Monte Carlo Event Generators

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Outline

- Introduction
- The NLO Revolution
- Small-x resummation
- Multiple interactions
- Related tools

I am so, so very sorry, I forgot to mention . . .

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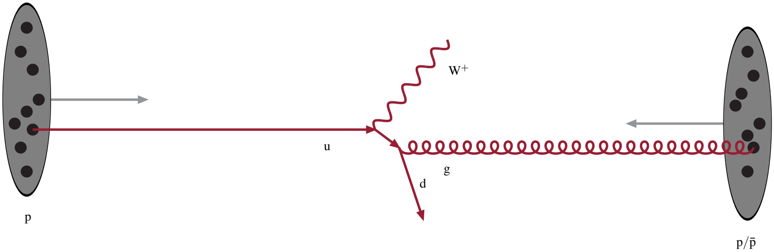
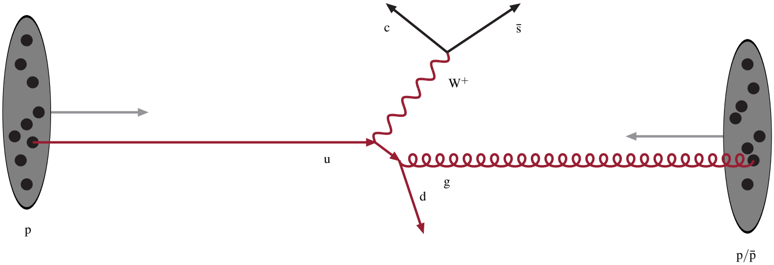
The structure of a proton collision

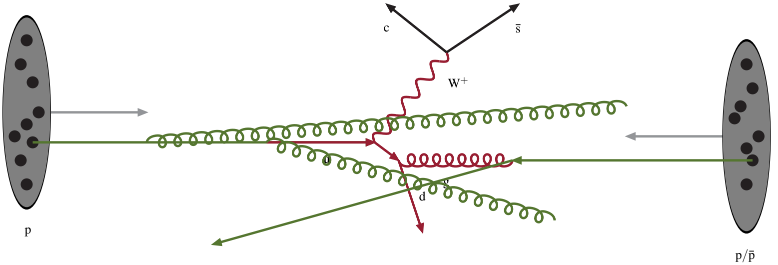
The hard/primary scattering



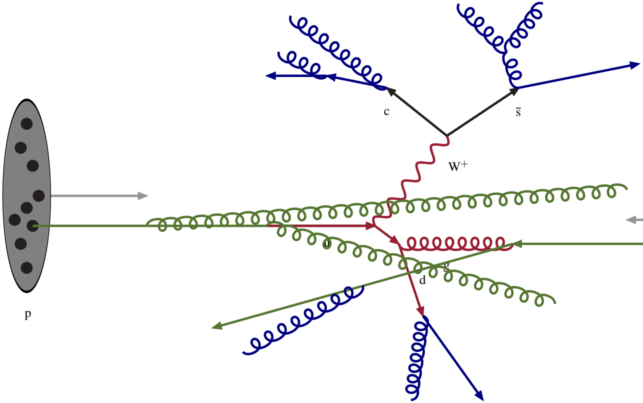
Immediate decay of unstable elementary particles



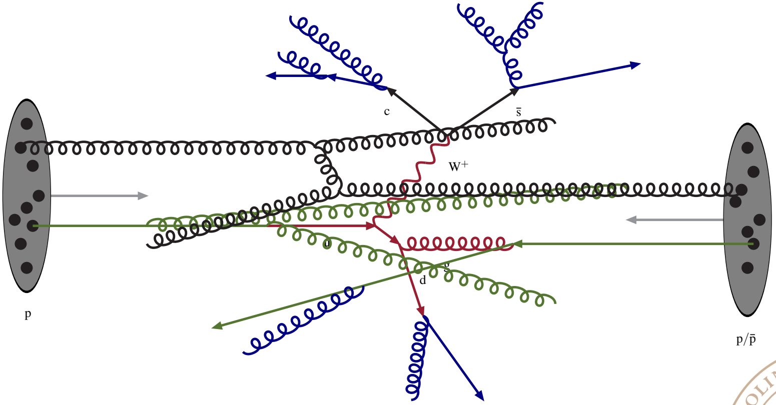
Radiation from particles before primary interaction



