LUND UNIVERSITY

"Multiple Interactions and Underlying Events"
DESY miniworkshop
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Monte Carlo Provocateur Intro:
Programs and Problems

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MI = Multiple Interactions

MB = Minimum Bias

UE = Underlying event

A nonperturbative approach

Event with s_c soft cut pomerons
t_c triple-pomeron vertices (single diffraction)
l_c pomeron loops (double diffraction)
h_c hard cut pomerons
has cross section

$$\sigma(s_c, t_c, l_c, h_c) = \frac{(2\chi_{\mathrm{soft}})^{s_c}}{s_c!} \frac{(-2\chi_{tp})^{t_c}}{t_c!} \frac{(-2\chi_{\mathrm{loop}})^{l_c}}{l_c!} \exp\left(-2\chi(b,s)\right) \frac{(2\chi_{\mathrm{hard}})^{h_c}}{h_c!}$$

$$\chi_i(b,s) = \frac{\sigma_i(s)}{8\pi b_i} \exp\left(-\frac{b^2}{4b_i}\right) \quad \Longrightarrow \quad \int 2\chi_i(b,s)\,\mathrm{d}^2 b = \sigma_i(s)$$

- closed framework with many relations but also many parameters
- a cut Pomeron $\Rightarrow$ two fragmenting low-$p_\perp$ chain of hadrons
- can explain rapidity plateau, multiplicity fluctuations, forward–backward correlations, etc.

but

- perturbative QCD jet production plays no natural role

$\Longrightarrow$ not relevant for Tevatron/LHC energies (?)

$\Longrightarrow$ need to add hard pomerons from perturbation theory

A perturbative approach

TS & M. van Zijl (1987) - still basis for most experimental studies

- all activity in MB & UE of perturbative origin

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\perp}^2}\right|_{\mathrm{QCD}} \times \left(\frac{p_{\perp}^2}{p_{\perp 0}^2 + p_{\perp}^2}\right)^2 \left(\frac{\alpha_{\mathrm{s}}(p_{\perp 0}^2 + p_{\perp}^2)}{\alpha_{\mathrm{s}}(p_{\perp}^2)}\right)^2$$

  $\Rightarrow p_{\perp 0} \approx 1.5 - 2$ GeV
- Poissonian number of interactions at fixed impact parameter
- Evolution in sequence of decreasing $p_{\perp}$ $\Rightarrow$ corrections
- double Gaussian matter distribution $\Rightarrow b$ dep. $\Leftrightarrow$ pedestal effect; height tunable but saturation $p_{\perp}$ scale predicted
- colour (re)arrangement for reduced string length to describe $\langle p_{\perp} \rangle (n_{\mathrm{charged}})$
- simplify process description after first interaction
- virtuality-ordered showers & string fragmentation
- MB & UE unified, diffraction not (too many uncertainties)
- once HERA PDF: $p_{\perp 0}(s) = p_{\perp 0}(s_0)(s/s_0)^{\epsilon}$, $\epsilon \approx 0.08$ (DL)

Programs

name	~year	features
(Orsay)	1982	cut Pomerons, unitarized (unpublished)
ISAJET	1982	cut Pomerons, no diff
PYTHIA4	1986	pert. MI, MB&UE unified, diff. separate
HERWIG	1988	UA5 nonpert. parametrization, no diff
DTUJET	1990	pert. MI and cut Pomerons, unitarized
PHOJET	1995	pert. MI and cut Pomerons, unitarized (PYTHIA)
JIMMY	1996	HERWIG add-on, pert. MI for UE, no MB, no diff
(IVAN)	2002	HERWIG add-on, pert. and nonpert. MI
PYTHIA6	2004	PYTHIA4 upgrade: interleaved MI + ISR, new PDF
SHERPA	2006	PYTHIA scheme + CKKW
PYTHIA8	2007	PYTHIA6 upgrade: interleaved MI + ISR + FSR

The weak strong-interactions assumption

Interactions between the two incoming hadrons

- can be cleanly separated into a set of uncorrelated hard interactions,
- each embedded in its separate initial-and final-state showering,
- with confinement forces acting inside each set of colour charges,
- to give hadronization exactly like in $\mathrm{e}^{+}\mathrm{e}^{-}$.

