Basics of Event Generators III

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Outline of Lectures

- Lecture I: Basics of Monte Carlo methods, the event generator strategy, matrix elements, LO/NLO, ...
- Lecture II: Parton showers, initial/final state, matching/merging, ...
- Lecture III: Matching/merging (cntd.), underlying events, multiple interactions, minimum bias, pile-up, hadronization, decays, ...
- Lecture IV: Protons vs. heavy ions, summary, ...

Buckley et al. (MCnet collaboration), *Phys. Rep.* **504** (2011) 145.

Outline

Matching: The Basic Idea

A fixed-order ME-generator gives the first few orders in α_s exactly.

The parton shower gives approximate (N)LL terms to all orders in α_s through the Sudakov form factors.

- Take a parton shower and correct the first few terms in the resummation with (N)LO ME.
- Take events generated with (N)LO ME with subtracted Parton Shower terms. Add parton shower.
- Take events samples generated with (N)LO ME, reweight and combine with Parton showers:

Tree-level Merging

Has been around the whole millennium: CKKW(-L), MLM, ...

Combines samples of tree-level (LO) ME-generated events for different jet multiplicities. Reweight with proper Sudakov form factors (or approximations thereof).

Needs a merging scales to separate ME and shower region and avoid double counting. Only observables involving jets above that scale will be correct to LO.

Typically the merging scale dependence is beyond the precision of the shower: $\sim \mathcal{O}(L^3\alpha_s^2)\frac{1}{N_c^2} + \mathcal{O}(L^2\alpha_s^2)$.

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CKKW(-L)

Generate inclusive few-jet samples according to exact tree-level $|\mathcal{M}_n|^2$ using some merging scale ρ_{MS}.

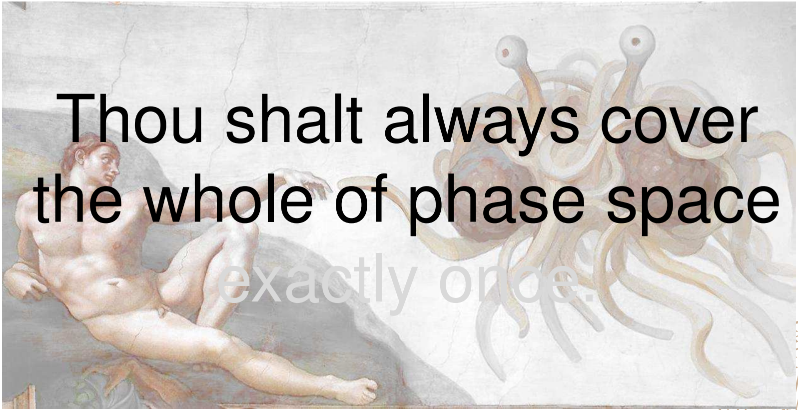
These are then made exclusive by reweighting no-emission probabilities (in CKKW-L generated by the shower itself)

Add normal shower emissions below ρ_{MS}.

Add all samples together.

- Dependence on the merging scale cancels to the precision of the shower.
- If the merging scale is not defined in terms of the shower ordering variable, we need vetoed and truncated showers.
- Breaks the unitarity of the shower.

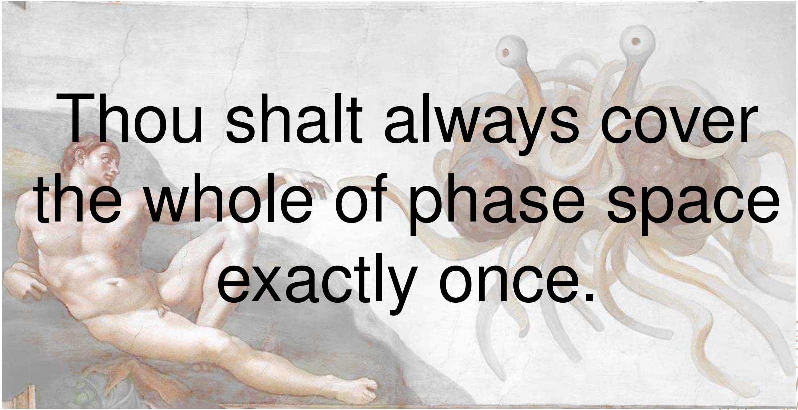
The Second Commandment of Event Generation



Thou shalt always cover the whole of phase space

exactly once.

The Second Commandment of Event Generation



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Multi-jet tree-level matching

$$\frac{d\sigma_0^{ex}}{d\phi_0} = F_0 \left|\mathcal{M}_0\right|^2 \left[1 - \alpha_S \int_{\rho_{\mathrm{MS}}}^{\rho_0} d\rho dz\, \mathcal{P}_1 + \frac{\alpha_S^2}{2}\left(\int_{\rho_{\mathrm{MS}}}^{\rho_0} d\rho dz\, \mathcal{P}_1\right)^2\right]$$

$$\frac{d\sigma_1^{ex}}{d\phi_0} = F_0 \left|\mathcal{M}_0\right|^2 \alpha_S \mathcal{P}_1^{ME} d\rho_1 dz_1$$

$$\times \left[1 - \alpha_S \int_{\rho_1}^{\rho_0} d\rho dz\, \mathcal{P}_1 - \alpha_S \int_{\rho_{\mathrm{MS}}}^{\rho_1} d\rho dz\, \mathcal{P}_2\right]$$

$$\frac{d\sigma_2}{d\phi_0} = F_0 \left|\mathcal{M}_0\right|^2 \alpha_S^2 \mathcal{P}_1^{ME} d\rho_1 dz_1 \mathcal{P}_2^{ME} d\rho_2 dz_2 \Theta(\rho_1 - \rho_2)$$

NOT unitary. Gives artificial dependence of ρ_{MS}.
e.g. extra contribution to $\int \alpha_S \mathcal{P}_1^{ME}$ is $\sim \alpha_S^2 L^3$.

