Ivan Vitev

Hard probes in heavy ion collisions: current status and prospects for application of QCD evolution techniques

QCD Evolution Workshop, Santa Fe, NM 2014

Outline of the talk

- Motivation for studying hard probes in heavy ion collisions at RHIC and the LHC
- The physics of inclusive particle quenching. Interpretation of the RHIC and LHC results
- Directions for improvement in leading particle phenomenology in A+A at RHIC and the LHC
- From leading particles to jets. New LHC discoveries
- Resummation and possible directions for improvement in jet substructure phenomenology in heavy ion reactions

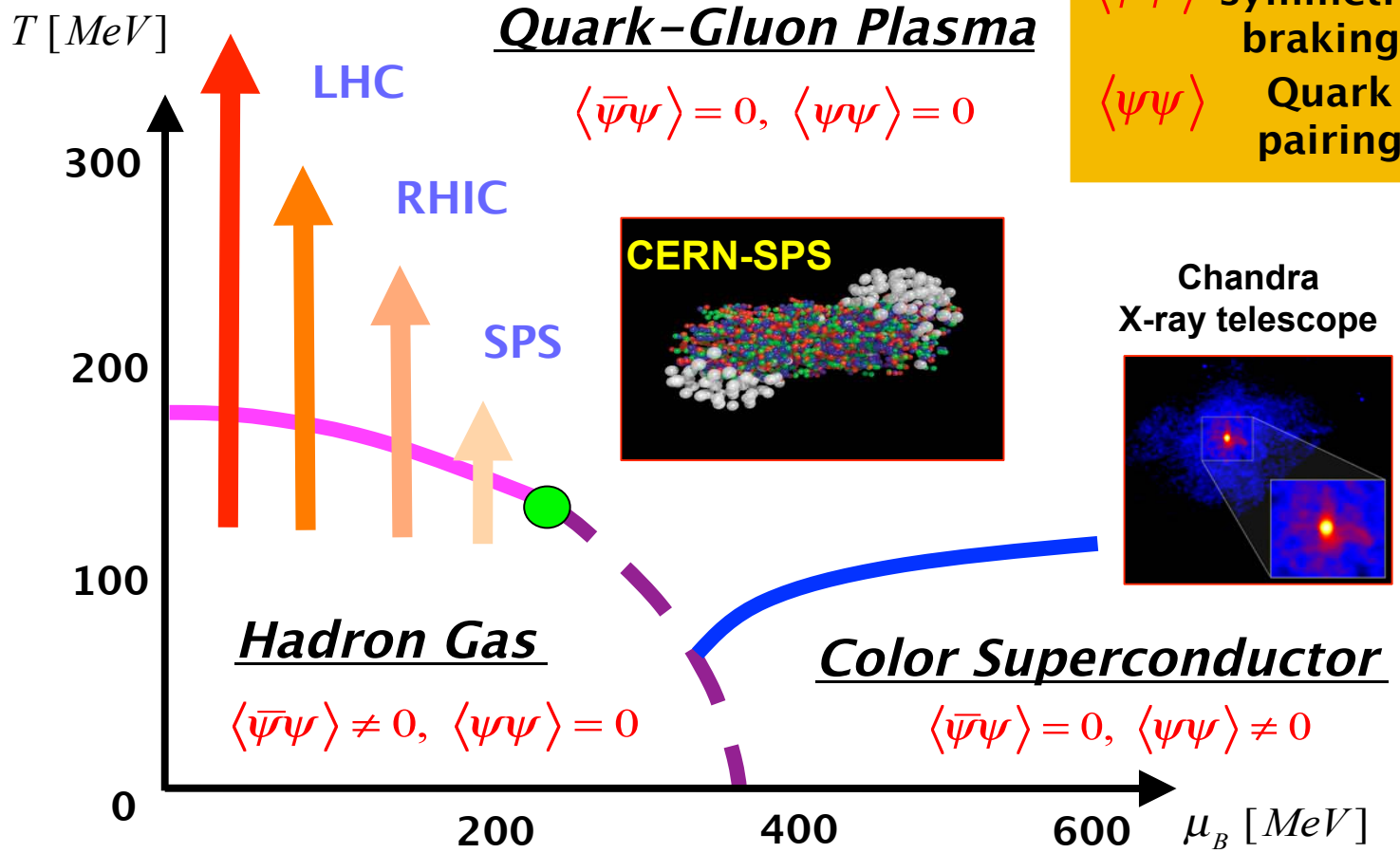
The phase diagram of QCD

Big Bang

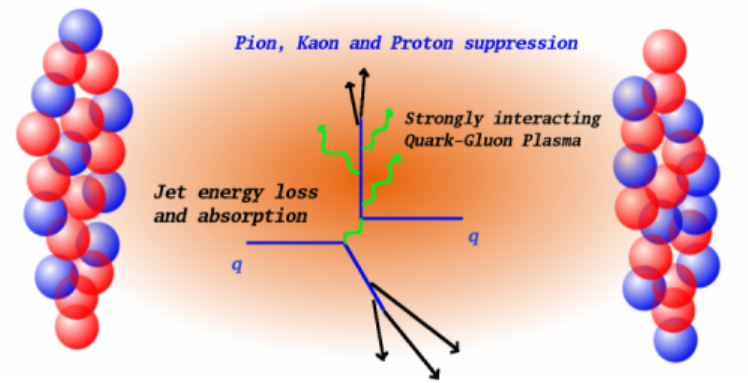
M. Stephanov et al. (2009)

$\langle \bar{\psi}\psi \rangle$ Chiral symmetry braking

$\langle \psi\psi \rangle$ Quark pairing

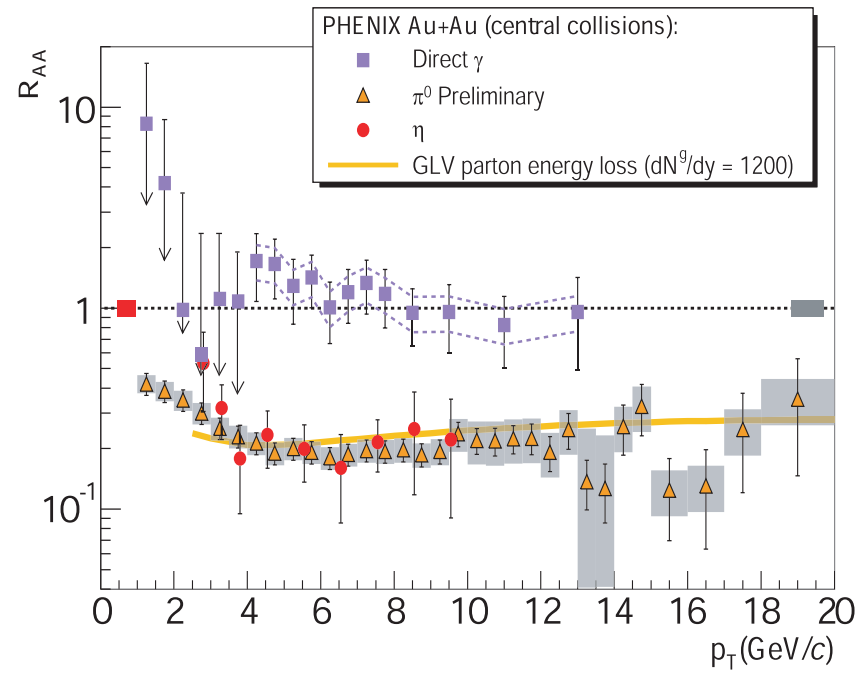


Jet quenching: RHIC



M. Gyulassy. et al (1992)

$$R_{AA}(I_{AA}\ldots) = \frac{\text{Yield}_{AA}/\langle N_{binary}\rangle_{AA}}{\text{Yield}_{pp}} = \frac{1}{\langle N_{binary}\rangle_{AuAu}} \frac{d\sigma_{AuAu}/dp_T dy}{d\sigma_{pp}/dp_T dy}$$



Jet quenching in A+A collisions has been regarded as one of the most important discoveries at RHIC

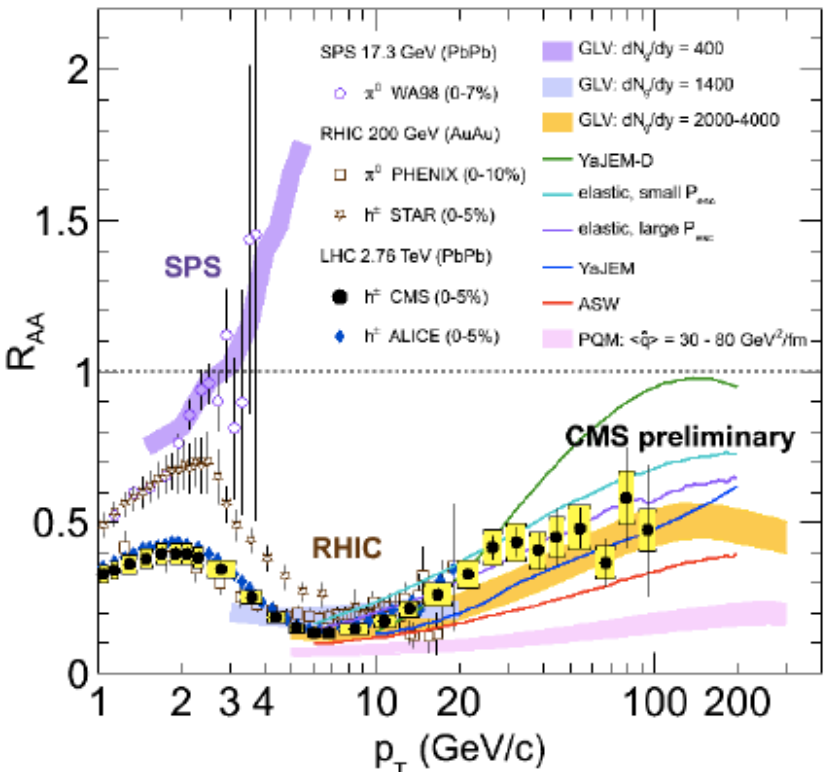
- Tested against alternative suggestions: CGC and hadronic transport models ✓
- Phenomenologically very successful ✓

