Lecture on Jet Quenching

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Outline

- Introduction
- Theory: HT
- Production of leading particles
- Full jet observables

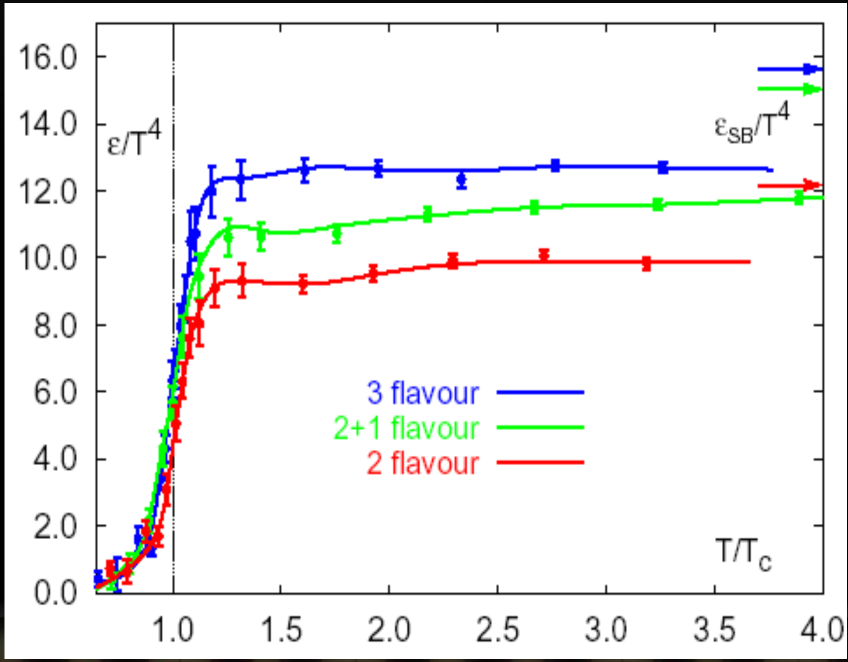
Introduction

Deconfinement and QGP

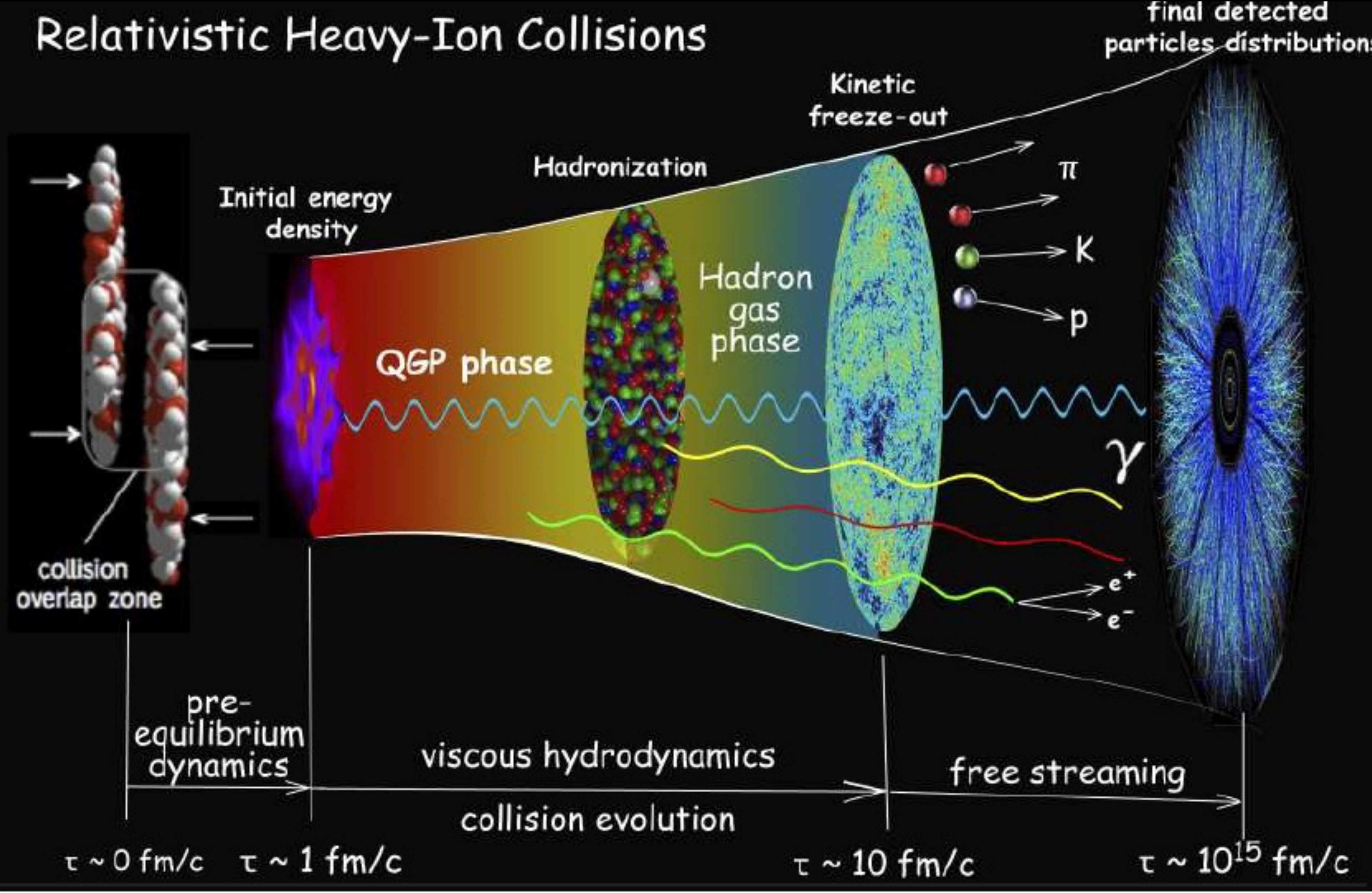
It would be interesting to explore new phenomena by distributing high energy or high nuclear density over a relatively large volume.

T. D. Lee (1978)

Lattice QCD predicts phase of thermal QCD matter with sharp rise in number of degrees of freedom near T_c=170MeV.



The Little Bang

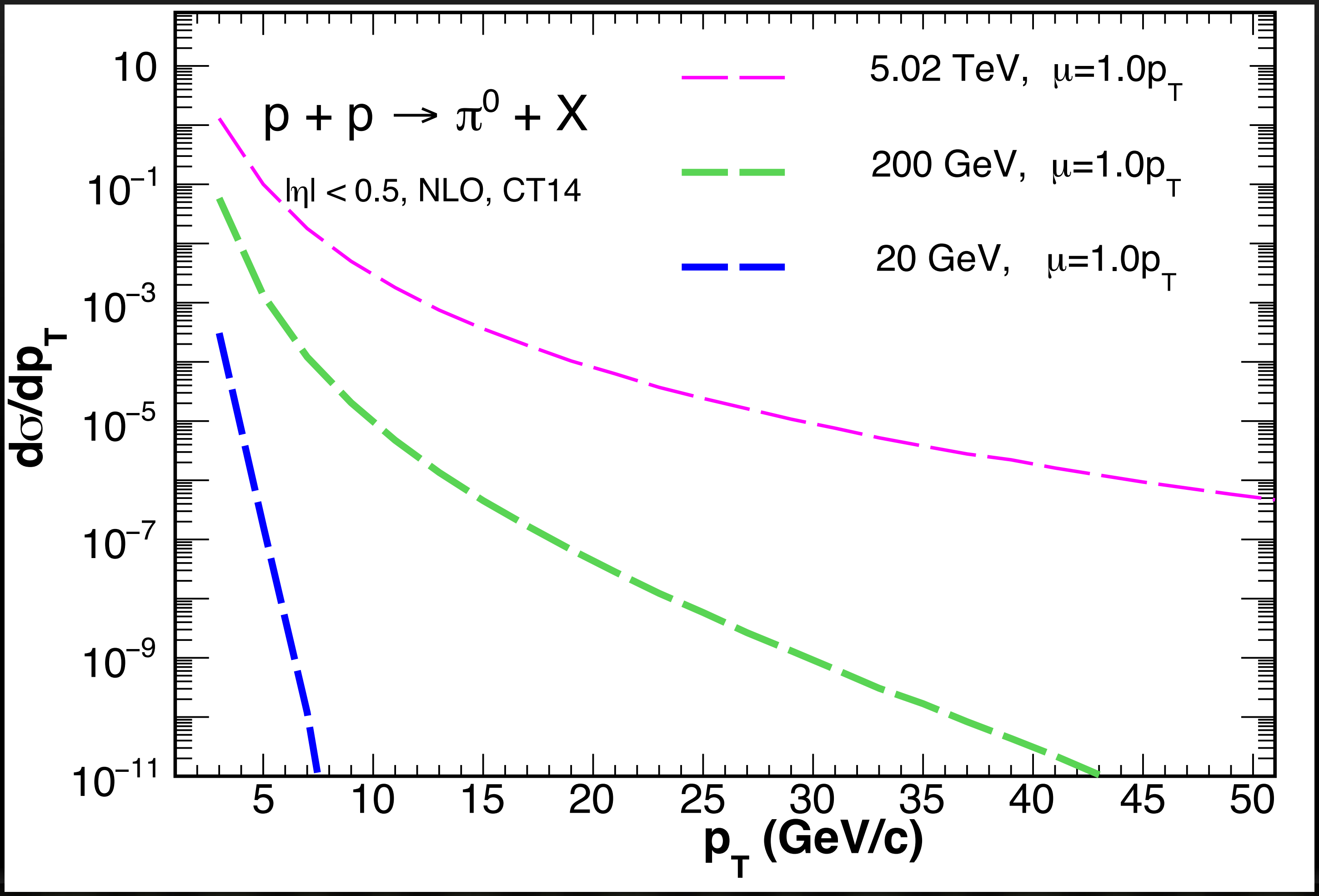


Signatures: Hard Probes

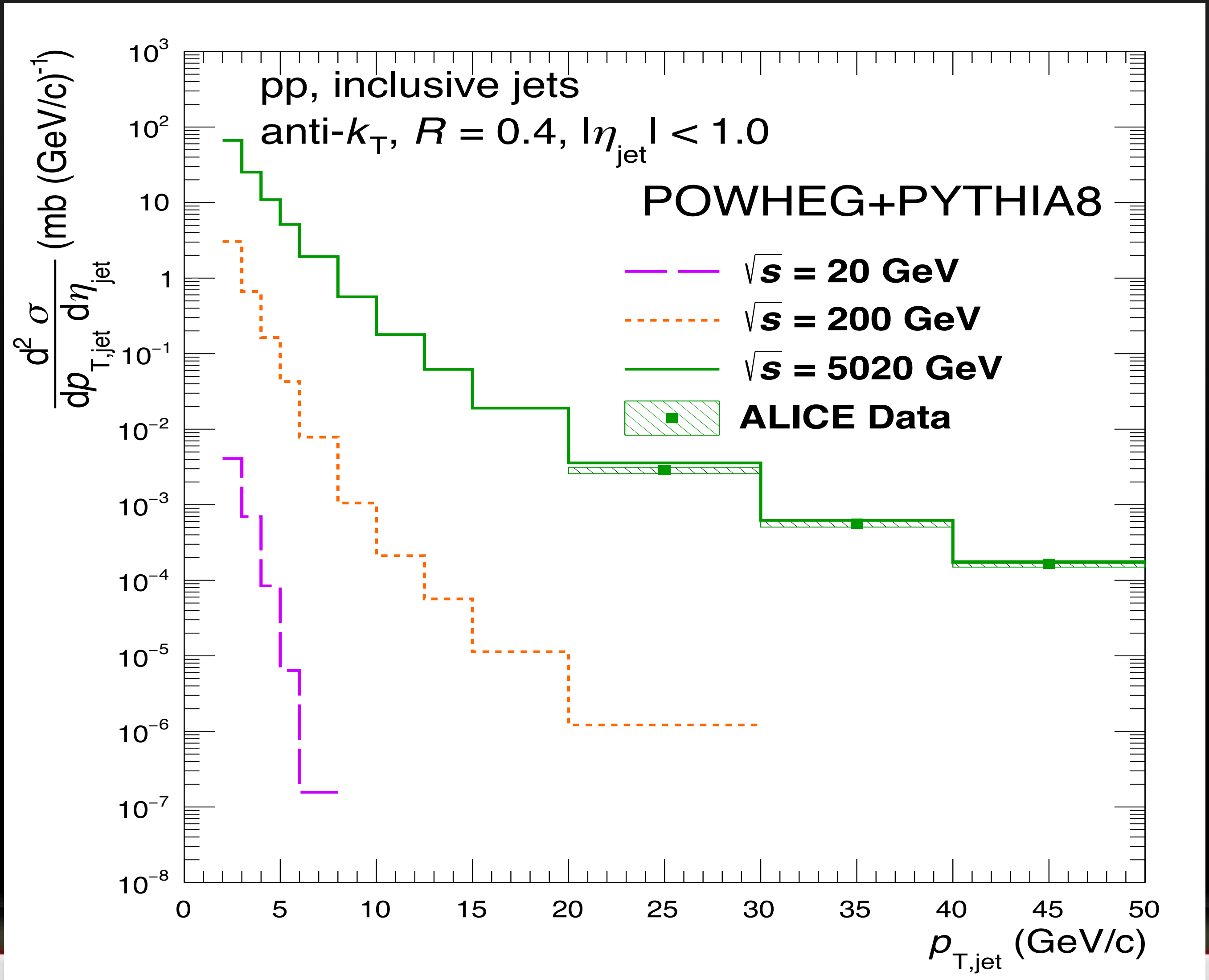
- We need signatures to tell whether a new kind of matter is produced in heavy-ion collision: dilepton production, J/psi suppress, HBT effect, strangeness enhancement, collective flow…
- From SPS to RHIC, and to LHC, the colliding energy is larger and larger, hard probes will become more and more important.
- Applications of hard probes depend on the asymptotic freedom and the factorization of pQCD.

$$\alpha_s(Q) \propto \frac{1}{\ln(\frac{Q^2}{\Lambda_c^2})}$$

Signatures: Hard Probes



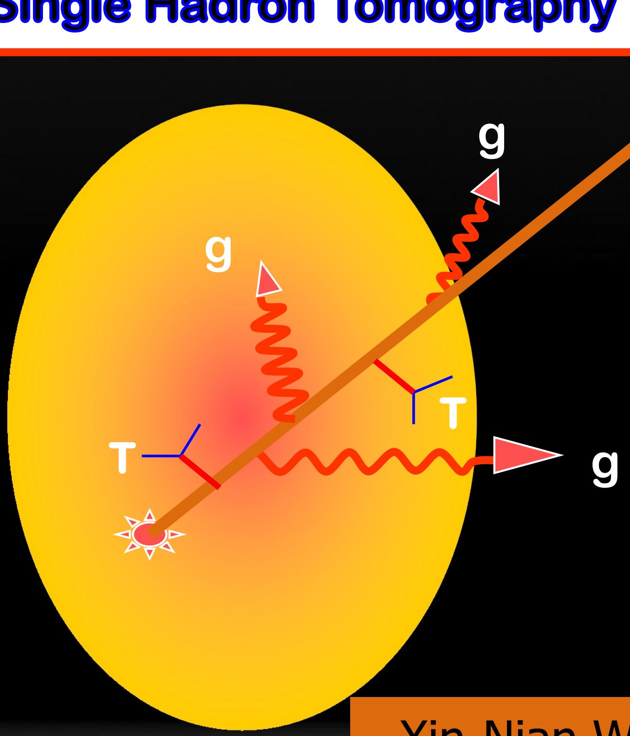
Signatures: Hard Probes

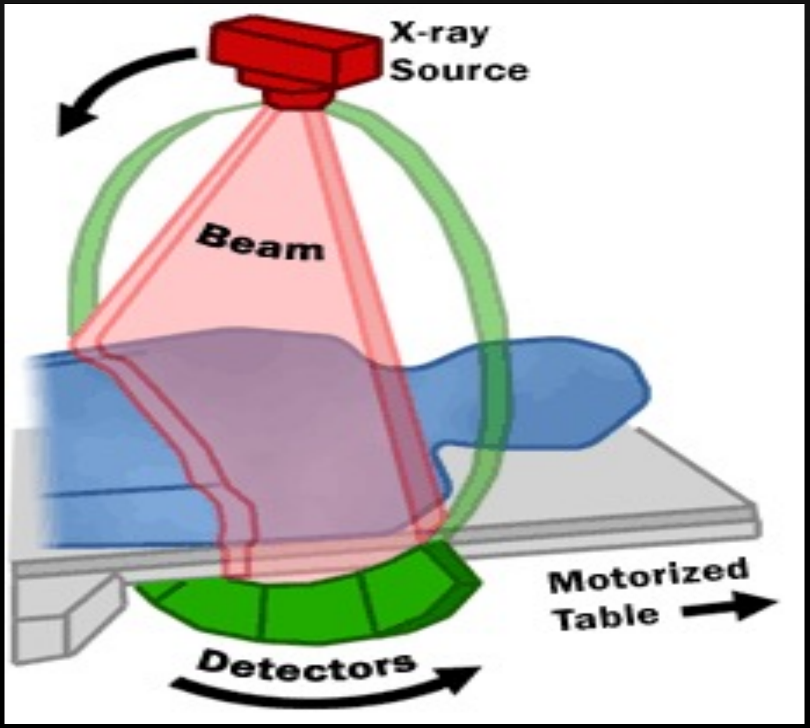


Jet quenching

Parton energy has been proposed as an excellent probe of the hot/dense matter created at HIC.

Single Hadron Tomography



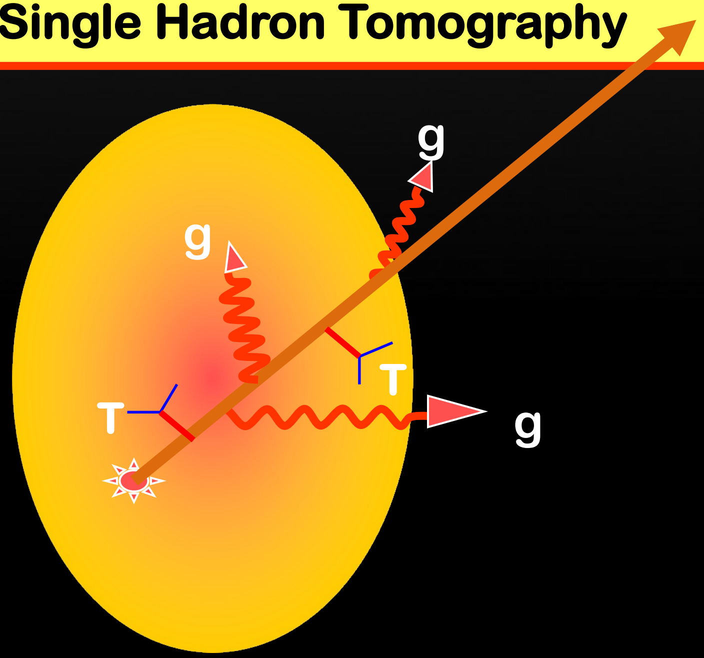


Xin-Nian Wang, M. Gyulassy, PRL68(1992)1480

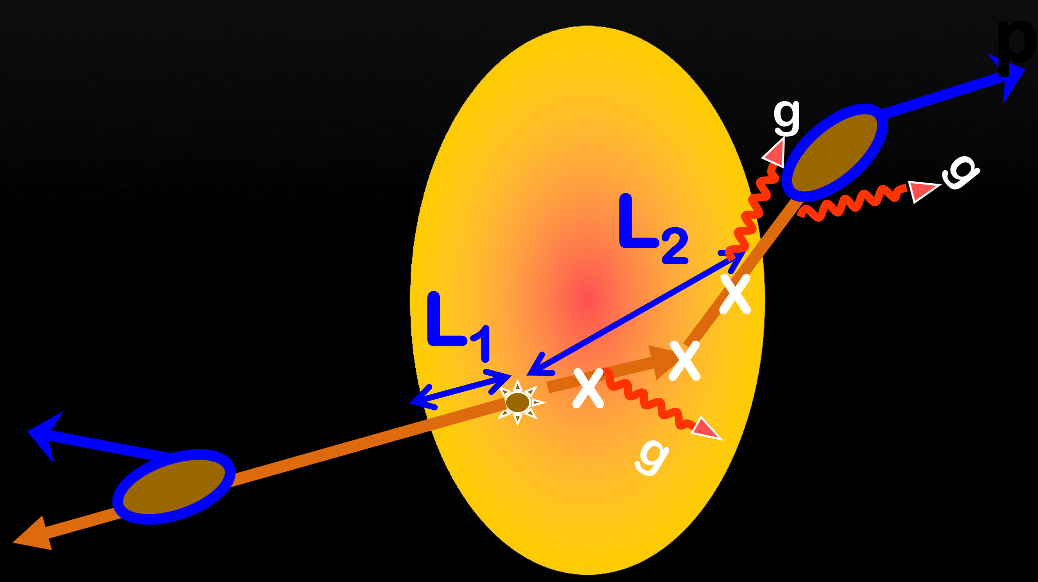
Jet quenching as a hard probe

Jet quenching has been proposed as an excellent probe of the hot/dense matter created at HIC.

Single Hadron Tomography



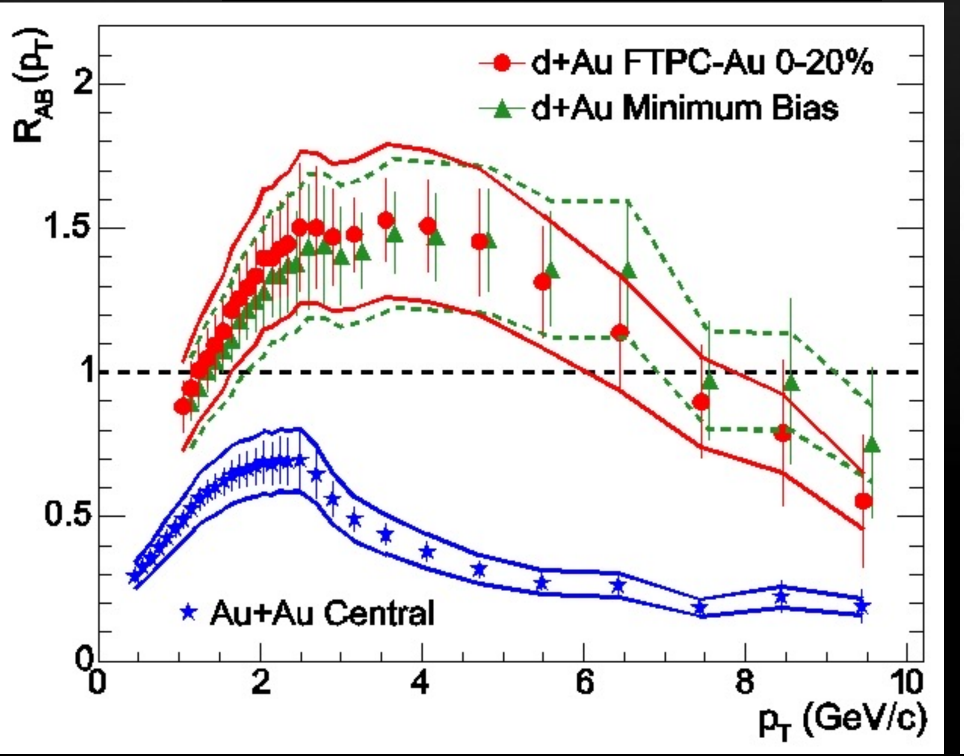
Di-Hadron Tomography

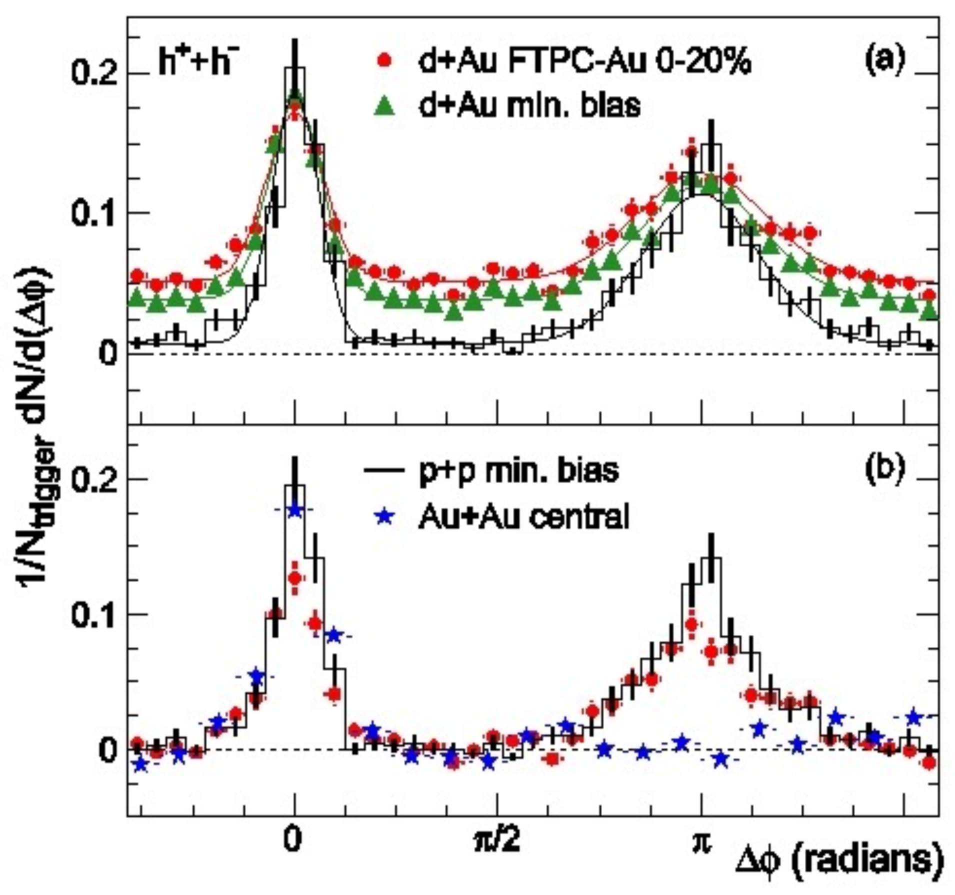


Xin-Nian Wang, M. Gyulassy, PRL68(1992)1480

Jet quenching at the RHIC

$$R_{AA} = \frac{\text{Yield}_{AuAu}/\langle N_{binary}\rangle_{AuAu}}{\text{Yield}_{pp}}$$



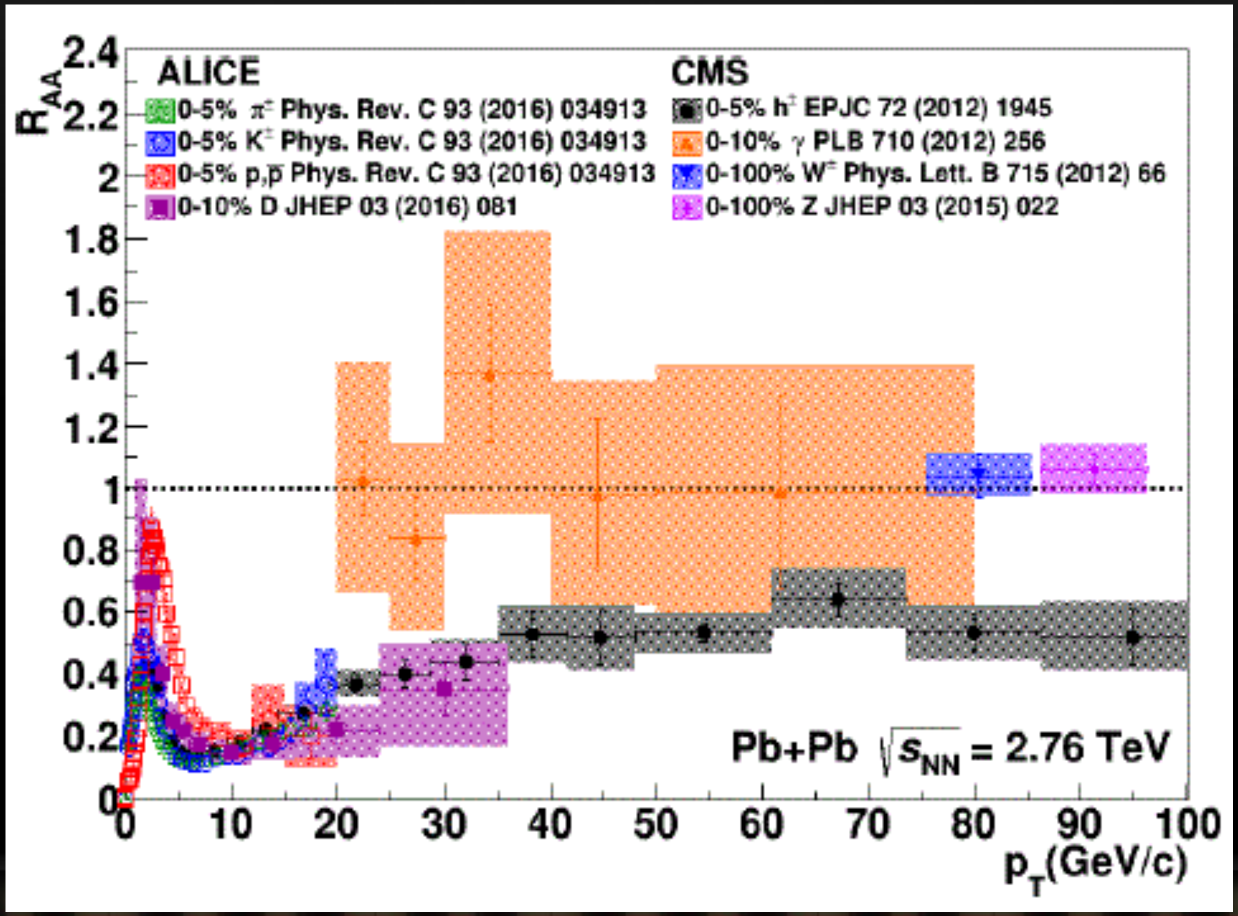


Finding of the jet quenching effect in A+A collisions has been regarded as one of the most important discoveries made at RHIC.

Xin-Nian Wang, Nucl. Phys. A 750,98(2005).

Jet quenching at the LHC

$$R_{AA} = \frac{\text{Yield}_{AA} / \langle N_{binary} \rangle_{AA}}{\text{Yield}_{pp}}$$

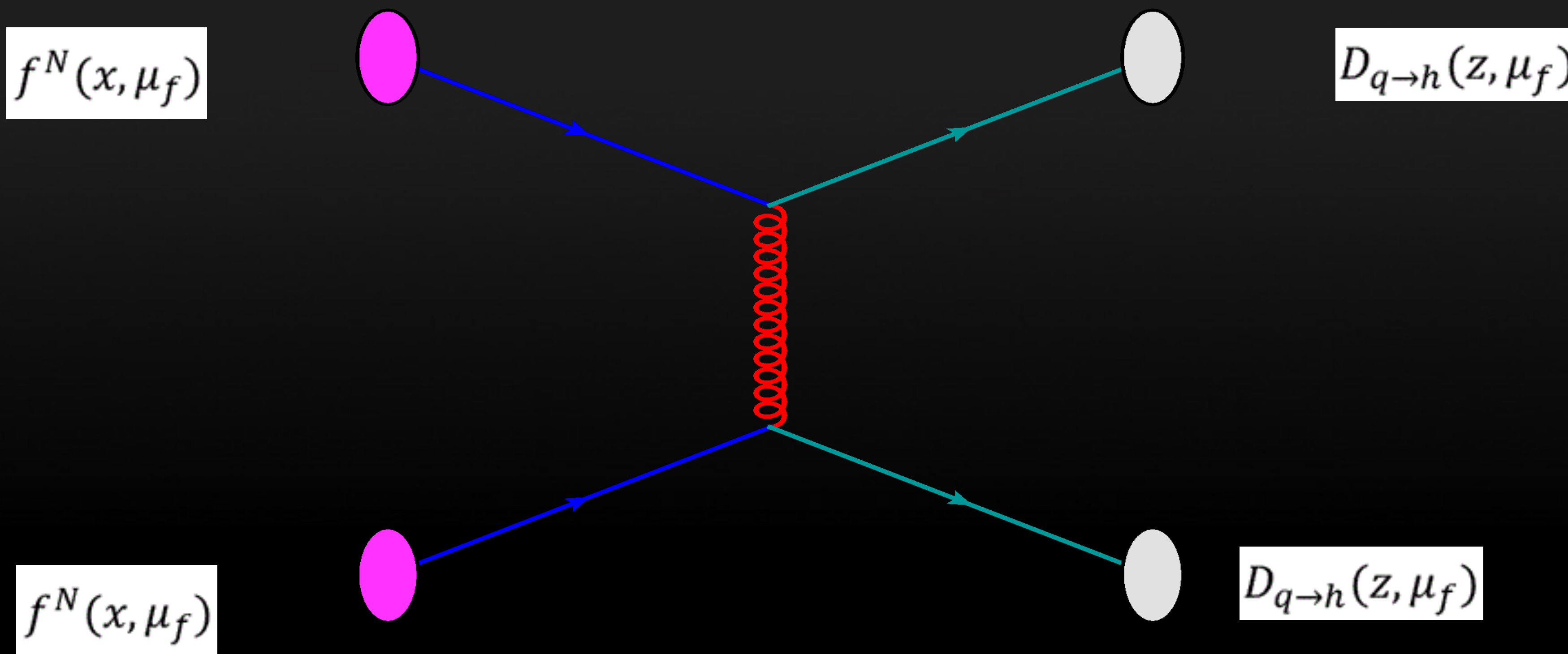


Fingerprints of jet quenching

领头强子

整体喷注

Leading hadron production



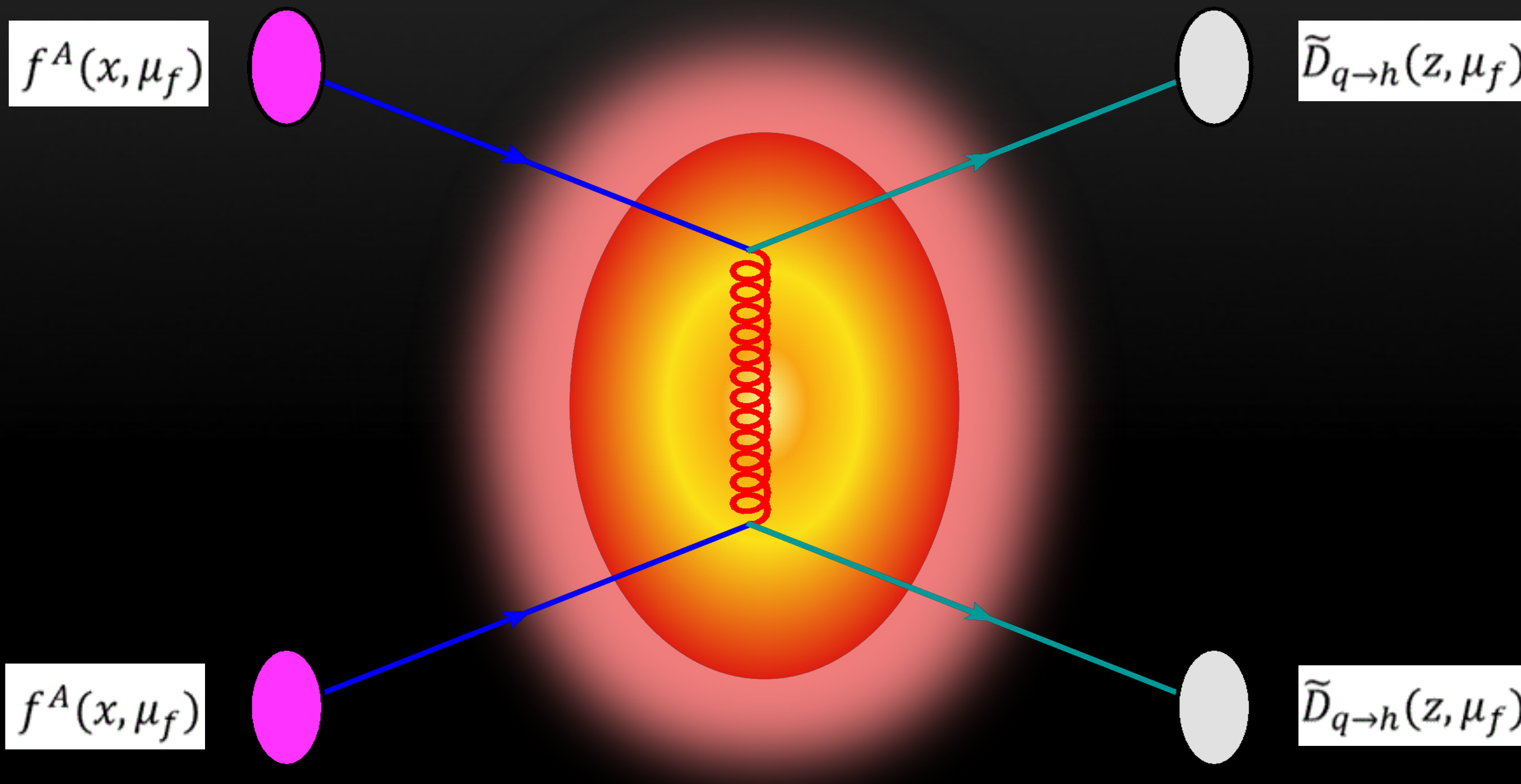
$$\frac{d\sigma^h_{pp}}{dyd^2p_T} = K\sum_{abcd}\int dx_a dx_b f_a(x_a,Q^2) f_b(x_b,Q^2) \frac{d\sigma}{d\hat{t}}(ab\to cd)\frac{D^0_{h/c}}{\pi z_c}$$

Parton distribution function — measured in DIS

Matrix element — pQCD

Fragmentation function — e^+e^-

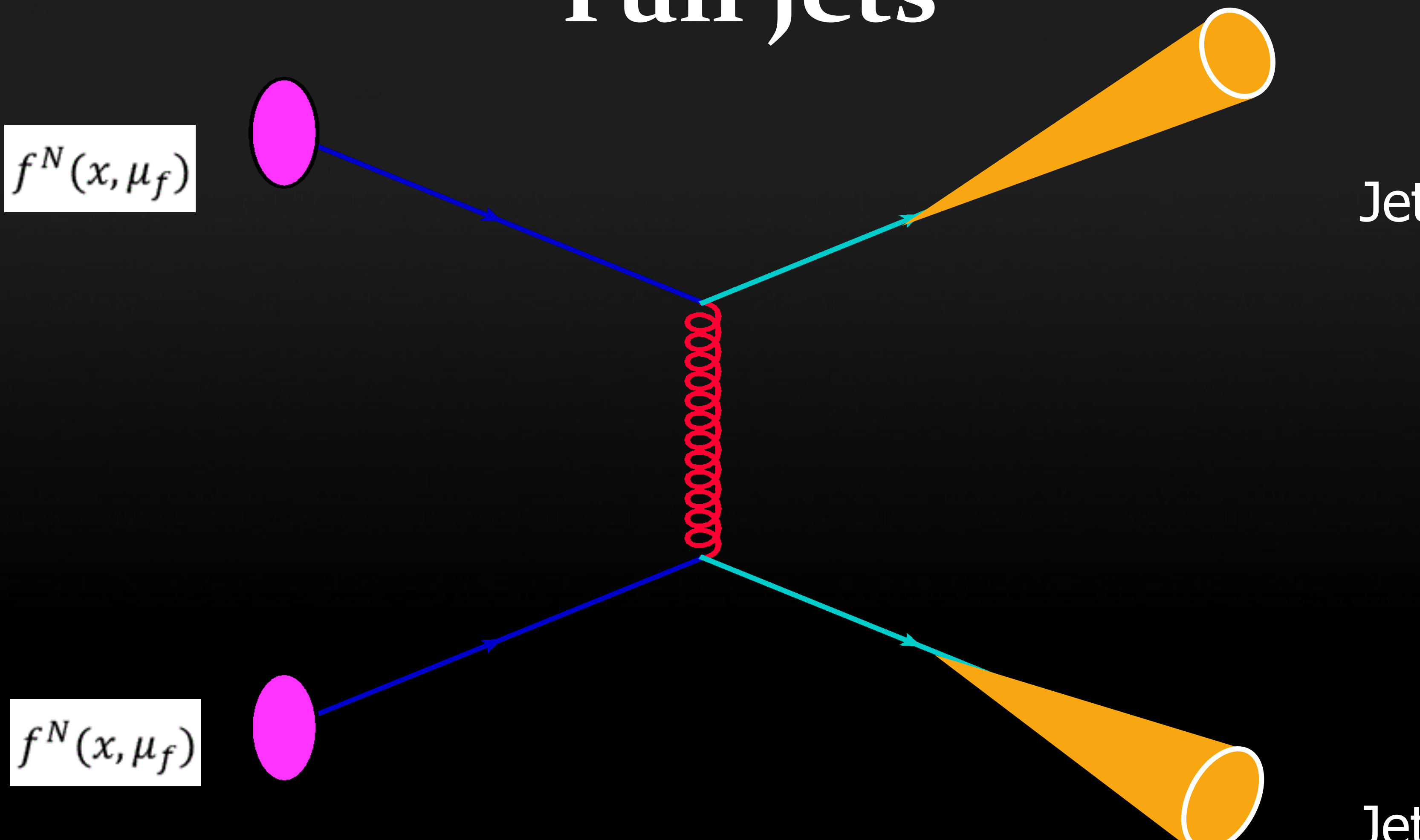
Leading hadron production



Observables related to leading particle productions

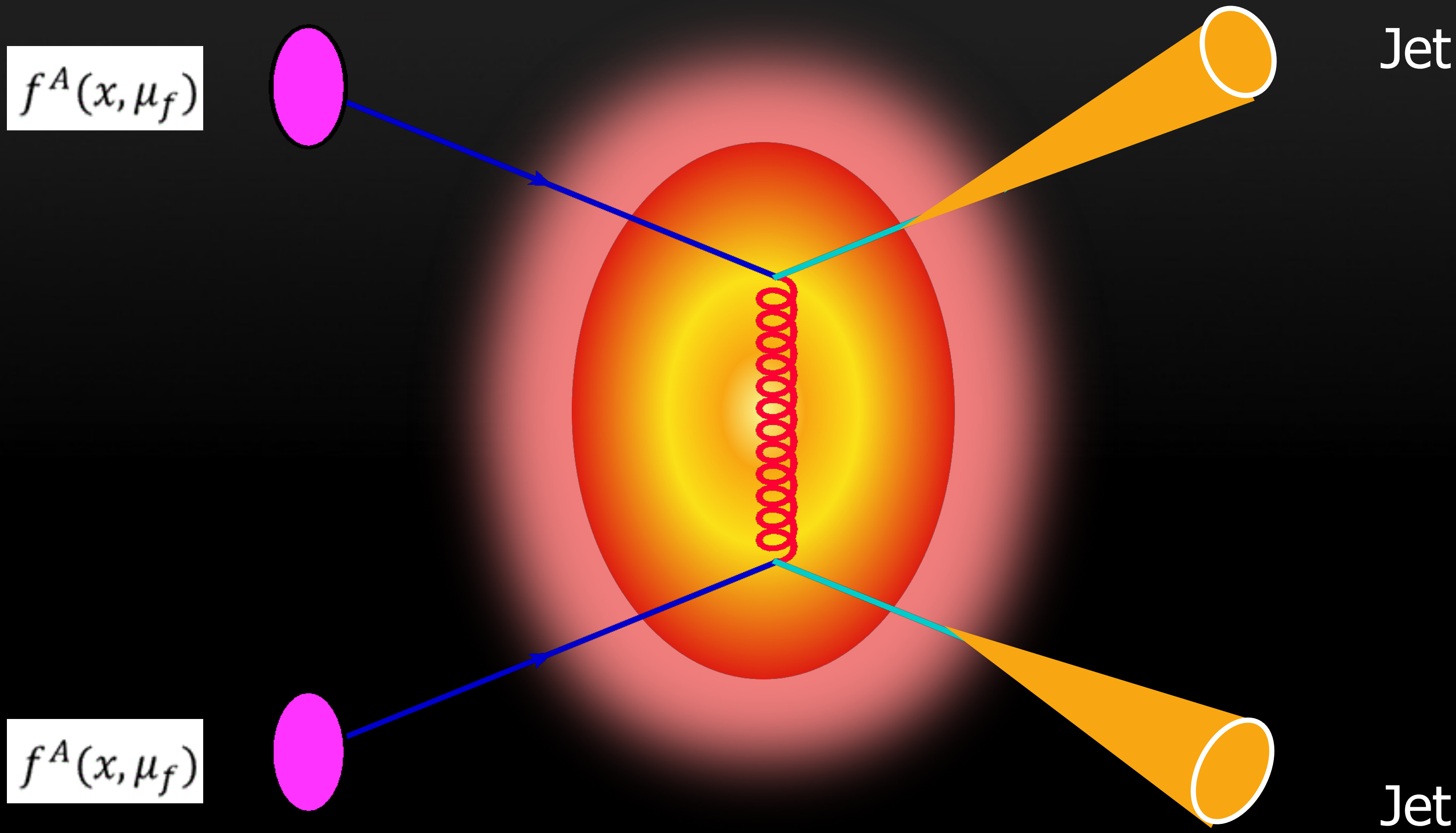
- Leading hadron productions: pion, kaon, eta, …
- Ratios of particles at large pT
- Di-hadron correlation
- Direction photon
- Gauge boson + hadron
- Heavy flavor hadrons: D, B, J/psi
- Flow of these particles
- ……

Full jets

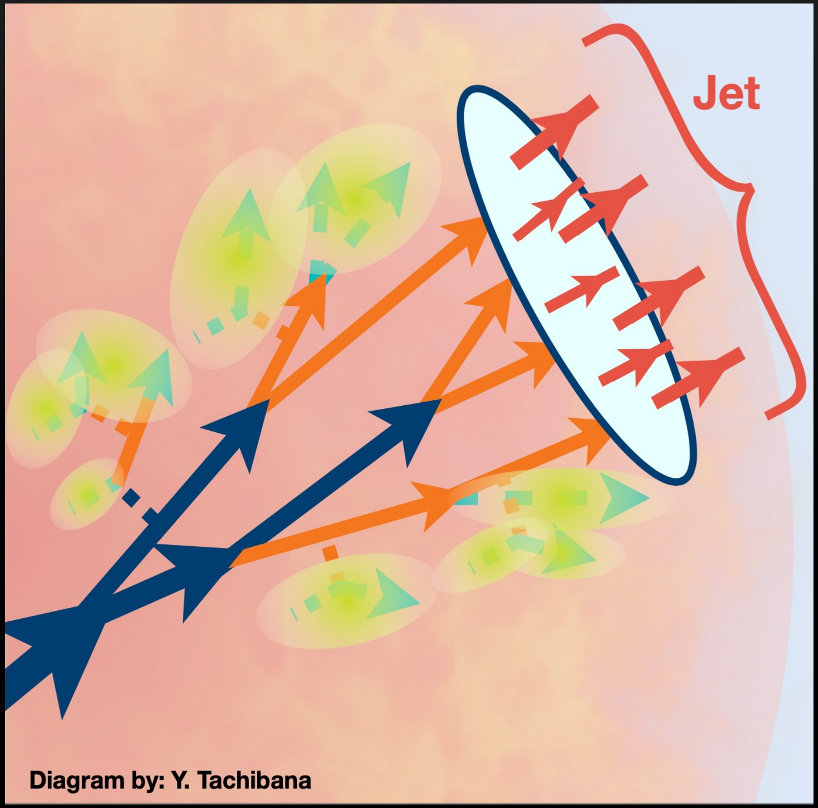


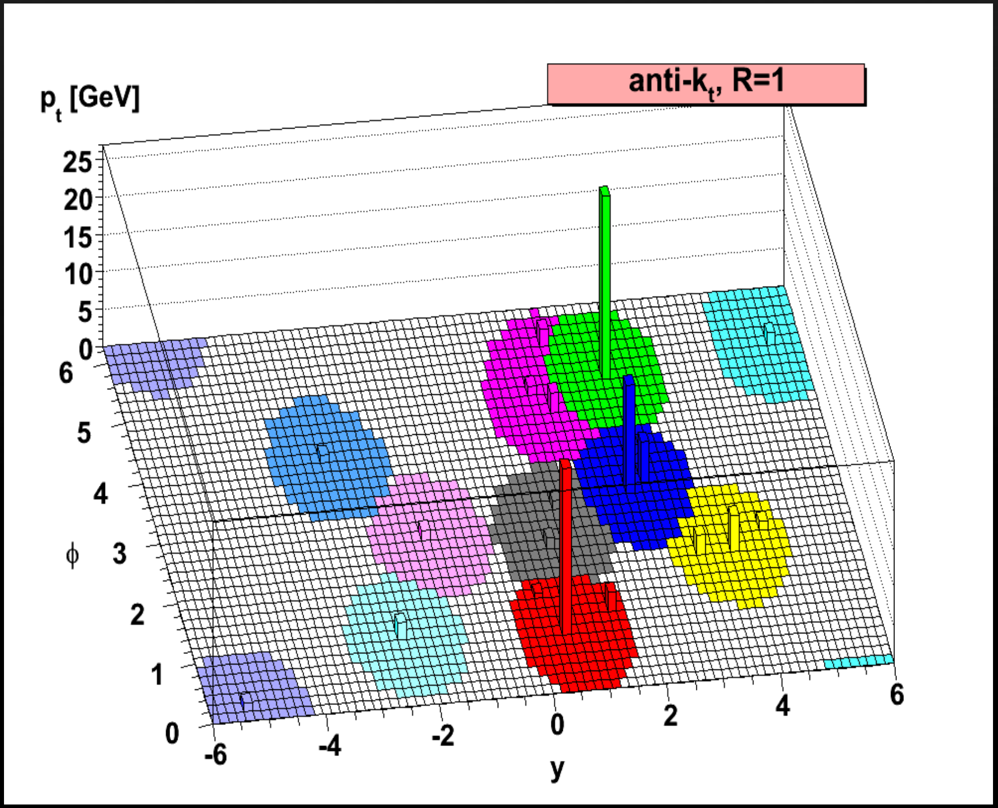
$$\frac{d\sigma^{\text{jet}}}{dE_T dy} = \frac{1}{2!}\int d\{E_T, y, \phi\}_2 \frac{d\sigma[2 \to 2]}{d\{E_T, y, \phi\}_2} S_2(\{E_T, y, \phi\}_2) + \frac{1}{3!}\int d\{E_T, y, \phi\}_3 \frac{d\sigma[2 \to 3]}{d\{E_T, y, \phi\}_3} S_3(\{E_T, y, \phi\}_3).$$

Full jets



World inside a jet





Observables related to full jets

inclusive jets;
di-jets;
gamma + jet;
Z/W + jet;
heavy flavor jets;
……

jet yields

jet shape;
jet FF;
angularity;
splitting scale;
groomed jets;
……

jet substructure

sphericity;
thrust;
broadening;
Fox-Wolfram moment;
……

Inter-jet properties

Bjorken's calculation

Bjorken (1982)

FERMILAB-Pub-82/59-THY
August, 1982

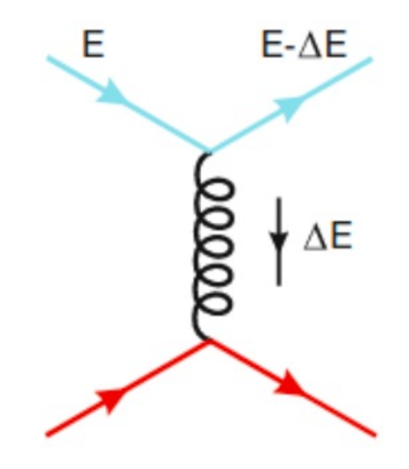
Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

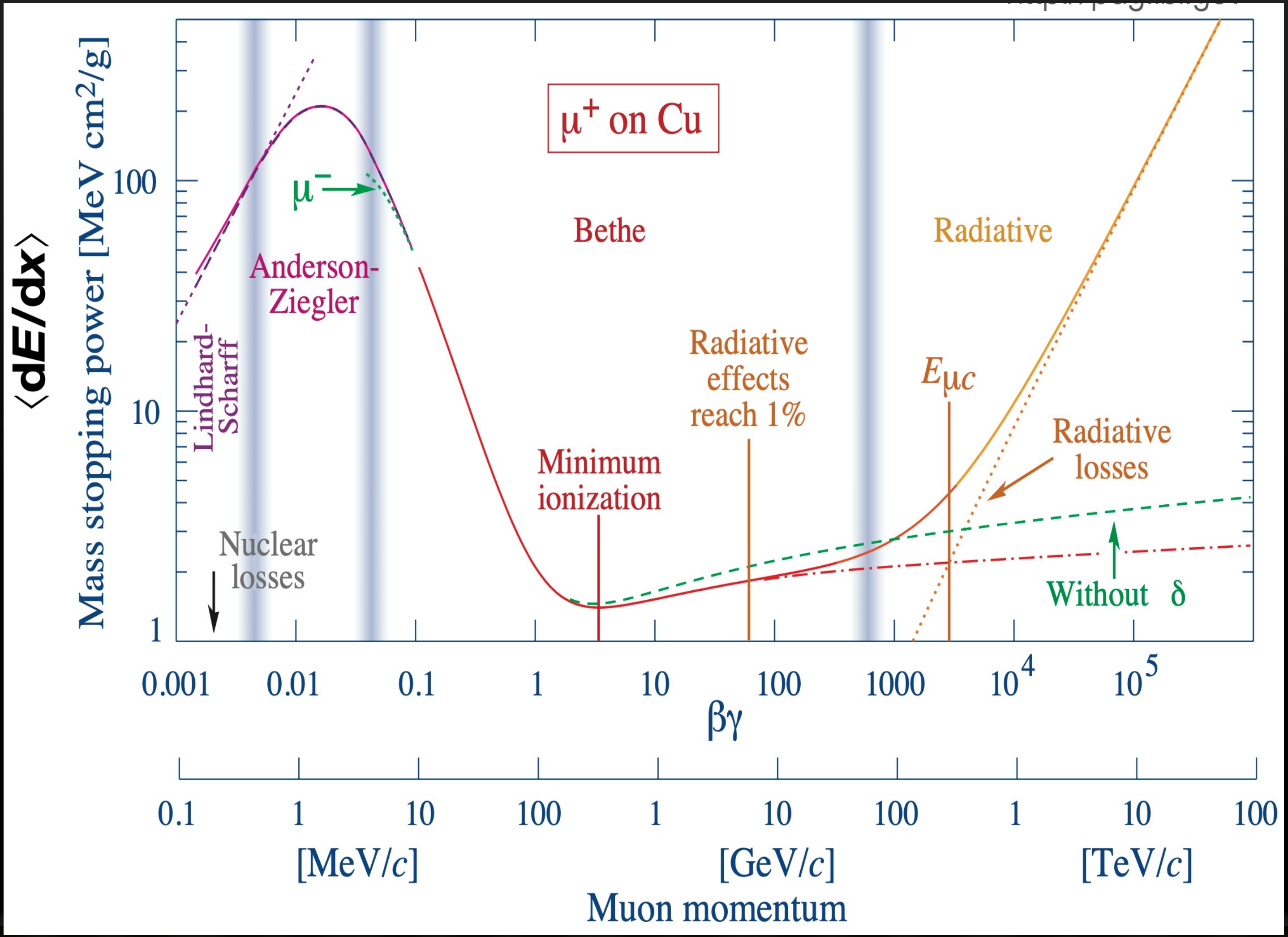
Abstract

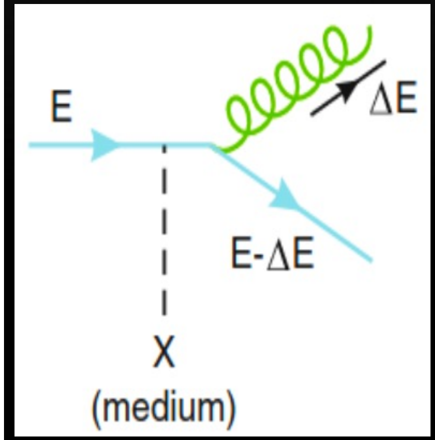
High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For

this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.



