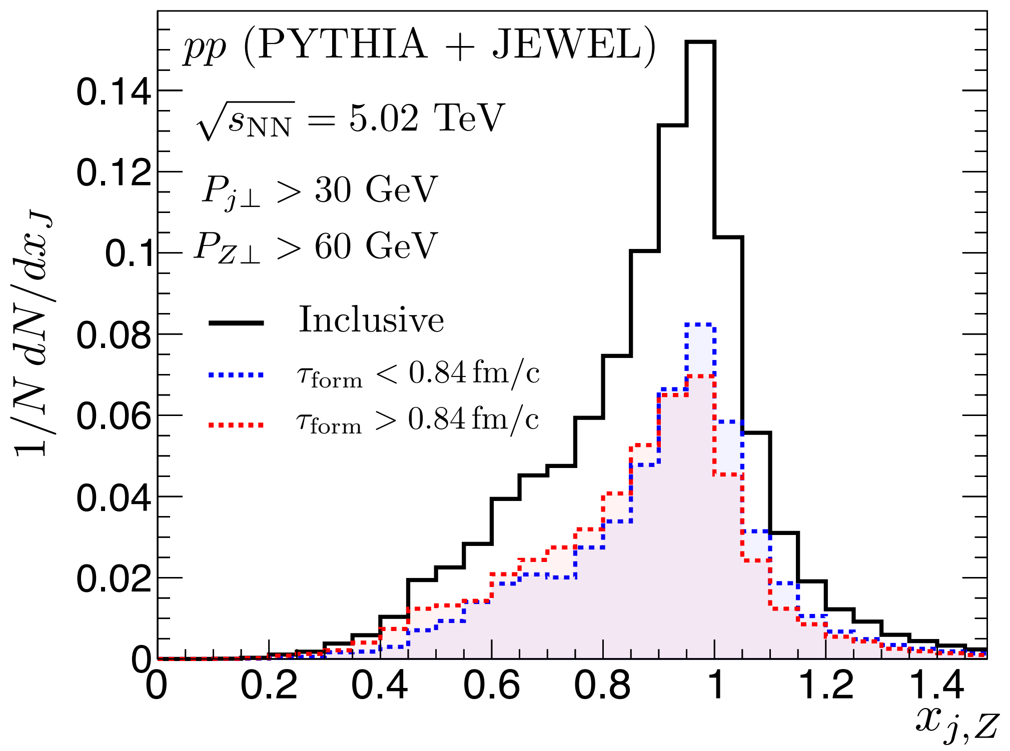
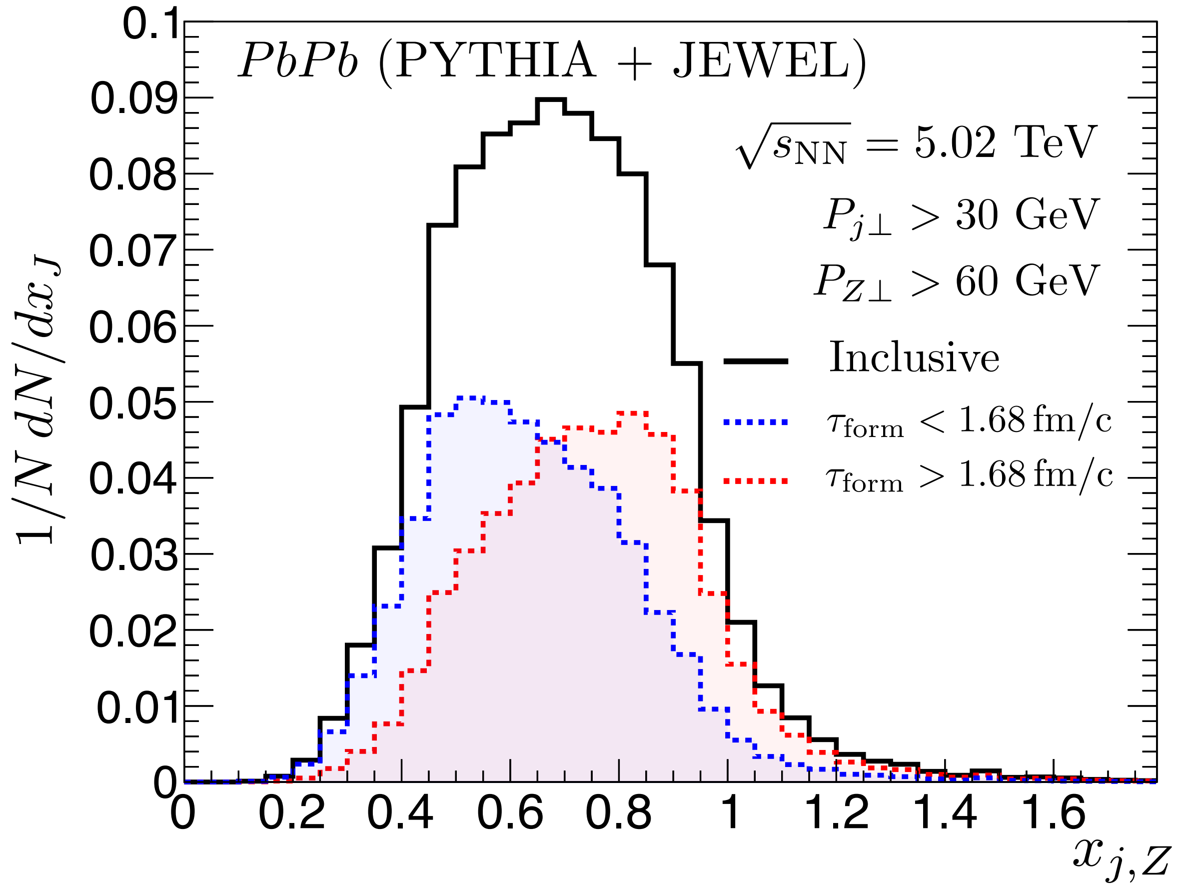


[LA, Guerrero-Rodriguez, Zapp (under preparation…)]



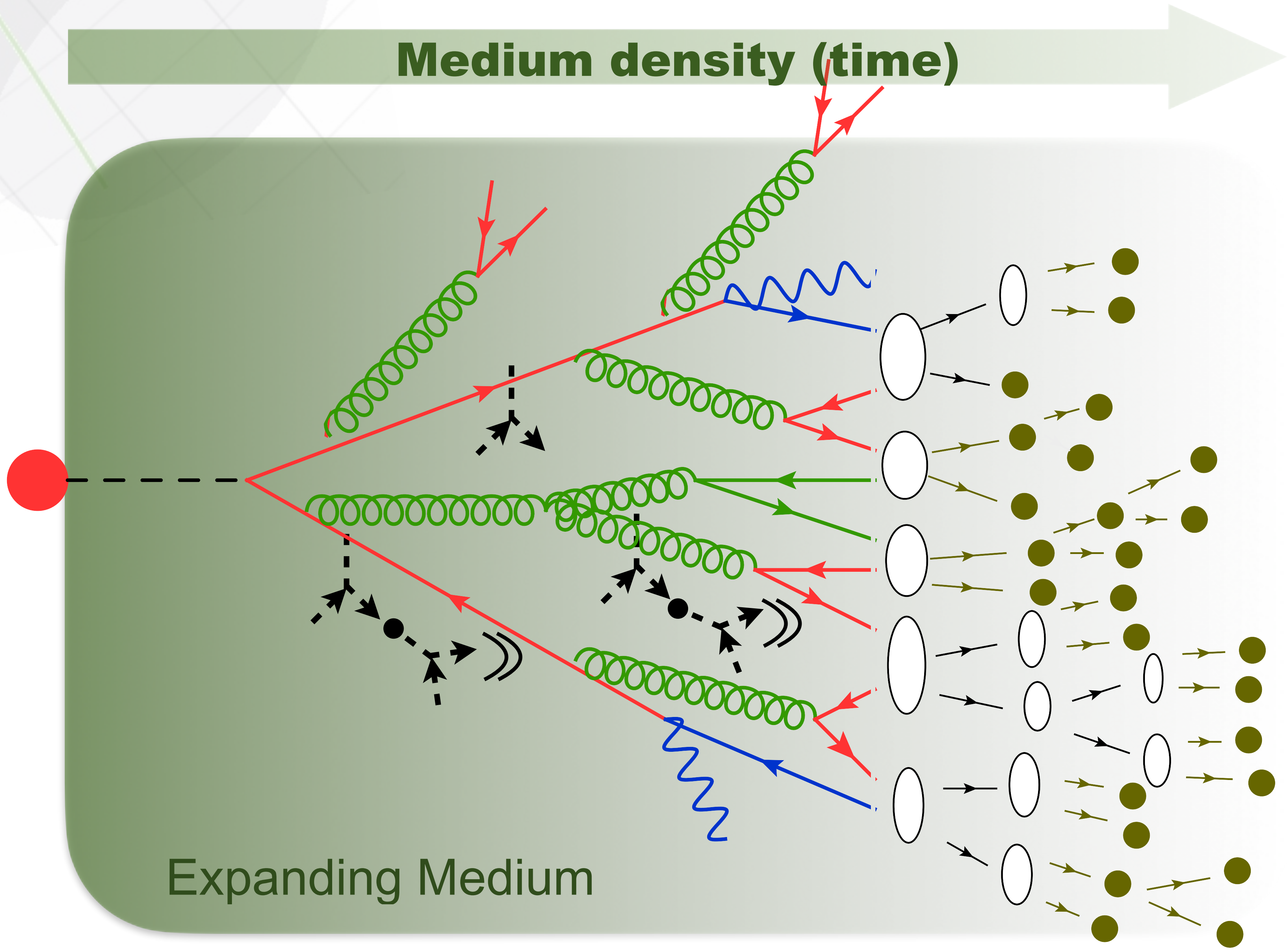
"Formation time" can also select jets with different degrees of quenching

Does it have a physical realisation in vacuum and/or medium?

Towards the Future

Parton Showers in heavy-ions

- Accuracy bounded by proton-proton
  - But have a qualitatively different problem: quantum system developing on top of an evolving medium



$Q^2 \equiv \mathcal{O}(100^2\mathrm{GeV}^2 \sim 1\mathrm{TeV}^2)$ → $Q^2 \equiv \mathcal{O}(1\mathrm{GeV}^2)$

pQCD → non pQCD

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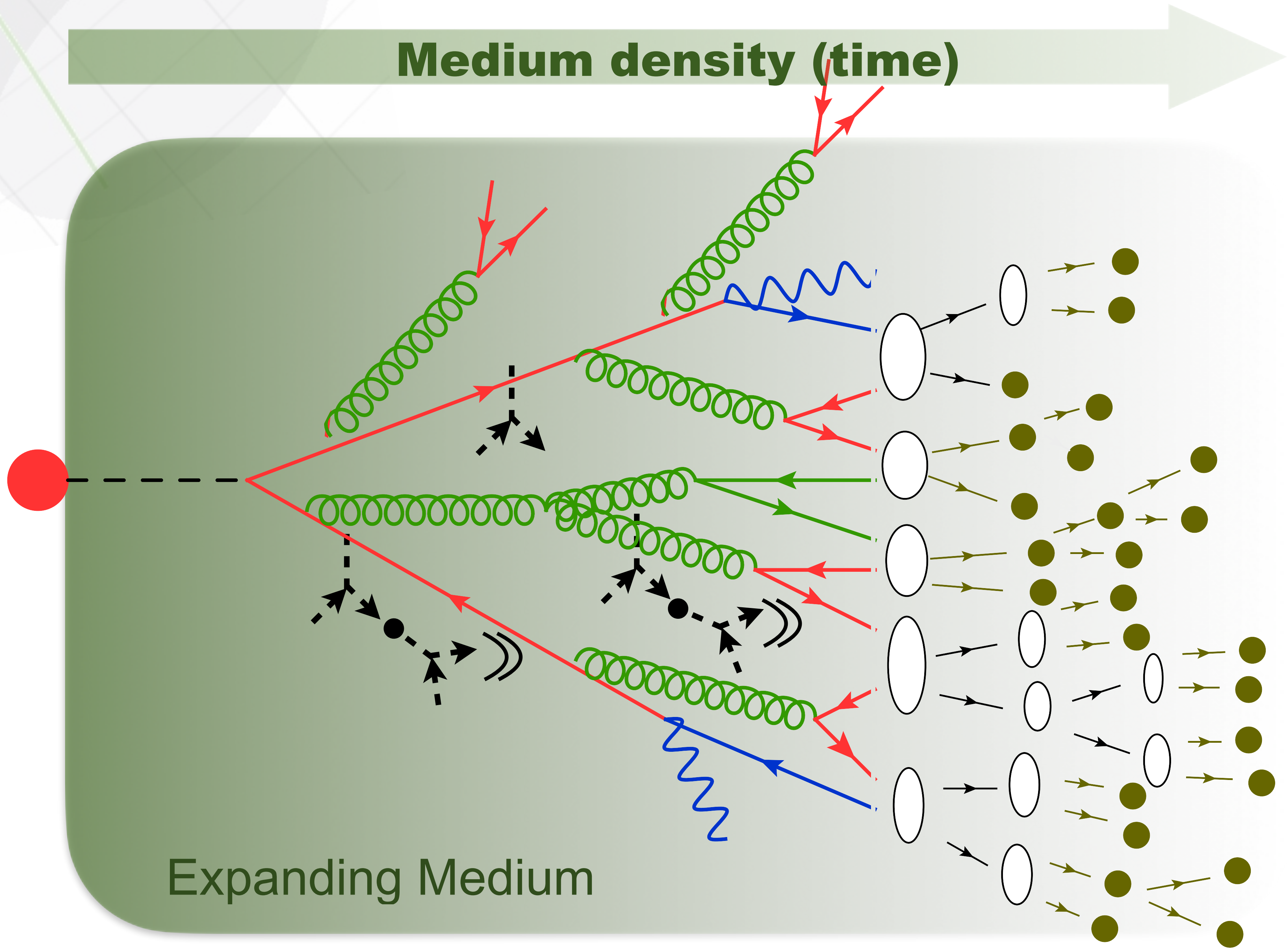

$Q^2 \equiv \mathcal{O}(100^2\mathrm{GeV}^2 \sim 1\mathrm{TeV}^2)$ ⟶ $Q^2 \equiv \mathcal{O}(1\mathrm{GeV}^2)$

pQCD — non pQCD

Heavy-ions are unique laboratory for:

- QGP tomography
- Interplay of parton showers with evolving medium
- Transition from perturbative to non-perturbative

Summary

Summary

- Monte Carlo event generators widely used tools to probe QGP physics
  - Require phenomenological extensions that need to be constantly tested and refined by analytical input
  - Ideal framework to probe novel QCD-related phenomena

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- Monte Carlo event generators widely used tools to probe QGP physics
  - Require phenomenological extensions that need to be constantly tested and refined by analytical input
  - Ideal framework to probe novel QCD-related phenomena
  - Invaluable instruments for:
    - Testing new observables in more “realistic” conditions as compared to analytical approaches
    - Phenomenological studies targeting phenomena whose analytical description is (still) challenging
    - Understanding biases in our experimental results

Thank you!

