Introduction to Monte Carlo Event Generation
Lecture 4: Underlying Event

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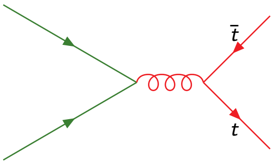
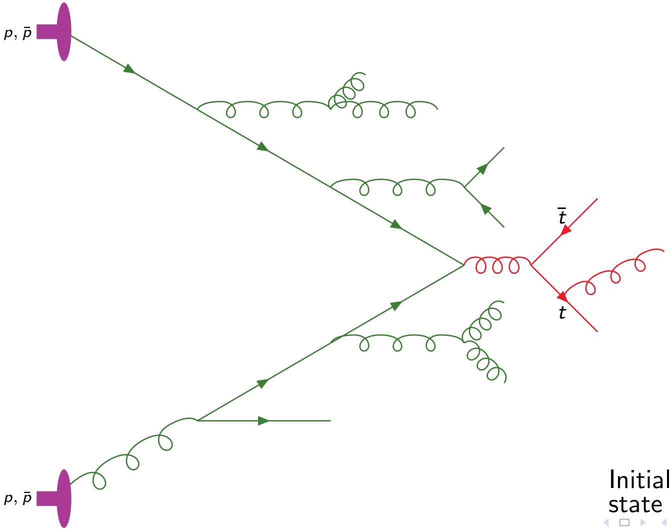
MCnet School: 5th August

A Monte Carlo Event



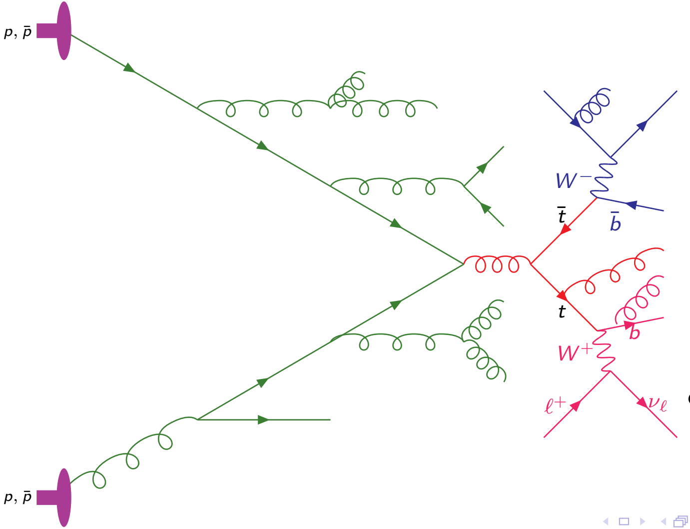
Hard Process, usually calculated at leading order

A Monte Carlo Event



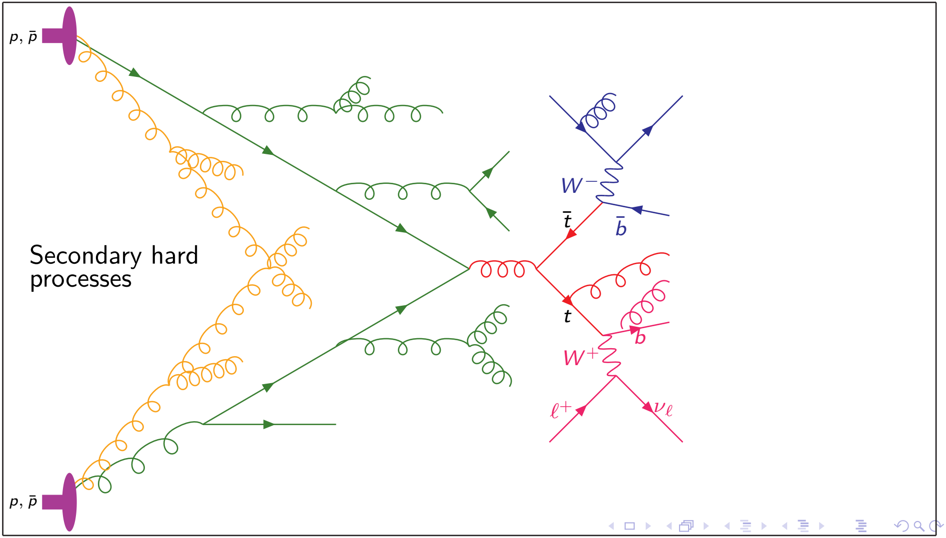
Initial- and final-state parton shower

A Monte Carlo Event

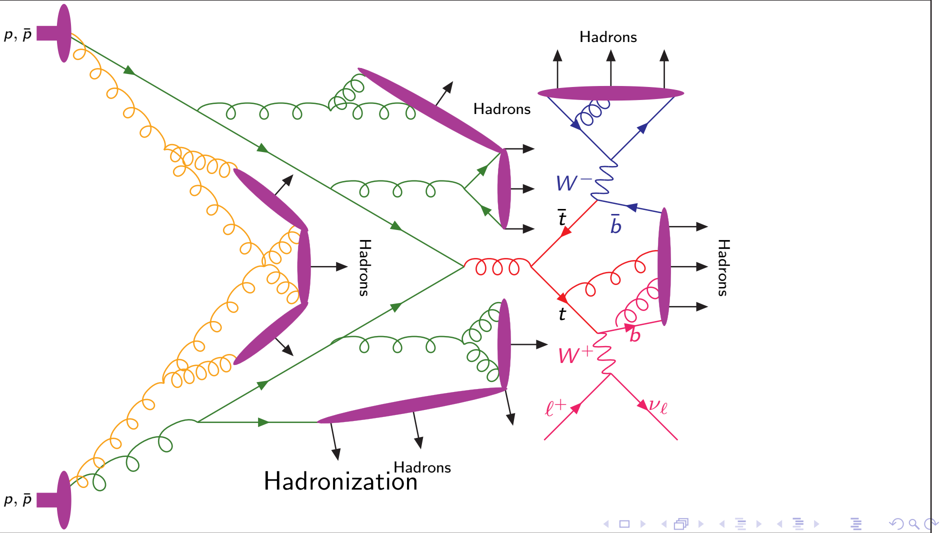


Perturbative decays of heavy particles

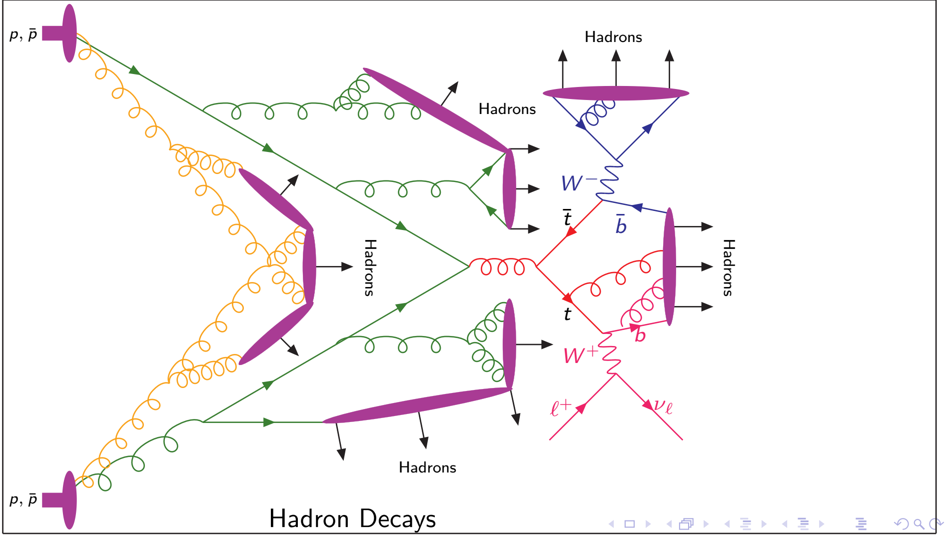
A Monte Carlo Event



A Monte Carlo Event



A Monte Carlo Event



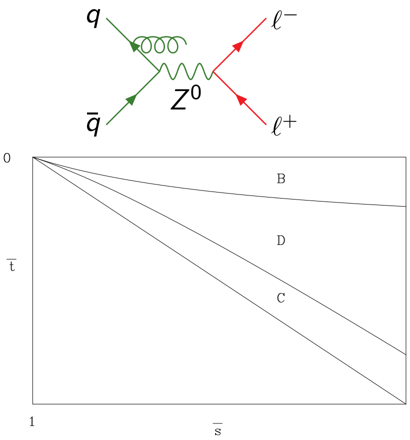
Hadron Decays

Matching

- Parton showers describe the bulk of the radiation correctly.
- While soft or collinear radiation dominates often we are interested in the emission of additional hard radiation.
- Should not described well by the parton shower, although often better than expected.
- Often there are regions of phase space which aren't filled at all.
- At high $p_\perp$ even if there is some radiation the rate is wrong.