Stopping power of ordinary matter





Basic quantities

- Consider a thermal static QCD medium "brick" with temperature T, the length L
- The mean free path: $\lambda = \frac{1}{\rho\sigma}$ $\rho \propto T^3$ $\sigma \propto 1/T^2$
- The opacity: $N = L/\lambda$
- The Debye mass: $\mu = m_D \sim gT$

It characterizes the typical momentum transfer in a scattering.

- The transport coefficient: $\hat{q} \equiv \mu^2/\lambda$

Gives the "scattering power" of the medium through the average transverse momentum squared (to the propagating particle) per unit path-length

Numerical estimates

- Consider an equilibrated *gluon* plasma at temperature T = 0. 4 GeV , with the length L
- The strong coupling:

$$\alpha_s \approx 0.5$$

- The particle density:

$$\rho_g = \frac{g_g}{(2\pi)^3}\int_0^\infty \frac{4\pi p^2}{e^{p/T}-1}dp = 16/\pi^2\zeta(3)\cdot T^3 \approx 15\, fm^{-3}$$

where $g_g = 2(N_c^2-1)$ is the degeneracy factor for gluon.

- The energy density:

$$\varepsilon_g = \frac{g_g}{(2\pi)^3}\int_0^\infty \frac{4\pi p^3}{e^{p/T}-1}dp = 8\pi^2/15\cdot T^4 \approx 17\, GeV/fm^3$$

100 times denser than normal nuclear matter $(\rho = 0.15\, fm^{-3})$

Numerical estimates

- The Debye mass: $m_D = (4\pi\alpha_s)^{1/2}T \approx 1\, GeV$

It characterizes the typical momentum transfer in a scattering.

- The gluon-gluon cross section: $\sigma_T^{gg} \simeq 9\pi\alpha_s^2/(2m_D^2) \approx 9\, mb$

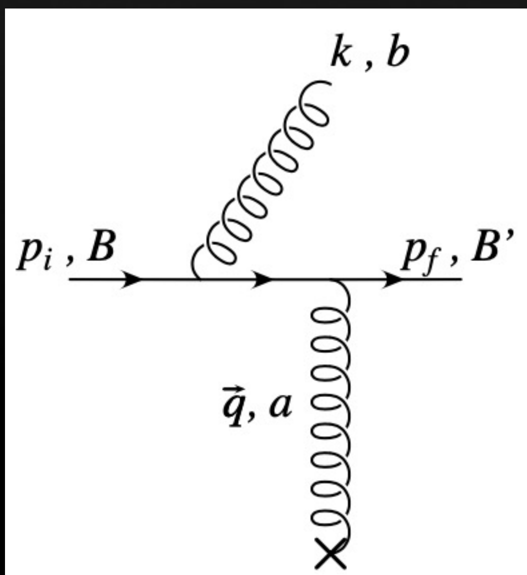
- The mean free path: $\lambda_g = 1/(\rho_g \sigma_T^{gg}) \simeq (18/\pi^2\zeta(3)\alpha_s T)^{-1} \simeq 0.45\, fm$

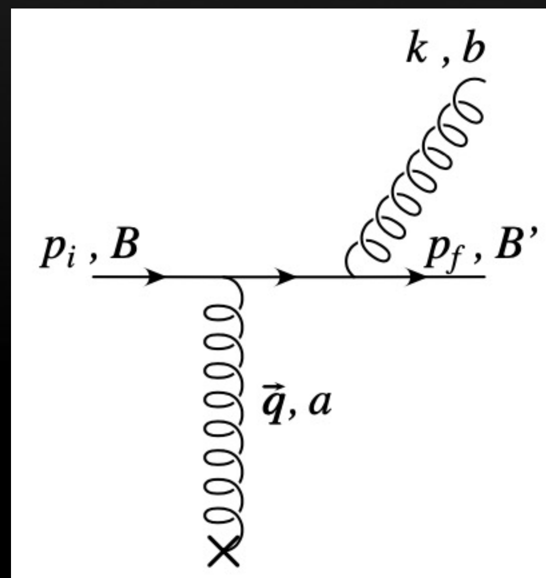
- The transport coefficient: $\hat{q} \simeq m_D^2/\lambda_g \simeq 2.2\, GeV^2/fm$

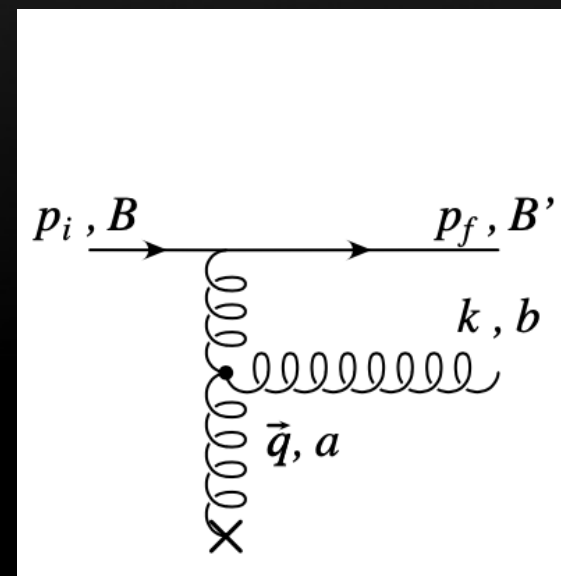
Gives the "scattering power" of the medium through the average transverse momentum squared (to the propagating particle) per unit path-length

Bethe-Heitler (BH) brems.

- BH bremsstrahlung: when L<λ; or when L> λ and the successive gluon emissions are independent

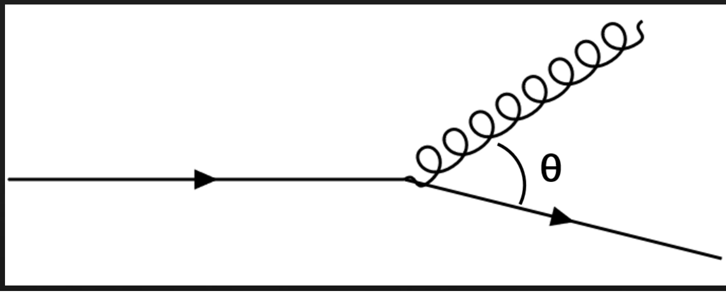






Bethe, Heitler, PRD (1982)

LPM effect



$$k^\mu = (\omega, \mathbf{k}) = (\omega, \mathbf{k}_\perp, k_z)$$

$$\omega = |\mathbf{k}|$$

$$\theta \simeq \frac{k_\perp}{\omega}, \quad k_\perp \simeq \omega\theta$$

Even though the qq̄g vertex in QCD is local, the emission process is truly non–local, as it takes some time for the emitted gluon to lose coherence w.r.t. its parent quark. Namely, when the gluon starts being emitted, its wavefunction is still overlapping with that of the quark, so the two quanta cannot be distinguished from each other. But with increasing time, the gluon separates from the quark and their quantum coherence gets progressively lost.

The transverse separation: $b_\perp = \theta \Delta t$

The transverse Compton wavelength $\lambda_\perp = 1/k_\perp \simeq 1/(\omega\theta)$

Gluon formation time $\theta\, t_{\rm form} \simeq \lambda_\perp \to t_{\rm form} \simeq \frac{\omega}{k_\perp^2} = \frac{1}{\omega\theta^2}$

$t_{\rm form} \gg \lambda$ Landau-Pomeranchuk-Migdal (LPM) effect

Theories of jet quenching

- M. Gyulassy, X.-N.Wang(1994): GW model
- Baier, et al: BDMPS / Zakharov
- Gyulassy, Levai, Vitev: GLV
- Arnold, Moore, Yaffe: AMY
- Higher twist approach

  X.-N. Wang, X. Guo, E. Wang, BWZ, Majumder, Qin,...
- Kovner, Salgado,Wiedemann
- AdS/CFT with Strong coupled QGP
- Color coherence: Tywoniuk, Mehtar-Tani,
- SCET
- Many others......

Formalisms to jet quenching

Fast parton weakly coupled to a weakly coupled medium	Fast parton weakly coupled to an arbitrary medium	Fast parton strongly coupled to a strongly coupled medium
AMY	**Higher Twist** **BDMPS-Z-ASW** **GLV…**	**AdS/CFT**

Monte Carlo codes on jet quenching

- PYQUEN (Lokhtin, Snigirev): BDMPS 1+1D Bjorken expansion http://lokhtin.web.cern.ch/lokhtin/pyquen/
- Q-Pythia (Armesto, Salgado) : BDMPS modified splitting https://igfae.usc.es/qatmc/
- YaJEM (Renk): increases virtuality of partons during evolution https://wiki.bnl.gov/TECHQM/index.php/YaJEM
- JEWEL (Zapp): BDMPS modified parton showering https://jewel.hepforge.org/
- PQM (Dainese, Loizides, Paic): BDMPS quenching weights arXiv:hep-ph/0406201

Monte Carlo codes on jet quenching

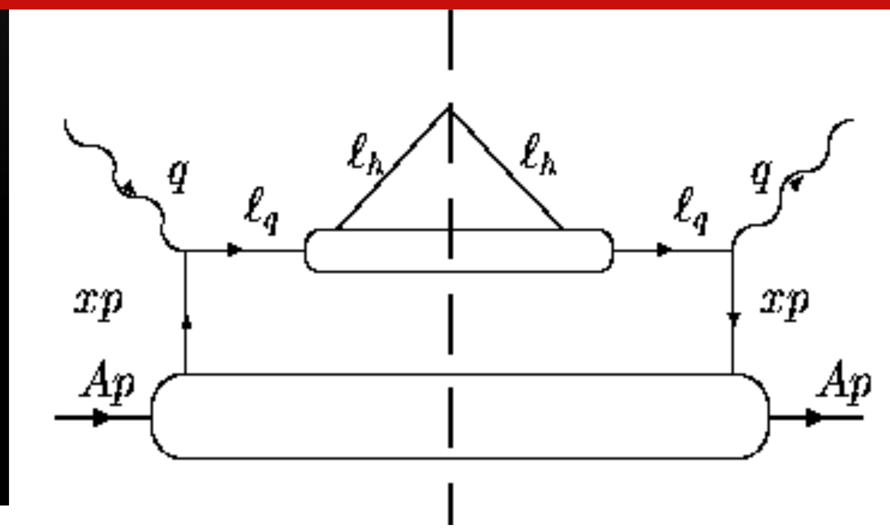
- MATTER (Majumder): higher-twist in-medium showering
  arXiv:1301.5323 arXiv:1301.5323
- CUJET (Jiechen Xu, Gyulassy): GLV 2+1D viscos hydro
  arXiv:1402.2956 arXiv:1508.00552 arXiv:1808.05461
- Martini (Schenke, Gale, Jeon) : AMY 2+1D viscos hydro
  arXiv:0909.2037
- Hybrid (Chesler, Rajagopal): Ads/CFT strongly coupled plasma
  arXiv:1402.6756
- LBT (X.N.Wang, Zhu, Luo, Cao…): higher-twist 3+1D hydro
  arXiv:1302.5874 arXiv:1605.06447 arXiv:1803.06785
- JETSCAPE

Higher Twist Approach

Factorization

- Long distance physics VS short distance physics
- Factorization:

systematically separate the long distance physics from the short distance physics

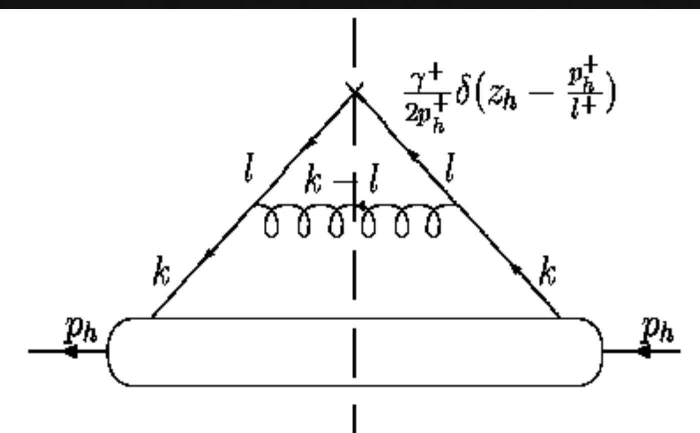


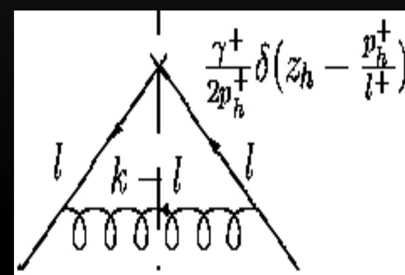
$$\frac{dW^{S(0)}_{\mu\nu}}{dz_h} = \sum_q \int dx\, f_q^A(x) H^{(0)}_{\mu\nu}(x, p, q) D_{q\to h}(z_h)$$

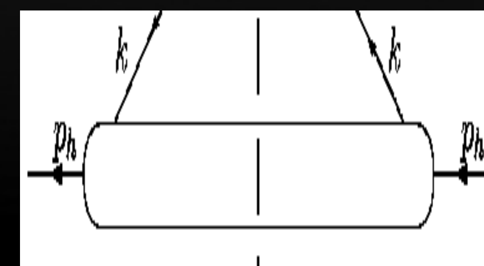
Evolution

$$A = (A^0, A^1, A^2, A^3) \quad \vec{A}_T = (A^1, A^2)$$

$$A^+ = \frac{1}{\sqrt{2}}(A^0 + A^3) \quad A^- = \frac{1}{\sqrt{2}}(A^0 - A^3)$$







$$dD^1_{q\to h}(z_h) = \frac{\alpha_s^2}{2\pi} \int \frac{dk_T^2}{k_T^2} \int_{z_h}^1 \frac{dz}{z} C_F \frac{1+z^2}{1-z} D_{q\to h}(z_h/z)$$

DGLAP Evolution Equations

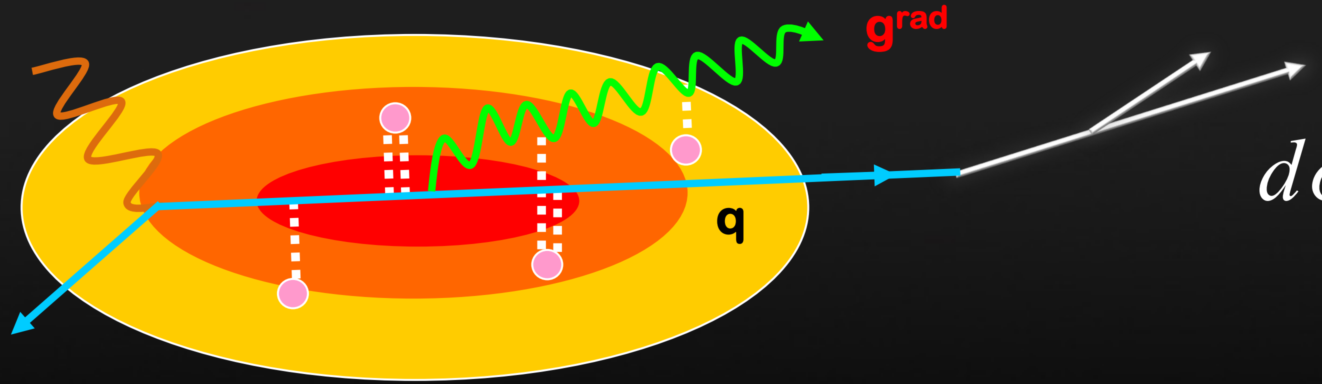
$$Q^2 \frac{d}{dQ^2} D_{q\to h}(z_h, Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \int_{z_h}^{1} \frac{dz}{z} \Big[\gamma_{qq}(z) D_{q\to h}(z_h/z, Q^2) + \gamma_{qg}(z) D_{g\to h}(z_h/z, Q^2)\Big] ,$$

$$Q^2 \frac{d}{dQ^2} D_{g\to h}(z_h, Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \int_{z_h}^{1} \frac{dz}{z} \Big[\gamma_{gq}(z) D_{s\to h}(z_h/z, Q^2) + \gamma_{gg}(z) D_{g\to h}(z_h/z, Q^2)\Big] .$$

$$Q^2 \frac{d}{dQ^2} f_{q/h}(z_h, Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \int_{z_h}^{1} \frac{dz}{z} \Big[P_{qq}(z) f_{q/h}(z_h/z, Q^2) + P_{qg}(z) f_{g/h}(z_h/z, Q^2)\Big] ,$$

$$Q^2 \frac{d}{dQ^2} f_{g/h}(z_h, Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \int_{z_h}^{1} \frac{dz}{z} \Big[P_{gq}(z) f_{s/h}(z_h/z, Q^2) + P_{gg}(z) f_{g/h}(z_h/z, Q^2)\Big] .$$

Modified Fragmentation



$d\sigma^{hadron}$

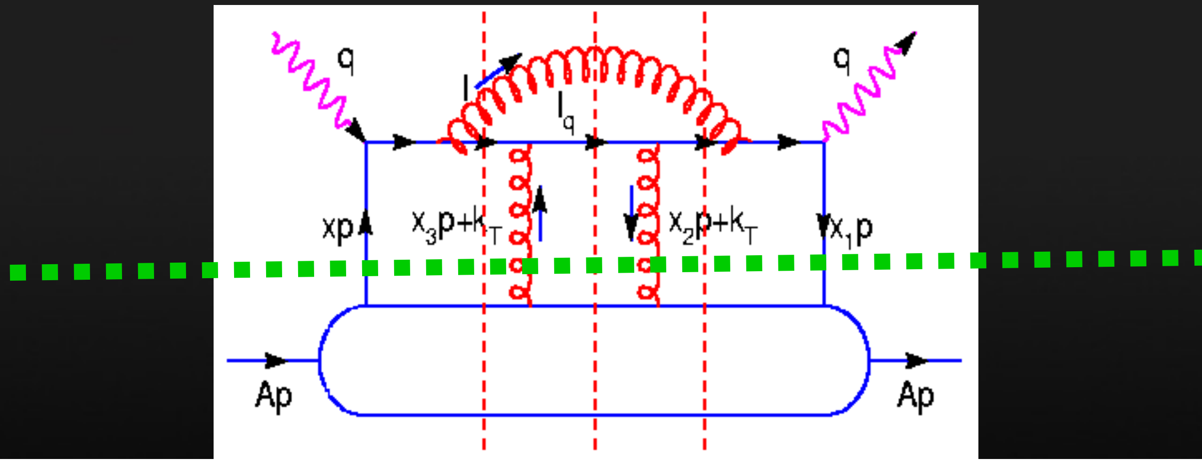
- **Modified fragmentation functions**

$$D_{q\to h}(z_h,\mu^2) \rightarrow \widetilde{D}_{q\to h}(z_h,\mu^2)$$

X.N.Wang, Z.Huang and I.Sarcevic, PRL 77(1996)231

Quark-Gluon Scattering in Nuclei: Light Quark Energy Loss

Generalized factorization theorem



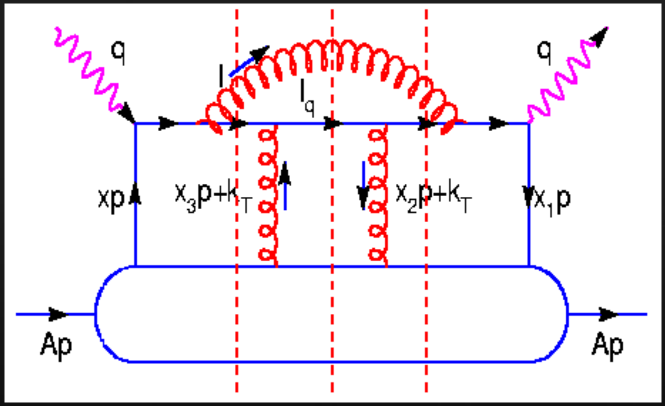
$$W_{\mu\nu} = \int \frac{dy^-}{2\pi} dy_1^- dy_2^- \frac{1}{2} \langle A|\bar{\psi}_q(0)\,\gamma^+ F_\tau{}^+(y_2^-)\, F^{+\tau}(y_1^-)\,\psi_q(y^-)|A\rangle$$
$$\times\left(-\frac{1}{2}g^{\alpha\beta}\right)\left[\frac{1}{2}\frac{\partial^2}{\partial k_T^\alpha \partial k_T^\beta}\overline{H}^D_{\mu\nu}(y^-, y_1^-, y_2^-, k_T, p, q, z)\right]_{k_T=0}$$

$$\overline{H}^D_{\mu\nu}(y^-, y_1^-, y_2^-, k_T, p, q, z) = \int dx\, dx_1\, dx_2\, e^{ix_1p^+y^- + ix_2p^+y_1^- + i(x-x_1-x_2)p^+y_2^-}$$
$$\times \mathrm{Tr}\left[\hat{H}^{\alpha\beta}_{\mu\nu}(xp^+, k_2, k_3)\not{p}\, p_\alpha p_\beta\right]\Big|_{k_T=0}$$

J. Qiu, G. Sterman, NPB 353(1991)105; NPB 353(1991)137.
M. Luo,J. Qiu, G. Sterman, PLB 279(1992)377;
M. Luo,J. Qiu, G. Sterman, PRD 49(1994)4493; PRD 50(1994)1951

Hard part of twist-4 processes

$$\overline{H}^D_{C\,\mu\nu}(y^-, y_1^-, y_2^-, k_T, p, q, z)$$
$$= \int dx \frac{dx_1}{2\pi}\frac{dx_2}{2\pi} e^{ix_1p^+y^- + ix_2p^+y_1^- + i(x-x_1-x_2)p^+y_2^-} \int \frac{d^4\ell}{(2\pi)^4}$$
$$\times \frac{1}{2}\mathrm{Tr}\left[p\cdot\gamma\gamma_\mu p^\sigma p^\rho \widehat{H}_{\sigma\rho}\gamma_\nu\right] 2\pi\delta_+(\ell^2)\,\delta(1-z-\frac{\ell^-}{q^-})$$



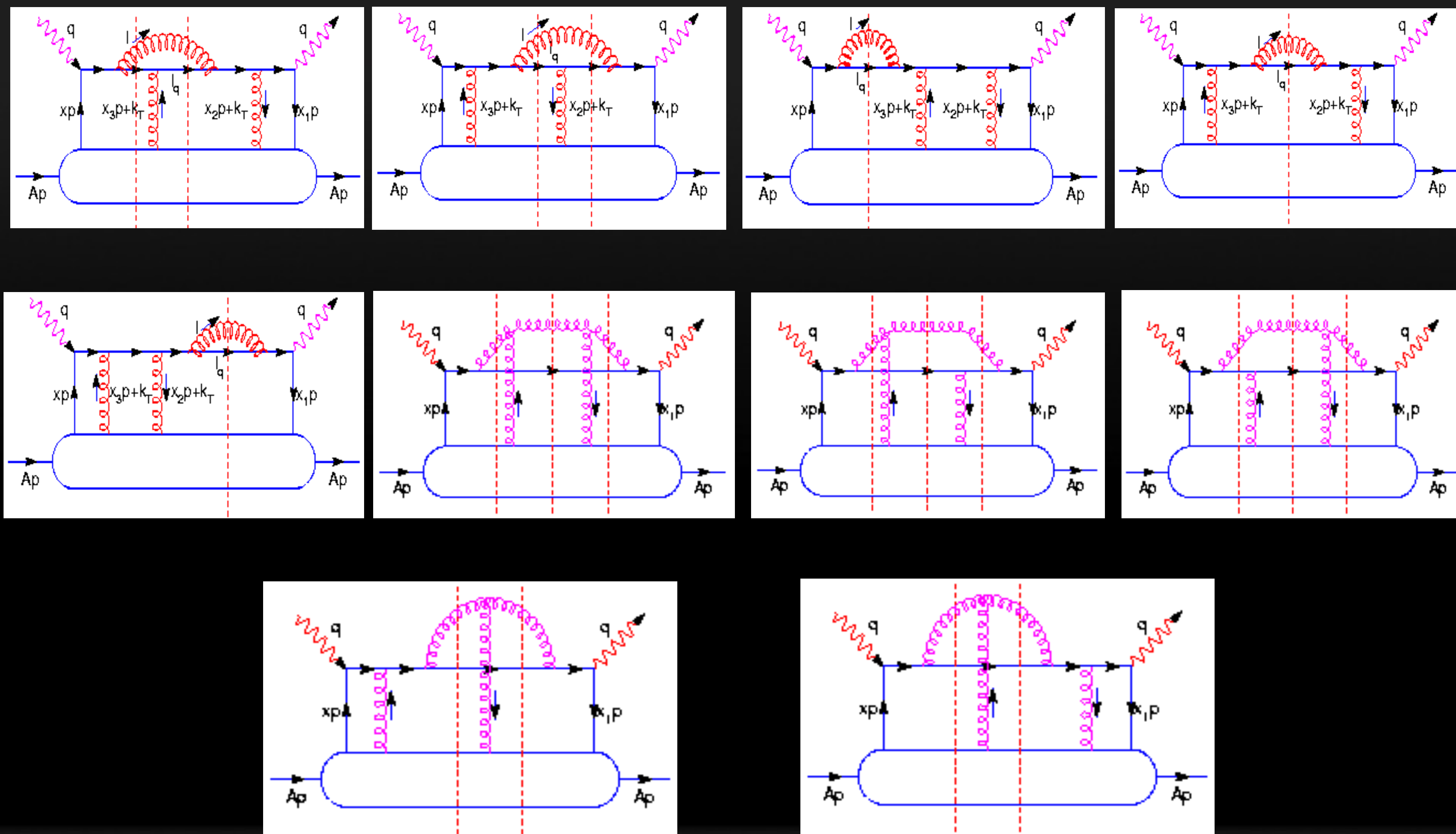
$$\overline{H}^D_{1,C}(y^-, y_1^-, y_2^-, k_T, x, p, q, z) = \int \frac{d\ell_T^2}{\ell_T^2}\frac{\alpha_s}{2\pi} C_F \frac{1+z^2}{1-z}$$
$$\times \frac{2\pi\alpha_s}{N_c}\overline{I}_{1,C}(y^-, y_1^-, y_2^-, \ell_T, k_T, x, p, q, z)$$

$$\overline{I}_{1,C}(y^-, y_1^-, y_2^-, \ell_T, k_T, x, p, q, z) = e^{i(x+x_L)p^+y^- + ix_Dp^+(y_1^- - y_2^-)}\theta(-y_2^-)\theta(y^- - y_1^-)$$
$$\times (1 - e^{-ix_Lp^+y_2^-})(1 - e^{-ix_Lp^+(y^- - y_1^-)})$$

LPM interference effect

Gluon formation time: $\tau_f^q \equiv \frac{1}{x_L p^+}$ $\quad x_L = \frac{\ell_T^2}{2p^+q^-z(1-z)}$

Other Processes



Modified FF of the Light Quark(I)

$$\frac{dW_{\mu\nu}}{dz_h} = \sum_q \int dx \tilde{f}_q^A(x, \mu_I^2) H_{\mu\nu}^{(0)}(x, p, q) \widetilde{D}_{q\to h}(z_h, \mu^2)$$

$$\begin{aligned}\widetilde{D}_{q\to h}(z_h, \mu^2) \equiv\ & D_{q\to h}(z_h, \mu^2) + \int_0^{\mu^2} \frac{d\ell_T^2}{\ell_T^2} \frac{\alpha_s}{2\pi} \int_{z_h}^1 \frac{dz}{z} \Big[\Delta\gamma_{q\to qg}(z, x, x_L, \ell_T^2) D_{q\to h}(z_h/z) \\ & + \Delta\gamma_{q\to gq}(z, x, x_L, \ell_T^2) D_{g\to h}(z_h/z)\Big]\end{aligned}$$

$$\begin{aligned}\Delta\gamma_{q\to qg}(z, x, x_L, \ell_T^2) &= \left[\frac{1+z^2}{(1-z)_+} T_{qg}^{A(m)}(x, x_L) + \delta(1-z)\Delta T_{qg}^{A(m)}(x, \ell_T^2)\right] \\ &\quad \times \frac{2\pi\alpha_s C_A}{\ell_T^2 N_c \tilde{f}_q^A(x, \mu_I^2)}, \\ \Delta\gamma_{q\to gq}(z, x, x_L, \ell_T^2) &= \Delta\gamma_{q\to qg}(1-z, x, x_L, \ell_T^2),\end{aligned}$$

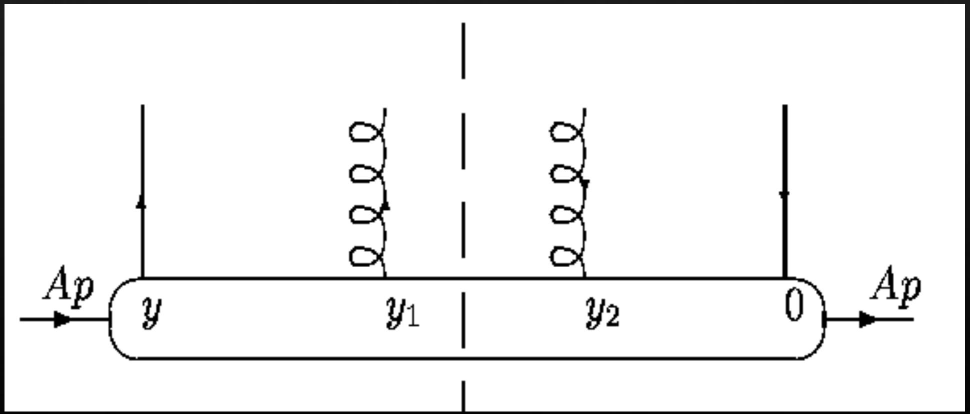
X. Guo, X. N. Wang, PRL 85 (2000) 3591;

X. N. Wang, X. Guo, NPA 696(2001) 788;

BWZ, X. N. Wang, NPA 720(2003) 429.

Two-parton correlation function

- Twist-4 parton correlation function is in principle not calculable.



We can estimate their value with some approx.

$$\int \frac{dy^-}{2\pi} dy_1^- dy_2^- e^{ix_1p^+y^- + ix_2p^+(y_1^- - y_2^-)}$$
$$\times \frac{1}{2}\langle A|\bar{\psi}_q(0)\gamma^+ F_\sigma{}^+(y_2^-) F^{+\sigma}(y_1^-) \psi_q(y^-)|A\rangle \theta(-y_2^-)\theta(y^- - y_1^-)$$
$$= \frac{C}{x_A} f_q^A(x_1)\, x_2 f_g^N(x_2)\,,$$

$$x_A = \frac{1}{m_N R_A}$$

Light quark energy loss

$$\langle \Delta z_g \rangle = \int_0^{\mu^2} \frac{d\ell_T^2}{\ell_T^2} \int_0^1 dz \frac{\alpha_s}{2\pi} z \Delta\gamma_{q\to gq} \sim \alpha_s^2 \frac{x_B}{x_A^2 Q^2} x_T f_g^N(x_T)$$

$$x_A = \frac{1}{m_N R_A}$$

- Light quark energy loss has a quadratical dependence on nuclear size because of LPM interference effect.
- Light quark energy loss due to quark-gluon double scattering is proportional to gluon density.

Quark-Gluon Scattering in Nuclei : Heavy Quark Energy Loss

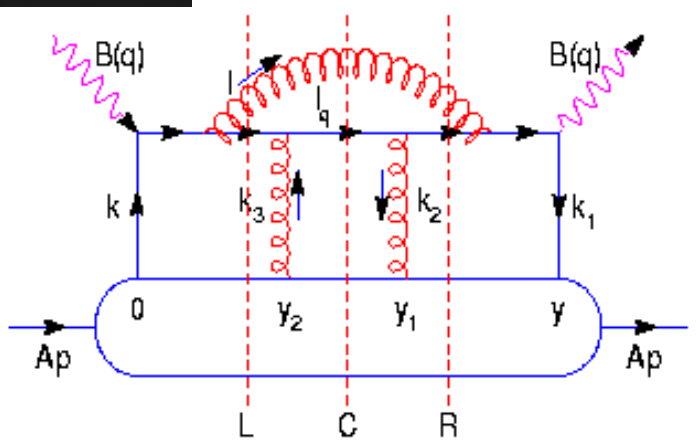
BWZ, E. Wang, X. N. Wang, PRL 93(2004)072301;

BWZ, E. Wang, X. N. Wang, NPA 757(2005)493;

Sharma, I Vitev, BWZ, PRC 80 (2009)054902.

LPM Effect and Formation Time

$$\overline{H}^D_{1,C}(y_i^-, k_T, x, p, q, m, z) = \int d\ell_T^2 \frac{(1+z^2)\ell_T^2 + (1-z)^4 m^2}{(1-z)(\ell_T^2 + (1-z)^2 m^2)^2} \frac{\alpha_s}{2\pi} \times C_F \frac{2\pi\alpha_s}{N_c} \overline{I}_{1,C}(y_i^-, \ell_T, k_T, x, p, q, m, z)$$



$$) = e^{i(x+x_L)p^+y^- + ix_D p^+(y_1^- - y_2^-)}\theta(-y_2^-)\theta(y^- - y_1^-) \times \left(1 - e^{-i(x_L + (1-z)x_M)p^+ y_2^-}\right) \times \left(1 - e^{-i(x_L+(1-z)x_M)p^+(y^- - y_1^-)}\right).$$

- LMP interference effect.
- The formation time of gluon radiation.

$$x_L = \frac{\ell_T^2}{2p^+q^-z(1-z)}$$

$$\tau_f^Q \equiv \frac{1}{(x_L + (1-z)x_M/z)p^+} < \tau_f^q \equiv \frac{1}{x_L p^+}$$

$$x_M = \frac{M^2}{2p^+q^-}$$

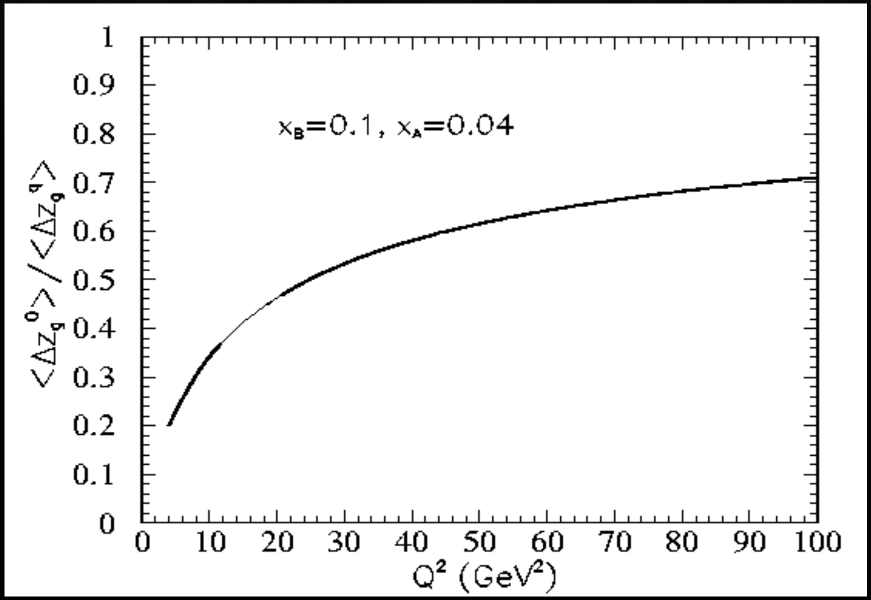
Dead-cone effect

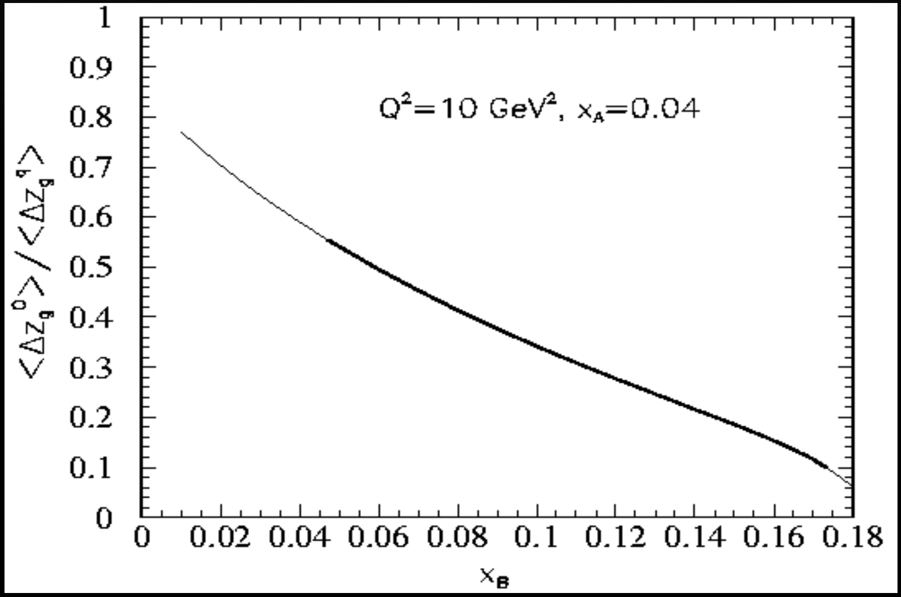
$$\nabla^2_{k_T} H^D_{C(L,R)}|_{k_T=0} = 4C_A \frac{1+z^2}{1-z} \frac{\ell_T^4}{[\ell_T^2 + (1-z)^2 M^2]^4} \widetilde{H^D}_{C(L,R)} + \mathcal{O}(x_B/Q^2 \ell_T^2)$$

Dead-Cone effect of heavy quark propagating

$$f_{Q/q} = \left[\frac{\ell_T^2}{\ell_T^2 + (1-z)^2 M^2}\right]^4 = \left[1 + \frac{\theta_0^2}{\theta^2}\right]^{-4}$$

$$\theta_0 = \frac{M}{q^-}, \quad \theta = \frac{\ell_T}{l^-}$$





Heavy Quark Energy Loss (I)

(1) When $x_B/Q^2 \gg x_A/M^2$ ⇒ $(1 - e^{-(x_L+(1-z)x_M)^2/x_A^2}) \simeq 1$

$$x_A = \frac{1}{m_N R_A}$$

$$\langle \Delta z_g^Q \rangle \sim C_A \frac{\widetilde{C}\alpha_s^2}{N_c} \frac{x_B}{x_A Q^2}$$

(2) For large values of Q^2 or small x_B, we have

$$\langle \Delta z_g^Q \rangle \sim C_A \frac{\widetilde{C}\alpha_s^2}{N_c} \frac{x_B}{x_A^2 Q^2}$$

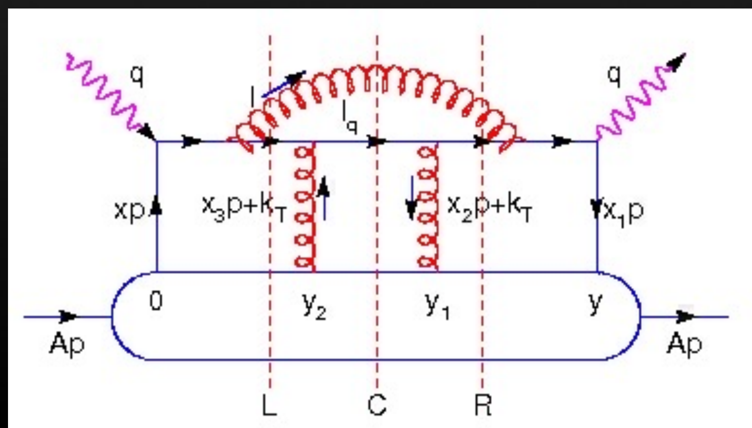
Quark-Quark Scattering in Nuclei

BWZ, X.N. Wang, A. Schaefer, NPA 783(2007)551;

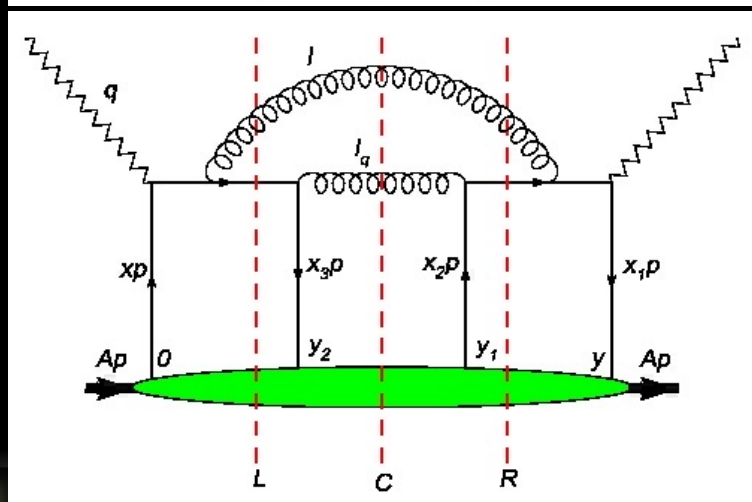
A. Schaefer, X.N. Wang, BWZ, NPA 793(2007)128.

Quark-Quark Double Scattering

- Two kinds of double scattering in eA DIS

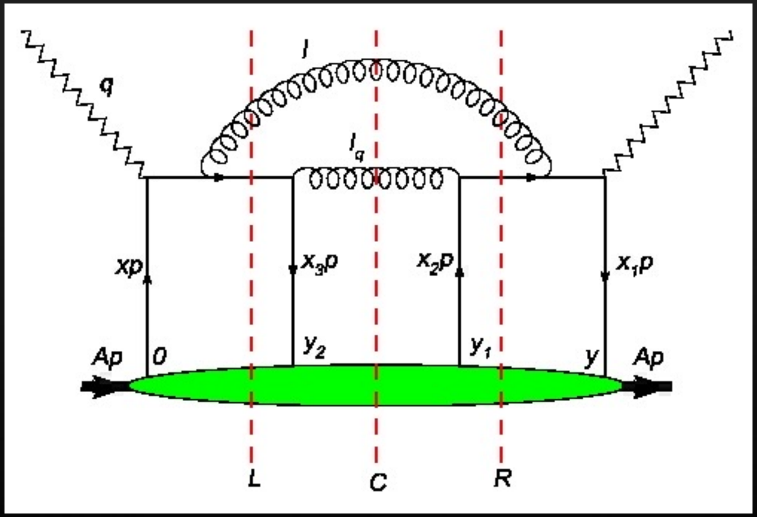


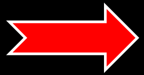
quark-gluon double scattering



quark-quark double scattering

Properties of Q-Q scattering

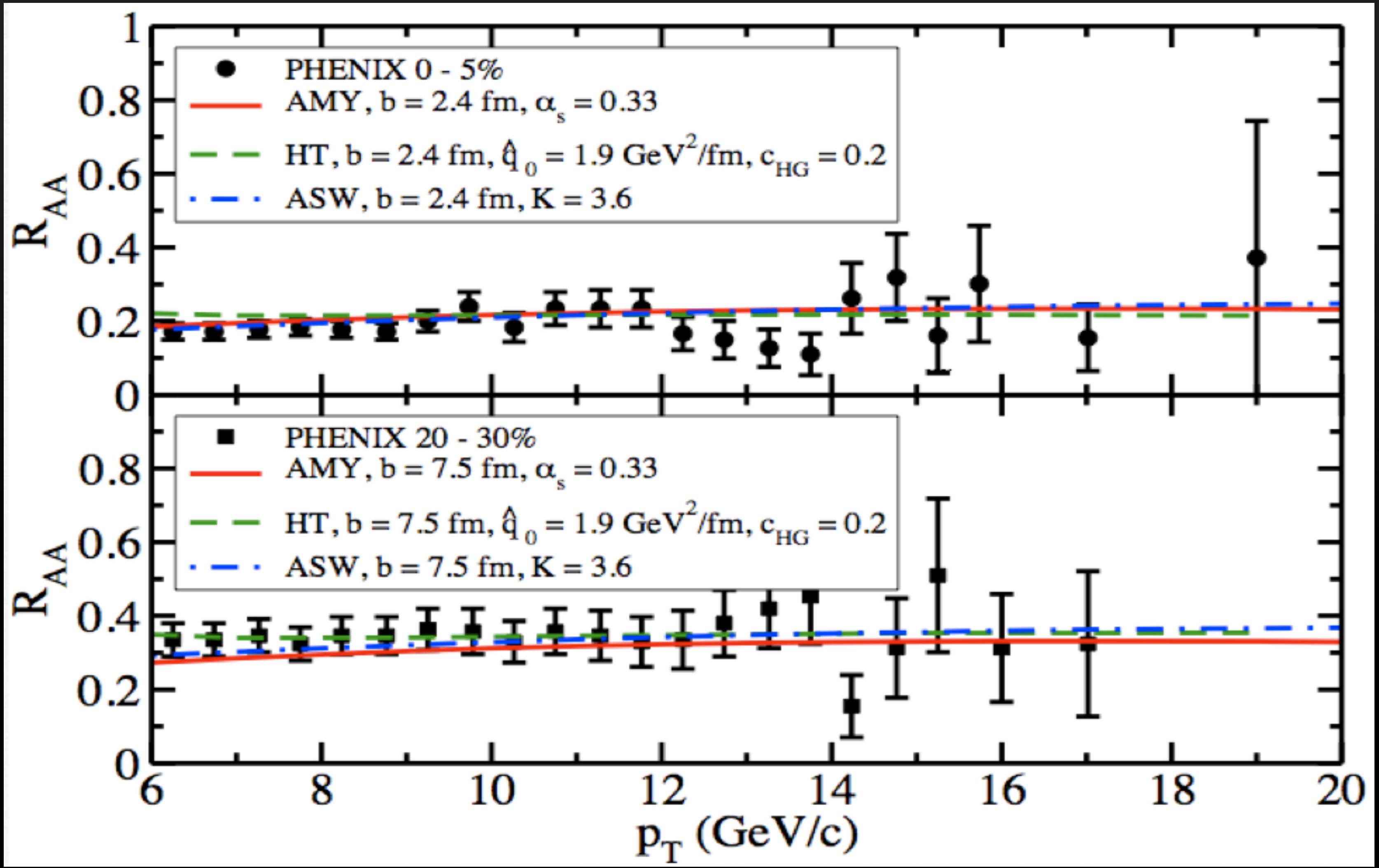


- Quark-quark double scattering mixes quark and gluon FF.  Jet conversion
- Quark-quark double scattering gives different modifications to quark FF and anti-quark FF.

BWZ, X.N. Wang, A. Schaefer, NPA 783(2007)551;

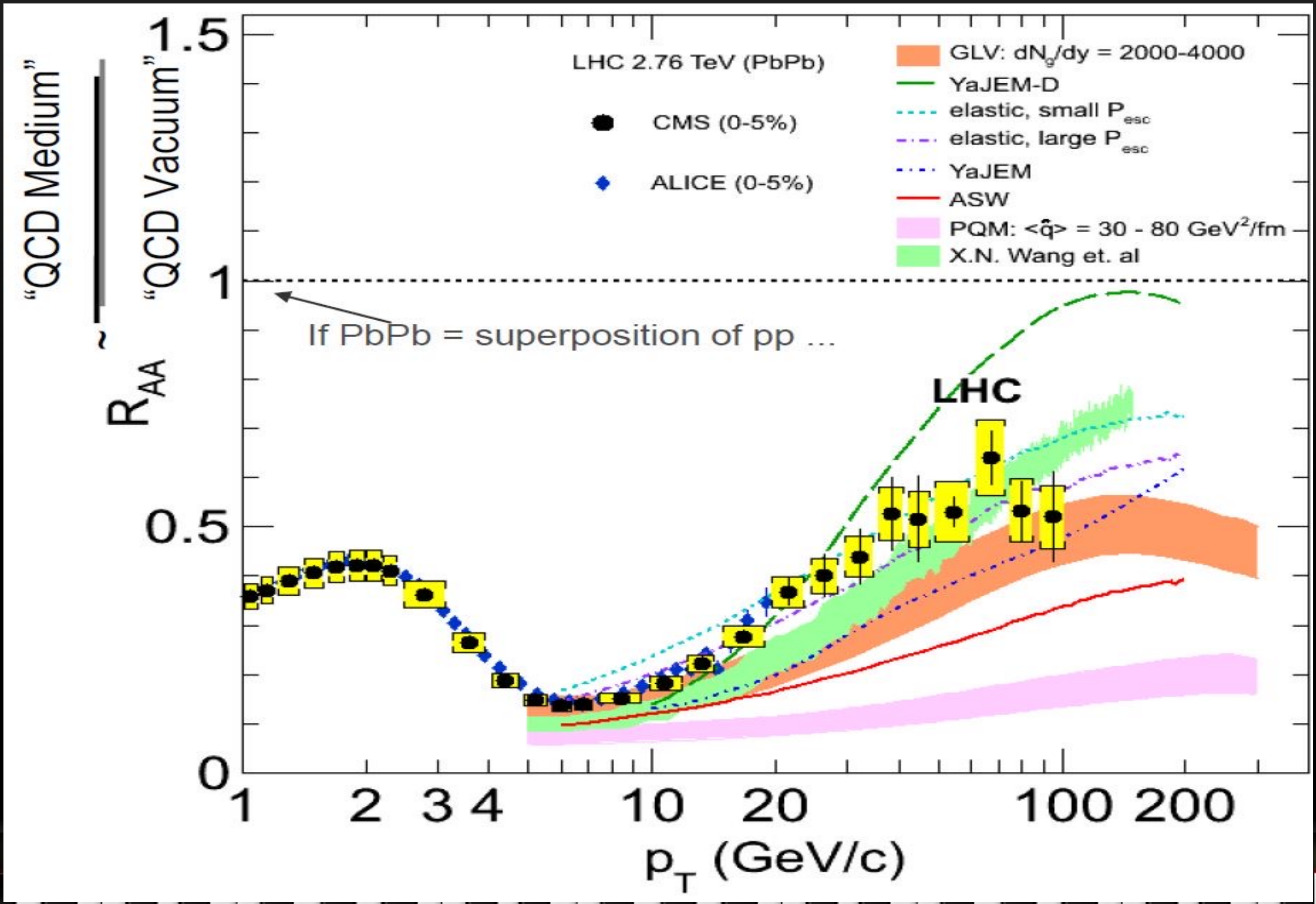
A. Schaefer, X.N. Wang, BWZ, NPA 793(2007)128.

