Parton interactions in the medium: theory

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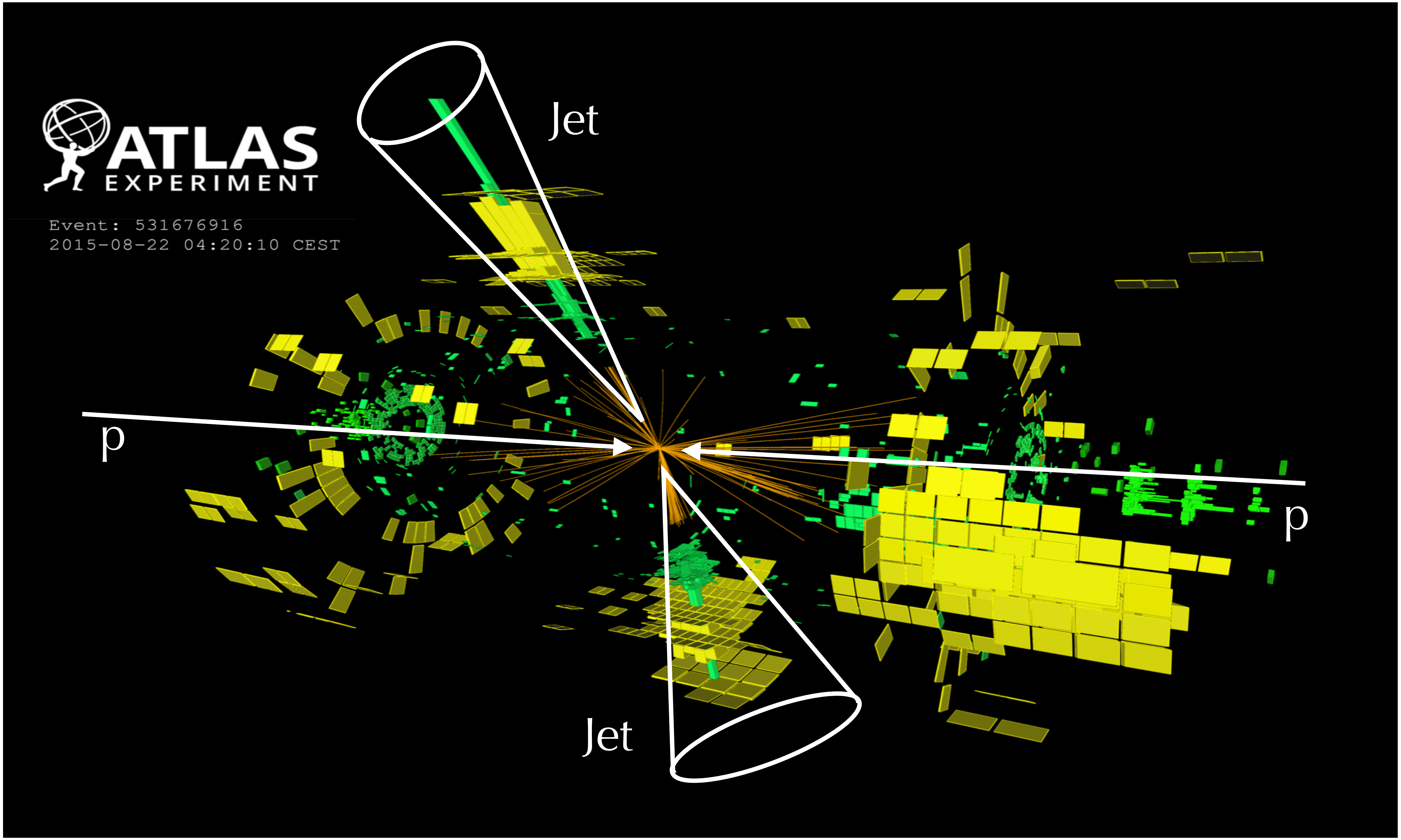
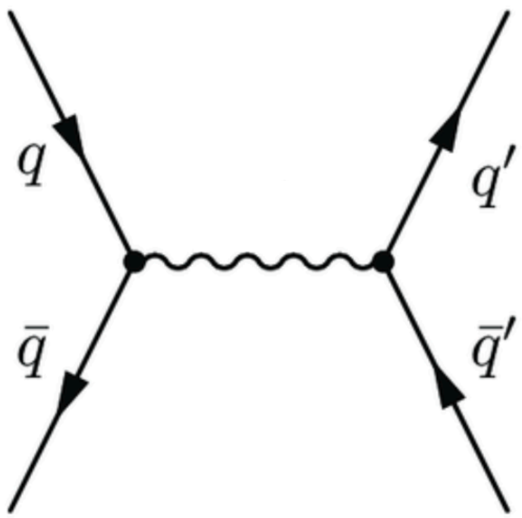
Some QCD in the vacuum


ATLAS
EXPERIMENT
Event: 531676916
2015-08-22 04:20:10 CEST
Jet
p
p
Jet

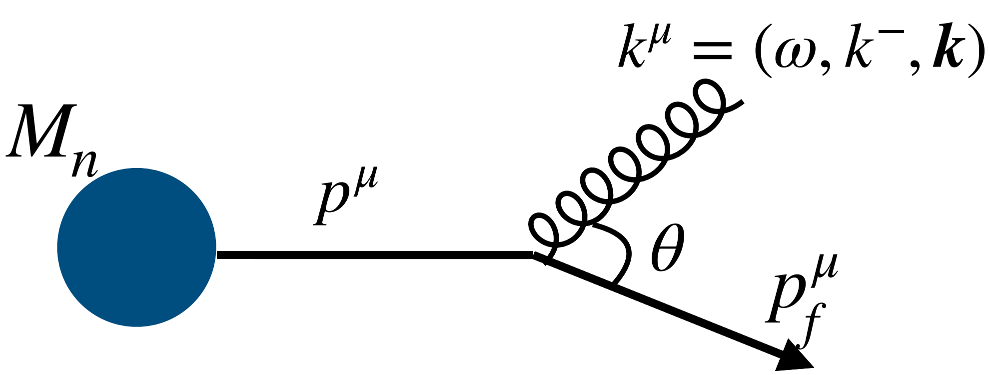
Why do we have jets?

Gluon emission off a quark



Take an emission off a massless quark:

- Soft: $\omega \ll \sqrt{s}$
- Collinear w.r.t. emitter: $\theta \ll 1$



$$M_{n+1} = \bar{u}(p_f)\,(-ig_s t^a \gamma^\mu)\,\varepsilon_\mu(k) \frac{i\,(p_f^\nu + k^\nu)\gamma_\nu}{(p_f + k)^2} M_n$$

$$\Big\downarrow \; k \ll p$$

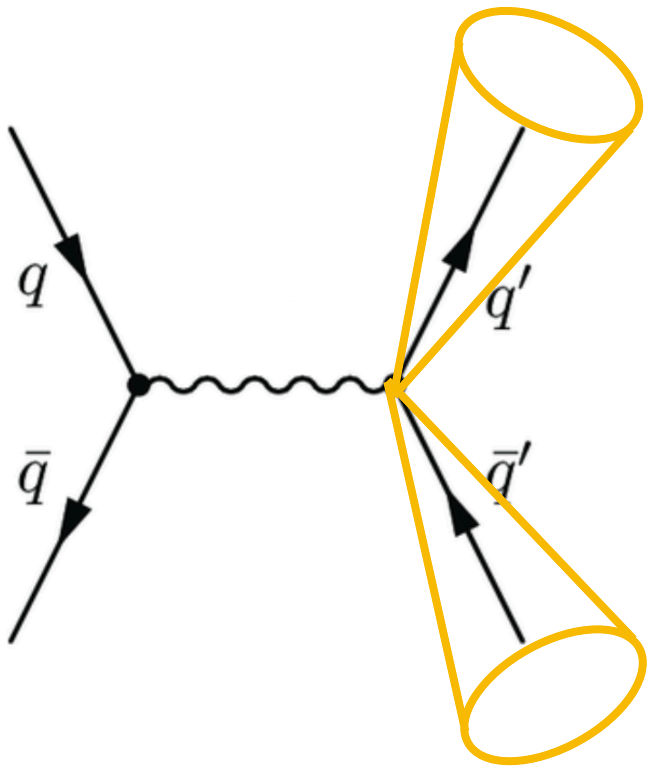
$$M_{n+1} \approx g_s t_a \frac{p_f \cdot \varepsilon}{p_f \cdot k}\, \bar{u}(p_f)\, M_n$$

$$\frac{d\omega d\boldsymbol{k}^2}{2\omega(2\pi)^3}$$

$$\boxed{d\sigma_{n+1} = d\sigma \, \frac{2\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta}{\theta}}$$

Soft and collinear divergences!

Gluon emission off a quark



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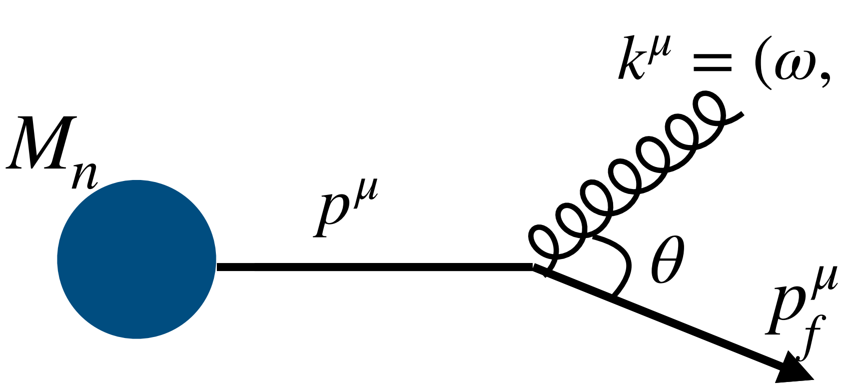

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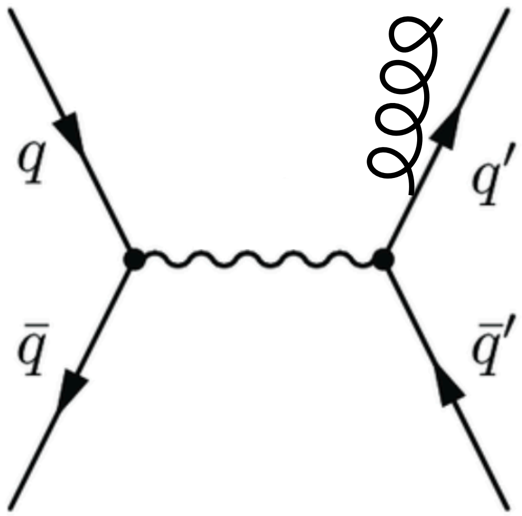

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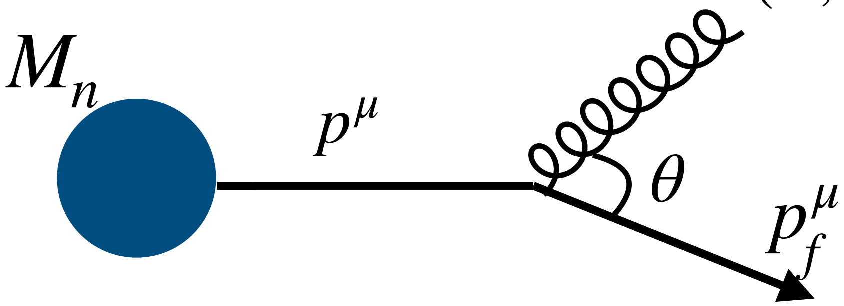

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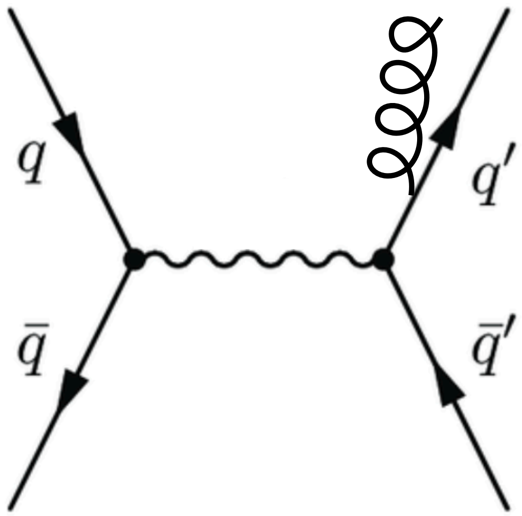

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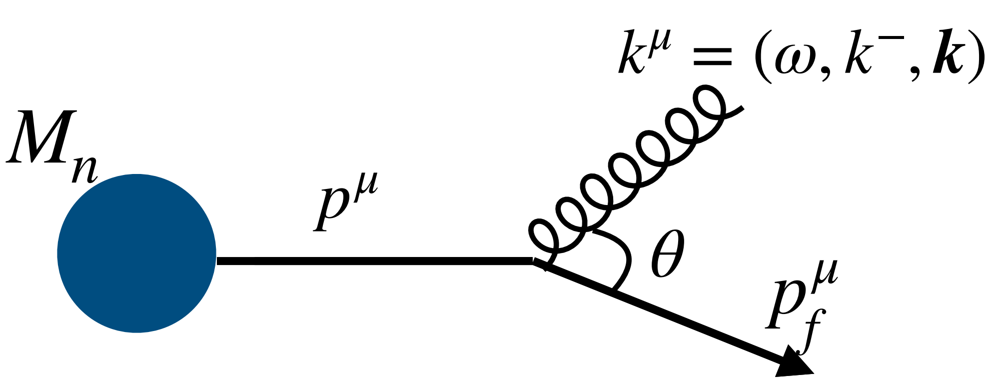

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$$\omega = zE$$

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Soft and collinear divergences!

Probability of the emission

Probability of emitting a gluon with energy ω_1 off a massless quark:

$$P_g \approx \frac{2\alpha_s C_F}{\pi} \int^{\omega_1} \frac{d\omega}{\omega} \int^{1} \frac{d\theta}{\theta} \, \Theta(\omega\theta > Q_0)$$

Transverse momentum of the gluon must be larger than some non-perturbative threshold: Q_0

Probability of the emission

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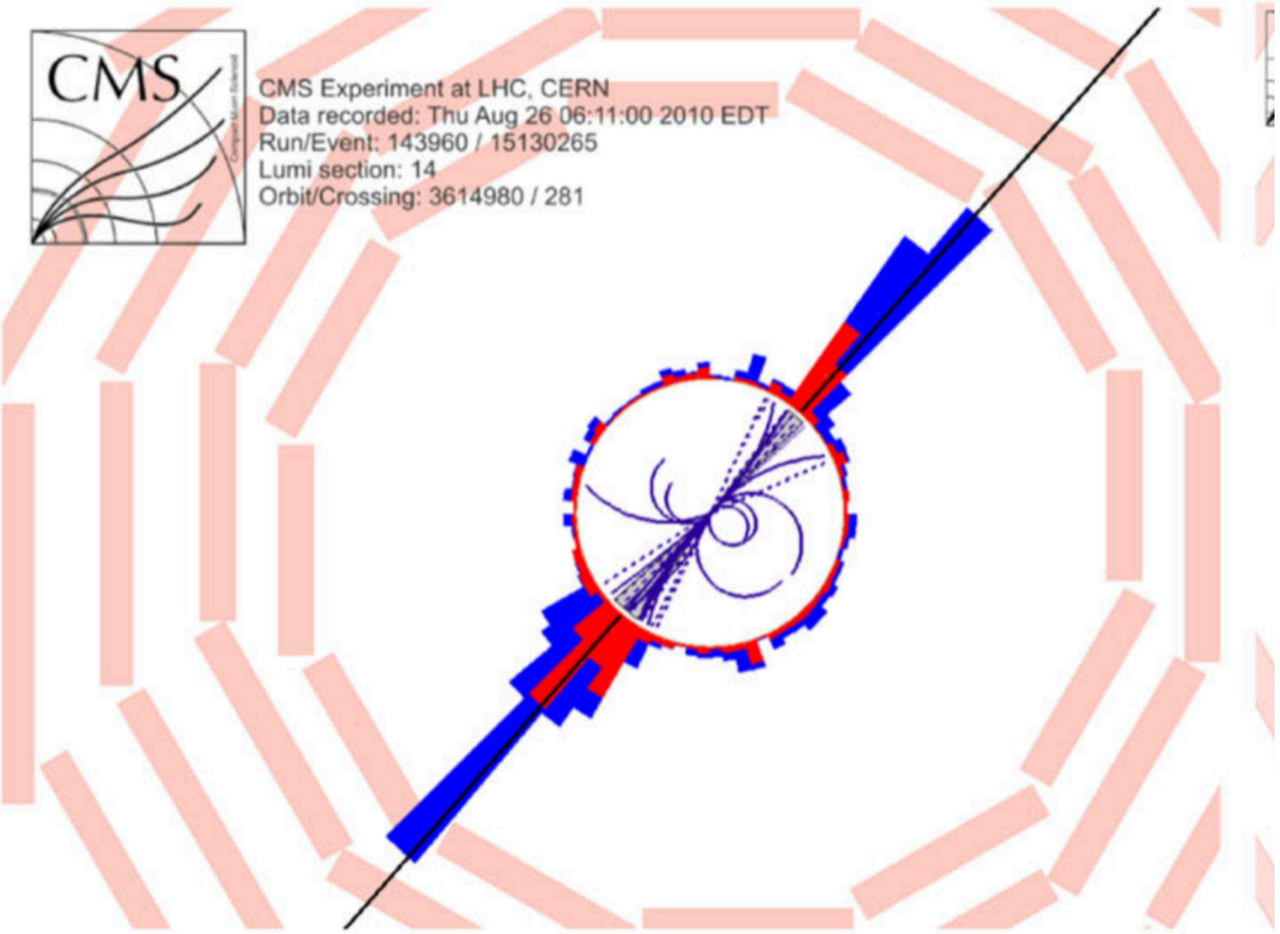
The result is:

$$P_g \approx \frac{\alpha_s C_F}{\pi} \ln^2 \frac{\omega_1}{Q_0} + \mathcal{O}\left(\alpha_s \ln \frac{\omega_1}{Q_0}\right)$$ **This is a double-logarithm!**

$\alpha_s \log^2 \frac{\omega_1}{Q_0} \sim 1$ It can be large: **resummation**

Dijet event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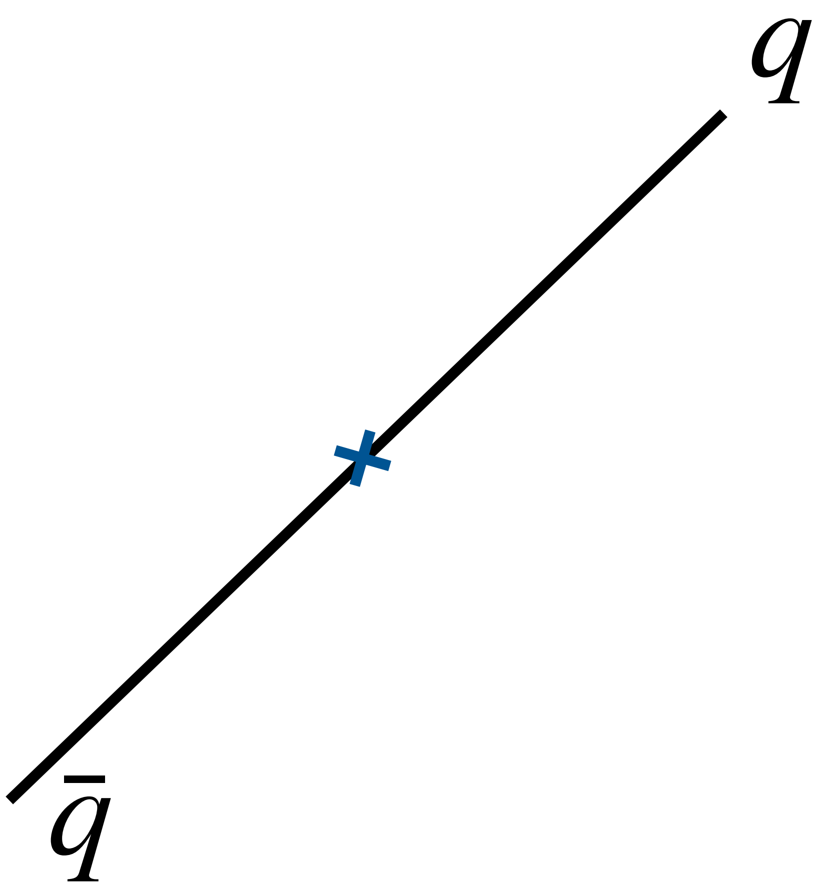
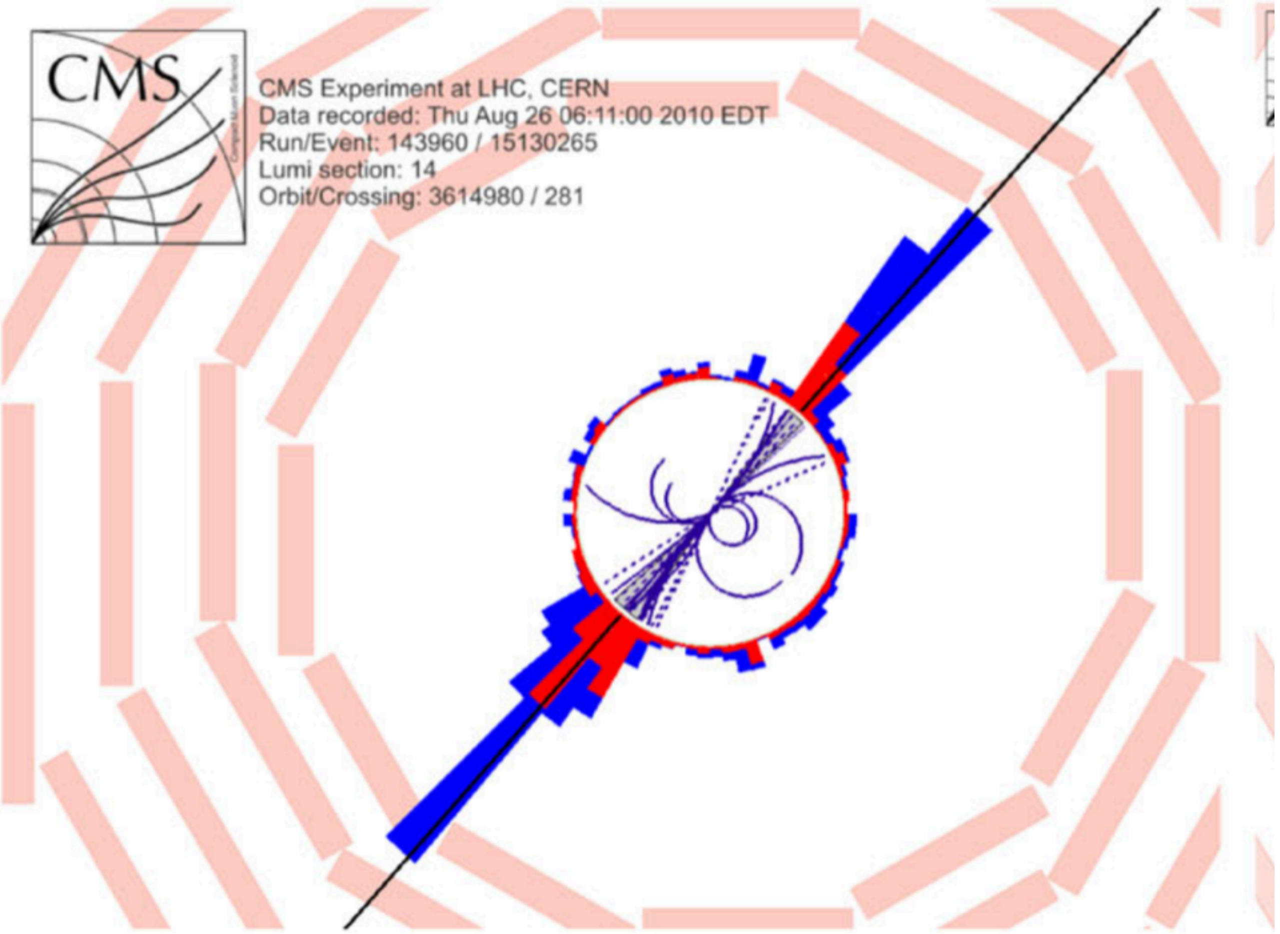
Lumi section: 14
Orbit/Crossing: 3614980 / 281


