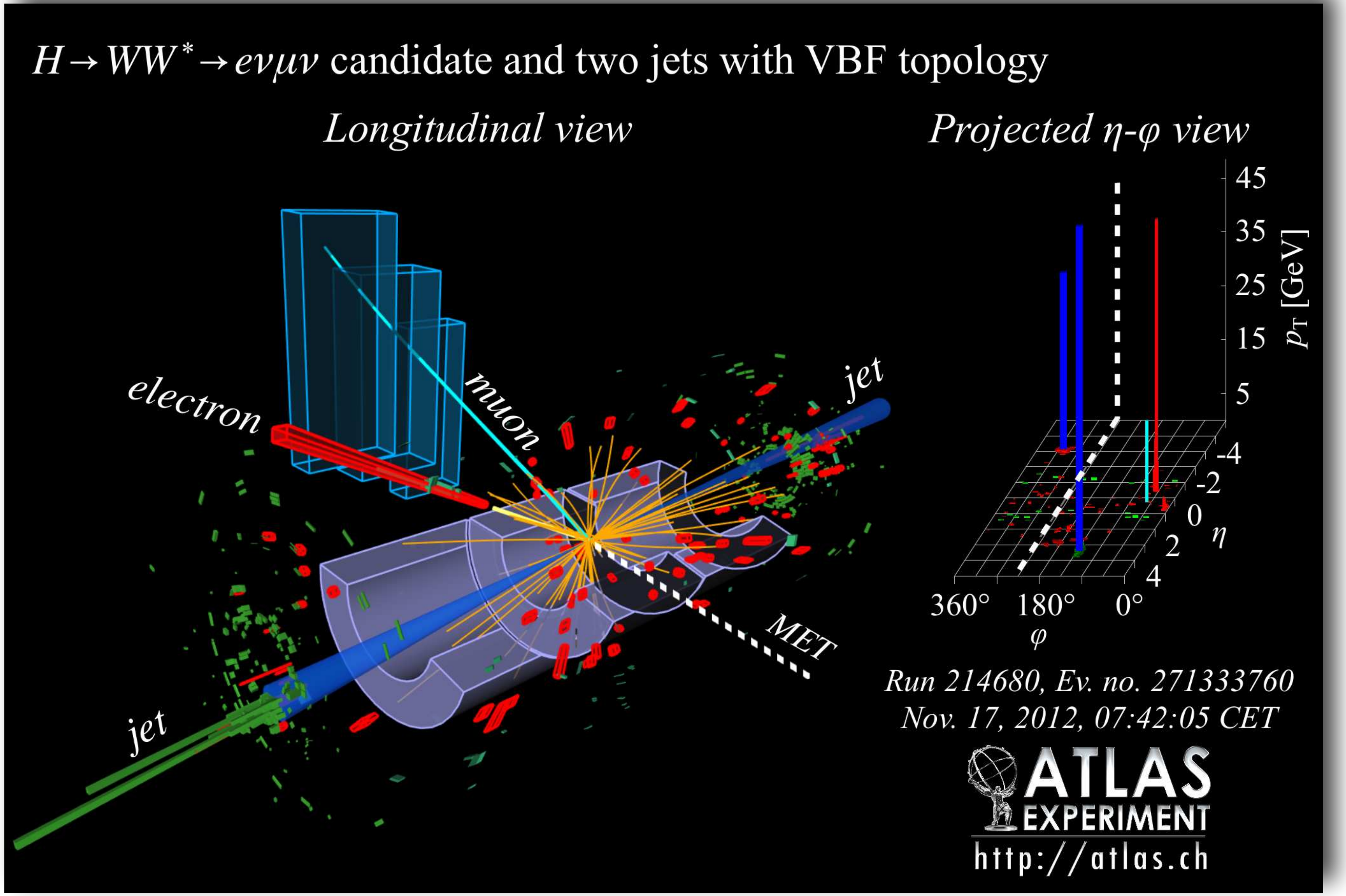
# Monte Carlo Generators at colliders

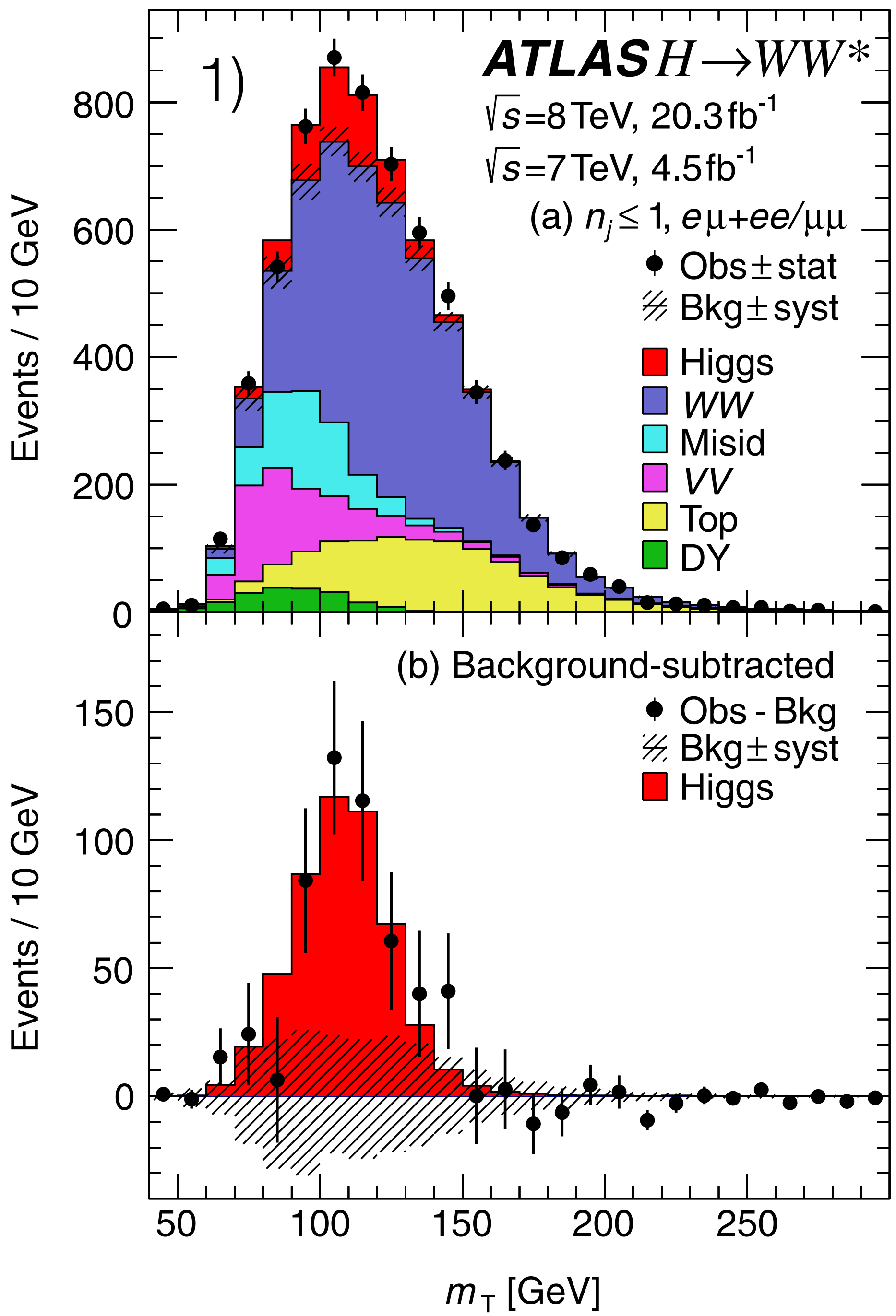
## High energy physics simulation



# Acknowledgements

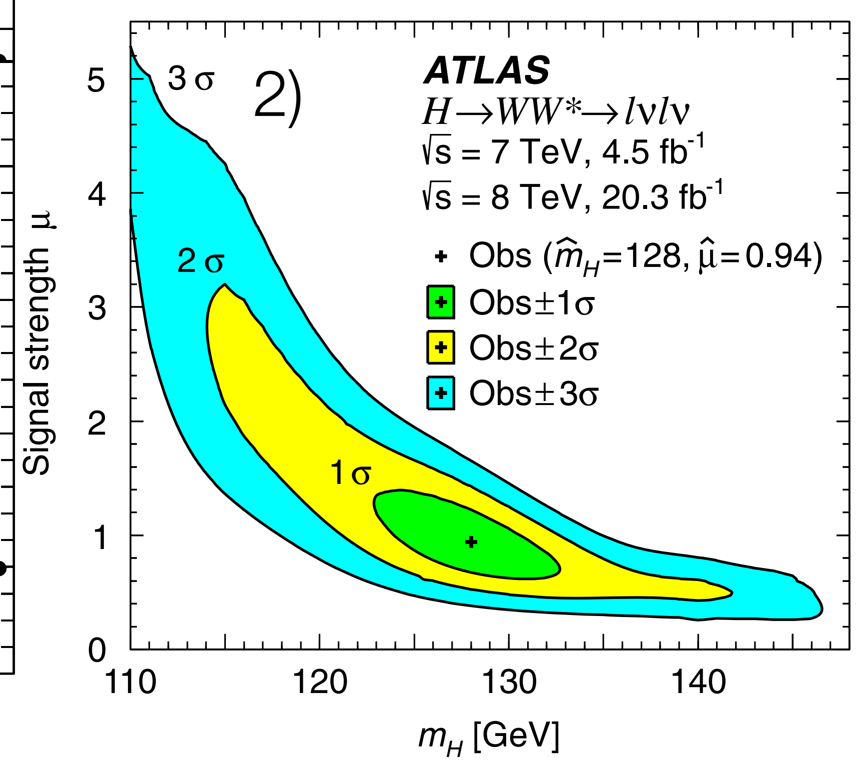
These slides have been prepared using heavily the material prepared by Christian Schultz Coulon and clarifying few points plus updating to recent developments in proton-proton physics.

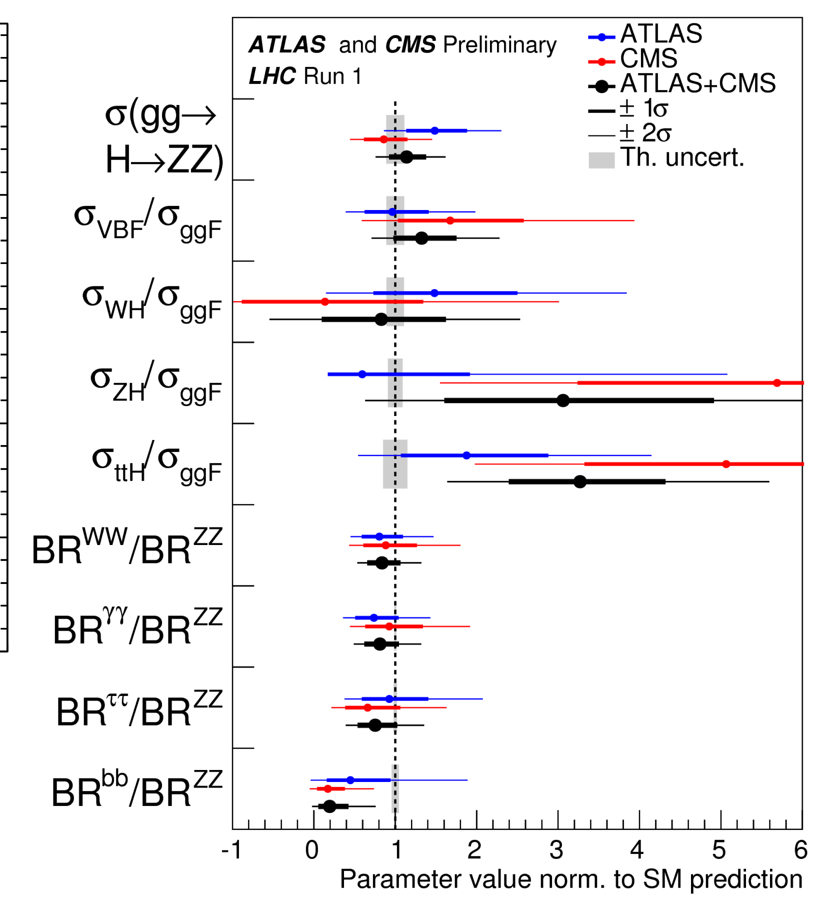
# Why MC simulation?




1) to extract an interesting signal we need to subtract the expectation from known processes;

2) signal needs also to be modelled in order to compute detection efficiency and estimate production cross sections and couplings

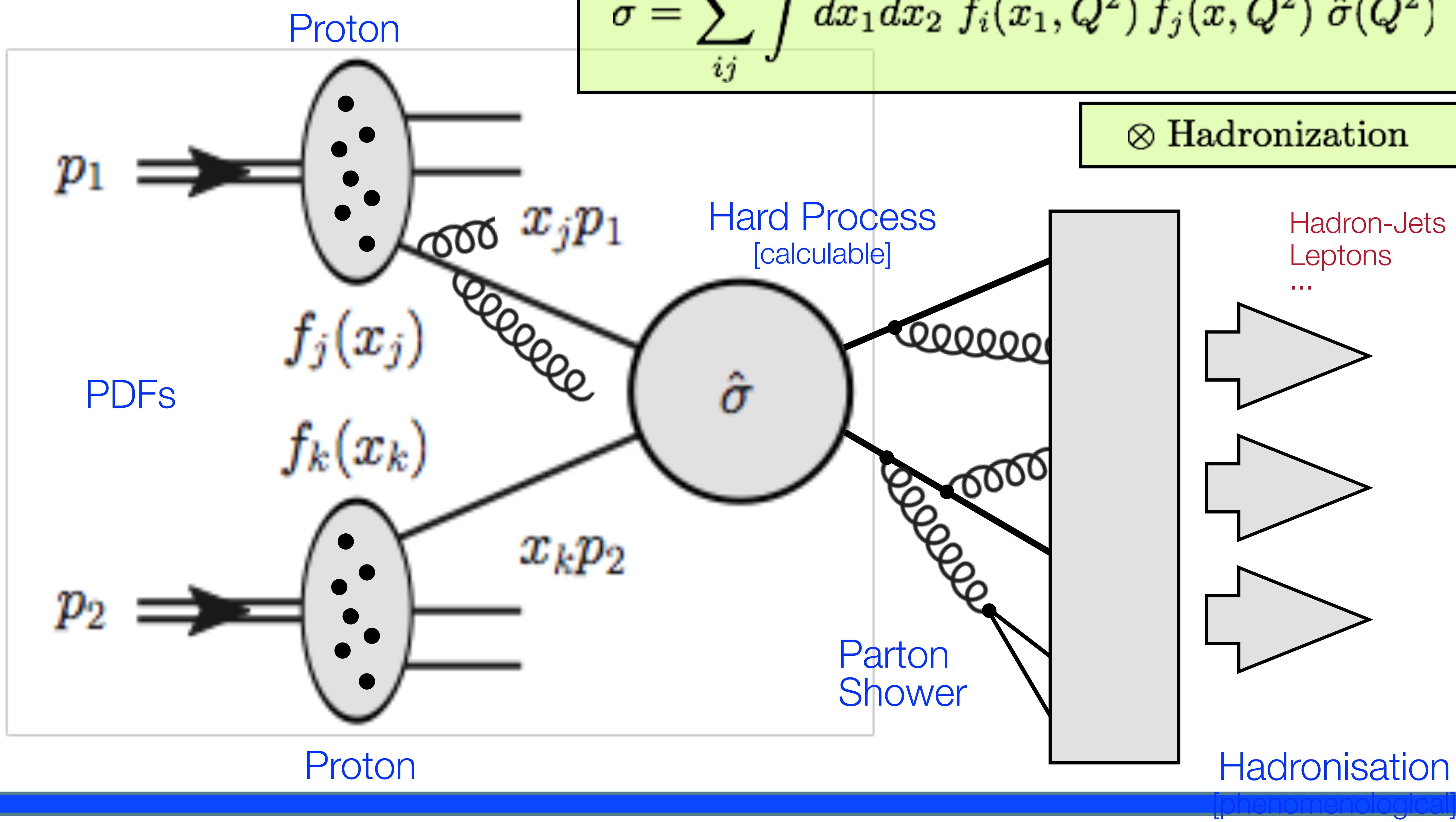


# The simulation chain

$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2)\, f_j(x, Q^2)\, \hat{\sigma}(Q^2)$$

$\otimes$ **Hadronization**



# MC simulations in particle physics

How Monte Carlo simulation works

- Numerical process generation based on random numbers
- Very powerful method in particle physics

**Event Generator**
simulate physics process
(quantum mechanics: probabilities!)

**Detector Simulation**
simulate interaction with detector material

**Digitisation**
translate interactions with detector into realistic signals

**Reconstruction/Analysis**
as for real data

**Event generation programs:**

**Pythia Herwig, Sherpa…**

**Hard partonic subprocess + fragmentation and hadronisation ...**

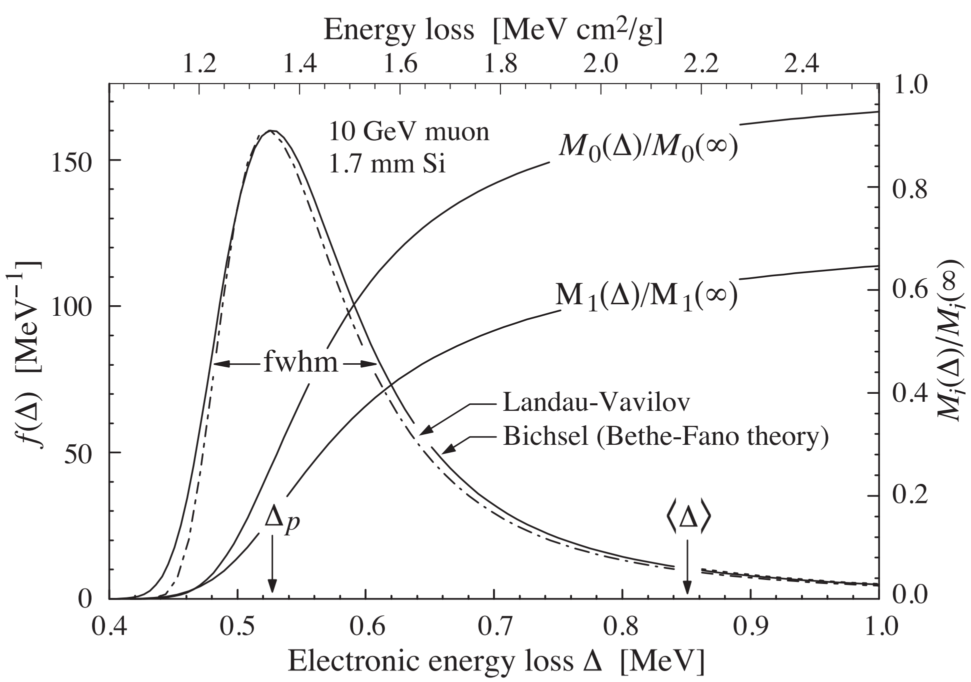
**Detector simulation:**

**Geant4**
**Fluka low energy hadron interactions…**

**interaction & response of all produced particles ...**

# Baseline of the simulation process

Typically, we need to generate a continuous variable following some distribution
i.e. energy loss of a particle in a given material segment;
angle of a photon in the h reference frame for the $h \rightarrow \gamma\gamma$ decay

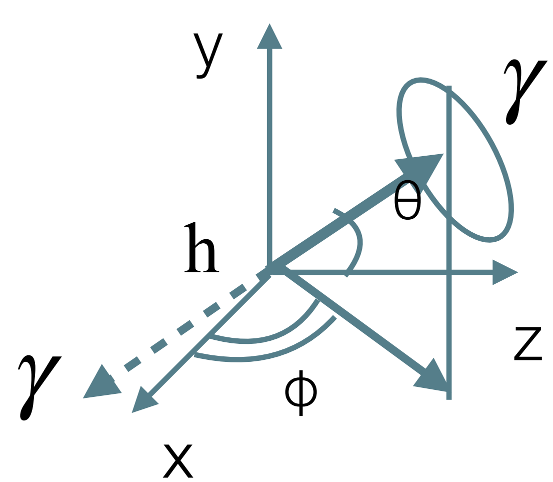



$$dP = f(x, ..)dx$$

distribution formula

probability to get an $x_0$ value between x and x+dx

if we want to simulate flat angular in 3D, that is uniform distribution on a sphere of radius 1:




$$dP = kdS = kd\Omega = ksin(\theta)d\theta d\phi$$

$$dP = f(\theta, \phi)d\theta d\phi = ksin(\theta)d\theta d\phi$$

$$f(\theta, \phi) = ksin(\theta)$$

flat distribution in ϕ
not flat in θ

# Distribution function transformation properties

1) software libraries provide basic functions to produce flat distributed random numbers in the interval [0,1] (ex. root TRandom3 class), they are typically fast and accurate uniform random numbers generators;
2) starting from uniform distributed random numbers, it is possible to generate numbers following any distribution using different techniques

$$dP_x = f(x)dx \qquad y = g(x)$$

$$x \in [x_a, x_b]$$

g(x) is a monotonic function of x
How "y" distributes in [g($x_a$), g($x_b$)]?

Because y is a monotonic function of x the probability to have y between g(x) and g(x+dx) is equal to the probability to have x between x and x+dx

$$dP_y = h(y)dy = h(y)g'(x)dx$$

$$dP_x = dP_y \qquad h(y)g'(x) = f(x) \Rightarrow h(y) = \frac{f(x)}{g'(x)} = \frac{f(g^{-1}(y))}{g'(g^{-1}(y))}$$

Ex1.: range map

$$[0,1] \to [a,b] \qquad y = (b-a)x + a$$

$$f(x) = 1 \quad g'(x) = b - a \quad h(y) = \frac{1}{b-a}$$

uniform

y is uniformly distributed in [a,b]

# Distribution function transformation properties

Ex. 2: integration method: we want to generate a distribution f(x) knowing that y is flat distributed, we want to find the transformation $g^{-1}(y)$ that allows it:

$$y = g(x) = \frac{1}{\int_a^b f(x')dx'} \int_a^x f(x')dx' \qquad g'(x) = \frac{f(x)}{\int_a^b f(x')dx'}$$

$$h(y) = \frac{f(x)}{g'(x)} = \frac{f[g^{-1}(y)]}{f[g^{-1}(y)]} \cdot \int_a^b f(x')dx' = \int_a^b f(x')dx'$$

y is flat distributed:

1) generate y flat in $[f_{min}, f_{max}]$;
2) compute $x = g^{-1}(y)$, x will be distributed in $g^{-1}(f_{min})$, $g^{-1}(f_{max})$

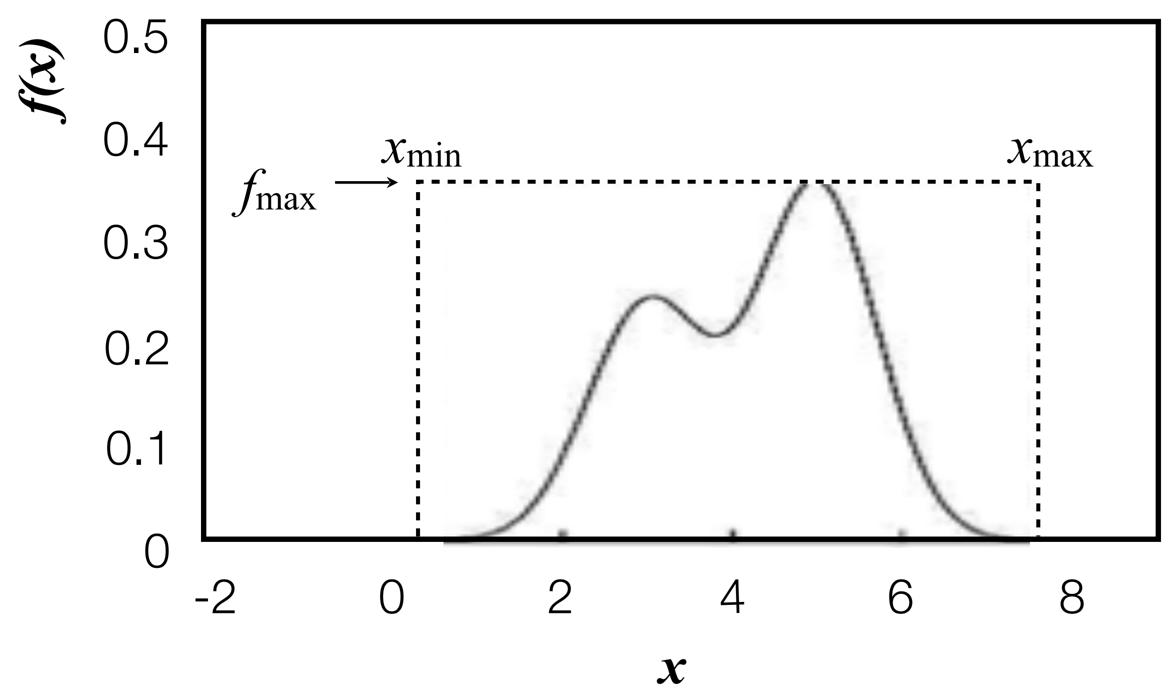
Finding $g^{-1}(y)$ is equivalent to solve the equation:

$$\frac{1}{\int_a^b f(x')dx'} \int_a^x f(x')dx' = y$$

often it can be done analytically
in general it can be solved numerically

# Hit or miss method.

1) generate x flat in $x_{min}$, $x_{max}$
2) generate y flat in 0, $f_{max}$
3) if y < f(x) accept the event, otherwise ignore it




for a given $x_0$ in x, x+dx the fraction of accepted events is proportional to f(x)dx -> dPx = f(x)dx

1) advantages:

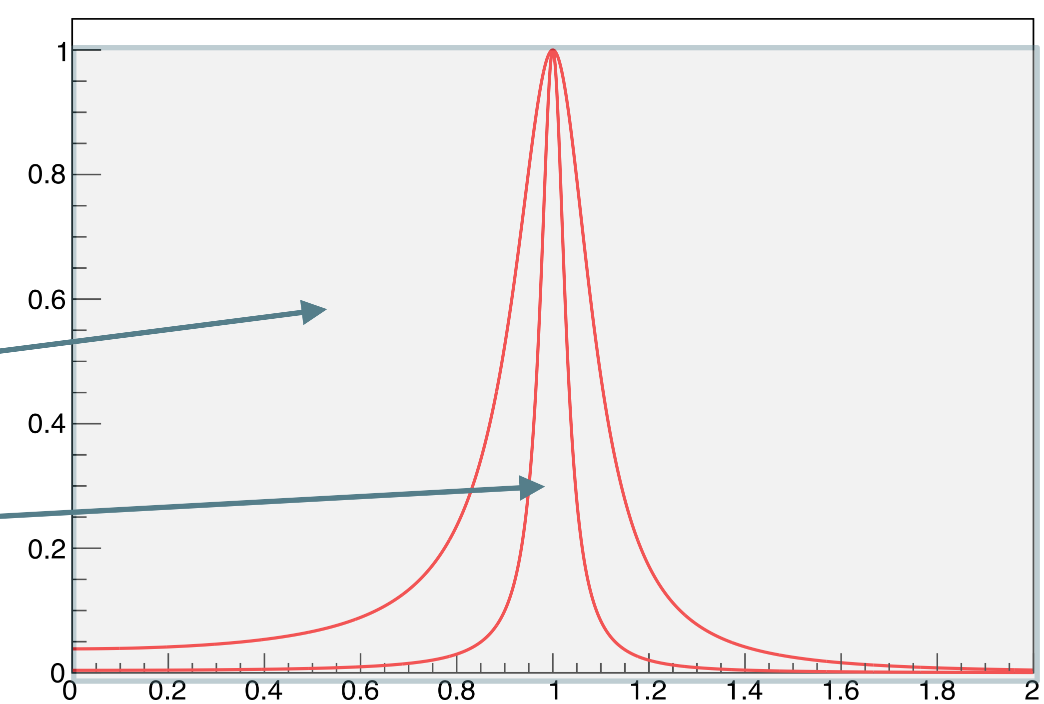
- can be used for all functions …
- can be extended to N-dimension (generate $x_1, x_2, \ldots, x_n$), y accept if $y < f(x_1, x_2, .., x_n)$

