Probing Quark-Gluon Plasma with Bottom Quark Jets at sPHENIX - Theory

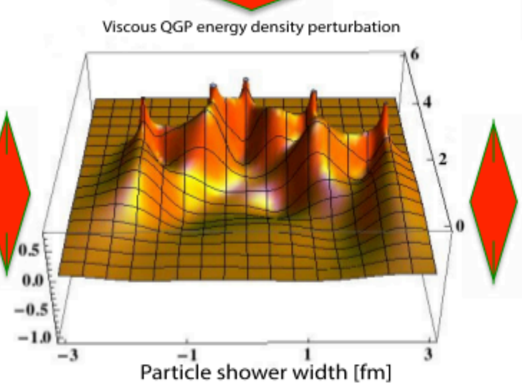
Expertise from T-2, T-5, CCS-7

Daligault, Gupta, Kang, Lee, Vitev (co-PI), Yoon

Theory budget ~ $600K/year

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






b-jet energy loss

pQCD / SCET

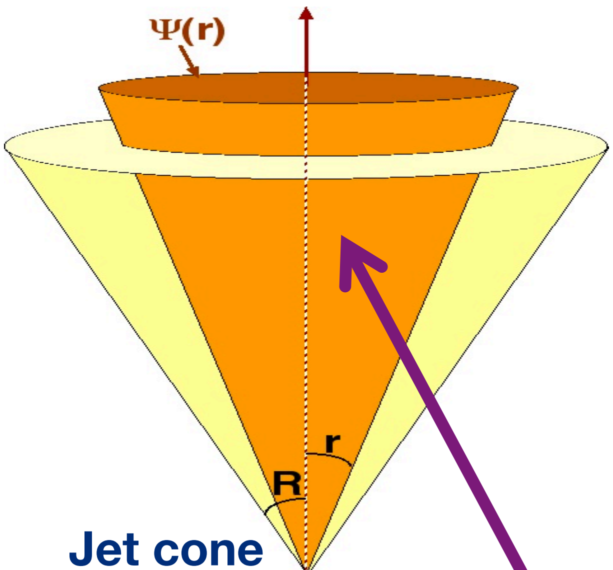
MD simulations / dE/dx

Lattice QCD / Hydro

Precision b-jets X sections and substructure

Kang, Lee, Vitev

- Powerful soft-collinear effective field theory (SCET) methods. Vast improvements in accuracy of jet cross sections in e^+e^-, *ep*, and *pp* collisions

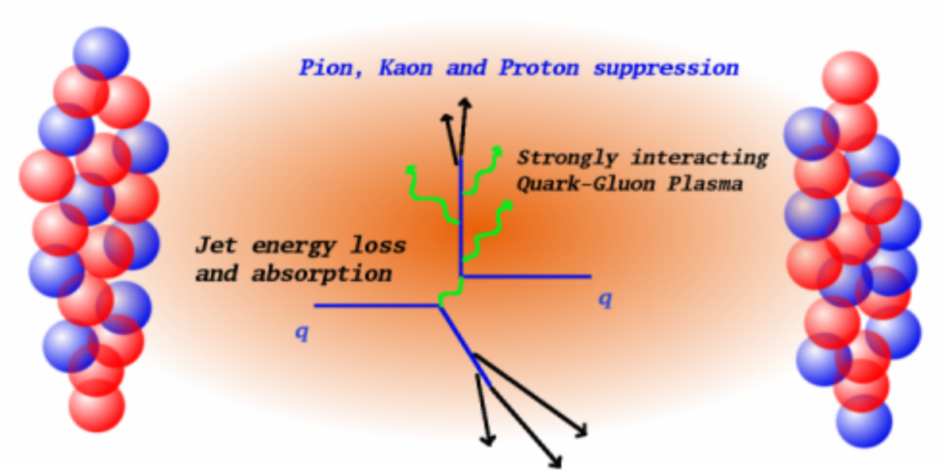


Improved formulations of SCET, compute b-jet cross sections with the highest accuracy to date

