Particle Physics Phenomenology
6. Multiparton interactions and MB/UE

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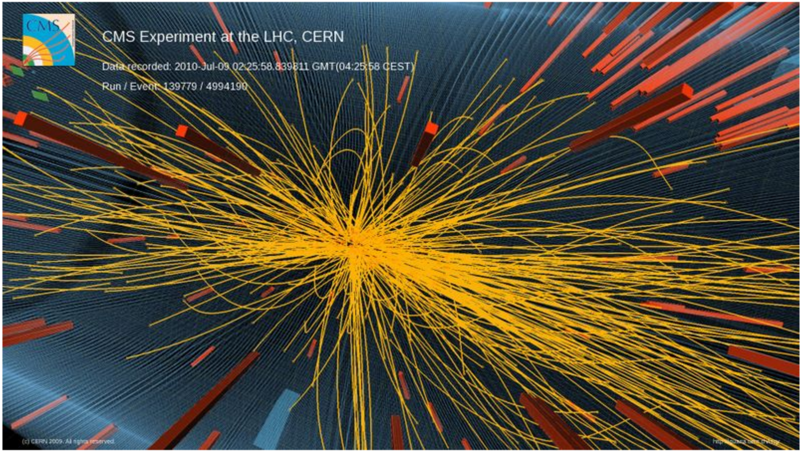
Event topologies



Expect and observe high multiplicities at the LHC.
What are production mechanisms behind this?

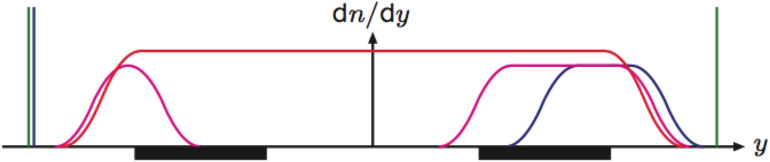
What is minimum bias (MB)?

MB $\approx$ "all events, with no bias from restricted trigger conditions"

$\sigma_{\mathrm{tot}} =$

$\sigma_{\mathrm{elastic}} + \sigma_{\mathrm{single-diffractive}} + \sigma_{\mathrm{double-diffractive}} + \cdots + \sigma_{\mathrm{non-diffractive}}$

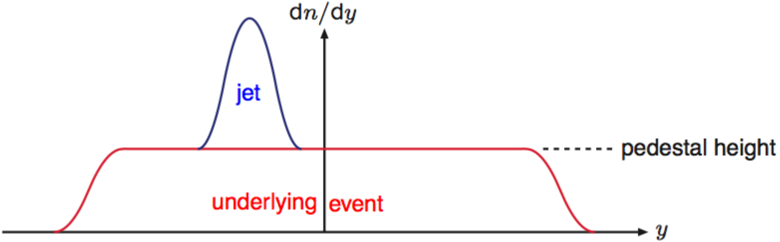
Schematically:



Reality: can only observe events with particles in central detector:
no universally accepted, detector-independent definition

$\sigma_{\mathrm{min-bias}} \approx \sigma_{\mathrm{non-diffractive}} + \sigma_{\mathrm{double-diffractive}} \approx 2/3 \times \sigma_{\mathrm{tot}}$

What is underlying event (UE)?

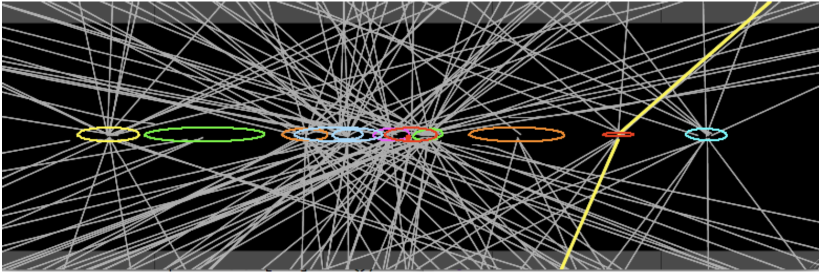


In an event containing a jet pair or another hard process, how much further activity is there, that does not have its origin in the hard process itself, but in other physics processes?

Pedestal effect: the UE contains more activity than a normal MB event does (even discarding diffractive events).

Trigger bias: a jet "trigger" criterion $E_{\perp \mathrm{jet}} > E_{\perp \mathrm{min}}$ is more easily fulfilled in events with upwards-fluctuating UE activity, since the UE $E_{\perp}$ in the jet cone counts towards the $E_{\perp \mathrm{jet}}$. *Not enough!*

What is pileup?



$\langle n \rangle = \overline{\mathcal{L}}\,\sigma$

where $\overline{\mathcal{L}}$ is machine luminosity per bunch crossing, $\overline{\mathcal{L}} \sim n_1 n_2 / A$ and $\sigma \sim \sigma_{\mathrm{tot}} \approx 100$ mb.

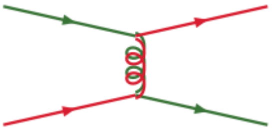
Current LHC machine conditions $\Rightarrow \langle n \rangle = \langle \mu \rangle \sim 20 - 80$.

Pileup introduces no new physics, and is thus not further considered here, but can be a nuisance.

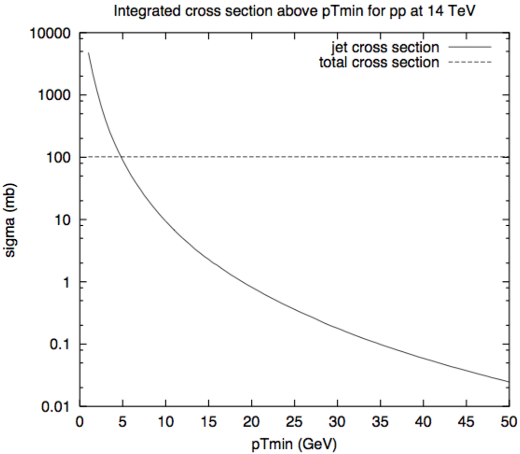
However, keep in mind concept of bunches of hadrons leading to multiple collisions.

The divergence of the QCD cross section

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



Integrate QCD $2 \to 2$
$\mathrm{qq}' \to \mathrm{qq}'$
$\mathrm{q\overline{q}} \to \mathrm{q}'\overline{\mathrm{q}}'$
$\mathrm{q\overline{q}} \to \mathrm{gg}$
$\mathrm{qg} \to \mathrm{qg}$
$\mathrm{gg} \to \mathrm{gg}$
$\mathrm{gg} \to \mathrm{q\overline{q}}$
(with CTEQ 5L PDF's)



What is Multiple Partonic Interactions (MPI)?

Note that $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}})$, the number of ($2 \to 2$ QCD) interactions above $p_{\perp\mathrm{min}}$, involves integral over PDFs,

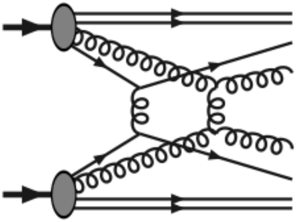
$$\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) = \iiint_{p_{\perp\mathrm{min}}} \mathrm{d}x_1 \, \mathrm{d}x_2 \, \mathrm{d}p_{\perp}^2 \, f_1(x_1, p_{\perp}^2) \, f_2(x_2, p_{\perp}^2) \, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_{\perp}^2}$$

with $\int \mathrm{d}x \, f(x, p_{\perp}^2) = \infty$, i.e. infinitely many partons.