Adler, S. et al (2003)

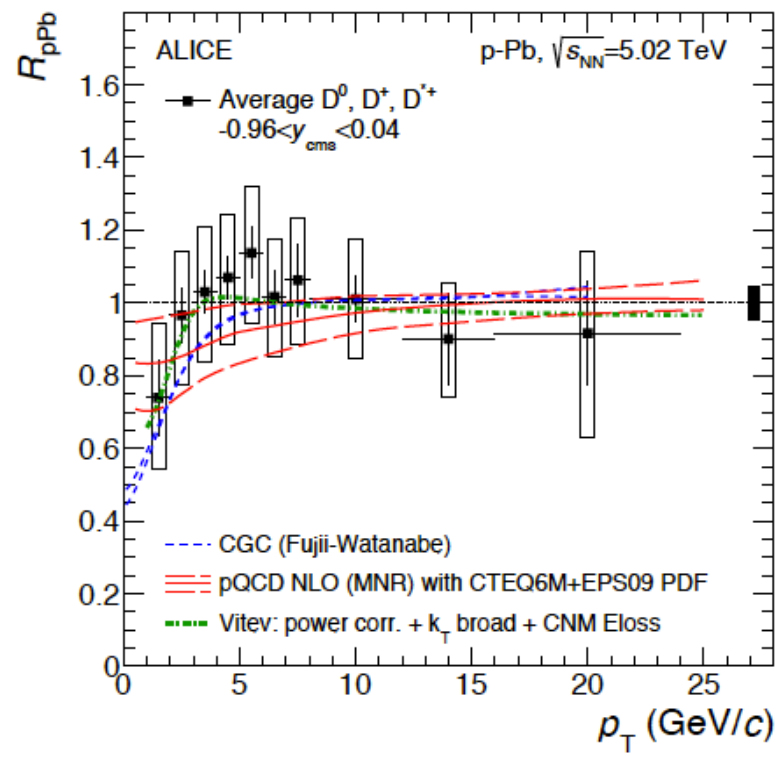
Adams, J. et al. (2003)

Experimental observations: LHC

The suppression of inclusive particle production in A+A is exclusively driven by final-state interactions. It is quite remarkable how small CNM effects are



Chatrachyan, S. et al (2012)

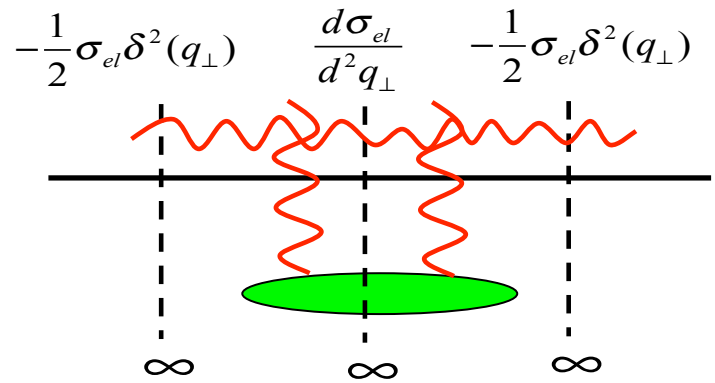


Abelev, B. et al. (2014)

An operator approach to multiple scattering in QCD

- A general approach

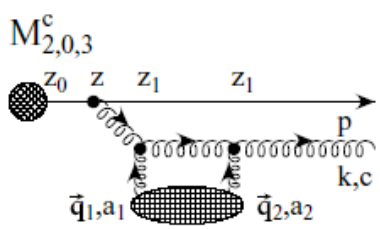
- Can be applied to various collinear parton systems: 1 parton broadening, 2 partons [3],[8] medium induced splitting, meson dissociation [1]



M. Gyulassy et al., (2001)

$$k^+\frac{dN_g^n}{dk^+d^2k_\perp} \propto Tr\sum_{i_1\ldots i_n}\bar{A}^{i_1\ldots i_n}A_{i_1\ldots i_n} = \bar{A}^{i_1\ldots i_{n-1}}\left(D^\dagger D + V^\dagger + V\right)A_{i_1\ldots i_{n-1}} = \bar{A}^{i_1\ldots i_{n-1}}\hat{R}\ A_{i_1\ldots i_{n-1}}$$

An operator that evolves suitably chosen initial conditions, discrete steps. Encodes the pole, phase and color structure



$$M^c_{2,0,3} \approx J(p)e^{ipx_0}(-i)\int\frac{d^2\mathbf{q}_1}{(2\pi)^2}v(0,\mathbf{q}_1)\,e^{-i\mathbf{q}_1\cdot\mathbf{b}_1}(-i)\int\frac{d^2\mathbf{q}_2}{(2\pi)^2}v(0,\mathbf{q}_2)\,e^{-i\mathbf{q}_2\cdot\mathbf{b}_2}\ \times$$
$$\times\ \frac{1}{2}\,(2ig_s)\,\frac{\epsilon\cdot(\mathbf{k}-\mathbf{q}_1-\mathbf{q}_2)}{(\mathbf{k}-\mathbf{q}_1-\mathbf{q}_2)^2}\,e^{i\omega_0 z_1}\left(1-e^{-i\omega_{(12)}(z_1-z_0)}\right)\ [[c,a_2],a_1](T_{a_2}T_{a_1})$$

Final-state radiative spectrum

- In the soft gluon emission limit

Number of scatterings **Momentum transfers**

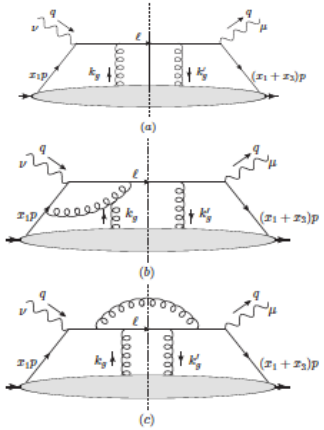
$$k^+\frac{dN_g}{dk^+d^2k_\perp}=\sum_{n=1}^{\infty}k^+\frac{dN^n{}_g}{dk^+d^2k_\perp}=\sum_{n=1}^{\infty}\frac{C_R\alpha_s}{\pi^2}\left[\prod_{i=1}^{n}\int_0^{L-\sum_{j=i+1}^{n}\Delta z_j}\frac{d\Delta z_i}{\lambda_g(z_i)}\int d^2q_i\left(\frac{1}{\sigma_{el}}\frac{d\sigma_{el}}{d^2q_i}-\delta^2(q_i)\right)\right]$$

$$\times\left[-2C_{(1\ldots n)}\cdot\sum_{m=1}^{n}B_{(m+1\ldots n)(m\ldots n)}\left(\cos\left(\sum_{k=2}^{m}\omega_{(k\ldots n)}\Delta z_k\right)-\cos\left(\sum_{k=1}^{m}\omega_{(k\ldots n)}\Delta z_k\right)\right)\right]$$

Color current propagators

Coherence phases (LPM effect)

- One can make a continuous approximation assuming that medium is infinite (BDMPS)
- In SIDIS one can replace the scattering lengths and momentum transfers with twist 4 quark-gluon correlation function. NLO calculation for the k_T-weighted cross section, evolution of the correlation function



See talk by H. Xing

Non-abelian energy loss

$$\Delta E^{(1)} \approx \frac{C_R \alpha_s}{4} \frac{\mu^2 L^2}{\lambda_g} \mathrm{Log} \frac{2E}{\mu^2(L) L} + \ldots ,$$