Matching

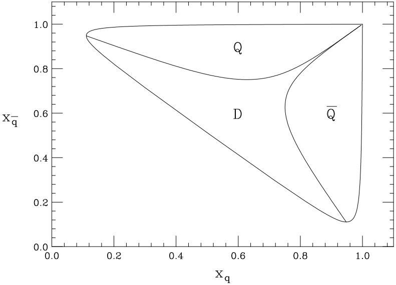
- Let's start by considering the example of $q\bar{q} \to Z^0$.
- If we have an additional gluon $q\bar{q} \to gZ^0$ then $\hat{s} = (p_q + p_{\bar{q}})^2$, $\hat{t} = (p_q - p_g)^2$ and $\bar{s} = \hat{s}/M_Z^2$, $\bar{t} = \hat{t}/M_Z^2$.
- In the Herwig++ angular ordered parton shower there is a dead-zone where there is no radiation in the parton-shower.



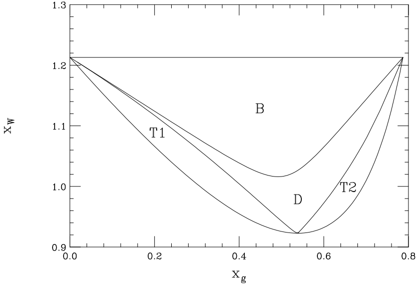
Matching

- Similar problems in all processes

$e^+e^- \to b\bar{b}$



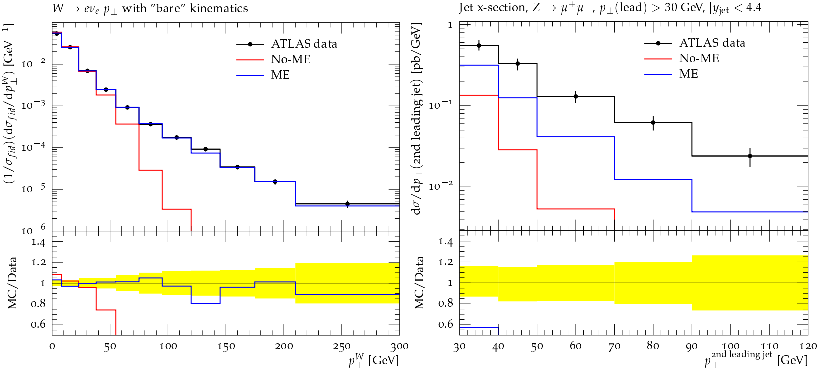
$t \to bW^+$



Matching

- Need to
  1. Correct the radiation in the filled region using the $q\bar{q} \to Z^0$ matrix element. In the already filled region have to correct any emission which is the hardest so far, exponentiates the full result.
  2. Fill the dead zone according to the $q\bar{q} \to Z^0$ matrix element.
- In PYTHIA the shower can be adjusted to fill the whole region so just need the first step.

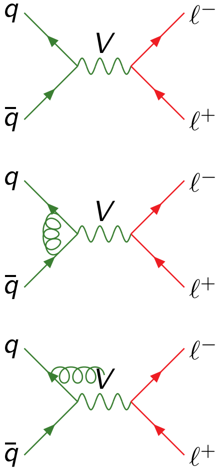
Matching


$W \to e\nu_e$ $p_\perp$ with "bare" kinematics
ATLAS data
No-ME
ME
$(1/\sigma_{fid})(\mathrm{d}\sigma_{fid}/\mathrm{d}p_\perp^W)$ [GeV^{-1}]
MC/Data
$p_\perp^W$ [GeV]
Jet x-section, $Z \to \mu^+\mu^-$, $p_\perp$(lead) > 30 GeV, $|y_{\rm jet} < 4.4|$
ATLAS data
No-ME
ME
$\mathrm{d}\sigma/\mathrm{d}p_\perp$(2nd leading jet) [pb/GeV]
MC/Data
$p_\perp^{\text{2nd leading jet}}$ [GeV]

Higher Order Corrections

- As the two separate parts of the NLO cross section are infinite calculating the cross section numerical is a problem.
- However, we can use the universal properties to construct a subtraction counter-term which has the same singularities as the matrix element for real emission.
- Pick a counter-term which can be analytically integrated in $d = 4 - 2\epsilon$ dimensions and added to the virtual piece

$$
\begin{aligned}
\mathrm{d}\sigma &= B(v)\mathrm{d}\Phi_v + (V(v) + C(v,r))\mathrm{d}\Phi_r\mathrm{d}\Phi_\mathrm{v} \\
&\quad +(R(v,r) - C(v,r))\mathrm{d}\Phi_v\mathrm{d}\Phi_r
\end{aligned}
$$



NLO Simulations

- NLO simulations rearrange the NLO cross section formula.
- Either choose $C(v,r)$ to be the shower approximation.

$$\begin{aligned} \mathrm{d}\sigma &= B(v)\mathrm{d}\Phi_v + (V(v) + C_{\mathrm{shower}}(v,r))\mathrm{d}\Phi_r\mathrm{d}\Phi_{\mathrm{v}} \\ &\quad +(R(v,r) - C_{\mathrm{shower}}(v,r))\mathrm{d}\Phi_v\mathrm{d}\Phi_r \end{aligned}$$

MC@NLO, Friction and Webber

- This was the first practical approach for combining next-to-leading-order calculations and the parton shower.

NLO Simulations

- A alternative rearrangement (POWHEG, Nason) is

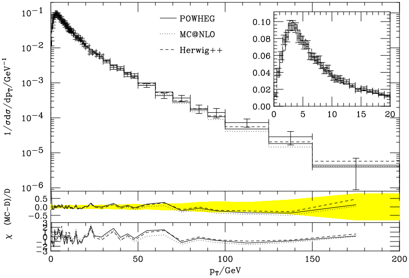
$$
\mathrm{d}\sigma = \bar{B}(v)\mathrm{d}\Phi_v \left[\Delta_R^{(\mathrm{NLO})}(0) + \Delta_R^{(\mathrm{NLO})}(p_\perp)\frac{R(v,r)}{B(v)}\mathrm{d}\Phi_r\right],
$$

where

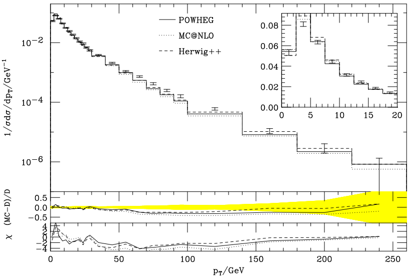
$$
\begin{aligned}
\bar{B}(v) &= B(v) + V(v) + \int \left[R(v,r) - C(v,r)\right]\mathrm{d}\Phi_r, \\
\Delta_R^{(\mathrm{NLO})}(p_\perp) &= \exp\left[-\int \mathrm{d}\Phi_r \frac{R(v,r)}{B(v)}\theta(k_\perp(v,r) - p_\perp)\right].
\end{aligned}
$$

- Looks more complicated but has the advantage that it is independent of the shower and only generates positive weights.

