Minimum-Bias and Underlying-Event Physics

Torbjörn Sjöstrand

Department of Theoretical Physics, Lund University
What is minimum bias?

≈ “all events, with no bias from restricted trigger conditions”

\[ \sigma_{\text{tot}} = \sigma_{\text{elastic}} + \sigma_{\text{single-diffractive}} + \sigma_{\text{double-diffractive}} + \ldots + \sigma_{\text{non-diffractive}} \]

reality: \( \sigma_{\text{min-bias}} \approx \sigma_{\text{non-diffractive}} + \sigma_{\text{double-diffractive}} \approx \frac{2}{3} \times \sigma_{\text{tot}} \)

What is underlying event?

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jet

underlying event

pedestal height
What is multiple interactions?

Cross section for $2 \rightarrow 2$ interactions is dominated by $t$-channel gluon exchange, so diverges like $d\hat{\sigma}/dp_{\perp}^2 \approx 1/p_{\perp}^4$ for $p_{\perp} \rightarrow 0$.

integrate QCD $2 \rightarrow 2$
- $qq' \rightarrow qq'$
- $q\bar{q} \rightarrow q'\bar{q}'$
- $q\bar{q} \rightarrow gg$
- $qg \rightarrow qg$
- $gg \rightarrow gg$
- $gg \rightarrow q\bar{q}$

with CTEQ 5L PDF's

Integrated cross section above $p_{T\text{min}}$ for $pp$ at 14 TeV

$
\begin{array}{c}
\text{jet cross section} \\
\text{total cross section}
\end{array}$

Integrated cross section above $p_{T\text{min}}$ for $pp$ at 14 TeV
\[ \sigma_{\text{int}}(p_{\perp \text{min}}) = \iiint_{p_{\perp \text{min}}} dx_1 \, dx_2 \, dp_{\perp}^2 \, f_1(x_1, p_{\perp}^2) \, f_2(x_2, p_{\perp}^2) \, \frac{d\sigma}{dp_{\perp}^2} \]

Half a solution to \( \sigma_{\text{int}}(p_{\perp \text{min}}) > \sigma_{\text{tot}} \): many interactions per event

\[ \sigma_{\text{tot}} = \sum_{n=0}^{\infty} \sigma_n \]
\[ \sigma_{\text{int}} = \sum_{n=0}^{\infty} n \, \sigma_n \]

If interactions occur independently then Poissonian statistics

\[ P_n = \frac{\langle n \rangle^n}{n!} \, e^{-\langle n \rangle} \]

but energy–momentum conservation \( \Rightarrow \) large \( n \) suppressed
Other half of solution:
perturbative QCD not valid at small $p_\perp$ since q, g not asymptotic states (confinement!).

Naively breakdown at

$$p_{\perp \text{min}} \approx \frac{\overline{\hbar}}{r_p} \approx \frac{0.2 \text{ GeV} \cdot \text{fm}}{0.7 \text{ fm}} \approx 0.3 \text{ GeV} \approx \Lambda_{\text{QCD}}$$

...but better replace $r_p$ by (unknown) colour screening length $d$ in hadron

\[ \lambda \sim \frac{1}{p_\perp} \]
so modify

\[
\frac{d\tilde{\sigma}}{dp^2_{\perp}} \propto \frac{\alpha_s^2(p^2_{\perp})}{p^4_{\perp}} \rightarrow \frac{\alpha_s^2(p^2_{\perp})}{p^4_{\perp}} \theta(p_{\perp} - p_{\perp \min}) \quad \text{(simpler)}
\]

or

\[
\rightarrow \frac{\alpha_s^2(p^2_{\perp 0} + p^2_{\perp})}{(p^2_{\perp 0} + p^2_{\perp})^2} \quad \text{(more physical)}
\]

where \(p_{\perp \min}\) or \(p_{\perp 0}\) are free parameters, empirically of order 2 GeV

