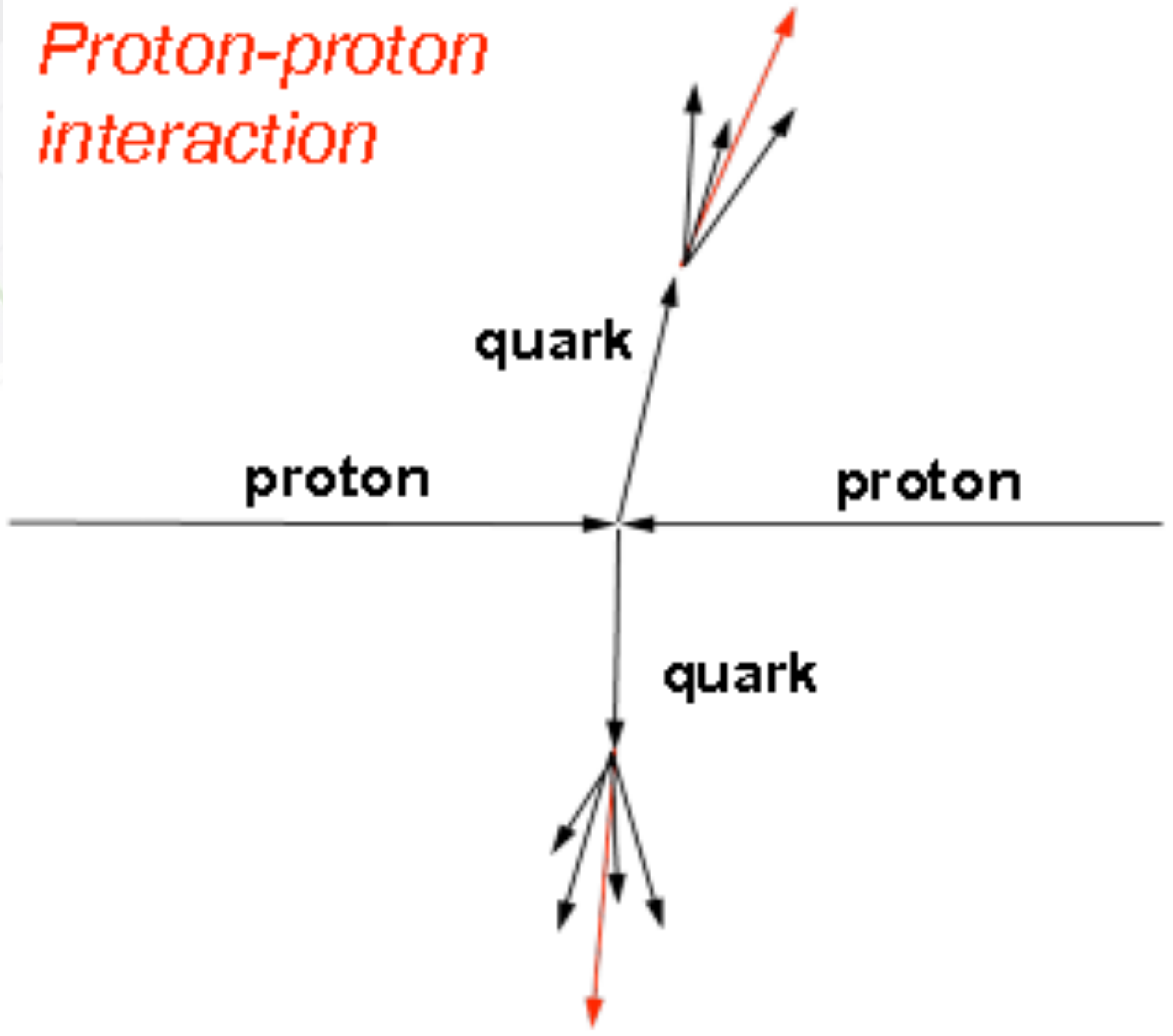
Jet Quenching

Liliana Apolinário

LIP

Proton-Proton Collision

- pp collision: a “simple” (few particles) system

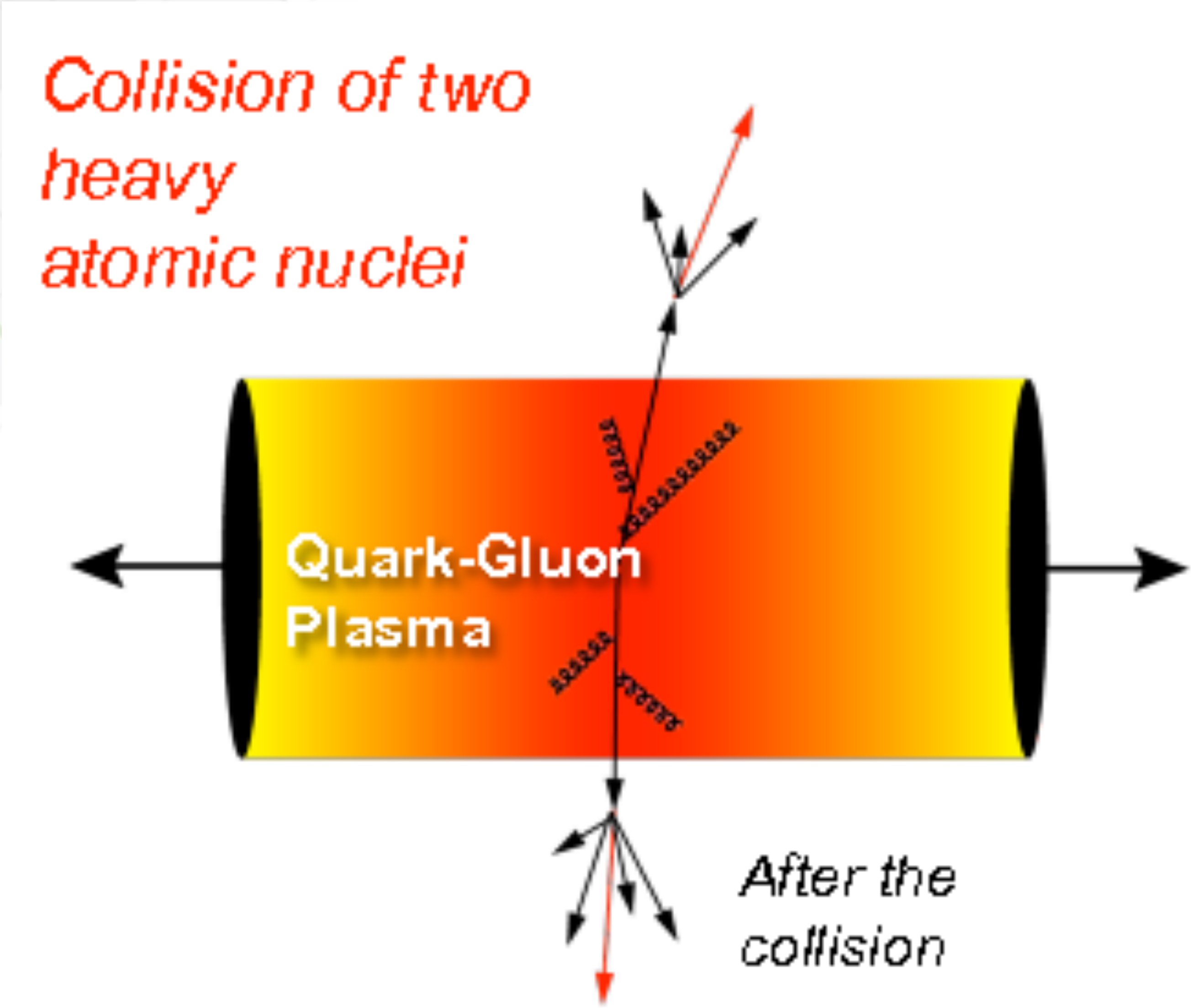


- Hard scattering:
  - Process evolution can be described with Quantum Field Theory first principles

See talk “Jets” (S. Prestel) Monday

Heavy-Ions Collision

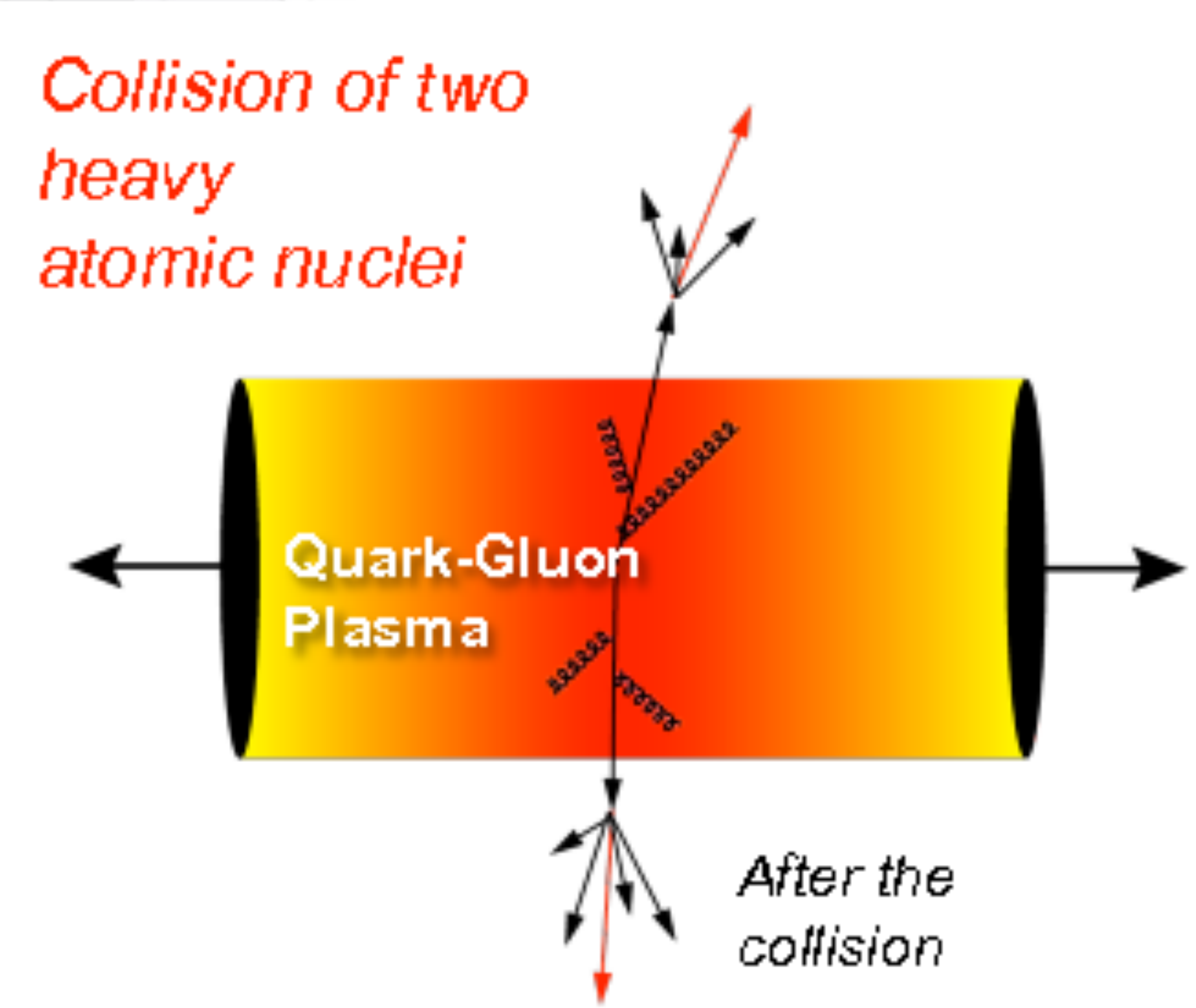
- PbPb collision: a complex multi-particle system



- Hard scattering
- Hot and dense medium (QGP)

Heavy-Ions Collision

- PbPb collision: a complex multi-particle system



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

Heavy-Ions Collision

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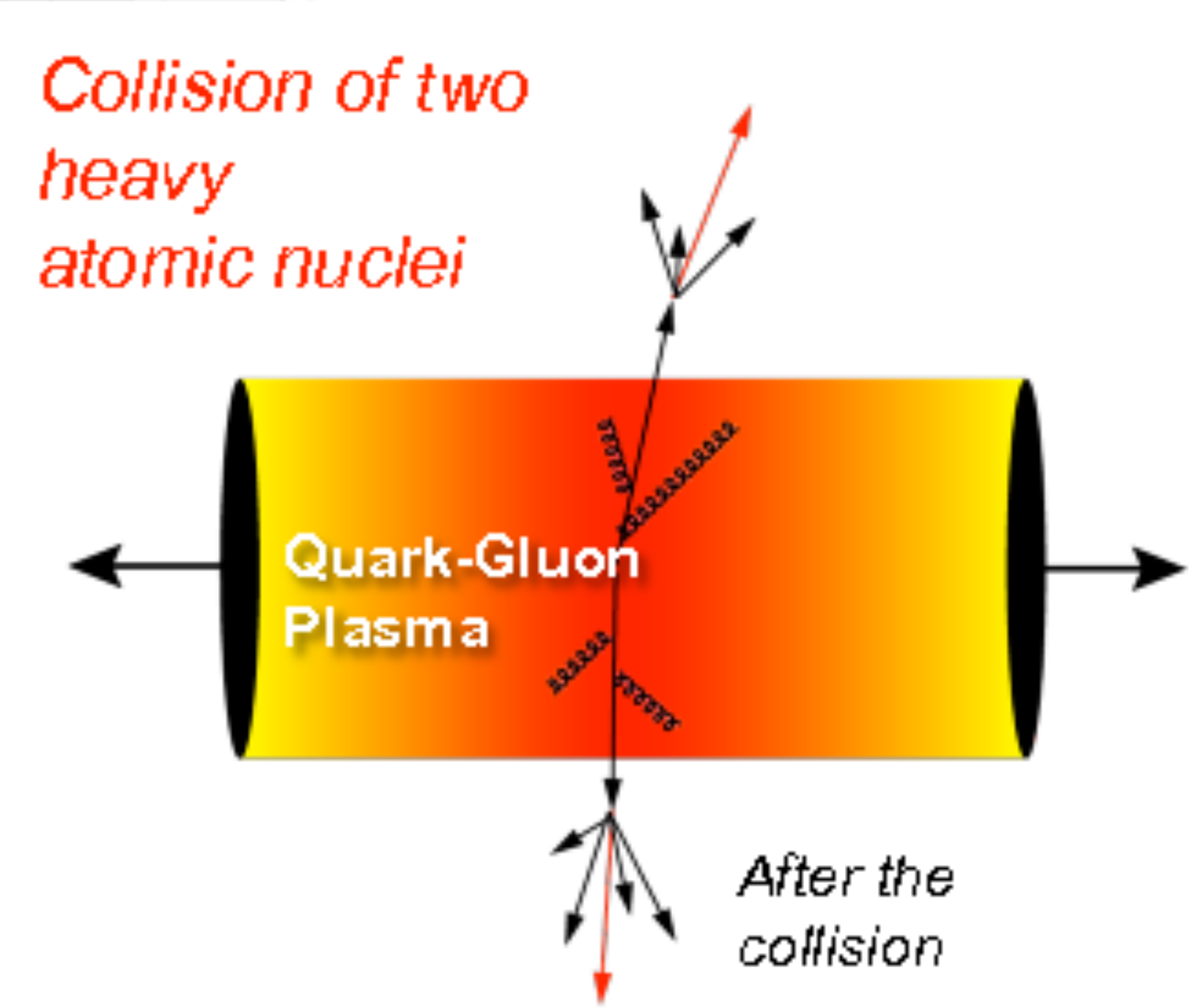

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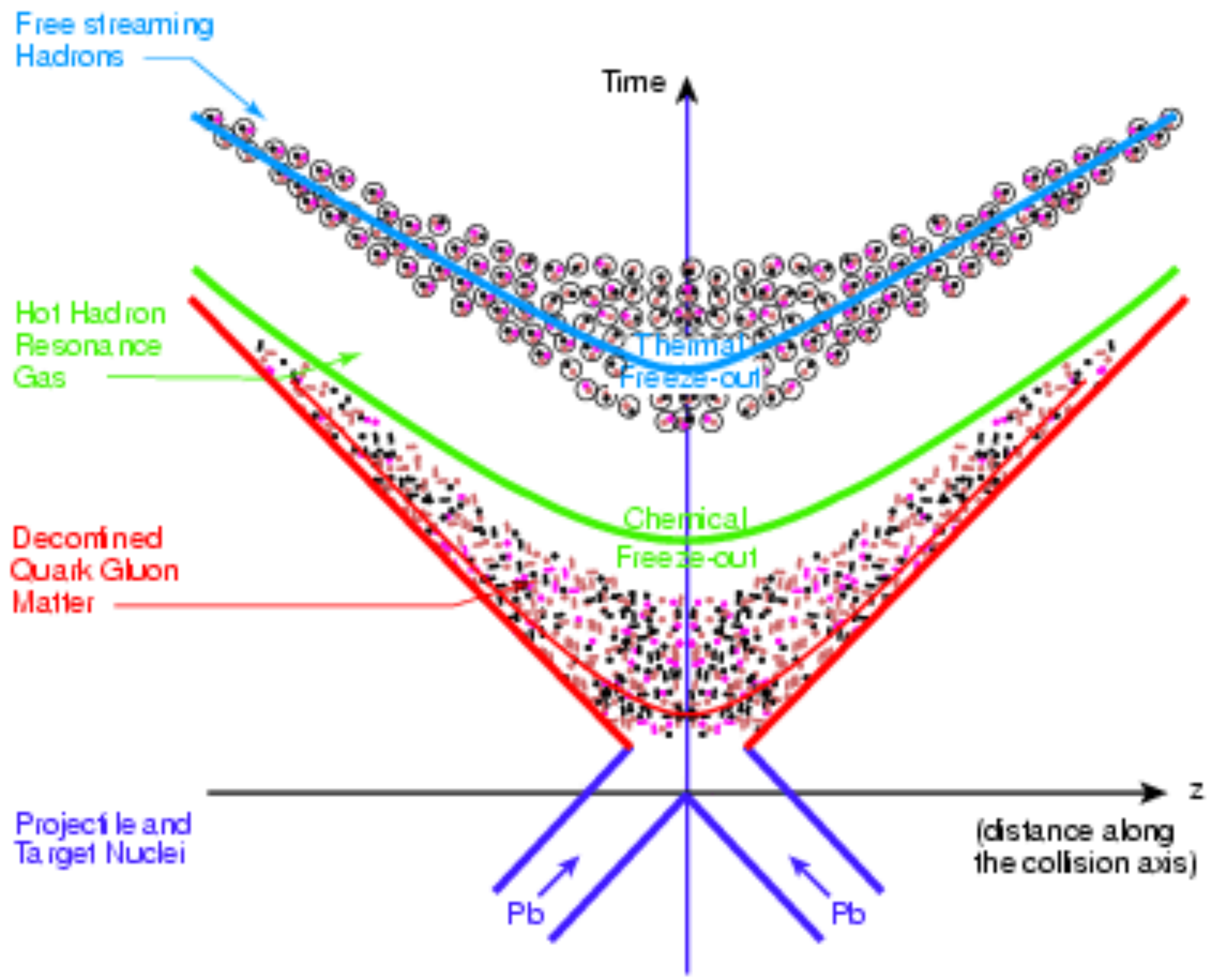
See talk “Flow” (C. Plumberg) today

Heavy-Ions: Open Questions

- PbPb collision evolution



- Final state particles (what we measure)
    - Is the QGP strongly coupled?
        - How is thermalized?
    - QCD description in all energy range
        - Quasi-particles?
- Initial state (incoming nuclei) ?
    - See talk “Nuclear PDFs” (I.Heleniums) today

Heavy-Ions: Open Questions

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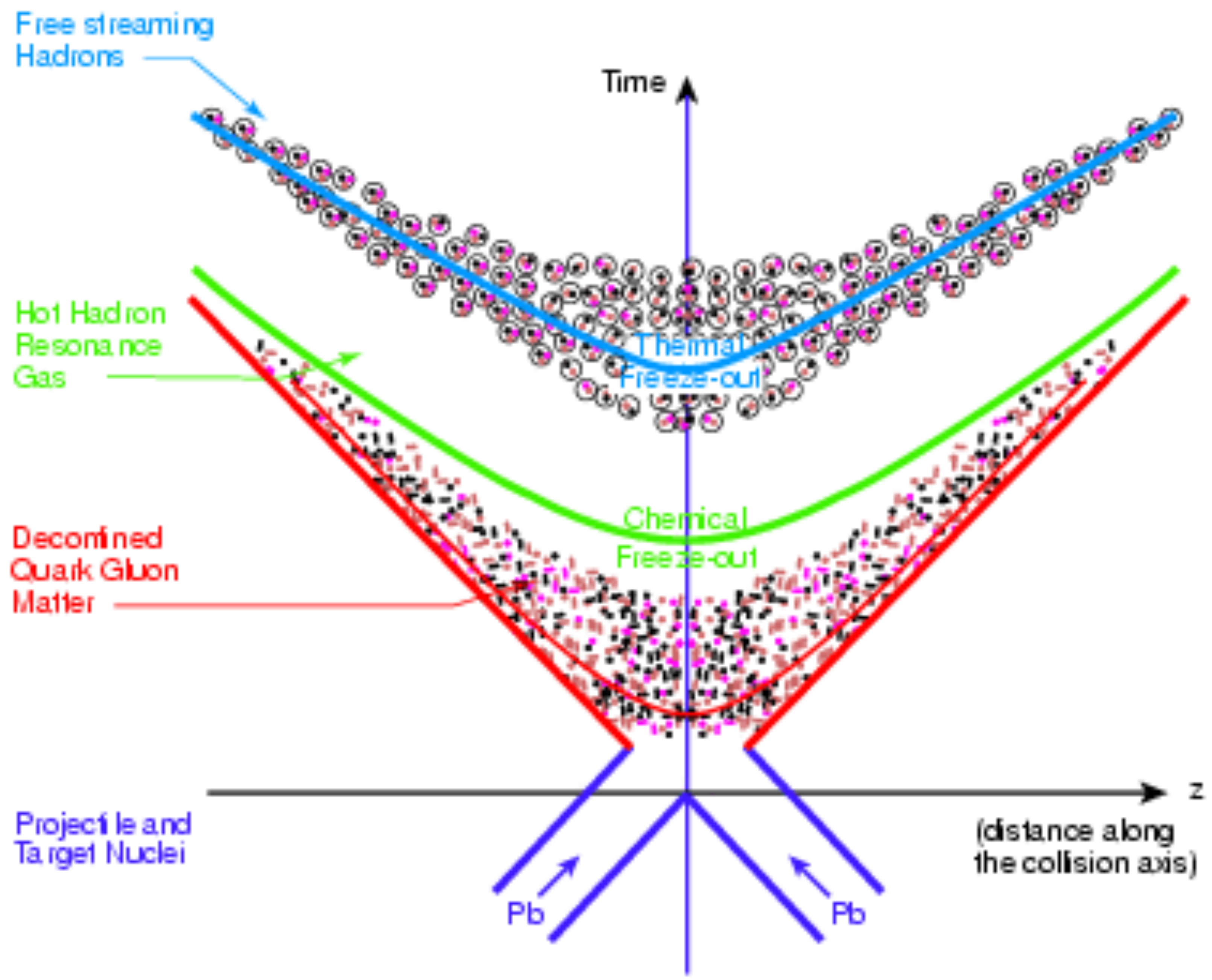

- Final state particles (what we measure)
  - Is the QGP strongly coupled?
    - How is thermalized?
  - QCD description in all energy range
    - Quasi-particles?
      - Identify well controlled observables/ probes to assess QGP properties!!
- Initial state (incoming nuclei) ?
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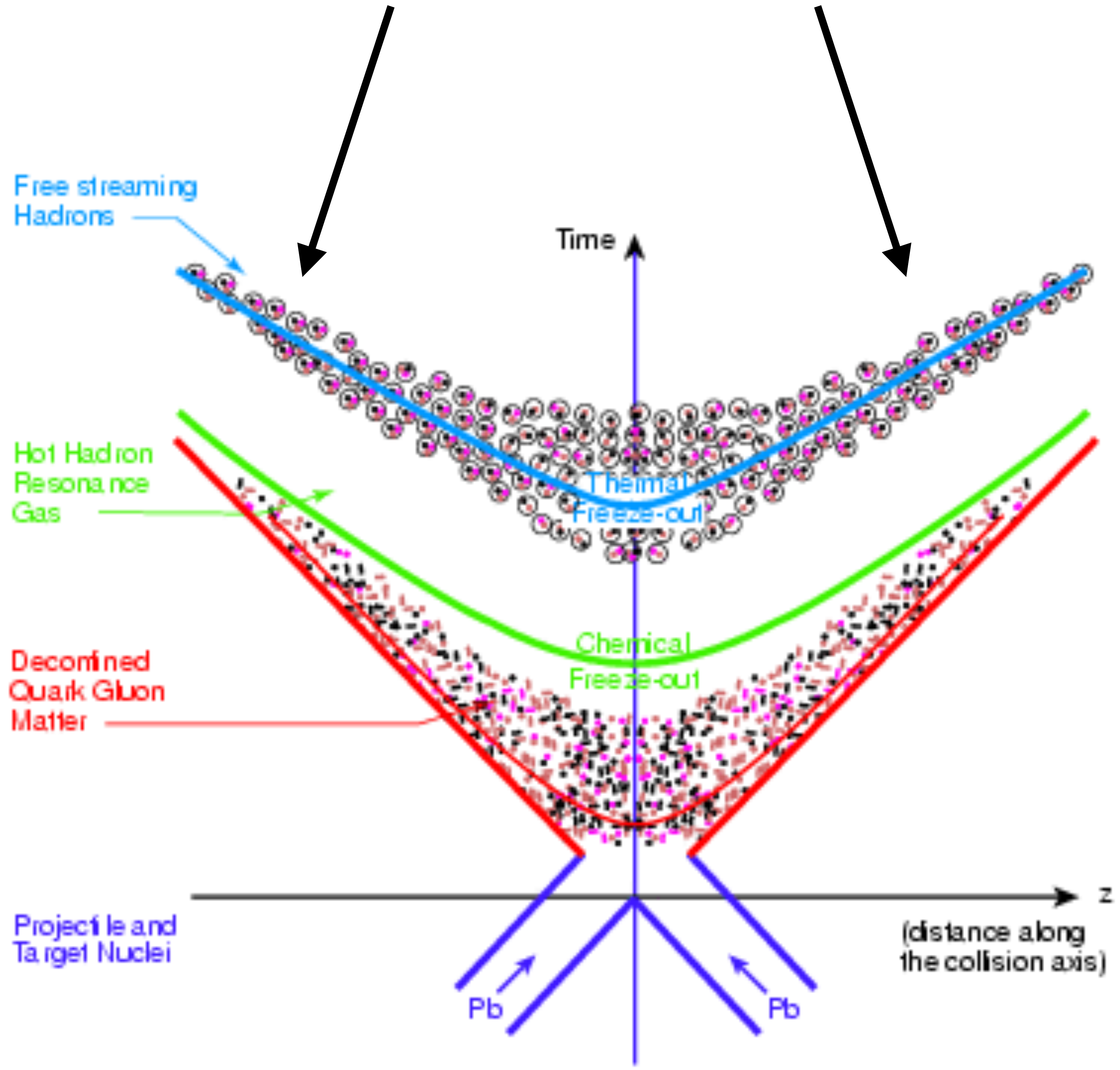
QGP Probes

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



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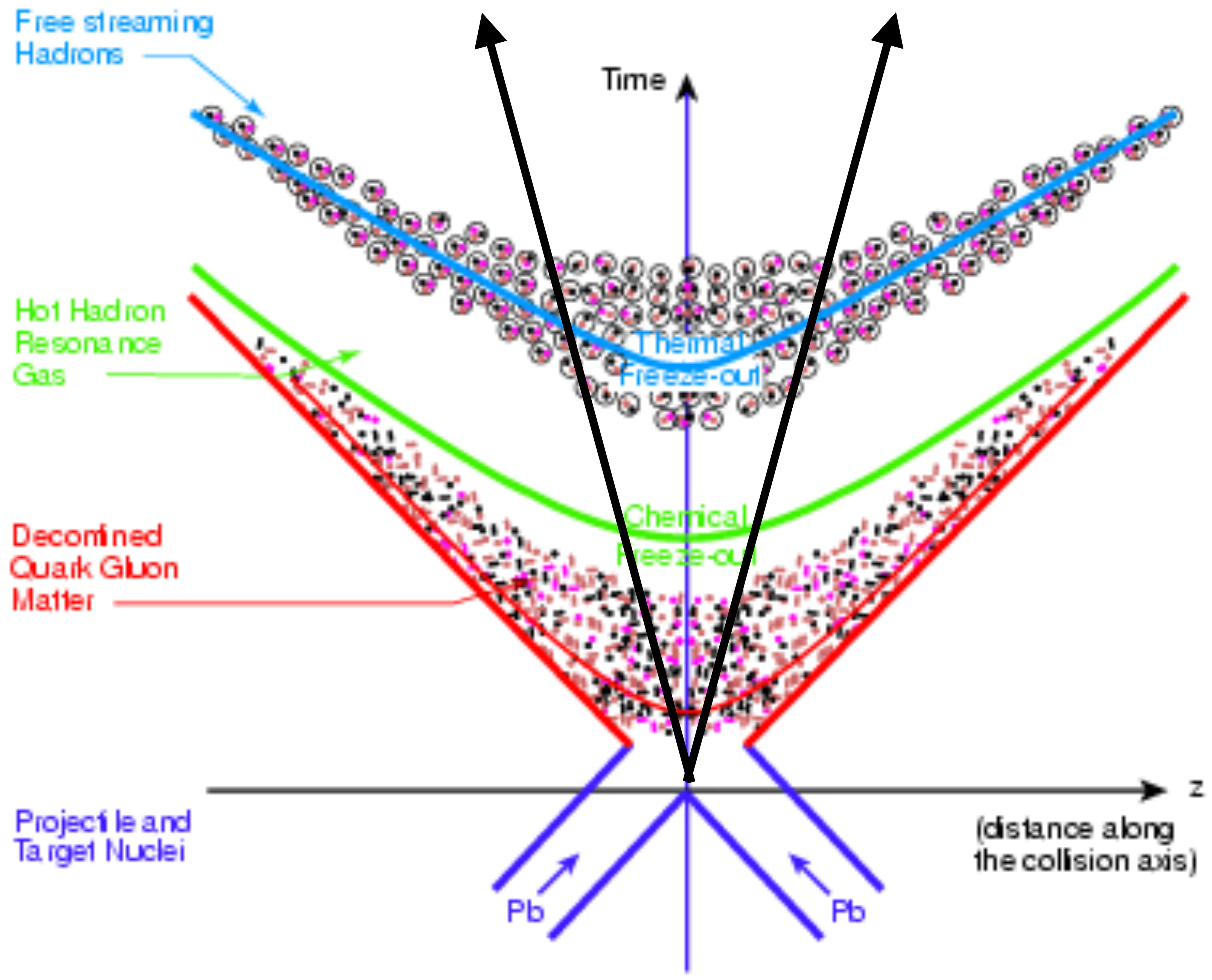

- Hard probes: Quarkonia, jets, …
  - Produced in a high momentum transfer process (hard scattering)
  - Indirect observation of the QGP effects
  - ➡ Observe the evolution of the QGP (temperature, density,…)

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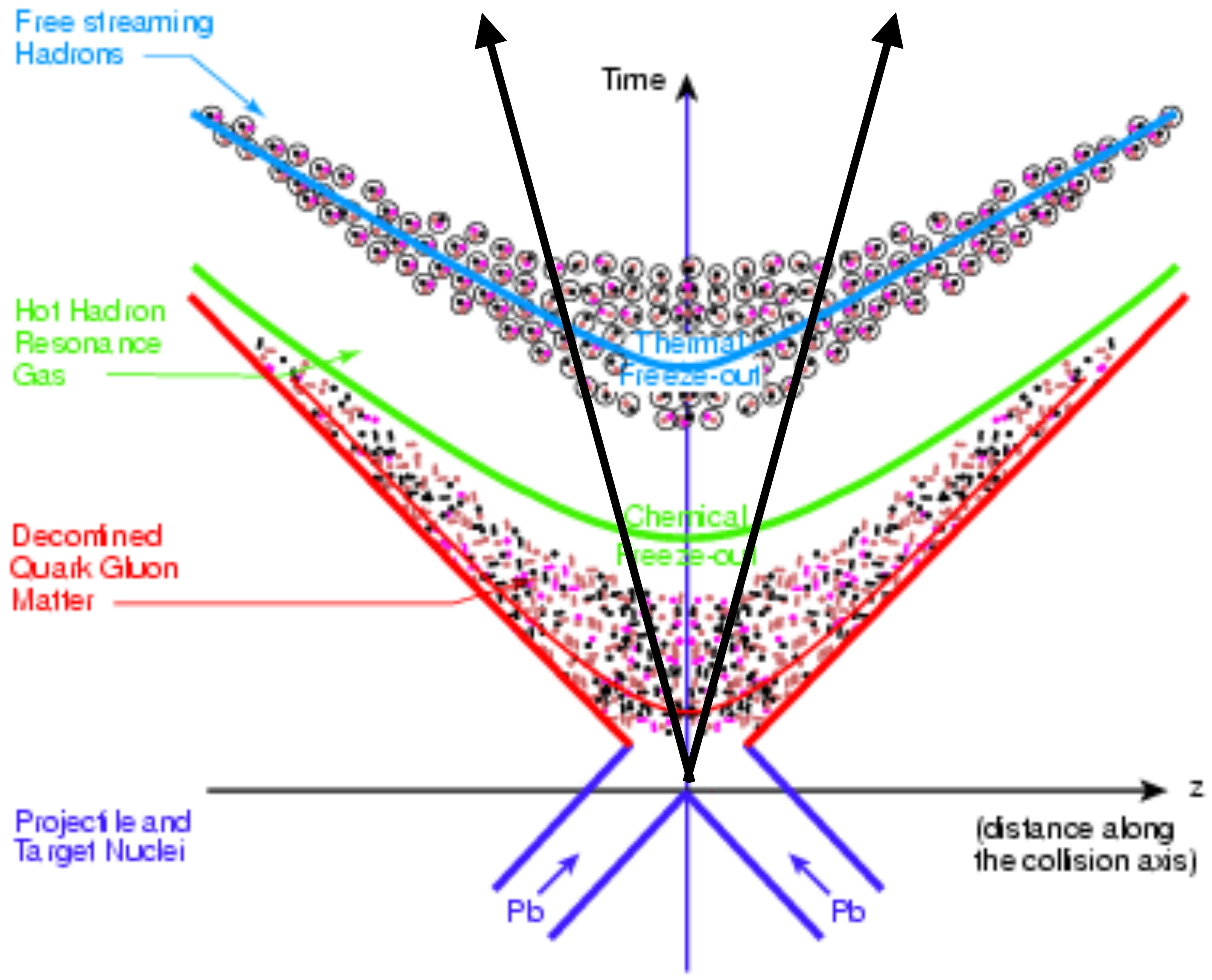

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Why Hard Probes?

- Better theoretical and experimental control!
  - Like in pp, less sensitive to (unknown) details of incoming nucleus (nPDFs)

PDFs FFs

$$d\sigma^{AA\to h+\text{rest}}_{(\text{vac})} = \sum_{ijk} f_{i/A}(x_1, Q^2) \otimes f_{j/A}(x_2, Q^2) \otimes \hat{\sigma}_{ij\to f+k} \otimes D^{(\text{vac})}_{f\to h}(z, \mu_F^2)\,.$$

Elementary “Hard” cross-section

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Unmodified by the QGP!

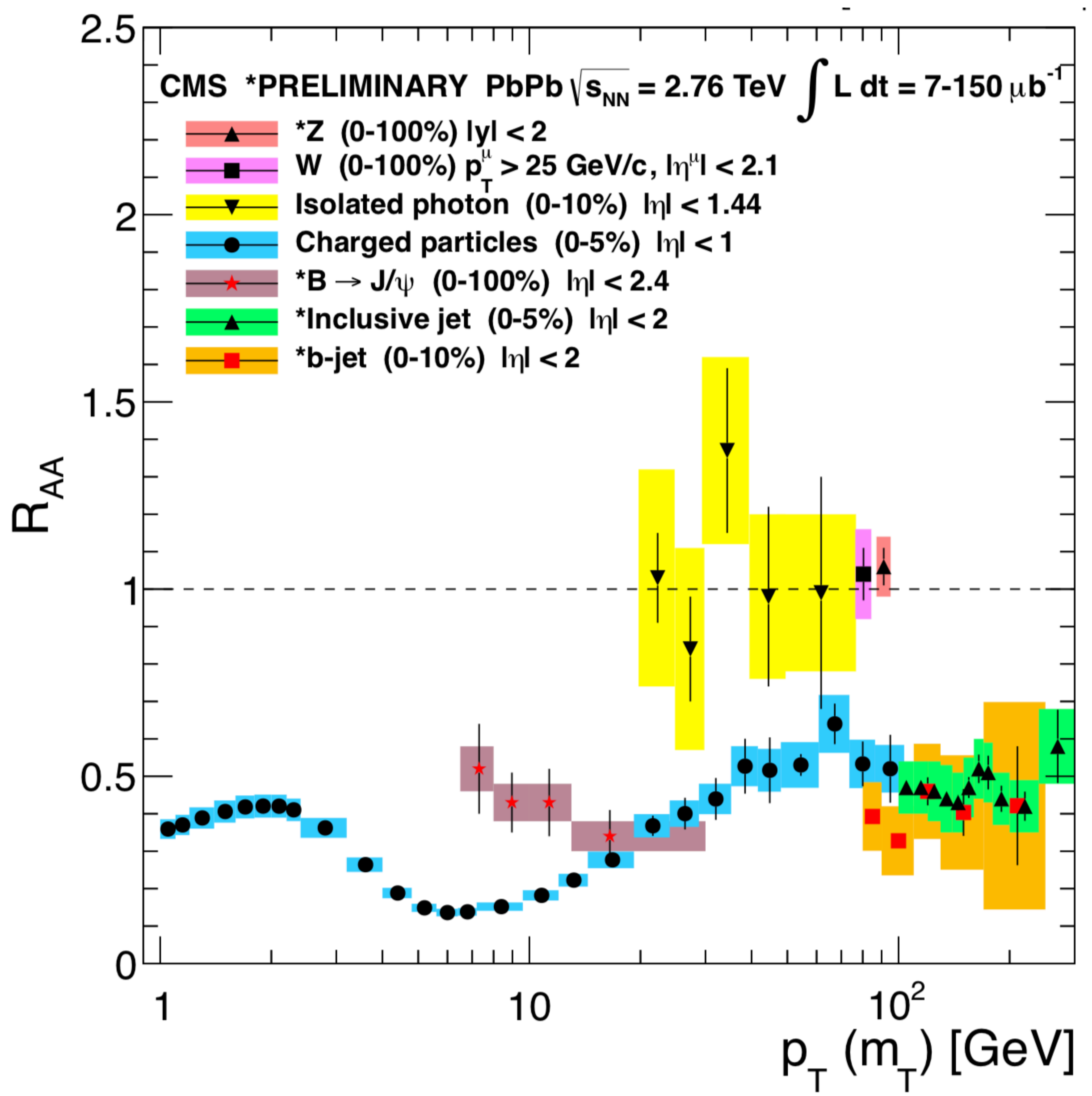
Elementary "Hard" cross-section

nPDFs

Medium-induced FF

$$d\sigma^{AA\to h+\text{rest}}_{(\text{med})} = \sum_{ijk} f_{i/A}(x_1, Q^2) \otimes f_{j/A}(x_2, Q^2) \otimes \hat{\sigma}_{ij\to f+k} \otimes P_f(\Delta E, L, \hat{q}, \ldots) \otimes D^{(\text{vac})}_{f\to h}(z, \mu_F^2)\,.$$

"Vacuum" Hadronization (?)



Why Jets?

- Formed in the beginning of the collision:
  - Allow detailed imaging of the QGP
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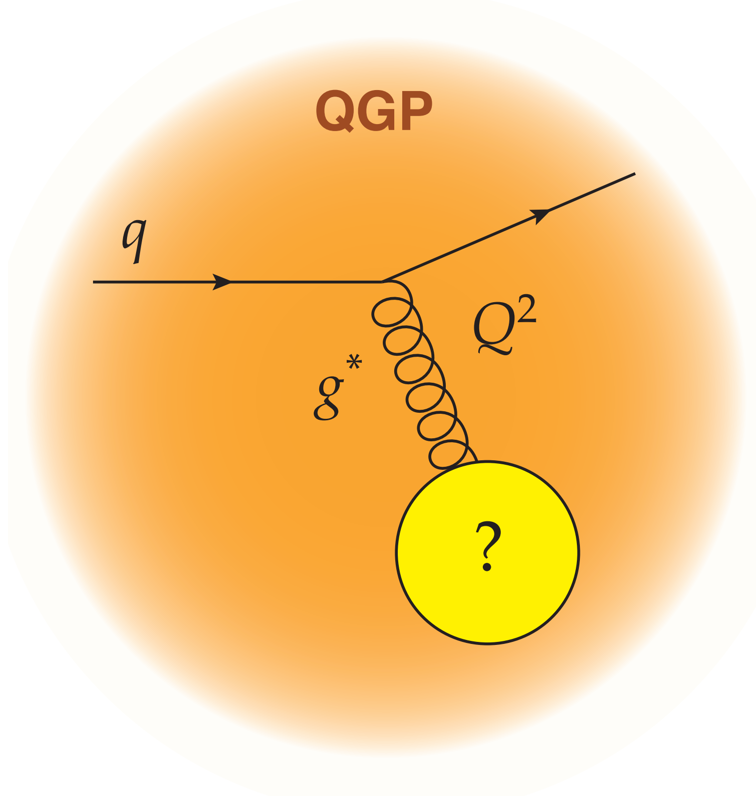
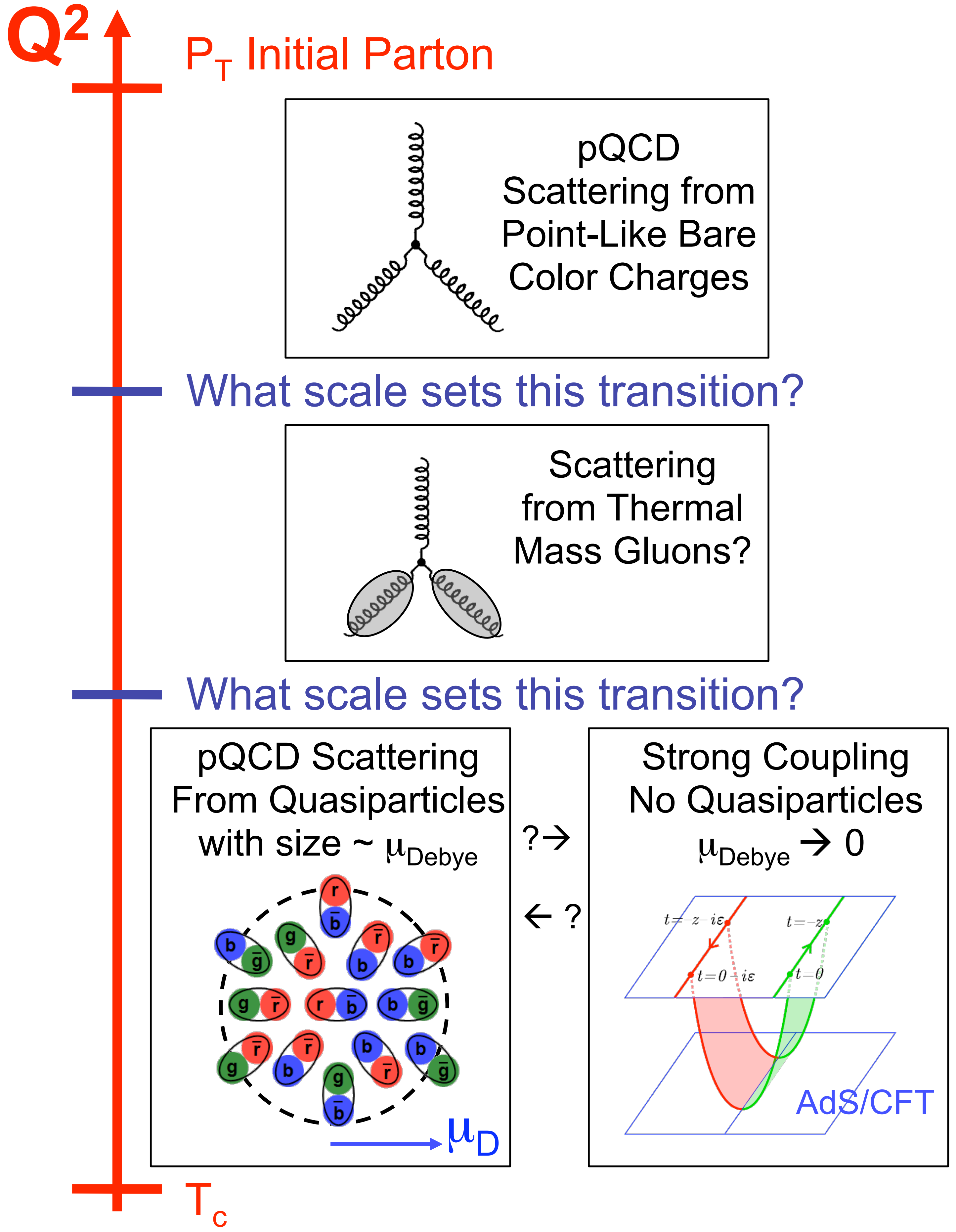
  - Allow QGP probing by different scales
    - Scale dependent quantities (Eg.: “quasi-particles”)





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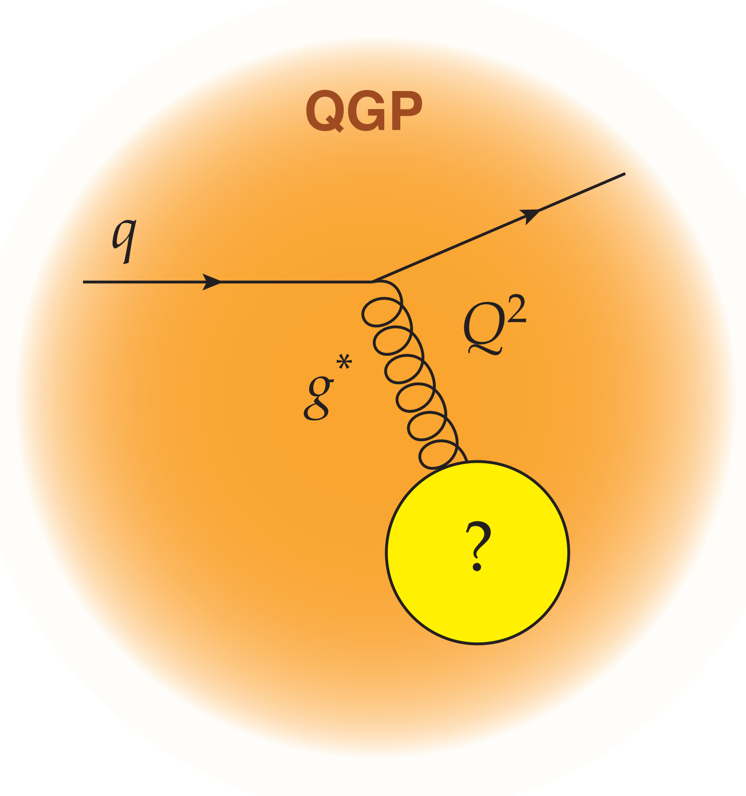

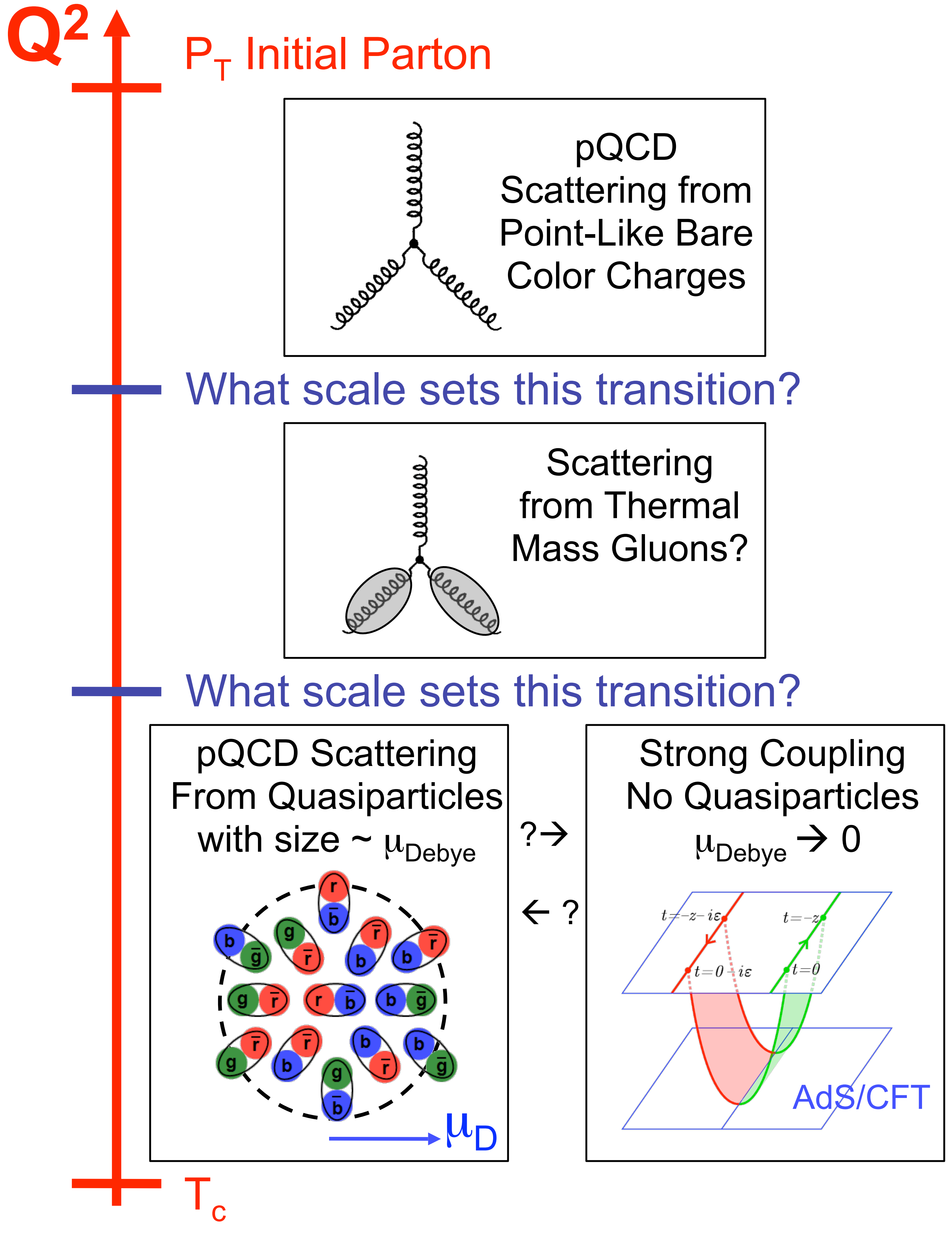

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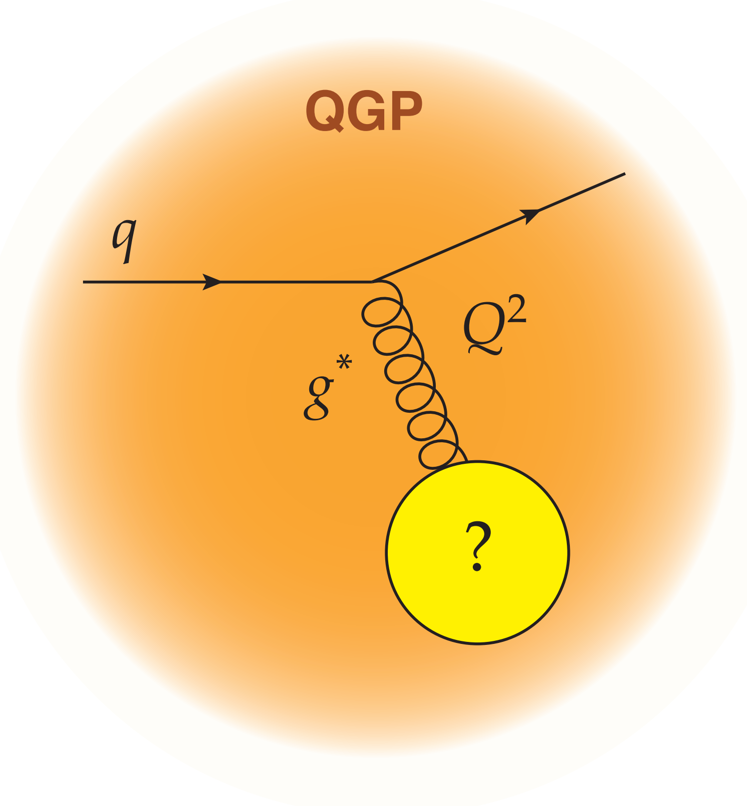
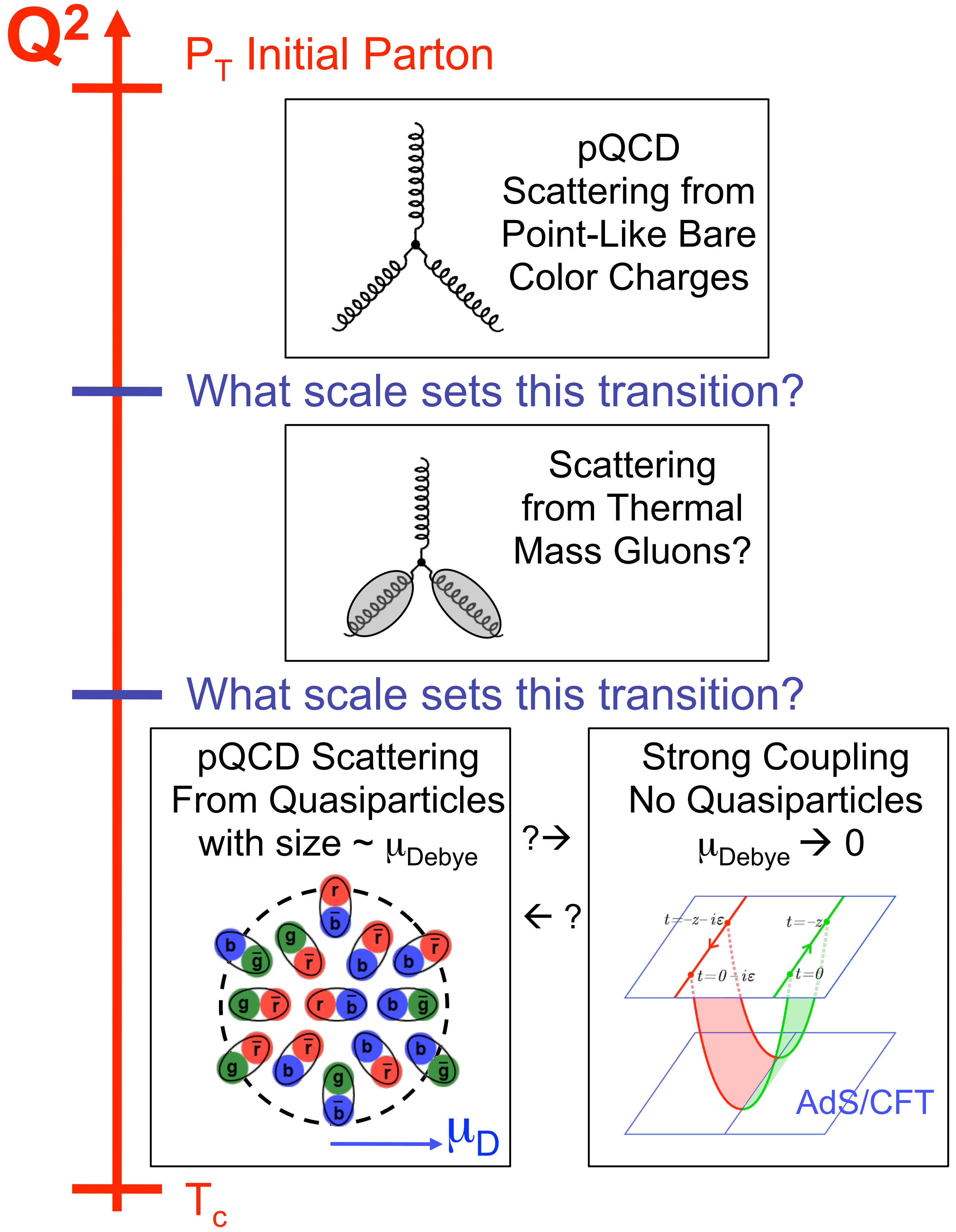




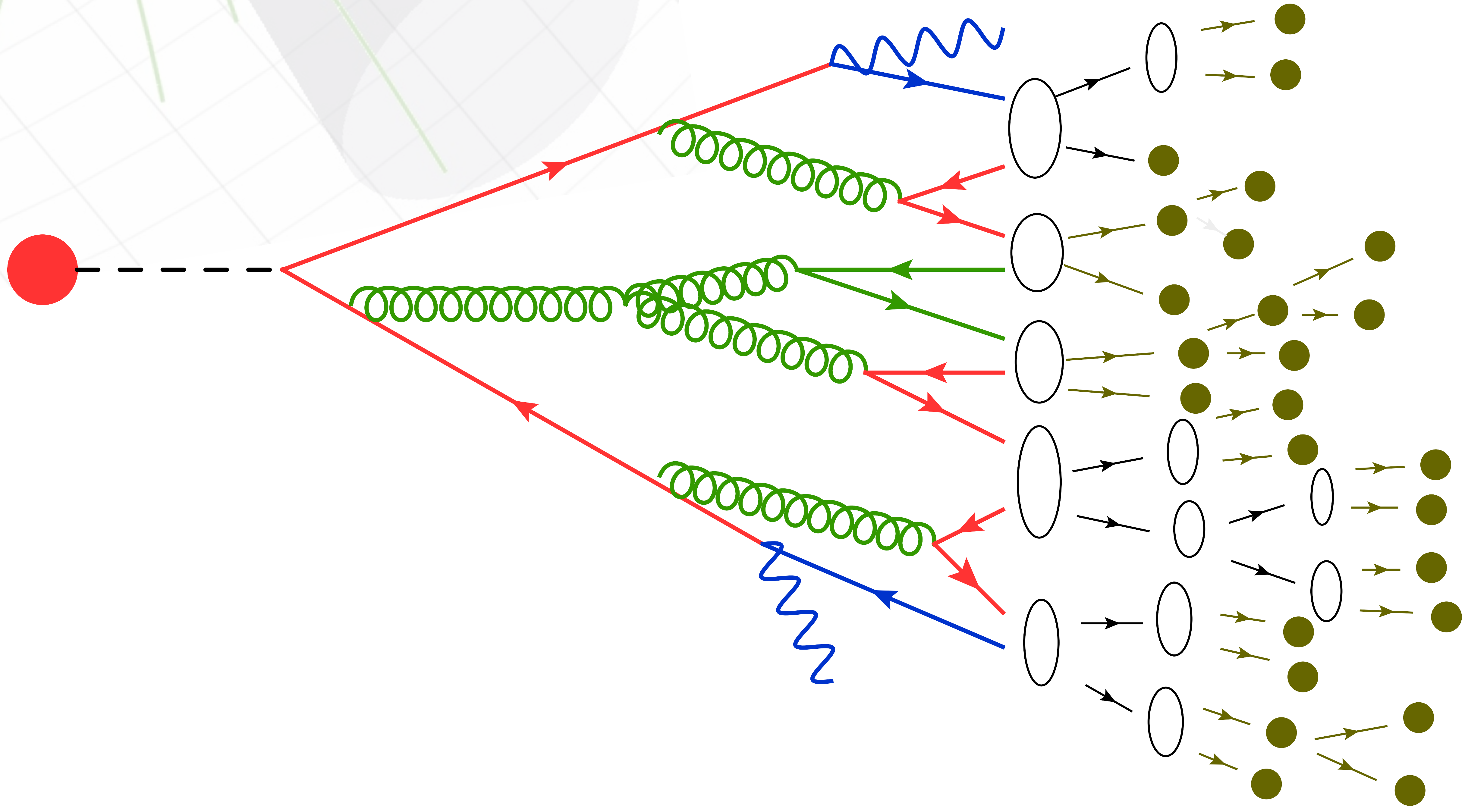
Welcome to the field of jet quenching!