Improved Simulations of Drell-Yan



CDF Run I Z p_T



D0 Run II Z p_T

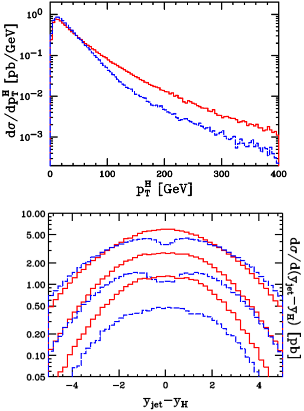
JHEP 0810:015,2008 Hamilton

Different Approaches

- The two approaches are the same to NLO.
- Differ in the sub-leading terms.
- In particular at large $p_\perp$

$$\mathrm{d}\sigma \simeq R(v,r)\mathrm{d}\Phi_v\mathrm{d}\Phi_r \qquad \text{MC@NLO}$$

$$\mathrm{d}\sigma \simeq \frac{\bar{B}(v)}{B(v)}R(v,r)\mathrm{d}\Phi_v\mathrm{d}\Phi_r \qquad \text{POWHEG}$$



JHEP 0904:002,2009 Alioli et. al.

Pros and Cons

POWHEG

- Positive weights.
- Implementation doesn't depend on the shower algorithm.
- Needs changes to shower algorithm for non-$p_\perp$ ordered showers.
- Differs from shower and NLO results, but changes can be made to give NLO result at large $p_\perp$.

MC@NLO

- Negative weights.
- Implementation depends on the specific shower algorithm used.
- No changes to parton shower.
- Reduces to the exact shower result at low p_T and NLO result at high $p_\perp$.

Multi-Jet Leading Order

- While the NLO approach is good for one hard additional jet and the overall normalization it cannot be used to give many jets.
- Therefore to simulate these processes use matching at leading order to get many hard emissions correct.
- The most sophisticated approaches are variants of the CKKW method (Catani, Krauss, Kuhn and Webber JHEP 0111:063,2001)
- Recent new approaches in SHERPA (Hoeche, Krauss, Schumann, Siegert, JHEP 0905:053,2009) and Herwig++(JHEP 0911:038,2009 Hamilton, PR, Tully)

CKKW Procedure

- In order to match the ME and PS we need to separate the phase space:
  - one region contains the soft/collinear region and is filled by the PS;
  - the other is filled by the matrix element.
- In these approaches the phase space is separated using in $k_\perp$-type jet algorithm.
- Radiation above a cut-off value of the jet measure is simulated by the matrix element and radiation below the cut-off by the parton shower.

CKKW Procedure

1. Select the jet multiplicity with probability

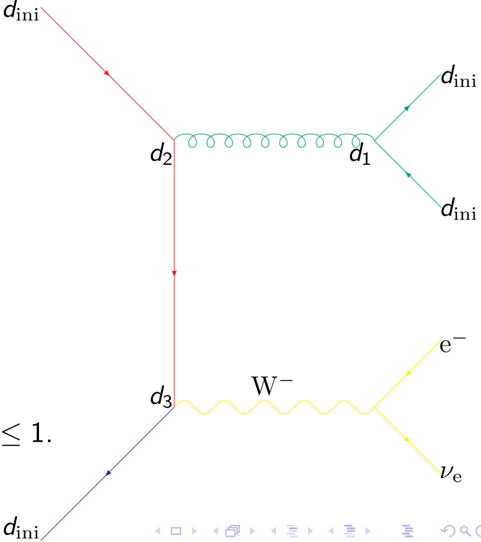
$$P_n = \frac{\sigma_n}{\sum_{k=0}^{k=N} \sigma_k},$$

where σ_n is the n-jet matrix element evaluated at resolution $d_{\rm ini}$ using $d_{\rm ini}$ as the scale for the PDFs and α_S, n is the number of additional jets.

2. Distribute the jet momenta according to the ME.

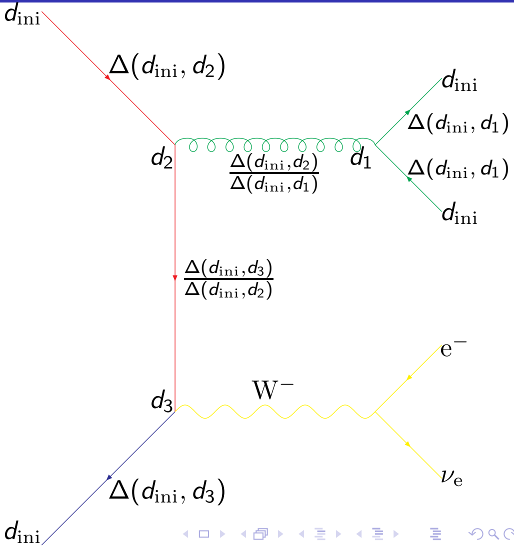
CKKW Procedure

3. Cluster the partons to determine the values at which 1,2,..n-jets are resolved. These give the nodal scales for a tree diagram.
4. Apply a coupling-constant reweighting $\alpha_S(d_1)\ldots\alpha_S(d_n)/(\alpha_S(d_{\mathrm{ini}}))^n \leq 1$.



CKKW Procedure

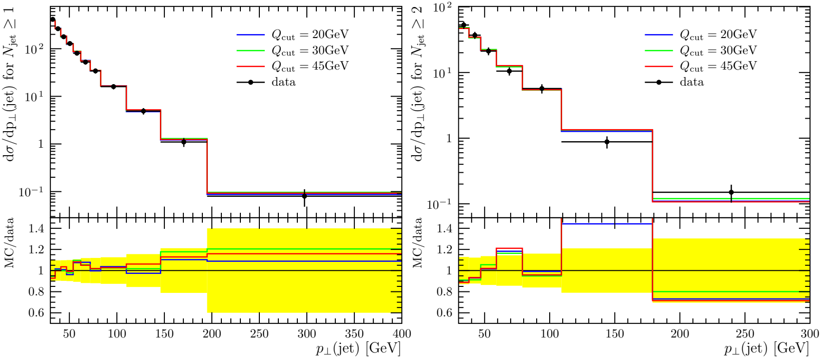
5. Reweight the lines by a Sudakov factor $\Delta(d_{\rm ini}, d_j)/\Delta(d_{\rm ini}, d_k)$.
6. Accept the configuration if the product of the α_S and Sudakov weight is less the $\mathcal{R} \in [0,1]$., otherwise return to step 1.
7. Generate the parton shower from the event starting the evolution of each parton at the scale it was created and vetoing emission above the scale $d_{\rm ini}$.



CKKW

- Recent improvements use an idea from POWHEG to simulate soft radiation rather than the enhanced emission scale.
- Gives improved results.
- Also first work on combine both higher orders and higher multiplicities.

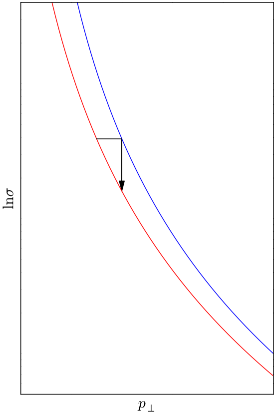
Z + Jets



SHERPA JHEP 0905:053,2009 compared to data from CDF Phys.Rev.Lett.100:102001,2008

Introduction

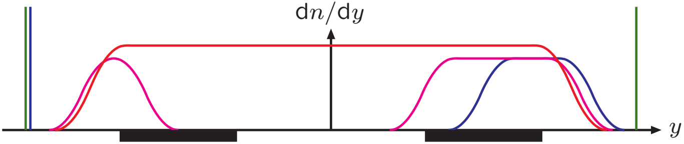
- As well as the hard perturbative scattering there is additional hadronic activity.
- This must be modelled as it is both observable and can have a large effect on jet energies.
- Before we can discuss the models we will first need to understand the definitions of the various types of event.
- We will then discuss the various different models.



