Flow excited by full jet shower in QGP fluid and its effect on jet shape

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Central China Normal University

in collaboration with Ning-Bo Chang, Guang-You Qin

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華中師範大學

Jet quenching in QGP medium

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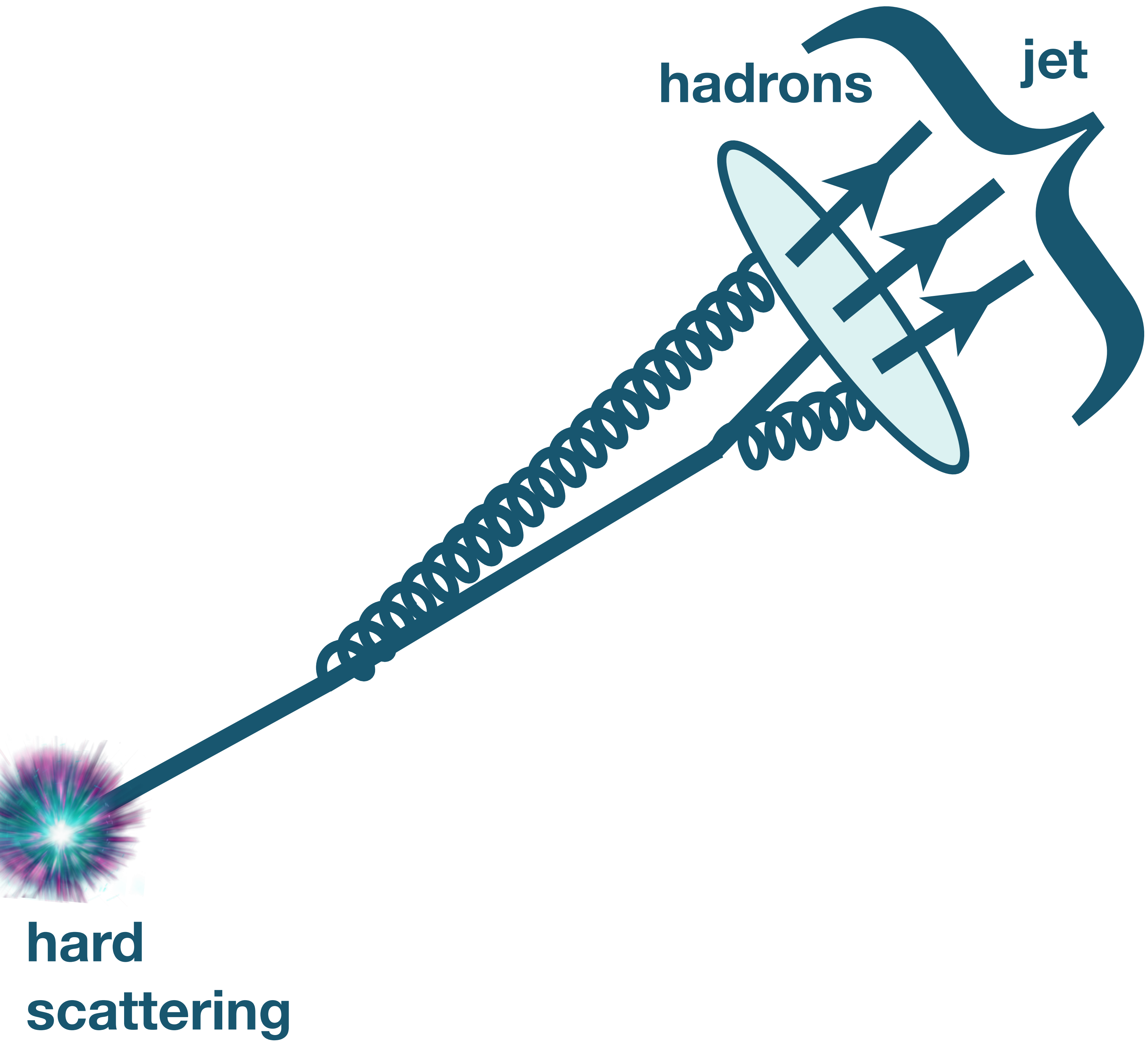

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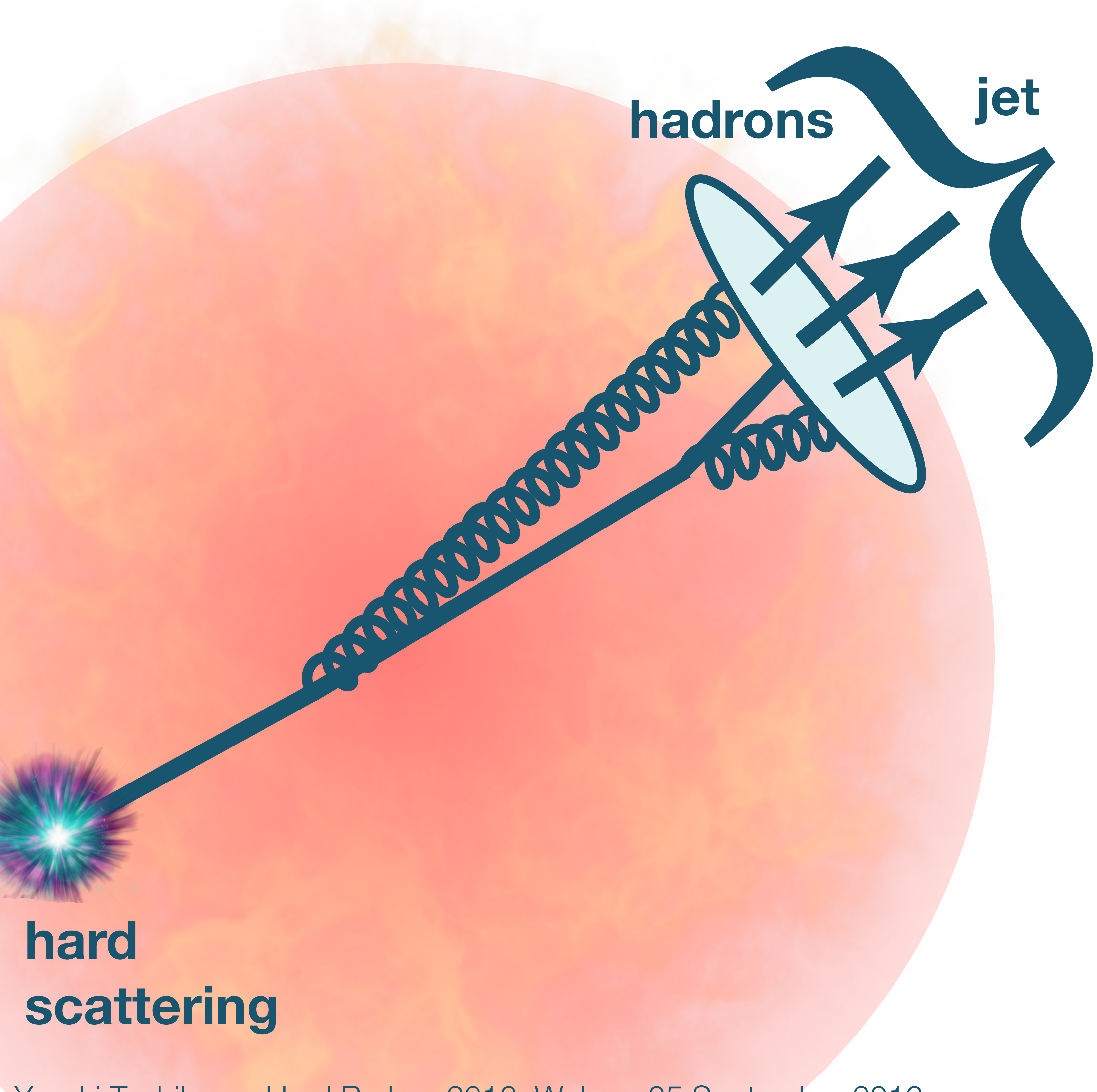

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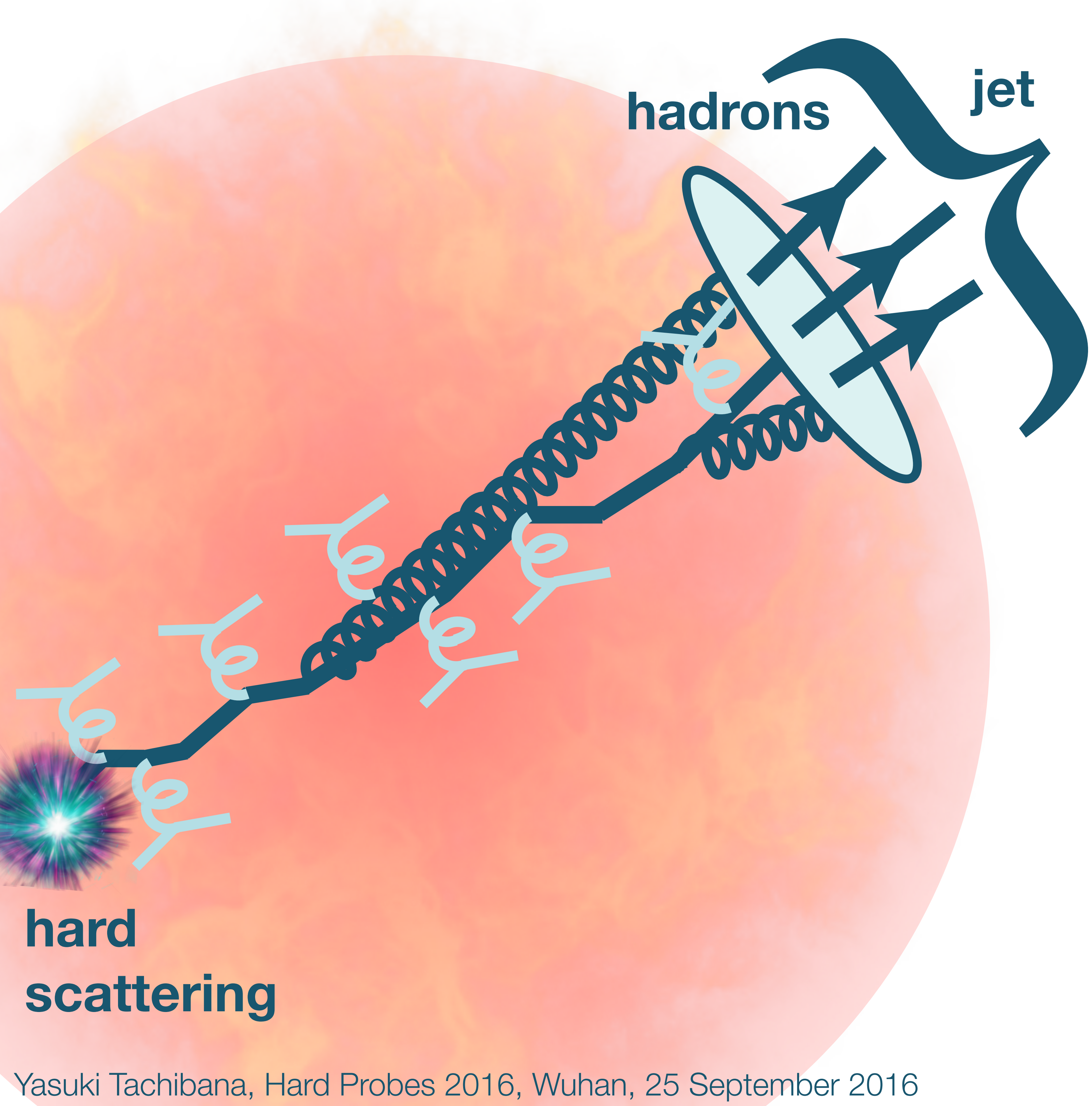

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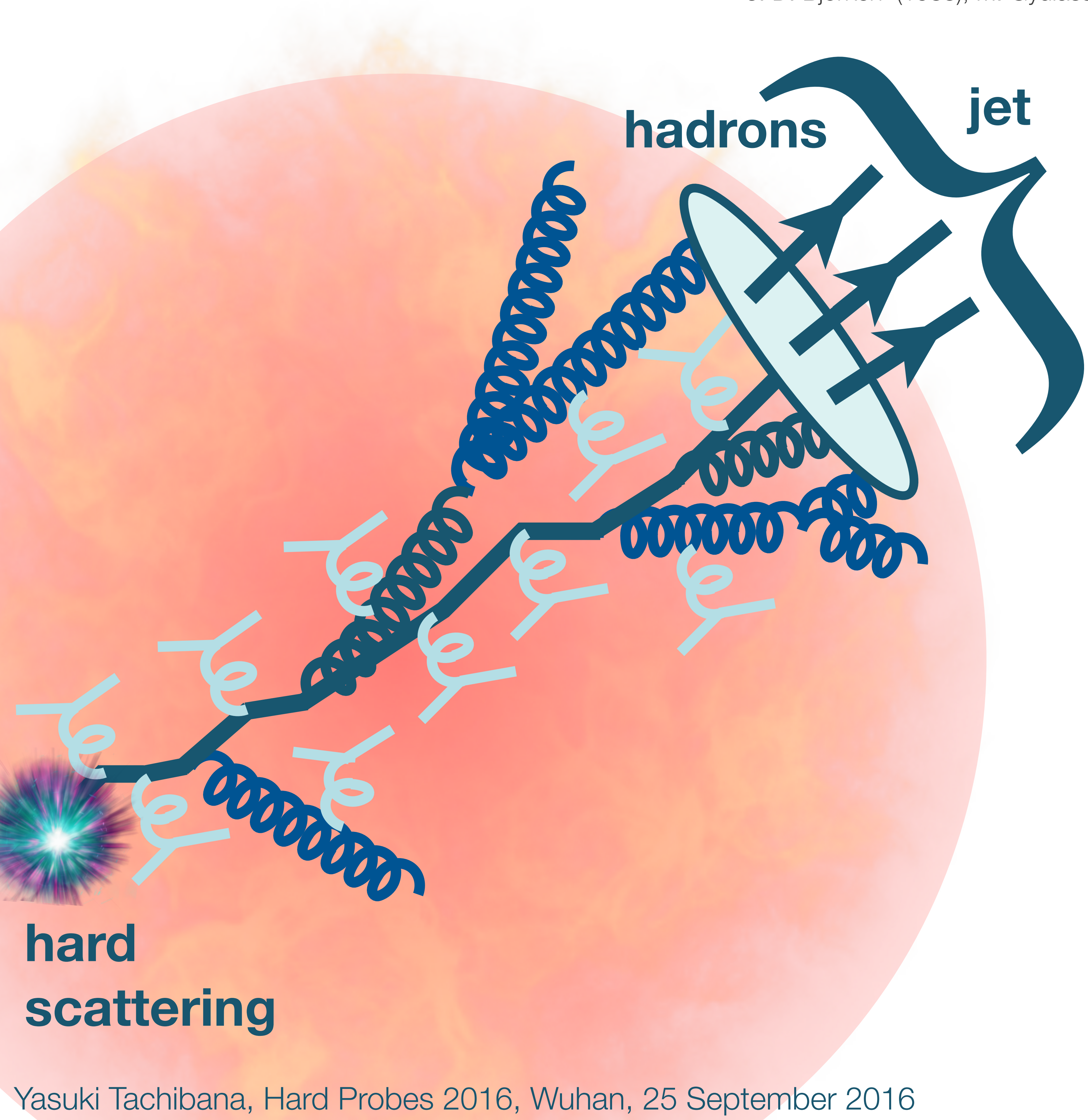

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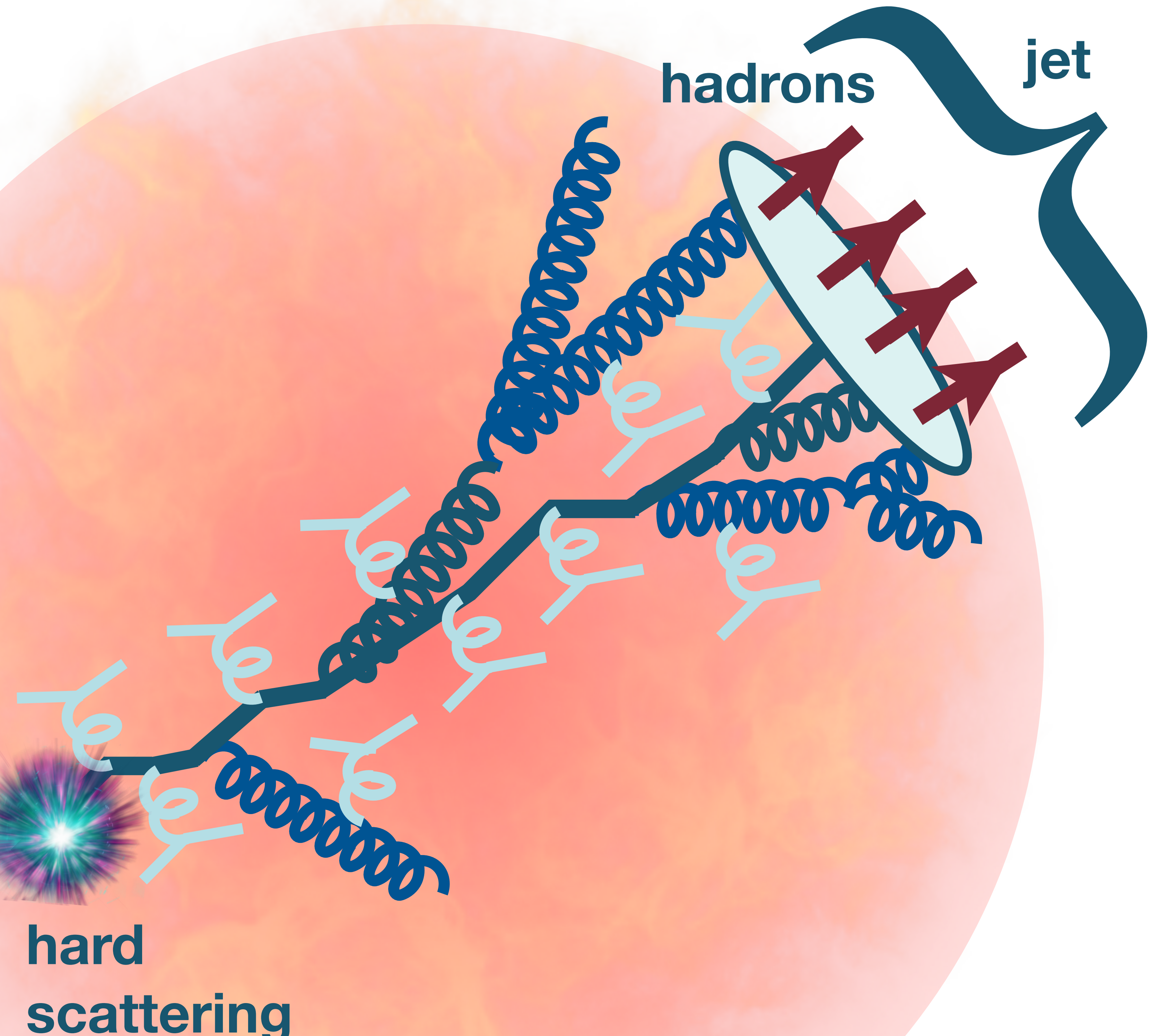

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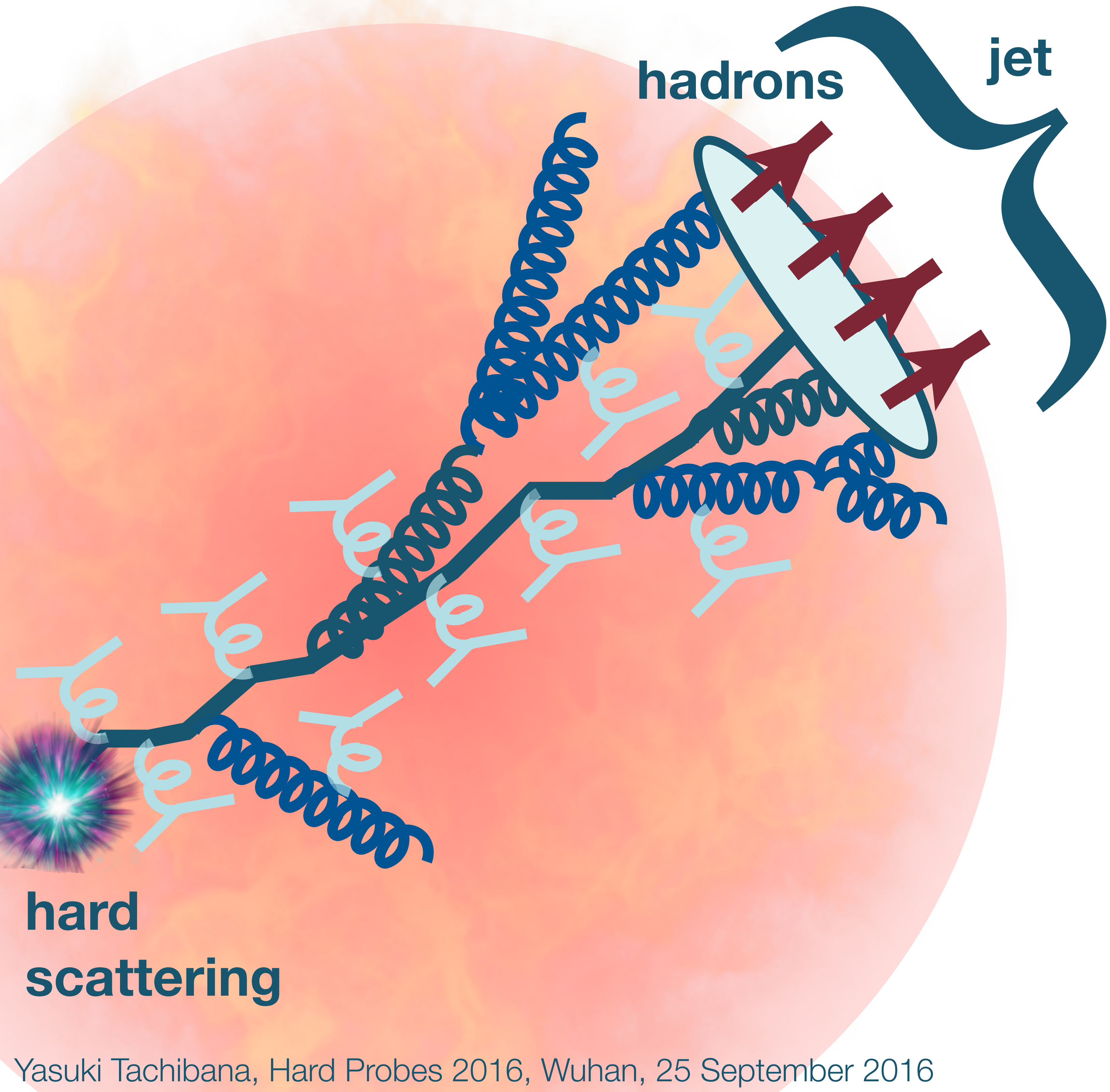
Jet energy loss
Modification of jet structure

Medium response to jet quenching

H. Stöcker ('05), J. Casalderrey-Solana, E. Shuryak, D. Teaney ('05),…



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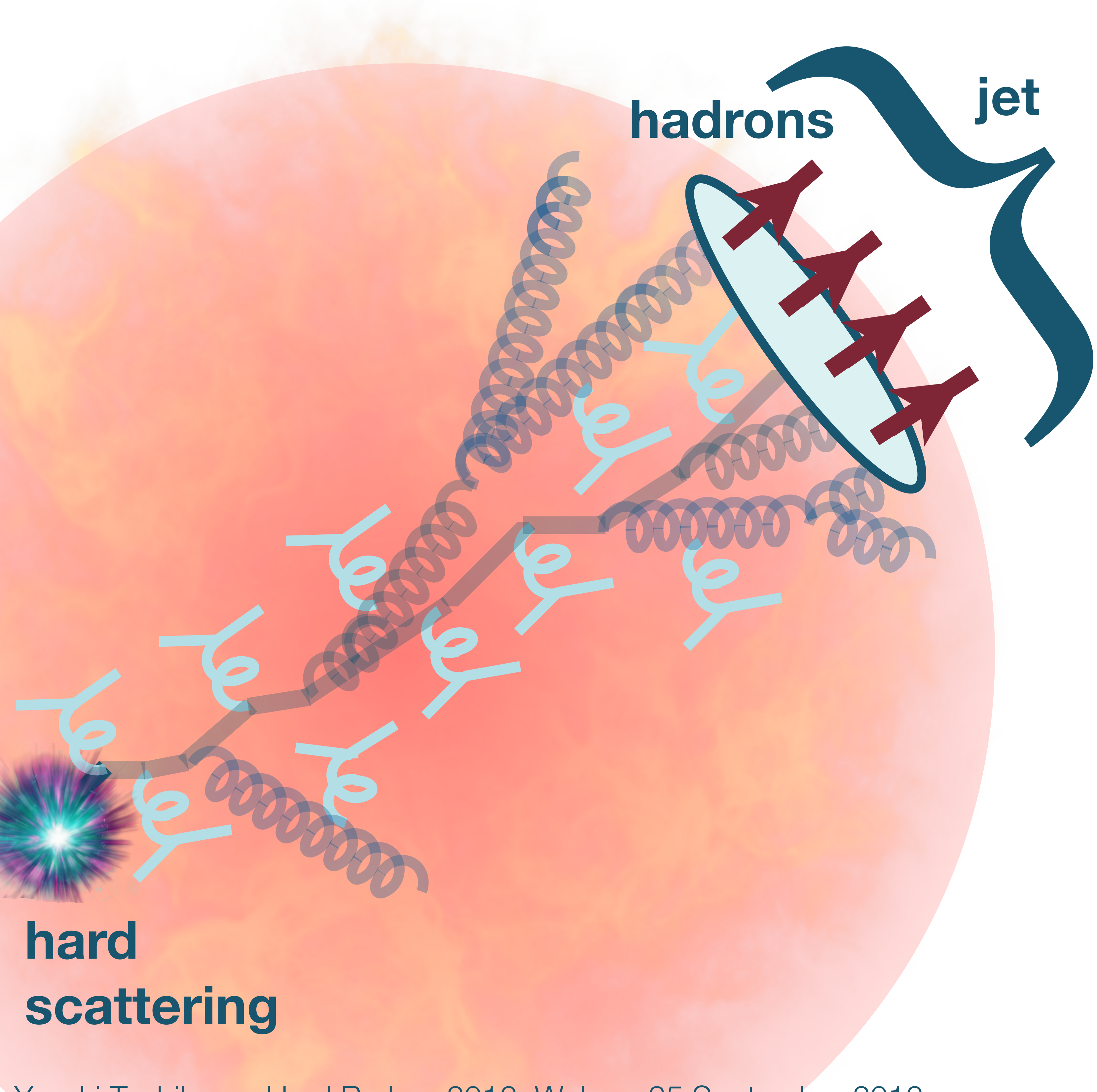

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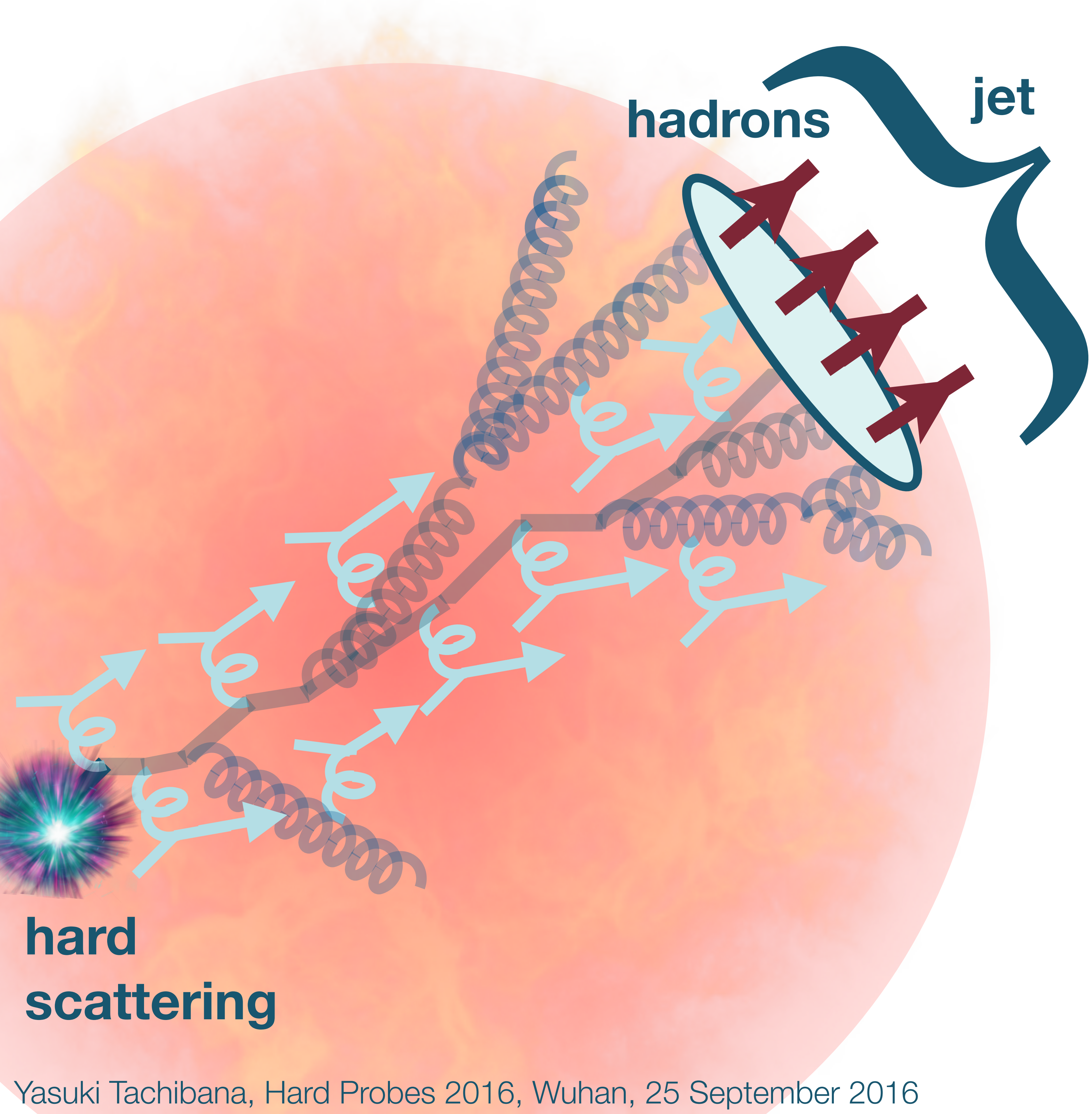

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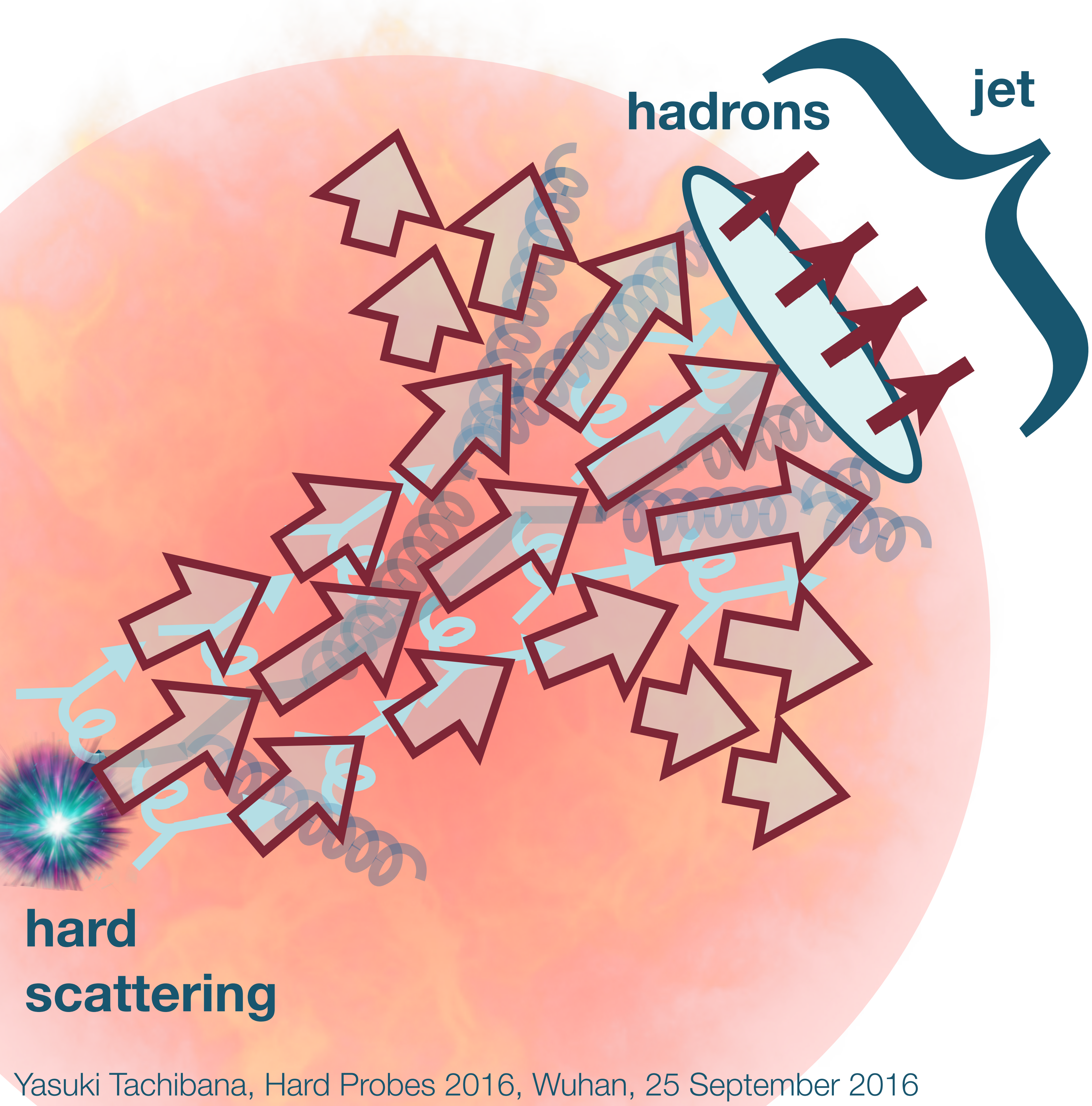

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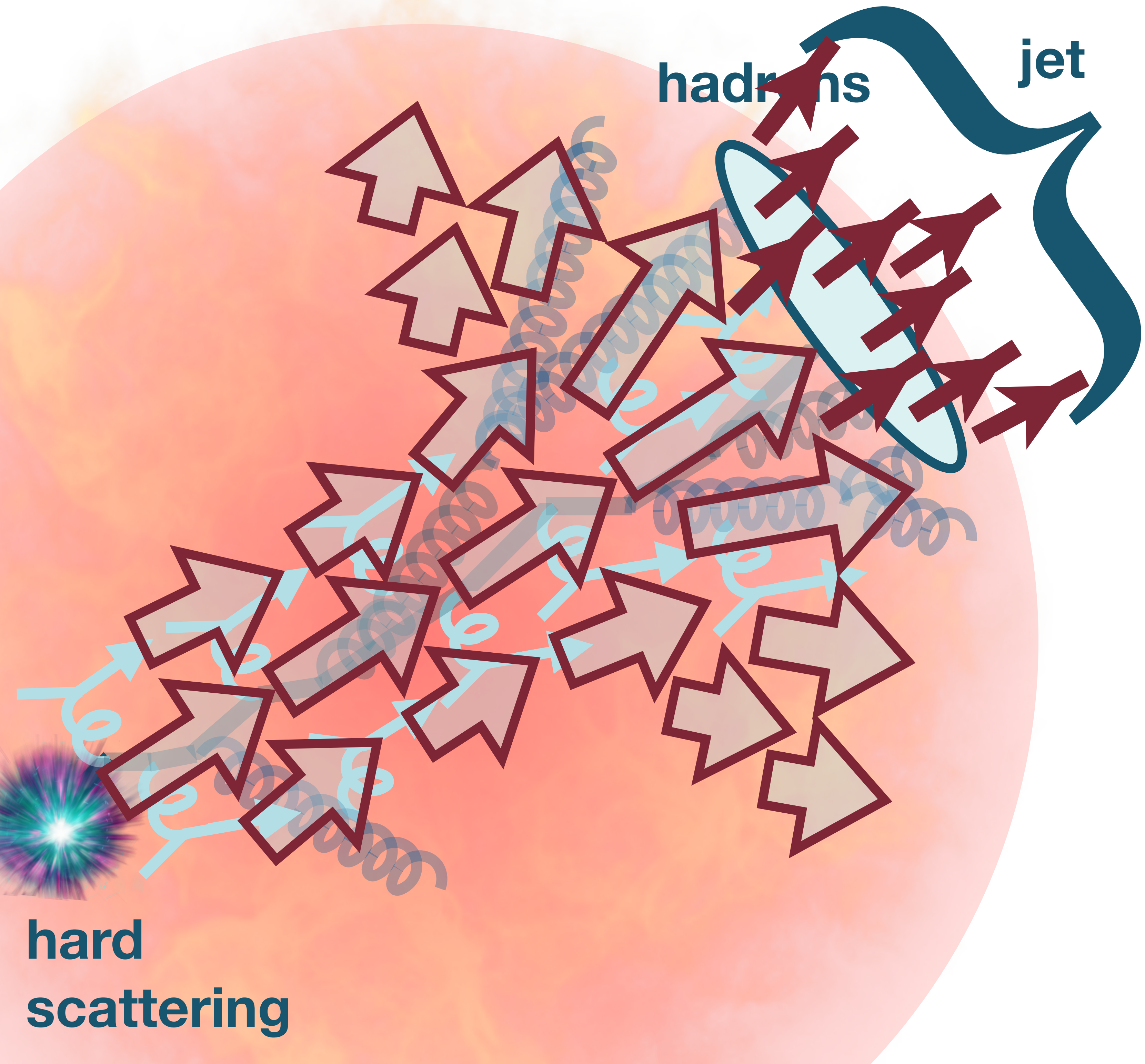

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Enhancement of particle emission from medium

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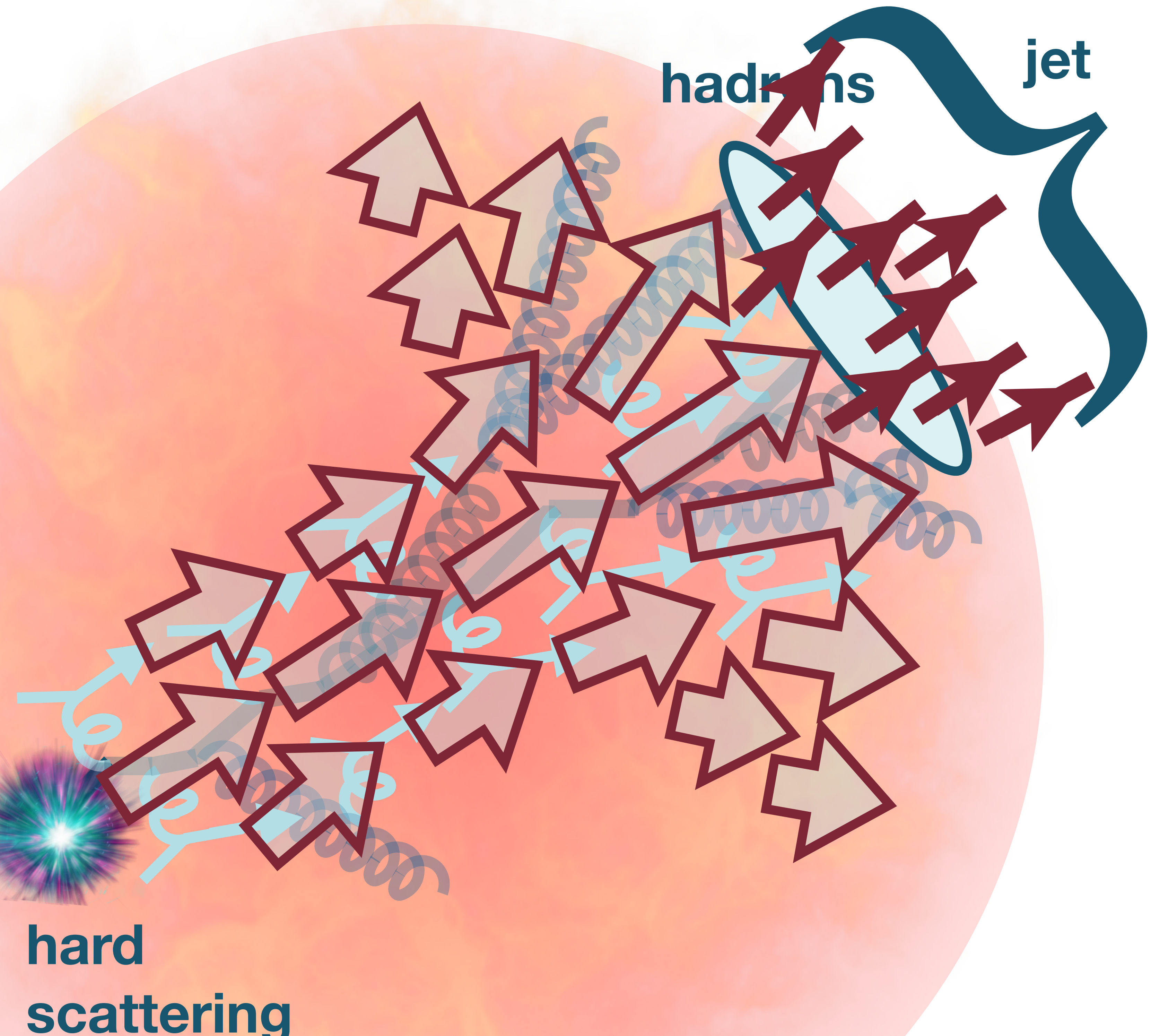