Based on the principle of the drunkard, the lost keys and the lamppost

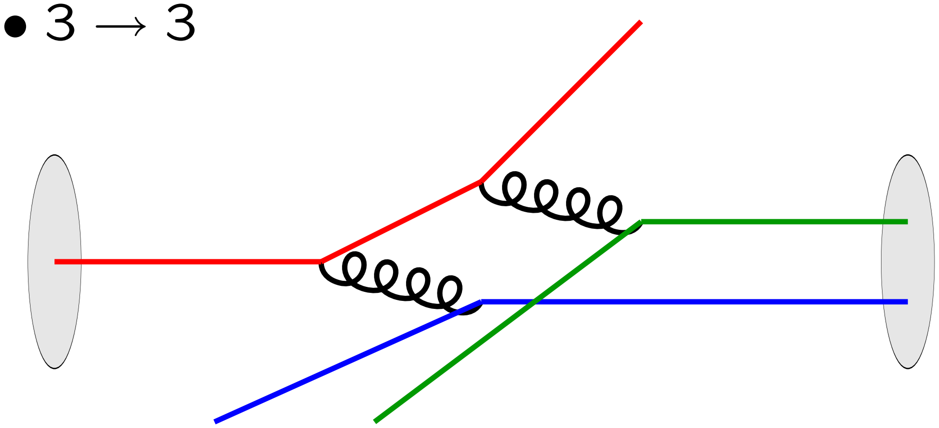
What if “new” collective effects are non-negligible?

Possible counterarguments:

- intertwined hard interactions? (next slide)
- close-packing in initial-state, especially at small x?
- rescattering between outgoing partons? (beginning of QG plasma)
- colour charges/strings closely packed $\Rightarrow$ coherent effects?
  (colour ropes? colour reconnection!)
- produced hadrons closely packed $\Rightarrow$ coherent effects?
  (interacting hadron gas? collective flow?)

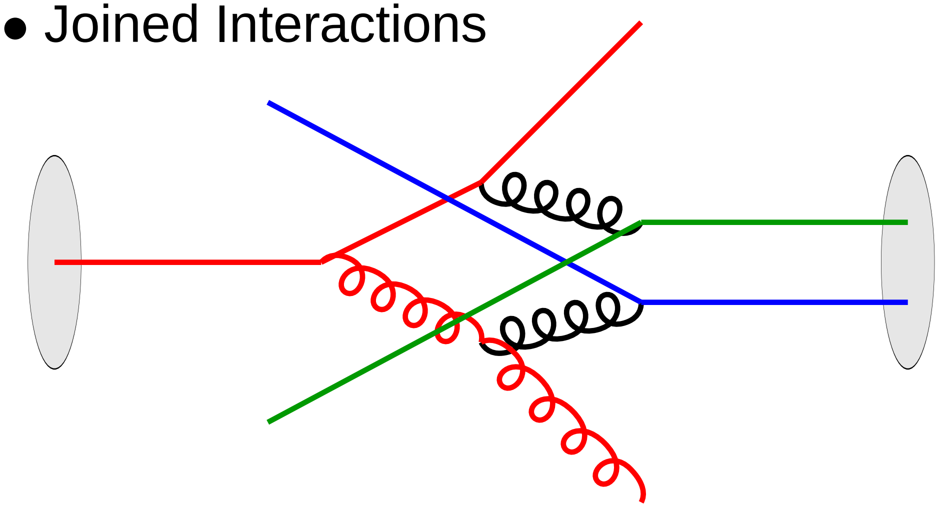
Missing topologies: intertwined hard interactions

- $3 \rightarrow 3$



expected to be small . . .
(Paver & Treleani)
. . . but what
consequences neglect?

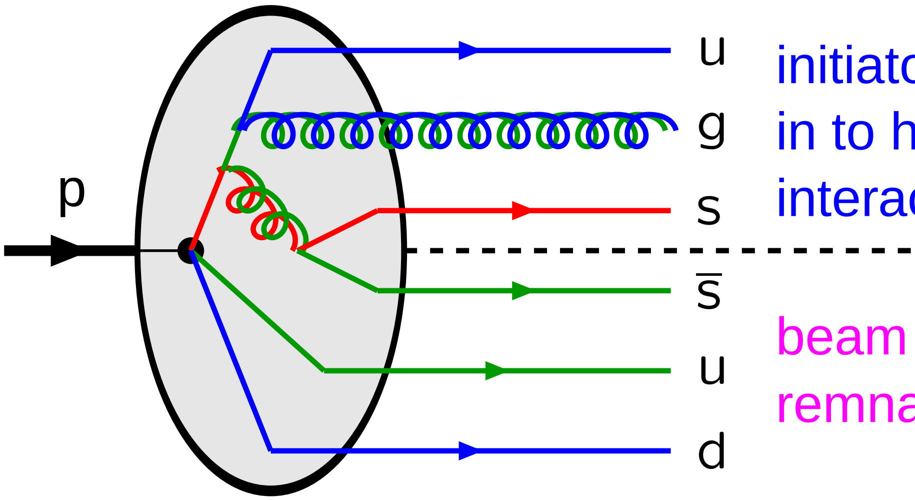
- Joined Interactions



expected to be small . . .
(Snigirev; Skands & TS)
. . . but again what
consequences neglect?

