Theory Summary

Sangyong Jeon（전상용 錢相蓉）

McGill University, Montreal, Canada

Summarizing a conference

- ... is worse than herding a hundred cats

Summarizing a conference

- ... is worse than herding a hundred cats
- It's like herding a hundred cats
  and persuading each of them to give up a piece of the jigsaw puzzle

Summarizing a conference

- ... is worse than herding a hundred cats
- It's like herding a hundred cats
  and persuading each of them to give up a piece of the jigsaw puzzle
- Should make this

Summarizing a conference

- ... is worse than herding a hundred cats
- It's like herding a hundred cats
  and persuading each of them to give up a piece of the jigsaw puzzle
- But it is going to be a personal picture – I apologize for any missing pieces and misplaced pieces

Summarizing a conference

- ... is worse than herding a hundred cats
- It's like herding a hundred cats
  and persuading each of them to give up a piece of the jigsaw puzzle
- But it is going to be a personal picture – I apologize for any missing pieces and misplaced pieces

Jet parallel talks

Advances in Jet Theory

- Escobedo [Sat.Jet.1]: Fluctuations in E-loss
- var der Schee [Sat.Jet.1]: Jet E-loss and cone-angle in AdS/CFT
- Nonaka [Sat.Jet.2]: The $\hat{q}$ from Lattice
- Apolinario [Sat.Jet.2], Dominguez [Sun.Jet.3]: Factorization beyond eikonal approximation
- Ringer [Sat.Jet.2]: Jet production from SCET
- Pablos [Sat.Jet.3]: Angular jet structure in a hybrid model
- Ayala [Sun.Jet.3], Transport coeff. from e-loss in linearized hydro
- Horowitz [Sun.Jet.3]: Wobbly limp noodle (Time dep. $\hat{q}$ from AdS/CFT)
- Majumder [Sun.High p_T.2]: PDF of QGP partons
- Rasonaivoa [Sun.High p_T.2], N-gluon emission amplitude

Event Generators for Jets

- Kordell [Sat.Sim.1], MATTER
- Branafoldi [Sat.Sim.1], HIJING++
- BierLich [Sat.Sim.1], General Purpose Event Generator
- PETRUSHANKO [Sat.Sim.1], HYDJET++
- Luo [Sat.RT.1], LBT
- Apolonario [Sat.RT.1], QPYTHIA
- Pablos [Sat.RT.1], Hybrid
- Kordell [Sat.RT.1], MATTER
- Jeon [Sat.RT.1], MARTINI

Advances in Jet parameter extractions

- Andres Casas [Sat.Jet.1]: QPYTHIA, New $\hat{q}$ puzzle
- Chang [Sun.Jet.6]: Jet shape using Boltzmann + Hydro
- Zhang [Sun.High p_T.1]: New fit for $\hat{q}$ and λ_0
- Chen [Sun.High p_T.2]: Jet charge using PYQUEN

Advances in Jet data descriptions

- Ma [Sat.Jet.3]: Jet reconstruction, Dijet asymmetry using AMPT
- Lapidus [Sat.Jet.3]: z_g discriminates JEWEL and YaJEM
- Kunnawalkam Elayavalli [Sat.Jet.3], JEWEL with recoil can do z_g distributions
- Dai [Sun.High p_T.1]: High p_T η's are mostly from quark jets
- Tachibana [Sun.Jet.6]: Jet-medium interaction can do jet shape functions

High p_T correlations parallel talks

Advances in high p_T correlations

Adv. in QGP param. extractions with the High p_T correlations

- Wei [Sun.Corr.3]: Sudakov resummation. Jet broadening through di-hadron ad hadron-jet corr. can measure $\hat{q}L$.

Advances in the High p_T correlations data descriptions

- Chen W. [Sat.Corr.1]: Linear Boltzmann Transport (LBT) can do gamma-jet
- Luo [Sat.Corr.2]: LBT can do gamma-jet and dijet

Electromagnetic Probes parallel talks

Advances in the EM Theory & Modelling

- Hauksson [Sat.EM.2]: Bulk viscosity δf corrections
- Greif [Sat.EM.2]: BAMP with LO photons
- Ru [Sat.EM.3]: Kulagin-Petti nPDF are better for W and Z
- Benic [Sat.EM.3]: LO CGC pA photons
- Ruggieri [Sat.EM.3]: Early stage photons from CGC is bright around $p_T \approx 2\,\text{GeV}$

Adv. in QGP param. extractions with the EM probes & Data descriptions

Bulk viscosity extraction

- Vujanovic [Sat.EM.1]: Bulk viscosity effect opposite in $l\bar{l}$ v_2 and h v_2

Photon v_2 puzzle

- Yang [Sat.EM.2]: Holographic models make both spectra and flow at high p_T go up

Heavy Flavor parallel talks

Advances in the HF Theory

- Hambrock [Sat.HF.2]: AdS/CFT inspired model
- Salgado [Sat.HF.2]: Use top for early time dynamics
- D'Enterria [Sat.HF.2]: Higgs and tops in HIC
- Hattori [Sat.HF.4]: Quark diffusion with strong B field
- Gossiaux [Sun.Quarko.2]: Schrödinger-Langevin approach
- Chen [Sun.HQ-Quarko.1]: Light front Hamiltonian

Adv. in QGP param. extractions with the HF probes & Data descriptions

Adv. in QGP param. extractions with the HF probes

- Xu [Sat.HF.3]: Data driven analysis of T dependent HF transport coefficient

Advances in the HF data descriptions

- Cao [Sat.HF.1]: R_{AA} and v_2 with LBT
- Noronha [Sat.HF.1]: R_{AA} and v_n with visc. hydro
- Xu [Sat.HF.1]: BAMP. Jet shape functions for b-tagged jets
- Greco [Sat.HF.3]: Fokker-Planck. Drag $D \sim T^{0-1}$
- He [Sat.HF.4]: T-matrix approach. R_{AA} and v_2.
- Lansberg [Sun.Quarko.2]: Understanding feed-down patterns with co-mover approach

Small systems parallel talks

Advances in the Small Systems Study

- Vogt [Sat.pp-pA.1]: Predictions for pA
- Levai [Sat.pp-pA.1]: Anisotropic gluon brem in GLVB
- Park [Sat.pp-pA.1]: Jets in MARTINI with L-dep and $\alpha(k)$
- Shen [Sat.EM.1]: Systematic study of small system EM probes
- Zhu [Sat.pp-pA.2]: NLO hadron cross-section with a rapidity (UV) cut-off
- Lappi [Sat.pp-pA.2]: NLO BK might spoil geometric scaling

Initial States parallel talks

Advances in the Initial State studies

- Fries [Sun.Init.1]: Small τ expansion of Glasma evolution
- Mantysaari [Sun.Init.1]: Fluctuating proton in pA
- McDonald [Sun.Init.1]: New IP-Glasma implementation
- Csernai [Sun.Init.1]: New skewed IS model for peripheral collisions

Plenary talks

Friday Plenary talks

- Armesto: Theory overview
- Kaczmarek: Hard probes on the Lattice
- Venugopalan: IS of Heavy-Ion collisions and Hard Probes
- Cacciari: Jet substructure
- Jets in strong coupling: Casalderry-Solana

Monday Plenary talks

- Tywoniuk: Parton energy loss in QCD matter
- Qin: Modification of jet rate, shape and structure model and phenomenology
- Vitev: SCET for jet physics in the vacuum and the medium
- Verweij: Monte Carlo simulations of hard probes
- Noronha-Hostler: Resolving R_{AA} and v_n puzzle
- Arleo: Hard processes in p+A collisions
- Gonzalez Ferreiro: Quarkonium production in pp and pA
- Evolution equations and factorization in pA collisions

Tuesday Plenary talks

- Nahrgang: Heavy Flavor Theory
- Strickland: Quarknoia production
- Paquet: Photons and dileptons production

Plenary speakers did amazing job in summarizing the state of each field.

Plenary speakers did amazing job in summarizing the state of each field.

That frees me to talk about what I want to talk about.

Plenary speakers did amazing job in summarizing the state of each field.

That frees me to talk about what I want to talk about.

I will mainly talk about parallel session talks.

Plenary speakers did amazing job in summarizing the state of each field.

That frees me to talk about what I want to talk about.

I will mainly talk about parallel session talks.

Again with apologies to those I won't be able to mention directly.

What do we really want to know about?

QCD properties

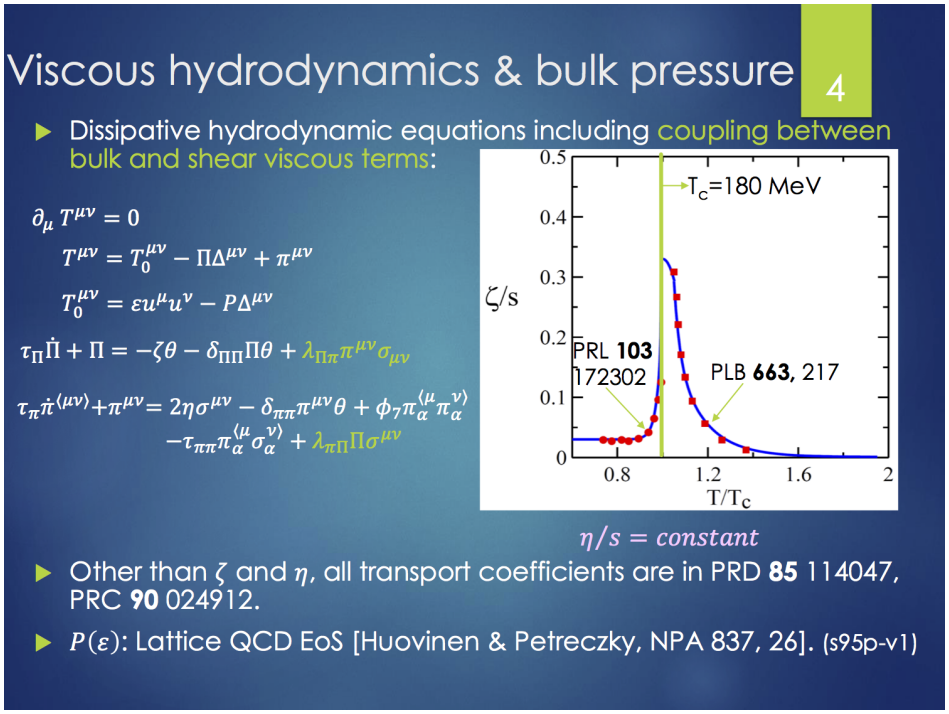
Hard probes are tools to study Many-body QCD.

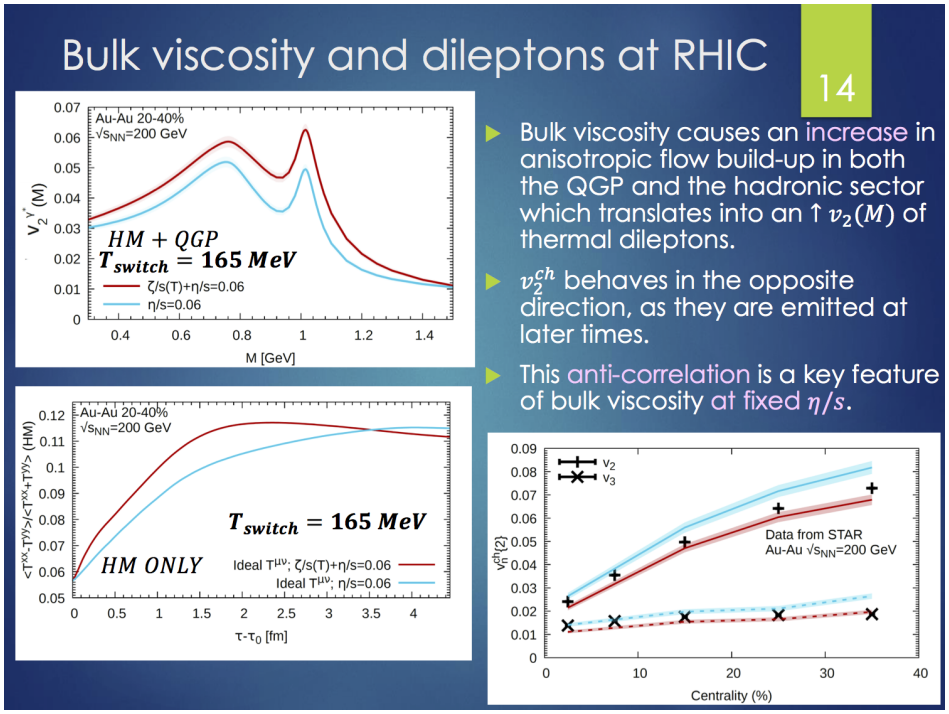
- *In particular, QGP properties*
  - Thermalization
  - Equation of state
  - $\alpha_S(T)$
  - Transport coefficients – $\eta/s, \zeta/s, \hat{q}, \hat{e}, \ldots$
- *Also how they are being modified – We want to understand the underlying physics*
- Caveat: *Modifications in hard probes are both means and ends of theory*

