Understanding Jet Innards Perturbatively

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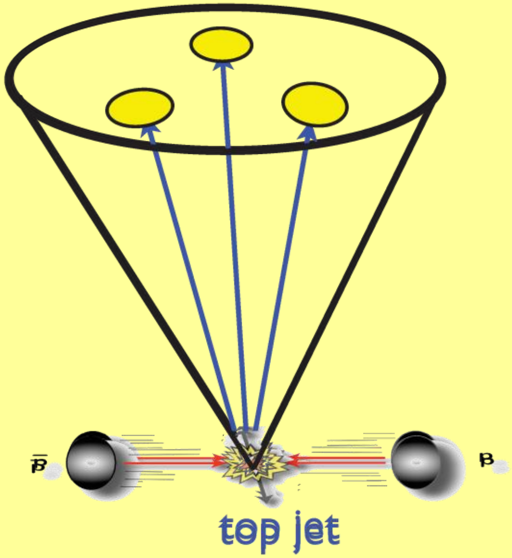
- Looking for physics beyond the Standard Model
  - Direction detection: new classes of events
  - Whole-event signatures: number of jets, total (transverse) energy, missing (transverse) energy
  - Tagging jets: *b* jets
  - New tools: tag lone jets as arising from a known (or unknown) highly-boosted heavy particle (*t* quark or **N**ew **H**eavy **B**oson)
- Looking for small discrepancies from the Standard Model
  - Detailed study of *t* quarks and NHB
  - Highly-boosted t and NHB are a window into high-$\hat{s}$ processes

Tools for Boosted Jets

- Tools may be sensitive to underlying event and pile-up, and thus may require prior cleanup
  - Filtering (Butterworth, Davison, Rubin, & Salam [2008]; Krohn, Thaler, & Wang [2009]; Ellis, Vermilion, & Walsh [2009])
  - Templates (Almeida, Lee, Perez, Sterman, & Sung [2010])



A Jet’s Innards

- First measure: jet mass, corresponding to two-parton intra-jet dynamics
  - ➢ Jets with two or more cores
- Additional measures: correspond to three- or more-parton intra-jet dynamics
  - ➢ Jets with three or more cores

- Study so-called planar flow

  measured by CDF and Atlas

- Differs from traditional “jet shape” (radial) distribution which focuses on one-core (low-mass) jets

Planar Flow

- Define a shape tensor

$$\mathcal{I} \equiv \sum_{i\in \text{jet}} p_{\mathrm{T}}^{i} \begin{pmatrix} \Delta\eta_i^2 & \Delta\eta_i\Delta\phi_i \\ \Delta\eta_i\Delta\phi_i & \Delta\phi_i^2 \end{pmatrix}$$

- Define the planar flow Pf

$$\mathrm{Pf} \equiv \frac{4\det\mathcal{I}}{(\mathrm{Tr}\,\mathcal{I})^2}$$

- Vanishes for one- and two-parton jets, nonvanishing for jets with three or more partons

$$0 \leq \mathrm{Pf} \leq 1$$

QCD Backgrounds

- QCD is omnipresent, can give rise to jets with similar measures of substructure
- To see genuine highly-boosted heavy objects, we need to understand the backgrounds
- Studies to date have used parton-shower codes
- We will take the first step in studying these quantities perturbatively

Using the Collinear Limit

- Jets are narrow
- Treat intra-jet radiation in the collinear approximation
  - Expect factorization from the short-distance subprocess
- Can't be too close to the collinear limit
  - Resummation would be required
- Kinematic limits due to fixed number of partons affect behavior near upper limits
  - Stay away from upper limits

Factorization

- Study $pp \to \mathit{Jet} + X$
- Jet defined by cone size R
- Differentially in p_T, η, and energy-flow observables O