Both of these are doable!

Initiators and Remnants



Need to assign:

- correlated flavours
- correlated $x_i = p_{zi}/p_{z\text{tot}}$
- correlated primordial $k_{\perp i}$
- correlated colours
- correlated showers

- **PDF after preceding MI/ISR activity:**

0) Squeeze range $0 < x < 1$ into $0 < x < 1 - \sum x_i$ (ISR: $i \neq i_{\text{current}}$)

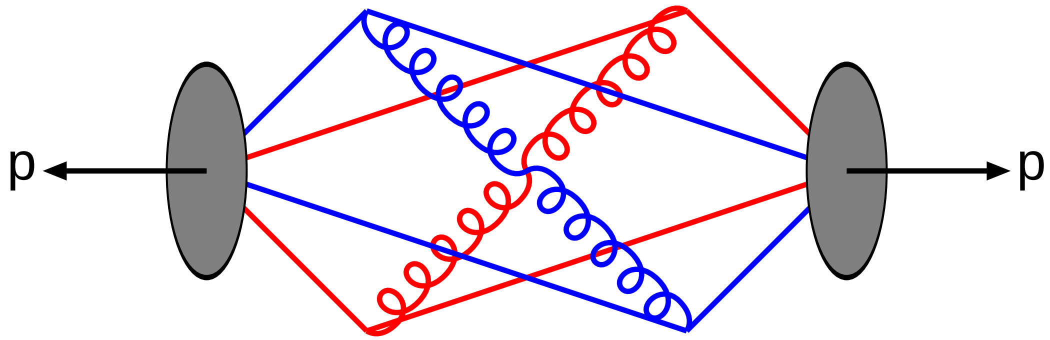
1) Valence quarks: scale down by number already kicked out

2) Introduce companion quark $\text{q}/\overline{\text{q}}$ to each kicked-out sea quark $\overline{\text{q}}/\text{q}$, with x based on assumed $\text{g} \to \text{q}\overline{\text{q}}$ splitting

3) Gluon and other sea: rescale for total momentum conservation

Certainly not perfect, but maybe good enough?

