Ivan Vitev

# Heavy Ion Theory

Boston Jet Workshop – Boston, MA, January 21 – 23, 2014

# Outline of the talk

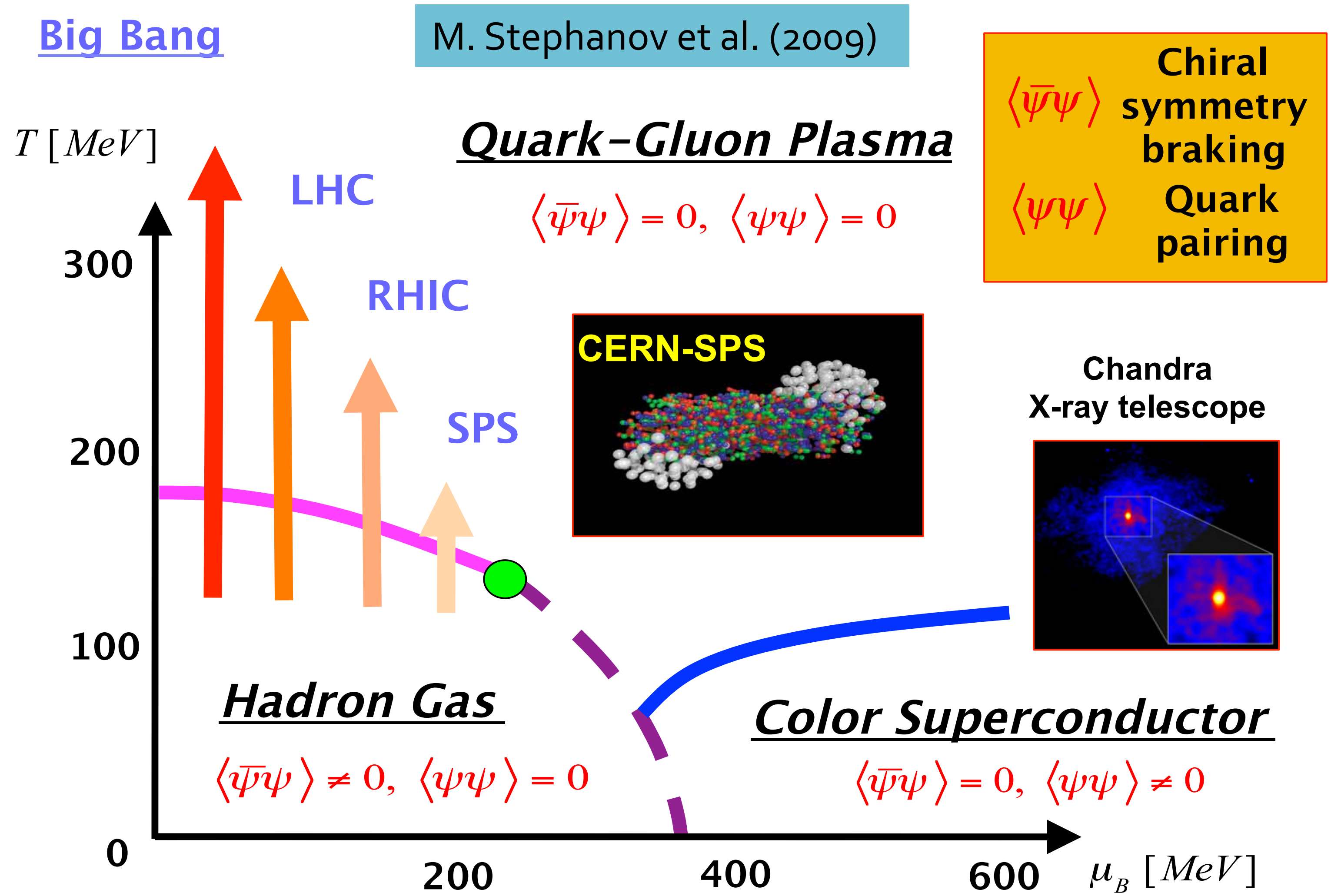
- An brief overview of leading particle suppression theory and measurements in the past decade: successes and challenges
- Results for inclusive jets,  tagged jets, di-jets and their asymmetry
- An effective theory for jet propagation in matter $SCET_G$ , gauge invariance of jet broadening and energy loss results. Factorization of medium-induced radiative corrections
- Future directions and applications

# A summer visitor program at LANL

- Plan: Visit for 1-2 months this summer. The program will cover travel, lodging and per diem
- Emphasis: jet physic in heavy ion collisions. The idea is to expose students to new areas of application of QCD and effective theories of QCD
- Expected results: new ideas/projects that lead to journal publications
- Past participants: Zhongbo Kang, Michael Fickinger, Philip Saad, Robin Lashoff-Regas, Hongxi Xing
- If interested: send expression of interest and a short CV to ivitev@lanl.gov.

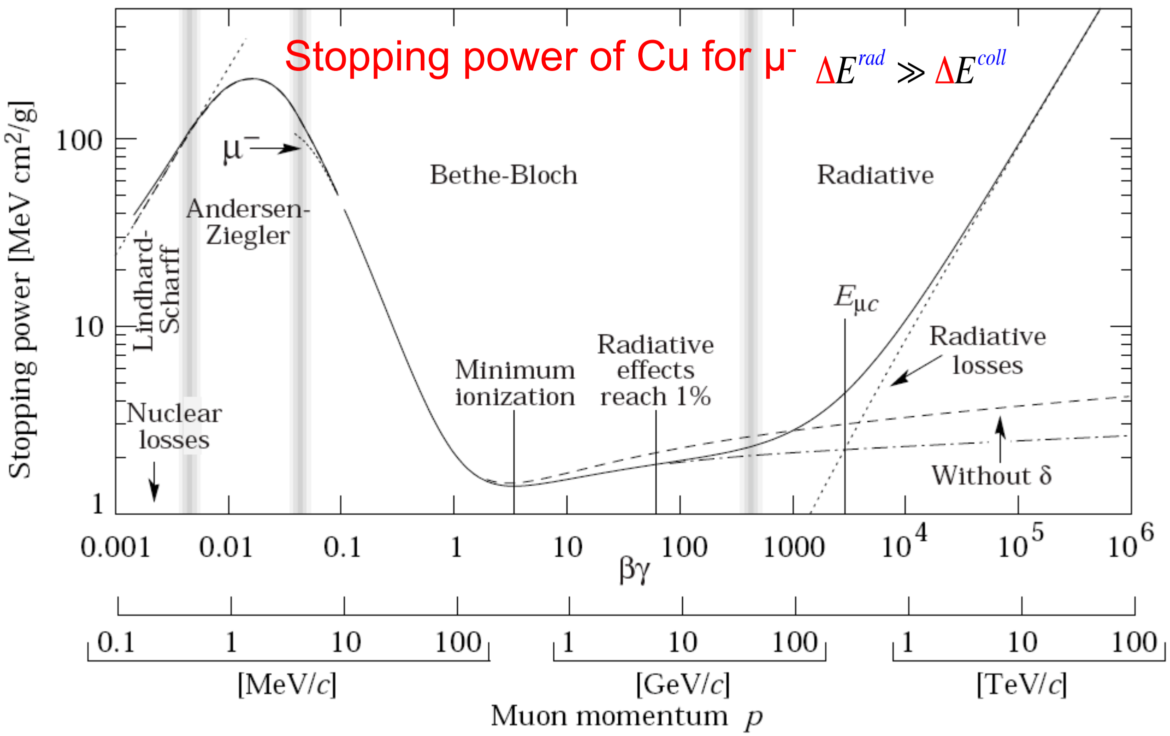
# The phase diagram of QCD



# The stopping power of matter

Groom, D.E. et al. (2001)




- Collisional energy loss
  - medium excitation

$$\frac{d\Delta E^{coll}}{dz} \approx 4\pi\alpha_{em}^2 z^2 Z\rho_{num}\frac{1}{\beta^2 m}\ln B_q$$

Bethe, H.A. (1930,1932)

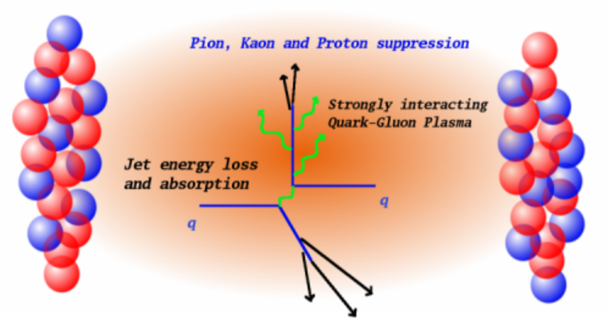
- Radiative energy loss
  - bremsstrahlung

$$\frac{d\Delta E^{rad}}{dz} \approx \frac{16}{3}\alpha_{em}^3 z^4 Z^2\rho_{num}\frac{1}{M^2}E\ln(\lambda\gamma)$$

Bethe, H. A. et al. (1934)

- The stopping power of materials for charged particles is a fundamental probe of the matter properties
- Arises from collisional and radiative energy loss processes. In QED known to 2%

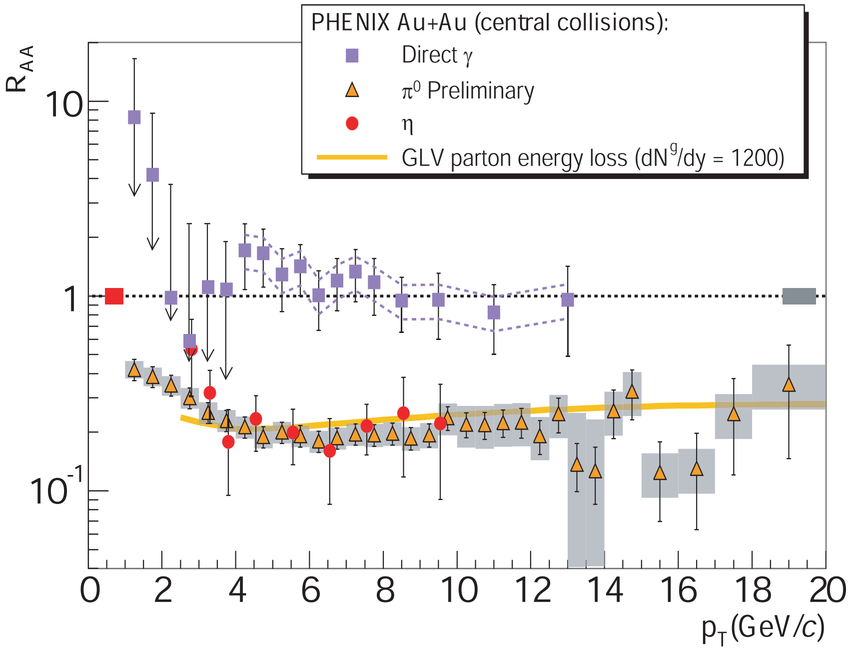
# Quenching of leading particles




- Jet quenching: suppression of inclusive particle production relative to a binary scaled p+p result

