Theory: Introduction and perturbative QCD

Ivan Vitev (co-PI)
T-2

The Quark-Gluon Plasma and Bottom Quark Jets

pQCD: b-jets and heavy flavor, energy loss and b-jet substructure in the QGP

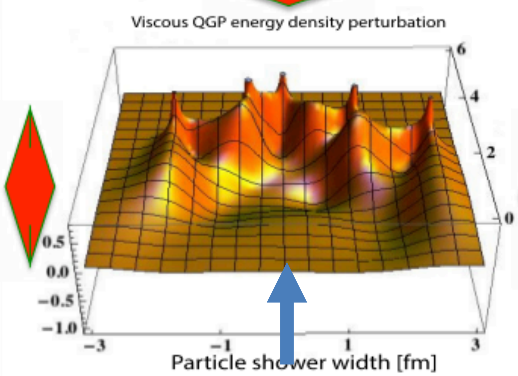
SCET: b-jets in p+p, energy correlators, resummation

MD: Transport properties of SCPs. Stopping power for heavy fermions

LQCD: EOS in fluctuating hydro, simulations of jet propagation

Perturbative QCD/SCET and jet simulations: most precise b-jet theory in proton collisions, new theory for heavy ion collisions, b-jet substructure, b-jet tomography of the QGP

QMD simulations: transport properties of plasmas, stopping power for heavy particles



Lattice QCD: EoS, input for hydro, charge number fluctuations near the phase transition

Experiment: Tracker design, prototype construction, jet finder development, ongoing and improved PHENIX and STAR BES II analyses

Integrated effort:

T-2, T-5 and CCS-7 groups in close collaboration with experiment

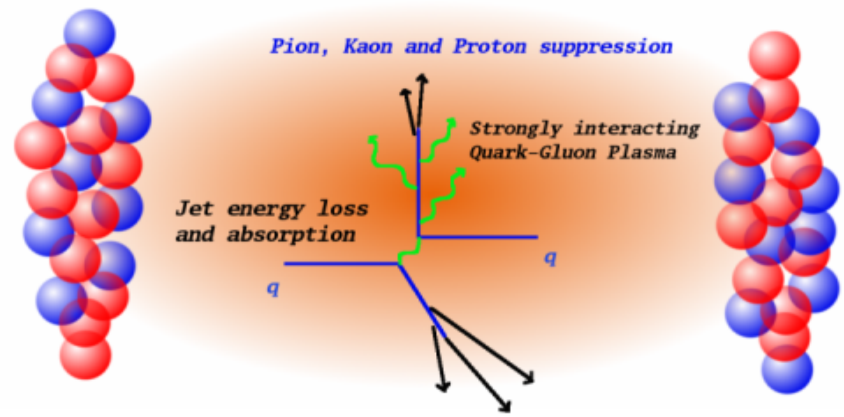
Staff: J. Daligault, R. Gupta, Z. Kang, C. Lee, I. Vitev, B. Yoon

PD: H. Li, F. Ringer, M. Sievert, V. Vaidya

Students: S. Aronson, D Bernstein, B. Odegard, J. Reiten, P. Shrivastava

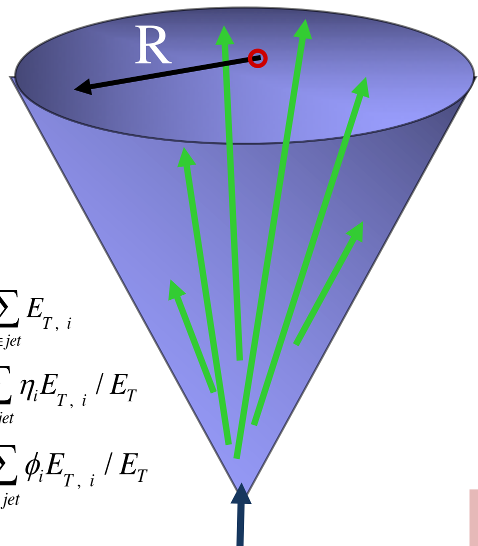
Theory deliverable: package for precision b-jet tomography at sPHENIX and predictions for experiment

Provide b-jet suppression magnitude input: assess exp. sensitivity to QGP properties



$$R = \sqrt{(\eta - \eta_{jet})^2 + (\phi - \phi_{jet})^2}$$

Jets present unique challenges



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

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

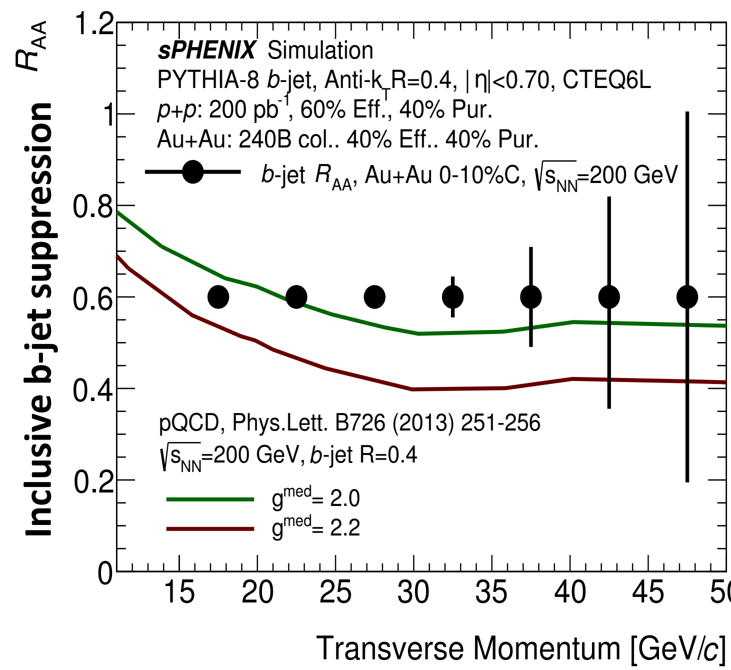
$$\phi = \sum_{i \in jet} \phi_i E_{T,\,i} / E_T$$

