Calculating Jet Shape Modifications in Heavy Ion Collisions Using Soft-Collinear Effective Theory

Yang-Ting Chien

Los Alamos National Laboratory

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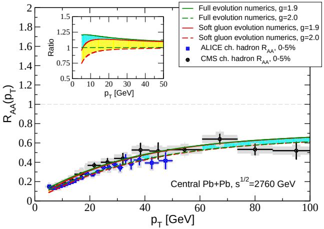
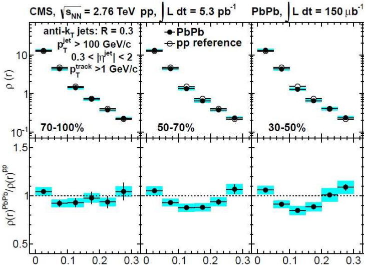
In collaboration with Ivan Vitev

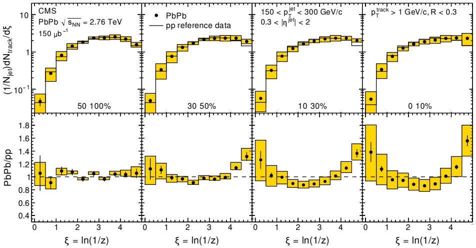
Outline

- Jet quenching and modification
  - Jet shapes in proton and heavy ion collisions
- Resummation using Soft-Collinear Effective Theory (SCET)
  - Factorization theorem
  - Renormalization group evolution
- Medium Modification using SCET with Glauber gluons ($\mathrm{SCET_G}$)
  - Medium induced splitting functions
  - Modifications at first order in opacity expansion
- Preliminary results

Jet quenching phenomenology

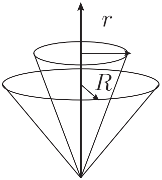






- Charged hadron suppression (R_{AA})
  - Hadron/Jet quenching
  - **Kinematics**
- Modifications of jet shapes and jet fragmentation functions
  - Medium modification
  - **Jet substructure**
- Measurements at CMS
  - PLB 730 (2014) 243
  - PRC 90 (2014) 024908

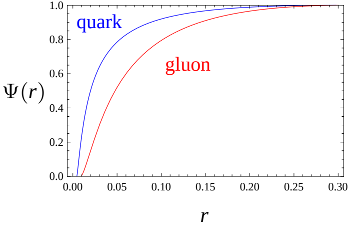
Jet shape, a classic jet substructure observable (Ellis, Kunszt, Soper)

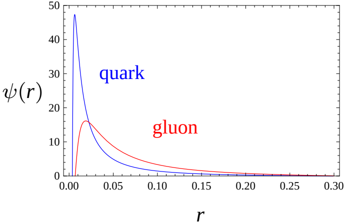


$$\Psi_J(r,R) = \frac{\sum_{r_i<r} E_{Ti}}{\sum_{r_i<R} E_{Ti}}$$

$$\langle\Psi\rangle = \frac{1}{N_J}\sum_{J}^{N_J}\Psi_J(r,R)$$

$$\psi(r,R) = \frac{d\langle\Psi\rangle}{dr}$$





- Jet shapes probe the energy distribution inside a jet
- Quark jets are more localized whereas gluon jets are more spread out
- Quark-gluon discrimination

- The infrared structure of QCD induces Sudakov logarithms
- Fixed order calculation breakdowns at small r
- Large logarithms of the form $\alpha_s^n \log^m r/R$ $(m \leq 2n)$ need to be resummed

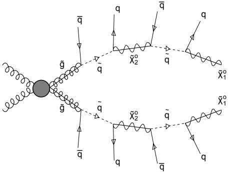
Jet shapes in proton and heavy ion collisions

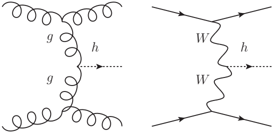
In **proton** collisions,

- Quark-gluon discrimination
  – Many SM and BSM signals are quark-heavy
  – QCD backgrounds are mostly gluon-heavy
- Boosted particle (H, W, Z, t) tagging
- Standard input for tuning Monte Carlo event generators