- **Energy-momentum deposition**
  - induced flow in QGP fluid

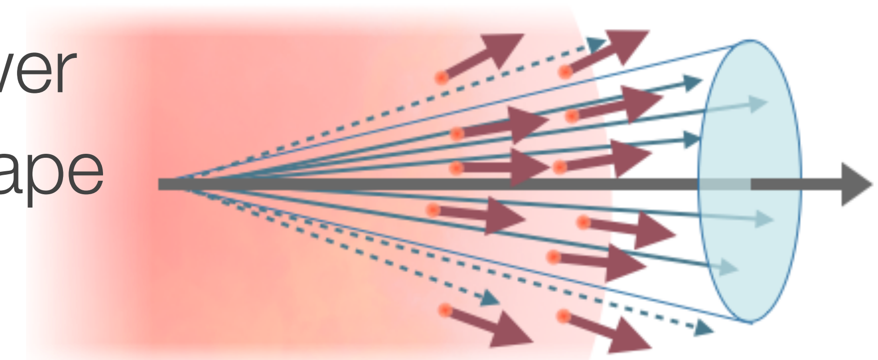
Enhancement of particle emission from medium

Further modification

Jet energy loss
Modification of jet structure

Motivation

- **Purpose**
  - Flow induced as medium response to jet shower
  - Medium contribution to jet energy loss and shape



- **Method**
  - Describe both jet shower and medium evolution
  - Interaction between them

→ Jet shower transport equation
\+
Hydrodynamic equation with source term

- **Other works about jet with medium response**

B. Betz, J. Noronha, G. Torrieri, M. Gyulassy, I. Mishustin, D. H. Rischke ('09), G.-Y. Qin, A. Majumder, H. Song, U. Heinz ('09), R. B. Neufeld, B. Muller ('10), R. B. Neufeld, T. Renk ('10), H. Li, F. Liu, G.-L. Ma, X.-N. Wang, Y. Zhu ('11), R. B. Neufeld, I. Vitev ('12), X.-N. Wang, Y. Zhu ('13), YT, T. Hirano ('14, '16), R. P. G. Andrade, J. Noronha, G. S. Denicol ('14), M. Schulc, B. Tomášik ('14), S. Floerchinger, K. C. Zapp ('14), Y. He, T. Luo, X.-N. Wang, Y. Zhu ('15), S. Cao, T. Luo, G.-Y. Qin and X.-N. Wang ('16), J. Casalderrey-Solana, D. C. Gulhan, J. G. Milhano, D. Pablos,K. Rajagopal ('16),…

Linearized Boltzmann Transport (LBT) Model — T. Luo (Saturday), SS. Cao (Saturday)

LBT + Hydro Model — W. Chen (Saturday)

Hybrid Strong/Weak Coupling Model by D. Pablos (Saturday), JEWEL by R. Kunnawalkam Elayavalli (Saturday), Multi-phase Transport Model by G.-L. Ma (Saturday), Linearized Hydro w/ Source Term by A. Ayala (Sunday)

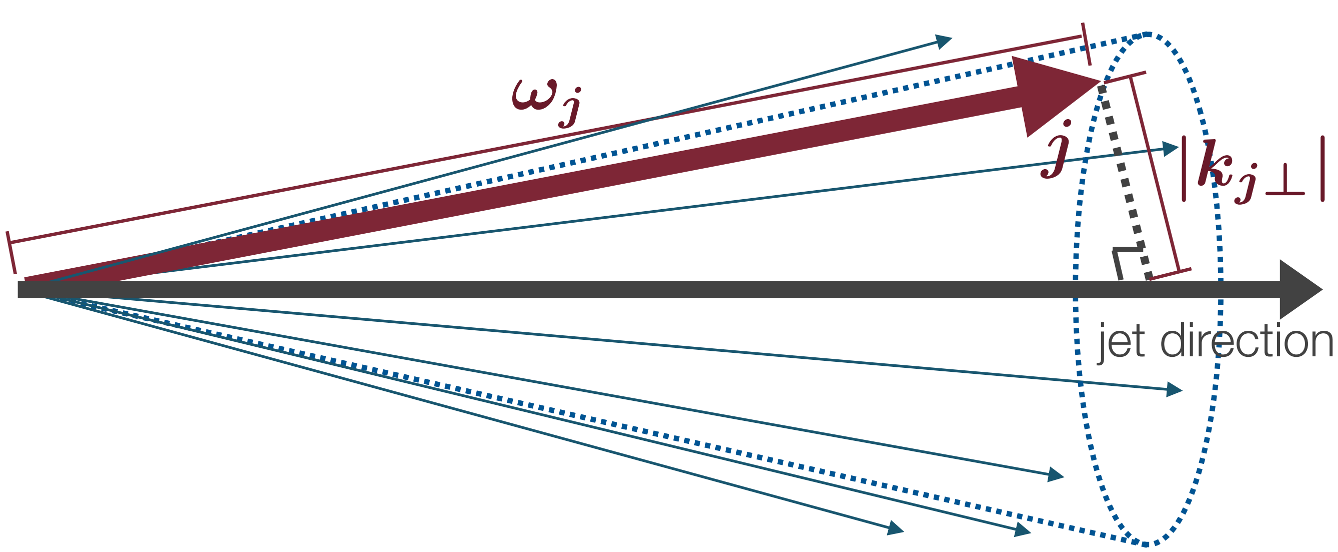
Full jet shower evolution

N.-B. Chang and G.-Y. Qin, Phys. Rev. C **94**, no. 2, 024902 (2016)

- **Transport equations for all partons in jet shower**
  - evolution of energy and transverse momentum distributions, $f_j(\omega_j, k_{j\perp}^2, t)$

(j: parton species)

$$\frac{df_j(\omega_j, k_{j\perp}^2, t)}{dt} = \hat{e}_j \frac{\partial f_j(\omega_j, k_{j\perp}^2, t)}{\partial \omega_j} + \frac{1}{4}\hat{q}_j \nabla_{k_\perp}^2 f_j(\omega_j, k_{j\perp}^2, t) + \sum_i \int d\omega_i dk_{i\perp}^2 \left[\frac{d\tilde{\Gamma}_{i\to j}(\omega_j, k_{j\perp}^2|\omega_i, k_{i\perp}^2)}{d\omega_j d^2k_{j\perp} dt} f_i(\omega_i, k_{i\perp}^2, t) - \frac{d\tilde{\Gamma}_{j\to i}(\omega_i, k_{i\perp}^2|\omega_j, k_{j\perp}^2)}{d\omega_i d^2k_{i\perp} dt} f_j(\omega_j, k_{j\perp}^2, t)\right]$$



$$\hat{e}_j = \frac{\hat{q}_j}{4T}$$

$$\frac{d\tilde{\Gamma}_{j\to i}(\omega_i, k_{i\perp}^2|\omega_j, 0)}{d\omega_i dk_{i\perp}^2 dt} = \frac{2\alpha_s}{\pi} \frac{xP_{j\to i}(x)\hat{q}_j(t)}{\omega k_{i\perp}^4} \sin^2\left(\frac{t-t_0}{2\tau_f}\right)$$

($P_{j\to i}(x=\omega_j/\omega_i)$: vacuum splitting function)

Initial jet profiles are generated by PYTHIA

N.-B. Chang (**NEXT** talk)

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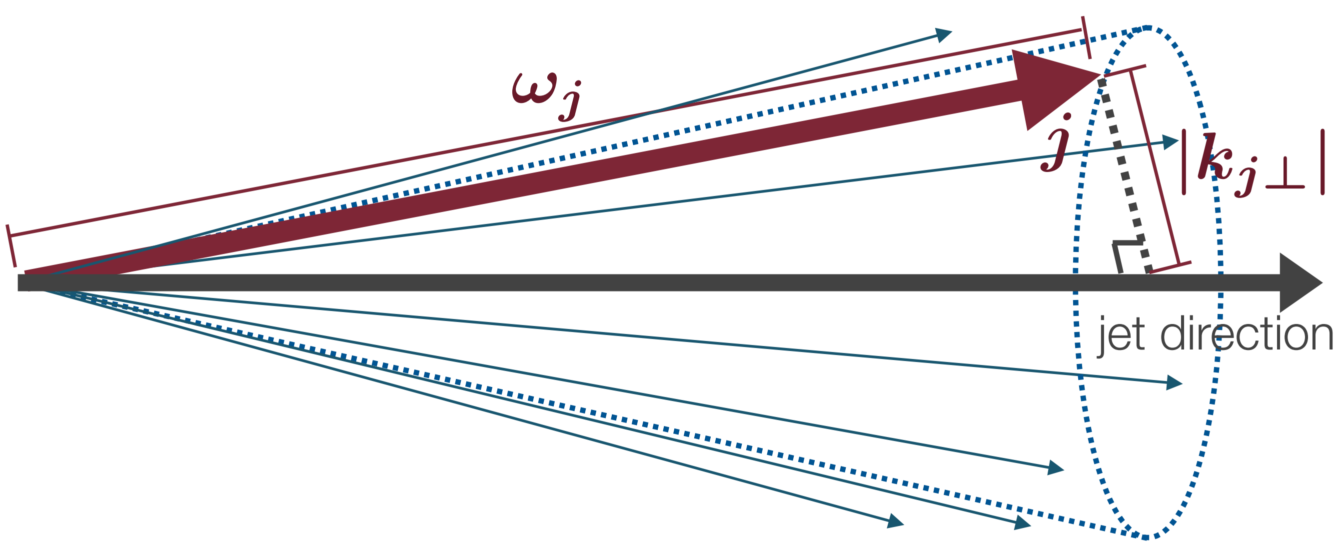
collisional energy loss (longitudinal)

$$+ \frac{1}{4}\hat{q}_j \nabla_{k_\perp}^2 f_j(\omega_j, k_{j\perp}^2, t)$$

momentum broadening (transverse)

$$+ \sum_i \int d\omega_i dk_{i\perp}^2 \left[\frac{d\tilde{\Gamma}_{i\to j}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2)}{d\omega_j d^2k_{j\perp} dt} f_i(\omega_i, k_{i\perp}^2, t) - \frac{d\tilde{\Gamma}_{j\to i}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2)}{d\omega_i d^2k_{i\perp} dt} f_j(\omega_j, k_{j\perp}^2, t) \right]$$



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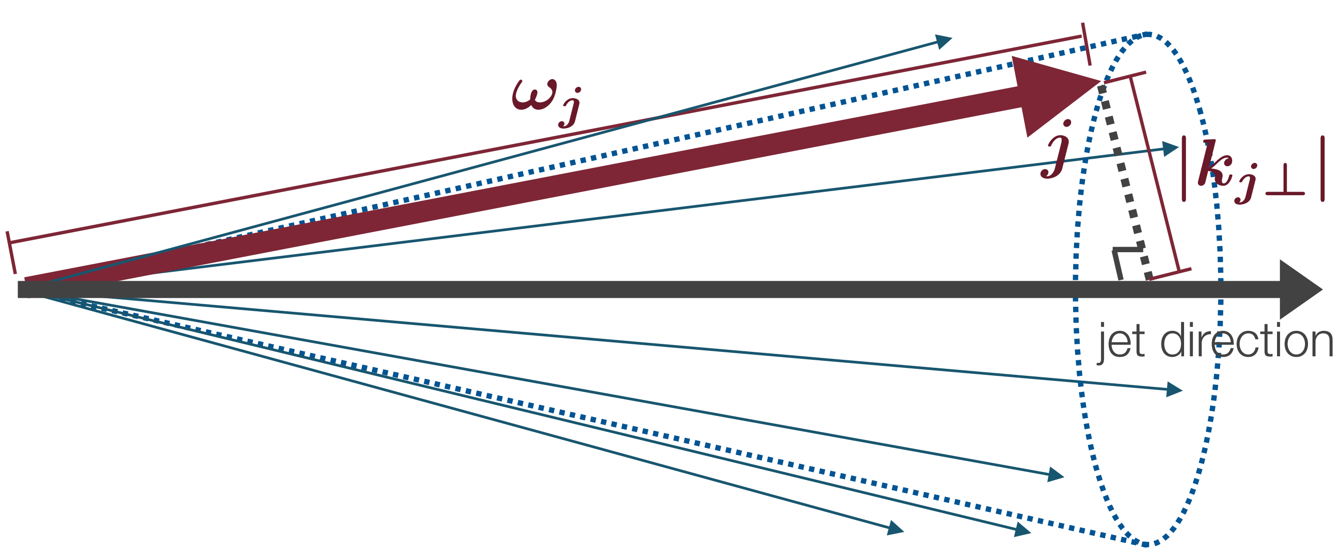
medium-induced radiation



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Initial jet profiles are generated by PYTHIA

N.-B. Chang (**NEXT** talk)

Space-time evolution of QGP medium

- **Hydrodynamic equation with source term**
  - describe hydrodynamic response to jet and background expansion

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

Energy-momentum tensor of the QGP fluid

Energy and momentum deposited from the jet

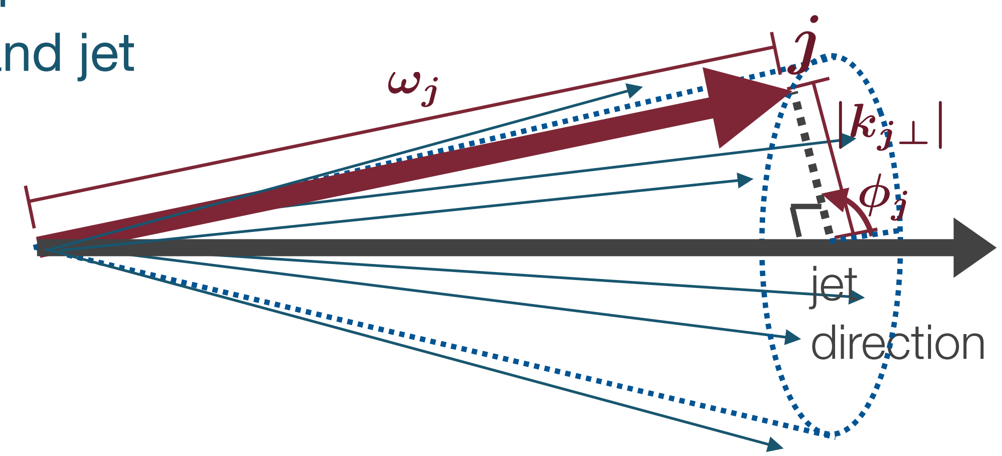
- **Source term**

$$J^\nu(x) = \sum_j \int \frac{d\omega_j dk_{j\perp}^2 d\phi_j}{2\pi} k_j^\nu \left.\frac{df_j(\omega_j, k_{j\perp}^2)}{dt}\right|_{\hat{e},\hat{q}} \delta^{(3)}(\boldsymbol{x} - \boldsymbol{x}_j(k,t))$$

momentum transfer between medium and jet

$$\left.\frac{df_j(\omega_j, k_{j\perp}^2)}{dt}\right|_{\hat{e},\hat{q}} = \left(\hat{e}_j \frac{\partial}{\partial\omega_j} + \frac{1}{4}\hat{q}_j \nabla_{k_\perp}^2\right) f_j(\omega_j, k_{j\perp}^2, t)$$

$$\boldsymbol{x}_j(k,t) = \boldsymbol{x}_0^{\text{jet}} + \frac{\boldsymbol{k}_j}{\omega_j} t$$

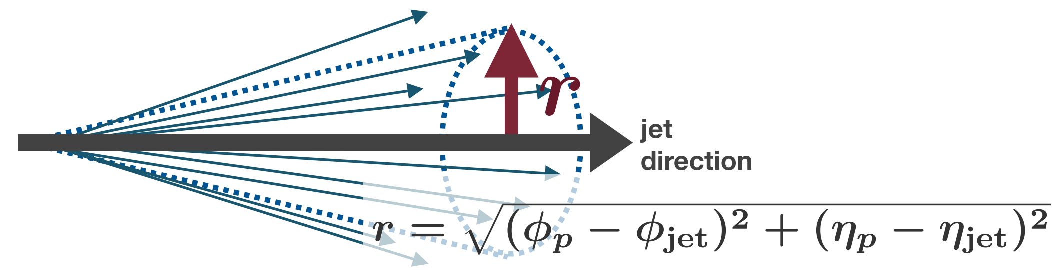


Assumption

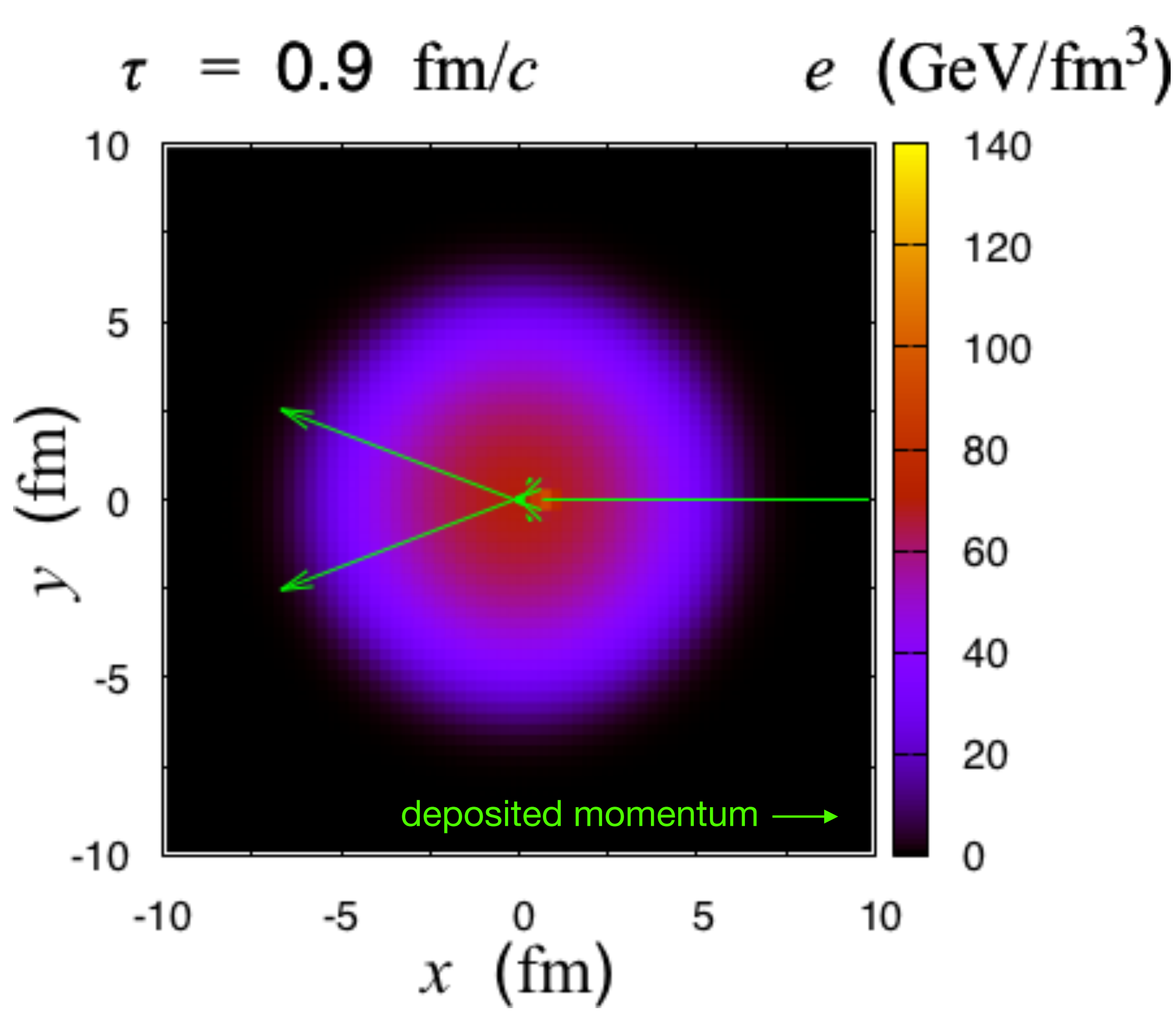
Instantaneous local thermalization of deposited energy and momentum

Flow in QGP fluid induced by jet shower

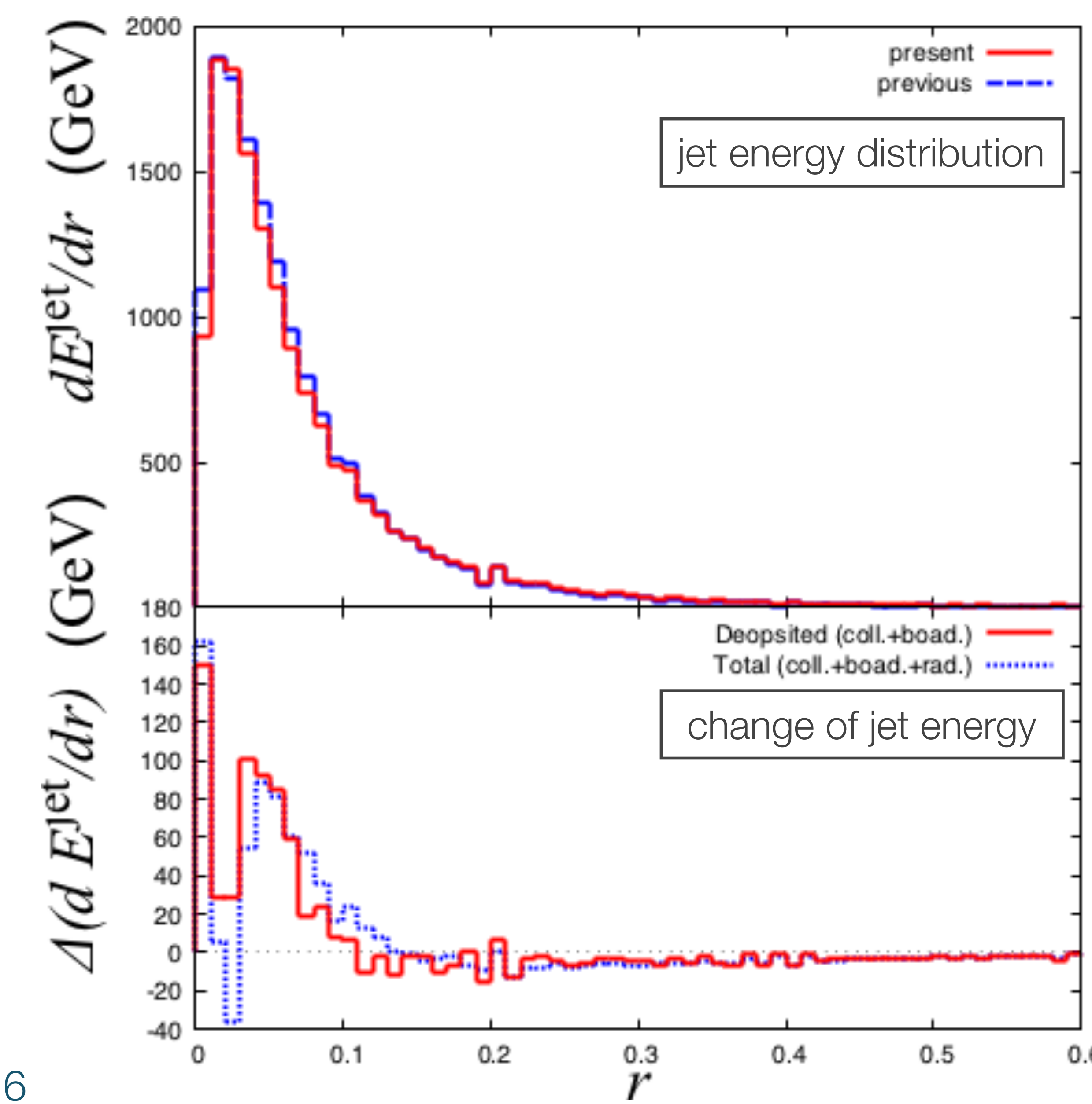
- **(3+1)-D ideal hydro**
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$
  - EoS from lattice QCD
- **Evolution of medium and jet shower**



medium energy density



Inital jet energy: 120 GeV



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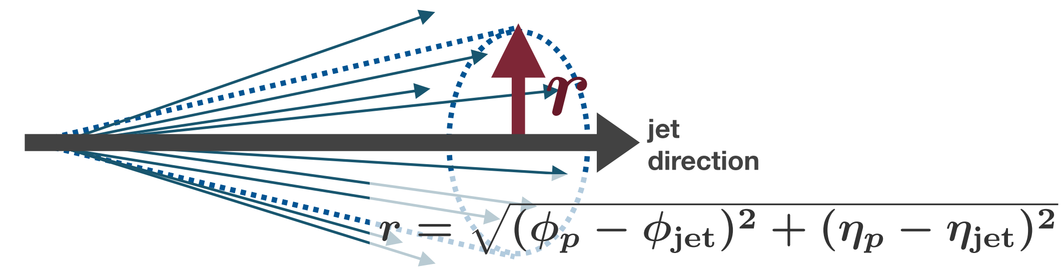

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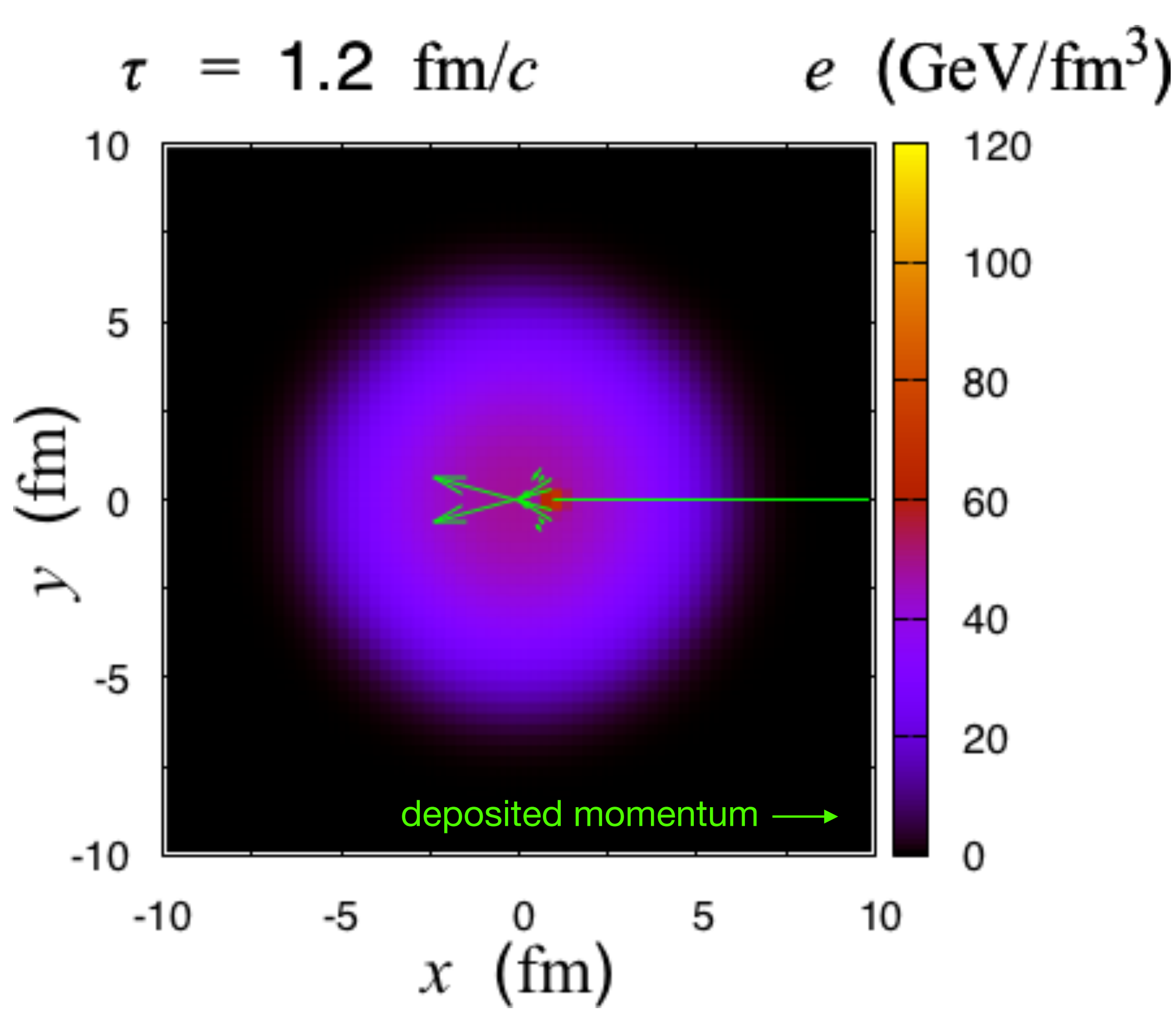

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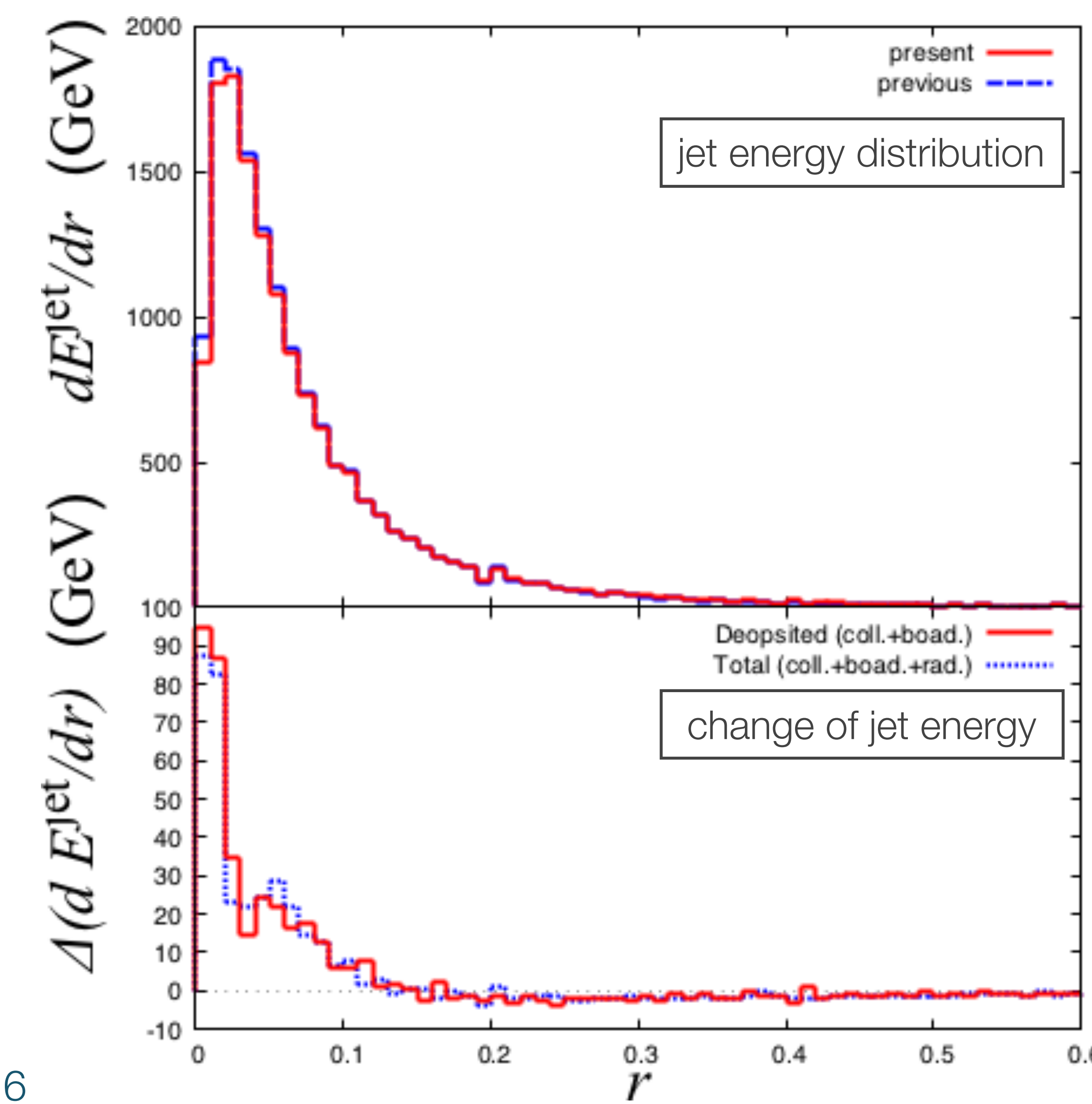

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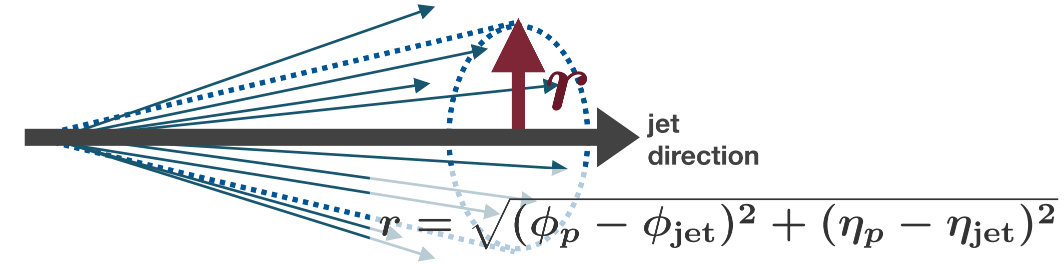

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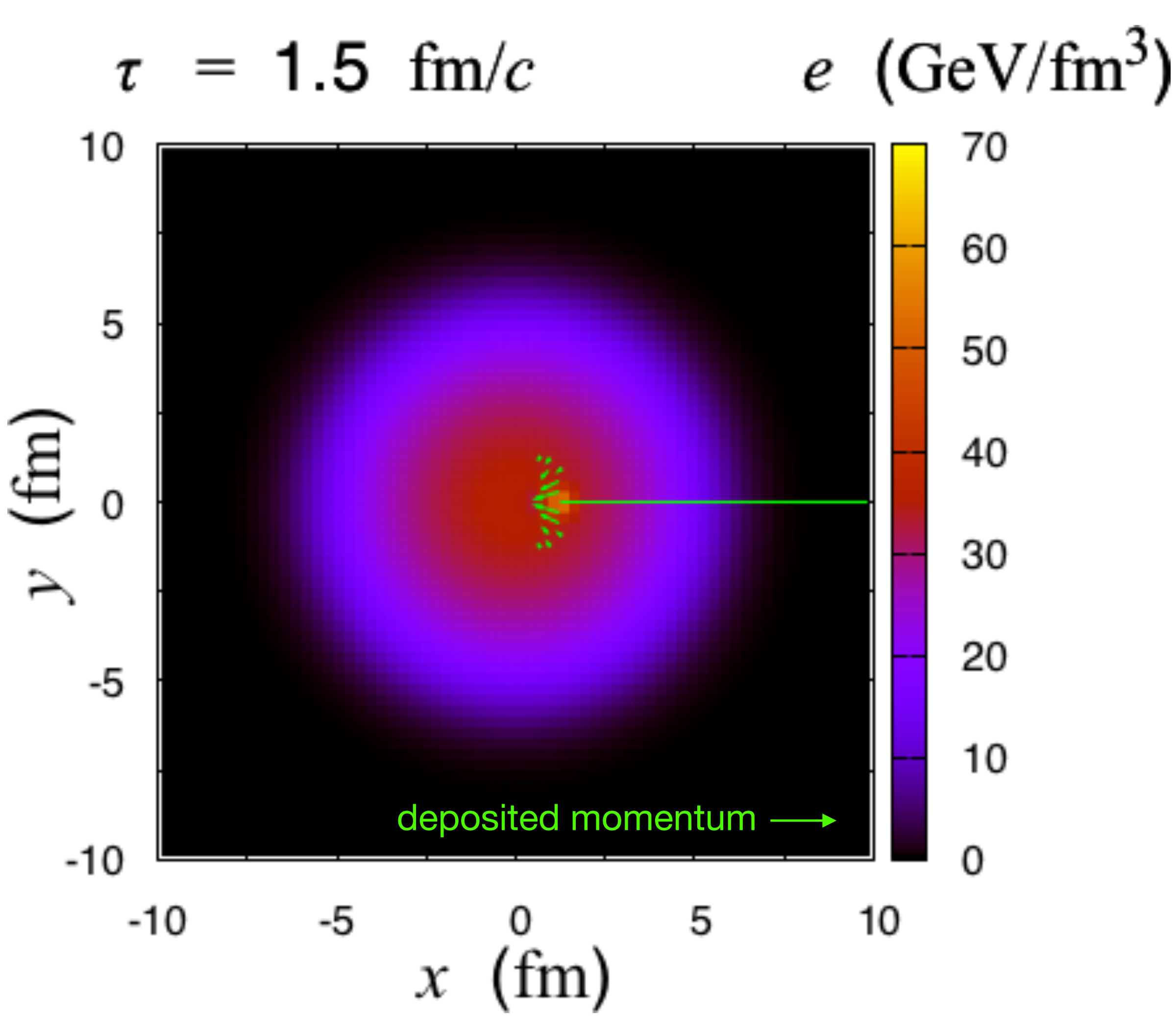

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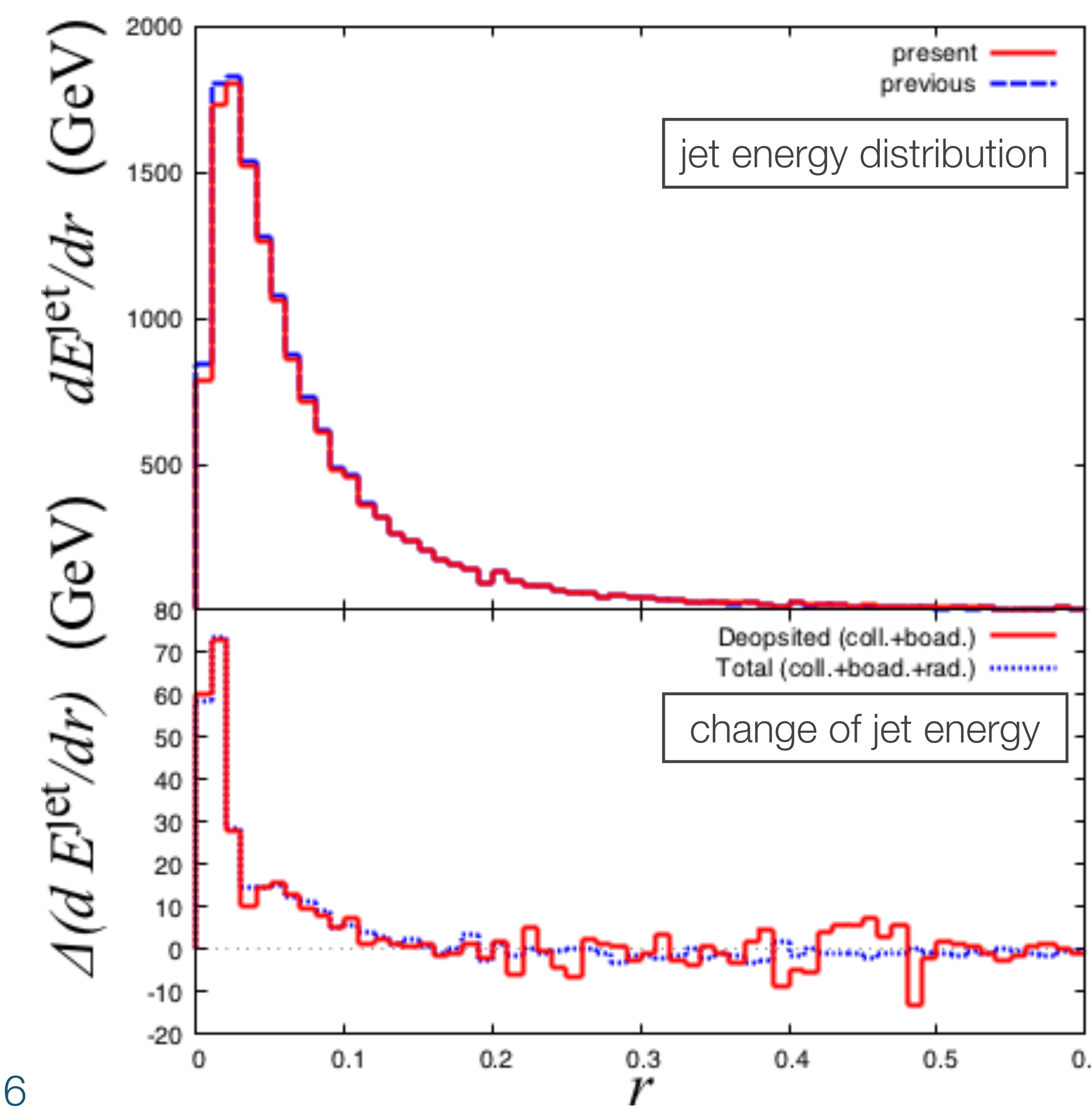

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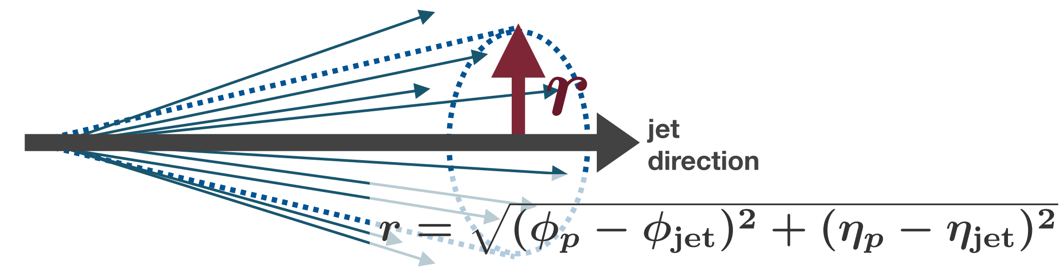

