Non-Perturbative Contributions to Jet Cross Sections

Markus Wobisch, Fermilab

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- introduction
- PYTHIA and HERWIG models / hadronization / underlying event
- corrections for cone and $k_\perp$ jet definitions
- investigate the discrepancy cone vs. $k_\perp$ cross sections in Run I

Data vs. Theory — so far ...

Tevatron Jet Cross Sections are measured at the **particle** level

i.e. the data is corrected for:

- detector effects
- “collider effects” (multiple proton collisions)

data are compared to theory: **pQCD at NLO**

$\Rightarrow$ we define a “jet-topology” both on high-multiplicity particle level and on low-multiplicity parton level — why should they be comparable??

missing: non-perturbative contributions in theory

QCD Cross Sections - Factorization

Any cross section in QCD:

$$\sigma_{\mathrm{QCD}} = \sigma^{\mathrm{perturbative}}(\mu_{\mathrm{match}}) \times \sigma^{\mathrm{non-perturb.}}(\mu_{\mathrm{match}})$$

matching of perturbative and non-perturbative contributions
at some matching scale: μ_{match}

Any QCD cross section in hadron-hadron collisions:

$$\sigma_{\mathrm{hadron}} = \sigma^{\mathrm{pert.}}_{\mathrm{parton}}(\mu_f,\, \mu_I) \times f_{a/h1}(\mu_f) \times f_{a/h2}(\mu_f) \times \sigma^{\mathrm{non-pert.}}_{\mathrm{final}}(\mu_I)$$

where:

$f_{a/h1,2}$: PDFs of hadrons 1,2

μ_f: factorization scale for initial state singularities

μ_I: infrared matching scale for soft physics in the final state

$\sigma^{\mathrm{pert.}}$, $\sigma^{\mathrm{non-pert.}}$ pert. and non-pert. contributions – matched at μ_I

Non-Perturbative Effects - Definitions

In the following: assume that final state corrections ($\rightarrow$ "non-perturbative") are small $\Rightarrow$ treat this contribution as a "correction":

$$\sigma_{\text{hadron}} = \sigma^{\text{pert.}}_{\text{parton}}(\mu_f,\, \mu_I) \;\times\; f_{a/h1}(\mu_f) \;\times\; f_{a/h2}(\mu_f) \;*\; (1 + \delta^{\text{non-pert.}}(\mu_I))$$

where: $\delta^{\text{non-pert.}}(\mu_I) \equiv \delta^{\text{hadronization}}(\mu_I) + \delta^{\text{underlying event}}$

$$\delta^{\text{hadronization}}(\mu_I) \equiv \frac{\sigma^{\text{after hadroniz.}}}{\sigma^{\text{before hadroniz.}}(\mu_I)} - 1.$$

associated with long-distance physics

$$\delta^{\text{underlying event}} \equiv \frac{\sigma^{\text{with UE}}}{\sigma^{\text{without UE}}} - 1.$$

associated with multiple parton interactions

neither $\sigma^{\text{after hadroniz.}}$ nor $\delta^{\text{hadronization}}(\mu_I)$ can be computed in QCD

Unitarity $\Longrightarrow$ $\delta^{\text{non-pert}}$ does not affect the **total** cross section

Non-Perturbative Effects in QCD models

... but $\delta^{\mathrm{non-pert}}$ may affect the final-state topology

$\Longrightarrow$ and thus they will affect jet cross sections

currently the only predictions for $\delta^{\mathrm{non-pert}}$ are available in QCD models:
MC event generators: PYTHIA, HERWIG, ARIADNE, ...

event generators: LO pQCD matrix elements + perturbative parton cascade
+ hadronization & fragmentation model + model for underlying event

LO matrixelement $\Rightarrow$ no absolute predictions for cross section

parton cascade + hadronization model + model for underlying event
$\Rightarrow$ good predictions for final state topology

$\Rightarrow$ use QCD models to determine non-perturbative corrections
to jet cross sections

Implementations of Non-Perturbative Effects

Parton Cascade

PYTHIA and HERWIG: different implementations of parton shower

Hadronization and Fragmentation Model

PYTHIA: Lund String Model
HERWIG: Cluster Model

Underlying Event

PYTHIA: multiple parton interactions (affects both parton & hadron level)
HERWIG: interaction of beam remnants (does not affect parton level — only hadron level)

Parameters

today's presentation: use PYTHIA 6.218 and HERWIG 6.5

proton's PDFs: CTEQ5L
HERWIG adjust QCDLAM=0.2039 $\rightarrow$ $\alpha_s(M_Z) = 0.118$