q
$\bar{q}$

Dijet event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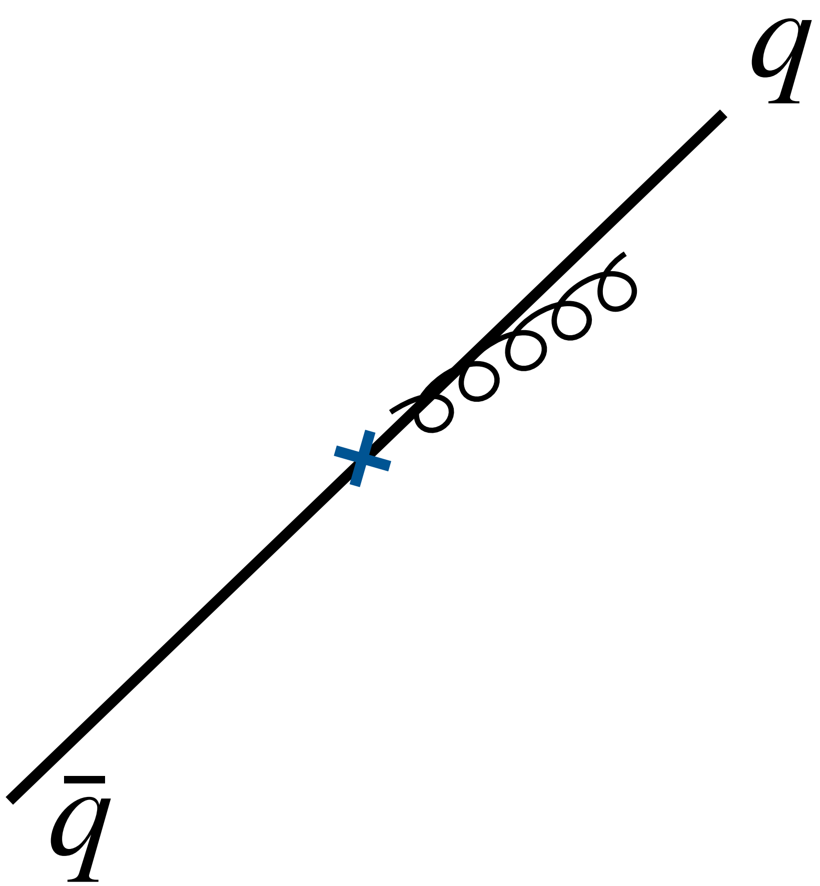
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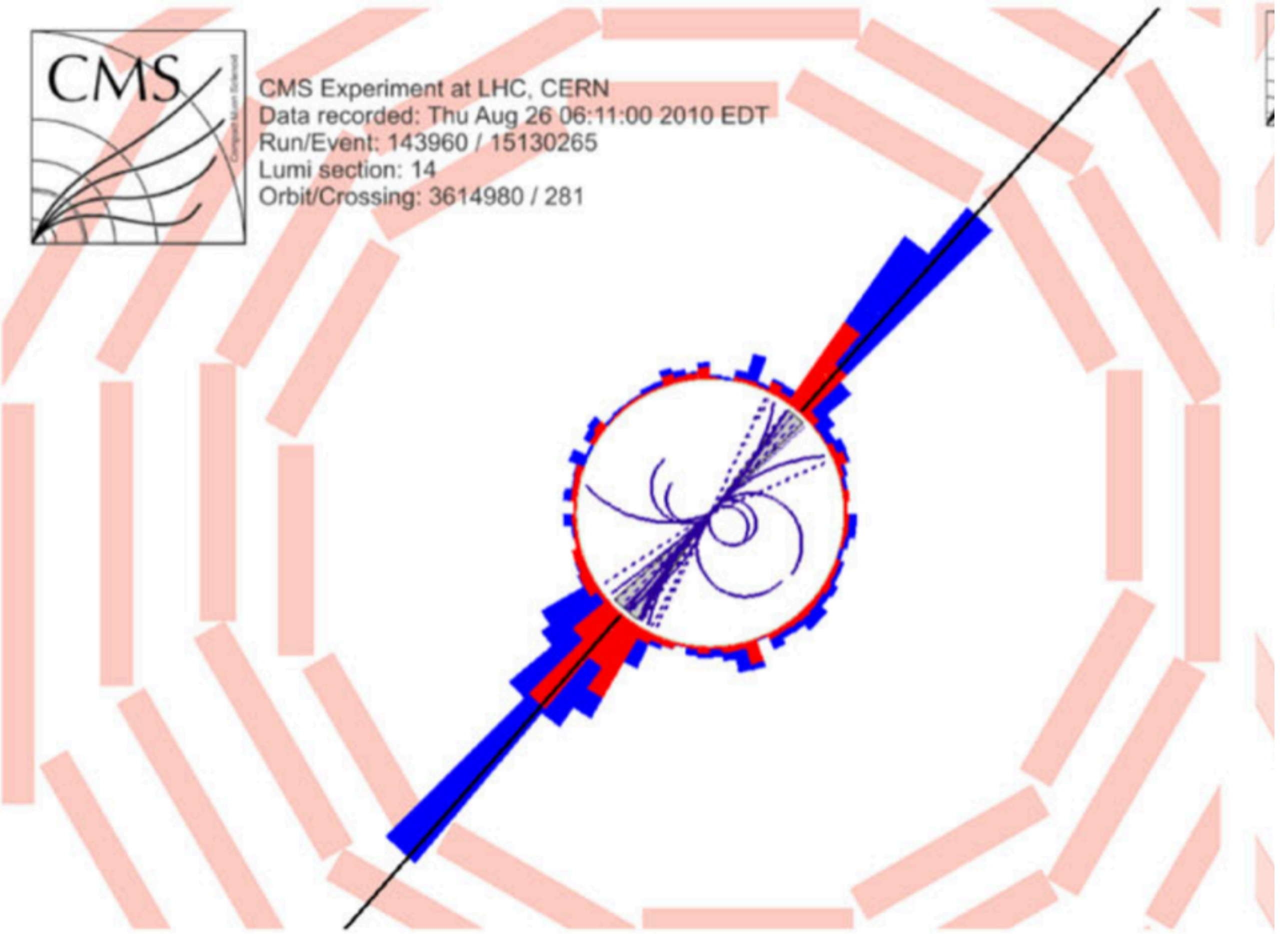
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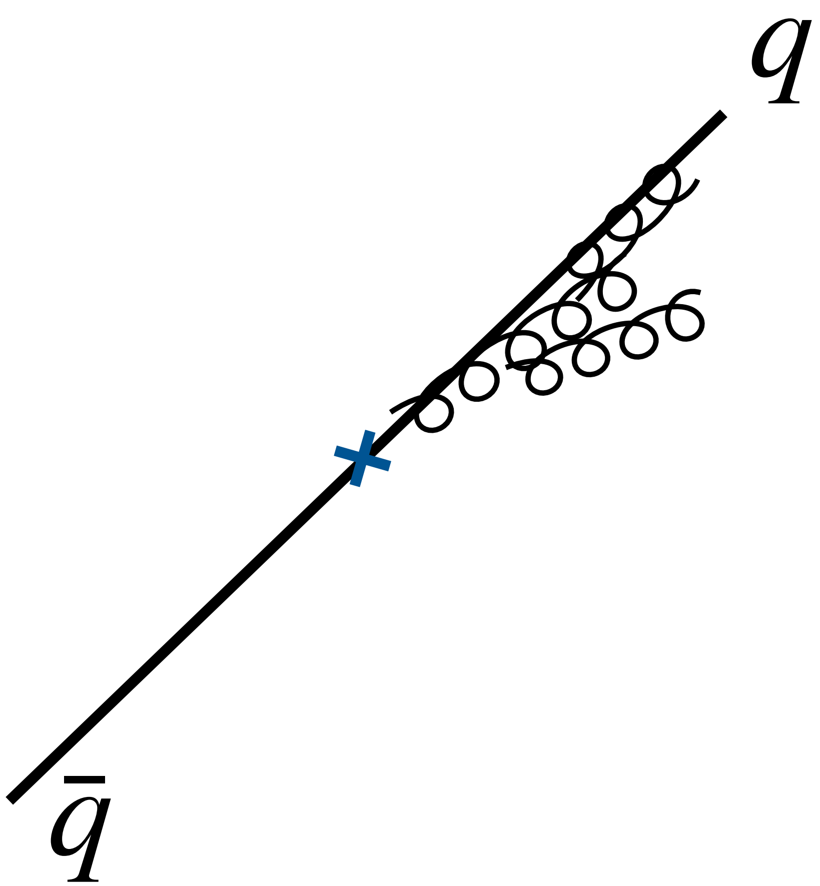
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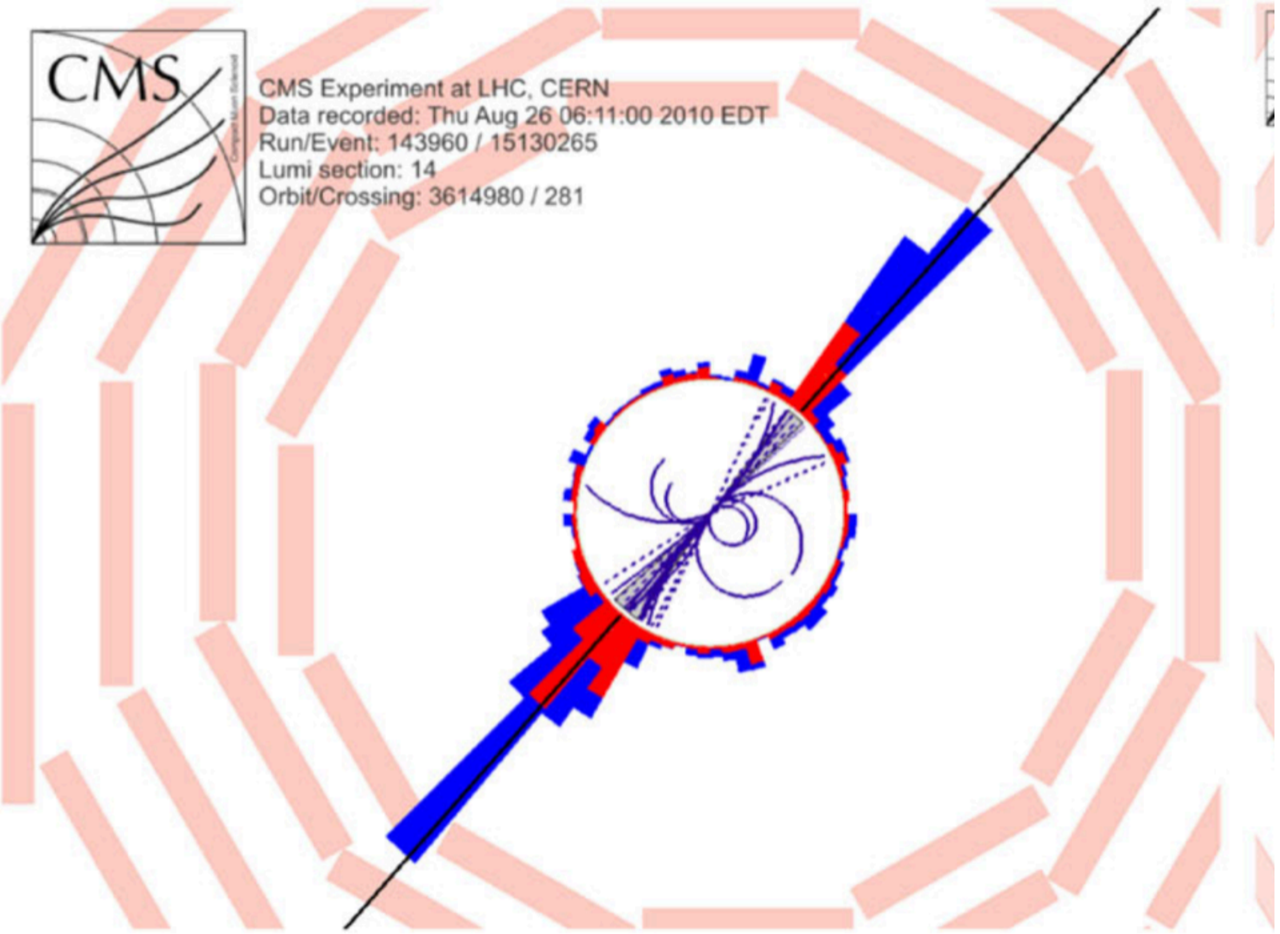

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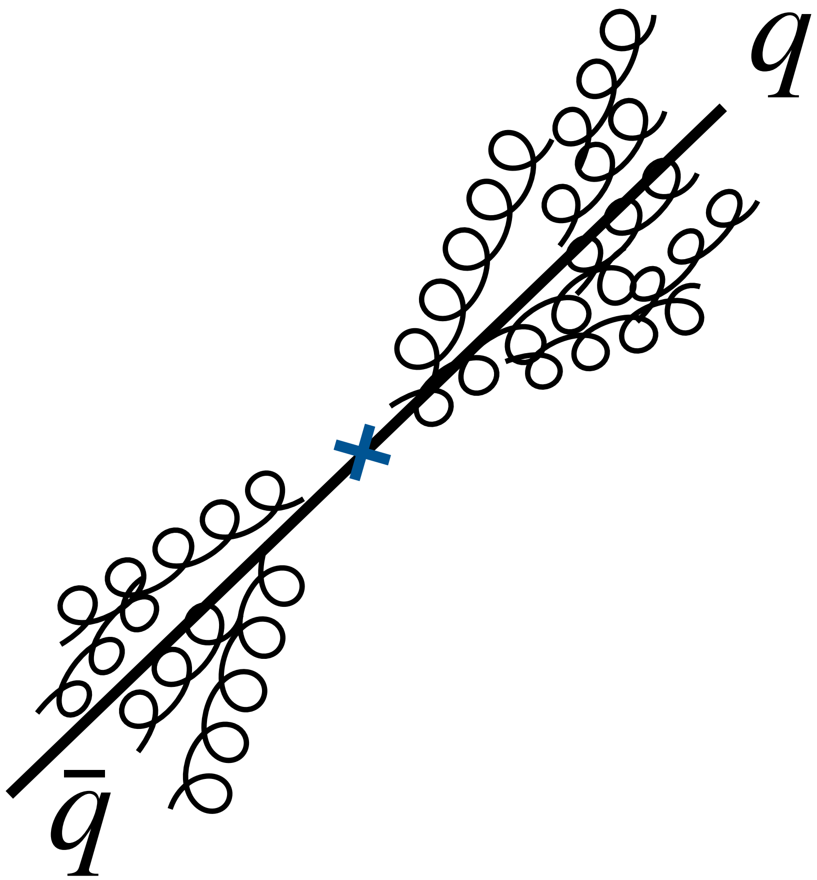

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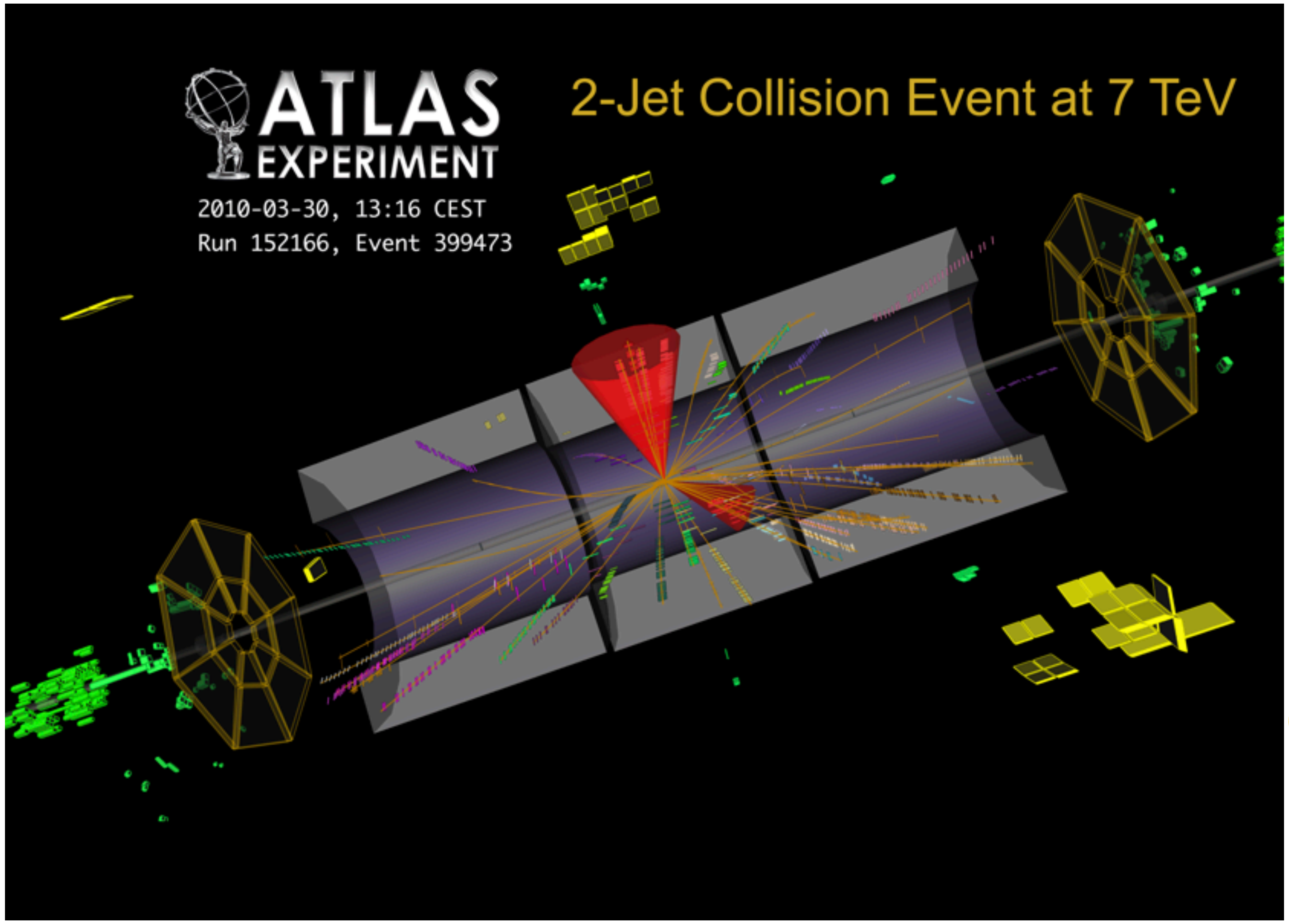
Dijet event



ATLAS
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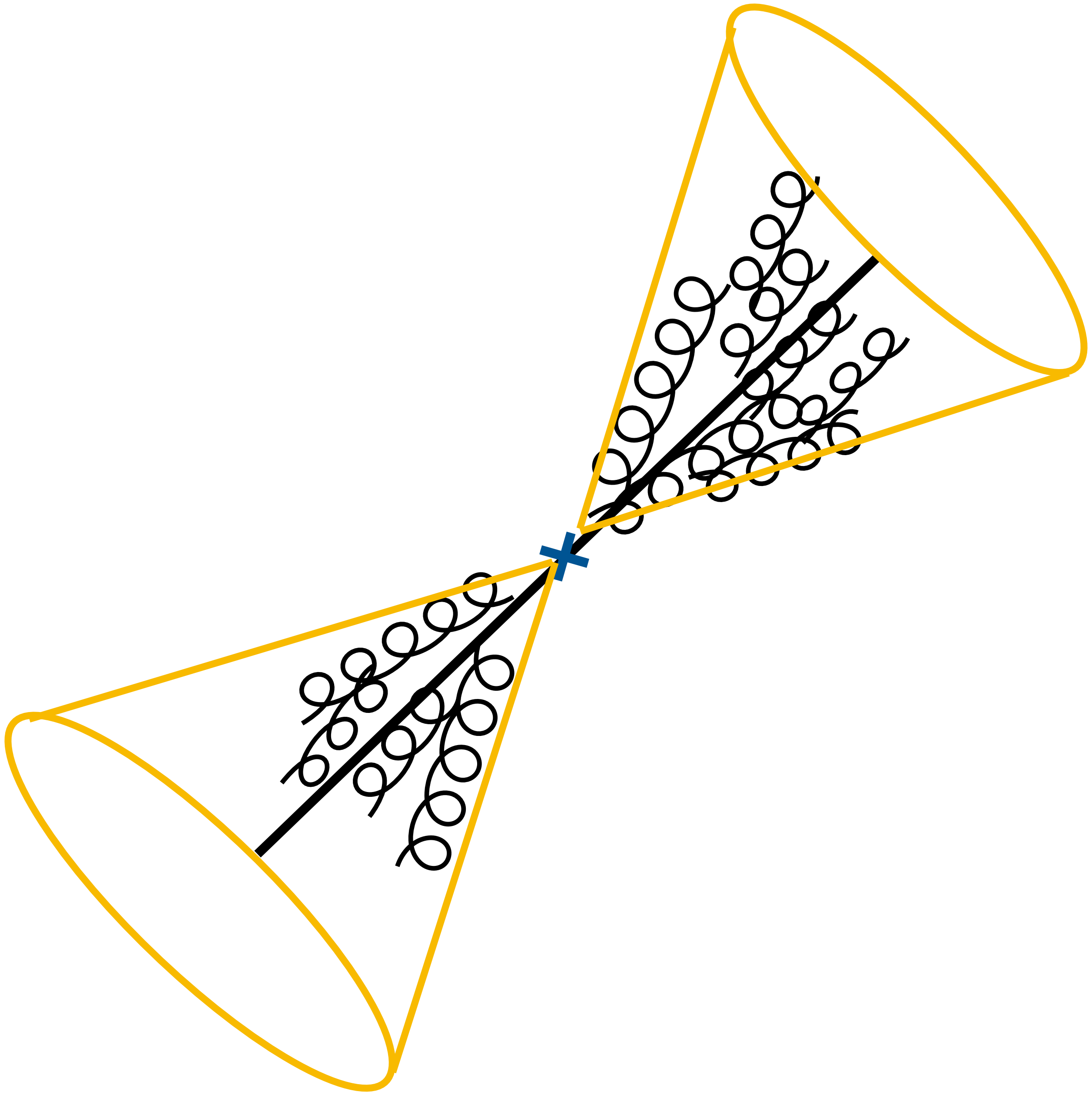
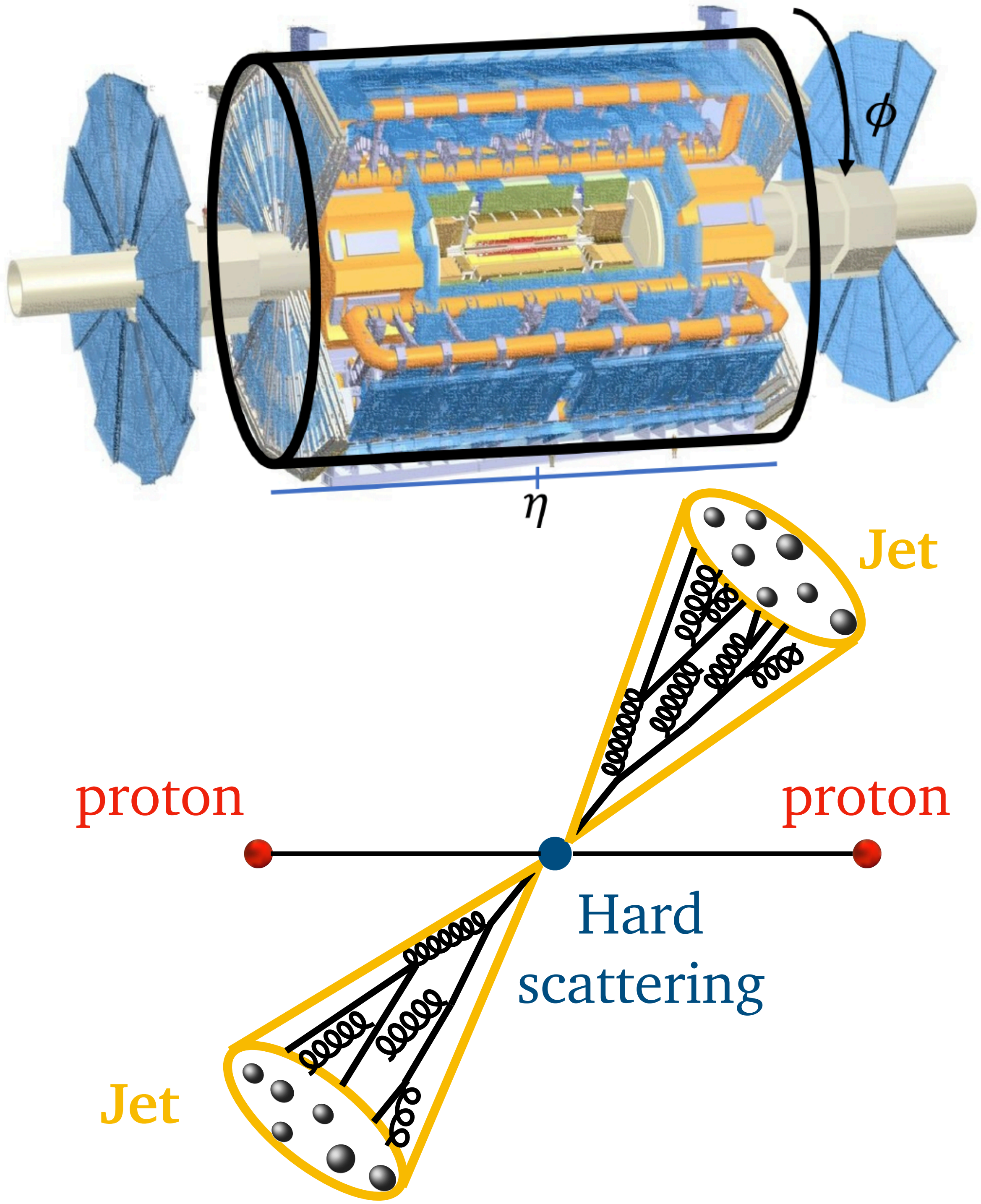
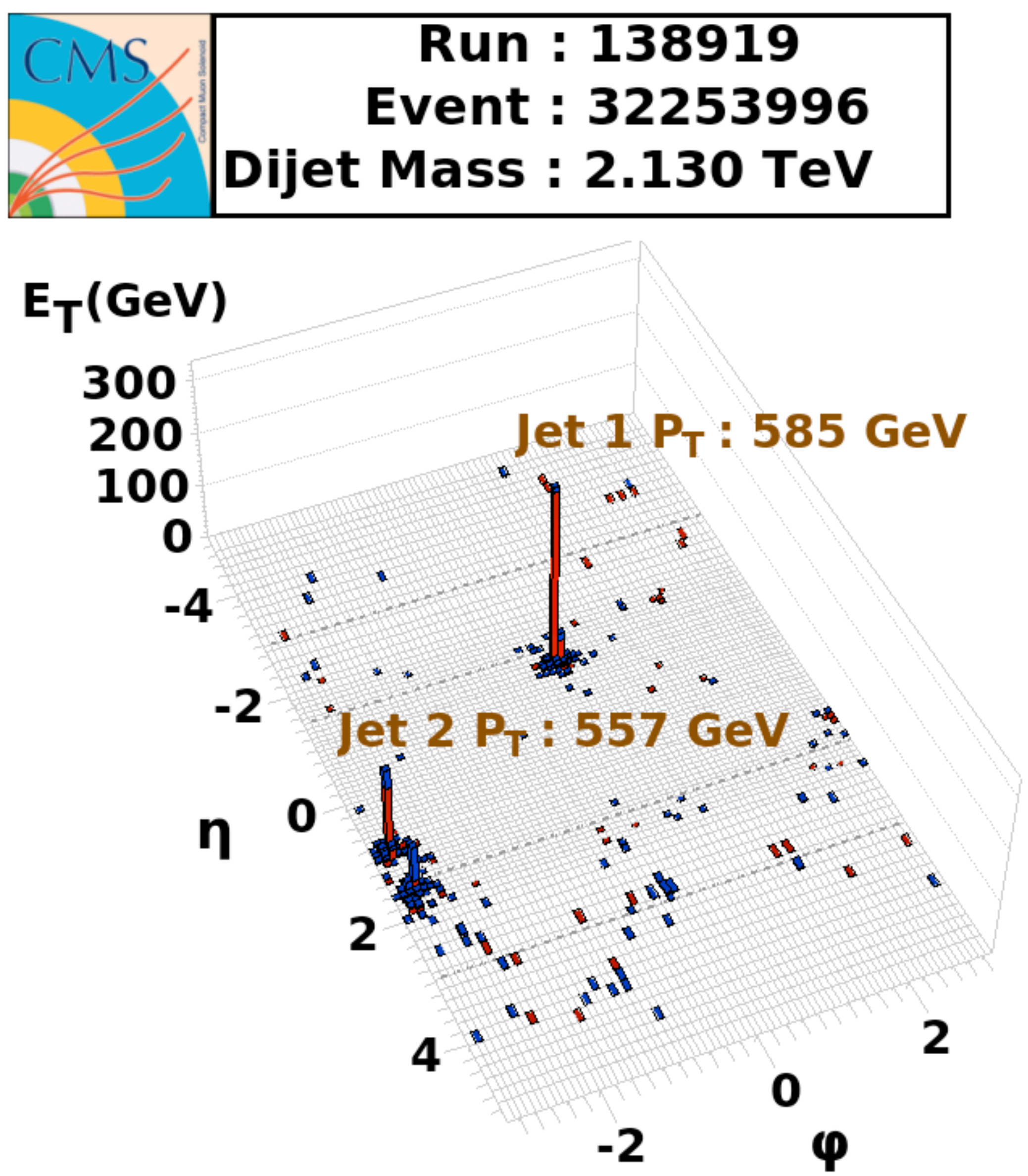
Run 152166, Event 399473
2-Jet Collision Event at 7 TeV



What are jets?

