Multiple Interactions in Sherpa
MC Results vs. Data

Stefan Höche
Dresden University of Technology

- MI Model review
- CKKW review
- Combining MIs and the CKKW Merging
- Preliminary Results
- Outlook

MI Model review

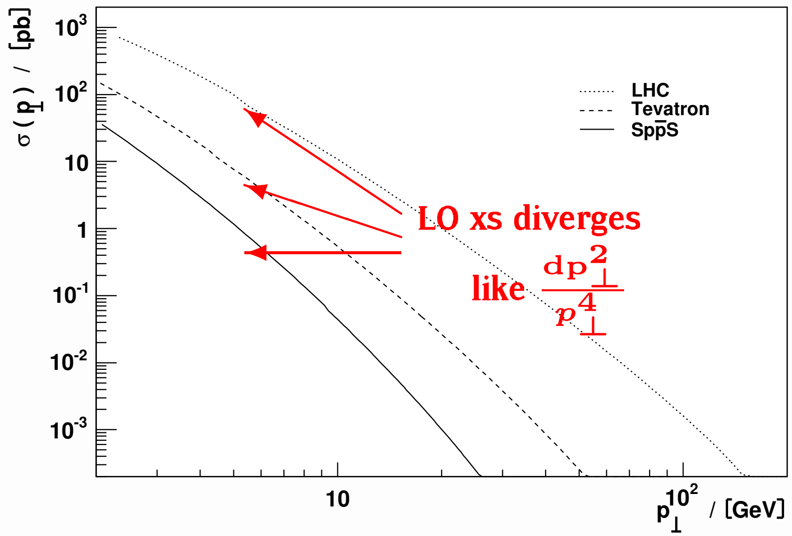
Multiple Interaction (MI) treatment in Sherpa ⟷ formalism by T. Sjöstrand[1]

[1] Phys. Rev. D36 (1987)

MI Model review

Multiple Interaction (MI) treatment in Sherpa ⟷ formalism by T. Sjöstrand[1]

Recall :
- Perturbative differential cross section $\sigma_{\mathbf{hard}}(p_\perp)$ divergent for $p_\perp \rightarrow 0$



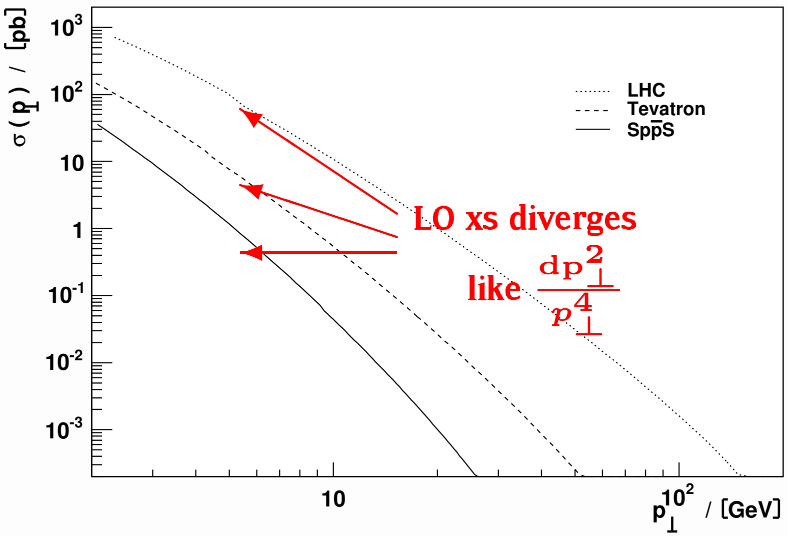
[1] Phys. Rev. D36 (1987)

MI Model review

Multiple Interaction (MI) treatment in Sherpa ⟷ formalism by T. Sjöstrand[1]

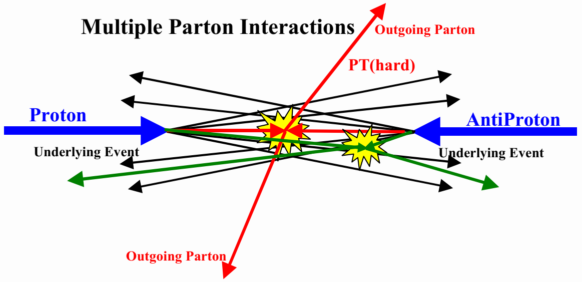
Recall [1]:

- Perturbative differential cross section $\sigma_{\rm hard}(p_\perp)$ divergent for $p_\perp \to 0$



- Assume multiple scatterings

$$< N_{\rm hard} > = \frac{\sigma_{\rm hard}}{\sigma_{\rm ND}}$$



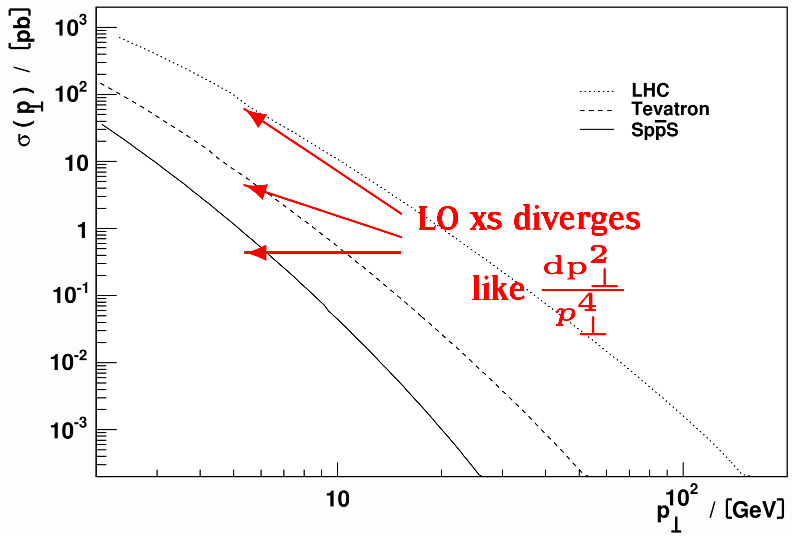
[1] Phys. Rev. D36 (1987)

MI Model review

Multiple Interaction (MI) treatment in Sherpa ⟷ formalism by T. Sjöstrand[1]

Recall [1]:

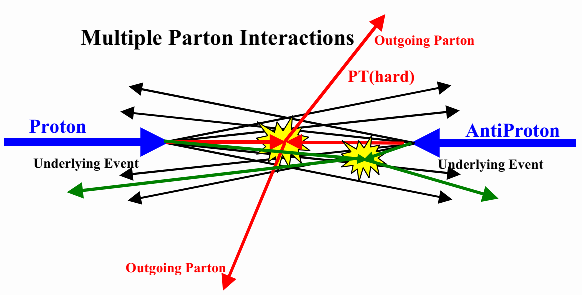
- Perturbative differential cross section $\sigma_{\mathrm{hard}}(p_\perp)$ divergent for $p_\perp \to 0$



- Assume multiple scatterings

$$< N_{\mathrm{hard}} > = \frac{\sigma_{\mathrm{hard}}}{\sigma_{\mathrm{ND}}}$$

Monte Carlo method: ➡ Distribute hard scatterings according to probability



$$p(p_\perp) = \frac{1}{\sigma_{\mathrm{ND}}} \frac{d\sigma_{\mathrm{hard}}(p_\perp)}{dp_\perp}$$

[1] Phys. Rev. D36 (1987)

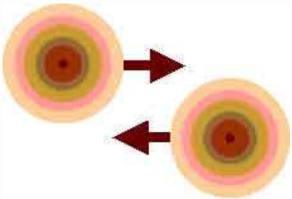
MI Model review

Recall :
- Hadrons are extended objects in position space

MI Model review

Recall :

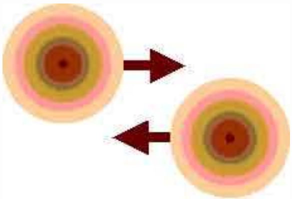
- Hadrons are extended objects in position space
  → must account for possible peripheral collisions



MI Model review

Recall [1]:

- Hadrons are extended objects in position space
  → must account for possible peripheral collisions



- Calculate impact parameter dependent time-integrated matter overlap

$$\tilde{O}(b) = \int \mathrm{d}^3x \, \mathrm{d}t \, \rho_1(x - \tfrac{1}{2}b, y, z - \tfrac{1}{2}t) \, \rho_2(x + \tfrac{1}{2}b, y, z + \tfrac{1}{2}t)$$

Assume linear relationship between $\tilde{O}(b)$ and the mean interaction number $< \tilde{n}(b) >$

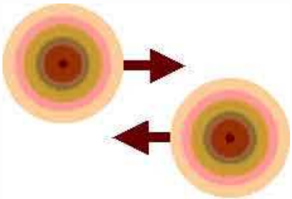
$$< \tilde{n}(b) > = k\tilde{O}(b)$$

[1] Phys. Rev. D36 (1987)

MI Model review

Recall [1]:

- Hadrons are extended objects in position space
  → must account for possible peripheral collisions



- Calculate impact parameter dependent time-integrated matter overlap

$$\tilde{O}(b) = \int \mathrm{d}^3x \, \mathrm{d}t \, \rho_1(x - \tfrac{1}{2}b, y, z - \tfrac{1}{2}t) \, \rho_2(x + \tfrac{1}{2}b, y, z + \tfrac{1}{2}t)$$

Assume linear relationship between $\tilde{O}(b)$ and the mean interaction number $< \tilde{n}(b) >$

$$< \tilde{n}(b) > = k\tilde{O}(b)$$

→ Distribute hard scatterings according to

$$p(p_\perp, b) = f_c f(b) \frac{1}{\sigma_{\mathrm{ND}}} \frac{d\sigma_{\mathrm{hard}}(p_\perp)}{dp_\perp}$$

[1] Phys. Rev. D36 (1987)

CKKW review

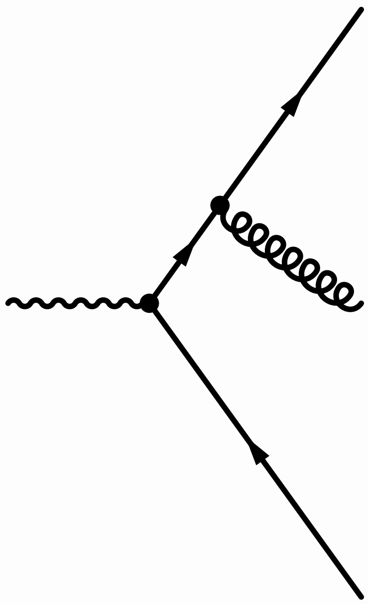
CKKW → General approach to combine multijet Matrix Elements (ME) and Parton Showers, implemented in Sherpa[1]

[1] hep-ph/0503281, hep-ph/0311263

CKKW review

CKKW → General approach to combine multijet Matrix Elements (ME) and Parton Showers, implemented in Sherpa[1]

