HEAVY IONS

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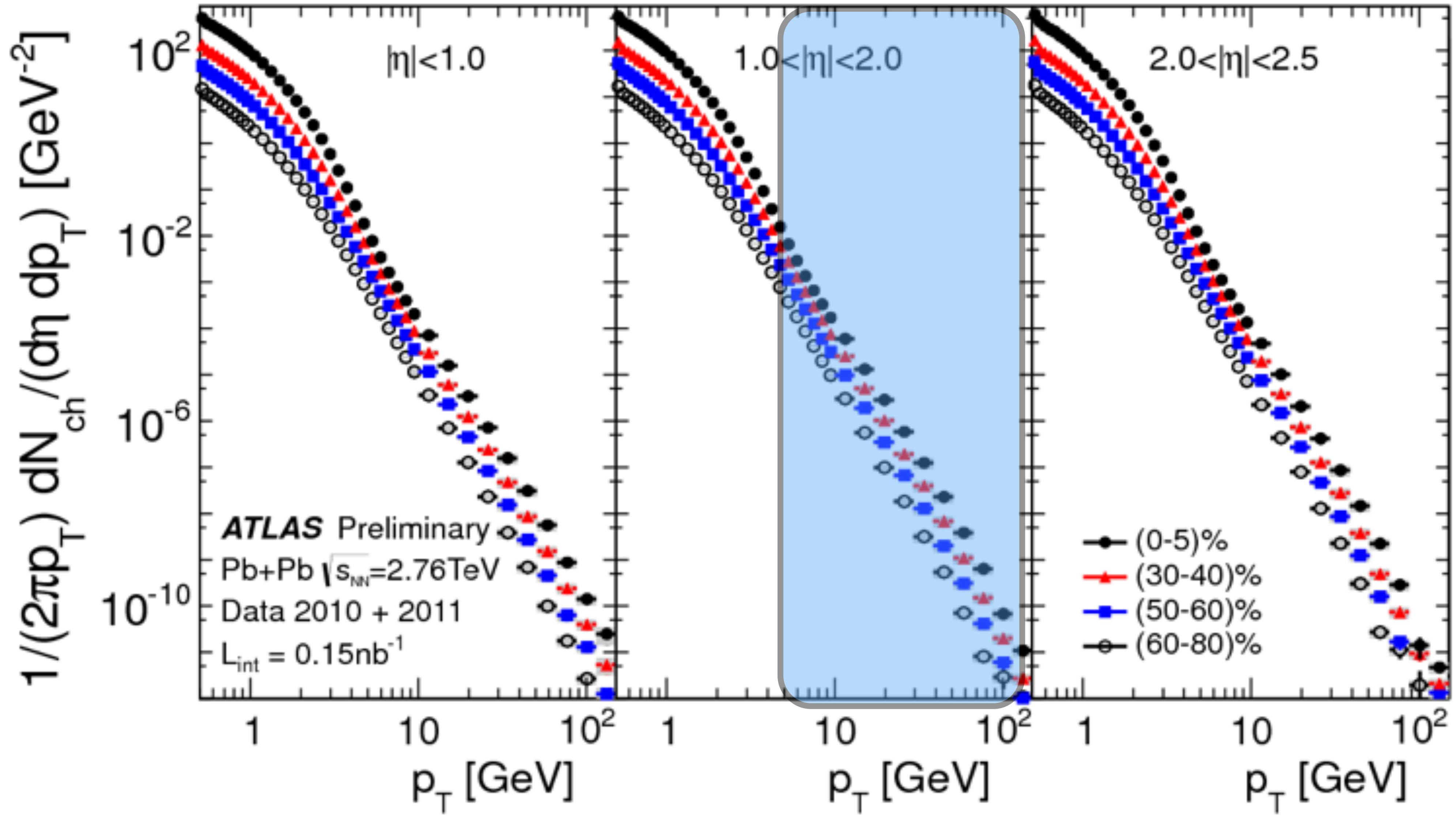
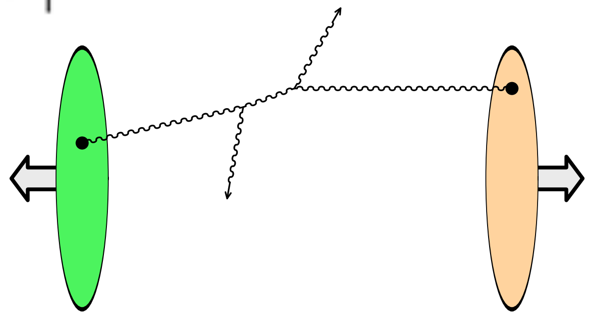
Lecture II

- quick repetition about jets
- medium-induced radiation
- jet decoherence

Charged particle spectrum

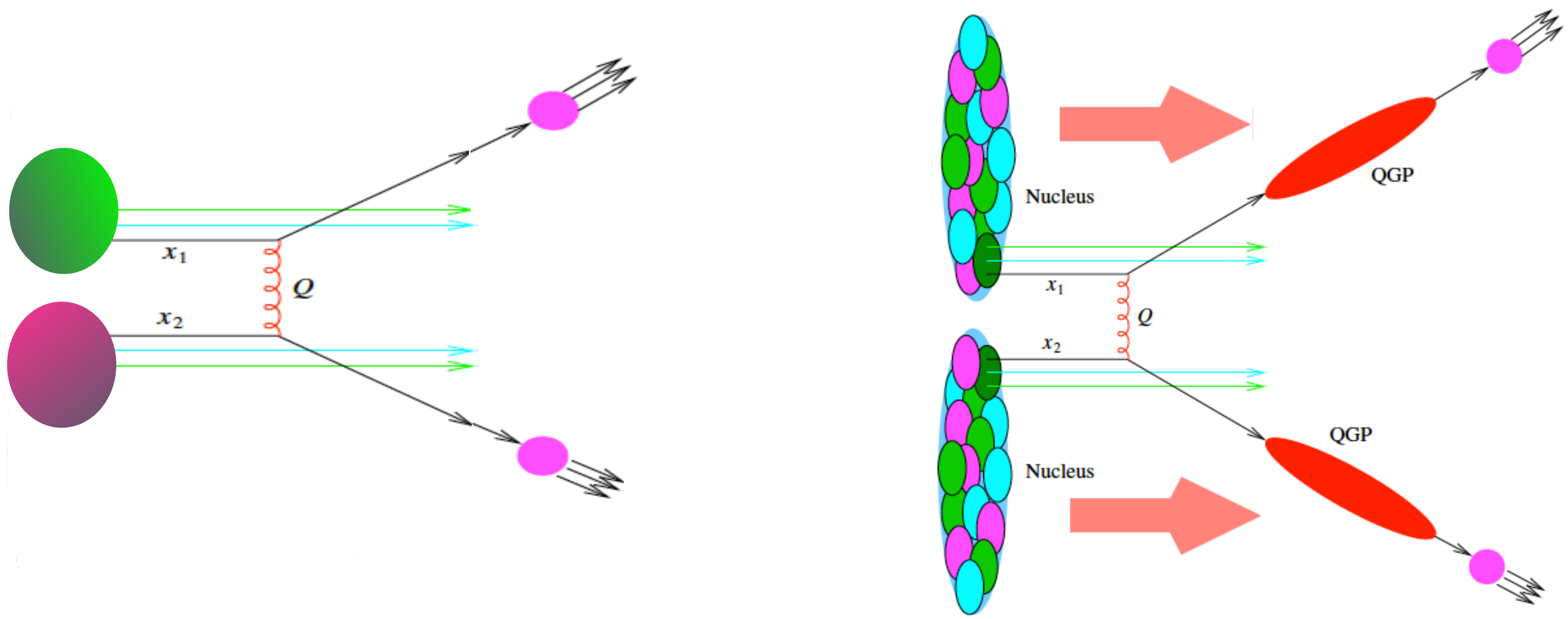


hard probes
dilute regime
power-like



Collinear factorization

Separation of initial- and final-state effects.

