Modelling of minimum bias and underlying events

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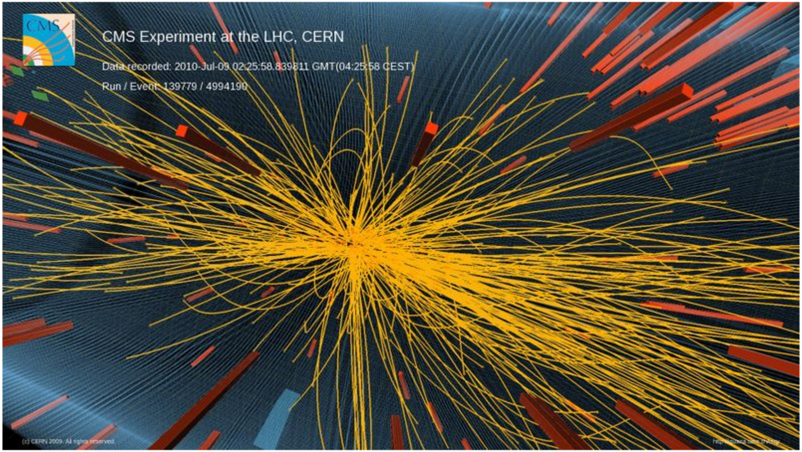
Event topologies



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

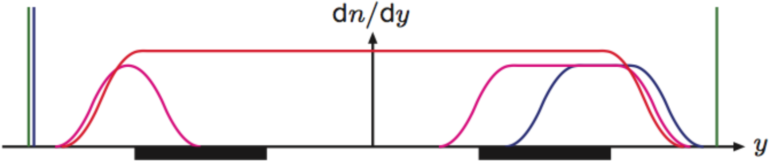
What is minimum bias (MB)?

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

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

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

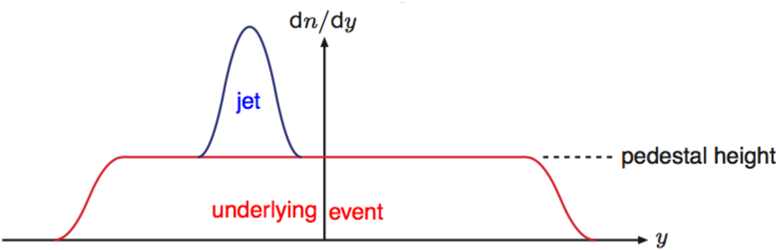
Schematically:



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)?

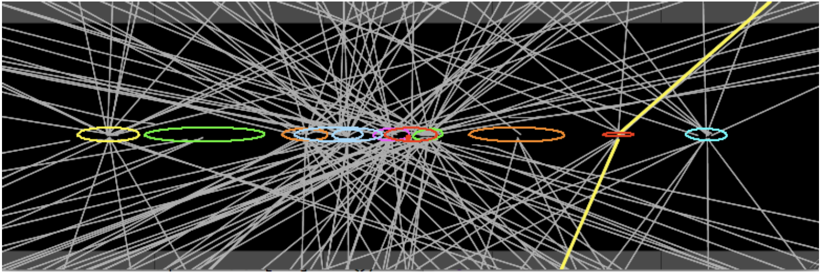


In an event containing a jet pair or another hard process, how much further activity is there, that does not have its origin in the hard process itself, but in other physics processes?

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.

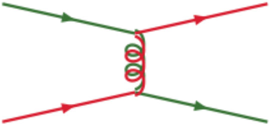
Current LHC machine conditions $\Rightarrow \langle n \rangle$ approaching 10.

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 $2 \to 2$

$\mathrm{qq}' \to \mathrm{qq}'$

$\mathrm{q\overline{q}} \to \mathrm{q}'\overline{\mathrm{q}}'$

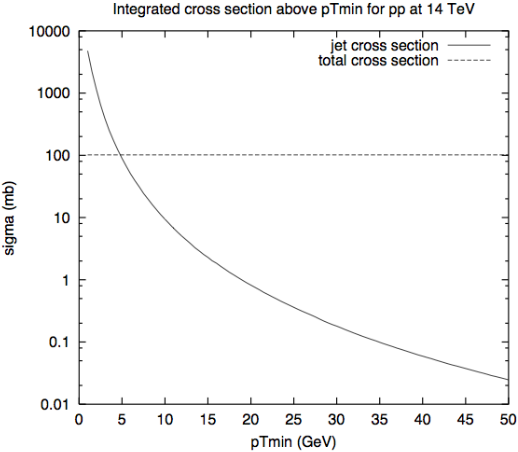
$\mathrm{q\overline{q}} \to \mathrm{gg}$

$\mathrm{qg} \to \mathrm{qg}$

$\mathrm{gg} \to \mathrm{gg}$

$\mathrm{gg} \to \mathrm{q\overline{q}}$

(with CTEQ 5L PDF's)



What is multiple partonic interactions (MPI)?