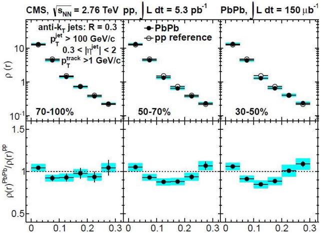
In **heavy ion** collisions,

- Probing the properties of the QGP
  – Modification of jet shapes is sensitive to the medium properties
  – Quark and gluon jets are modified differently
- Underlying events are a big issue
  – η-reflected background subtraction at CMS
- As in proton collisions, initial state radiation and non-perturbative effects are power corrections which have sizable effects at the peripheral of jets
- Precision calculation of jet shapes involves a lot more complications





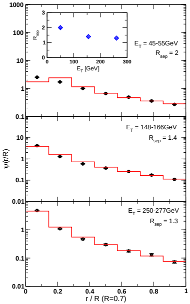
gluon fusion | vector boson fusion

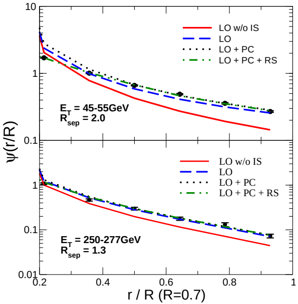


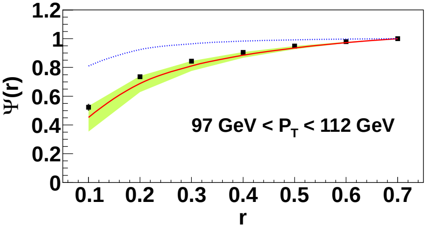
Jet shape calculations with pQCD (Seymour, Vitev et al, and Yuan et al.)

In **proton** collisions,

- pQCD calculation with a parameter R_{sep} fits the CDF data.
  – R_{sep}: effective angular separation in leading-order parton splitting
  – Resummation using the modified leading logarithmic approximation
  – Initial state radiation and power corrections examined
- Resummation performed differently in another pQCD calculation
  – The LO result is not enough
- The jet algorithm dependence still needs to be explored
  – iterative cone algorithm at Tevatron
  – anti-k_T algorithm at the LHC
- Formation of jets (physical) from partons (unphysical) is already quite nontrivial in proton collisions







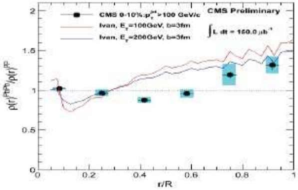
Jet shape calculations with pQCD and energy loss (Vitev et al)

In **heavy ion** collisions,

- The jet shape modification is not well described by the energy loss formalism
- We will use effective field theory techniques to expand the full QCD contributions with a systematic power counting

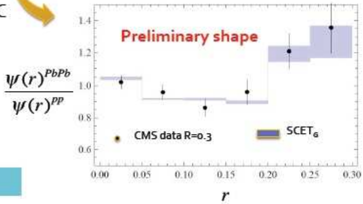
- A *preliminary* result

  - Need to combine with the splitting functions evalualted numerically for the same medium geometry and expansion, present predictions for the upcoming run at the LHC



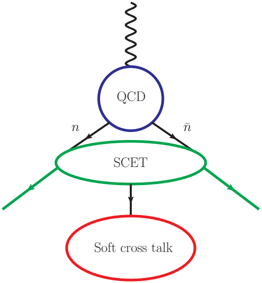
- Even with the caveats, the improvement in the calculation can be significant

Y.-T. Chien et al. In preparation



Soft-Collinear Effective Theory (SCET)

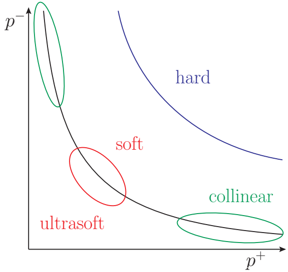
- Effective field theory techniques are most useful when there is clear scale separation
- SCET separates physical degrees of freedom in QCD by a systematic expansion in power counting
  - Match SCET with QCD at the hard scale by integrating out the hard modes
  - Integrating out the off-shell modes gives collinear Wilson lines which describe the collinear radiation
  - The soft sector is described by soft Wilson lines along the jet directions



- Soft-collinear decoupling holds at leading power in the Lagrangian, which leads to the factorization theorems of cross sections

