Soft-Drop event shapes

Talk by Jeremy Baron
University at Buffalo
October 31st, 2018

Soft-Drop event shapes

Talk by Jeremy Baron
University at Buffalo
October 31st, 2018

Soft-Drop event shapes

Talk by Jeremy Baron
University at Buffalo
October 31st, 2018

Outline

- Motivation
  - α_s extraction (see Vincent's talk)
  - Soft drop thrust
  - Bottom-up soft drop (BUSD)

- Fixed-order (EVENT2)
  - Other event shapes
  - Local BUSD vs Global BUSD
  - Modification of observables

- Monte Carlo (Pythia)
  - Reduction in NP effects

Introduction

- Some α_s-extractions contaminated by N.P. effects
  - Often determined by event shapes from LEP
  - Results in tension with lattice QCD
- Soft drop useful for reduction of N.P. effects
  - Invented and mostly used for LHC

Introduction

- Some α_s-extractions contaminated by N.P. effects
  - Often determined by event shapes from LEP
  - Results in tension with lattice QCD
- Soft drop useful for reduction of N.P. effects
  - Invented and mostly used for LHC
- Is soft drop natural for event shapes?
  - Event shapes are event-wide parameters (global)
  - Soft drop is locally applied groomer
- Generalized grooming scheme for event shapes?
  - Akin to CAESAR/ARES

Soft-Drop algorithm

- $\frac{\min(E_1,E_2)}{E_1+E_2} > z_{\text{cut}}\left(1-\cos(\theta_{12})\right)^{\beta/2}$ for e^+e^-
- $\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\text{cut}}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$ for pp

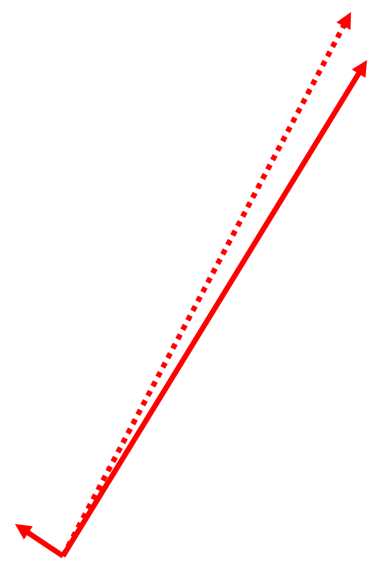
1) Undo last step of clustering
2) Check Soft-Drop criterion
3) If fail, drop softer subjet and iterate
4) If pass, declare final jet and end

Larkoski, Marzani, Soyez, Thaler: Soft Drop (2014)

Soft-Drop algorithm

- $\frac{\min(E_1,E_2)}{E_1+E_2} > z_{\text{cut}}\left(1-\cos(\theta_{12})\right)^{\beta/2}$ for e^+e^-
- $\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\text{cut}}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$ for pp

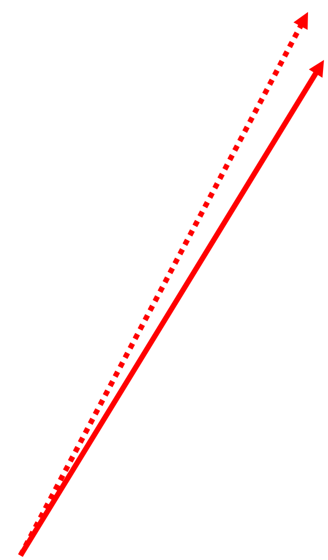
1) Undo last step of clustering
2) Check Soft-Drop criterion
3) If fail, drop softer subjet and iterate
4) If pass, declare final jet and end



Larkoski, Marzani, Soyez, Thaler: Soft Drop (2014)

Soft-Drop algorithm

- $\frac{\min(E_1,E_2)}{E_1+E_2} > z_{\mathrm{cut}}\left(1-\cos(\theta_{12})\right)^{\beta/2}$ for e^+e^-
- $\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\mathrm{cut}}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$ for pp



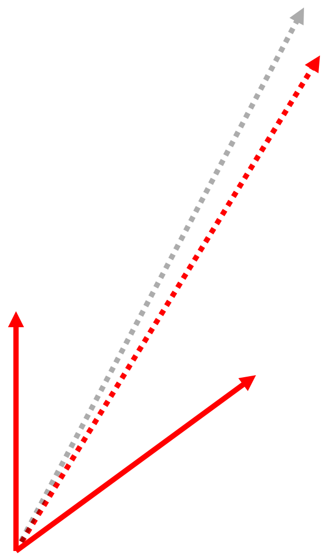
1) Undo last step of clustering
2) Check Soft-Drop criterion
3) If fail, drop softer subjet and iterate
4) If pass, declare final jet and end

Larkoski, Marzani, Soyez, Thaler: Soft Drop (2014)

Soft-Drop algorithm

- $\frac{\min(E_1,E_2)}{E_1+E_2} > z_{\mathrm{cut}}\left(1-\cos(\theta_{12})\right)^{\beta/2}$ for e^+e^-
- $\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\mathrm{cut}}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$ for pp

1) Undo last step of clustering
2) Check Soft-Drop criterion
3) If fail, drop softer subjet and iterate
4) If pass, declare final jet and end

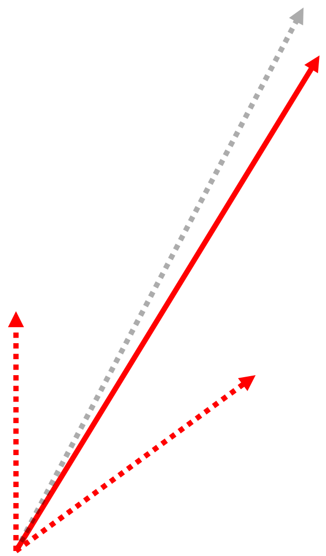


Larkoski, Marzani, Soyez, Thaler: Soft Drop (2014)

Soft-Drop algorithm

- $\frac{\min(E_1,E_2)}{E_1+E_2} > z_{\text{cut}}\left(1-\cos(\theta_{12})\right)^{\beta/2}$ for e^+e^-
- $\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\text{cut}}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$ for pp

1) Undo last step of clustering
2) Check Soft-Drop criterion
3) If fail, drop softer subjet and iterate
4) If pass, declare final jet and end



Larkoski, Marzani, Soyez, Thaler: Soft Drop (2014)

Soft-Drop Thrust

- For an event ε, thrust is defined to be

$$T = \max_{\vec{n}} \left(\frac{\sum_{i \in \varepsilon} |\vec{n} \cdot \vec{p}_i|}{\sum_{i \in \varepsilon} |\vec{p}_i|} \right)$$

- Soft-Drop thrust is defined as:

$$T_{\mathrm{SD}} = \max_{\vec{n}} \left(\frac{\sum_{i \in \varepsilon_{\mathrm{SD}}} |\vec{n} \cdot \vec{p}_i|}{\sum_{i \in \varepsilon_{\mathrm{SD}}} |\vec{p}_i|} \right)$$

Soft-Drop Thrust

- For an event ε, thrust is defined to be

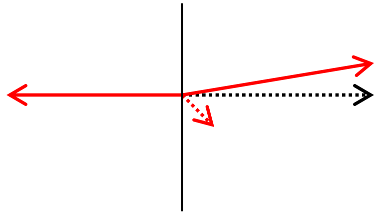
$$T = \max_{\vec{n}} \left(\frac{\sum_{i \in \varepsilon} |\vec{n} \cdot \vec{p}_i|}{\sum_{i \in \varepsilon} |\vec{p}_i|} \right)$$

- Soft-Drop thrust is defined as:
  1. Calculate the the thrust axis
  2. Divide event into left/right hemispheres
  3. Apply soft-drop on each hemisphere separately
  4. The remaining particles constitute soft-dropped event $\varepsilon_{\mathrm{SD}}$

$$T_{\mathrm{SD}} = \max_{\vec{n}} \left(\frac{\sum_{i \in \varepsilon_{\mathrm{SD}}} |\vec{n} \cdot \vec{p}_i|}{\sum_{i \in \varepsilon_{\mathrm{SD}}} |\vec{p}_i|} \right)$$

Soft-Drop Thrust (Redefined)

$$T_{\mathrm{SD}} = \max_{\vec{n}} \left(\frac{\sum_{i \in \varepsilon_{\mathrm{SD}}} |\vec{n} \cdot \vec{p}_i|}{\sum_{i \in \varepsilon_{\mathrm{SD}}} |\vec{p}_i|} \right)$$

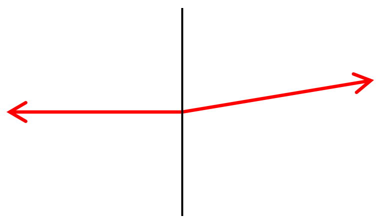


Expect: $T = 1$ for 2-particle back-to-back event

- Small problem: consider 3-particle event..
  - $q\bar{q}$g with $E_g \ll E_q \approx E_{\bar{q}}$
  - E_g groomed away

Soft-Drop Thrust (Redefined)

$$T_{\mathrm{SD}} = \max_{\vec{n}} \left(\frac{\sum_{i \in \varepsilon_{\mathrm{SD}}} |\vec{n} \cdot \vec{p}_i|}{\sum_{i \in \varepsilon_{\mathrm{SD}}} |\vec{p}_i|} \right)$$



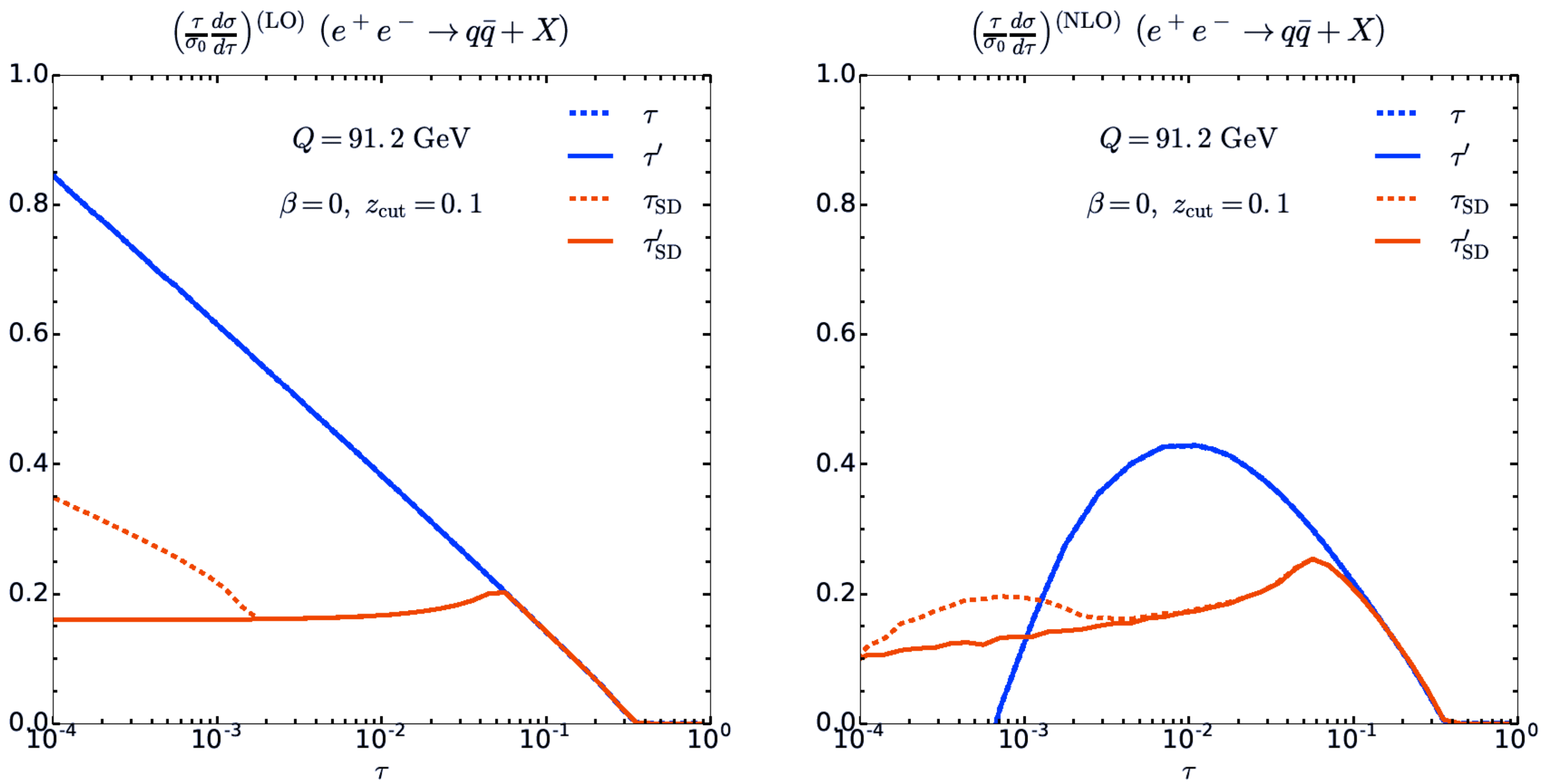
Expect: $T = 1$ for 2-particle back-to-back event

