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Jet charge

Based on: 1908.06979 with Haitao Li

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Jet charge calculation in SCET

P. Berge et al . (1981)

C. Bauer *et al.* (2001)

M. Beneke *et al.* (2004)

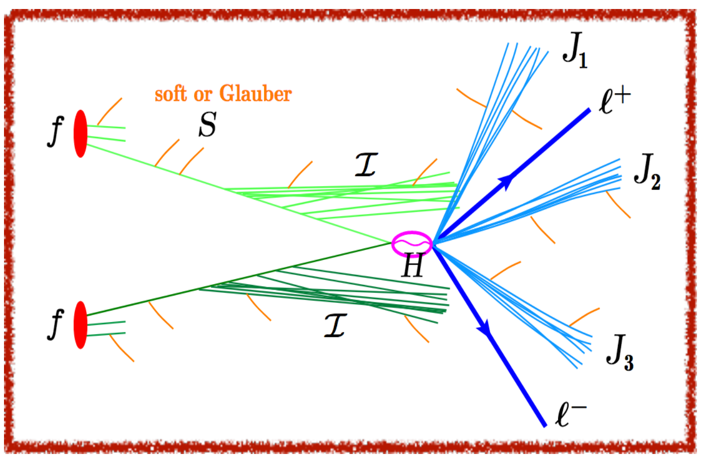
Jet charge : The weighted sum of the charges of particle in the jet. Used extensively since the late 70s, early 80s to determine the partonic flavor of the jet

- Modes in the theory: collinear quarks and gluons, soft gluons
- Factorization formulas written down as a convolution of Beam, Hard, Soft, and Jet functions

Proposed by R. Field *et al.* (1978)

The definition we use

$$Q_{\kappa,\,\mathrm{jet}} = \frac{1}{\left(p_T^{\mathrm{jet}}\right)^{\kappa}} \sum_{\mathrm{h\ in\ jet}} Q_h \left(p_T^h\right)^{\kappa}$$



Cross section for Jet production with a hadron inside jet

$$\frac{d\sigma_{h\in q-\mathrm{jet}}}{dz} = \int d\Phi_N \,\mathrm{tr}\left[H_N S_N\right] \left(\prod_{\ell=1}^{N-1} J_\ell\right) \mathcal{G}_i^h(E,R,z,\mu)$$

Fragmenting jet function

$$\mathcal{G}_i^h(E,R,z,\mu) = \sum_i \int_z^1 \frac{dz'}{z'} \mathcal{J}_{ij}\left(E,R,z',\mu\right) D_j^h\left(\frac{z}{z'},\mu\right)$$

Note that there are developments with semi-inclusive jet functions

Perturbative and non-perturbative contributions

- With this as a starting point

D. Krohn et al. (2012)

W. Waalewijn (2012)

$$\langle Q_{\kappa,q}\rangle = \int dz\; z^\kappa \sum_h Q_h \frac{1}{\sigma_{\text{q-jet}}} \frac{d\sigma_{h\in\text{q-jet}}}{dz}$$

$$\langle Q_{\kappa,q}\rangle = \frac{\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)}{J_q(E,R,\mu)} \tilde{D}_q^Q(\kappa,\mu)$$

- Expressed in (k+1) Mellin moment of the jet matching coefficient and charge-weighted frag. function

The normalization is the inclusive jet function

$$\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu) = \int_0^1 dz\; z^\kappa \mathcal{J}_{qq}(E,R,z,\mu)\;,$$

$$\tilde{D}_q^Q(\kappa,\mu) = \int_0^1 dz\; z^\kappa \sum_h Q_h D_q^h(z,\mu)$$

The non–perturbative part sums over all the hadrons in the jet

$$\tilde{D}_q^Q(\kappa,\mu) = \sum_h Q_h \tilde{D}_q^h(\kappa,\mu)$$

And obeys the evolution equation

$$\mu\frac{d}{d\mu}\tilde{D}_q^Q(\kappa,\mu) = \frac{\alpha_s(\mu)}{\pi}\tilde{P}_{qq}(\kappa)\tilde{D}_q^Q(\kappa,\mu)$$

Note that gluons do not contribute to the jet charge *on average*. We will need quark jet and fragmentation functions and matching coefficients

Matching coefficient and scale violation

- Calculation of the jet matching coefficient & jet function
- The calculation has been done before to NLO. The important observation here is that it can be expressed as an integral over splitting kernels. In medium only numerical grids possible

- The jet charge can be used to study the scale violation in QCD

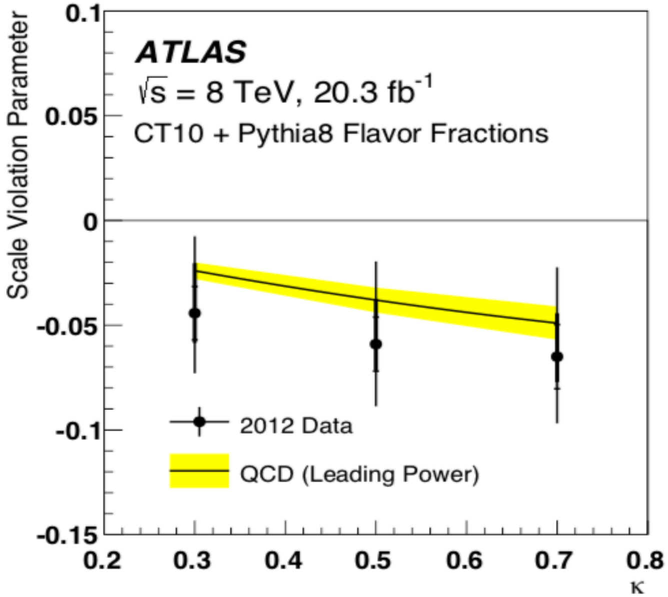
$$\frac{p_T}{\langle Q_\kappa \rangle} \frac{d}{dp_T} \langle Q_\kappa \rangle = \frac{\alpha_s}{\pi} \widetilde{P}_{qq}(\kappa) \equiv c_\kappa \approx \begin{cases} -0.024 \pm 0.004 & \kappa = 0.3 \\ -0.038 \pm 0.006 & \kappa = 0.5 \\ -0.049 \pm 0.008 & \kappa = 0.7 \end{cases}$$

$$\widetilde{P}_{qq}(\kappa) = C_F \int_0^1 dz \, (z^\kappa - 1) \frac{1+z^2}{1-z}$$

$$\mathcal{J}_{qq}^{(1)}(E,R,x,\mu) = \frac{C_F \alpha_s}{2\pi} \frac{e^{\epsilon \gamma_E}}{\Gamma(1-\epsilon)} \int \frac{dl_\perp^2}{l_\perp^2} \left(\frac{\mu^2}{l_\perp^2} \right)^\epsilon \frac{1+x^2-\epsilon(1-x)^2}{1-x}$$