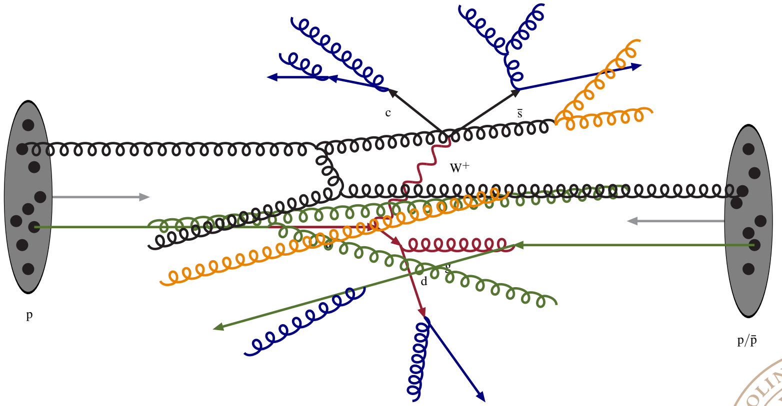
Radiation from produced particles



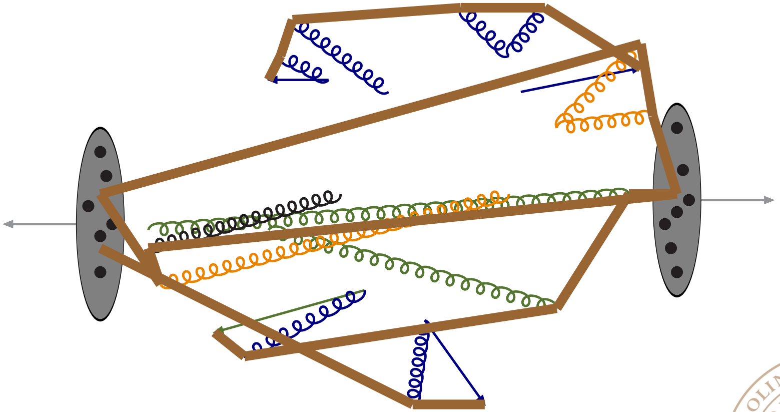
Additional sub-scatterings



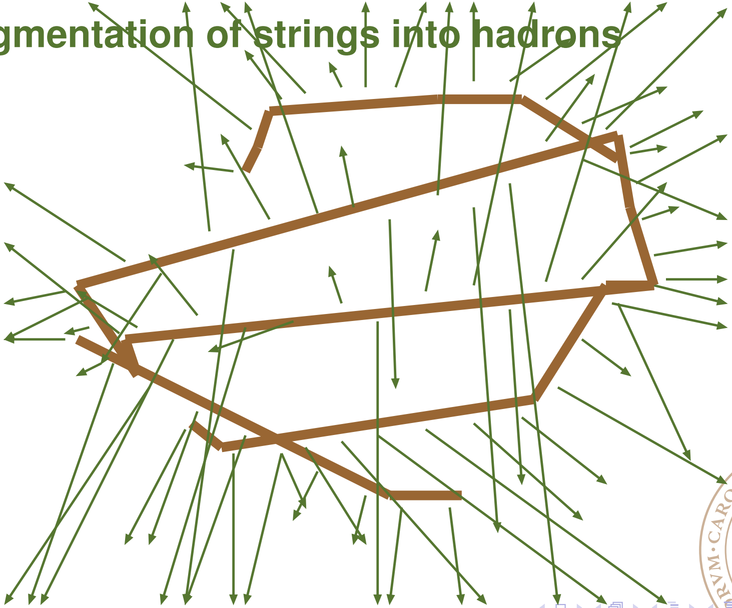
. . . with accompanying radiation



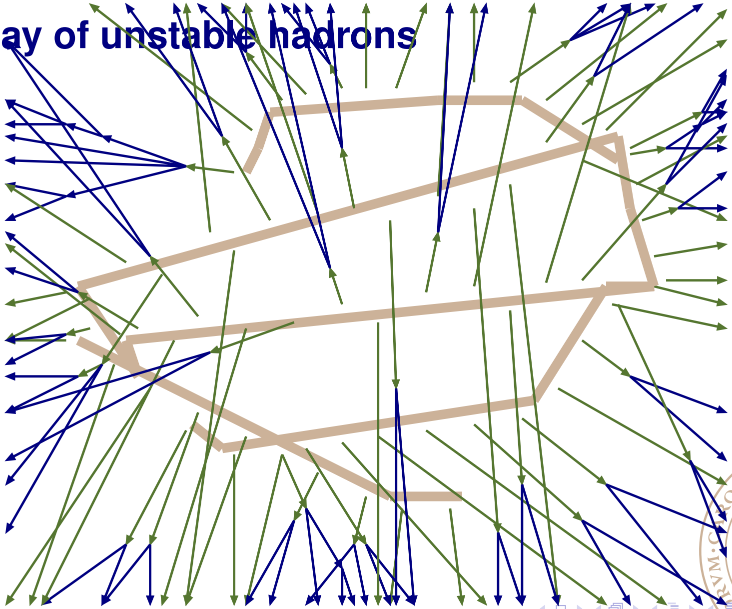
Formation of *colour strings*



Fragmentation of strings into hadrons



Decay of unstable hadrons



The Main Contenders

- HERWIG
- PYTHIA8
- SHERPA

HERWIG

(Seymour et al.)

- Angular ordered shower (+ dipoles)
- Cluster fragmentation
- ME + matching via *Matchbox*
- Built-in BSM features
- MPI-based UE
- ...

PYTHIA8

(Sjöstrand et al.)

- String fragmentation
- MPI-based UE
- Dipole-based shower
- ME via LHEF (+ NLO matching)
- …

SHERPA

(Krauss et al.)

- Built-in ME-generator
- Built-in matching (LO + NLO)
- Dipole-based shower
- Simple MPI/UE
- ...

The NLO Revolution

The NLO Matrix Element Revolution is well on its way.

The matching/merging with Parton Showers to get the full picture of hadronic final states is on its way.

NLO matching is technically very complicated!

Perturbative QCD prediction for an observable

$$
\begin{aligned}
\langle\mathcal{O}\rangle &= C_0 \rightarrow 1\\
&+ C_1\alpha_s \rightarrow L^2\alpha_s + L\alpha_s + \alpha_s\\