Hadron suppression at RHIC



S A Bass, et al, PRC 79 (2009) 024901

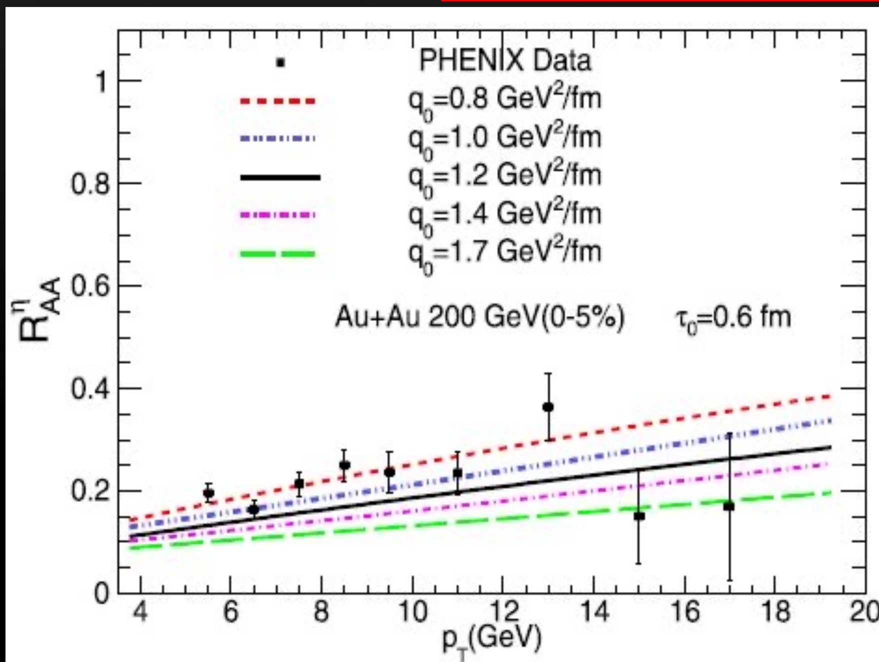
Hadron suppression at LHC



η in heavy-ion collisions at NLO

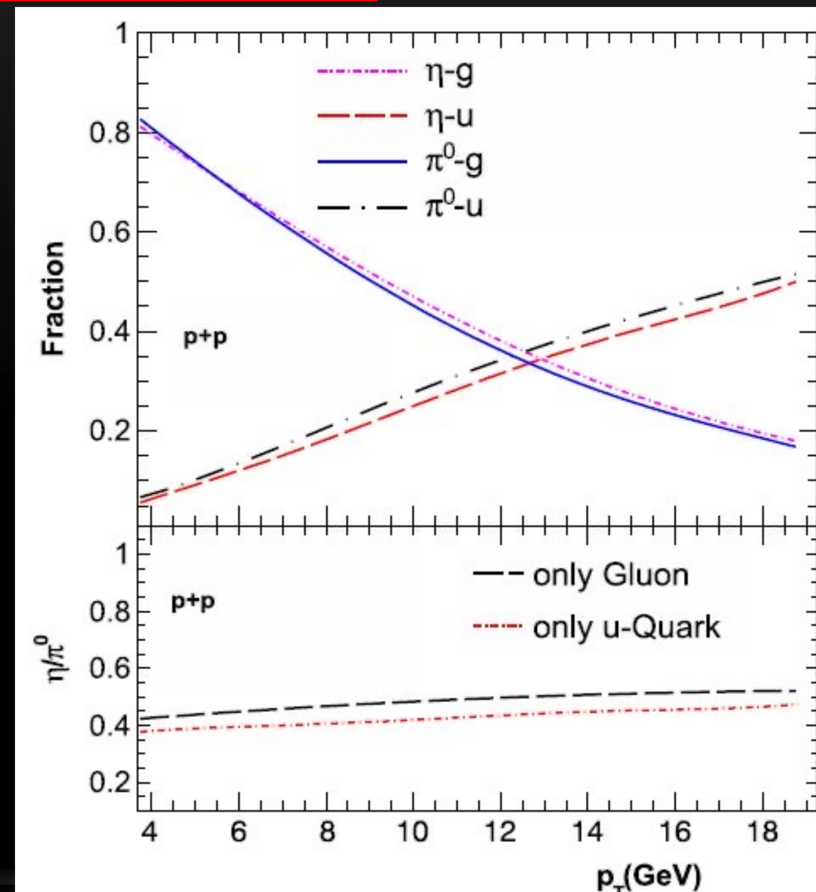
- Production of eta meson in HIC has been calculated;
- Flavor composition has very small effect on the ratio η/π^0 .

$$(dE/dx)_{\rm rad} = -C_2 \hat{q} L$$



$$G^{\eta,\pi^0}(p_T) = \frac{\int f_g(\frac{p_T}{z_h}) \cdot D_{g\to\eta,\pi^0}(z_h, p_T)\frac{dz_h}{z_h^2}}{\frac{1}{p_T}\frac{d\sigma_{\pi^0,\eta}}{dp_T}}$$

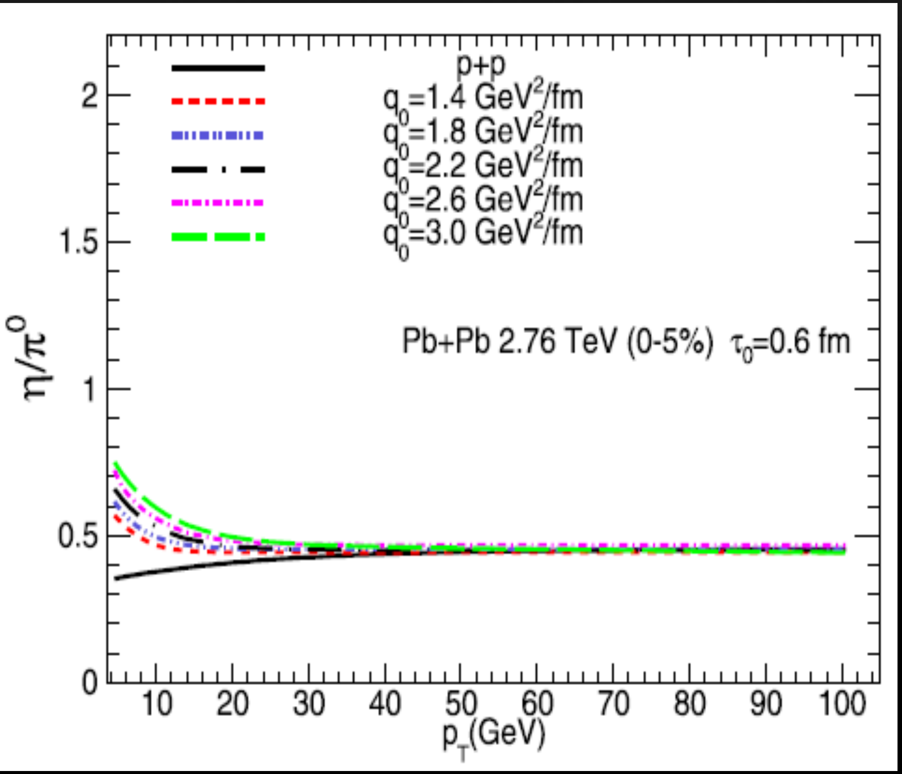
$$G^{\pi^0}(p_T) \approx G^{\eta}(p_T)$$

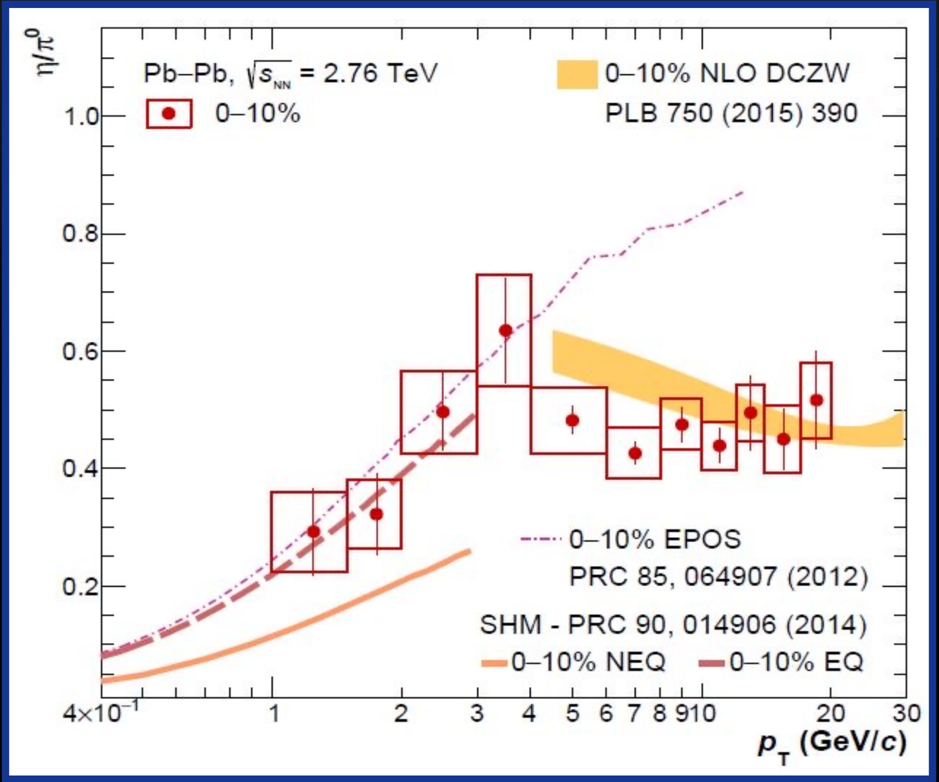


W Dai, X Chen, BWZ, E Wang， Phys. Lett. B (2015)

η/π^0 in HIC at NLO

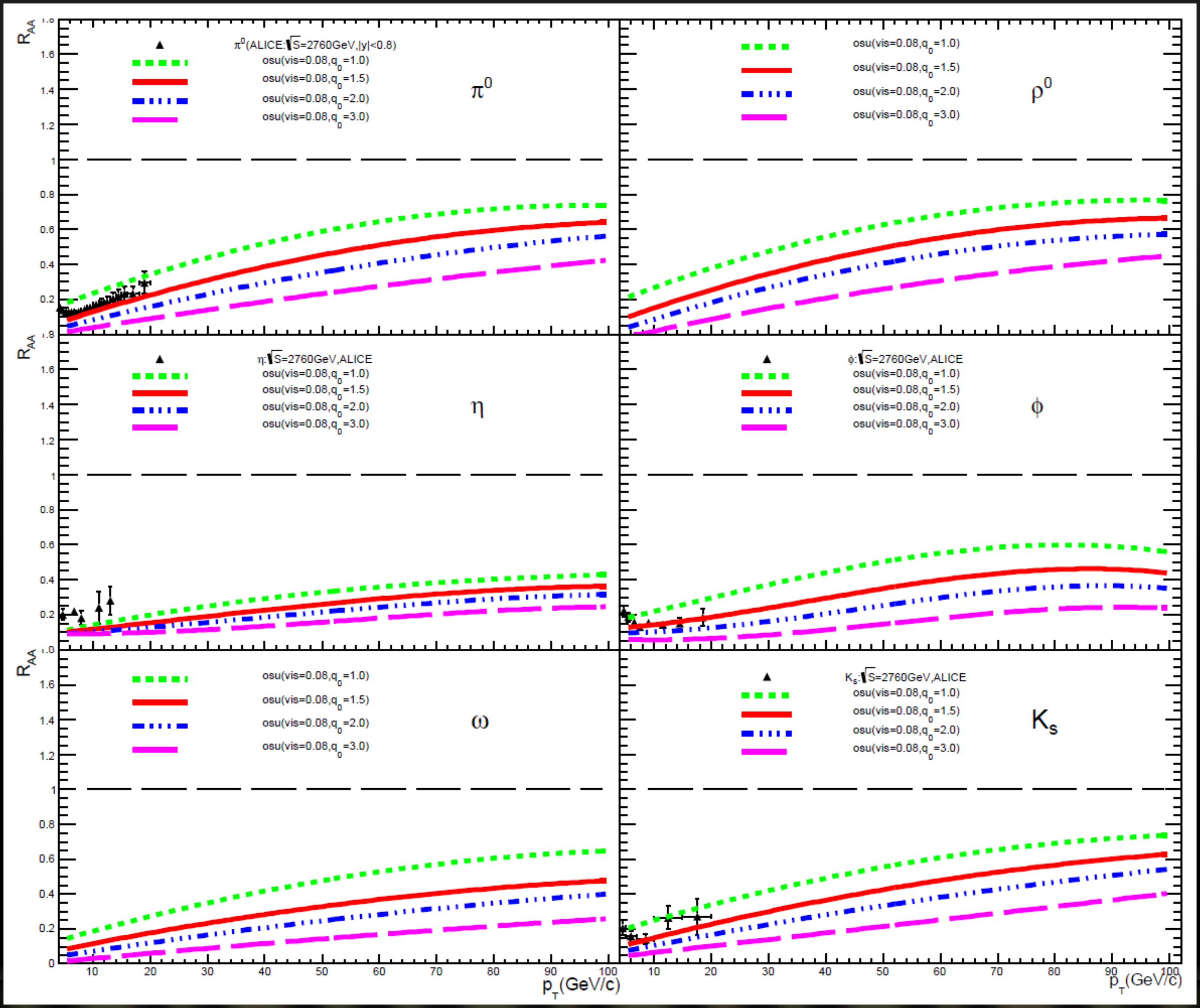
- η/π^0 ratio is almost same (~0.5) for p+p, Au+Au and Pb+Pb collision.
- Prediction on η/π^0 ratio has been confirmed by ALICE.





ALICE, PRC 98(2018)044901

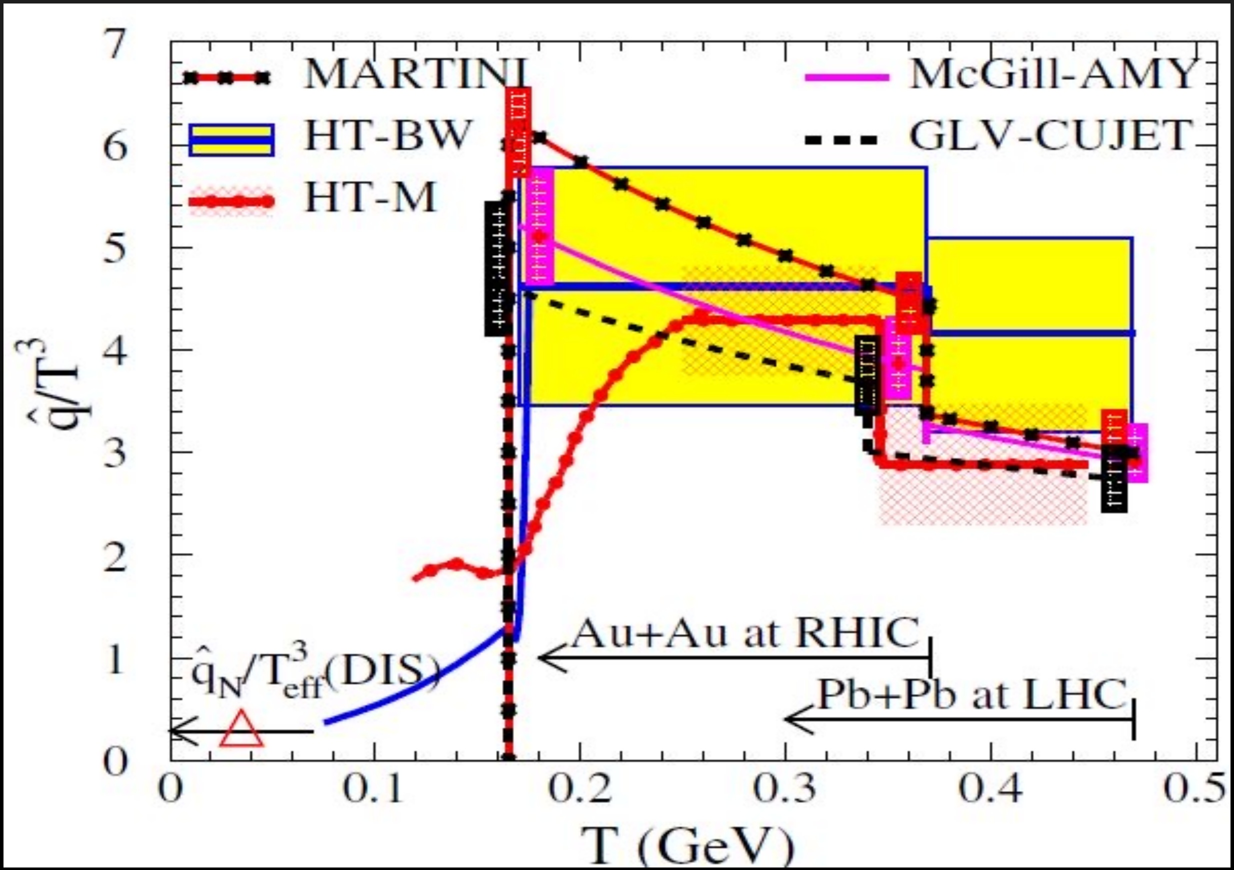
Identified meson in HIC at NLO



iEBE-VISHNU
hydro

G Ma, W Dai, BWZ, E Wang, EPJC 79 (2019) 518

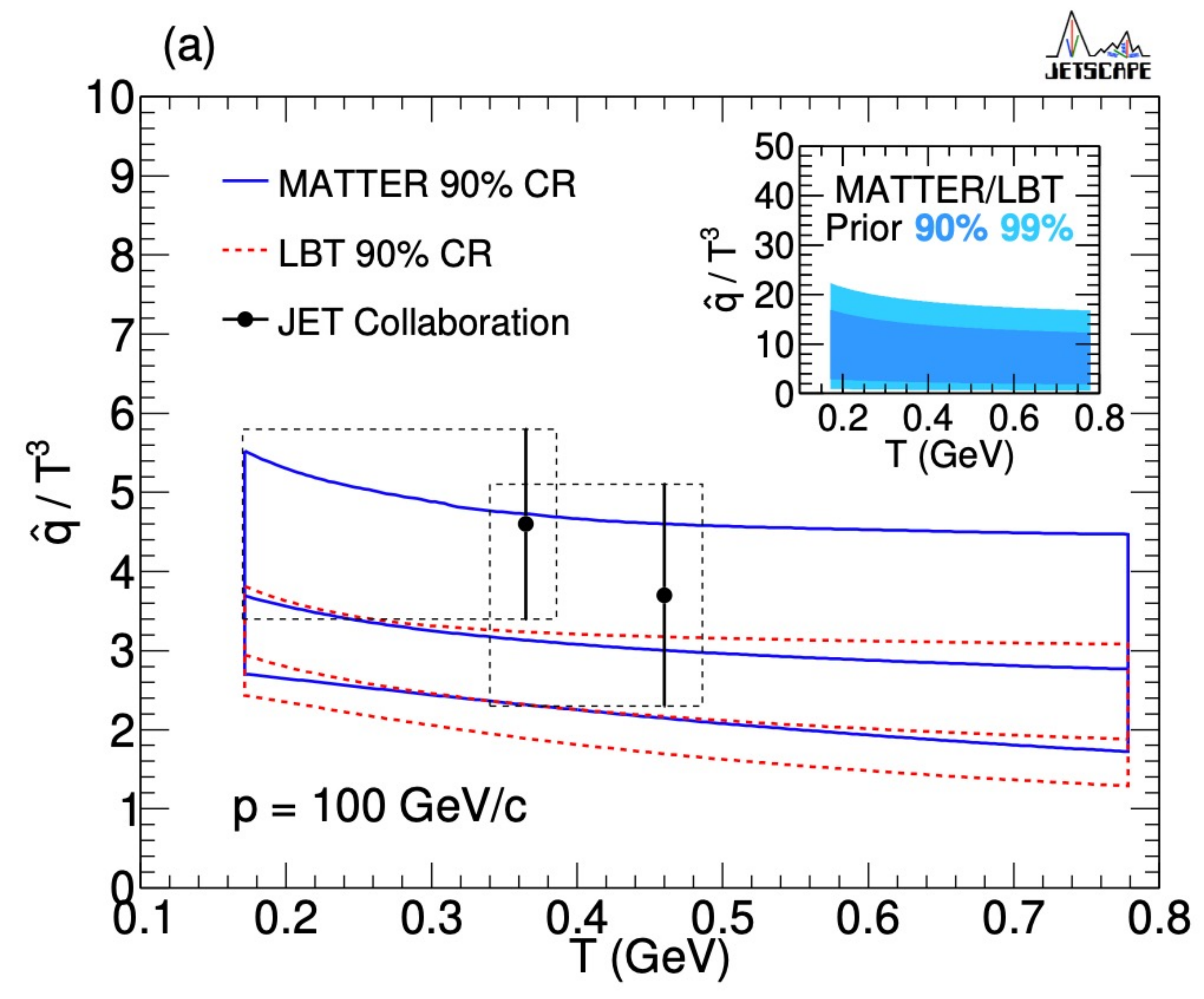
Jet transport coefficient



QGP at the LHC: qhat ~ 1.9 GeV²/fm
eA DIS at HERMES: qhat ~ 0.02 GeV²/fm

JET Collaboration, PRC (2014)

Jet transport coefficient



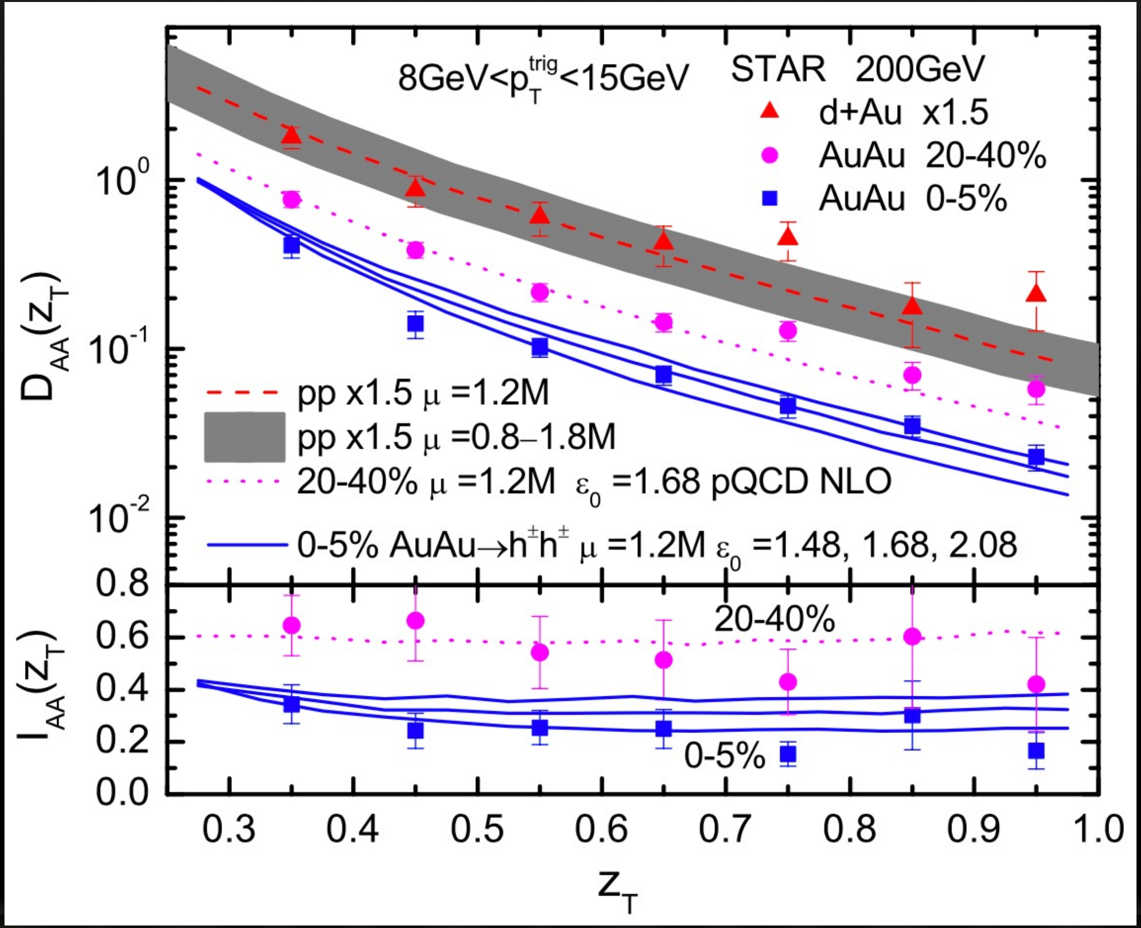
JETSCAPE Collaboration, S Cao, et al , PRC (2021)

Di-hadron correlation

$$D_{AA}(z_T, p_T^{\text{trig}}) \equiv p_T^{\text{trig}} \frac{d\sigma_{AA}^{h_1 h_2}/dy^{\text{trig}} dp_T^{\text{trig}} dy^{\text{asso}} dp_T^{\text{asso}}}{d\sigma_{AA}^{h_1}/dy^{\text{trig}} dp_T^{\text{trig}}}$$

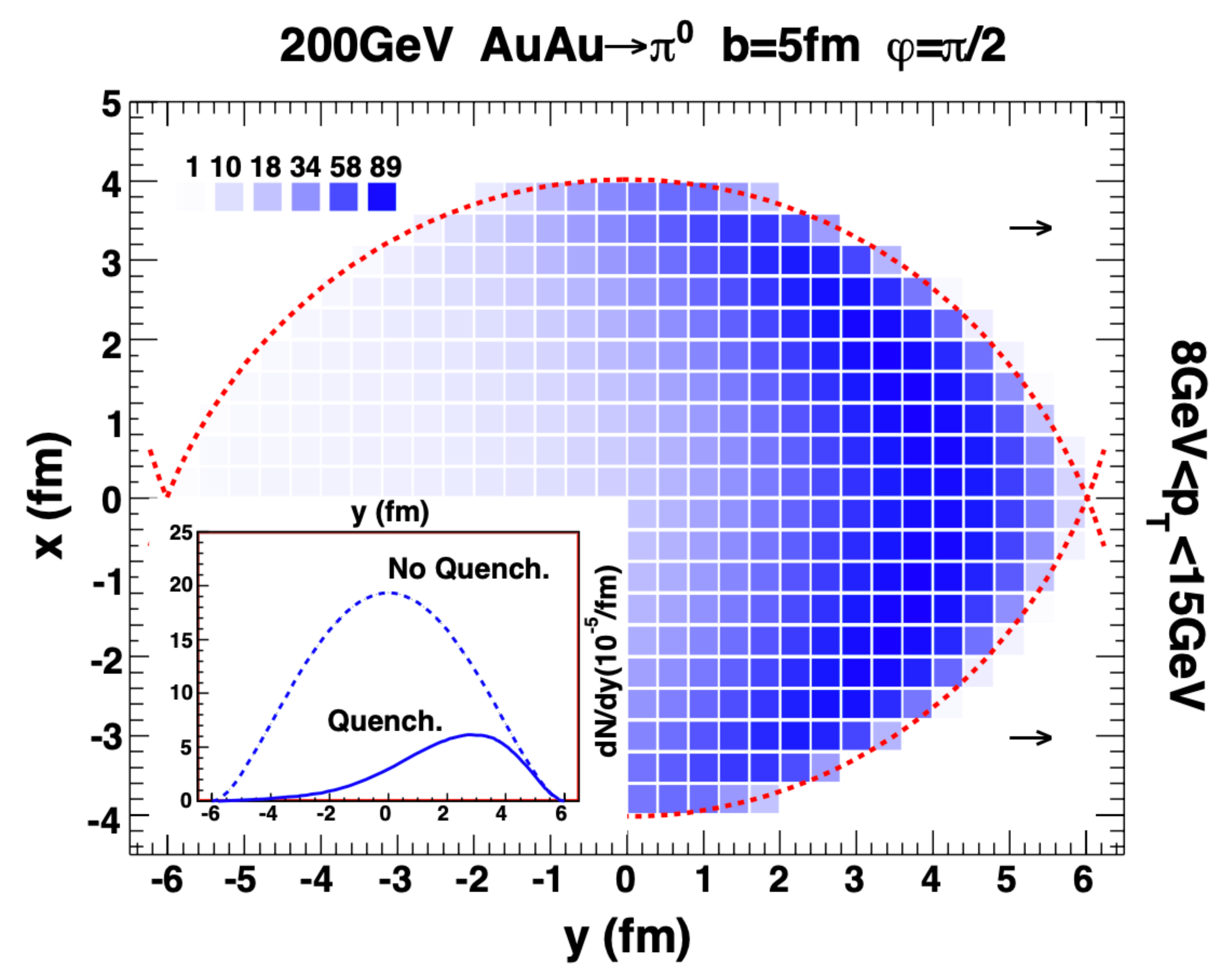
$$I_{AA} = \frac{D_{AA}(z_T, p_T^{\text{trig}})}{D_{pp}(z_T, p_T^{\text{trig}})}$$

$$z_T = p_T^{\text{asso}}/p_T^{\text{trig}}$$



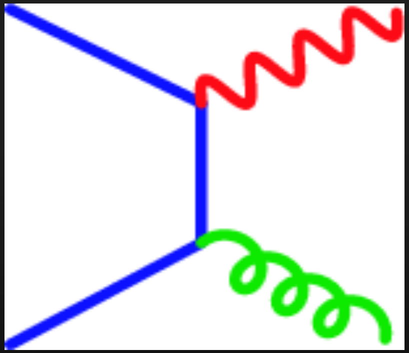
H Zhang, Owens, E Wang, X N Wang, PRL (2007)

Di-hadron correlation

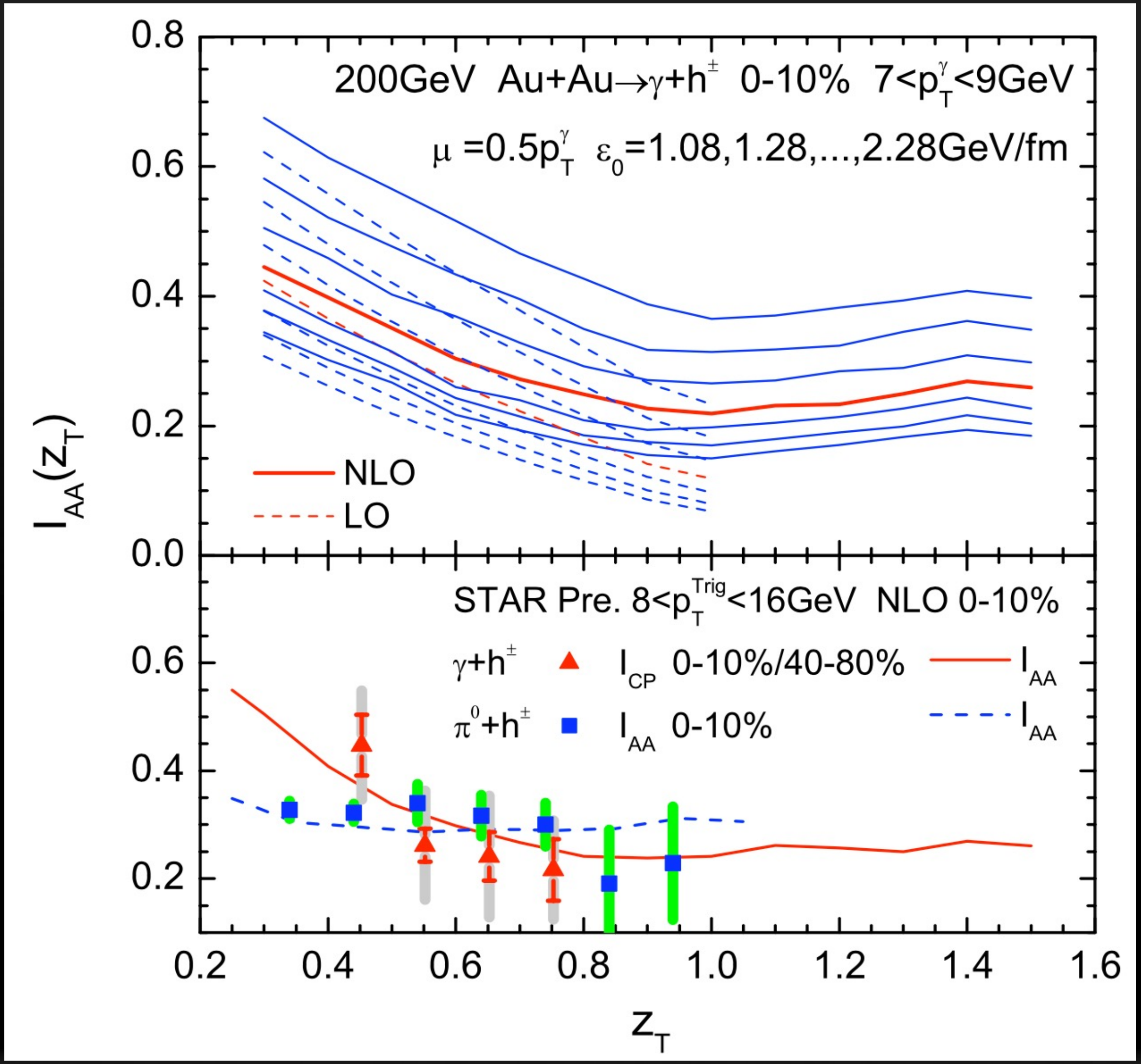


H Zhang, Owens, E Wang, X N Wang, PRL (2007)

Gamma-hadron correlation



$$z_T = p_T^h / p_T^\gamma$$



H Zhang, Owens, E Wang, X N Wang, PRL (2009)

Direct photon in HIC

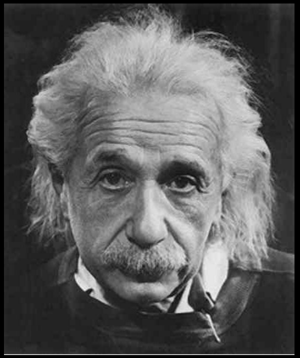
Photon Production

- God's answer: God Said, "Let there be light". And there was light. God saw that the light was good, …

  ------ From *HOLY BIBLE*

- Physicists' eyes:

1) Photon doesn't strongly interact with the produced medium ($\alpha << \alpha_s$), so direct photon is a good tool to study cold nuclear matter effect (Cronin, Shadowing…)
2) Medium-induced photon emission in the QGP: enhancement
3) Jet-photon conversion in the QGP: large contribution

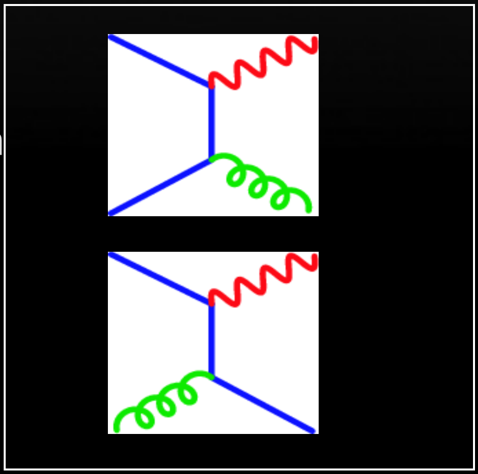


Direct photon in pp collisions

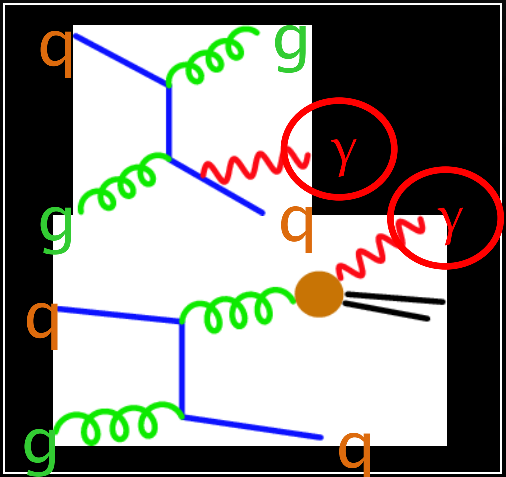
Direct photon: annihilation, Compton, bremmstrahlung } LO LO

Annihilation

Compton



$\alpha\alpha_s$



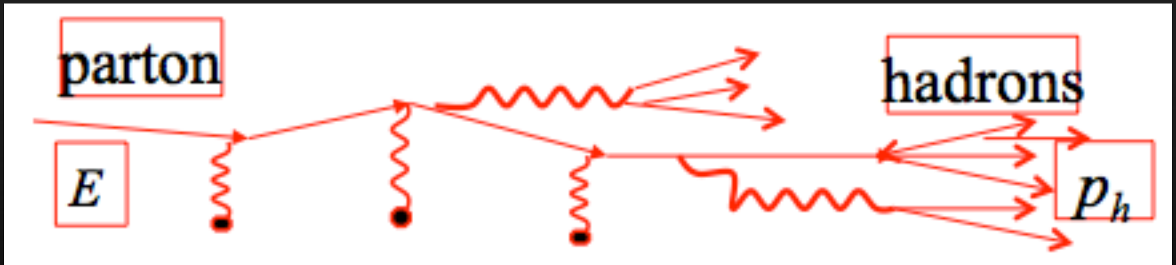
Bremmstrahlung $\alpha\alpha_s^2$

$$\alpha_s(Q) \propto \ln^{-1}(\frac{Q^2}{\Lambda^2})$$

$$D_{\gamma/c}(z, Q^2) \propto \ln(\frac{Q^2}{\Lambda^2})$$

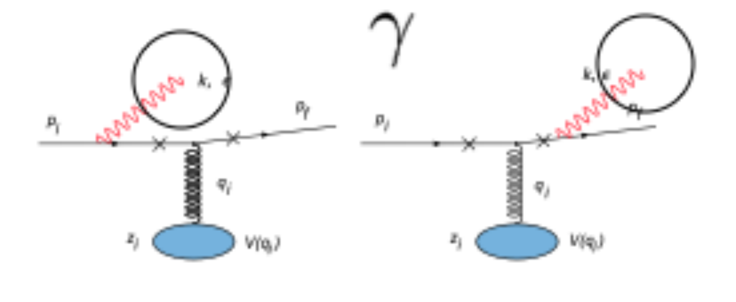
$$\alpha\alpha_s^2 D_{\gamma/c} \propto \alpha\alpha_s$$

Medium-induced photon bremmstrahlung



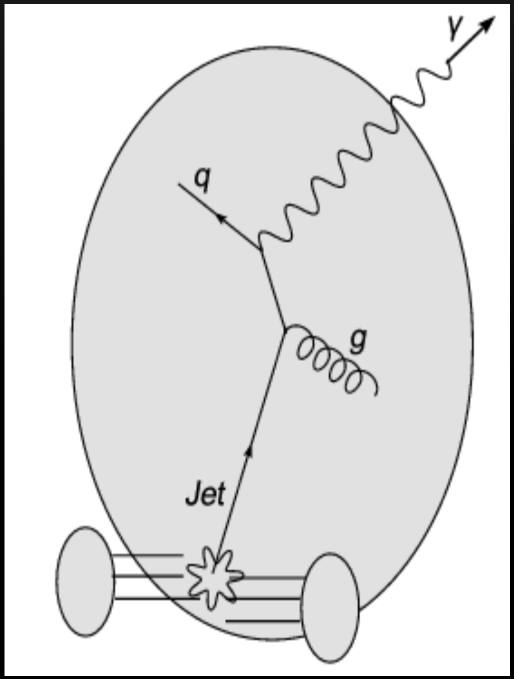
- An energetic parton propagating in hot medium may radiate photons as well as gluons: another source of photon production

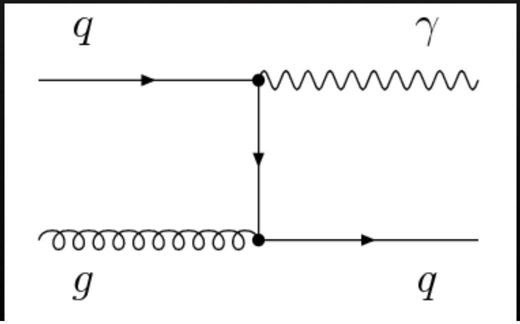
Induced gluons → Induced photons



Jet-photon conversion in QGP

- High-energy photon could be produced by conversion of a jet passing through the QGP due to jet-thermal interaction.





$$E_\gamma \frac{d\sigma^{(C)}}{d^3p_\gamma} \approx \sigma^{(C)}(s)\, E_\gamma \delta\left(\mathbf{p}_\gamma - \mathbf{p_q}\right).$$

$$\sigma^{qg\to\gamma q} = \frac{\pi\alpha_s\alpha_{em}}{6m_D E}\ln\frac{E}{2m_D}$$

$$N^\gamma_{\mathrm{conv.}}(c) = \int_{t_0}^{L} dt\ \rho(T)\sigma^{qg\to\gamma q}_{tot}(T)$$

R.Fries et al., PRL90,132301(2003)

Medium modified FF

- Effective fragmentation functions for obtaining photons from partons are:

$$D_{\gamma/c}(z) \Rightarrow \int_0^{1-z} d\epsilon\, P(\epsilon)\, \frac{1}{1-\epsilon} D_{\gamma/c}\left(\frac{z}{1-\epsilon}\right)$$

← Jet quenching

$$+ \frac{dN^{\gamma}_{\rm med.}(c)}{dz}$$

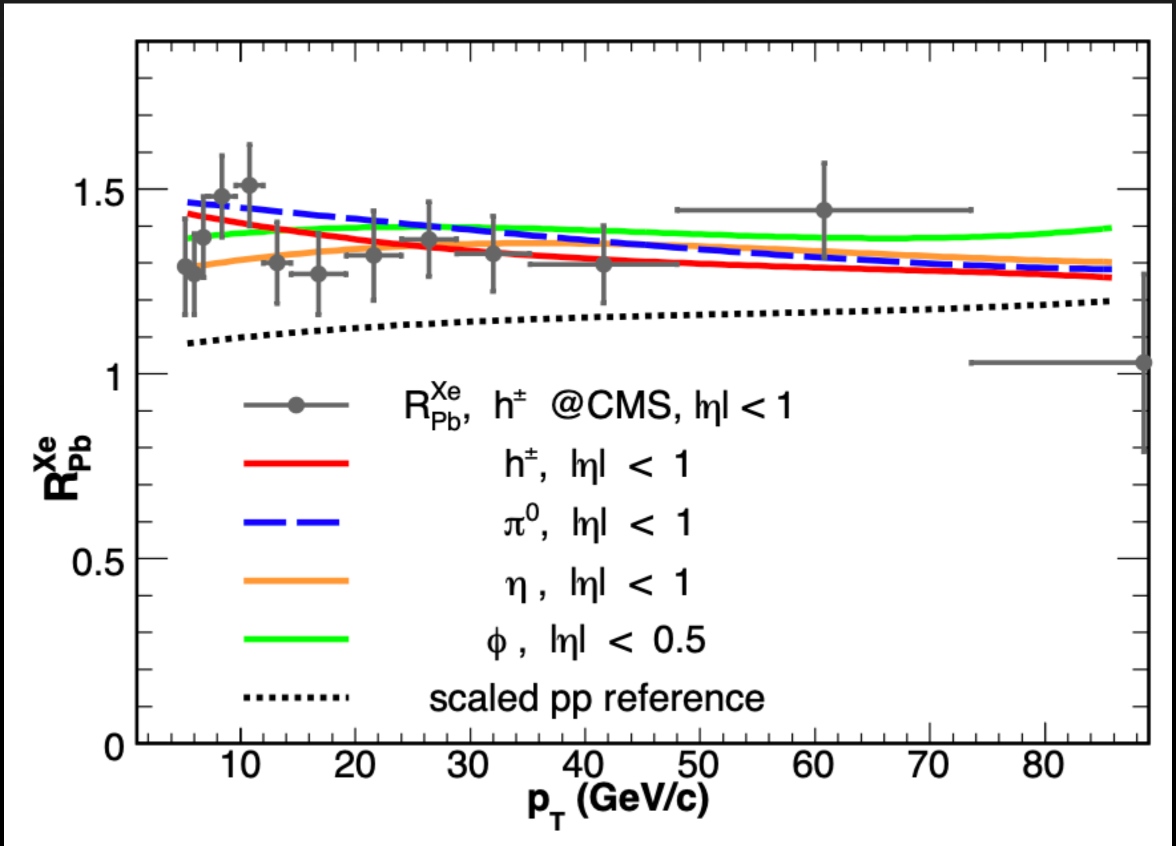
← Photon emission

$$+ N^{\gamma}_{\rm conv.}(c)\delta(1-z)$$

← Jet conversion

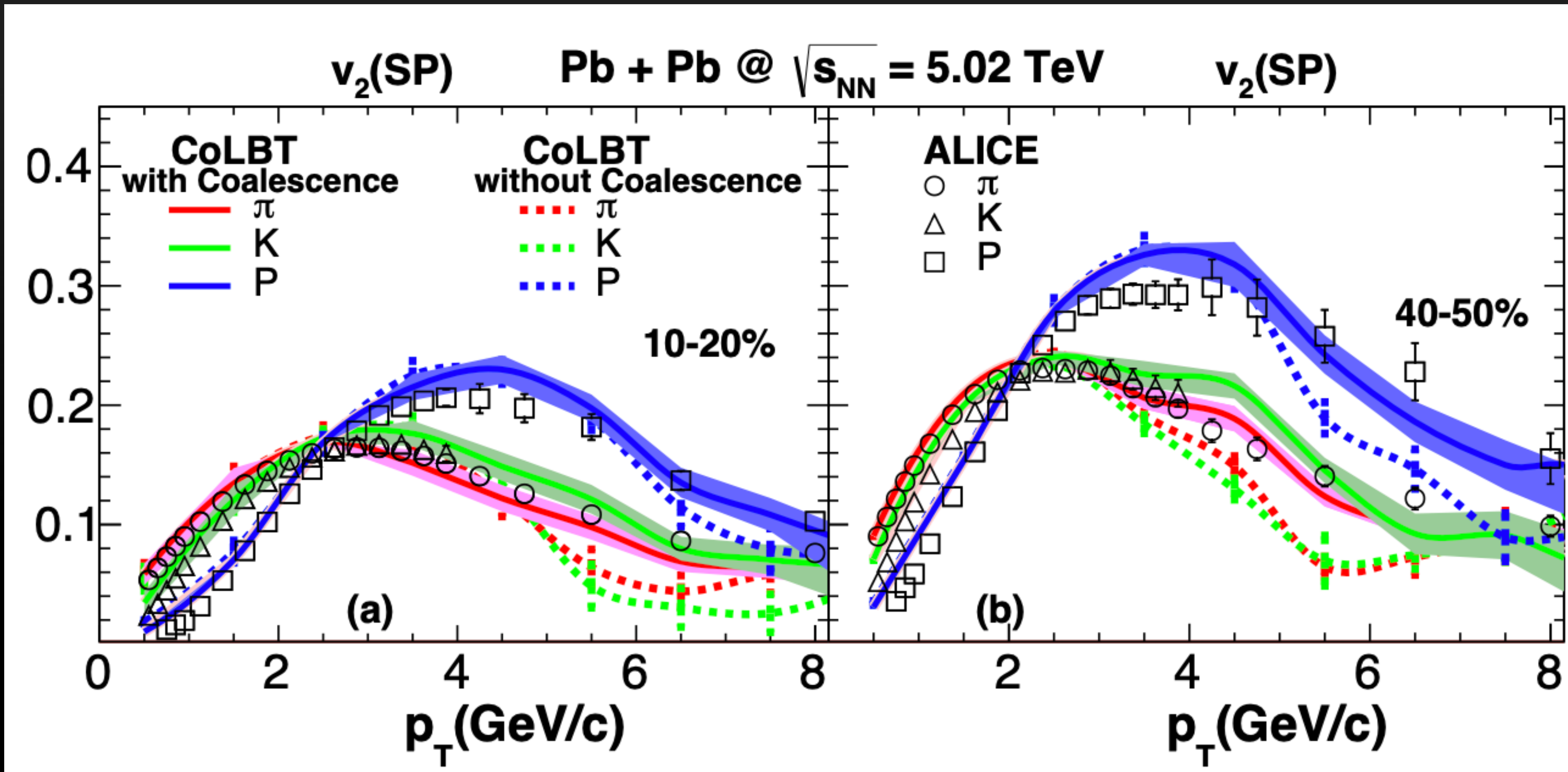
Jet quenching in Xe+Xe

$$R_{\mathrm{Pb}}^{\mathrm{Xe}}(p_{\mathrm{T}}) = \frac{dN^{\mathrm{XeXe}}/dp_{\mathrm{T}}}{dN^{\mathrm{PbPb}}/dp_{\mathrm{T}}} \frac{T_{\mathrm{PbPb}}}{T_{\mathrm{XeXe}}}$$



Q Zhang, W Dai, L Wang, BWZ, E Wang， CPC (2023)

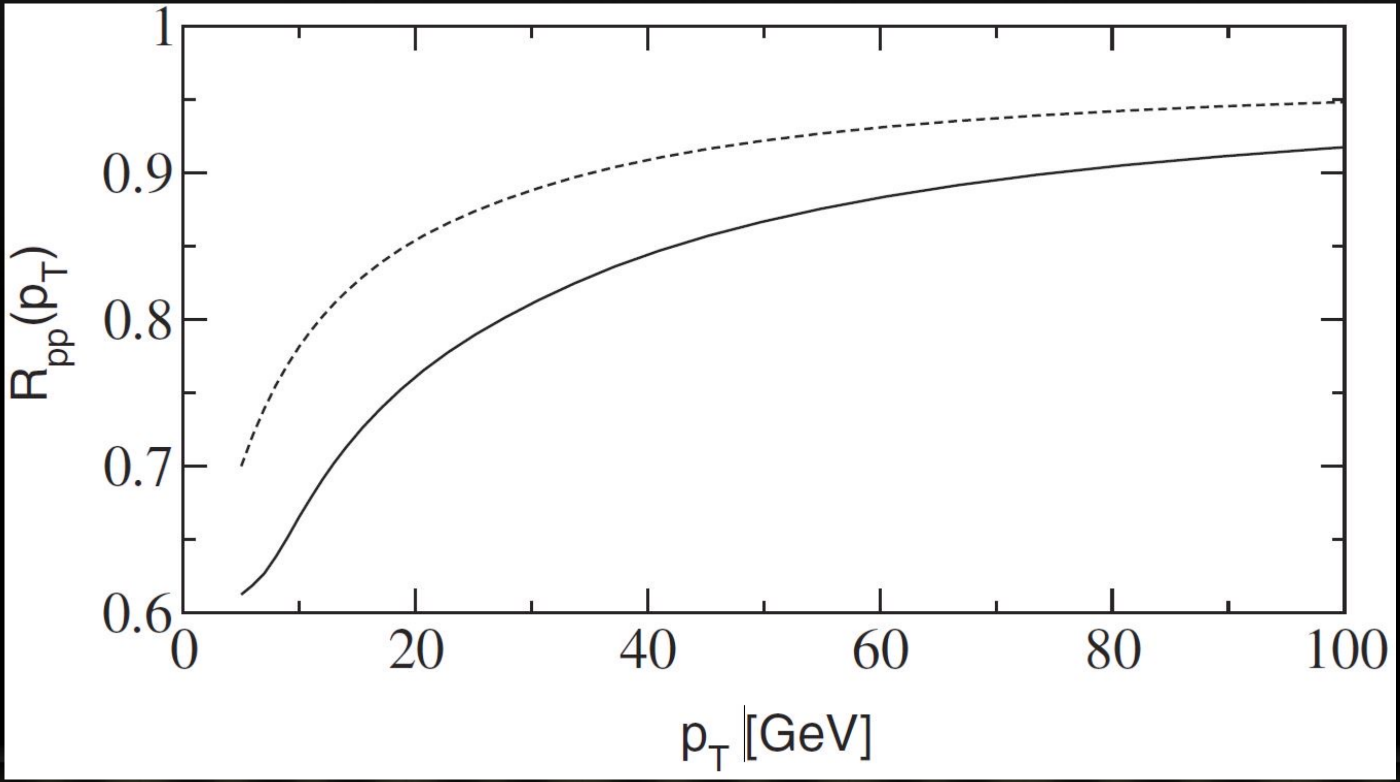
Large v2 at high pT



Y Zhao, W Ke, et al， PRL (2022)

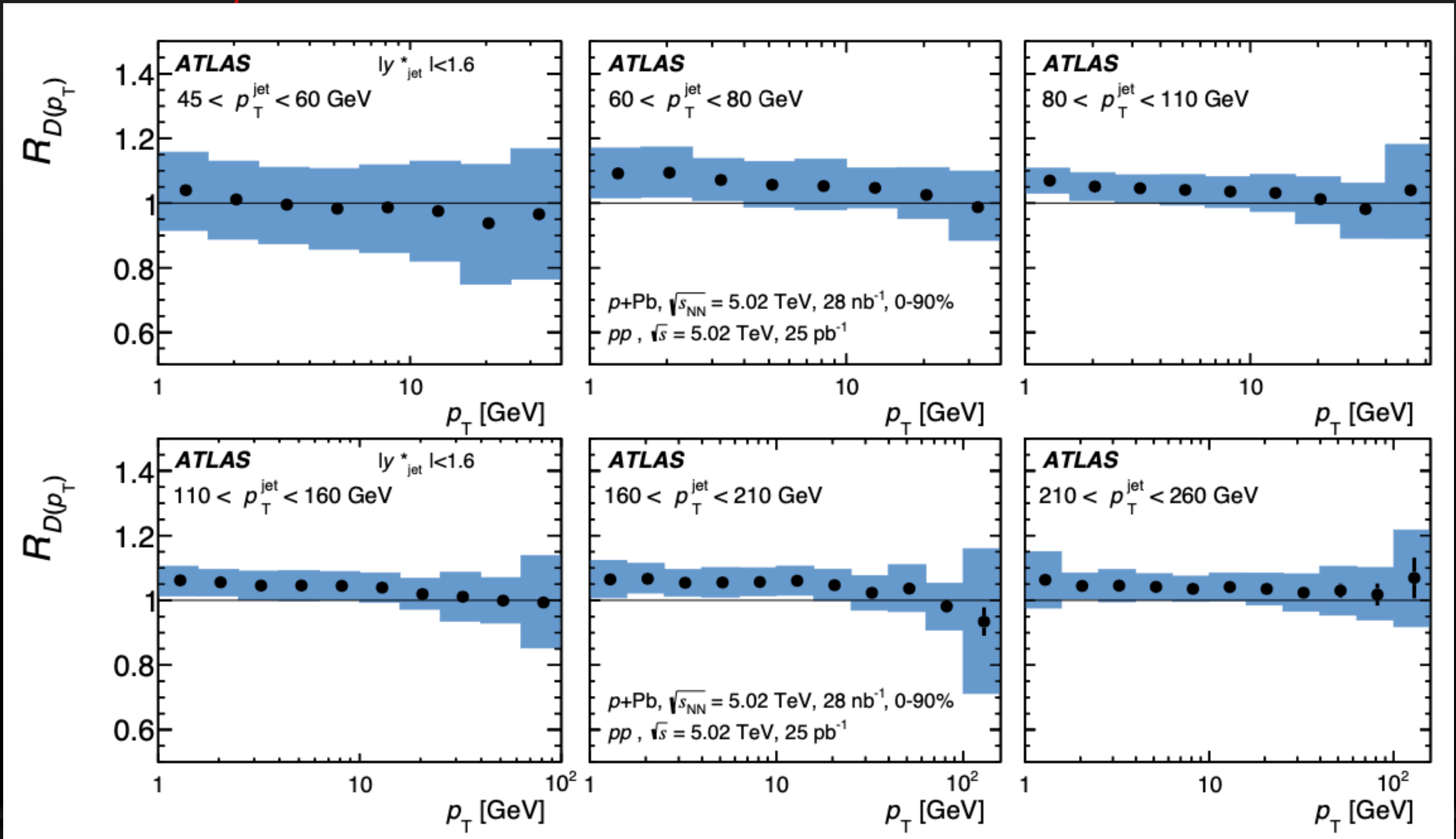
Jet quenching in small systems

$$R_{pp}(p_T) = \frac{\sum_i \int_0^1 \frac{dz}{z^2} D_{h/i}(z, p_T^i) \frac{d\sigma(pp\to iX)}{d\mathbf{p}_T^i dy}}{\sum_i \int_0^1 \frac{dz}{z^2} D_{h/i}^{\mathrm{vac}}(z, p_T^i) \frac{d\sigma(pp\to iX)}{d\mathbf{p}_T^i dy}}$$



Zakharov, PRL 112, 032301 (2014)

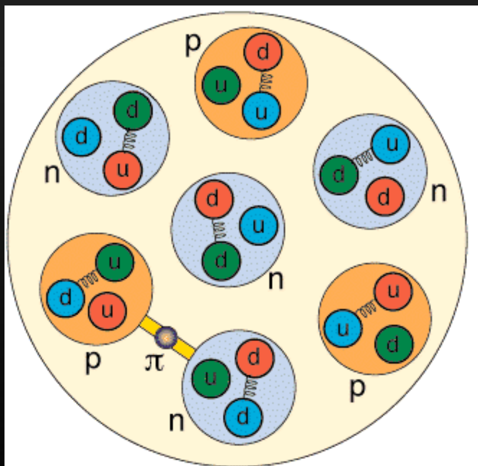
Jet quenching in small systems?