Phase space constraints $0 < l_\perp < 2x(1-x)E \tan(R/2)$ **tell us how much of the parton shower falls within the jet of radius parameter R**

$$J_q(E,R,\mu) = \int_0^1 dz z \left[\mathcal{J}_{qq}(E,R,z,\mu) + \mathcal{J}_{qg}(E,R,z,\mu) \right]$$



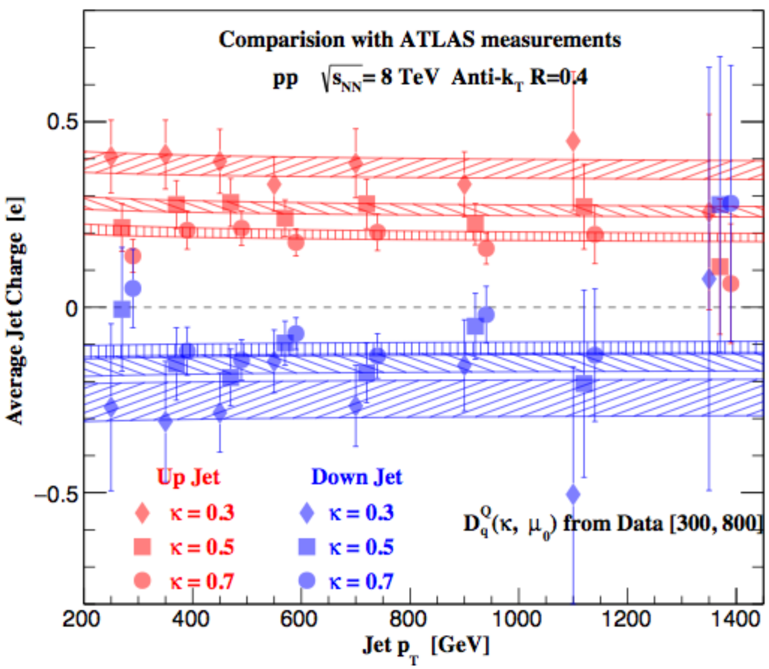
ATLAS (2012)

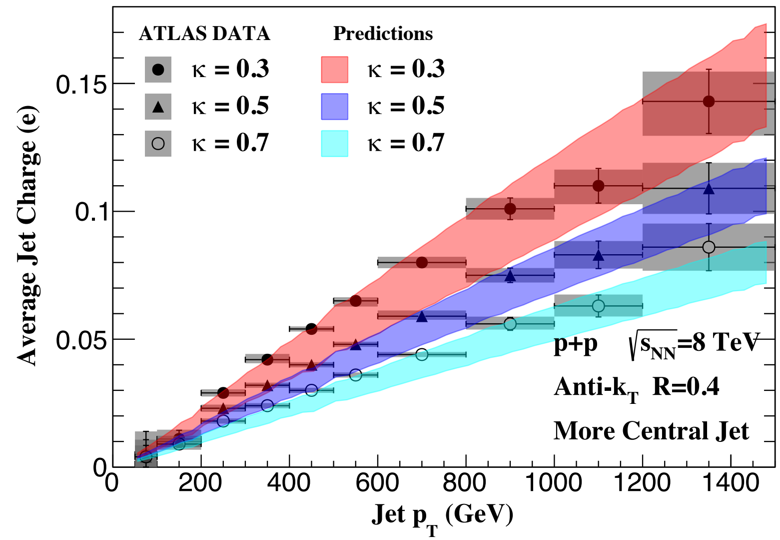
Effect of non-perturbative input

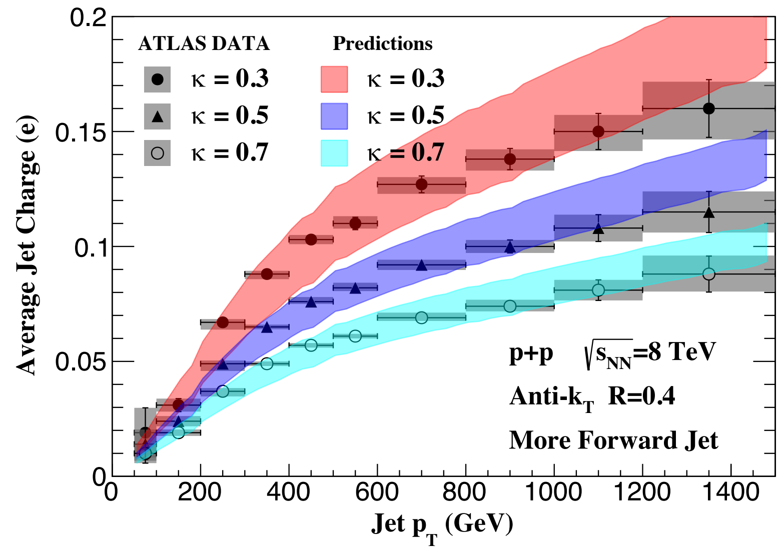
Initial condition at the lowest scale

$$D_q^Q(\kappa,\mu) = D_q^Q(\kappa,\mu_0)\exp\left[\int_{\mu_0}^{\mu}\frac{d\bar{\mu}}{\bar{\mu}}\frac{\alpha_s(\bar{\mu})}{\pi}\tilde{P}_{qq}(\kappa,\mu)\right]$$

