Monte... ...ers

High en...

Run 189483, Ev. no. 90659667
Sep. 19, 2011, 10:11:20 CEST

ATLAS
EXPERIMENT
http://atlas.ch

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ candidate and two jets with VBF topology

Longitudinal view

Projected η-φ view

electron

muon

jet

MET

jet

p_T [GeV]

45
35
25
15
5

-4
-2
0
2
4

η

360°   180°   0°
φ

Run 214680, Ev. no. 271333760
Nov. 17, 2012, 07:42:05 CET

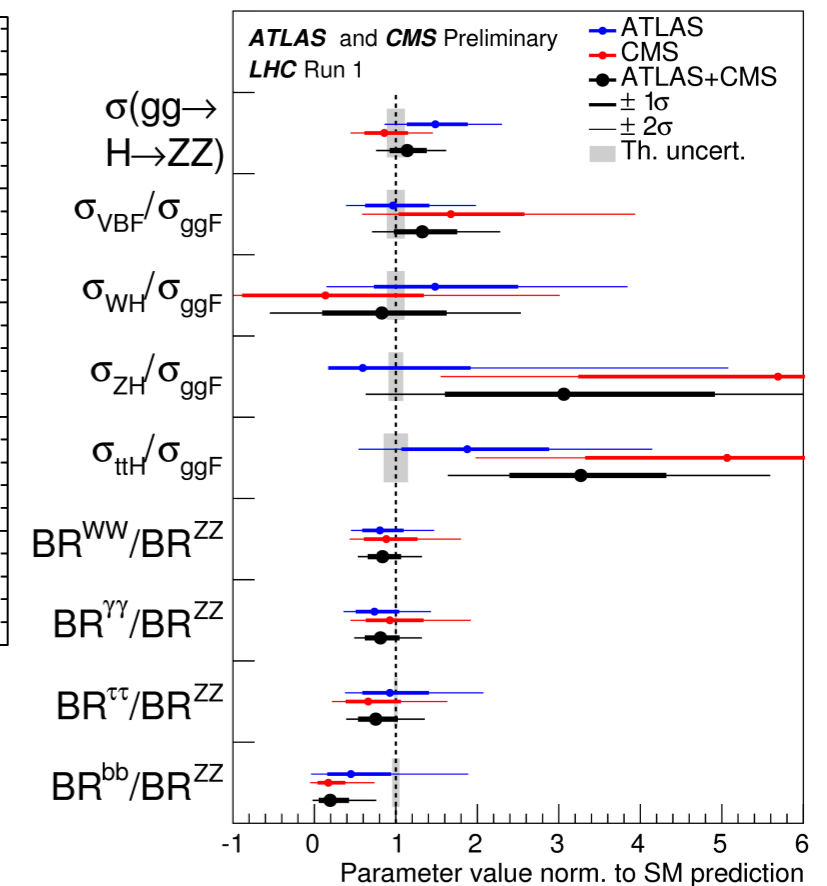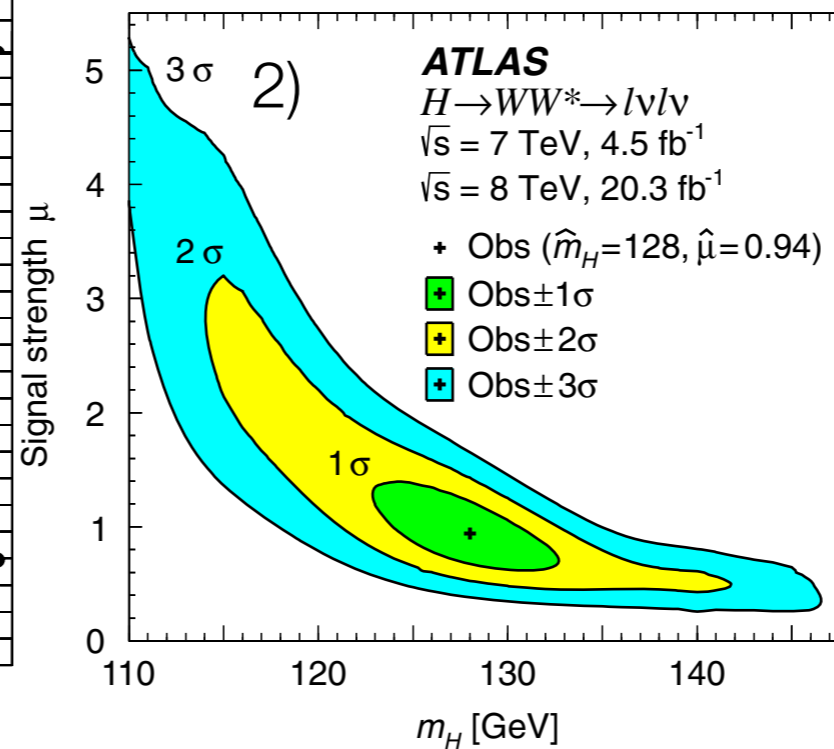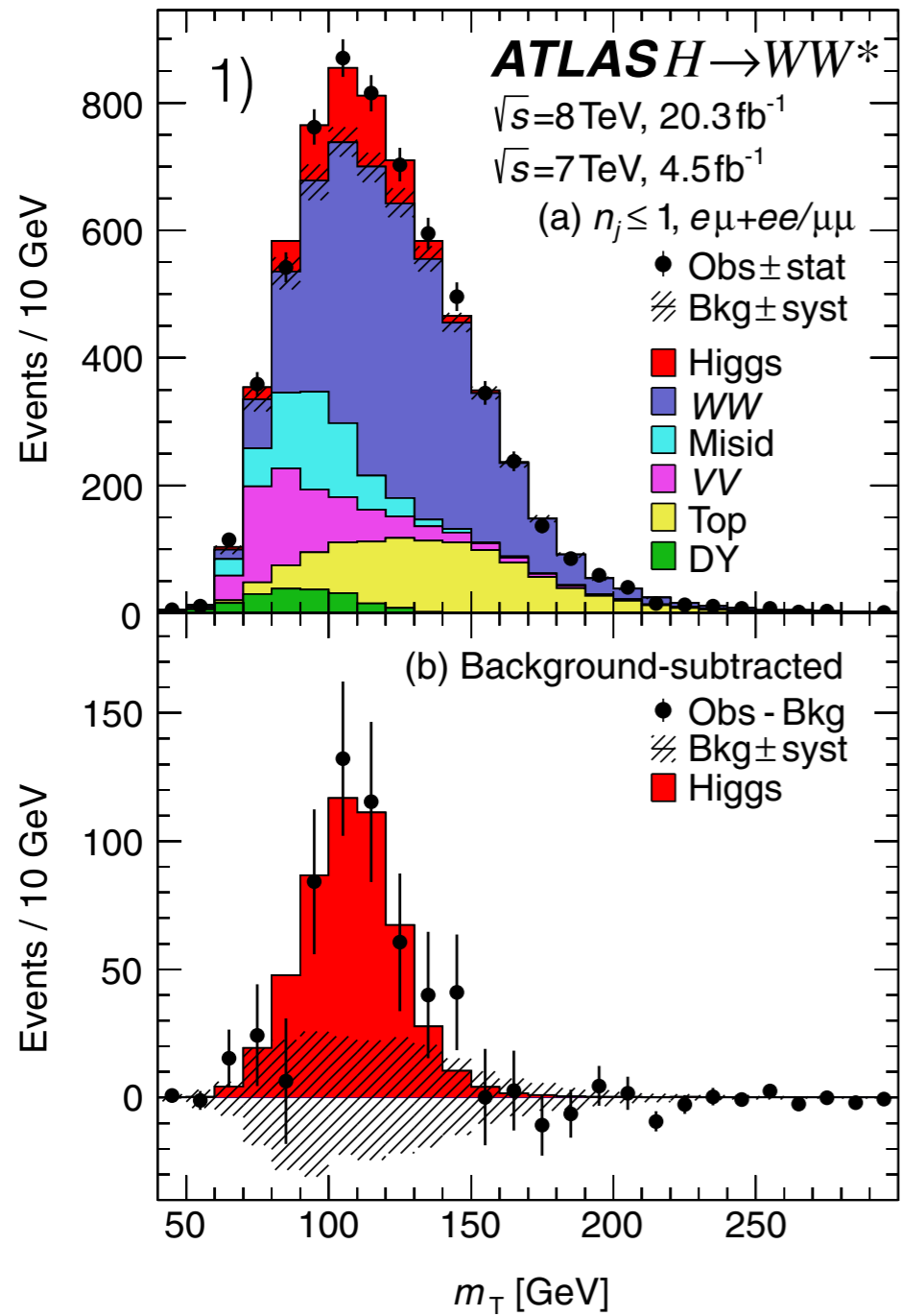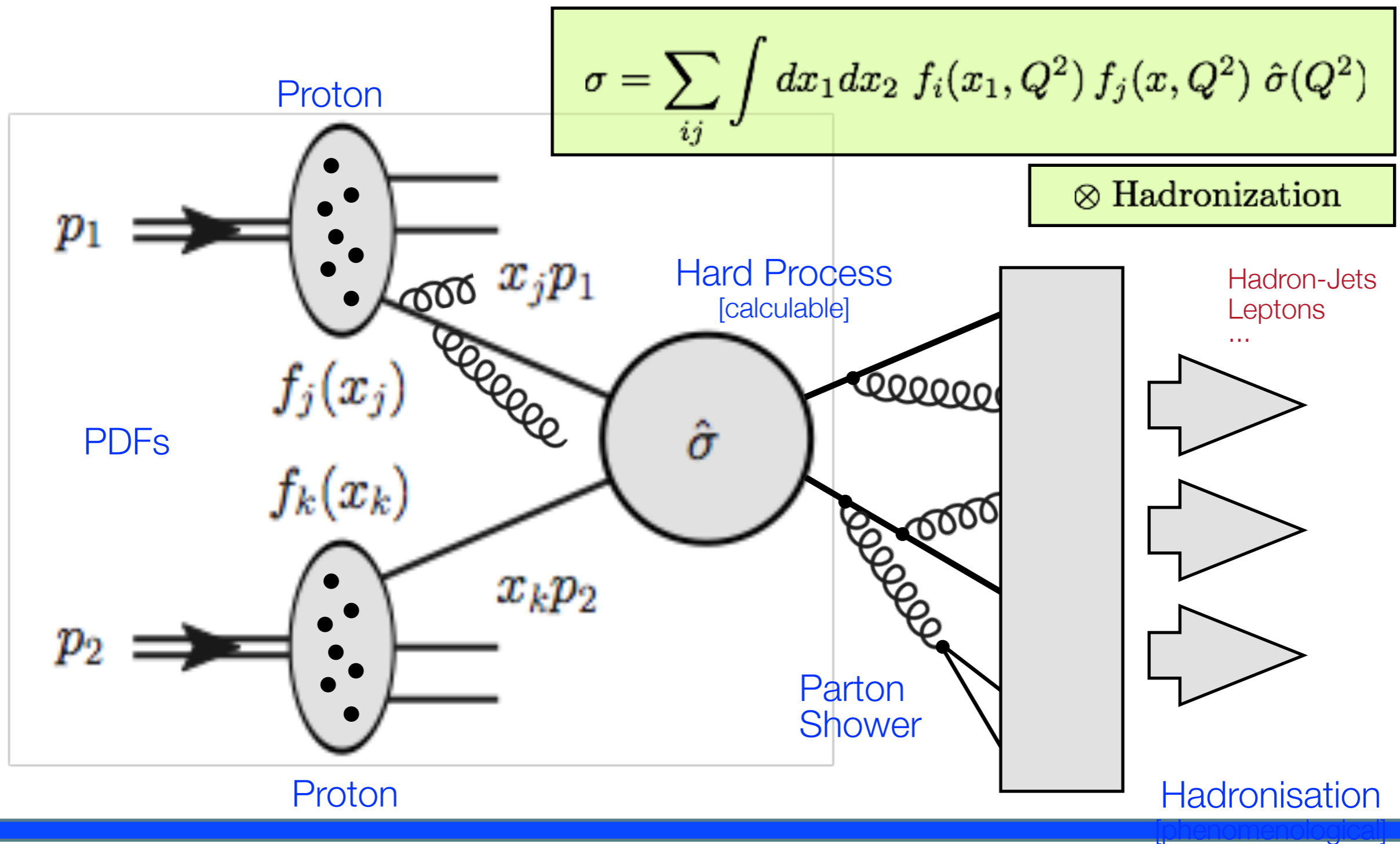**ATLAS**
EXPERIMENT
http://atlas.ch

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

Proton

p_1

$f_j(x_j)$

$x_j p_1$

PDFs

$f_k(x_k)$

$x_k p_2$

p_2

Proton

Hard Process
[calculable]

$\hat{\sigma}$

Parton
Shower

Hadron-Jets
Leptons
...

Hadronisation
[phenomenological]

MC simulations in particle physics

How Monte Carlo simulation works

- Numerical process generation based on random numbers

- Very powerful method in particle physics
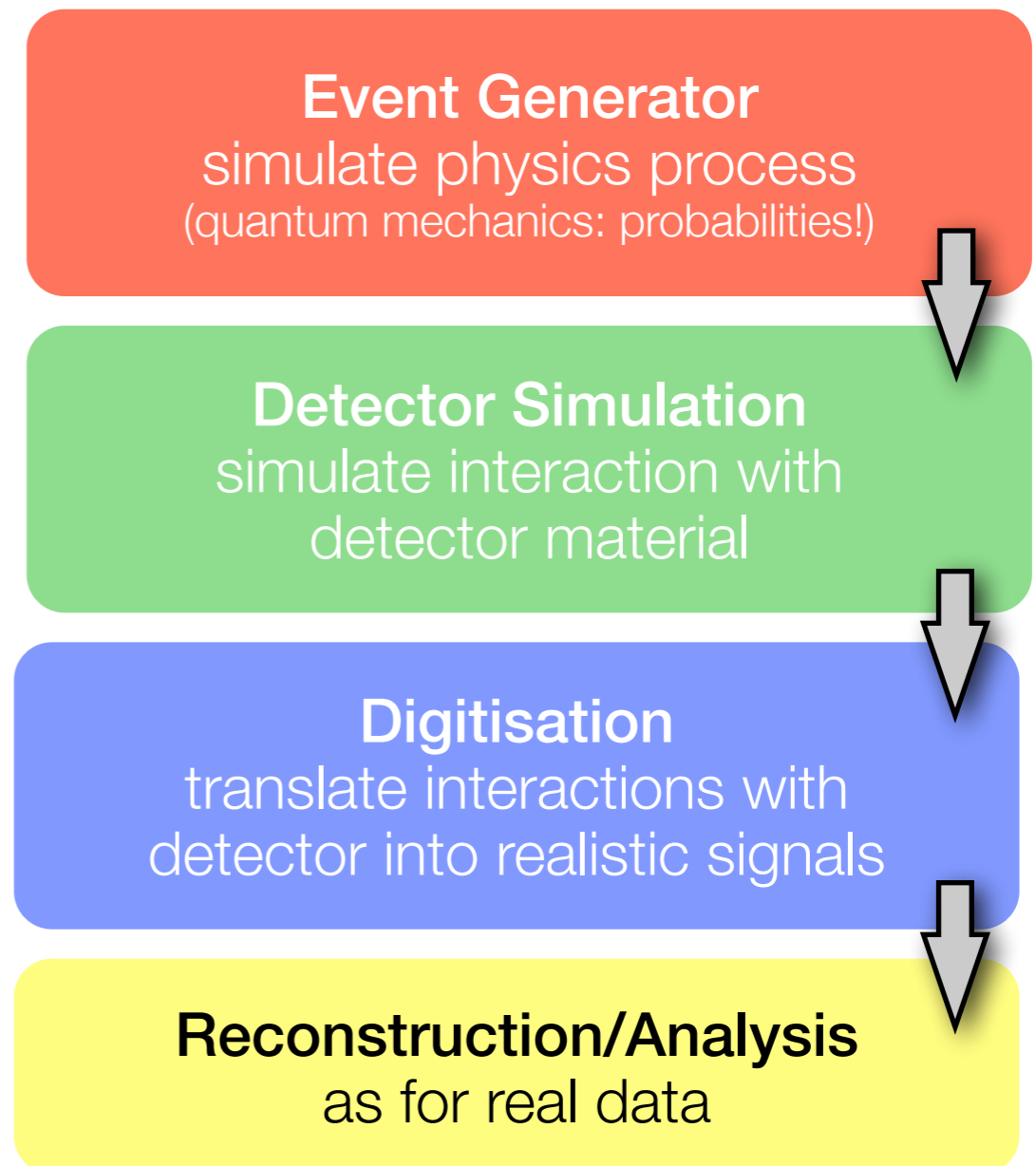
Event generation programs:

Pythia Herwig, Sherpa…

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

Detector simulation:

**Geant4
Fluka low energy hadron interactions…**

interaction & response
of all produced particles …

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

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 $h \to \gamma\gamma$ decay
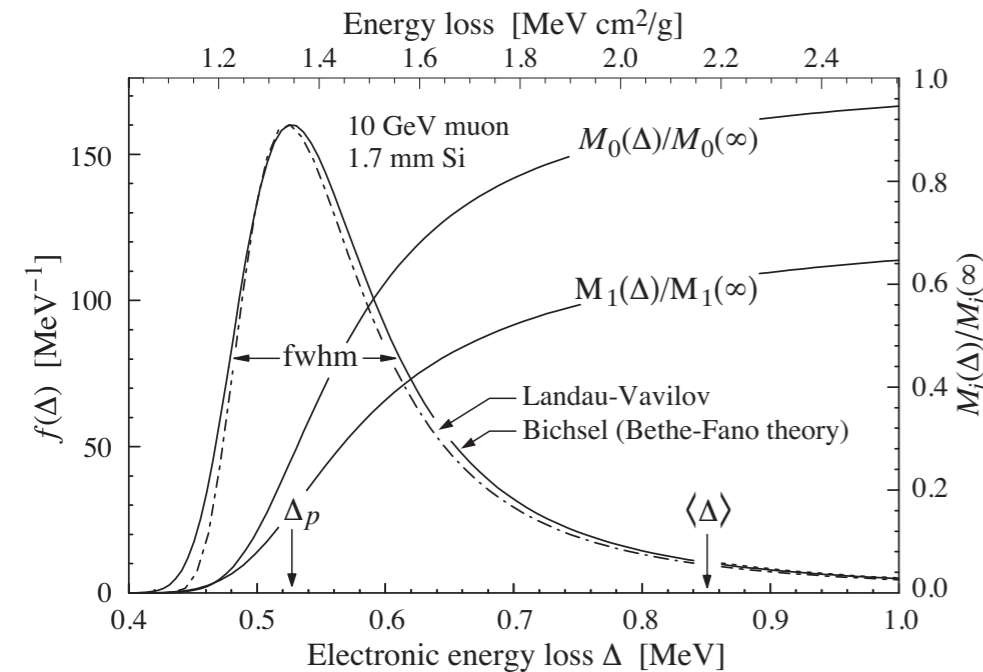
$$dP = f(x,..)dx$$

↳   ↳ distribution formula
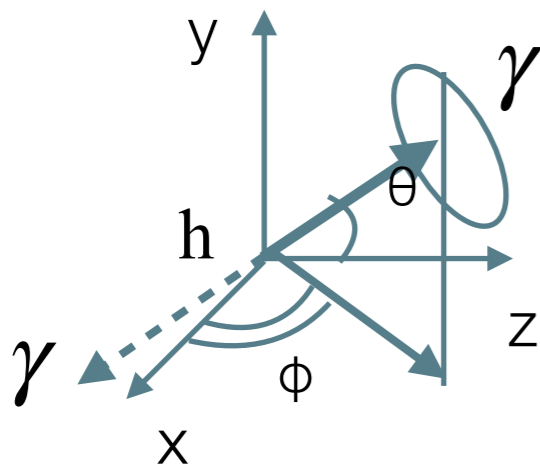
probability to get an x_0 value between x and x+dx

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

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

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

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

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

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

Ex1.: range map

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

$$f(x) = 1 \quad g'(x) = b - a \quad h(y) = \frac{1}{b-a} \qquad$$ y is uniformly distributed in [a,b]

uniform

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 -> $dP_x = f(x)dx$

1) advantages:

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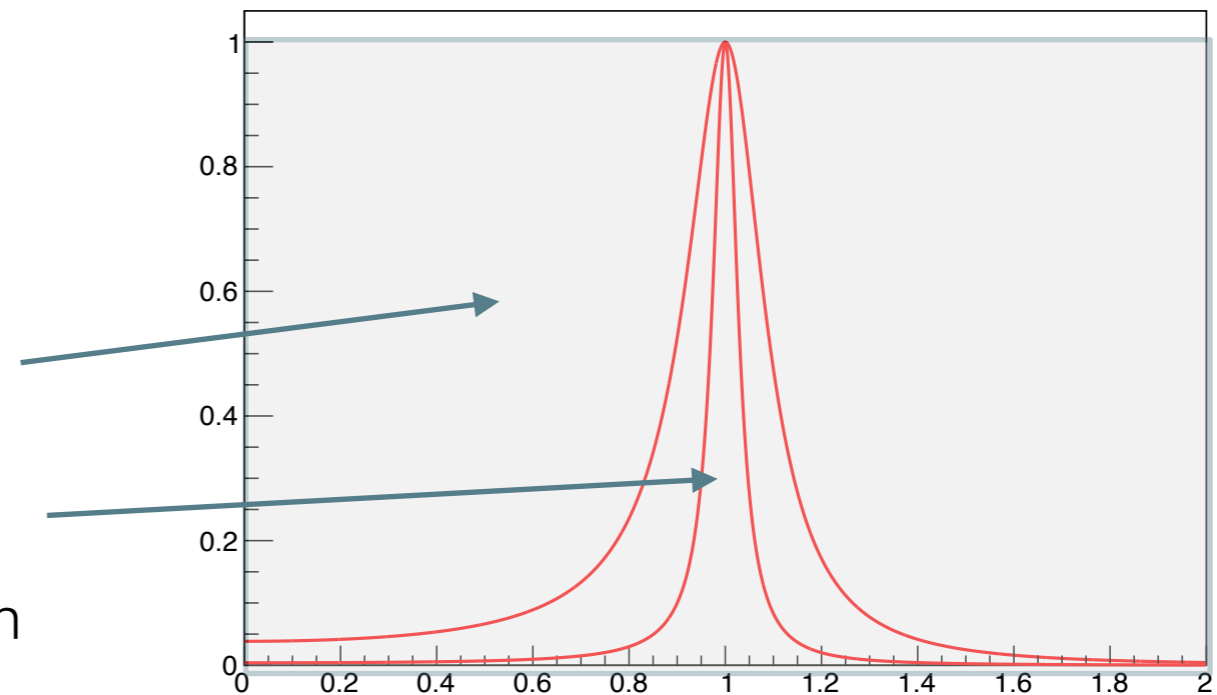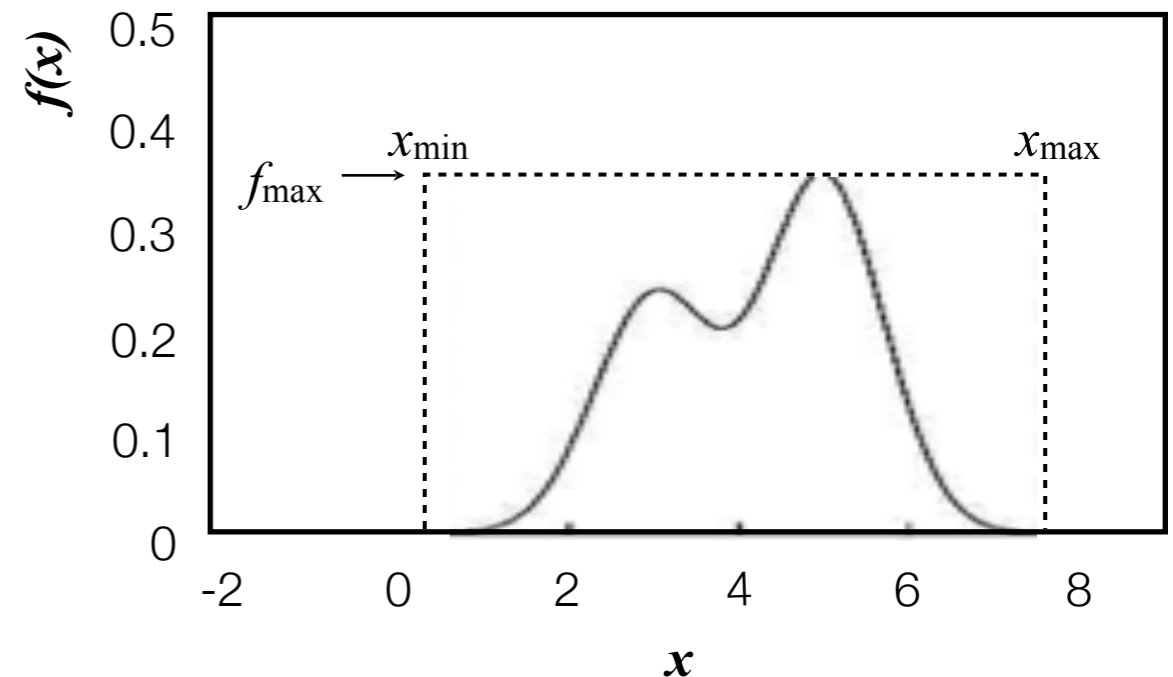- can be extended to N-dimension (generate $x_1, x_2, …, x_n$), y accept if y < f($x_1, x_2, .., x_n$)

2) disadvantages

- can be extremely slow

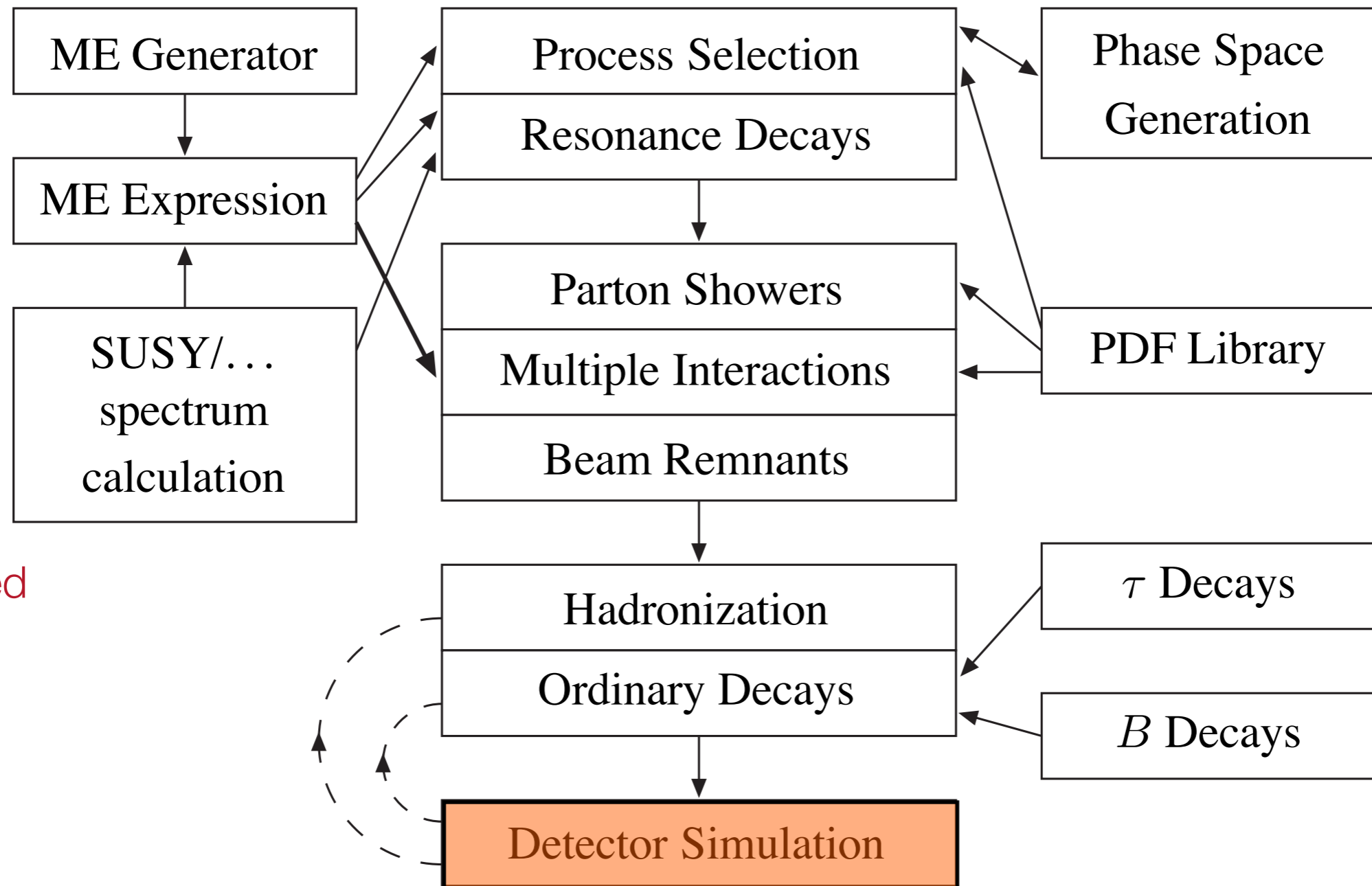points generated uniformly in the square

points accepted only below the curve

MC generators implement "smart" generation
techniques to increase efficiencies

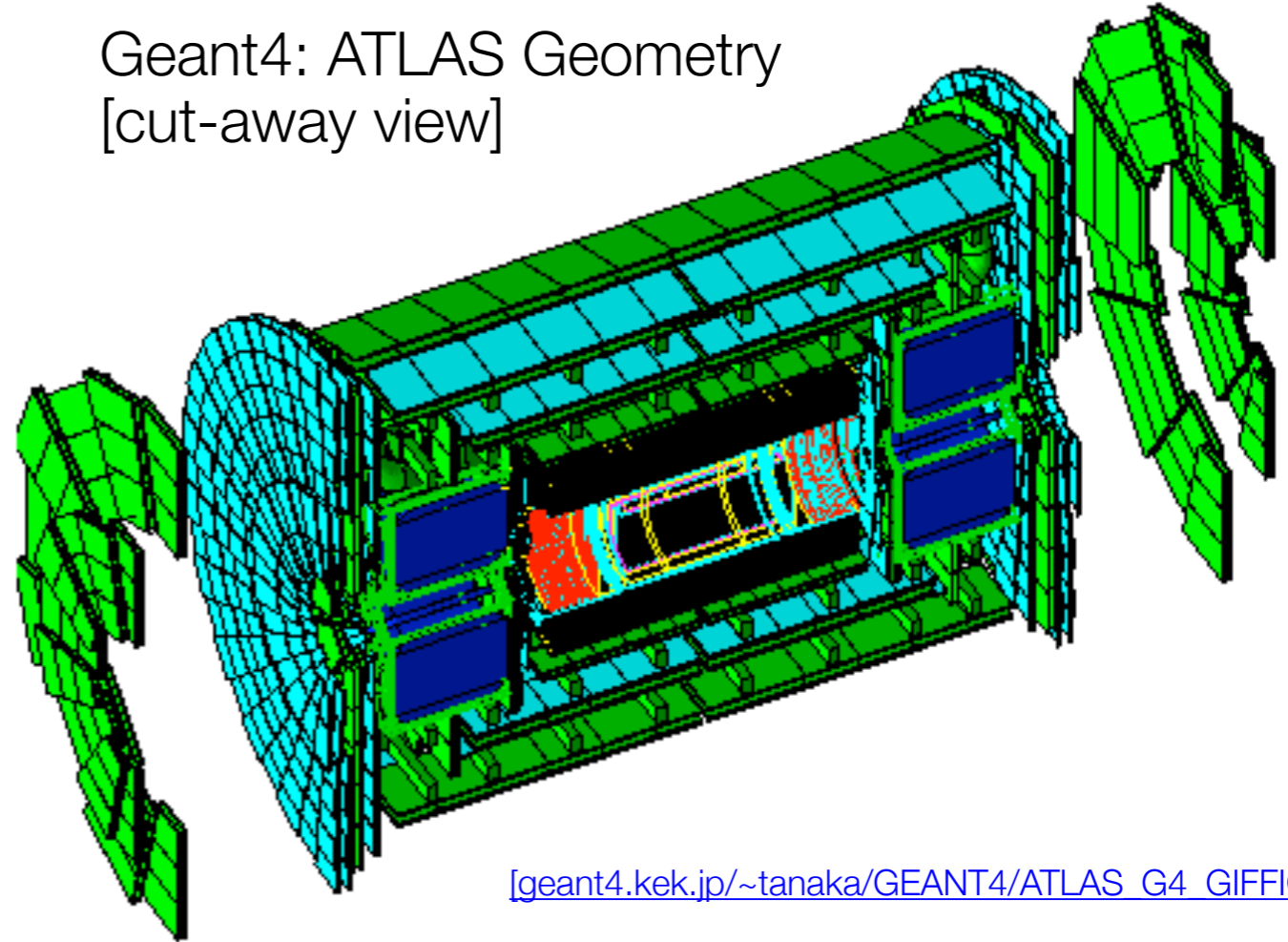# Comparison between real and simulated events

"Real" "Virtual"

LHC collisions
Events

Produce
events

Event Generator
Pythia8, Herwig++

Detector, DAQ
ATLAS,CMS, LHCb, ALICE

Observe/store
events

Detector Simulation
Geant4, ...

Event Reconstruction
Athena (ATLAS), ...

Physics Analysis
Root based analysis packages

Compare
data & simulation

"Quick & Inaccurate"

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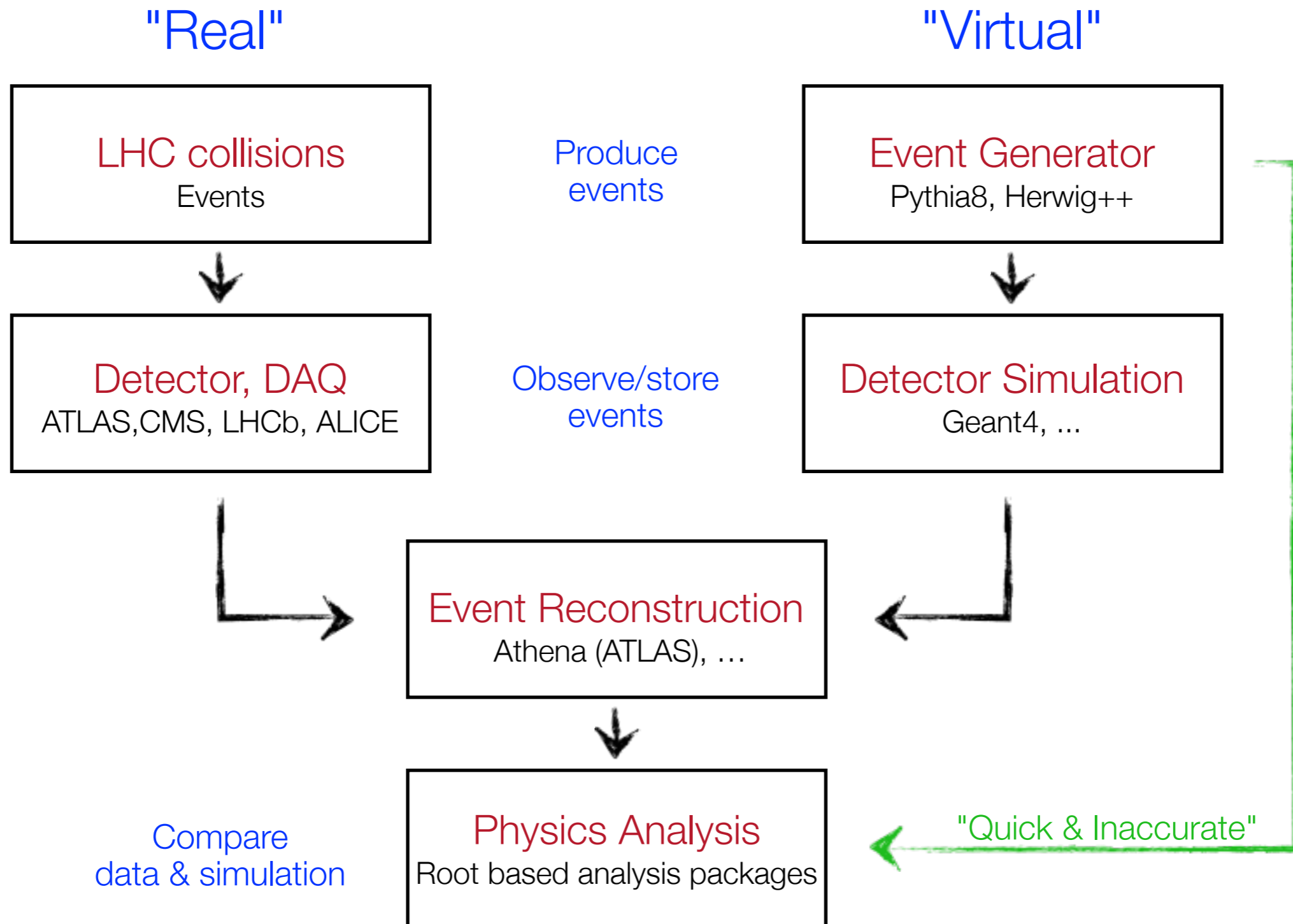
Simulation elements

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

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++]
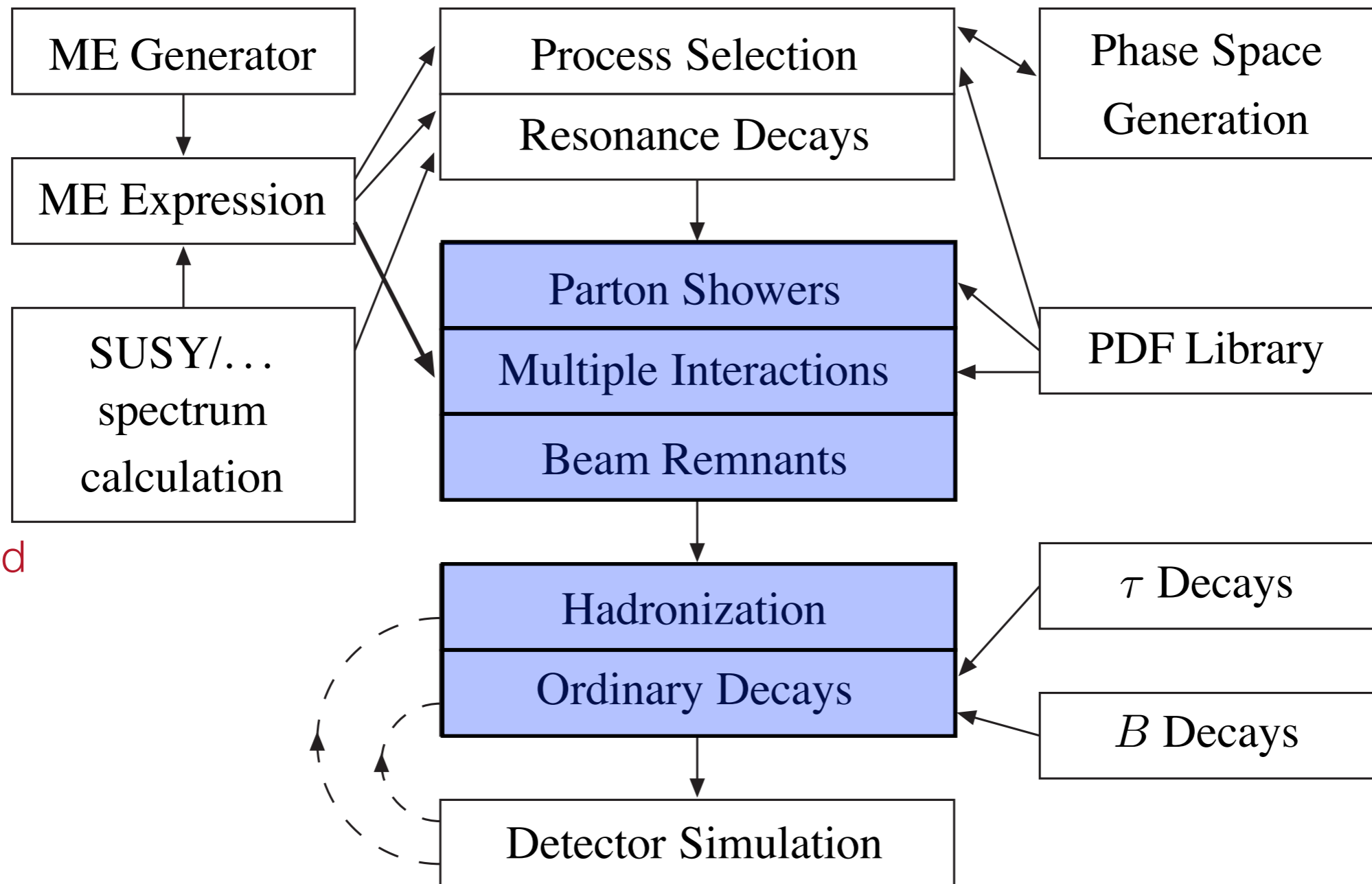
Strong interactions:

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]
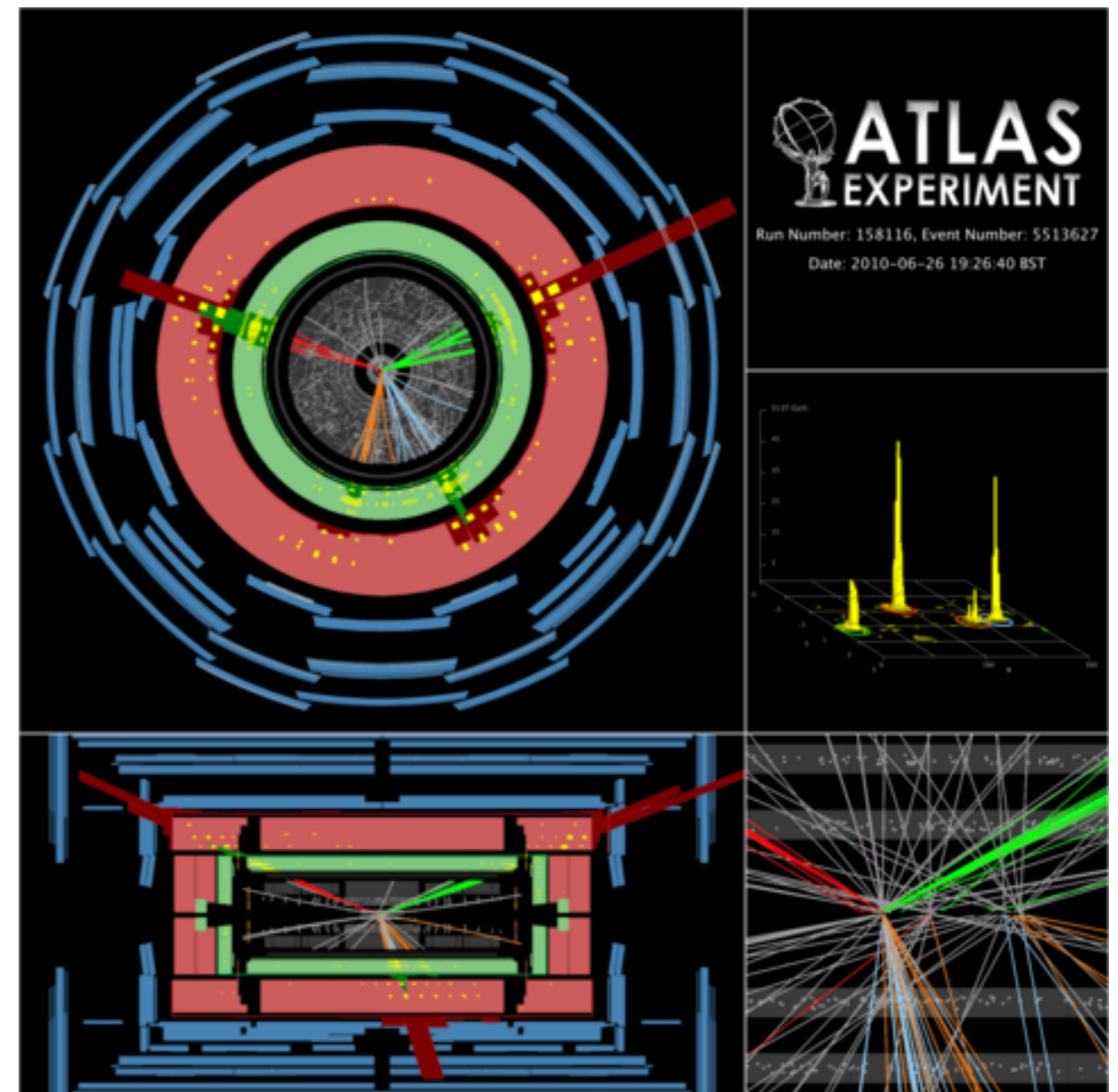
An event with 4 jets @ LHC

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

Hadronisation & Decay

Parton Shower

Hard Process

Incoming Proton

Incoming Proton

Underlying Event

Università degli Studi di Roma Tre

[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 ⊗ 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