&+ C_2\alpha_s^2 \rightarrow L^4\alpha_s^2 + L^3\alpha_s^2 + L^2\alpha_s^2 + L\alpha_s^2 + \alpha_s^2\\
&\vdots\\
&+ C_n\alpha_s^n \rightarrow L^{2n}\alpha_s^n + L^{2n-1}\alpha_s^n + L^{2n-2}\alpha_s^n + L^{2n-3}\alpha_s^n + \cdots\\
&\vdots
\end{aligned}
$$

$\alpha_s \rightarrow \alpha_s(\mu_R)$ can be reabsorbed into C_i but residual dependence if series is cut off.

Any jet observable will have an additional resolution scale, ρ, giving a dependence of C_i on the logarithm $L = \log \mu_R/\rho$.

We clearly have a problem if $L^2\alpha_s \sim 1$

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& \vdots & & \\
& + C_n \alpha_s^n & \rightarrow & L^{2n}\alpha_s^n + L^{2n-1}\alpha_s^n + L^{2n-2}\alpha_s^n + L^{2n-3}\alpha_s^n + \cdots \\
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For any non-inclusive observable we may get large logarithms and it is not enough to go to NLO, we also need to resum terms $\propto L^{2n}\alpha_s^n$ (LL) and maybe even $L^{2n-1}\alpha_s^n$ (NLL) or higher.

And then we need to worry about non-perturbative effects.

For a given observable we can use analytic resummation techniques and for some of these there are also analytic techniques for calculating *power corrections*.