Mature procedure. Available in HERWIG++, SHERPA, PYTHIA8.

The MLM-procedure (ALPGEN + HERWIG/PYTHIA) is similar, but even less control over the perturbative expansion.

There are recent procedures to restore unitarity:

- Vincia exponentiates the full *n*-parton matrix elements.
- UMEPS uses a add/subtract procedure combined with a re-clustering algorithm.

UMEPS – Restoring unitarity

$$\frac{d\sigma_0^{ex}}{d\phi_0} = F_0 \left|\mathcal{M}_0\right|^2 \left[1 - \alpha_S \int_{\rho_{MS}}^{\rho_0} d\rho dz\, \mathcal{P}_1 + \frac{\alpha_S^2}{2}\left(\int_{\rho_{MS}}^{\rho_0} d\rho dz\, \mathcal{P}_1\right)^2\right]$$

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UMEPS – Restoring unitarity

$$\frac{d\sigma_0^{fx}}{d\phi_0} = F_0 \left|\mathcal{M}_0\right|^2 \left[1 - \alpha_S \int_{\rho_{MS}}^{\rho_0} d\rho dz\, \mathcal{P}_1 + \frac{\alpha_S^2}{2}\left(\int_{\rho_{MS}}^{\rho_0} d\rho dz\, \mathcal{P}_1\right)^2\right]$$

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$$- \int d\rho_1 dz_1 \frac{d\sigma_1^{fx}}{d\phi_0 d\rho_1 dz_1}$$

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$$- \int d\rho_2 dz_2 \frac{d\sigma_2^{fx}}{d\phi_0 d\rho_1 dz_1 d\rho_2 dz_2}$$

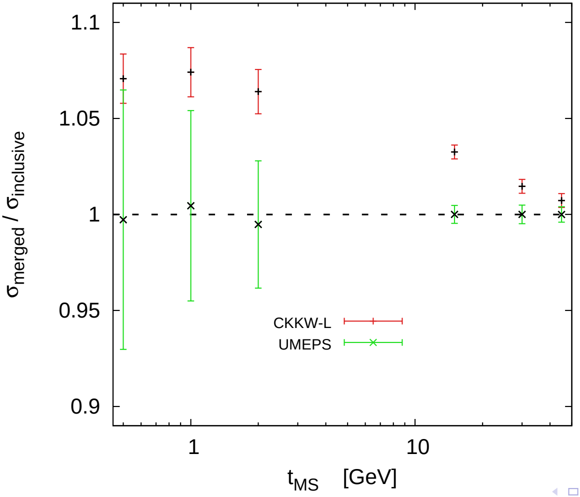
$$\frac{d\sigma_2}{d\phi_0} = F_0 \left|\mathcal{M}_0\right|^2 \alpha_S^2 \mathcal{P}_1^{ME} d\rho_1 dz_1 \mathcal{P}_2^{ME} d\rho_2 dz_2 \Theta(\rho_1 - \rho_2)$$

In CCKW we need to recreate the sequence of emissions.

In CKKW-L this is done by selecting a full parton shower history of an *n*-parton state.

In UMEPS performing the integration is simply to replace the *n*-jet the state with the one with one jet less in the history.

But why worry about unitarity, the cross sections are never better than LO anyway, so scale uncertainties are huge.



NLO

The anatomy of NLO calculations.

$$\langle\mathcal{O}\rangle = \int d\phi_n (B_n + V_n)\,\mathcal{O}_n(\phi_n) + \int d\phi_{n+1} B_{n+1}\mathcal{O}_{n+1}(\phi_{n+1}).$$

Not practical, since V_n and B_{n+1} are separately divergent, although their sum is finite.

The standard subtraction method:

$$\begin{aligned}\langle\mathcal{O}\rangle &= \int d\phi_n \left(B_n + V_n + \sum_p \int d\psi_{n,p}^{(a)} S_{n,p}^{(a)}\right)\mathcal{O}_n(\phi_n)\\ &+ \int d\phi_{n+1}\left(B_{n+1}\mathcal{O}_{n+1}(\phi_{n+1}) - \sum_p S_{n,p}^{(a)}\mathcal{O}_n\left(\frac{\phi_{n+1}}{\psi_{n,p}^{(a)}}\right)\right),\end{aligned}$$

MC@NLO

(Frixione et al.)

The subtraction terms must contain all divergencies of the real-emission matrix element. A parton shower splitting kernel does exactly that.

Generating two samples, one according to $B_n + V_n + \int S_n^{\mathrm{PS}}$, and one according to $B_{n+1} - S_n^{\mathrm{PS}}$, and just add the parton shower from which S_n is calculated.

POWHEG

(Nason et al.)

Calculate $\overline{B}_n = B_n + V_n + \int B_{n+1}$ and generate n-parton states according to that.

Generate a first emission according to B_{n+1}/B_n, and then add any[1] parton shower for subsequent emissions.