Hadronic Cross Sections

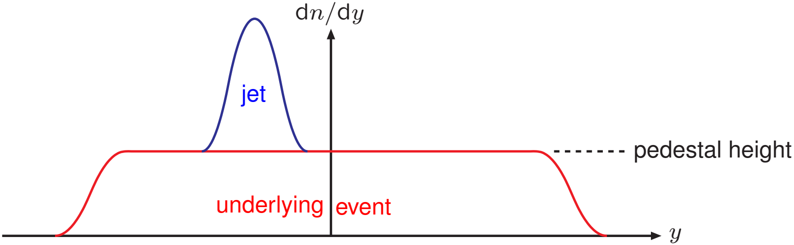
- The total hadronic cross section consists of various components

$$\sigma_{\rm total} = \sigma_{\rm elastic} + \sigma_{\rm single-diffractive} + \sigma_{\rm double-diffractive} + \cdots + \sigma_{\rm non-diffractive}$$



- Experimentally minimum bias $\approx$ all events with no bias from trigger conditions
- Theoretically $\sigma_{\rm min-bias} \approx \sigma_{double-diffractive} + \sigma_{non-diffractive}$

Hadronic Cross Sections



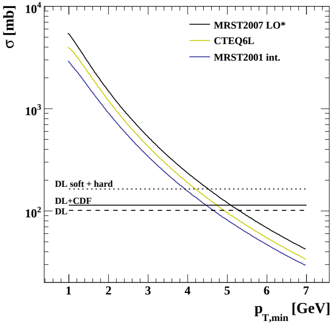
- The underlying is the additional activity from soft interactions in additional to the primary hard partonic process.
- This is a theoretical definition and such a separate is model dependent.
- However we except the description to be similar to the one we need for the bulk of non-diffractive events.

Multiparton Interaction Models

- The cross-section for $2 \to 2$ scattering is dominated by t-channel channel gluon exchange.
- It diverges like

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} = \frac{1}{p_\perp^4} \quad \text{for} \quad p_\perp \to 0$$

- This must be regulated used a cut $p_\perp > p_\perp^{\mathrm{min}}$.



- For small values of $p_\perp^{\mathrm{min}}$ this is larger than the total hadron–hadron cross section.
- More than one parton-parton scattering per hadron collision.

Matter Distribution

- Hadrons are extended objects so we also need the matter distribution.
- Assume the dependence in x ($\|$ to the beam) and b ($\perp$ to the beam) factorizes

$$G_i(x, \vec{b}; \mu^2) = f_i(x; \mu^2) S(\vec{b}).$$

and the n-parton distributions are "independent"

$$G(x_i, x_j, \vec{b}_i, \vec{b}_j, \mu^2) = G_i(x_i, \vec{b}_i; \mu^2) G_j(x_j, \vec{b}_j; \mu^2)$$

Matter Distribution

- The inclusive cross section for $pp \to \mathrm{jets}$ is

$$\sigma_{\mathrm{inc}} = \int_{p_\perp^{\mathrm{min}}}^{\frac{E_{\mathrm{CMF}}}{2}} \int \mathrm{d}x_1 \int \mathrm{d}x_2 \sum_{ij} f_i(x_1, p_\perp^2) f_j(x_2, p_\perp^2) \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_\perp}$$

- The b dependence from

$$A(b) = \int \mathrm{d}^2 b_1 S(b_1) \int \mathrm{d}^2 b_2 S(b_2) \delta(b - b_1 + b_2)$$

  is normalised such that $\int \mathrm{d}b^2 A(b) = 1$.
- If we assume the separate scatters are uncorrelated, *i.e.* they obey Poissonian statistics.
- The average number of scatters per event is

$$\langle n \rangle = \frac{\sigma_{\mathrm{inc}}}{\sigma_{\mathrm{nd}}}.$$

Matter Distribution

- Alternatively the probability of m scatters is

$$P_m = \frac{\left[A(b)\sigma_{\rm inc}\right]^m}{m!}\exp\left(-A(b)\sigma_{\rm inc}\right).$$

- The total cross (non-diffractive) cross section is

$$\sigma_{\rm nd} = \int {\rm d}b^2 \sum_{m=1}^{\infty} P_m = \int {\rm d}b^2 \left[1-\exp\left(-A(b)\sigma_{\rm inc}\right)\right]$$

- Therefore

$$\langle n\rangle = \frac{\int {\rm d}b^2 \sum_{m=1}^{\infty} m P_m}{\int {\rm d}b^2 \sum_{m=1}^{\infty} P_m} = \frac{\int {\rm d}b^2 \langle n(b)\rangle}{\int {\rm d}b^2 \left[1-\exp\left(-\langle n(b)\rangle\right)\right]} = \frac{\sigma_{\rm inc}}{\sigma_{\rm nd}}$$

Matter Distribution

- Use either the electromagnetic form factor

$$S_P(\vec{b}) = \int \frac{\mathrm{d}^2\vec{k}}{2\pi} \frac{e^{i\vec{k}\cdot\vec{b}}}{1+|\vec{k}|}$$

giving

$$A(b) = \frac{\mu^2}{96\pi}(\mu b)^2 K_3(\mu b).$$

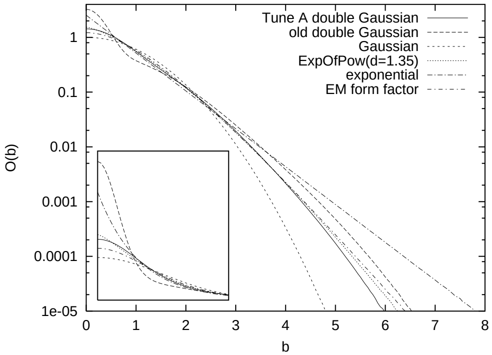
- or an empirical double Gaussian double Gaussian

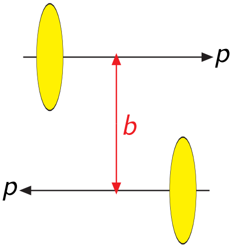
$$\rho_{\mathrm{matter}}(r) = N_1 \exp\left(-\frac{r^2}{r_1^2}\right) + N_2 \exp\left(-\frac{r^2}{r_2^2}\right)$$

where $r_1 \neq r_2$ gives "hot spots" and

$$A(b) = \int \mathrm{d}^3\mathrm{d}t\,\rho^{\mathrm{boosted}}_{1,\mathrm{matter}}(x,t)\rho^{\mathrm{boosted}}_{2,\mathrm{matter}}(x,t)$$

Matter Distribution





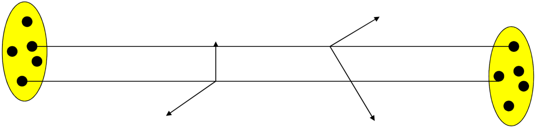
- Average activity at b proportional to $A(b)$
- Central collisions more active, broader than Poissonian
- Peripheral collisions normally give few if any collisions.

Multiparton Interaction Models

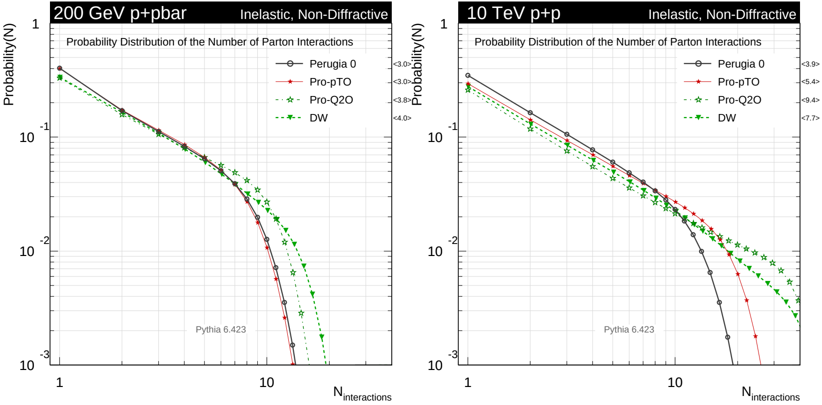
- If the interactions occur independently obeys Poissonian statistics

$$P_n = \frac{\langle n \rangle^n}{n!} e^{-\langle n \rangle}$$

- However energy-momentum conservation tends to suppressed large numbers of parton scatterings.



