The Dead Cone

in (winner-take-) all shapes and flavors

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Based on: 2309.xxxxx and 2309.xxxxx

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ALICE measured the dead-cone effect!

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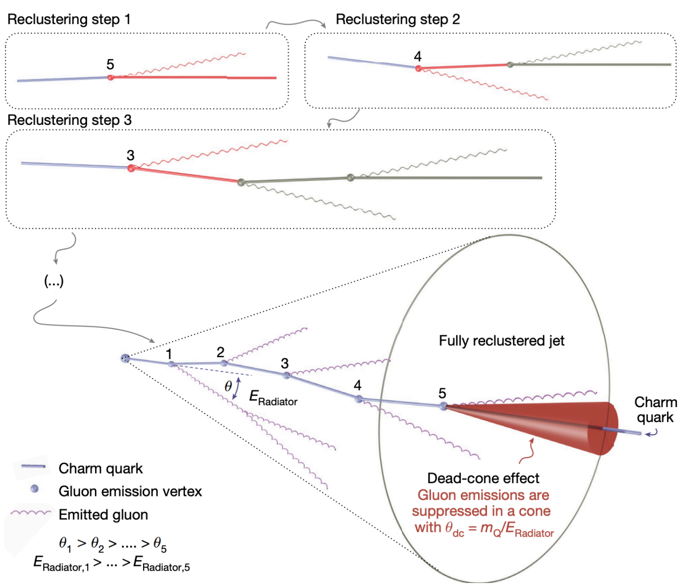
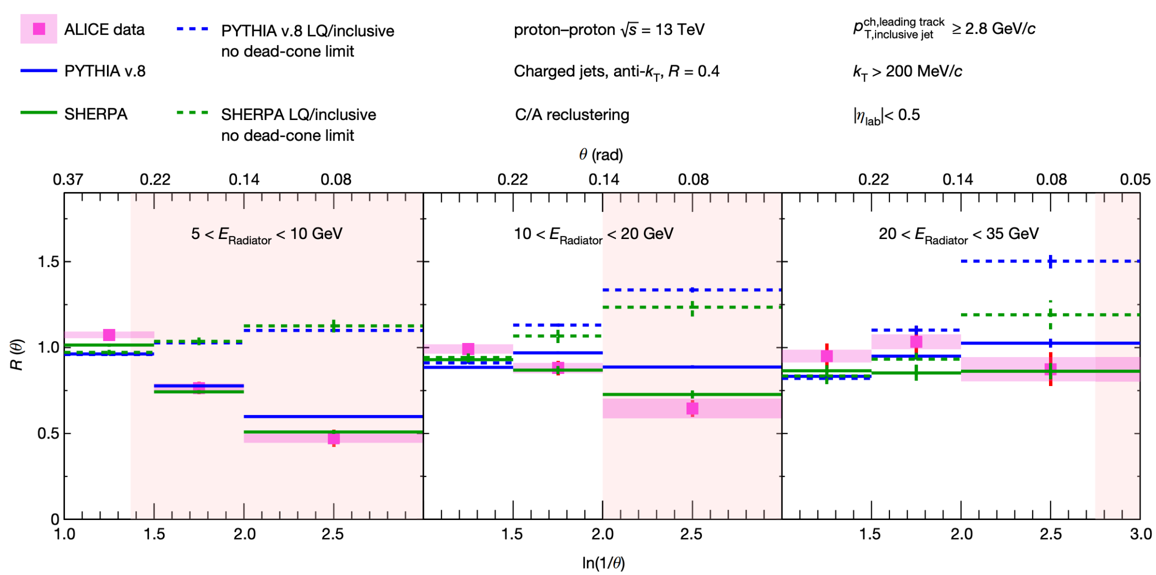
ALICE

ALICE makes first direct observation of the dead cone: a fundamental effect in QCD



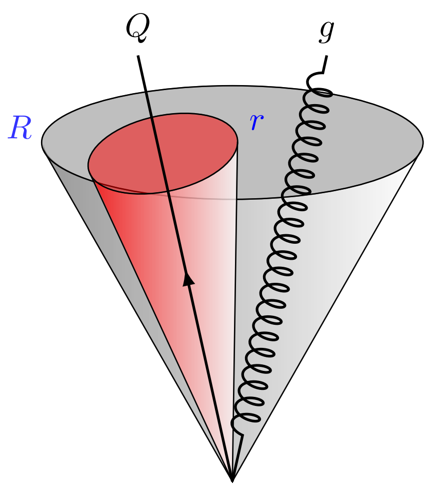
Nature **605**, 440–446 (2022)