To learn: QGP property – $\frac{\zeta}{s}$

QGP Property – Bulk Viscosity

- Vujanovic [Sat.EM.1]: Dileptons and hadrons behave oppositely



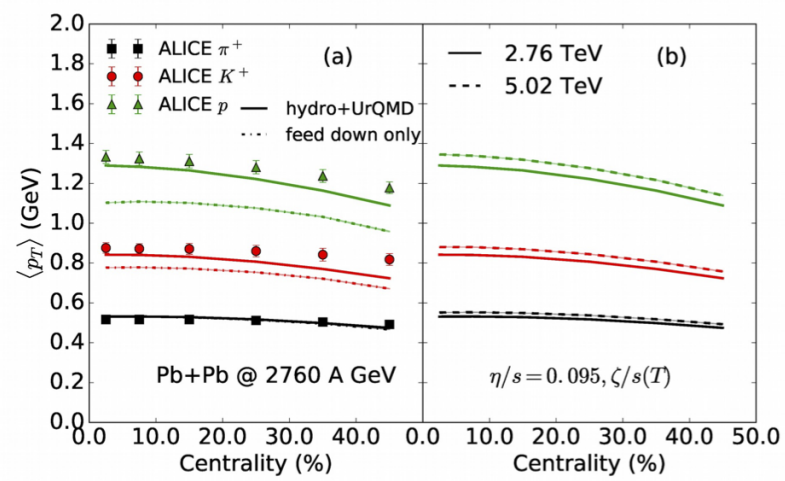


QGP Property – Bulk Viscosity

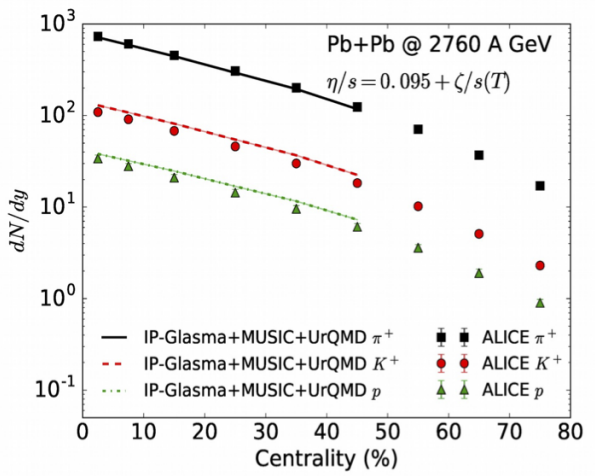
- McDonald [Sun.Init.1]: With the same ζ and new implementation of IP-Glasma

Testing the Model and Making Predictions

Identifed Particle $\langle p_T \rangle$



Identifed Particle dN/dy

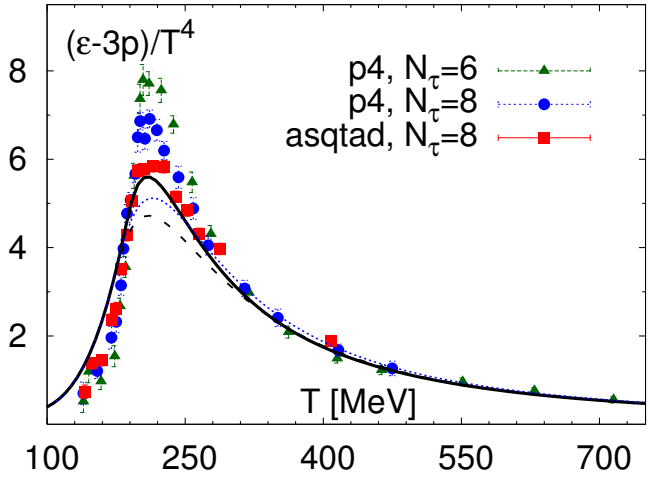


- *Effects of hadronic re-scatterings and bulk viscosity*
  - *Prediction for 5.02 TeV shows slight increase over 2.76 TeV*

- *Particle sampling is able to reproduce particle multiplicities.*

McDonald, et. al. (arXiv:1609.02958)

Mini Summary – Bulk Viscosity



Lattice QCD

[Bazavov et al. Phys.Rev. D80 (2009) 014504]

- The conformal anomaly $\theta = T^{\mu}_{\ \mu}$ also has a peak near T_c
- In FTFT: $\zeta \propto \theta^2$
- In AdS/(broken CFT): $\zeta \propto \theta$
- One of very few ways to get at the conformal anomaly
- More observables sensitive to ζ/s desirable

To learn: QGP property – $\hat{q}$

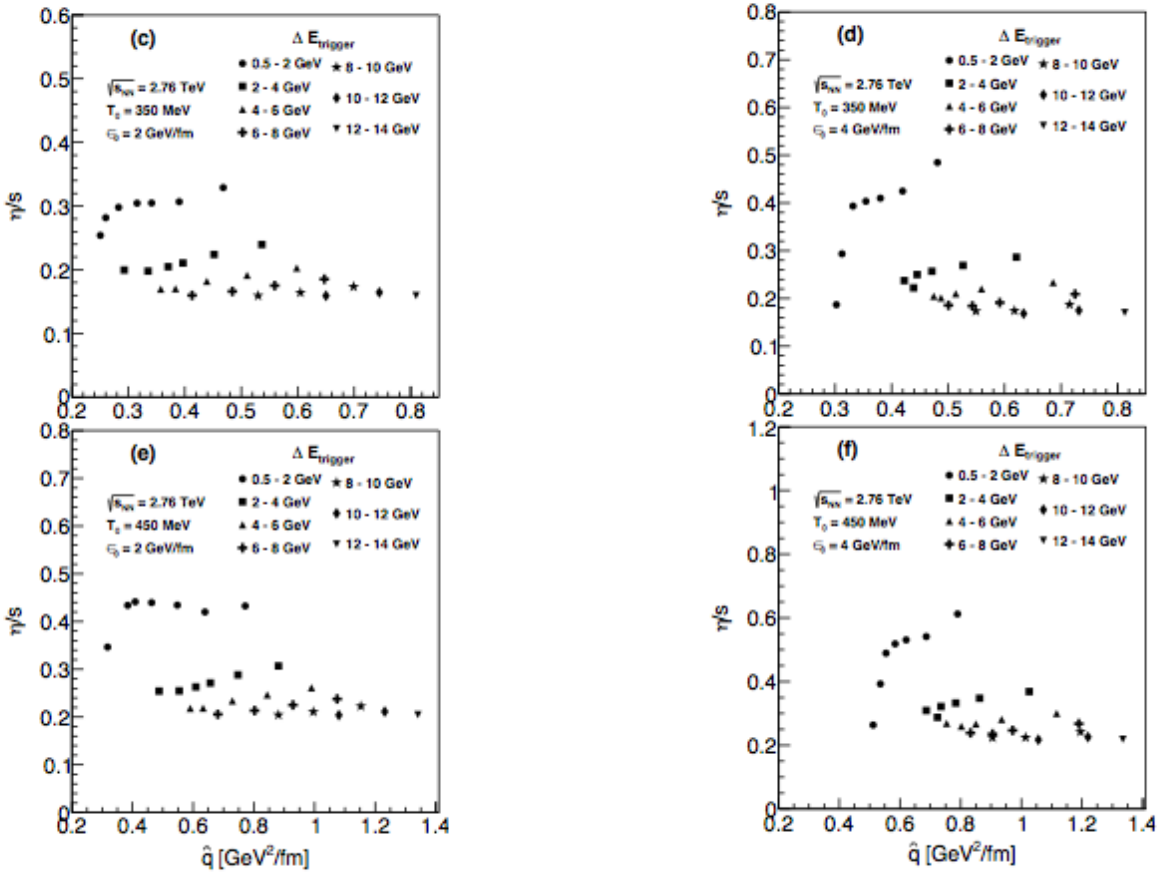
QGP Property – $\hat{q}$

- $\hat{q}$ through jet-medium interactions

  Ayala [Sun.Jet.3]: Medium excitation is sensitive to dE/dx

25

$\hat{q}$ vs η/s (trigger particle)

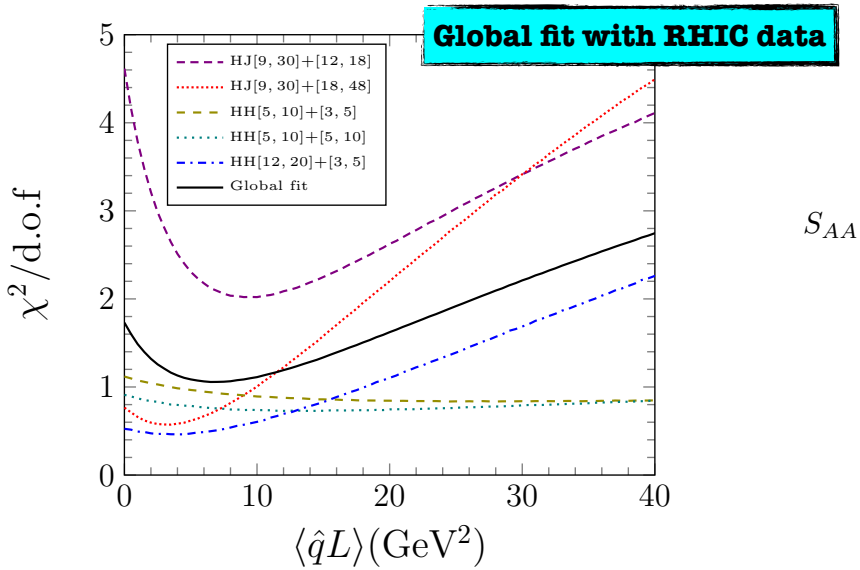


QGP Property – $\hat{q}$

- $\hat{q}L$ through jet-medium interactions

  Wei [Sun.Corr.3]: Di-hadron and hadron jet angular correlation sensitive to $\hat{q}L$

Dihadron & hadron-jet correlations



$$S_{AA}(Q,b) = S_{pp}(Q,b) + \frac{\langle \hat{q}L \rangle b^2}{4}$$

$$\langle \hat{q}L \rangle_{\rm tot} = 14^{+42}_{-14}\ {\rm GeV}^2$$

larger than the value, $\hat{q} = 1.2 \pm 0.3\ {\rm GeV}^2/{\rm fm}$ extracted from single hadron R_{AA} by JET Collaboration

- ☑ Radiative correction
- ☑ Effective length

QGP Property – $\hat{q}$

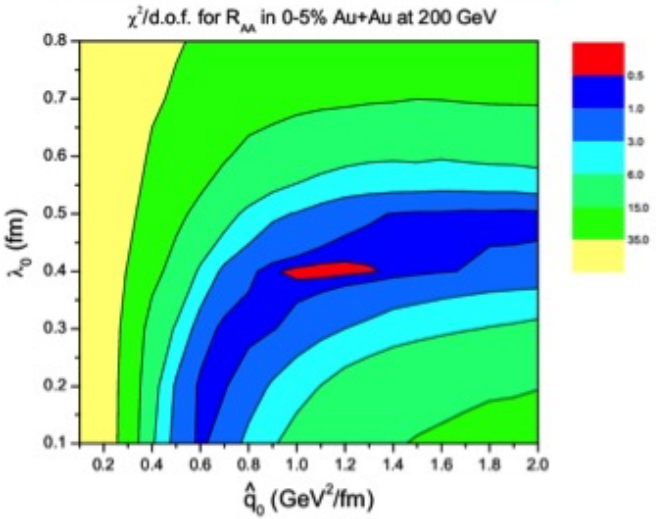
- Zhang [Sun.High p_T.1]: Bracketing $\hat{q}$

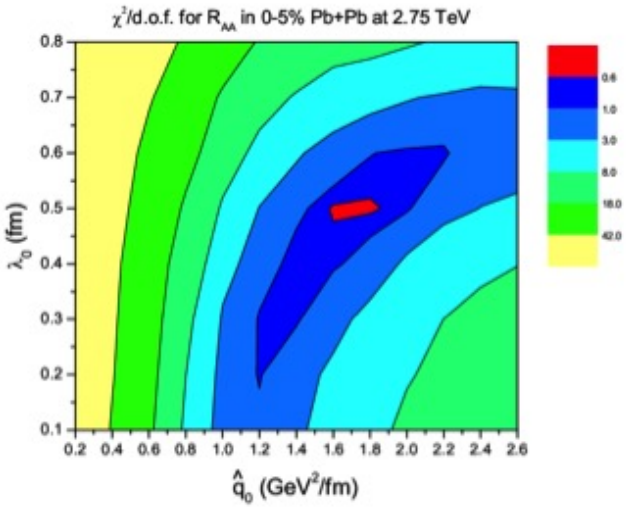
Extracting parameters $\hat{q}_0$ and λ_0 at RHIC/LHC