Acknowledgments

REPÚBLICA PORTUGUESA

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Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

LIP

TÉCNICO LISBOA

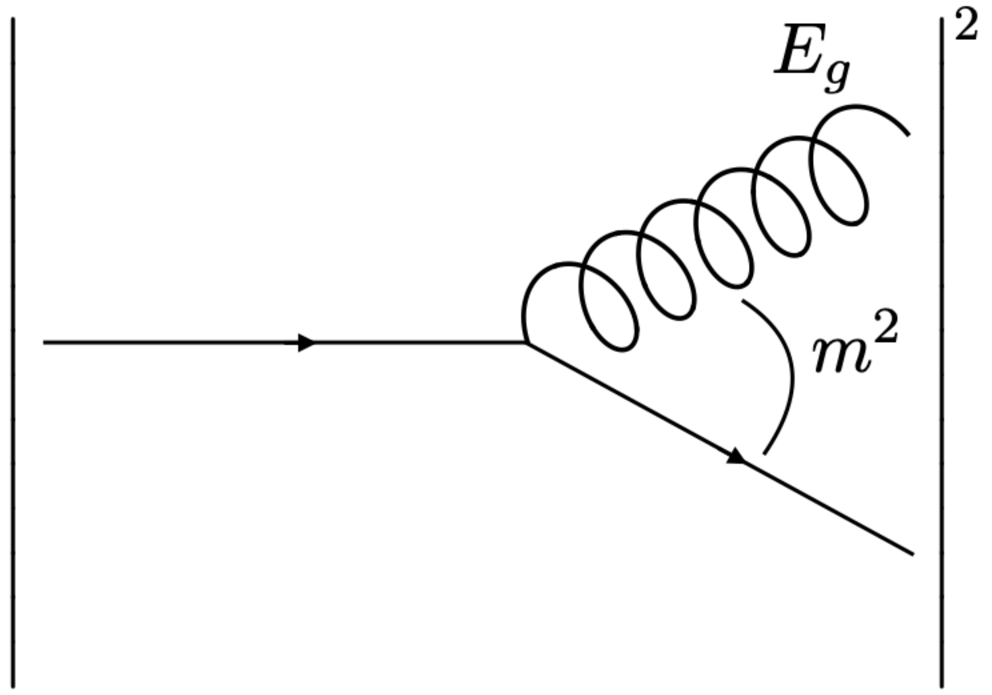
Backup Slides

Bibliography

- Monte Carlo models for jet quenching:
  - CUJET: [Buzzatti, Liao, Gyulassy, Shi (14, 16, 18)]
  - Dreena: [Zigic, Salom, Auvinen, Djordjevic, M. Djordjevic (19, 22)]
  - Hybrid Strong/Weak coupling: [Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal (14;17); Helcher, Pablos, Rajagopal (18)]
  - JETSCAPE: [JETSCAPE Collab. (17)]
  - JEWEL: [Krauss, Wiedemann, Zapp(13); Zapp (14); Elayavalli, Zapp (16;17)]
  - LBT/Co-LBT: [Wang and Y. Zhu (16); Cao, Luo, Qin, Wang (15); He, Luo, Wang, Zhu (17);]
  - MARTINI: [Schenke, Gale, Jeon (09); Park, Jeon, Gale (18)]
  - MATTER: [Majumder (13); Kordell, Majumder (17); Cao, Majumder (18)]
  - PYQUEN: [Lokhtin, Snigirev (06)]
  - Q-PYTHIA: [Armesto, Cunquero, Salgado (09)]
  - Jetmed(Saclay): [Caucal, Iancu, Mueller, Soyez (18)]

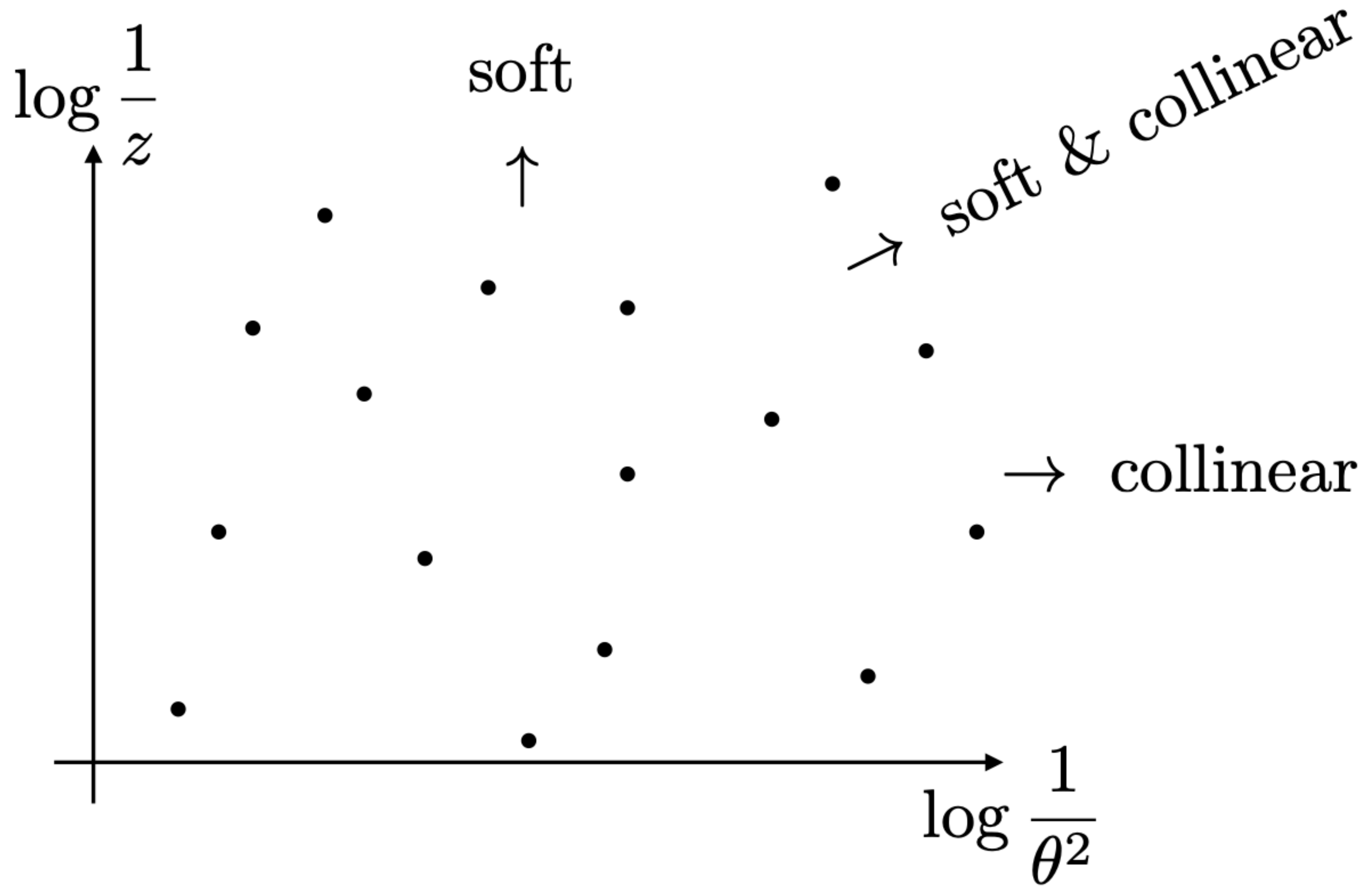
Sudakov & Lund Planes

$P(E_g, m^2) =$



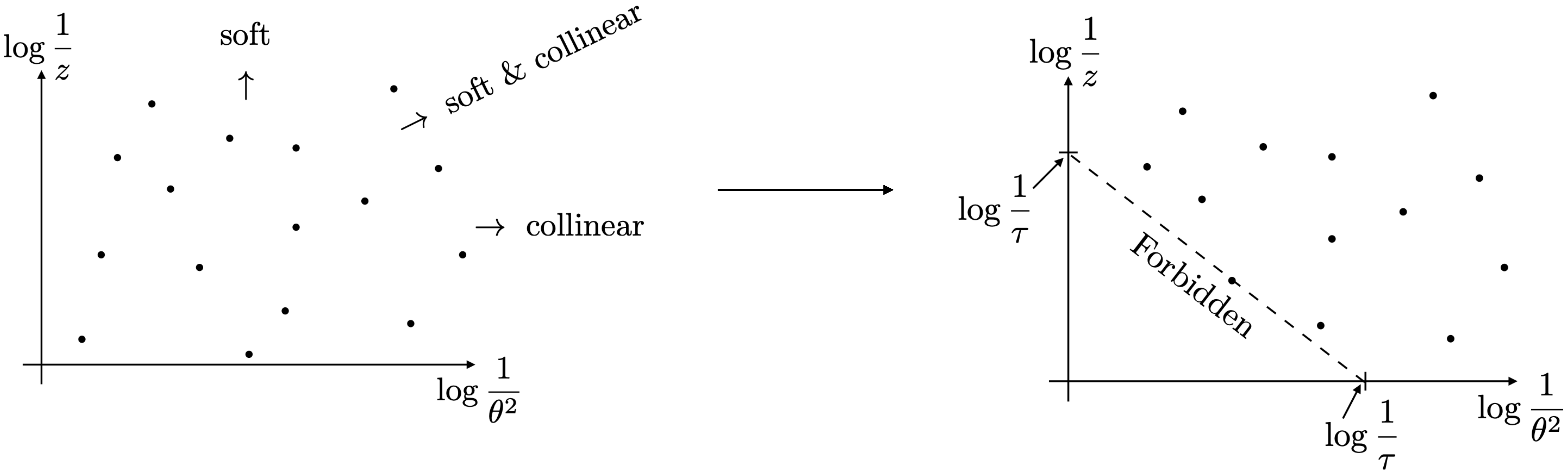
$$P(E_g, m^2)\, dE_g\, dm^2 = \frac{\alpha_s C_F}{\pi} \frac{dE_g}{E_g} \frac{dm^2}{m^2} \xrightarrow[\text{Collinear Limit}]{\text{Soft and}} P(z, \theta^2)\, dz\, d\theta^2 \to \frac{\alpha_s C_F}{\pi} \frac{dz}{z} \frac{d\theta^2}{\theta^2}$$

$$P(z, \theta^2)\, dz\, d\theta^2 = \frac{\alpha_s C_F}{\pi} \frac{dz}{z} \frac{d\theta^2}{\theta^2} = \frac{\alpha_s C_F}{\pi}\, d\left(\log \frac{1}{z}\right)\, d\left(\log \frac{1}{\theta^2}\right)$$



Sudakov & Lund Planes

- Invariant mass distribution: $\tau = \frac{m^2}{E^2} = \sum_{i=\text{gluon}} z_i \theta_i^2 \longrightarrow \log\tau = \log z + \log\theta^2$



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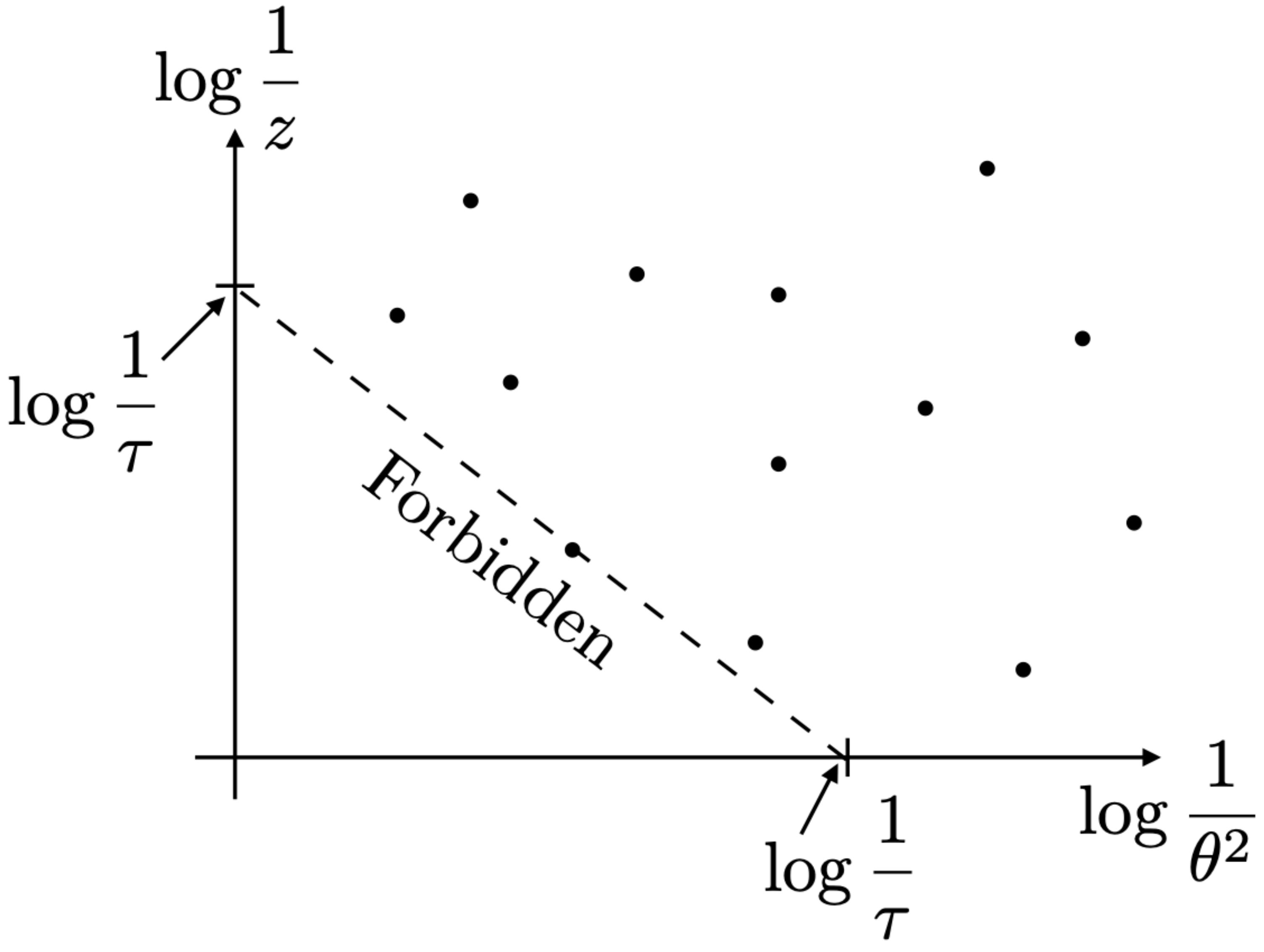
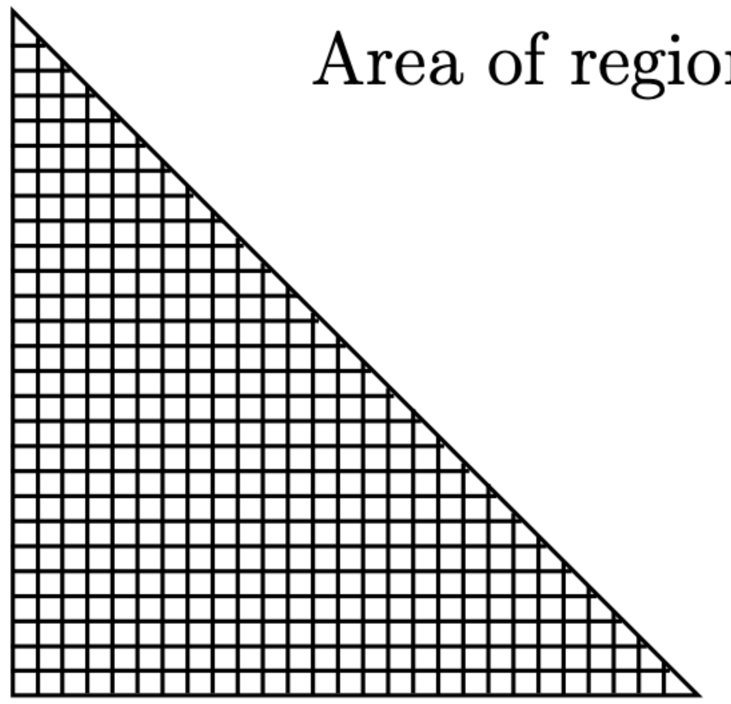