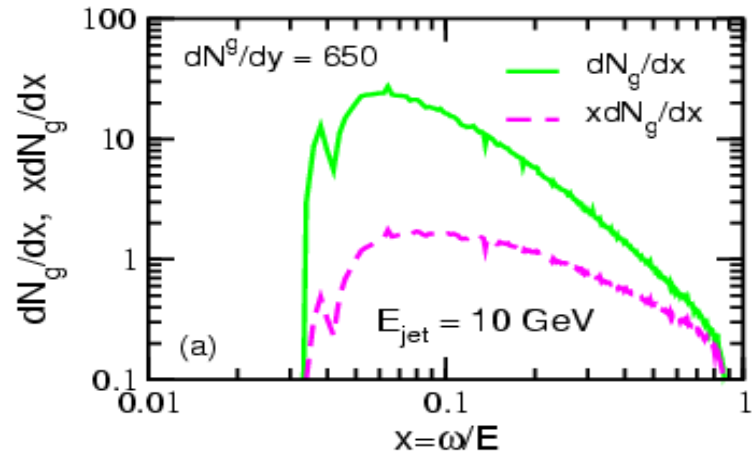
– Static medium

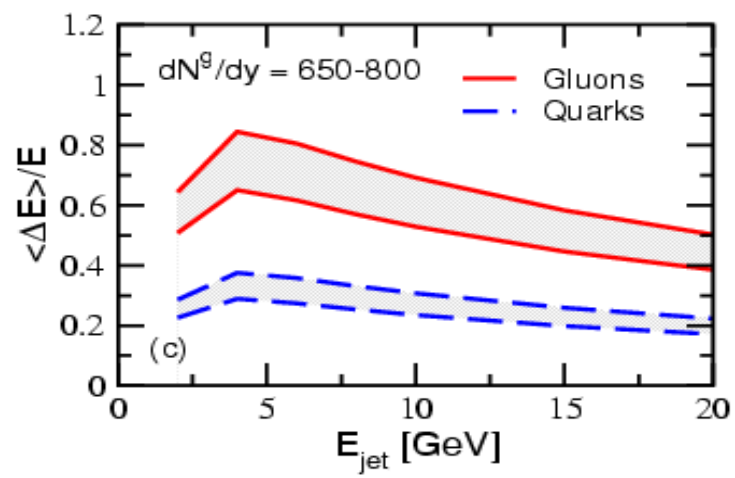
$$\Delta E^{(1)} \approx \frac{9\pi C_R \alpha_s^3}{4} L \frac{1}{A_\perp} \frac{dN^g}{dy} \mathrm{Log} \frac{2E}{\mu^2(L) L} + \ldots ,$$

– 1+1D Bjorken

μ^2 / λ - transport coefficient

dN^g / dy - effective gluon rapidity density

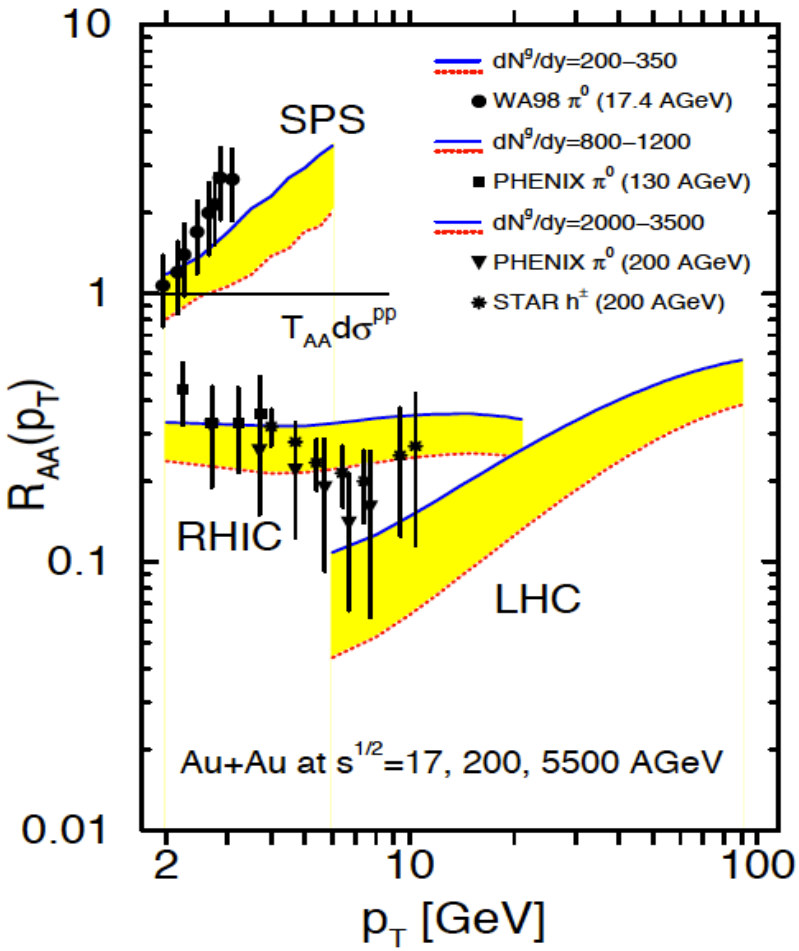




- Difference between static and an expanding medium: SIDIS and A+A

- Numerical example relevant to the 62 GeV run at RHIC

Understanding of inclusive particle suppression

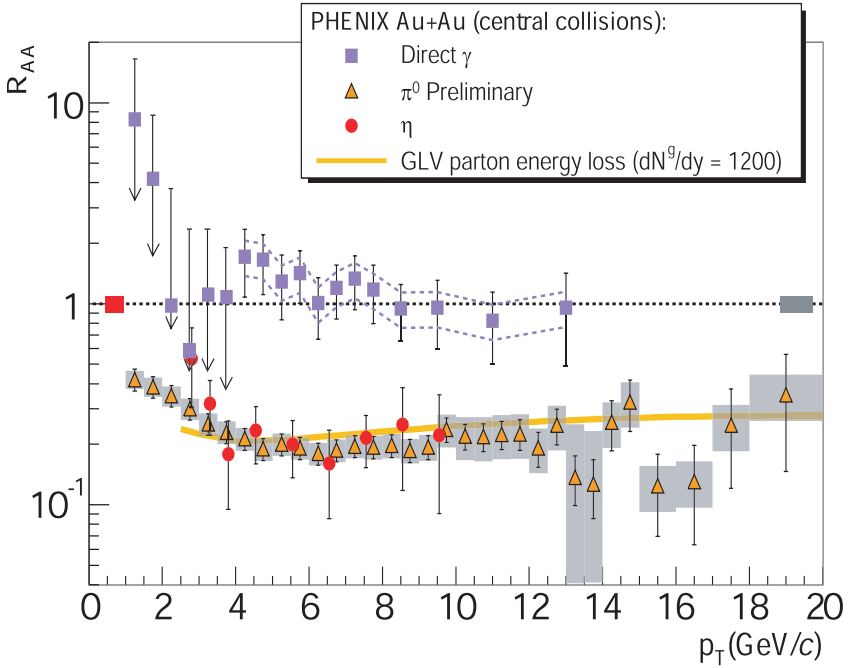


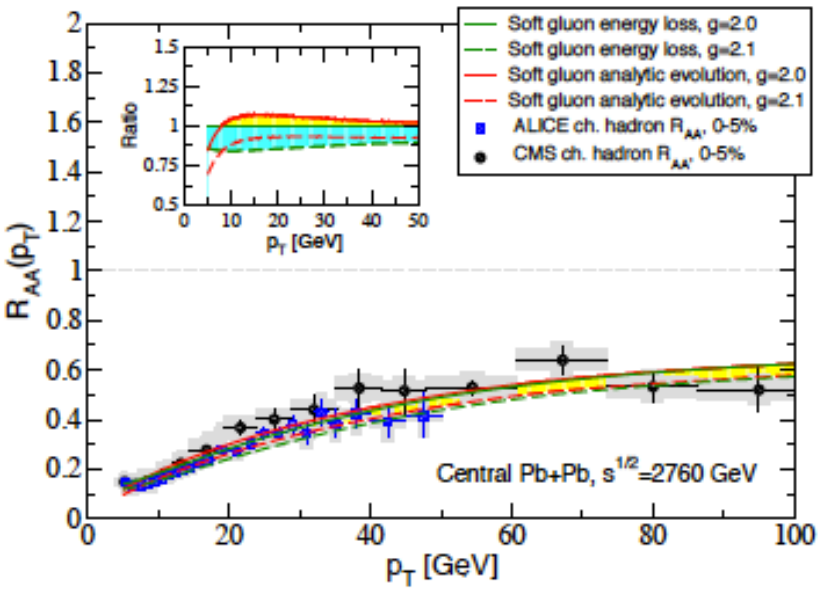
I. V. et al. (2002)

- Below p_T = 10 GeV important nuclear effects beyond energy loss contribute to the R_{AA} shape: Cronin, power corrections, shadowing
- Parton energy loss is relatively small and R_{AA} is driven by its interplay with the power law parton spectrum

- The number of emitted gluons is not small (>10 for g jet at LHC)
- Role of geometry is as expected

