Jet Charge and Track-Based Observables at the LHC

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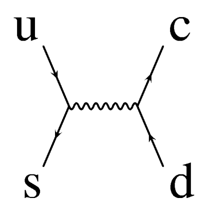
UCSD



SCET 2013

With: David Krohn,Tongyan Lin and Matthew Schwartz
arXiv: 1209.2421, 1209.3019

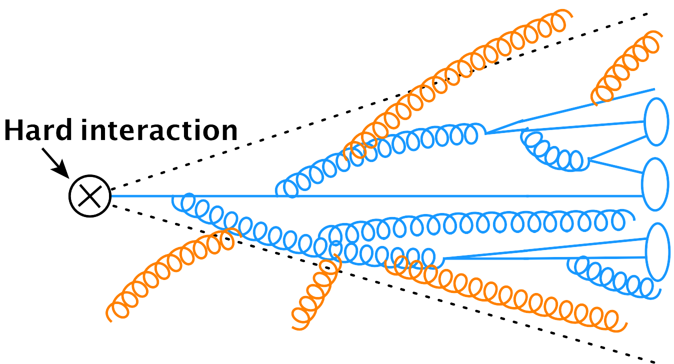
Hsi-Ming Chang, Massimiliano Procura, Jesse Thaler
arXiv: 1303.xxxx

Outline

Introduction

Jet Charge

- Motivation: separate q and $\bar{q}$ jets, flavor tag



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

[Feynman, Field (1977)]

Jet Charge

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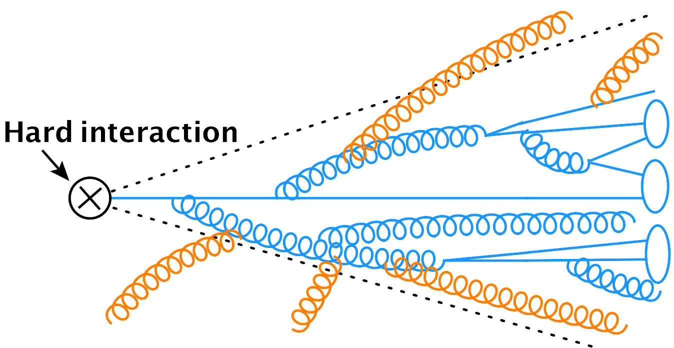

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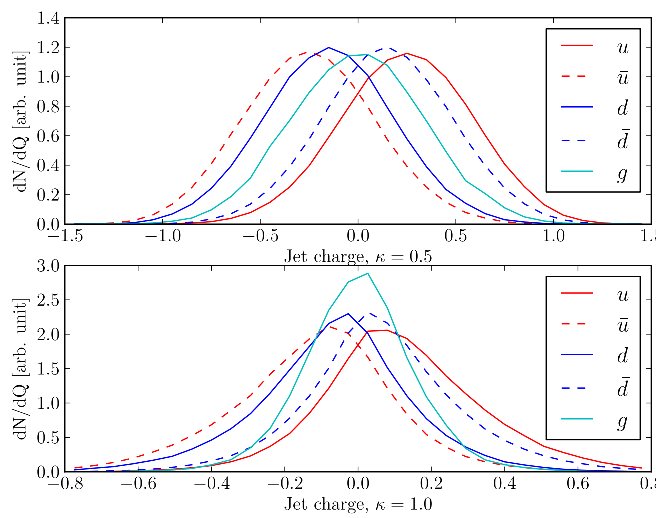
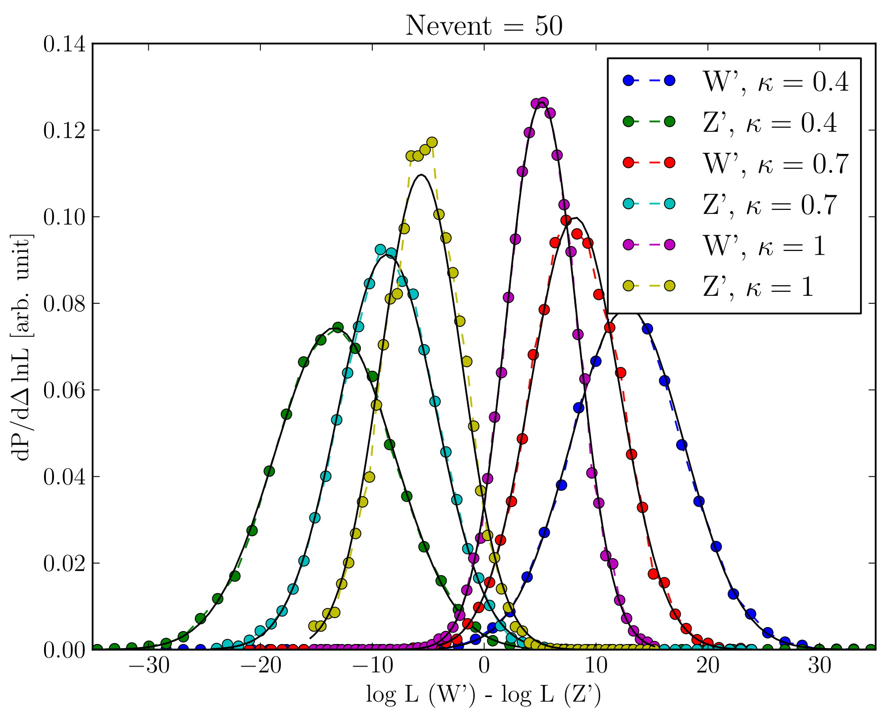
[Feynman, Field (1977)]



- κ too small: measurement sensitive to soft hadrons → contamination
- κ too large: need more statistics to separate flavors

LHC Application: W' vs. Z'



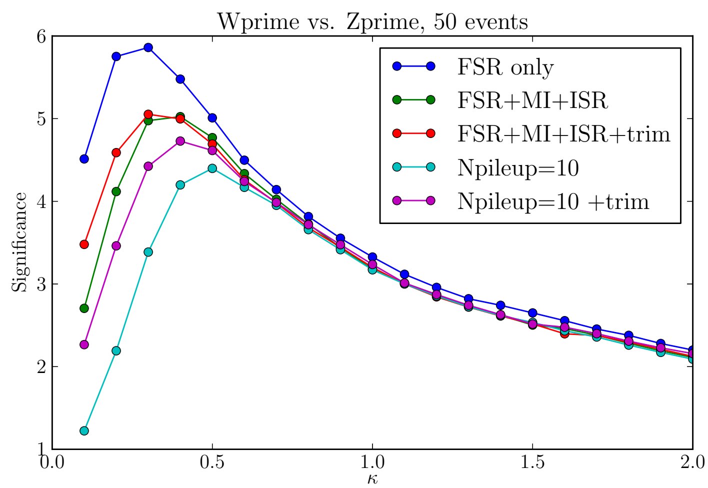
- Hadronically decaying W' and Z' with mass 1 TeV
- Likelihood discriminant based on charge of both jets
- With 50 events $\sim 4\sigma$ separation

LHC Challenges

Contamination:

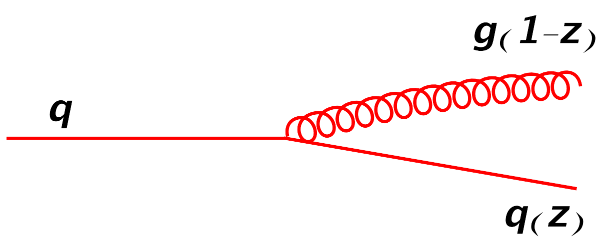
- Initial-state radiation (ISR)
- Multi-parton interactions (MI)
- Pile-up

Soft effects → issue for small κ



Jet Charge Not Infrared Safe

- Example: consider $q \to qg$ in collinear limit



$$Q_q \neq z^\kappa Q_q$$

- Jet charge only defined for hadrons

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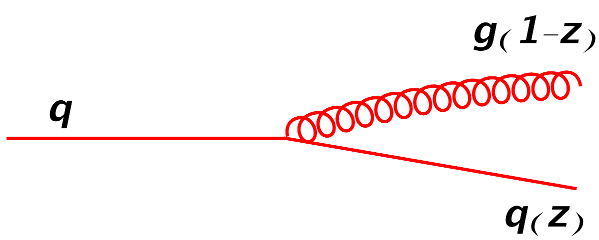

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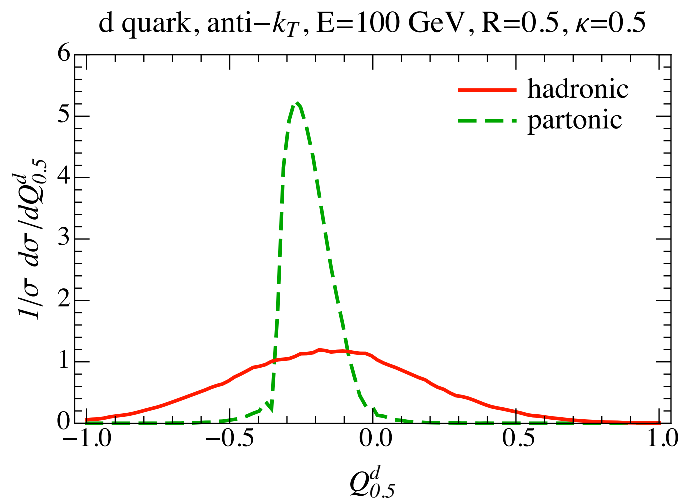
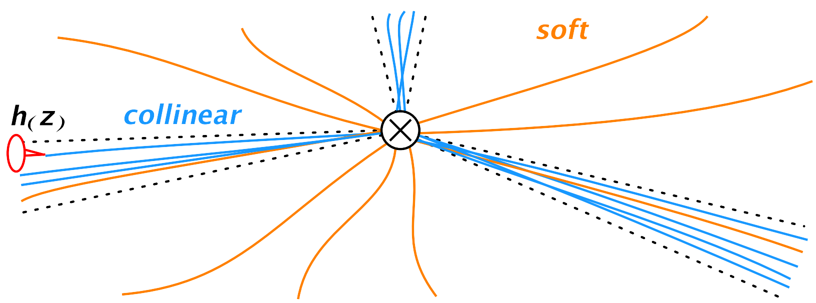


- Jet charge only defined for hadrons
- Importance of hadronization observed in PYTHIA

Calculation

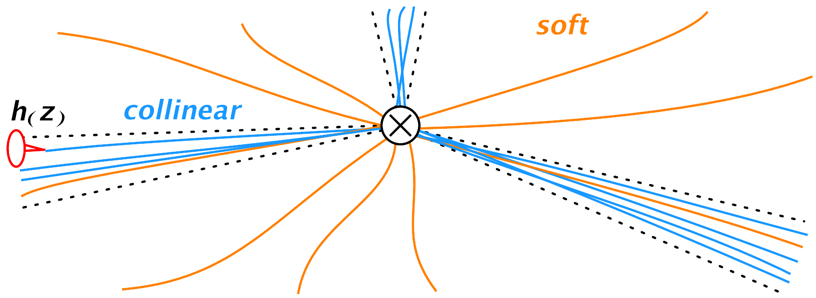
Average Jet Charge



Jet with energy E and radius R:

$$\langle Q_\kappa^q \rangle = \underbrace{\sum_h \int \mathrm{d}z}_{\text{hadron h with z}} \; \underbrace{z^\kappa Q_h}_{\text{charge}} \; \underbrace{\frac{1}{\sigma_{\text{jet}}} \frac{\mathrm{d}\sigma_{h\in\text{jet}}}{\mathrm{d}z}}_{\text{weight}}$$

Average Jet Charge

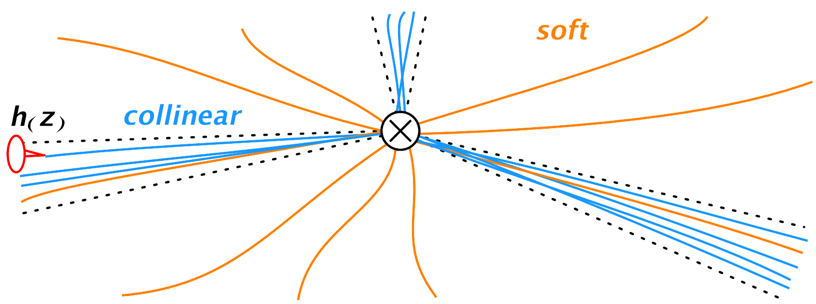


Jet with energy E and radius R: [Using Ellis, Hornig, Lee, Vermilion and Walsh (2010)]

$$\langle Q_\kappa^q \rangle = \sum_h \int dz \; z^\kappa Q_h \frac{1}{\sigma_{\text{jet}}} \frac{d\sigma_{h\in\text{jet}}}{dz} = \sum_h \int dz \, z^\kappa Q_h \frac{\mathcal{G}_q^h(ER, z, \mu)}{J_q(ER, \mu)}$$

- Dependence on hard collision, soft radiation and other jets suppressed

Average Jet Charge



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- Dependence on hard collision, soft radiation and other jets suppressed
- Dependence on perturbative ER calculable:

$$\mathcal{G}_i^h(ER, z, \mu) = \sum_j \int_z^1 \frac{\mathrm{d}x}{x} \mathcal{J}_{ij}(ER, x, \mu) D_j^h\Big(\frac{z}{x}, \mu\Big)$$

[Procura, Stewart (2010), Jain, Procura, WW (2011)]

- μ-dependence cancels between $\mathcal{G}_q^h$ and J_q
- Evaluate at jet scale $\mu \sim ER$ to avoid large logs

Interpretation

- At leading order:

$$\langle Q_\kappa^q \rangle = 1 \times \sum_h Q_h \widetilde{D}_q^h(\kappa, \mu = ER)$$

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$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} \widetilde{D}_i^h(\kappa, \mu) = \sum_j \frac{\alpha_s(\mu)}{\pi} \widetilde{P}_{ji}(\kappa) \widetilde{D}_j^h(\kappa, \mu)\,,$$