Using ATLAS data to fit initial conditions – results in good description but large error bars
[ATLAS measured in 2 rapidity intervals]







Phenomenological results in proton collisions

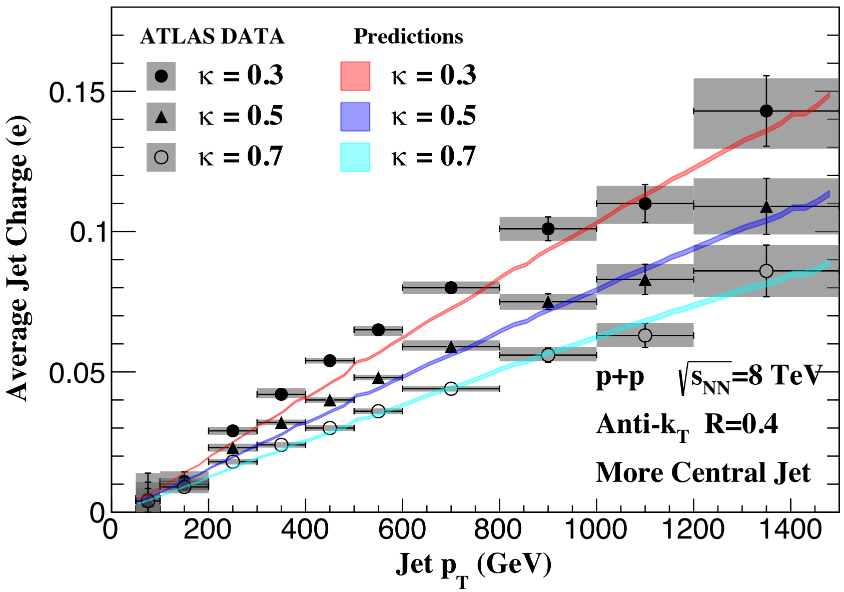
- Use PYTHIA simulated initial conditions
- Also depends on the simulation of jets in hadronic collisions (jets flavor fractions)

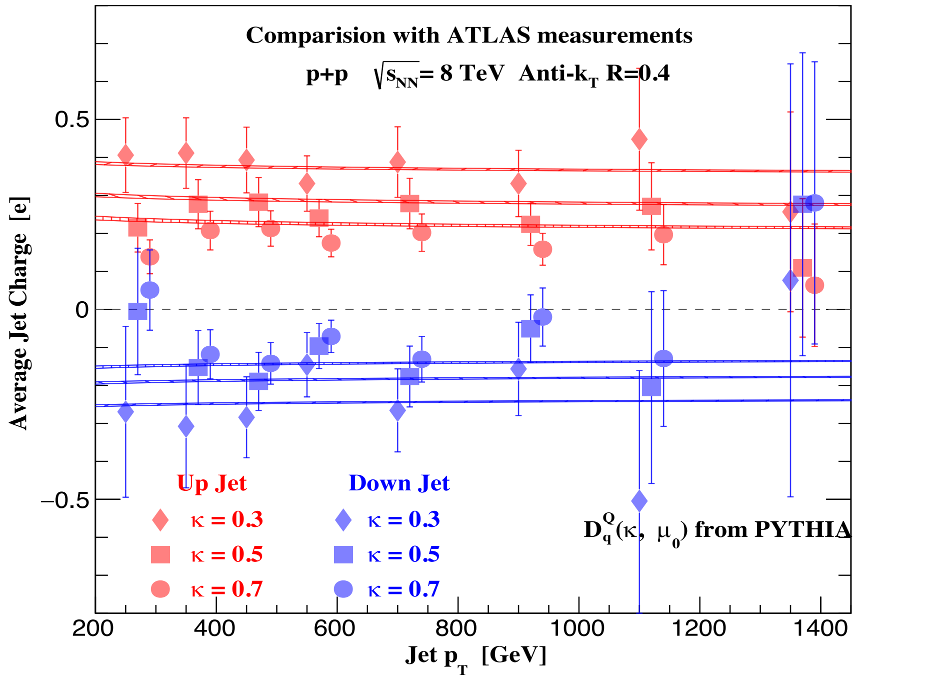
$$d\sigma_J = d\sigma_{J_g} + d\sigma_{J_u} + d\sigma_{J_{\bar{u}}} + d\sigma_{J_d} + d\sigma_{J_{\bar{d}}} + \cdots$$

$$\left\langle Q_\kappa^{f/c} \right\rangle = \underbrace{\left(f_u^{f/c} - f_{\bar{u}}^{f/c}\right)}_{\text{u-quark fraction}} \langle Q_\kappa^u \rangle + \underbrace{\left(f_d^{f/c} - f_{\bar{d}}^{f/c}\right)}_{\text{d-quark fraction}} \langle Q_\kappa^d \rangle$$