Comparison to data

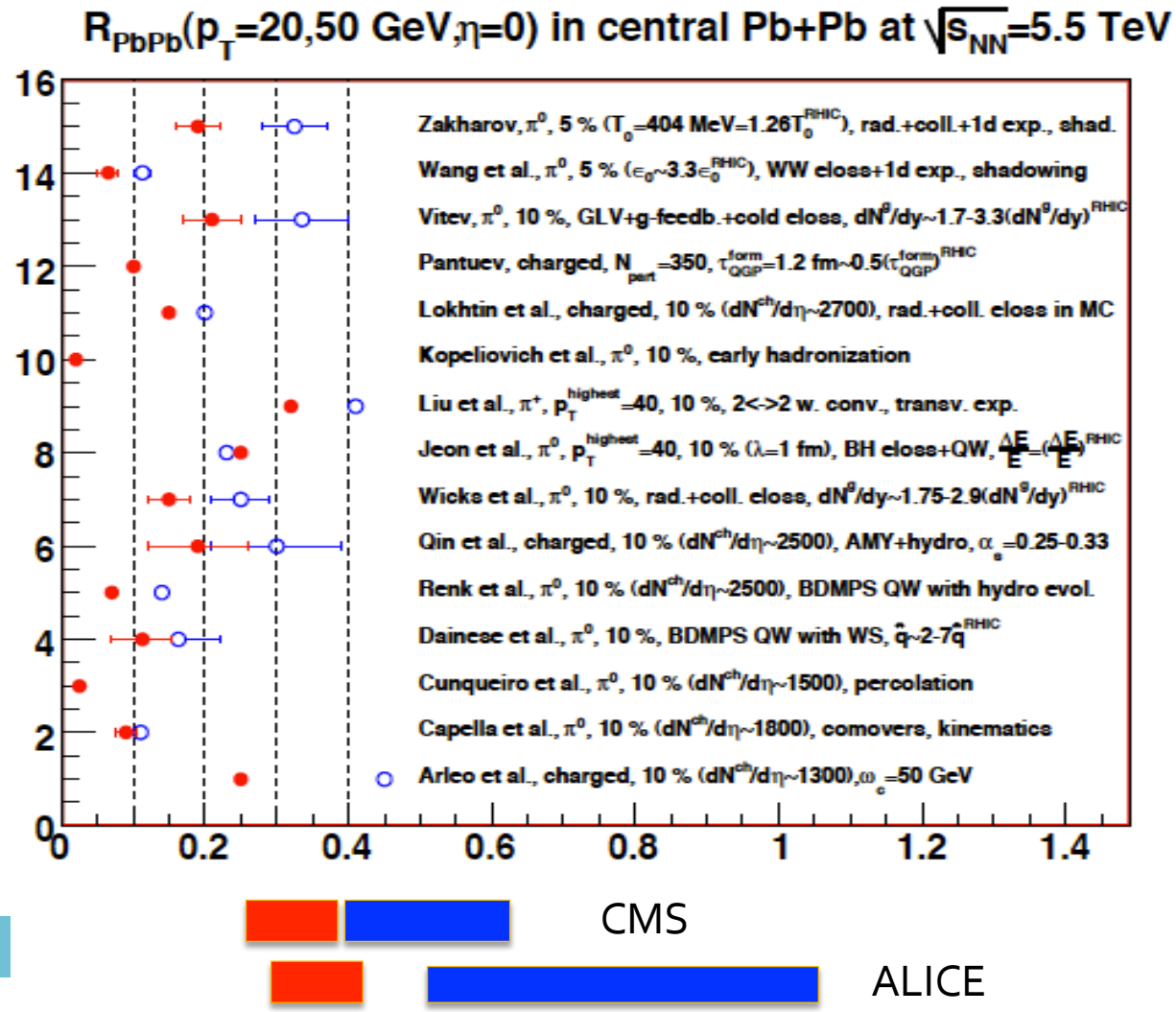




- What is the relevant regime of medium-induced radiative corrections (E-loss) incoherent Gunion-Bertsch or coherent Landau-Pomeranchuk-Migdal
- How do jets see the medium? Are they strongly coupled or are they weakly coupled to it?

Predictions for the LHC

- Caveat: predictions are made at different C.M. energy
- Even if an error is added for this most calculations will be incompatible with data



N. Armesto (2009)

What did we learn?

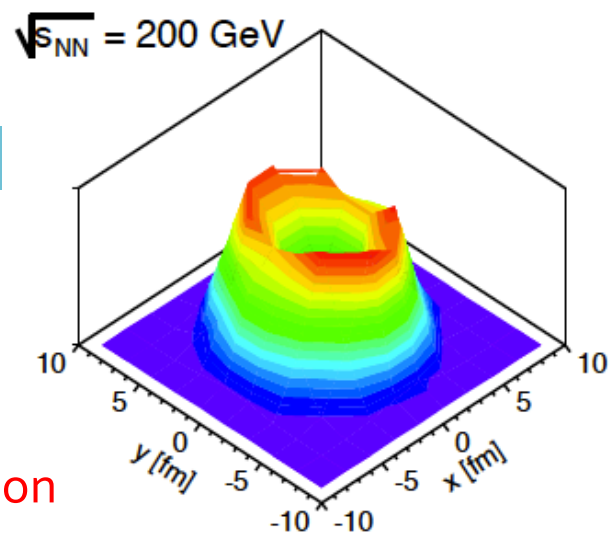
- Surprisingly, we have learned a lot form the ALICE and CMS results in spite of the postdiction avalanche

- Geometry is not the driving factor behind the shape and magnitude of jet and particle suppression
- Energy loss models with large E-loss and large no-radiation probability are excluded

V. Pantuev (2007), T.Renk (2007)

A.Dainese et al. (2004)

SW "Quenching weights" (2003)



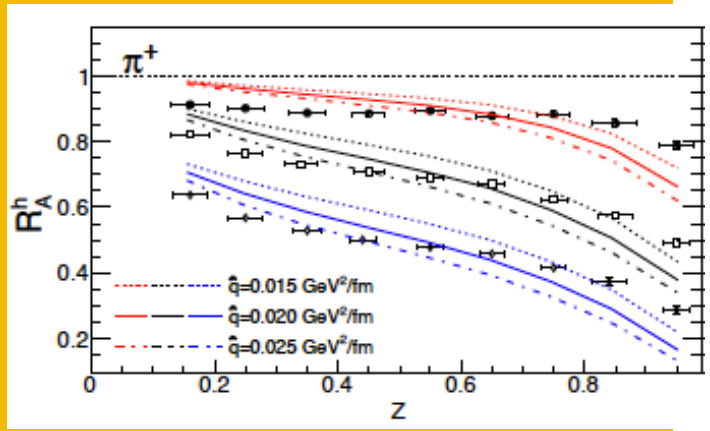
- It is unlikely that the Bethe-Heitler / Bertsch-Gunion regime is relevant to final-state E-loss
- The Landau-Pomeranchuk-Migdal (LPM) effect is critical to understand the suppression pattern of hadrons

S. Jeon (2007)

Directions for improvement

- Only in the soft gluon emission limit can the splitting processes be interpreted as energy loss
- Need to go beyond the soft gluon approximation, obtain all one-loop medium induced splitting kernels. Needs to unify the treatment of vacuum and medium-induced parton showers
- First work was done for SIDIS where E-loss was used to set "quenched" initial conditions for the fragmentation functions

Deng et al. (2014)

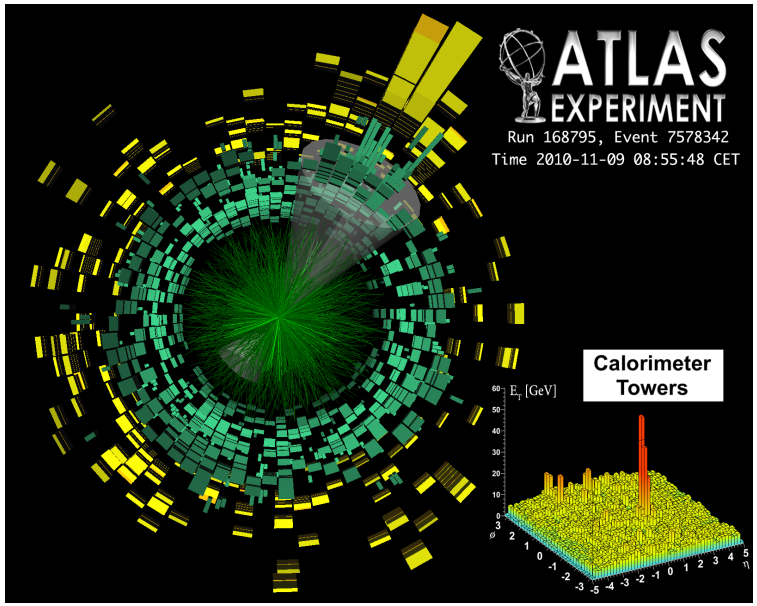


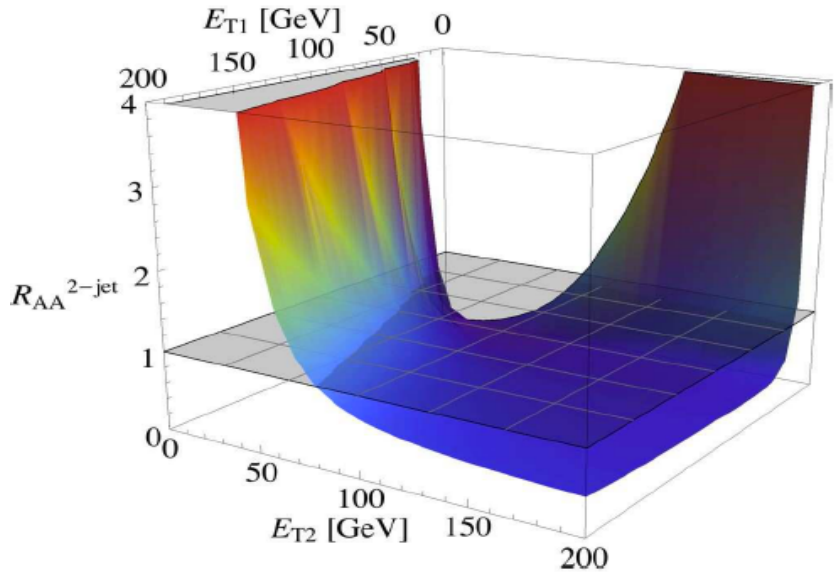
Need to understand the connection between traditional energy loss approaches and the ECD evolution and resummation