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

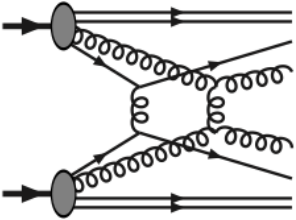
$$\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) = \iiint_{p_{\perp\mathrm{min}}} \mathrm{d}x_1 \, \mathrm{d}x_2 \, \mathrm{d}p_{\perp}^2 \, f_1(x_1, p_{\perp}^2) \, f_2(x_2, p_{\perp}^2) \, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_{\perp}^2}$$

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

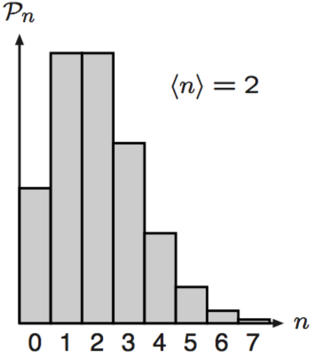
So half a solution to $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) > \sigma_{\mathrm{tot}}$ is

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

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



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 $p_{\perp\mathrm{min}} \to 0$?

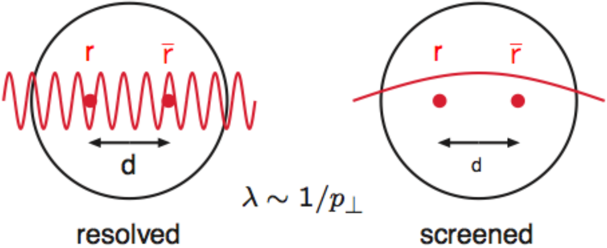
Colour screening

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:

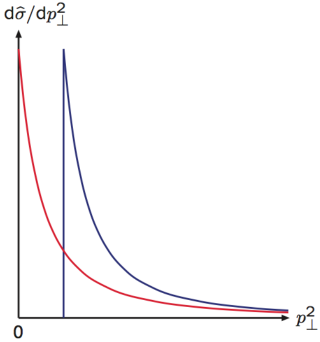


Regularization of low-$p_\perp$ divergence

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

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

$$\text{or} \quad \to \quad \frac{\alpha_s^2(p_{\perp0}^2 + p_\perp^2)}{(p_{\perp0}^2 + p_\perp^2)^2} \qquad \text{(more physical)}$$



where $p_{\perp\mathrm{min}}$ or $p_{\perp0}$ 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 multiple interactions – 1

without MPI:

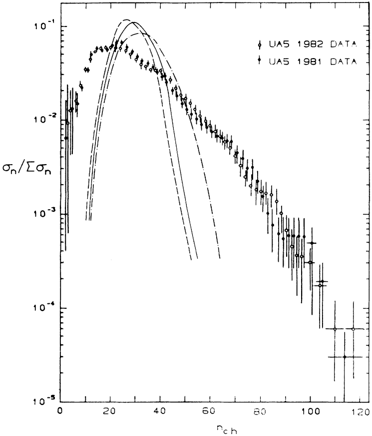


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

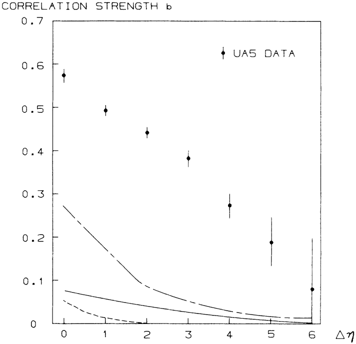


FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

Indirect evidence for multiple interactions – 2

with MPI included:

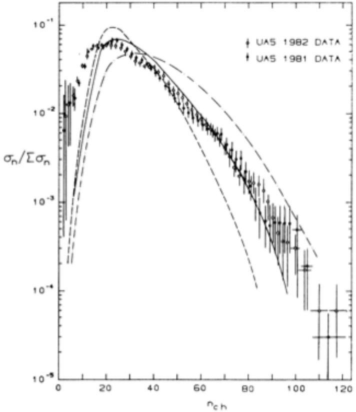


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min}=2.0$ GeV; solid line, $p_{T\min}=1.6$ GeV; dashed-dotted line, $p_{T\min}=1.2$ GeV.

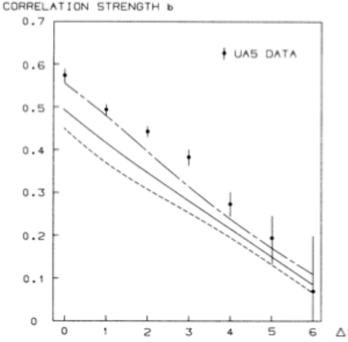


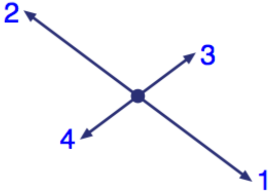
FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.