Example: $e^+e^- \longrightarrow hadrons$



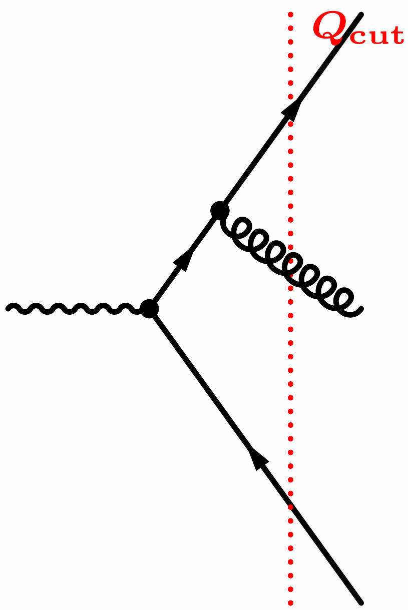
[1] hep-ph/0503281, hep-ph/0311263

CKKW review

CKKW → General approach to combine multijet Matrix Elements (ME) and Parton Showers, implemented in Sherpa[1]

Example: $e^+e^- \rightarrow hadrons$

- Define phase space cut $Q_{\rm cut}$



Q ⟷ Durham jet measure ($Q_{ij}^2 = 2\min\{E_i^2, E_j^2\}\,(1-\cos\theta_{ij})$)
(for $hh \rightarrow X$: $Q_{ij}^2 = 2\min\{p_{\perp,i}^2, p_{\perp,j}^2\}\,(\cosh(\eta_i-\eta_j)-\cos\phi_{ij})$)

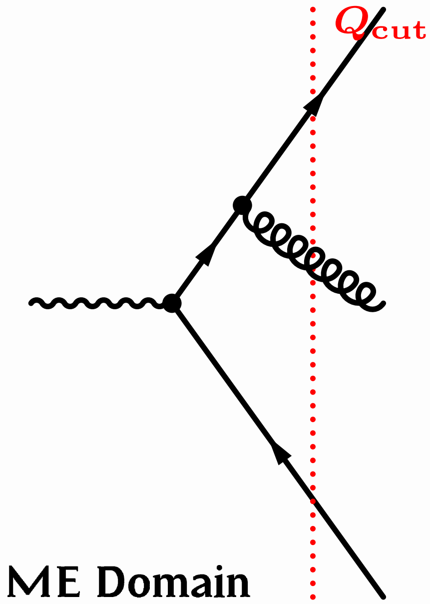
[1] hep-ph/0503281, hep-ph/0311263

CKKW review

CKKW ➡ General approach to combine multijet Matrix Elements (ME) and Parton Showers, implemented in Sherpa[1]

Example: $e^+e^- \rightarrow hadrons$

- Define phase space cut $Q_{\rm cut}$
- Evaluate ME at scale $Q_{\rm cut}$



$Q \longleftrightarrow$ Durham jet measure ($Q_{ij}^2 = 2\min\{E_i^2, E_j^2\}\,(1-\cos\theta_{ij})$)

(for $hh \longrightarrow X$: $Q_{ij}^2 = 2\min\{p_{\perp,i}^2, p_{\perp,j}^2\}\,(\cosh(\eta_i-\eta_j)-\cos\phi_{ij})$)

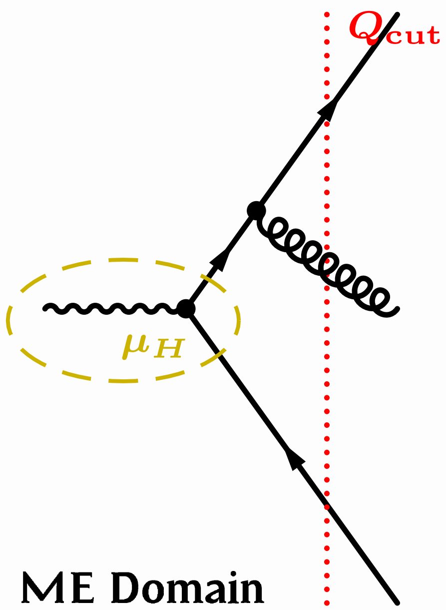
[1] hep-ph/0503281, hep-ph/0311263

CKKW review

CKKW → General approach to combine multijet Matrix Elements (ME) and Parton Showers, implemented in Sherpa[1]

Example: $e^+e^- \longrightarrow hadrons$

- Define phase space cut $Q_{\rm cut}$
- Evaluate ME at scale $Q_{\rm cut}$
- Define $2{\rightarrow}2$ core process



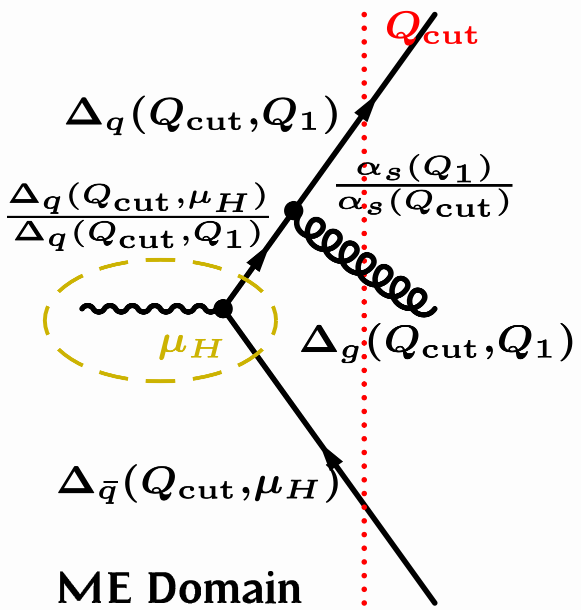
$Q \longleftrightarrow$ Durham jet measure ($Q_{ij}^2 = 2\min\{E_i^2, E_j^2\}\,(1 - \cos\theta_{ij})$)
(for $hh \longrightarrow X$: $Q_{ij}^2 = 2\min\{p_{\perp,i}^2, p_{\perp,j}^2\}\,(\cosh(\eta_i - \eta_j) - \cos\phi_{ij})$)

[1] hep-ph/0503281, hep-ph/0311263

CKKW review

CKKW → General approach to combine multijet Matrix Elements (ME) and Parton Showers, implemented in Sherpa[1]

Example: $e^+e^- \rightarrow hadrons$



- Define phase space cut $Q_{\rm cut}$
- Evaluate ME at scale $Q_{\rm cut}$
- Define $2\rightarrow 2$ core process
- Reject ME according to Sudakov × coupling weight

$$W=\Delta_{\bar q}(\mu_H)\Delta_q(Q_1)\frac{\Delta_q(\mu_H)}{\Delta_q(Q_1)}\Delta_g(Q_1)\frac{\alpha_s(Q_1)}{\alpha_s(Q_{\rm cut})}$$

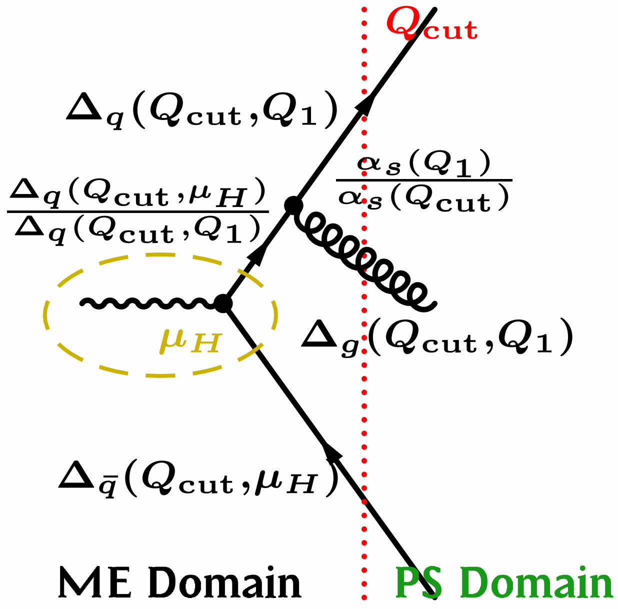
Q ↔ Durham jet measure ($Q_{ij}^2 = 2\min\{E_i^2,E_j^2\}\,(1-\cos\theta_{ij})$)
(for $hh \rightarrow X$: $Q_{ij}^2 = 2\min\{p_{\perp,i}^2,p_{\perp,j}^2\}\,(\cosh(\eta_i-\eta_j)-\cos\phi_{ij})$)

[1] hep-ph/0503281, hep-ph/0311263

CKKW review

CKKW ➔ General approach to combine multijet Matrix Elements (ME) and Parton Showers, implemented in Sherpa[1]

Example: $e^+e^- \rightarrow hadrons$



- Define phase space cut $Q_{\rm cut}$
- Evaluate ME at scale $Q_{\rm cut}$
- Define $2\rightarrow 2$ core process
- Reject ME according to Sudakov × coupling weight

$$W=\Delta_{\bar q}(\mu_H)\Delta_q(Q_1)\frac{\Delta_q(\mu_H)}{\Delta_q(Q_1)}\Delta_g(Q_1)\frac{\alpha_s(Q_1)}{\alpha_s(Q_{\rm cut})}$$

- Start PS at scale μ_H

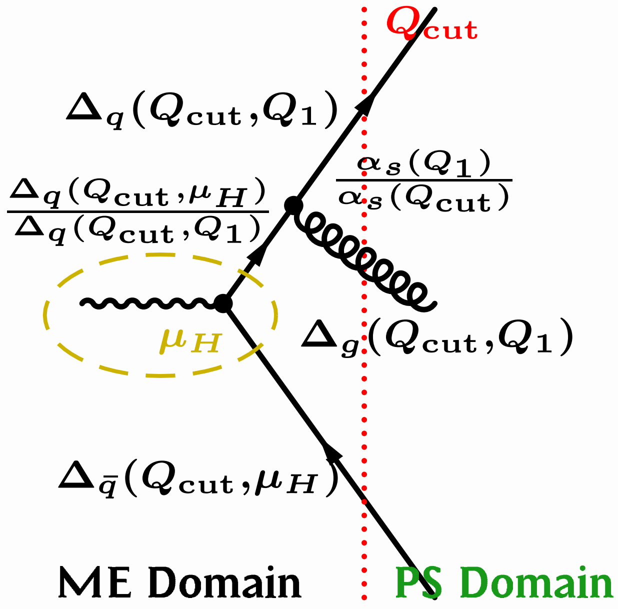
$Q \leftrightarrow$ Durham jet measure ($Q_{ij}^2 = 2\min\{E_i^2,E_j^2\}(1-\cos\theta_{ij})$)
(for $hh \rightarrow X$: $Q_{ij}^2 = 2\min\{p_{\perp,i}^2,p_{\perp,j}^2\}(\cosh(\eta_i-\eta_j)-\cos\phi_{ij})$)

[1] hep-ph/0503281, hep-ph/0311263

CKKW review

CKKW → General approach to combine multijet Matrix Elements (ME) and Parton Showers, implemented in Sherpa[1]

Example: $e^+e^- \rightarrow hadrons$



- Define phase space cut $Q_{\rm cut}$
- Evaluate ME at scale $Q_{\rm cut}$
- Define $2\rightarrow 2$ core process
- Reject ME according to Sudakov × coupling weight

$$W = \Delta_{\bar q}(\mu_H)\Delta_q(Q_1)\frac{\Delta_q(\mu_H)}{\Delta_q(Q_1)}\Delta_g(Q_1)\frac{\alpha_s(Q_1)}{\alpha_s(Q_{\rm cut})}$$