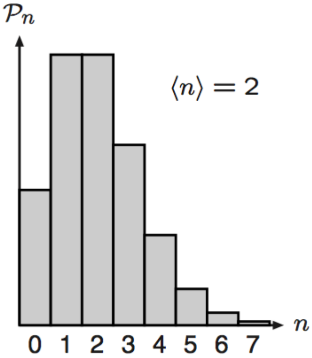
So half a solution to $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) > \sigma_{\mathrm{tot}}$ is

many interactions per event: MPI (historically MI or MPPI)

$$\begin{aligned}
\sigma_{\mathrm{tot}} &= \sum_{n=0}^{\infty} \sigma_n \\
\sigma_{\mathrm{int}} &= \sum_{n=0}^{\infty} n \, \sigma_n \\
\sigma_{\mathrm{int}} &> \sigma_{\mathrm{tot}} \iff \langle n \rangle > 1
\end{aligned}$$



Poissonian statistics



If interactions occur independently
then Poissonian statistics

$$\mathcal{P}_n = \frac{\langle n \rangle^n}{n!} \, e^{-\langle n \rangle}$$

but $n = 0 \Rightarrow$ no event (in many models)
and energy–momentum conservation
$\Rightarrow$ large n suppressed
so narrower than Poissonian

MPI is a logical consequence of the composite nature of protons,
$n_{\mathrm{parton}} \sim \sum_{\mathrm{q},\overline{\mathrm{q}},\mathrm{g}} \int f(x)\,\mathrm{d}x > 3$, which allows $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) > \sigma_{\mathrm{tot}}$,
but what about the limit $p_{\perp\mathrm{min}} \to 0$?

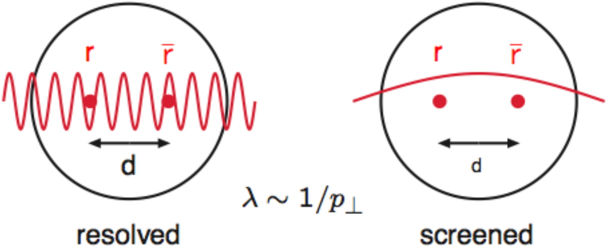
Colour screening

Other half of solution is that perturbative QCD is not valid at small $p_\perp$ since q, g are not asymptotic states (confinement!).

Naively breakdown at

$$p_{\perp\mathrm{min}} \simeq \frac{\hbar}{r_\mathrm{p}} \approx \frac{0.2\ \mathrm{GeV} \cdot \mathrm{fm}}{0.7\ \mathrm{fm}} \approx 0.3\ \mathrm{GeV} \simeq \Lambda_\mathrm{QCD}$$

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

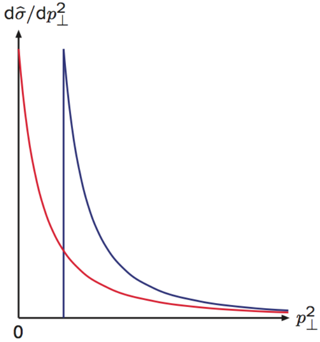


Regularization of low-$p_\perp$ divergence

so need $\boxed{\textbf{nonperturbative regularization for } p_\perp \to 0}$, e.g.

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \quad \to \quad \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4}\,\theta\,(p_\perp - p_{\perp\min}) \qquad \text{(simpler)}$$

$$\text{or} \quad \to \quad \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2} \qquad \text{(more physical)}$$



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.

Indirect evidence for multiparton interactions – 1

without MPI:

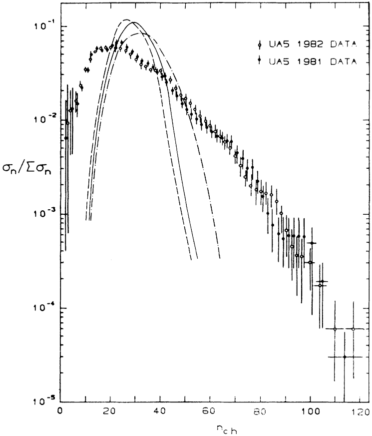


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

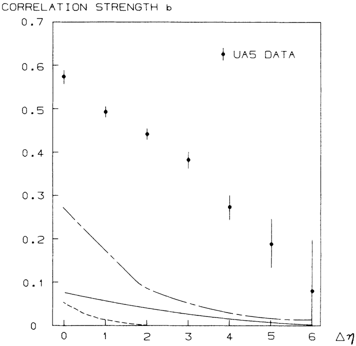


FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

with MPI included:

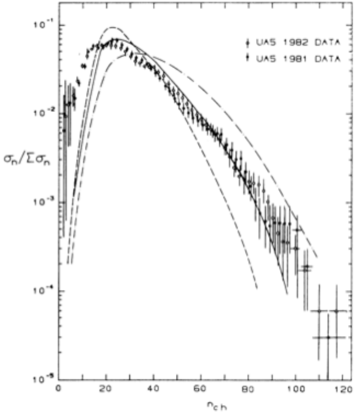


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min}=2.0$ GeV; solid line, $p_{T\min}=1.6$ GeV; dashed-dotted line, $p_{T\min}=1.2$ GeV.

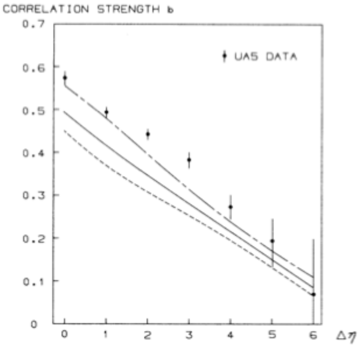


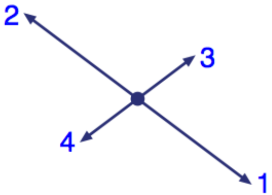
FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.

Direct observation of multiparton interactions – 1

Five pre-LHC studies: AFS (1987), UA2 (1991), CDF (1993, 1997), D0 (2009)

Order 4 jets $\mathbf{p}_{\perp 1} > \mathbf{p}_{\perp 2} > \mathbf{p}_{\perp 3} > \mathbf{p}_{\perp 4}$ and define φ
as angle between $\mathbf{p}_{\perp 1} \mp \mathbf{p}_{\perp 2}$ and $\mathbf{p}_{\perp 3} \mp \mathbf{p}_{\perp 4}$ for AFS/CDF

Double Parton Scattering



$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \approx 0$

$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \approx 0$

$\mathrm{d}\sigma/\mathrm{d}\varphi$ flat

Double BremsStrahlung

$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \gg 0$

$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \gg 0$

$\mathrm{d}\sigma/\mathrm{d}\varphi$ peaked at $\varphi \approx 0/\pi$ for AFS/CDF

Direct observation of multiparton interactions – 2

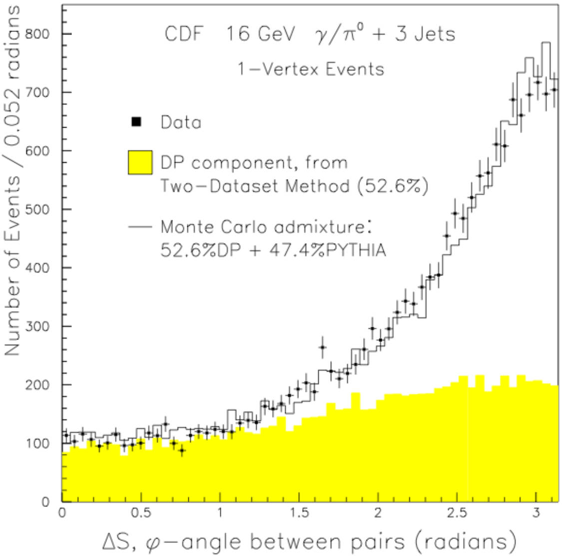
AFS 4-jet analysis (pp at 63 GeV; Copenhagen group):
observe 6 times Poissonian prediction,
with impact parameter expect 3.7 times Poissonian,
but big errors $\Rightarrow$ low acceptance, also UA2

CDF: 3-jet + prompt photon analysis (simplifies)

$$\sigma_{\mathrm{DPS}} = \frac{\sigma_A \sigma_B}{\sigma_{\mathrm{eff}}} \quad \text{for } A \neq B \qquad \Longrightarrow \sigma_{\mathrm{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3}\ \mathrm{mb}$$

Note inverse relationship on σ_{eff}.
Natural scale is $\sigma_{\mathrm{ND}} \approx 40$ mb, so $\sigma_{\mathrm{eff}} \ll \sigma_{\mathrm{ND}}$
is strong enhancement relative to naive expectations!
Consistent with (strongly) uneven matter distribution in proton.

