Introduction to Event Generators 3

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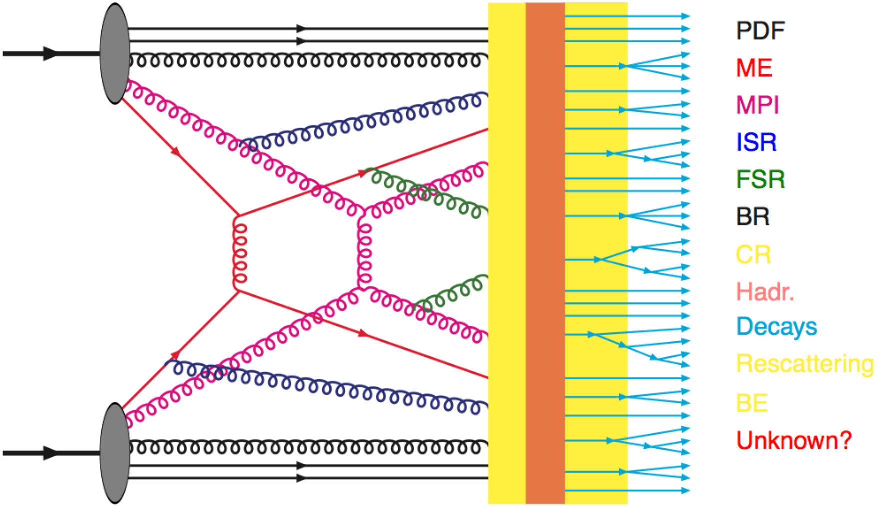
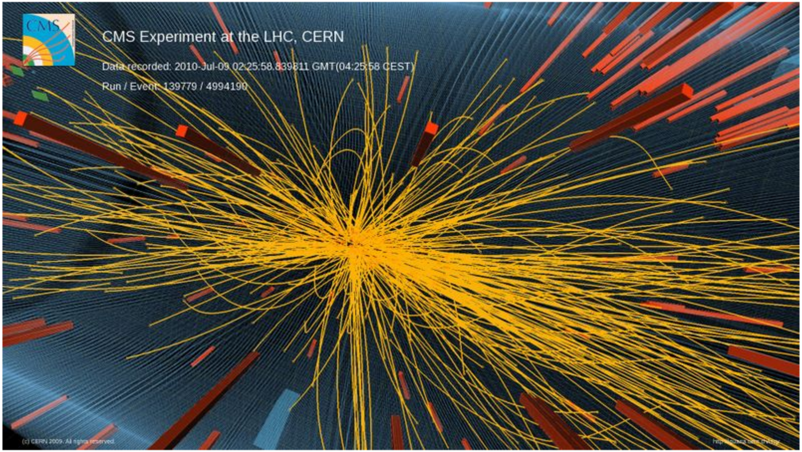
Event Generators Reminder

An event consists of many different physics steps, which have to be modelled by event generators:



Event topologies



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

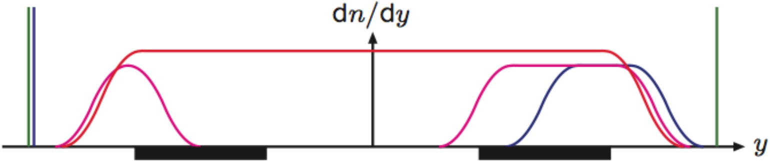
What is minimum bias (MB)?

MB ≈ "all events, with no bias from restricted trigger conditions"

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

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

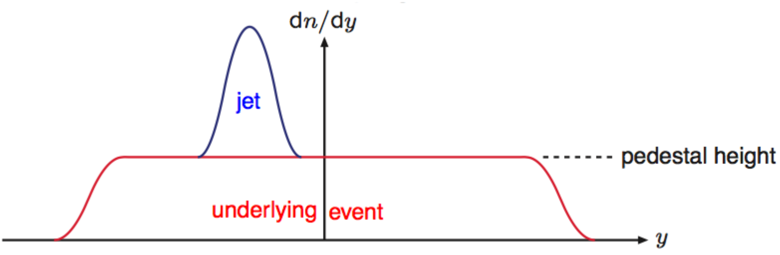
Schematically:



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)?

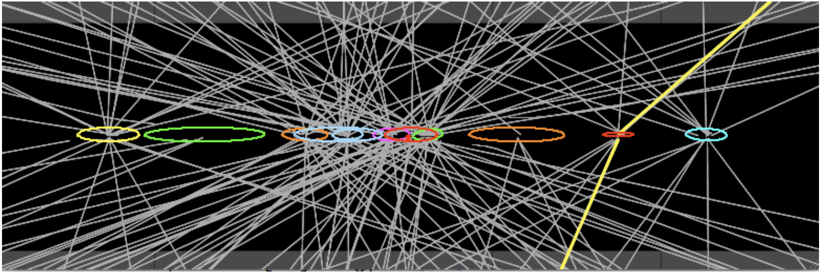


In an event containing a jet pair or another hard process, how much further activity is there, that does not have its origin in the hard process itself, but in other physics processes?