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

$$R_{AA} = \frac{Observable\ in\ A+A}{Norm * Observable in\ p+p}$$

Theory uncertainties cancel in the ratio

I. Vitev *et al.* (2018)



Provided results to sPHENIX for the full DOE proposal.
Constraints on the coupling "g" between the jet and the medium better than 10%, transport coefficients ~ 30%

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Evaluating the In-medium Jet Function and Heavy Ion Phenomenology

Beyond traditional energy loss: incorporate the technology of higher order calculations and resummation from HEP

- Inclusive jet cross sections can be formulated in terms of semi-inclusive jet functions J(z,ωR,μ)

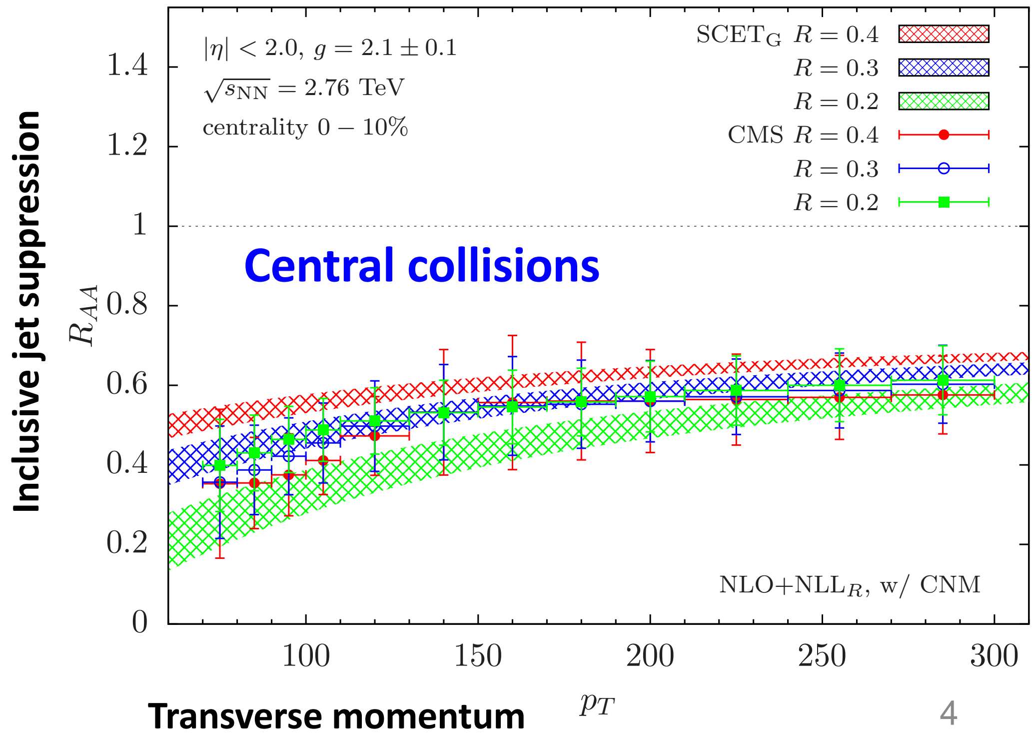
$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T\,d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

- Demonstrated that J(z,ωR,μ) is related to the Altarelli-Parisi splitting functions (parton showers)

$$J_q^{\mathrm{med},(1)}(z,\omega R,\mu) = \left[\int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{qq}(z,q_\perp)\right]_+ + \int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{gq}(z,q_\perp)\,.$$

$$d\sigma_{\mathrm{PbPb}}^{\mathrm{jet}} = d\sigma_{pp}^{\mathrm{jet,vac}} + d\sigma_{\mathrm{PbPb}}^{\mathrm{jet,med}}$$

$$d\sigma_{\mathrm{PbPb}}^{\mathrm{jet,med}} = \sum_{i=q,\bar{q},g} \sigma_i^{(0)} \otimes J_i^{\mathrm{med}}$$