Phenomenology

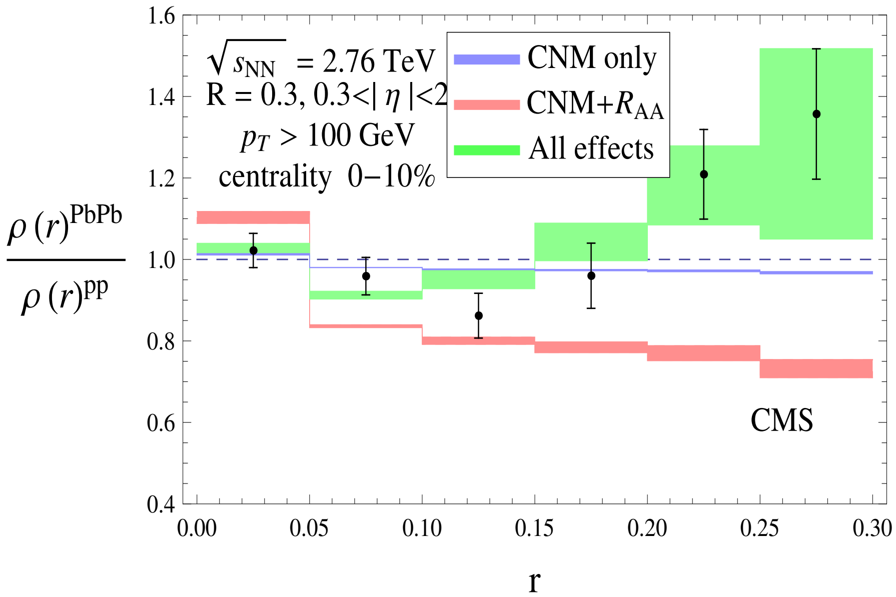
ATLAS *(2015)*





H. Li *et al.* (2019)

The jet charge in heavy ion collisions

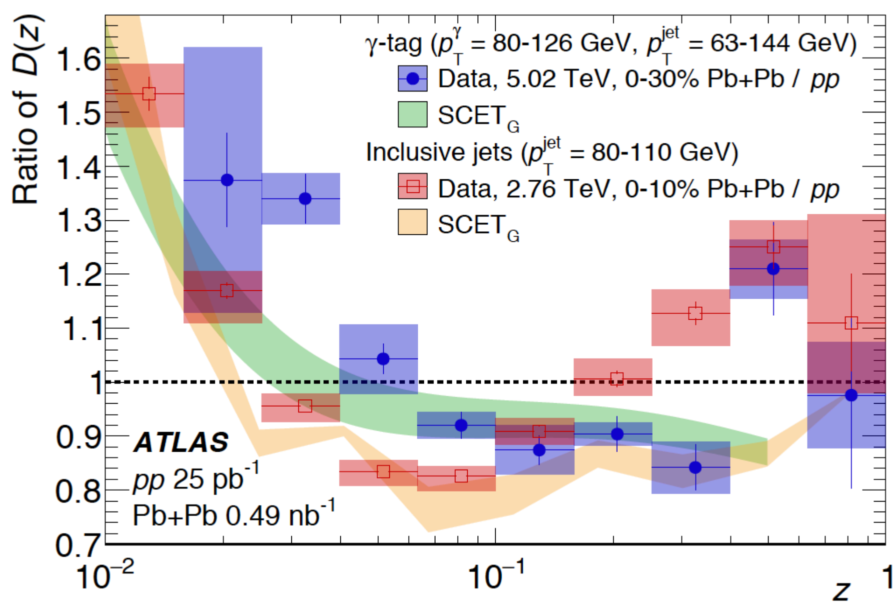


Y.T. Chien *et al. (2015)*

- In-medium parton showers differ significantly from the ones in the vacuum
- Manifested in the modification of jet substructure observables in heavy ion vs proton collisions

- In medium modification depends on the flavor of jets. Separation is essential to advance the understanding of medium effects

Significance: different flavor jets in HIC



M. Aaboud et al . (2019)

$SCET_G$ and in-medium parton splittings

Ovanesyan et al. (2012)

- Direct sum

$$\frac{dN(tot.)}{dxd^2k_\perp} = \frac{dN(vac.)}{dxd^2k_\perp} + \frac{dN(med.)}{dxd^2k_\perp}$$

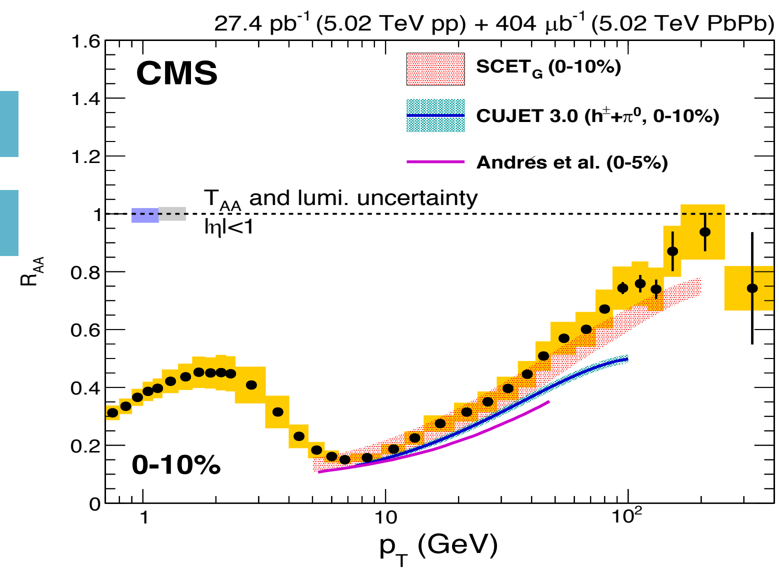
$$\left(\frac{dN}{dxd^2\mathbf{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2}C_F\frac{1+(1-x)^2}{x}\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\mathbf{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\,\mathrm{medium}}}{d^2\mathbf{q}_\perp}\Bigg[-\left(\frac{A_\perp}{A_\perp^2}\right)^2+\frac{B_\perp}{B_\perp^2}\cdot\left(\frac{B_\perp}{B_\perp^2}-\frac{C_\p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

- Factorize form the hard part
- Gauge-invariant
- Depend on the properties of the medium
- Can be expressed as proportional to Altarelli-Parisi

$$N.B.\;\; x \to 1-x \qquad A,..D,\Omega_1..\Omega_5 - functions(x,k_\perp,q_\perp)$$

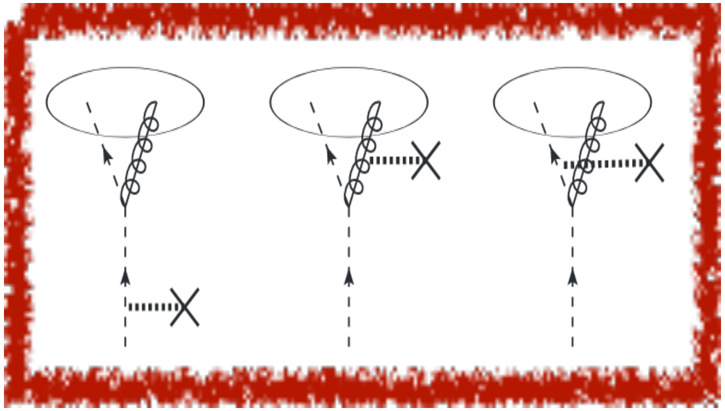
Y.T.Chien *et al.* (2014)