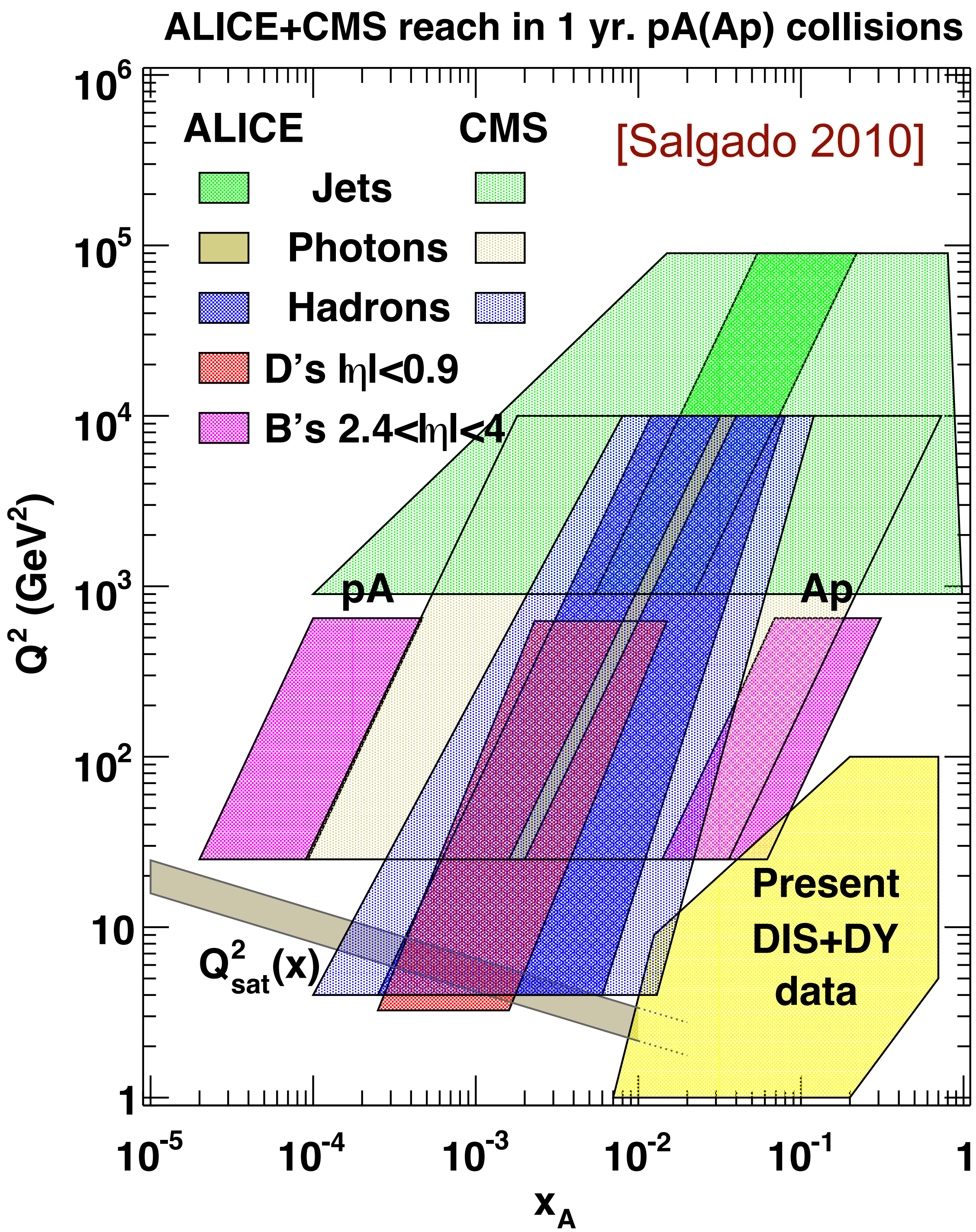


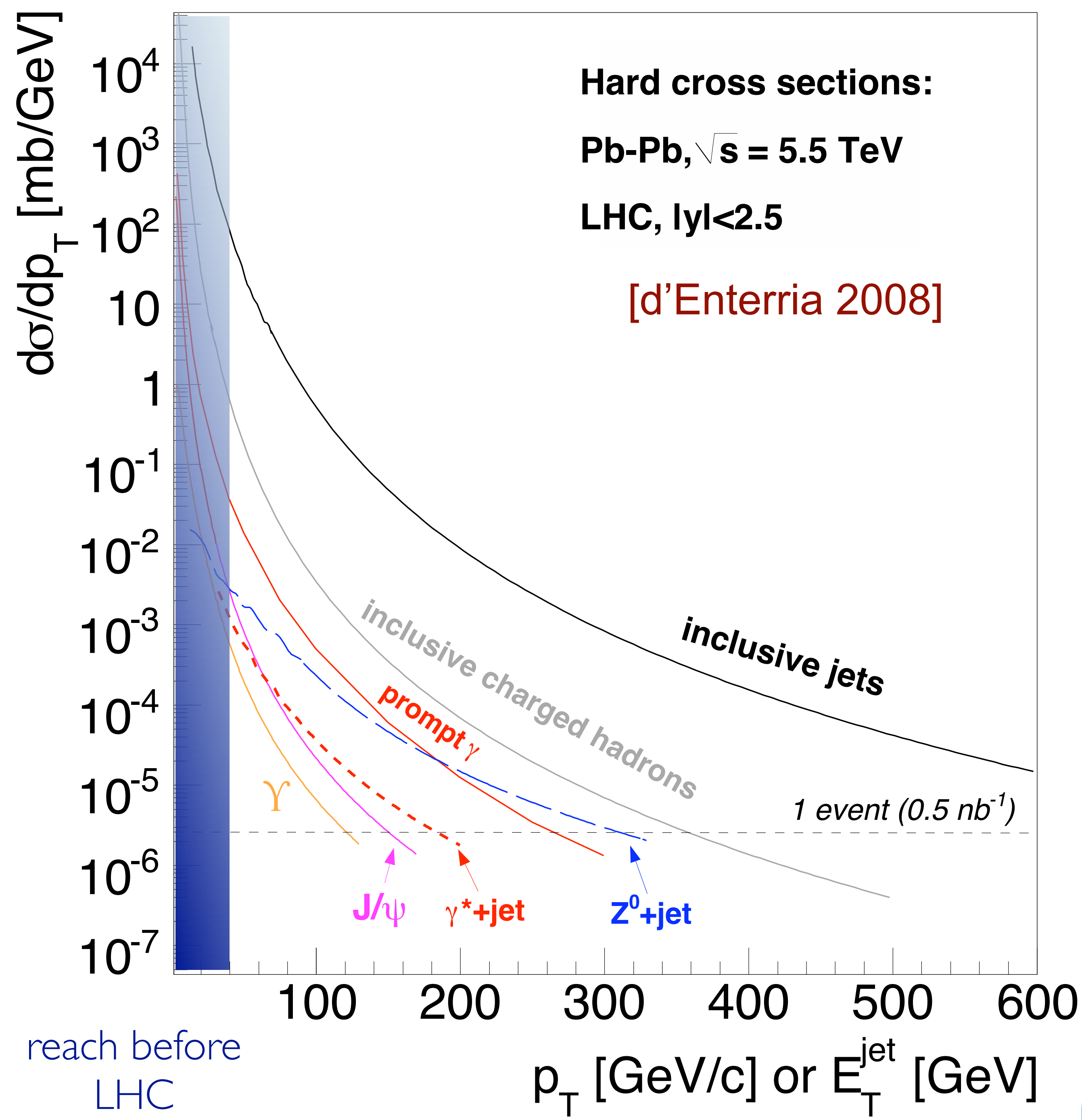
$$\sigma^{pp\to h} = \boxed{f_p(x_1,Q^2) \otimes f_p(x_2,Q^2)} \otimes \sigma(x_1,x_2,Q^2) \otimes \boxed{D(z,Q^2)}$$

Nuclear PDFs

Modified FFs

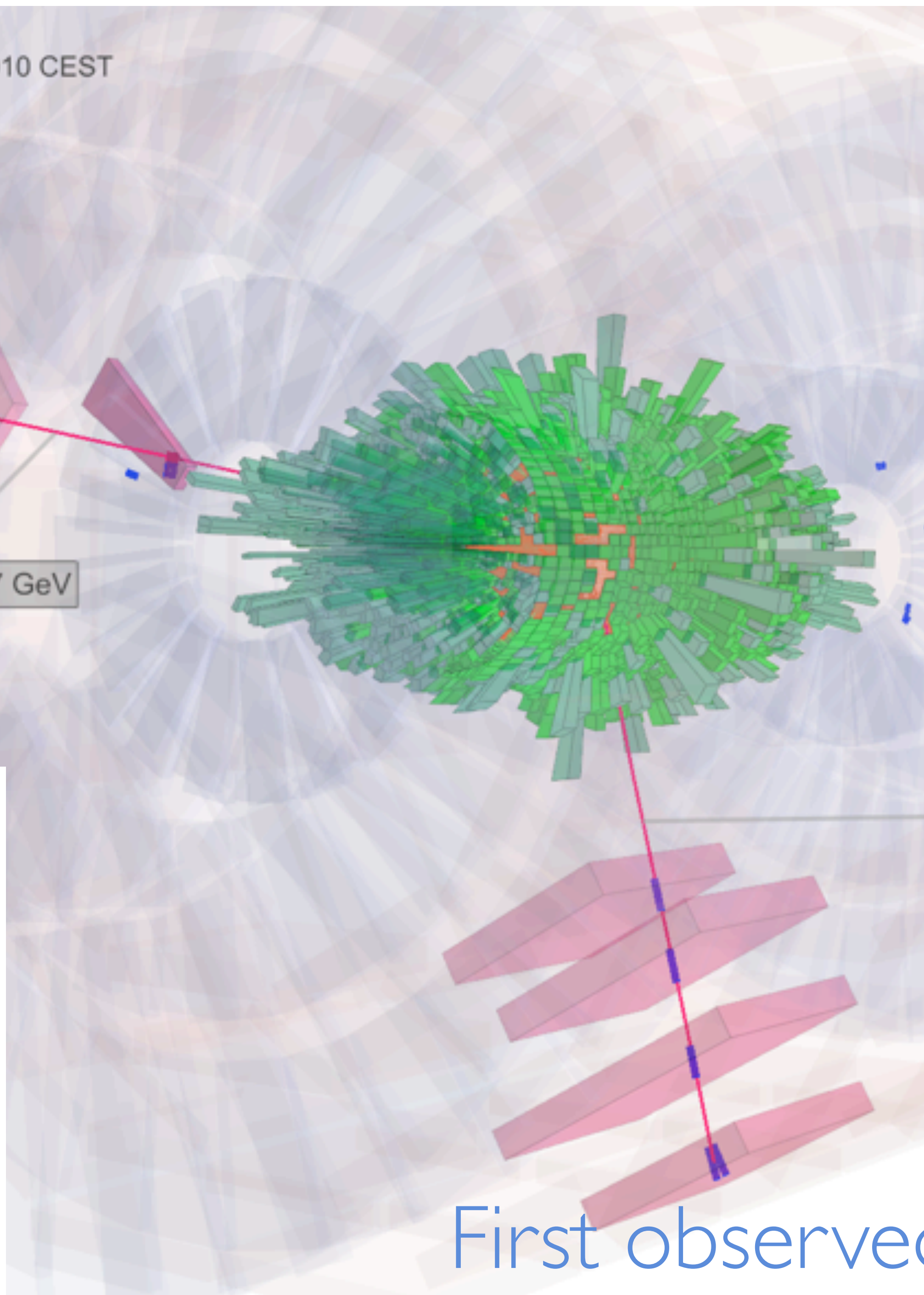
Hard probes at LHC

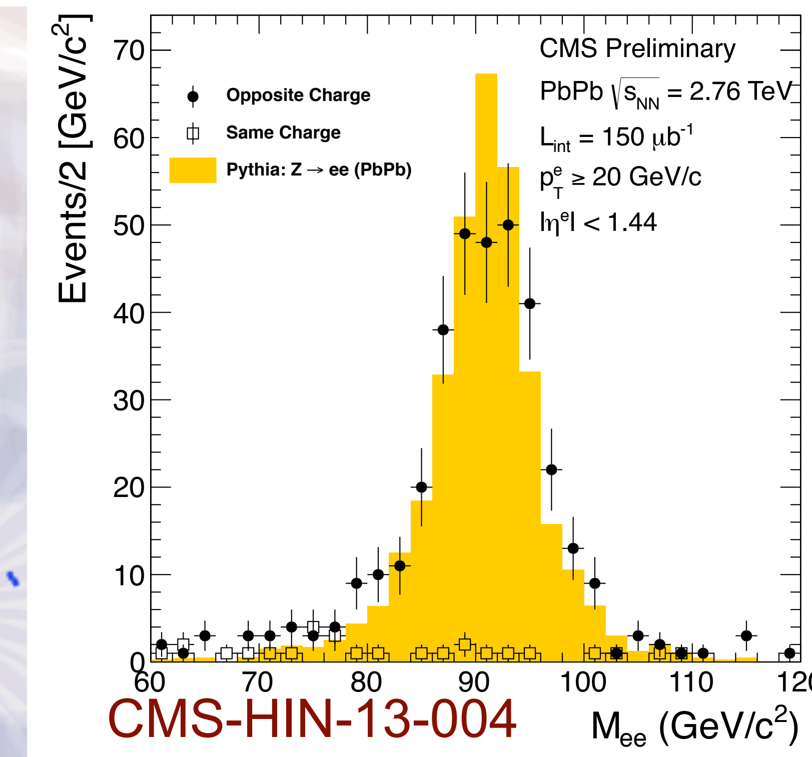




reach before LHC

Standard candles in pPb





First observed Z-production event in heavy-ion collisions!