- Mixing into gluons will vanish, since $D_g^{h^+} - D_g^{h^-} = 0$

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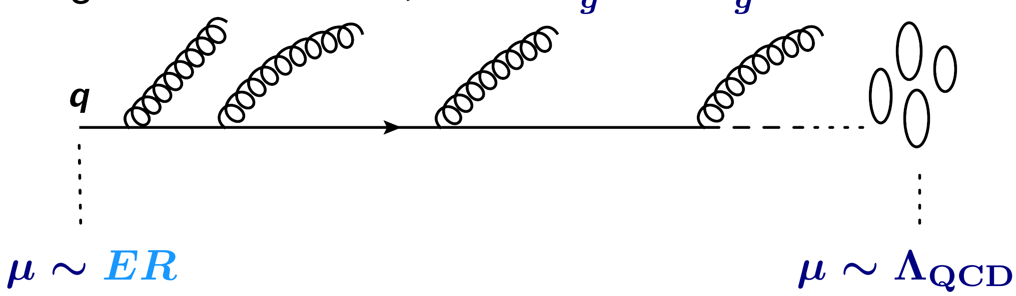

- Showering starts at jet scale not hard scale

Interpretation

- At next-to-leading order:

$$\langle Q_\kappa^q \rangle = \widetilde{\mathcal{J}}_{qq}(ER, \kappa, \mu = ER) \sum_h Q_h \widetilde{D}_q^h(\kappa, \mu = ER)$$

- ER dependence from moment-space evolution:

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} \widetilde{D}_i^h(\kappa, \mu) = \sum_j \frac{\alpha_s(\mu)}{\pi} \widetilde{P}_{ji}(\kappa) \widetilde{D}_j^h(\kappa, \mu),$$

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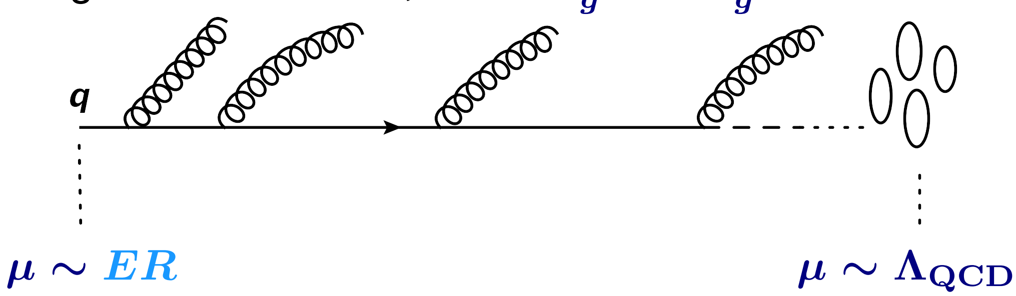
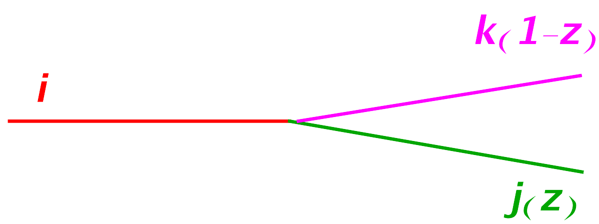


- Showering starts at jet scale not hard scale
- Perturbative splittings at beginning of shower

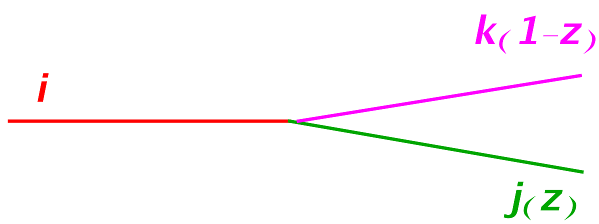
Charge Distribution



Nonperturbative charge distribution $D_i(Q_\kappa, \mu)$

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} D_i(Q_\kappa, \mu) = \sum_j \int \mathrm{d}z \, \frac{\alpha_s}{2\pi} P_{ji}(z) \int \mathrm{d}Q_\kappa^a \, D_j(Q_\kappa^a, \mu) \int \mathrm{d}Q_\kappa^b \, D_k(Q_\kappa^b, \mu) \times \delta[Q_\kappa - z^\kappa Q_\kappa^a - (1-z)^\kappa Q_\kappa^b]$$

Charge Distribution



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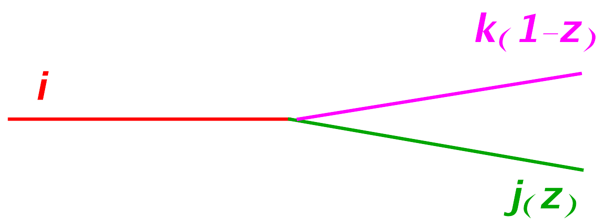

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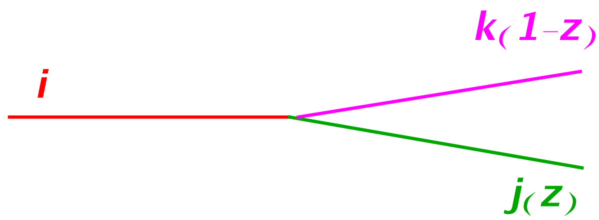
$$\times\, \delta[Q_\kappa - z^\kappa Q_\kappa^a - (1-z)^\kappa Q_\kappa^b]$$

Charge Distribution



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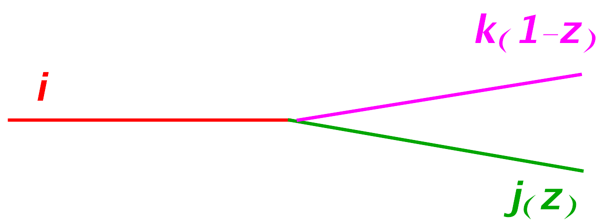

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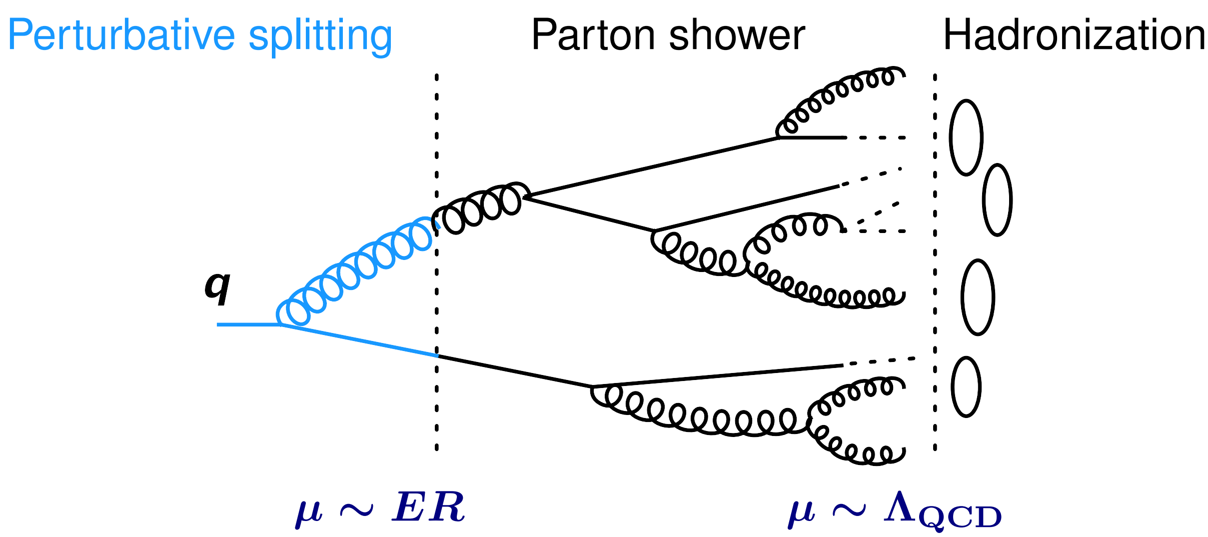
- Preserves norm:

$$\frac{\mathrm{d}}{\mathrm{d}\mu} \int \mathrm{d}Q_\kappa\, D_i(Q_\kappa,\mu) = 0$$