Phys. Rev. D90 (2014) 094503

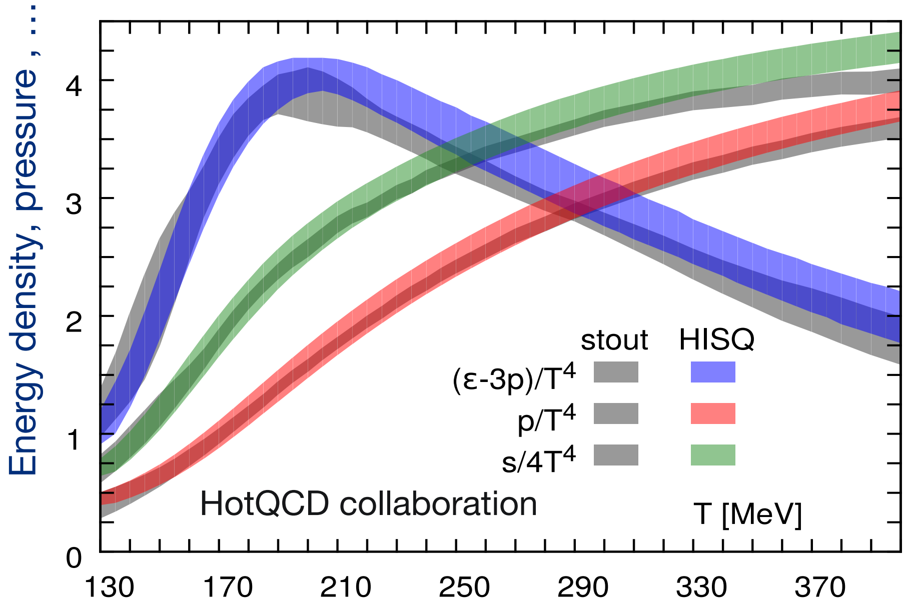
Develop first-principles theory of heavy quark propagation in nuclear matter and the process of shower formation

Evaluate jet substructure observables (shapes, fragmentation functions) and their modification in the QGP



Mass, charge, transport properties

Lattice QCD EoS and Charge Fluctuations



Phys. Rev. D90 (2014) 094503

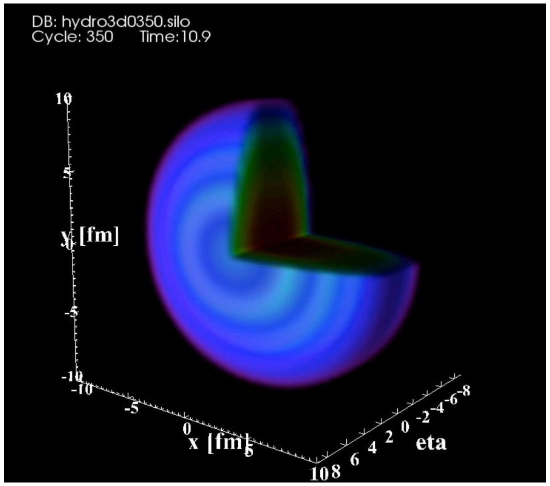
Gupta, Yoon

- Incorporate the current state-of-the art EoS in hydrodynamic simulations, describe time, temperature evolution of the QGP

Accurate medium dynamics for b-jet quenching simulations will be available

- Phase transitions near the critical point characterized by fluctuations (charge number fluctuation for QGP to ordinary nuclear matter) $\sim(\pi^{+}-\pi^{-})$

Evaluate charge fluctuations on the lattice and compare our results to measurements form Beam Energy Scan II at RHIC