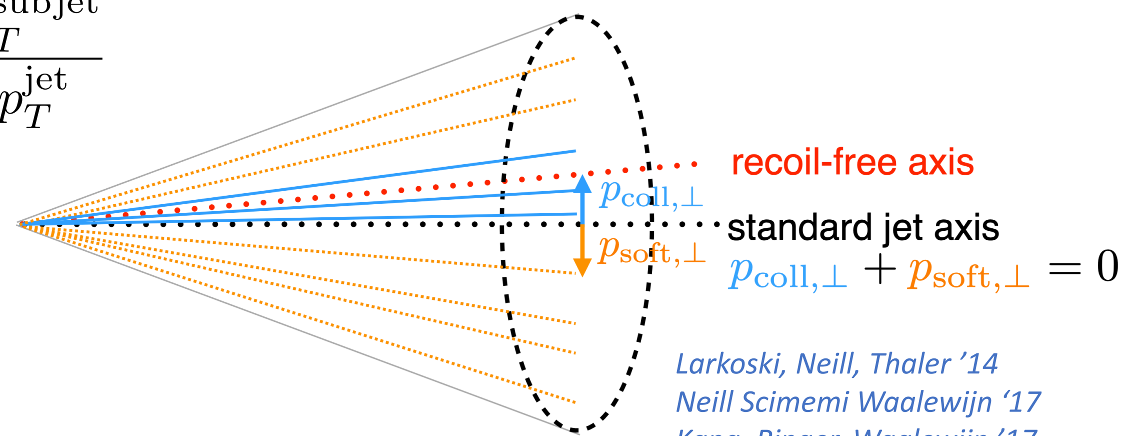
Where exactly is $\theta_{\text{dc}} \sim m_Q/p_T$?

Can it be captured through simpler observables?

Winner-take-all subjet fragmentation function



$$z_r \equiv \frac{p_T^{\text{subjet}}}{p_T^{\text{jet}}}$$



Larkoski, Neill, Thaler '14
Neill Scimemi Waalewijn '17
Kang, Ringer, Waalewijn '17
Neill Papaefstathiou Waalewijn, Zoppi '19

$$F\left(z_r; p_T, r, R\right) = \frac{d\sigma}{dz_r\, dp_T} \Big/ \frac{d\sigma}{dp_T}$$

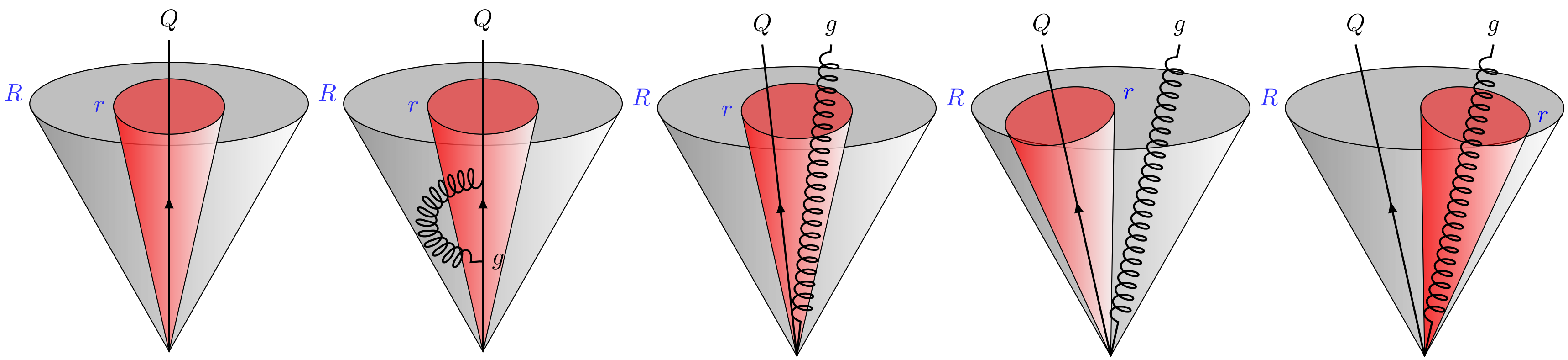
$$\frac{d\sigma}{dz_r\, dp_T} = \frac{d\hat{\sigma}_Q}{dp_T} \times \mathcal{G}_Q^{\text{jet}}(z_r, m_Q, p_T, r, R)$$

$$\frac{d\sigma}{dp_T} = \frac{d\hat{\sigma}_Q}{dp_T} \times \mathcal{J}_Q(m_Q, p_T, R)$$