- First two moments reproduce average and width
- NLO perturbative splittings similar form: $P_{ji} \to \mathcal{J}_{ij}$

Parton Shower



- DGLAP evolution following all branches instead of single parton
- This parton shower does not yield full final-state kinematics
- Perturbative splitting generates perturbative scales (e.g. mass)

Comparison with PYTHIA

Comparison with Fragmentation Functions

$$\langle Q_\kappa^q \rangle = \widetilde{\mathcal{J}}_{qq}(ER, \kappa, \mu = ER) \sum_h Q_h \widetilde{D}_q^h(\kappa, \mu = ER)$$

Average jet charge for $E = 100$ GeV and $R = 0.5$:

κ	u-quark PYTHIA	u-quark DSS	u-quark AKK08	d-quark PYTHIA	d-quark DSS	d-quark AKK08
0.5	0.271	0.237	0.221	-0.162	-0.184	-0.062
1	0.144	0.122	0.134	-0.078	-0.088	-0.046
2	0.055	0.046	0.064	-0.027	-0.030	-0.027

[DSS = de Florian, Sassot, Stratmann (2007), AKK08 = Albino, Kniehl, Kramer (2008)]

- PYTHIA consistent with fragmentation functions

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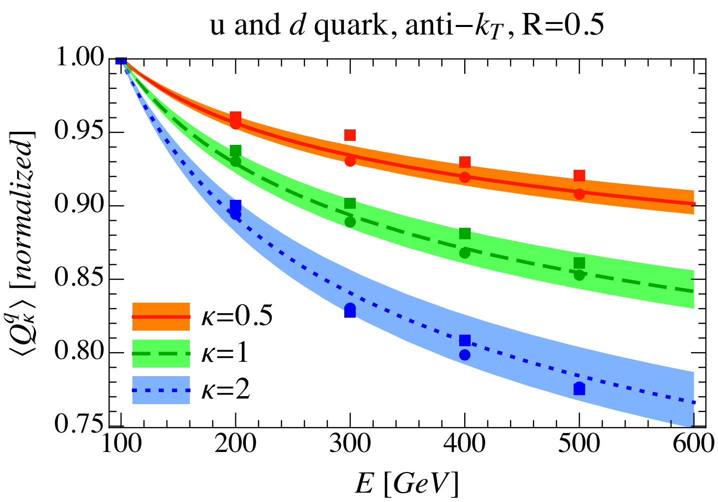
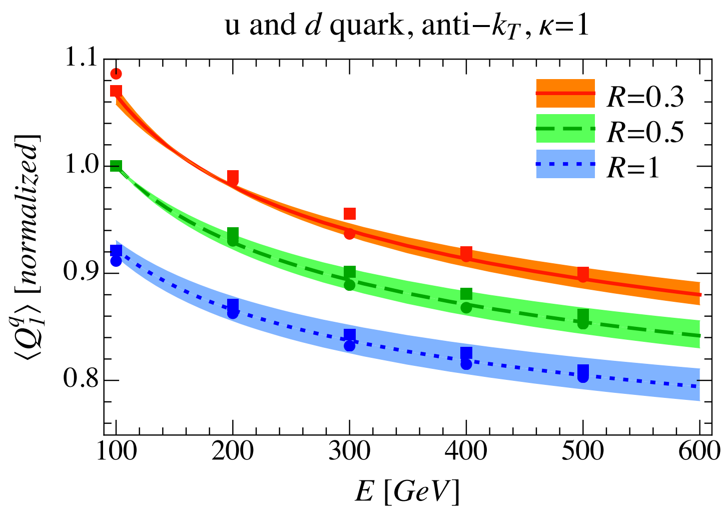
- PYTHIA consistent with fragmentation functions
- Large uncertainties because we need $D_q^{h^+} - D_q^{h^-} = D_q^{h^+} - D_{\bar{q}}^{h^+}$
  Most fragmentation data is e^+e^- giving $D_q^{h^+} + D_{\bar{q}}^{h^+}$