HERWIG with default settings – PYTHIA using Rick Field's "tune A":

PARP(67): 4.0 (1.0) — "tune A" value (default value)

MSTP(81): 1 (1) (or $= 0$ to switch off underlying event)

MSTP(82): 4 (1)

PARP(82): 2.0 (1.9)

PARP(83): 0.5 (0.5)

PARP(84): 0.4 (0.2)

PARP(85): 0.9 (0.33)

PARP(86): 0.95 (0.66)

PARP(89): 1,800.0 (1,000.0)

PARP(90): 0.25 (0.16)

Presentation / Interpretation of Results

measured cross section: particle- (= “hadron-”) level

theoretical predictions:
perturbative: NLO / JETRAD $\rightarrow$ σ_{NLO}
non-perturbative: QCD models $\delta^{\mathsf{hadroniz.}}$, $\delta^{\mathsf{underlying\ evt.}}$

best theoretical prediction: $\sigma_{\mathsf{QCD}} = \sigma_{\mathsf{NLO}} * (1. + \delta^{\mathsf{hadroniz.}} + \delta^{\mathsf{UE}})$

problem: $\delta^{\mathsf{non-pert.}}$ is not matched to σ_{NLO} !!!

$\Rightarrow$ increased uncertainty — but still best prediction!

non-perturbative corrections will be different for different jet algorithms!!!