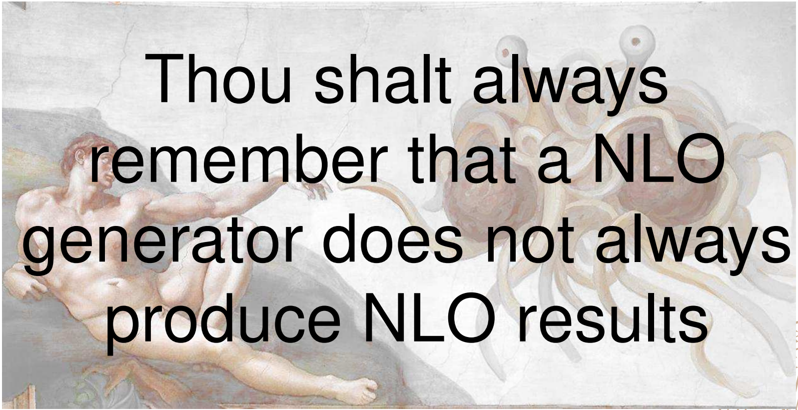
[1] As long as it is transverse-momentum ordered in the same way as in POWHEG or properly truncated

POWHEG and MC@NLO are very similar. They are both correct to NLO, but differ at higher orders

- POWHEG exponentiates also non singular pieces of the $n+1$ parton cross section
- POWHEG multiplies the $n+1$ parton cross section with $\overline{B}_n/B_n$ (the phase-space dependent K-factor).

POWHEG may also resum $k_\perp > \mu_R$, and will then generate additional logarithms, $log(S/\mu_R) \sim \log(1/x)$.

The Sixth Commandment of Event Generation



Really NLO?

Do NLO-generators always give NLO-predictions?

For simple Born-level processes such as $h \to \gamma\gamma$ production, all inclusive higgs observables will be correct to NLO.

- y_h
- y_γ
- $p_{\perp\gamma}$

But note that for $p_{\perp\gamma} > m_h/2$ the prediction is only leading order!

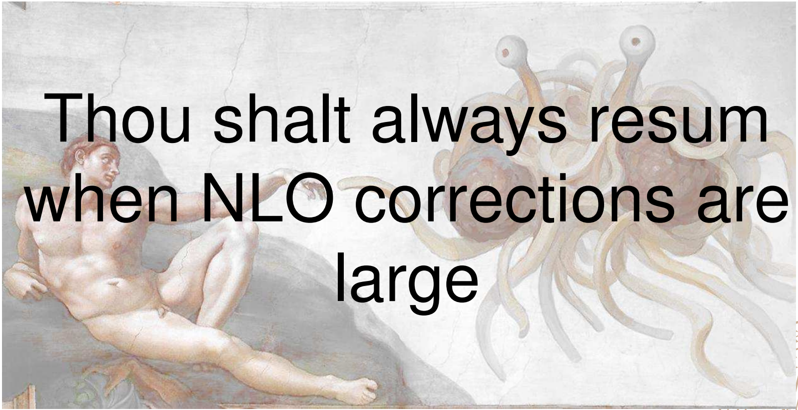
Also $p_{\perp h}$ is LO. To get NLO we need to start with H+jet at Born-level and calculate full α_S^2.

But for small $p_{\perp h}$ the NLO cross section diverges due to $L^{2n}\alpha_s^n$, $L = \log(p_{\perp h}/\mu_R)$.

If $L^2\alpha_s \sim 1$, the α_s^2 corrections are parametrically as large as the NLO corrections.

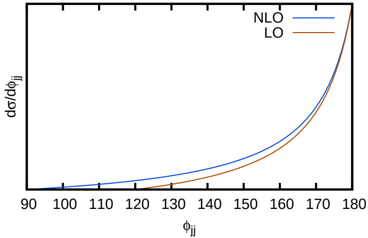
Can be alleviated by clever choices for μ_R, but in general you need to resum.

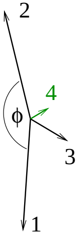
The Seventh Commandment of Event Generation



Thou shalt always resum when NLO corrections are large

Di-jet decorrelation





Measure the azimuthal angle between the two hardest jets. Clearly the 2-jet matrix element will only give back-to back jets, so the three-jet matrix element will give the leading order. And an NLO 3-jet generator will give us NLO.

But for $\phi_{jj} < 120^\circ$, the two hardest jets needs at least two softer jets to balance. So the NLO becomes LO here.

Multi-leg Matching

We need to be able to combine several NLO calculations and add (parton shower) resummation in order to get reliable predictions.

- No double (under) counting.
  - No parton shower emissions which are already included in (tree-level) ME states.
  - No terms in the PS no-emission resummation which are already in the NLO
- Dependence of any merging scale must not destroy NLO accuracy.
  - The NLO 0-jet cross section must not change too much when adding NLO 1-jet.
  - Dependence on logarithms of the merging scale should be less than $L^3\alpha_s^2$ in order for predictions to be stable for small scales.

SHERPA

First *working* solution for hadronic collisions.

CKKW-like combining of (MC@)NLO-generated events, fixing up double counting of NLO real and virtual terms.

Any jet multiplicity possible.

Dependence on merging scale canceled at NLO and parton-shower precision.

Residual dependence: $L^3\alpha_s^2/N_C^2$ — can't take merging scale too low.

MINLO

No merging scale!

- Take e.g. POWHEG Higgs+1-jet calculation down to *very* low $p_\perp$.
- Use clever (nodal) renormalization scales
- Multiply with (properly subtracted) Sudakov form factor
- Add non-leading terms to Sudakov form factor to get correct NLO 0-jet cross section.

Possible to go to NNLO!

Not clear how to go to higher jet multiplicities.

UNLOPS

Start from UMEPS (unitary version of CKKW-L).
Add (and subtract) *n*-jet NLO samples, fixing up double counting of NLO real and virtual terms.

$$\frac{d\sigma_1^{sub}}{d\phi_0} = \alpha_S \mathcal{P}_1^{ME} d\rho_1 dz_1 \left[\Pi_0(\rho_0, \rho_1) - 1 + \alpha_S \int_{\rho_1}^{\rho_0} d\rho dz\, \mathcal{P}_1 \right]$$

Note that PS uses $\alpha_S(\rho)$ and $f(x, \rho)$
rather than $\alpha_S(\mu_R)$ and $f(x, \mu_F)$

Any jet multiplicity possible.