- Expect a factorization of the form

$$\frac{d\hat{\sigma}_{ab\to JX}}{dp_{\mathrm{T}}\,d\eta\,d\mathcal{O}}(x_a, x_b, p_{\mathrm{T}}, \eta, \mathcal{O}; R) \simeq \sum_f \frac{d\hat{\sigma}_{ab\to fX}}{dp_{\mathrm{T}}\,d\eta}(x_a, x_b, p_{\mathrm{T}}, \eta)\, J_f(\mathcal{O}; p_{\mathrm{T}}, \eta; R)$$

where J_f is like a fragmentation function

Planar-Flow Jet Function

- Use collinear factorization of squared matrix element M with *n* partons inside a jet

$$\mathcal{M}_{2\to n+1} \simeq \mathcal{M}_{2\to 2} \cdot |\,\mathrm{Split}_{1\to n}\,|^2$$

- Phase-space factorization

$$\int d\,\mathrm{LIPS}_{2\to n+1}\,\mathcal{M}_{2\to n+1} \simeq \int d\,\mathrm{LIPS}_{2\to 2}\,\mathcal{M}_{2\to 2} \cdot \int d\,\mathrm{LIPS}_{1\to n}\,|\,\mathrm{Split}_{1\to n}\,|^2$$

- Specialize to *n*=3 and the central region to obtain an expression for the planar-flow jet function

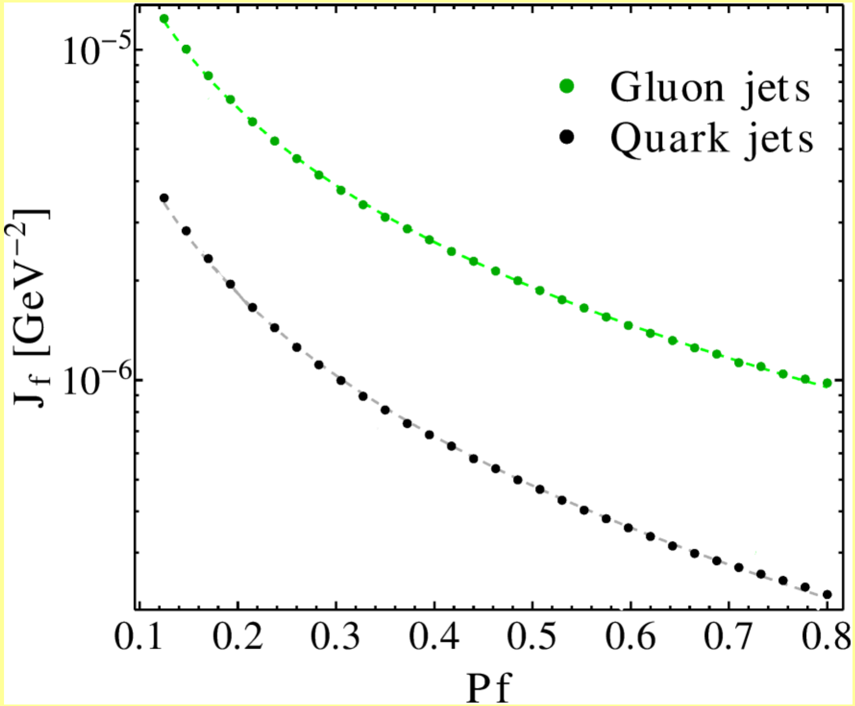
$$J_f(m^2, \mathrm{Pf}; \vec{p}; R) \quad \simeq \frac{\alpha_s(m)E}{4\pi^4 m^4} \int \prod_{i=1}^{3} \left[\frac{d^3 p_i}{E_i}\Theta(R-\theta_i)\right] \alpha_s(\mu(p_i))|\,\mathrm{Split}_{f\to 3}(\vec{p}_i)|^2$$

$$\times\, \delta\big(m^2(\vec{p}_i) - m^2\big)\ \delta(\mathrm{Pf}(\vec{p}_i) - \mathrm{Pf})\ \delta^3(\vec{p} - \textstyle\sum \vec{p}_i)$$

characterizing fragmentation into a jet of fixed *m* and Pf

- Compute some integrals analytically, and the remainder numerically: semi-analytic

- Compute as a function of Pf for fixed p_T and m
- Separately for gluon and quark seeds



- Where is the computation useful and reliable?

