Lund University

MC4LHC – MIN-BIAS

MULTIPLE INTERACTIONS

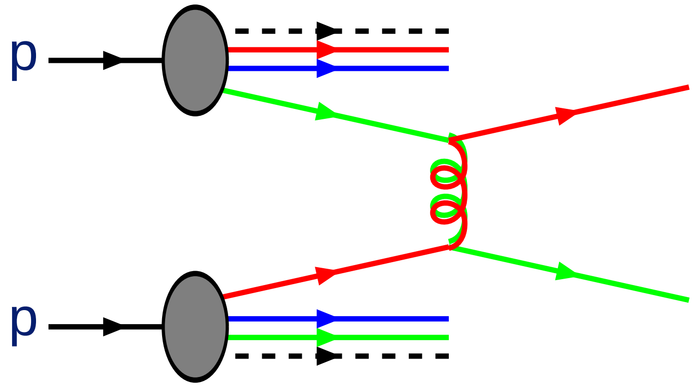
A new model for the underlying event in hadron-hadron collisions

P. Skands (speaker) & T. Sjöstrand

1. Basic Phenomenology (recap of yesterday).
2. Towards a realistic model $\longrightarrow$ PYTHIA 6.3.
3. Outlook.

Basic Phenomenology.

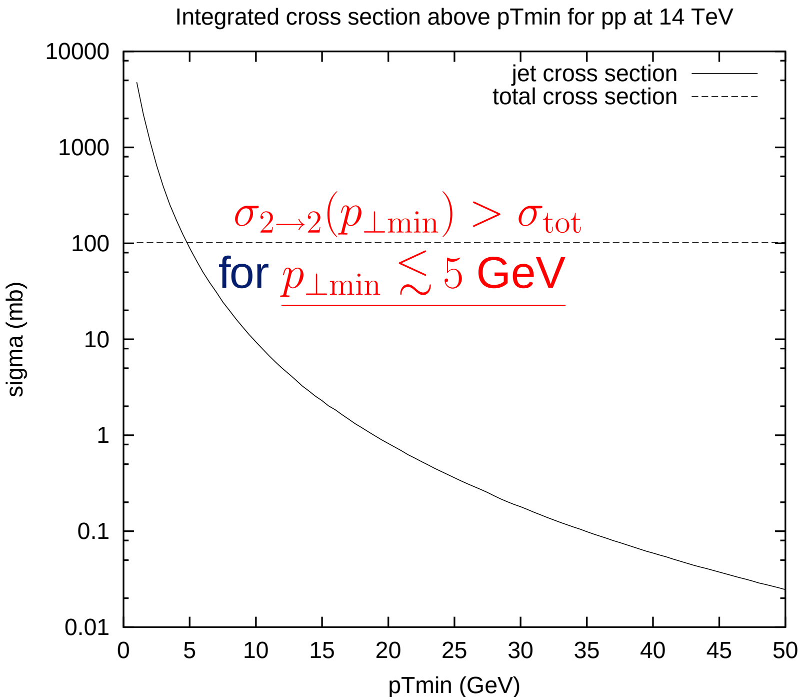
✧ QCD $2 \to 2$ cross section:



$\mathrm{qq}' \to \mathrm{qq}'$
$\mathrm{q\bar{q}} \to \mathrm{q'\bar{q}'}$
$\mathrm{q\bar{q}} \to \mathrm{gg}$
$\mathrm{qg} \to \mathrm{qg}$
$\mathrm{gg} \to \mathrm{gg}$
$\mathrm{gg} \to \mathrm{q\bar{q}}$

