MC Generator for Exp Usage

Qiang Li 2020.02

Caveats

1. Mainly From a user’s point of view
2. Try to be practical.
3. Focusing on hadron collider
4. Not meant to be exhaustive

Refs: arXiv:1101.2599

MG School 2015 Shanghai
http://www.physics.sjtu.edu.cn/madgraphschool/

CMS MC page

Main generators:

Generator
Pythia6
Pythia8
MadGraph5_aMCatNLO
POWHEG
SherpaNLO

Package
LHAPDF

Photos
EvtGen
Particle Guns
Tauola++ and TauSpinner

Other generators which could be of interest:

Generator
Herwig6
ThePEG (for Herwig++)
ALPGEN
MC@NLO
gg2VV
Phantom
Hydjet
Hydjet++
Pyquen
Cosmic Muon Generator
ExHuME
Pomwig
BCVEGPY
HARDCOL

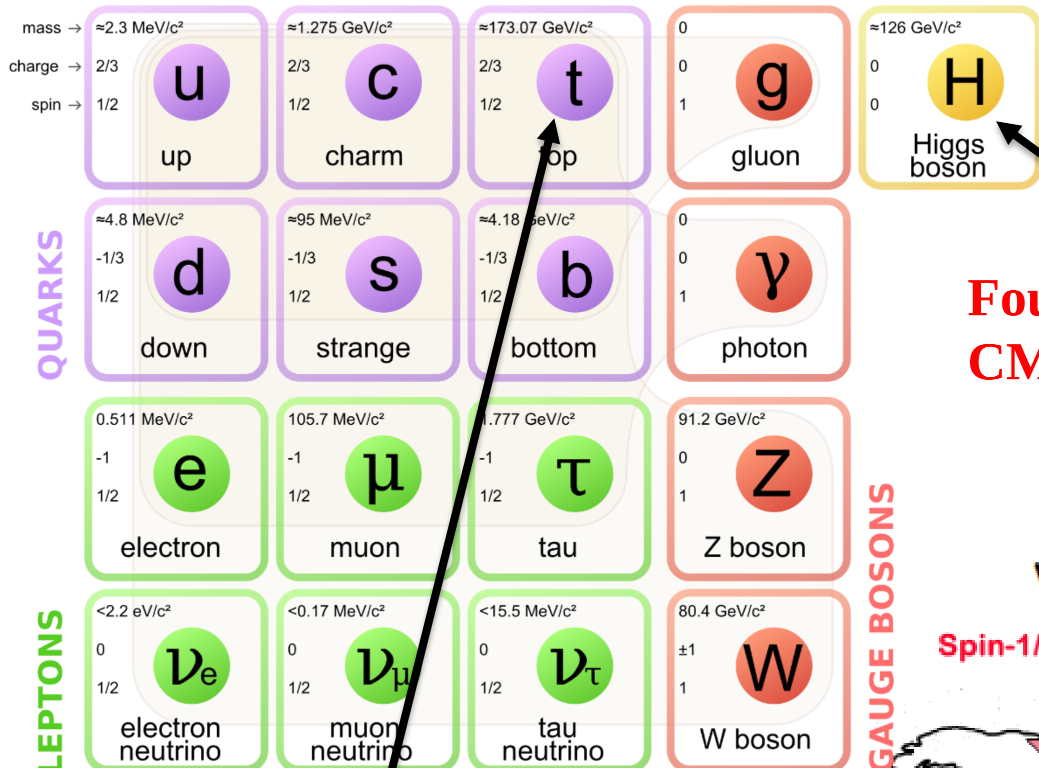
Generator
CompHEP
TopRex
Charybdis
EDDE
HELAC

PHOJET
Regge-Gribov Generators (EPOS, QGSJetII, Sibyll)
CASCADE
Herwig++

Outline

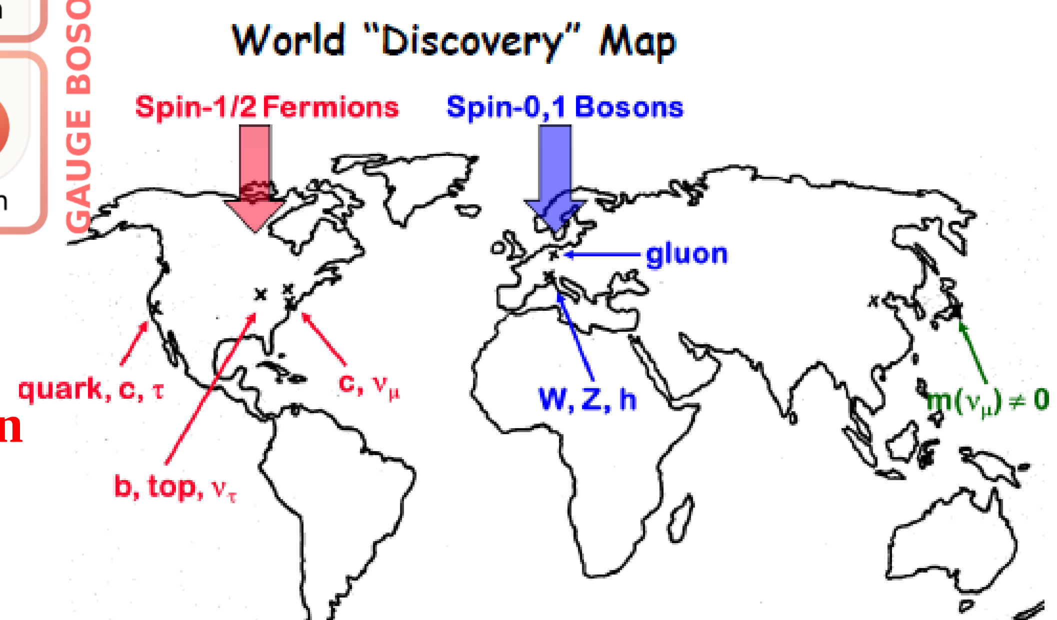
1. Collider, Collision, Simulation
2. Hard Scattering: PDF, LO, NLO
3. Parton Shower: Pythia6(8), Herwig(++)
4. Event Format: LHE, HEP
5. ME-PS Matching/Merging
6. Overview of Tools
7. New Physics
8. Detector Simulation: Delphes
9. Advanced Topics

The SM: 3 interactions



SU(3) x SU(2) x U(1)

Found in 2012 by LHC ATLAS and CMS. Nobel prize in 2013



Found in 1995 by Fermilab Tevatron CDF and D0

The Nobel Prize in Physics 1957

Chen Ning Yang

Prize share: 1/2

Tsung-Dao (T.D.) Lee

Prize share: 1/2

宇称破坏
弱作用

The Nobel Prize in Physics 1957 was awarded jointly to Chen Ning Yang and Tsung-Dao (T.D.) Lee *"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"*

The Nobel Prize in Physics 1958

高速粒子切伦科夫辐射

Pavel Alekseyevich Cherenkov

Prize share: 1/3

Il´ja Mikhailovich Frank

Prize share: 1/3

Igor Yevgenyevich Tamm

Prize share: 1/3

The Nobel Prize in Physics 1958 was awarded jointly to Pavel Alekseyevich Cherenkov, Il´ja Mikhailovich Frank and Igor Yevgenyevich Tamm *"for the discovery and the interpretation of the Cherenkov effect"*.

The Nobel Prize in Physics 1959

Emilio Gino Segrè

Prize share: 1/2

Owen Chamberlain

Prize share: 1/2

反质子

The Nobel Prize in Physics 1959 was awarded jointly to Emilio Gino Segrè and Owen Chamberlain *"for their discovery of the antiproton"*

The Nobel Prize in Physics 1960

气泡室
弱中性流

Donald Arthur Glaser

Prize share: 1/1

The Nobel Prize in Physics 1960 was awarded to Donald A. Glaser *"for the invention of the bubble chamber".*

The Nobel Prize in Physics 1965

量子电动力学

Sin-Itiro Tomonaga

Prize share: 1/3

Julian Schwinger

Prize share: 1/3

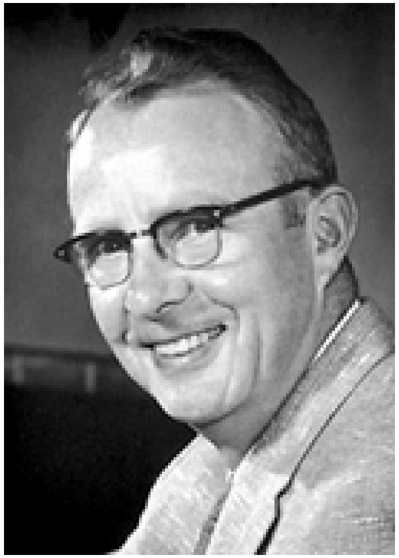
Richard P. Feynman

Prize share: 1/3

The Nobel Prize in Physics 1965 was awarded jointly to Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman *"for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"*.

The Nobel Prize in Physics 1968

液氢气泡室
一批共振态



Luis Walter Alvarez

Prize share: 1/1

The Nobel Prize in Physics 1968 was awarded to Luis Alvarez *"for his decisive contributions to elementary particle physics, in particular the discovery of a large number of resonance states, made possible through his development of the technique of using hydrogen bubble chamber and data analysis".*

The Nobel Prize in Physics 1969

强相互作用
夸克

Murray Gell-Mann

Prize share: 1/1

The Nobel Prize in Physics 1969 was awarded to Murray Gell-Mann *"for his contributions and discoveries concerning the classification of elementary particles and their interactions".*

The Nobel Prize in Physics 1976

粲夸克

Burton Richter

Prize share: 1/2

Samuel Chao Chung Ting

Prize share: 1/2

The Nobel Prize in Physics 1976 was awarded jointly to Burton Richter and Samuel Chao Chung Ting *"for their pioneering work in the discovery of a heavy elementary particle of a new kind"*

The Nobel Prize in Physics 1979

电弱理论

Sheldon Lee Glashow

Prize share: 1/3

Abdus Salam

Prize share: 1/3

Steven Weinberg

Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

The Nobel Prize in Physics 1984

W，Z玻色子

Carlo Rubbia

Prize share: 1/2

Simon van der Meer

Prize share: 1/2

The Nobel Prize in Physics 1984 was awarded jointly to Carlo Rubbia and Simon van der Meer *"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"*

The Nobel Prize in Physics 1988

缪子中微子

Leon M. Lederman

Prize share: 1/3

Melvin Schwartz

Prize share: 1/3

Jack Steinberger

Prize share: 1/3

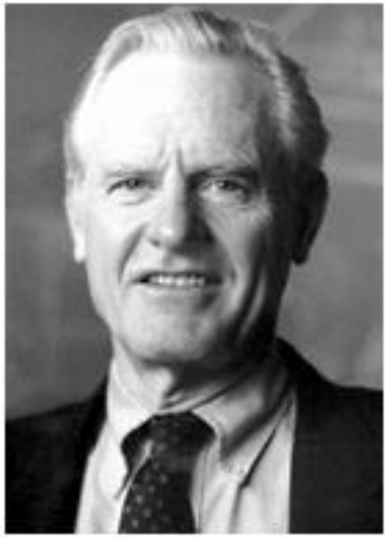
The Nobel Prize in Physics 1988 was awarded jointly to Leon M. Lederman, Melvin Schwartz and Jack Steinberger *"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"*.

The Nobel Prize in Physics 1990

深度非弹，夸克模型

Jerome I. Friedman

Prize share: 1/3



Henry W. Kendall

Prize share: 1/3

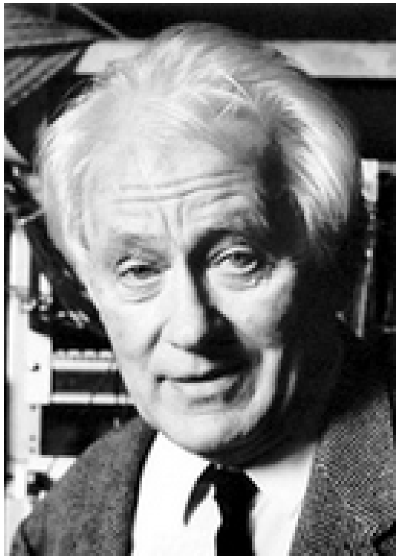
Photo: T. Nakashima

Richard E. Taylor

Prize share: 1/3

The Nobel Prize in Physics 1990 was awarded jointly to Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor *"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics".*

The Nobel Prize in Physics 1992



Georges Charpak

Prize share: 1/1

多丝正比室

快速电子读出

Drift Tube

Time Projection Chamber

The Nobel Prize in Physics 1992 was awarded to Georges Charpak *"for his invention and development of particle detectors, in particular the multiwire proportional chamber".*

The Nobel Prize in Physics 1995

Martin L. Perl

Prize share: 1/2

© University of California Regents

Frederick Reines

Prize share: 1/2

Tau轻子

首次探测中微子

电子反中微子

The Nobel Prize in Physics 1995 was awarded *"for pioneering experimental contributions to lepton physics"* jointly with one half to Martin L. Perl *"for the discovery of the tau lepton"* and with one half to Frederick Reines *"for the detection of the neutrino"*.

The Nobel Prize in Physics 1999

Gerardus 't Hooft

Prize share: 1/2

Martinus J.G. Veltman

Prize share: 1/2

标准模型重整化

The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Martinus J.G. Veltman *"for elucidating the quantum structure of electroweak interactions in physics"*

The Nobel Prize in Physics 2002

中微子振荡

Raymond Davis Jr.

Prize share: 1/4

Masatoshi Koshiba

Prize share: 1/4

Riccardo Giacconi

Prize share: 1/2

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

The Nobel Prize in Physics 2008

Photo: University of Chicago

Yoichiro Nambu

Prize share: 1/2

© The Nobel Foundation Photo: U. Montan

Makoto Kobayashi

Prize share: 1/4

© The Nobel Foundation Photo: U. Montan

Toshihide Maskawa

Prize share: 1/4

对称性自发破缺

CKM，top夸克

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

The Nobel Prize in Physics 2013

Photo: A. Mahmoud

François Englert

Prize share: 1/2

Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

Higgs Boson
BEH

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

QED vs QCD

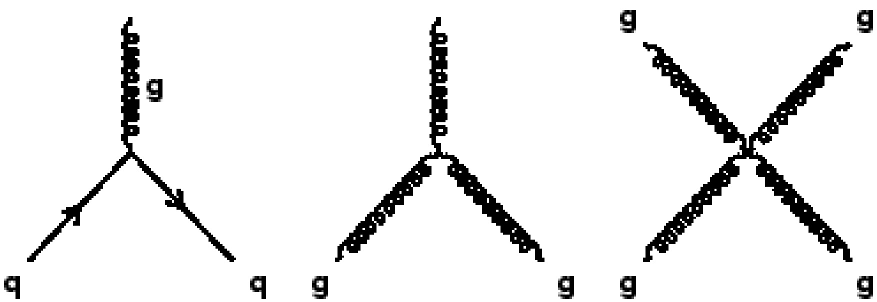
$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\alpha_{em} = \frac{e^2}{4\pi} \sim \frac{1}{137}$$

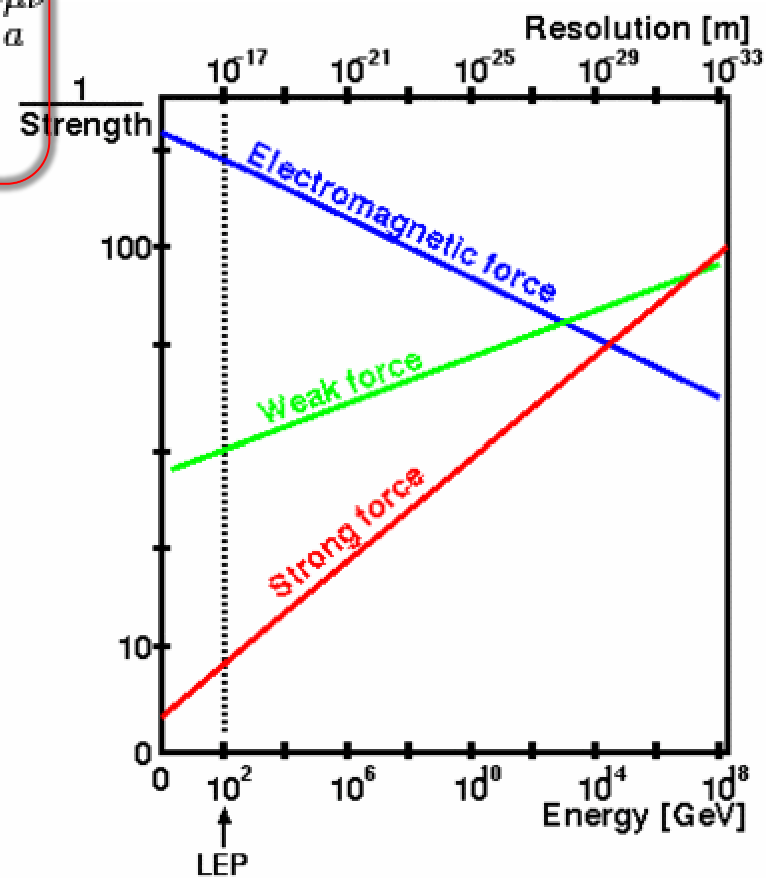
$$\alpha_{QCD}(100GeV) = \frac{g_{s^2}}{4\pi} \sim 0.13$$

$$\mathcal{L}_{\rm QCD} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij}\right)\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$
$$G^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu + g f^{abc} \mathcal{A}^b_\mu \mathcal{A}^c_\nu\,,$$

a=1…8,
i=1,2,3 QCD colors



Self-interactions



The Nobel Prize in Physics 2004

QCD渐进自由

David J. Gross

Prize share: 1/3

H. David Politzer

Prize share: 1/3

Frank Wilczek

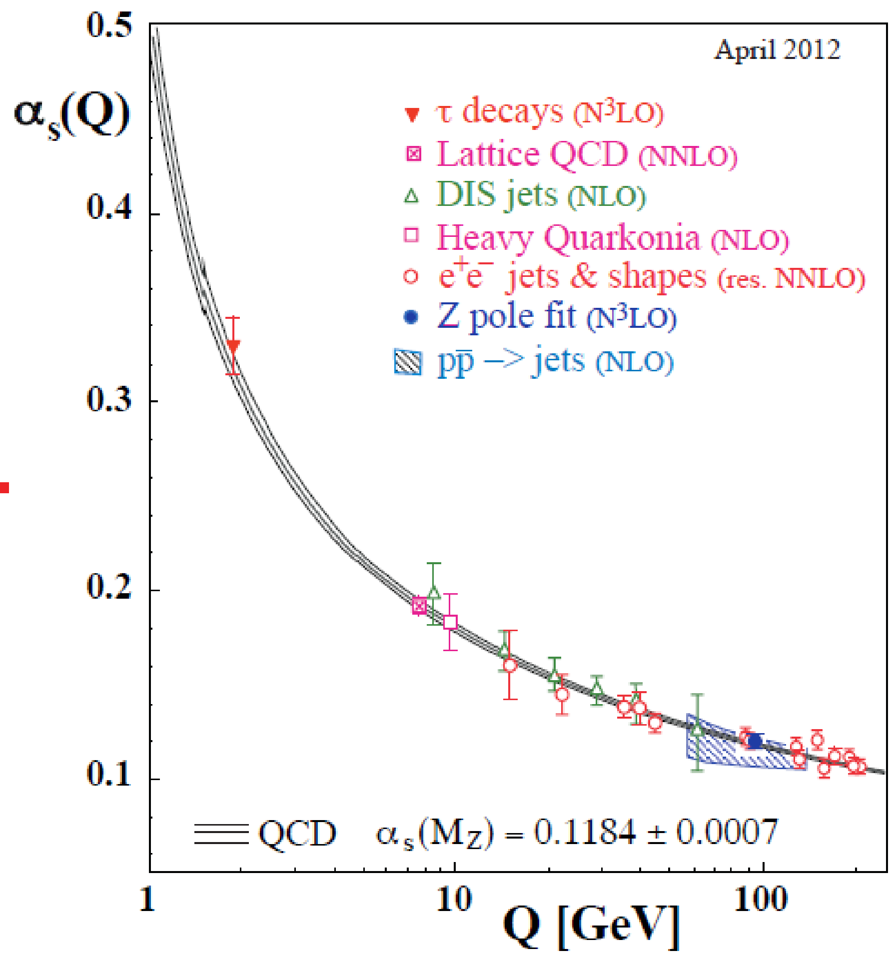
Prize share: 1/3

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.