Typically 2 – 3 interactions/event at the Tevatron, 4 – 5 at the LHC, but may be more in “interesting” high-\(p_{\perp}\) ones.
Basic generation of multiple interactions

• For now exclude diffractive (and elastic) topologies, i.e. only model nondiffractive events, with $\sigma_{nd} \simeq 0.6 \times \sigma_{tot}$

• Differential probability for interaction at $p_{\perp}$ is

$$\frac{dP}{dp_{\perp}} = \frac{1}{\sigma_{nd}} \frac{d\sigma}{dp_{\perp}}$$

• Average number of interactions naively

$$\langle n \rangle = \frac{1}{\sigma_{nd}} \int_{0}^{E_{cm}/2} \frac{d\sigma}{dp_{\perp}} dp_{\perp}$$

• Require $\geq 1$ interaction in an event or else pass through without anything happening

$$P_{\geq 1} = 1 - P_{0} = 1 - \exp(-\langle n \rangle)$$

(Alternatively: allow soft nonperturbative interactions even if no perturbative ones.)
Can pick \( n \) from Poissonian and then generate \( n \) independent interactions according to \( d\sigma/dp_\perp \) (so long as energy left), or better...

...generate interactions in ordered sequence \( p_\perp 1 > p_\perp 2 > p_\perp 3 > \ldots \)

- recall “Sudakov” trick used e.g. for parton showers:
  if probability for something to happen at “time” \( t \) is \( P(t) \) and happenings are uncorrelated in time (Poissonian statistics) then the probability for a \textit{first} happening after 0 at \( t_1 \) is

\[
P(t_1) = P(t_1) \exp \left( - \int_0^{t_1} P(t) \, dt \right)
\]

and for an \( i \)'th at \( t_i \) is

\[
P(t_i) = P(t_i) \exp \left( - \int_{t_{i-1}}^{t_i} P(t) \, dt \right)
\]

- Apply to ordered sequence of decreasing \( p_\perp \), starting from \( E_{\text{cm}}/2 \)

\[
P(p_\perp = p_{\perp i}) = \frac{1}{\sigma_{\text{nd}}} \frac{d\sigma}{dp_\perp} \exp \left[ - \int_{p_\perp}^{p_{\perp(i-1)}} \frac{1}{\sigma_{\text{nd}}} \frac{d\sigma}{dp'_\perp} dp'_\perp \right]
\]

- Use rescaled PDF’s taking into account already used momentum

\( \implies n_{\text{int}} \) narrower than Poissonian
Impact parameter dependence

So far assumed that all collisions have equivalent initial conditions, but hadrons are extended, e.g. empirical double Gaussian:

\[ \rho_{\text{matter}}(r) = N_1 \exp\left(-\frac{r^2}{r_1^2}\right) + N_2 \exp\left(-\frac{r^2}{r_2^2}\right) \]

where \( r_2 \neq r_1 \) represents "hot spots", and overlap of hadrons during collision is

\[ \mathcal{O}(b) = \int d^3x \, dt \, \rho_{1,\text{matter}}(x, t) \rho_{2,\text{matter}}(x, t) \]

or electromagnetic form factor:

\[ S_p(b) = \int \frac{d^2k}{2\pi} \frac{\exp(i k \cdot b)}{(1 + k^2/\mu^2)^2} \]

where \( \mu = 0.71 \text{ GeV} \rightarrow \) free parameter, which gives

\[ O(b) = \frac{\mu^2}{96\pi} (\mu b)^3 K_3(\mu b) \]
- Events are distributed in impact parameter $b$
- Average activity at $b$ proportional to $\mathcal{O}(b)$
  - central collisions more active $\Rightarrow P_n$ broader than Poissonian
  - peripheral passages normally give no collisions at all $\Rightarrow$ finite $\sigma_{\text{tot}}$
- Also crucial for pedestal effect (more later)
PYTHIA implementation

(1) Simple scenario (1985):
first model for event properties based on perturbative multiple interactions
no longer used (no impact-parameter dependence)