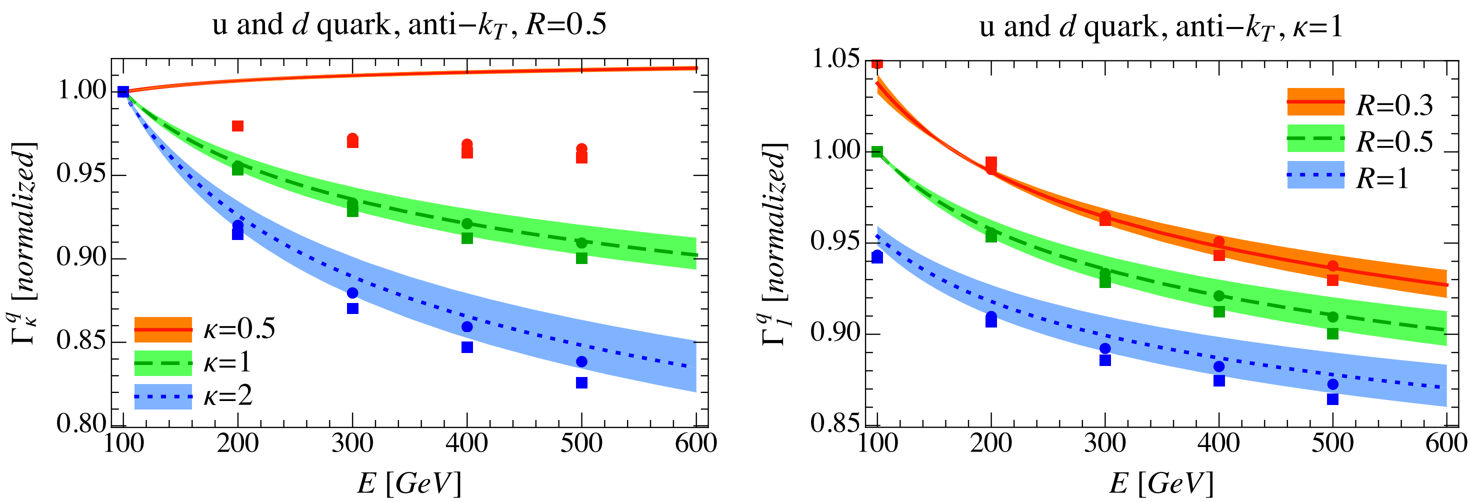
Average Jet Charge





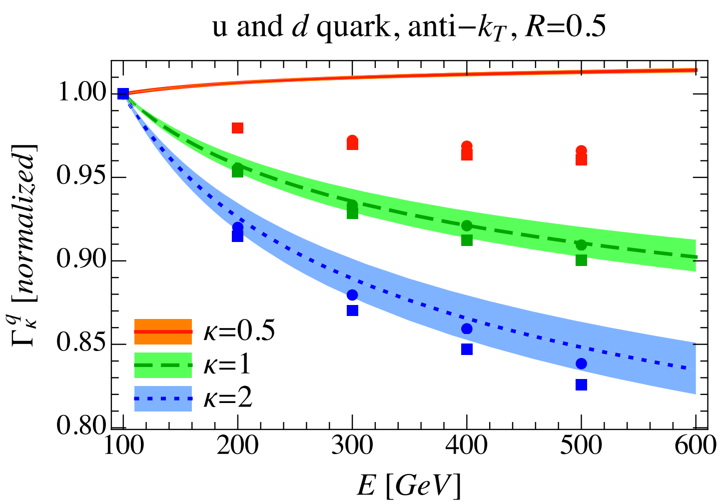
- PYTHIA results for d = squares, u = circles
- Normalizing removes dependence on nonperturbative input and flavor
- Uncertainty bands from varying μ by factors of 2
- Good agreement

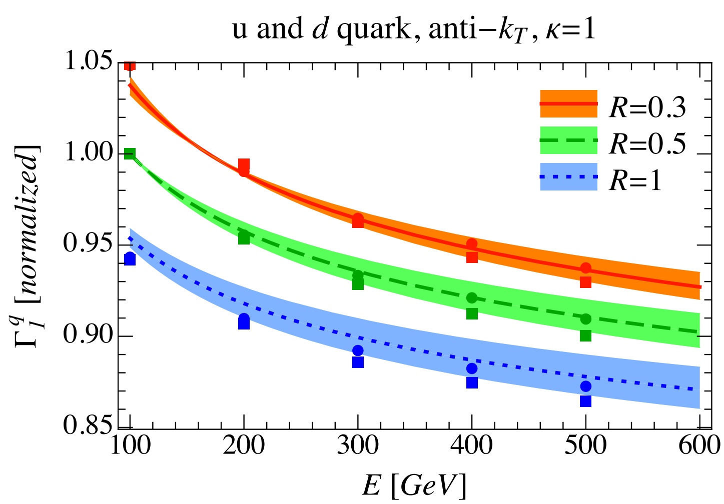
Width of Quark Jet Charge



- Good agreement for $\kappa \gtrsim 1$

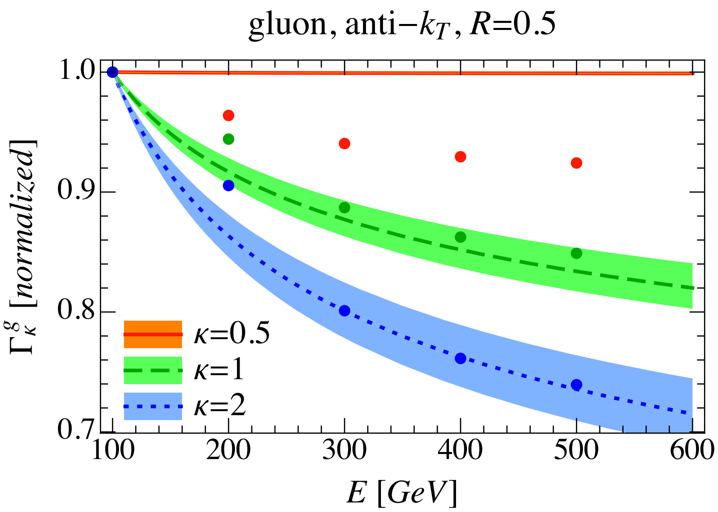
Width of Quark Jet Charge





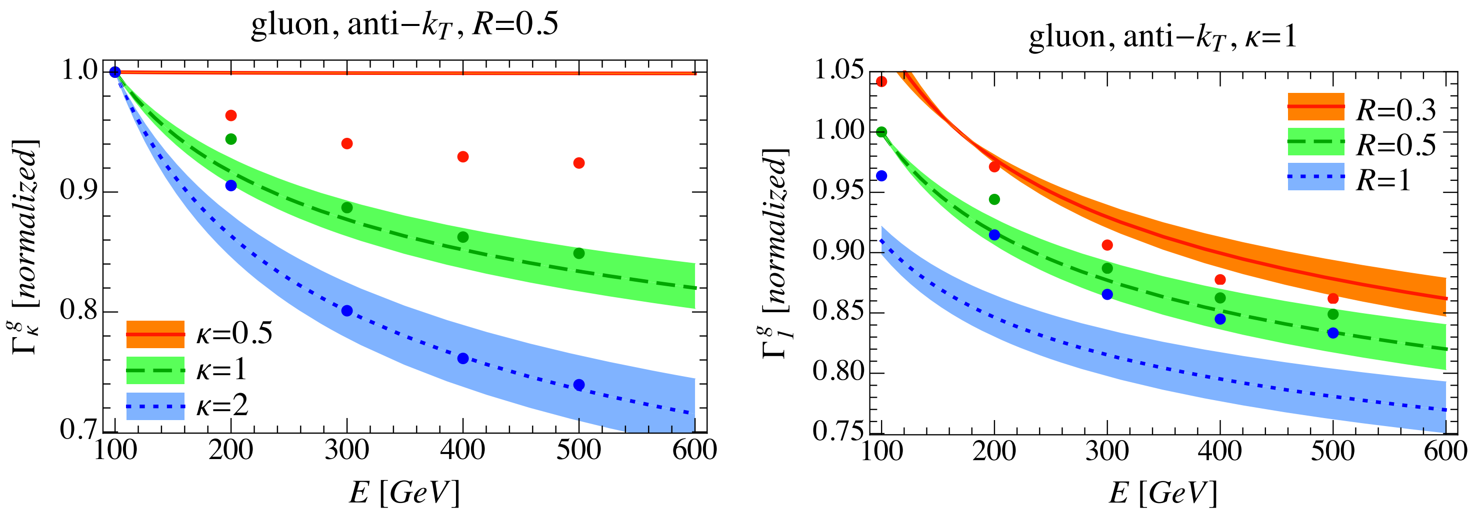
- Good agreement for $\boldsymbol{\kappa \gtrsim 1}$
- Disagreement for $\boldsymbol{\kappa = 0.5}$:
  - Rise caused by mixing with gluons
  - Large power corrections? (scale like $\sim \boldsymbol{\lambda^{2\kappa}}$, absent for average)
  - Issue with PYTHIA? (rises when hadronization off)

Width of Gluon Jet Charge



- Good agreement for $\boldsymbol{\kappa \gtrsim 1}$
- Disagreement for $\boldsymbol{\kappa = 0.5}$ (same possible explanations)

