Basics of Event Generators III

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Correlations between partons in nucleons
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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: Underlying events, multiple interactions, minimum bias, pile-up, hadronization, decays, . . .
- Lecture IV: Correlations between partons in nucleons, summary, . . .

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

Outline

Underlying Events
- Multiple Interactions
- Interleaved showers
- Colour connections
- Minimum Bias and Pile-Up

Hadronization
- Local Parton–Hadron Duality
- Cluster Hadronization
- String Hadronization

Particle Decays
- Standard Hadronic Decays

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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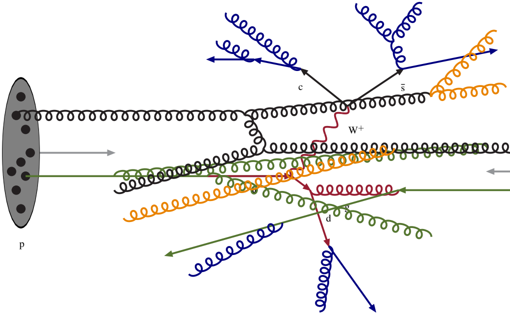
NO!

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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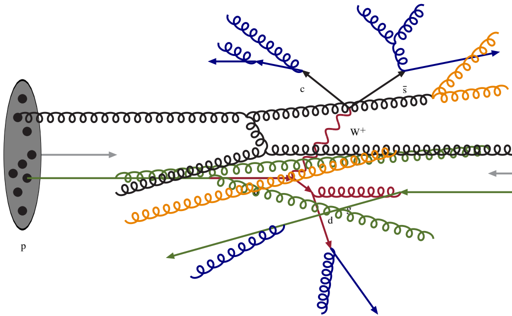
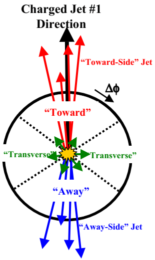
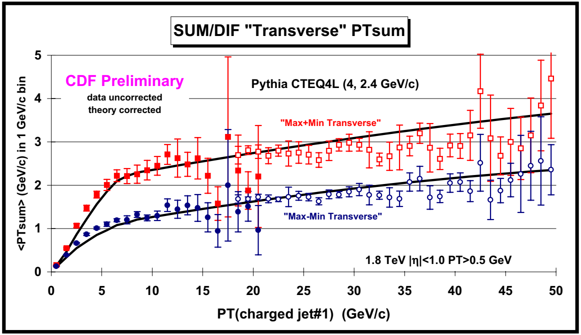


Everything except the hard sub-process
and initial- and final-state showers?


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)
0
1
2
3
4
5
0
5
10
15
20
25
30
35
40
45
50

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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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?

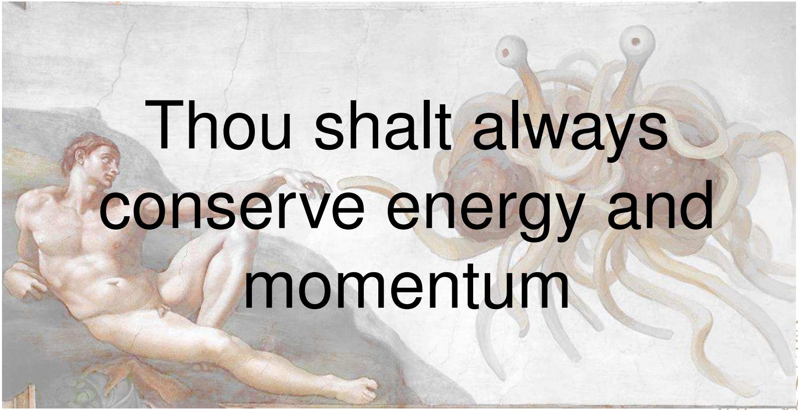
Energy–momentum conservation

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

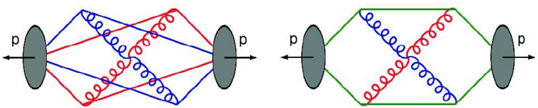
Let them compete

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

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?

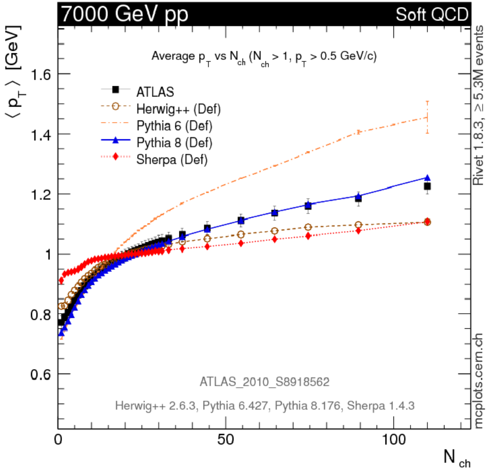
Normally it is assumed that the proton remnant has a di-quark, giving rise to a leading baryon in the target fragmentation.

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
1.6
1.4
1.2
1
0.8
0.6
0
50
100

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,

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

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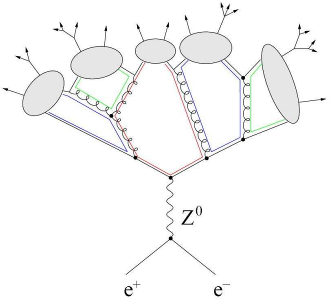
Cannot generate real events with this though.