Number of Interactions



PYTHIA Model

- Don't use a strict cut-off in $p_\perp$

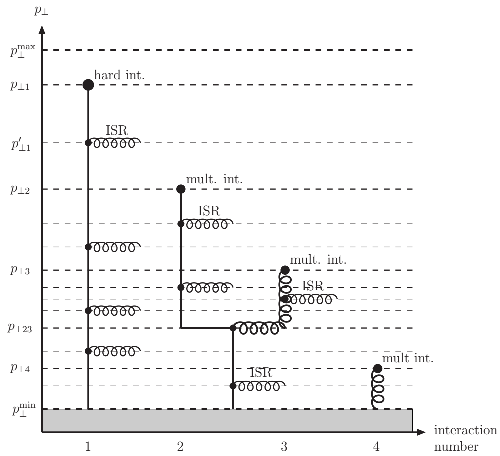
$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_S^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_S^2(p_\perp^2)}{(+pp_\perp^2)^2}$$

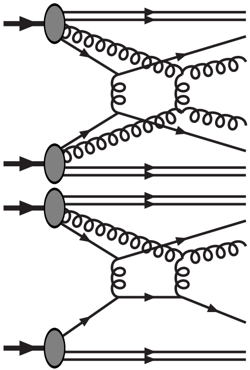
- double Gaussian matter distribution,
- PDFs rescaled for momentum conservation
- Trace flavour content of remnant, including baryon number.
- Colour arrangement among outgoing partons
- Interactions ordered in decreasing $p_\perp$, and evolution interleaved with ISR

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_\perp} + \frac{\mathrm{d}\mathcal{P}\mathrm{ISR}}{\mathrm{d}p_\perp}\right) \exp\left(-\int_{p_\perp}^{p_{\perp,i-1}} \left[\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_\perp} + \frac{\mathrm{d}\mathcal{P}\mathrm{ISR}}{\mathrm{d}p_\perp}\right] \mathrm{d}p'_\perp\right)$$

- Includes rescattering

PYTHIA Model





Herwig++ Model

- In terms of the eikonal function $\chi(b,s)$.

$$\sigma_{\rm tot} = 2\int_0^\infty {\rm d}b^2\left[1-e^{-\chi(b,s)}\right] \quad \sigma_{\rm ela} = \int_0^\infty {\rm d}b^2\left|1-e^{-\chi(b,s)}\right|^2$$

$$\sigma_{\rm inel} = \int_0^\infty {\rm d}b^2\left[1-e^{-2\chi(b,s)}\right]$$

- Take eikonal + partonic scattering seriously

$$\sigma_{\rm tot} = 2\int {\rm d}^2b\left(1-\exp\left[-\frac{1}{2}A(b)\sigma_{\rm inc}\right]\right)$$

- Given the form of the matter distribution predict $\sigma_{\rm inc}$

Herwig++ Model

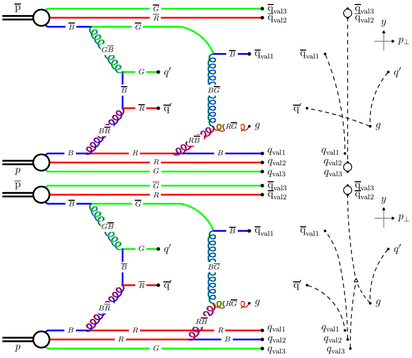
- Too restrictive

$$\sigma_{\rm tot} = 2\int \mathrm{d}^2 b \left(1 - \exp\frac{1}{2}\left[A_{\rm soft}(b)\sigma_{\rm soft,inc} + A_{\rm hard}(b)\sigma_{\rm hard,inc}\right]\right)$$

- Gives two free parameters.
- Independent perturbative scattering above $p_\perp^{\rm min}$
- Gluon scattering below $p_\perp^{\rm min}$ with $\sigma_{\rm soft,inc}$ and a Gaussian $p_\perp$ distribution.
- $\frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp}$ continuous at $p_\perp^{\rm min}$.
- Includes colour reconnection of the partons in clusters produced via MPI.

Colour Correlations

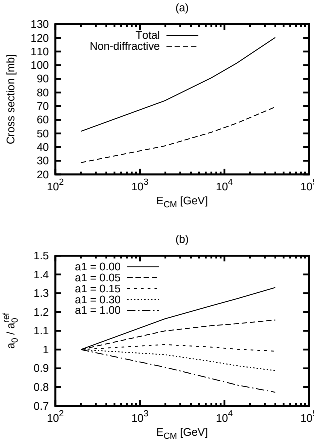
- Colour correlations can have a big influence on the final state.
- In particular $\langle p_\perp \rangle$ vs $n_{\rm ch}$ is very sensitive to the colour flow.
- Long string to remnants many charged particles
- Short strings less charged particles.



x-Dependent Matter Distributions

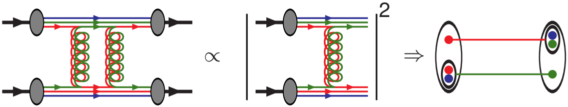
- Most models have a factorization of the x and b matter dependence.
- Corke & Sjöstrand JHEP 1105 (2011) 009 consider a Gaussian matter distribution with width

$$a(x) = a_0 \left(1 + a_1 \ln \frac{1}{x}\right)$$



Older Models

- UA5 Model (FORTRAN HERWIG)
  - Distribute a ($\sim$negative binomial) number of clusters independently in rapidity and transverse momentum according to parametrisation/extrapolation of data;
  - modify for overall energy/momentum/flavour conservation $\mathrm{d}\sigma/\mathrm{d}p_\perp$;
  - no minijets; correlations only by cluster decays.
- PHOJET
  - Use the optical theorem and pomerons
  - Unified framework of non-diffractive and diffractive interactions
  - Purely low-$p_\perp$: only primordial $k_\perp$ fluctuations
  - Usually simple Gaussian matter distribution



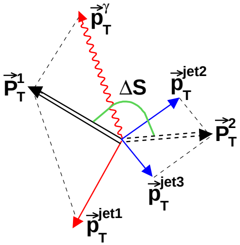
Measurements

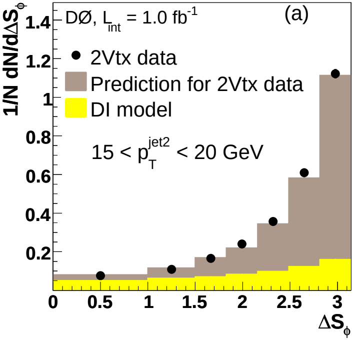
- In principle all measurements at hadron collisions can be sensitive to the underlying event.
- There are three main types of measurement which are used to study, constrain, and fit the parameters of the models.
  1. Measurements which are sensitive to a second hard scattering of a particular type.
  2. Measurements of particle numbers, $p_\perp$, etc. in phase-space regions where we don't expect perturbative radiation in hard events.
  3. Measurements of min-bias events.

Double-Parton Scattering

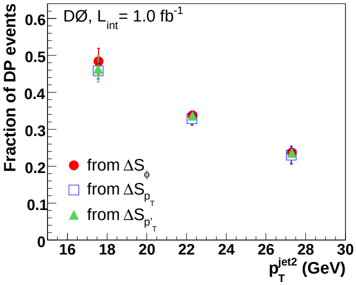
- Look at γ+jets events.
- One pure QCD scattering and one γ+jet.
- Define an effective cross section s.t.