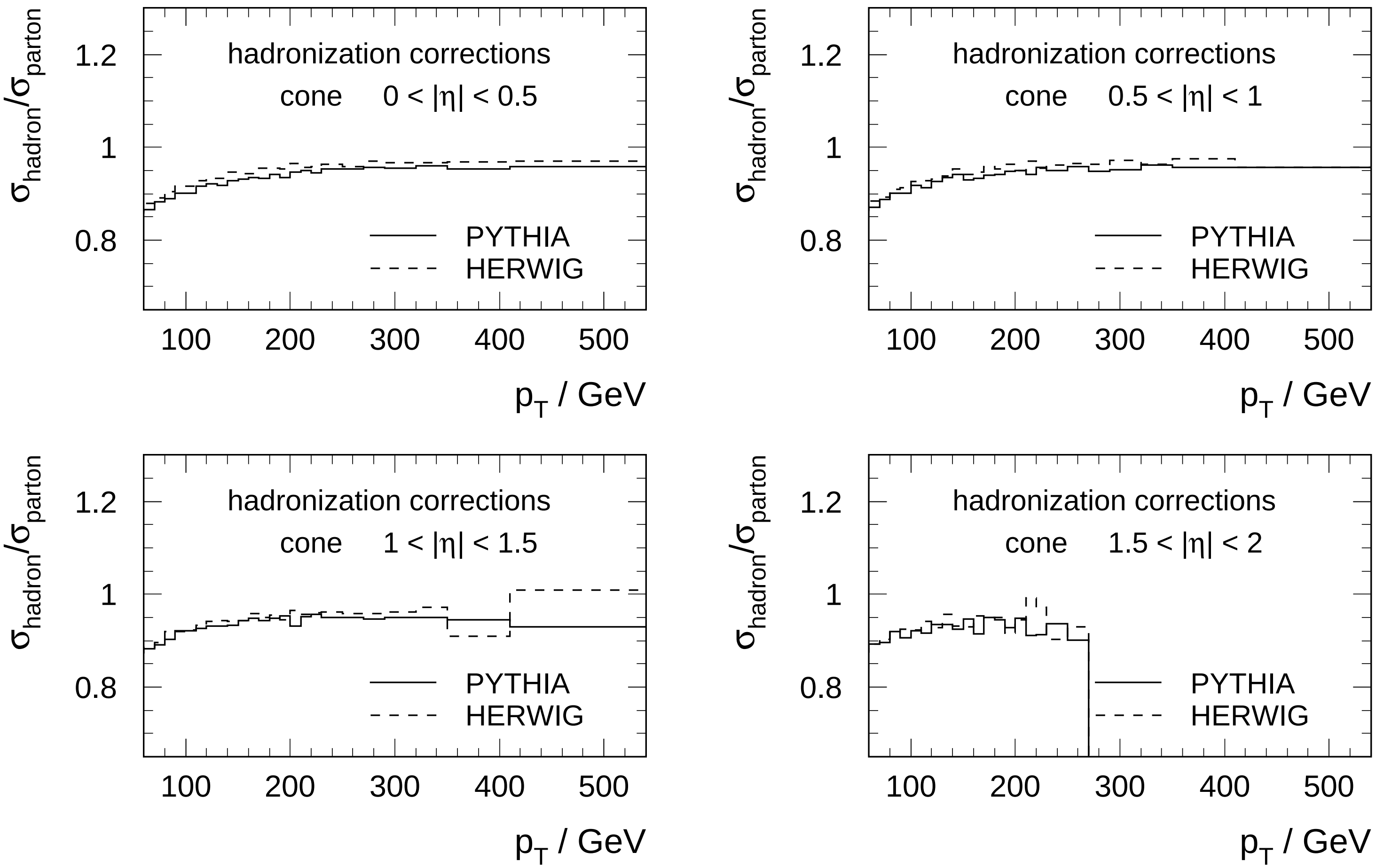
Phase Space

All plots in the following phase space (unless otherwise stated):

- inclusive jet cross section
- Run I – $\sqrt{s} = 1800\,\mathrm{GeV}$
- $|\eta| < 0.5$
- cone algorithm – R=0.7
- $k_\perp$ algorithm – D=1.0

plot: $\sigma_{\text{hadron}}/\sigma_{\text{parton}} = 1 + \delta^{\text{hadroniz.}}$, $\sigma_{\text{with UE}}/\sigma_{\text{w/o UE}} = 1 + \delta^{\text{underlying evt.}}$

Hadronization Corrections — cone — (η)