With simultaneous χ2 /d.o.f. fits for $R_{AA}(p_T)$ in central A+A collisions

A couple of inputs: $\hat{q}_0$, λ_0

$$\chi^2/\text{d.o.f} = \sum_{i=1}^{N} \left[\frac{(V_{th} - V_{exp})^2}{\sum_t \sigma_t^2} \right]_i \Big/ N$$





RHIC $\begin{cases} \hat{q}_0 = 1.1 \pm 0.2 GeV^2/fm \\ \lambda_0 = 0.4 \pm 0.03 fm \end{cases}$

LHC $\begin{cases} \hat{q}_0 = 1.7 \pm 0.3 GeV^2/fm \\ \lambda_0 = 0.5 \pm 0.05 fm \end{cases}$

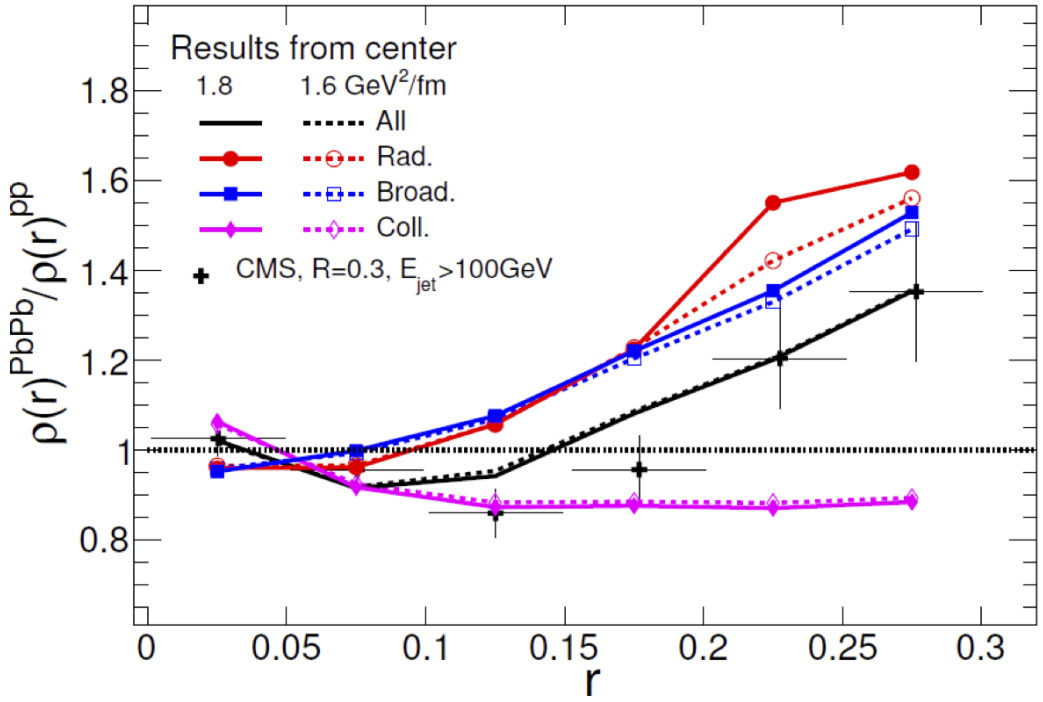
Z. Liu , H. Z. Zhang, B. W. Zhang and E. Wang, Eur.Phys.J. C76 (2016) 20

9

QGP Property – $\hat{q}$

- Chang [Sun.Jet.6]: With Boltzmann + Hydro
- $\hat{q}_{30-40} = (1.8-1.6\,\mathrm{GeV}^2/\mathrm{fm})\dfrac{T^3_{30-40}}{T^3_{0-10}}$

Sensitivity to the value of qhat



Every mechanism has sensitivity to qhat,
but the sensitivity become modest when all of them exist

QGP Property – HF $\hat{q}$

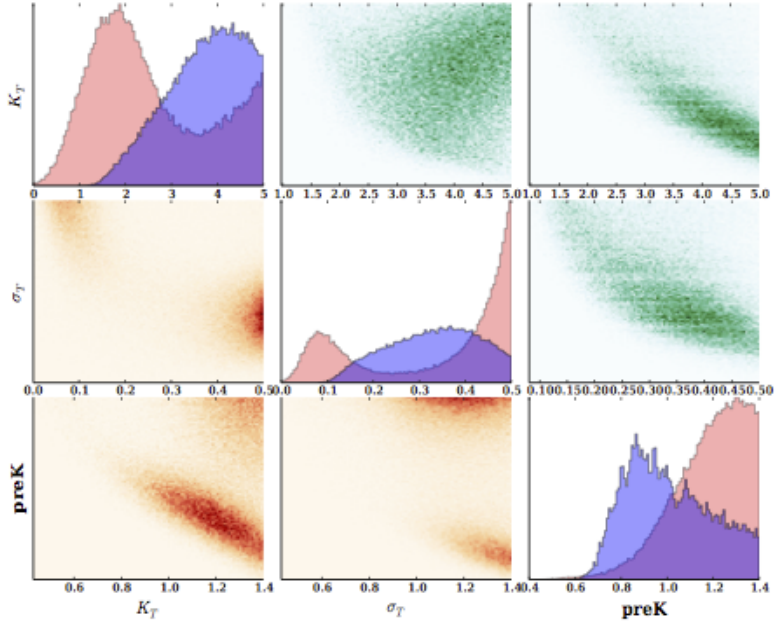
- Xu Y. [Sat.HF.3]: Bayesian revolution is coming

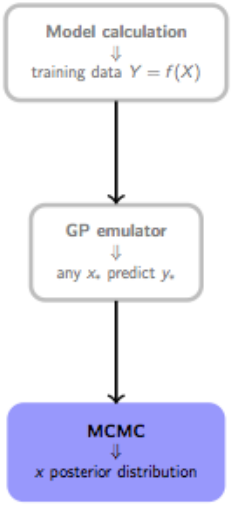
$$D_s = T^2/\hat{q},\ \hat{q} = \hat{q}_{pQCD} preK \left(1 + K_T e^{-(T-T_c)^2/2\sigma_T^2}\right)$$

T-dependence results: MCMC (calibration)

posterior probability distribution of parameters

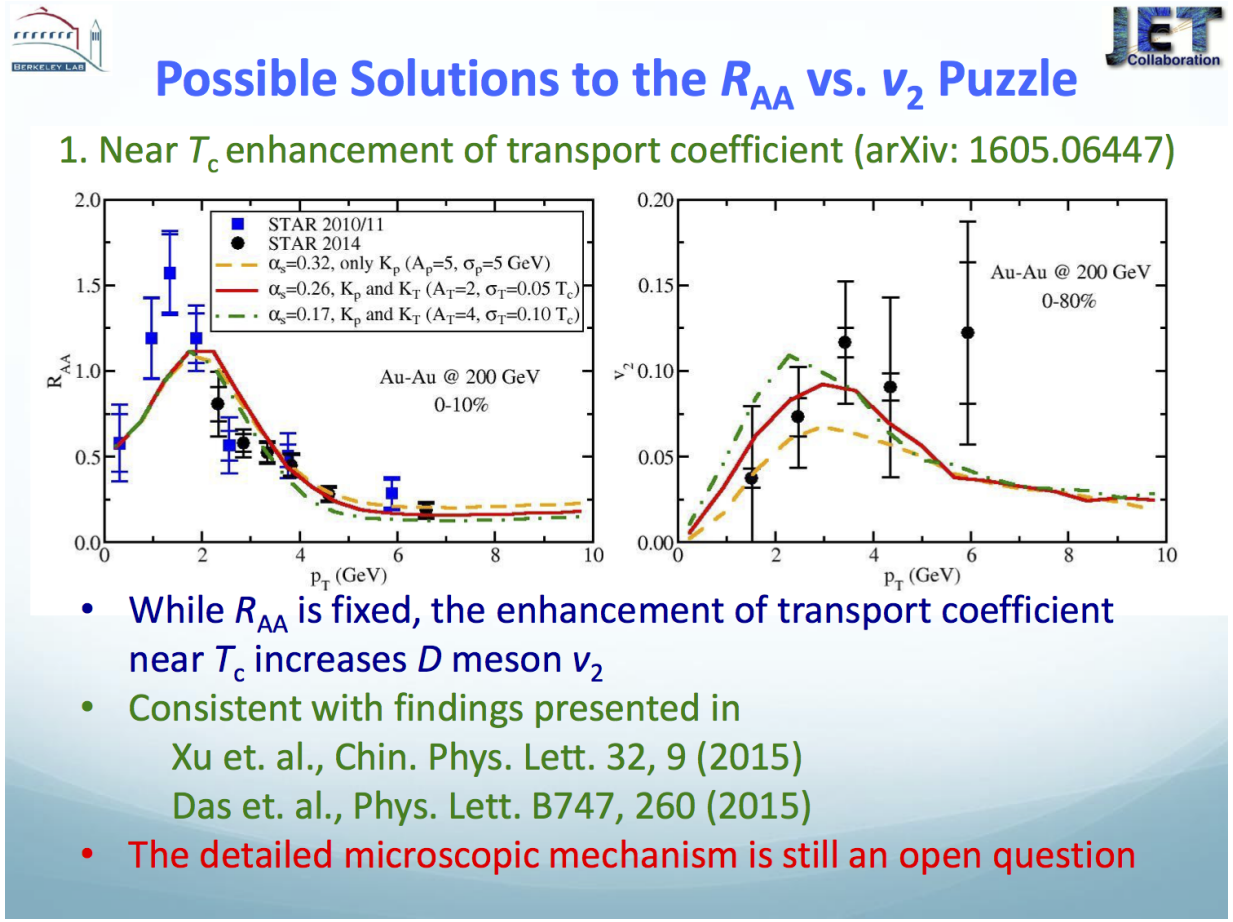
param	range	80% CR (PbPb)	80%CR (AuAu)	mean (PbPb)	mean(AuAu)
k_T	0-5	1.08 - 2.51	2.51-4.73	2.52	3.71
σ_T	0.001-0.5	0.07-0.48	0.19-0.45	.033	0.33
prek	0.1-1.4	0.96-1.36	0.78-1.28	1.18	1.00





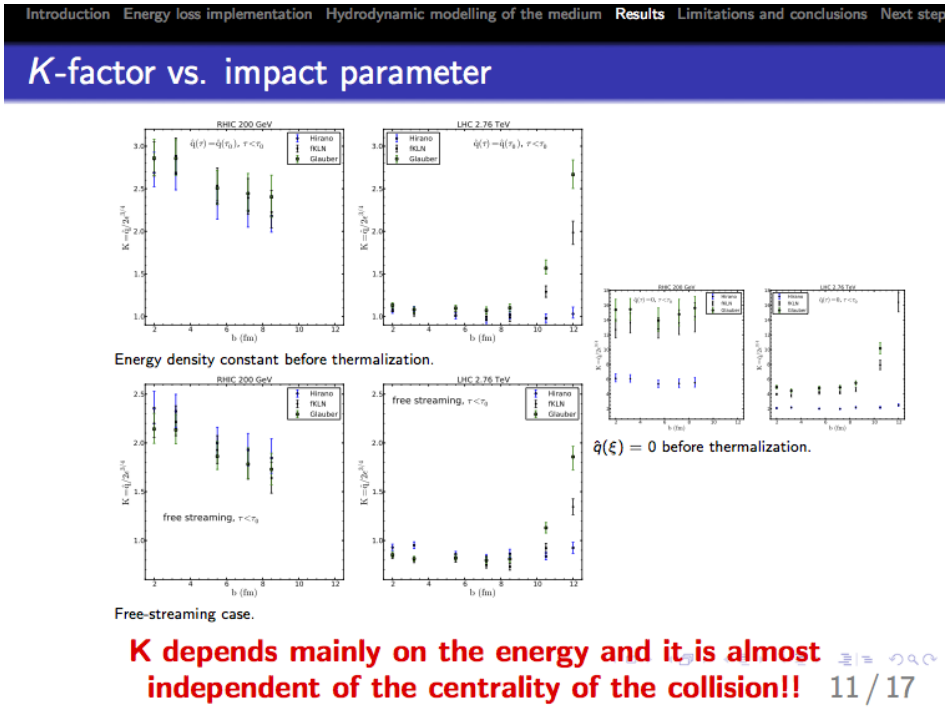
With that $\hat{q}$ ...