- Small problem: consider 3-particle event..
  - $q\bar{q}$g with $E_g \ll E_q \approx E_{\bar{q}}$
  - E_g groomed away
  - $T_{\mathrm{SD}} \neq 1$ for remaining 2-particle event (bad!!!)
  - Redefine:

$$T'_{\mathrm{SD}} = \frac{\sum_{i \in \mathcal{H}^{\mathrm{L}}_{\mathrm{SD}}} |\vec{n}_L \cdot \vec{p}_i|}{\sum_{i \in \varepsilon_{SD}} |\vec{p}_i|} + \frac{\sum_{i \in \mathcal{H}^{\mathrm{R}}_{\mathrm{SD}}} |\vec{n}_R \cdot \vec{p}_i|}{\sum_{i \in \varepsilon_{SD}} |\vec{p}_i|}$$

- $\vec{n}_{\mathrm{L}}$ and $\vec{n}_{\mathrm{R}}$ are jet axes.
- $\mathcal{H}^L, \mathcal{H}^R$ are left and right hemispheres

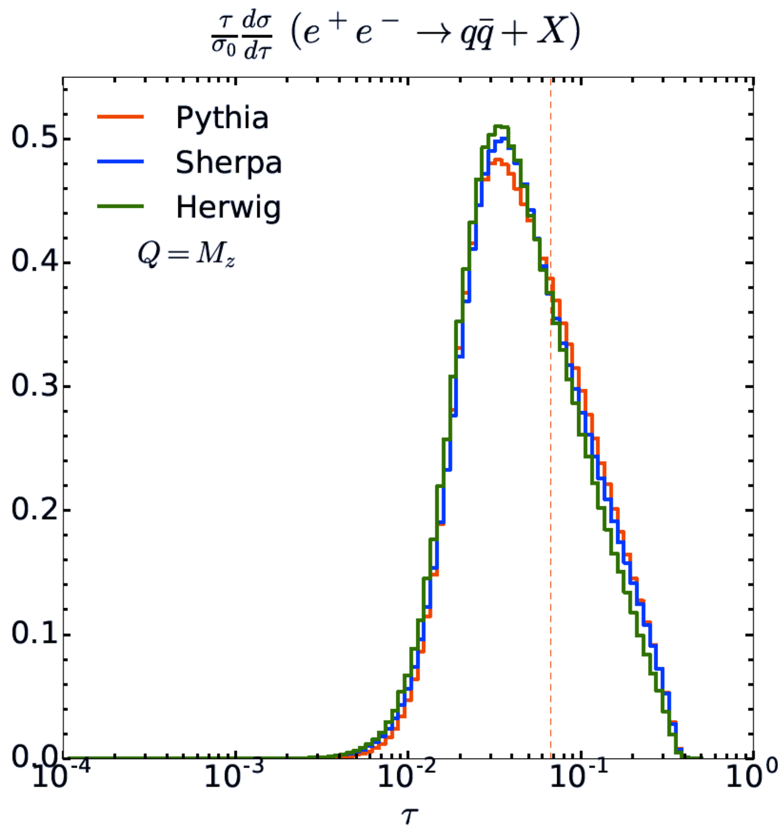
Fixed Order

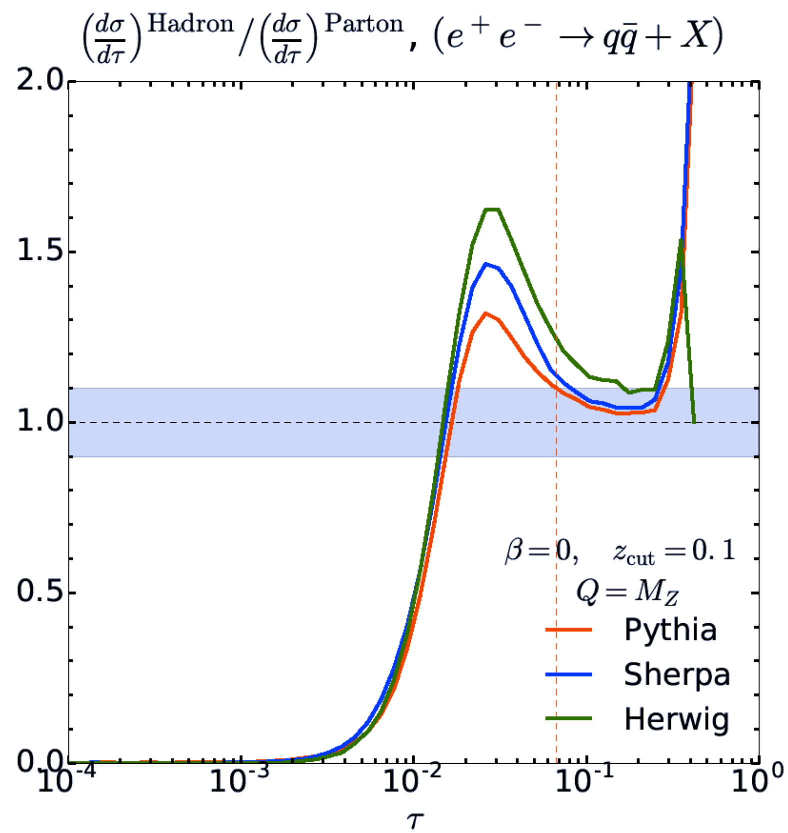


JB, Marzani, Theeuwes
Soft Drop Thrust (2018)

Note: $\tau = 1 - T$

Parton Shower

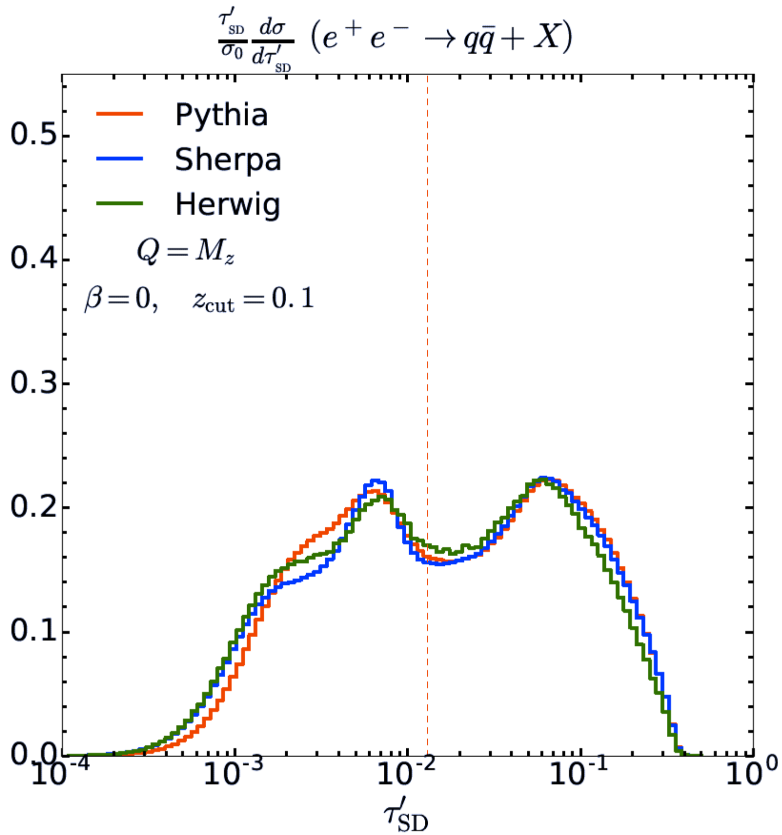


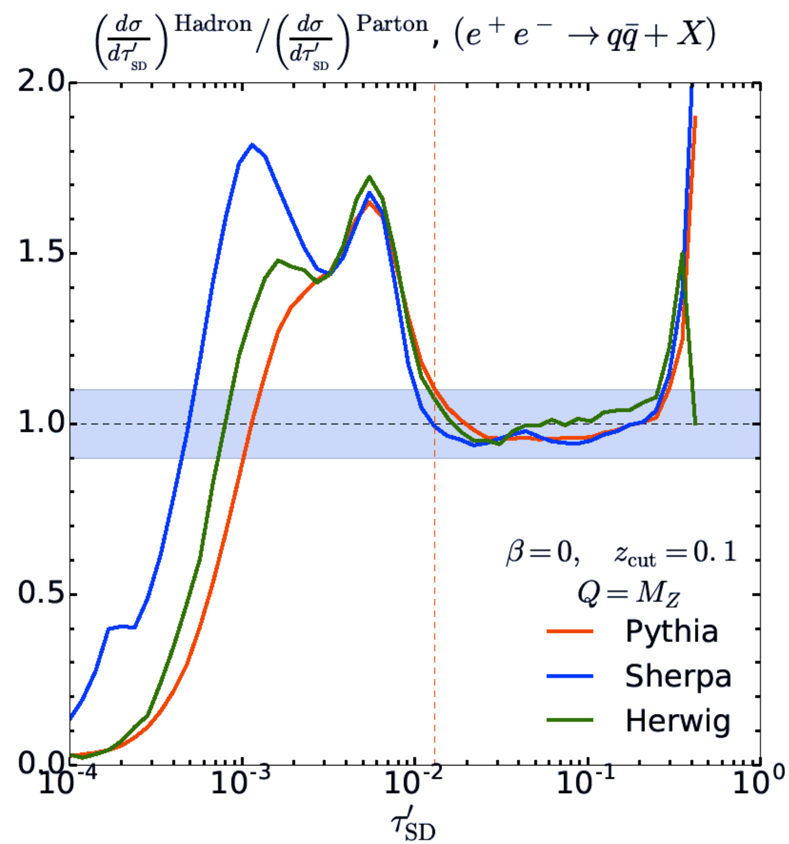


JB, Marzani, Theeuwes
Soft Drop Thrust (2018)