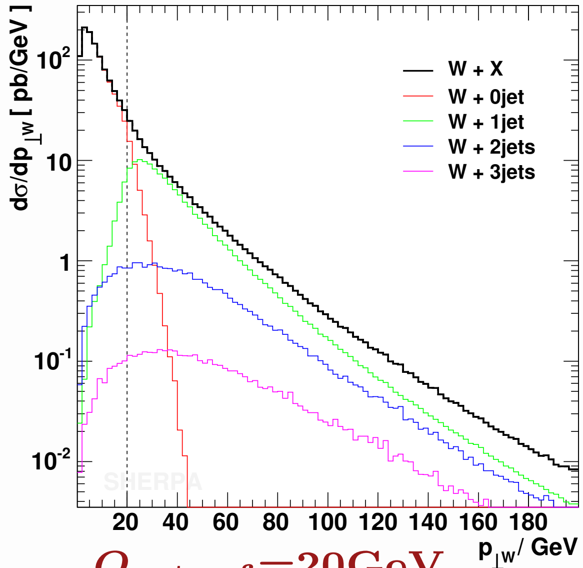
- Start PS at scale μ_H
- Veto PS emissions above $Q_{\rm cut}$

$Q \longleftrightarrow$ Durham jet measure ($Q_{ij}^2 = 2\min\{E_i^2, E_j^2\}(1-\cos\theta_{ij})$)
(for $hh \rightarrow X$: $Q_{ij}^2 = 2\min\{p_{\perp,i}^2, p_{\perp,j}^2\}(\cosh(\eta_i-\eta_j)-\cos\phi_{ij})$)

[1] hep-ph/0503281, hep-ph/0311263

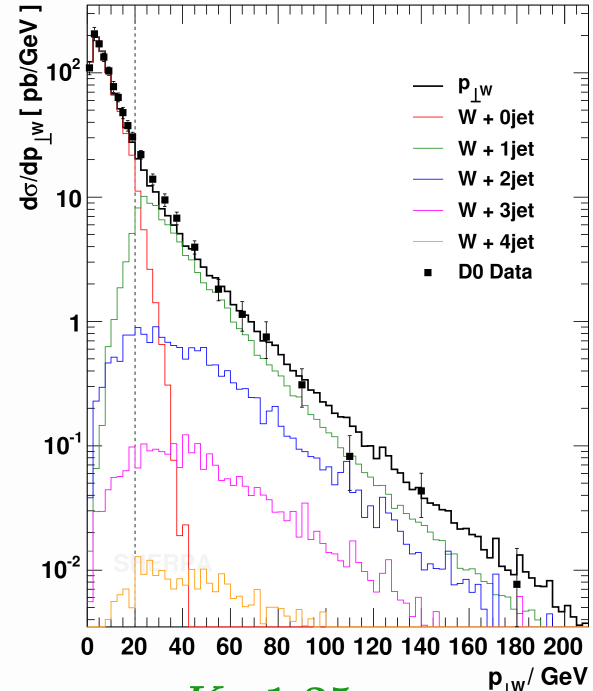
CKKW review

➡ Example : W+jets at Tevatron Run II [1]

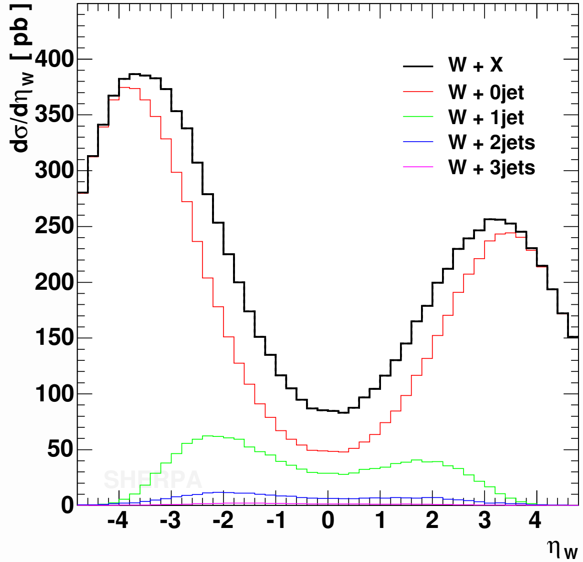


$Q_{\mathrm{cut,ref}}$=20GeV

➡ $p_{T,W}$



K=1.25



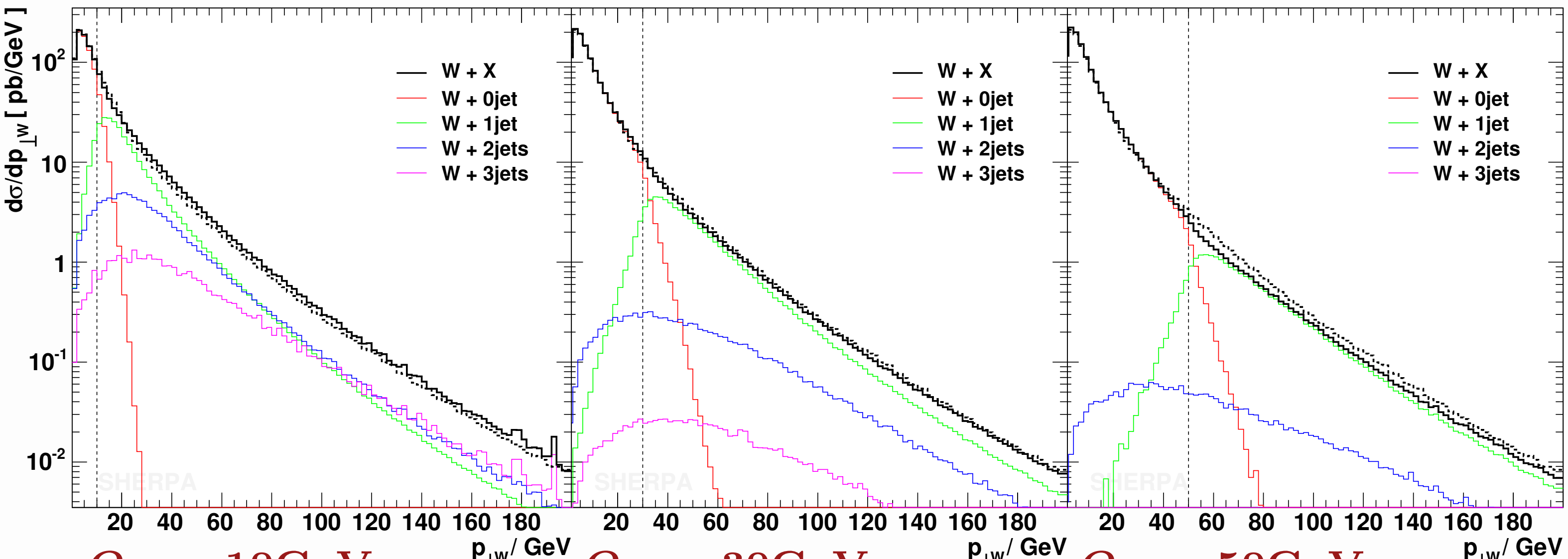
➡ η_W

Data: hep−ex/0010026

[1] hep-ph/0409106

CKKW review

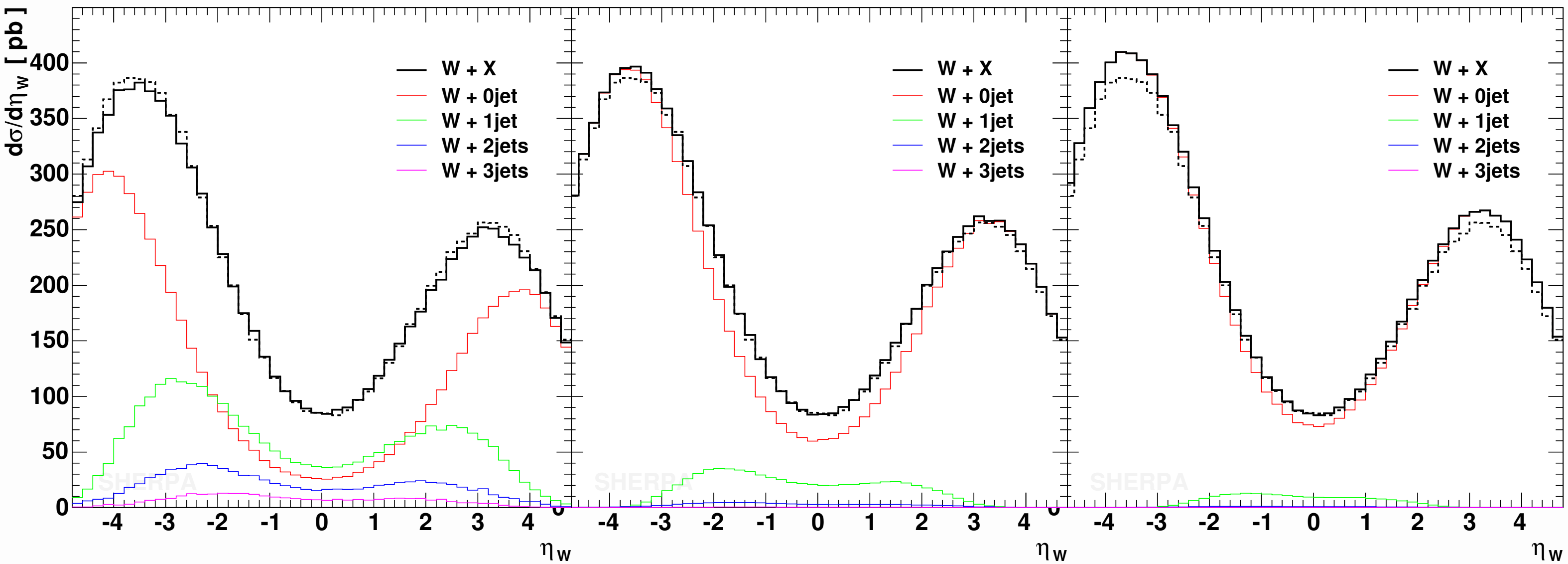
➡ Example : W+jets at Tevatron Run II [1]



$Q_{\mathrm{cut}}=10\mathrm{GeV}$ $Q_{\mathrm{cut}}=30\mathrm{GeV}$ $Q_{\mathrm{cut}}=50\mathrm{GeV}$