Z. Kang *et al* . PLB (2017)

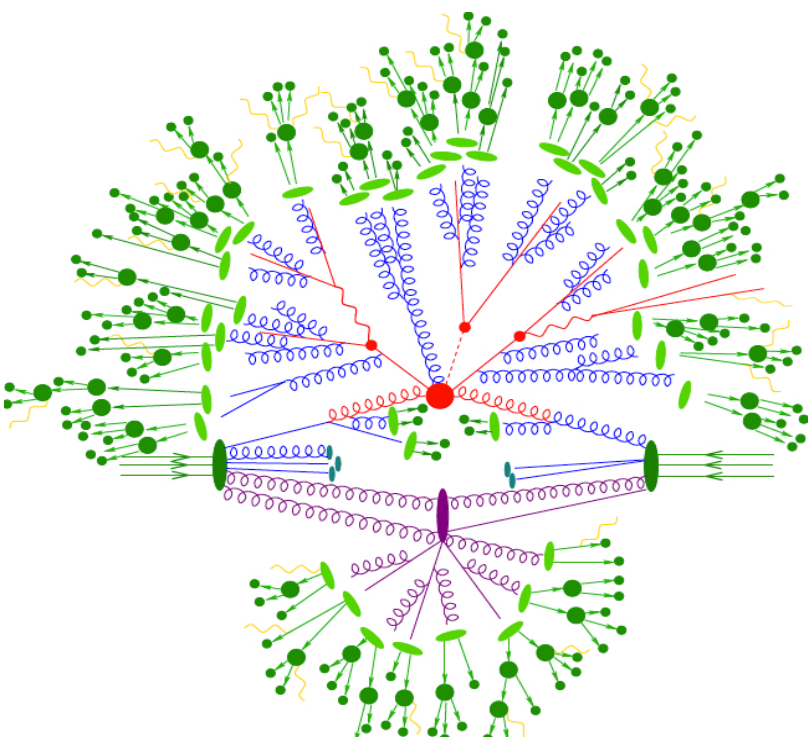
Effective Theory of Heavy Quark Propagation in Nuclear Matter

Formulated a new effective theory $\text{SCET}_{\text{M,G}}$ – for massive quarks & Glauber gluon interactions

$$\mathcal{L}_{\text{QCD}} = \bar{\psi}(i\not{D} - m)\psi \qquad iD^{\mu} = \partial^{\mu} + gA^{\mu} \qquad A^{\mu} = A^{\mu}_{c} + A^{\mu}_{s} + A^{\mu}_{\text{G}}$$

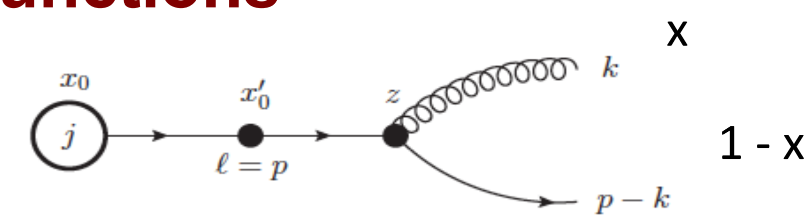
- With the field scaling in the covariant gauge for the Glauber field there is no room for interplay with mass in the LO Lagrangian

Result: $\text{SCET}_{\text{M,G}} = \text{SCET}_{\text{M}} \times \text{SCET}_{\text{G}}$



Z. Kang *et al* . JHEP (2017)

Splitting functions



$Q \to Qg$
$Q \to gQ$
$g \to Q\bar{Q}$
$g \to gg$

- **Precise understanding of the mass dependence.**

$$\left(\frac{dN}{dx d^2 k_\perp}\right)_{g\to Q\bar{Q}} = T_R \frac{\alpha_s}{2\pi^2} \frac{1}{k_\perp^2 + m^2} \left[x^2 + (1-x)^2 + \frac{2x(1-x)m^2}{k_\perp^2 + m^2}\right]$$

$$\left(\frac{dN}{dx d^2 k_\perp}\right)_{Q\to Qg} = C_F \frac{\alpha_s}{\pi^2} \frac{1}{k_\perp^2 + x^2 m^2} \left[\frac{1 - x + x^2/2}{x} - \frac{x(1-x)m^2}{k_\perp^2 + x^2 m^2}\right]$$

Full in-medium splitting functions

$$
\begin{aligned}
\left(\frac{dN^{\rm med}}{dx\,d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} &= \frac{\alpha_s}{2\pi^2}C_F\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\boldsymbol{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp}\left\{\left(\frac{1+(1-x)^2}{x}\right)\left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right.\right.\\
&\times\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}-\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])+\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right.\\
&\left.-\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z])+\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z])\\
&+\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right)(1-\cos[\Omega_4\Delta z])-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}(1-\cos[\Omega_5\Delta z])\\
&\left.+\frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}-\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\right]\\
&\left.+x^3m^2\left[\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}-\frac{1}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])+\ldots\right]\right\}
\end{aligned}
$$

Kinematic variables

$$\boldsymbol{A}_\perp=\boldsymbol{k}_\perp,\ \boldsymbol{B}_\perp=\boldsymbol{k}_\perp+x\boldsymbol{q}_\perp,\ \boldsymbol{C}_\perp=\boldsymbol{k}_\perp-(1-x)\boldsymbol{q}_\perp,\ \boldsymbol{D}_\perp=\boldsymbol{k}_\perp-\boldsymbol{q}_\perp$$

$$\Omega_1-\Omega_2=\frac{\boldsymbol{B}_\perp^2+\nu^2}{p_0^+x(1-x)},\ \Omega_1-\Omega_3=\frac{\boldsymbol{C}_\perp^2+\nu^2}{p_0^+x(1-x)},\ \Omega_4=\frac{\boldsymbol{A}_\perp^2+\nu^2}{p_0^+x(1-x)},$$