QCD cutoff : Non-perturbative Region

Landau Pole

& Confinement



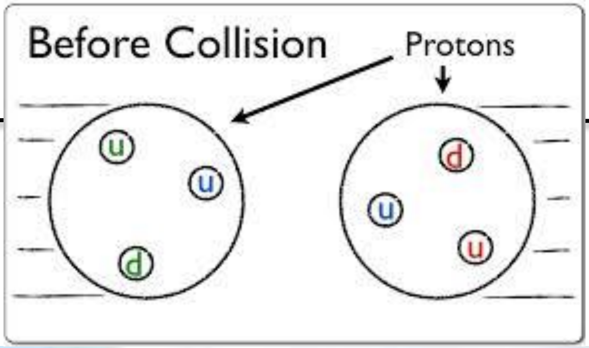
Asymptotic Freedom

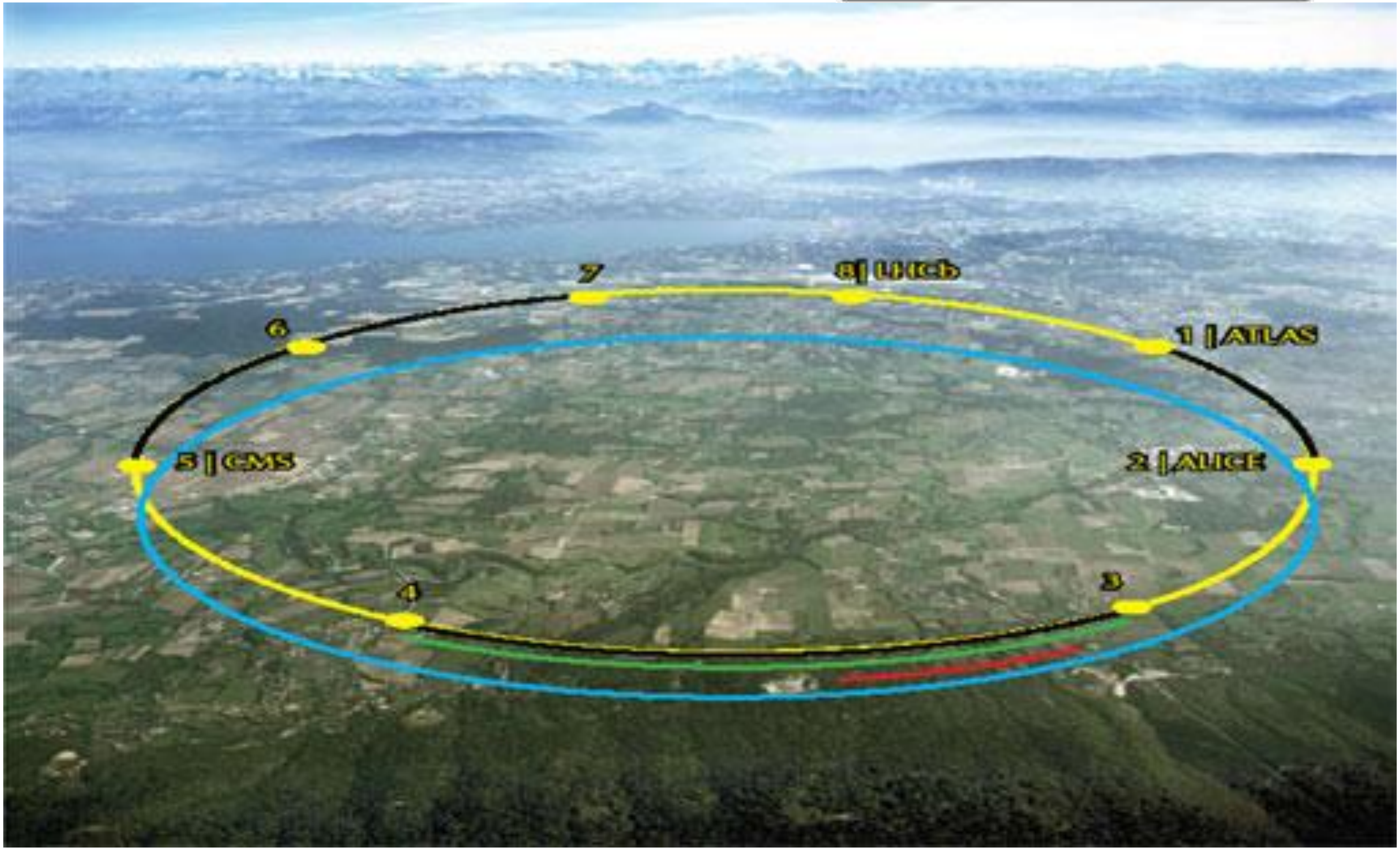
& Grand Unification?

$$\alpha_s(Q^2) = \frac{1}{b_0 \ln \frac{Q^2}{\Lambda^2}}, \quad \longrightarrow \quad \Lambda \sim 200\,\text{MeV}$$

Collider

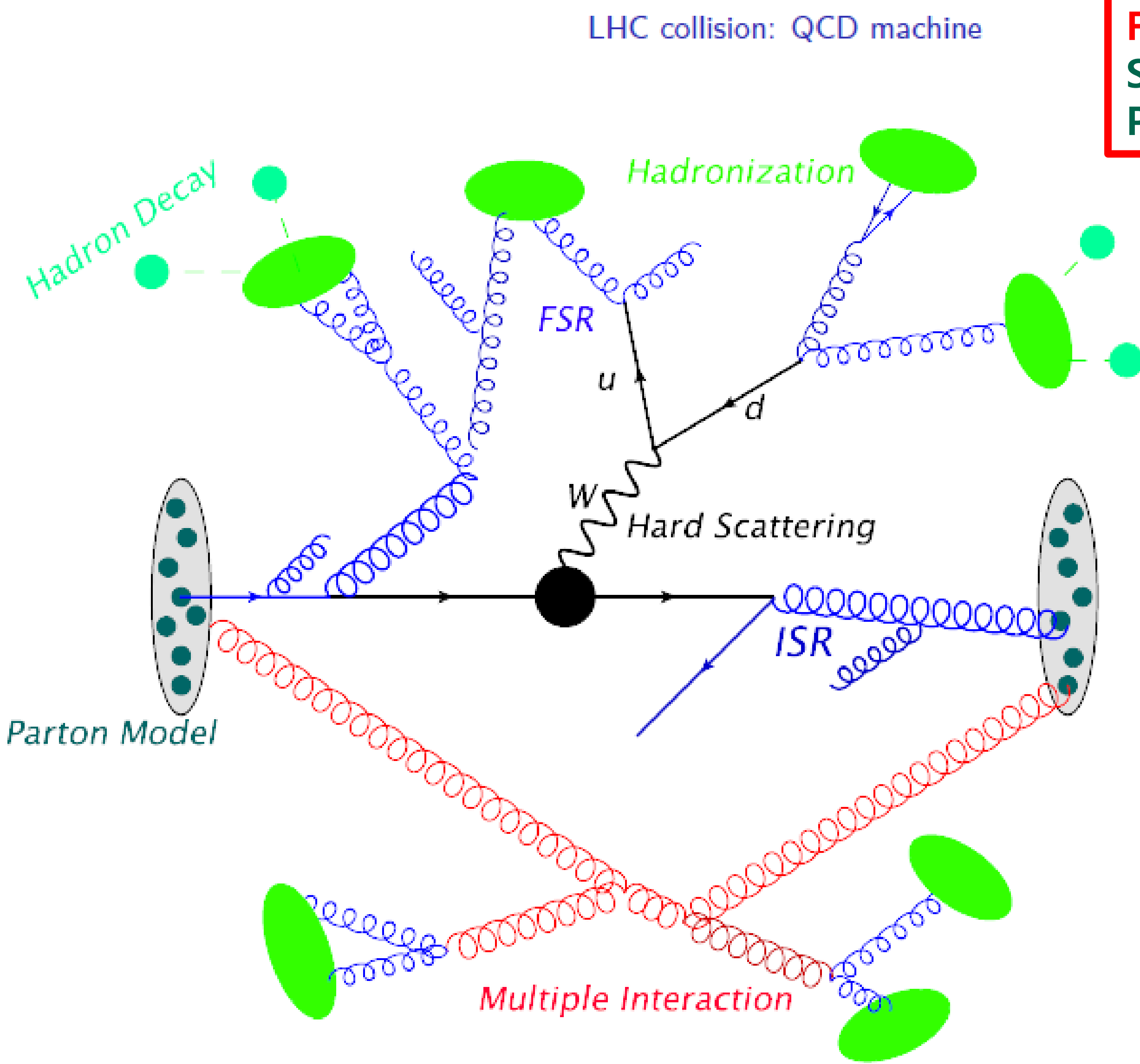
$$1\,fm \sim 5GeV^{-1}$$





Anatomy of a LHC Collision

Factorization Theorem:
Separate Short Distance Physics from Soft one

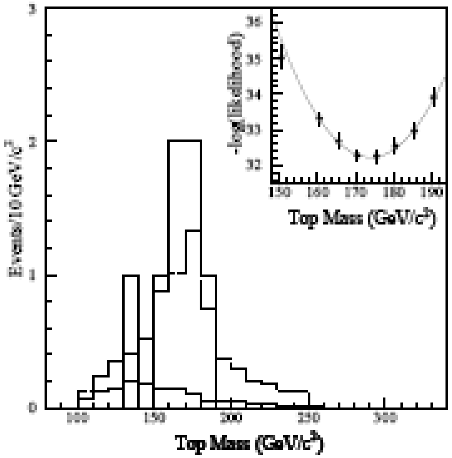


QCD Machine

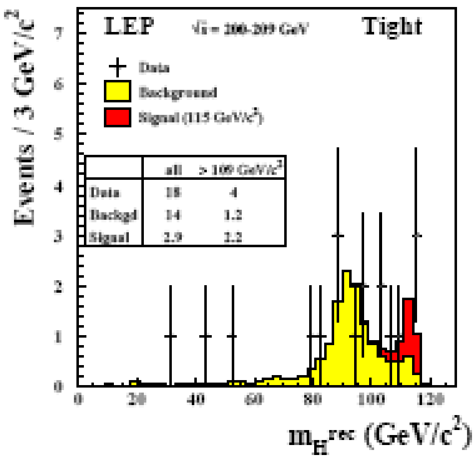
Factorization

Multi-level

Why Generators? Torbjörn Sjöstrand

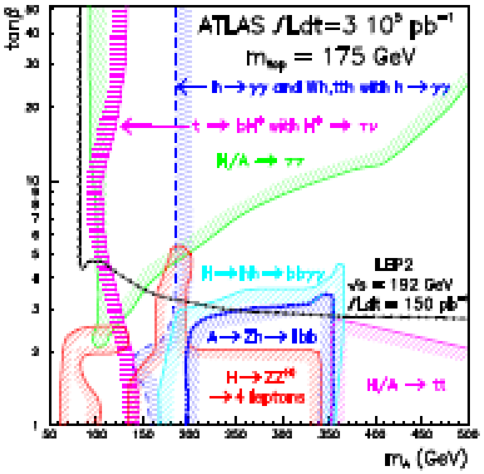


top discovery and mass determination



	all	> 109 GeV/c²
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2

Higgs (non) discovery



Higgs and supersymmetry exploration

not feasible without generators

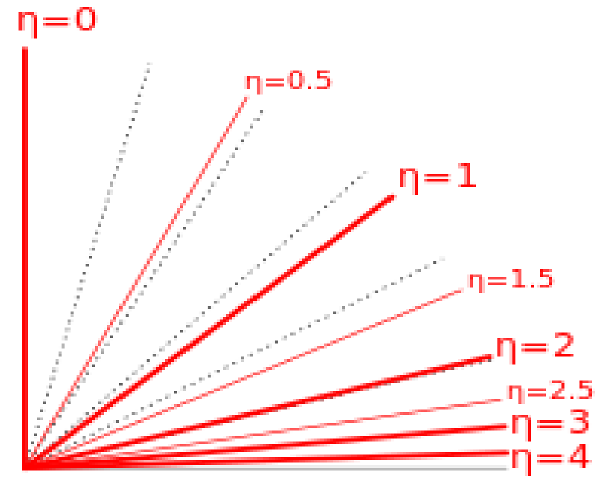
PT and (pseudo-)Rapidity

$$y \equiv \frac{1}{2}\ln\left(\frac{E+p_{\mathrm{L}}}{E-p_{\mathrm{L}}}\right)$$

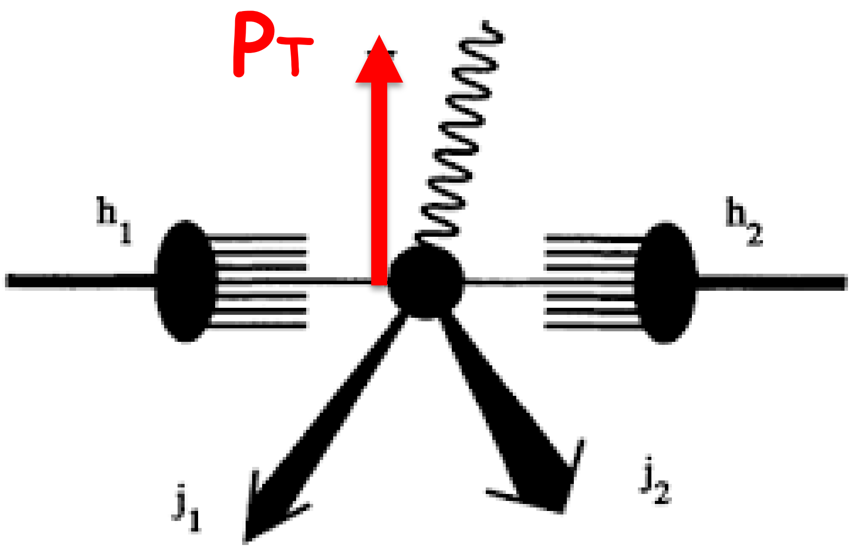
$$\eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}|+p_{\mathrm{L}}}{|\mathbf{p}|-p_{\mathrm{L}}}\right) = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

$$p_{\mathrm{T}} \equiv \sqrt{p_x^2+p_y^2}$$

$$(\Delta R)^2 \equiv (\Delta\eta)^2 + (\Delta\phi)^2$$



Lorentz Invariant Distance



LHC typical:

PT>20-30GeV

$|\eta|$<2.5, 4.7

$\Delta R > 0.3, 0.4, 0.5, 0.7, 0.8$

Lightcone kinematics and boosts

Introduce (lightcone) $p^+ = E + p_z$ and $p^- = E - p_z$.
Note that $p^+ p^- = E^2 - p_z^2 = m_\perp^2$.
Consider boost along z axis with velocity β, and $\gamma = 1/\sqrt{1-\beta^2}$.

$$
\begin{aligned}
p'_{x,y} &= p_{x,y} \\
p'_z &= \gamma(p_z + \beta\, E) \\
E' &= \gamma(E + \beta\, p_z) \\
p'^+ &= \gamma(1+\beta)p^+ = \sqrt{\frac{1+\beta}{1-\beta}}\, p^+ = k\, p^+ \\
p'^- &= \gamma(1-\beta)p^+ = \sqrt{\frac{1-\beta}{1+\beta}}\, p^- = \frac{p^-}{k} \\
y' &= \frac{1}{2}\ln\frac{p'^+}{p'^-} = \frac{1}{2}\ln\frac{k\,p^+}{p'^-/k} = y + \ln k \\
y'_2 - y'_1 &= (y_2 + \ln k) - (y_1 + \ln k) = y_2 - y_1
\end{aligned}
$$

Pseudorapidity

If experimentalists cannot measure m they may assume $m = 0$.
Instead of rapidity y they then measure pseudorapidity η:

$$y = \frac{1}{2} \ln \frac{\sqrt{m^2 + \mathbf{p}^2} + p_z}{\sqrt{m^2 + \mathbf{p}^2} - p_z} \quad \Rightarrow \quad \eta = \frac{1}{2} \ln \frac{|\mathbf{p}| + p_z}{|\mathbf{p}| - p_z} = \ln \frac{|\mathbf{p}| + p_z}{p_\perp}$$

or

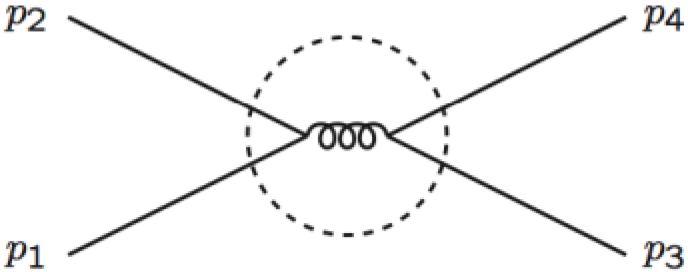
$$\begin{aligned} \eta &= \frac{1}{2} \ln \frac{\underline{p} + \underline{p} \cos\theta}{\underline{p} - \underline{p} \cos\theta} = \frac{1}{2} \ln \frac{1 + \cos\theta}{1 - \cos\theta} \\ &= \frac{1}{2} \ln \frac{2\cos^2\theta/2}{2\sin^2\theta/2} = \ln \frac{\cos\theta/2}{\sin\theta/2} = -\ln\tan\frac{\theta}{2} \end{aligned}$$

which thus only depends on polar angle.
η is **not** simple under boosts: $\eta'_2 - \eta'_1 \neq \eta_2 - \eta_1$.
You may even flip sign!
Assume $m = m_\pi$ for all charged $\Rightarrow y_\pi$; intermediate to y and η.

Mandelstam variables

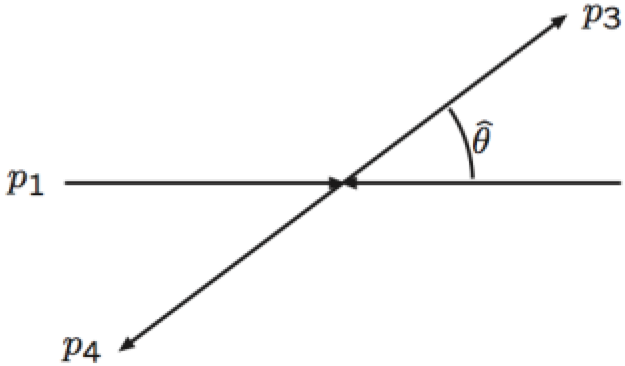
For process $1 + 2 \to 3 + 4$

$$
\begin{aligned}
s &= (p_1 + p_2)^2 = (p_3 + p_4)^2 \\
t &= (p_1 - p_3)^2 = (p_2 - p_4)^2 \\
u &= (p_1 - p_4)^2 = (p_2 - p_3)^2
\end{aligned}
$$



In rest frame, massless limit: $m_1 = m_2 = m_3 = m_4 = 0$,

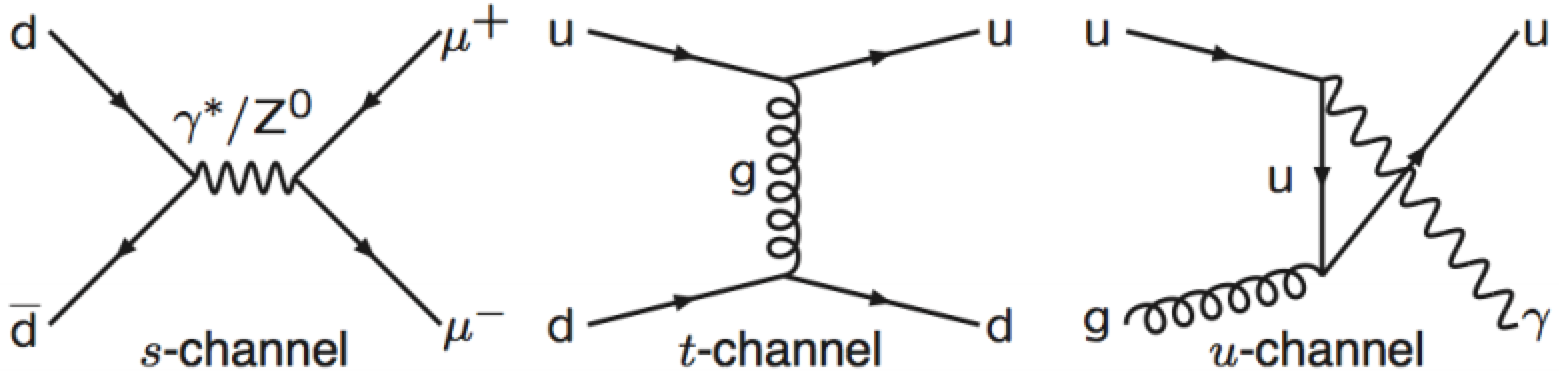
$$
\begin{aligned}
p_{1,2} &= \frac{E_{\rm cm}}{2}(1; 0, 0, \pm) \\
p_{3,4} &= \frac{E_{\rm cm}}{2}(1; \pm\sin\hat{\theta}, 0, \pm\cos\hat{\theta}) \\
s &= E_{\rm cm}^2 \\
t &= -2p_1p_3 = -\frac{s}{2}(1 - \cos\hat{\theta}) \\
u &= -2p_2p_4 = -\frac{s}{2}(1 + \cos\hat{\theta})
\end{aligned}
$$



$$s + t + u = 0$$

s-, t- and u-channel processes

Classify $2 \to 2$ diagrams by character of propagator, e.g.



Singularities reflect channel character, e.g. pure t-channel:

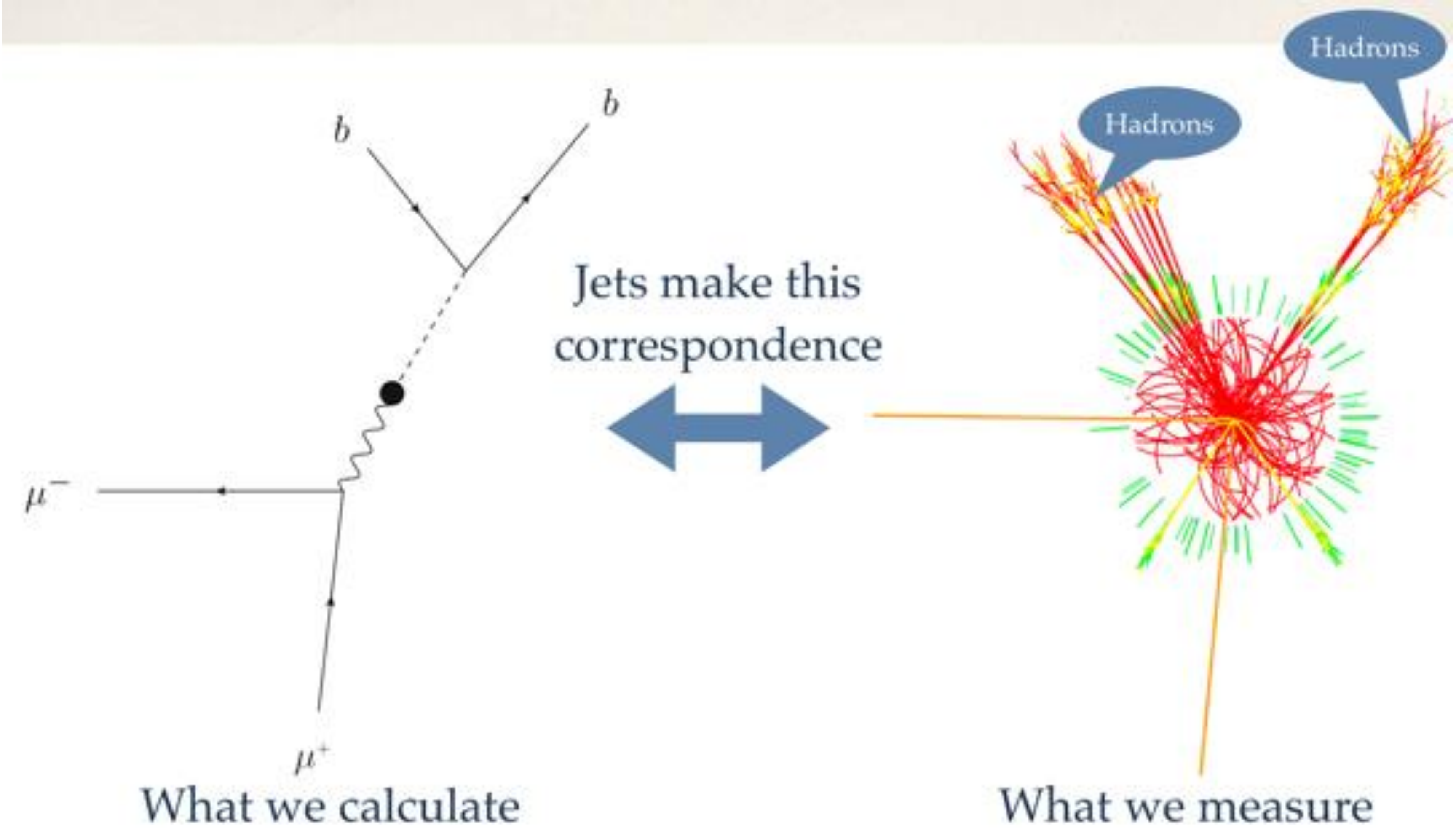
$$\frac{\mathrm{d}\sigma(\mathrm{qq}' \to \mathrm{qq}')}{\mathrm{d}t} = \frac{\pi}{s^2}\frac{4}{9}\alpha_s^2 \frac{s^2+u^2}{t^2}$$

peaked at $t \to 0 \Rightarrow u \approx -s$, so

$$\frac{\mathrm{d}\sigma(\mathrm{qq}' \to \mathrm{qq}')}{\mathrm{d}t} \approx \frac{8\pi\alpha_s^2}{9t^2} = \frac{32\pi\alpha_s^2}{9s^2(1-\cos\hat{\theta})^2} = \frac{8\pi\alpha_s^2}{9s^2\sin^4\hat{\theta}/2} \approx \frac{8\pi\alpha_s^2}{9p_\perp^4}$$

i.e. Rutherford scattering!

