A Fragmentation Approach to Jet Flavor

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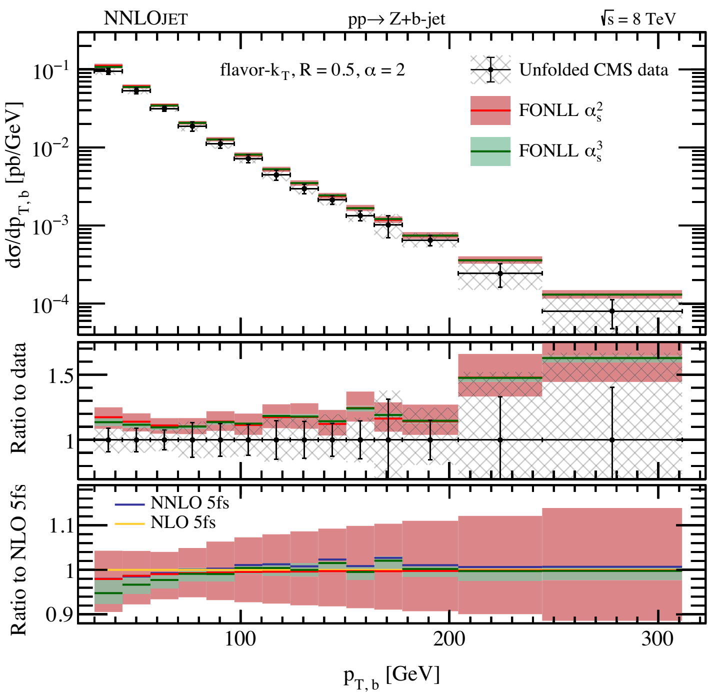
with Simone Caletti, Simone Marzani, Daniel Reichelt 2205.01117

Uses of Jet Flavor

Whatever your taste, there's a jet flavor for you



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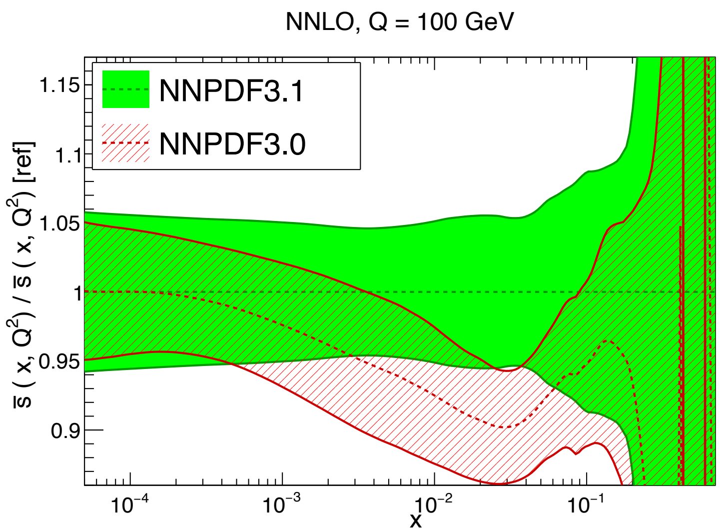
NNLO predictions for heavy flavor jets



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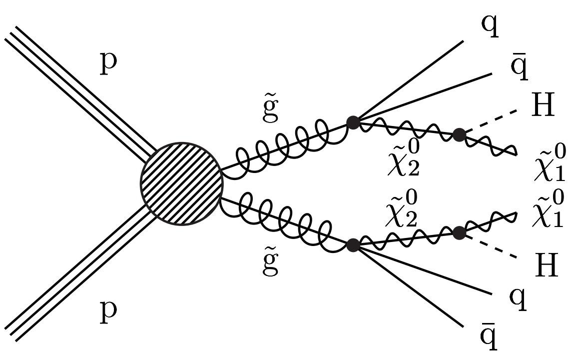
Correlation between jet flavor and initial state



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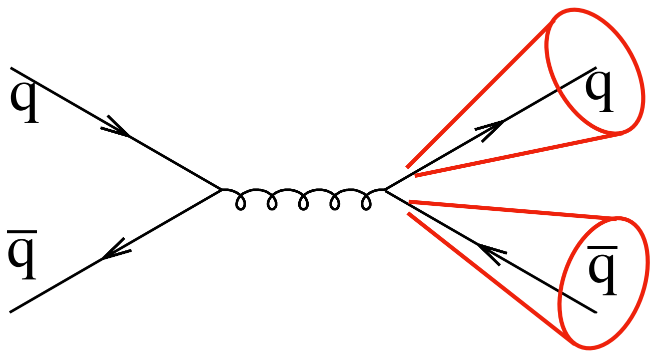
New physics searches

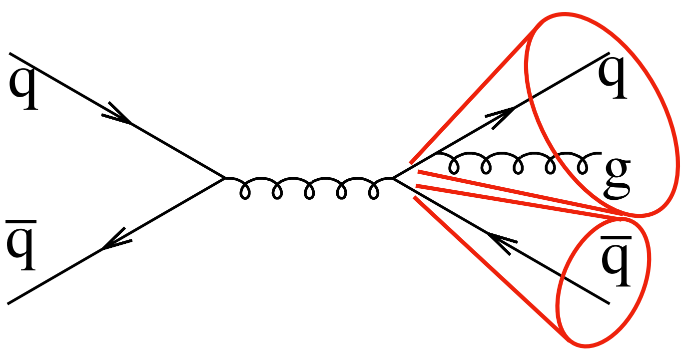
BSZ Flavor

Come on, just sum the flavors of partons in the jet

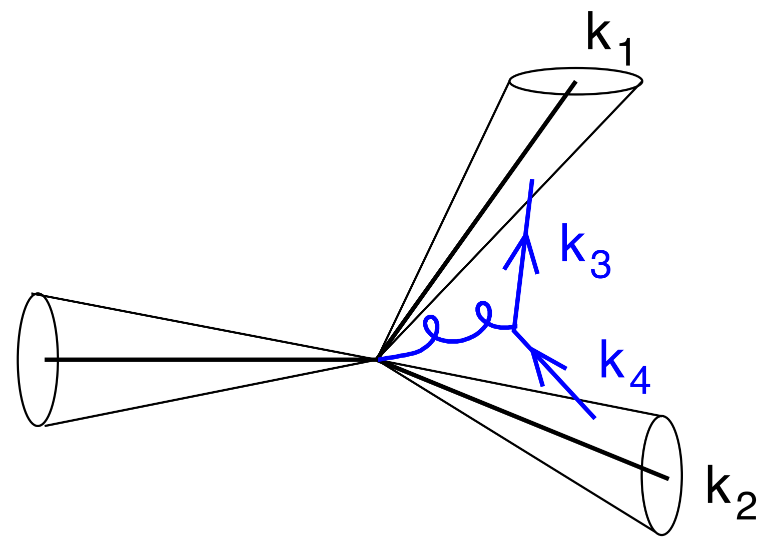
Unambiguous at LO



Unambiguous at NLO



Soft gluon splitting to quarks at NNLO spoils IR safety



hep-ph/0601139

BSZ Flavor

Oh. What if you changed the clustering algorithm?