Note: $\tau = 1 - T$

Parton Shower

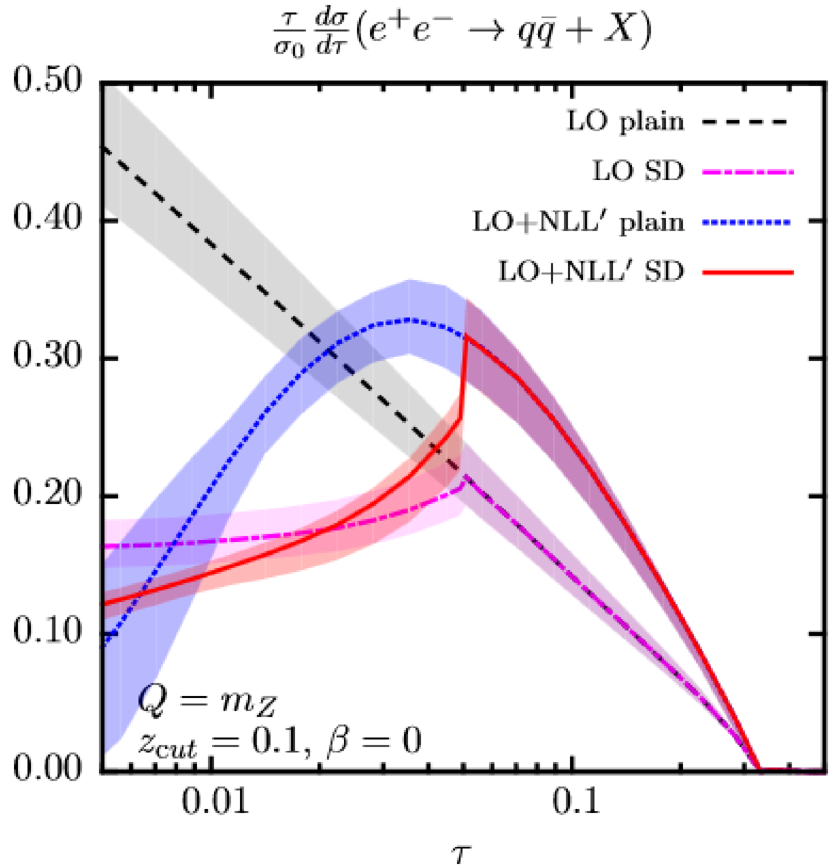




JB, Marzani, Theeuwes
Soft Drop Thrust (2018)

Note: $\tau = 1 - T$

Resummation+Matching



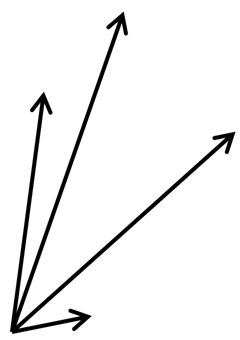
JB, Marzani, Theeuwes
Soft Drop Thrust (2018)

Note: $\tau = 1 - T$

Bottom-up soft drop

- $\frac{\min(E_1, E_2)}{E_1+E_2} > z_{\text{cut}}\left(1 - \cos(\theta_{12})\right)^{\beta/2}$ for e^+e^-
- $\frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} > z_{\text{cut}}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$ for pp

1) Find closest pair of particles with C/A
2) Check Soft drop criterion
3) If fail, drop softer and iterate
4) If pass, combine particles and iterate
5) End with one final jet

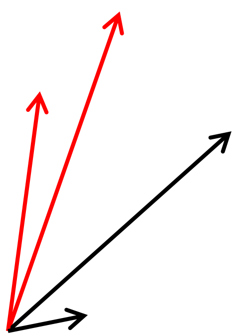


Dreyer, Necib, Soyez, Thaler: Recursive Soft Drop

Bottom-up soft drop

- $\frac{\min(E_1,E_2)}{E_1+E_2} > z_{\mathrm{cut}}\left(1-\cos(\theta_{12})\right)^{\beta/2}$ for e^+e^-
- $\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\mathrm{cut}}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$ for pp

1) Find closest pair of particles with C/A
2) Check Soft drop criterion
3) If fail, drop softer and iterate
4) If pass, combine particles and iterate
5) End with one final jet

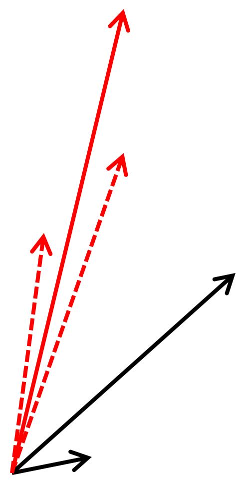


Dreyer, Necib, Soyez, Thaler: Recursive Soft Drop

Bottom-up soft drop

- $\frac{\min(E_1,E_2)}{E_1+E_2} > z_{\text{cut}}(1-\cos(\theta_{12}))^{\beta/2}$ for e^+e^-
- $\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\text{cut}}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$ for pp

1) Find closest pair of particles with C/A
2) Check Soft drop criterion
3) If fail, drop softer and iterate
4) If pass, combine particles and iterate
5) End with one final jet

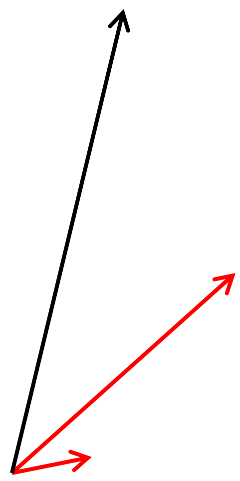


Dreyer, Necib, Soyez, Thaler: Recursive Soft Drop

Bottom-up soft drop

- $\frac{\min(E_1, E_2)}{E_1 + E_2} > z_{\text{cut}}\left(1 - \cos(\theta_{12})\right)^{\beta/2}$ for e^+e^-
- $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$ for pp

1) Find closest pair of particles with C/A
2) Check Soft drop criterion
3) If fail, drop softer and iterate
4) If pass, combine particles and iterate
5) End with one final jet

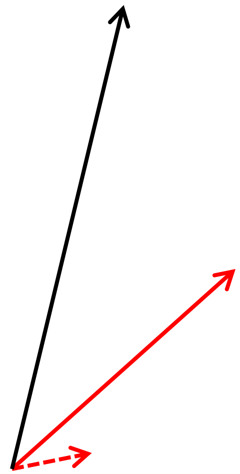


Dreyer, Necib, Soyez, Thaler: Recursive Soft Drop

Bottom-up soft drop

- $\frac{\min(E_1,E_2)}{E_1+E_2} > z_{\rm cut}\left(1-\cos(\theta_{12})\right)^{\beta/2}$ for e^+e^-
- $\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\rm cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$ for pp

1) Find closest pair of particles with C/A
2) Check Soft drop criterion
3) If fail, drop softer and iterate
4) If pass, combine particles and iterate
5) End with one final jet

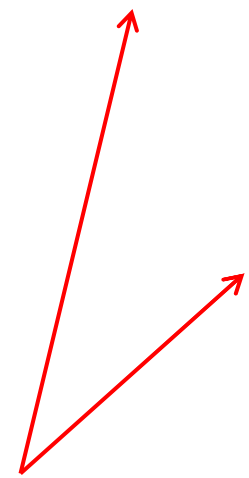


Dreyer, Necib, Soyez, Thaler: Recursive Soft Drop

Bottom-up soft drop

- $\frac{\min(E_1,E_2)}{E_1+E_2} > z_{\text{cut}}(1-\cos(\theta_{12}))^{\beta/2}$ for e^+e^-
- $\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\text{cut}}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$ for pp

1) Find closest pair of particles with C/A
2) Check Soft drop criterion
3) If fail, drop softer and iterate
4) If pass, combine particles and iterate
5) End with one final jet

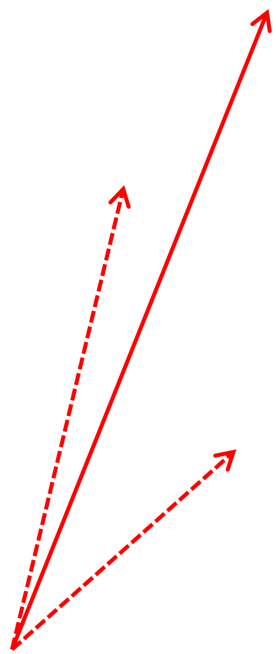


Dreyer, Necib, Soyez, Thaler: Recursive Soft Drop

Bottom-up soft drop

- $\frac{\min(E_1,E_2)}{E_1+E_2} > z_{\text{cut}}\left(1-\cos(\theta_{12})\right)^{\beta/2}$ for e^+e^-
- $\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\text{cut}}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$ for pp

1) Find closest pair of particles with C/A
2) Check Soft drop criterion
3) If fail, drop softer and iterate
4) If pass, combine particles and iterate
5) End with one final jet

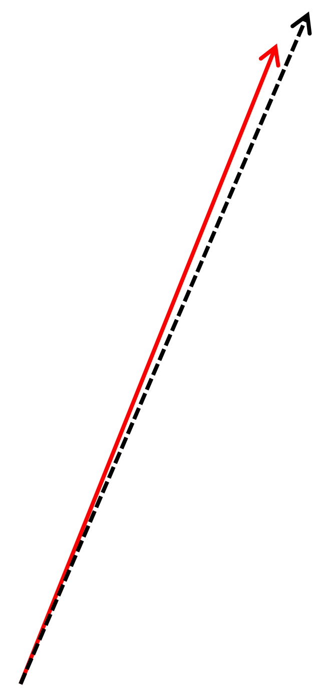


Dreyer, Necib, Soyez, Thaler: Recursive Soft Drop

Bottom-up soft drop

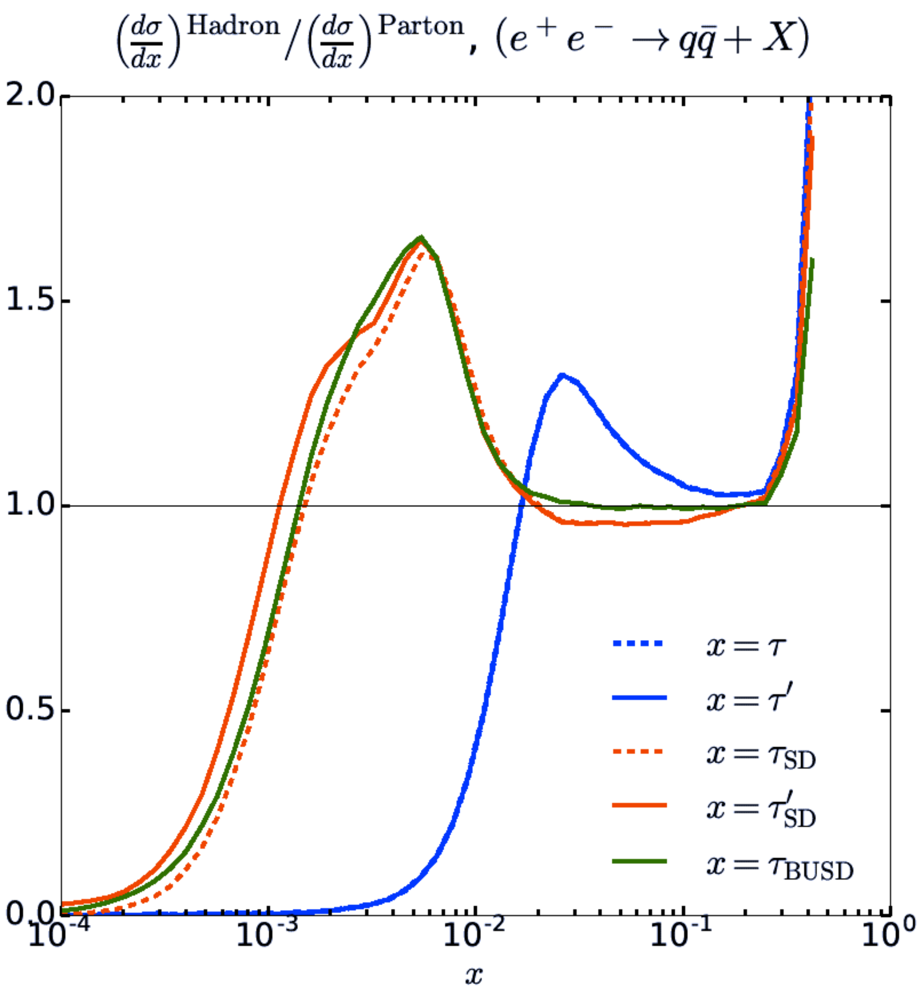
- $\frac{\min(E_1,E_2)}{E_1+E_2} > z_{\text{cut}}\left(1-\cos(\theta_{12})\right)^{\beta/2}$ for e^+e^-
- $\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\text{cut}}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$ for pp