➡ $p_{T,W}$ varying cuts

$(Q_{\mathrm{cut,ref}}=20\mathrm{GeV})$

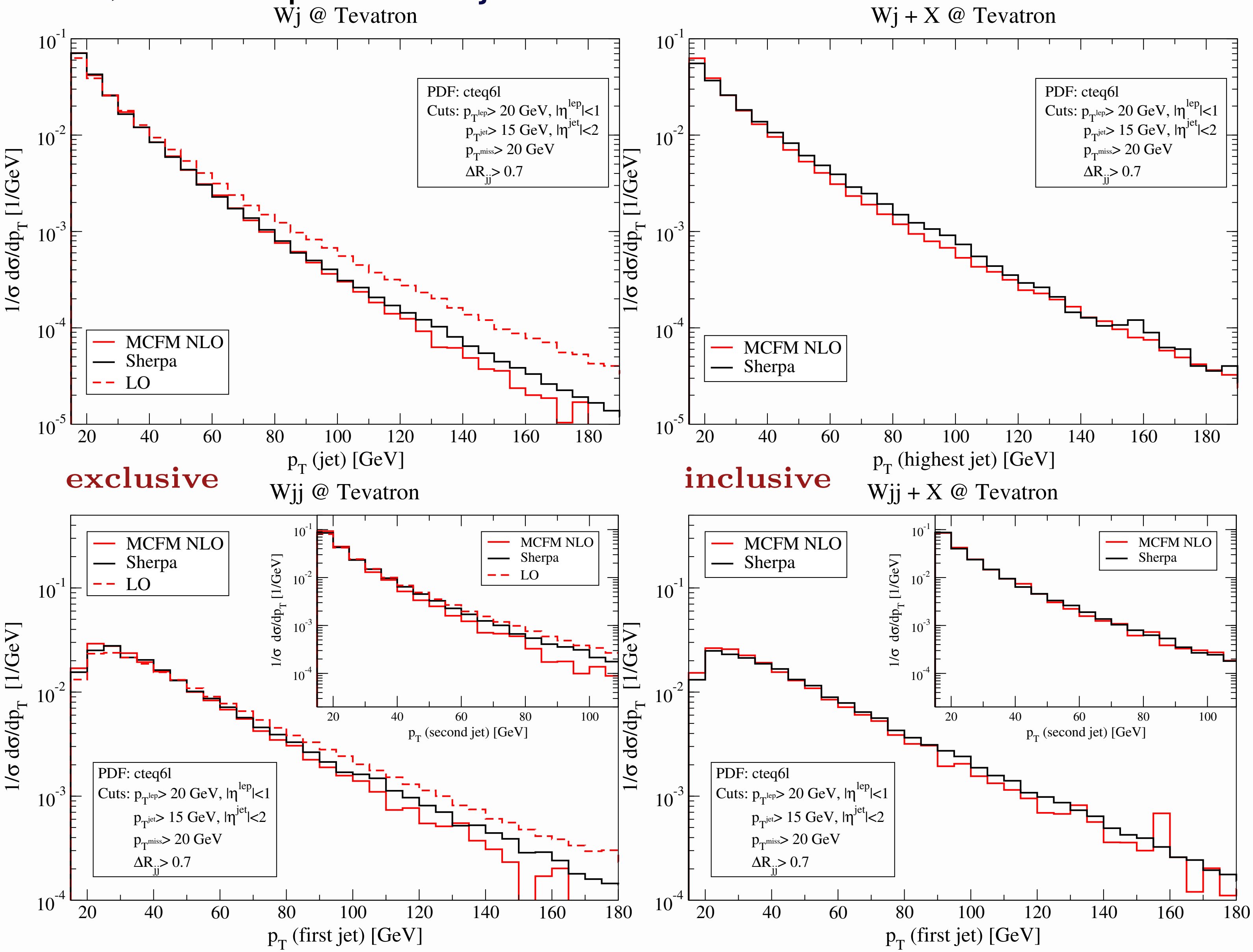


➡ η_W varying cuts

[1] hep-ph/0409106

CKKW review

Example : W+jets at Tevatron Run II [1]



$p_{T,\mathrm{jet}}$

W+1 jet

$p_{T,\mathrm{jet}}$

W+2 jets

[1] hep-ph/0409106

Combining MIs and the CKKW Merging

➡ Original ordering parameter for MI evolution is $p_{\perp\mathrm{out}}^{2\to2}$

Combining MIs and the CKKW Merging

- Original ordering parameter for MI evolution is $p_{\perp\mathrm{out}}^{2\to 2}$
- Need similar ordering parameter, μ_{MI},
  in hard processes with higher or lower multiplicity

Combining MIs and the CKKW Merging

- Original ordering parameter for MI evolution is $p_{\perp\mathrm{out}}^{2\to 2}$
- Need similar ordering parameter, μ_{MI}, in hard processes with higher or lower multiplicity
  - μ_{MI} must reduce to $p_{\perp\mathrm{out}}^{2\to 2}$ for pure QCD $2 \to 2$ scattering

Combining MIs and the CKKW Merging

- Original ordering parameter for MI evolution is $p_{\perp \mathrm{out}}^{2\to 2}$
- Need similar ordering parameter, μ_{MI}, in hard processes with higher or lower multiplicity
  - μ_{MI} must reduce to $p_{\perp \mathrm{out}}^{2\to 2}$ for pure QCD $2 \to 2$ scattering
  - μ_{MI} must be a QCD scale in electroweak boson production (e.g. W/Z+jets)

Combining MIs and the CKKW Merging

- Original ordering parameter for MI evolution is $p_{\perp\mathrm{out}}^{2\to2}$
- Need similar ordering parameter, μ_{MI},
  in hard processes with higher or lower multiplicity
  - μ_{MI} must reduce to $p_{\perp\mathrm{out}}^{2\to2}$
    for pure QCD $2 \longrightarrow 2$ scattering
  - μ_{MI} must be a QCD scale
    in electroweak boson production (e.g. W/Z+jets)
- Use k_T-algorithm to define core process

Combining MIs and the CKKW Merging

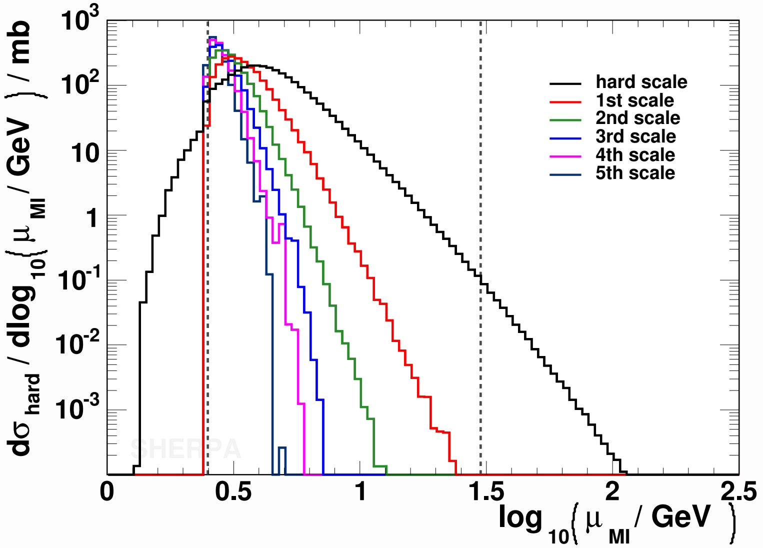
- Original ordering parameter for MI evolution is $p_{\perp \mathrm{out}}^{2\to 2}$
- Need similar ordering parameter, μ_{MI},
  in hard processes with higher or lower multiplicity
  - μ_{MI} must reduce to $p_{\perp \mathrm{out}}^{2\to 2}$
    for pure QCD $2 \longrightarrow 2$ scattering
  - μ_{MI} must be a QCD scale
    in electroweak boson production (e.g. W/Z+jets)
- Use k_T-algorithm to define core process
  - $2{\to}2$ QCD process in pure QCD

Combining MIs and the CKKW Merging

- Original ordering parameter for MI evolution is $p_{\perp\mathrm{out}}^{2\to2}$
- Need similar ordering parameter, μ_{MI},
  in hard processes with higher or lower multiplicity
  - μ_{MI} must reduce to $p_{\perp\mathrm{out}}^{2\to2}$
    for pure QCD $2 \to 2$ scattering
  - μ_{MI} must be a QCD scale
    in electroweak boson production (e.g. W/Z+jets)
- Use k_T-algorithm to define core process
  - $2{\to}2$ QCD process in pure QCD
  - $V + 1jet$ in EW boson production

Combining MIs and the CKKW Merging

- Original ordering parameter for MI evolution is $p_{\perp\text{out}}^{2\to2}$
- Need similar ordering parameter, μ_{MI},
  in hard processes with higher or lower multiplicity
  - μ_{MI} must reduce to $p_{\perp\text{out}}^{2\to2}$
    for pure QCD $2 \longrightarrow 2$ scattering
  - μ_{MI} must be a QCD scale
    in electroweak boson production (e.g. W/Z+jets)
- Use k_T-algorithm to define core process
  - $2{\to}2$ QCD process in pure QCD
  - $V + 1jet$ in EW boson production
- Starting scale for MI is $p_{\perp\text{out}}$
  of QCD partons from this core process



Combining MIs and the CKKW Merging

- Original MI algorithm does not allow parton radiation except for the hard scattering

Combining MIs and the CKKW Merging

- Original MI algorithm does not allow parton radiation except for the hard scattering
- Need to define starting conditions for PS which do not spoil the ME-PS merging procedure

Combining MIs and the CKKW Merging

- Original MI algorithm does not allow parton radiation except for the hard scattering
- Need to define starting conditions for PS which do not spoil the ME-PS merging procedure
- Set PS starting scale to QCD scale

$$\frac{2\, s\, t\, u}{s^2 + t^2 + u^2}$$

Combining MIs and the CKKW Merging

- Original MI algorithm does not allow parton radiation except for the hard scattering
- Need to define starting conditions for PS which do not spoil the ME-PS merging procedure
- Set PS starting scale to QCD scale