Measuring the substructure of leading jet in back-to-back heavy quark jet pairs allows for nice cancellation of initial-state effects

$$\boxed{\frac{d\sigma}{dz_r\, dp_T} \Big/ \frac{d\sigma}{dp_T} = \mathcal{G}_Q^{\text{jet}}(z_r, m_Q, p_T, r, R) \Big/ \mathcal{J}_Q\left(m_Q, p_T, R\right)}$$

Winner-take-all subjet fragmentation function



$\mathcal{O}(1)$

$\mathcal{O}(\alpha_s)$

Trivial zr-dependence $\propto \delta(1 - z_r)$

Trivial subjet radius r-dependence

Non-trivial zr-dependence

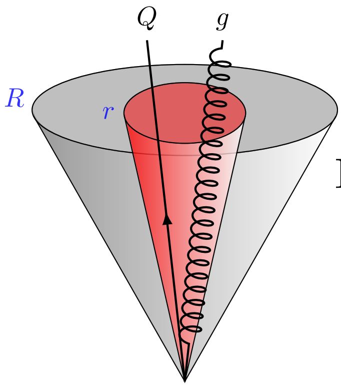
Non-trivial subjet radius r-dependence

These diagrams will reveal the dead-cone

$$\hat{P}_{Qg\leftarrow Q}\left(z,\ell_\perp \,|\, m_Q\right) = \frac{C_F}{\ell_\perp^2 + (1-z)^2 m_Q^2} \times \left(\frac{1+z^2}{1-z} - \epsilon\,(1-z) - \frac{2m_Q^2\, z(1-z)}{\ell_\perp^2 + (1-z)^2 m_Q^2} \right)$$

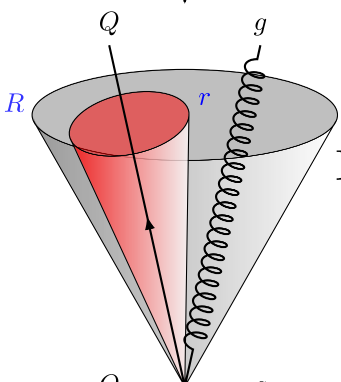
$$\hat{P}_{gQ\leftarrow Q}\left(z,\ell_\perp \,|\, m_Q\right) = \frac{C_F}{\ell_\perp^2 + z^2 m_Q^2} \times \left(\frac{1+(1-z)^2}{z} - \epsilon\, z - \frac{2m_Q^2\, z(1-z)}{\ell_\perp^2 + z^2 m_Q^2} \right)$$

Heavy quark splitting functions



$$\Pi_A\left(z_r \,|\, r, m_Q, p_T\right) \propto \int_0^1 dz \int_0^{z(1-z)p_T r} \frac{d\ell_\perp^2}{\ell_\perp^{2\epsilon}} \hat{P}_{Qg\leftarrow Q}\left(z,\ell_\perp \,|\, m_Q\right) \times \delta(1-z_r)$$

Both partons in subjet, initial Quark is WTA

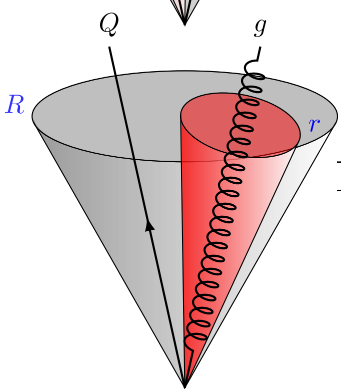


$$\Pi_B\left(z_r \,|\, r, m_Q, p_T\right) \propto \int_0^1 dz \int_{z(1-z)p_T r}^{z(1-z)p_T R} \frac{d\ell_\perp^2}{\ell_\perp^{2\epsilon}} \hat{P}_{Qg\leftarrow Q}\left(z,\ell_\perp \,|\, m_Q\right) \times \delta(z-z_r)$$