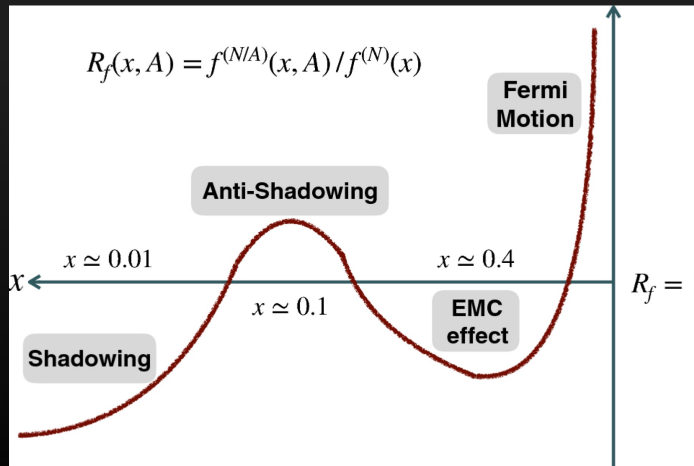


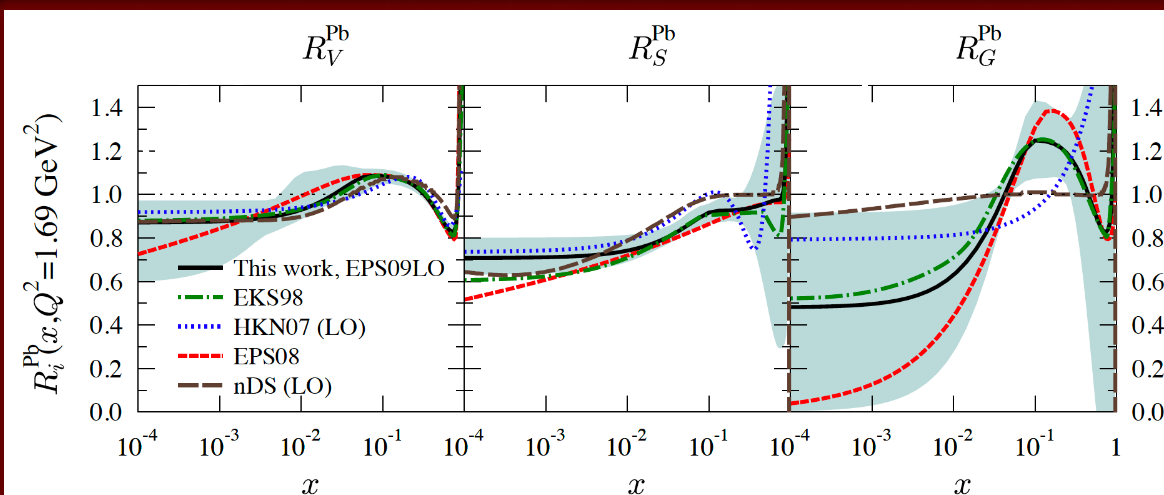
ATLAS, NPA (2018)

The nuclear parton distribution functions (nPDFs)

Modifications relative to free proton PDFs







JHEP04(2009)065

by EPPS16

Global QCD analysis

Eur. Phys. J. C (2017) 77:163

Table 1 The data sets used in the EPPS16 analysis, listed in the order of growing nuclear mass number. The number of data points and their contribution to χ^2 counts only those data points that fall within the kinematic cuts explained in the EPS09 analysis are marked with

Experiment	Observable	Collisions	Data points
SLAC E139	DIS	e^-He(4), e^-D	21
CERN NMC 95, re	DIS	μ^-He(4), μ^-D	16
CERN NMC 95	DIS	μ^-Li(6), μ^-D	15
CERN NMC 95, Q^2 dep	DIS	μ^-Li(6), μ^-D	153
SLAC E139	DIS	e^-Be(9), e^-D	20
CERN NMC 96	DIS	μ^-Be(9), μ^-C	15
SLAC E139	DIS	e^-C(12), e^-D	7
CERN NMC 95	DIS	μ^-C(12), μ^-D	15
CERN NMC 95, Q^2 dep	DIS	μ^-C(12), μ^-D	165
CERN NMC 95, re	DIS	μ^-C(12), μ^-D	16
CERN NMC 95, re	DIS	μ^-C(12), μ^-Li(6)	20
FNAL E772	DY	pC(12), pD	9
SLAC E139	DIS	e^-Al(27), e^-D	20
CERN NMC 96	DIS	μ^-Al(27), μ^-C(12)	15
SLAC E139	DIS	e^-Ca(40), e^-D	7
FNAL E772	DY	pCa(40), pD	9
CERN NMC 95, re	DIS	μ^-Ca(40), μ^-D	15
CERN NMC 95, re	DIS	μ^-Ca(40), μ^-Li(6)	20
CE[illegible] 96	D[illegible]	μ^-[illegible](12)	[illegible]
SLA[illegible]	D[illegible]	e^-[illegible]	[illegible]
FNAL E772	DY	e^-Fe(56), e^-D	9
CERN NMC 96	DIS	μ^-Fe(56), μ^-C(12)	15
FNAL E866	DY	pFe(56), pBe(9)	28
CERN EMC	DIS	μ^-Cu(64), μ^-D	19
SLAC E139	DIS	e^-Ag(108), e^-D	7
CERN NMC 96	DIS	μ^-Sn(117), μ^-C(12)	15
CERN NMC 96, Q^2 dep	DIS	μ^-Sn(117), μ^-C(12)	144
FNAL E772	DY	pW(184), pD	9
FNAL E866	DY	pW(184), pBe(9)	28
CERN NA10[a]	DY	π^-W(184), π^-D	10
FNAL E615[a]	DY	π^+W(184), π^-W(184)	11
CERN NA3[a]	DY	π^-Pt(195), π^-H	7
SLAC E139	DIS	e^-Au(197), e^-D	21
RHIC PHENIX	π^0	dAu(197), pp	20
CERN NMC 96	DIS	μ^-Pb(207), μ^-C(12)	15
CERN CMS[a]	$W^\pm$	pPb(208)	10
CERN CMS[a]	Z	pPb(208)	6
CERN ATLAS[a]	Z	pPb(208)	7
CERN CMS[a]	dijet	pPb(208)	7
CERN CHORUS[a]	DIS	νPb(208), $\bar{\nu}$Pb(208)	824
Total			1811

The earlier generations of nuclear PDFs

	EPS09	DSSZ12	KA15	nCTEQ15	EPPS16	nNNPDF1.0
Order in α_s	LO / NLO	NLO	NNLO	NLO	NLO	NNLO
lA NC DIS	✓	✓	✓	✓	✓	✓
νA CC DIS		✓			✓	
pA Drell-Yan	✓	✓	✓	✓	✓	
RHIC dAu pion	✓	✓		✓	✓	
LHC pPb W, Z					✓	
LHC pPb Dijet					✓	
LHC pPb D^0						
LHC pPb hadron/ γ						
Free parameters	15	25	16	16	20	~183
Q cut (GeV)	1.3	1.0	1.0	2.0	1.3	1.87
Proton PDFs	CTEQ6.1	MSTW08	JR09	CTEQ6M	CT14	NNPDF3.1
Flavor separation	no	no	no	Yes(valence)	Yes(6)	no
Reference	JHEP (2009)	PRD (2012)	PRD (2016)	PRD (2016)	EPJC (2017)	EPJC (2019)

Courtesy of Peng Ru

The new generation of nuclear PDFs

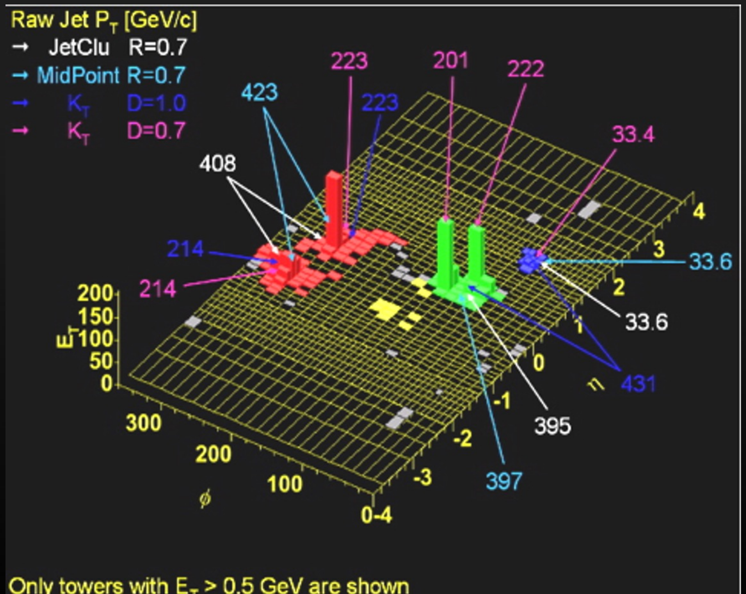
	EPS16	EPPS21	KA20	nCTEQ15 WZSIH	TUJU21	nNNPDF3.0
Order in α_s	NLO	NLO	NNLO	NLO	NLO/ NNLO	NNLO
lA NC DIS	✓	✓	✓	✓	✓	✓
νA CC DIS	✓	✓	✓		✓	✓
pA Drell-Yan	✓	✓	✓	✓		✓
RHIC dAu pion	✓	✓		✓		
LHC pPb W, Z	✓	✓		✓	✓	✓
LHC pPb Dijet	✓	✓				✓
LHC pPb D^0		✓				✓
LHC pPb hadron/ γ				hadron ✓		γ ✓
Free parameters	20	24	9	19	16	256
Q cut (GeV)	1.3	1.3	1.3	2.0	1.87	1.87
Proton PDFs	CT14	CT18A	CT18	CTEQ6M	own fit	NNPDF4.0
Flavor separation	Yes(6)	Yes(6)	Yes(3)	Yes(5)	Yes(4)	Yes(6)
Reference	EPJC (2017)	EPJC(2022)	PRD (2021)	PRD (2021)	PRD (2022)	EPJC (2022)

Courtesy of Peng Ru

Full jet observables

Jets: new opportunity at HIC

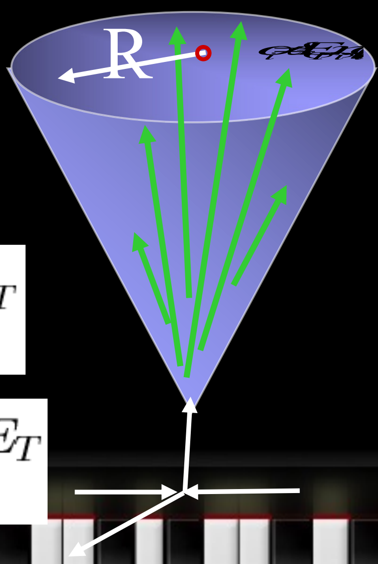
- R_{AA} for single particle or I_{AA} for two particle correlations only measure the leading fragments of a jet.
- Jets: a spray of final-state particles moving roughly in the same direction.
- Jet observables: more differential, less non-perturbative input, precise pQCD calculations.



$$E_T = \sum_{i \in jet} E_{T,i}$$

$$y = \sum_{i \in jet} y_i E_{T,i} / E_T$$

$$\phi = \sum_{i \in jet} \phi_i E_{T,i} / E_T$$



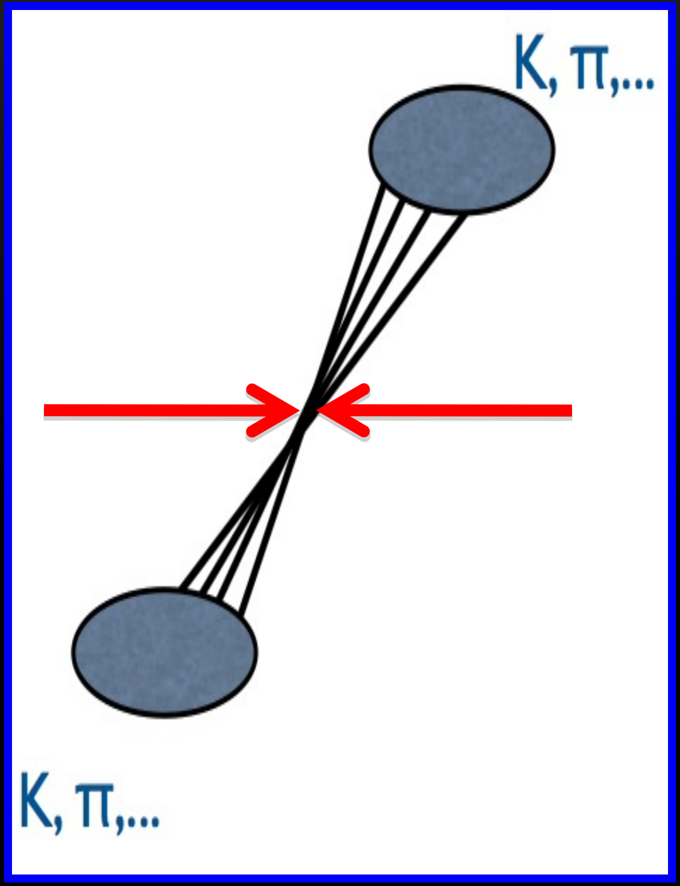
$$R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$$


WEST
11


WEST
11

Briefing: jets at HEP

- Sterman &Weinberg('77) defined a two-jet event and made an analytic calculation.
- Feynman, Field, Fox ('77) made a numerical calculation of the inclusive jet prod.
- Discovery of three-jet events in e+e- gave a first evidence of for gluons.
- Precise extraction of α_s is made by measuring jet event shapes.
- New physics beyond Standard Model by studying jets.



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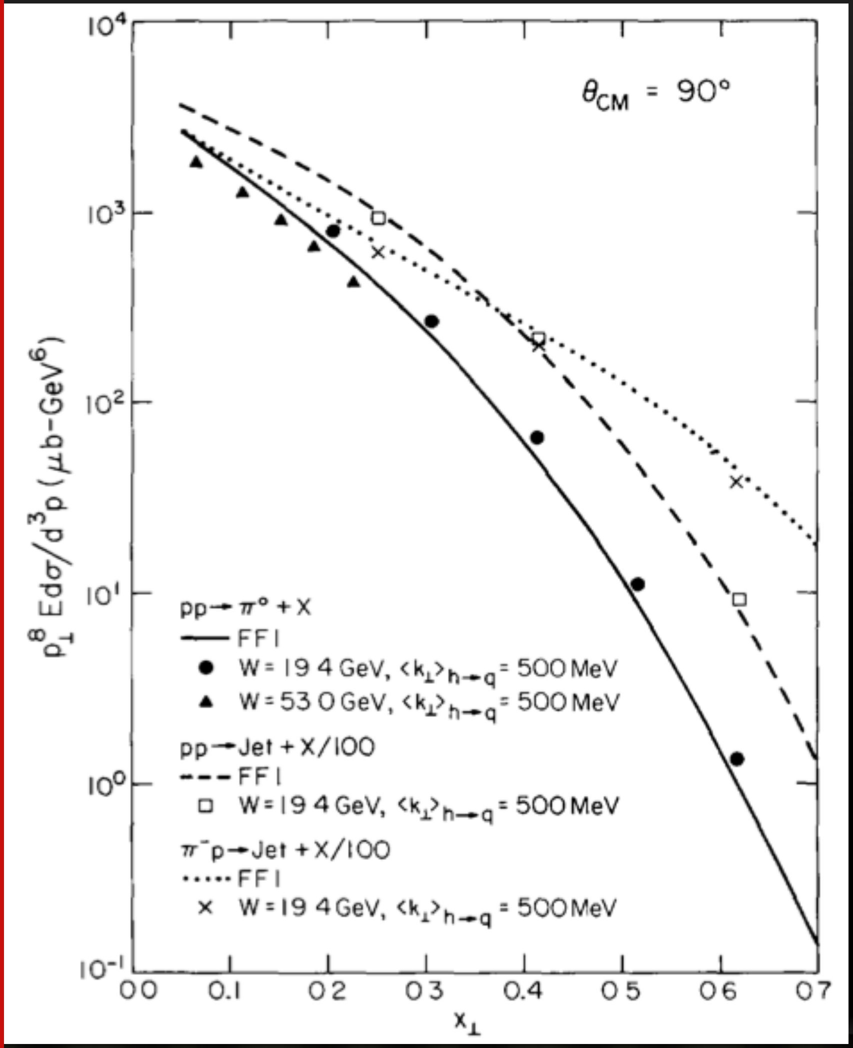

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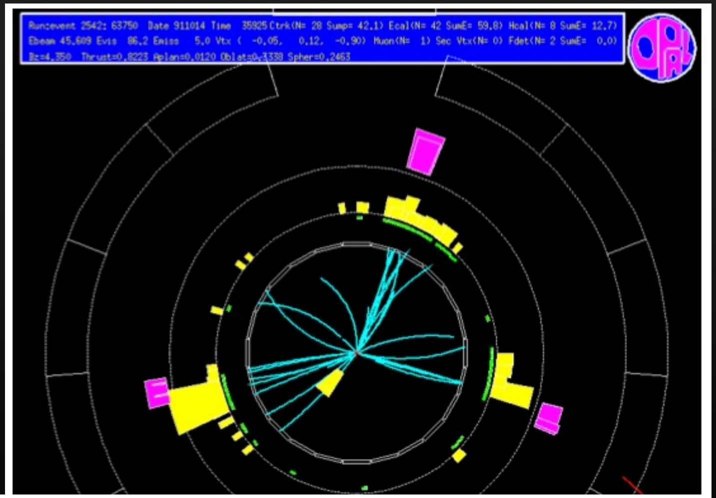
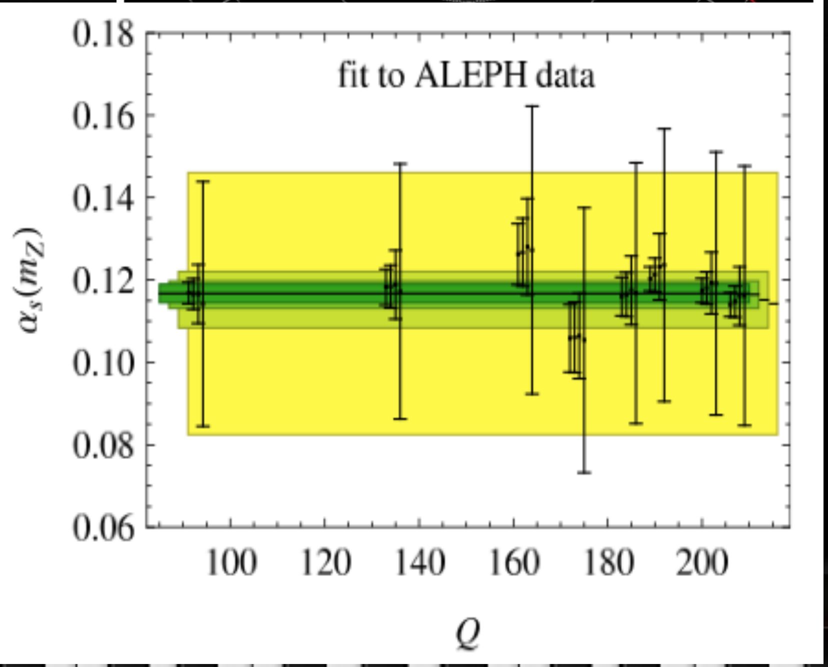
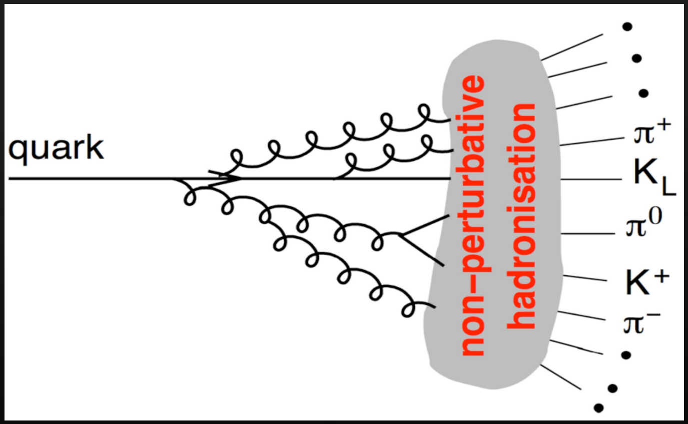
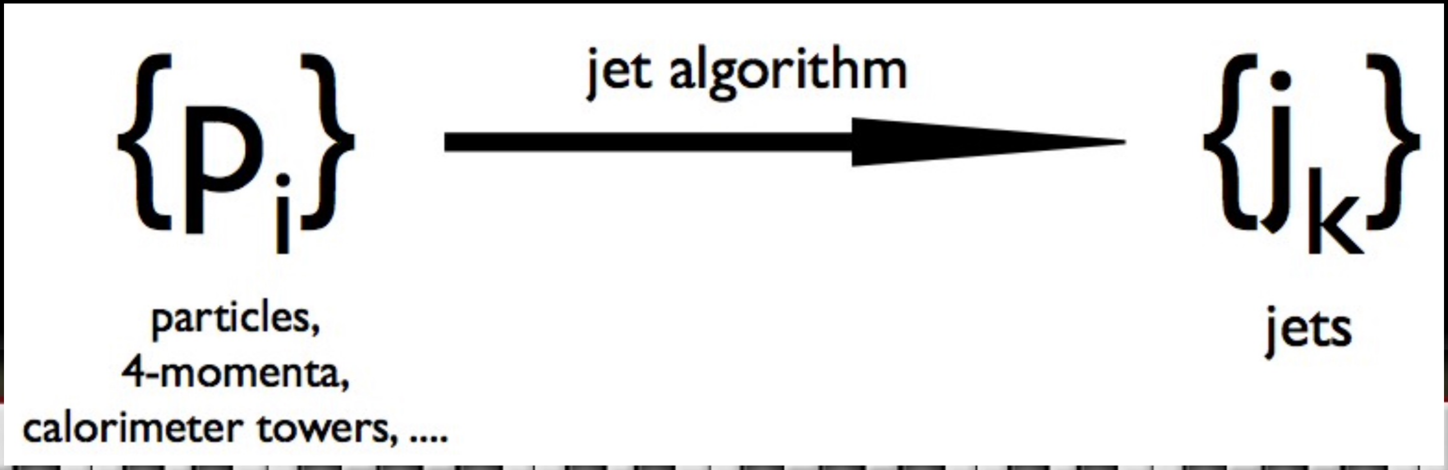




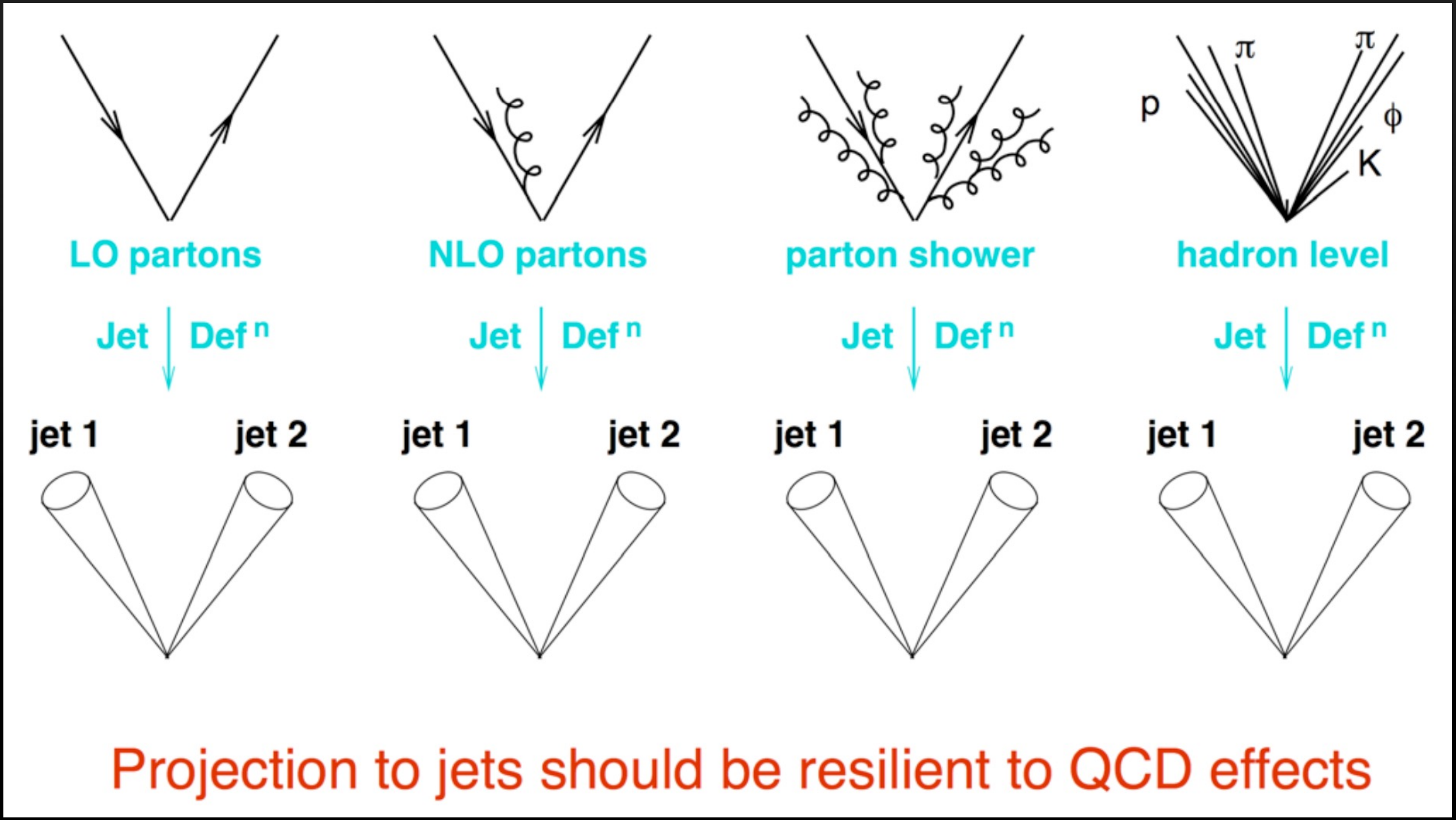
What is a Full Jet?



- Jet is an approximate image of the parent parton. Jet is defined by a jet finding algorithm, which maps the momenta of the final state particles into the momenta of a certain number of jets:



Jet definition



Projection are NOT unique:
a jet is not equivalent to a parton.

Diagram from
M Cacciari

Iterative cone algorithm

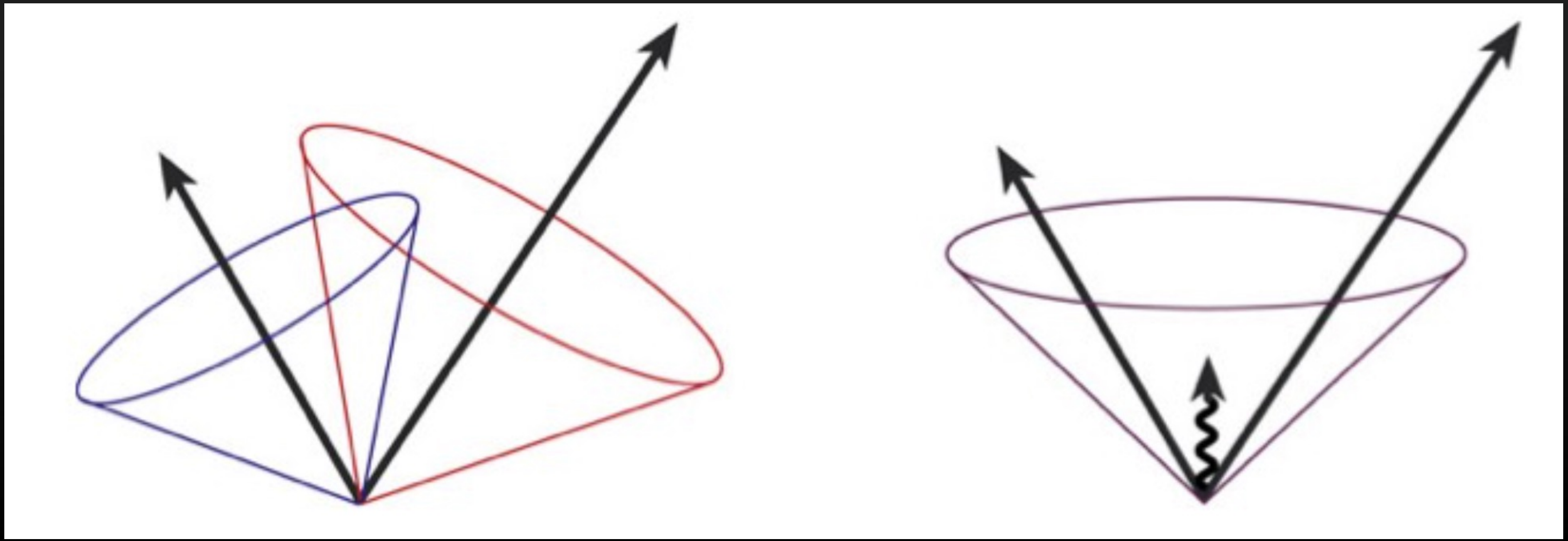
$$k \subset C \quad \text{iff} \quad \sqrt{(y_k - y_C)^2 + (\phi_k - \phi_C)^2} \leq R_{\text{cone}},$$

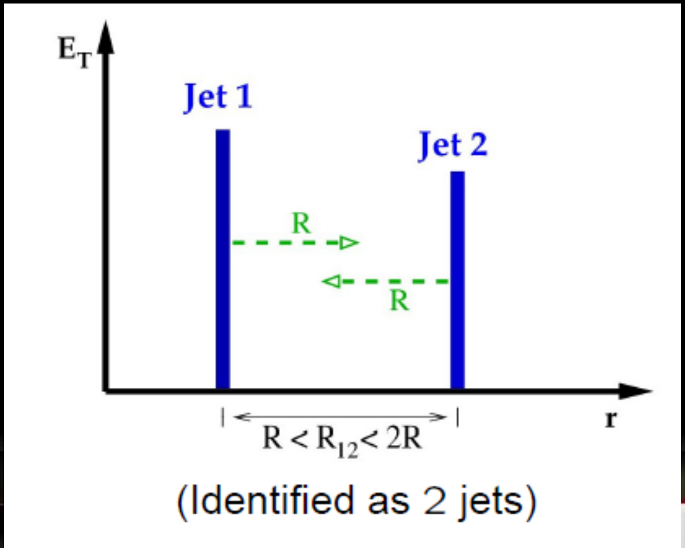
$$\bar{y}_C \equiv \frac{\sum\limits_{k \subset C} y_k \cdot p_{T,k}}{\sum\limits_{l \subset C} p_{T,l}}, \qquad \bar{\phi}_C \equiv \frac{\sum\limits_{k \subset C} \phi_k \cdot p_{T,k}}{\sum\limits_{l \subset C} p_{T,l}}.$$

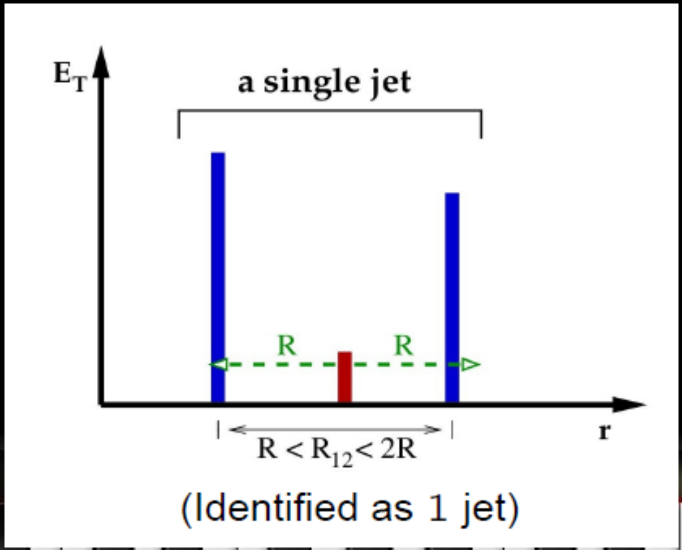
$$(\bar{y}_C, \bar{\phi}_C) \neq (y_C, \phi_C),$$

$$(\bar{y}_C, \bar{\phi}_C) = (y_C, \phi_C),$$

Infrared/collinear safe







kt algorithm

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta y^2 + \Delta \phi^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$

$$R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$$

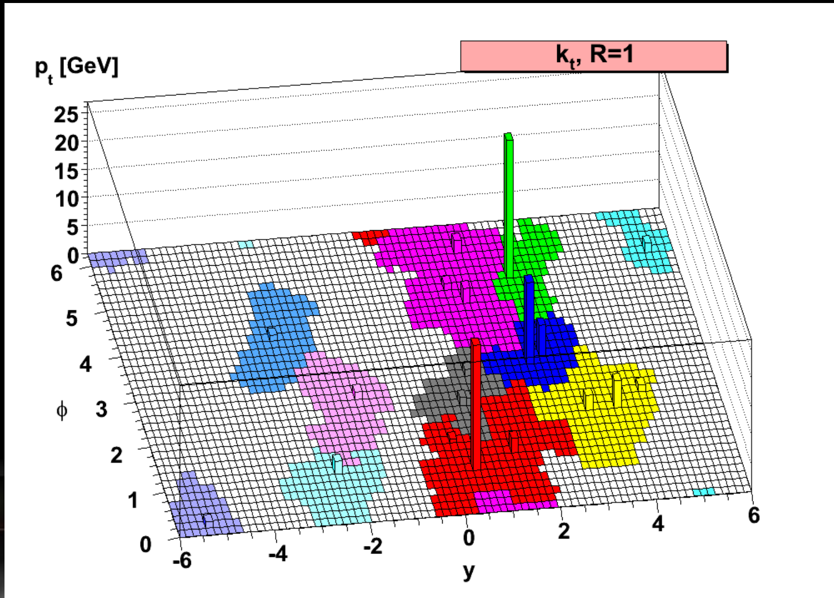
p = 1

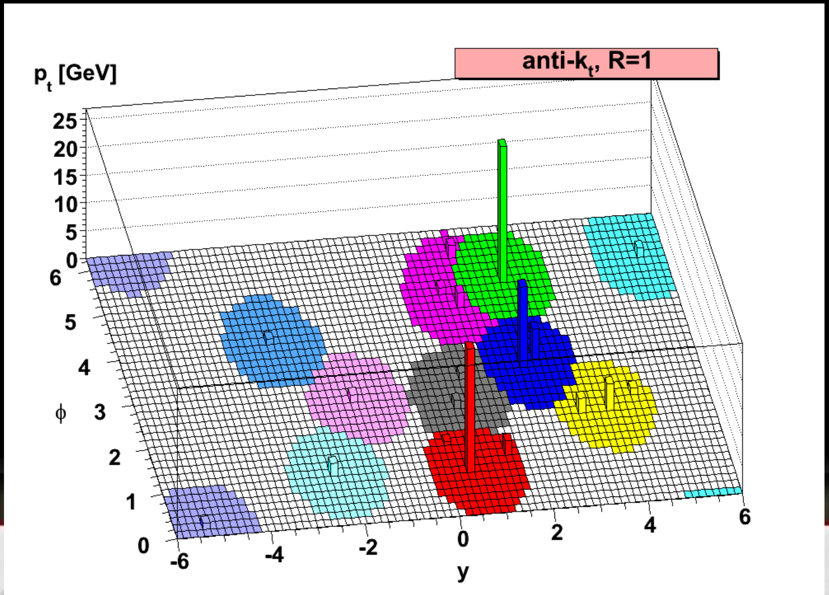
- Compute d_{ij} and d_{iB} for all particles in the final state, and find the minimum value.
- If the minimum is a d_{iB}, declare particle i a jet, remove it from the list, and go back to step one.
- If the minimum is a d_{ij}, combine particles i and j, and go back to step one.
- Iterate until all particles have been declared jets.

anti-kt and C/A algorithms

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta y^2 + \Delta\phi^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$

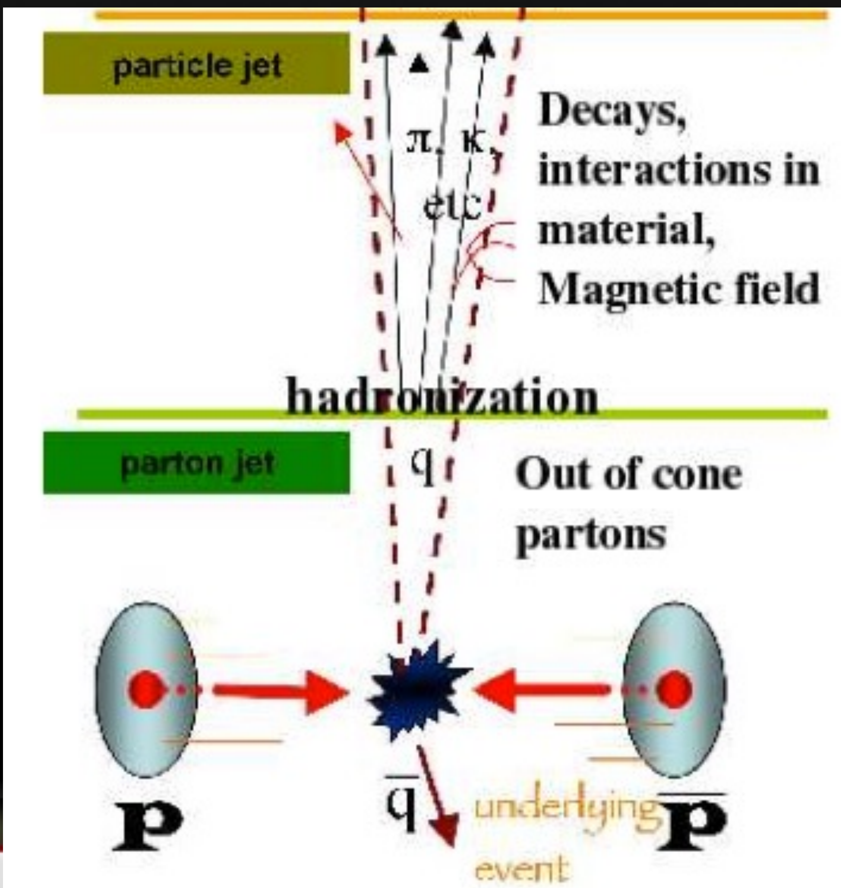
- The Cambridge/Aachen algorithm: **p = 0**
- The anti-kt algorithm: **p = -1**

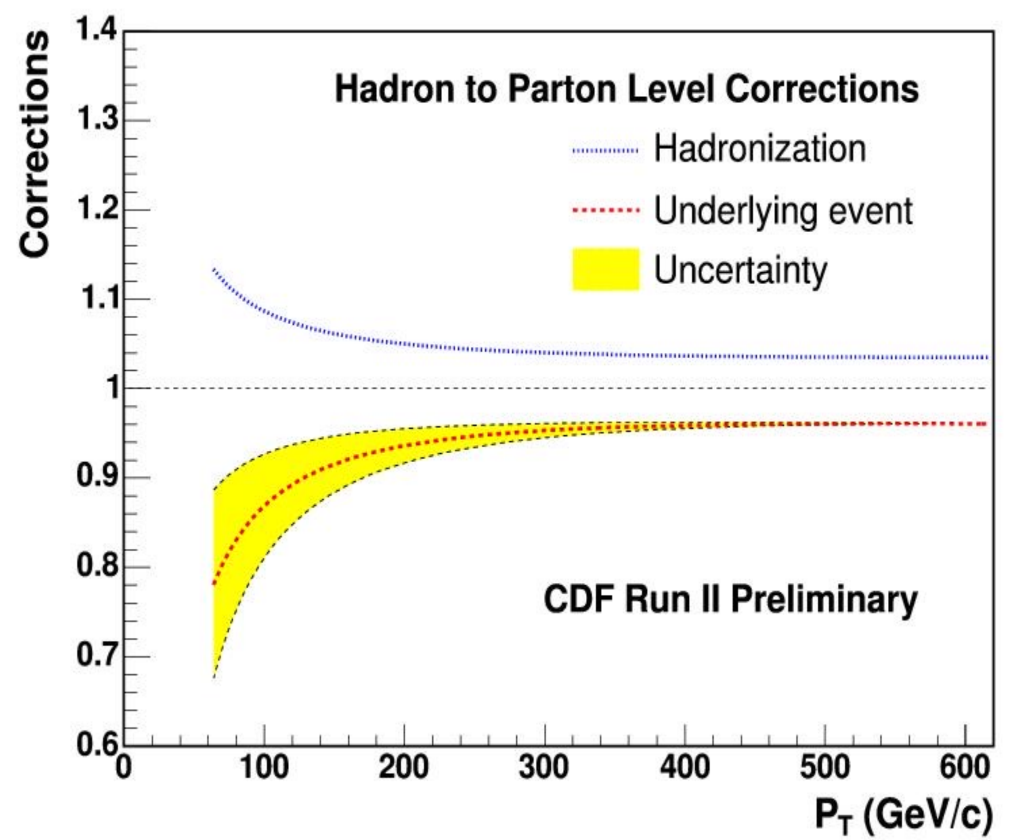




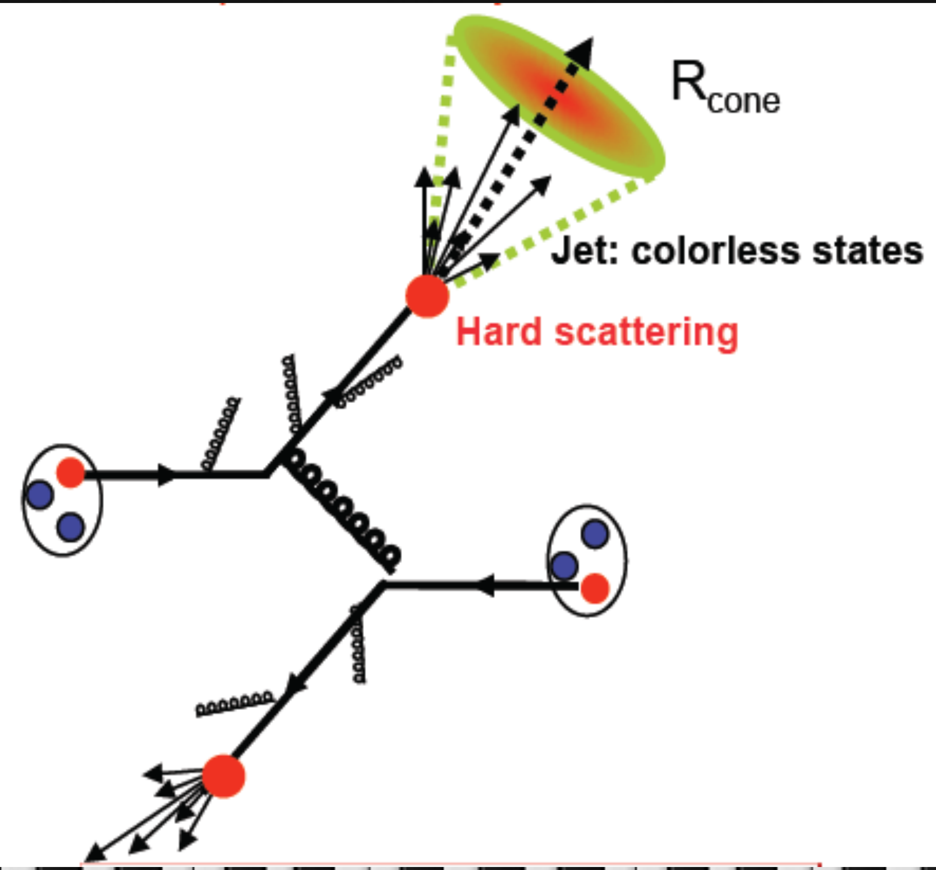
Non-perturbative effects

- Non-perturbative effects: hadronization & underlying event.
- Two effects will go in opposite direction: partial cancellation between "splash-out" effect and "splash-in" effect.