Power counting in SCET

- The scaling of modes:
  $p_h : Q(1,1,1)$, $p_c : Q(1,\lambda^2,\lambda)$ and $p_s : Q(\lambda,\lambda,\lambda)$
- Q is at the hard scale which is the energy of the jet
- λ is the power counting parameter satisfying $\lambda < R$
  – The energy outside jets is power suppressed
- QCD $= \mathcal{O}(\lambda^0) + \mathcal{O}(\lambda^1) + \cdots$ in SCET
- $Q\lambda$ is the jet scale which is significantly lower than Q



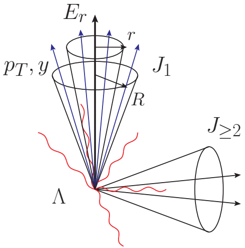
- Jet shapes have dominant contributions from the collinear sector

$$\Psi(r) = \frac{E_c^{<r} + E_s^{<r}}{E_c^{<R} + E_s^{<R}} = \frac{E_c^{<r}}{E_c^{<R}} + \mathcal{O}(\lambda)$$

  – Contributions from the (ultra)soft mode are power suppressed
  – λ is typically small because of dynamical threshold enhancement
  – For high p_T and small jets, power corrections are small and the leading power contribution is a very good approximation of the full QCD result
- Contributions of $\mathcal{O}(r)$ and $\mathcal{O}(R)$ are small and power suppressed, but contributions of $\mathcal{O}(r/R)$ are not necessarily small

Factorization theorem for jet shapes in proton collisions

- Without loss of generality, we demonstrate the calculation in e^+e^- collisions since the initial state radiation in proton collisions contributes as power corrections



- The factorization theorem for the differential cross section of the production of N jets with $p_{T\,i}, y_i$, the energy E_r inside the cone of size r in **one** jet, and an energy cutoff Λ outside all the jets is the following,

$$\frac{d\sigma}{dp_{T\,i}dy_i dE_r} = H(p_{T\,i}, y_i, \mu) J_1^{\omega_1}(E_r, \mu) J_2^{\omega_2}(\mu) \ldots S_{1,2,\ldots}(\Lambda, \mu)$$

- For the differential jet rate (without measuring E_r)

$$\frac{d\sigma}{dp_{T\,i}dy_i} = H(p_{T\,i}, y_i, \mu) J_1^{\omega_1}(\mu) J_2^{\omega_2}(\mu) \ldots S_{1,2,\ldots}(\Lambda, \mu)$$

– Here $J_1^{\omega}(E_r, \mu) = \sum_{X_c} \langle 0|\bar{\chi}_\omega(0)|X_c\rangle\langle X_c|\chi_\omega(0)|0\rangle \delta(E_r - \hat{E}^{<r}(X_c, \text{algorithm}))$ and $\omega = 2E_J$ is twice the jet energy and is the label of the collinear jet field in SCET

– $J_i^{\omega}(\mu)$ are the "unmeasured jet functions" (Ellis et al)

– All the jet and soft functions have the R dependence from the jet algorithm

Factorization theorem for jet shapes (continued)

The averaged energy inside the cone of size r in jet 1 is the following

$$\langle E_r\rangle_\omega = \frac{1}{\frac{d\sigma}{dp_{T\,i}dy_i}}\int dE_r E_r \frac{d\sigma}{dp_{T\,i}dy_i dE_r} = \frac{H(p_{T\,i},y_i,\mu)J^{\omega_1}_{E,r_1}(\mu)J^{\omega_2}_2(\mu)\ldots S_{1,2,\ldots}(\Lambda,\mu)}{H(p_{T\,i},y_i,\mu)J^{\omega_1}_1(\mu)J^{\omega_2}_2(\mu)\ldots S_{1,2,\ldots}(\Lambda,\mu)} = \frac{J^{\omega_1}_{E,r_1}(\mu)}{J^{\omega_1}_1(\mu)}$$

Here $J^\omega_{E,r}(\mu) = \int dE_r E_r J^\omega(E_r,\mu)$ is referred to as the "jet energy function."