(2) Impact-parameter-dependence (1987):
still in frequent use (Tune A, Tune DWT, ATLAS tune, . . . )
• double Gaussian matter distribution,
• interactions ordered in decreasing $p_\perp$,
• PDF’s rescaled for momentum conservation,
• but no showers for subsequent interactions and simplified flavours

(3) Improved handling of PDFs and beam remnants (2004)
• Trace flavour content of remnant,
  including baryon number (junction)
• Study colour (re)arrangement
  among outgoing partons (ongoing!)
• Allow radiation for all interactions
(4) Evolution interleaved with ISR (2004)

- Transverse-momentum-ordered showers

\[ \frac{d\mathcal{P}}{dp_\perp} = \left( \frac{d\mathcal{P}_{\text{MI}}}{dp_\perp} + \sum \frac{d\mathcal{P}_{\text{ISR}}}{dp_\perp} \right) \exp \left( - \int_{p_\perp}^{p_{\perp i-1}} \left( \frac{d\mathcal{P}_{\text{MI}}}{dp'_\perp} + \sum \frac{d\mathcal{P}_{\text{ISR}}}{dp'_\perp} \right) dp'_\perp \right) \]

with ISR sum over all previous MI

(5) Rescattering (in progress)

is 3 → 3 instead of 4 → 4:
HERWIG implementation

(1) Soft Underlying Event (1988), based on UA5 Monte Carlo

- Distribute a ($\sim$ negative binomial) number of clusters independently in rapidity and transverse momentum according to parametrization/extrapolation of data
- Modify for overall energy/momentum/flavour conservation
- No minijets; correlations only by cluster decays

(2) Jimmy (1995; HERWIG add-on; part of HERWIG++)

- Only model of underlying event, not of minimum bias
- Similar to PYTHIA (2) above; but details different
- Matter profile by electromagnetic form factor (with tuned size)
- No $p_{\perp}$-ordering of emissions, no rescaling of PDF: abrupt stop when (if) run out of energy

(3) Ivan (2002, code not public; in progress)

- Also handles minimum bias
- Soft and hard multiple interactions together fill whole $p_{\perp}$ range
SHERPA implementation

(1) Conventional approach (2005)
- Based on formalism of PYTHIA (2) but
- Full showers for all interactions, with CKKW matching

(2) $k_\perp$-factorization-based approach (2007)
- unintegrated PDFs and off-shell matrix elements
- consistent with BFKL evolution (small $x$)
- combination with multiple interactions in progress
PhoJet (& relatives) implementation

(1) Cut Pomeron (1982)
- Pomeron predates QCD; nowadays \( \sim \) glueball tower
- Optical theorem relates \( \sigma_{\text{total}} \) and \( \sigma_{\text{elastic}} \)

\[
\sigma_{\text{total}} \propto \sigma_{\text{elastic}}^2
\]

- Unified framework of nondiffractive and diffractive interactions
- Purely low-\( p_\perp \): only primordial \( k_\perp \) fluctuations
- Usually simple Gaussian matter distribution

(2) Extension to large \( p_\perp \) (1990)
- distinguish soft and hard Pomerons (cf. Ivan):
  - soft = nonperturbative, low-\( p_\perp \), as above
  - hard = perturbative, “high”-\( p_\perp \)
- hard based on PYTHIA code, with lower cutoff in \( p_\perp \)
FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low $p_T$ only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

without multiple interactions
with multiple interactions

FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\text{min}} = 2.0$ GeV; solid line, $p_{T\text{min}} = 1.6$ GeV; dashed-dotted line, $p_{T\text{min}} = 1.2$ GeV.

FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.
Direct observation of multiple interactions


Order 4 jets $p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > p_{\perp 4}$ and define $\varphi$ as angle between $p_{\perp 1} \mp p_{\perp 2}$ and $p_{\perp 3} \mp p_{\perp 4}$ for AFS/CDF

**Double Parton Scattering**

\[ |p_{\perp 1} + p_{\perp 2}| \approx 0 \]
\[ |p_{\perp 3} + p_{\perp 4}| \approx 0 \]
\[ \frac{d\sigma}{d\varphi} \text{ flat} \]

**Double BremsStrahlung**

\[ |p_{\perp 1} + p_{\perp 2}| \gg 0 \]
\[ |p_{\perp 3} + p_{\perp 4}| \gg 0 \]
\[ \frac{d\sigma}{d\varphi} \text{ peaked at } \varphi \approx 0/\pi \text{ for AFS/CDF} \]

AFS 4-jet analysis (pp at 63 GeV): observe 6 times Poissonian prediction, with impact parameter expect 3.7 times Poissonian, but big errors $\Rightarrow$ low acceptance, also UA2
CDF 3-jet + prompt photon analysis

Yellow region = double parton scattering (DPS)

The rest = PYTHIA showers

\[ \sigma_{\text{DPS}} = \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \quad \text{for} \quad A \neq B \quad \implies \sigma_{\text{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3} \text{ mb} \]

Strong enhancement relative to naive expectations!
Same study also planned for LHC

Selection for DPS

delicate balance:

showers dominate at large $p_\perp$

$\Rightarrow$ too large background

multiple interactions dominate at small $p_\perp$, but there jet identification difficult

\begin{align*}
\text{ISR/FSR off} \\
\text{MI off}
\end{align*}

Pythia 8.108

$pp \rightarrow \gamma + X @ 14 \text{ TeV}$
Jet pedestal effect

Events with hard scale (jet, W/Z, …) have more underlying activity! Events with \( n \) interactions have \( n \) chances that one of them is hard, so “trigger bias”: hard scale \( \Rightarrow \) central collision \( \Rightarrow \) more interactions \( \Rightarrow \) larger underlying activity.

Centrality effect saturates at \( p_{\perp\text{hard}} \sim 10 \text{ GeV} \).

Studied in detail by Rick Field, comparing with CDF data:

“MAX/MIN Transverse” Densities

- Define the MAX and MIN “transverse” regions on an event-by-event basis with MAX (MIN) having the largest (smallest) density.
“Leading Jet” events correspond to the leading calorimeter jet (MidPoint $R = 0.7$) in the region $|\eta| < 2$ with no other conditions.

“Inclusive 2-Jet Back-to-Back” events are selected to have at least two jets with Jet#1 and Jet#2 nearly “back-to-back” ($\Delta \phi_{12} > 150^\circ$) with almost equal transverse energies ($P_T(jet#2)/P_T(jet#1) > 0.8$) with no other conditions.

“Exclusive 2-Jet Back-to-Back” events are selected to have at least two jets with Jet#1 and Jet#2 nearly “back-to-back” ($\Delta \phi_{12} > 150^\circ$) with almost equal transverse energies ($P_T(jet#2)/P_T(jet#1) > 0.8$) and $P_T(jet#3) < 15$ GeV/c.

“Leading ChgJet” events correspond to the leading charged particle jet ($R = 0.7$) in the region $|\eta| < 1$ with no other conditions.

“Z-Boson” events are Drell-Yan events with $70 < M(\text{lepton-pair}) < 110$ GeV with no other conditions.
Tuned PYTHIA 6.206
“Transverse” $P_T$ Distribution

Comparing the average “transverse” charge particle density ($|\eta|<1$, $P_T>0.5$ GeV) versus $P_T$(charged jet#1) and the $P_T$ distribution of the “transverse” density, $dN_{\text{chg}}/d\eta d\phi dP_T$ with the QCD Monte-Carlo predictions of two tuned versions of PYTHIA 6.206 ($P_T$(hard) > 0, CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

- PARP(67)=4.0 (old default) is favored over PARP(67)=1.0 (new default)!