But before we start…

Revisiting our baseline: pp

From parton to jets in pp

- "Vacuum" parton shower:



- ➡ A jet is a subsequent process of single parton emissions
  - ➡ Avoid non perturbative effects (e.g: hadronization)

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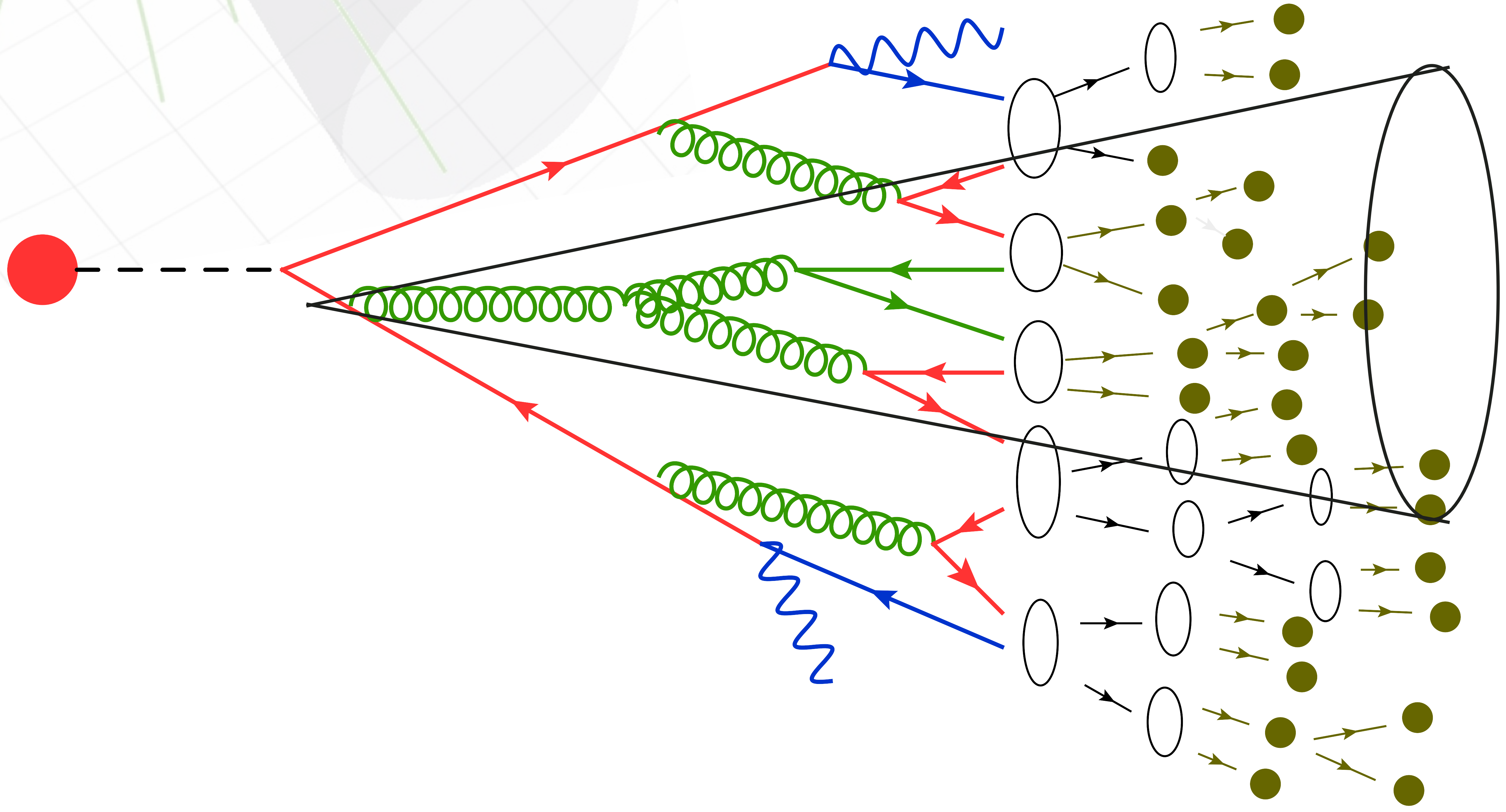

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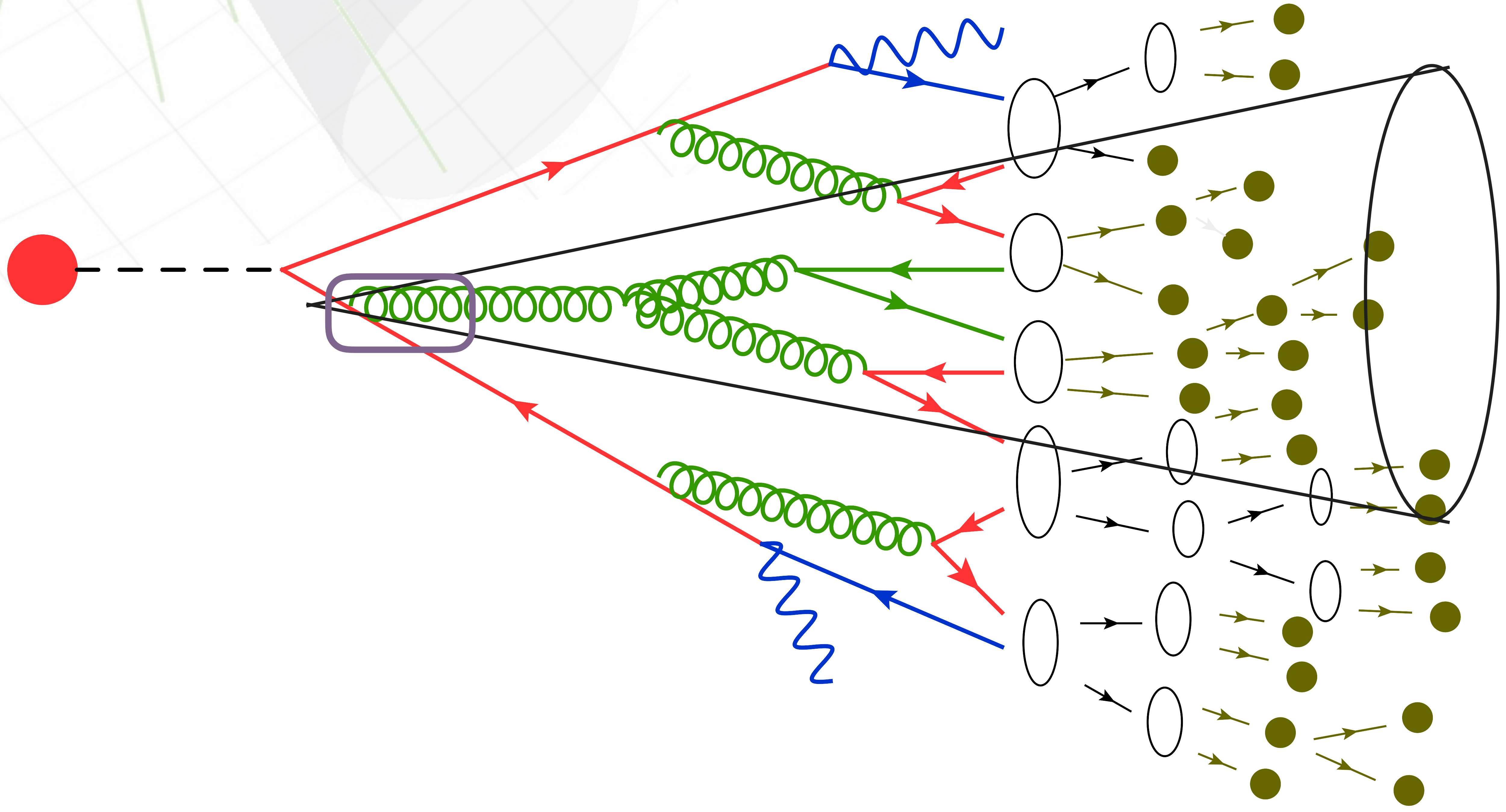

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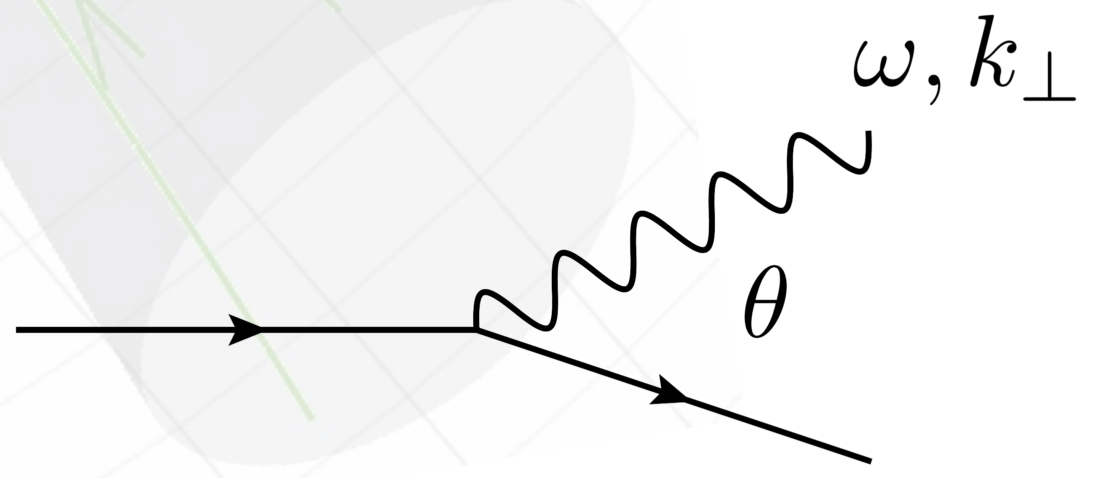
Revisiting building blocks!

Single parton emission

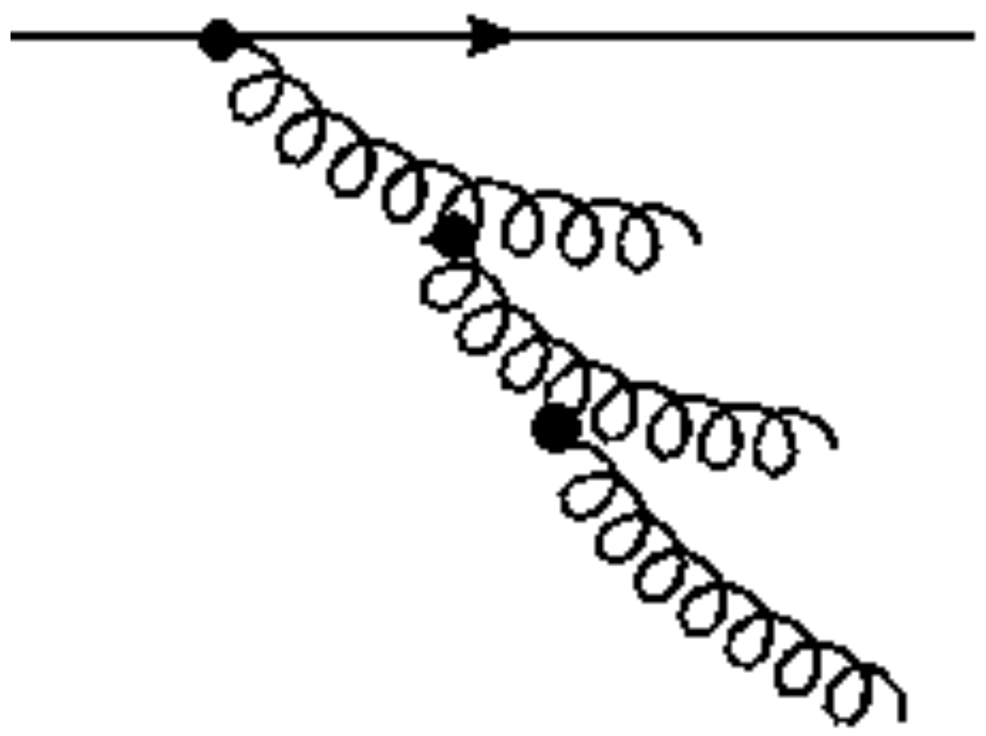
- Gluon bremsstrahlung from an off-shell (virtual) quark:



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

➡ Soft and collinear divergent

➡ Needs re-summation: evolution equations (DGLAP, MLLA,…)



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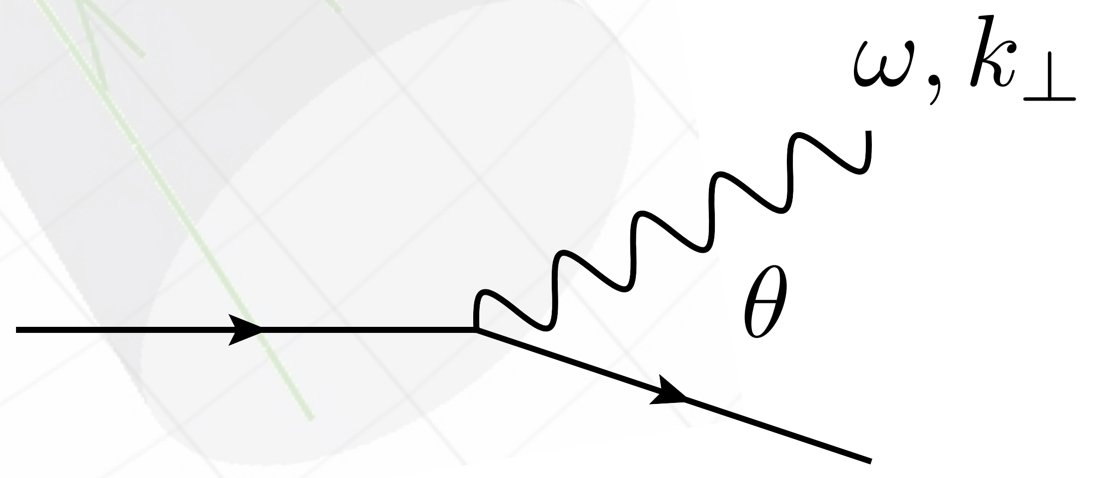

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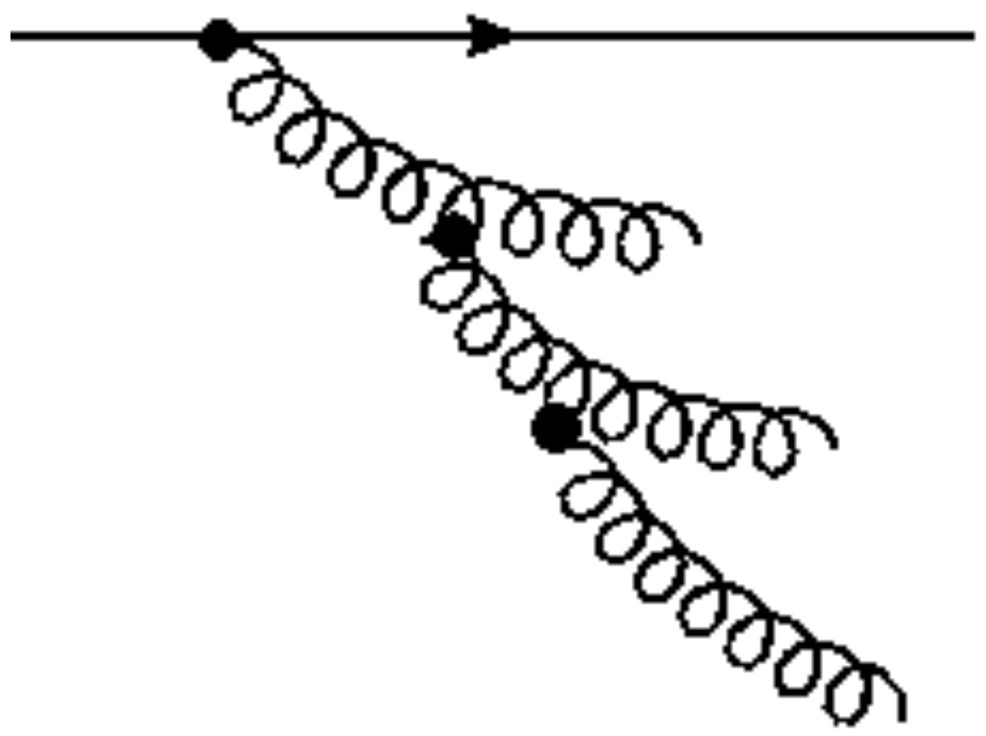
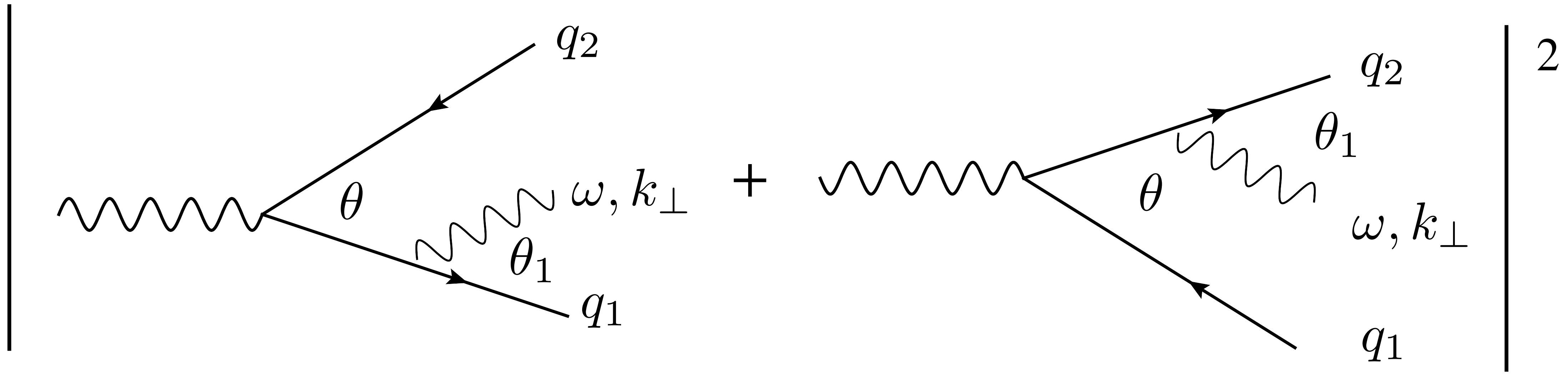


…

Are they all independent?

Jet Coherence

- Soft gluon radiation from a quark - anti-quark pair:
  - color singlet configuration:



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11

Jet Coherence

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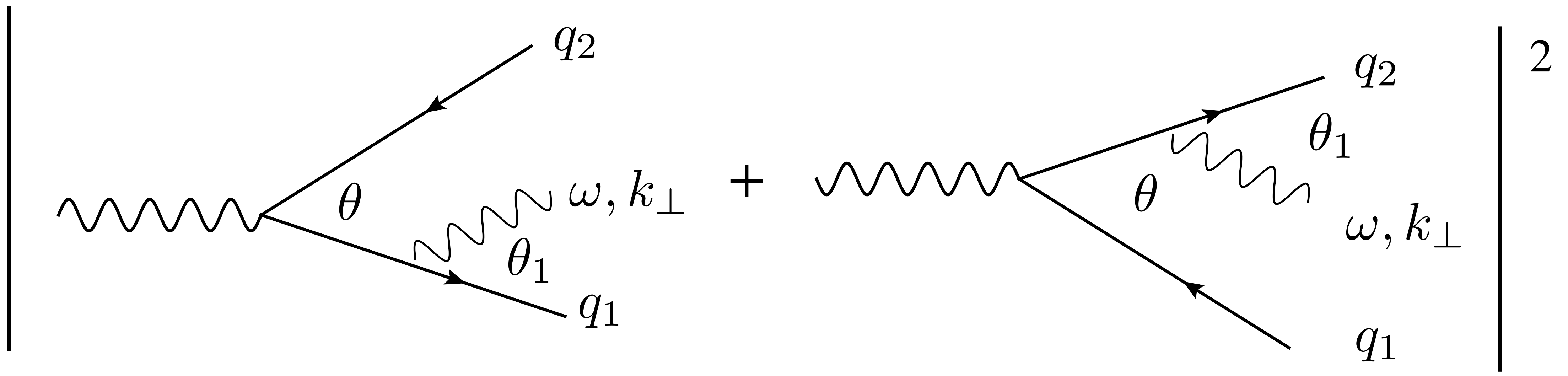

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Integrating in azimuthal angle…

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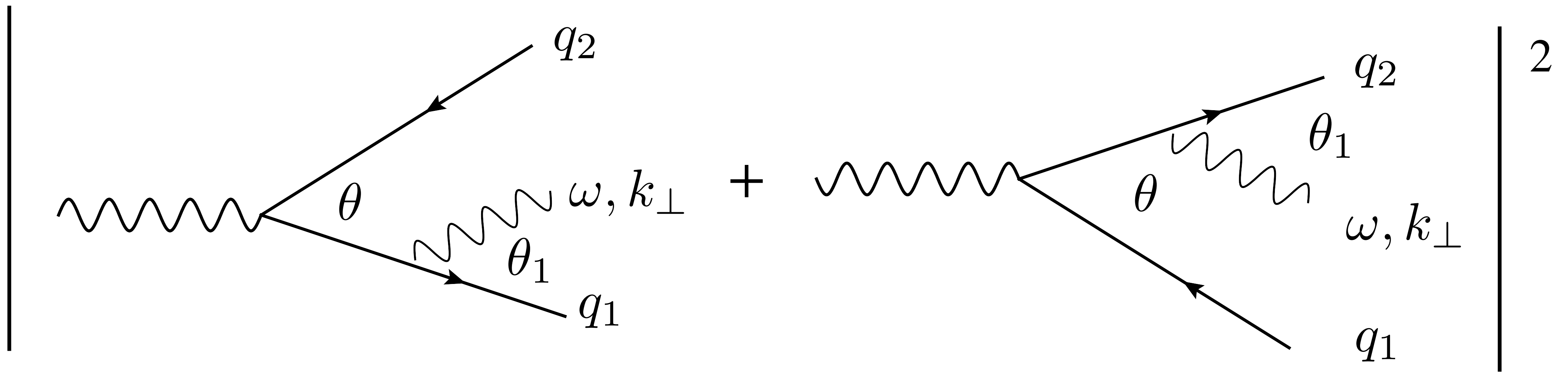

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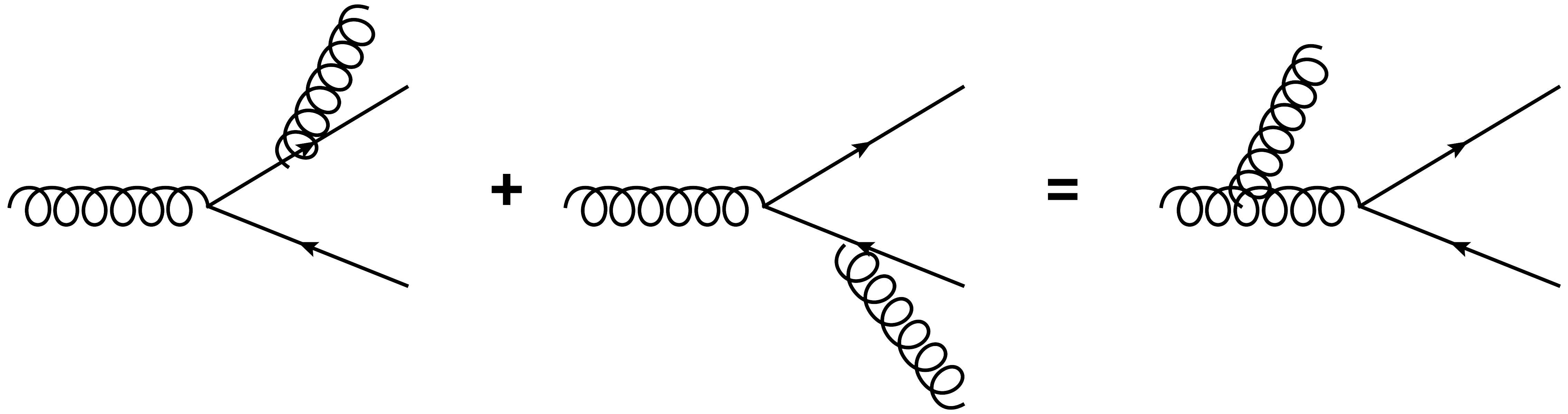

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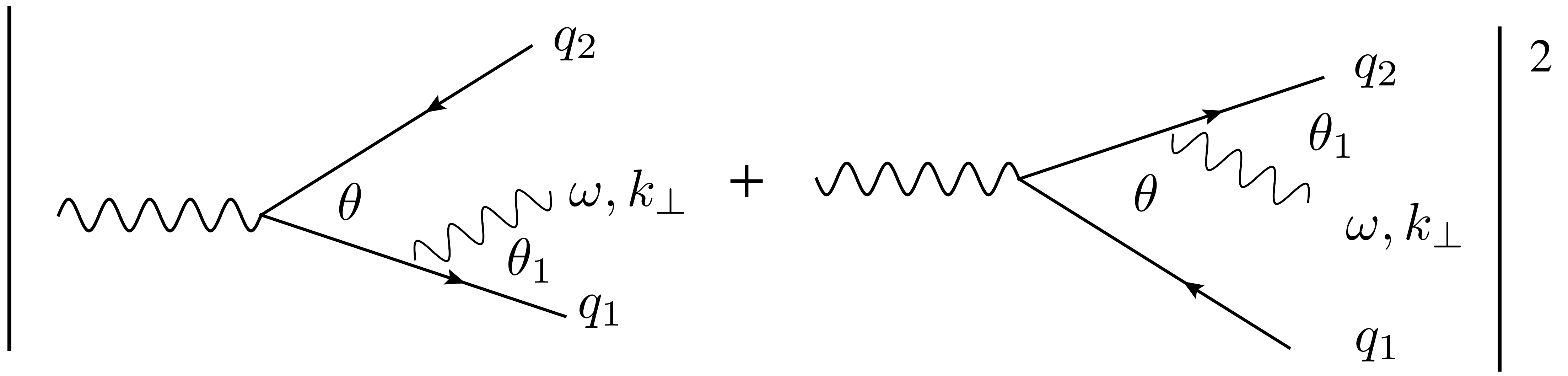

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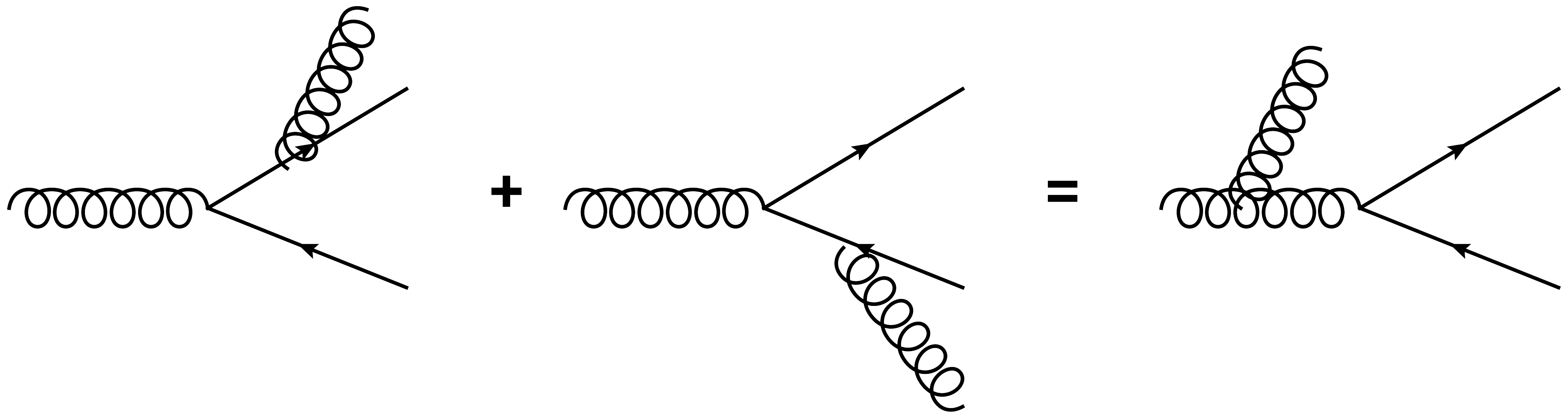

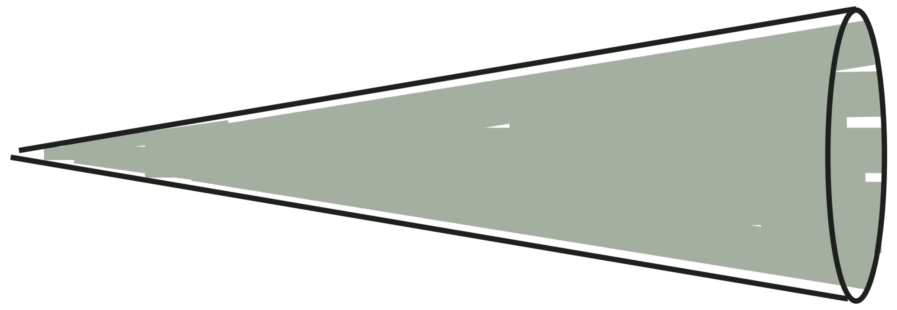

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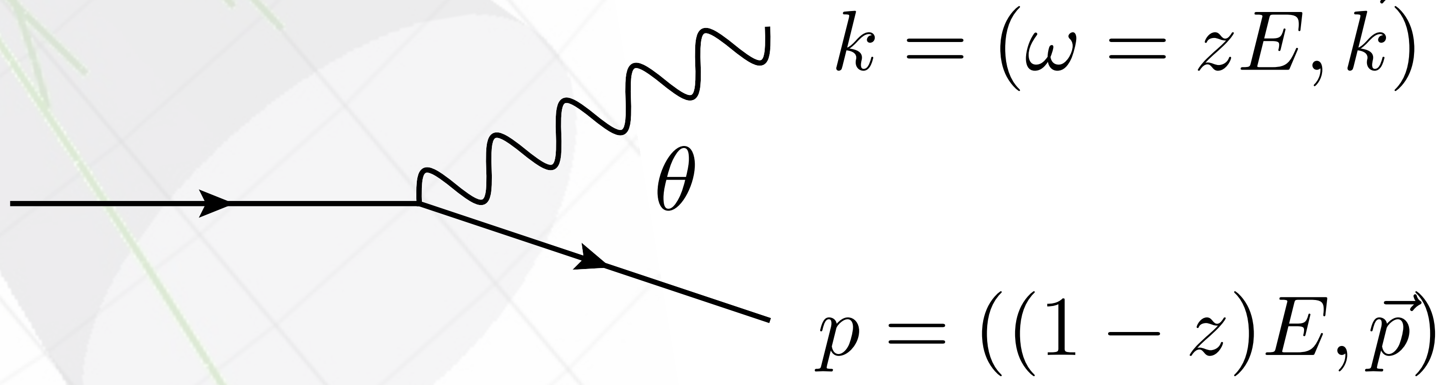
Vacuum formation time

See: Basics of Perturbative QCD, 1991

- Formation time of an emission:



Uncertainty principle: $\Delta E \Delta t = 1$

$$\Delta E = m_{virtual}$$

$$\tau_{form} = \Delta t \gamma_{boost} = \Delta t \frac{\Delta E}{m_{virtual}}$$

$$\Rightarrow \tau_{form} = \frac{1}{m_{virtual}} \frac{E}{m_{virtual}}$$

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where: $k_\perp \sim \omega \sin\theta \sim \omega\theta$, $\lambda_\perp \sim k_\perp^{-1}$

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$k = (\omega = zE, \vec{k})$

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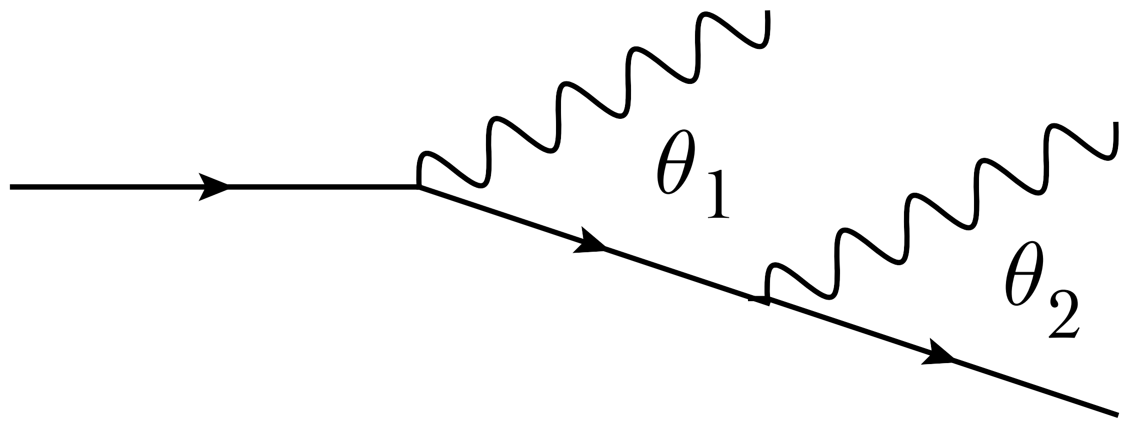

$$\tau_{form,2} = \frac{\lambda_{\perp,2}}{\theta_2}$$

During this time, the previous "antenna" separated:

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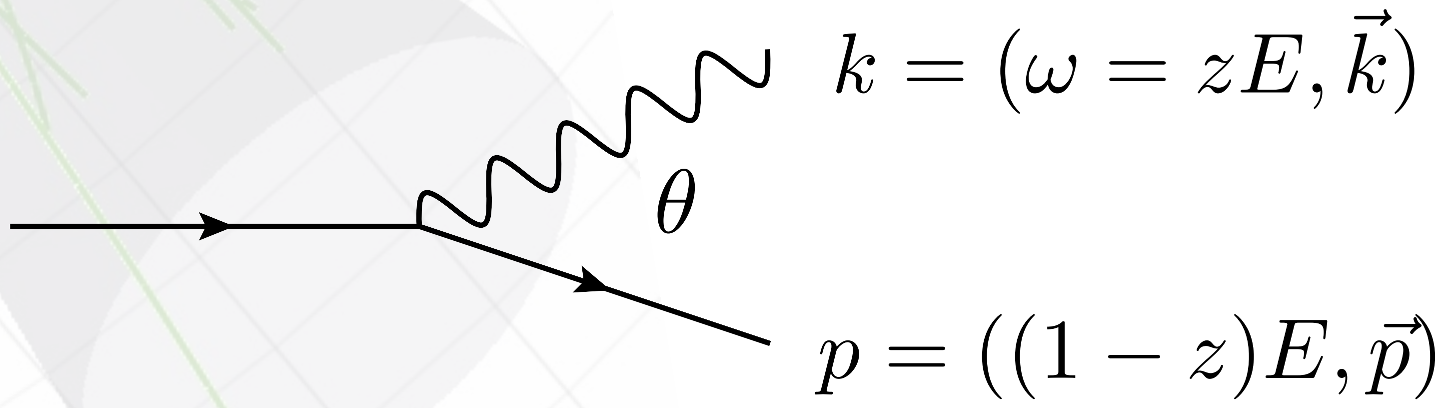

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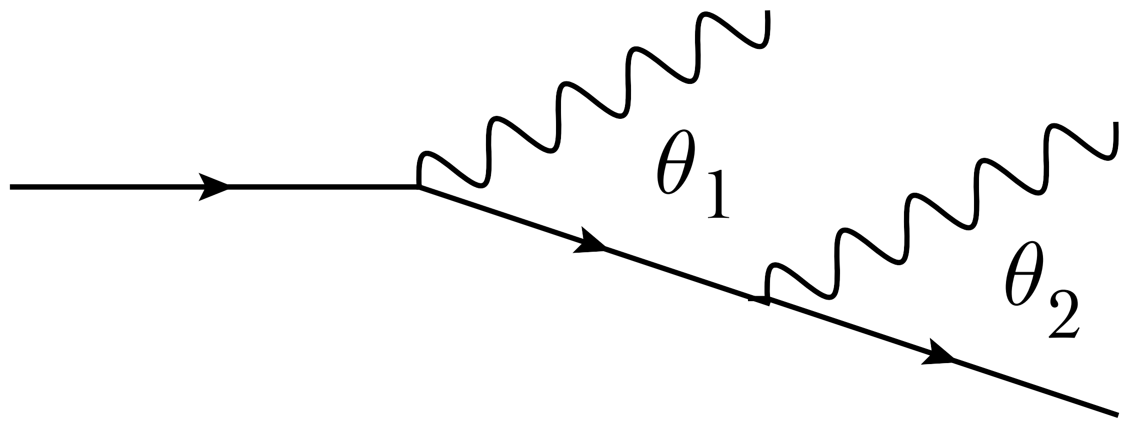

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$\theta_2 > \theta_1 \Rightarrow r_T < \lambda_T$ → Sensitive to the "antenna" charge

$\theta_2 > \theta_1 \Rightarrow r_T > \lambda_T$ → Sensitive to the "leg" charge

Now back to Heavy-Ions

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    - Described by a classical field $A_\mu^a(x)$ (recoil effects are neglected)

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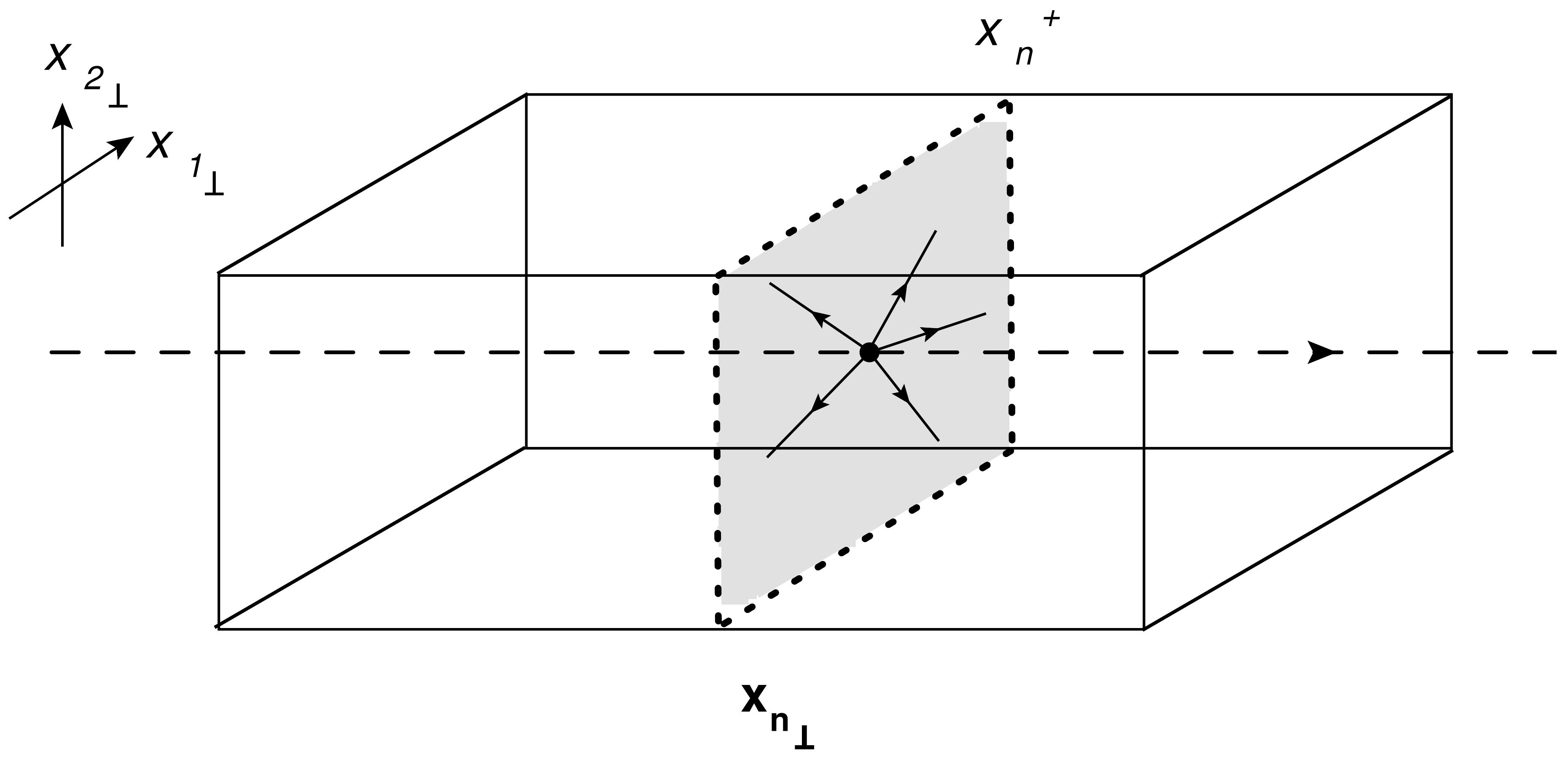
    - Described by a classical field $A_\mu^a(x)$ (recoil effects are neglected)
- High-energy particles propagating through a medium:
  - Particle propagation time < timescale for changes in the medium fields
    - Medium can be considered in a static configuration
    - Only transverse momentum exchange

Light Cone Gauge

- Particle moving in the x_3 direction: Light Cone Gauge $A_+ = 0$
- Light Cone Coordinates: $p_+ \gg \mathbf{p_T} \gg p_-$
  - $x_\pm = \frac{x_0 \pm x_3}{\sqrt{2}}$ and $x_\perp = (x_1, x_2)$
- Due to Lorentz contraction one can further assume $A(x_+, x_-, x_\perp) = A(x_+, x_\perp)$



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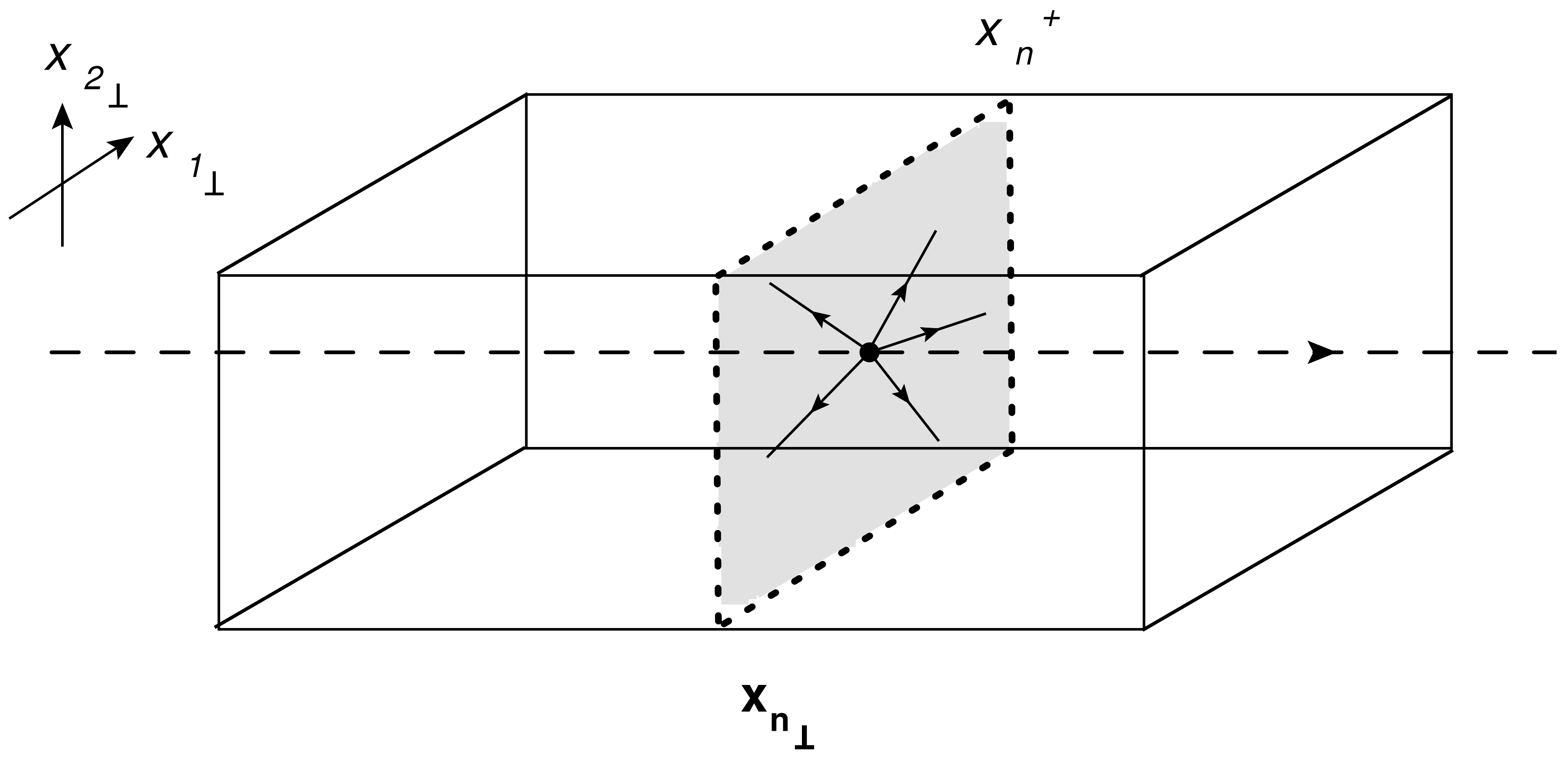
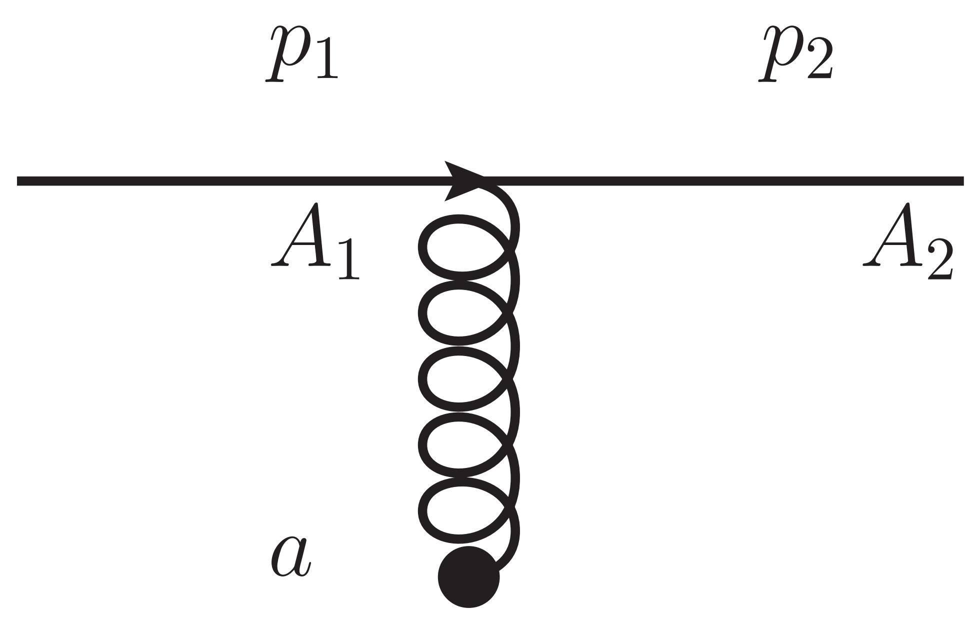


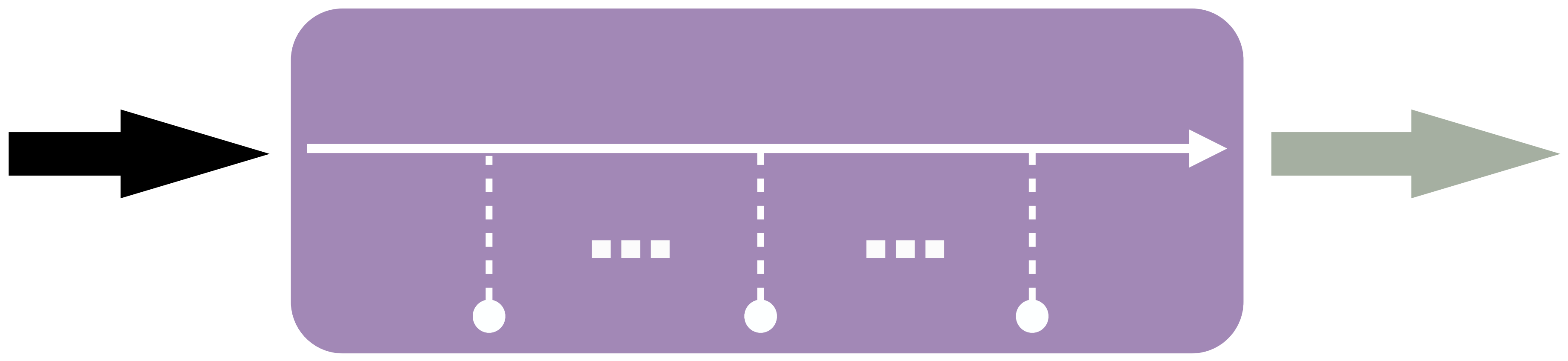
Additional notation:



$$igA^aT^a_{AA_2} = igA_{AA_2}$$

Eikonal Approximation

- Consider a high energetic particle propagating through a collection of static scattering centres:
  - Result will be only a color phase rotation:
    - ➡ In-medium propagator: Wilson Line



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

Path-ordering

Medium colour field

Transverse coordinate

Eikonal Approximation

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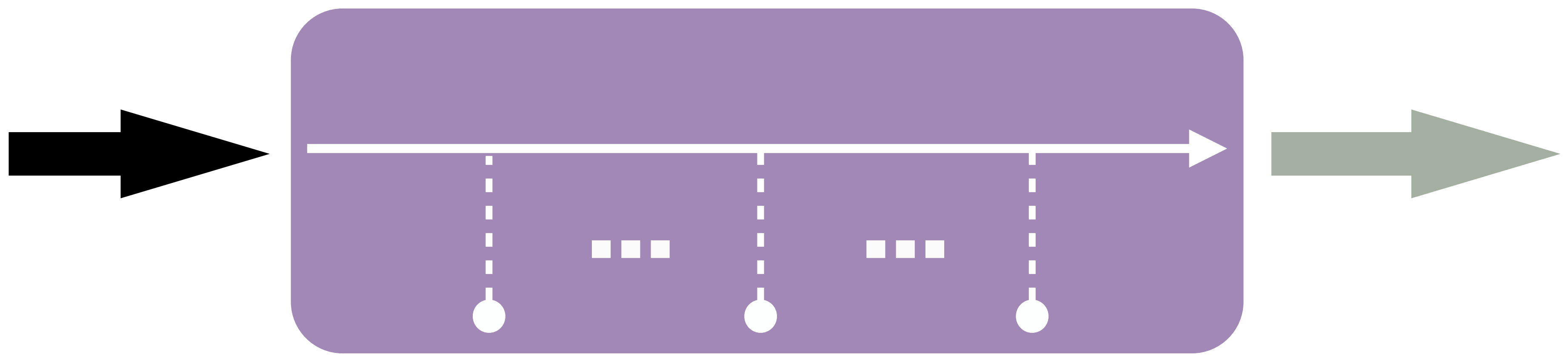

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Let's re-derive this propagator!