Z. Kang *et al.* (2016)



Additional scale violation due to the medium-induced shower. Theory and predictions verified

Jet charge in the medium



$$\langle Q_{q,\kappa}^{\mathrm{AA}}\rangle = \frac{\tilde{J}_{qq}(E,R,\kappa,\mu)+\tilde{\mathcal{J}}_{qq}^{\mathrm{med}}(E,R,\kappa,\mu)}{J_q(E,R,\mu)+J_q^{\mathrm{med}}(E,R,\mu)}\tilde{D}_q^{Q,\mathrm{full}}(\kappa,\mu)$$

- Modifications to jet matching coefficient, jet function and FF evolution

$$\frac{d}{d\ln\mu}\tilde{D}_q^{Q,\,\mathrm{full}}(\kappa,\mu) = \frac{\alpha_s(\mu)}{\pi}\left(\tilde{P}_{qq}(\kappa)+\tilde{P}_{qq}^{\mathrm{med}}(\kappa,\mu)\right)\tilde{D}_q^{Q,\,\mathrm{full}}(\kappa,\mu)$$

- Jet matching coefficient in matter

- Note that the virtual correction does not give a contribution. All contained in the LO result

$$\begin{aligned}\mathcal{J}_{qq}^{\mathrm{med}}(E,R,x,\mu) =\ & \frac{\alpha_s(\mu)}{2\pi^2}\Bigg[-\delta(1-x)\int_0^1 dz\int_0^\mu \frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2}P_{q\to qg}^{\mathrm{med}}(z,\mathbf{k}_\perp) \\ & + \int_0^{2Ex(1-x)\tan R/2}\frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2}P_{q\to qg}^{\mathrm{med}}(x,\mathbf{k}_\perp)\Bigg] \\ =\ & \frac{\alpha_s(\mu)}{2\pi^2}\int_0^{2Ex(1-x)\tan R/2}\frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2}P_{q\to qg}^{\mathrm{med}}(x,\mathbf{k}_\perp)\end{aligned}$$

Note the upper limit of k_T integration – jet quenching

Final result for jet charge in heavy ion collisions

- The in-medium jet function

$$J_q^{\text{med}}(E,R,\mu) = \int_0^1 dx\, x\left(\mathcal{J}_{qq}^{\text{med}}(E,R,x,\mu) + \mathcal{J}_{qg}^{\text{med}}(E,R,x,\mu)\right)$$
$$= \frac{\alpha_s(\mu)}{2\pi^2}\int_0^1 dx \int_0^{2Ex(1-x)\tan R/2} \frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\left(x P_{q\to qg}^{\text{med,real}}(x,\mathbf{k}_\perp) + x P_{q\to gq}^{\text{med,real}}(x,\mathbf{k}_\perp)\right)$$
$$= \frac{\alpha_s(\mu)}{2\pi^2}\int_0^1 dx \int_0^{2Ex(1-x)\tan R/2} \frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2} P_{q\to qg}^{\text{med,real}}(x,\mathbf{k}_\perp)\,,$$

Up to NLO in QCD and LO in opacity combining all corrections

$$\langle Q_{q,\kappa}^{\text{pp}}\rangle\left(1+\tilde{\mathcal{J}}_{qq}^{\text{med}} - J_q^{\text{med}}\right)\exp\left[\int_{\mu_0}^{\mu}\frac{d\bar{\mu}}{\bar{\mu}}\frac{\alpha_s(\bar{\mu})}{\pi}\tilde{P}_{qq}^{\text{med}}\right] + \mathcal{O}\left(\alpha_s^2,\chi^2\right)$$

$$\tilde{\mathcal{J}}_{qq}^{\text{med}} - J_q^{\text{med}} = \frac{\alpha_s(\mu)}{2\pi^2}\int_0^1 dx\,(x^\kappa - 1)\int_0^{2Ex(1-x)\tan R/2}\frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2}P_{q\to qg}^{\text{med,real}}(x,\mathbf{k}_\perp)$$

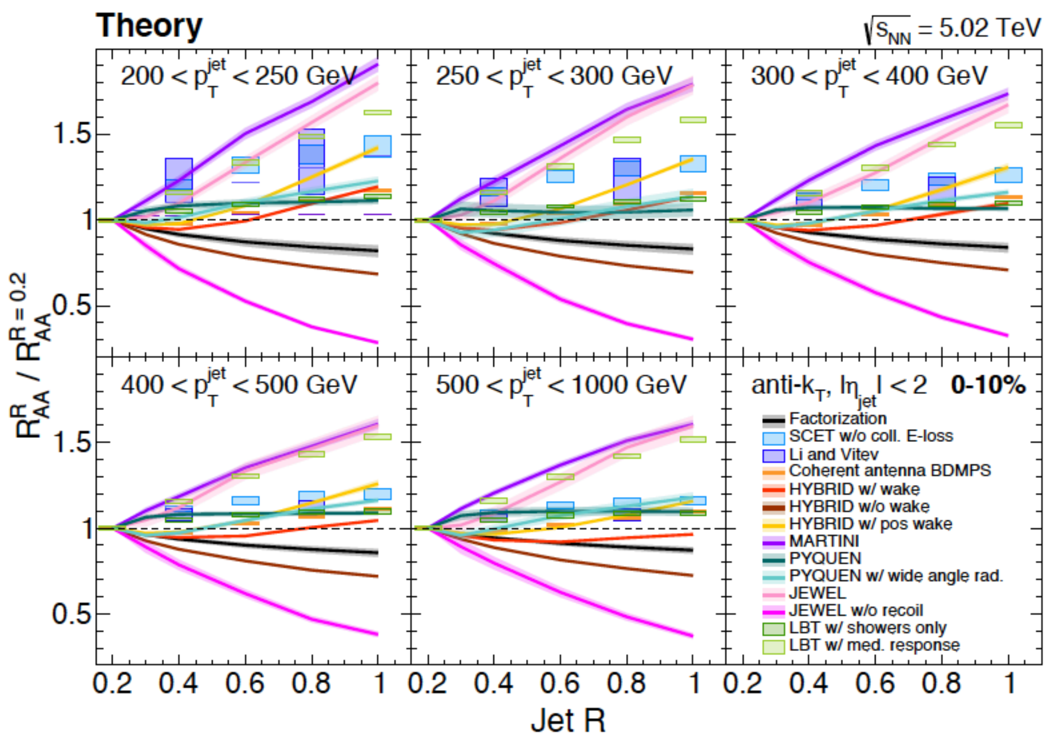
H. Li *et al.* (2019)