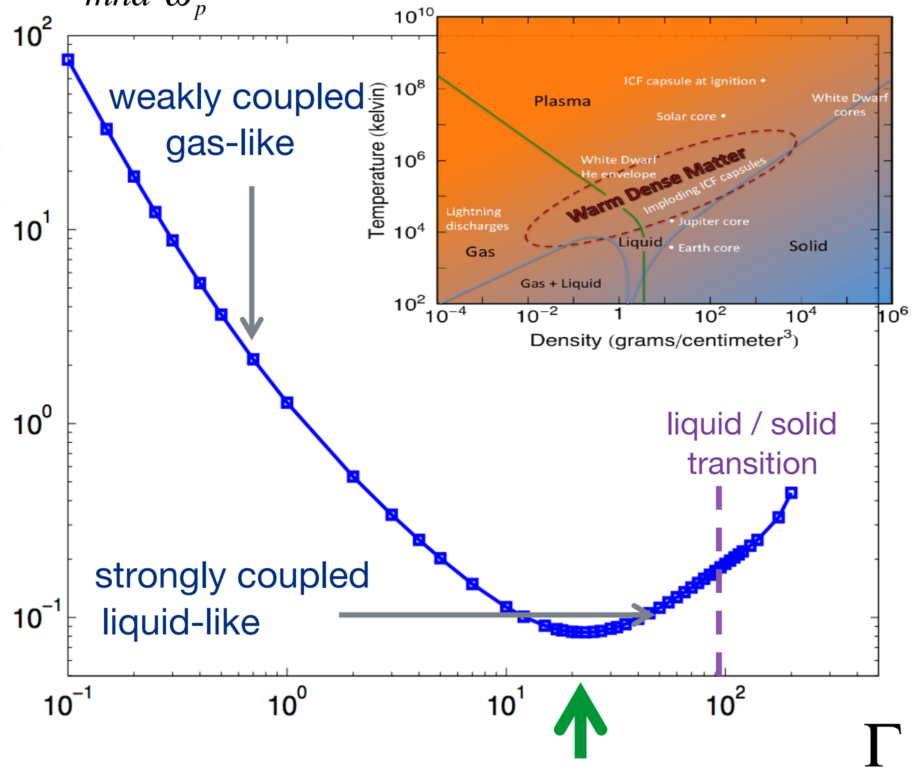
Hydro simulation of the QGP energy density at 10^{-23} s

dE/dx in Strongly-Coupled Plasmas

$$\eta^* = \frac{\eta}{mna^2\omega_p}$$

Phys. Rev. Lett.113, 155006 (2015)

Daligault, Vitev



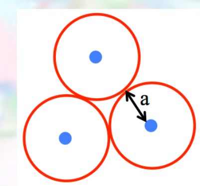
QGP-like minimum

- The strongly coupled nature of the QGP makes it tantalizingly similar to warm dense matter (WDM). Microscopic MD simulations