Starting by two scatterings…

Eikonal Approximation

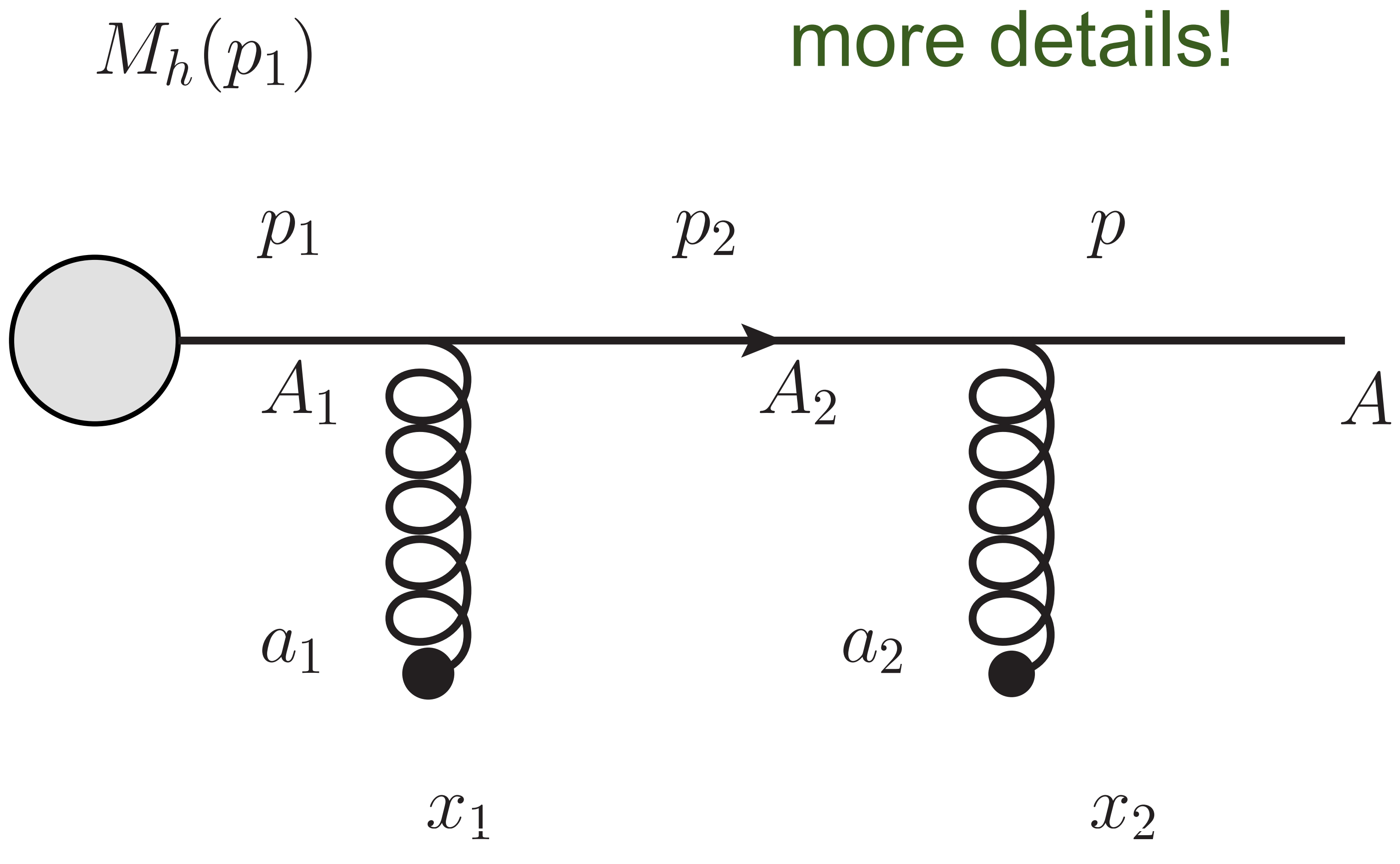
See: arXiv:0712.3443

- Consider a high energetic particle propagating interacting twice with the medium:

See backup slides for more details!

$$S_2 = \int d^4x_1 d^4x_2 \frac{d^4p_1}{(2\pi)^4}\frac{d^4p_2}{(2\pi)^4}\bar{u}(p)e^{ix_2(p-p_2)+ix_1(p_2-p_2)}$$

$$\not{A}_{AA_2}(x_{2+},x_{2\perp})\frac{i\not{p}_2}{p_2^2+i\varepsilon}ig\not{A}_{A_2A_1}(x_{1+},x_{1\perp})\frac{i\not{p}_1}{p_1^2+i\varepsilon}M_h(p_1)$$



Consider only the leading terms:

$$\bar{u}(p)\not{A}_{AA_2}\not{p}_2 = 2p_2\cdot A_{AA_2}\bar{u}(p) - \bar{u}(p)\not{p}_2\not{A}_{AA_2}$$

$$p_i^2 = 2p_{i+}p_{i-} - p_{i\perp}^2$$

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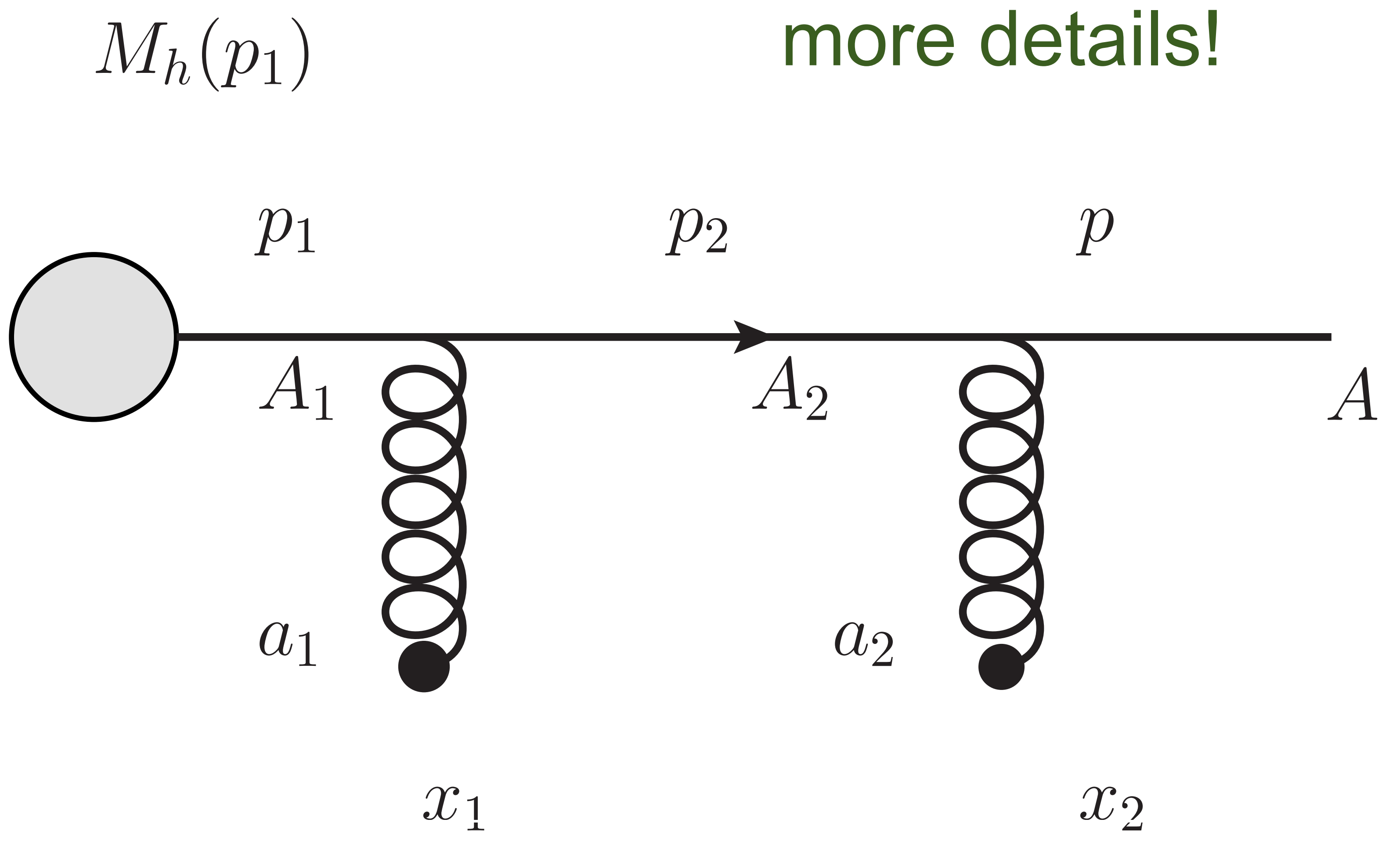

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sub-leading

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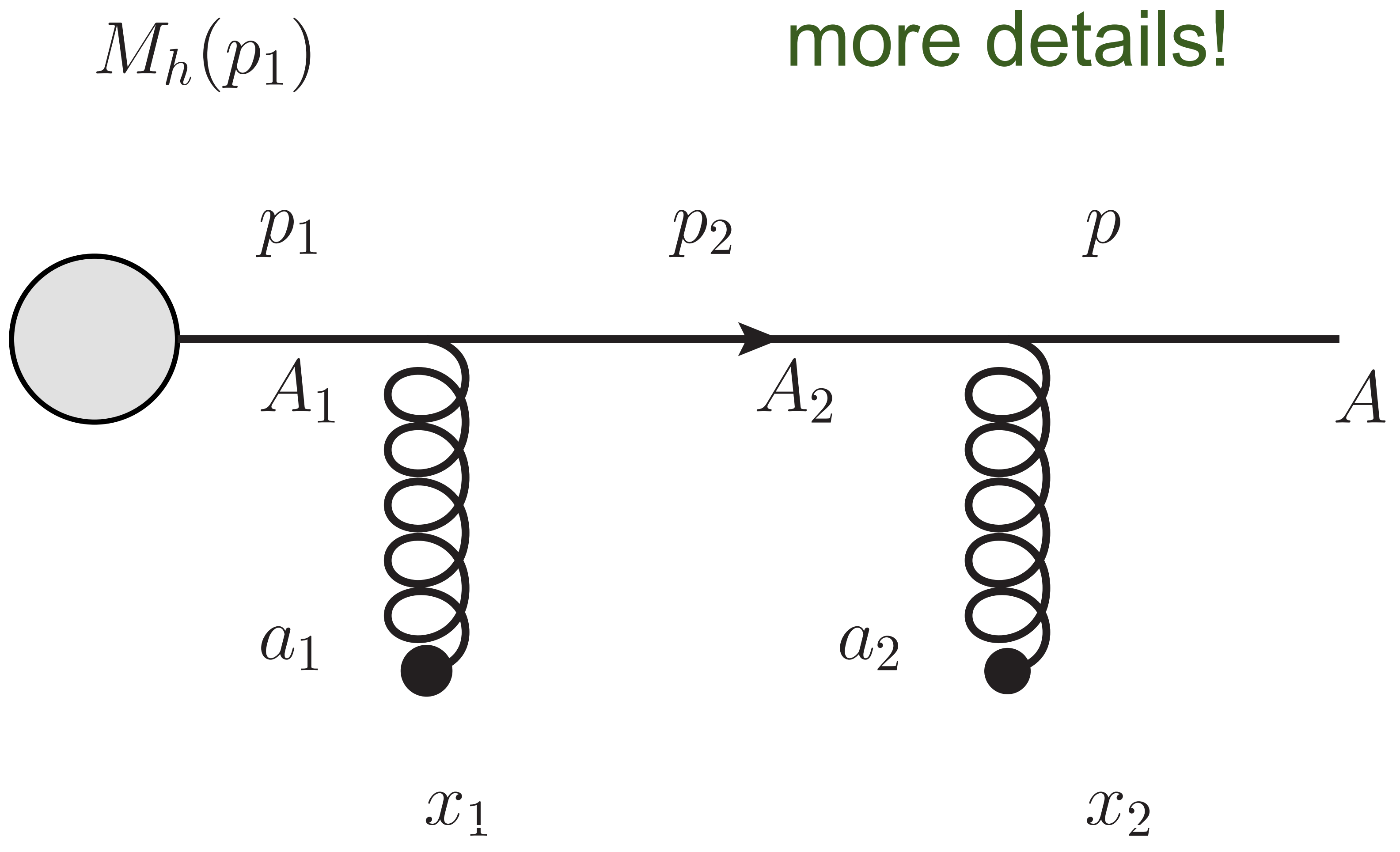

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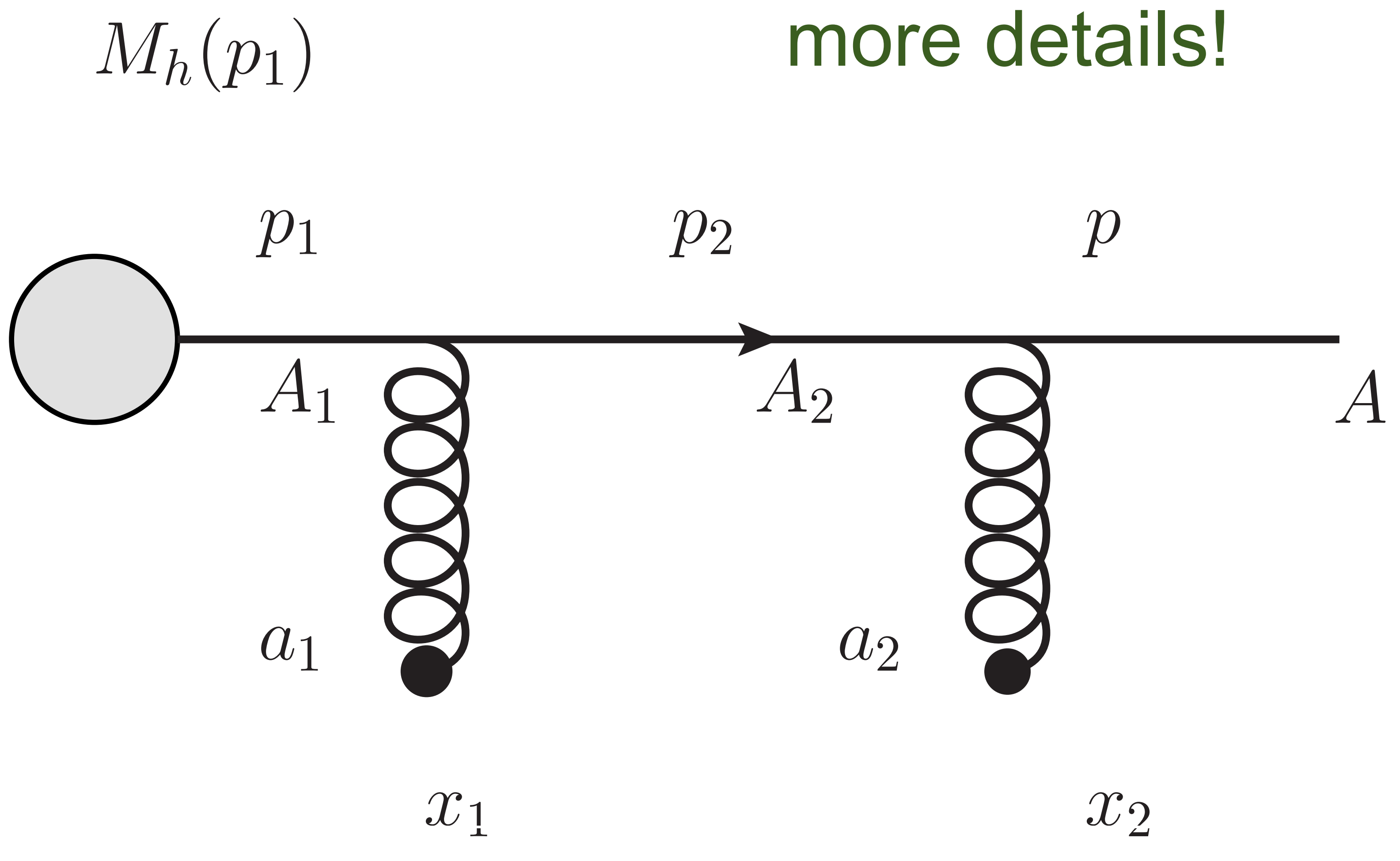

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sub-leading

Residues theorem in p_{i-} coordinates will bring the “ordering” of the fields:

$$\int \frac{dp_{2-}}{2\pi}e^{ip_{2-}(x_1-x_2)_+}\frac{i}{p_{2-}-(-i\varepsilon)} = \theta(x_2-x_1)_+$$

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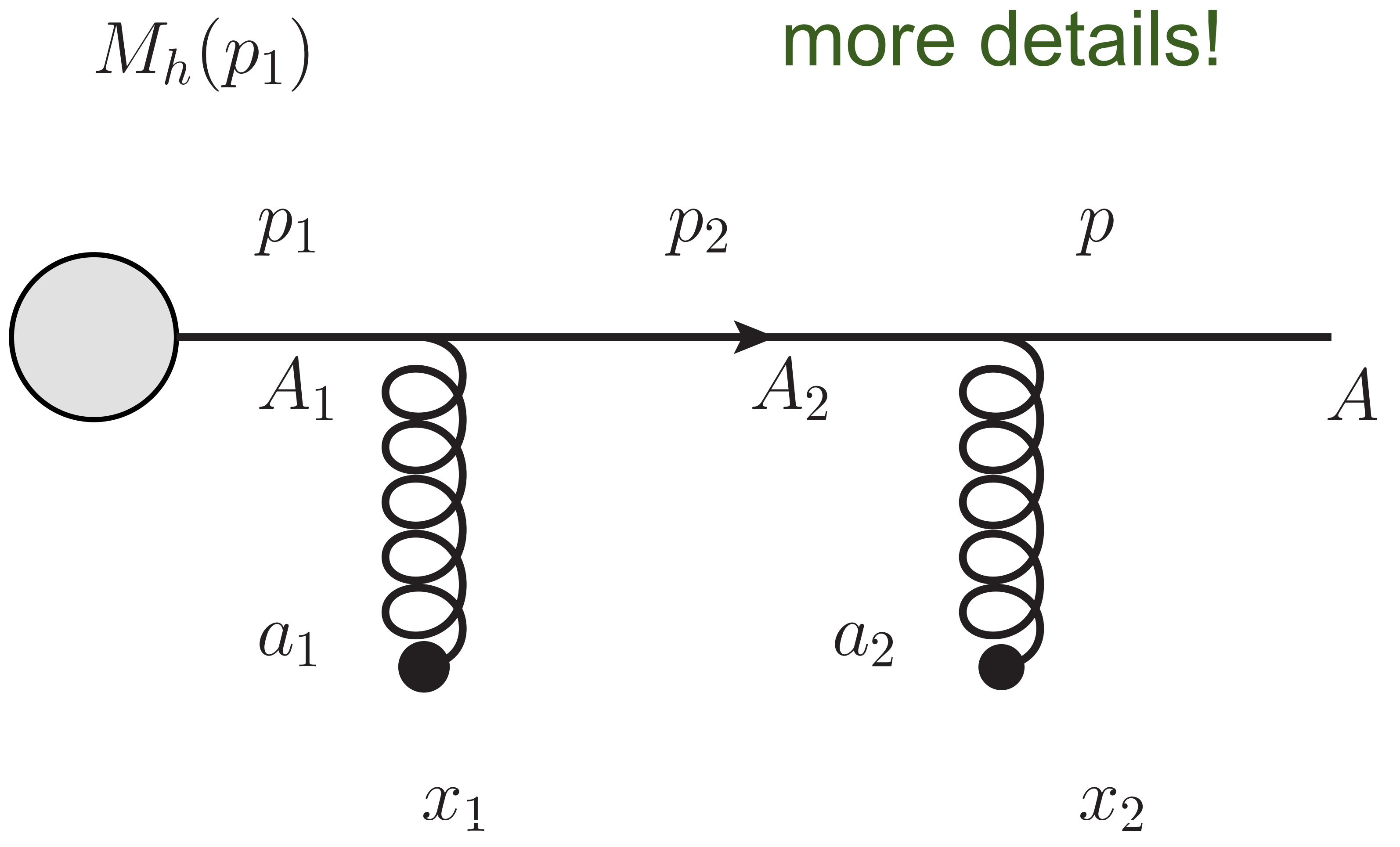

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Integrals on p_{it} will just set:

$$\Rightarrow x_{1\perp} = x_{2\perp} = 0$$

Eikonal Approximation

See: arXiv:0712.3443

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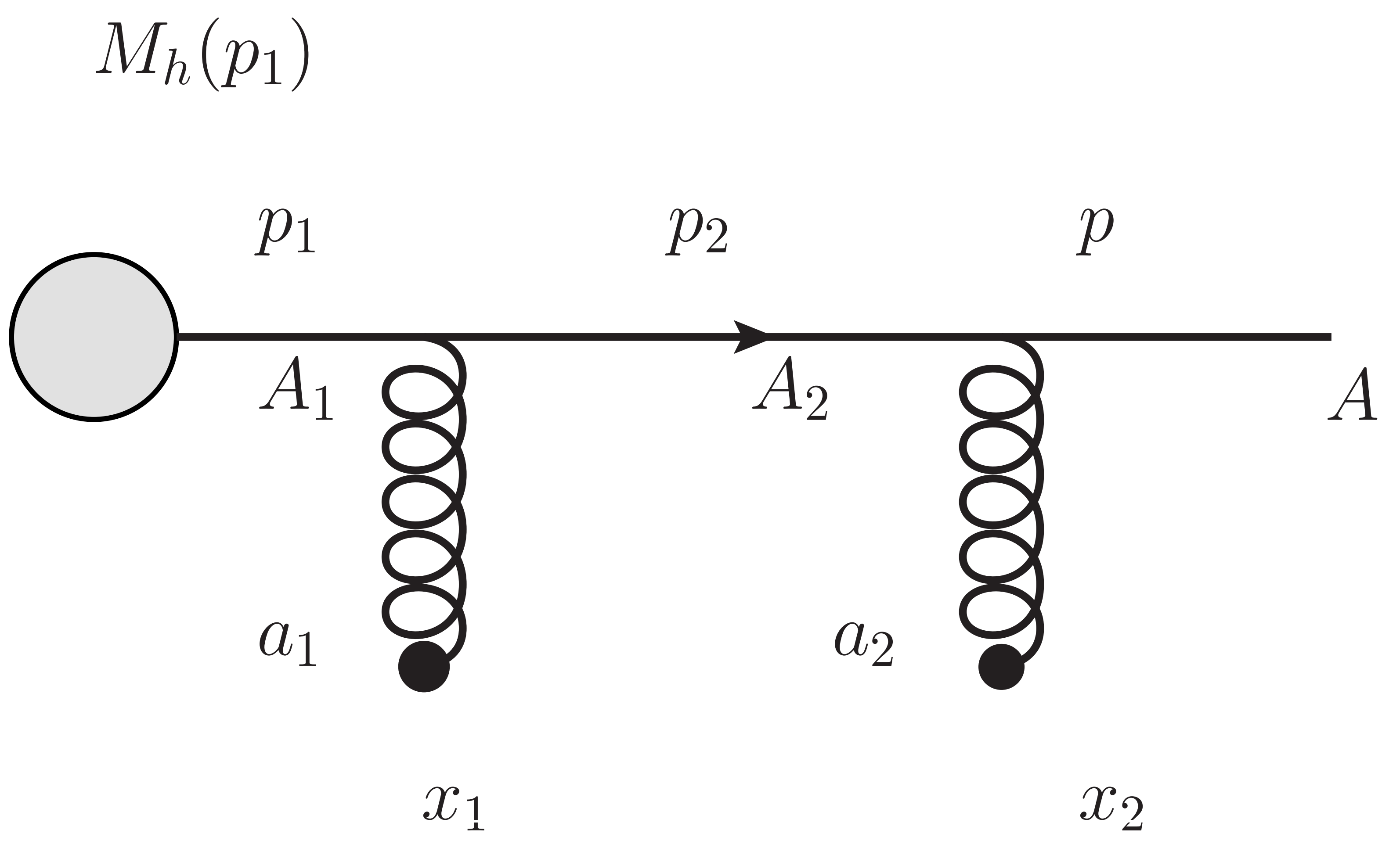

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After some work…

$$\simeq \int dx_{1+}dx_{2+}ig(A_-)_{AA_2}(x_{2+},0_\perp)\theta(x_2-x_1)_+ig(A_-)_{A_2A_1}(x_{1+},0_\perp)\theta(x_1)_+$$

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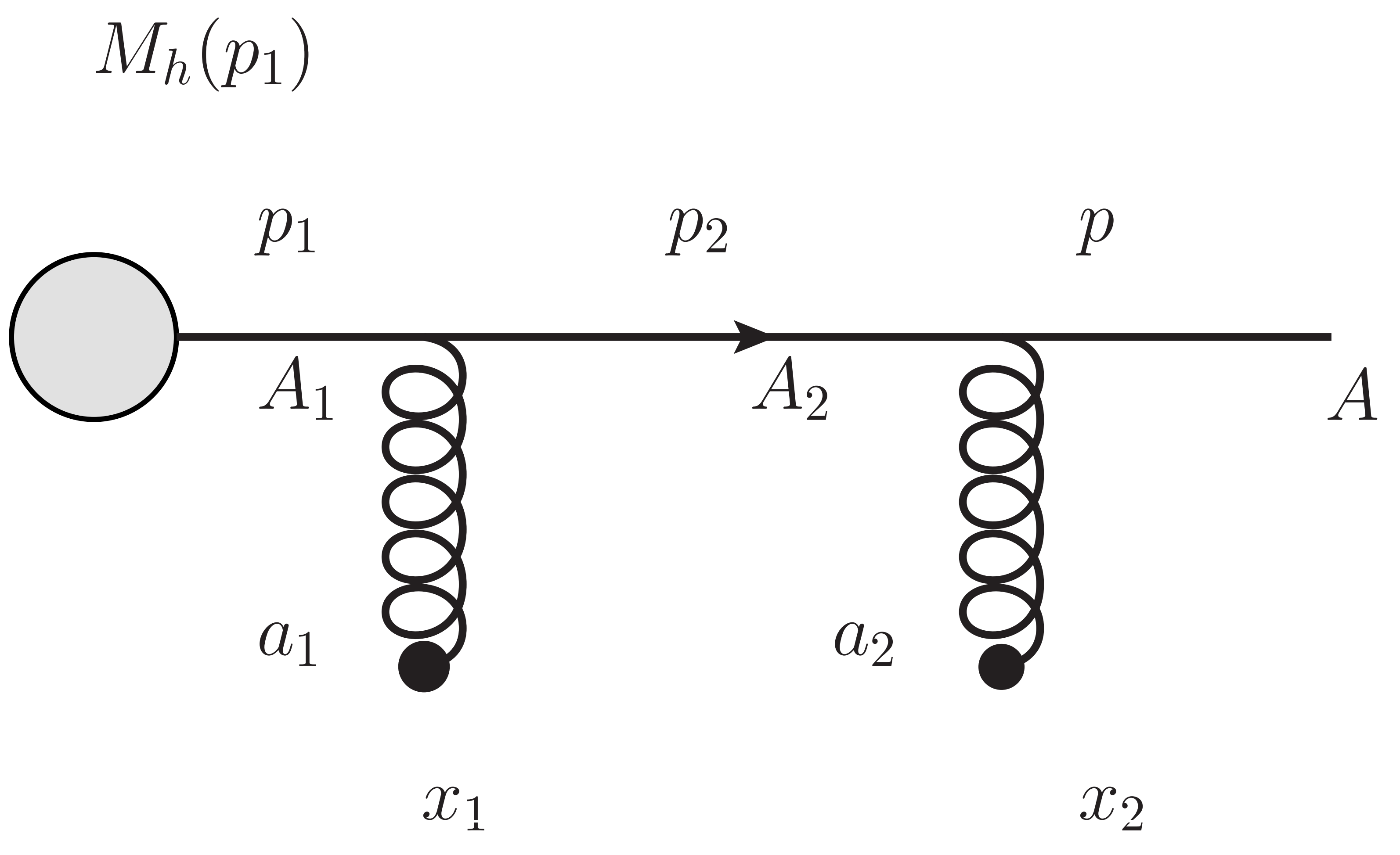

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No interaction term

Eikonal Approximation

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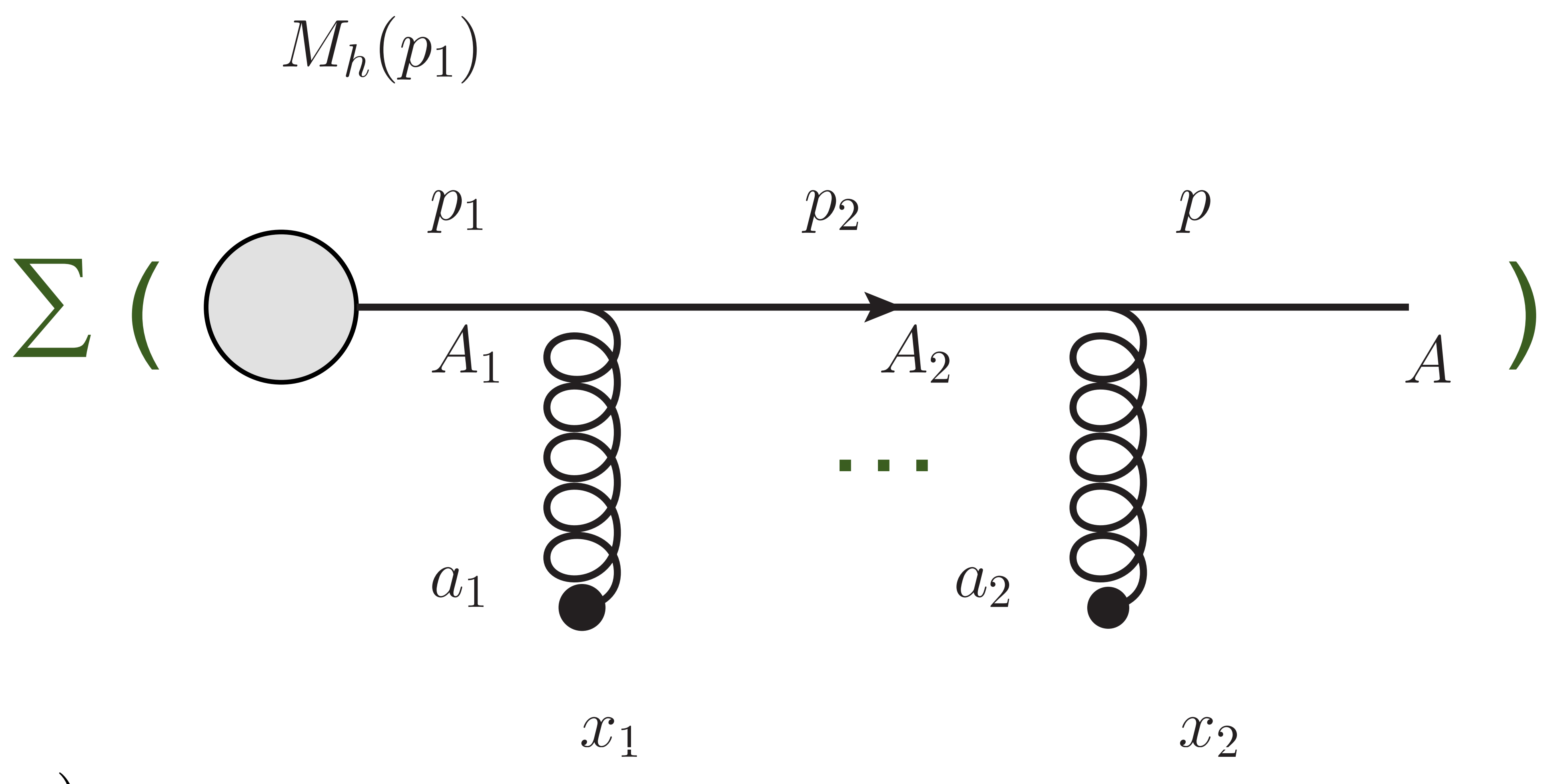

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summing over all 'n' interaction terms

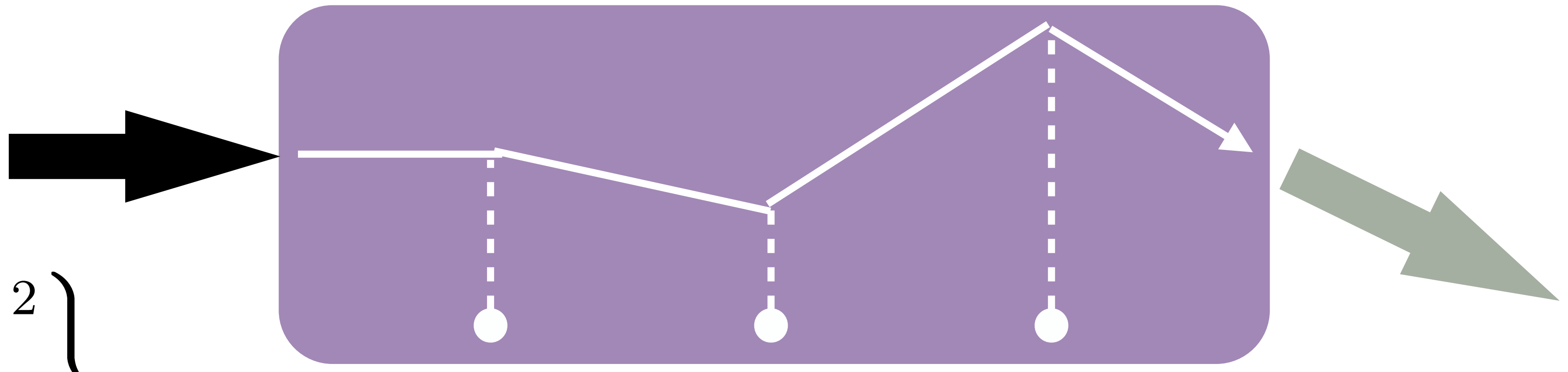
No interaction term

$$\mathcal{P}\exp\left\{ig\int_{x_{1+}}^{x_{n+}}dx_+A_-(x_+,x_\perp=0)\right\} = W(x_{n+},x_{1+};x_\perp=0)$$

Non-eikonal corrections

See: arXiv:0712.3443

- Consider a (not so) high energetic particle propagating through a collection of static scattering centres:
  - Should include a small "kick" in the transverse plane:



$$G(x_{0+}, \mathbf{x_{0}}_\perp; L_+, \mathbf{x}_\perp | p_+) = \int_{\mathbf{r}_\perp(x_{0+})=\mathbf{x_0}_\perp}^{\mathbf{r}_\perp(L_+)=\mathbf{x}_\perp} \mathcal{D}\mathbf{r}_\perp(\xi) \exp\left\{ \frac{ip_+}{2} \int_{x_{0+}}^{L_+} d\xi \left(\frac{d\mathbf{r}_\perp}{d\xi} \right)^2 \right\}$$
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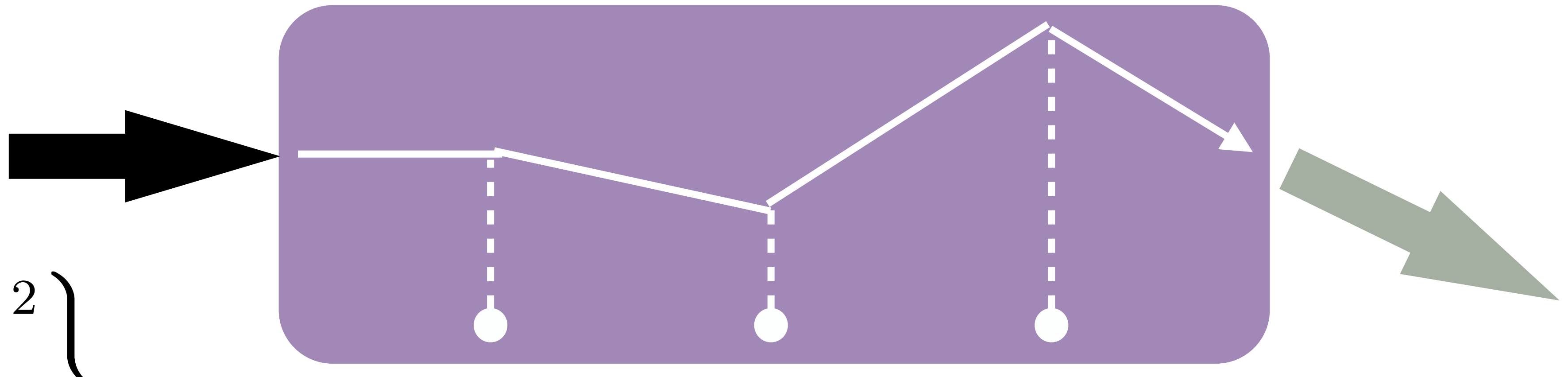

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Initial/Final coordinates

How to get this in-medium propagator?

sub-leading terms in denominator

$$p_i^2 = 2p_{i+}p_{i-} - p_{i\perp}^2$$

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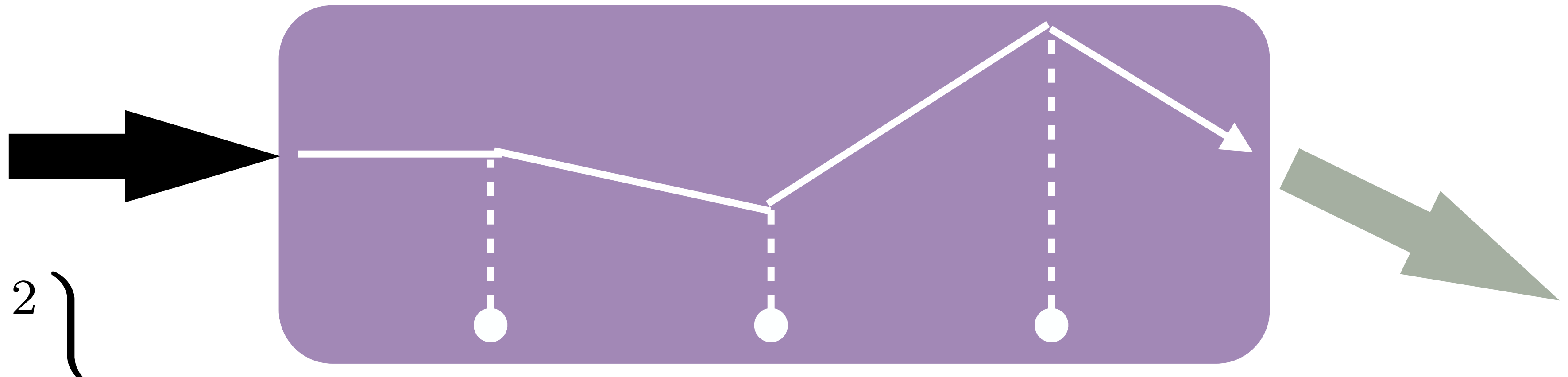

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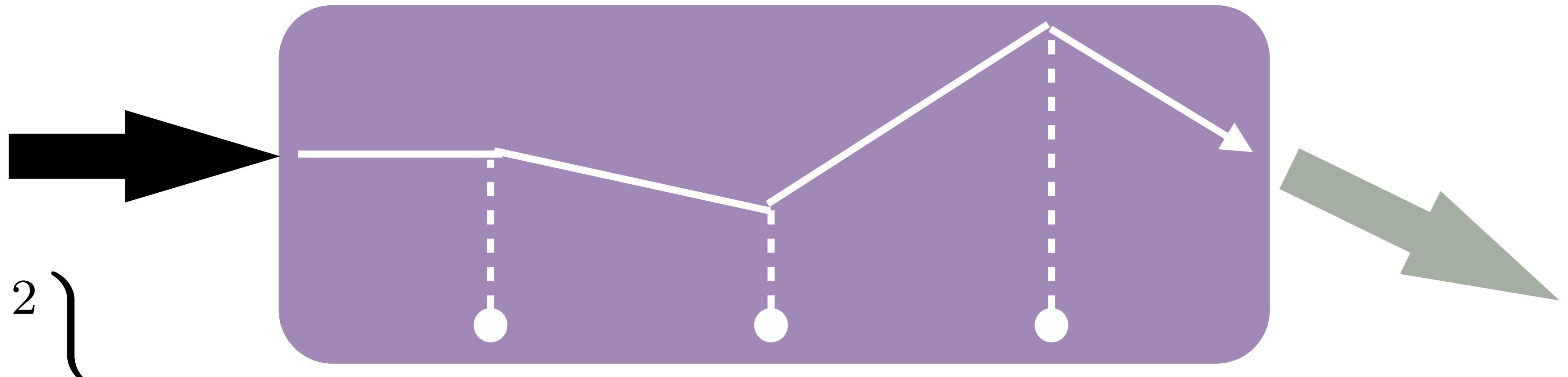

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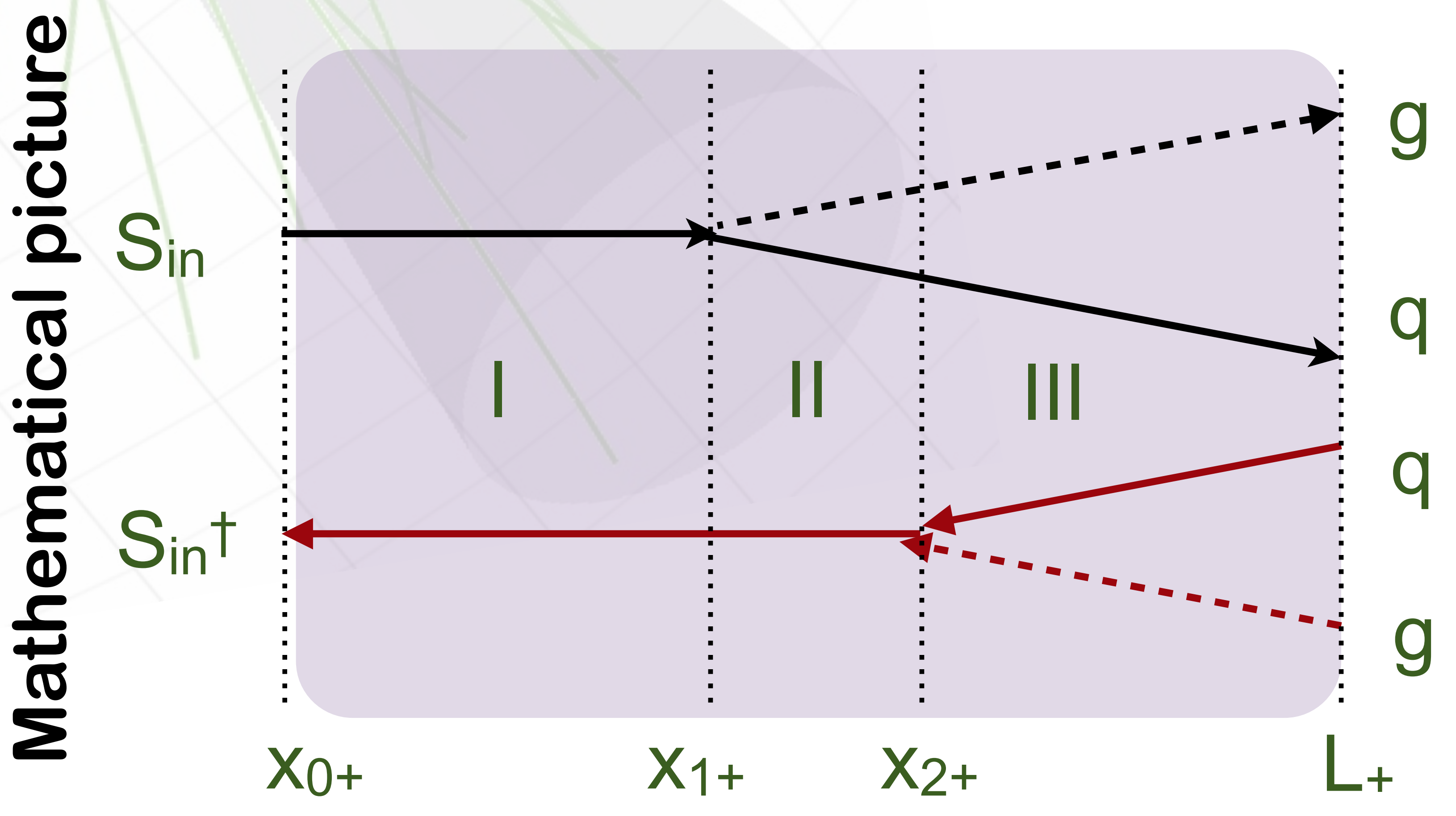
Integral in p_T: $$\int \frac{d^2p_{i\perp}}{(2\pi)^2} e^{i\frac{p_{i\perp}^2}{2p_+}(x_{i-1}-x_i)-ip_{i\perp}(x_{i-1}-x_i)_\perp} = \frac{p_+}{2\pi i(x_{i-1}-x_i)_+}\exp\left\{i\frac{p_+}{2}\frac{(x_{i-1}-x_i)_\perp^2}{(x_{i-1}-x_i)_+}\right\} =$$

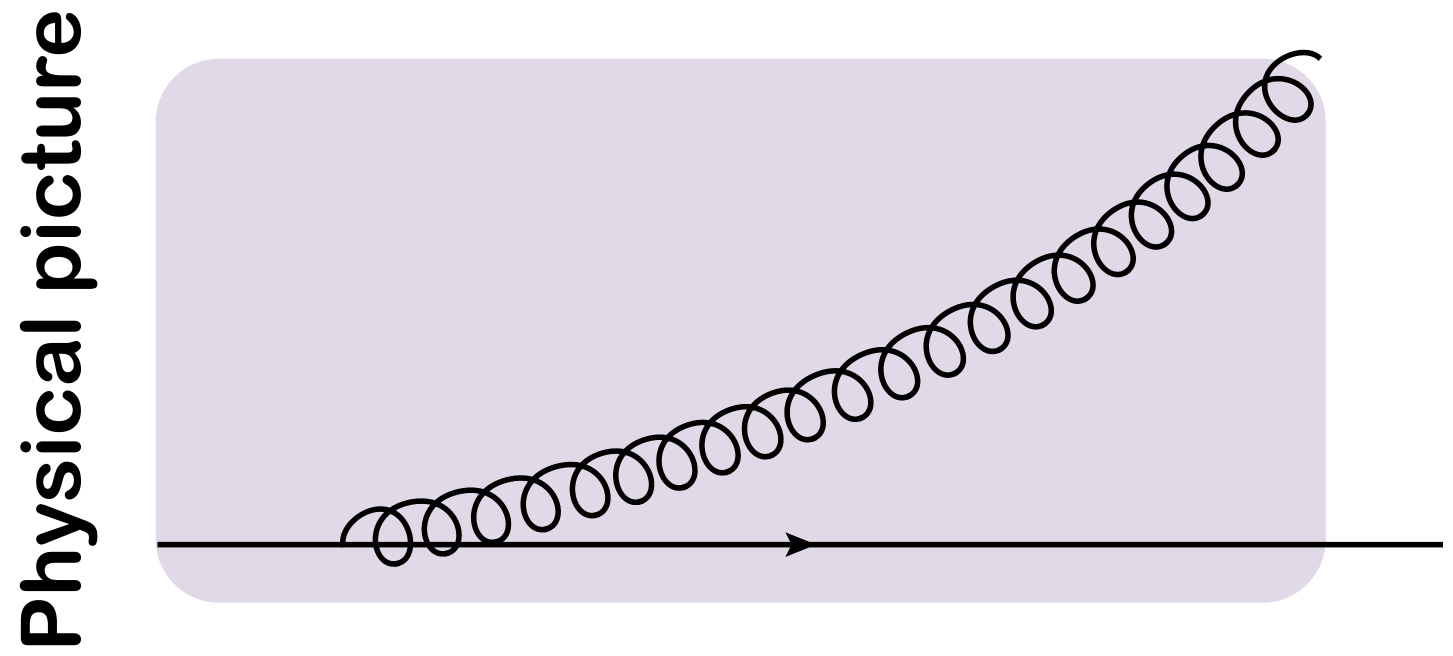
$$\int_{x_{(i-1)\perp}}^{x_{i\perp}} \mathcal{D}(x_\perp)\exp\left\{\frac{ip_+}{2}\int_{x_{(i-1)+}}^{x_{i+}}\left(\frac{dx_\perp}{dx_+}\right)^2\right\} = G_0(x_{i+},x_{i\perp};x_{(i-1)+},x_{(i-1)\perp}|p_+)$$

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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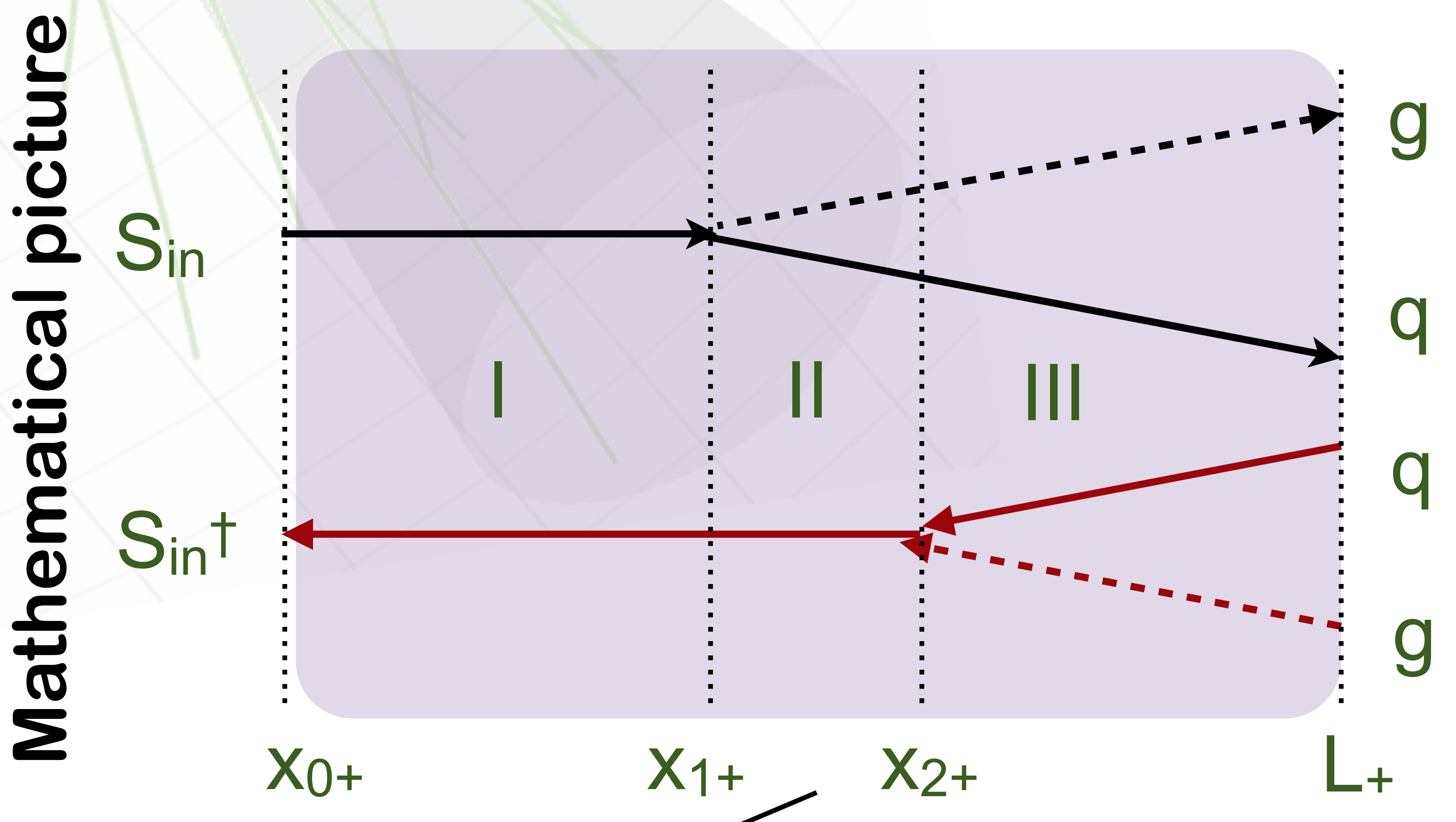

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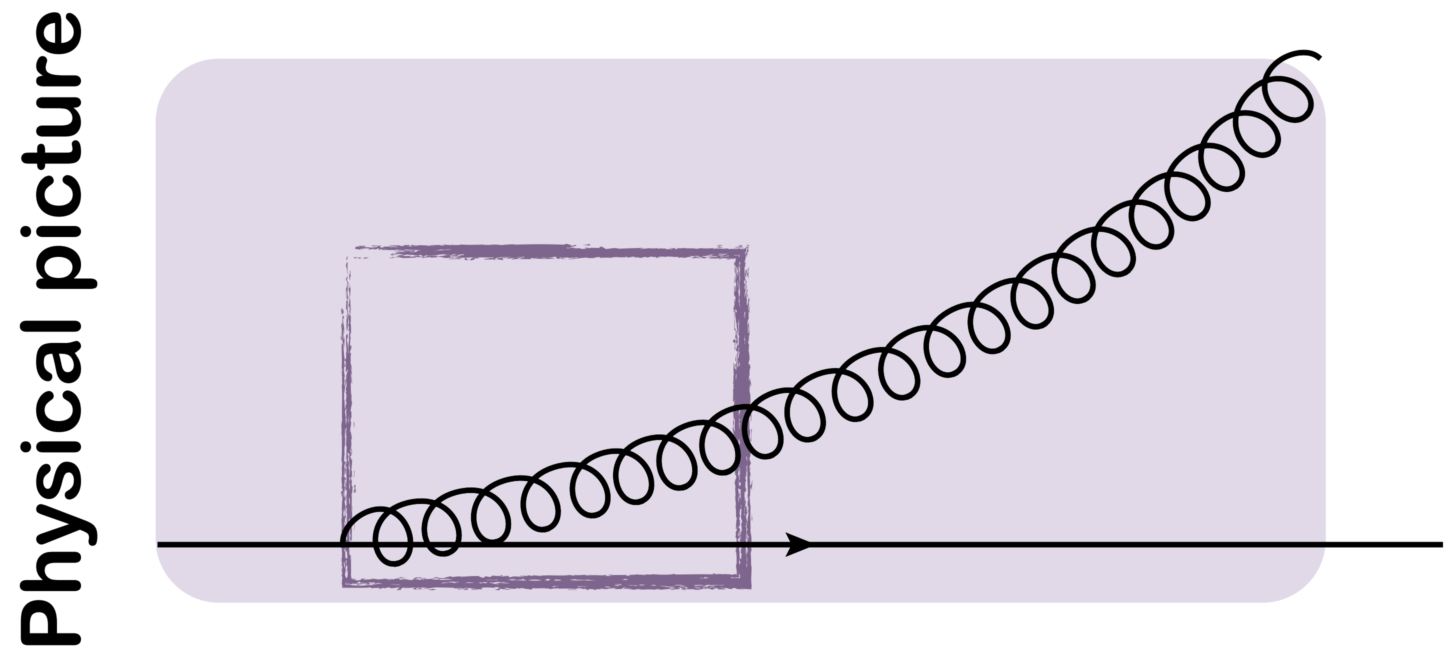

Emission Kernel

$$\boxed{Tr\left\langle W_A(r_g)W_A^\dagger(0)\right\rangle}$$

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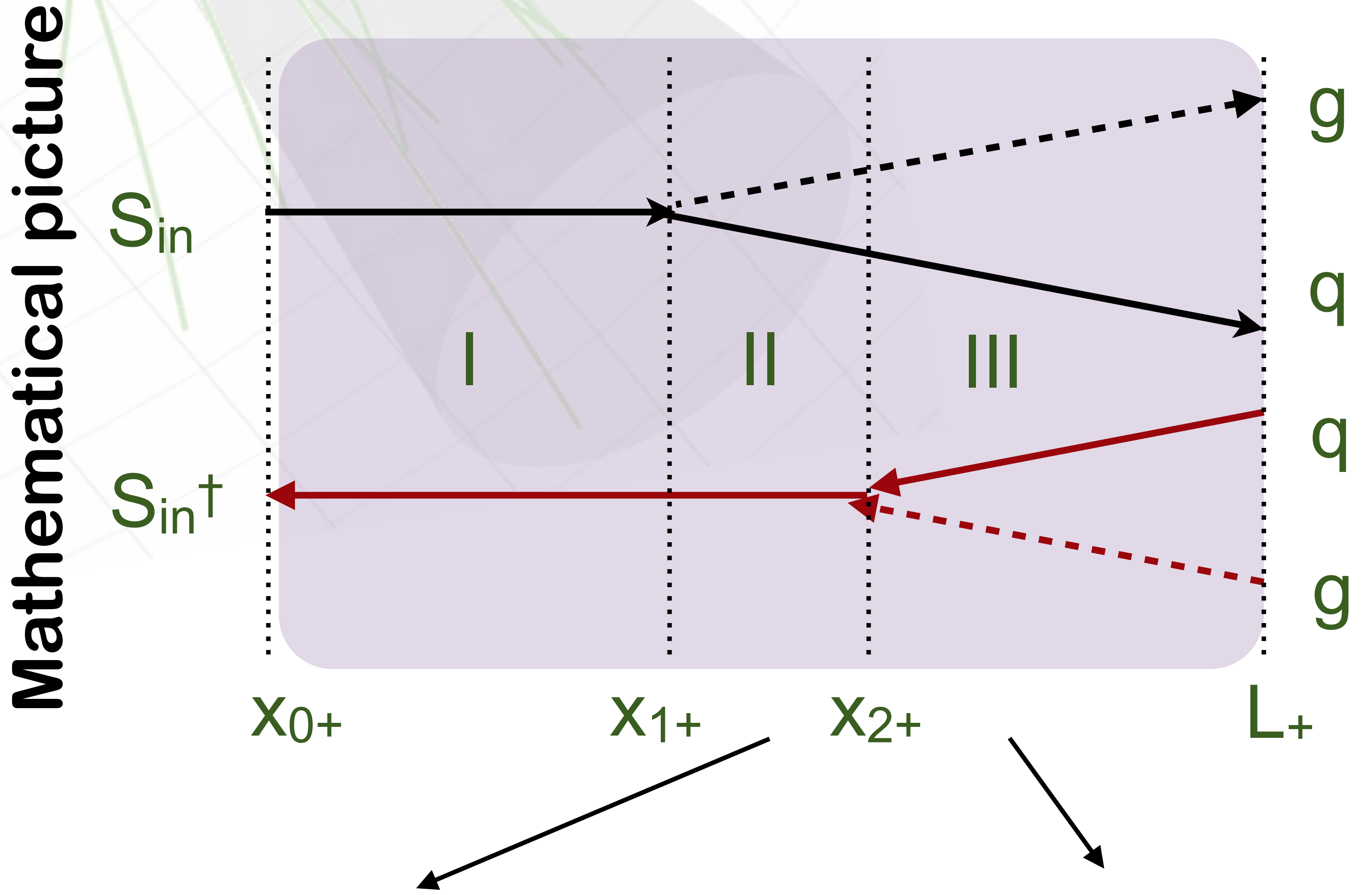