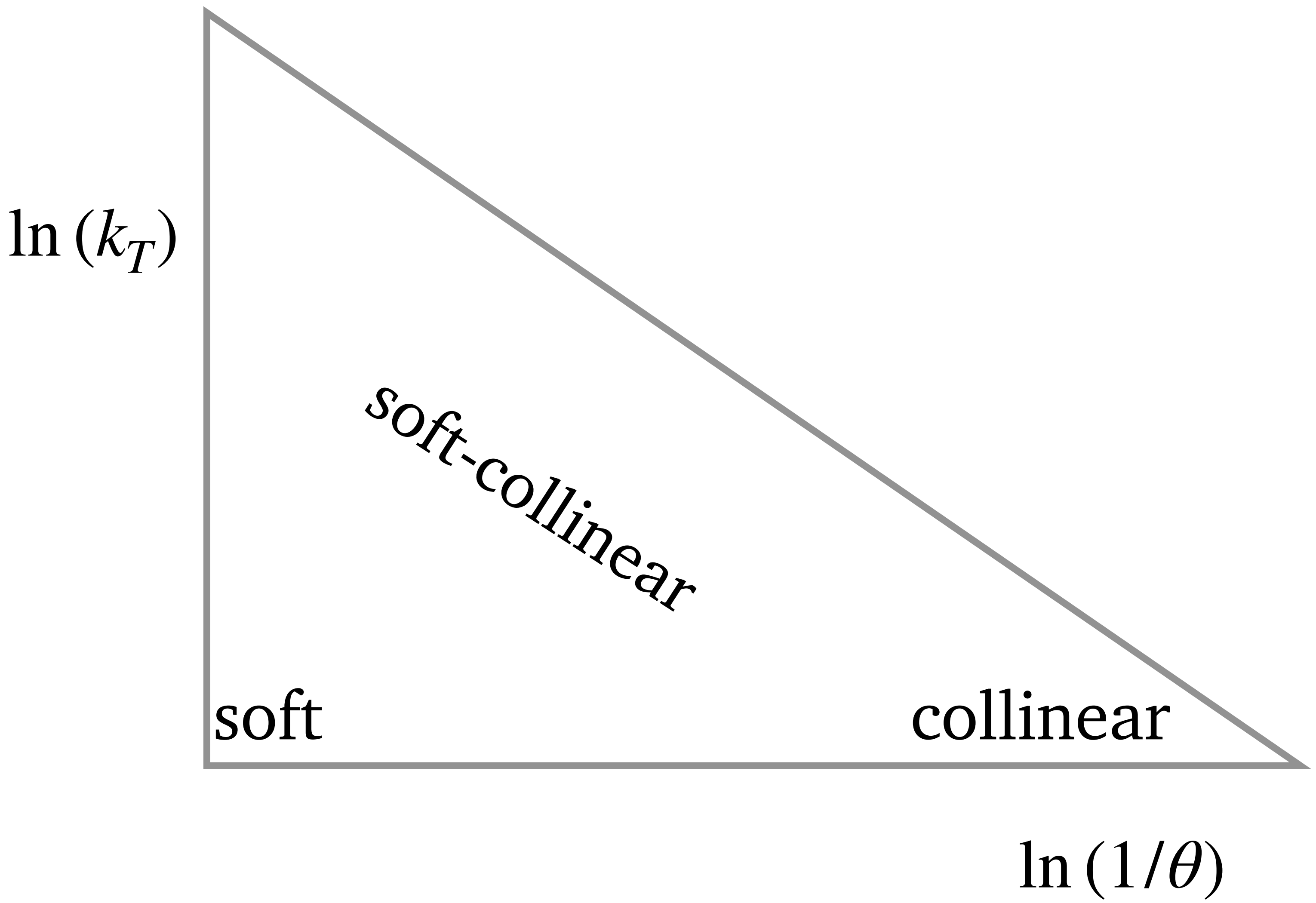


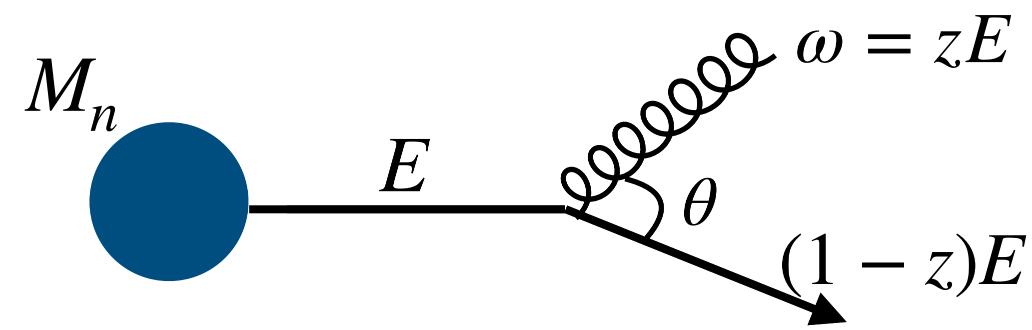
Defined through a clustering algorithm



Jets are proxies of the quarks and gluons produced in the hard scattering

Lund diagram





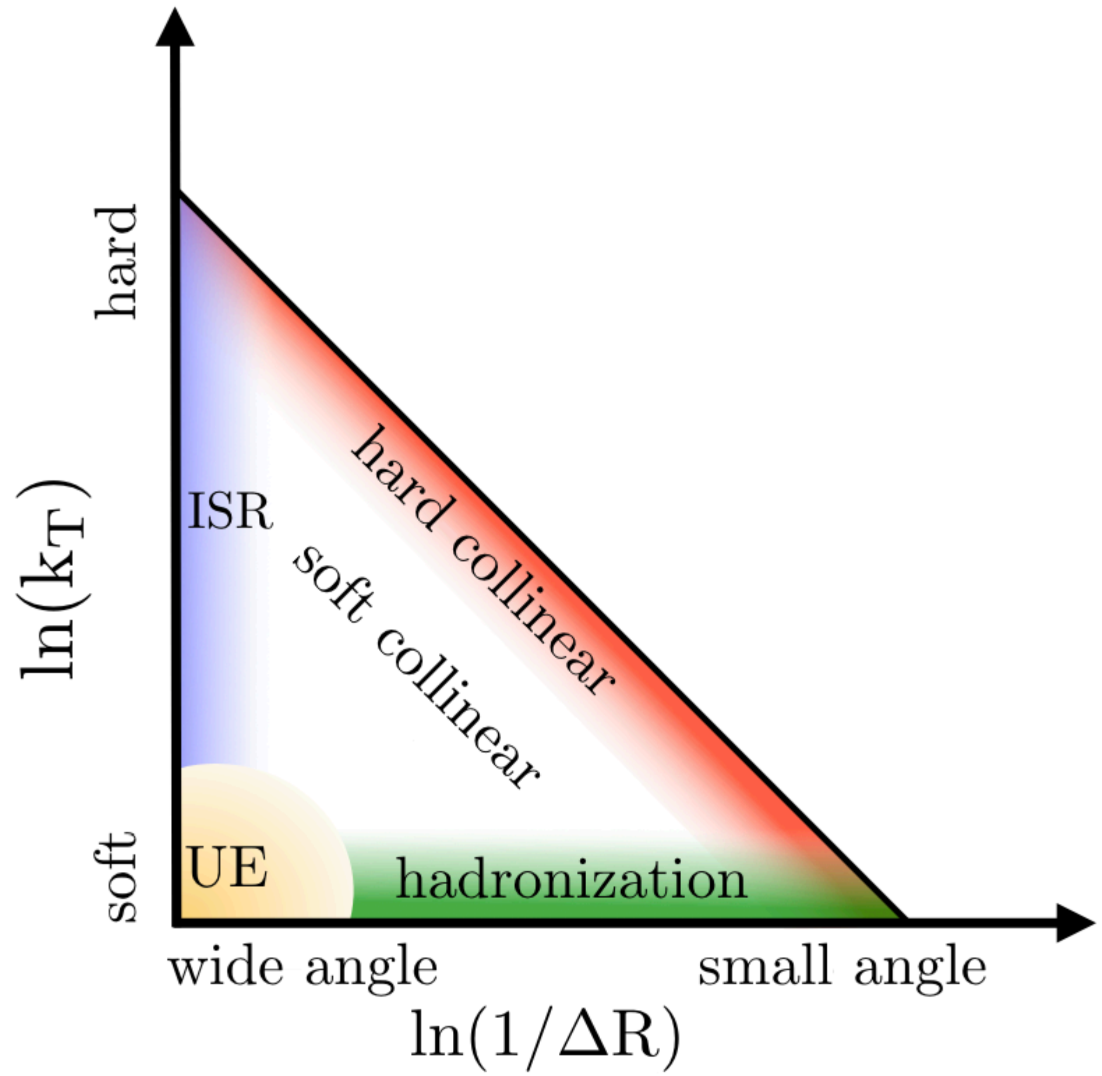
$$k_T = \omega\theta$$

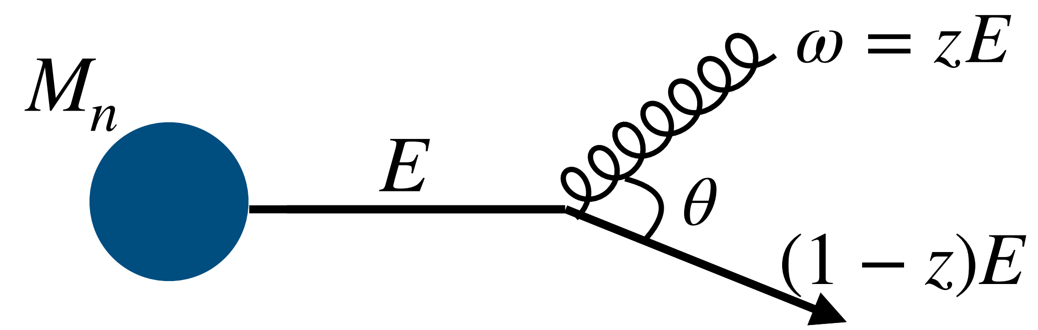
$$d\sigma_{n+1} = d\sigma \frac{2\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta}{\theta}$$

Soft and/or collinear emissions are **uniformly** distributed!

Corrections due to higher orders and running coupling apply

Lund diagram





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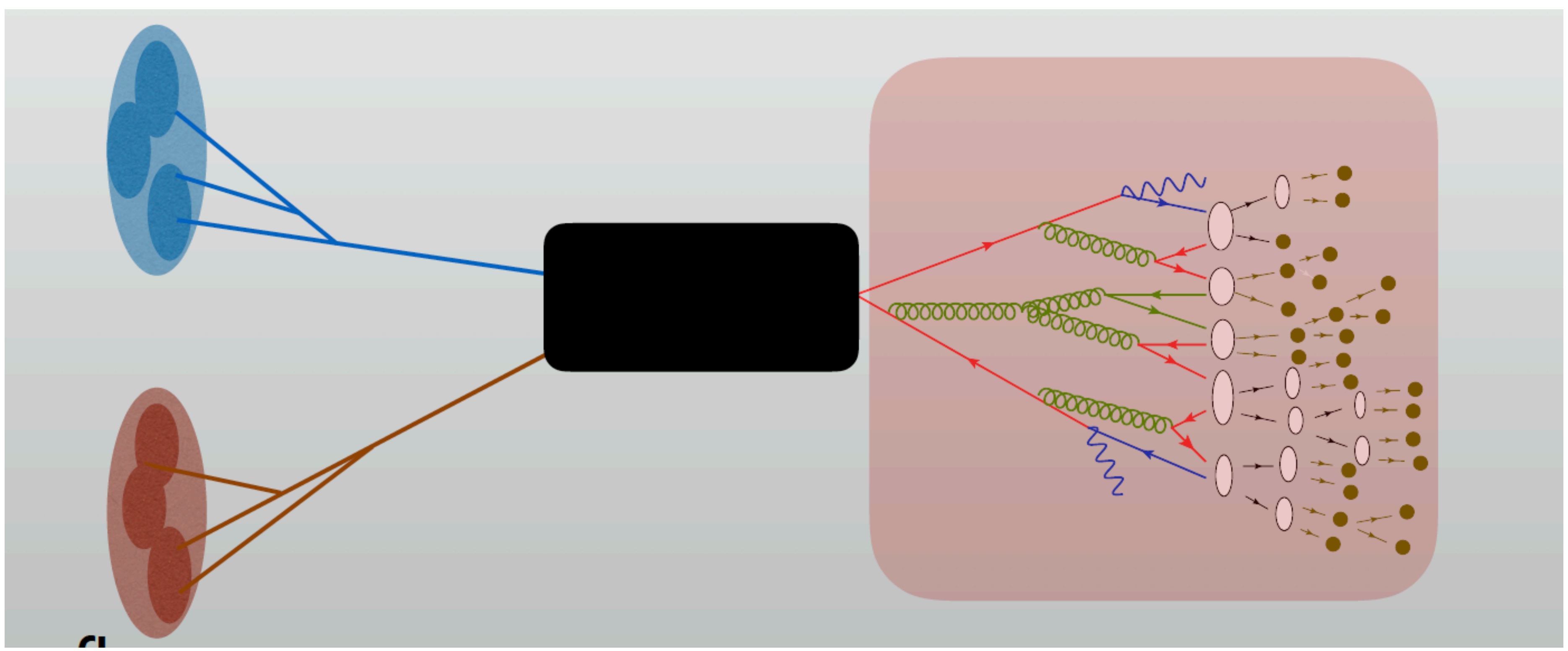
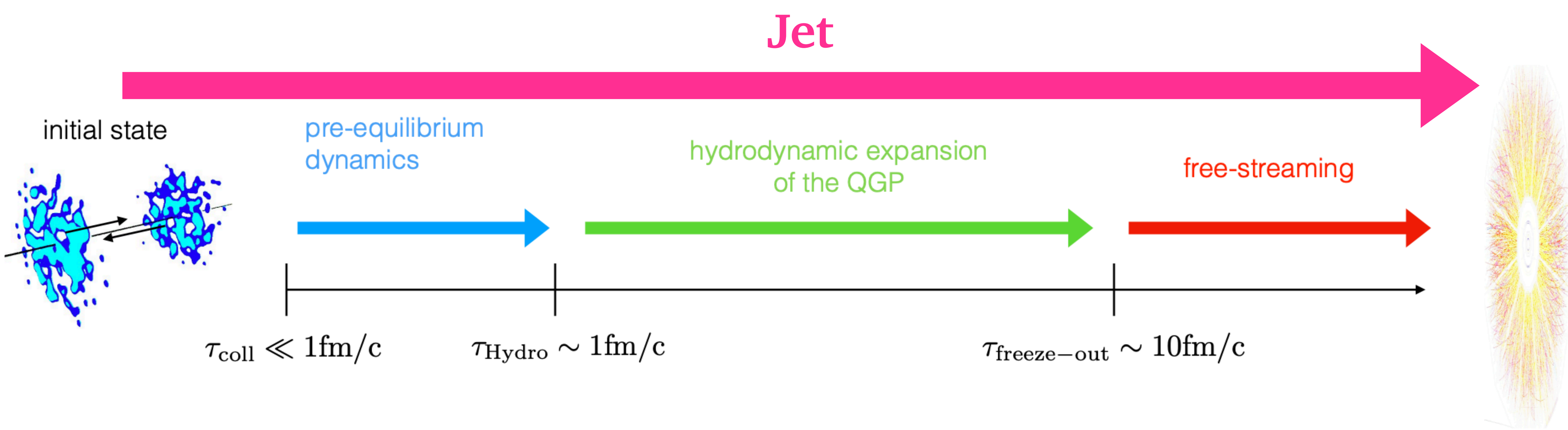
Some QCD in the medium



Jets in heavy-ion collisions

- Hard probes/jets ($Q \sim p_T$) are **produced** in the **initial hard scattering**

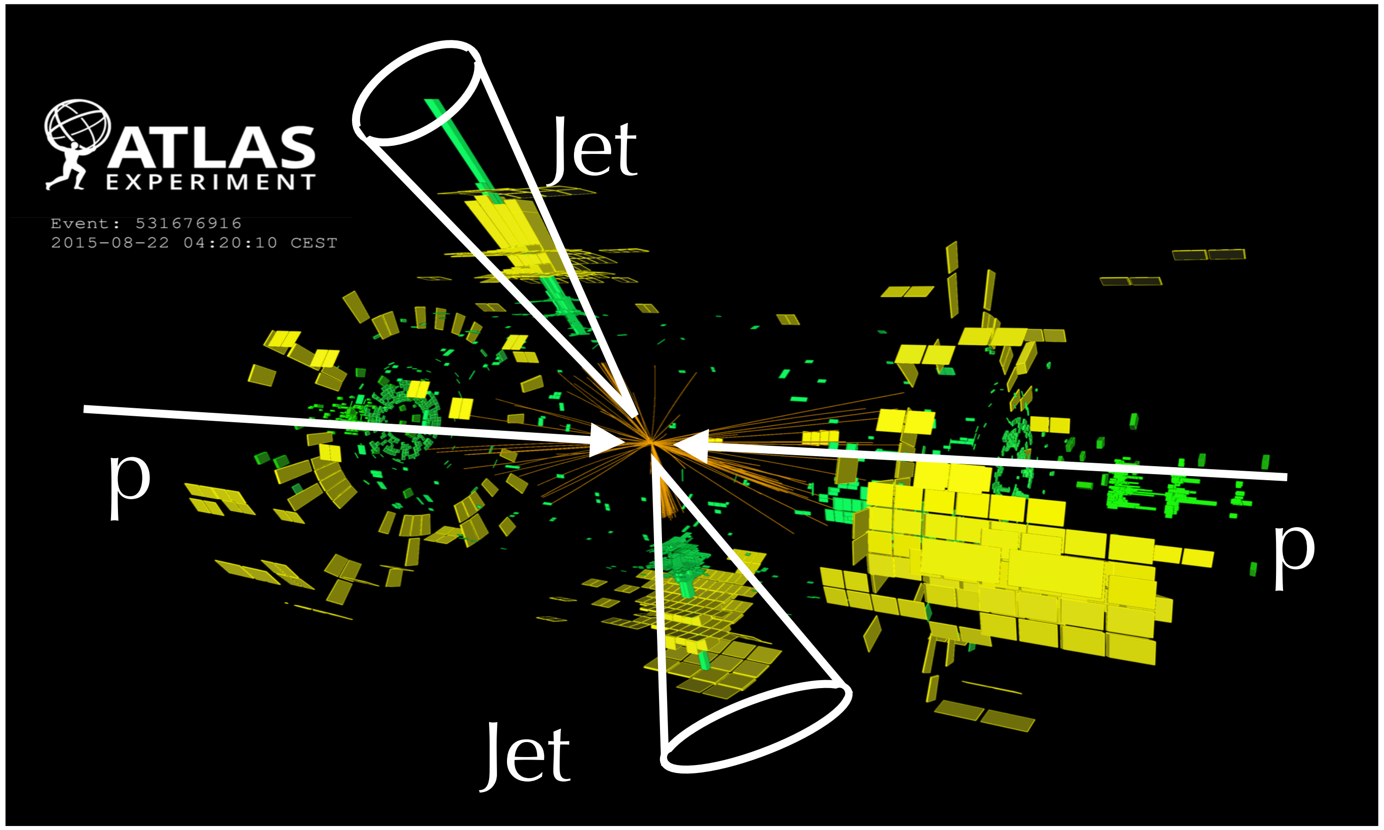
$$\tau_p \sim \frac{1}{Q} \ll \tau_{\rm hydro} \sim 1\ \text{fm/c}$$



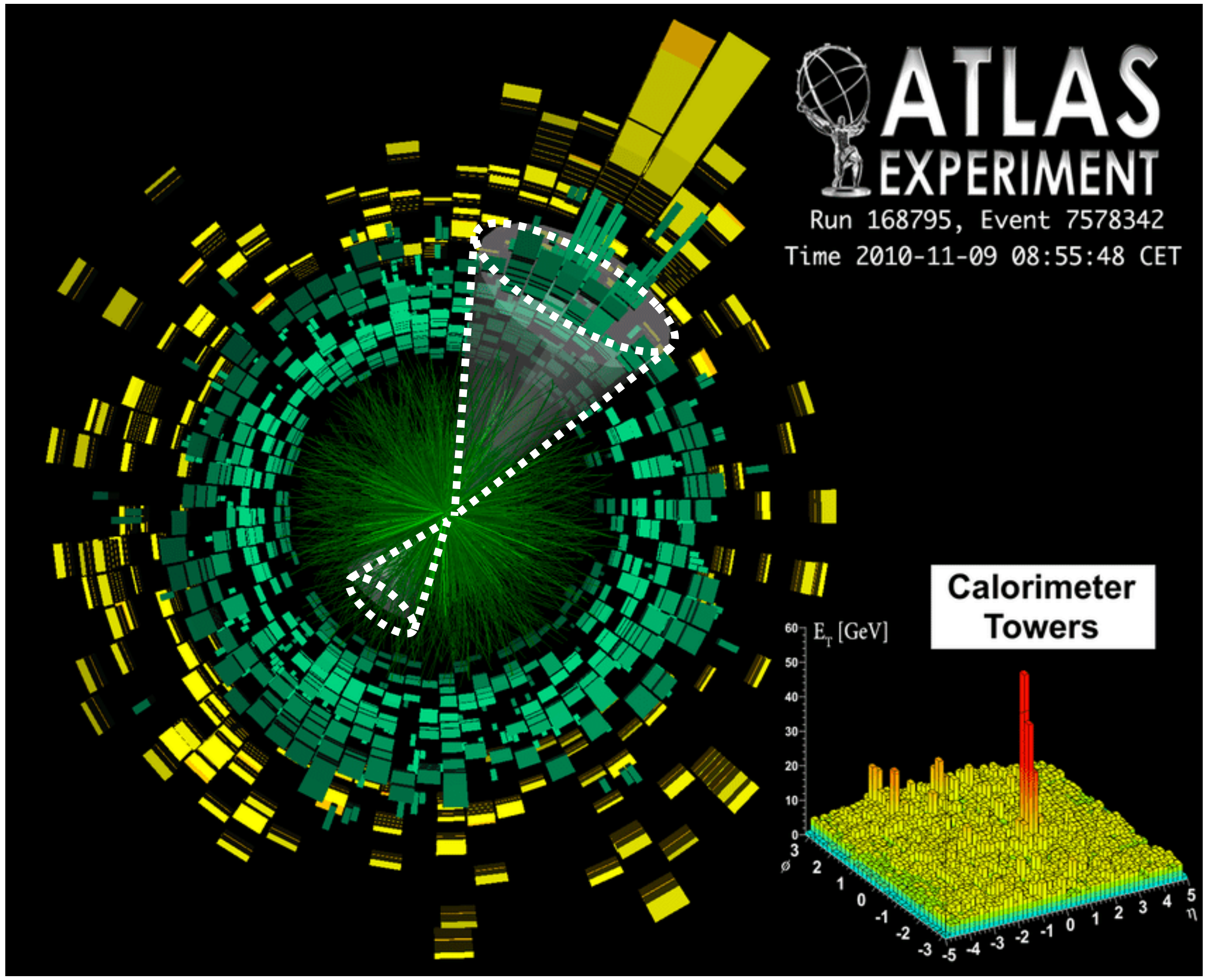
- They **interact with the medium** through the strong interaction

Jets are extended objects: ideal to **probe the medium at different times and resolution scales**

Jets in p-p vs. A-A

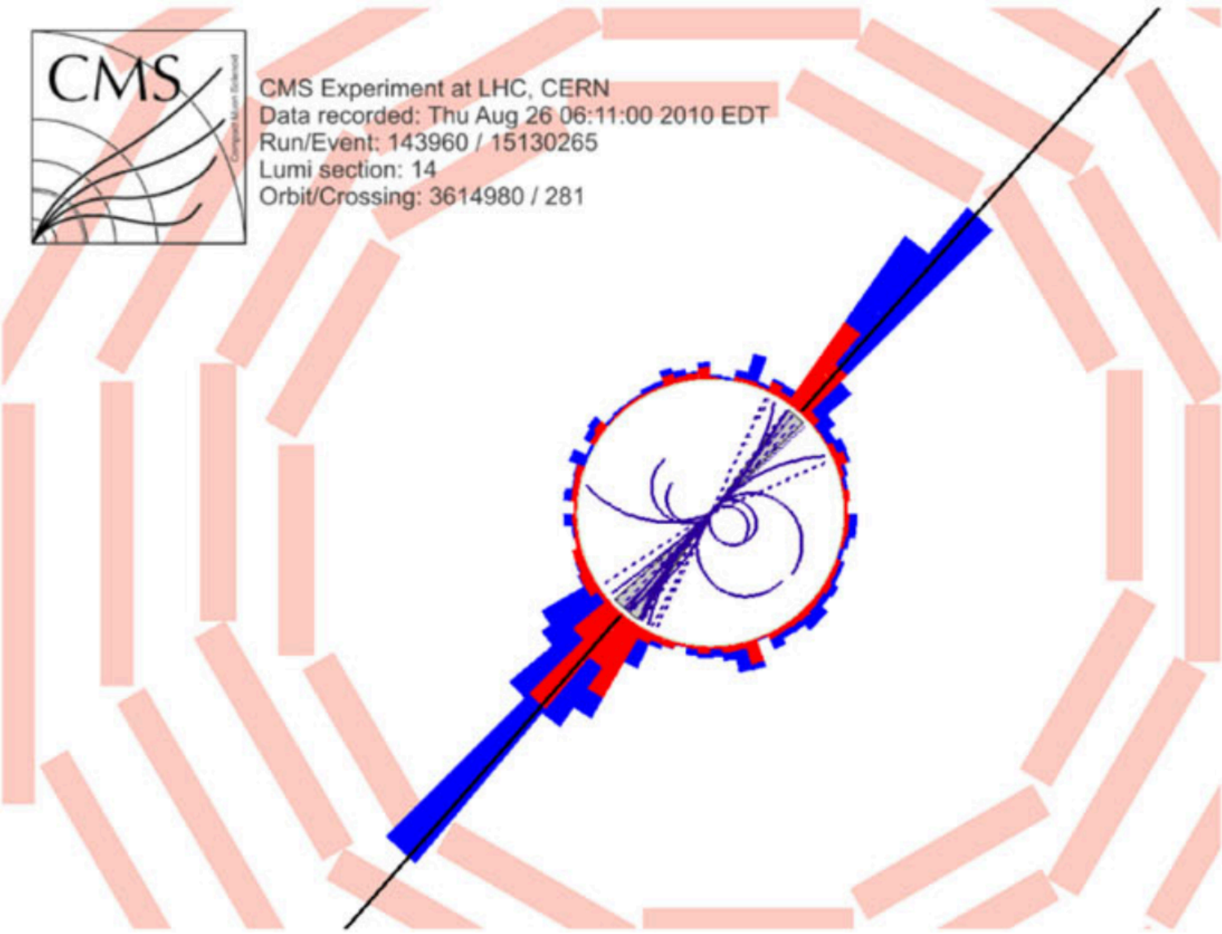


Jet quenching in A-A

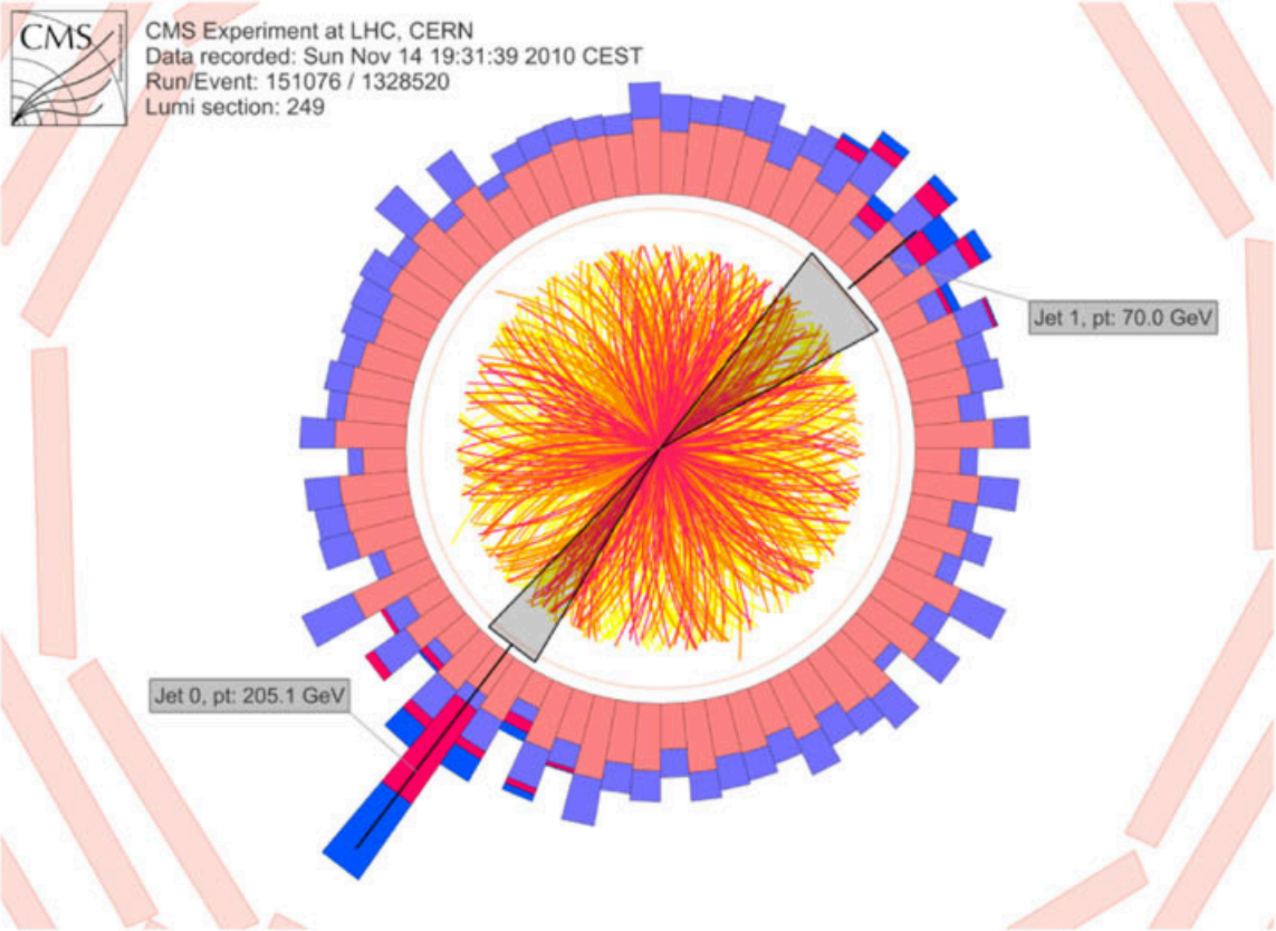


Energy loss

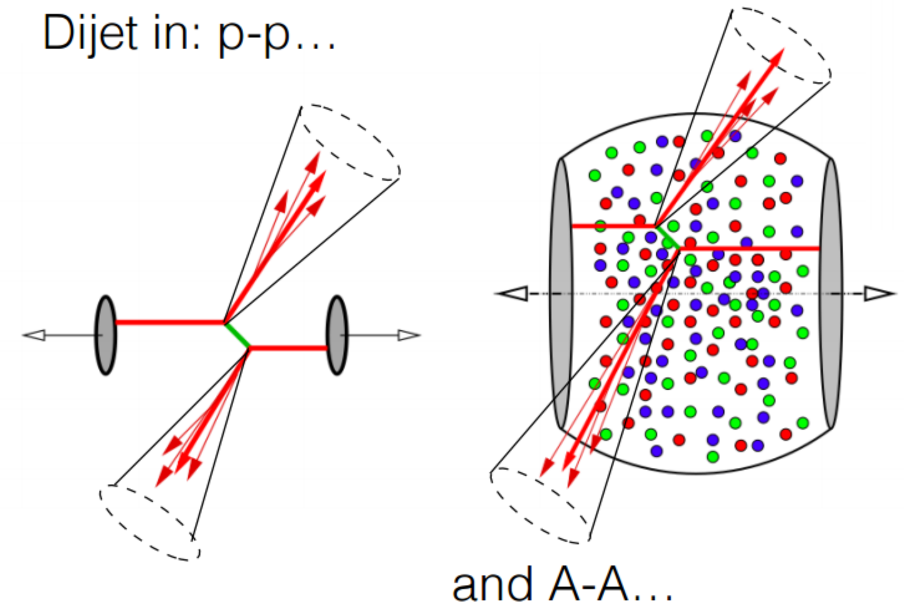
Dijet in p-p



Dijet in Pb-Pb

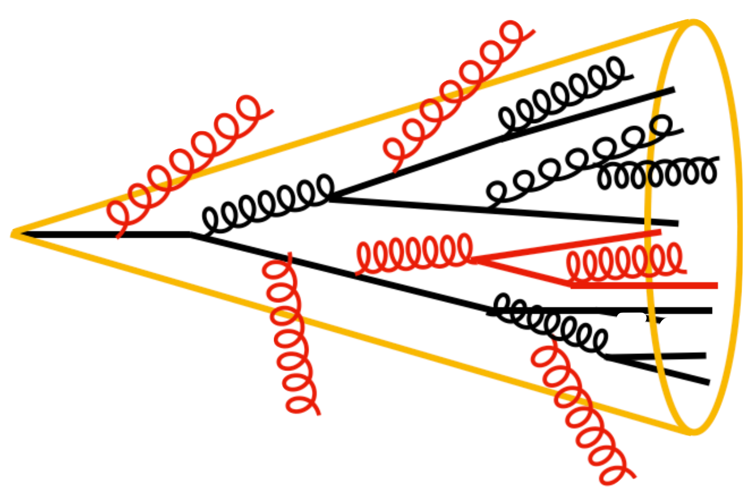


Jet quenching



- **Jet quenching: partons** interact with the medium losing energy

- How does a parton lose energy in a QCD medium?
  - Collisions - Important for heavy particles
  - **Radiation** - Dominant for light quarks and gluons