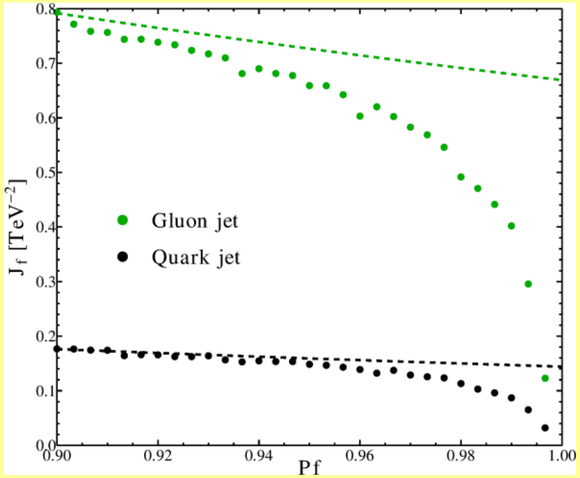
Probing the Forbidden Zone

- At small Pf, one can evaluate the integral analytically

$$J_f \simeq \frac{A_f}{\mathrm{Pf}} \log\left(\frac{B_f}{\mathrm{Pf}}\right) + \cdots$$

- In this region, the fixed-order perturbative evaluation is not valid: requires resummation

- At Pf = 1, the dimension of the phase space drops by one, and the function vanishes (kinematic constraint removed by additional radiation)



- Need m above the resummation zone, and below the kinematic limit:

$$\alpha_s p_{\mathrm{T}} R \ll m \ll p_{\mathrm{T}} R$$

- Satisfied for pT ~ 1 TeV and m ~ 180 GeV
- Need Pf above the resummation zone, and below the kinematic limit:

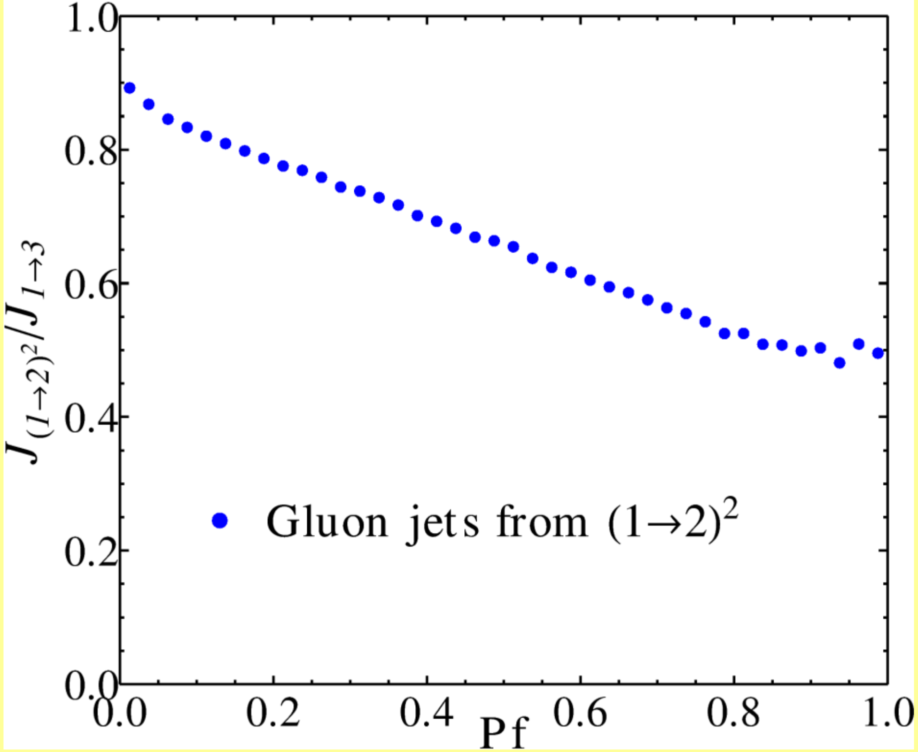
$$\mathrm{small} \ll \mathrm{Pf} < 1 - \delta$$