Parton, Jet

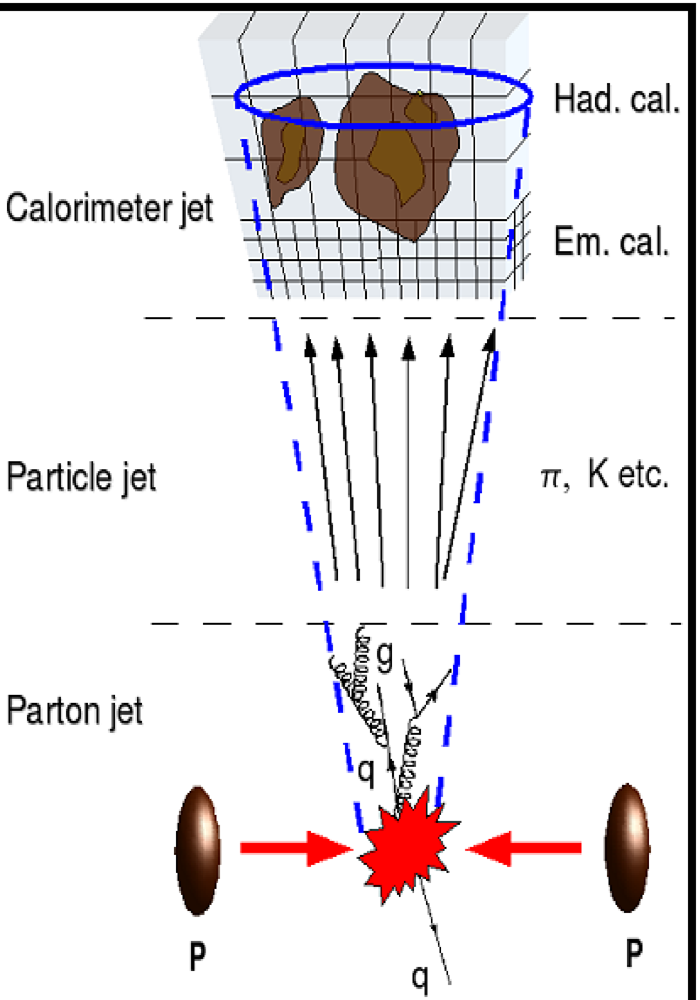


b
b
μ^-
μ^+
Jets make this correspondence
Hadrons
Hadrons
What we calculate
What we measure

Type of event	N
$e^+e^- \rightarrow$ hadrons event on the Z peak	40
HERA direct photoproduction (dijet) or DIS	40
HERA resolved photoproduction (dijet)	60
Tevatron ($\sqrt{s} = 1.96$ TeV) dijet event	200
LHC ($\sqrt{s} = 14$ TeV) dijet event	400
LHC low-luminosity event (5 pileup collisions)	1000
RHIC Au Au event ($\sqrt{s} = 200$ GeV/nucleon)	3000
LHC high-luminosity event (20 pileup collisions)	4000
LHC Pb Pb event ($\sqrt{s} = 5.5$ TeV/nucleon)	30000

Table 3: Orders of magnitude of the event multiplicities N (charged + neutral) for various kinds of event. The e^+e^-, photoproduction, DIS and pp results have been estimated with Pythia 6.4[102, 100], LHC PbPb with Pythia + Hydjet [103] and RHIC has been deduced from [104]. Note that experimentally, algorithms may run on calorimeter towers or cells, which may be more or less numerous than the particle multiplicity.

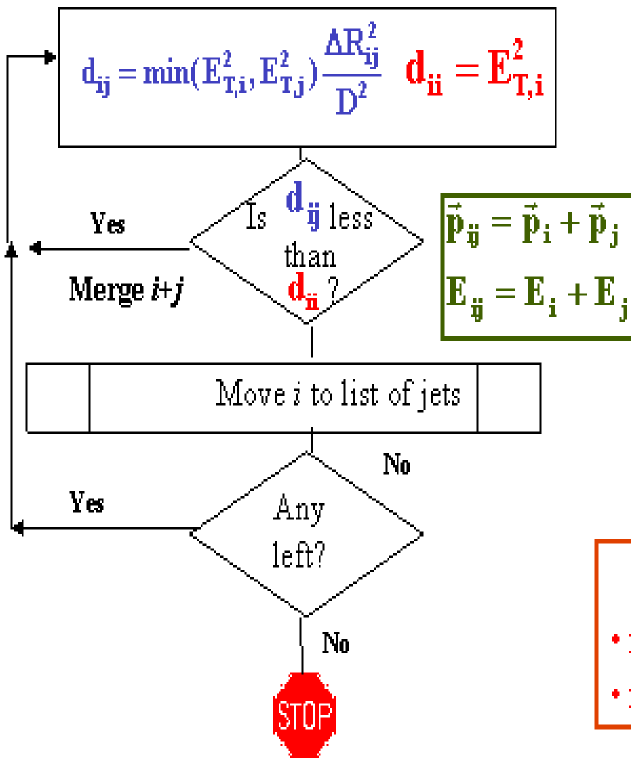
Parton, Jet

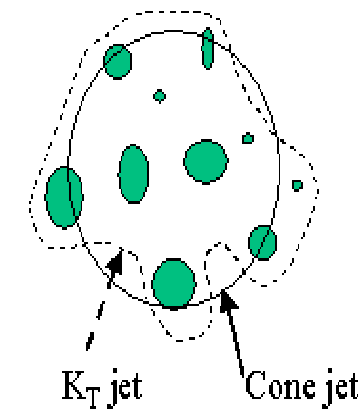


K_T Jet Algorithm

- **Form preclusters out of seed towers**

  cone with R = 0.4, R=0.7 or R=1.0





All clusters with r < D are merged

Clusters with r > D can be merged if $\Delta E_T >> 0$

Jet Shapes are more natural

- **no arbitrary spl/mer param**
- **no R_{sep} param at parton level**

- **Produce list of jets** ($\Delta R \geq D$)

Jet Algorithm

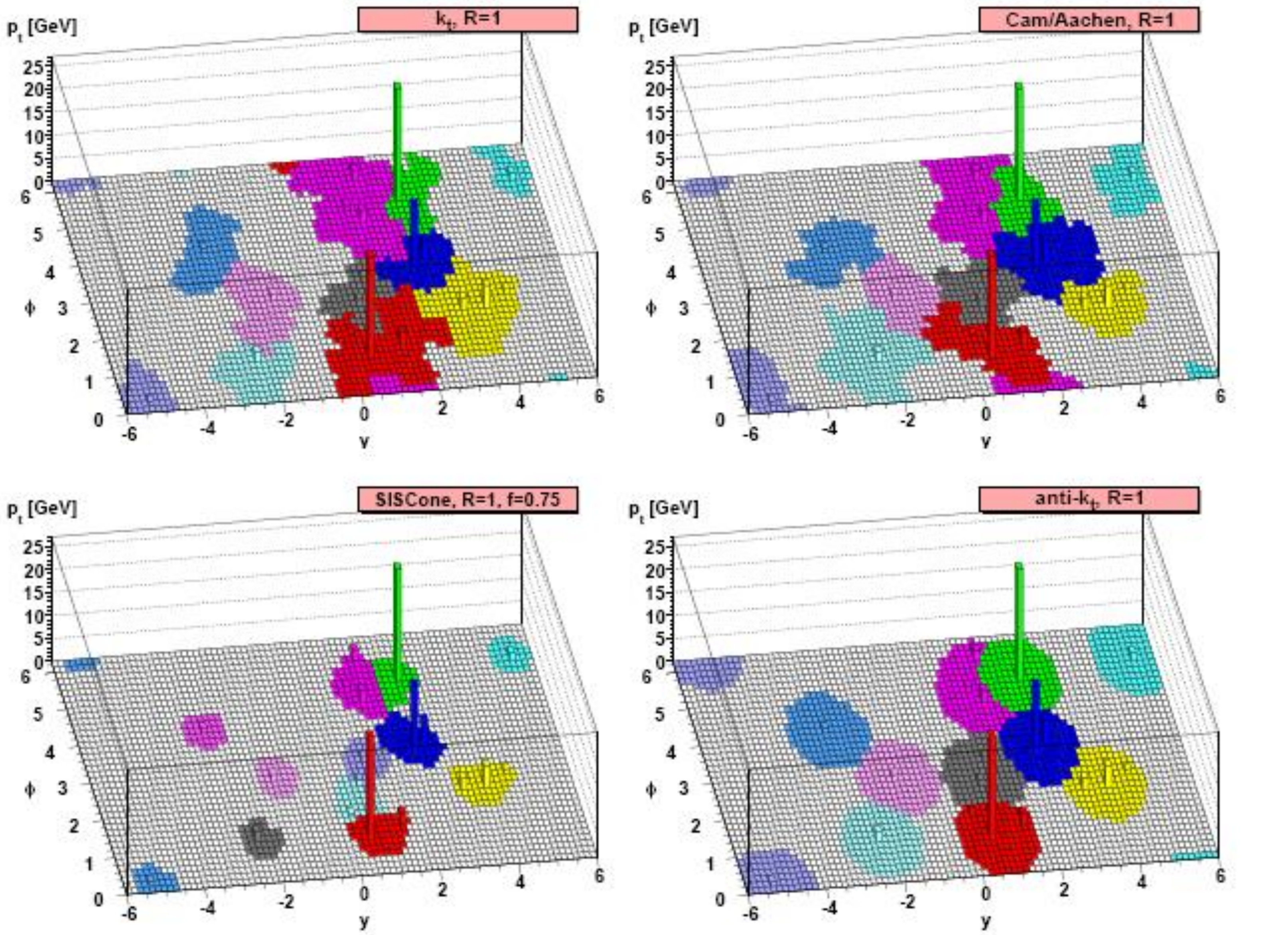
$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2,$$

$$d_{iB} = p_{ti}^{2p},$$

1. Work out all the d_{ij} and d_{iB} according to eq. (8).
2. Find the minimum of the d_{ij} and d_{iB}.
3. If it is a d_{ij}, recombine i and j into a single new particle and return to step 1.
4. Otherwise, if it is a d_{iB}, declare i to be a [final-state] jet, and remove it from the list of particles. Return to step 1.
5. Stop when no particles remain.

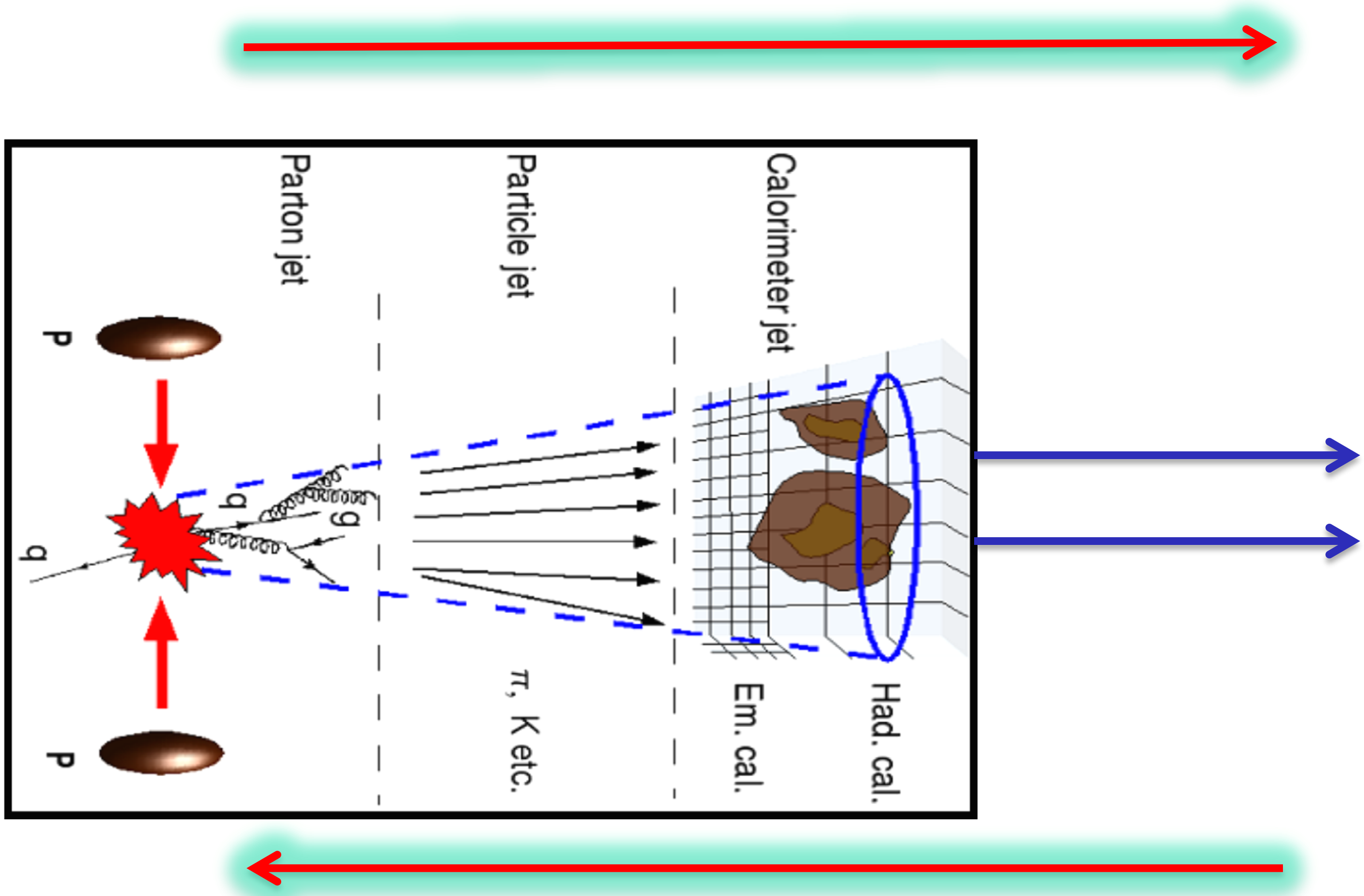
P=-1 ,0 ,1

k_T	$d_{j_1 j_2} = \frac{\Delta R^2_{j_1 j_2}}{D^2} \min(p^2_{T,j_1}, p^2_{T,j_2})$	$d_{j_1 B} = p^2_{T,j_1}$
Cambridge/Aachen	$d_{j_1 j_2} = \frac{\Delta R^2_{j_1 j_2}}{D^2}$	$y_{j_1 B} = 1$
anti-k_T	$d_{j_1 j_2} = \frac{\Delta R^2_{j_1 j_2}}{D^2} \min\left(\frac{1}{p^2_{T,j_1}}, \frac{1}{p^2_{T,j_2}}\right)$	$d_{j_1 B} = \frac{1}{p^2_{T,j_1}}$.



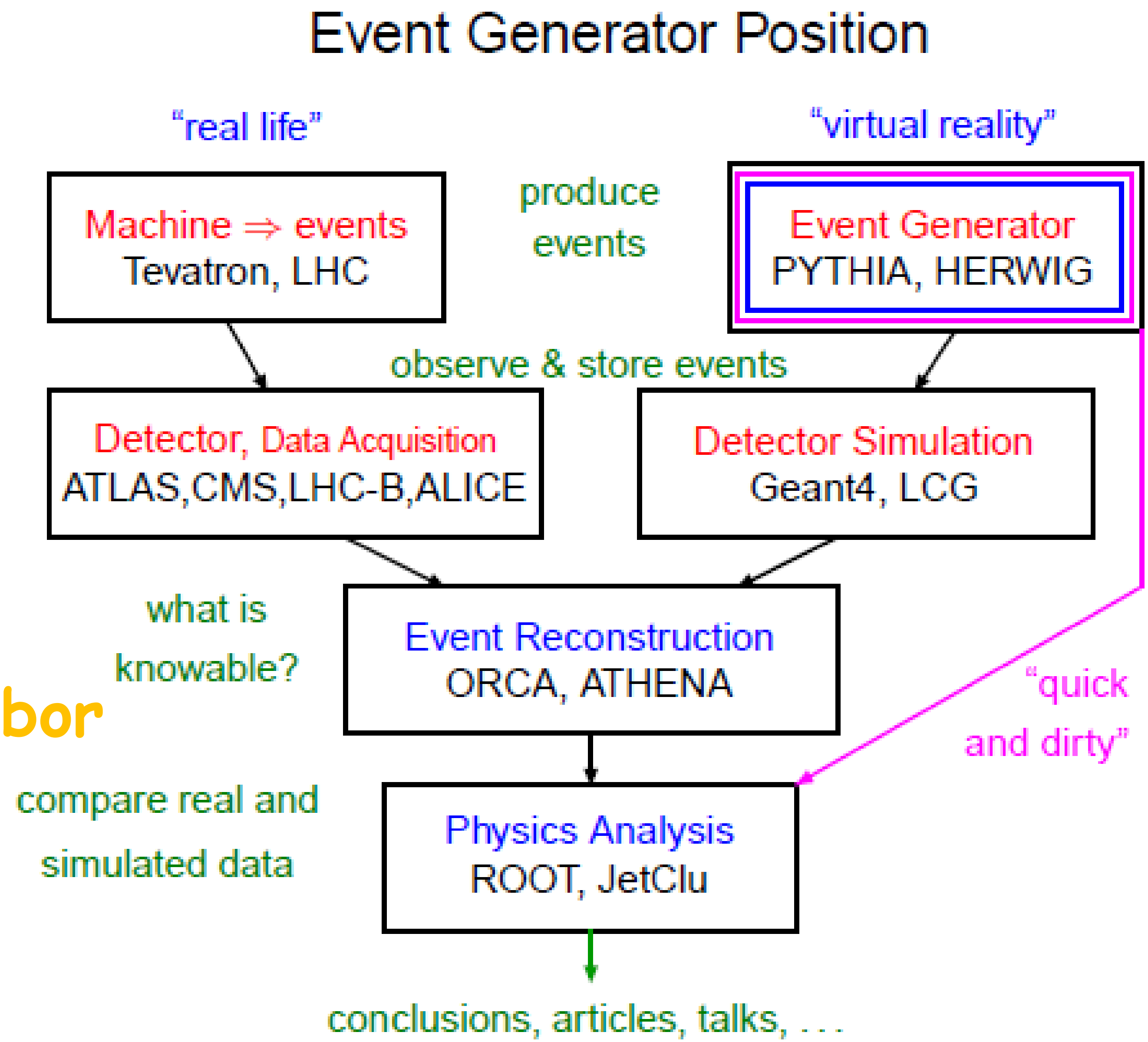
k_t, R=1
Cam/Aachen, R=1
SISCone, R=1, f=0.75
anti-k_t, R=1
p_t [GeV]
ϕ
y

4-momenta, hits/deposits, digitalize



Your study can be cut at some level, depending on what you want

Simulation at all levels



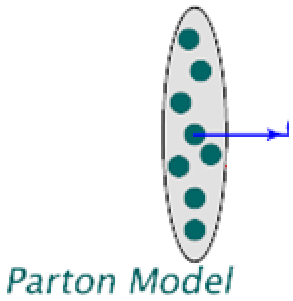
PF
Arbor

Generator Landscape

	General-Purpose	Specialized
Hard Processes	HERWIG, PYTHIA, ISAJET, SHERPA	a lot
Resonance Decays		HDECAY, . . .
Parton Showers		Ariadne/LDC, NLLjet
Underlying Event		DPMJET
Hadronization		none (?)
Ordinary Decays		TAUOLA, EvtGen

specialized often best at given task, but need General-Purpose core

Parton Distribution Function



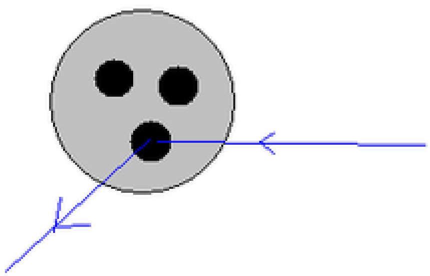
parton interactions

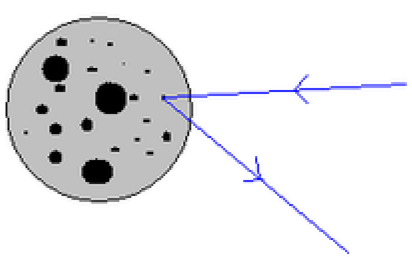
$f_{i/h}(x,\mu_F^2)$: **parton density function**

x **is momentum fraction**

μ_F *is factorization scale*

Non-perturbative functions, from global fit

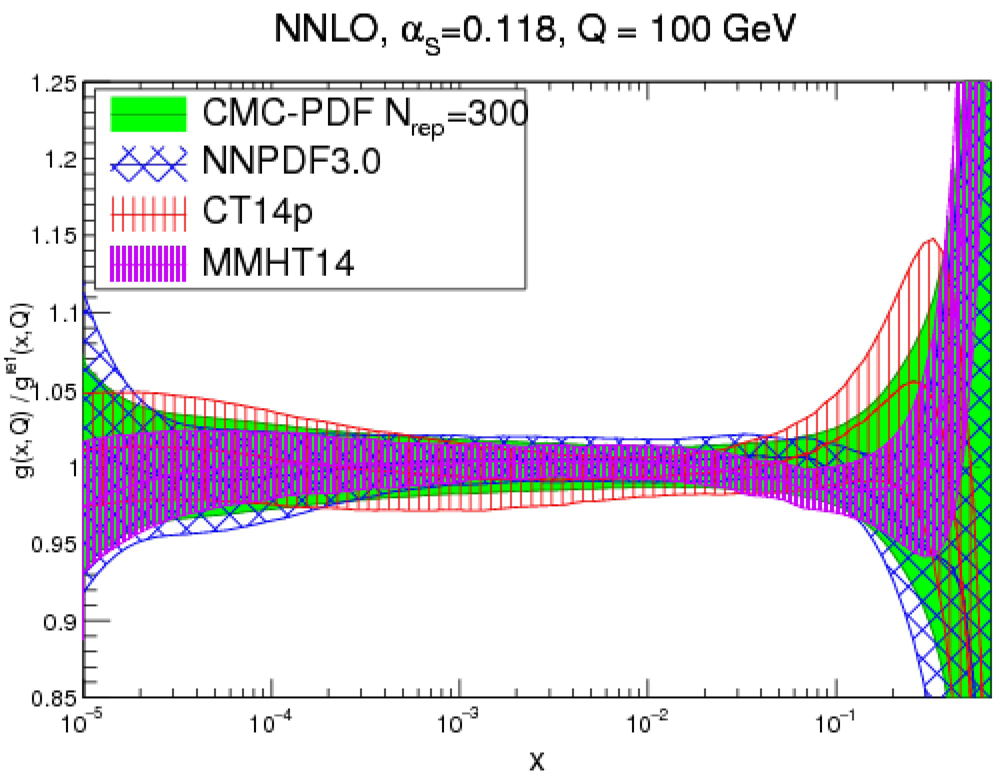




The scattering particle only sees the valence partons. At higher energies, the scattering particles also detects the sea partons.