Direct observation of multiparton interactions – 3



CDF 3-jet + prompt photon analysis

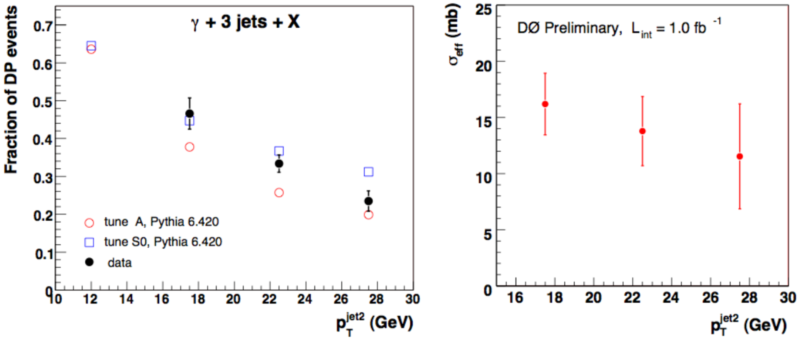
Yellow region = double parton scattering (DPS)

The rest = PYTHIA showers

Warning: PYTHIA here used without DPS

Direct observation of multiparton interactions – 4

D0 results:



$$\sigma_{\mathrm{eff}} = 15.1 \pm 1.9 \text{ mb}$$

Agreement and precision "too good to be true";
tunes several years earlier, and not to this kind of data.
More recent tunes have less matter fluctuations, i.e. higher σ_{eff},
so possibly do worse, but nontrivial.

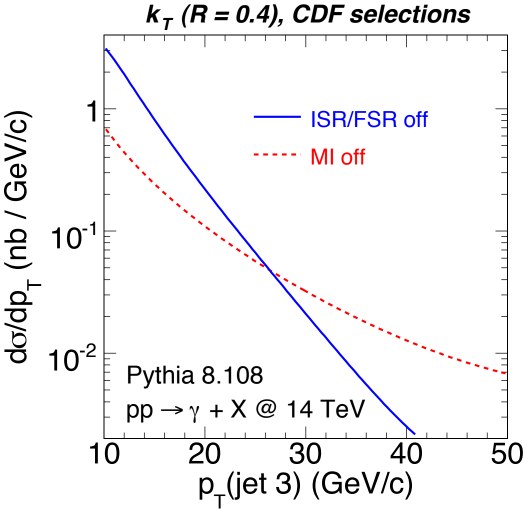
Direct observation of multiparton interactions – LHC

Same study also studied for LHC

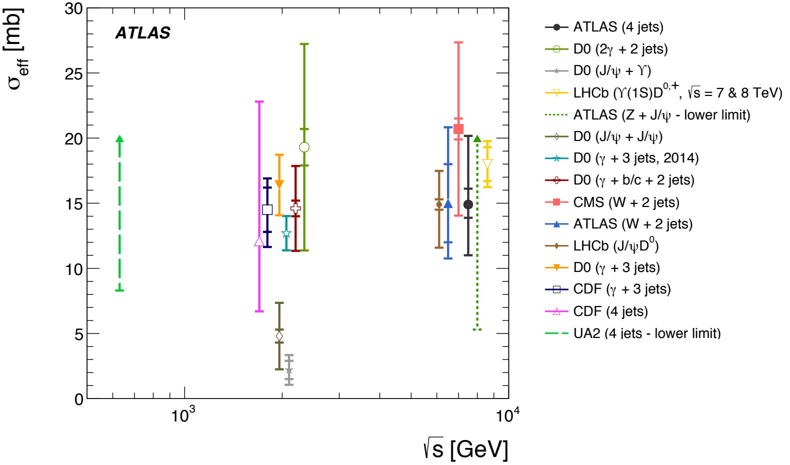
Selection for DPS delicate balance:

showers dominate at large $p_\perp$
$\Rightarrow$ too large background

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



Status summer 2016; new channels steadily added, but no upheaval



Note: big error bars, uncertain methodology, but consistent.

Event generators

No first-principles theory; non-generator models primitive, but ...

all modern general-purpose generators are built on MPI concepts

but details differ, both physics and technology, e.g.

- a single regularized hard component
  or separate hard + soft components
- MPIs generated ordered in $p_{\perp}$ or not
- energy/momentum/flavour conservation
- impact-parameter profile
- colour connection & reconnection strategies
- energy dependence
- ...

In the following PYTHIA, Herwig++, Phojet;
current Sherpa $\approx$ PYTHIA; new Sherpa framework non-default

Reminder: the Sudakov form factor

A Poissonian process is one where "events" (e.g. radioactive decays) can occur uncorrelated in "time" t (or other ordering variable).
If the probability for an "event" to occur at "time" t is $P(t)$ then the probability for a *first* "event" after $t_0 = 0$ at t_1 is

$$\mathcal{P}(t_1) = P(t_1) \exp\left(-\int_0^{t_1} P(t)\,\mathrm{d}t\right)$$

and for an i'th at t_i is

$$\mathcal{P}(t_i) = P(t_i) \exp\left(-\int_{t_{i-1}}^{t_i} P(t)\,\mathrm{d}t\right)$$

Example: Sudakov form factor for parton showers,
where increasing $t \to$ decreasing evolution variable Q
and "event" $\to$ parton branchings
...but relevant for MPIs as well ...

Basic generation of MPI – 1

- For now exclude diffractive (and elastic) topologies,
  i.e. only model nondiffractive events, with $\sigma_{\mathrm{nd}} \simeq 0.6 \times \sigma_{\mathrm{tot}}$
- Differential probability for interaction at $p_\perp$ is

$$\frac{\mathrm{d}P}{\mathrm{d}p_\perp} = \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp}$$

- Average number of interactions naively

$$\langle n \rangle = \frac{1}{\sigma_{\mathrm{nd}}} \int_0^{E_{\mathrm{cm}}/2} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp} \, \mathrm{d}p_\perp$$

- Require ≥ 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.)