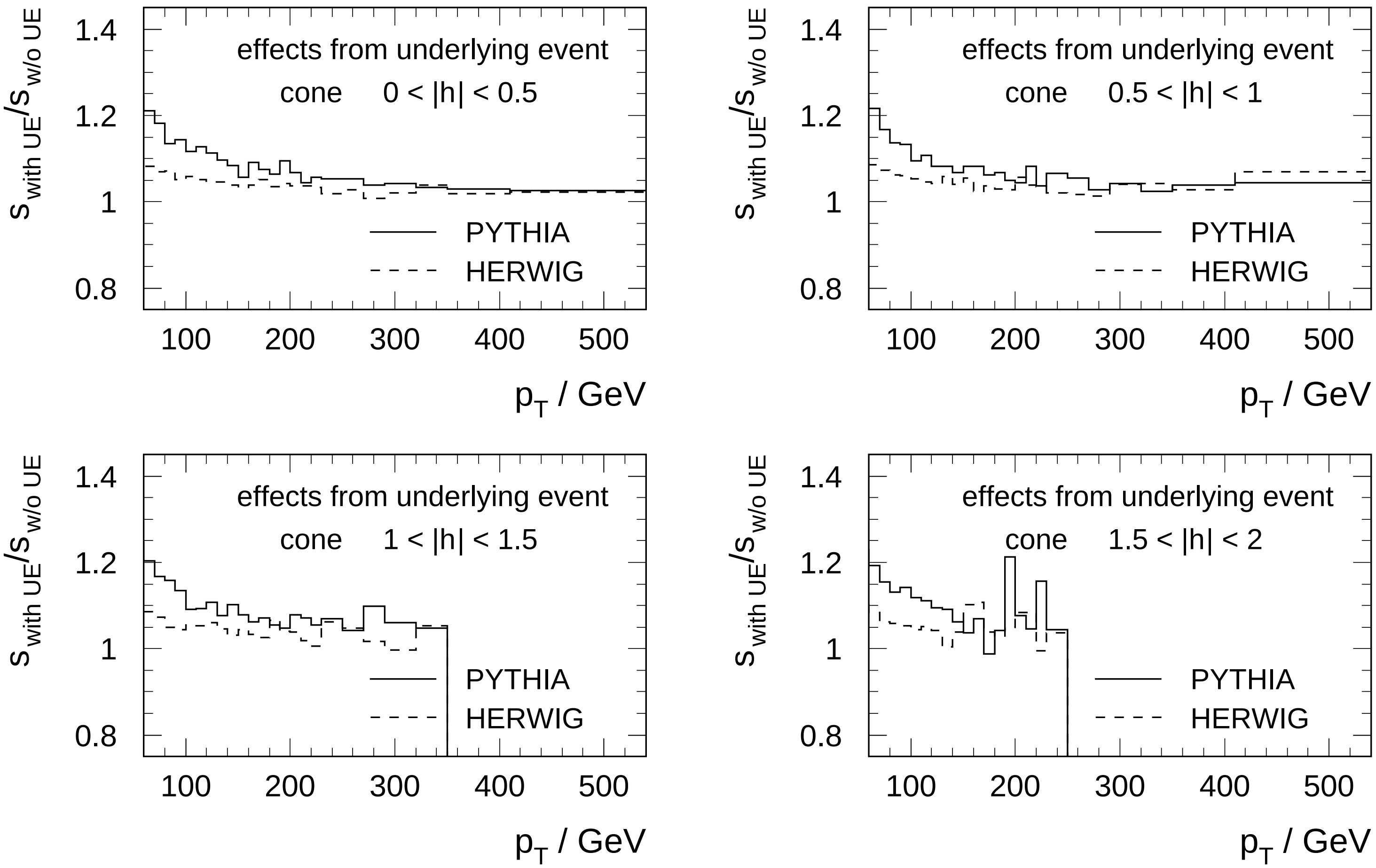


good agreement between PYTHIA and HERWIG

$\rightarrow$ hadronization corrections at low p_T: -12% / smaller toward high p_T

$\Rightarrow$ clear p_T dependence / weak η dependence

Underlying Event — cone — (η)