M. Gyulassy, et al. (1992)

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



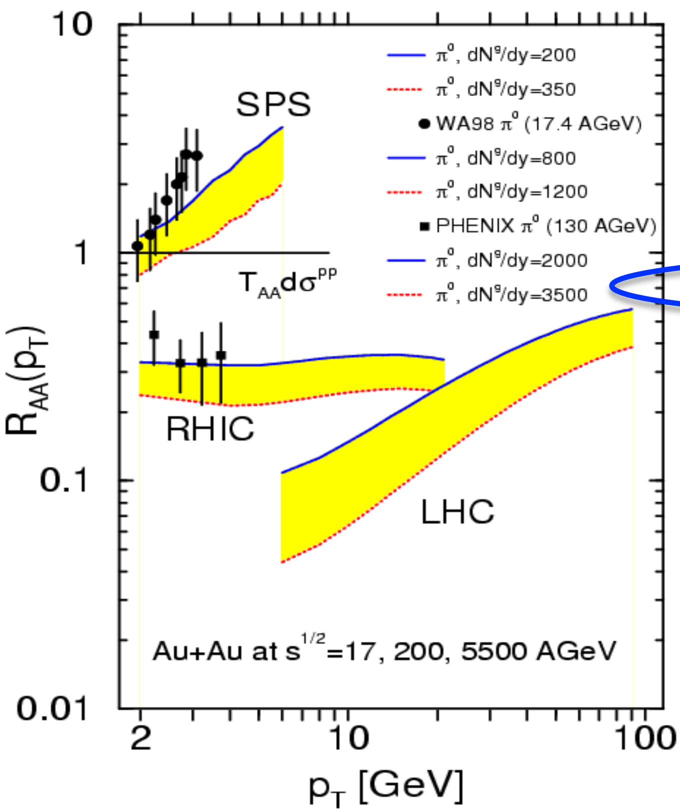

Jet quenching in A+A collisions has been regarded as one of the most important discoveries at RHIC

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

Adler, S. et al (2003)

Adams, J. et al. (2003)

# Jet tomograhy



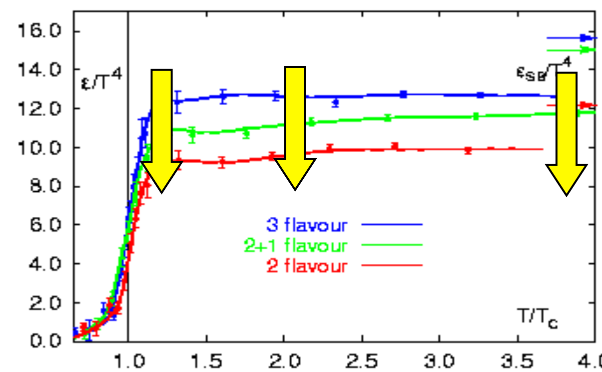

$$I(r) = e^{-\int_0^r dr'/\lambda_{abs}(r')} = e^{-\int_0^r dr'\,\rho(r')\sigma(r')}$$

| | $\tau_0$ [fm] | $\tau_{tot}$ [fm] | $T_0$ [MeV] | $\epsilon_0$ $\left[\frac{\text{GeV}}{\text{fm}^3}\right]$ | $\frac{dN^g}{dy}$ |
|---|---|---|---|---|---|
| SPS | 0.8 | 1.3 – 2.3 | 205 – 245 | 1.2 – 2.6 | 200 – 350 |
| RHIC | 0.6 | 5.5 – 8 | 360 – 410 | 12 – 20 | 800 – 1200 |
| LHC | 0.2 | 13 – 23 | 710 – 850 | 170 – 350 | 2000 – 3500 |

I.Vitev et al. (2002)

$$\epsilon_A \simeq 0.16\,\frac{\text{GeV}}{\text{fm}^3}.$$

$$\epsilon \approx \frac{p_0}{\tau_0 \pi R^2}\,\frac{dN_g}{dy} \approx 15 - 20\,\frac{\text{GeV}}{\text{fm}^3},$$

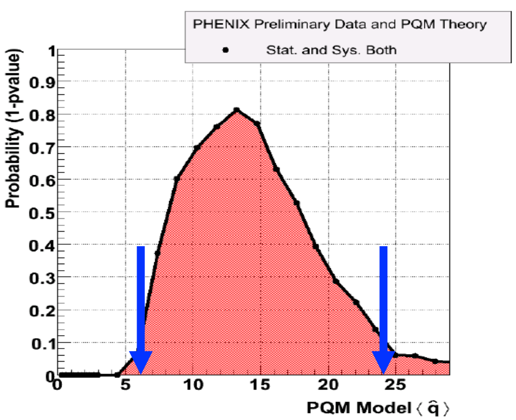



- Advantage of $R_{AA}$ : providing useful information for the hot/dense medium within a simple physics picture

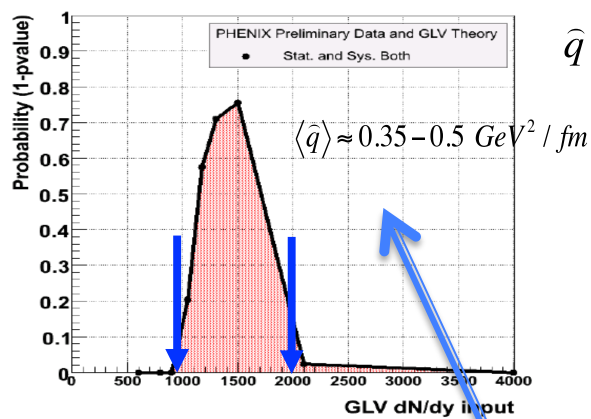
# Limitations of leading particle observables

- Disadvantage: cannot distinguish between competing models of parton energy loss and theoretical approximations

BDMPS, GLV, AMY, HT



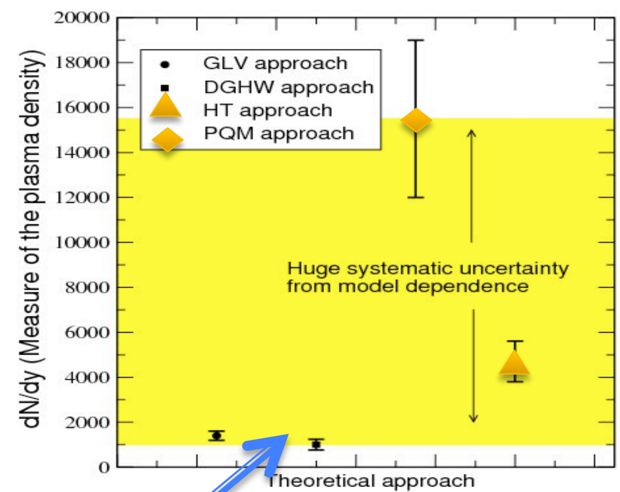

$$6 \le \langle \hat{q} \rangle \le 24 \ \text{GeV}^2/\text{fm}$$
(Probability > 10%)




$$1000 \le dN_g/dy \le 2000$$
(Probability > 10%)

$$\hat{q} \sim \frac{\mu^2}{\lambda_g} O(1)$$

A. Adare et al. (2008)




- If we present results for the same quantity $dN^g/dy$ (or <q-hat>) the problem becomes apparent
- Important update: Recent convergence of $\hat{q}(t = 0.6\,fm) \approx 1.3(\pm 0.2) - 1.9(\pm 0.7) \ GeV^2/fm$ for GLV-like, AMY-like and HT-like simulations

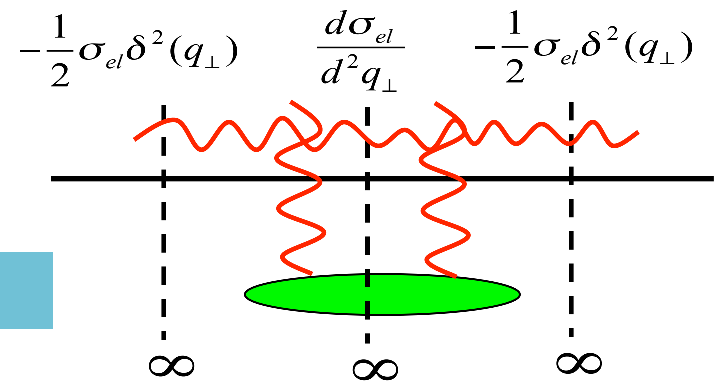
JET collaboration (2013)

# An operator approach to multiple scattering in QCD

- Most E-loss approaches gave ΔE, or xdN/dx. Not sufficient
- Very general algebraic approach

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

M. Gyulassy et al. (2001)




**Number of scatterings** **Momentum transfers**

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

**Color current propagators**

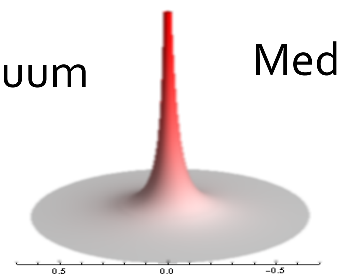
**Coherence phases (LPM effect)**

# Exploting the jet variables in heavy-ion collisions

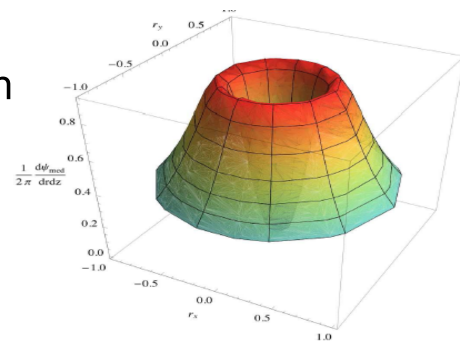
$$\Delta E^{rad}_{\text{LPM suppressed}} \Rightarrow \frac{dI^g}{d\omega}(\omega \sim E)_{\text{LPM suppressed}}$$

$$\Rightarrow \frac{dI^g}{d\omega d^2k_T}(k_T \ll \omega)_{\text{LPM suppressed}} \sim \frac{dI^g}{d\omega dr}(r \ll R)_{\text{suppressed}}$$

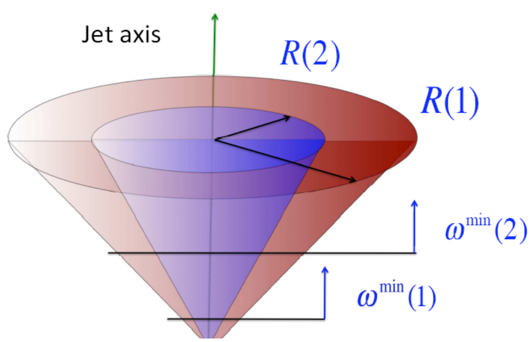
Vacuum



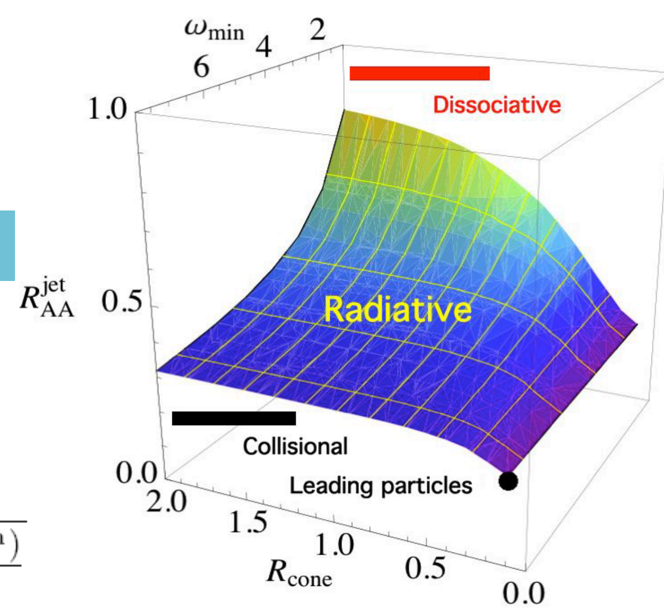
Medium



- 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)