Direct observation of multiple 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 multiple interactions – 2

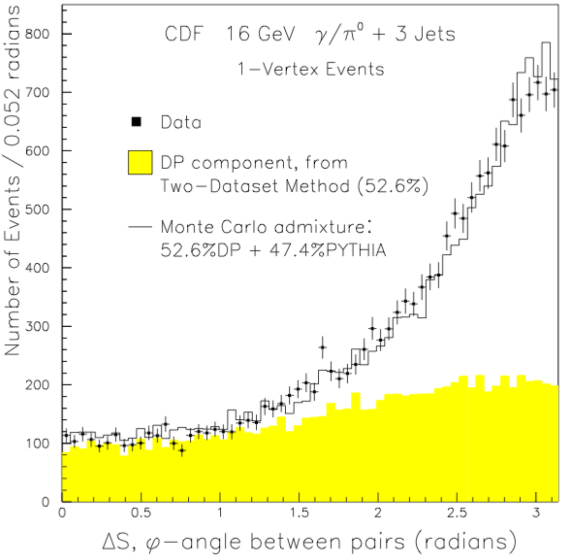
AFS 4-jet analysis (pp at 63 GeV; Copenhagen group):
observe 6 times Poissonian prediction,
with impact parameter expect 3.7 times Poissonian,
but big errors ⇒ low acceptance, also UA2

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 multiple interactions – 3



CDF 3-jet + prompt photon analysis

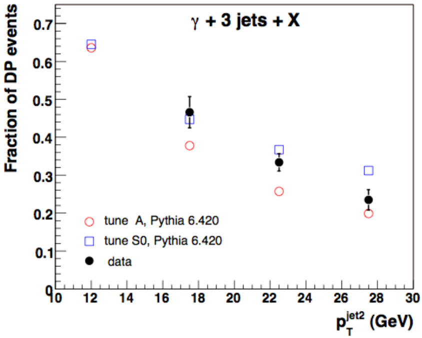
Yellow region = double parton scattering (DPS)

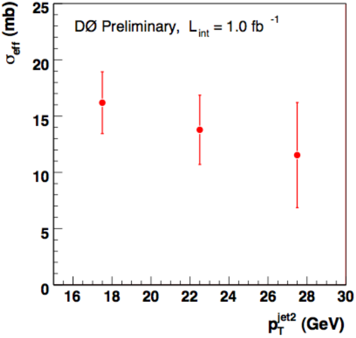
The rest = PYTHIA showers

Warning: PYTHIA here used without DPS

Direct observation of multiple interactions – 4

D0 results:





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

Agreement and precision "too good to be true";
tunes 8 and 4 years old, respectively, and not to this kind of data.
More recent tunes have less matter fluctuations, i.e. higher σ_{eff}, so likely to do worse.

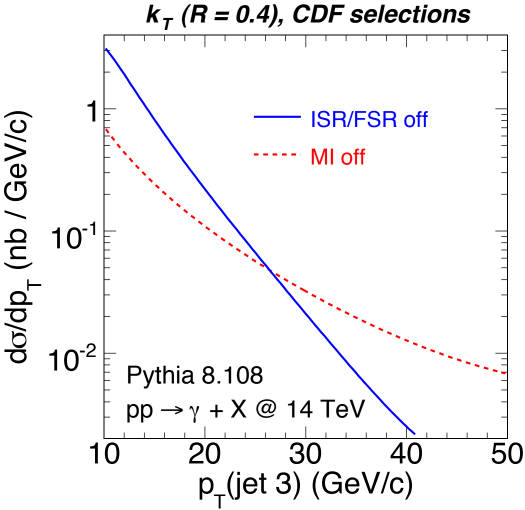
Direct observation of multiple interactions – LHC

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



Event generators

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 ≈ PYTHIA; tomorrow future Sherpa

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" → 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

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

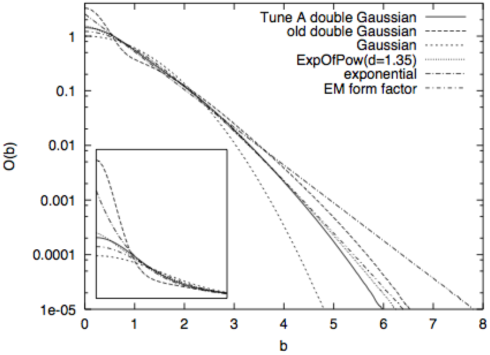
or electromagnetic form factor:

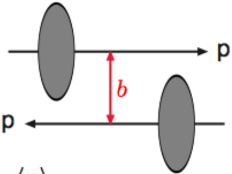
$$S_{\mathrm{p}}(\mathbf{b}) = \int \frac{\mathrm{d}^2\mathbf{k}}{2\pi} \, \frac{\exp(i\mathbf{k}\cdot\mathbf{b})}{(1 + \mathbf{k}^2/\mu^2)^2}$$

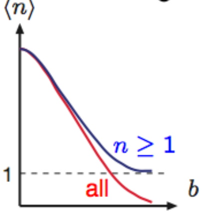
where $\mu = 0.71$ GeV → free parameter, which gives

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

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)

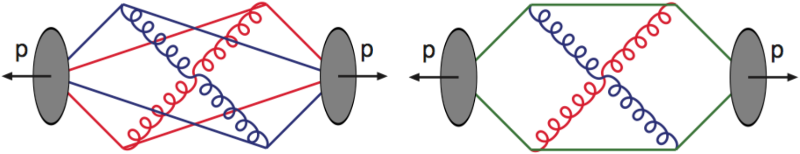
Colour correlations

(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?