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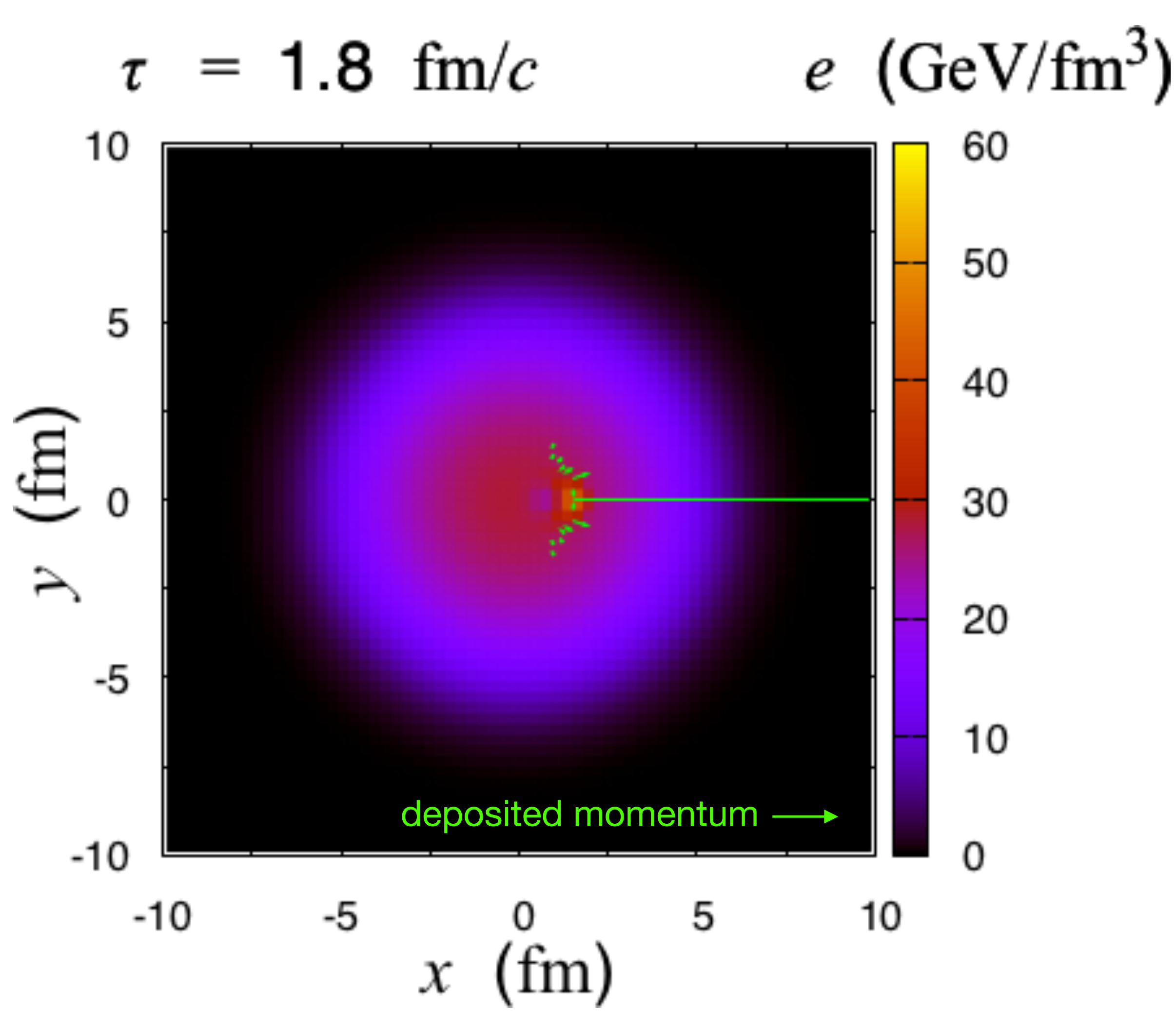

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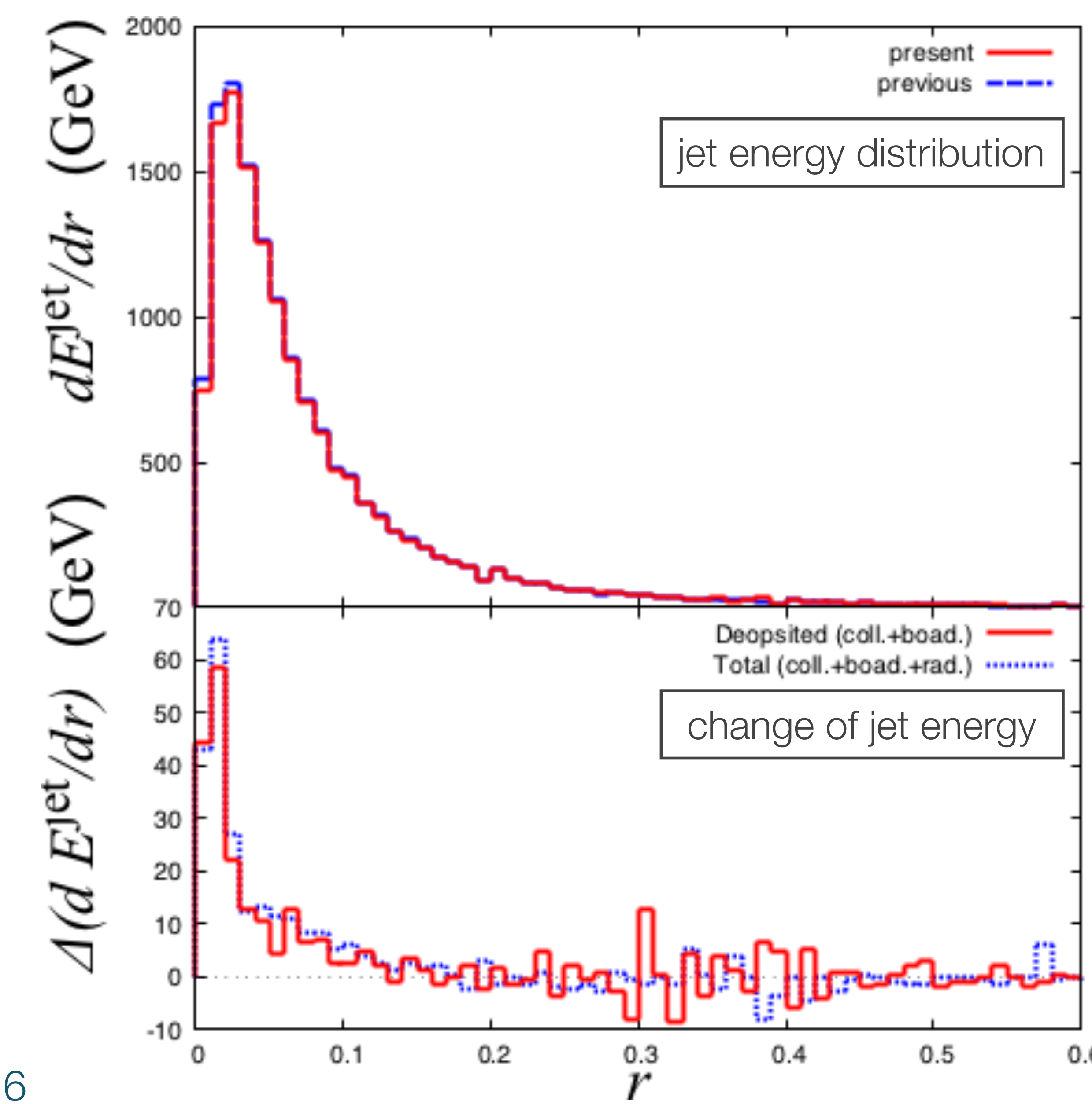

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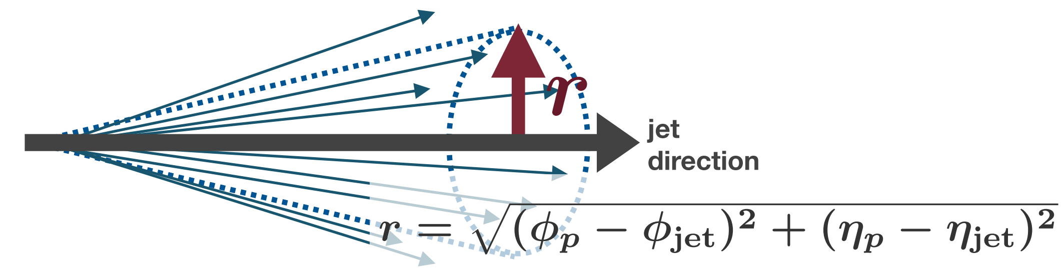

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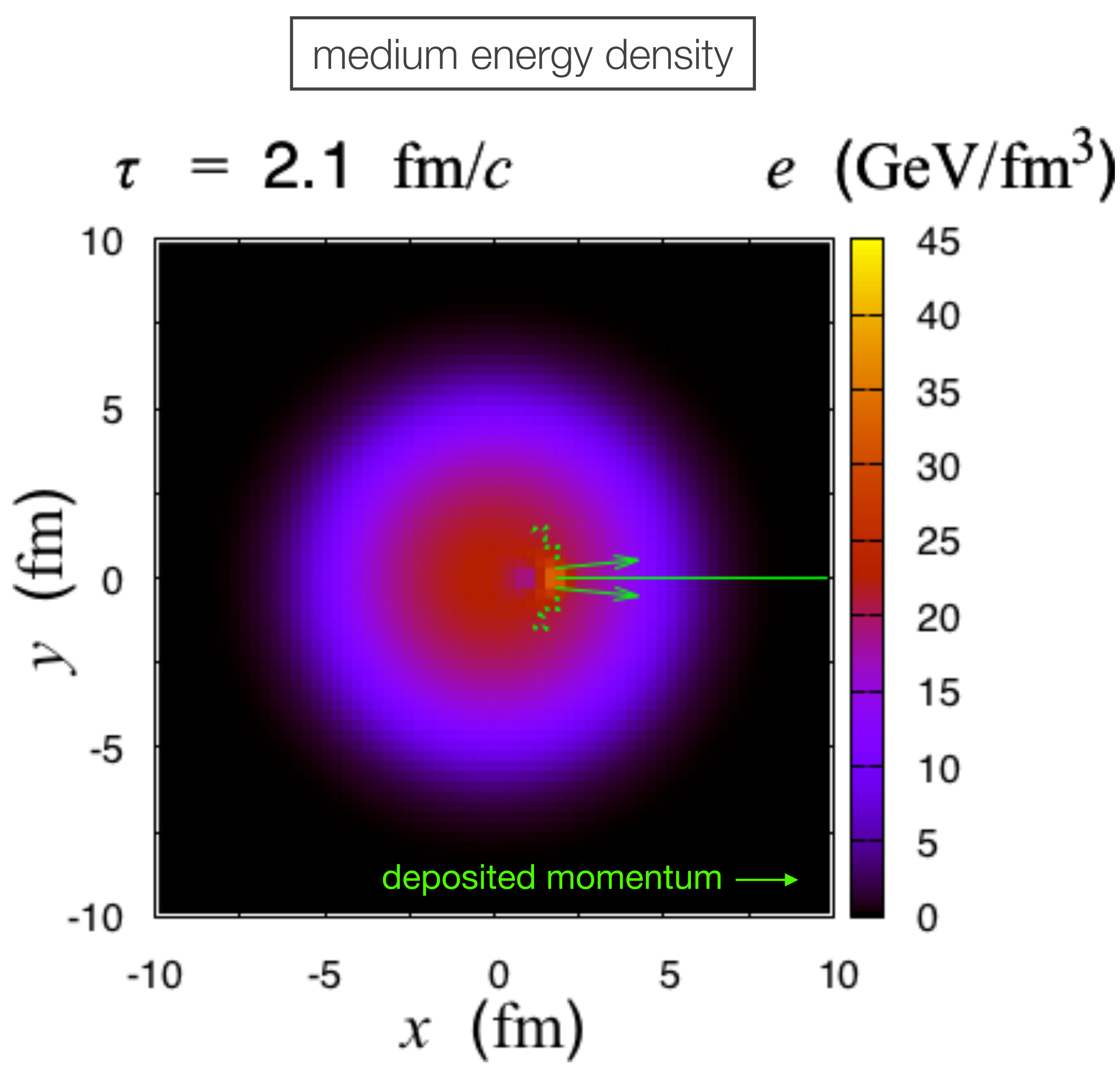

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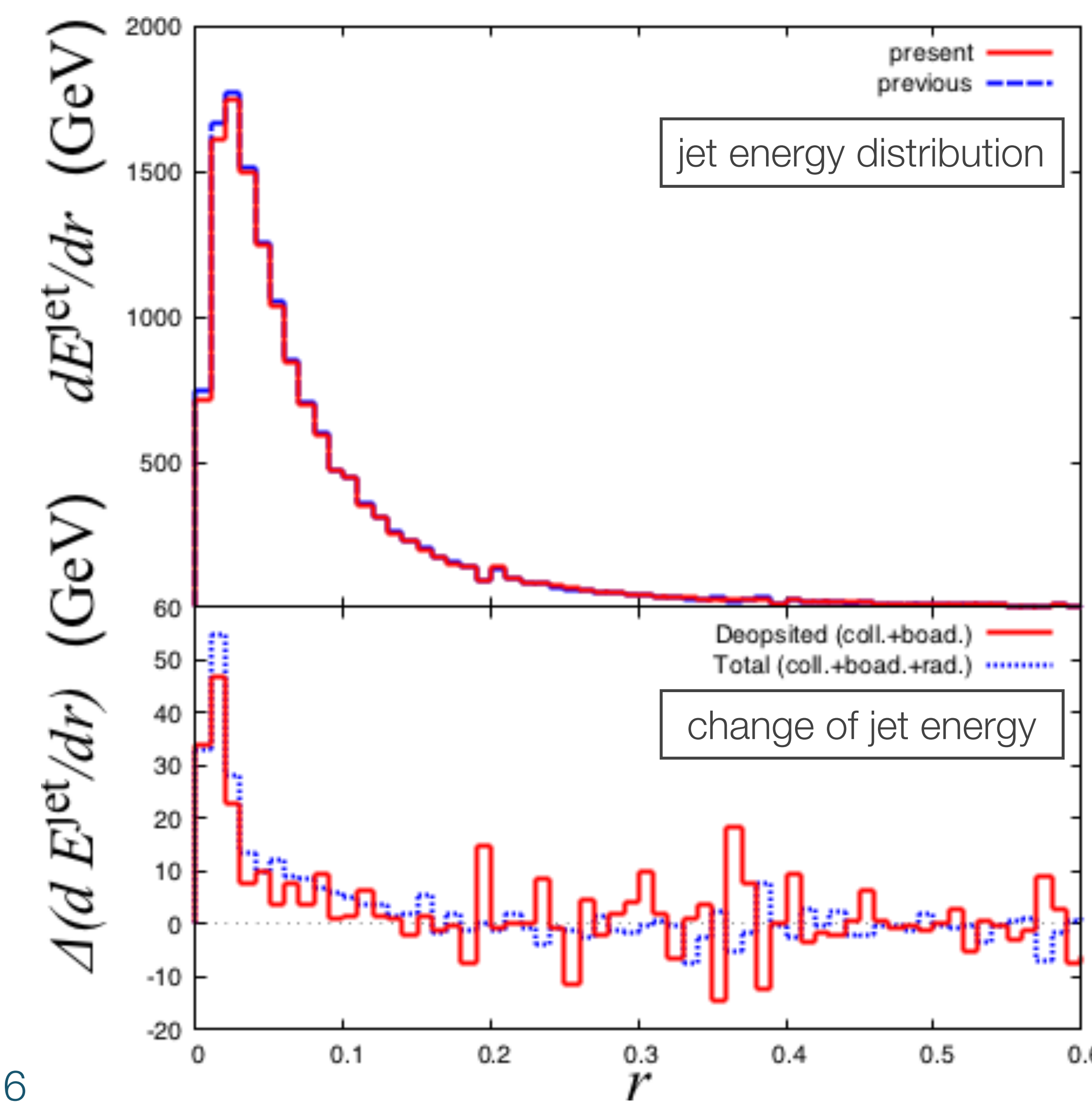

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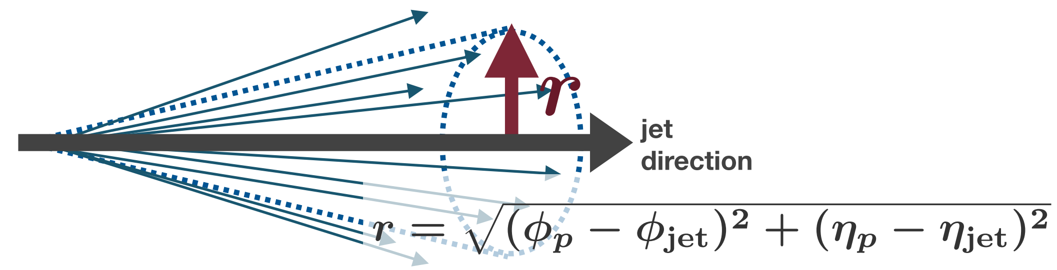

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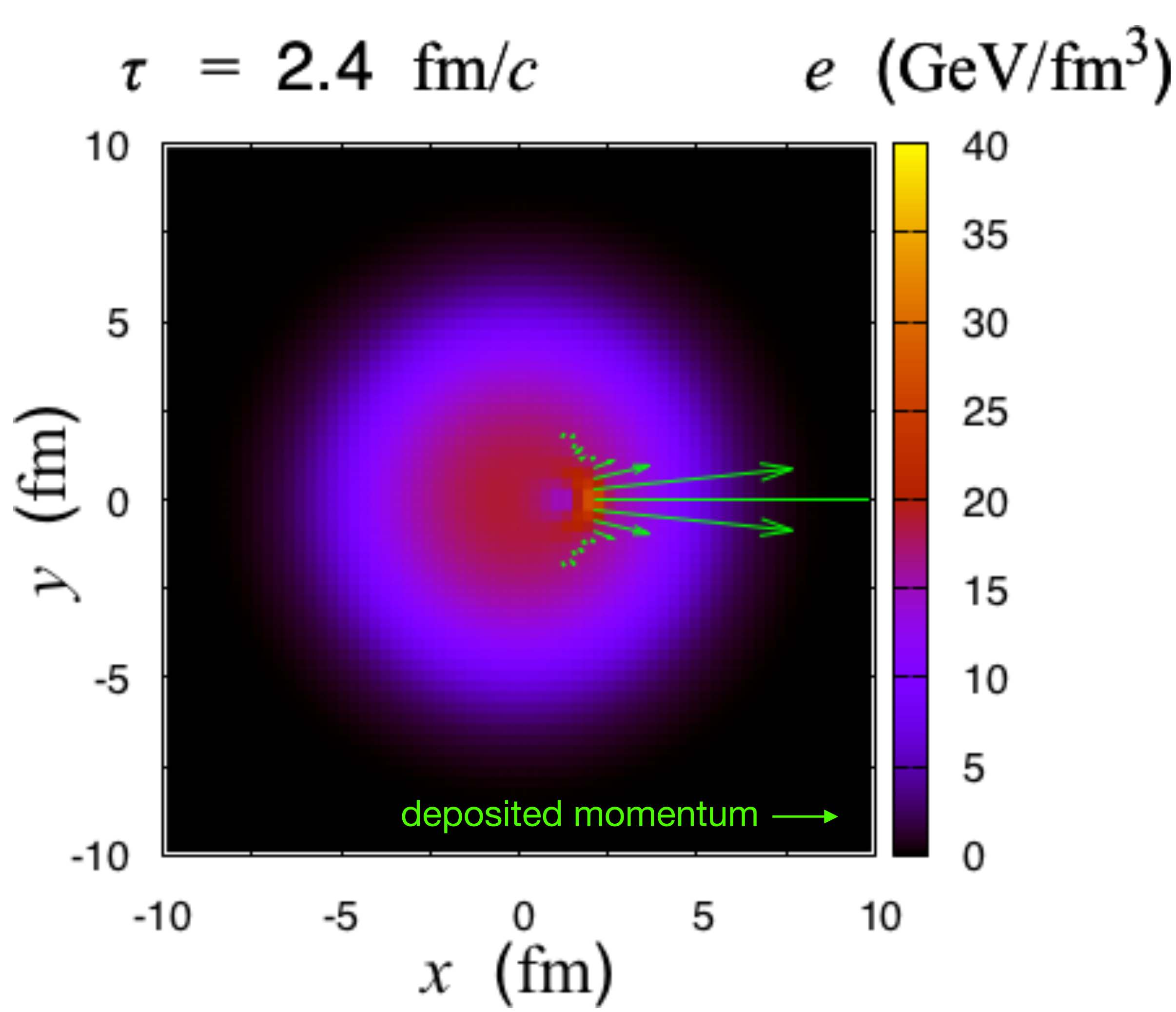

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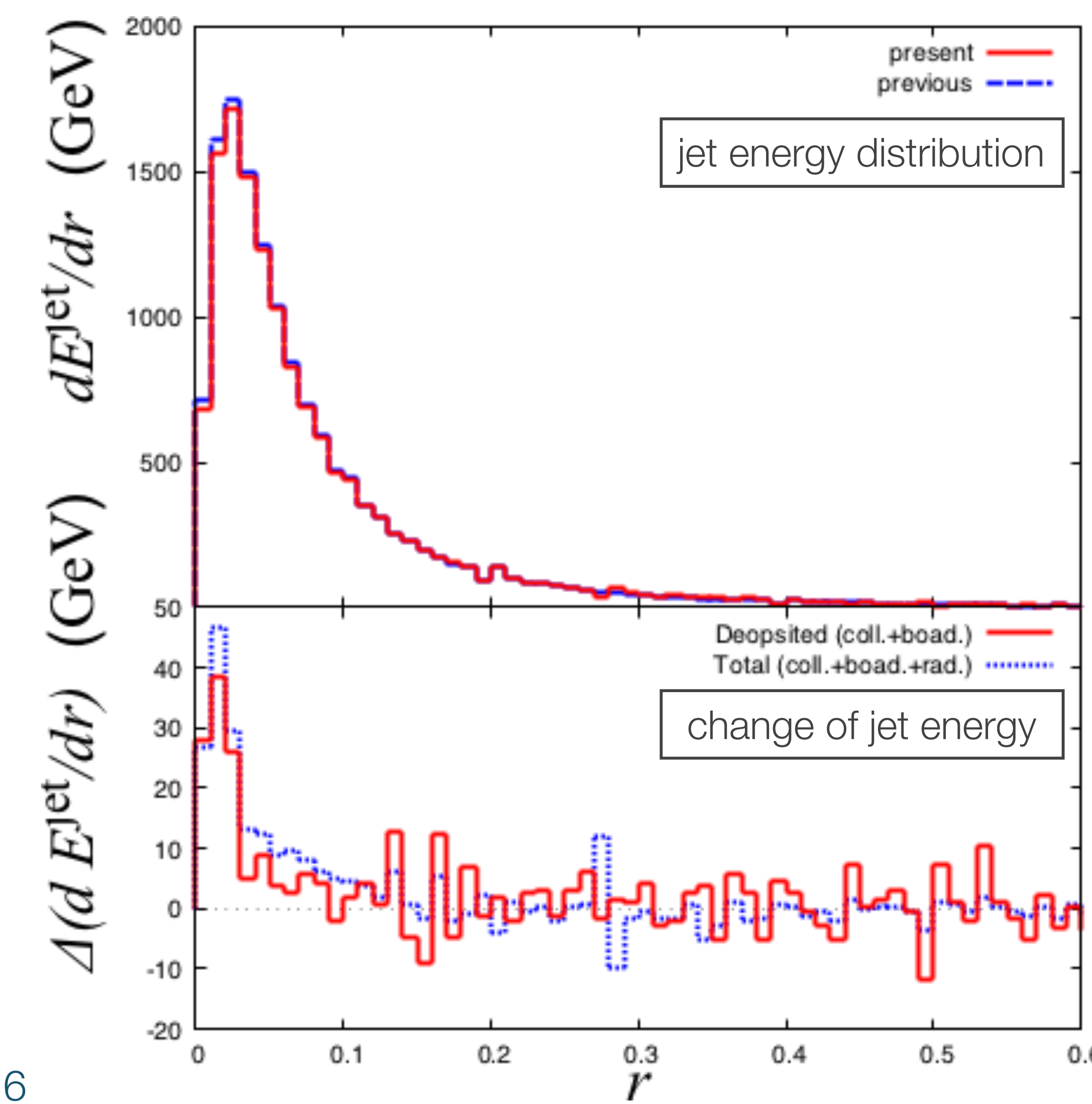

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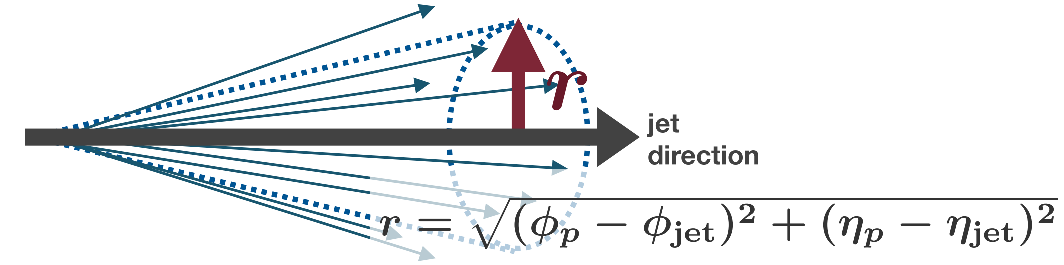

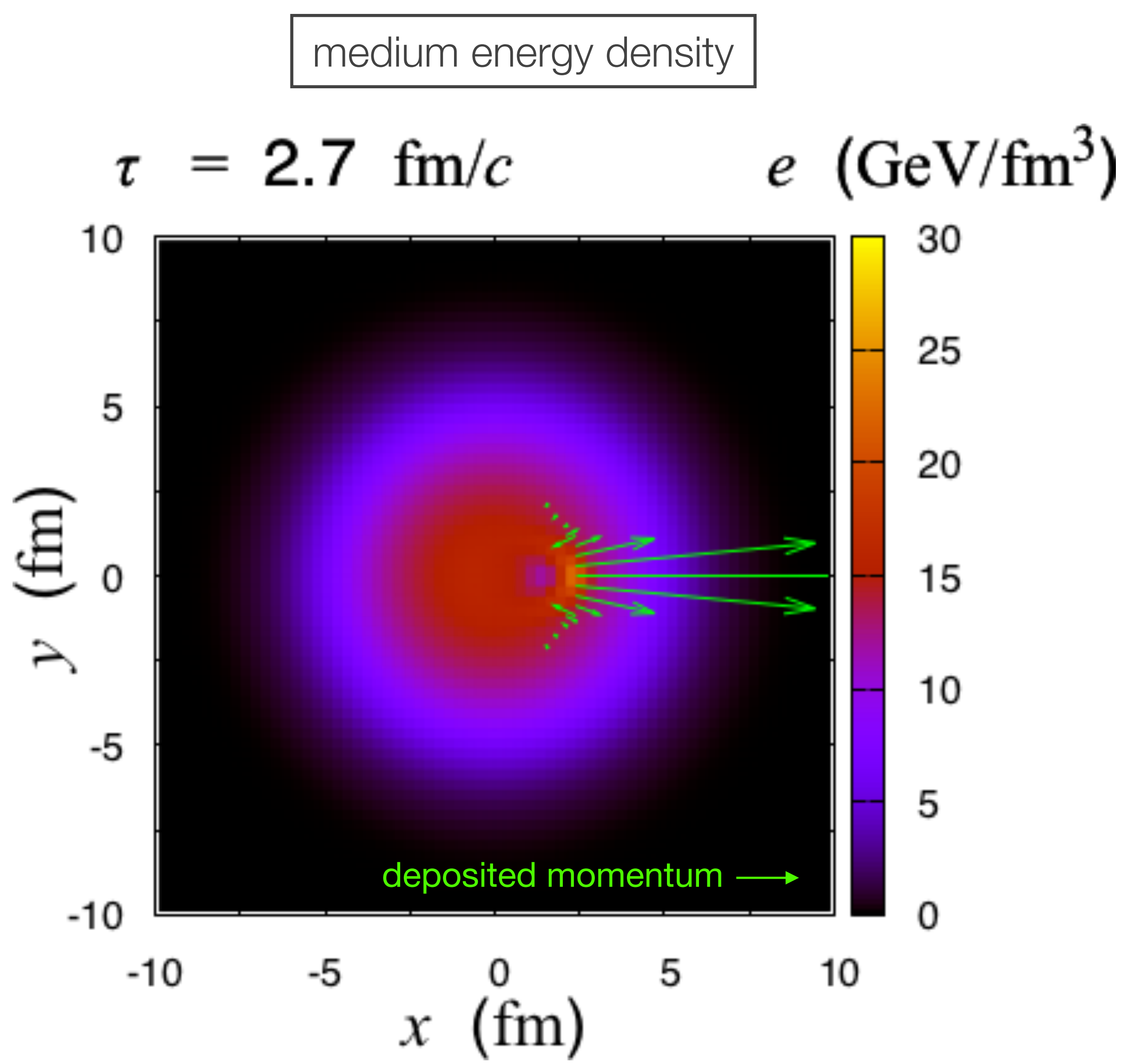

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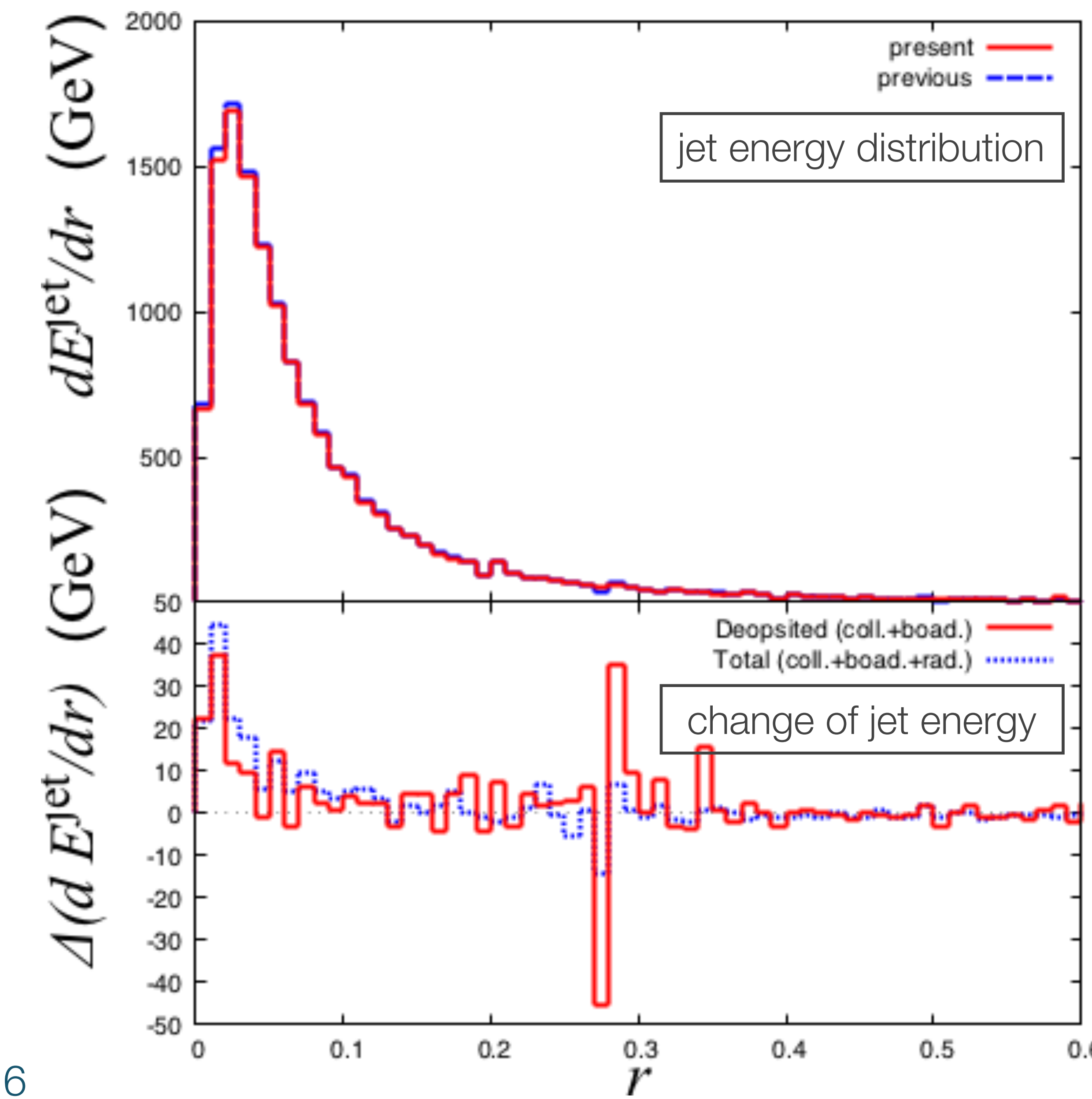

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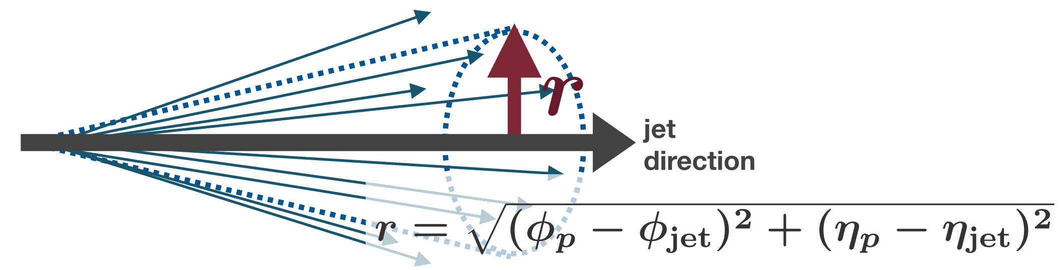
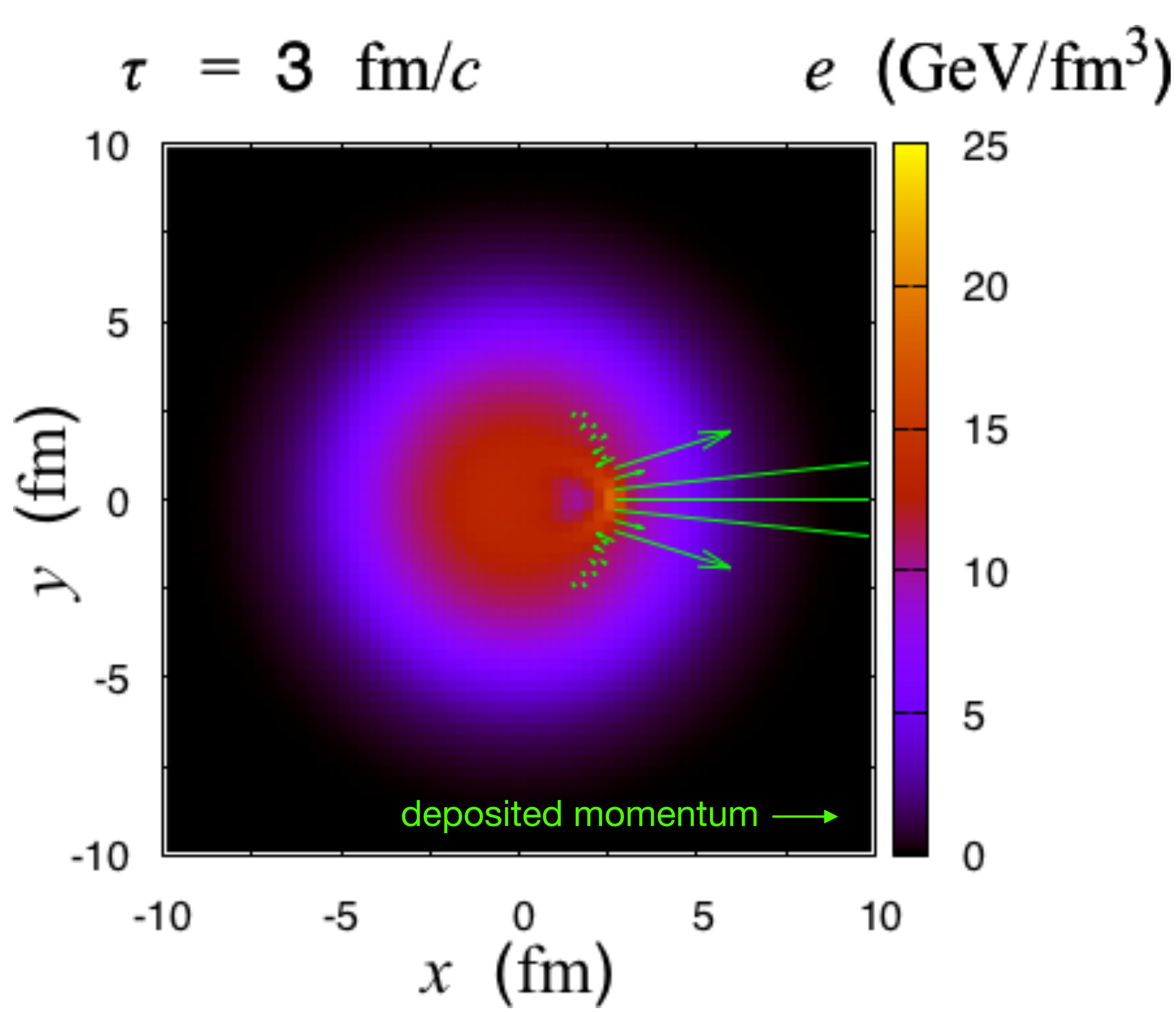
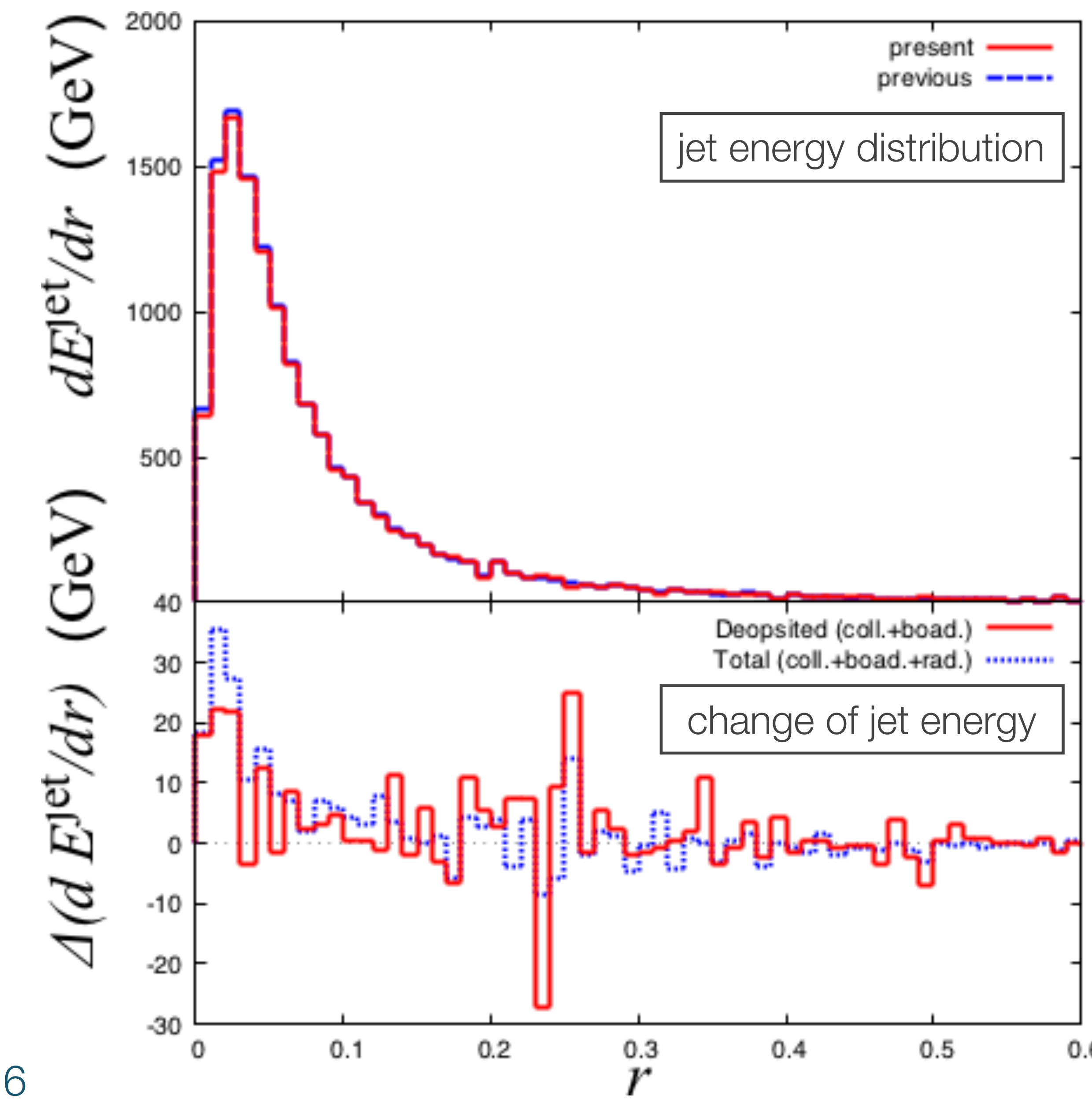


medium energy density



Inital jet energy: 120 GeV



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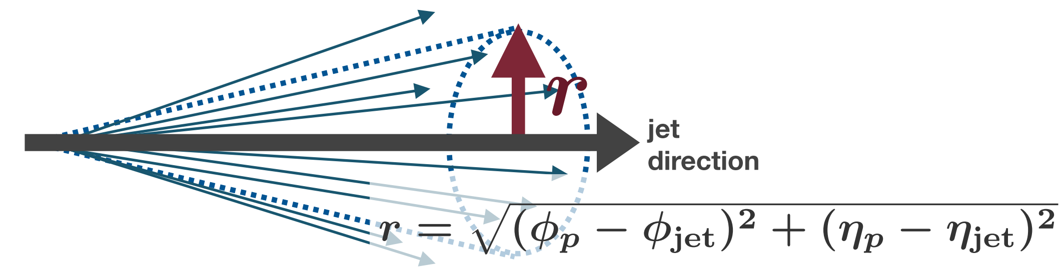