Basic generation of MPI – 2

Can pick n from Poissonian and then generate n independent interactions according to $\mathrm{d}\sigma/\mathrm{d}p_\perp$ (so long as energy left), or better...

generate interactions in ordered sequence $p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > \ldots$

- Apply to ordered sequence of decreasing $p_\perp$, starting from $E_{\mathrm{cm}}/2$

$$\mathcal{P}(p_\perp = p_{\perp i}) = \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp} \exp\left[- \int_{p_\perp}^{p_{\perp(i-1)}} \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p'_\perp} \mathrm{d}p'_\perp \right]$$

- Use rescaled PDF's taking into account already used momentum and flavours $\Longrightarrow$ n_{int} narrower than Poissonian

Impact parameter dependence – 1

So far assumed that all collisions have equivalent initial conditions, but hadrons are extended, e.g. empirical 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 $r_2 \neq r_1$ represents "hot spots", and overlap of hadrons during collision is

$$\mathcal{O}(b) = \int \mathrm{d}^3\mathbf{x}\,\mathrm{d}t\; \rho_{1,\mathrm{matter}}^{\mathrm{boosted}}(\mathbf{x},t)\rho_{2,\mathrm{matter}}^{\mathrm{boosted}}(\mathbf{x},t)$$

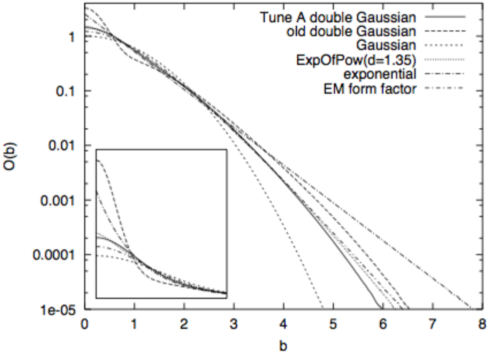
or electromagnetic form factor:

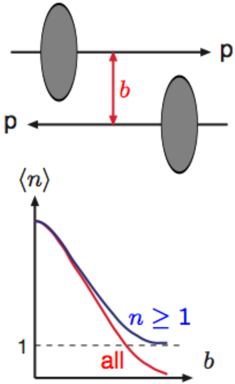
$$S_{\mathrm{p}}(\mathbf{b}) = \int \frac{\mathrm{d}^2\mathbf{k}}{2\pi}\,\frac{\exp(i\mathbf{k}\cdot\mathbf{b})}{(1+\mathbf{k}^2/\mu^2)^2}$$

where $\mu = 0.71$ GeV $\rightarrow$ free parameter, which gives

$$\mathcal{O}(b) = \frac{\mu^2}{96\pi}\,(\mu b)^3\,K_3(\mu b)$$

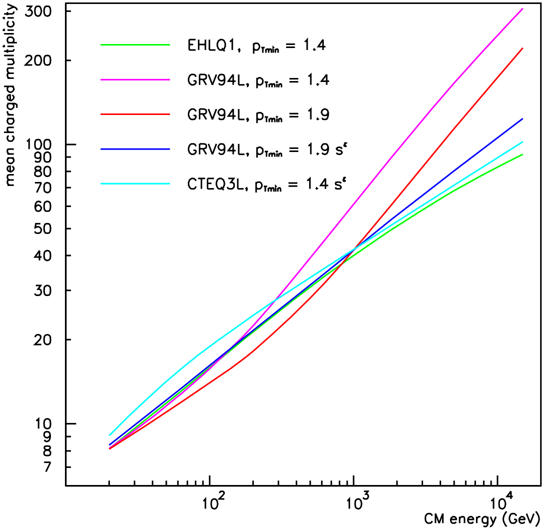
Impact parameter dependence – 2





- Events are distributed in impact parameter b
- Average activity at b proportional to $\mathcal{O}(b)$
  - ⋆ central collisions more active ⇒ $\mathcal{P}_n$ broader than Poissonian
  - ⋆ peripheral passages normally give no collisions ⇒ finite σ_{tot}
- Also crucial for *pedestal effect* (more later)

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



Larger collision energy
$\Rightarrow$ probe parton ($\approx$ gluon) density at smaller x
$\Rightarrow$ smaller colour screening length d
$\Rightarrow$ larger $p_{\perp\min}$ or $p_{\perp 0}$
$\Rightarrow$ dampened multiplicity rise

PYTHIA implementations – the original

(1) Simple scenario (1985):
first model for event properties based on perturbative multiparton 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
- colour reconnections

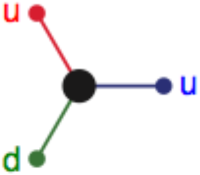
(3) Energy dependence of $p_{\perp\mathrm{min}}$ and $p_{\perp 0}$ ($\sim$ 1998):
PYTHIA default (inherited in Tune A), tied to CTEQ 5L, became

$$p_{\perp\mathrm{min}}(s) = 2.0\ \mathrm{GeV} \left(\frac{E_{\mathrm{CM}}}{1.8\ \mathrm{TeV}} \right)^{0.16}$$

PYTHIA implementations – beams and interleaving

(4) 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



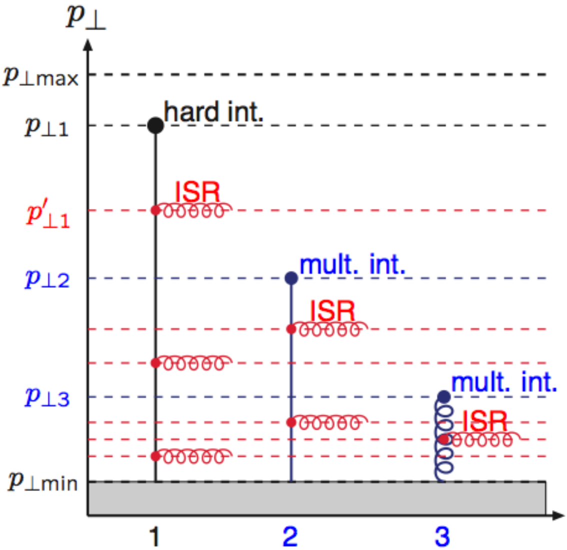
(5) Evolution interleaved with ISR (2004)
(and FSR in PYTHIA 8 (2005))

- Transverse-momentum-ordered showers

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

with ISR sum over all previous MPI

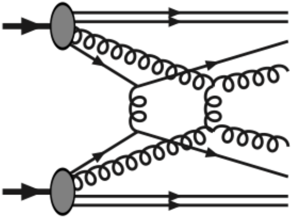
PYTHIA implementations – interleaving



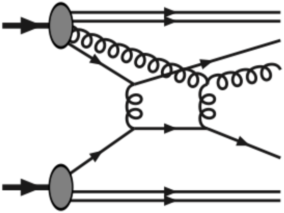
Interleaving of MPI and ISR in one common chain of decreasing $p_\perp$ values.

(6) Rescattering (2009)

Often assume that MPI =



. . . but should also include



Same order in α_{s}, $\sim$ same propagators, but

- one PDF weight less $\Rightarrow$ smaller σ
  LHC MB: $\sim$ 5 normal, $\sim$ 1 rescattering
  LHC jet: $\sim$ 12 normal, $\sim$ 4 rescattering
- one jet less
  $\Rightarrow$ QCD radiation background $2 \rightarrow 3$ larger than $2 \rightarrow 4$
  $\Rightarrow$ will be tough to find direct evidence.

PYTHIA implementations – x-dependent proton size – 1

(7) An x-dependent proton size (2011)

Normally assume that PDFs factorize:

$$f(x, r) = f(x)\,\rho(r)$$

In contradiction with

- intuitive picture of partons spreading out by cascade to lower x
- formally BFKL, Balitsky-JIMWLK, Colour Glass Condensate
- Mueller's dipole cascade (Lund program: DIPSY; see Avsar)
- Froissart-Martin $\sigma_{\mathrm{tot}} \propto \ln^2 s$ by Gribov related to $r_{\mathrm{p}} \propto \ln(1/x)$
- generalized parton distributions, ...