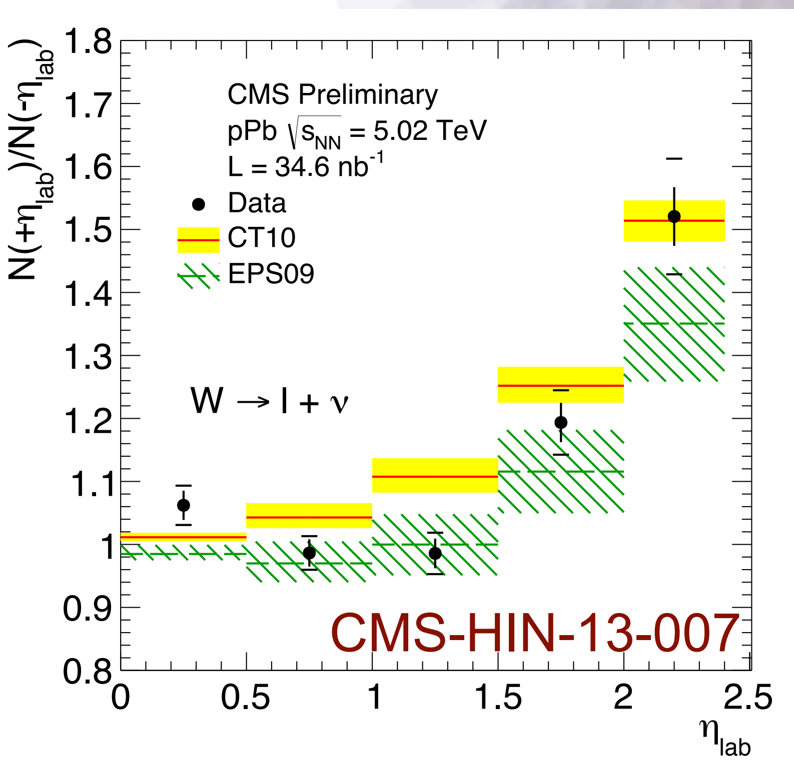
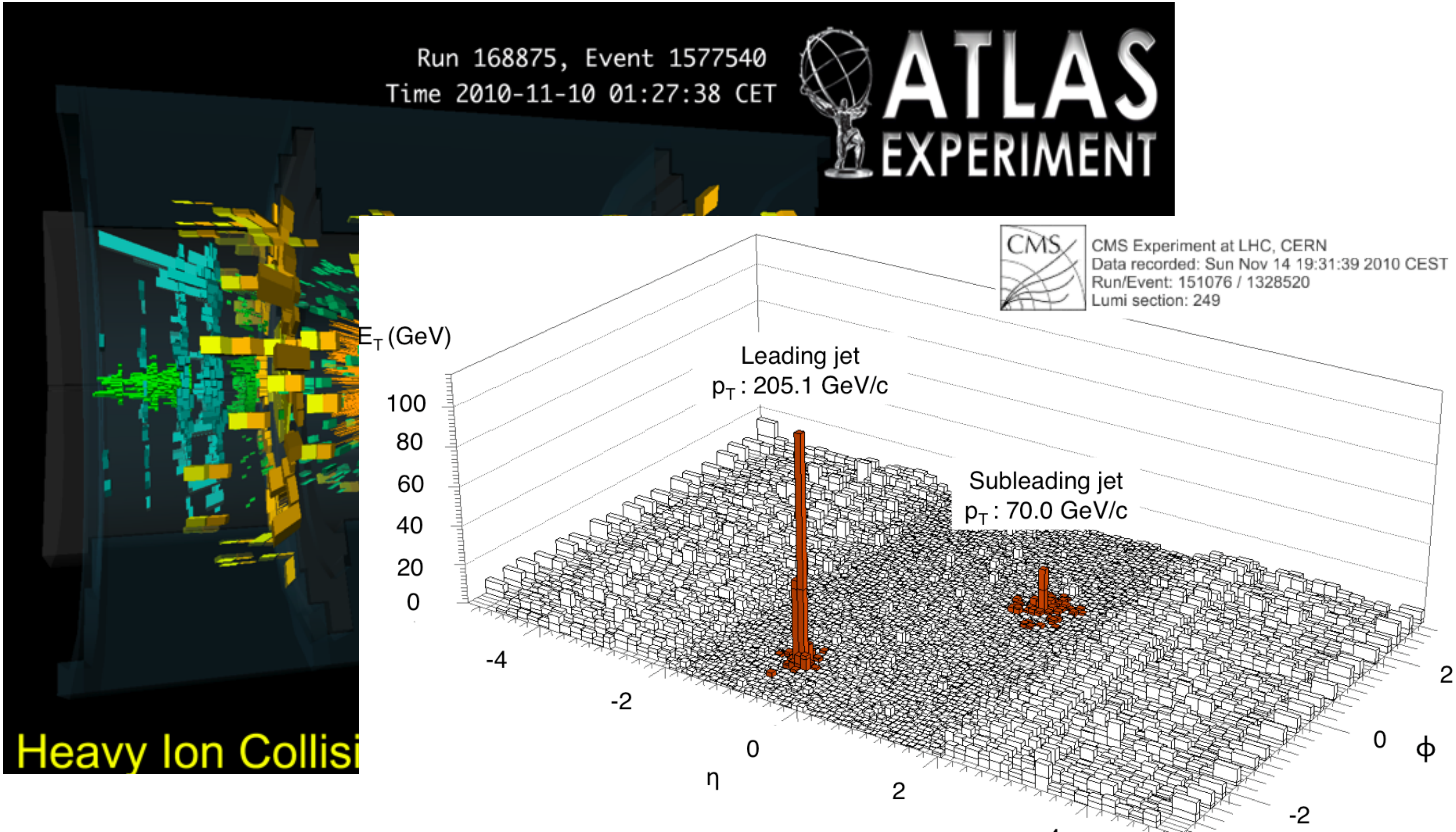
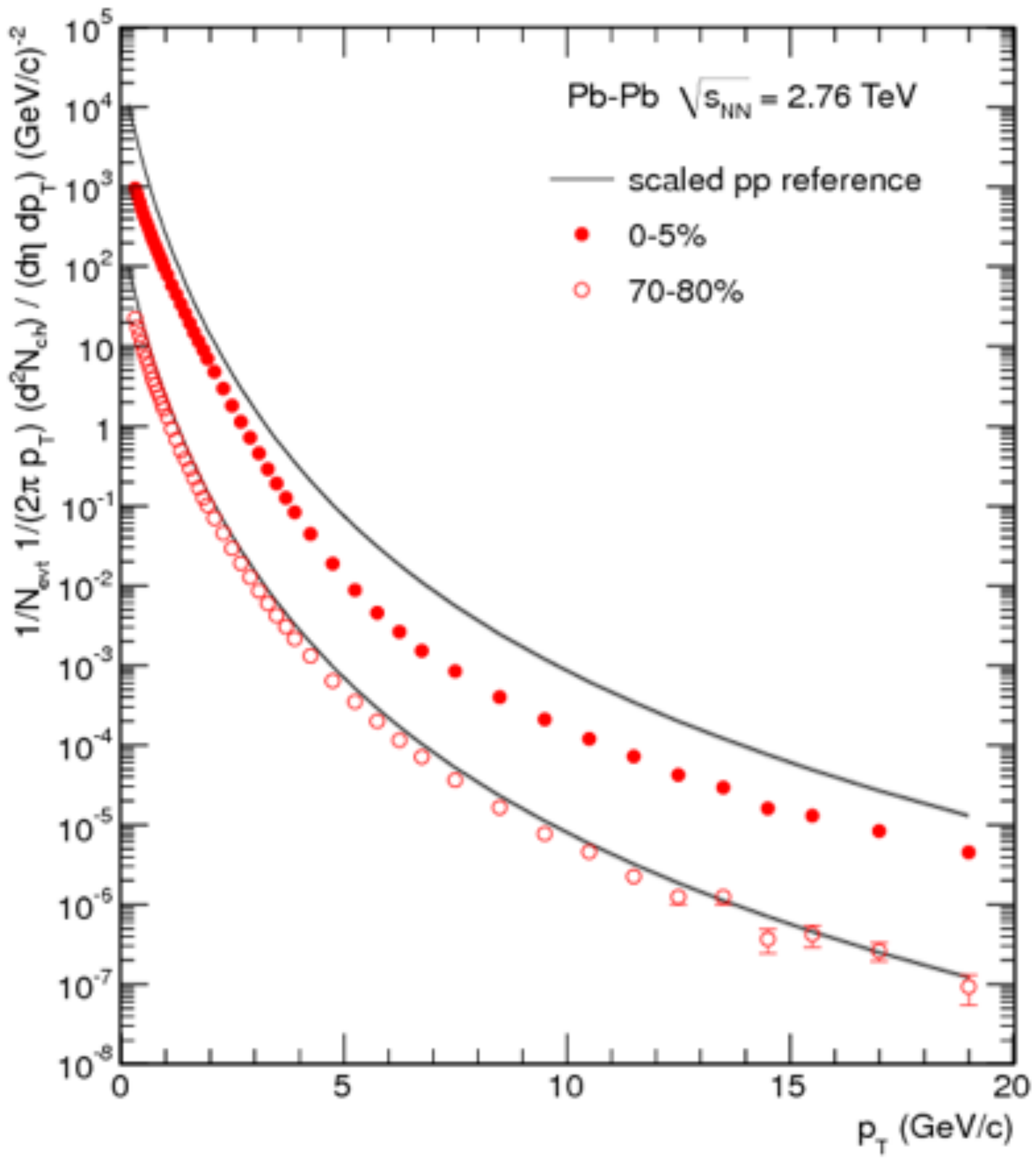
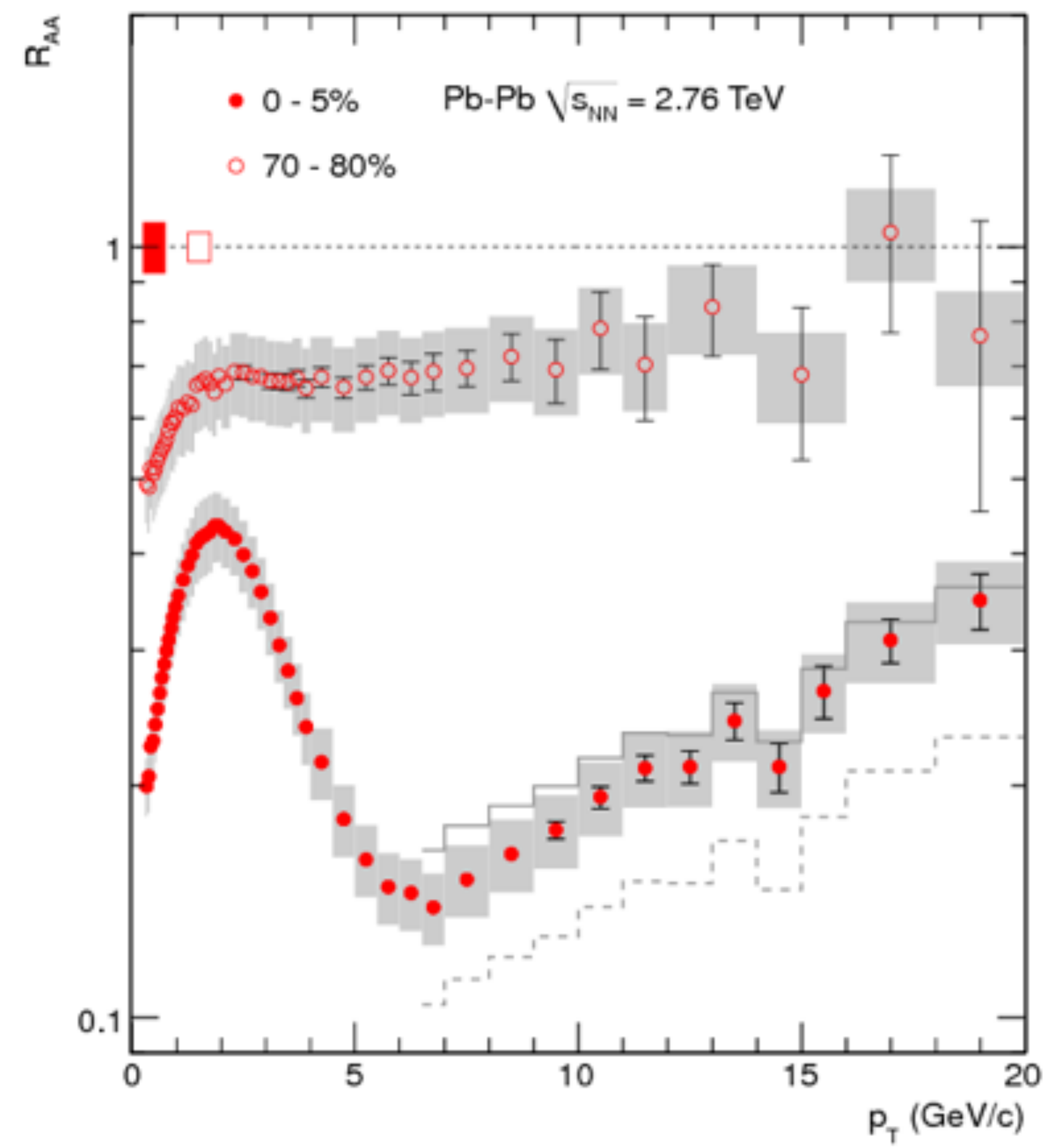


Figure 6: The $N(+\eta_{lab})/N(-\eta_{lab})$ asymmetry.