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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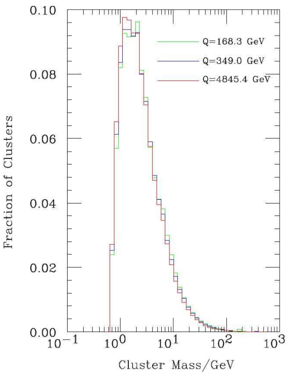
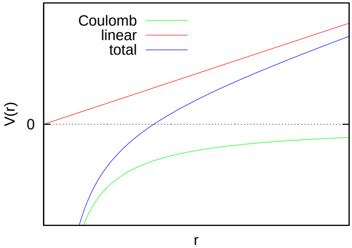


- Cluster masses can be large (finite probability for no gluon emission): Introduce *string-like* decays of heavy clusters into lighter ones
(with special treatment of proton remnant).
- In clusters including a heavy quark (or a di-quark) the heavy meson (or baryon) should go in this direction: introduce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

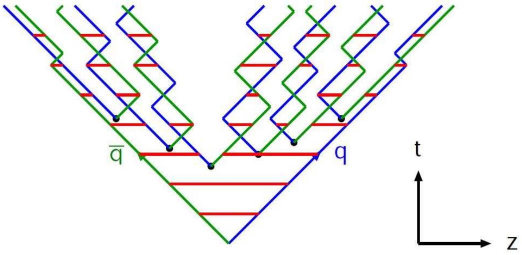
As a $\mathrm{q\bar{q}}$-pair moves apart, they are slowed down and more and more energy is stored in the string.

If the energy is small, the $\mathrm{q\bar{q}}$-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 $\mathrm{q\bar{q}}$-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.

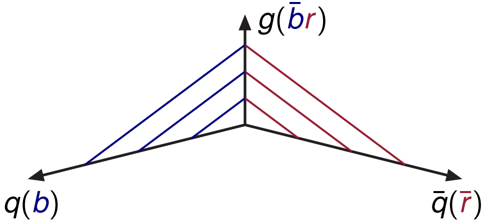
In particular we could start from either end and go inwards.

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.

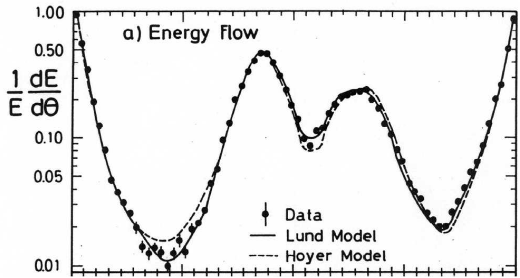
Gluons complicates the picture somewhat. They can be interpreted as a “kinks” on the string carrying energy and momentum



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

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 $g-q$ and $g-\bar{q}$ jets than between $q-\bar{q}$.

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?

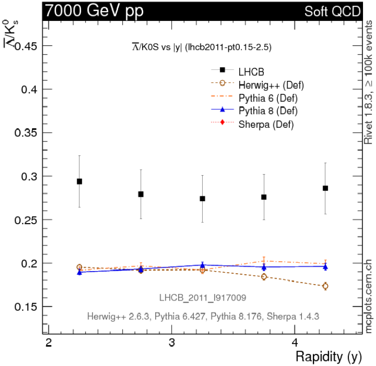
Jet universality

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
$\overline{\Lambda}/K^0_s$
$\overline{\Lambda}$/K0S vs |y| (lhcb2011-pt0.15-2.5)
LHCB
Herwig++ (Def)
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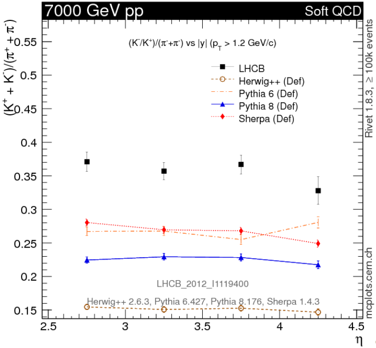
Herwig++ 2.6.3, Pythia 6.427, Pythia 8.176, Sherpa 1.4.3
Rivet 1.8.3, ≥ 100k events
mcplots.cern.ch
Rapidity (y)


7000 GeV pp
Soft QCD
$(K^+ + K^-)/(\pi^+ + \pi^-)$
$(K^-/K^+)/(\pi^- + \pi^-)$ vs |y| (p_T > 1.2 GeV/c)
LHCB
Herwig++ (Def)
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LHCB_2012_I1119400
Herwig++ 2.6.3, Pythia 6.427, Pythia 8.176, Sherpa 1.4.3
Rivet 1.8.3, ≥ 100k events
mcplots.cern.ch
η

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.

$$B^{\star 0} \to \gamma \; B^0$$

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

$$\hookrightarrow \pi^+ \; D^0$$

$$\hookrightarrow K^- \; \rho^+$$

$$\hookrightarrow \pi^+ \; \pi^0$$

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

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EM decays

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Weak mixing

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

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

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Strong decay

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$$\hookrightarrow K^- \; \rho^+$$
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Weak decay, displaced vertex, ρ mass smeared

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

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

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

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: Underlying events, multiple interactions, minimum bias, pile-up, hadronization, decays, . . .
- Lecture IV: Correlations between partons in nucleons, summary, . . .

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