For now address only inelastic nondiffrative events with ansatz:

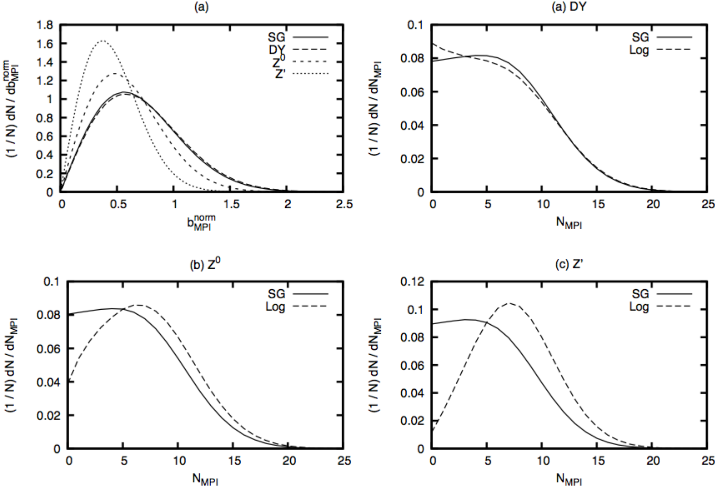
$$\rho(r, x) \propto \frac{1}{a^3(x)} \exp\left(-\frac{r^2}{a^2(x)}\right) \quad \text{with} \quad a(x) = a_0 \left(1 + a_1 \ln\frac{1}{x}\right)$$

$a_1 \approx 0.15$ tuned to **rise** of σ_{ND}

a_0 tuned to **value** of σ_{ND}, given PDF, $p_{\perp 0}$, ...

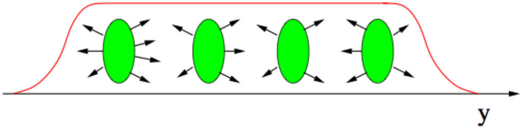
PYTHIA implementations – x-dependent proton size – 2

Consequence: collisions at large x will have to happen at small b, and hence further large-to-medium-x MPIs are enhanced, while low-x partons are so spread out that it plays less role.



HERWIG implementations

(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)

- only model of underlying event, not of minimum bias
- similar to PYTHIA (2) above; but details different
- matter profile by electromagnetic form factor (tuned)
- no $p_\perp$-ordering of emissions, no rescaling of PDF: abrupt stop when (if) run out of energy

Herwig++ implementation – 1

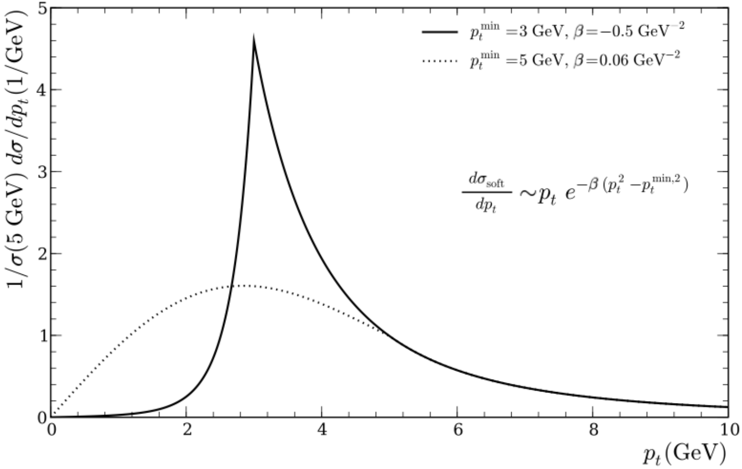
Old non-MPI Soft Underlying Event thoroughly killed.
Jimmy add-on to HERWIG does UE, but not MB.

$\Rightarrow$ Herwig++ first complete alternative:

- number of interactions first picked;
  thereafter generated unordered in $p_\perp$
- interactions uncorrelated, up until energy used up
- force ISR to reconstruct back to gluon after first interaction
- impact parameter by electromagnetic form factor shape,
  but with tunable width ($\sim$ factor 3 different from em width)
- $p_{\perp\mathrm{min}}$ scale to be tuned energy-by-energy

Herwig++ implementation – 2

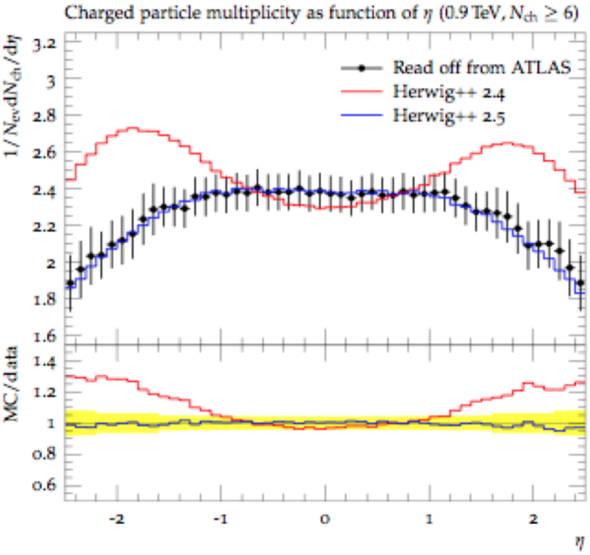
Key point: two-component model



$p_\perp > p_{\perp\min}$: pure perturbation theory (no modification)

$p_\perp < p_{\perp\min}$: pure nonperturbative ansatz

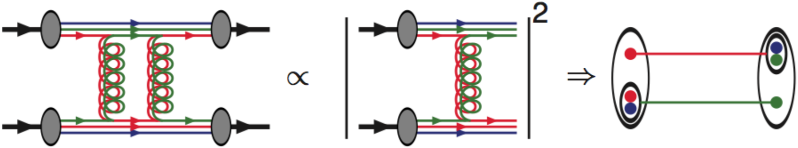
Colour reconnection essential to get $\mathrm{d}n/\mathrm{d}\eta$ correct:



PhoJet (& relatives) implementations

(1) Cut Pomeron (1982)

- Pomeron predates QCD; nowadays $\sim$ glueball tower
- Optical theorem relates σ_{total} and $\sigma_{\mathrm{elastic}}$



- 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:
  soft = nonperturbative, low-$p_\perp$, as above
  hard = perturbative, "high"-$p_\perp$
- hard based on PYTHIA code, with lower cutoff in $p_\perp$

Jet pedestal effect – 1

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 $p_{\perp\mathrm{hard}} \sim 10$ GeV, as follows.

$$\frac{\mathrm{d}\mathcal{P}_{\mathrm{hardest}}}{\mathrm{d}^2 b \, \mathrm{d}p_{\perp}} = \mathcal{O}(b) \, P(p_{\perp}) \exp\left(-\mathcal{O}(b) \int_{p_{\perp}}^{E_{\mathrm{cm}}/2} P(p'_{\perp}) \, \mathrm{d}p'_{\perp} \right) ,$$

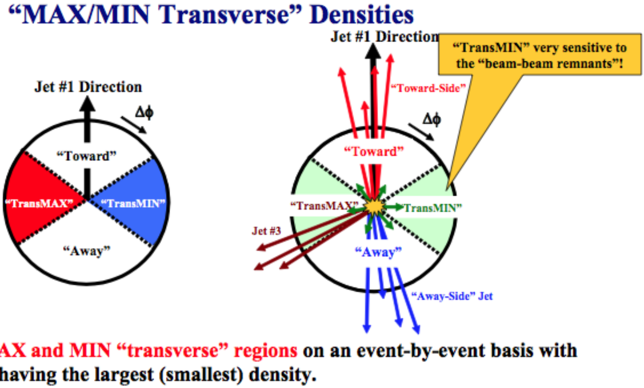
with $P(p_{\perp}) = (1/\sigma_{\mathrm{nd}}) \mathrm{d}\sigma / \mathrm{d}p_{\perp}$ and $\mathcal{O}(b)$ suitably normalized.
At small $p_{\perp}$ the exponent kills small b ($\Leftrightarrow$ large $\mathcal{O}(b)$),

$$\text{but at large } p_{\perp} : \int_{p_{\perp}}^{E_{\mathrm{cm}}/2} \frac{\mathrm{d}\sigma}{\mathrm{d}p'_{\perp}} \ll \sigma_{\mathrm{nd}} \Rightarrow \exp(- \cdots) \approx 1$$

and then b and $p_{\perp}$ selections decouple, i.e. saturation.