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

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

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.
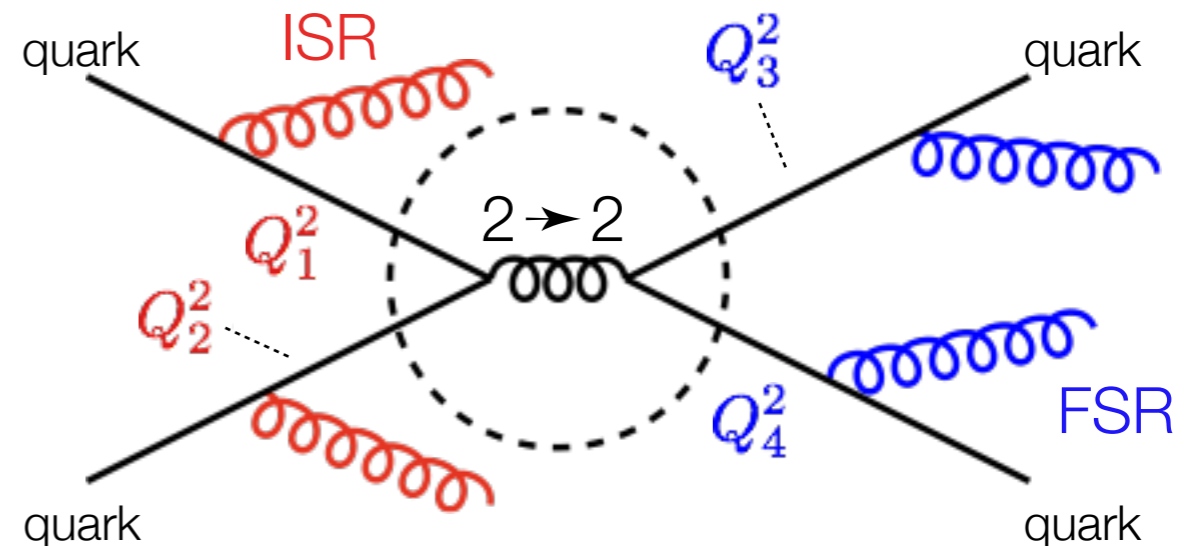
Parton showers

$e^+e^- \rightarrow qqg$

$Q^2 = m^2_{13}$

$Q^2 = m_{23}^2$
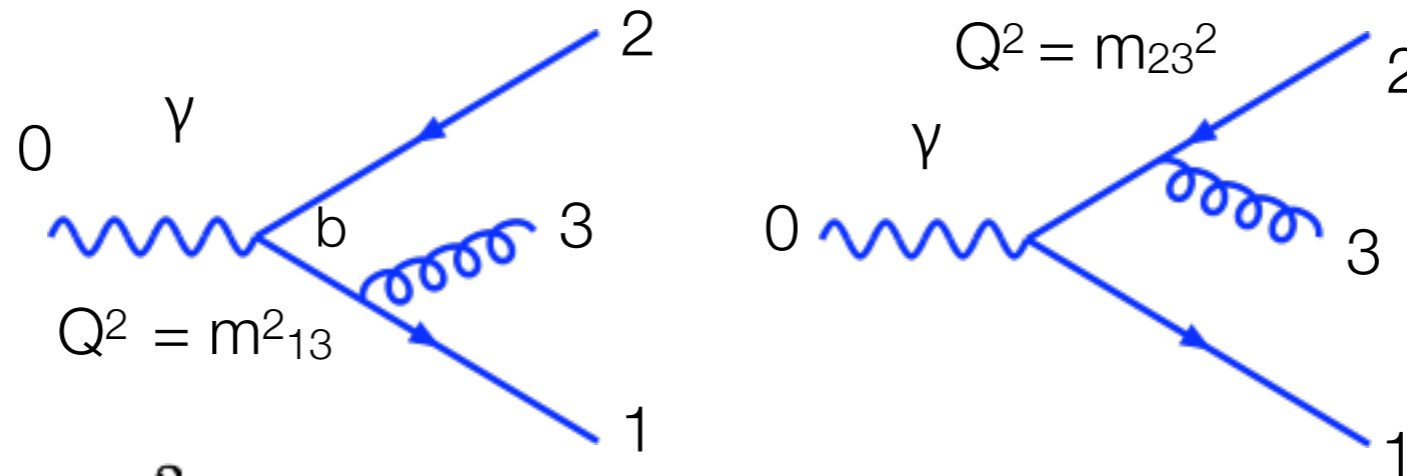
$$x_i = \frac{2E_i}{E_{cm}} \qquad x_1 + x_2 + x_3 = 2$$

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

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

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

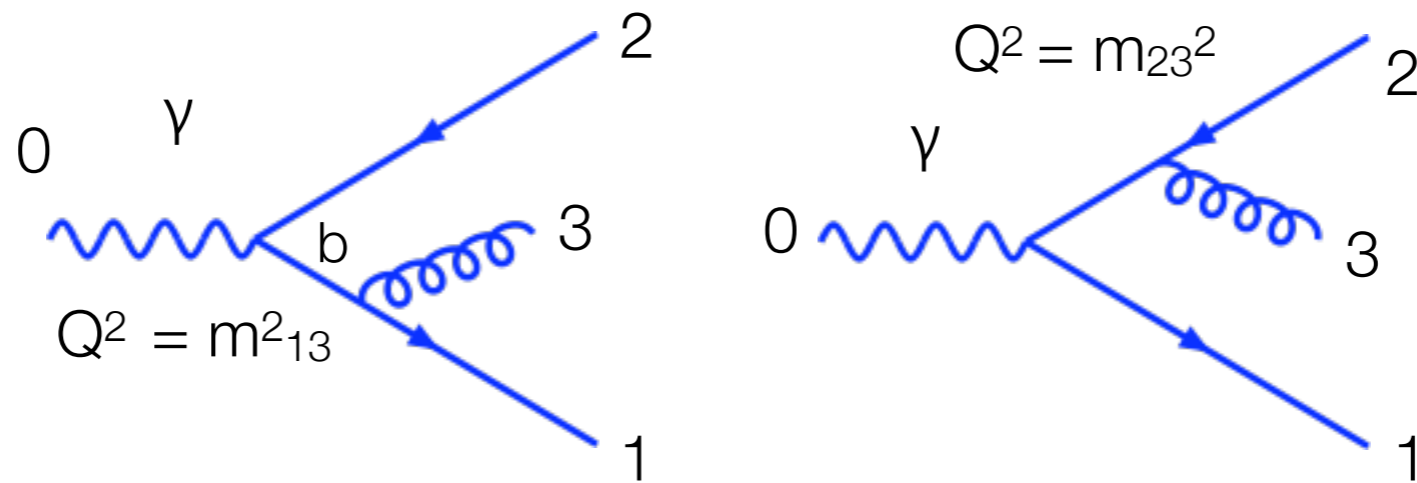$$p_1 + p_2 + p_3 = (E_{cm}, 0) \qquad\qquad E_1 + E_2 + E_3 = E_{cm}$$
$$\vec{p}_1 + \vec{p}_2 + \vec{p}_3 = 0$$

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

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

gluon splitting

e⁺e⁻ ➤ qqg

$$1 - x_2 = \frac{m_{13}^2}{E_{cm}^2} = \frac{Q^2}{E_{cm}^2} \qquad m_{13}^2 = 2E_1 E_3 (1 - cos\theta) \quad x_2 \to 1 \Rightarrow m_{13}^2 \to 0 \Rightarrow \theta \to 0 \text{ collinear limit}$$

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

$$E_q = E_1 = zE_b$$

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

$$x_1 + x_2 + x_3 = 2$$

Rewrite for x₂ ➤ 1: [qg collinear limit]

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

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

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

$$dx_1 \approx dz$$
$$x_3 \approx 1 - z$$

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

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

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

Splitting Function
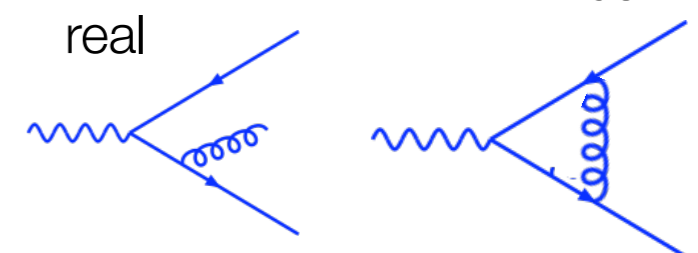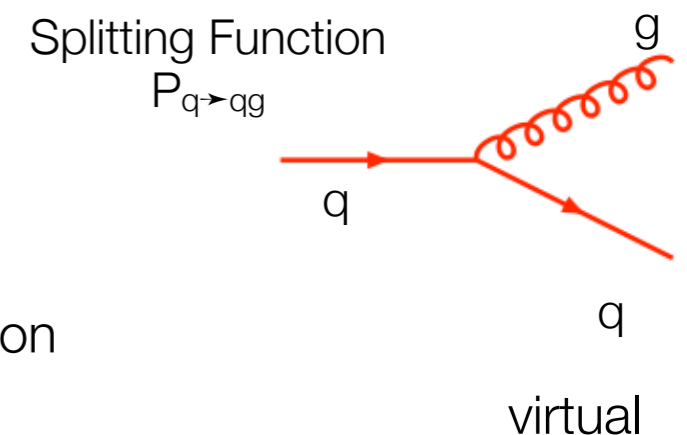$P_{q \to qg}$

g

q

Analogous splitting functions used in PDF evolution

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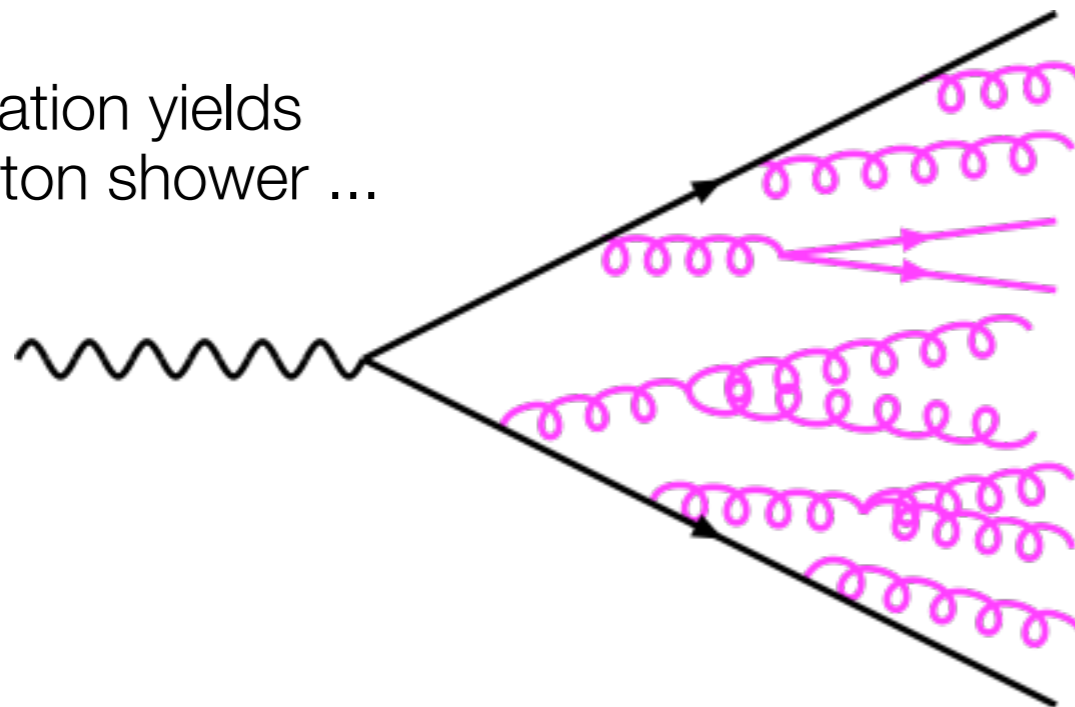
$$P_{g \to gg} = 3 \frac{(1 - z(1 - z))^2}{z(1 - z)}$$

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

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.

q

virtual

real

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

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Parton shower evolution 1

Conservation of total probability:

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

Time evolution:

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

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

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

[Taylor]

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

Parton shower evolution 2

Instead of evolving to later and later times
need to evolve to smaller and smaller Q^2 ...

[Heisenberg: $Q \sim 1/t$]

**Sudakov
Form Factor**

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

Probability to radiated
with virtuality Q^2

No radiation for higher
virtualities i.e. for Q^2 ... $Q^2_{\max}$

Note that $\sum_{b,c}\iint \mathrm{d}P_{a\to bc} \equiv 1$...

[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

$Q_1^2 > Q_2^2 > Q_3^2$
$Q_1^2 > Q_4^2 > Q_5^2$

$Q_4^2 \qquad Q_5^2$

Q_1^2

Q_2^2

Q_3^2
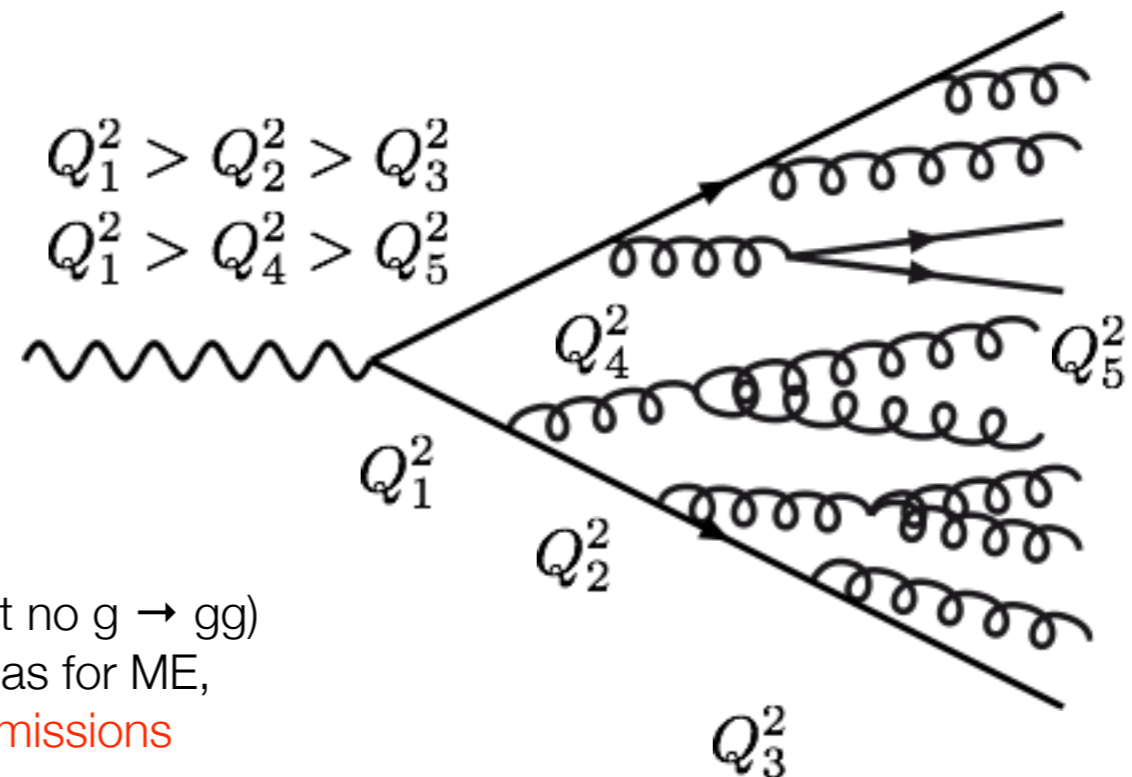
Sudakov picture of parton showers

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]
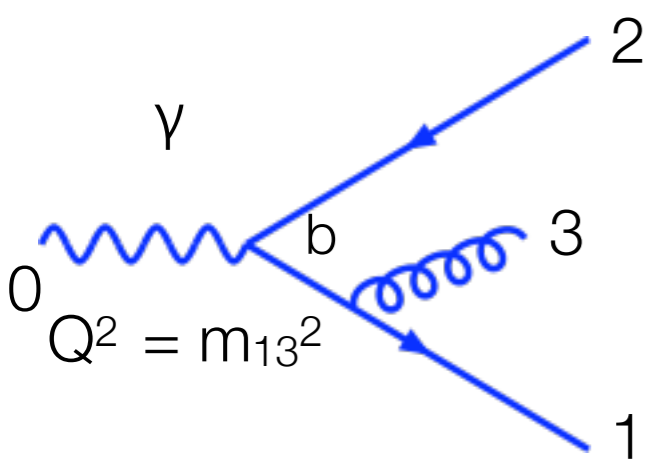
Probability to not have $Q_x > Q_2$

using:

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

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 $x_1 \sim z$

γ

0 $Q^2 = m_{13}^2$ b 3   2   1

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

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

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

real

$\alpha_s(Q_1)$ Q_1

α_s

$\alpha_s(Q_1)$ Q_1 Q_2

$\alpha_s(Q_2)$

α_s^2

$\alpha_s(Q_1)$ Q_1 Q_2

$\alpha_s(Q_2)$

Q_n

α_s^n $\alpha_s(Q_n)$
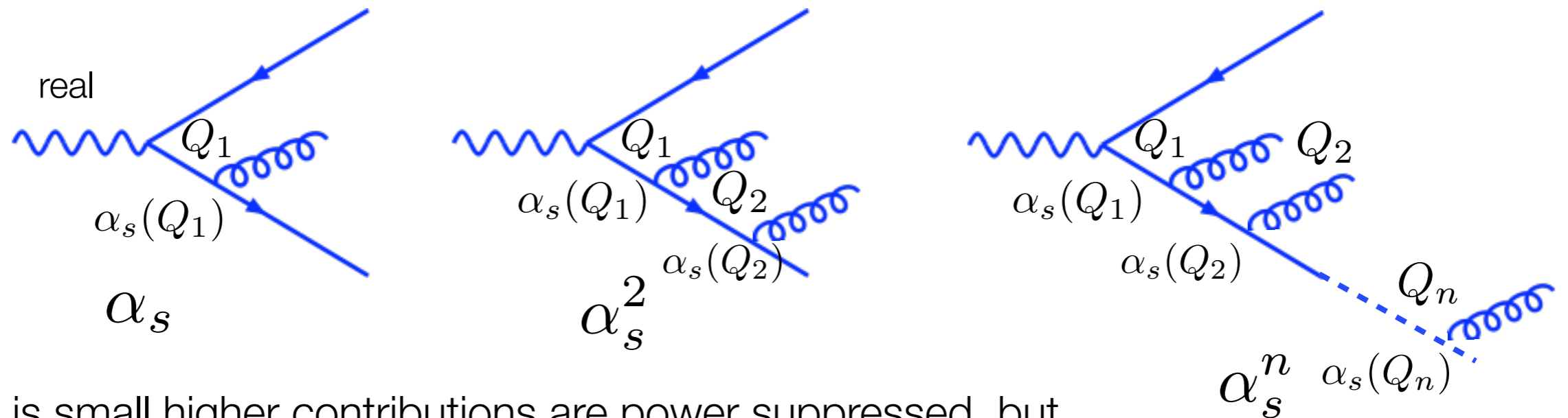
If α_s is small higher contributions are power suppressed, but…

α_s increases at small Q^2

October 2015

$\alpha_s(Q^2)$

▼ τ decays (N³LO)
△ DIS jets (NLO)
□ Heavy Quarkonia (NLO)
○ e⁺e⁻ jets & shapes (res. NNLO)
● e.w. precision fits (NNLO)
▽ p$\bar{\text{p}}$ –> jets (NLO)
▼ pp –> tt (NNLO)

0.3

0.2

0.1

≡ QCD $\alpha_s(M_Z) = 0.1181 \pm 0.0013$

1   10   100   1000

Q [GeV]
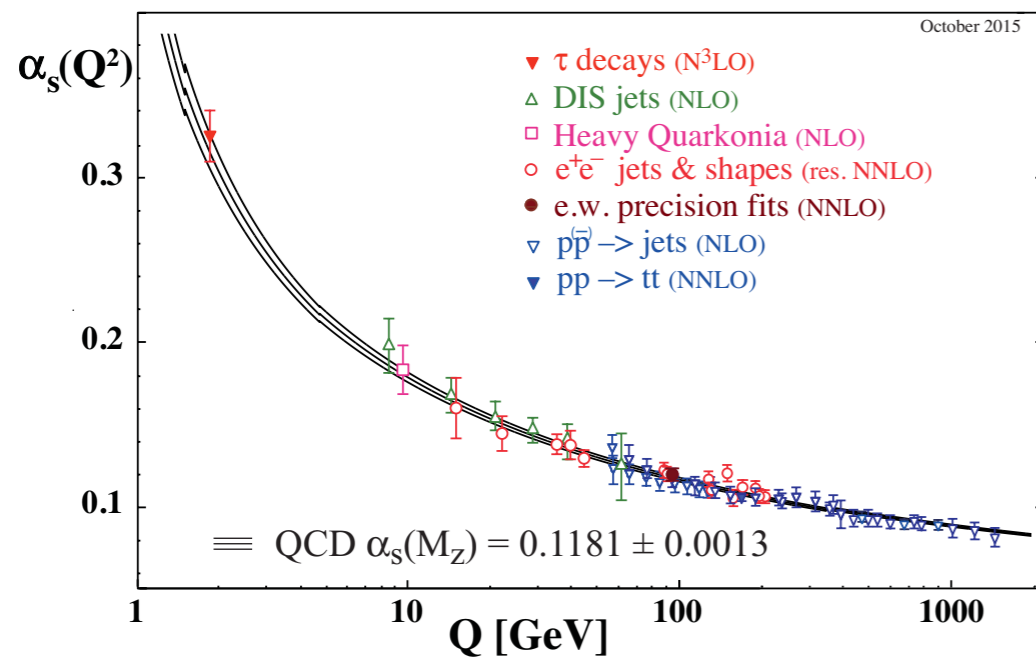
$$\alpha_s(Q_n) \sim \alpha_s(Q_1) ln(Q_1/Q_n)$$

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

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

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

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

In the splitting function appears only dQ2/Q2, therefore if P = f(z)Q2 dP/P = dQ2/Q2

Three main approaches to showering in use:

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

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

HERWIG, HERWIG++ : Q2 ≈ E2(1 − cosθ) ≈ E2θ2/2
PYTHIA, 8 (basic)   : Q2 = m2 (timelike) or = −m2 (spacelike)
PYTHIA6, 8 (pT oredered) : mixture: collinear splitting but di-pole kinematic