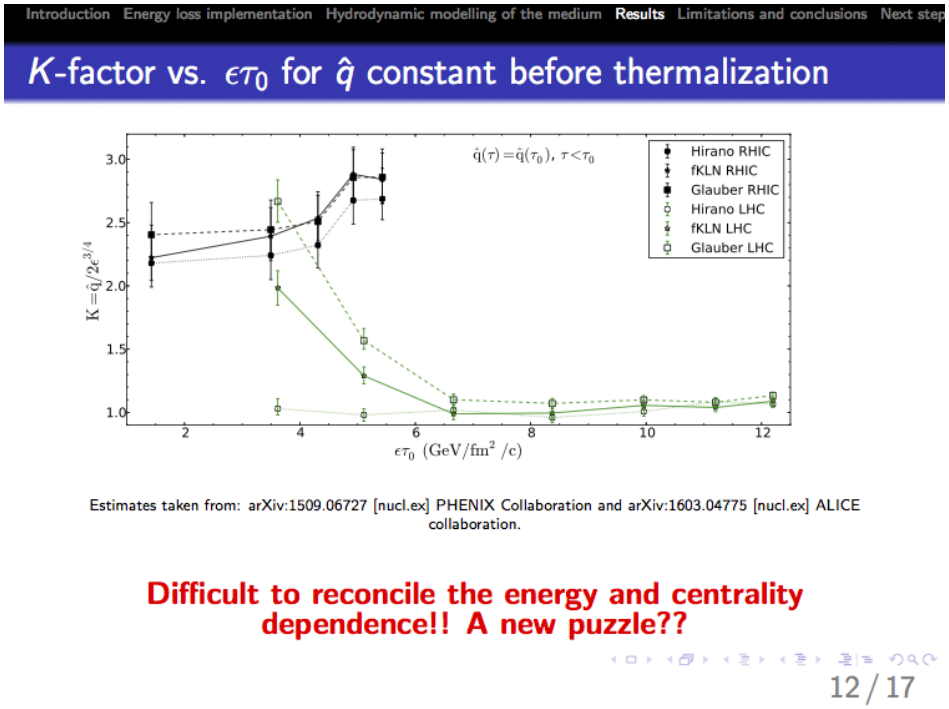
- Cao [Sat.HF.1]: With LBT



QGP Property – $\hat{q}$

- Andres Casas [Sat.Jet.1]: A puzzle?

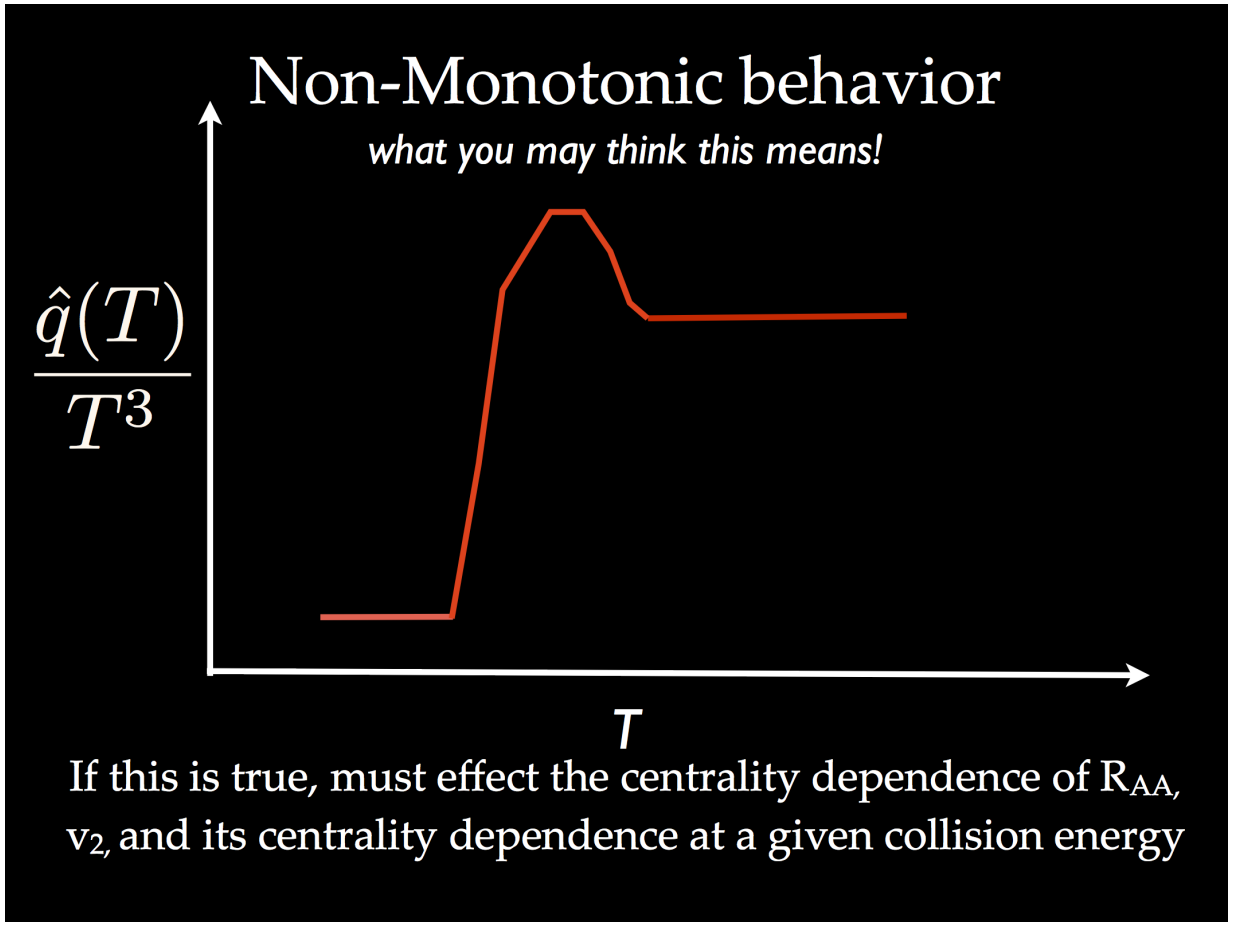




- $\hat{q} \approx 2.2\varepsilon^{3/4}$
- Why is $K = \hat{q}/2\varepsilon^{3/4}$ (almost) independent of centrality but sharply dependent upon $\varepsilon\tau_0$?

Mini Summary – QGP property extractions

- $\hat{q}(T)$
  Majumder [Sun.High p_T.2]: "What you may think this means!"



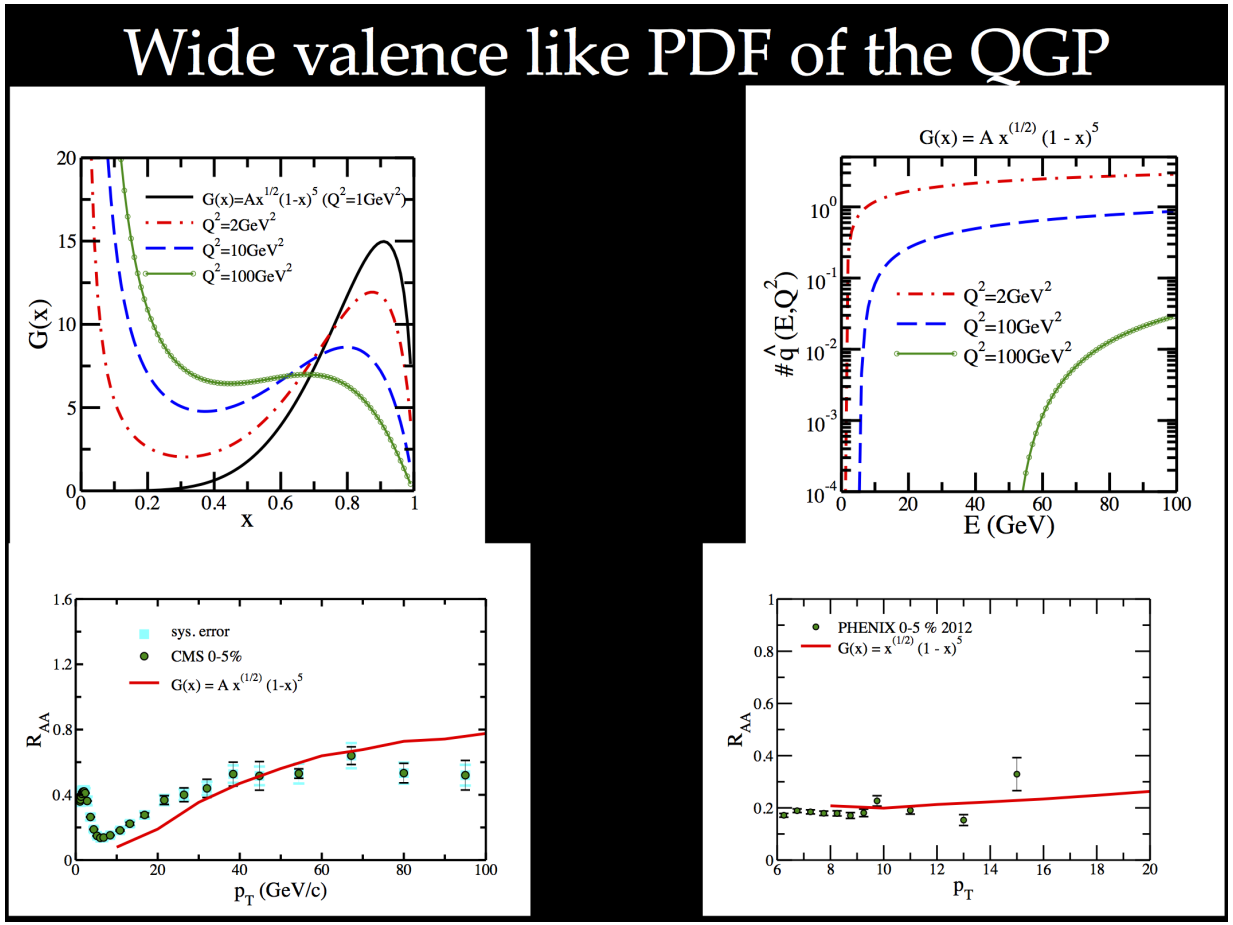
To learn: Fluctuations are everywhere and they are important

Fluctuations are everywhere

- Fluctuations
  - Geometrical fluctuations – Initial condition
  - Branching number fluctuations – Nature is probabilistic
  - Thermal fluctuations – Langevin noise
  - Vacuum fluctuations – Virtual parton cloud of a thermal parton
  - ...
- They have *all* become important
- Caveat: If you do not have a good reason and theory behind it, it may end up being just another knob to turn

Virtual parton cloud

- Majumder [Sun.High p_T.2]: "Consistent Q evolution of $\hat{q}$ ... May solve the JET puzzle"



NLO BK resummation

- Lappi [Sat.pp-pA.2]: Resummed NLO BK might spoil geometric scaling

Anomalous dimension

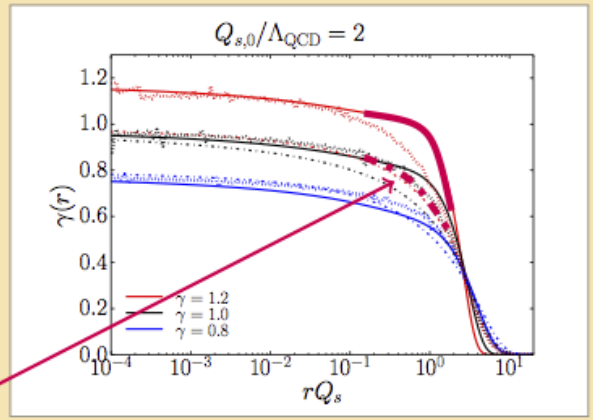
Recall initial condition: $N(r) = 1 - e^{-\frac{(r^2 Q_{s0}^2)^\gamma}{4} \ln\left(\frac{1}{r\Lambda_{QCD}} + e\right)}$,

Define

$$\gamma(r) \equiv -\frac{d \ln N(r)}{d \ln r^2}$$

Geometric scaling?