2) disadvantages

- can be extremely slow

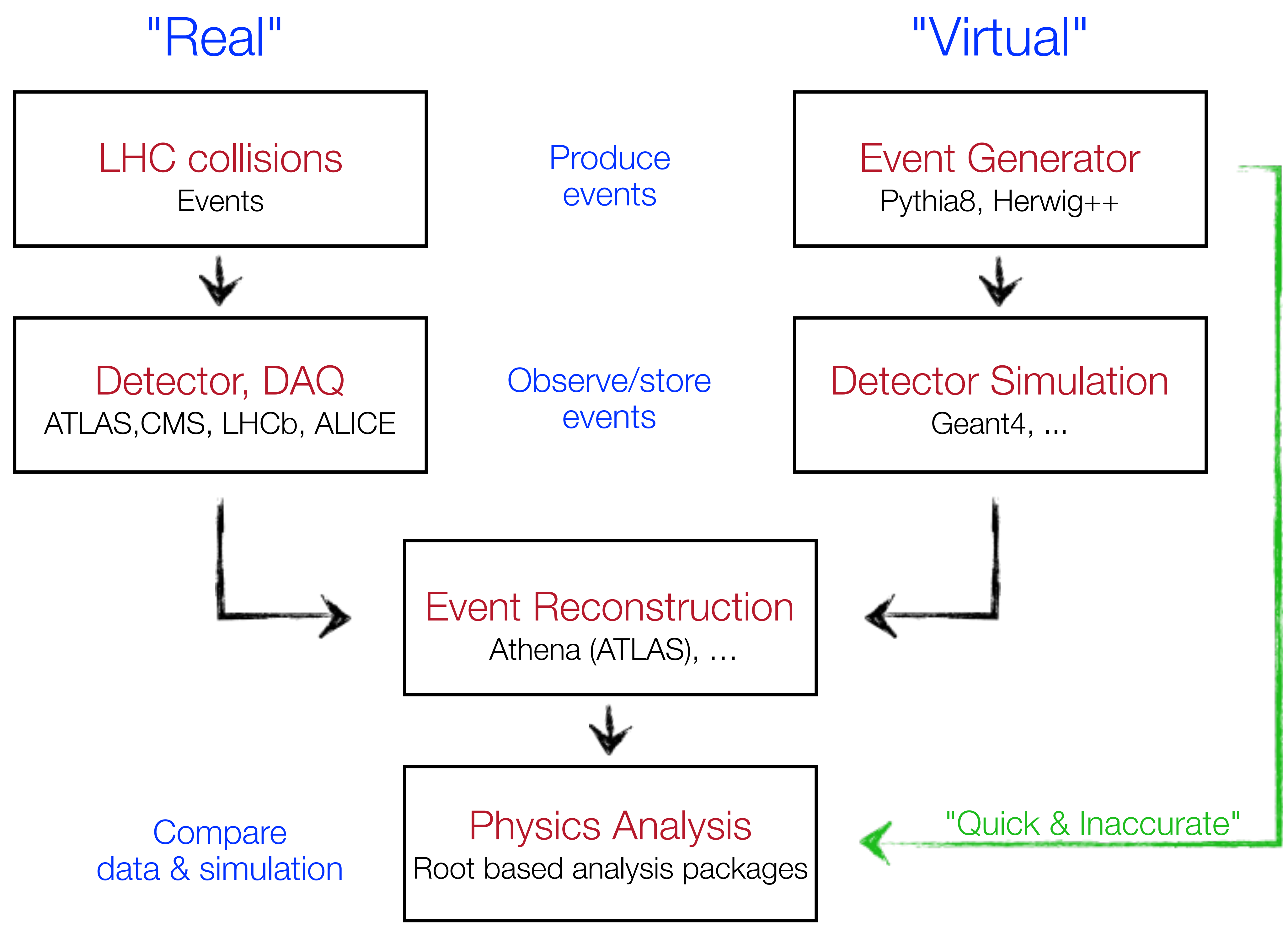
points generated uniformly in the square

points accepted only below the curve

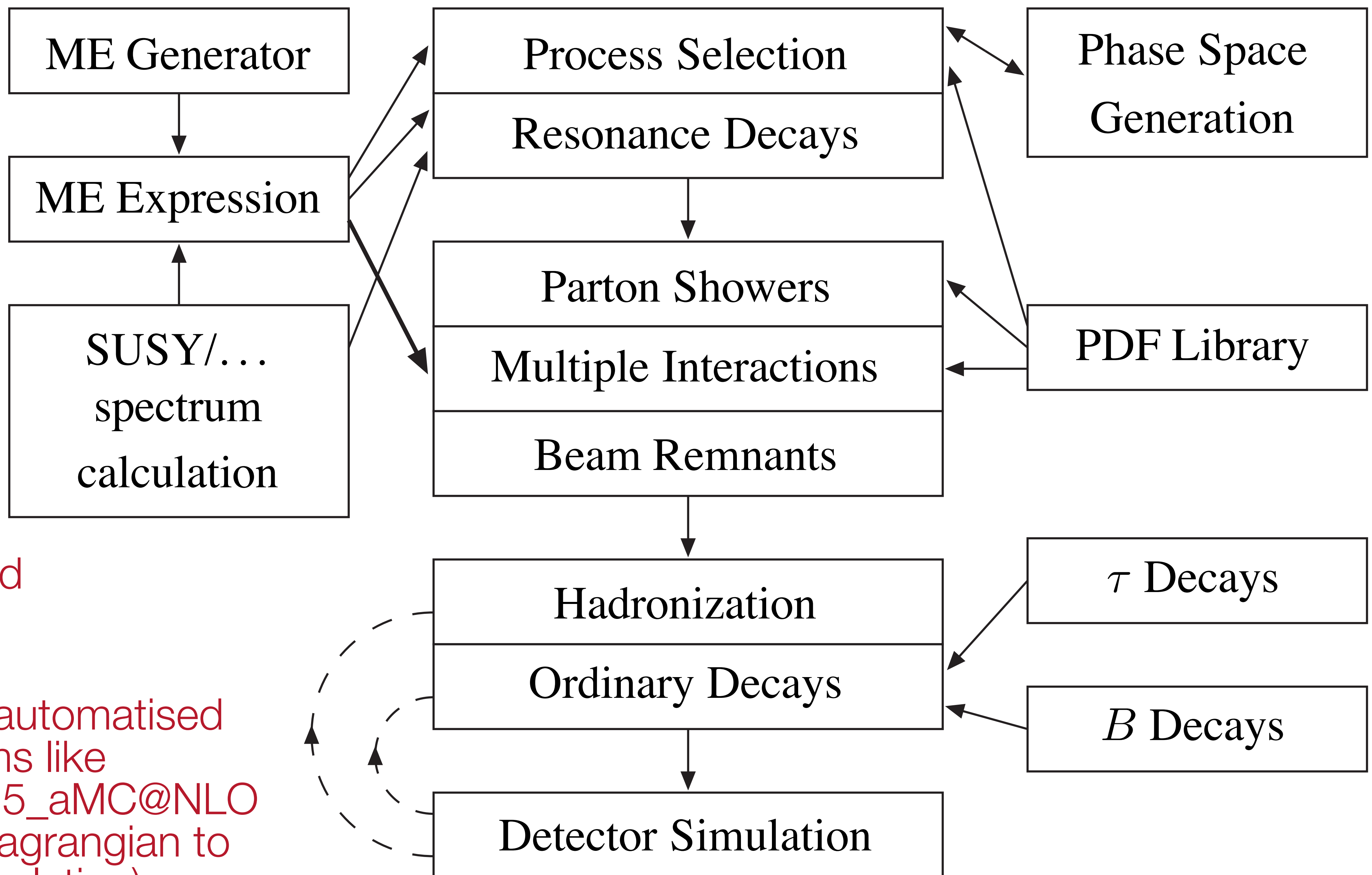



MC generators implement “smart” generation techniques to increase efficiencies

# Comparison between real and simulated events



# Simulation elements



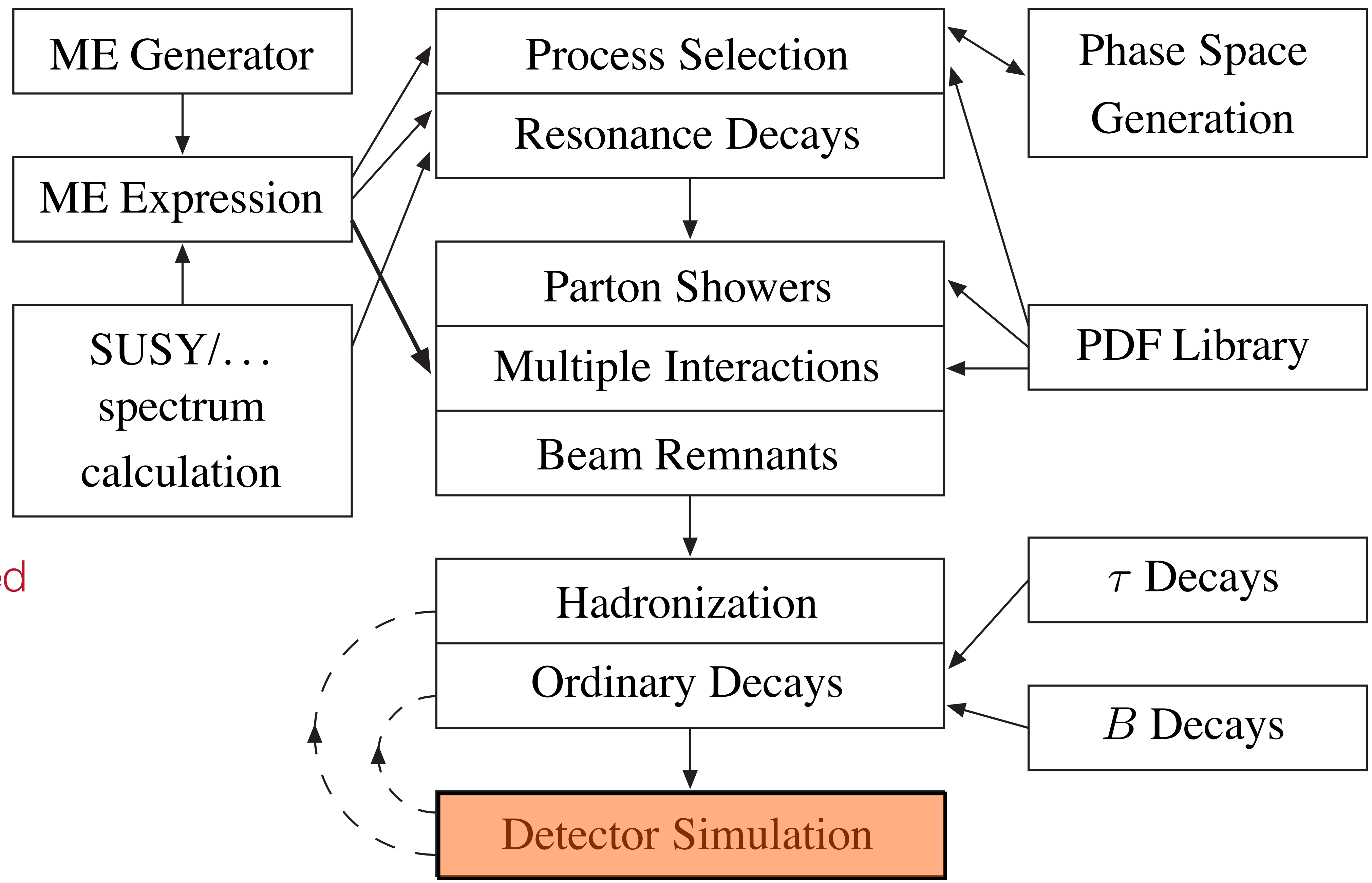

Use specialised programs

Now fully automatised in programs like Madgraph5_aMC@NLO (from the lagrangian to the full simulation)



[Sjöstrand, arXiv:hep-ph/0611247v1]

# Simulation elements



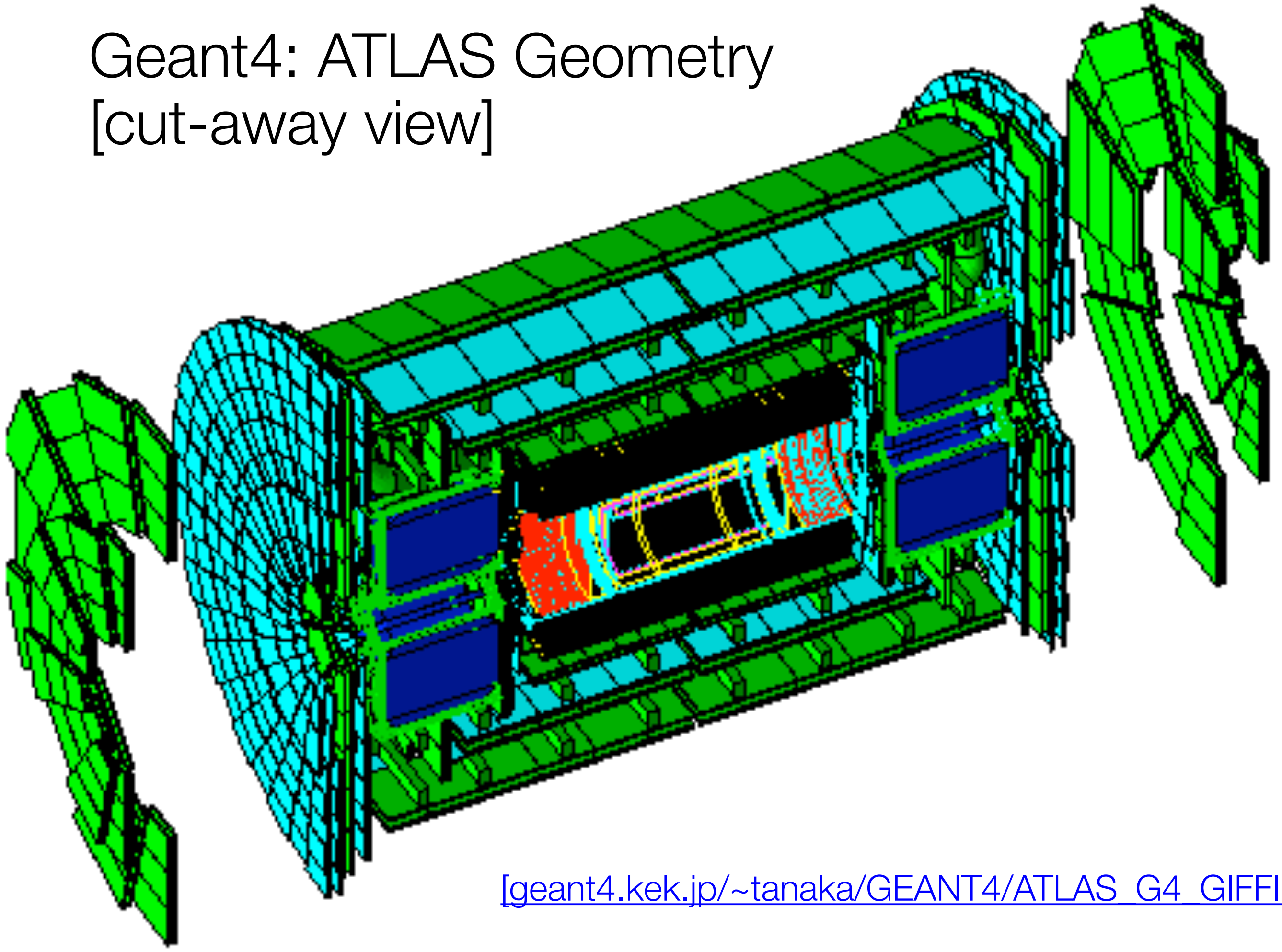

Use specialised programs



[Sjöstrand, arXiv:hep-ph/0611247v1]

# GEANT Geometry And Tracking

Geant4: ATLAS Geometry
[cut-away view]



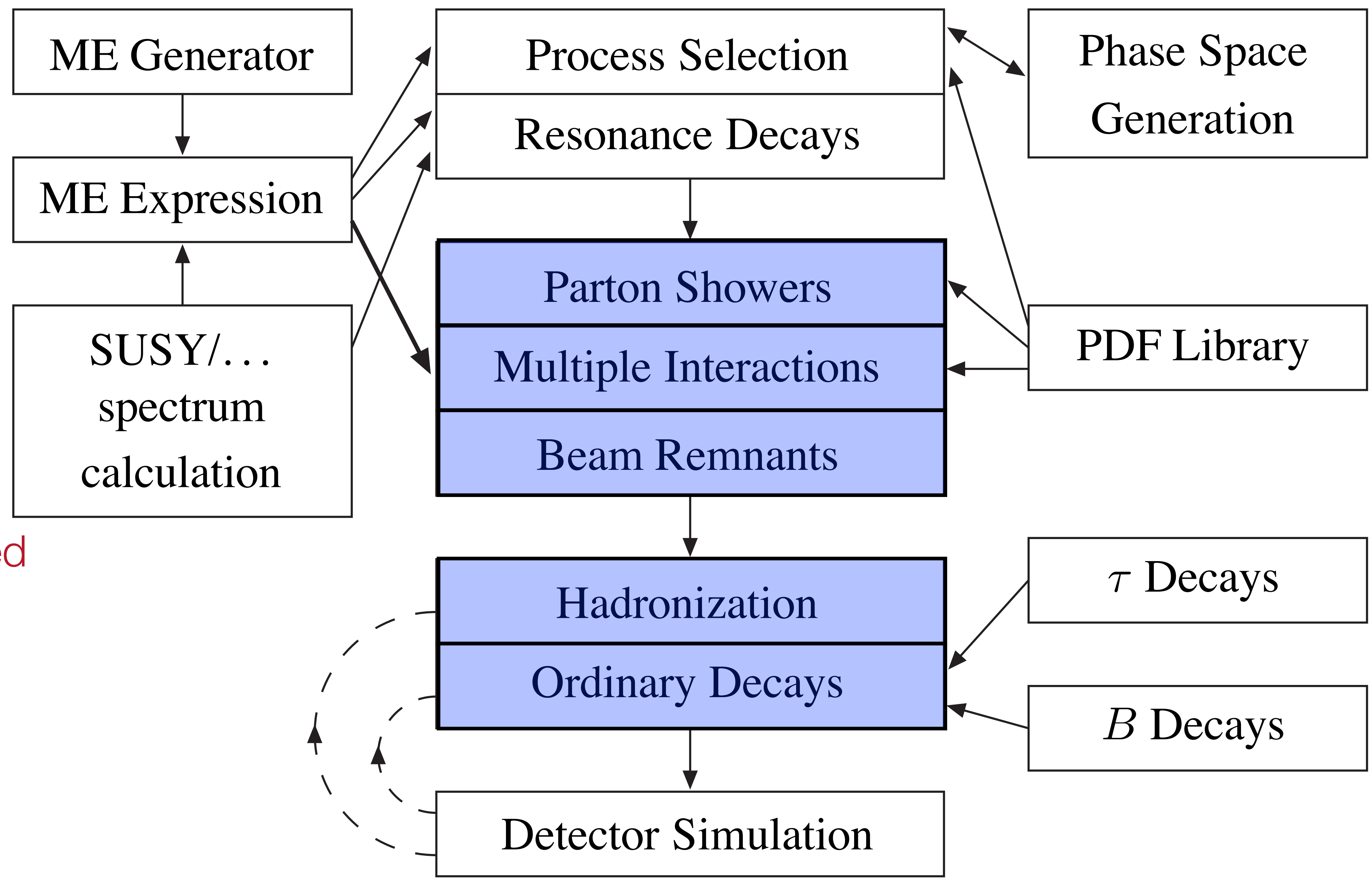
[geant4.kek.jp/~tanaka/GEANT4/ATLAS_G4_GIFFIG/]

Detailed description of detector geometry
[sensitive & insensitive volumes]

Tracking of all particles through detector material ...

➛ Detector response

Developed at CERN since 1974 (FORTRAN)
[Today: Geant4; programmed in C++]




Use
specialised
programs



[Sjöstrand, arXiv:hep-ph/0611247v1]

Strong interactions:

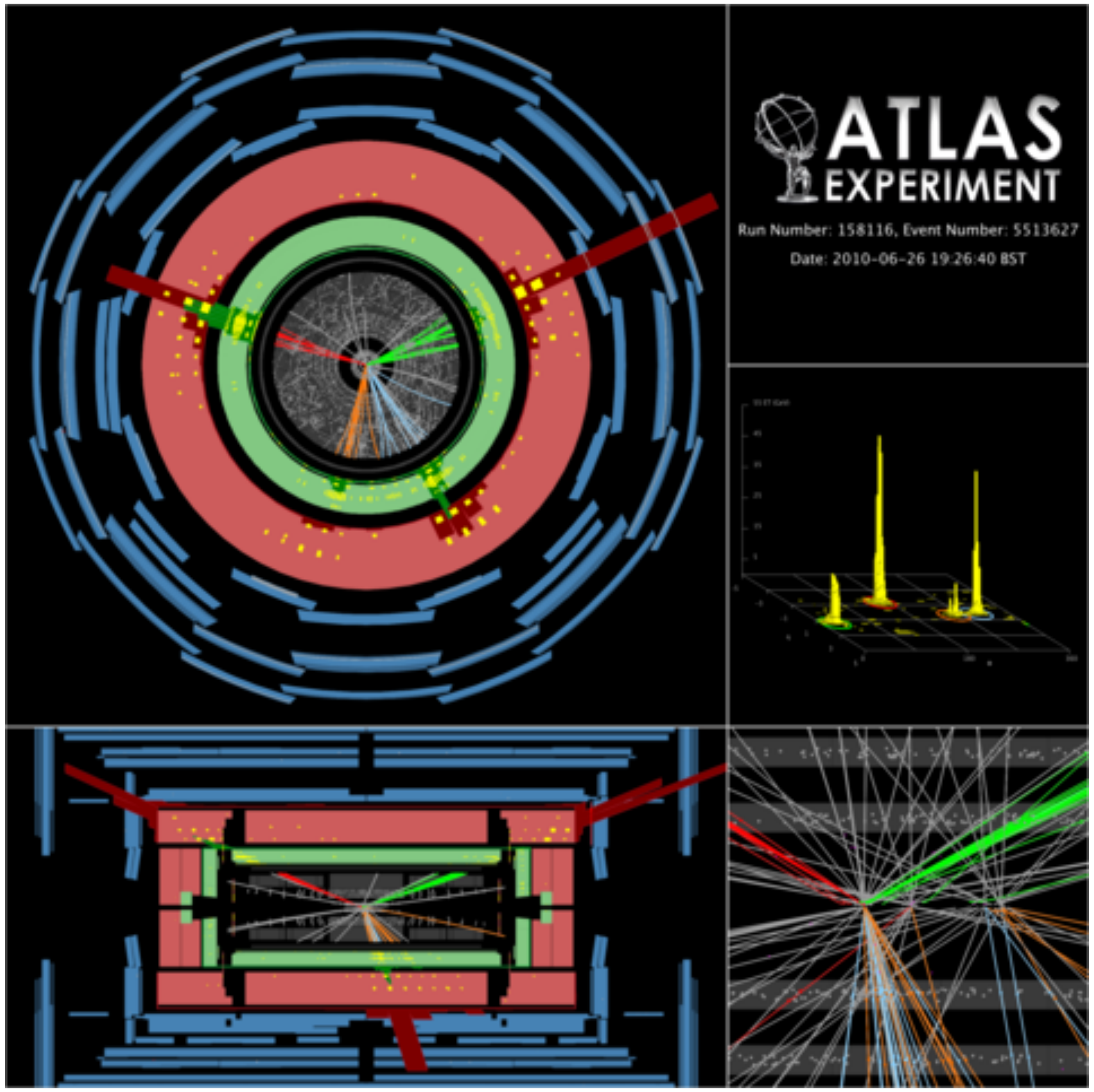
No free Quarks

Expect jets

i.e. bundles of particles at high energies
[hadron $p_T$ range limited w.r.t. initial parton]

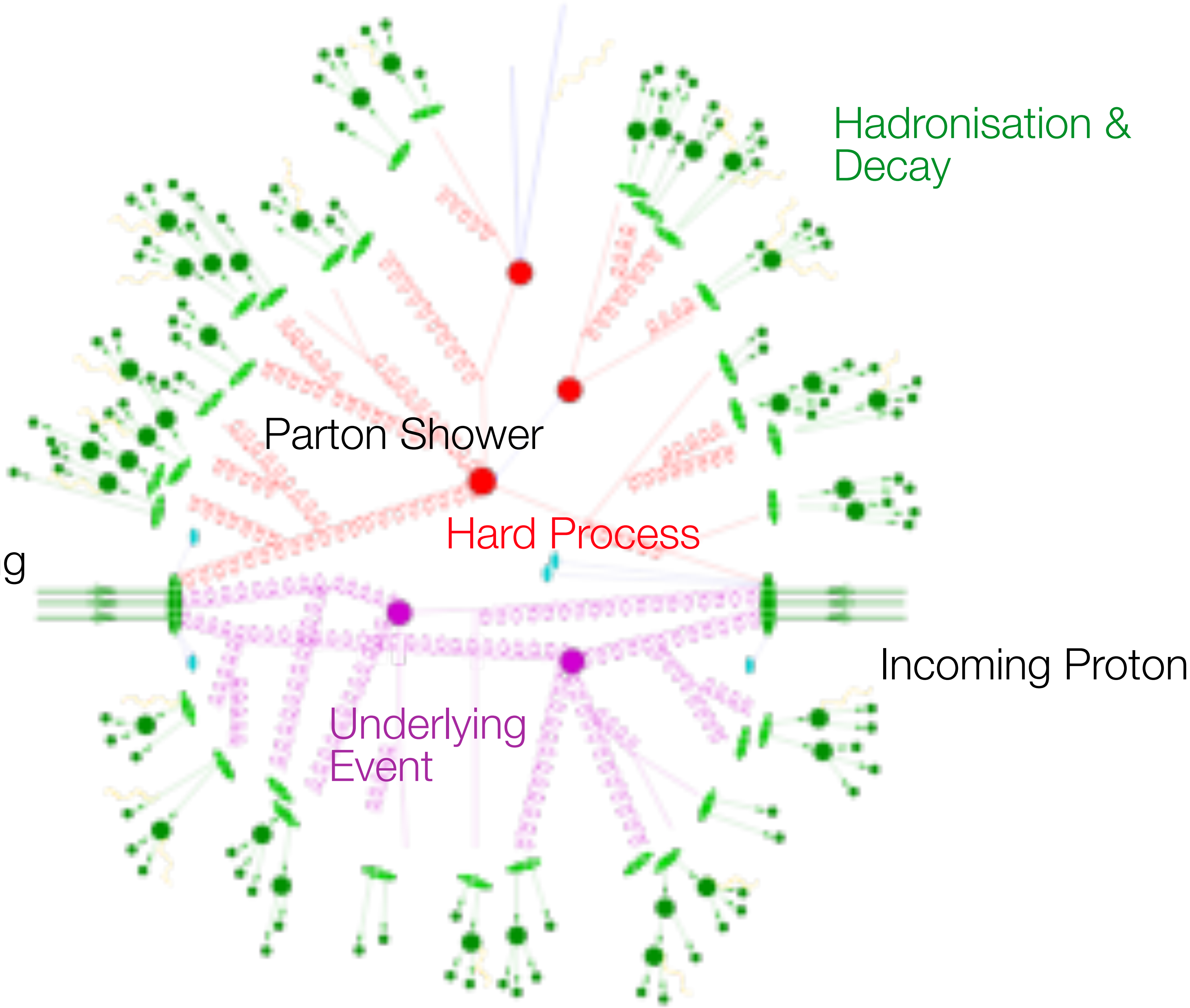
First observation of jets
in $e^+e^-$ collisions @ $E_{CMS}$ > 6 GeV
[SPEAR, SLAC, 1975]

Later also observed in
hadron-hadron collisions
[e.g. @ CERN ISR]




An event with 4 jets @ LHC

Goal: Infer parton properties from jet properties
[need to calculate and/or model fragmentation & hadronisation process]






[T. Gleisberg et al., JHEP02 (2004) 056]

# Possible simulation approaches

Pure matrix element (ME) simulation:

MC integration of cross section & PDFs, no hadronisation
(recall: cross section = |matrix element|$^2$ $\otimes$ phase space)

Useful for theoretical studies, no exclusive events generated

[Example: MCFM (http://mcfm.fnal.gov); many LHC processes up to NLO,
HNNLO (http://theory.fi.infn.it/grazzini/codes.html) Higgs production at NNLO]

Event generators:

Combination of ME and parton showers ...