See talk by G. Ovanesyan

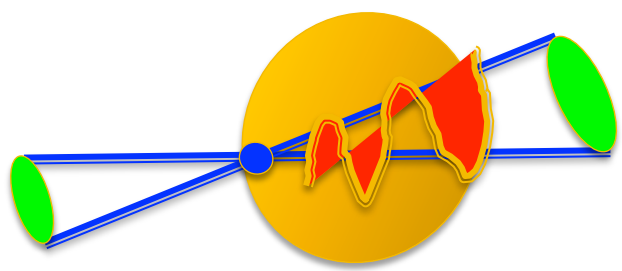
Di-jet suppression

- Interestingly, the first observation if jet quenching at the LHC was for approximately back-to-back jets

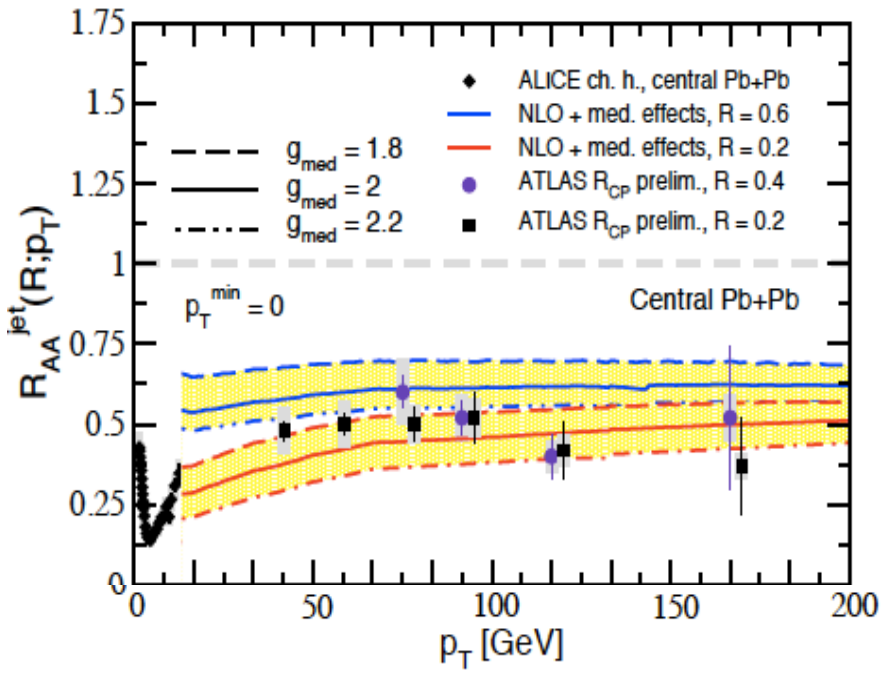




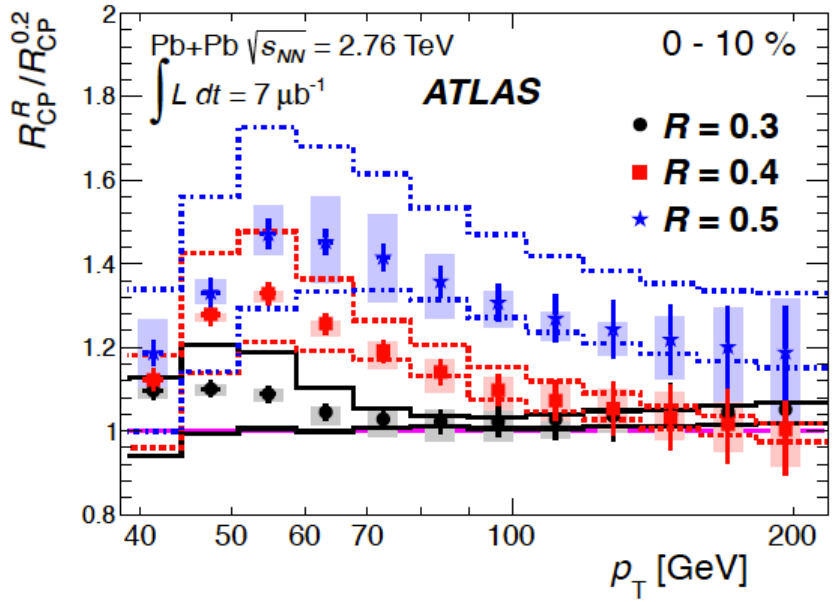
$$\frac{d\sigma}{dA_J} = \int_{y_{1\,\min}}^{y_{1\,\max}} dy_1 \int_{y_{2\,\min}}^{y_{2\,\max}} dy_2 \int_{E_{T\,2\,\min}}^{E_{T\,1}} dE_{T\,2}\, \frac{2E_{T\,2}}{(1-A_J)^2} \times \frac{d\sigma[E_{T\,1}(A_J, E_{T\,2})]}{dy_1 dy_2 dE_{T\,1} dE_{T\,2}}, \qquad A_J = \frac{E_{T\,1} - E_{T\,2}}{E_{T\,1} + E_{T\,2}}$$



Comparison to data



- Most recent experimental data form the LHC



- Both the predicted magnitude and R dependence observed by experiment

The medium induced parton shower is not fully dissipated in the medium

Y. He et al. (2011)

ATLAS Collab. (2011)

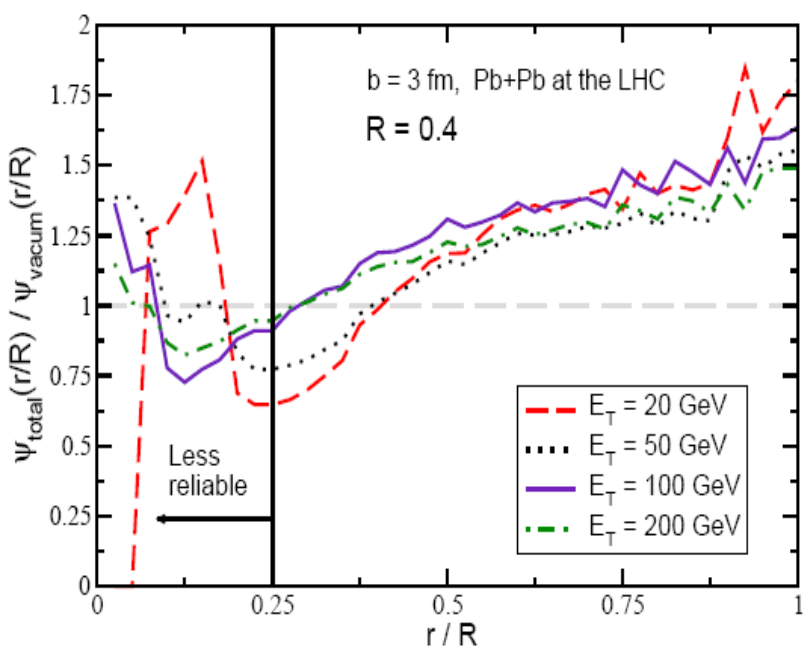
Medium – modified jet shapes

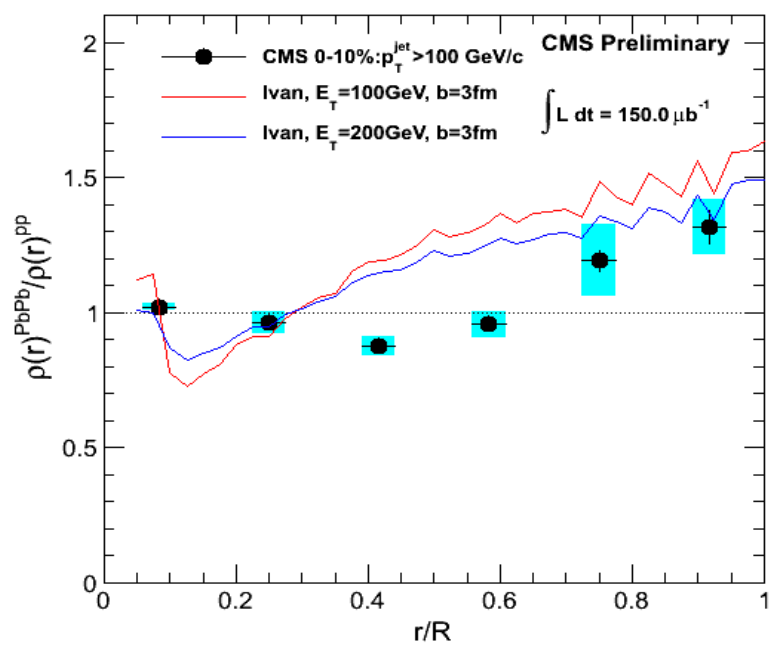
$$\Psi_{\rm int}(r;R) = \frac{\sum_i (E_T)_i \Theta(r-(R_{\rm jet})_i)}{\sum_i (E_T)_i \Theta(R-(R_{\rm jet})_i)}$$

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

- Surprisingly, there is no big difference between the jet shape in vacuum and the total jet shape in the medium
- Take a ratio of the differential jet shapes