One is based on a picture of dipole emission:
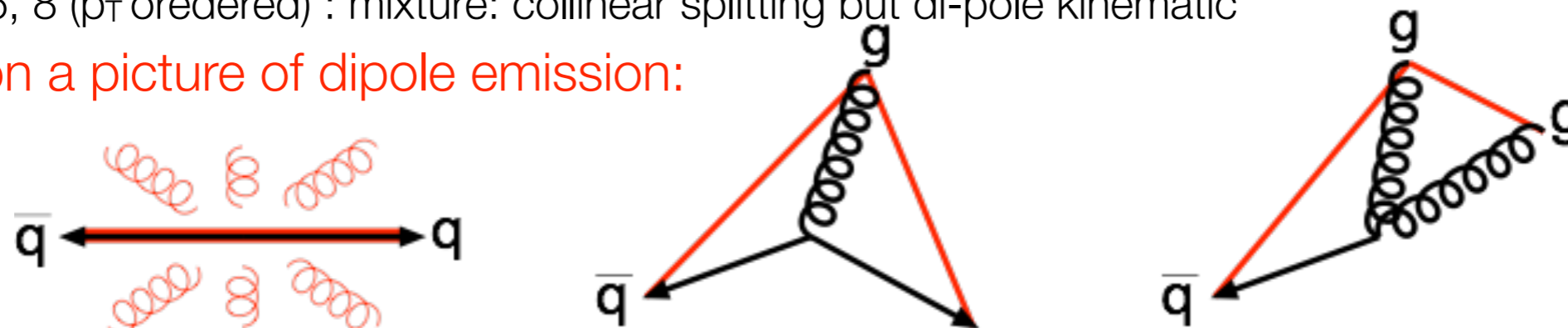
Ariadne   : Q2 = p2⊥; FSR mainly, ISR is primitive …   consider the full recoil and not only the branching
                used also in sherpa and Pythia8

[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: $Q^2 = m^2$ HERWIG/++: $Q^2 \sim E^2\theta^2$ ARIADNE/Pythia8: $Q^2 = p^2_\perp$
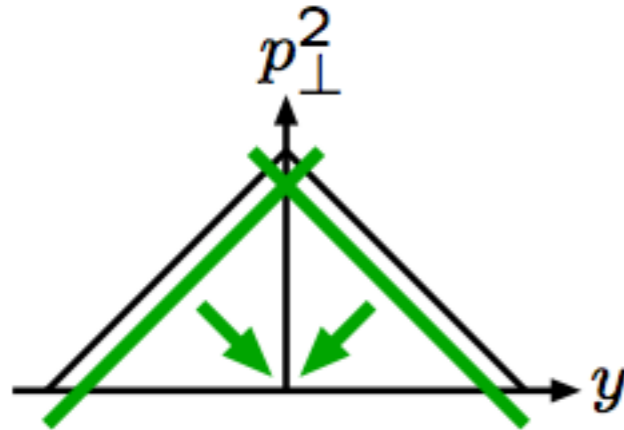
Large mass first
["hardness" ordered]

Large angle first
[not "hardness" ordered]

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

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

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

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

ISR: m^2 ➤ $-m^2$

ISR: θ ➤ θ

ISR: complicated

Color coherence

QED: Chudakov effect (mid-fifties)

cosmic ray γ atom

e^+
e^-

g_S

$g_1 \rightarrow g_2 g_3$

emulsion plate   reduced ionization   normal ionization
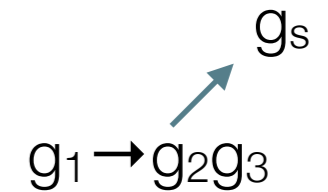
1. soft gluons see the pair of split gluons as a whole, color screening reduce their emission

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
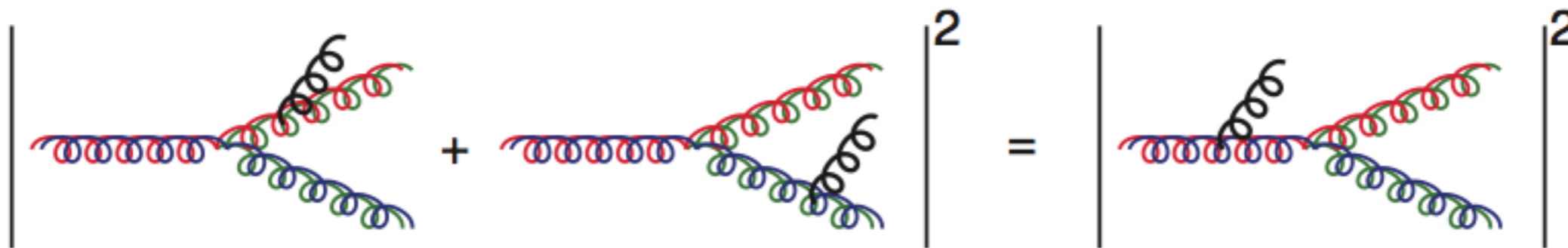
solved by • requiring emission angles to be decreasing

or • requiring transverse momenta to be decreasing

[from G.Herten]

Compariosn to LHC data

4jets cross section: $p_T^{(1)} > p_T^{(2)} > p_T^{(3)} > p_T^{(4)}$
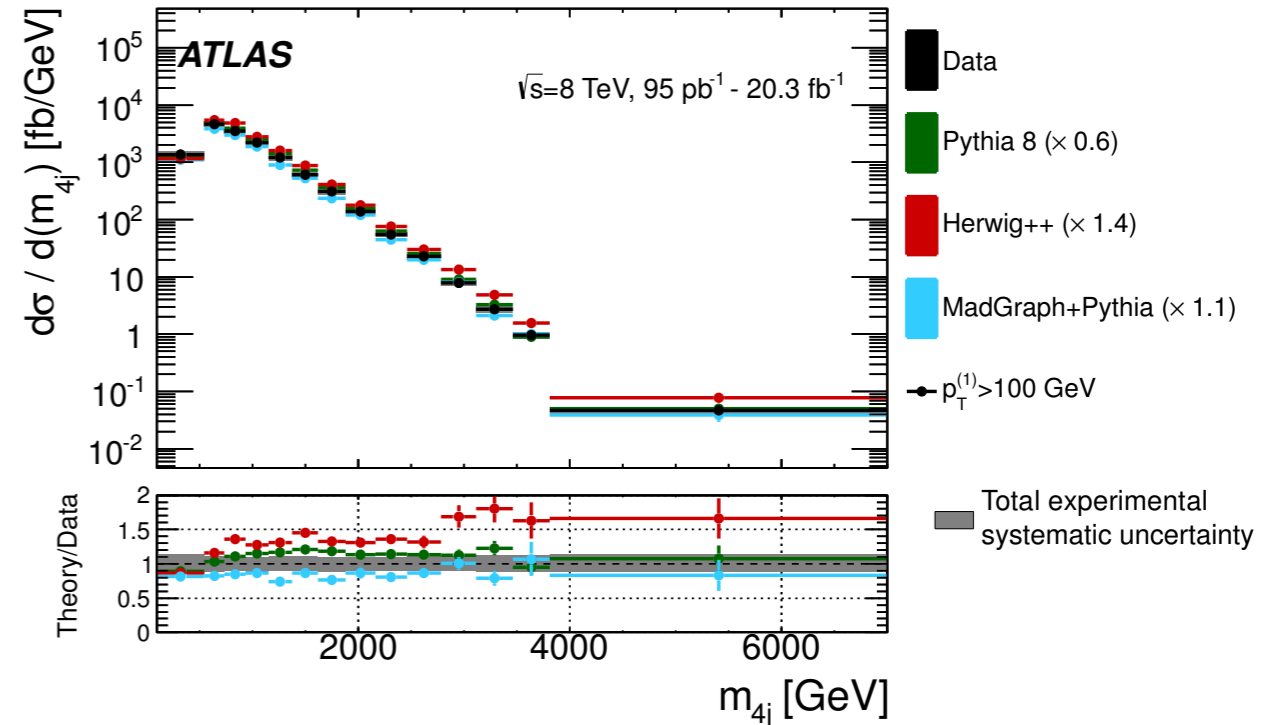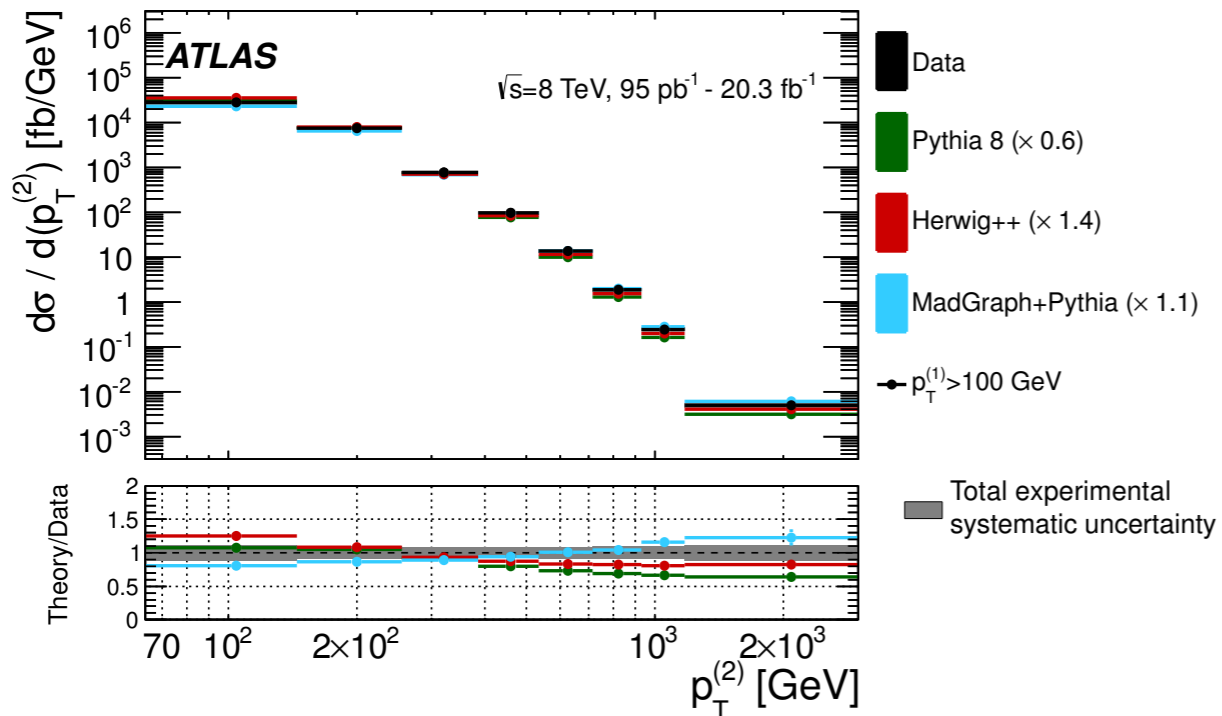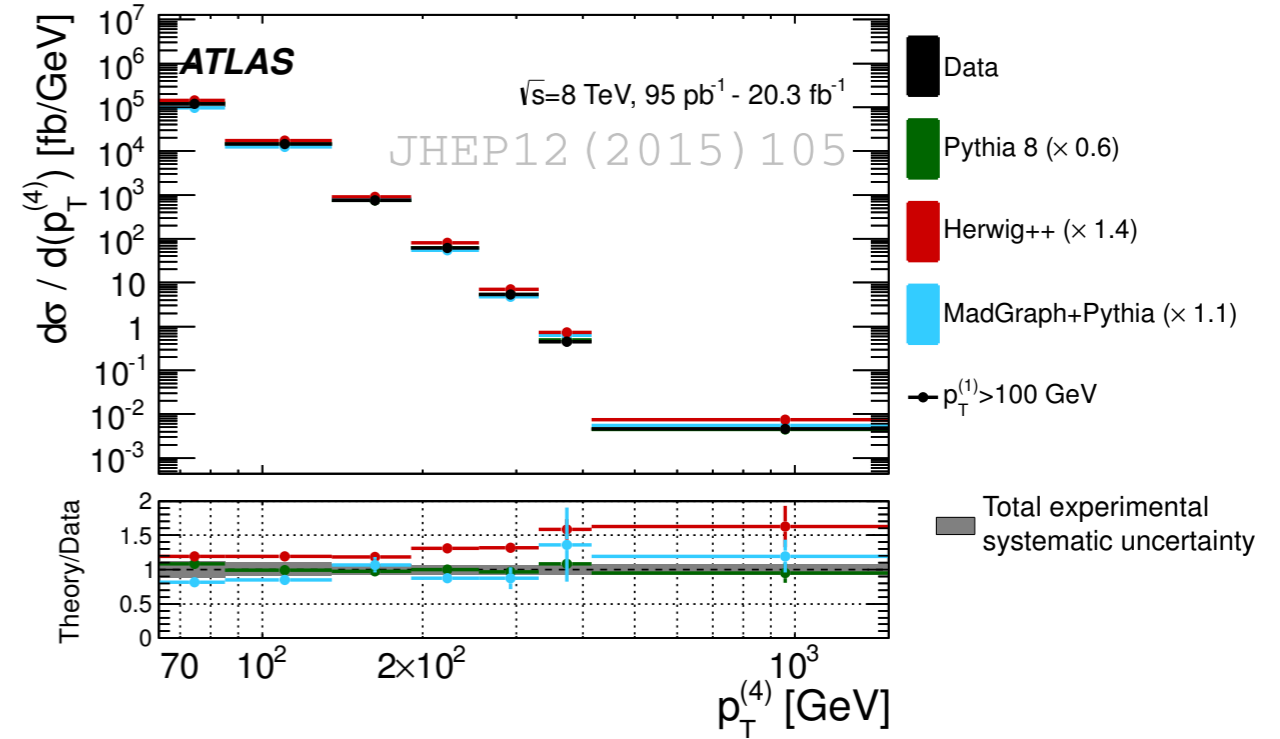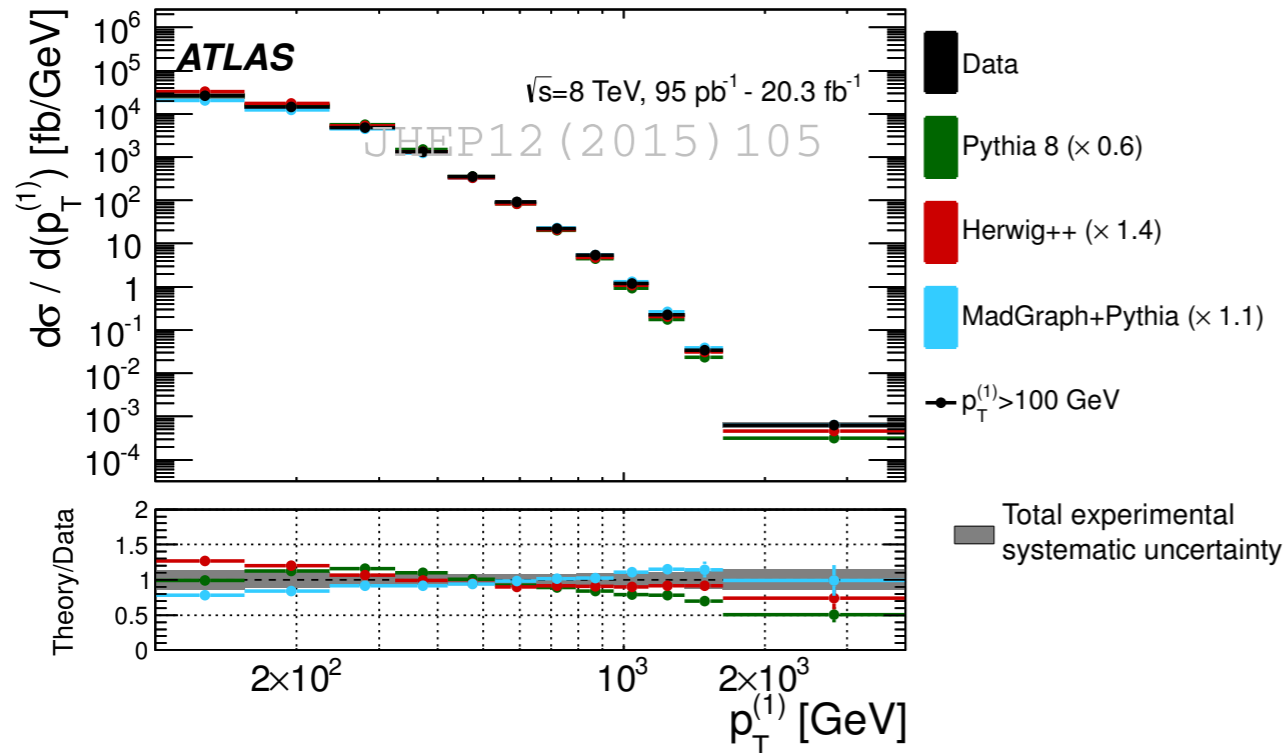
Example of processes implemented in Pythia6

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	$\gamma\gamma \to J/\psi\, g$
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	$f_i f_j \to R$
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	$f_i f_j \to H^+$
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	$f_i f_j \to H^\pm h^0$
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	$f_i f_j (\to W^\pm) \to f_k \bar{f}_l$
Extra Dimensions:	
391	$ff \to G^*$
392	$gg \to G^*$
393	$q\bar{q} \to g G^*$
394	$qg \to q G^*$
395	$gg \to g G^*$
Left-right symmetry:	
341	$\ell_i \ell_j \to H^{\pm\pm}_L$
342	$\ell_i \ell_j \to H^{\pm\pm}_R$
343	$\ell^\mp_i \gamma \to H^{\pm\pm}_L e^\mp$
344	$\ell^\mp_i \gamma \to H^{\pm\pm}_R e^\mp$
345	$\ell^\mp_i \gamma \to H^{\pm\pm}_L \mu^\mp$
346	$\ell^\mp_i \gamma \to H^{\pm\pm}_R \mu^\mp$
347	$\ell^\mp_i \gamma \to H^{\pm\pm}_L \tau^\mp$
348	$\ell^\mp_i \gamma \to H^{\pm\pm}_R \tau^\mp$
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	$f_i f_j \to W^\pm_R$
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	$f_i f_j \to \tilde{\ell}_L \tilde{\nu}_\ell^* +$
211	$f_i f_j \to \tilde{\tau}_1 \tilde{\nu}_\tau^* +$
212	$f_i f_j \to \tilde{\tau}_2 \tilde{\nu}_\tau^* +$
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	$f_i g \to \tilde{q}_{iL} \tilde{\chi}^\pm_1$
256	$f_i g \to \tilde{q}_{iL} \tilde{\chi}^\pm_2$
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	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jL}^*$
275	$f_i f_j \to \tilde{q}_{iR} \tilde{q}_{jR}^*$
276	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jR}^* +$
277	$f_i \bar{f}_i \to \tilde{q}_{iL} \tilde{q}_{jL}^*$
278	$f_i \bar{f}_i \to \tilde{q}_{iR} \tilde{q}_{jR}^*$
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
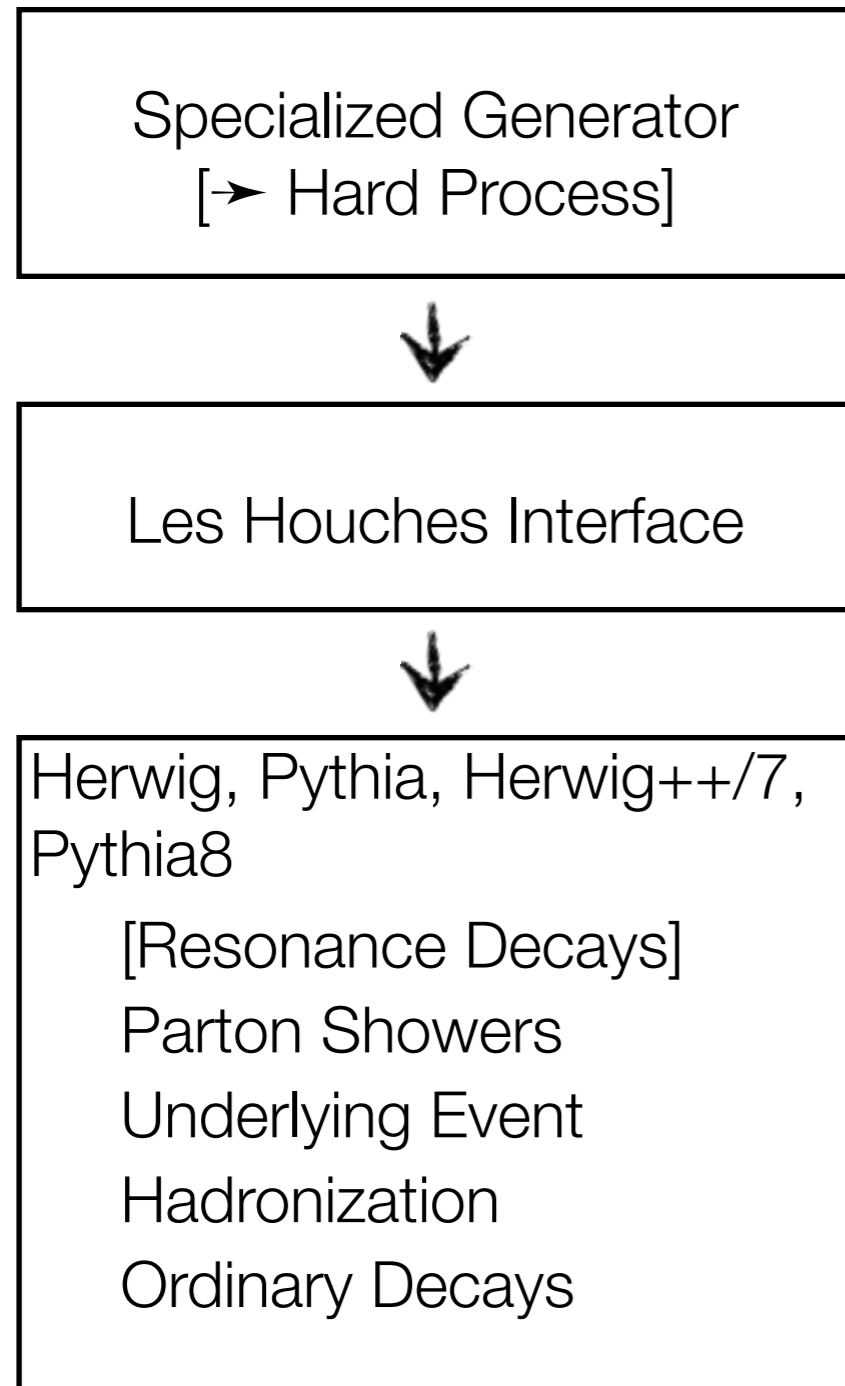
AcerMC :   ttbb, .single top

ALPGEN   : W/Z + ≤ 6j,
                      nW + mZ + kH + ≤ 3j, ...