Although there is a merging scale, the dependence of an *n*-jet cross section due to addition of higher multiplicities drops out completely. Merging scale can be taken arbitrarily small.

— Lots of negative weights.

Possible to go to NNLO?

Available in PYTHIA8
(and HERWIG++ in Simon Plätzer's incarnation)

GENEVA

- Analytic (SCET) resummation of NLO cross section to NLL (or even NNLL!) in the merging scale variable.
- Only $\mathrm{e}^+\mathrm{e}^-$ so far (W-production in *pp* on its way).

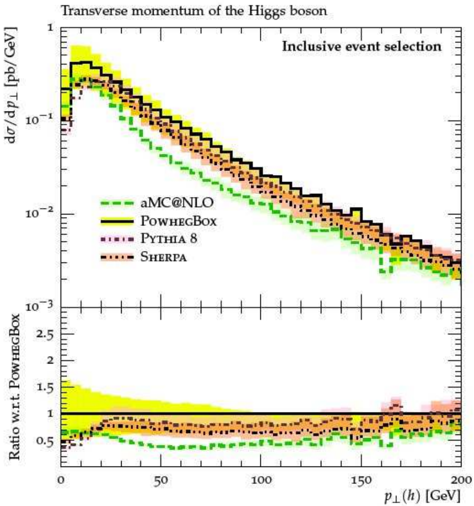
VINCIA

- Exponentiate NLO Matrix Elements in no-emission probability — no merging scale.
- Only $\mathrm{e}^+\mathrm{e}^-$ so far

FxFx

- MLM-like merging of different MC@NLO calculations.
- Difficult to understand merging scale dependence

Les Houches comparison



Now we have hard partons and in addition softer and more colliniear partons added with a parton shower, surely we should be able to compare a parton jet with a jet measured in our detector.

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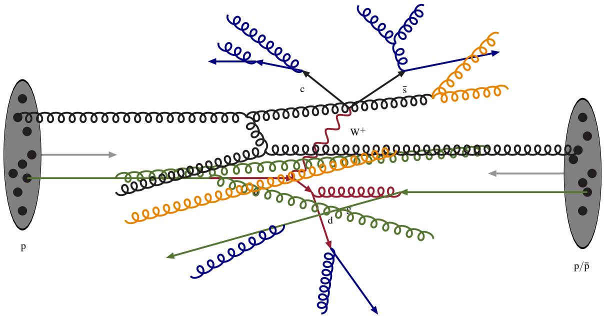
NO!

We also have to worry about hadronization, underlying events and pile-up.

What is the underlying event?



Everything except the hard sub-process?

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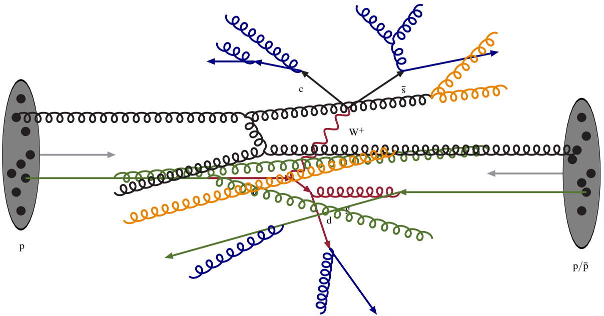
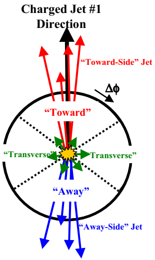
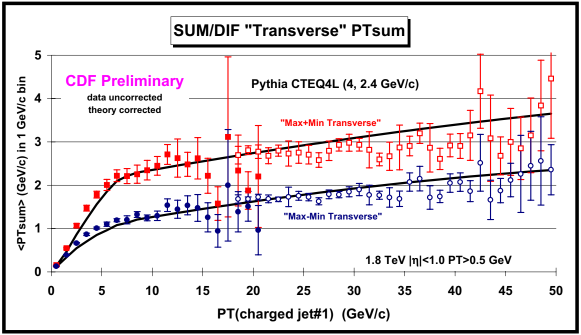


Everything except the hard sub-process
and initial- and final-state showers?


Charged Jet #1 Direction
"Toward-Side" Jet
Δϕ
"Toward"
"Transverse"
"Transverse"
"Away"
"Away-Side" Jet


SUM/DIF "Transverse" PTsum
CDF Preliminary
data uncorrected
theory corrected
Pythia CTEQ4L (4, 2.4 GeV/c)
"Max+Min Transverse"
"Max-Min Transverse"
1.8 TeV |η|<1.0 PT>0.5 GeV
<PTsum> (GeV/c) in 1 GeV/c bin
PT(charged jet#1) (GeV/c)

The typical *pp* collision

The underlying event is assumed to be mostly soft, like most of the *pp* collisions are.

- low-$p_\perp$ parton–parton scatterings ($d\hat{\sigma}_{gg} \propto 1/\hat{t}^2$)
- Elastic scattering $pp \to pp$ ($\sim$ 20% at the Tevatron, $\to$ half the cross section for asymptotic energies)
- Diffractive excitation $pp \to N^*p$, $pp \to N^*N'^*$

Particles are distributed more or less evenly in (η, ϕ).

Maybe we can measure the typical *pp* collisions and then add random low-$p_\perp$ particles at random to our generated events.

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Maybe we can measure the typical *pp* collisions and then add random low-$p_\perp$ particles at random to our generated events.

We want to do better than that.

Multiple Interactions

Starting Point:

$$\frac{d\sigma_H}{dk_\perp^2} = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \frac{d\hat{\sigma}_{Hij}}{dk_\perp^2}$$

The perturbative QCD $2 \to 2$ cross section is divergent. $\int_{k_{\perp c}^2} d\sigma_H$ will exceed the total *pp* cross section at the LHC for $k_{\perp c} \lesssim 10$ GeV.

