Monte Carlo event generation: Introduction II

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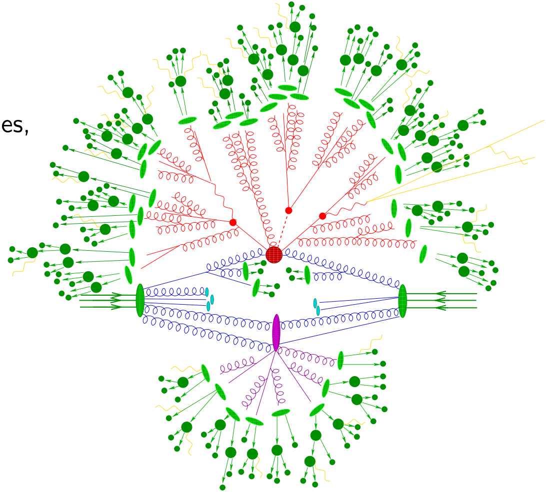
A hadron collider event

Event structure

Factorise into event stages according to characteristic scales, use relevant approximation in each regime

- Hard scattering
- Parton evolution
- Multiple interactions
- Hadronisation
- Hadron decays
- QED corrections



Monte Carle event generation: Introduction II

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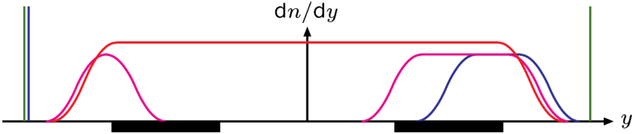
1. Multi-parton interactions
2. Hadronisation
3. Hadron decays & QED corrections
4. Analysis and tuning
5. Summary

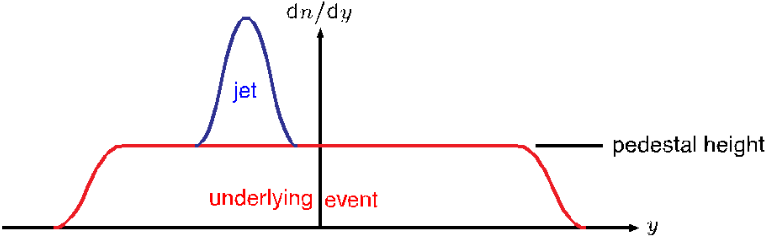
Classification

- Soft inclusive collision

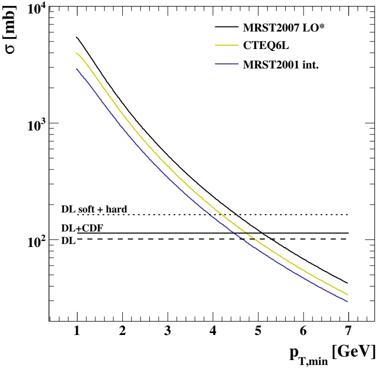
$\sigma_{\text{tot}} = \sigma_{\text{elastic}} + \sigma_{\text{single diffractive}} + \sigma_{\text{double diffractive}} + \sigma_{\text{non-diffractive}}$



- underlying event



Modelling the pedestal



Sjöstrand, van Zijl Phys.Rev.D36(1987)2019

- partonic cross sections diverge like $\mathrm{d}p_\perp^2/p_\perp^4$

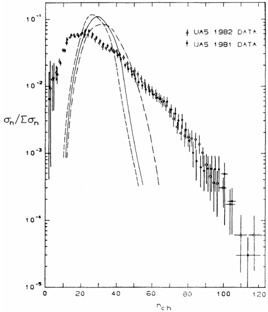
$\Rightarrow$ for small $p_\perp \approx 2 - 5$ GeV $\sigma_{\text{partonic}} > \sigma_{\text{non-diffractive}}$

- interprete as multiple hard scatters with

$$\langle n \rangle = \frac{\sigma_{\text{partonic}}(p_{\perp,\text{min}})}{\sigma_{\text{non-diffractive}}}$$

- main parameter is $p_{\perp,\text{min}}$, determines multiplicity $\langle n \rangle$

Modelling the pedestal



- simple model with

  $$\langle n\rangle = \frac{\sigma_{\text{partonic}}}{\sigma_{\text{non-diffractive}}}$$