AMEGIC++   : generic LO

CompHEP   : generic LO

GRACE   : generic LO
[+Bases/Spring]   [+ some NLO loops]

GR@PPA   : bbbb

MadCUP   : W/Z+ ≤ 3j, ttbb

HELAS &   : generic LO
MadGraph

MCFM   : NLO W/Z+ ≤ 2j,
                      WZ, WH, H+ ≤ 1j

O'Mega &   : generic LO
WHIZARD

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)

ME+PS

Herwig++/
Pythia6/8

SingleTop, TopRex
Phantom
AcerMC
GRAPPA
CompHEP

ME+PS+merging

Alpgen
MadGraph
Sherpa

NLO+PS

MC@NLO
POWHEG

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

LO ME for hard processes
[2→1 or 2→2]

1)
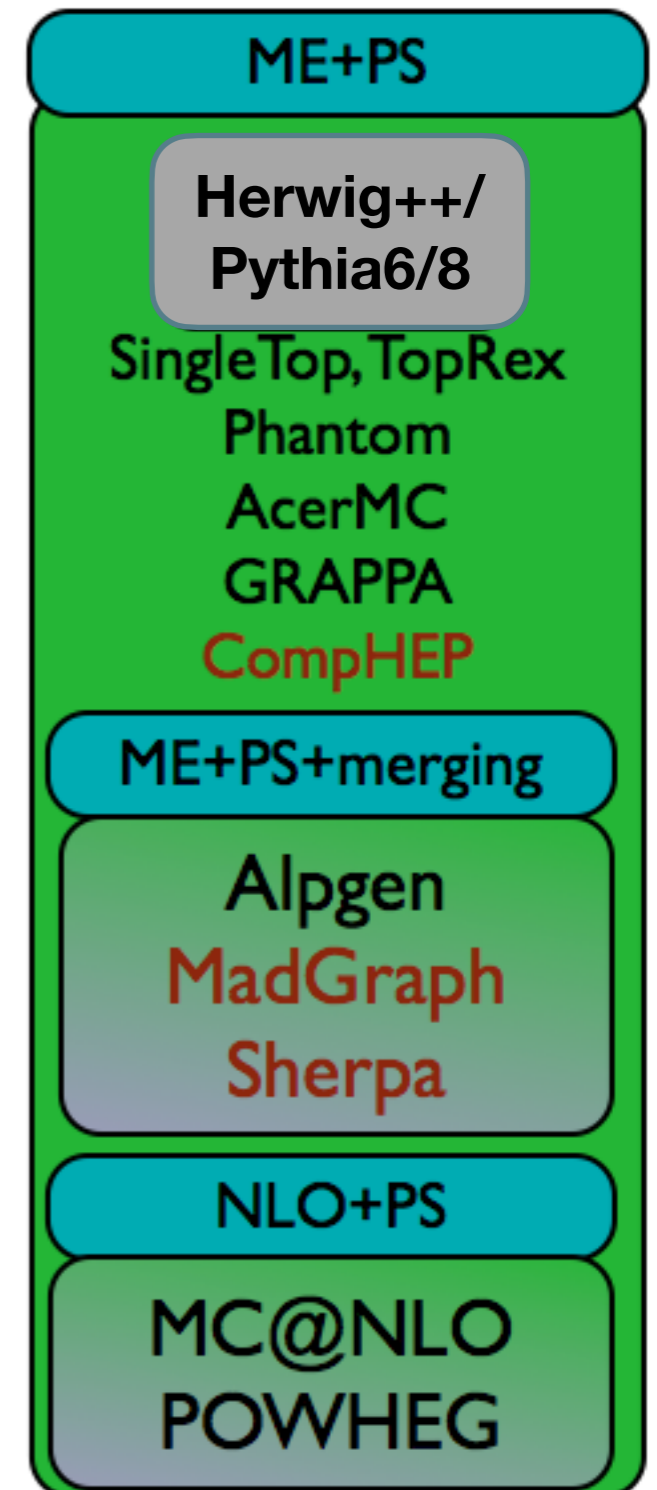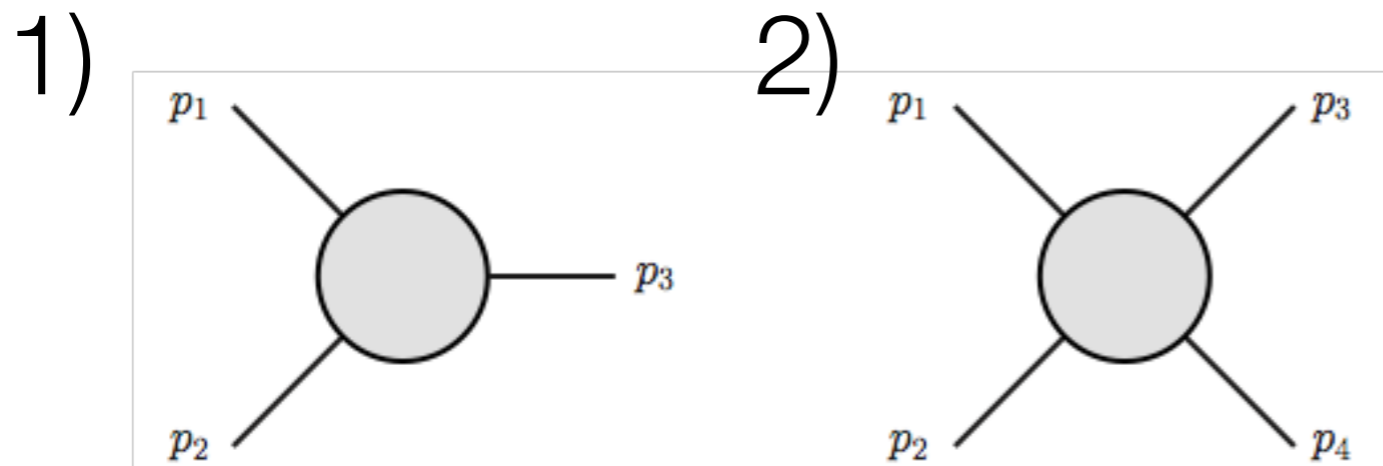
2)
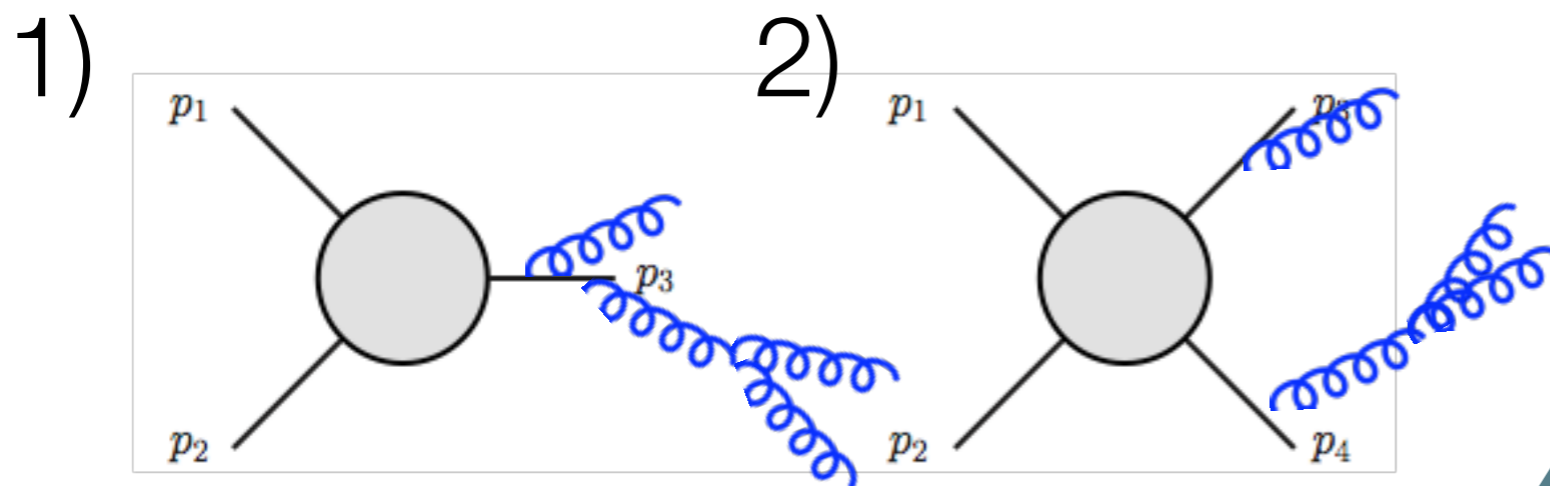
- Parton Shower: attaches gluons at each leg.

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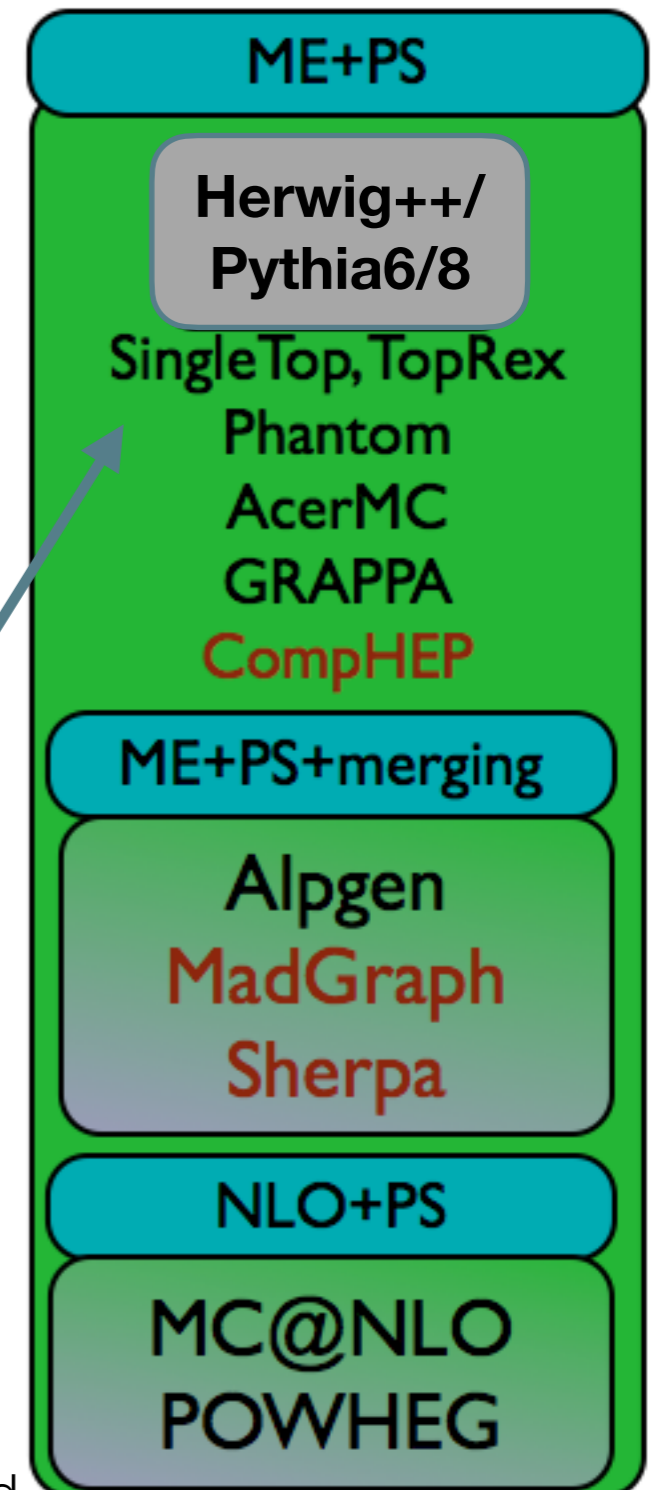
Type 2 : Leading order matrix element & leading log parton shower + merging

LO ME for hard processes
[2→1 or 2→2]

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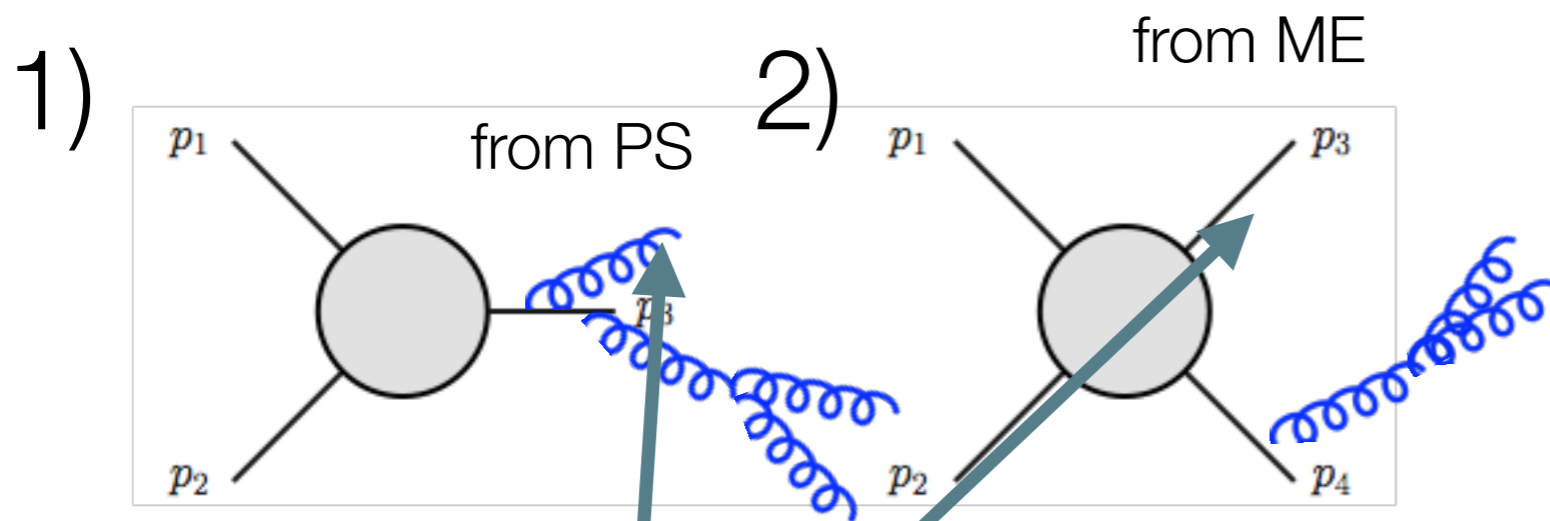
- Type 1 can be improved using 1) + 2)
- use ME calculation for hard/large angle jets
- but needs to remove double-counting: merging
  - CKKW: Catani, Krauss, Kuhn, Weber (Sherpa)
  - MLM
- very good description of high jet multiplicity kinematics

ME+PS

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MC@NLO
POWHEG
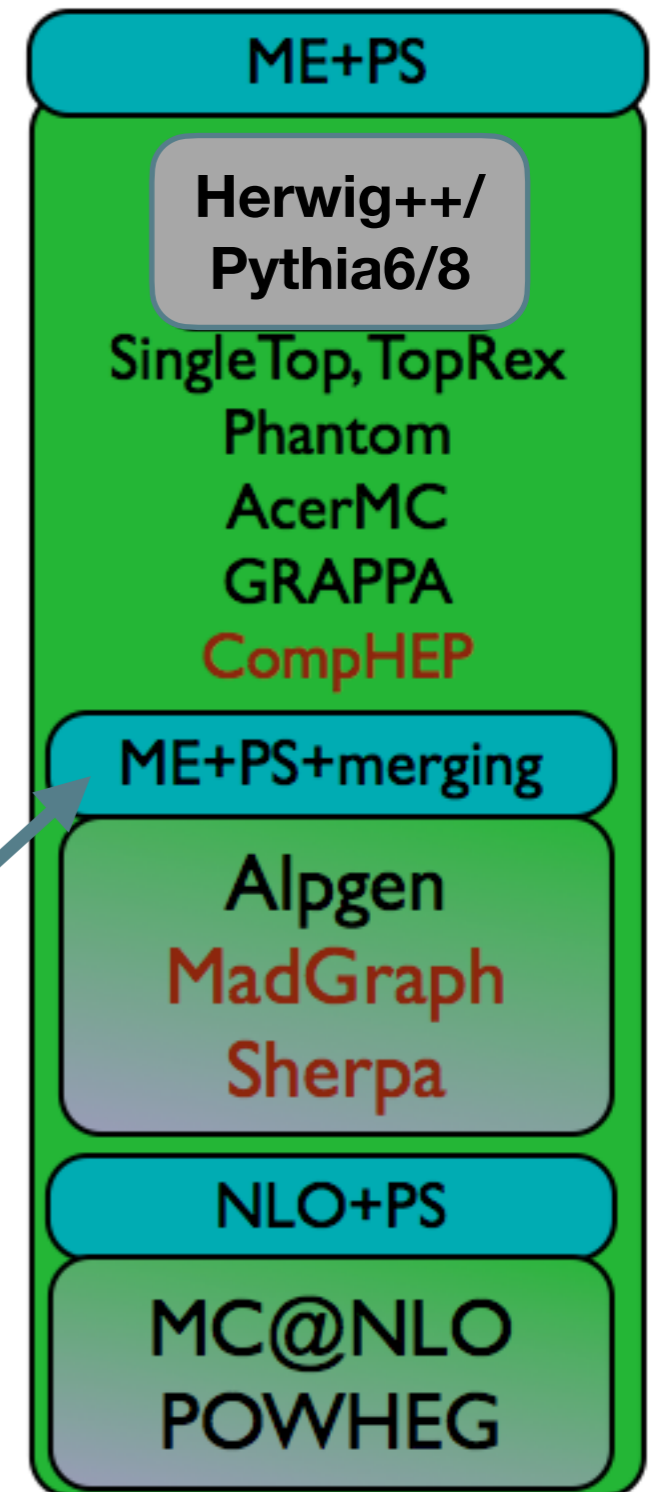
Merging @LO

MLM matching (simplified)

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

Merging @LO

MLM matching (simplified)

1 parton

2 partons

1) define matching cuts:
for example $p_T^J > 20$ GeV, $\Delta R = 0.4$
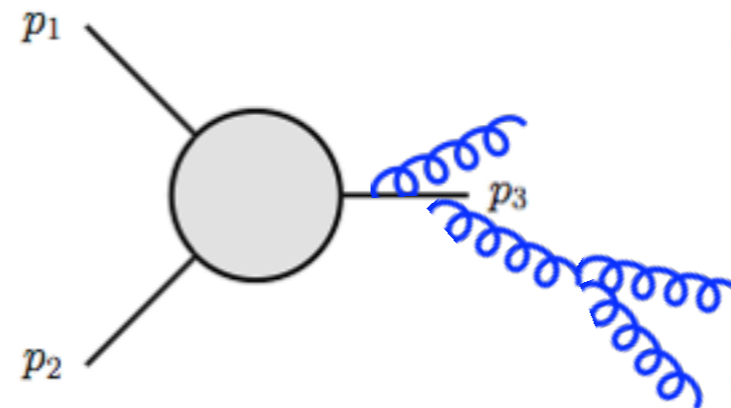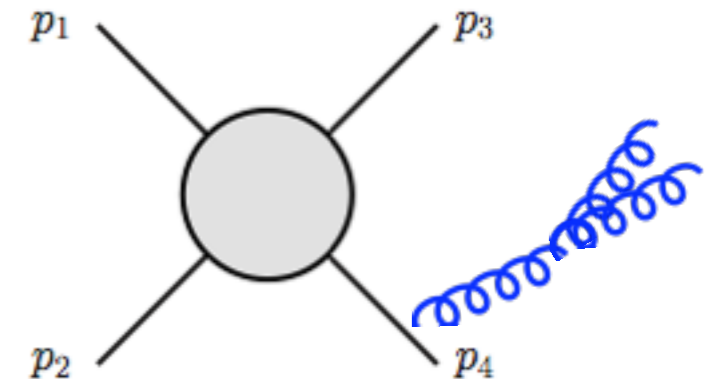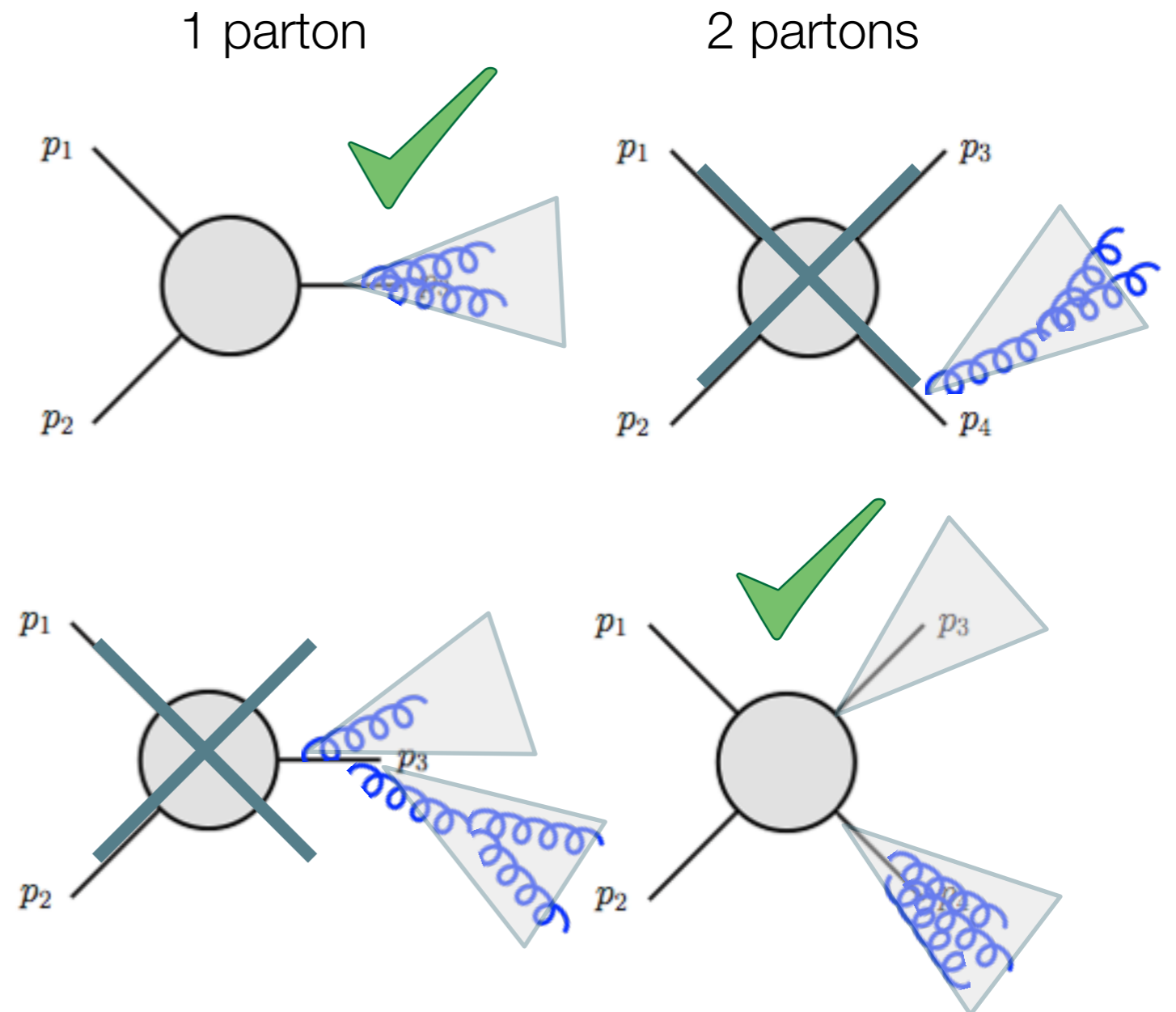
2) generate ME with 1, 2, ...n jets