Inclusive jet cross section in HIC



Jet cross section at NLO in p+p

- Jet cross sections at NLO in p+p :

$$\frac{d\sigma^{\text{jet}}}{dE_T dy} = \frac{1}{2!}\int d\{E_T,y,\phi\}_2 \frac{d\sigma[2\to 2]}{d\{E_T,y,\phi\}_2} S_2(\{E_T,y,\phi\}_2) + \frac{1}{3!}\int d\{E_T,y,\phi\}_3 \frac{d\sigma[2\to 3]}{d\{E_T,y,\phi\}_3} S_3(\{E_T,y,\phi\}_3)$$

- Function S_2 and S_3 contain jet find algorithm:

2 --→ 2

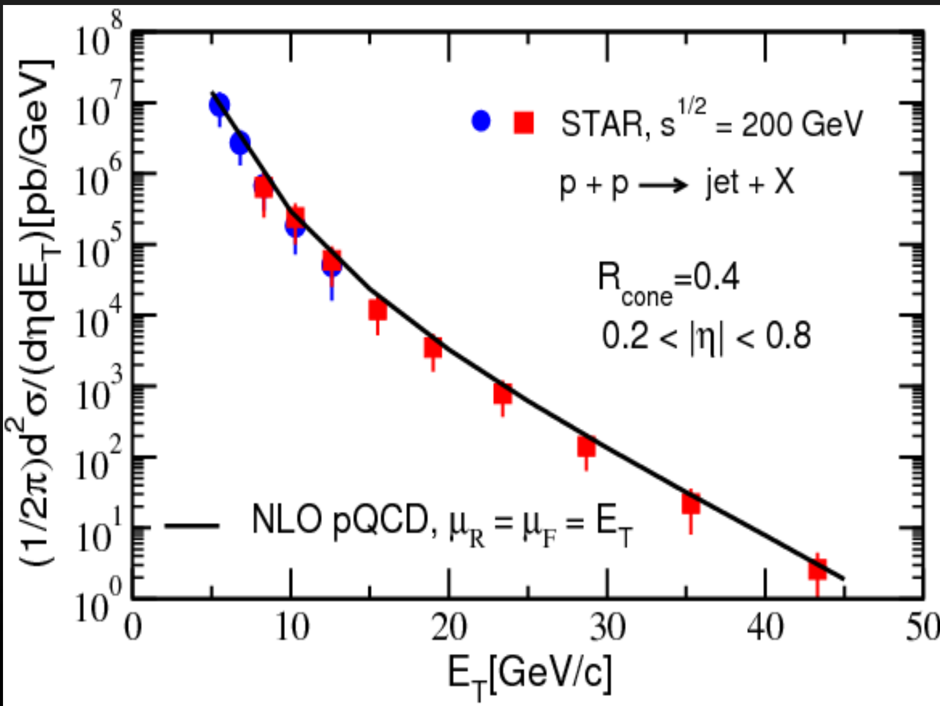
$$S_2 = \sum_{i=1}^{2} S(i) = \sum_{i=1}^{2} \delta(E_{T_i} - E_T)\delta(y_i - y)$$

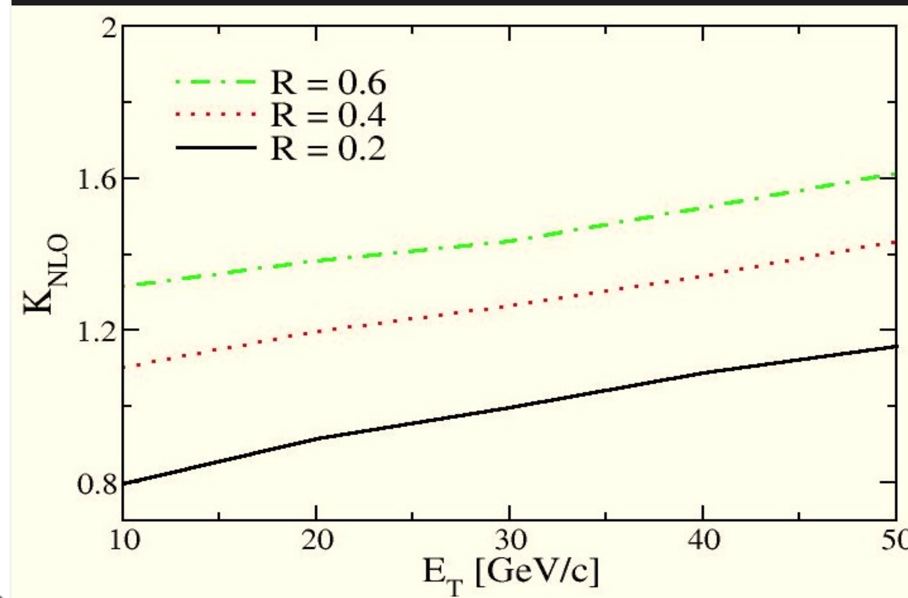
2 --→ 3

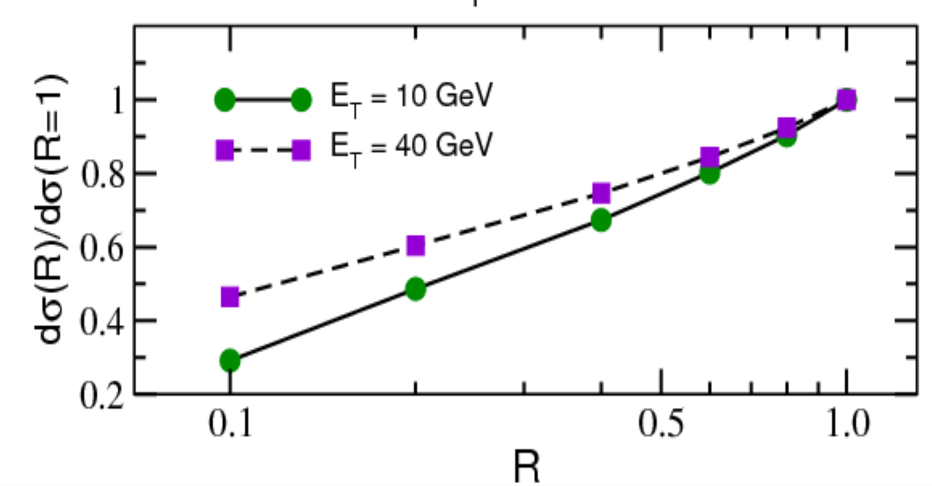
$$S_3 = \sum_i \delta(p_i - p_J)\delta(y_i - y_J) \prod_{j(j\neq i)} \theta\left(R_{ij} > \frac{p_i + p_j}{\max(p_i,p_j)} R\right) + \sum_{i,j(i<j)} \delta(p_i + p_j - p_J)\delta\left(\frac{p_i y_i + p_j y_j}{p_i + p_j} - y_J\right)\theta(R_{ij} < R_{\text{rc}})$$

Ellis, Kunszt, Soper, PRL 64:2121(1990); PRL 69:1496(1992)

Inclusive jet in p+p at NLO

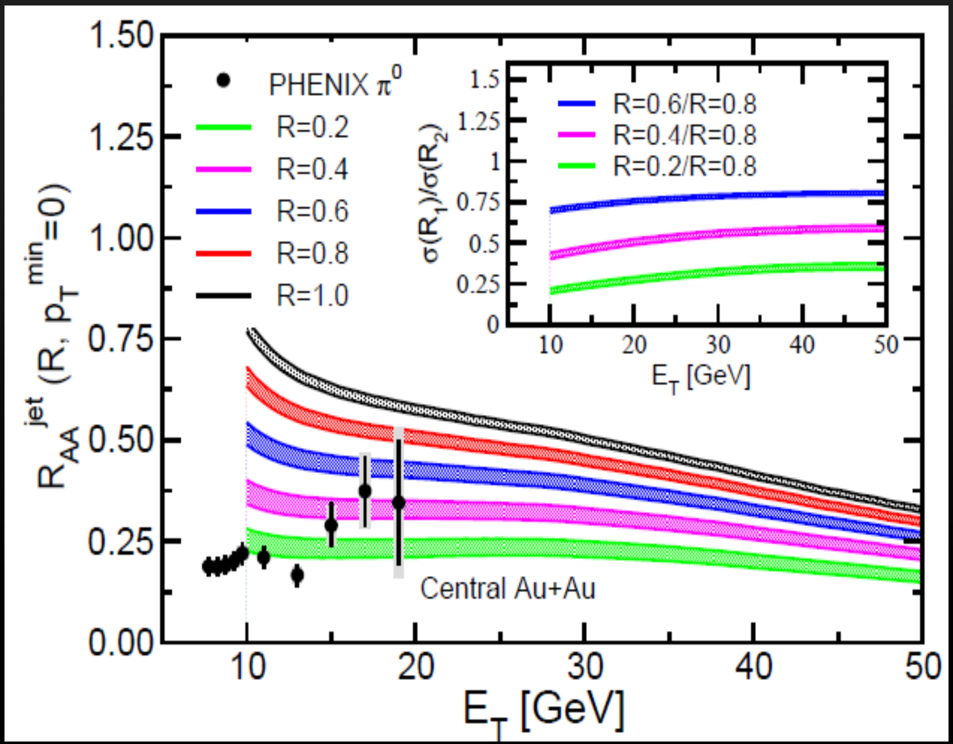




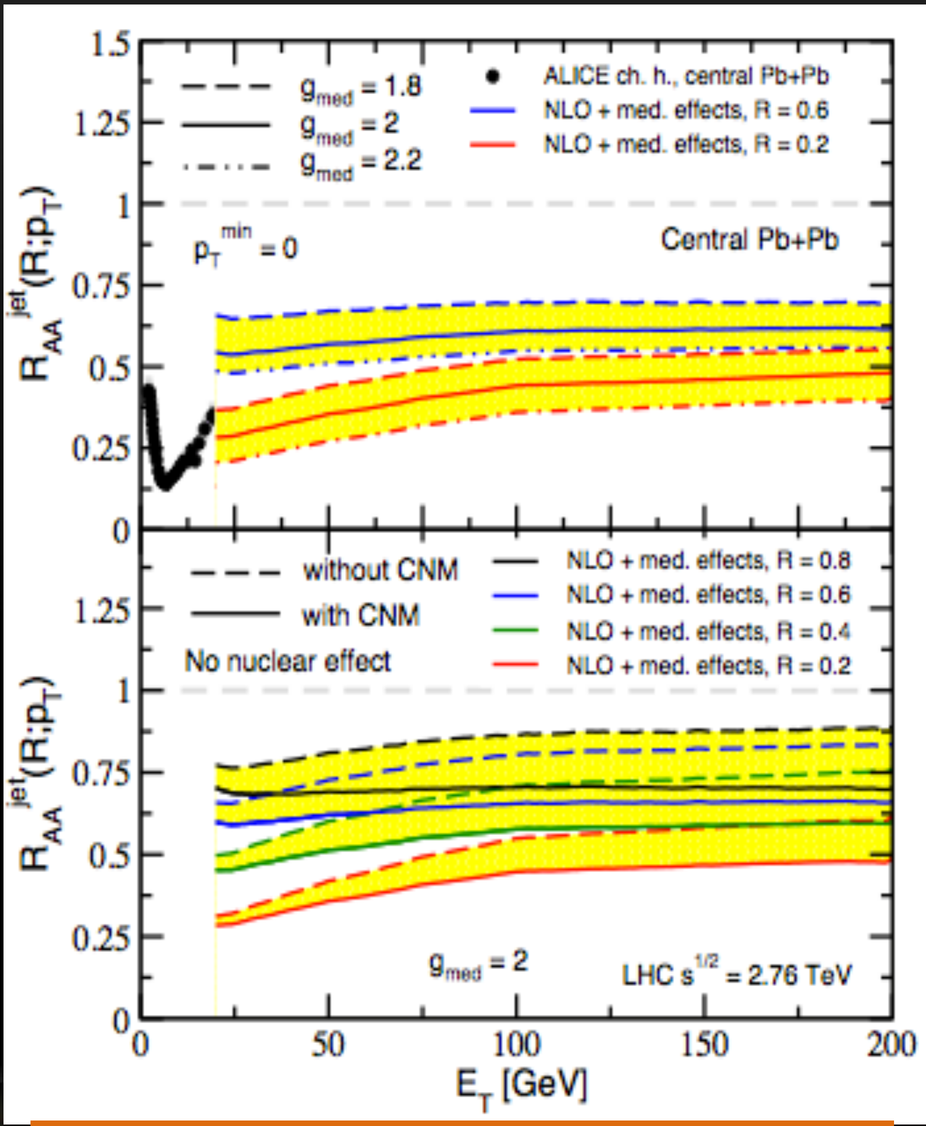


- Very good agreement between data and theory is achieved;
- K_{NLO}=NLO/LO can be smaller than 1 at small cone radius.

Inclusive jets in A+A at RHIC



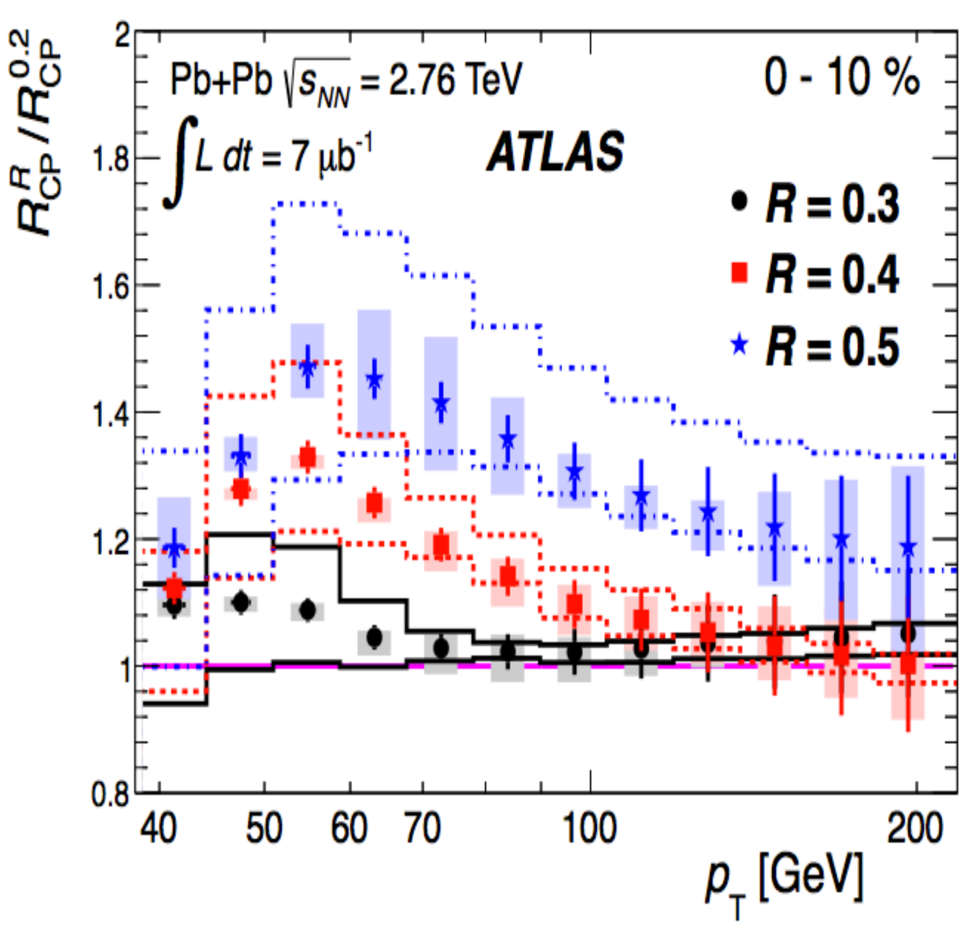
I Vitev, BWZ, PRL (2010).



Y He, Vitev, BWZ, PLB (2012)

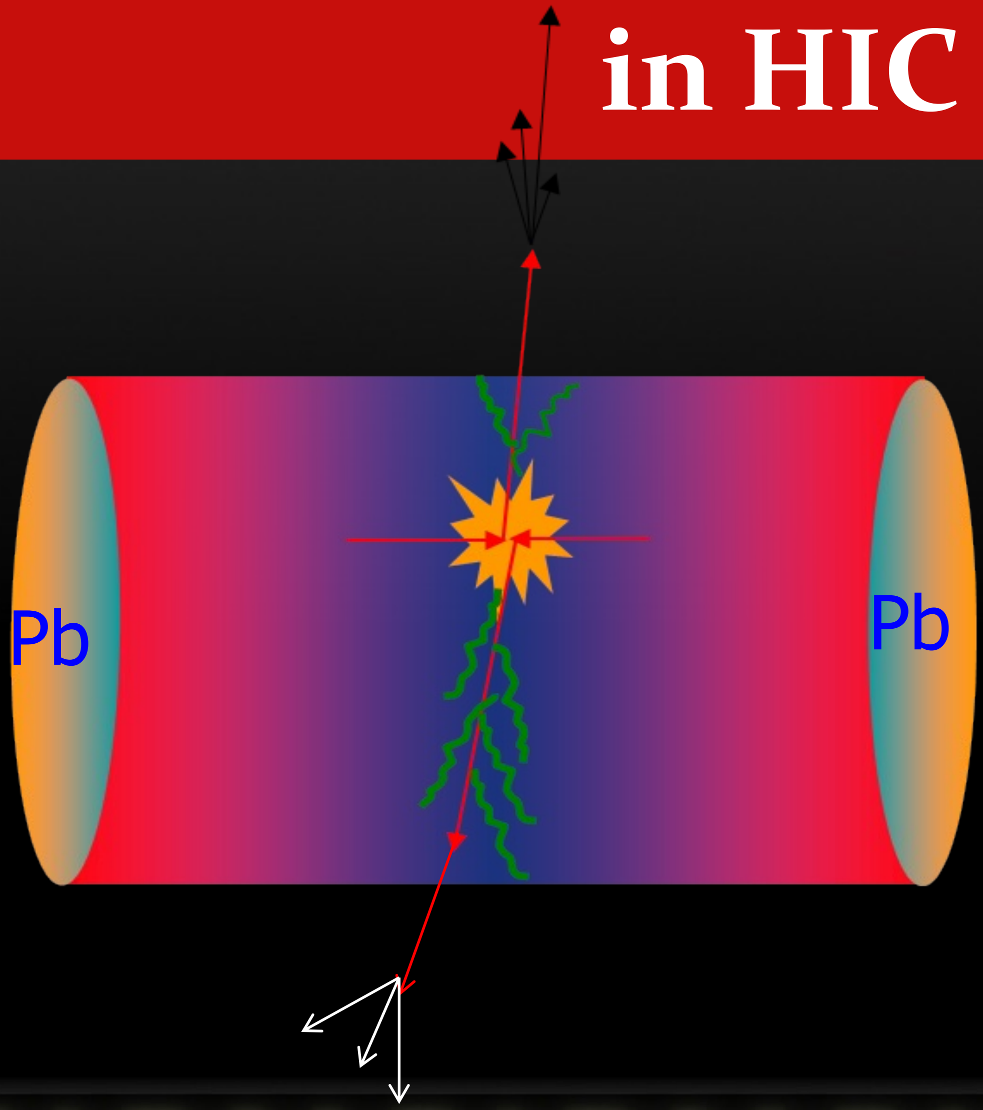
Inclusive jet in Pb+Pb: Exp.

- The jet radius dependence of Raa on inclusive jets has been confirmed by ATLAS measurements most recently.



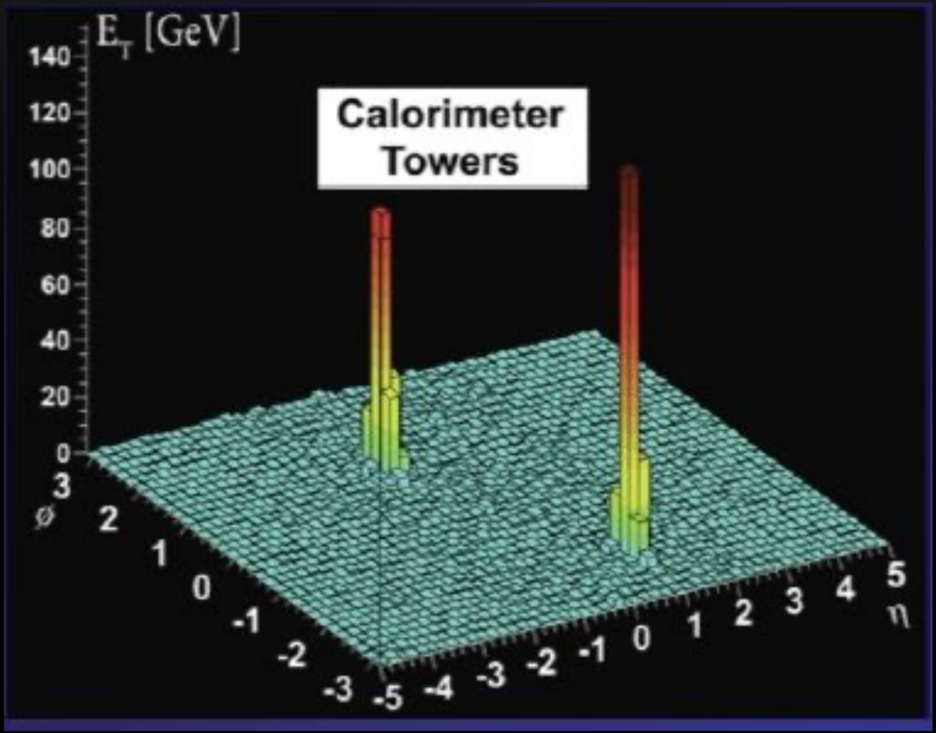
ATLAS, PLB (2013)

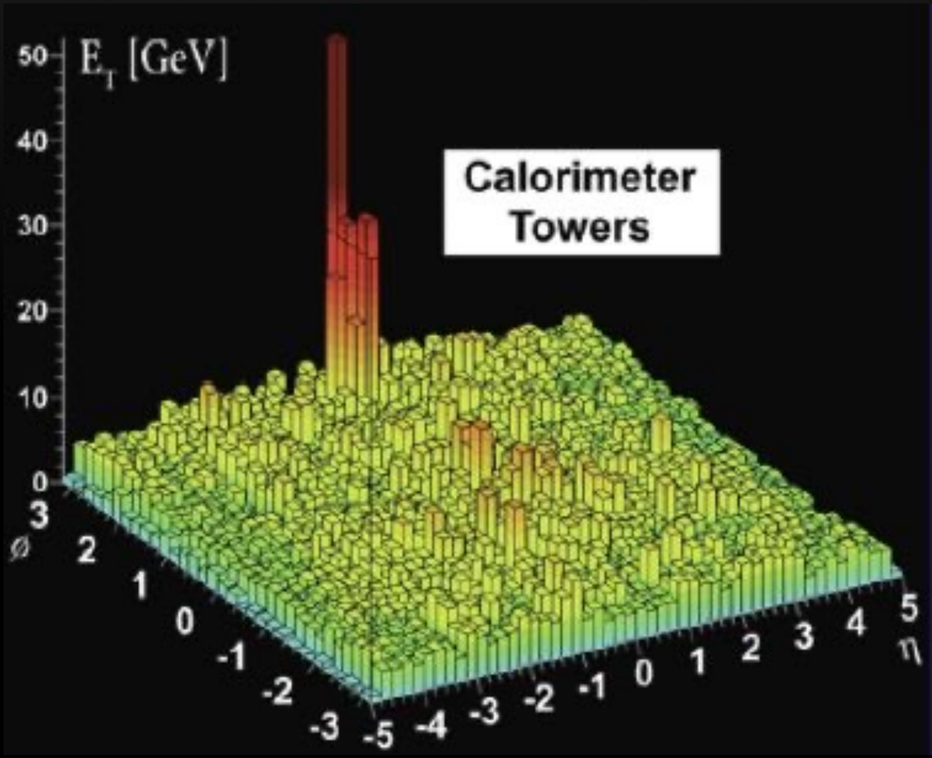
Dijet momentum imbalance in HIC



Measuring Dijets in Pb+Pb

- Jet quenching at LHC has been observed for the first time in dijet productions at Pb+Pb by ATLAS and CMS。

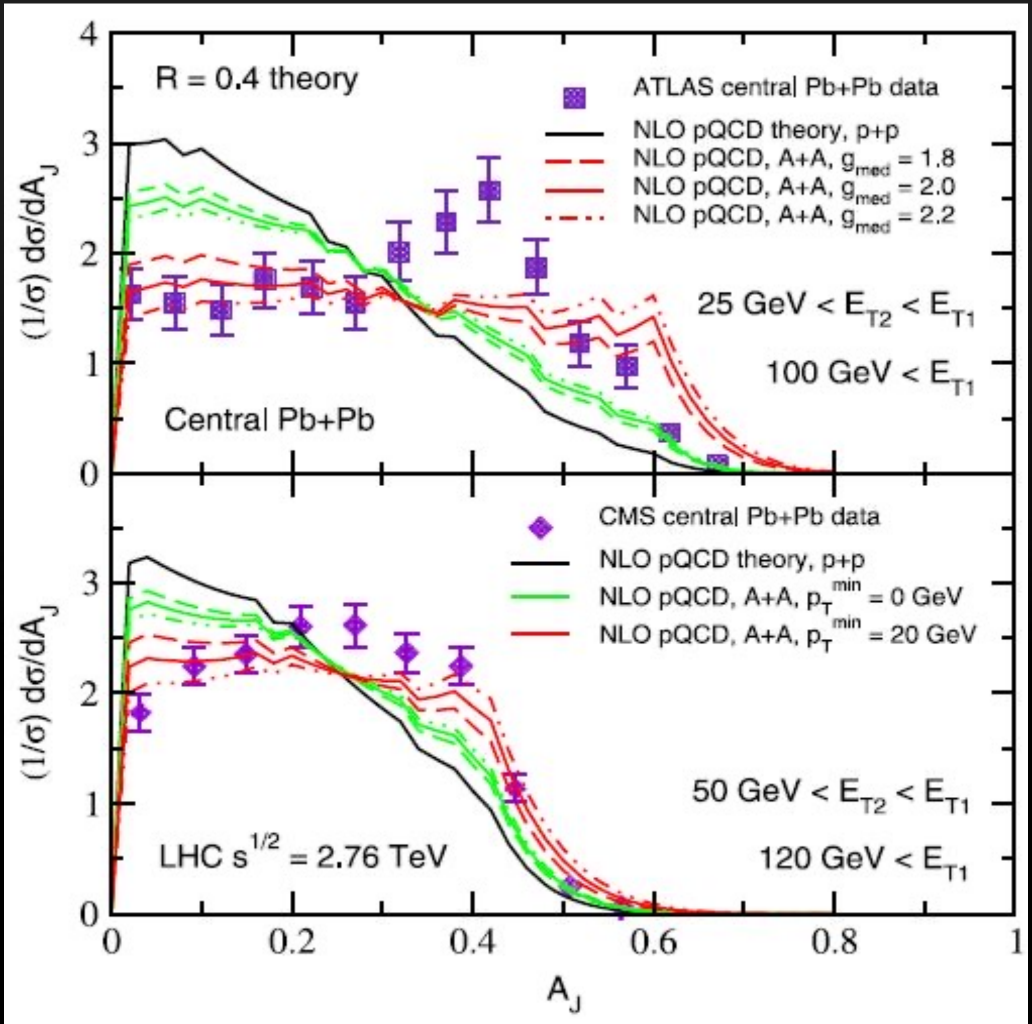




ATLAS, arXiv:1011.6182, PRL (2011); CMS, arXiv: 1102.1957, PRC(2012)

Dijet in Pb+Pb at LHC

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$



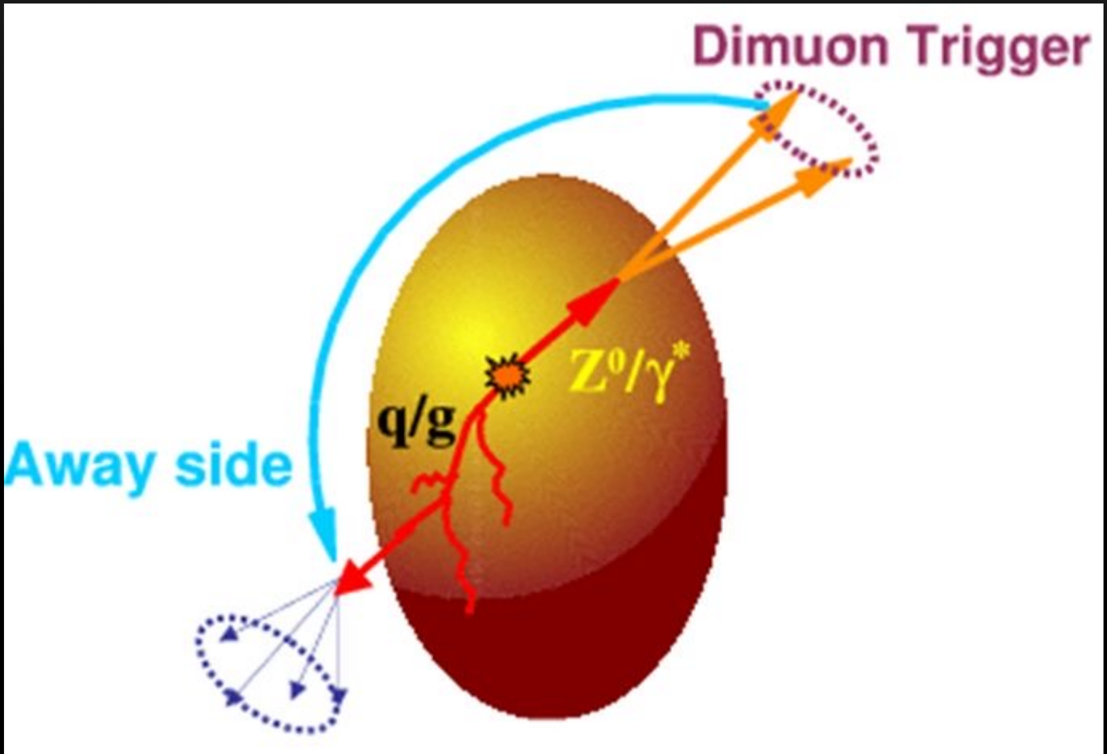
G Qin, B Muller, PRL (2011)

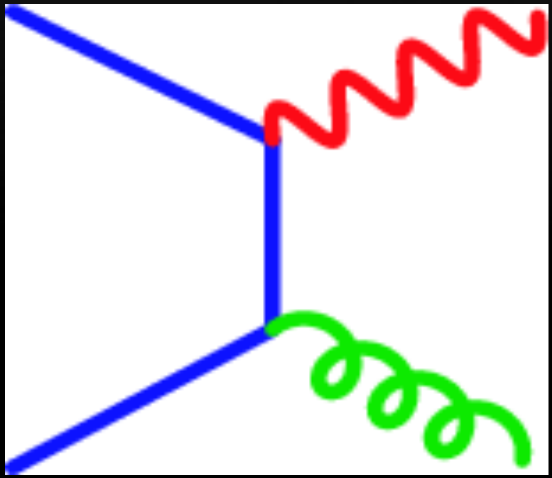
Y He, Vitev, BWZ, PLB (2012)

ATLAS, arXiv:1011.6182, PRL (2011);

CMS, arXiv: 1102.1957, PRC (2012) .

Tagged jet production in HIC





Tagged jet production in HIC

photon + jet

- Advantage: large yield
- Disadvantage: final-state effects

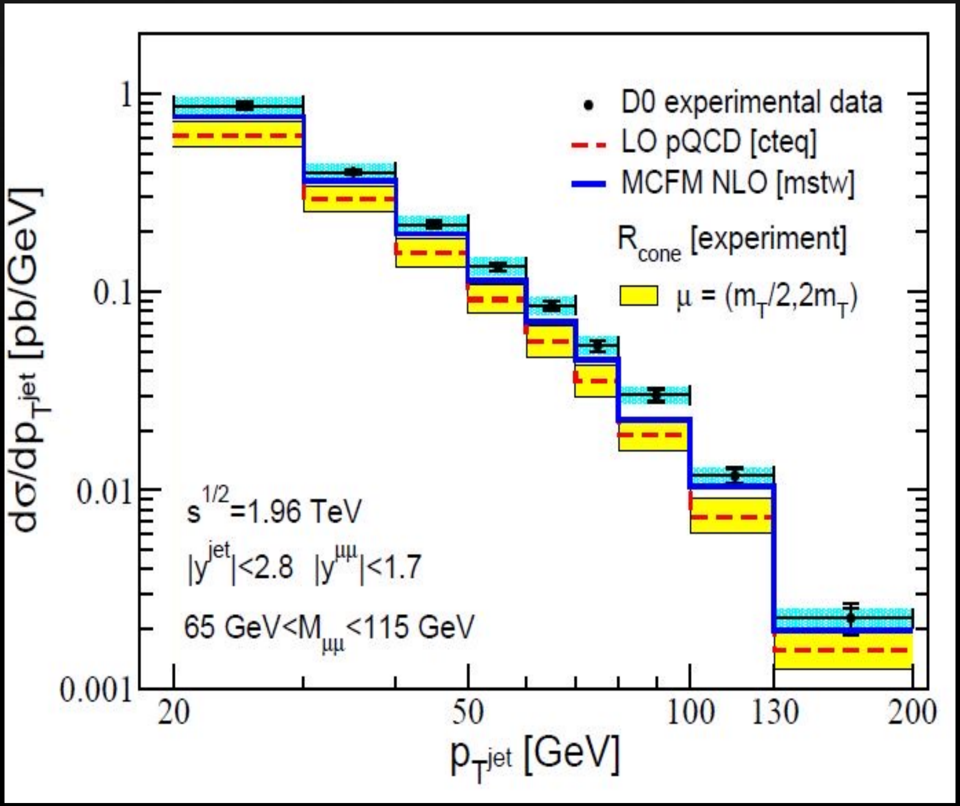
Z^0 + jet

- Disadvantage: small cross section
- Advantage: no final-state effects

You are so light, I am too heavy.

Zº in pp and PbPb

- pQCD gives a good description of the data at the LHC and D0.
- The CNM effects for Z boson is small.

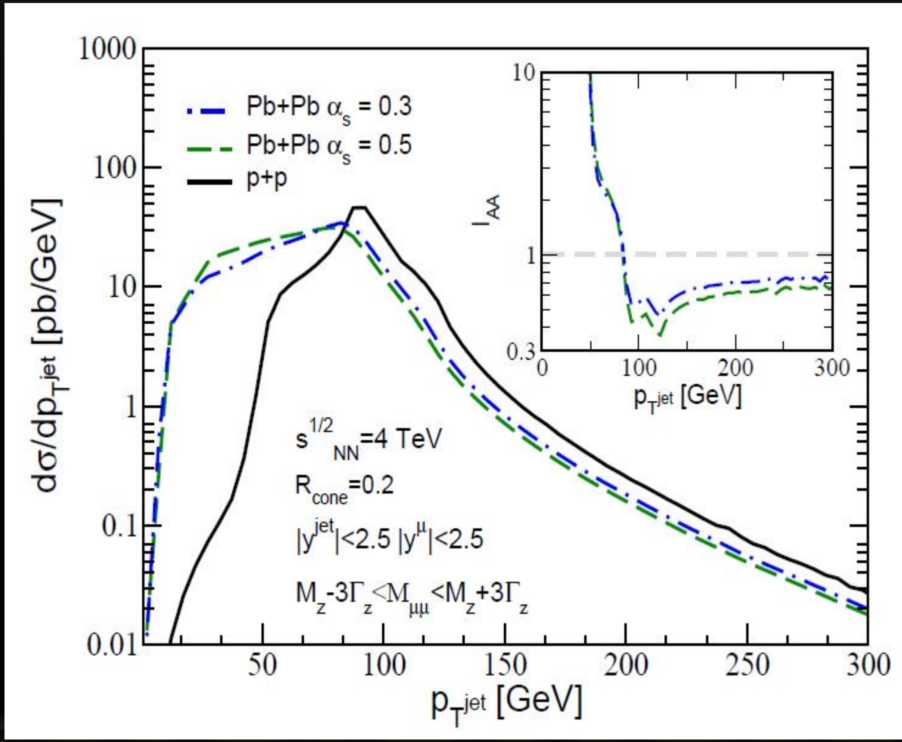


Neufeld, Vitev, BWZ, PRC (2011).

Z° + jet in A+A: Iaa

- A sharp transition from tagged jet suppression above ~pT of Z to tagged jet enhancement below ~pT of Z

$$I_{AA}^{\rm jet}(R,\omega_{\rm min}) = \frac{1}{\langle N_{\rm bin}\rangle} \frac{d\sigma_{AA}}{dp_{T\,(Z)}dp_{T\,(Q)}} \bigg/ \frac{d\sigma_{pp}}{dp_{T\,(Z)}dp_{T\,({\rm jet})}}$$

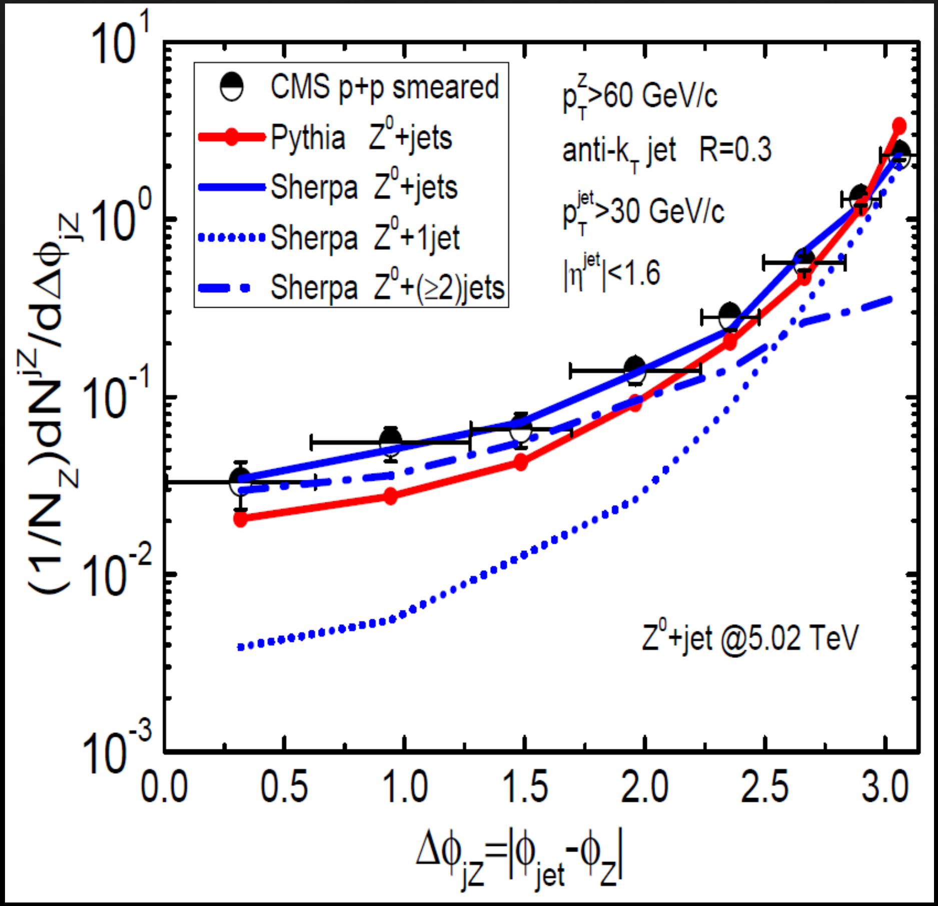


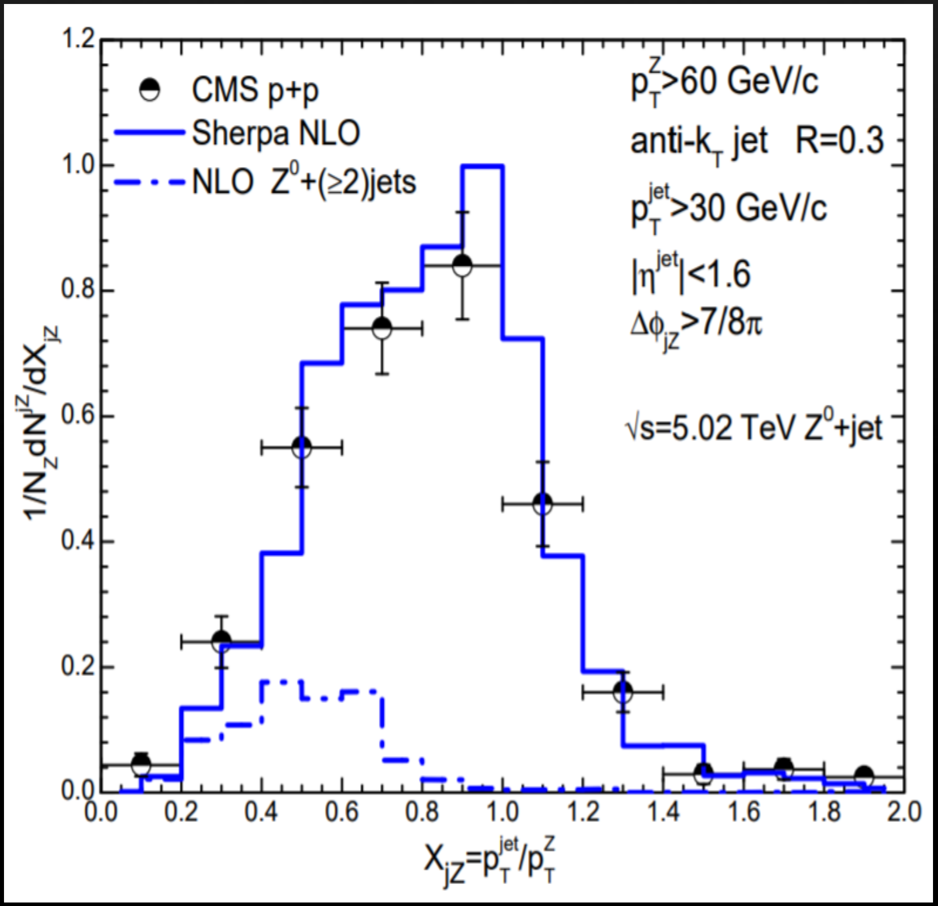
Neufeld, Vitev, BWZ, PRC (2011).

$p_T \in (92.5{\rm GeV}, 112.5{\rm GeV})$

Z+jet in p+p: NLO+PS

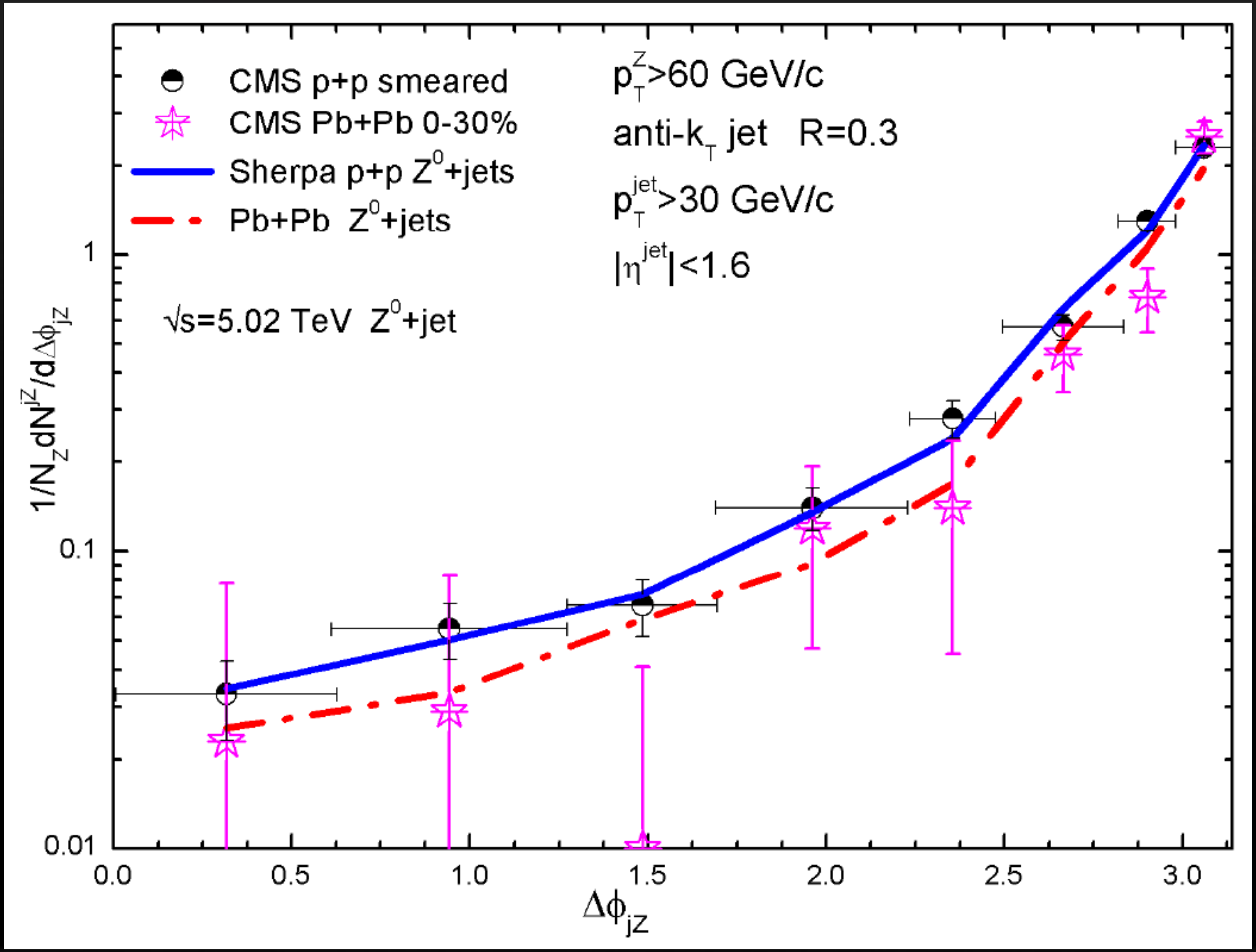
- Results with NLO+PS by Sherpa give good descriptions on angular correlation and momentum imbalance of in p+p





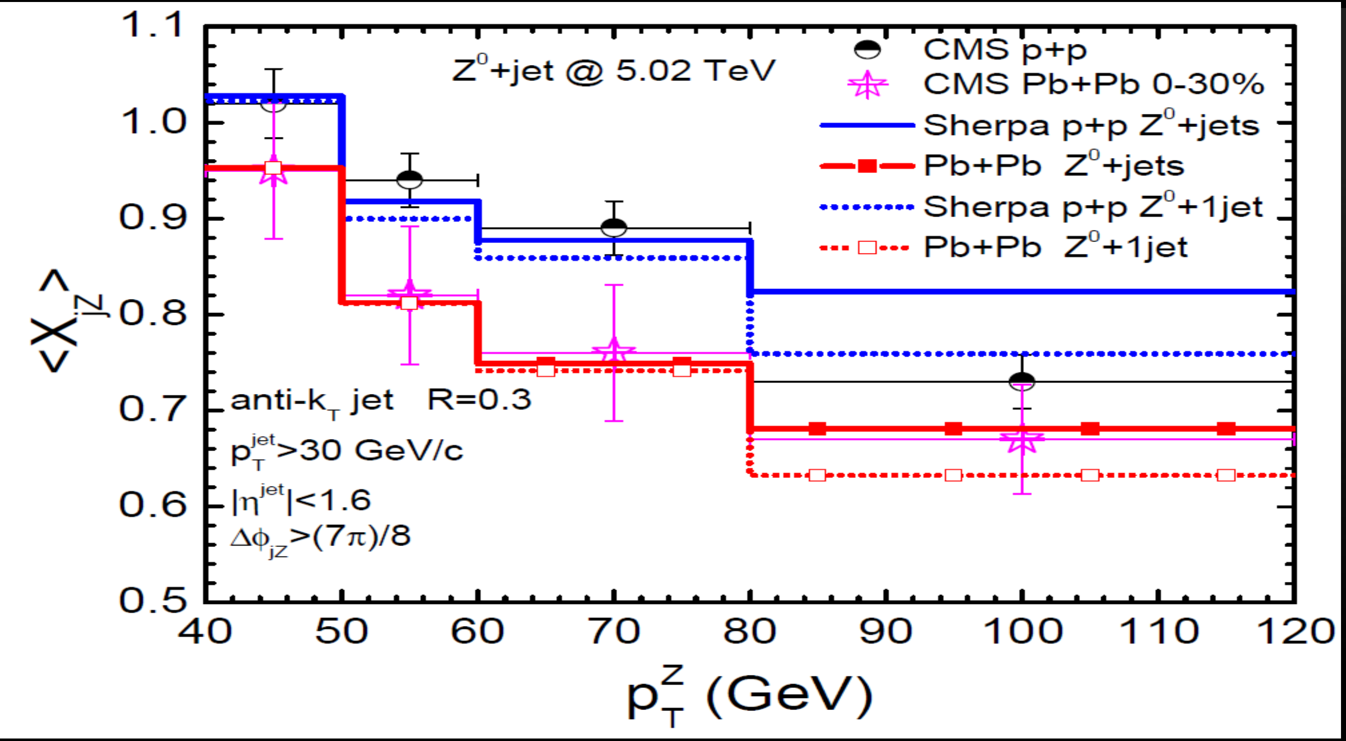
S Zhang, T Luo, X Wang, BWZ, PRC (2018)

Angular Correlation of Z+jet



S Zhang, T Luo, X Wang, BWZ, PRC (2018)

Momentum imbalance



$$\Delta\langle x_{jZ}\rangle = \langle x_{jZ}\rangle_{p+p} - \langle x_{jZ}\rangle_{Pb+Pb}$$

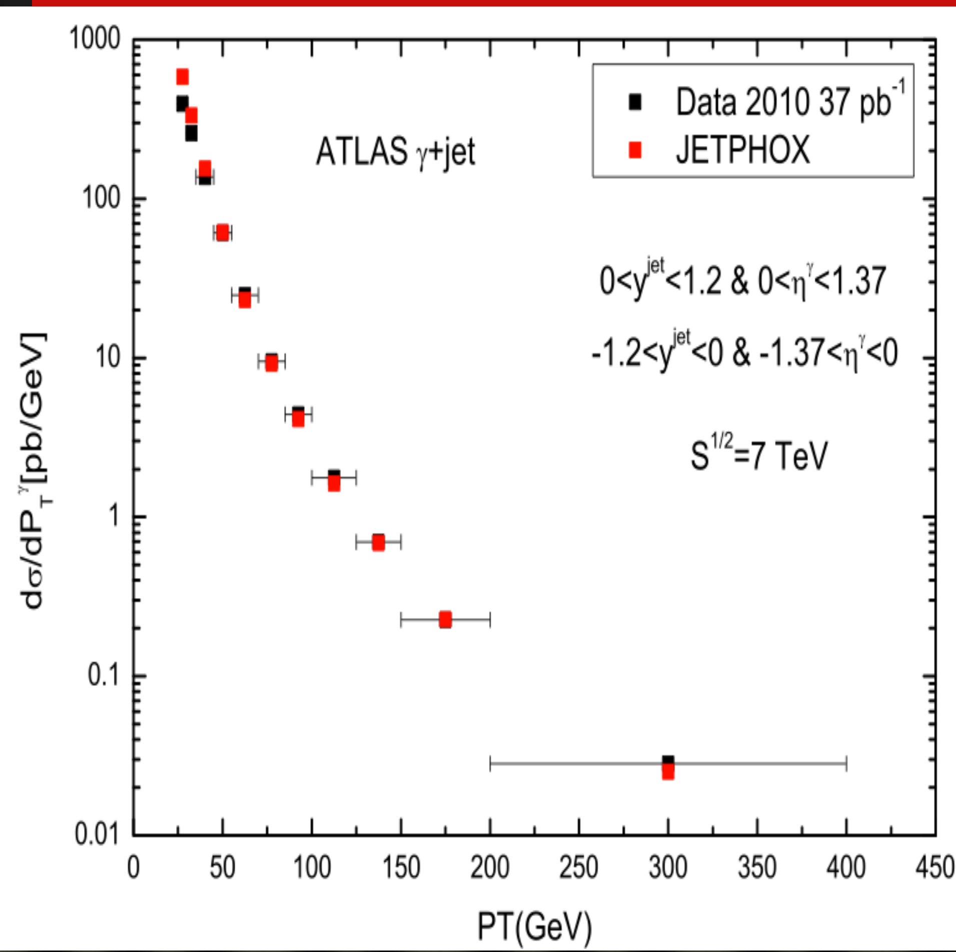
$$x_{JV} = p_T^J / p_T^V$$

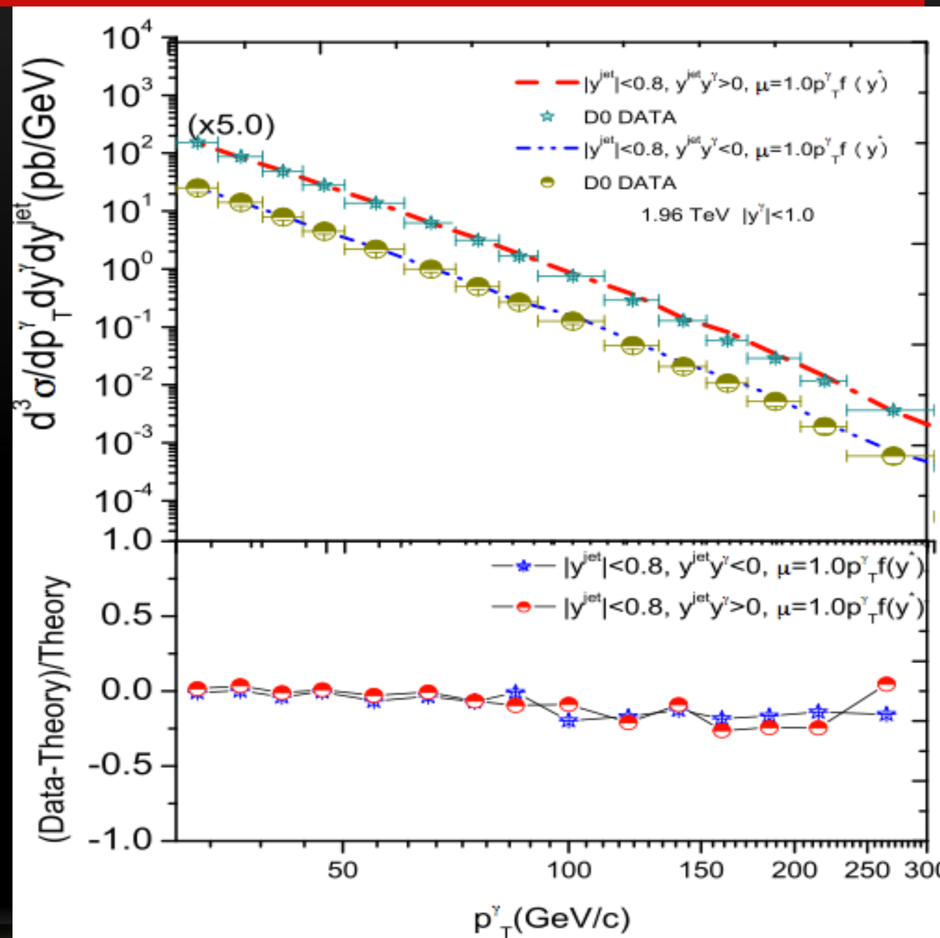
p_T^Z(GeV)	40-50	50-60	60-80	> 80
CMS data	0.07 ± 0.106	0.12±0.148	0.13±0.158	0.06±0.088
$\Delta\langle x_{jZ}\rangle$	0.075	0.106	0.128	0.143

S Zhang, T Luo, X Wang, BWZ, PRC (2018)

Photon + jet in p+p at NLO

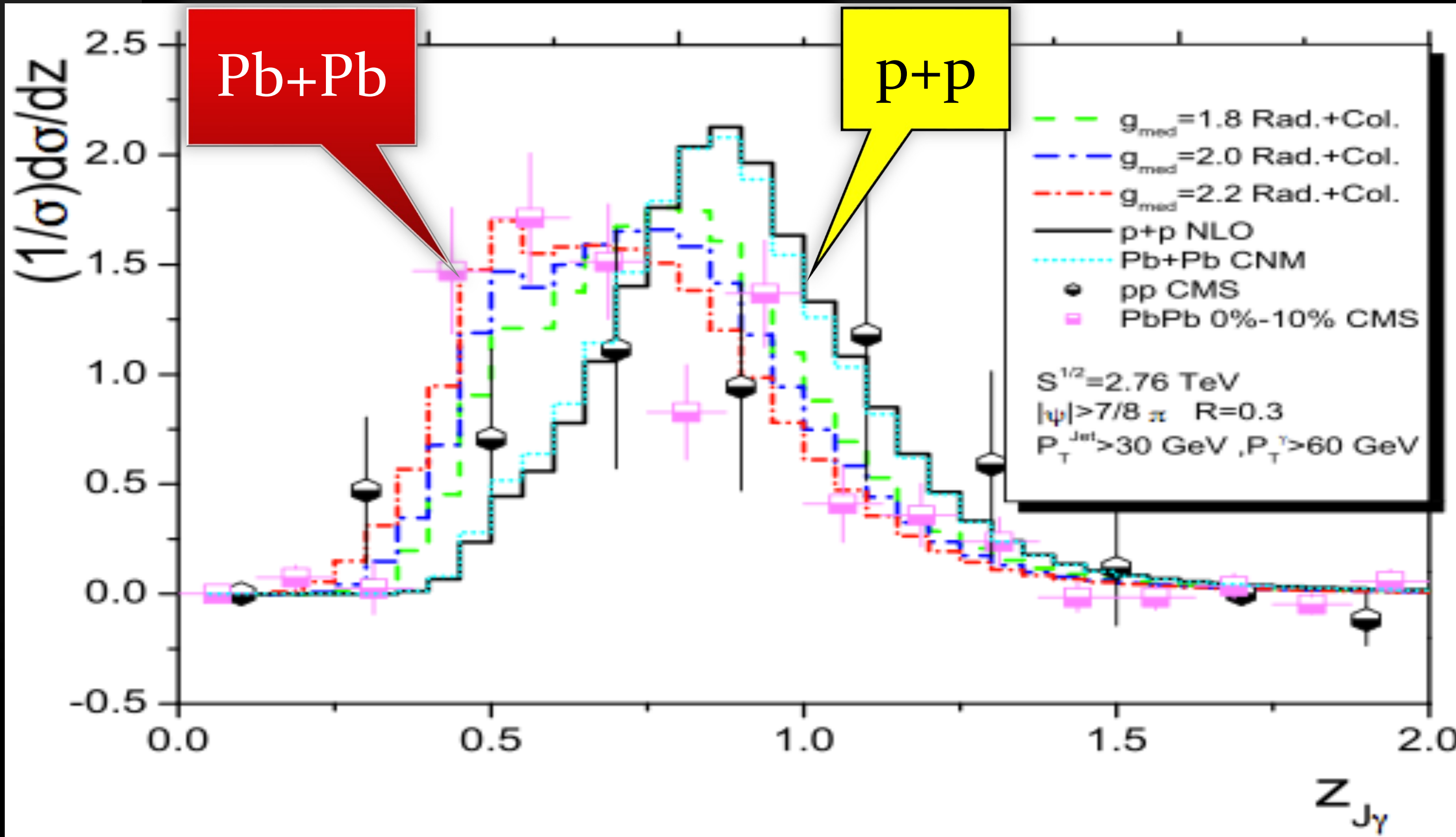
- A good baseline for photon+jet in hadron-hadron production has been given by the NLO pQCD.