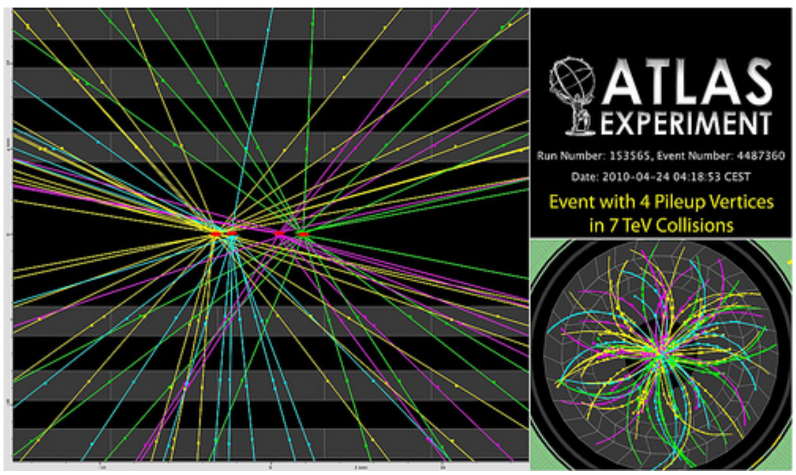
Width of Gluon Jet Charge



- Good agreement for $\boldsymbol{\kappa \gtrsim 1}$
- Disagreement for $\boldsymbol{\kappa = 0.5}$ (same possible explanations)
- PYTHIA has smaller $\boldsymbol{R}$-dependence than we predicted

Track-Based Observables

Tracks Rule!



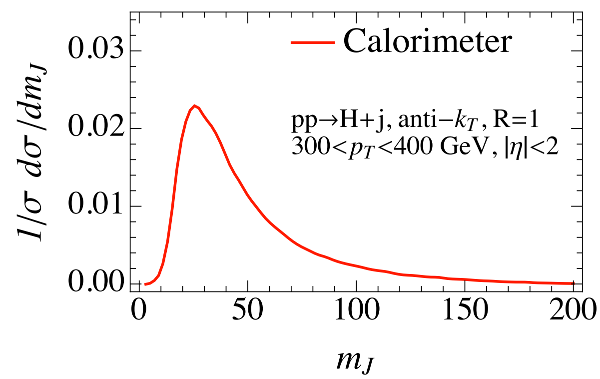
Advantages:

- Better angular resolution
- Much better pointing $\rightarrow$ less sensitive to pile-up

Disadvantages:

- Smearing of (resonance) peaks
- Not infrared safe

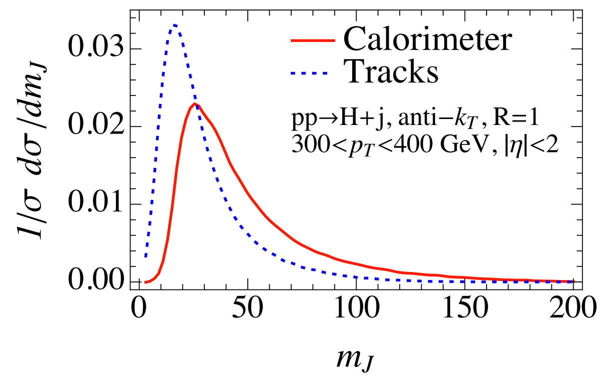
Track-Based Observables



- IR safe observable e:

$$\frac{d\sigma}{de} = \sum_N \int d\Pi_N \frac{d\sigma_N}{d\Pi_N} \delta[e - \hat{e}(\{p_i^\mu\})]$$

Track-Based Observables



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- Track-based version $\bar{e}$:

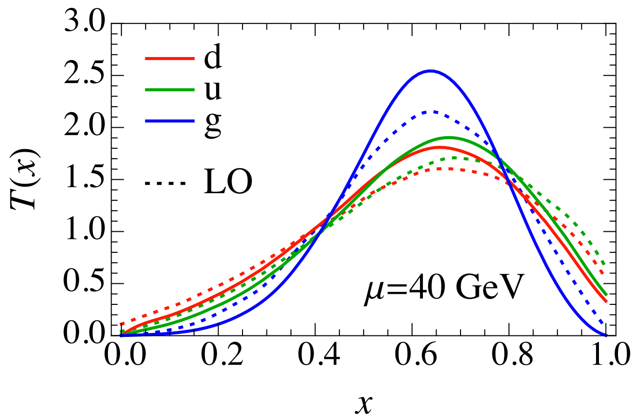
$$\frac{d\sigma}{d\bar{e}} = \sum_N \int d\Pi_N \frac{d\bar{\sigma}_N}{d\Pi_N} \underbrace{\int \prod_{i=1}^{N} dx_i\, T_i(x_i)}_{\text{hadronization}} \delta[\bar{e} - \hat{e}(\{x_i p_i^\mu\})]$$

- Partons hadronize independently at leading power
- Momentum of charged particles

$$\bar{p}_i^\mu = x_i p_i^\mu + \mathcal{O}(\Lambda_{\mathrm{QCD}})$$

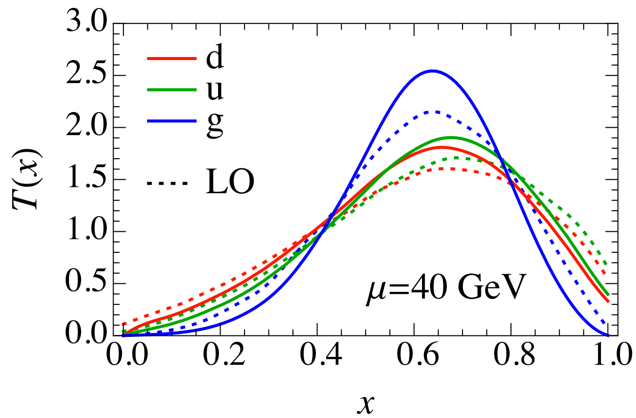
- Distribution in x_i described by track function $T_i(x_i)$

Track Function



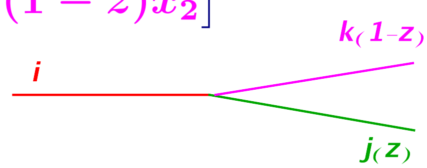
- Extracted using $x =$ track/total jet energy at $\mu = ER$