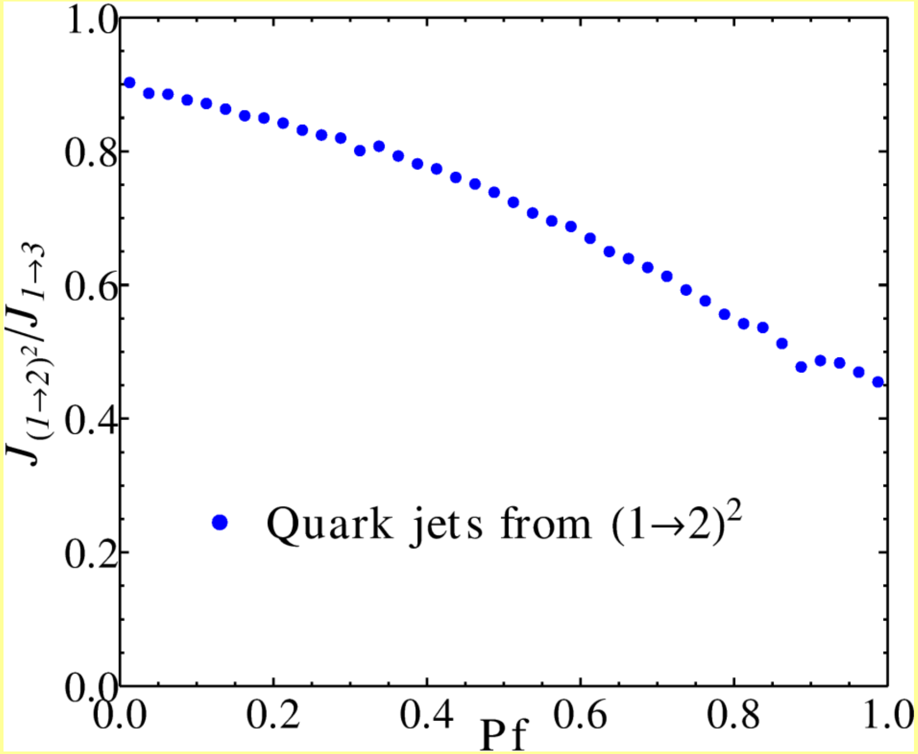
- In practice

$$0.4 < \mathrm{Pf} < 0.95$$

Strongly Ordered Approximation

- Can approximate the jet by a sequence of two 1→2 splittings

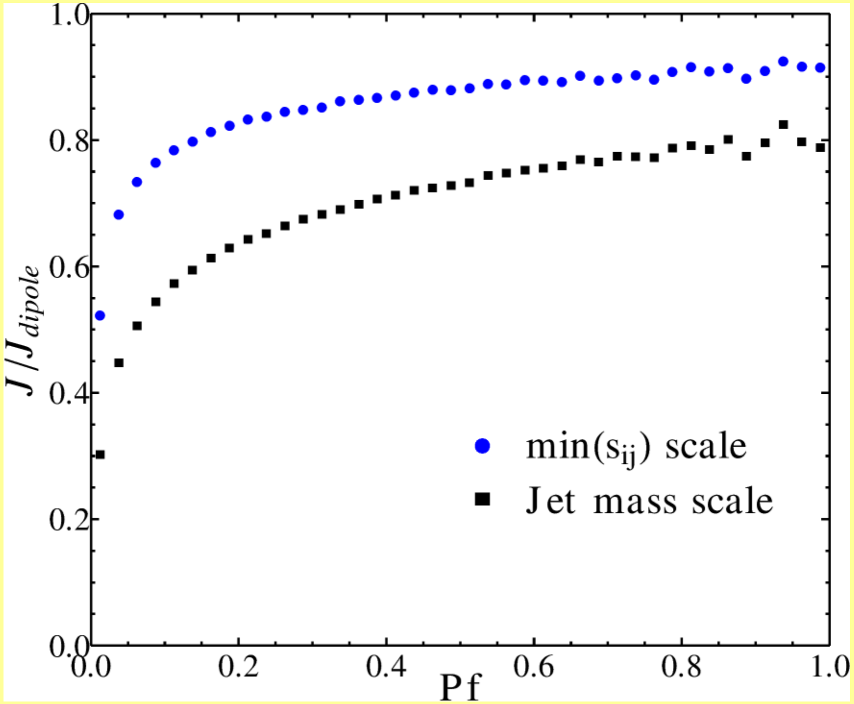




- Corrections are substantial, and not uniform in planar flow
- Unmatched parton showers will not get this right