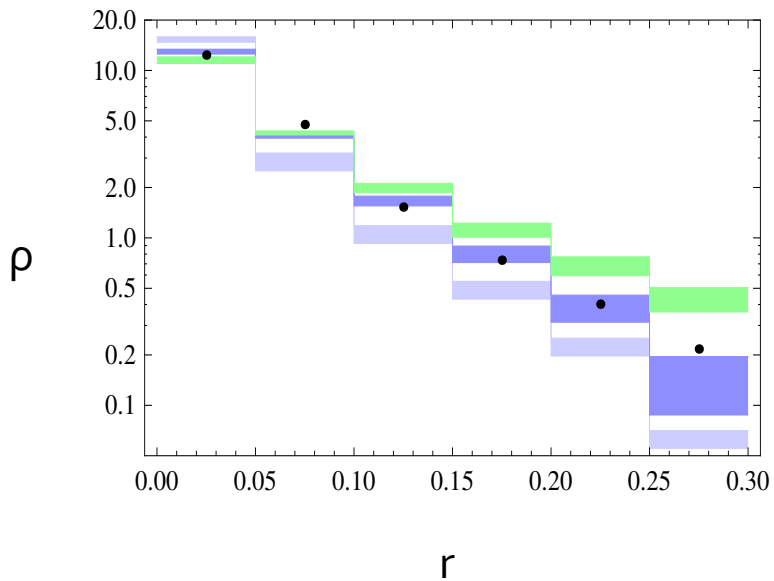
I.V. et al. (2008)

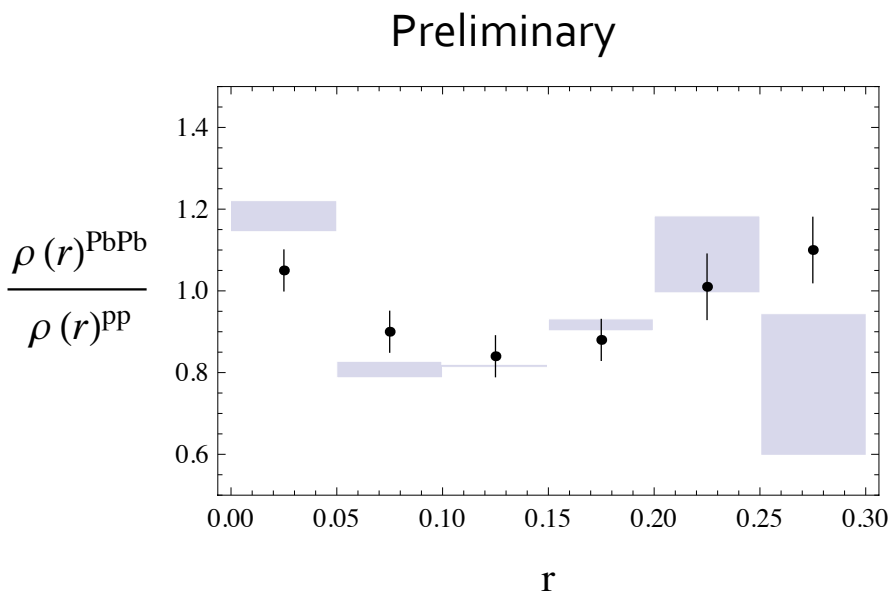




Directions for improvement

- Understand how the calculation has to be performed using the full medium-induced splitting functions
- Use SCET resummatuion techniques to improve the accuracy of the jet shape calculations





Talk was given by Y.T. Chien

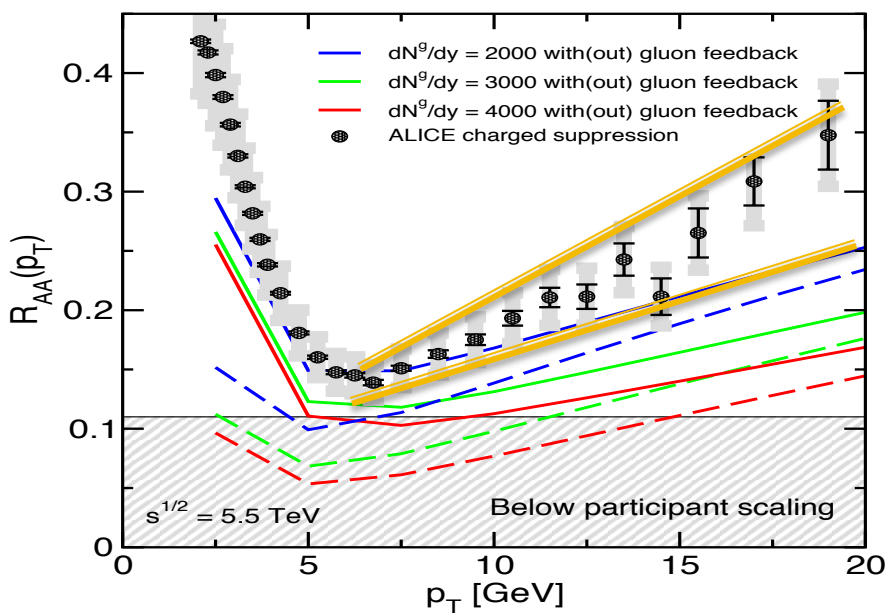
Conclusions

- Heavy ion physics has attracted attention from a large number of fields
- Hard particle and jet production are the ones most closely related to pQCD and SCET. The energy-loss jet quenching phenomenology (inclusive particle suppression) has been very successful at RHIC,LHC
- To make connection between the treatment of vacuum and the medium-induced parton shower one needs to go beyond the soft gluon approximation. Evolution, discussed in SIDIS and now in A+A. Also directly calculating medium induced radiative corrections
- The field is transitioning to understanding parton shower modification in the A+A and to study of jet observables that are sensitive to such modification. We already have results for inclusive jet production at the LHC, Z^0/γ-tagged jets and di-jets at the LHC in the soft gluon energy loss approximation
- The direction to improve is to use resummation and SCET techniques and to look into the jet substructure, jet shapes and jet fragmentation

Understanding of inclusive particle suppression

- Problems are evident in extending the jet quenching calculations below 5 GeV-10 GeV at the LHC

$$D_{h/c}(z) \Rightarrow \int_0^{1-z} d\epsilon\, P(\epsilon)\, \frac{1}{1-\epsilon} D_{h/c}\left(\frac{z}{1-\epsilon}\right) + \int_z^1 d\epsilon\, \frac{dN^g}{d\epsilon}(\epsilon)\, \frac{1}{\epsilon} D_{h/g}\left(\frac{z}{\epsilon}\right)$$

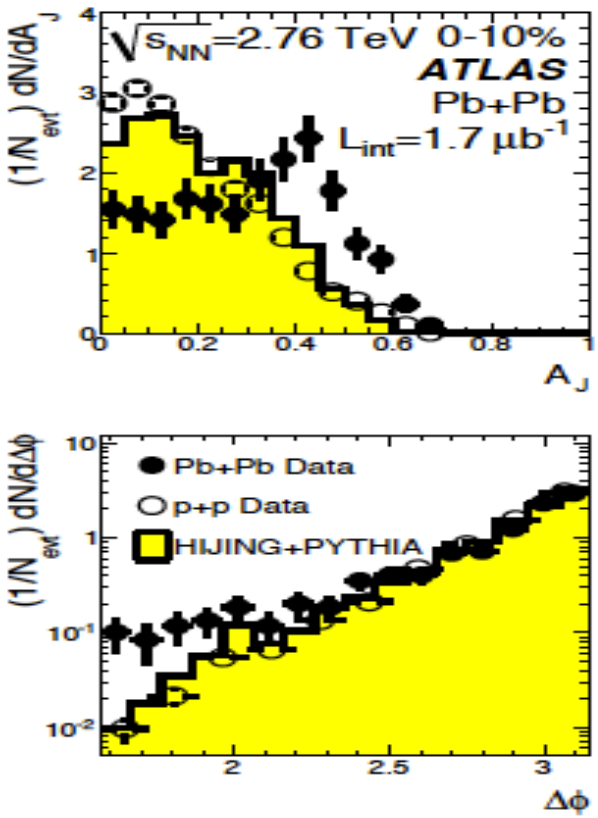


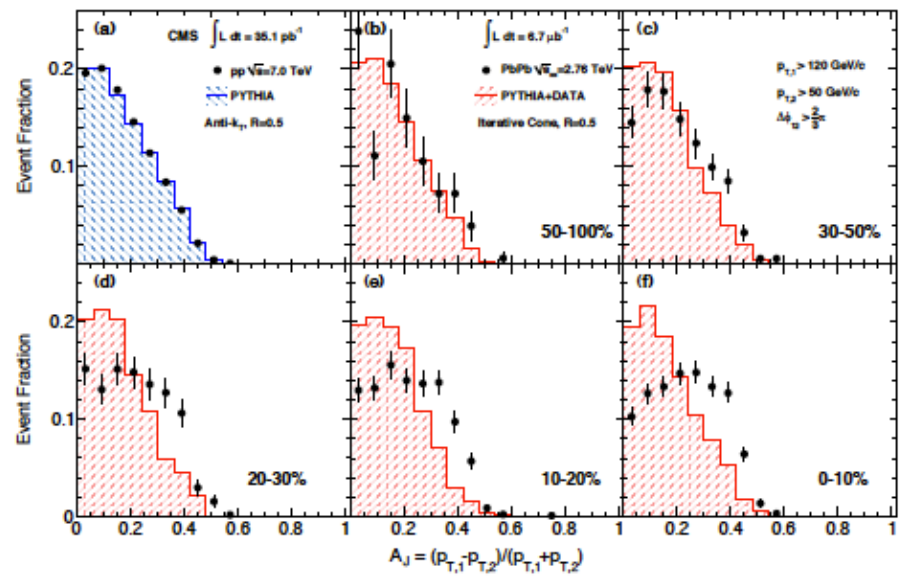
I. V. (2006)

- The radiative gluon contribution is important at the LHC (energy conservation)

• Not a proof that all important physics is considered / included physics is correct.
• As the only prediction that gave qualitative and even quantitative description at both high and low p_T it is strongly suggestive