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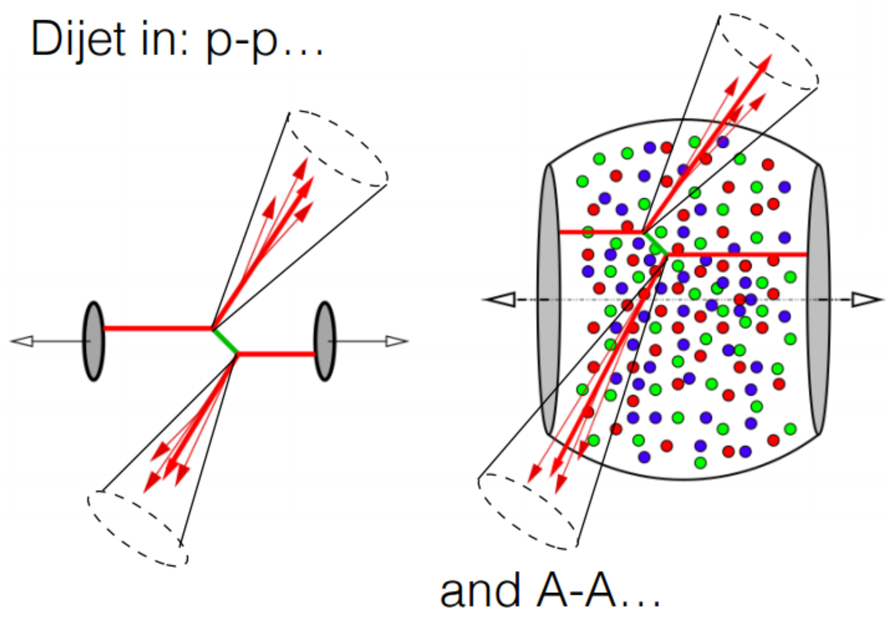

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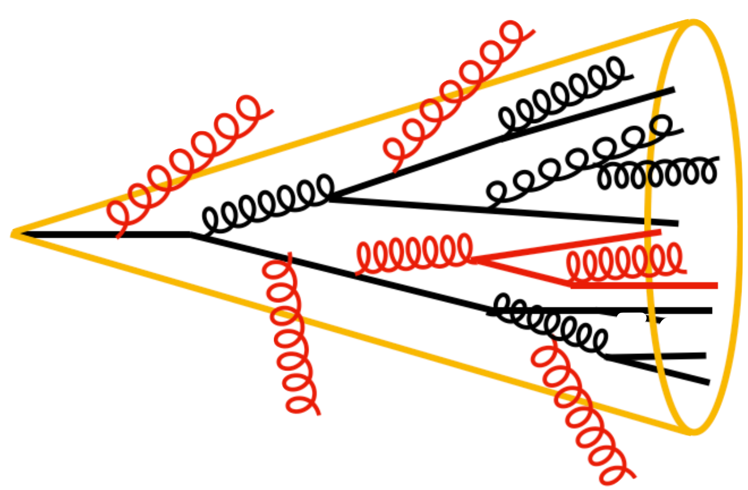
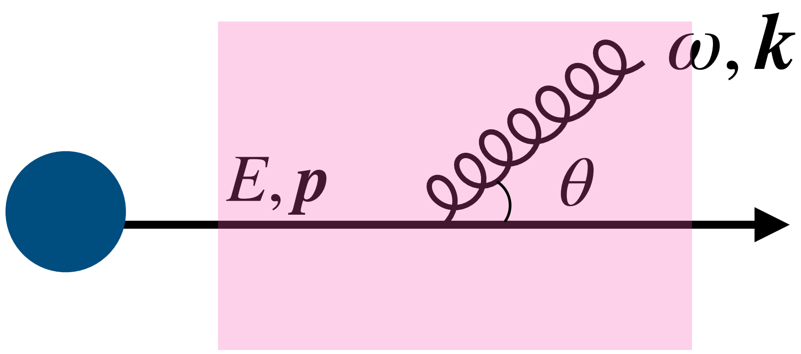


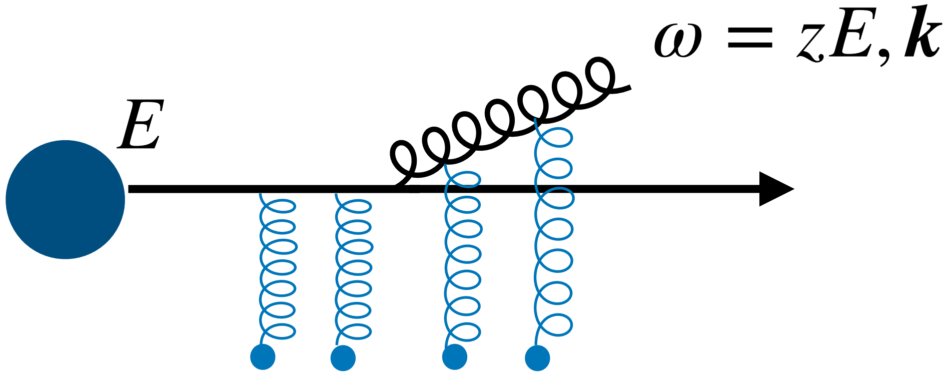
Medium-induced radiation

Assumptions



- The gluon is emitted at small angles and $\mu \ll \boldsymbol{k}, \boldsymbol{p} \ll \omega, E$

- The radiation is due to elastic scatterings mediated by gluons

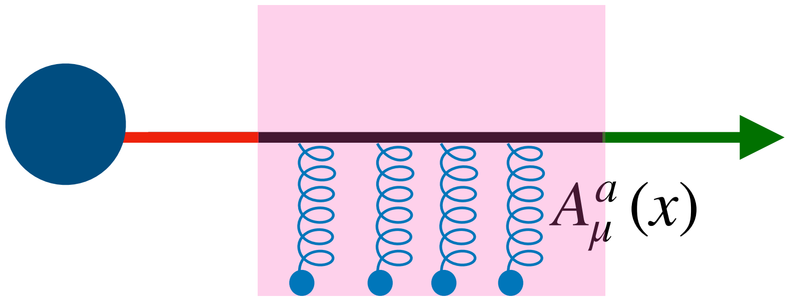


Medium as a recoilless background field $A_-^a(t, \boldsymbol{x})$

- The interactions are instantaneous. The medium is seen as recoilless background field

In-medium parton propagation

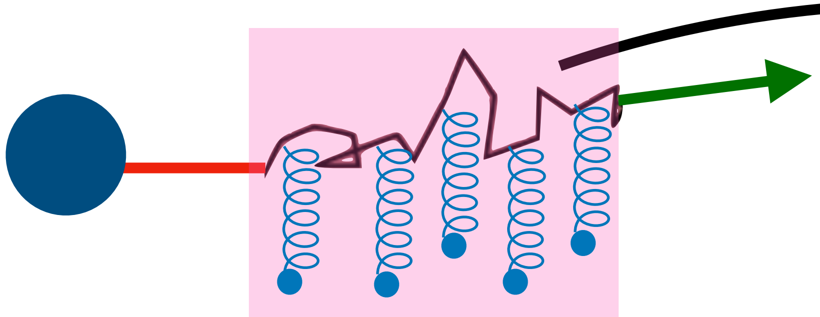
Color rotation



$$W(\boldsymbol{x}) = \mathscr{P} \exp\left\{ ig_s \int dt\, A^-(t,\boldsymbol{x}) \right\}$$

$$p^+ \equiv E \gg \boldsymbol{p} \gg \mu$$

Color rotation + $\boldsymbol{p}$-broadening

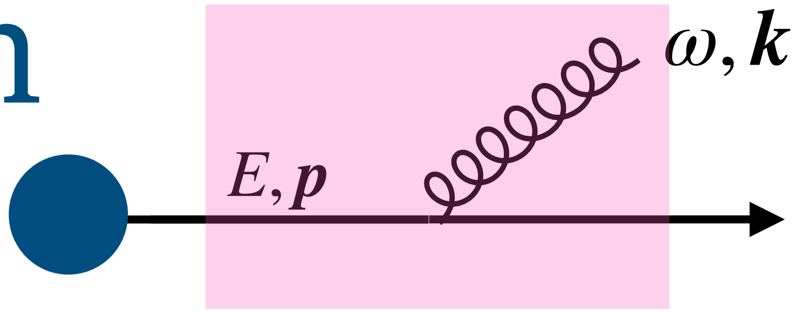


Brownian motion

$$p^+ \equiv E > \boldsymbol{p} \gg \mu$$

$$G(t_2, \boldsymbol{x_2};\, t_1, \boldsymbol{x_1} | E) = \mathscr{P} \int \mathscr{D}\boldsymbol{r}(t) \exp\left\{ i\frac{E}{2} \int dt \left[\frac{d\boldsymbol{r}}{dt}\right]^2 + ig_s \int dt\, A^-(t,\boldsymbol{x}) \right\}$$

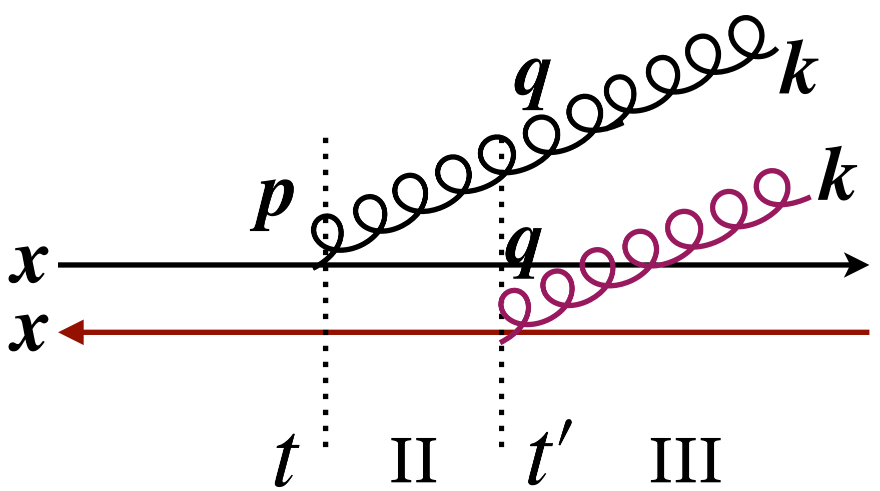
Medium-induced radiation

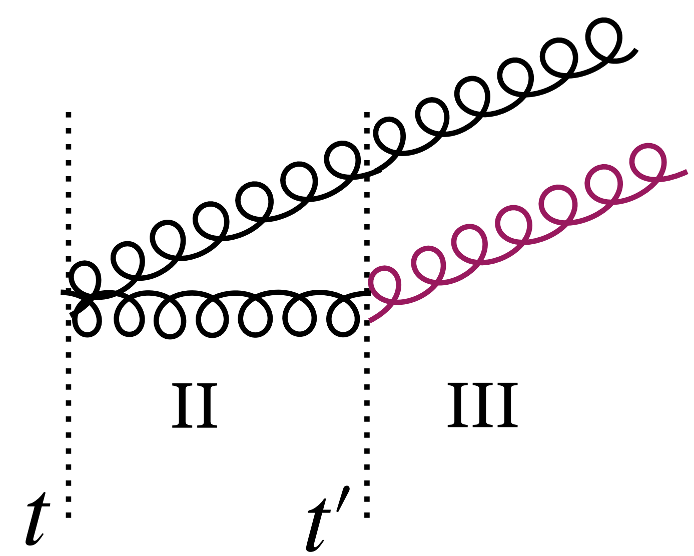


- Emission of a soft gluon off a high energy quark: $\omega \ll E$

BDMPS-Z formalism (1990's)

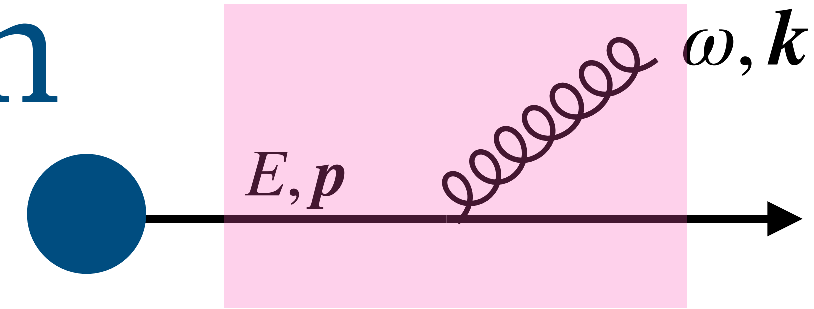
$$\omega \frac{dI^{\text{med}}}{d\omega d^2\boldsymbol{k}} = \frac{2\alpha_s C_R}{(2\pi)^2\omega^2} \text{Re} \int_0^\infty dt' \int_0^{t'} dt \int_{\boldsymbol{pq}} \boldsymbol{p}\cdot\boldsymbol{q}\, \widetilde{\mathcal{K}}(t', \boldsymbol{q}; t, \boldsymbol{p}) \mathcal{P}(\infty, \boldsymbol{k}; t', \boldsymbol{q})$$





Baier, Dokshitzer, Mueller, Peigné, Schiff; and Zakharov

Medium-induced radiation



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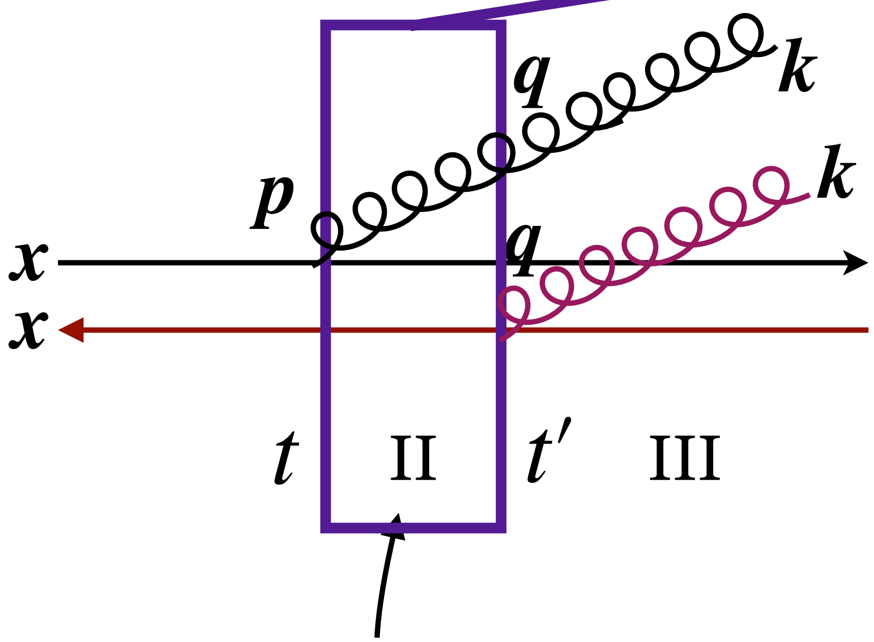
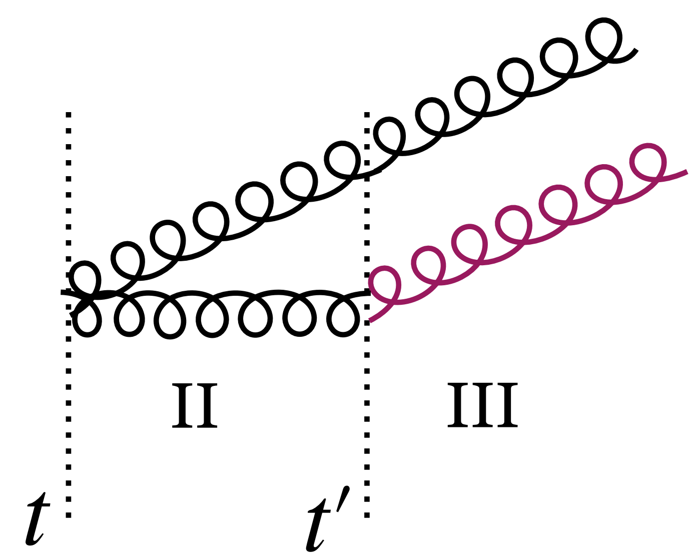


Kernel

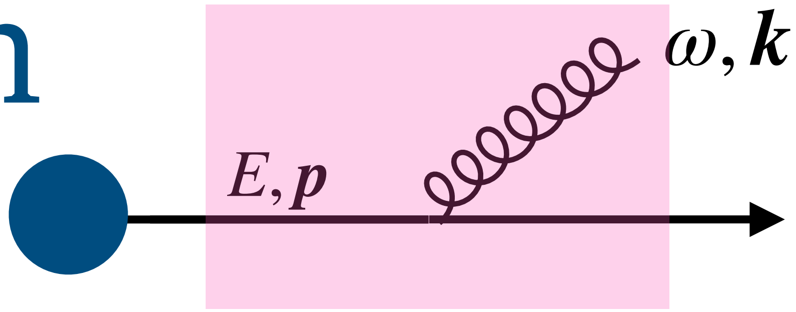


2-point function

$\mathcal{K} \sim Tr\langle W_A \mathcal{G}\rangle$

Baier, Dokshitzer, Mueller, Peigné, Schiff; and Zakharov

Medium-induced radiation



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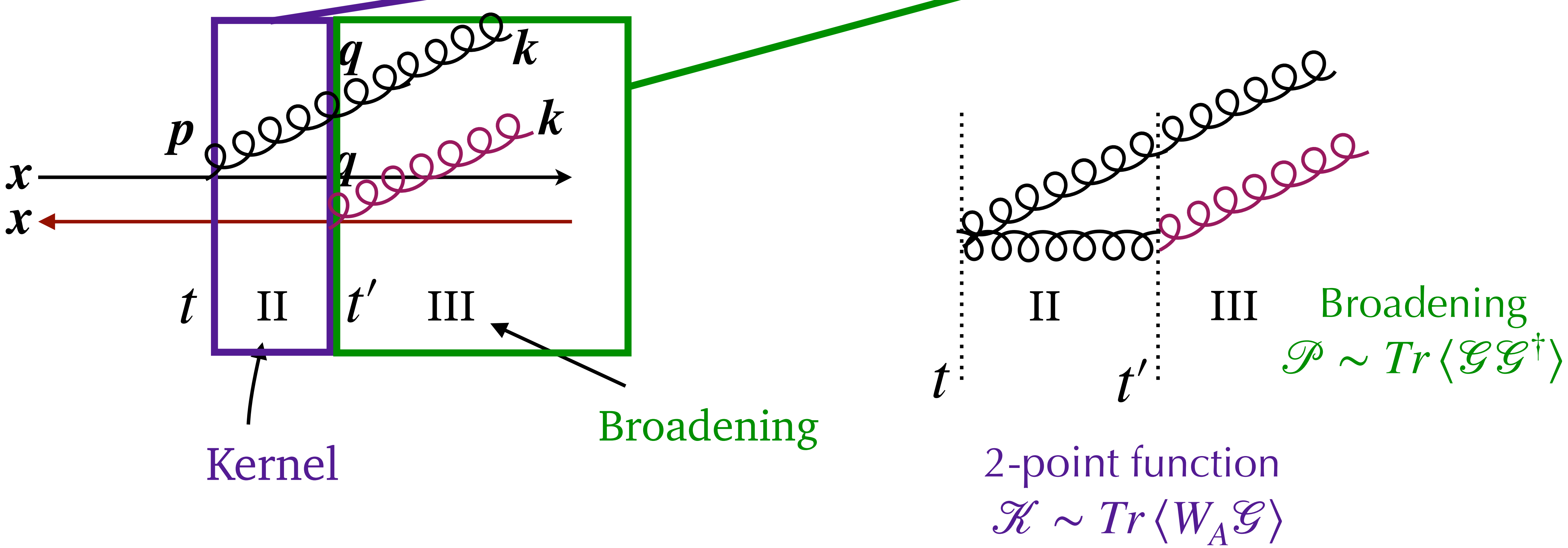
BDMPS-Z formalism (1990's)

$$\omega \frac{dI^{\mathrm{med}}}{d\omega d^2\boldsymbol{k}} = \frac{2\alpha_s C_R}{(2\pi)^2\omega^2} \mathrm{Re} \int_0^\infty dt' \int_0^{t'} dt \int_{\boldsymbol{pq}} \boldsymbol{p}\cdot\boldsymbol{q} \boxed{\widetilde{\mathcal{K}}(t', \boldsymbol{q}; t, \boldsymbol{p})} \boxed{\mathcal{P}(\infty, \boldsymbol{k}; t', \boldsymbol{q})}$$



Baier, Dokshitzer, Mueller, Peigné, Schiff; and Zakharov

Medium averages

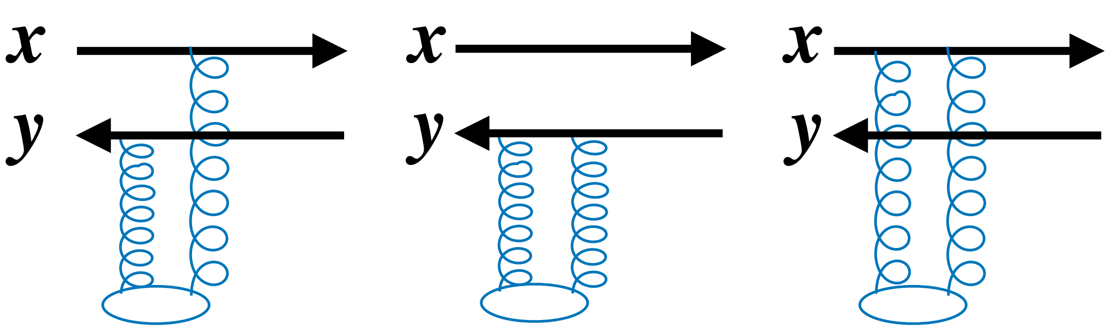
- Medium average:

$$\langle A^{a,-}(t,\boldsymbol{x})\, A^{b,-\dagger}(t',\boldsymbol{y})\rangle = \delta^{ab}\delta(t-t')\,\gamma(\boldsymbol{x}-\boldsymbol{y})$$

medium information

- Medium average:

$$\frac{1}{N_c}\mathrm{Tr}\,\langle W(\boldsymbol{x})W^{\dagger}(\boldsymbol{y})\rangle = \exp\left\{-\frac{1}{2}\int ds\, n(s)\,\sigma(\boldsymbol{x}-\boldsymbol{y})\right\}$$



$$\sigma(\boldsymbol{x}-\boldsymbol{y}) = 2g_s^2\,\big(\gamma(\boldsymbol{x}-\boldsymbol{y})-\gamma(\boldsymbol{0})\big)$$

- Broadening and Kernel

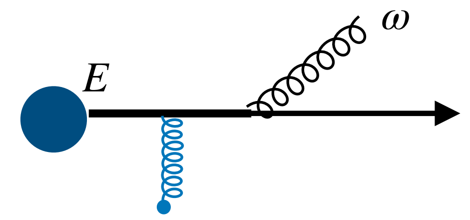
$$\mathscr{P}(\boldsymbol{x},t;\boldsymbol{y},t') = \exp\left\{-\frac{1}{2}\int_t^{t'} ds\, n(s)\,\sigma(\boldsymbol{x}-\boldsymbol{y})\right\}$$

$$\mathcal{K}(t',\boldsymbol{z};t,\boldsymbol{y}) = \int_{\boldsymbol{r}(t)=\boldsymbol{y}}^{\boldsymbol{r}(t')=\boldsymbol{z}} \mathcal{D}\boldsymbol{r}\,\exp\left[\int_t^{t'} ds\,\left(\frac{i\omega}{2}\dot{\boldsymbol{r}}^2-\frac{1}{2}n(s)\sigma(\boldsymbol{r})\right)\right]$$

Medium-induced radiation

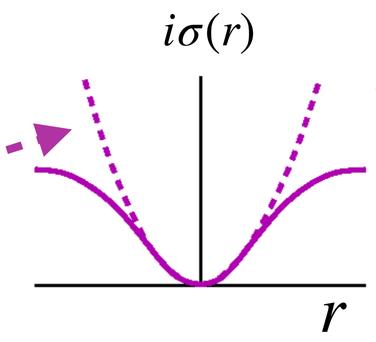
- In practice, solved for some approximations
  - **Opacity expansion** in the number of scatterings

    $N = 1$: GLV Gyulassy, Levai, Vitev (2000)



  - **Harmonic oscillator (HO):** multiple <u>soft</u> scatterings (Gaussian approximation)

    $$n\sigma(r) \approx \frac{1}{2}\hat{q}r^2$$



  - **AMY:** <u>infinite length</u> medium Arnold, Moore, Yaffe (2002)

- Recent approaches going beyond these approximations $\gamma(\boldsymbol{q}) \propto \frac{1}{\boldsymbol{q}^4}$
  - **Improved opacity expansion**