- All the hard, unmeasured jet and soft functions cancel
- The integral jet shape, averaged over all jets, is the following

$$\langle\Psi\rangle = \frac{1}{\sigma_{\text{total}}}\int_{PS} dp_T dy \frac{d\sigma}{dp_T dy}\Psi_\omega\ ,\ \text{where}\ \Psi_\omega = \frac{J_{E,r}(\mu)/J(\mu)}{J_{E,R}(\mu)/J(\mu)} = \frac{J_{E,r}(\mu)}{J_{E,R}(\mu)}$$

- Using the collinear SCET Feynman rules, the jet energy function $J_{E,r}(\mu)$ and its anomalous dimension are calculated at $\mathcal{O}(\alpha_s)$ for both quark jets and gluon jets

Renormalization group evolution of jet energy functions

$$\frac{dJ^q_{E,r}(r,R,\mu)}{d\ln\mu} = \Big[-C_F\Gamma_{\rm cusp}\ln\frac{\omega^2\tan^2\frac{R}{2}}{\mu^2} - 2\gamma_{J^q}\Big]J^q_{E,r}(r,R,\mu)$$
$$\frac{dJ^g_{E,r}(r,R,\mu)}{d\ln\mu} = \Big[-C_A\Gamma_{\rm cusp}\ln\frac{\omega^2\tan^2\frac{R}{2}}{\mu^2} - 2\gamma_{J^g}\Big]J^g_{E,r}(r,R,\mu)$$

- The anomalous dimensions of the jet energy functions are

$$\gamma_{J^q} = -3C_F\ , \qquad \gamma_{J^g} = -\beta_0 = -\frac{11}{3}C_A + \frac{4}{3}T_F n_f$$

  – The same anomalous dimensions as the unmeasured jet functions
  – The anomalous dimensions are R dependent and r independent

- Ψ_ω is renormalization group invariant

$$\Psi_\omega = \frac{J_{E,r}(\mu)}{J_{E,R}(\mu)} = \frac{J_{E,r}(\mu_{j_r})}{J_{E,R}(\mu_{j_R})}U_J(\mu_{j_r},\mu_{j_R})$$

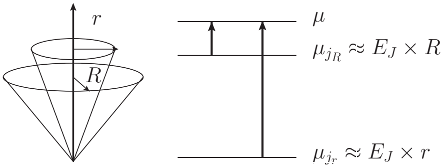
- Identify the natural scale μ_{j_r} to eliminate large logarithms in $J_{E,r}(\mu_{j_r})$
- The RG evolution kernel $U_J(\mu_{j_r},\mu_{j_R})$ resums the large logarithms

Natural scales

- The quark jet energy function at $\mathcal{O}(\alpha_s)$ is the following

$$\frac{2}{\omega}J^q_{E,r} = \frac{\alpha_s C_F}{2\pi}\Big[\frac{1}{2}\ln^2\frac{\omega^2\tan^2\frac{r}{2}}{\mu^2} - \frac{3}{2}\ln\frac{\omega^2\tan^2\frac{r}{2}}{\mu^2} - 2\ln X\ln\frac{\omega^2\tan^2\frac{r}{2}}{\mu^2} + 2 - \frac{3\pi^2}{4} + 6X - \frac{3}{2}X^2 - \left(\frac{1}{2}X^2 - 2X^3 + \frac{3}{4}X^4 + 2X^2\log X\right)\tan^2\frac{R}{2}\Big]\,, \text{ where } X = \frac{\tan\frac{r}{2}}{\tan\frac{R}{2}} \approx \frac{r}{R}$$

– The scale $\mu_{j_r} = \omega\tan\frac{r}{2} \approx E_J \times r$ eliminates large logarithms in $J^q_{E,r}$ at $\mathcal{O}(\alpha_s)$
– $J_{E,r}(\mu)$ and $J_{E,R}(\mu)$ have the same anomalous dimensions but different scales



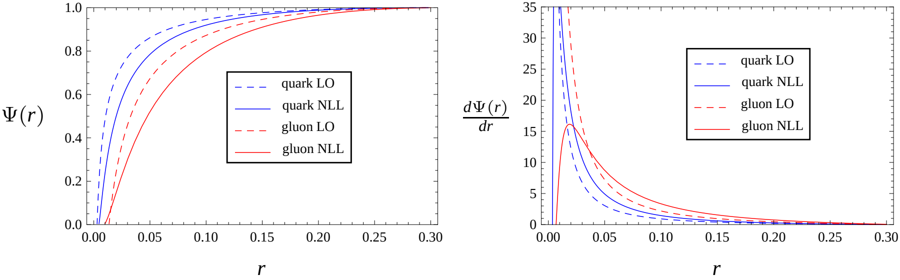
RG evolution between μ_{j_r} and μ_{j_R} resums $\log \mu_{j_r}/\mu_{j_R} = \log r/R$