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

# 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

- In the soft gluon approximation it has an interpretation of energy loss

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

The probability to lose energy due to multiple gluon emission

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

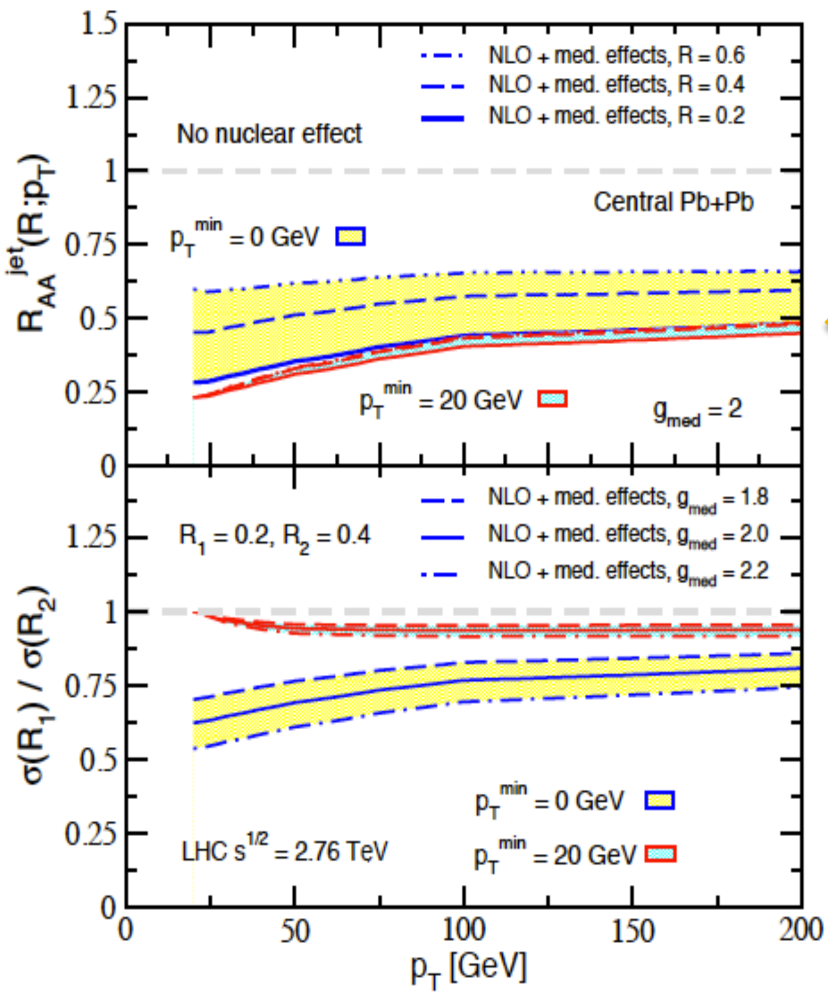
Fraction of the energy redistributed inside the jet

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

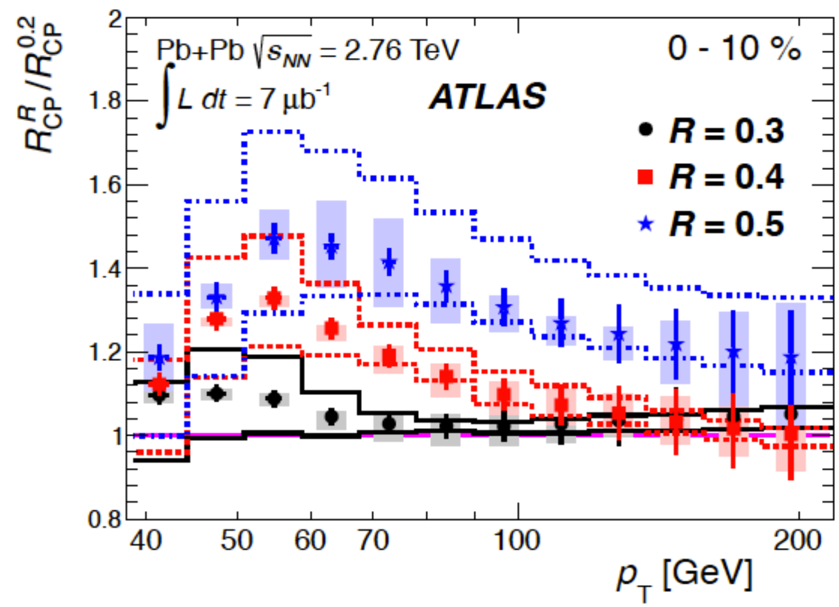
- Evaluate the suppression of jets

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

# Comparison to data




- Can easily wipe out the Radius dependence of jet observables (also for di-jets)




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

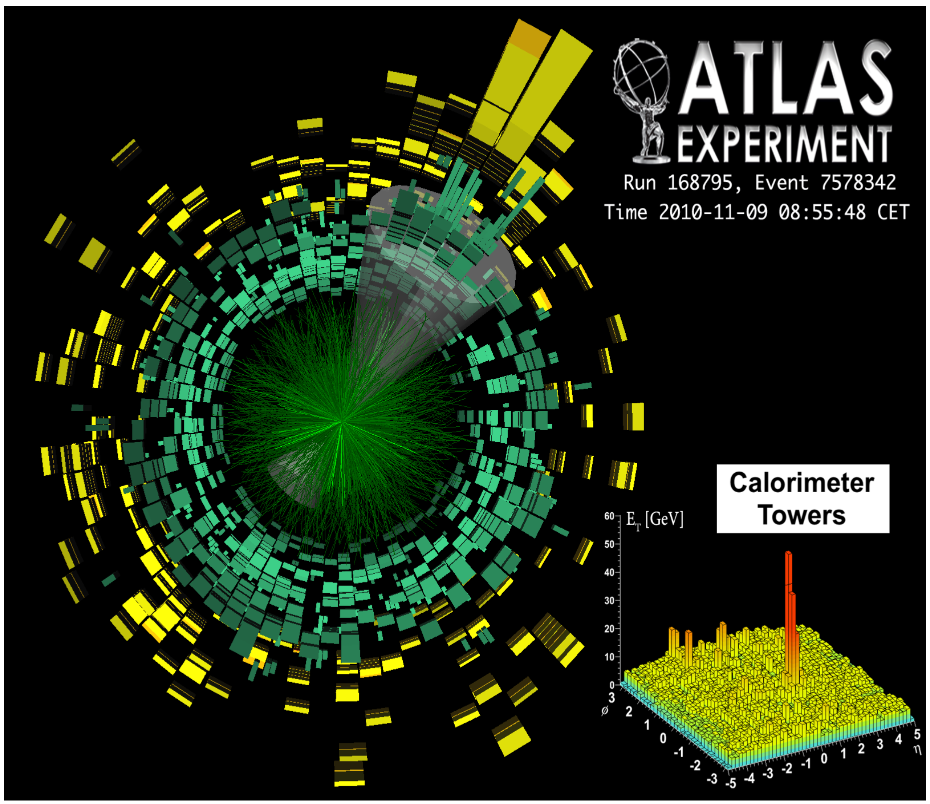
Y. He et al. (2011)

ATLAS Collab. (2011)

A. Angerami (2012)

# Di-jet suppression

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




$$R_{AA}^{\text{n-jet}}(E_{T\,1}\cdots E_{T\,n}; R_1\cdots R_n, p_{T\,1}^{\min}\cdots p_{T\,n}^{\min})$$

$$= \frac{\dfrac{d\sigma^{AA}(E_{T\,1}\cdots E_{T\,n}; R_1\cdots R_n, p_{T\,1}^{\min}\cdots p_{T\,n}^{\min})}{dy_1\cdots dy_n dE_{T\,1}\cdots dE_{T\,n}}}{\langle N_{\text{bin}}\rangle \dfrac{d\sigma^{pp}(E_{T\,1}\cdots E_{T\,n}; R_1\cdots R_n, p_{T\,1}^{\min}\cdots p_{T\,n}^{\min})}{dy_1\cdots dy_n dE_{T\,1}\cdots dE_{T\,n}}}$$

- Generalized multi-jet suppression

$$\frac{1}{\langle N_{\text{bin}}\rangle}\frac{d\sigma^{AA}(R)}{dy_1 dy_2 dE_{T\,1} dE_{T\,2}} = \sum_{qq,qg,gg} \int_{\epsilon_1=0}^{1} d\epsilon_1 \int_{\epsilon_2=0}^{1} d\epsilon_2$$

$$\frac{P_{q,g}(\epsilon_1, E_{T\,1})}{\left(1-[1-f(R_1, p_{T\,1}^{\min})_{q,g}]\epsilon_1\right)} \frac{P_{q,g}(\epsilon_2, E_{T\,2})}{\left(1-[1-f(R_2, p_{T\,2}^{\min})_{q,g}]\epsilon_2\right)}$$

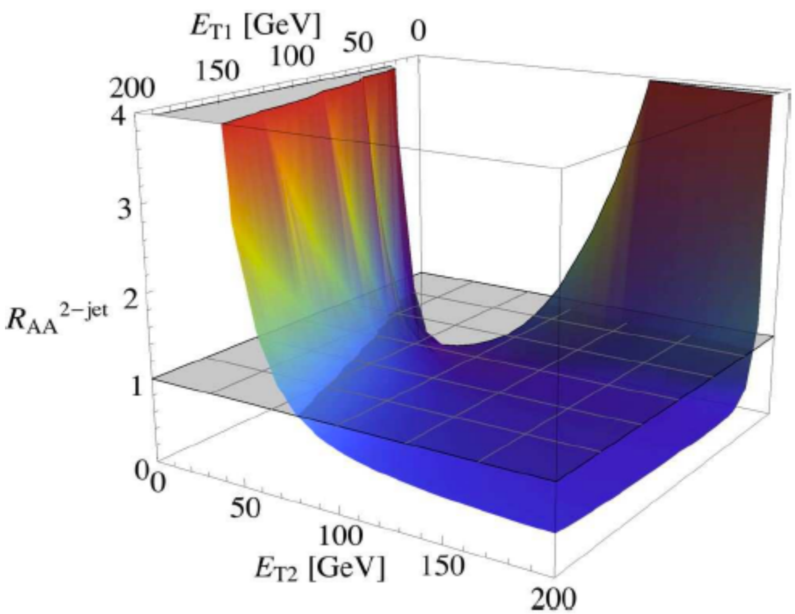
$$\times \frac{d\sigma_{qq,qg,gg}^{\text{CNM,NLO}}(E'_{T\,1}, E'_{T\,2})}{dy_1 dy_2 dE'_{T\,1} dE'_{T\,2}}$$

Y. He et al. (2011)

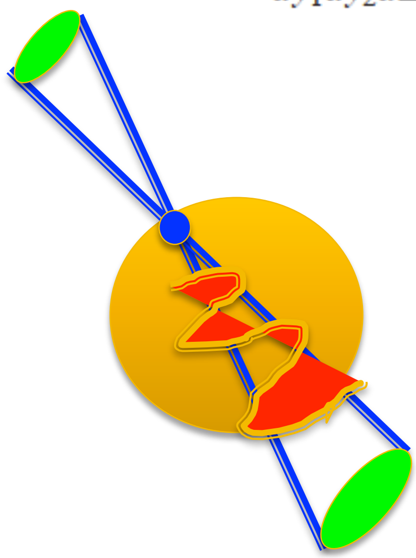
# Evaluating the di-jet asymmetry

- All information about the suppressed di-jets is in $R_{AA}{}^2$

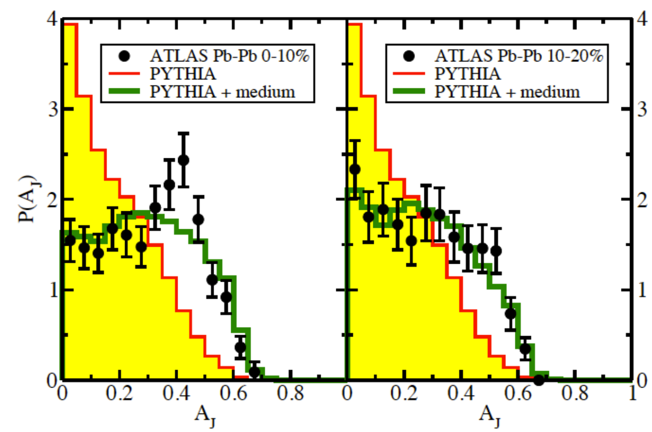
$$\frac{d\sigma}{dA_J} = \int_{y_{1\,\mathrm{min}}}^{y_{1\,\mathrm{max}}} dy_1 \int_{y_{2\,\mathrm{min}}}^{y_{2\,\mathrm{max}}} dy_2 \int_{E_{T\,2\,\mathrm{min}}}^{E_{T\,1}} dE_{T\,2} \, \frac{2E_{T\,2}}{(1-A_J)^2} \times \frac{d\sigma[E_{T\,1}(A_J, E_{T\,2})]}{dy_1 dy_2 dE_{T\,1} dE_{T\,2}} \,, \qquad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