    Semi-analytical expansion around the HO

    Mehtar-Tani, Barata, Soto-Ontoso, Tywoniuk, 1903.00506, 2004.02323, 2106.07402

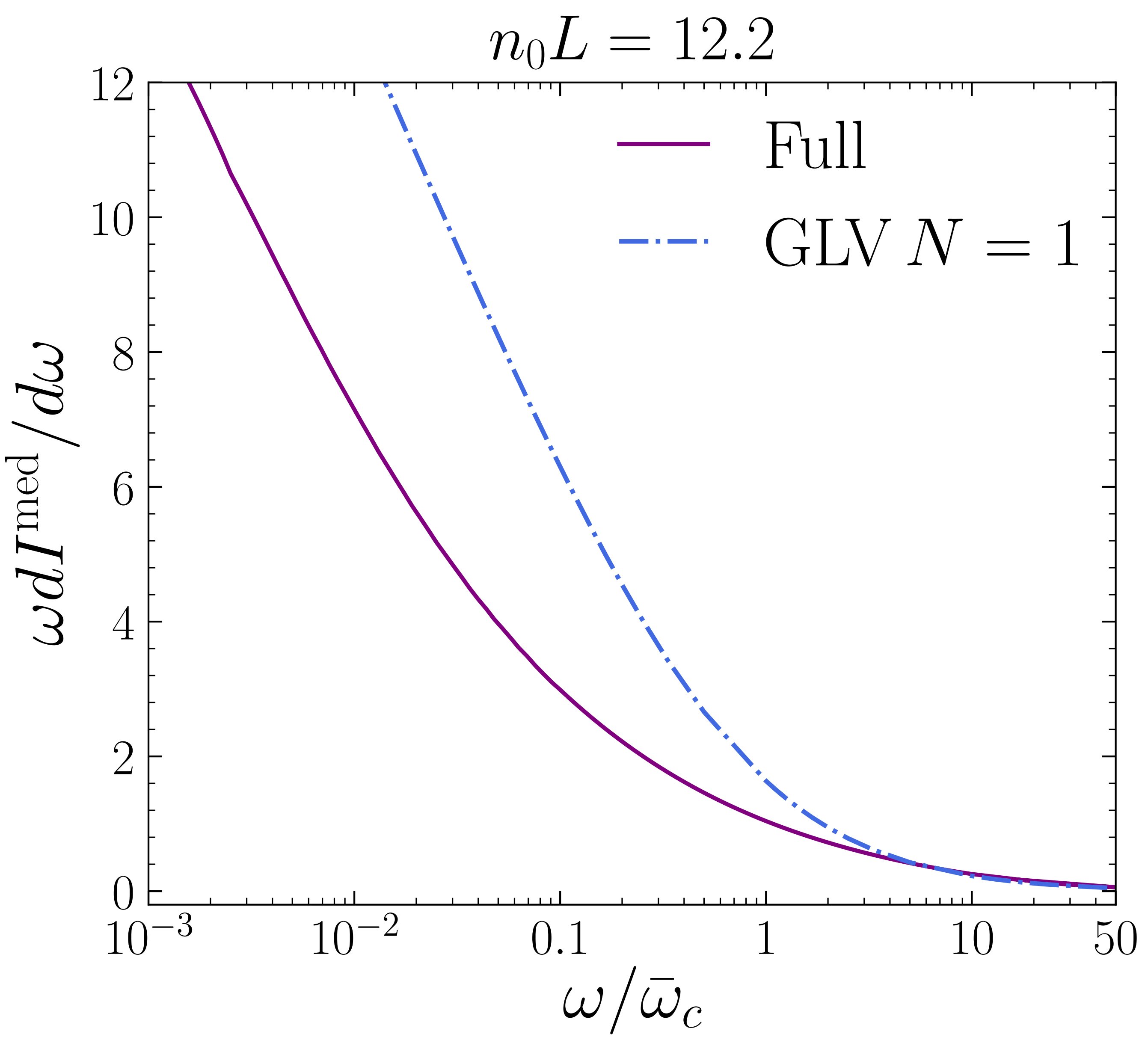
  - **Fully resummed spectrum**

    Kernel as a time dependent Schrödinger equation

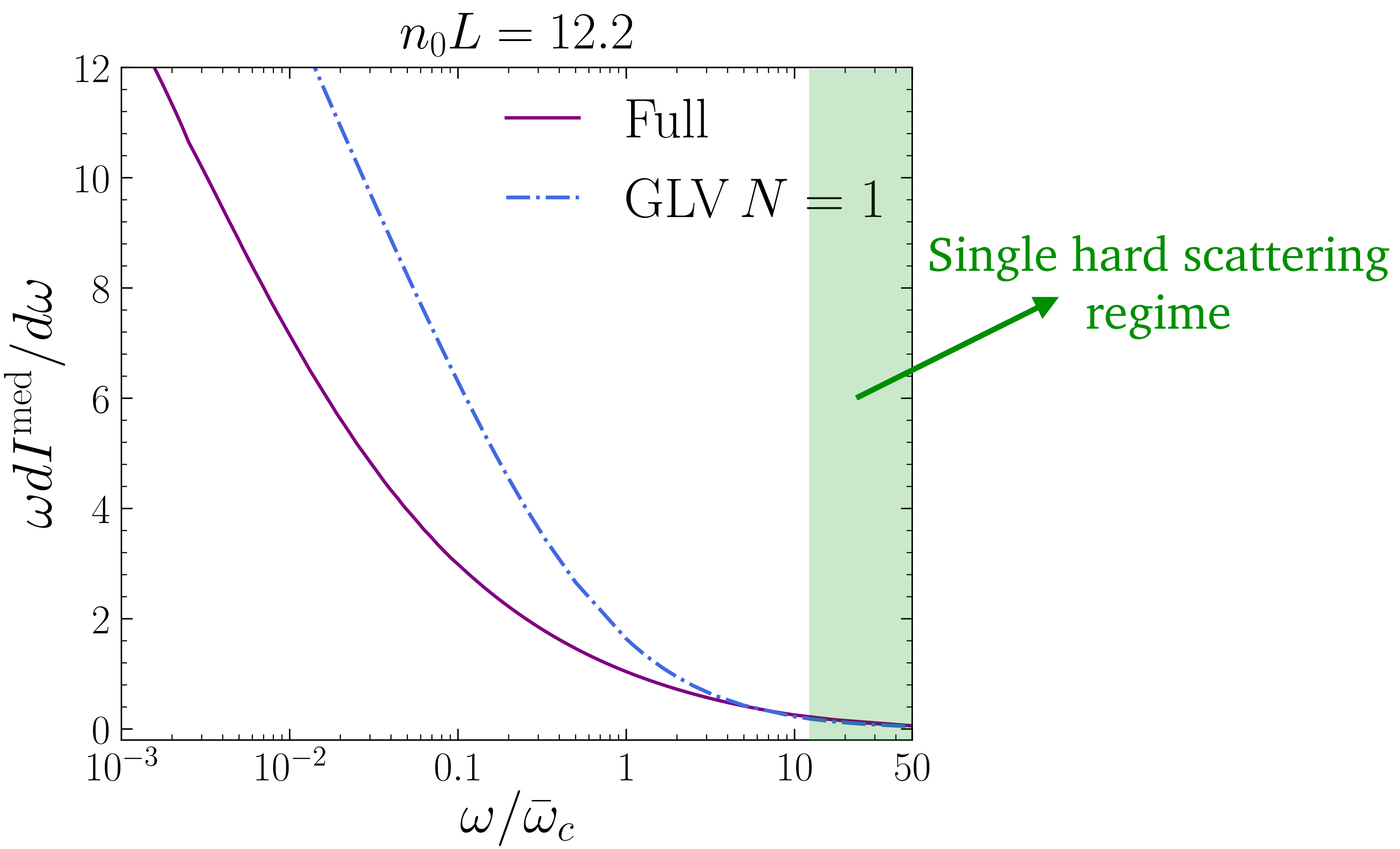
    CA, Apolinario, Martinez, Dominguez, 2002.01517, 2011.06522

    Beyond the soft limit but integrated in k_T: Caron-Huot and Gale, 1006.2379

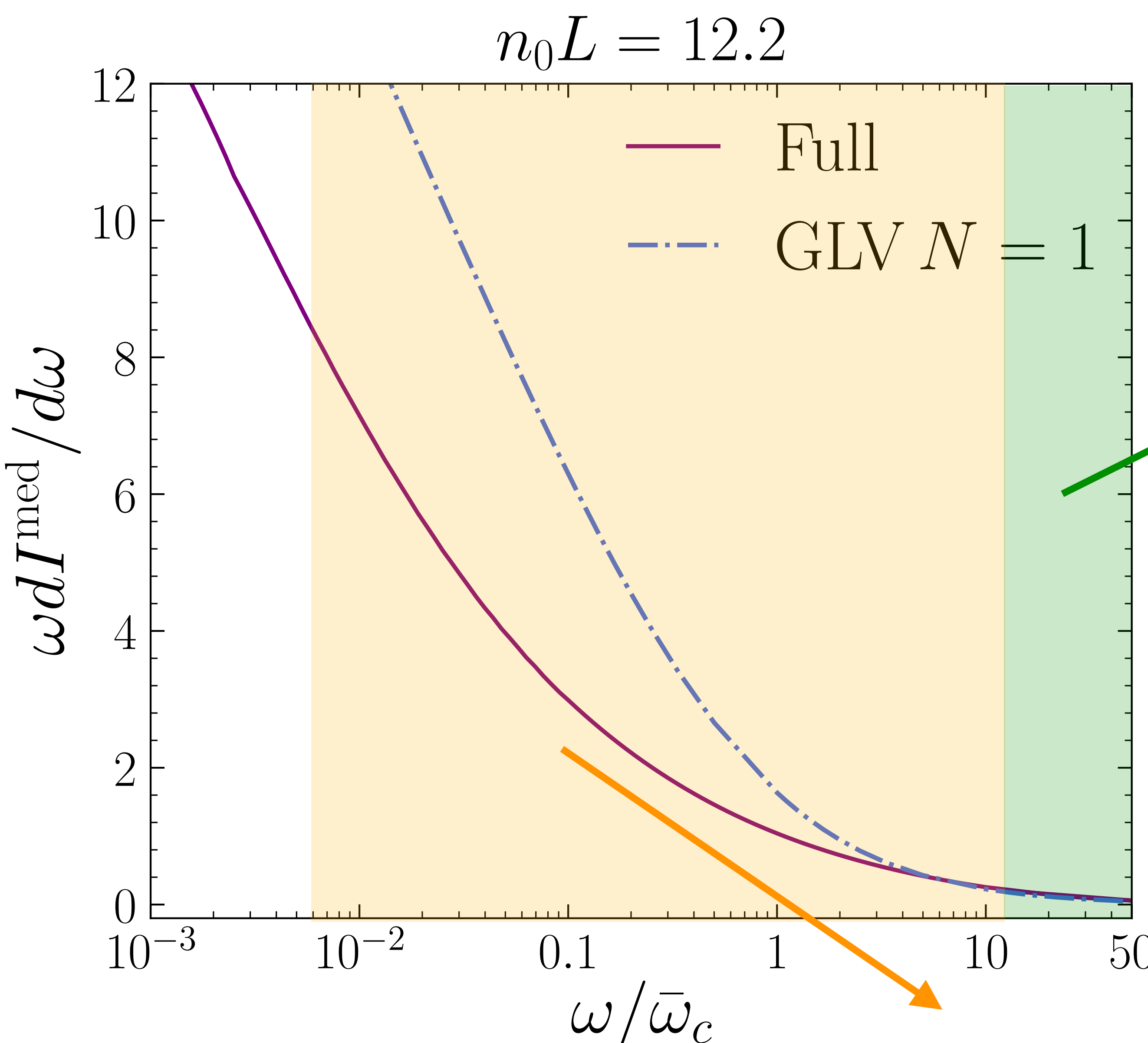
BDMPS-Z spectrum



BDMPS-Z spectrum



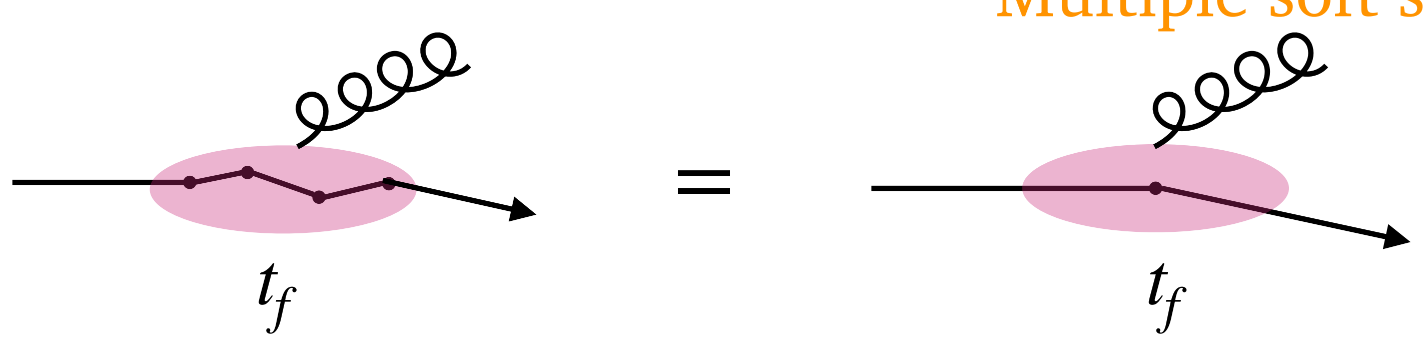
BDMPS-Z spectrum



Single hard scattering regime

Multiple soft scattering regime: LPM effect

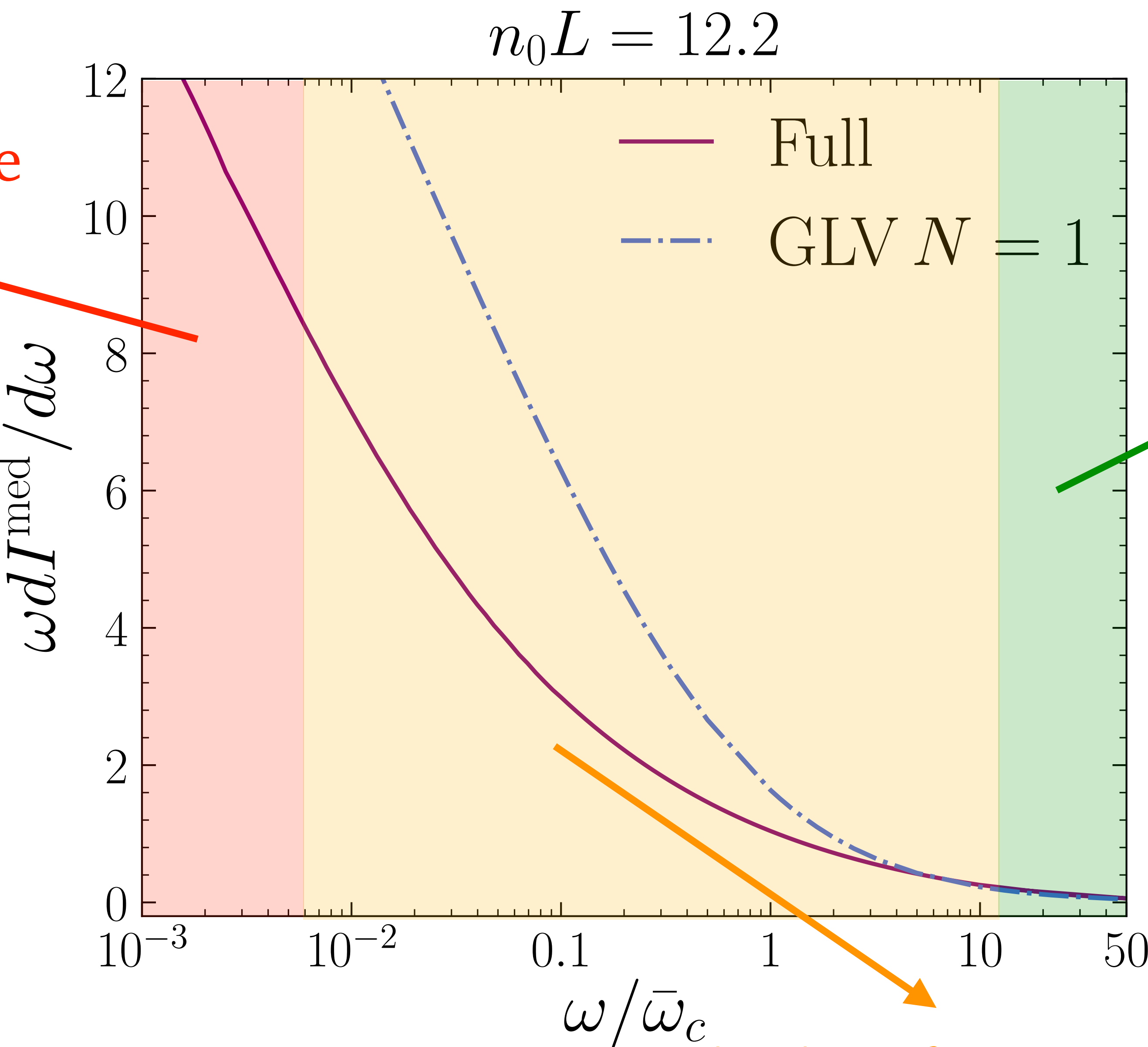
$t_f \sim \dfrac{2\omega}{\boldsymbol{k}^2}$



Landau, Pomeranchuk, Migdal for QED

BDMPS-Z spectrum

Bethe-Heitler regime



Single hard scattering regime

Multiple soft scattering regime: LPM effect

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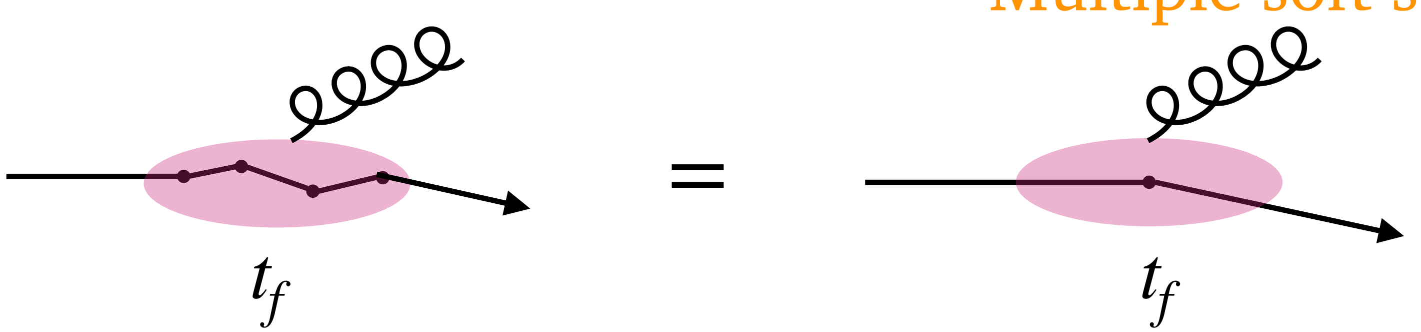
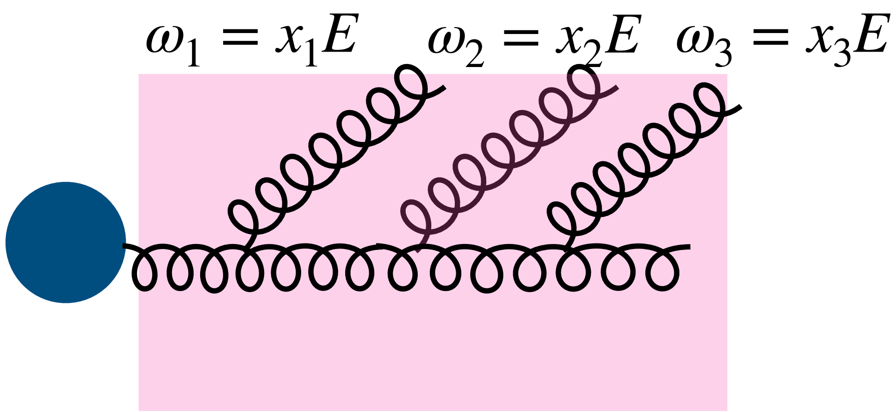


Landau, Pomeranchuk, Migdal for QED

Multiple emissions



- Independent emissions:

Jeon, Moore (2005), Blaizot, Dominguez, Iancu, Mehtar-Tani (2014)

$$\frac{\partial}{\partial t} D(x,t) = \frac{1}{t_*} \int \mathrm{d}z\, \mathcal{K}(z) \left[\sqrt{\frac{z}{x}} D\left(\frac{x}{z}, t\right) - \frac{z}{\sqrt{x}} D\left(x, t\right) \right]$$

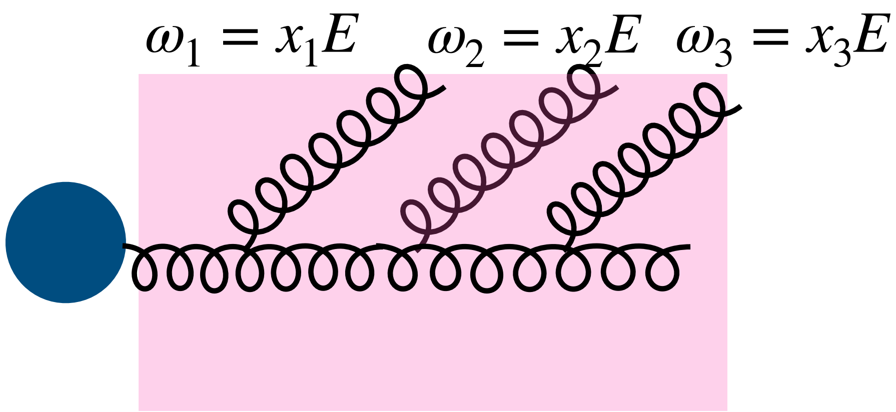
- In the soft limit ($x \to 0, E \to \infty$)

Baier, Dokshitzer, Mueller, Schiff (2001), Wiedemann, Salgado (2003)

$$P(\epsilon) = \sum_{N=0}^{\infty} \frac{1}{N!} \prod_{i=1}^{N} \left[\int \mathrm{d}\omega_i \frac{\mathrm{d}I}{\mathrm{d}\omega} \right] \delta\left(\epsilon - \sum_{i=1}^{N} \omega_i\right) \exp\left[- \int_0^{\infty} \mathrm{d}\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \right] \qquad \omega_i = x_i E$$

Probability of energy loss

Multiple emissions



- Independent emissions:

Jeon, Moore (2005), Blaizot, Dominguez, Iancu, Mehtar-Tani (2014)

$$\frac{\partial}{\partial t} D(x,t) = \frac{1}{t_*} \int \mathrm{d}z\, \mathcal{K}(z) \left[\sqrt{\frac{z}{x}} D\left(\frac{x}{z}, t\right) - \frac{z}{\sqrt{x}} D(x,t) \right]$$

Inclusive gluon distribution

Gain term

Loss term

- In the soft limit ($x \to 0, E \to \infty$)

Baier, Dokshitzer, Mueller, Schiff (2001), Wiedemann, Salgado (2003)

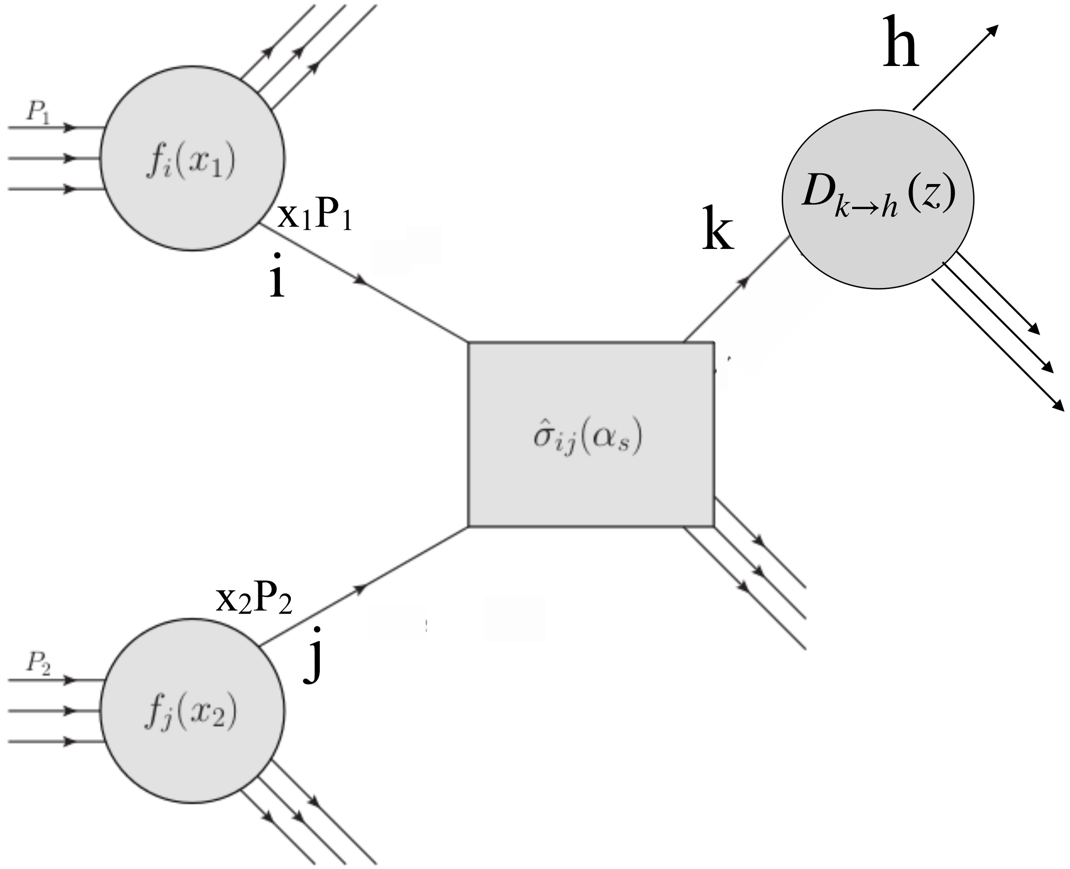
$$P(\epsilon) = \sum_{N=0}^{\infty} \frac{1}{N!} \prod_{i=1}^{N} \left[\int \mathrm{d}\omega_i \frac{\mathrm{d}I}{\mathrm{d}\omega} \right] \delta\left(\epsilon - \sum_{i=1}^{N} \omega_i \right) \exp\left[- \int_0^{\infty} \mathrm{d}\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \right] \qquad \omega_i = x_i E$$

Probability of energy loss

Collinear factorization

$$d\sigma^{pp\to hX} = \sum_{ijk} f_i(x_1,\mu_f^2) \otimes f_j(x_2,\mu_f^2) \otimes d\sigma_{ij\to k} \otimes D_{k\to h}(z,\mu_f^2) + \mathcal{O}(\mu_f^{-2n})$$

- Non perturbative
  But universal



- Their evolution
  is perturbative ⟶ DGLAP

$$Q^2\frac{\partial f_i(x,Q^2)}{\partial Q^2} = \sum_j \boxed{P_{ij}} \otimes f_j(x,Q^2)$$

Splitting functions (pQCD)

Collinear factorization

pQCD

$$d\sigma^{pp\to hX} = \sum_{ijk} f_i(x_1,\mu_f^2) \otimes f_j(x_2,\mu_f^2) \otimes \boxed{d\sigma_{ij\to k}} \otimes D_{k\to h}(z,\mu_f^2) + \mathcal{O}(\mu_f^{-2n})$$