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?



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

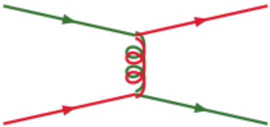
where $\overline{\mathcal{L}}$ is machine luminosity per bunch crossing, $\overline{\mathcal{L}} \sim n_1 n_2 / A$
and $\sigma \sim \sigma_{\mathrm{tot}} \approx 100$ mb.
Current LHC machine conditions $\Rightarrow \langle n \rangle \sim 10 - 20$.

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 $2 \to 2$

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

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

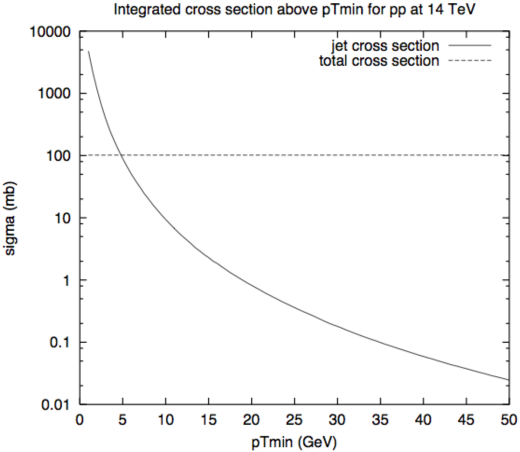
$\mathrm{q\overline{q}} \to \mathrm{gg}$

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

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

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

(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.

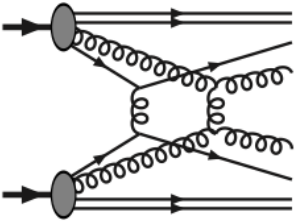
So half a solution to $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) > \sigma_{\mathrm{tot}}$ is

many interactions per event: MPI

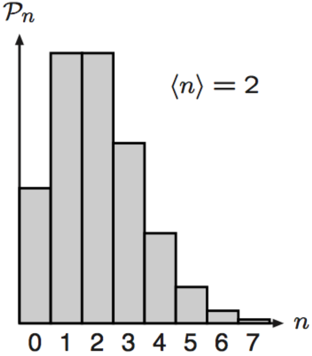
$$\sigma_{\mathrm{tot}} = \sum_{n=0}^{\infty} \sigma_n$$

$$\sigma_{\mathrm{int}} = \sum_{n=0}^{\infty} n \, \sigma_n$$

$$\sigma_{\mathrm{int}} > \sigma_{\mathrm{tot}} \iff \langle n \rangle > 1$$



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

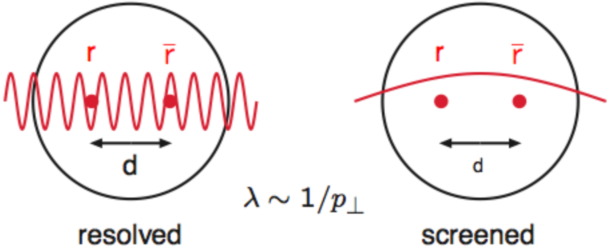
Colour screening

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:

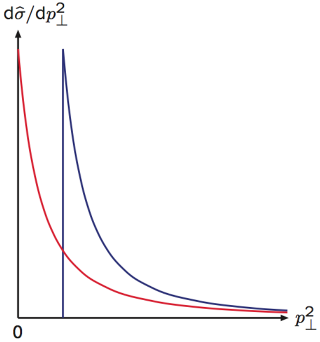


Regularization of low-$p_\perp$ divergence

so need **nonperturbative regularization for $p_\perp \to 0$**, e.g.

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

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

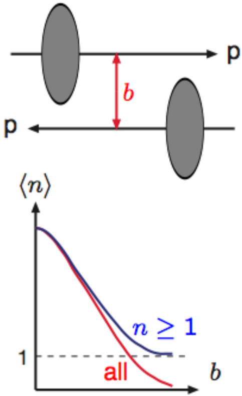


where $p_{\perp\mathrm{min}}$ or $p_{\perp 0}$ are free parameters, empirically of order **2–3 GeV**.

Typical number of interactions/event is 3 at 2 TeV, 4 – 5 at 13 TeV, but may be twice that in "interesting" high-$p_\perp$ ones.

Impact parameter dependence

So far assumed that all collisions have equivalent initial conditions, but hadrons are extended, so dependence on impact parameter b.



Overlap of protons during encounter is

$$\mathcal{O}(b) = \int \mathrm{d}^3\mathbf{x}\,\mathrm{d}t\;\rho_1(\mathbf{x},t)\,\rho_2(\mathbf{x},t)$$

where ρ is (boosted) matter distribution in p, e.g. Gaussian or electromagnetic form factor.