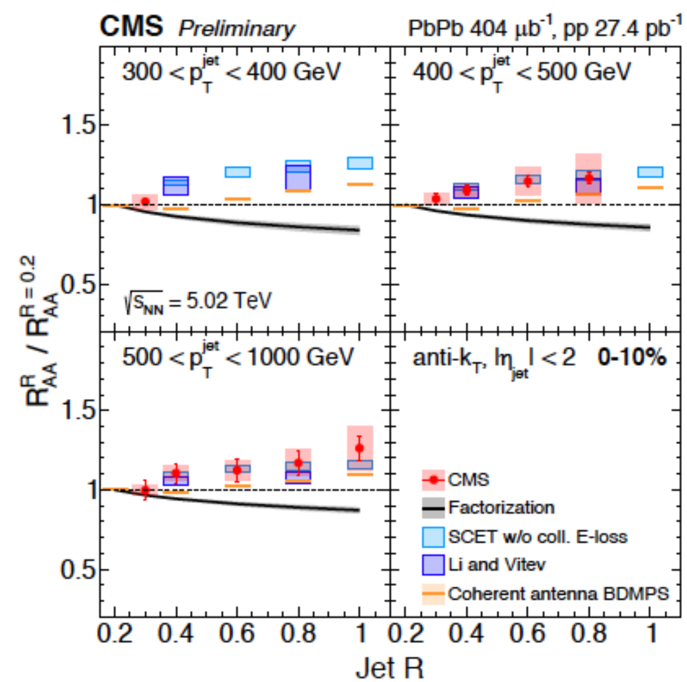
- This also implies medium-induced scaling violation of the average jet charge

$$\frac{d}{d\ln p_T}\ln\langle Q_{q,\kappa}^{\text{AA}}\rangle = \frac{\alpha_s(p_T R)}{\pi}\left[\tilde{P}_{qq}(\kappa) + \tilde{P}_{qq}^{\text{med}}(\kappa, p_T R) + \int_0^1 dx\,(x^\kappa - 1)\,P_{qq}^{\text{med}}(\kappa, k_\perp = x(1-x)p_T R)\right]$$

Very recent results on R dependence of jet quenching

Recall the upper limit of the k_T integration





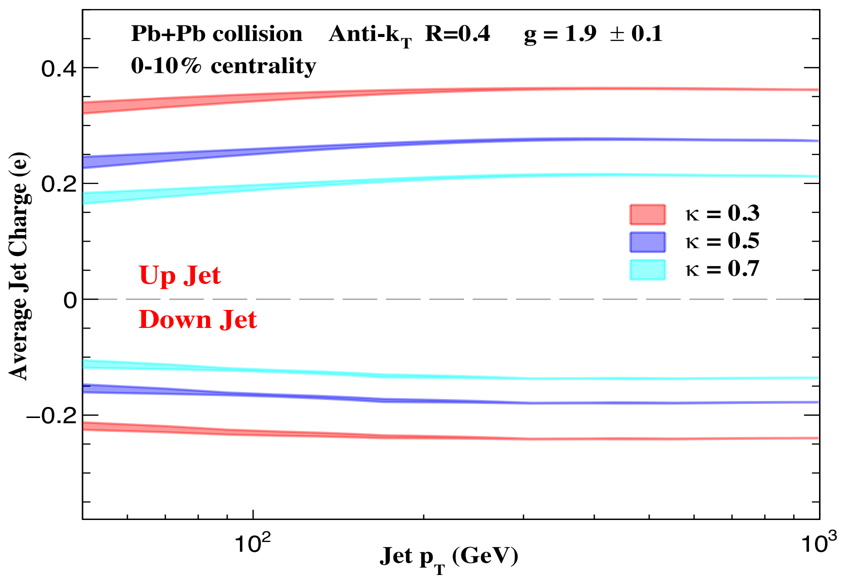
M. Taylor et al . / CMS (2019)

- SCET describes very well the data

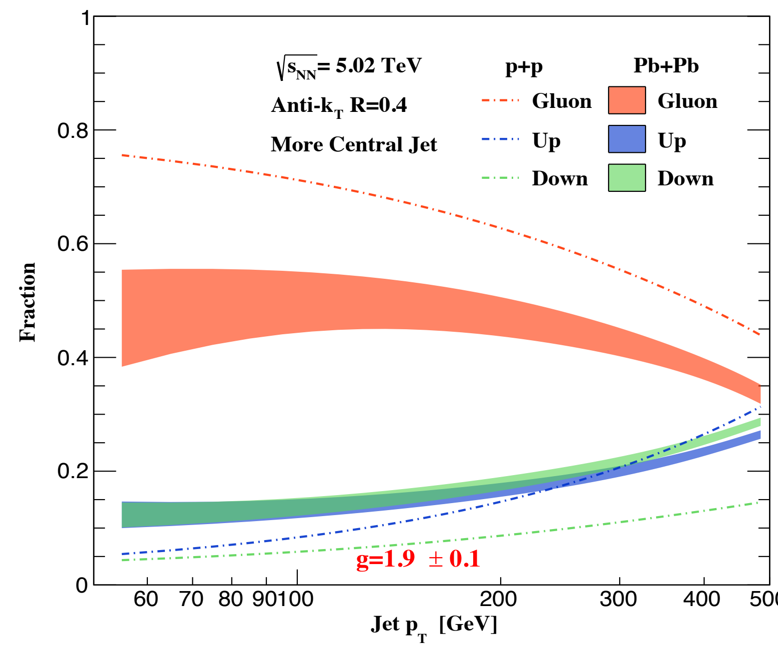
- Observable strongly challenges models

Phenomenological predictions for heavy ion collisions

- The effects that are important
- Isospin, many more down quarks
- Energy loss effects, quark jets lose less energy than gluon jets (C_F vs C_A)
- Medium induced splitting effects on the jet functions ands the fragmentation function evolution