$$y_{ij}^{(F)} = \frac{2(1-\cos\theta_{ij})}{Q^2} \times \begin{cases} \max(E_i^2, E_j^2)\,, & \text{softer of } i,j \text{ is flavoured,} \\ \min(E_i^2, E_j^2)\,, & \text{softer of } i,j \text{ is flavourless} \end{cases}$$

Modification to Durham k_T algorithm

Phys. Lett. B 269, 432 (1991)

Only cluster soft quarks together if they have equal and opposite flavor

- Pros
  - It works and is IRC safe
  - Can be easily implemented in partonic fixed order calculation
- Cons
  - Modifies constituents of jets and no one uses k_T to find jets anymore

    anti-k_T flavor algorithm, 2205.11879
  - Complete non-starter in experiment; cannot begin to identify flavored jets

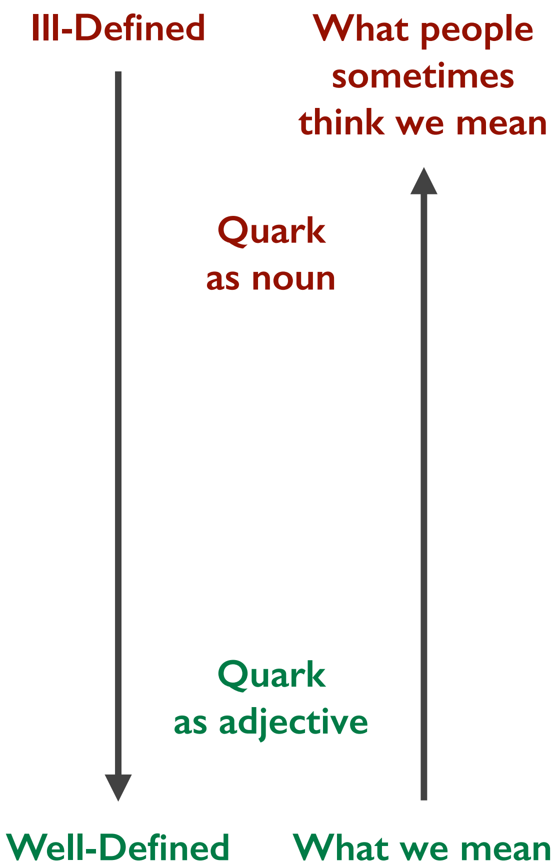
hep-ph/0601139

What We Mean By “Jet Flavor”

Les Houches Study

What is a Quark Jet?

From lunch/dinner discussions



A quark parton

A Born-level quark parton

The initiating quark parton in a final state shower

An eikonal line with baryon number 1/3
and carrying triplet color charge

A quark operator appearing in a hard matrix element
in the context of a factorization theorem

A parton-level jet object that has been quark-tagged
using a soft-safe flavored jet algorithm (automatically
collinear safe if you sum constituent flavors)

A phase space region (as defined by an unambiguous
hadronic fiducial cross section measurement) that yields
an enriched sample of quarks (as interpreted by some
suitable, though fundamentally ambiguous, criterion)

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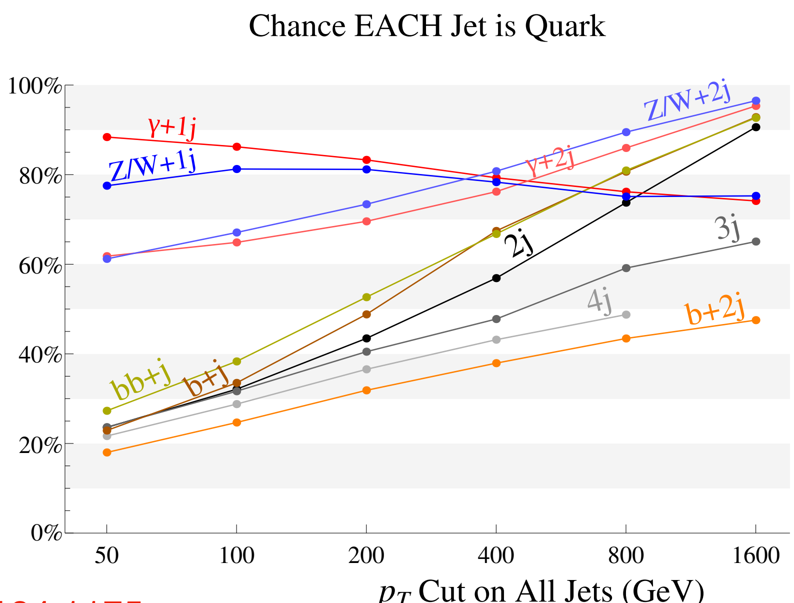
What We Mean By “Jet Flavor”

Focus on in-principle observables

- Many, many results in the literature about “quark vs. gluon discrimination”



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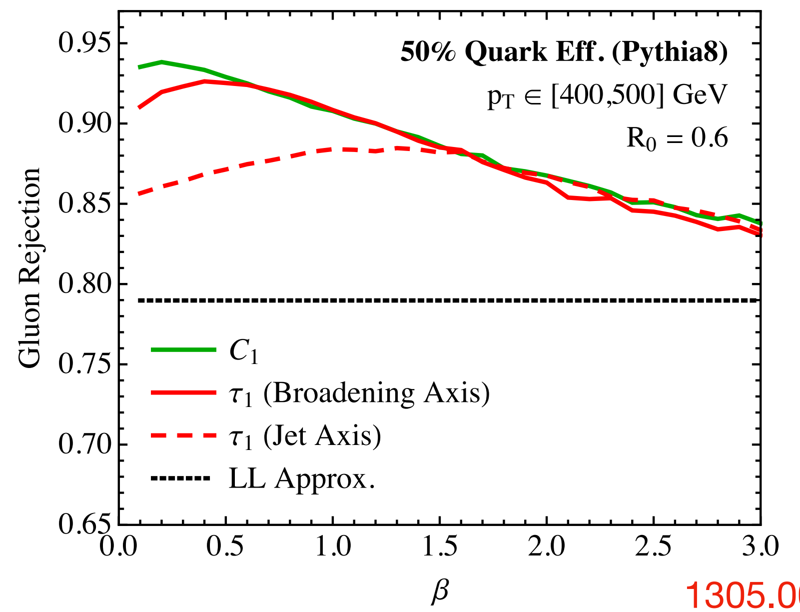


1305.0007

De facto but flawed definition:
jet flavor defined by requested process in event simulation

What We Mean By “Jet Flavor”

Focus on in-principle observables

- Many, many results in the literature about “quark vs. gluon discrimination”

- By asymptotic freedom, jet flavor is unambiguous in deep UV

User requests short distance process in event simulator

What We Mean By “Jet Flavor”

Focus on in-principle observables

- Many, many results in the literature about “quark vs. gluon discrimination”
- By asymptotic freedom, jet flavor is unambiguous in deep UV
- Measurements are performed in the deep IR