- LO: fast to $\gamma \sim 0.8$
- NLO: stay at initial γ



LO $y = 0$ to $y = 5$

- Solid: initial condition
- Dotted: $y = 5$ NLO
- Dot-dashed: $y = 5$ LO (rc)

15/16

Branching number fluctuations

- Escobedo [Sat.Jet.1]: $\langle \Delta E^2 \rangle \neq 0$

Fluctuations in energy and fluctuations in size

Average of all back-to-back jets created in a heavy-ion collision with initial energy E taking into account both fluctuations in energy and in size

$$\langle E_1 - E_2 \rangle^2 = (N_c \alpha_s \hat{q})^2 (\langle L_1^2 \rangle - \langle L_2^2 \rangle)^2$$

$$\sigma^2_{E_1 - E_2} = \langle (E_1 - E_2)^2 \rangle - \langle E_1 - E_2 \rangle^2 = (N_c \alpha_s \hat{q})^2 \left[\frac{1}{3} (\langle L_1^4 \rangle + \langle L_2^4 \rangle) + \sigma^2_{L_1^2} + \sigma^2_{L_2^2} \right]$$

The dijet asymmetry is produced

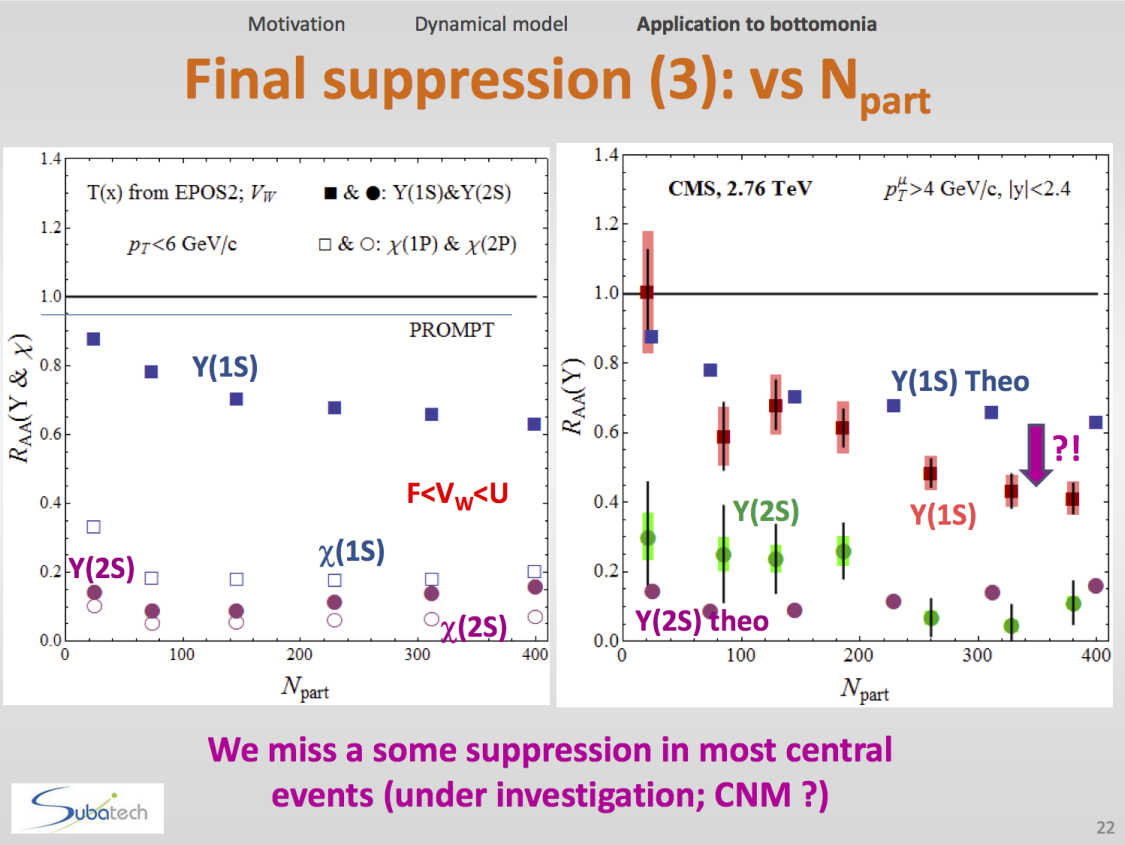
- Asymmetry between the path lengths of the 2 jets in the medium.
- Fluctuations of the energy loss that are present even if the size is fixed.
- Fluctuations in the size of the medium seen by the jet.
- Fluctuations dominate over average whenever $L_1 \sim L_2$.

Miguel A. Escobedo (IPhT Saclay) | Event-by-event | 24th September, 2016 | 27 / 34

Leads to KNO type scaling

Thermal fluctuations

- Gossiaux [Sun.Quarko.2]: Schrödinger-Langevin approach to the bottomoniums



Geometrical fluctuations

- Mantysaari [Sun.Init.1]: Proton is round *only* on average.
  Actual shape fluctuates

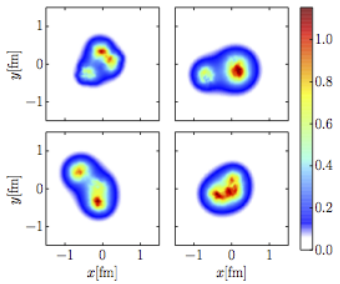
Adding color charge fluctuations: IP-Glasma

- Obtain saturation scale $Q_s(b_T)$ from IPsat (with constituent quarks)
- Sample color charges $\rho(b_T) \sim Q_s(b_T)$
- Solve Yang-Mills equations to obtain the Wilson lines

$$V(x_T) = P \exp\left(-ig \int \mathrm{d}x^- \frac{\rho(x^-, x_T)}{\nabla^2 + m^2}\right)$$

- Dipole amplitude: $N(x_T, y_T) = 1 - \mathrm{Tr}\, V(x_T) V^\dagger(y_T)/N_c$
- Fix parameters B_{qc}, B_q and m with HERA data

Example configurations:
$1 - \mathrm{Re}(\mathrm{Tr}\, V(x_T))/N_c$



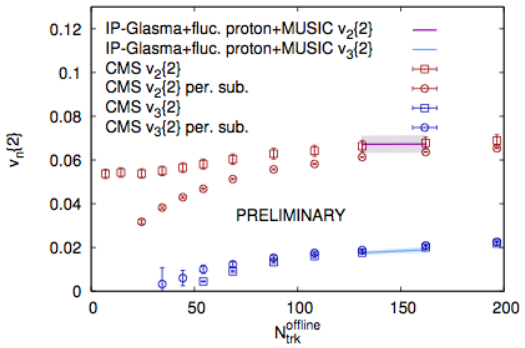
Heikki Mäntysaari (BNL) Fluctuations HP2016 25.9.2016 8 / 14

Fluctuating protons in pA collisions

Preliminary hydro calculations with proton fluctuations from HERA

Hydro numbers

- $\tau_0 = 1$ fm
- $T_{fo} = 160$ MeV
- Viscosity as in arXiv:1512.01538



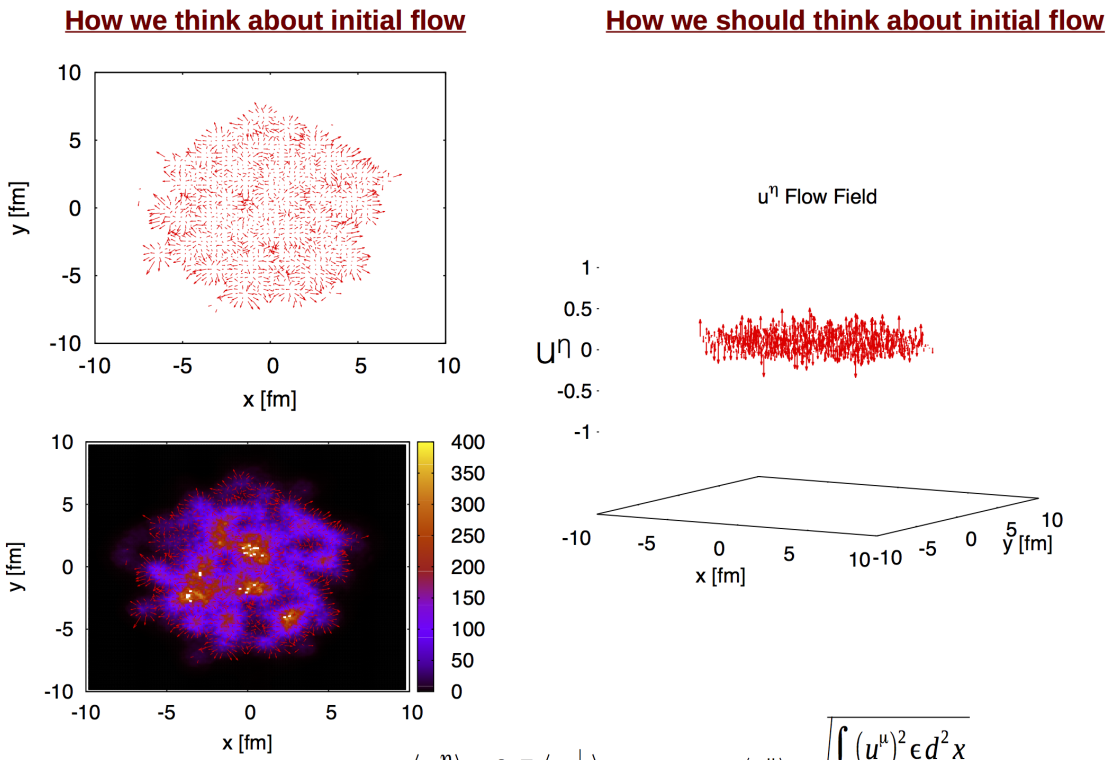
Large v_2 and v_3 at largest centrality bins reproduced well.

Work in progress (centrality dependence, initial $\pi^{\mu\nu}$,...)

Heikki Mäntysaari (BNL) Fluctuations HP2016 25.9.2016 13 / 14

Pre-equilibrium flow fluctuations

- McDonald [Sun.Init.1]: Even in the boost invariant case (IP-Glasma) $|u^\eta| \sim |u_\perp|$



On average, $\langle u^\eta \rangle \approx 0.5 \langle u^\perp \rangle$

$$\langle u^\mu \rangle = \sqrt{\frac{\int (u^\mu)^2 \epsilon \, d^2x}{\int \epsilon \, d^2x}}$$

Mini Summary – Fluctuations

- Nature reminds us that she is quantum mechanical
- To understand physics and distinguish models, one needs at least the first and the second moment
- Challenge: Include vacuum fluctuations in Glasma based models
- Fluctuations crucial in small systems

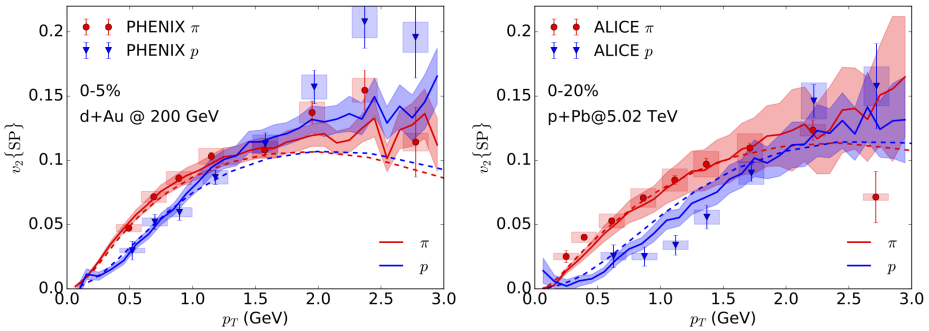
To learn: QGP droplets in small systems

Small systems

- Shen [Sat.EM.1]: QGP flows in dA and shines in pA (with MC-Glauber IC)

pid $v_2(p_T)$ mass splitting in small systems

C. Shen, *et al.*, arXiv:1609.02590

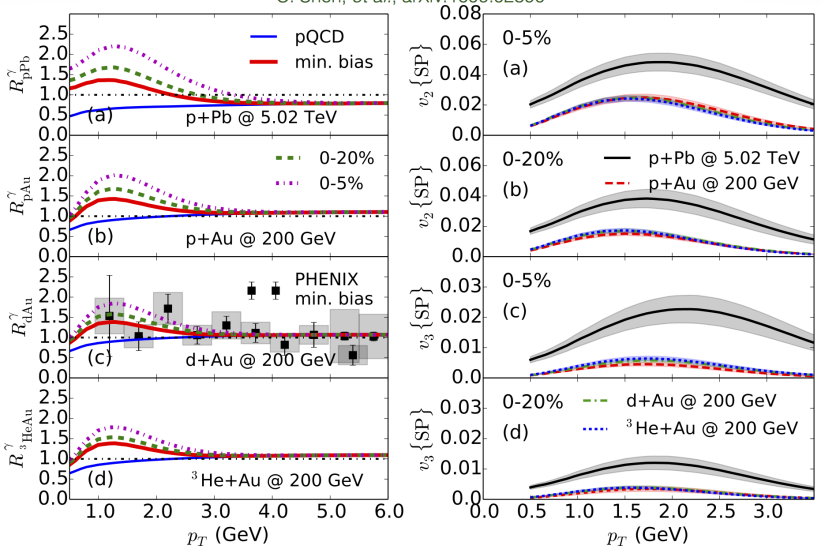


- The interplay between radial and elliptic flow in the hydrodynamic simulations can reproduce the mass splitting of pid $v_2(p_T)$ in small collision systems

Indication of a strongly coupled QCD matter?