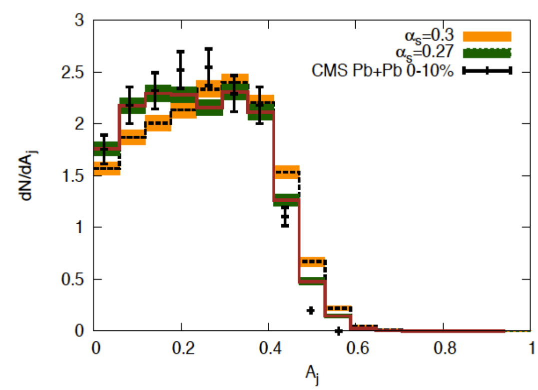



Y. He et al. (2011)



Y. Quin et al. (2011)



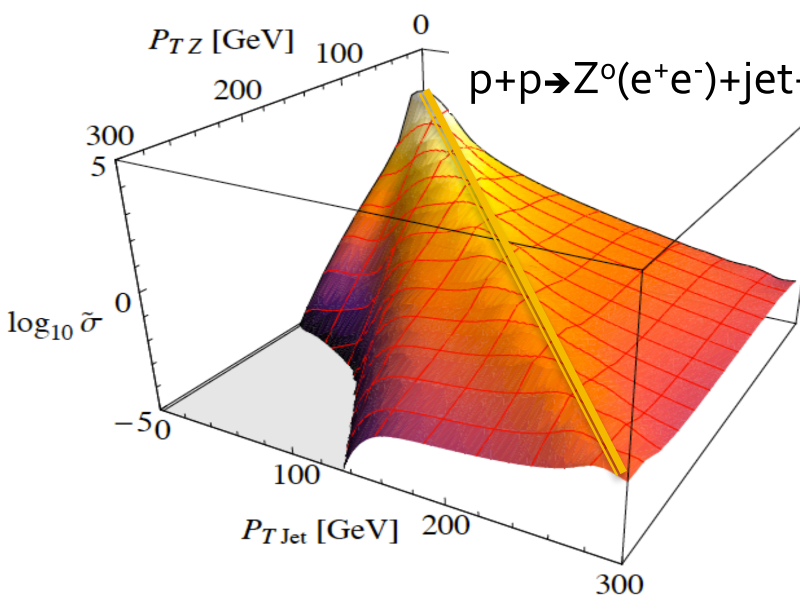




C. Young et al. (2011)

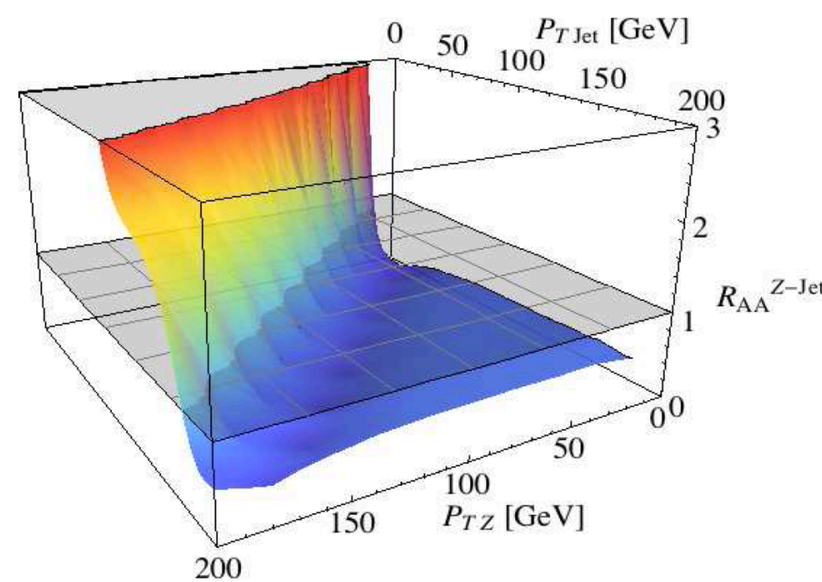
# $Z^o$-tagged and γ-tagged jets

- The idea is that the $Z^o$/γ do not interact strongly in the medium. Provide reference $p_T$ for the jet

T. Awes et al. (2011)




$$R_{AA}^{Z-\mathrm{jet}}(p_{T\,Z}, p_{T\,\mathrm{Jet}}; R, \omega_{\min}) = \frac{\frac{d\sigma_{AA}}{dp_{T\,Z}\,dp_{T\,\mathrm{Jet}}}}{\langle N_{\mathrm{bin}}\rangle \frac{d\sigma_{pp}}{dp_{T\,Z}\,dp_{T\,\mathrm{Jet}}}}$$




- For the double differential cross section - lowest non-trivial order $O(\alpha_s^2 G_F)$, $O(\alpha_s^2 \alpha_{em})$

R.B.Neufeld et al. (2011)

R.B.Neufeld at al. (2012)

# Imbalance of Photon-tagged jets

- Evaluating the γ-Jet momentum imbalance distribution.

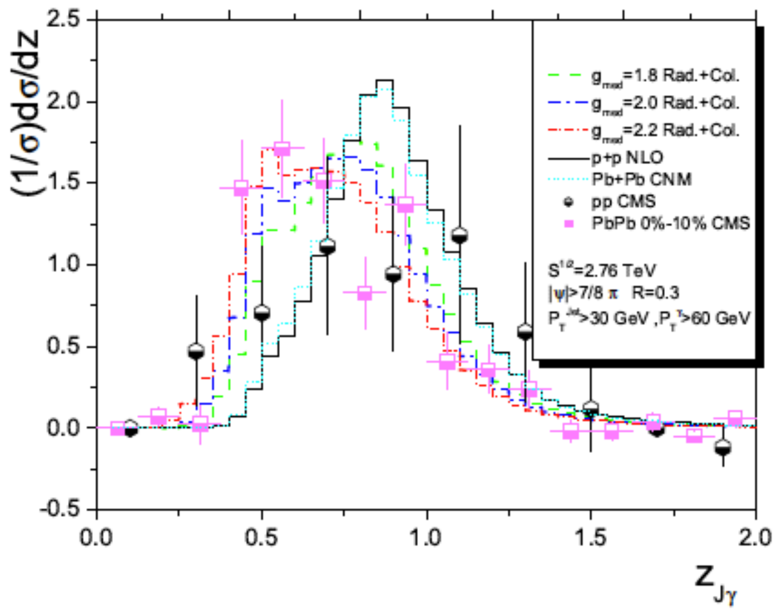
Imbalance variable

$$Z_J = \frac{p_{T\ jet}}{p_{T\ \gamma}}$$

W.Dai, et al (2012)

$$\frac{d\sigma}{dz_{J\gamma}} = \int_{p_{T_{\rm jet}}^{min}}^{p_{T_{\rm jet}}^{max}} dp_{T_{\rm jet}} \frac{p_{T_{\rm jet}}}{z_{J\gamma}^2} \frac{d\sigma[z_{J\gamma}, p_{T_\gamma}(z_{J\gamma}, p_{T_{\rm jet}})]}{dp_{T_\gamma} dp_{T_{\rm jet}}}$$

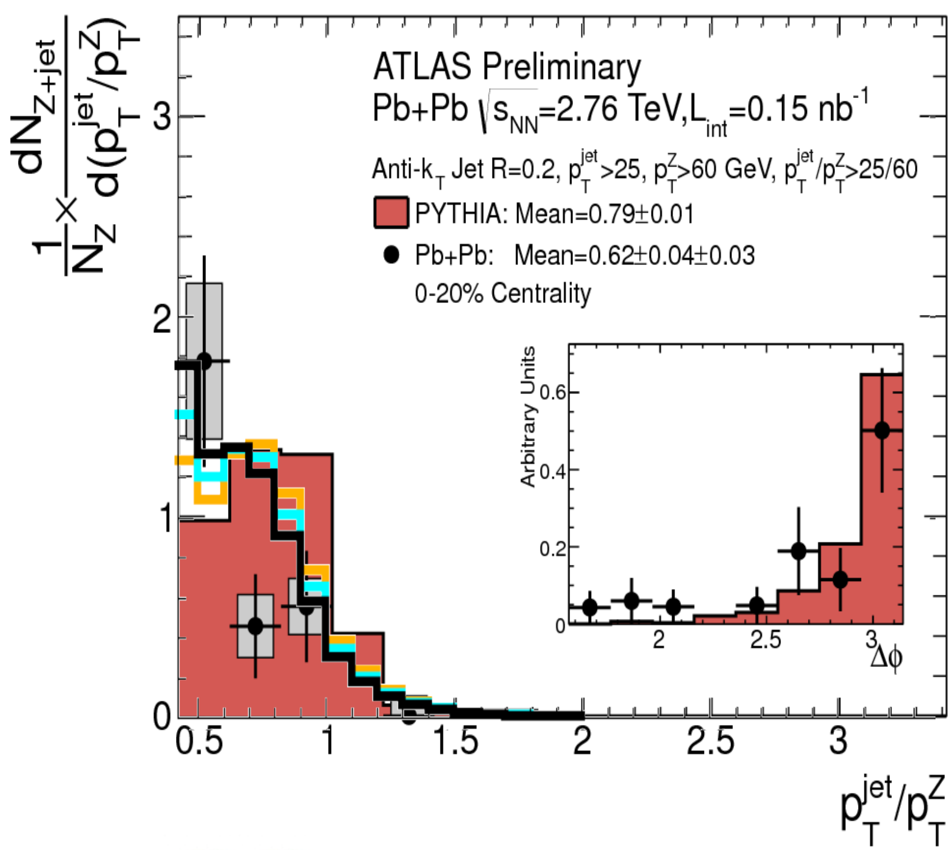
$$\langle z_{J\gamma} \rangle = \int dz_{J\gamma} z_{J\gamma} \frac{1}{\sigma} \frac{d\sigma}{dz_{J\gamma}}$$