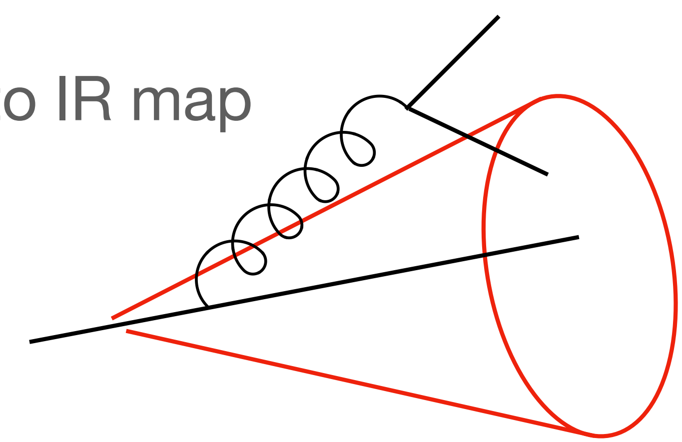
Flow to IR governed by renormalization group/DGLAP

What We Mean By “Jet Flavor”

Focus on in-principle observables

- Many, many results in the literature about “quark vs. gluon discrimination”
- By asymptotic freedom, jet flavor is unambiguous in deep UV
- Measurements are performed in the deep IR
- Flow from UV to IR is not invertible

Jet boundary destroys one-to-one UV to IR map



What We Mean By “Jet Flavor”

Focus on in-principle observables

- Many, many results in the literature about “quark vs. gluon discrimination”
- By asymptotic freedom, jet flavor is unambiguous in deep UV
- Measurements are performed in the deep IR
- Flow from UV to IR is not invertible
- Give up on trying to get UV jet flavor; just focus on IR

Desired Properties for Jet Flavor

Your Tastes May Vary

- Only returns a QCD parton flavor (up, down, strange,…,gluon)

Simplifies classification

Desired Properties for Jet Flavor

Your Tastes May Vary

- Only returns a QCD parton flavor (up, down, strange,…,gluon)
- Can be applied to any set of partons

Does not require re-associating constituents of a jet

Desired Properties for Jet Flavor

Your Tastes May Vary

- Only returns a QCD parton flavor (up, down, strange,…,gluon)
- Can be applied to any set of partons
- IR safe, completely insensitive to soft particles

Ignores contribution to jet flavor from soft particles

Desired Properties for Jet Flavor

Your Tastes May Vary

- Only returns a QCD parton flavor (up, down, strange,…,gluon)
- Can be applied to any set of partons
- IR safe, completely insensitive to soft particles
- Inclusive over exactly collinear splittings

Absorb collinear divergences into fragmentation functions

Desired Properties for Jet Flavor

Your Tastes May Vary

- Only returns a QCD parton flavor (up, down, strange,…,gluon)
- Can be applied to any set of partons
- IR safe, completely insensitive to soft particles
- Inclusive over exactly collinear splittings
- Described by linear evolution equations

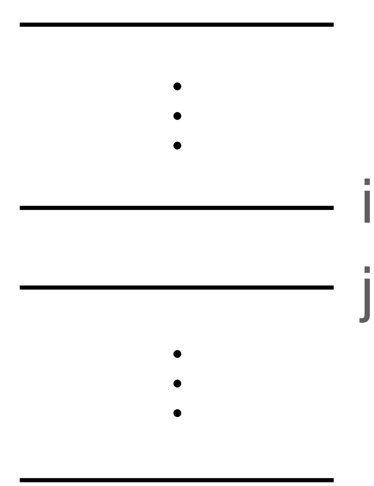
Use DGLAP as a guide and enables analytic solutions

Definition of WTA Jet Flavor

Welcome to Flavortown!

The partonic flavor of a jet is defined to be the net flavor of the particle(s) whose momentum lies exactly along the WTA axis of the jet

Find closest pair of particles according to clustering metric d_{ij}



1310.7584,1401.2158

Definition of WTA Jet Flavor

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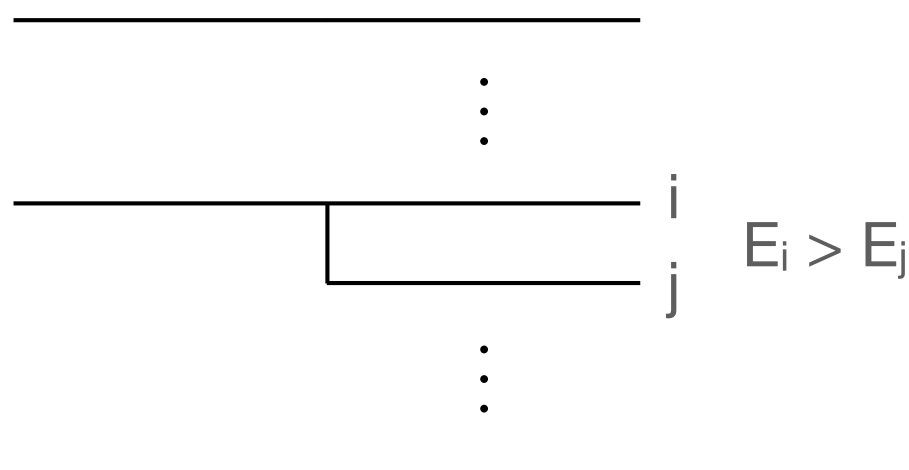
The partonic flavor of a jet is defined to be the net flavor of the particle(s) whose momentum lies exactly along the WTA axis of the jet

Sum energies and new momentum points along direction of harder particle



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Definition of WTA Jet Flavor

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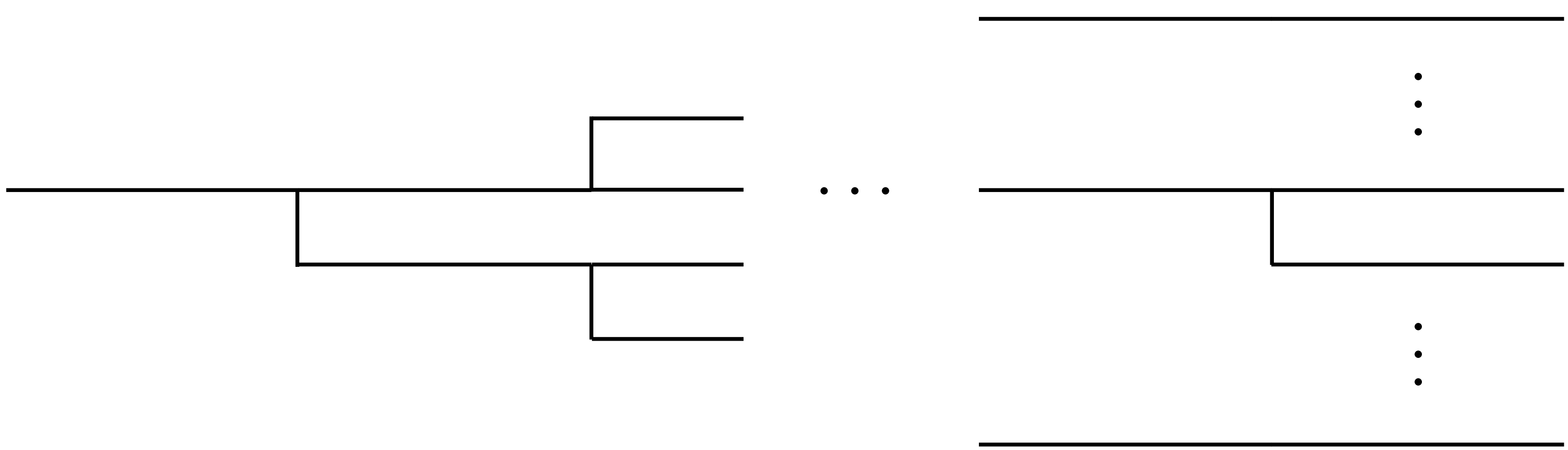
Continue pairwise combination until one particle remains