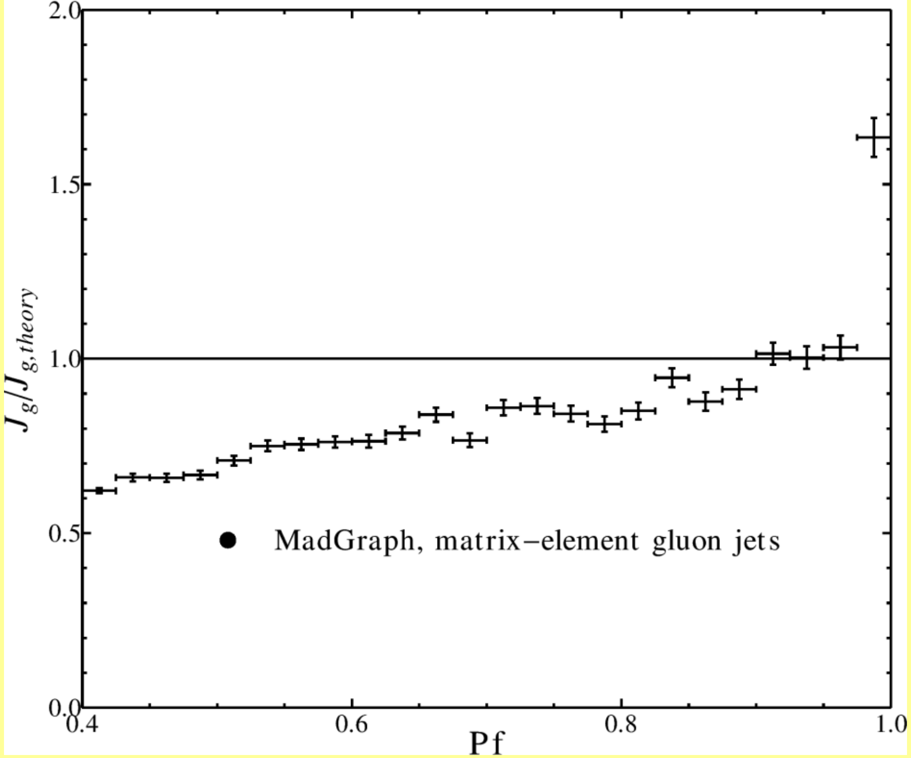
Coupling and Scales

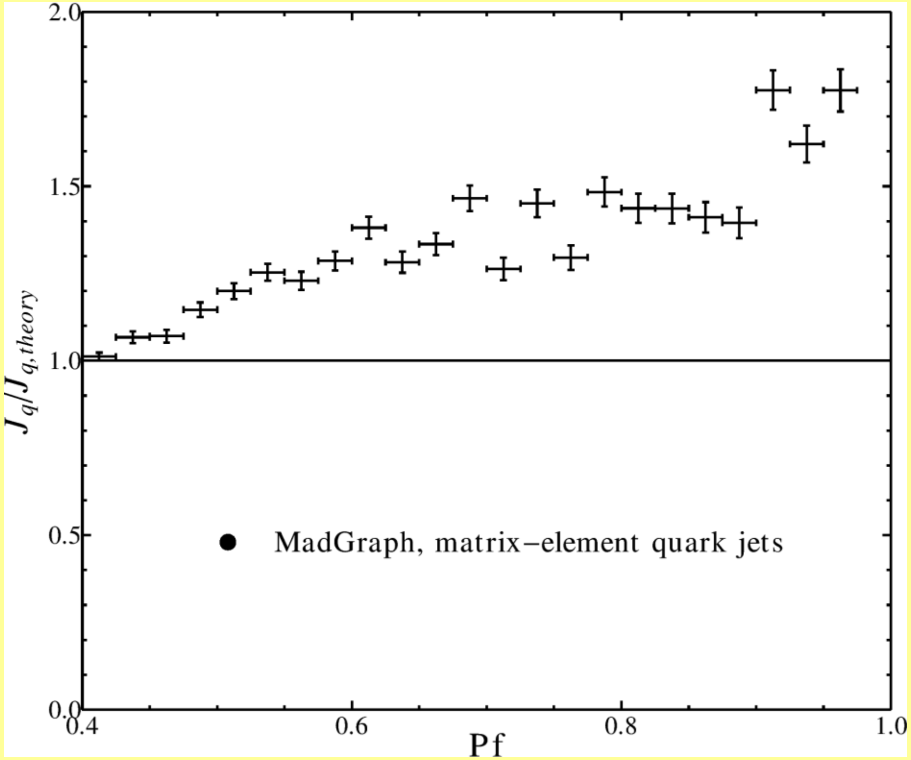
- Two powers of α_s: evaluate first at jet mass (first splitting)
- Several choices for second:
  - Jet mass
  - Min s_{ij} ~ invariant at second splitting (appropriate for quark pair)
  - p_T wrt to leading pair for gluons, invariant for quarks
- Leading order — value is sensitive to choice
- Sensitivity differs across planar flow distribution