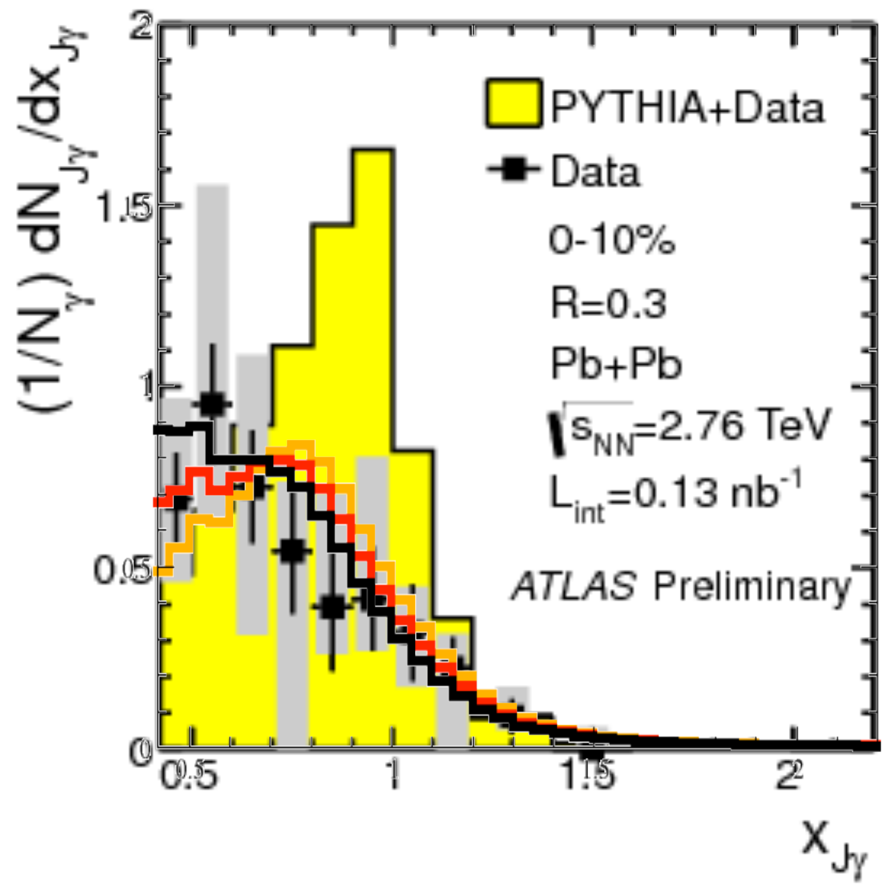


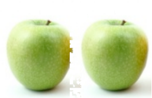

| System | $\langle z_{J\gamma}\rangle_{\rm LHC}$ | $\langle z_{J\gamma}\rangle_{\rm RHIC}$ |
|---|---|---|
| p+p | 0.94 | 0.90 |
| A+A, CNM | 0.94 | 0.89 |
| A+A, $g_{med} = 1.8$ ,Rad.+Col | 0.84 | 0.78 |
| A+A, $g_{med} = 2.0$ ,Rad.+Col | 0.80 | 0.74 |
| A+A, $g_{med} = 2.2$ ,Rad.+Col | 0.71 | 0.70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

- Theoretical simulations with jet-medium couplings that predict the inclusive jet suppression g≈2 can describe quantitatively the modification of event asymmetry distributions

# Comparison to ATLAS data



Theory: prediction, recalculated from **Phys.Rev.Lett. 108 (2012) 242001,** using kinematic cuts (private communications).

S. Milov, J. Cassaldery-Solana (2012)

# SCET formulation

Energetic quarks and leptons
collinear modes

Include also soft quarks and gluons

C. Bauer et al. (2001)

D. Pirol et al. (2004)

$$p_c = (p_+, p_-, p_\perp) \sim (\frac{\Lambda^2}{Q}, Q, \Lambda) = Q(\lambda^2, 1, \lambda)$$

$$p_s = (p_+, p_-, p_\perp) \sim (\Lambda, \Lambda, \Lambda) = Q(\lambda, \lambda, \lambda)$$

- SCET Lagrangian to all orders in λ [Can expand to LO, NLO,…]

| | |
|---|---|
| Collinear quarks, antiquarks | $\xi_n,\ \bar{\xi}_n$ |
| Collinear gluons, soft gluons | $A_n,\ A_s$ |

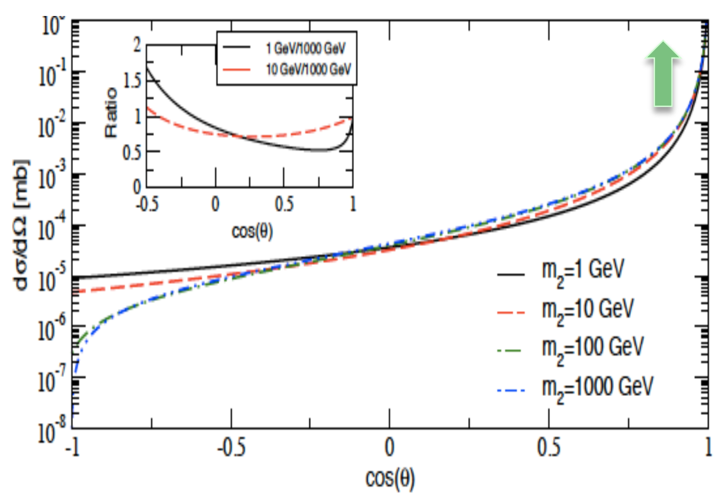
- What is missing

$$\mathcal{L}_{\rm SCET}(\xi_n, A_n, A_s) = \bar{\xi}_n \left[ in\cdot D + i\not{D}^\perp \frac{1}{i\bar{n}\cdot D} i\not{D}^\perp \right] \frac{\not{\bar{n}}}{2}\xi_n + \mathcal{L}_{\rm YM}(A_n, A_s)$$

$$\mathcal{L}_{\rm YM}(A_n, A_s) = \frac{1}{2g^2}{\rm tr}\left\{\left[iD_s^\mu + gA^\mu_{n,q}, iD_s^\nu + gA^\nu_{n,q'}\right]\right\}^2 + \mathcal{L}_{\rm G.F.}\ ,$$

$$\mathcal{L}_{\rm G.F.}(R_\xi) = \frac{1}{\xi}{\rm tr}\left\{\left[iD_{s\mu}, A^\mu_{n,q}\right]\right\}^2 ,$$

$$\mathcal{L}_{\rm G.F.}({\rm LCG}(b)) = \frac{1}{\xi}{\rm tr}\left\{b_\mu A^\mu_{n,q}\right\}^2\ .$$

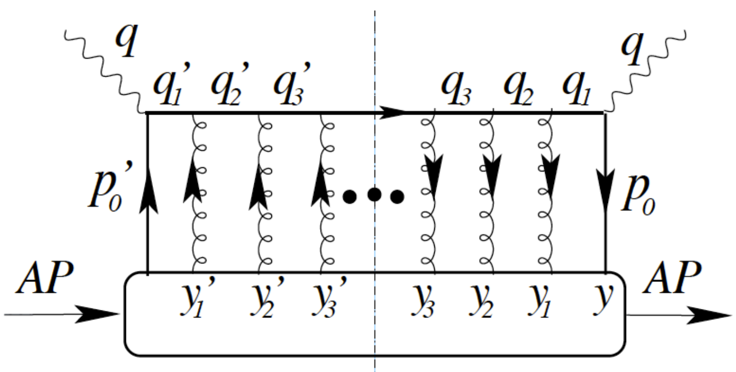


# Applications to nuclear collisions – parton broadening

- Final state parton broadening in semi-inclusive DIS.

A. Idilbi et al. (2008)

**Glauber gluons** $q \sim [\lambda^2, \lambda^2, \lambda]$ $\Gamma_1^{\mu,a} = igT^a n^\mu \frac{\bar{n}}{2}$,




$$\frac{d^2W^{\mu\nu}}{d^2l_\perp} = e^{(DL^-)\nabla^2_{l_\perp}} \frac{d^2W_0^{\mu\nu}}{d^2l_\perp}$$

- Have argued to recover the general QCD result in the Gaussian broadening region

Gyulassy et al. (2002)

- Formulation of a transport coefficient as a Wilson line

$\hat{q} = \langle q_\perp^2 \rangle / \lambda_g$ F. D'Eramo et al. (2010) $W_F[y^+, y_\perp] \equiv P\left\{\exp\left[ig\int_0^{L^-} dy^-\, A^+(y^+, y^-, y_\perp)\right]\right\}$

$$\sum_{m=1,n=1}^{\infty} \frac{d^2 A_{nm}}{d^2 k_\perp} = \frac{\sqrt{2}}{L^3\, N_c} \int dy^+ dy_\perp dy'_\perp\, e^{-ik_\perp\cdot(y_\perp - y'_\perp)} \left\langle \mathrm{Tr}\left[\left(W_F^\dagger[y^+, y'_\perp] - 1\right)\left(W_F[y^+, y_\perp] - 1\right)\right]\right\rangle$$

# The Glauber gluon lagrangian

$$\mathcal{L}_{\rm G}(\xi_n, A_n, \eta) = \sum_{p,p',q} e^{-i(p-p'+q)x} \left( \bar{\xi}_{n,p'} \Gamma^{\mu,a}_{\rm qqA_G} \frac{\bar{\not n}}{2} \xi_{n,p} - i \Gamma^{\mu\nu\lambda,abc}_{\rm ggA_G} \left(A^c_{n,p'}\right)_\lambda \left(A^b_{n,p}\right)_\nu \right) \bar{\eta}\, \Gamma^{\delta,a}_{\rm s}\, \eta\, \Delta_{\mu\delta}(q)$$

- Feynman rules for different sources and gauges

Effective potential

G. Ovanesyan et al. (2011)

| Gauge | Object | Collinear source | Static source | Soft source |
|---|---|---|---|---|
| | $p$ | $[\lambda^2, 1, \boldsymbol{\lambda}]$ | $[1, 1, \boldsymbol{\lambda}]$ | $[\lambda, \lambda, \boldsymbol{\lambda}]$ |
| | $a_{\boldsymbol{p}}, a^\dagger_{\boldsymbol{p}}$ | $\lambda^{-1}$ | $\lambda^{-3/2}$ | $\lambda^{-3/2}$ |
| | $u(p)$ | $1$ | $1$ | $\lambda^{1/2}$ |
| | $\bar{u}(p_2)\gamma_\nu u(p_1)$ | $[\lambda^2, 1, \boldsymbol{\lambda}]$ | $[1, 1, \boldsymbol{\lambda}]$ | $[\lambda, \lambda, \boldsymbol{\lambda}]$ |
| $R_\xi$ | $A^\mu(x)$ | $[\lambda^4, \lambda^2, \boldsymbol{\lambda}^3]$ | $[\lambda^2, \lambda^2, \boldsymbol{\lambda}^3]$ | $[\lambda, \lambda, \boldsymbol{\lambda}]$ |
| | $\Gamma_{\rm qqA_G}$ | $\Gamma^\mu_1$ | $\Gamma^\mu_1$ | $\Gamma^\mu_1$ |
| | $\Gamma_{\rm ggA_G}$ | $\Sigma^{\mu\nu\lambda}_1$ | $\Sigma^{\mu\nu\lambda}_1$ | $\Sigma^{\mu\nu\lambda}_1$ |
| | $\Gamma_{\rm s}$ | $\Gamma^\mu_1\,(n \leftrightarrow \bar{n})$ | $\Gamma^\mu_3$ | $\Gamma^\mu_4$ |
| $A^+ = 0$ | $A^\mu(x)$ | $[0, \lambda^2, \boldsymbol{\lambda}^3]$ | $[0, \lambda^2, \boldsymbol{\lambda}]$ | $[0, \lambda, \mathbf{1}]$ |
| | $\Gamma_{\rm qqA_G}$ | $\Gamma^\mu_1$ | $\Gamma^\mu_1 + \Gamma^\mu_2$ | $\Gamma^\mu_1 + \Gamma^\mu_2$ |
| | $\Gamma_{\rm ggA_G}$ | $\Sigma^{\mu\nu\lambda}_2$ | $\Sigma^{\mu\nu\lambda}_2$ | $\Sigma^{\mu\nu\lambda}_2$ |
| | $\Gamma_{\rm s}$ | $\Gamma^\mu_2\,(n \leftrightarrow \bar{n})$ | $\Gamma^\mu_3$ | $\Gamma^\mu_4$ |
| $A^- = 0$ | $A^\mu(x)$ | $[\lambda^2, 0, \boldsymbol{\lambda}]$ | $[\lambda^2, 0, \boldsymbol{\lambda}]$ | $[\lambda, 0, \mathbf{1}]$ |
| | $\Gamma_{\rm qqA_G}$ | $\Gamma^\mu_2$ | $\Gamma^\mu_2$ | $\Gamma^\mu_2$ |
| | $\Gamma_{\rm ggA_G}$ | $\Sigma^{\mu\nu\lambda}_3$ | $\Sigma^{\mu\nu\lambda}_3$ | $\Sigma^{\mu\nu\lambda}_3$ |
| | $\Gamma_{\rm s}$ | $\Gamma^\mu_1\,(n \leftrightarrow \bar{n})$ | $\Gamma^\mu_3$ | $\Gamma^\mu_4$ |