$\longrightarrow$



$$\text{Area of region } i = \frac{\frac{1}{2}\log^2\tau}{N}$$

$$P(\text{emit in region } i) = \frac{\alpha_s C_F}{\pi} \cdot (\text{Area of region } i)$$

$$P(\text{no emit in region } i) = 1 - \frac{\alpha_s C_F}{\pi} \cdot (\text{Area of region } i)$$

$$P(\text{no emissions}) = \left(1 - \frac{\frac{\alpha_s}{\pi}\frac{C_F}{2}\log^2\tau}{N}\right)^N$$

$$P(\text{no emissions}) = \exp\left[-\frac{\alpha_s}{\pi}\frac{C_F}{2}\,\mathrm{lo}\right.$$

Sudakov & Lund Planes

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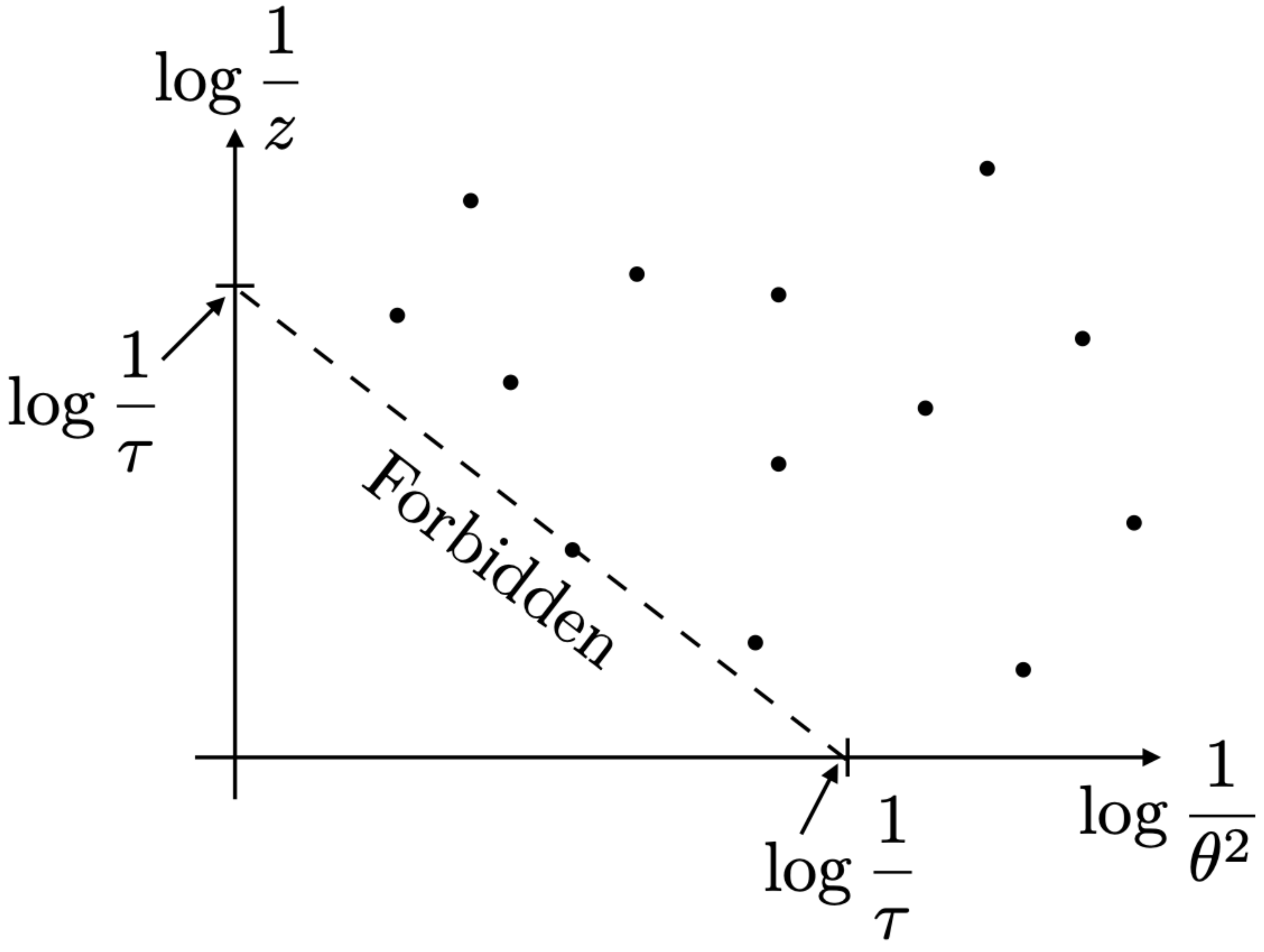

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Large N limit: Sudakov Form Factor

$$\Delta_i(t) \equiv \exp\left[-\sum_j \int_{t_0}^{t}\frac{dt'}{t'}\int dx \frac{\alpha_s}{2\pi}P_{i\leftarrow j}(x)\right]$$

$$P(\text{no emissions}) = \exp\left[-\frac{\alpha_s}{\pi}\frac{C_F}{2}\log^2\tau\right]$$

Toy Parton Shower

No-emission probability:

$$\Delta(s_{\rm prev}, s) = \exp\left\{-\frac{\alpha C_R}{\pi}\int_s^{s_{\rm prev}}\frac{{\rm d}\mu}{\mu}\int_{z_{\rm cut}(\mu)}^1\frac{{\rm d}z}{z}\right\}$$

Interpretations for the scale:

$$s \to t_{\rm form}^{-1} = \frac{|\boldsymbol{\ell}|^2}{2p^+ z(1-z)}$$

(Formation time)

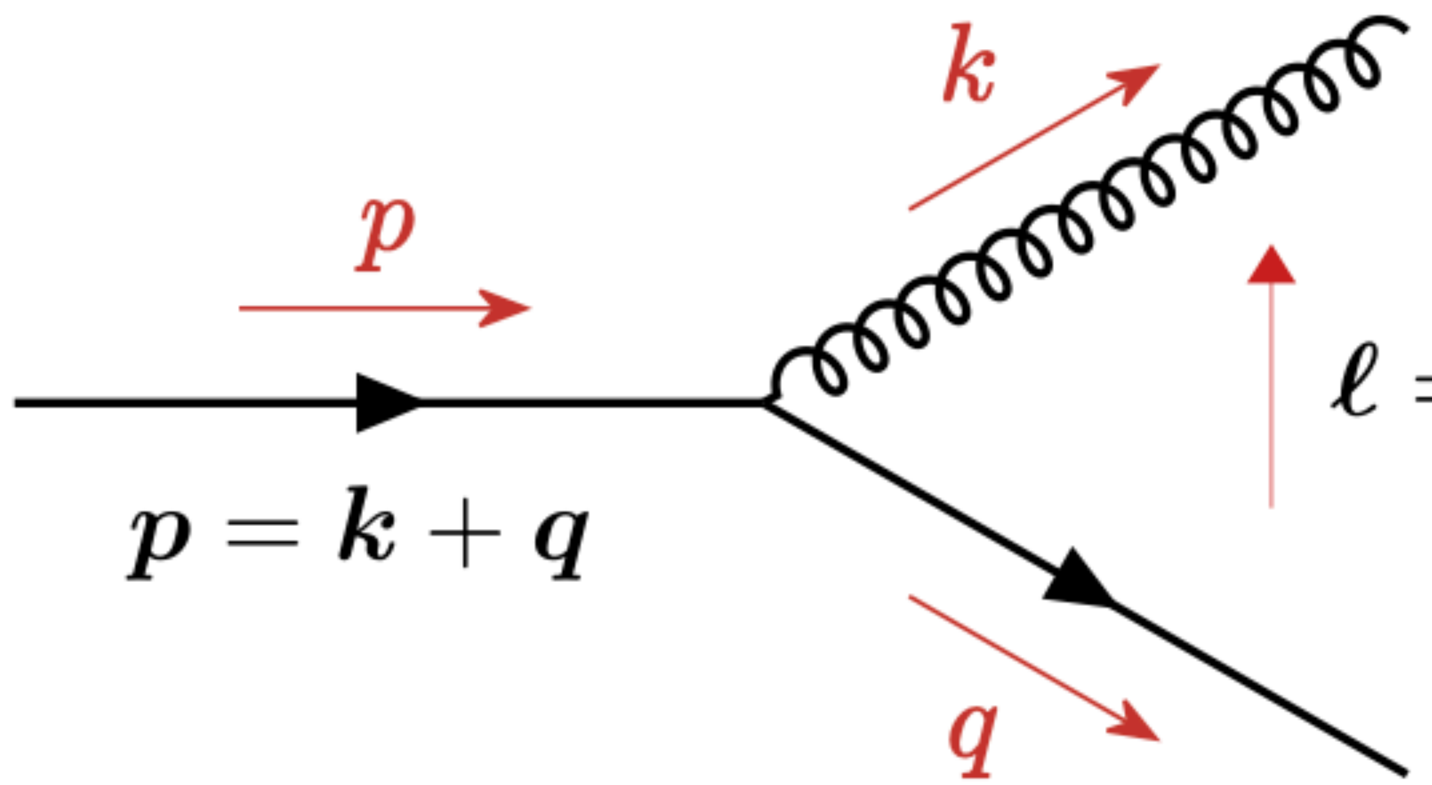
$$s \to \tilde{m}^2 = 2p^+ t_{\rm f}^{-1}$$

(Virtuality)

$$s \to \tilde{\theta}^2 = \frac{|\boldsymbol{\ell}|^2}{(p^+)^2[z(1-z)]^2}$$

(Angle)

To generate a splitting:



$$z = k^+/p^+$$

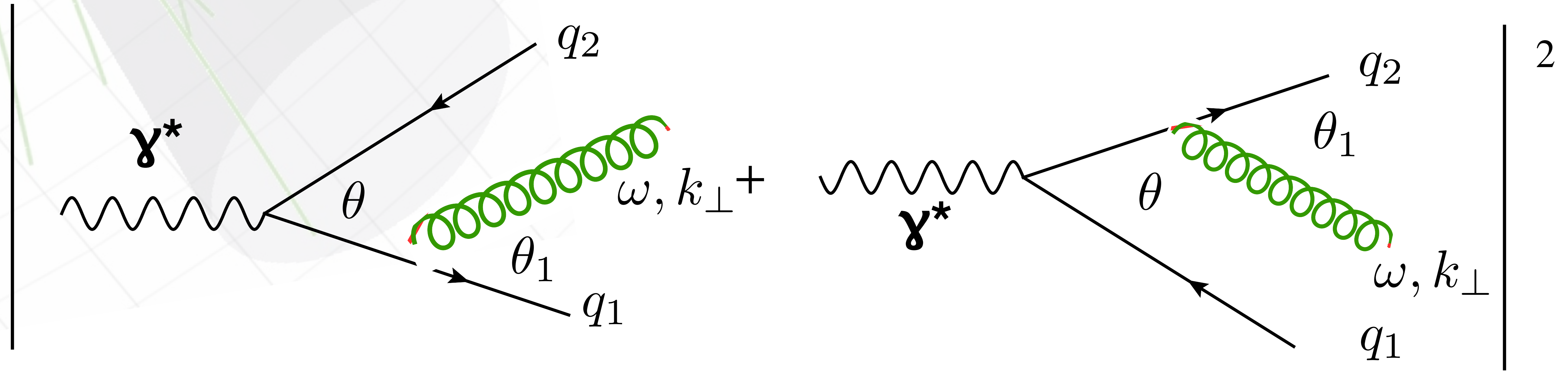
$$\boldsymbol{\ell} = (1-z)\boldsymbol{k} - z\boldsymbol{q}$$

1. Sample a scale from $\Delta(s_{\rm prev}, s)$
2. Sample a fraction from $\hat{P}(z) \propto 1/z$
3. Retrieve the momenta $\{p_i^+, \boldsymbol{p}_i\}$

Ensure that $|\boldsymbol{\ell}|^2 > k_{\rm had}^2$

Introducing angular ordering

- QCD Antenna setup: emission from a qqbar pair:



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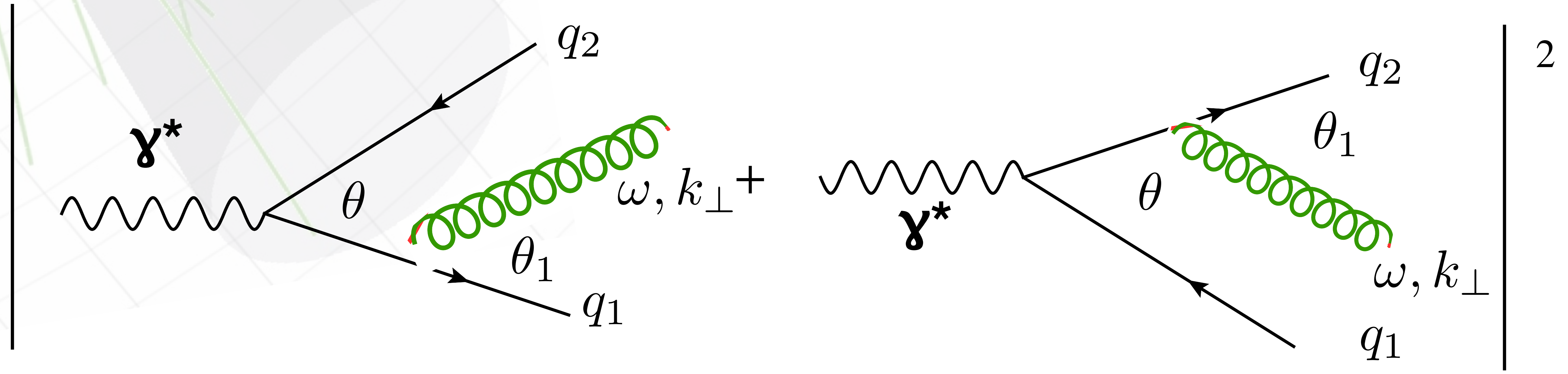

Probability of emitting "soft" (low-energy) gluons:

$$dN_q^{\omega\to 0} \sim \alpha_s C_R \frac{d\omega}{\omega}\frac{sin\theta\, d\theta}{1-\cos\theta}\Theta(\cos\theta_1 - \cos\theta)$$