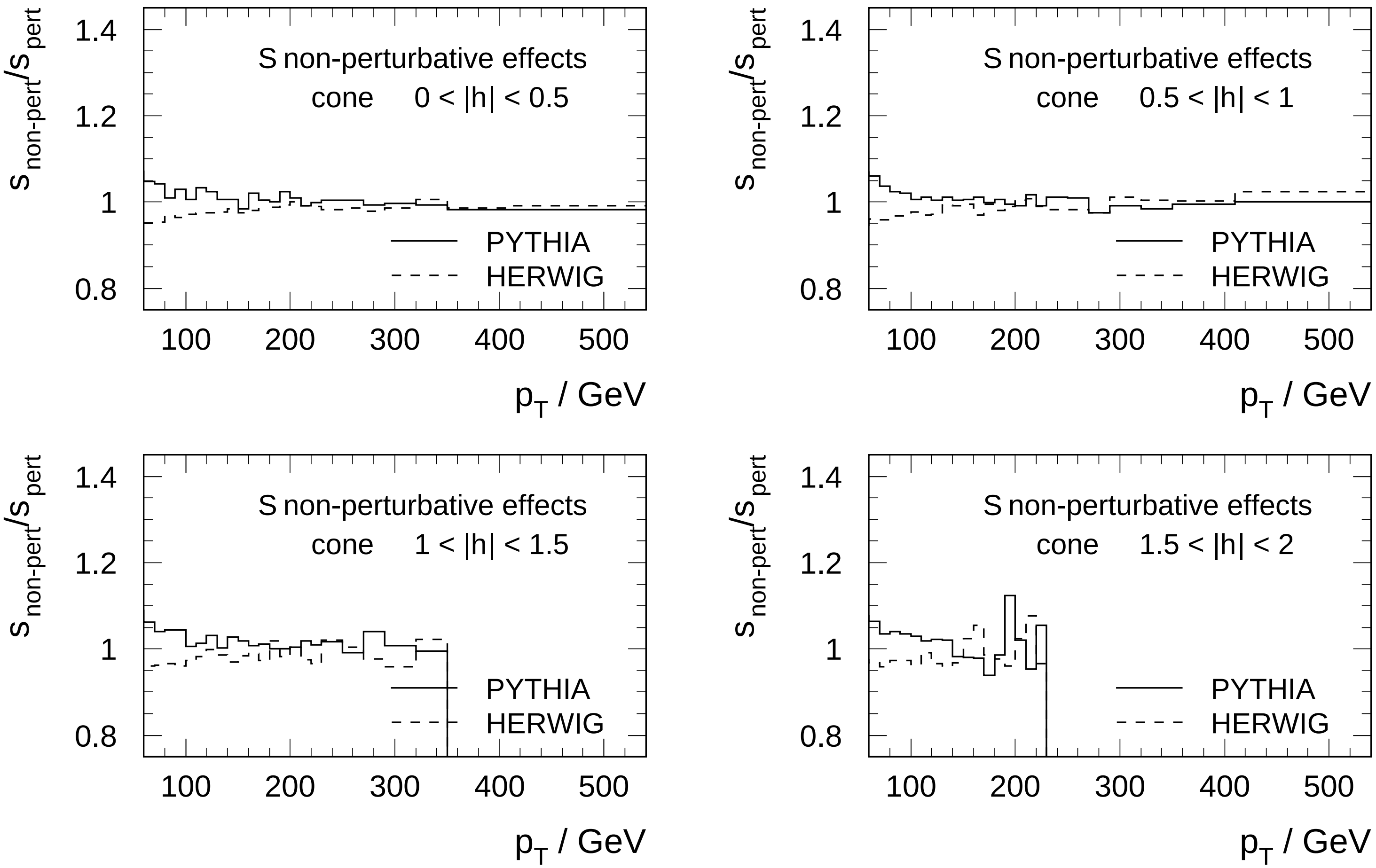


discrepancies between PYTHIA and HERWIG ($\approx 15\%$)

- at low p_T: 8% - 22% / decreasing towards high p_T

$\Rightarrow$ clear p_T dependence / weak η dependence

Sum of Non-Perturbative Corrections — cone (η)