$$\Gamma^{\mu,a}_1 = igT^a\, n^\mu \frac{\bar{\not n}}{2}\,,$$

$$\Gamma^{\mu,a}_2 = igT^a \frac{\gamma^\mu_\perp \not p_\perp + \not p'_\perp \gamma^\mu_\perp}{\bar{n}\cdot p} \frac{\bar{\not n}}{2}\,,$$

$$\Gamma^{\mu,a}_3 = igT^a\, v^\mu\,,$$

$$\Gamma^{\mu,a}_4 = igT^a\, \gamma^\mu\,,$$

$$\Sigma^{\mu\nu\lambda,abc}_1 = gf^{abc} n^\mu \left[ g^{\nu\lambda}\, \bar{n}\cdot p + \bar{n}^\nu \left(p'^\lambda_\perp - p^\lambda_\perp\right) - \bar{n}^\lambda \left(p'^\nu_\perp - p^\nu_\perp\right) - \frac{1-\frac{1}{\xi}}{2} \left(\bar{n}^\lambda p^\nu + \bar{n}^\nu p'^\lambda\right) \right],$$

$$\Sigma^{\mu\nu\lambda,abc}_2 = gf^{abc} \left[ g^{\mu\lambda}_\perp \left(-\frac{n^\nu}{2} p^+ + p^\nu_\perp - 2p'^\nu_\perp\right) + g^{\mu\nu}_\perp \left(-\frac{n^\lambda}{2} p^+ + p'^\lambda_\perp - 2p^\lambda_\perp\right) + g^{\nu\lambda}_\perp \left(n^\mu\, \bar{n}\cdot p + p^\mu_\perp + p'^\mu_\perp\right) \right],$$

$$\Sigma^{\mu\nu\lambda,abc}_3 = gf^{abc} \left[ g^{\mu\lambda}_\perp \left(\frac{\bar{n}^\nu}{2}(p^- - 2p'^-) + p^\nu_\perp - 2p'^\nu_\perp\right) + g^{\mu\nu}_\perp \left(\frac{\bar{n}^\lambda}{2}(p'^- - 2p^-) + p'^\lambda_\perp - 2p^\lambda_\perp\right) + g^{\nu\lambda}_\perp \left(p^\mu_\perp + p'^\mu_\perp\right) \right].$$

# In-medium parton splitting and gauge independence

| | $R_\xi$ | $A^+$ | Hyb. |
|---|---|---|---|
| $W^+$ | ✔ | ✖ | ✖ |
| $T_n$ | ✖ | ✔ | ✖ |

$$\begin{aligned}\left(\frac{dN}{dx\,d^2\boldsymbol{k}_\perp}\right)_{q\to qg} &= \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm medium}}{d^2\mathbf{q}_\perp} \Bigg[ -\left(\frac{A_\perp}{A_\perp^2}\right)^2 + \frac{B_\perp}{B_\perp^2}\cdot\left(\frac{B_\perp}{B_\perp^2} - \frac{C_\perp}{C_\perp^2}\right) \\ &\times (1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{C_\perp}{C_\perp^2}\cdot\left(2\frac{C_\perp}{C_\perp^2} - \frac{A_\perp}{A_\perp^2} - \frac{B_\perp}{B_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) \\ &+ \frac{B_\perp}{B_\perp^2}\cdot\frac{C_\perp}{C_\perp^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z]) + \frac{A_\perp}{A_\perp^2}\cdot\left(\frac{A_\perp}{A_\perp^2}-\frac{D_\perp}{D_\perp^2}\right)\cos[\Omega_4\Delta z] \\ &+ \frac{A_\perp}{A_\perp^2}\cdot\frac{D_\perp}{D_\perp^2}\cos[\Omega_5 \Delta z] + \frac{1}{N_c^2}\frac{B_\perp}{B_\perp^2}\cdot\left(\frac{A_\perp}{A_\perp^2}-\frac{B_\perp}{B_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\Bigg].\end{aligned}$$

$$N.B.\ x \to 1-x$$

$$\begin{aligned}\left(\frac{dN}{dx\,d^2\boldsymbol{k}_\perp}\right)_{\left\{\begin{matrix} g\to q\bar{q} \\ g\to gg\end{matrix}\right\}} &= \left\{\begin{matrix} \frac{\alpha_s}{2\pi^2} T_R\left(x^2+(1-x)^2\right) \\ \frac{\alpha_s}{2\pi^2} 2C_A\left(\frac{x}{1-x}+\frac{1-x}{x}+x(1-x)\right)\end{matrix}\right\} \int d\Delta z \left\{\begin{matrix}\frac{1}{\lambda_q(z)} \\ \frac{1}{\lambda_g(z)}\end{matrix}\right\} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm medium}}{d^2\mathbf{q}_\perp} \\ &\times \Bigg[2\frac{B_\perp}{B_\perp^2}\cdot\left(\frac{B_\perp}{B_\perp^2}-\frac{A_\perp}{A_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + 2\frac{C_\perp}{C_\perp^2}\cdot\left(\frac{C_\perp}{C_\perp^2}-\frac{A_\perp}{A_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) \\ &+ \left\{\begin{matrix}\frac{1}{N_c^2-1} \\ -\frac{1}{2}\end{matrix}\right\}\Bigg(2\left(\frac{A_\perp}{A_\perp^2}-\frac{B_\perp}{B_\perp^2}\right)\cdot\left(\frac{A_\perp}{A_\perp^2}-\frac{C_\perp}{C_\perp^2}\right) + 2\frac{B_\perp}{B_\perp^2}\cdot\left(\frac{A_\perp}{A_\perp^2}-\frac{C_\perp}{C_\perp^2}\right)\cos[(\Omega_1-\Omega_2)\Delta z] \\ &+ 2\frac{C_\perp}{C_\perp^2}\cdot\left(\frac{A_\perp}{A_\perp^2}-\frac{B_\perp}{B_\perp^2}\right)\cos[(\Omega_1-\Omega_3)\Delta z] + 2\frac{C_\perp}{C_\perp^2}\cdot\frac{B_\perp}{B_\perp^2}\cos[(\Omega_2-\Omega_3)\Delta z] \\ &- 2\frac{A_\perp}{A_\perp^2}\cdot\left(\frac{A_\perp}{A_\perp^2}-\frac{D_\perp}{D_\perp^2}\right)\cos[\Omega_4\Delta z] - 2\frac{A_\perp}{A_\perp^2}\cdot\frac{D_\perp}{D_\perp^2}\cos[\Omega_5\Delta z]\Bigg)\Bigg].\end{aligned}$$

- First proof of gauge invariance

G. Ovanesyan et al. , (2011)

# Factorization of medum-induced radiative corrections

- First proof beyond the soft gluon approximation

$$d\sigma(\epsilon_1,\cdots,\epsilon_n)^{n-\text{jet}}_{\text{quench.}} = d\sigma(\epsilon_1,\cdots,\epsilon_n)^{n-\text{jet}}_{\text{pp}} \otimes P_1(\epsilon_1)\cdots \otimes P_n(\epsilon_n)\ |J_1(\epsilon_1)|\cdots|J_n(\epsilon_n)|\,.$$

Final-state medium-induced radiative corrections factorize form the hard scattering cross section in QCD

G. Ovanesyan et al. (2011)

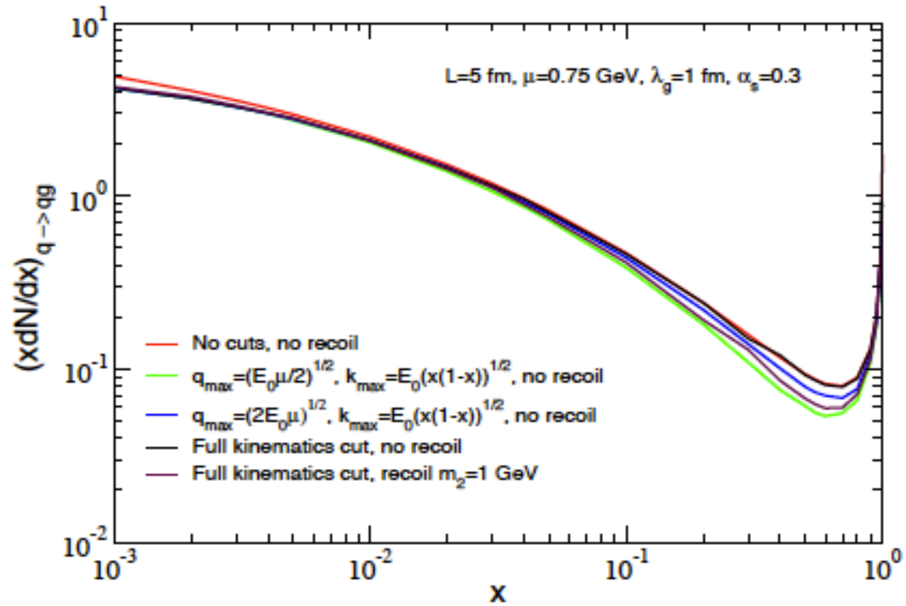
$$x\left(\frac{dN}{dx d^2\boldsymbol{k}_\perp}\right)_{\begin{Bmatrix} q\to qg \\ g\to gg \\ q\to gq \\ g\to q\bar{q}\end{Bmatrix}} = \frac{\alpha_s}{\pi^2}\begin{Bmatrix} C_F[1+\mathcal{O}(x)] \\ C_A[1+\mathcal{O}(x)] \\ C_F[0+\frac{x}{2}+\mathcal{O}(x^2)] \\ T_R[0+\frac{x}{2}+\mathcal{O}(x^2)]\end{Bmatrix}$$
$$\times\int d\Delta z \begin{Bmatrix} \frac{1}{\lambda_g(z)} \\ \frac{1}{\lambda_g(z)} \\ \frac{1}{\lambda_q(z)} \\ \frac{1}{\lambda_q(z)}\end{Bmatrix} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\text{medium}}}{d^2\mathbf{q}_\perp}$$
$$\times\frac{2\boldsymbol{k}_\perp\cdot\boldsymbol{q}_\perp}{\boldsymbol{k}_\perp^2(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2}\left[1-\cos\frac{(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2}{xp_0^+}\Delta z\right].$$

- In the soft limit we recover the GLV results (1st order in opacity)
- Only in this limit there is a natural energy loss interpretation

# Phenomenology with $SCET_G$

G. Ovanesyan, P. Saad,
R. Lashoff- Regas

- New Monte Carlo code was written
- Improved kinematics to go beyond the soft gluon approximation