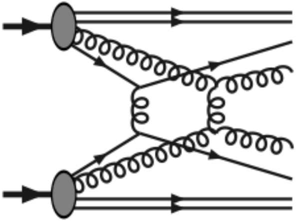
Average activity at b proportional to $\mathcal{O}(b)$:

$\star$ central collisions more active
$\Rightarrow \mathcal{P}_n$ broader than Poissonian;

$\star$ peripheral passages normally give
no collisions $\Rightarrow$ finite σ_{tot}.

Double parton scattering

Double parton scattering (DPS): two hard processes in same event.



$$\sigma_{\mathrm{DPS}} = \begin{cases} \frac{\sigma_A \sigma_B}{\sigma_{\mathrm{eff}}} & \text{for } A \neq B \\ \frac{\sigma_A \sigma_B}{2\,\sigma_{\mathrm{eff}}} & \text{for } A = B \end{cases}$$

(Poissonian $\Rightarrow 1/2$; $AB + BA \Rightarrow 2$)

Note inverse relationship on σ_{eff}.
Natural scale is $\sigma_{\mathrm{ND}} \approx 50$ mb,
but "reduced" by b dependence.

Studied by

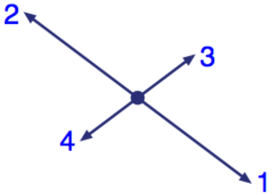
- 4 jets
- $\gamma +$ 3 jets
- 4 jets, whereof two b- or c-tagged
- J/ψ or Υ + 2 jets (including $\upsilon \mathrm{c}\bar{\mathrm{c}}$)
- W/Z + 2 jets
- $\mathrm{W}^-\mathrm{W}^-$

Double parton scattering backgrounds

Always non-DPS backgrounds, so kinematics cuts required.

Example: 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

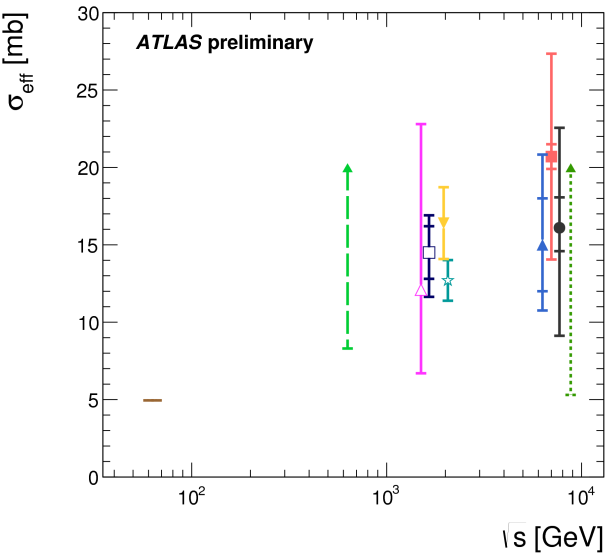
Double BremsStrahlung

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

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

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

Experimental summary on DPS rate



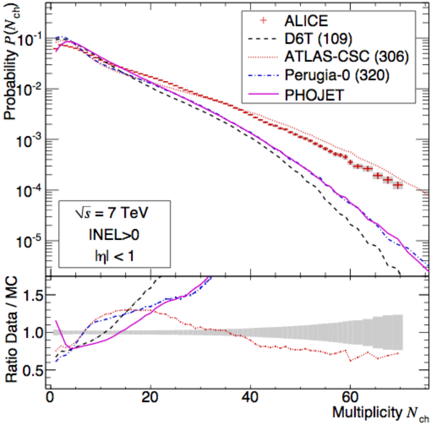
Note:
big error bars,
uncertain
methodology,
but consistent:

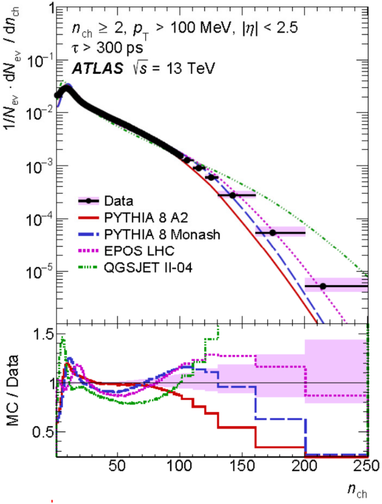
$\sigma_{\text{eff}} \approx \sigma_{\text{ND}}/3$