1) Find closest pair of particles with C/A
2) Check Soft drop criterion
3) If fail, drop softer and iterate
4) If pass, combine particles and iterate
5) End with one final jet



Dreyer, Necib, Soyez, Thaler: Recursive Soft Drop

Bottom-up soft drop thrust



τ is naïve definition

τ' is new definition

New definition matches old in region of interest

Soft drop is more resilient against hadronization!
(Global BUSD even better)

$$T'_{\text{SD}} = \frac{\sum_{i \in \mathcal{H}^{\text{L}}_{\text{SD}}} |\vec{n}_L \cdot \vec{p}_i|}{\sum_{i \in \varepsilon_{SD}} |\vec{p}_i|} + \frac{\sum_{i \in \mathcal{H}^{\text{R}}_{\text{SD}}} |\vec{n}_R \cdot \vec{p}_i|}{\sum_{i \in \varepsilon_{SD}} |\vec{p}_i|}$$

Other event shapes

Thrust

- $\tau = \min\limits_{\vec{n}} \left(1 - \frac{\sum_{i \in \varepsilon} |\vec{n} \cdot \vec{p}_i|}{\sum_{i \in \varepsilon} |\vec{p}_i|}\right)$

Other event shapes

Thrust, Jet broadening

- $\tau = \min_{\vec{n}} \left(1 - \frac{\sum_{i\in\varepsilon} |\vec{n}\cdot\vec{p}_i|}{\sum_{i\in\varepsilon}|\vec{p}_i|} \right)$
- $B = B_L + B_R = \frac{1}{2}\frac{\sum_{i\in\mathcal{H}L} |\vec{n}\times\vec{p}_i|}{\sum_{i\in\varepsilon}|\vec{p}_i|} + \frac{1}{2}\frac{\sum_{i\in\mathcal{H}R} |\vec{n}\times\vec{p}_i|}{\sum_{i\in\varepsilon}|\vec{p}_i|}$

Other event shapes

Thrust, Jet broadening, C-parameter

- $\tau = \min_{\vec{n}} \left(1 - \frac{\sum_{i \in \varepsilon} |\vec{n} \cdot \vec{p}_i|}{\sum_{i \in \varepsilon} |\vec{p}_i|} \right)$

- $B = B_L + B_R = \frac{1}{2} \frac{\sum_{i \in \mathcal{H}L} |\vec{n} \times \vec{p}_i|}{\sum_{i \in \varepsilon} |\vec{p}_i|} + \frac{1}{2} \frac{\sum_{i \in \mathcal{H}R} |\vec{n} \times \vec{p}_i|}{\sum_{i \in \varepsilon} |\vec{p}_i|}$

- $C = 3 \frac{\sum_{i \leq j \in \varepsilon} |\vec{p}_i| |\vec{p}_j| \sin^2 \theta_{ij}}{\left(\sum_{i \in \varepsilon} |\vec{p}_i| \right)^2}$

Other event shapes

Thrust, Jet broadening, C-parameter, and heavy hemisphere jet mass

- $\tau = \min_{\vec{n}} \left(1 - \frac{\sum_{i \in \varepsilon} |\vec{n} \cdot \vec{p}_i|}{\sum_{i \in \varepsilon} |\vec{p}_i|} \right)$
- $B = B_L + B_R = \frac{1}{2} \frac{\sum_{i \in \mathcal{H}L} |\vec{n} \times \vec{p}_i|}{\sum_{i \in \varepsilon} |\vec{p}_i|} + \frac{1}{2} \frac{\sum_{i \in \mathcal{H}R} |\vec{n} \times \vec{p}_i|}{\sum_{i \in \varepsilon} |\vec{p}_i|}$
- $C = 3 \frac{\sum_{i \leq j \in \varepsilon} |\vec{p}_i| |\vec{p}_j| \sin^2 \theta_{ij}}{\left(\sum_{i \in \varepsilon} |\vec{p}_i| \right)^2}$
- $\rho = \max(\rho_L, \rho_R)\,; \quad \rho_i = \frac{m_i^2}{E_i^2}$

Local vs Global BUSD

- Local BUSD clusters a single *jet* into one C/A tree
- Global BUSD clusters the entire *event* into one C/A tree

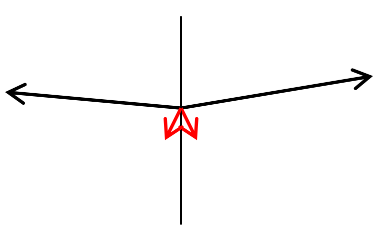
Local vs Global BUSD

- Local BUSD clusters a single *jet* into one C/A tree
- Global BUSD clusters the entire *event* into one C/A tree
- Split event shapes into two hemispheres
  -Apply BUSD to each hemisphere independently (Local BUSD)
- Or: apply BUSD to entire event (Global BUSD)

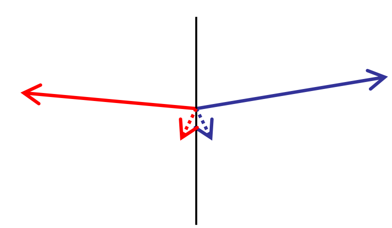
Local vs Global BUSD

- Local BUSD clusters a single *jet* into one C/A tree
- Global BUSD clusters the entire *event* into one C/A tree
- Split event shapes into two hemispheres
  -Apply BUSD to each hemisphere independently (Local BUSD)
- Or: apply BUSD to entire event (Global BUSD)
- Local BUSD slightly more aggressive (at Fixed order)

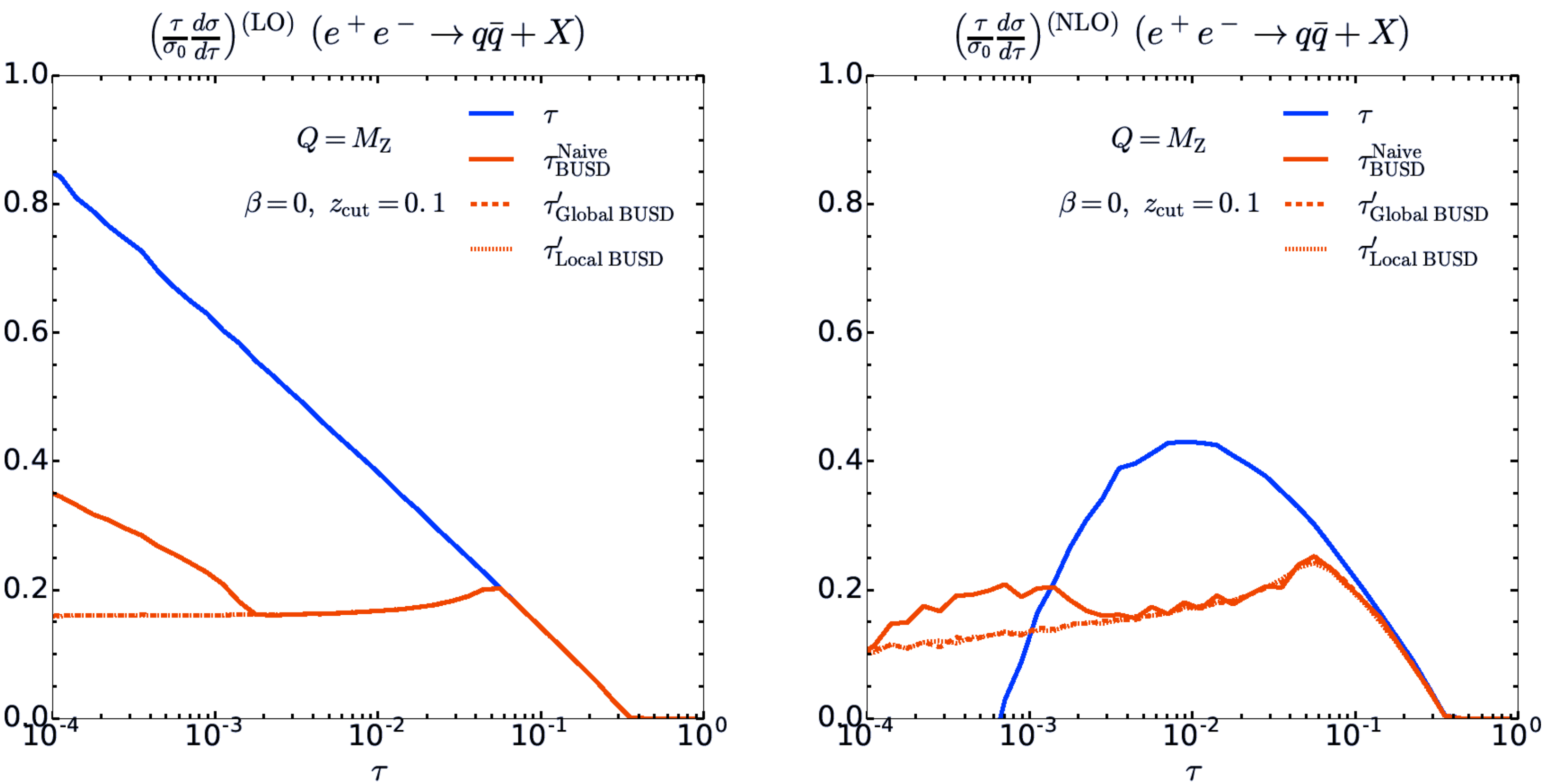
Global:



Local:

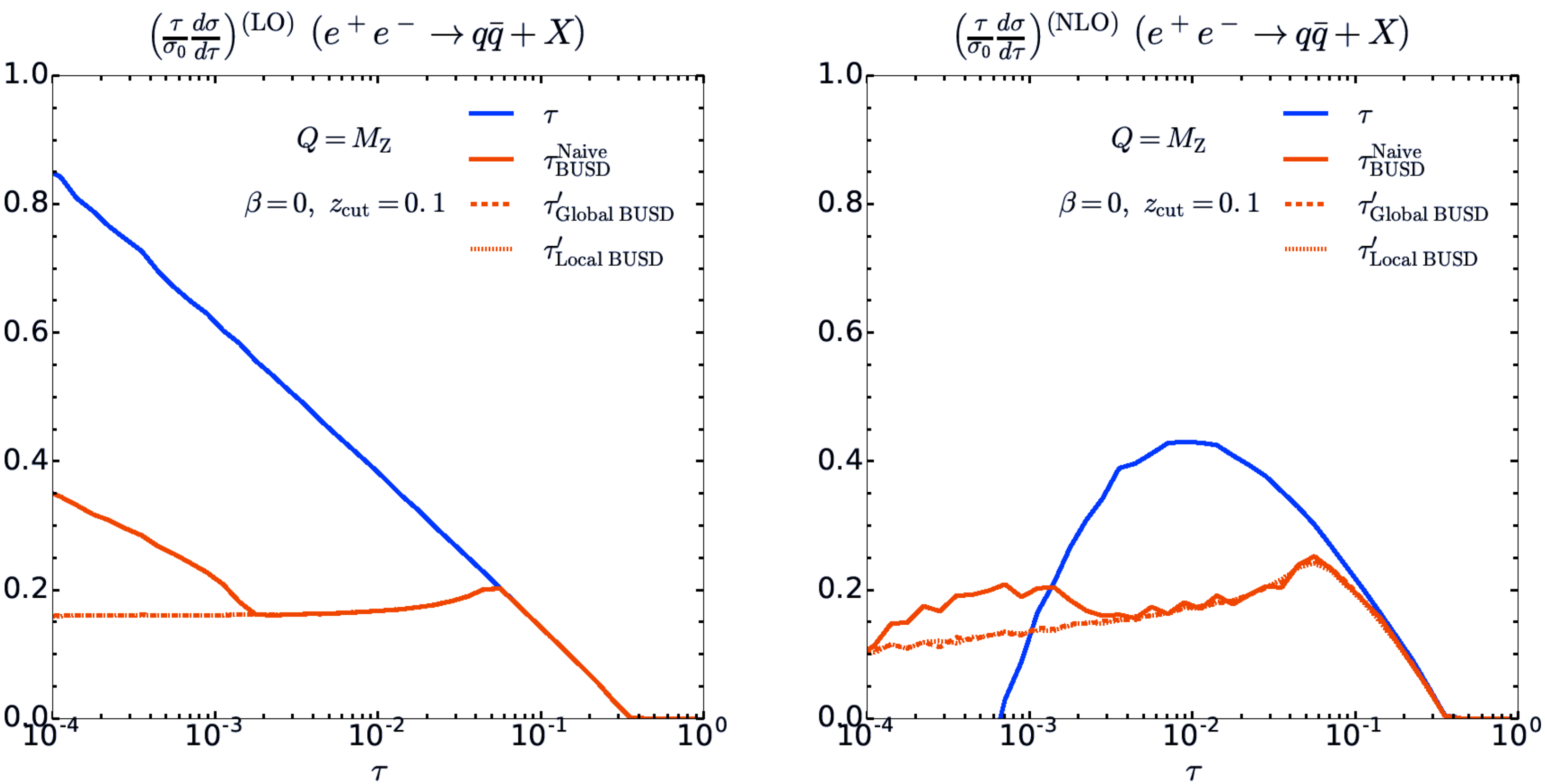


EVENT2



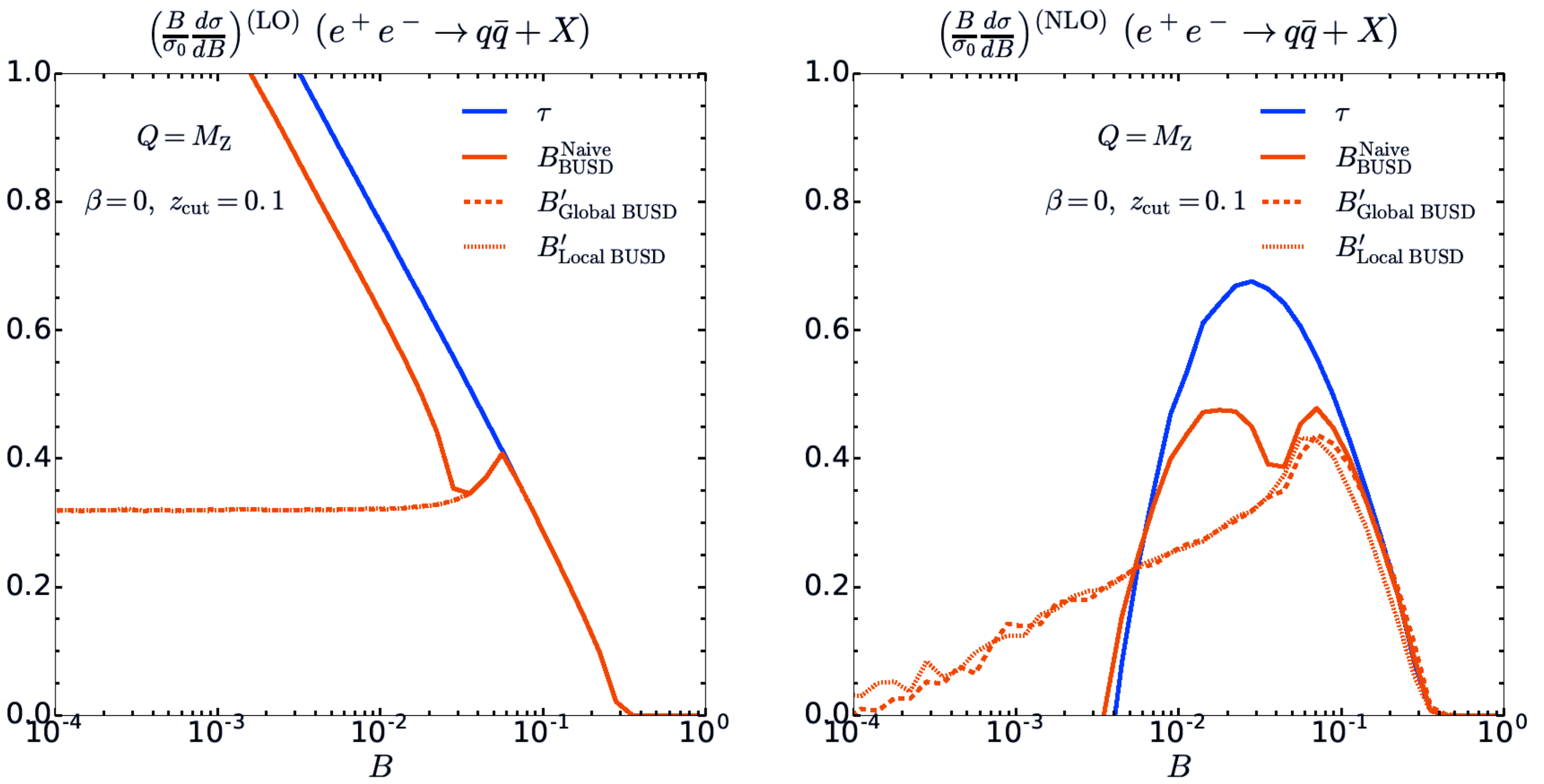
NB: Naïve BUSD is Global BUSD on old definition

EVENT2



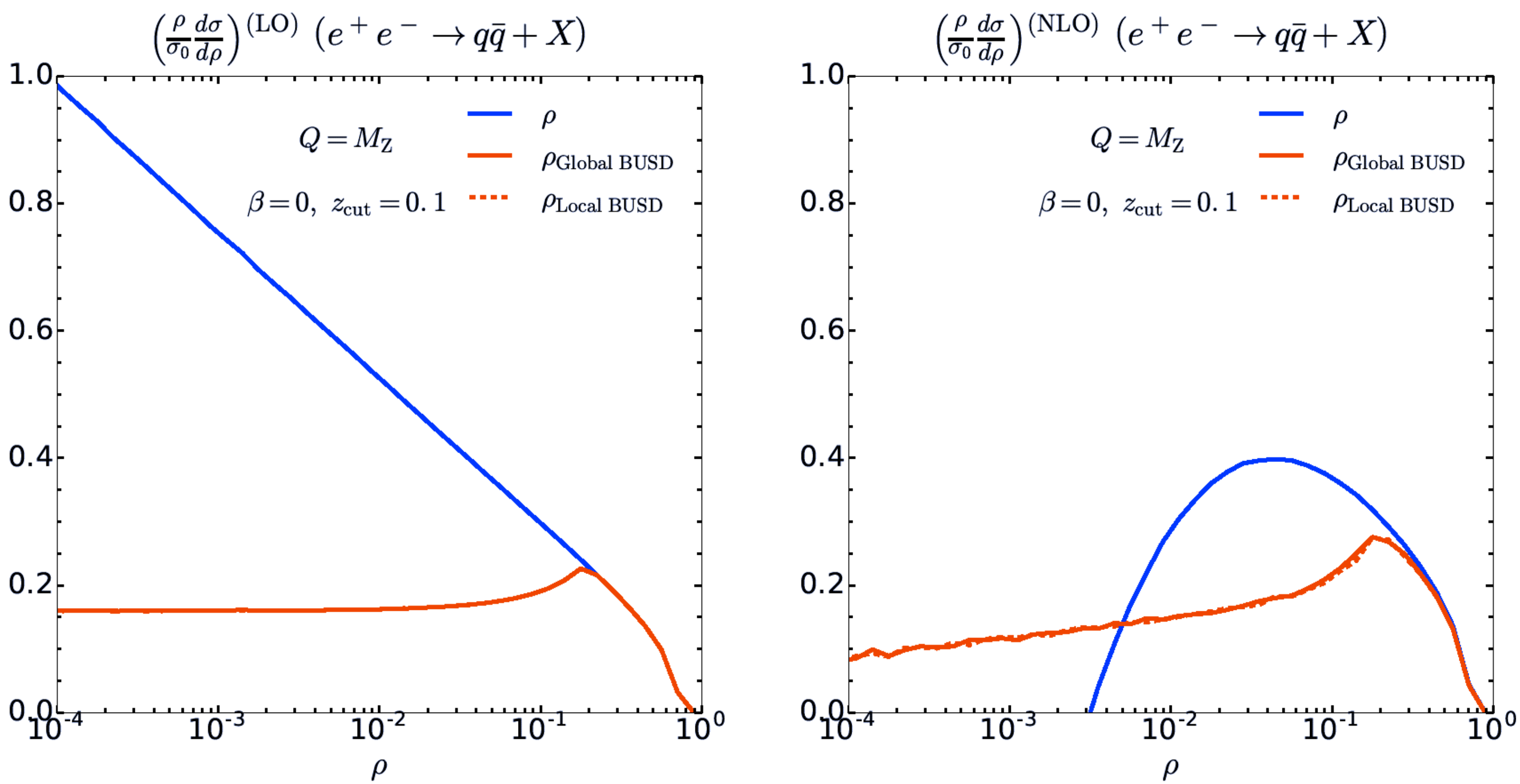
- Single log expectance broken with BUSD
- Same fix as regular SD
- Local & Global BUSD perform very similarly!

EVENT2



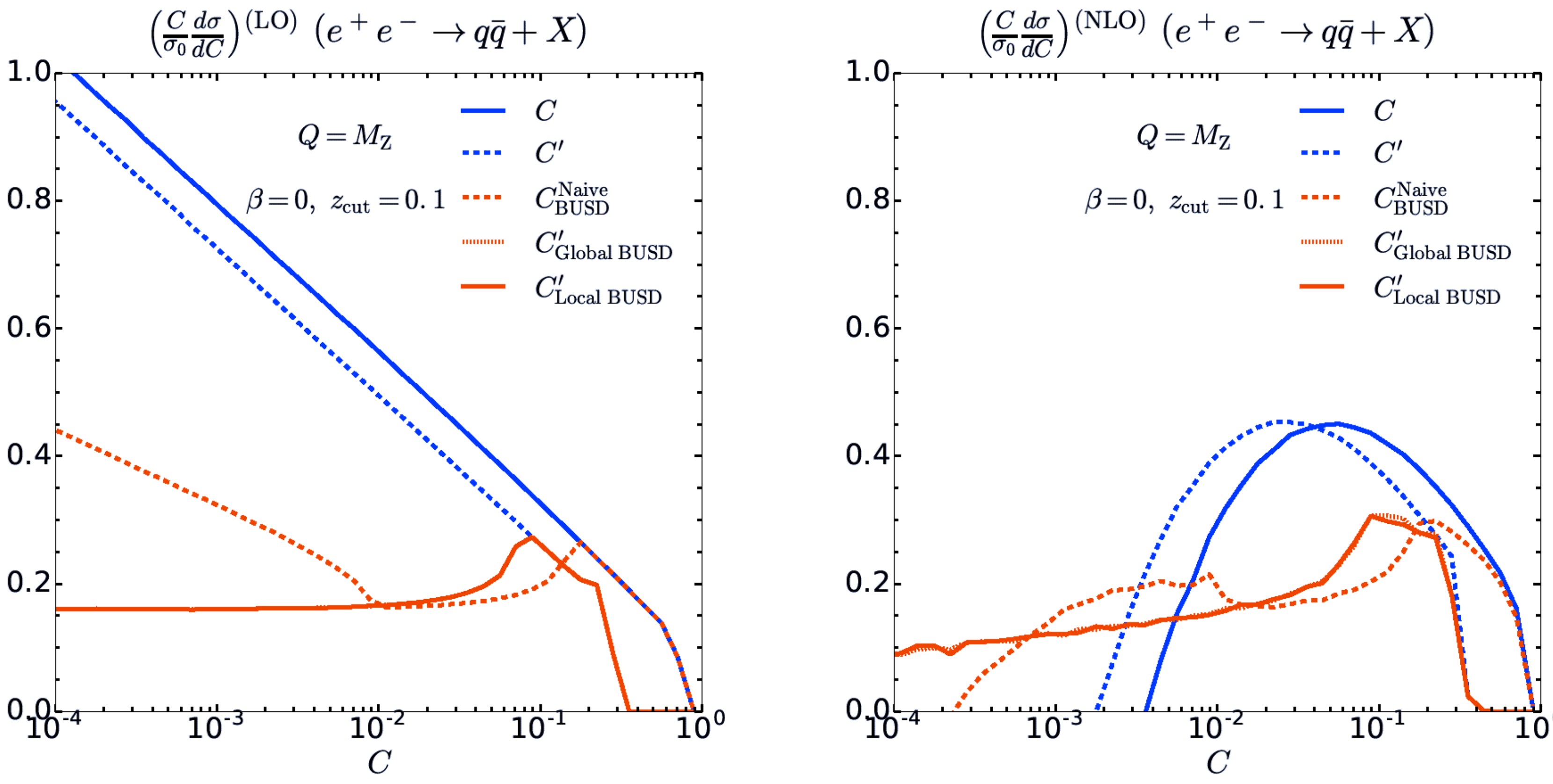
- Single log expectance also broken with broadening
- Same fix as thrust
- Difference b/w Global & Local BUSD more pronounced