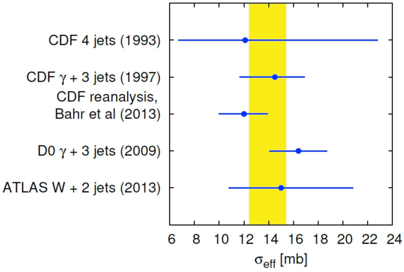
$$\sigma_{ab} = \frac{\sigma_a \sigma_b}{\sigma_{\rm eff}}$$



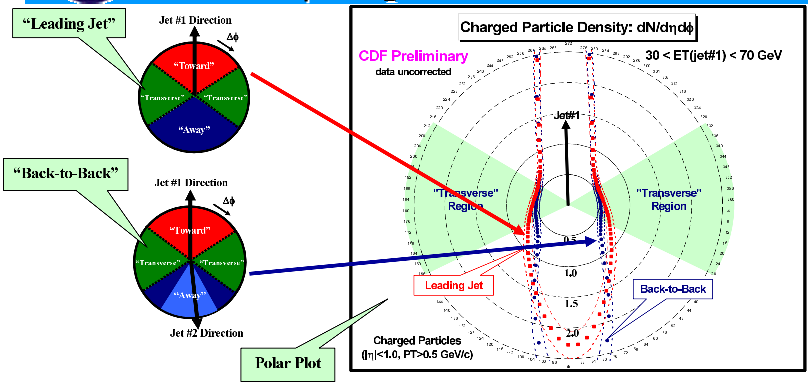


Double-Parton Scattering

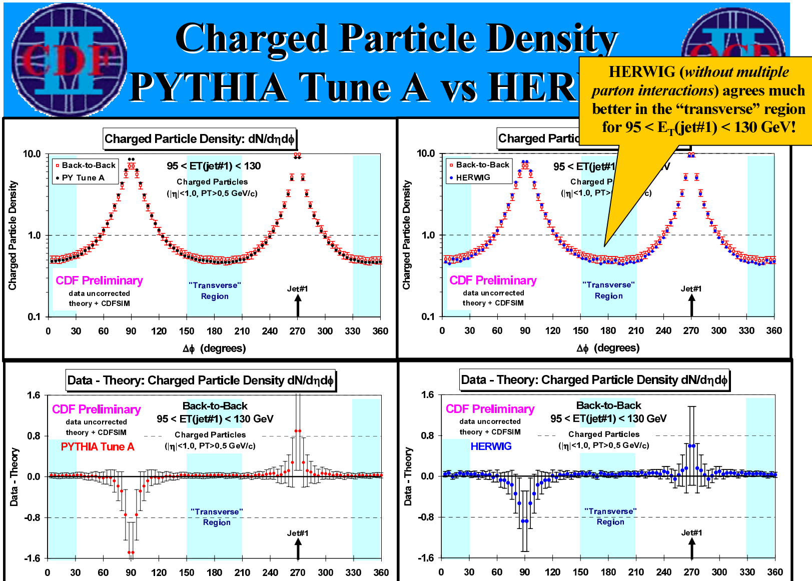




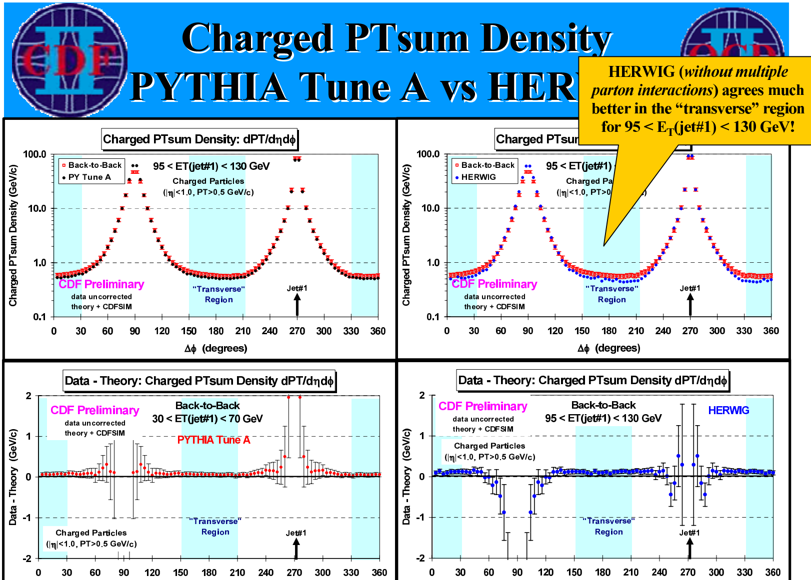
Charged Particle Density $\Delta\phi$ Dependence



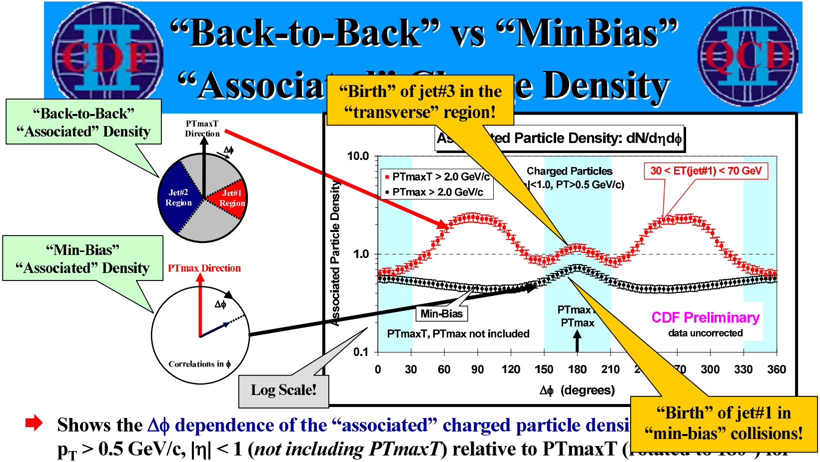
- Shows the $\Delta\phi$ dependence of the charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles in the range $p_T > 0.5$ GeV/c and $|\eta| < 1$ relative to jet#1 (rotated to 270^o) for $30 < E_T(\text{jet\#1}) < 70$ GeV for "Leading Jet" and "Back-to-Back" events.



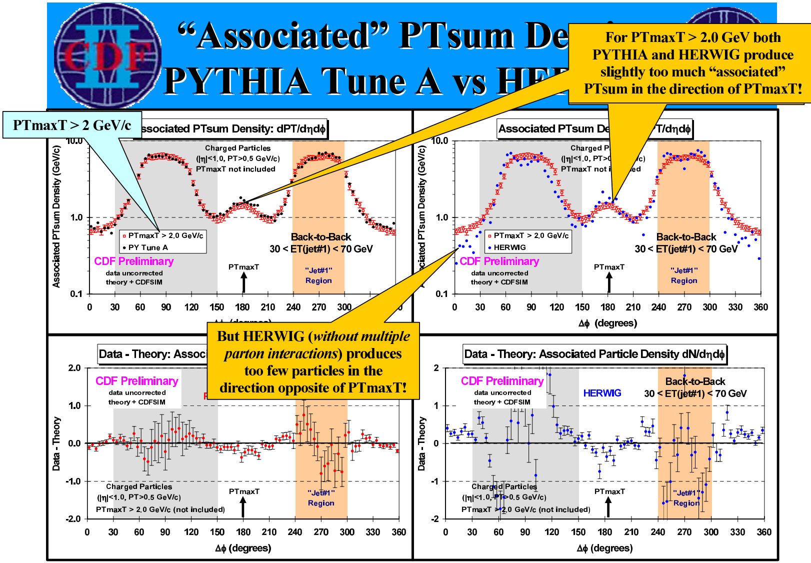
Charged Particle Density
PYTHIA Tune A vs HER
HERWIG (*without multiple parton interactions*) agrees much better in the "transverse" region for 95 < E_T(jet#1) < 130 GeV!
Charged Particle Density: dN/dηdφ
Back-to-Back
PY Tune A
95 < ET(jet#1) < 130
Charged Particles
(|η|<1.0, PT>0.5 GeV/c)
CDF Preliminary
data uncorrected
theory + CDFSIM
"Transverse" Region
Jet#1
Charged Particle Density
Δφ (degrees)
Back-to-Back
HERWIG
Data - Theory: Charged Particle Density dN/dηdφ
Back-to-Back
95 < ET(jet#1) < 130 GeV
PYTHIA Tune A
Data - Theory