$\Rightarrow$ factor ~ 3 enhancement relative to naive expectations

Multiplicity and MPI effects

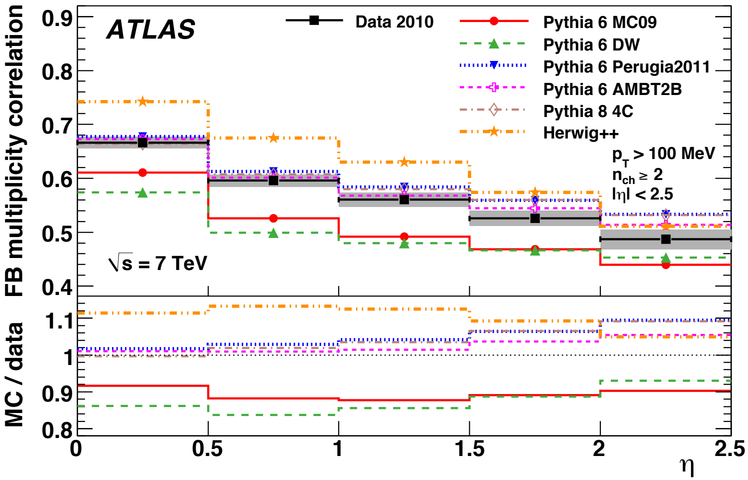
DPS only probes high-$p_\perp$ tail of effects.
More dramatic are effects on multiplicity distributions:





Forward-backward correlations

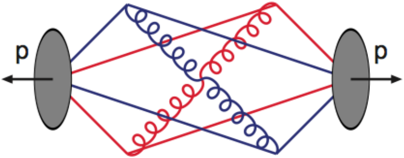
Global number, such as #MPI, affects activity everywhere:



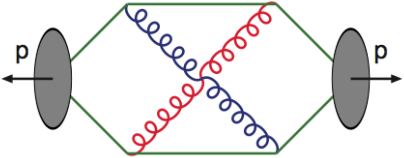
(note suppressed zero on vertical axis ⇒ big effects!)

Colour (re)connections and $\langle p_\perp \rangle(n_{ch})$

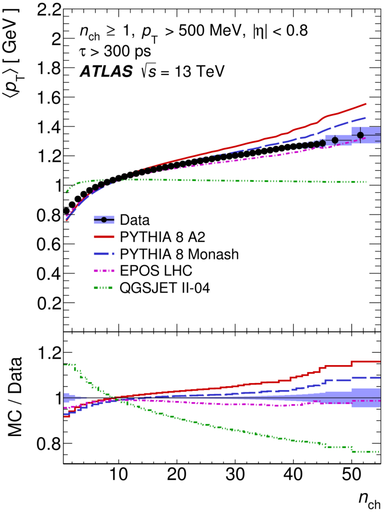
$\langle p_\perp \rangle(n_{ch})$ is very sensitive to colour flow



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



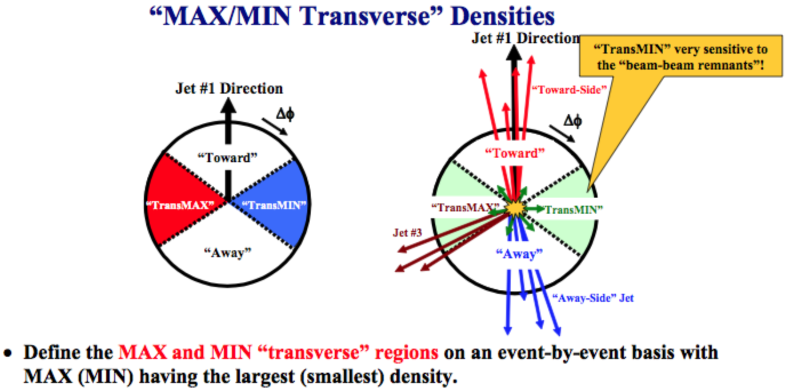
short strings (more central) $\Rightarrow$ less n_{ch}/interaction $\Rightarrow$ $\langle p_\perp \rangle(n_{ch})$ rising



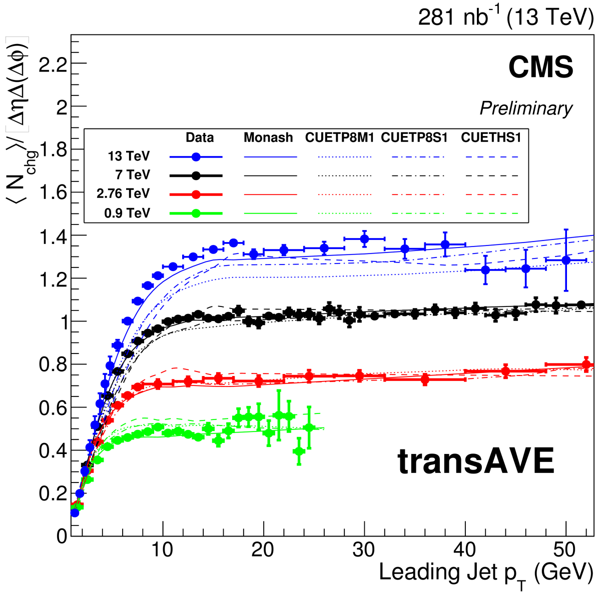
Jet pedestal effect – 1

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.