Colour correlations



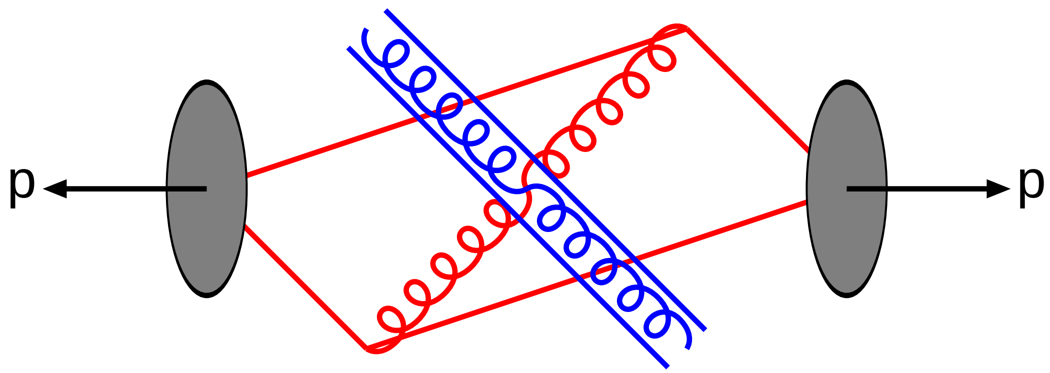
long strings to remnants

$\Rightarrow$ much n_{ch}/interaction

$\Rightarrow$ few interactions

$\Rightarrow$ little $p_{\perp\text{pert}}$

$\Rightarrow$ $\langle p_\perp \rangle(n_{\text{ch}}) \sim$ flat



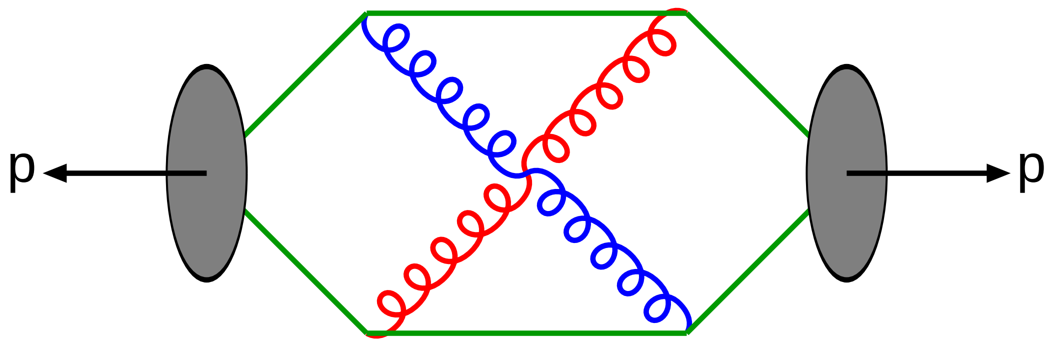
PYTHIA4 simplification:

after hardest interaction

stretch further strings

between scattered gluons

$\Rightarrow$ $\langle p_\perp \rangle(n_{\text{ch}})$ flattens out



short strings (more central)

$\Rightarrow$ less n_{ch}/interaction

$\Rightarrow$ more interactions

$\Rightarrow$ more $p_{\perp\text{pert}}$

$\Rightarrow$ $\langle p_\perp \rangle(n_{\text{ch}})$ rising

Studied in many variants of PYTHIA:

1987:

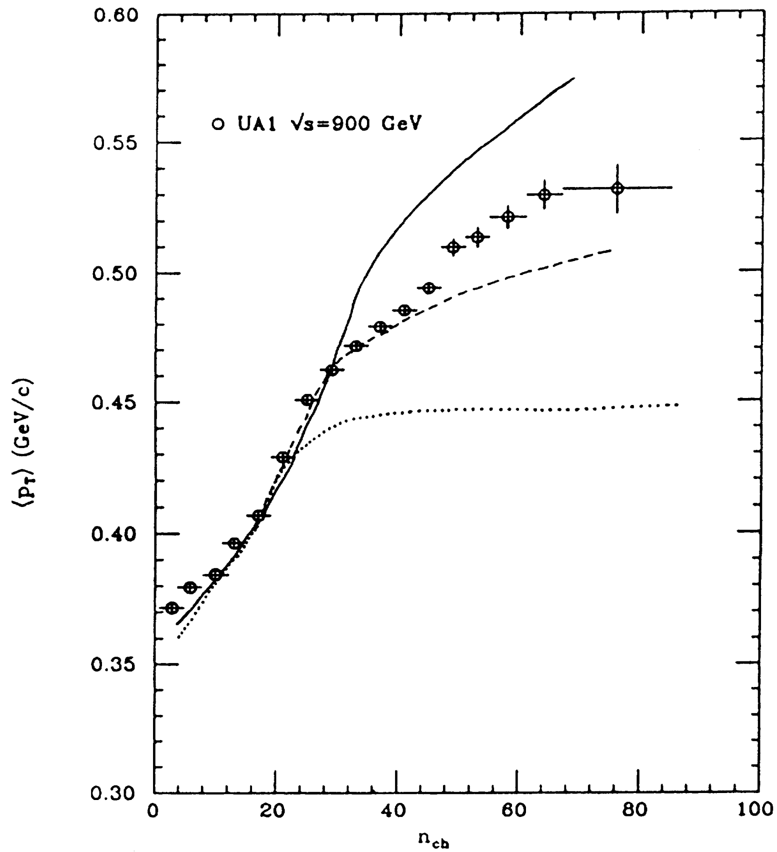
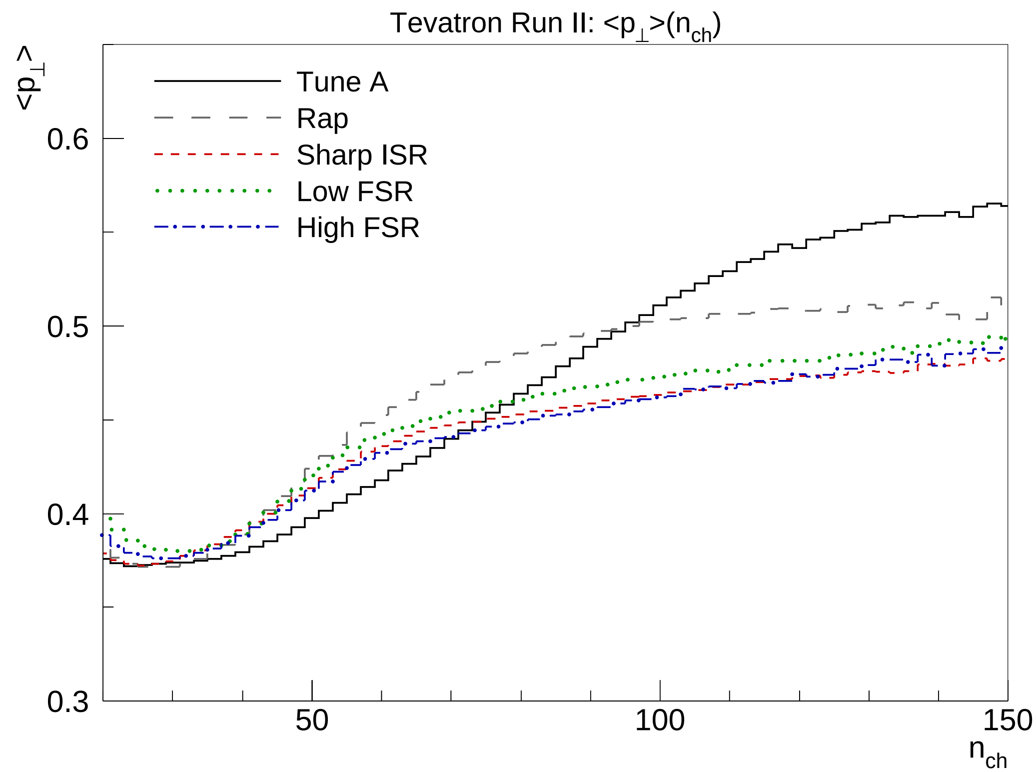
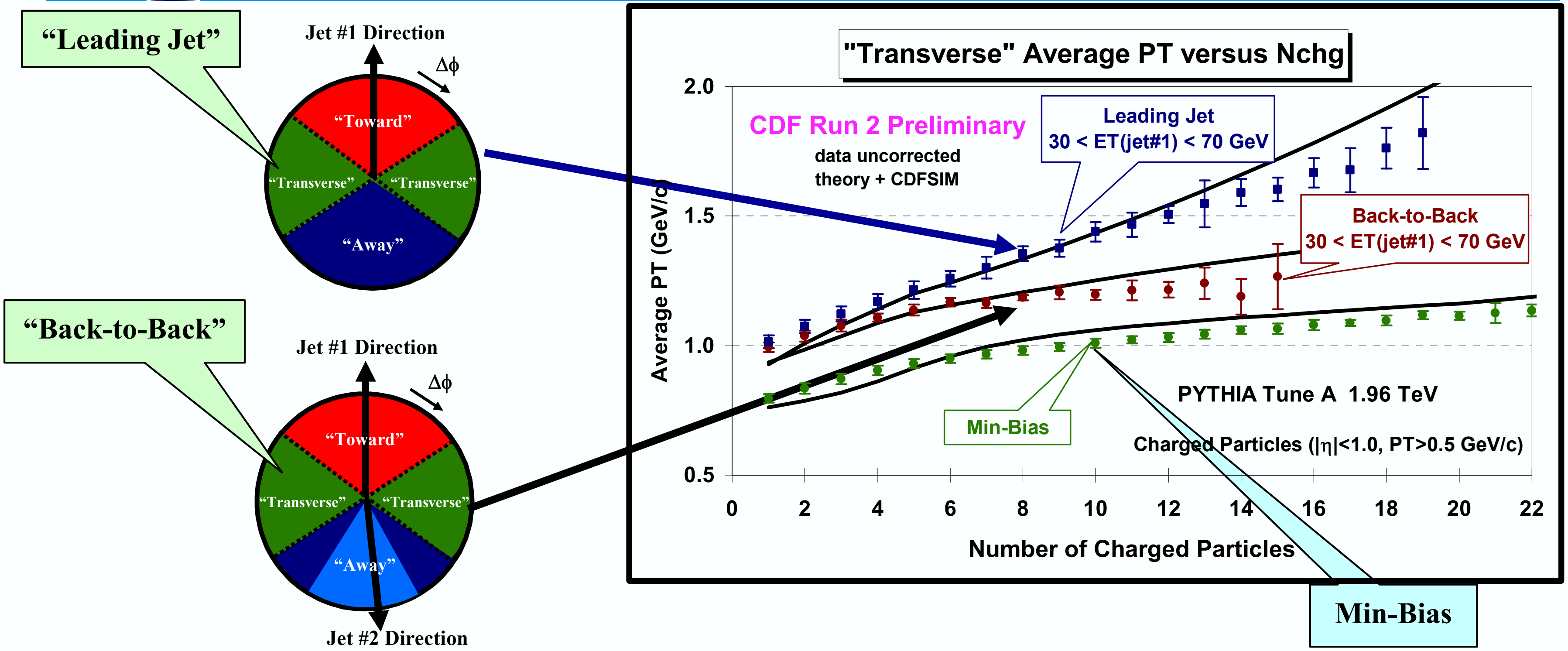


FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings only; dotted line, gg scatterings with "maximal" string length; solid line gg scatterings with "minimal" string length.

2004:

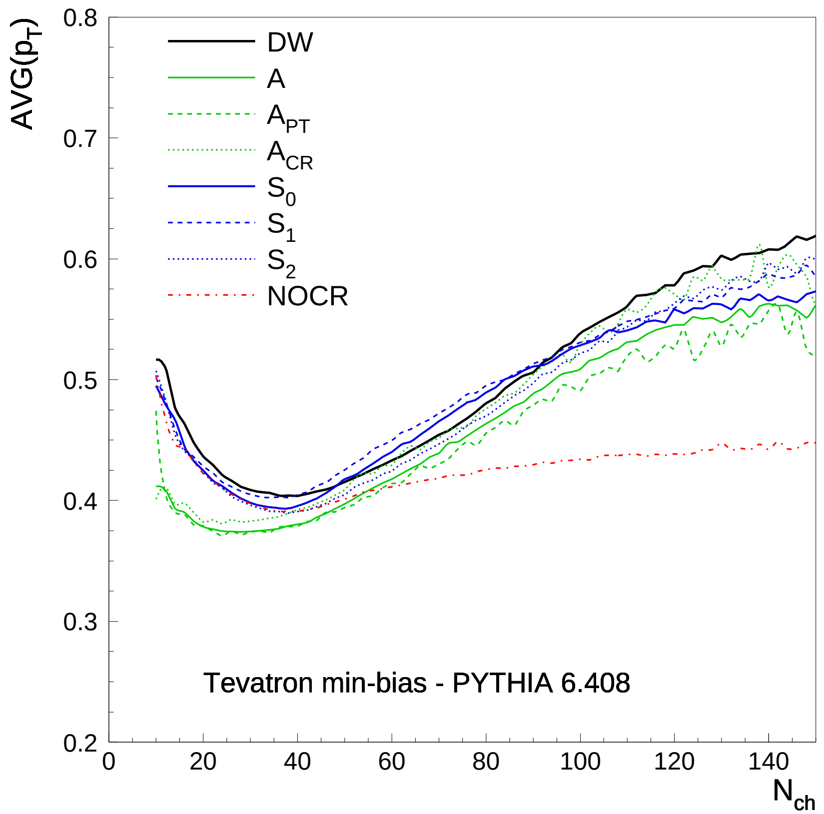


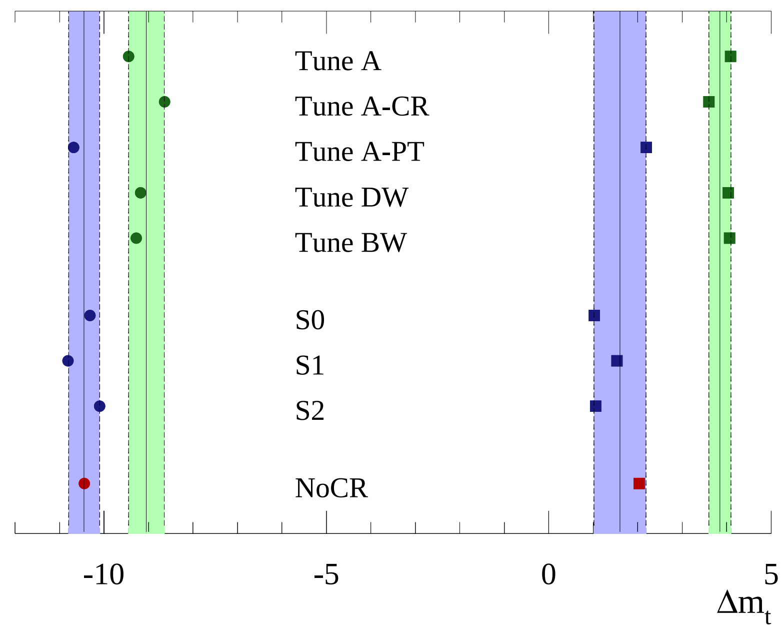
"Transverse" $\langle p_T \rangle$ versus "Transverse" Nchg