Track Function



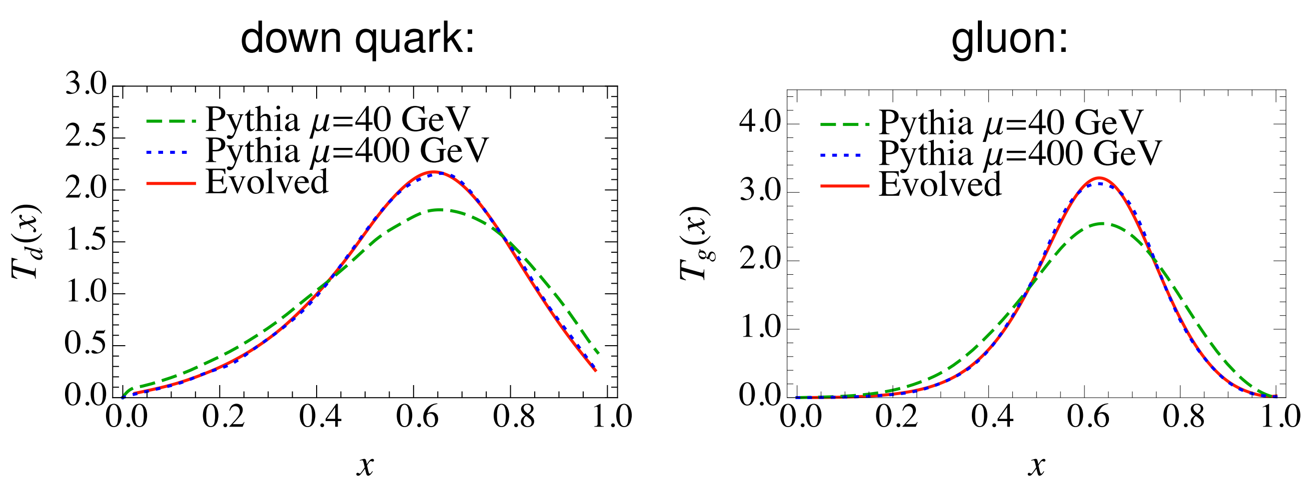
- Extracted using $x =$ track/total jet energy at $\mu = ER$
- NLO partonic track function:

$$T_{i,\text{bare}}^{(1)}(x) = \sum_j \int \mathrm{d}z \left[\frac{\alpha_s(\mu)}{4\pi}\left(\frac{1}{\epsilon_{\text{UV}}} - \frac{1}{\epsilon_{\text{IR}}}\right)P_{ji}(z)\right] \int \mathrm{d}x_1\, T_j^{(0)}(x_1,\mu)$$
$$\times \int \mathrm{d}x_2\, T_k^{(0)}(x_2,\mu)\,\delta\left[x - zx_1 - (1-z)x_2\right]$$



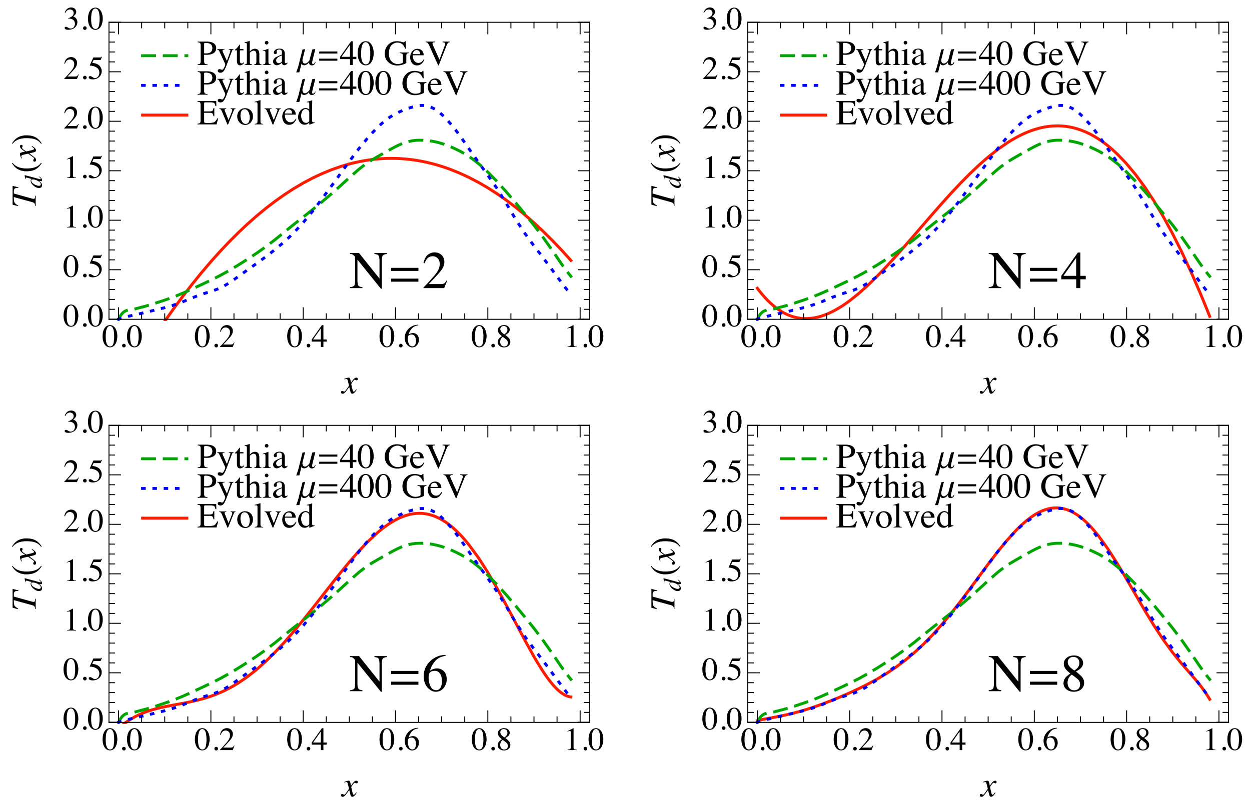
- IR divergence cancels in matching
- UV divergence gives parton shower evolution

Track Function Evolution



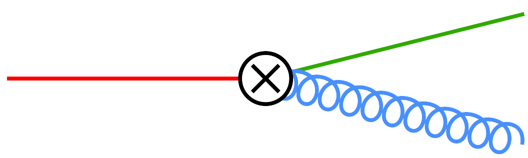
- Excellent agreement with PYTHIA
- Track functions for q and g similar at small μ

Comparison to Moment Space Evolution



- Evolving $N+1$ moments and matching onto $\{1, x, \ldots, x^N\}$

Energy Fraction w of Charged Particles in e^+e^-



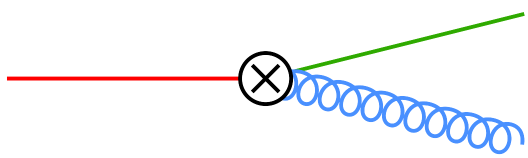
- Up to NLO:

$$\frac{d\sigma}{dw} = \int dy_1 dy_2 \, \frac{d\bar{\sigma}}{dy_1 dy_2} \int dx_1 \, T_q(x_1) \int dx_2 \, T_q(x_2) \int dx_3 \, T_g(x_3) \times \delta\{w - [x_1 y_1 + x_2 y_2 + x_3(2 - y_1 - y_2)]/2\}$$

- Hard scattering:

$$\frac{d\sigma^{(0)}}{dy_1 dy_2} = \sigma^{(0)} \, \delta(1 - y_1)\delta(1 - y_2)$$

Energy Fraction w of Charged Particles in e^+e^-



- Up to NLO:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}w} = \int \mathrm{d}y_1 \mathrm{d}y_2 \, \frac{\mathrm{d}\bar{\sigma}}{\mathrm{d}y_1 \mathrm{d}y_2} \int \mathrm{d}x_1 \, T_q(x_1) \int \mathrm{d}x_2 \, T_q(x_2) \int \mathrm{d}x_3 \, T_g(x_3) \times \delta\{w - [x_1 y_1 + x_2 y_2 + x_3(2 - y_1 - y_2)]/2\}$$