Studied in particular by Rick Field, with CDF/CMS data:



Jet pedestal effect – 2



MPI in PYTHIA

- MPIs are gererated in a falling sequence of $p_{\perp}$ values; recall Sudakov factor approach to parton showers.
- Energy, momentum and flavour conserved step by step: subtracted from proton by all "previous" collisions.
- Protons modelled as extended objects, allowing both central and peripheral collisions, with more or less activity.
- (Partons at small x more broadly spread than at large x.)
- Colour screening increases with energy, i.e. $p_{\perp 0} = p_{\perp 0}(E_{\mathrm{cm}})$, as more and more partons can interact.
- (Rescattering: one parton can scatter several times.)
- Colour connections: each interaction hooks up with colours from beam remnants, but also correlations inside remnants.
- Colour *re*connections: many interaction "on top of" each other $\Rightarrow$ tightly packed partons $\Rightarrow$ colour memory loss?

Interleaved evolution in PYTHIA

- Transverse-momentum-ordered parton showers for ISR and FSR
- MPI also ordered in $p_{\perp}$

$\Rightarrow$ Allows interleaved evolution for ISR, FSR and MPI:

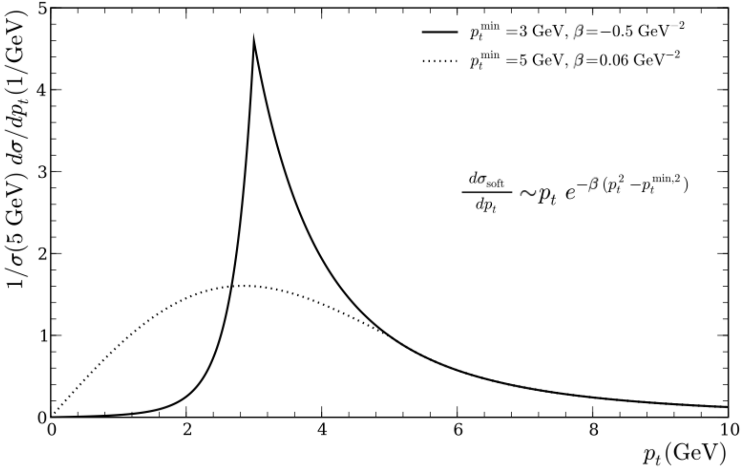
$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_{\perp}} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_{\perp}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_{\perp}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_{\perp}} \right)$$
$$\times \quad \exp\left(-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

Ordered in decreasing $p_{\perp}$ using “Sudakov” trick.
Corresponds to increasing “resolution”:
smaller $p_{\perp}$ fill in details of basic picture set at larger $p_{\perp}$.

- Start from fixed hard interaction $\Rightarrow$ underlying event
- No separate hard interaction $\Rightarrow$ minbias events
- Possible to choose two hard interactions, e.g. $\mathrm{W}^-\mathrm{W}^-$

MPI in Herwig

Key point: two-component model

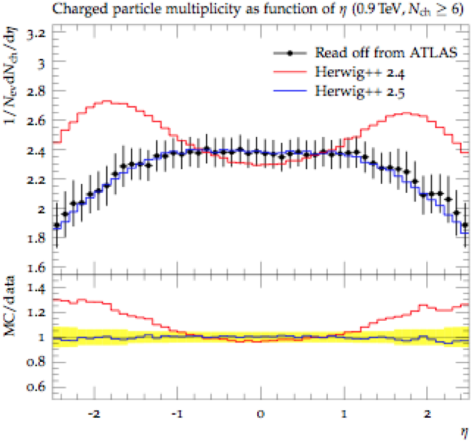


$p_\perp > p_{\perp\min}$: pure perturbation theory (no modification)

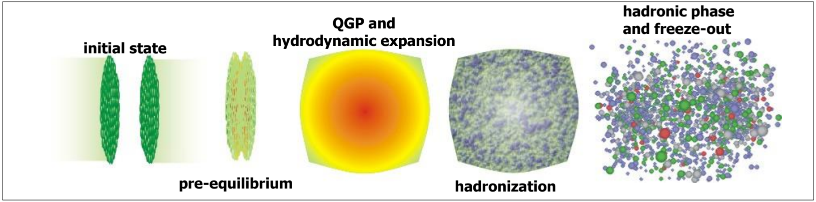
$p_\perp < p_{\perp\min}$: pure nonperturbative ansatz

MPI in Herwig – 2

- Number of MPIs first picked; then 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 em form factor shape, but tunable width.
- $p_{\perp\mathrm{min}}$ scale to be tuned energy-by-energy.
- Colour reconnection essential to get $\mathrm{d}n/\mathrm{d}\eta$ correct.