There are more than one partonic interaction per *pp*-collision

$$\langle n \rangle (k_{\perp c}) = \frac{\int_{k_{\perp c}^2} d\sigma_H}{\sigma_{tot}}$$

The trick in PYTHIA is to treat everything as if it is perturbative.

$$\frac{d\hat{\sigma}_{Hij}}{dk_\perp^2} \to \frac{d\hat{\sigma}_{Hij}}{dk_\perp^2} \times \left(\frac{\alpha_S(k_\perp^2 + k_{\perp 0}^2)}{\alpha_S(k_\perp^2)} \cdot \frac{k_\perp^2}{k_\perp^2 + k_{\perp 0}^2} \right)^2$$

Where $k_{\perp 0}^2$ is motivated by colour screening and is dependent on collision energy.

$$k_{\perp 0}(E_{\mathrm{CM}}) = k_{\perp 0}(E_{\mathrm{CM}}^{\mathrm{ref}}) \times \left(\frac{E_{\mathrm{CM}}}{E_{\mathrm{CM}}^{\mathrm{ref}}} \right)^\epsilon$$

with $\epsilon \sim 0.16$ with some handwaving about the the rise of the total cross section.

The total and non-diffractive cross section is put in by hand (or with a Donnachie—Landshoff parameterization).

- Pick a hardest scattering according to $d\sigma_H/\sigma_{\mathrm{ND}}$ (for small $k_\perp$, add a Sudakov-like form factor).
- Pick an impact parameter, b, from the overlap function (high $k_\perp$ gives bias for small b).
- Generate additional scatterings with decreasing $k_\perp$ according to $d\sigma_H(b)/\sigma_{\mathrm{ND}}$

Hadronic matter distributions

We assume that we have factorization

$$\mathcal{L}_{ij}(x_1, x_2, b, \mu_F^2) = \mathcal{O}(b) f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2)$$

$$\mathcal{O}(b) = \int dt \int dxdydz \rho(x, y, z) \rho(x + b, y, z + t)$$

Where ρ is the matter distribution in the proton
(note: general width determined by σ_{ND})

- A simple Gaussian (too flat)
- Double Gaussian (hot-spot)
- x-dependent Gaussian (New Model)

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x-dependent overlap

Small-x partons are more spread out

$$\rho(r, x) \propto \exp\left(-\frac{r^2}{a^2(x)}\right)$$

with $a(x) = a_0(1 + a_1 \log 1/x)$

Note that high $k_\perp$ generally means higher x and more narrow overlap distribution.

x-dependent overlap

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Is it reasonable to use collinear factorization even for very small $k_\perp$?

Soft interactions means very small x,
should we not be using $k_\perp$-factorization and BFKL?

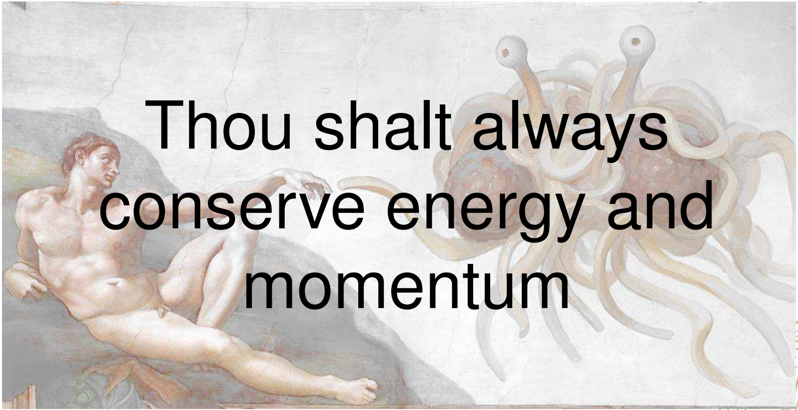
Energy–momentum conservation

Each scattering consumes momentum from the proton, and eventually we will run out of energy.

- Continue generating MI's with decreasing $k_\perp$, until we run out of energy.
- Or rescale the PDF's after each additional MI. (Taking into account flavour conservation).

Note that also initial-state showers take away momentum from the proton.

The Eighth Commandment of Event Generation



Thou shalt always conserve energy and momentum

Interleaved showers

When do we shower?

- First generate all MI's, then shower each?
- Generate shower after each MI?

Is it reasonable that a low-$k_\perp$ MI prevents a high-$k_\perp$ shower emission? Or vice versa?

- Include MI's in the shower evolution

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After the primary scattering we can have

- Initial-state shower splitting, P_{ISR}
- Final-state shower splitting, P_{FSR}
- Additional scattering, P_{MI}
- Rescattering of final-state partons, P_{RS}

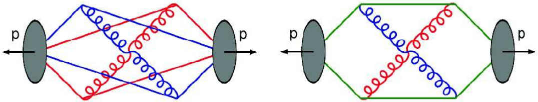
Let them compete

$$\frac{d\mathcal{P}_a}{dk_\perp^2} = \frac{dP_a}{dk_\perp^2} \times \exp - \left(\int_{k_\perp^2} (dP_{\mathrm{ISR}} + dP_{\mathrm{FSR}} + dP_{\mathrm{MI}} + dP_{\mathrm{RS}}) \right)$$

Colour Connections

Every MI will stretch out new colour-strings.

Evidently not all of them can stretch all the way back to the proton remnants.



To be able to describe observables such as $\langle p_\perp \rangle(n_{\mathrm{ch}})$ we need a lot of colour (re-)connections.

Beyond simple strings

What if we kick out two valens quarks from the same proton?