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Definition of WTA Jet Flavor

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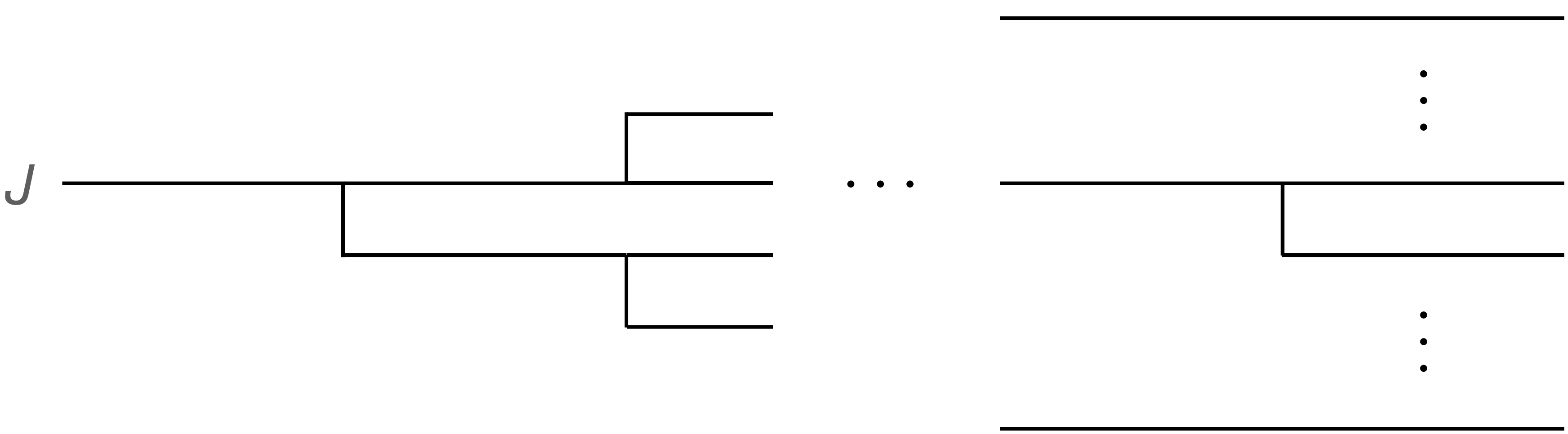
Final momentum lies along direction of particle in jet



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Properties of Evolution Equations

Ain't they beautiful?

$$Q^2\frac{df_q(Q^2)}{dQ^2} = \frac{\alpha_s}{2\pi}\left[-C_F\left(2\log 2 - \frac{5}{8}\right)f_q(Q^2) + \frac{1}{3}T_R f_g(Q^2)\right]$$

$$Q^2\frac{df_g(Q^2)}{dQ^2} = \frac{\alpha_s}{2\pi}\left[C_F\left(2\log 2 - \frac{5}{8}\right) - \left(C_F\left(2\log 2 - \frac{5}{8}\right) + \frac{2}{3}n_f T_R\right)f_g(Q^2)\right]$$

- Linear, inhomogeneous evolution equations

Vastly simpler than nonlinear evolution for hardest subjet, NGLs, track functions,… 1411.5182 hep-ph/0206076 1209.3019

Properties of Evolution Equations

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- Linear, inhomogeneous evolution equations
- Independent of the color of the gluon

Gluon emissions of gluons can't change WTA flavor

Properties of Evolution Equations

Ain't they beautiful?

$$Q^2\frac{df_q(Q^2)}{dQ^2} = \frac{\alpha_s}{2\pi}\left[-C_F\left(2\log 2-\frac{5}{8}\right)f_q(Q^2)+\frac{1}{3}T_R f_g(Q^2)\right]$$

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- Linear, inhomogeneous evolution equations
- Independent of the color of the gluon
- Deep IR fixed points of jet flavor:

$$\lim_{Q_0^2\to\infty} f_q(Q^2) = \frac{\frac{1}{3}T_R}{C_F\left(2\log 2-\frac{5}{8}\right)+\frac{2}{3}n_f T_R} \approx 0.062149$$

QCD with $n_f = 5$

$$\lim_{Q_0^2\to\infty} f_g(Q^2) = \frac{C_F\left(2\log 2-\frac{5}{8}\right)}{C_F\left(2\log 2-\frac{5}{8}\right)+\frac{2}{3}n_f T_R} \approx 0.37851$$

cf. 2007.06578

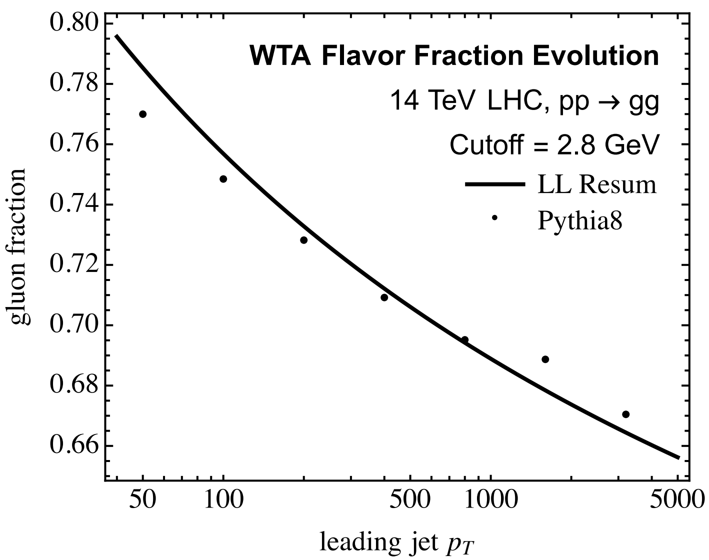
Comparison to Parton Shower

Evolution of WTA Gluon Flavor from Jet p_T to IR

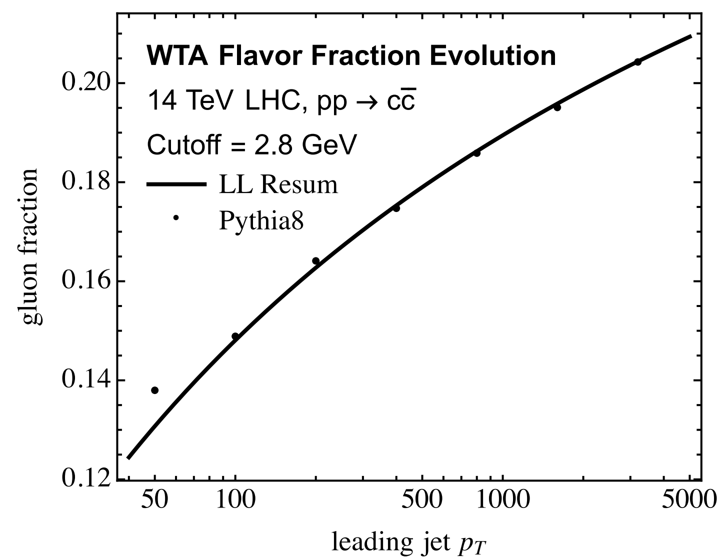
pp → cc or pp → gg events generated in Pythia8