Resummed jet energy functions

- $\log r/R$ are resummed using the RG kernels in SCET ($i = q, g$)

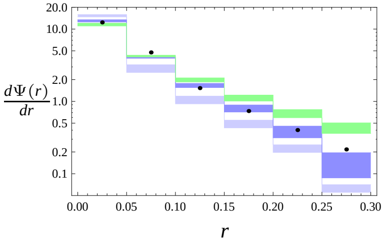
$$\Psi^i_\omega(r,R) = \frac{J^{iE}_r(r,R,\mu_{j_r})}{J^{iE}_R(R,\mu_{j_R})}\exp[-2\,C_i\,S(\mu_{j_r},\mu_{j_R})+2\,A_{J^i}(\mu_{j_r},\mu_{j_R})]\left(\frac{\mu^2_{j_r}}{\omega^2\tan^2\frac{R}{2}}\right)^{C_i\,A_\Gamma(\mu_{j_R},\mu_{j_r})}$$

$$S(\nu,\mu) = -\int_{\alpha_s(\nu)}^{\alpha_s(\mu)} d\alpha\,\frac{\Gamma_{\rm cusp}(\alpha)}{\beta(\alpha)}\int_{\alpha_s(\nu)}^{\alpha}\frac{d\alpha'}{\beta(\alpha')},\quad A_X(\nu,\mu) = -\int_{\alpha_s(\nu)}^{\alpha_s(\mu)} d\alpha\,\frac{\gamma_X(\alpha)}{\beta(\alpha)}$$



– Integral and differential jet shapes of 100 GeV quark and gluon jets at LO and NLL

Comparison with the CMS data at 2.76 TeV

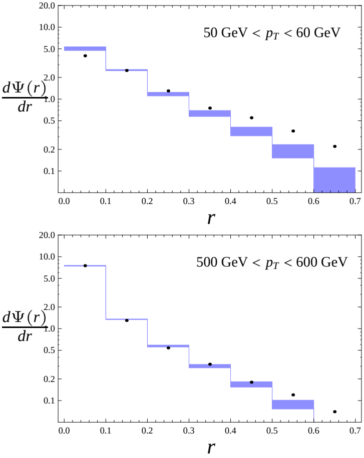


– Differential jet shapes in proton collisions with the center of mass energy at 2.76 TeV

- The blue bands (LO and NLL) are for R=0.3 anti-k_T jets with $p_T > 100$ GeV and $0.3 < |\eta| < 2$
  – Resummation is necessary
- The green band is for R=0.3 cone jets

  – The difference for jets reconstructed using different algorithms is of $\mathcal{O}(r/R)$
- Bands are theory uncertainties estimated by varying μ_{j_r} and μ_{j_R}
- In the region $r \approx R$ we may need higher fixed order calculations and include power corrections

Comparison with the CMS data at 7 TeV

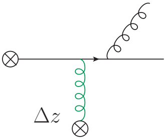


- The blue band (NLL) is for R=0.7 anti-k_T jets with $|\eta| < 1$
- For low p_T jets, power corrections give significant contributions
- For high p_T jets, the SCET calculation reproduces the peak region very well

SCET works in jet shapes in proton collisions

– Differential jet shapes in proton collisions with the center of mass energy at 7 TeV

Jets in heavy ion collisions



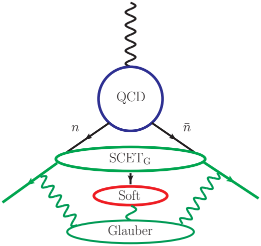
- Ultra-relativistic heavy ion collisions create a strongly interacting medium which is referred to as the Quark-Gluon Plasma (QGP)
- Jets passing through QGP are observed to be quenched
- Coherent multiple scattering and induced radiation play an important role in jet modifications
- From thermal field theory and lattice QCD calculations, the picture of quasi-particles with Debye-screened potentials and masses seems to be a reasonable modeling of the local properties of QGP (the Gyulassy-Wang model)
- Depending on the relative sizes of radiation formation time and parton mean free path, the Landau-Pomeranchuk-Migdal (LPM) effect can be sizable

$$\frac{x\,E}{(q_\perp - k_\perp)^2} \text{ v.s. } \Delta z$$

- There have been at least four approaches in capturing the LPM effect in the context of parton multiple scattering (AMY, BDMPS/Z, Higher-Twist and GLV)
- Can we extend SCET to describe the formation of jets in the QGP?