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 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

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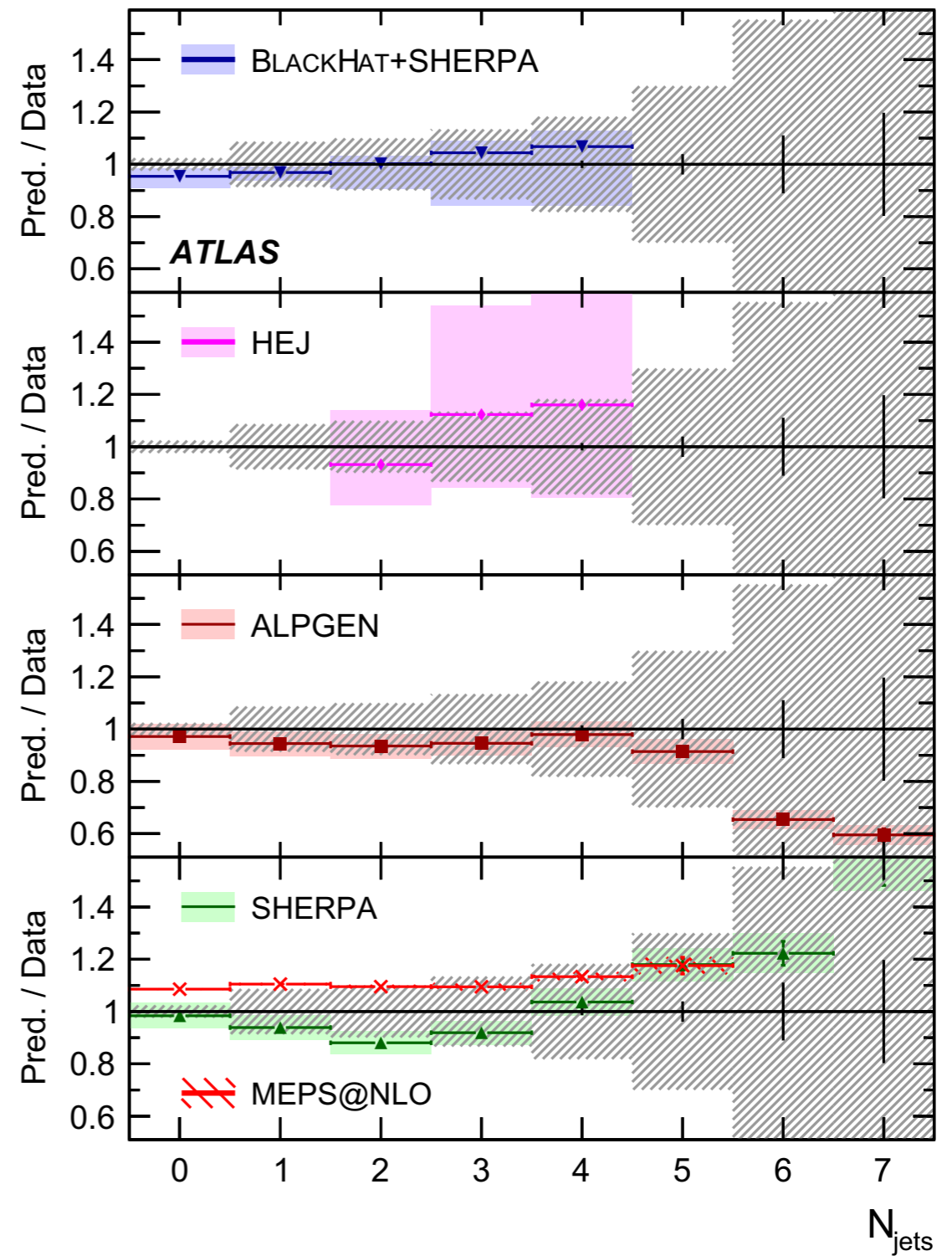partons

# 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

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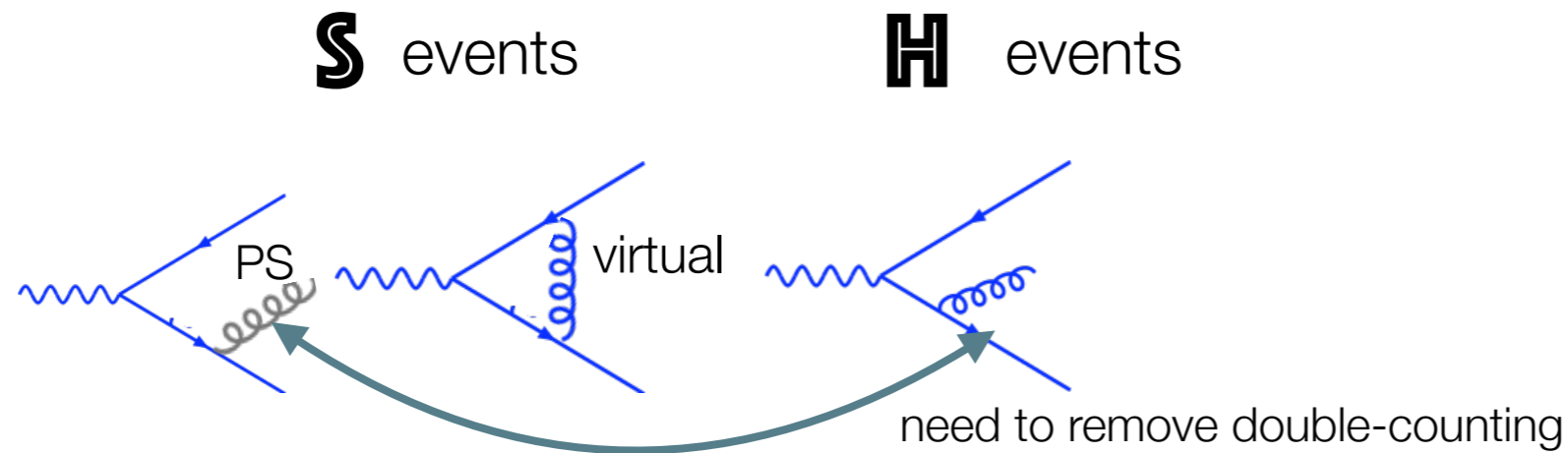cut match with final partons

Consequences:
all jets with $p_T > 20$ GeV and $\Delta R > 0.4$ to other jets come from ME
collinear and soft jets come from PS
Use ME and PS where they perform better.
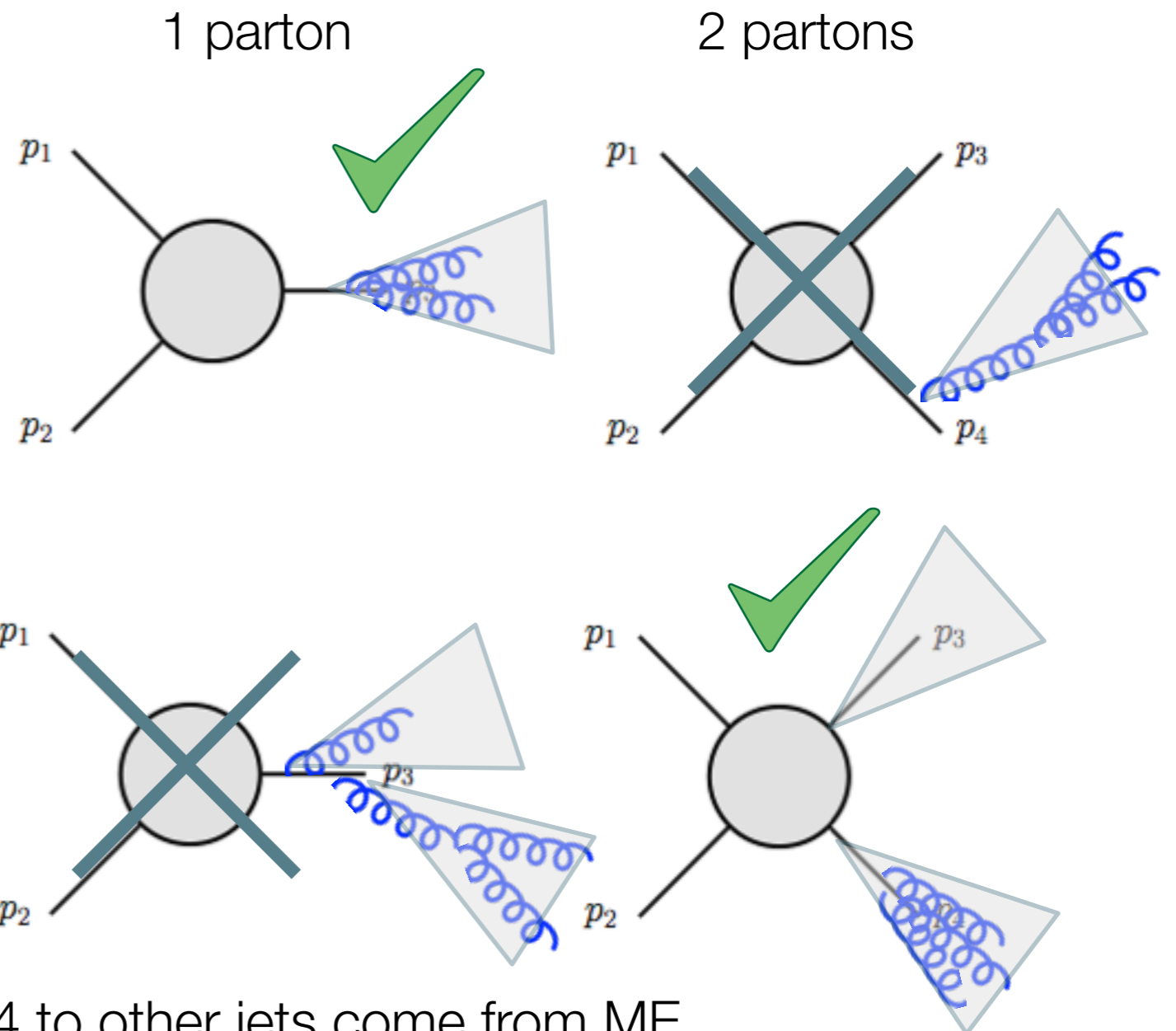
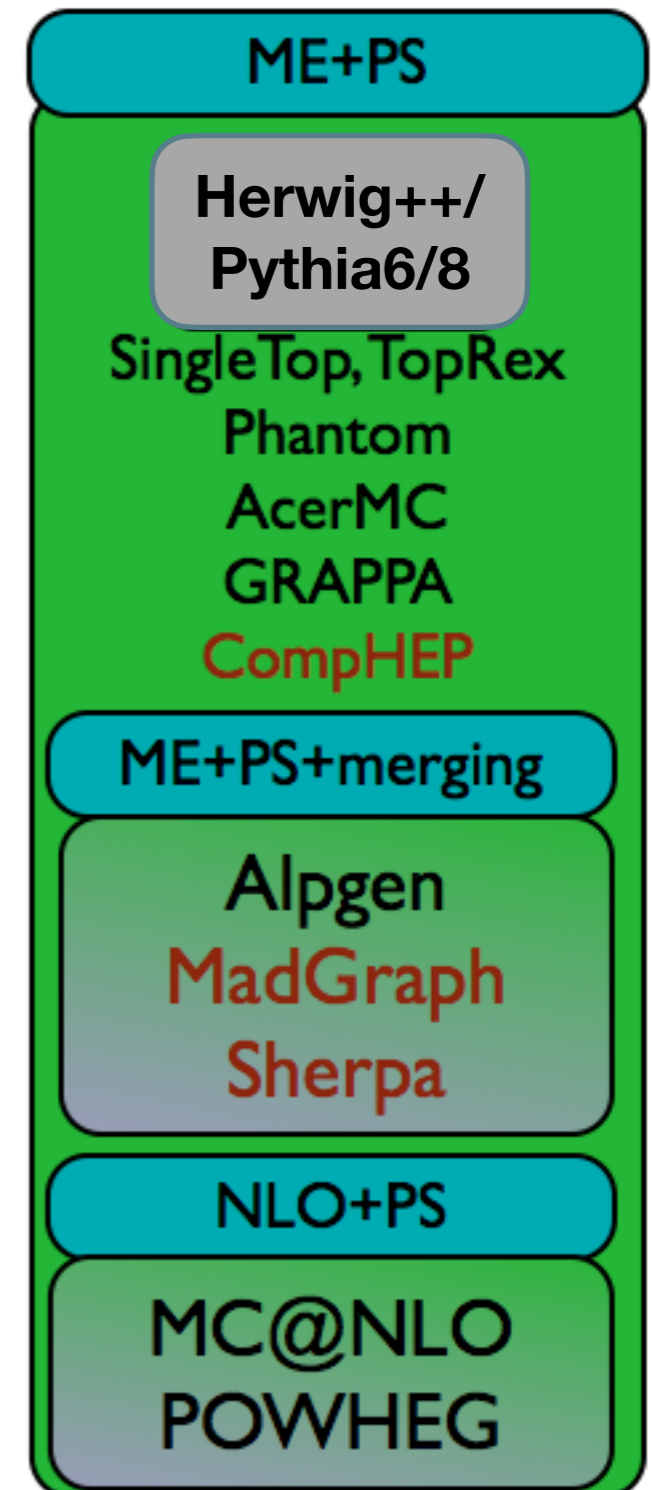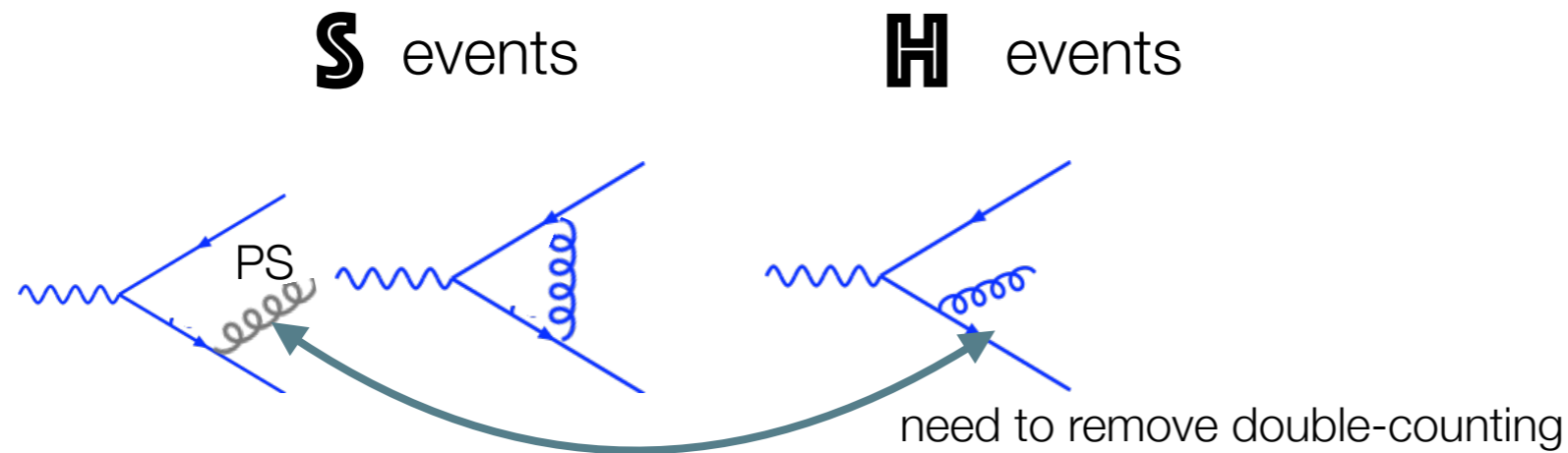# W+jets distributions
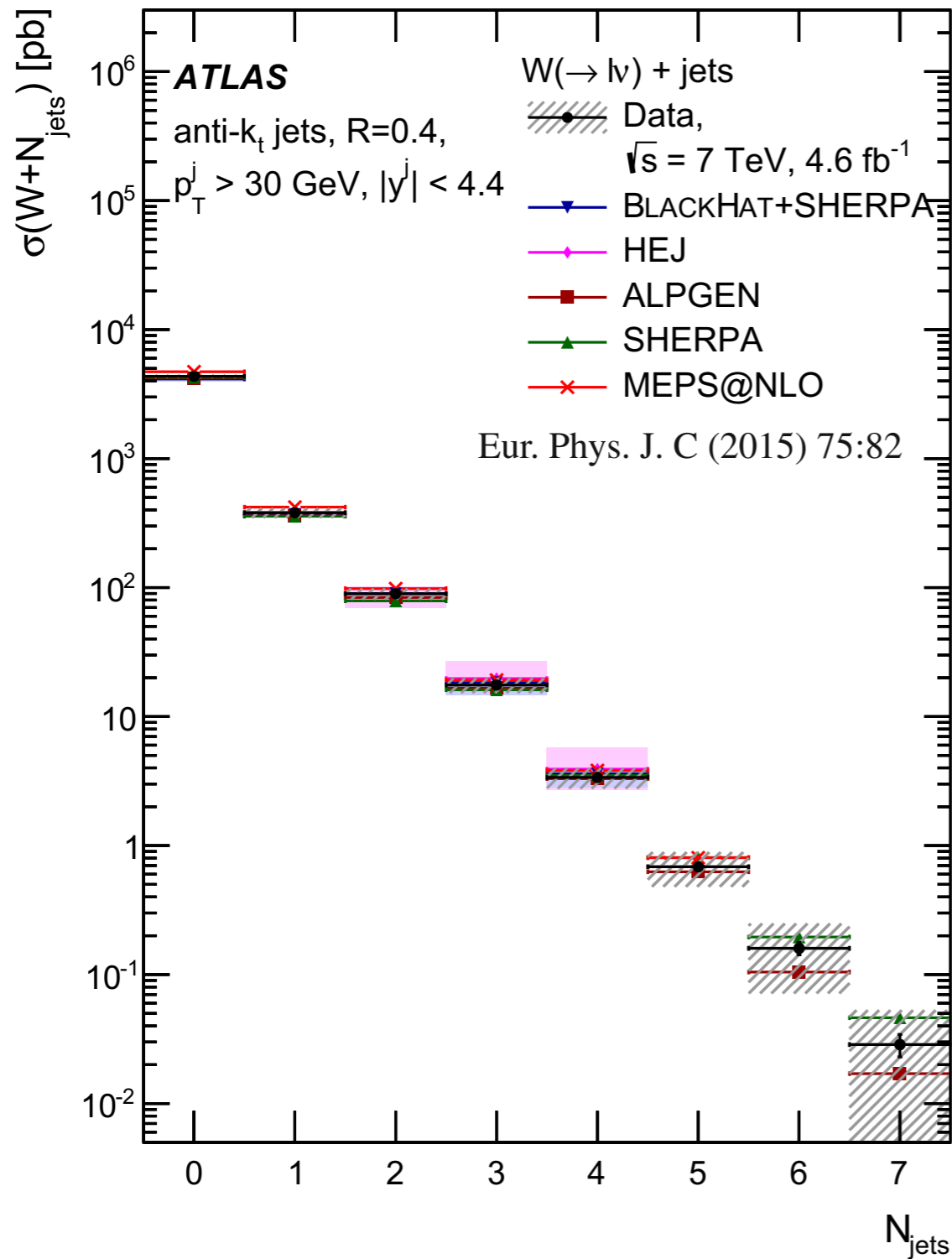
Type III : Next-to-leading order ME & leading-log parton shower

𝕊 events   ℍ events

PS

virtual

need to remove double-counting

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

ME+PS

Herwig++/
Pythia6/8

SingleTop, TopRex
Phantom
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ME+PS+merging

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NLO+PS

MC@NLO
POWHEG

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

S events   **H** events

PS

need to remove double-counting

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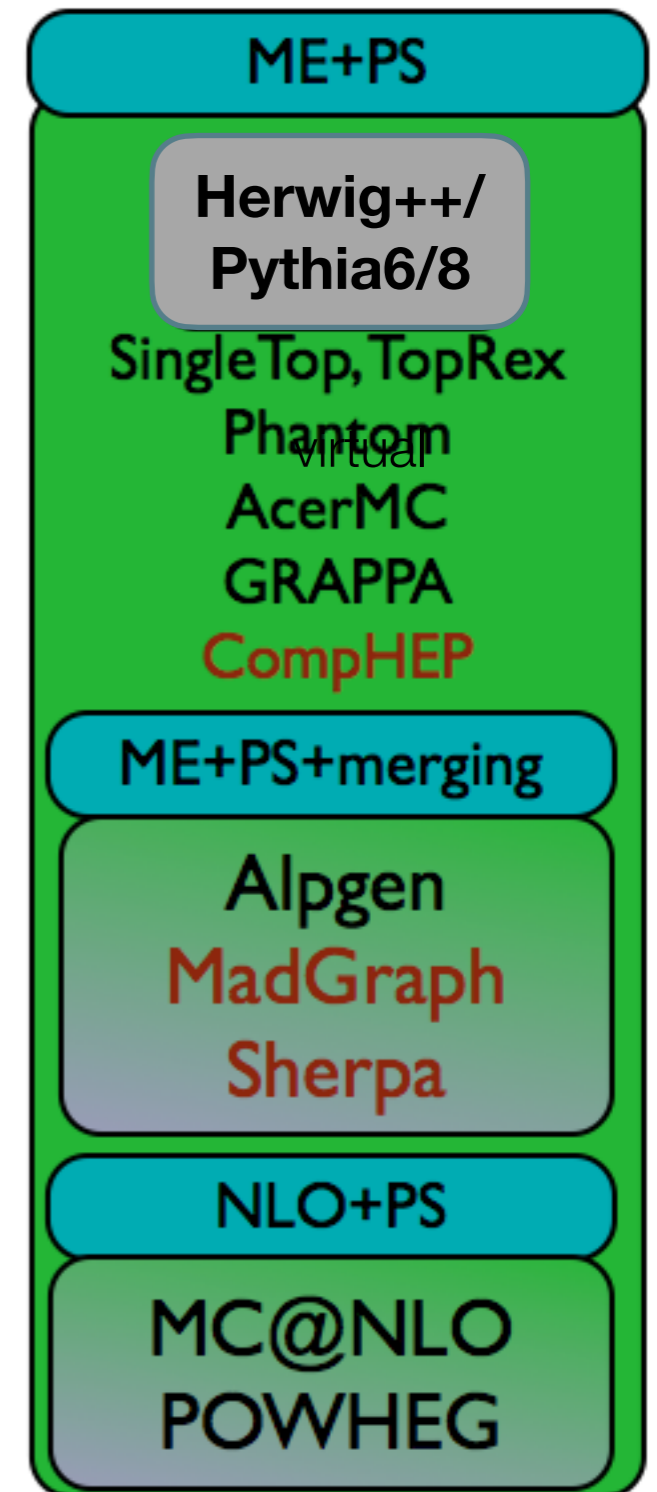
Two matching methods:

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 (contains unbalanced higher order terms)

2. MC@NLO:

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

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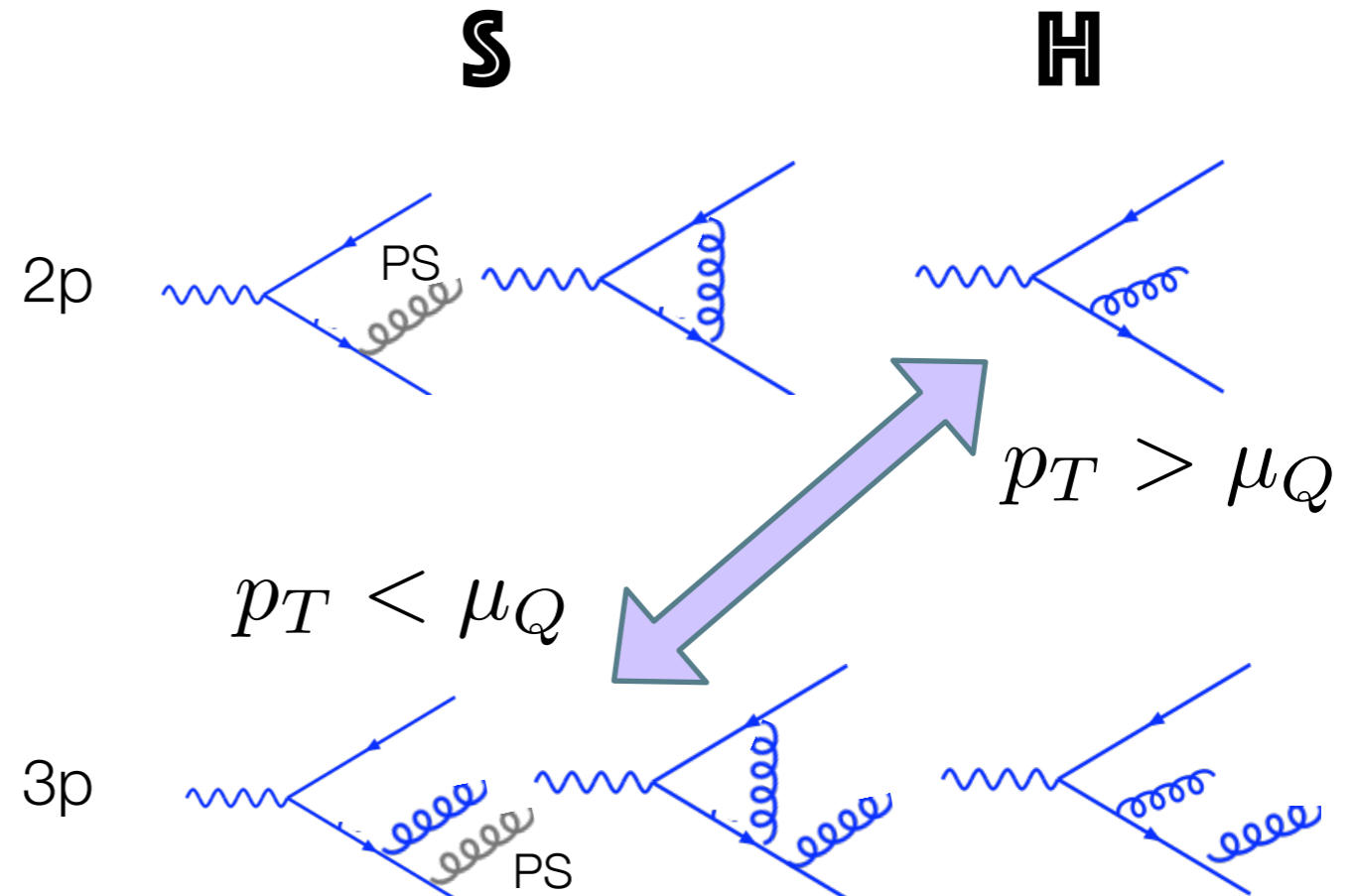   - produce some negative weights, it needs retuning for each PS

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)

FxFx (Frederix-Frixione) merging

1) define a matching scale μ_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)

S   **H**

2p

$p_T > \mu_Q$

$p_T < \mu_Q$

3p

Let's recap

Hadronization & Decay

Parton Shower

Hard Process

Incoming Proton

Incoming Proton

Underlying Event

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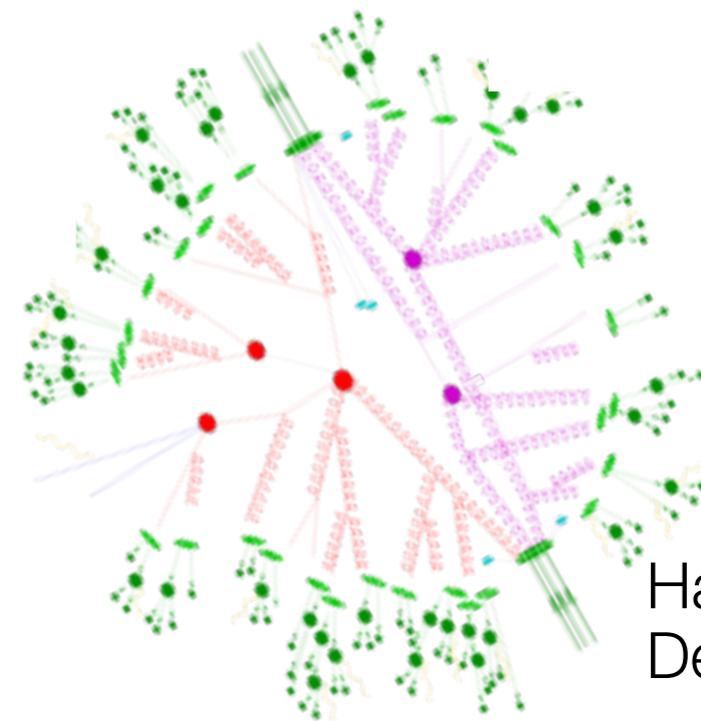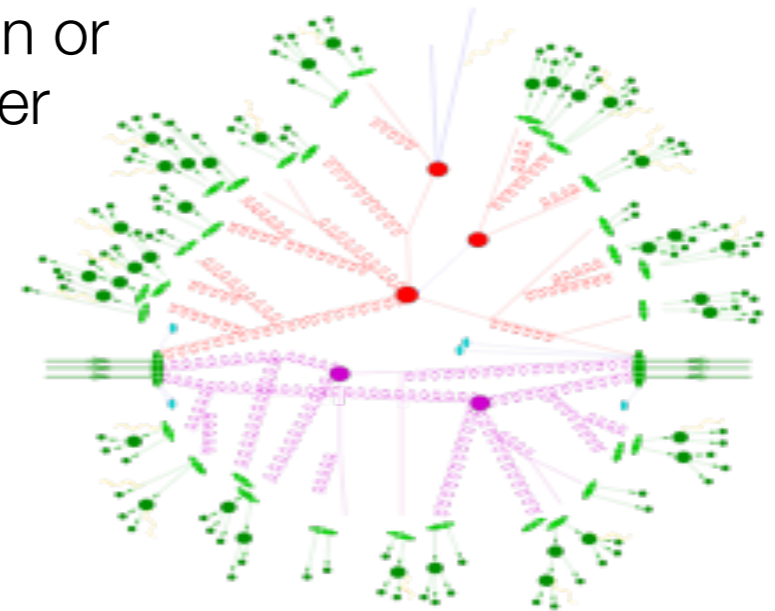# From partons to color neutral hadrons

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]

Fragmentation or
Parton Shower

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

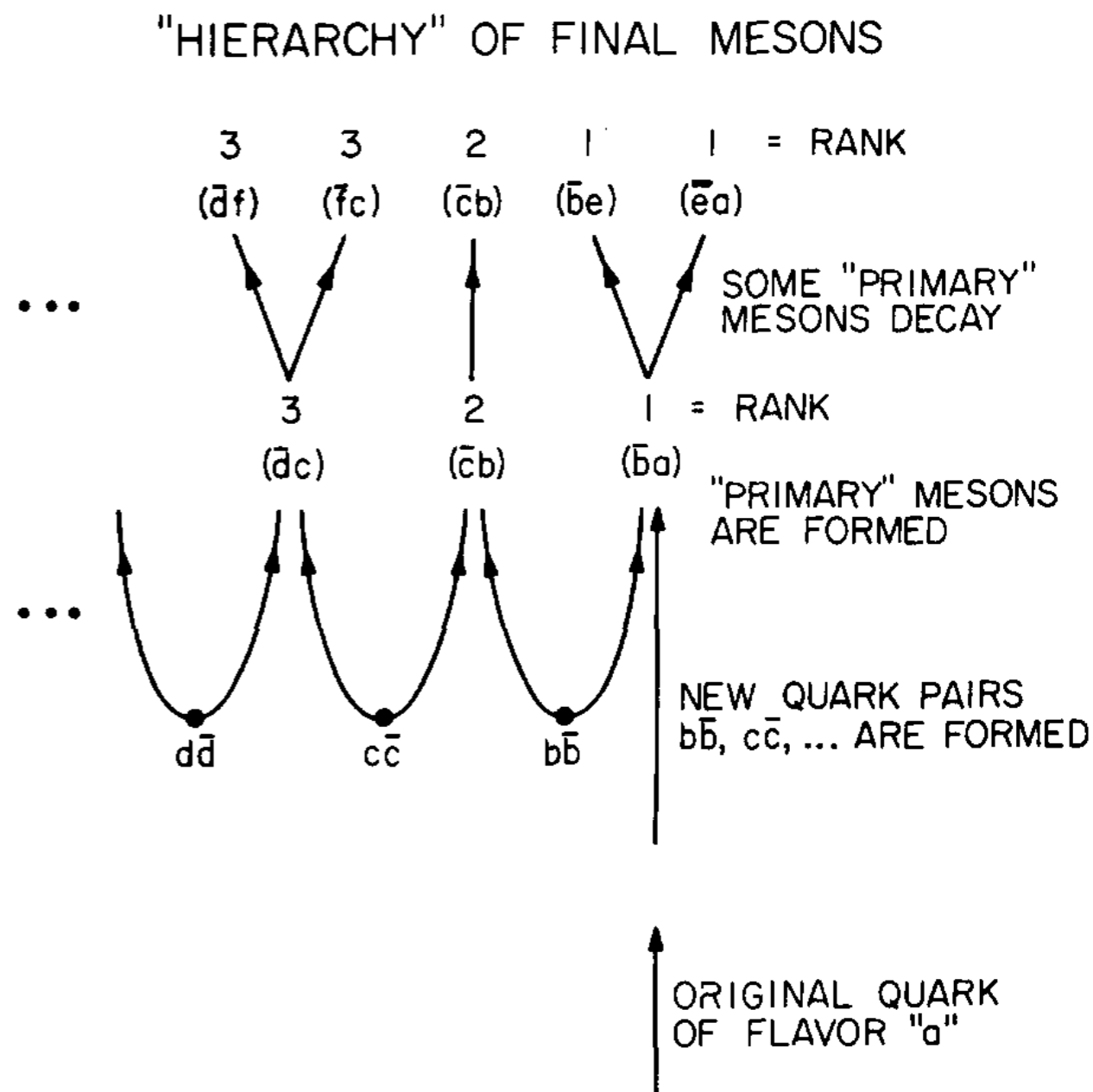Generate quark-antiquark pairs from vacuum

➤ 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)

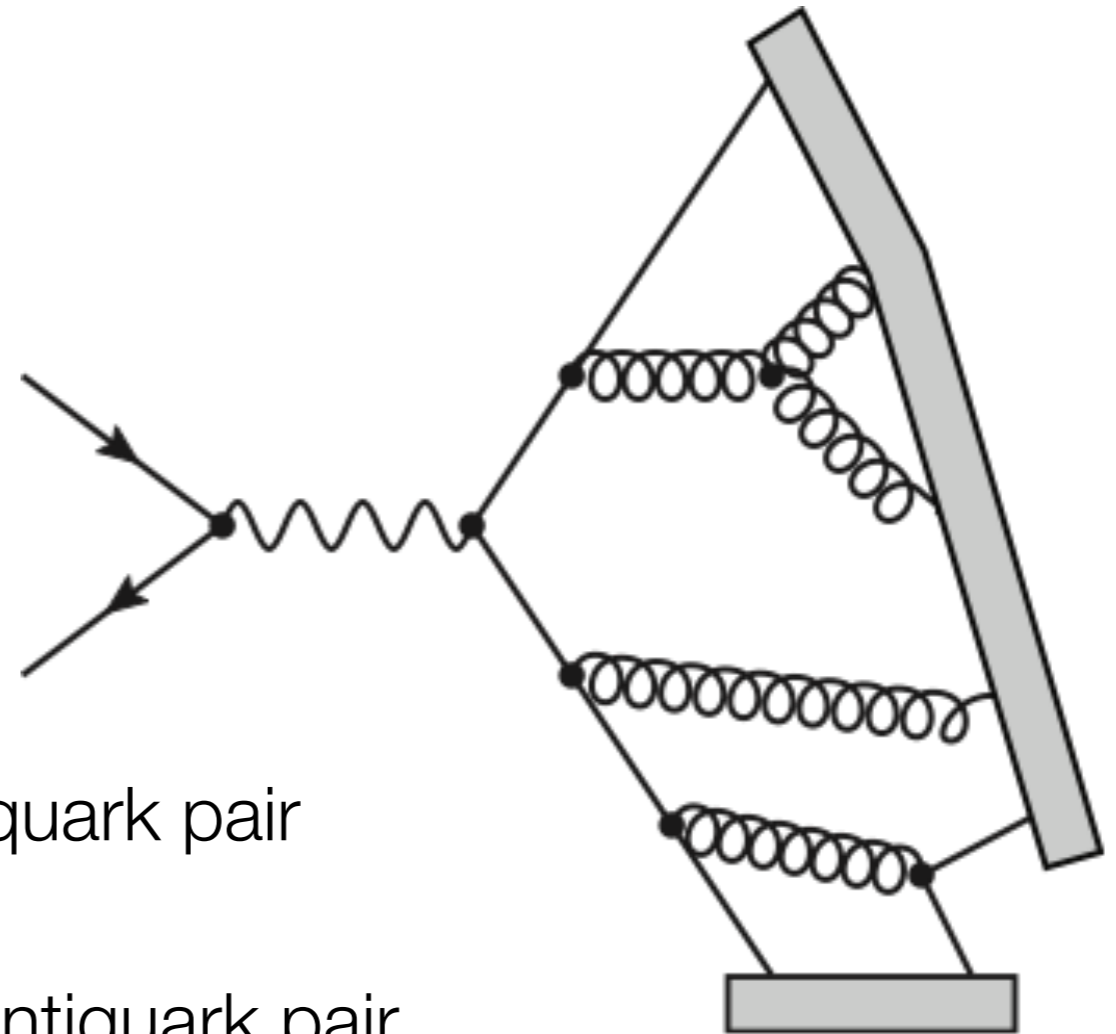D(z): probability to find a meson/hadron with energy fraction z in jet ...

"HIERARCHY" OF FINAL MESONS

3   3   2   1   1 = RANK
(d̄f) (f̄c) (c̄b) (b̄e) (ēa)

SOME "PRIMARY" MESONS DECAY

3   2   1 = RANK
(d̄c) (c̄b) (b̄a)

"PRIMARY" MESONS ARE FORMED

dd̄   cc̄   bb̄

NEW QUARK PAIRS bb̄, cc̄, ... ARE FORMED

ORIGINAL QUARK OF FLAVOR "a"

Lund String Model

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

QCD potential:

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

neglected

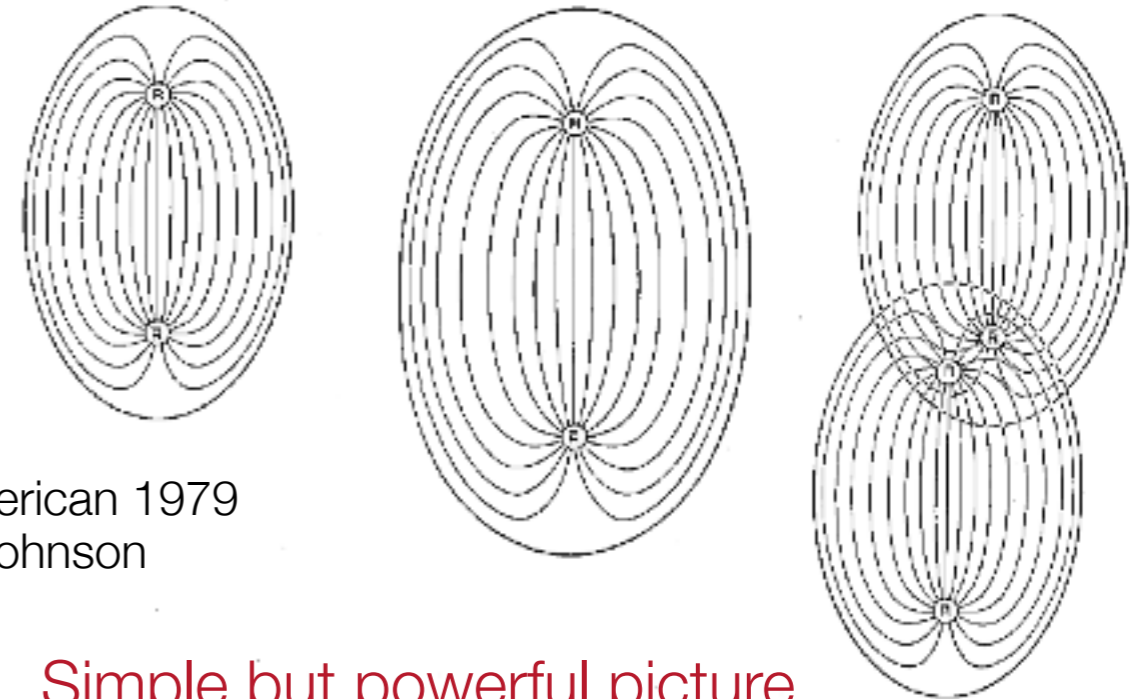String formation between initial quark-antiquark pair

- 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 $V(r) = \kappa \cdot r$

$$\left|\frac{dE}{dz}\right| = \left|\frac{dp_z}{dz}\right| = \left|\frac{dE}{dt}\right| = \left|\frac{dp_z}{dt}\right| = \kappa$$

Energy-momentum quantities can be
read from space-time quantities …
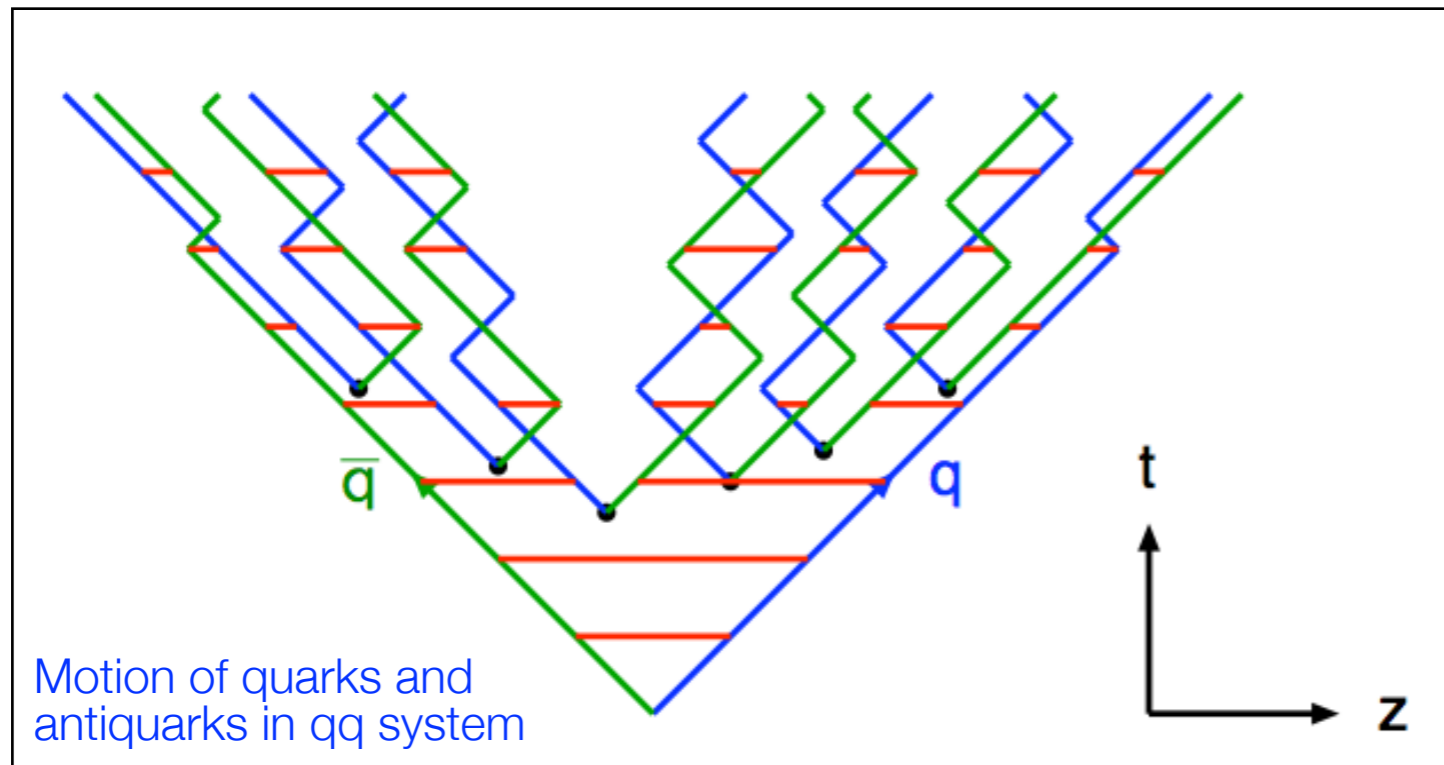
Scientific American 1979
Kenneth A. Johnson