No hadronization; parton shower terminated at fixed IR scale

Study evolution as a function of the UV scale; the jet p_T



$g_{UV} \rightarrow g_{IR}$



$c_{UV} \rightarrow g_{IR}$

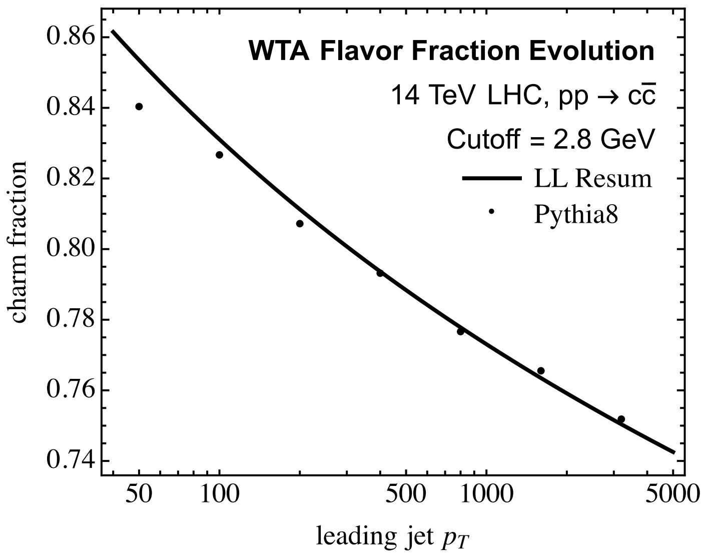
Comparison to Parton Shower

Evolution of WTA Quark Flavor from Jet p_T to IR

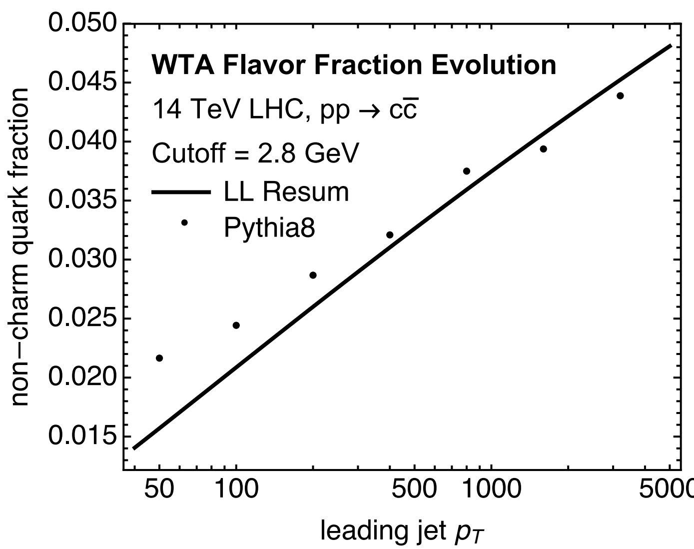
pp → cc or pp → gg events generated in Pythia8

No hadronization; parton shower terminated at fixed IR scale

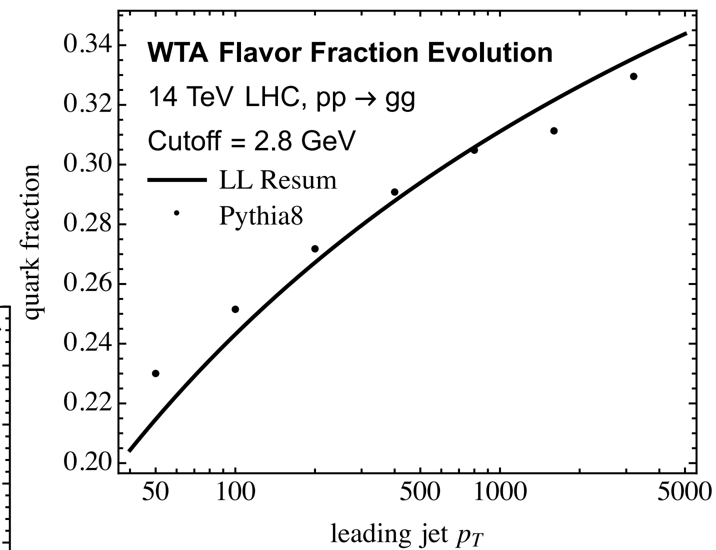
Study evolution as a function of the UV scale; the jet p_T



$c_{UV} \longrightarrow c_{IR}$



$c_{UV} \longrightarrow$ ~~c~~$_{IR}$



$g_{UV} \longrightarrow q_{IR}$

Summary

- Collinear divergences aren't that scary!
- Let fragmentation functions be your friend
- Other things:
  - Can WTA flavor be embedded in a factorization theorem?
  - FO matches to pdfs all the time; can they match to WTA flavor?
  - WTA axis is extremely robust to contamination
  - Observables measured about WTA axis may connect partonic flavor to realistic hadronic jets

Bonus

Derivation of Evolution Equations

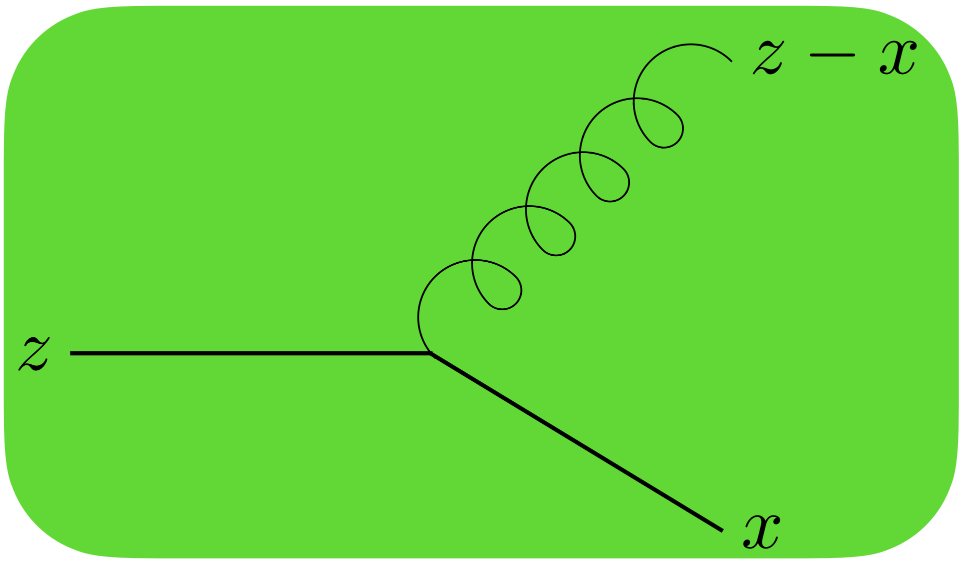
Just DGLAP + Hardest Energy Constraint

$$Q^2 \frac{df_q(x,Q^2)}{dQ^2} = \frac{\alpha_s}{2\pi} \int_x^{\min[1,2x]} \frac{dz}{z} \left[P_{qg\leftarrow q}\left(\frac{x}{z}\right) f_q(z,Q^2) + P_{q\bar{q}\leftarrow g}\left(\frac{x}{z}\right) f_g(z,Q^2) \right]$$