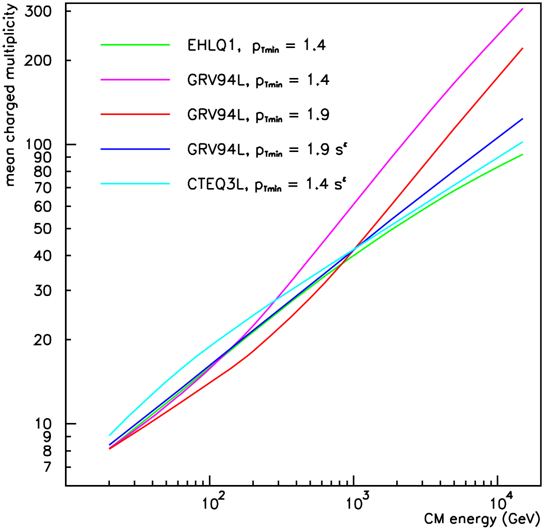
(2) Colour *re*connections:

Many interaction "on top of" each other ⇒ tightly packed partons!
Is there a strict colour memory when partons recede?



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

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

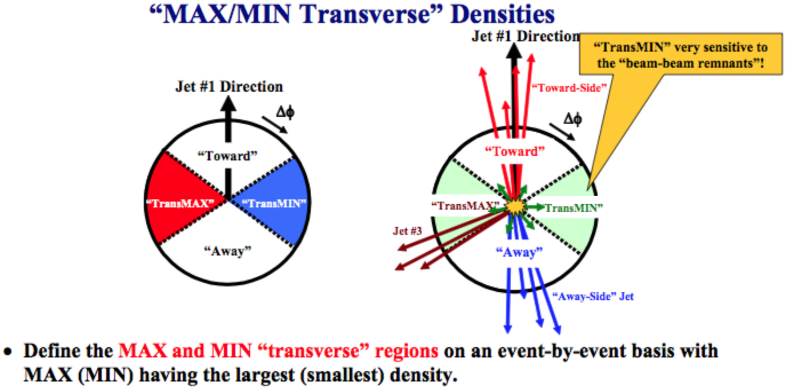
Jet pedestal effect – 1

Events with hard scale have more underlying activity!

Trigger bias: hard scale ⇒ central collision ⇒ large UE.

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

`http://www.phys.ufl.edu/~rfield/cdf/rdf_talks.html)`

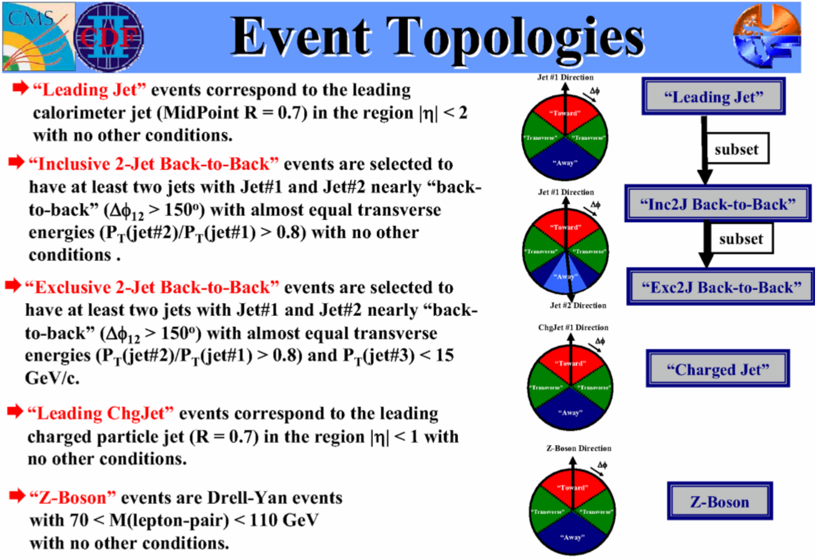


"MAX/MIN Transverse" Densities

"TransMIN" very sensitive to the "beam-beam remnants"!