Current experimental results for jet A_J and R_{AA}



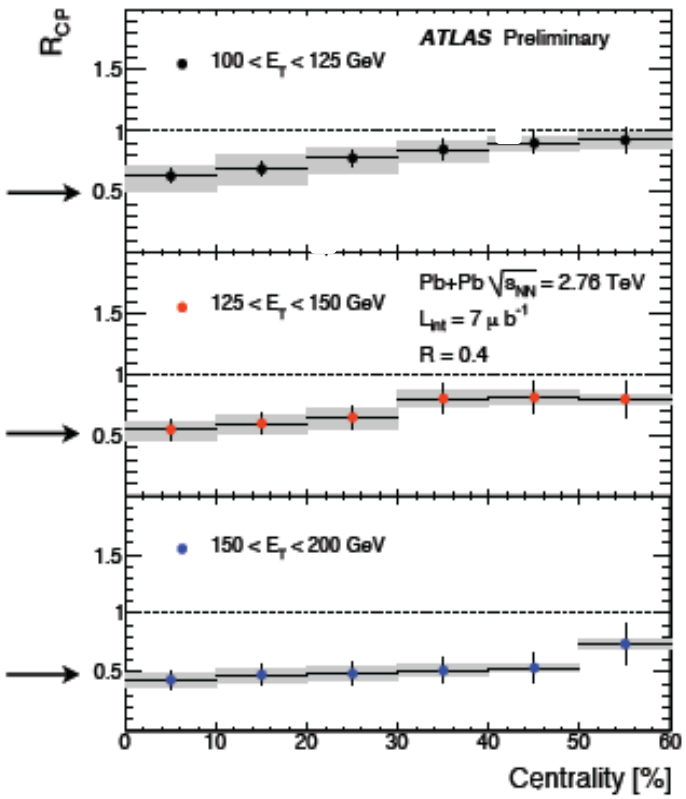


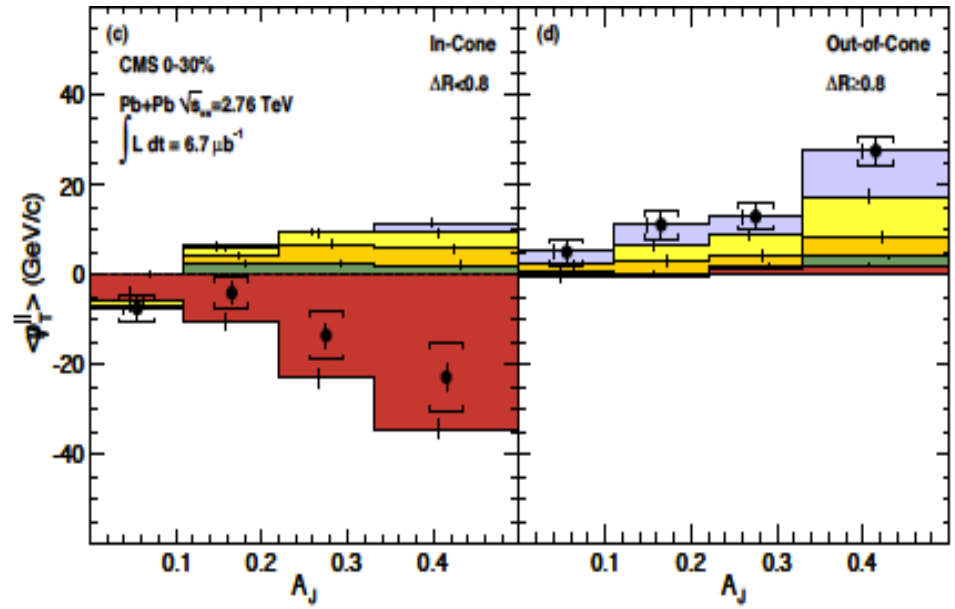
S. Chatrchyan et al. (2011)

G. Aad et al. (2011)

- Significantly enhanced di-jet asymmetry in central Pb+Pb collisions. Suggests large energy loss of the subleading jet

Current experimental results for jet A_J and R_{AA}



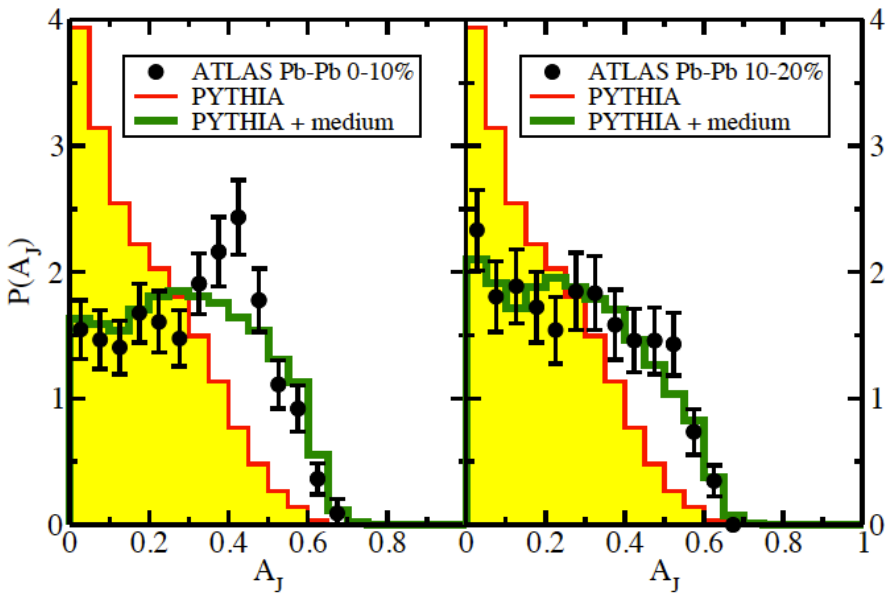


CMS Collab. (2010)

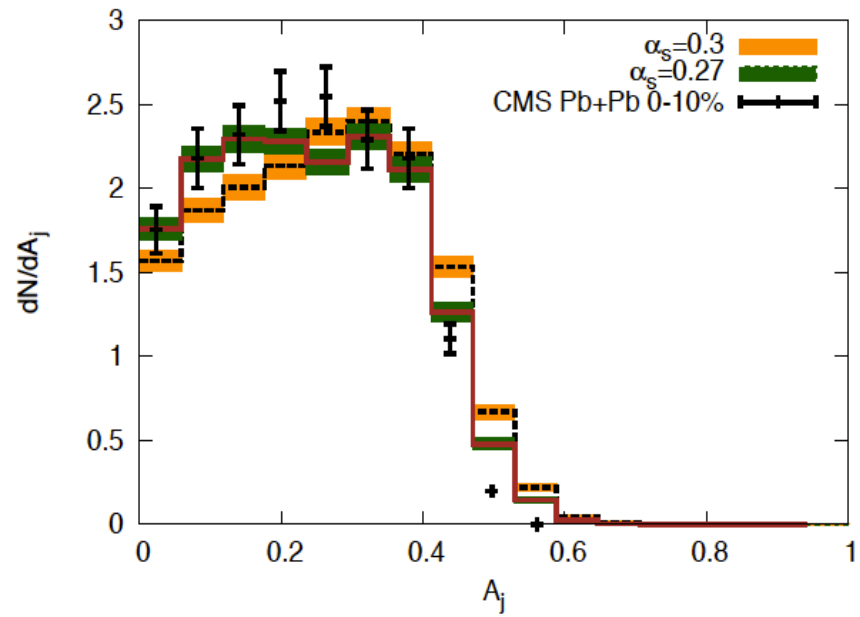
ATLAS Collab. (2011)

- These results are even more important since they give an independent observable and help understand what happens with the jet energy balance

III. Monte Carlo simulation approaches



Y. Quin et al. (2011)



C. Young et al. (2011)

- Both approaches include collisional and radiative energy loss contributions
- Based upon the HT and AMY formalisms, respectively
- The approaches can be tuned to the A_J measurement
- The second approach is presented as a part of the MARTINI Monte Carlo

III. Inclusive and di-jet cross sections at NLO and p+p results

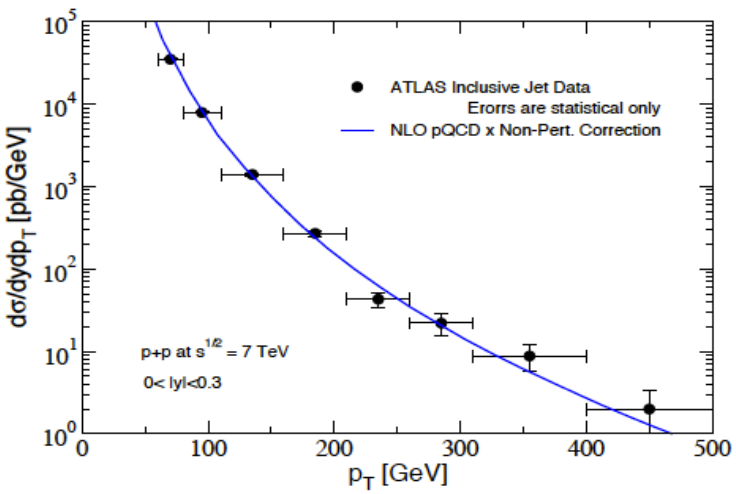
- Includes 2- and 3-parton final states

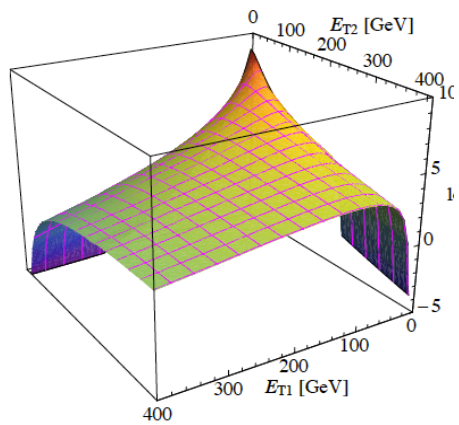
$$\frac{d\sigma^{\rm jet}}{dE_T dy} = \frac{1}{2!}\int d\{E_T,y,\phi\}_2 \frac{d\sigma[2\to 2]}{d\{E_T,y,\phi\}_2} S_2(\{E_T,y,\phi\}_2) + \frac{1}{3!}\int d\{E_T,y,\phi\}_3 \frac{d\sigma[2\to 3]}{d\{E_T,y,\phi\}_3} S_3(\{E_T,y,\phi\}_3)$$