Run 168875, Event 1577540
Time 2010-11-10 01:27:38 CET
ATLAS
EXPERIMENT
Heavy Ion Collisi
CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
E_T (GeV)
Leading jet
p_T : 205.1 GeV/c
Subleading jet
p_T : 70.0 GeV/c
100
80
60
40
20
0
-4
-2
0
2
4
η
2
0
-2
ϕ

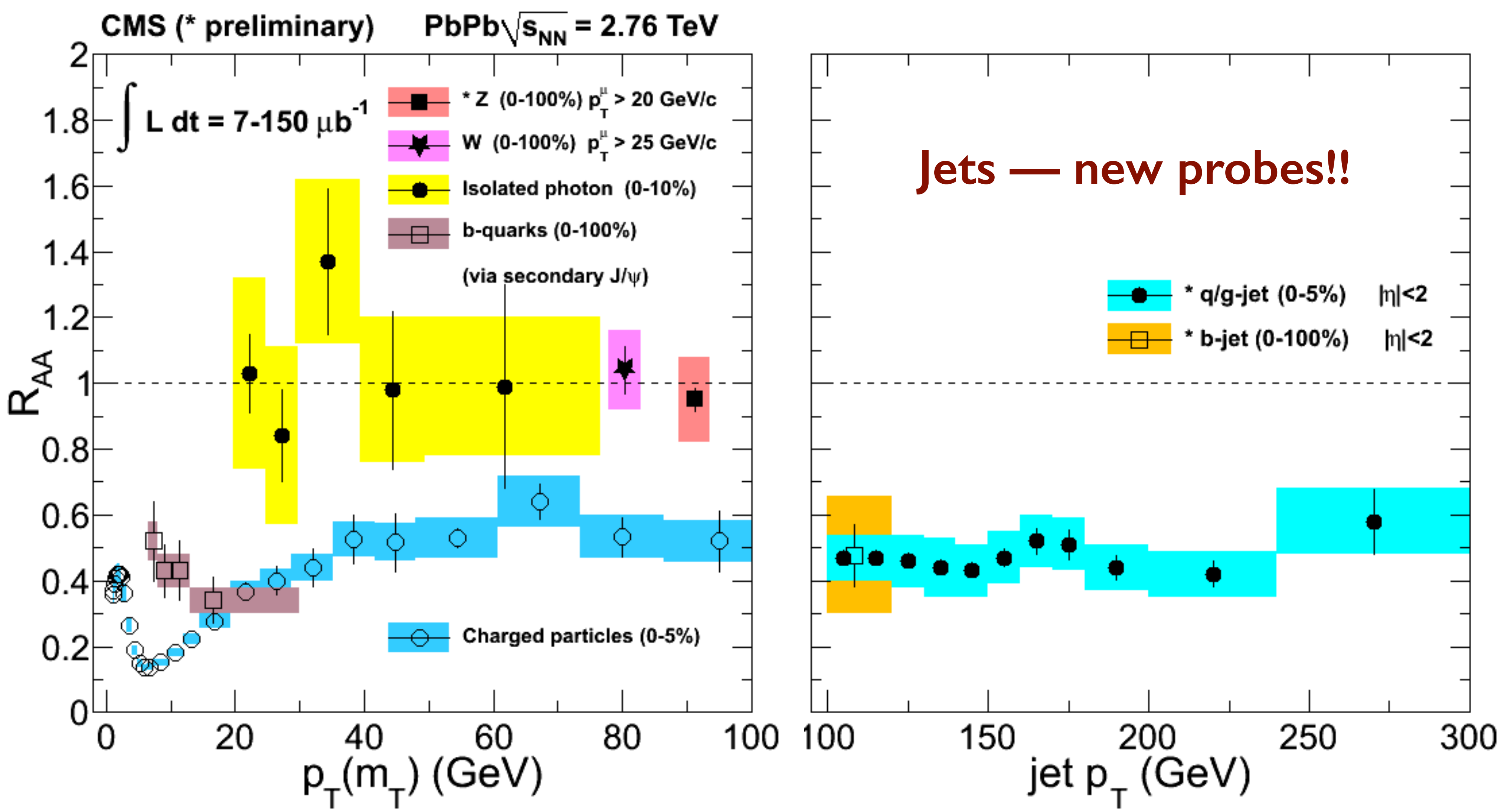
The nuclear modification factor





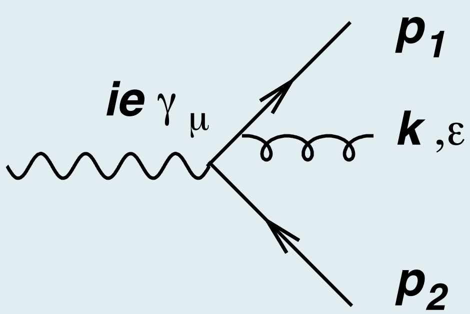
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{\rm ch}^{AA}/d\eta\, dp_T}{\langle N_{\rm coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{\rm ch}^{pp}/d\eta\, dp_T}$$

The T-shirt plot

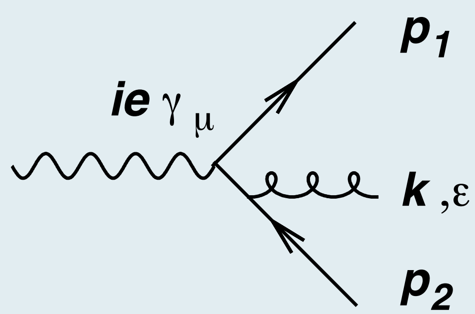


- no modification for colorless probes :: baseline ok!
- light & heavy hadrons/jets suppressed by a factor 2-5

Repetition:



$+$



$$= \bar{u}(p_1)\left(-ig_s t^a\right)\not{\epsilon}\,\frac{i(\not{p}_1+\not{k})}{(p_1+k)^2}\left(-ie_q\gamma_\mu\right)v(p_2)$$

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

:: strong energy ordering!

$$i\mathcal{M}_{q\bar{q}g} = i\mathcal{M}_{q\bar{q}} \times g_s t^a \left(\frac{p_1\cdot\epsilon}{p_1\cdot k} - \frac{p_2\cdot\epsilon}{p_2\cdot k}\right) \quad \Rightarrow \quad J^\mu = \boldsymbol{Q}_1 \frac{p_1^\mu}{p_1\cdot k} + \boldsymbol{Q}_2 \frac{p_2^\mu}{p_2\cdot k}$$

:: classical current

$$\sum |\mathcal{M}_{q\bar{q}g}|^2 = \sum |\mathcal{M}_{q\bar{q}}|^2 \times g_s^2 C_F \frac{2p_1\cdot p_2}{(p_1\cdot k)(p_2\cdot k)}$$

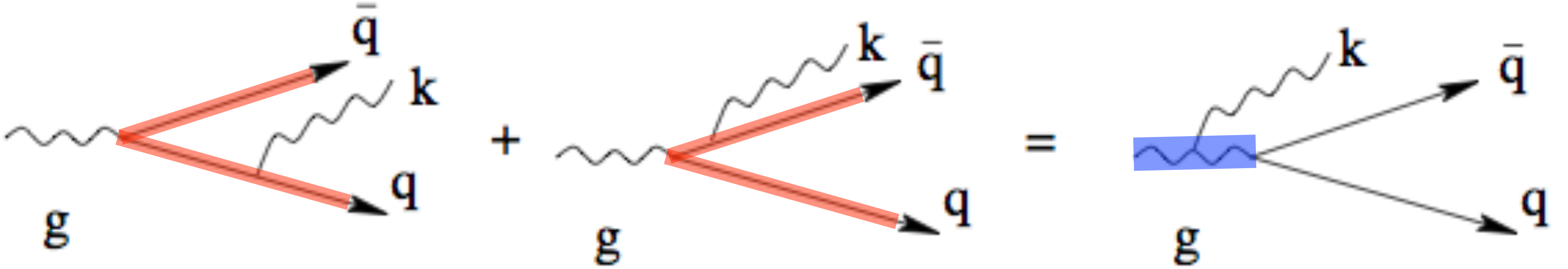
- factorization q$\bar{\text{q}}$ ➞ q$\bar{\text{q}}$ + g :: separation of time-scales!
- holds for higher order emissions too (leading logs)!

Angular ordering

$$J^\mu = \boldsymbol{Q}_1 \frac{p_1^\mu}{p_1 \cdot k} + \boldsymbol{Q}_2 \frac{p_2^\mu}{p_2 \cdot k} \quad \Rightarrow \quad |J|^2 = \boldsymbol{Q}_1^2 \mathcal{R}_1 + \boldsymbol{Q}_2^2 \mathcal{R}_2 + 2\boldsymbol{Q}_1 \cdot \boldsymbol{Q}_2 \mathcal{J}$$

$$(\boldsymbol{Q}_1 + \boldsymbol{Q}_2)^2 = 0 \ \Rightarrow \ \boldsymbol{Q}_1 \cdot \boldsymbol{Q}_2 = -C_F$$ :: singlet

$$(\boldsymbol{Q}_1 + \boldsymbol{Q}_2)^2 = C_A \ \Rightarrow \ \boldsymbol{Q}_1 \cdot \boldsymbol{Q}_2 = \frac{C_A}{2} - C_F$$ :: octet etc...



large-angle emissions are restored with the total charge!

$$\omega \frac{dN_g}{d\omega d^2 k_\perp} \propto \frac{\alpha_s C_F}{k_\perp^2} + (q \to \bar{q})$$

$$\theta \ll \theta_{q\bar{q}} \ (k_\perp \ll \omega \theta_{q\bar{q}})$$

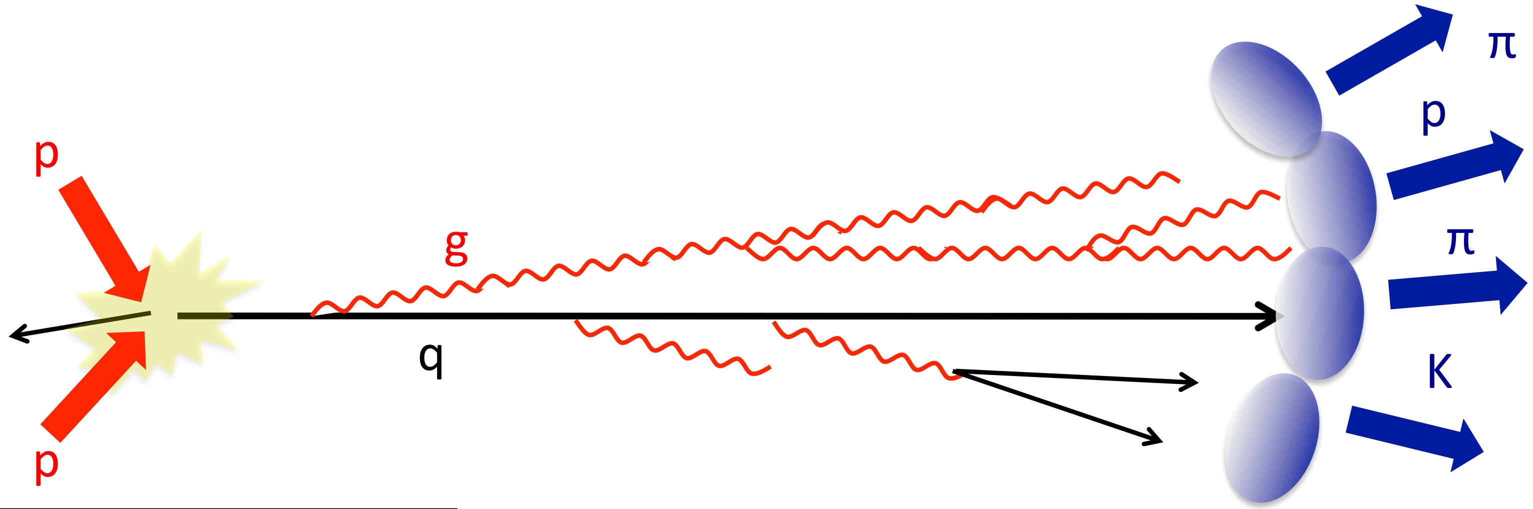
$$\omega \frac{dN_g}{d\omega d^2 k_\perp} \propto \frac{\alpha_s C_A}{k_\perp^2}$$