- **Define the MAX and MIN "transverse" regions on an event-by-event basis with MAX (MIN) having the largest (smallest) density.**

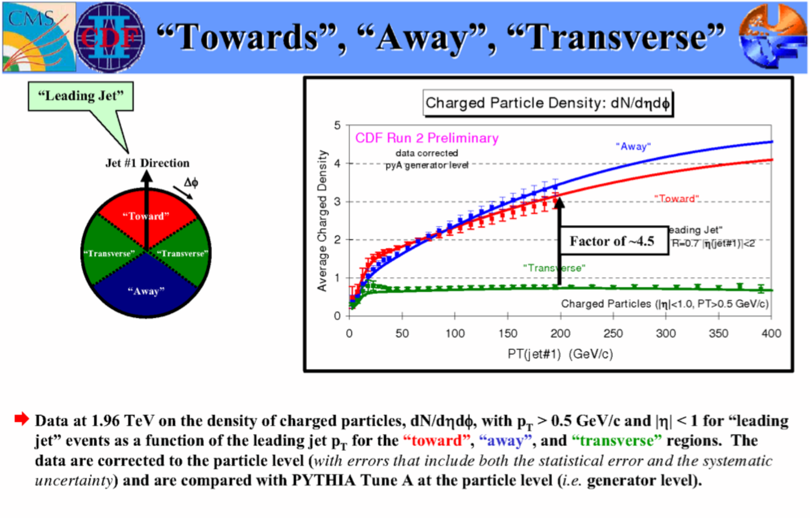
Jet pedestal effect – 2 (Rick Field)



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" ($\Delta\phi_{12} > 150^\circ$) with almost equal transverse energies ($P_T(\text{jet\#2})/P_T(\text{jet\#1}) > 0.8$) 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 ($P_T(\text{jet\#2})/P_T(\text{jet\#1}) > 0.8$) and $P_T(\text{jet\#3}) < 15$ 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.

Jet pedestal effect – 3 (Rick Field)

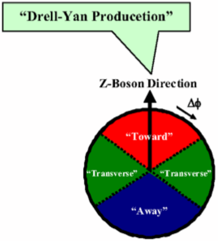


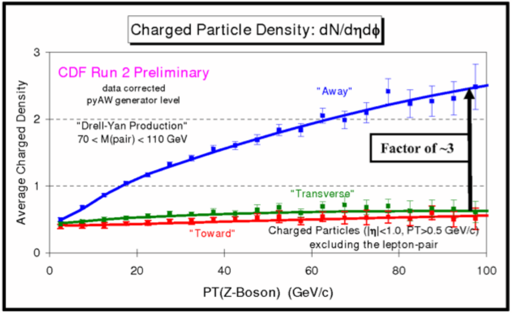
"Towards", "Away", "Transverse"

- Data at 1.96 TeV on the density of charged particles, dN/dηdφ, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "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 – 4 (Rick Field)

“Towards”, “Away”, “Transverse”

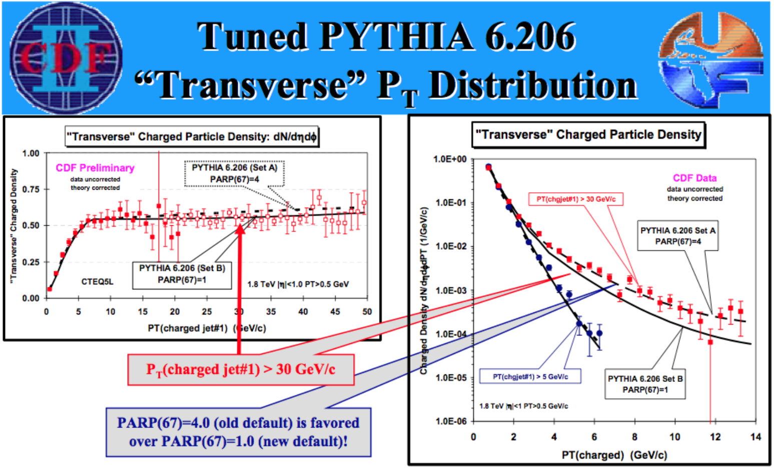




➡ **Data at 1.96 TeV on the density of charged particles, dN/dηdϕ, with $p_T > 0.5$ GeV/c and $|\eta| < 1$ for “Z-Boson” events as a function of the leading jet p_T for the “toward”, “away”, and “transverse” regions. The data are corrected to the particle level (*with errors that include both the statistical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

Deepak Kar’s Thesis

Jet pedestal effect – 5 (Rick Field)



Tuned PYTHIA 6.206 “Transverse” P_T Distribution

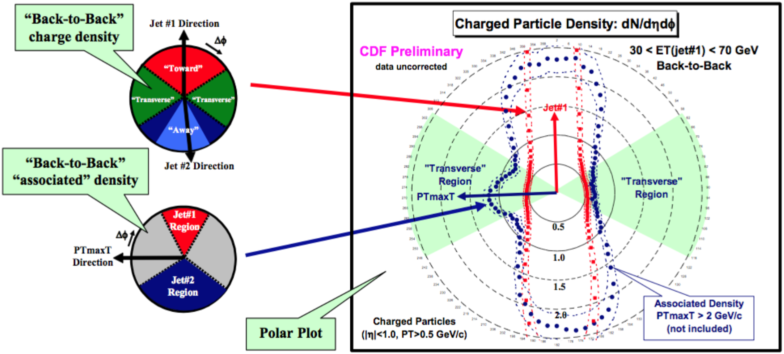
P_T(charged jet#1) > 30 GeV/c

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

- Compares 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, $dN_{chg}/d\eta d\phi dP_T$ 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)).