Jet pedestal effect – 2

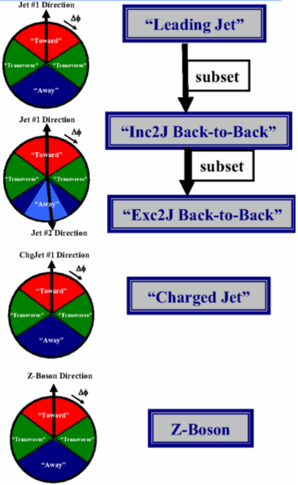
Studied in particular by Rick Field, comparing with CDF data:
http://www.phys.ufl.edu/∼rfield/cdf/rdf_talks.html)

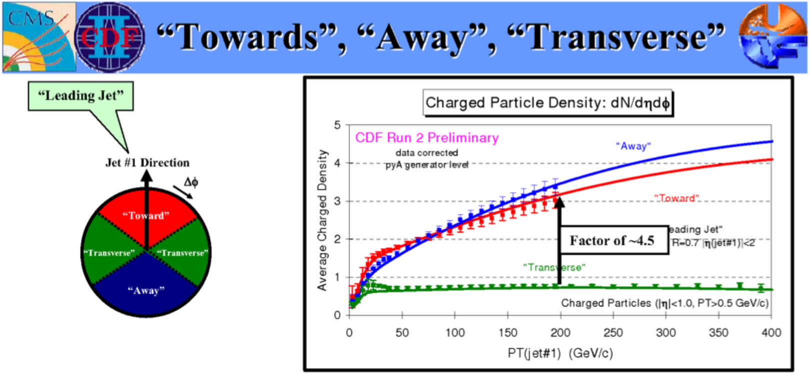


Jet pedestal effect – 3 (Rick Field)

Event Topologies

- **"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" ($\Delta\phi_{12} > 150^o$) 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" ($\Delta\phi_{12} > 150^o$) 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(lepton-pair) < 110 GeV with no other conditions.

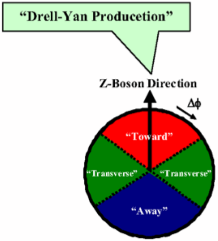


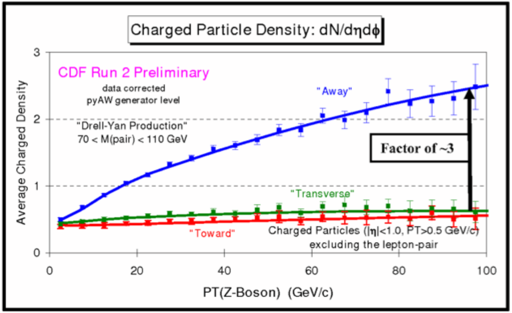


- **Data at 1.96 TeV on the density of charged particles, dN/dηdφ, with p_T > 0.5 GeV/c and |η| < 1 for "leading jet" events as a function of the leading jet p_T for the "toward", "away", and "transverse" regions. The data are corrected to the particle level (*with errors that include both the statistical error and the systematic uncertainty*) and are compared with PYTHIA Tune A at the particle level (*i.e.* generator level).**

Jet pedestal effect – 5 (Rick Field)

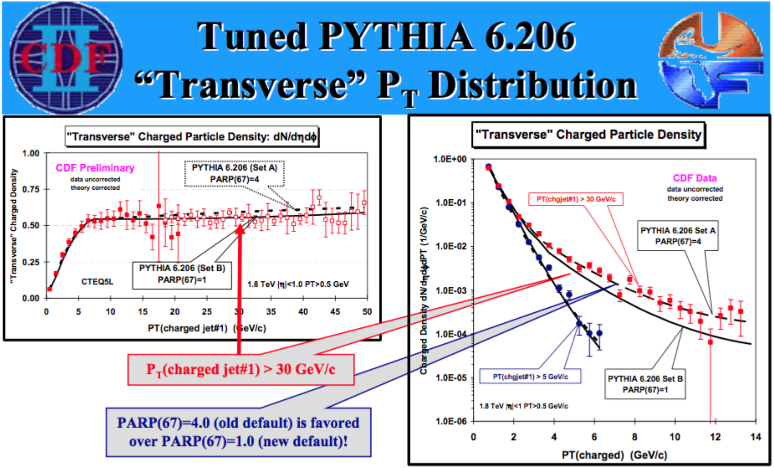
“Towards”, “Away”, “Transverse”





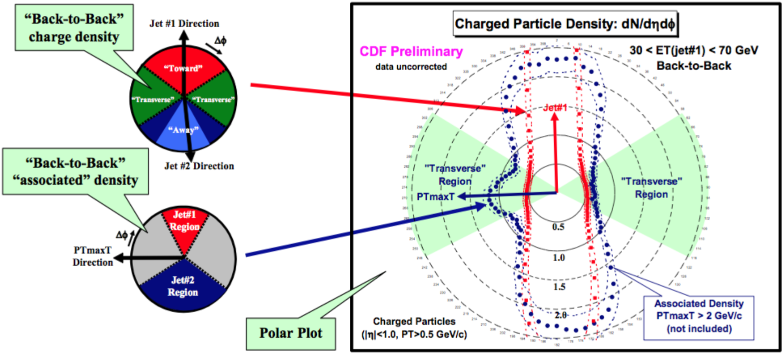
➡ Data at 1.96 TeV on the density of charged particles, dN/dηdϕ, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for “Z-Boson” events as a function of the leading jet p_T for the “toward”, “away”, and “transverse” regions. The data are corrected to the particle level (*with errors that include both the statistical error and the systematic uncertainty*) and are compared with PYTHIA Tune AW at the particle level (*i.e.* generator level).

Deepak Kar’s Thesis



- **Compares the average "transverse" charge particle density (|η|<1, P_T>0.5 GeV) versus P_T(charged jet#1) and the P_T distribution of the "transverse" density, $dN_{chg}/d\eta d\phi dP_T$ 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)).**

Back-to-Back "Associated" Charged Particle Densities

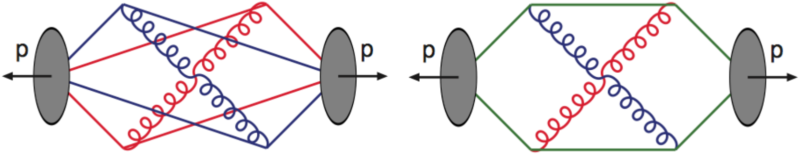


- Shows the $\Delta\phi$ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180°) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to 270°) for "back-to-back events" with $30 < E_T(\text{jet\#1}) < 70$ GeV.