Dominated by t-chanel gluon exchange $\Rightarrow$

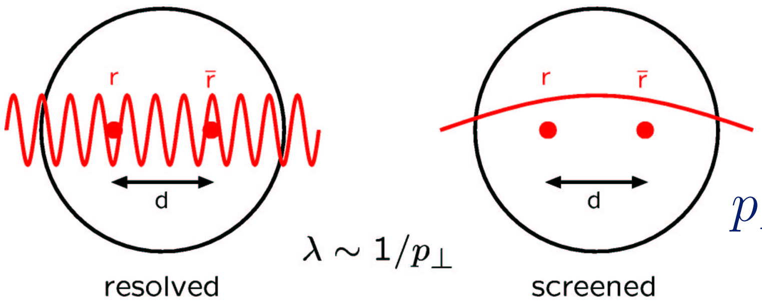
$$\sigma_{2\to2}(p_{\perp\min}) = \int_{p_{\perp\min}}^{\sqrt{s}/2} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp}\mathrm{d}p_\perp \propto \frac{1}{p_{\perp\min}^2}$$



✧ Many interactions / event: $\langle n \rangle > 1$

$$\sigma_{\mathrm{tot}} = \sum_{n=0}^{\infty} \sigma_n \quad ; \quad \sigma_{2\to2} = \sum_{n=0}^{\infty} n\,\sigma_n$$

✧ Breakdown of pQCD, colour screening.



$p_{\perp 0} \sim 2$ GeV

Why care?

$\langle n \rangle_{\text{Tevatron}} \sim 2 - 4$, $\langle n \rangle_{\text{LHC}} \sim 5 - 10$

So multiple interactions are responsible for:

- ☞ Large fraction of total multiplicity.
- ☞ Fluctuations to large multiplicities.
- ☞ Rapidity correlations in activity.
- ☞ Multiple (mini)jet production.
- ☞ Jet profile and jet pedestal.
- ☞ Shifts in jet energy scale.

$\Longrightarrow$ precision physics involving jets or underlying events impossible without understanding of multiple interactions.

Non-trivial example: $H \to \gamma\gamma$: $(M^2_{\gamma\gamma} = 2E_{\gamma 1}E_{\gamma 2}(1 - \cos\theta_{\gamma\gamma}))$

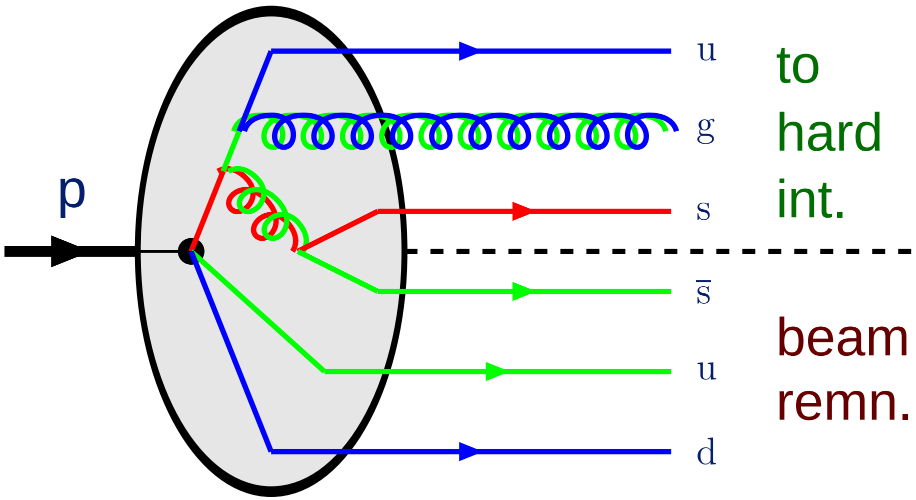
$\theta_{\gamma\gamma} \Longrightarrow$ select one primary vertex between $\sim$ 30 pp events.

Q: Is the primary vertex of some or most of the charged tracks the correct one?

This talk is about PYTHIA 6.3

"A solemn Hellenic assembly had met at Pytho, to celebrate the death of the Pythic serpent (v. 6.2), when Eunomos sang the reptile's epitaph. Whether his ode was a hymn in praise of the serpent, or a dirge, I am not able to say." [Clement of Alexandria: Exhortation to the Heathen ($\sim$ 200 AD)]

Towards a realistic model



How are the hard scattering initiators and beam remnant partons correlated:

- In flavour?
- In longitudinal momentum?
- In primordial transverse momentum?
- In colour?