Derivation of Evolution Equations

Just DGLAP + Hardest Energy Constraint

$$Q^2 \frac{df_q(x,Q^2)}{dQ^2} = \frac{\alpha_s}{2\pi}\int_x^{\min[1,2x]} \frac{dz}{z}\left[P_{qg\leftarrow q}\left(\frac{x}{z}\right) f_q(z,Q^2) + P_{q\bar{q}\leftarrow g}\left(\frac{x}{z}\right) f_g(z,Q^2)\right]$$



$\&$ $\quad x > z - x$

Derivation of Evolution Equations

Integrate Over Energy Fractions

$$Q^2 \frac{df_q(x,Q^2)}{dQ^2} = \frac{\alpha_s}{2\pi} \int_x^{\min[1,2x]} \frac{dz}{z} \left[P_{qg\leftarrow q}\left(\frac{x}{z}\right) f_q(z,Q^2) + P_{q\bar{q}\leftarrow g}\left(\frac{x}{z}\right) f_g(z,Q^2) \right]$$

$$\int_0^1 dx\, f_i(x,Q^2) = f_i(Q^2)$$

Fraction of jets with parton *i* along WTA axis

$$Q^2 \frac{df_q(Q^2)}{dQ^2} = \int_{1/2}^1 dy \left[P_{qg\leftarrow q}(y)\, f_q(Q^2) + P_{q\bar{q}\leftarrow g}(y)\, f_g(Q^2) \right]$$

Just need reduced moments of splitting functions

Derivation of Evolution Equations

Final WTA Fraction Evolution Equations

$$Q^2 \frac{df_q(Q^2)}{dQ^2} = \frac{\alpha_s}{2\pi}\left[-C_F\left(2\log 2 - \frac{5}{8}\right) f_q(Q^2) + \frac{1}{3} T_R f_g(Q^2)\right]$$

Quark flavor *q* evolution equation

$$Q^2 \frac{df_g(Q^2)}{dQ^2} = \frac{\alpha_s}{2\pi}\left[C_F\left(2\log 2 - \frac{5}{8}\right) - \left(C_F\left(2\log 2 - \frac{5}{8}\right) + \frac{2}{3} n_f T_R\right) f_g(Q^2)\right]$$

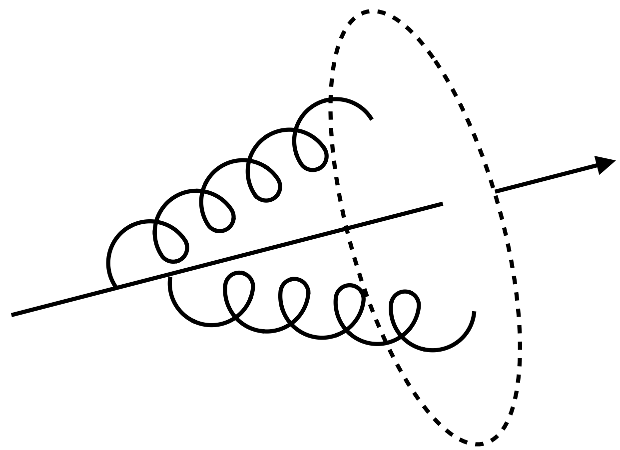
Gluon flavor evolution equation

cf. 1612.04817

Flavored Observables

Measuring WTA Axis

Energy fraction carried by WTA axis



$$Q^2 \frac{df_{q_i}(x,Q^2)}{dQ^2} = \frac{\alpha_s}{2\pi}\int_x^{\min[1,2x]} \frac{dz}{z}\left[P_{qg\leftarrow q}\left(\frac{x}{z}\right) f_{q_i}(z,Q^2) + P_{q\bar{q}\leftarrow g}\left(\frac{x}{z}\right) f_g(z,Q^2)\right]$$

$$Q^2 \frac{df_g(x,Q^2)}{dQ^2} = \frac{\alpha_s}{2\pi}\int_x^{\min[1,2x]} \frac{dz}{z}\left[P_{gq\leftarrow q}\left(\frac{x}{z}\right)\sum_{i=1}^{n_f}\left(f_{q_i}(z,Q^2) + f_{\bar{q}_i}(z,Q^2)\right) + P_{gg\leftarrow g}\left(\frac{x}{z}\right) f_g(z,Q^2)\right]$$

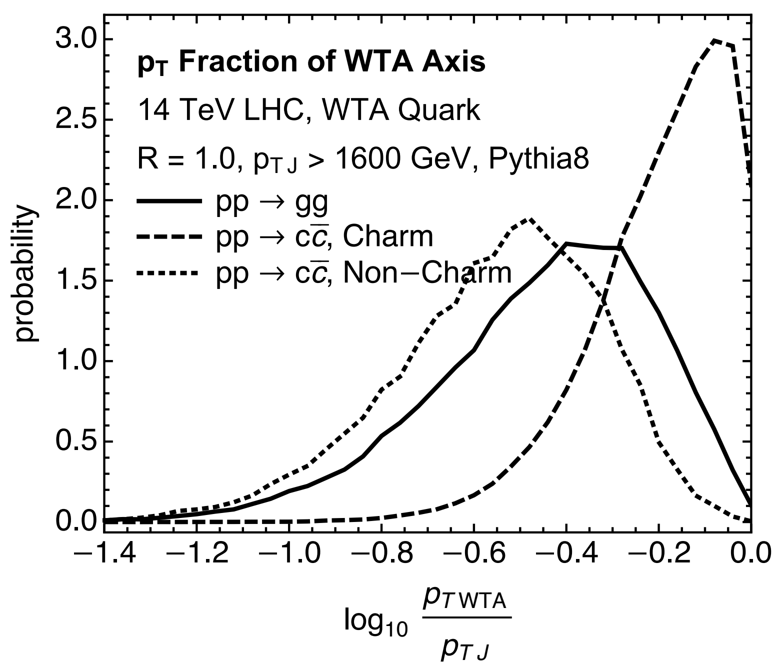
Solve $2n_f+1$ coupled integro-differential equations