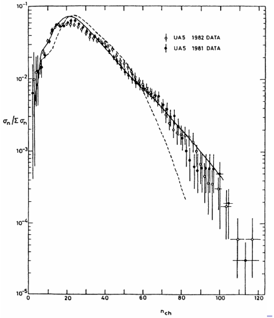
  gives wrong charged multi distribution
- incorporate hadron shape into prediction

$$\Downarrow$$

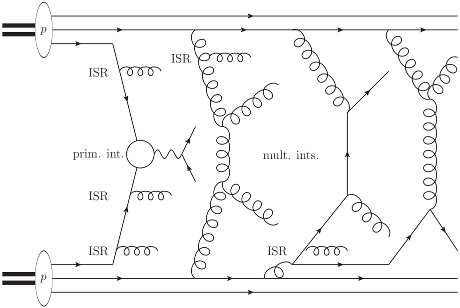
- various shape models to determine hadron-hadron overlap

  $$\langle n(b)\rangle = f_c f(b)\,\frac{\sigma_{\text{partonic}}}{\sigma_{\text{non-diffractive}}}$$

- hardness of the collision determines overlap



Combination with parton showers



- **naïve**: $\langle n(b) \rangle$ independent secondary interactions

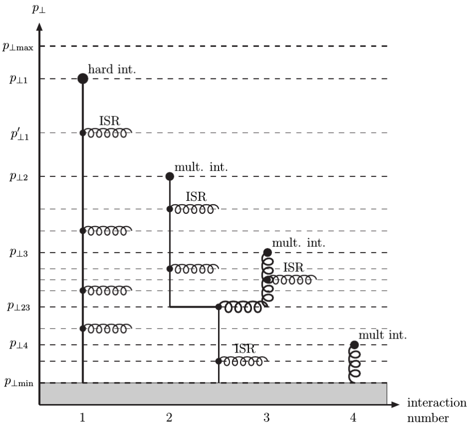
$\Rightarrow$ separation of perturbative picture of hard interaction

– no way to include rescattering

– completely seperate colour and momentum evolution

Combination with parton showers

Sjöstrand, Skands hep-ph/0408302



- **improvement**: interleaving
  - $\mathcal{P}_{\mathrm{MPI}}$ evolution kernel, combine w/ pert. IS evol.

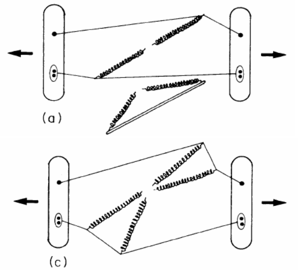
$$\mathcal{P} = \mathcal{P}_{\mathrm{ISR}} + \mathcal{P}_{\mathrm{MPI}}$$

⇒ interleaved colour and momentum structure, rescattering effects

– IS evolution not completely perturbative anymore

Colour connections and beam remnants

Sjöstrand, Skands hep-ph/0402078



- secondary scatterings need to be colour-connected to something
- simplest model would decouple them from proton remnants
- next-to-simplest model would put all scatters on one colour string

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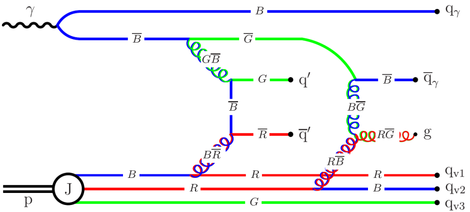
- embed scatters into existing topologies
- three options:
  - at random
  - rapidity ordered
  - minimal string length



A model for minimum bias collisions

Butterworth, Forshaw, Seymour hep-ph/9601371

Borozan, Seymour hep-ph/0207283

- Assume parton distribution within proton is

$$\frac{\mathrm{d}n_a(x,\mathbf{b})}{\mathrm{d}^2\mathbf{b}\,\mathrm{d}x} = f_a(x)\,G(\mathbf{b})$$

- Use electromagnetic form factor

$$G(\mathbf{b}) = \int \frac{\mathrm{d}^2\mathbf{k}}{(2\pi)^2}\,\frac{\exp(\mathbf{k}\cdot\mathbf{b})}{(1+\mathbf{k}^2/\mu^2)^2}$$

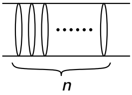
- EM measurements indicate $\mu = 0.71$ GeV,
  but left as free model parameter
- continue model below $p_{\perp,\mathrm{min}}$ with same b-space parametrisation, but cross section as Gaussian in $p_\perp$
  → inclusive non-diffractive events