Charged PTsum Density
PYTHIA Tune A vs HERWIG
HERWIG (*without multiple parton interactions*) agrees much better in the "transverse" region for 95 < E_T(jet#1) < 130 GeV!
Charged PTsum Density: dPT/dηdφ
Back-to-Back
PY Tune A
95 < ET(jet#1) < 130 GeV
Charged Particles
(|η|<1.0, PT>0.5 GeV/c)
CDF Preliminary
data uncorrected
theory + CDFSIM
"Transverse" Region
Jet#1
Charged PTsum Density (GeV/c)
Δφ (degrees)
HERWIG
Data - Theory: Charged PTsum Density dPT/dηdφ
Back-to-Back
30 < ET(jet#1) < 70 GeV
PYTHIA Tune A
95 < ET(jet#1) < 130 GeV
Data - Theory (GeV/c)

"Back-to-Back" vs "MinBias" "Associated" Charge Density

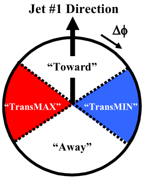


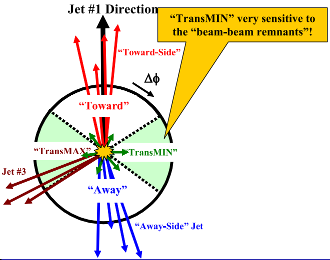
- Shows the Δϕ dependence of the "associated" charged particle density, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (*not including PTmaxT*) relative to PTmaxT (rotated to 180°) for PTmaxT > 2.0 GeV/c, for "back-to-back" events with $30 < E_T(\text{jet\#1}) < 70$ GeV.
- Shows the data on the Δϕ dependence of the "associated" charged particle density, dNchg/dηdϕ, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (*not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 2.0 GeV/c.


"Associated" PTsum De
PYTHIA Tune A vs HE
For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too much "associated" PTsum in the direction of PTmaxT!
PTmaxT > 2 GeV/c
But HERWIG (without multiple parton interactions) produces too few particles in the direction opposite of PTmaxT!
ssociated PTsum Density: dPT/dηdϕ
Associated PTsum Density (GeV/c)
Charged Particles
(|η|<1.0, PT>0.5 GeV/c)
PTmaxT not included
PTmaxT > 2.0 GeV/c
PY Tune A
HERWIG
CDF Preliminary
data uncorrected
theory + CDFSIM
Back-to-Back
30 < ET(jet#1) < 70 GeV
PTmaxT
"Jet#1" Region
Δϕ (degrees)
Data - Theory: Associated Particle Density dN/dηdϕ
Data - Theory
PTmaxT > 2.0 GeV/c (not included)

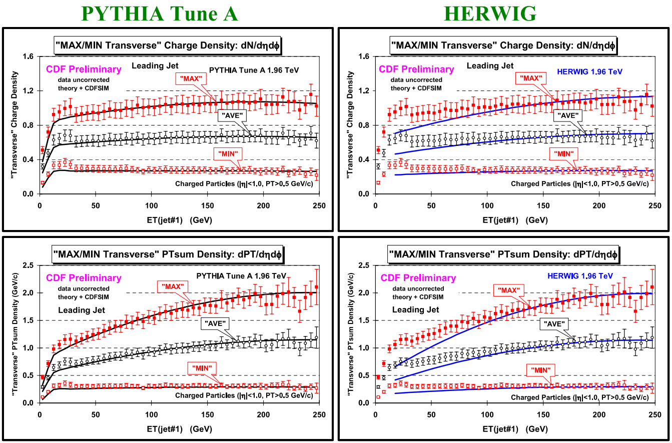
Underlying event measurements

- Classic approach is to define the event using a hard jet, or other particle, *e.g.* Z^0.
- The define toward, away, transverse max and transverse min regions.
- The transverse min region is most sensitive to the underlying event, while transverse max can also be sensitive to perturbative radiation.



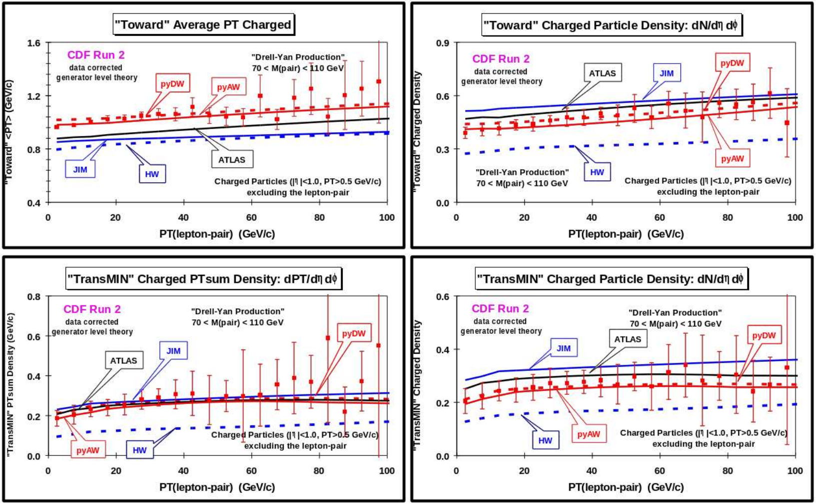


CDF Results Jets

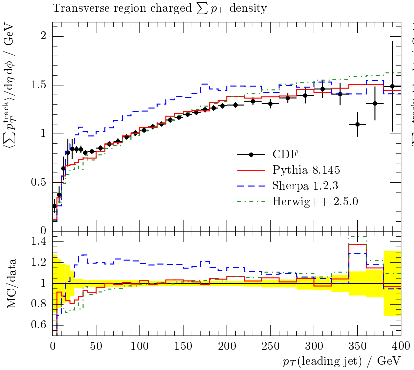


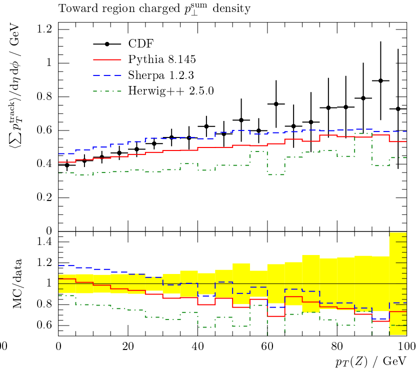
Charged particle density and PTsum density for "leading jet" events versus E_T(jet#1) for PYTHIA Tune A and HERWIG.

CDF Results Drell-Yan



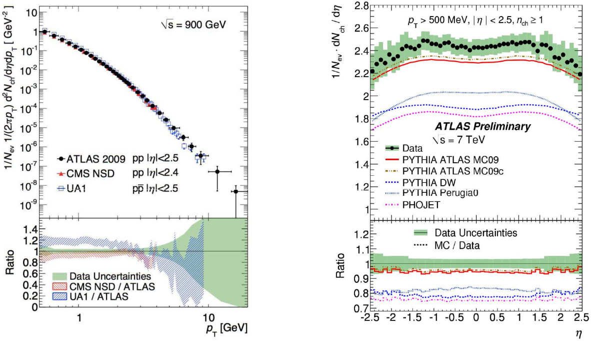
CDF Results


Transverse region charged $\sum p_\perp$ density
$\langle \sum p_T^{\mathrm{track}} \rangle / d\eta\, d\phi$ / GeV
CDF
Pythia 8.145
Sherpa 1.2.3
Herwig++ 2.5.0
MC/data
p_T(leading jet) / GeV


Toward region charged $p_\perp^{\mathrm{sum}}$ density
$\langle \sum p_T^{\mathrm{track}} \rangle / d\eta\, d\phi$ / GeV
CDF
Pythia 8.145
Sherpa 1.2.3
Herwig++ 2.5.0
MC/data
$p_T(Z)$ / GeV

First LHC Results

Charged Particle Multiplicities at √s=0.9, 7 TeV



Monte Carlo underestimates the track multiplicity seen in ATLAS

Christophe Clement

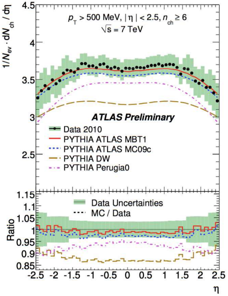
Physics at LHC, DESY, June 9th, 2010 – ATLAS First Physics Results