Coupling strength: $\Gamma = \frac{PE}{KE}$

$\Gamma > 1$ Interactions among particles dramatically affect their dynamics

In WDM, $\Gamma = \frac{Q^2/a}{k_B T}$



In QGP, $\Gamma = few$

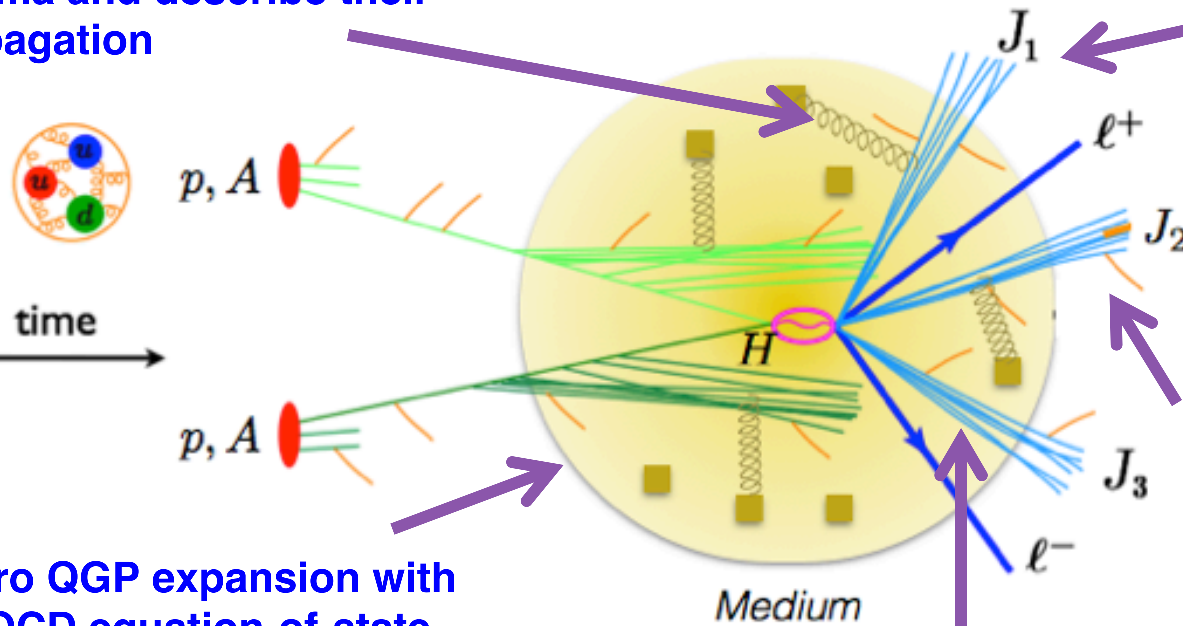
Perform molecular dynamics (MD) simulations of stopping power of charged particles in WDM near the viscosity minimum

Obtain much-needed physical insights and theoretical guidance for b-jet stopping power phenomenology in the QGP

Theory Deliverables: a Unified Picture

First-principles effective theory to couple b-jets to the plasma and describe their propagation

Most accurate resummed calculations of b-jet cross sections and b-jet substructure in proton-proton collisions at RHIC and LHC



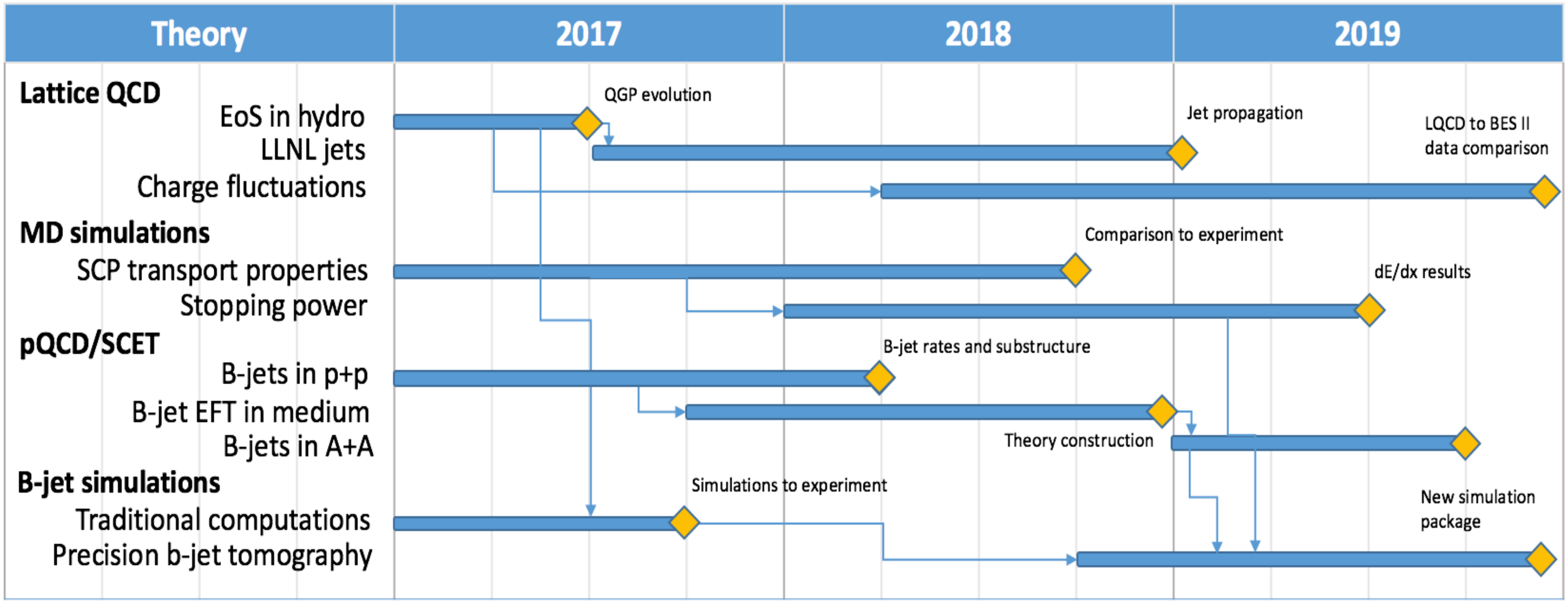
Set of observables sensitive to the transport properties and quasiparticle nature of the QGP