W Dai, I Vitev, BWZ, PRL (2013)

Asymmetry in photon + jet



$$z_{J\gamma} = \frac{p_{T_{\rm jet}}}{p_{T_\gamma}}$$

System	$\langle z_{J\gamma}\rangle_{\rm LHC}$	$\langle z_{J\gamma}\rangle_{\rm RHIC}$
p+p	0.94	0.90
A+A, CNM	0.94	0.89
A+A, $g_{med} = 1.8$,Rad.+Col.	0.84	0.78
A+A, $g_{med} = 2.0$,Rad.+Col.	0.80	0.74
A+A, $g_{med} = 2.2$,Rad.+Col.	0.71	0.70

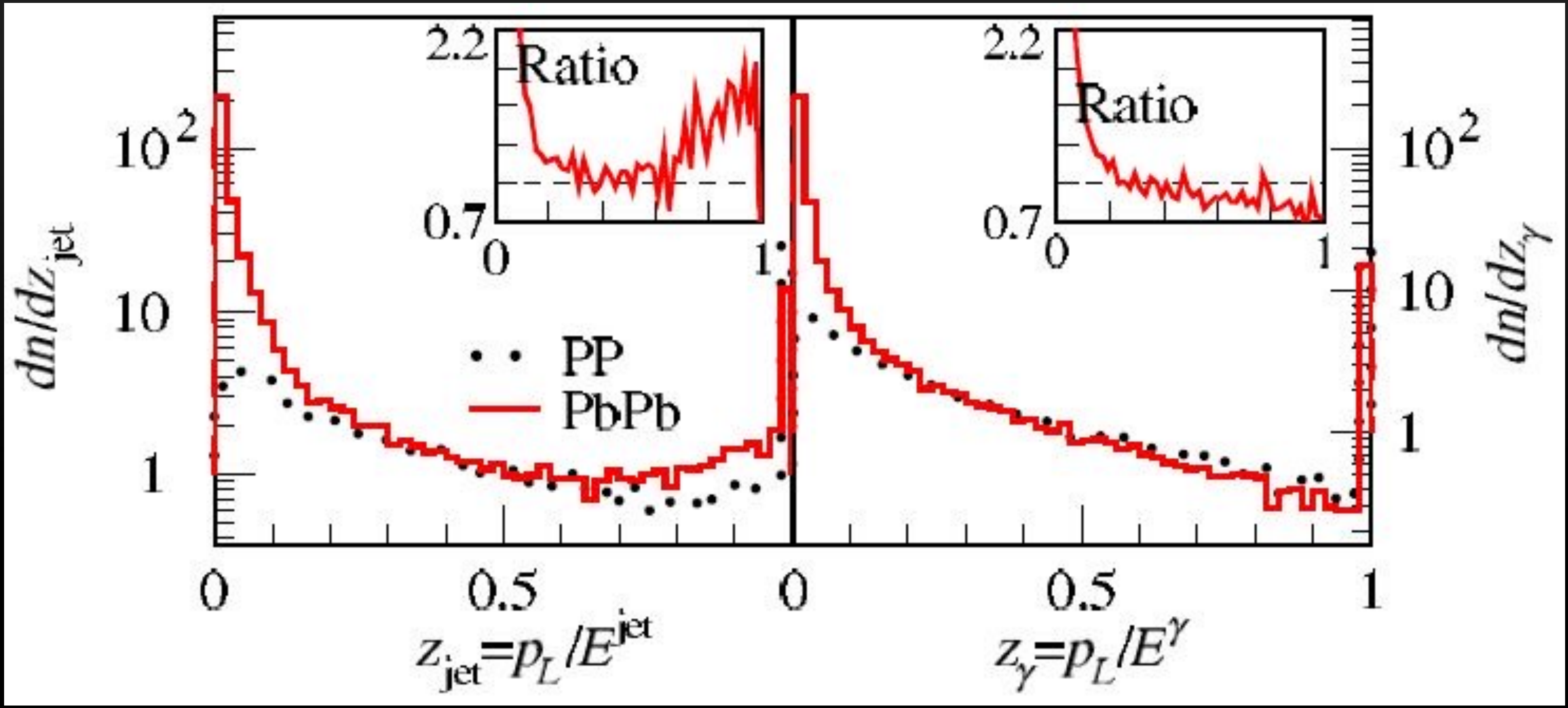
CMS, PLB(2013)

$$\langle z_{J\gamma}\rangle = 0.73 \pm 0.02$$

Dai, Vitev, BWZ, PRL(2013)

photon + jet with LBT

$$p \cdot \partial f(p) = -C(p)$$



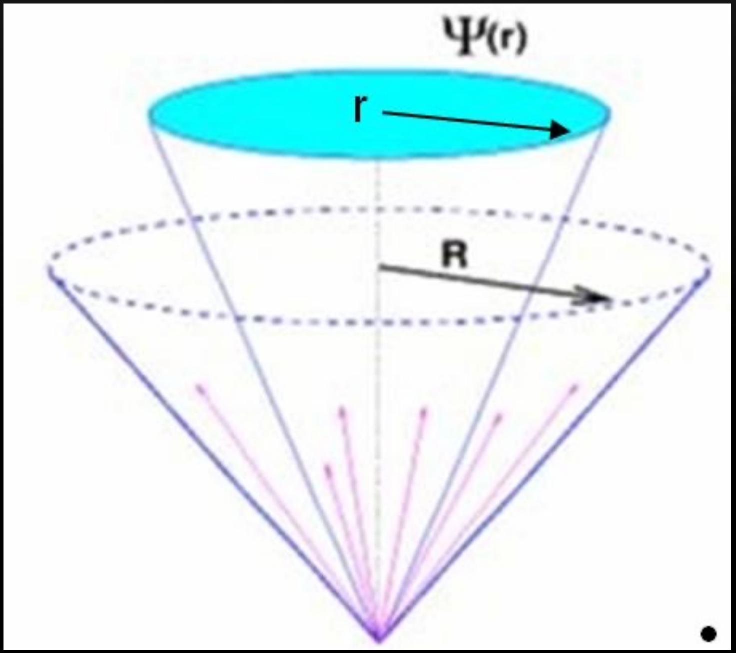
Xin-Nian Wang, Yan Zhu, PRL (2013)

Jet shape in HIC

$$\Psi_{\rm int}(r;R) = \frac{\sum_i (E_T)_i \Theta(r - (R_{\rm jet})_i)}{\sum_i (E_T)_i \Theta(R - (R_{\rm jet})_i)},$$

$$\psi(r;R) = \frac{d\Psi_{\rm int}(r;R)}{dr}.$$

$$\Psi_{\rm int}(r = R, R) = 1$$

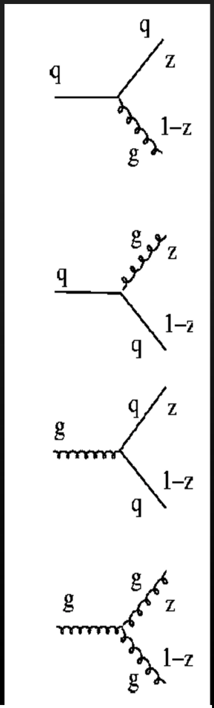


LO & Resummation: p+p

An analytic approach to the energy distribution of jet

Seymour, M. (1998)

Jet shape at LO with the acceptance cut



$$P^{(1)}_{qq}(x) = C_2(F)\left[(1+x^2)\left(\frac{1}{1-x}\right)_+ + \frac{3}{2}\delta(1-x)\right]$$

$$P^{(1)}_{gq}(x) = C_2(F)\,\frac{(1-x)^2+1}{x}$$

$$P^{(1)}_{qg}(x) = T(F)\left[(1-x)^2 + x^2\right]$$

$$P^{(1)}_{gg}(x) = 2C_2(A)\left[\frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x)\right] + \left(\frac{11}{6}C_2(A) - \frac{2}{3}T(F)n_f\right)\delta(1-x),$$

$$\psi_a(r;R) = \sum_b \frac{\alpha_s}{2\pi}\frac{2}{r}\int_{z_{min}}^{1-Z} dz\, z P_{a\to bc}(z).$$

$$z_{min} = \omega^{min}/E_T$$

Collinear divergence requires Sudakov resummation:

$$P(<r) = \exp(-P_1(>r)) = \exp\left(-\int_r^R dr'\,\psi_{\text{coll}}(r')\right)$$

$$\psi_{\text{RS}}(r) = \frac{dP(r)}{dr}$$

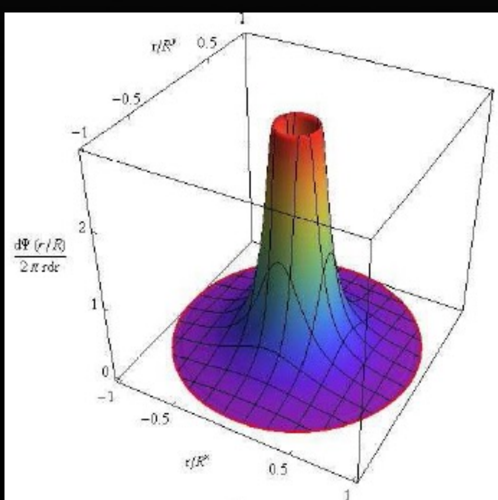
Jet shape p+p: baseline

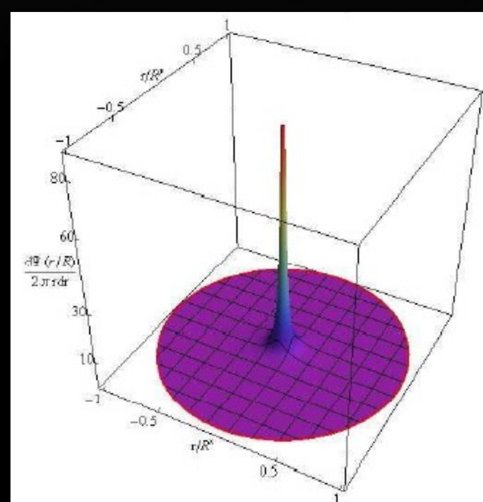
$$\psi(r) = \psi_{\rm coll}(r)\,(P(r)-1) + \psi_{\rm LO}(r) + \psi_{i,{\rm LO}}(r) + \psi_{\rm PC}(r) + \psi_{i,{\rm PC}}(r)\,,$$

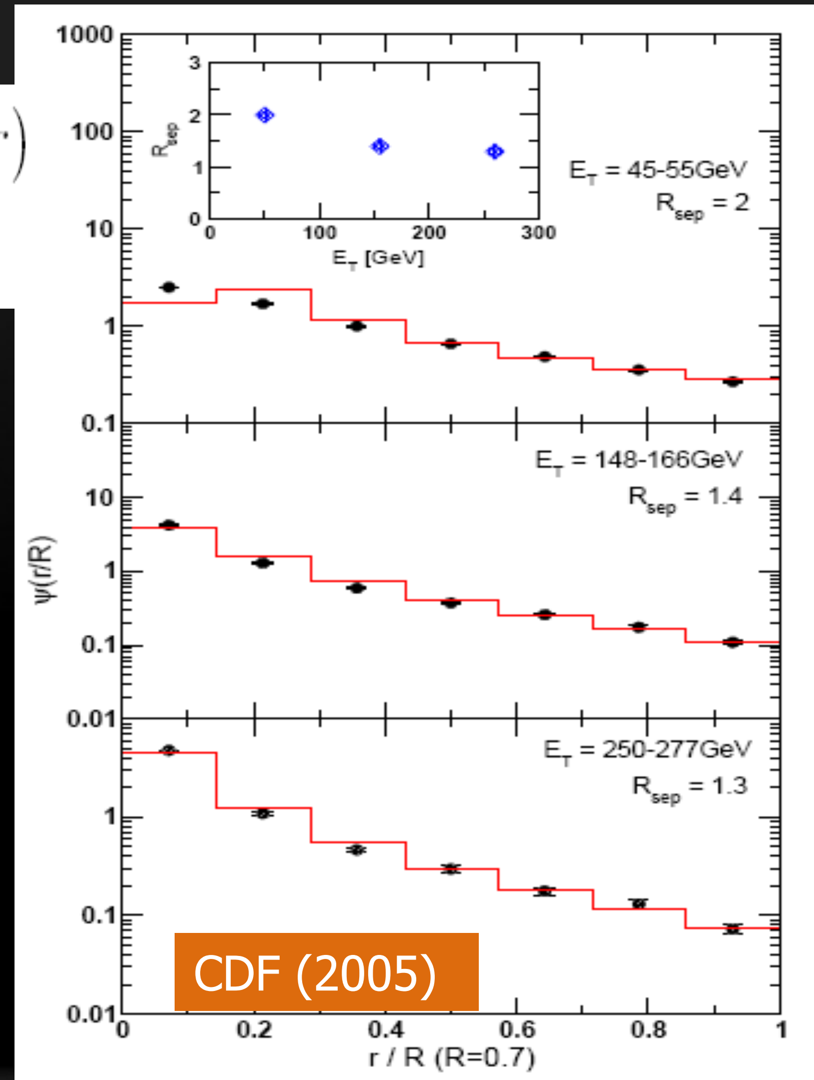
LHC

20 GeV

500 GeV







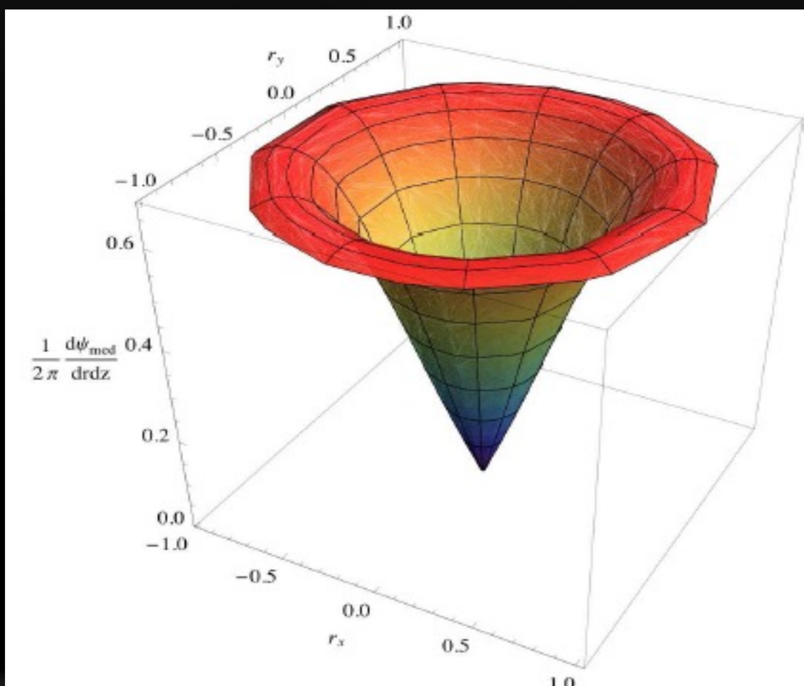
I Vitev, S Wicks, BWZ, JHEP 0811,093 (2008)

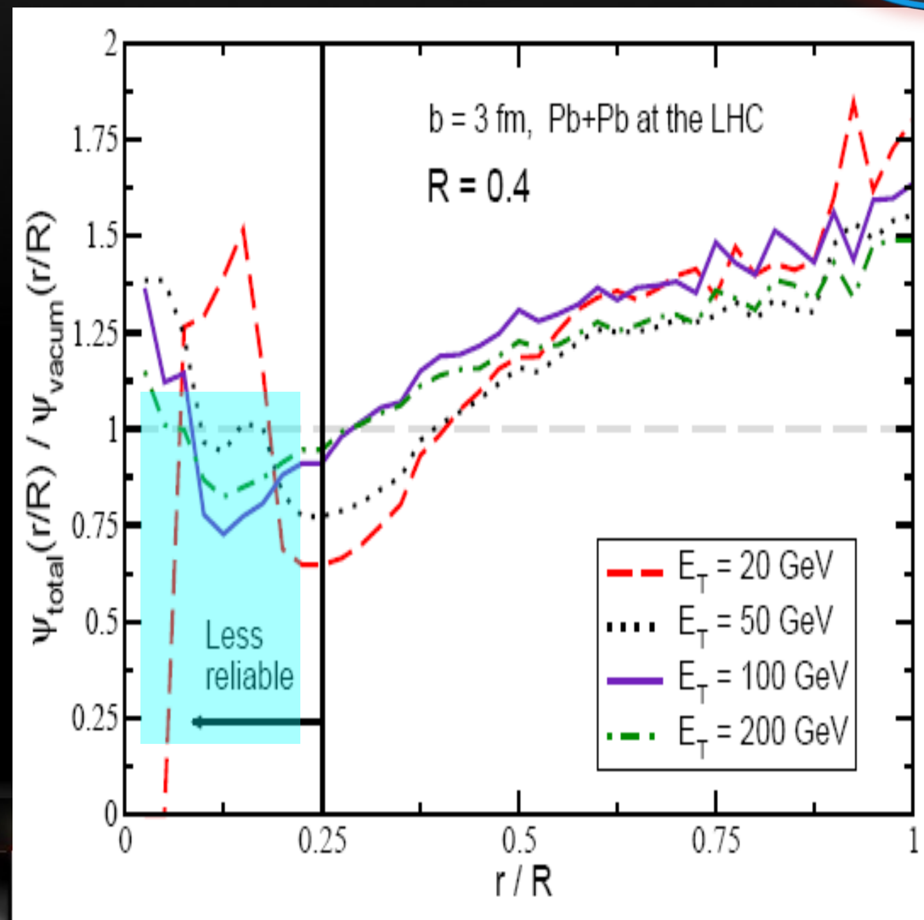
$\sqrt{s} = 1960$ GeV

Total jet shape in HIC

Medium-induced jet shape is much broader than the jet shape in p+p

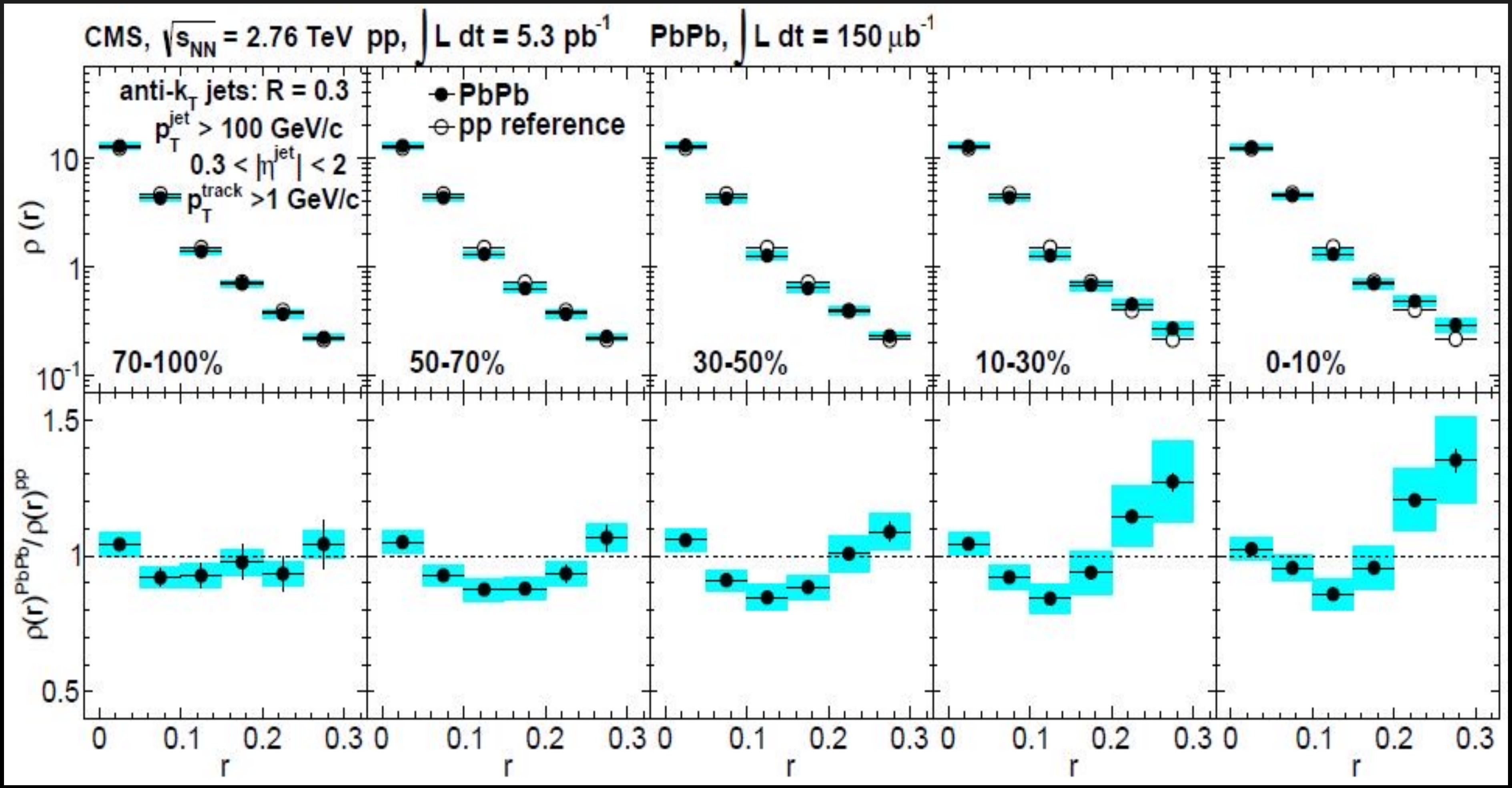
$$\psi_{\text{tot.}}(r/R) = \frac{1}{\text{Norm}}\int_{\epsilon=0}^{1} d\epsilon \sum_{q,g} P_{q,g}(\epsilon)\frac{1}{(1-(1-f_{q,g})\cdot\epsilon)^3} \times \frac{\sigma_{q,g}^{NN}(R,\omega^{\min})}{d^2E'_T\,dy}\left[(1-\epsilon)\,\psi^{q,g}_{\text{vac.}}(r/R)+f_{q,g}\cdot\epsilon\,\psi^{q,g}_{\text{med.}}(r/R)\right]$$





I Vitev, S Wicks, BWZ (2008)

Jet shapes measured at LHC

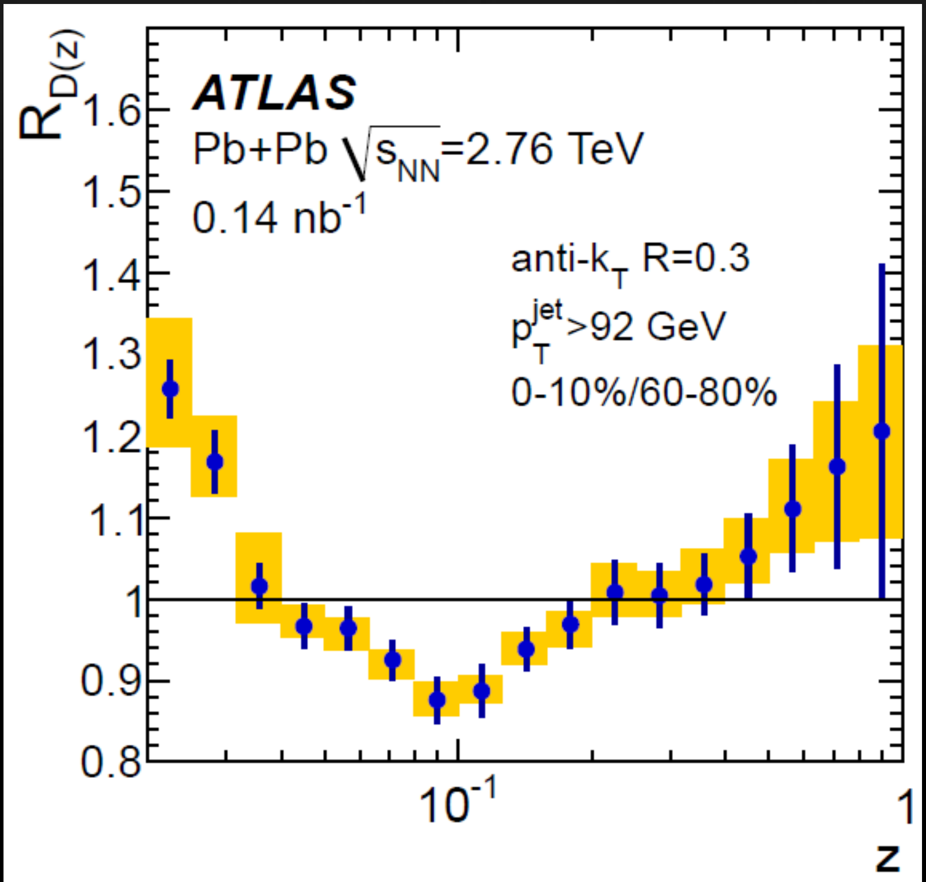


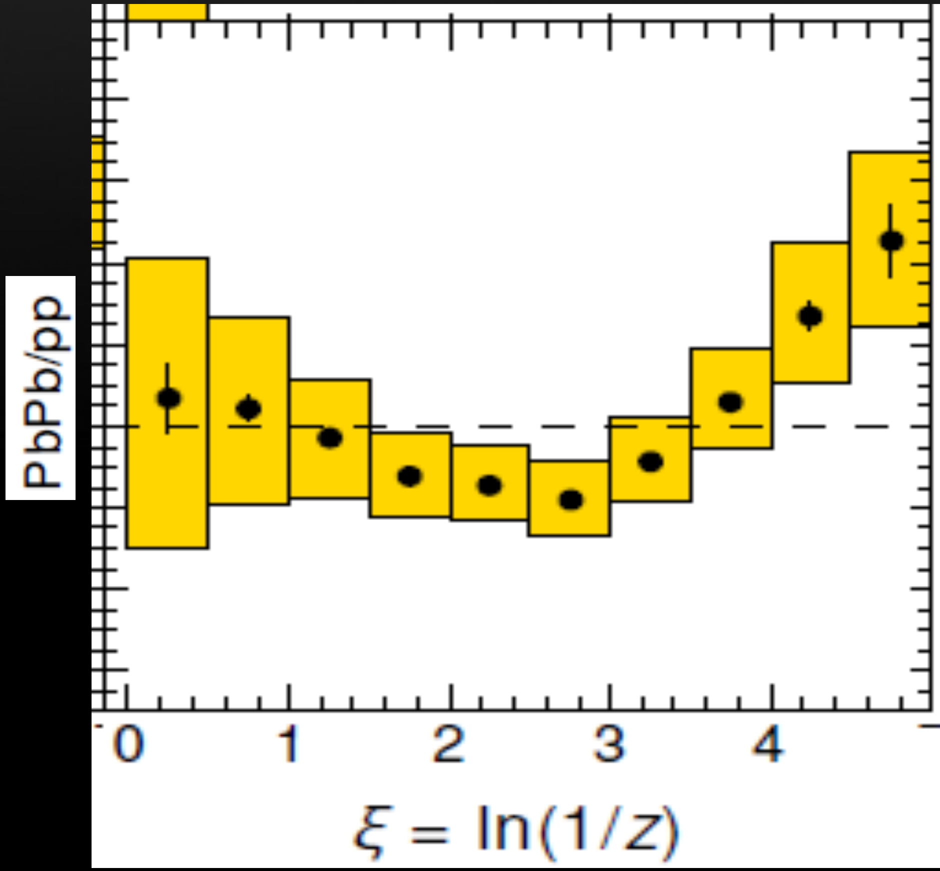
CMS, arXiv:1310.0878

Jet Fragmentation Function

$$D(z) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}z}$$

$z = p_T^h / p_T^{jet}$





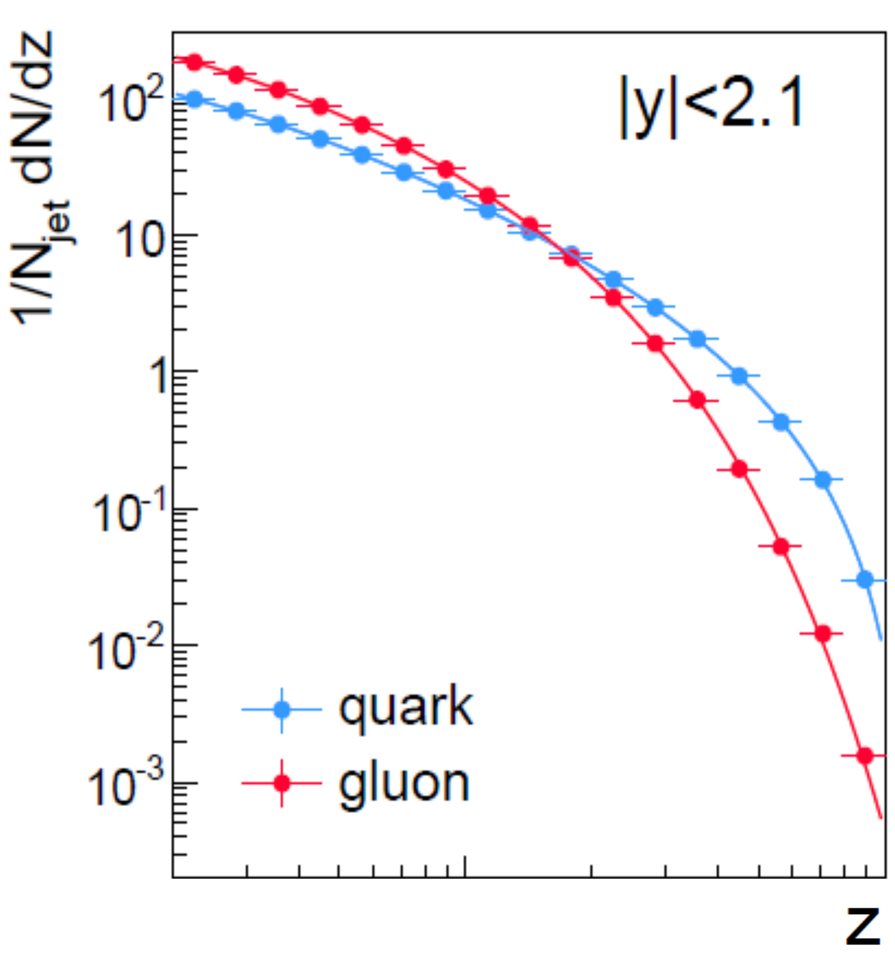
ATLAS, 1406.2979

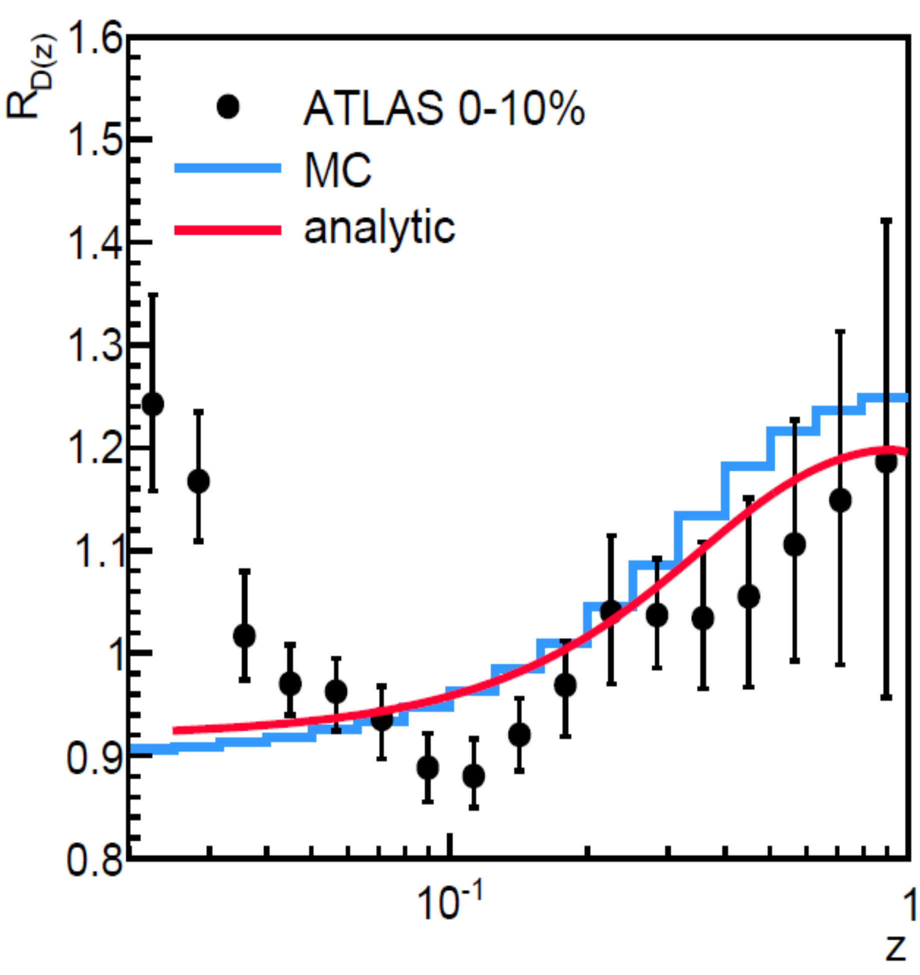
CMS, 1406.0932

Jet FF: Quark VS Gluon

$$D(z) \equiv \frac{1}{N_{\rm jet}} \frac{{\rm d}N_{\rm ch}}{{\rm d}z}$$

$z = p_T^h / p_T^{jet}$

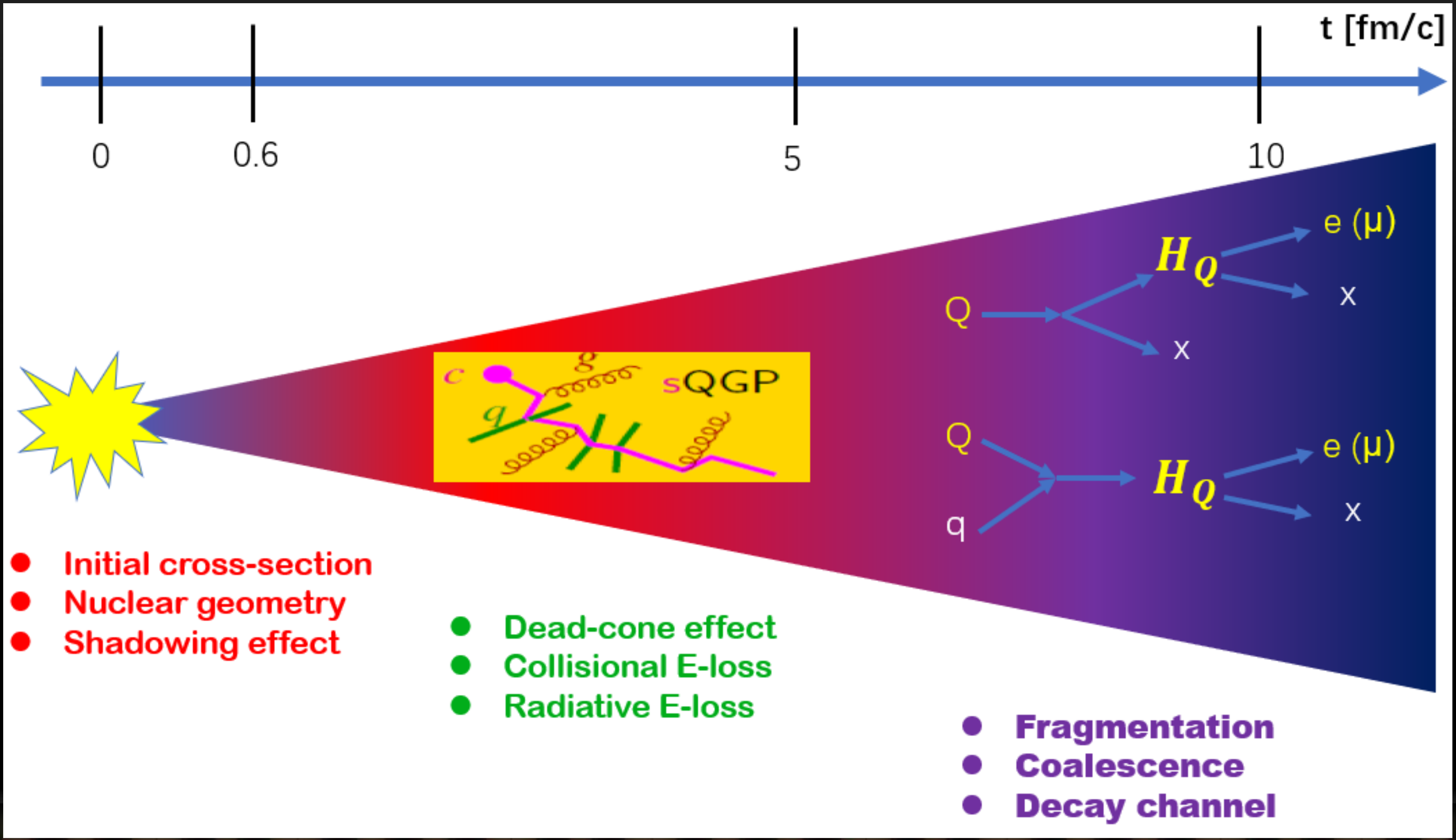




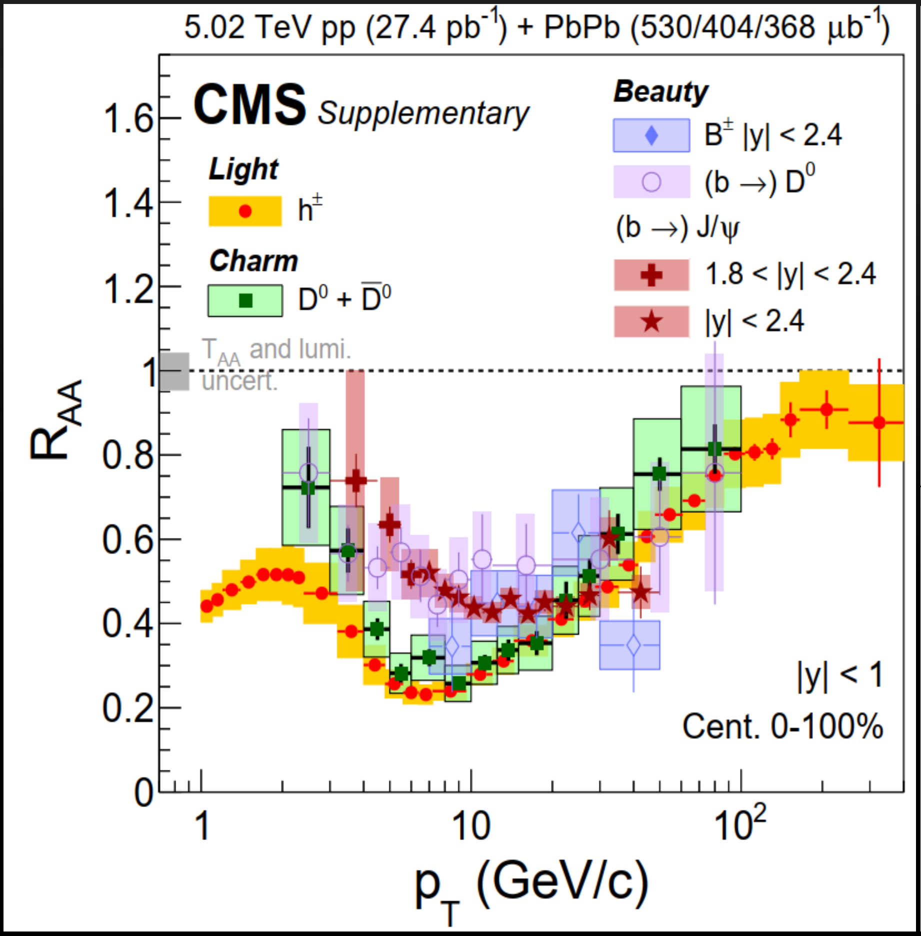
M Spousta, B Cole, 1504.05169

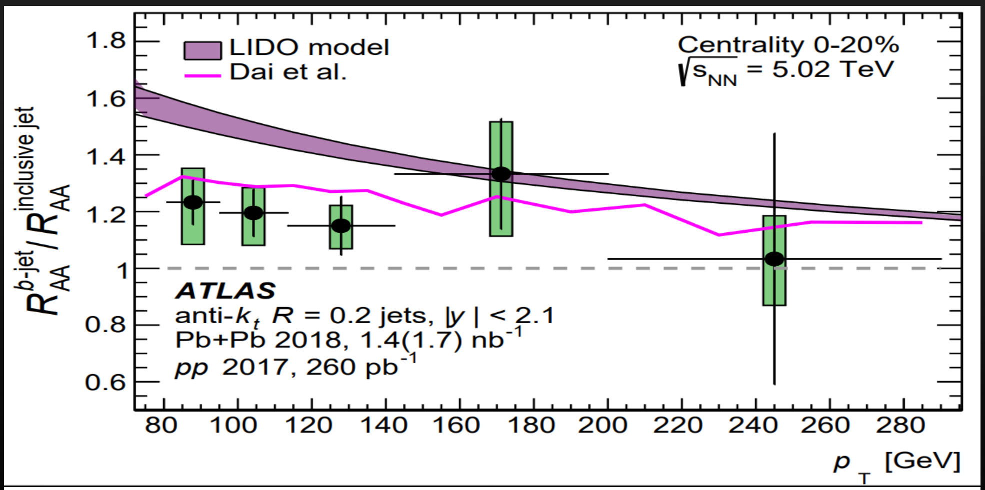
Heavy flavor quarks and jets

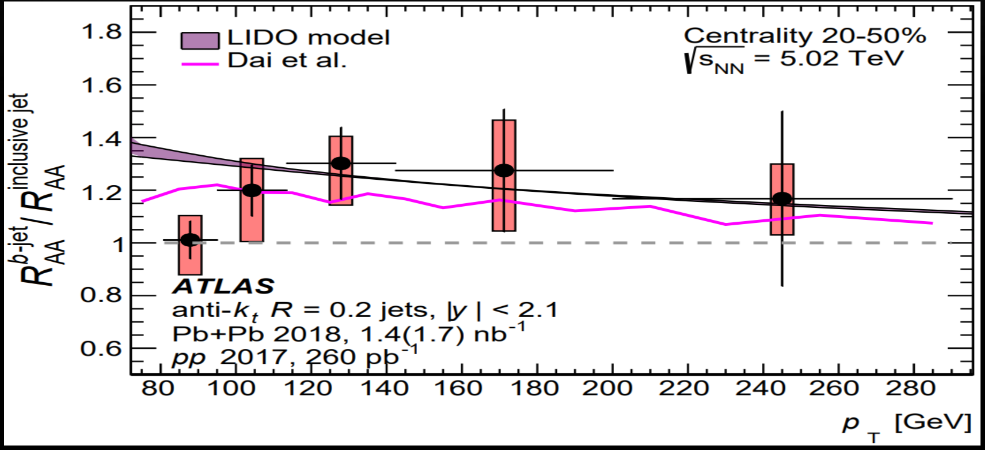
Evolution of HQ in A+A collisions



Mass hierarchy of jet energy loss

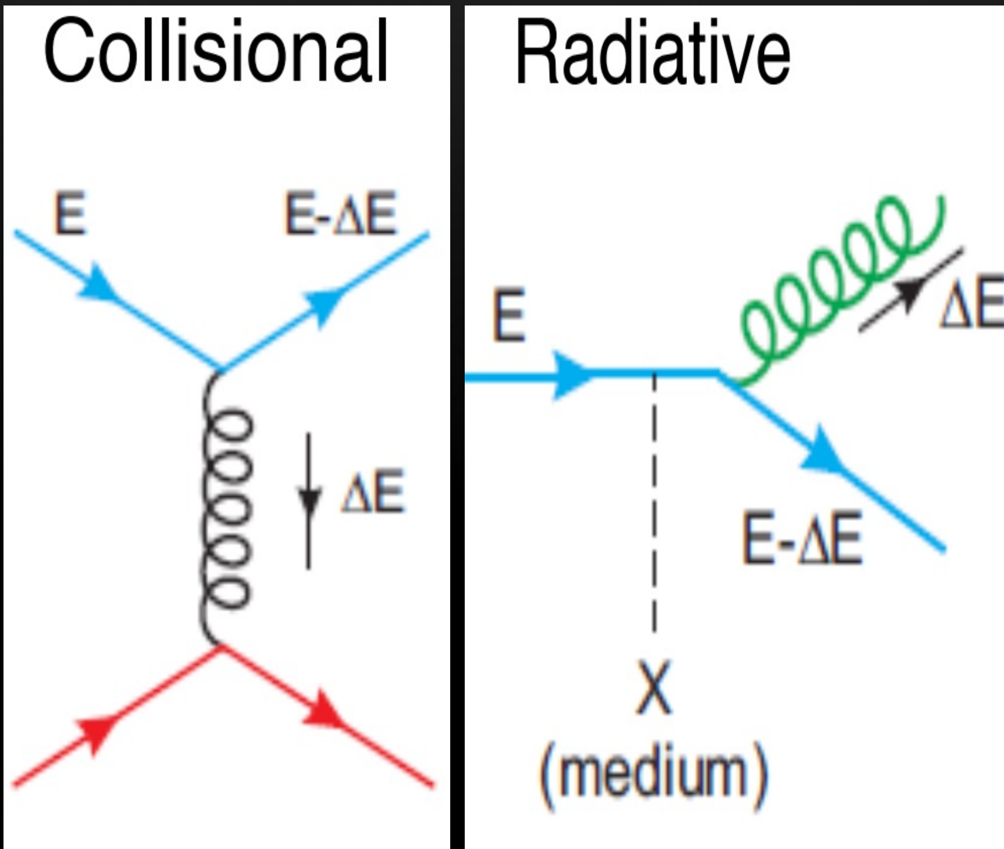


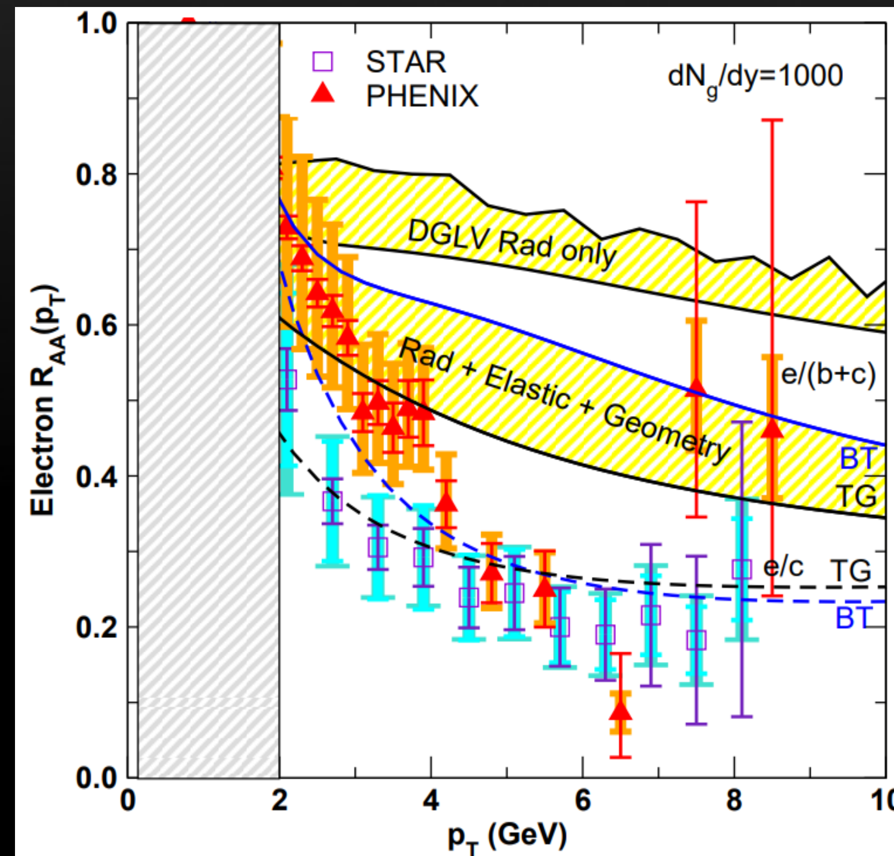




$$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$$

Energy loss of heavy quark





Simon Wicks et al. Nucl.Phys.A 784 (2007) 426-442

Improved Langevin equations

SHELL: Simulating Heavy quark Energy Loss by Langevin equations

$$\vec{x}(t+\Delta t) = \vec{x}(t) + \frac{\vec{p}(t)}{E}\Delta t$$
$$\vec{p}(t+\Delta t) = \vec{p}(t) - \Gamma(p)\vec{p}\Delta t + \vec{\xi}(t)\Delta t - \vec{p}_g$$