Minimum bias as multiple pomeron scatterings

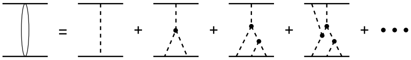
exploits optical theorem,
eikonal ansatz:

$$A_{\text{el}}(s,b) = i\left(1 - e^{-\Omega(s,b)/2}\right)$$

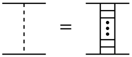
$$= i\sum_{n=1}^{\infty}$$



Khoze-Martin-Ryskin model:

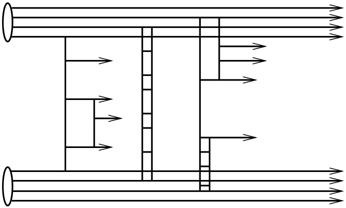


where



'gluon' ladder with effective vertices and propagators

- cut KMR diagrams to obtain differential total cross section



- allow for parton showering of final state legs
- hadronise

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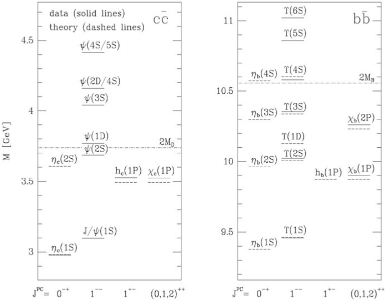
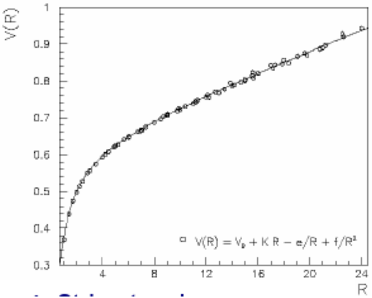
Confinement and interquark potential

- Hadronisation is QCD at low scales where α_s is $\mathcal{O}(1)$

$\Rightarrow$ non-perturbative dynamics, not easily calculable from first principles





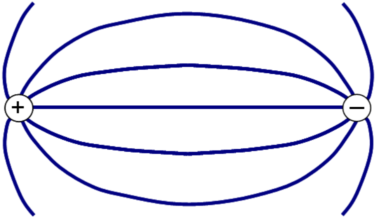
- measure QCD potential from quarkonia masses
- or calculate using lattice QCD

$\Rightarrow$ approximately linear potential

Confinement and interquark potential

- Hadronisation is QCD at low scales where α_s is $\mathcal{O}(1)$

⇒ non-perturbative dynamics, not easily calculable from first principles



QED dipole

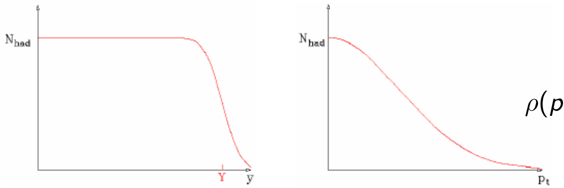
QCD dipole

⇒ formation of flux tubes in QCD

Feynman-Field model

Feynman, Field NPB136(1978)1

Experimental findings:



$$\rho(p_\perp^2) = \exp\left(-p_\perp^2/\sigma^2\right)$$

Realisation:

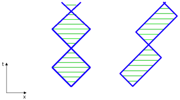
- recursively split $q \to q' +$ hadron
  - transverse momentum from fitted Gaussian
  - longitudinal momentum arbitrary (fitted to measurements)
  - flavour from symmetry arguments+measurements
- **problems:** frame dependent, "last quark", infrared safety, no link to perturbation theory

Lund string model

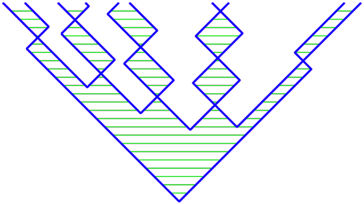
Andersson, Gustafson, Ingelman, Sjöstrand PR97(1983)31

- start with $e^+e^- \to q\bar{q}$
- QCD flux tube with constant energy per unit rapidity ↔ 
- new $q\bar{q}$-pairs by pair creation in the flux tube (κ-string tension)

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}x\mathrm{d}t} = \exp\left\{-\frac{\pi^2 m_q^2}{\kappa}\right\}$$