SCET with Glauber gluons (SCET_G)

- From the pinch analysis, the Glauber region of phase space is the other relevant mode
- SCET_G was constructed from SCET bottom up (Idilbi et al, Vitev et al)
  - Glauber gluon momentum scales as $p_G : Q(\lambda^2, \lambda^2, \lambda)$
  - Glauber gluons are off-shell modes providing momentum transfer transverse to the jet direction
  - Glauber gluons are treated as background fields generated from the colored charges in the QGP



- In principle, Glauber gluons interact with both the collinear and the soft modes
- However, jet shapes have dominant contributions from the collinear sector so the Glauber-collinear interaction is the most relevant

Jet shape modifications in heavy ion collisions

- The jet energy function can be calculated from integrating the splitting functions $dN_{i\to jk}/dxd^2k_\perp$ over an appropriate phase space. At leading order,

$$J^i_{E,r}(\mu) = \sum_{j,k}\int_{PS} dxdk_\perp \frac{dN_{i\to jk}}{dxd^2k_\perp}E_r(x,k_\perp)$$

- Medium-induced splitting functions have been calculated using $\mathrm{SCET_G}$ (Vitev et al). Just to illustrate, in the small-x limit,

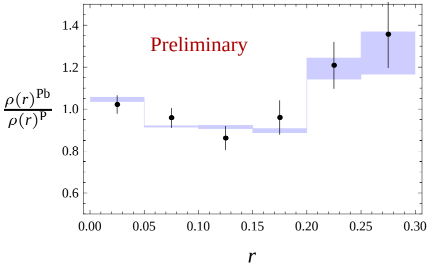
$$\frac{dN^{med}_{q\to qg}}{dxd^2k_\perp} = \frac{C_F\alpha_s}{\pi^2}\frac{1}{x}\int_0^L\frac{d\Delta z}{\lambda}\int d^2q_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}}{d^2q_\perp}\frac{2k_\perp\cdot q_\perp}{k_\perp^2(q_\perp-k_\perp)^2}\left[1-\cos\left(\frac{(q_\perp-k_\perp)^2\Delta z}{x\omega}\right)\right]$$

- Jet shapes get modified through the modification of jet energy functions

$$\Psi(r) = \frac{J^{vac}_{E,r}+J^{med}_{E,r}}{J^{vac}_{E,R}+J^{med}_{E,R}} = \frac{J^{vac}_{E,r}}{J^{vac}_{E,R}}\frac{J^{vac}_{E,R}}{J^{vac}_{E,R}+J^{med}_{E,R}} + \frac{J^{med}_{E,r}}{J^{vac}_{E,R}+J^{med}_{E,R}}$$

  - Large logarithms in $\Psi^{vac}(r) = J^{vac}_{E,r}/J^{vac}_{E,R}$ have been resummed
  - There are no large logarithms in $J^{med}_{E,r}$ at first order in opacity $\mathcal{O}(L/\lambda)$ due to the LPM effect
  - The RG evolution of medium-modified jet energy functions is the same

Preliminary result



- We plot the ratio of the differential jet shapes in lead-lead and proton collisions for gluon jets with $p_T = 100$ GeV and $y = 0$
- The data is for the centrality bin between $30 - 50\%$
- Jet shapes have to be averaged with the appropriate cross sections
- Power corrections are important around $r \approx R$
- The preliminary result above uses a static QGP model with $\lambda_g = 1$ fm, $L = 3$ fm, $m = 0.75$ GeV

Conclusions

- Jet shapes in proton collisions are calculated in the SCET collinear sector
  - The factorization theorem is written down
  - Jet energy functions are calculated at $\mathcal{O}(\alpha_s)$ for quark and gluon jets
  - Large logarithms are resummed to NLL using RG evolution
- Jet shapes in heavy ion collisions are calculated in $\mathrm{SCET_G}$
  - Medium-induced splitting functions are used to calculate the modification of jet energy function
  - Preliminary results agree with the CMS data very well
- Work in progress and future work
  - Check the numerics of jet shape modifications with a more realistic QGP model
  - Making predictions for the LHC Run-2
  - Paper in preparation (hopefully arXiv:150n.xxxx with $2 \leq n \leq 4$)
  - Calculate the modification of jet fragmentation function using $\mathrm{SCET_G}$
  - ...