$$\times\Theta\left(z > \frac{1}{2}\right)$$

Quark is WTA subjet

WTA constraint



$$\Pi_C\left(z_r \,|\, r, m_Q, p_T\right) \propto \int_0^1 dz \int_{z(1-z)p_T r}^{z(1-z)p_T R} \frac{d\ell_\perp^2}{\ell_\perp^{2\epsilon}} \hat{P}_{gQ\leftarrow Q}\left(z,\ell_\perp \,|\, m_Q\right) \times \delta(z-z_r)$$

$$\times\Theta\left(z > \frac{1}{2}\right)$$

Gluon is WTA subjet

Winner-take-all subjet fragmentation function

$$\int_0^1 dz_r\; \mathcal{G}_Q^{\rm jet}(z_r\,|\,r,R,m_Q,p_T) = \mathcal{J}_Q(R,m_Q,p_T)$$

$$\frac{d\sigma}{dz_r\,dp_T}\Big/\frac{d\sigma}{dp_T} = \frac{\mathcal{G}_Q\left(z_r\,\middle|\,r,R,m_Q,p_T\right)}{\mathcal{J}_Q\left(R,m_Q,p_T\right)} \equiv p\left(z_r\,\middle|\,r,R,m_Q,p_T\right)$$

$$\int_0^1 dz_r\, p\left(z_r\,\middle|\,r,R,m_Q,p_T\right) = 1$$

Key is that in computation of moments, virtual contributions cancel, leaving only appearances of m_Q that appear on equal footing with either $p_T r$ or $p_T R$

$$p\left(z_r\,\middle|\,r,R,m_Q,p_T\right) \to p\left(z_r\,\middle|\,r,R,\theta_{\rm dc},p_T\right)\;, \quad \theta_{\rm dc} = \frac{m_Q}{p_T}$$

All moments are essentially functions of 3 angles

Heavy quark mass imprints itself as the third angle

WTA jet shape and momentum dispersion

$$\Psi(r) = \sum_{i\in \text{jet}} z_i\, \Theta\left(r - r_{\hat{b}i}\right)$$

Integrated jet shape

$$\Psi_Q\left(r; R, \theta_{\text{dc}}\right) = \int_0^1 dz_r\, z_r\, p\left(z_r \,\middle|\, r, R, \theta_{\text{dc}}\right) = \langle z_r \rangle$$

Moments/integrated observables evolve according to WTA-modified DGLAP

$$\Xi(r) = \sum_{i\in \text{jet}} z_i^2\, \Theta\left(r - r_{\hat{b}i}\right)$$

Integrated momentum dispersion

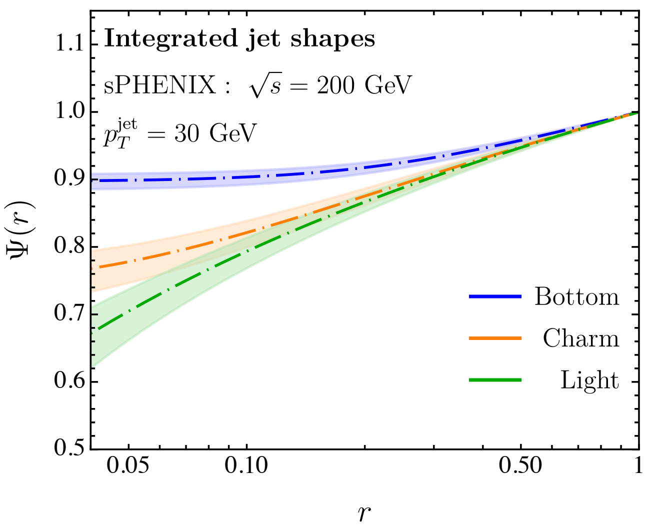
$$\Xi_Q\left(r; R, \theta_{\text{dc}}\right) = \int_0^1 dz_r\, \left(z_r^2 + (1-z_r)^2\right) p\left(z_r \,\middle|\, r; R, \theta_{\text{dc}}\right) = 1 - 2\langle z_r\rangle + 2\left\langle z_r^2 \right\rangle$$