(How) are the showers correlated / intertwined?

Correlations in flavour and x_i

> Q: What are the pdf's for a proton with 1 valence quark, 2 sea quarks, and 5 gluons kicked out of it?

Overall momentum conservation (old):

$$x_n \in [0, x_{\mathrm{rem}}] \implies \text{squeeze pdf's: } f_n(x_n) \sim \frac{1}{x_{\mathrm{rem}}} f_0\left(\frac{x_n}{x_{\mathrm{rem}}}\right)$$

flavour and shape (new):

QUARKS:

- Use pdf info to determine whether sea or valence was kicked out.

If valence $\implies$ reduce valence distribution; $f_q^{\mathrm{val}}(x) \to \frac{n_{\mathrm{rem}}}{n_{\mathrm{org}}} f_q^{\mathrm{val}}(x)$

If sea $\implies$ add "companion quark" (assuming sea origin = gluon splitting):

$$P_{q^{\mathrm{sea}}}(x_k) \propto \int_0^1 \mathrm{d}z \int_{x_k}^1 \mathrm{d}y\, g(y) P_{g\to q\bar{q}}(z)\delta(x_k - zy) = \int_x^1 \mathrm{d}y \frac{g(y)}{y} P_{g\to q\bar{q}}\left(\frac{x_k}{y}\right)$$

The integrand is the probability of having a sea quark at x_k that came from a gluon at y. Now, $y = x_k + x_c$ gives us the double differential distribution:

$$q_k^{\mathrm{comp},i}(x_c; x_k) \propto \frac{g(x_c + x_k)}{x_c + x_k} P_{\mathrm{g}\to q_k\bar{q}_k}\left(\frac{x_k}{x_c + x_k}\right)$$

(with normalization given by number integral = 1)

Correlations in flavour and x_i

Remnant PDFs

$$\text{quarks}: \quad q_n^i(x) = \frac{1}{x_{\text{rem}}}\left[\frac{n_{\text{rem}}}{n_{\text{org}}} q_0^{\text{val},i}\left(\frac{x}{x_{\text{rem}}}\right) + \sum_k^{n_{\text{comp},i}} q_k^{\text{comp},i}\left(\frac{x}{x_{\text{rem}}}; \tilde{x}_k\right) + N\, q_0^{\text{sea},i}\left(\frac{x}{x_{\text{rem}}}\right)\right]$$

$$\text{gluons}: \quad g_n(x) = \frac{1}{x_{\text{rem}}} N\, g_0\left(\frac{x}{x_{\text{rem}}}\right)$$

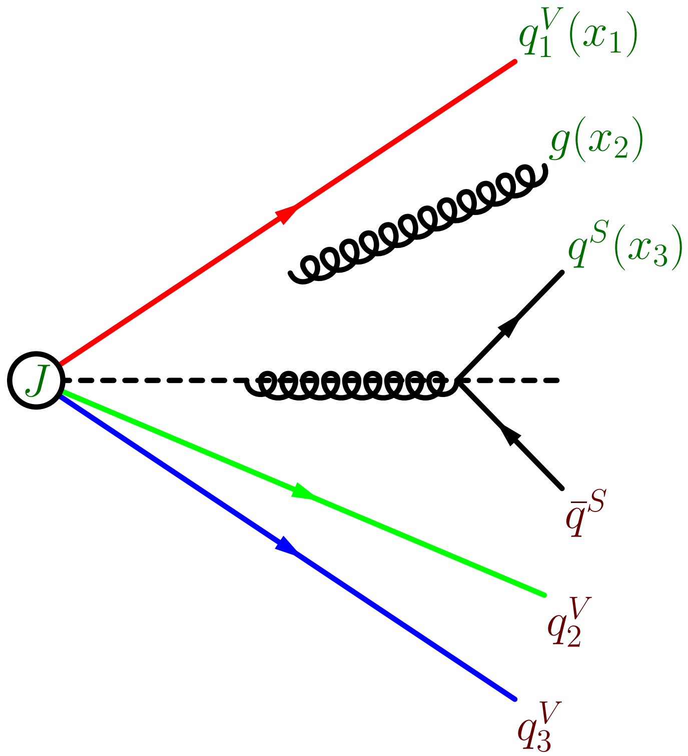
$$\text{companion quarks}: \quad q_k^{\text{comp},i}(x_c; x_k) \propto \frac{g(x_c + x_k)}{x_c + x_k} P_{\mathrm{g}\to q_i \bar{q}_i}\left(\frac{x_k}{x_c + x_k}\right)$$