Hydro QGP expansion with HotQCD equation-of-state. LQCD for charge fluctuations

Stopping power for heavy particles in strongly-coupled plasmas form MD. Simulations validated against experiment

Package for precision b-jet tomography at sPHENIX and predictions to experiment

Theory Timetable



- **Individual theory discussion on weekly basis, keeping track of progress**
- **Well-defined responsibilities, researchers matched to tasks**
- **Monthly combined theory and experiment meetings**
- **Progress on items with milestones this year (hydro simulations with LQCD EoS and b-jet simulations with energy loss)**
- **One item completed ahead of schedule – EFT for heavy quark propagation in the QGP**

One Theory Highlight

Develop an effective theory of b-jet propagation in matter

FY 2018

- Develop first-principles theory of heavy quark propagation in nuclear matter and the process of shower formation

Earlier developments

Phys. Lett. B564 (2003) 231-234

JHEP 1106 (2011) 080

It was possible to carry this simplification since we realized the sectors of the theory decouple, very explicit in the hybrid gauge

LO SCET Lagrangian

$$\mathcal{L}_0 = \sum_{\tilde{p},\tilde{p}',\tilde{q}} e^{-ix\cdot\mathcal{P}}\,\bar{\xi}_{n,p'}\left[in\cdot D + (\mathcal{P}\!\!\!/_\perp + gA\!\!\!/^\perp_{n,q})W_n\frac{1}{\bar{\mathcal{P}}}W_n^\dagger(\mathcal{P}\!\!\!/_\perp + gA\!\!\!/^\perp_{n,q'})\right]\frac{\bar{n}\!\!\!/}{2}\xi_{n,p} + \mathcal{L}_m$$