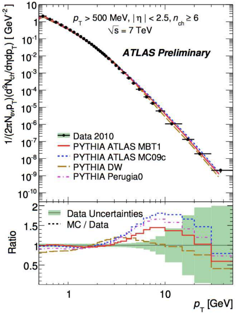
First LHC Results

Pythia Tune to ATLAS MinBias and Underlying Event

Used for the tune

ATLAS UE data at 0.9 and 7 TeV
ATLAS charged particle densities at 0.9 and 7 TeV
CDF Run I underlying event analysis (leading jet)
CDF Run I underlying event "Min-Max" analysis
D0 Run II dijet angular correlations
CDF Run II Min bias
CDF Run I Z pT





Result

This tune describes most of the MinBias and the UE data
Significant improvement compared to pre-LHC tunes
Biggest remaining deviation in $\frac{1}{N_{\rm ev}} \cdot \frac{1}{2\pi p_{\rm T}} \cdot \frac{{\rm d}^2 N_{\rm ch}}{{\rm d}\eta {\rm d}p_{\rm T}}$
These deviations could not be removed
Needs further investigations

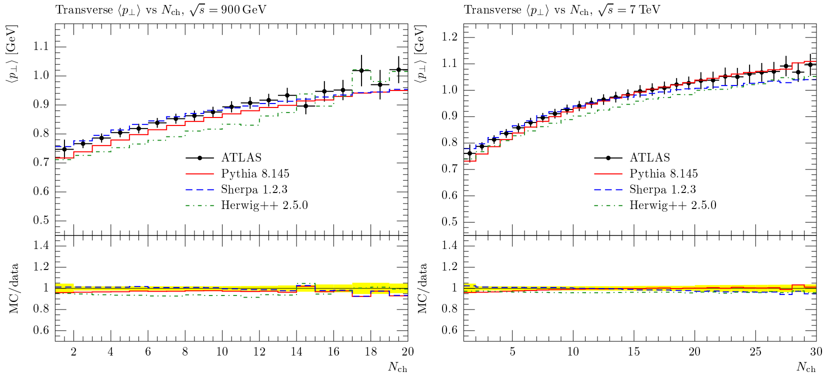
Christophe Clement

Physics at LHC, DESY, June 9th, 2010 – ATLAS First Physics Results

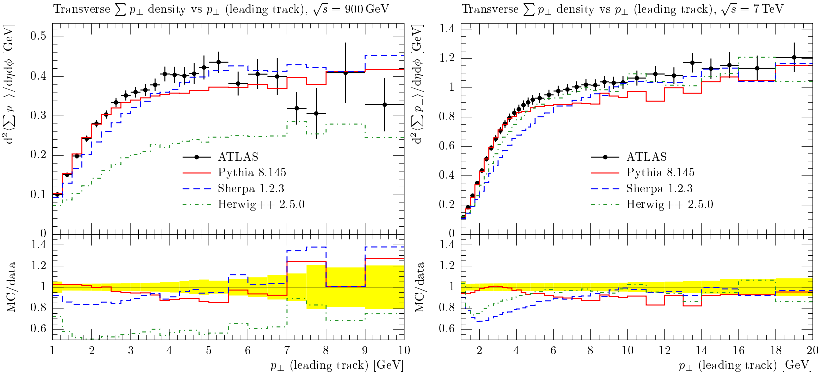
First LHC Results

- Before the LHC start there was some worry that the models would completely fail.
- In reality in good agreement with the early data.
- Better agreement now after some tuning of the parameters.
- In both Herwig++ and PYTHIA this needs the $p_\perp^{\rm min}$ parameter to be energy dependent.
- Older soft models don't describe the data.

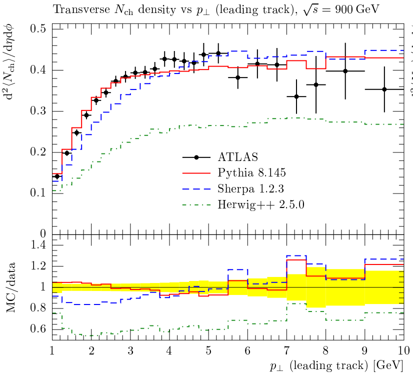
Average transverse $p_\perp$ vs N_{ch}

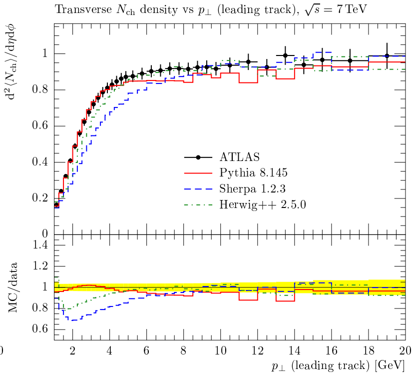


Transverse $p_\perp$ density vs $p_\perp$

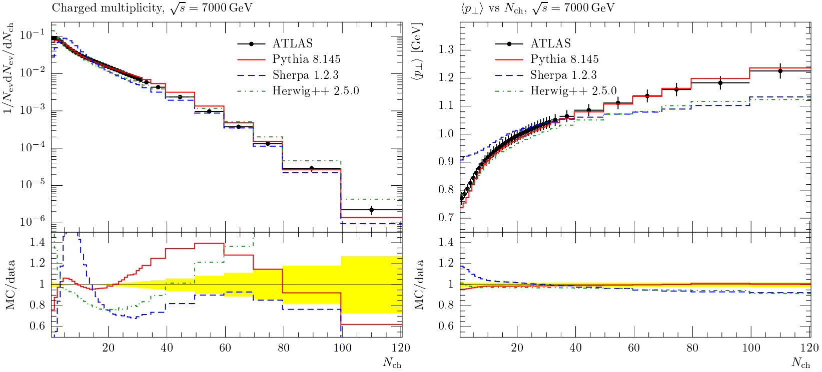


Transverse $N_{\rm ch}$ density vs $p_\perp$



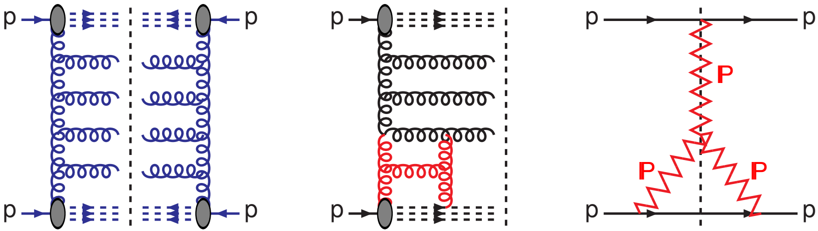


Charged Multiplicity

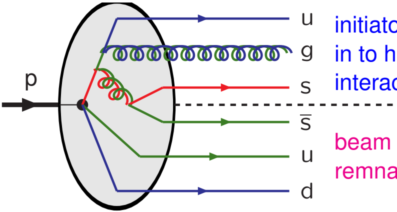


Diffraction

- In Regge theory scattering by resonance exchange, predates QCD.
- The Pomeron is the Regge trajectory of states with vacuum quantum numbers, in QCD glueballs.
- Gives the rates but not what the event look like.



Beam 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:
  1. Squeeze range $0 < x < 1$ into $0 < x < 1 \sum_i x_i$
  2. Valence quarks reduce by the number already kicked out.
  3. Introduce companion quark $q/\bar{q}$ to each kicked-out sea quark $q/\bar{q}$,with x based on assumed $g \to q\bar{q}$ splitting
  4. Gluon and sea: rescale for total momentum conservation.
- Colour flow connects hard scattering to beam remnants which can have consequences.

Summary

- Underlying event is one of the least least understood aspects of event generation.e
- Modelled and only weakly constrained by existing data.
- Models based on MPI describe the data well with a number of refinements.