PDF and LHAPDF

Many choices on the market



Default choice in
MG_aMC@NLO
Is NNPDF2

It was CTEQ6L1 before

https://lhapdf.hepforge.org/

LHAPDF is a general purpose C++ interpolator, used for evaluating PDFs from discretised data files.

Scale/PDF Uncertainties: PDF4LHC

UCL DEPARTMENT OF PHYSICS AND ASTRONOMY »
PDF4LHC

http://www.hep.ucl.ac.uk/pdf4lhc/

PDF4LHC

Recommendation for LHC cross section calculations

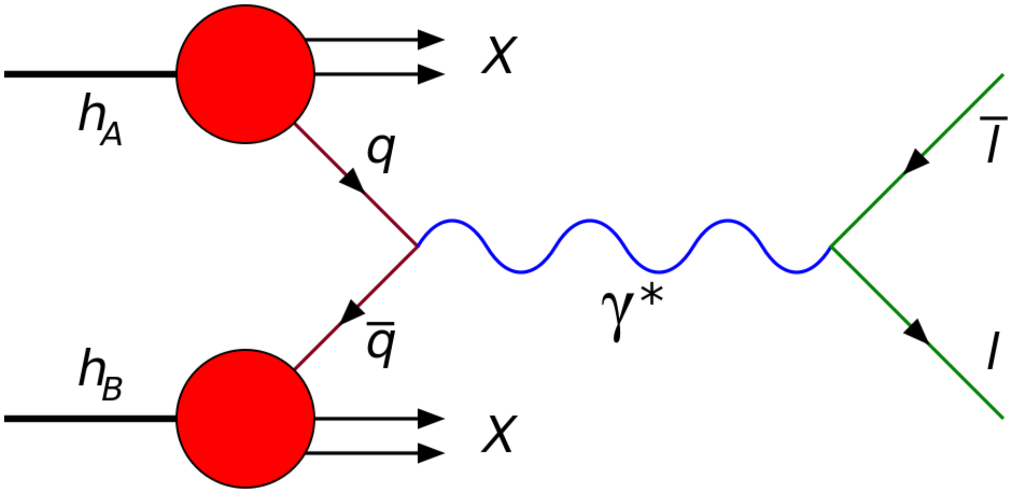
The LHC experiments are currently producing cross sections from the 7 TeV data, and thus need accurate predictions for these cross sections and their uncertainties at NLO and NNLO. Crucial to the predictions and their uncertainties are the parton distribution functions (PDFs) obtained from global fits to data from deep-inelastic scattering, Drell-Yan and jet data. A number of groups have produced publicly available PDFs using different data sets and analysis frameworks. Given the necessity of having an official recommendation from the PDF4LHC working group available on a short time frame, the prescription outlined at the the link below has been adopted.

NLO Summary:

For the calculation of uncertainties at the LHC, use the envelope provided by the central values and PDF+α_s errors from the MSTW08, CTEQ6.6 and NNPDF2.0 PDFs, using each group's prescriptions for combining the two types of errors. We propose this definition of

Hard Scattering:

Hard Scattering:
LO, NLO, NNLO QCD, QED..



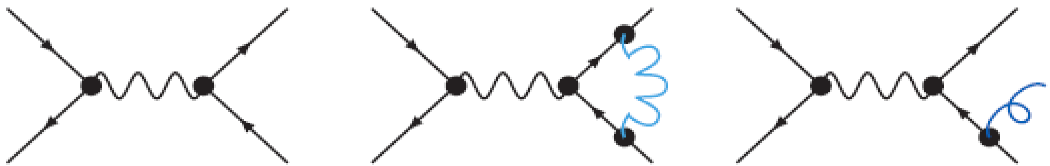
LO: Born term

$$d\sigma_{h_1h_2} = \sum_{i,j} \int_0^1 dx_i \int_0^1 dx_j \sum_f \int d\Phi_f \, f_{i/h_1}(x_i, \mu_F^2) \, f_{j/h_2}(x_j, \mu_F^2) \frac{d\hat{\sigma}_{ij\to f}}{dx_i \, dx_j \, d\Phi_f}$$

Factorization scale μ_F
Renormalization Scale μ_r
Phase Space $d\Phi_f$

Hard Scattering: Higher order

loops (virtual corrections) or legs (real corrections)



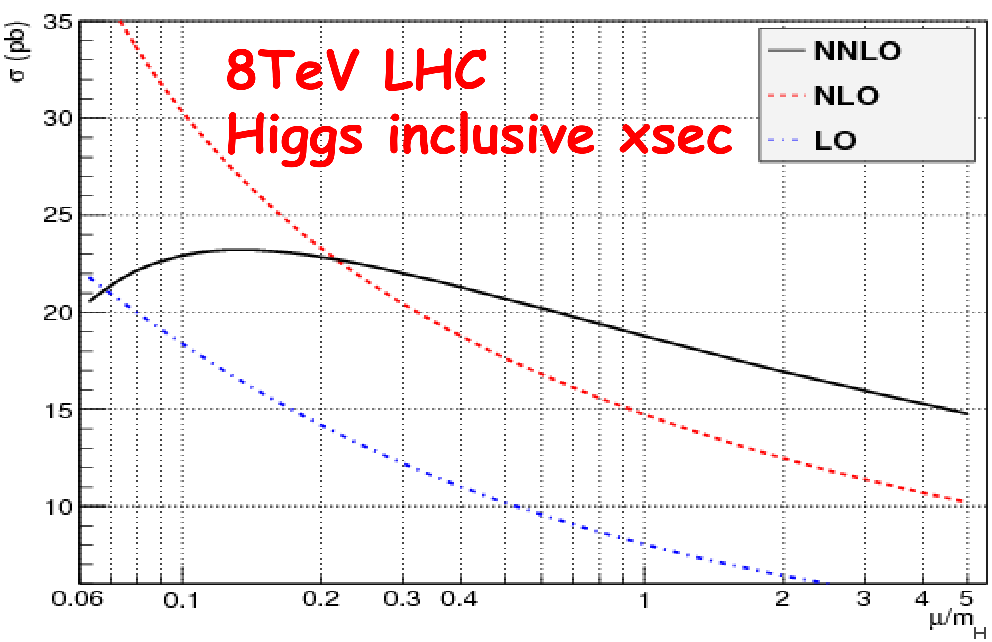
- effect: reducing the dependence on μ_R & μ_F

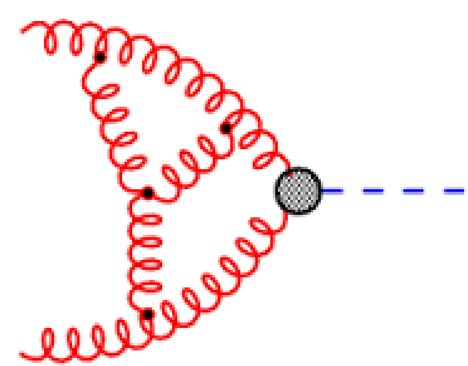
(NLO first order allowing for meaningful estimate of uncertainties)

- additional difficulties when going NLO:

  ultraviolet divergences in virtual correction

  infrared divergences in real and virtual correction



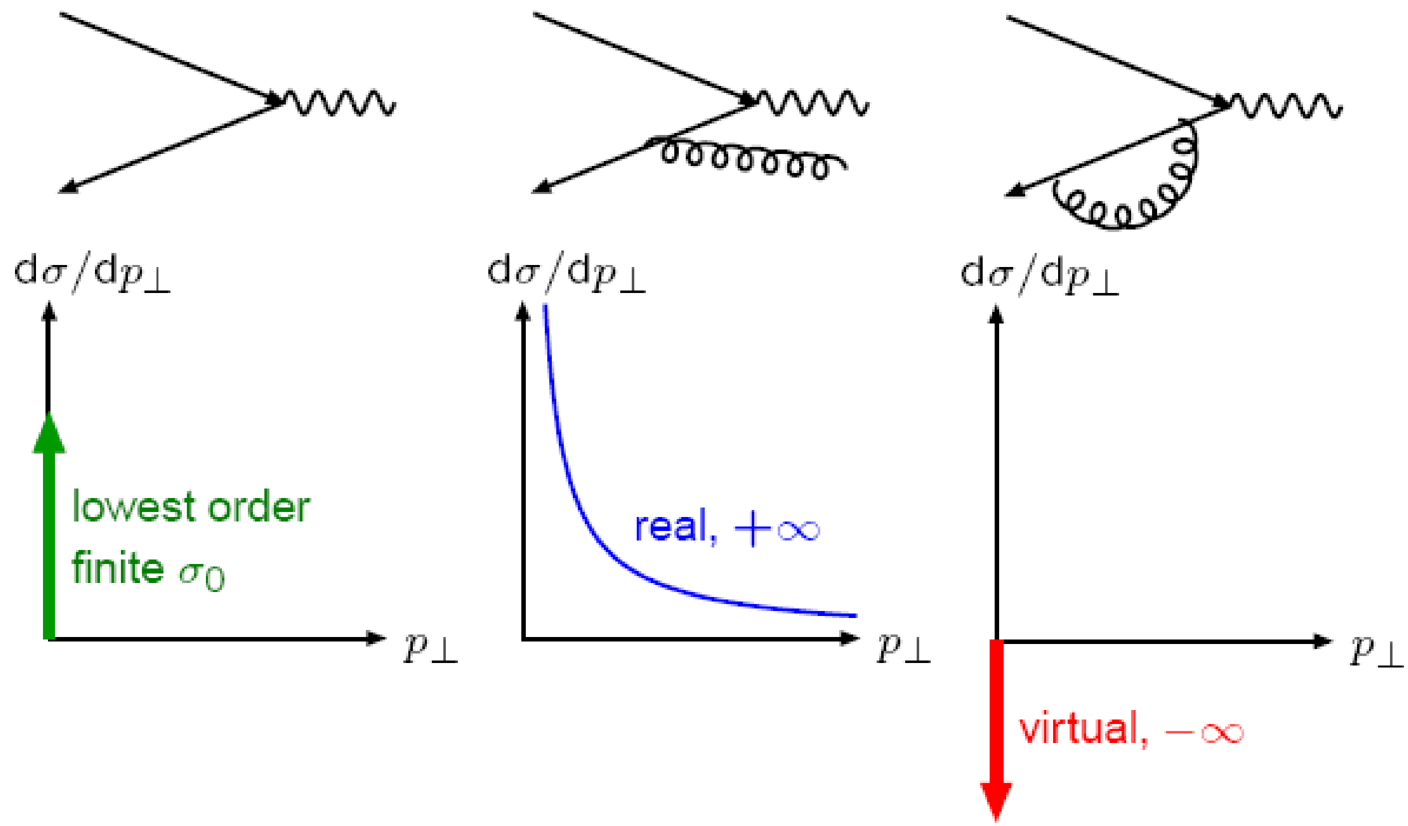


Next-to-leading order (NLO) calculations

I. Lowest order,
$\mathcal{O}(\alpha_{\mathrm{em}})$:
$q\bar{q} \to Z^0$

II. First-order real,
$\mathcal{O}(\alpha_{\mathrm{em}}\alpha_{\mathrm{s}})$:
$q\bar{q} \to Z^0 g$ etc.

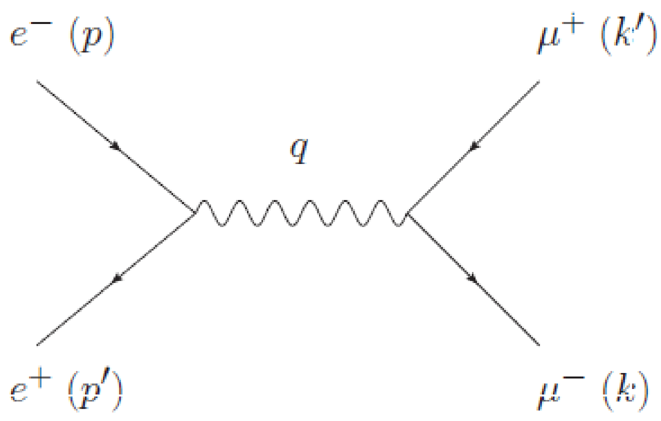
III. First-order virtual,
$\mathcal{O}(\alpha_{\mathrm{em}}\alpha_{\mathrm{s}})$:
$q\bar{q} \to Z^0$ with loops



Higher order Calculation is not easy

pp → W + 0 jet	1978	Altarelli, Ellis, Martinelli
pp → W + 1 jet	1989	Arnold, Ellis, Reno
pp → W + 2 jets	2002	Campbell, Ellis
pp → W + 3 jets	2009	BH+Sherpa Ellis, Melnikov, Zanderighi
pp → W + 4 jets	2010	BH+Sherpa
pp -> W + 5 jets	2013	BH+Sherpa

Hard Scattering: Matrix Element



Feynman Rules ->

$$i\mathcal{M} = \bar{v}^{s'}(p')(-ie\gamma^\lambda)u^s(p)\left(\frac{-ig_{\lambda\nu}}{q^2}\right)\bar{u}^r(k)(-ie\gamma^\nu)v^{r'}(k')\ ,$$

Squared ->

$$|\mathcal{M}|^2 = \frac{e^4}{q^4}(\bar{v}(p')\gamma^\lambda u(p)\bar{u}(p)\gamma^\nu v(p'))(\bar{u}(k)\gamma_\lambda v(k')\bar{v}(k')\gamma_\nu u(k))$$

Sum over spin, Trace

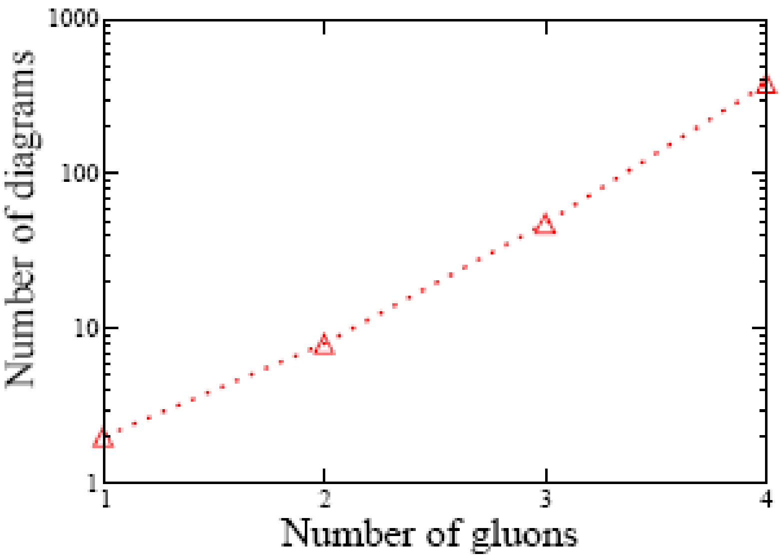
$$\frac{1}{2}\sum_s \frac{1}{2}\sum_{s'}\sum_r\sum_{r'}|\mathcal{M}|^2 = \frac{e^4}{4q^4}\mathrm{Tr}[\not{p}'\gamma^\lambda\not{p}\gamma^\nu]\mathrm{Tr}[\not{k}\gamma_\lambda\not{k}'\gamma_\nu] = \frac{8e^4}{q^4}\left[(p\cdot k)(p'\cdot k') + (p\cdot k')(p'\cdot k)\right]$$

This works well for a few diagrams, however, for 2->n process, there can be huge number of diagrams

$$O(n^2)$$

Complexity: factorial growth in $e^+e^- \to q\bar{q} + ng$

n	$\#_{\rm diags}$
0	1
1	2
2	8
3	48
4	384



HELAS

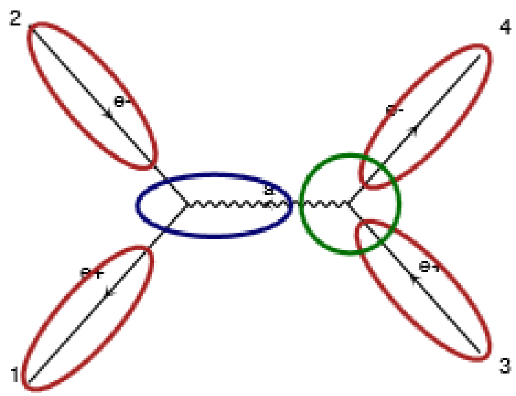
[MURAYAMA, WATANABE, HAGIWARA, 1992]

Helicity Method, numerical way, sum over spin later:

$O(n)$

Basics: Helicity amplitudes

Idea: Evaluate $\mathcal{M}$ for fixed helicity of external particles



$$\mathcal{M} = \bar{u}\gamma^{\mu} v P_{\mu\nu} \bar{u}\gamma^{\nu} v$$

Numbers for given helicity and momenta

Calculate propagator wavefunctions

Finally evaluate amplitude (c-number)

Helicity amplitude calls written by MadGraph

```
CALL OXXXXX(P(0,1),ZERO,NHEL(1),-1*IC(1),W(1,1))
CALL IXXXXX(P(0,2),ZERO,NHEL(2),+1*IC(2),W(1,2))
CALL IXXXXX(P(0,3),ZERO,NHEL(3),-1*IC(3),W(1,3))
CALL OXXXXX(P(0,4),ZERO,NHEL(4),+1*IC(4),W(1,4))
CALL JIOXXX(W(1,2),W(1,1),GAL,ZERO,ZERO,W(1,5))
CALL IOVXXX(W(1,3),W(1,4),W(1,5),GAL,AMP(1))
```

Automation of ME

→automatic Feynman Diagram generating and evaluating

- For 2->n processes, generating all possible topology
- Trying filling particles in the SM or new physics
- Writing down HELAS subroutine and codes

Process	Amplitudes	Wavefunctions		Run time	
		MG 4	MG 5	MG 4	MG 5
$u\bar{u} \to e^+e^-$	2	6	6	$< 6\mu s$	$< 6\mu s$
$u\bar{u} \to e^+e^-e^+e^-$	48	62	32	0.22 ms	0.14 ms
$u\bar{u} \to e^+e^-e^+e^-e^+e^-$	3474	3194	301	46.5 ms	19.0 ms
$u\bar{u} \to d\bar{d}$	1	5	5	$< 4\mu s$	$< 4\mu s$
$u\bar{u} \to d\bar{d}g$	5	11	11	27 μs	27 μs
$u\bar{u} \to d\bar{d}gg$	38	47	29	0.42 ms	0.31 ms
$u\bar{u} \to d\bar{d}ggg$	393	355	122	10.8 ms	6.75 ms
$u\bar{u} \to u\bar{u}gg$	76	84	40	1.24 ms	0.80 ms
$u\bar{u} \to u\bar{u}ggg$	786	682	174	35.7 ms	17.2 ms
$u\bar{u} \to d\bar{d}d\bar{d}$	14	28	19	84 μs	83 μs
$u\bar{u} \to d\bar{d}d\bar{d}g$	132	178	65	1.88 ms	1.15 ms
$u\bar{u} \to d\bar{d}d\bar{d}gg$	1590	1782	286	141 ms	34.4 ms
$u\bar{u} \to d\bar{d}d\bar{d}d\bar{d}$	612	758	141	42.5 ms	6.6 ms

Time for matrix element evaluation on a Sony Vaio TZ laptop

Alwall 2012

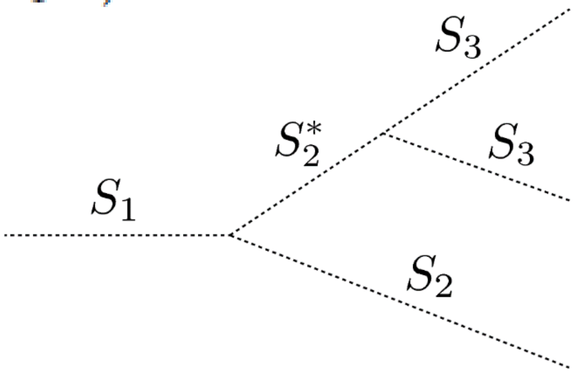
Hard Scattering: Phase Space

$$d\Phi_n(P,p_1,...,p_n) = \prod_{i=1}^{n}\frac{d^4p_i}{(2\pi)^3}\Theta(p_i^0)\delta(p_i^2-m_i^2)(2\pi)^4\delta^4\left(P-\sum_{i=1}^{n}p_i\right)$$

$$= \prod_{i=1}^{n}\frac{d^3p_i}{(2\pi)^3 2E_i}(2\pi)^4\delta^4\left(P-\sum_{i=1}^{n}p_i\right).$$

3n-4

+2 =3n-2 dimension



An example of Phase space factorization

-> Recursive in numerical

$$d\Phi_n(P,p_1,...,p_n) = \frac{1}{2\pi}dQ^2 d\Phi_j(Q,p_1,...,p_j)d\Phi_{n-j+1}(P,Q,p_{j+1},...,p_n).$$

MC Technique

$$I = \int_{x1}^{x2} \mathrm{d}x \; f(x) = (x_2 - x_1) \langle f(x) \rangle$$

$$I \approx (x_2 - x_1) \frac{1}{N} \sum_{i=1}^{N} f(x_i)$$

N points randomly distributed in [x1,x2]

Weight: $W_i = (x_2 - x_1) f(x_i)$.

Average of Weight: $I \approx I_N = \frac{1}{N} \sum_{i=1}^{N} W_i$

Variance: $V_N = \frac{1}{N} \sum_i W_i^2 - \left[\frac{1}{N} \sum_i W_i \right]^2 \equiv \sigma^2$

'Central Limit Theorem $I \approx I_N \pm \sqrt{\frac{V_N}{N}}$.