G.D. Moore et al., PRC71(2005)064904;
S. Cao G.Y. Qin and S.A. Bass, PRC88 (2013) 044907

Diffusion coefficient κ and drag coefficient Γ are correlated by

$$\kappa = 2\Gamma E T = \frac{2T^2}{D_s}$$

$$\frac{dE}{dL} = -\frac{\alpha_s C_s \mu_D^2}{2} ln \frac{\sqrt{ET}}{\mu_D}$$

Stochastic term obeys a Gaussian distribution

$$W[\vec{\xi}(t)] = N\exp[\frac{\vec{\xi}(t)^2}{2\kappa/\Delta t}]$$

$$\langle \xi_i(t) \rangle = 0$$
$$\langle \xi_i(t)\xi_j(t') \rangle = \kappa\delta_{ij}(t-t')$$

Medium-induced gluon radiation

Phys.Rev.Lett. 85 (2000) 3591-3594;
Phys.Rev.Lett. 93 (2004)072301;
Phys.Rev. D85 (2012) 014023

Higher-Twist approach:

$$\frac{dN}{dxdk_\perp^2\,dt} = \frac{2\alpha_s C_s P(x)\hat{q}}{\pi k_\perp^4}\sin^2(\frac{t-t_i}{2\tau_f})(\frac{k_\perp^2}{k_\perp^2+x^2m^2})^4$$

Parton splitting function and gluon formation time:

$$P_{q\to qg}(x) = \frac{(1-x)(1+(1-x)^2)}{x}$$

$$P_{g\to gg}(x) = \frac{2(1-x+x^2)^3}{x(1-x)}$$

$$\tau_f = \frac{2Ex(1-x)}{k_\perp^2+x^2M^2}$$

W.T. Deng et al., RC81(2010) 024902;

Jet transport coefficient: $\hat{q} \equiv d\left\langle p_\perp^2\right\rangle/dL$

$$\hat{q}(\tau,\vec{r}) = q_0\frac{\rho^{QGP}(\tau,\vec{r})}{\rho^{QGP}(\tau_0,0)}\frac{p^\mu u_\mu}{p^0}$$

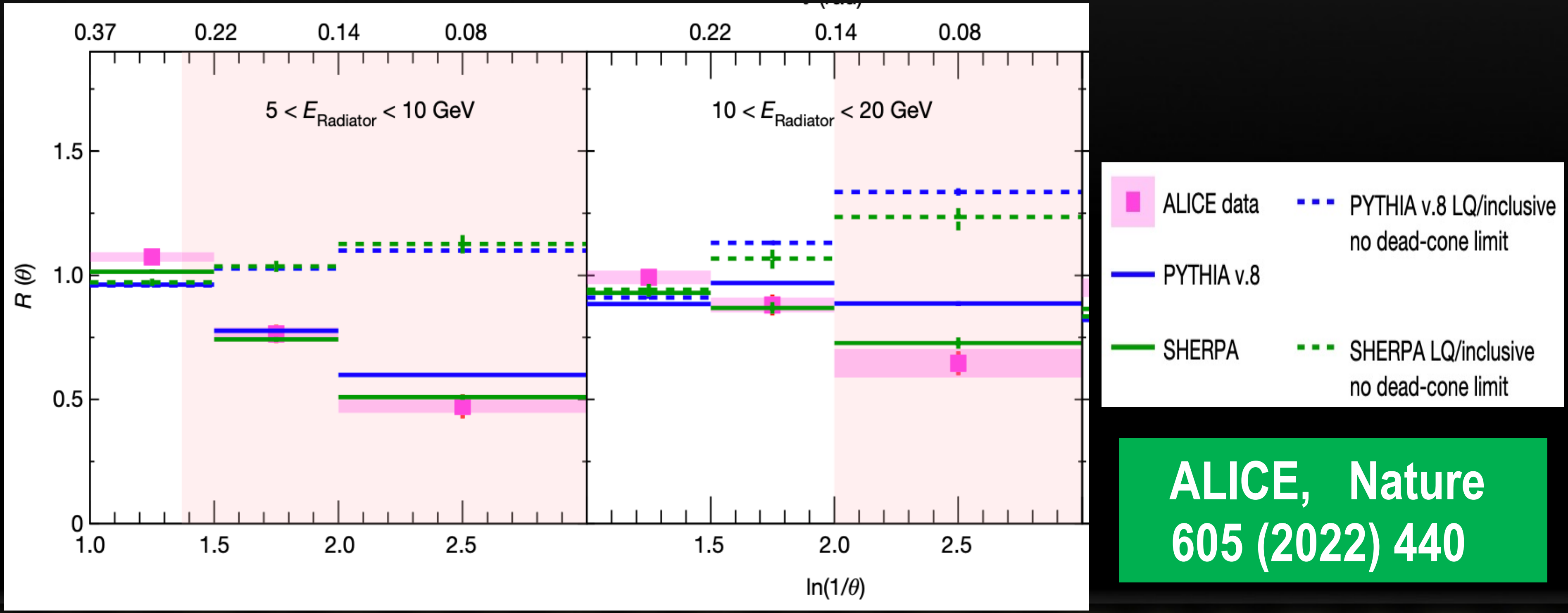
X.F. Chen et al., Phys.Rev. C81 (2010) 064908;

Dead-cone effect in vacuum

- A direct observation of dead-cone effect in p+p is made with an iterative declustering techniques by ALICE.

$$dP_{HQ} \simeq \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{k_\perp^2 dk_\perp^2}{(k_\perp^2+\omega^2\theta_0^2)^2} = dP_0\left(1+\frac{\theta_0^2}{\theta^2}\right)^2$$

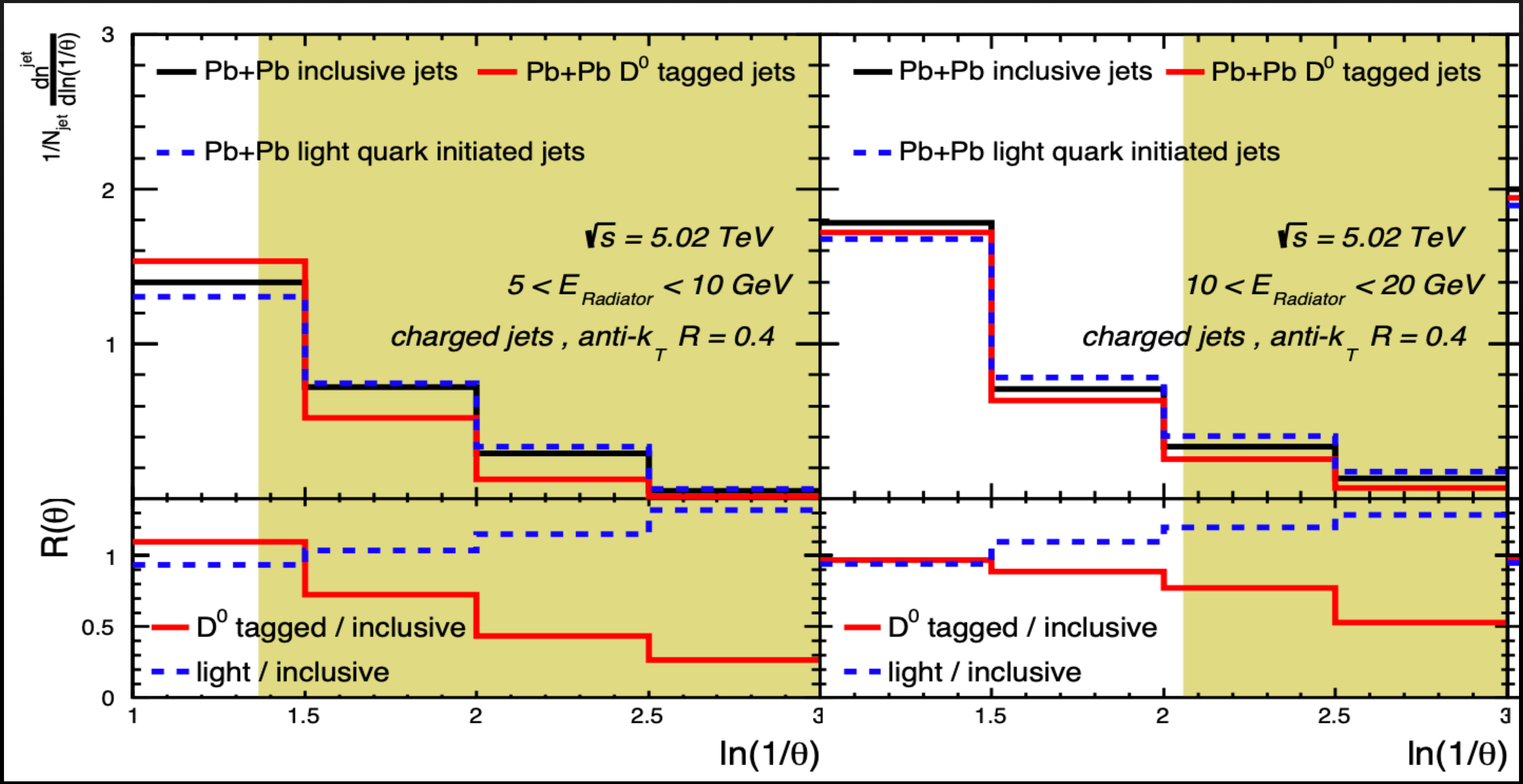
$$\mathrm{R}(\theta) = \frac{1}{\mathrm{N}^{\mathrm{D^0 jets}}}\frac{\mathrm{dn}^{\mathrm{D^0 jets}}}{\mathrm{dln}(1/\theta)} \Big/ \frac{1}{\mathrm{N}^{\text{inclusive jet}}}\frac{\mathrm{dn}^{\text{inclusive jet}}}{\mathrm{dln}(1/\theta)}$$



ALICE, Nature 605 (2022) 440

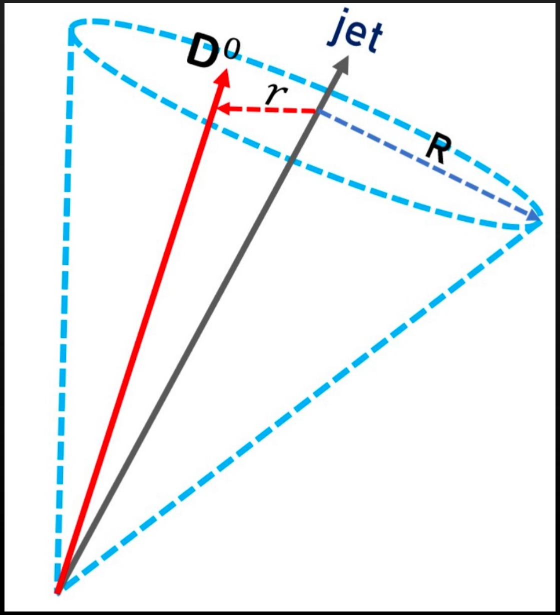
Dead-cone effect in A+A

$$R(\theta) = \frac{1}{N^{D^0 jets}} \frac{dn^{D^0 jets}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{inclusive\ jet}} \frac{dn^{inclusive\ jet}}{d\ln(1/\theta)}$$

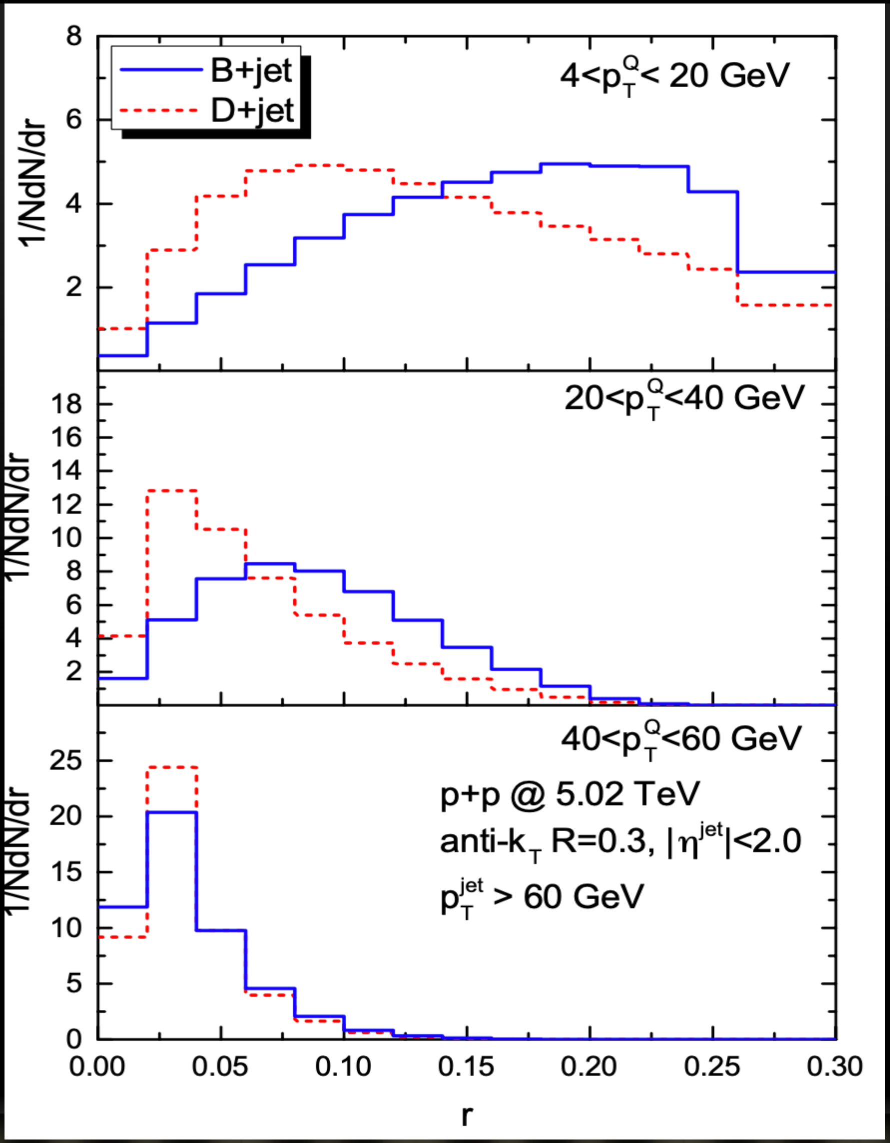


W Dai, M Z Li, BWZ, E Wang, arXiv: 2205.14668

Heavy meson-jet in p+p

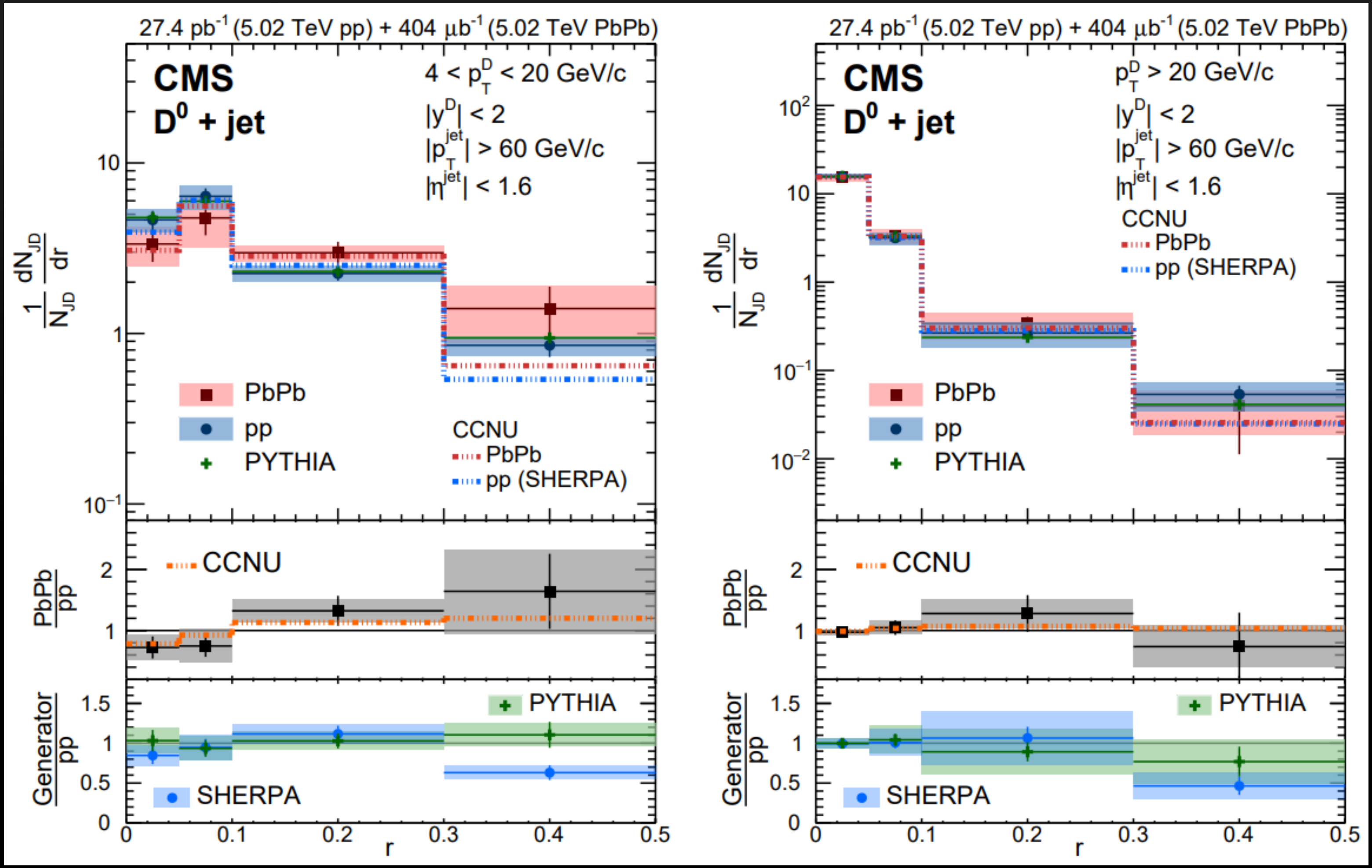


$$r = \sqrt{(\Delta\phi_{JD})^2 + (\Delta\eta_{JD})^2}$$



S Wang, W Dai, BWZ, E Wang, CPC 45, 064105 (2021)

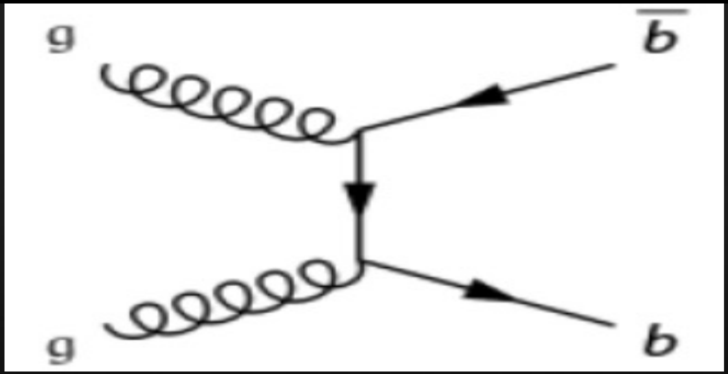
Radial profile of heavy-flavor jet



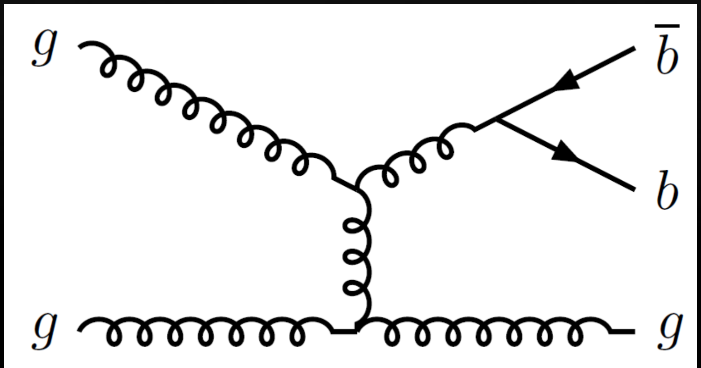
CMS, PRL (2020)

S Wang, W Dai, BWZ, E Wang, EPJC (2019)

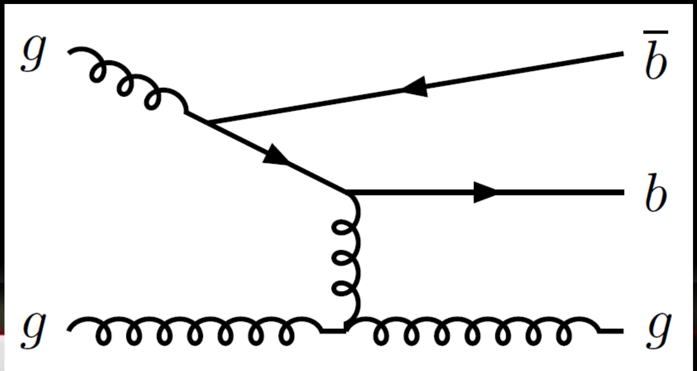
double b-jet production



flavor creation (FCR)



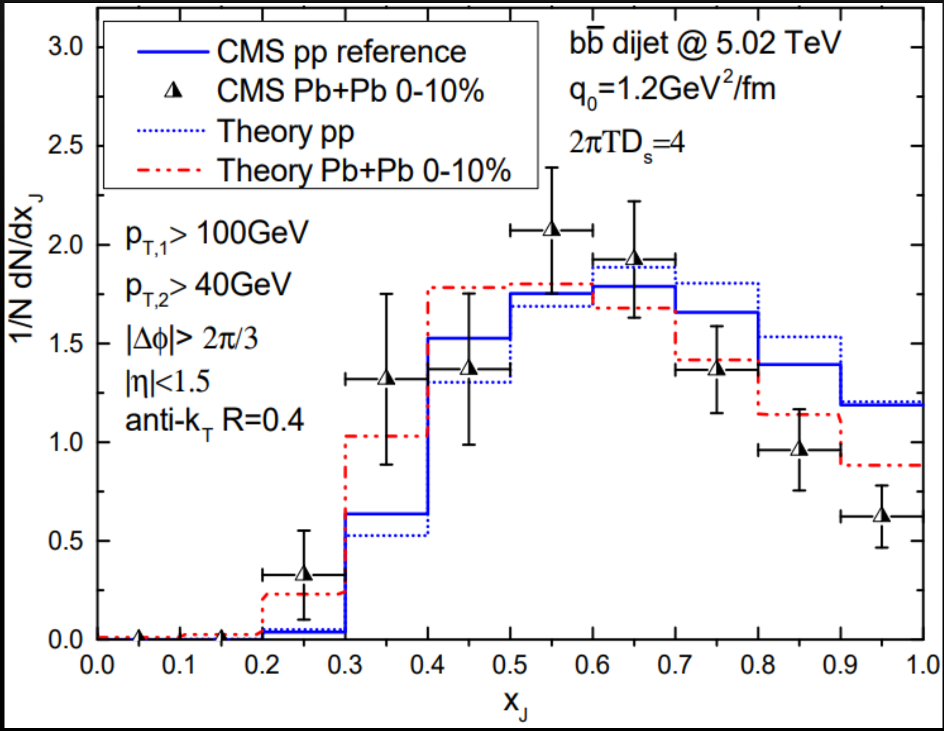
gluon splitting (GSP)



flavor excitation (FEX)

p_T imbalance of $b\bar{b}$ dijets

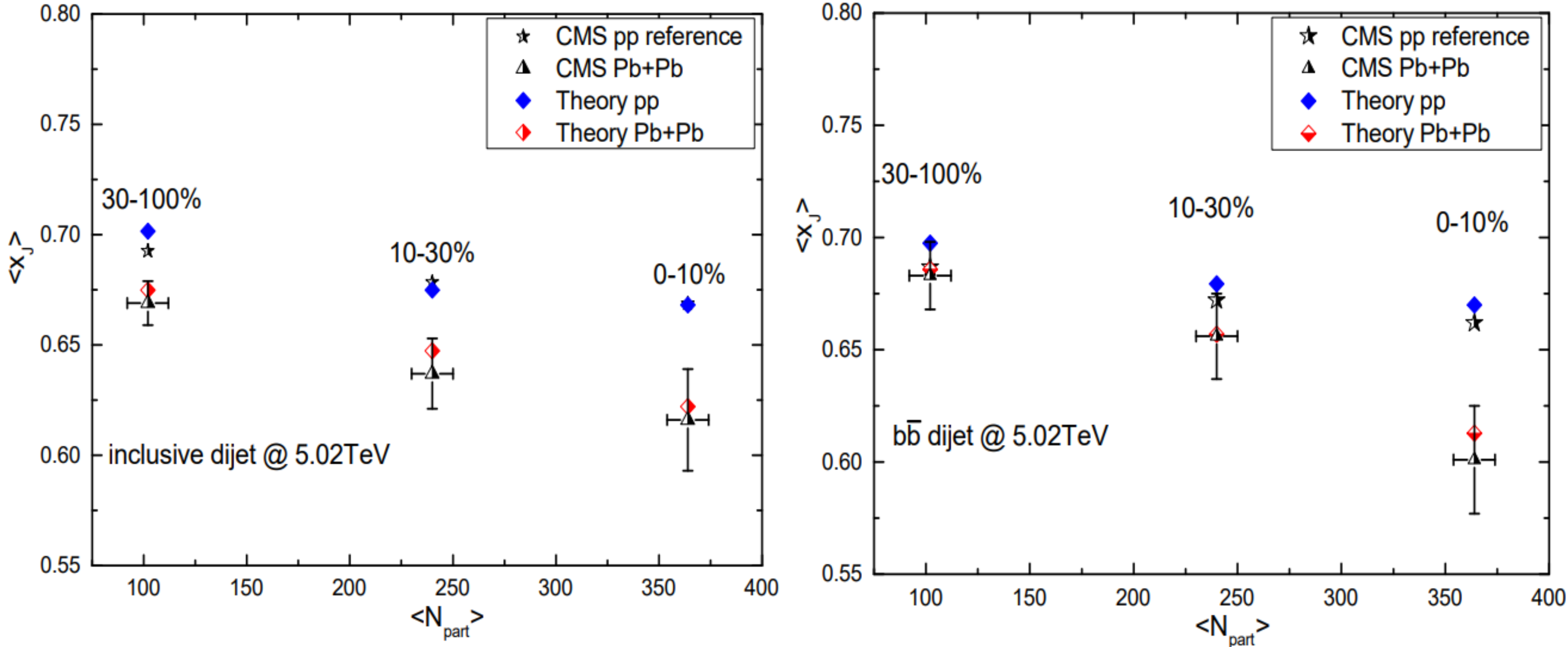
$$x_J = p_{\mathrm{T},2}/p_{\mathrm{T},1}$$



W Dai, S Wang, BWZ, E Wang, arXiv: 1806.06332, CPC (2020)

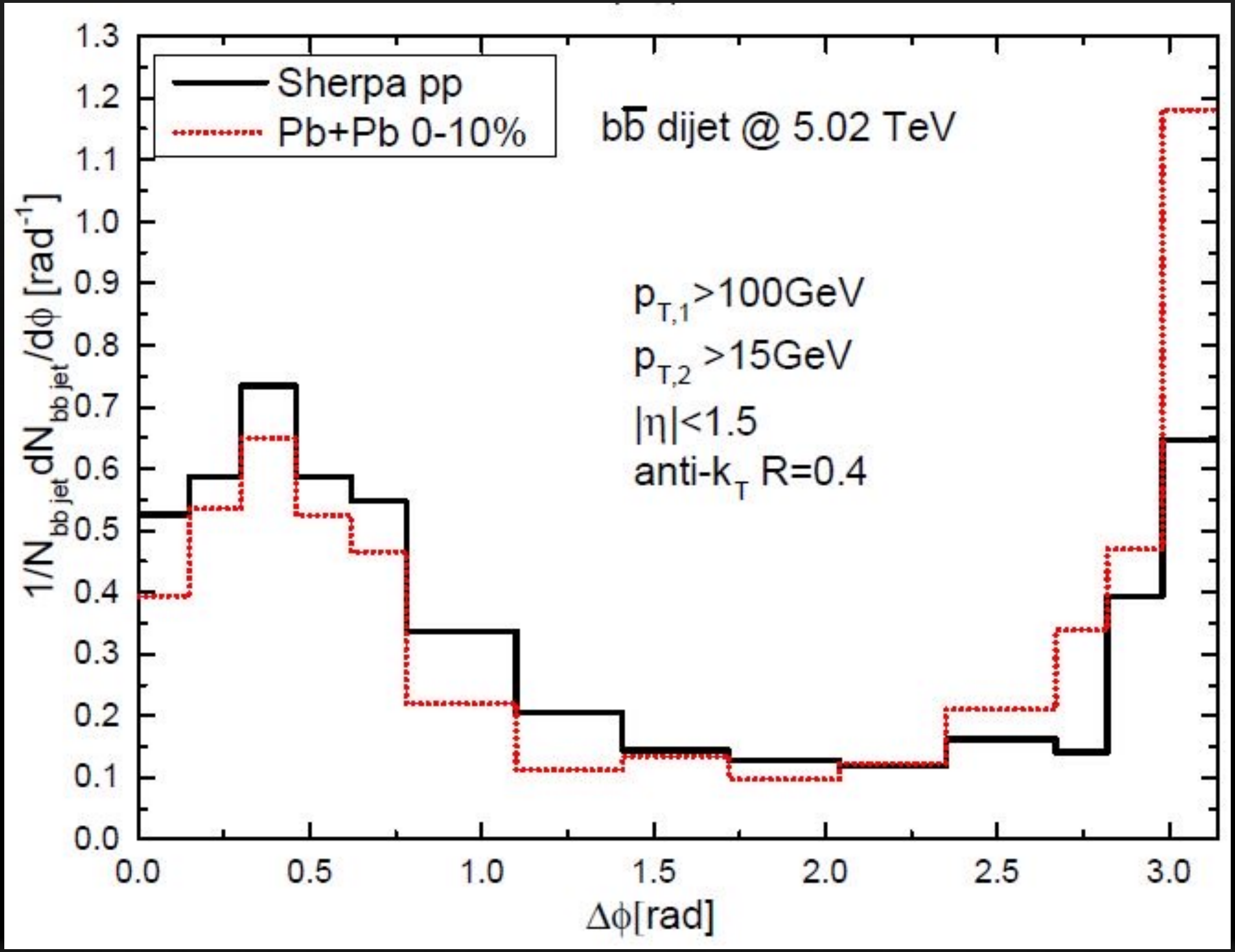
p_T imbalance of $b\bar{b}$ dijets

$$x_J = p_{\mathrm{T},2}/p_{\mathrm{T},1}$$



W Dai, S Wang, S Zhang, BWZ, E Wang, arXiv: 1806.06332, CPC (2020)

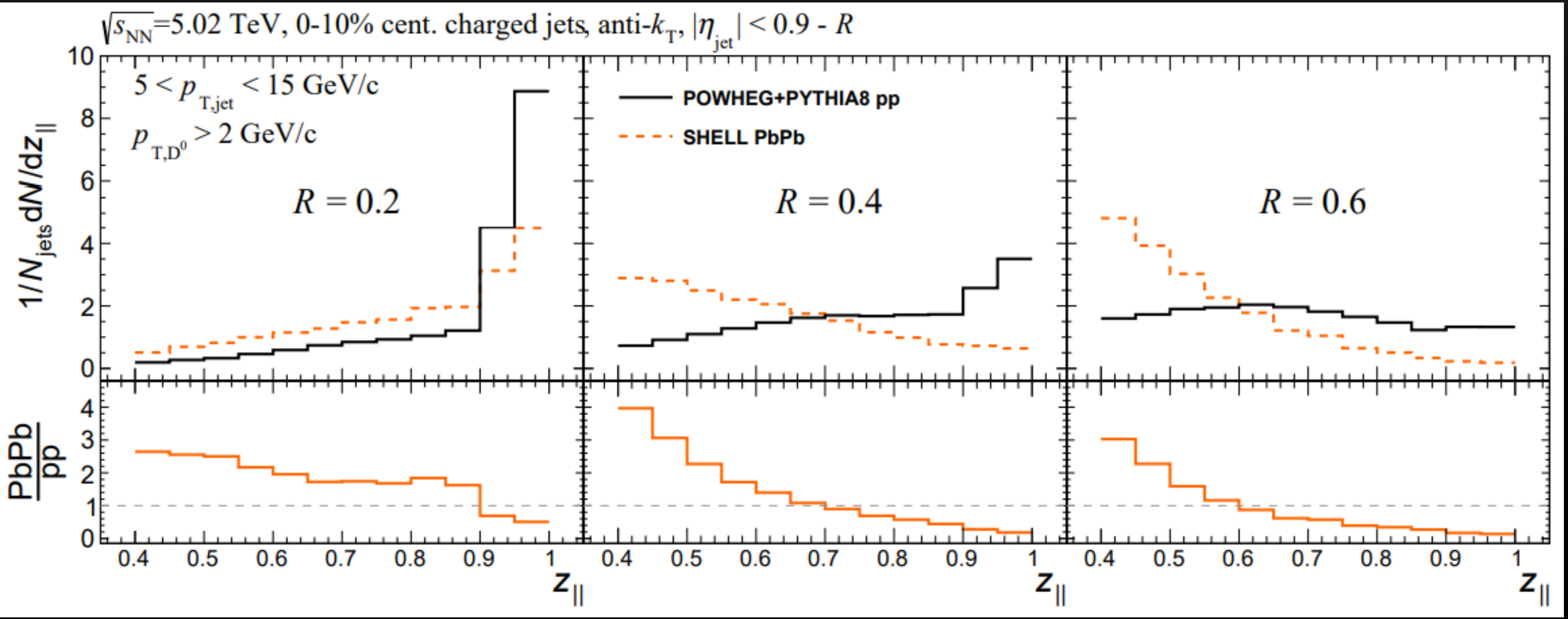
Angle correlation of double b-jet



W Dai, S Wang, BWZ, E Wang, arXiv: 1806.06332, CPC (2020)

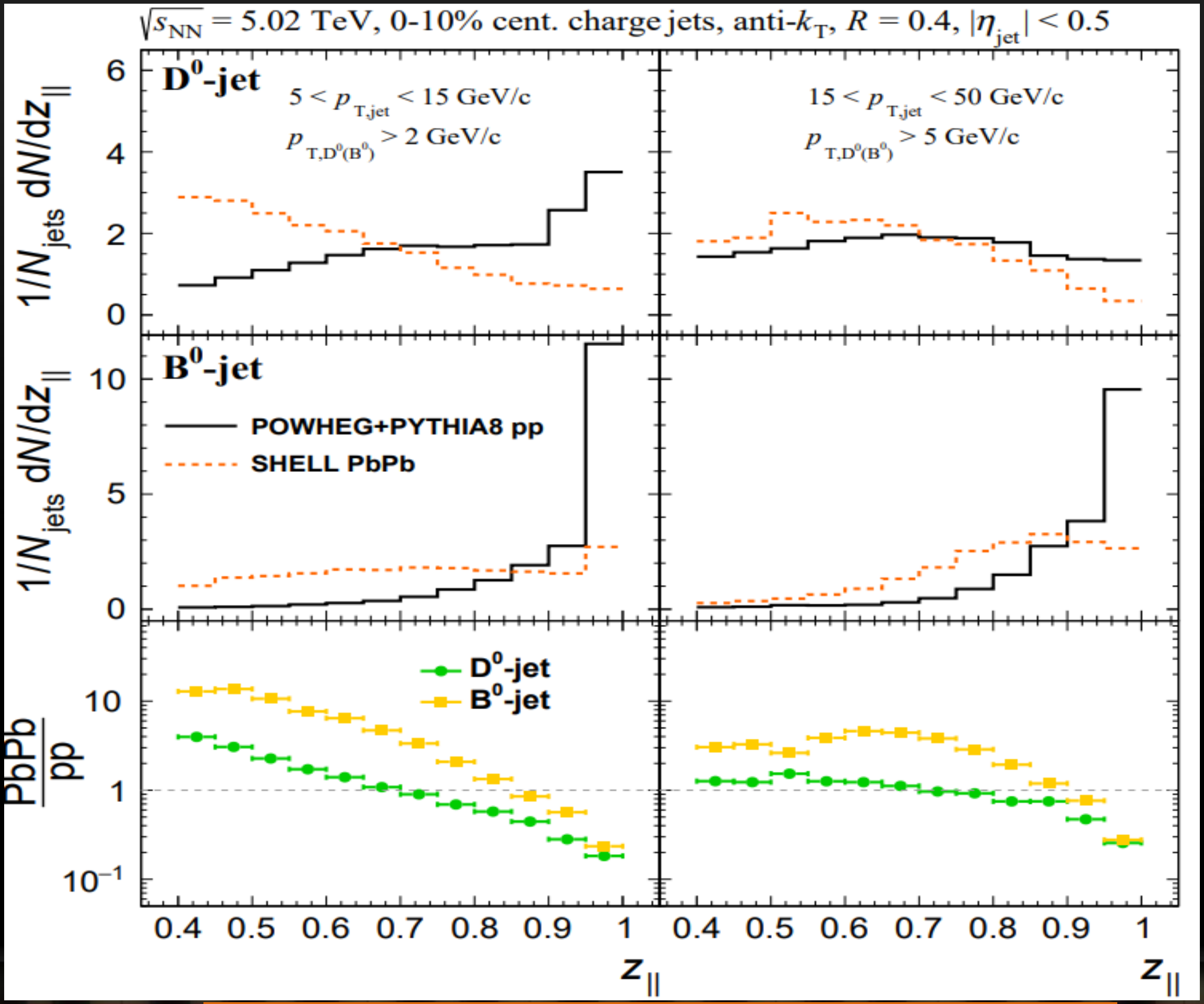
Fragmentation function of HF-jet

$$z_{||} = \frac{\vec{p}_{\rm jet} \cdot \vec{p}_{\rm D^0}}{\vec{p}_{\rm jet} \cdot \vec{p}_{\rm jet}} = \frac{\left|\vec{p}_{\rm D^0}\right|}{\left|\vec{p}_{\rm jet}\right|} \cos\theta$$



Y.Li, S.Wang BWZ, arXiv: 2209.00548

Fragmentation function of HF-jet



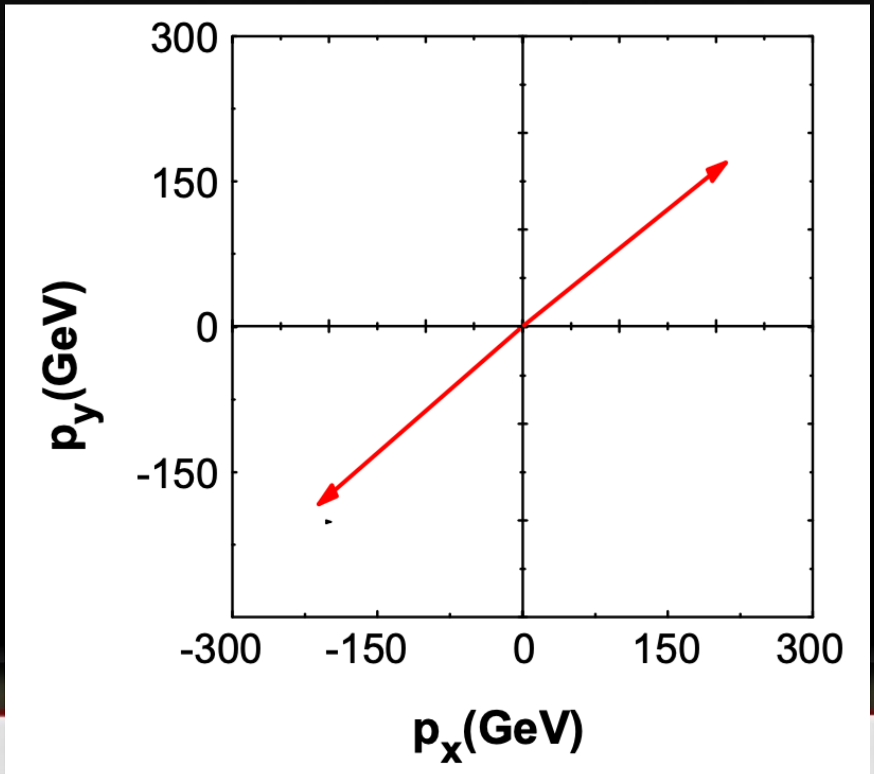
Y.Li, S.Wang BWZ, arXiv: 2209.00548

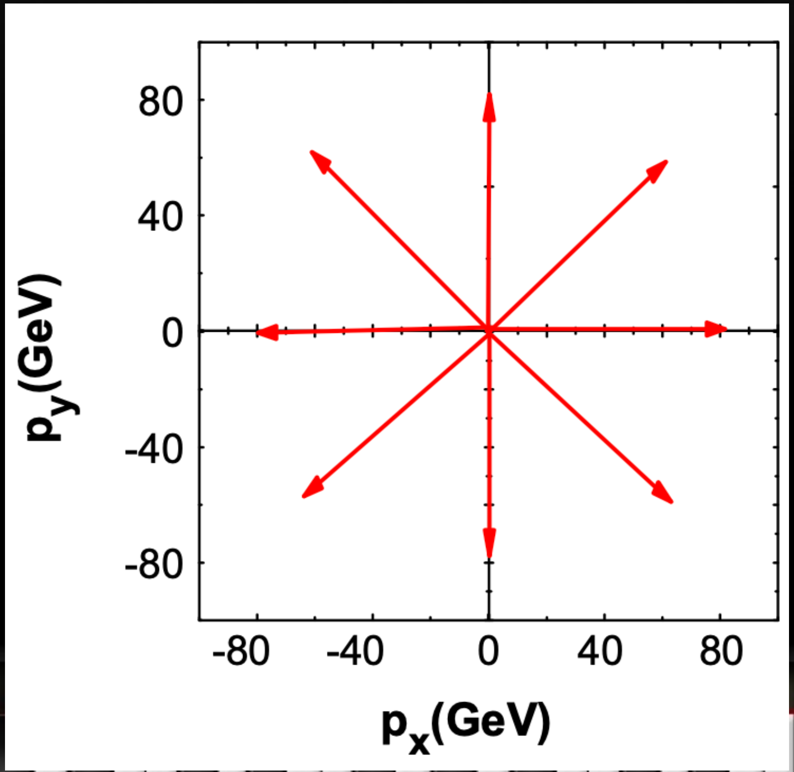
Event shape: sphericity

$$M = \sum_i \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} & p_{xi}p_{zi} \\ p_{yi}p_{xi} & p_{yi}^2 & p_{yi}p_{zi} \\ p_{zi}p_{xi} & p_{zi}p_{yi} & p_{zi}^2 \end{pmatrix}$$

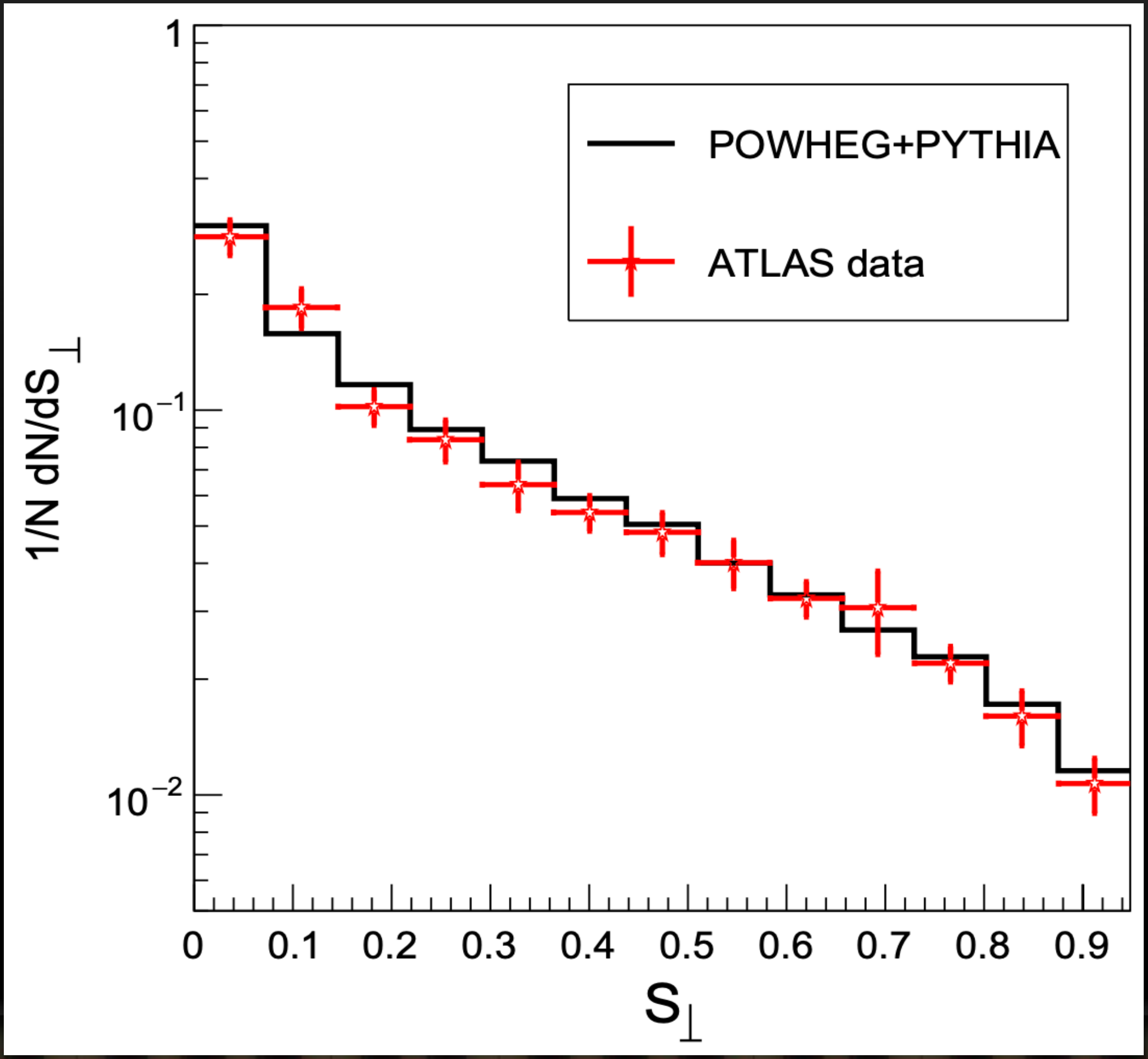
$$\lambda_1 > \lambda_2 > \lambda_3$$

$$S_\perp = \frac{2\lambda_2}{\lambda_1 + \lambda_2}$$

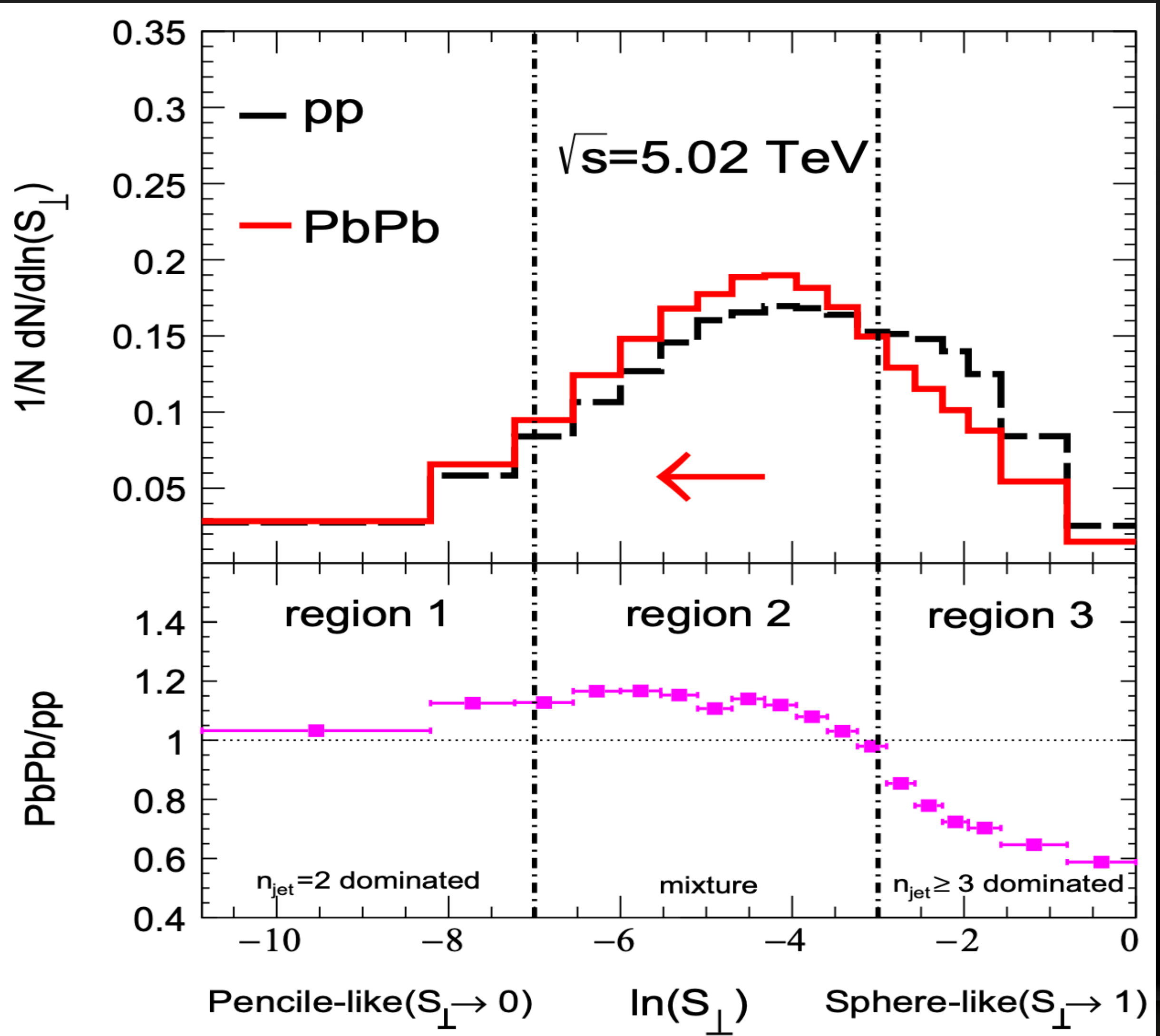




Sphericity in p+p



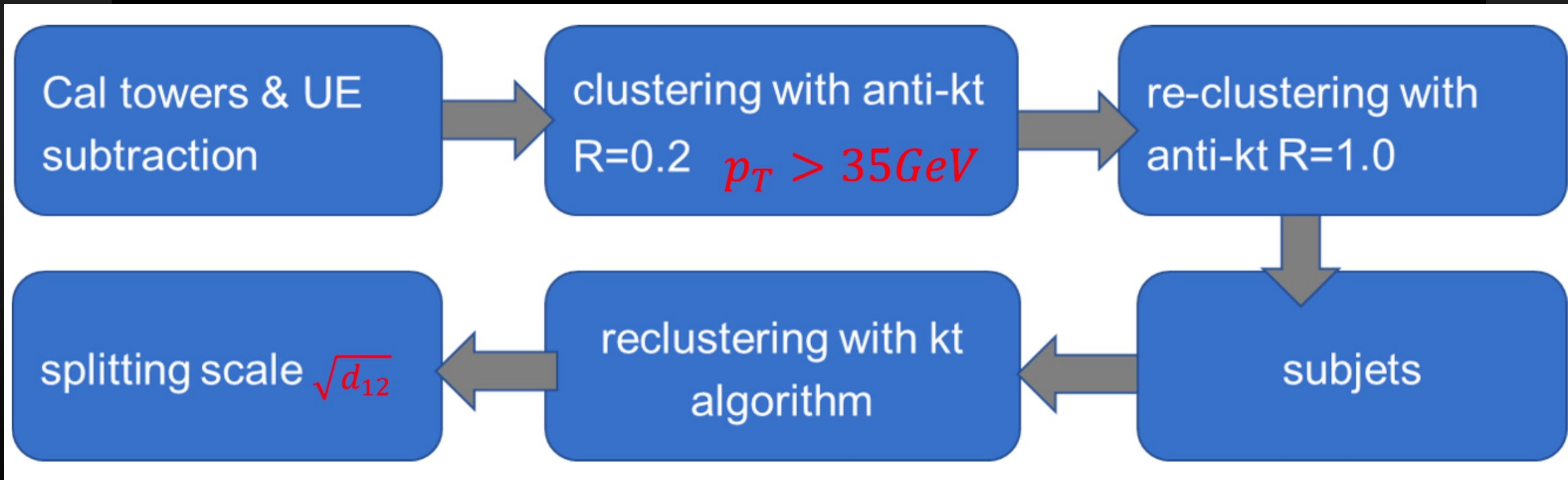
Sphericity in Pb+Pb

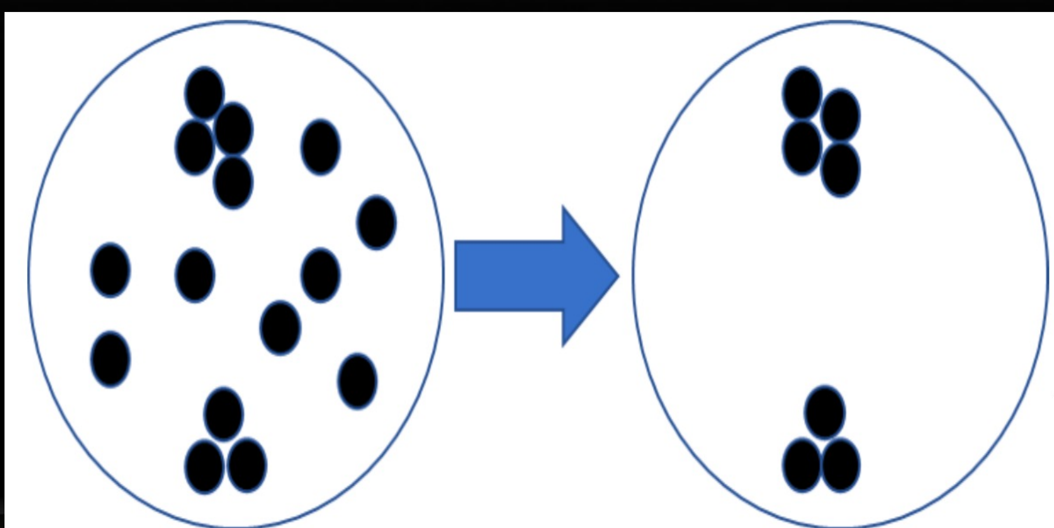


S Chen, W Dai, S Zhang, Q Zhang, BWZ, EPJC (2020)