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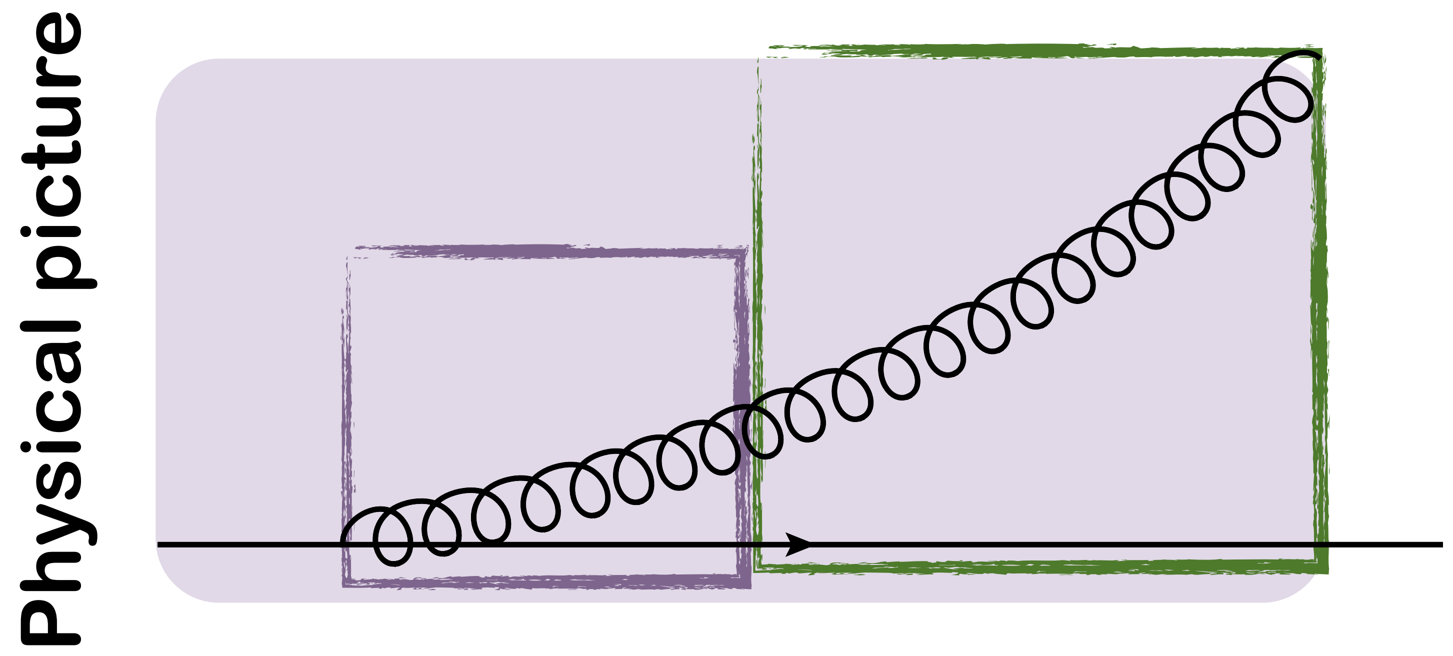

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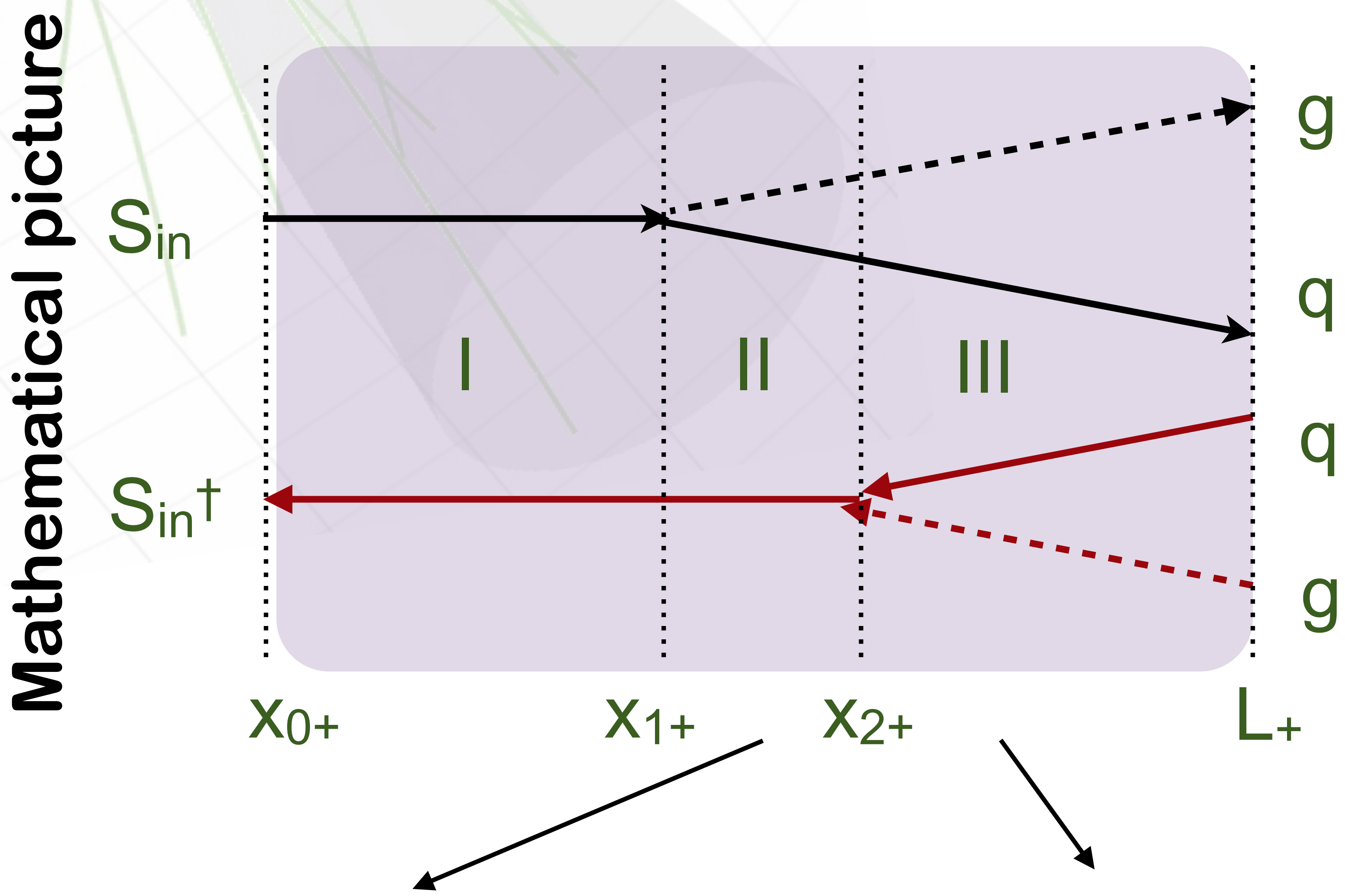

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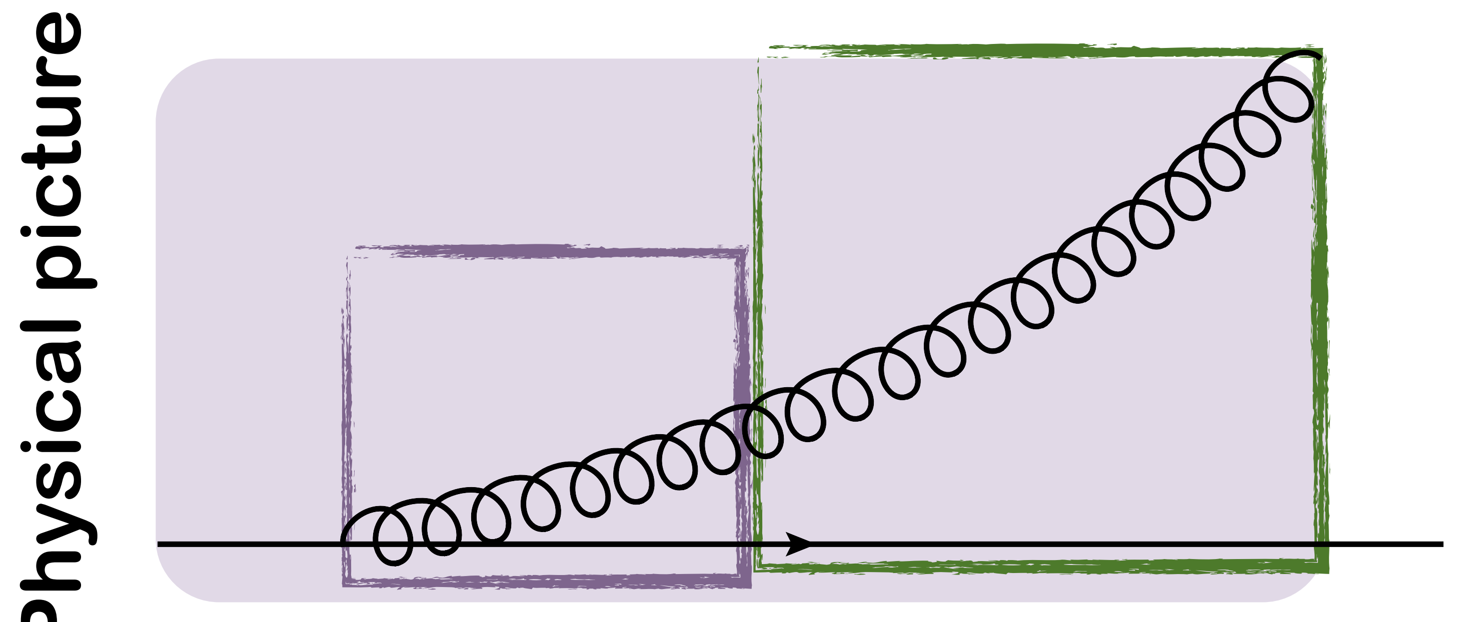

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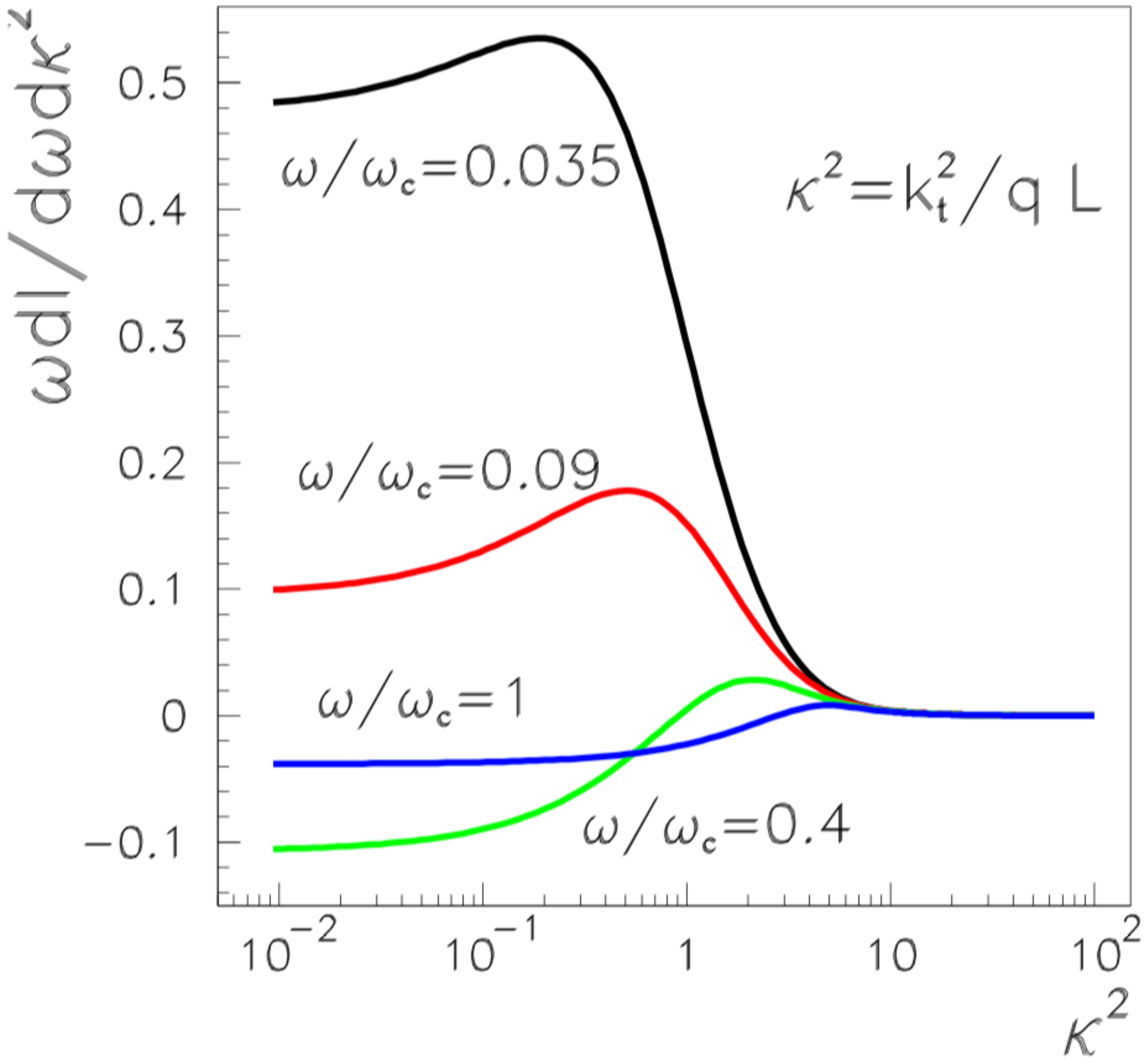
And, finally, some numerics:



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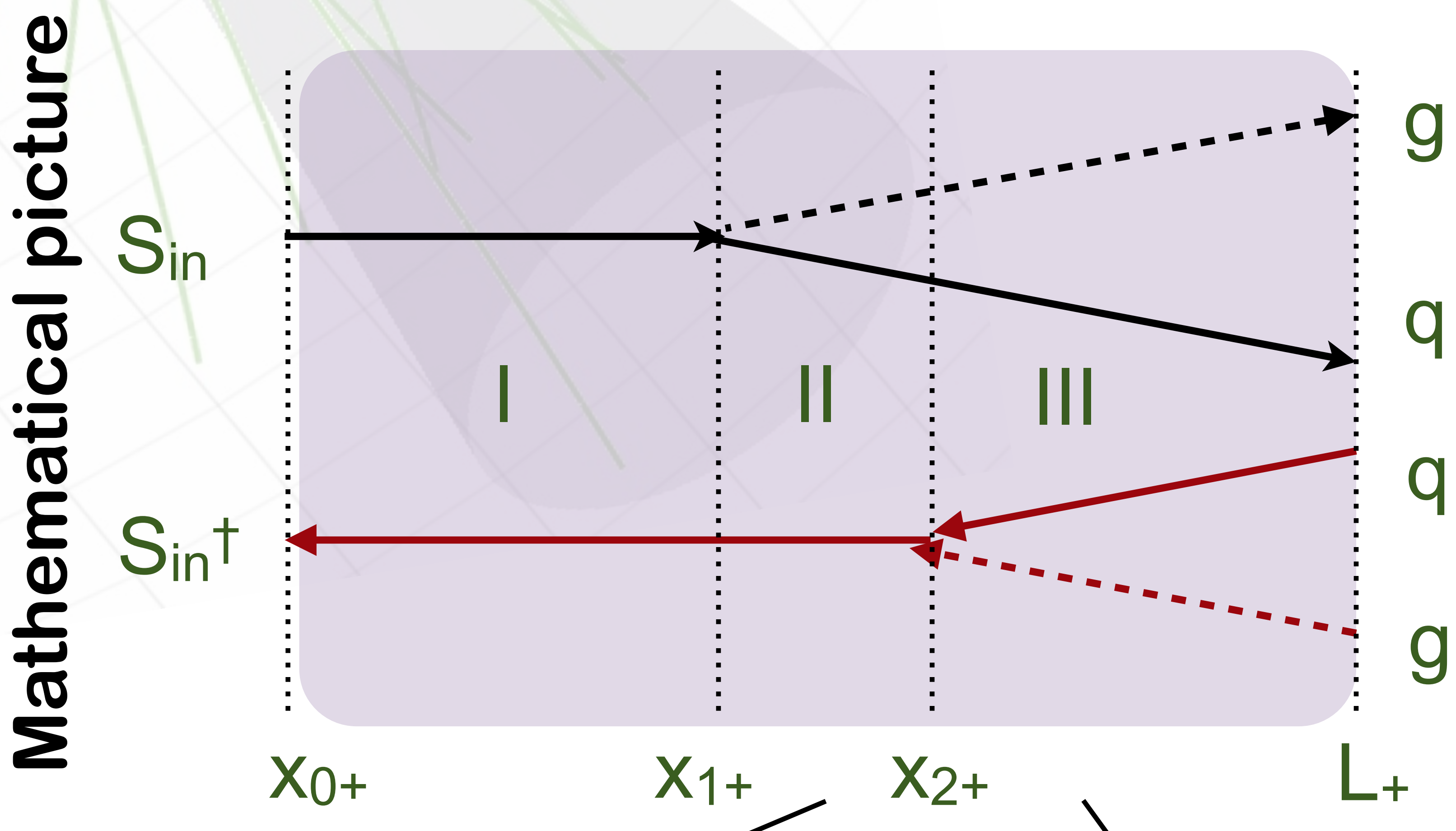

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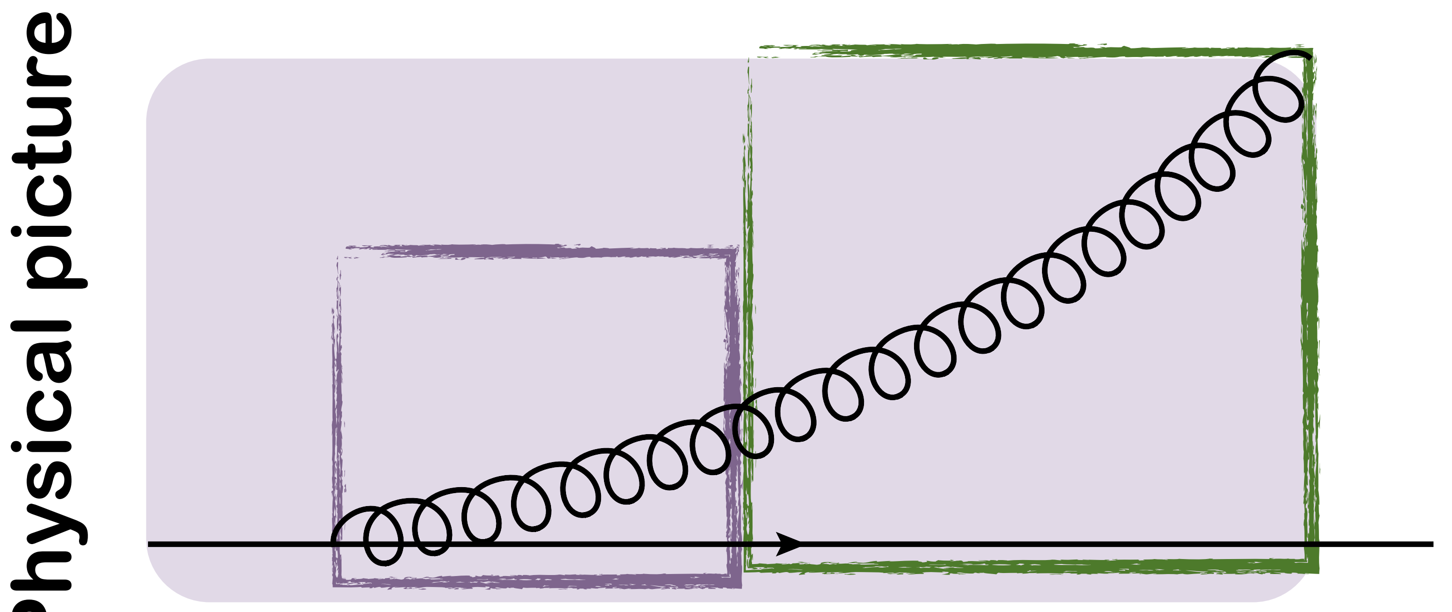

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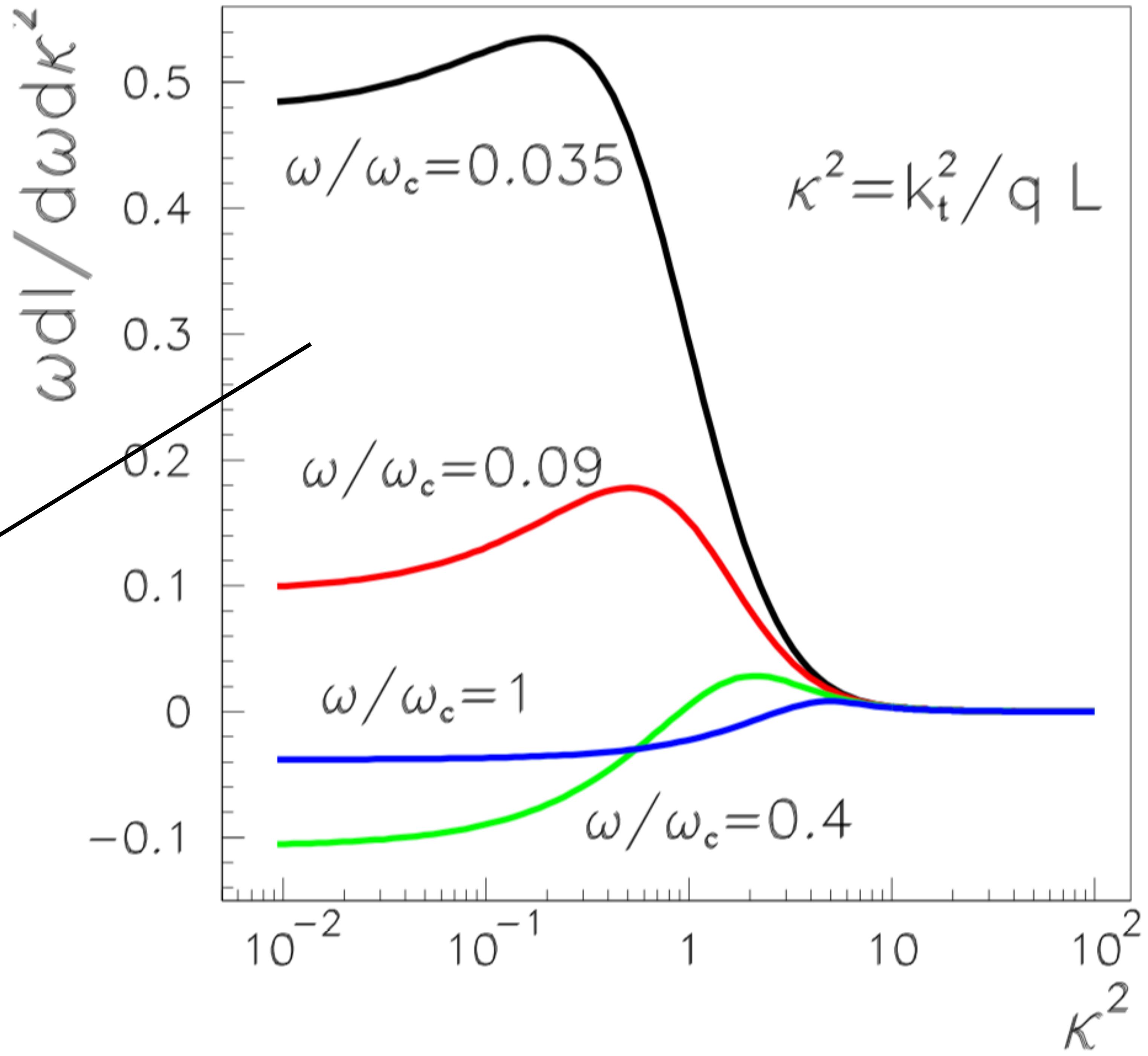
Classical Broadening

$$\boxed{Tr\left\langle W_A(r_g)W_A^\dagger(\bar{r}_g)\right\rangle}$$

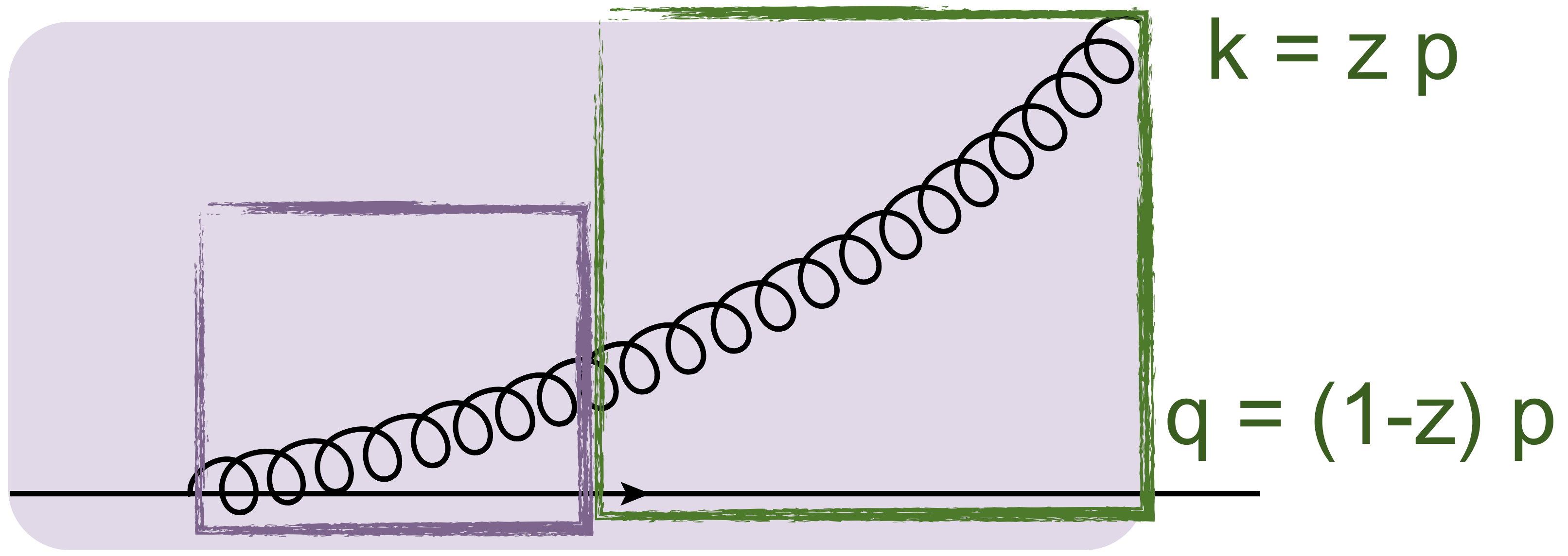
And, finally, some numerics:



LPM (QCD) suppression

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

LPM effect



- Heuristic discussion on single gluon emission spectrum (BDMPS):

Transport coefficient:

$$\hat{q} = \frac{< k_\perp^2 >}{\lambda_{mfp}}$$

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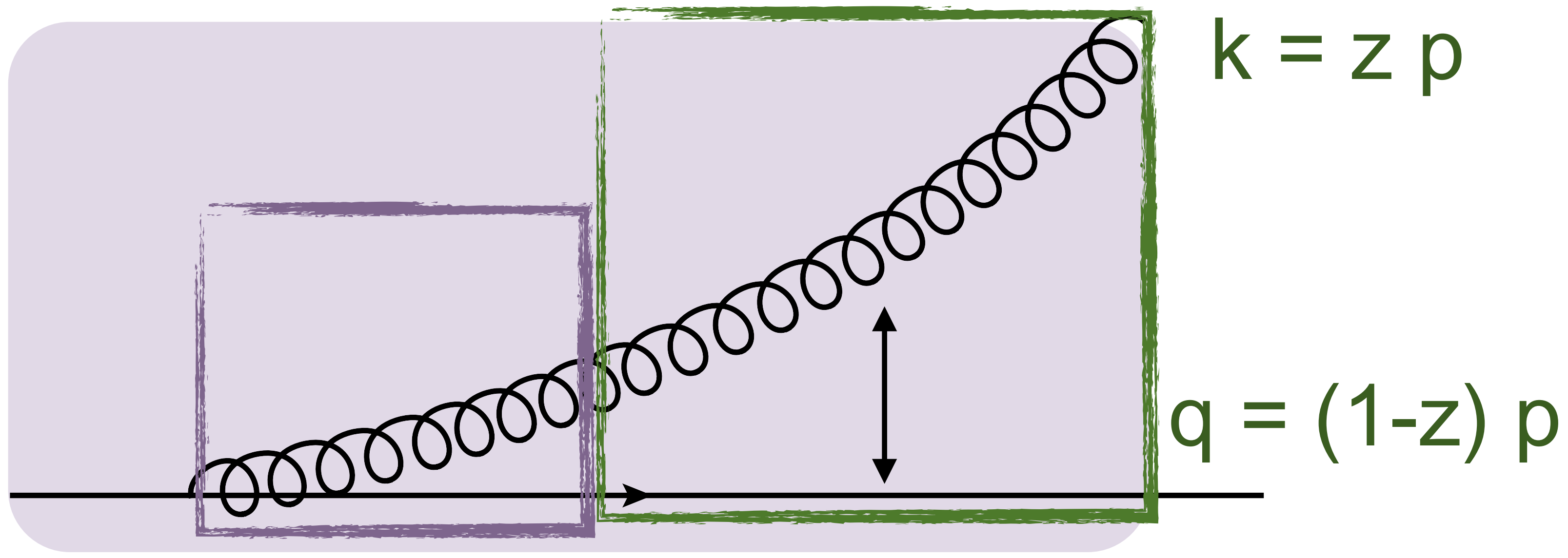

Soft gluons have shorter formation times

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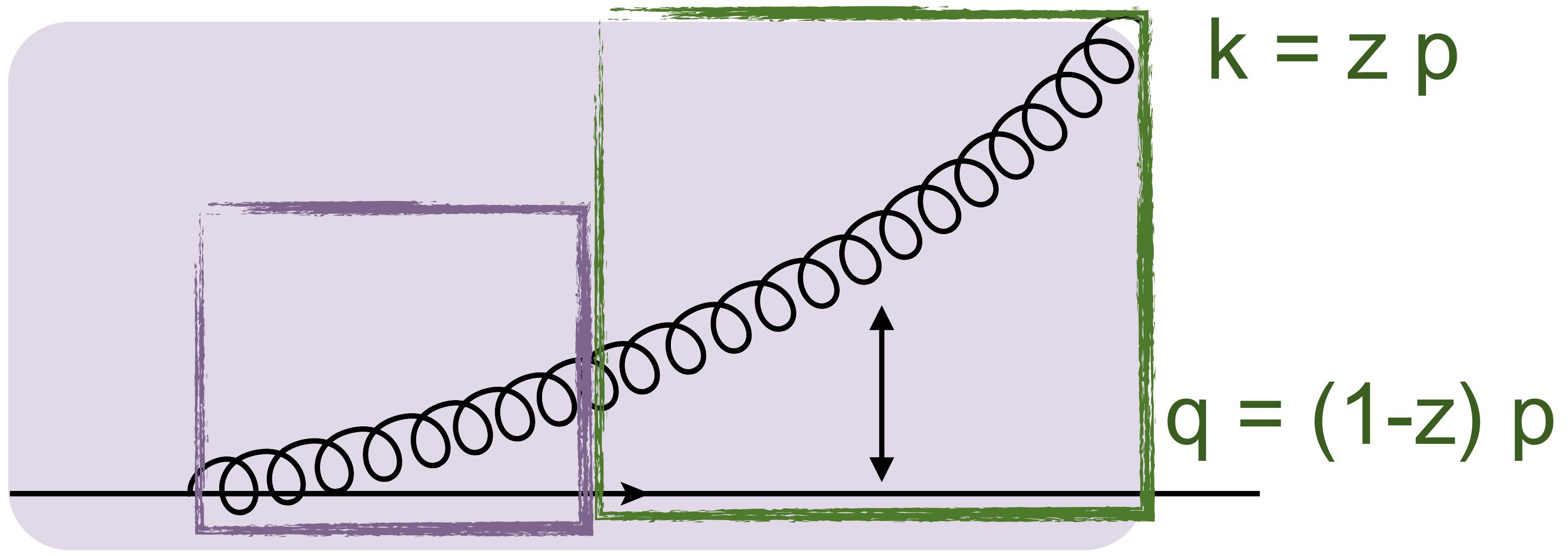

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Number of emitted gluons during L: $N_g \propto \frac{L}{\tau_{form}}$

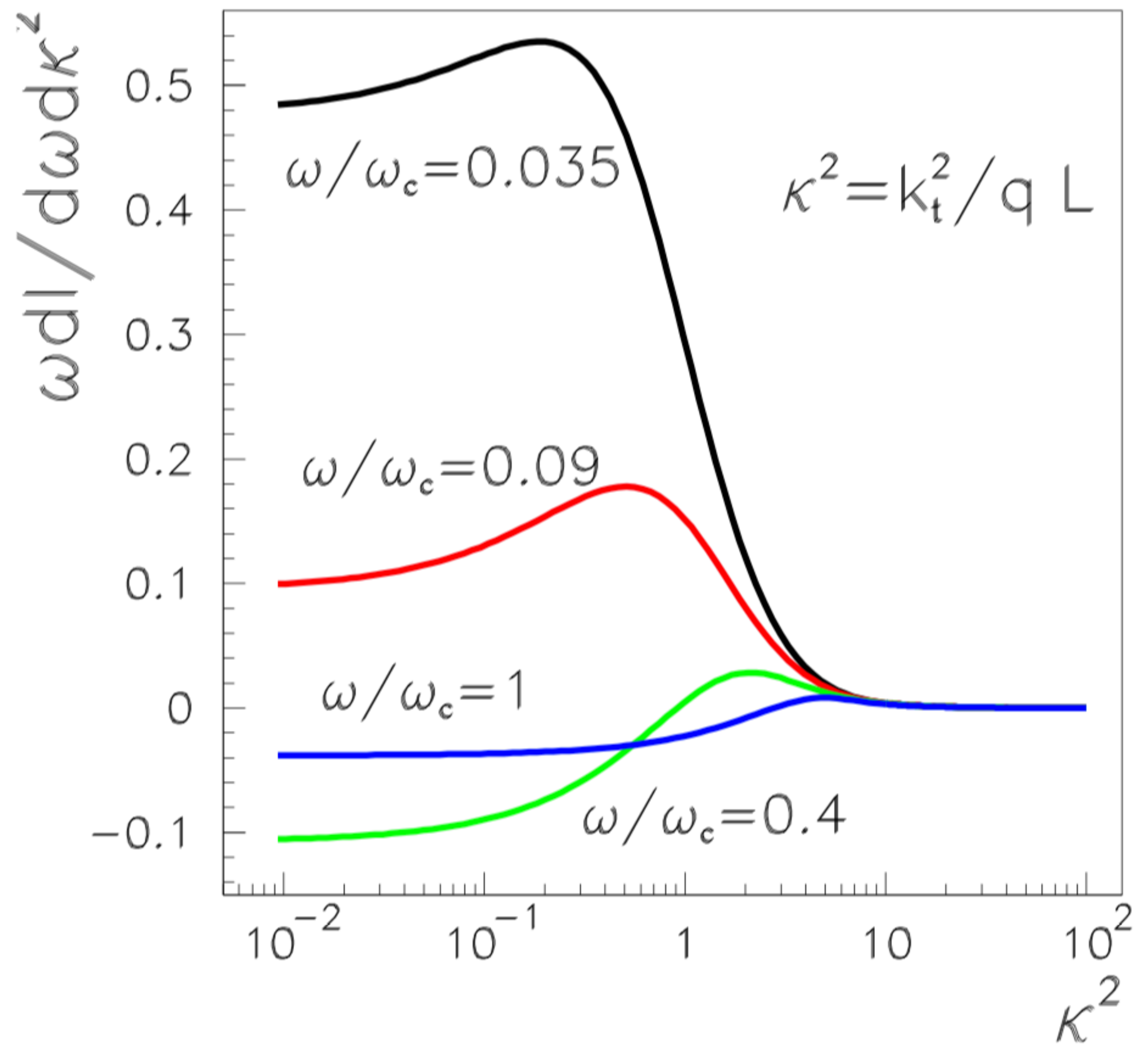
$\tau_{form} \ll L$ Multiple soft emissions (incoherent scatterings)

$$\boxed{\omega \frac{dI}{d\omega}\bigg|_{\omega \leq \omega_c} \sim \alpha_s C_R \sqrt{\frac{\omega_c}{\omega}}}$$

$\tau_{form} \gg L$ Hard gluon spectrum is suppressed (scattering centres act as a whole)

$$\boxed{\omega \frac{dI}{d\omega}\bigg|_{\omega > \omega_c} \sim \alpha_s C_R \left(\frac{\omega_c}{\omega}\right)^2}$$

Critical energy: $\omega_c(\tau_{form} = L) = \frac{1}{2}\hat{q}L^2$

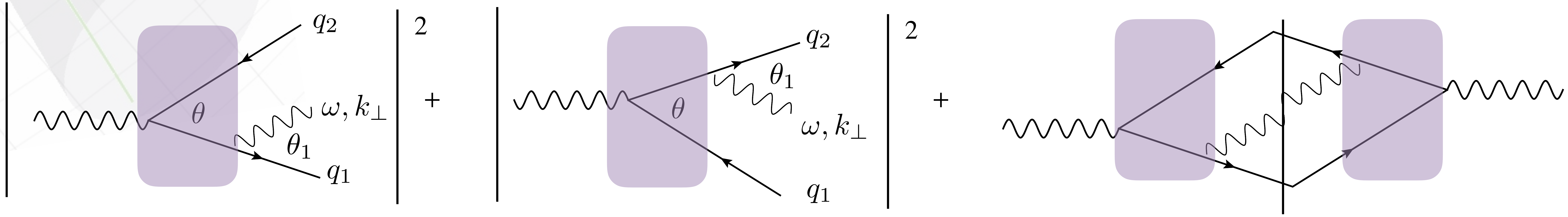


Intra-jet (de)coherence?

[Mehtar-Tani, Salgado, Tywoniuk (2010-2011)]

[Casalderrey-Solana, Iancu (2011)]

- Considering the in-medium singlet quark - antiquark antenna in the simplest case:
  - Soft gluon emission outside medium



Eikonal approximation: $$\frac{dI}{d\Omega_k} = R_q + R_{\bar{q}} - 2J(1-\Delta_{med}) = R_{coh} + 2J\Delta_{med}$$

$$R_q \sim \alpha_s C_F \frac{q_{1+}}{(k\cdot q_1)}$$

$$R_{\bar{q}} \sim \alpha_s C_F \frac{q_{2+}}{(k\cdot q_2)}$$

$$2J \sim \alpha_s C_F \left[\frac{q_{1+}}{(k\cdot q_1)} + \frac{q_{2+}}{(k\cdot q_2)} - \frac{k_+(q_1\cdot q_2)}{(k\cdot q_1)(k\cdot q_2)}\right]$$

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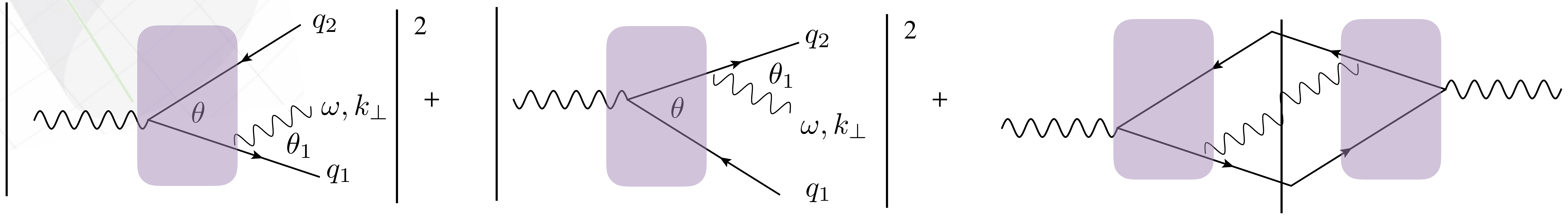

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new in-medium contribution:

$$1 - \Delta_{med} = \frac{1}{N_c^2}\mathrm{Tr}\left\langle W_A(\mathbf{x}_q)W_A^\dagger(\mathbf{x}_{\bar{q}})\right\rangle$$

as in vacuum: $R_{coh} \sim \alpha_s C_F \frac{k_+(q_1\cdot q_2)}{(k\cdot q_1)(k\cdot q_2)}$

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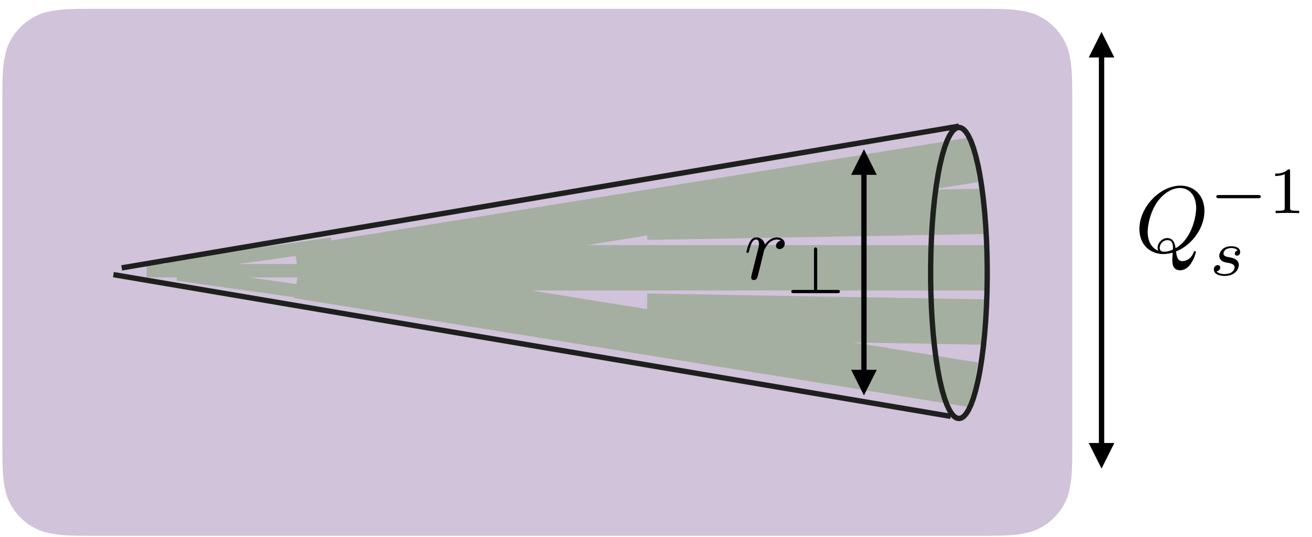
Angular ordering



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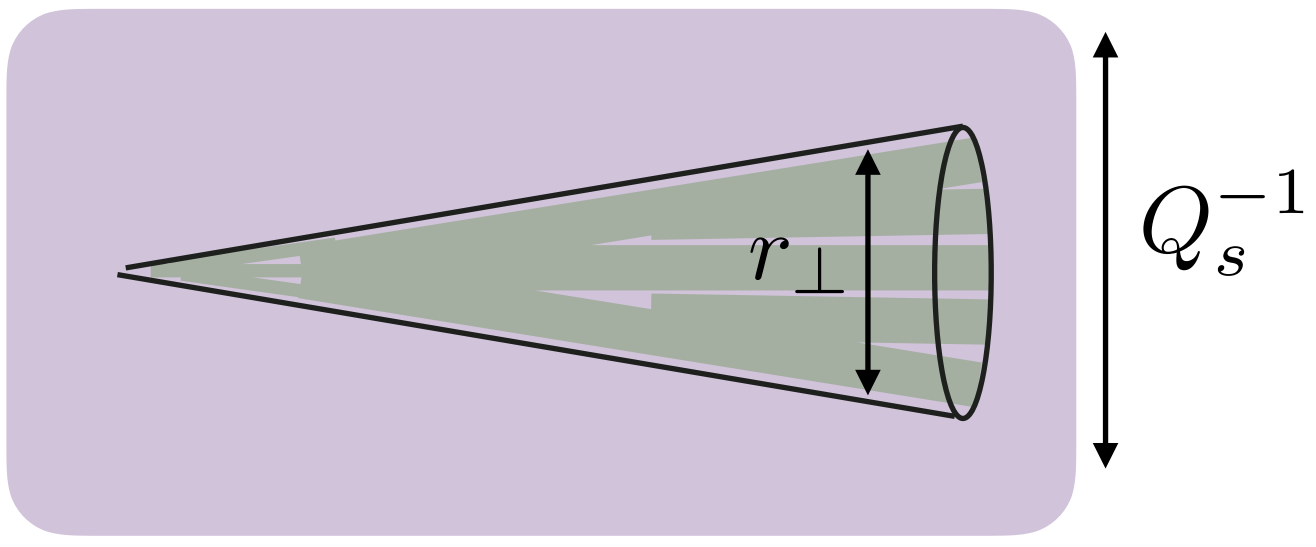

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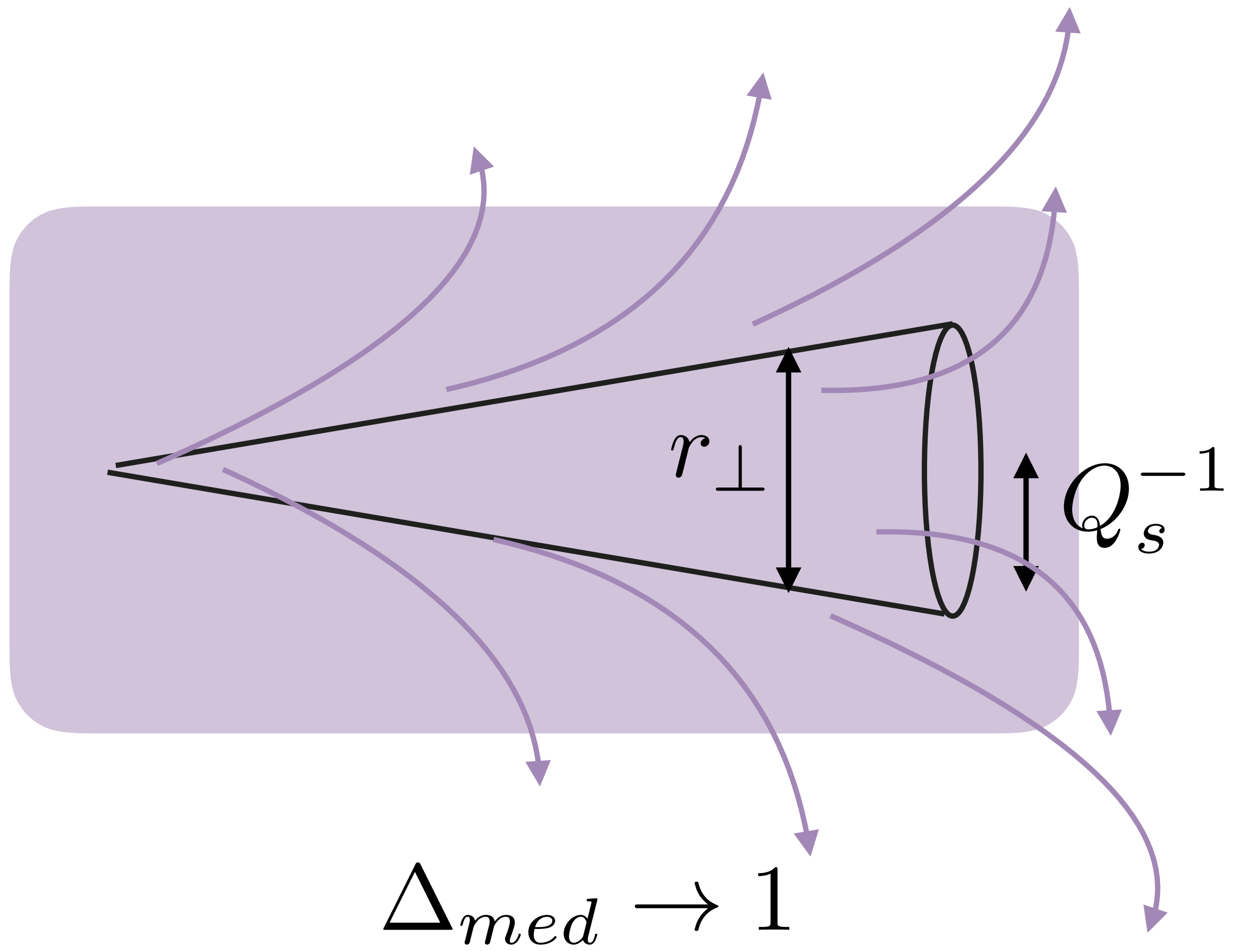
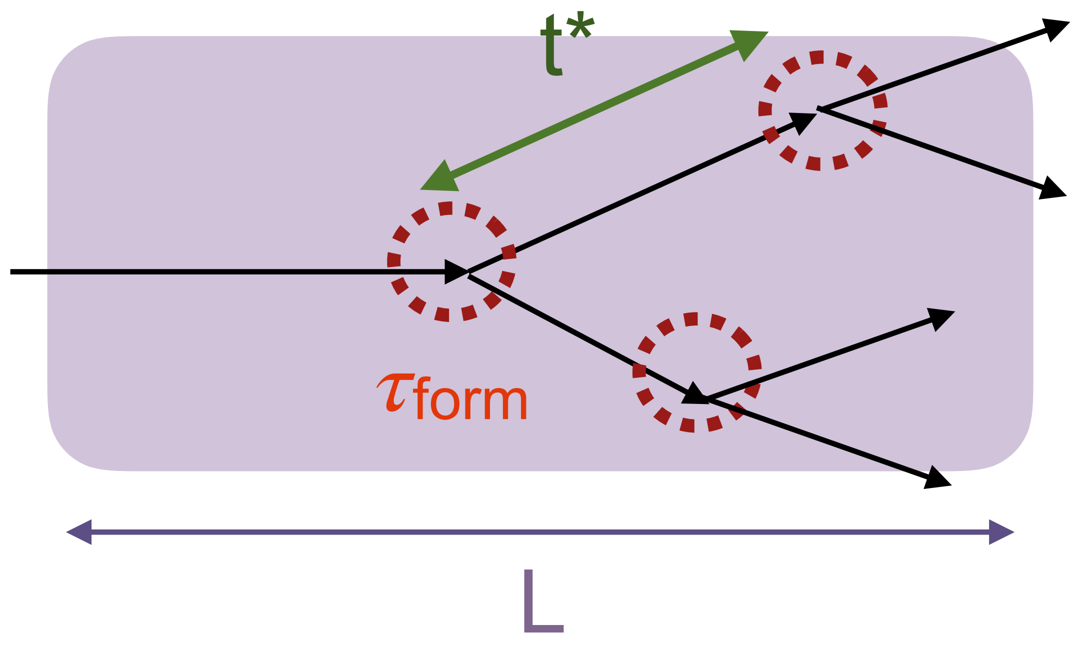
Anti-Angular ordering



$\Delta_{med} \to 1$

More th developments



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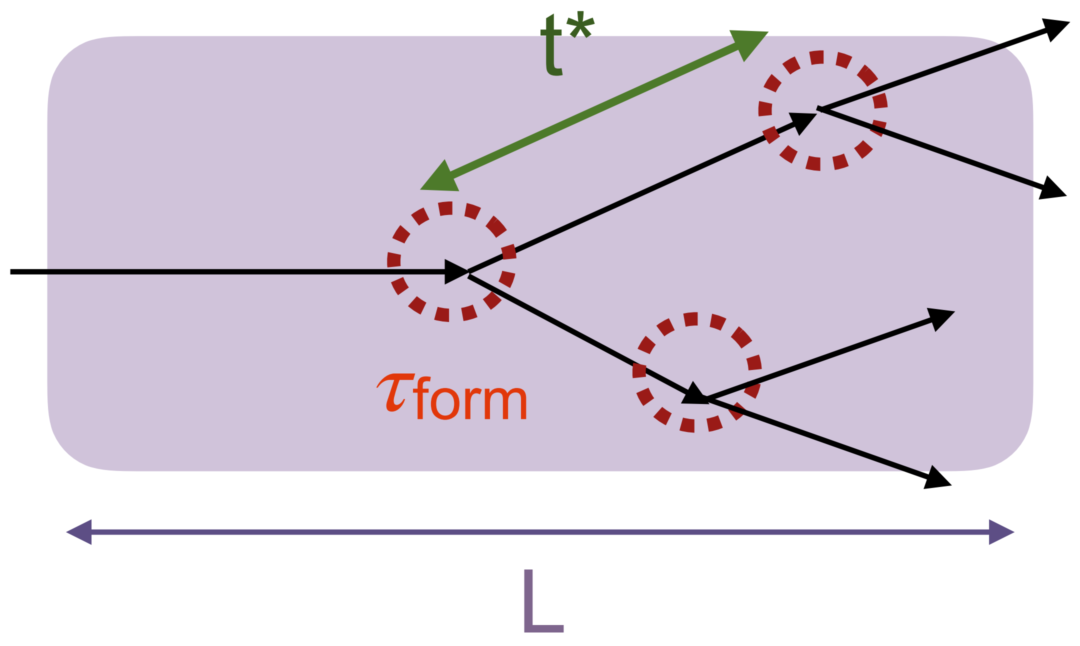

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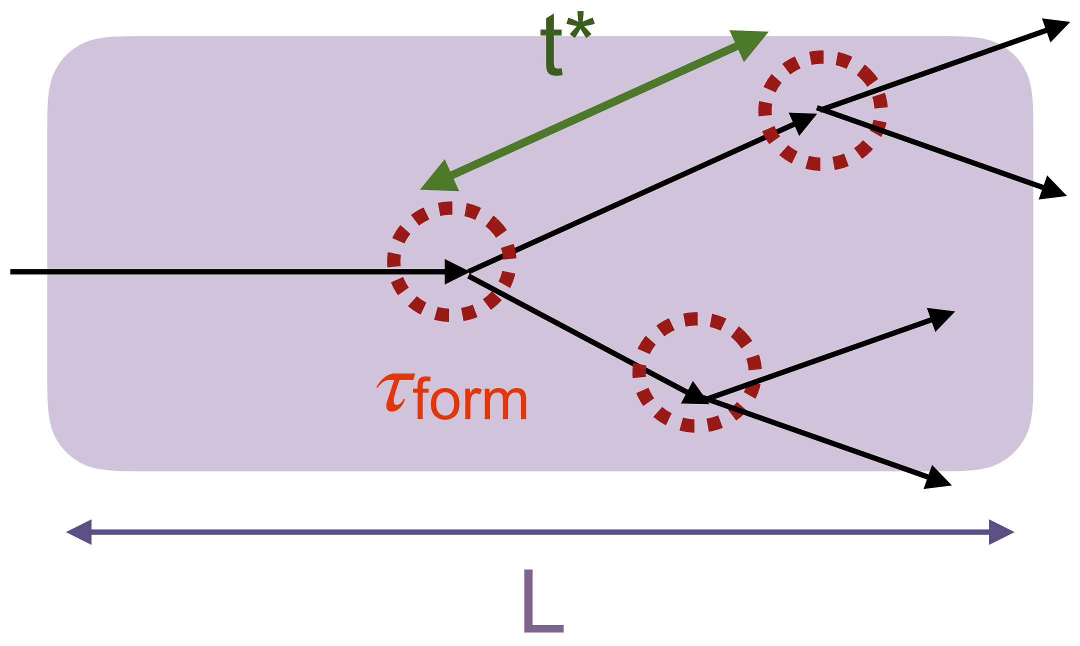
⇒ Interplay Coherence/Decoherence