The same thing is done in event generators with Parton Showers and hadronization models.

"Maeh, all event generators do is to squirt reasonably distributed mixture of particles in our detector simulation programs to understand our detector, and give a reasonable feeling for systematical errors on QCD predictions due to hadronization"

But what if we can systematically improve event generators to give predictions with formally controllable precision?

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. Reweights 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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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:

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

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 $\bar{B}_n = B_n + V_n + \int B_{n+1}$ 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

Really NLO?

Do NLO-generators always give NLO-predictions?

For simple Born-level processes such as Z^0-production, all inclusive Z^0 observables will be correct to NLO.

- y_Z
- y_e
- $p_{\perp e}$

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

Also $p_{\perp Z}$ is LO. To get NLO we need to start with Z+jet at Born-level

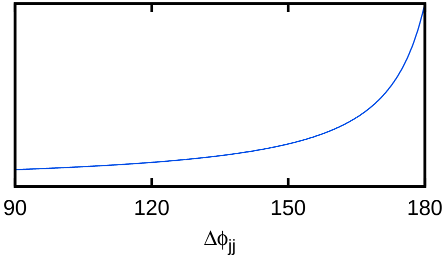
But for small $p_{\perp Z}$ the NLO cross section diverges due to $L^{2n}\alpha_s^n$, $L = \log(p_{\perp Z}/\mu_R)$.

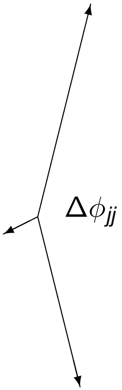
If $L^2\alpha_s \sim 1$, the α_s^2 corrections are parametrically as large as the NLO corrections.

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

Assume we have a generator capable of doing three jets to NLO ($B_3 + V_3 + B_4$)

Azimuth angle between the two hardest jets





Not always obvious when NLO stops being NLO

Multi-leg Matching

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

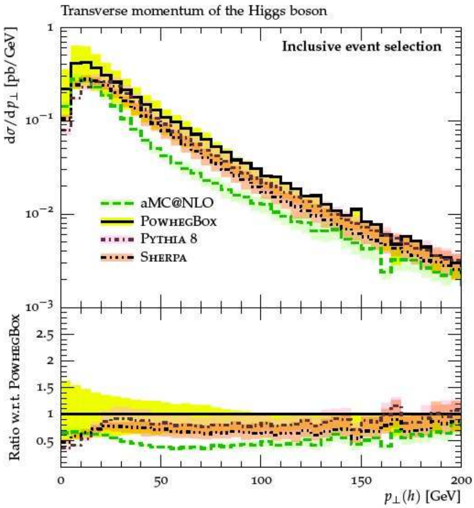
- No double (under) counting.
  - No parton shower emissions which are already included in (tree-level) ME states.
  - No terms in the PS no-emission resummation which are already in the NLO
- Dependence of any merging scale must not destroy NLO accuracy.
  - The NLO 0-jet cross section must not change 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.

The playing field

- SHERPA-MEPS@NLO: (Höche et al.) CKKW-based using a merging scale. Any jet multiplicity possible if NLO is available. Residual dependence: $L^3\alpha_s^2/N_C^2$ — can't take merging scale too low.
- POWHEG-MiNLO: (Hamilton et al.) No merging scale. $0+1$-jet to NLO. NNLO possible?
- PYTHIA8-UNLOPS: (Prestel et al.) CKKW-L-based, with merging scale, but can be taken arbitrarily low. Lots of negative weights. Possible to go to NNLO?
- FxFx: (Frederix et al.) MLM-like merging procedure. Uncertain dependency on the merging scale. Any number of jets.

Also: GENEVA, VINCIA, but only for e^+e^-.

Les Houches comparison



Small-x resummation

HERA was all about small-x, looking for the break-down of collinear factorization.

LHC probes even smaller x...

But all general purpose Event Generators are based on collinear factorization and DGLAP.

CASCADE

(Jung et al.)