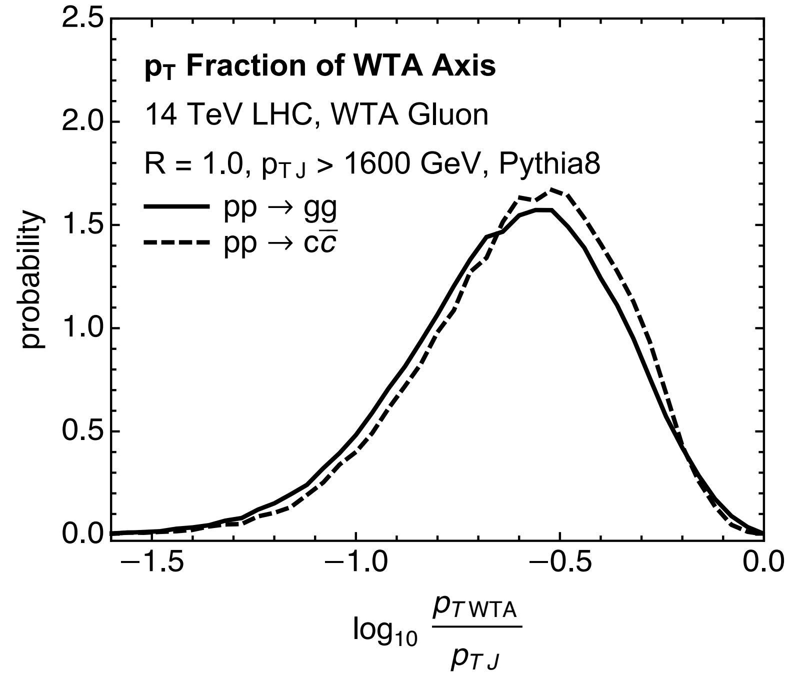
Just as complicated as DGLAP; solve in conjugate space and invert

Flavored Observables

Measuring WTA Axis

Simplest Solution: Parton Shower Monte Carlo



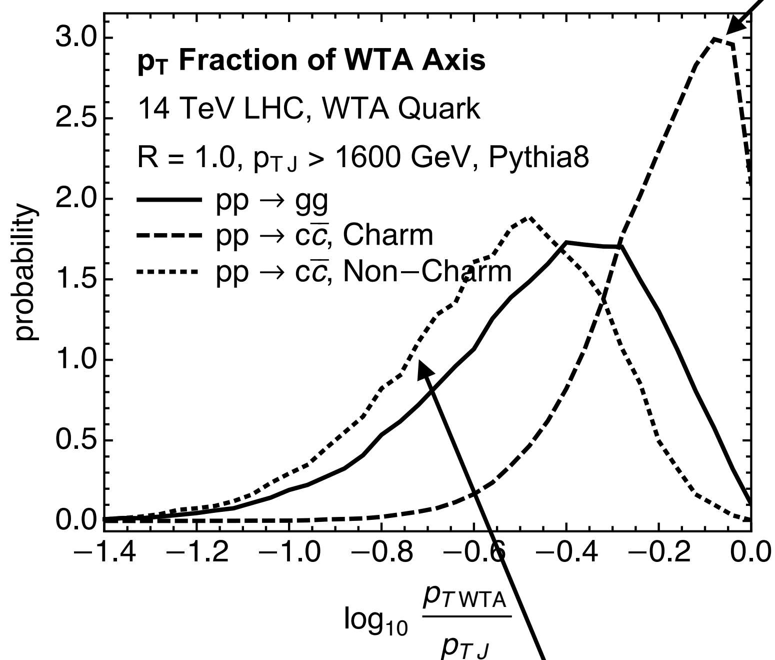


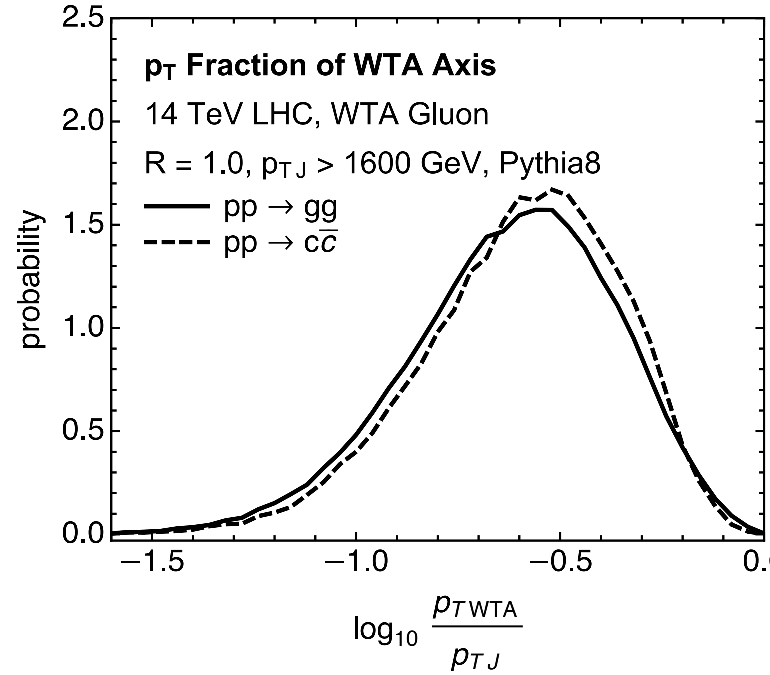
Flavored Observables

Measuring WTA Axis

Simplest Solution: Parton Shower Monte Carlo

Flavor conservation = only soft emissions





Flavor change = need two hard emissions

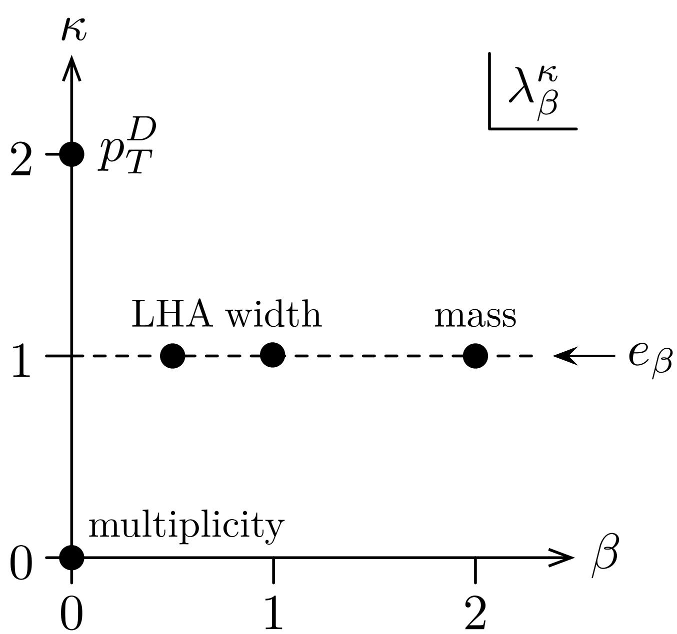
UV universality of IR gluons

Flavored Observables

Measuring about WTA Axis

Generalized Angularities

$$\lambda_\beta^\kappa = \sum_{i \in J} z_i^\kappa \theta_i^\beta$$



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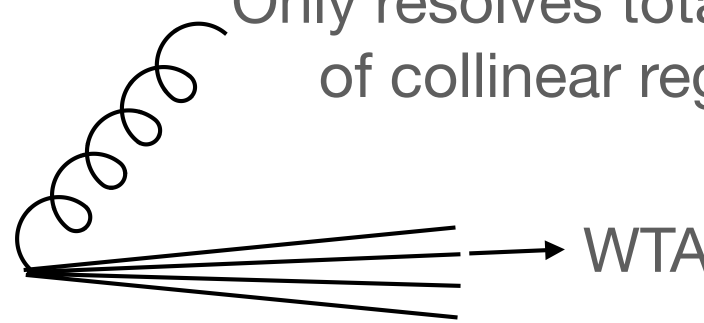
Flavor-Inclusive Distribution

$$p(\lambda_\beta) = \frac{d\sigma^{\text{fo}}}{d\lambda_\beta} \Delta_{\text{Sud}}(\lambda_\beta)$$