QCD Angular ordering

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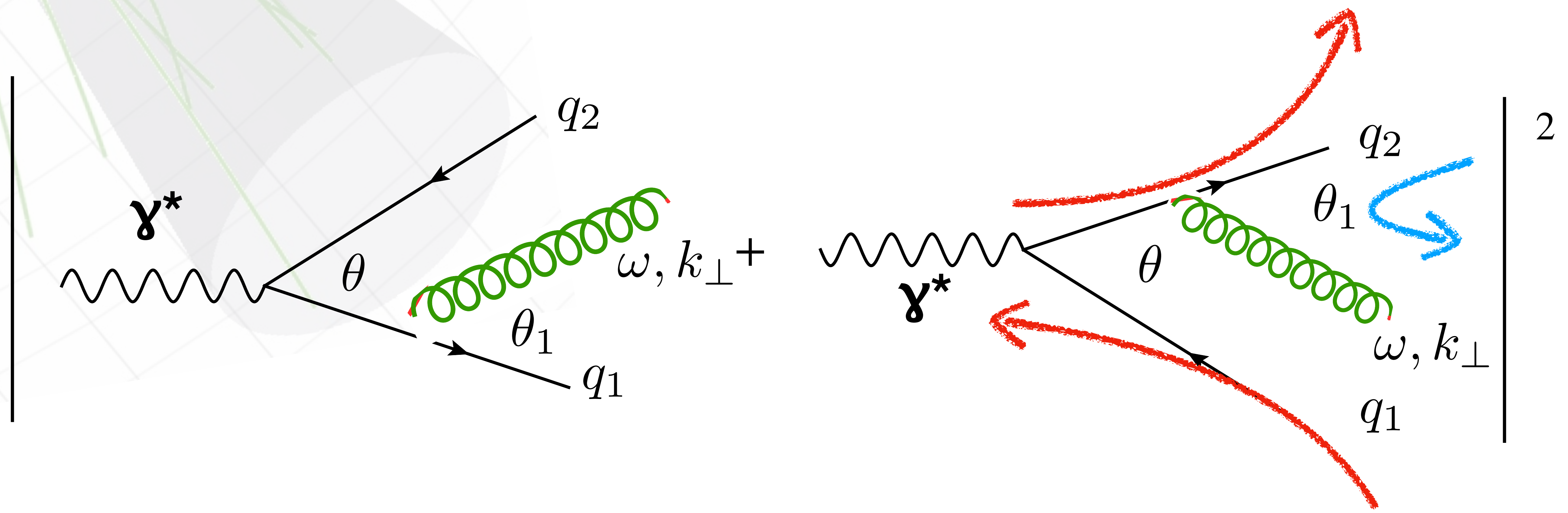

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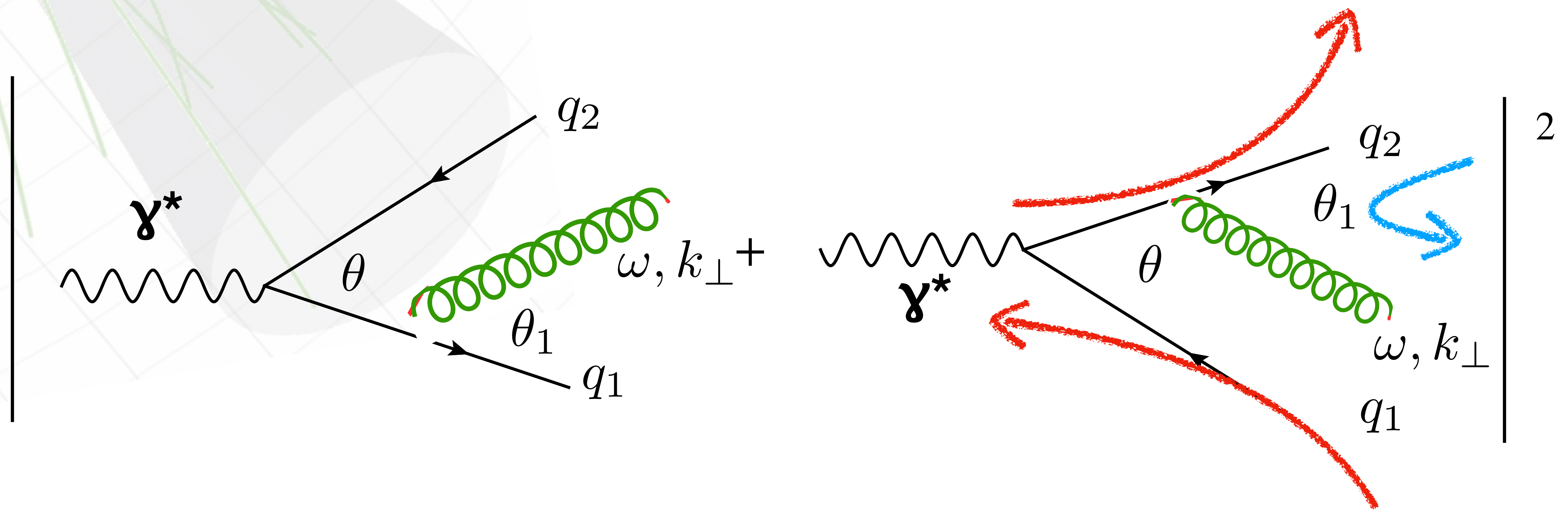
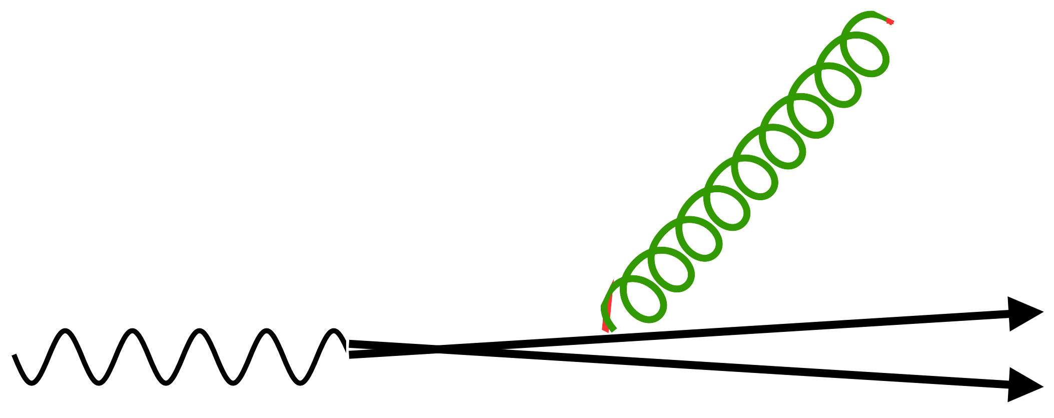


For large angle emissions:



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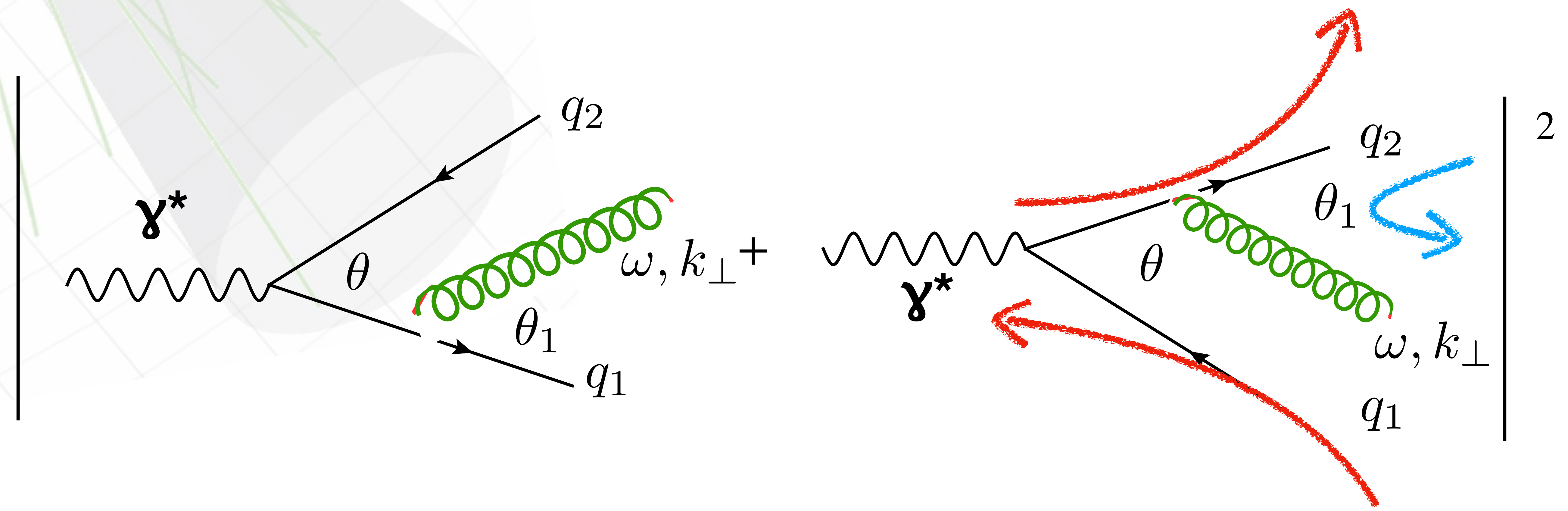

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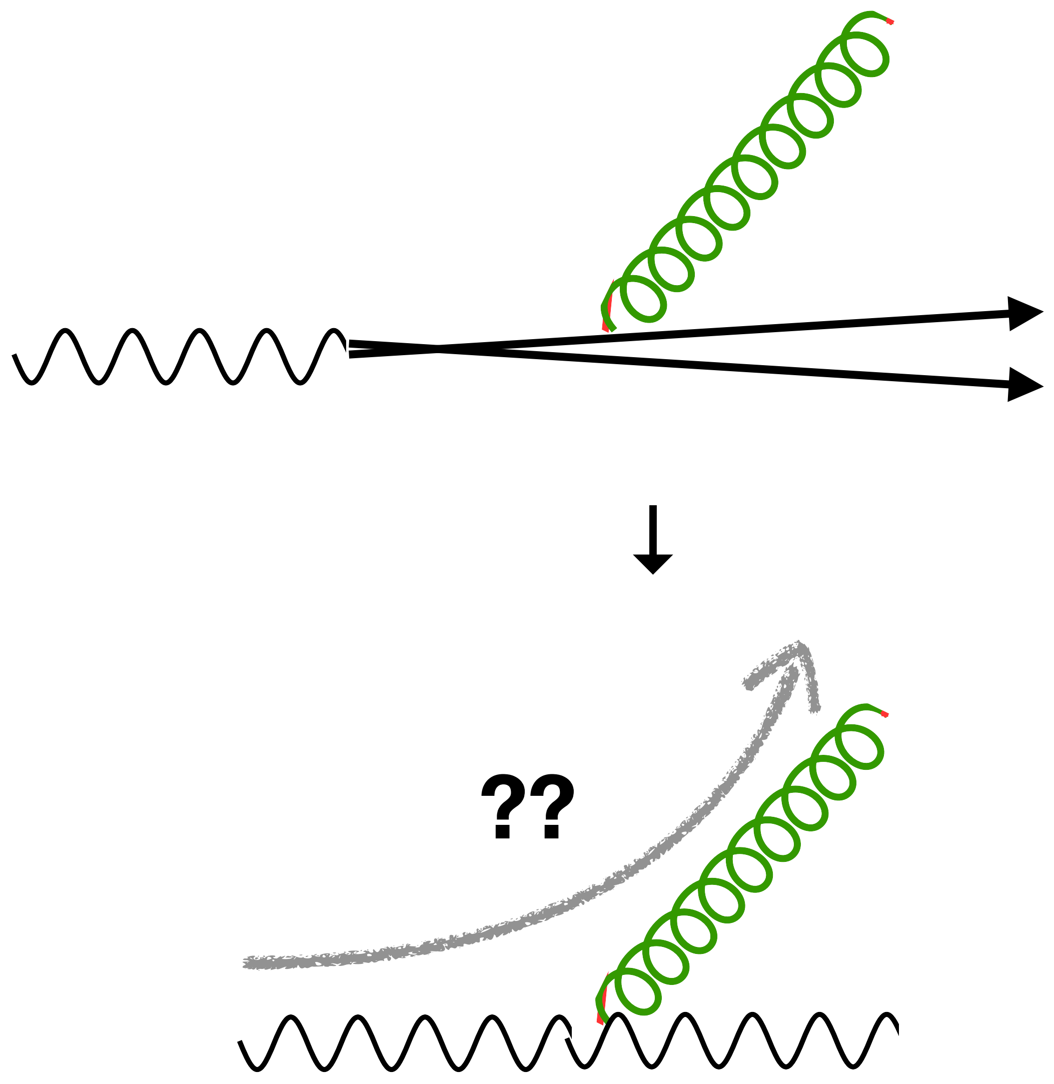

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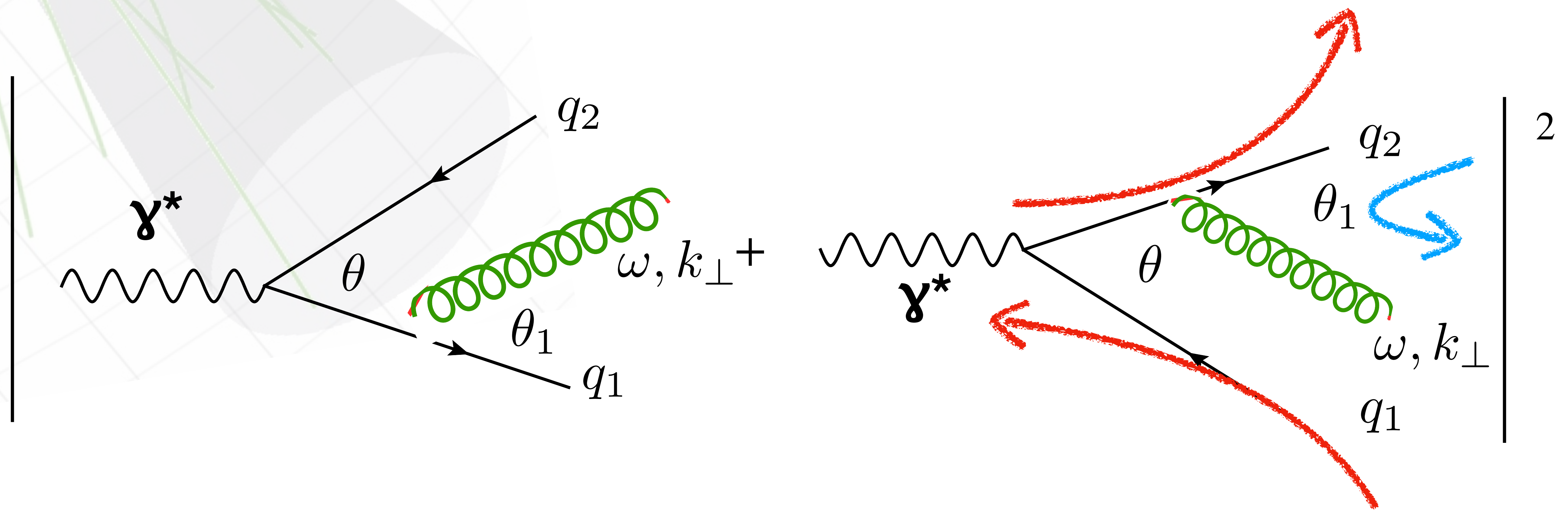