Typical: generator for leading order ME
combined with leading log (LL) parton shower MC (see later)

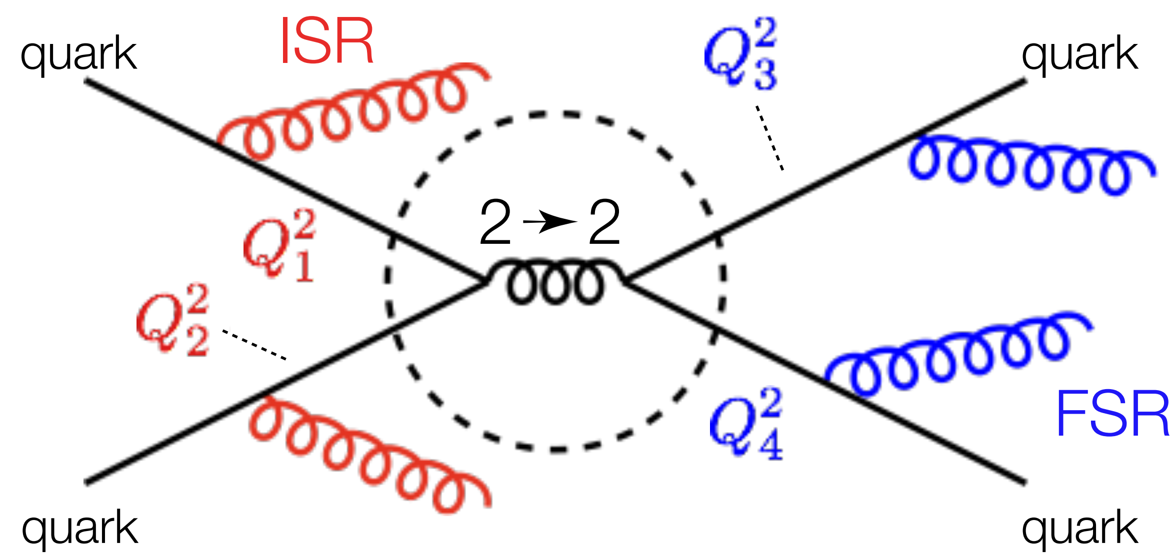
Exclusive events ➛ useful for experimentalists ...

# Parton showers

A realistic simulation needs many particles in the final state, it is quite difficult (sometimes impossible) to compute a pp (2) → many particles process

$$(2 \to n) = \ldots$$

$$\ldots = (2 \to 2) \oplus \text{ISR} \oplus \text{FSR}$$




FSR: Final state radiation

$Q^2 \sim p_{\text{quark in}}^2 \sim m^2 > 0$ decreasing

[time-like shower]

$$p_{\text{quark in}} = p_{\text{quark out}} + p_{\text{gluon}}$$

ISR: Initial state radiation

$Q^2 \sim p_{\text{quark out}}^2 \sim -m^2 > 0$ increasing

[space-like shower]

$$p_{\text{quark out}} = p_{\text{quark in}} - p_{\text{gluon}}$$

Calculable

Hard process [2 ➛ 2]:

$$\sigma = \iiint \mathrm{d}x_1\, \mathrm{d}x_2\, \mathrm{d}\hat{t}\; f_i(x_1, Q^2)\, f_j(x_2, Q^2)\, \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}\hat{t}}$$

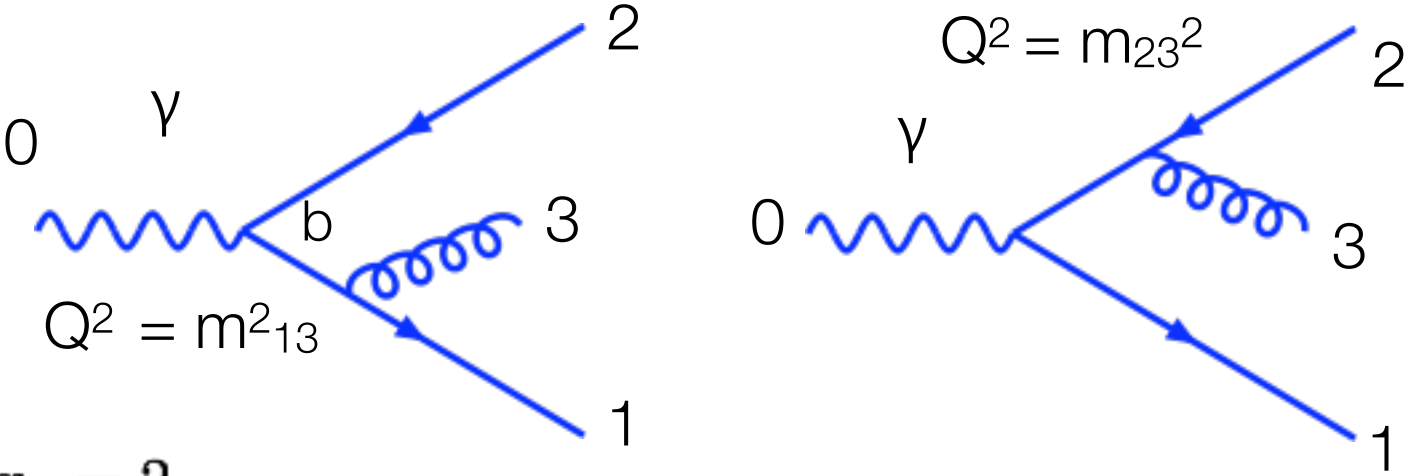
Shower evolution:

Viewed as probabilistic process, which occurs with unit total probability; cross section not directly affected; only indirectly via changed event shape.

[Sjöstrand, arXiv:hep-ph/0611247v1]

# Parton showers

$e^+e^- \to q\bar{q}g$




$$x_i = \frac{2E_i}{E_{\mathrm{cm}}} \qquad x_1 + x_2 + x_3 = 2$$

Cross Section: $$\frac{d\sigma_{\mathrm{qqg}}}{dx_1 dx_2} = \frac{4}{3}\frac{\alpha_s}{2\pi} \cdot \sigma_0 \cdot \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$

Cross section has large contributions for $x_1$, $x_2 \to 1$

[$m_q = 0$; see e.g. Halzen/Martin]

$$p_1 + p_2 + p_3 = (E_{\mathrm{cm}}, 0)$$

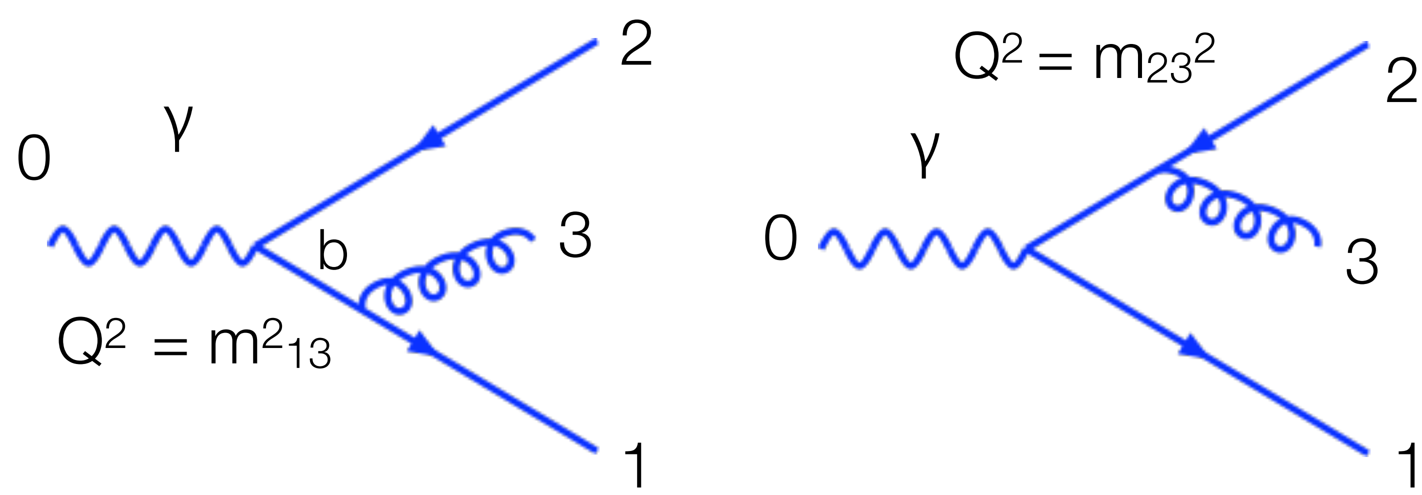
$$E_1 + E_2 + E_3 = E_{\mathrm{cm}}$$
$$\vec{p}_1 + \vec{p}_2 + \vec{p}_3 = 0$$

$$Q^2 = m_{13}^2 = (p_1 + p_3)^2 = (E_1 + E_3, \vec{p}_1 + \vec{p}_3)^2 = (E_{\mathrm{cm}} - E_2, -\vec{p}_2)^2 = E_{\mathrm{cm}}^2 + E_2^2 - 2E_{\mathrm{cm}}E_2 - |\vec{p}_2|^2$$

$$= E_{\mathrm{cm}}^2\left(1 - \frac{2E_2}{E_{\mathrm{cm}}}\right) + E_2^2 - |\vec{p}_2|^2 \qquad \Rightarrow \frac{Q^2}{E_{\mathrm{cm}}^2} = 1 - x_2$$

# gluon splitting

$e^+e^- \rightarrow qqg$




$$1 - x_2 = \frac{m_{13}^2}{E_{\rm cm}^2} = \frac{Q^2}{E_{\rm cm}^2}$$

$$m_{13}^2 = 2E_1E_3(1 - cos\theta) \quad x_2 \to 1 \Rightarrow m_{13}^2 \to 0 \Longrightarrow \theta \to 0$$ collinear limit

$$dx_2 = -\frac{dQ^2}{E_{\rm cm}^2}$$

Rewrite for $x_2 \rightarrow 1$: [qg collinear limit]

$$x_1 + x_2 + x_3 = 2$$

$$z = \frac{E_1}{E_b} = \frac{2E_1}{E_{\rm cm}} = x_1$$

$$E_q = E_1 = zE_b$$

$$E_b = E_1 + E_3 = \frac{E_{cm}}{2}(x_1 + x_3) = \frac{E_{\rm cm}}{2}(2 - x_2) = \frac{E_{\rm cm}}{2}$$

$$E_g = E_3 = (1 - z)E_b$$

$$d\mathcal{P} = \frac{d\sigma_{\rm qqg}}{\sigma_0} = \frac{4}{3}\frac{\alpha_s}{2\pi} \cdot \frac{dx_2}{(1 - x_2)} \cdot \frac{x_1^2 + x_2^2}{(1 - x_1)} dx_1 \approx \frac{\alpha_s}{2\pi} \cdot \frac{dQ^2}{Q^2} \cdot \frac{4}{3}\left[\frac{1 + z^2}{1 - z}\right] dz$$

$$dx_1 \approx dz$$

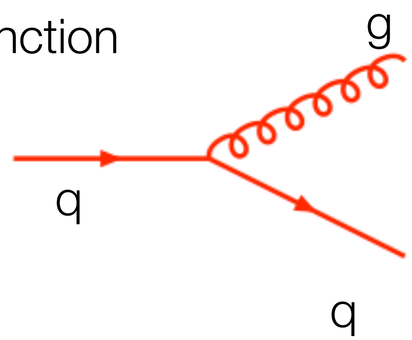
$$x_3 \approx 1 - z$$

$z \to 1 \Rightarrow E_g \to 0$ soft divergence

$$d\mathcal{P}_{a\to bc} = \frac{\alpha_s}{2\pi}\frac{dQ^2}{Q^2}P_{a\to bc}(z)dz$$

Splitting probability determined by splitting functions $P_{q\to qg}$

Splitting Function $P_{q\to qg}$




Analogous splitting functions used in PDF evolution

$$P_{q\to qg} = \frac{4}{3}\frac{1+z^2}{1-z}$$

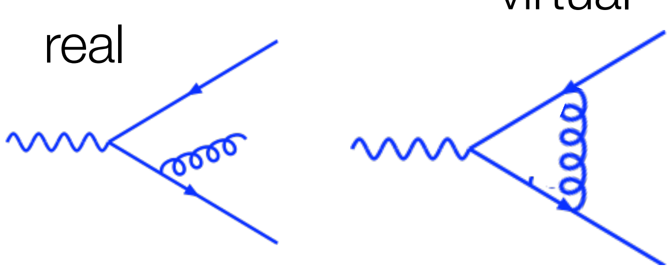
$$P_{g\to gg} = 3\frac{(1-z(1-z))^2}{z(1-z)}$$

$$P_{g\to q\bar{q}} = \frac{n_f}{2}(z^2+(1-z)^2)$$

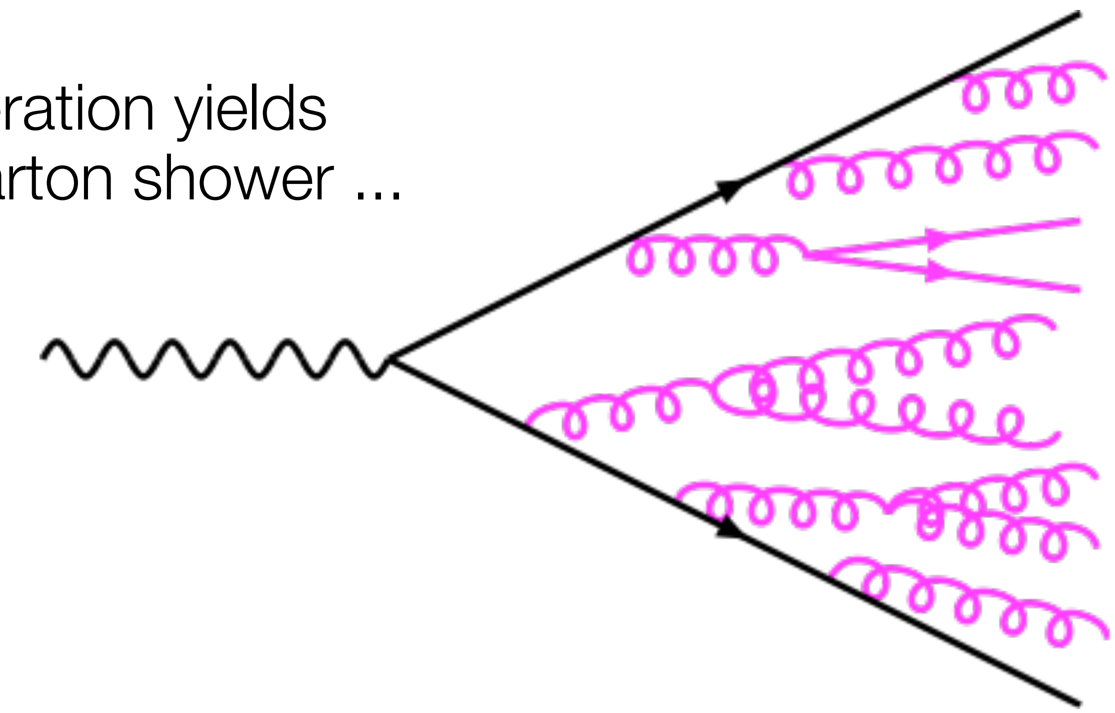
$z$ : fractional momentum of radiated parton

$n_f$ : number of quark flavours

In NLO calculations soft and collinear divergencies cancelled by virtual contributions: they persist in LO calculations.




Iteration yields parton shower ...



Need soft/collinear cut-offs to avoid non-perturbative regions ... [divergencies!]

Details model-dependent

e.g. $Q > m_0 = \min(m_{ij}) \approx 1$ GeV,
$z_{min}(E,Q) < z < z_{max}(E,Q)$ or
$p_\perp > p_{\perp min} \approx 0.5$ GeV

# Parton shower evolution 1

[Sjöstrand, arXiv:hep-ph/0611247v1]

Conservation of total probability:

$$\mathcal{P}(\text{nothing happens}) = 1 - \mathcal{P}(\text{something happens})$$

Time evolution:

$$\mathcal{P}_{\text{nothing}}(0 < t \le T) = \mathcal{P}_{\text{nothing}}(0 < t \le T_1)\, \mathcal{P}_{\text{nothing}}(T_1 < t \le T)$$

$$\begin{aligned}
\mathcal{P}_{\text{nothing}}(0 < t \le T) &= \lim_{n\to\infty} \prod_{i=0}^{n-1} \mathcal{P}_{\text{nothing}}(T_i < t \le T_{i+1}) \\
&= \lim_{n\to\infty} \prod_{i=0}^{n-1} \left(1 - \mathcal{P}_{\text{something}}(T_i < t \le T_{i+1})\right) \\
&= \exp\left(-\lim_{n\to\infty} \sum_{i=0}^{n-1} \mathcal{P}_{\text{something}}(T_i < t \le T_{i+1})\right) \\
&= \exp\left(-\int_0^T \frac{d\mathcal{P}_{\text{something}}(t)}{dt}\, dt\right)
\end{aligned}$$

$e^{-x} \approx 1 - x$

[Taylor]

$$\rightarrow \quad d\mathcal{P}_{\text{first}}(T) = d\mathcal{P}_{\text{something}}(T)\, \exp\left(-\int_0^T \frac{d\mathcal{P}_{\text{something}}(t)}{dt}\, dt\right)$$

[Sjöstrand, arXiv:hep-ph/0611247v1]

# Parton shower evolution 2

Instead of evolving to later and later times
need to evolve to smaller and smaller $Q^2$ ...
[Heisenberg: Q ~ 1/t]

Sudakov
Form Factor

$$d\mathcal{P}_{a\to bc} = \underbrace{\frac{\alpha_s}{2\pi}\frac{dQ^2}{Q^2}P_{a\to bc}(z)\,dz}_{\text{Probability to radiated with virtuality } Q^2}\ \underbrace{\exp\left(-\sum_{b,c}\int_{Q^2}^{Q^2_{\max}}\frac{dQ'^2}{Q'^2}\int\frac{\alpha_s}{2\pi}P_{a\to bc}(z')\,dz'\right)}_{\text{No radiation for higher virtualities i.e. for } Q^2 \ldots Q^2_{\max}}$$

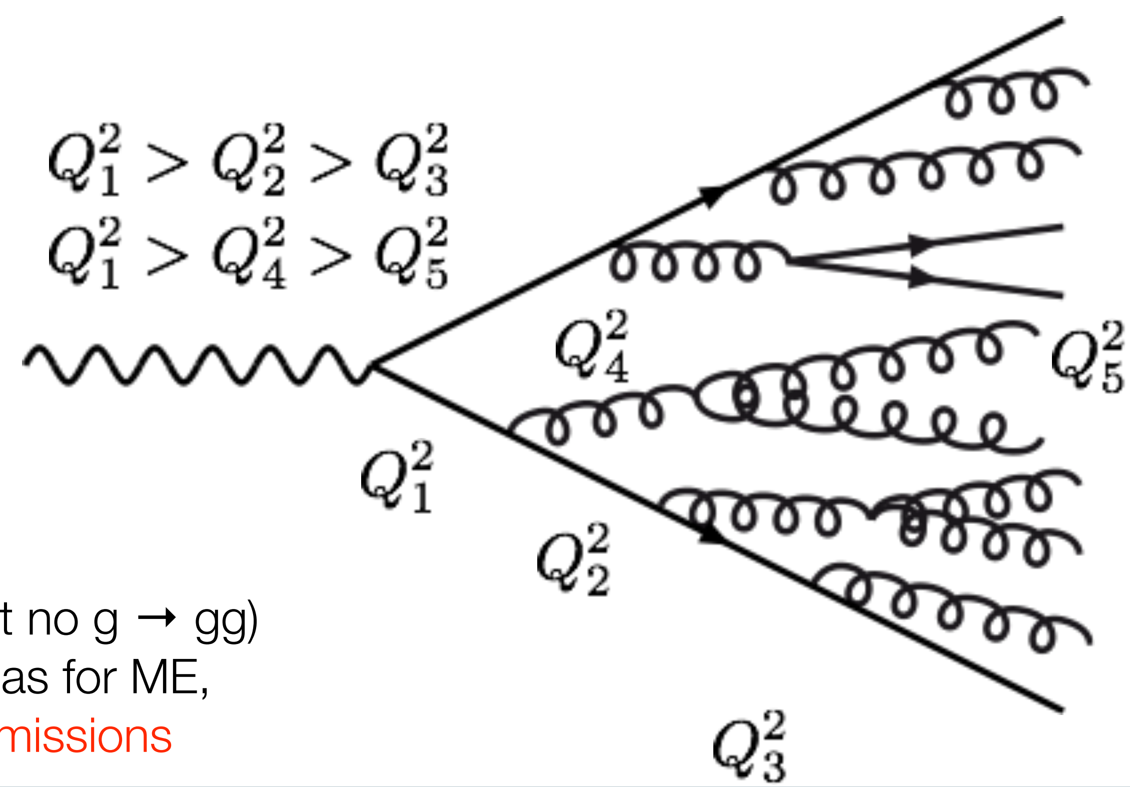
Note that $\sum_{b,c}\iint d\mathcal{P}_{a\to bc} \equiv 1$...
[Convenient for Monte Carlo]

Sudakov form factor ...

... provides "time" ordering of shower ...
[lower $Q^2$ ⇔ longer times]

... regulates singularity for first emission ...

But in the limit of repeated soft emissions q → qg (but no g → gg)
one obtains the same inclusive Q emission spectrum as for ME,
i.e. divergent ME spectrum ⇔ infinite number of PS emissions



# Sudakov picture of parton showers

## Basic algorithm: Markov chain

[each step requires only knowledge of the previous step]

(i) Start with virtuality $Q_1$ and momentum fraction $x_1$

(ii) Generate target virtuality $Q_2$ with random number $R_T$ uniform distributed in [0,1]

Probability to not have $Q_x > Q_2$

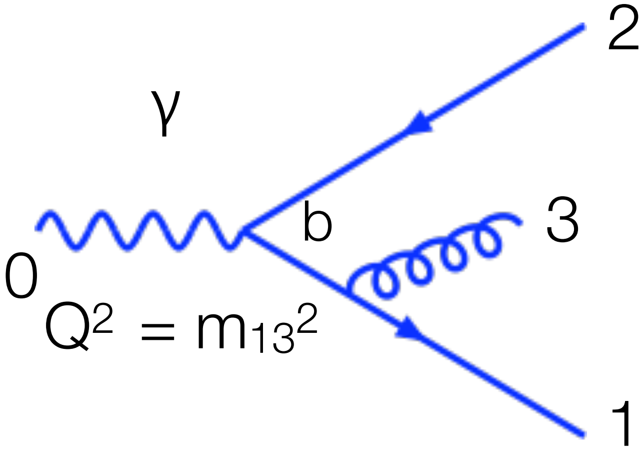
using:

$$\Delta(Q_i^2) = \exp\left(-\sum_{b,c}\int_{Q_i^2}^{Q^2_{\max}} \frac{dQ'^2}{Q'^2}\int \frac{\alpha_s}{2\pi} P_{a\to bc}(z')\,dz'\right)$$

solve the equation for $Q_2$

$$R_t = \frac{\Delta(Q_2^2)}{\Delta(Q_1^2)}$$

[probability to evolve from $t_1$ to $t_2$ without radiation]




(iii) $Q_2$ known ($x_2$ known), need to compute $x_1 \sim z$

$$P_{q\to qg} = \frac{4}{3}\frac{1+z^2}{1-z}$$

$$R_z = \frac{\int_0^z P(z')dz'}{\int_0^1 P(z')dz'}$$

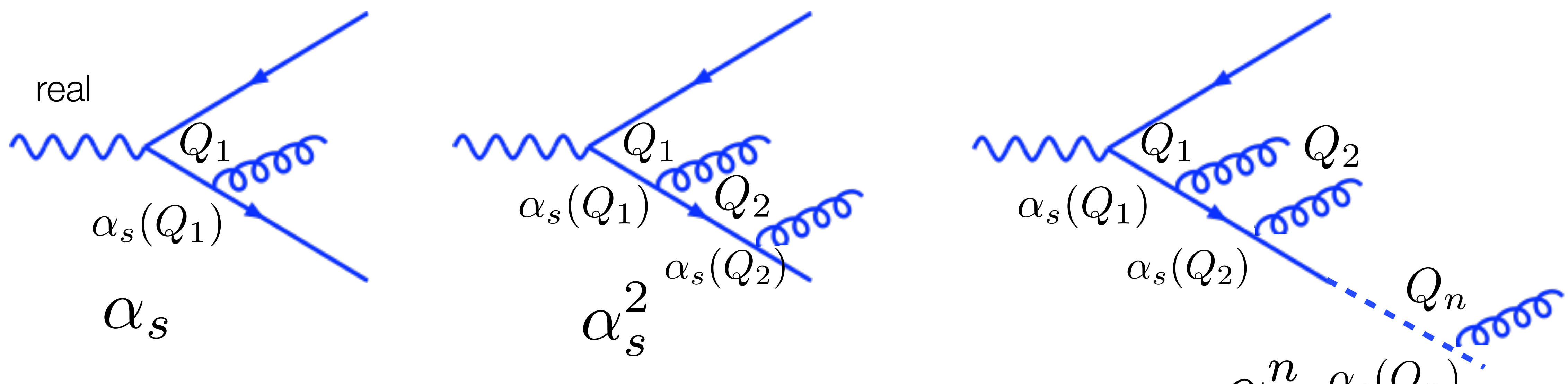
flat distributed

$$R_z \in [0,1]$$

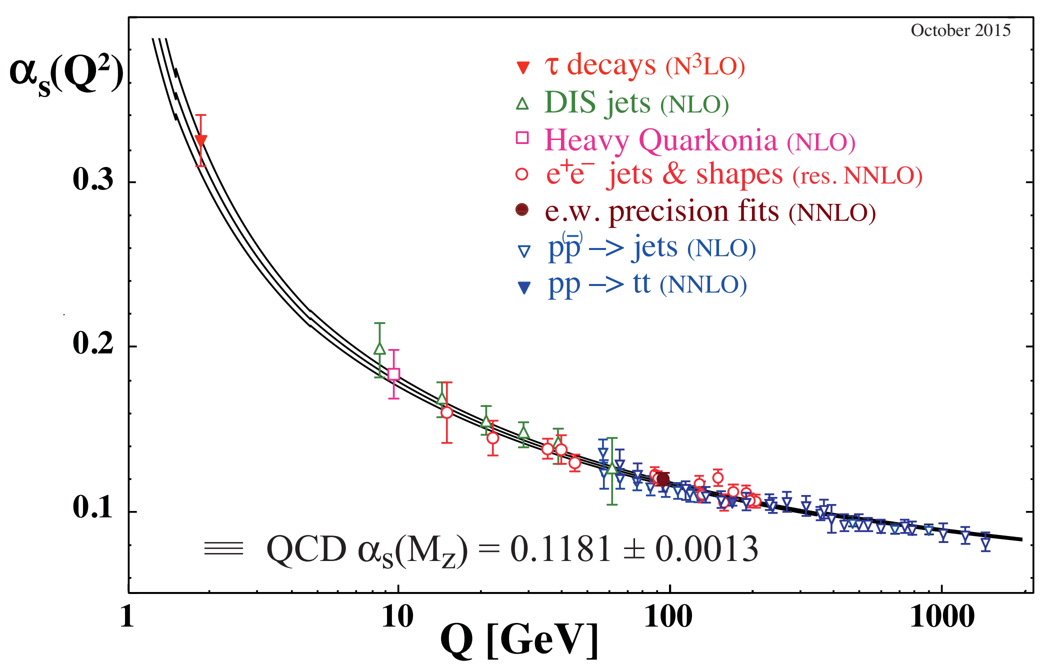
(iv) Generate random azimuthal angle Φ flat distributed