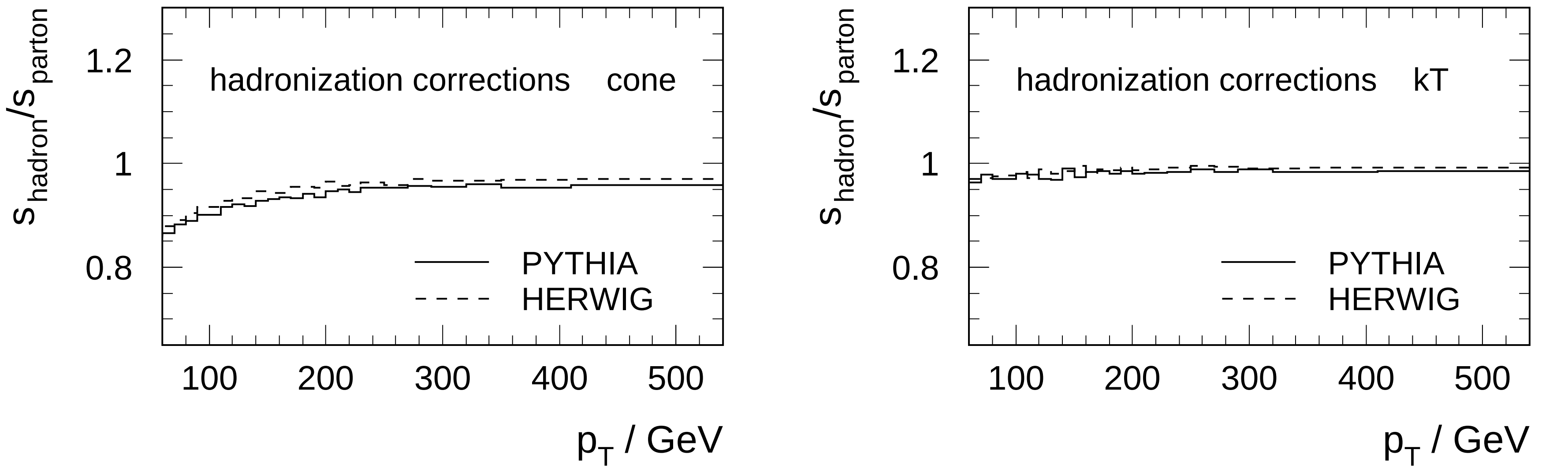


compensating effects from hadronization & underlying event

- total corrections are relatively small

$\Rightarrow$ some uncertainty at lower p_T: $\pm 10\%$

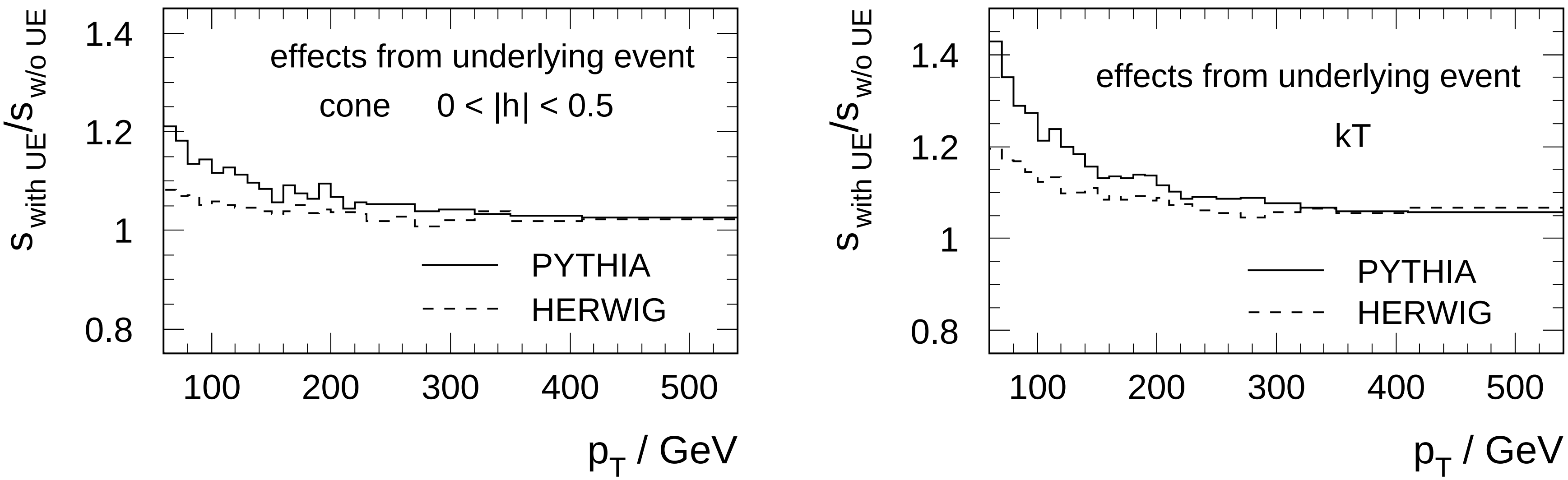
Hadronization Corrections — compare cone / kT



PYTHIA and HERWIG predictions in very good agreement
– large effects for the cone algorithm large at low p_T (12%)
– at highest p_T effects for the cone algorithm still 4%
– effects for $k_\perp$ algorithm very small $< 3\%$

$\Rightarrow$ clear advantage for the $k_\perp$ algorithm

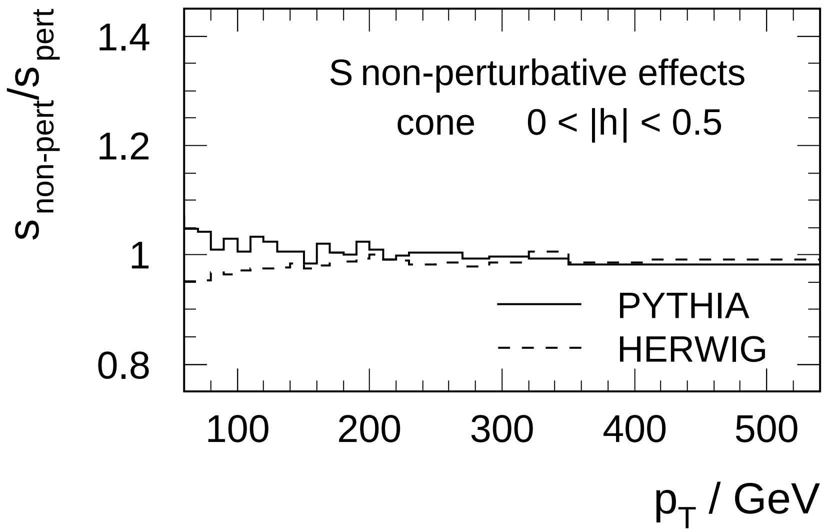
Underlying Event — compare cone / kT

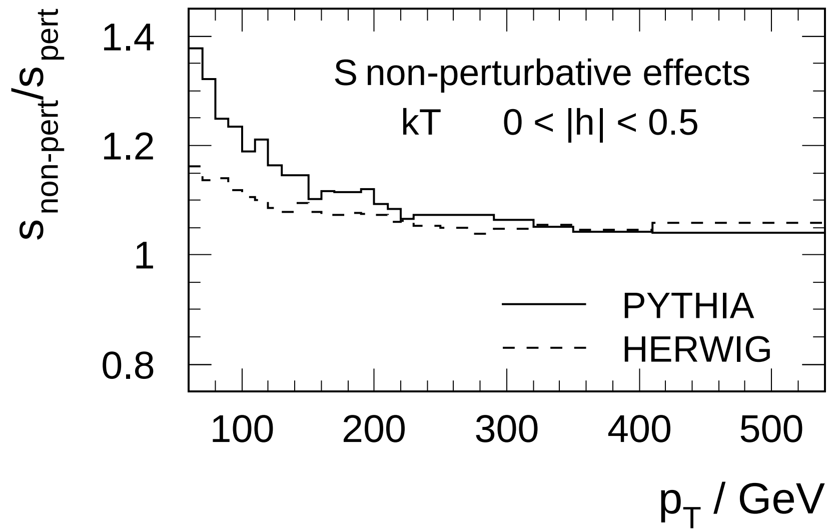


disagreement between PYTHIA and HERWIG is bigger for kT
– effects for kT algorithm are significantly larger for kT than for cone
$\rightarrow$ up to $> 40\%$ at low p_T