Non-Universal Corrections

- Compute (2→Jet(3 partons)+X)/(2→Jet(1 parton)+X)
- Parton-level
- Full leading-order matrix element

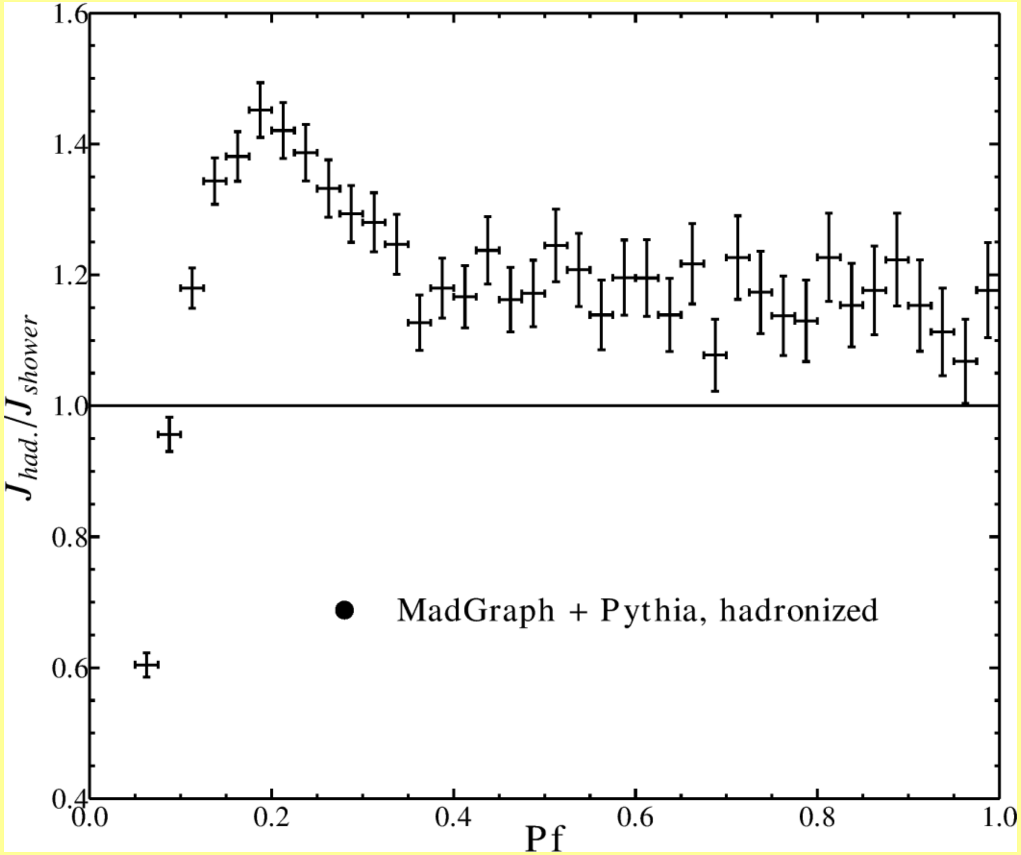




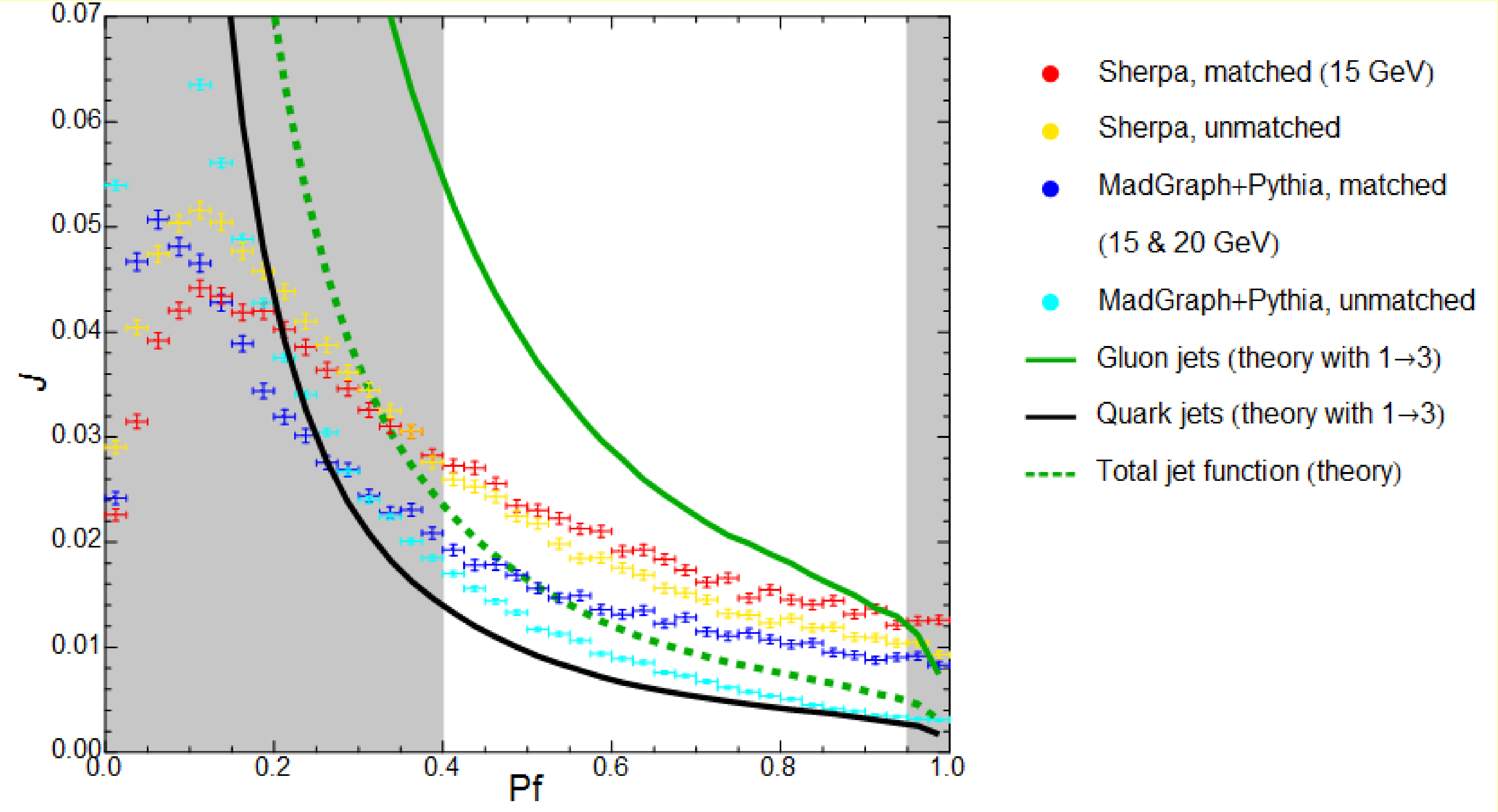
- 20–30% corrections

Hadronization Corrections

- Compare parton shower calculation without hadronization to one with hadronization
- In region of interest ($0.4 < Pf < 0.95$), 15% correction