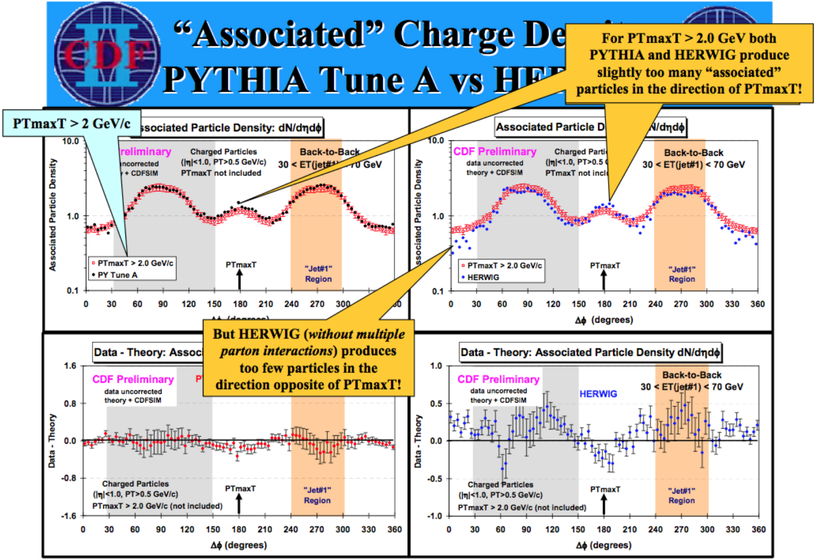
Jet pedestal effect – 6 (Rick Field)

Back-to-Back "Associated" Charged Particle Densities



- Shows the Δϕ dependence of the "associated" charged particle density, dNchg/dηdϕ, $p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180°) and the charged particle density, dNchg/dηdϕ, $p_T > 0.5$ 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.

Jet pedestal effect – 7 (Rick Field)



"Associated" Charge De

PYTHIA Tune A vs HE

For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too many "associated" particles 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!

PYTHIA implementation – 1

Has gradually evolved from the MPI start in 1985;
still older versions in use.
Current version involves (among others):

- MPI ordered in $p_\perp$, and also
- transverse-momentum-ordered parton showers for ISR and FSR.

Allows interleaved evolution for MPI, ISR and FSR:

$$\begin{aligned}\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} &= \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_\perp}\right) \\ &\times \exp\left(-\int_{p_\perp}^{p_{\perp\max}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_\perp}\right) \mathrm{d}p'_\perp\right)\end{aligned}$$

ordered in decreasing $p_\perp$ using “Sudakov” trick.

Corresponds to increasing “resolution” of partonic final state:
smaller $p_\perp$ fill in details of the basic picture set at larger $p_\perp$.

PYTHIA implementation – 2

Other aspects in line with previous discussions:

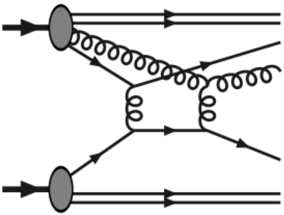
- smooth dampening $\mathrm{d}\hat{\sigma}/\mathrm{d}p_{\perp}^2 \propto 1/(p_{\perp 0}^2 + p_{\perp}^2)^2$
  $\Rightarrow$ all interactions belong to same "hard" kind
- energy-dependent $p_{\perp 0}$

$$p_{\perp 0}(E_{\mathrm{cm}}) = p_{\perp 0}(E_{\mathrm{cm,ref}}) \left(\frac{E_{\mathrm{cm}}}{E_{\mathrm{cm,ref}}} \right)^k$$

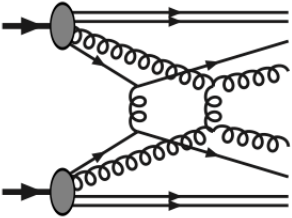
- matter profile flexible, Gaussian or more spiked
- PDF rescaling for energy/momentum/flavour conservation
- colour connection/reconnection important component
- drift of baryon number by junction topology

PYTHIA implementation – 3

- Rescattering (optional since 2009)



in addition to



Same order in α_{s}, $\sim$ same propagators, but one PDF weight less $\Rightarrow$ smaller σ, and one jet less $\Rightarrow$ $2 \to 3$ QCD radiation background larger