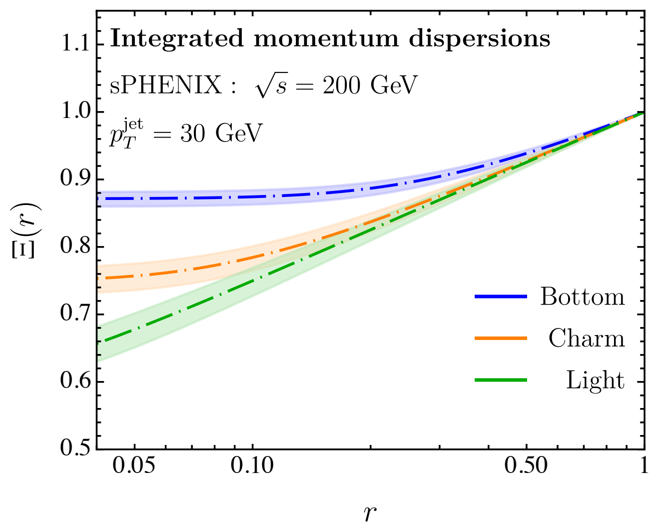
$$\psi(r) = \frac{d}{dr}\Psi(r) = \sum_{i\in \text{jet}} z_i\, \delta\left(r - r_{\hat{b}i}\right)$$

Differential jet shape

$$\xi(r) = \frac{d}{dr}\Xi(r) = \sum_{i\in \text{jet}} z_i^2\, \delta\left(r - r_{\hat{b}i}\right)$$

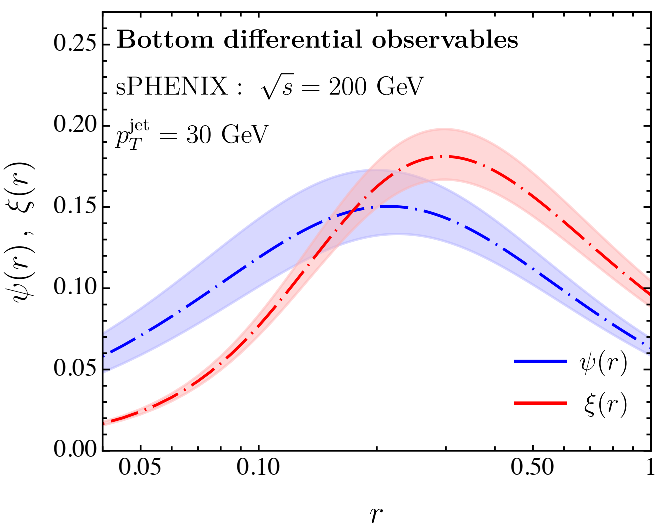
Differential momentum dispersion

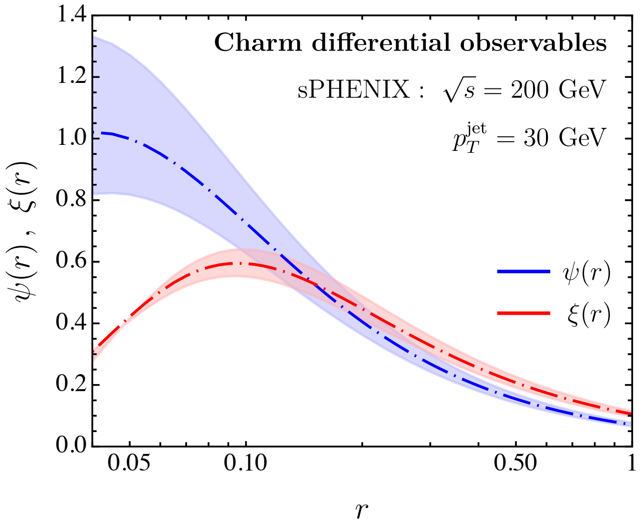


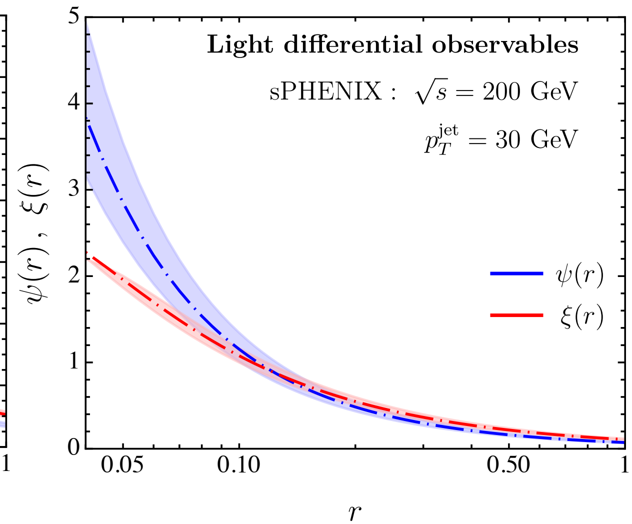


WTA pins itself on the heavy quark

Slow accumulation of pT before θ_{dc} !