$$\theta \gg \theta_{q\bar{q}} \ (k_\perp \gg \omega \theta_{q\bar{q}})$$

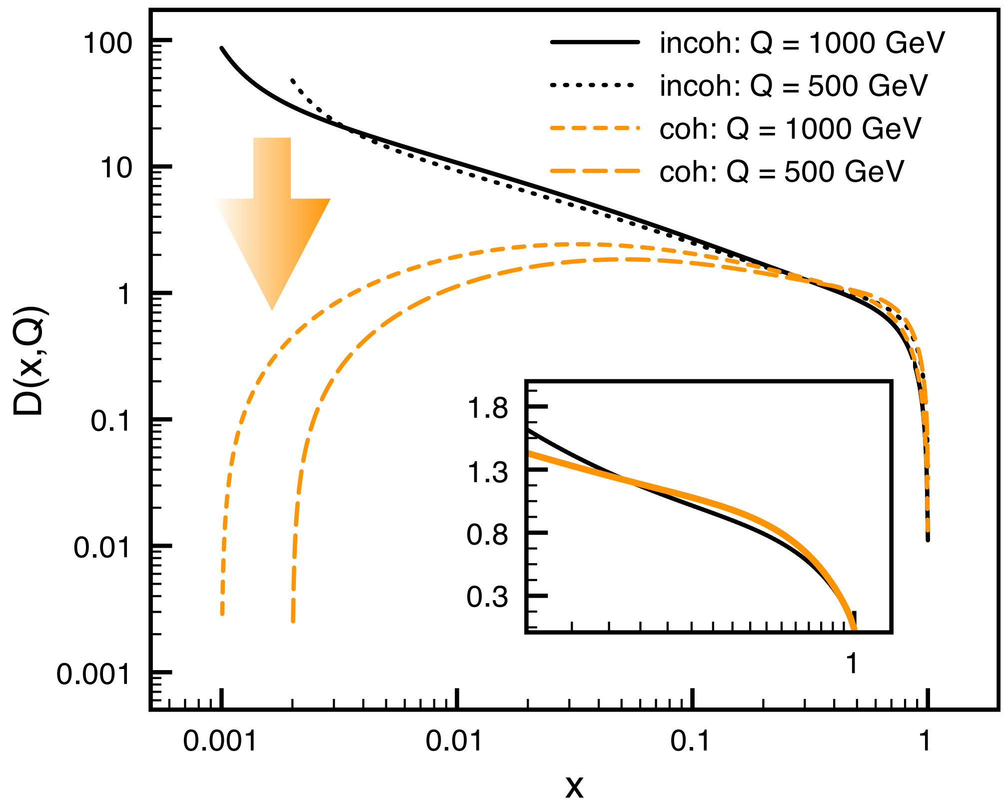
Jets in vacuum

[Bassetto, Ciafaloni, Marchesini, Mueller, Dokshitzer, Fadin, Lipatov (80's)]

$$t_{form} \simeq \frac{k_{||}}{k_\perp^2}$$

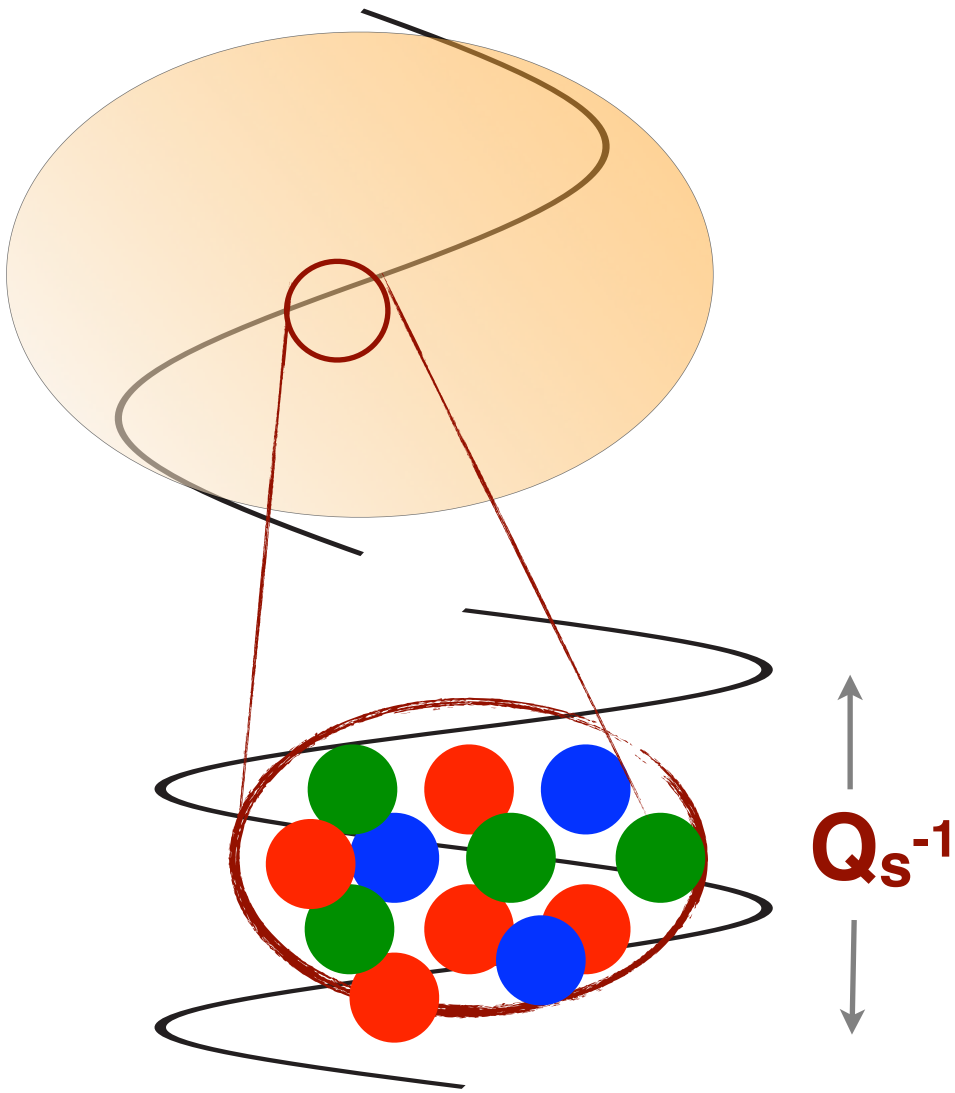


$$t_{hadr} \simeq \frac{k_{||}}{\Lambda_{\rm QCD}^2}$$



- separation of scales $Q \gg \Lambda_{QCD}$ allows for resummation of branchings
- probabilistic picture (including quantum interference)
- delicate treatment of the soft sector
- basis for precision pQCD

A new scale in the medium

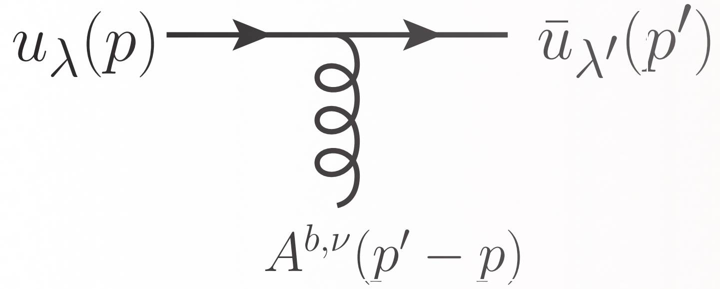


- the jet scale $Q=E\Theta_{jet}$
- the medium fluctuates with with typical transverse wave-length Q_s^{-1}
- medium "charge" is zero for $\lambda>Q_s^{-1}$
- resolved by $\lambda<Q_s^{-1}$

$$Q_s^2(t) = \hat{q}t$$

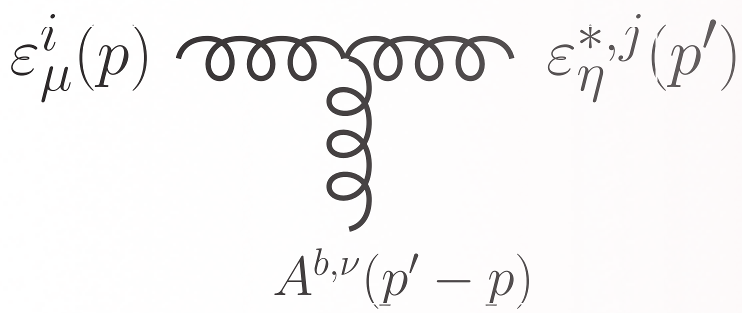
squared transverse momentum per unit length

Eikonal propagation



spin

$$\simeq -ig_s \delta_{\lambda\lambda'}\, 2p^+ A^{a,-} t^a$$



polarization

$$\simeq -ig_s \delta^{ij}\, 2p^+ A^{a,-} \left(T^a\right)_{bc}$$

- conservation of energy during scattering
  - no elastic energy loss
- no spin-flip, polarization
- color precession

S-matrix:

$$S(p',p) = \sum_{n=0}^{\infty} S_n(p',p)$$

$$\simeq 2\pi\delta(p'^+ - p^+)\, 2p^+ \int d^2\boldsymbol{x}\, e^{-i(\boldsymbol{p}'-\boldsymbol{p})\cdot\boldsymbol{x}}\, U(x^+, x_0^+; [\boldsymbol{x}])$$

Wilson line:

$$U(x^+, 0; [\boldsymbol{r}]) \equiv \mathcal{P}_\xi \exp\left[ig \int_0^{x^+} d\xi\, T\cdot A^-_{\text{med}}(\xi, \boldsymbol{r}(\xi))\right]$$

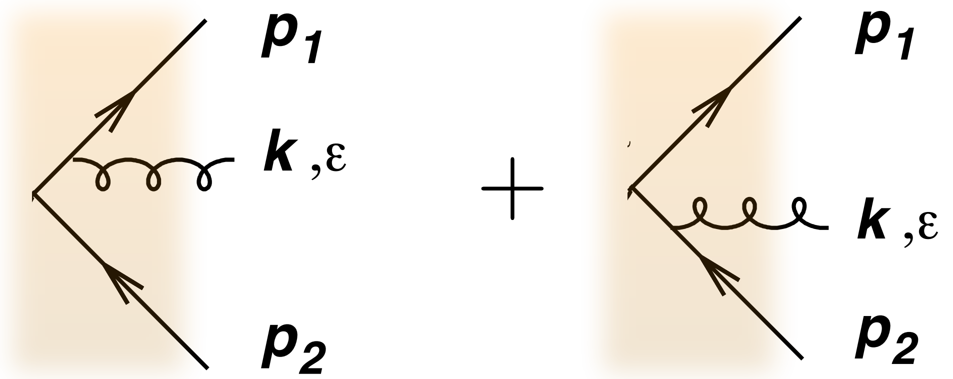
Antenna in the medium

Classical current:

$$J^\mu = \sum_{i=1}^{2} \boldsymbol{Q}_i \frac{k_i^\mu}{k_i \cdot k} \quad \Rightarrow \quad J^\mu = \sum_{i=1}^{2} \boldsymbol{Q}_i \, U\left(x^+, 0; \left[\boldsymbol{r} = \frac{\boldsymbol{k_i}}{k_i^+}\xi\right]\right) \frac{k_i^\mu}{k_i \cdot k}$$

Survival probability of the dipole:

$$\Delta_{\text{med}} = 1 - \frac{1}{N_c}\langle \mathrm{Tr}\, U_1\left(x_L^+, 0\right) U_2^\dagger\left(0, x_L^+\right)\rangle$$
$$= 1 - \exp\left[-\frac{1}{12} r_\perp^2(x_L^+) Q_s^2(x_L^+)\right]$$



Only the interferences are modified!

$$\omega \frac{dN}{d^3k} = \frac{\alpha_s}{(2\pi)\omega^2}\left[\boldsymbol{Q}_1^2 \mathcal{R}_1 + \boldsymbol{Q}_2^2 \mathcal{R}_2 + 2\boldsymbol{Q}_1 \cdot \boldsymbol{Q}_2 \left(1 - \Delta_{\text{med}}\right) \mathcal{J}\right]$$

In some detail…

Two-point function:

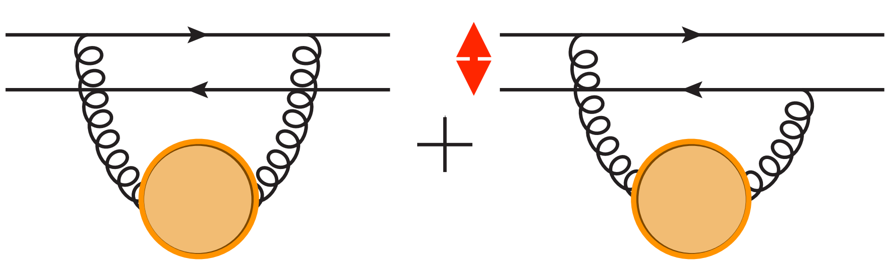
comes from the number of quarks

$$C_q^{(2)}(x_L^+ - x_0^+; \boldsymbol{x} - \bar{\boldsymbol{x}}) = \frac{1}{N_c}\left\langle \mathrm{Tr}\, U(x_L^+, x_0^+; \boldsymbol{x}) U^\dagger(x_0^+, x_L^+; \bar{\boldsymbol{x}}) \right\rangle$$