- <u>Non perturbative</u>
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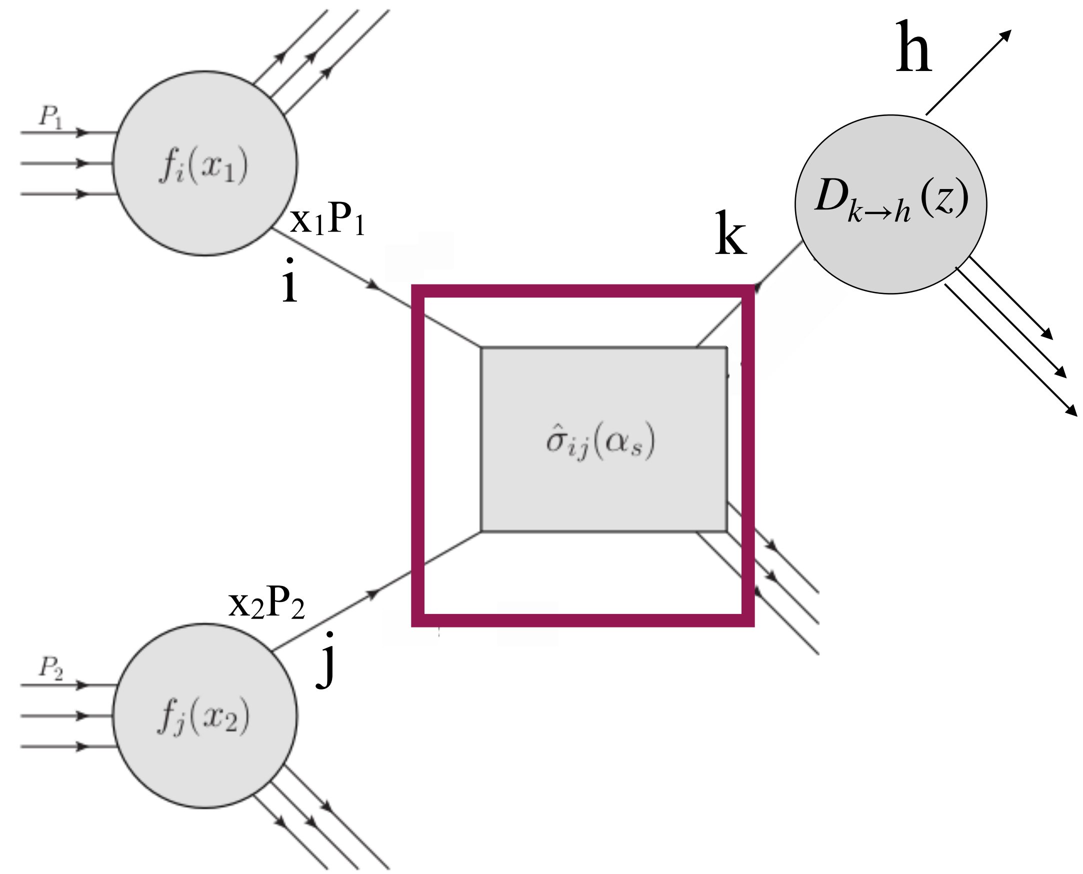

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Splitting functions (pQCD)

Collinear factorization

PDFs **pQCD** **FFs**

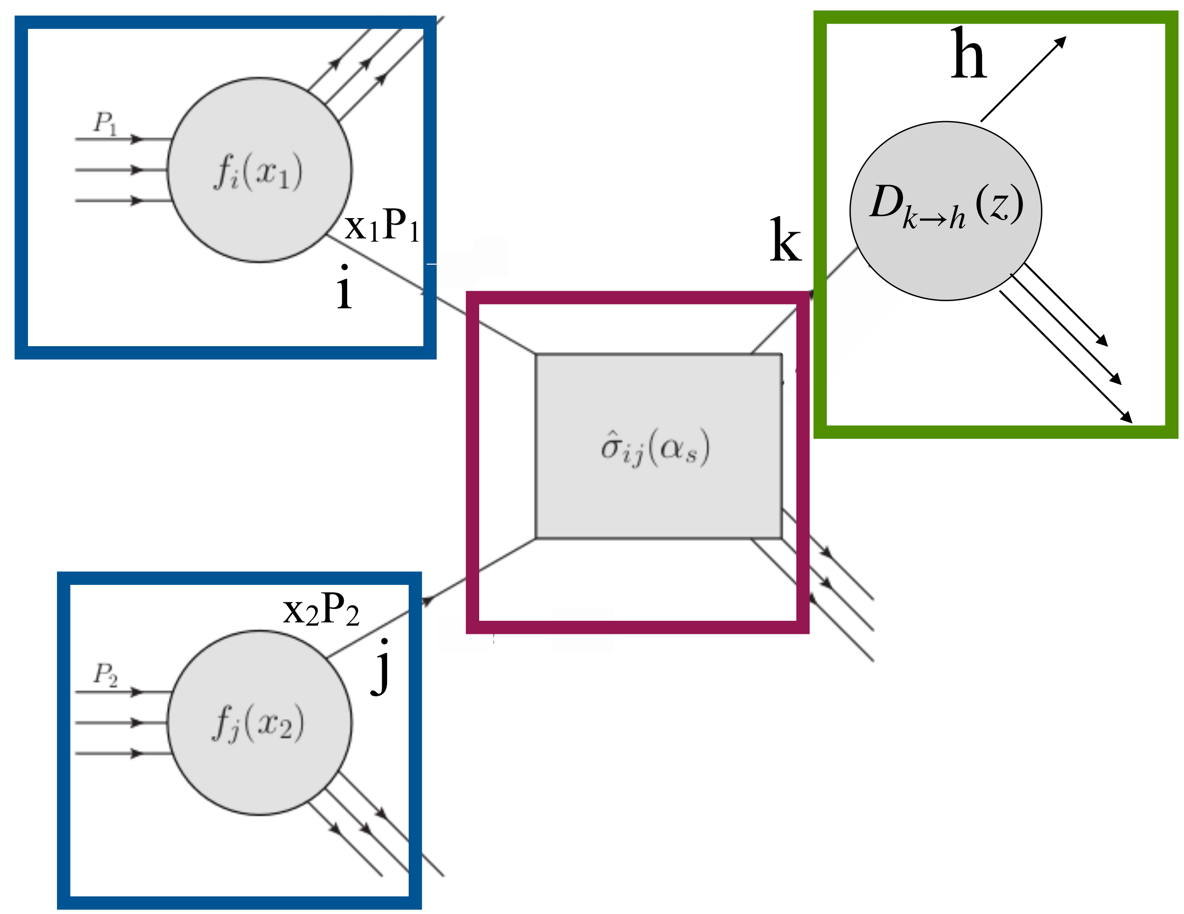
$$d\sigma^{pp\to hX} = \sum_{ijk} \boxed{f_i(x_1,\mu_f^2)} \otimes \boxed{f_j(x_2,\mu_f^2)} \otimes \boxed{d\sigma_{ij\to k}} \otimes \boxed{D_{k\to h}(z,\mu_f^2)} + \mathcal{O}(\mu_f^{-2n})$$

- <u>Non perturbative</u>
  But universal

- Their evolution
  is perturbative ⟶ DGLAP

$$Q^2 \frac{\partial f_i(x,Q^2)}{\partial Q^2} = \sum_j \boxed{P_{ij}} \otimes f_j(x,Q^2)$$

Splitting functions (pQCD)



Collinear factorization

Energy loss

n PDFs

pQCD

FFs

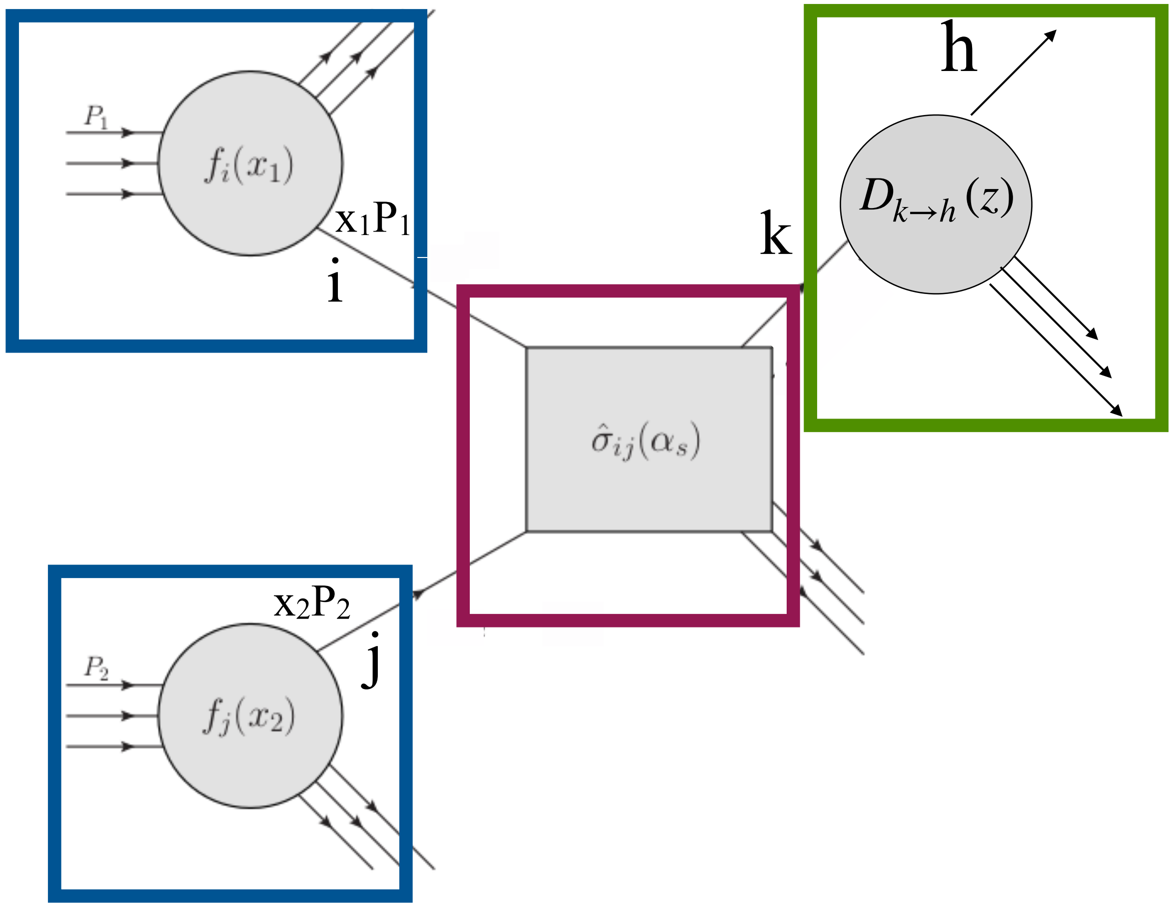
$$d\sigma^{AA\to hX} = \sum_{ijk} \boxed{f_i(x_1,\mu_f^2)} \otimes \boxed{f_j(x_2,\mu_f^2)} \otimes \boxed{d\sigma_{ij\to k}} \otimes \boxed{P(\epsilon)} \otimes \boxed{D_{k\to h}(z,\mu_f^2)} + \mathcal{O}(\mu_f^{-2n})$$

- Non perturbative
  But universal

- Their evolution
  is perturbative $\longrightarrow$ DGLAP

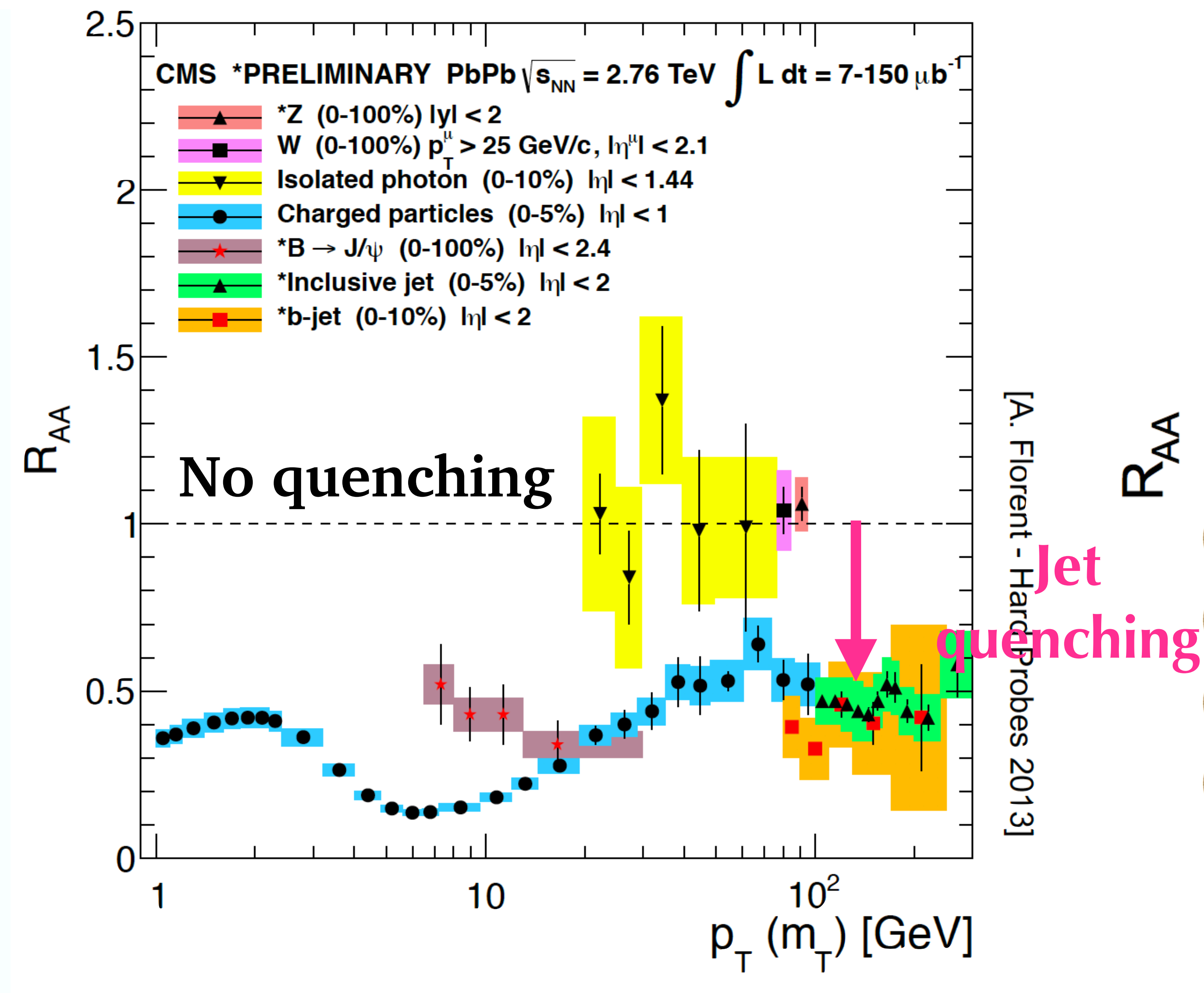
$$Q^2 \frac{\partial f_i(x,Q^2)}{\partial Q^2} = \sum_j \boxed{P_{ij}} \otimes f_j(x,Q^2)$$

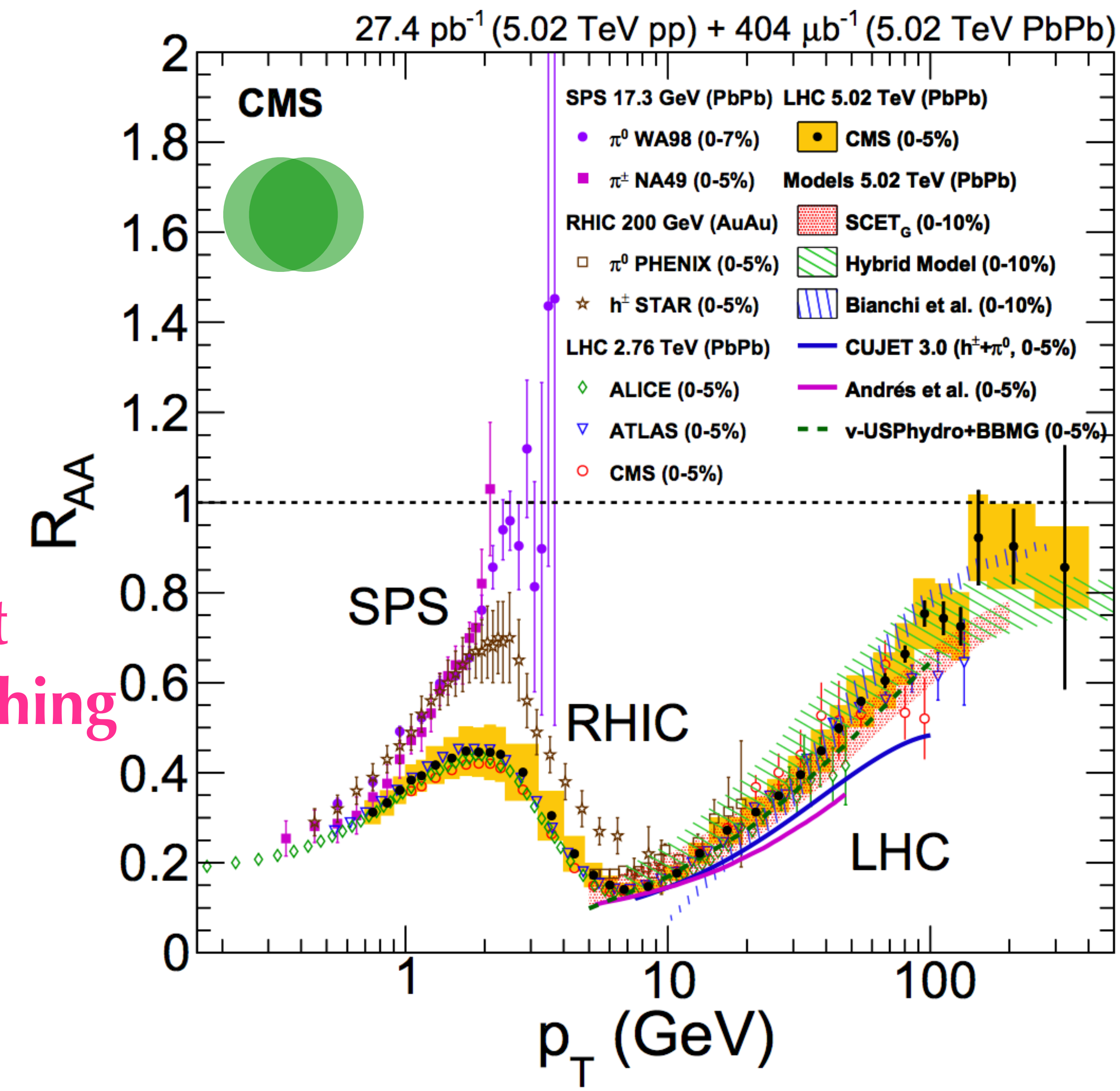
Splitting functions (pQCD)



Hadron suppression

$$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled}\otimes\text{pp}}$$



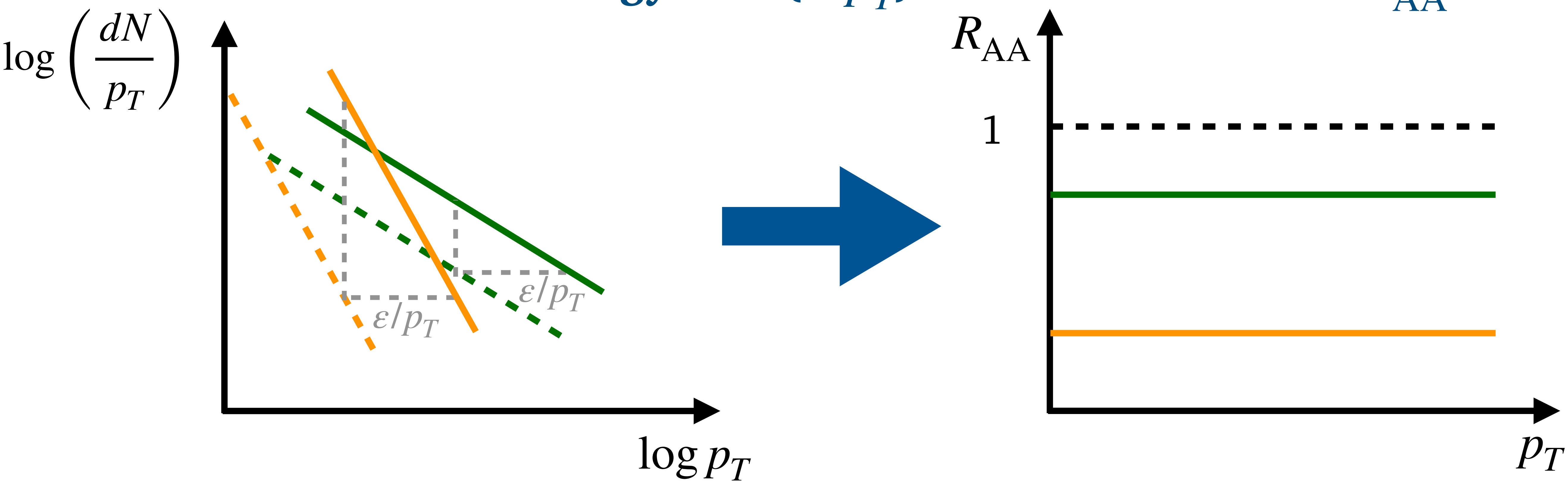


CMS Collaboration, JHEP 04 039 (2017)

Understanding the R_{AA}

In p-p, the spectrum for high-p_T particles behaves as $\dfrac{dN^{pp}}{p_T} \propto \dfrac{1}{p_T^n}$

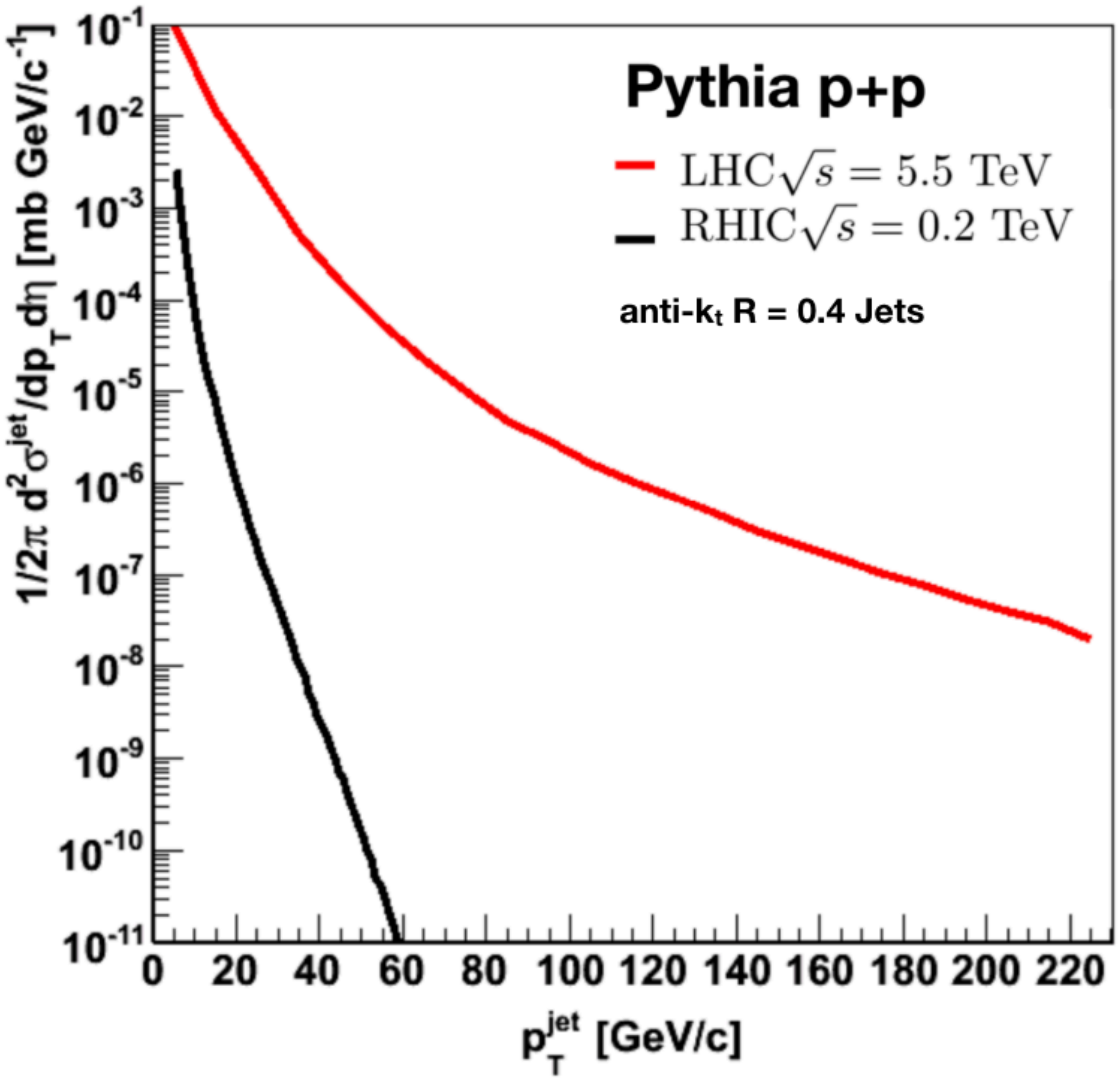
Same fractional energy loss (ε/p_T) **Different R_{AA}**



At parton level:

$$R_{\mathrm{AA}} \sim \int d\varepsilon\, P(\varepsilon)\, \frac{d\sigma^{pp}(p_T+\varepsilon)/dp_T}{d\sigma^{pp}(p_T)/dp_T} = \int d\epsilon\, P(\epsilon)\, \frac{p_T^n}{\left(p_T+\varepsilon\right)^n} \approx \int d\epsilon\, P(\varepsilon)\, \left(1 - \frac{n\varepsilon}{p_T}\right)$$

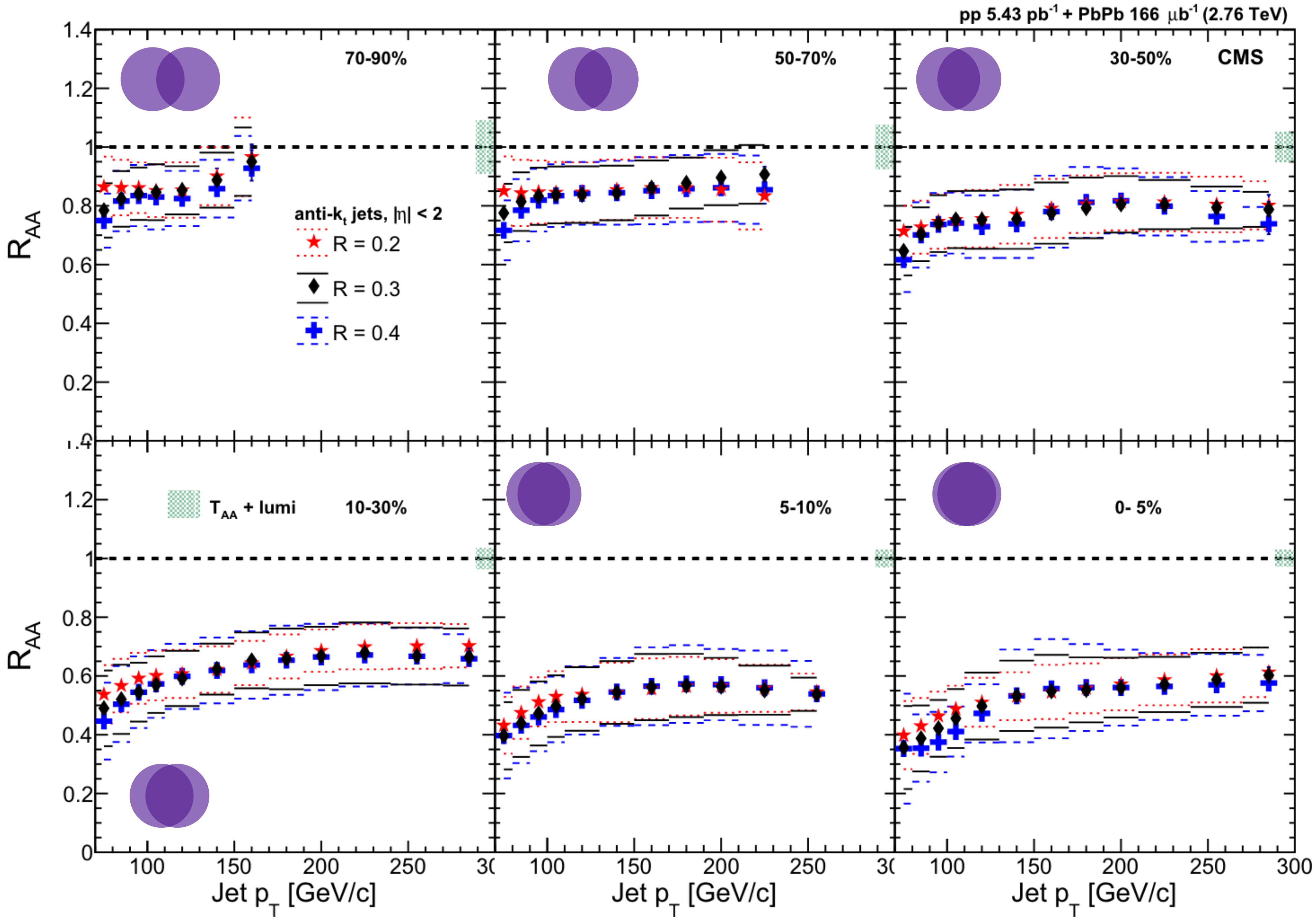
Understanding the R_{AA}



- Jet p-p spectrum steeper at RHIC than at LHC
- R_{AA} at RHIC similar to R_{AA} at LHC

At a given p_T, do jets at RHIC or at LHC lose more fractional energy?