  $$\frac{2\,s\,t\,u}{s^2+t^2+u^2}$$

  - Veto on parton shower emissions harder than $p_{\perp \mathrm{out\,MI}}$

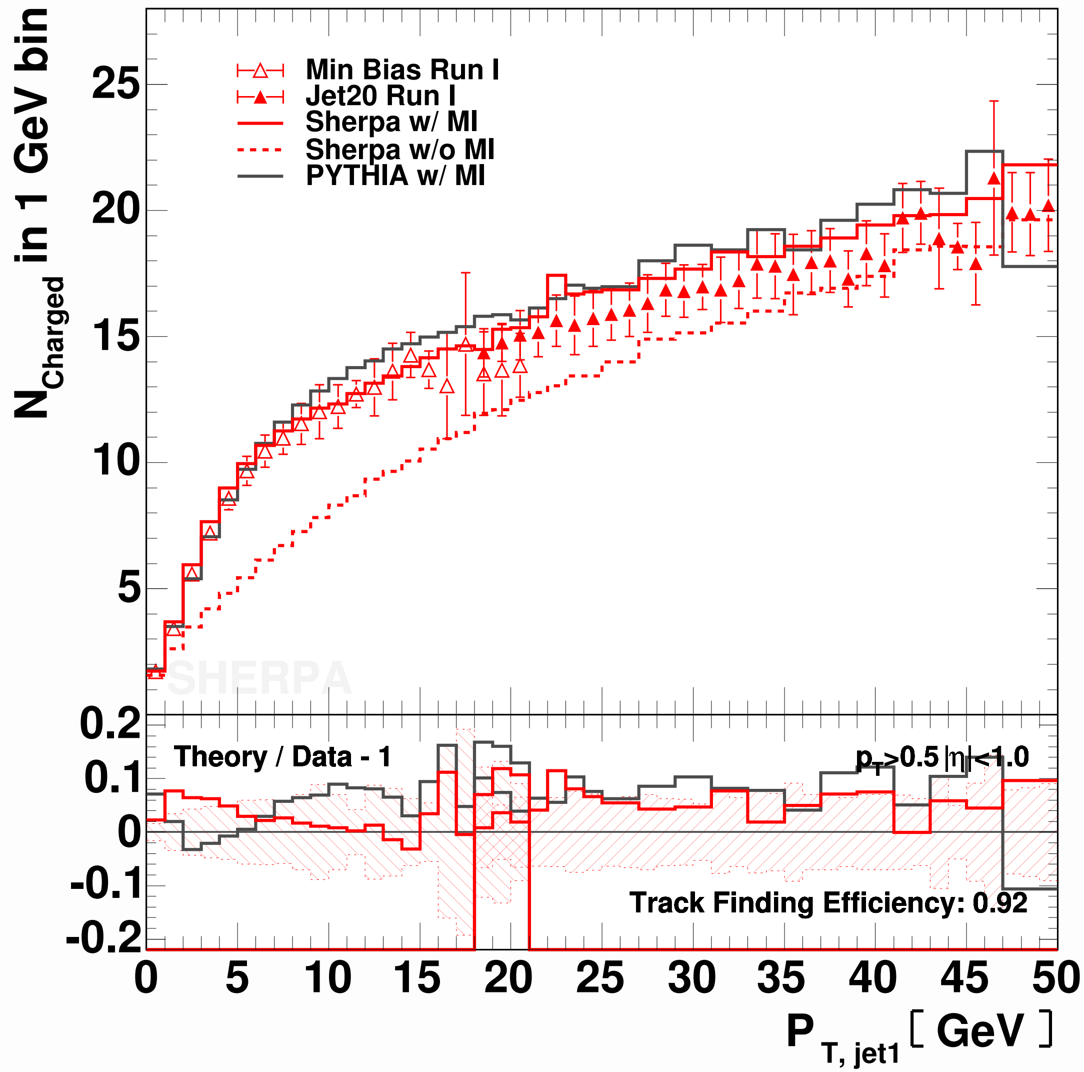
Combining MIs and the CKKW Merging

- Original MI algorithm does not allow parton radiation except for the hard scattering
- Need to define starting conditions for PS which do not spoil the ME-PS merging procedure
- - Set PS starting scale to QCD scale

$$\frac{2\,s\,t\,u}{s^2 + t^2 + u^2}$$

  - Veto on parton shower emissions harder than $p_{\perp \mathrm{out\,MI}}$

- Highest Multiplicity Treatment of CKKW approach

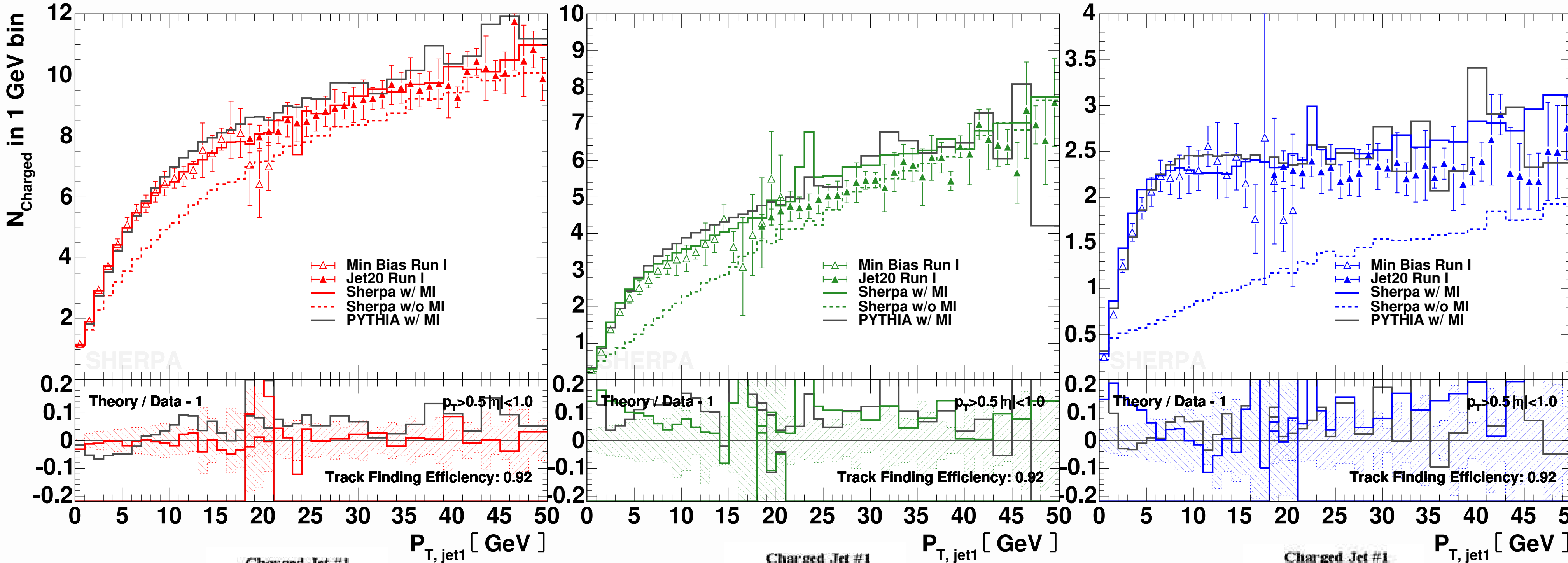


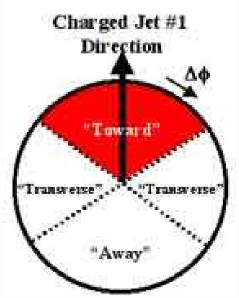
- MC results corrected for track finding efficiency
- Sherpa produces correct shape
- Total charged multiplicity agrees

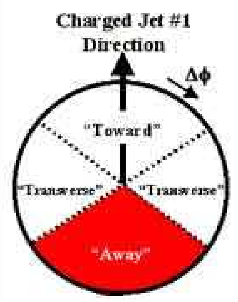
➡ Charged multiplicity vs. P_T of the leading charged particle jet [1]

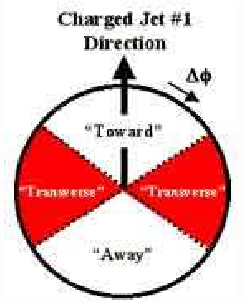
[1] Phys. Rev. D65 (2002) 092002

Preliminary Results





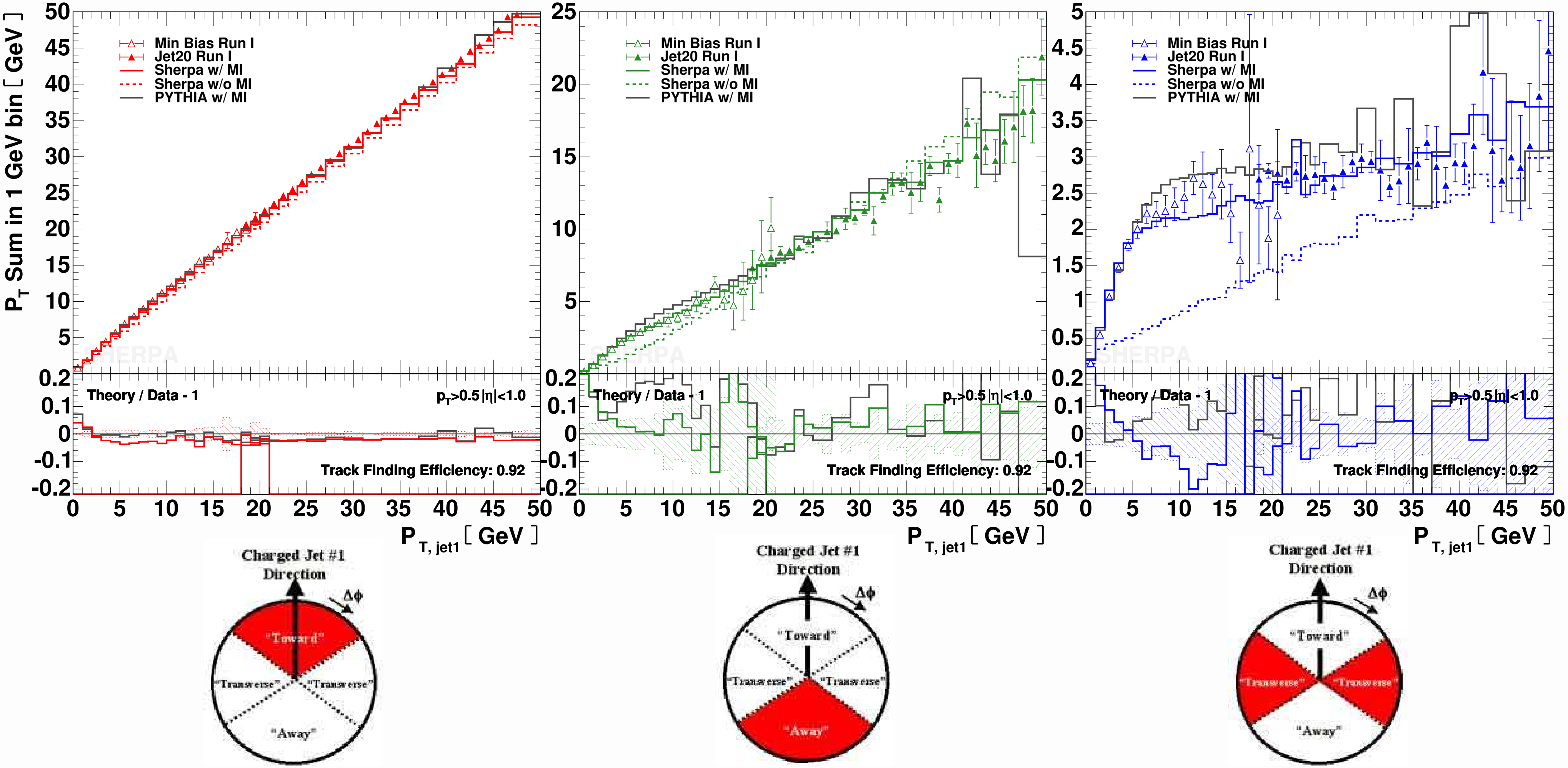




- Charged multiplicity vs. P_T of leading charged particle jet in $\Delta\phi_{\to \mathrm{jet1}}$ regions [1]