MC Technique

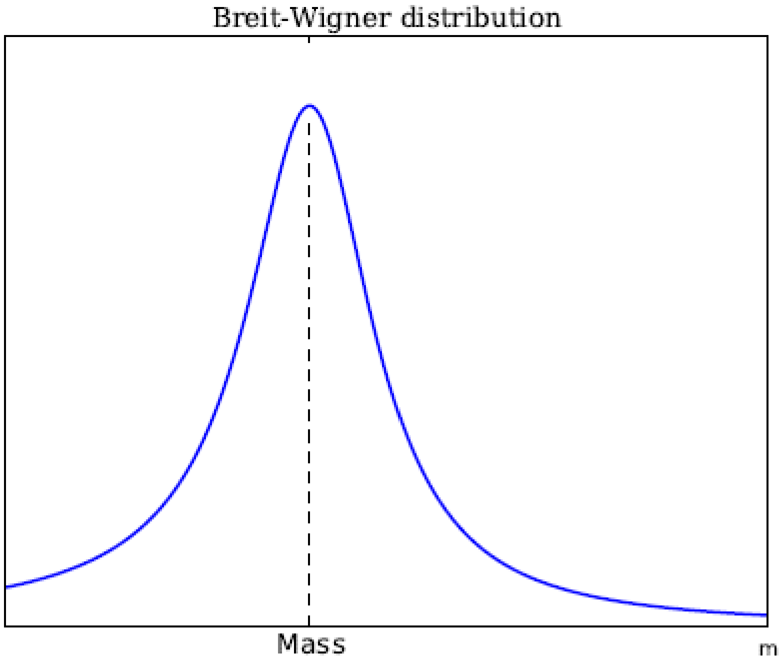
$$I \approx I_N \pm \sqrt{\frac{V_N}{N}}$$

- Good convergence for high dimension integrals
- We also got events randomly distributed
- V_N should be small: importance sampling

$$I = \int_{M^2_{\min}}^{M^2_{\max}} \mathrm{d}m^2 \frac{1}{(m^2 - M^2)^2 + M^2\Gamma^2}$$

$$m^2 = M\Gamma \tan\rho + M^2$$

$$I = \int_{\rho_{\min}}^{\rho_{max}} \mathrm{d}\rho \left|\frac{\partial m^2}{\partial \rho}\right| \frac{1}{(m^2 - M^2)^2 + M^2\Gamma^2} = \frac{1}{M\Gamma}\int_{\rho_{\min}}^{\rho_{max}} \mathrm{d}\rho\,.$$



Unweighting

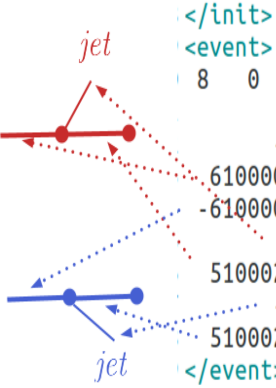
We often want events without weights as mother Nature produce

1. **Monte Carlo integration and scanning are performed:**
   N points are picked randomly

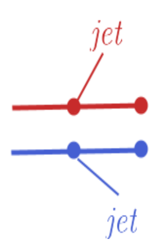
2. **The phase-space point which give the maximum weight, Wmax is stored**

3. **'hit-or-miss': go through randomly chosen phase-space points and compare the probability of each, given by Wi/Wmax to a random number R in (0, 1).**
   If Wi/Wmax > R, we 'accept' the event, otherwise wereject it. This is done until we have collected the desired number of events, Nevents.

Les Houches Event File hep-ph/0609017




```
<LesHouchesEvents version="1.0">
<header>
#Additional information
</header>
<init>
     2212     2212  0.40000000000E+04  0.40000000000E+04 0 0 10042 10042 3  1
  0.13448000000E+02  0.11328000000E+00  0.26896000000E+01   0
</init>
<event>
 8   0  0.2689600E+01  0.1000000E+04  0.7957747E-01  0.9421117E-01
        2   -1    0    0  501    0  0.00000000000E+00  0.00000000000E+00  0.12216473395E+04  0.12216473395E+04  0.30000000261E-02 0.  1.
       -2   -1    0    0    0  501  0.00000000000E+00  0.00000000000E+00 -0.95840193959E+03  0.95840193960E+03  0.30000000261E-02 0. -1.
  6100002    2    1    2  502    0  0.12085632485E+03 -0.21778312976E+03  0.82072277461E+03  0.11732307109E+04  0.80000000000E+03 0.  0.
 -6100002    2    1    2    0  502 -0.12085632485E+03  0.21778312976E+03 -0.55747737471E+03  0.10068185682E+04  0.80000000000E+03 0.  0.
        2    1    3    3  502    0 -0.84181441025E+02 -0.27383300132E+03  0.36569663377E+03  0.46454822740E+03  0.30000000261E-02 0.  1.
  5100022    1    3    3    0    0  0.20503776588E+03  0.56049871558E+02  0.45502614084E+03  0.70868248348E+03  0.50000000000E+03 0.  1.
       -2    1    4    4    0  502  0.10854022679E+03  0.26478799687E+03 -0.18273879961E+03  0.33953958975E+03  0.30000000261E-02 0. -1.
  5100022    1    4    4    0    0 -0.22939655164E+03 -0.47004867115E+02 -0.37473857510E+03  0.66727897847E+03  0.50000000000E+03 0.  1.
</event>
<event>
...
```



Weight: $\frac{13.448\ pb}{\#events}$

Mass Array:

$[[800\ GeV, 500\ GeV], [800\ GeV, 500\ GeV]]$

Example: MG_aMC@NLO

PP > Z LO & NLO

Generate processes online using MadGraph5_aMC@NLO

Example: PP > Z LO & NLO

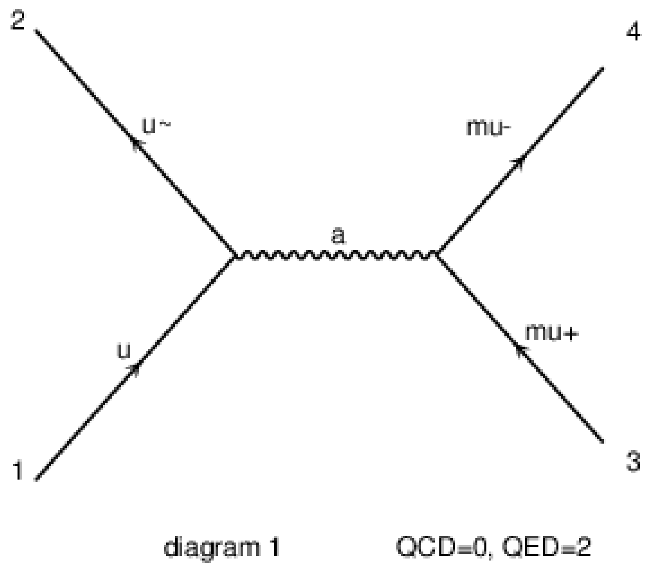
qliphy@qiangqiang: ~/Desktop/MG5_aMC_v2_3_0

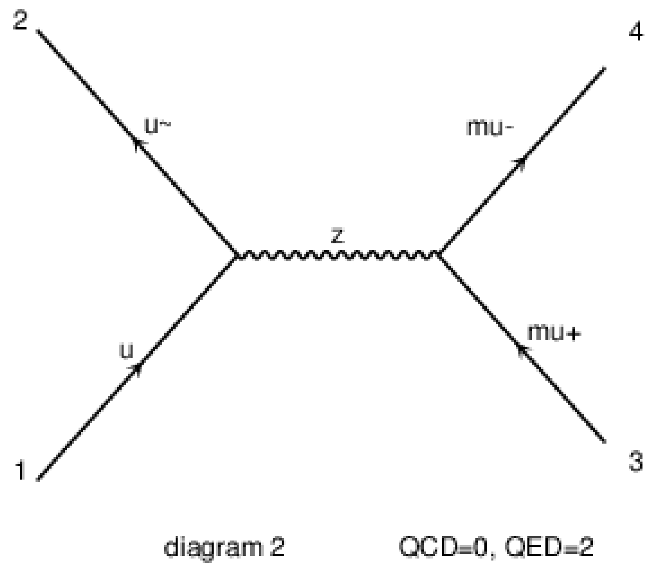
```
*         VERSION 2.3.0                  2015-07-01          *
*                                                            *
*    The MadGraph5_aMC@NLO Development Team - Find us at     *
*    https://server06.fynu.ucl.ac.be/projects/madgraph       *
*                           and                              *
*            http://amcatnlo.web.cern.ch/amcatnlo/           *
*                                                            *
*               Type 'help' for in-line help.                *
*           Type 'tutorial' to learn how MG5 works           *
*    Type 'tutorial aMCatNLO' to learn how aMC@NLO works     *
*    Type 'tutorial MadLoop' to learn how MadLoop works      *
*                                                            *
************************************************************
load MG5 configuration from input/mg5_configuration.txt
set fastjet to fastjet-config
set lhapdf to lhapdf-config
Using default text editor "vi". Set another one in ./input/mg5_configuration.txt
Using default eps viewer "evince". Set another one in ./input/mg5_configuration.txt
Using default web browser "firefox". Set another one in ./input/mg5_configuration.txt
Loading default model: sm
INFO: Restrict model sm with file models/sm/restrict_default.dat .
INFO: Run "set stdout_level DEBUG" before import for more information.
INFO: Change particles name to pass to MG5 convention
Defined multiparticle p = g u c d s u~ c~ d~ s~
Defined multiparticle j = g u c d s u~ c~ d~ s~
Defined multiparticle l+ = e+ mu+
Defined multiparticle l- = e- mu-
Defined multiparticle vl = ve vm vt
Defined multiparticle vl~ = ve~ vm~ vt~
Defined multiparticle all = g u c d s u~ c~ d~ s~ a ve vm vt e- mu- ve~ vm~ vt~ e+ mu+ t b t~ b~ z w+ h w- ta- ta+
MG5_aMC>tutorial
```

Example: PP > Z LO & NLO

```
MG5_aMC>generate p p > mu+ mu-
INFO: Checking for minimal orders which gives processes.
INFO: Please specify coupling orders to bypass this step.
INFO: Trying process: g g > mu+ mu- WEIGHTED=4
INFO: Trying process: u u~ > mu+ mu- WEIGHTED=4
INFO: Process has 2 diagrams
INFO: Trying process: u c~ > mu+ mu- WEIGHTED=4
INFO: Trying process: c u~ > mu+ mu- WEIGHTED=4
INFO: Trying process: c c~ > mu+ mu- WEIGHTED=4
INFO: Process has 2 diagrams
INFO: Trying process: d d~ > mu+ mu- WEIGHTED=4
INFO: Process has 2 diagrams
INFO: Trying process: d s~ > mu+ mu- WEIGHTED=4
INFO: Trying process: s d~ > mu+ mu- WEIGHTED=4
INFO: Trying process: s s~ > mu+ mu- WEIGHTED=4
INFO: Process has 2 diagrams
INFO: Process u~ u > mu+ mu- added to mirror process u u~ > mu+ mu-
INFO: Process c~ c > mu+ mu- added to mirror process c c~ > mu+ mu-
INFO: Process d~ d > mu+ mu- added to mirror process d d~ > mu+ mu-
INFO: Process s~ s > mu+ mu- added to mirror process s s~ > mu+ mu-
4 processes with 8 diagrams generated in 0.043 s
Total: 4 processes with 8 diagrams
MG5_aMC>
```

Example: PP > Z LO & NLO





You can choose QCD or QED vertex number

Example: PP > Z LO & NLO

```
*                                                         *
*                 *                       *               *
*                   *        * *          *               *
*                     * * * * 5 * * * *                   *
*                   *        * *          *               *
*                 *                       *               *
*                                                         *
*         VERSION 2.3.0                2015-07-01         *
*                                                         *
*    The MadGraph5_aMC@NLO Development Team - Find us at  *
*    https://server06.fynu.ucl.ac.be/projects/madgraph    *
*                                                         *
*               Type 'help' for in-line help.             *
*                                                         *
***********************************************************
INFO: load configuration from /home/qliphy/Desktop/MG5_aMC_v2_3_0/LO-DY/Cards/me5_configuration.tx
INFO: load configuration from /home/qliphy/Desktop/MG5_aMC_v2_3_0/input/mg5_configuration.txt
INFO: load configuration from /home/qliphy/Desktop/MG5_aMC_v2_3_0/LO-DY/Cards/me5_configuration.tx
Using default text editor "vi". Set another one in ./input/mg5_configuration.txt
generate_events run_01
The following switches determine which programs are run:
 1 Run the pythia shower/hadronization:                   pythia=OFF
 2 Run PGS as detector simulator:                            pgs=OFF
 3 Run Delphes as detector simulator:                    delphes=NOT INSTALLED
 4 Decay particles with the MadSpin module:              madspin=OFF
 5 Add weight to events based on coupling parameters:   reweight=OFF
  Either type the switch number (1 to 5) to change its default setting,
  or set any switch explicitly (e.g. type 'madspin=ON' at the prompt)
  Type '0', 'auto', 'done' or just press enter when you are done.
 [0, 1, 2, 4, 5, auto, done, pythia=ON, pythia=OFF, ... ][60s to answer]
>0
```

Output
Launch
You can choose pythia run
Or not

Example: PP > Z LO & NLO

Parameter Card

```
###################################
## INFORMATION FOR MASS
###################################
Block mass
    5 4.700000e+00 # MB
    6 1.730000e+02 # MT
   15 1.777000e+00 # MTA
   23 9.118800e+01 # MZ
   25 1.250000e+02 # MH
## Dependent parameters, given by model restrictions.
## Those values should be edited following the
## analytical expression. MG5 ignores those values
## but they are important for interfacing the output of MG5
## to external program such as Pythia.
  1 0.000000 # d : 0.0
  2 0.000000 # u : 0.0
  3 0.000000 # s : 0.0
  4 0.000000 # c : 0.0
  11 0.000000 # e- : 0.0
  12 0.000000 # ve : 0.0
  13 0.000000 # mu- : 0.0
  14 0.000000 # vm : 0.0
  16 0.000000 # vt : 0.0
  21 0.000000 # g : 0.0
  22 0.000000 # a : 0.0
  24 80.419002 # w+ : cmath.sqrt(MZ__exp__2/2. + cmath.sqrt(MZ
)
```

Example: PP > Z LO & NLO

Run Card

```
*********************************************************************
                MadGraph5_aMC@NLO                                   *
                                                                    *
              run_card.dat MadEvent                                 *
                                                                    *
 This file is used to set the parameters of the run.               *
                                                                    *
 Some notation/conventions:                                         *
                                                                    *
  Lines starting with a '# ' are info or comments                   *
                                                                    *
  mind the format:   value    = variable     ! comment              *
*********************************************************************

******************
 Running parameters
******************

*********************************************************************
 Tag name for the run (one word)                                    *
*********************************************************************
 tag_1     = run_tag ! name of the run
*********************************************************************
 Run to generate the grid pack                                      *
*********************************************************************
 False     = gridpack  !True = setting up the grid pack
*********************************************************************
 Number of events and rnd seed
 Warning: Do not generate more than 1M events in a single run
 If you want to run Pythia, avoid more than 50k events in a run.
```

```
 100 = nevents ! Number of unweighted events requested
 0   = iseed   ! rnd seed (0=assigned automatically=default))
*************************************************************
 Collider type and energy
 lpp: 0=No PDF, 1=proton, -1=antiproton, 2=photon from proton
                                         3=photon from electr
*************************************************************
    1          = lpp1     ! beam 1 type
    1          = lpp2     ! beam 2 type
    6500.0     = ebeam1   ! beam 1 total energy in GeV
    6500.0     = ebeam2   ! beam 2 total energy in GeV
```

```
nn23lo1      = pdlabel       ! PDF set
```

```
 BW cutoff (M+/-bwcutoff*Gamma)
*******************************
 50  = bwcutoff      ! (M+/-bwcutoff*Gamma)
```

```
 20  = ptj        ! minimum pt for the jets
  0  = ptb        ! minimum pt for the b
 10  = pta        ! minimum pt for the photons
  0  = ptl        ! minimum pt for the charged leptons
```

```
50  = mmll    ! min invariant mass of l+l- (same flavour) lepton pair
```

Example: PP > Z LO & NLO

```
  === Results Summary for run: run_03 tag: tag_1 ===

     Cross-section :   1508 +- 1.32 pb
     Nb of events :  10000

running syscalc on mode parton
store_events
INFO: Storing parton level results
INFO: End Parton
reweight -from_cards
decay_events -from_cards
quit
INFO:

INFO:

more information in /home/qliphy/Desktop/MG5_aMC_v2_1_2/LO-DY/index.html
```

Example: PP > Z LO & NLO

```
qliphy@qiangqiang:~/Desktop/MG5_aMC_v2_1_2/LO-DY/Events/run_03$ ls -lrt
total 6084
-rw-rw-r-- 1 qliphy qliphy   25298 Jul 25 15:57 run_03_tag_1_banner.txt
-rw-rw-r-- 1 qliphy qliphy 2423197 Jul 25 15:57 events.lhe.gz
-rw-rw-r-- 1 qliphy qliphy 1223983 Jul 25 15:57 unweighted_events.lhe.gz
-rw-r--r-- 1 qliphy qliphy 2551366 Jul 25 15:57 unweighted_events.root
```

```
<init>
    2212      2212   0.65000000000E+04   0.65000000000E+04 0 0   200400   200400 3    1
  0.15075857952E+04   0.13200875619E+01   0.15076000000E+00     0
</init>
<event>
 5    0   0.1507600E+00   0.9150336E+02   0.7546771E-02   0.1299251E+00
      -2    -1     0     0     0   501   0.00000000000E+00   0.00000000000E+00   0.18656257017E+03   0.18656257017E+03   0.0
0000000000E+00 0.   1.
       2    -1     0     0   501     0   0.00000000000E+00   0.00000000000E+00 -0.11219916338E+02   0.11219916338E+02   0.0
0000000000E+00 0.  -1.
      23     2     1     2     0     0   0.00000000000E+00   0.00000000000E+00   0.17534265383E+03   0.19778248651E+03   0.9
1503364508E+02 0.   0.
     -13     1     3     3     0     0   0.11524939937E+02   0.32111804980E+00 -0.80281596142E+01   0.14049545513E+02   0.1
0499999672E+00 0.  -1.
      13     1     3     3     0     0 -0.11524939937E+02 -0.32111804980E+00   0.18337081345E+03   0.18373294100E+03   0.1
0499999672E+00 0.   1.
</event>
```

Example: PP > Z LO & NLO


```
<event>
 4    0  0.1507600E+00  0.5358854E+02  0.7546771E-02  0.1426894E+00
        2   -1    0    0  501    0  0.00000000000E+00  0.00000000000E+00  0.10676719678E+04  0.10676719678E+04  0.0
0000000000E+00 0.  1.
       -2   -1    0    0    0  501  0.00000000000E+00  0.00000000000E+00 -0.67242837278E+00  0.67242837278E+00  0.0
0000000000E+00 0. -1.
      -13    1    1    2    0    0  0.74865892338E+01  0.90736026926E+01  0.53565199808E+02  0.54841780967E+02  0.1
0499999672E+00 0. -1.
       13    1    1    2    0    0 -0.74865892338E+01 -0.90736026926E+01  0.10134343396E+04  0.10135026152E+04  0.1
0499999672E+00 0.  1.
</event>
```


PP to Photon to mumbar

Example: PP > Z LO & NLO

```
MG5_aMC>generate p p > mu+ mu- [QCD]
```

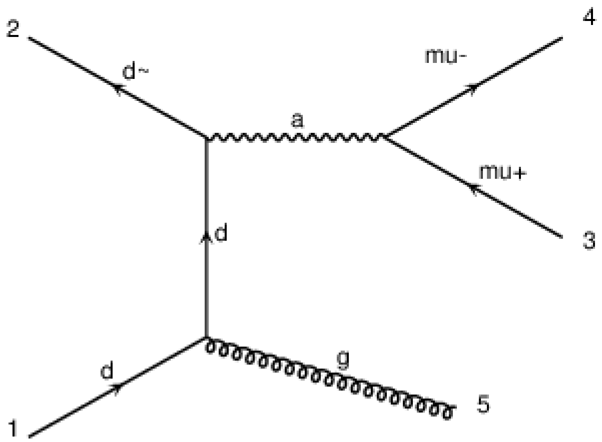
```
# Collider type and energy
#****************************************
1     = lpp1     ! beam 1 type (0 = no PDF)
1     = lpp2     ! beam 2 type (0 = no PDF)
6500     = ebeam1   ! beam 1 energy in GeV
6500     = ebeam2   ! beam 2 energy in GeV
#****************************************
# PDF choice: this automatically fixes also
#****************************************
nn23nlo     = pdlabel     ! PDF set
244600      = lhaid       ! if pdlabel=lhapdf,
```

NLO PDF for NLO, LO PDF for LO

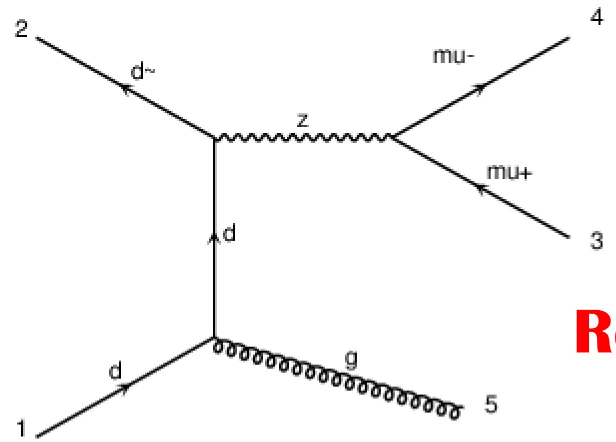
```
HERWIG6     = parton_shower
```

ME + PS, to be mentioned later

Example: PP > Z LO & NLO



real diagram 1 QCD=1, QED=2



real diagram 2 QCD=1, QED=2

Real emission

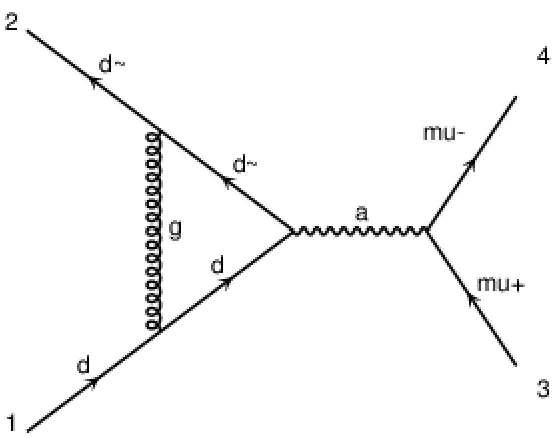


diagram 1 QCD=2, QED=2

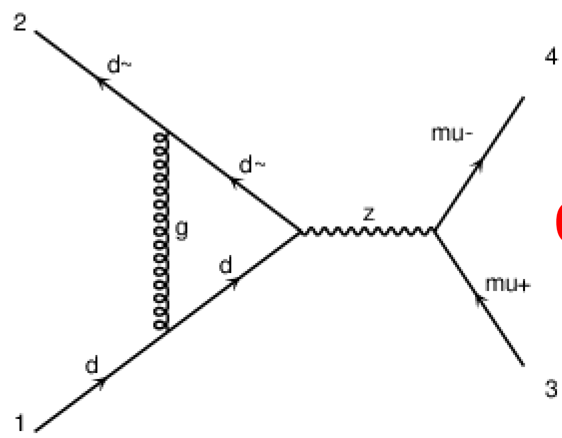


diagram 2 QCD=2, QED=2

One Loop virtual

Example: PP > Z LO & NLO

```
Intermediate results:
Random seed: 34
Total cross-section:      1.824e+03 +- 2.9e+00 pb
Total abs(cross-section): 2.056e+03 +- 2.6e+00 pb
```

```
Summary:
Process p p > mu+ mu- [QCD]
Run at p-p collider (6500 + 6500 GeV)
Total cross-section: 1.824e+03 +- 2.9e+00 pb
Number of events generated: 10000
Parton shower to be used: HERWIG6
Fraction of negative weights: 0.06
Total running time :  1m 19s
```

K Facor: 1824/1508 ~ 1.21

2.056*(0.94-0.06)=1.81

Example: PP > Z LO & NLO

Z/a* (50)	FEWZ 3.1	m(ll)>50 GeV	NNLO	Z -> mm	2008.4	+13.2 -7.5 (± 75.0)