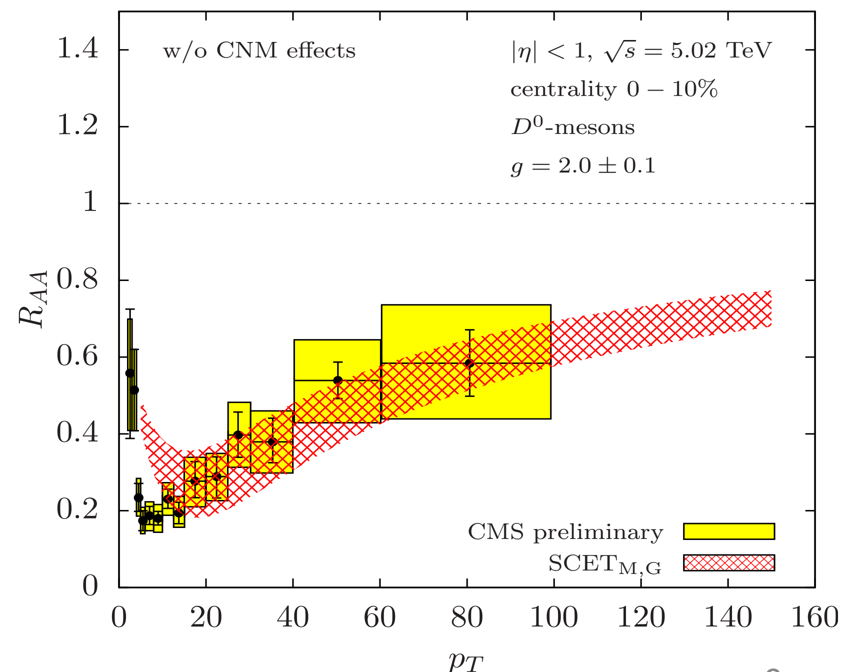
$$
\begin{aligned}
\nu &= m & (g\to Q\bar{Q}),\\
\nu &= x\,m & (Q\to Qg),\\
\nu &= (1-x)\,m & (Q\to gQ),
\end{aligned}
$$

See talk by B. Yoon on the evaluation of the splitting functions

Performed the First NLO heavy flavor calculation in HIC

$$d\sigma^H_{\rm PbPb}=d\sigma^{H,\rm NLO}_{pp}+d\sigma^{H,\rm med}_{\rm PbPb}$$

Gives an improved description of open heavy flavor suppression from radiative processed down to lower p_T

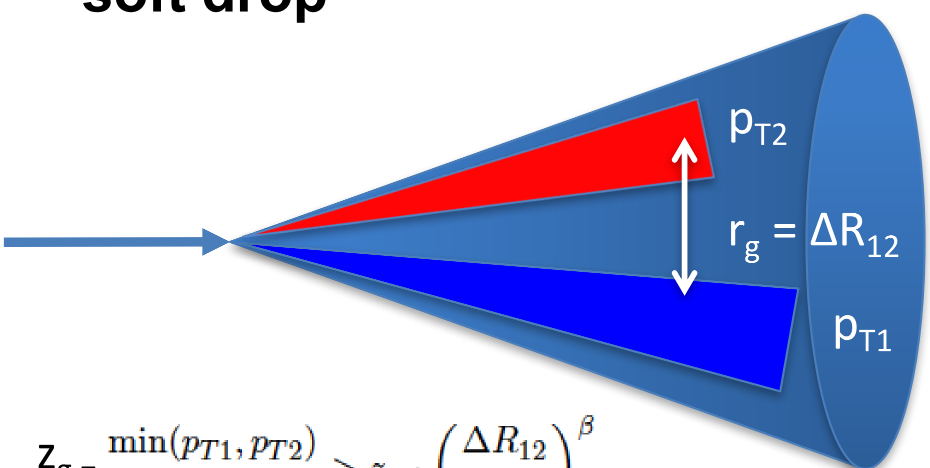


Z. Kang *et al* . JHEP (2017)

Groomed Soft Dropped Jet Distributions in $SCET_G$

Substructure of jets: the longitudinal and transverse momentum distribution of particles within jets, jets within jets

Groomed jet distribution using "soft drop"



$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

They are calculable from first principles and directly related to the splitting functions

$$p_i(z_g) = \frac{\int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(z_g, k_\perp)}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x, k_\perp)}$$