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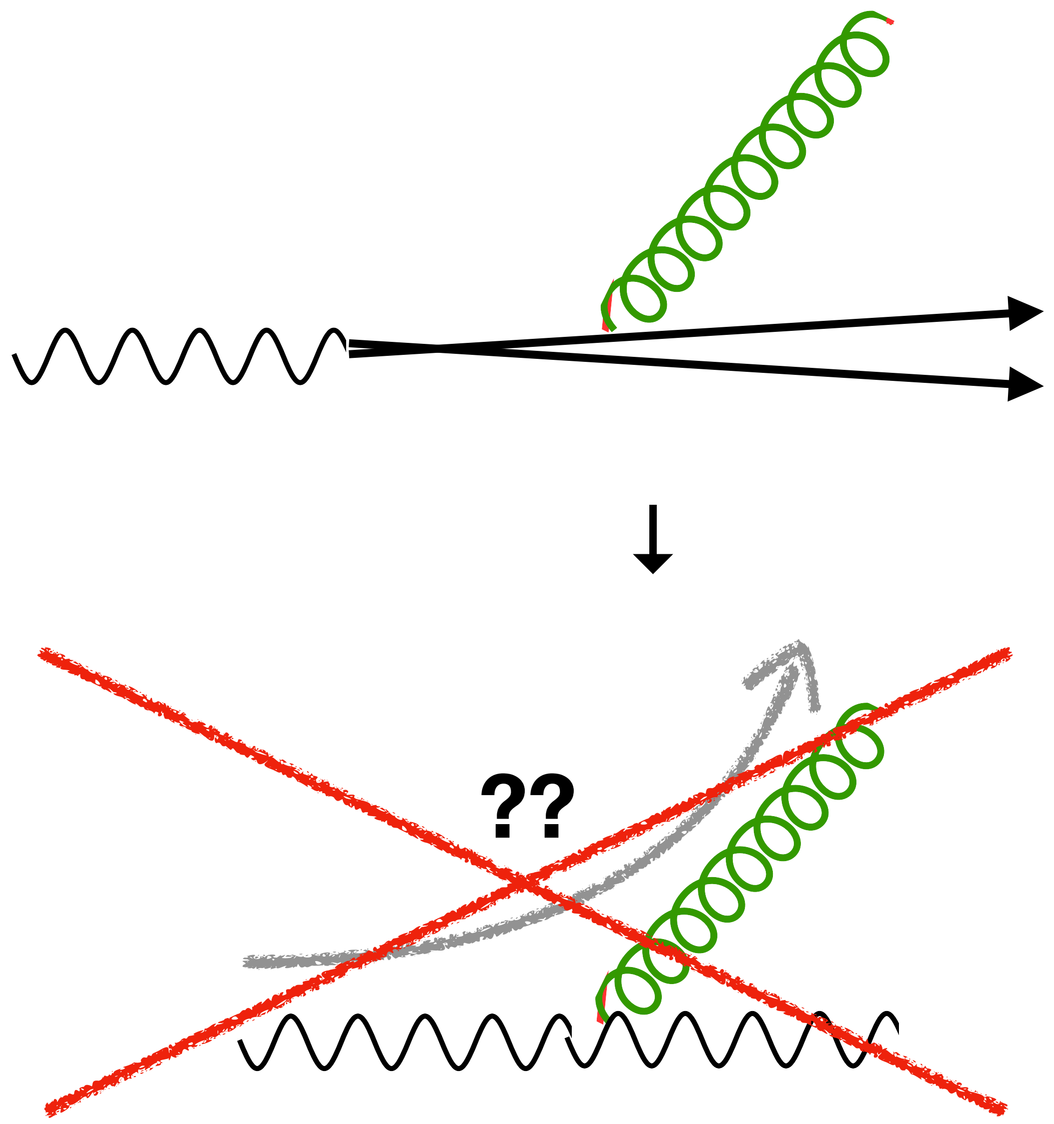

Photons do not carry colour charge…

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QCD Antenna Setup

- Two in-medium emissions: emission from a qqbar pair:

Vacuum QCD

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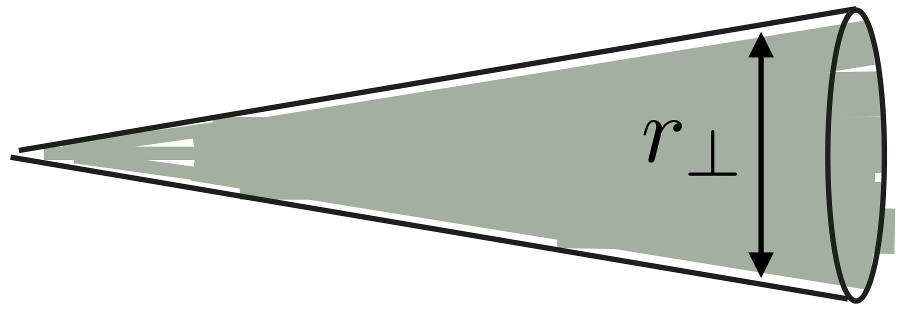

QCD Antenna Setup

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Vacuum QCD $\Longrightarrow$ In-medium QCD

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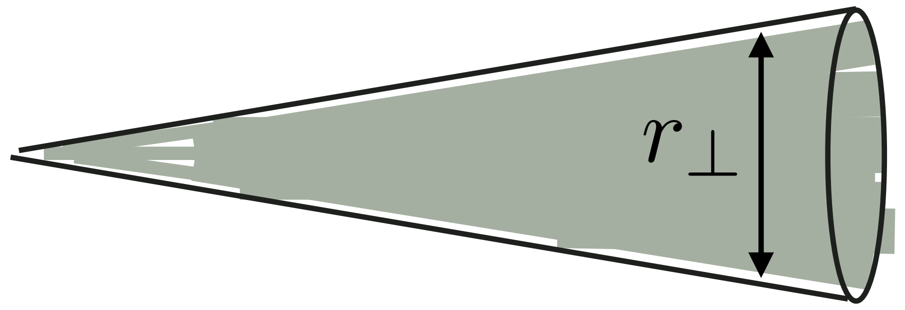

QCD Antenna Setup

[Mehtar-Tani, Tywoniuk, Salgado (1009.2965)]

- Two in-medium emissions: emission from a qqbar pair:

$$\Delta_{med} \approx 1 - \mathrm{e}^{-\frac{1}{12} Q_s^2 r_\perp^2}$$

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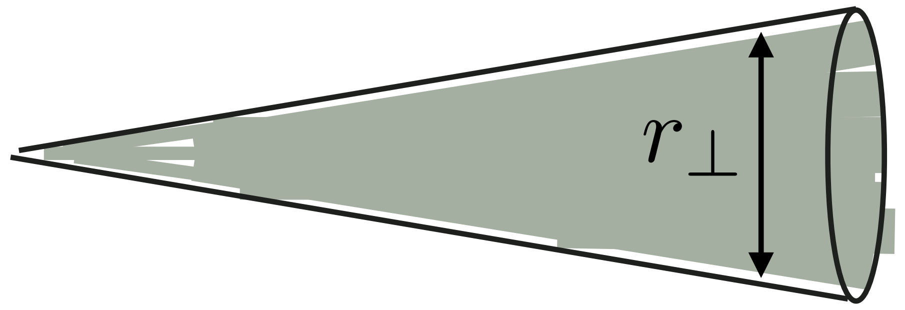
QCD Anti-Angular ordering



Antenna Transverse resolution: $r_\perp = \theta L$

Medium Transverse Scale: $Q_s^{-1} = \sqrt{(\hat{q} L)}^{-1}$

[Mehtar-Tani, Tywoniuk, Salgado (1009.2965)]

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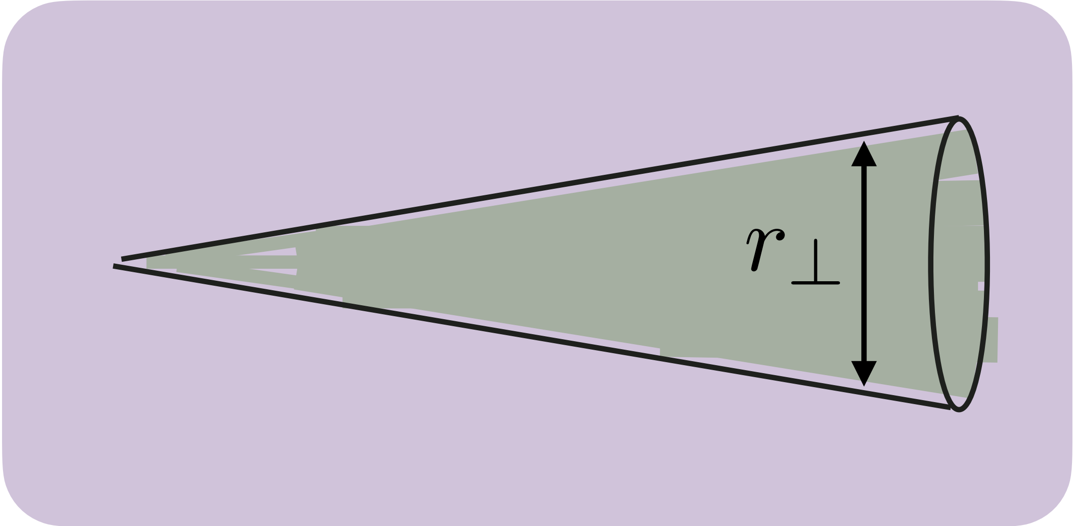
QCD Anti-Angular ordering

Angular ordering



$$\Delta_{med} \to 0$$

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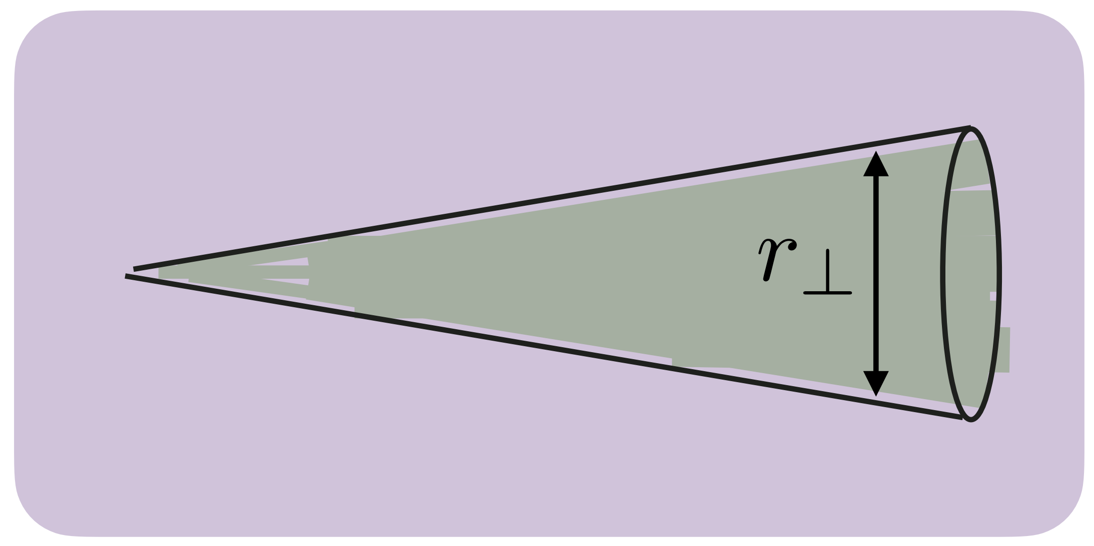
QCD Anti-Angular ordering

Angular ordering



$\Delta_{med} \to 0$

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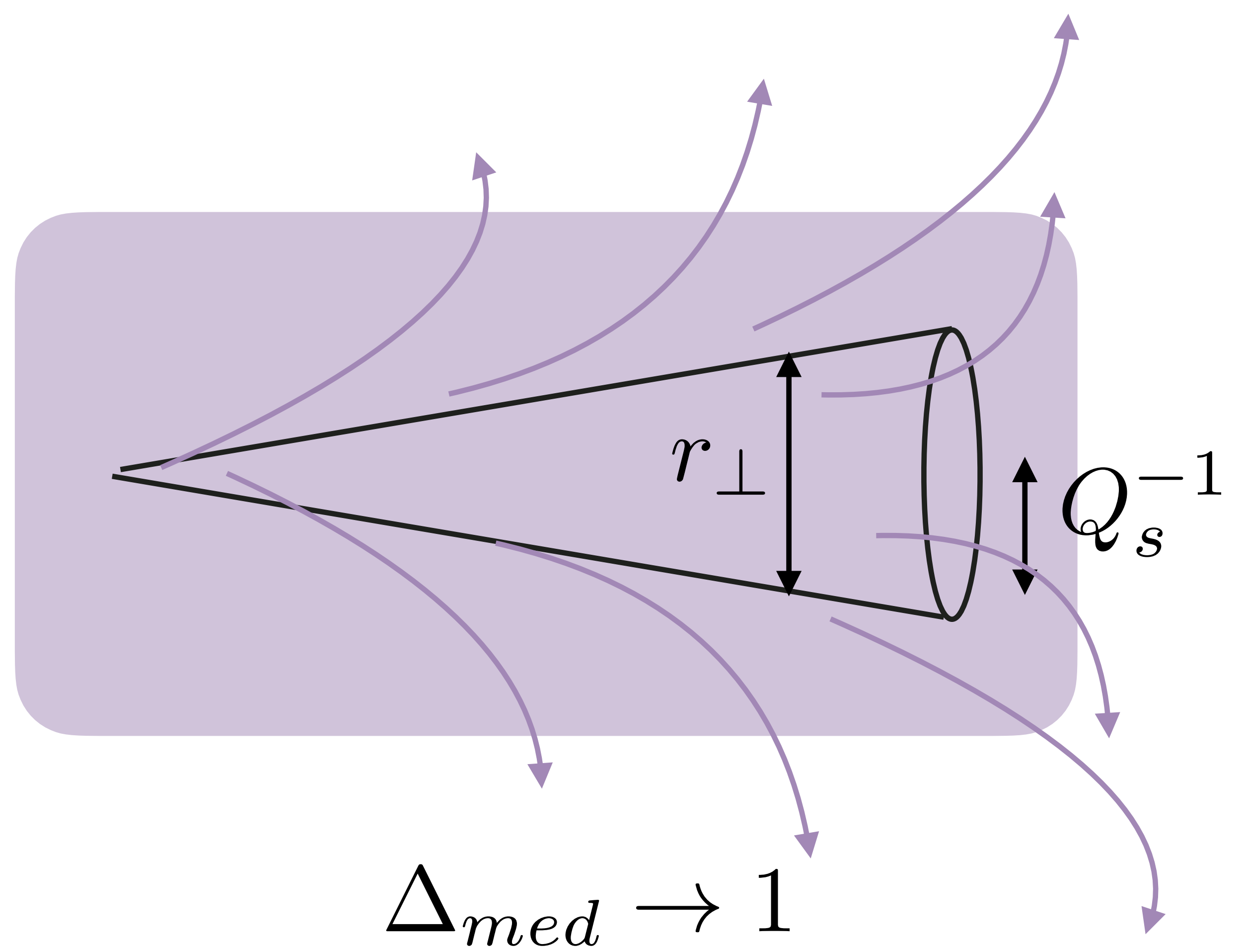
Anti-Angular ordering