NLO/LO 1824/1508 ~ 1.21

NNLO/NLO 2008.4/1824 ~ 1.1

NLO EWK also included

arXiv.org > hep-ph > arXiv:1208.5967

High Energy Physics - Phenomenology

Combining QCD and electroweak corrections to dilepton production in FEWZ

Ye Li, Frank Petriello

Example: PP > Z LO & NLO

NLO events: additional parton in the final state

```
<event>
6     66 0.20557722E+04 0.88575911E+02 0.75467716E-02 0.11800000E+00
        2 -1    0    0  501    0 0.00000000E+00 0.00000000E+00 0.32758644E+02 0.32760207E+02 0.32000000E+00 0.0000E
+00 0.0000E+00
       21 -1    0    0  502  501 0.00000000E+00 0.00000000E+00 -.25056521E+03 0.25056633E+03 0.75000000E+00 0.0000E
+00 0.0000E+00
       23  2    1    2    0    0 0.12823333E+02 0.44733748E+01 -.29224945E+02 0.94256237E+02 0.88575911E+02 0.0000E
+00 0.0000E+00
      -13  1    3    3    0    0 -.28120157E+02 0.10814566E+02 -.41280973E+02 0.51106046E+02 0.10565837E+00 0.0000E
+00 0.0000E+00
       13  1    3    3    0    0 0.40943489E+02 -.63411912E+01 0.12056028E+02 0.43150191E+02 0.10565837E+00 0.0000E
+00 0.0000E+00
        2  1    1    2  502    0 -.12823333E+02 -.44733748E+01 -.18858162E+03 0.18907030E+03 0.32000000E+00 0.0000E
+00 0.0000E+00
 </event>
 <event>
5     66 0.20557722E+04 0.90465747E+02 0.75467716E-02 0.11800000E+00
       -1 -1    0    0    0  501 0.00000000E+00 0.00000000E+00 0.21814416E+01 0.22047874E+01 0.32000000E+00 0.0000E
+00 0.0000E+00
        1 -1    0    0  501    0 0.00000000E+00 0.00000000E+00 -.93290233E+03 0.93290239E+03 0.32000000E+00 0.0000E
+00 0.0000E+00
       23  2    1    2    0    0 0.00000000E+00 0.00000000E+00 -.93072089E+03 0.93510717E+03 0.90465747E+02 0.0000E
+00 0.0000E+00
      -13  1    3    3    0    0 -.69025294E+01 0.30106640E+02 -.12379180E+03 0.12758713E+03 0.10565837E+00 0.0000E
+00 0.0000E+00
       13  1    3    3    0    0 0.69025294E+01 -.30106640E+02 -.80692909E+03 0.80752005E+03 0.10565837E+00 0.0000E
+00 0.0000E+00
 </event>
```

Example: PP > Z LO & NLO

```
  <event>
  6      66 0.20557722E+04 0.90245145E+02 0.75467716E-02 0.11800000E+00
          1 -1    0    0  501    0 0.00000000E+00 0.00000000E+00 0.28116668E+03 0.28116686E+03 0.32000000E+00 0.0000E
+00 0.0000E+00
         21 -1    0    0  502  501 0.00000000E+00 0.00000000E+00 -.11545208E+02 0.11569543E+02 0.75000000E+00 0.0000E
+00 0.0000E+00
         23  2    1    2    0    0 -.14953236E+02 0.39115154E+01 0.25685826E+03 0.27268893E+03 0.90245145E+02 0.0000E
+00 0.0000E+00
        -13  1    3    3    0    0 0.22518246E+02 0.33607604E+02 0.82360116E+02 0.91759154E+02 0.10565837E+00 0.0000E
+00 0.0000E+00
         13  1    3    3    0    0 -.37471482E+02 -.29696088E+02 0.17449815E+03 0.18092978E+03 0.10565837E+00 0.0000E
+00 0.0000E+00
          1  1    1    2  502    0 0.14953236E+02 -.39115154E+01 0.12763203E+02 0.20047468E+02 0.32000000E+00 0.0000E
+00 0.0000E+00
  </event>
  <event>
  6      66 -.20557722E+04 0.90513342E+02 0.75467716E-02 0.13309765E+00
          1 -1    0    0  502    0 0.00000000E+00 0.00000000E+00 0.11320220E+03 0.11320265E+03 0.32000000E+00 0.0000E
+00 0.0000E+00
         -1 -1    0    0    0  501 0.00000000E+00 0.00000000E+00 -.20704302E+02 0.20706775E+02 0.32000000E+00 0.0000E
+00 0.0000E+00
         23  2    1    2    0    0 -.11153127E+01 0.59566449E+01 0.86275318E+02 0.12519114E+03 0.90513342E+02 0.0000E
+00 0.0000E+00
        -13  1    3    3    0    0 0.22273578E+02 -.32858044E+02 0.62434766E+02 0.73985637E+02 0.10565837E+00 0.0000E
+00 0.0000E+00
         13  1    3    3    0    0 -.23388890E+02 0.38814689E+02 0.23840552E+02 0.51205501E+02 0.10565837E+00 0.0000E
+00 0.0000E+00
         21  1    1    2  502  501 0.11153127E+01 -.59566449E+01 0.62225773E+01 0.87182860E+01 0.75000000E+00 0.0000E
+00 0.0000E+00
  </event>
```

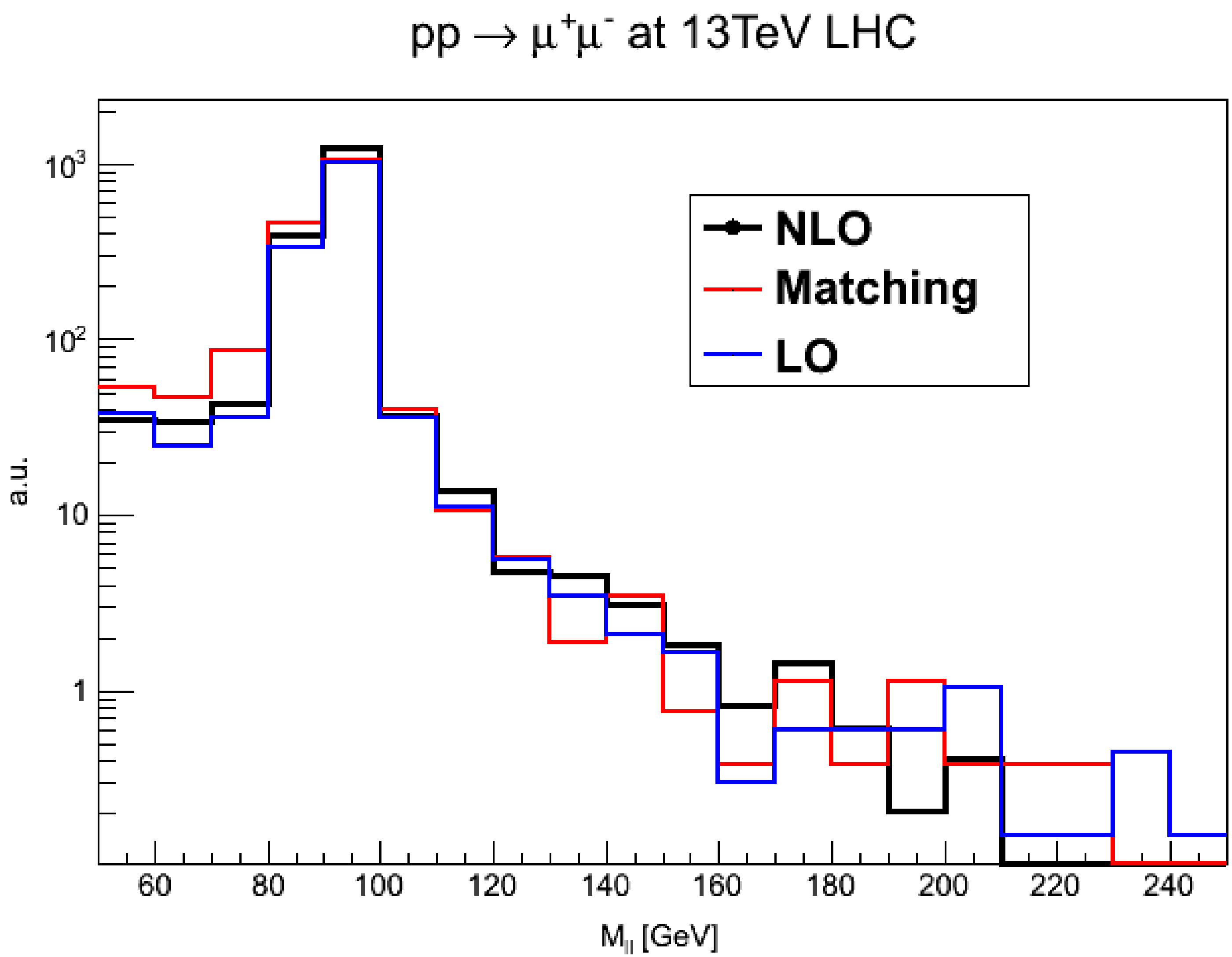
NLO events: negative weight

Example: PP > Z LO & NLO

```
-rw-rw-r-- 1 qliphy qliphy     19704 Jul 25 15:59 run_02_tag_1_banner.txt
-rw-rw-r-- 1 qliphy qliphy    158832 Jul 25 15:59 alllogs_0.html
-rw-rw-r-- 1 qliphy qliphy      3426 Jul 25 15:59 res_0.txt
-rw-rw-r-- 1 qliphy qliphy    165095 Jul 25 16:00 alllogs_1.html
-rw-rw-r-- 1 qliphy qliphy      3426 Jul 25 16:00 res_1.txt
-rw-rw-r-- 1 qliphy qliphy    121037 Jul 25 16:00 alllogs_2.html
-rw-rw-r-- 1 qliphy qliphy   1161895 Jul 25 16:00 events.lhe.gz
-rw-rw-r-- 1 qliphy qliphy       302 Jul 25 16:00 summary.txt
-rw-rw-r-- 1 qliphy qliphy      6810 Jul 25 16:00 RunMaterial.tar.gz
-rw-rw-r-- 1 qliphy qliphy 157955294 Jul 25 16:00 events_HERWIG6_0.hep.gz
```

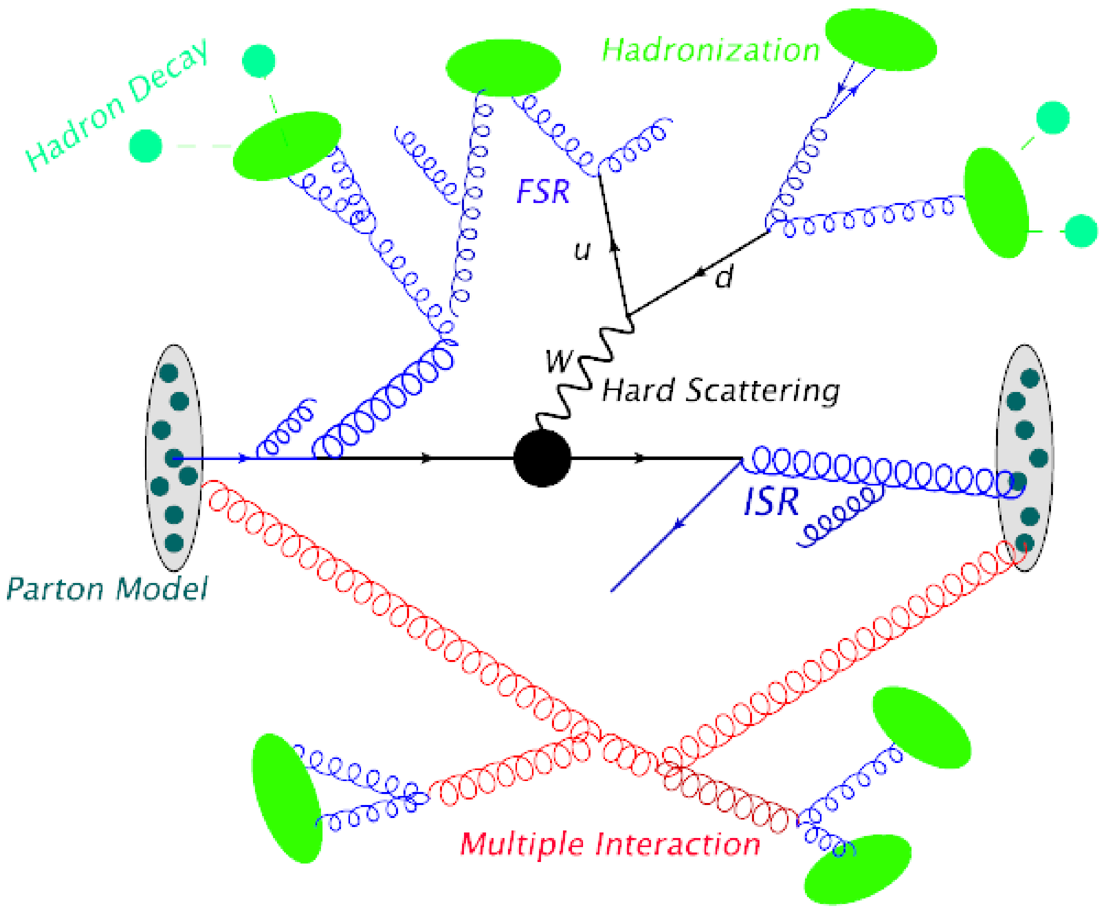
hep file is after Parton Shower, huge size

Example: LO vs NLO vs Matching



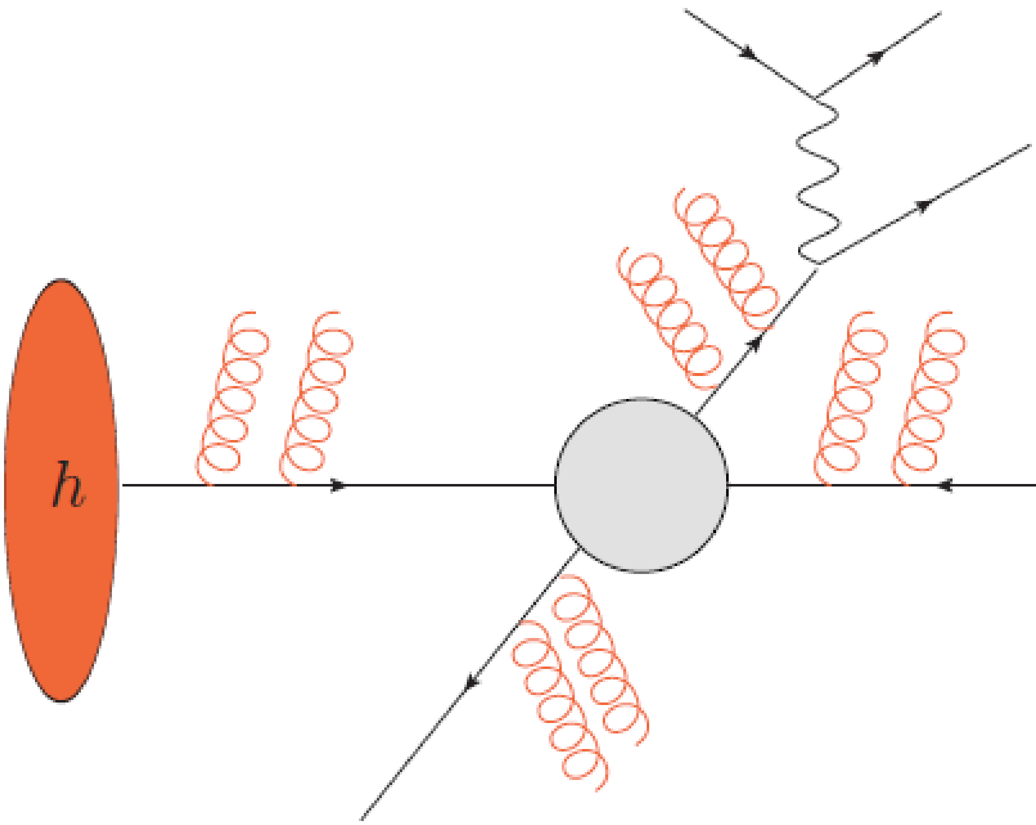
Anatomy of a LHC Collision

LHC collision: QCD machine



Only hard scattering by now

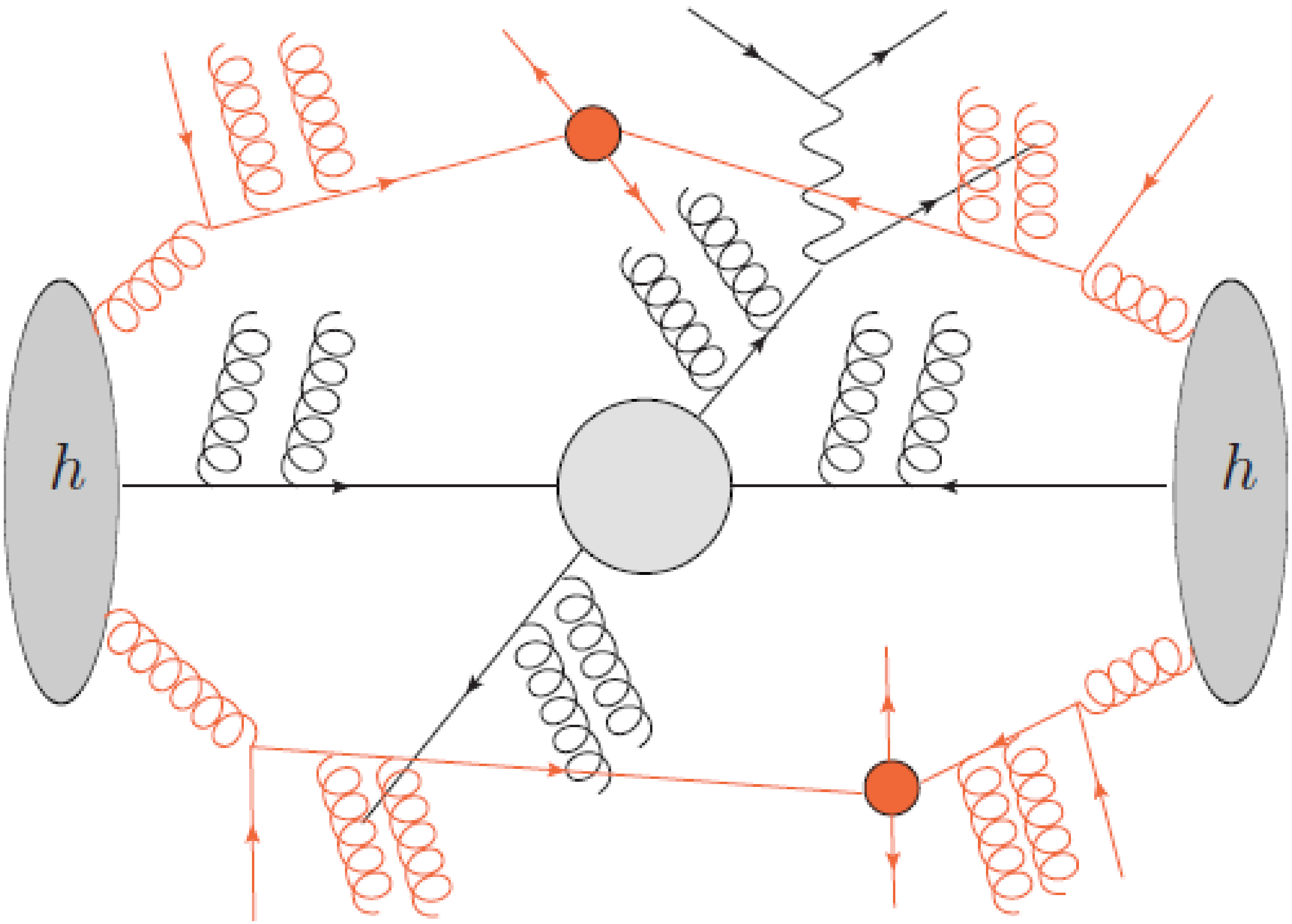
Parton Shower



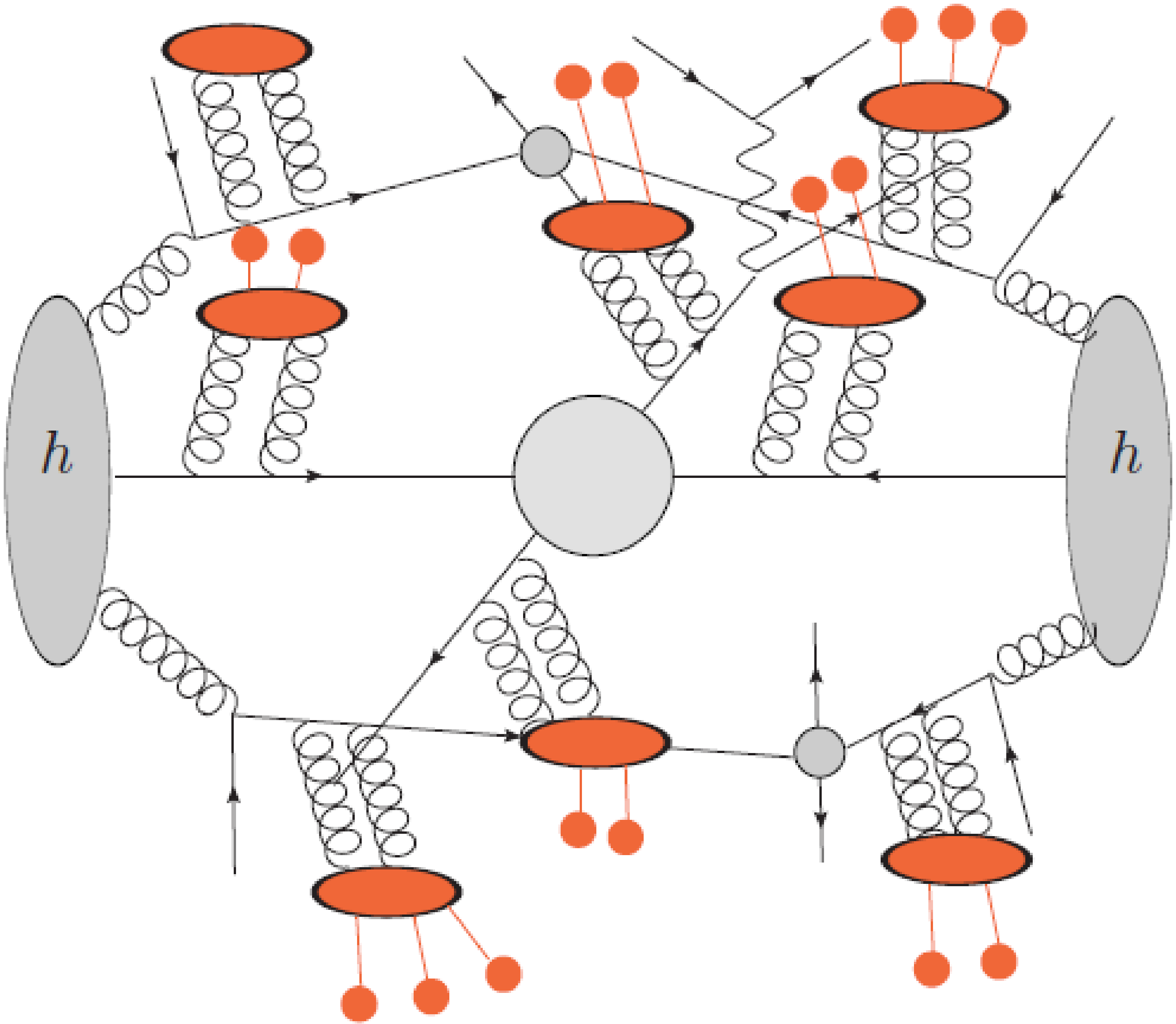
We will see a TeV quark/gluon splits all the way down to low scale