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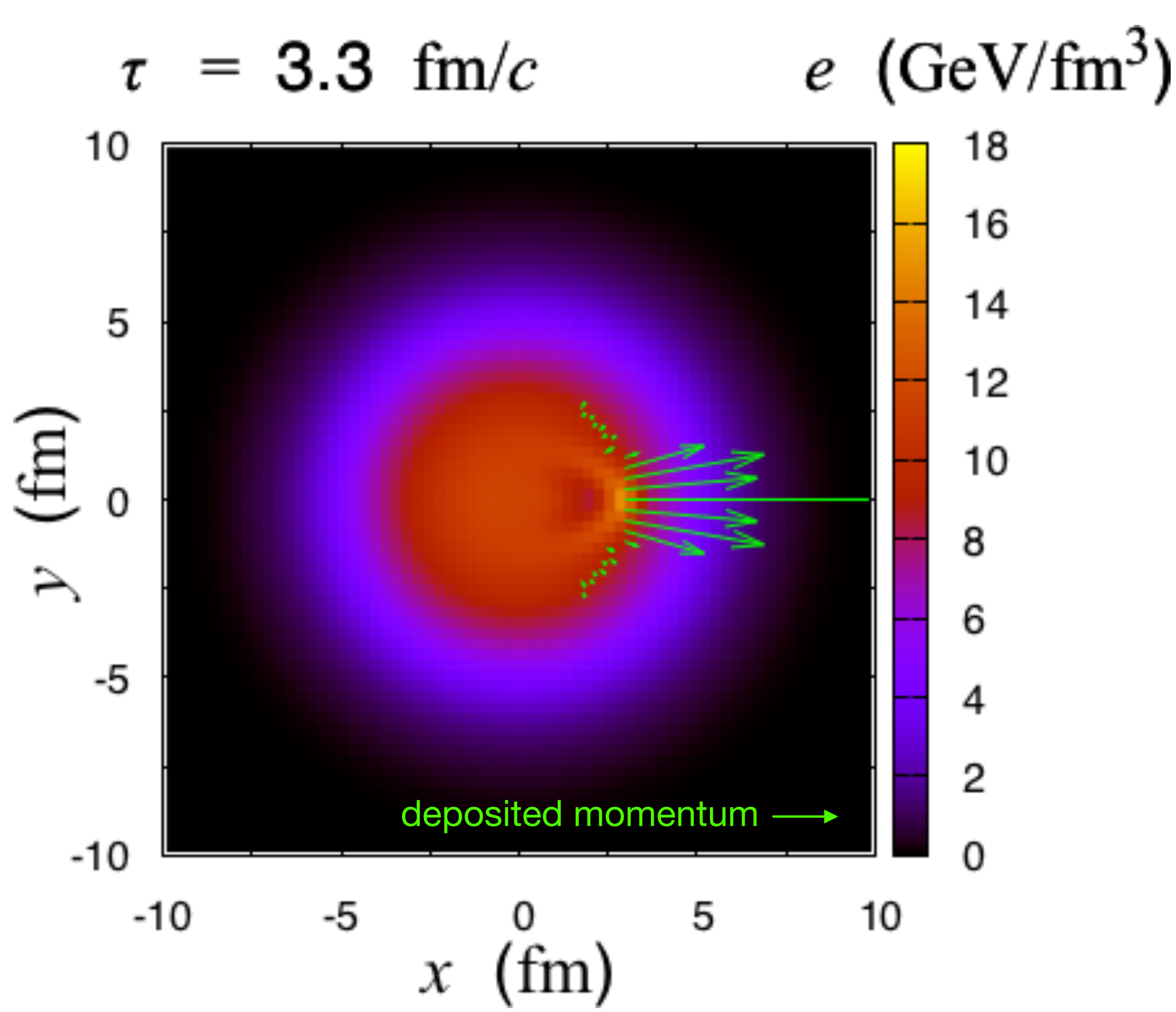

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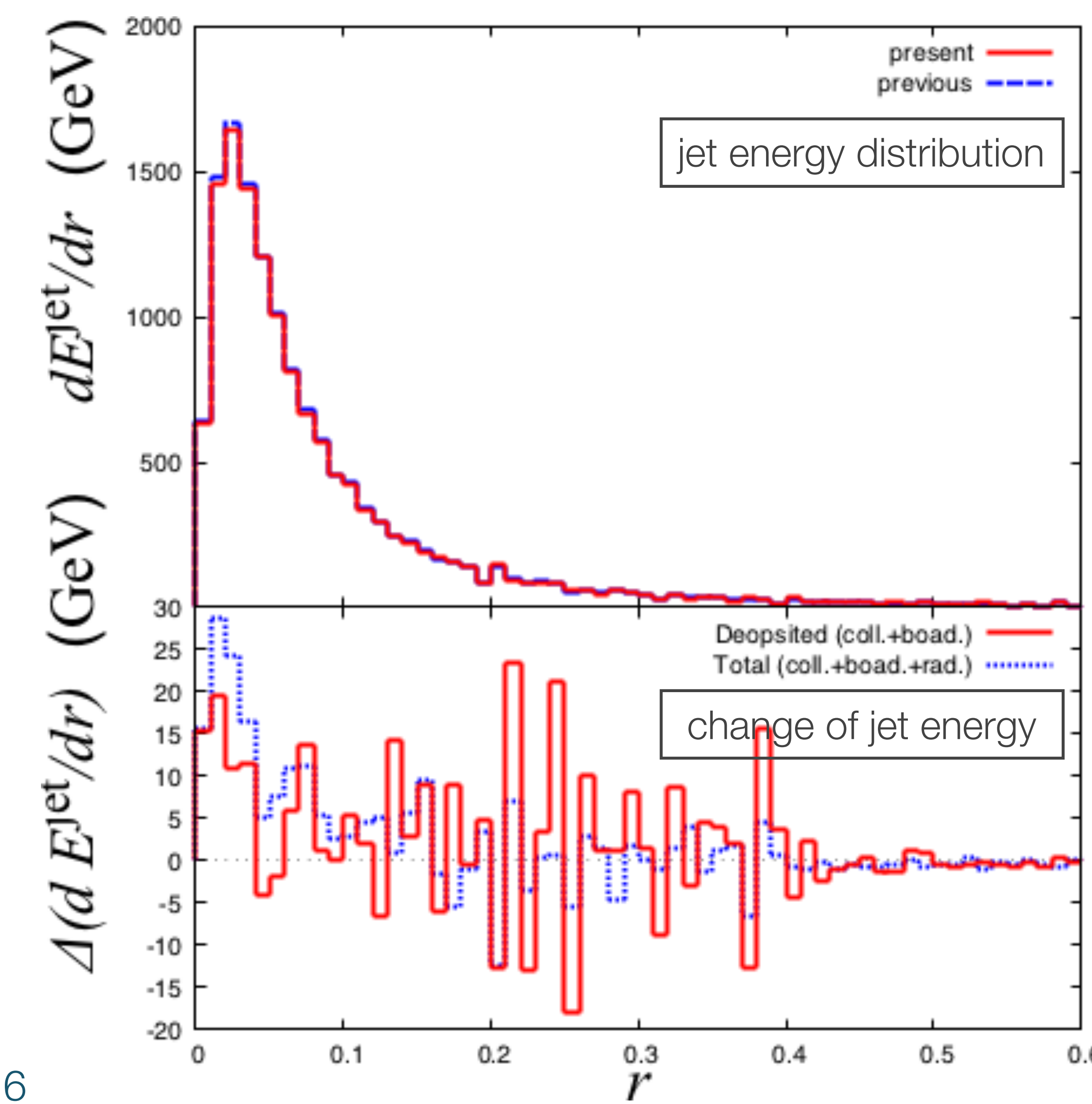

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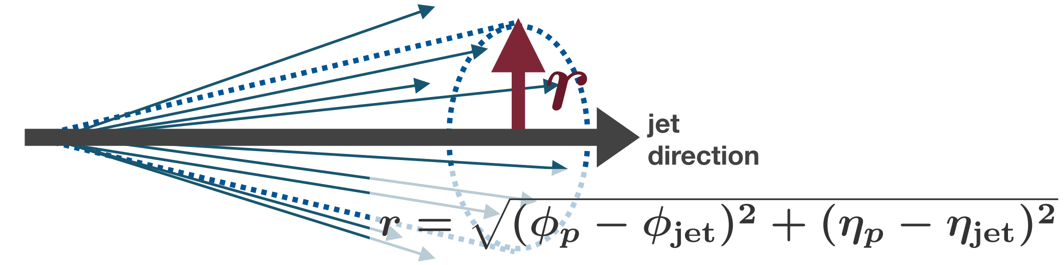

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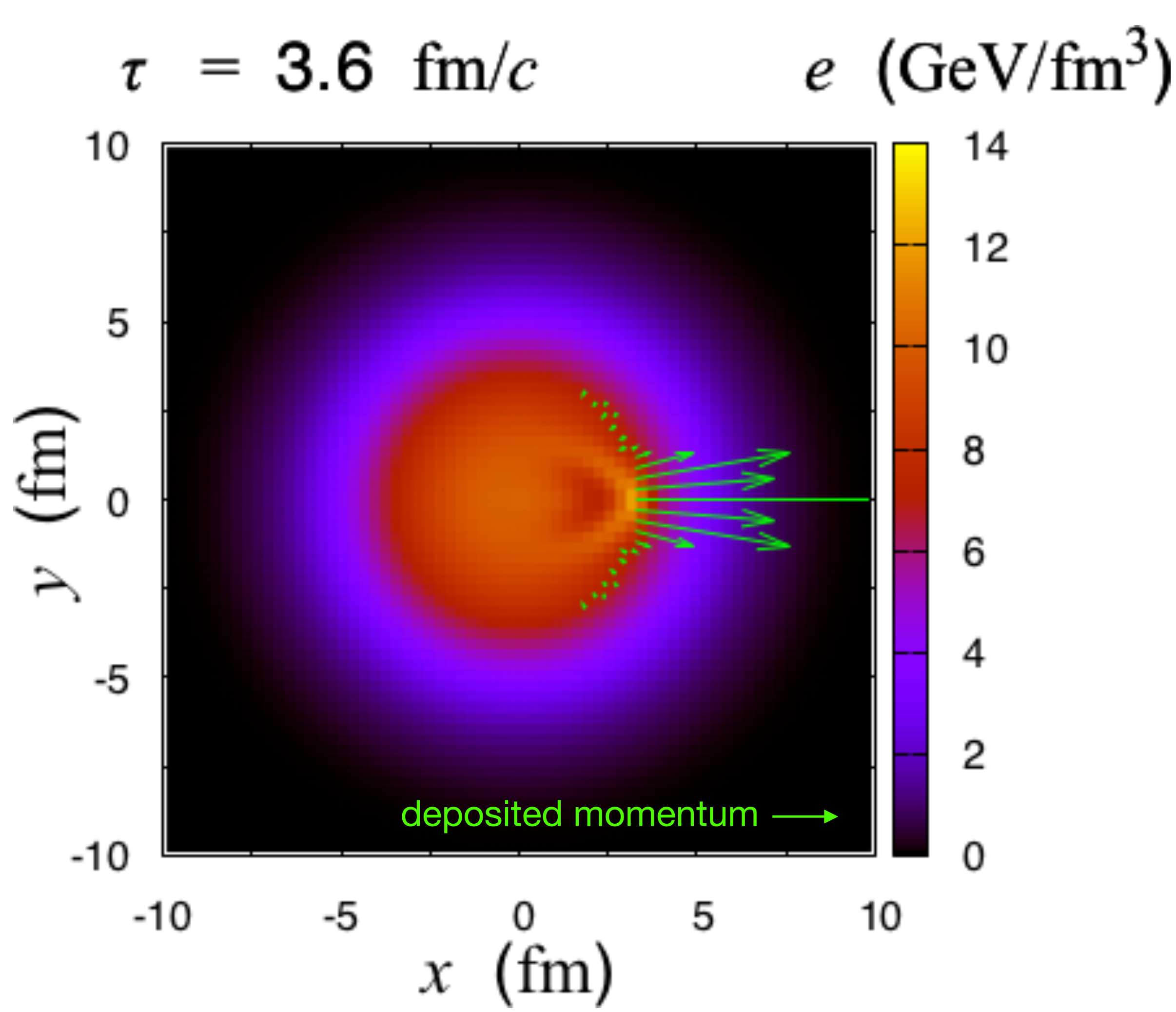

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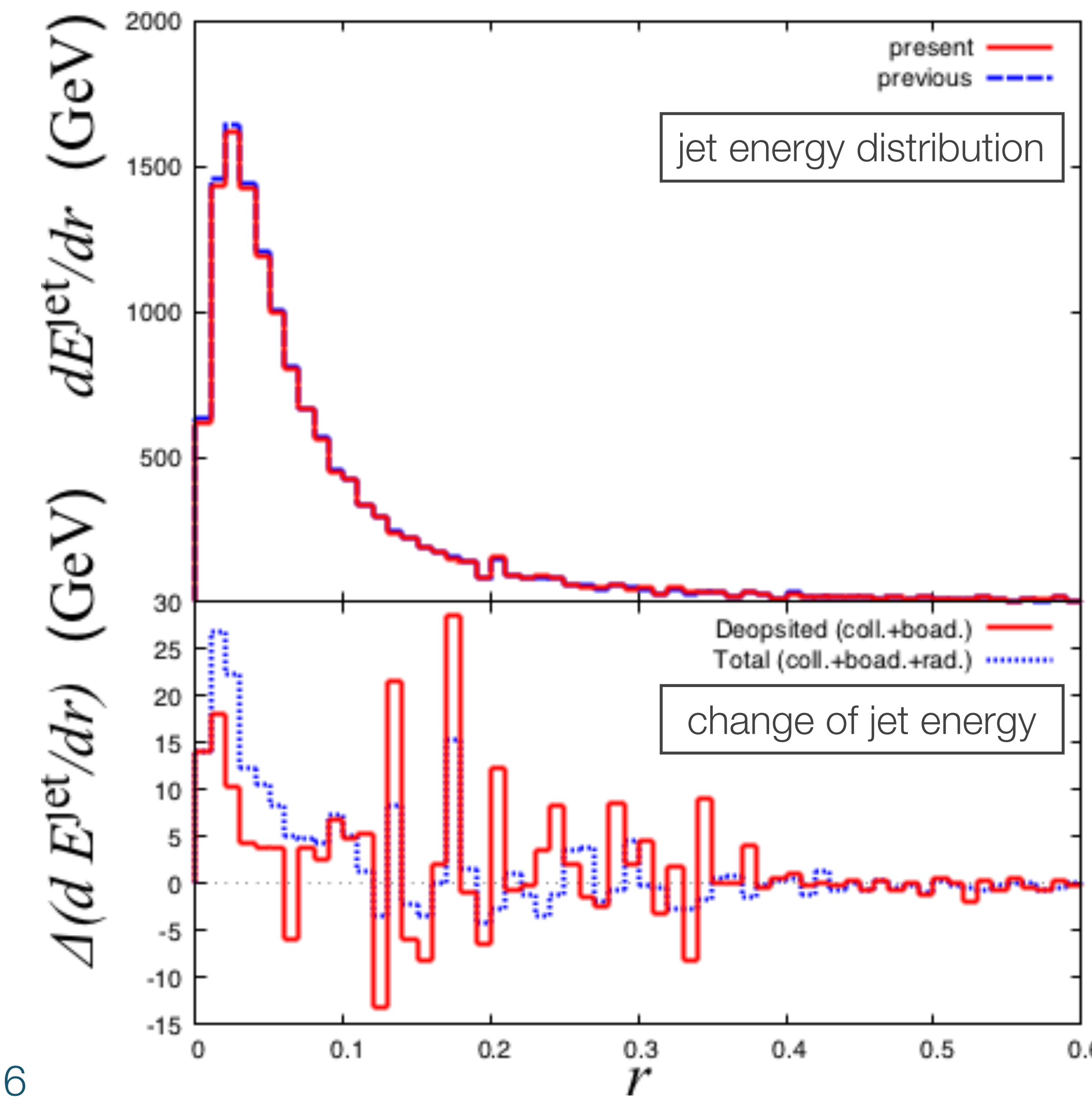

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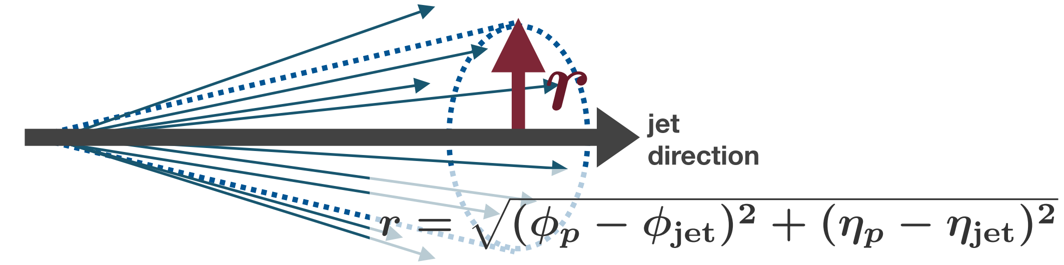

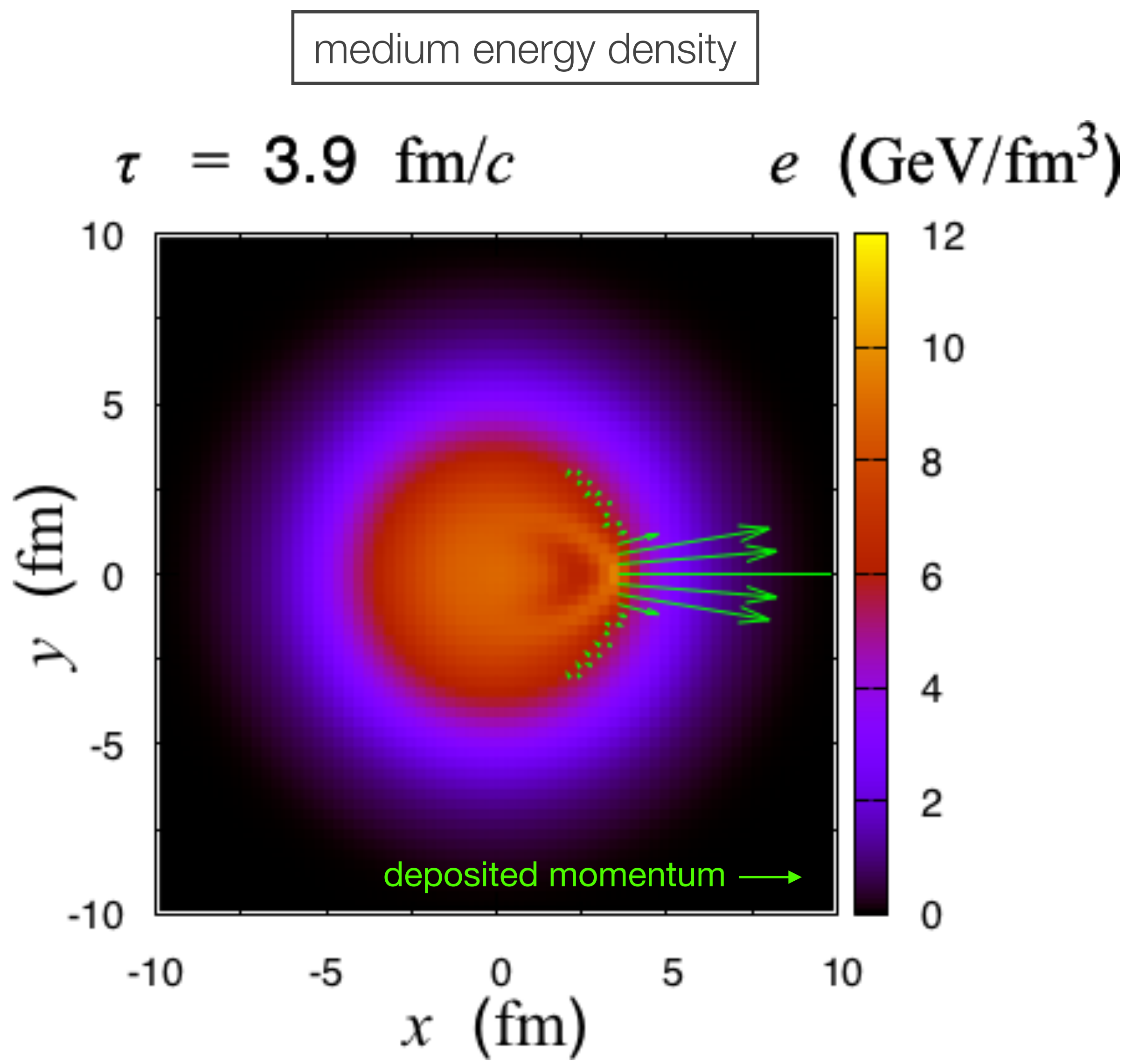

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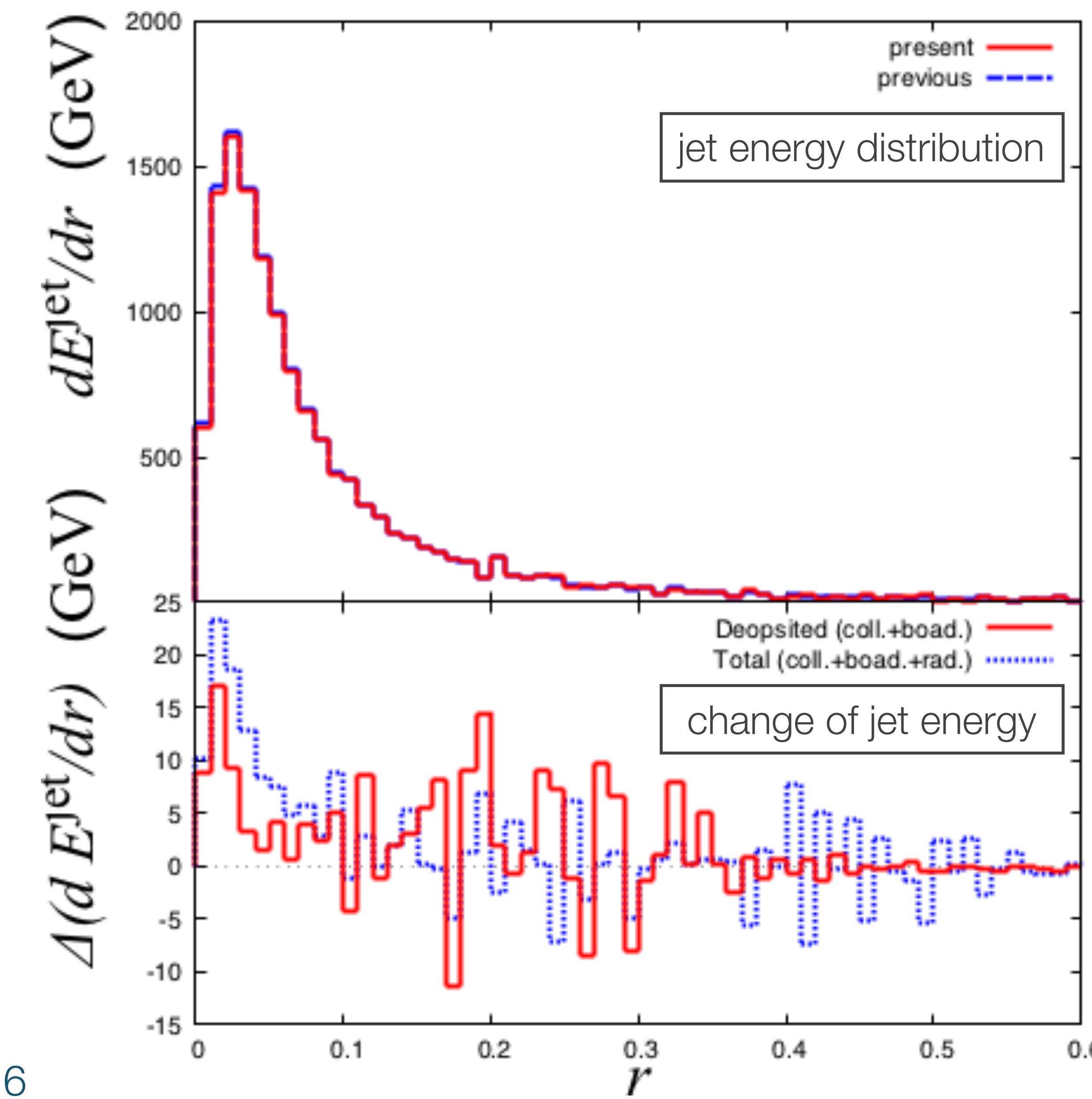

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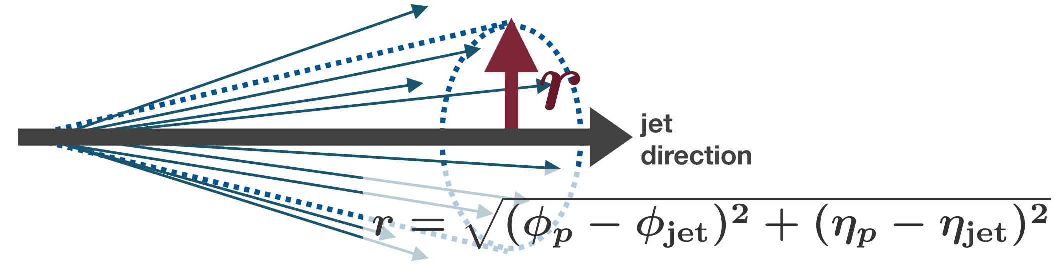

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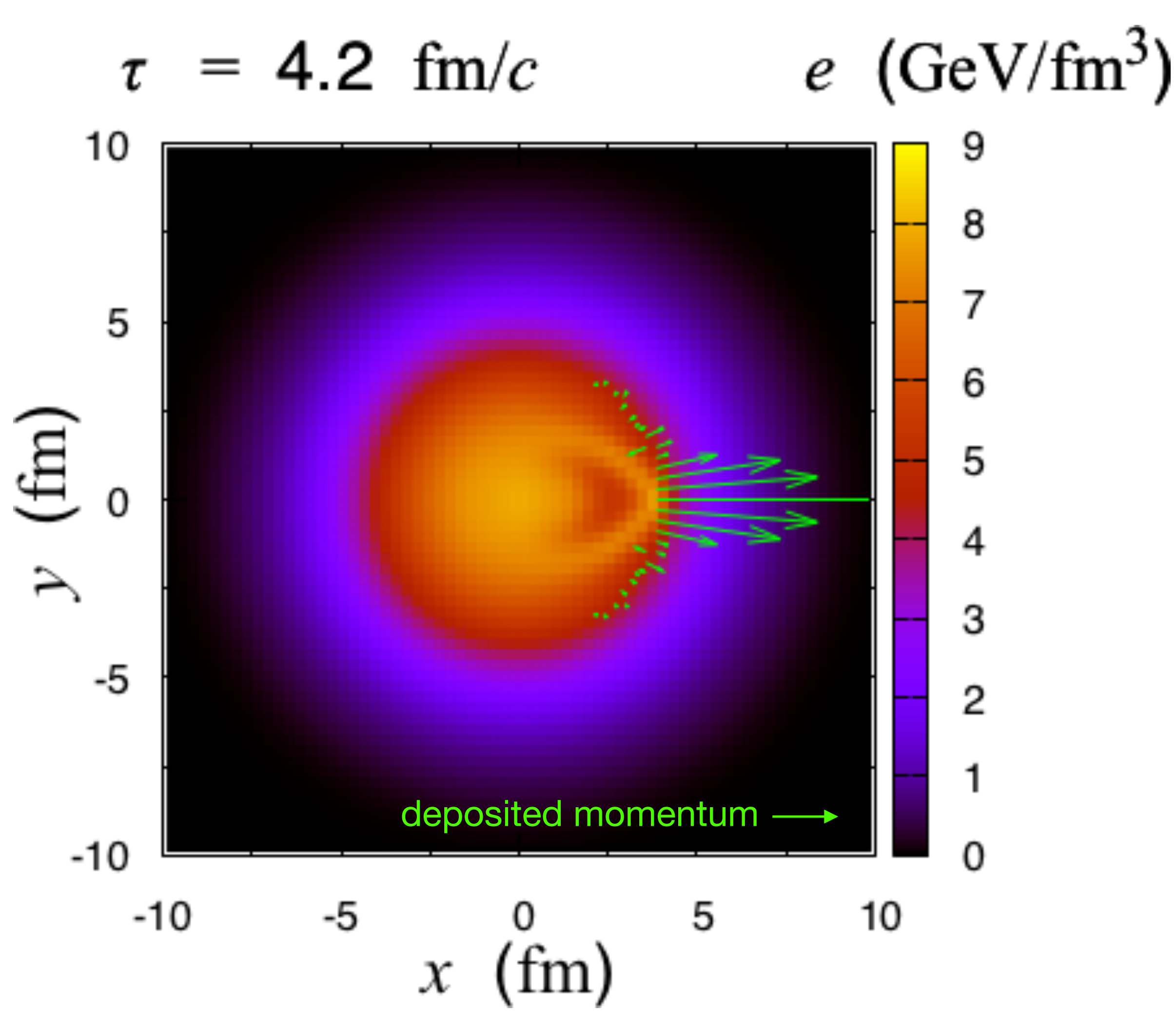

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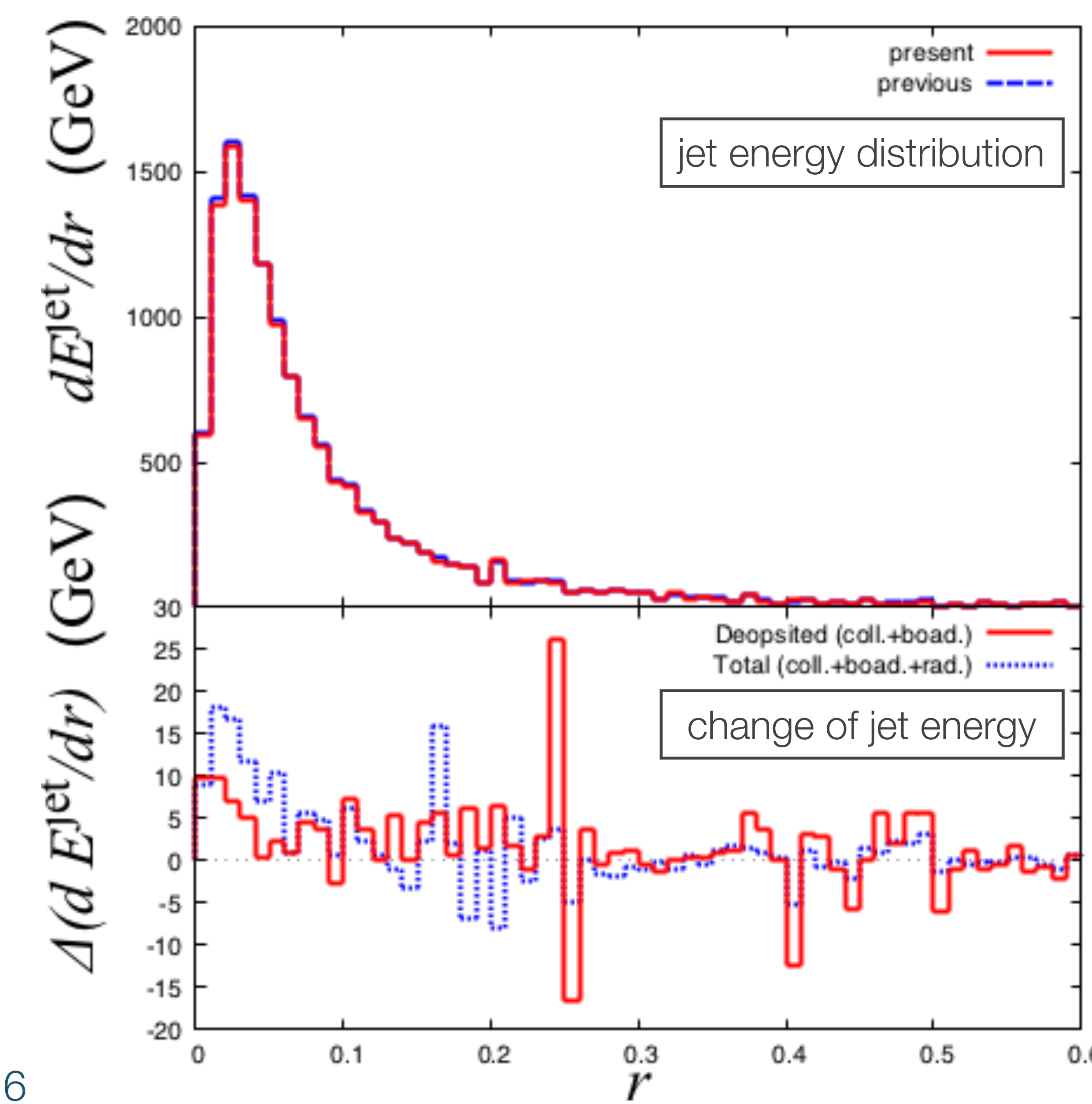

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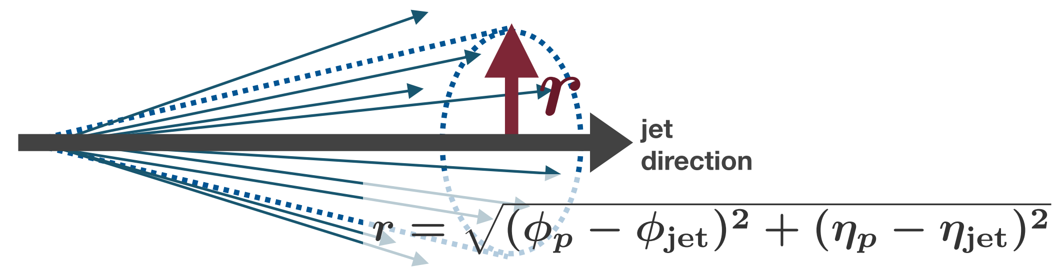

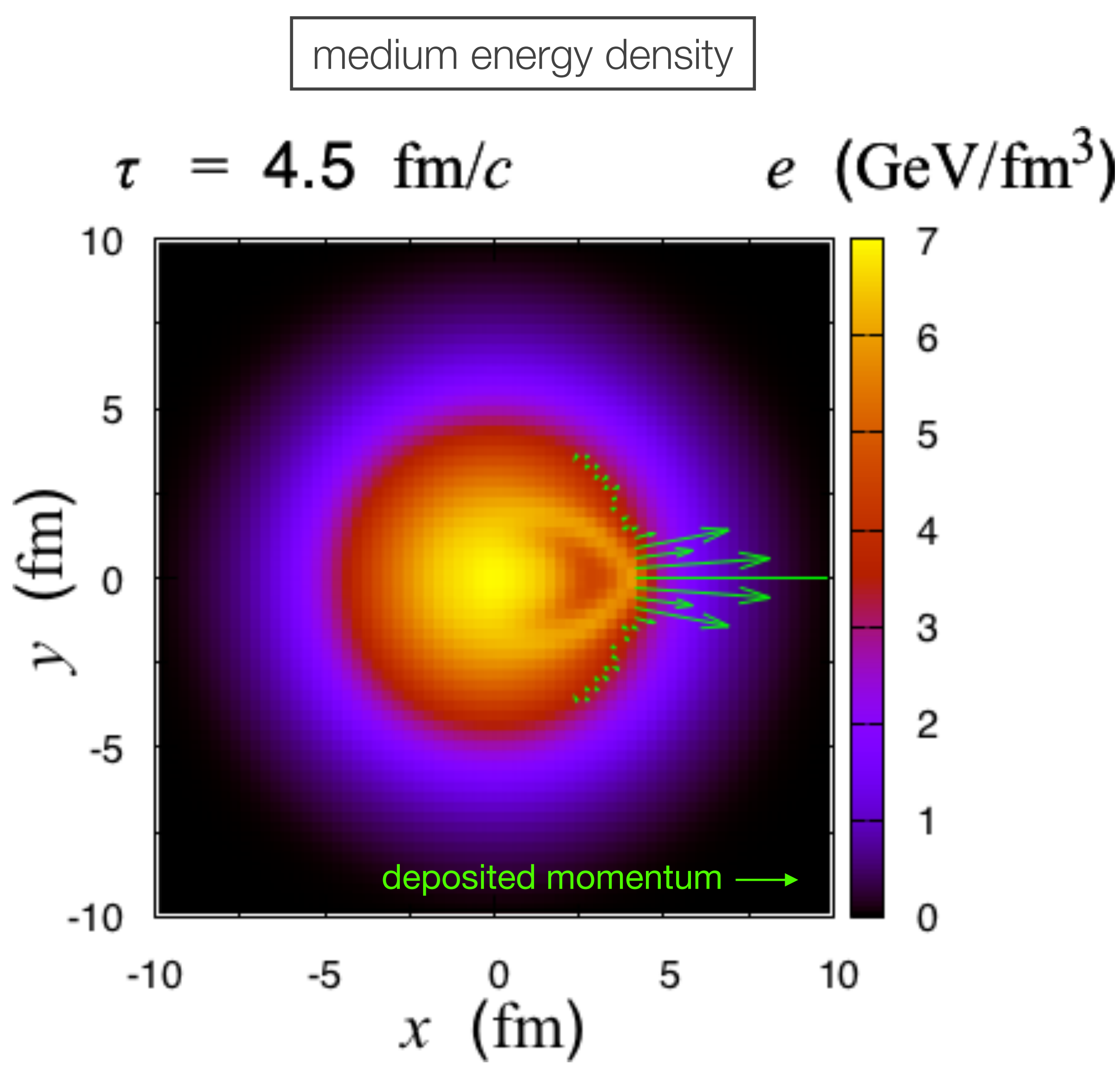

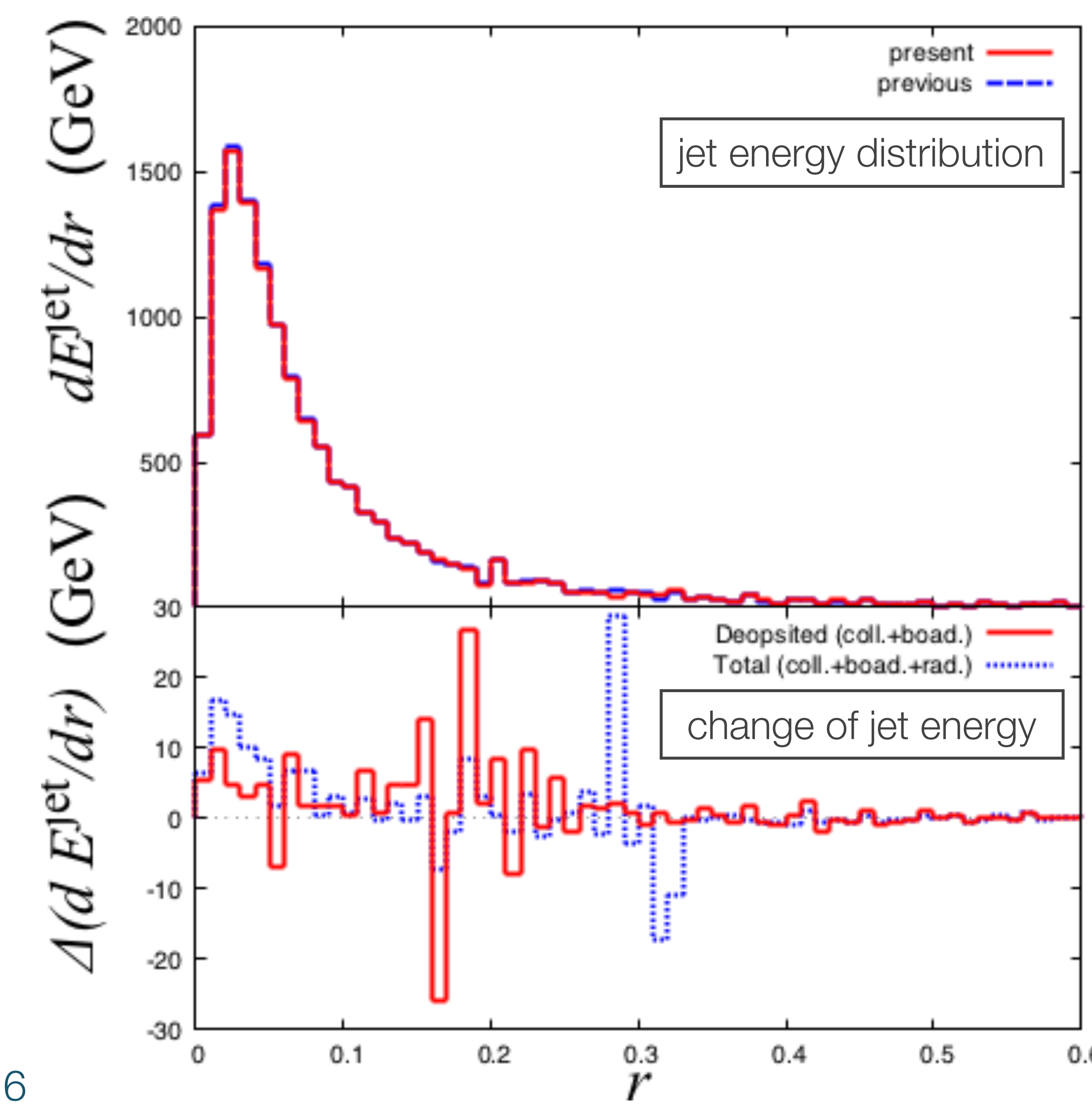

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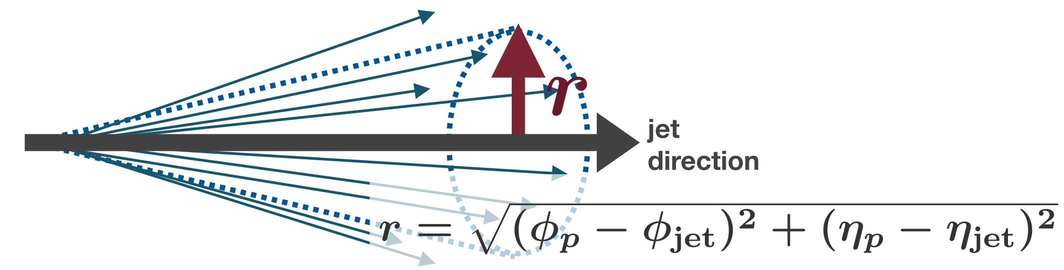