- Hard scattering:

$$\frac{\mathrm{d}\sigma^{(1)}}{\mathrm{d}y_1 \mathrm{d}y_2} = \sigma^{(0)} \, \frac{\alpha_s C_F}{2\pi} \Big[-\frac{1}{\epsilon_{\mathrm{IR}}} P_{qq}(y_1) \delta(1 - y_2) + \dots \Big]$$

- IR divergence cancels against T_q $\rightarrow$ finite remainder is $\bar{\sigma}$

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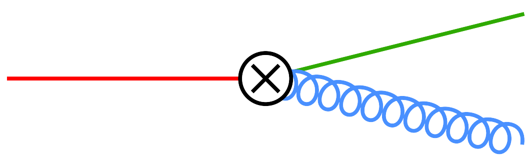

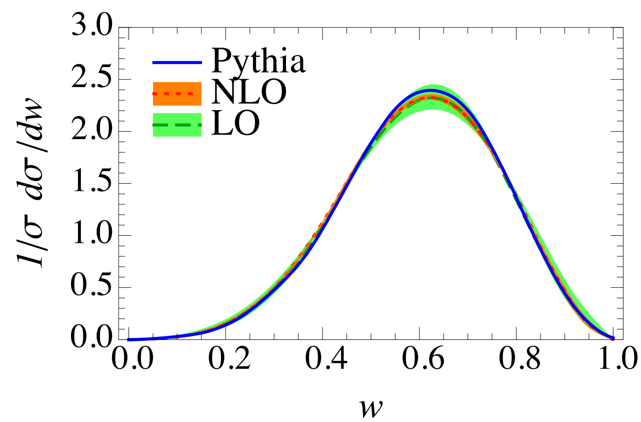

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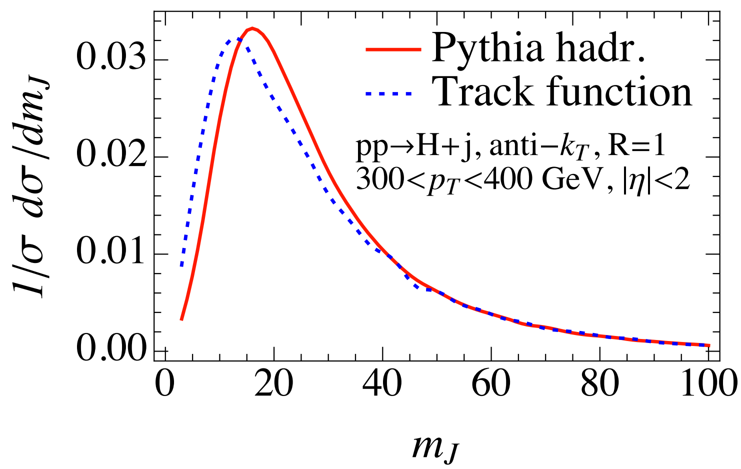
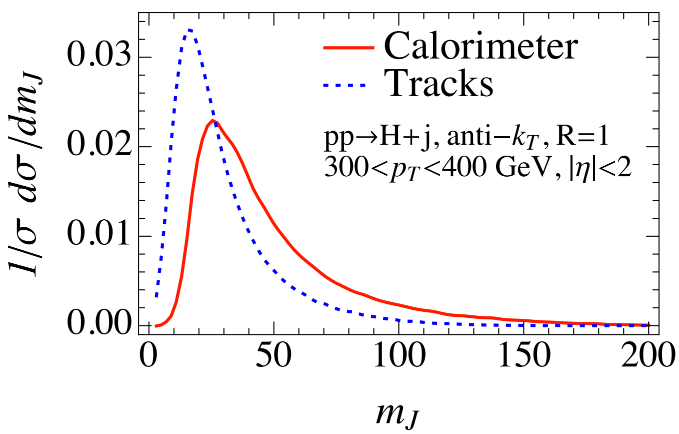
Track Mass



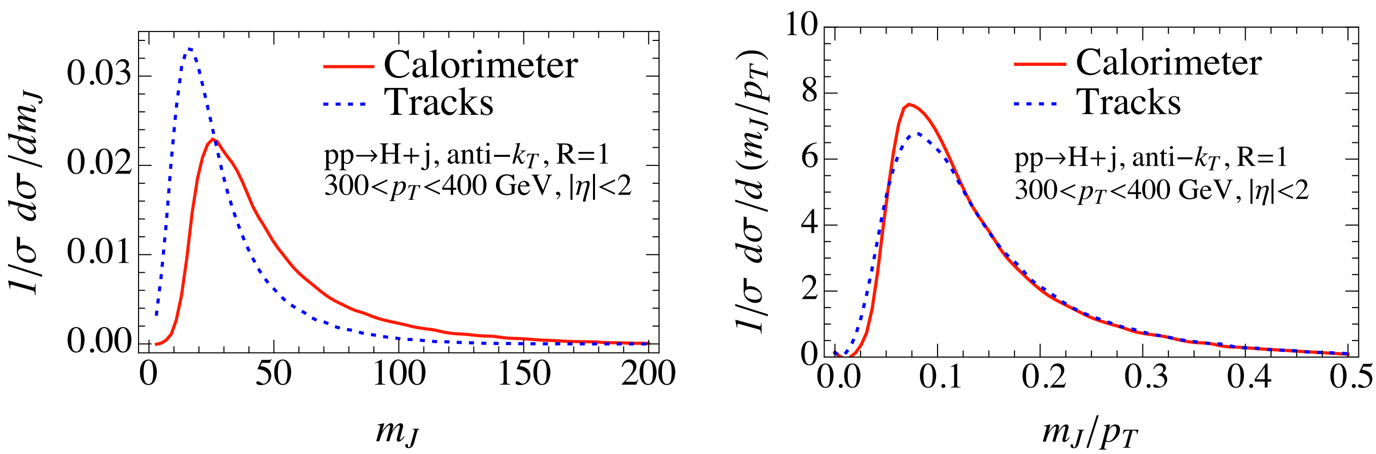
- Pythia with hadronization replaced by track functions:
  Each emission in shower/resummation hadronizes independently
- Good agreement (difference is usual nonperturbative shift)
- Working on resummed track mass calculation

Ratio Observables



- Smearing from hadronization fluctuations (width of track function)

Ratio Observables



- Smearing from hadronization fluctuations (width of track function)
- Reduced smearing for ratio observables since fluctuations correlated
- E.g. ratios of energy correlation functions [Andrew's talk]
  N-subjettiness ratios [Thaler, Tilburg (2010)]

Conclusions

- Jet charge is old tool with new LHC applications
- Track-based observables less sensitive to pile-up, better angular resolution
- Partonic calculation not IR safe → hadronization crucial
- Calculational framework:
  - Match on track function (charge distr.) with parton-shower evolution
  - Agrees with PYTHIA (except $\kappa = 0.5$)
  - Systematically improvable

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Thank You!