However, we can not calculate 2->nj with n~>8-10

Multiple Interactions

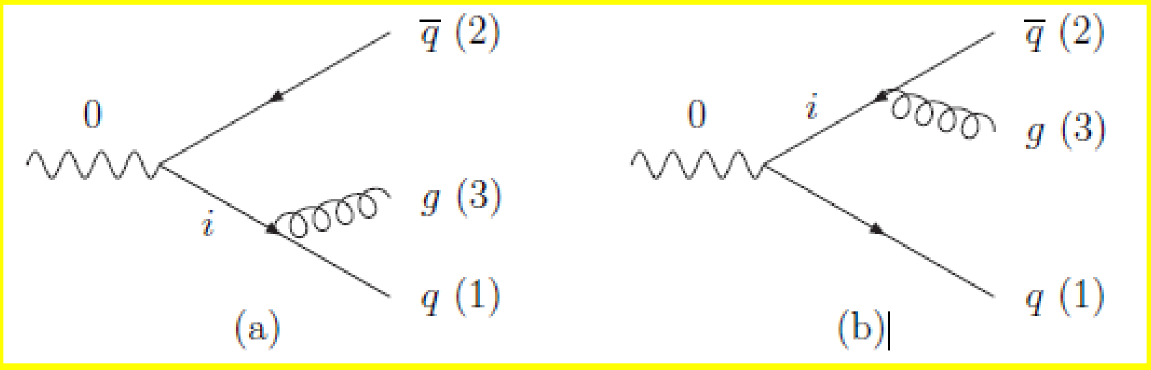


Hadronization and Decay



A bit about PS

$$e^+e^- \to \gamma^*/Z^0 \to q\overline{q}.$$



$x_j = 2E_j/E_{\rm cm}$ in the rest frame

$E_q = zE_i$ and $E_g = (1-z)E_i$

$$\frac{d\sigma_{\rm ME}}{\sigma_0} = \frac{\alpha_s}{2\pi}\frac{4}{3}\frac{x_1^2+x_2^2}{(1-x_1)(1-x_2)}\,dx_1\,dx_2$$

$x_2 \to 1.$ → **1,3 collinear**

Factorization
Universal
Incoherent

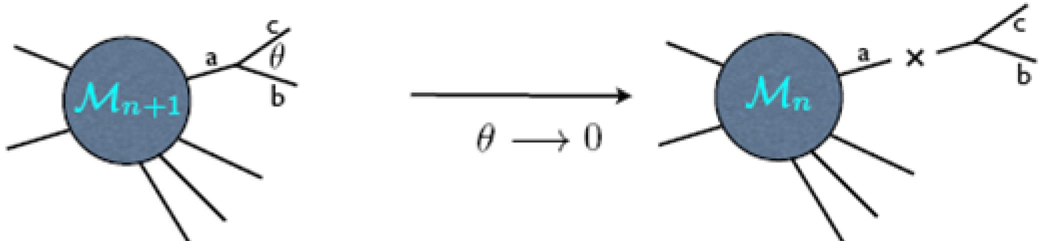
$$1 - x_2 = \frac{m_{13}^2}{E_{\rm cm}^2} = \frac{Q^2}{E_{\rm cm}^2} \implies dx_2 = \frac{dQ^2}{E_{\rm cm}^2}$$

$$x_1 \approx z \implies dx_1 \approx dz$$

$$x_3 \approx 1 - z$$

$$\frac{d\sigma_{\rm ME}}{\sigma_0} \approx \frac{\alpha_s}{2\pi}\frac{dQ^2}{Q^2}\frac{4}{3}\frac{1+z^2}{1-z}\,dz$$

A bit about PS



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

where

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

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

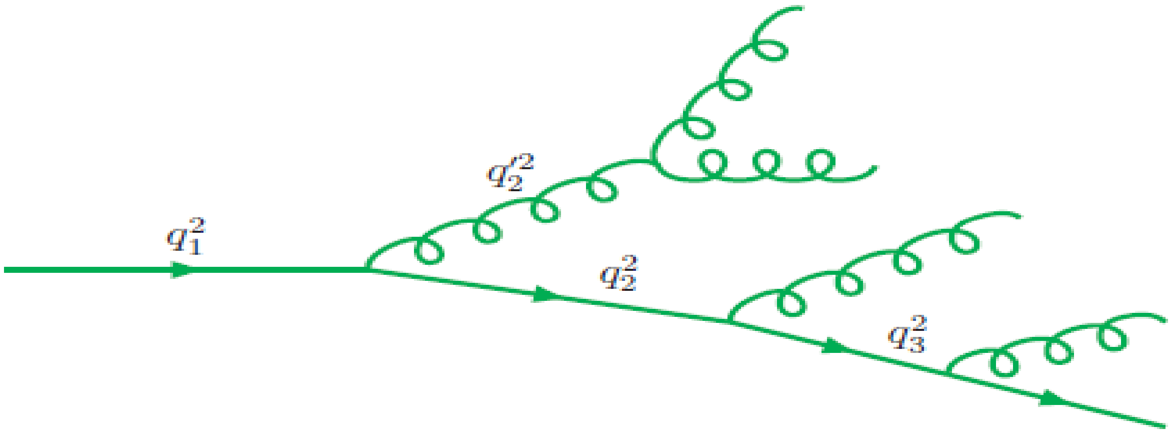
$$P_{g\to q\bar{q}} = \frac{n_f}{2}(z^2+(1-z)^2) \quad (n_f = \text{no. of quark flavours})$$

DGLAP function

This splitting can be separated from previous Probability way to handle QCD emission

Q is ordering parameter: can be virtuality, PT, or angle

A bit about PS



Probability that particle a does not emit between scales Q^2 and t:

$$\Delta(Q^2,t) = \prod_k \left[1 - \sum_{bc} \frac{dt_k}{t_k} \int dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)\right] =$$

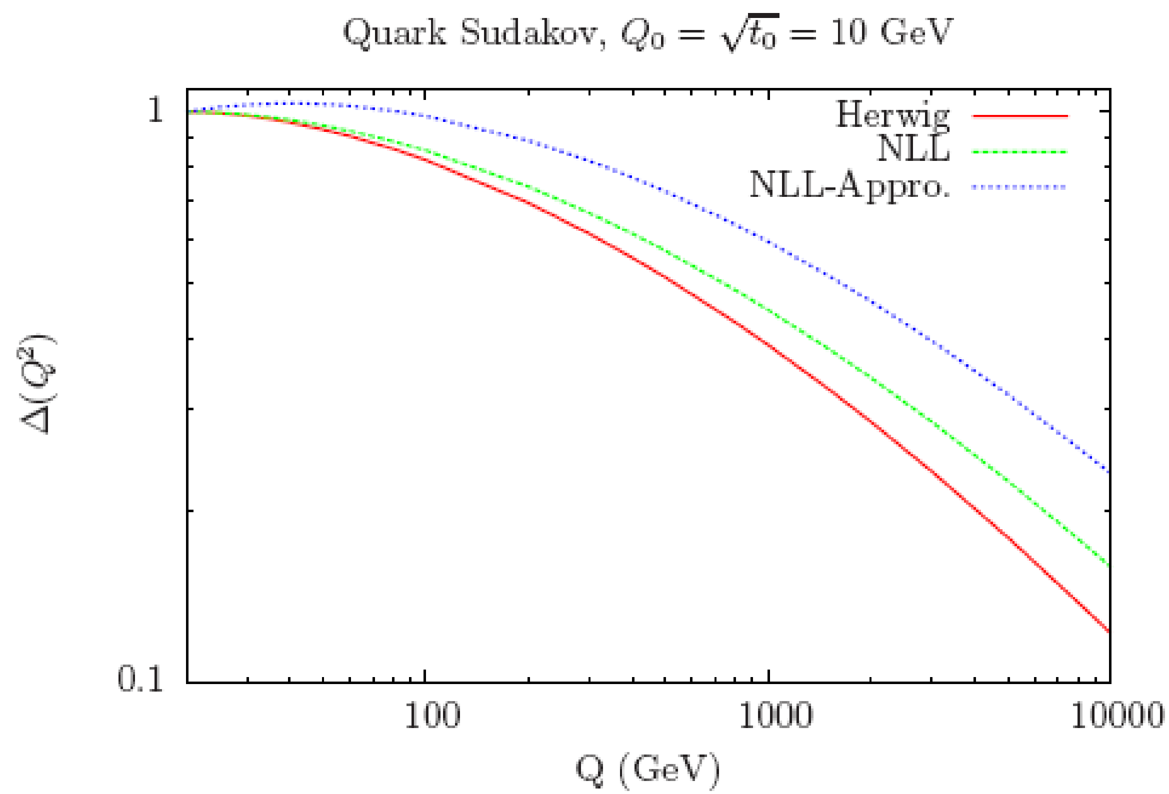
$$\exp\left[-\sum_{bc} \int_t^{Q^2} \frac{dt'}{t'} dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)\right] = \exp\left[-\int_t^{Q^2} dp(t')\right].$$

- $\Delta(Q^2,t)$ is the Sudakov form factor.
- Property: $\Delta(A,B) = \Delta(A,C)\Delta(C,B)$.

Sudakov Factor

$$\Delta^{\mathsf{HW}}_{a\to bc}(\tilde{t}) = \exp\left\{-\int_{4t_0}^{\tilde{t}} \frac{dt'}{t'} \int_{\sqrt{\frac{t_0}{t'}}}^{1-\sqrt{\frac{t_0}{t'}}} \frac{dz}{2\pi} \alpha_S(z^2(1-z)^2 t') \hat{P}_{ba}(z)\right\},$$

A TeV quark has large probability to split



$$\Delta^{\mathsf{NLL}}_{a\to bc}(t) = \exp\left\{-\int_{4t_0}^{t} \frac{dt'}{t'} \int_{\sqrt{\frac{t'}{4t}}}^{1-\sqrt{\frac{t'}{4t}}} \frac{dz}{2\pi} \alpha_S(t') \hat{P}_{ba}(z)\right\}$$

$$\Delta_{a\to bc}(Q) = \exp\left\{-\int_{Q_1=2\sqrt{t_0}}^{Q} dq \Gamma_{a\to bc}(q,Q)\right\}$$

$$\Gamma_{q\to qg} = \frac{2C_F}{\pi} \frac{\alpha_S(q)}{q} \left(\ln\frac{Q}{q} - \frac{3}{4}\right)$$

A bit about PS

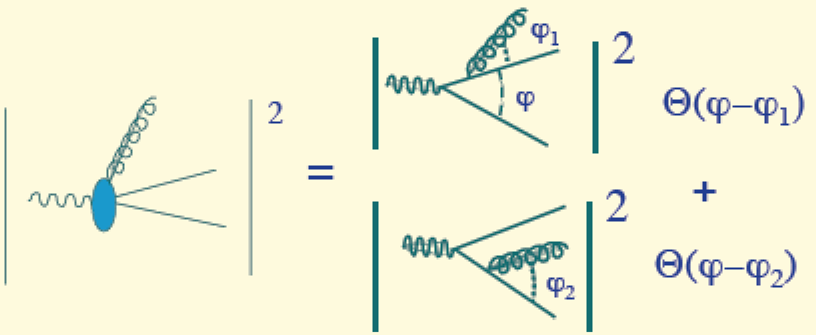
$$\frac{d\sigma_{\mathrm{ME}}}{\sigma_0} \approx \frac{\alpha_s}{2\pi}\frac{dQ^2}{Q^2}\frac{4}{3}\frac{1+z^2}{1-z}\,dz$$

Angular ordering
(slide by M. Mangano)

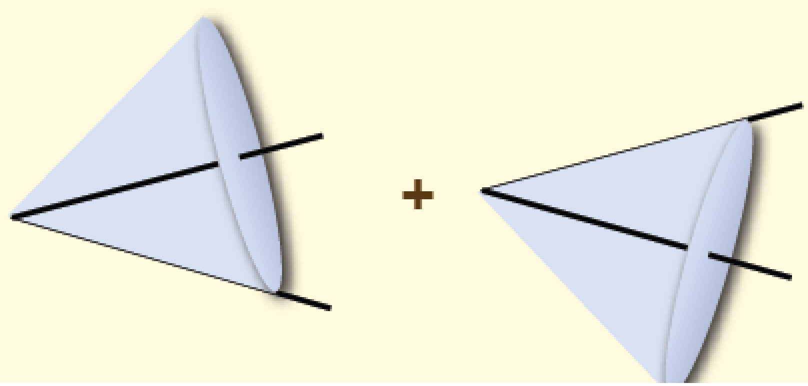
Soft limit: E3->0 i.e. z->1
Not like in collinear limit, There will be interference

Fortunately, we can implement the effects by angular ordering

Angular ordering

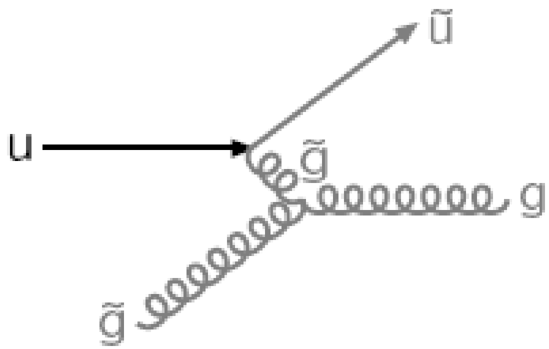


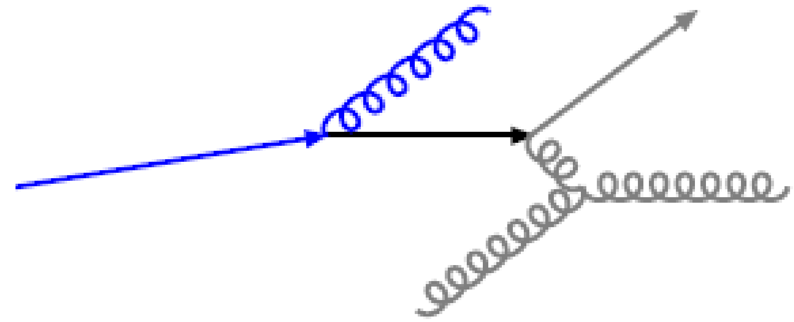
Radiation inside the cones is allowed, and described by the eikonal probability, radiation outside the cones is suppressed and averages to 0 when integrated over the full azimuth



A bit about PS

ISR Involves PDF





Monte Carlo approach, based on *conditional probability*: recast

$$\frac{\mathrm{d}f_b(x,Q^2)}{\mathrm{d}t} = \sum_a \int_x^1 \frac{\mathrm{d}z}{z} f_a(x',Q^2) \frac{\alpha_s}{2\pi} P_{a\to bc}(z)$$

with $t = \ln(Q^2/\Lambda^2)$ and $z = x/x'$ to

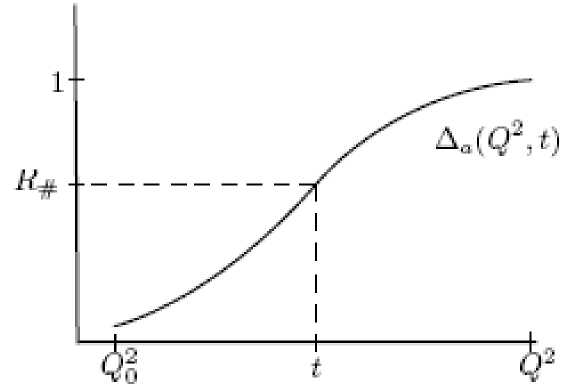
$$\mathrm{d}\mathcal{P}_b = \frac{\mathrm{d}f_b}{f_b} = |\mathrm{d}t| \sum_a \int \mathrm{d}z \frac{x' f_a(x',t)}{x f_b(x,t)} \frac{\alpha_s}{2\pi} P_{a\to bc}(z)$$

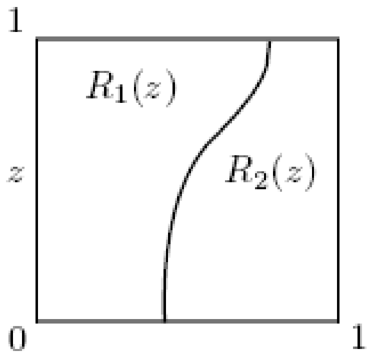
then solve for *decreasing* t, i.e. backwards in time, starting at high Q^2 and moving towards lower, with Sudakov form factor $\exp(-\int \mathrm{d}\mathcal{P}_b)$

PS in numerical

Implementation

- Extract the evolution variable t of the branching by solving the equation $\Delta(Q^2, t) = R_\#$, with $R_\#$ a flat random number between 0 and 1.
  This correctly reproduces the probability distribution since the probability of extracting a splitting scale t between t_1 and t_2 is $\Delta(Q^2, t_2) - \Delta(Q^2, t_1)$.





- Extract the energy sharing z and the daughter identities b and c according to $P_{a\to bc}(z)$.
  For two possible branchings $P_1(z)$ and $P_2(z)$ one can call $R_i(z) = P_i(z)/(P_1(z) + P_2(z))$, and choose z and parton identities by extracting a random point in the plane.
- Extract ϕ (flat).
- Reiterate (updating the maximum scale for the Sudakov) until all the 'external' partons are characterized by a scale smaller than a threshold $Q_0^2 \sim 1$ GeV.
- Put partons on shell and hadronize.

Pythia6 and Pythia8

Main Monte Carlos available on the market: PYTHIA

Choice of evolution variables for Fortran and C++ versions:

- PYTHIA 6: $t = (p_b + p_c)^2 \sim z(1-z)\theta^2 E_a^2$.
- Pythia 8: $t = (p_b)_\perp^2$.

Simpler variables, but decreasing angles not guaranteed: PYTHIA has to reject the events that don't respect the angular ordering (though this is not completely equivalent to ordering in angle).

Not implementing directly angular ordering, the phase space can be filled entirely, even without matrix element corrections, so one can have the so called "power shower" (use with a certain care).

- Hadronization: string model.

Note. Usually PYTHIA is faster than HERWIG.

Herwig6 and Herwig++

Main Monte Carlos available on the market: HERWIG

All HERWIG versions (Fortran and C++) implement the angular-ordering: subsequent emissions are characterized by smaller and smaller angles.

- HERWIG 6: $t = \frac{p_b \cdot p_c}{E_b E_c} \simeq 1 - \cos\theta$.
- Herwig++: $t = \frac{(p_{b\perp})^2}{z^2(1-z)^2} = t(\theta)$.

Implementing angular ordering, the parton shower (without matrix element corrections) cannot populate the full phase space (without matrix element corrections): empty regions of the phase space, called "dead zones", will arise.

Note. It may seem that the presence of dead zones is a weakness, but it is not so: they implement correctly the collinear approximation, in the sense that they constrain the shower to live uniquely in the region where it is reliable.

- Hadronization: cluster model.

Sherpa's PS

Main Monte Carlos available on the market: SHERPA

- A new and completely different kind of shower not based on the collinear $1 \to 2$ branching, but on more complex $2 \to 3$ elementary process: emission of the daughter off a color dipole.
- The real emission matrix element squared is decomposed into a sum of terms $D_{ij,k}$ (dipoles) that capture the soft and collinear singularities in the limits i collinear to j, i soft (k is the spectator), and a factorization formula is deduced in the leading color approximation:

$$D_{ij,k} \to B \frac{\alpha_S}{p_i \cdot p_j} K_{ij,k}.$$

- The shower is developed from a Sudakov form factor

$$\Delta = \exp\left(- \int \frac{dt}{t} \int dz \ \alpha_S \ K_{ij,k} \right).$$

- It treats correctly the soft gluon emission off a color dipole, so angular ordering is built in.
- Hadronization: cluster model.

ME+PS Matching: MLM, CKKW

- Parton shower describes the collinear and soft region quite well, but breaks down for the production of hard and widely separated jets.

- $G + 0j$: LO, NLO done; NNLO easier; High accuracy on Graviton inclusive production rates; No trustable jet information;
- $G + 1j$: LO, NLO done; NNLO hard; NLO information for Graviton and the leading jet; LO information for the 2nd jet; jet PT untrustable below or around PTG.
- $G + 2, 3j$: LO done; NLO hard; LO information for Graviton, the leading jet and the 2nd/3rd jet; large scale uncertainty.

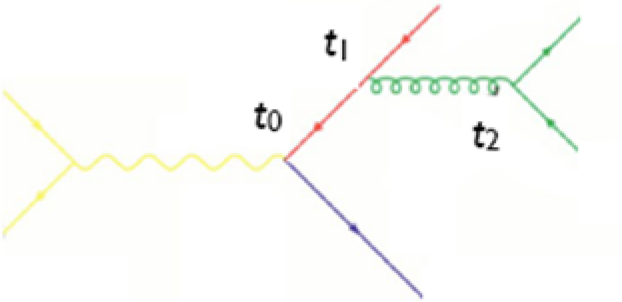
Can we give a trustable inclusive event sample, with all information ($\sim NLO$ accuracy) can be extracted easily by experimentalists?

ME+PS Matching: MLM, CKKW

- Yes, combining PS and ME consistently without double counting, by reweighting and veto
  - the CKKW method, based on shower veto and therefore on event re-weightning.
    S. Catani, F. Krauss, R. Kuhn and B. R. Webber,JHEP **0111**, 063 (2001); F. Krauss, JHEP **0208**, 015 (2002)
  - the MLM-based scheme, based on event rejection.
    S. Hoche, F. Krauss, N. Lavesson, L. Lonnblad, M. Mangano, A. Schalicke and S. Schumann, arXiv:hep-ph/0602031.