$$N \text{ chosen to maintain } \int_0^{x_{\text{rem}}} x \left(\sum_i q_n^i(x) + g_n(x)\right) \mathrm{d}x = x_{\text{rem}}$$

Note: flavour conservation $\Rightarrow$ flavour content of beam remnant.

Hooking it up

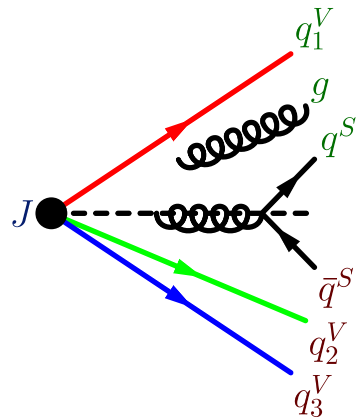
Assume initial valence topology + gluons (one parent gluon for each sea pair). *Some* colour flow must exist, but no perturbative information available (since showers not intertwined).



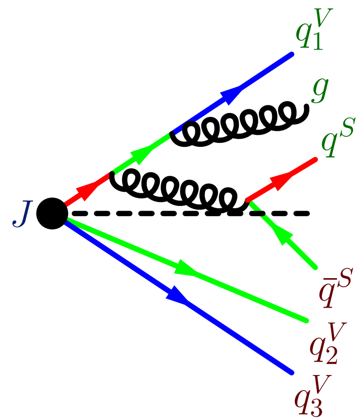
What is the colour flow?

Hooking it up

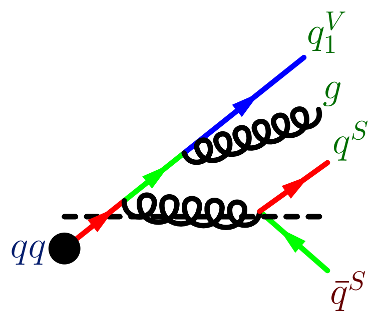
Non-perturbative ordering mechanisms must be appealed to, a priori unknown, but guidelines exist. E.g. only physical colour flows are acceptable (no colour singlet gluons) and *some* kind of minimization of total potential energy is likely at play. *One* possibility is (PYTHIA 6.3 implementation):



Iteratively attach gluons to original con£guration: randomly, rapidity ordered, or ordered by smallest resulting string lengths $\sim$ multiplicities (MSTP(89)). Attachments breaking up the beam remnant are suppressed.



Collapses in the beam remnant may occur. E.g. system of two quarks + junction may be collapsed to diquark. (+ possibly reordering of colour connections in £nal state, but not well modelled yet.)