- expanding string breaks into hadrons, then yoyo modes 

- mesons as quark-antiquark pairs, baryons as quark-diquark pairs



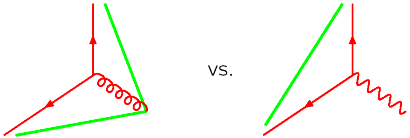
Lund string model

Andersson, Gustafson, Ingelman, Sjöstrand PR97(1983)31

- Lund string model very well motivated, but many parameters

⇒ gives genuine prediction of "string effect"

- strings span between quarks and anti-quarks, gluons form kinks in string
  → string accelerated in direction of gluon
- infrared safe matching to parton showers
  gluons with $k_\perp \lesssim 1/\kappa$ irrelevant



Cluster model

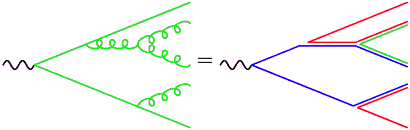
Webber NPB238(1984)492

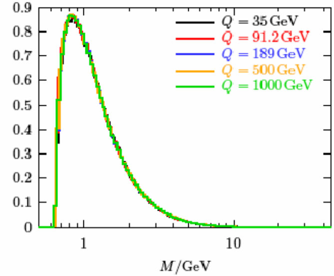
- underlying idea: preconfinement

⇒ follow colour structure of parton showers, colour singlets end up close in phase space

- singlet mass $\mathcal{O}(t_c)$

⇒ **primordial clusters** independent of collider energy





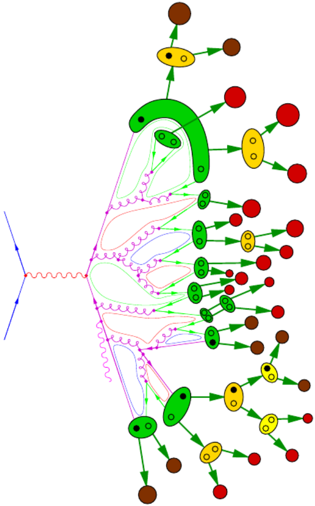
Cluster model

Naïve model:

- split gluons non-perturbatively into $q\bar{q}$-pairs
- colour-adjacent pairs form primordial clusters
- clusters decay into hadrons according to phase space → diquark & heavy quark production suppressed

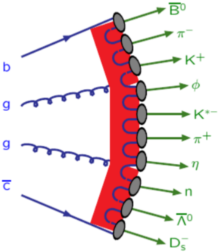
Improved model:

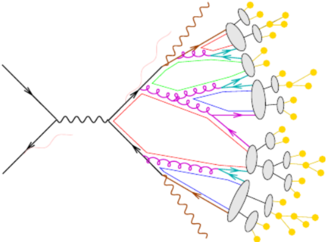
- heavy cluster decay first into lighter cluster, or radiate a hadron C→CC, C→CH, C→HH
- leading particle effects incorporated naturally



String vs cluster

Sjöstrand, Durham '09





program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

"There ain't no such thing as a parameter-free *good* description"

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Hadron decays

Manyfold task:

- Primordial hadrons are mostly unstable → will decay
- $>$ 1000 different decay channels
- vast amount of measured decay tables in PDG
- form factor models for many decays known

Problems:

- BR's in PDG decay tables have uncertainties and in many cases do not add up to one
- specifics of many decays are unknown

Non-trivial effects:

- significantly effects hadronisation yields, event shapes, etc.

Hadron decays: Many aspects

Example decay chain:

$$B^{*0} \to \gamma B^0$$

$$\to \bar{B}^0$$

$$\to e^- \bar{\nu}_e D^{*+}$$

$$\to \pi^+ D^0$$

$$\to K^- \rho^+$$

$$\to \pi^+ \pi^0$$

$$\to \gamma\gamma$$

Hadron decays: Many aspects

Example decay chain:

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$$\to \pi^+ \pi^0$$
$$\to \gamma\gamma$$

EM decay

Hadron decays: Many aspects

Example decay chain:

$$
\begin{aligned}
B^{*0} &\to \gamma B^0 \\
&\qquad \to \bar{B}^0 \\
&\qquad\quad \to e^- \bar{\nu}_e D^{*+} \\
&\qquad\qquad\quad \to \pi^+ D^0 \\
&\qquad\qquad\qquad\quad \to K^- \rho^+ \\
&\qquad\qquad\qquad\qquad\quad \to \pi^+ \pi^0 \\
&\qquad\qquad\qquad\qquad\qquad\quad \to \gamma\gamma
\end{aligned}
$$