- Look at the $\langle p_T \rangle$ of particles in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus the number of particles in the "transverse" region: $\langle p_T \rangle$ vs Nchg.
- Shows $\langle p_T \rangle$ versus Nchg in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) for "Leading Jet" and "Back-to-Back" events with $30 < E_T(\text{jet}\#1) < 70$ GeV compared with "min-bias" collisions.

2007 (Skands & Wicke): also top mass determinations affected





Any other independent program/approach with possibility to check this?

Impact-parameter and Pomeron pictures

- No reason except laziness for simple universal Gaussian
  - ⋆ JIMMY proton EM form factor $\approx$ double Gaussian
  - ⋆ "true" form or representing averaged "hot spots"?
- (x, b) correlations, e.g.
  - ⋆ large-x partons more central?
  - ⋆ valence quarks more central?

- Are separate hard and soft pomerons required?
  - ⋆ how to merge consistently? with smooth transition?
  - ⋆ different energy dependence?
  - ⋆ different impact-parameter profile?
  - ⋆ how to test for it experimentally?
- Does eikonalization uniquely predict diffractive cross section?
  - ⋆ diffraction from soft colour exchanges?
    (Buchmüller & Hebecker, Ingelman & Rathsman)
  - ⋆ in any scenario, how many parameters & unproven assumptions?
  - ⋆ numerics unstable, e.g. colour flow choice
    $\Rightarrow p_{\perp 0}$ value $\Rightarrow \sigma_{\text{jet}} \Rightarrow$ eikonal $\chi(b, s) \Rightarrow \sigma_{\text{diffraction}}$

Low-$p_\perp$ regularization

- $p_{\perp 0}$ regularization scale $\approx$ 2 GeV unexpectedly large
  $\Rightarrow r_0 = 0.1$ fm average colour screening separation?
  $\star$ any support for existence of such a scale?
  $\star$ Gustafson & Miu: effectively arises with unintegrated PDF's
  $\star$ non-universality for x and flavour? (cf. impact parameter)
- energy dependence $p_{\perp 0}(s) = p_{\perp 0}(s_0)(s/s_0)^\epsilon$, $\epsilon \approx 0.08$
  not based on any sound theory
  $\star$ Gustafson & Miu: $p_{\perp 0}(s)$ should flatten out

$\Longrightarrow$ MI model based on unintegrated PDF's (& CCFM showers) highly desirable!

- Typically primordial $k_\perp \sim 2$ GeV needed for W/Z $p_\perp$ spectrum
  missing understood BFKL/CCFM showering?
  missing not understood showering?
  nontrivial nonperturbative/collective effects?
  any relationship to $p_{\perp 0} \sim 2$ GeV?

What cross-section to unitarize?

Accuracy requires "correct" starting $\mathrm{d}\sigma_{\mathrm{jet}}/\mathrm{d}p_{\perp}\mathrm{d}y$ at all $p_{\perp} \gtrsim p_{\perp 0}/2$.

Higher-order corrections e.g. from

- higher-order ME's and PDF's, or
- K-factors (fix or in α_{s} scale choice)
- showering effects

Watch out: NLO PDF's ill-behaved at small x & Q^2 from compensating $\ln(1/x)$ terms in NLO ME's.

Tune QWT: $p_{\perp 0} = 1.1$ GeV.

Tune QKT: $K = 1.8$ (at all $p_{\perp}$!).