Colour correlations

(1) Colour connections:
Each interaction hooks up with colours from beam remnants,
but how does the colours in the remnant hook up with each other?

(2) Colour *re*connections:
Many interaction "on top of" each other $\Rightarrow$ tightly packed partons!
Is there a strict colour memory when partons recede?



Recall: $N_C = 3$, not $N_C = \infty$!

$\langle p_\perp \rangle(n_{\mathrm{ch}})$ is sensitive to colour flow:
long strings to remnants $\Rightarrow$ much n_{ch}/MPI $\Rightarrow$ $\langle p_\perp \rangle(n_{\mathrm{ch}}) \sim$ flat
short strings (more central) $\Rightarrow$ less n_{ch}/MPI $\Rightarrow$ $\langle p_\perp \rangle(n_{\mathrm{ch}}) \sim$ rising

Colour correlations and $\langle p_\perp \rangle (n_{\mathrm{ch}})$

$\langle p_\perp \rangle (n_{\mathrm{ch}})$ issue has survived from 1987 to today:

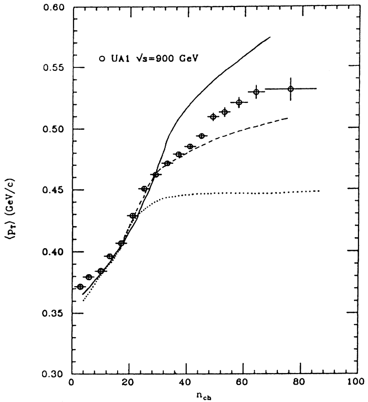
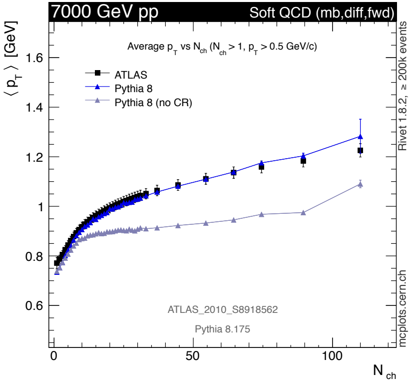


FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings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



CR reduces total string length
$\Rightarrow$ reduces hadronic multiplicity

Many models (more later, if time)

A QCD-based Colour reconnection model

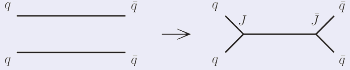
Model by Christiansen & Skands relies on two main principles

⋆ **SU(3)** colour rules give allowed reconnections

Ordinary string reconnection

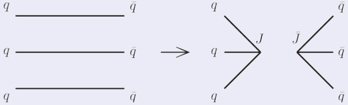
($q\bar{q}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection



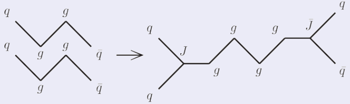
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection



($q\bar{q}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection

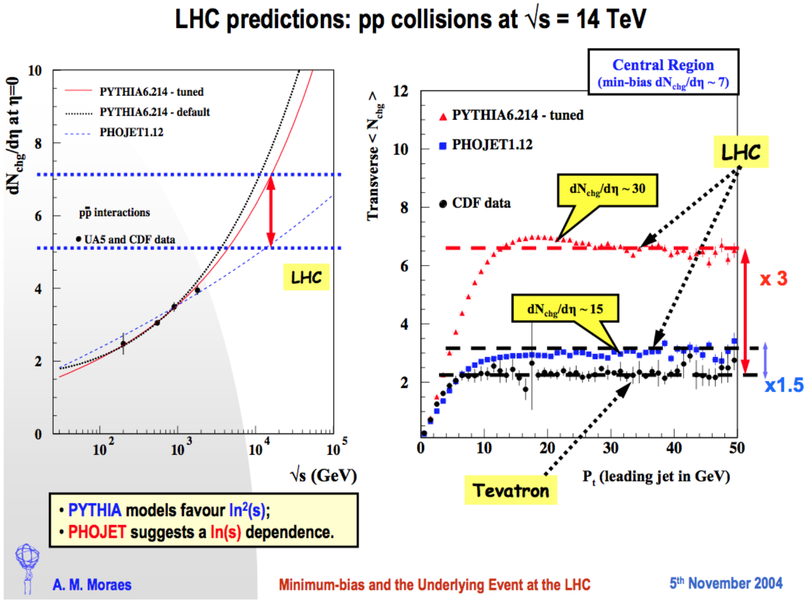


(Depends on number of gluons)

⋆ minimal λ measure gives preferred reconnections

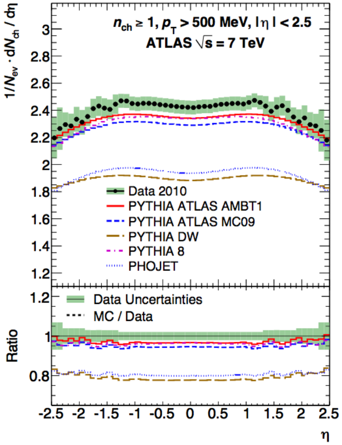
$\lambda \approx \sum_{\mathrm{dipoles}} \ln(1 + m_{ij}^2/m_0^2)$ measure of string length, $\propto n_{\mathrm{hadronic}}$

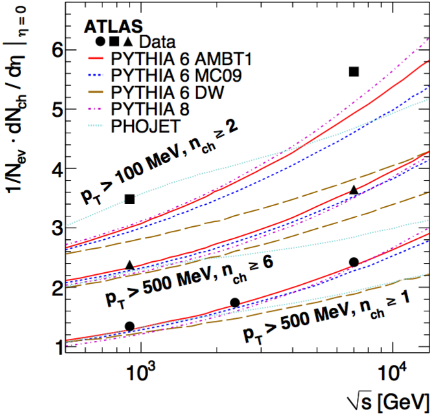
LHC predictions



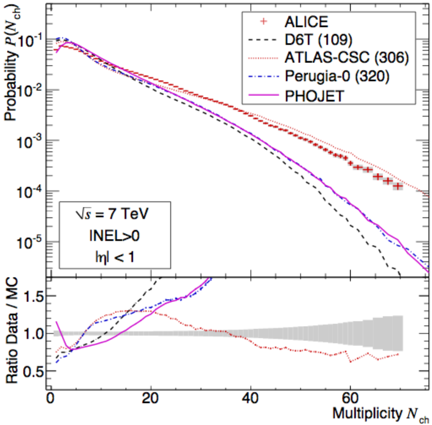
LHC outcome – 1

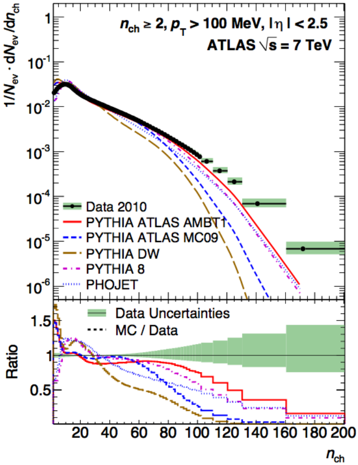
First/most LHC comparisons to old versions of generators, e.g.:



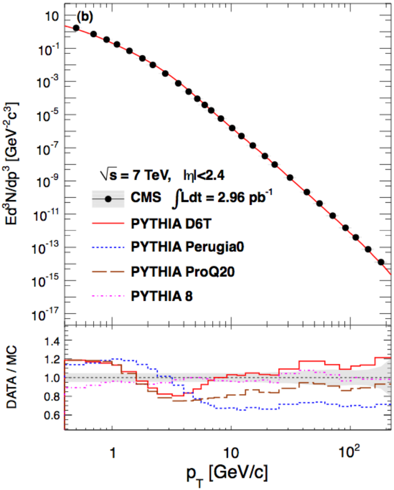


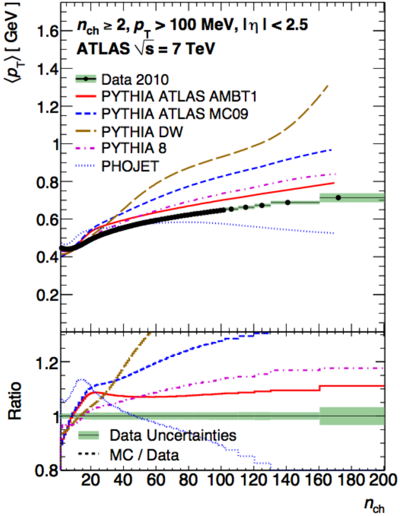
First/most LHC comparisons to old versions of generators, e.g.:



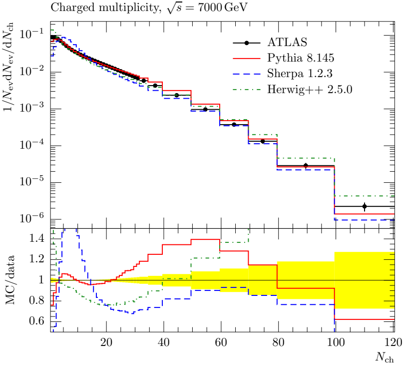


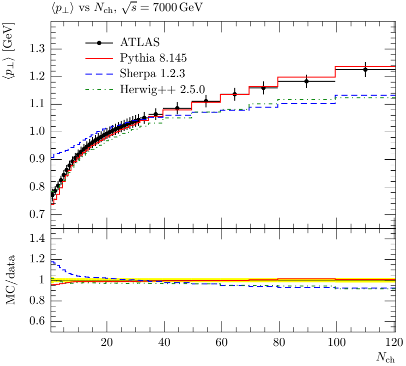
First/most LHC comparisons to old versions of generators, e.g.:





State of new generators early 2011:

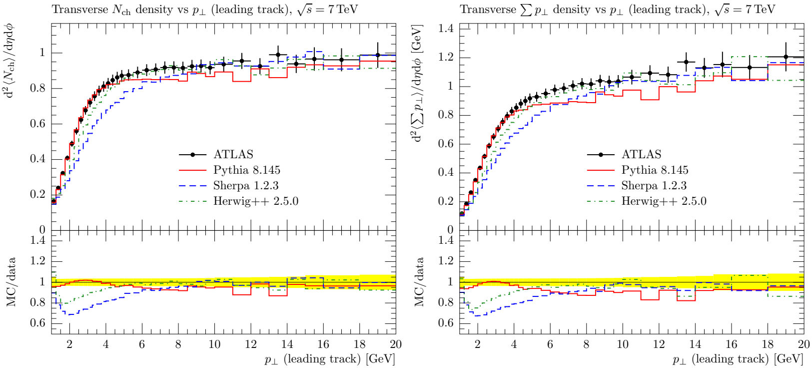




A. Buckley et al., Phys. Rep. 504 (2011) 145 [arXiv:1101.2599[hep-ph]]

LHC outcome – 5

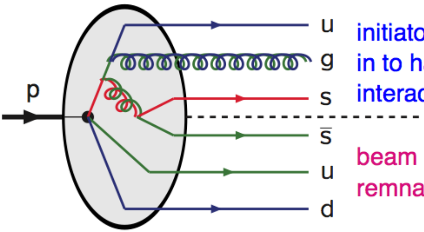
State of new generators early 2011:



A. Buckley et al., Phys. Rep. 504 (2011) 145 [arXiv:1101.2599[hep-ph]]

Later: more recent tunes (Monash etc.)

Initiators and remnants



Need to assign:

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

PDF after preceding MI/ISR activity:

1. Squeeze range $0 < x < 1$ into $0 < x < 1 - \sum x_i$ (ISR: $i \neq i_{\mathrm{current}}$)
2. Valence quarks: scale down by number already kicked out
3. Introduce companion quark $\mathrm{q}/\overline{\mathrm{q}}$ to each kicked-out sea quark $\overline{\mathrm{q}}/\mathrm{q}$, with x based on assumed $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ splitting
4. Gluon and other sea: rescale for total momentum conservation

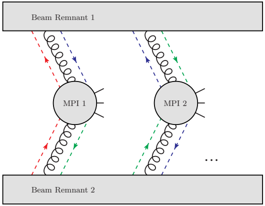
The QCD-based beam remnant model

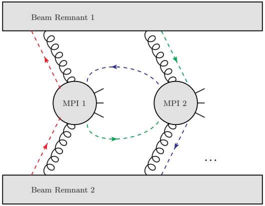
Possible colour states for the two gluons:

$$\mathbf{8} \otimes \mathbf{8} = \mathbf{27} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1}$$

27	$\overline{\mathbf{10}}$	**10**	**8**	**1**
2 C & 2 AC + 1 gluon	0 C & 3 AC + 0 gluon (junction)	3 C & 0 AC + 1 gluon (junction)	1 C & 1 AC + 0 gluon	0 C & 0 AC + 0 gluon (not allowed)

Examples of the **27** and the **8** configurations:

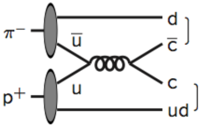




Old model: $\mathbf{8} \otimes \mathbf{8} = \mathbf{8}$, i.e. minimal nonvanishing colour, no junctions in BR (but possible in the event as a whole)

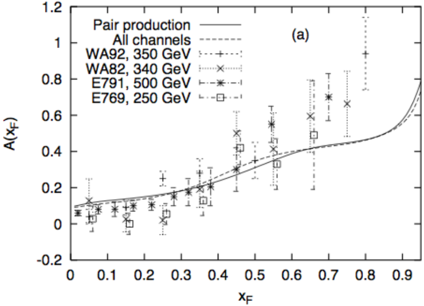
Beam remnant physics

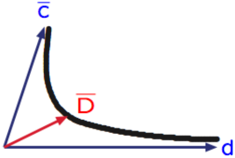
Colour flow connects hard scattering to beam remnants. Can have consequences, e.g. in $\pi^- p$



$$A(x_F) = \frac{\#D^- - \#D^+}{\#D^- + \#D^+}$$

If low-mass string e.g.:
$\bar{c}d$: D^-, D^{*-}
cud: Λ_c^+, Σ_c^+, Σ_c^{*+}
$\Rightarrow$ flavour asymmetries





Can give D 'drag' to larger x_F than c quark for any string mass

(also B asymmetries at LHC, but small)

Summary

- **MPI concept compelling**; it **has to** exist at some level
- By now, **strong** direct evidence, **overwhelming** indirect
- **Understanding of MPI crucial for LHC precision physics**
- Many details uncertain:
  ⋆ physics and form of $p_{\perp\mathrm{min}}/p_{\perp 0}$ regularization
  ⋆ non-factorized impact parameter picture
  ⋆ multiparton densities in incoming hadron
  ⋆ colour correlations between interactions
  ⋆ energy dependence $\Rightarrow$ predictivity
  ⋆ dense-packing of partons and hadrons $\Rightarrow$ collective effects?
  ⋆ diffraction, forward physics, ...
- Above physics aspects must all be present, and more?
  If a model is simple, it is wrong!
- So stay tuned for ever more complicated models in the future!