Weak neutral meson mixing

Hadron decays: Many aspects

Example decay chain:

$$
\begin{aligned}
B^{*0} \to \gamma B^0 & \\
& \to \bar{B}^0 \\
& \quad \to e^- \bar{\nu}_e D^{*+} \\
& \qquad \to \pi^+ D^0 \\
& \qquad\quad \to K^- \rho^+ \\
& \qquad\qquad \to \pi^+ \pi^0 \\
& \qquad\qquad\quad \to \gamma\gamma
\end{aligned}
$$

Weak decay, three body with form factor models

Hadron decays: Many aspects

Example decay chain:

$$
\begin{aligned}
B^{*0} \to \gamma B^0 & \\
& \to \bar{B}^0 \\
& \quad \to e^- \bar{\nu}_e D^{*+} \\
& \qquad \to \pi^+ D^0 \\
& \qquad\quad \to K^- \rho^+ \\
& \qquad\qquad \to \pi^+ \pi^0 \\
& \qquad\qquad\quad \to \gamma\gamma
\end{aligned}
$$

Strong decay

Hadron decays: Many aspects

Example decay chain:

$$
\begin{aligned}
B^{*0} \to \gamma B^0 & \\
& \to \bar{B}^0 \\
& \quad \to e^- \bar{\nu}_e D^{*+} \\
& \qquad \to \pi^+ D^0 \\
& \qquad\quad \to K^- \rho^+ \\
& \qquad\qquad \to \pi^+ \pi^0 \\
& \qquad\qquad\quad \to \gamma\gamma
\end{aligned}
$$

Weak decay, ρ mass smearing $\Gamma \sim m$

Hadron decays: Many aspects

Example decay chain:

$$
\begin{aligned}
B^{*0} &\to \gamma B^0 \\
&\qquad \to \bar{B}^0 \\
&\qquad\quad \to e^- \bar{\nu}_e D^{*+} \\
&\qquad\qquad \to \pi^+ D^0 \\
&\qquad\qquad\quad \to K^- \rho^+ \\
&\qquad\qquad\qquad \to \pi^+ \pi^0 \\
&\qquad\qquad\qquad\quad \to \gamma\gamma
\end{aligned}
$$

ρ polarised, angular correlations

Hadron decays: Many aspects

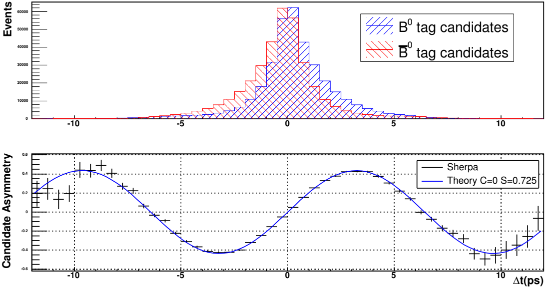
Example decay chain:

$$\begin{aligned}
B^{*0} &\to \gamma B^0 \\
&\qquad\to \bar{B}^0 \\
&\qquad\qquad\to e^- \bar{\nu}_e D^{*+} \\
&\qquad\qquad\qquad\to \pi^+ D^0 \\
&\qquad\qquad\qquad\qquad\to K^- \rho^+ \\
&\qquad\qquad\qquad\qquad\qquad\to \pi^+ \pi^0 \\
&\qquad\qquad\qquad\qquad\qquad\qquad\to \gamma\gamma
\end{aligned}$$

EM decay

Hadron decays

- previous generation of generators relied on external packages for most important decays: EVTGEN (B-decays) & TAUOLA (τ-decays)
- HERWIG++ & SHERPA contain in-built modules with at least as good a description including spin-correlations and neutral meson mixing
- no interfacing issues as complete information can be passed internally

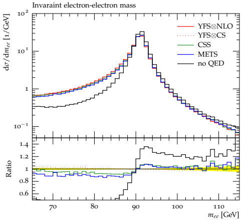


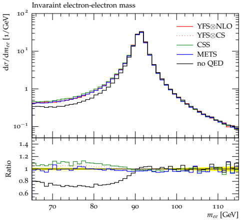
QED corrections

- previous generation of generators relied on external package for QED corrections: PHOTOS
- HERWIG++ & SHERPA contain in-built modules with at least as good a description including higher order corrections and preserving spin-correlations,