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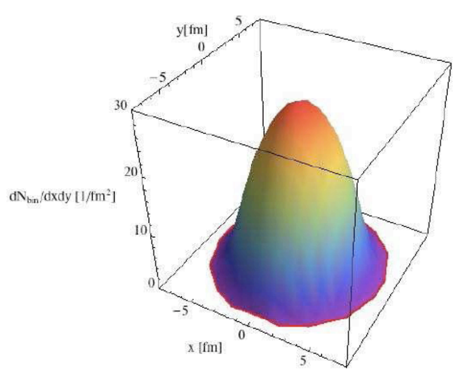
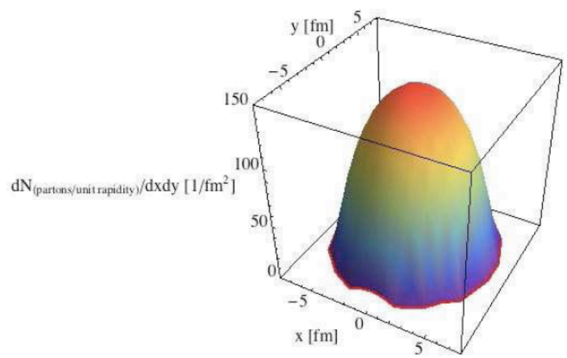
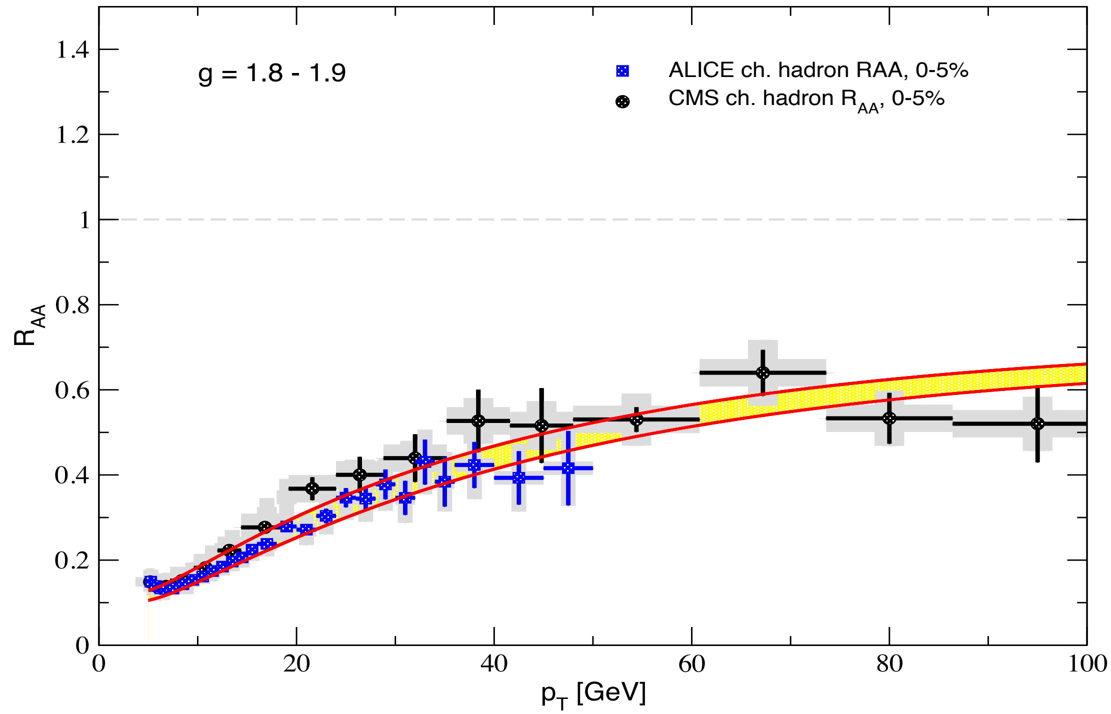



- Can evaluate the full-medium induced splitting kernels
- The energy loss limit results are obtained much faster

# The new energy loss limit versus LHC data

- The energy loss approach gives (not surprisingly) a good description of the ALICE and CMS charged hadron suppression data
- At very high $p_T$ $R_{AA}$ may be sensitive to CNM effects
- The effective coupling between the jet and the medium g = 1.8 – 1.9 is 10% smaller, reflective of the updated kinematic constraints




To be further compared to
1) the in-medium evolution in the soft gluon limit
2) The use of the full medium-induced splitting kernels

See talk by G. Ovanesyan (2014)

# QGP – modified jet shapes

- Differential and integral jet shapes

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

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

- Similar idea to the cross section evaluation.

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

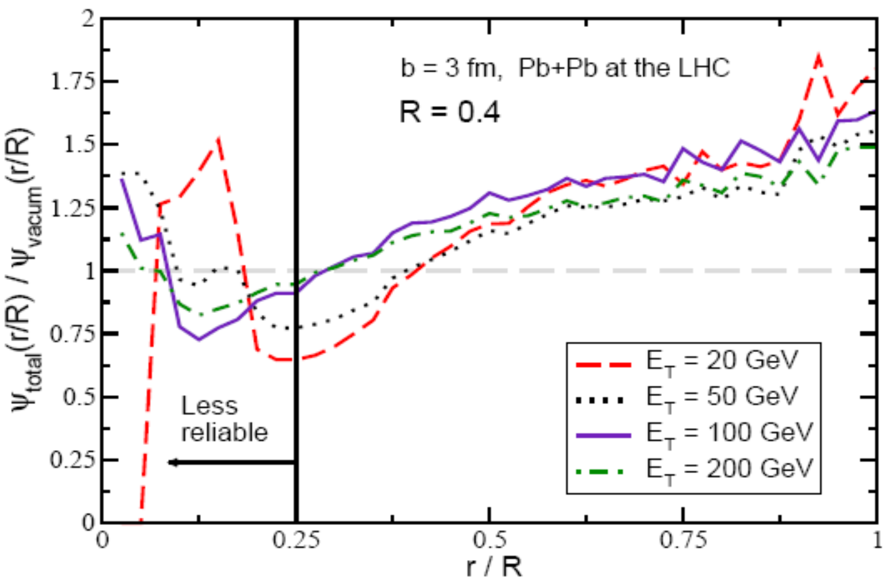
| R=0.4 | Vacuum | Complete E-loss | Realistic Case |
|---|---|---|---|
| <r/R>, $E_T$=20GeV | 0.41 | 0.57 | 0.45 |
| <r/R>, $E_T$=50GeV | 0.35 | 0.53 | 0.38 |
| <r/R>, $E_T$=100GeV | 0.28 | 0.42 | 0.32 |
| <r/R>, $E_T$=200GeV | 0.25 | 0.42 | 0.28 |

- 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

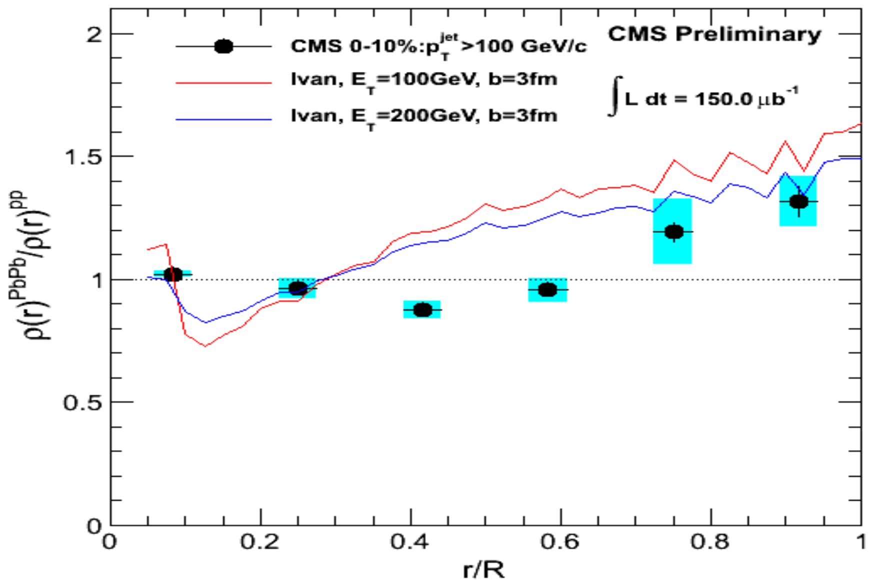
I. Vitev et al. (2008)

# Phenomenology with $SCET_G$

- Qualitative features predicted. Quantitatively, the enhancement near the periphery of the jet
- The exact details of the shape deviate at small and intermediate r/R




**"Comparison" to CMS data**




- This is the region where we hope we can improve using SCET resummation techniques and full $SCET_G$ medium-induced splittings

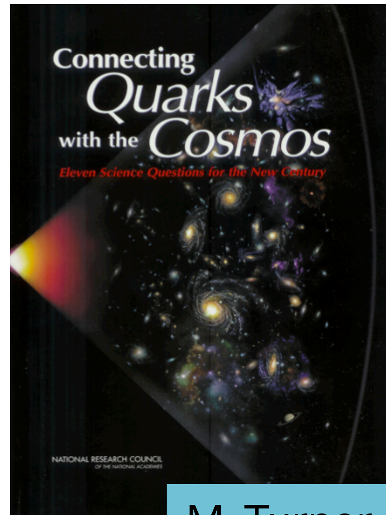
See talk by Y.-T.Chien (2014)

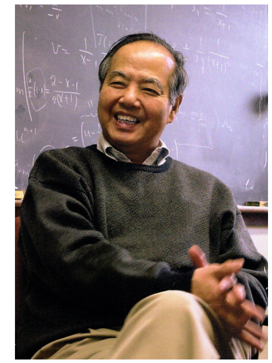
# Conclusions

- Heavy ion physics is a fascinating field: it spawned and attracts attention a large number of theoretical approaches: relativistic hydrodynamics, transport models, lattice QCD, pQCD, jet physics, small-x/gluon saturation, AdS/CFT
- Jet quenching/energy loss observable are the ones most closely related to pQCD.
- The energy-loss jet quenching phenomenology (inclusive particle suppression) has been very successful at RHIC,LHC. Tested against competing hypotheses. Some problems were identified with the jet tomography application. Now they appear largely resolved
- The field I transitioning to understanding parton shower modification in the QGP and to studying jet observables that are sensitive to such modification. Presented results for inclusive jet production at RHIC and the LHC, $Z^0/\gamma$-tagged jets and di-jets at the LHC.
- An effective theory of jet propagation in matter was developed with complete set of Feynman rules in different sources and gauges. Proved gauge invariance of the jet broadening and energy loss results. Showed factorization of the medium-induced radiative corrections for the hard scattering, accurate results beyond the soft gluon approximation for the medium-induced parton splitting.
- Work in progress for the first applications of $SCET_G$ results to heavy ion phenomenology, such as jet shapes and hadron $R_{AA}$. Aim is to understand the qualitative similarities and quantitative differences w.r.t. energy loss approaches