Note that there is some modification of different flavor jets. This is LO – max difference

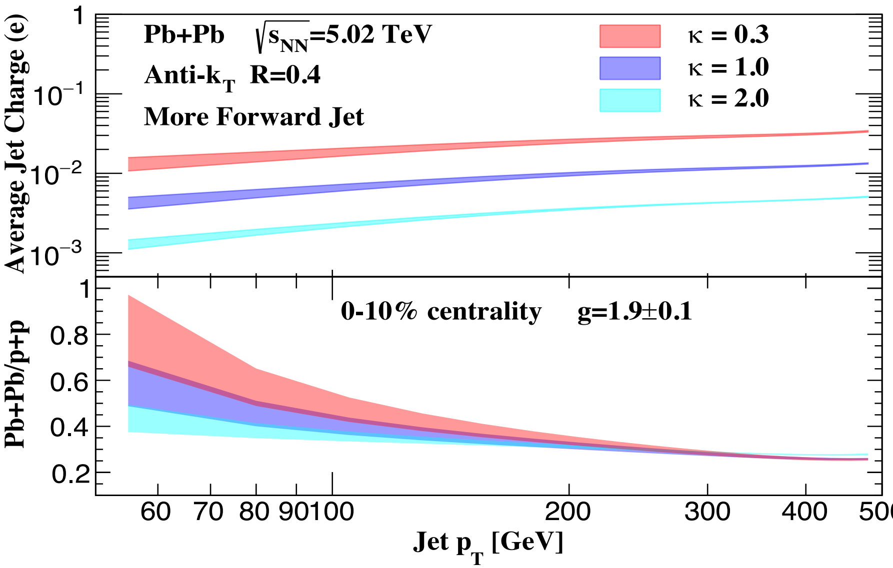


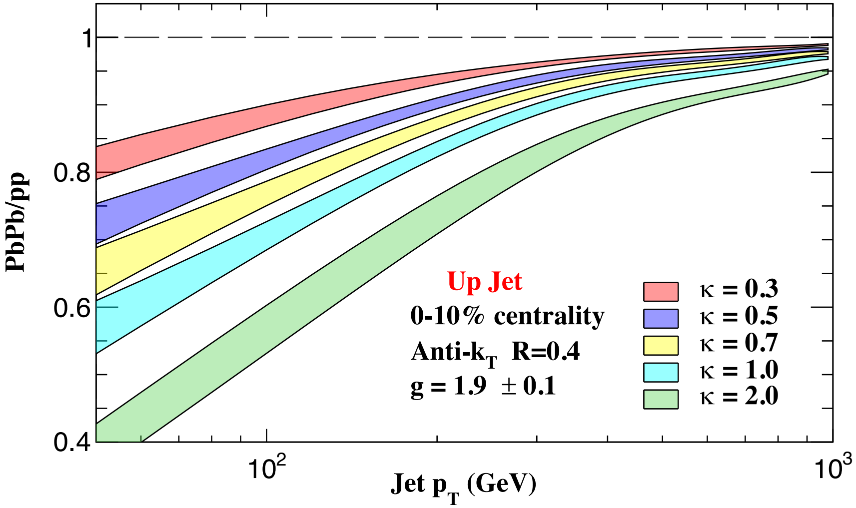
First important result: different flavor jet charges remain distinct in heavy ion collision

Phenomenological predictions for heavy ion collisions

H. Li *et al.* (2019)

- At very large transverse momenta isospin effects dominate.
- At lower transverse momenta p_T<200 GeV we are beginning to see the effects of in-medium parton showers and different evolution





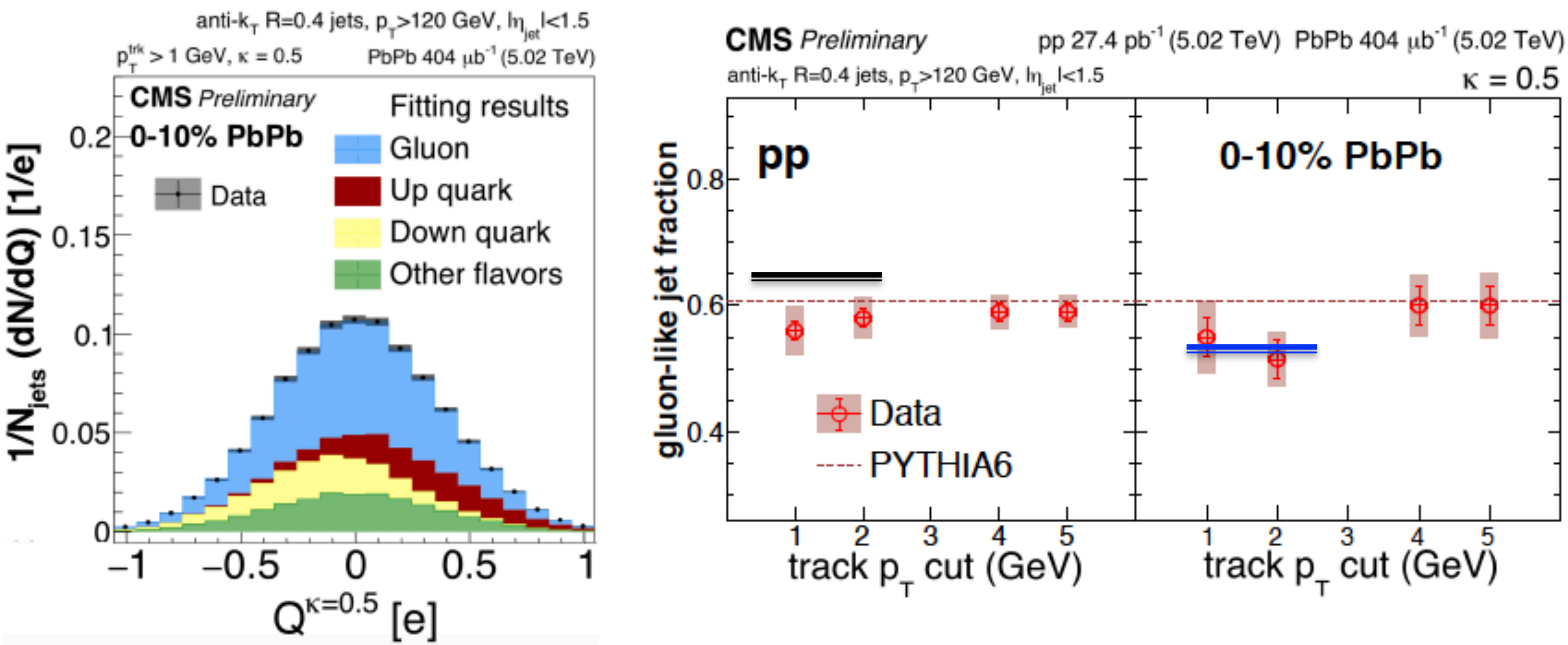
Proposed new measurement – the charge of individual flavor jets