More th developments



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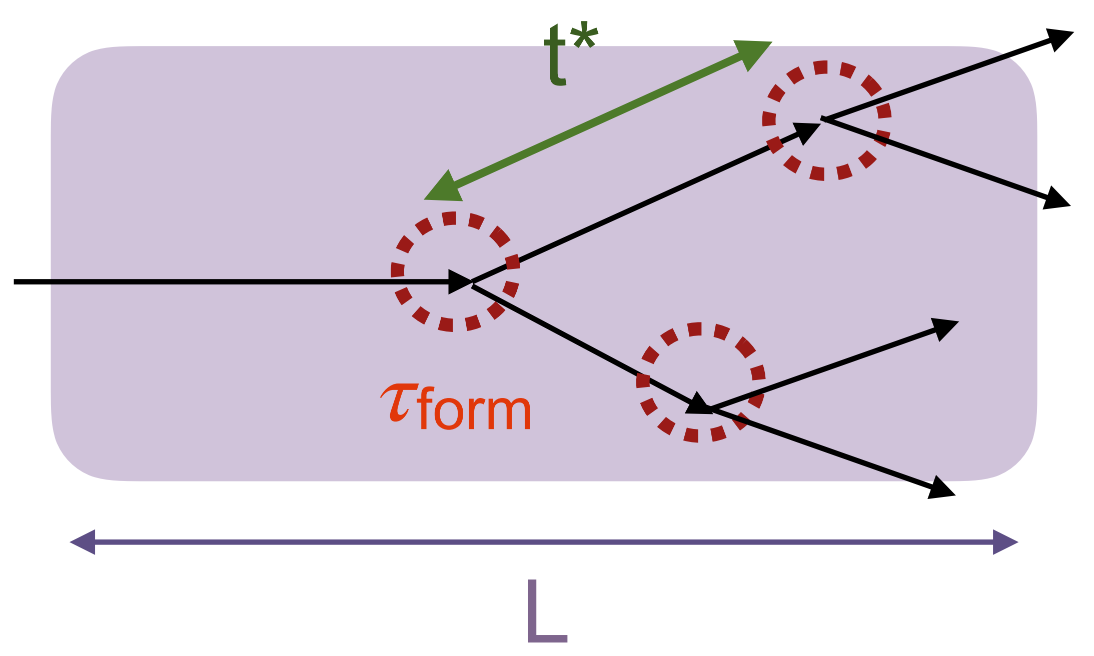

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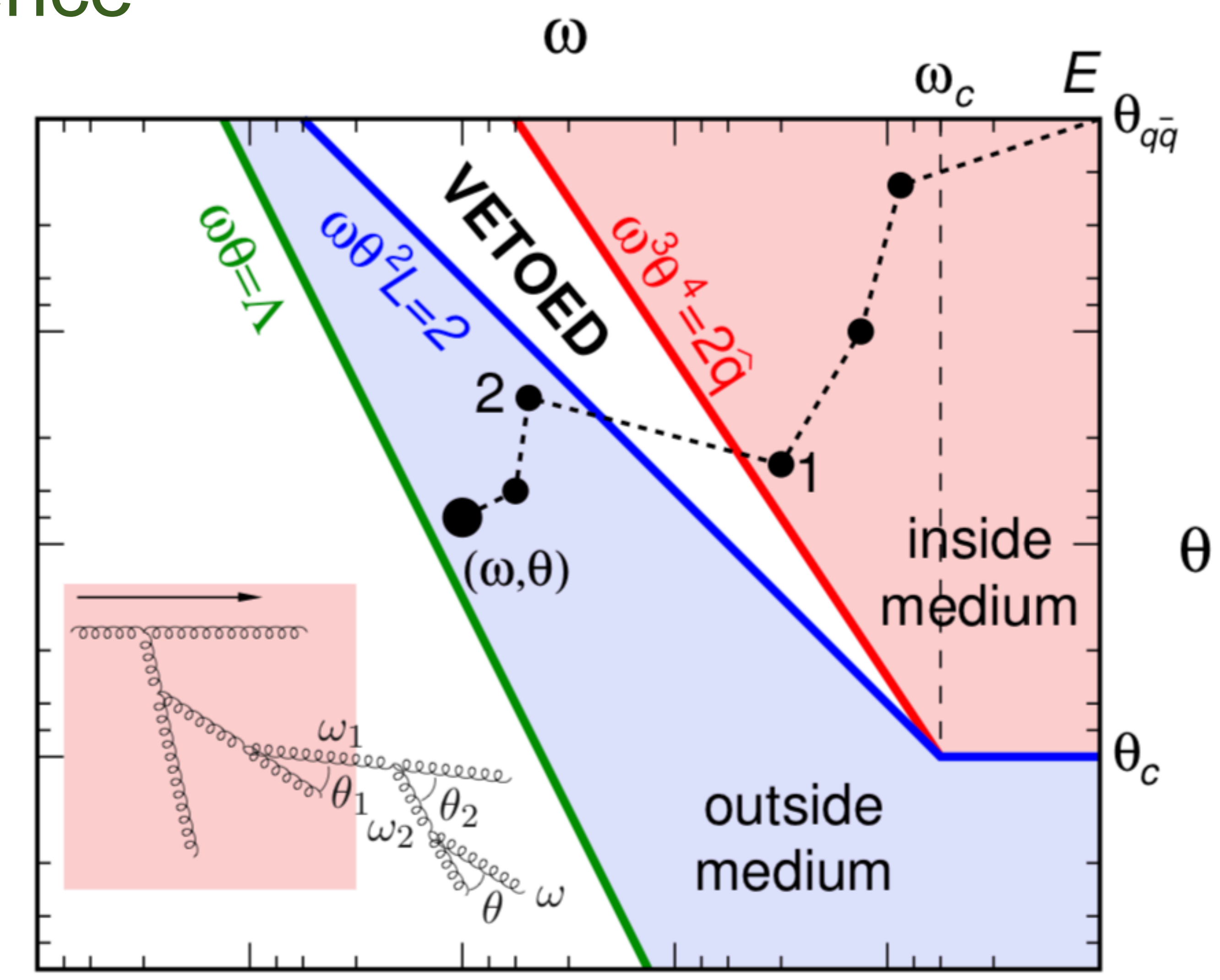
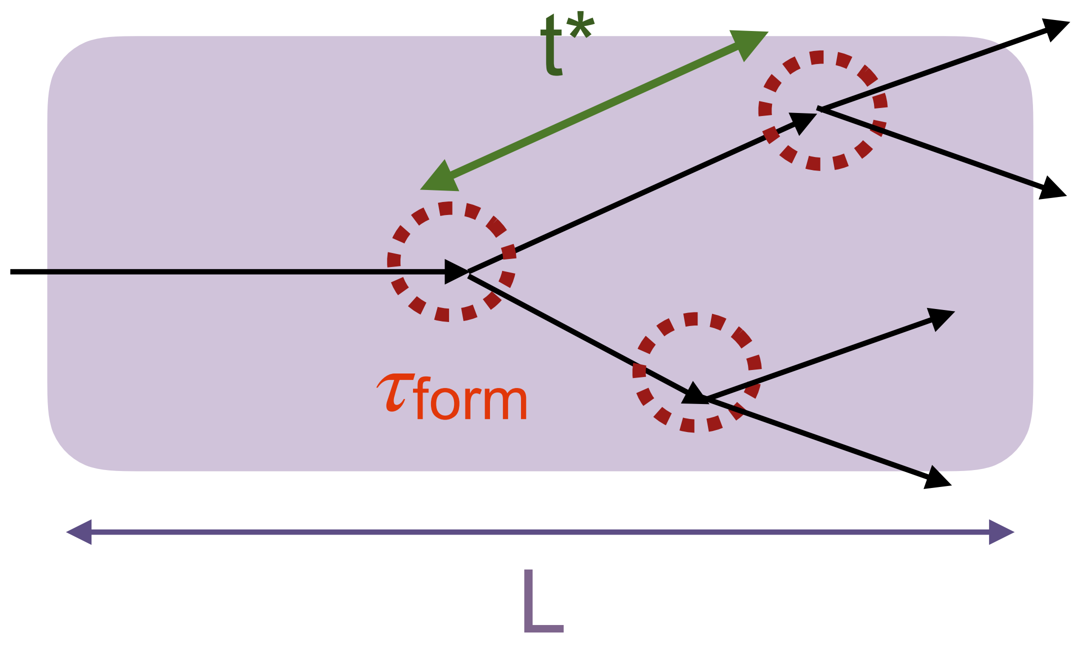


More th developments

See K. Tywoniuk (Thursday)



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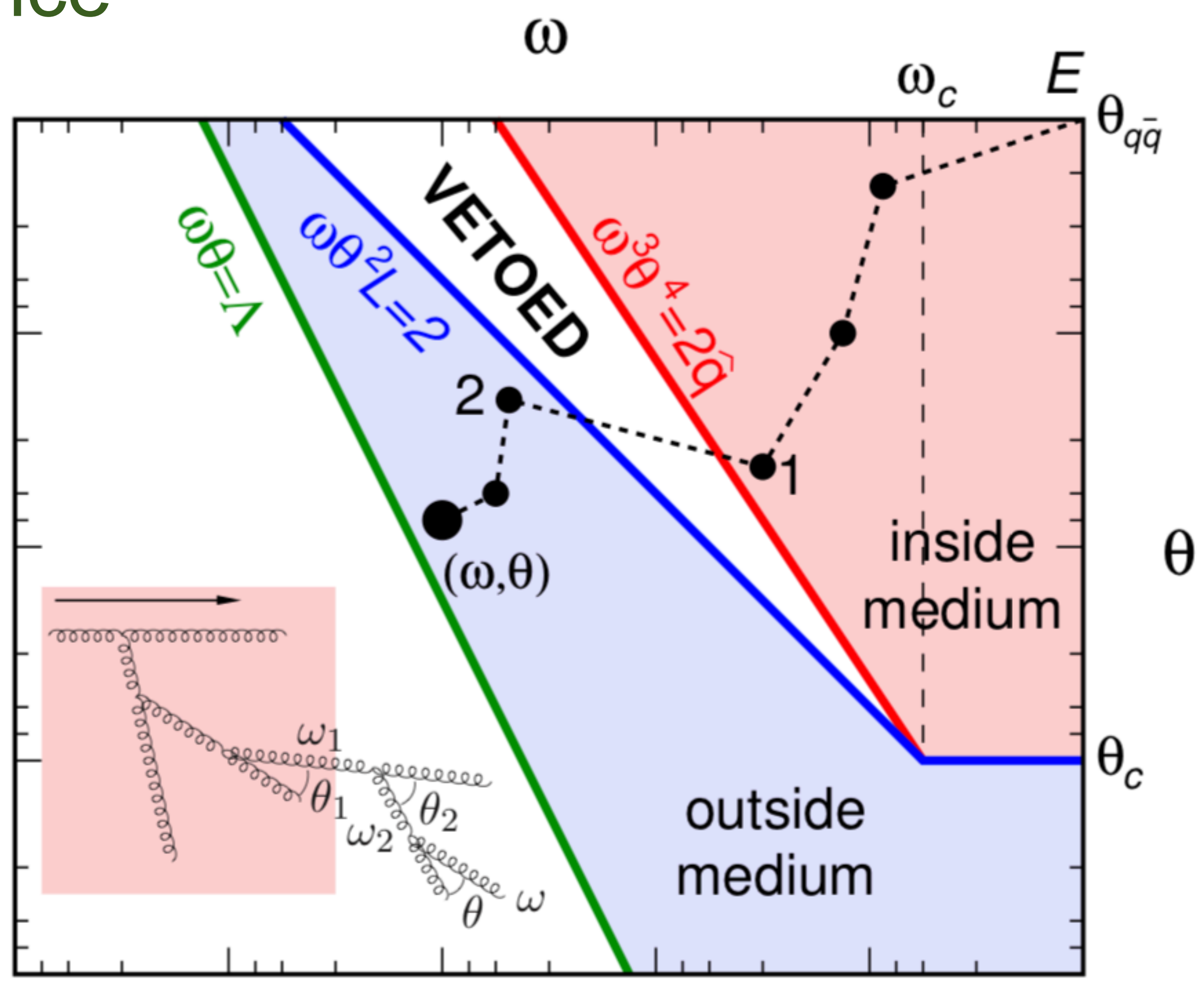
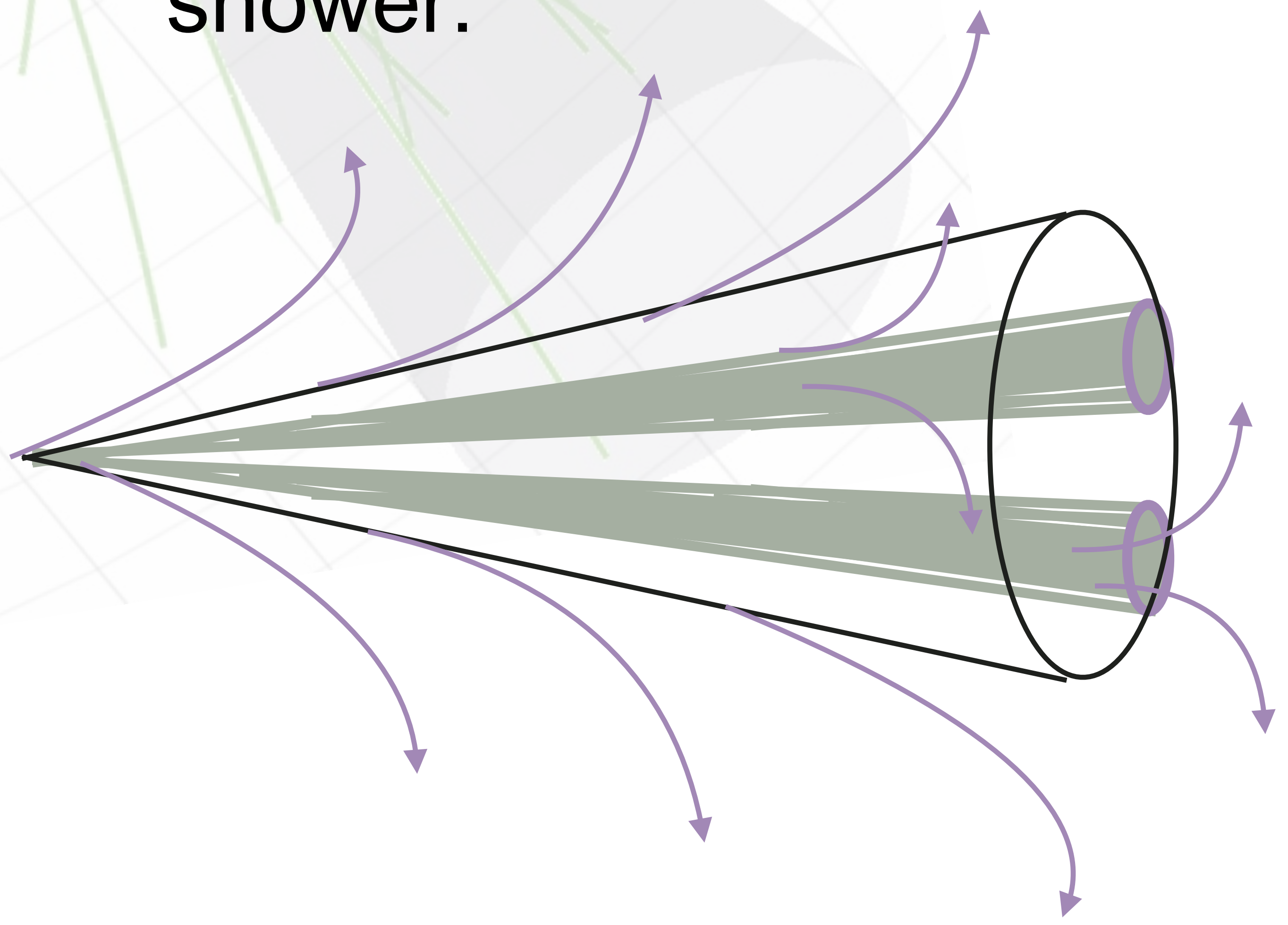


Resulting picture

[See also: 1801.09703]

[1401.8293]

- Resulting picture of a medium-modified parton shower:



Finite size "pp-like" structures
(Angular Ordering)

Medium-induced radiation
(not collinear)

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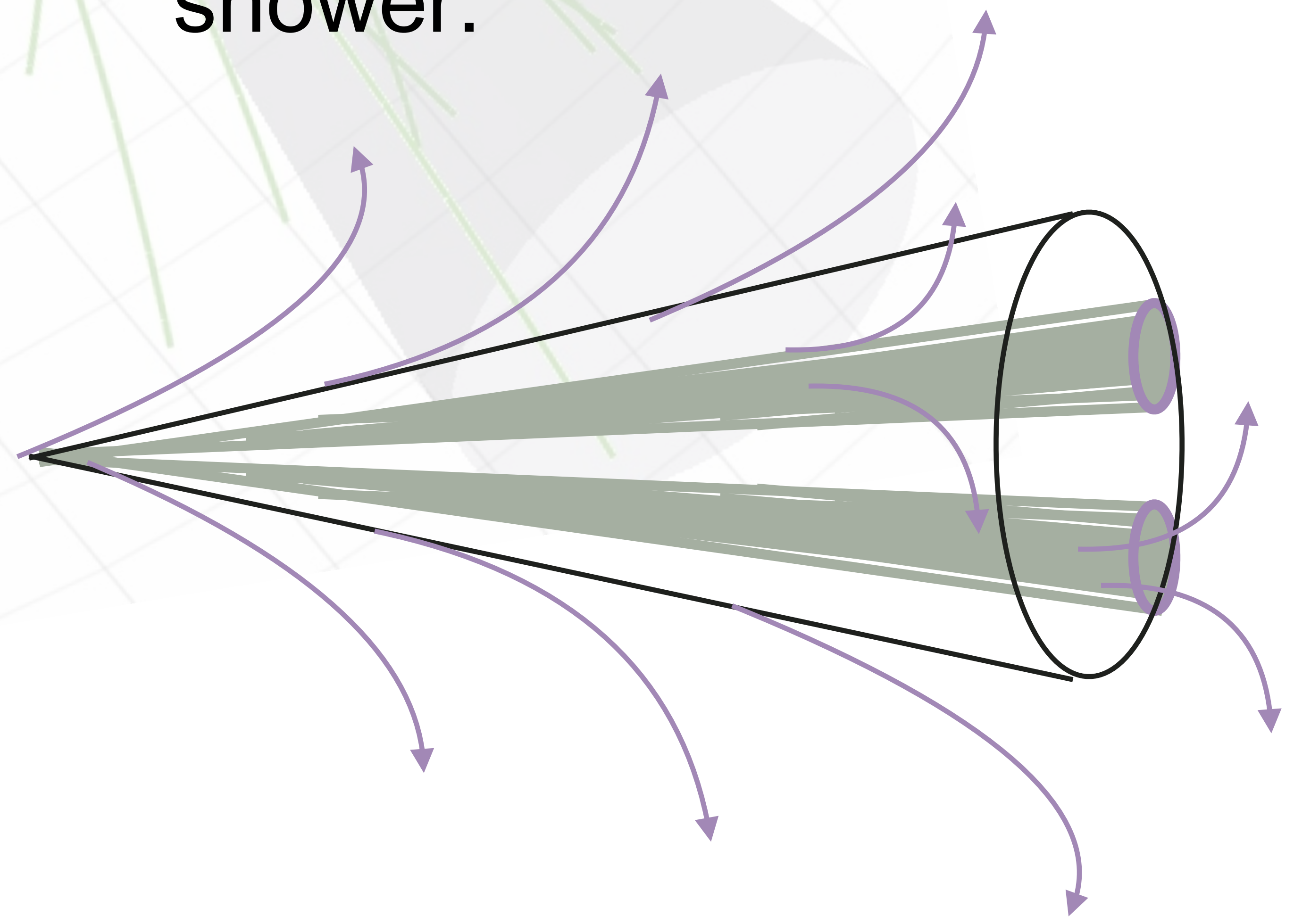

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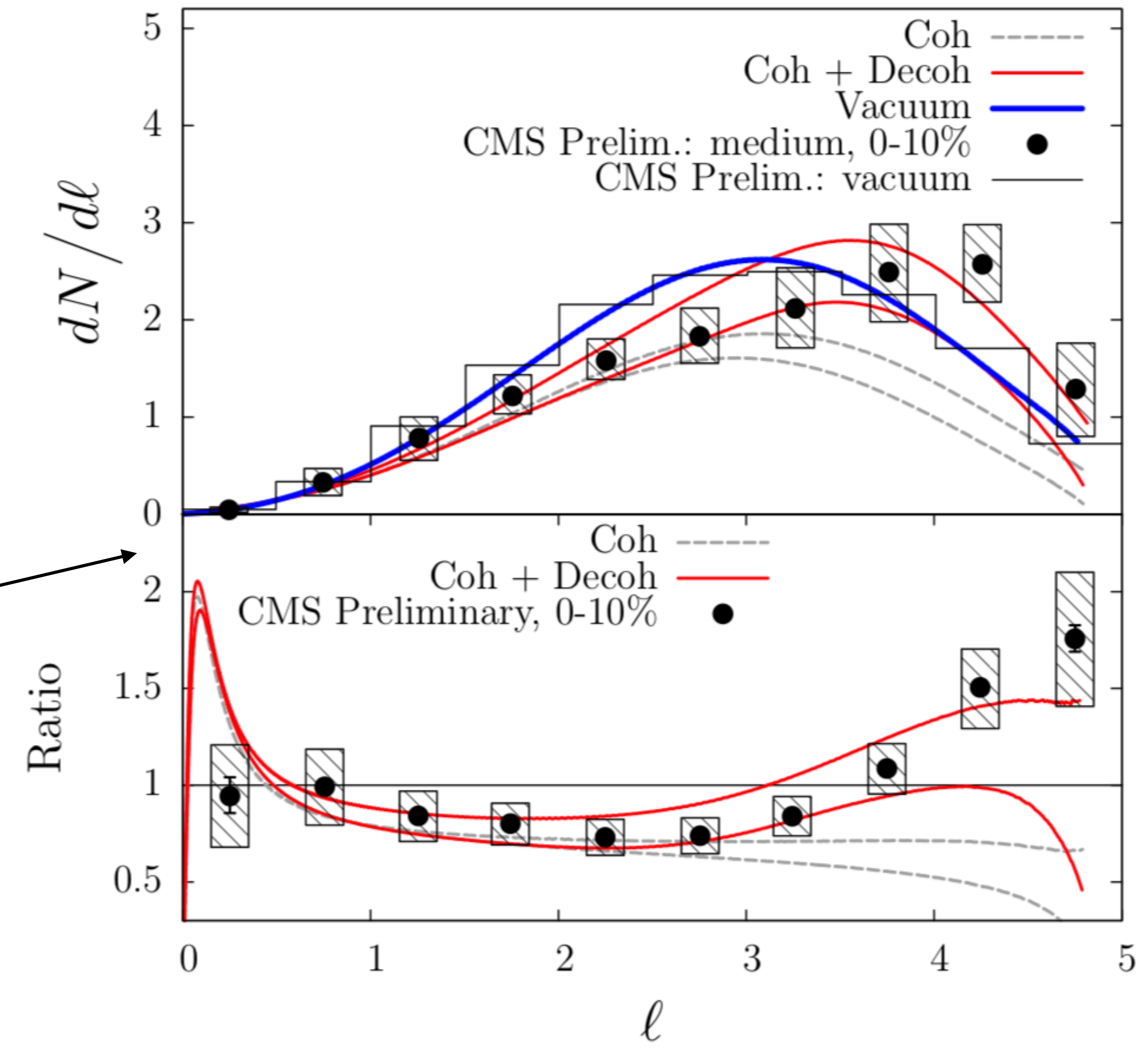

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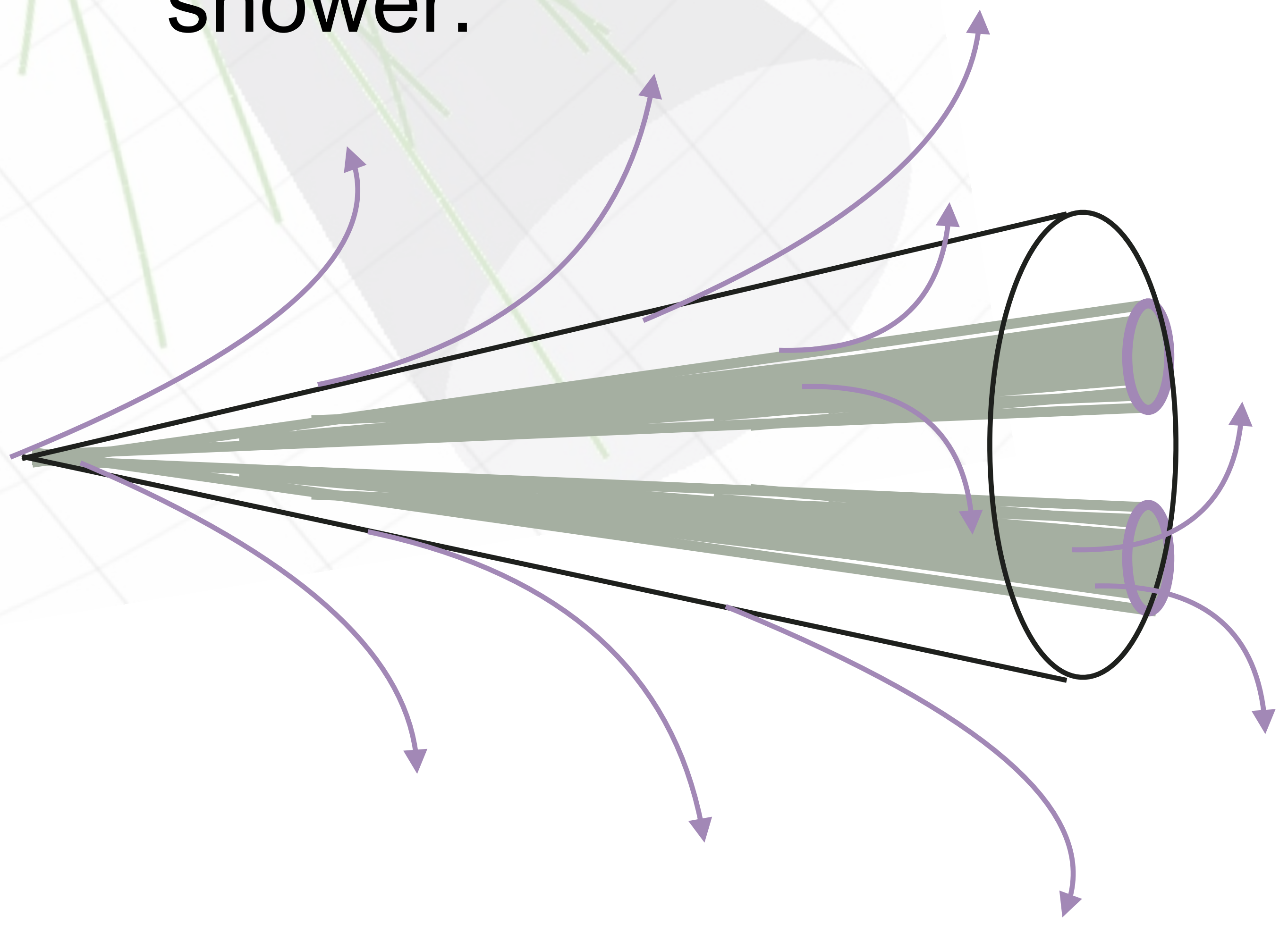

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hard structure:
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increase of soft
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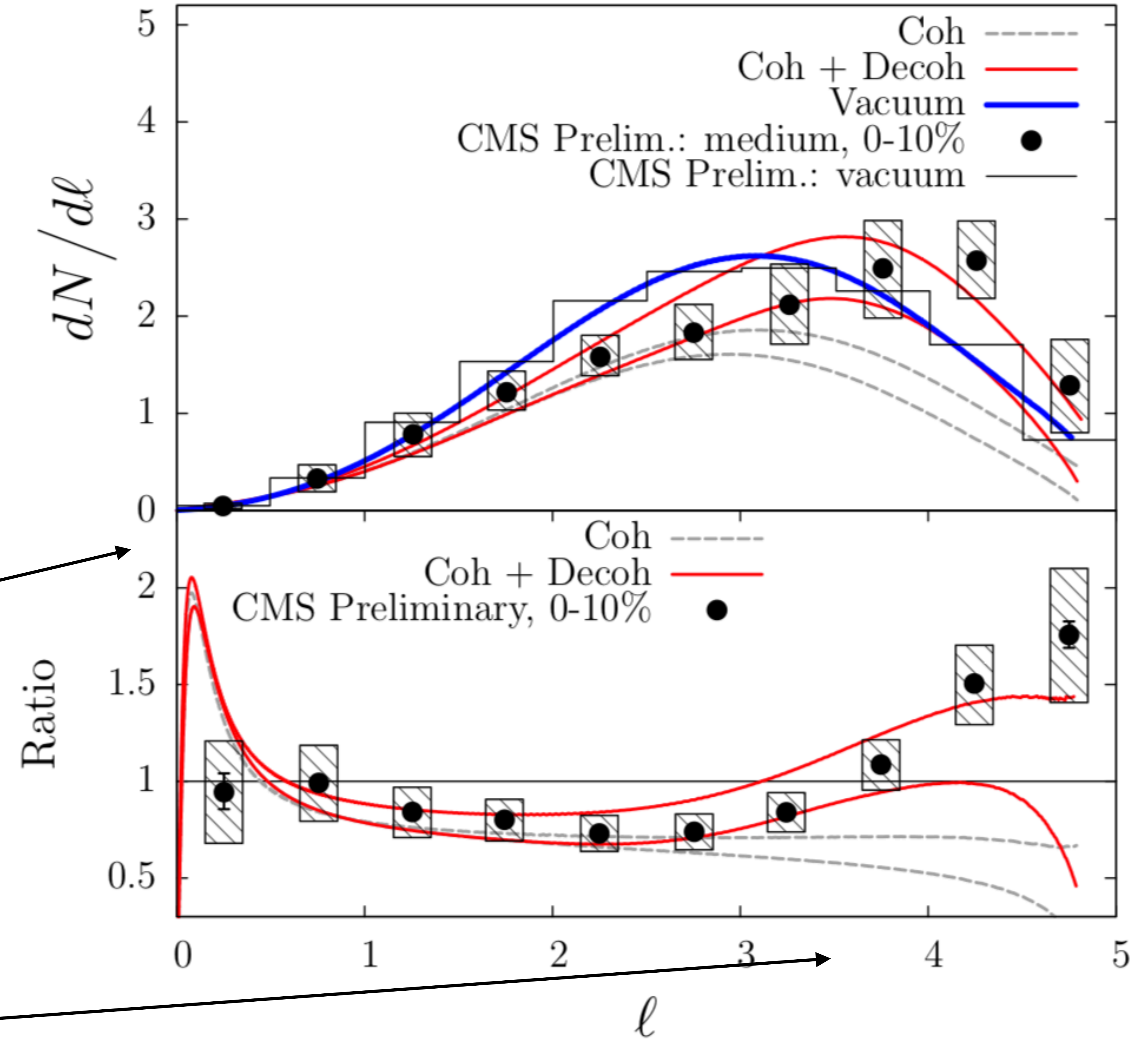

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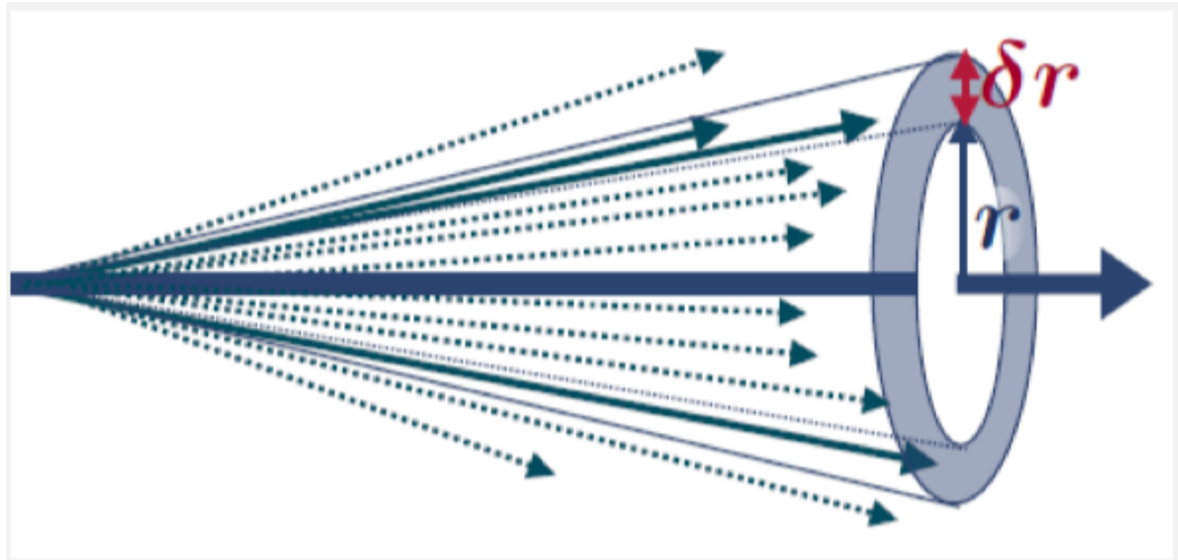

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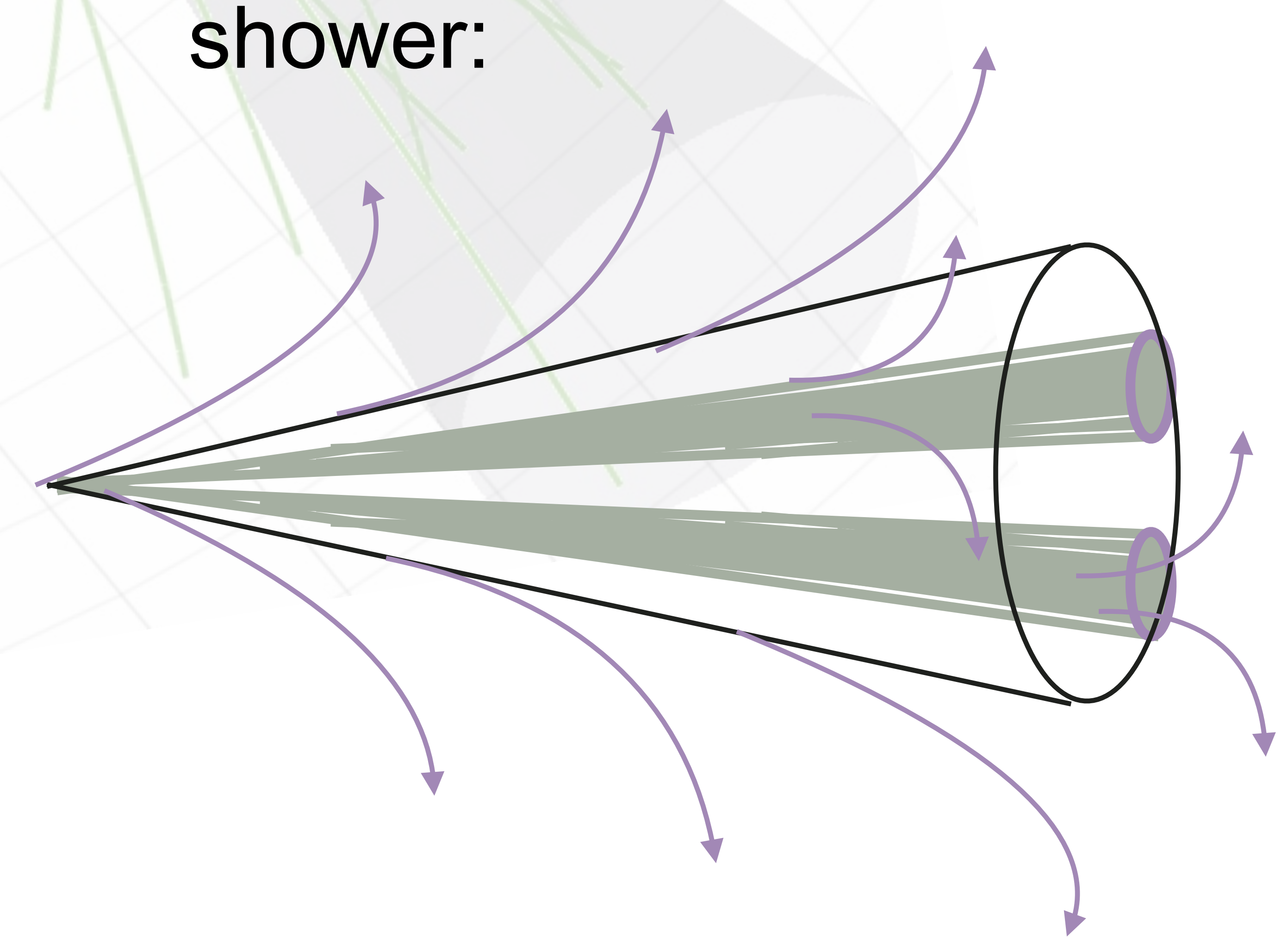
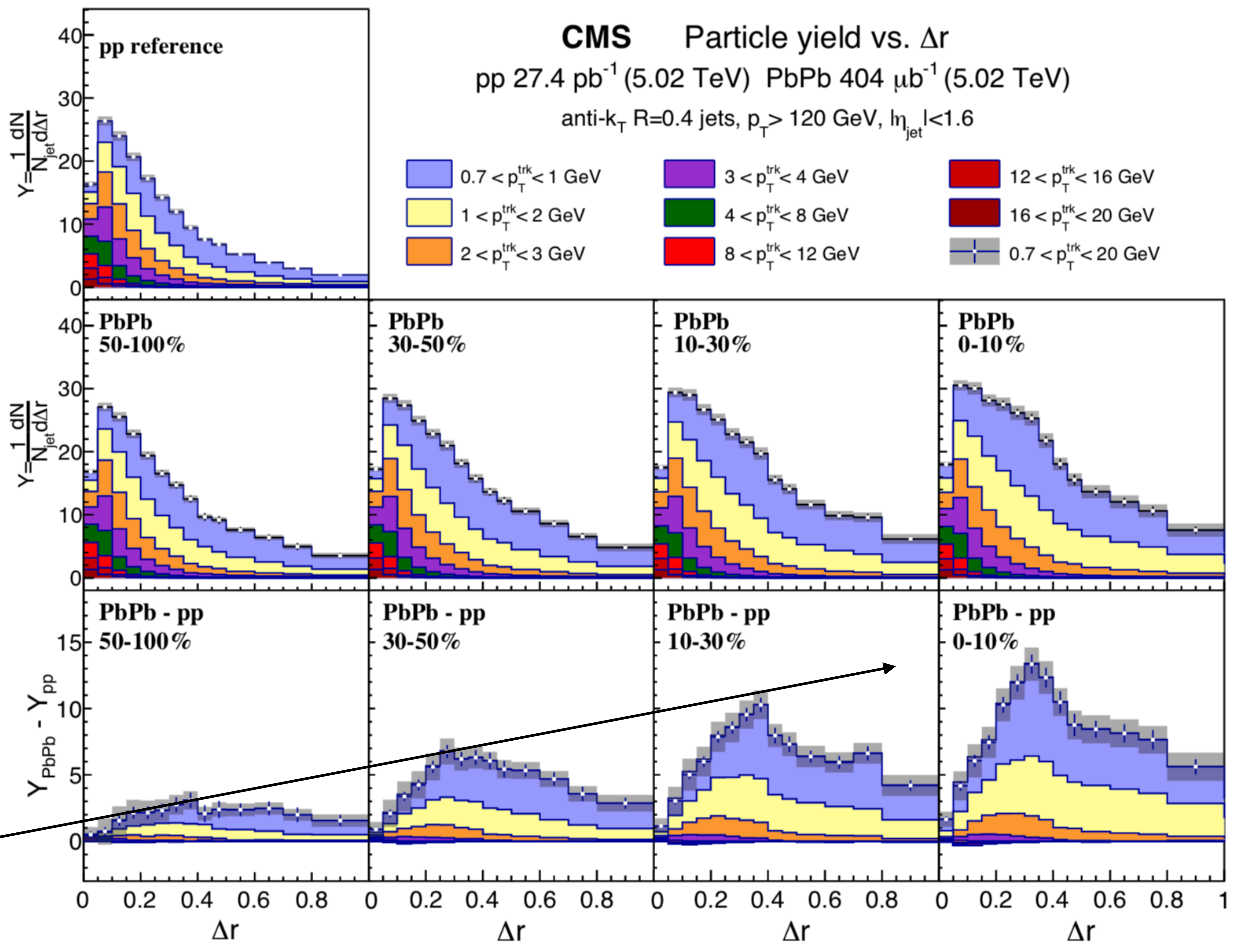


Finite size "pp-like" structures
(Angular Ordering)

Soft fragments radiated up to large angles

Medium-induced radiation
(not collinear)

arXiv:1803.00042



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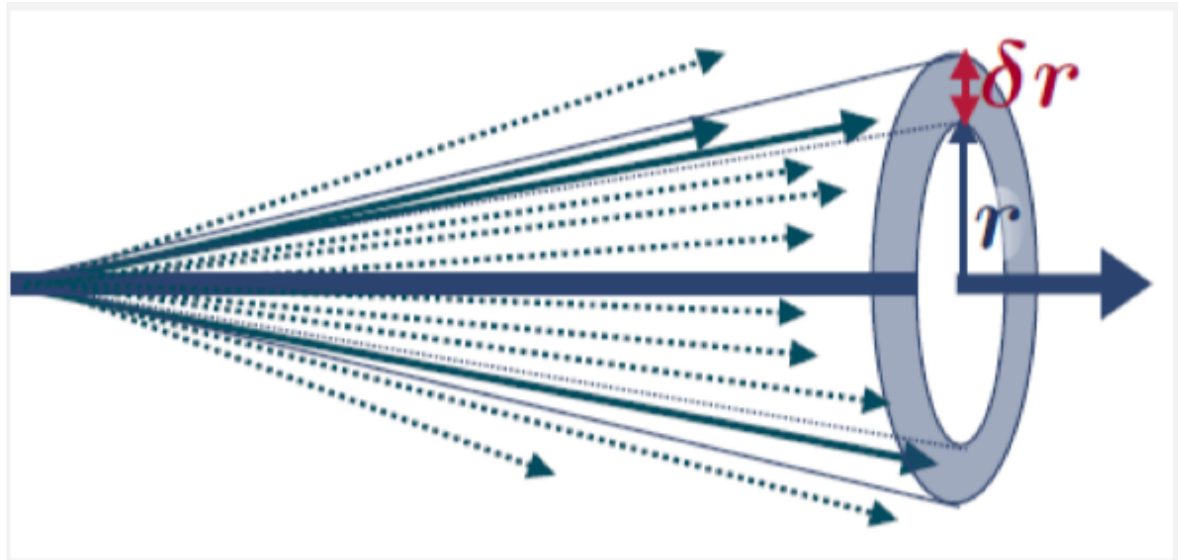

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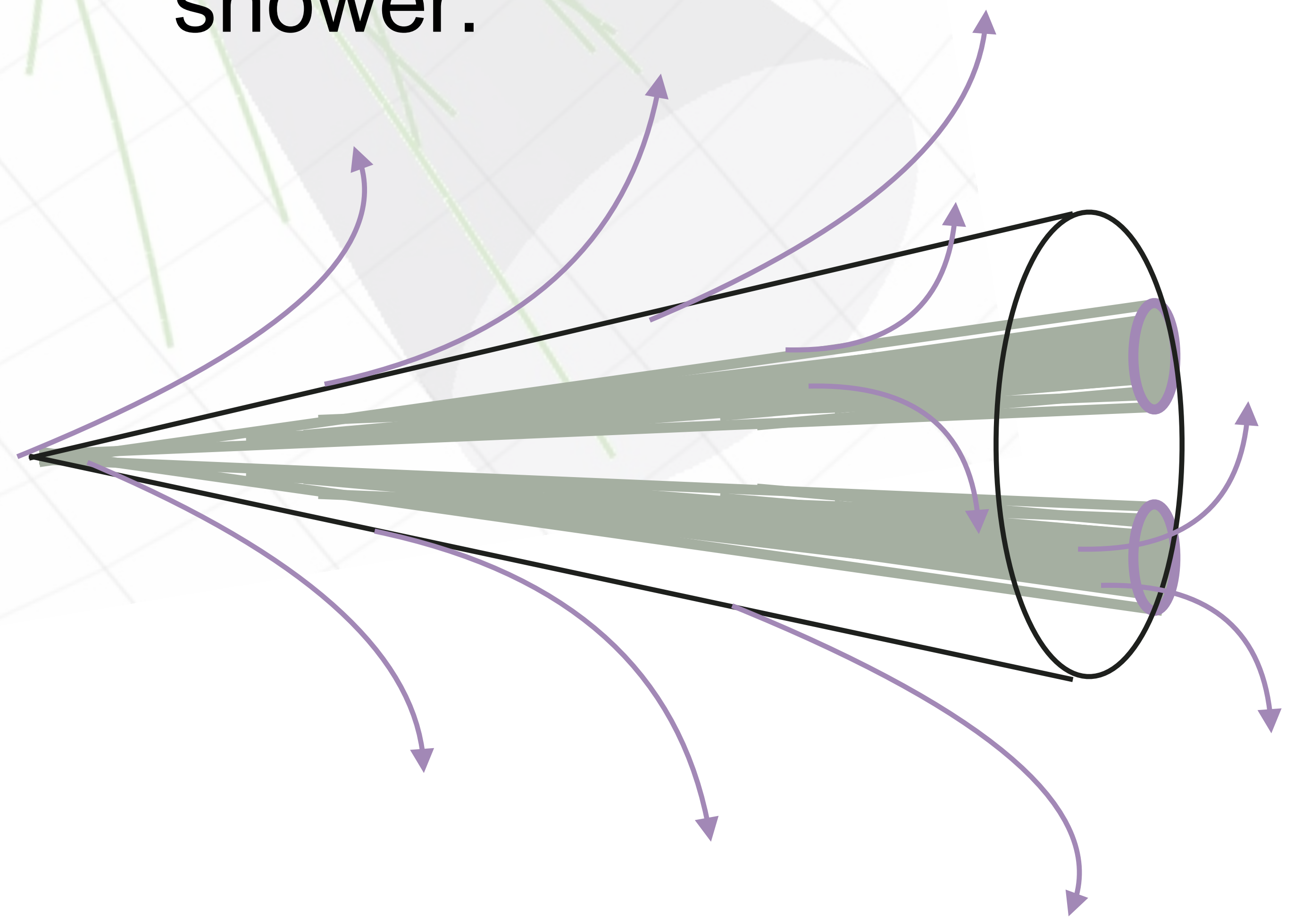

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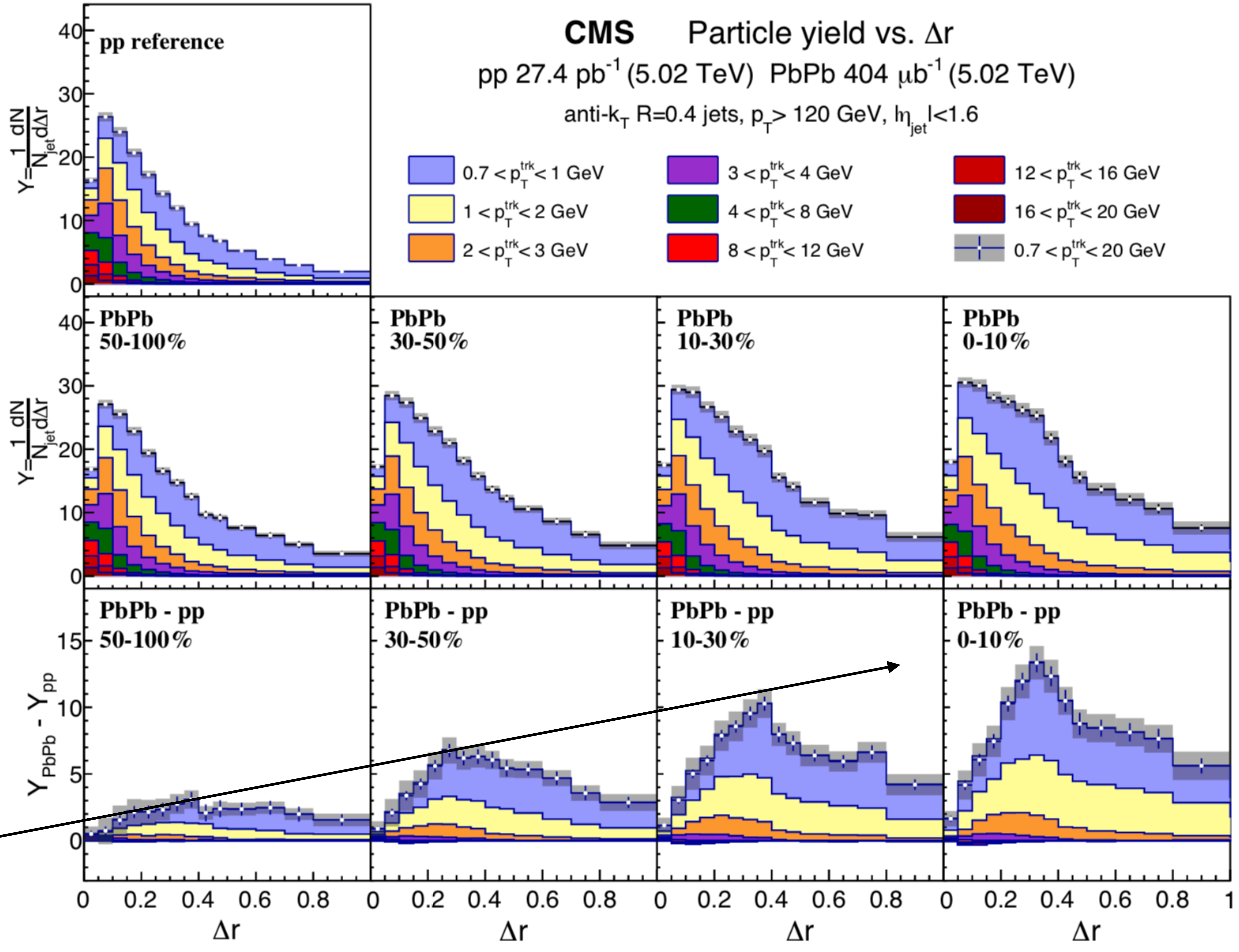
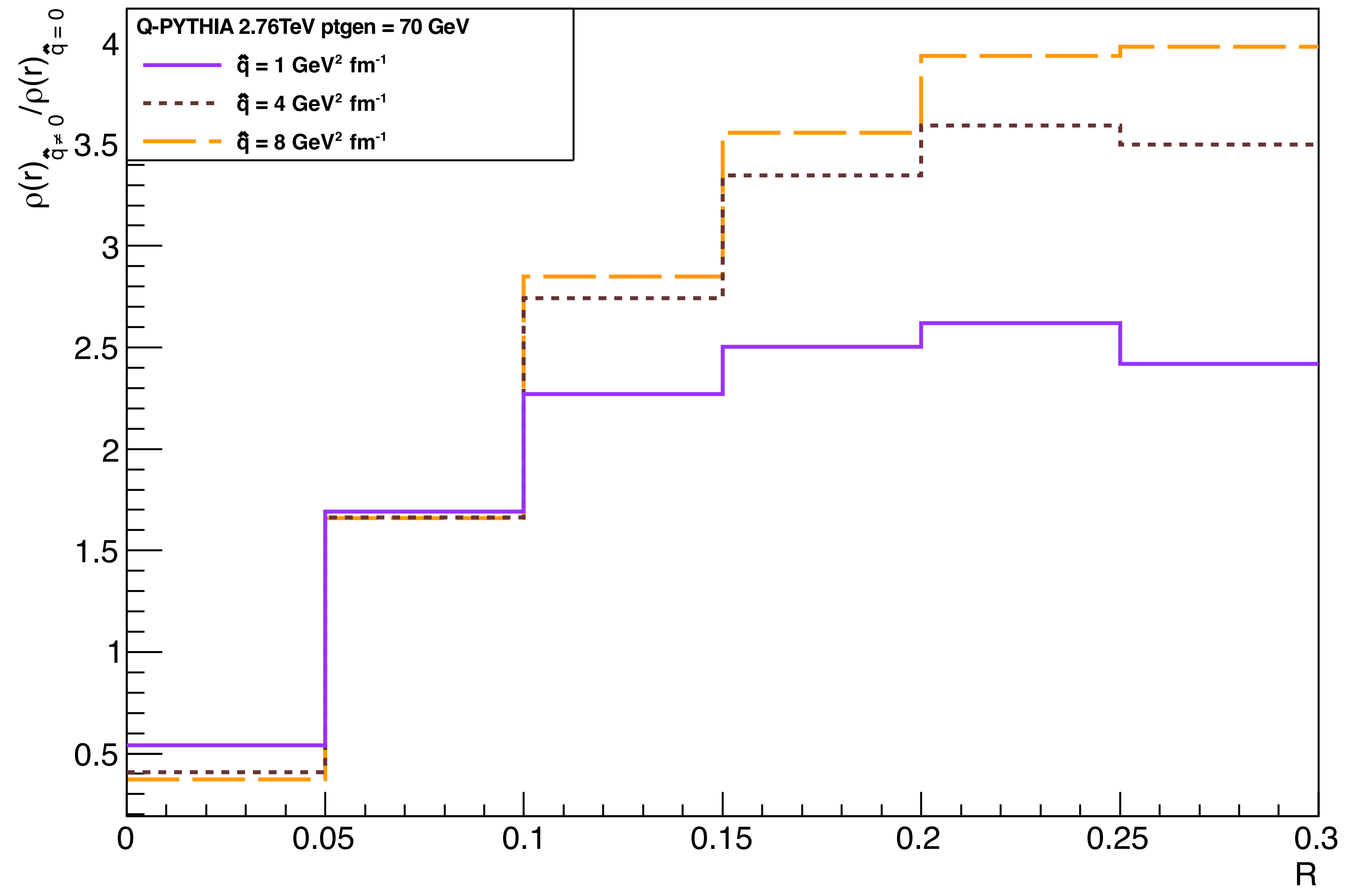


Everything seems to work, we can go home!

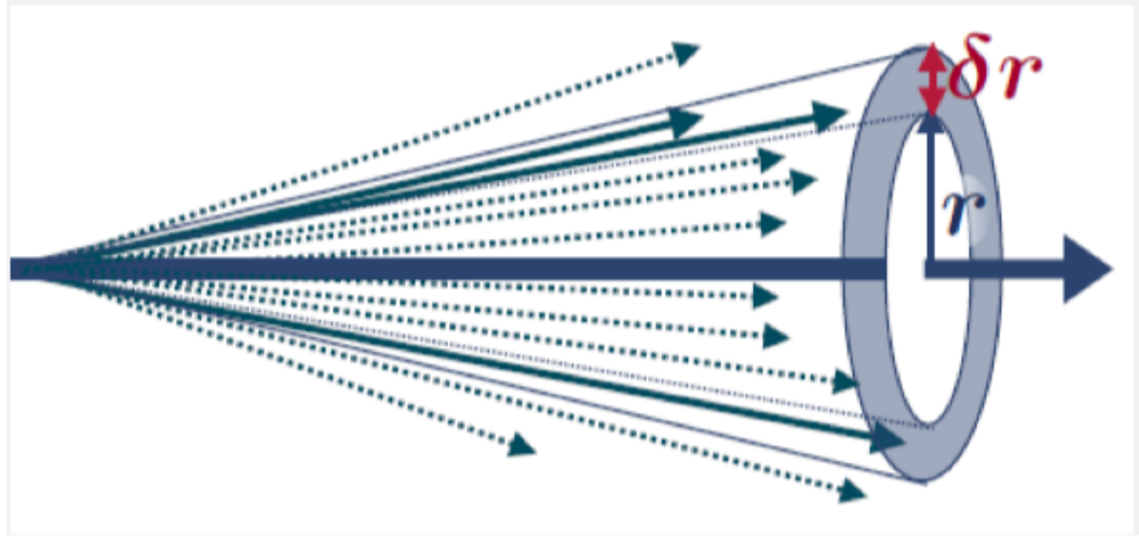
Not so fast…

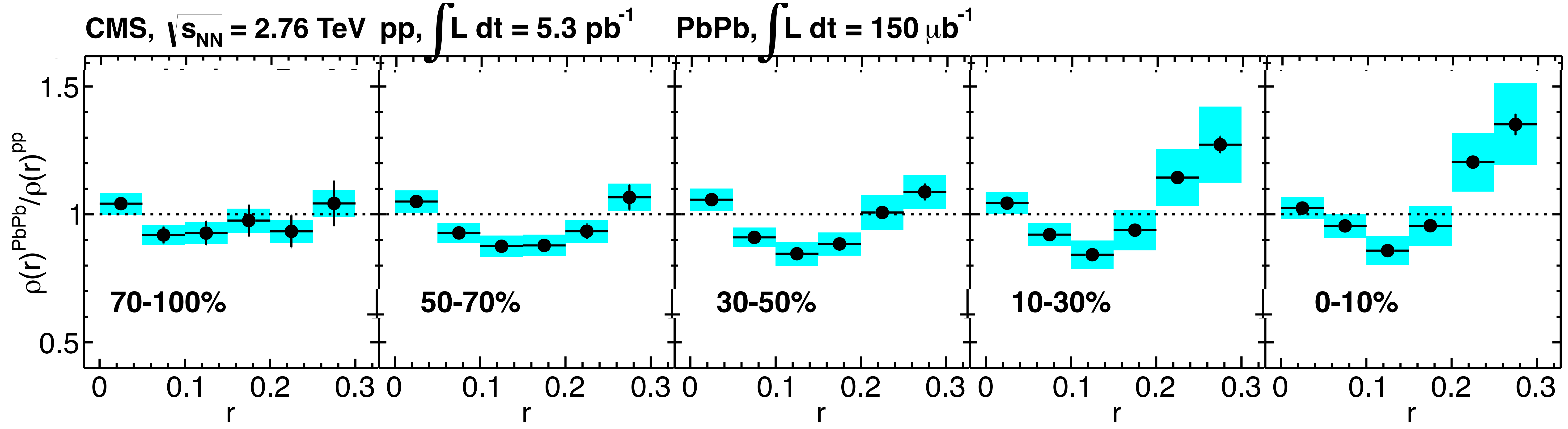
[L.Apolinário, QCD Forward Physics 2014]



- Quantitative comparisons show some disagreement…
  - Monte Carlo approaches based on in-medium single gluon radiation fail to describe some of the intra-jet features!