Process ends when partons are below threshold ($p_T$,Q)

# Parton shower and logarithmic resummation




If $\alpha_s$ is small higher contributions are power suppressed, but…




$\alpha_s$ increases at small $Q^2$

$$\alpha_s(Q_n) \sim \alpha_s(Q_1) ln(Q_1/Q_n)$$

$$\alpha_s(Q_1) + \alpha_s(Q_1)\alpha_s(Q_2) + ... + \alpha_s(Q_1) \cdot ... \cdot \alpha_s(Q_n)$$

$$\sim [\alpha_s(Q_1) ln(Q_1)]^2 \sim [\alpha_s(Q_1) ln(Q_1)]^n$$

if $\alpha_s(Q_1) ln(Q_1)$ is large, the expansion is broken, PS allows to sum up all the large contributions [Leading Log resummation]

# Parton shower ordering

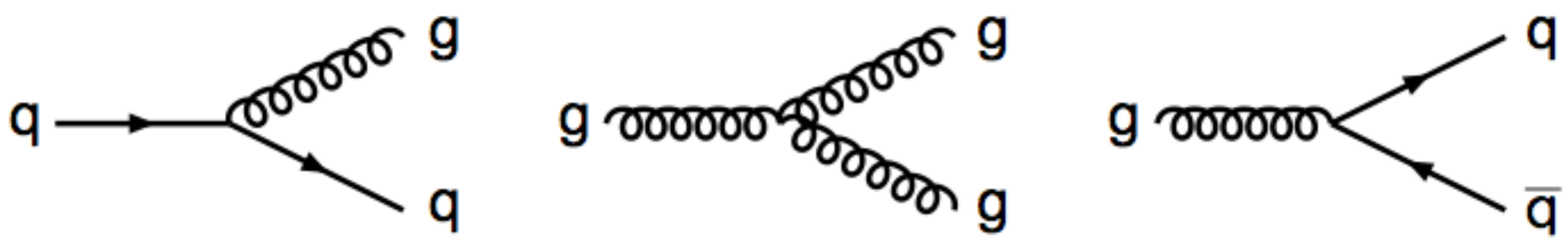
$$\mathrm{d}\mathcal{P}_{a\to bc} = \frac{\alpha_s}{2\pi}\frac{\mathrm{d}Q^2}{Q^2}P_{a\to bc}(z)\,\mathrm{d}z\ \exp\left(-\sum_{b,c}\int_{Q^2}^{Q^2_{\max}}\frac{\mathrm{d}Q'^2}{Q'^2}\int\frac{\alpha_s}{2\pi}P_{a\to bc}(z')\,\mathrm{d}z'\right)$$

In the splitting function appears only $dQ^2/Q^2$, therefore if $P = f(z)Q^2$ $dP/P = dQ^2/Q^2$

Three main approaches to showering in use:

$p_\perp^2 \approx z(1-z)m^2$ $p_T$ ordered showers  $E^2\theta^2 \approx m^2/(z(1-z))$ angular ordered showers

Two are based on the standard shower language of a ➛ bc successive branchings:

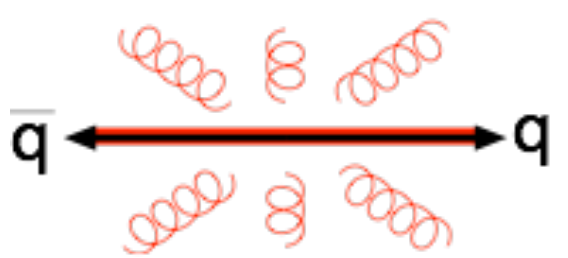


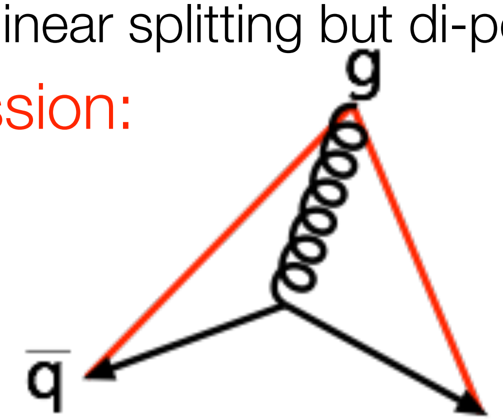

HERWIG, HERWIG++ : $Q^2 \approx E^2(1-\cos\theta) \approx E^2\theta^2/2$

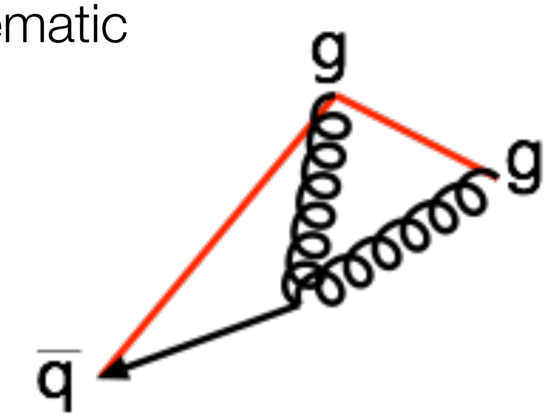
PYTHIA, 8 (basic) : $Q^2 = m^2$ (timelike) or $= -m^2$ (spacelike)

PYTHIA6, 8 ($p_T$ oredered) : mixture: collinear splitting but di-pole kinematic

One is based on a picture of dipole emission:




Ariadne : $Q^2 = p^2_\perp$; FSR mainly, ISR is primitive …
used also in sherpa and Pythia8

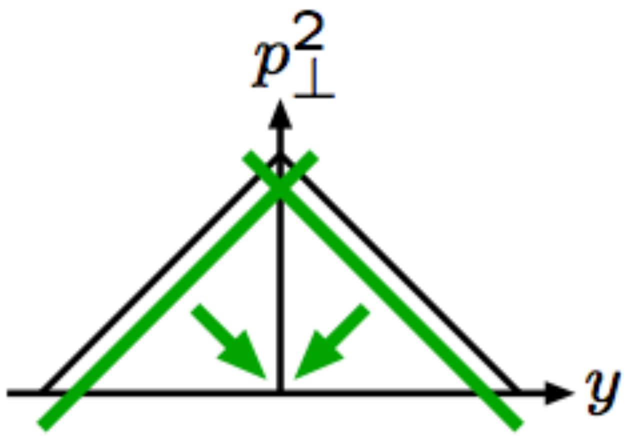
consider the full recoil and not only the branching



[from G.Herten]

$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right) \sim \eta = -\ln\left[\left(\tan\frac{\theta}{2}\right)\right]$$

PYTHIA: $Q^2 = m^2$

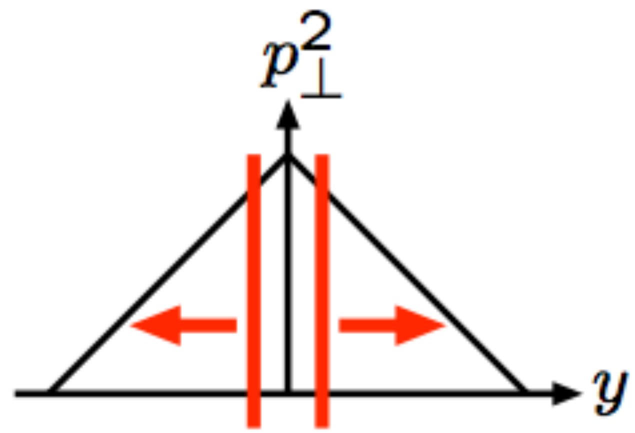



Large mass first
["hardness" ordered]

Covers phase space
ME merging simple
g ➛ qq simple
not Lorentz invariant
no stop/restart

ISR: $m^2$ ➛ $-m^2$

HERWIG/++: $Q^2 \sim E^2\theta^2$

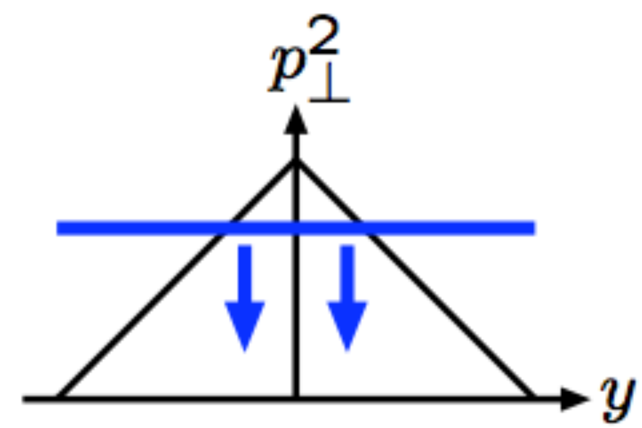



Large angle first
[not "hardness" ordered]

Gaps in coverage
ME merging messy
g ➛ qq simple
not Lorentz invariant
no stop/restart

ISR: θ ➛ θ

ARIADNE/Pythia8: $Q^2 = p^2_\perp$




Large $p_\perp$ first
["hardness" ordered]

Covers phase space
ME merging simple
g ➛ qq messy
Lorentz invariant
can stop/restart

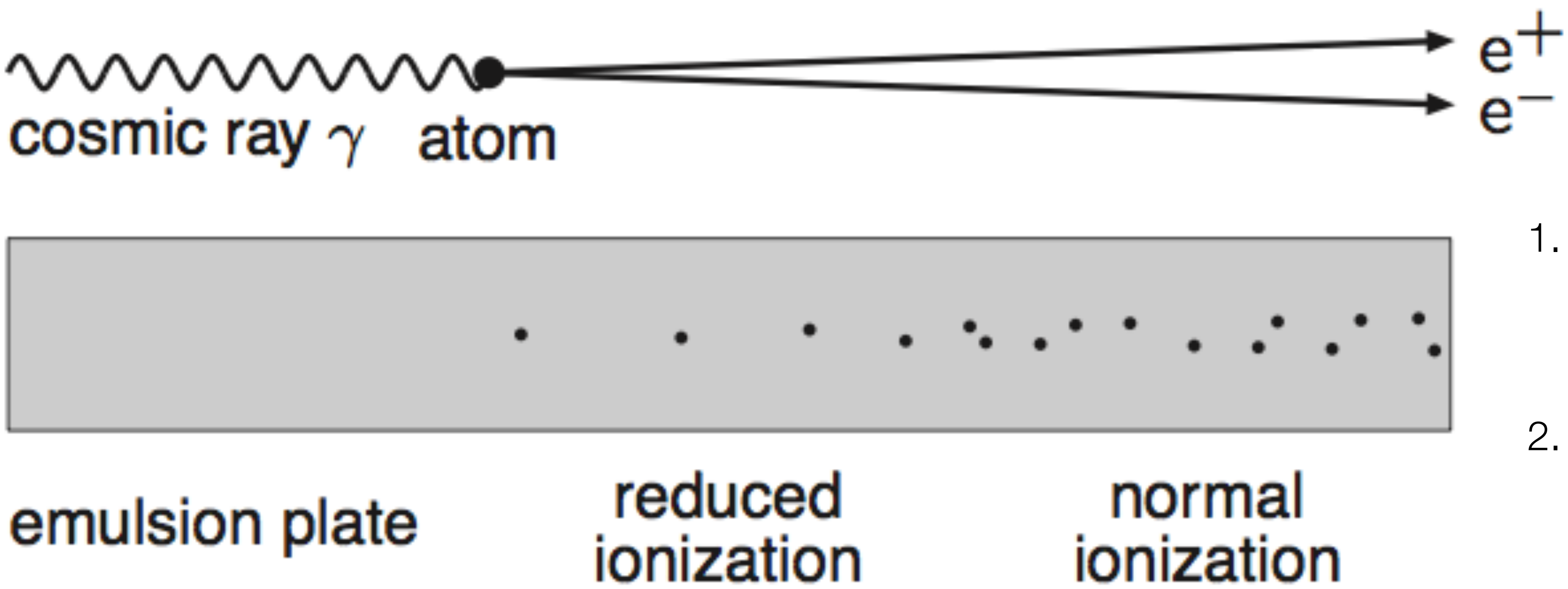
ISR: complicated

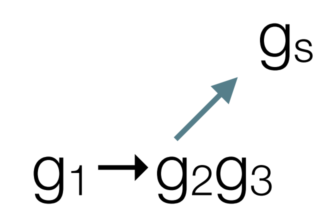


[from G.Herten]

# Color coherence

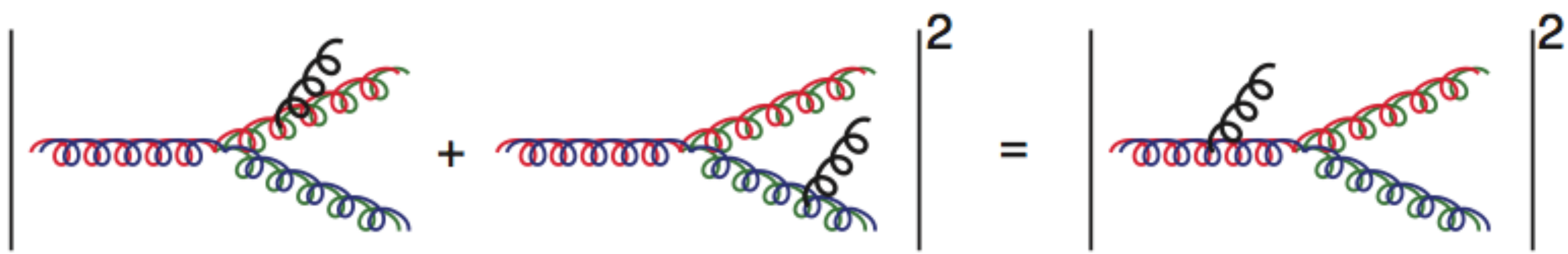
QED: Chudakov effect (mid-fifties)




1. soft gluons see the pair of split gluons as a whole, color screening reduce their emission
2. angular ordered and $p_T$ ordered PS reproduce the correct color coherence
3. Pythia $Q^2$ needs a-posteriori corrections

QCD: colour coherence for **soft** gluon emission




solved by • requiring emission angles to be decreasing

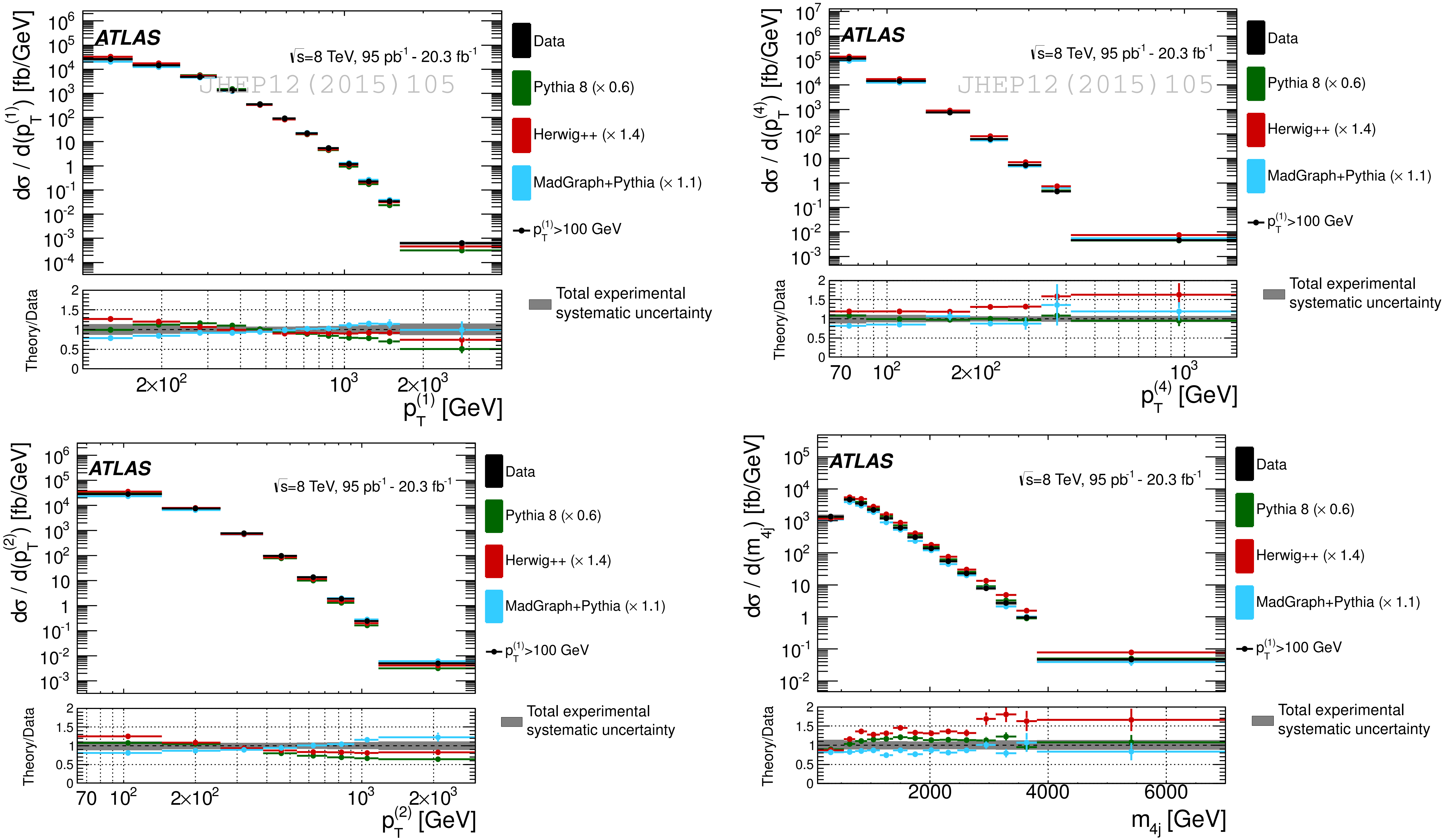
or • requiring transverse momenta to be decreasing



[from G.Herten]

# Compariosn to LHC data

4jets cross section: $p_T^{(1)} > p_T^{(2)} > p_T^{(3)} > p_T^{(4)}$



# Example of processes implemented in Pythia6

| No. | Subprocess |
|---|---|
| Hard QCD processes: | |
| 11 | $f_i f_j \to f_i f_j$ |
| 12 | $f_i \bar{f}_i \to f_k \bar{f}_k$ |
| 13 | $f_i \bar{f}_i \to gg$ |
| 28 | $f_i g \to f_i g$ |
| 53 | $gg \to f_k \bar{f}_k$ |
| 68 | $gg \to gg$ |
| Soft QCD processes: | |
| 91 | elastic scattering |
| 92 | single diffraction $(XB)$ |
| 93 | single diffraction $(AX)$ |
| 94 | double diffraction |
| 95 | low-$p_\perp$ production |
| Open heavy flavour: (also fourth generation) | |
| 81 | $f_i \bar{f}_i \to Q_k \bar{Q}_k$ |
| 82 | $gg \to Q_k \bar{Q}_k$ |
| 83 | $q_i f_j \to Q_k f_l$ |
| 84 | $g\gamma \to Q_k \bar{Q}_k$ |
| 85 | $\gamma\gamma \to F_k \bar{F}_k$ |
| Closed heavy flavour: | |
| 86 | $gg \to J/\psi g$ |
| 87 | $gg \to \chi_{0c} g$ |
| 88 | $gg \to \chi_{1c} g$ |
| 89 | $gg \to \chi_{2c} g$ |
| 104 | $gg \to \chi_{0c}$ |
| 105 | $gg \to \chi_{2c}$ |
| 106 | $gg \to J/\psi\gamma$ |
| 107 | $g\gamma \to J/\psi g$ |
| 108 | $\gamma\gamma \to J/\psi\gamma$ |
| W/Z production: | |
| 1 | $f_i \bar{f}_i \to \gamma^*/Z^0$ |
| 2 | $f_i \bar{f}_j \to W^\pm$ |
| 22 | $f_i \bar{f}_i \to Z^0 Z^0$ |
| 23 | $f_i \bar{f}_j \to Z^0 W^\pm$ |
| 25 | $f_i \bar{f}_i \to W^+ W^-$ |
| 15 | $f_i \bar{f}_i \to g Z^0$ |
| 16 | $f_i \bar{f}_j \to g W^\pm$ |
| 30 | $f_i g \to f_i Z^0$ |
| 31 | $f_i g \to f_k W^\pm$ |
| 19 | $f_i \bar{f}_i \to \gamma Z^0$ |
| 20 | $f_i \bar{f}_j \to \gamma W^\pm$ |
| 35 | $f_i \gamma \to f_i Z^0$ |

| No. | Subprocess |
|---|---|
| 36 | $f_i \gamma \to f_k W^\pm$ |
| 69 | $\gamma\gamma \to W^+ W^-$ |
| 70 | $\gamma W^\pm \to Z^0 W^\pm$ |
| Prompt photons: | |
| 14 | $f_i \bar{f}_i \to g\gamma$ |
| 18 | $f_i \bar{f}_i \to \gamma\gamma$ |
| 29 | $f_i g \to f_i \gamma$ |
| 114 | $gg \to \gamma\gamma$ |
| 115 | $gg \to g\gamma$ |
| Deeply Inel. Scatt.: | |
| 10 | $f_i f_j \to f_k f_l$ |
| 99 | $\gamma^* q \to q$ |
| Photon-induced: | |
| 33 | $f_i \gamma \to f_i g$ |
| 34 | $f_i \gamma \to f_i \gamma$ |
| 54 | $g\gamma \to f_k \bar{f}_k$ |
| 58 | $\gamma\gamma \to f_k \bar{f}_k$ |
| 131 | $f_i \gamma^*_T \to f_i g$ |
| 132 | $f_i \gamma^*_L \to f_i g$ |
| 133 | $f_i \gamma^*_T \to f_i \gamma$ |
| 134 | $f_i \gamma^*_L \to f_i \gamma$ |
| 135 | $g\gamma^*_T \to f_i \bar{f}_i$ |
| 136 | $g\gamma^*_L \to f_i \bar{f}_i$ |
| 137 | $\gamma^*_T \gamma^*_T \to f_i \bar{f}_i$ |
| 138 | $\gamma^*_T \gamma^*_L \to f_i \bar{f}_i$ |
| 139 | $\gamma^*_L \gamma^*_T \to f_i \bar{f}_i$ |
| 140 | $\gamma^*_L \gamma^*_L \to f_i \bar{f}_i$ |
| 80 | $q_i \gamma \to q_k \pi^\pm$ |
| Light SM Higgs: | |
| 3 | $f_i \bar{f}_i \to h^0$ |
| 24 | $f_i \bar{f}_i \to Z^0 h^0$ |
| 26 | $f_i \bar{f}_j \to W^\pm h^0$ |
| 32 | $f_i g \to f_i h^0$ |
| 102 | $gg \to h^0$ |
| 103 | $\gamma\gamma \to h^0$ |
| 110 | $f_i \bar{f}_i \to \gamma h^0$ |
| 111 | $f_i \bar{f}_i \to g h^0$ |
| 112 | $f_i g \to f_i h^0$ |
| 113 | $gg \to g h^0$ |
| 121 | $gg \to Q_k \bar{Q}_k h^0$ |
| 122 | $q_i \bar{q}_i \to Q_k \bar{Q}_k h^0$ |
| 123 | $f_i f_j \to f_i f_j h^0$ |
| 124 | $f_i f_j \to f_k f_l h^0$ |

| No. | Subprocess |
|---|---|
| New gauge bosons: | |
| 141 | $f_i \bar{f}_i \to \gamma/Z^0/Z'^0$ |
| 142 | $f_i \bar{f}_j \to W'^+$ |
| 144 | $f_i \bar{f}_j \to R$ |
| Heavy SM Higgs: | |
| 5 | $Z^0 Z^0 \to h^0$ |
| 8 | $W^+ W^- \to h^0$ |
| 71 | $Z^0_L Z^0_L \to Z^0_L Z^0_L$ |
| 72 | $Z^0_L Z^0_L \to W^+_L W^-_L$ |
| 73 | $Z^0_L W^\pm_L \to Z^0_L W^\pm_L$ |
| 76 | $W^+_L W^-_L \to Z^0_L Z^0_L$ |
| 77 | $W^\pm_L W^\pm_L \to W^\pm_L W^\pm_L$ |
| BSM Neutral Higgs: | |
| 151 | $f_i \bar{f}_i \to H^0$ |
| 152 | $gg \to H^0$ |
| 153 | $\gamma\gamma \to H^0$ |
| 171 | $f_i \bar{f}_i \to Z^0 H^0$ |
| 172 | $f_i \bar{f}_j \to W^\pm H^0$ |
| 173 | $f_i f_j \to f_i f_j H^0$ |
| 174 | $f_i f_j \to f_k f_l H^0$ |
| 181 | $gg \to Q_k \bar{Q}_k H^0$ |
| 182 | $q_i \bar{q}_i \to Q_k \bar{Q}_k H^0$ |
| 183 | $f_i \bar{f}_i \to g H^0$ |
| 184 | $f_i g \to f_i H^0$ |
| 185 | $gg \to g H^0$ |
| 156 | $f_i \bar{f}_i \to A^0$ |
| 157 | $gg \to A^0$ |
| 158 | $\gamma\gamma \to A^0$ |
| 176 | $f_i \bar{f}_i \to Z^0 A^0$ |
| 177 | $f_i \bar{f}_j \to W^\pm A^0$ |
| 178 | $f_i f_j \to f_i f_j A^0$ |
| 179 | $f_i f_j \to f_k f_l A^0$ |
| 186 | $gg \to Q_k \bar{Q}_k A^0$ |
| 187 | $q_i \bar{q}_i \to Q_k \bar{Q}_k A^0$ |
| 188 | $f_i \bar{f}_i \to g A^0$ |
| 189 | $f_i g \to f_i A^0$ |
| 190 | $gg \to g A^0$ |
| Charged Higgs: | |
| 143 | $f_i \bar{f}_j \to H^+$ |
| 161 | $f_i g \to f_k H^+$ |
| 401 | $gg \to \bar{t} b H^+$ |
| 402 | $q\bar{q} \to \bar{t} b H^+$ |