Thermal radiation in small systems

C. Shen, *et al.*, arXiv:1609.02590



Signature of a nearly thermalized medium in small systems

Small systems

- Vogt [Sat.pp-pA.1]: "The J/ψ and υ results are compatible with both shadowing only and energy loss only but not really with CGC+CEM"

$R_{p\mathrm{Pb}}(y)$ for J/ψ and Υ

NLO shadowing does not describe curvature of data, LO band is larger due to greater uncertainty of EPS09 LO (only min/max used in Lansberg calculation)

Energy loss alone does well for J/ψ $R_{p\mathrm{Pb}}$ but stronger curvature for R_{FB}, unclear for Υ

CGC + CEM (Fujii) below data, CGC + NRQCD (not shown) may agree better

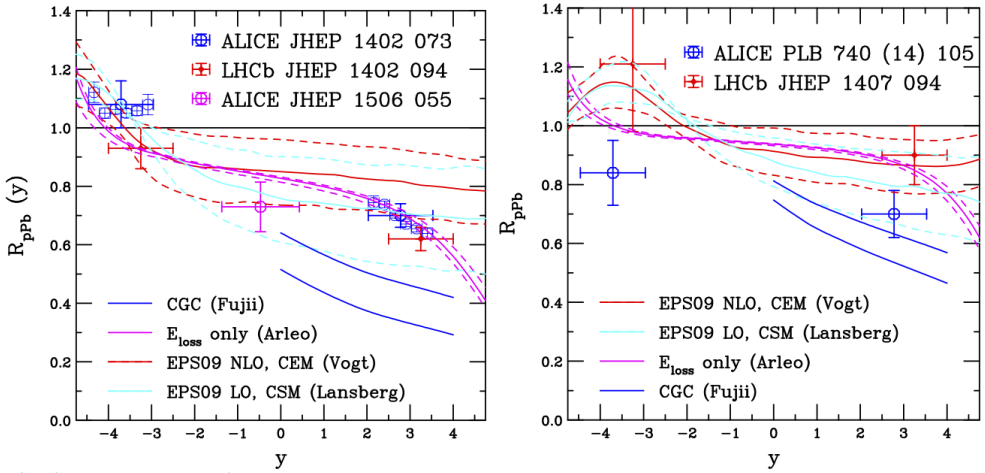


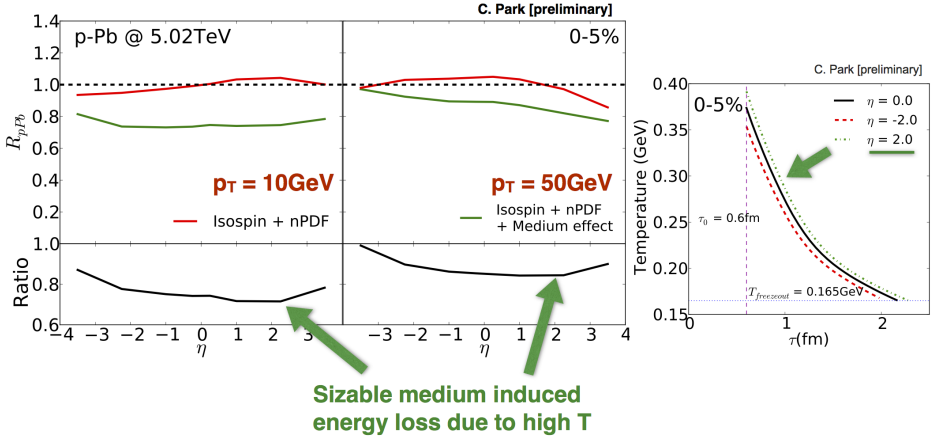
Figure 9: (Left) The $R_{p\mathrm{Pb}}$ ratio for J/ψ as a function of y. The dashed red histogram shows the EPS09 NLO CEM uncertainties. The EPS09 LO CSM calculation by Lansberg *et al.* is shown in cyan. The energy loss calculation of Arleo and Peigne is shown in magenta. The upper and lower limits of the CGC calculation by Fujii *et al* are in blue at forward rapidity. (Right) The $R_{p\mathrm{Pb}}$ ratio for Υ as a function of y. The dashed red histogram shows the EPS09 NLO CEM uncertainties. The EPS09 LO CSM calculation by Lansberg *et al.* is shown in cyan. The energy loss calculation of Arleo and Peigne is shown in magenta. The upper and lower limits of the CGC calculation by Fujii *et al* are in blue at forward rapidity.

Small systems

- Park [Sat.pp-pA.1]: Prediction of QGP droplets in pA

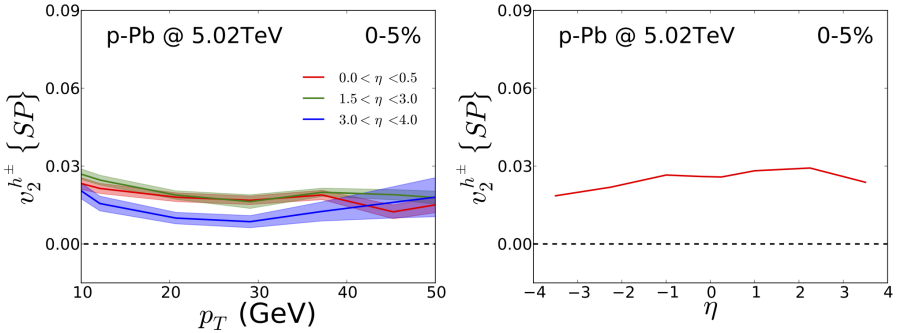
Rapidity dependent energy loss

- Net QGP medium energy loss related to temperature and energy
  - a clear signature of QGP droplet in central collisions is predicted



14

Charged hadron v_2 at high p_T



- Scalar product method; reference flow integrated from 0.3 - 3GeV
- 1~3% v_2 in central p-Pb collisions
- Medium induced energy loss dependency on integrated v_2

15

Mini Summary – Small systems

- Do we have QGP in small systems?
  - Yes, maybe.
  - Will Horowitz: "[We] are faced with a need to reassess the applicability of the large formation time assumption in any description of energy loss." [1511.09313]
  - Also need other signs of collective motion such as $c_2\{4\}$
  - If not QGP droplet, what are alternatives?

AdS/CFT modelling comes of age

To learn: Strong g_S dynamics

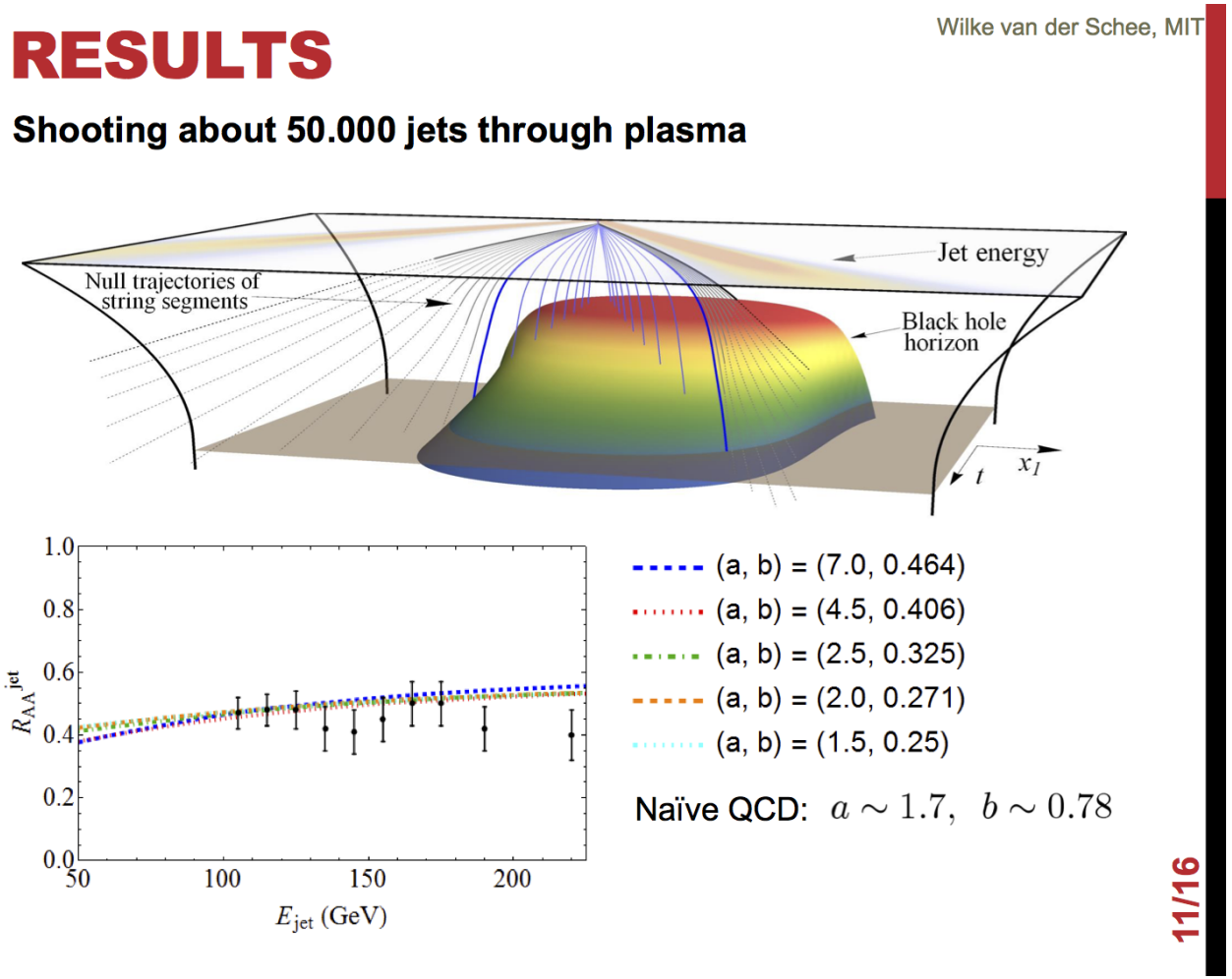
$\hat{q}$ from AdS/CFT

- Horowitz [Sat.Jet.3]: Wobbly limp noodle

$$s^2 \approx 2Dt = 8(T^2/v\hat{q})t$$

Jet quenching from AdS/CFT

- van der Schee [Sat.Jet.1]: Tracking both energy and angle

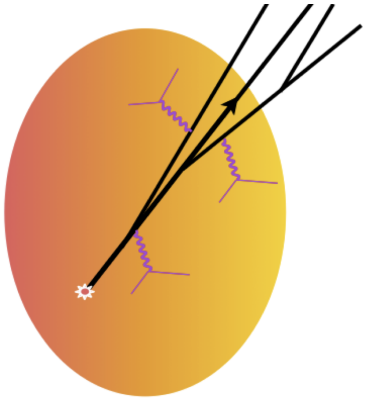


Hybrid Model

- Pablos [Sat.Jet.3]: Energy loss by AdS/CFT

$$\frac{1}{E_{\rm in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{\rm stop}2^2}\frac{1}{\sqrt{x_{\rm stop}^2 - x^2}} \quad \text{where} \quad x_{\rm stop} = \frac{1}{2\kappa_{\rm sc}\frac{E_{\rm in}^{1/3}}{T^{4/3}}}$$

Monte Carlo Implementation



Jet production and evolution in PYTHIA

Assign spacetime description to parton shower (formation time argument) $\tau_f = \frac{2E}{Q^2}$

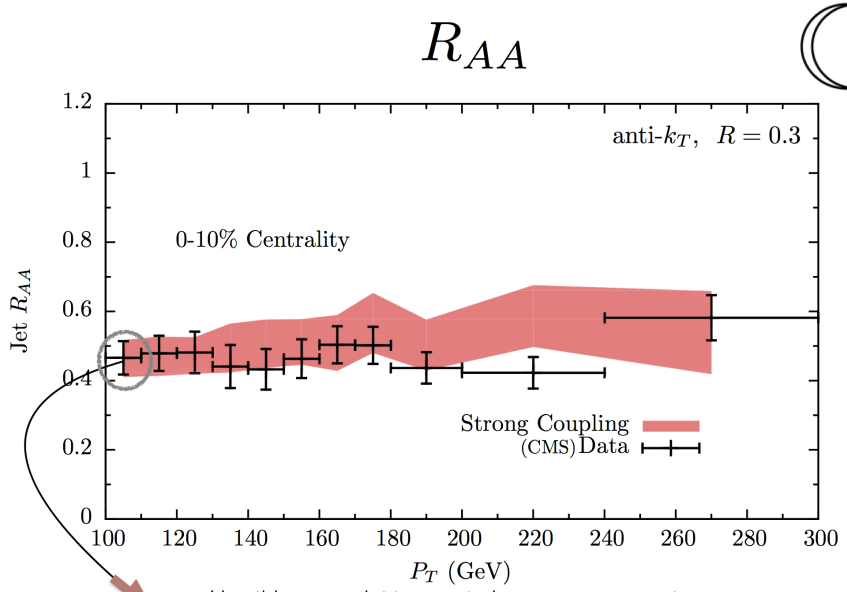
Embed the system into a hydrodynamic background (2+1 hydro code from Heinz and Shen)