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}}\frac{\sum_{\text{tracks}\,\in\,[r_a,\,r_b)} p_T^{\text{track}}}{p_T^{\text{jet}}}$$





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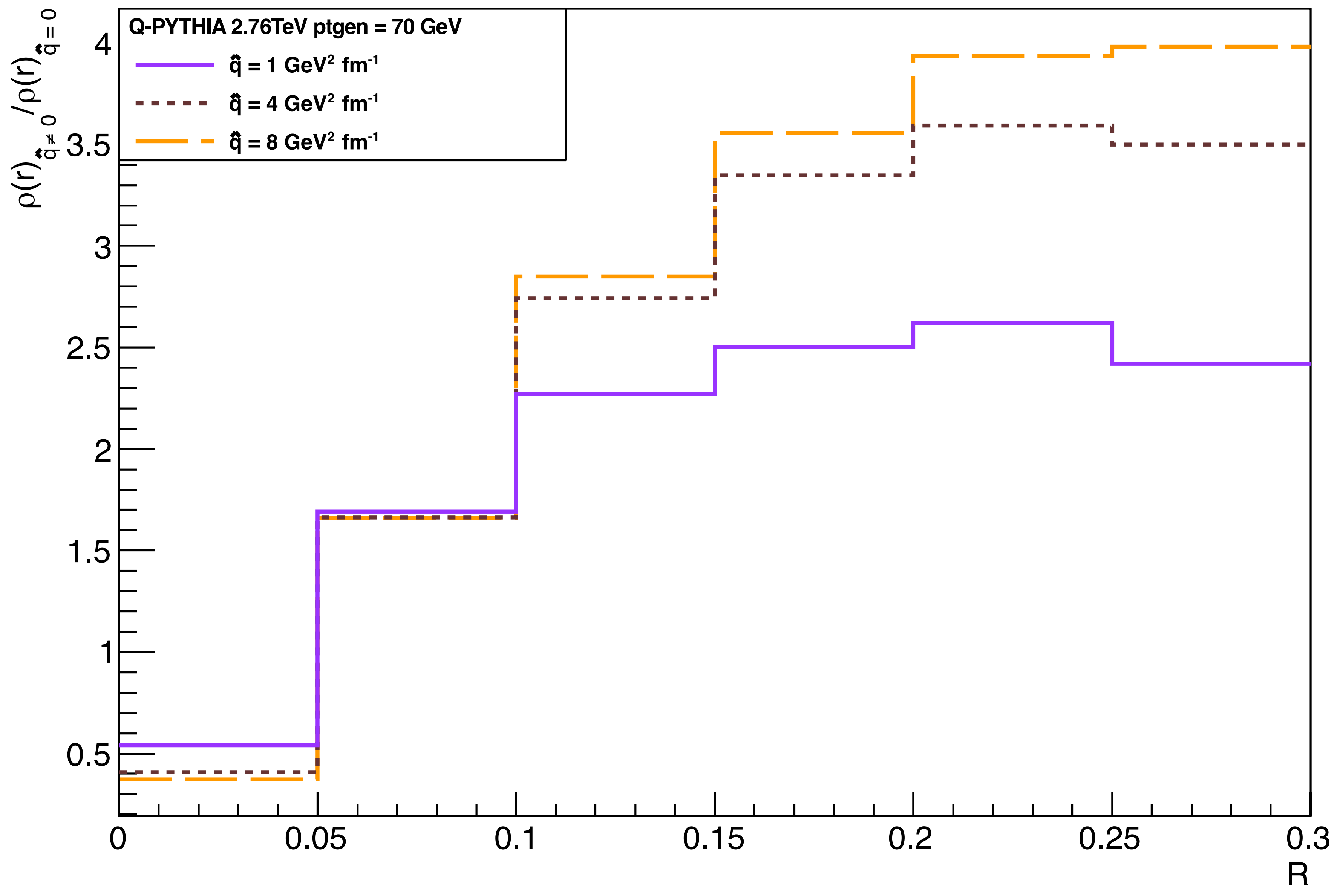

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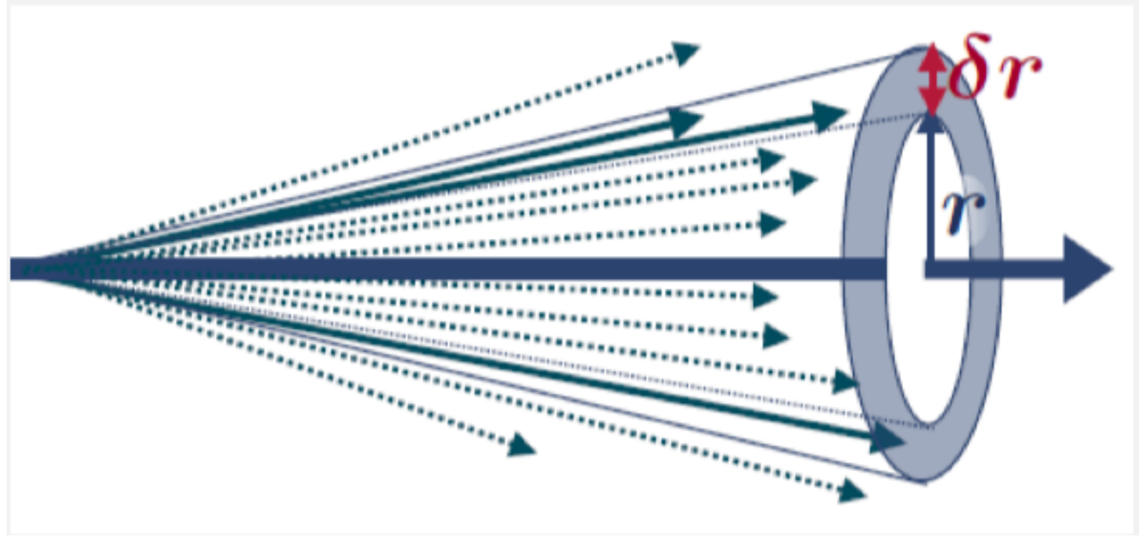

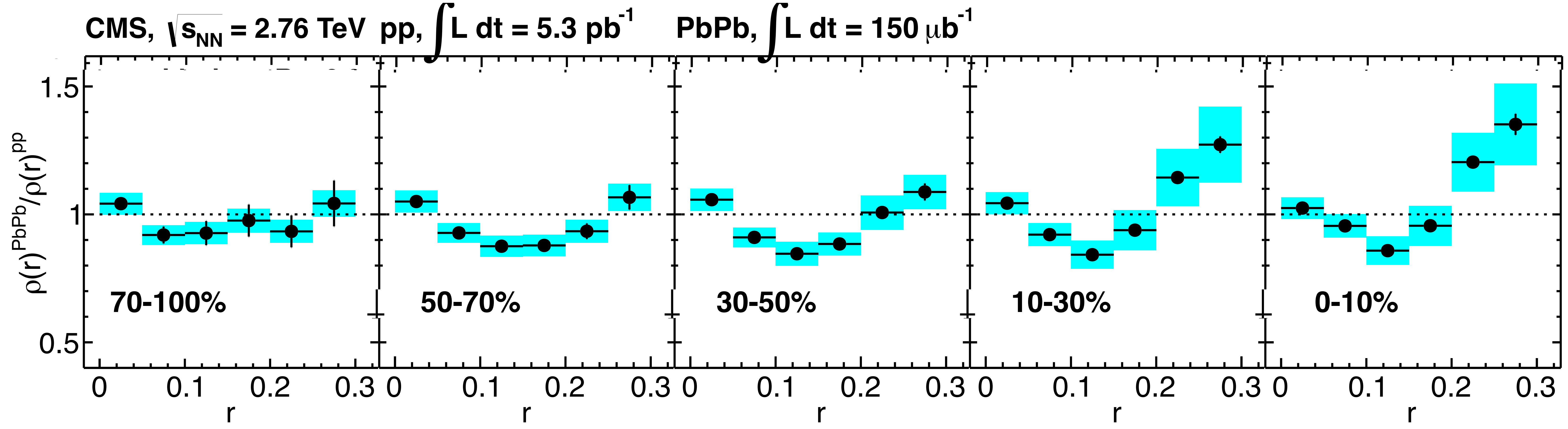

Qualitative disagreement…

Let’s go back again…

What is a jet?

- A jet in pp:
  - Defined with a jet clustering algorithm based (or not) in QCD principles: anti-k_T, k_T, C/A,…
    - ➡ Have an object that can be related to the parton shower
    - ➡ Have an object that can be equally treated at parton, particle or calorimetric level

What is a jet?

- A jet in heavy-ions:
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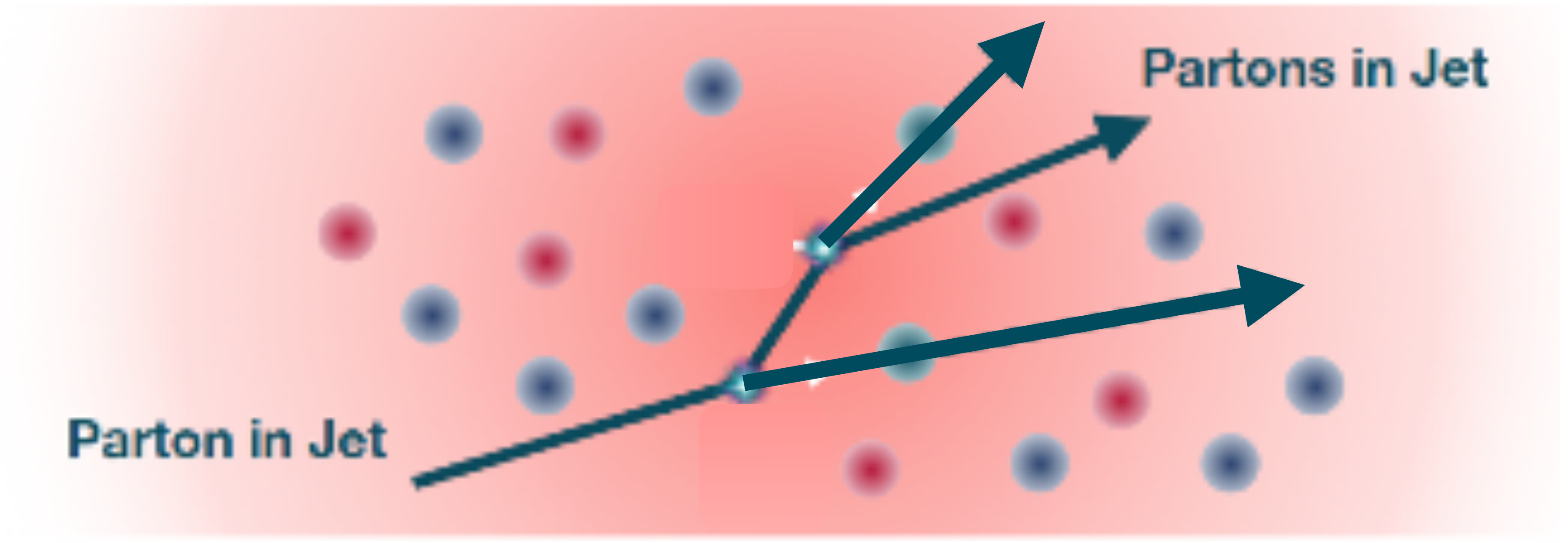

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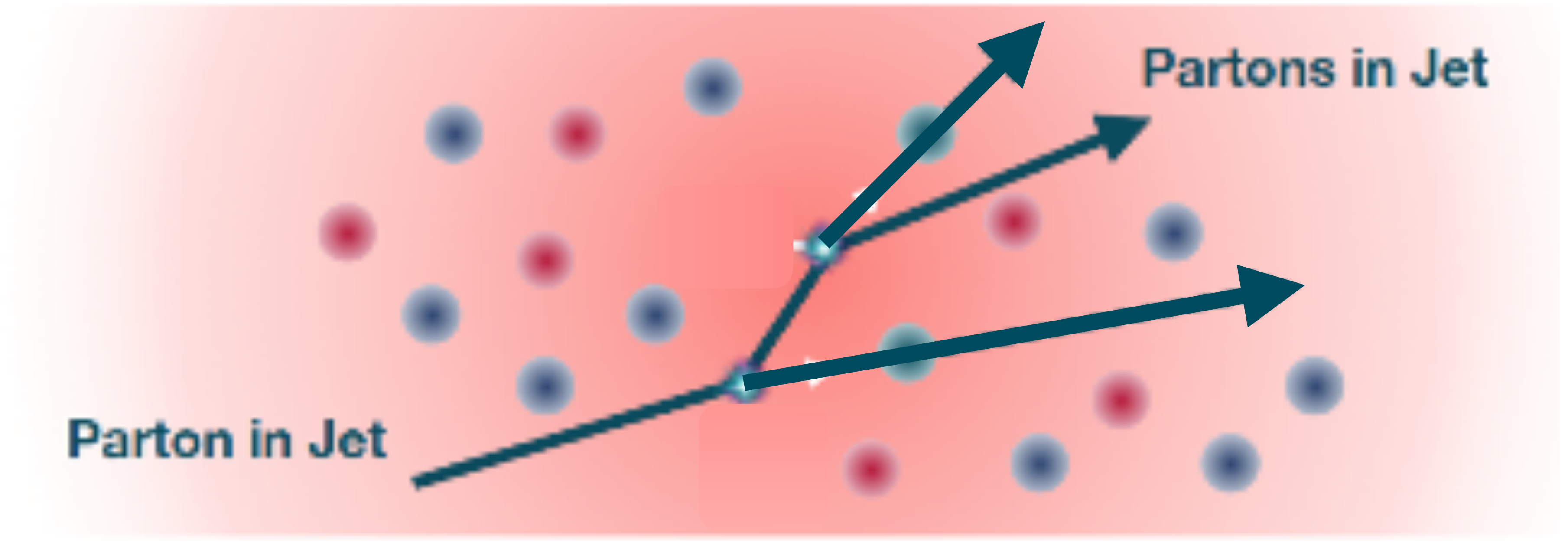
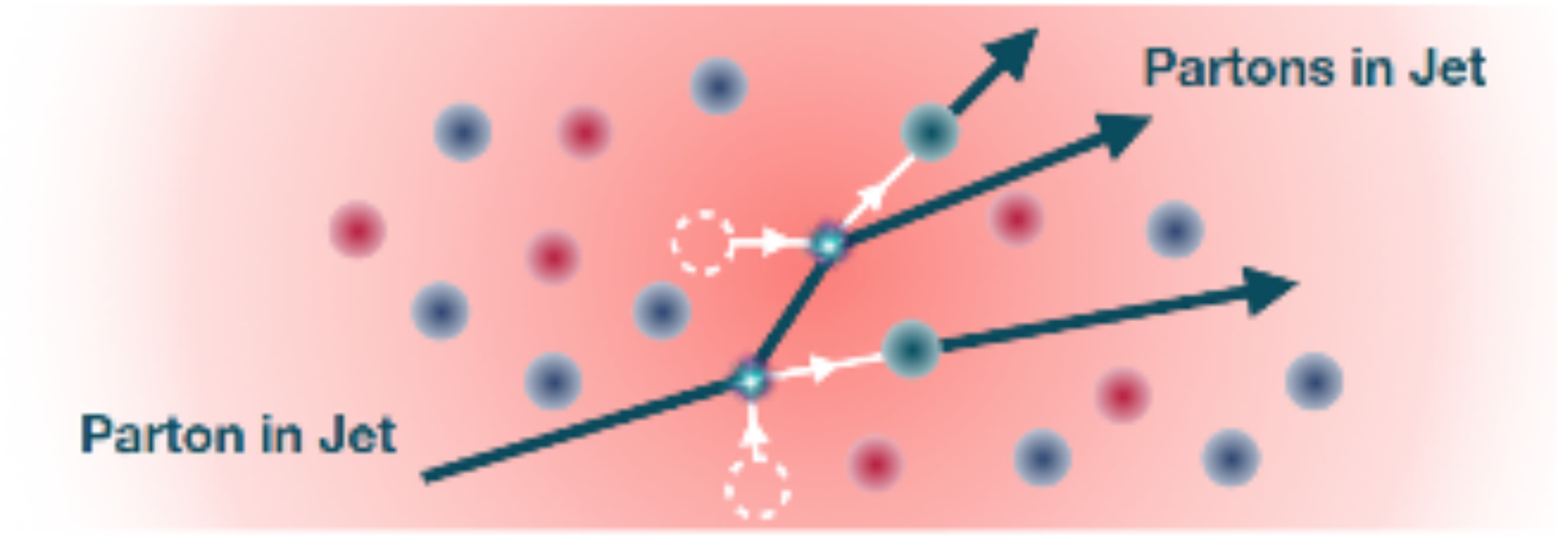
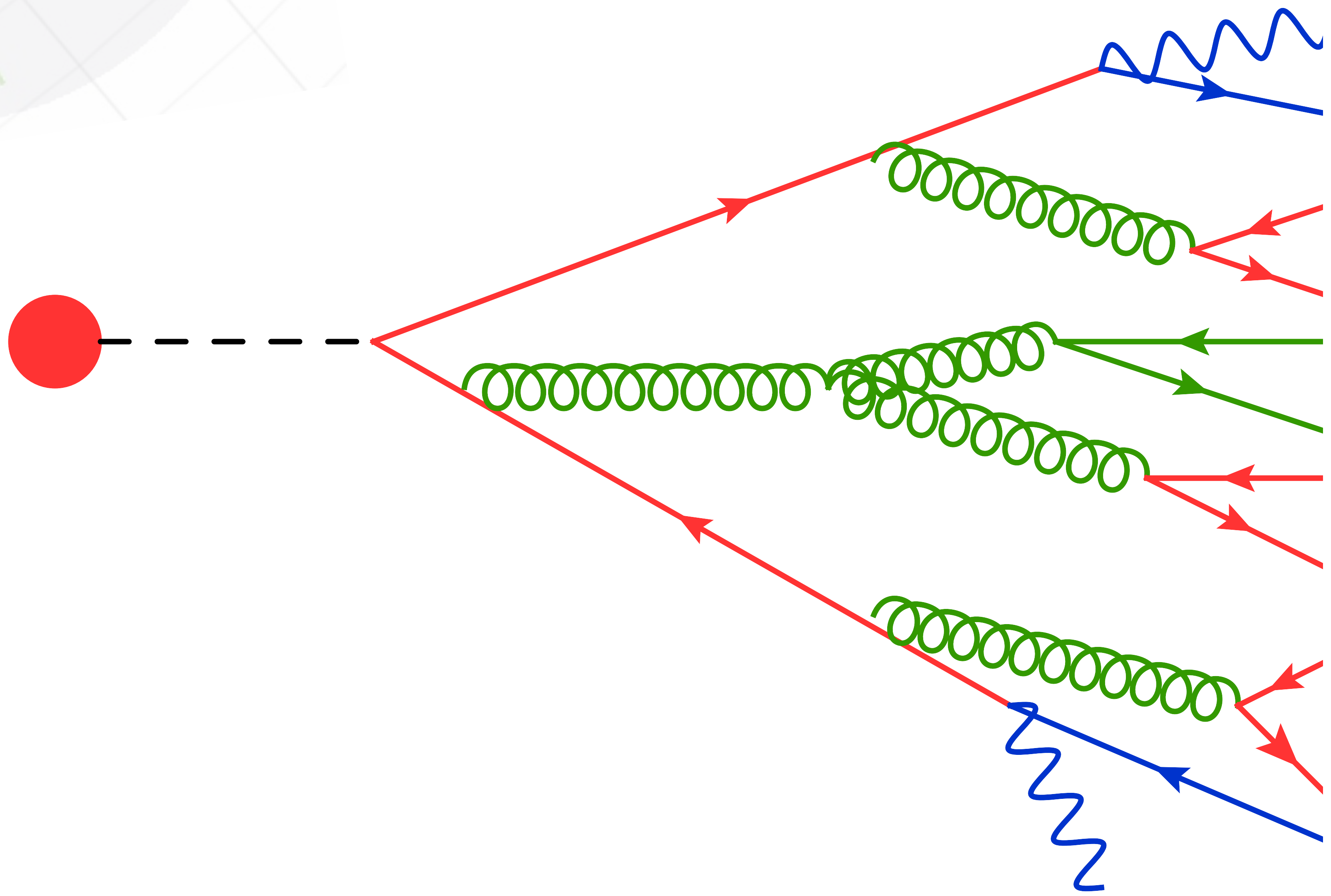




How to define a jet in a heavy-ion?

Jet Quenching v2.0

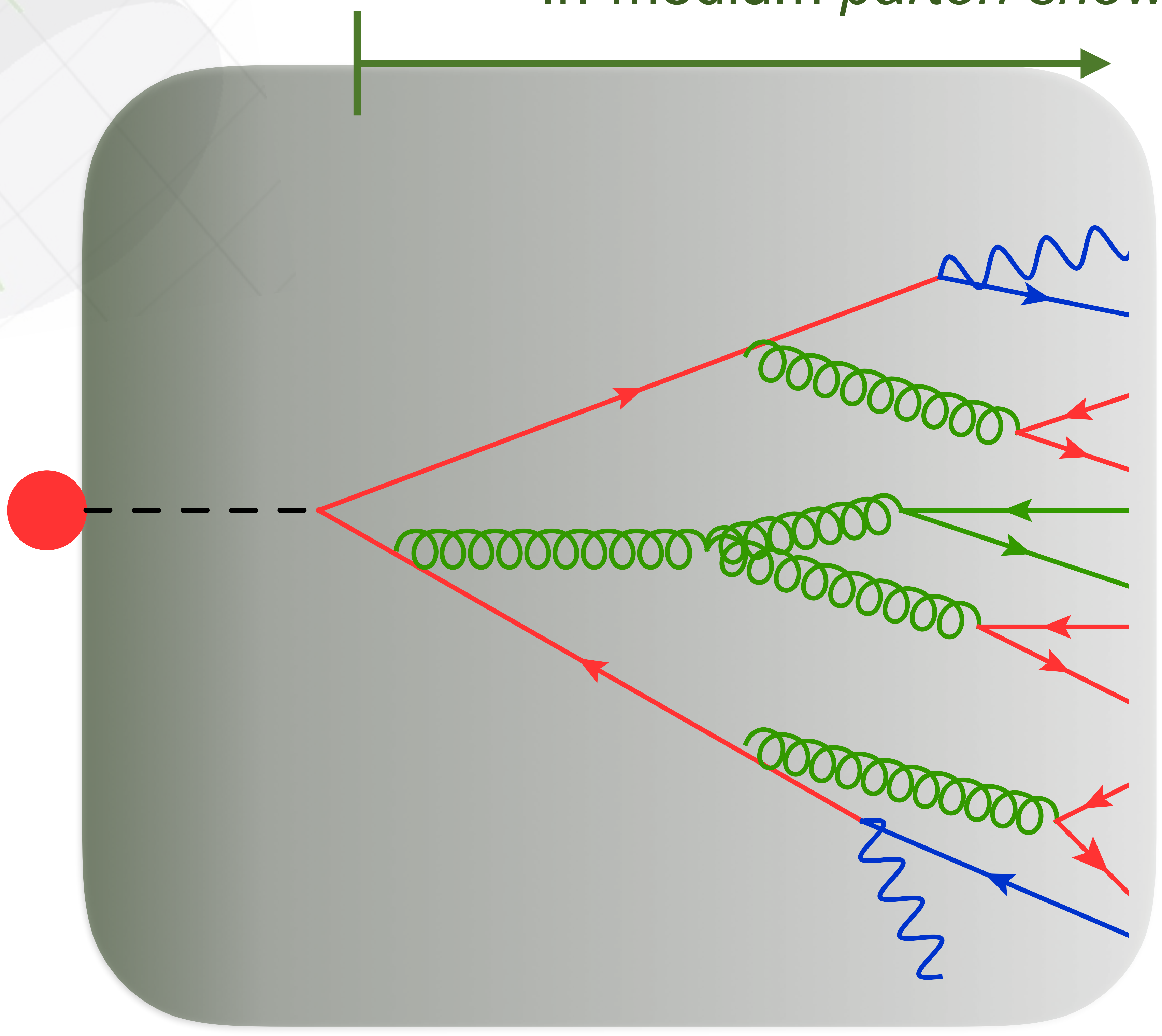
- The way we see and define a jet should include all momentum scales:



Jet Quenching v2.0

- The way we see and define a jet should include all momentum scales:

In-medium *parton shower*



Expanding *Medium*

Jet Quenching v2.0

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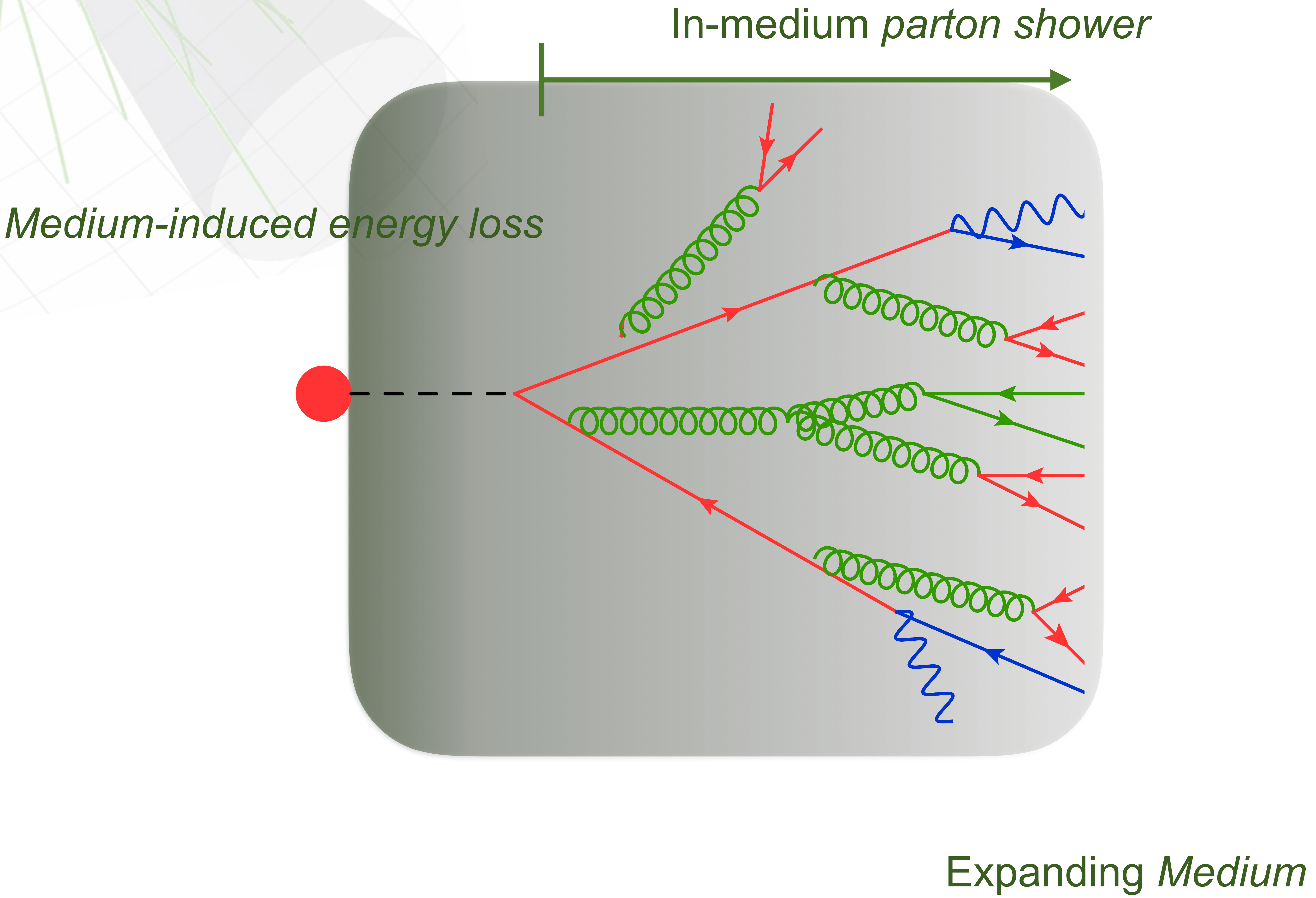

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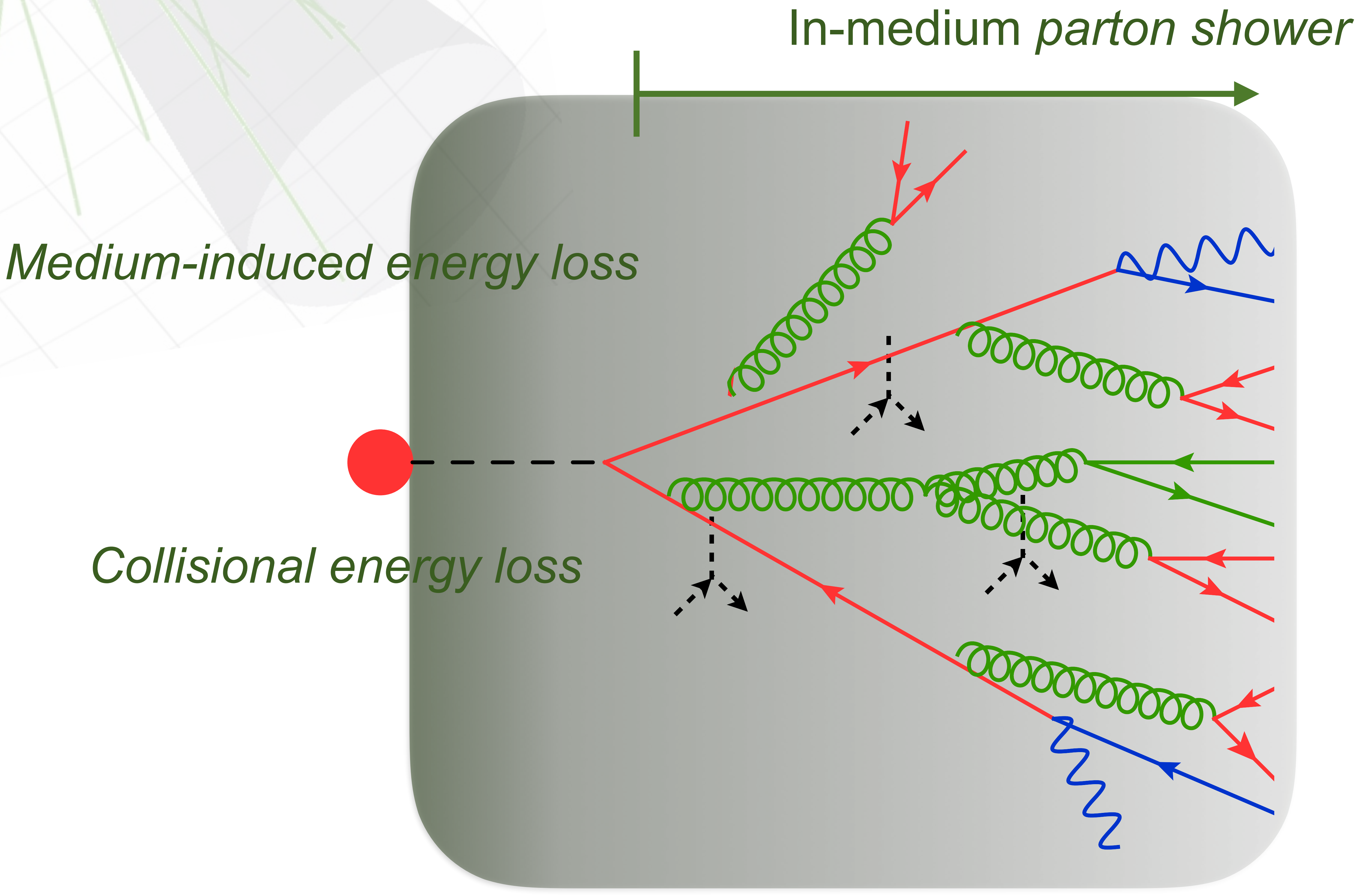

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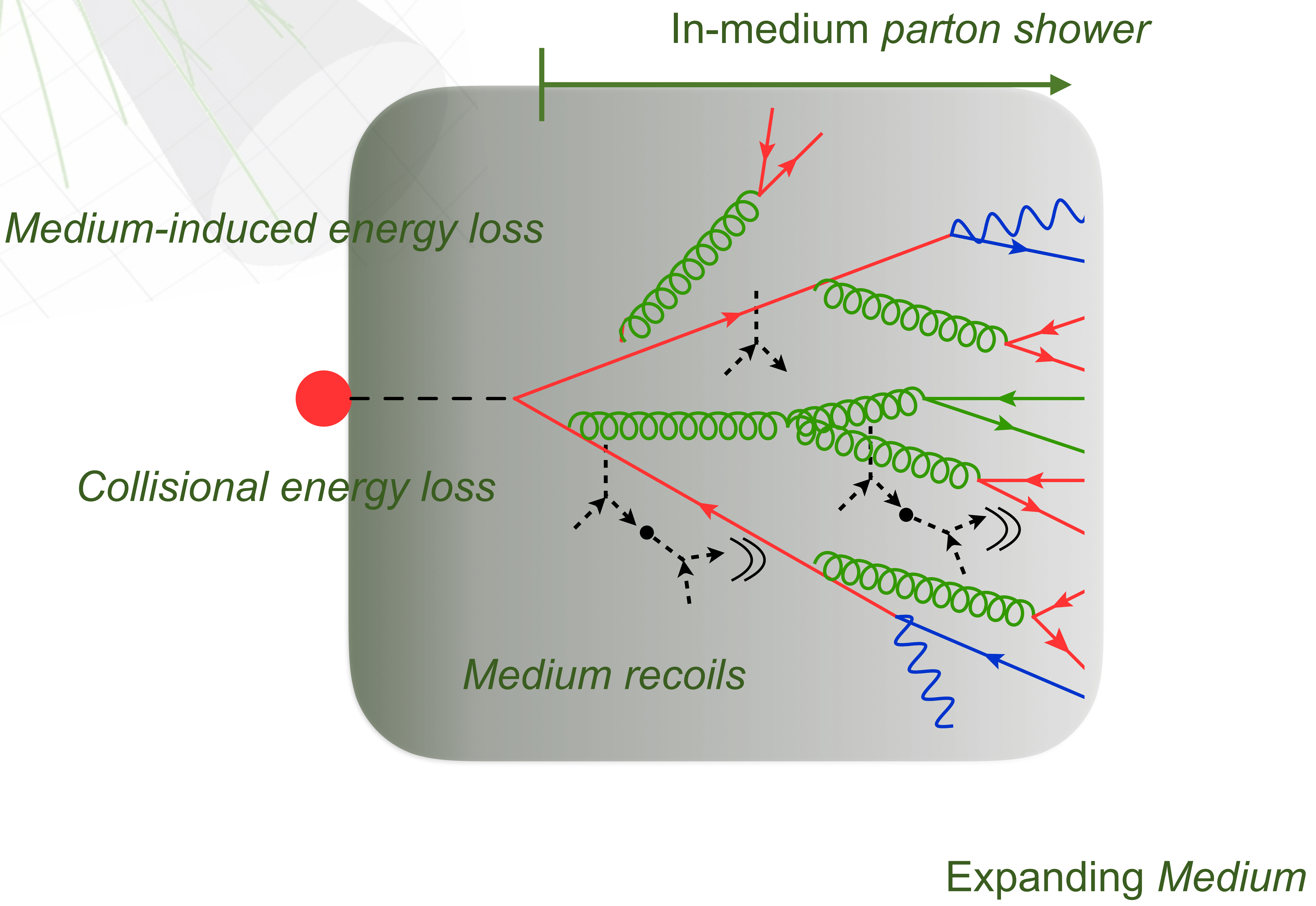

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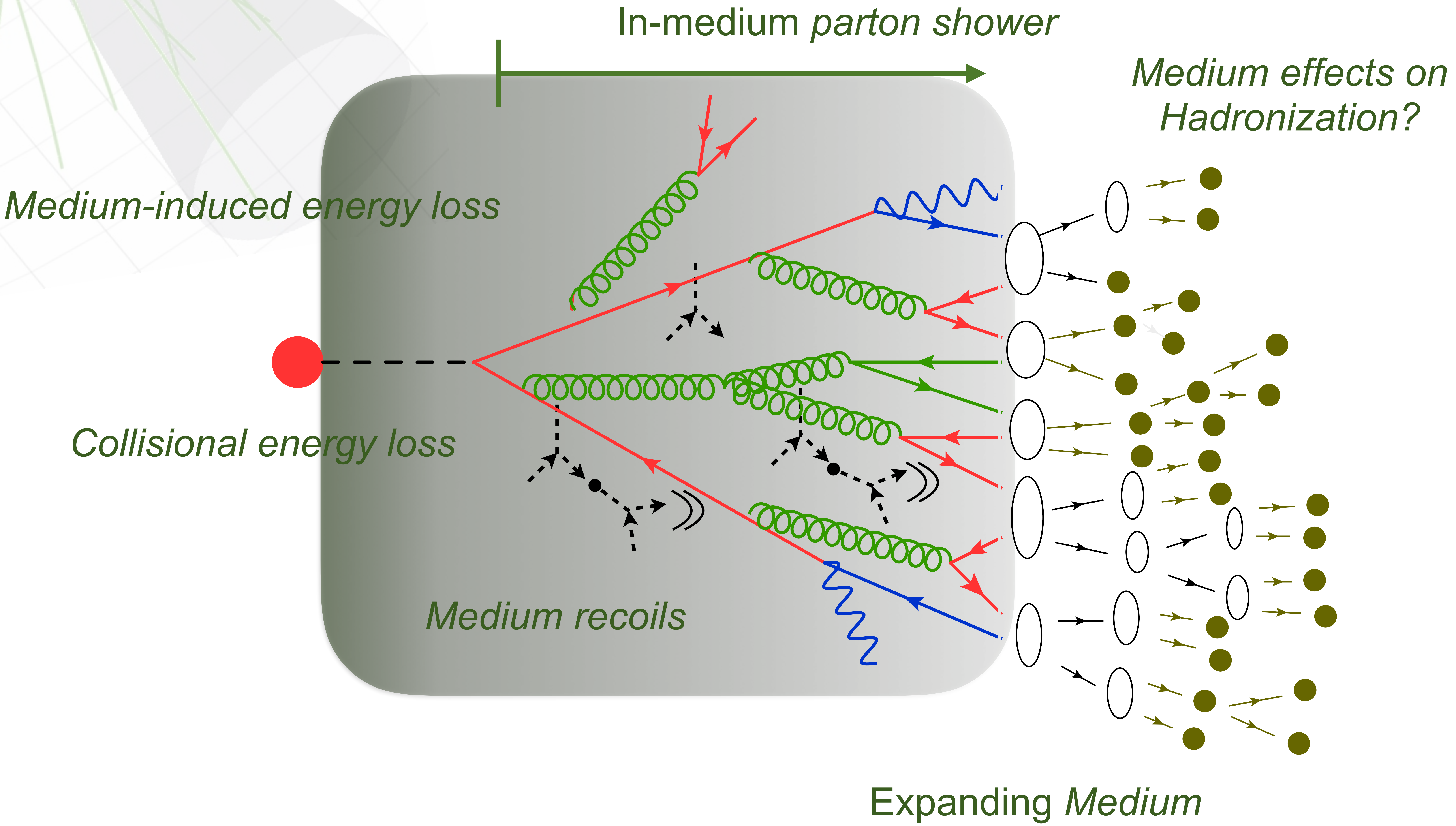

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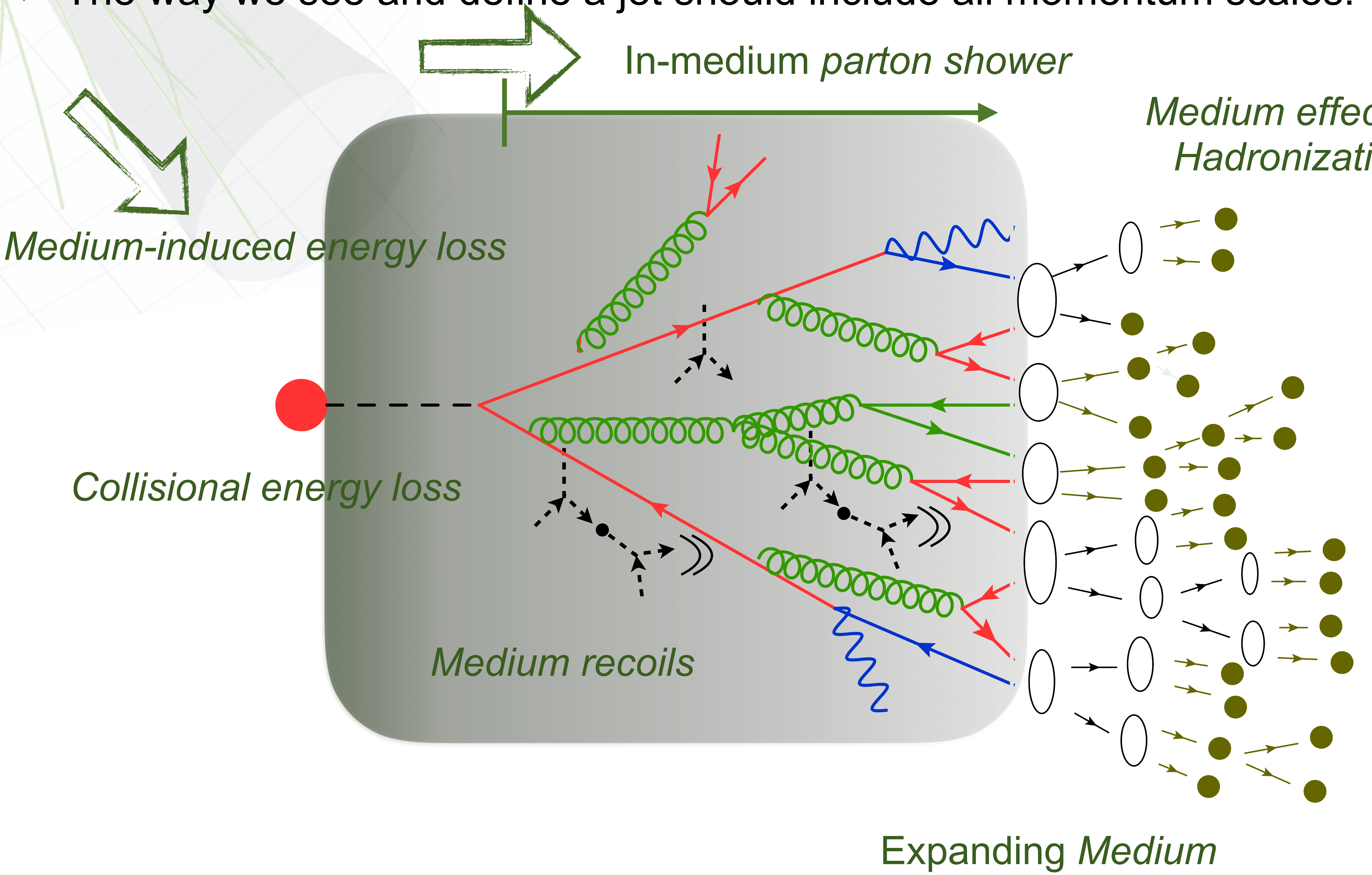

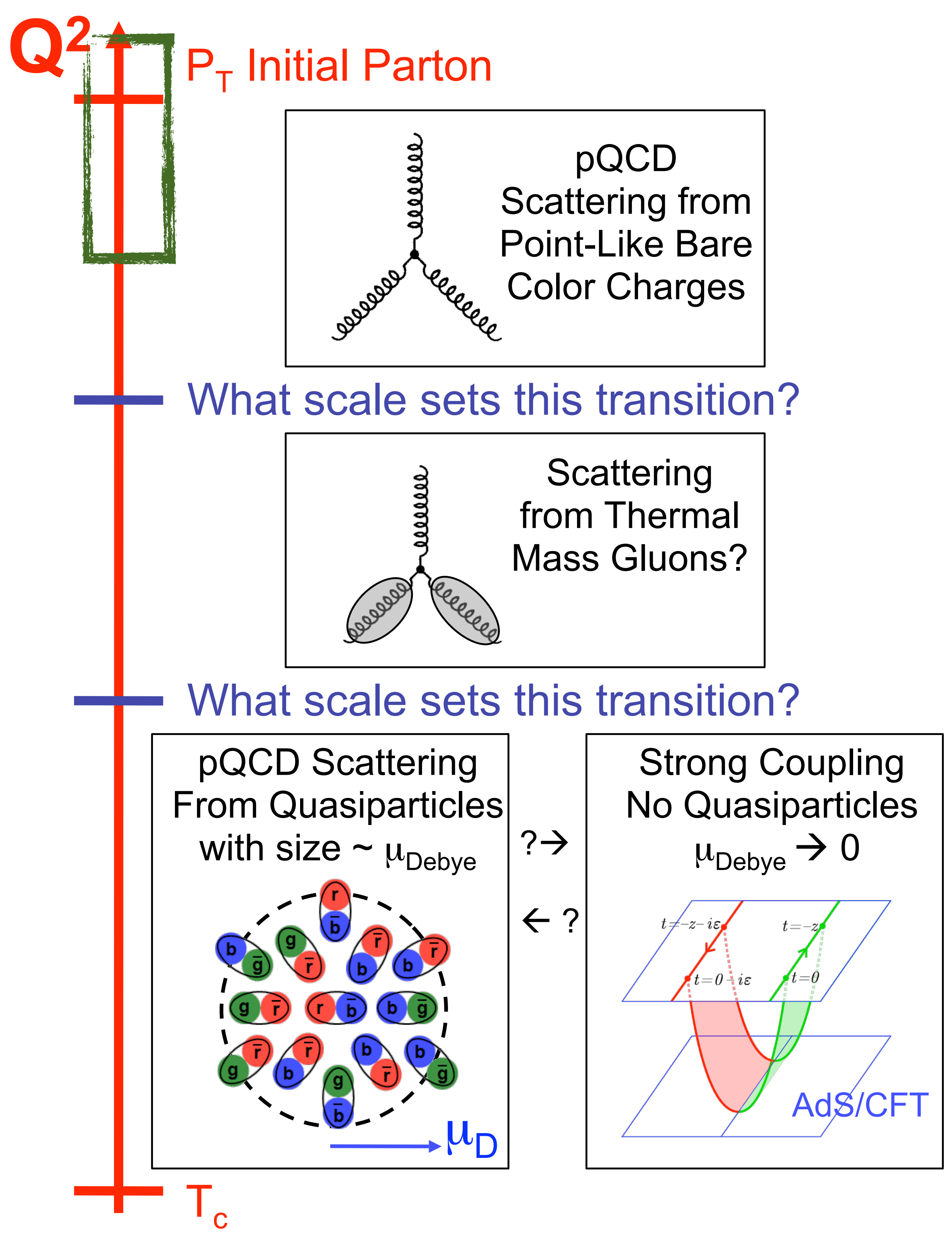

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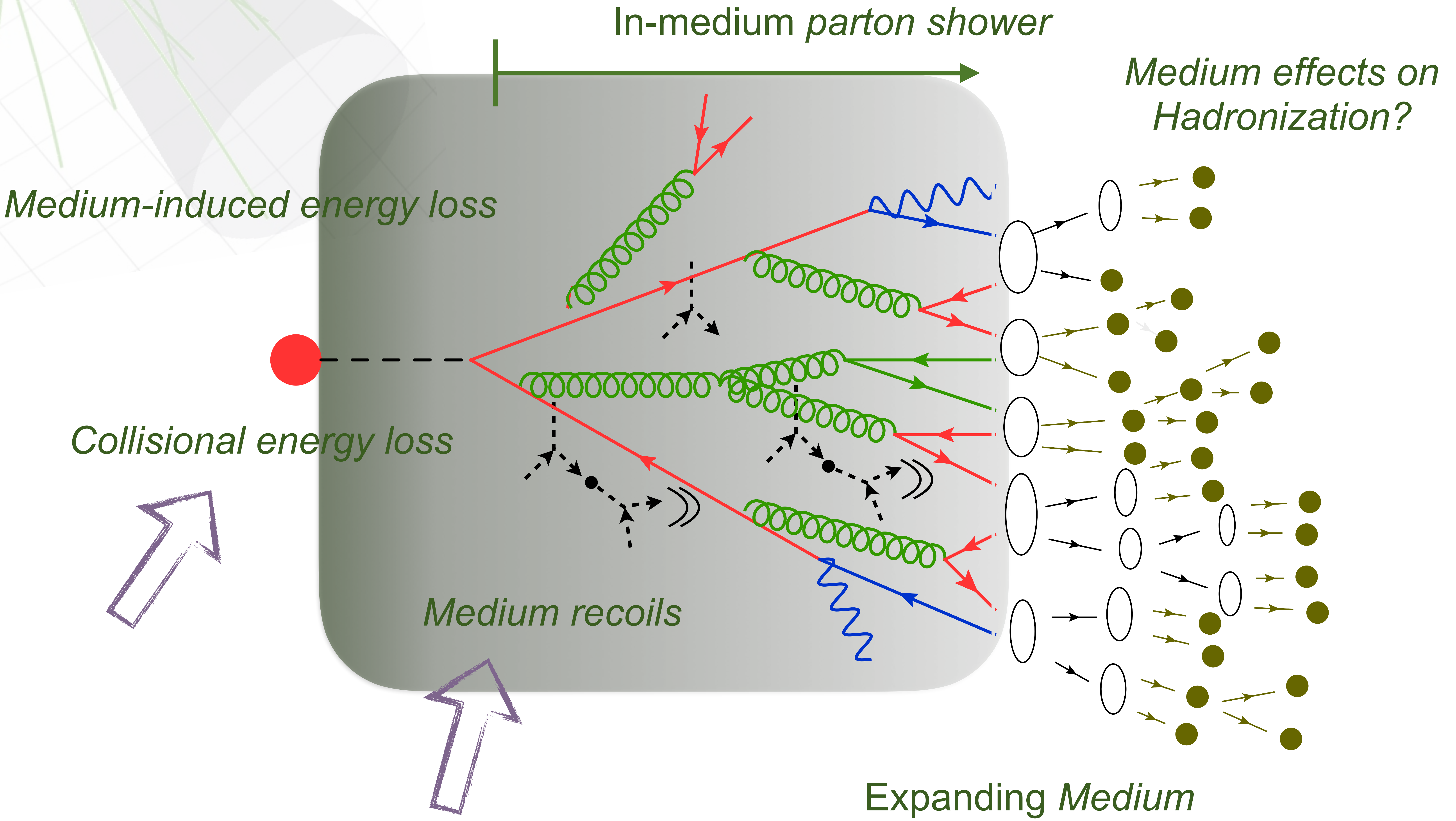
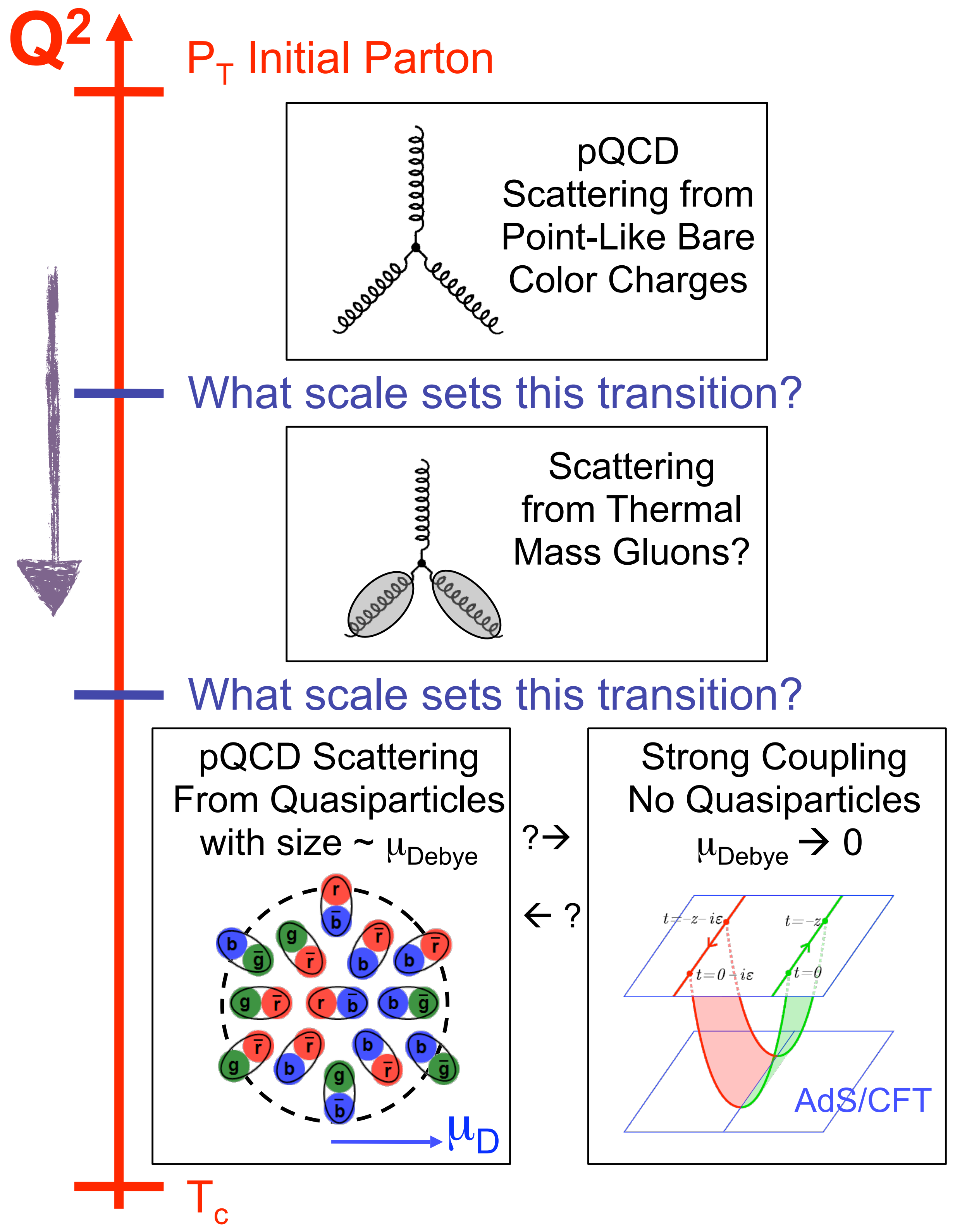