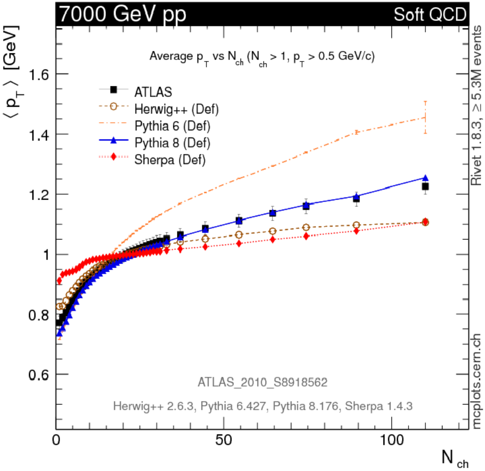
Normally it is assumed that the proton remnant has a di-quark, giving rise to a leading baryon in the target fragmentation.

PYTHIA8 has can hadronize string junctions
(also used for baryon-number violating BSM models)

Non-trivial baryon number distribution in rapidity.

Lots of other stuff

- Elastic, single and double (soft) diffraction
- Hard diffraction (Ingelman–Schlein)
- Intrinsic $k_\perp$
- ...


7000 GeV pp
Soft QCD
Average p_T vs N_{ch} (N_{ch} > 1, p_T > 0.5 GeV/c)
ATLAS
Herwig++ (Def)
Pythia 6 (Def)
Pythia 8 (Def)
Sherpa (Def)
ATLAS_2010_S8918562
Herwig++ 2.6.3, Pythia 6.427, Pythia 8.176, Sherpa 1.4.3
⟨ p_T ⟩ [GeV]
N_{ch}
Rivet 1.8.3, ≥ 5.3M events
mcplots.cern.ch

Minimum Bias and Pile-Up

Minimum Bias events is not no-bias typical *pp* collisions. You still need a trigger.

But if we look at a pile-up event overlayed with a triggered event, surely that is a no-bias *pp* collision.

Minimum Bias and Pile-Up

Minimum Bias events is not no-bias typical *pp* collisions. You still need a trigger.

But if we look at a pile-up event overlayed with a triggered event, surely that is a no-bias *pp* collision.

No, even pile-up events may be correlated with the trigger collision.

Nature is efficient

Consider trigger on a calorimeter jet with $E_{\perp} > E_{\perp cut}$.

This can either be accomplished by a parton–parton scattering with $p_{\perp} > E_{\perp cut}$

Or by a parton–parton scattering with lower $p_{\perp}$(which has a higher cross section $\propto (E_{\perp cut}/p_{\perp})^4$ and some random particles coming from the underlying event or pile-up events which happens to fluctuate upwards.

We bias ourselves towards pile-up events with higher activity than a no-bias *pp* collision.

Hadronization

Now that we are able to generate partons, both hard, soft, collinear and from multiple scatterings, we need to convert them to hadrons.

This is a non-perturbative process, and all we can do is to construct models, and try to include as much as possible of what we know about non-perturbative QCD.

Local Parton–Hadron Duality

An analytic approach ignoring non-perturbative difficulties.

Run shower down to scales $\sim \Lambda_{\mathrm{QCD}}$.

Each parton corresponds to one (or 1.something) hadron.

Can describe eg. momentum spectra surprisingly well.

Can be used to calculate power corrections to NLO predictions for event shapes,

- $\langle 1 - T \rangle = c_1 \alpha_{\mathrm{s}}(E_{\mathrm{cm}}) + c_2 \alpha_{\mathrm{s}}^2(E_{\mathrm{cm}}) + c_p / E_{\mathrm{cm}}$

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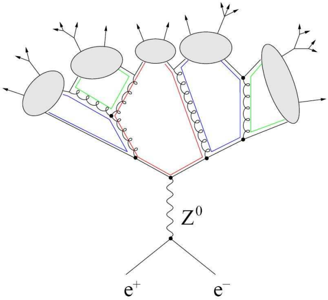
Cannot generate real events with this though.

Cluster Hadronization

Close to local parton–hadron duality in spirit. Based on the idea of Preconfinement:

The pattern of perturbative gluon radiation is such that gluons are emitted mainly between colour-connected partons. If we emit enough gluons the colour-dipoles will be small.



After the shower, force $g \to q\bar{q}$ splittings giving low-mass, colour-singlet clusters

Decay clusters isotropically into two hadrons according to phase space weight
$\sim (2s_1 + 1)(s_2 + 1)(2p/m)$

Cluster hadronization is very simple and clean.
Maybe too simple...

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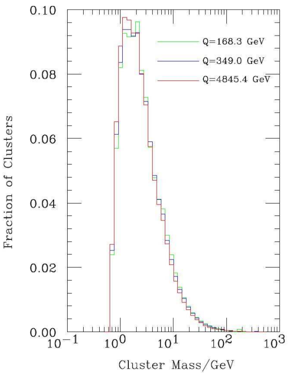
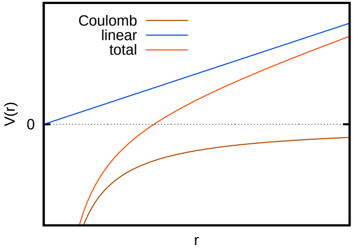
Maybe too simple...



- Cluster masses can be large (finite probability for no gluon emission): Introduce *string-like* decays of heavy clusters into lighter ones (with special treatment of proton remnant).
- In clusters including a heavy quark (or a di-quark) the heavy meson (or baryon) should go in this direction: introduce anisotropic cluster decays.
- ...

String Hadronization

What do we know about non-perturbative QCD?