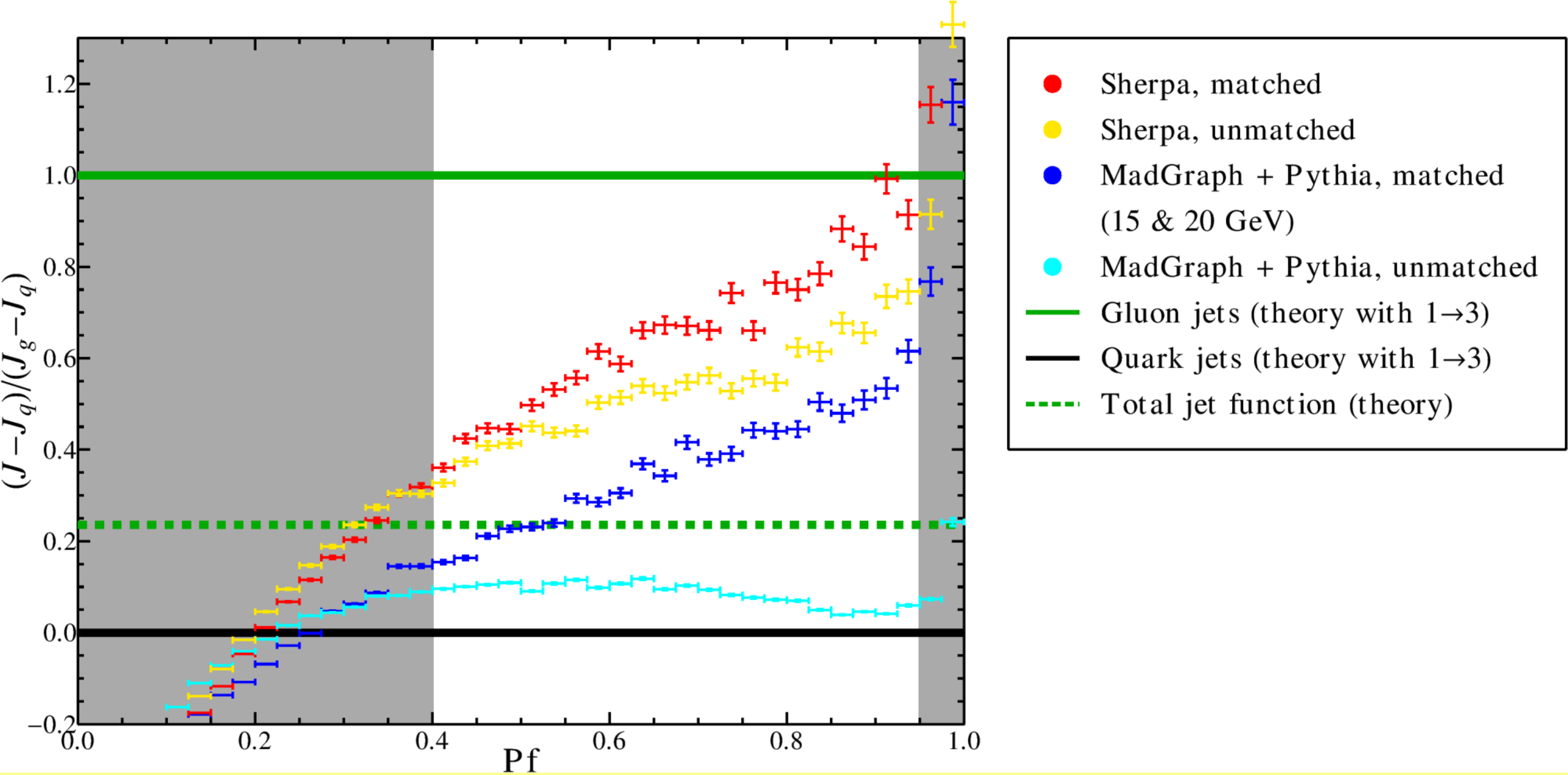


Parton-Shower Results



- All results using CTEQ6L PDFs

Comparisons



Summary and Outlook

- Boosted jets will be a useful tool in new-physics searchs and precision studies of top quarks and the NHB

- First fixed-order perturbative study of backgrounds to finding single-jet top quarks, using the planar flow
- Semi-analytic evaluation of function characterizing jet

- Other energy-flow observables

- Next-to-leading order corrections