CDF Preliminary data uncorrected
theory corrected

1.8 TeV $|\eta|<1$ PT>0.5 GeV

CDF Data
data uncorrected
theory corrected

$P_T$(charged jet#1) > 30 GeV/c

$P_T$(charged jet#1) > 5 GeV/c
Jet-Jet Correlations (DØ)

Jet#1-Jet#2 $\Delta \phi$ Distribution

- MidPoint Cone Algorithm ($R = 0.7$, $f_{\text{merge}} = 0.5$)
- $\mathcal{L} = 150$ pb$^{-1}$ (Phys. Rev. Lett. 94 221801 (2005))
- Data/NLO agreement good. Data/HERWIG agreement good.
- Data/PYTHIA agreement good provided PARP(67) = 1.0→4.0 (i.e. like Tune A, best fit 2.5).
Leading Jet: “MAX & MIN Transverse” Densities

PYTHIA Tune A

HERWIG

Charged particle density and PTsum density for “leading jet” events versus E_{T}(jet#1) for PYTHIA Tune A and HERWIG.
"Transverse 1" Region vs "Transverse 2" Region

CDF Run 2 Preliminary
Leading Jet
30 < ET(jet#1) < 70 GeV

1.96 TeV

Charged Particles (|η|<1.0, PT>0.5 GeV/c)

CDF Run 2 Preliminary
Back-to-Back
30 < ET(jet#1) < 70 GeV

1.96 TeV

Charged Particles (|η|<1.0, PT>0.5 GeV/c)

CDF Run 2 Preliminary
Leading Jet
30 < ET(jet#1) < 70 GeV

1.96 TeV

Charged Particles (|η|<1.0, PT>0.5 GeV/c)

CDF Run 2 Preliminary
Back-to-Back
30 < ET(jet#1) < 70 GeV

1.96 TeV

Charged Particles (|η|<1.0, PT>0.5 GeV/c)
PYTHIA Tune A vs JIMMY: “Transverse Region”

- (left) Run 2 data for charged scalar PTsum density (|\eta|<1, p_T>0.5 GeV/c) in the MAX/MIN/AVE “transverse” region versus p_T(jet#1) compared with PYTHIA Tune A (after CDFSIM).

- (right) Shows the generator level predictions of PYTHIA Tune A (dashed) and JIMMY (P_Tmin=1.8 GeV/c) for charged scalar PTsum density (|\eta|<1, p_T>0.5 GeV/c) in the MAX/MIN/AVE “transverse” region versus p_T(jet#1).

- The tuned JIMMY now agrees with PYTHIA for P_T(jet#1) < 100 GeV but produces much more activity than PYTHIA Tune A (and the data?) in the “transverse” region for P_T(jet#1) > 100 GeV!
"Associated" charged particle density

Shows the $\Delta \phi$ dependence of the "associated" charged particle density, $dN_{\text{chg}} / d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, $\text{PTmaxT} > 2.0$ GeV/c (not including $\text{PTmaxT}$) relative to $\text{PTmaxT}$ (rotated to $180^\circ$) and the charged particle density, $dN_{\text{chg}} / d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to $270^\circ$) for "back-to-back events" with $30 < E_T(\text{jet#1}) < 70$ GeV.
“Associated” Charge Density
PYTHIA Tune A vs HERWIG

PTmaxT > 2 GeV/c

Associated Particle Density: \(\frac{dN}{d\eta d\phi}\)

- Charged Particles (|\(\eta|<1.0, \text{PT}>0.5 \text{GeV/c}\))
- PTmaxT not included

Back-to-Back
30 < ET(jet\#1) < 70 GeV
Charged Particles (|\(\eta|<1.0, \text{PT}>0.5 \text{GeV/c}\))

PTmaxT not included

CDF Preliminary data uncorrected
theory + CDFSIM

PTmaxT > 2.0 GeV/c

For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too many “associated” particles in the direction of PTmaxT!

But HERWIG (without multiple parton interactions) produces too few particles in the direction opposite of PTmaxT!
CDF Run 1 $P_T(Z)$

**PYTHIA 6.2 CTEQ5L**

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> Shows the Run 1 Z-boson $p_T$ distribution ($<p_T(Z)> \approx 11.5$ GeV/c) compared with PYTHIA Tune DW, and HERWIG.