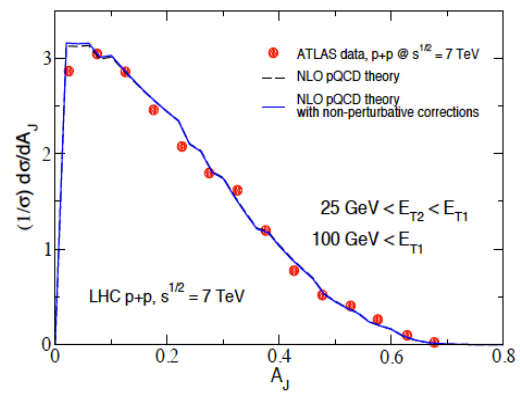
S.D. Ellis et al. (1990)

Z. Kunszt et al. (1992)

- At one loop – jet size/algorithm dep.







$$\frac{d\sigma}{dA_J} = \int_{y_{1\,\rm min}}^{y_{1\,\rm max}} dy_1 \int_{y_{2\,\rm min}}^{y_{2\,\rm max}} dy_2 \int_{E_{T2\,\rm min}}^{E_{T2\,\rm max}} dE_{T2}\, \frac{2E_{T2}}{(1-A_J)^2} \times \frac{d\sigma[E_{T1}(A_J,E_{T2})]}{dy_1 dy_2 dE_{T1} dE_{T2}}, \qquad A_J = \frac{E_{T1}-E_{T2}}{E_{T1}+E_{T2}}$$

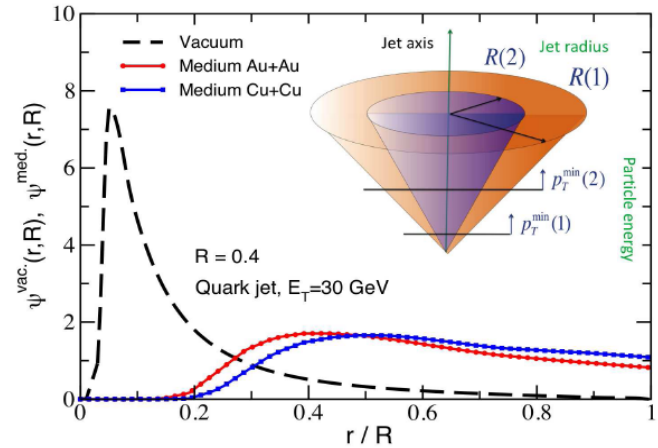
- Excellent description of the cross sections at RHIC and the LHC

Y.He et al. (2011)

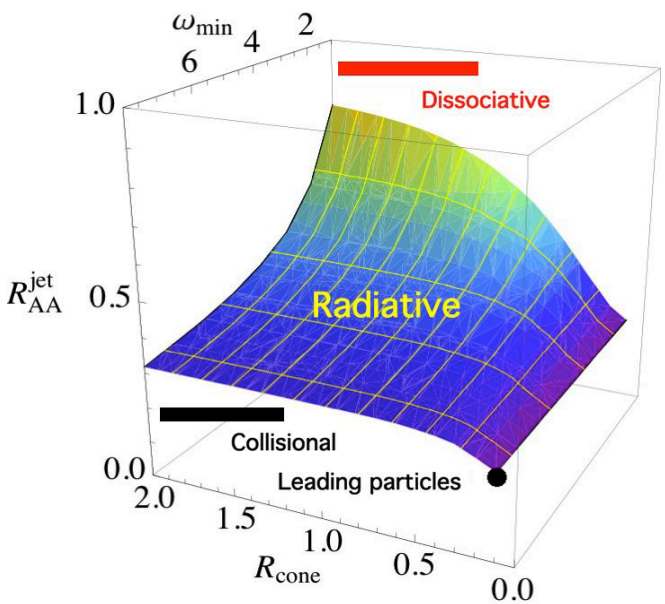
III. Exploting the jet variables in heavy-ion collisions

- One can leverage the differences between the vacuum parton showers, the medium-induced showers and the medium response to jets to experimental signatures of parton interaction in matter

I.Vitev et al. (2008)



- Calculations at NLO



$$R_{AA}^{\rm jet}(E_T;R^{\rm max},\omega^{\rm min}) = \frac{\frac{d\sigma^{AA}(E_T;R^{\rm max},\omega^{\rm min})}{dyd^2E_T}}{\langle N_{\rm bin}\rangle \frac{d\sigma^{pp}(E_T;R^{\rm max},\omega^{\rm min})}{dyd^2E_T}}$$

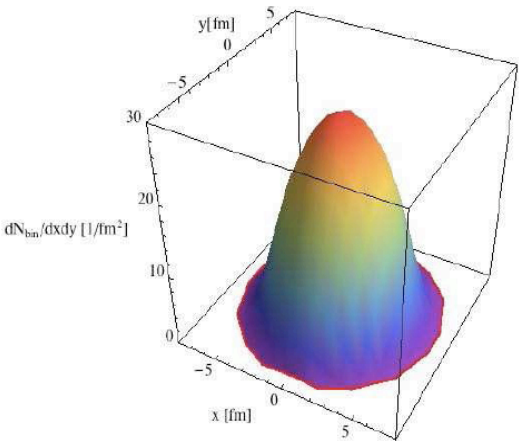
Mechanism	Signature
Radiative	Continuous variation of R_{AA}^{jet} with R, w_{min}
Collisional	~ Constant R_{AA}^{jet}= $R_{AA}^{particle}$ (Large suppression)

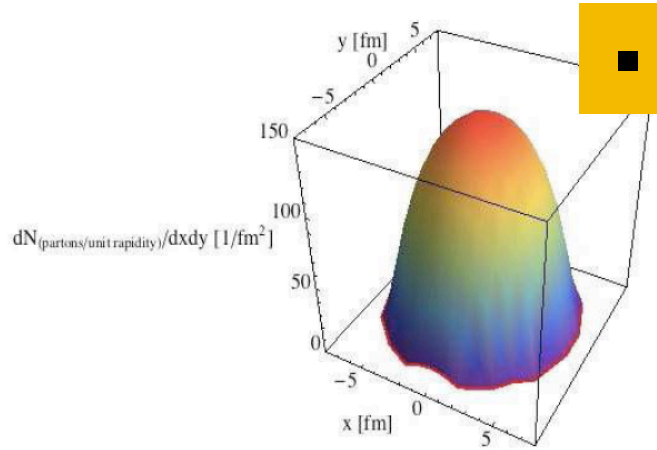
III. Inclusive jet cross sections in A+A reactions

- Jet cross sections with cold nuclear matter and final-state parton energy loss effect are calculated for different R

$$\frac{\sigma^{AA}(R,\omega^{\min})}{d^2E_T dy} = \int_{\epsilon=0}^{1} d\epsilon \sum_{q,g} P_{q,g}(\epsilon) \frac{1}{(1-(1-f_{q,g})\cdot\epsilon)^2} \frac{\sigma^{NN}_{q,g}(R,\omega^{\min})}{d^2E'_T dy}$$

$$|J_i(\epsilon_i)| = 1/\left(1-[1-f(R_i,p_{T\,i}^{\min})_{q,g}]\epsilon_i\right)$$





I. Vitev et al (2008)

- Calculate in real time

Fraction of the energy redistributed inside the jet

$$f(R_i,p_{T\,i}^{\min})_{q,g} = \frac{\int_0^{R_i} dr \int_{p_{T\,i}^{\min}}^{E_{T\,i}} d\omega \frac{dI^{\rm rad}_{q,g}(i)}{d\omega dr}}{\int_0^{R_i^\infty} dr \int_0^{E_{T\,i}} d\omega \frac{dI^{\rm rad}_{q,g}(i)}{d\omega dr}}$$

The probability to lose energy due to multiple gluon emission

$$\int_0^1 P_{q,g}(\epsilon_i)d\epsilon_i = 1\,, \quad \int_0^1 \epsilon_i P_{q,g}(\epsilon_i)d\epsilon_i = \frac{\Delta E_{q,g\,i}}{E_i}$$

- Obtain

$$R^{\rm jet}_{AA}(E_T;R,p_T^{\min}) = \frac{\frac{d\sigma^{AA}(E_T;R,p_T^{\min})}{dyd^2E_T}}{\langle N_{\rm bin}\rangle \frac{d\sigma^{pp}(E_T;R,p_T^{\min})}{dyd^2E_T}}$$