EVENT2



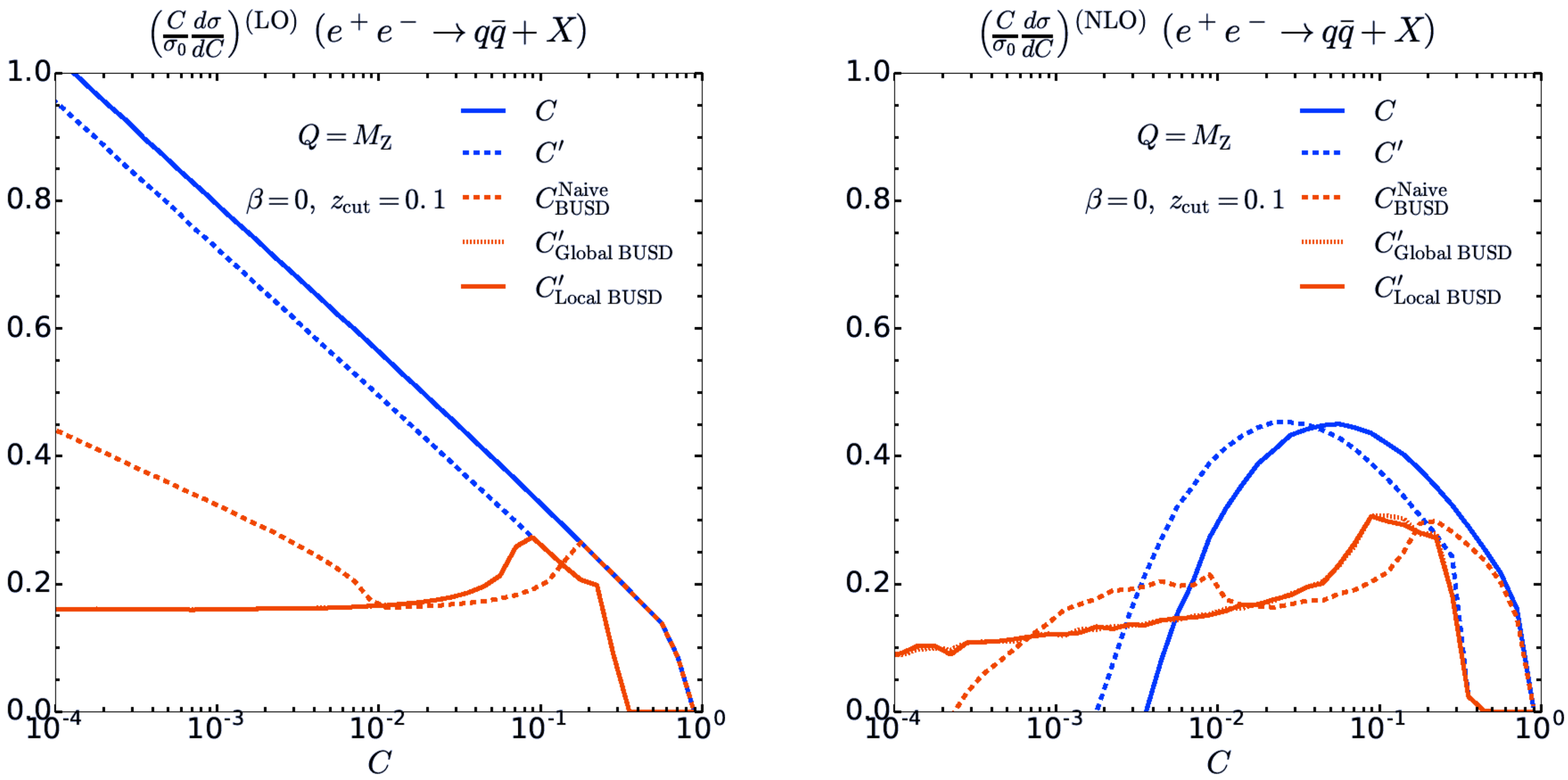
Single log expectance holds!

EVENT2



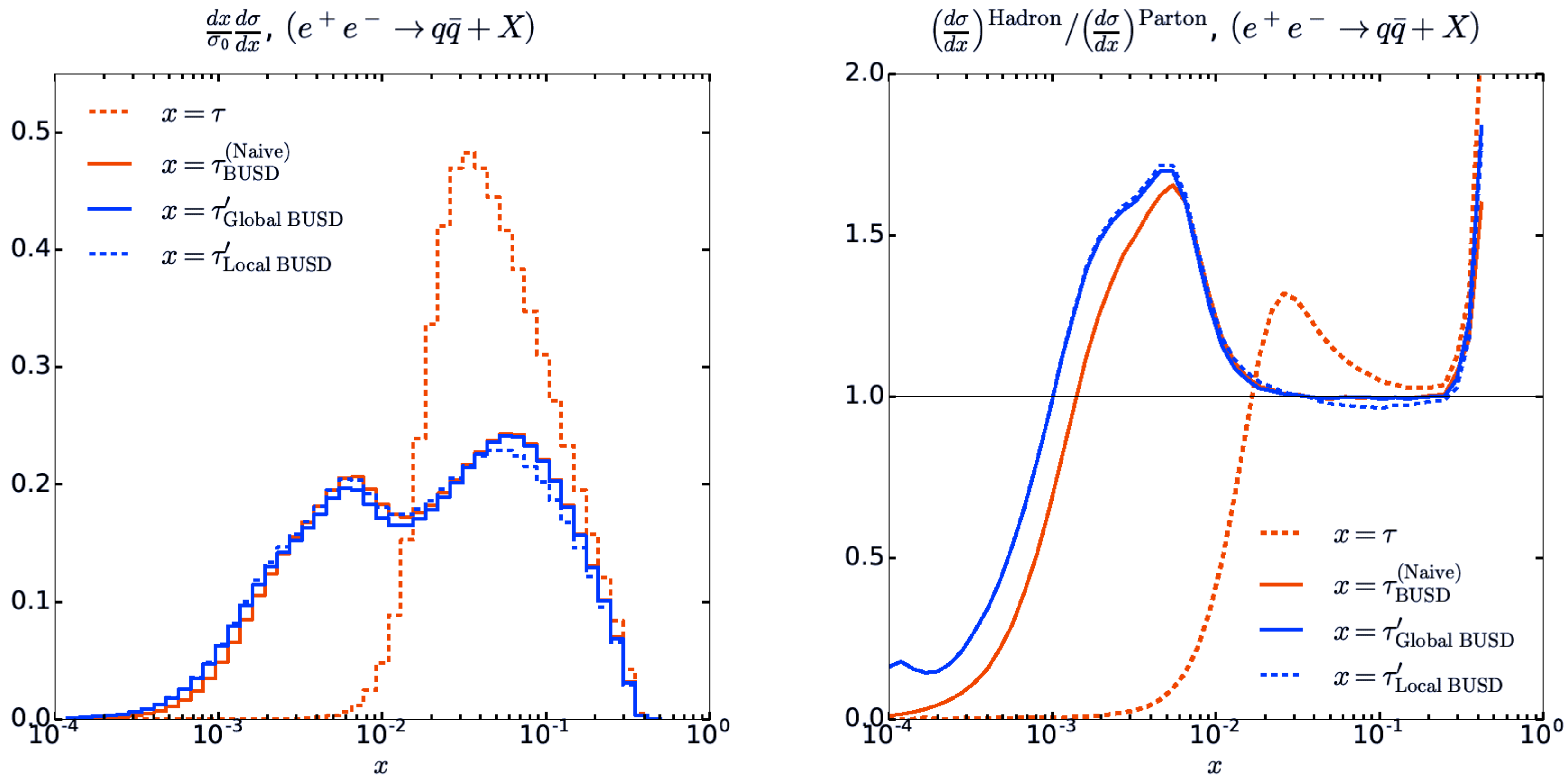
$$C' = 3\,\frac{\sum_{i\le j\in\mathcal{H}_{BUSD}^{L}} |\vec{p}_i||\vec{p}_j|\sin^2\theta_{ij}}{\left(\sum_{i\in\varepsilon_{BUSD}}|\vec{p}_i|\right)^2} + 3\,\frac{\sum_{i\le j\in\mathcal{H}_{BUSD}^{R}} |\vec{p}_i||\vec{p}_j|\sin^2\theta_{ij}}{\left(\sum_{i\in\varepsilon_{BUSD}}|\vec{p}_i|\right)^2}$$