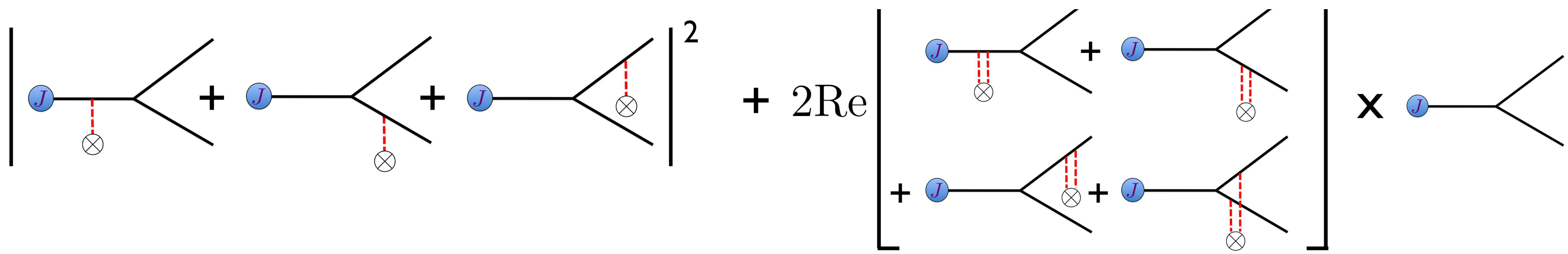
The mass term

$$\mathcal{L}_m = \sum_{\tilde{p},\tilde{p}',\tilde{q}} e^{-ix\cdot\mathcal{P}}\left[m\,\bar{\xi}_{n,p'}\left[(\mathcal{P}\!\!\!/_\perp + gA\!\!\!/^\perp_{n,q}), W_n\frac{1}{\bar{\mathcal{P}}}W_n^\dagger\right]\frac{\bar{n}\!\!\!/}{2}\xi_{n,p} - m^2\,\bar{\xi}_{n,p'}W_n\frac{1}{\bar{\mathcal{P}}}W_n^\dagger\frac{\bar{n}\!\!\!/}{2}\xi_{n,p}\right]$$

The mass $m/p^+ \sim \lambda$ in SCET_M already counts as the small parameter. So any term that will include mass and the Glauber field will be power suppressed

Necessary Ingredient - Massive Splittings

Diagrams corresponding to first order in opacity

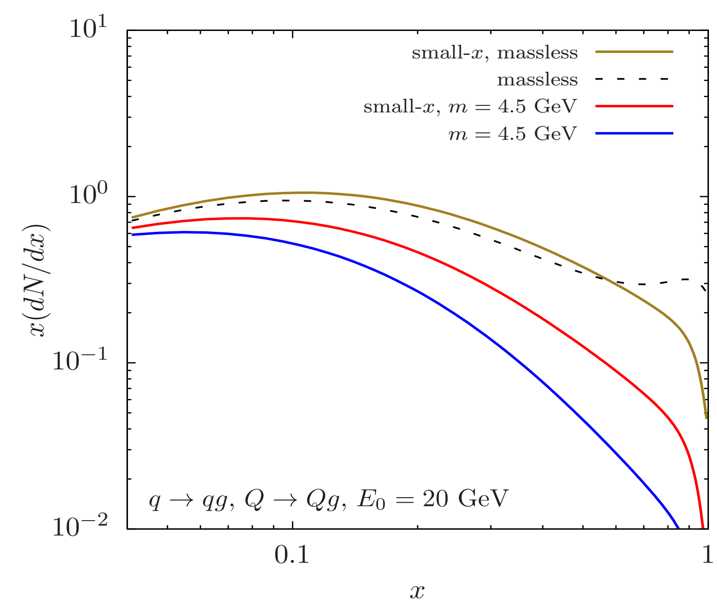


- First recover the massive vacuum splittings
- Evaluate the 3 massive in medium splittings