- Isolate the medium induced contribution to jet functions and fragmentation functions evolution.
- Mellin moments of in-medium splittings

Effect of non-perturbative input

CMS has made a first attempt at measuring the jet charge

D. Hangal *et al.* (2019)



- Use a template method assuming simulated charge distributions
- Don't see significant differences in p+p and heavy ion collisions

Conclusions

- The jet charge is a substructure observable extensively used for jet flavor discrimination. This is extremely important to advance jet studies in heavy ion collisions
- We developed a theoretical approach based on SCET to calculate the jet charge in heavy ion collisions. This complements Monte Carlo studies
- Input based on an effective theory for jet propagation in matter $SCET_G$ and derived medium-induced parton splitting kernels. Validated against hadron and jet suppression, substructure
- The modification of jet charge at high transverse momenta – isospin effects. For moderate p_T - sensitive to the in-medium shower evolution. Proposed ways to study this more precisely with individual flavor jets
- First experimental measurements have appeared. Working to understand the exp. technique and results

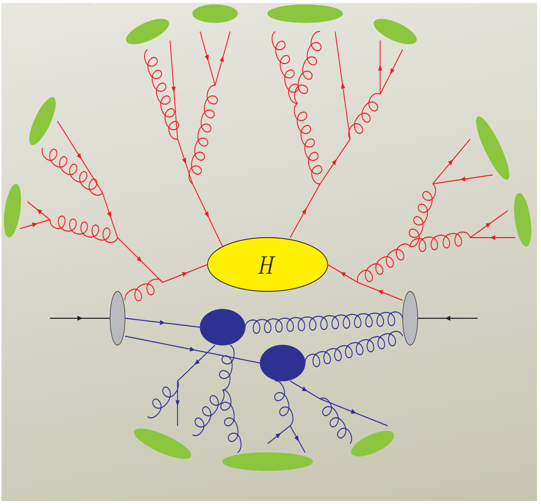
SCET in QCD matter

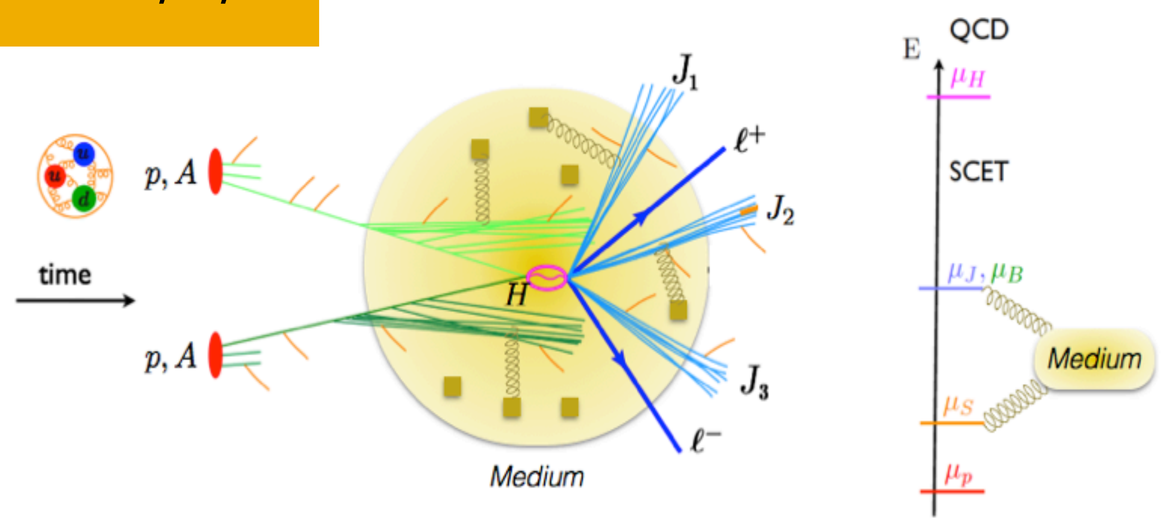
- QCD in the medium remains a multi-scale problem
- Factorization, with modified J, B, S

Ovanesyan et al. (2011)

Need to introduce a Glauber mode

$$q = (\lambda^2, \lambda^2, \lambda)Q$$





- Splitting functions are related to beam (B) and jet (J) functions in SCET
- Higher order calculations
- Resummation
- Paton showers in Monte Carlos

Ovanesyan et al. (2012)

Kang et al. (2016)