Tune DW uses D0’s preferred value of PARP(67)!

Tune DW has a lower value of PARP(67) and slightly more MPI!
Data at 1.96 TeV on the density of charged particles, dN/dηdφ, with p_T > 0.5 GeV/c and |η| < 1 for “leading jet” events as a function of the leading jet p_T for the “toward”, “away”, and “transverse” regions. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune A at the particle level (i.e. generator level).
Data at 1.96 TeV on the density of charged particles, \( dN/d\eta d\phi \), with \( p_T > 0.5 \text{ GeV/c} \) and \( |\eta| < 1 \) for "Z-Boson" events as a function of the leading jet \( p_T \) for the "toward", "away", and "transverse" regions. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW at the particle level (i.e. generator level).
Data at 1.96 TeV on the density of charged particles, $dN/d\eta d\phi$, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for “Z-Boson” and “Leading Jet” events as a function of the leading jet $p_T$ or $p_T(Z)$ for the “toward”, “away”, and “transverse” regions. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW and Tune A, respectively, at the particle level (i.e. generator level).
Data at 1.96 TeV on the density of charged particles, dN/dηdφ, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for the “toward” region for “Z-Boson” and the “transverse” region for “Leading Jet” events as a function of the leading jet $p_T$ or $P_T(Z)$. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW and Tune A, respectively, at the particle level (i.e. generator level). The Z-Boson data are also compared with PYTHIA Tune DW, the ATLAS tune, and HERWIG (without MPI).
Multiple interactions also preferred by HERA photoproduction data:
underlying activity in photoproduction vs. DIS

(anti)correlations in energy flow around jet

ZEUS 1994 Preliminary

CDF II Preliminary
Colour correlations

\[ \langle p_\perp \rangle (n_{\text{ch}}) \] is very sensitive to colour flow

long strings to remnants ⇒ much
\[ n_{\text{ch}} / \text{interaction} \Rightarrow \langle p_\perp \rangle (n_{\text{ch}}) \sim \text{flat} \]

short strings (more central) ⇒ less
\[ n_{\text{ch}} / \text{interaction} \Rightarrow \langle p_\perp \rangle (n_{\text{ch}}) \text{ rising} \]
"Transverse" $<p_T>$ versus "Transverse" $N_{chg}$

Look at the $<p_T>$ of particles in the “transverse” region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus the number of particles in the “transverse” region: $<p_T>$ vs $N_{chg}$.

Shows $<p_T>$ versus $N_{chg}$ in the “transverse” region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) for “Leading Jet” and “Back-to-Back” events with $30 < E_T(jet#1) < 70$ GeV compared with “min-bias” collisions.
Data at 1.96 TeV on the average $p_T$ of charged particles versus the number of charged particles ($p_T > 0.4$ GeV/c, $|\eta| < 1$) for “min-bias” collisions at CDF Run 2. The data are corrected to the particle level and are compared with PYTHIA Tune A at the particle level (i.e. generator level).
Data at 1.96 TeV on the charged fraction, PTsum/ETsum, for PTsum ($p_T > 0.5 \text{ GeV/c, } |\eta| < 1$) and ETsum (all $p_T, |\eta| < 1$) for “leading jet” events as a function of the leading jet $p_T$ for the “transverse” region. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune A and HERWIG (without MPI) at the particle level (i.e. generator level).
Extrapolation to LHC

Energy dependence of $p_{\perp \text{min}}$ and $p_{\perp 0}$:

Larger collision energy
⇒ probe parton (≈ gluon) density at smaller $x$
⇒ smaller colour screening length $d$
⇒ larger $p_{\perp \text{min}}$ or $p_{\perp 0}$

Post-HERA PDF fits steeper at small $x$
⇒ stronger energy dependence

Current PYTHIA 8 default, tied to CTEQ 5L, is

$$p_{\perp 0}(s) = 2.15 \text{ GeV} \left( \frac{s}{(1.8 \text{ TeV})^2} \right)^{0.08}$$
LHC predictions: pp collisions at $\sqrt{s} = 14$ TeV

- PYTHIA models favour $\ln^2(s)$;
- PHOJET suggests a $\ln(s)$ dependence.