$\Rightarrow$ advantage for cone algorithm

Sum of Non-Pert. Effects — compare cone / kT





total effects are small for the cone algorithm
huge effects for the kT algorithm (cannot be neglected!)

⇒ need to consider non-perturbative effects when comparing kT data and theory

but remember:

small effects for cone are result from a cancellation of two non-negligible effects!

incl. jet cross section — $k_\perp$ vs. cone algorithm

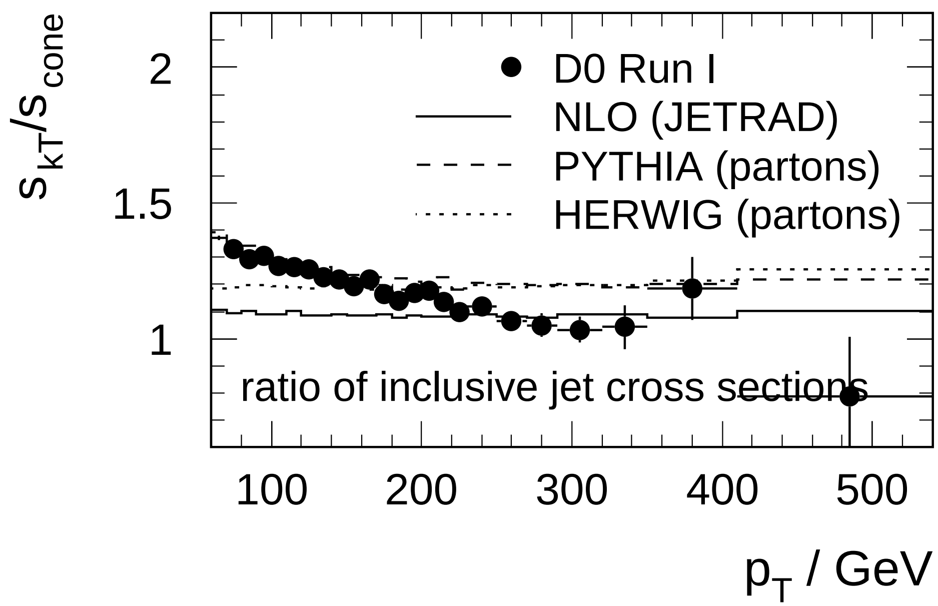
remember Run I: inclusive jet cross section, measured with k_T algorithm was much higher, compared to theory than the cone result! (especially at low p_T)

however: data have only been compared to purely perturbative predictions!

question 1:

What does pQCD predict for the ratio $\sigma_{\mathrm{kT}}/\sigma_{\mathrm{cone}}$?

compare NLO
and parton-shower predictions



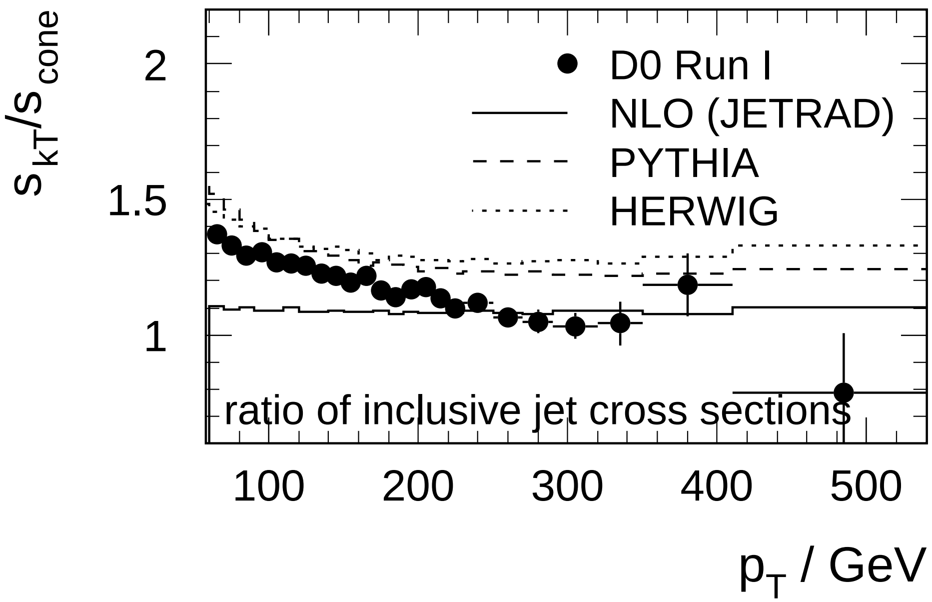
NLO: flat in p_T / 10% difference (depending on R_{sep} for σ_{cone})
parton-shower MCs: p_T dependent effect (up to 40% at low p_T)