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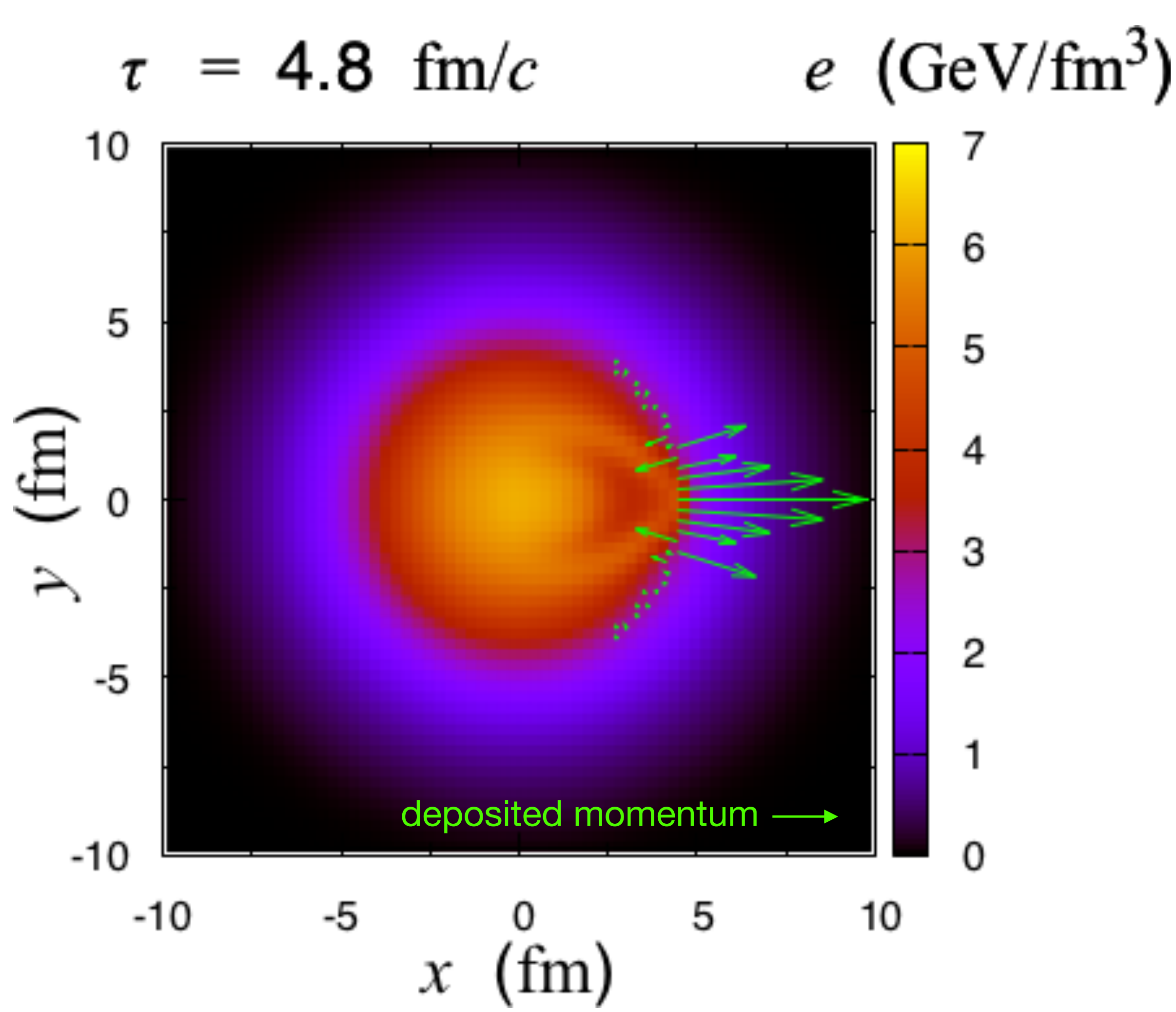

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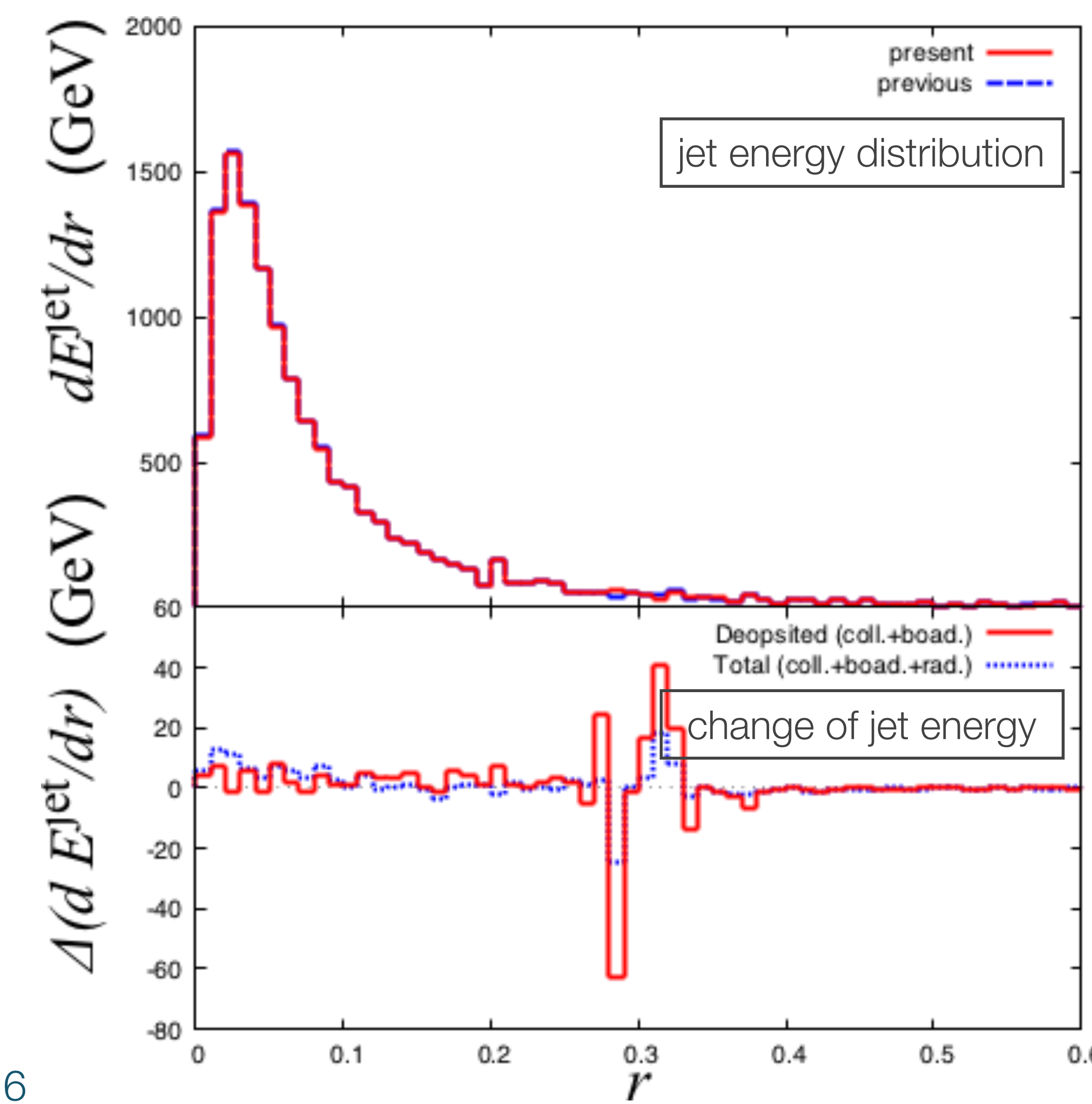

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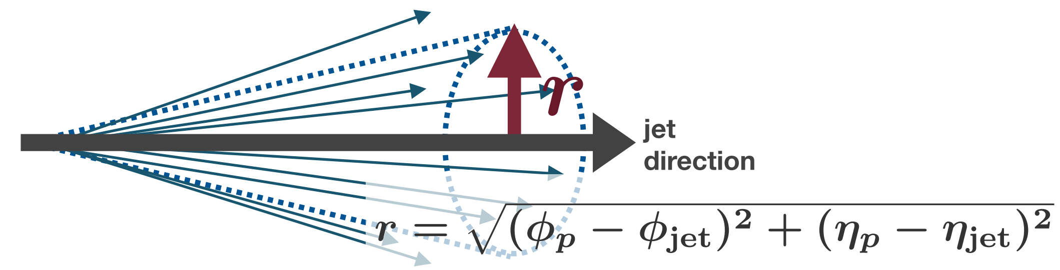

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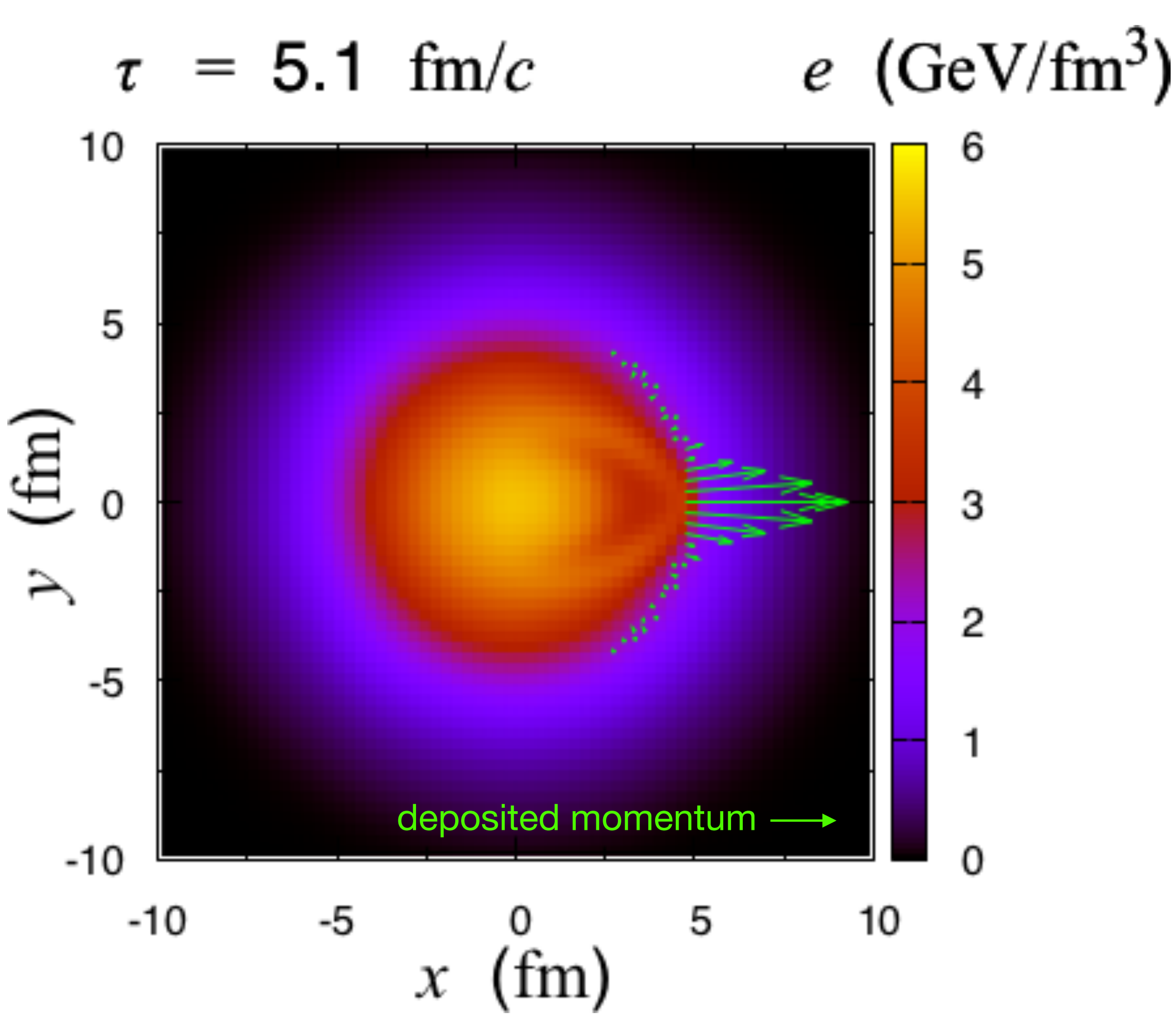

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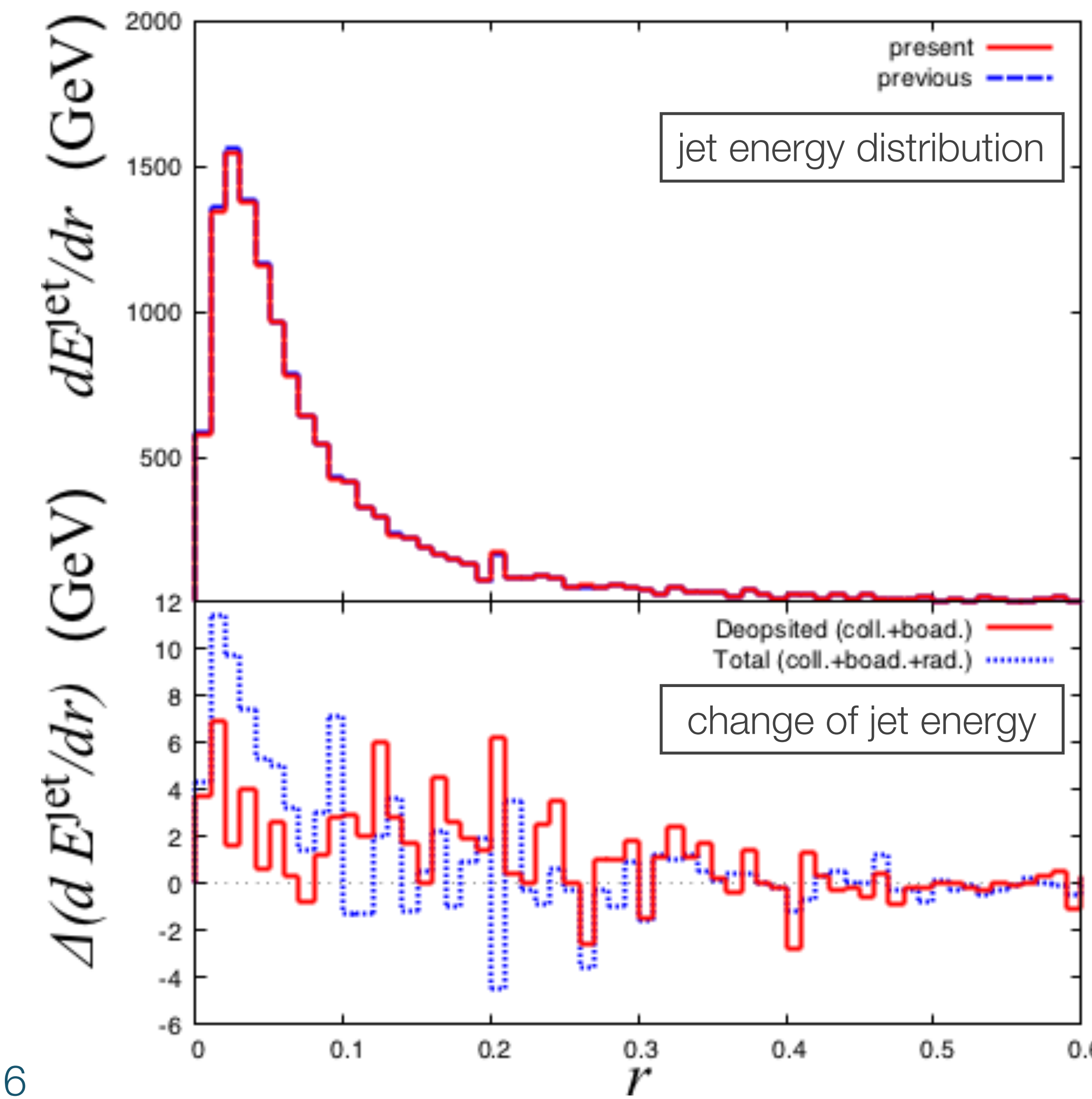

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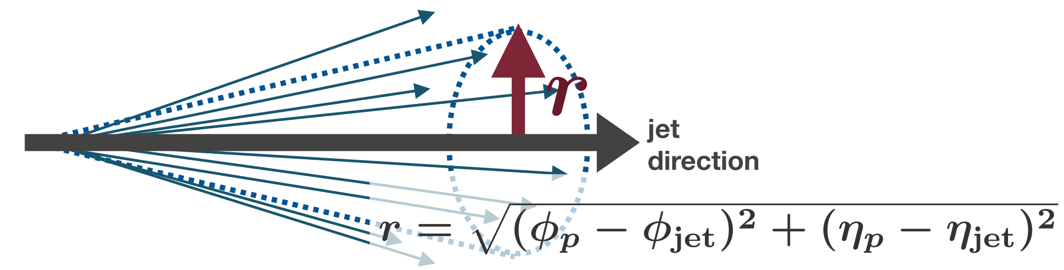

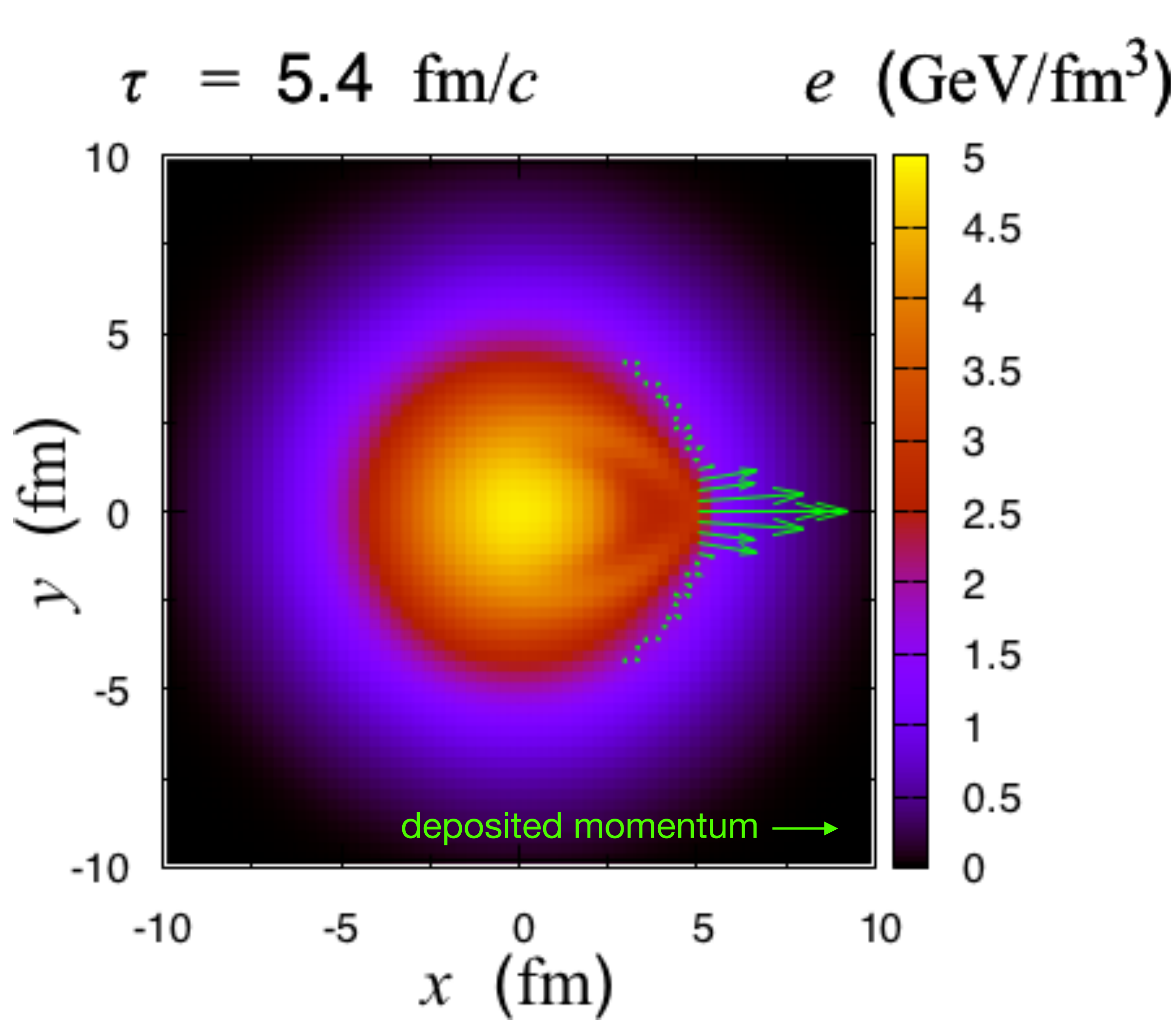

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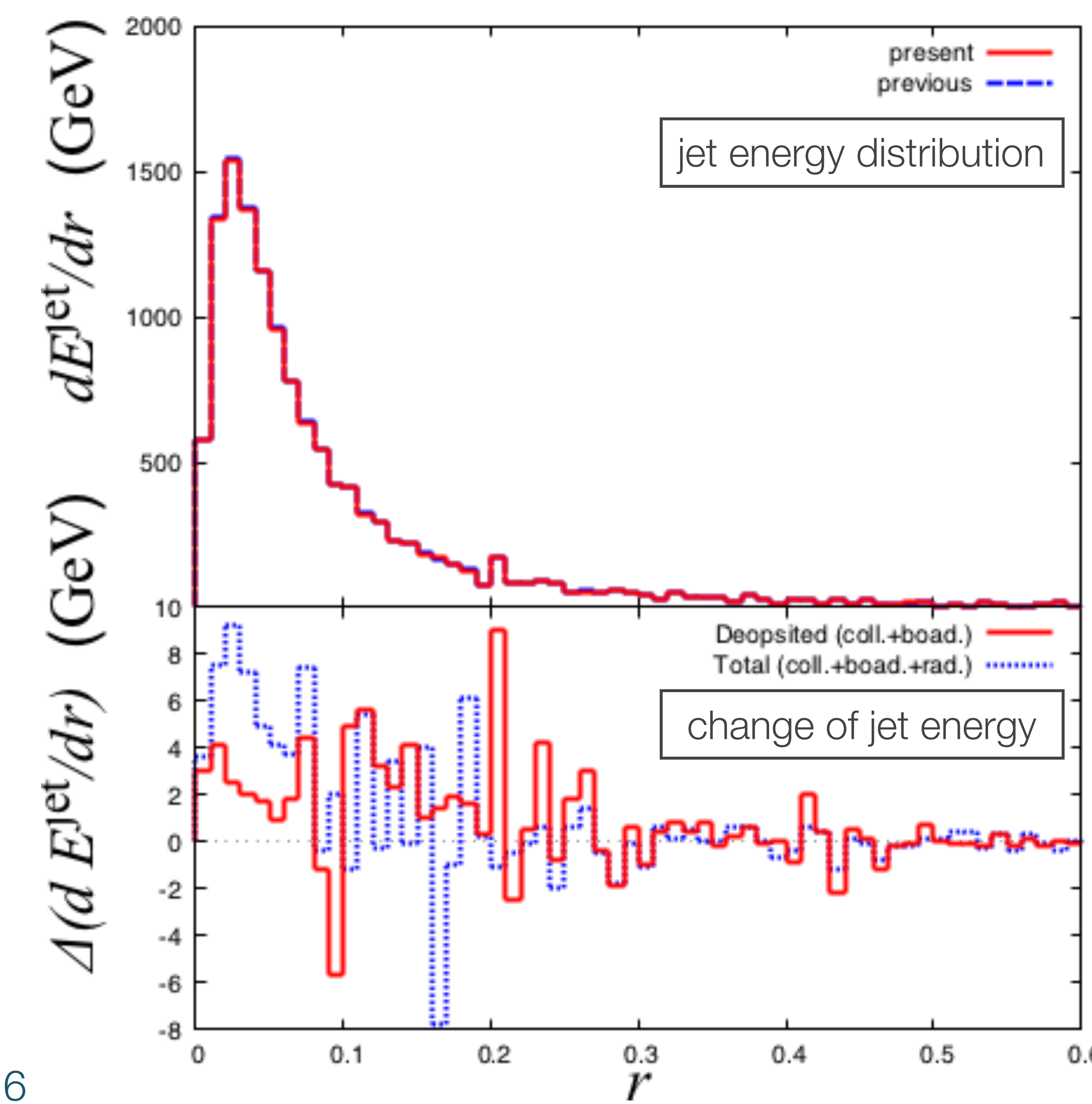

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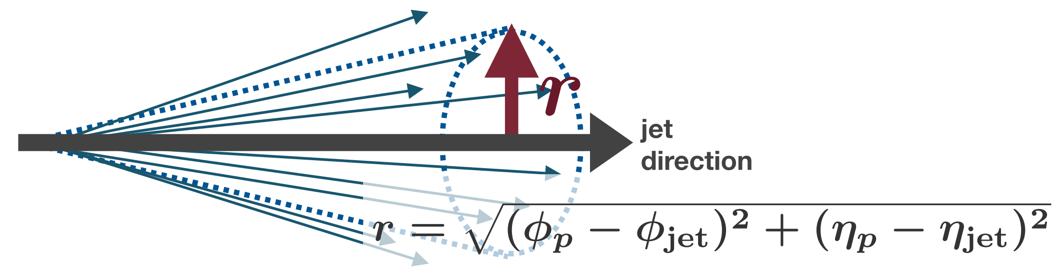

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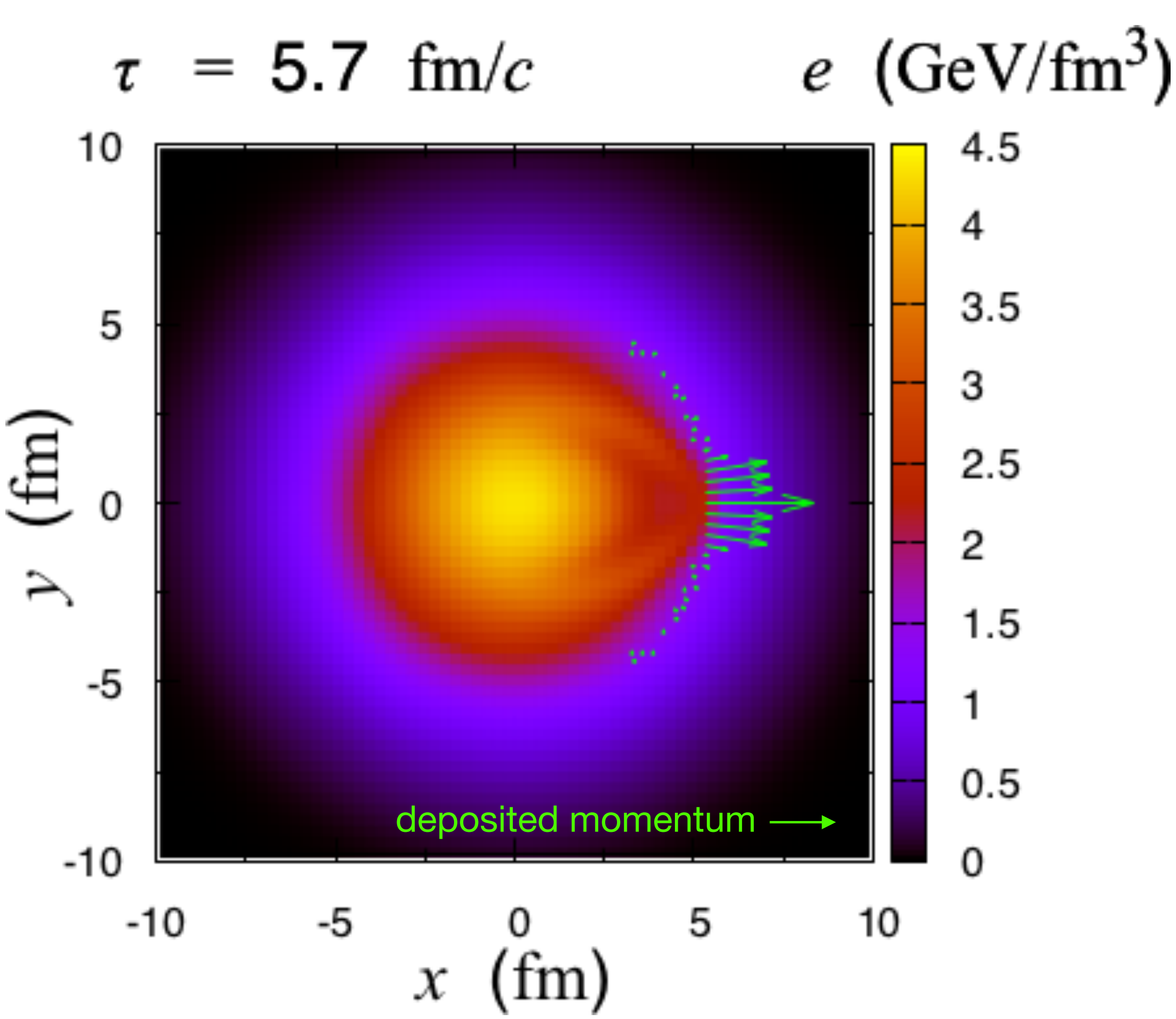

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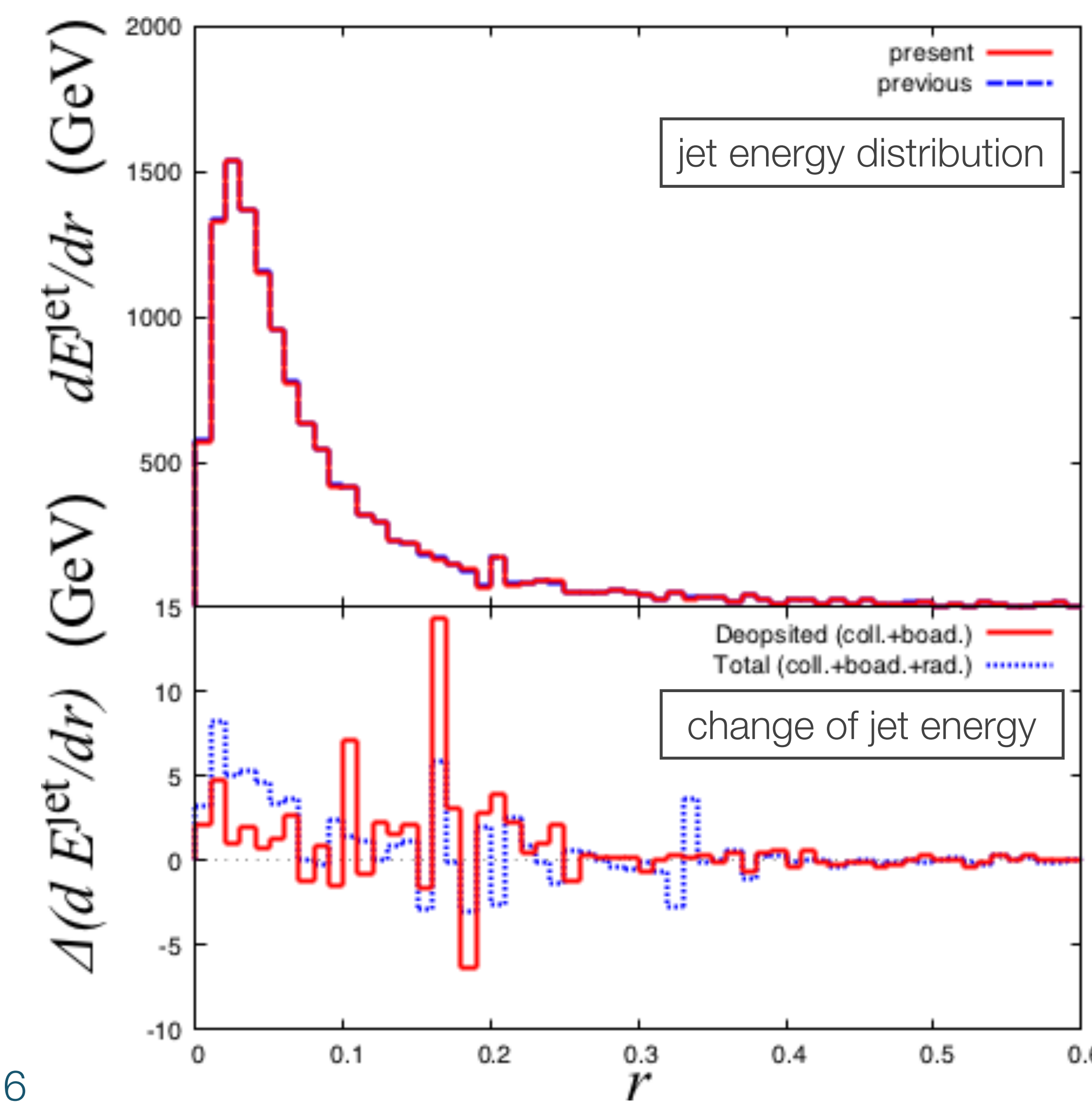

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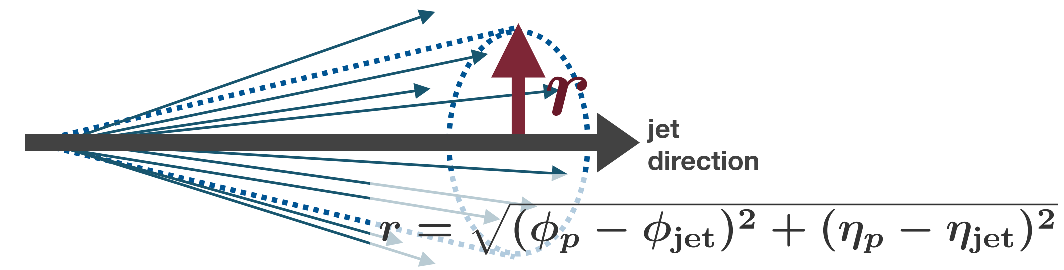

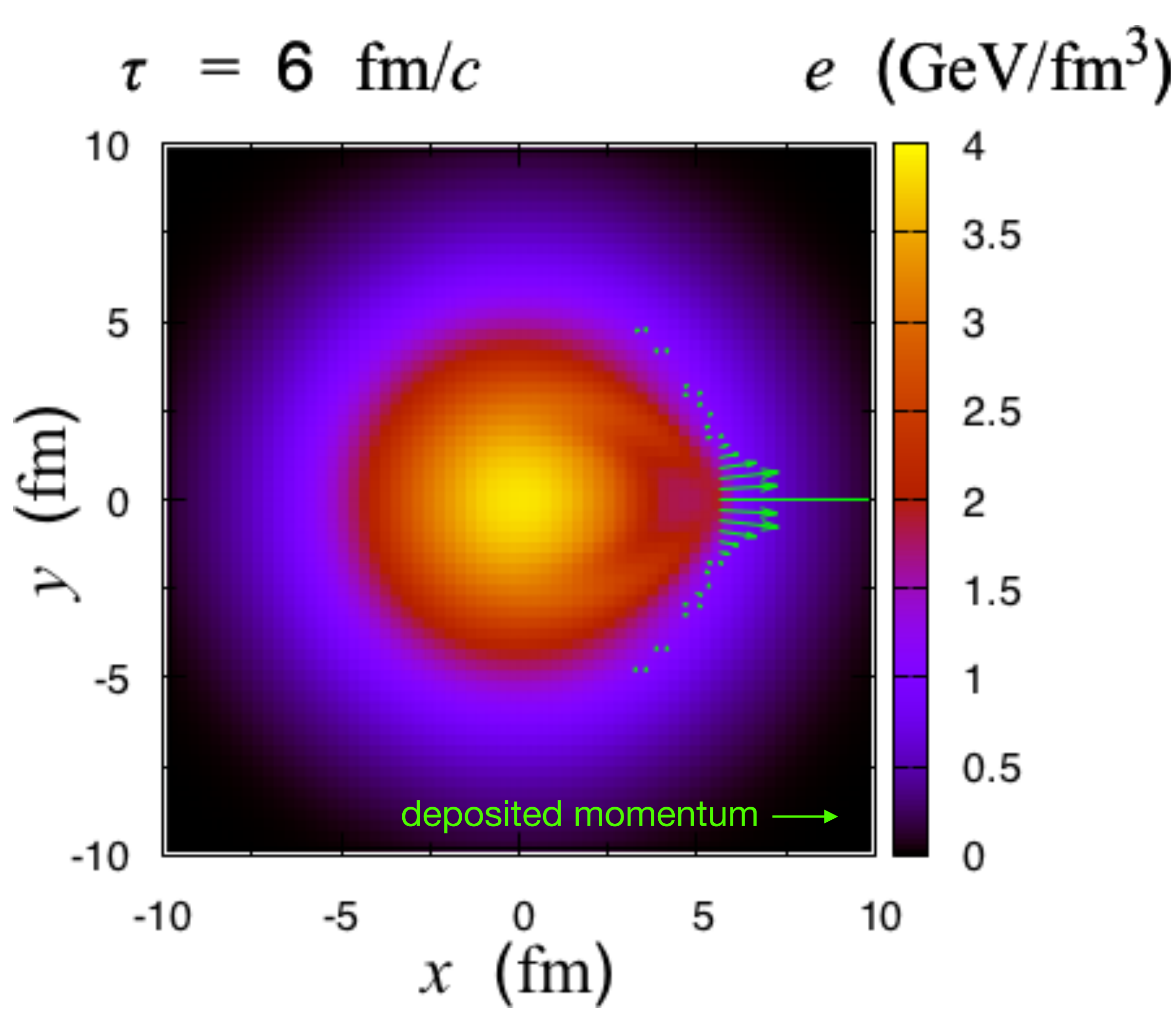

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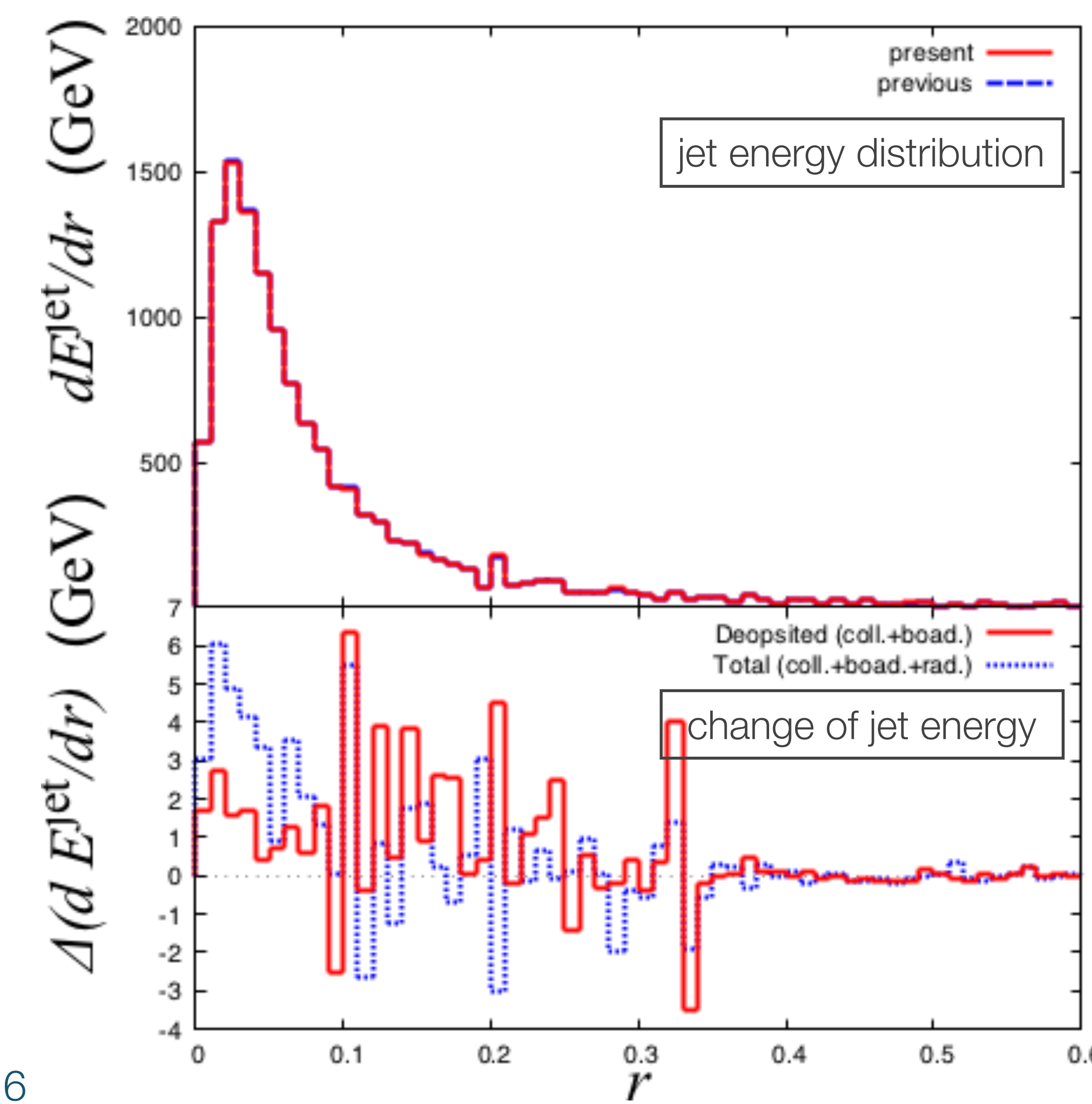

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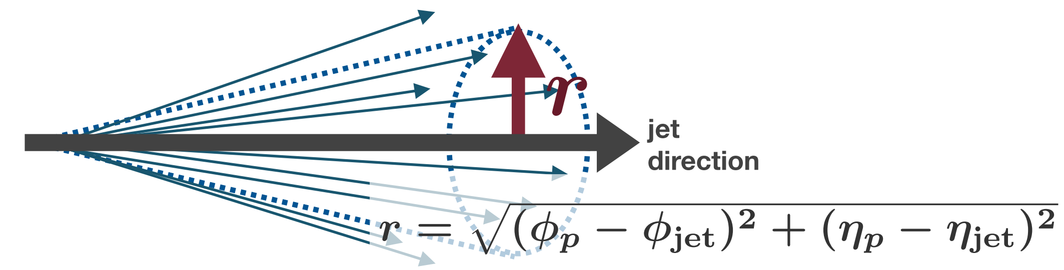