Between splittings, partons in the shower interact with QGP, lose energy

Turn off energy loss below a T_c that we vary over $145 < T_c < 170\,\mathrm{MeV}$

Extract jet observables from parton shower

more details in
MCs Round Table today



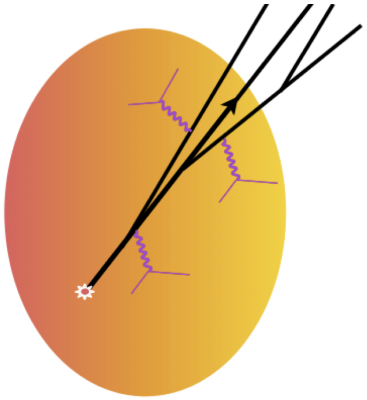
Use this one point to constrain our one parameter.
Bands come from experimental uncertainty on this point
plus varying T_c over $145 < T_c < 170\,\mathrm{MeV}$

Hybrid Model

- Pablos [Sat.Jet.3]: Energy loss by AdS/CFT

$$\frac{1}{E_{\rm in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{\rm stop}2^2}\frac{1}{\sqrt{x_{\rm stop}^2 - x^2}} \quad \text{where} \quad x_{\rm stop} = \frac{1}{2\kappa_{\rm sc}\frac{E_{\rm in}^{1/3}}{T^{4/3}}}$$

Monte Carlo Implementation



Jet production and evolution in PYTHIA

Assign spacetime description to parton shower (formation time argument) $\tau_f = \frac{2E}{Q^2}$

Embed the system into a hydrodynamic background (2+1 hydro code from Heinz and Shen)

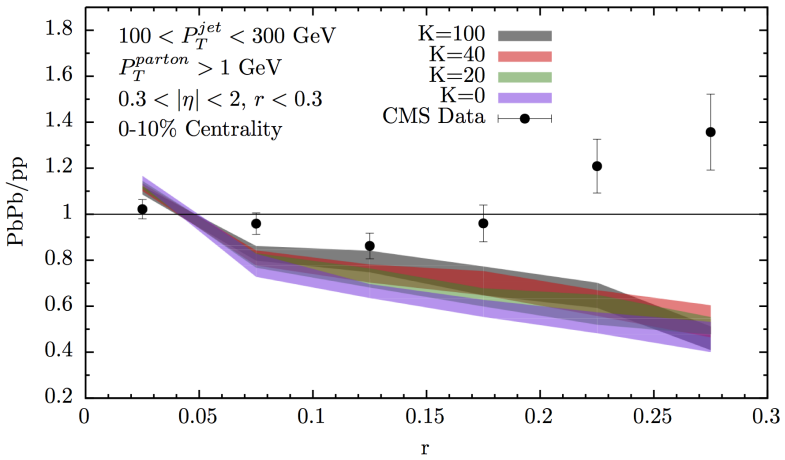
Between splittings, partons in the shower interact with QGP, lose energy

Turn off energy loss below a T_c that we vary over $145 < T_c < 170\,\mathrm{MeV}$

Extract jet observables from parton shower

more details in
MCs Round Table today

Small sensitivity of standard jet shapes to broadening

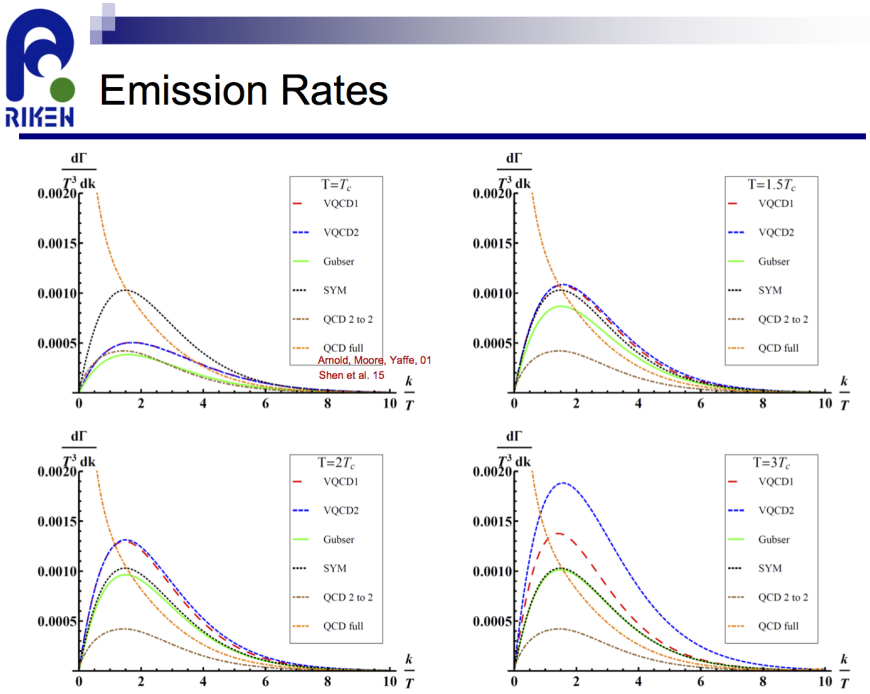


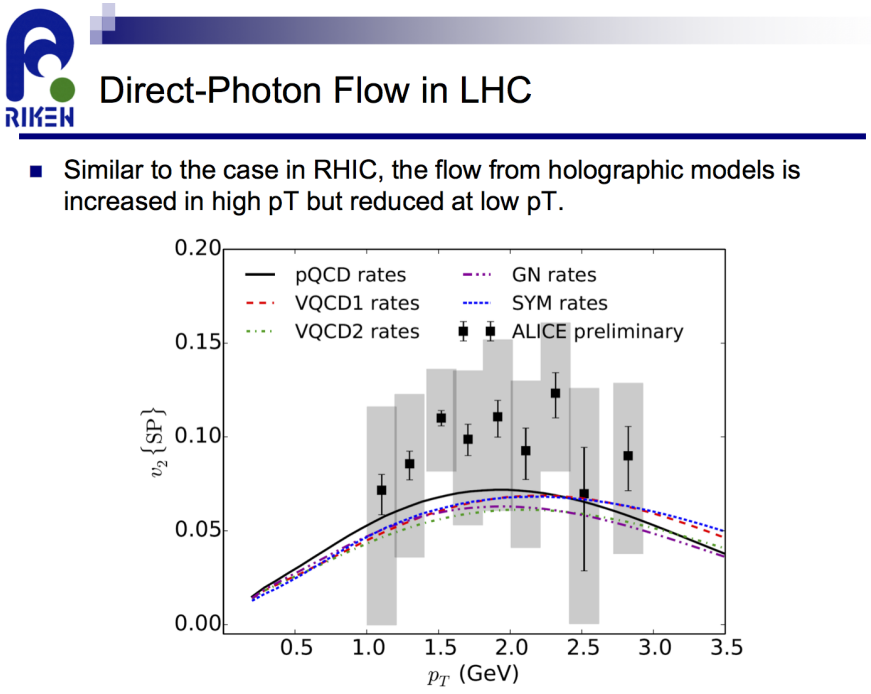
Small sensitivity of jet shapes to broadening:

- strong quenching removes soft fragments that appear early
- remaining soft tracks fragment late

Holography helps resolving the photon v_2 puzzle

- Yang [Sat.EM.2]: – Holographic models make both yield and v_2 go up





Mini Summary – AdS/CFT modelling

- In Finite temperature field theory, expansion parameter is g_S *not* $\alpha_S = g_S^2/4\pi$
- At $Q = M_Z$, $g_S \approx 1$
- At $Q = T_{\rm QGP}$, $g_S \approx 2$
- In principle, perturbation theory expressions are not really applicable
- g_S is not ∞, either – Phenomenolgy looks close to it, though.
- Reality is somewhere in between – How do we get at it?
- Eventually, we need to construct AdS/QCD models

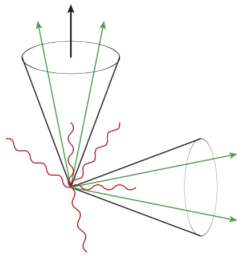
SCET comes of age

To learn: The right way to separate scales (and factorize)

HF production

- Ringer [Sat.Jet.2]: Jets and HF in SCET

SCET$_{\mathrm{M,G}}$



$$\mathcal{L}_{\mathrm{SCET_{M,G}}} = \mathcal{L}_{\mathrm{SCET_M}} + \mathcal{L}_G(\xi_n, A_n, A_G)$$

Kang, FR, Vitev `16

- $$\mathcal{L}_{\mathrm{SCET_M}} = \bar{\xi}_{n,p'}\left\{in\cdot\partial + (\not{\mathcal{P}}_\perp + g\not{A}^\perp_{n,q})W_n\frac{1}{\bar{\mathcal{P}}}W_n^\dagger(\not{\mathcal{P}}_\perp + g\not{A}^\perp_{n,q'})\right\}\frac{\bar{\not{n}}}{2}\xi_{n,p}$$
$$+\ m\bar{\xi}_{n,p'}\left[(\not{\mathcal{P}}_\perp + g\not{A}^\perp_{n,q}), W_n\frac{1}{\bar{\mathcal{P}}}W_n^\dagger\right]\frac{\bar{\not{n}}}{2}\xi_{n,p} - m^2\bar{\xi}_{n,p'}W_n\frac{1}{\bar{\mathcal{P}}}W_n^\dagger\frac{\bar{\not{n}}}{2}\xi_{n,p}$$

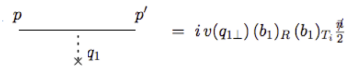
Leibovich, Ligeti, Wise `03

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

Ovanesyan, Vitev '12

Feynman rules for interaction with the medium do not depend on the mass to leading-power!

Bauer, Fleming, Luke, Pirjol, Rothstein, Stewart `00-`02
Idilbi, Majumder `08, D'Eramo, Liu, Rajagopal `10



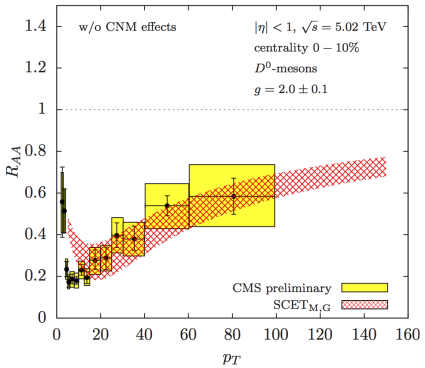
$$= i\,v(q_{1\perp})\,(b_1)_R\,(b_1)_{T_1}\frac{\bar{\not{n}}}{2}$$

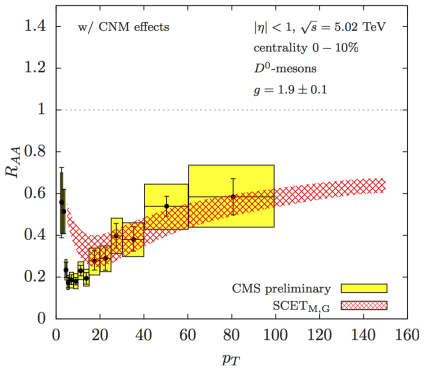
Los Alamos NATIONAL LABORATORY EST. 1943

12

Comparison to LHC data

D-mesons





CMS-PAS-HIN-16-010

Los Alamos NATIONAL LABORATORY EST. 1943

18

The z_g power

or "I'll harangue anyone who uses the term." – Brian Cole on modified splitting function

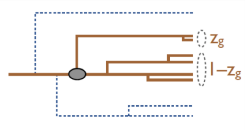
The z_g power

- Lapidus [Sat.Jet.3]: z_g has discrimination power

Hard Jet Splitting probed with Soft Drop

10

A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler JHEP 05 (2014) 146
A. J. Larkoski, S. Marzani, J. Thaler PRD 91, 111501(R)



$$\frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} > z_{\rm cut}$$

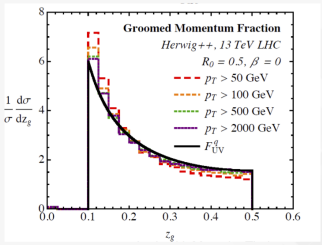
recursively removes soft subjets, until a hard splitting is identified

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}}$$

groomed momentum fraction

$$p(z_g) = \frac{\overline{P}_i(z_g)}{\int_{z_{\rm cut}}^{1/2} dz\, \overline{P}_i(z)} \Theta(z_g - z_{\rm cut})$$

$$\overline{P}_i(z) = P_i(z) + P_i(1-z)$$



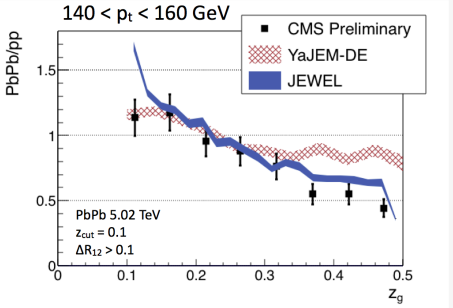
$p(z_g)$ is approx. independent of:
— jet p_t and radius
— α_s
— collision energy

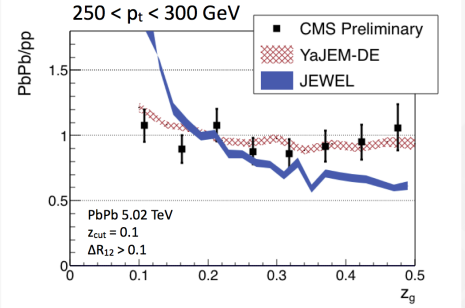
What MC including jet quenching effects predicts?