[1] Phys. Rev. D65 (2002) 092002

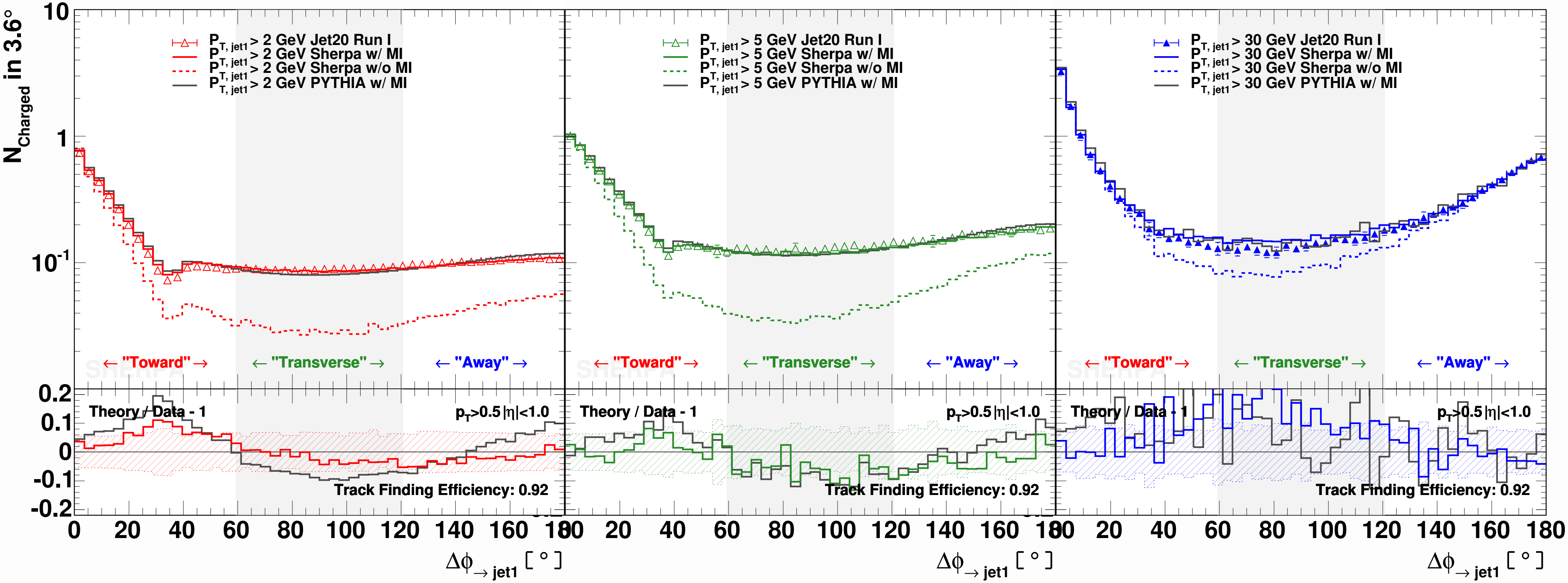
Preliminary Results



- Scalar P_T sum vs. P_T of the leading charged particle jet in $\Delta\phi_{\rightarrow \mathrm{jet1}}$ regions [1]

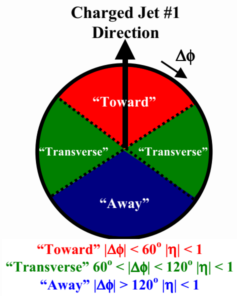
[1] Phys. Rev. D65 (2002) 092002

Preliminary Results



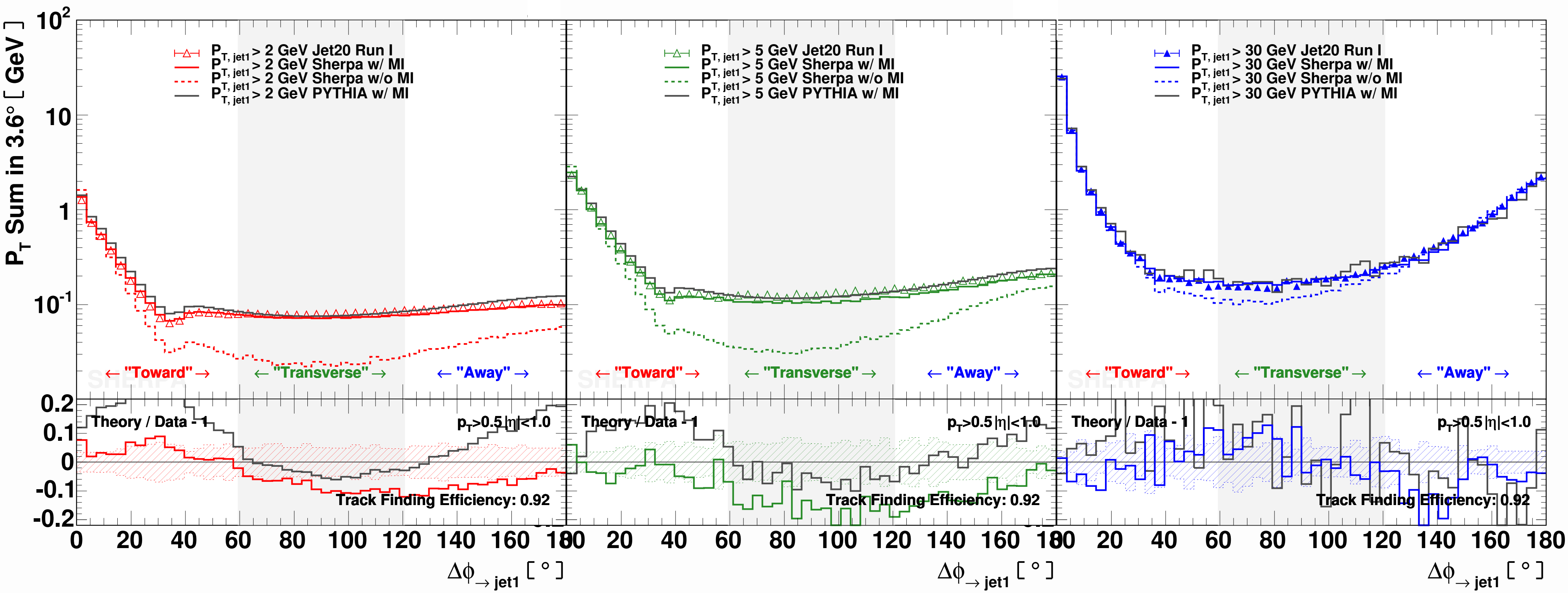
$p_{T,\text{jet1}} > 2\text{GeV}$ $p_{T,\text{jet1}} > 5\text{GeV}$ $p_{T,\text{jet1}} > 30\text{GeV}$

- Charged multiplicity vs. $\Delta\phi_{\rightarrow jet1}$ relative to leading charged particle jet for different $p_{T,\text{jet1}}$ [1]



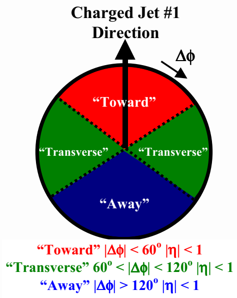
[1] Phys. Rev. D65 (2002) 092002

Preliminary Results



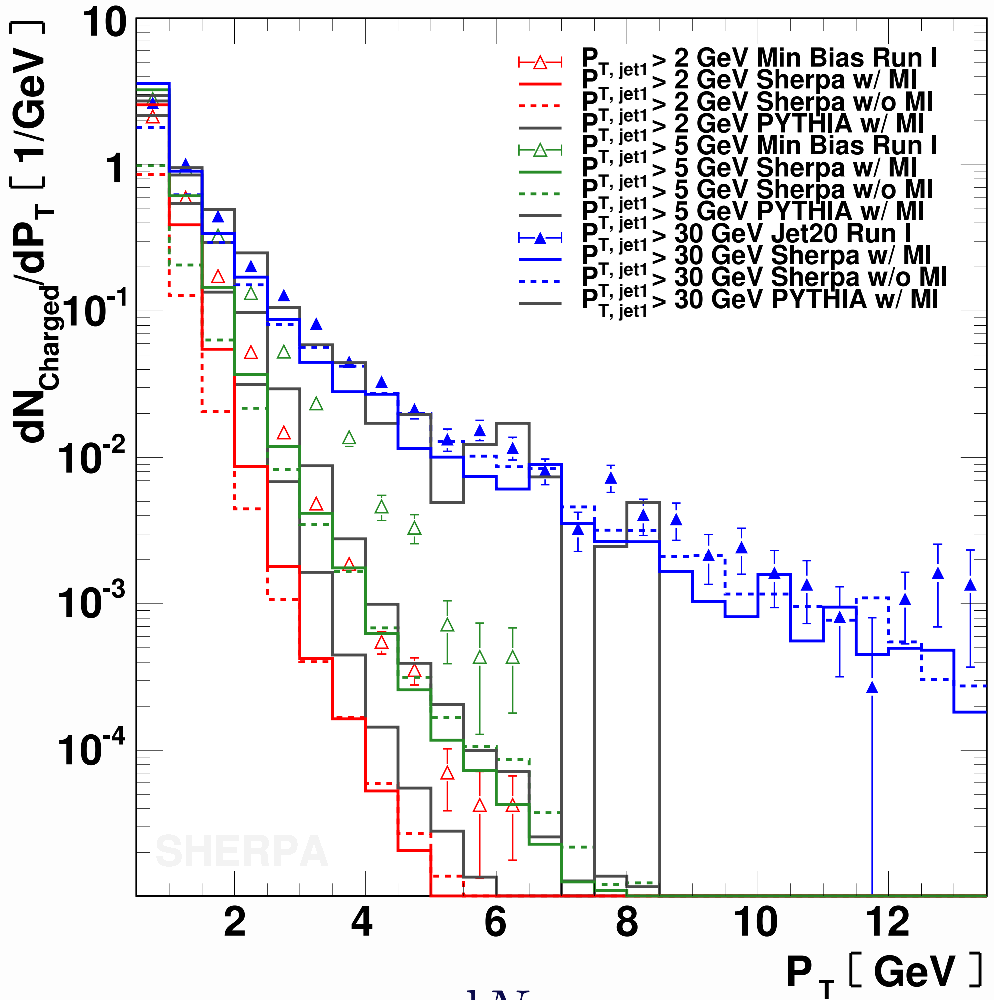
$p_{T,\mathrm{jet1}} > 2\mathrm{GeV}$ $p_{T,\mathrm{jet1}} > 5\mathrm{GeV}$ $p_{T,\mathrm{jet1}} > 30\mathrm{GeV}$

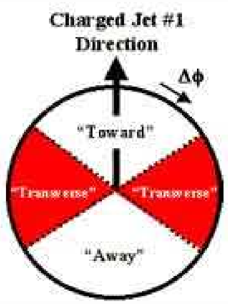
- Scalar P_T sum vs. $\Delta\phi_{\rightarrow jet1}$ relative to leading charged particle jet for different $p_{T,\mathrm{jet1}}$ [1]