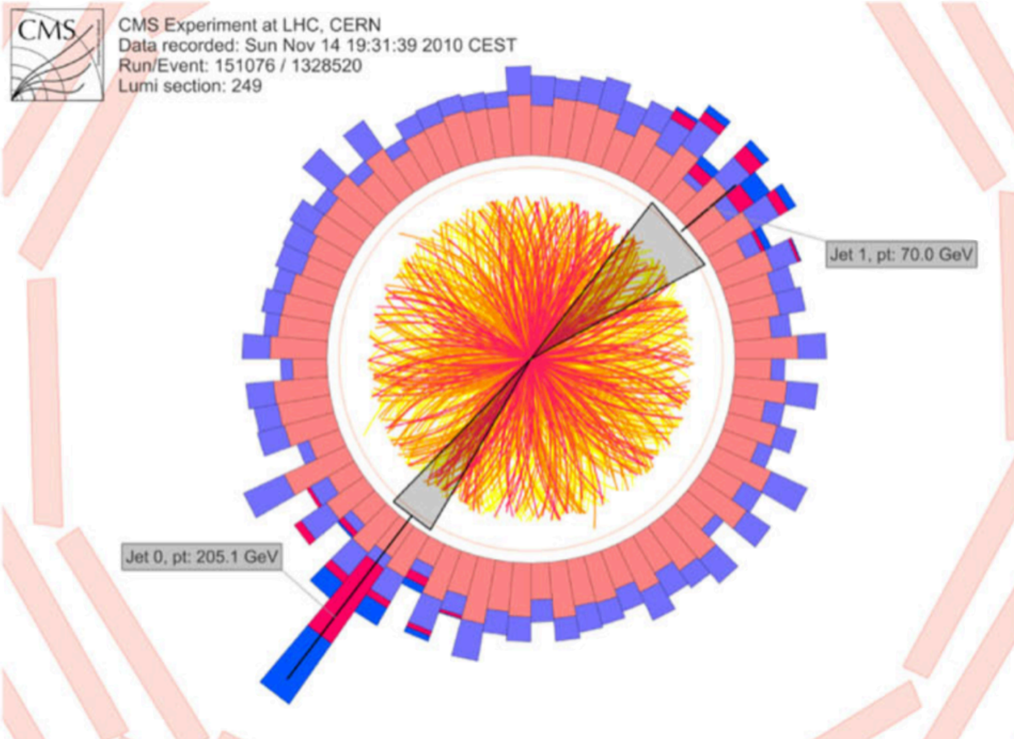
Reconstructed jets



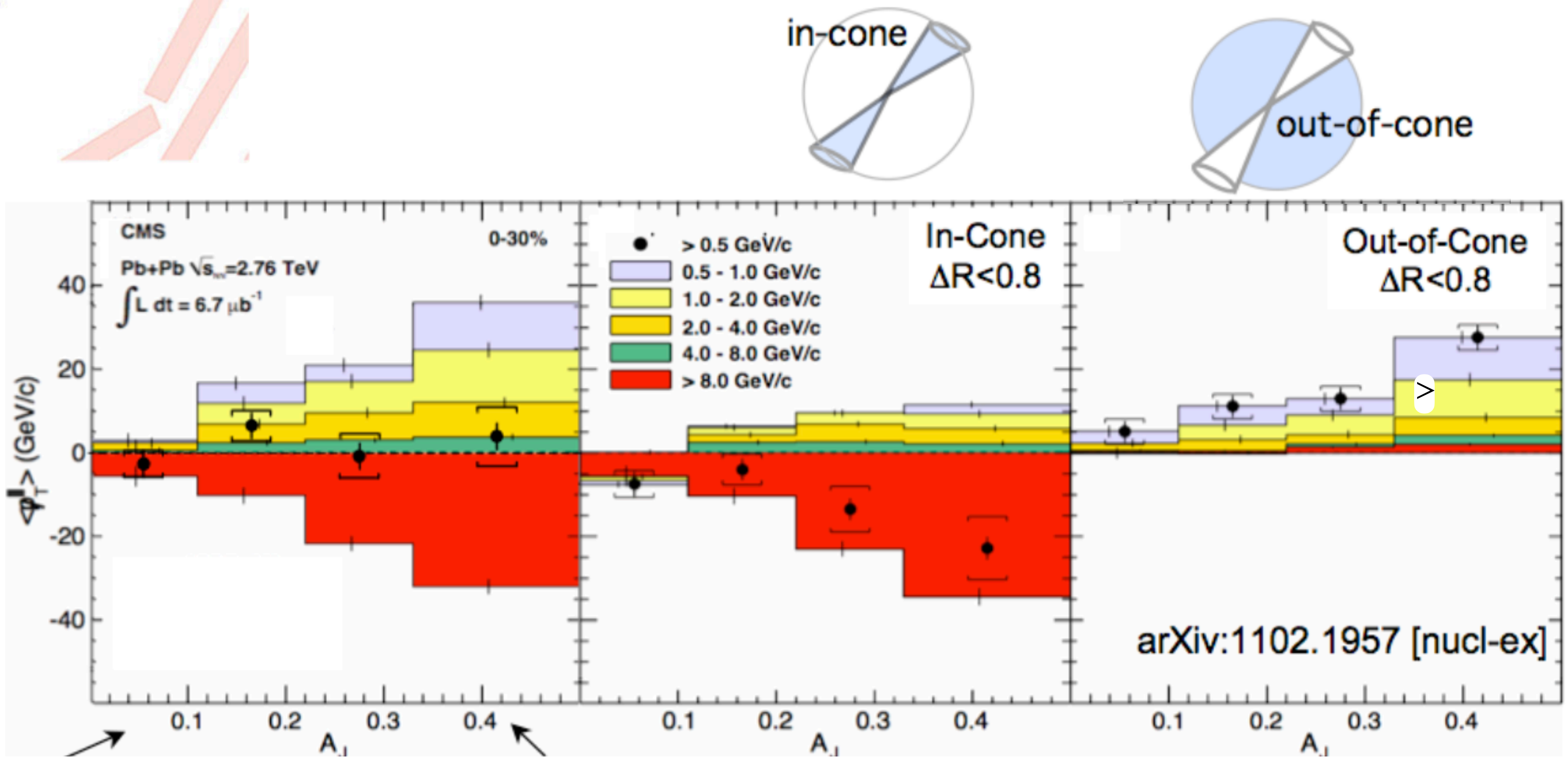
CMS, Phys. Rev. C 96 (2017) 015202

Reconstructed jets are suppressed!

Where does the energy go?



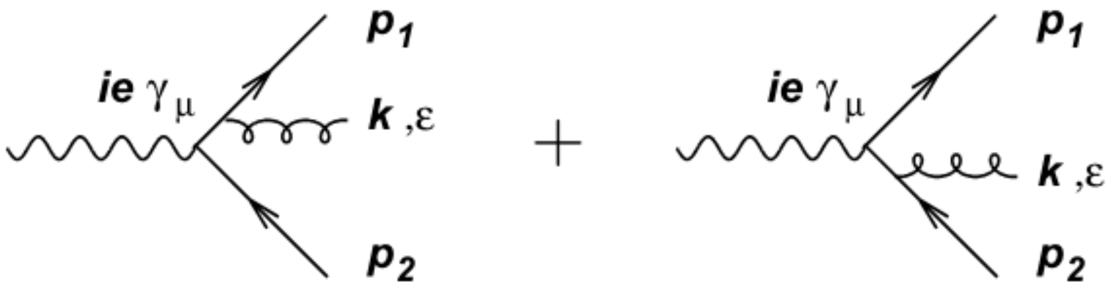
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$



balanced jets unbalanced jets

At large angles. Soft particles

Antenna in the vacuum



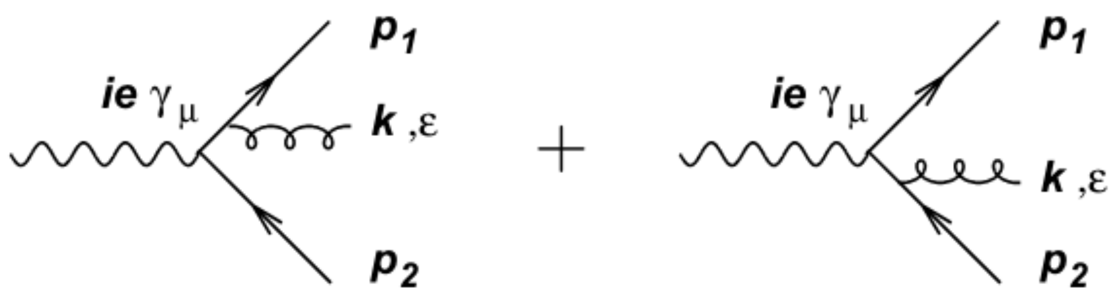
$$M_{q\bar{q}g} = \bar{u}(p_1)\left(-ig_s t^a\right) \not{\epsilon}(k) \frac{i(\not{p}_1 + \not{k})}{(p_1+k)^2} \left(ie\gamma^\mu\right) v(p_2)$$

$$+ \bar{u}(p_1)\left(ie\gamma^\mu\right) \frac{-i\left(\not{p}_2 + \not{k}\right)}{(p_2+k)^2} \not{\epsilon}(k) \left(-ig_s t^a\right) v(p_2)$$

$k \ll p_1, p_2$

$$M_{q\bar{q}g} \approx g_s t^a \left(\frac{p_1 \cdot \varepsilon(k)}{p_1 \cdot k} - \frac{p_2 \cdot \varepsilon(k)}{p_2 \cdot k}\right) \bar{u}(p_1) ie\gamma^\mu v(p_2)$$

Antenna in the vacuum



$$M_{q\bar{q}g} = \bar{u}(p_1)\,(-ig_s t^a)\,\not{\epsilon}(k)\,\frac{i(\not{p}_1+\not{k})}{(p_1+k)^2}\,(ie\gamma^\mu)\,v(p_2)$$

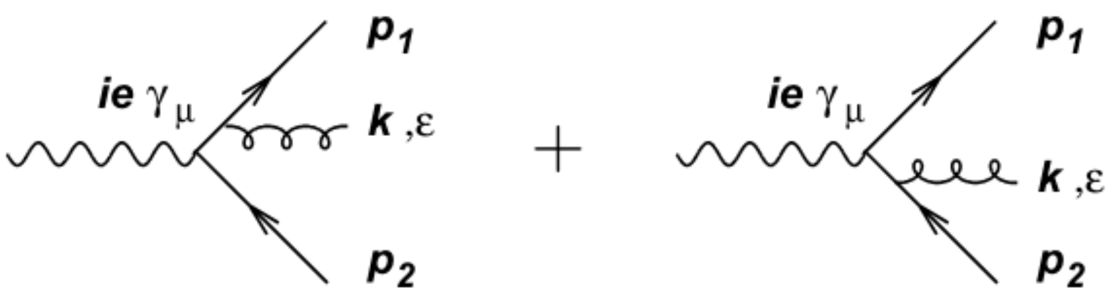
$$+\,\bar{u}(p_1)\,(ie\gamma^\mu)\,\frac{-i\,(\not{p}_2+\not{k})}{(p_2+k)^2}\,\not{\epsilon}(k)\,(-ig_s t^a)v(p_2)$$

$k \ll p_1, p_2$

$$M_{q\bar{q}g} \approx g_s t^a \left(\frac{p_1\cdot\varepsilon(k)}{p_1\cdot k} - \frac{p_2\cdot\varepsilon(k)}{p_2\cdot k}\right) \bar{u}(p_1)ie\gamma^\mu v(p_2)$$

$M_{q\bar{q}}$

Antenna in the vacuum



$$M_{q\bar{q}g} = \bar{u}(p_1)\,(-ig_s t^a)\,\not{\varepsilon}(k)\,\frac{i(\not{p}_1 + \not{k})}{(p_1+k)^2}\,(ie\gamma^\mu)\,v(p_2) + \bar{u}(p_1)\,(ie\gamma^\mu)\,\frac{-i\left(\not{p}_2 + \not{k}\right)}{(p_2+k)^2}\,\not{\varepsilon}(k)\,(-ig_s t^a)v(p_2)$$

$k \ll p_1, p_2$

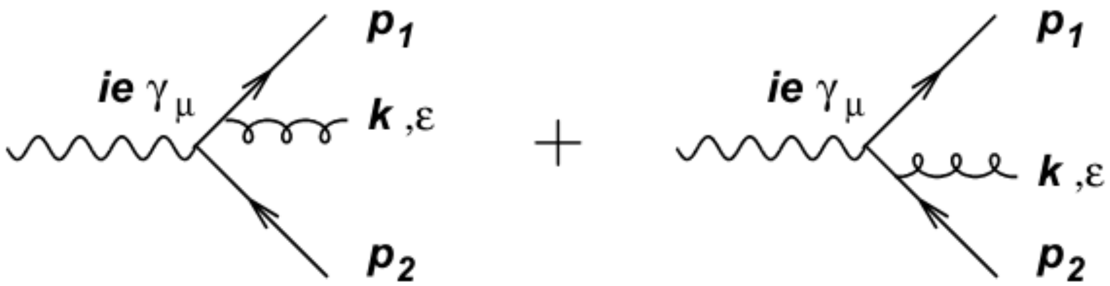
$$M_{q\bar{q}g} \approx g_s t^a \left(\frac{p_1 \cdot \varepsilon(k)}{p_1 \cdot k} - \frac{p_2 \cdot \varepsilon(k)}{p_2 \cdot k}\right) \underbrace{\bar{u}(p_1) ie\gamma^\mu v(p_2)}_{M_{q\bar{q}}}$$

- Squaring the amplitude:

$$\sum_{\text{col}} \mathrm{Tr}\,(t^a t^a) = C_F N_c \qquad \sum_{\text{pol}} \varepsilon_\mu(k)\varepsilon_\nu^*(k) = -g_{\mu\nu} + \dots$$

$$|M_{q\bar{q}g}|^2 \approx \frac{1}{N_c} \sum_{\text{col,pol}} g_s^2\, \mathrm{Tr}\,(t^a t^a) \left(\frac{p_1 \cdot \varepsilon(k)}{p_1 \cdot k} - \frac{p_2 \cdot \varepsilon(k)}{p_2 \cdot k}\right)^2 |M_{q\bar{q}}|^2 = g_s^2 C_F \frac{2\, p_1 \cdot p_2}{(p_1 \cdot k)\,(p_2 \cdot k)} |M_{q\bar{q}}|^2$$

Antenna in the vacuum



$$M_{q\bar{q}g} = \bar{u}(p_1)\left(-ig_s t^a\right)\not{\epsilon}(k)\frac{i(\not{p}_1+\not{k})}{(p_1+k)^2}\left(ie\gamma^\mu\right)v(p_2)$$

$$+\,\bar{u}(p_1)\left(ie\gamma^\mu\right)\frac{-i\left(\not{p}_2+\not{k}\right)}{(p_2+k)^2}\not{\epsilon}(k)\left(-ig_s t^a\right)v(p_2)$$

$k \ll p_1, p_2$

$$M_{q\bar{q}g} \approx g_s t^a \left(\frac{p_1\cdot\varepsilon(k)}{p_1\cdot k} - \frac{p_2\cdot\varepsilon(k)}{p_2\cdot k}\right)\underbrace{\bar{u}(p_1)ie\gamma^\mu v(p_2)}_{M_{q\bar{q}}}$$

- Squaring the amplitude:

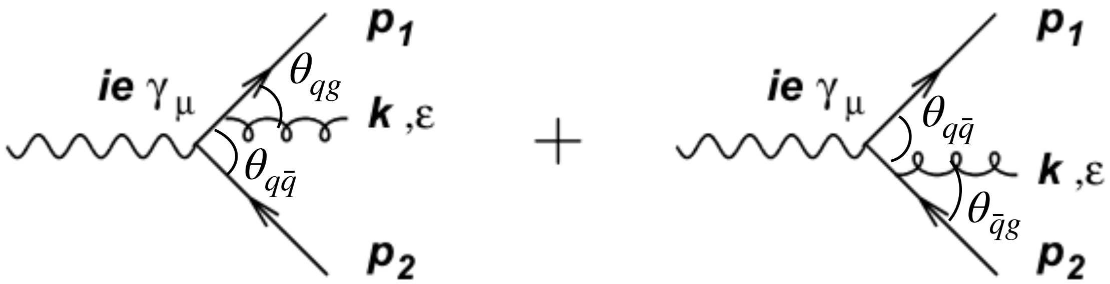
$$\sum_{\text{col}} \mathrm{Tr}\left(t^a t^a\right) = C_F N_c \qquad \sum_{\text{pol}} \varepsilon_\mu(k)\varepsilon^*_\nu(k) = -g_{\mu\nu} + \ldots$$

$$|M_{q\bar{q}g}|^2 \approx \frac{1}{N_c}\sum_{\text{col,pol}} g_s^2\,\mathrm{Tr}\left(t^a t^a\right)\left(\frac{p_1\cdot\varepsilon(k)}{p_1\cdot k} - \frac{p_2\cdot\varepsilon(k)}{p_2\cdot k}\right)^2 |M_{q\bar{q}}|^2 = g_s^2 C_F \frac{2\,p_1\cdot p_2}{(p_1\cdot k)\,(p_2\cdot k)}|M_{q\bar{q}}|^2$$

$\downarrow$ Including phase space factors $\dfrac{d\omega d^2\mathbf{k}}{2\omega(2\pi)^3}$

$$\omega\frac{dN}{d\omega d^2\mathbf{k}} = \frac{\alpha_s C_F}{(2\pi)^2}\,\frac{2\,p_1\cdot p_2}{(p_1\cdot k)\,(p_2\cdot k)}$$

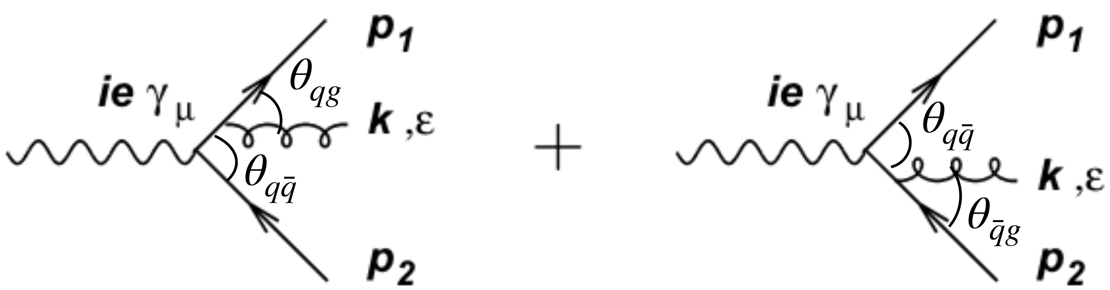
Antenna in the vacuum II



$$\omega \frac{dN}{d\omega d^2\boldsymbol{k}} = \frac{\alpha_s C_F}{2\pi^2\omega^2} \frac{1-\cos\theta_{q\bar{q}}}{(1-\cos\theta_{qg})\,(1-\cos\theta_{\bar{q}g})}$$

Collinear and soft divergences!

Antenna in the vacuum II

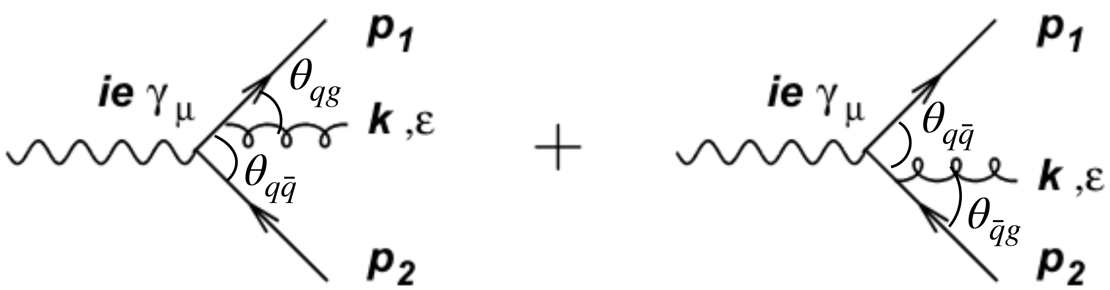


$$W_{q\bar{q}}$$

$$\omega \frac{dN}{d\omega d^2\boldsymbol{k}} = \frac{\alpha_s C_F}{2\pi^2\omega^2} \boxed{\frac{1-\cos\theta_{q\bar{q}}}{(1-\cos\theta_{qg})(1-\cos\theta_{\bar{q}g})}}$$

Collinear and soft divergences!

Antenna in the vacuum II



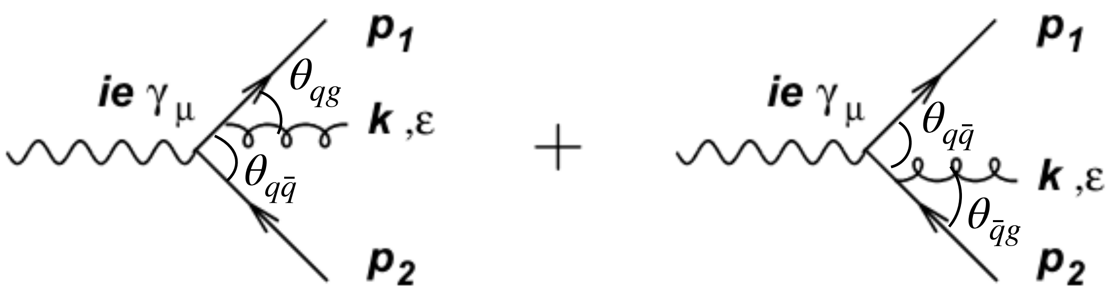
$$\omega \frac{dN}{d\omega d^2\boldsymbol{k}} = \frac{\alpha_s C_F}{2\pi^2\omega^2} \overbrace{\frac{1-\cos\theta_{q\bar{q}}}{(1-\cos\theta_{qg})\,(1-\cos\theta_{\bar{q}g})}}^{W_{q\bar{q}}}$$

Collinear and soft divergences!

Defining: $-2J = W_{q\bar{q}} - \left(\underbrace{\frac{1}{1-\cos\theta_{qg}}}_{R_q} + \underbrace{\frac{1}{1-\cos\theta_{\bar{q}g}}}_{R_{\bar{q}}} \right)$

$$\omega \frac{dN}{d\omega d^2\boldsymbol{k}} = \frac{\alpha_s C_F}{2\pi^2\omega^2} \left(R_q + R_{\bar{q}} - 2J \right)$$

Antenna in the vacuum II



$$\omega \frac{dN}{d\omega d^2\boldsymbol{k}} = \frac{\alpha_s C_F}{2\pi^2\omega^2} \overbrace{\frac{1-\cos\theta_{q\bar{q}}}{(1-\cos\theta_{qg})(1-\cos\theta_{\bar{q}g})}}^{W_{q\bar{q}}}$$

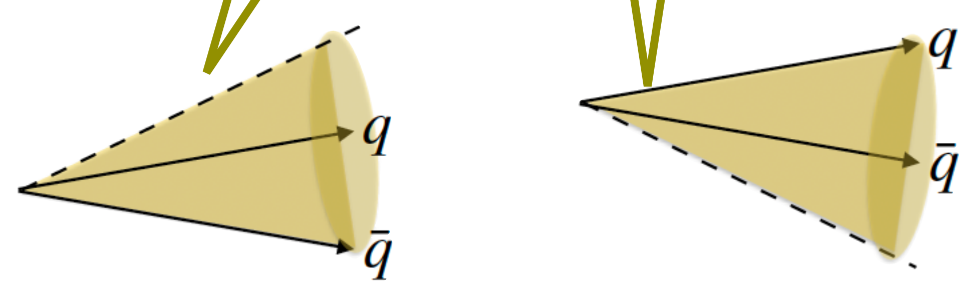
Collinear and soft divergences!