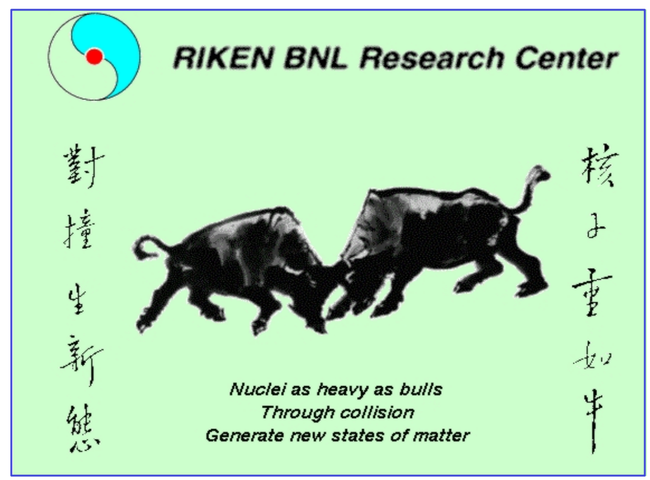
# XI Science questions for the new century

- ***What is the dark matter?***
- ***What is the nature of the dark energy?***
- ***How did the universe begin?***
- ***Did Einstein have the last word on gravity?***
- ***What are the masses of the neutrinos, and how have they shaped the evolution of the universe?***
- ***How do cosmic accelerators work and what are they accelerating?***
- ***Are protons unstable?***
- ***Are there new states of matter at exceedingly high density and temperature?***
- ***Are there additional spacetime dimensions?***
- ***How were the elements from iron to uranium made?***
- ***Is a new theory of matter and light needed at the highest energies?***



M. Turner et al. (2009)



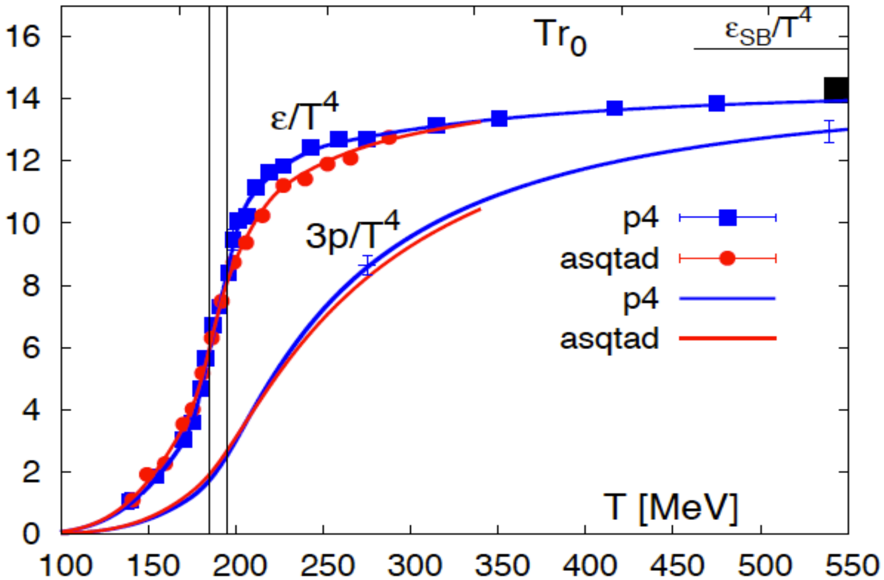
# Lattice QCD results

Livermore Blue Gene supercomputer

QCD - $\alpha_s = 0.1 - 1$ (different techniques for different regimes)

- QGP equation-of-state, speed of sound have been “measured” on the lattice
- The phase transition temperature has been determined: 175-190 MeV

- Topics of interest further include, melting of quarkonia, transport coefficients
- Other techniques: AdS/CFT correspondence




HotQCD Collaboration (2009)

# Quantitative constraints form RHIC and the LHC using viscous hydro

$u^{\mu}(x)$

$T^{\mu\nu}(x) = \left(\varepsilon(x) + p(x)\right)u^{\mu}(x)u^{\nu}(x) - p(x)g^{\mu\nu}$

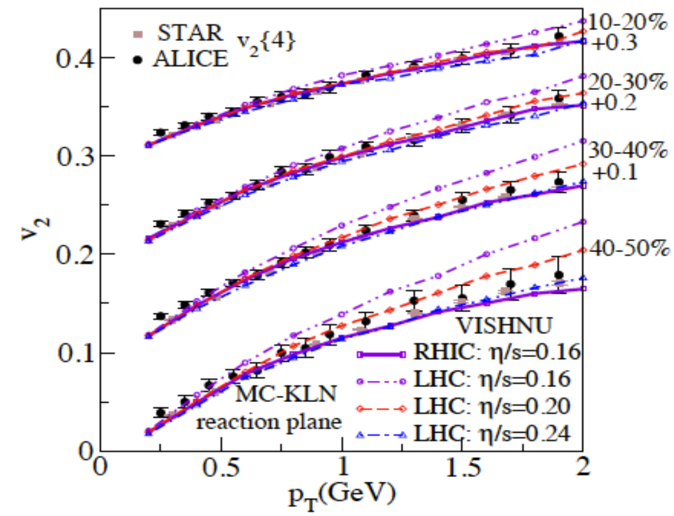
$j_{\alpha}^{\mu}(x) = n_{\alpha}u^{\mu}(x)$

$$\partial_{\mu}T^{\mu\nu}(x) = 0$$

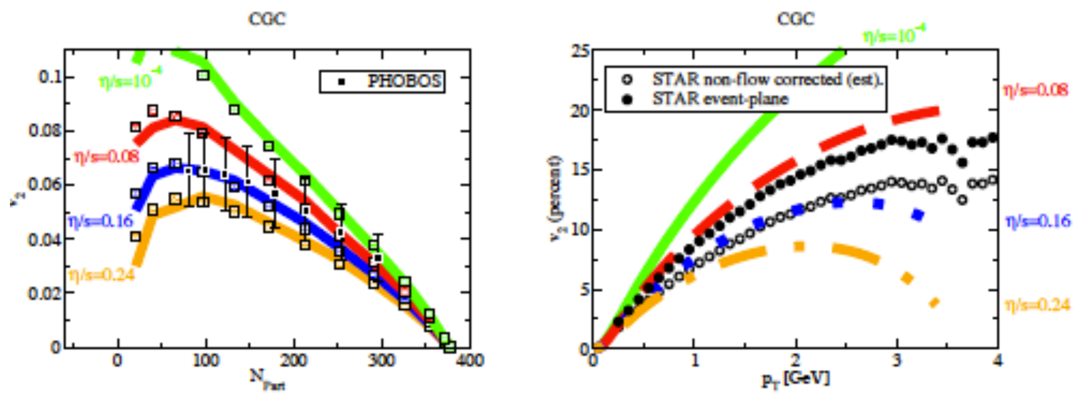
$$\partial_{\mu}j_{\alpha}^{\mu}(x) = 0$$

**Note: ideal hydro, not viscous**

**Hydro fit to LHC data**




H. Song et al. (2011)

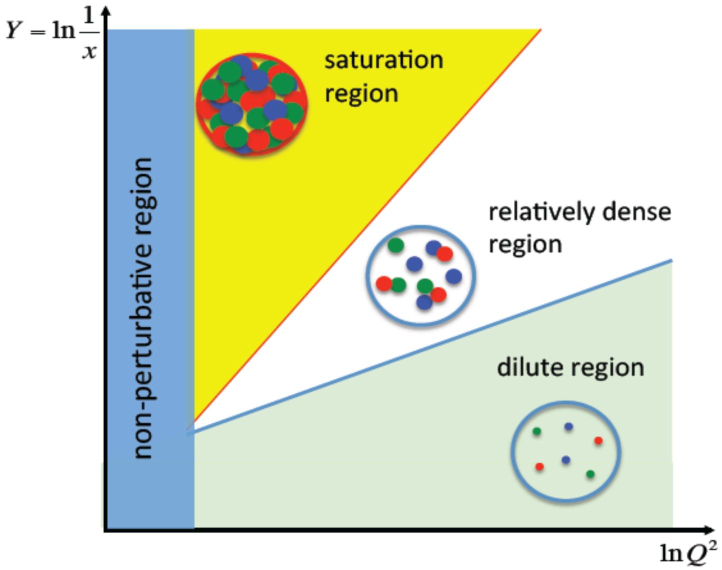


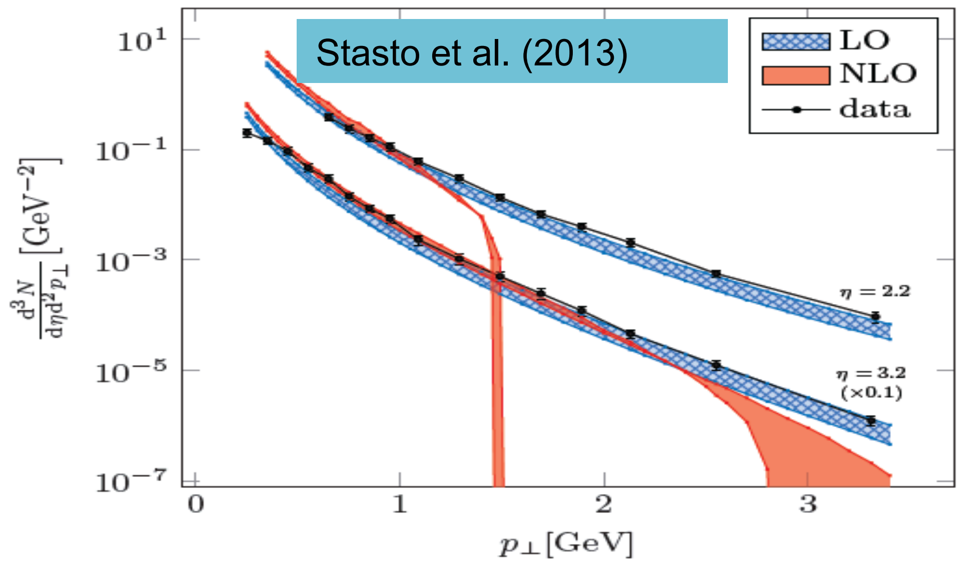

**Hydro fit to RHIC data**

M.Luzum et al. (2009)

- Within the scope of explored uncertainties and if relativistic hydrodynamic is applicable η/s=(2-3) 1/4π. At the LHC the viscosity to entropy density ratio is slightly higher than at RHIC

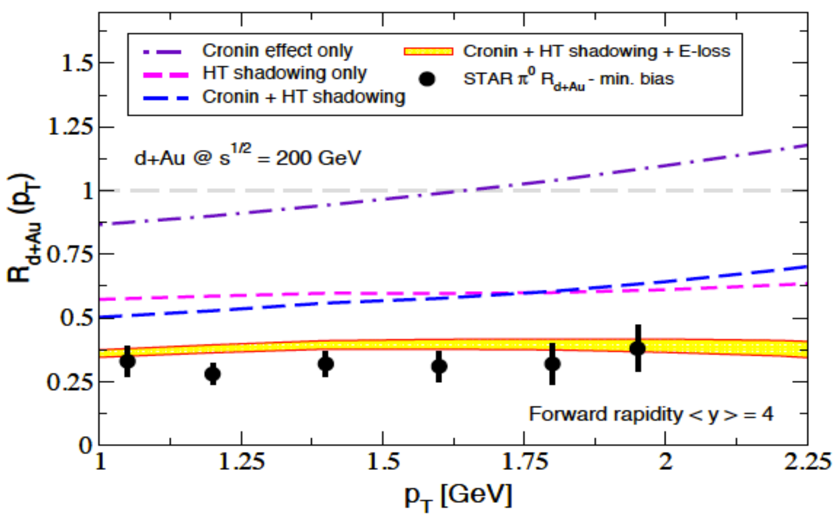
# CGC models and small-x physics




**Applicability:** $x << 10^{-2},\ Q \le Q_s(1-2\ GeV)$

- In heavy ion collisions: initial conditions for hydro evolution as a Glauber model alternative, multiplicity distributions, soft long-range rapidity correlations




Neufeld et al. (2011)