We have input for description of the in-medium parton showers of heavy quarks

One example. Can be evaluated numerically

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

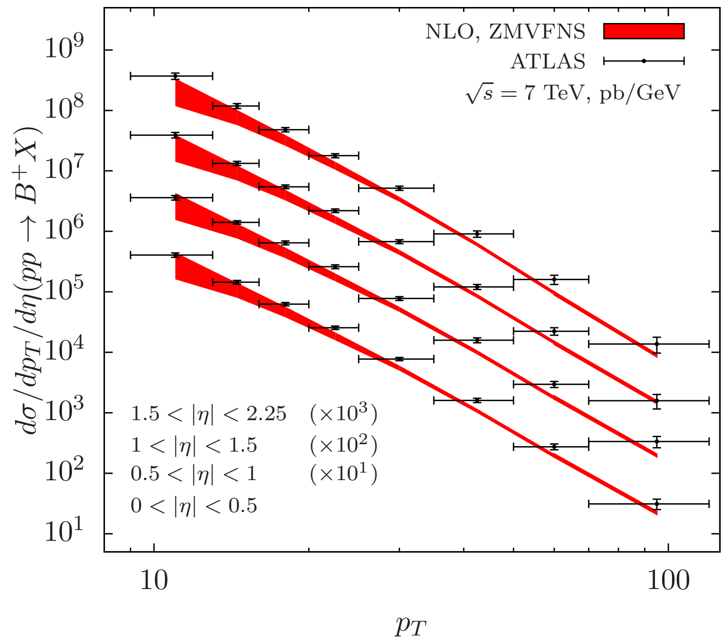


Largest mass effects in the sPHENIX b-jet acceptance range

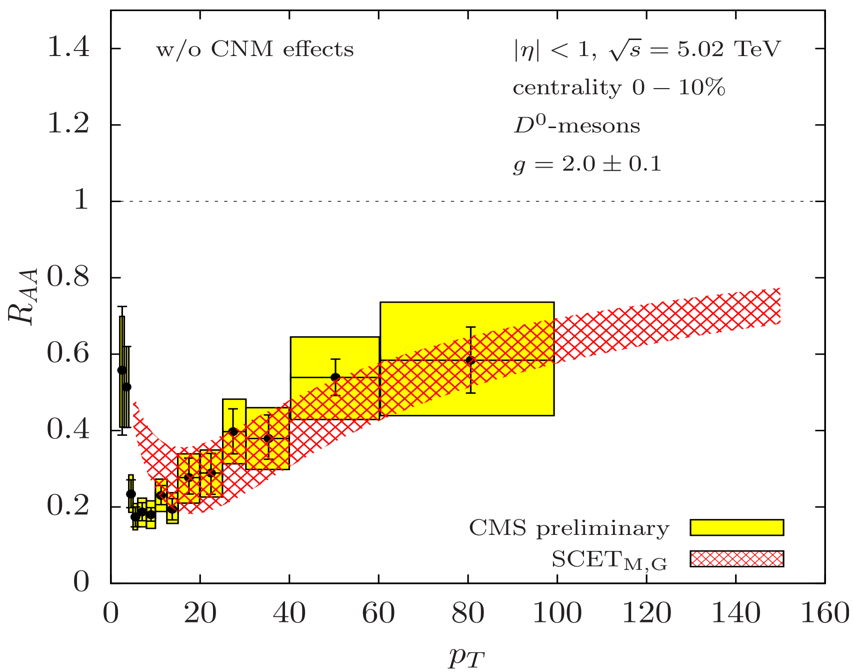
Application Consistent with NLO

Two advances – a) including gluon fragmentation contribution to heavy flavor, b) going beyond energy loss

$$\frac{d\sigma_{pp}^{H}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^{1}\frac{dx_a}{x_a}f_a(x_a,\mu)\int_{x_b^{\min}}^{1}\frac{dx_b}{x_b}f_b(x_b,\mu) \times \int_{z_c^{\min}}^{1}\frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab}^{c}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{dvdz}D_c^H(z_c,\mu),$$



- Gluon fragmentation plays an important role ~50%



- First cascade contribution

$$d\sigma_{\mathrm{PbPb}}^{H} = d\sigma_{pp}^{H,\mathrm{NLO}} + d\sigma_{\mathrm{PbPb}}^{H,\mathrm{med}}$$

This leaves us time for a stretch goal – include collisional energy losses in the SCET framework. This can go well trough the second year

Conclusions

- **Theory is an integral part of this LDRD DR**

- **There are project management mechanisms in place and ways to track theory progress. Milestones, clear responsibilities assigned**

- **At present, the theory part is on schedule**
  [Hydro code installed, tests being run]
  [HF parton shower in the soft emission limit simulated]

- **One milestone completed ahead of schedule [Effective theory for open heavy propagation in matter]**