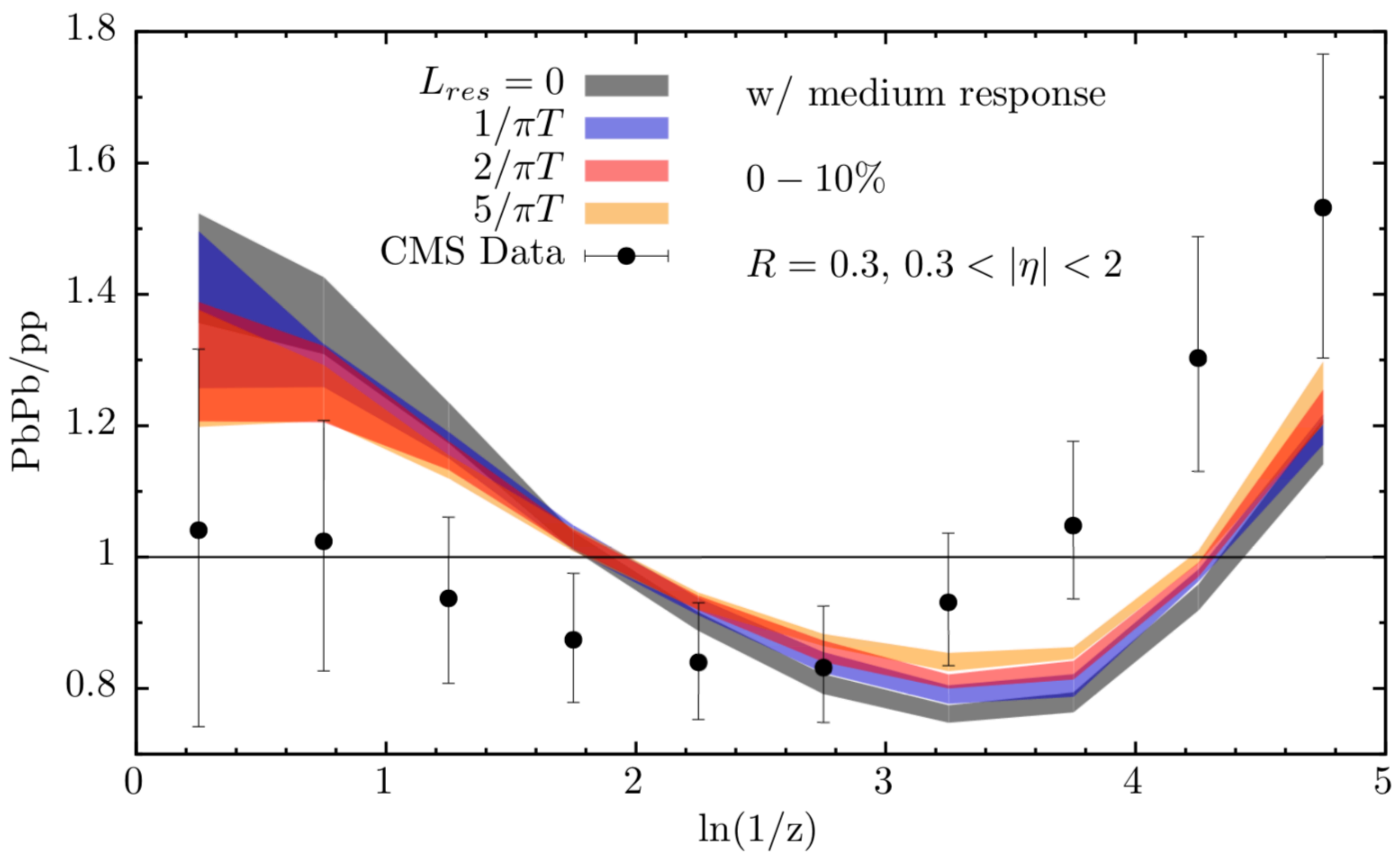
$\Delta_{med} \to 1$

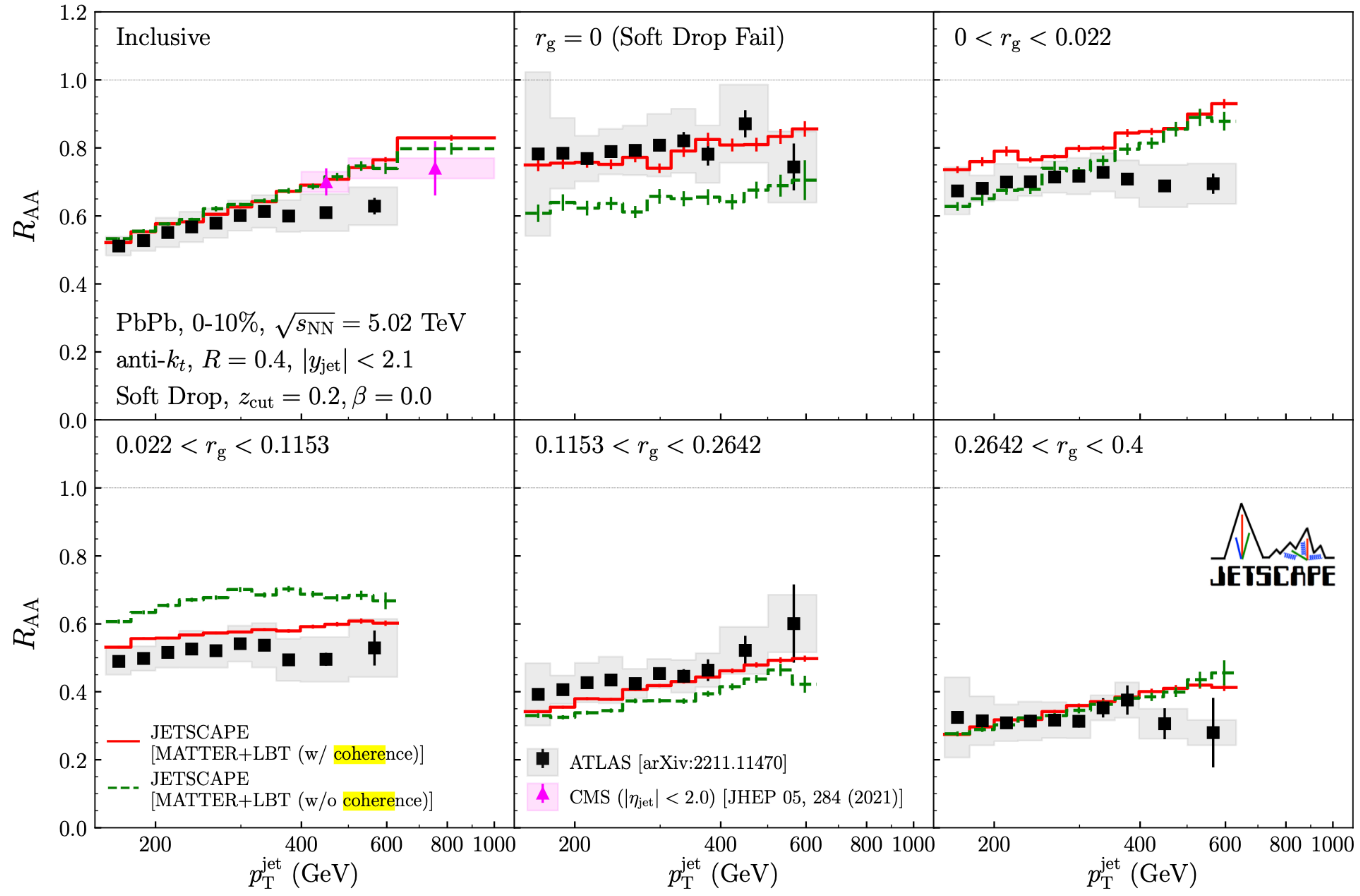
Color (de)coherence

JETSCAPE

[Tachibana et al (2301.02485)]

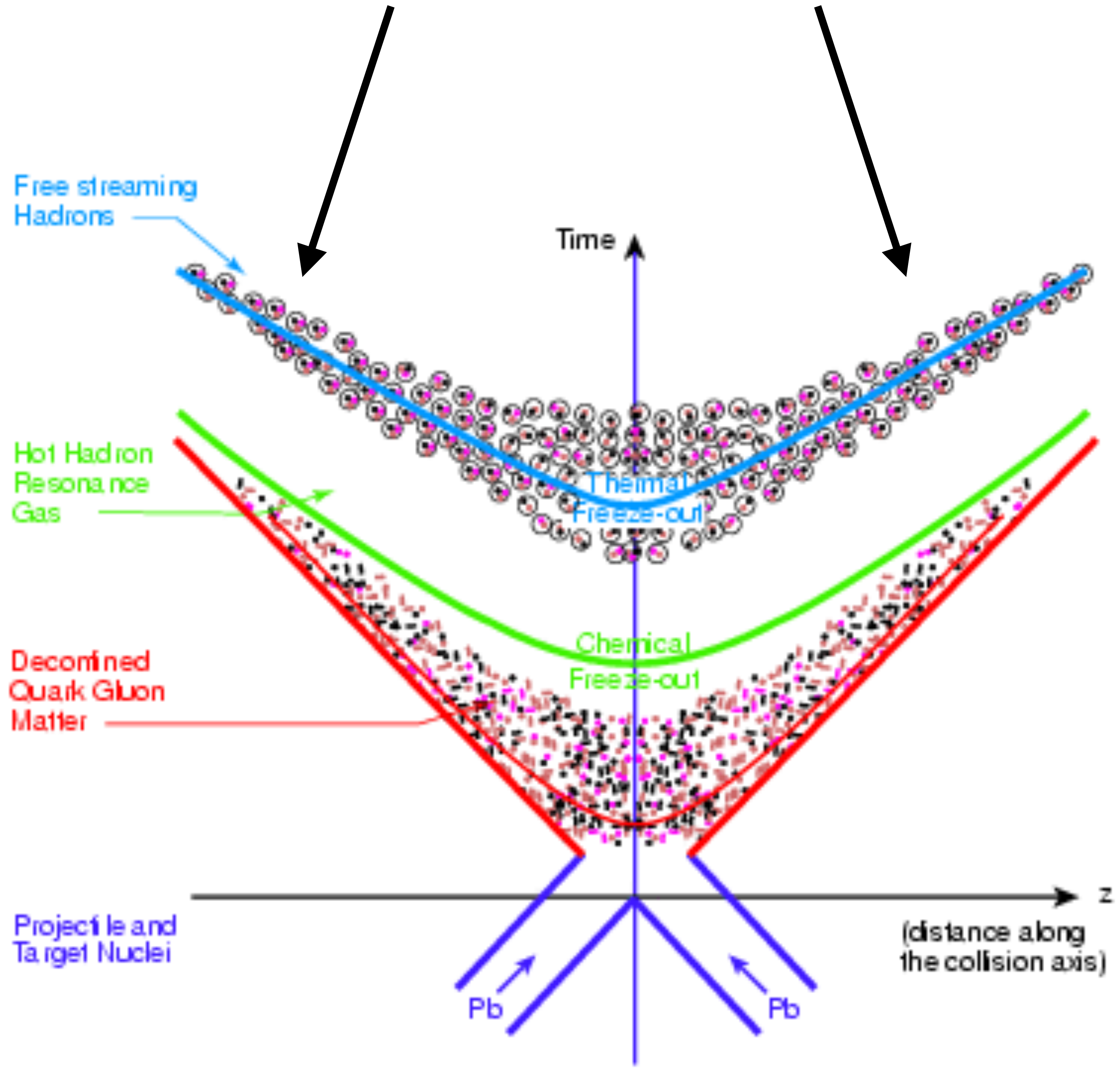
Hybrid





QGP Probes

- Soft probes: flow, hydrochemistry, …
  - Direct result of the QGP evolution
  - ➡ Collective properties and hydrodynamical evolution of the medium



QGP Probes

- Soft probes: flow, hydrochemistry, …
  - Direct result of the QGP evolution
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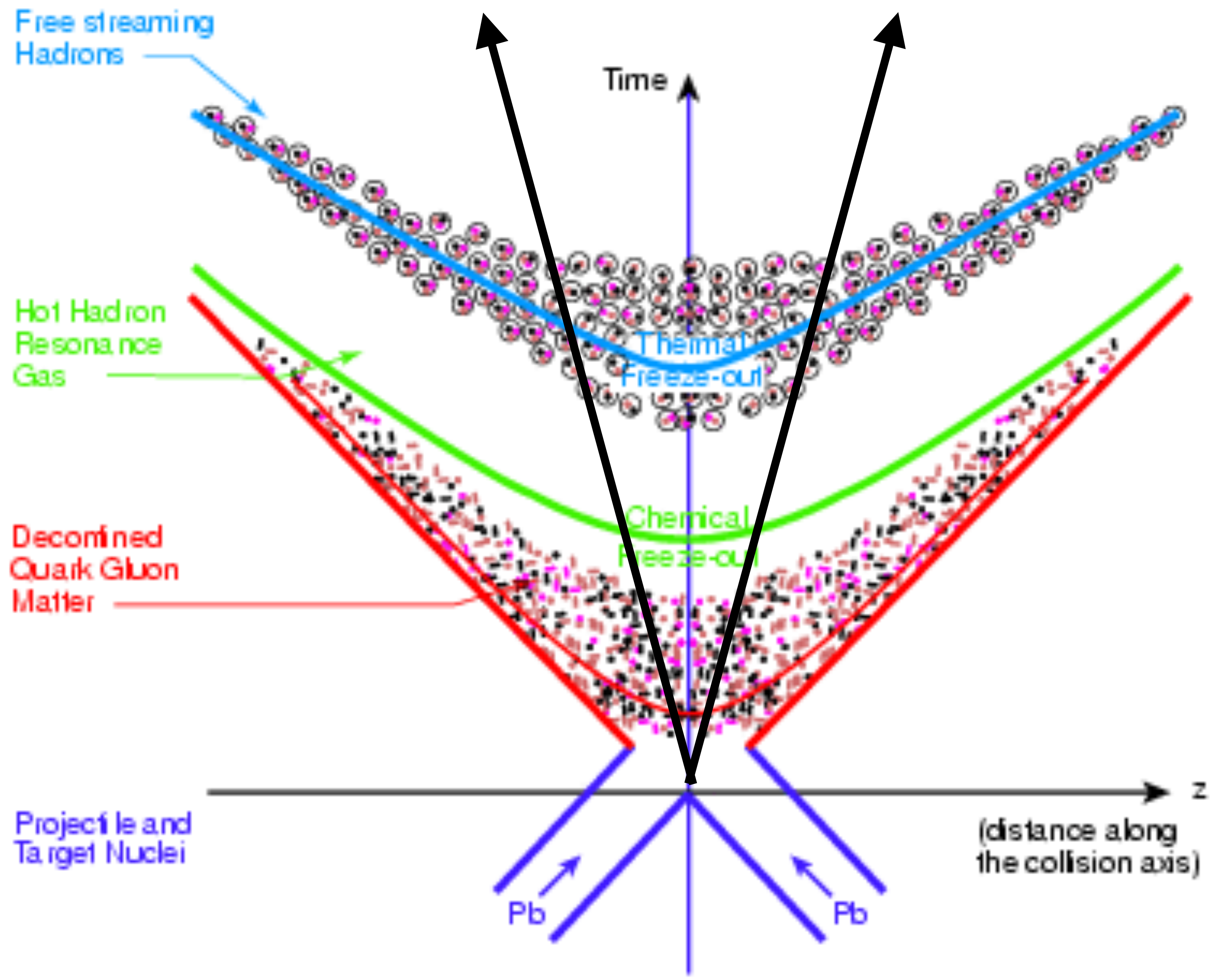
See Monday lectures