| No. | Subprocess |
|---|---|
| Higgs pairs: | |
| 297 | $f_i \bar{f}_j \to H^\pm h^0$ |
| 298 | $f_i \bar{f}_j \to H^\pm H^0$ |
| 299 | $f_i \bar{f}_i \to A^0 h^0$ |
| 300 | $f_i \bar{f}_i \to A^0 H^0$ |
| 301 | $f_i \bar{f}_i \to H^+ H^-$ |
| Leptoquarks: | |
| 145 | $q_i \ell_j \to L_Q$ |
| 162 | $qg \to \ell L_Q$ |
| 163 | $gg \to L_Q \bar{L}_Q$ |
| 164 | $q_i \bar{q}_i \to L_Q \bar{L}_Q$ |
| Technicolor: | |
| 149 | $gg \to \eta_{tc}$ |
| 191 | $f_i \bar{f}_i \to \rho^0_{tc}$ |
| 192 | $f_i \bar{f}_j \to \rho^+_{tc}$ |
| 193 | $f_i \bar{f}_i \to \omega^0_{tc}$ |
| 194 | $f_i \bar{f}_i \to f_k \bar{f}_k$ |
| 195 | $f_i \bar{f}_j \to f_k \bar{f}_l$ |
| 361 | $f_i \bar{f}_i \to W^+_L W^-_L$ |
| 362 | $f_i \bar{f}_i \to W^\pm_L \pi^\mp_{tc}$ |
| 363 | $f_i \bar{f}_i \to \pi^+_{tc} \pi^-_{tc}$ |
| 364 | $f_i \bar{f}_i \to \gamma \pi^0_{tc}$ |
| 365 | $f_i \bar{f}_i \to \gamma \pi'^0_{tc}$ |
| 366 | $f_i \bar{f}_i \to Z^0 \pi^0_{tc}$ |
| 367 | $f_i \bar{f}_i \to Z^0 \pi'^0_{tc}$ |
| 368 | $f_i \bar{f}_i \to W^\pm \pi^\mp_{tc}$ |
| 370 | $f_i \bar{f}_j \to W^\pm_L Z^0_L$ |
| 371 | $f_i \bar{f}_j \to W^\pm_L \pi^0_{tc}$ |
| 372 | $f_i \bar{f}_j \to \pi^\pm_{tc} Z^0_L$ |
| 373 | $f_i \bar{f}_j \to \pi^\pm_{tc} \pi^0_{tc}$ |
| 374 | $f_i \bar{f}_j \to \gamma \pi^\pm_{tc}$ |
| 375 | $f_i \bar{f}_j \to Z^0 \pi^\pm_{tc}$ |
| 376 | $f_i \bar{f}_j \to W^\pm \pi^0_{tc}$ |
| 377 | $f_i \bar{f}_j \to W^\pm \pi'^0_{tc}$ |
| 381 | $q_i q_j \to q_i q_j$ |
| 382 | $q_i \bar{q}_i \to q_k \bar{q}_k$ |
| 383 | $q_i \bar{q}_i \to gg$ |
| 384 | $f_i g \to f_i g$ |
| 385 | $gg \to q_k \bar{q}_k$ |
| 386 | $gg \to gg$ |
| 387 | $f_i \bar{f}_i \to Q_k \bar{Q}_k$ |
| 388 | $gg \to Q_k \bar{Q}_k$ |

| No. | Subprocess |
|---|---|
| Compositeness: | |
| 146 | $e\gamma \to e^*$ |
| 147 | $dg \to d^*$ |
| 148 | $ug \to u^*$ |
| 167 | $q_i q_j \to d^* q_k$ |
| 168 | $q_i q_j \to u^* q_k$ |
| 169 | $q_i \bar{q}_i \to e^\pm e^{*\mp}$ |
| 165 | $f_i \bar{f}_i (\to \gamma^*/Z^0) \to f_k \bar{f}_k$ |
| 166 | $f_i \bar{f}_j (\to W^\pm) \to f_k \bar{f}_l$ |
| Extra Dimensions: | |
| 391 | $f\bar{f} \to G^*$ |
| 392 | $gg \to G^*$ |
| 393 | $q\bar{q} \to gG^*$ |
| 394 | $qg \to qG^*$ |
| 395 | $gg \to gG^*$ |
| Left–right symmetry: | |
| 341 | $\ell_i \ell_j \to H^{\pm\pm}_L$ |
| 342 | $\ell_i \ell_j \to H^{\pm\pm}_R$ |
| 343 | $\ell^\pm_i \gamma \to H^{\pm\pm}_L e^\mp$ |
| 344 | $\ell^\pm_i \gamma \to H^{\pm\pm}_R e^\mp$ |
| 345 | $\ell^\pm_i \gamma \to H^{\pm\pm}_L \mu^\mp$ |
| 346 | $\ell^\pm_i \gamma \to H^{\pm\pm}_R \mu^\mp$ |
| 347 | $\ell^\pm_i \gamma \to H^{\pm\pm}_L \tau^\mp$ |
| 348 | $\ell^\pm_i \gamma \to H^{\pm\pm}_R \tau^\mp$ |
| 349 | $f_i \bar{f}_i \to H^{++}_L H^{--}_L$ |
| 350 | $f_i \bar{f}_i \to H^{++}_R H^{--}_R$ |
| 351 | $f_i f_j \to f_k f_l H^{\pm\pm}_L$ |
| 352 | $f_i f_j \to f_k f_l H^{\pm\pm}_R$ |
| 353 | $f_i \bar{f}_i \to Z^0_R$ |
| 354 | $f_i \bar{f}_j \to W^\pm_R$ |
| SUSY: | |
| 201 | $f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_L$ |
| 202 | $f_i \bar{f}_i \to \tilde{e}_R \tilde{e}^*_R$ |
| 203 | $f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_R +$ |
| 204 | $f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_L$ |
| 205 | $f_i \bar{f}_i \to \tilde{\mu}_R \tilde{\mu}^*_R$ |
| 206 | $f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_R +$ |
| 207 | $f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_1$ |
| 208 | $f_i \bar{f}_i \to \tilde{\tau}_2 \tilde{\tau}^*_2$ |
| 209 | $f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_2 +$ |

| No. | Subprocess |
|---|---|
| 210 | $f_i \bar{f}_j \to \tilde{\ell}_L \tilde{\nu}^*_\ell +$ |
| 211 | $f_i \bar{f}_j \to \tilde{\tau}_1 \tilde{\nu}^*_\tau +$ |
| 212 | $f_i \bar{f}_j \to \tilde{\tau}_2 \tilde{\nu}^*_\tau +$ |
| 213 | $f_i \bar{f}_i \to \tilde{\nu}_\ell \tilde{\nu}_\ell{}^*$ |
| 214 | $f_i \bar{f}_i \to \tilde{\nu}_\tau \tilde{\nu}^*_\tau$ |
| 216 | $f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$ |
| 217 | $f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_2$ |
| 218 | $f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_3$ |
| 219 | $f_i \bar{f}_i \to \tilde{\chi}_4 \tilde{\chi}_4$ |
| 220 | $f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_2$ |
| 221 | $f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_3$ |
| 222 | $f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_4$ |
| 223 | $f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_3$ |
| 224 | $f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_4$ |
| 225 | $f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$ |
| 226 | $f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$ |
| 227 | $f_i \bar{f}_i \to \tilde{\chi}^\pm_2 \tilde{\chi}^\mp_2$ |
| 228 | $f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_2$ |
| 229 | $f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_1$ |
| 230 | $f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_1$ |
| 231 | $f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_1$ |
| 232 | $f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_1$ |
| 233 | $f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_2$ |
| 234 | $f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_2$ |
| 235 | $f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_2$ |
| 236 | $f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_2$ |
| 237 | $f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_1$ |
| 238 | $f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_2$ |
| 239 | $f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_3$ |
| 240 | $f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_4$ |
| 241 | $f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_1$ |
| 242 | $f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_2$ |
| 243 | $f_i \bar{f}_i \to \tilde{g}\tilde{g}$ |
| 244 | $gg \to \tilde{g}\tilde{g}$ |
| 246 | $f_i g \to \tilde{q}_{iL} \tilde{\chi}_1$ |
| 247 | $f_i g \to \tilde{q}_{iR} \tilde{\chi}_1$ |
| 248 | $f_i g \to \tilde{q}_{iL} \tilde{\chi}_2$ |
| 249 | $f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$ |

| No. | Subprocess |
|---|---|
| 250 | $f_i g \to \tilde{q}_{iL} \tilde{\chi}_3$ |
| 251 | $f_i g \to \tilde{q}_{iR} \tilde{\chi}_3$ |
| 252 | $f_i g \to \tilde{q}_{iL} \tilde{\chi}_4$ |
| 253 | $f_i g \to \tilde{q}_{iR} \tilde{\chi}_4$ |
| 254 | $f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_1$ |
| 256 | $f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_2$ |
| 258 | $f_i g \to \tilde{q}_{iL} \tilde{g}$ |
| 259 | $f_i g \to \tilde{q}_{iR} \tilde{g}$ |
| 261 | $f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_1$ |
| 262 | $f_i \bar{f}_i \to \tilde{t}_2 \tilde{t}^*_2$ |
| 263 | $f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_2 +$ |
| 264 | $gg \to \tilde{t}_1 \tilde{t}^*_1$ |
| 265 | $gg \to \tilde{t}_2 \tilde{t}^*_2$ |
| 271 | $f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jL}$ |
| 272 | $f_i f_j \to \tilde{q}_{iR} \tilde{q}_{jR}$ |
| 273 | $f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jR} +$ |
| 274 | $f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jL}$ |
| 275 | $f_i \bar{f}_j \to \tilde{q}_{iR} \tilde{q}^*_{jR}$ |
| 276 | $f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jR} +$ |
| 277 | $f_i \bar{f}_i \to \tilde{q}_{jL} \tilde{q}^*_{jL}$ |
| 278 | $f_i \bar{f}_i \to \tilde{q}_{jR} \tilde{q}^*_{jR}$ |
| 279 | $gg \to \tilde{q}_{iL} \tilde{q}^*_{iL}$ |
| 280 | $gg \to \tilde{q}_{iR} \tilde{q}^*_{iR}$ |
| 281 | $bq_i \to \tilde{b}_1 \tilde{q}_{iL}$ |
| 282 | $bq_i \to \tilde{b}_2 \tilde{q}_{iR}$ |
| 283 | $bq_i \to \tilde{b}_1 \tilde{q}_{iR} +$ |
| 284 | $b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iL}$ |
| 285 | $b\bar{q}_i \to \tilde{b}_2 \tilde{q}^*_{iR}$ |
| 286 | $b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iR} +$ |
| 287 | $f_i \bar{f}_i \to \tilde{b}_1 \tilde{b}^*_1$ |
| 288 | $f_i \bar{f}_i \to \tilde{b}_2 \tilde{b}^*_2$ |
| 289 | $gg \to \tilde{b}_1 \tilde{b}^*_1$ |
| 290 | $gg \to \tilde{b}_2 \tilde{b}^*_2$ |
| 291 | $bb \to \tilde{b}_1 \tilde{b}_1$ |
| 292 | $bb \to \tilde{b}_2 \tilde{b}_2$ |
| 293 | $bb \to \tilde{b}_1 \tilde{b}_2$ |
| 294 | $bg \to \tilde{b}_1 \tilde{g}$ |
| 295 | $bg \to \tilde{b}_2 \tilde{g}$ |
| 296 | $b\bar{b} \to \tilde{b}_1 \tilde{b}^*_2 +$ |

# Process simulation

## Many specialised processes already available in Pythia8/Herwig++

but, processes usually only implemented at the lowest non-trivial order ...

Need external programs that ...

1. include higher order loop corrections or, alternatively, do kinematic dependent rescaling

3. allow matching of higher order ME generators [otherwise need to trust parton shower description …]

5. provide correct spin correlations often absent in PS ...[e.g. top produced unpolarised, while t ➛ bW ➛ blv decay correct]

7. simulate newly available physics scenarios …[appear quickly; need for many specialised generators]

## Les Houches Accord ...

Specifies how parton-level information about the hard process and sequential decays can be encoded and passed on to a general-purpose generator.

Les Houches: regular annual meeting between theoreticians and experimentalists on MC generator developments.

# Specialised Generators [some examples]

Specialized Generator
[➛ Hard Process]

↓

Les Houches Interface

↓

Herwig, Pythia, Herwig++/7, Pythia8

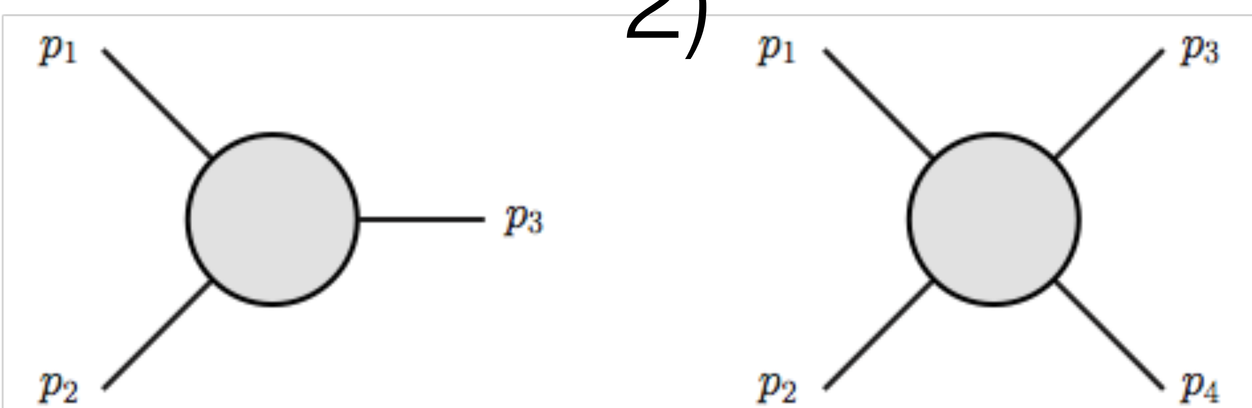
- [Resonance Decays]
- Parton Showers
- Underlying Event
- Hadronization
- Ordinary Decays

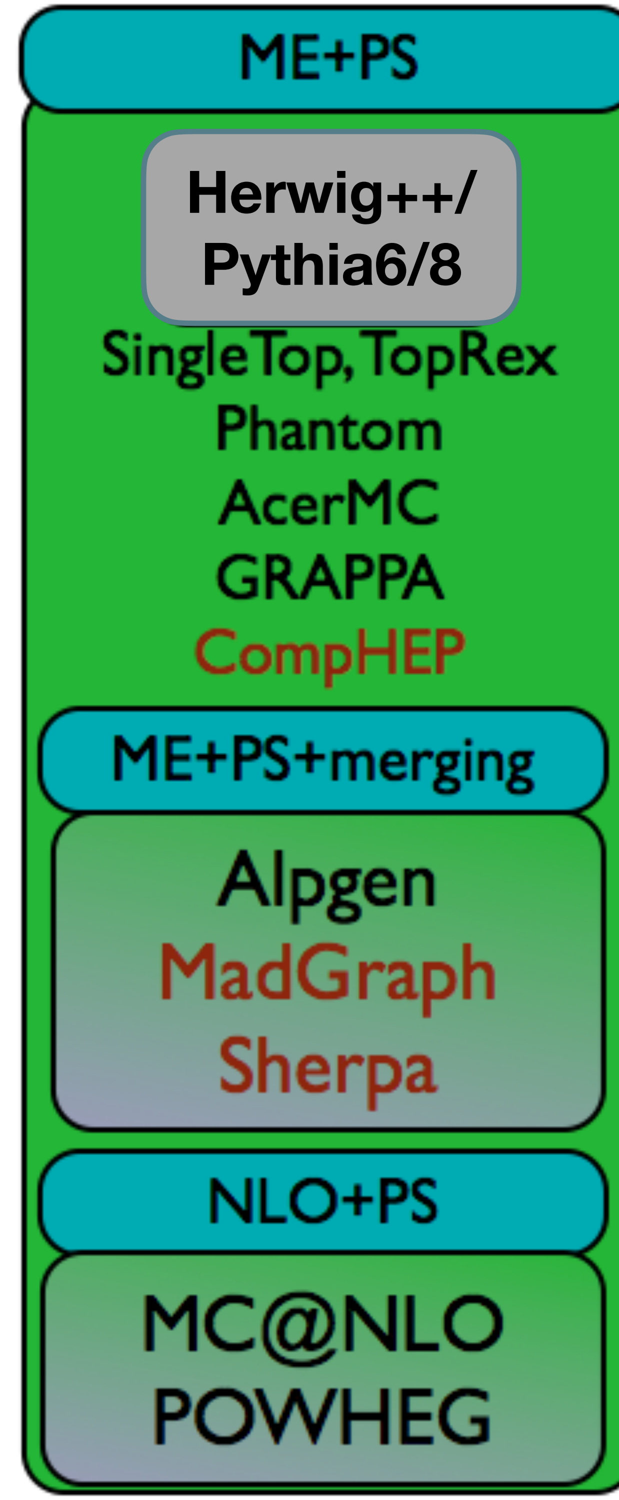
| | |
|---|---|
| AcerMC : | ttbb, .single top |
| ALPGEN : | W/Z + ≤ 6j,<br>nW + mZ + kH + ≤ 3j, ... |
| AMEGIC++ : | generic LO |
| CompHEP : | generic LO |
| GRACE [+Bases/Spring] : | generic LO [+ some NLO loops] |
| GR@PPA : | bbbb |
| MadCUP : | W/Z+ ≤ 3j, ttbb |
| HELAS & MadGraph : | generic LO |
| MCFM : | NLO W/Z+ ≤ 2j,<br>WZ, WH, H+ ≤ 1j |
| O'Mega & WHIZARD : | generic LO |
| VECBOS : | W/Z+ ≤ 4j |
| HRES : | Higgs boson production @NNLO |
| DYNNLO : | W/Z production @NNLO |

# Type I : Leading order matrix element & leading log parton shower

LO ME for hard processes
[2→1 or 2→2]

1) 2)



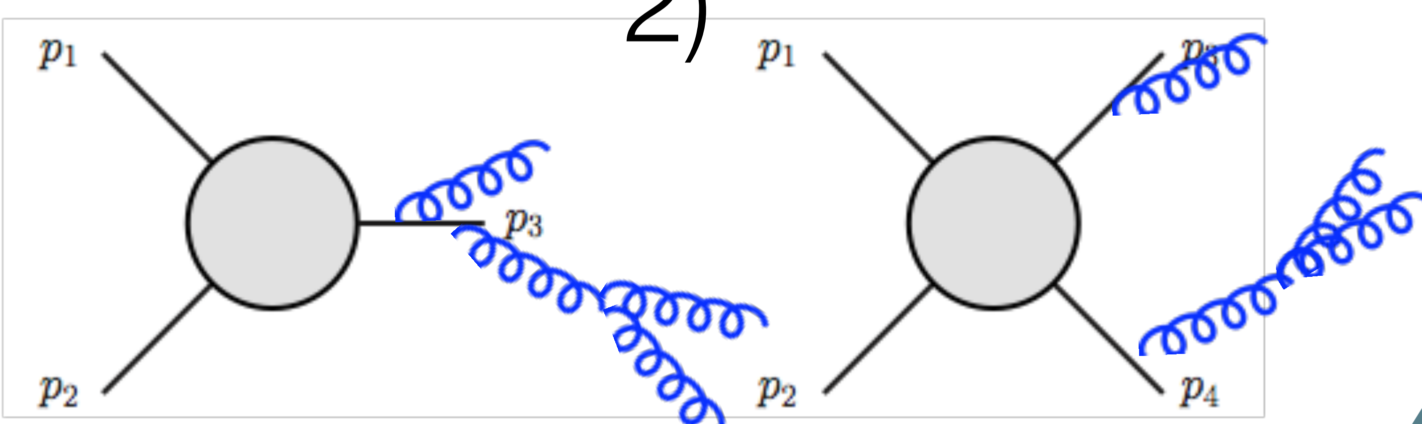




 [F. Maltoni]

# Type I : Leading order matrix element & leading log parton shower

LO ME for hard processes
[2→1 or 2→2]

1) 2)




- Parton Shower: attaches gluons at each leg.
- only in soft-collinear approximation
- typically underestimate large angle/hard emission
- 1) or 2) at ME (different generations, different accuracy: cannot be combined

**ME+PS**

**Herwig++/ Pythia6/8**

SingleTop, TopRex
Phantom
AcerMC
GRAPPA
CompHEP

**ME+PS+merging**

Alpgen
MadGraph
Sherpa

**NLO+PS**

MC@NLO
POWHEG



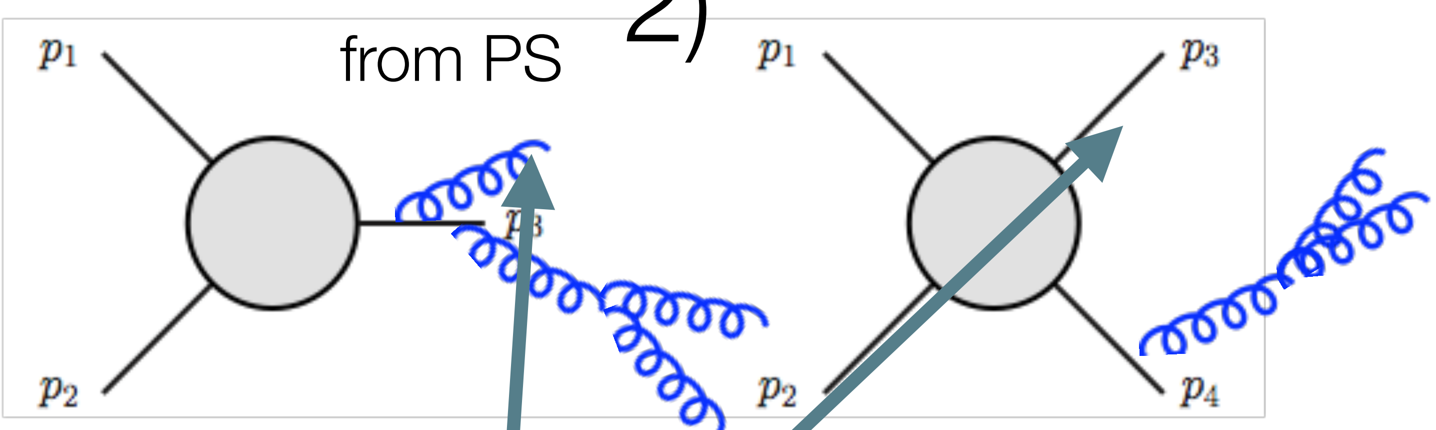
[F. Maltoni]

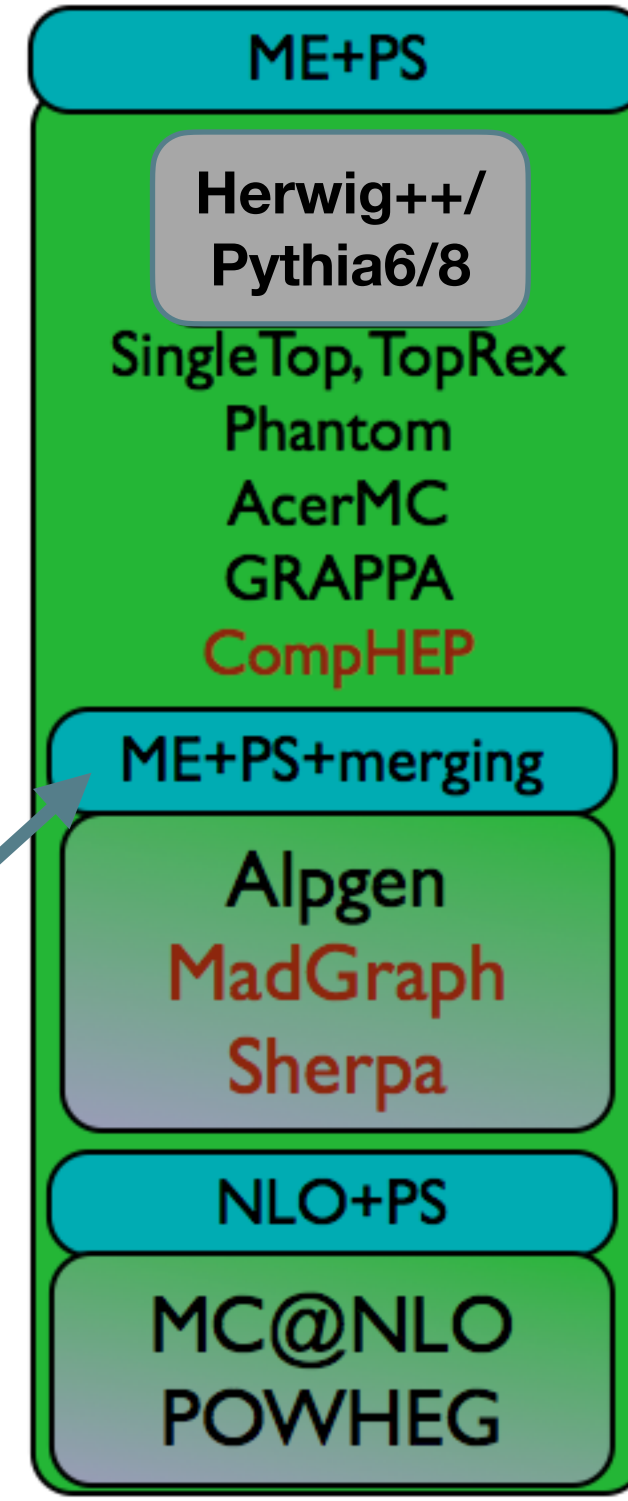
# Type 2 : Leading order matrix element & leading log parton shower + merging

LO ME for hard processes
[2→1 or 2→2]

1) 2)

from ME




- Type 1 can be improved using 1) + 2)
- use ME calculation for hard/large angle jets
- but needs to remove double-counting: merging
  - CKKW: Catani, Krauss, Kuhn, Weber (Sherpa)
  - MLM
- very good description of high jet multiplicity kinematics



[F. Maltoni]

# Merging @LO

MLM matching (simplified)

1) define matching cuts:

for example $p_T^J > 20$ GeV, $\Delta R=0.4$

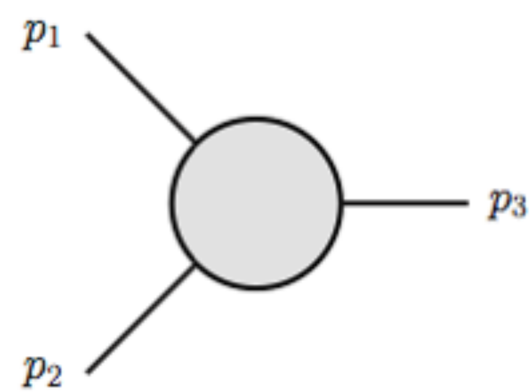
# Merging @LO

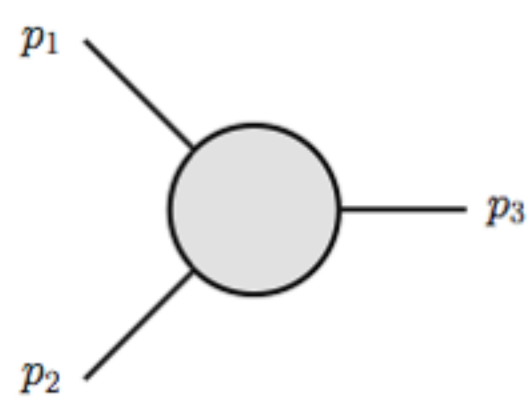
MLM matching (simplified)