Backup

Reclustered large radius jets





remove soft radiation

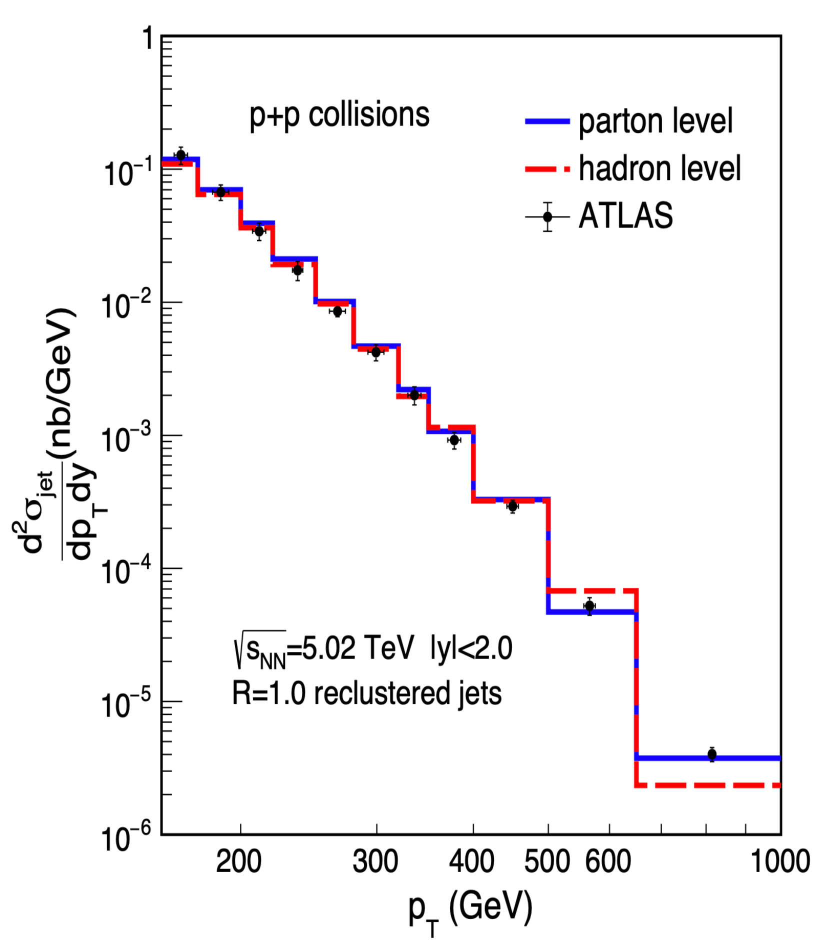
splitting scale

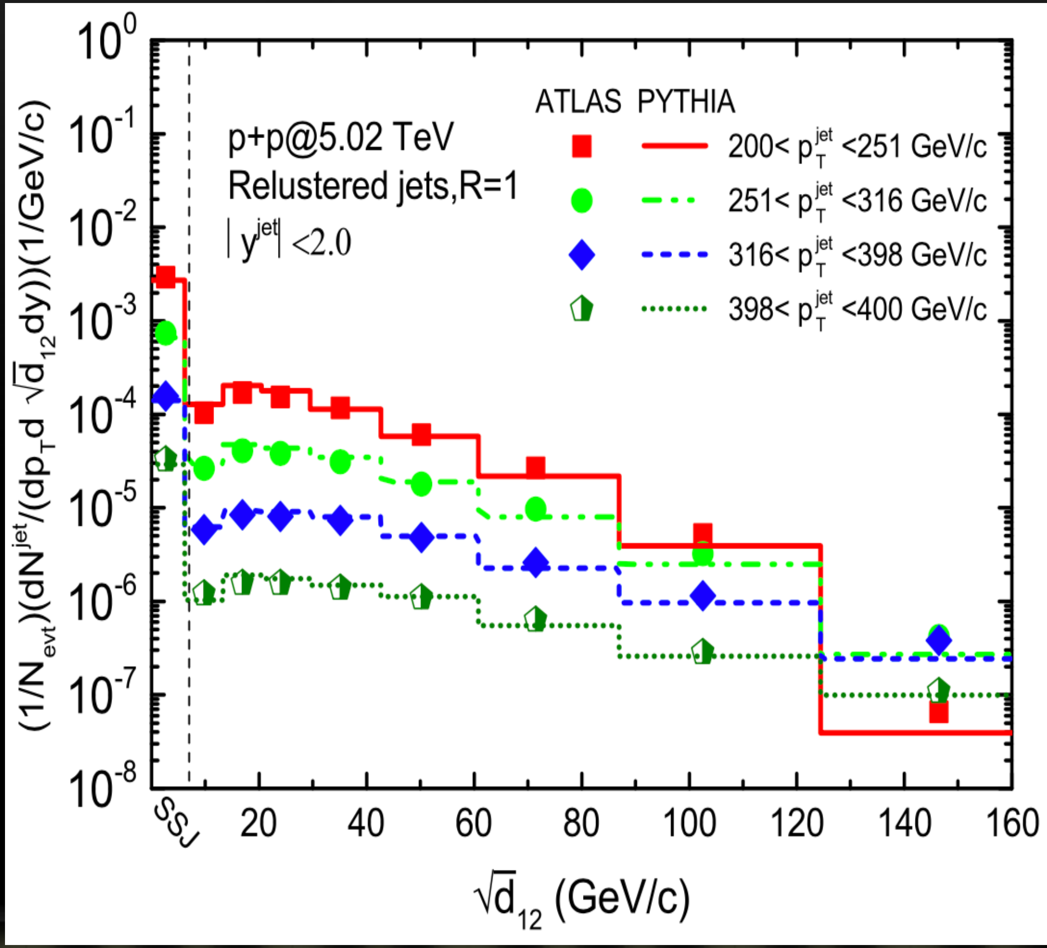
$$d_{12} = min(p_{T1}^2, p_{T2}^2) \cdot \Delta R_{12}^2 / R^2,$$

$$\Delta R_{12} = \sqrt{\Delta\phi_{12}^2 + \Delta y_{12}^2}$$

Reclustered LR jets in p+p

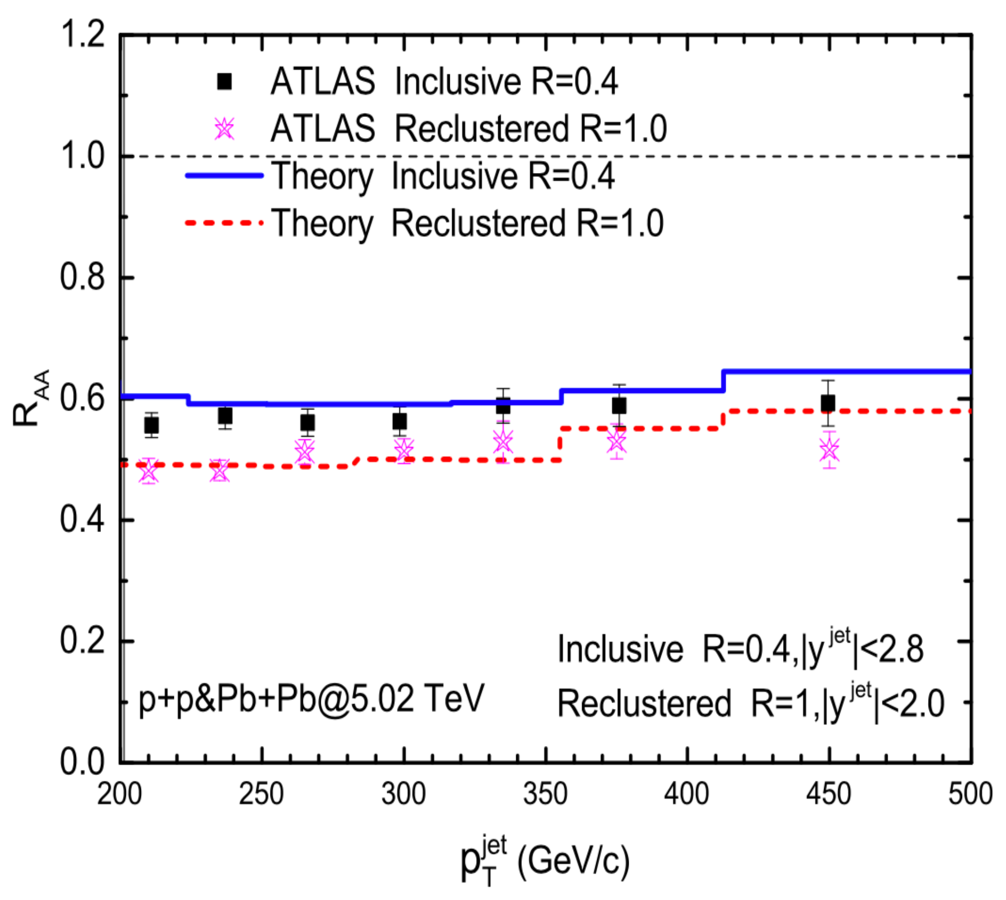
$$\sqrt{d_{12}} = \sqrt{min(p_{T,1}^2, p_{T,2}^2) * \Delta R_{12}^2}$$

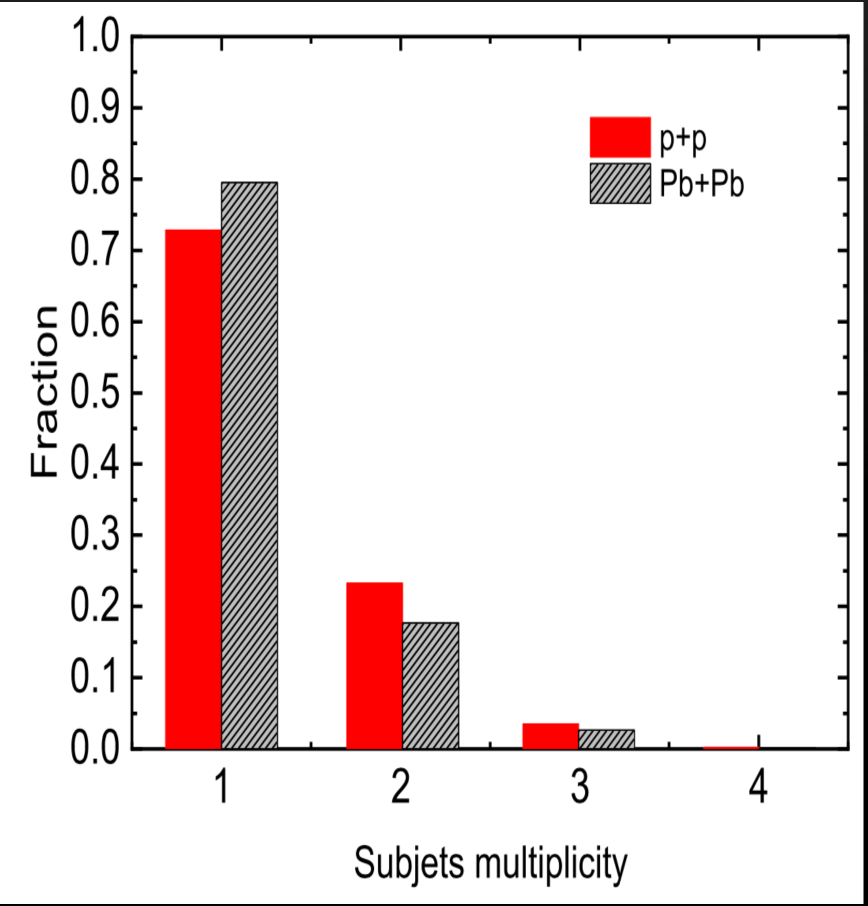




Nuclear modifications

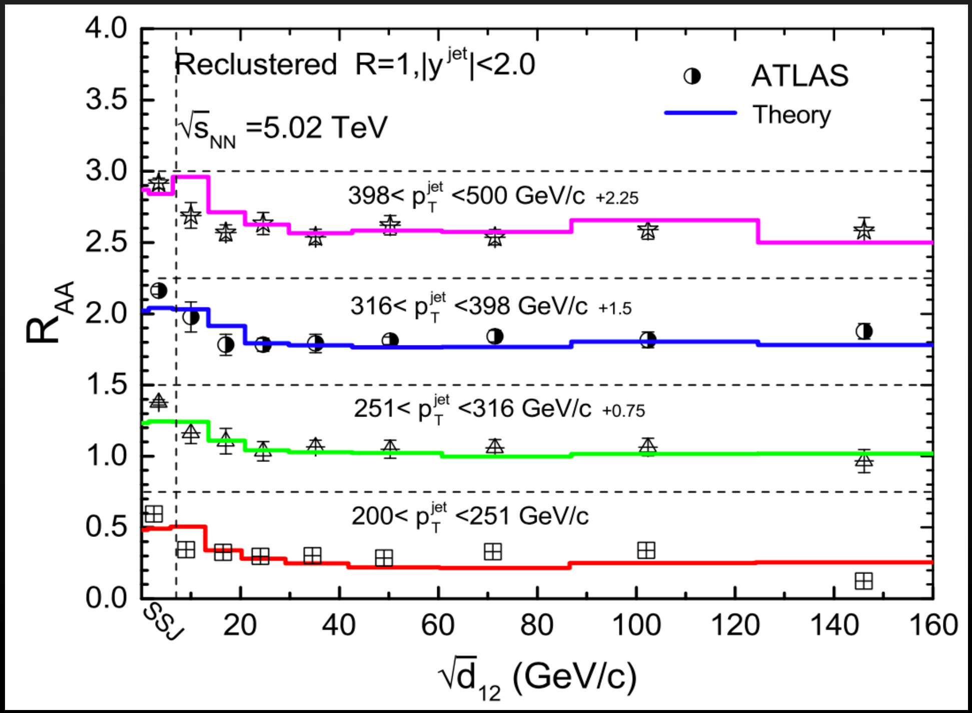
- Nuclear suppression of reclustered LR jets at R=1.0 is larger than that of inclusive jets with R=0.4.

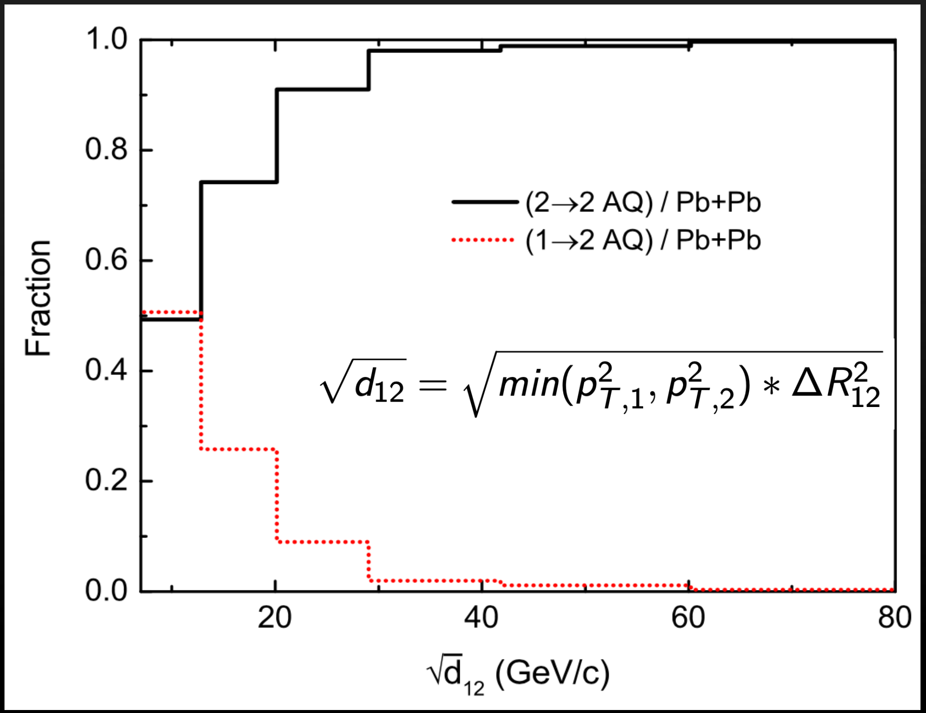


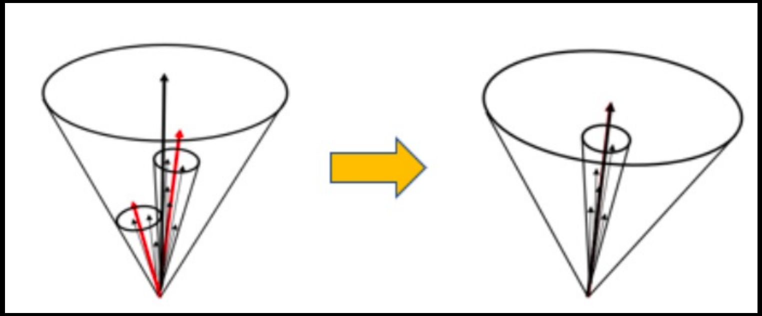


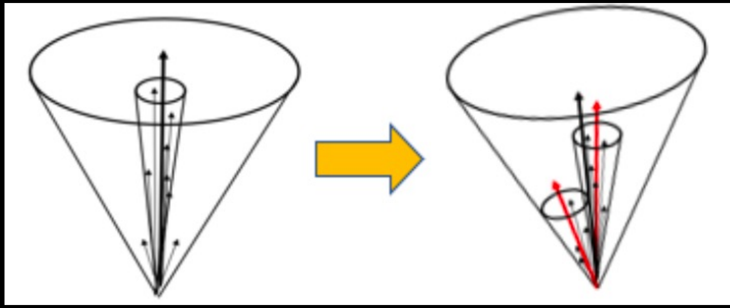
S L Zhang, M Q Yang, BWZ, EPJC (2022)

Energy loss of reclustered jets









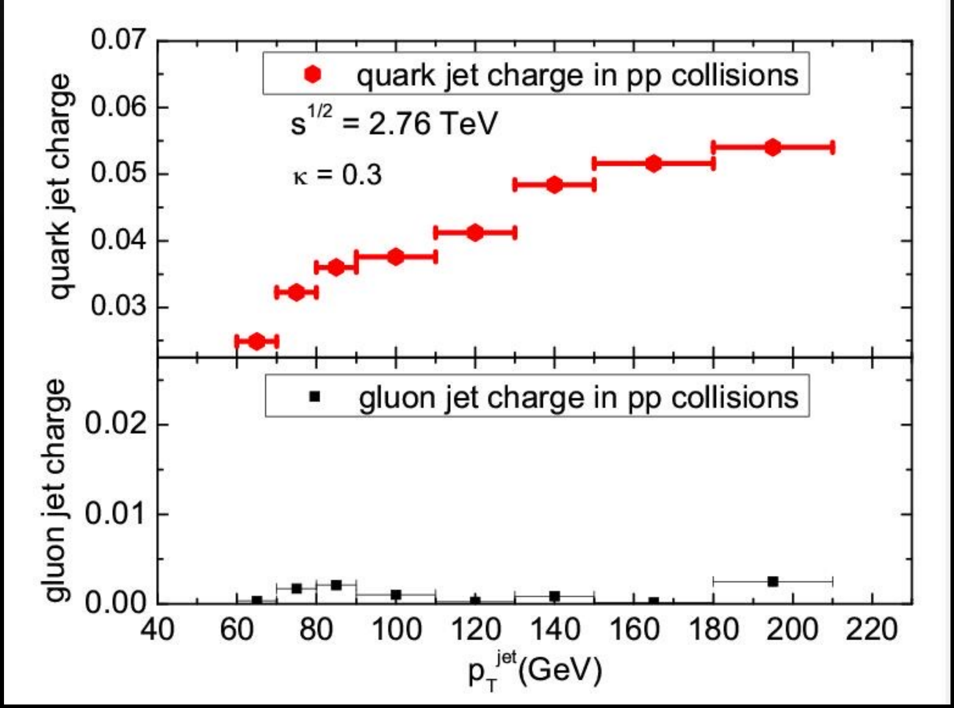
S L Zhang, M Q Yang, BWZ, EPJC (2022)

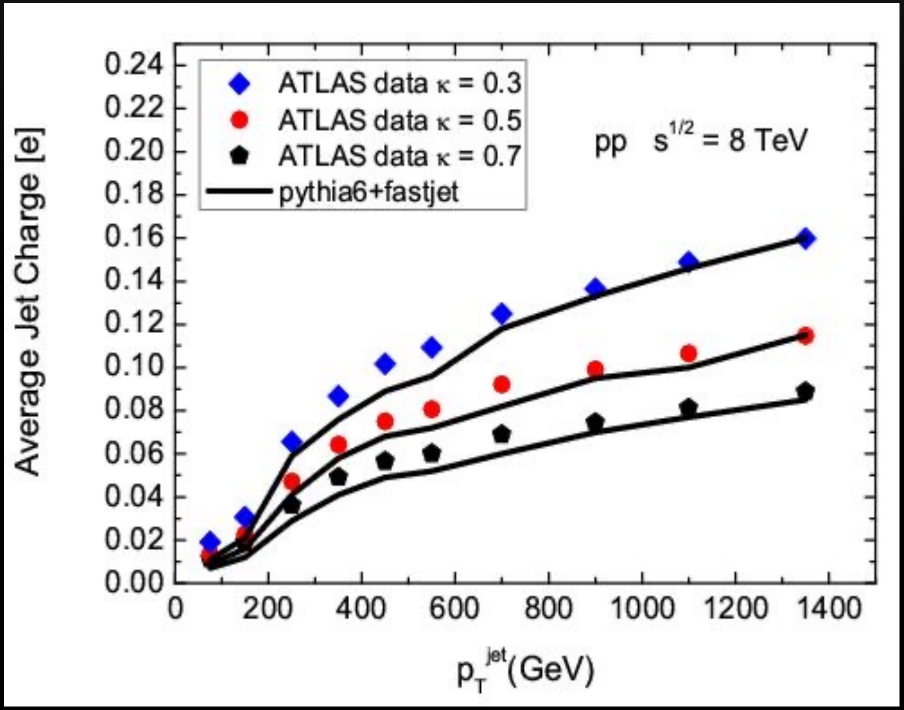
Jet charge in p+p

- Proposed by Feynman & Field (1978)
- Very useful to discriminate q/g

$$Q_\kappa^i = \sum_{h \in jet} z_h^\kappa Q_h$$

Krohn, Schwartz, T. Lin, Waalewijn, PRL (2013)



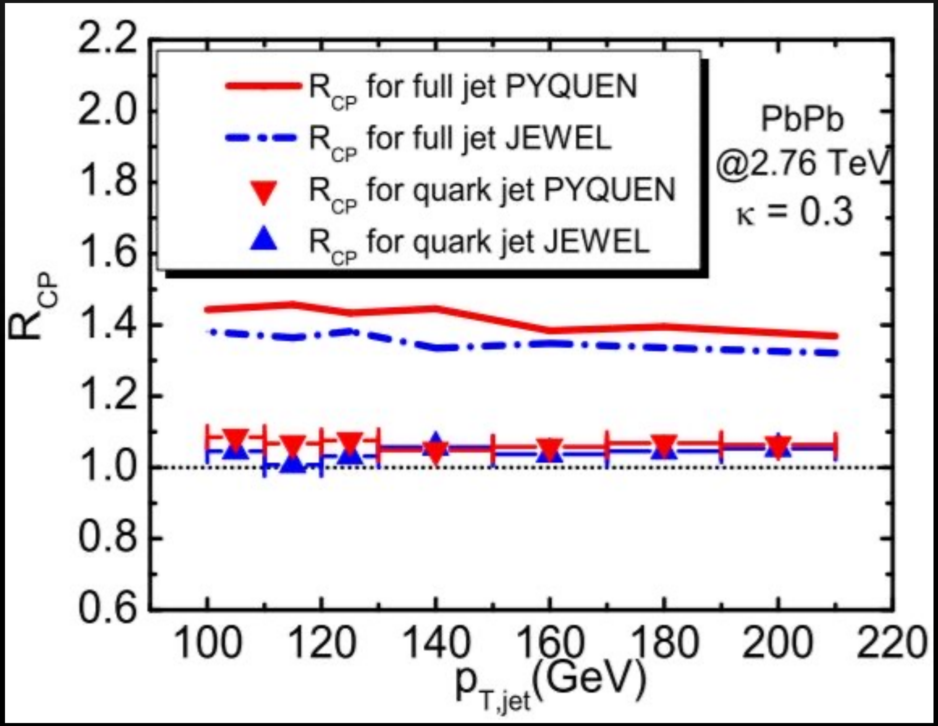


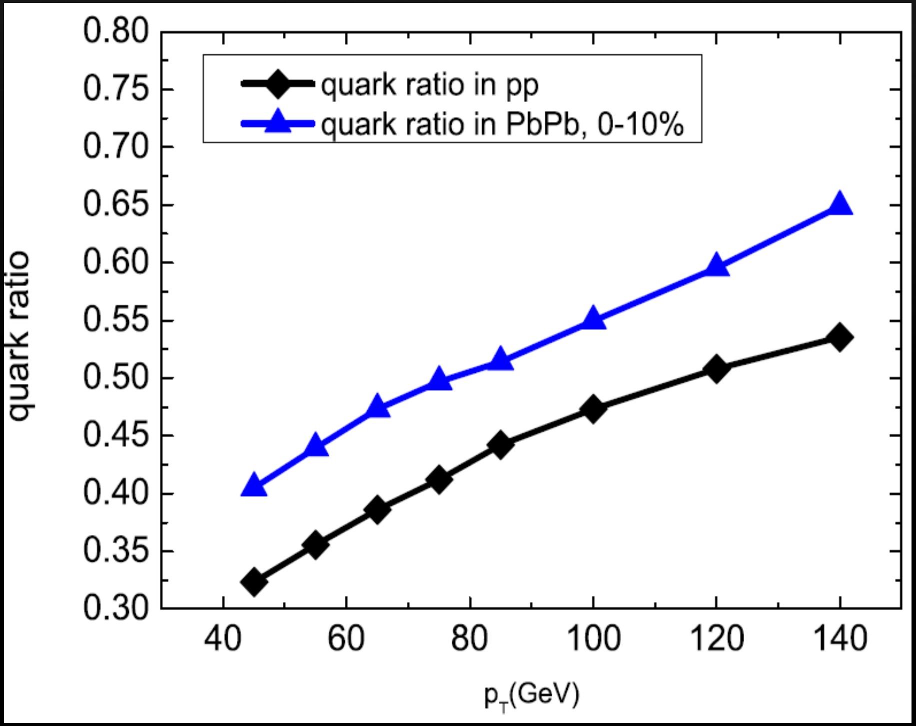
S-Y Chen, BWZ, E Wang, CPC (2020)

Jet charge in A+A

- Rcp of jet charge in A+A is larger than unity.
- Very useful to discriminate q/g

$$R_{CP} = \frac{\langle Q_j \rangle_{PbPb\_0-10\%}}{\langle Q_j \rangle_{PbPb\_60-80\%}}$$



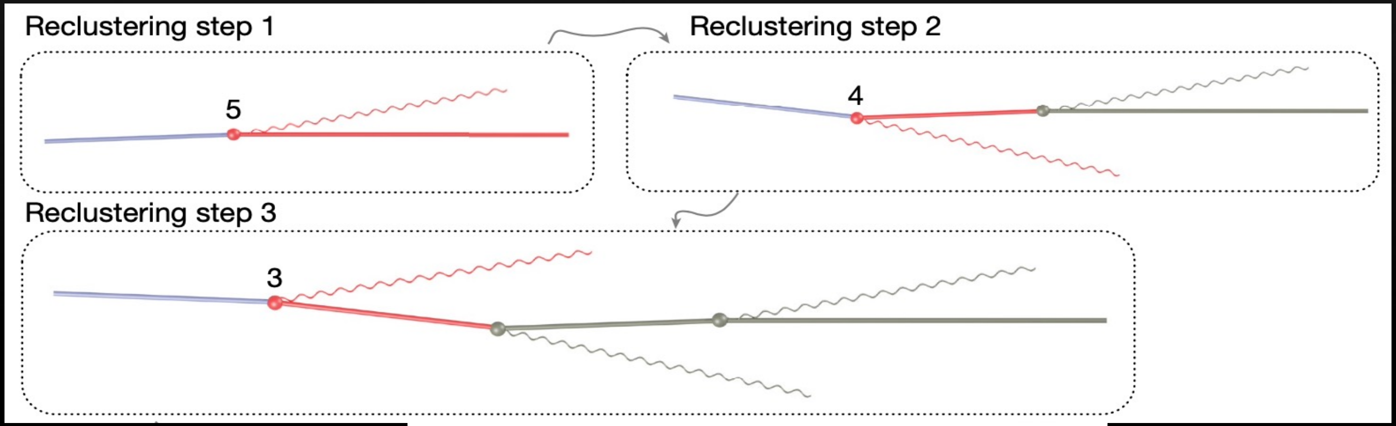


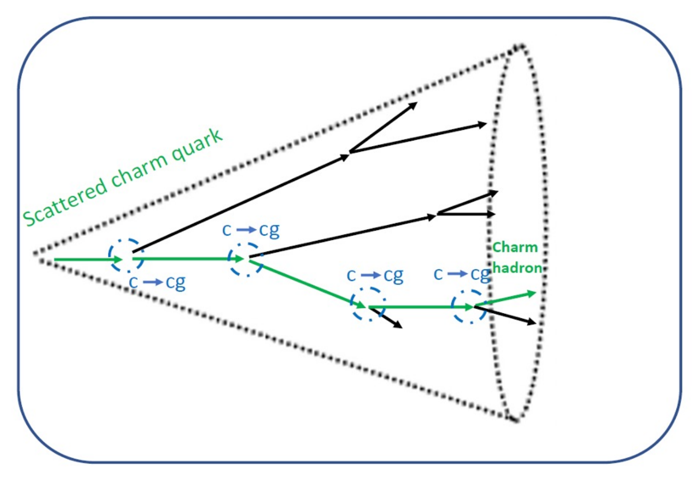
S-Y Chen, BWZ, E Wang, CPC(2020)

Dead-cone effect in vacuum

- A direct observation of dead-cone effect in p+p is made with an iterative declustering techniques by ALICE.

$$dP_{HQ} \simeq \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{k_\perp^2 dk_\perp^2}{(k_\perp^2+\omega^2\theta_0^2)^2} = dP_0\left(1+\frac{\theta_0^2}{\theta^2}\right)^2$$

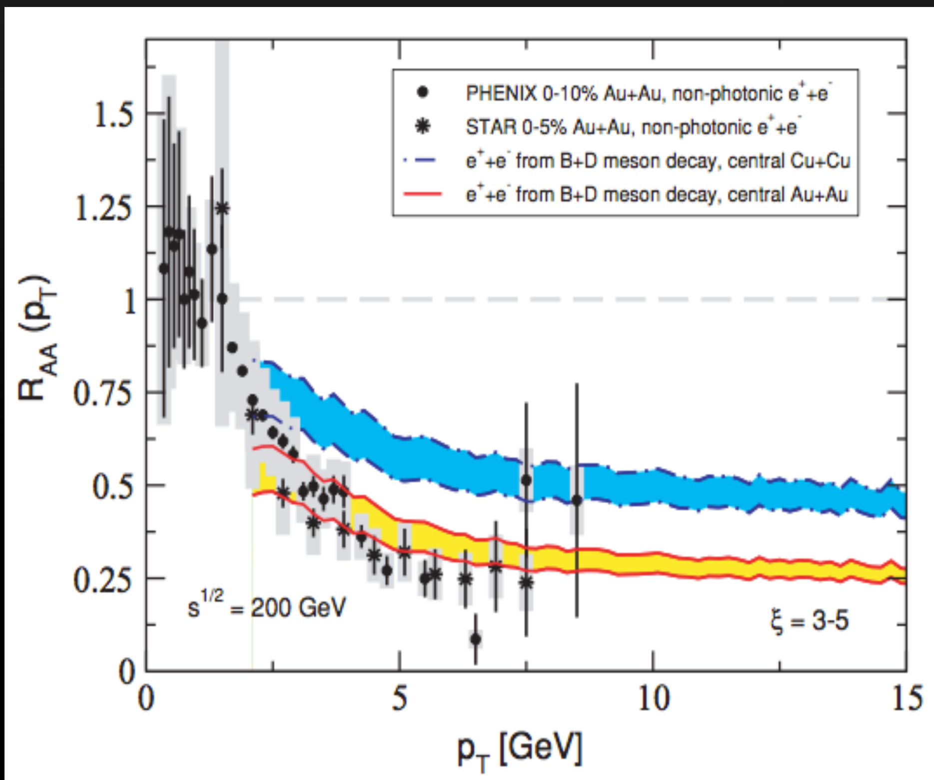


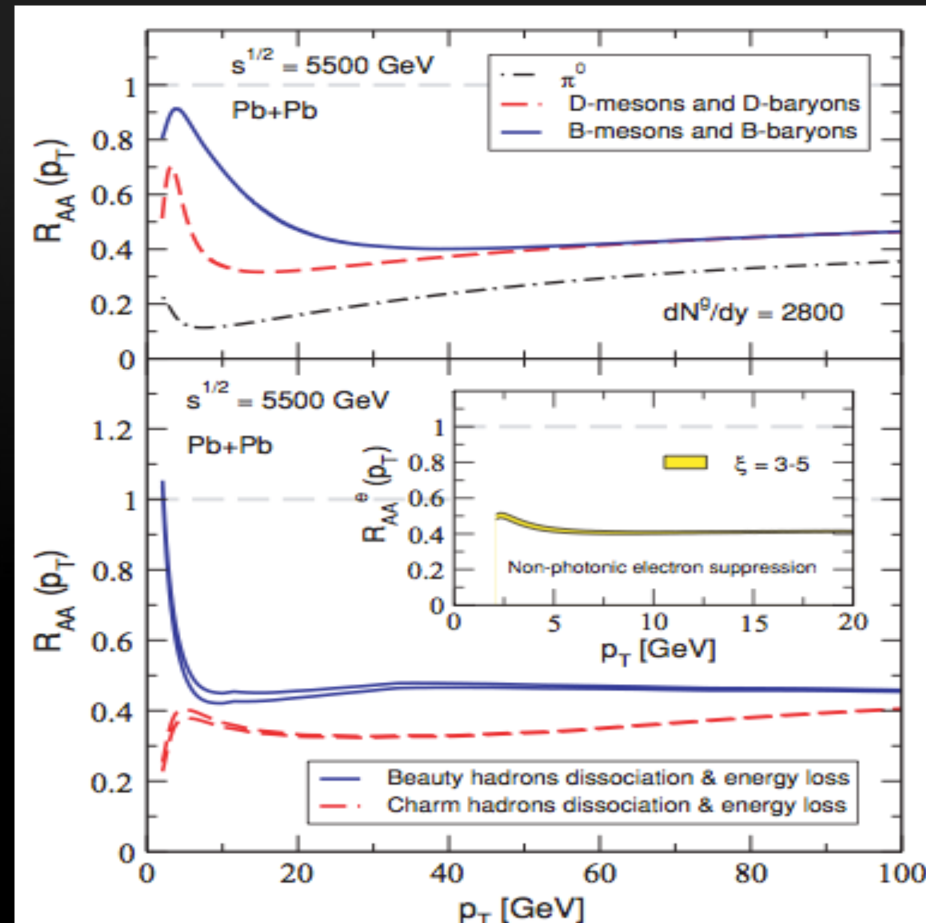


ALICE, Nature 605 (2022) 440

heavy meson dissociation

$$\tau_{\rm form} = \frac{1}{1+\beta_h} \frac{2z(1-z)p^+}{(k^\perp)^2 + (1-z)M_h^2 - z(1-z)M_Q^2}$$

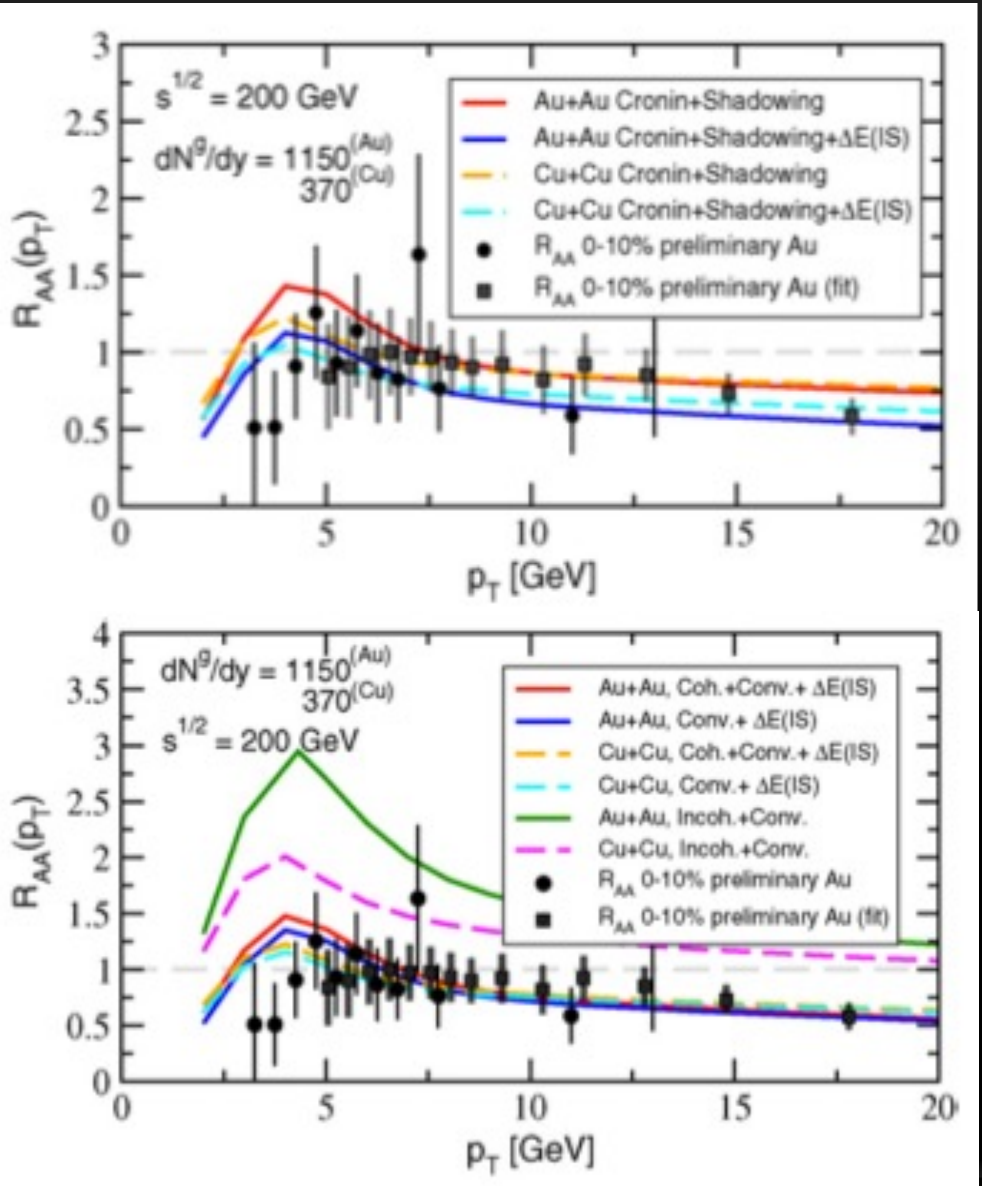




Sharma, Vitev, BWZ, PRC 80 (2009) 054902

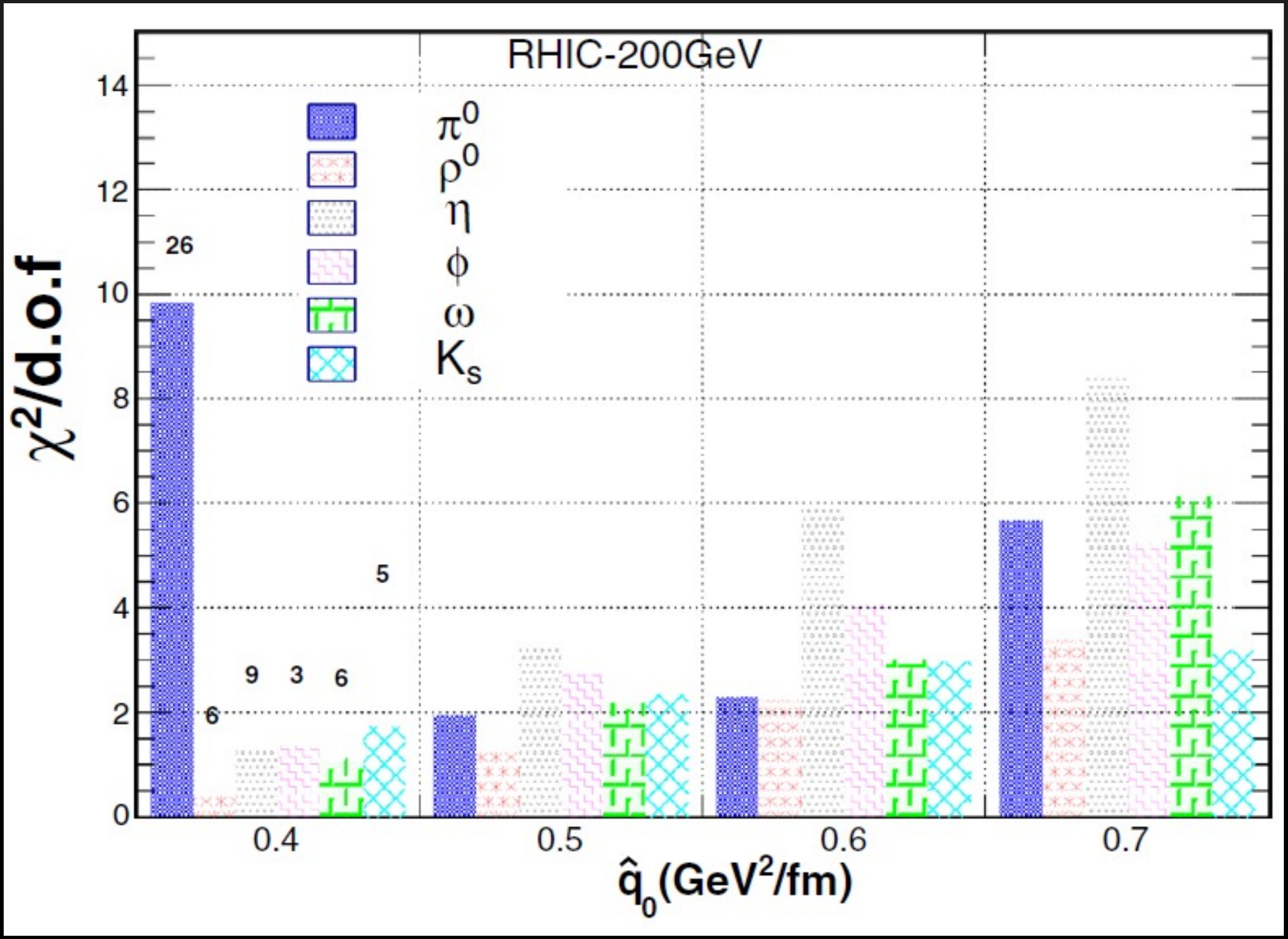
Direct photon in A+A collisions

- Incoherent photon emission is ruled out.
- Jet conversion contributes at $p_T < 5$ GeV, ~ 25%.
- Medium-induced photon is limited to ~ 10%.
- At high p_T region, total enhancement contribution is found to be ~5%.
- Reduction of fragment. photons contributes at large p_T .
- No large enhancement of direct photon production due to medium-induced photon emission and jet-photon conversion.



I Vitev, BWZ, PLB (2008).

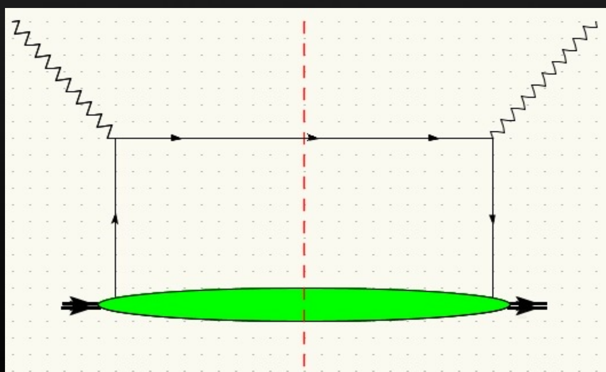
Global extraction of qhat



G Ma, W Dai, BWZ, E Wang, EPJC (2019)

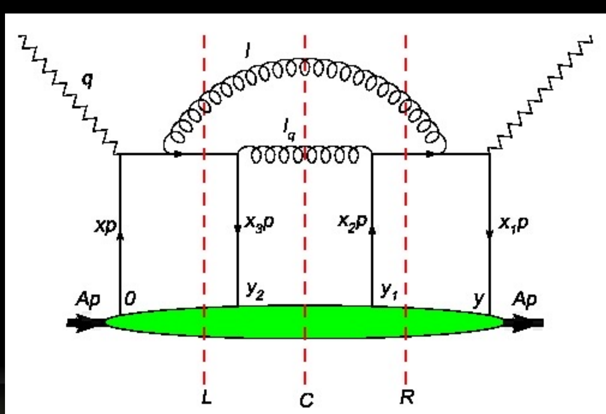
Q-Q single and double scattering

- Single Scattering: leading twist contribution



$$\propto f_q^A(x,\mu_I^2) \bigotimes H_{\mu\nu} \bigotimes D_{q\to h}(z_h,\mu^2)$$

- Double Scattering: twist-4 contribution

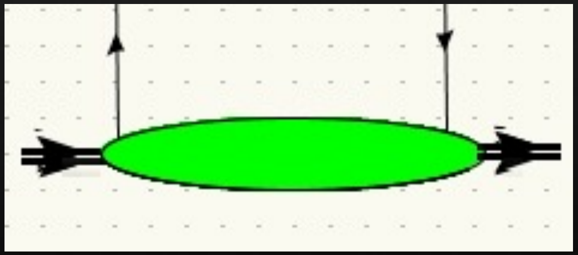


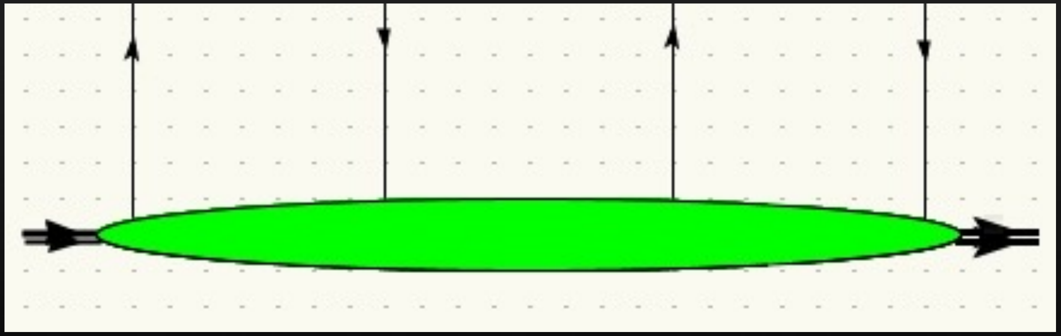
$$\propto T_{q\bar{q}}(x) \bigotimes H_{\mu\nu} \bigotimes C(z) \bigotimes D_{i\to h}(\frac{z_h}{z},\mu^2)$$

$$= f_q^A(x,\mu_I^2) \bigotimes H_{\mu\nu} \bigotimes \Delta D_{q\to h}(z_h,\mu^2)$$

$$\Delta\, D_{q\to h}(z_h,\mu^2) \equiv C(z) \bigotimes D_{i\to h}(\frac{z_h}{z}) \bigotimes \frac{T_{q\bar{q}}(x)}{f_q^A(x,\mu_I^2)}$$

quark-quark correlation function





$$f_q^A(x)$$

$$T_{q\bar{q}}^A \propto \frac{1}{x_A} f_q^A(x_1)\, f_{\bar{q}}^N(x_2)$$

$$\Delta D_{q\to h}(z_h, \mu^2) \propto \frac{T_{q\bar{q}}(x)}{f_q^A(x, \mu_I^2)} \propto f_{\bar{q}}^N(x_2)$$

$$\Delta D_{\bar{q}\to h}(z_h, \mu^2) \propto \frac{T_{\bar{q}q}(x)}{f_{\bar{q}}^A(x, \mu_I^2)} \propto f_q^N(x_2)$$