- Hard probes: Heavy-flavour, Quarkonia, jets, …
  - Produced in a high momentum transfer process (hard scattering)
  - Indirect observation of the QGP effects
  - ➡ Observe the evolution of the QGP (temperature, density,…)



In-medium propagators

- Adapt Feynman rules to account for a hot and dense QCD medium:

Vacuum QCD
Feynman rules

$$= i\delta^{ab}\frac{\not{p}+m}{p^2-m^2+i\varepsilon}$$

In-medium propagators

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Vacuum QCD Feynman rules $\Longrightarrow$ In-medium QCD Feynman rules

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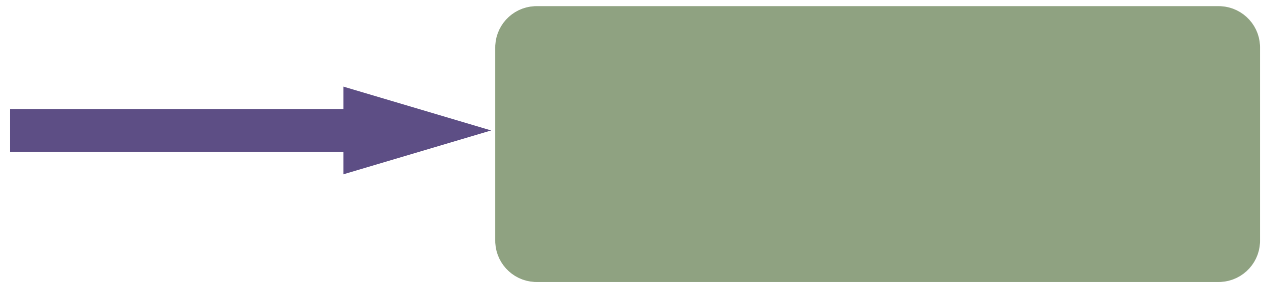

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Vacuum QCD Feynman rules $\Longrightarrow$ In-medium QCD Feynman rules

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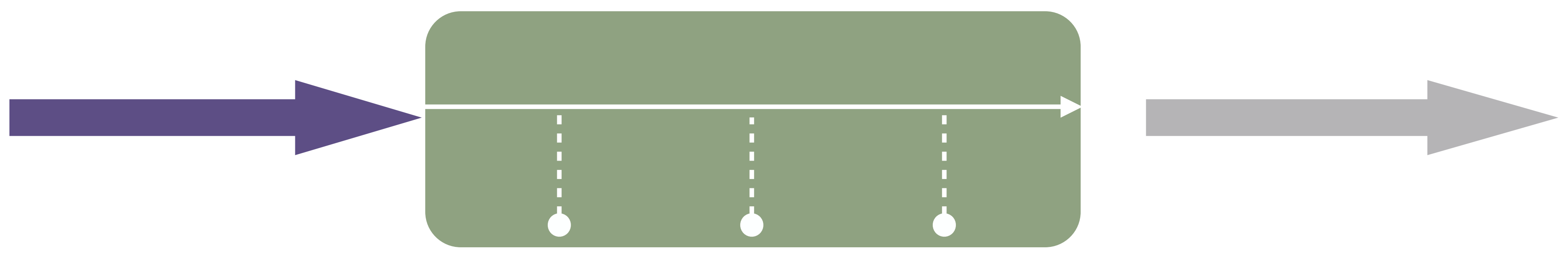


Wilson line (change in colour):

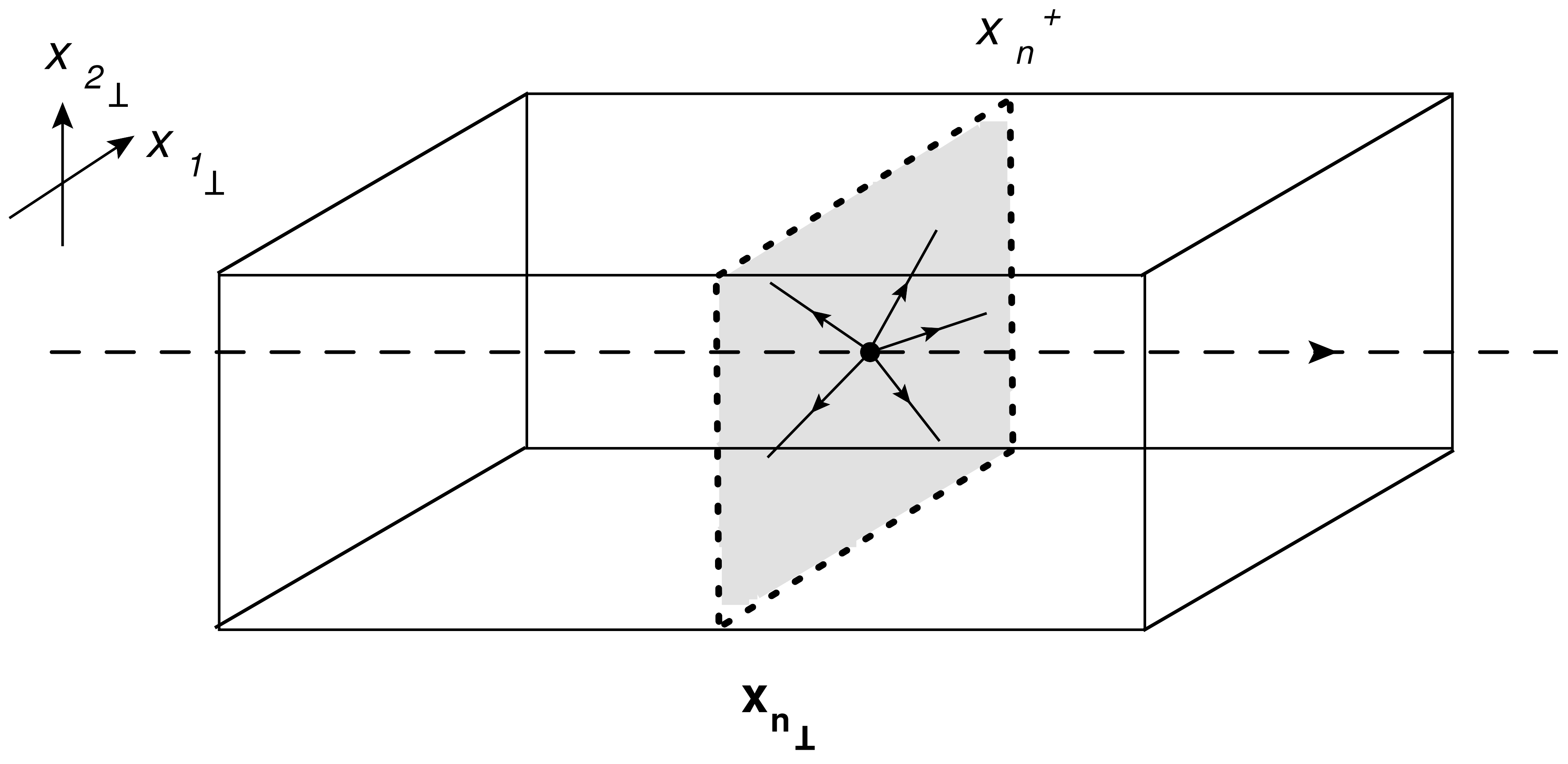
$$W(x_{0+},L_+;\mathbf{x}_\perp)=\mathcal{P}\exp\left\{ig\int_{x_{0+}}^{L_+}dx_+A_-(x_+,\mathbf{x}_\perp)\right\}$$

In-medium propagators

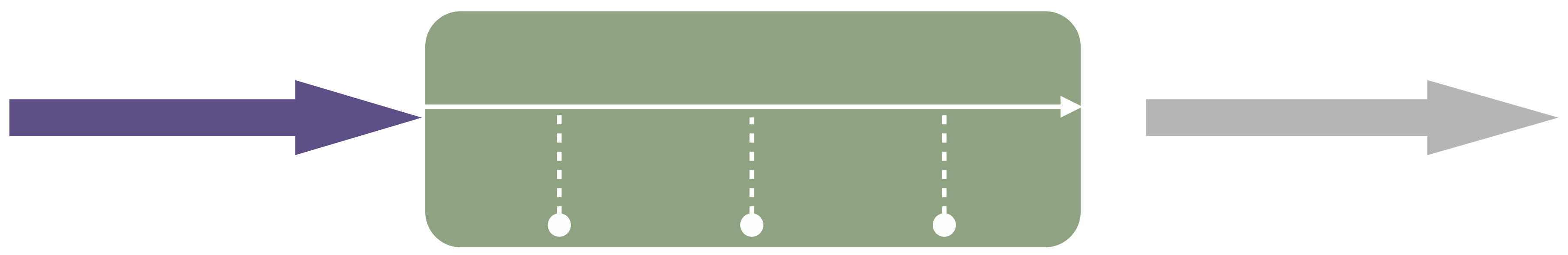
- Adapt Feynman rules to account for a hot and dense QCD medium:

Due to Lorentz contraction one can further assume

$$A(x_+, x_-, x_\perp) = A(x_+, x_\perp)$$



In-medium QCD Feynman rules



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Gluon fields

Path-ordered gluon fields

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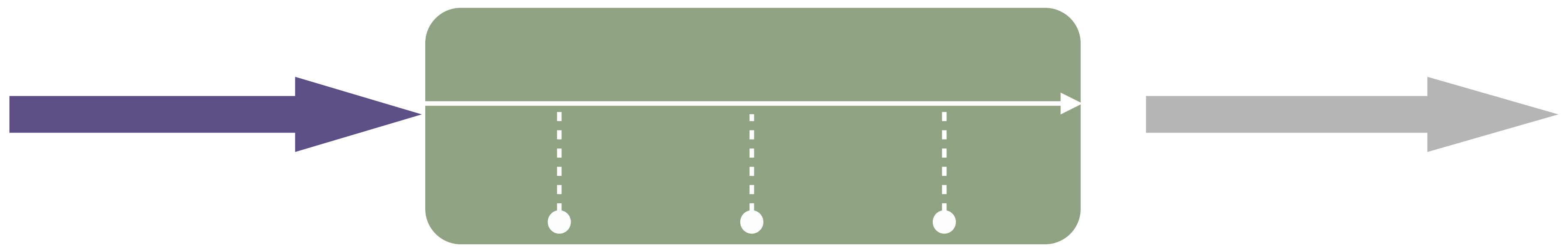

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Gluon fields

Medium longitudinal limits from [x_{0+},L_+]

Path-ordered gluon fields

Transverse coordinate of the incoming parton

Parton Shower Models

- Modifications on a developed shower

Medium-induced emissions inside them medium: $t_f \leq \sqrt{2\omega/\hat{q}}$

(But no double logarithmic enhancement)

Parton formation time: $t_f \simeq 2\omega/k_\perp^2$

Transverse momentum acquired via multiple soft scatterings: $k_f^2 = \hat{q}t_f$.

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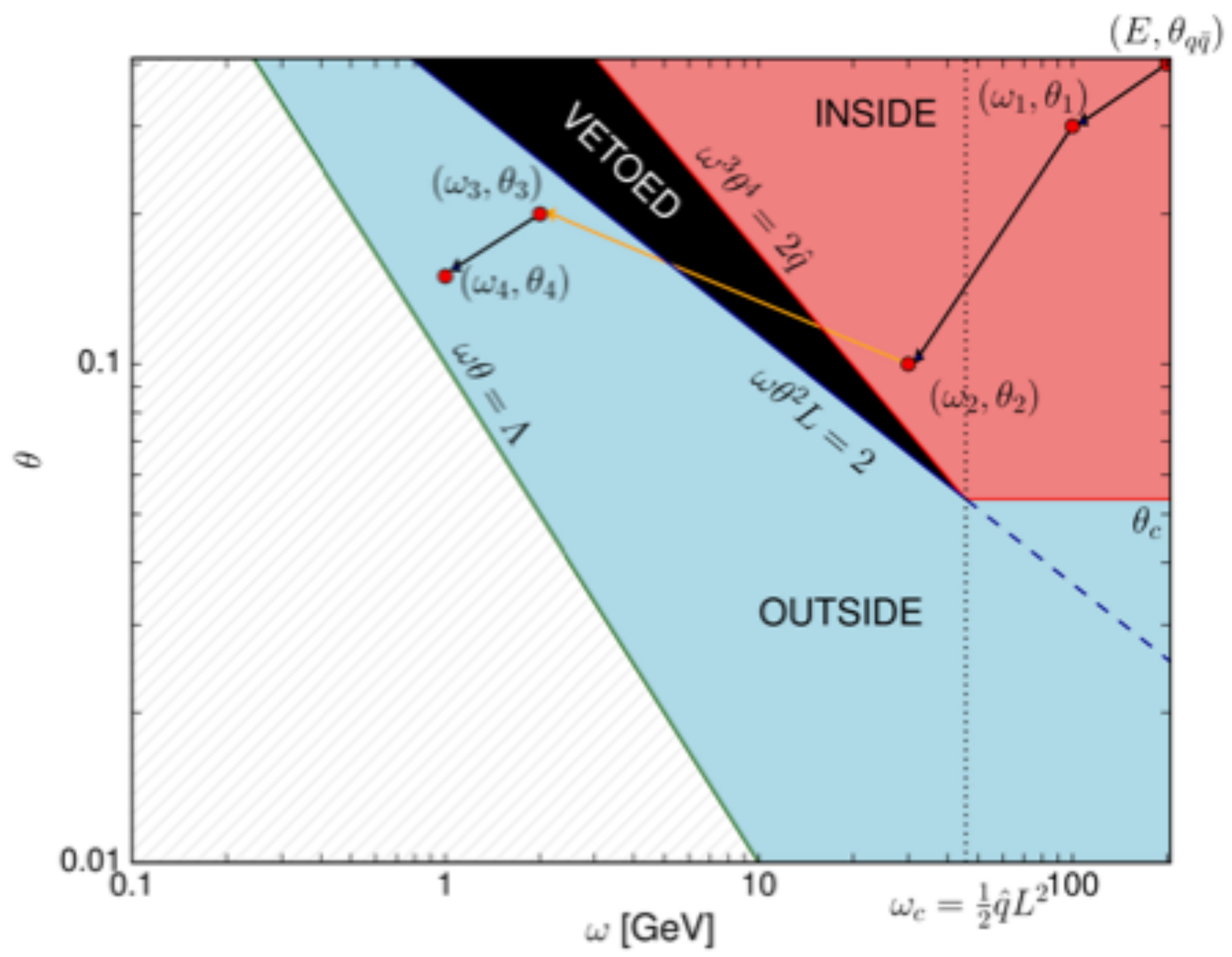