1) define matching cuts:
for example $p_T^J > 20$ GeV, $\Delta R = 0.4$

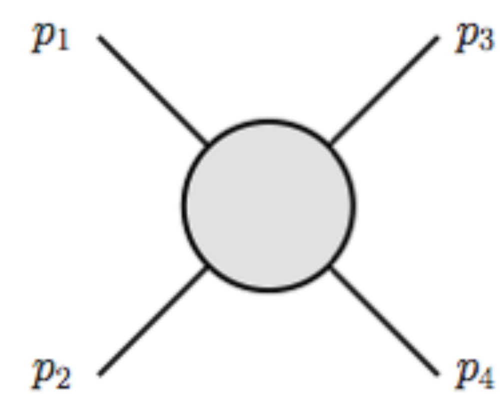
2) generate ME with 1, 2, …n jets

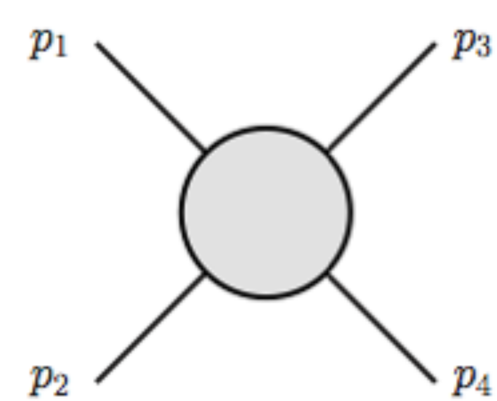
1 parton




2 partons



# Merging @LO

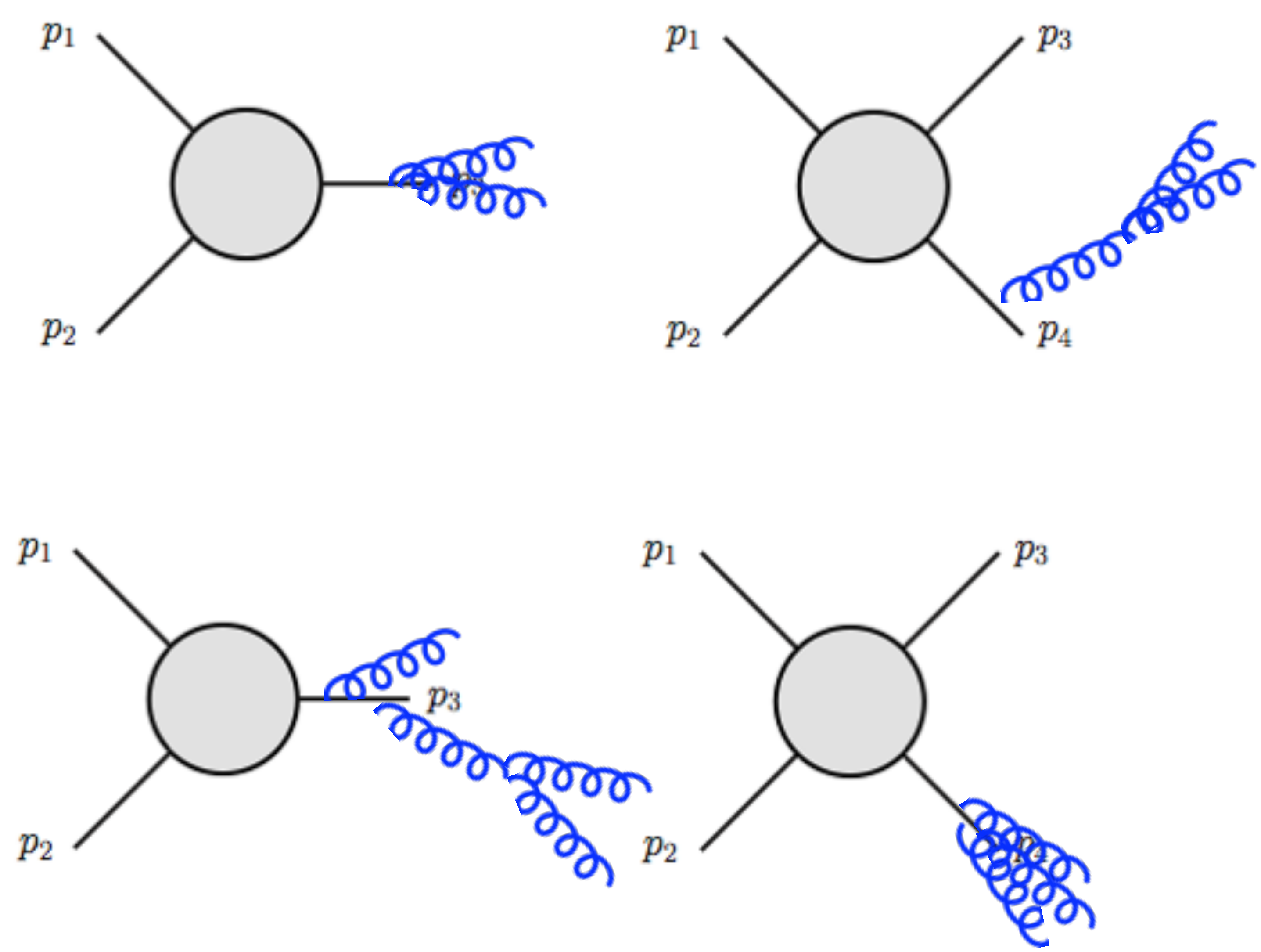
MLM matching (simplified)

1 parton | 2 partons

1) define matching cuts:
for example $p_T^J > 20$ GeV, $\Delta R$=0.4

2) generate ME with 1, 2, …n jets

3) shower all events



# Merging @LO

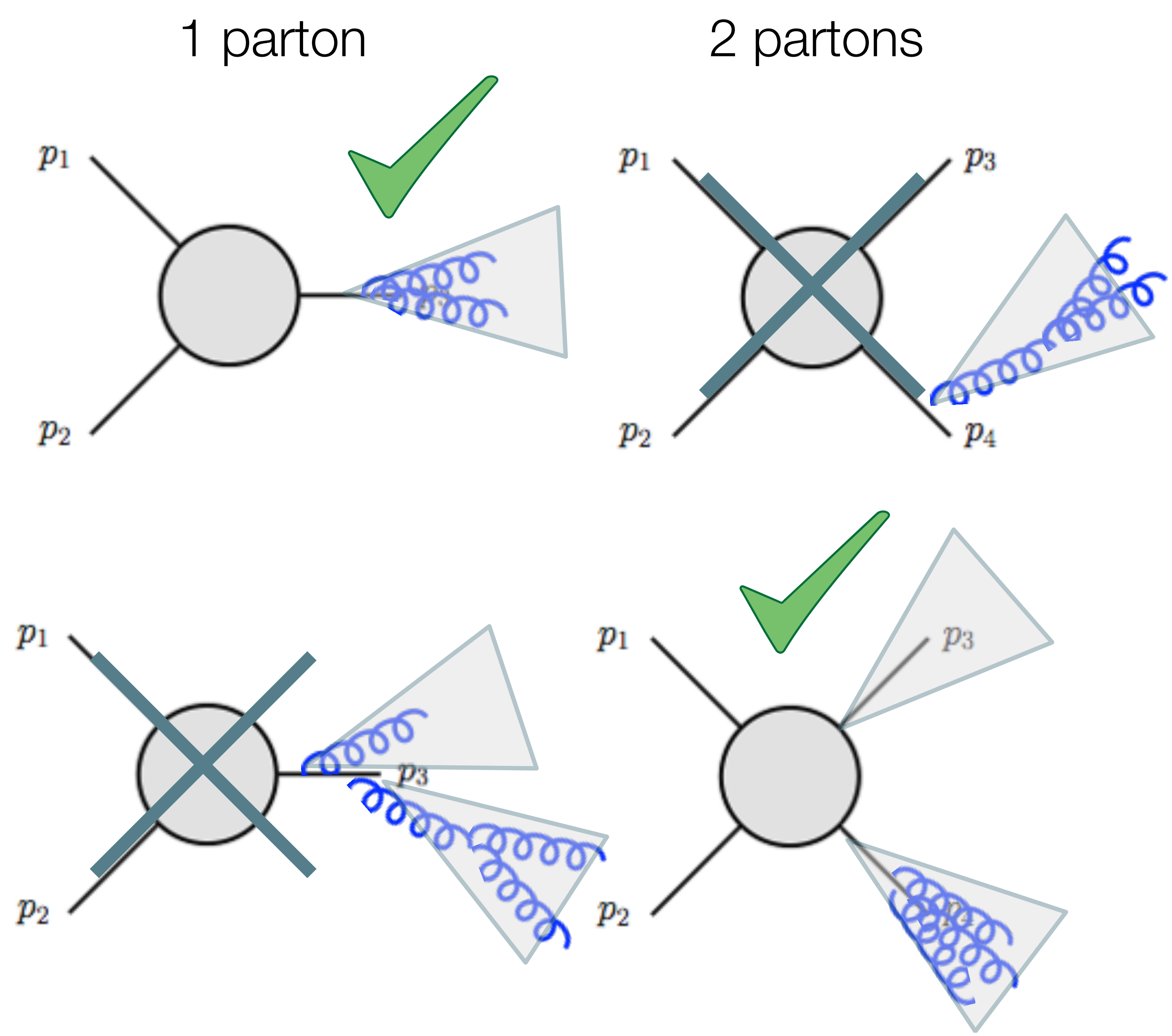
MLM matching (simplified)

1) define matching cuts:
for example $p_T^J$ > 20 GeV, ΔR=0.4

2) generate ME with 1, 2, …n jets

3) shower all events

4) select only events where jets above the $p_T$ threshold match with final partons



# Merging @LO

MLM matching (simplified)

1) define matching cuts:
for example $p_T^J$ > 20 GeV, ΔR=0.4

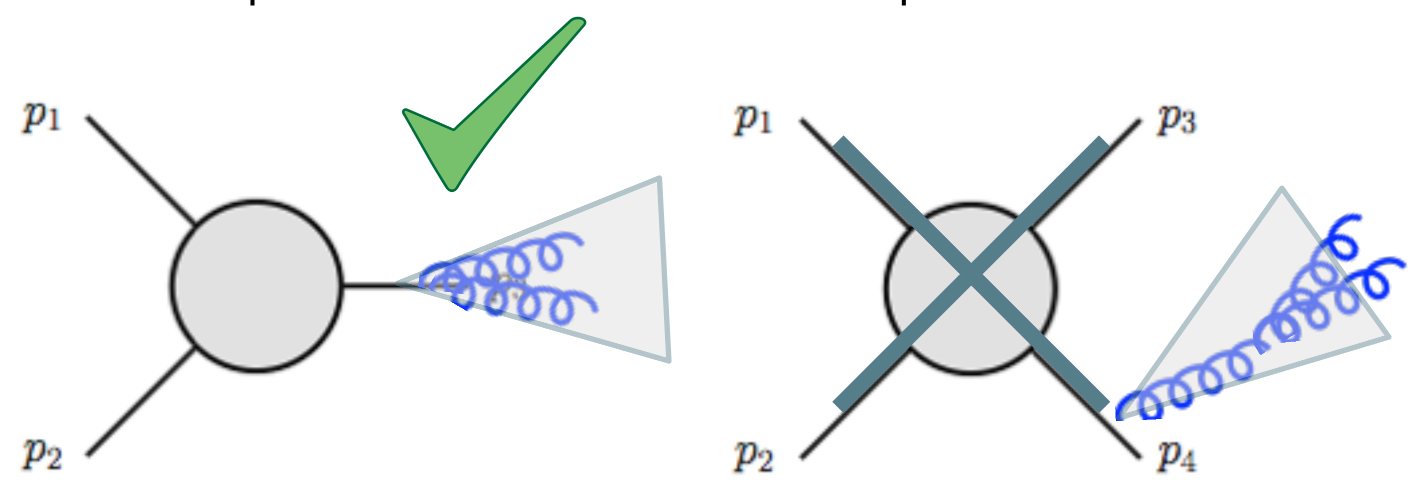
2) generate ME with 1, 2, …n jets

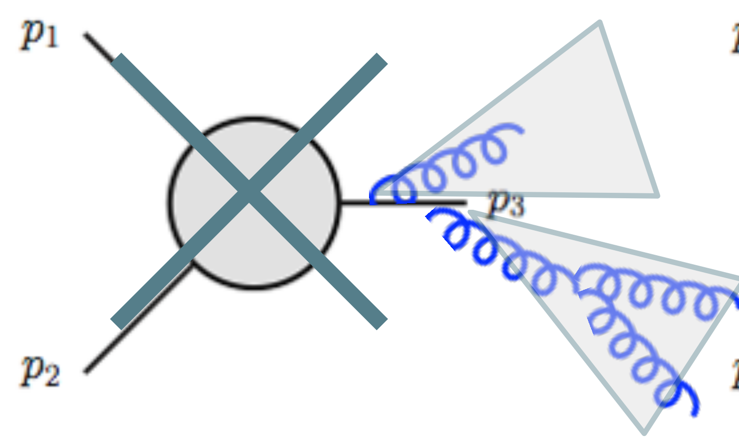
3) shower all events

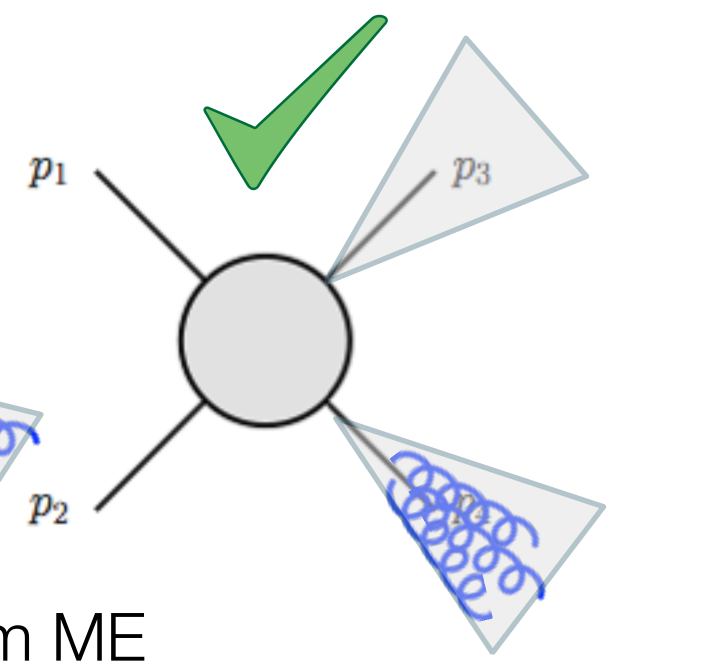
4) select only events where jets above the $p_T$ threshold and satisfying the ΔR cut match with final partons

1 parton

2 partons



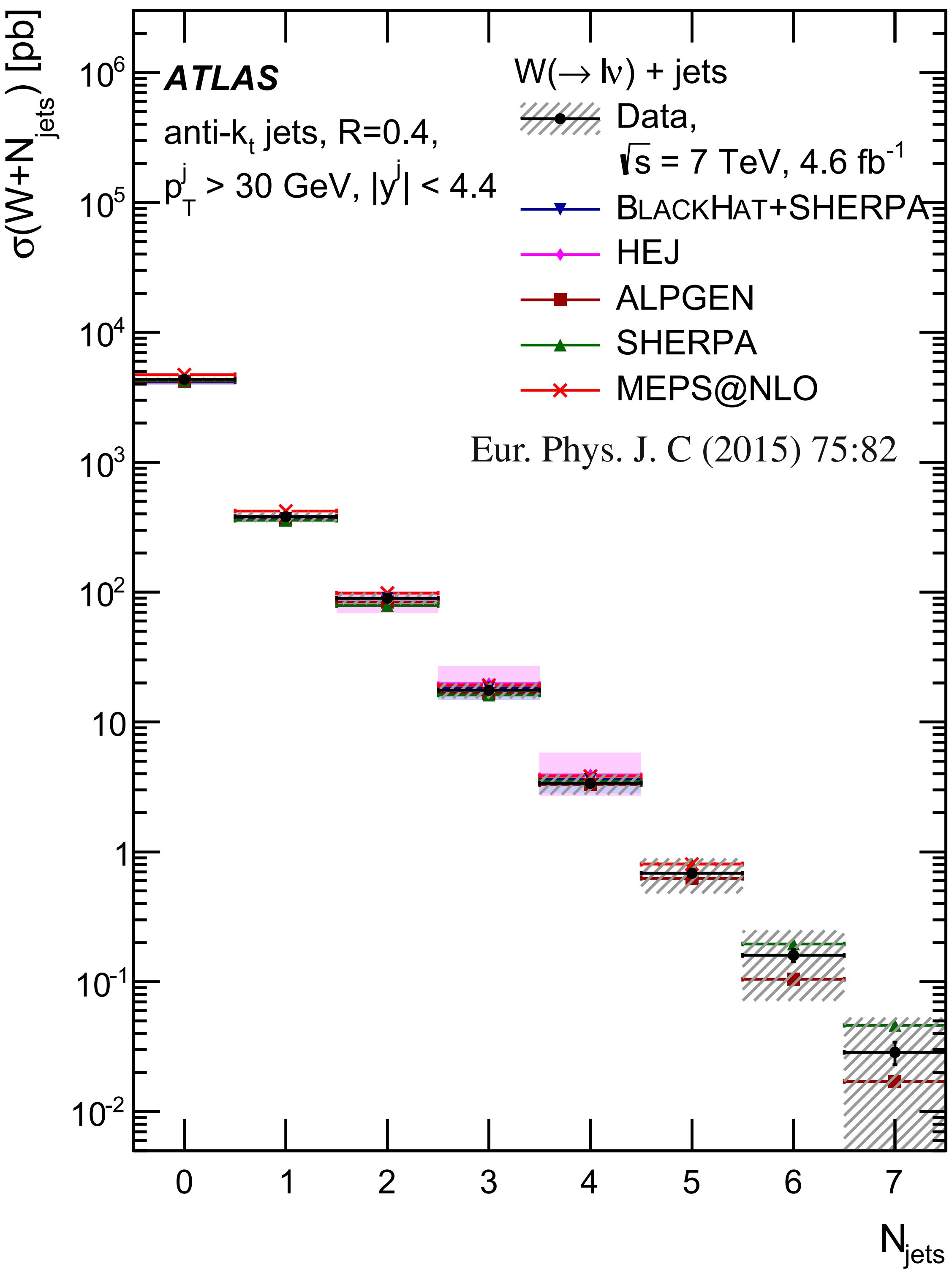



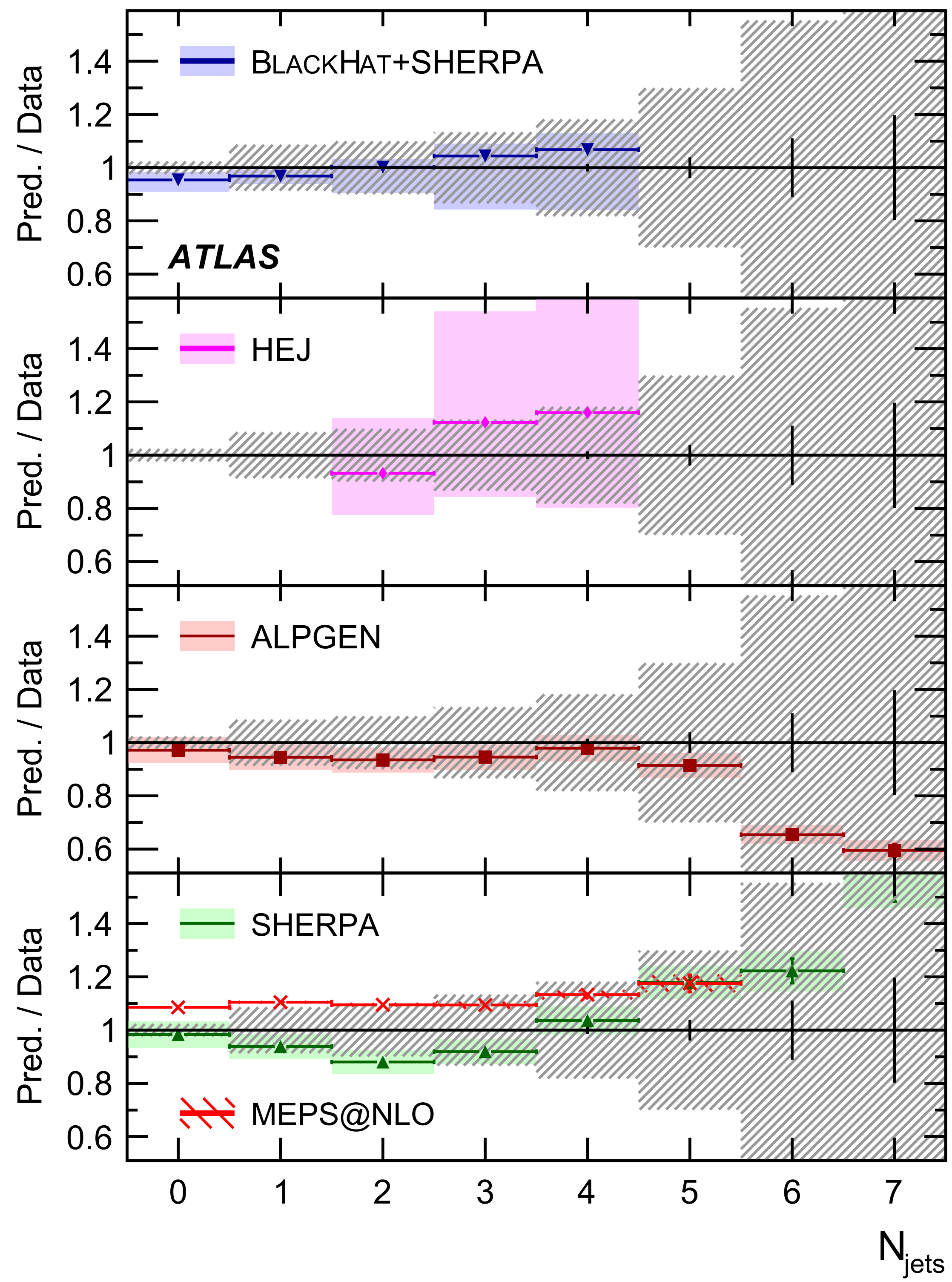




Consequences:

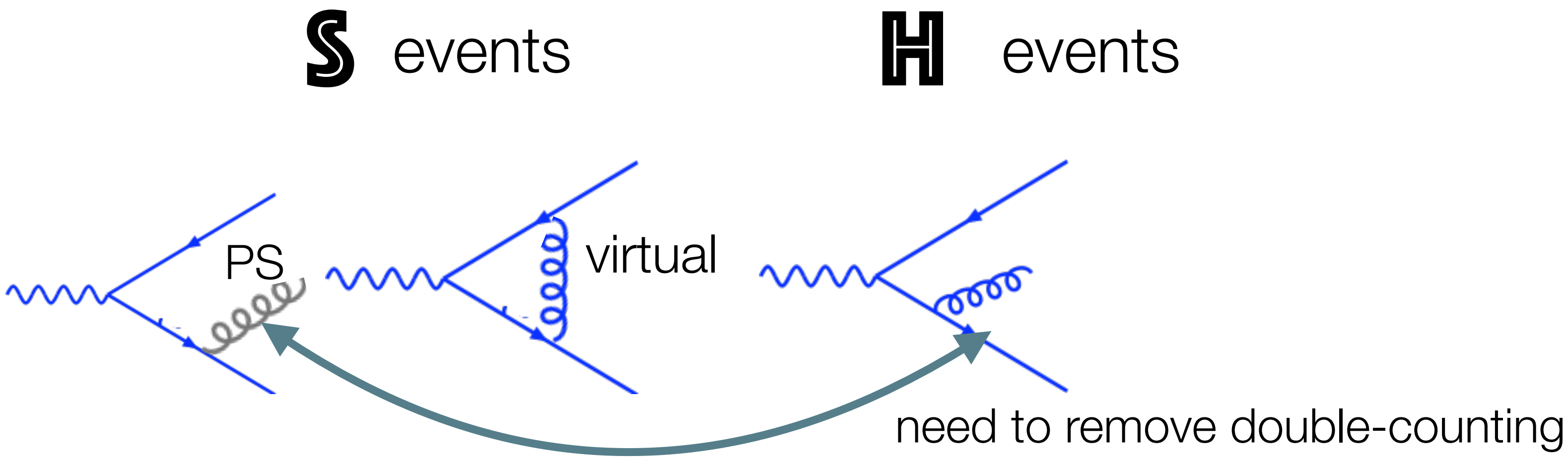
all jets with $p_T$ > 20 GeV and ΔR>0.4 to other jets come from ME
collinear and soft jets come from PS
Use ME and PS where they perform better.