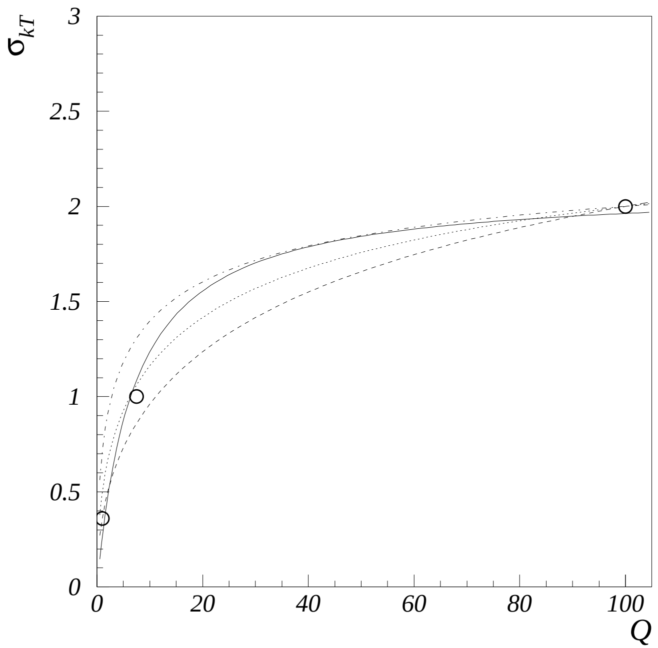
✧ Correlated primordial $k_\perp$.

Assume gaussian distributed primordial $k_\perp$ for each hard scattering initiator:

$$\frac{\mathrm{d}^2 N}{\mathrm{d}k_x\,\mathrm{d}k_y} \propto e^{-k_\perp^2/\sigma^2(Q)}$$

$$\sigma(1\ \mathrm{GeV}) \approx 0.36\ \mathrm{GeV}\ (hadr.)$$
$$\sigma(10\ \mathrm{GeV}) \approx 1\ \mathrm{GeV}\ (EMC)$$
$$\sigma(m_Z) \approx 2\ \mathrm{GeV}\ (Tevatron)$$

which recoils along colour neighbours or onto all initiators and beam remnant partons equally (MSTP(90)). (k_z rescaled to maintain energy conservation.)



Solid: $\frac{2.1Q}{7+Q}$ (hardcoded default)

Dashed: $\frac{4\sqrt{Q}}{10+\sqrt{Q}}$

Dotted: $\frac{3\sqrt{Q}}{5+\sqrt{Q}}$

Dot-dashed: $\frac{2.5\sqrt{Q}}{2.5+\sqrt{Q}}$

Sharing of $x_{\rm rem}$ in beam remnant

Each hard scattering subsystem has light-cone momenta:

$$\begin{aligned} p_+ &= \gamma(E_1^{CM(z)} + E_2^{CM(z)}) + \gamma\beta(E_1^{CMz} + E_2^{CMz}) \\ &= \sqrt{\frac{1+\beta}{1-\beta}\left(\hat{s} + (\vec{p}_\perp^{(1)} + \vec{p}_\perp^{(2)})^2\right)} \\ &= \sqrt{\frac{x_1}{x_2}}\sqrt{\hat{s}_\perp} \\ p_- &= \gamma(1-\beta)(E_1^{CM(z)} + E_2^{CM(z)}) \\ &= \sqrt{\frac{x_2}{x_1}}\sqrt{\hat{s}_\perp} \end{aligned}$$

Remaining light-cone momenta available for BR:

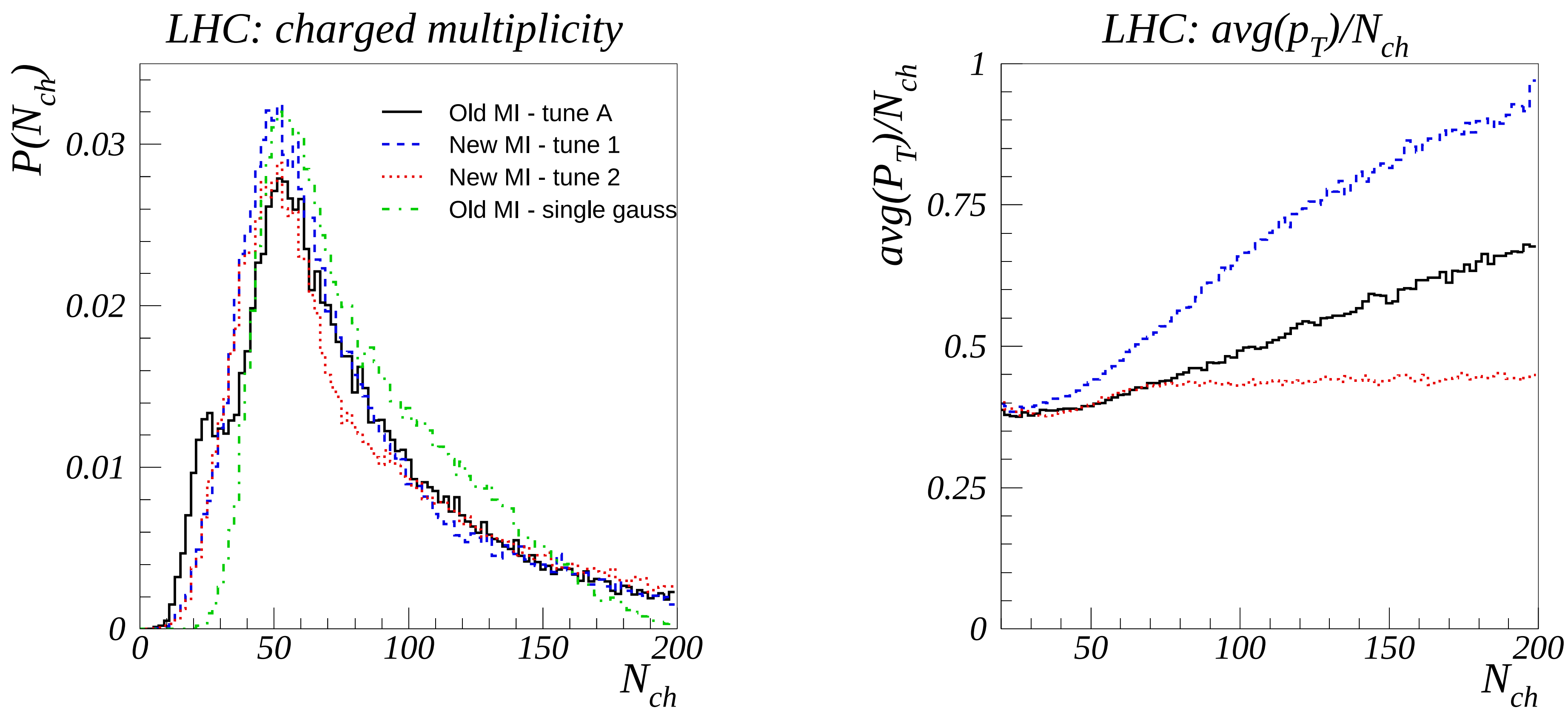
$$p^+_{rem} = \sqrt{s} - \sum_i \sqrt{\frac{x_i^{(+)}}{x_i^{(-)}}\left(\hat{s}_i + (\vec{p}_{\perp i}^{(+)} + \vec{p}_{\perp i}^{(-)})^2\right)} \;;\; p^-_{rem} = \sqrt{s} - \sum_i \sqrt{\frac{x_i^{(-)}}{x_i^{(+)}}\left(\hat{s}_i + (\vec{p}_{\perp i}^{(+)} + \vec{p}_{\perp i}^{(-)})^2\right)}$$

Def: "+" side partons have x_j of p^+_{rem}, "–" side partons fractions x_k of p^-_{rem}.

$\diamondsuit$ Assume $x_{j,k}$ distributed according to generalized pdf's and fragmentation functions (modulo overall rescalings to ensure (E,p) conserved).