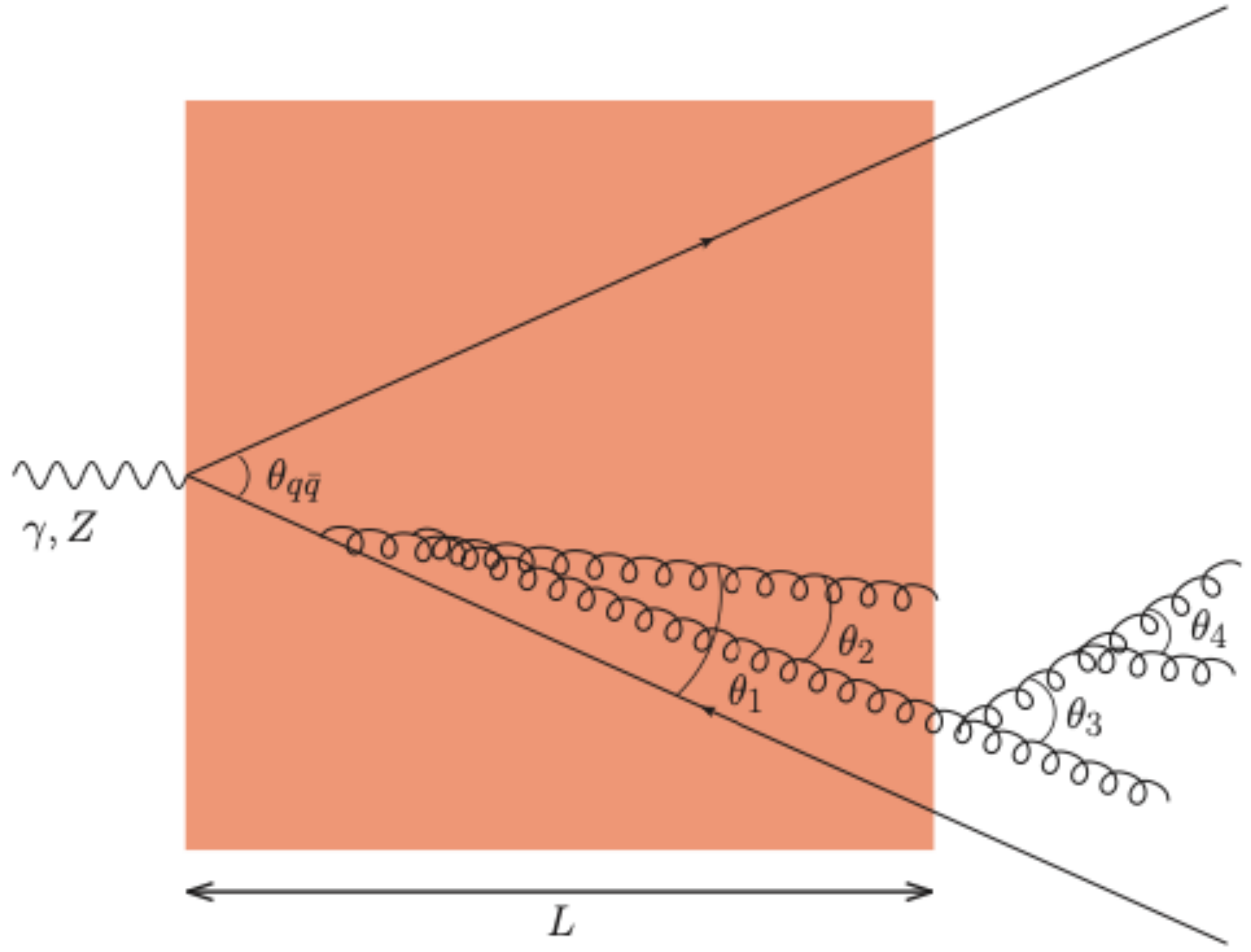

At double logarithmic accuracy, medium-induced radiation is vetoed

Parton Shower Models

E.g:JetMed..

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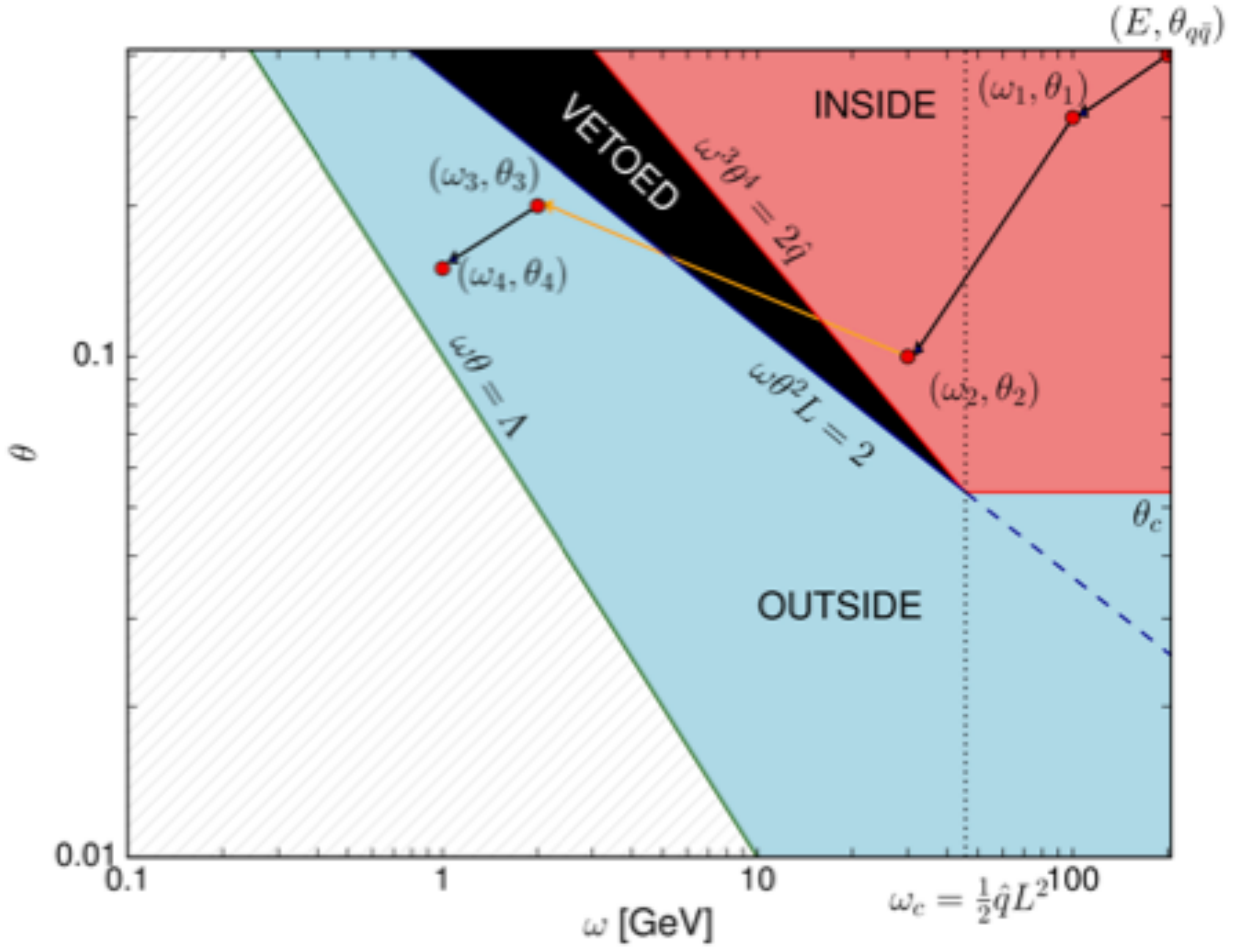

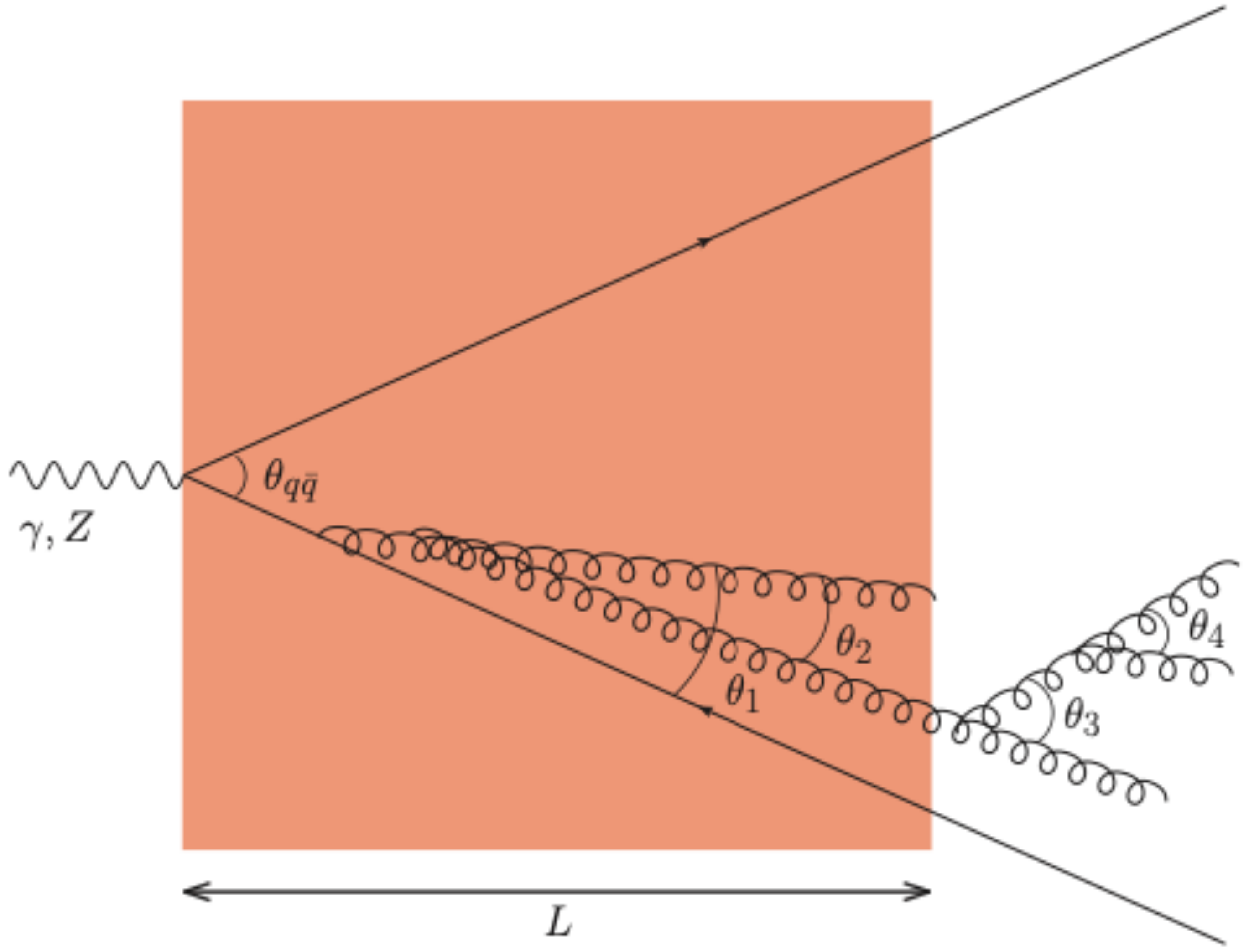

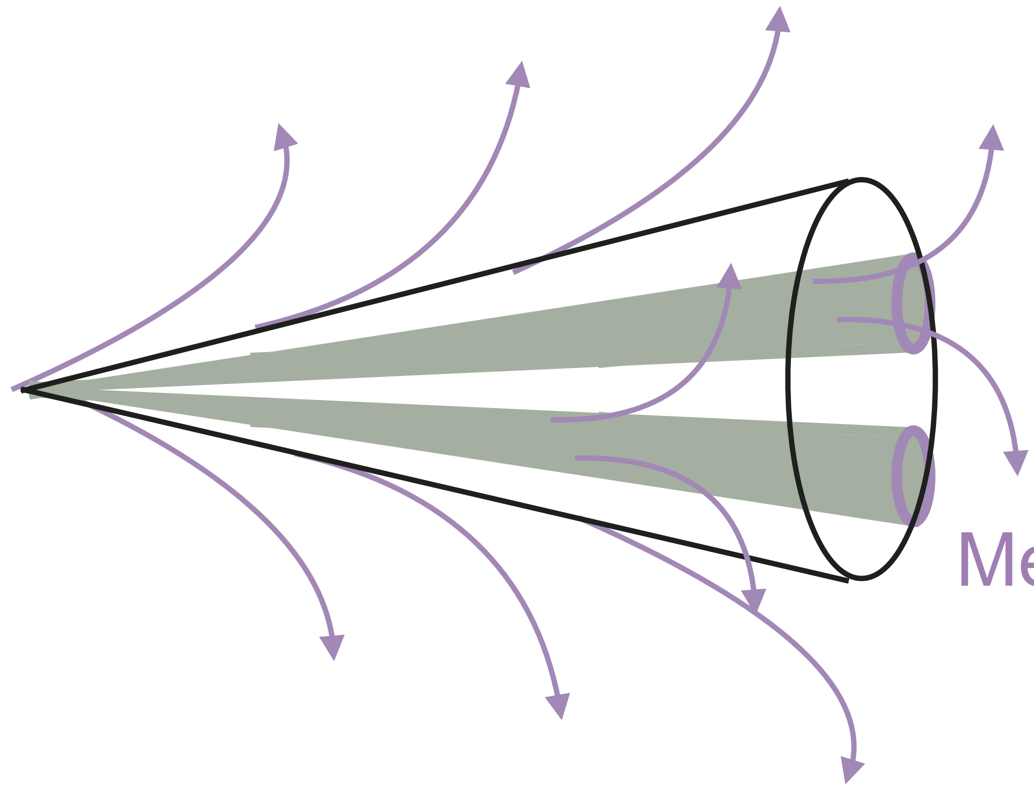

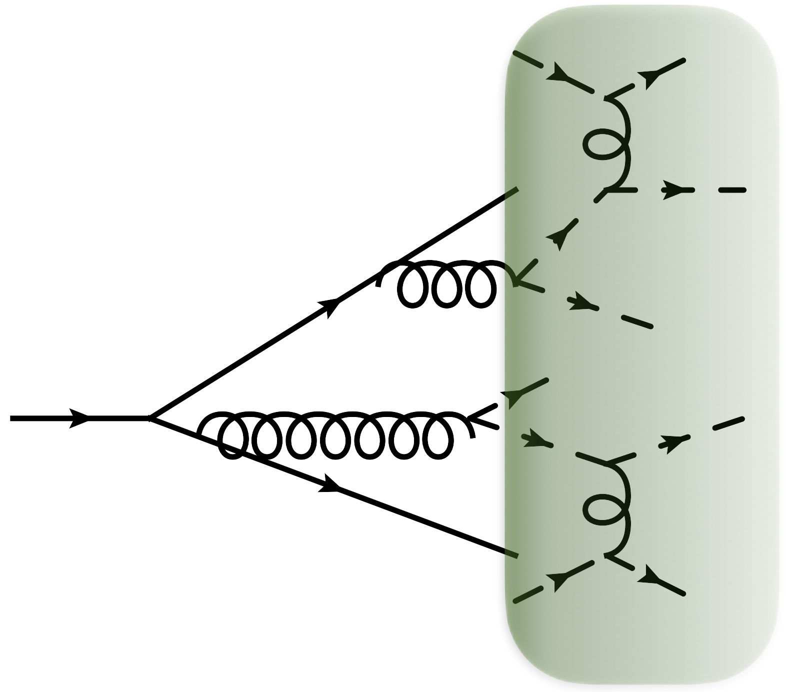

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