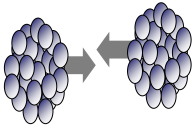
Heavy Ion Collisions

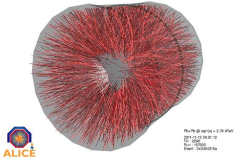


- The only way we can create the QGP in the laboratory!
- By colliding heavy ions it is possible to create a large (»1fm^3) zone of hot and dense QCD matter
- Goal is to create and study the properties of the Quark Gluon Plasma
- Experimentally mainly the final state particles are observed, so the conclusions have to be inferred via models

The three systems — understanding before 2012

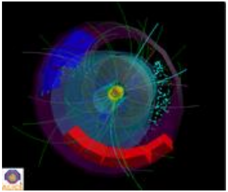
Pb-Pb





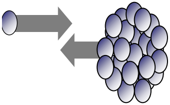
Hot QCD matter:
This is where we expect the QGP to be created in central collisions.

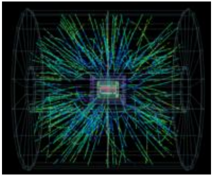
pp



QCD baseline:
This is the baseline for “standard” QCD phenomena.

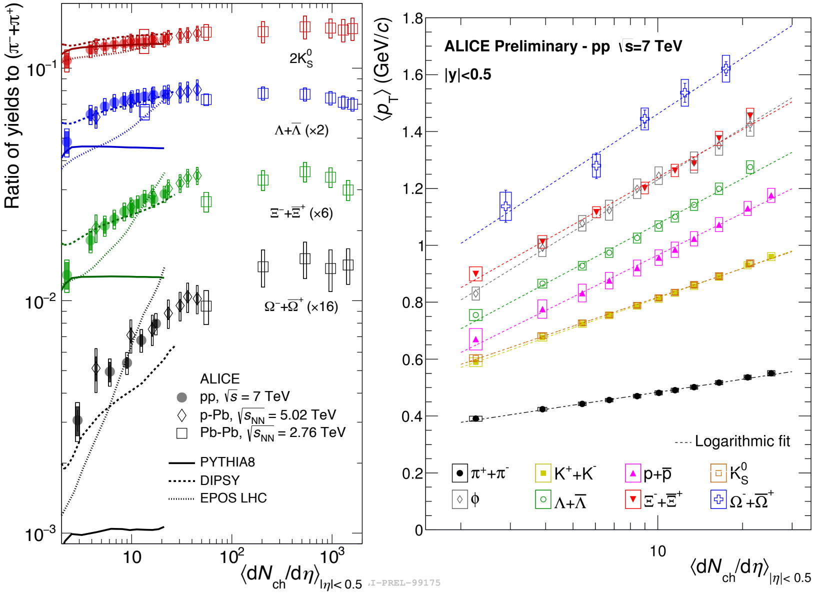
p-Pb



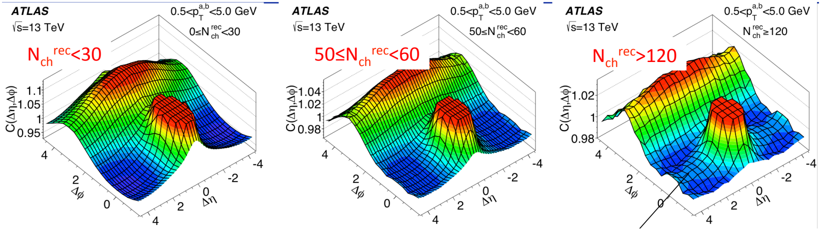


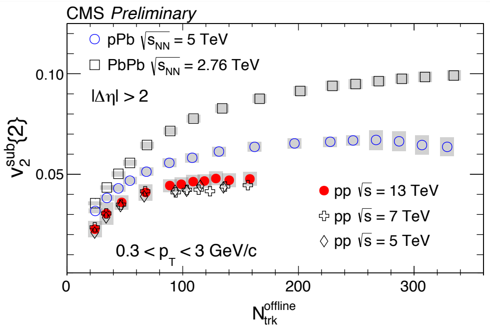
Cold QCD matter:
This is to isolate nuclear effects, e.g. nuclear pdfs.