[1] Phys. Rev. D65 (2002) 092002

Preliminary Results



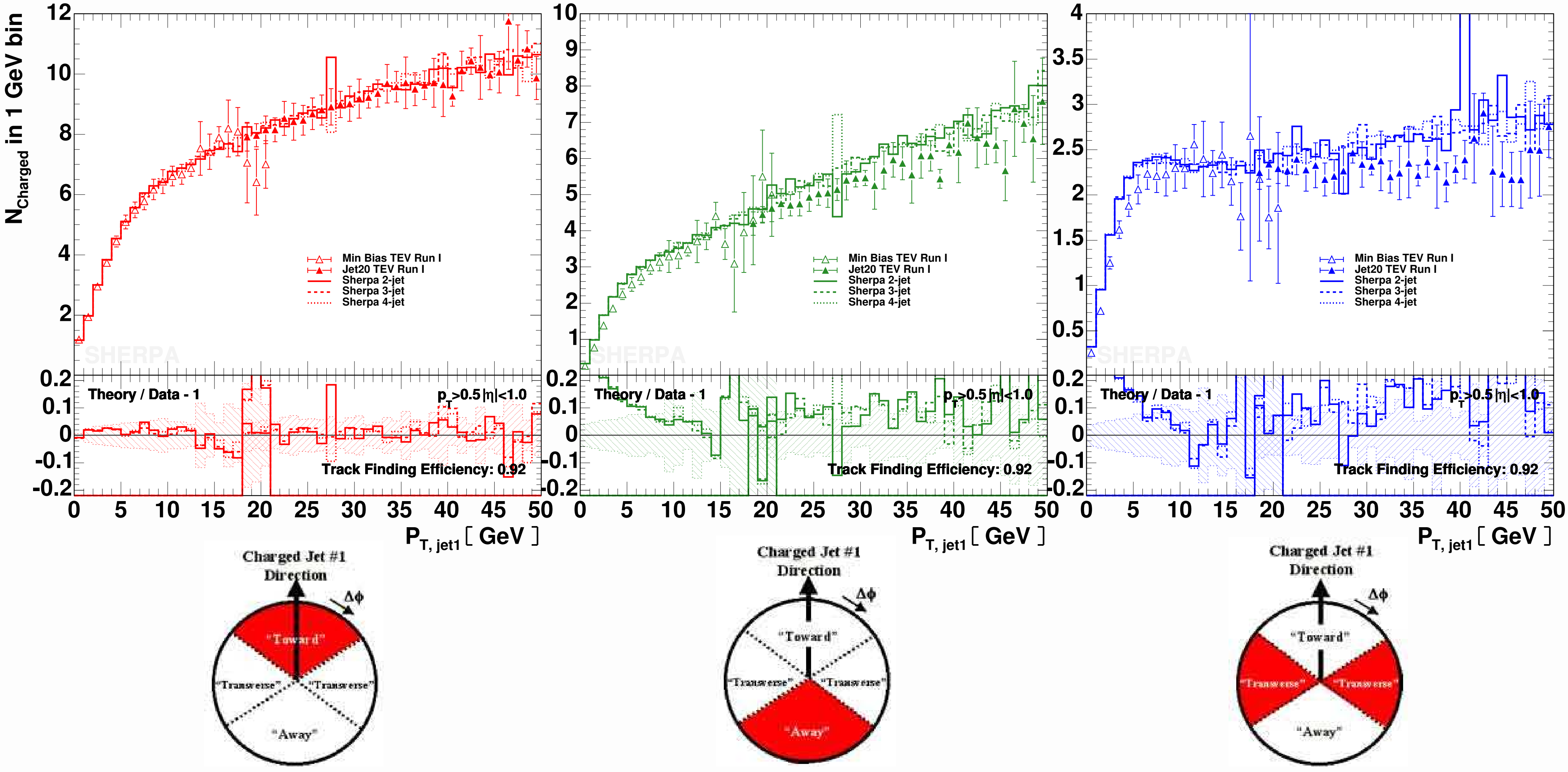


- High P_T Shape dominated by MEs
- Low P_T Shape dominated by MIs
  - ➡ Increased Multiplicity

➡ "Transverse" $\frac{\mathrm{d}N_{charged}}{\mathrm{d}P_T}$ [1]

[1] Phys. Rev. D65 (2002) 092002

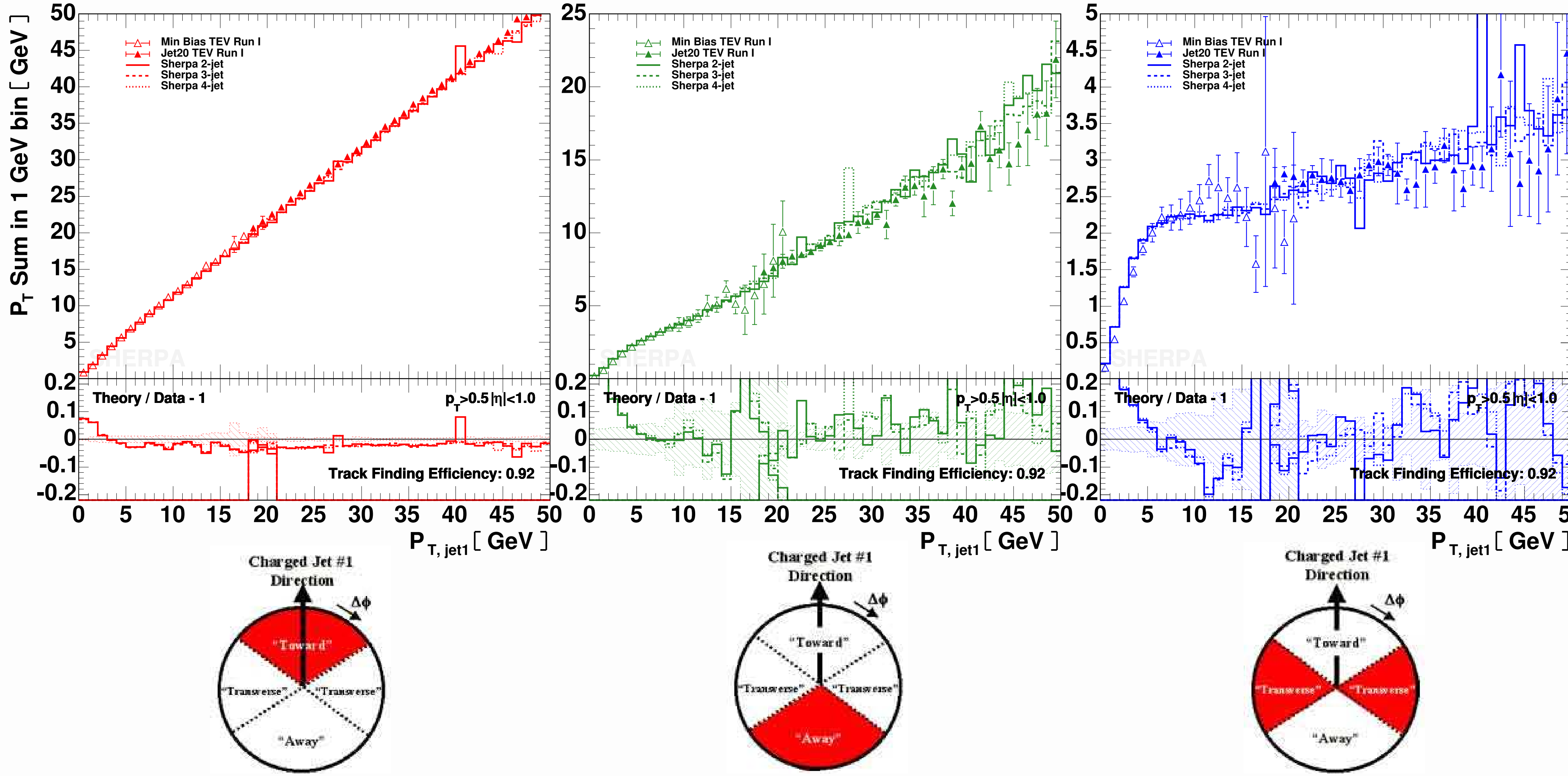
Consistency check: vary $n_{\rm jet}^{\rm max}$



➡ Charged multiplicity vs. P_T of leading charged particle jet in $\Delta\phi_{\rightarrow \rm jet1}$ regions [1]

[1] Phys. Rev. D65 (2002) 092002

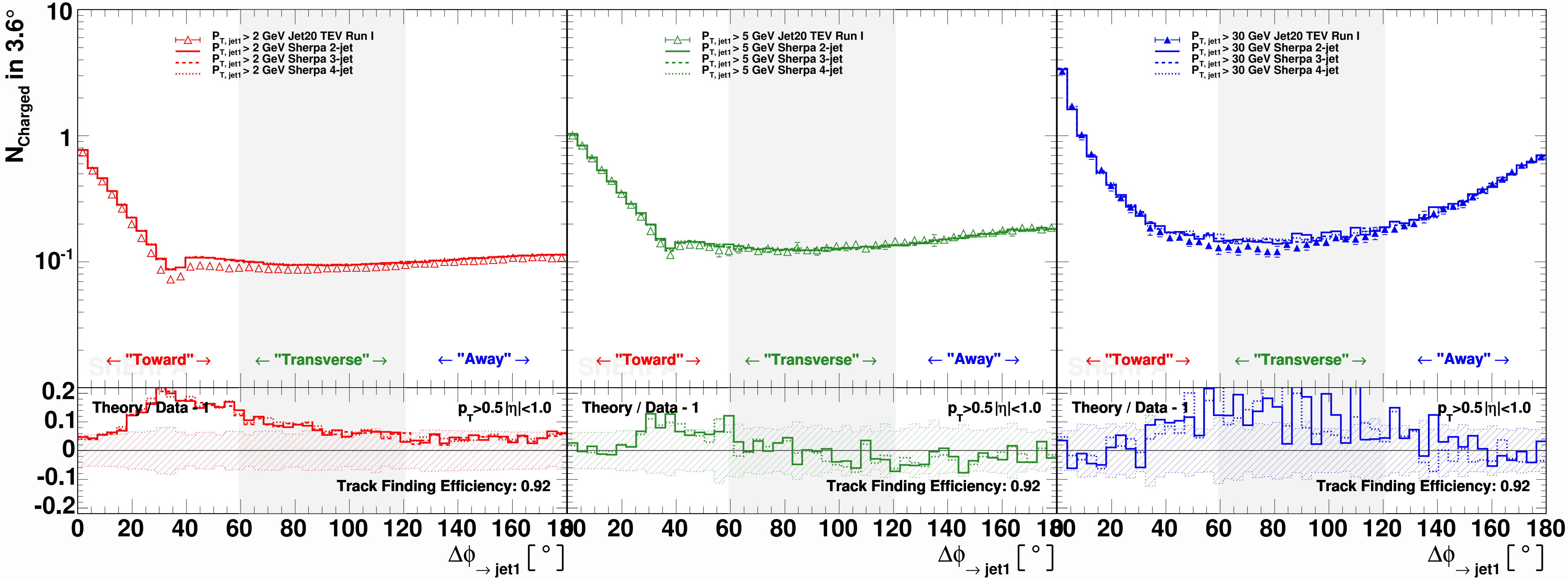
Consistency check: vary $n_{\rm jet}^{\rm max}$



- Scalar P_T sum vs. P_T of leading charged particle jet in $\Delta\phi_{\to \rm jet1}$ regions [1]