# W+jets distributions

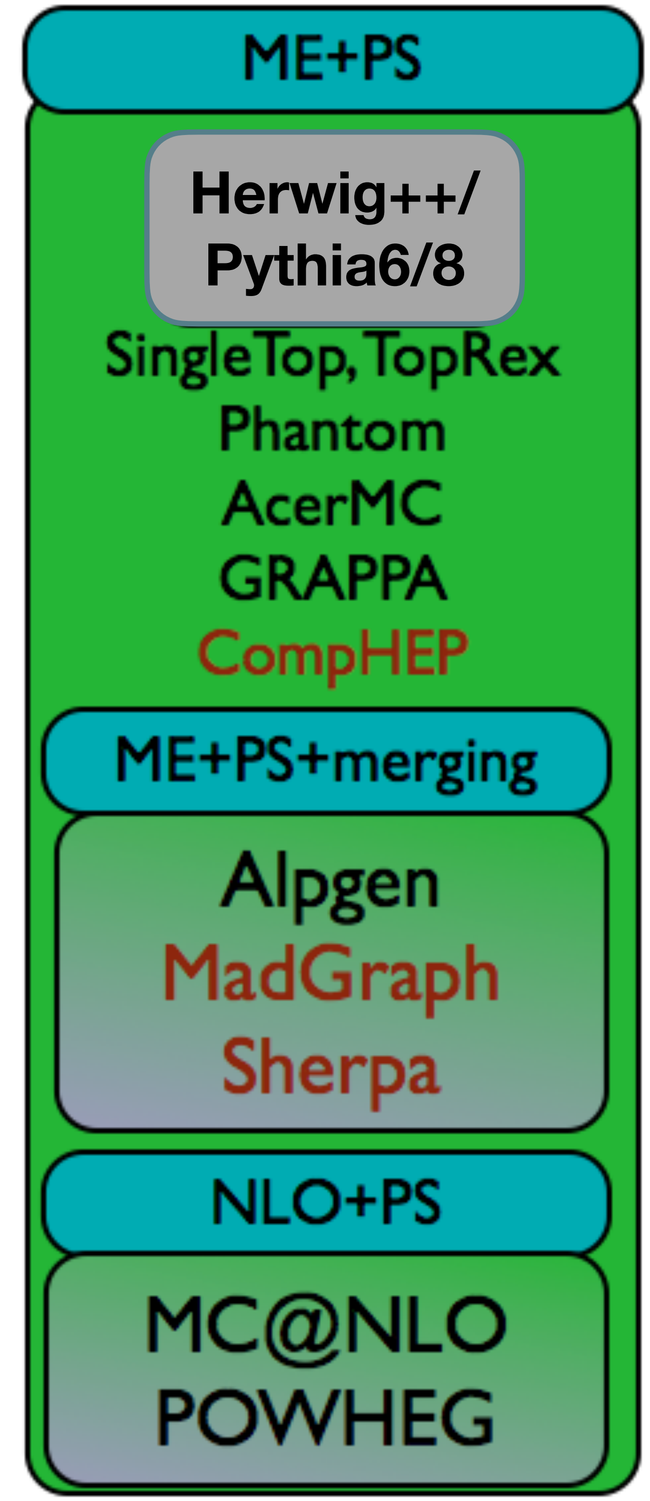


# Type III : Next-to-leading order ME & leading-log parton shower



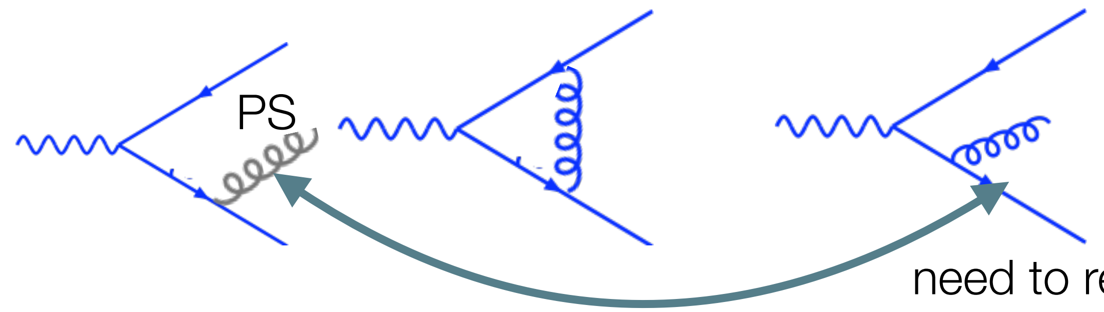

- hard processes simulated at NLO accuracy including real & virtual corrections ...
- improved description of cross sections & kinematic distributions




[F. Maltoni]

# Type 3 : Next-to-leading order ME & leading-log parton shower

S events H events




need to remove double-counting

- hard processes simulated at NLO accuracy including real & virtual corrections ...
- improved description of cross sections & kinematic distributions

Two matching methods:

1. Powheg

Truncated showers:

1) first emission produced by the ME;
2) don't allow the PS to produce patrons harder than the first emission;
3) not exact at NLO (containes unbalanced higher order terms)

2. MC@NLO:

$$|ME|^2 = |ME + PS - PS(\text{up to } \alpha_s^2)|^2$$

+ Result is exact at NLO…
- produce some negative weights, it needs retuning for each PS

**ME+PS**

Herwig++/ Pythia6/8

SingleTop, TopRex

Phantom

virtual

AcerMC

GRAPPA

CompHEP

**ME+PS+merging**

Alpgen

MadGraph

Sherpa

**NLO+PS**

MC@NLO

POWHEG

# Merging @NLO (  used starting from LHC at 13 TeV)

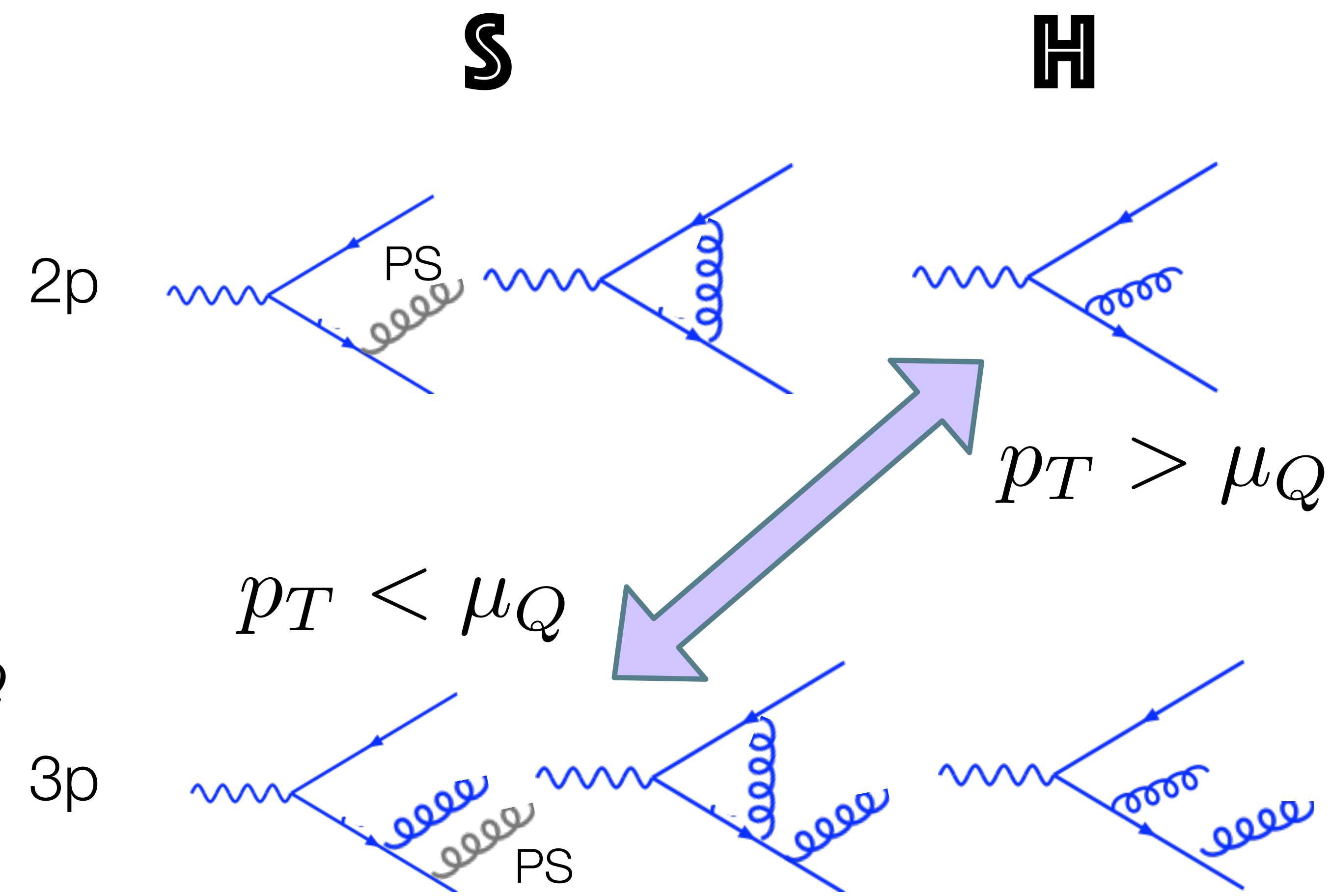
JHEP12(2012)061

FxFx (Frederix-Frixione)  merging

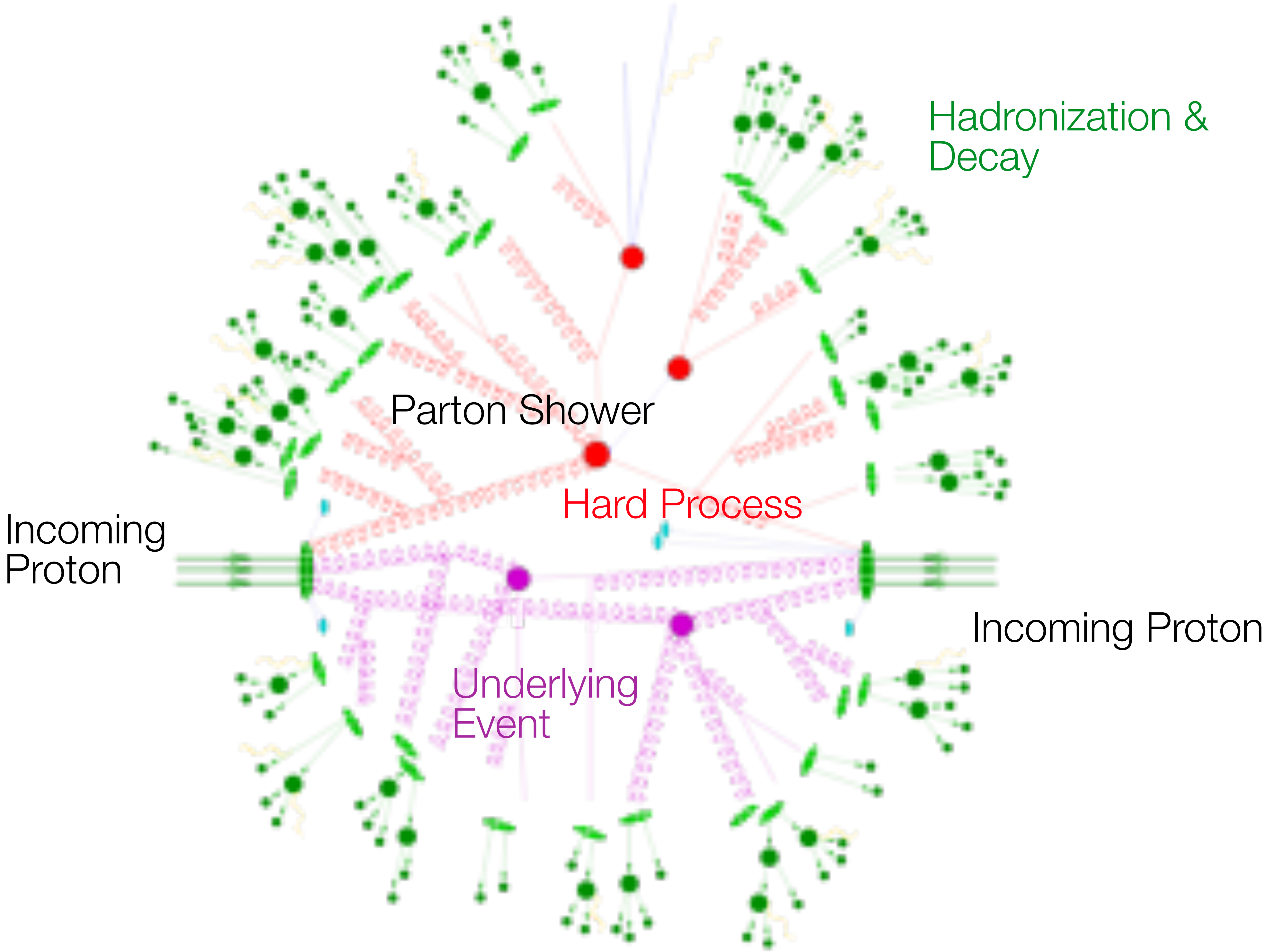
1) define a matching scale $\mu_Q$;

2) don't allow 𝕊 events with $p_T > \mu_Q$
(those will be provided by ℍ events of
n-1 partons NLO real emission);
the restriction is imposed both at ME
and on the shower starting scale $\mu < \mu_Q$

3) treat the obtained events as LO ones
and apply an LO-style merging (this
allow to produce smoother
distributions)



# Let’s recap

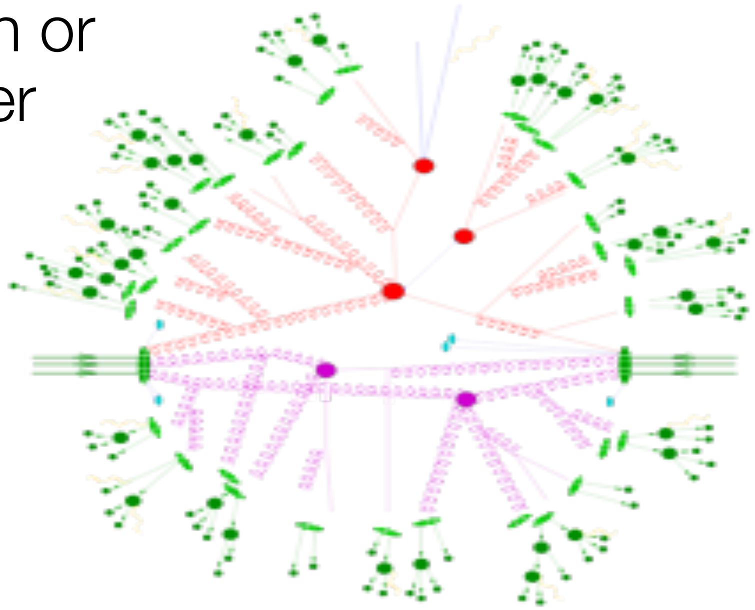





[T. Gleisberg et al., JHEP02 (2004) 056]

# From partons to color neutral hadrons

Fragmentation or
Parton Shower



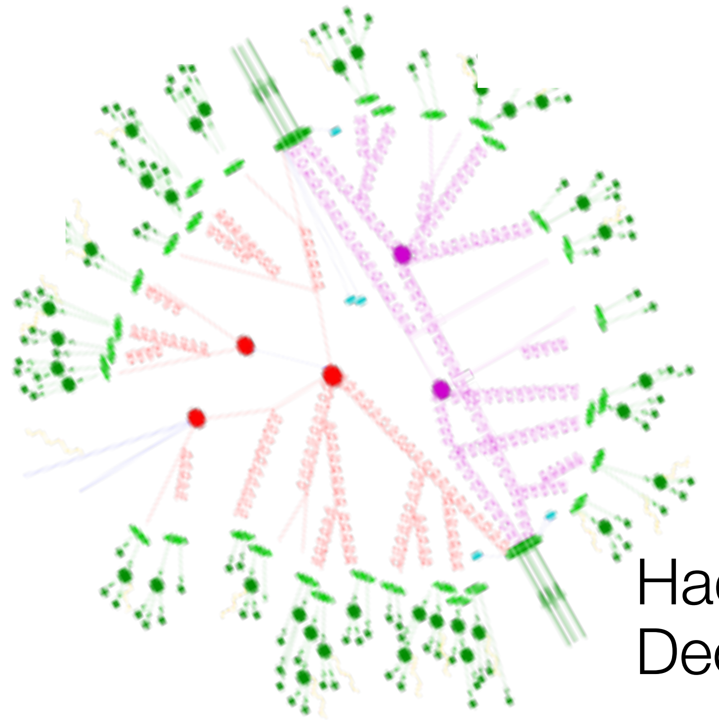
Fragmentation:

Parton splitting into other partons
[QCD: re-summation of leading-logs]
["Parton shower"]

Hadronization:

Parton shower forms hadrons
[non-perturbative, only models]

Decay of unstable hadrons
[perturbative QCD, electroweak theory]



Hadronization &
Decays

# Non-perturbative transition from partons to hadrons ...

[Modelling relies on phenomenological models available]

Models based on MC simulations
very successful:

Generation of complete final states ...
[Needed by experimentalists in detector simulation]

Caveat: tunable ad-hoc parameters

Most popular MC models:

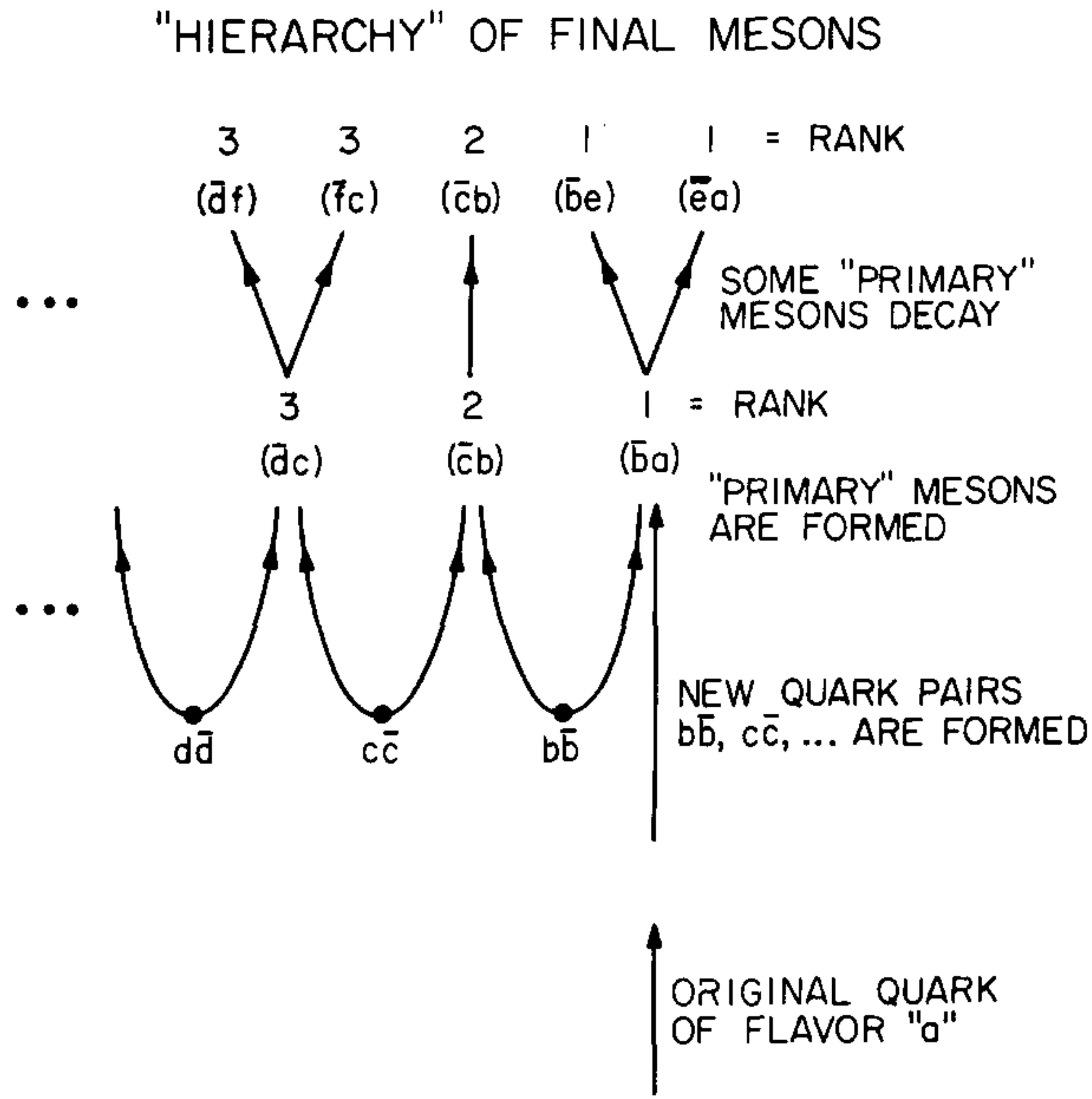
Pythia/8 : Lund string model
Sherpa, Herwig/++: Cluster model

# Independent fragmentation of each parton

Simplest approach:
[Field, Feynman, Nucl. Phys. B136 (1978) 1]

- Start with original quark
- Generate quark-antiquark pairs from vacuum
  - ➛ form "primary meson" with energy fraction z
- Continue with leftover quark with energy fraction 1–z
- Stop at low energies (cut-off)
- Include flavour non-perturbative fragmentation functions D(z)

D(z): probability to find a meson/hadron with energy fraction z in jet ...



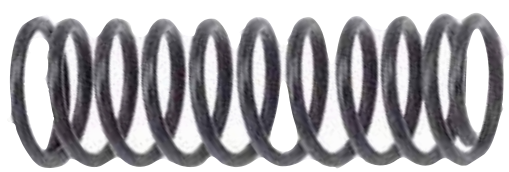
# Lund String Model

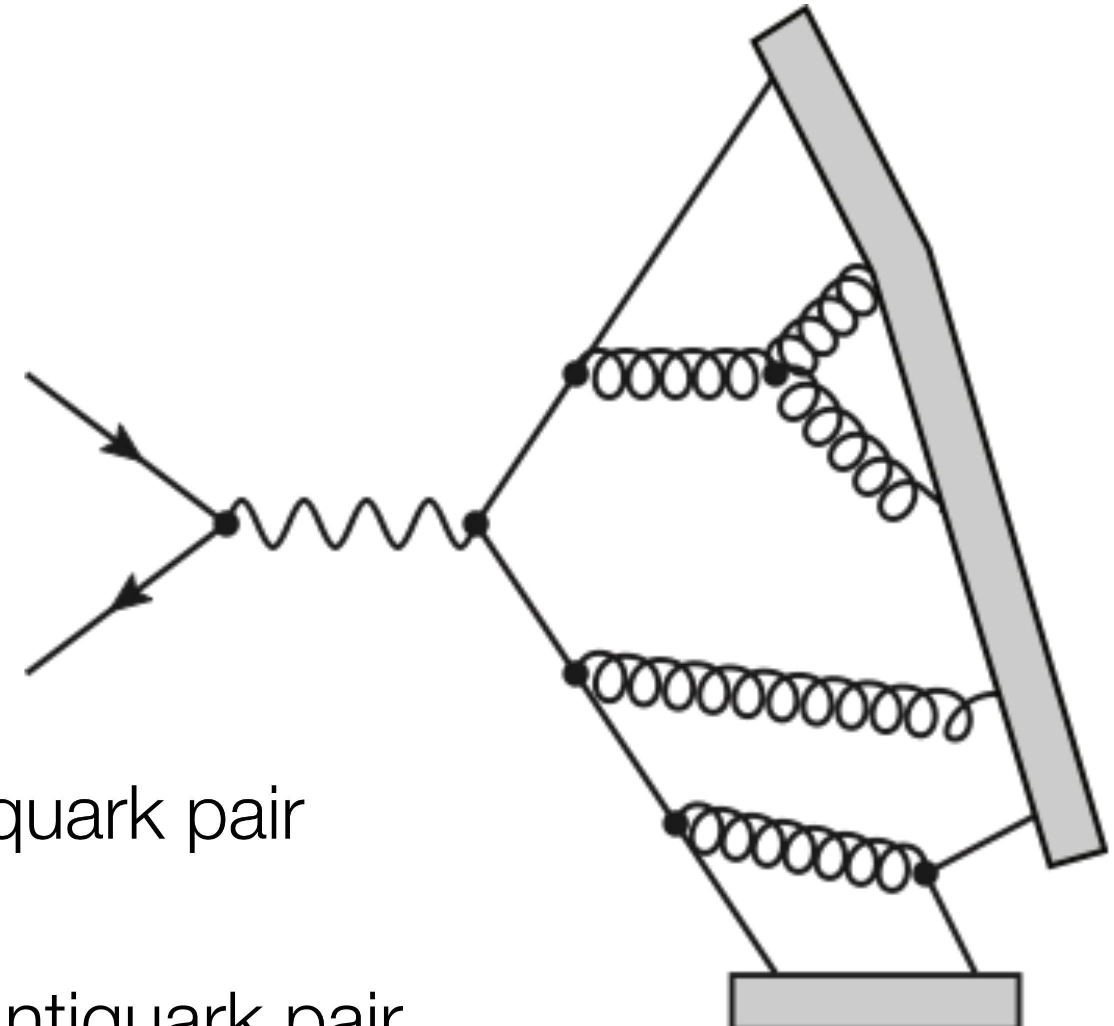
[Andersson et al., Phys. Rep. 97 (1983) 31]

QCD potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s(1/r^2)}{r} + kr$$

neglected





String formation between initial quark-antiquark pair

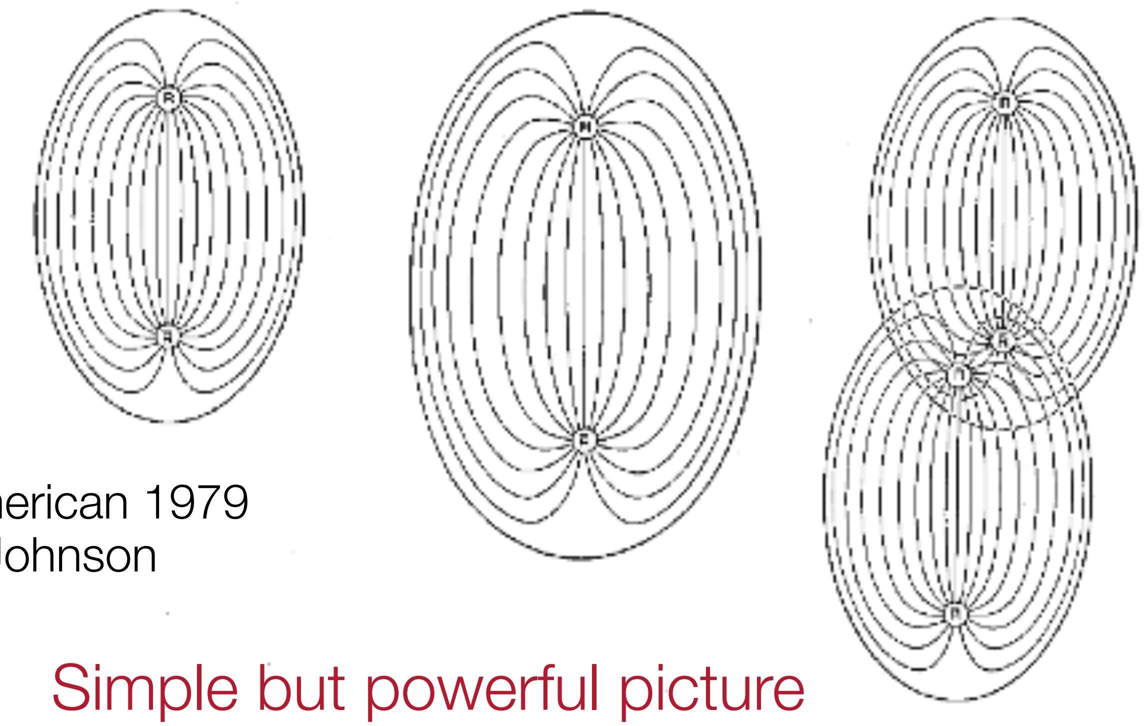
- String breaks up if potential energy is
  large enough to produce a new quark-antiquark pair
- Gluons = 'kinks' in string
- At low energy: hadron formation
- Very widely used … [default in Pythia 6/8]

# Lund String Model

Repeated string breaks for large system with pure V(r) = κ·r

$$\left|\frac{\mathrm{d}E}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}t}\right| = \kappa$$