Strangeness enhancement



Collective flow



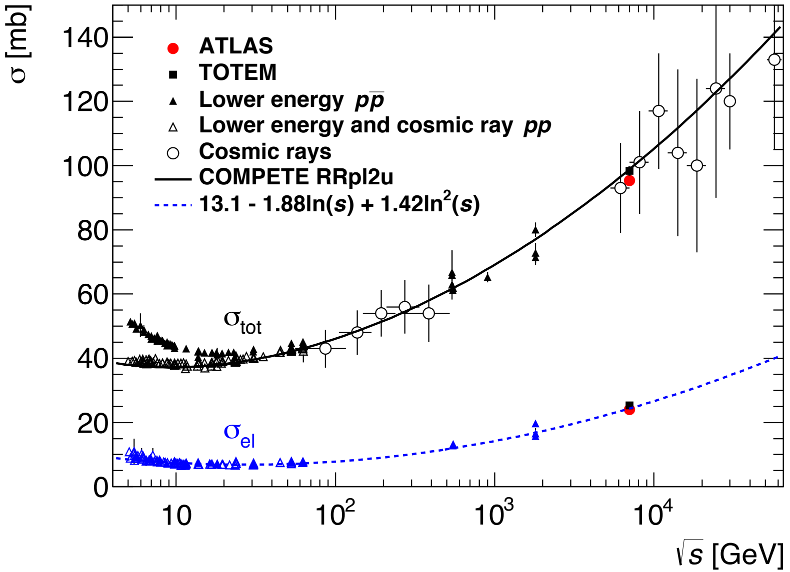


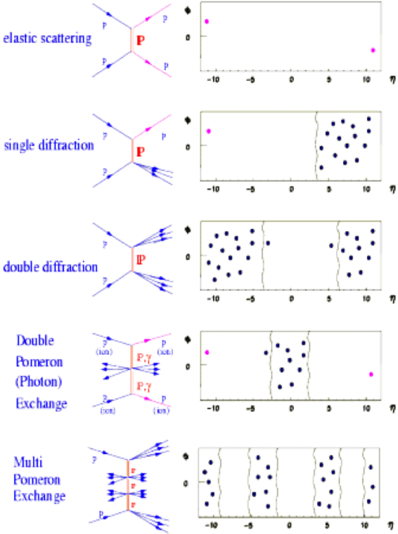
Increasingly blurred line between pp, pA and AA!

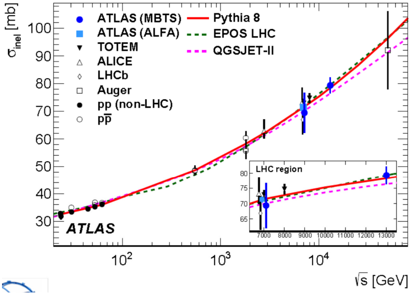
QGP theory wrong?
Much smaller systems enough for QGP?

Standard pp generators wrong! Need mechanism for collectivity.

Total cross section



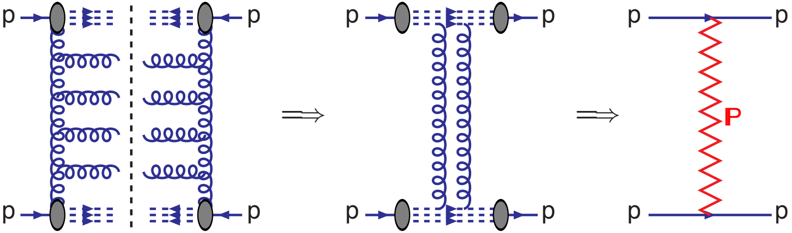




- Phase space for diffractive masses and rapidity gaps roughly like $\mathrm{d}M^2/M^2 = \mathrm{d}y$, i.e. flat in rapidity.
- Rapidity integration means σ_{sd} grows faster that σ_{tot}, σ_{dd} even faster, etc. $\Rightarrow$ Need damping.

The Pomeron

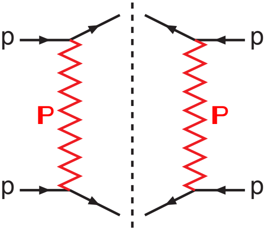
Amplitude for (forward) elastic scattering from total cross section:



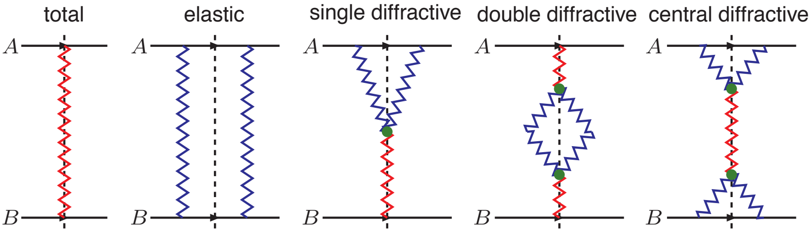
introducing the Pomeron $\mathbb{P}$ as shorthand for the effective 2-gluon exchange.

Since $\mathrm{p} \to \mathrm{p}\,\mathbb{P}$ the Pomeron must have the quantum numbers of the vacuum: 0^{+} colour singlet.

Recall: elastic cross section requires squaring one more time:



Regge–Pomeranchuk theory of cross sections



$$\sigma_{\mathrm{tot}}^{AB} = \beta_A(0)\,\beta_B(0)\,\mathrm{Im}\,G_{I\!P}(s/s_0, 0)$$