- At small distances we have a Coulomb-like asymptotically free theory
- At larger distances we have a linear confining potential

For large distances, the field lines are compressed to vortex lines like the magnetic field in a superconductor

1+1-dimensional object $\sim$ a massless relativistic string

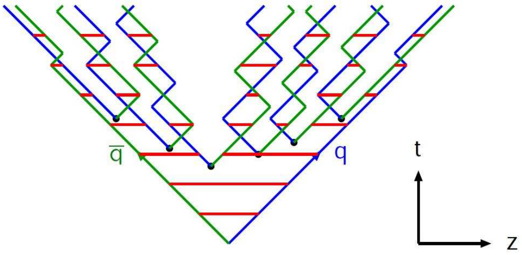
As a $q\bar{q}$-pair moves apart, they are slowed down and more and more energy is stored in the string.

If the energy is small, the $q\bar{q}$-pair will eventually stop and move together again. We get a “YoYo”-state which we interpret as a meson.

If high enough energy, the string will break as the energy in the string is large enough to create a new $q\bar{q}$-pair.

The energy in the string is given by the string tension

$$\kappa = \left|\frac{dE}{dz}\right| = \left|\frac{dE}{dt}\right| = \left|\frac{dp_z}{dz}\right| = \left|\frac{dp_z}{dt}\right| \sim 1\text{GeV/fm}$$



The quarks obtain a mass and a transverse momentum in the breakup through a tunneling mechanism

$$\mathcal{P} \propto e^{-\frac{\pi m_{q\perp}^2}{\kappa}} = e^{-\frac{\pi m_q^2}{\kappa}} e^{-\frac{\pi p_\perp^2}{\kappa}}$$

Gives a natural supression of heavy quarks
$\mathrm{d\bar{d}} : \mathrm{u\bar{u}} : \mathrm{s\bar{s}} : \mathrm{c\bar{c}} \approx 1 : 1 : 0.3 : 10^{-11}$

The break-ups starts in the middle and spreads outward, but they are causually disconnected. So we should be able to start anywhere.

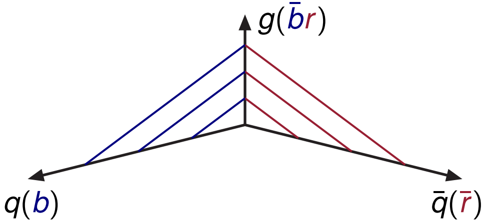
In particular we could start from either end and go inwards.

Requiring left-right symmetry we obtain a unique *fragmentation function* for a hadron taking a fraction z of the energy of a string end in a breakup

$$p(z) = \frac{(1-z)^a}{z} e^{-bm_\perp^2/z}$$

The Lund symmetric fragmentation function.

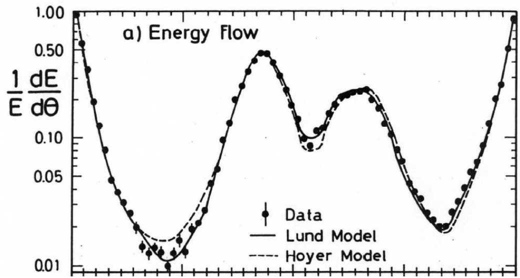
Gluons complicates the picture somewhat. They can be interpreted as a "kinks" on the string carrying energy and momentum



The gluon carries twice the charge ($N_C/C_F \rightarrow 2$ for $N_C \rightarrow \infty$)

A bit tricky to go around the gluon corners, but we get a consistent picture of the energy–momentum structure of an event with no extra parameters.

The Lund string model predicted the string effect measured by Jade.



In a three-jet event there are more energy between the $\mathrm{g} - \mathrm{q}$ and $\mathrm{g} - \bar{\mathrm{q}}$ jets than between $\mathrm{q} - \bar{\mathrm{q}}$.

For the flavour structure the picture becomes somewhat messy.

Baryons can be produced by having $\mathrm{qq}-\bar{\mathrm{q}}\bar{\mathrm{q}}$-breakups (diquarks behaves like an anti-colour), but more complicated mechanisms ("popcorn") needed to describe baryon correlations.

We also need special suppression of strange mesons, baryons. Parameters for different spin states, ...

There are *lots* of parameters i PYTHIA.

The Ninth Commandment of Event Generation

Thou shalt not be afraid of parameters

Strings vs. Clusters

Model	string (PYTHIA)	cluster (HERWIG)
energy–momentum picture	powerful, predictive few parameters	simple, unpredictive many parameters
flavour composition	messy, unpredictive many parameters	simple, reasonably predictive few parameters

There will always be parameters...

Most hadronization parameters have been severely constrained by LEP data. Does this mean we can use the models directly at LHC?

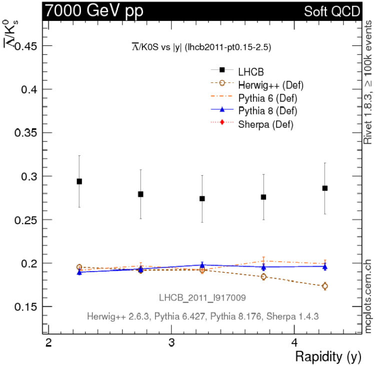
Jet universality

There may be problems with flavour and meson/baryon issues.

Also at LEP there were mainly quark jets, gluon jets are softer and not very well measured.

At LHC there will be very hard gluon jets.

We need to check that jet universality works.