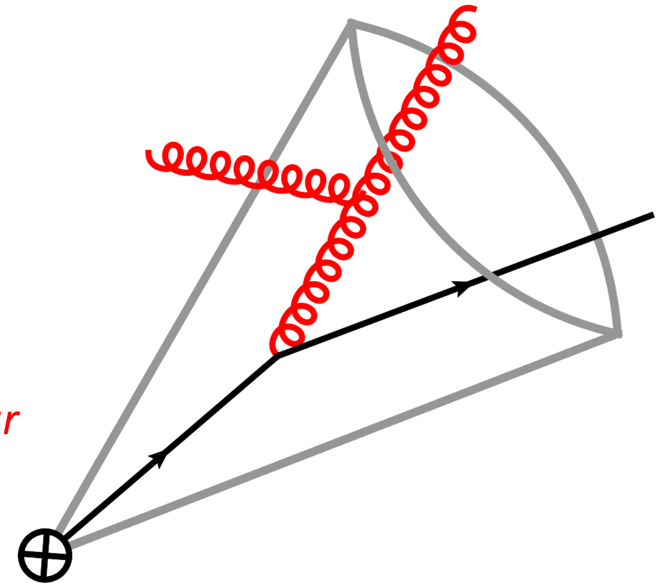
Peaks in differential observables occur at angular scale:

$$r \sim \mathcal{O}(1) \times \theta_{\text{dc}}$$

Jet flavor with WTA axis

Flavor of a jet in the UV is *clear* and *unambiguous*:
single particle, completely isolated, no jet boundary

Jets are measured in the IR where flavor is *not clear* and *maximally ambiguous*:
many particles, contaminated by soft radiation falling within jet boundary



Net flavor along WTA axis is *clear* and *unambiguous*:
single particle, unaffected by presence of soft contamination falling within jet boundary

Net flavor along WTA axis = IR Jet flavor*

*not the *only* definition, just a *very nice* definition (this is where Andrew quotes our great bard: “Welcome to Flavortown!”)

Jet flavor with WTA axis

Consider a heavy quark in the UV radiating a gluon at some resolution scale $k_\perp$

If the emission occurs below the resolution scale, the heavy quark defines the WTA axis

$$\Pi_Q^{(\mathrm{U})}\left(z_r, f_{\mathrm{IR}}=Q \,\middle|\, k_\perp, m_Q, f_{\mathrm{UV}}=Q\right) \propto \int_0^1 dz \int_0^{k_\perp} \frac{d\ell_\perp^2}{\ell_\perp^{2\epsilon}} \hat{P}_{Qg\leftarrow Q}\left(z, \ell_\perp \,\middle|\, m_Q\right)$$

Unresolved contribution

If the emission occurs above the resolution scale, and the heavy quark carries the bulk of the pT, the heavy quark defines the WTA axis

$$\Pi_Q^{(\mathrm{R})}\left(z_r, f_{\mathrm{IR}}=Q \,\middle|\, k_\perp, m_Q, f_{\mathrm{UV}}=Q\right) \propto \int_0^1 dz \int_0^{k_\perp} \frac{d\ell_\perp^2}{\ell_\perp^{2\epsilon}} \hat{P}_{Qg\leftarrow Q}\left(z, \ell_\perp \,\middle|\, m_Q\right) \times \Theta\left(z-\frac{1}{2}\right)$$