Medium response

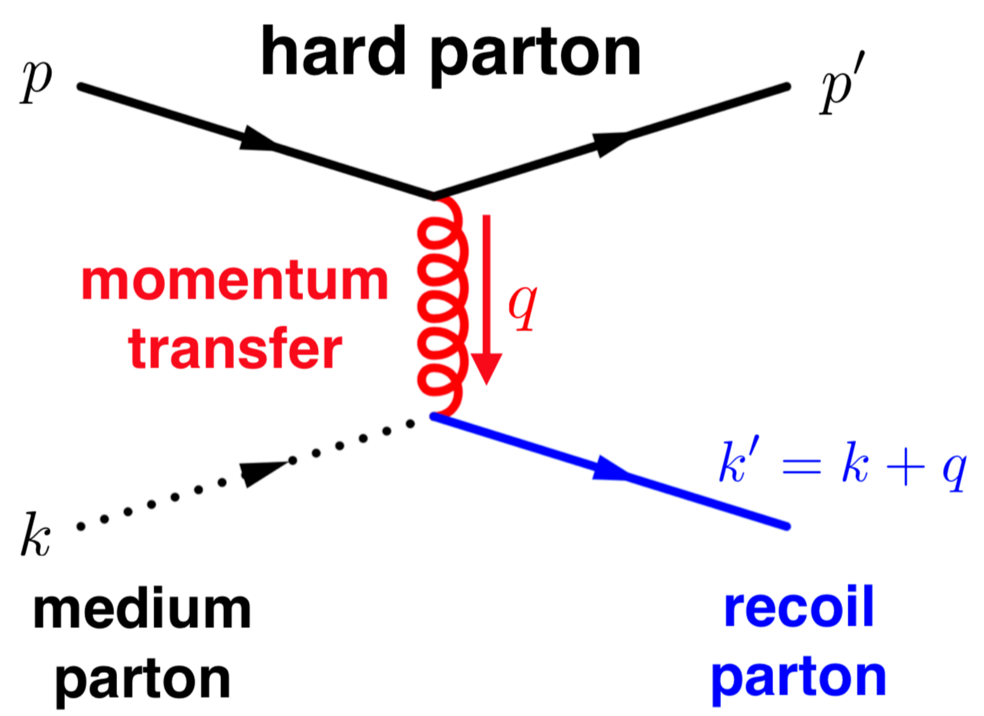
LBT: [Cao, Luo, Qin, Wang (16) He, Luo, Wang, Zhu (17)]

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

JEWEL: [Elayavalli, Zapp (17)]

- QGP part that become correlated with the jet (not to be subtracted!)
  - Seen as (pQCD approach):
    - Recoils from jet-medium interactions with a thermal/3D hydro particle distribution
      - ➡ Recoiled particle makes part of the jet: JEWEL

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



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      - ➡ Recoiled particle can further interact with medium constituents: MARTINI, LBT

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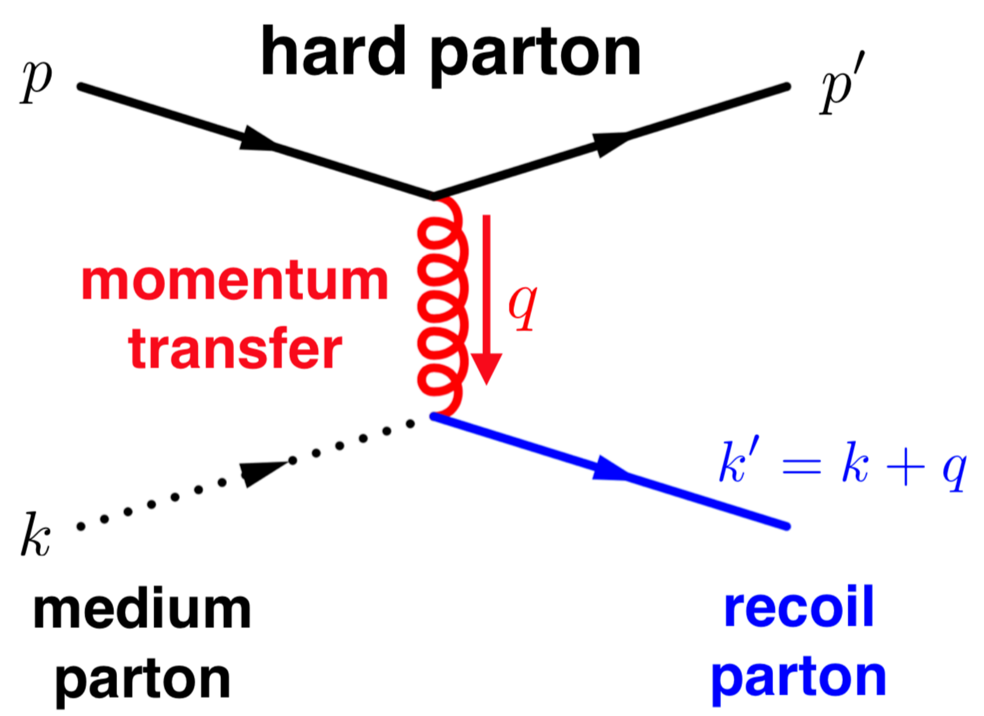
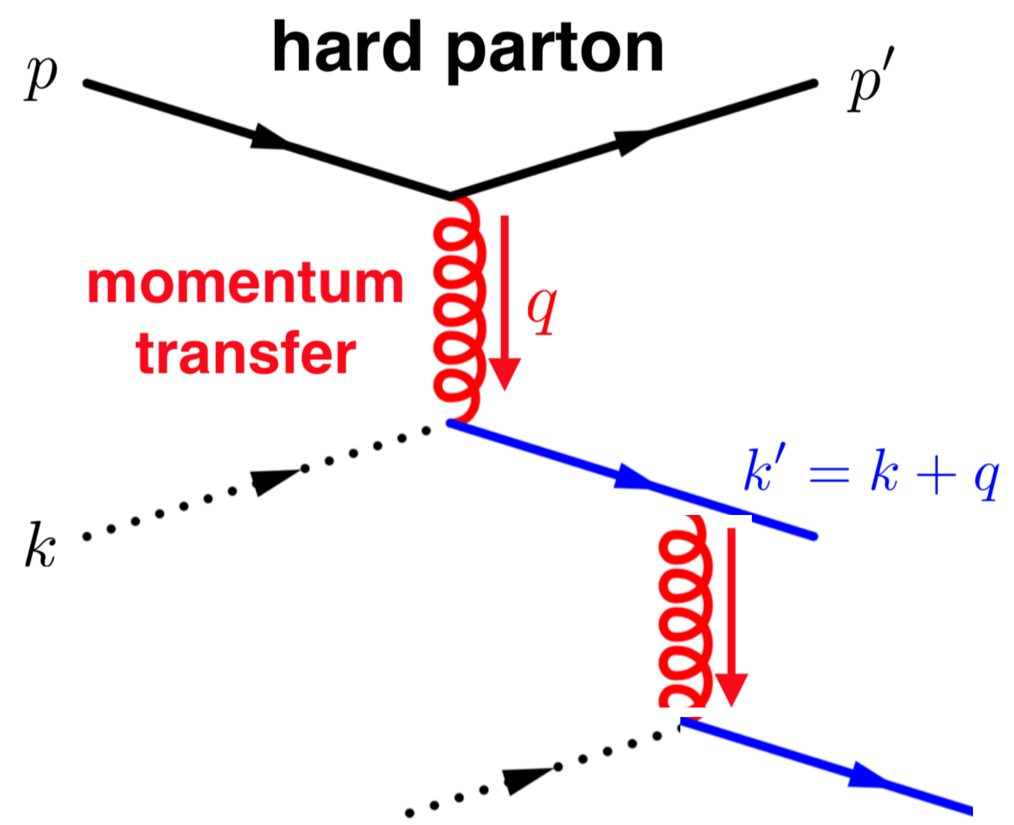


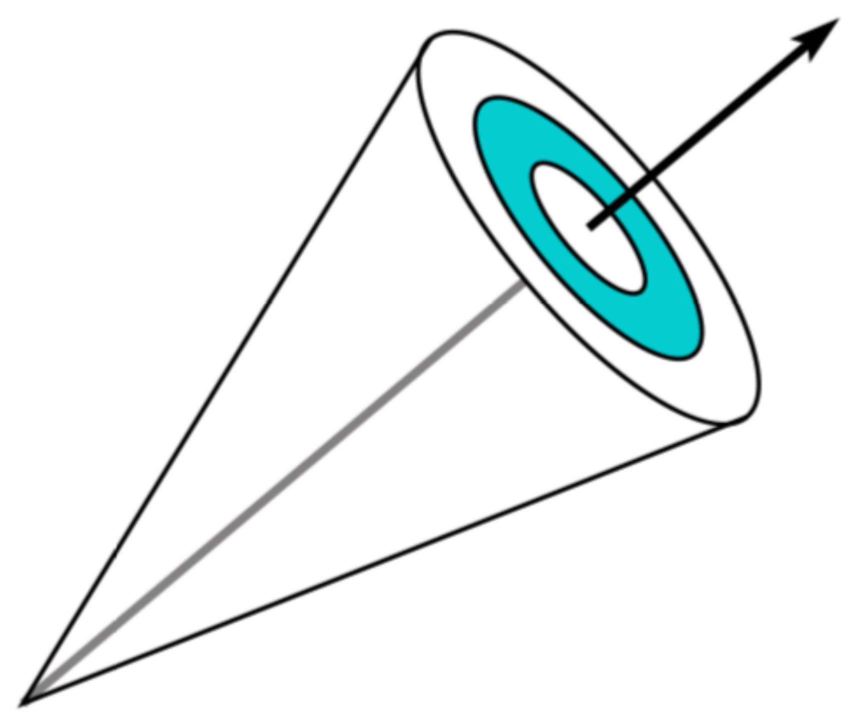
E.g: MARTINI



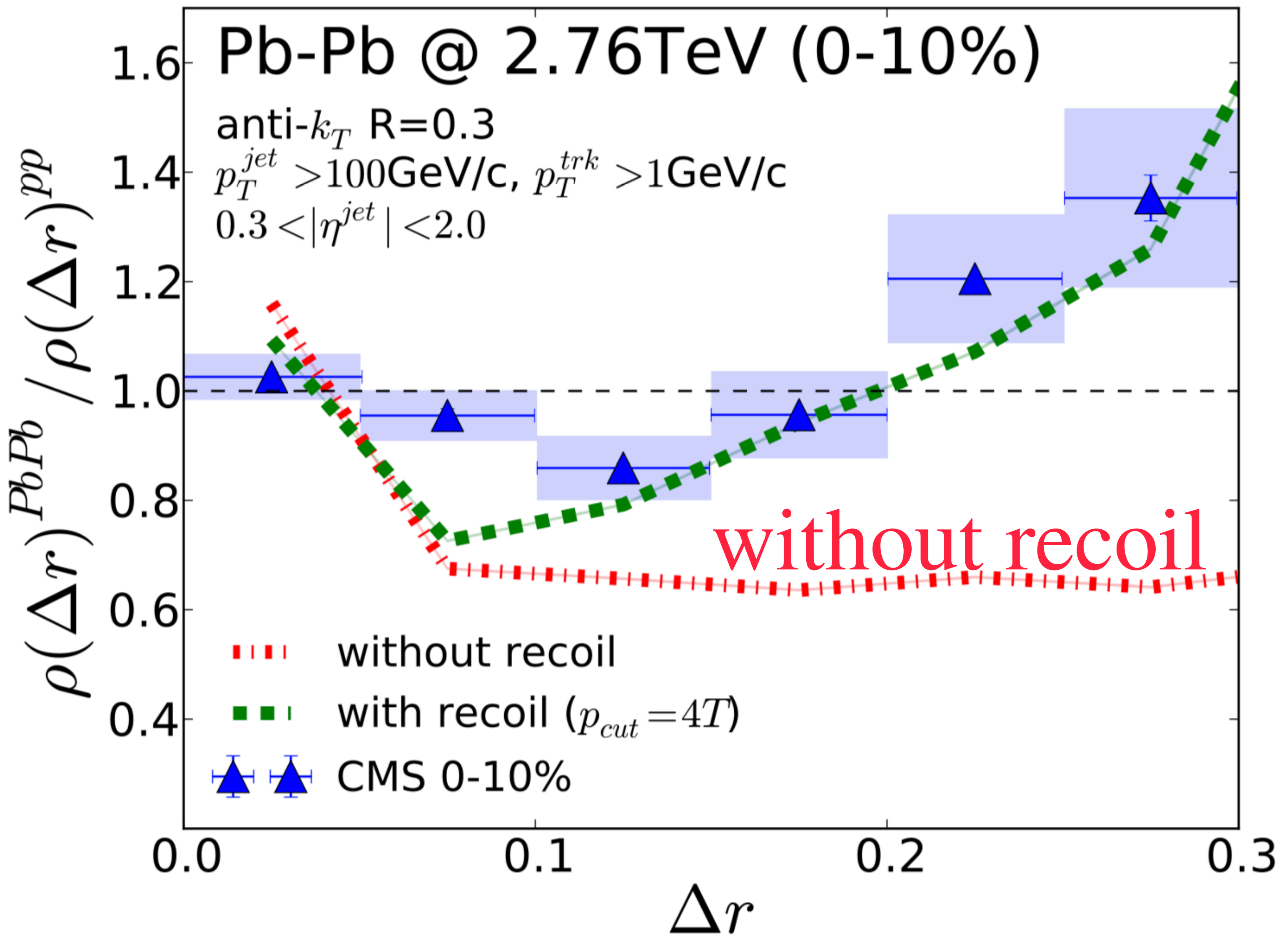
There are still problems…

- Magnitude of the medium recoil component to the jet varies from model to model…
  - Coupled Jet-Fluid (Analytical approach)
  - MARTINI (Monte Carlo approach based on in-medium gluon radiation)

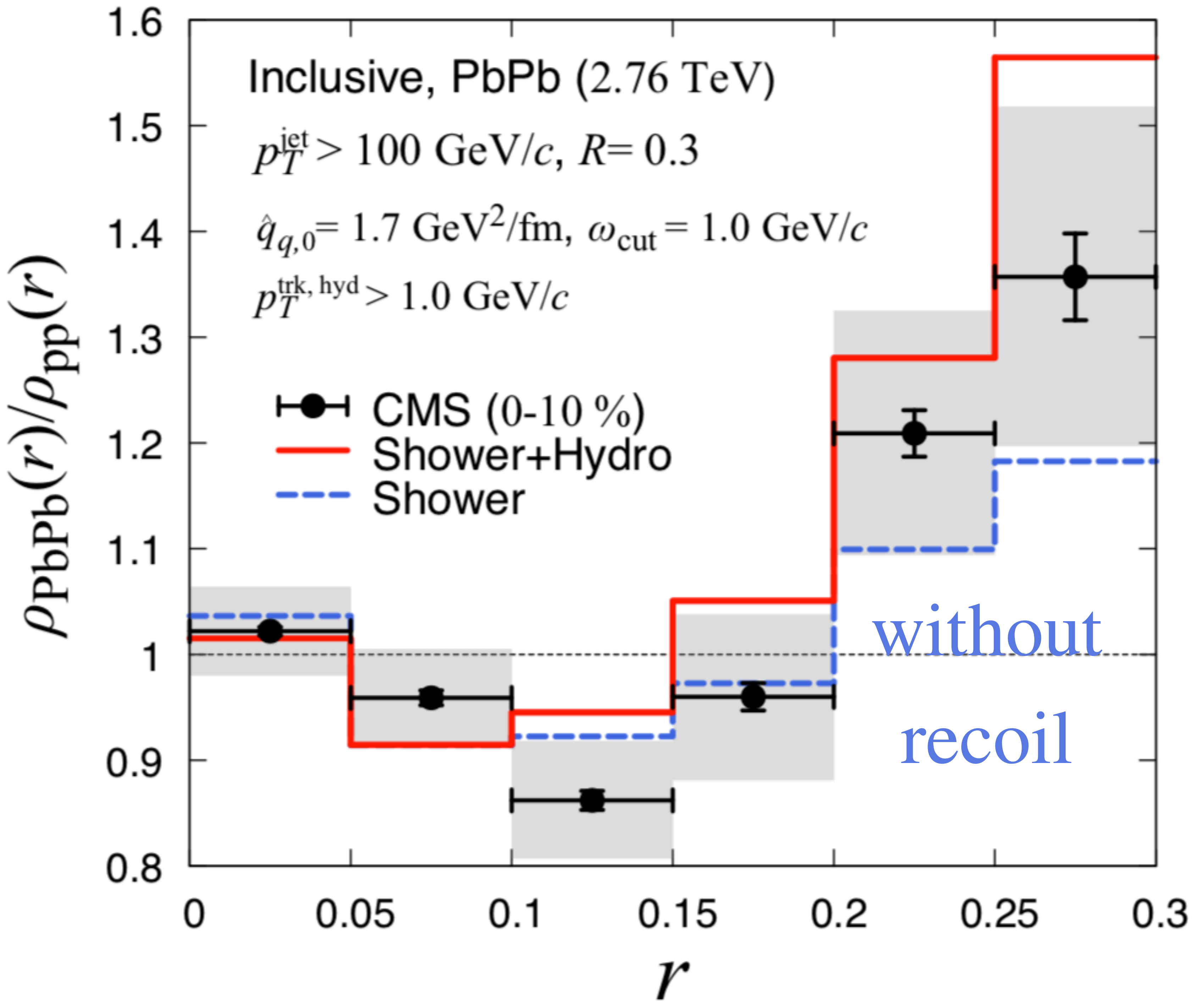
Recoil component
Best observed in the
"jet radial profile"



[MARINI: Park QM18]



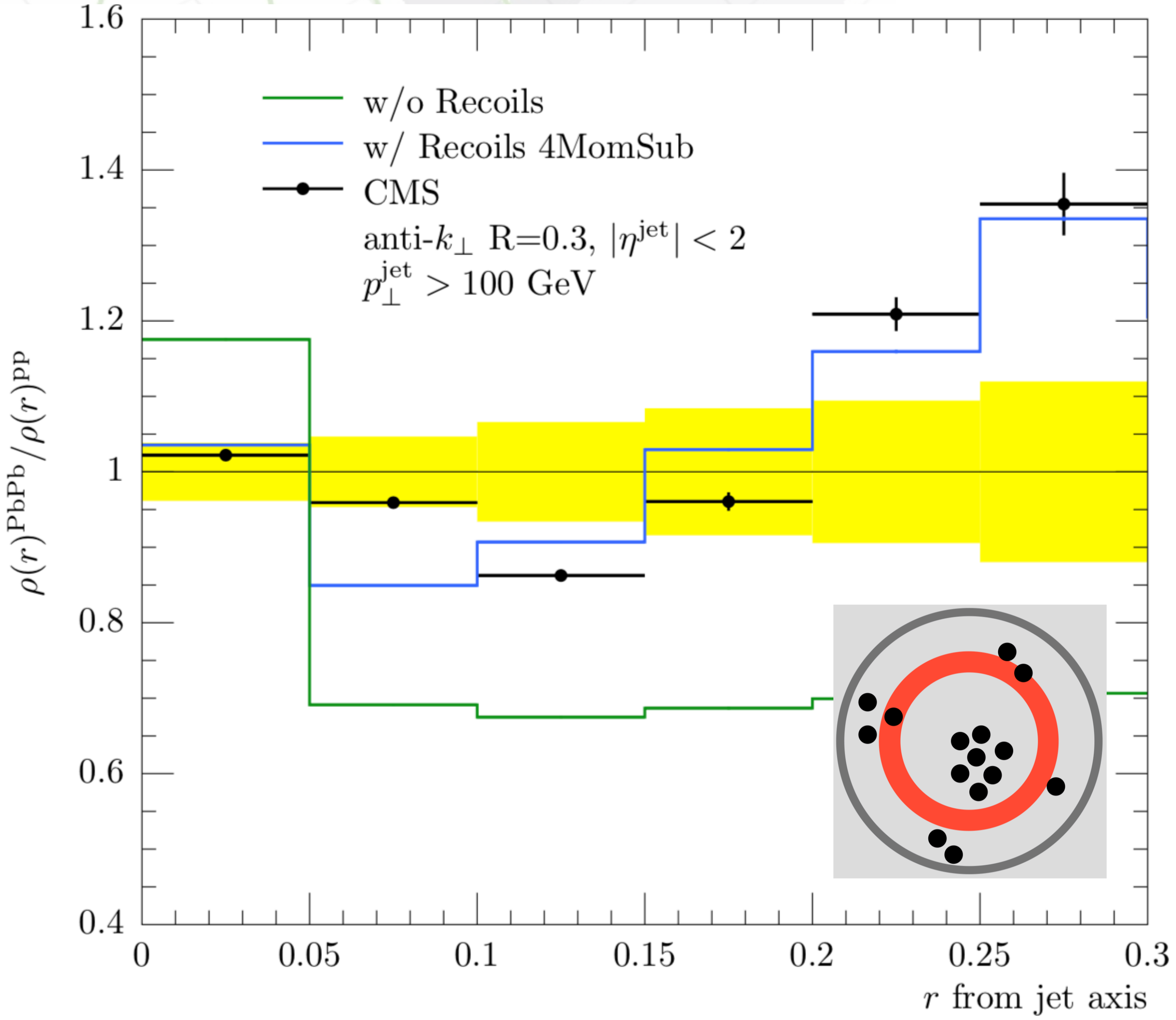
Couple Jet-Fluid: [arXiv: 1701.07951]



And more problems…

- Within the same model, not so easy to simultaneously describe jet radial profile and jet mass:

[JEWEL:1707.01539]



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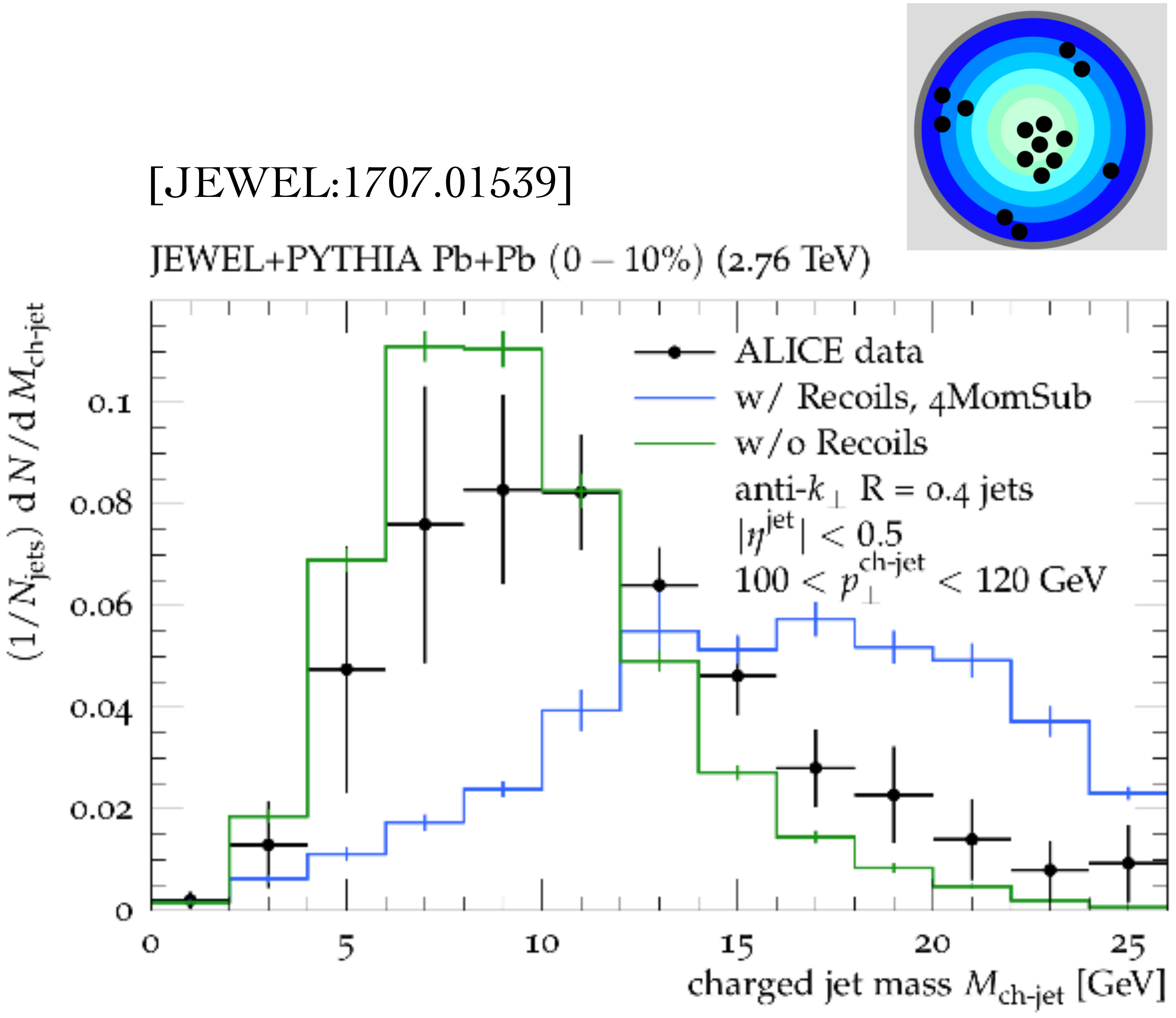

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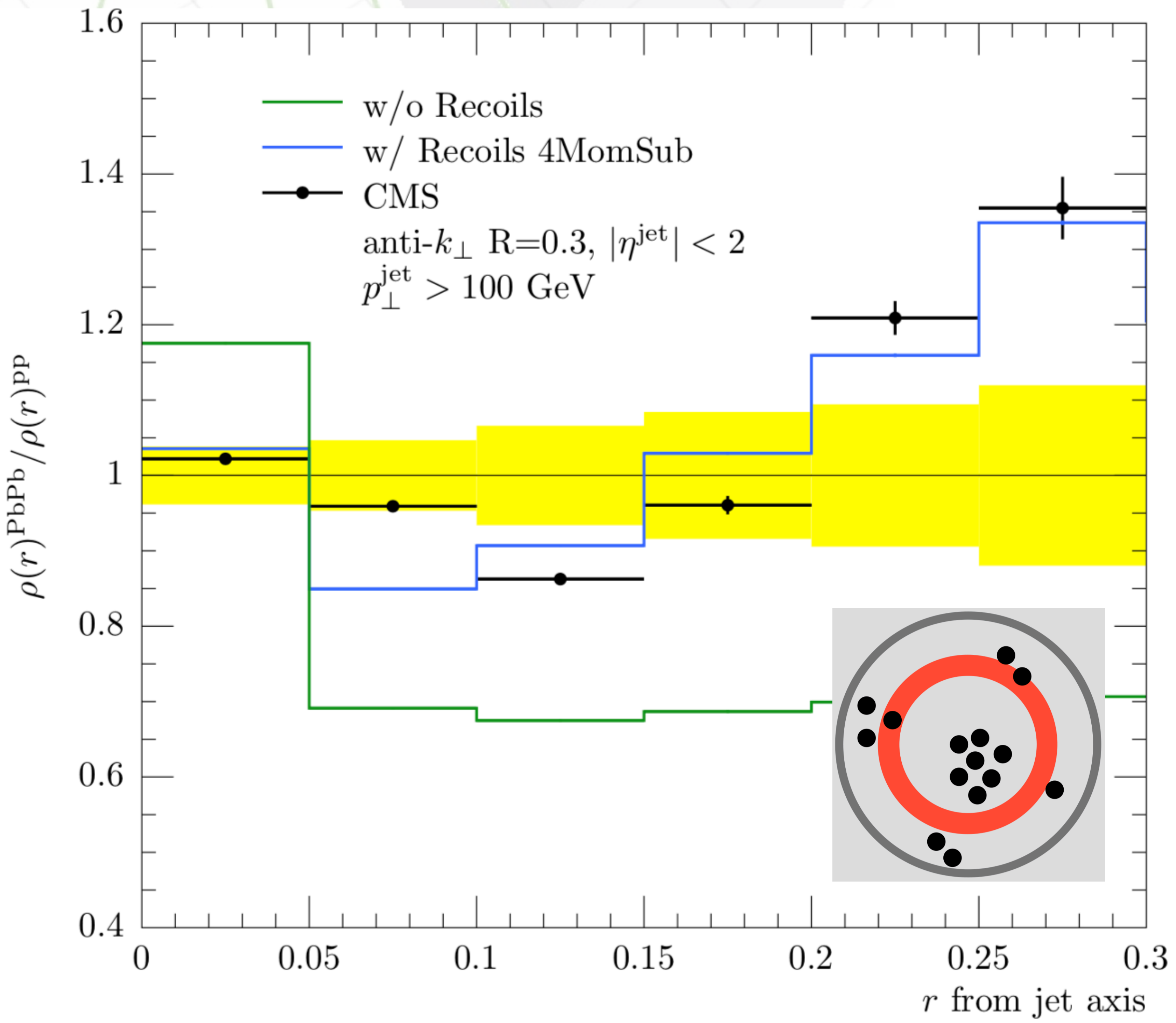

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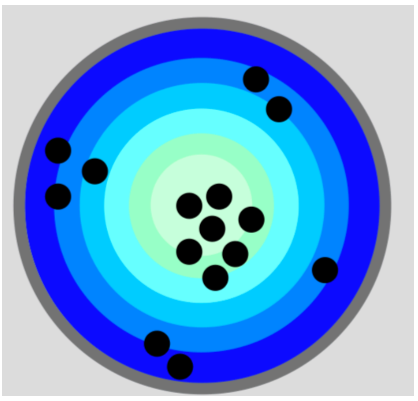

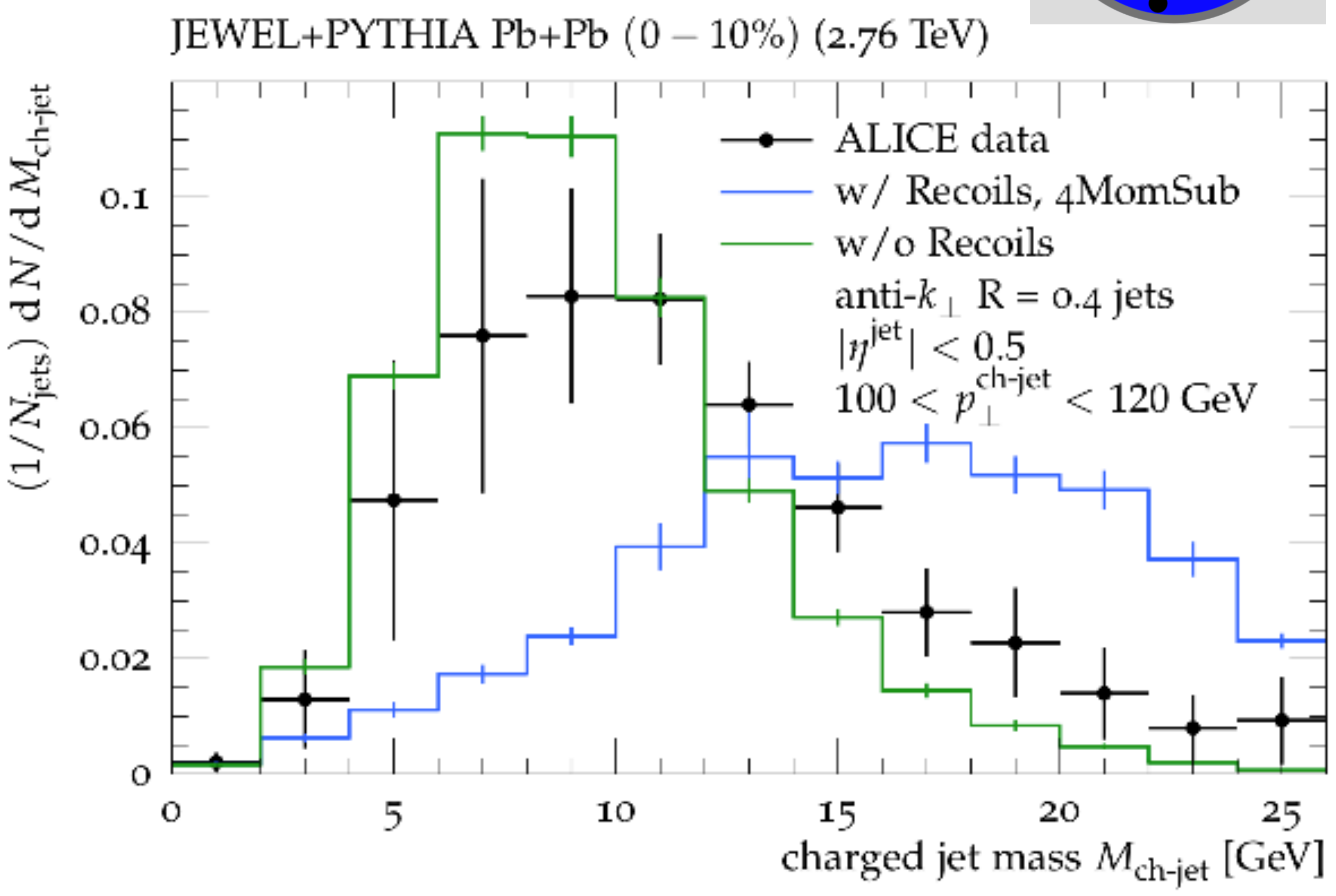

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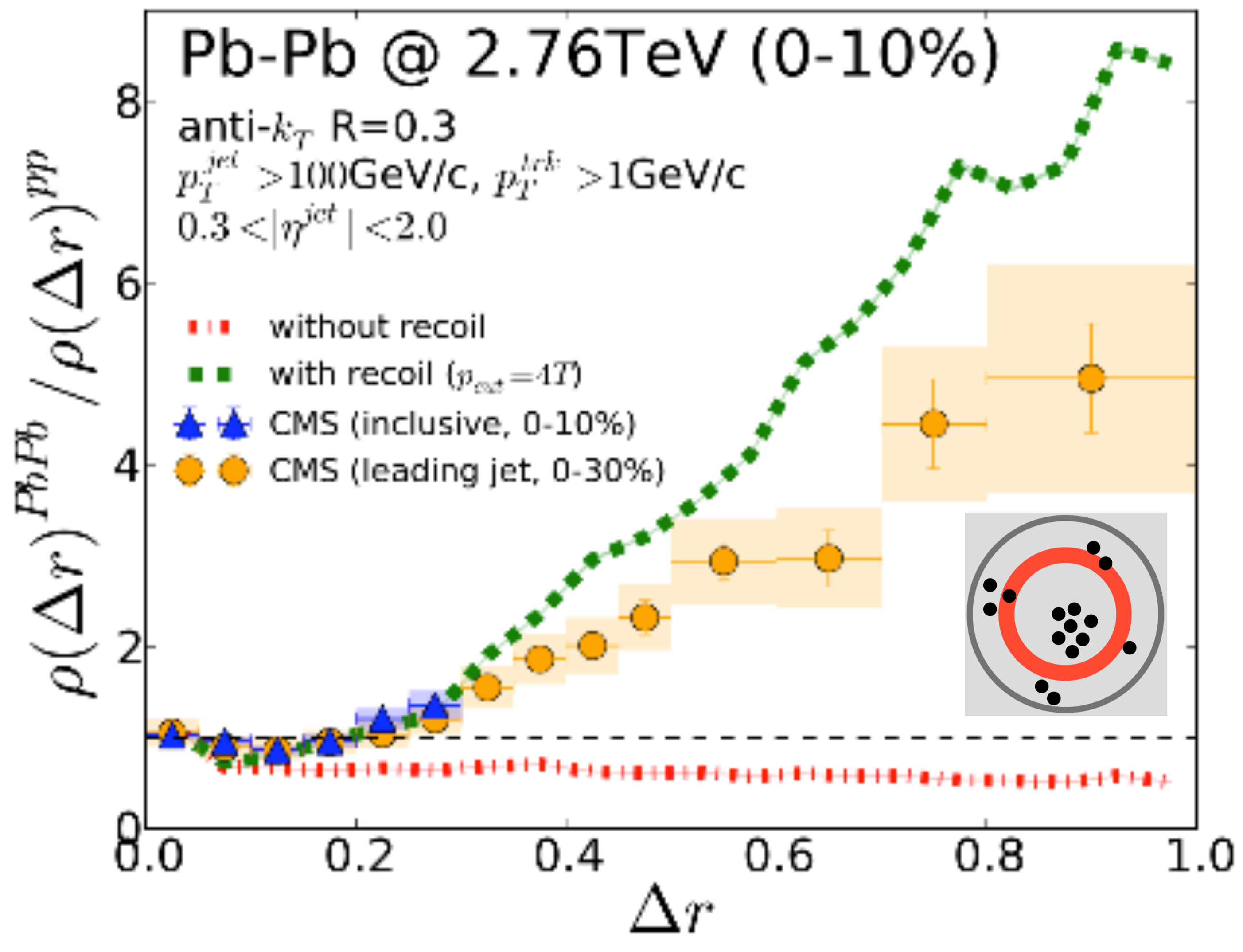
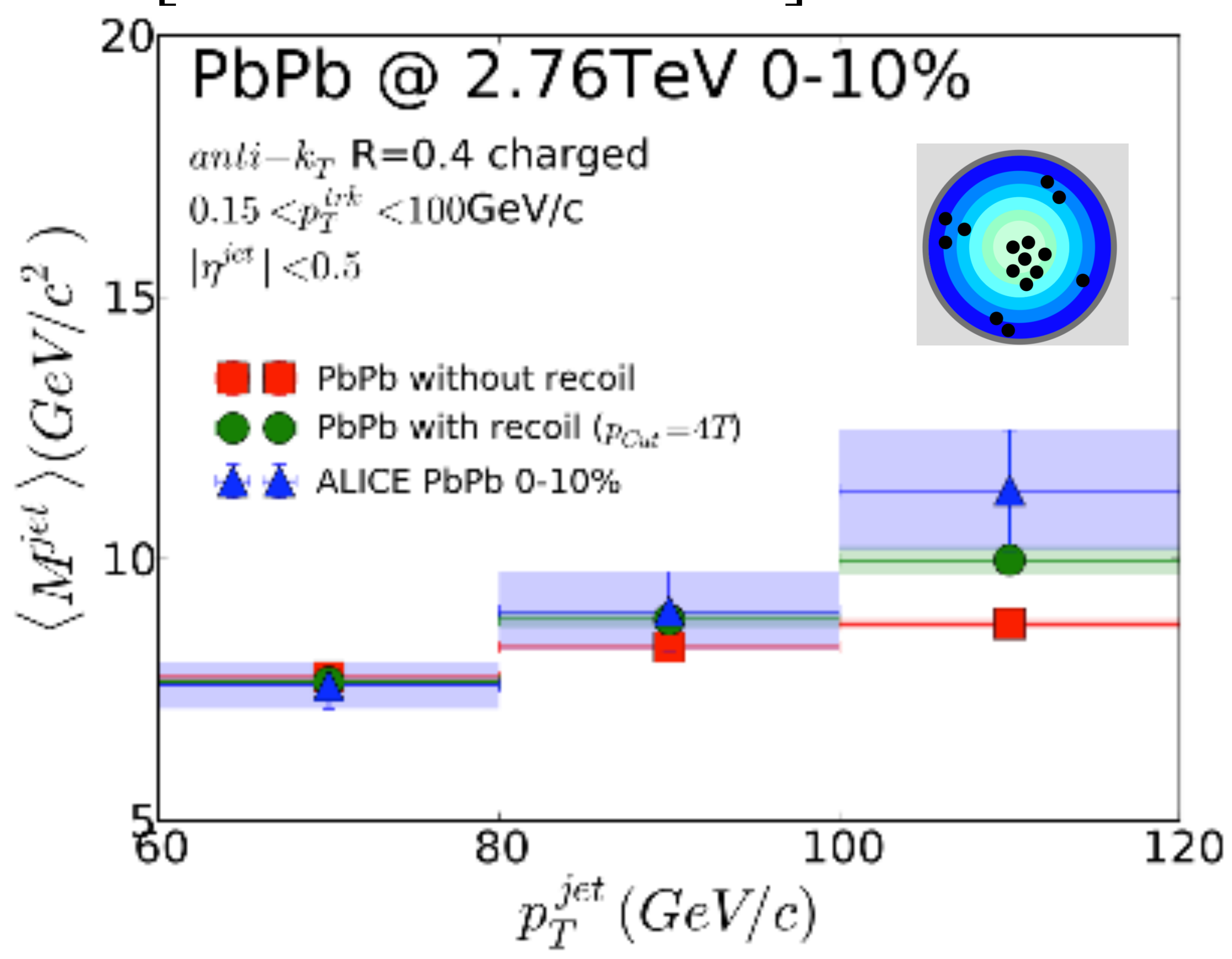


[MARTINI:1807.06550]



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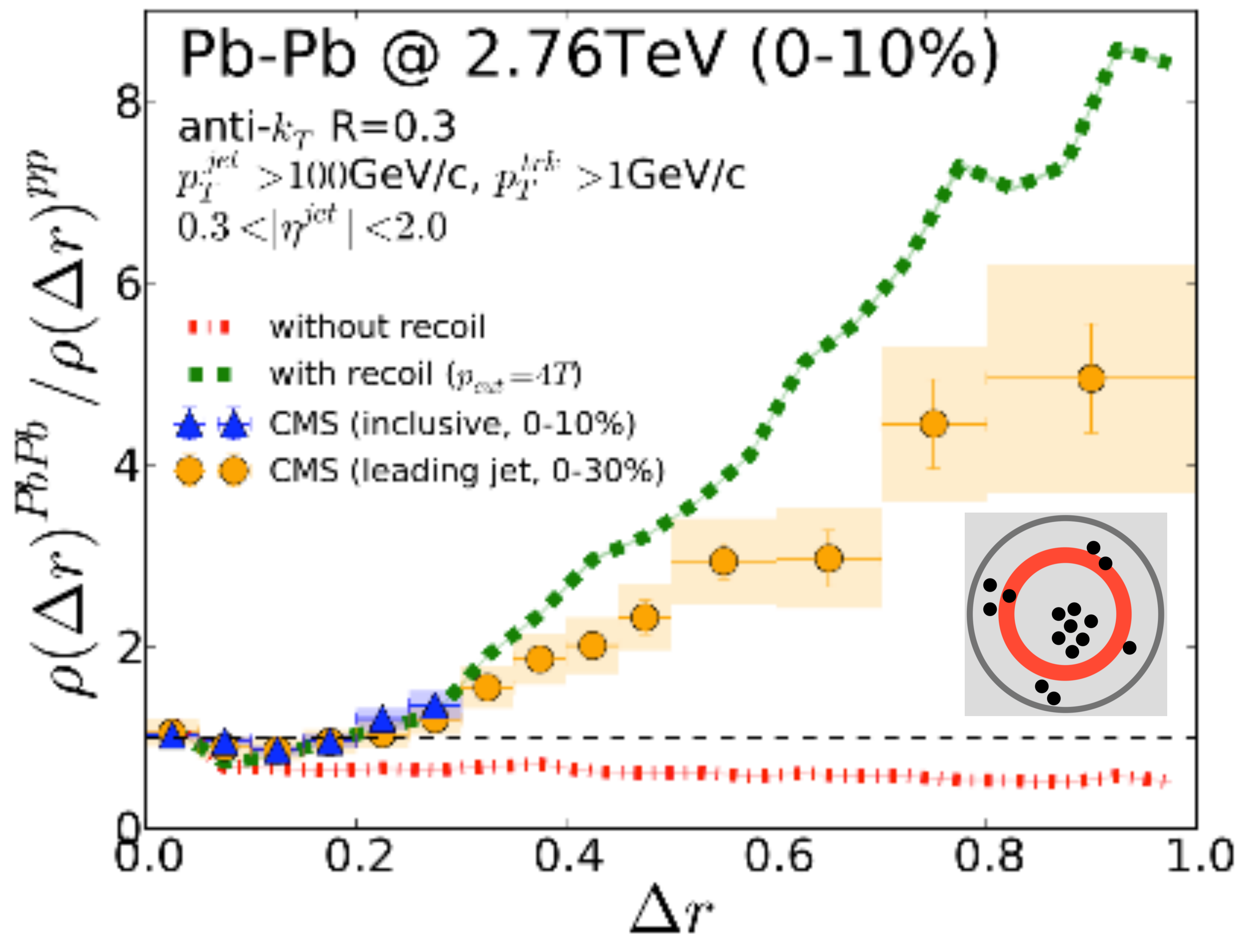

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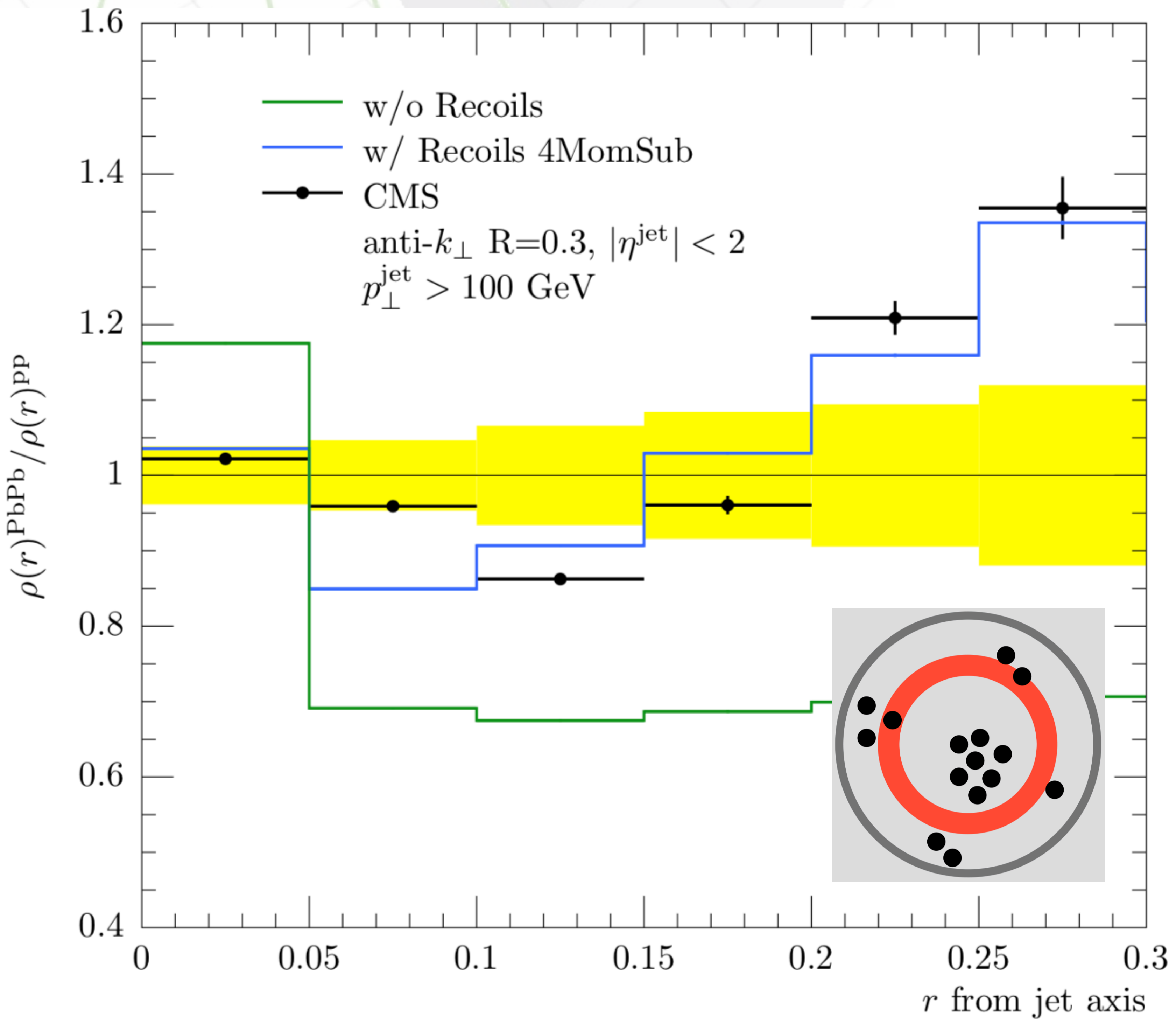

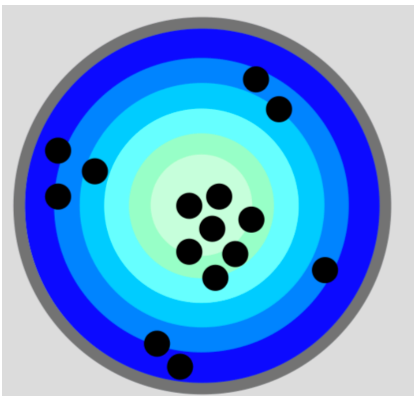

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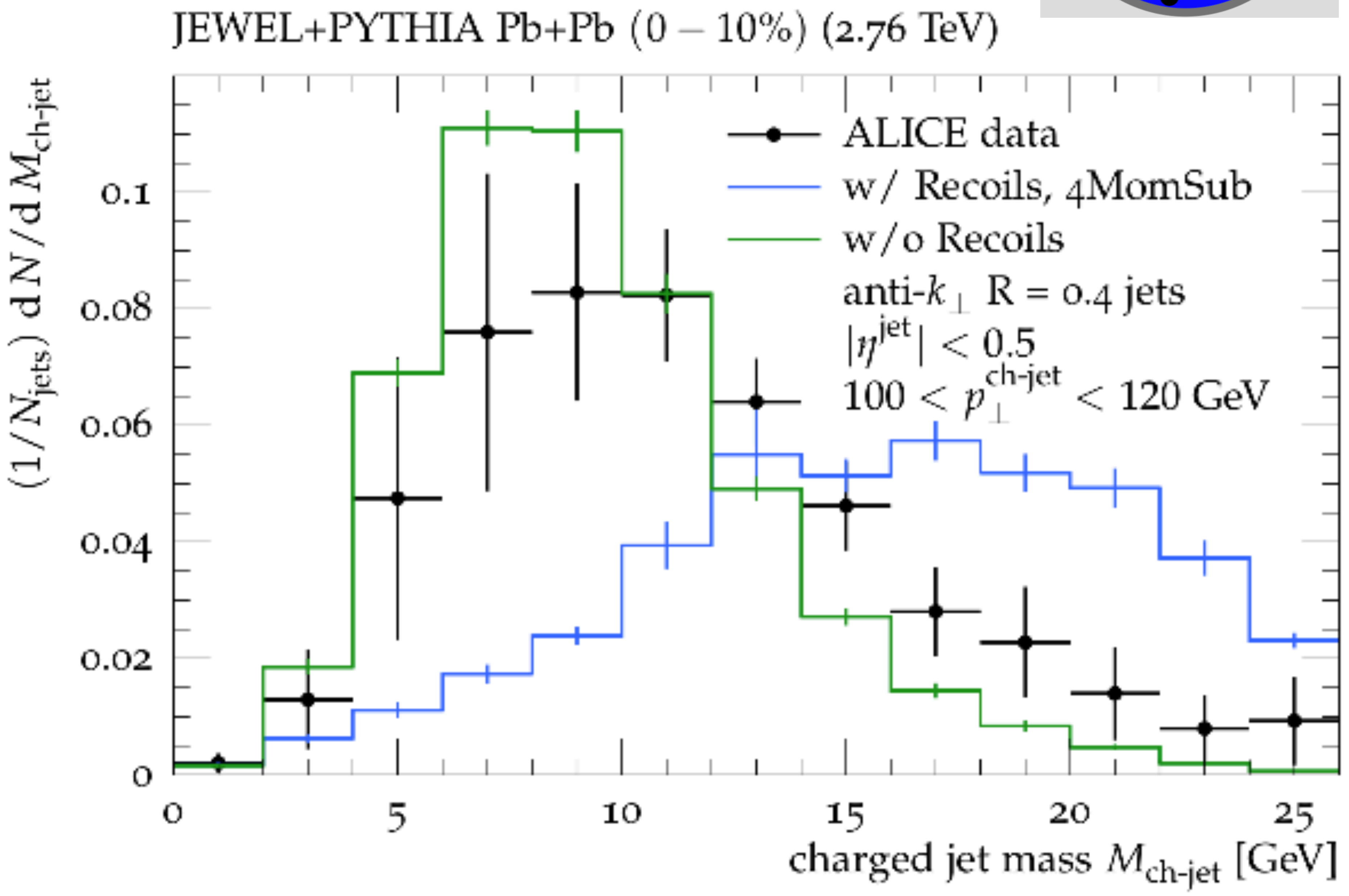

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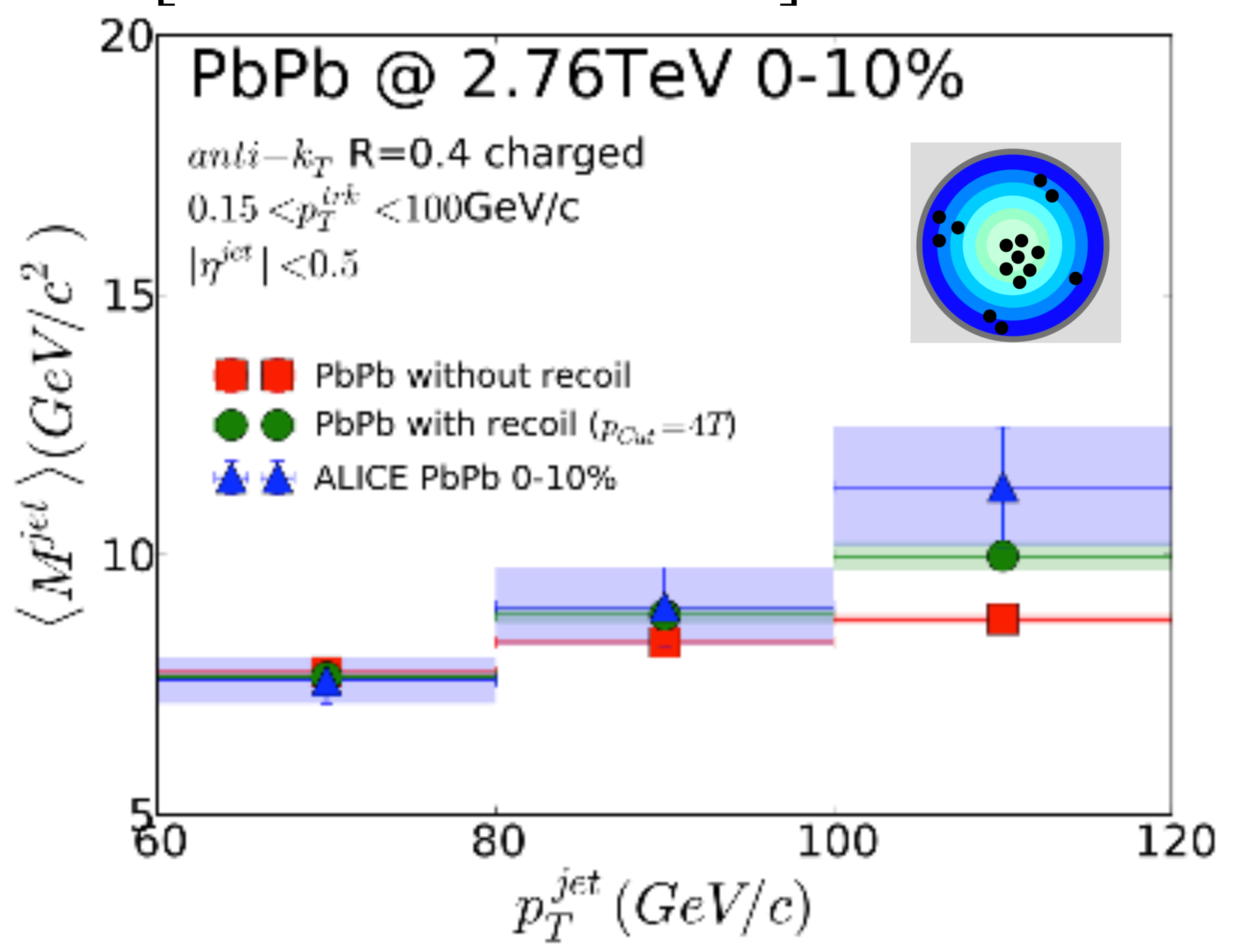


See K. Zapp (Thursday) for news about JEWEL

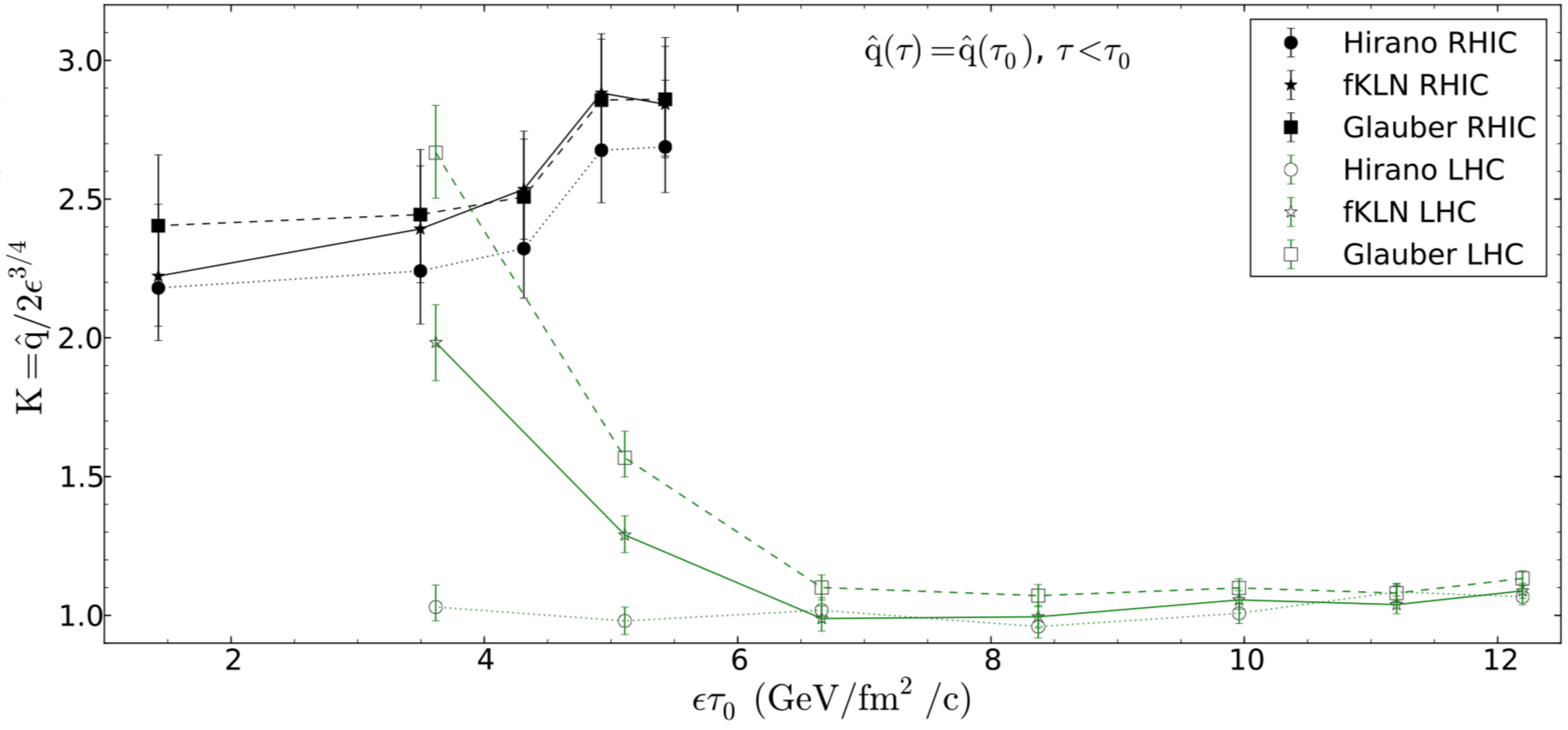
And even more problems…

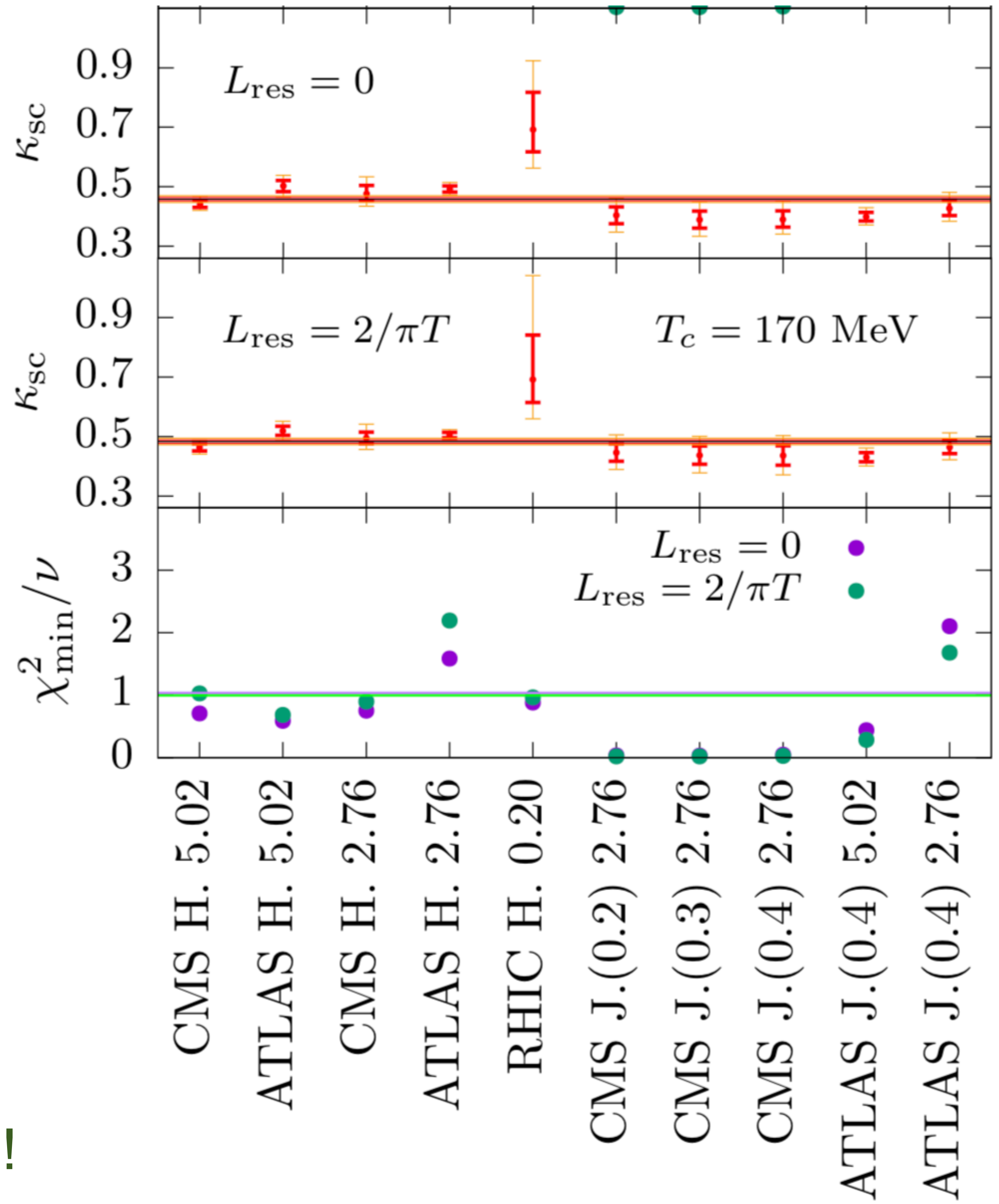
[Jet collaboration (13)]

[Andrés, Armesto, Luzum, Salgado, Zurita (17)]

[Casalderrey-Solana, Hulcher, Milhano, Pablos, Rajagopal (18)]

- Quenching parameter (qhat) at RHIC larger is than at LHC
  - Not clearly understood so far…





both pQCD and non-pQCD approaches!