Simple but powerful picture
of hadron production

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

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

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

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

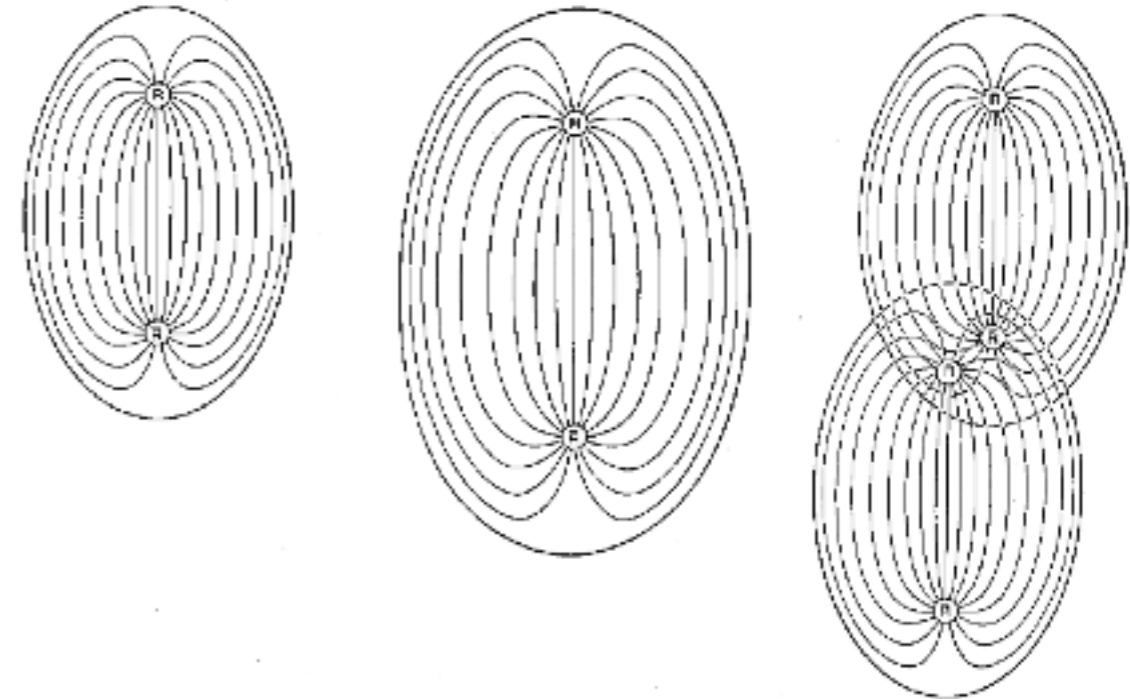Yields: Common Gaussian p⊥ spectrum
Heavy quark suppression

q̄   q   t

Motion of quarks and
antiquarks in qq system

z

Lund String Model

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

$$\left|\frac{dE}{dz}\right| = \left|\frac{dp_z}{dz}\right| = \left|\frac{dE}{dt}\right| = \left|\frac{dp_z}{dt}\right| = \kappa$$

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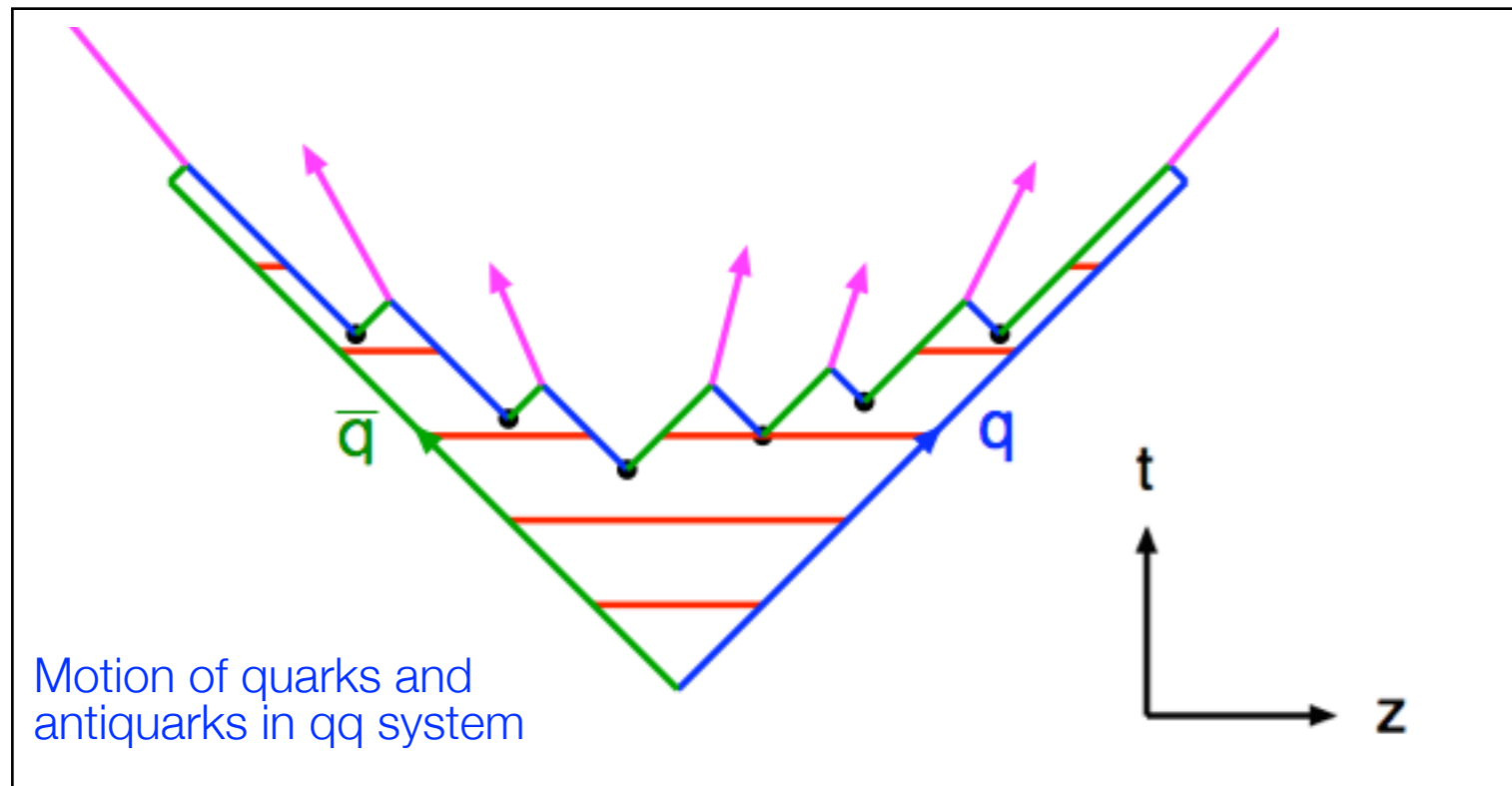read from space-time quantities ...

Kenneth A. Johnson

Simple but powerful picture
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$$\mathcal{P} \propto \exp\left(-\frac{\pi\, m_{\perp q}^2}{\kappa}\right)$$

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

Yields: Common Gaussian p⊥ spectrum
Heavy quark suppression

$\overline{q}$ q   t

Motion of quarks and
antiquarks in qq system

z

Cluster Model

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

Color flow confined during
hadronisation process
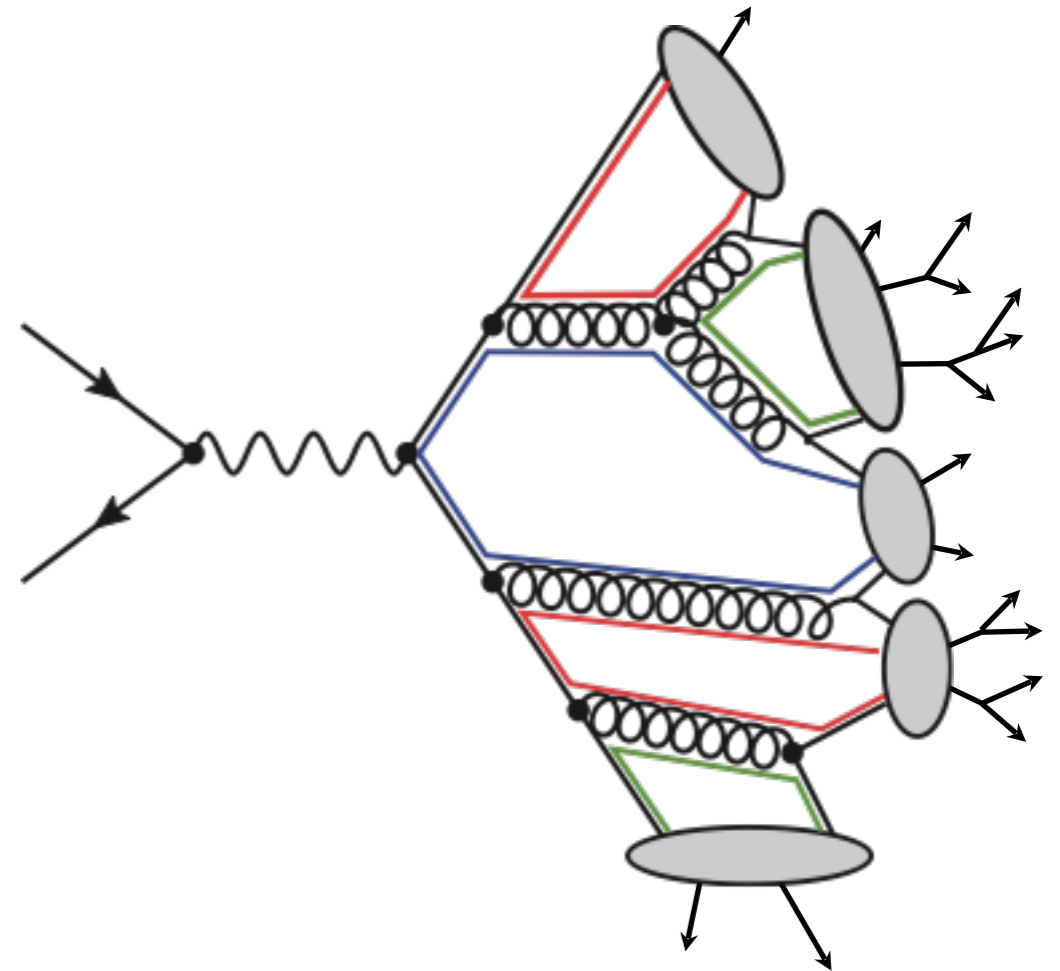
➤ Formation of color-neutral
   parton clusters

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

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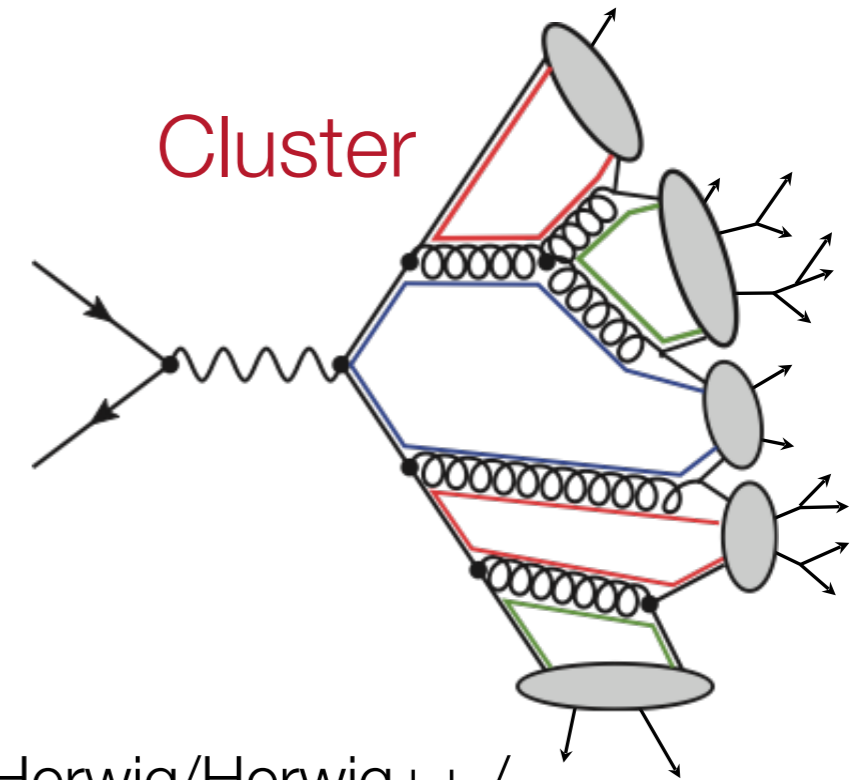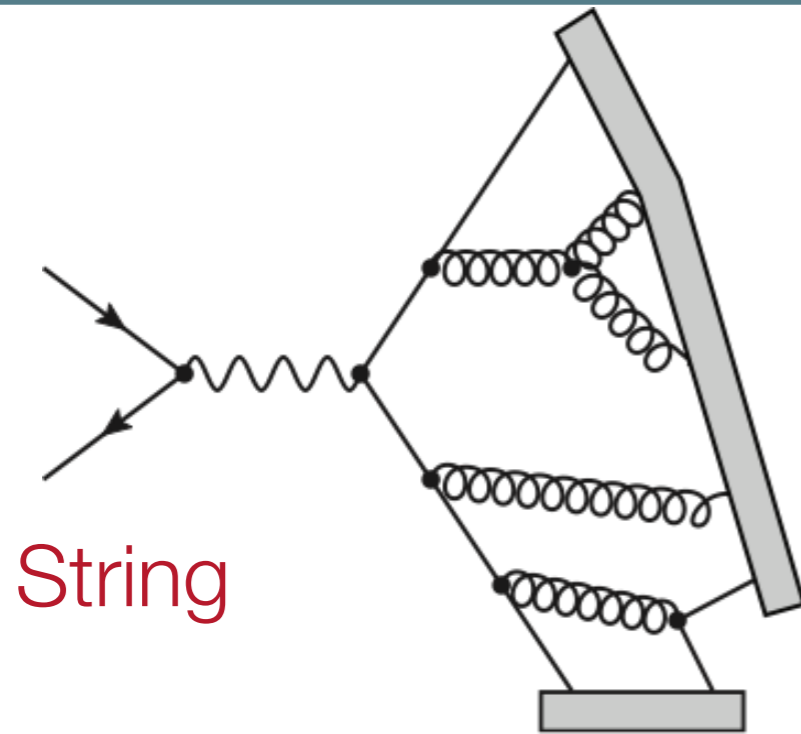to phase-space, i.e. isotropically

➤ no free tuning parameters
   parton clusters

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

Hadronisation models summary

String

Cluster

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]

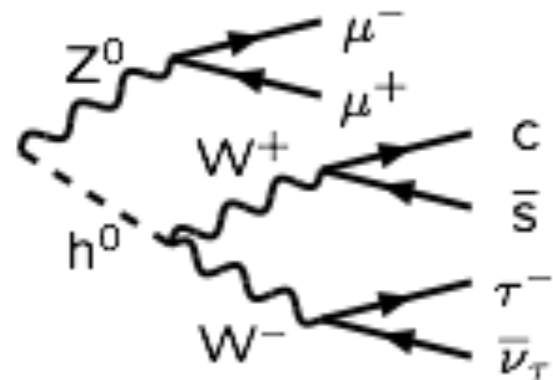# Structure of basic generator process [by order of consideration]

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

Matrix elements (ME)

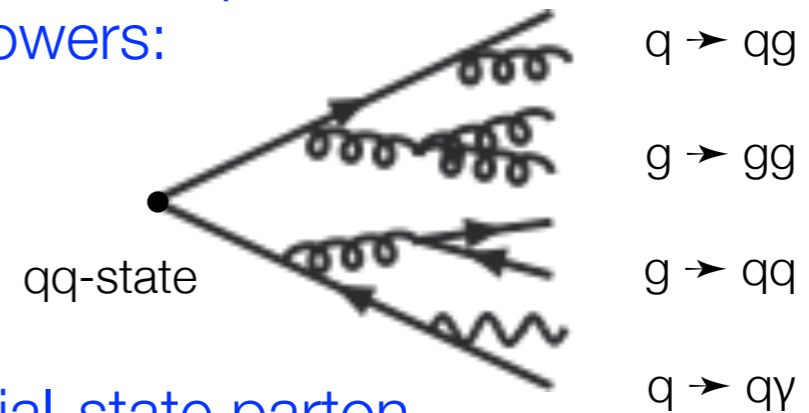1. Hard subprocess:
   $|M|^2$, Breit Wigners, PDFs
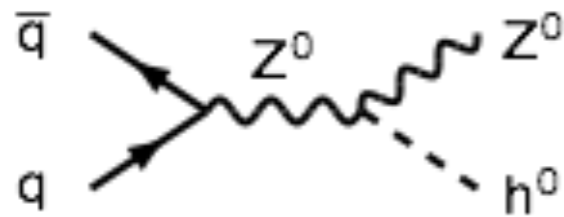
2. Resonance decays:
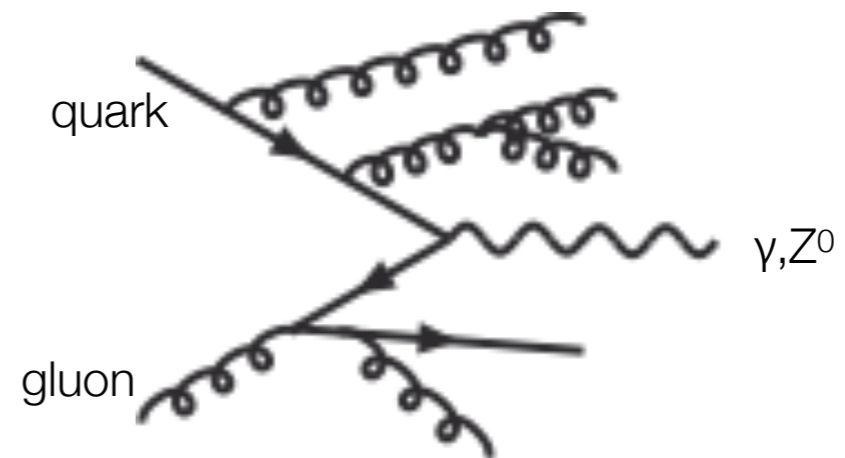   Includes particle correlations

Parton Shower (PS)

3. Final-state parton showers:

4. Initial-state parton showers:

B. Di Micco

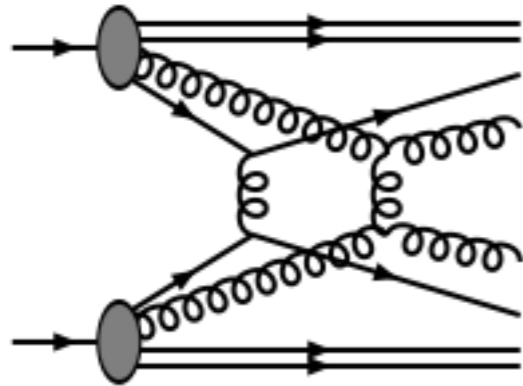Università degli Studi di Roma Tre

[from G.Herten]

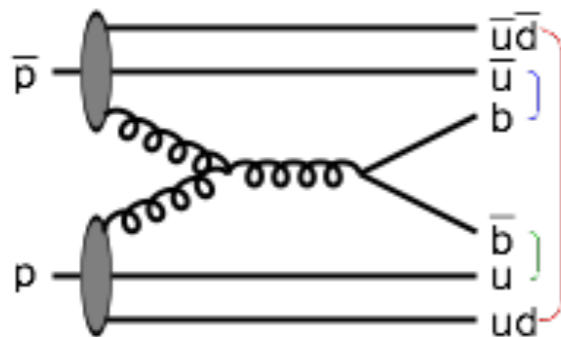# Conclusions: Structure of basic generator process

From the 'simple' to the 'complex' or
from 'calculable' at large scales to 'modelled; at small
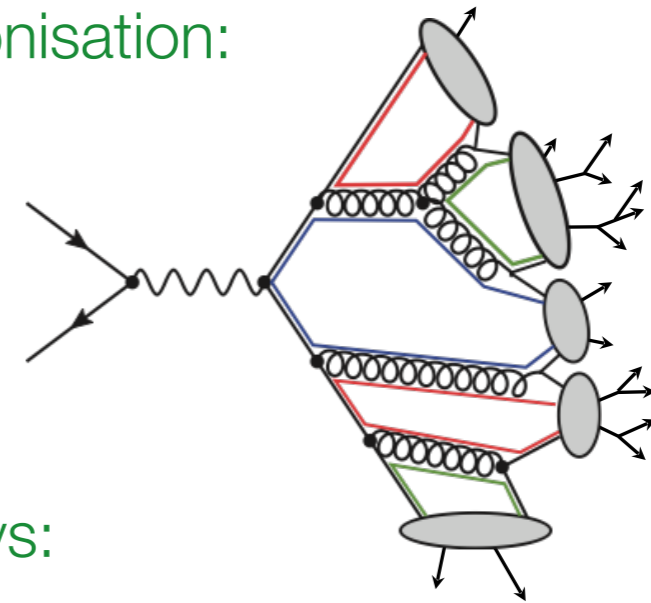
Underlying Event (UE)

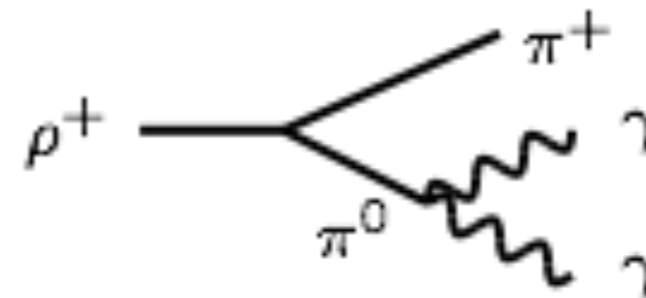### 5. Multi-parton interaction:

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:

$$f(x,t) = f_0(x) + \int_{t_0}^{t} \frac{dt'}{t'} \frac{\alpha_s(t')}{2\pi} \int_{x}^{1} \frac{dz}{z} P(z) \, q\left(\frac{x}{z}, t'\right)$$

$$= f_0(x) + \int_{t_0}^{t} \frac{dt'}{t'} \frac{\alpha_s}{2\pi} \int_{x}^{1} \frac{dz}{z} P(z) \left\{ f_0\left(\frac{x}{z}\right) + \right.$$

$$\left. + \int_{t_0}^{t'} \frac{dt''}{t''} \frac{\alpha_s}{2\pi} \int_{x/z}^{1} \frac{dz'}{z'} P(z') \left[f_0\left(\frac{x}{zz'}\right) + \cdots \right] \right\}$$

$$= f_0(x) + \frac{\alpha_s}{2\pi} \ln\left(\frac{t}{t_0}\right) \int_{x}^{1} \frac{dz}{z} P(z) f_0\left(\frac{x}{z}\right) +$$

$$+ \frac{1}{2!} \left[\frac{\alpha_s}{2\pi} \ln\left(\frac{t}{t_0}\right) \right]^2 \int_{x}^{1} \frac{dz}{z} P(z) \int_{x/z}^{1} \frac{dz'}{z'} P(z') f_0\left(\frac{x}{zz'}\right) + \cdots$$

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

B. Di Miccc