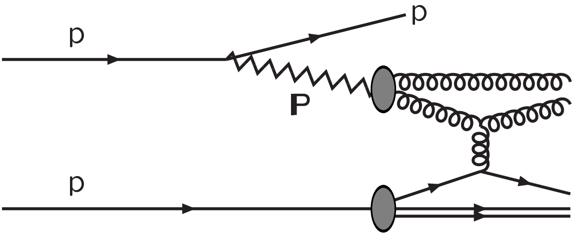
$$\frac{\mathrm{d}\sigma_{\mathrm{el}}^{AB}}{\mathrm{d}t} = \frac{1}{16\pi}\,\beta_A^2(t)\,\beta_B^2(t)\,|G_{I\!P}(s/s_0, t)|^2$$

$$\frac{\mathrm{d}\sigma_{\mathrm{sd}}^{AB\to AX}}{\mathrm{d}t\,\mathrm{d}M^2} = \frac{1}{16\pi\,M^2}\,g_{3I\!P}\,\beta_A^2(t)\,\beta_B(0)|G_{I\!P}(s/M^2, t)|^2\,\mathrm{Im}\,G(M^2/s_0, 0)$$

$$\frac{\mathrm{d}\sigma_{\mathrm{dd}}^{AB\to X_1X_2}}{\mathrm{d}t\,\mathrm{d}M_1^2\,\mathrm{d}M_2^2} = \frac{1}{16\pi\,M_1^2\,M_2^2}\,g_{3I\!P}^2\,\beta_A(0)\,\beta_B(0)\,|G_{I\!P}(ss_0/(M_1^2 M_2^2), t)|^2 \times \mathrm{Im}\,G(M_1^2/s_0, 0)\,\mathrm{Im}\,G(M_2^2/s_0, 0)$$

Diffraction

Ingelman-Schlein: Pomeron as hadron with partonic content
Diffractive event = (Pomeron flux) $\times$ ($\mathbb{P}$p collision)



Used e.g. in
POMPYT
POMWIG
PHOJET

1) σ_{SD} and σ_{DD} set by Reggeon theory.

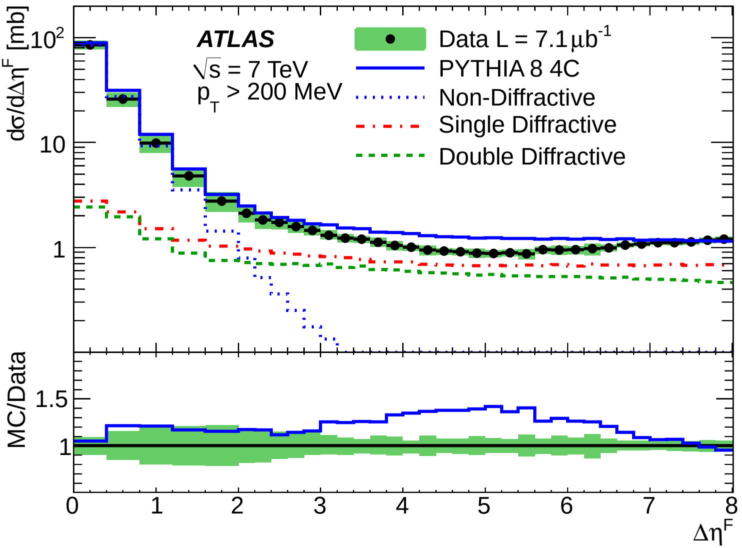
2) $f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t) \Rightarrow$ diffractive mass spectrum, $p_{\perp}$ of proton out.

3) Smooth transition from simple model at low masses to $\mathbb{P}$p with full pp machinery: multiple interactions, parton showers, etc.

4) Choice between different Pomeron PDFs.

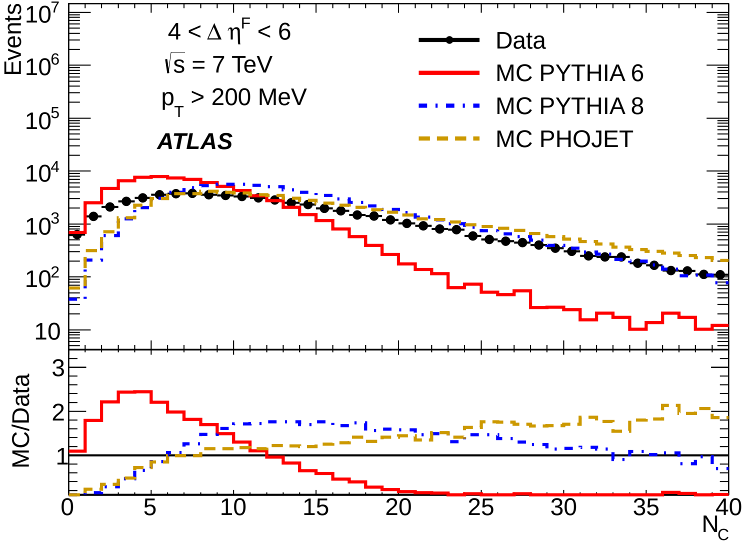
5) Free parameter $\sigma_{\mathbb{P}\mathrm{p}}$ needed to fix $\langle n_{\mathrm{interactions}} \rangle = \sigma_{\mathrm{jet}} / \sigma_{\mathbb{P}\mathrm{p}}$.

Gaps by subprocess



Non-diffractive fine, but wrong gap spectrum for diffraction.

Multiplicity in diffractive events



PYTHIA 6 lacks MPI, ISR, FSR in diffraction, so undershoots.