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- To ultimately assess QGP properties, also need new jet observables (from pp and new for heavy-ions):
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See L. Apolinário (Thursday)

Wrapping-up

Summary

- This was a brief lecture/overview of “jet quenching”:
  - Things I didn’t cover: Heavy-quarks, AdS/CFT approaches, Monte Carlo approaches,…
  - Several developments towards the understanding of what is a jet in a heavy-ion environment!
    - But no consistent picture has emerged yet…
      - Not clear the role of medium recoil effects, missing in-medium evolution equation (coupled to vacuum radiation), …
      - ➡ Several developments in building new observables (particular QGP effect, a particular type of probe (q/g-jets) and/or different QGP timescales ⇒ Jet substructure!)

See J. Barata (Thursday)

Summary

Questions?

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See J. Barata (Thursday)

Acknowledgements

REPÚBLICA PORTUGUESA

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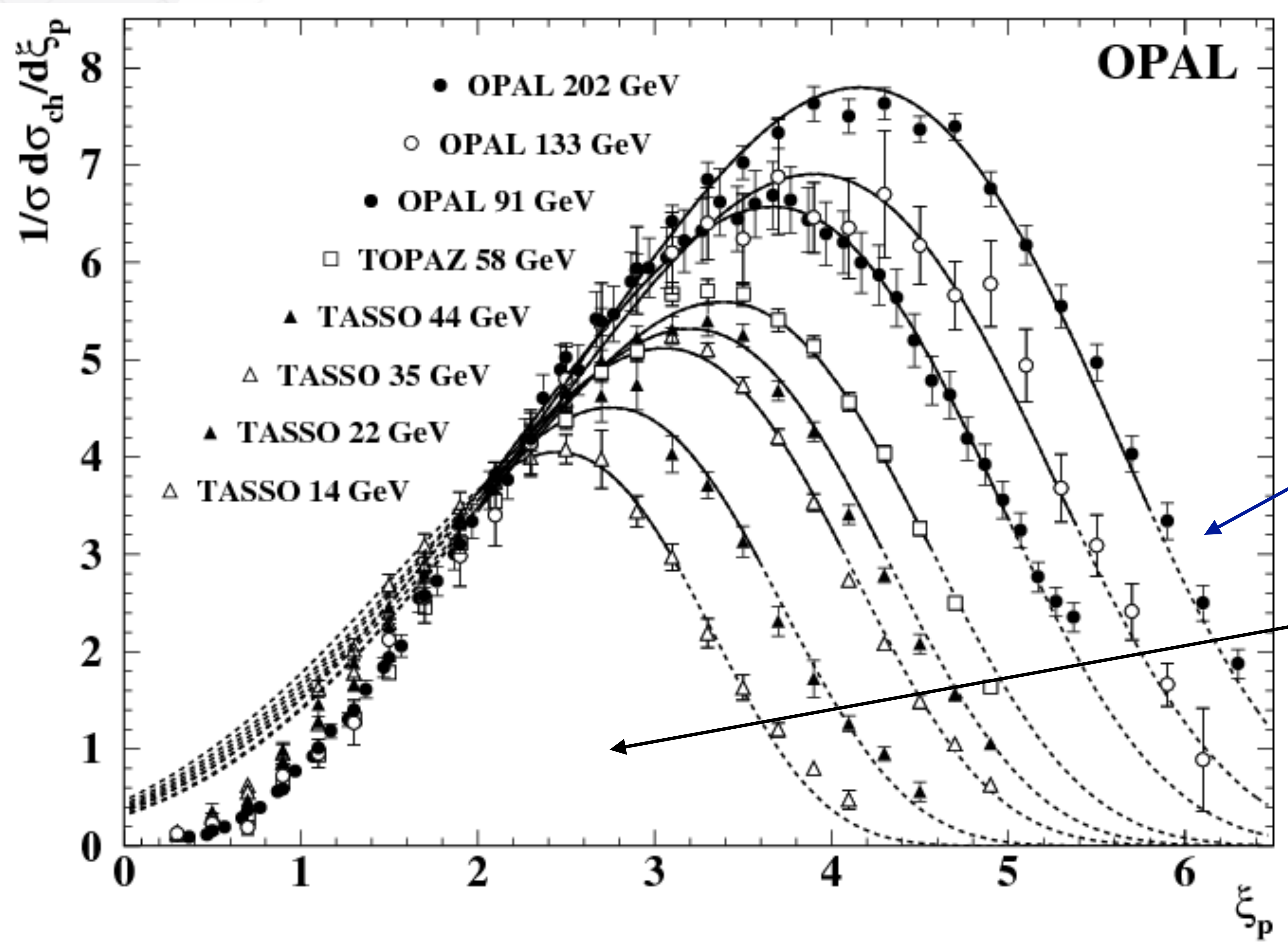
Backup Slides

Experimental Evidences

- MLLA: only the leading behaviour,
  - Good description in the hard region (two different energies)



$$\xi_p = \log(\frac{1}{z}) = \log(\frac{p_{jet}}{p_{had}})$$

Soft jet fragments

Hard jet fragments

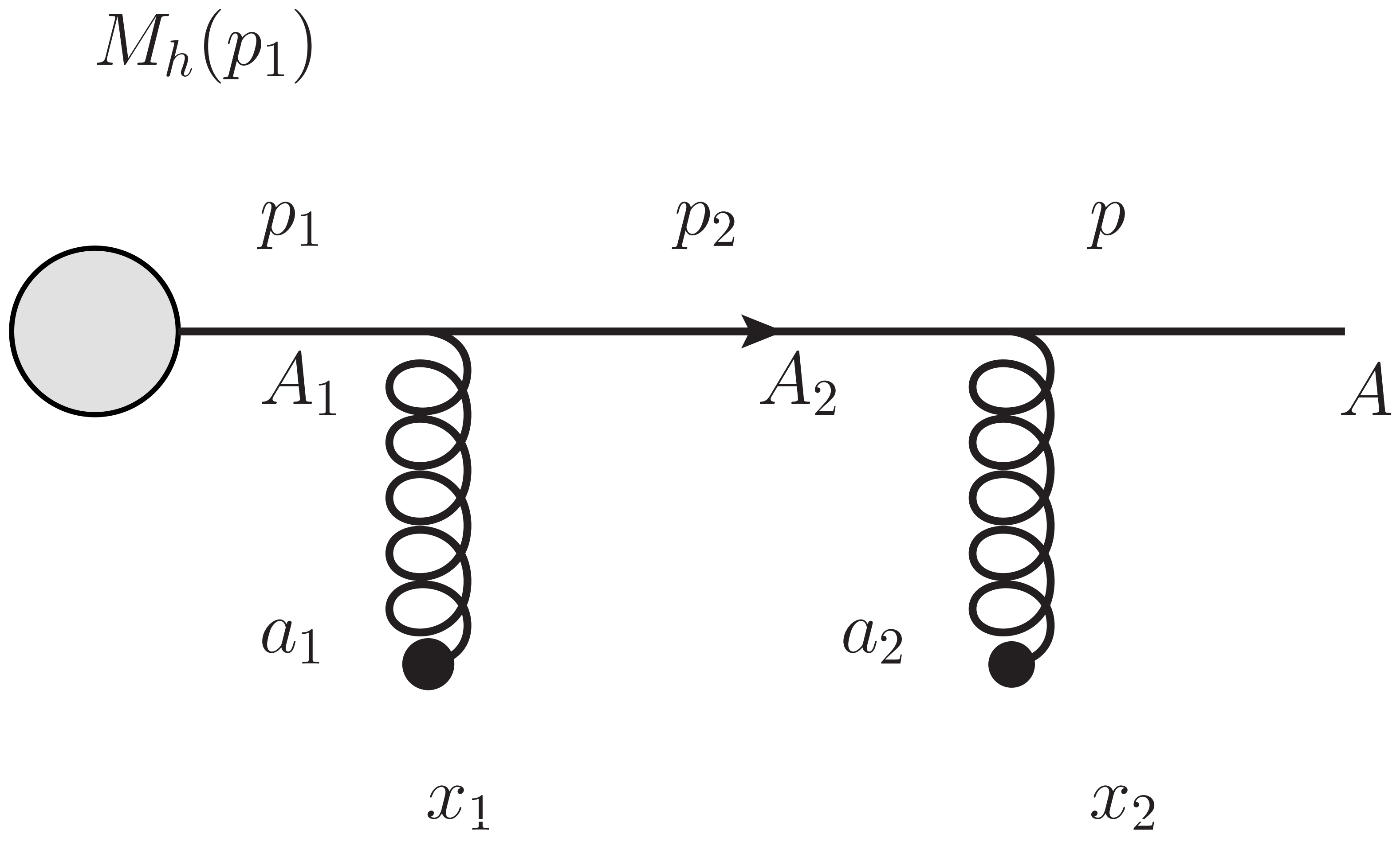
Eikonal Approximation

See: arXiv:0712.3443

- Consider a high energetic particle propagating interacting twice with the medium:

$$S_2 = \int d^4x_1 d^4x_2 \frac{d^4p_1}{(2\pi)^4}\frac{d^4p_2}{(2\pi)^4}\bar{u}(p)e^{ix_2(p-p_2)+ix_1(p_2-p_2)}$$

$$\not{A}_{AA_2}(x_{2+},x_{2\perp})\frac{i\not{p}_2}{p_2^2+i\varepsilon}ig\not{A}_{A_2A_1}(x_{1+},x_{1\perp})\frac{i\not{p}_1}{p_1^2+i\varepsilon}M_h(p_1)$$



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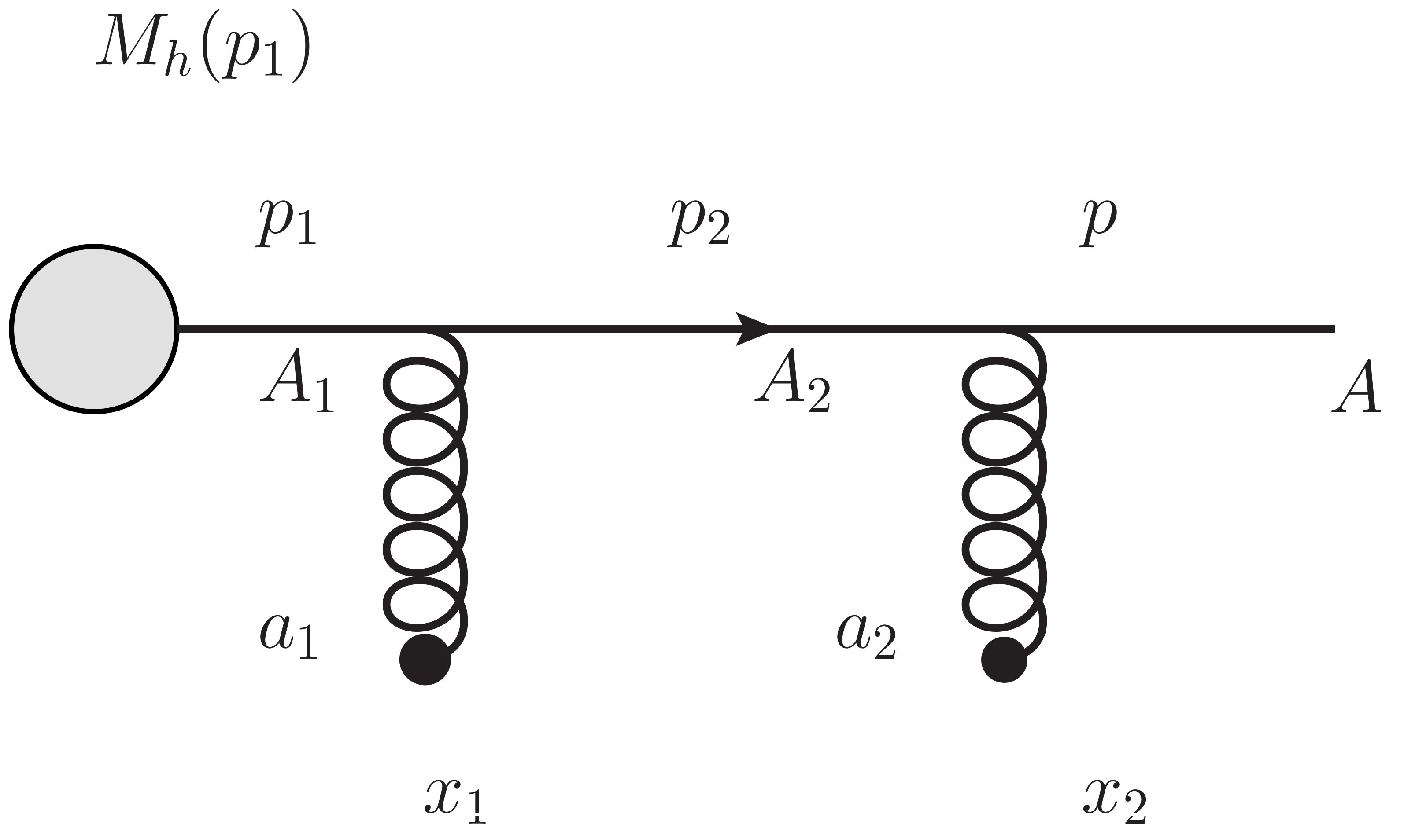

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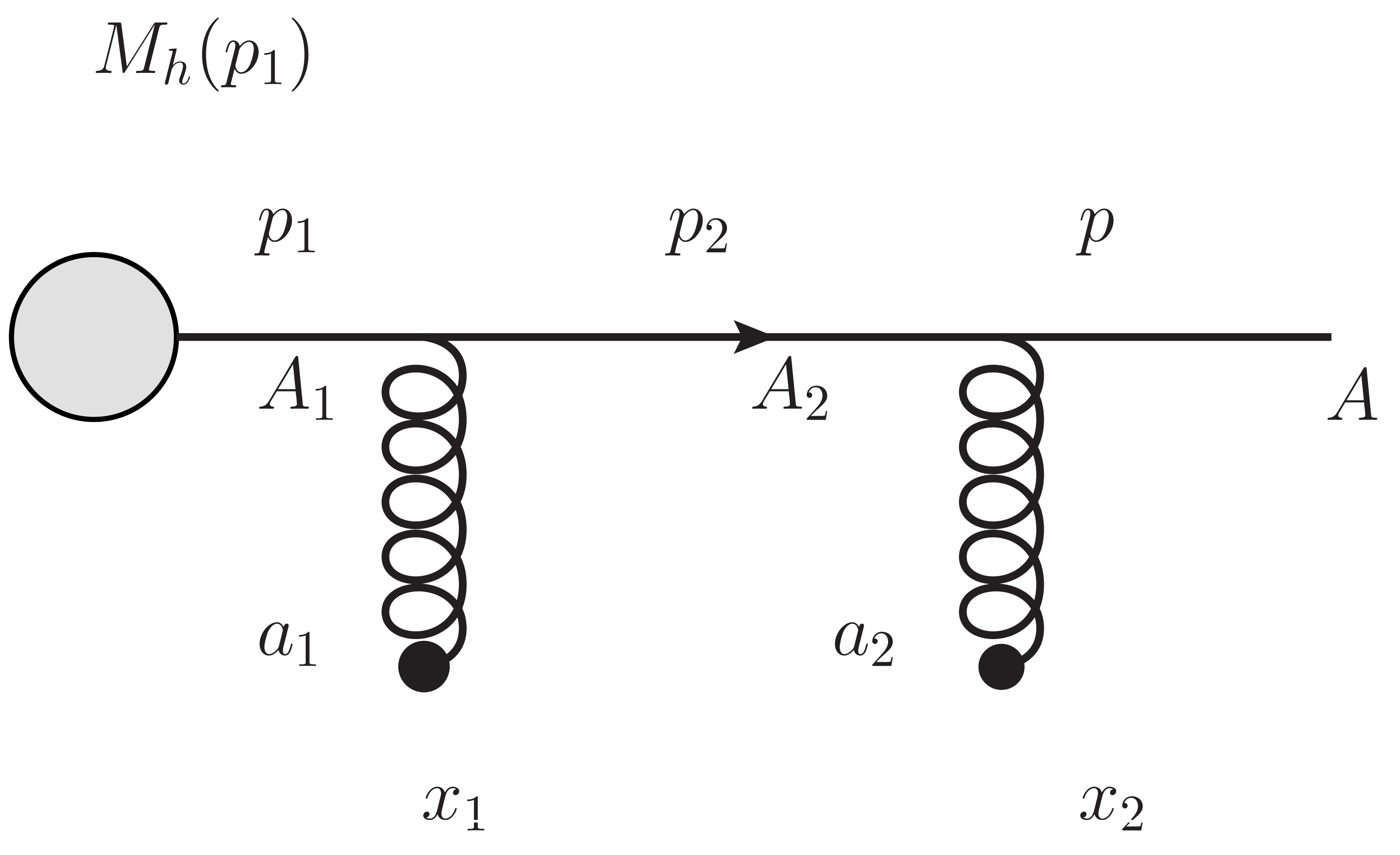

No dependence on x_{i-}: $\int dx_{1-}dx_{2-}e^{ix_{2-}(p-p_2)_+ + ix_{1-}(p_2-p_1)_+} = (2\pi)^2\delta(p-p_2)_+\delta(p_2-p_1)_+ \Rightarrow p_+ = p_{1+} = p_{2+}$

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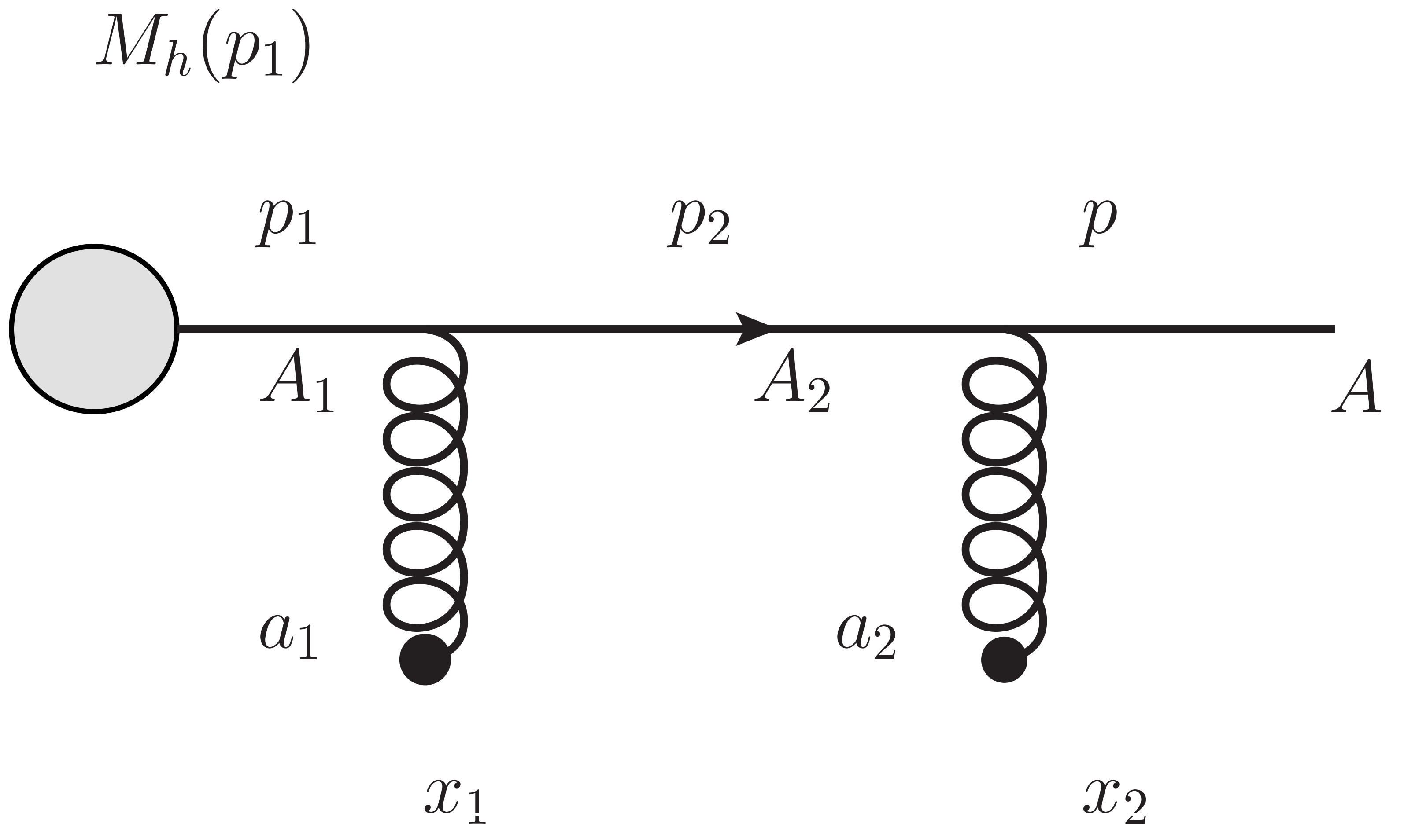

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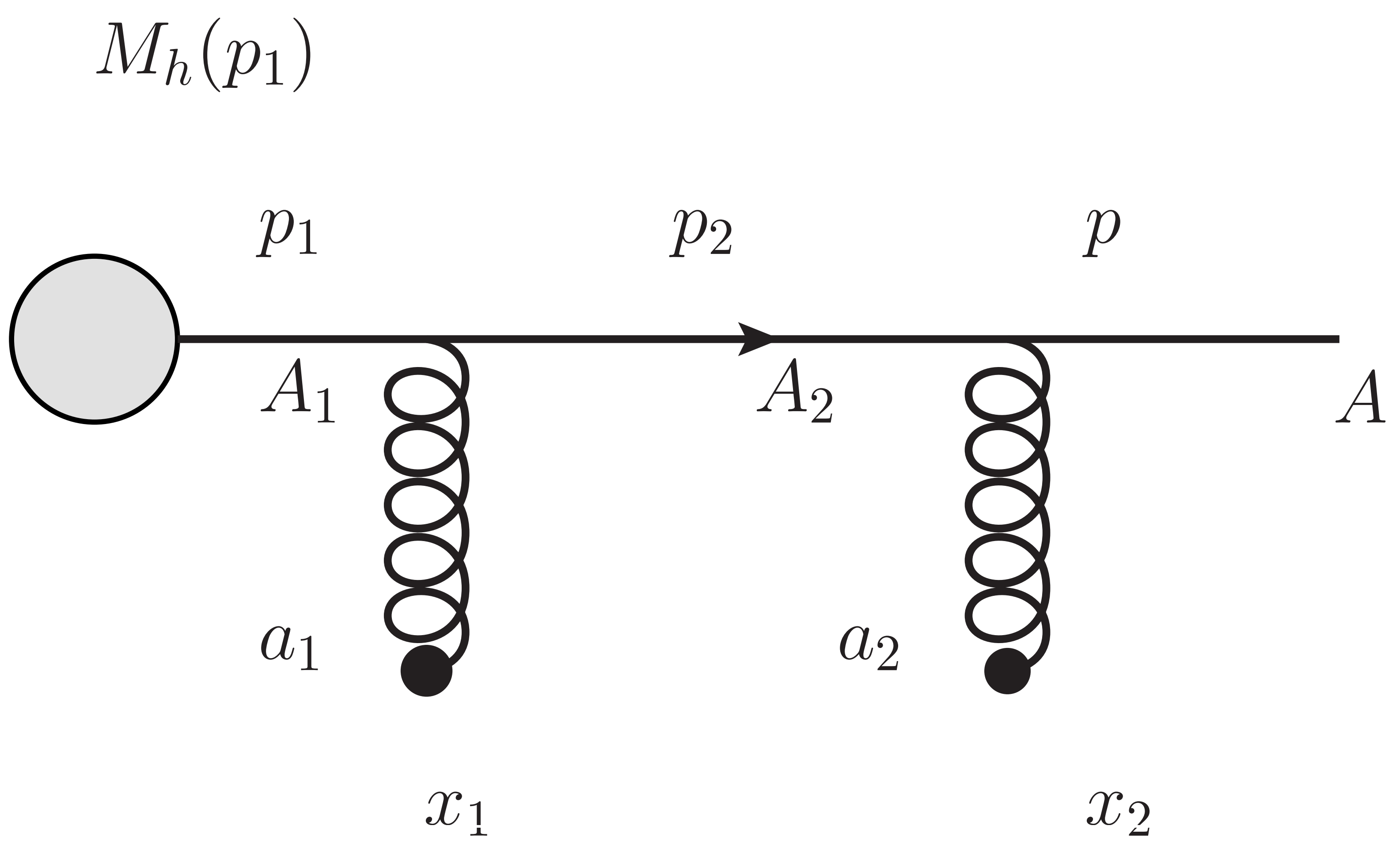

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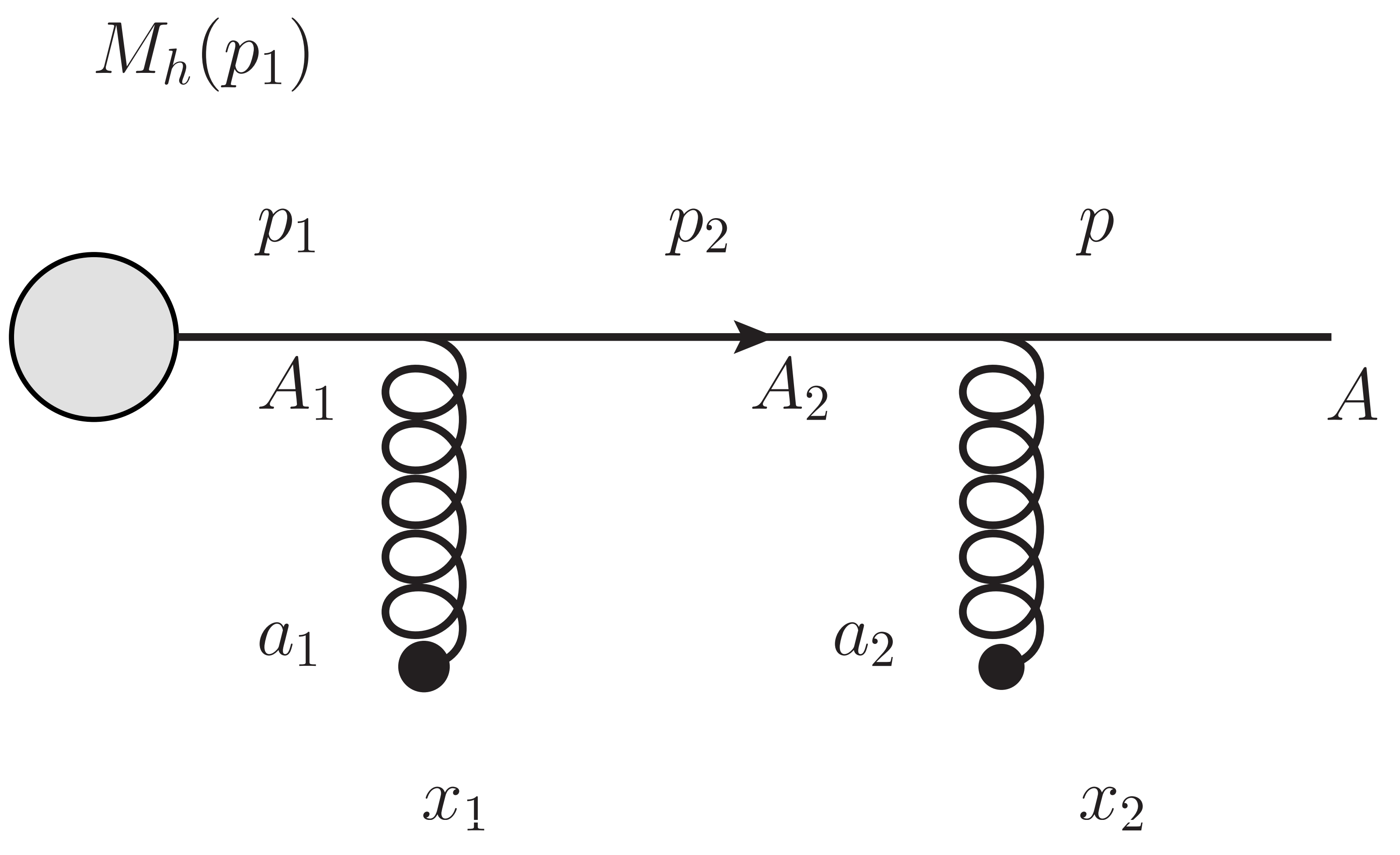

Resulting fractions: $$\frac{i2p_2\cdot(igA_{AA_2})}{p_2^2+i\varepsilon} \simeq \frac{i2p_{2+}(igA_-)_{AA_2}}{2p_{2+}p_{2-}+i\varepsilon} = (igA_-)_{AA_2}\frac{i}{p_{2-}+i\varepsilon}$$

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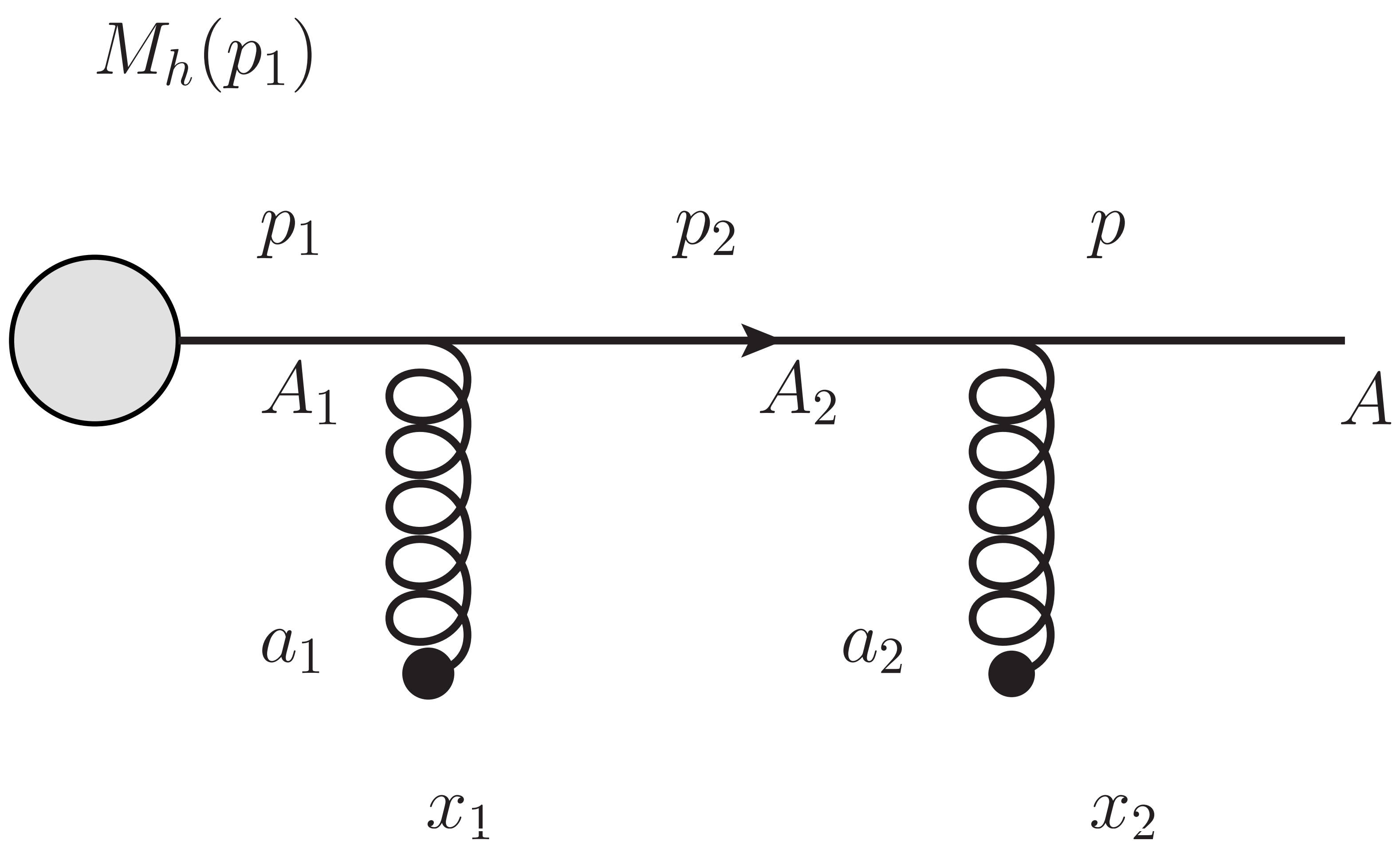

$$S_2 = \int d^4x_1 d^4x_2 \frac{d^4p_1}{(2\pi)^4}\frac{d^4p_2}{(2\pi)^4}\bar{u}(p)e^{ix_2(p-p_2)+ix_1(p_2-p_2)}$$

$$\not{A}_{AA_2}(x_{2+},x_{2\perp})\frac{i\not{p}_2}{p_2^2+i\varepsilon}ig\not{A}_{A_2A_1}(x_{1+},x_{1\perp})\frac{i\not{p}_1}{p_1^2+i\varepsilon}M_h(p_1)$$

Resulting fractions: $$\frac{i2p_2\cdot(igA_{AA_2})}{p_2^2+i\varepsilon} \simeq \frac{i2p_{2+}(igA_-)_{AA_2}}{2p_{2+}p_{2-}+i\varepsilon} = (igA_-)_{AA_2}\frac{i}{p_{2-}+i\varepsilon}$$

Integral in p_{i-}: $$\int\frac{dp_{2-}}{2\pi}e^{ip_{2-}(x_1-x_2)_+}\frac{i}{p_{2-}-(-i\varepsilon)} = \theta(x_2-x_1)_+$$ Residues theorem (and same for x_1)

Eikonal Approximation

See: arXiv:0712.3443

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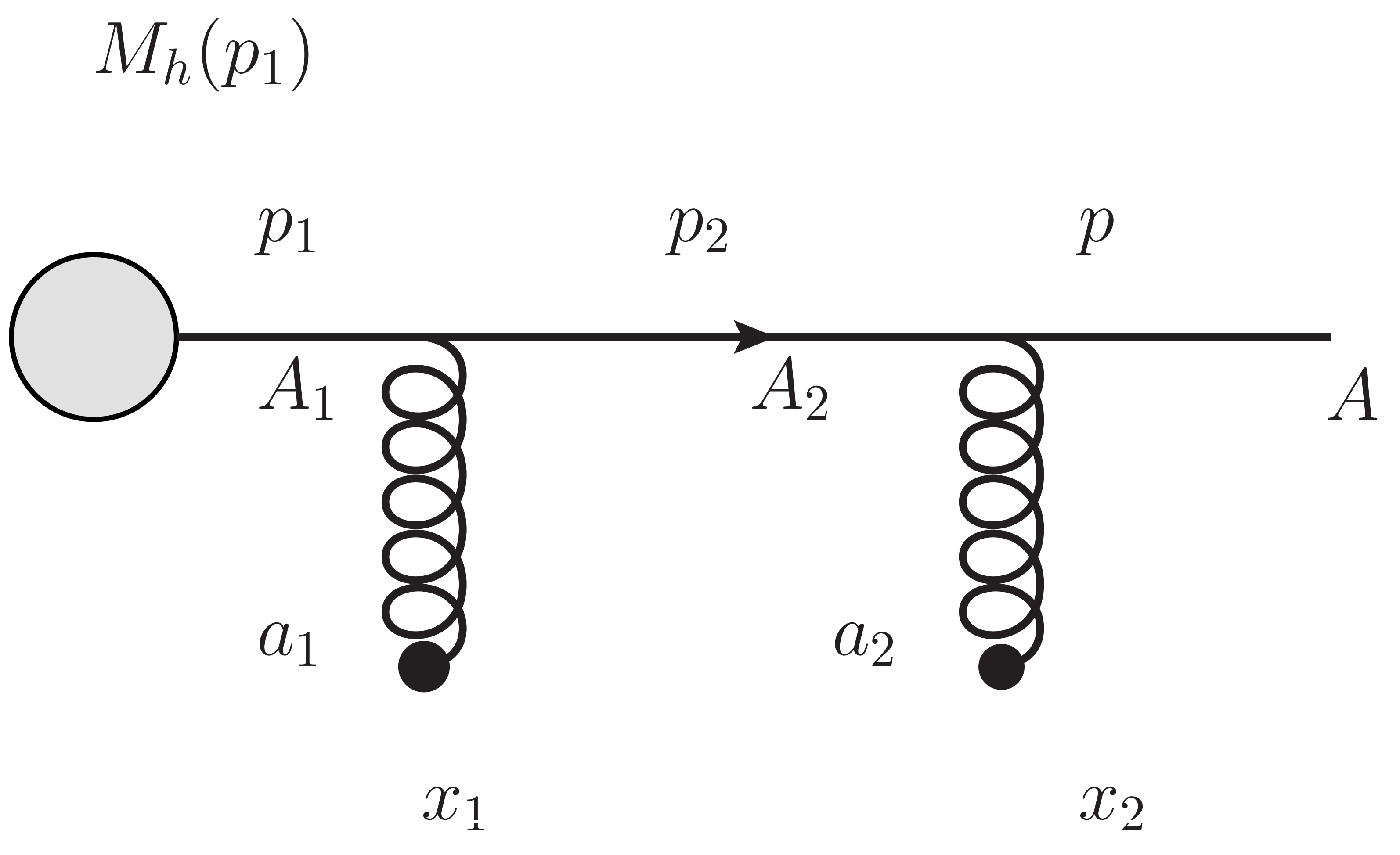

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Integral in p_T: $\int \frac{d^2p_{2\perp}}{(2\pi)^2}\frac{d^2p_{1\perp}}{(2\pi)^2}e^{-i(x_1-x_2)_\perp - i(0-x_1)_\perp} = \delta^2(x_1-x_2)_\perp\delta^2(x_1) \;\Rightarrow x_{1\perp}=x_{2\perp}=0$

Eikonal Approximation

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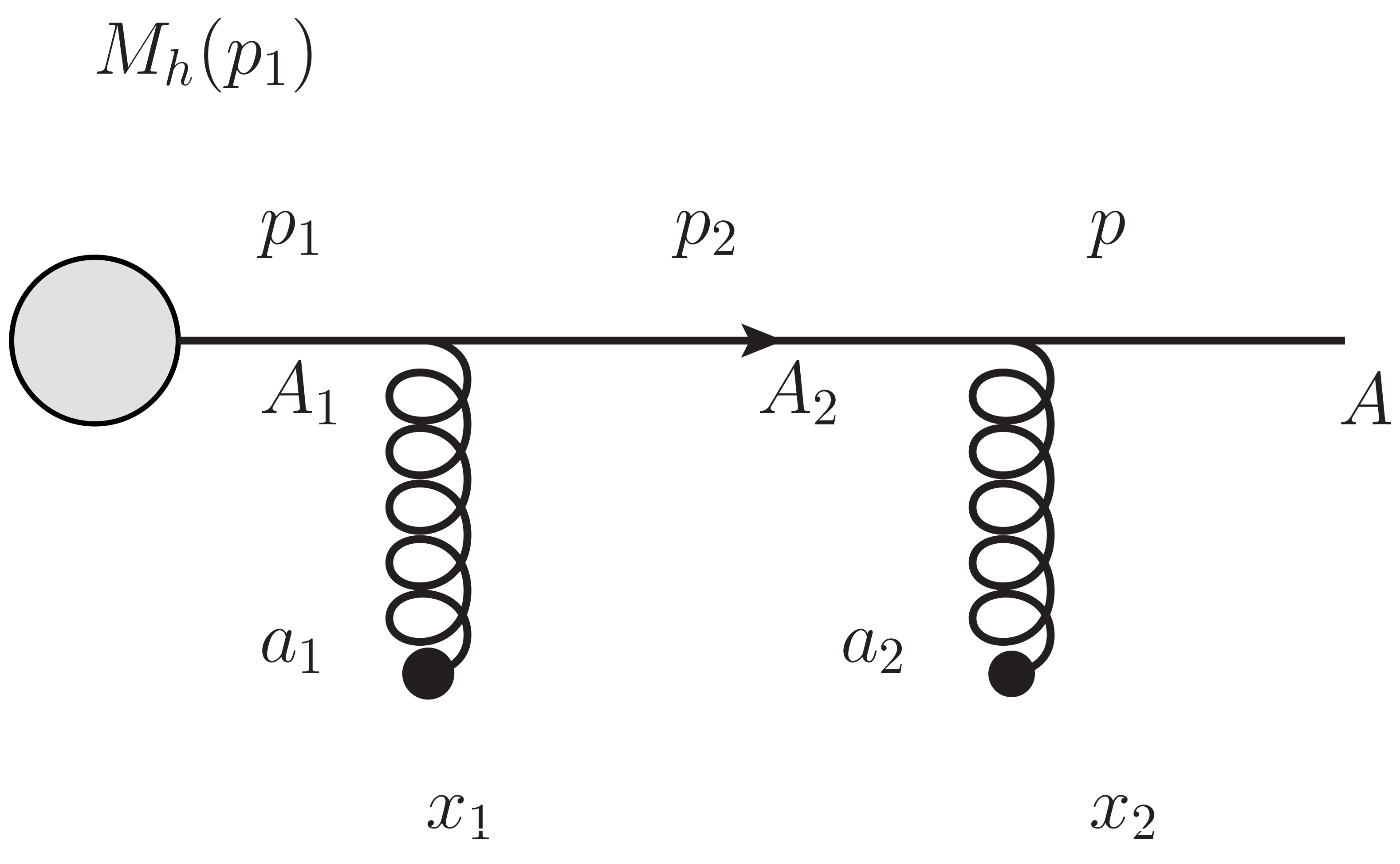

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Eikonal Approximation

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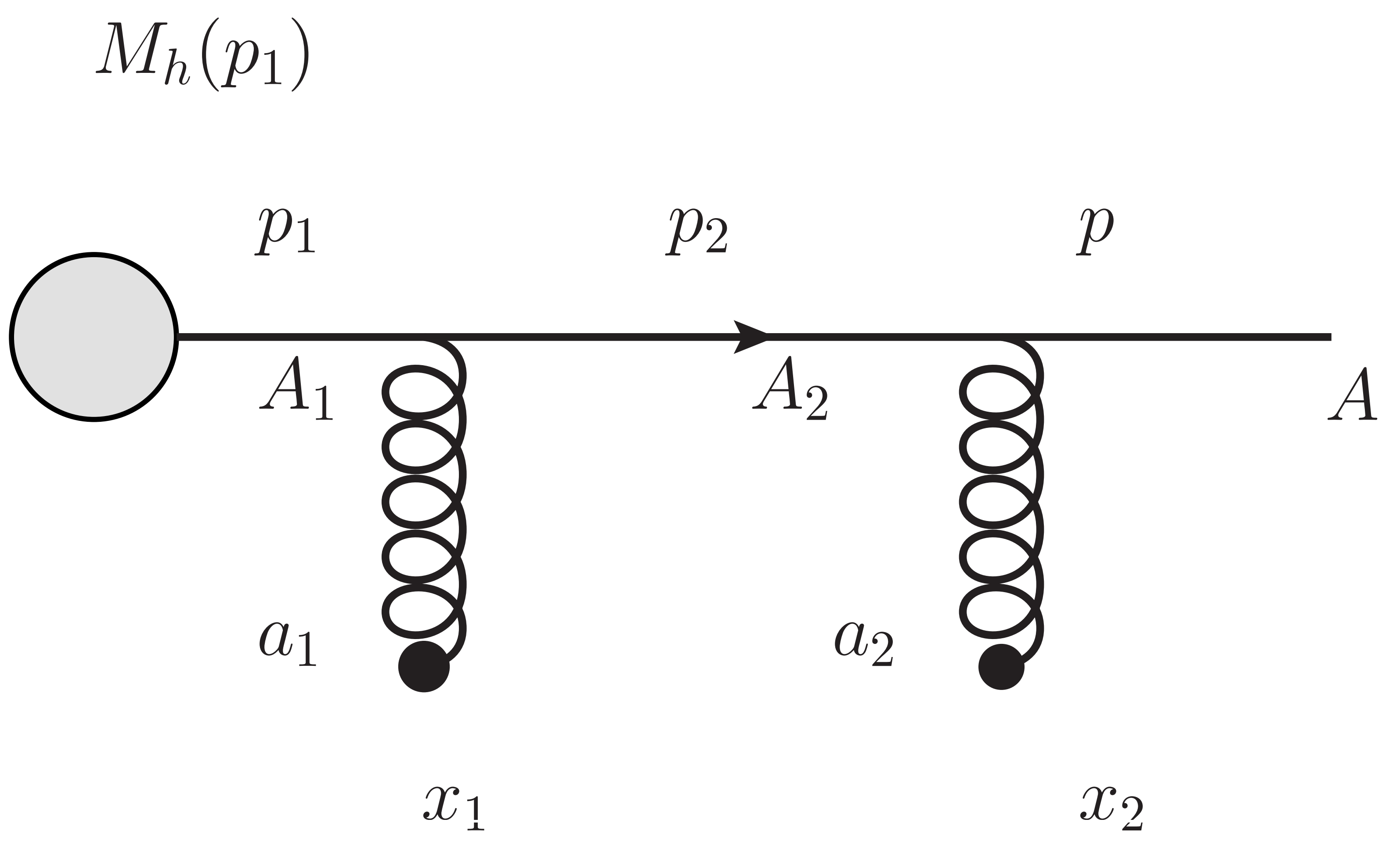

No interaction term

Eikonal Approximation

See: arXiv:0712.3443

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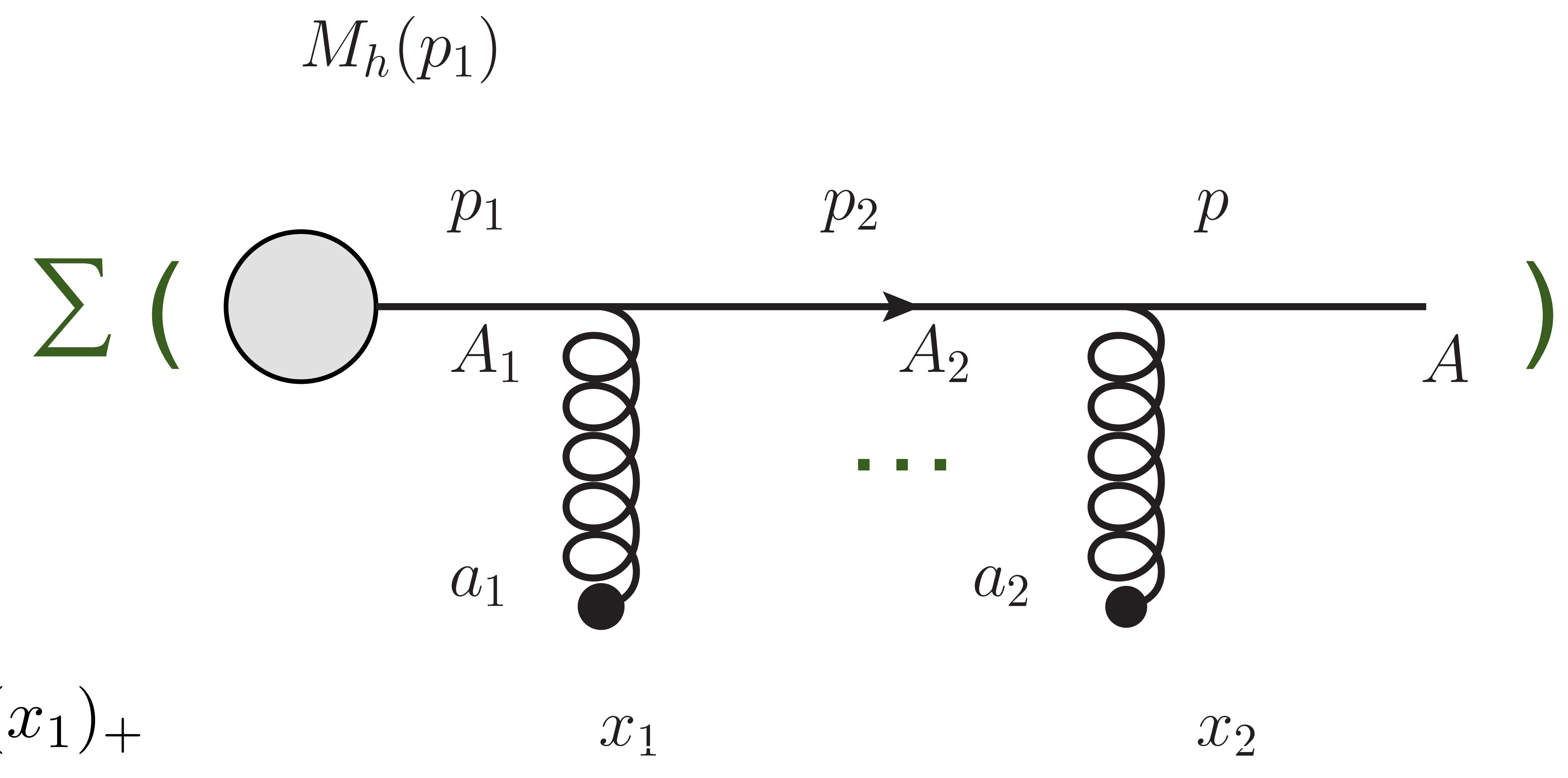

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No interaction term

summing over all 'n' interaction terms

$$\mathcal{P}\exp\left\{ig\int_{x_{1+}}^{x_{n+}} dx_+A_-(x_+,x_\perp=0)\right\} = W(x_{n+},x_{1+};x_\perp=0)$$

MC Bibliography

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  - 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)]

MC Bibliography

- Monte Carlo models for heavy-ions:
  - AMPT: [Ko, Li, Lin, Pal, Zhang (00; 01)]
  - BAMPS: [Xu, Greiner (03; 07)]
  - CUJET: [Buzzatti and Gyulassy (11; 12)]
  - HiJING/HIJING++: [Gyulassy, Wang (91; 94); Barnaföldi et al (17)]
  - HYDJET/HYDJET++: [Lokhtin, Malinina, Petrushanko, Snigirev , Arsene, Tywoniuk (09)]

- Analytical approaches:
  - Coupled Jet-Fluid: [Tachibana, Chang, Qin (17)]