→ both employ YFS-type soft photon resummation

- no interfacing issues as complete information can be passed internally





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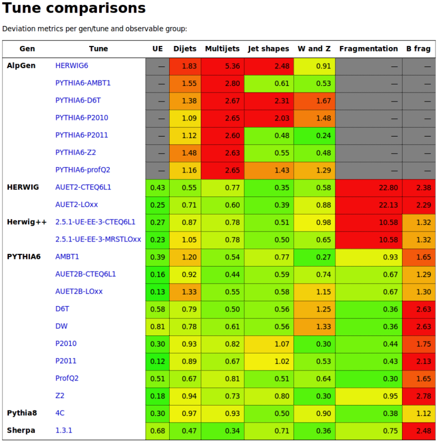
Analysis and tuning

RIVET Buckley et.al. arXiv:0103.0694

- LHC successor to HZTOOL collection of exp. data & corresponding analyses
- spirit: "right MC describes everything simultanously"

PROFESSOR Buckley et.al. arXiv:0907.2973

- tuning in multi-dimensional model parameter space
- calculate observables at random parameter points
- parametrise to approximate generator response for each observable (bin)
- find parameter point of min. χ^2



Tune comparisons

Deviation metrics per gen/tune and observable group:

Gen	Tune	UE	Dijets	Multijets	Jet shapes	W and Z	Fragmentation	B frag
AlpGen	HERWIG6	—	1.83	5.36	2.48	0.91	—	—
	PYTHIA6-AMBT1	—	1.55	2.80	0.61	0.53	—	—
	PYTHIA6-D6T	—	1.38	2.67	2.31	1.67	—	—
	PYTHIA6-P2010	—	1.09	2.65	2.03	1.48	—	—
	PYTHIA6-P2011	—	1.12	2.60	0.48	0.24	—	—
	PYTHIA6-Z2	—	1.48	2.63	0.55	0.48	—	—
	PYTHIA6-profQ2	—	1.16	2.65	1.43	1.29	—	—
HERWIG	AUET2-CTEQ6L1	0.43	0.55	0.77	0.35	0.58	22.80	2.38
	AUET2-LOxx	0.25	0.71	0.60	0.39	0.88	22.13	2.29
Herwig++	2.5.1-UE-EE-3-CTEQ6L1	0.27	0.87	0.78	0.51	0.98	10.58	1.32
	2.5.1-UE-EE-3-MRSTLOxx	0.23	1.05	0.78	0.50	0.65	10.58	1.32
PYTHIA6	AMBT1	0.39	1.20	0.54	0.77	0.27	0.93	1.65
	AUET2B-CTEQ6L1	0.16	0.92	0.44	0.59	0.74	0.67	1.29
	AUET2B-LOxx	0.13	1.33	0.55	0.58	1.15	0.67	1.30
	D6T	0.58	0.79	0.50	0.56	1.25	0.36	2.63
	DW	0.81	0.78	0.61	0.56	1.33	0.36	2.63
	P2010	0.30	0.93	0.82	1.07	0.30	0.44	1.75
	P2011	0.12	0.89	0.67	1.02	0.53	0.43	2.13
	ProfQ2	0.51	0.67	0.81	0.51	0.64	0.30	1.65
	Z2	0.18	0.94	0.73	0.80	0.30	0.95	2.78
Pythia8	4C	0.30	0.97	0.93	0.50	0.90	0.38	1.12
Sherpa	1.3.1	0.68	0.47	0.34	0.71	0.36	0.75	2.48

LH'11 SM WG arXiv:1203.6803

Summary: MC event generators II

Lecture:

- low energy QCD calculated not from first priciples but using phenomenological models
  → many parameters, need tuning to data
- underlying event typically calculated as multiple parton interactions
- two models (string & cluster) for parton to hadron fragmentation
- hadron decays important, $\mathcal{O}(100)$ hadrons with $\mathcal{O}(1000)$ decay channels
- higher order QED corrections from first principles

Tutorial II:

- Matching & merging using PYTHIA8 & SHERPA

Thank you for your attention!