Opacity expansion:

$$U\left(x_L^+, x_0^+; [\boldsymbol{r}]\right) = 1 + ig \int_{x_0^+}^{x_L^+} d\xi\, T \cdot A^-_{\mathrm{med}}(\xi, \boldsymbol{r}) + (ig)^2 \int_{x_0^+}^{x_L^+} d\xi\, T \cdot A^-_{\mathrm{med}}(\xi, \boldsymbol{r}) \int_{\xi}^{x_L^+} d\xi'\, T \cdot A^-_{\mathrm{med}}(\xi', \boldsymbol{r})$$

$$\boldsymbol{r} = \bar{\boldsymbol{x}} - \boldsymbol{x}$$



$$\langle U^{(2)}(\boldsymbol{x})\rangle \sim \int_{\xi}^{x_L^+} d\xi' \int_{x_0^+}^{x_L^+} d\xi\, T^a T^b \langle A^{a,-}_{\mathrm{med}}(\xi', \boldsymbol{x}) A^{b,-}_{\mathrm{med}}(\xi, \boldsymbol{x})\rangle$$
$$\sim \gamma(\boldsymbol{r} = 0)$$

$$\langle U^{(1)}(\boldsymbol{x}) U^{\dagger(1)}(\bar{\boldsymbol{x}})\rangle \sim \int_{x_0^+}^{x_L^+} d\xi' \int_{x_0^+}^{x_L^+} d\xi\, T^a T^b \langle A^{a,-}_{\mathrm{med}}(\xi', \boldsymbol{x}) A^{\dagger b,-}_{\mathrm{med}}(\xi, \bar{\boldsymbol{x}})\rangle$$
$$\sim \gamma(\boldsymbol{r})$$

Medium averages

$$\langle A^{a,-}_{\rm med}(x^+,\boldsymbol{q})A^{b,-\dagger}_{\rm med}(x'^+,\boldsymbol{q}')\rangle = \delta^{ab}\, n(x^+)\delta(x^+-x'^+)\,(2\pi)^2\delta(\boldsymbol{q}-\boldsymbol{q}')\gamma(\boldsymbol{q})$$

Medium average

:: instantaneous correlator $\lambda_{\rm mfp} > r_{\rm scr}$
:: no cross-talk between scattering centers

Perturbatively: $\lambda_{mfp}\sim 1/(g^2T)$ and $r_{scr}\sim 1/m_D\sim 1/gT$ :: ok!

Resumming all such contributions gives rise to exponentiation!

$$\begin{aligned} C^{(2)}_q(x^+_L-x^+_0;\boldsymbol{r}) &= \frac{1}{N_c}\Big\langle {\rm Tr}\, U(x^+_L,x^+_0;\boldsymbol{x})U^\dagger(x^+_0,x^+_L;\bar{\boldsymbol{x}})\Big\rangle \\ &= \exp\Big\{-g_s^2N_c(x^+_L-x^+_0)n_0\big[\gamma(0)-\gamma(\boldsymbol{r})\big]\Big\} \\ &= \exp\Big\{-\frac{1}{2}\int dx^+\Gamma_2(\boldsymbol{r},x^+)\Big\} \end{aligned}$$

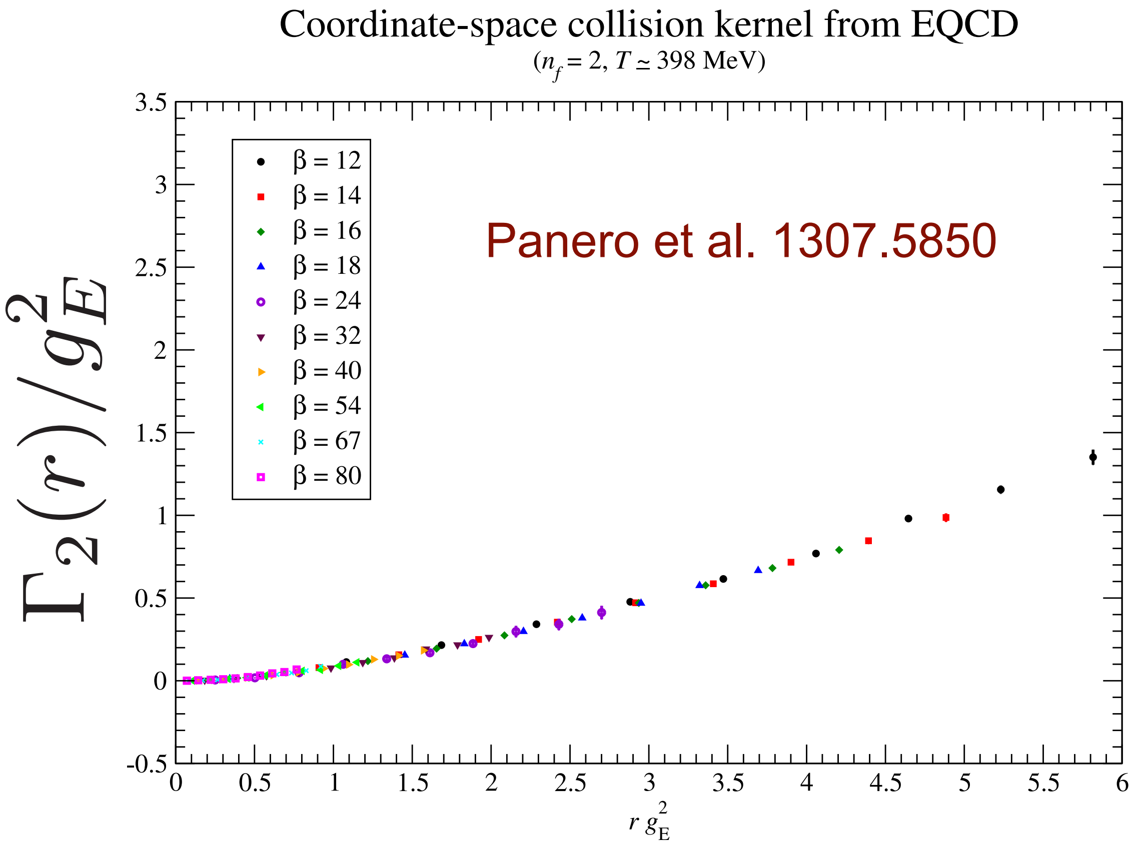
dipole scattering rate!

Enter q̂

$$\Gamma_2(\boldsymbol{r},x^+)\simeq\frac{1}{2}\hat{q}\boldsymbol{r}^2 \qquad \Rightarrow \qquad C_q^{(2)}(\Delta x^+;\boldsymbol{r})=\exp\left(-\frac{\hat{q}\Delta x^+}{4}\boldsymbol{r}^2\right)$$

"harmonic oscillator"/dipole approximation

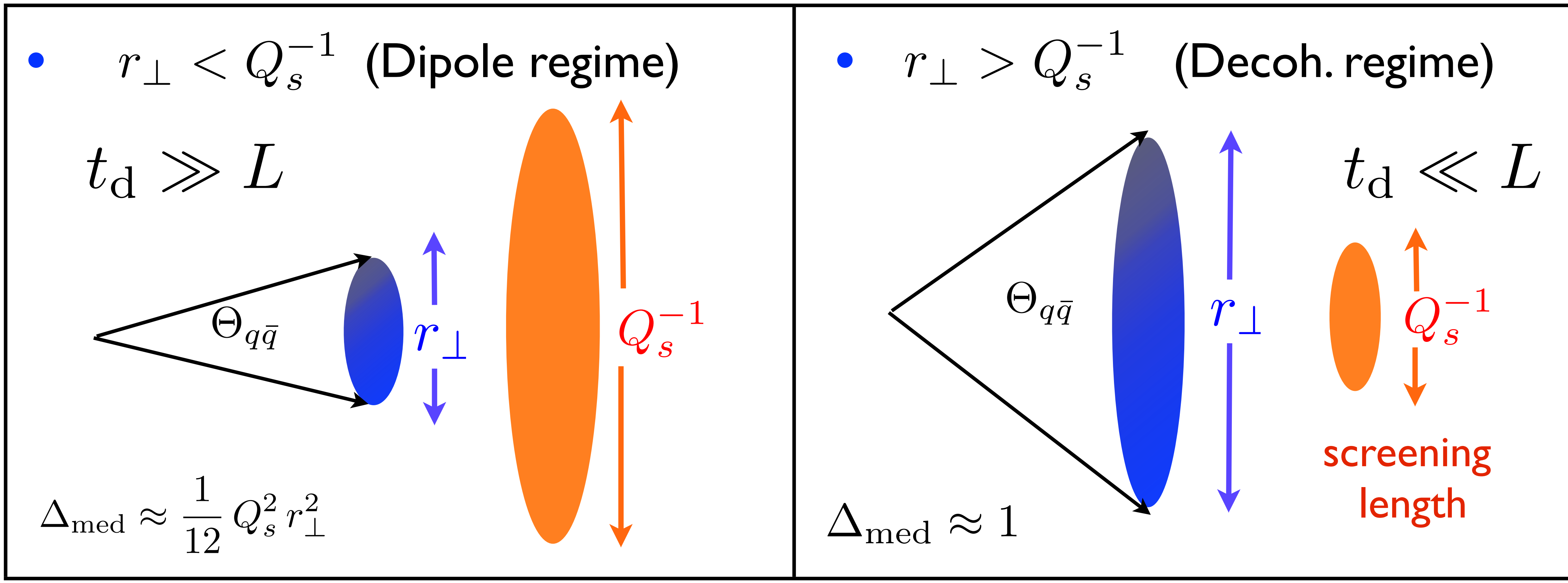
In momentum space: $$\mathcal{P}(\boldsymbol{p}-\boldsymbol{p}_0,\Delta x^+)=\int d^2\boldsymbol{r}e^{-i(\boldsymbol{p}-\boldsymbol{p}_0)\cdot\boldsymbol{r}}C_q^{(2)}(\Delta x^+;\boldsymbol{r})$$



$$\mathcal{P}(\Delta\boldsymbol{p},\Delta x^+)=\frac{4\pi}{\hat{q}\Delta x^+}e^{-\frac{\Delta\boldsymbol{p}^2}{\hat{q}\Delta x^+}}$$

- is a transport coefficient controlling Brownian motion/Gaussian broadening
- intuitively q̂~1/η
- can be measured on the lattice in the high-energy limit