EVENT2



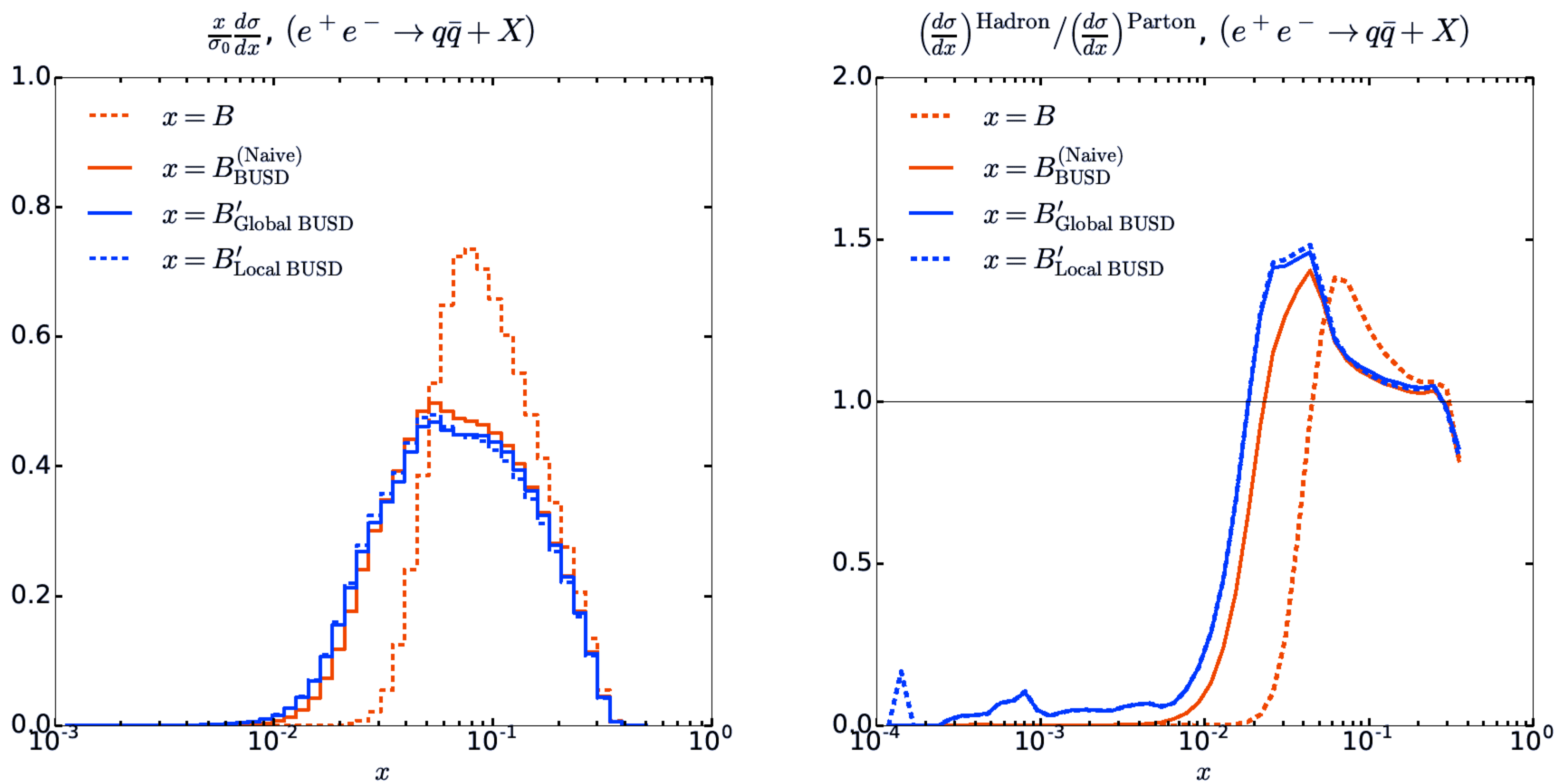
- Single log expectance broken with regular C
- Single log expectance holds with C'!
- … but comes at price of extra kink in ungroomed C' ☹

Pythia



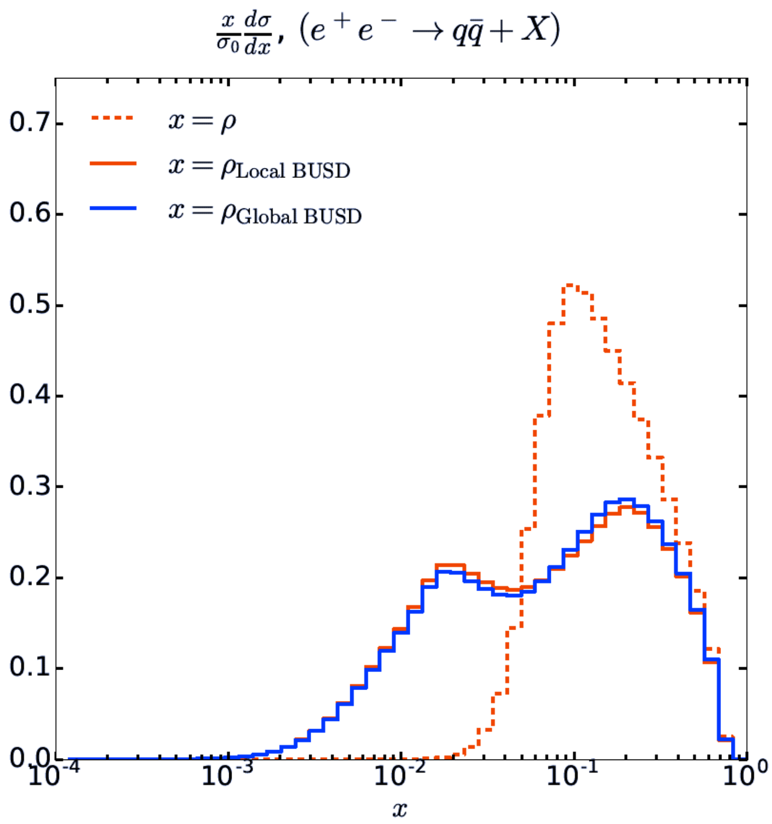
Global BUSD performs better than Local BUSD

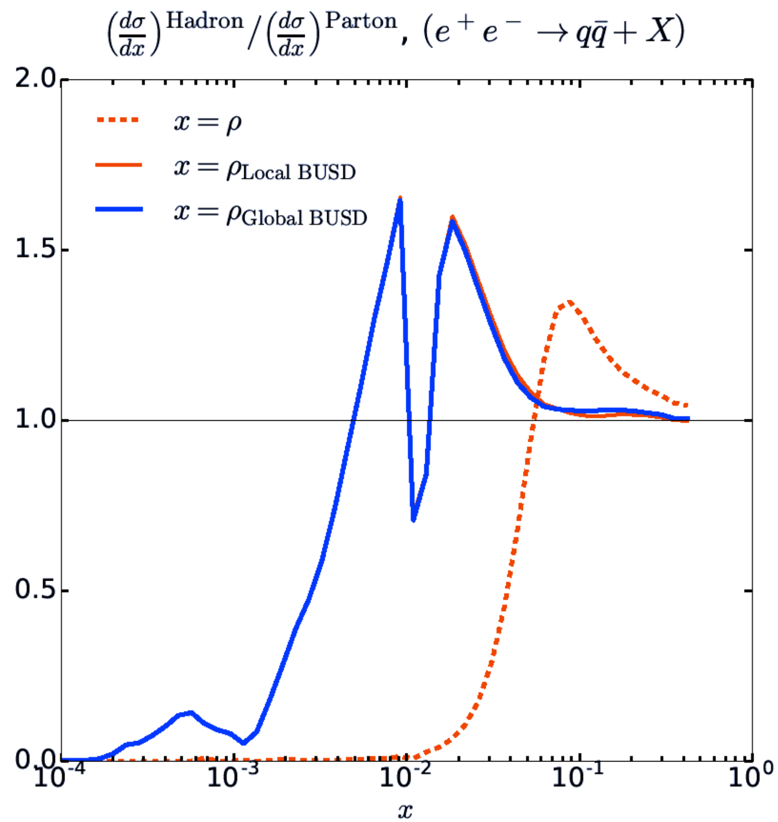
Pythia



- BUSD gives modest improvement
- Broadening in general not good with soft drop?

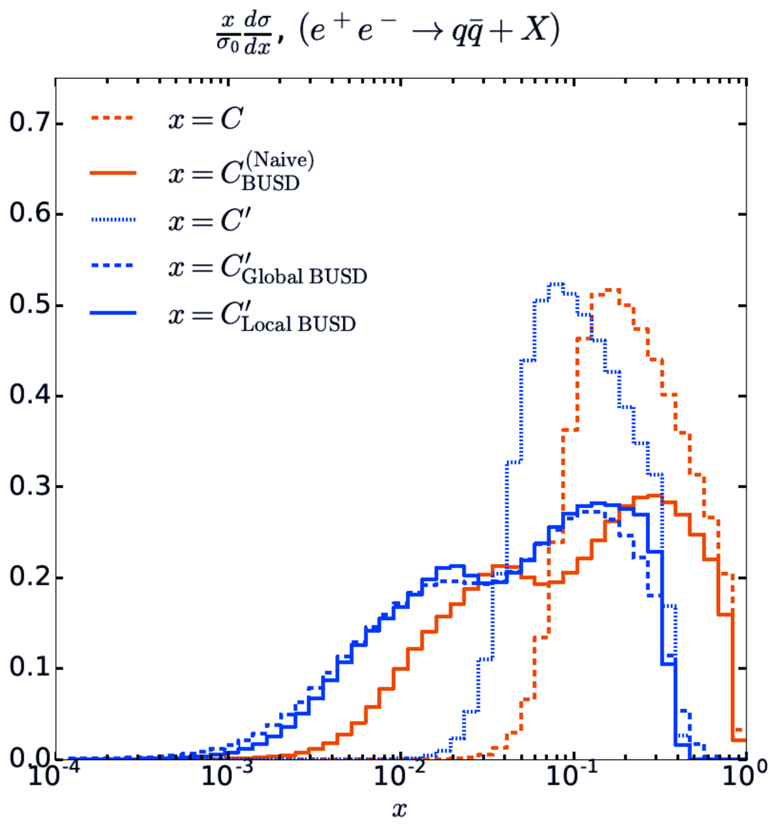
Pythia

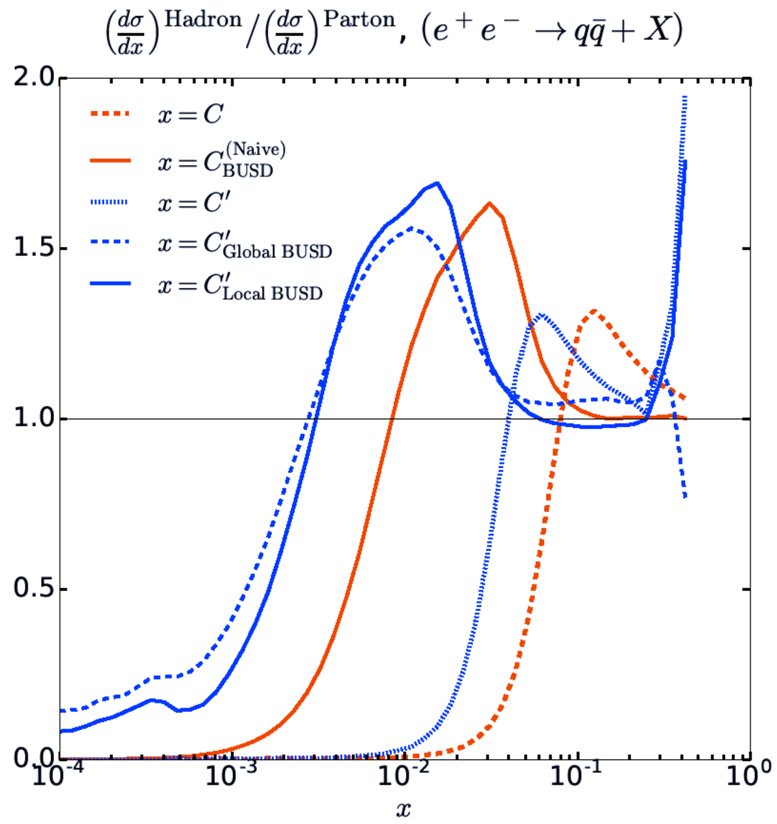




Local BUSD better than Global BUSD

Pythia





- C with naïve BUSD is best
- Local BUSD preferred for C’

Conclusions

- Need a way to groom general event shapes
  - BUSD is a natural choice
  - Option to apply globally or locally
  - But which event shapes are best to use?

Conclusions

- Need a way to groom general event shapes
  - BUSD is a natural choice
  - Option to apply globally or locally
  - But which event shapes are best to use?