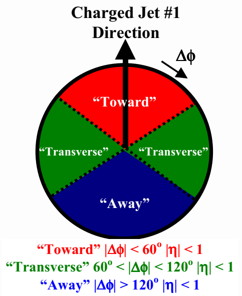
[1] Phys. Rev. D65 (2002) 092002

Consistency check: vary $n_{\text{jet}}^{\text{max}}$



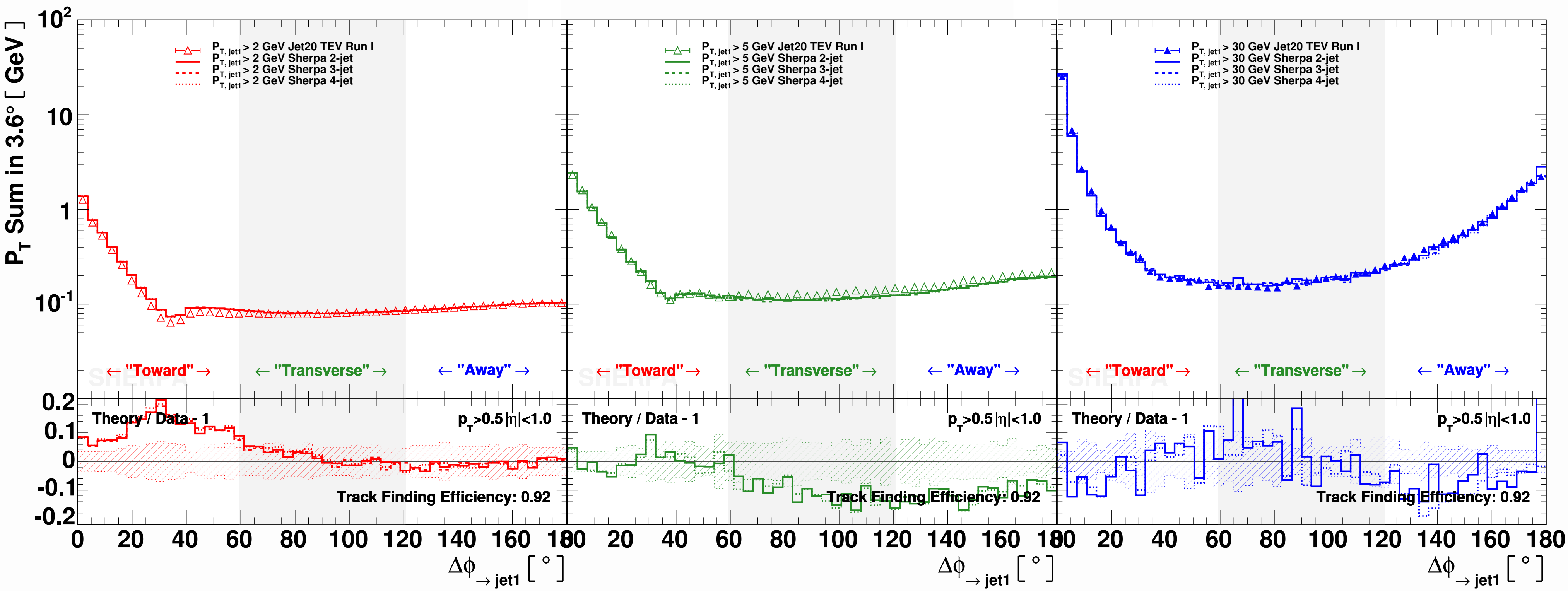
$p_{T,\text{jet1}} > 2\text{GeV}$ $\quad$ $p_{T,\text{jet1}} > 5\text{GeV}$ $\quad$ $p_{T,\text{jet1}} > 30\text{GeV}$

- Charged multiplicity vs. $\Delta\phi_{\rightarrow jet1}$ relative to leading charged particle jet for different $p_{T,\text{jet1}}$ [1]



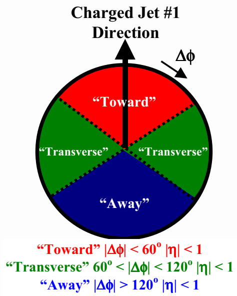
[1] **Phys. Rev. D65 (2002) 092002**

Consistency check: vary $n_{\mathrm{jet}}^{\mathrm{max}}$



$p_{T,\mathrm{jet1}} > 2\mathrm{GeV}$ $p_{T,\mathrm{jet1}} > 5\mathrm{GeV}$ $p_{T,\mathrm{jet1}} > 30\mathrm{GeV}$

- Scalar P_T sum vs. $\Delta\phi_{\rightarrow jet1}$ relative to leading charged particle jet for different $p_{T,\mathrm{jet1}}$ [1]



[1] Phys. Rev. D65 (2002) 092002

Preliminary Results

Current “Best Fit” Parameters:

- $p_{\perp\text{out min}}^{2\to2}$ = 2.4 GeV
- Gaussian matter distribution

Preliminary Results

Current "Best Fit" Parameters:

- $p_{\perp\text{out min}}^{2\to2}$ = 2.4 GeV
- Gaussian matter distribution

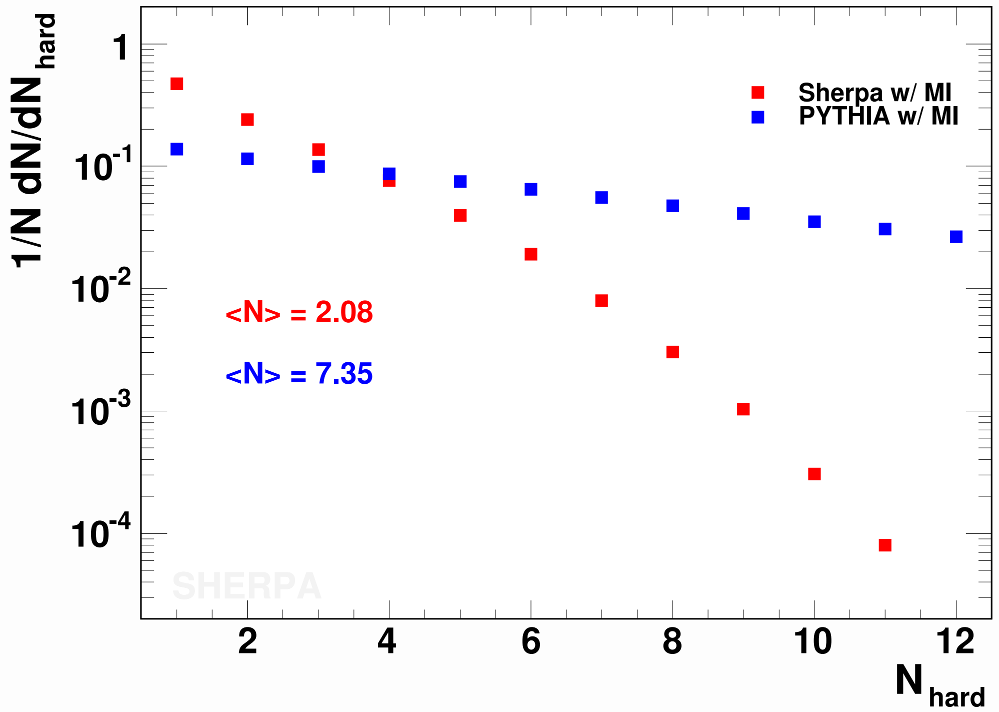
PDF set has been CTEQ6L to have consistent PS evolution

Preliminary Results

Current “Best Fit” Parameters:

- $p^{2\to 2}_{\perp\mathrm{out\ min}}$ = 2.4 GeV
- Gaussian matter distribution

PDF set has been CTEQ6L to have consistent PS evolution



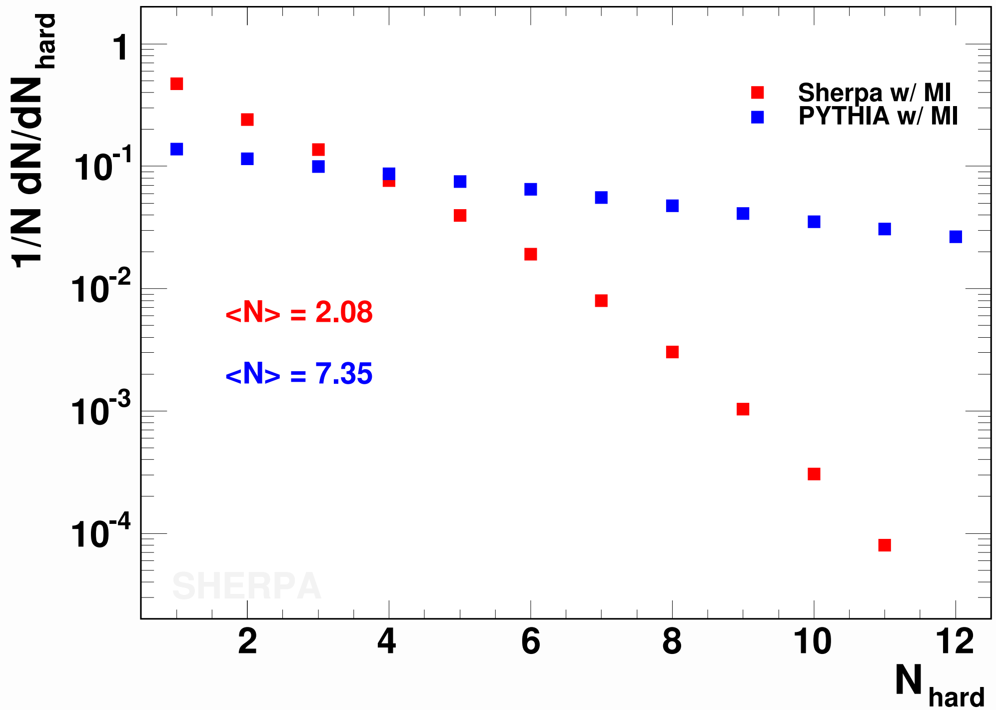
→ MI Distribution

Preliminary Results

Current "Best Fit" Parameters:

- $p_{\perp\text{out min}}^{2\to 2}$ = 2.4 GeV
- Gaussian matter distribution

PDF set has been CTEQ6L to have consistent PS evolution



→ MI Distribution

- moderate interaction number

$< N_{\text{hard}}^{2\to 2} >= 2.08$

in Sherpa

Outlook

Done:

- MIs included in Sherpa ✓
- MIs combined consistently with CKKW

Outlook

Done:

- MIs included in Sherpa ✓
- MIs combined consistently with CKKW

Now:

- Test MI treatment for Vector boson production
- Check MC results vs. Tevatron Run II data
- Examine energy dependence of MI parameters

Outlook

Done:

- MIs included in Sherpa ✓
- MIs combined consistently with CKKW

Now:

- Test MI treatment for Vector boson production
- Check MC results vs. Tevatron Run II data
- Examine energy dependence of MI parameters

The Sherpa group are:

Tanju Gleisberg, S.H., Frank Krauss, Thomas Laubrich, Andreas Schälicke, Steffen Schumann, Caroline Semmling and Jan Winter

CKKW details

- Highest Multiplicity Treatment
  - Find $Q_{\rm min}$ as smallest nodal value in k_T clustering of ME
  - Evaluate ME at factorisation scale $Q_{\rm min}$
  - Apply Sudakov weights with lower scale $Q_{\rm min}$
  - Veto PS emissions above $Q_{\rm min}$

- Multi-Cut Treatment
  - Define multiple separation cuts $Q_{{\rm cut},i}$
  - Apply CKKW approach in each phase space region $Q_{{\rm cut},i} \leq Q \leq Q_{{\rm cut},i+1}$

  - Indispensible for pure QCD !

    ME always at least 2-jet process

    Requires Highest Multiplicity Treatment with $n^{\rm jet}_{\rm max} = 2$