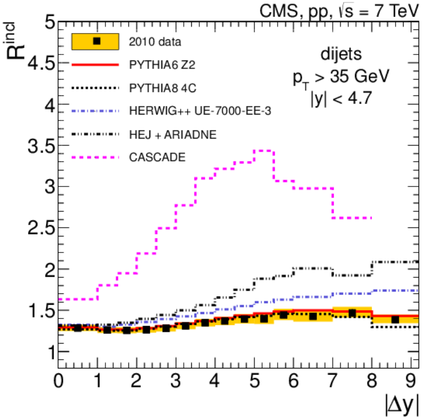
- CCFM-based, unordered backward evolution.
- Off-shell matrix elements.
- Feed to PYTHIA for hadronization.

HEJ — High Energy Jets

(Andersen et al.)

- Base on FKL formalism.
- Add fixed order MEs from MadGraph.
- Optional final-state shower with ARIADNE.
- Hadronization with PYTHIA.

Where are the small-x effects?



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 PYTHIA8 model

The trick 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

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

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

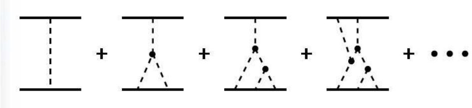
Where ρ is the matter distribution in the proton
(note: general width determined by σ_{ND})

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

Note that HERWIG and SHERPA has similar MPI abilities.

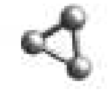
Regge-based approaches

Mainly for minimum-bias and diffraction.



- PHOJET: (Engel et al.) Two-channel eikonal unitarization with hard component. PYTHIA final-state shower and hadronization.
- EPOS: (Werner et al.) Similar but possibility to add hydro-dynamical evolution and describe heavy ion collisions.
- SHRIMPS: (Zapp et al.) Based on the KMR model with multi-channel eikonal unitarization. Interfaced to SHERPA.

DIPSY



DIPSY

(Flensburg et al.)

- Initial-state dipole evolution in rapidity and impact-parameter.
- Muellers formulation of BFKL
- LL-BFKL but including non-leadin effects (energy-momentum conservation)
- $1/N_c^2$ corrections with swing mech
- Final state dipole showe with ARIADNE, hadronization in PYTHIA8.
- Heavy Ion collisions possible (but slow)

Related Tools

Matrix Element Generators

- MadGraph5(aMC@NLO)
- ALPGEN
- HELAC
- CompHEP
- . . . (see previous talk by de Florian)

PDF parametrizations

- LHAPDF

Rivet.hepforge.org

(Buckley et al.)

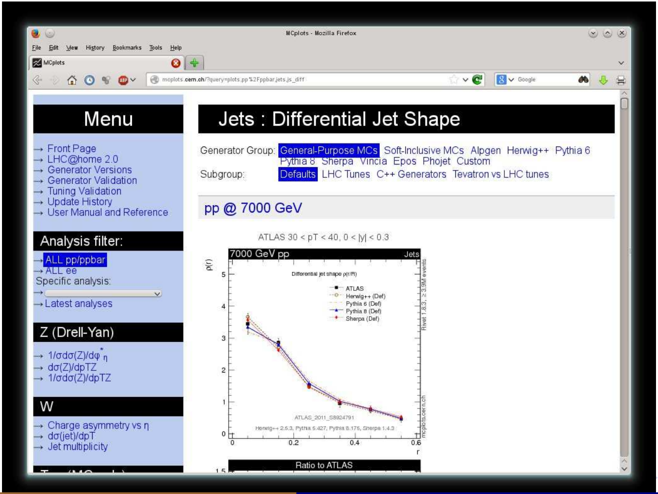
The successor of HZTools!

250+ analyses are already in there.

If you want to make your analyses useful for others —
publish them in Rivet!

MCplots.cern.ch

(Skands et al.)



Summary

- Event Generators are entering the precision era.
- Small-x is difficult.
- Soft QCD is difficult.
- Heavy Ions?
- Apologies to . . .

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Monte Carlo
training studentships

3-6 month fully funded studentships for current PhD students at one of the MCnet nodes. An excellent opportunity to really understand and improve the Monte Carlos you use!

Application rounds every 3 months.

MCnet

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MC*net* projects
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Herwig
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MadGraph
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