Ansatz Flavor-Sensitive Distribution

$$p_i(\lambda_\beta) = \frac{d\sigma_i^{\text{fo}}}{d\lambda_\beta} \Delta_{\text{Sud}}(\lambda_\beta)$$

Only resolves total color of collinear region

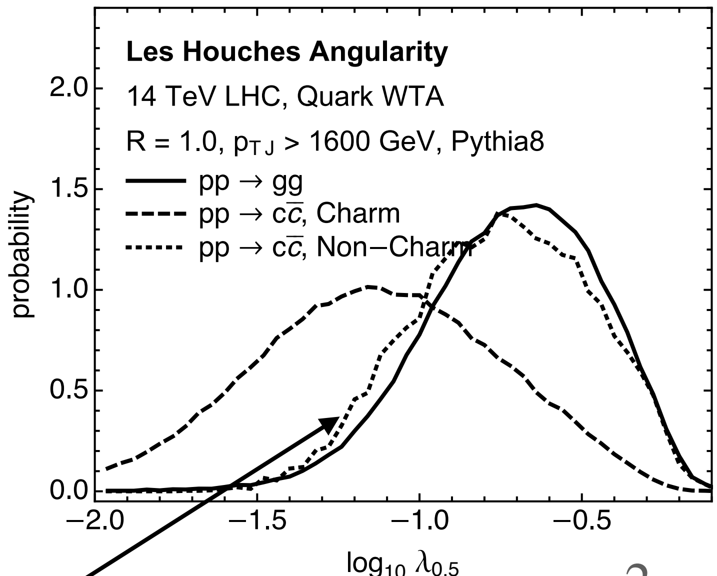


Flavored Observables

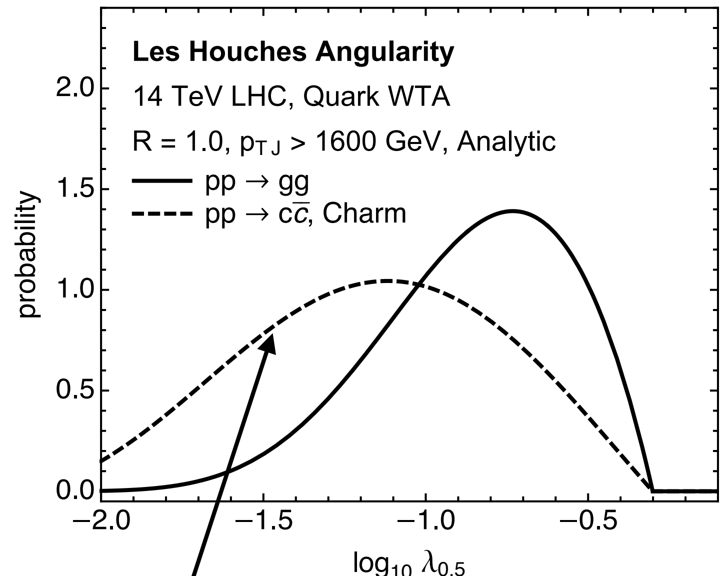
Measuring about WTA Axis

WTA Flavor Quark Jets

Pythia



Analytic



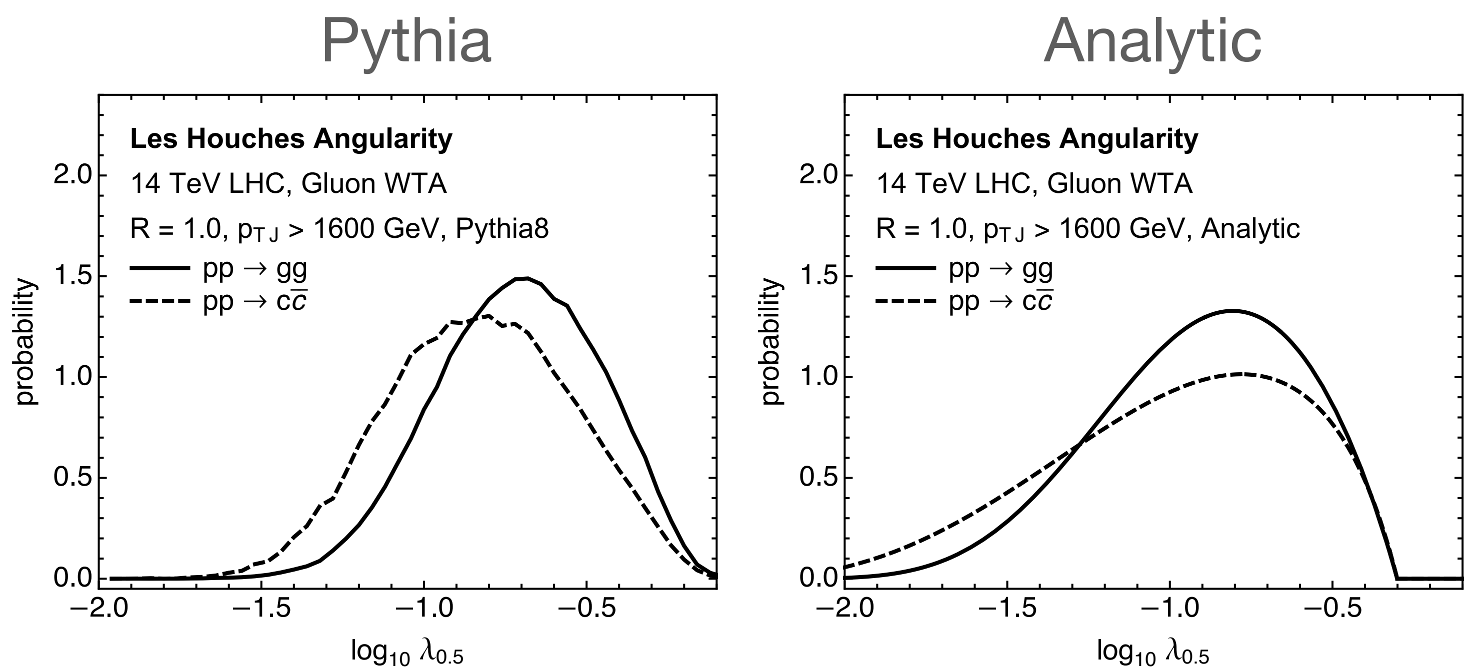
Flavor change starts at order-α_s^2

Energy is clustered close to WTA axis

Flavored Observables

Measuring about WTA Axis

WTA Flavor Gluon Jets



Good qualitative agreement

Can this be systematic? Is there a factorization that enables calculation?