Hard scale analysis

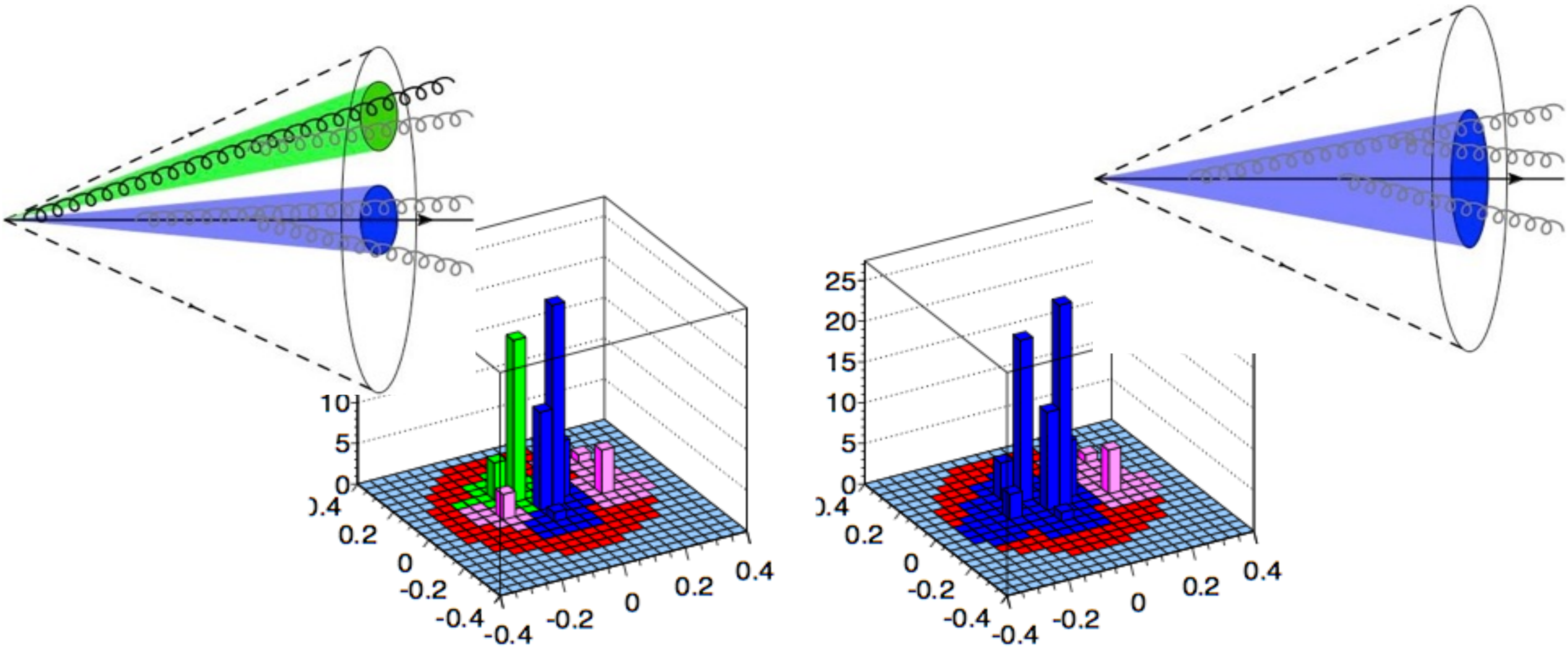


$$\Delta_\mathrm{med} \approx 1 - \exp[-\frac{1}{12} Q_s^2 r_\perp^2]$$

$r_\perp = \theta_{q\bar{q}} L$

$\mathbf{Q_s}$: characteristic momentum scale of the medium

Resolved jets



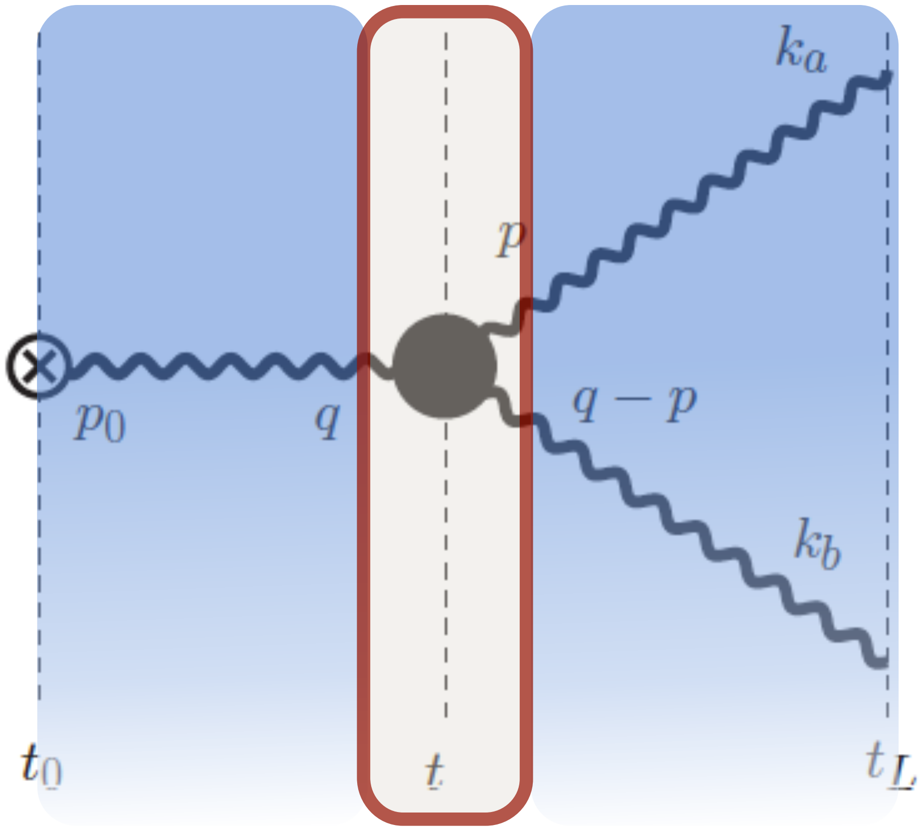
Dynamical process:

- medium resolves inner structure of the jet
- every resolved sub-jet = color current interacts incoherently with the medium

Radiation in the medium

$$\frac{d^2\sigma}{d\Omega_{k_a}\, d\Omega_{k_b}} = 2g^2 z(1-z)\int_{t_0}^{t_L} \mathrm{d}t \int_{\boldsymbol{p}_0,\boldsymbol{q},\boldsymbol{p}} \mathcal{P}(\boldsymbol{k}_a - \boldsymbol{p}, t_L - t)\,\mathcal{P}(\boldsymbol{k}_b - \boldsymbol{q} + \boldsymbol{p}, t_L - t)$$

$$\times\, \mathcal{K}(\boldsymbol{p} - z\boldsymbol{q}, z, p_0^+, t)\,\mathcal{P}(\boldsymbol{q} - \boldsymbol{p}_0, t - t_0)\,\frac{\mathrm{d}\sigma_{hard}}{\mathrm{d}\Omega_{p_0}}\,,$$

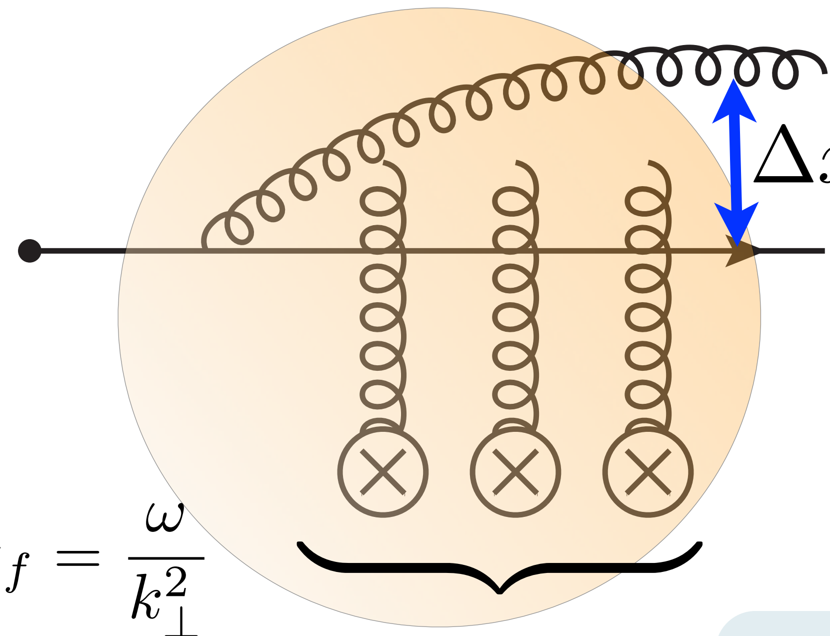


- factorization in the LPM regime
- P describes $k_\perp$-broadening
- K describes (quasi-instantaneous) emission
  → splitting function

$$\mathcal{K}(\boldsymbol{p}, z, p_0^+) = \frac{2P_A^{gC}(z)}{z(1-z)p_0^+}\sin\left(\frac{\boldsymbol{p}^2}{2k_{\rm br}^2}\right)\exp\left(-\frac{\boldsymbol{p}^2}{2k_{\rm br}^2}\right)$$

$$k_{\rm br}^2 = \sqrt{z(1-z)p_0^+\hat{q}_{\rm eff}} \qquad \hat{q}_{\rm eff} = \hat{q}\Big[(1-z)N_c - zC_R\Big]$$

Decoherence redux



$$\Delta x_\perp = k_{\rm br}^{-1}$$

$$t_f = \frac{\omega}{k_\perp^2}$$

$$t_{\rm br}$$

Longitudinal coherence induces a characteristic formation time larger than mean free path

$$\left.\begin{aligned} t_{\rm br} &= \lambda_{\rm mfp} N_{\rm coh} \\ k_{\rm br}^2 &= \mu^2 N_{\rm coh} \end{aligned}\right\} \qquad \begin{aligned} t_{\rm br} &= \sqrt{\omega/\hat{q}} \\ k_{\rm br}^2 &= \sqrt{\hat{q}\omega} \end{aligned}$$

$\lambda_{\rm mfp} \to t_{\rm br}$ :: **L**andau-**P**omeranchuk-**M**igdal effect

LPM spectrum: $$\omega \frac{dI^{\rm ind}}{d\omega} \propto \alpha_s \frac{L}{t_{\rm br}} = \alpha_s \sqrt{\frac{\hat{q}L^2}{\omega}} \qquad \omega \ll \omega_c$$

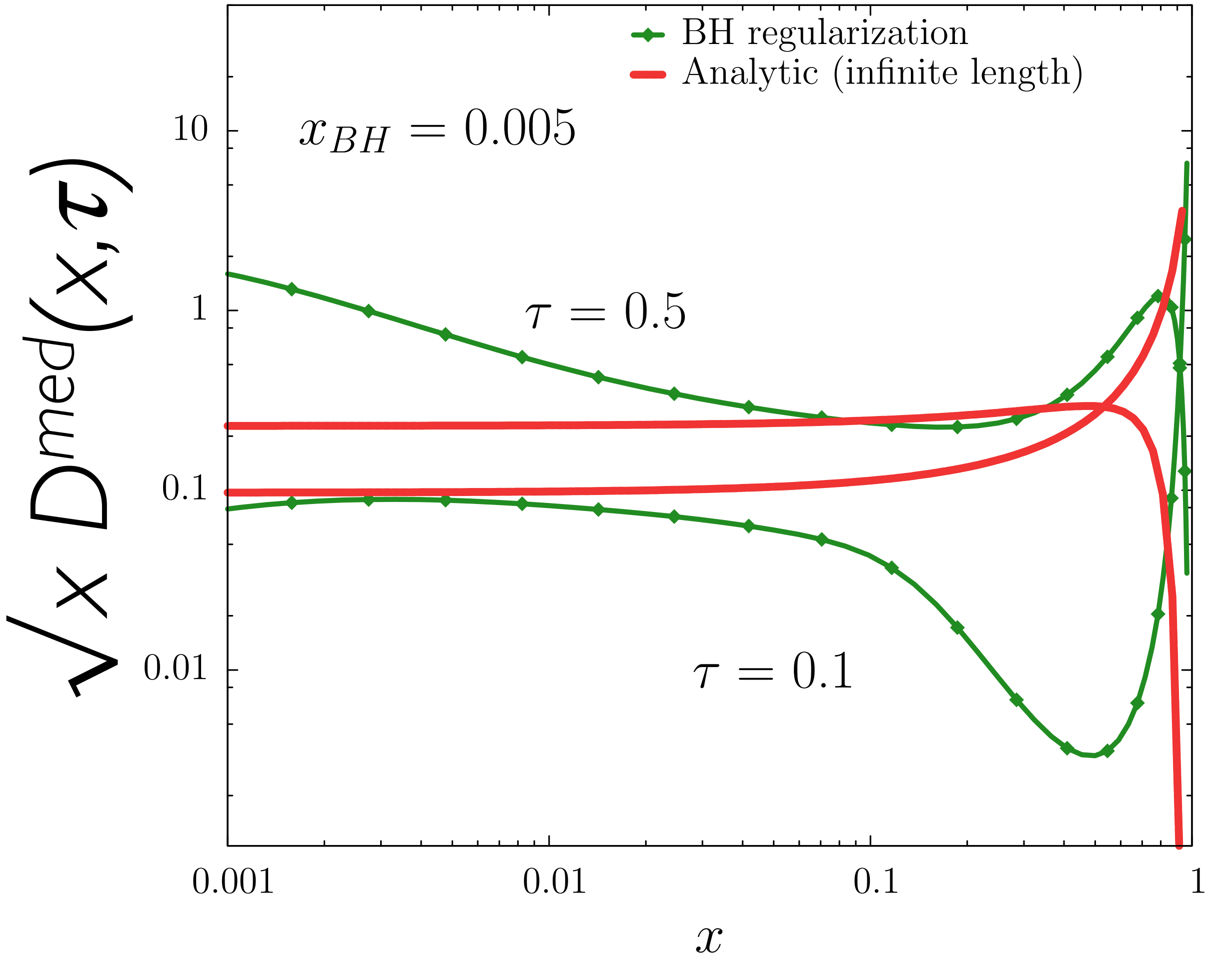
Mean energy loss: $$\Delta E = \int_0^\infty \omega \frac{dI^{\rm ind}}{d\omega} \propto \alpha_s C_R \omega_c \qquad \omega_c = \frac{1}{2}\hat{q}L^2$$