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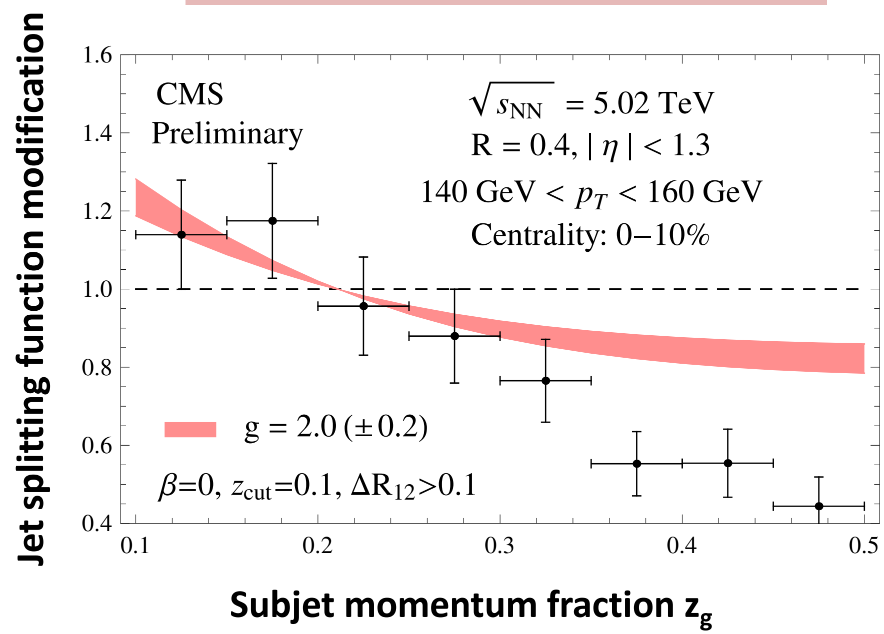
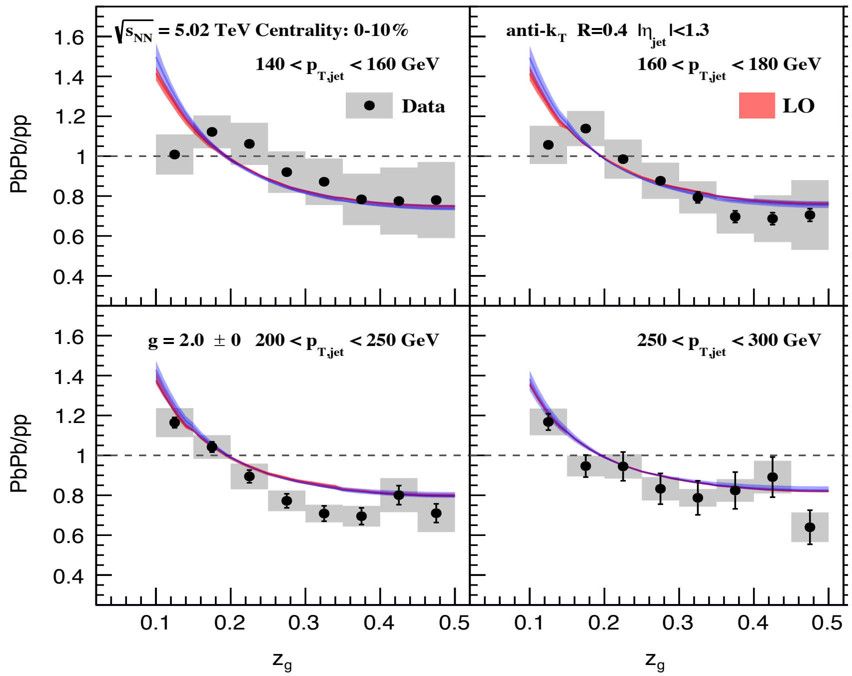
Demonstrated the great utility of these new distributions:

- Probe the early time dynamics / splitting when the jet forms *in* the QGP

Y. T. Chien *et al.* PRL (2017)

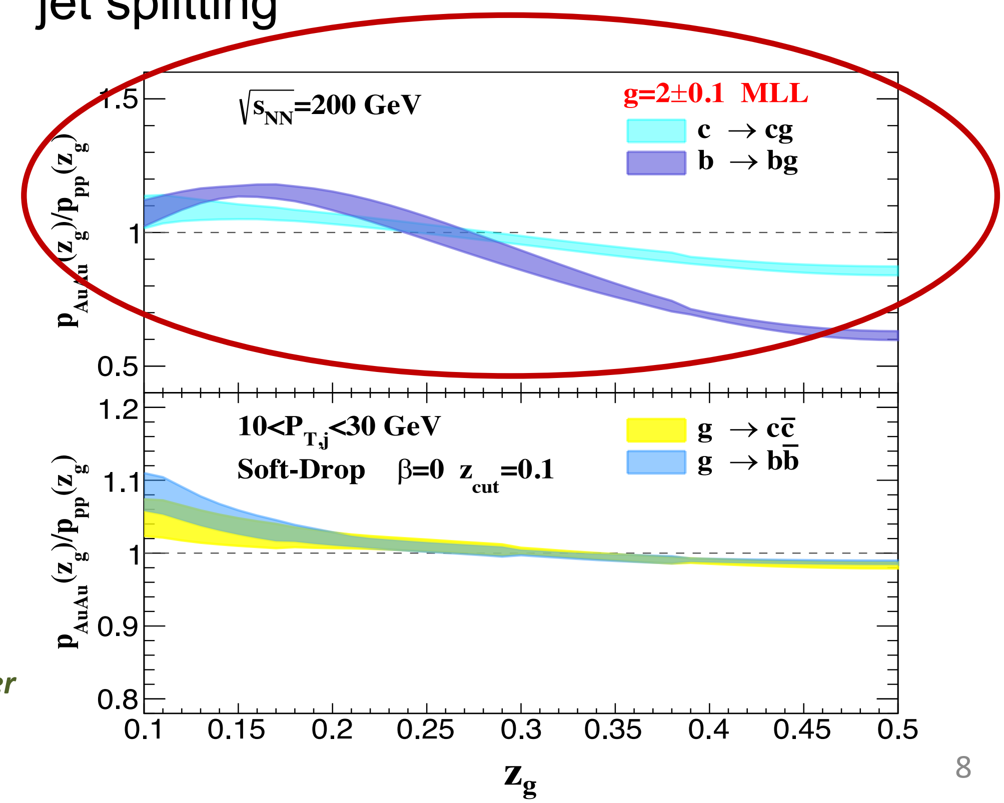


Inverting the Mass Hierarchy of Jet Quenching Effects



B-jet substructure in heavy ion collisions:

- Discovered a new way to constrain mass effects in parton showers
- At RHIC jet energies, we predict a unique reversal of the mass hierarchy effects on jet splitting



Sudakov resummation:

accounts for multiple branchings

$$\frac{dN_j^{\text{vac,MLL}}}{dz_g d\theta_g} = \sum_i \left(\frac{dN^{\text{vac}}}{dz_g d\theta_g}\right)_{j\to i\bar{i}} \underbrace{\exp\left[-\int_{\theta_g}^{1} d\theta \int_{z_{\text{cut}}}^{1/2} dz \sum_i \left(\frac{dN^{\text{vac}}}{dz\, d\theta}\right)_{j\to i\bar{i}}\right]}_{\text{Sudakov Factor}}$$

H. Li *et al* . (2018)

See talk by C. Lee on other substructure observables

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New Constraints on Gluon Fragmentation in Heavy Mesons

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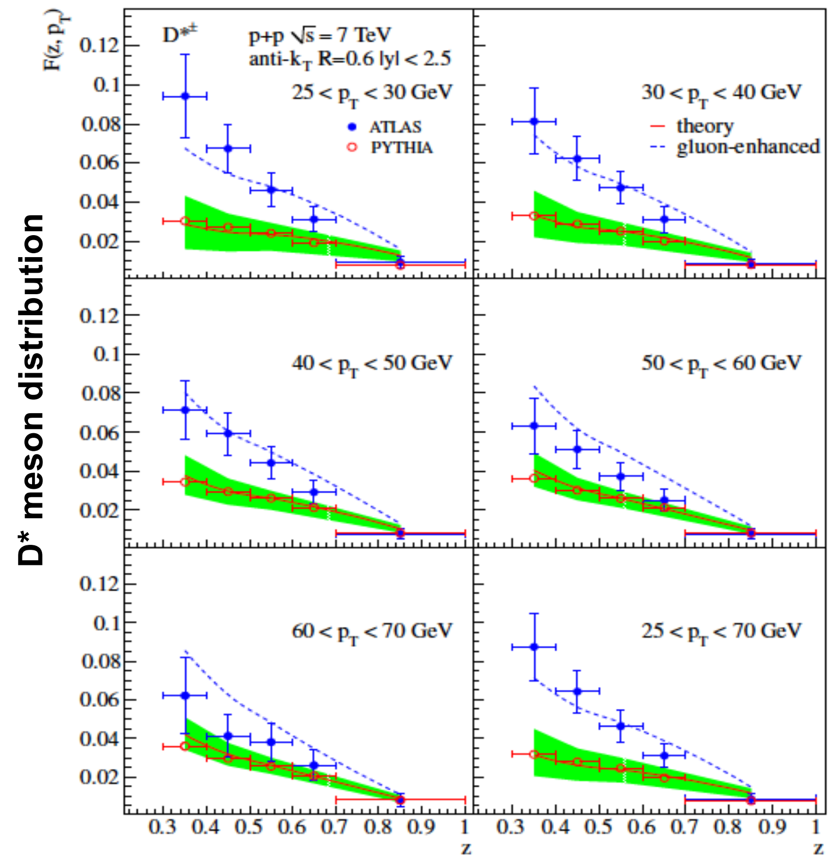
Milestones met: achievements beyond the original research scope

- Clearly the gluon contribution to heavy flavor is very important for reactions with nuclei

experiment		data type	$\mathcal{N}_i$	#data in fit	χ^2
ALEPH [50]		incl.	0.991	17	31.0
OPAL [51]		incl.	1.000	9	6.5
		c tag	1.002	9	8.6
		b tag	1.002	9	5.6
ATLAS [34]		$D^{*\pm}$	1	5	13.8
ALICE [37]	$\sqrt{S} = 7$ TeV	D^{*+}	1.011	3	2.4
ALICE [38]	$\sqrt{S} = 2.76$ TeV	D^{*+}	1.000	1	0.3
CDF [39]		D^{*+}	1.017	2	1.1
LHCb [36]	$2 \leq \eta \leq 2.5$	$D^{*\pm}$	1	5	8.2
	$2.5 \leq \eta \leq 3$	$D^{*\pm}$	1	5	1.6
	$3 \leq \eta \leq 3.5$	$D^{*\pm}$	1	5	6.5
	$3.5 \leq \eta \leq 4$	$D^{*\pm}$	1	1	2.8
ATLAS [26]	$25 \leq \frac{p_T^{jet}}{\text{GeV}} \leq 30$	(jet $D^{*\pm}$)	1	5	5.5
	$30 \leq \frac{p_T^{jet}}{\text{GeV}} \leq 40$	(jet $D^{*\pm}$)	1	5	4.1
	$40 \leq \frac{p_T^{jet}}{\text{GeV}} \leq 50$	(jet $D^{*\pm}$)	1	5	2.4
	$50 \leq \frac{p_T^{jet}}{\text{GeV}} \leq 60$	(jet $D^{*\pm}$)	1	5	0.9
	$60 \leq \frac{p_T^{jet}}{\text{GeV}} \leq 70$	(jet $D^{*\pm}$)	1	5	1.6
TOTAL:				96	102.9