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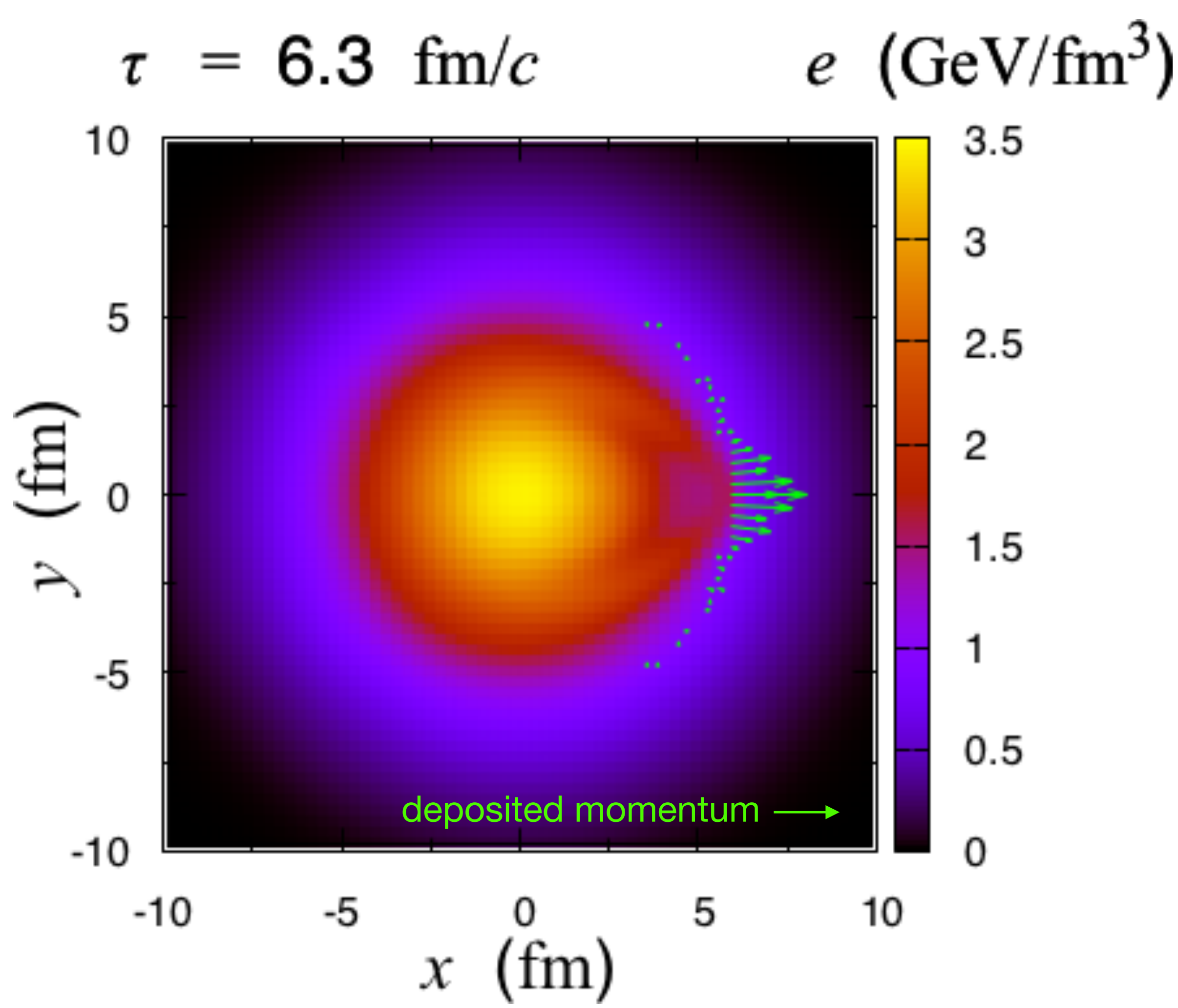

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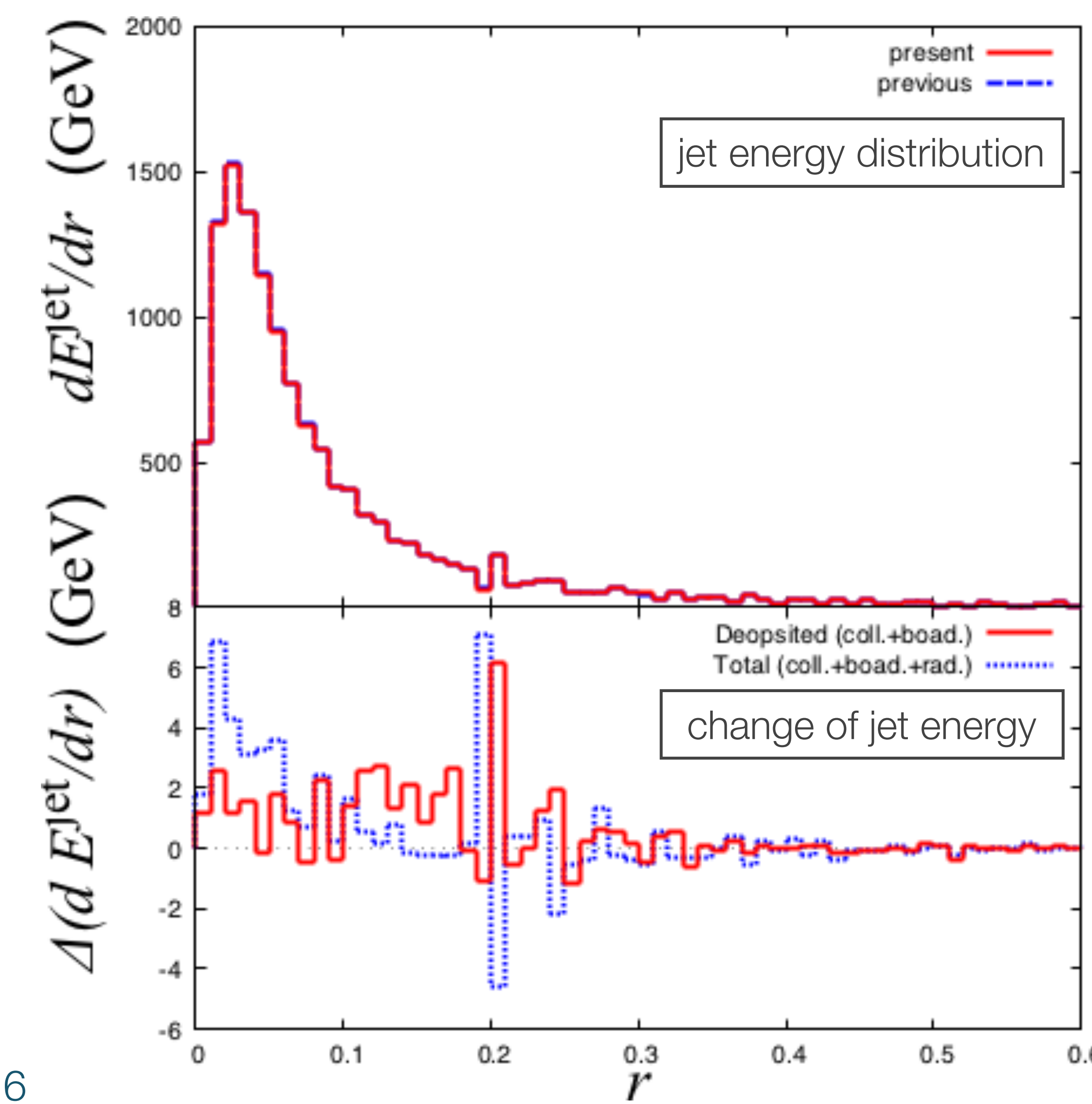

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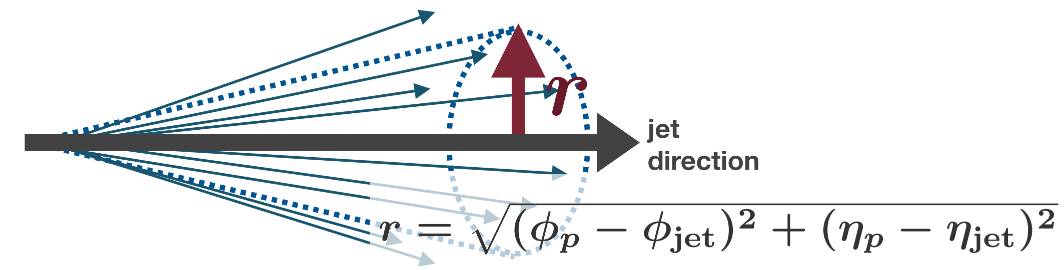

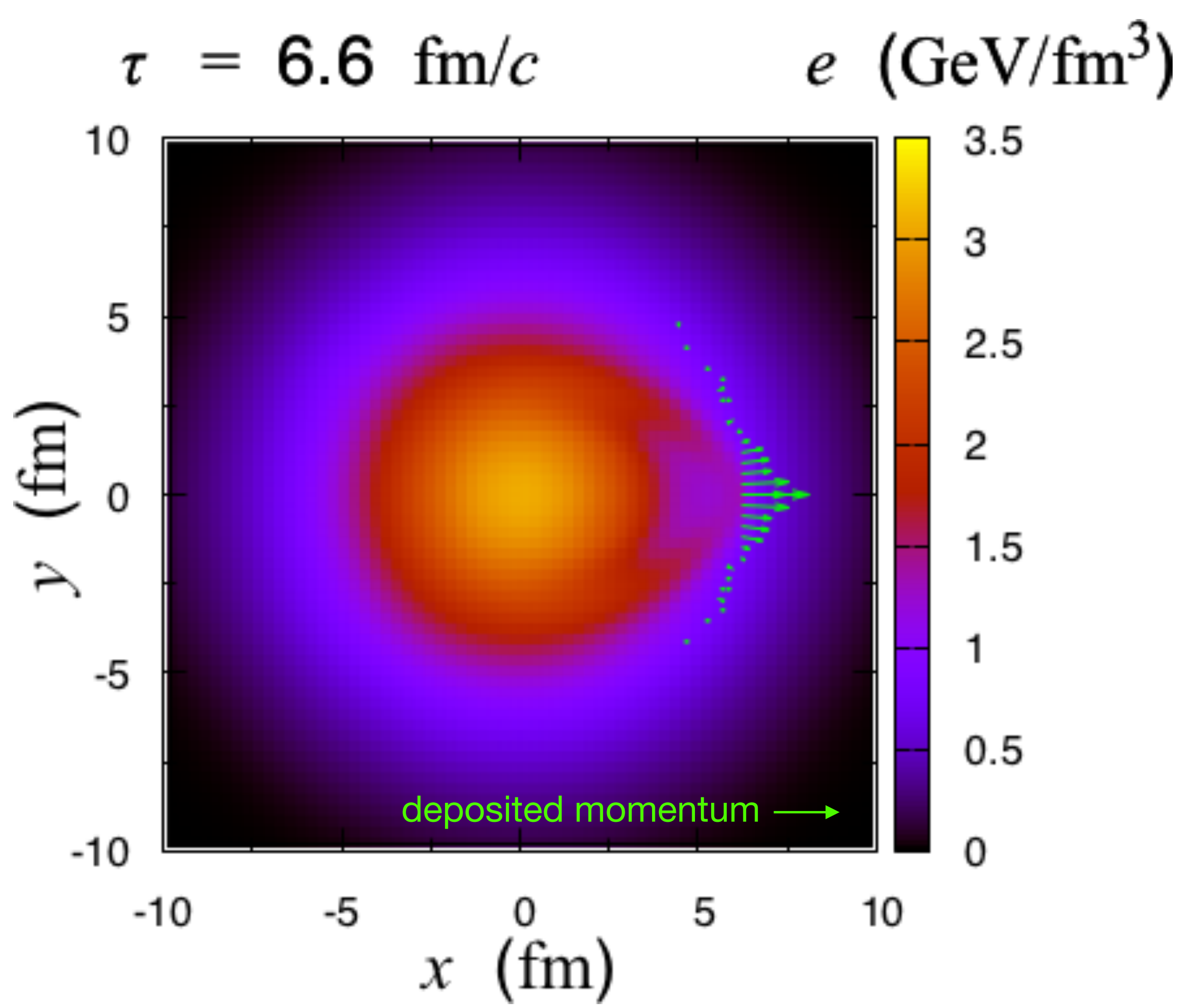

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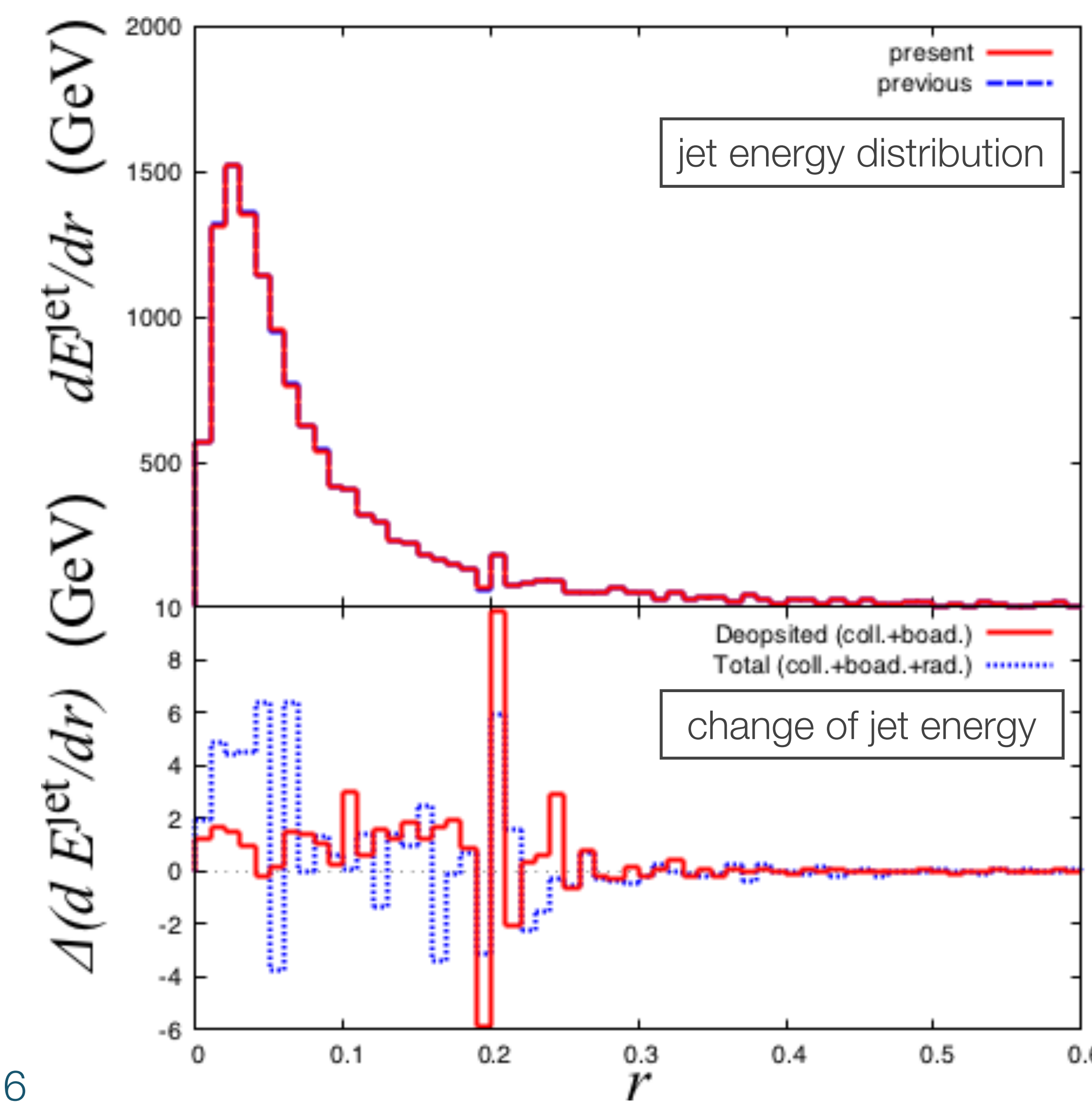

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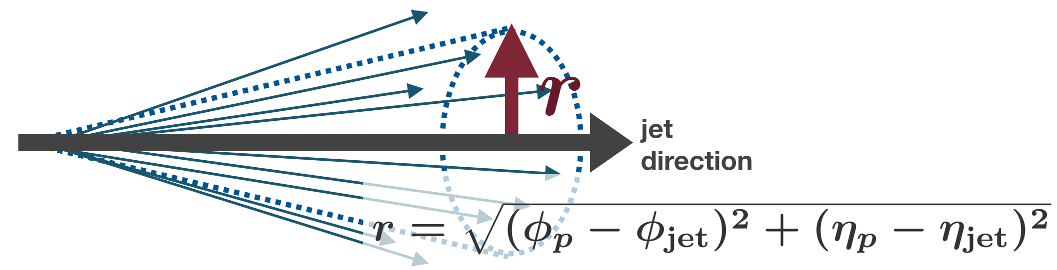

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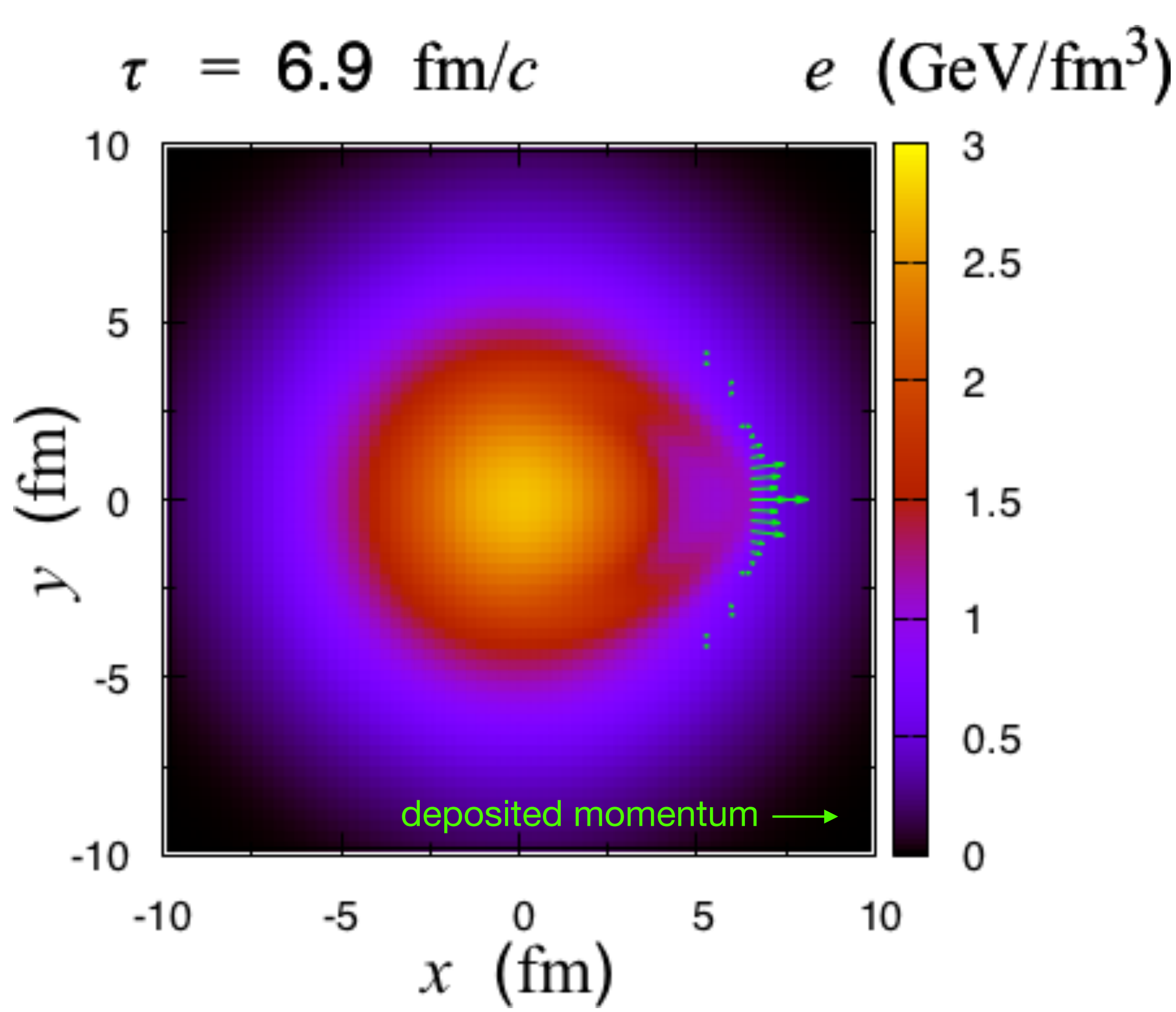

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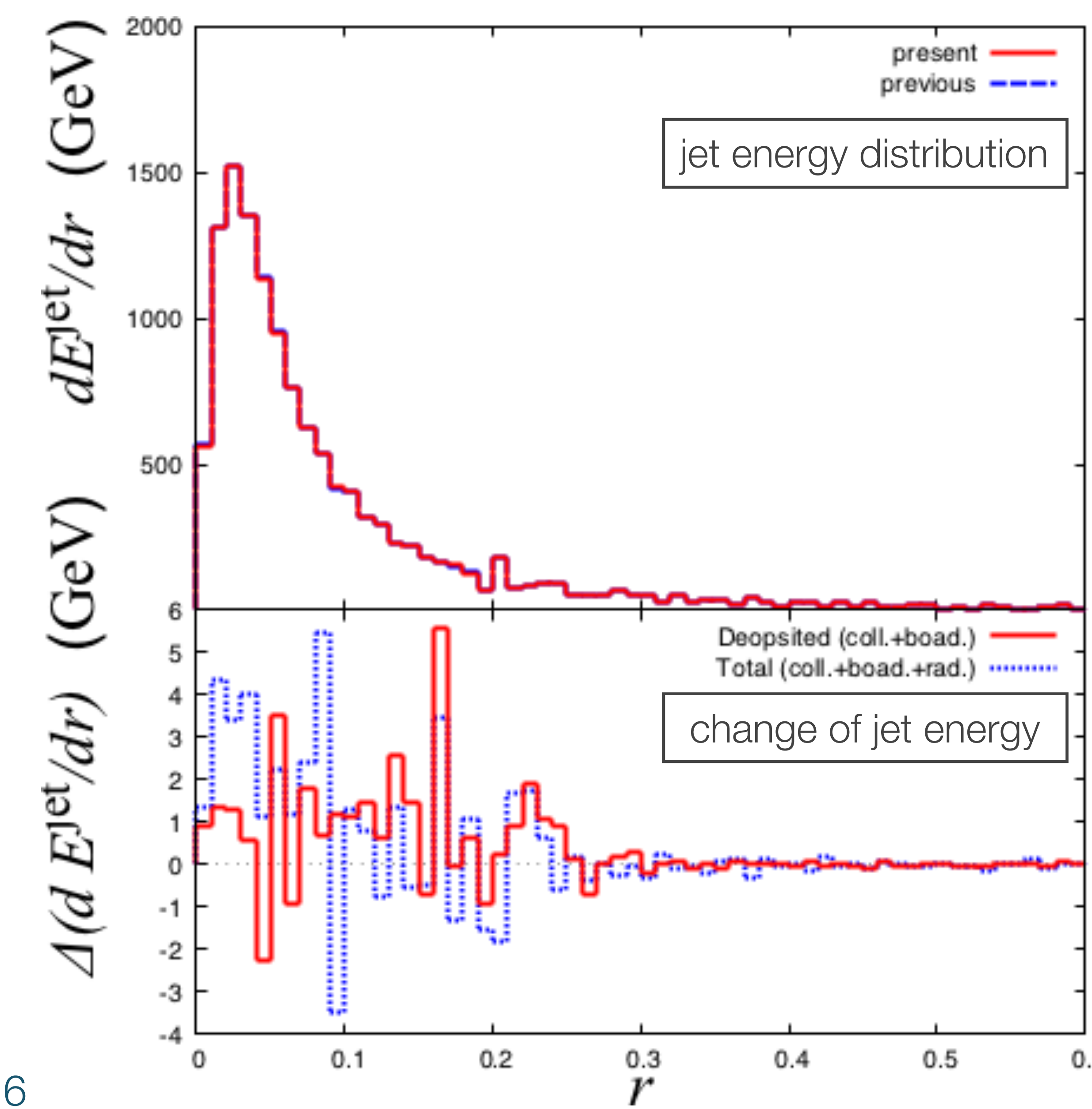

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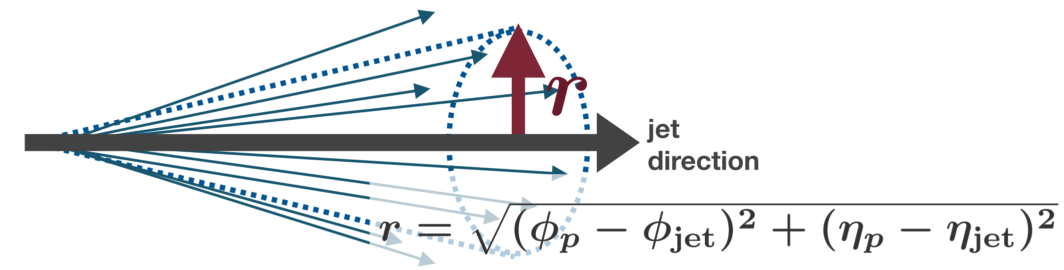

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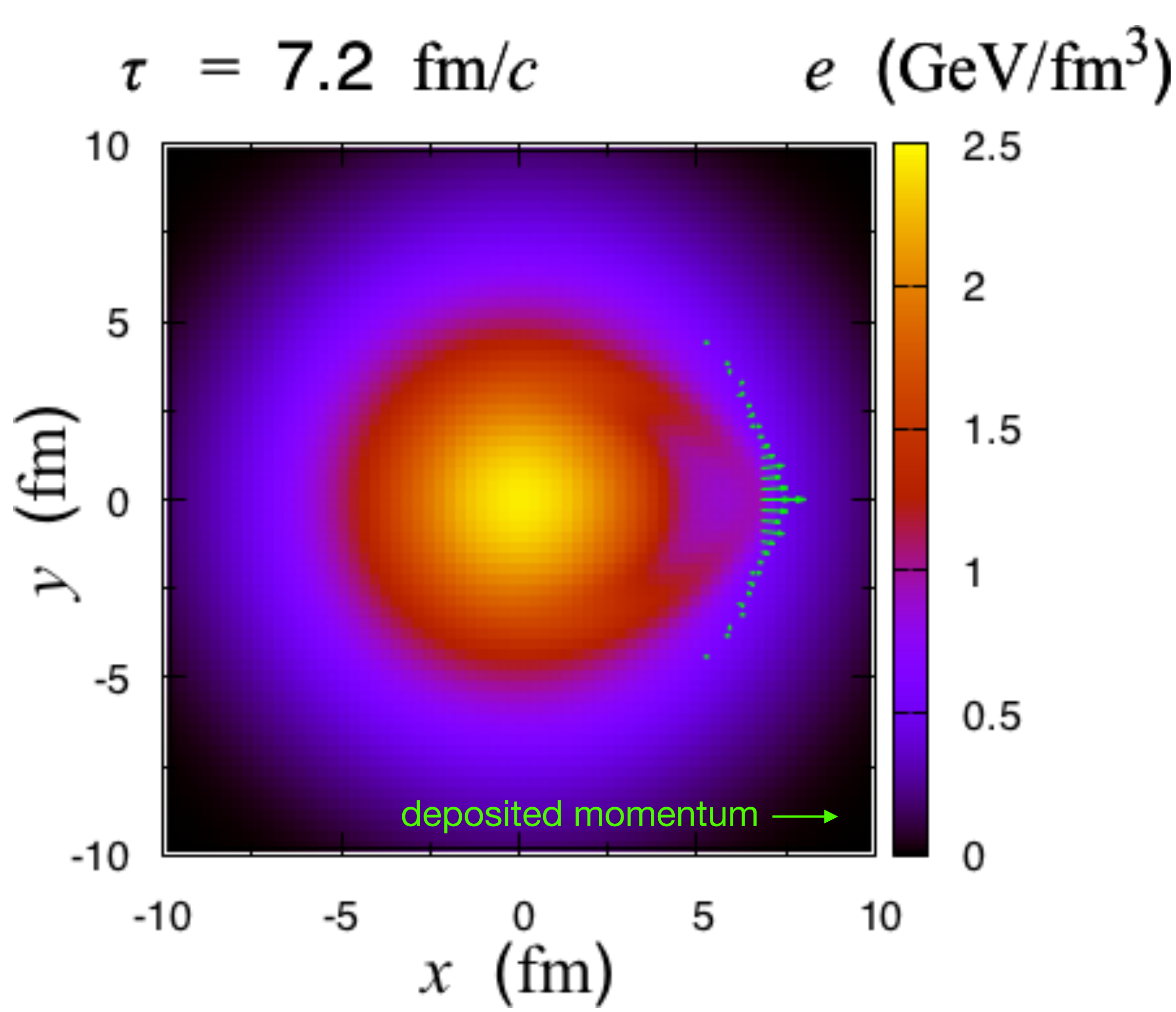

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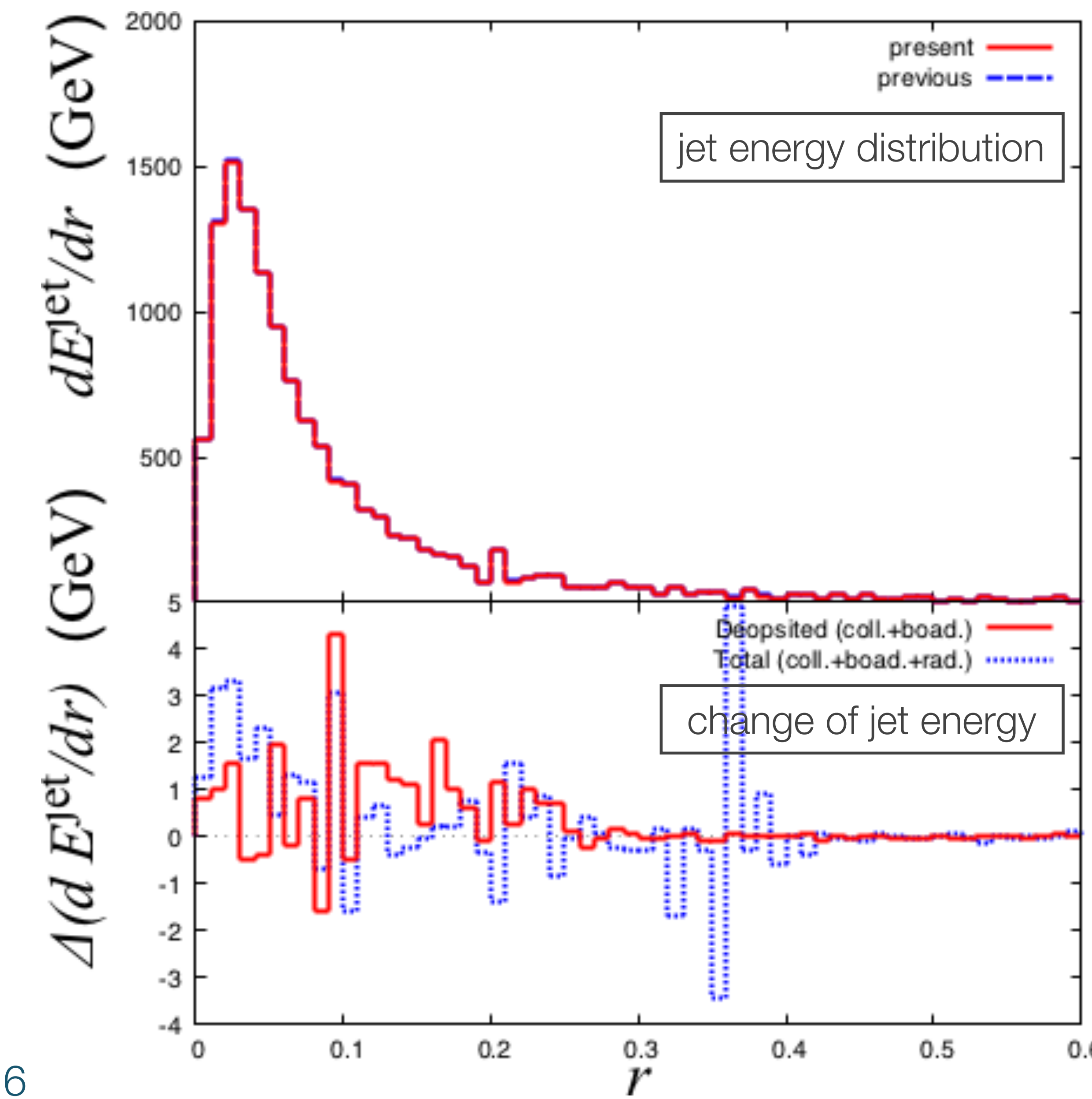
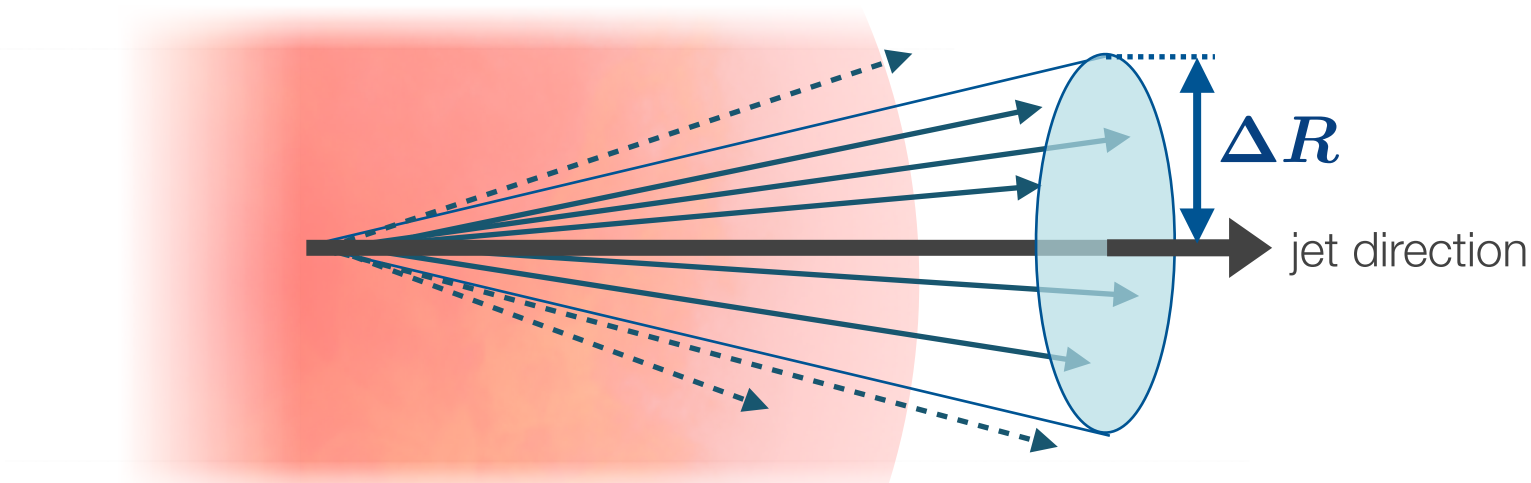


Medium contribution to jet energy loss

- **Contribution of particles emitted from excited medium**

(jets are generated by PYTHIA & MC Glauber)



ΔR: jet-cone size

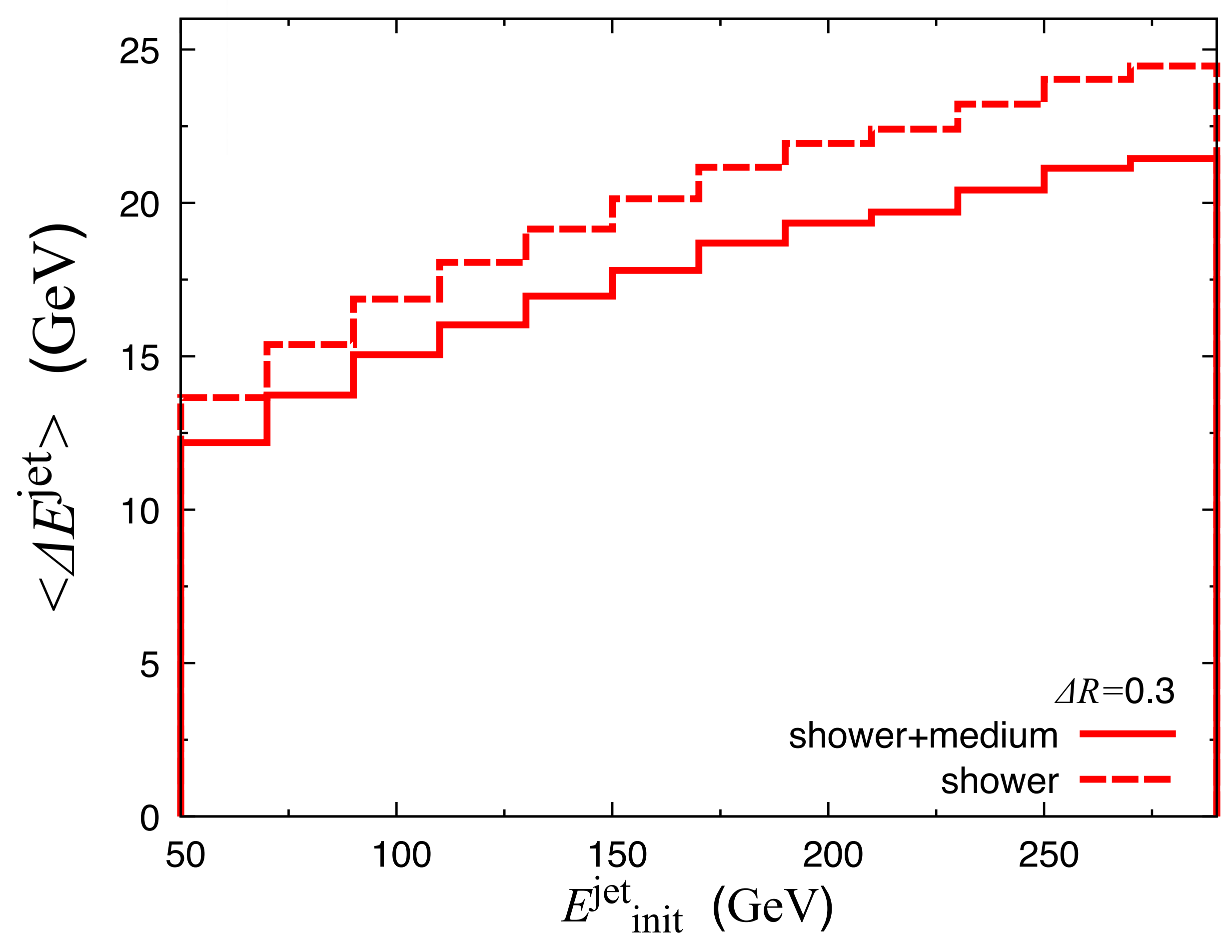
$$r = \sqrt{(\eta_p - \eta_{\rm jet})^2 + (\phi_p - \phi_{\rm jet})^2} < \Delta R$$

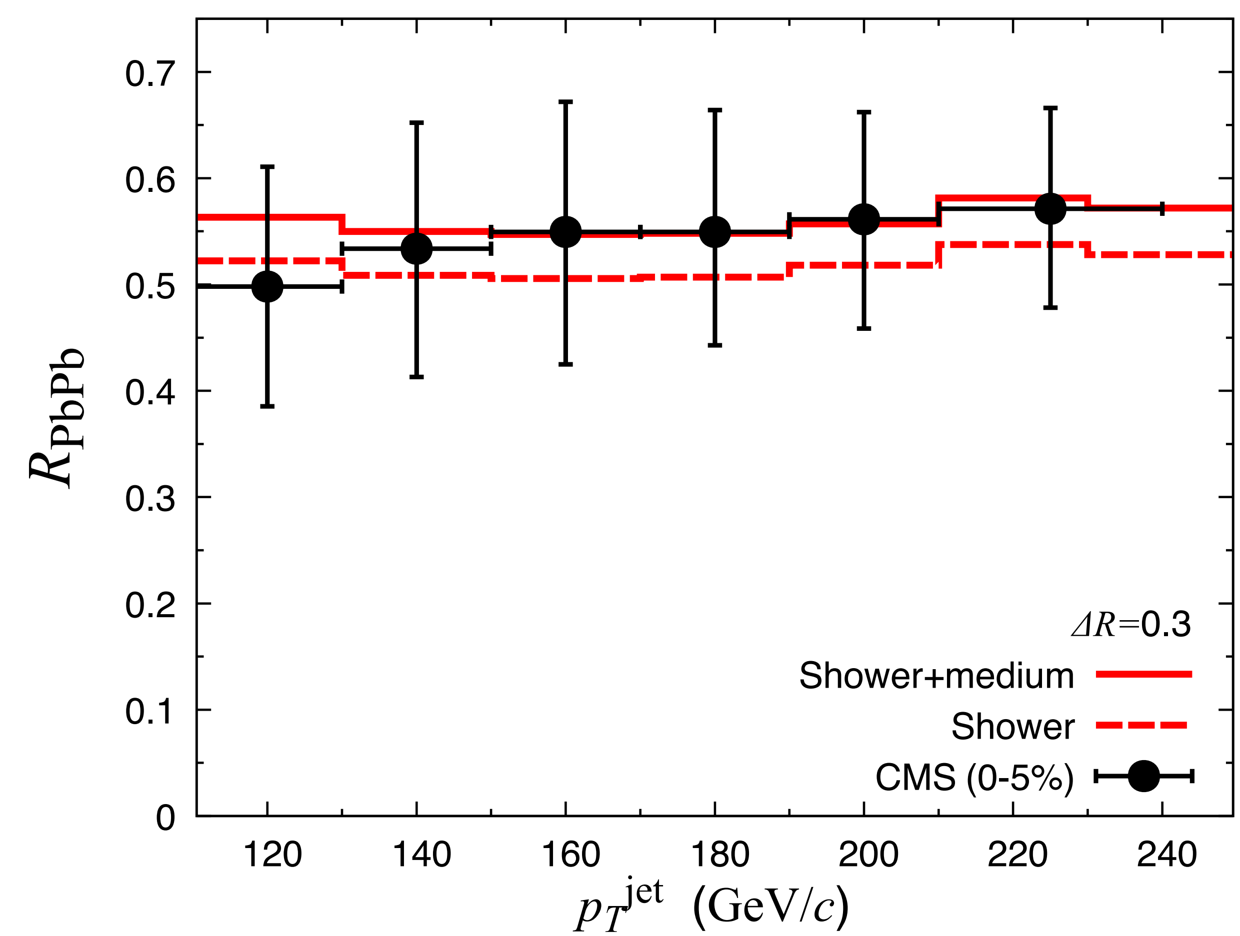
⟶ counted as part of jet

The nuclear modification factor

$$R_{\rm PbPb} = \frac{1}{\langle N_{\rm coll}\rangle} \frac{d^2N_{\rm PbPb}/d\eta_p dp_T^{\rm jet}}{d^2N_{\rm pp}/d\eta_p dp_T^{\rm jet}},$$