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000), Zakharov (1996), Wiedemann (2000), Gyulassy, Levai, Vitev (2000), Arnold, Moore, Yaffe (2001)

Rate equation

$$\frac{\partial}{\partial L} D_i^{\rm med}(x,p_\perp,L) = \int_0^1 {\rm d}z\, \mathcal{K}_{ij}\left(z, \frac{x}{z}p_\perp; L\right) \times \left[D_j^{\rm med}\left(\frac{x}{z}, p_\perp, L\right) - z\, D_j^{\rm med}(x,p_\perp,L)\right]$$

Distribution of energy in "time": $\tau = \frac{\alpha_s N_c}{\pi}\sqrt{\frac{\hat{q}L^2}{E}}$

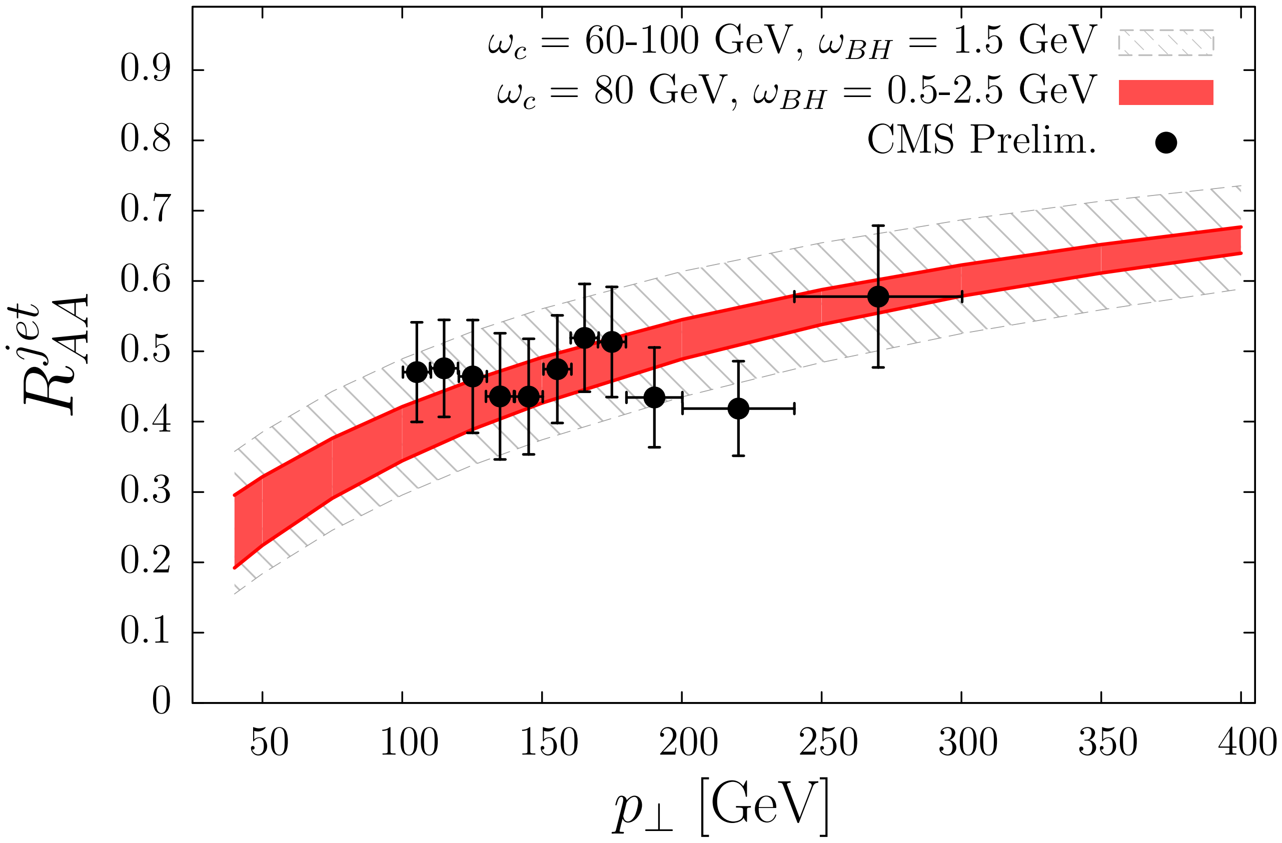


- $D_q(0)=\delta(1-x)$ and $D_g(0)=0$
- probabilistic interpretation
- turbulent flow: no intrinsic accumulation of energy
- effective in transporting sizable energy to large angles

Jeon, Moore hep-ph/0309332; Baier, Mueller, Schiff, Son hep-ph/0009237; Blaizot, Iancu, Mehtar-Tani 1301.6102

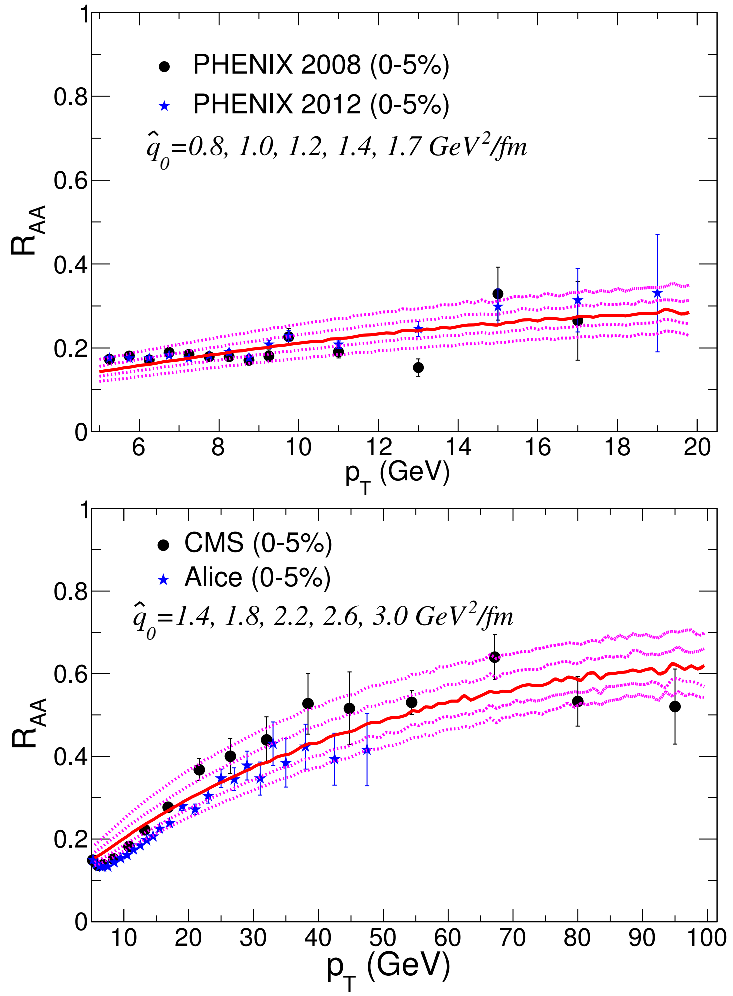
Jet quenching

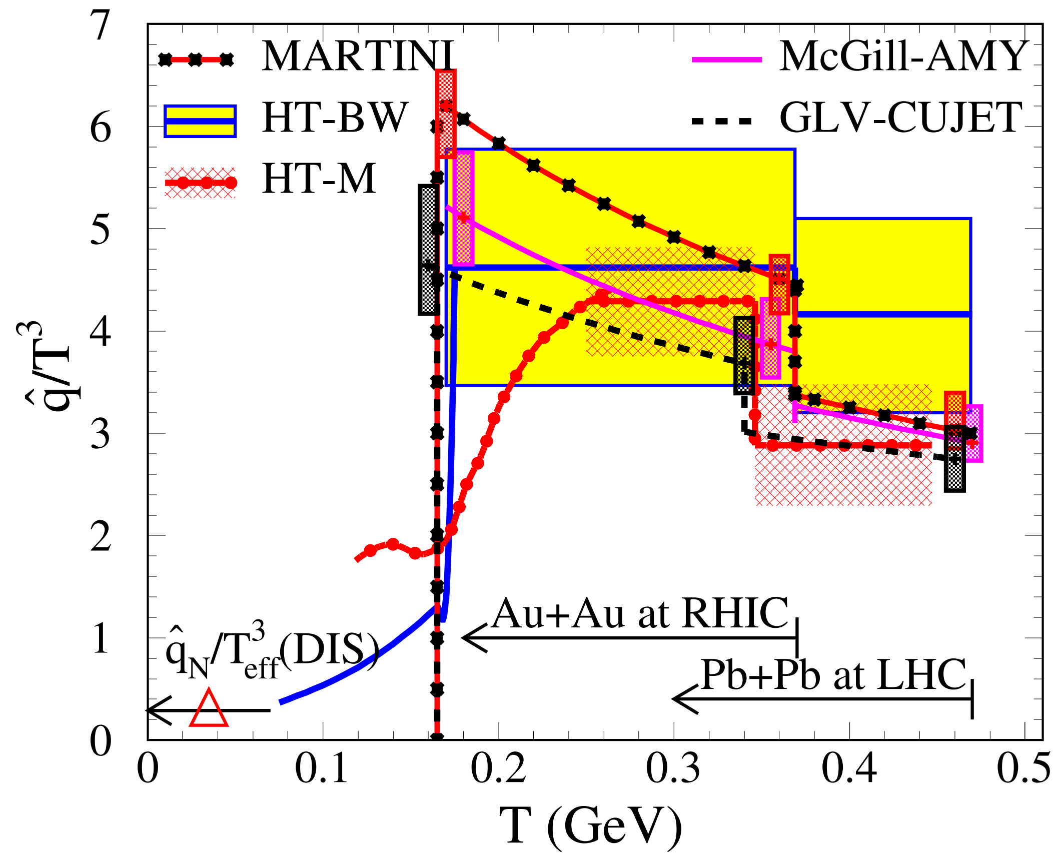
$$\frac{\mathrm{d}^2 N^{\mathrm{jet}}_{\text{Pb-Pb}}(p_\perp)}{T_{\mathrm{AA}}\,\mathrm{d}^2 p_\perp} \simeq \int_0^1 \frac{\mathrm{d}x}{x} D_q^{\mathrm{med}}\left(x, \frac{p_\perp}{x}, L\right) \frac{\mathrm{d}^2\sigma^{\mathrm{jet}}_{\text{p-p}}\left(\frac{p_\perp}{x}\right)}{\mathrm{d}^2 p_\perp}$$



- assuming the jet is not resolved by the medium
- two medium parameters (q̂ and the mean free path) + geometry
- first step — improvements needed to study jet substructure

Extraction of q̂





Attempt at making a systematical comparison — still many caveats!

Within errors, a decreasing trend with T/collision energy — similar trend for $1/\eta$!

Summary: quenched jets

- jets are excellent tools to study the QGP — vacuum baseline under control
- involves dynamical processes: fragmentation — resolution — radiation
- still many improvements to be made!