- An x-dependent proton size (optional since 2011)

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

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

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

Herwig++ implementation – 1

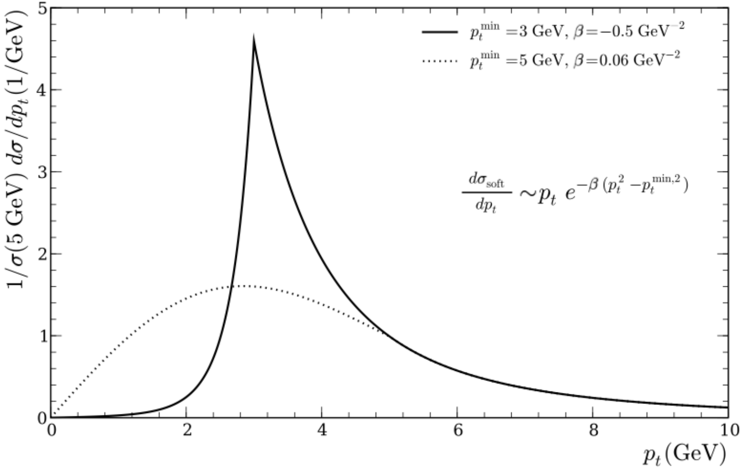
Old non-MPI Soft Underlying Event thoroughly killed.
Jimmy add-on to HERWIG does UE, but not MB.

⇒ 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

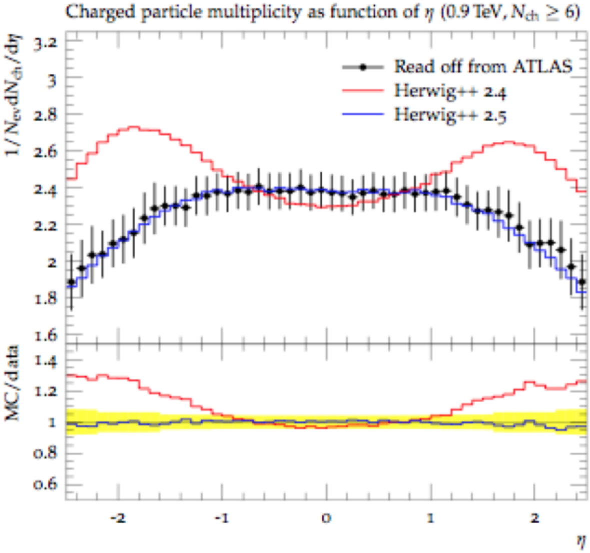


$p_\perp > p_{\perp\mathrm{min}}$: pure perturbation theory (no modification)

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

Herwig++ implementation – 3

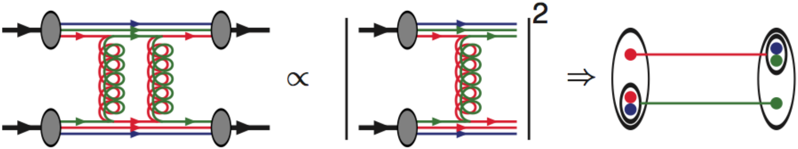
Colour reconnection essential to get $\mathrm{d}n/\mathrm{d}\eta$ correct:



PhoJet (& relatives) implementation

(1) Cut Pomeron (1982)

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



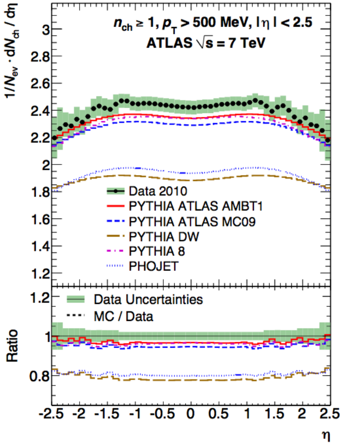
- Unified framework of nondiffractive and diffractive interactions
- Purely low-$p_\perp$: only primordial $k_\perp$ fluctuations
- Usually simple Gaussian matter distribution

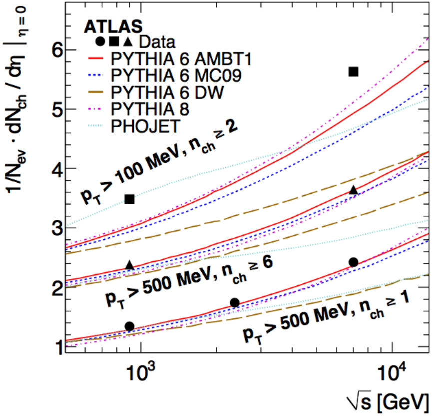
(2) Extension to large $p_\perp$ (1990)