Momentum fraction

Performed global refit of fragmentation functions to world's data including semi-inclusive annihilation, inclusive hadron production and hadrons in jets

Excellent χ^2/DOF ~ 1

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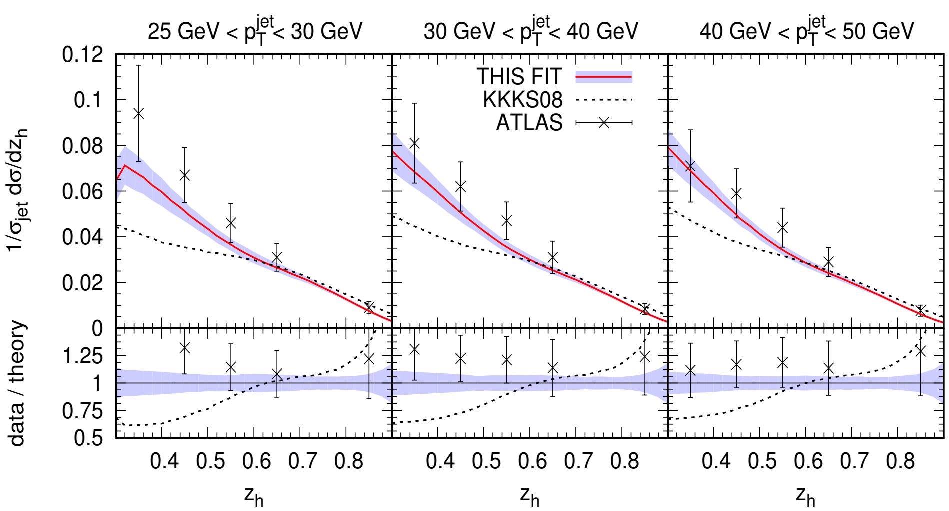
Final Results for D* Fragmentation Functions

- **Fit at NLO in Mellin space**

$$\frac{d\sigma^{pp\to(\text{jet}\,h)X}}{dp_T^{\text{jet}}\,d\eta^{\text{jet}}\,dz_h} = \frac{2p_T^{\text{jet}}}{S}\sum_{a,b,c}\int_{x_a^{\min}}^{1}\frac{dx_a}{x_a}f_a(x_a,\mu)$$

$$\times\int_{x_b^{\min}}^{1}\frac{dx_b}{x_b}f_b(x_b,\mu)\int_{z_c^{\min}}^{1}\frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab}^{c}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{v\,dv\,dw}$$

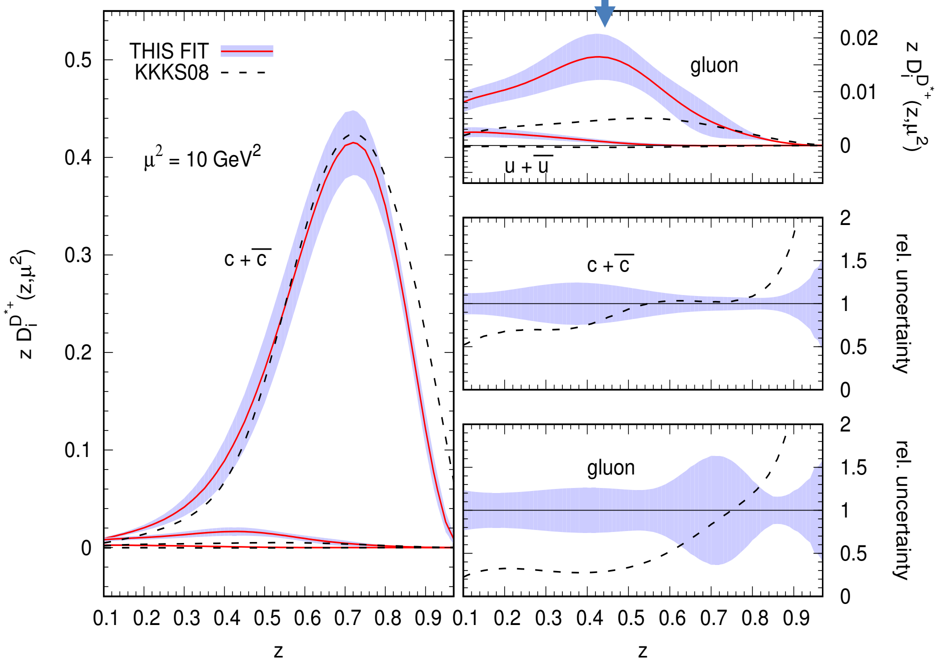
$$\times\,\mathcal{G}_c^h(z_c,z_h,\mu,R)\,,$$