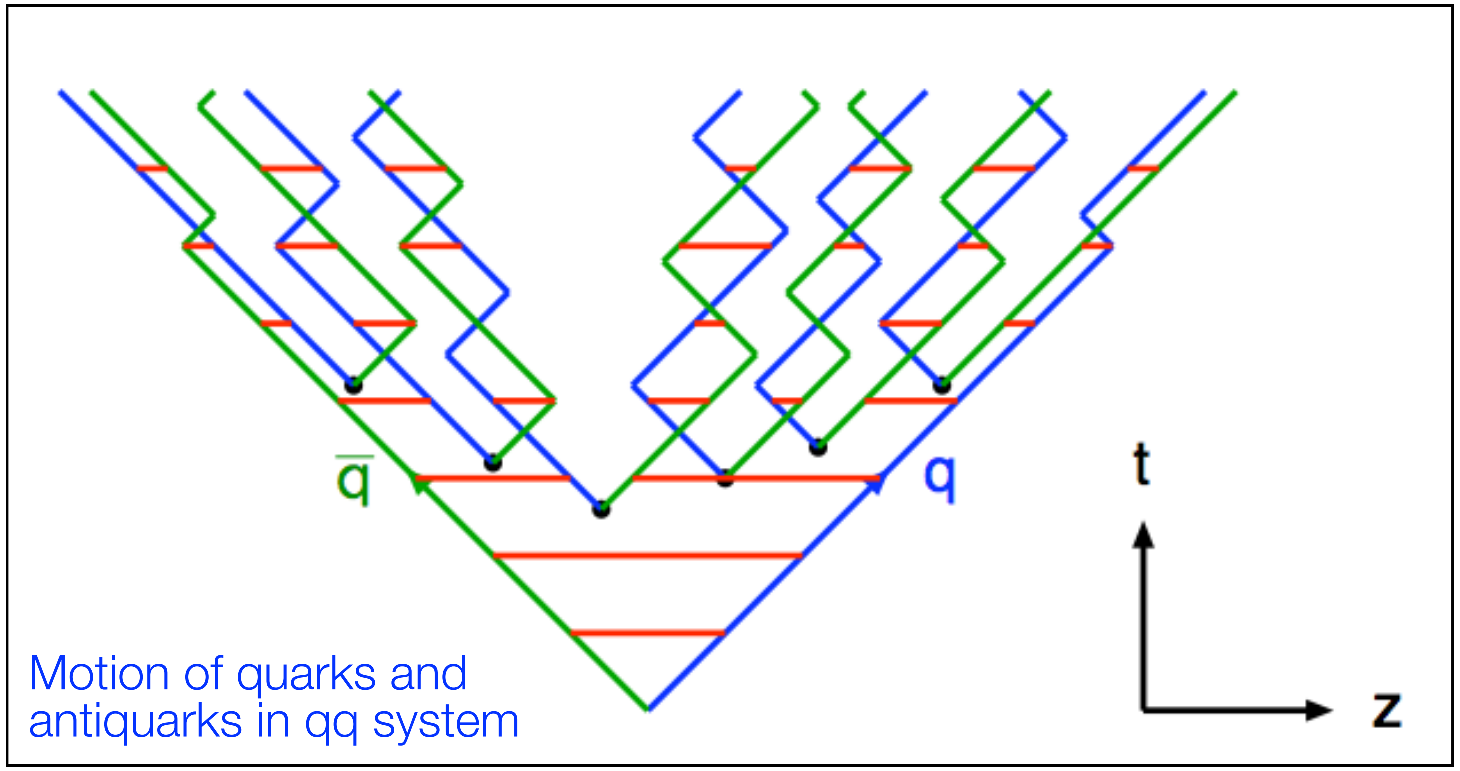
Energy-momentum quantities can be read from space-time quantities …



Scientific American 1979
Kenneth A. Johnson

Simple but powerful picture of hadron production

[with extensions to massive quarks, baryons, ...]




$$m_\perp^2 \equiv m_T^2 \equiv p_\perp^2 + m^2 = |\vec{p}_T|^2 + m^2$$

$$\mathcal{P} \propto \exp\left(-\frac{\pi\, m_{\perp q}^2}{\kappa}\right) \propto \exp\left(-\frac{\pi\, p_{\perp q}^2}{\kappa}\right) \exp\left(-\frac{\pi\, m_q^2}{\kappa}\right)$$

Yields: Common Gaussian p⊥ spectrum
Heavy quark suppression

# Cluster Model

[Webber, Nucl. Phys. B238 (1984) 492]

Color flow confined during hadronisation process

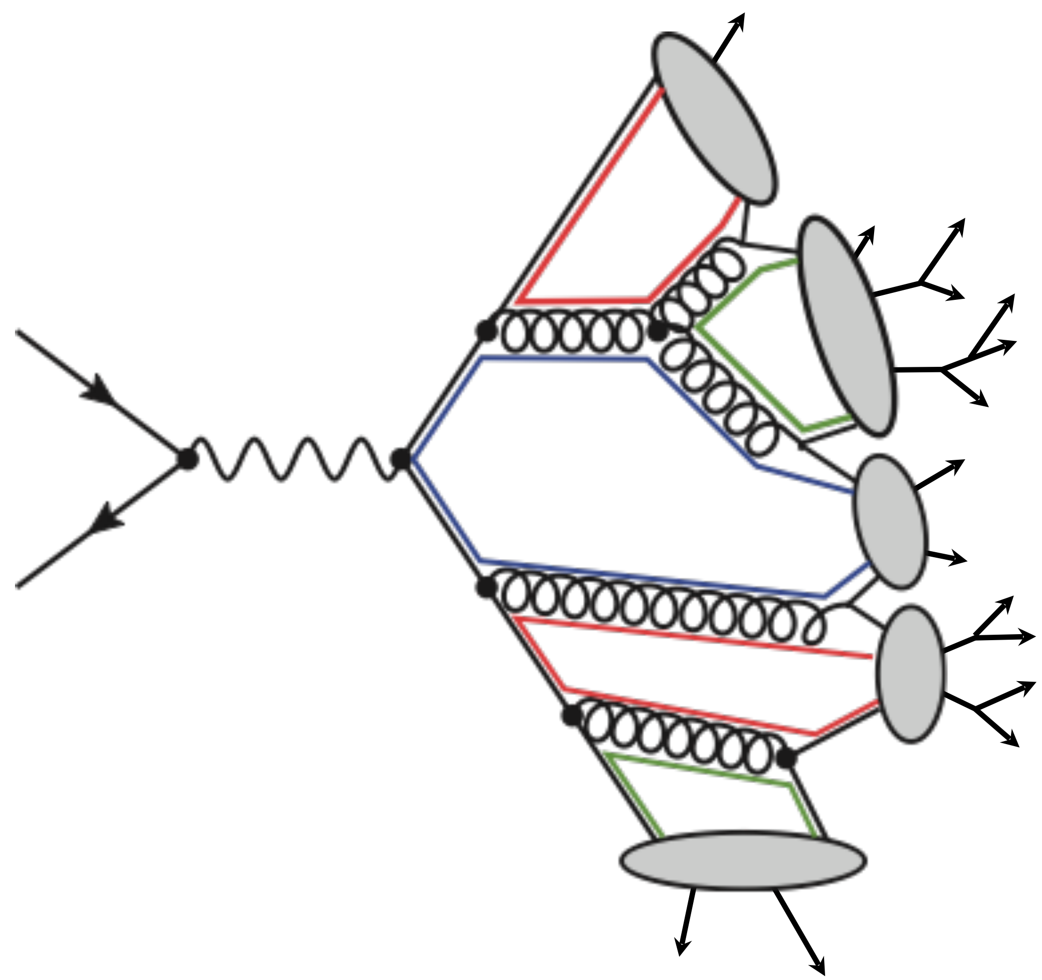
➢ Formation of color-neutral parton clusters

Gluons (color-anticolor) split to quark-antiquark pairs

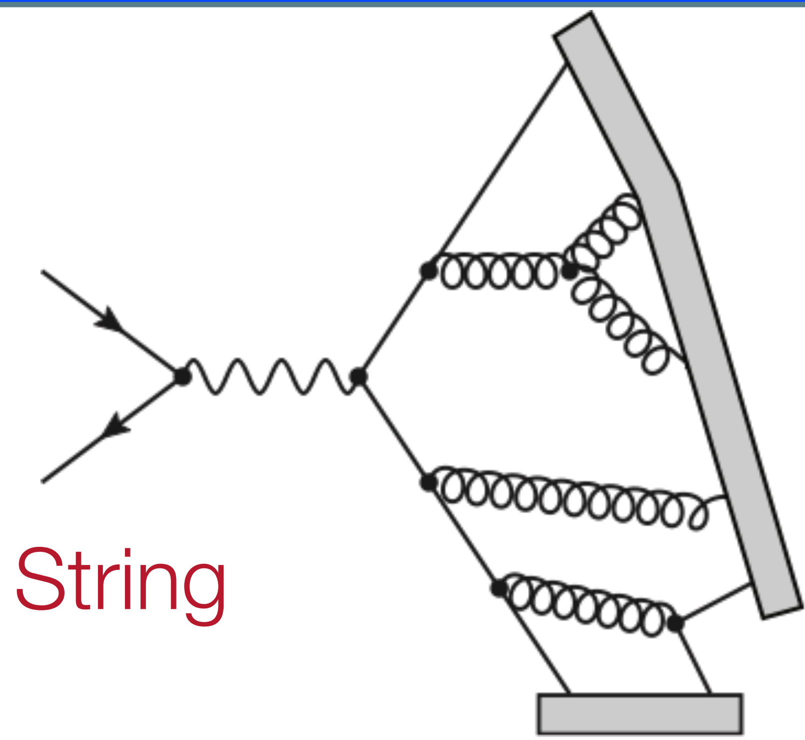
Clusters decay into 2 hadrons according to phase-space, i.e. isotropically

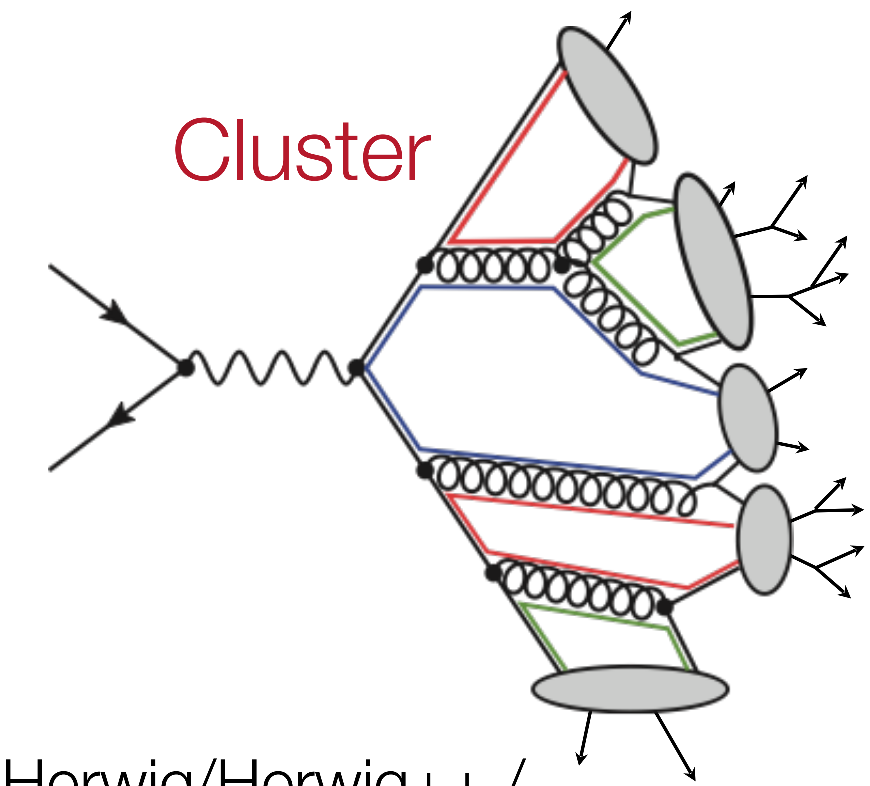
➢ no free tuning parameters parton clusters

Very widely used ...
[default in Herwig/Herwig++, Sherpa with some modifications]



# Hadronisation models summary




| Model | Pythia6/8 (string) | Herwig/Herwig++ / Sherpa(cluster) |
|---|---|---|
| Energy-mom. picture | powerful | simple |
| | predictive | unpredictive |
| Parameters | few | many |
| Flavour composition | messy | simple |
| | unpredictive | in-between |
| Parameters | many | few |



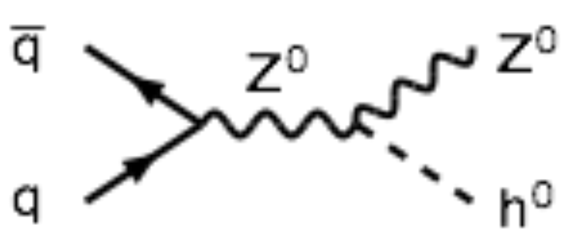
[from G.Herten,T.Sjöstrand]

# Structure of basic generator process [by order of consideration]

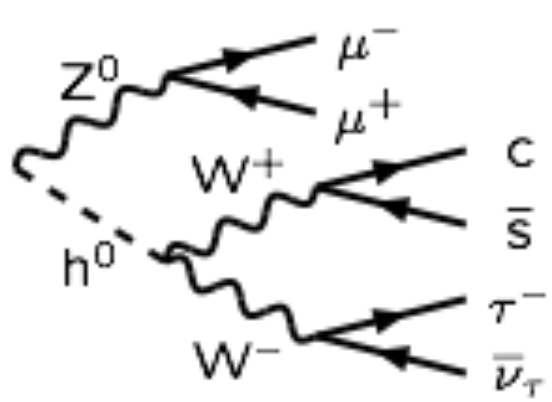
From the 'simple' to the 'complex' or
from 'calculable' at large scales to 'modelled; at small

## Matrix elements (ME)

1. Hard subprocess:
   $|M|^2$, Breit Wigners, PDFs

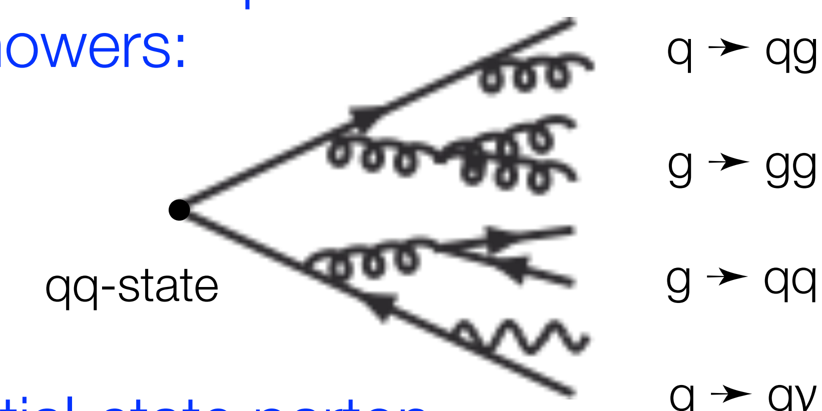



2. Resonance decays:
   Includes particle correlations

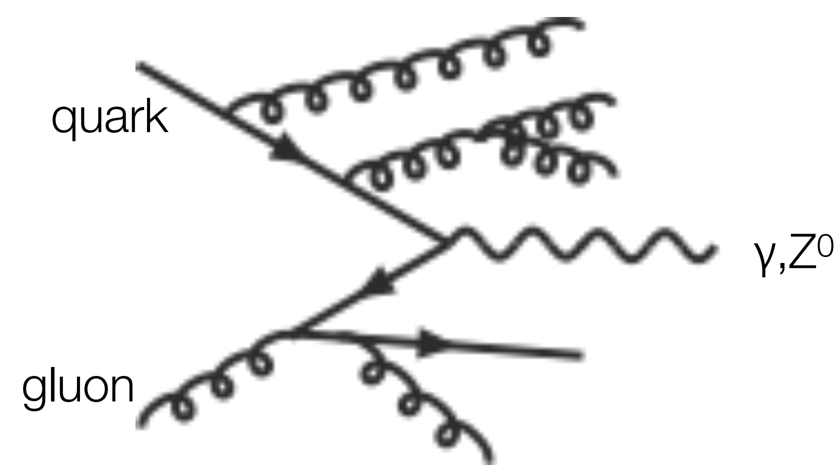



## Parton Shower (PS)

3. Final-state parton
   showers:




4. Initial-state parton
   showers:





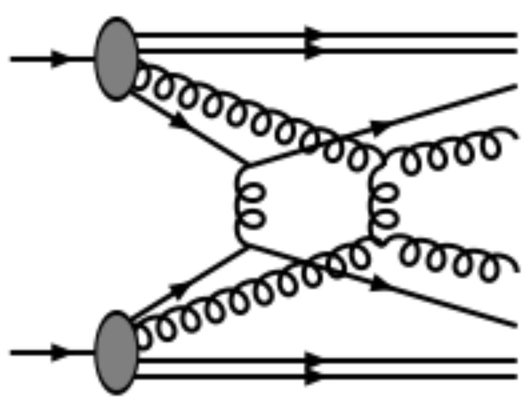

[from G.Herten]

# Conclusions: Structure of basic generator process

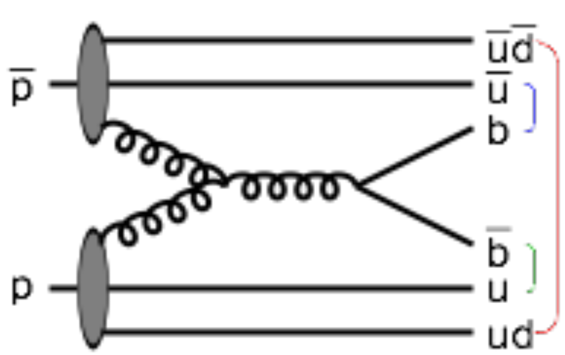
From the 'simple' to the 'complex' or
from 'calculable' at large scales to 'modelled; at small

## Underlying Event (UE)

5. Multi-parton interaction:

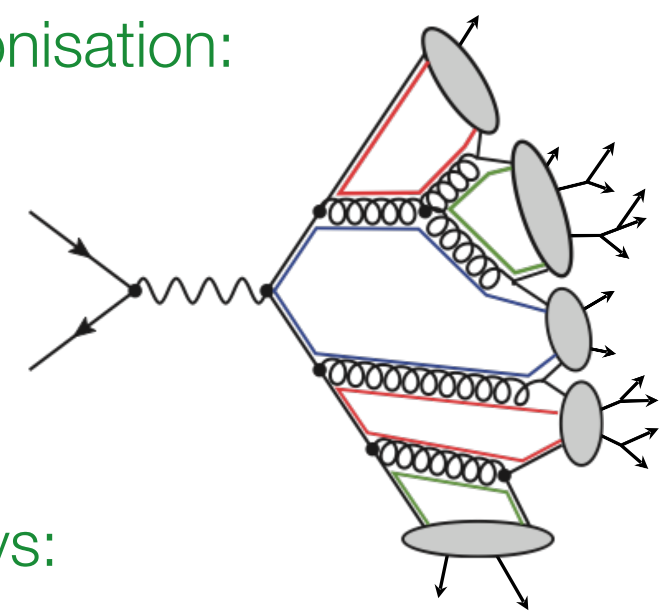


6. Beam remnants:

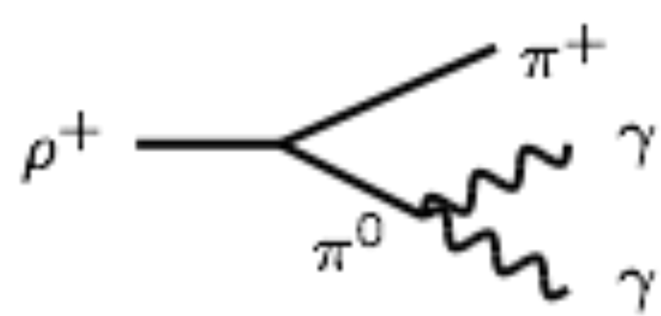



## Stable Particle State

7. Hadronisation:



8. Decays:






[from G.Herten]

The DGLAP evolution equation is said to resum large collinear logarithms. So where are these logarithsm, and where is the resummation?

Let's perform the integration of the DGLAP equation and expand the result:

$$
\begin{aligned}
f(x,t) &= f_0(x) + \int_{t_0}^{t} \frac{dt'}{t'} \frac{\alpha_s(t')}{2\pi} \int_x^1 \frac{dz}{z} P(z)\, q\left(\frac{x}{z}, t'\right) \\
&= f_0(x) + \int_{t_0}^{t} \frac{dt'}{t'} \frac{\alpha_s}{2\pi} \int_x^1 \frac{dz}{z} P(z) \Bigg\{ f_0\left(\frac{x}{z}\right) + \\
&\qquad + \int_{t_0}^{t'} \frac{dt''}{t''} \frac{\alpha_s}{2\pi} \int_{x/z}^1 \frac{dz'}{z'} P(z') \left[ f_0\left(\frac{x}{zz'}\right) + \ldots \right] \Bigg\} \\
&= f_0(x) + \frac{\alpha_s}{2\pi} \ln\left(\frac{t}{t_0}\right) \int_x^1 \frac{dz}{z} P(z)\, f_0\left(\frac{x}{z}\right) + \\
&\quad + \frac{1}{2!} \left[ \frac{\alpha_s}{2\pi} \ln\left(\frac{t}{t_0}\right) \right]^2 \int_x^1 \frac{dz}{z} P(z) \int_{x/z}^1 \frac{dz'}{z'} P(z')\, f_0\left(\frac{x}{zz'}\right) + \ldots
\end{aligned}
$$

As suggested by the last step, it is indeed a resummation of all terms proportional to $\left[\frac{\alpha_s}{2\pi} \ln\left(\frac{t}{t_0}\right)\right]^n$.



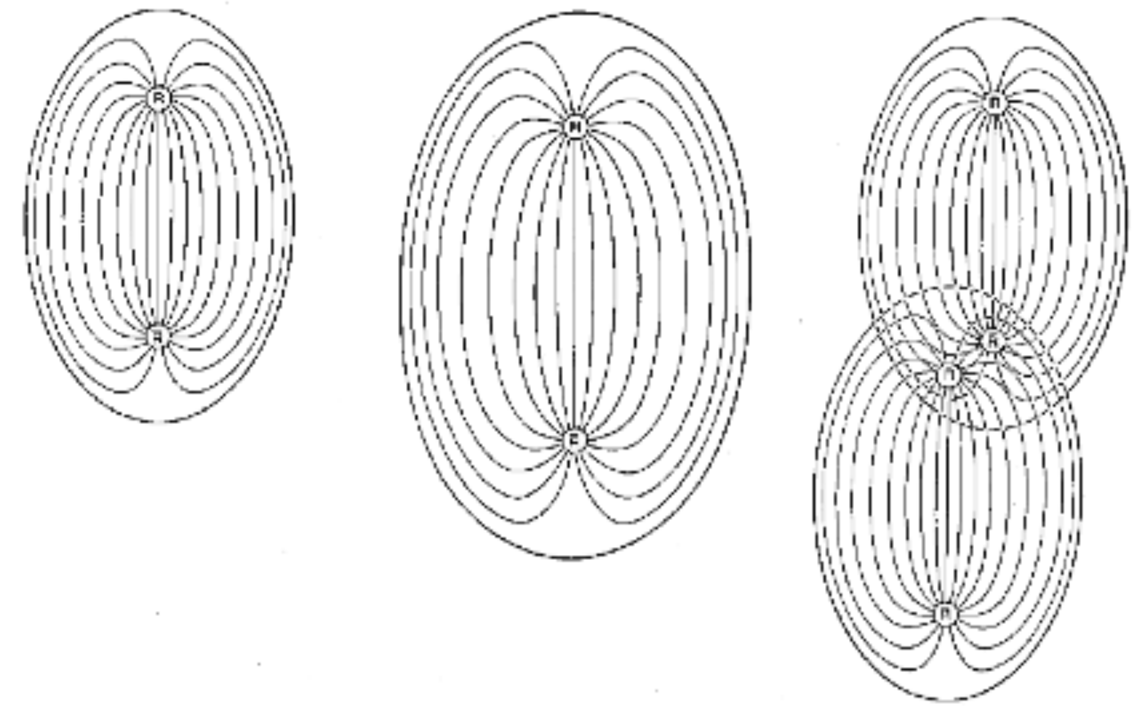
[from J.Alwall]

# Lund String Model

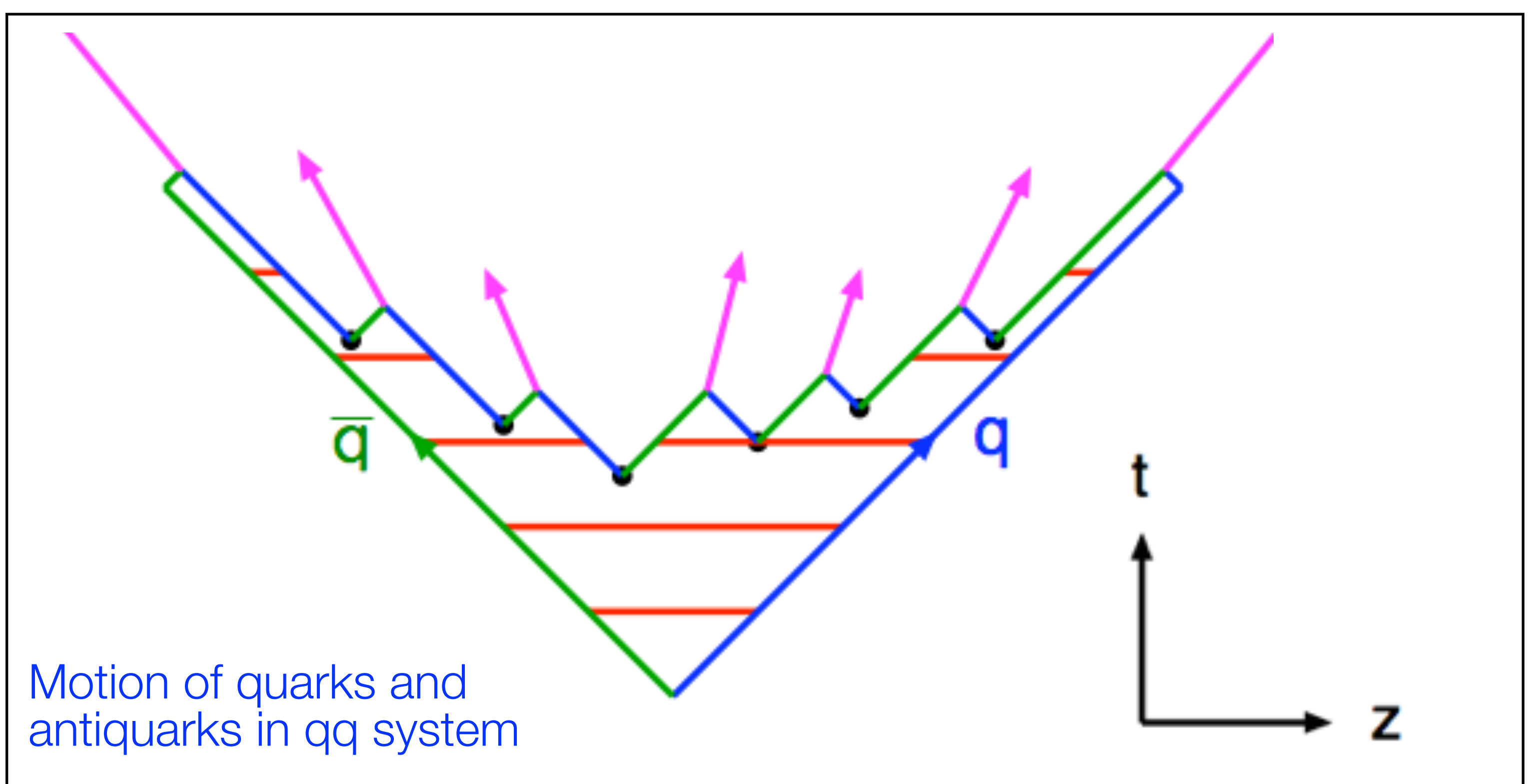
Repeated string breaks for large system
with pure V(r) = κ·r

$$\left|\frac{\mathrm{d}E}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}t}\right| = \kappa$$

Energy-momentum quantities can be
read from space-time quantities ...



Kenneth A. Johnson




Motion of quarks and
antiquarks in qq system

Simple but powerful picture
of hadron production

[with extensions to massive quarks, baryons, ...]

$$\mathcal{P} \propto \exp\left(-\frac{\pi\, m_{\perp q}^2}{\kappa}\right)$$
$$\propto \exp\left(-\frac{\pi\, p_{\perp q}^2}{\kappa}\right) \exp\left(-\frac{\pi\, m_q^2}{\kappa}\right)$$

Yields: Common Gaussian p⊥ spectrum
Heavy quark suppression