NB: composite BR systems (w. pion/gluon clouds?) $\Rightarrow$ larger x? (PARP(79))

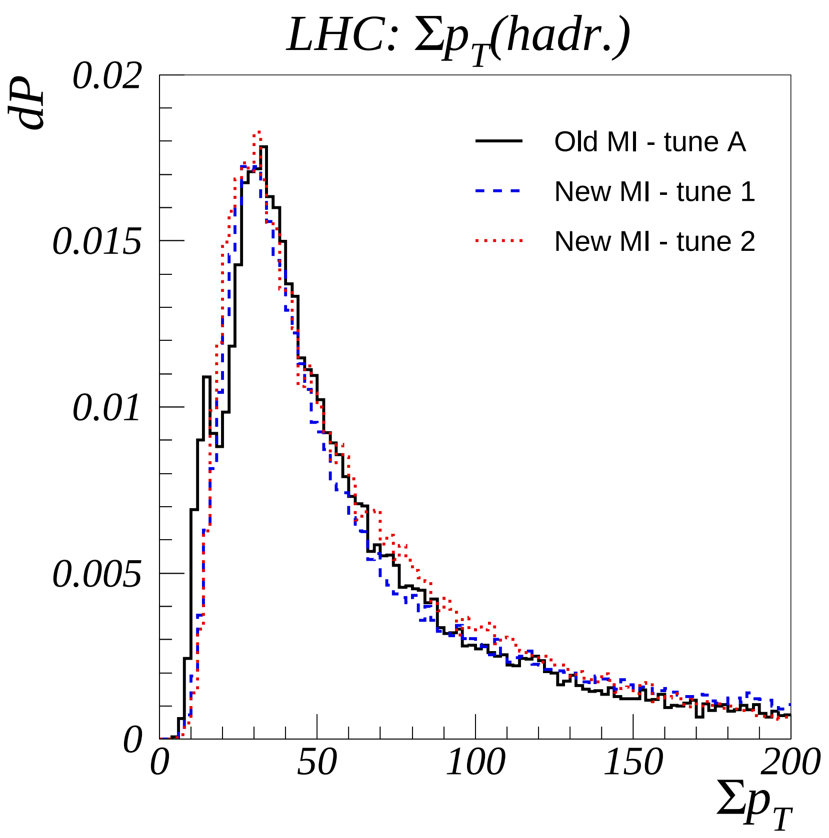
Forecast for the LHC (preliminary!)

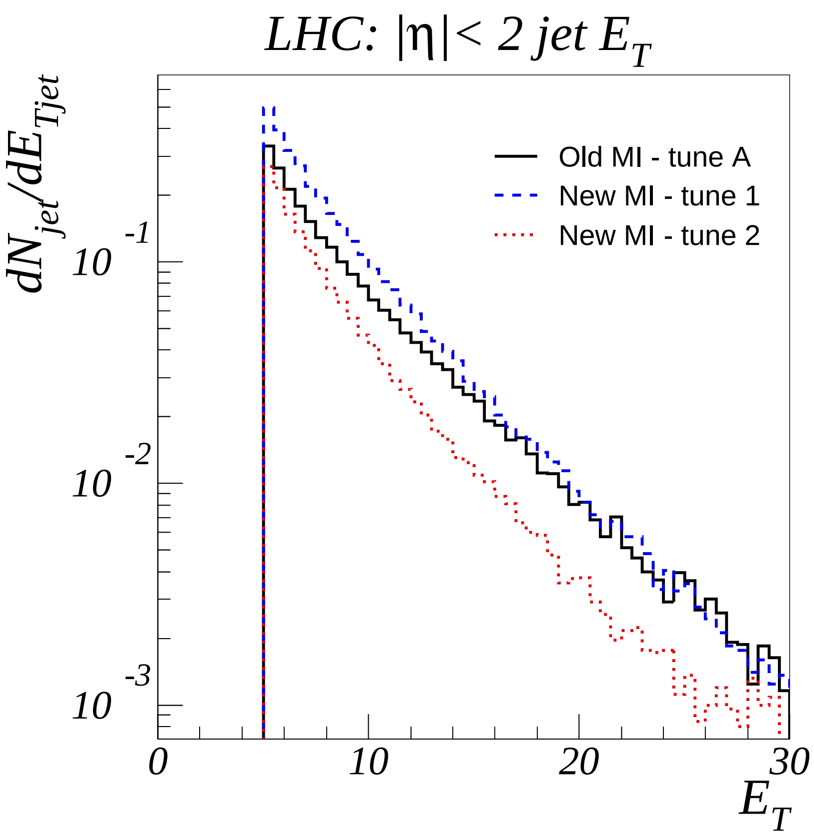


Tune 1: Example with colour reordering: MSTP(95)=1.