Total Energy Loss





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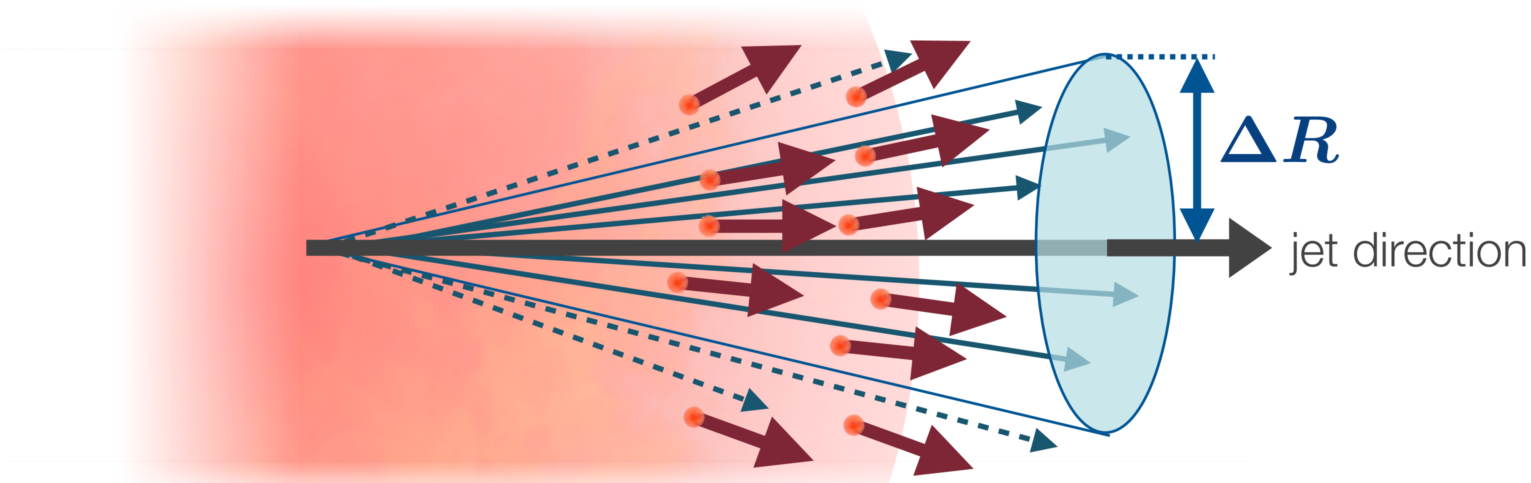

ΔR: jet-cone size

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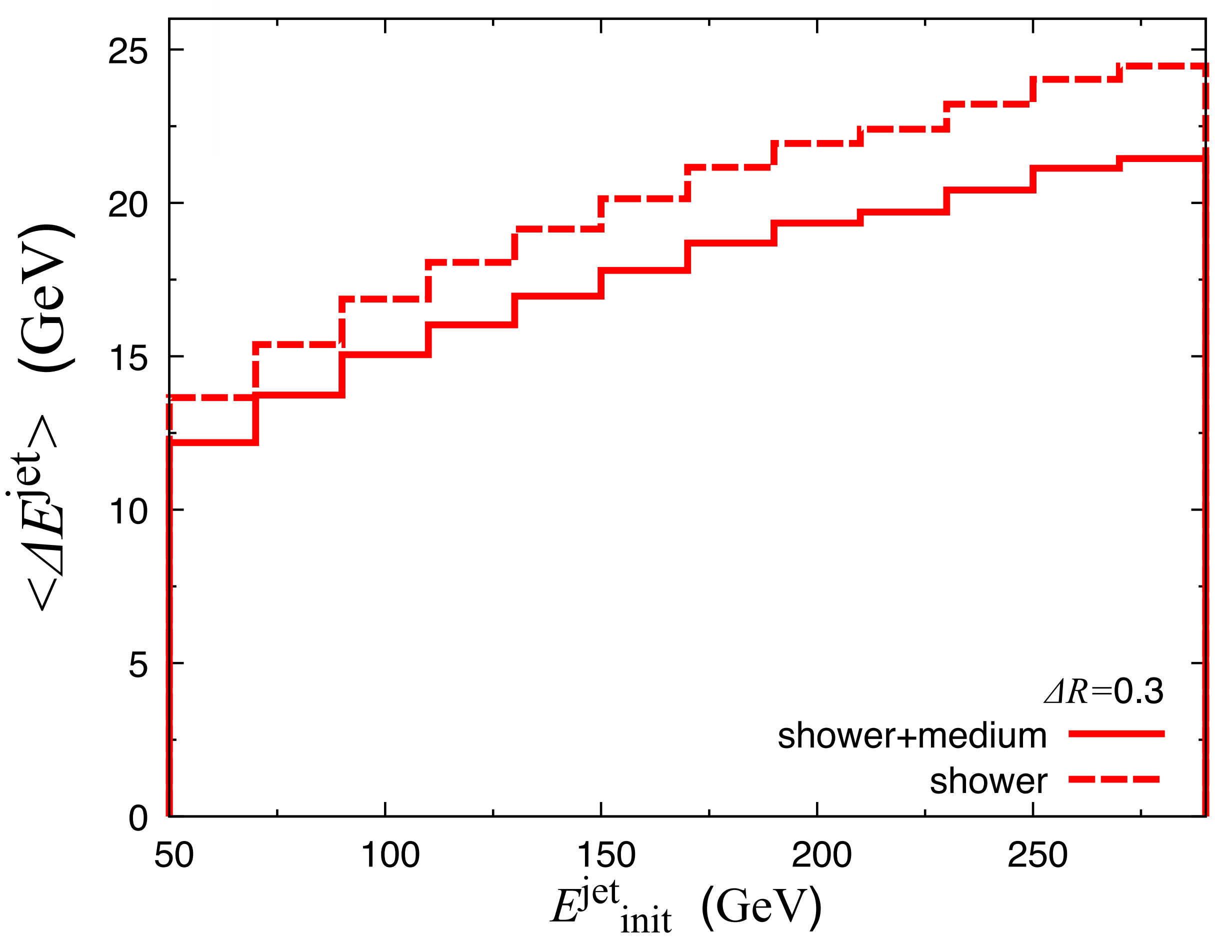

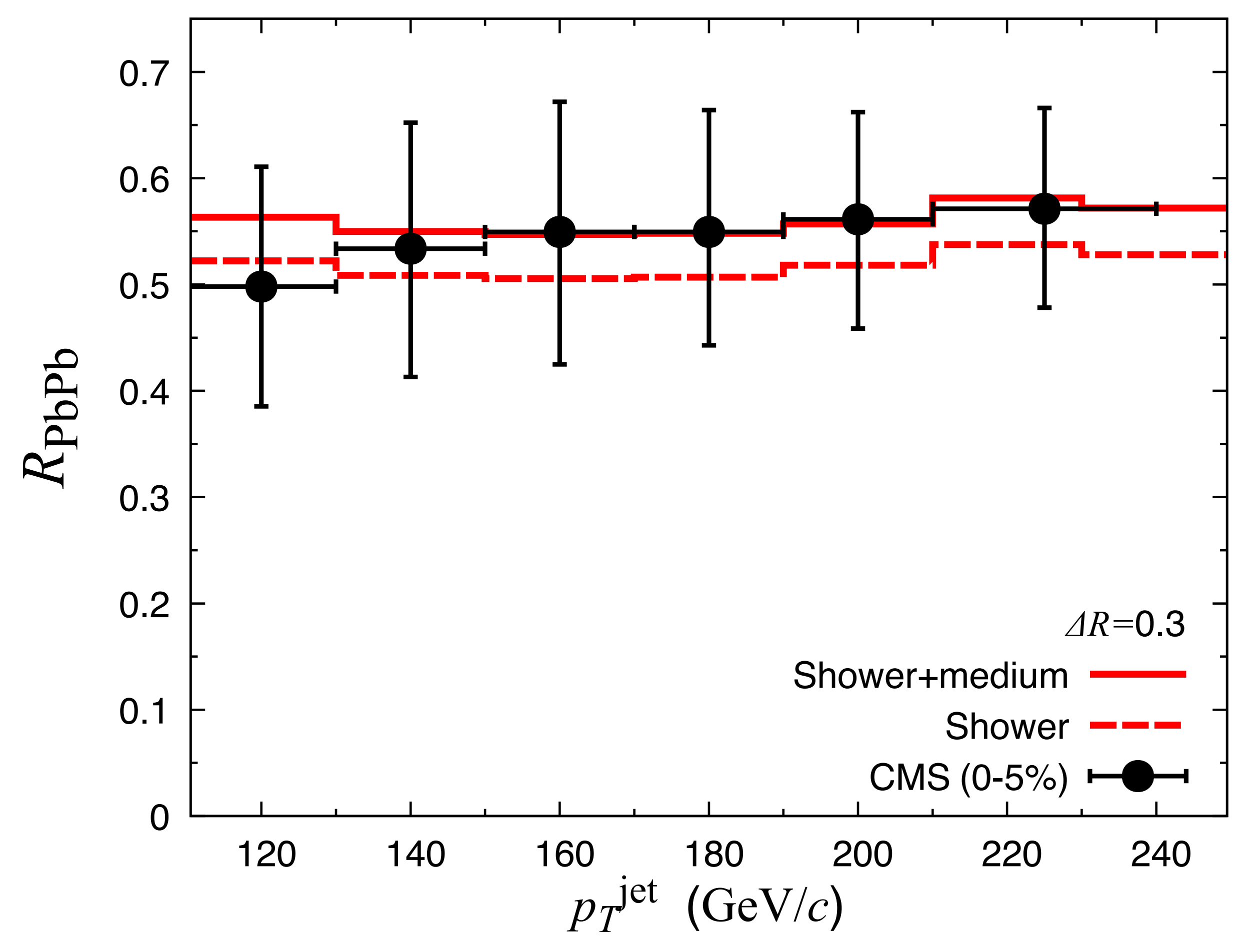

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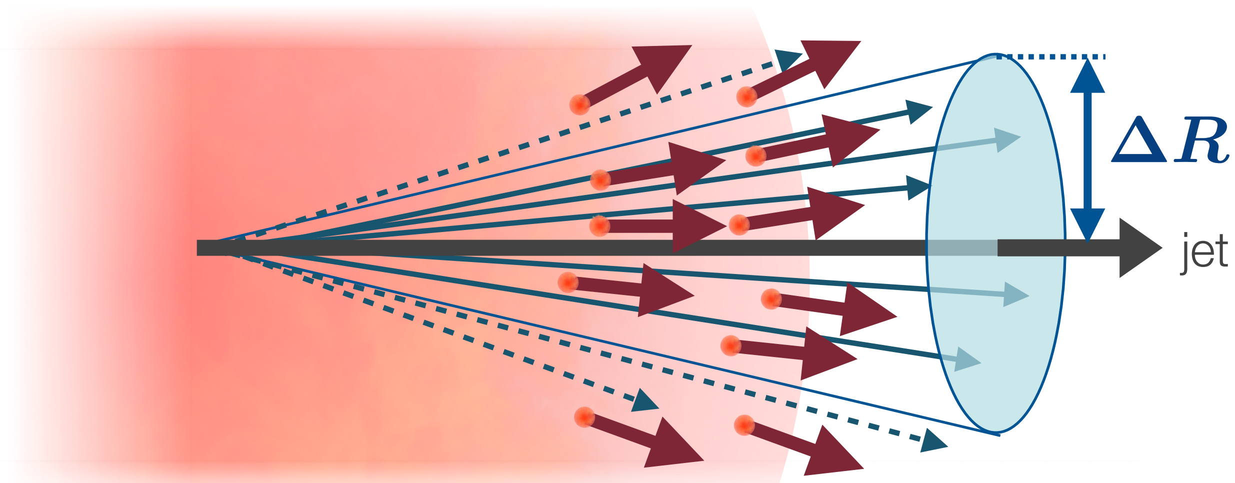

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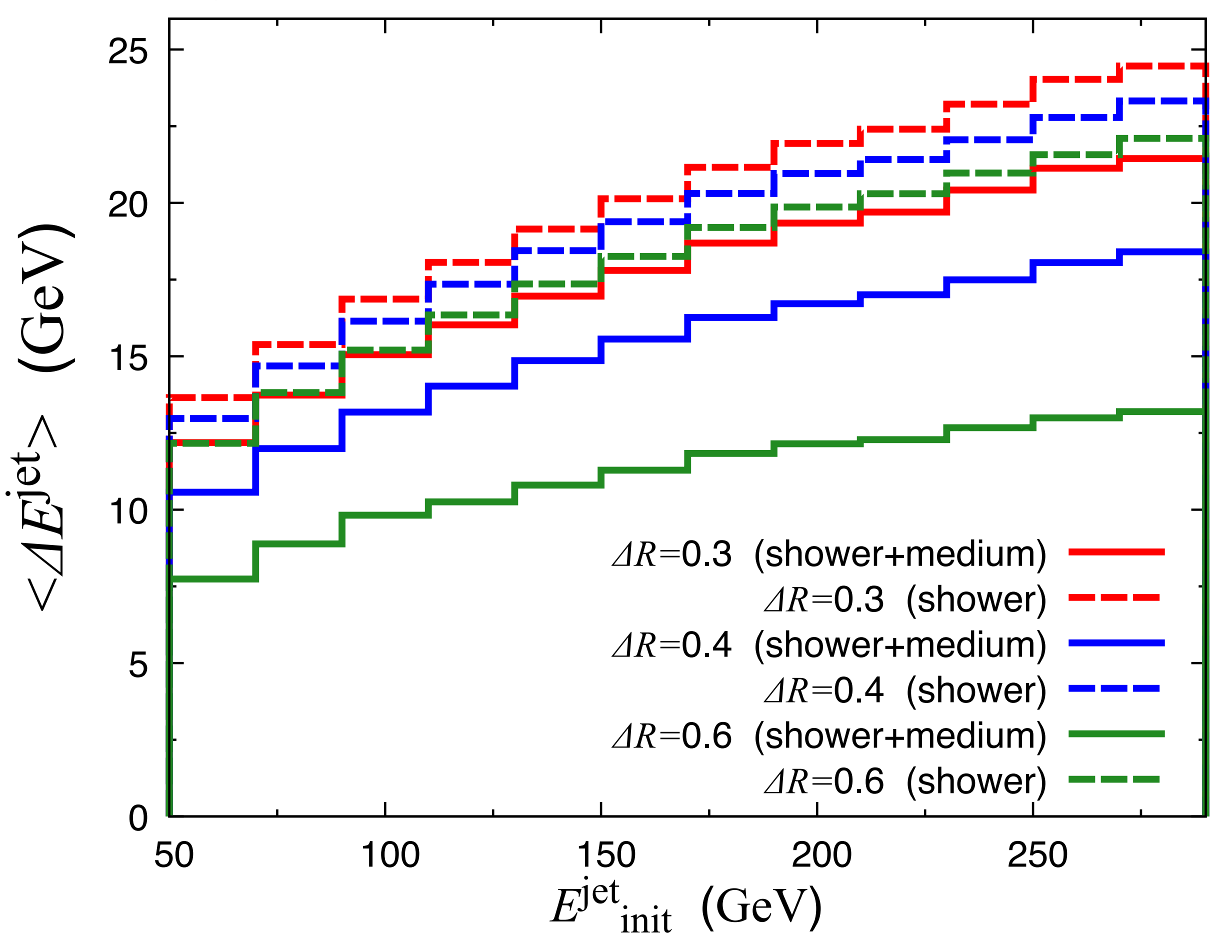

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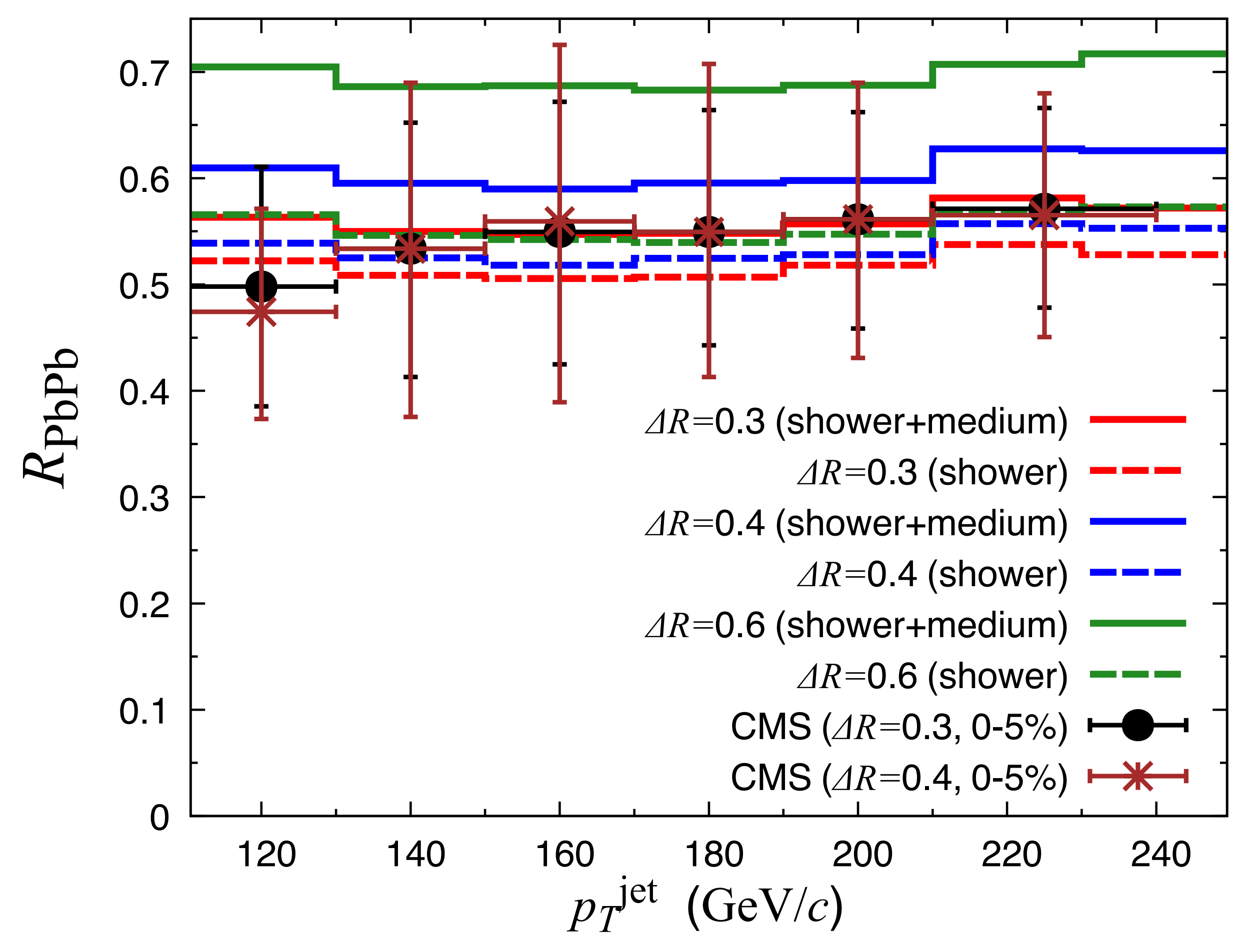

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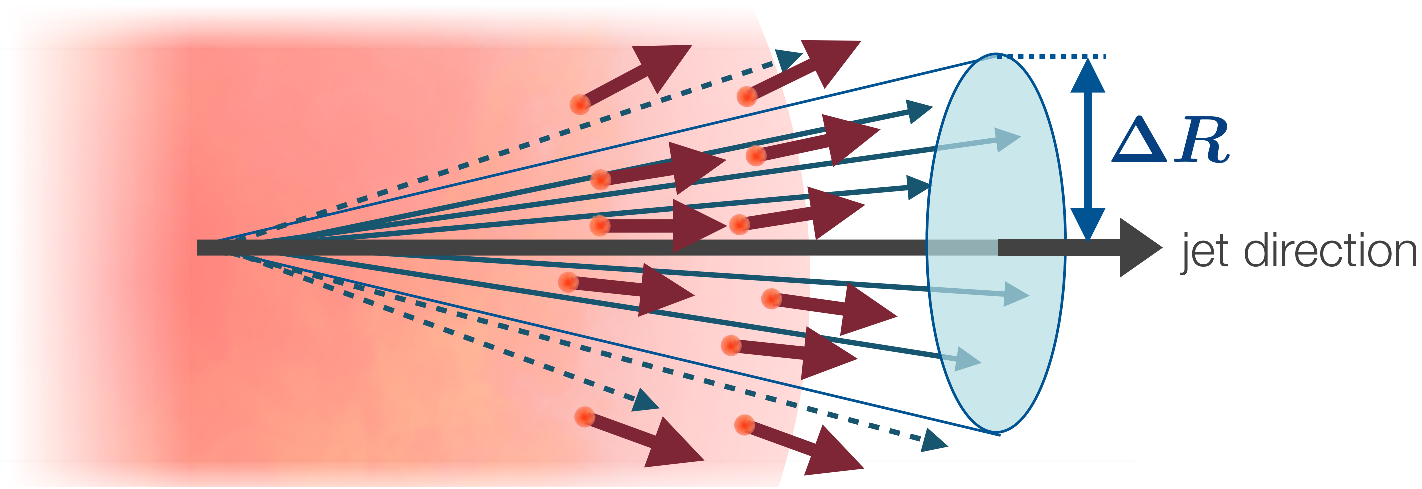
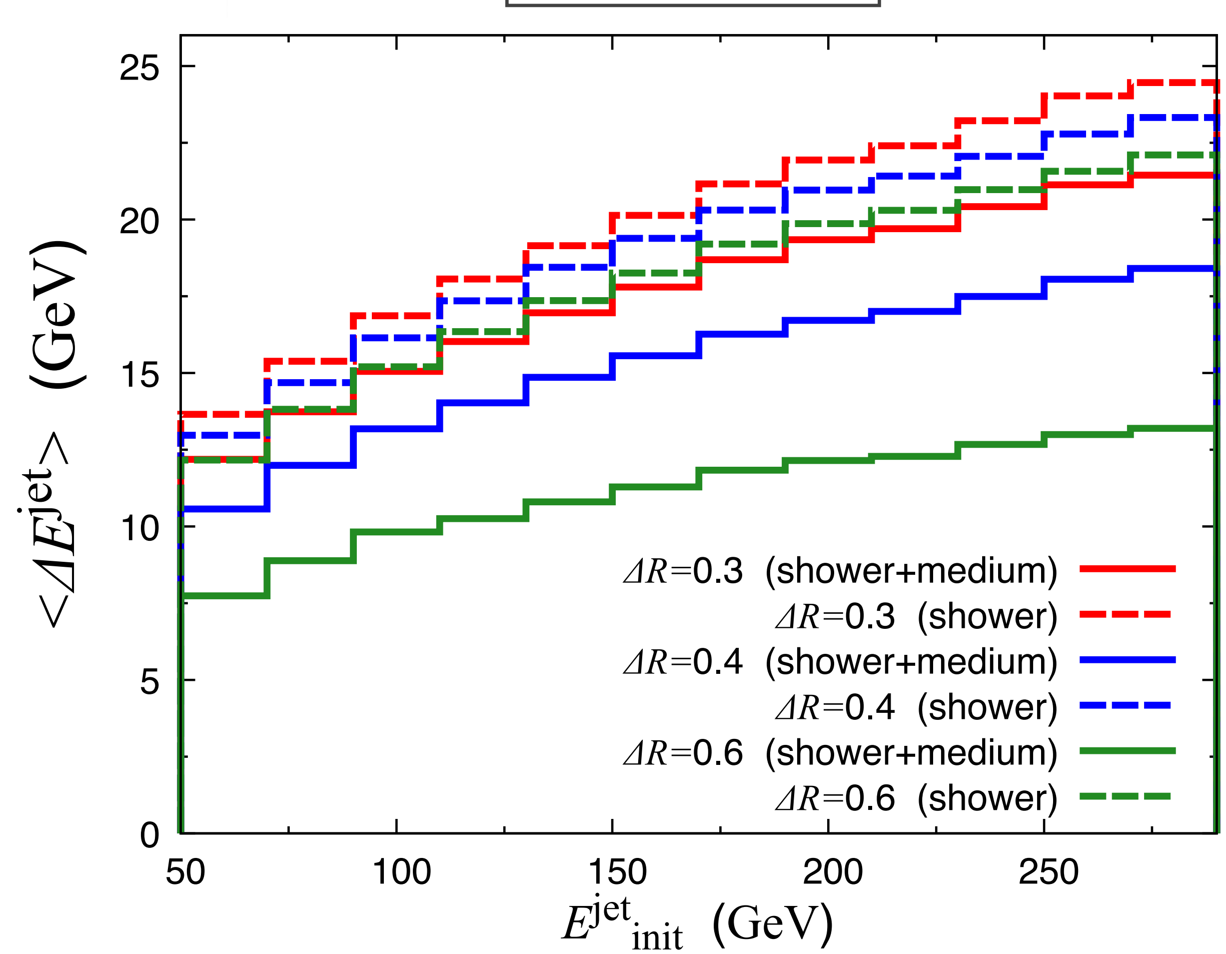


ΔR: jet-cone size

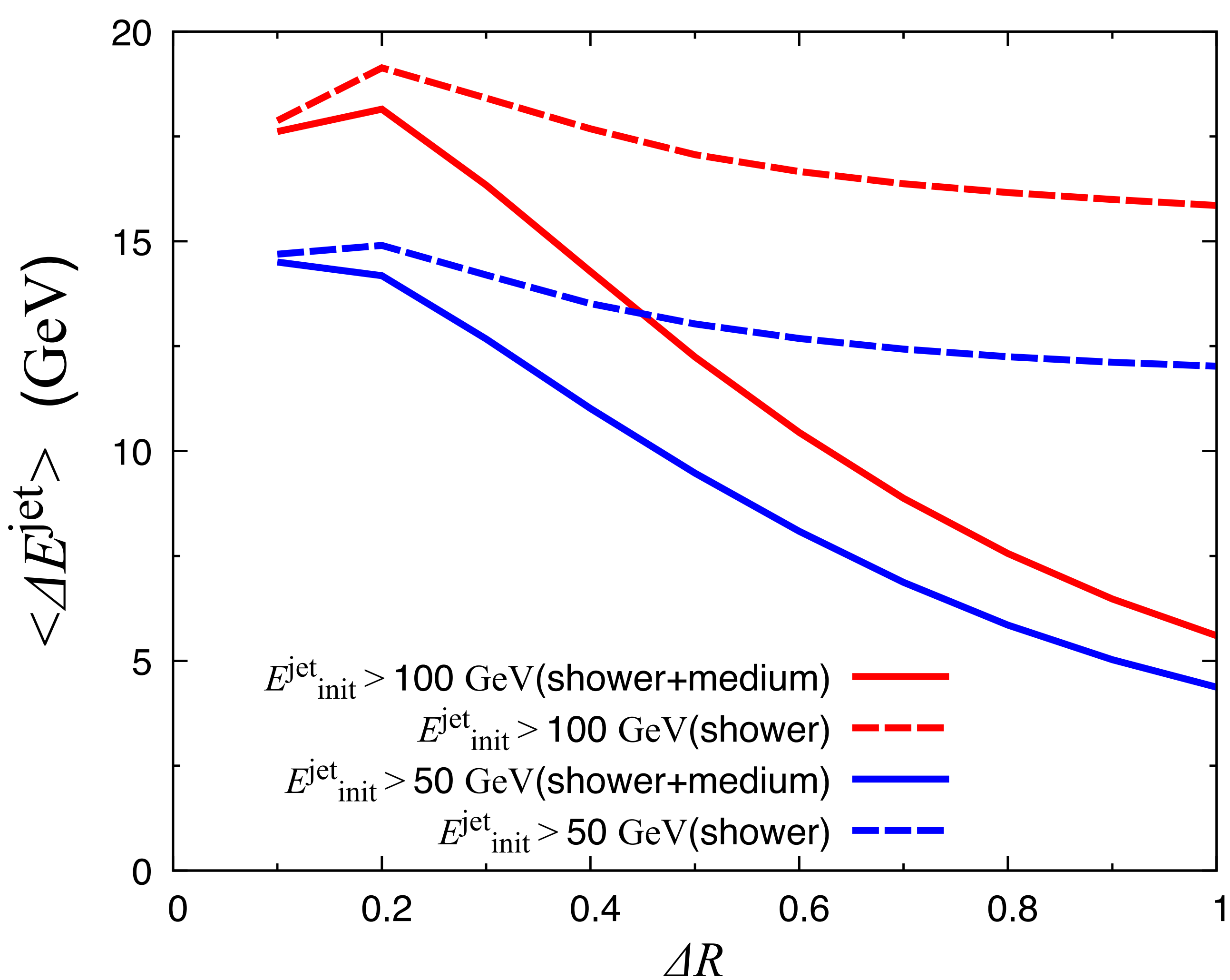
$$r = \sqrt{(\eta_p - \eta_{\mathrm{jet}})^2 + (\phi_p - \phi_{\mathrm{jet}})^2} < \Delta R$$

→ counted as part of jet

Total Energy Loss



Jet-cone Size Dependence



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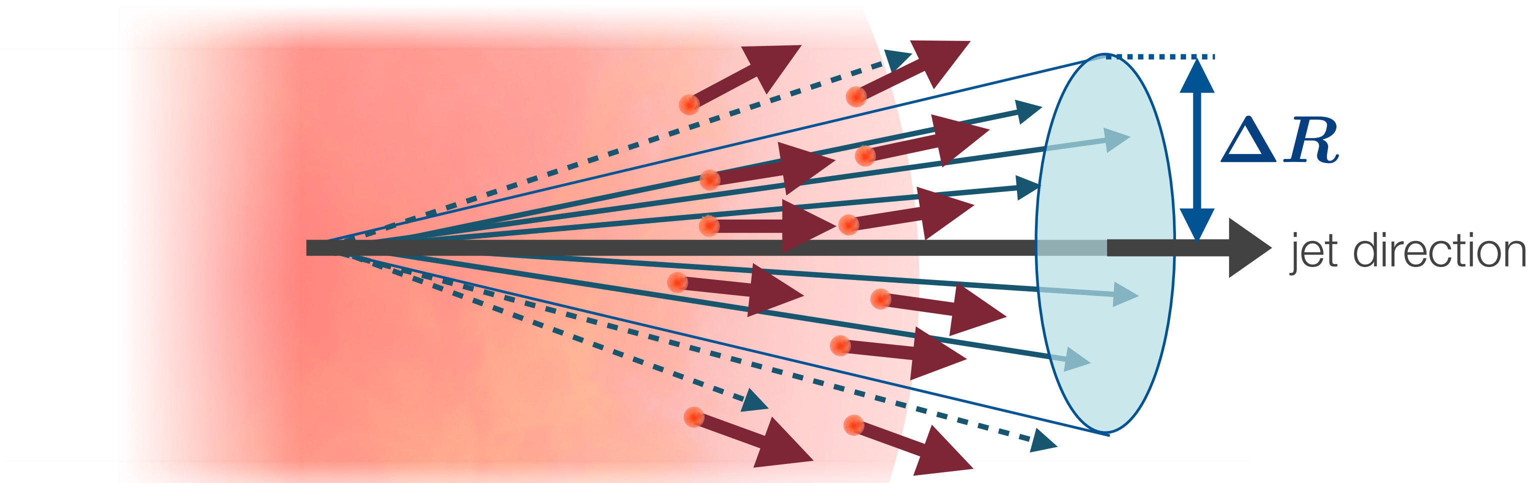

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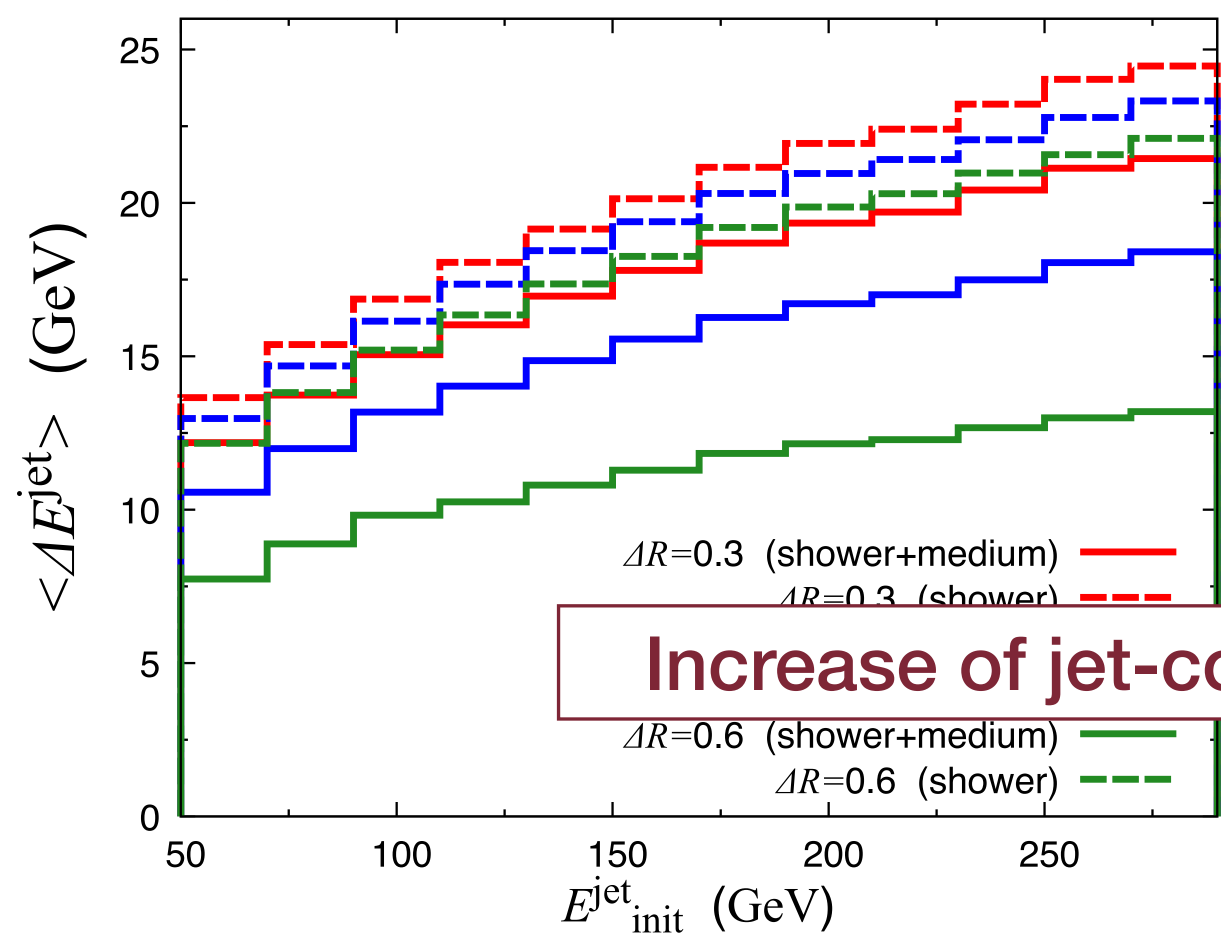
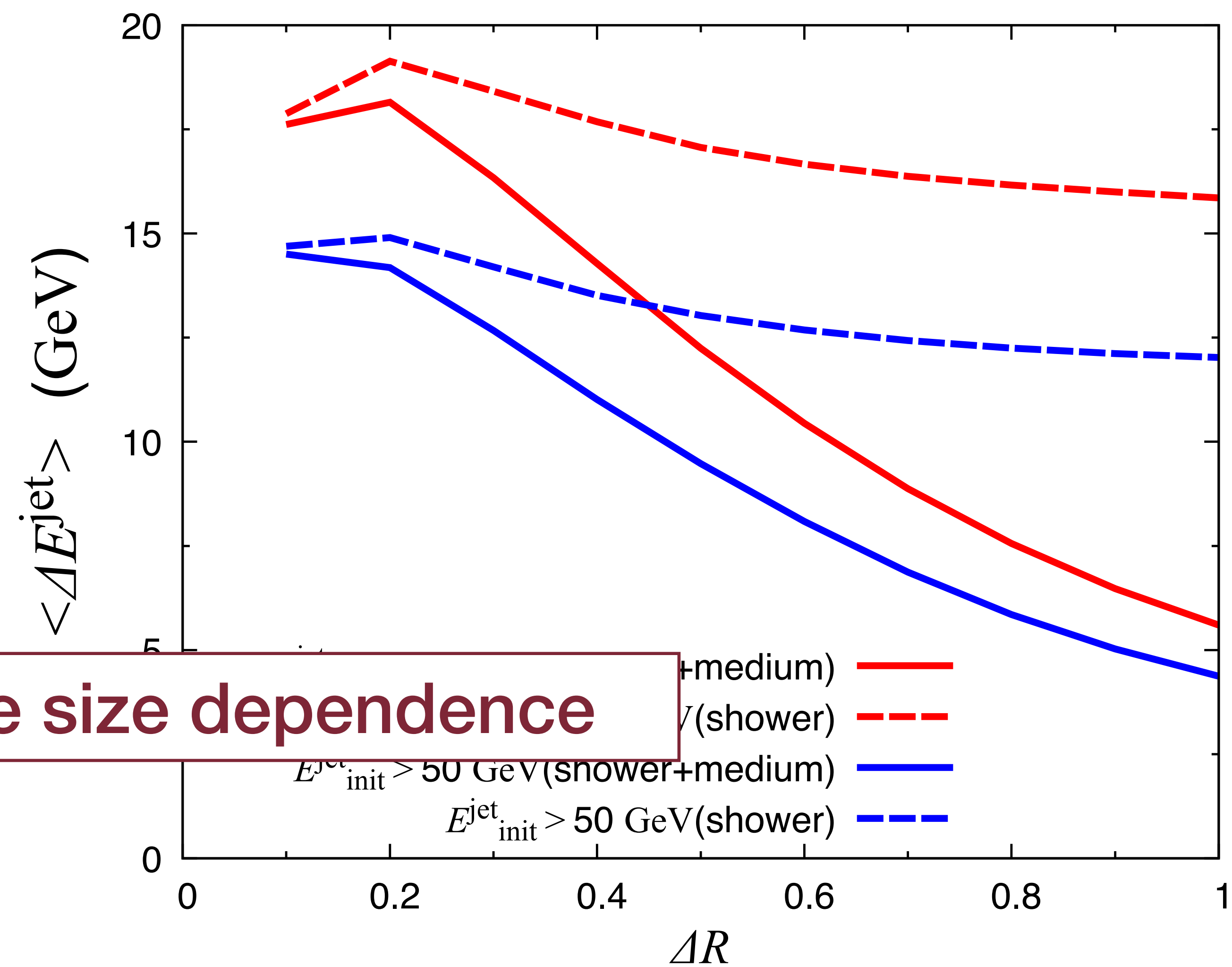




Increase of jet-cone size dependence

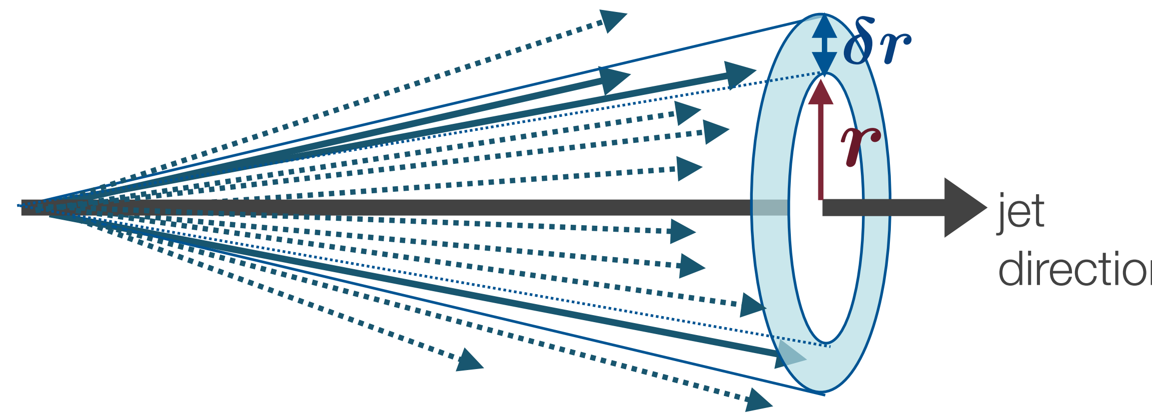
Jet shape modification

- **Jet shape function**

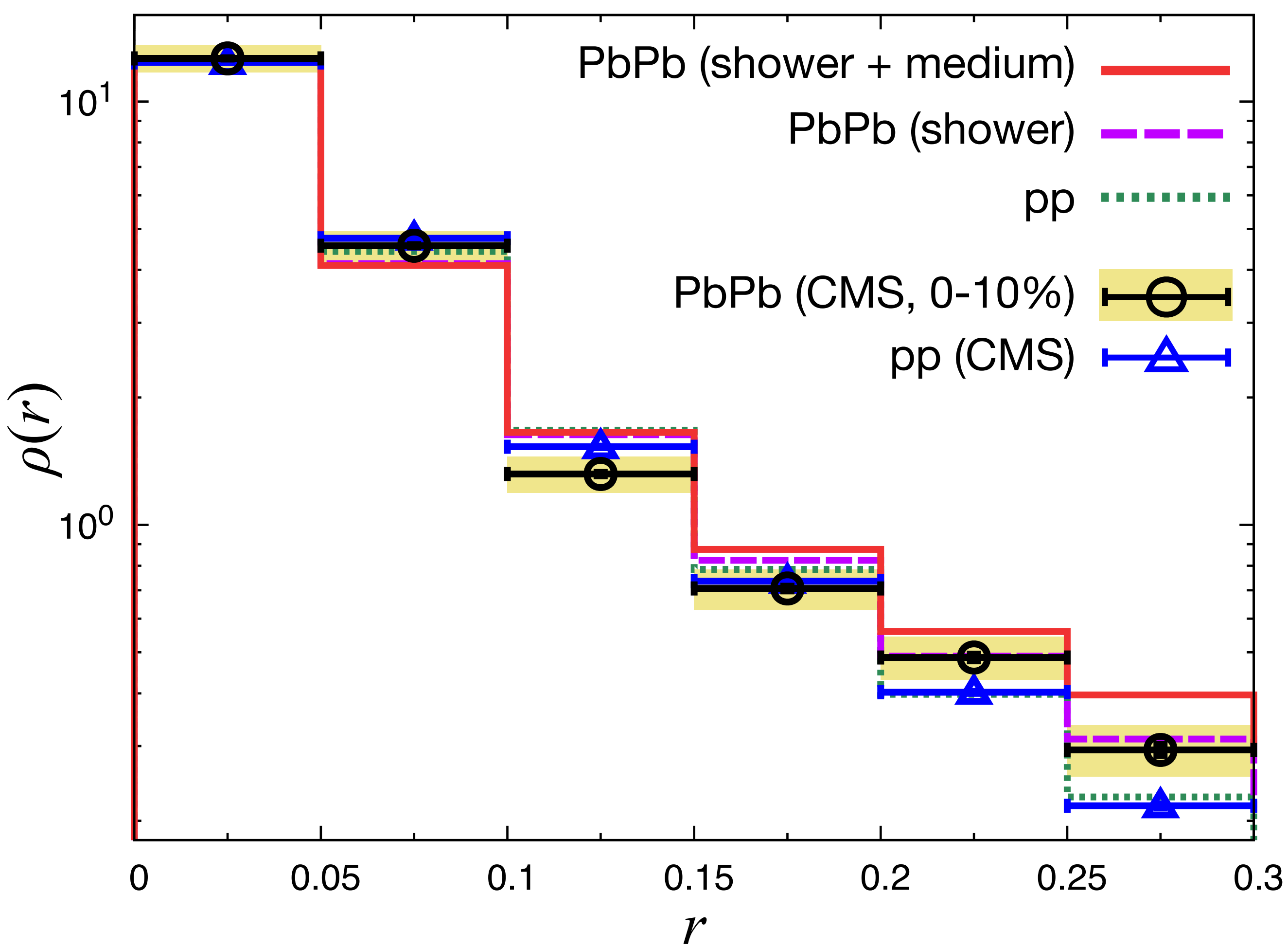
(jets are generated by PYTHIA & MC Glauber)