Central Region
(min-bias $dN_{\text{chg}}/d\eta \sim 7$)

- PYTHIA6.214 - tuned
- PHOJET1.12

pp interactions
- UA5 and CDF data

LHC

Tevatron

$P_t$ (leading jet in GeV)

$\sqrt{s}$ (GeV)

$dN_{\text{chg}}/d\eta \sim 15$

$dN_{\text{chg}}/d\eta \sim 30$
LHC predictions: JIMMY4.1 Tunings A and B vs. PYTHIA6.214 – ATLAS Tuning (DC2)

Transverse $N_{\text{chg}}$

$P_t$ (leading jet in GeV)

CDF data

LHC

Tevatron

$x \times 3$

$x \times 4$

$x \times 5$
**UE tunings: Pythia vs. Jimmy**

- **LHC**
  - PYTHIA6.214 - Rome (CTEQ5L)
  - JIMMY4.1 - DC3 (CTEQ6L)

- **CDF data**

- **Tevatron**

- **ATLAS**

- **PTJIM = 4.9**
  - $= 2.8 \times (14 / 1.8)^{0.27}$

- Energy dependent PTJIM generates UE predictions similar to the ones generated by PYTHIA6.2 - ATLAS.
Data at 1.96 TeV on the density of charged particles, dN/d\eta d\phi, with p_T > 0.5 GeV/c and |\eta| < 1 for "Z-Boson" events as a function of P_T(Z) for the "toward" region. The data are corrected to the particle level (with errors that include both the statistical error and the systematic uncertainty) and are compared with PYTHIA Tune AW and HERWIG (without MPI) at the particle level (i.e. generator level).
Multiple Interactions Outlook

Issues requiring further thought and study:

- Multi-parton PDF’s $f_{a_1 a_2 a_3 \ldots} (x_1, Q_{1}^2, x_2, Q_{2}^2, x_3, Q_{3}^2, \ldots)$
- Close-packing in initial state, especially small $x$
- Impact-parameter picture and $(x, b)$ correlations e.g. large-$x$ partons more central!, valence quarks more central?
- Details of colour-screening mechanism
- Rescattering: one parton scattering several times
- Intertwining: one parton splits in two that scatter separately
- Colour sharing: two FS–IS dipoles become one FS–FS one
- Colour reconnection: required for $\langle p_{\perp} \rangle (n_{\text{charged}})$
- Collective effects (e.g. QGP, cf. Hadronization above)
- Relation to diffraction: eikonalization, multi-gap topologies, …

Action items:

- Vigorous experimental program at LHC
- Study energy dependence: RHIC (pp) → Tevatron → LHC
- Develop new frameworks and refine existing ones

Much work ahead!
Welcome to the first International Workshop on Multiple Partonic Interactions at the LHC "1st MPI@LHC".

The objective of this first workshop on Multiple Partonic Interactions (MPI) at the LHC is to raise the profile of MPI studies, summarizing the legacy from the older phenomenology at hadronic colliders and favouring further specific contacts between the theory and experimental communities. The MPI are experiencing a growing popularity and are currently widely invoked to account for observations that would not be explained otherwise: the activity of the Underlying Event, the cross sections for multiple heavy flavour production, the survival probability of large rapidity gaps in hard diffraction, etc. At the same time, the implementation of the MPI effects in the Monte Carlo models is quickly proceeding through an increasing level of sophistication and complexity that in perspective achieves deep general implications for the LHC physics. The ultimate ambition of this workshop is to promote the MPI as unification concept between seemingly heterogeneous research lines and to profit of the complete experimental picture in order to constrain their implementation in the models, evaluating the spin offs on the LHC physics program.