Benchmark $\hat{\sigma}(\mathrm{NLO}) \otimes \mathrm{PDF(NLO)}$

vs. $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF(LO)} \otimes$ showers

vs. $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF(NLO)} \otimes$ showers

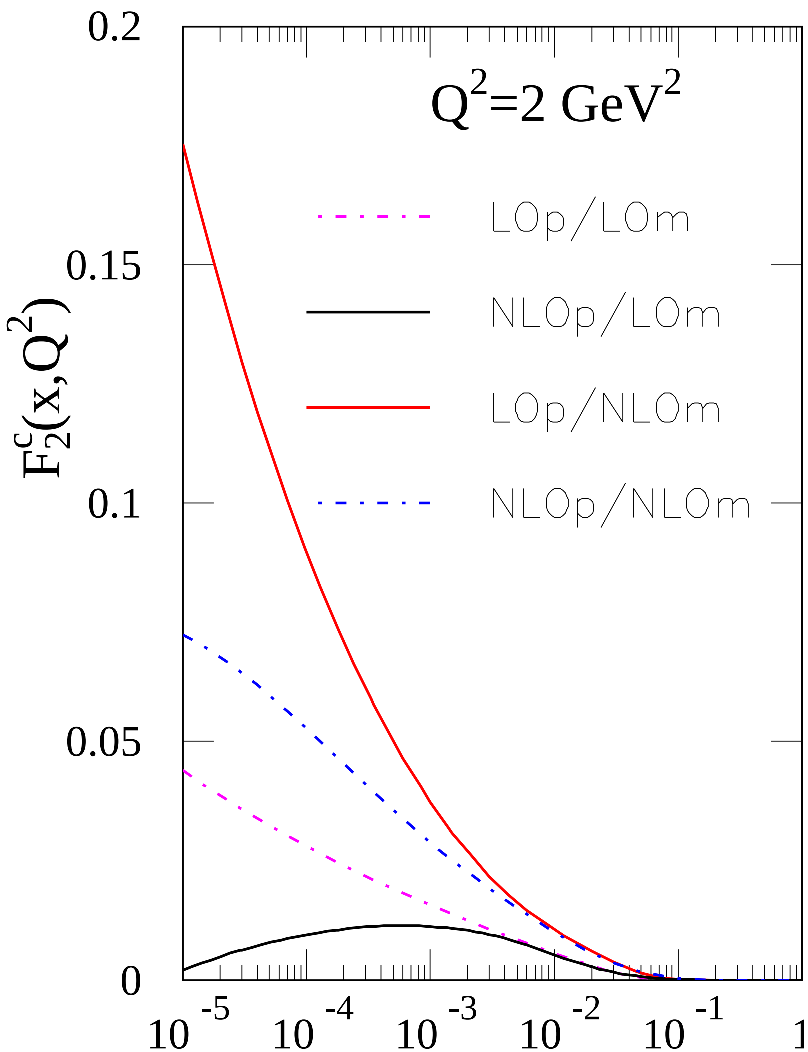
vs. jet + minijet data (where possible)

Alternative: improved LO PDF's

e.g. Thorne LO* relaxed p sum rule

Robert Thorne

(ATLAS mtg, 14 Dec 2006):



Conclusions

PYTHIA has sufficiently many parameters that decent tunes to much Tevatron data can be achieved, but also some successful predictions.

HERWIG standalone fails $\Rightarrow$ minijet scenario success.

HERWIG+JIMMY has fewer (but many!) parameters, can describe a lot but misses out on connection MB $\Leftrightarrow$ UE

PHOJET should be better studied: can it be tuned to Tevatron data? Different energy dependence than PYTHIA. Could probe role of soft pomeron.

SHERPA does away with PYTHIA showering parameters (e.g. PARP(67)) by CKKW $\Rightarrow$ more predictive?

Some "obvious" improvements should be addressed.
+ Explore non-obvious variants, in particular unintegrated PDF's.

"real theory" has been largely decoupled from experiment for last 20 years
$\Rightarrow$ time to popularize progress in useful form?

For experimental discussion

Need more experimentalists who understand, analyze and communicate:
fixed-target $\to$ ISR $\to$ **RHIC(pp)** $\to$ Sp$\overline{\text{p}}$S $\to$ **Tevatron** $\to$ LHC
with special responsibility for running experiments

Need reproducible data, not necessarily corrected but with fully specified comparison procedures (HZtool $\to$ Rivet)

Examples of useful distributions:

- charged multiplicity distributions
- flavour composition
- single-particle and jet $p_\perp$ spectra
- $\langle p_\perp \rangle (n_{\text{charged}})$
- $p_\perp$ spectra of Drell-Yan pairs as a function of mass and energy
- jet profiles (mass, angular shape, substructure, . . .)
- underlying-event activity
- number of minijets as a function of cone size and jet energy
- forward–backward and other correlations