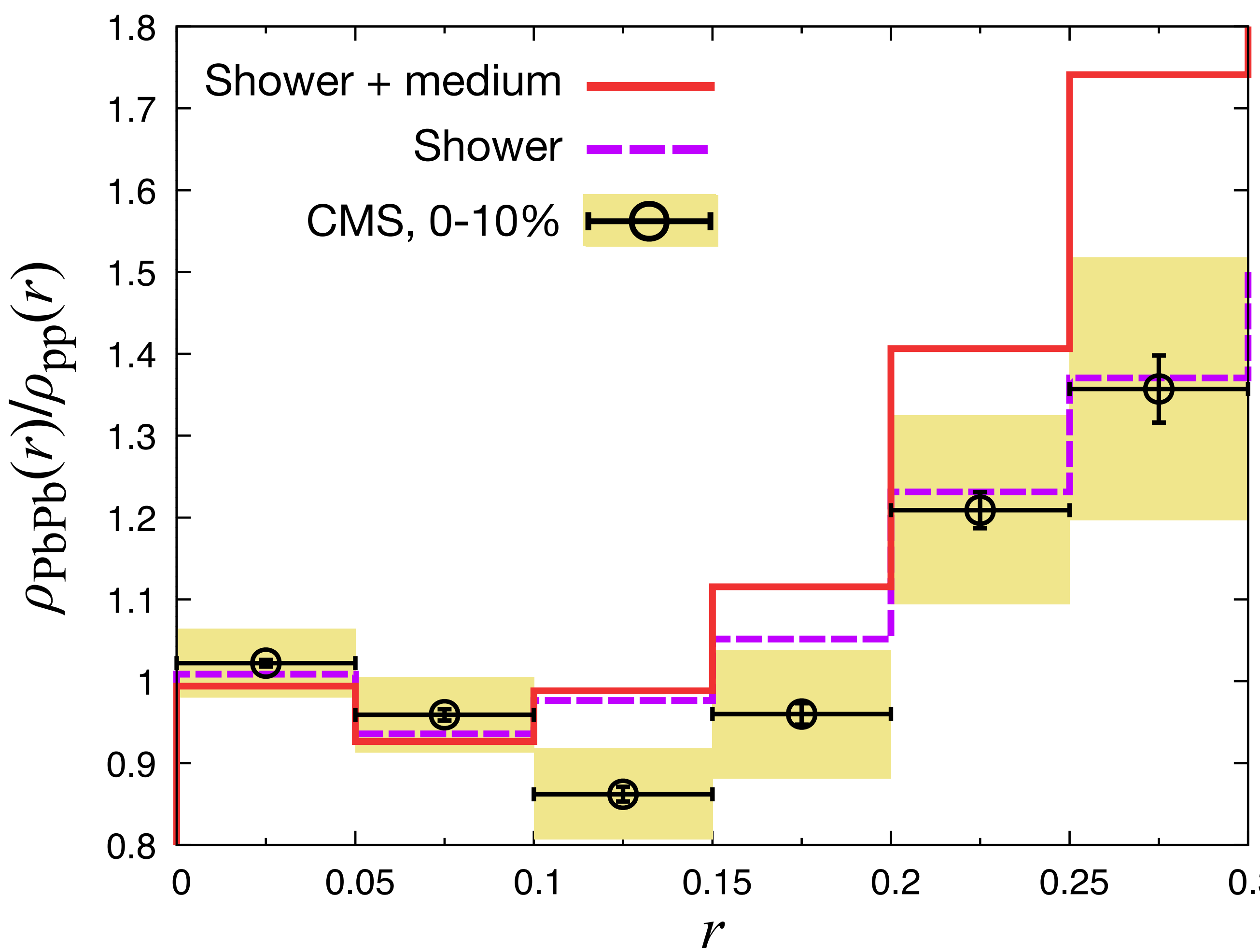
$$r = \sqrt{(\phi_p - \phi_{\rm jet})^2 + (\eta_p - \eta_{\rm jet})^2}$$

$$\rho(r) = \sum_i \frac{p_T^i}{p_T^{\rm jet}} \frac{\theta[r_i - (r - \frac{1}{2}\delta r)]\theta[(r + \frac{1}{2}\delta r) - r_i]}{\delta r}$$



- Inclusive, $E_{\rm jet} \geq 100\,{\rm GeV}\ (\Delta R = 0.3)$





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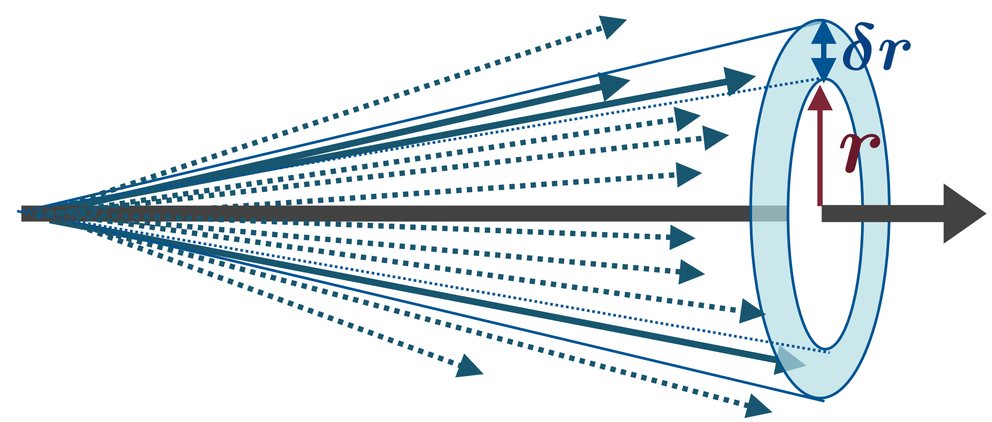

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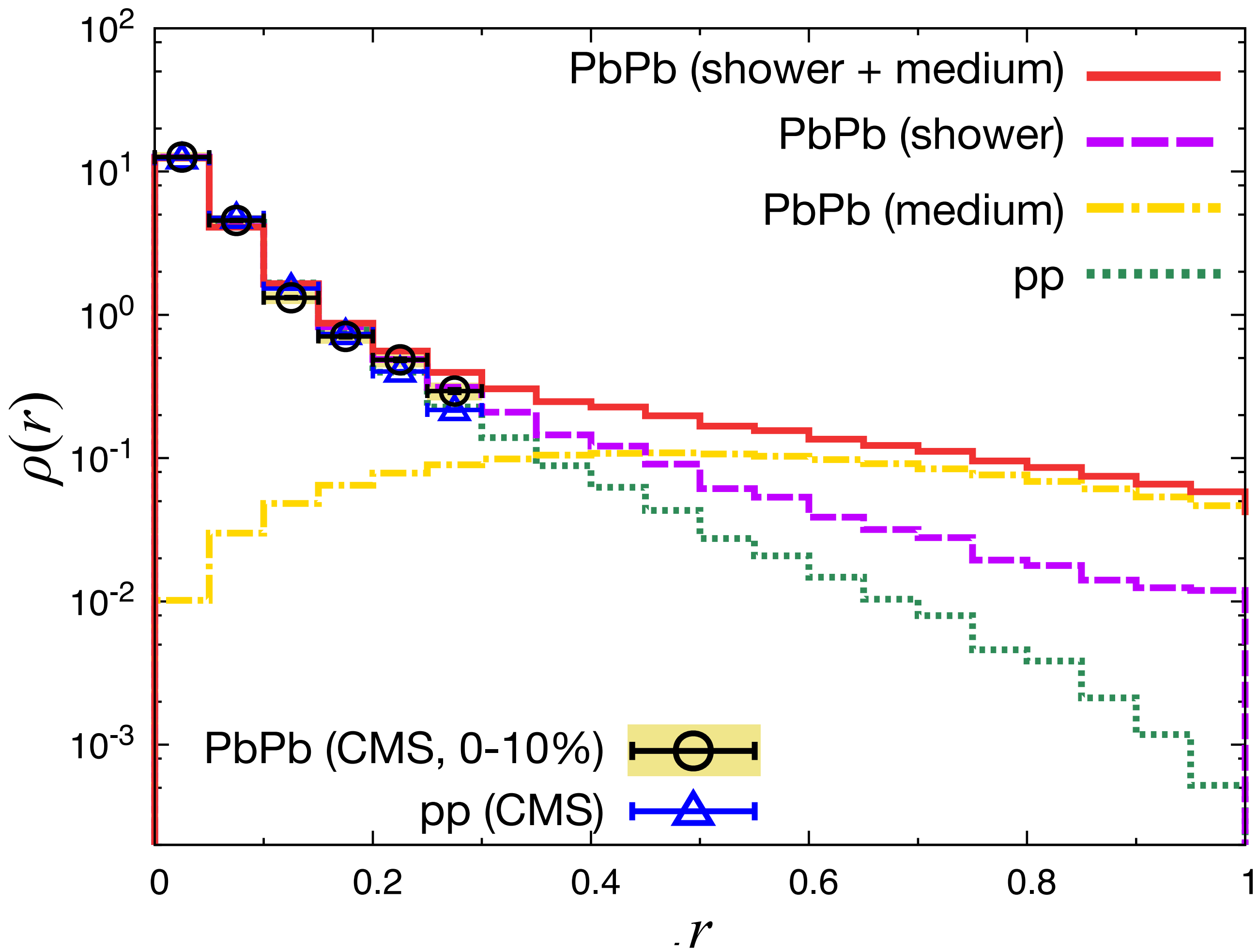

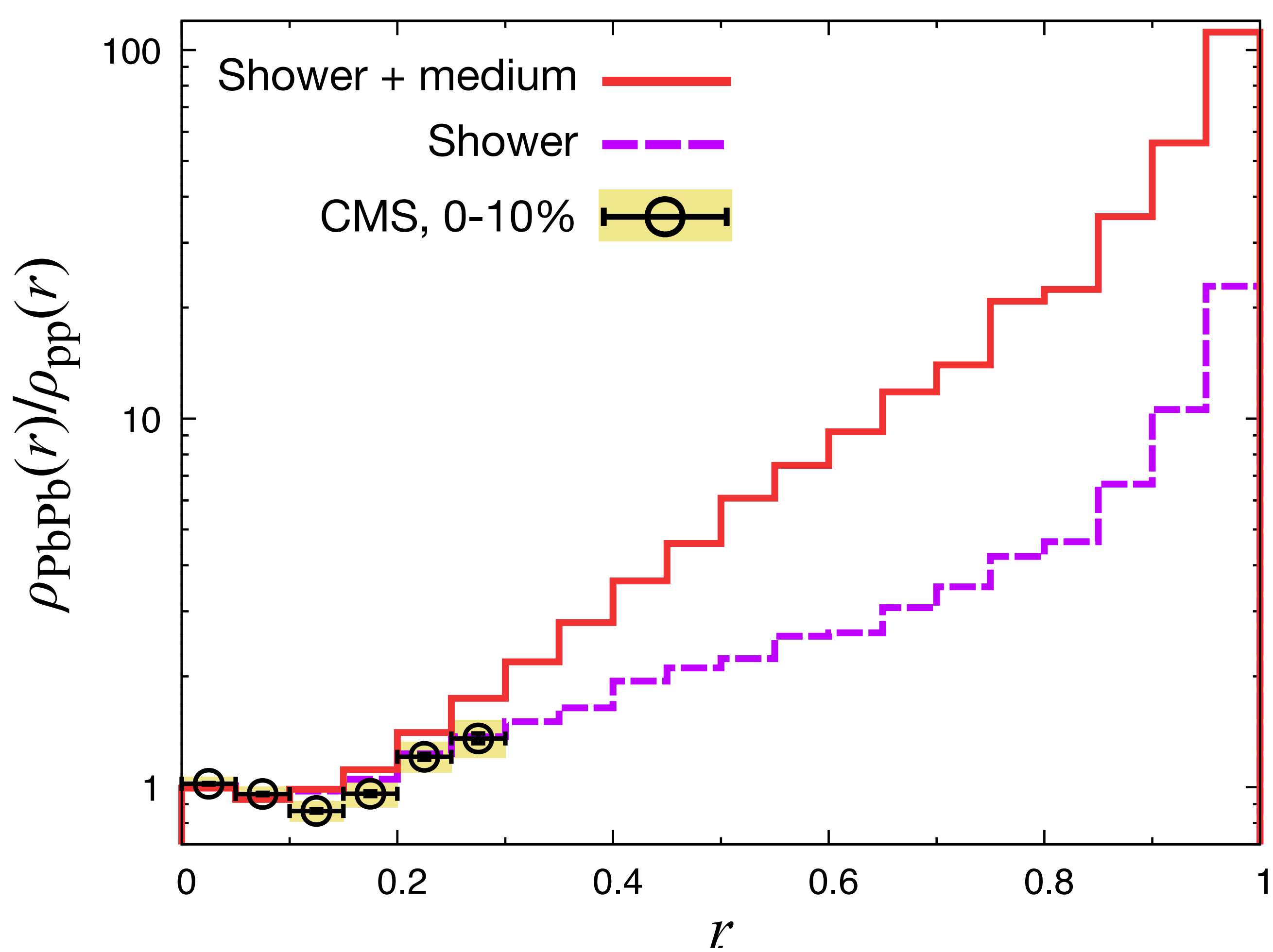

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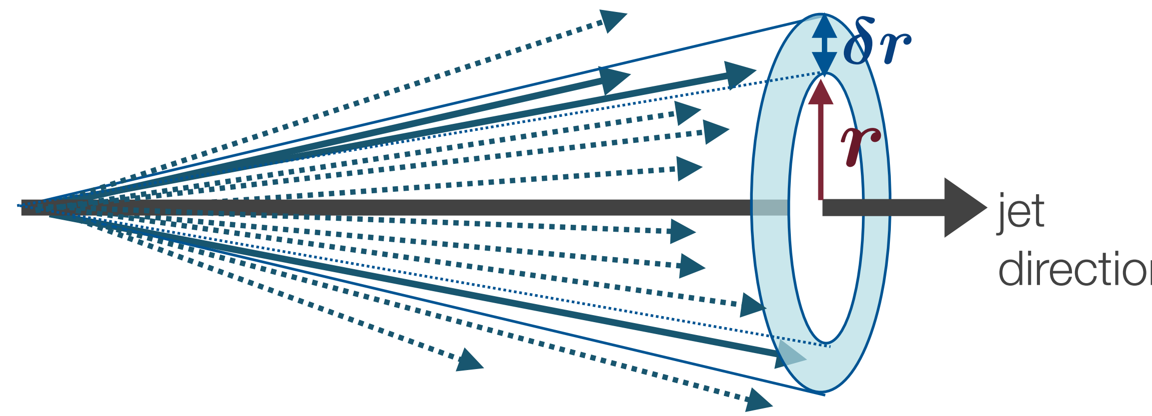

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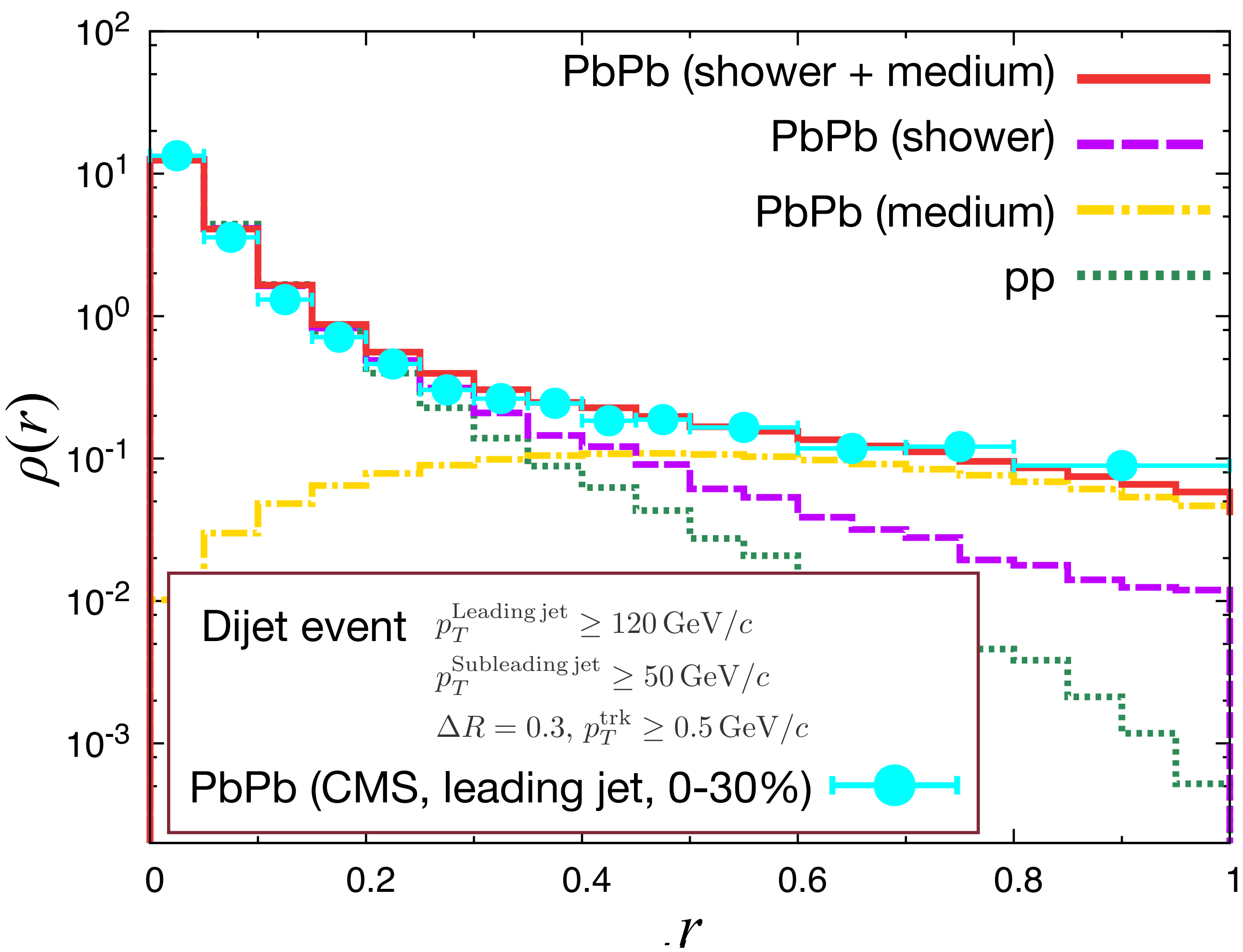

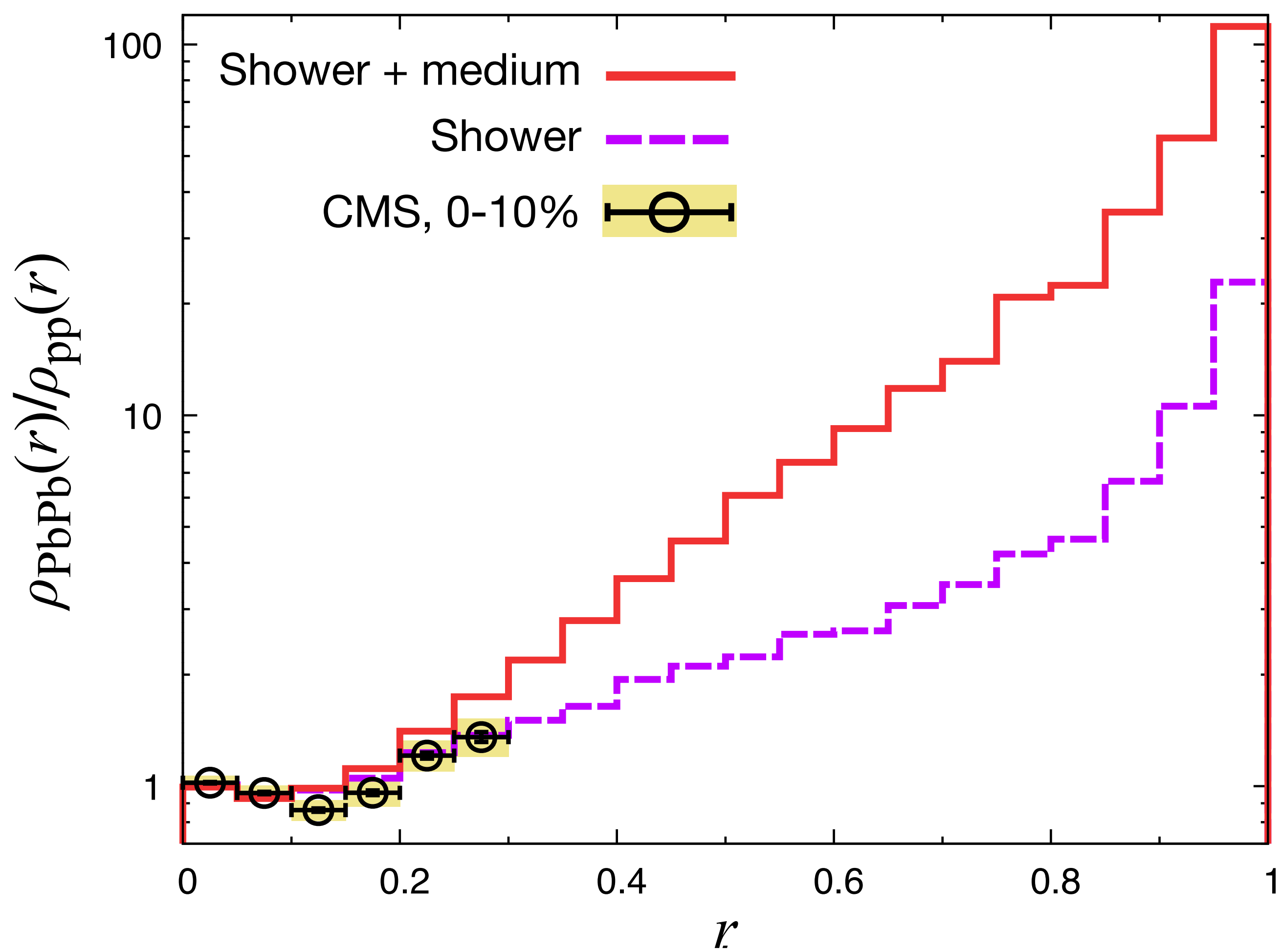

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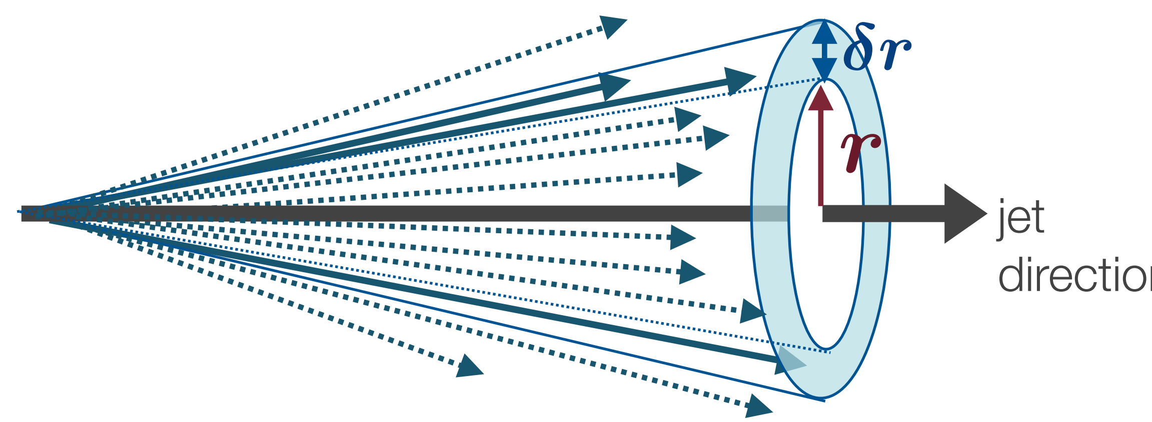

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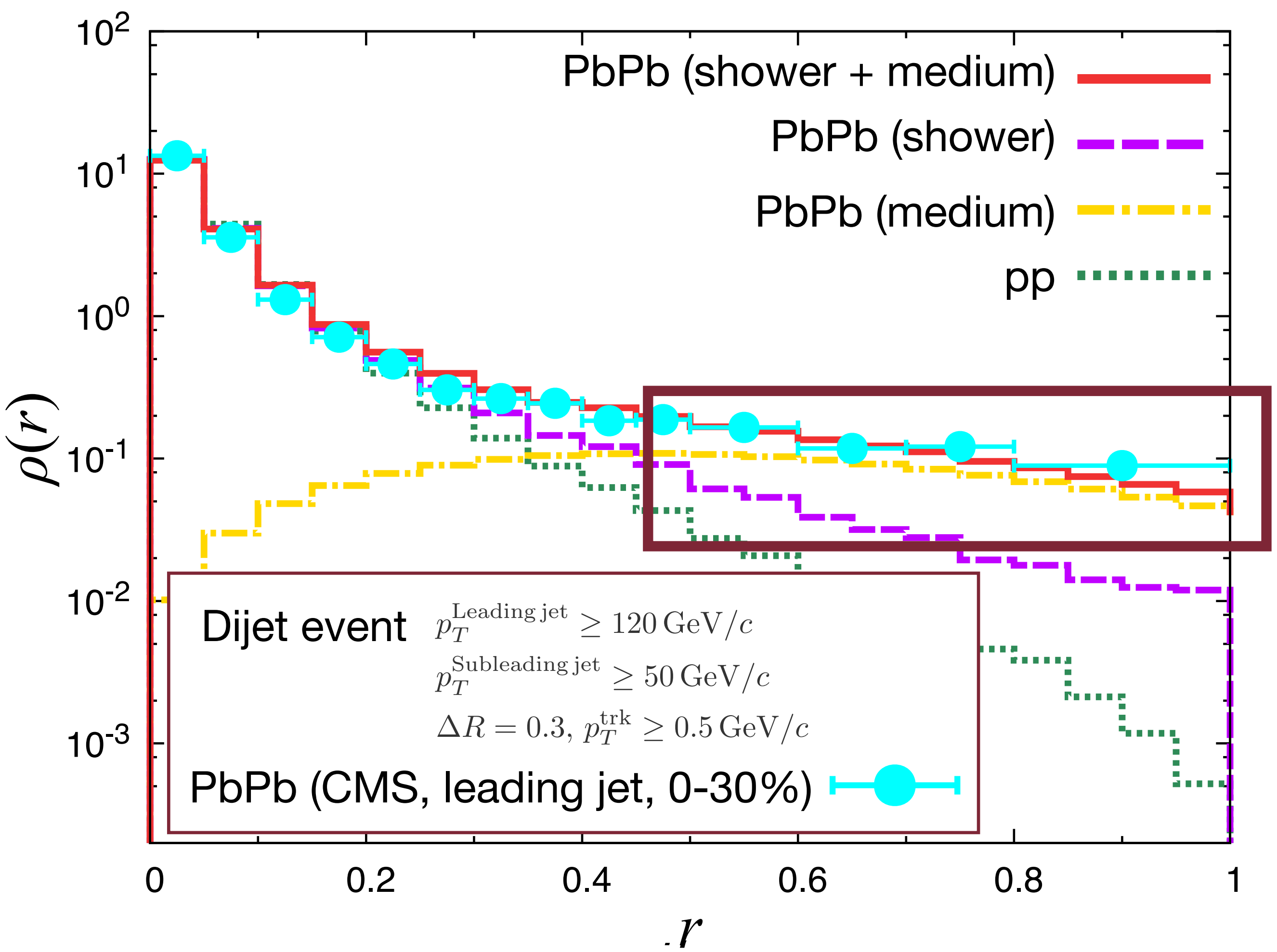

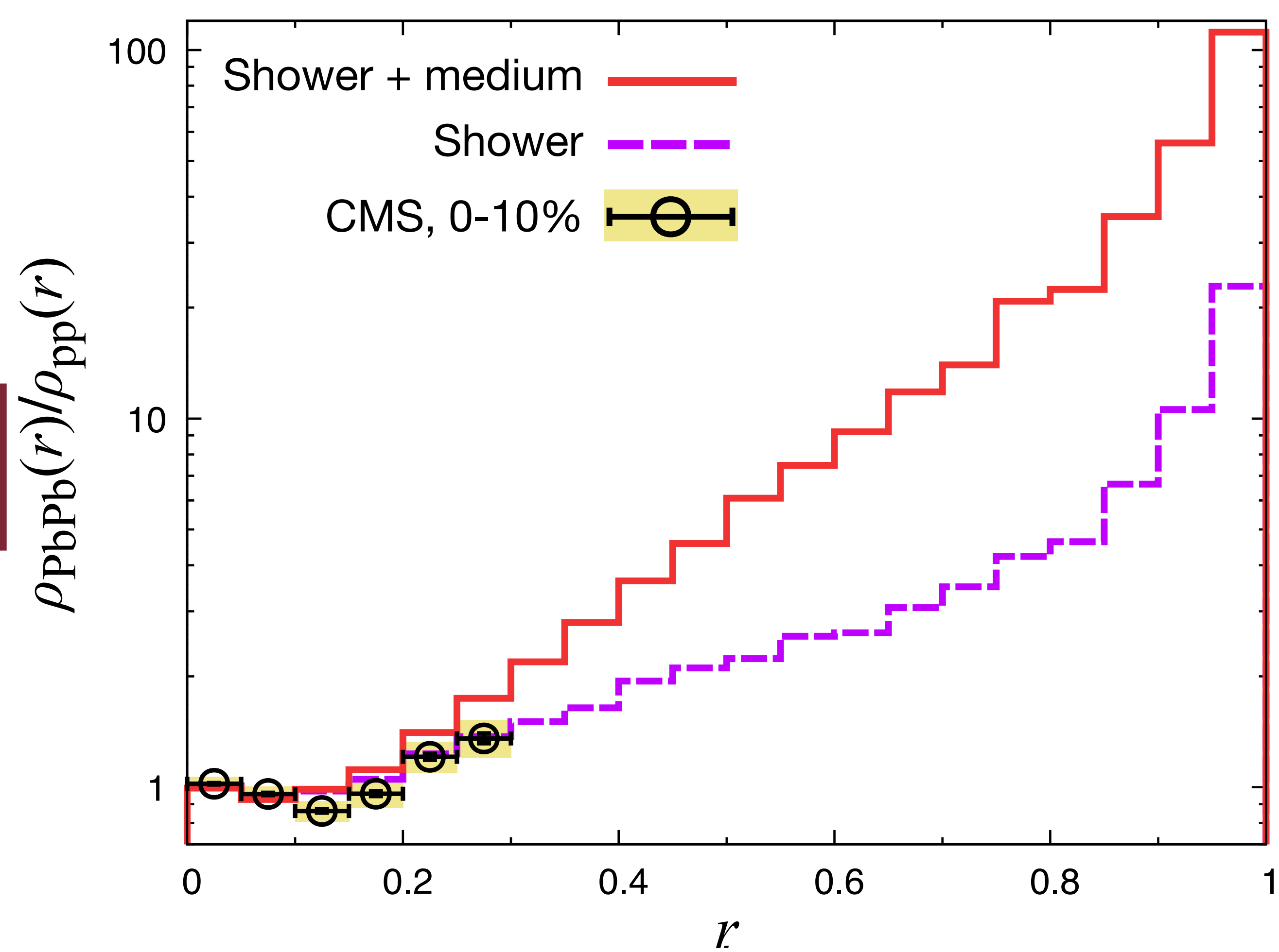

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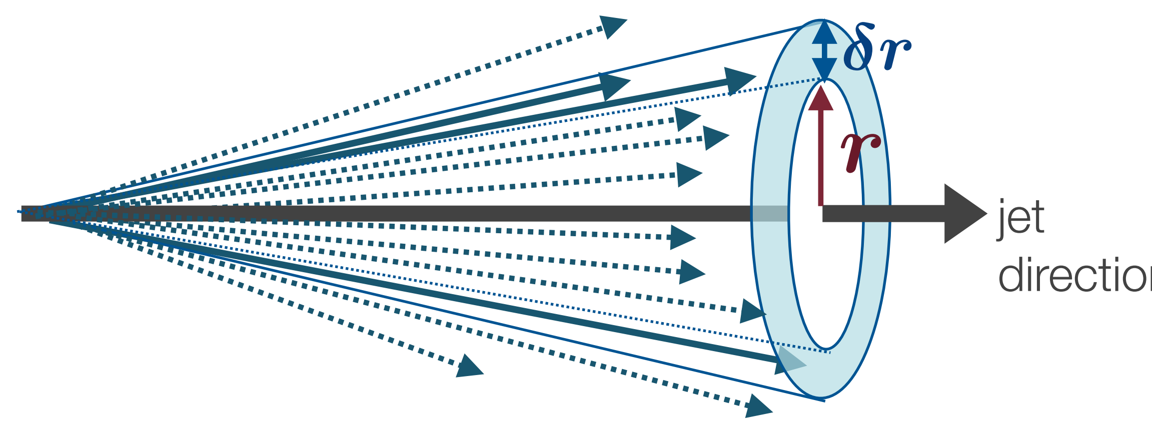

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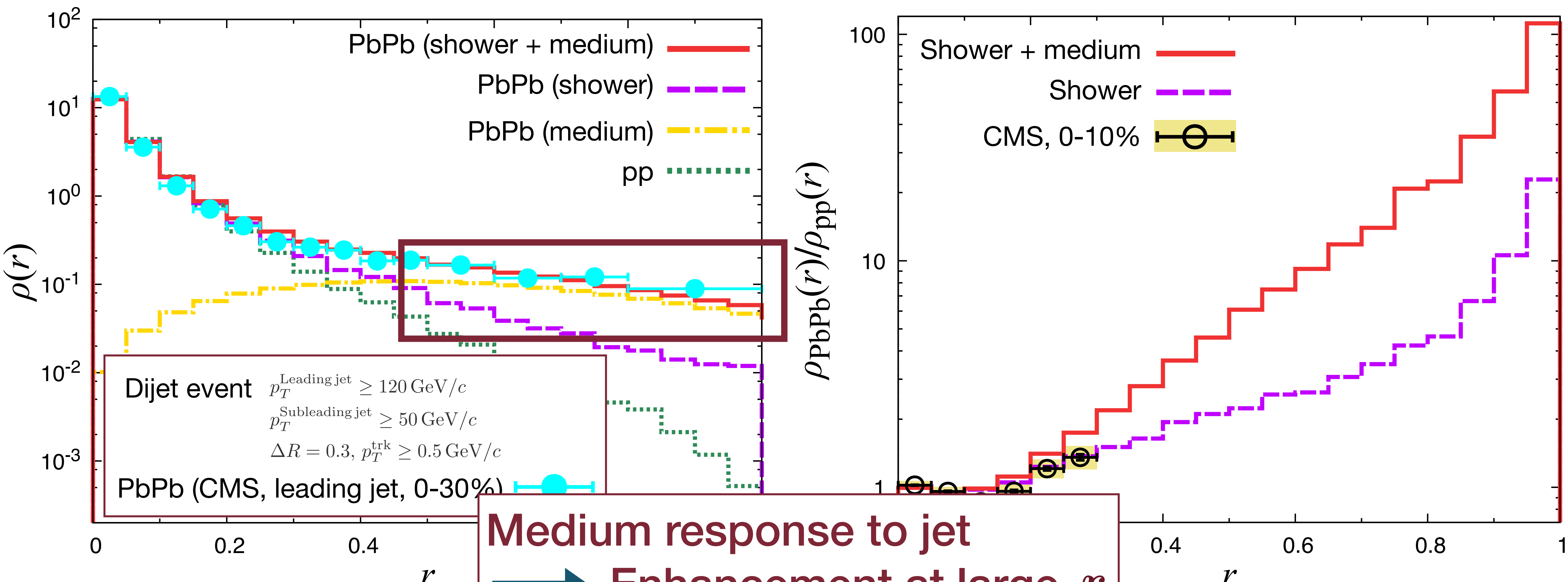

Medium response to jet
→ Enhancement at large-r

Summary

- **Full jet shower + hydro model**
  - Jet shower evolution: transport equations for partons in jet
    → N.-B. Chang's talk (NEXT)
  - Medium evolution: hydrodynamic equation with source term
    ↑ Constructed from jet transport equation
- **Medium contribution to jet energy loss**
  - Increase of jet cone size dependence
- **Medium contribution to jet shape modification**
  - Further broadening of jet shape
  - Significantly modification except for very small-r
  - Medium contribution dominates large-r region

Backup

Source term

- **Energy momentum conservation for QGP + jet system**

$$\partial_\mu \left[T^{\mu\nu}_{\rm QGP}(x) + T^{\mu\nu}_{\rm jet}(x)\right] = 0$$

⬇

$$\partial_\mu T^{\mu\nu}_{\rm QGP}(x) = J^\nu(x),\ J^\nu(x) \equiv -\partial_\mu T^{\mu\nu}_{\rm jet}(x)$$

$$= -\sum_j \int \frac{d^3k_j}{\omega_j} k_j^\nu k_j^\mu \partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)$$

$$= -\sum_j \int \frac{d^3k_j}{\omega_j} k_j^\nu k_j^\mu \left[\partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)|_{\hat{e},\hat{q}}\right]$$

Only coll. & broad. contribution
Energy-momentum conservation during rad. processes;

$$\sum_j \int \frac{d^3k_j}{\omega_j} k_j^\nu k_j^\mu \left[\partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)|_{\rm rad.}\right] = 0$$

Approximation: $\boldsymbol{x}_j(k,t) = \boldsymbol{x}_0^{\rm jet} + \frac{\boldsymbol{k}_j}{\omega_j}t$

→ $$J^\nu(x) = \sum_j \int \frac{d\omega_j dk_{j\perp}^2 d\phi_j}{2\pi} k_j^\nu \left.\frac{df_j(\omega_j, k_{j\perp}^2)}{dt}\right|_{\hat{e},\hat{q}} \delta^{(3)}(\boldsymbol{x} - \boldsymbol{x}_j(k,t))$$

Some details of model

- **Jet quenching parameter** $\hat{q}$

$$\hat{q}_q(x_{\rm jet}) = \hat{q}_{q,0}\frac{T^3(x_{\rm jet})}{T_0^3}\frac{p_{\rm jet}\cdot u(x_{\rm jet})}{p^0_{\rm jet}}$$

$$\hat{q}_{q,0} = 2.0\,{\rm GeV}^2/{\rm fm}$$ (chosen to fit the experimental data of $R_{\rm PbPb}$)

$$T_0 = T(\boldsymbol{x}=0, \tau=\tau_0) = 0.514\ {\rm GeV}$$

$$\hat{q}_{g,0} = \frac{C_A}{C_F}\hat{q}_{q,0}$$

- **Initial profile of medium**
  - initial proper time $\tau_0 = 0.6\,{\rm fm}/c$
  - optical Glauber model with $\boldsymbol{b}=0$

$$s(\tau_0, \boldsymbol{x}_\perp, \eta_{\rm s}) = s_T(\boldsymbol{x}_\perp)\,H(\eta_{\rm s})$$

$$s_T(\boldsymbol{x}_\perp) = \frac{C}{\tau_0}\left[\frac{(1-\alpha)}{2}n^{\boldsymbol{b}}_{\rm part}(\boldsymbol{x}_\perp) + \alpha n^{\boldsymbol{b}}_{\rm coll}(\boldsymbol{x}_\perp)\right],\ H(\eta_{\rm s}) = \exp\left[-\frac{(|\eta_{\rm s}|-\eta_{\rm flat}/2)^2}{2\sigma_\eta^2}\theta\left(|\eta_{\rm s}|-\frac{\eta_{\rm flat}}{2}\right)\right]$$

$$C = 19.8,\ \alpha = 0.14,\quad \eta_{\rm flat} = 3.8,\ \sigma_\eta = 3.2.$$

- **Generation of inclusive jet events**
  - PYTHIA + MC Glauber Model $b = 3.5\,{\rm fm}$
  - created and traveling in transverse plane $\eta_{\rm s} = 0$

Jet Shape, hydro, and Jet energy deposition profile are 3D

Jet reconstruction

- **Jet-** p_T

$$p_T^{\rm jet} = p_{T,\rm shower}^{\rm jet} + p_{T,\rm medium}^{\rm jet}$$

$$p_{T,\rm shower}^{\rm jet} = \sum_j p_{T,\rm shower}^{j} \, \theta(\Delta R - r_j)$$

$$p_{T,\rm medium}^{\rm jet} = \sum_i p_{T,\rm medium}^{i} \, \theta(\Delta R - r_i)\Big|_{\rm w/\ jet} - \sum_i p_{T,\rm medium}^{i} \, \theta(\Delta R - r_i)\Big|_{\rm w/o\ jet}$$

j: partons with $p_{T,\rm shower}^{j} > 2\ {\rm GeV}/c$, i: hadrons with $p_{T,\rm medium}^{i} > 1\ {\rm GeV}/c$

- p_T **of hadrons emitted from medium (** $p_{T,\rm medium}^{i}$ **)**
  - Cooper-Frye formula

$$E_i^0 \frac{dN_i}{d^3p_i} = \frac{g_i}{(2\pi)^3} \int \frac{p^\mu d\sigma_\mu}{\exp\left[p^\mu u_\mu(x)/T(x)\right] \mp_{\rm BF} 1} \longrightarrow \sum_i p_{T,\rm medium}^{i} = \sum_i \int d^3p_i \; p_{T,i} \frac{dN_i}{d^3p_i}$$

$u^\mu(x)$: flow velocity, $T(x)$: temperature, g_i: degeneracy

(No hadronic interaction after the hydrodynamic evolution)