- 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 $p_\perp$

LHC outcome – 1

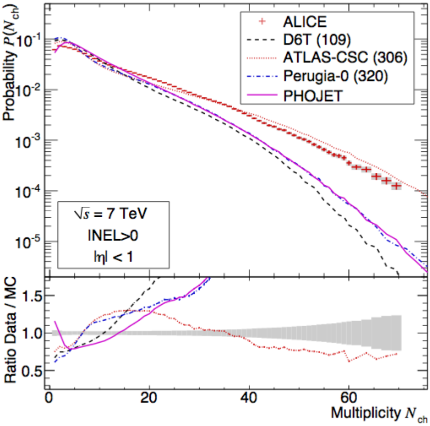
First/most LHC comparisons to old versions of generators, e.g.:

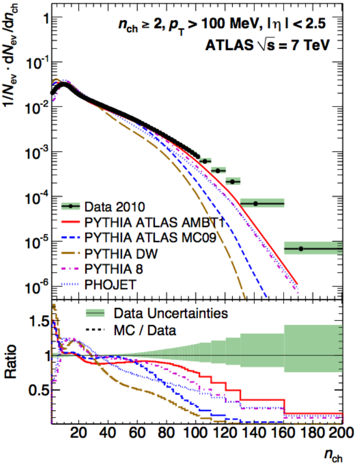




LHC outcome – 2

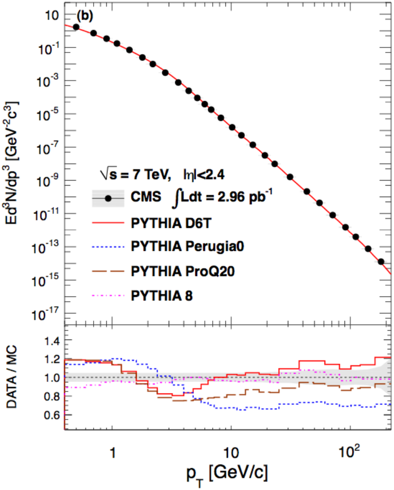
First/most LHC comparisons to old versions of generators, e.g.:

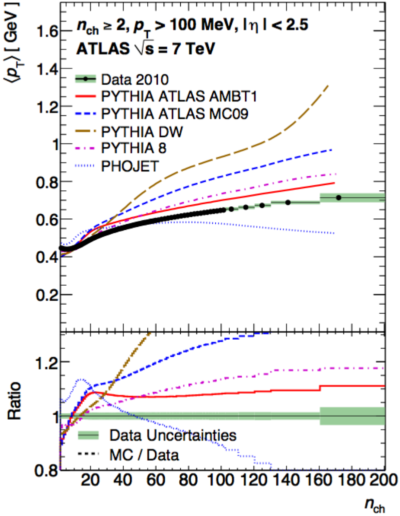




LHC outcome – 3

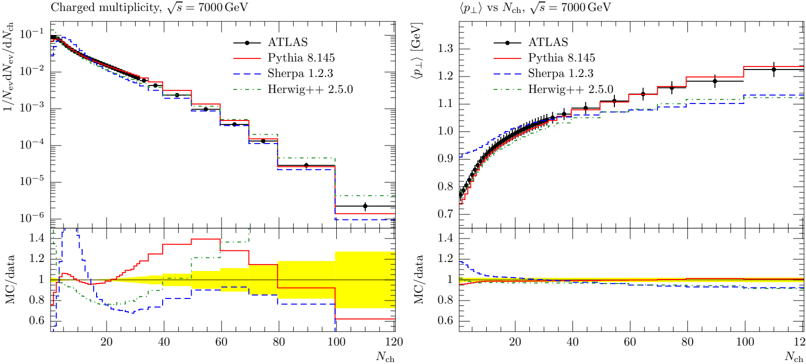
First/most LHC comparisons to old versions of generators, e.g.:





LHC outcome – 4

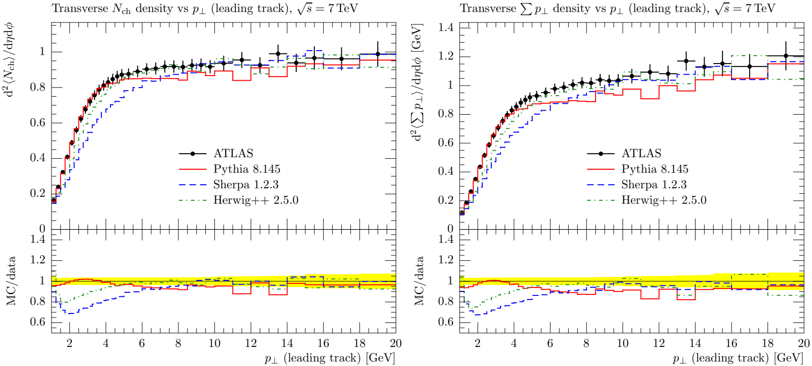
State of new generators early 2011:



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]]

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 ⇒ predictivity
  - ⋆ dense-packing of partons and hadrons ⇒ 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!