Obtained much improved description of D* in jets

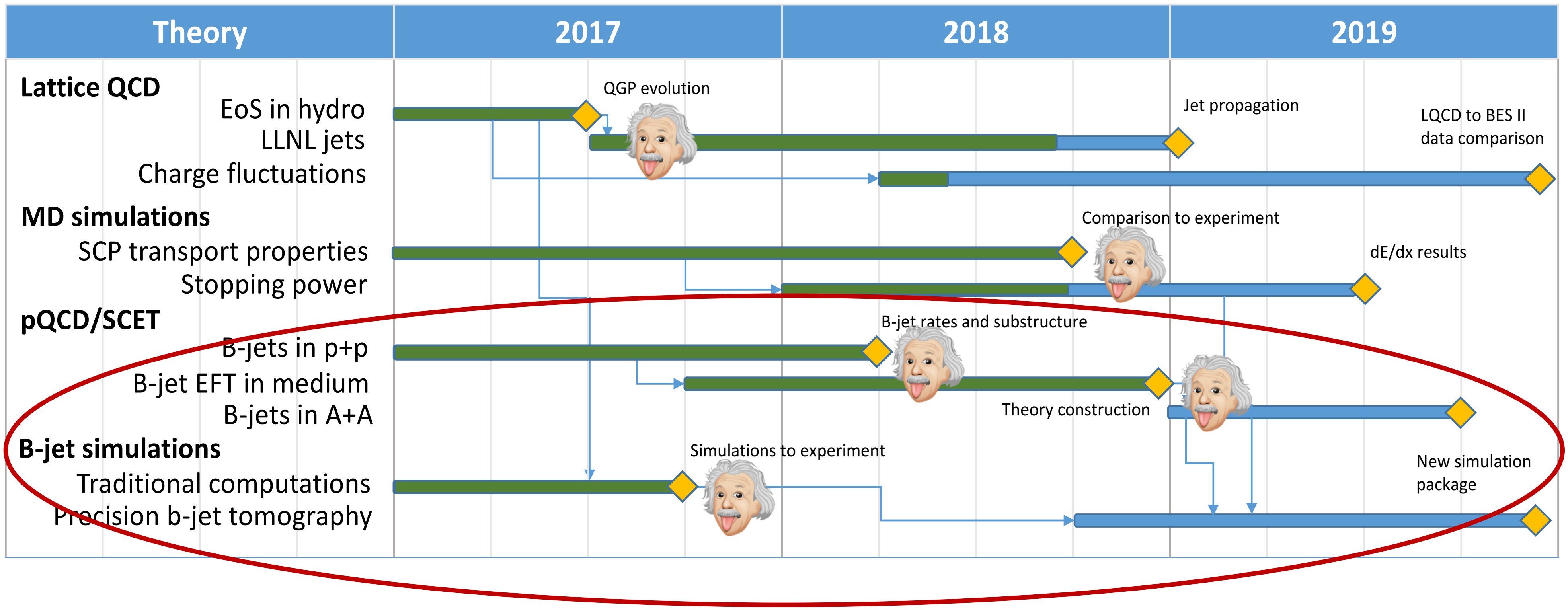
D. Anderle *et al.* PRD (2017)

Significant enhancement of the gluon fragmentation component to HF at small and intermediate z



Important implications for heavy flavor suppression in the QGP: larger color charge = larger suppression

Theory Timetable and Future pQCD Work



Future work:

- **Main focus:** the new simulation package milestone, combining all theory advances
- **Specific tasks:** b-jet quenching from semi-inclusive jet functions, incorporation of HF splitting functions in a hydrodynamic background, collisional E-loss; extend several calculations down to RHIC energies
- **New opportunities:** di b-jet correlations, c-jets, soft-Glauber interactions

See talk by J. Daligault on transport properties and stopping power of SCPs

Summary of pQCD Accomplishments

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- **Publications** – 9 refereed publications in the leading journals in the field (including 3 letters), 1 more near completion. 4 refereed conference proceedings
  - Y. Chien, I. Vitev, Physical Review Letters **119**: 112301 (2017)
  - Z. Kang, F. Ringer, and I. Vitev, Journal of High Energy Physics. **1703**: 146 (2017)
  - Z. Kang, F. Ringer, and I. Vitev, Physics Letters B. **769**: 242-248 (2017)
  - D. Anderle, T. Kaufmann, M. Strattman, F. Ringer, I. Vitev, Physical Review D **96** 034028 (2017) …

- **Talks** – given 16 talks and seminars, many invited, including plenary
  - I. Vitev, "Jets in SCET", Precision spectroscopy of the QGP with jets and heavy flavor, INT, Seattle, WA, 2017
  - F. Ringer, "Inclusive jets and their substructure in SCET", Jets@LHC, Bangalore, India, 2017
  - H. Li, "Inverting the mass hierarchy of jet quenching effects with b-jet substructure sPHENIX Collaboration Workshop, Santa Fe, NM 2017 …

- **Summary** - Work is well on track, we have met all milestones (some considerably ahead of time). This allowed us to seize the opportunity to expand the originally proposed scope and impact, better understand heavy flavor fragmentation and work on collisional energy loss / b-jet correlations

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The Broader Impact of pQCD/SCET Theory

- ## Follow on projects / grants:
  NSF three year award $60K/y, "Perturbative QCD Study for Jet and Heavy Flavor Production". August 2017 – August 2020

- ## Conferences:
  Co-organized conferences related to jet and heavy flavor physics– Santa Fe Jets and Heavy Flavor workshop, 2017, 2018. UCLA jet physics workshop 2017. Selected to host 2019 International Symposium on Multiparticle Dynamics in Santa Fe, NM (in competition with Scotland)

- ## Personnel
  F. Ringer to LBNL, now on UIUC shortlist; H. Xing to ANL/Northwestern, standing Assistant Professorship offer from Southern China Normal U.; D. Kang to Fudan U., professor; M. Sievert was a finalist at NMSU, to Rutgers U.; H. Li joined us from Monash U. Australia; Consult with D. Neill, Feynman to staff.