Kirill Lapidus, Yale

z_g: Data vs. Models

12





- Good discriminating potential of the z_g observable
- Momentum dependence is not described well
- Both models (YaJEM-DE and JEWEL) incorporate unmodified splitting functions

K. Zapp, Phys.Lett. B735 (2014) 157-163

Is z_g sensitive to a modified P(z)?

Kirill Lapidus, Yale

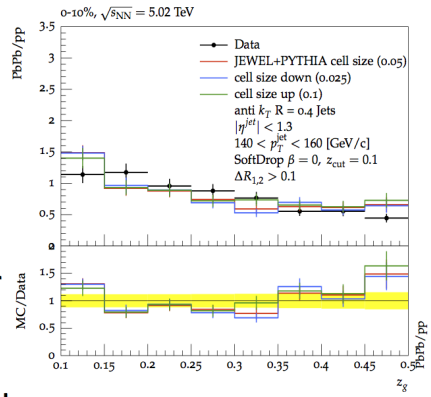
The z_g power

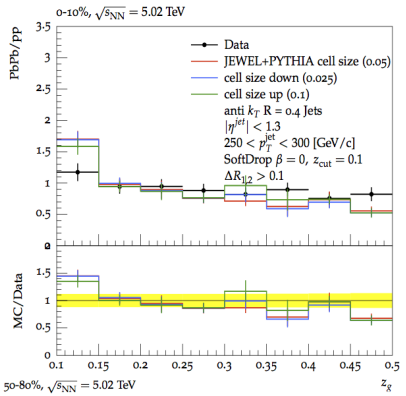
- Kunnawalkam Elayavalli [Sat.Jet.3]: – JEWEL with medium recoil can do z_g

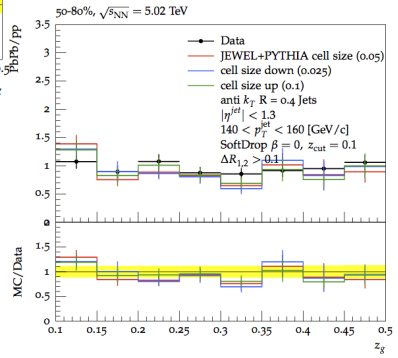
Comparing with Data

CMS-PAS-HIN-16-006

- Good description!
- The PbPb jets prefer to be more asymmetric as compared to pp (and general qcd) which features harder splitting







9/24/16 Recoils in JEWEL, HP, Raghav 17

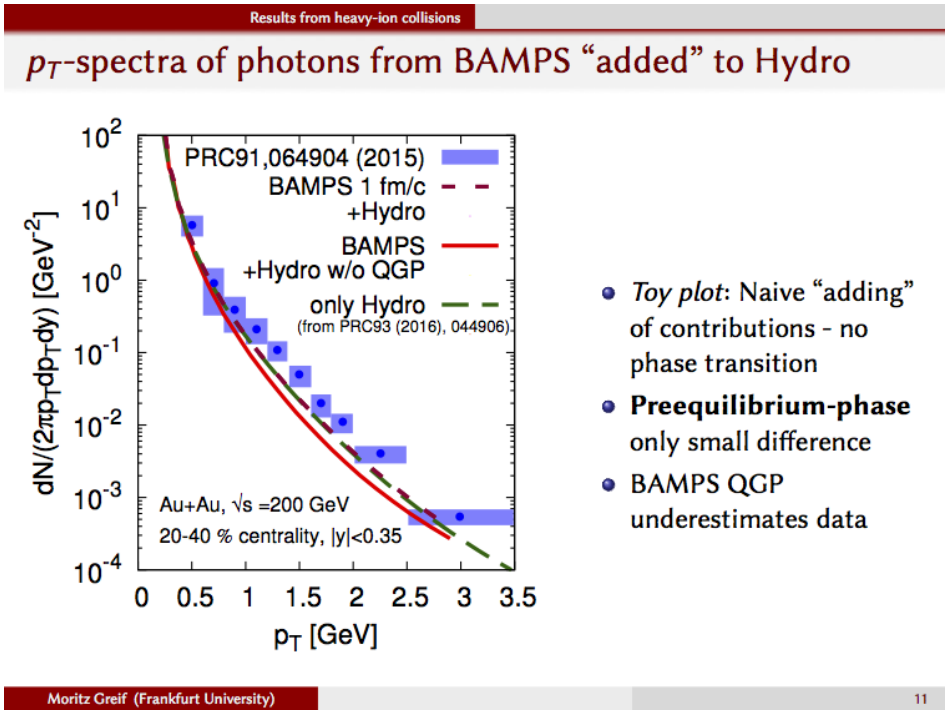
Mini Summary – z_g power

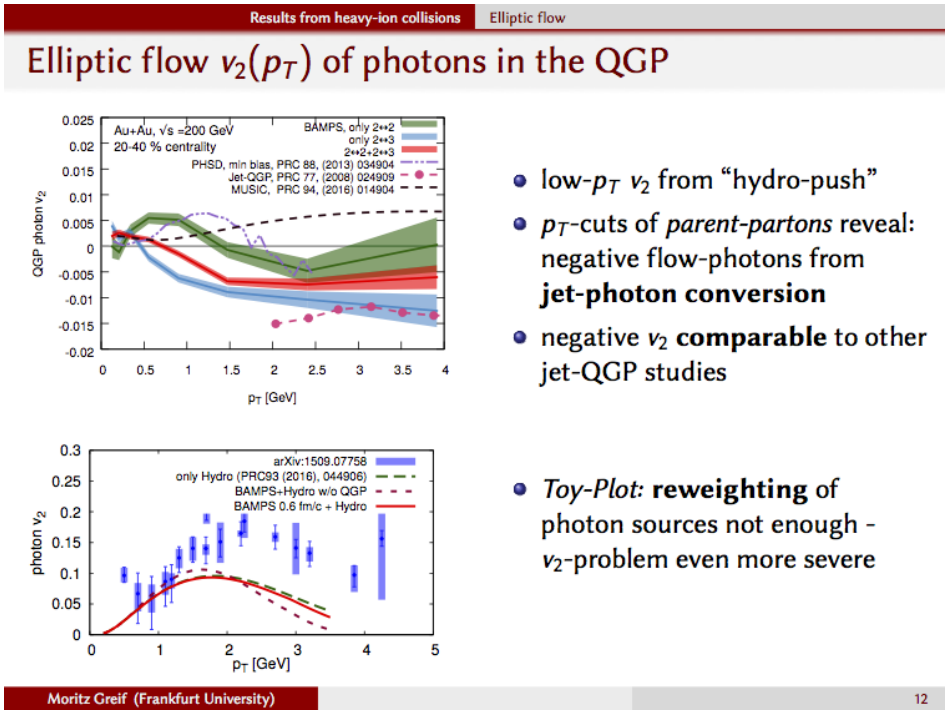
- New tool that's sensitive to the first branching
- Sensitive to the details of branching and soft p_T stripping
- When refined, this can provide a good way to select more refined way of selecting jet classes

Direct photon puzzle

It's still a good puzzle

- Greif [Sat.EM.2]: – BAMP with LO photons





- Also Yang [Sat.EM.2]: – Holographic models make both yield and v_2 go up

Mini Summary – Direct photon puzzle

- It's still a good puzzle but what don't we understand?
- Pre-hydro?
- Post-hydro?
- Jet-medium photons?
- Opportunity abounds!

Heroic feats of calculations

By students

- Rasonaivoa [Sun.High p_T.2]: Resumming N-gluon emission amplitudes

Maximal Helicity Violating (MHV)

Two pillars of MHV amplitudes

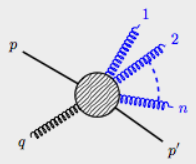
- Color decomposition

$$\mathcal{M} = \sum_{\text{perm}} C_{a_1,\ldots,a_n} A(1,2,\ldots,n)$$

- Spinor helicity formalism

$$\begin{cases} p^\mu & \longrightarrow \quad p^{a\dot{a}} = \lambda^a \widetilde{\lambda}^{\dot{a}} \\ k_1.k_2 & \longrightarrow \quad \langle 12\rangle = \epsilon_{ab}\lambda_1^a\lambda_2^b \text{ and } [12] = \epsilon_{\dot{a}\dot{b}}\widetilde{\lambda}_1^{\dot{a}}\widetilde{\lambda}_2^{\dot{b}} \end{cases}$$

Partial amplitude for n gluon emissions



$$= g^{n-1}\frac{\langle pq\rangle^3\langle qp'\rangle}{\langle pp'\rangle\langle p'q\rangle\langle q1\rangle\langle 12\rangle\cdots\langle np\rangle}$$

Resummation beyond ordering

- The probability distribution P_n of n gluon emissions is given by

$$P_n \sim \sum_{i=0}^{n} \int |J_i(1,\ldots,n)|^2$$

- Resummation decoupled into a sum over different symmetry

$$\sum_{i=0}^{n}\int |J_n|^2 = \sum_{i=0}^{n} N_c^i \int |J_i^s|^2 + \sum_{i=0}^{n}\text{tr}(|C_i^a|^2)\int |J_i^a|^2 + \sum_{i=0}^{n}\int |\text{Mixed}|^2$$

- The purely symmetric, QED like factor, can be exponentiate

$$\sum_{i=0}^{n} N_c^i \int |J_i^s|^2 \to \exp\left(N_c \int |J_1(k_1)|^2\right)$$

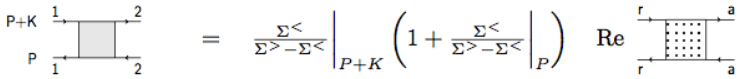
- J_n^a computed with no exponentiation pattern (Week ago).
- Now! working on the mixed symmetry case for general n.

By students

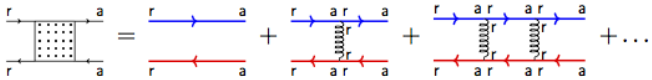
- Hauksson [Sat.EM.2]: Out-of equilibrium calculation of the photon AMY rate

Out-of-equilibrium case

Without using the KMS condition we derived that out of equilibrium



where



Exactly the same diagrams contribute in and out of equilibrium.

Need the quark and gluon self energies.

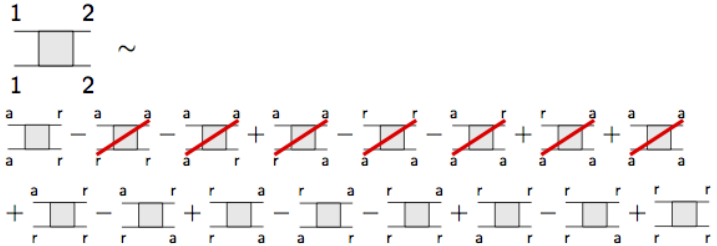
The diagrams can be summed up giving an integral equation that needs to be solved numerically.

Out-of-equilibrium case

Need to check that we have the same power counting scheme out of equilibrium.

Calculations so far show that the power counting scheme is still valid for $\delta f \sim f_{\rm eq}$.

We can always write



aa quark lines vanish and ra and ar lines are simple

Summary summary

These two beasts still surprising us after all these years

- Theory community vibrant and strong
- Enering the precision measurement era – Eyes on the prize!

Thank you organizers and volunteers for a great conference!