incl. jet cross section — $k_\perp$ vs. cone algorithm

question 2:

... and if we include hadronization?

compare data, NLO and full PYTHIA, HERWIG predictions



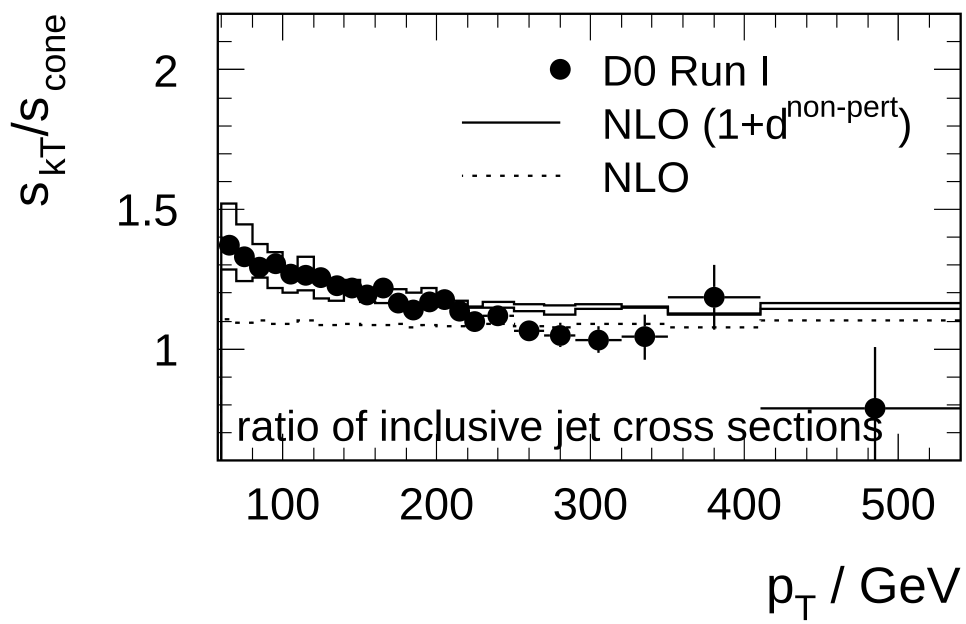
including non-perturbative effects:
better agreement!
both PYTHIA and HERWIG predict a significant p_T dependence
$\Rightarrow \approx$ as observed in the data

incl. jet cross section — $k_\perp$ vs. cone algorithm

question 3:

... and if we add the non-perturbative effects to the NLO prediction?

compare data and theory
= NLO $(1+\delta^{\mathrm{non-pert}})$
$\delta^{\mathrm{non-pert}}$ from PYTHIA, HERWIG



adding non-perturbative effects to NLO:
perfect agreement between data and the **full** theoretical prediction

(data: stat. errors only)

Conclusions

Studies of non-perturbative effects using PYTHIA and HERWIG:

- hadronization effects and underlying event are not negligible:
  up to 20% for the cone algorithm / 40% for the $k\perp$ algorithm
  both: strong p_T dependence — important for any interpretation!!
  $\Rightarrow$ CDF/D0 analyses — and CTEQ/MRST pdf fits!

- for the cone algorithm:
  effects from hadronization and underlying event cancel approximately
  $\Rightarrow$ but there are uncertainties for both which don't cancel!!

- for the $k_\perp$ algorithm:
  very small hadronization corrections ¡ 4%
  very large effects from underlying event up to 40%
  $\Rightarrow$ these effects can explain the discrepancy in the Run I data

- $\Rightarrow$ propose to include non-perturbative corrections in all
  future quantitative jet analyses at the Tevatron (like at LEP, HERA)