7000 GeV pp
Soft QCD
$\bar{\Lambda}/K^0_s$
$\bar{\Lambda}$/K0S vs |y| (lhcb2011-pt0.15-2.5)
LHCB
Herwig++ (Def)
Pythia 6 (Def)
Pythia 8 (Def)
Sherpa (Def)
LHCB_2011_I917009
Herwig++ 2.6.3, Pythia 6.427, Pythia 8.176, Sherpa 1.4.3
Rapidity (y)
Rivet 1.8.3, ≥ 100k events
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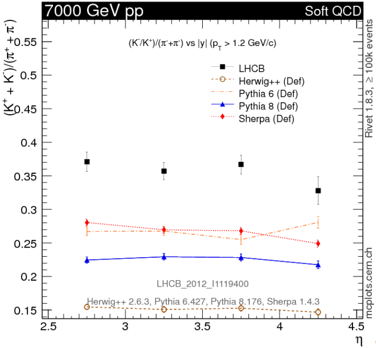
7000 GeV pp
Soft QCD
$(K^+ + K^-)/(\pi^+ + \pi^-)$
$(K^-/K^+)/(\pi^- + \pi^-)$ vs |y| (p_T > 1.2 GeV/c)
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LHCB_2012_I1119400
Herwig++ 2.6.3, Pythia 6.427, Pythia 8.176, Sherpa 1.4.3
η
Rivet 1.8.3, ≥ 100k events
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The PDG decay tables

The Particle Data Group has machine-readable tables of decay modes.

But they are not complete and cannot be used directly in an event generator.

- Branching ratios need to add up to unity.
- Some decays are listed as $B^{\star 0} \to \mu^+\nu_\mu X$.
- ...

Most decays need to be coded by hand

Particle Decays

Not the most sexy part of the event generators,
but still essential.

$$
\begin{array}{l}
B^{\star 0} \to \gamma \;\; B^0 \\
\qquad\qquad \hookrightarrow \overline{B}^0 \to e^- \bar{\nu}_e \;\; D^{\star +} \\
\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow \pi^+ \;\; D^0 \\
\qquad\qquad\qquad\qquad\qquad\qquad\qquad \hookrightarrow K^- \;\; \rho^+ \\
\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow \pi^+ \;\; \pi^0 \\
\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow e^+ e^- \gamma
\end{array}
$$

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$$\hookrightarrow e^+ e^- \gamma$$

EM decays

Particle Decays

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\begin{array}{l}
B^{\star 0} \to \gamma \;\; B^0 \\
\qquad\qquad \hookrightarrow \overline{B}^0 \to e^- \bar{\nu}_e \;\; D^{\star +} \\
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\qquad\qquad\qquad\qquad\qquad\qquad \hookrightarrow K^- \;\; \rho^+ \\
\qquad\qquad\qquad\qquad\qquad\qquad\qquad \hookrightarrow \pi^+ \;\; \pi^0 \\
\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \hookrightarrow e^+ e^- \gamma
\end{array}
$$

Weak mixing

Particle Decays

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$$B^{\star 0} \to \gamma \; B^0$$
$$\hookrightarrow \overline{B}^0 \to e^- \bar{\nu}_e \; D^{\star +}$$
$$\hookrightarrow \pi^+ \; D^0$$
$$\hookrightarrow K^- \; \rho^+$$
$$\hookrightarrow \pi^+ \; \pi^0$$
$$\hookrightarrow e^+ e^- \gamma$$

Weak decay, displaced vertex, $|\mathcal{M}|^2 \propto (p_{\bar{B}} p_{\bar{\nu}})(p_e p_{D^\star})$

Particle Decays

Not the most sexy part of the event generators,
but still essential.

$$B^{\star 0} \to \gamma \;\; B^0$$
$$\hookrightarrow \overline{B}^0 \to e^- \bar{\nu}_e \;\; D^{\star +}$$
$$\hookrightarrow \pi^+ \;\; D^0$$
$$\hookrightarrow K^- \;\; \rho^+$$
$$\hookrightarrow \pi^+ \;\; \pi^0$$
$$\hookrightarrow e^+ e^- \gamma$$

Strong decay

Particle Decays

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$$\hookrightarrow \pi^+ \;\; D^0$$
$$\hookrightarrow K^- \;\; \rho^+$$
$$\hookrightarrow \pi^+ \;\; \pi^0$$
$$\hookrightarrow e^+ e^- \gamma$$

Weak decay, displaced vertex, ρ mass smeared

Particle Decays

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but still essential.

$$B^{\star 0} \to \gamma \;\; B^0$$
$$\hookrightarrow \overline{B}^0 \to e^- \bar{\nu}_e \;\; D^{\star +}$$
$$\hookrightarrow \pi^+ \;\; D^0$$
$$\hookrightarrow K^- \;\; \rho^+$$
$$\hookrightarrow \pi^+ \;\; \pi^0$$
$$\hookrightarrow e^+ e^- \gamma$$

ρ polarized, $|\mathcal{M}|^2 \propto \cos^2\theta$ in ρ rest frame

Particle Decays

Not the most sexy part of the event generators,
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$$B^{\star 0} \to \gamma \;\; B^0$$
$$\hookrightarrow \overline{B}^0 \to e^- \bar{\nu}_e \;\; D^{\star +}$$
$$\hookrightarrow \pi^+ \;\; D^0$$
$$\hookrightarrow K^- \;\; \rho^+$$
$$\hookrightarrow \pi^+ \;\; \pi^0$$
$$\hookrightarrow e^+ e^- \gamma$$

Dalitz decay, $m_{e^+e^-}$ peaked

Outline of Lectures

- Lecture I: Basics of Monte Carlo methods, the event generator strategy, matrix elements, LO/NLO, . . .
- Lecture II: Parton showers, initial/final state, matching/merging, . . .
- Lecture III: Matching/merging (cntd.), underlying events, multiple interactions, minimum bias, pile-up, hadronization, decays, . . .
- Lecture IV: Protons vs. heavy ions, summary, . . .

Buckley et al. (MCnet collaboration), *Phys. Rep.* **504** (2011) 145.