Defining: $-2J = W_{q\bar{q}} - \left(\underbrace{\frac{1}{1-\cos\theta_{qg}}}_{R_q} + \underbrace{\frac{1}{1-\cos\theta_{\bar{q}g}}}_{R_{\bar{q}}} \right)$

$$\omega \frac{dN}{d\omega d^2\boldsymbol{k}} = \frac{\alpha_s C_F}{2\pi^2\omega^2} \left(R_q + R_{\bar{q}} - 2J \right)$$

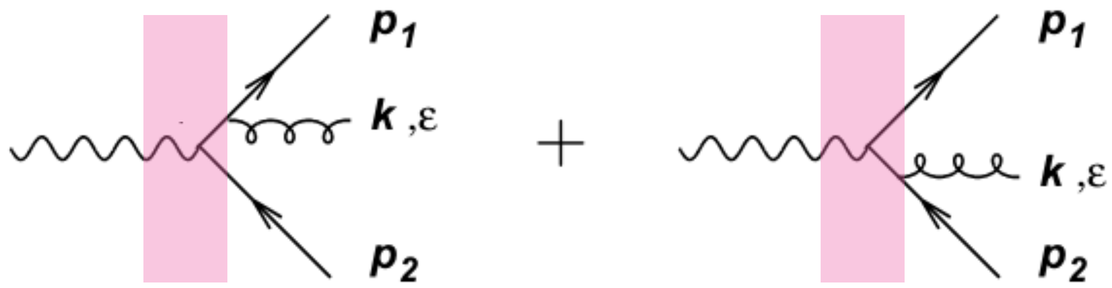
Integrating over the azimuthal angle: angular ordering

$$\omega \frac{dN}{d\omega d^2\boldsymbol{k}} = \frac{\alpha_s C_F}{2\pi^2\omega^2} \left(\boxed{R_q - J} + \boxed{R_{\bar{q}} - J} \right)$$



Antenna in the medium

Mehtar-Tani, Salgado, Tywoniuk, Phys. Rev. Lett. 106 (2011) 122002,
Phys. Lett B 707 (2012) 156, JHEP 10 (2012) 197 ,
J. Casalderrey-Solana and E. Iancu, JHEP 08 (2011) 015



$$M_{q\bar{q}g} \sim M_{q\bar{q}}\, t^a g_s\, W(r_1) W^\dagger(r_2) \frac{p_1 \cdot \varepsilon(k)}{p_1 \cdot k} + M_{q\bar{q}}\, W(r_1) W^\dagger(r_2)\, t^a g_s \frac{p_2 \cdot \varepsilon(k)}{p_2 \cdot k}$$

$$\boxed{\omega \frac{dN}{d\omega d^2\boldsymbol{k}} = \frac{\alpha_s C_F}{2\pi^2 \omega^2} \left(R_q - S J + R_{\bar{q}} - S J \right)}$$

If $S \rightarrow 0$: independent emissions (decoherence)

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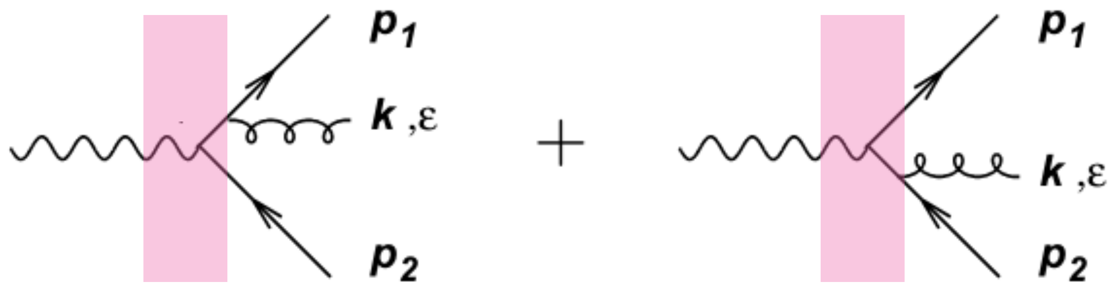

$$M_{q\bar{q}g} \sim M_{q\bar{q}}\, t^a g_s\, W(r_1)W^\dagger(r_2)\frac{p_1\cdot\varepsilon(k)}{p_1\cdot k} + M_{q\bar{q}}\, W(r_1)W^\dagger(r_2)\, t^a g_s \frac{p_2\cdot\varepsilon(k)}{p_2\cdot k}$$

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If $S \to 0$: independent emissions (decoherence)

- What is S?

$$S(\boldsymbol{r_1},\boldsymbol{r_2}) \equiv \frac{1}{N_c^2-1}\mathrm{Tr}\,\langle W_A(\boldsymbol{r_1})W_A^\dagger(\boldsymbol{r_2})\rangle = \exp\left\{-\frac{1}{2}\int ds\, n(s)\,\sigma(\boldsymbol{r_1}-\boldsymbol{r_2})\right\}$$

$$S(\boldsymbol{r_1},\boldsymbol{r_2}) \approx \exp\left\{-\frac{1}{12}\hat{q}\theta_{q\bar{q}}^2 L^3\right\} = \exp\{-\theta_{q\bar{q}}^2/\theta_c^2\} \qquad \theta_c = \sqrt{\frac{12}{\hat{q}L^3}}$$

Harmonic oscillator, static medium

Antenna in the medium

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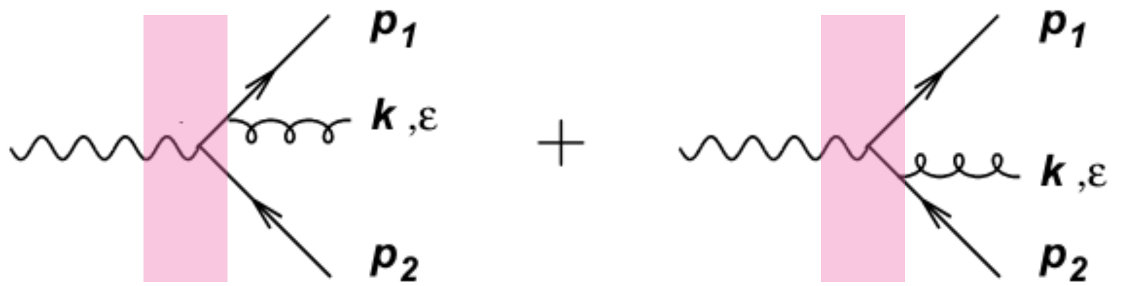

$$M_{q\bar{q}g} \sim M_{q\bar{q}}\, t^a g_s\, W(r_1) W^\dagger(r_2) \frac{p_1 \cdot \varepsilon(k)}{p_1 \cdot k} + M_{q\bar{q}}\, W(r_1) W^\dagger(r_2)\, t^a g_s \frac{p_2 \cdot \varepsilon(k)}{p_2 \cdot k}$$

$$\boxed{\omega \frac{dN}{d\omega d^2\boldsymbol{k}} = \frac{\alpha_s C_F}{2\pi^2\omega^2}\left(R_q - SJ + R_{\bar{q}} - SJ\right)}$$

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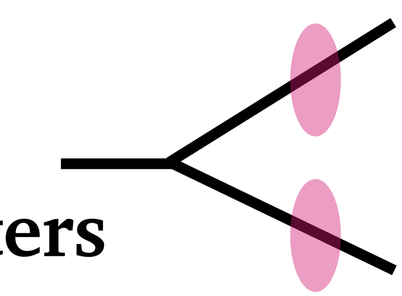
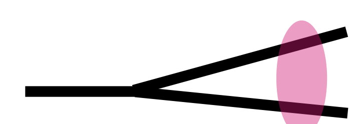
Harmonic oscillator, static medium

$\theta_{q\bar{q}} > \theta_c$: The medium resolves the antenna.
Color coherence is broken: **two-independent emitters**

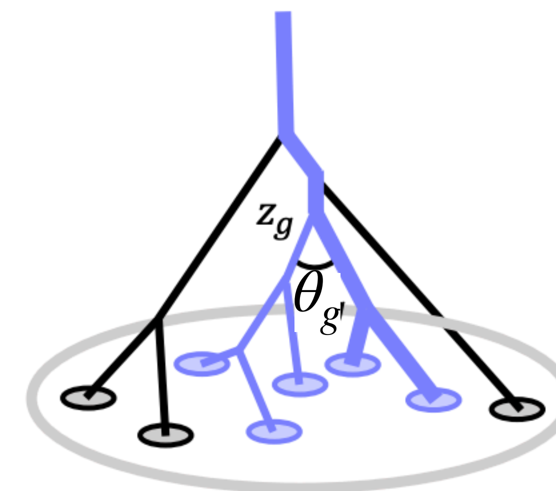


$\theta_{q\bar{q}} < \theta_c$: The medium cannot resolve the antenna.
Color coherence maintained. **Vacuum-like**



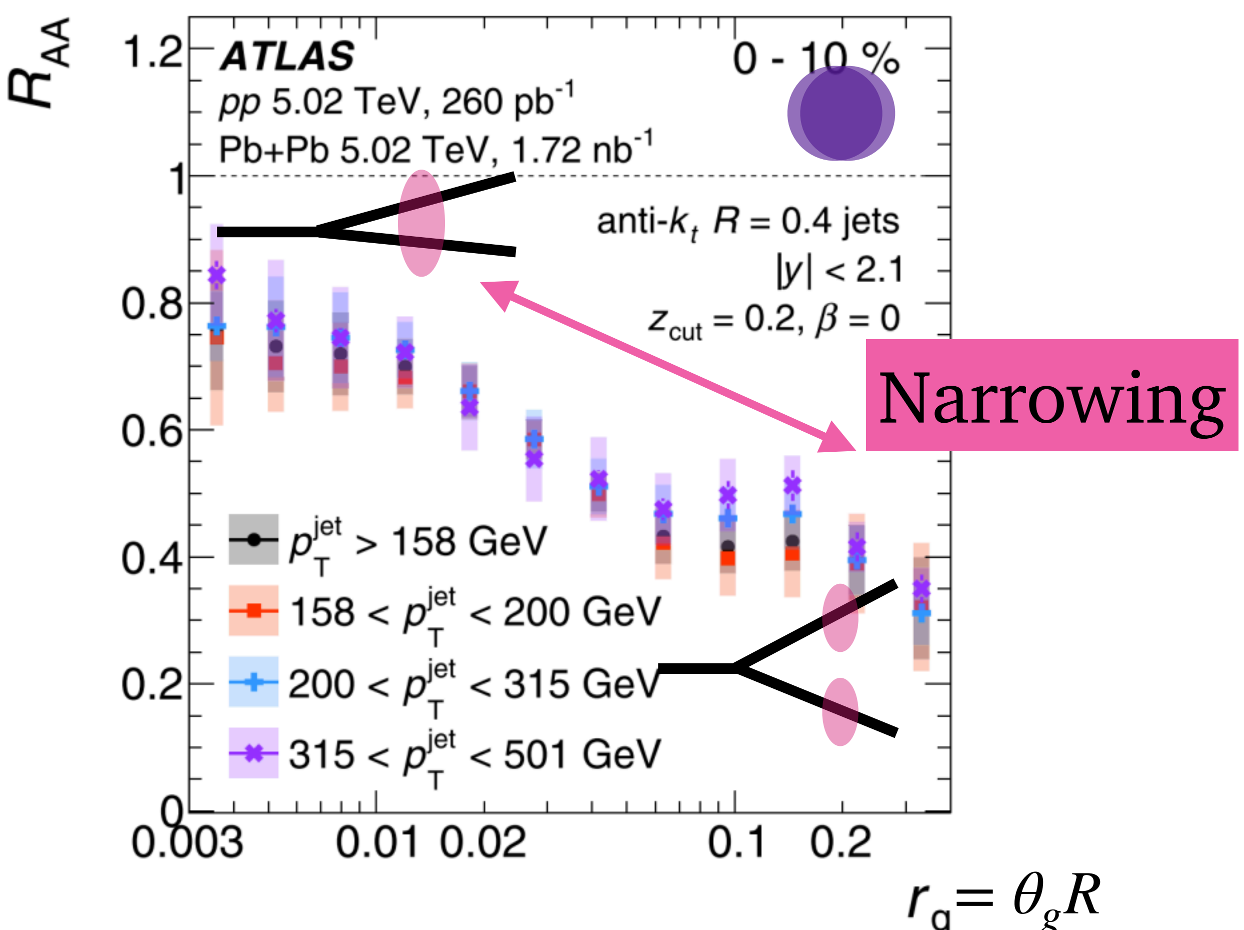
Color (de)coherence

Jet constituents are re-clustered (through C/A) and soft/wide angle radiation is rejected in this process



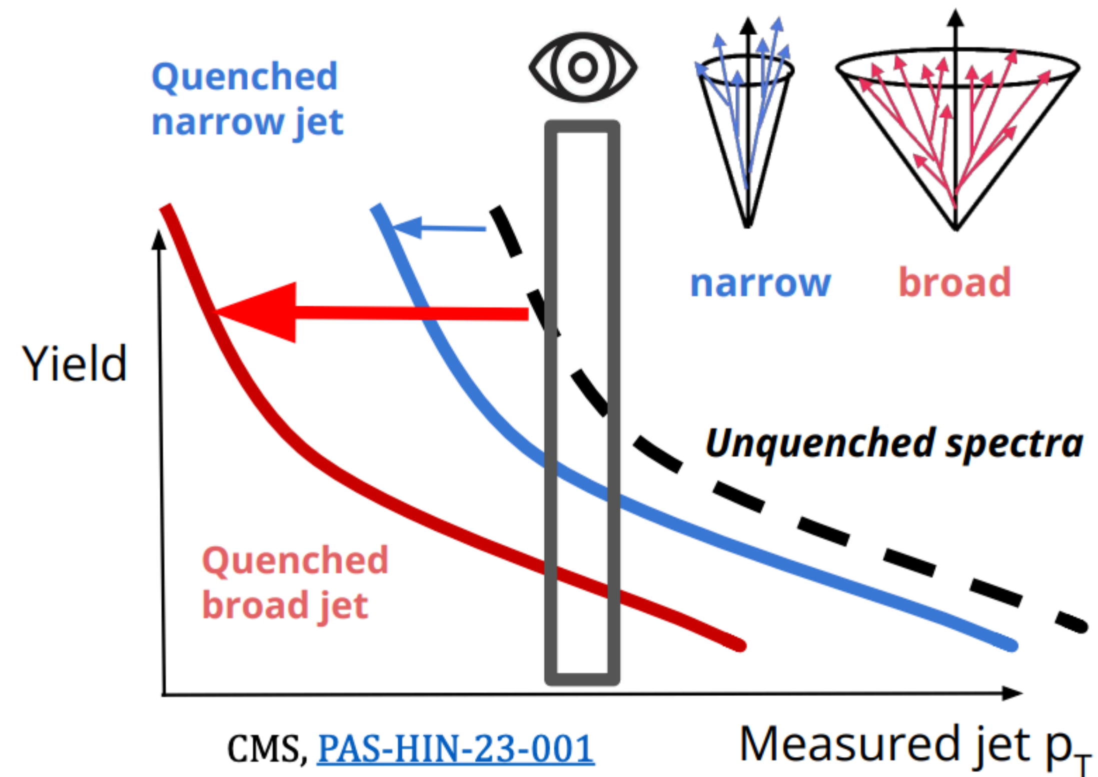
Groomed jet radius

$$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled}\otimes\text{pp}}$$



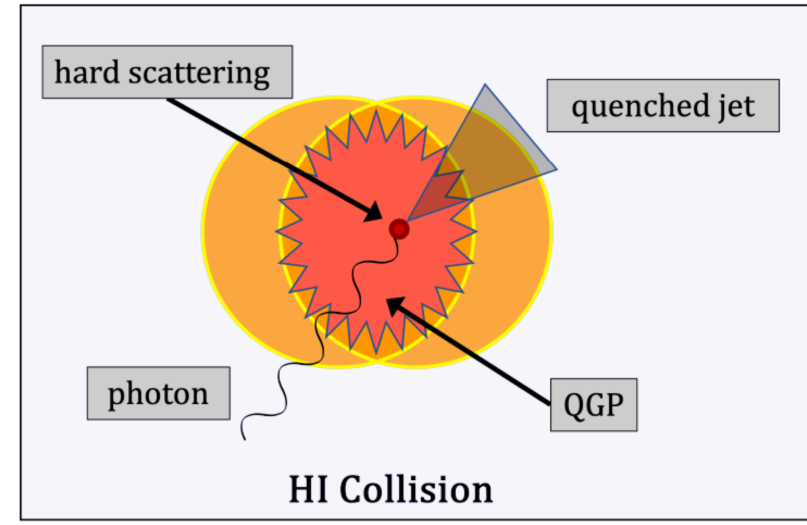
ATLAS, PRC 107 (2023) 054909

Jet quenching bias



CMS, PAS-HIN-23-001

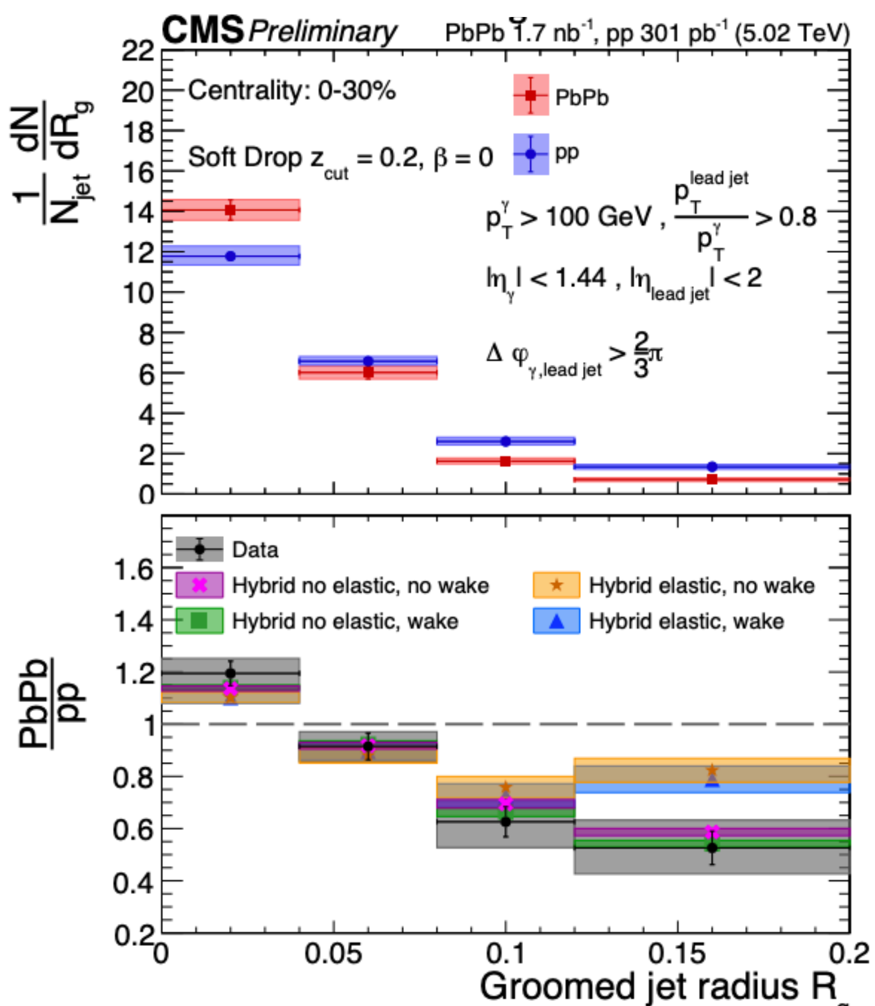
Color (de)coherence



- Use photon-tagged jets

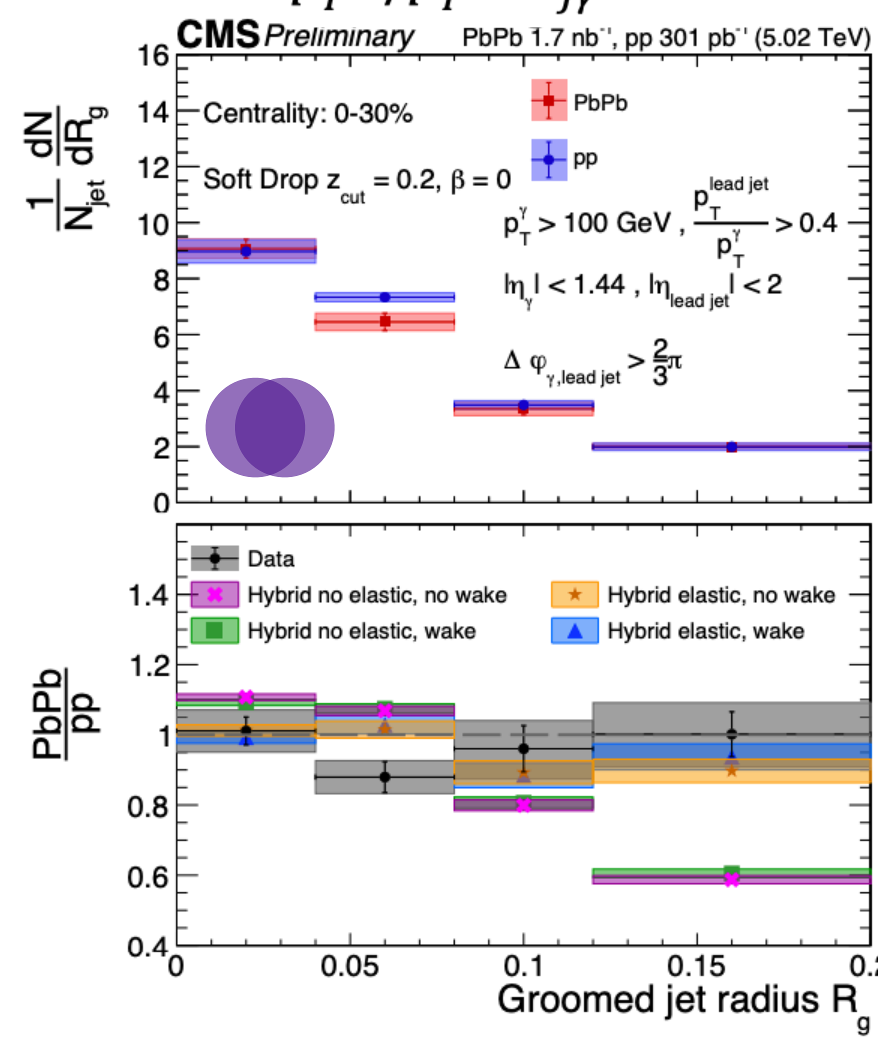
CMS-PAS-HIN-23-001

$p_T^{jet}/p_T^{\gamma} = x_{j\gamma} > 0.8$



Less quenched jets
Narrowing

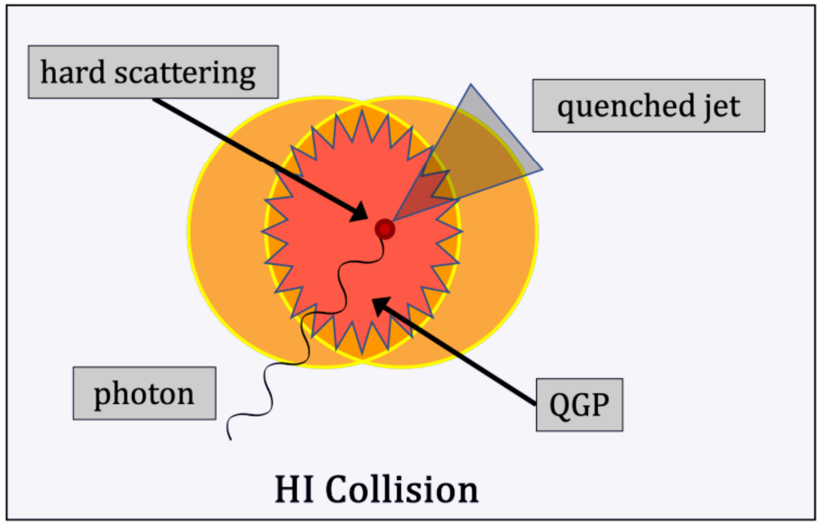
$p_T^{jet}/p_T^{\gamma} = x_{j\gamma} > 0.4$



Quenched and unquenched jets
No narrowing

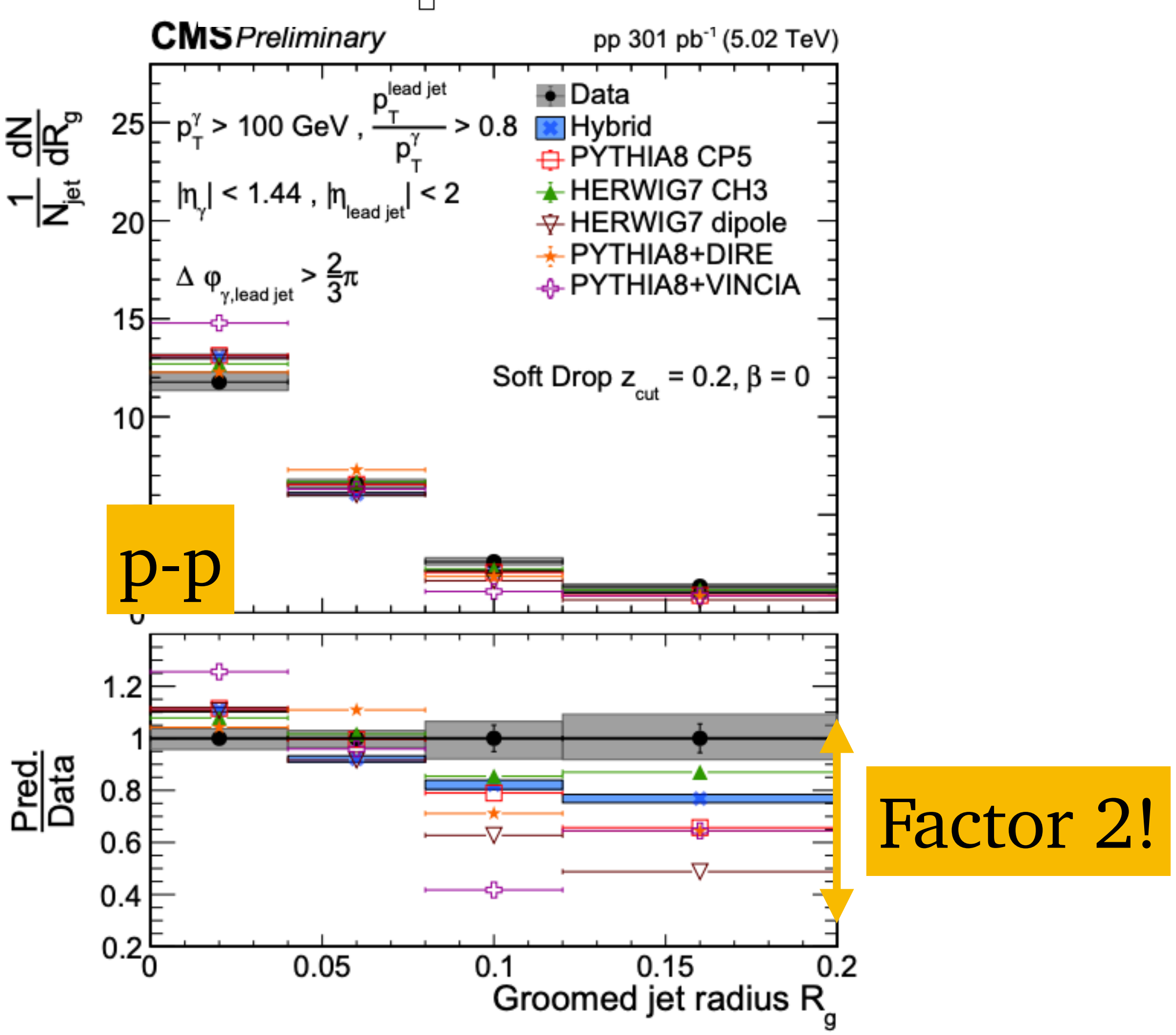
Color (de)coherence

- Use photon-tagged jets



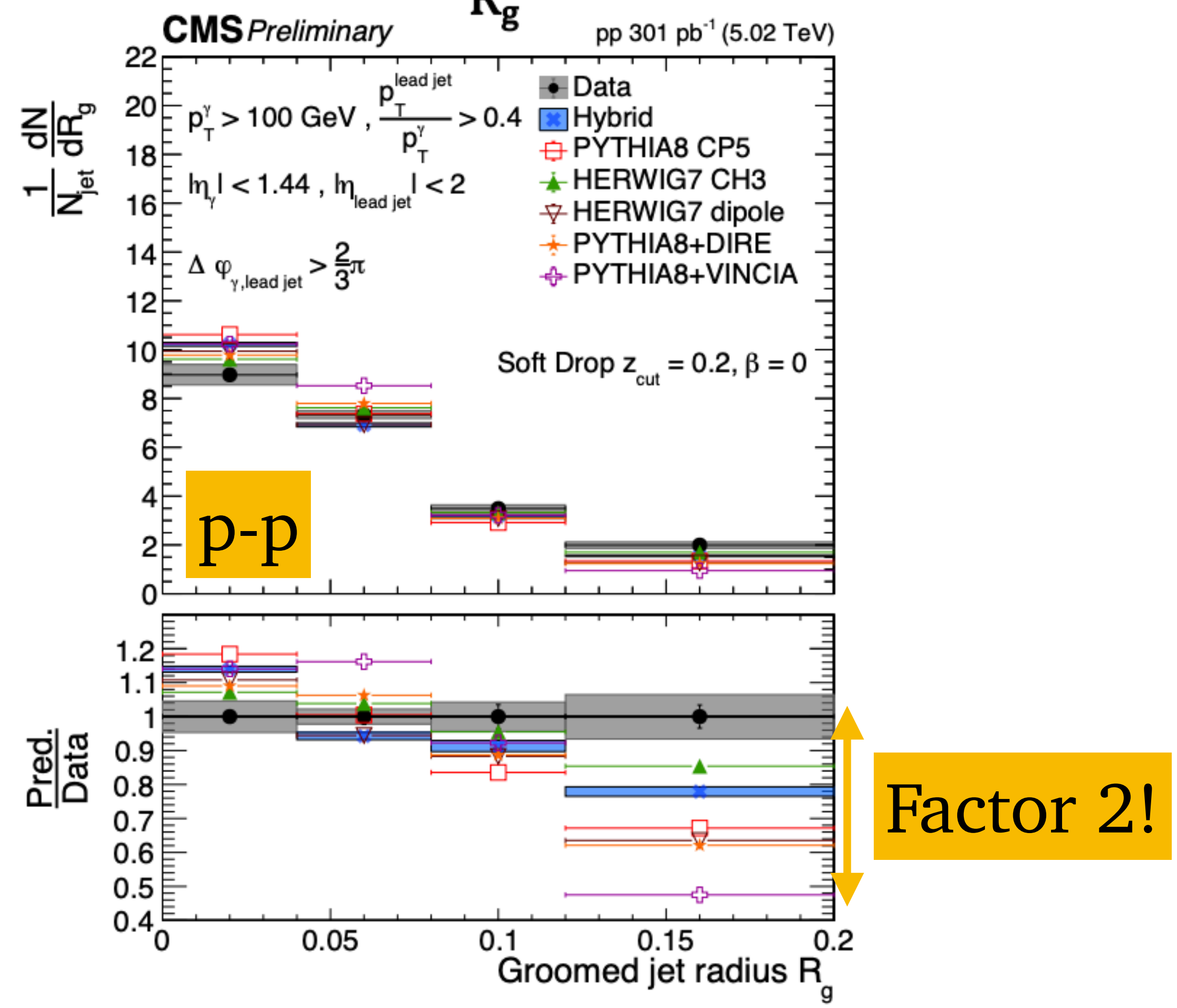
CMS-PAS-HIN-23-001

$p_T^{jet}/p_T^{\gamma} = x_{j\gamma} > 0.8$



$p_T^{jet}/p_T^{\gamma} = x_{j\gamma} > 0.4$

$\mathbf{R_g}$



p-p baseline not under control!

Thank you!