- Outlook:
  - Analytic understanding of F.O. needed (in the works)
  - More event shapes? (D-param, E-param, etc.)
  - Resummation? (CAESAR, ARES)

Conclusions

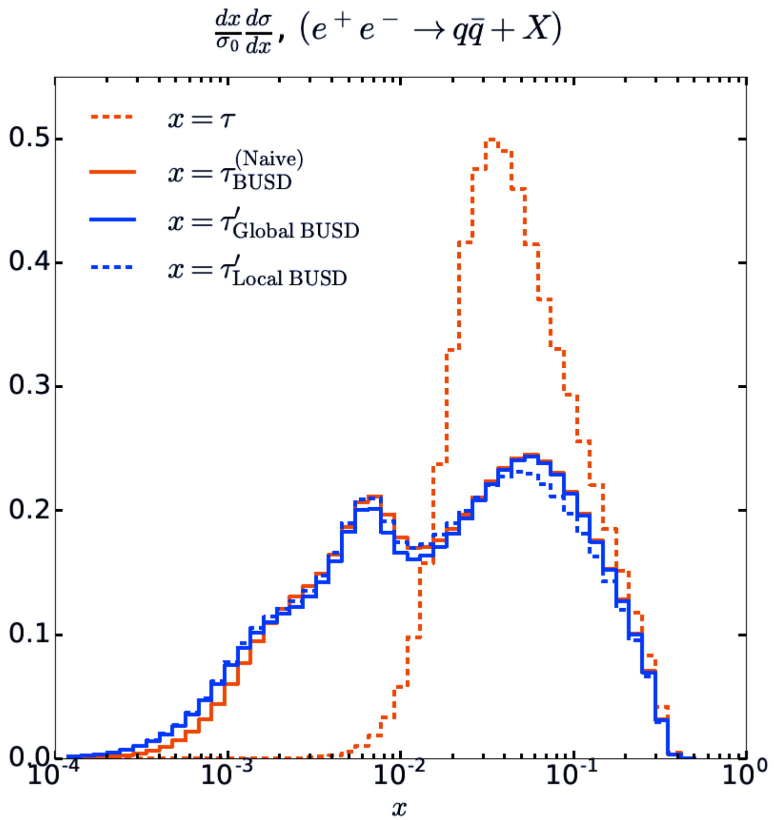
- Need a way to groom general event shapes
  - BUSD is a natural choice
  - Option to apply globally or locally
  - But which event shapes are best to use?

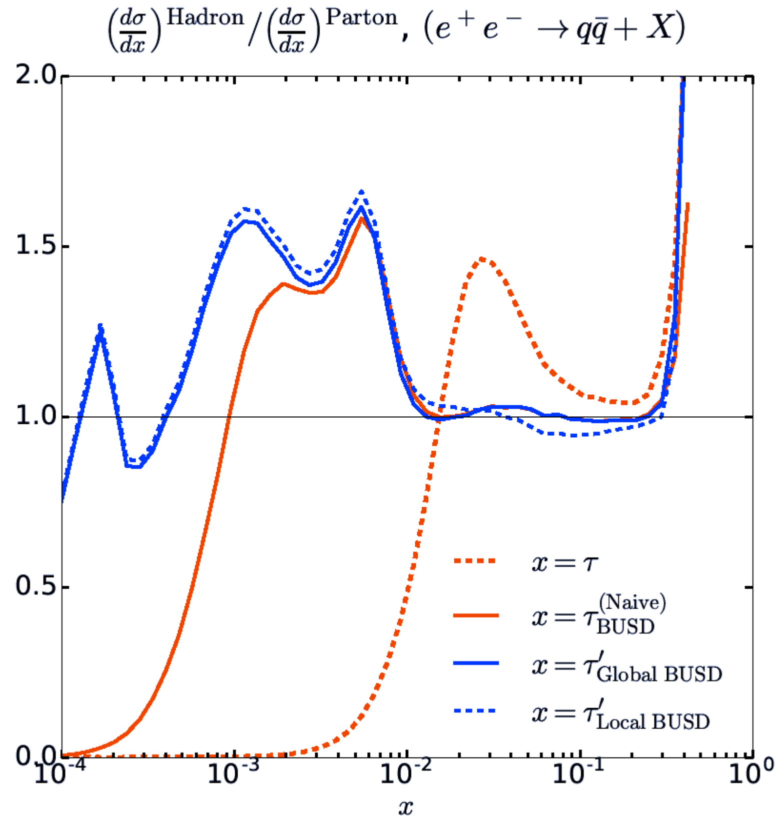
- Outlook:
  - Analytic understanding of F.O. needed (in the works)
  - More event shapes? (D-param, E-param, etc.)
  - Resummation? (CAESAR, ARES)

Thank you for your attention!!

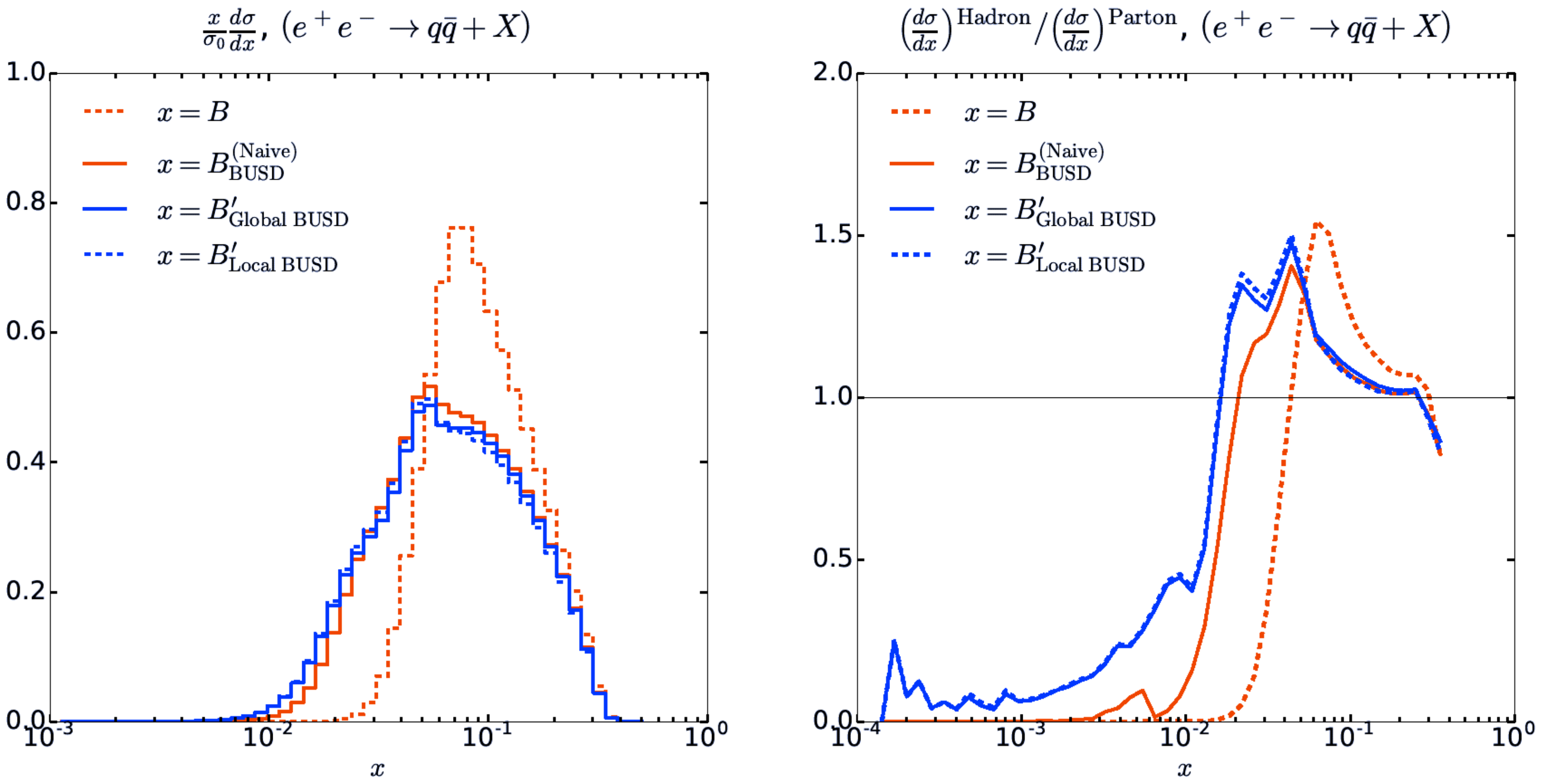
Backup Slides

Sherpa plots

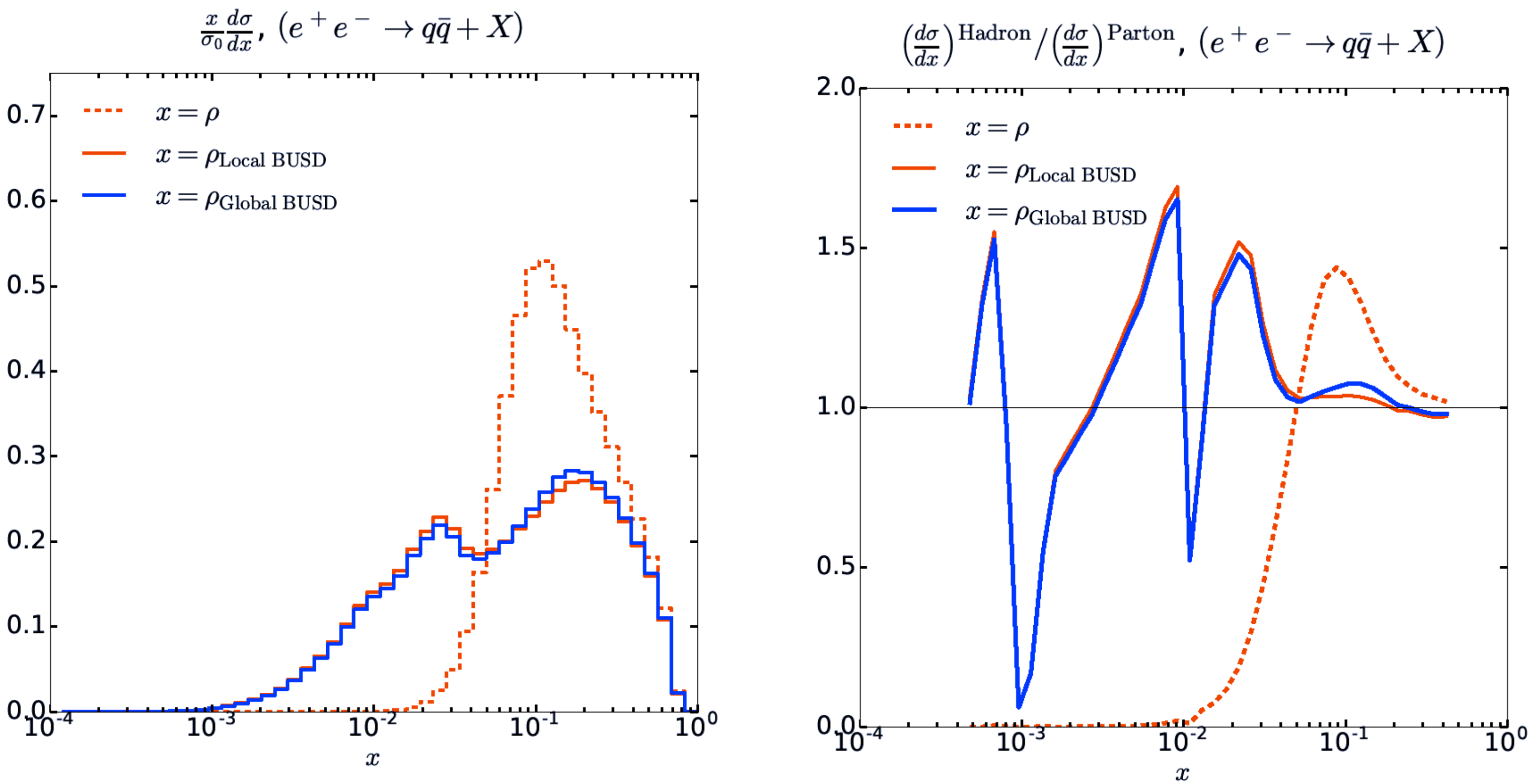




Sherpa plots



Sherpa plots



Sherpa plots