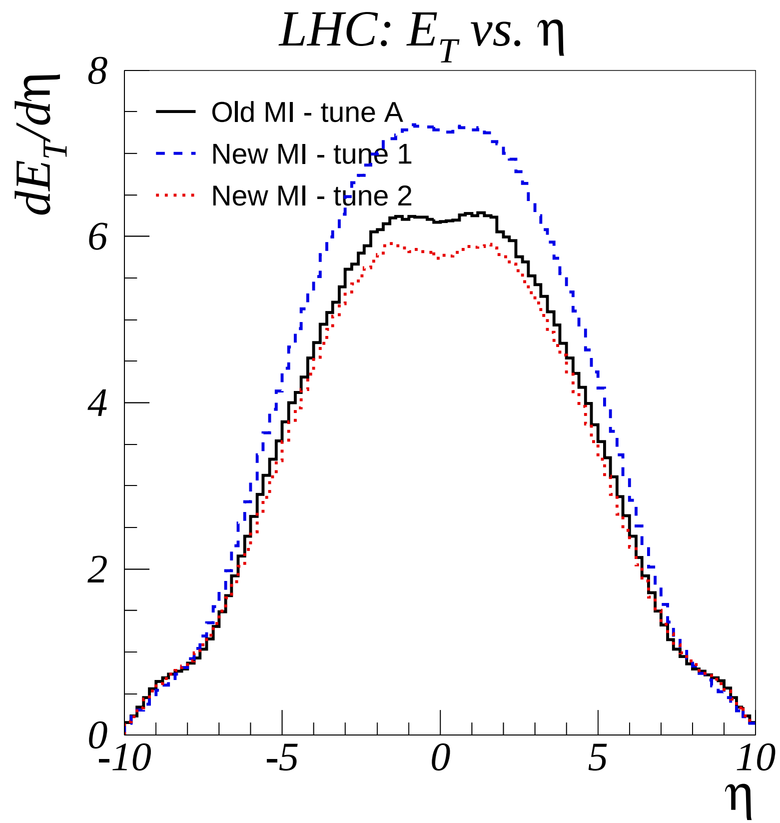
Tune 2: Example without colour reordering: MSTP(95)=0.

Forecast for the LHC (preliminary!)





Forecast for the LHC (preliminary!)



Outlook – Multiple Interactions

☞ Overwhelming amount of data confirms basic idea.

(AFS, UA1, UA5, E735, H1, CDF)

☞ Past modelling has consisted of crude parametrizations + some more or less unphysical models. MUCH remains uncertain!

- ⋆ $p_{\perp\min}/p_{\perp 0}$ cutoff.
- ⋆ Impact parameter dependence.
- ⋆ Energy dependence.
- ⋆ Multiparton densities in incoming hadrons.
- ⋆ Colour correlations between scatterings.
- ⋆ Colour reconnections in the final state.
- ⋆ Interferences between showers.

☞ These issues are important to understand for hadron–hadron collider physics. PYTHIA 6.3 contains a first attempt at a complete and physical model that allows detailed studies.

Ordering principles

✧ 1. random ordering

Beam remnant breakup suppression is applied (PARP(80)).
Colour connections otherwise random.

✧ 2. rapidity ordering

Rapidity of each hard scattering system is calculated, beam remnant partons assigned (arbitrarily) $y_{BR} = \pm 100$.
Connections made so systems which are neighbours in rapidity also are neighbours in colour.

✧ 3. ordering by string length

That connection (out of all possible) is selected which has the smallest total lambda measure $\sim$ string length $\sim$ multiplicity.