Resolved contribution

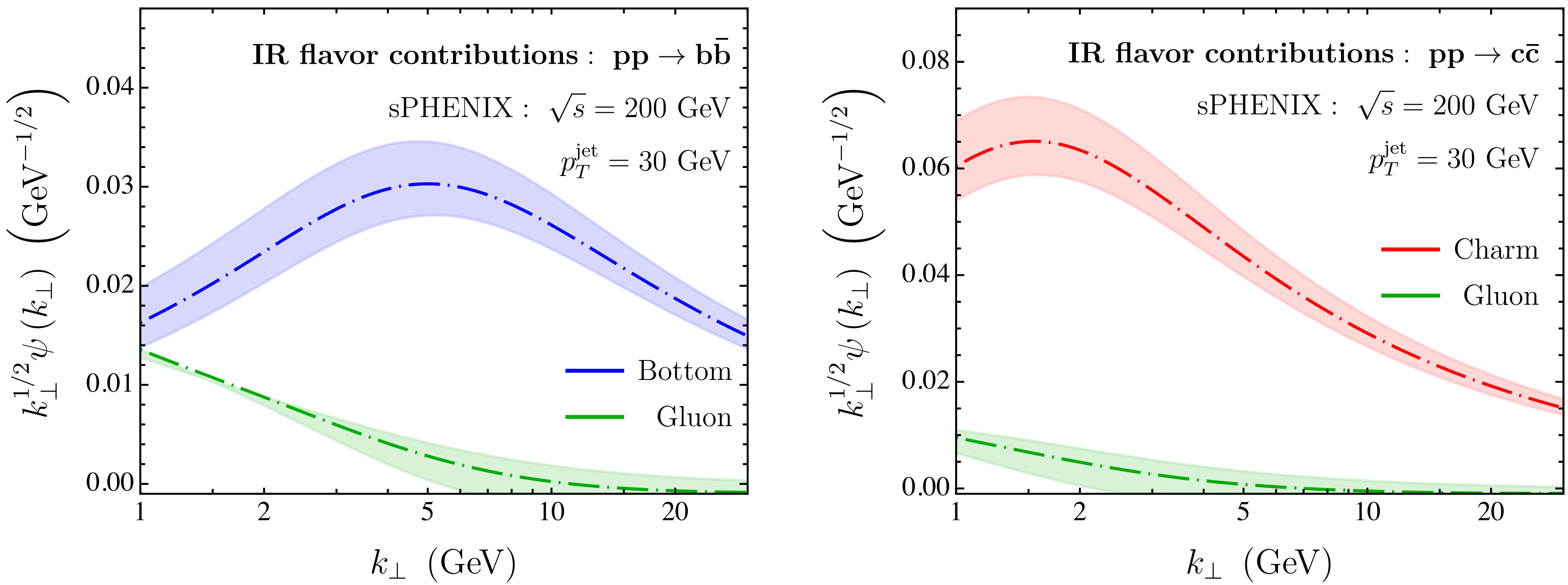
These are two particular channels leading to a heavy quark flavor in the IR

$$\Pi_Q \supset \Pi_Q^{(\mathrm{U})} + \Pi_Q^{(\mathrm{R})}$$

If the emission occurs above the resolution scale, but the gluon carries the bulk of the pT, then gluon defines the WTA axis, and thus the jet flavor

$$\Pi_g^{(\mathrm{U})}\left(z_r, f_{\mathrm{IR}}=g \,\middle|\, k_\perp, m_Q, f_{\mathrm{UV}}=Q\right) \supset \int_0^1 dz \int_0^{k_\perp} \frac{d\ell_\perp^2}{\ell_\perp^{2\epsilon}} \hat{P}_{Qg\leftarrow Q}\left(z, \ell_\perp \,\middle|\, m_Q\right) \times \Theta\left(z-\frac{1}{2}\right)$$

Flavored resolution scale shape



$$\psi(k_\perp) = \sum_{i \in \text{jet}} z_i \, \delta\left(k_\perp - k_{\perp,bi}\right)$$

Differential observables peak at $k_\perp \sim \mathcal{O}(1) \times m_Q$!

Location of peak is independent of jet pT, thus universal for sPHENIX and LHC

Summary

- We have demonstrated how simple angular-dependent shape observables/higher moments of the heavy-quark-initiated subjet fragmentation function reveal the dead cone angle in a clear and unambiguous fashion

- We have proposed a new shape observable, differential in the resolution scale of an IR splitting, as well as the net IR flavor flowing along the WTA axis.

- Due to its dependence on scale as opposed to an angle, this new observable exhibits a universal shape which makes the “heavy quark flavor” of a jet manifest

Thank you!