ME+PS Matching: MLM, CKKW

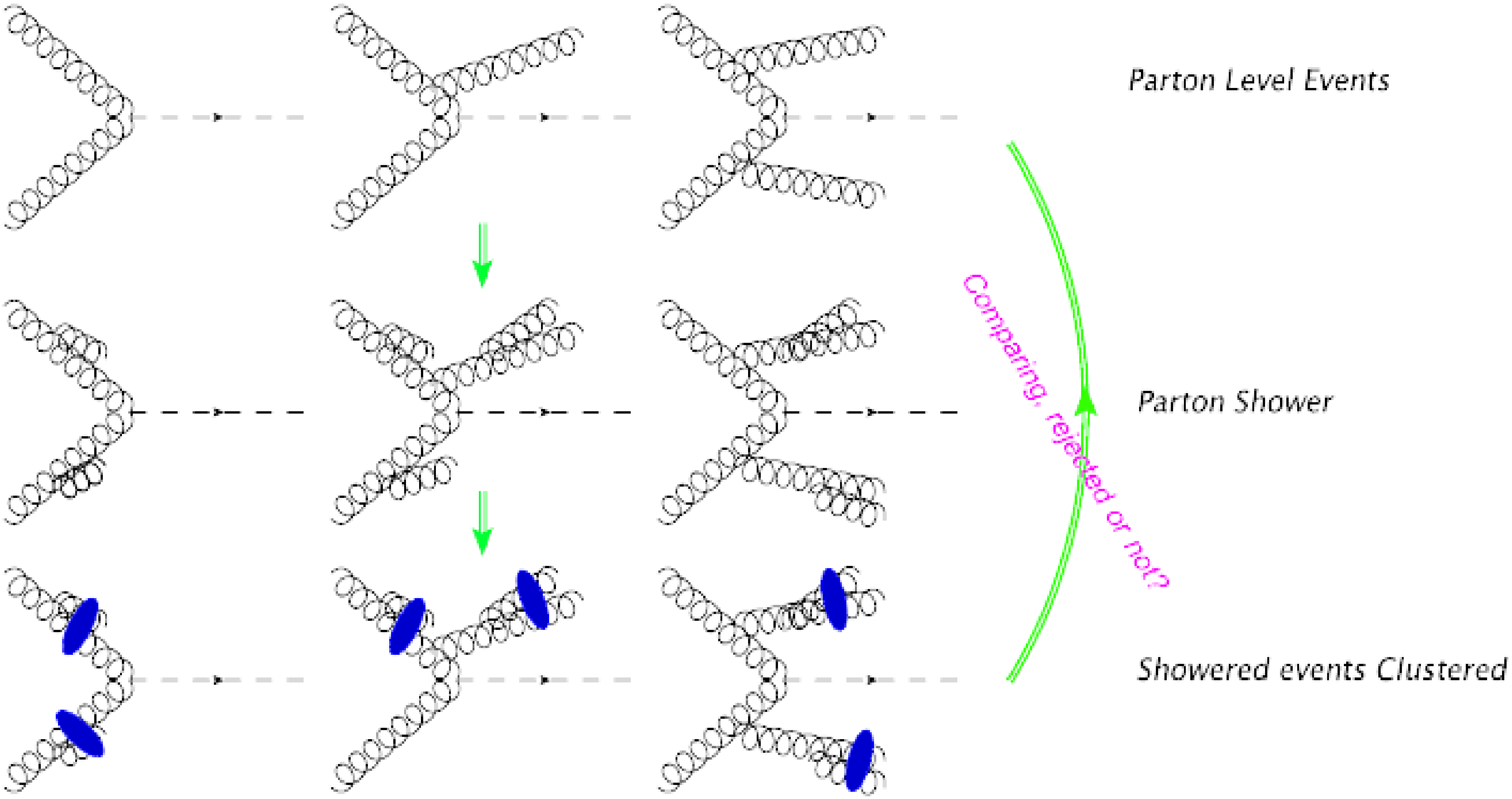
Mimic PS history



$$|\mathcal{M}|^2(\hat{s}, p_3, p_4, \ldots)$$

- To get an equivalent treatment of the corresponding matrix element, do as follows:
  1. Cluster the event using some clustering algorithm
     - this gives us a corresponding "parton shower history"
  2. Reweight α_s in each clustering vertex with the clustering scale
     $$|\mathcal{M}|^2 \to |\mathcal{M}|^2 \frac{\alpha_s(t_1)}{\alpha_s(t_0)} \frac{\alpha_s(t_2)}{\alpha_s(t_0)}$$
  3. Use some algorithm to apply the equivalent Sudakov suppression $(\Delta_q(t_{\rm cut}, t_0))^2 \Delta_g(t_2, t_1)(\Delta_q({\rm cut}, t_2))^2$

Multi-leg Matrix Element Matching



Example: PP > Z+0,1,2 Jets Matching

```
MG5_aMC>generate p p > mu+ mu-

MG5_aMC>add process  p p > mu+ mu- j

MG5_aMC>add process  p p > mu+ mu- j j
```

```
# Matching - Warning! ickkw > 1 is still beta
#**********************************************
1          = ickkw          ! 0 no matching, 1 MLM, 2 CKKW matching
```

```
 0   = ptj          ! minimum pt for the jets

 0.  = drjj      ! min distance between jets

 10     = xqcut    ! minimum kt jet measure between partons
```

Example: PP > Z+0,1,2 Jets Matching

Pythia Card

```
!...Parton showering on or off
      MSTP(61)=1
      MSTP(71)=1

!...Fragmentation/hadronization on or off
      MSTJ(1)=0

!...Multiple interactions on or off
      MSTP(81)=20

    QCUT=20.0

!...Don't stop execution after 10 errors
      MSTU(21)=1
```

Example: PP > Z+0,1,2 Jets Matching

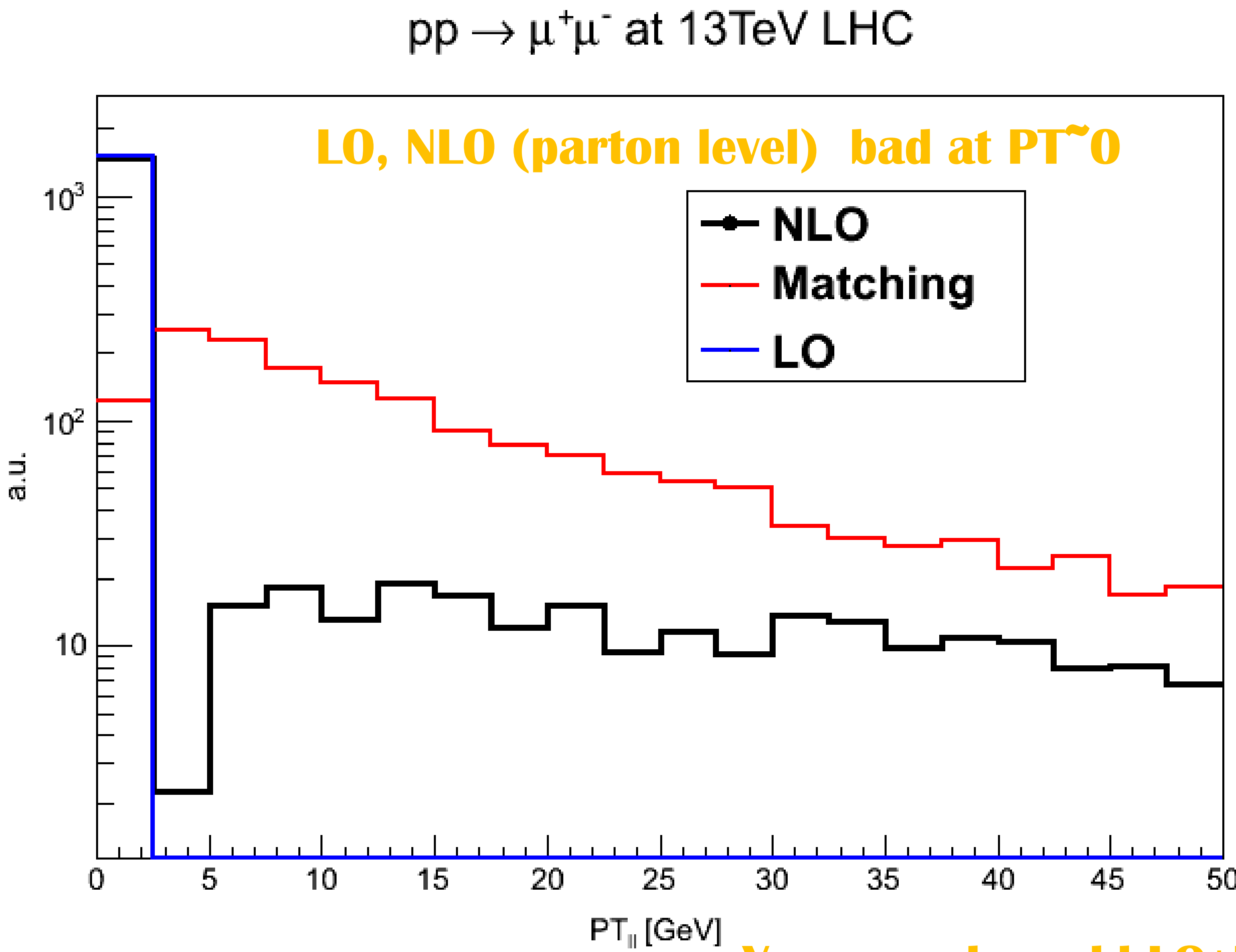
```
=================================================================
|                          |                    |         |
|   0 All included subprocesses   |     4711      10000 |  1.790D-06 |
|   4 User process 0          |    3173       4175 |  1.206D-06 |
|   6 User process 1          |     982       3326 |  3.732D-07 |
|   7 User process 2          |     556       2499 |  2.113D-07 |
|                          |                    |         |
=================================================================

********* Total number of errors, excluding junctions =       0 *************
********* Total number of errors, including junctions =       0 *************
********* Total number of warnings =                          0 *************
********* Fraction of events that fail fragmentation cuts =  0.52890 *********

Cross section (pb):    1790.4565567581010
```

```
Cross-section :    3799 +- 8.8 pb
Nb of events :  10000
Matched Cross-section :   1790 +- 19.41 pb
Nb of events after Matching :  4711
```

Example: LO vs NLO vs Matching

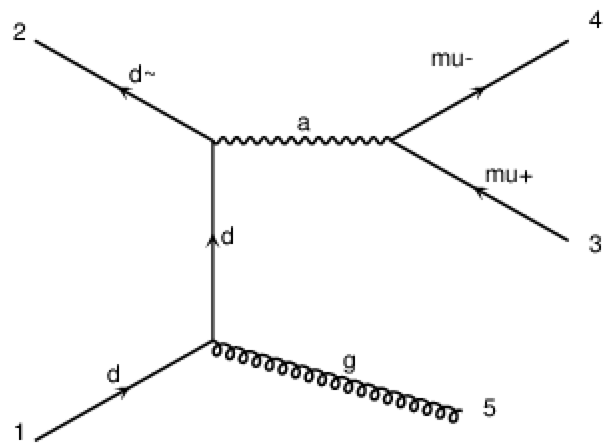


You can also add LO+Pythia

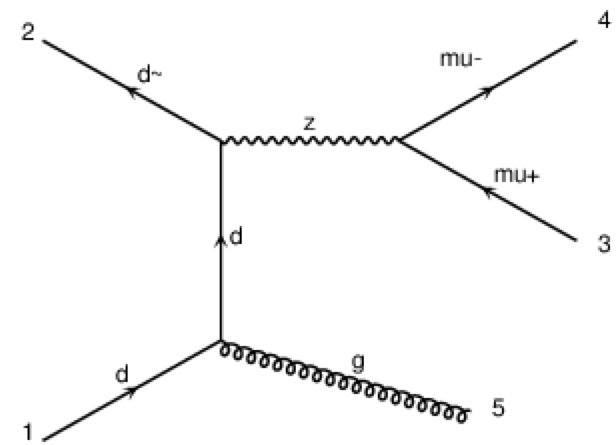
NLO+PS Matching: MC@NLO, POWHEG

NLO has one additional parton emission
NLO has higher accurate xsec
PS generate 1or more emissions
To avoid double counting, needs to be very careful

MC@NLO, POWHEG
MC@NLO + MG -> MG5_aMC@NLO



real diagram 1 QCD=1, QED=2



real diagram 2 QCD=1, QED=2

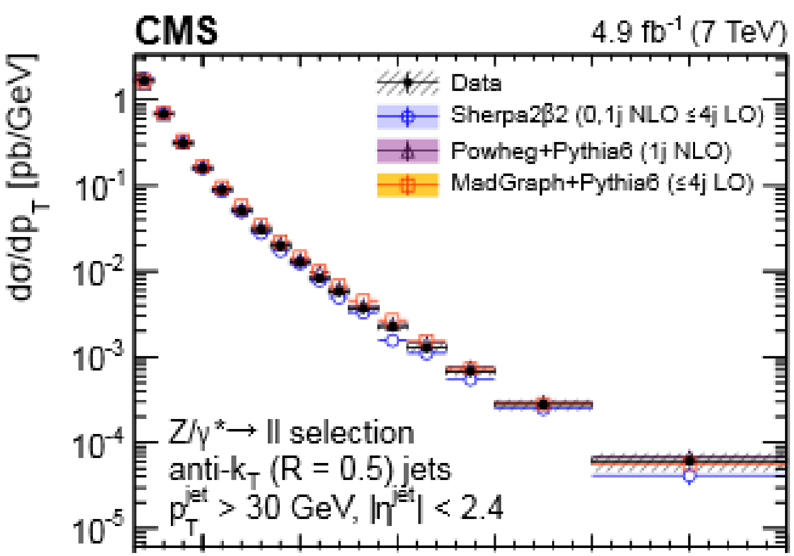
1. **Matching NLO QCD computations with Parton Shower simulations: the POWHEG method**
Stefano Frixione (INFN, Genoa), Paolo Nason (INFN, Milan Bicocca), Carlo Oleari (INFN, Milan Bicocca & Milan Bicocca U.). Sep 2007. 91 pp.
Published in **JHEP 0711 (2007) 070**
BICOCCA-FT-07-9, GEF-TH-21-2007
DOI: 10.1088/1126-6708/2007/11/070
e-Print: **arXiv:0709.2092 [hep-ph] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service; JHEP Electronic Journal Server
详细记录 - Cited by 785 records 500+

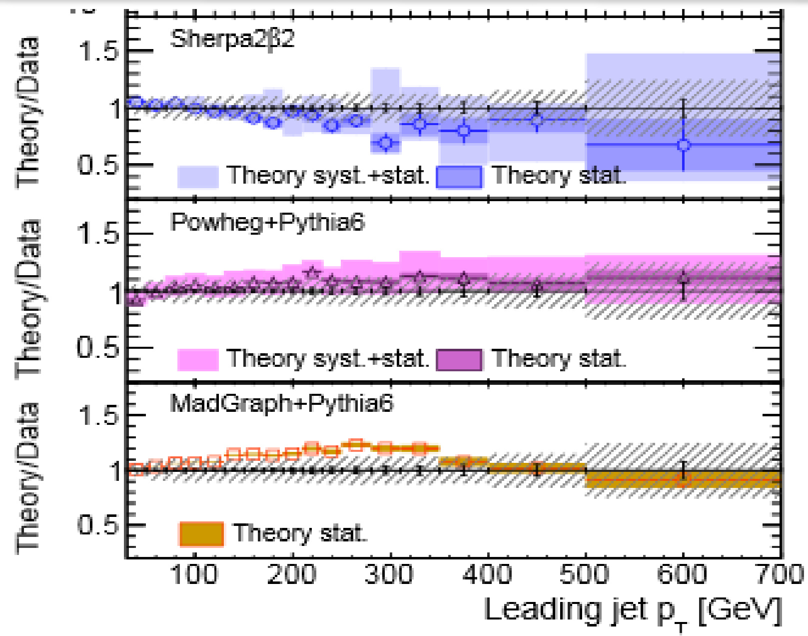
2. **Matching NLO QCD and parton showers in heavy flavor production**
Stefano Frixione (INFN, Genoa), Paolo Nason (INFN, Milan), Bryan R. Webber (CERN & Cambridge U.). May 2003. 70 pp.
Published in **JHEP 0308 (2003) 007**
BICOCCA-FT-03-11, CAVENDISH-HEP-03-03, CERN-TH-2003-102, GEF-TH-5-2003
DOI: 10.1088/1126-6708/2003/08/007
e-Print: **hep-ph/0305252 | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; CERN Server; JHEP Electronic Journal Server
详细记录 - Cited by 687 records 500+

3. **Matching NLO QCD computations and parton shower simulations**
Stefano Frixione (Annecy, LAPP), Bryan R. Webber (Cambridge U.). Apr 2002. 69 pp.
Published in **JHEP 0206 (2002) 029**
CAVENDISH-HEP-02-01, LAPTH-905-02, GEF-TH-2-2002
DOI: 10.1088/1126-6708/2002/06/029
e-Print: **hep-ph/0204244 | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; CERN Library Record; JHEP Electronic Journal Server
详细记录 - Cited by 1438 records 1000+

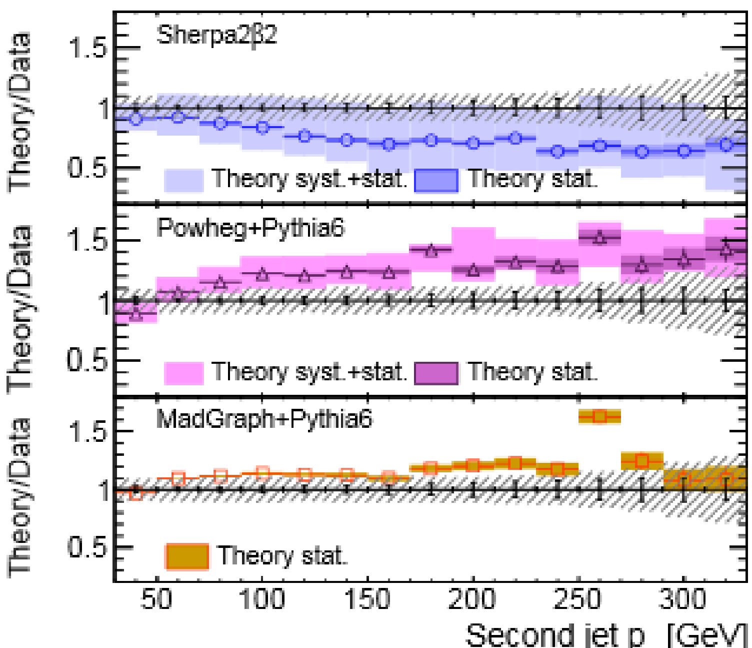
Until 2014/03/12

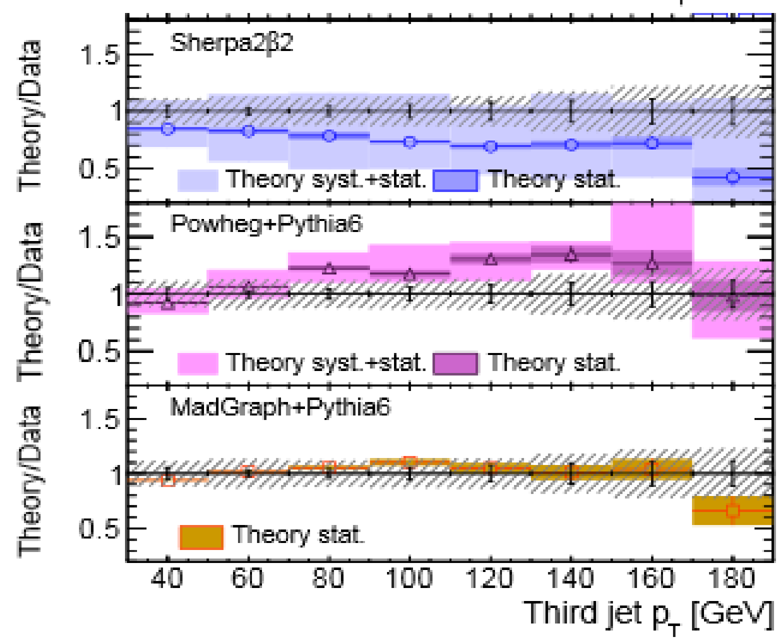
Experimental Usage CMS 7TeV Z+Jets





arXiv:1408.3104



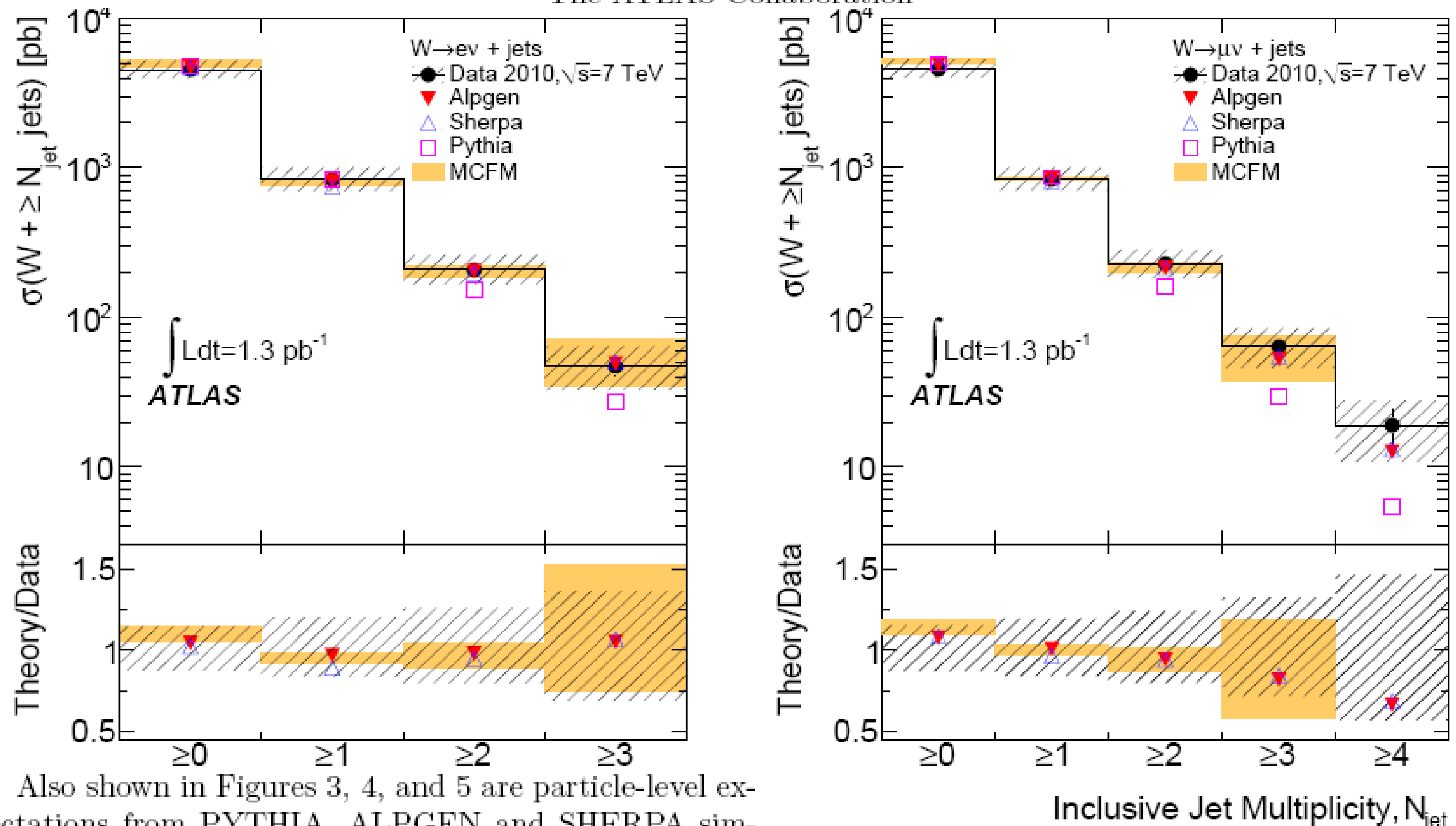


Experimental Usage

ATLAS 7TeV W+Jets

Measurement of the production cross section for W-bosons in association with jets in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

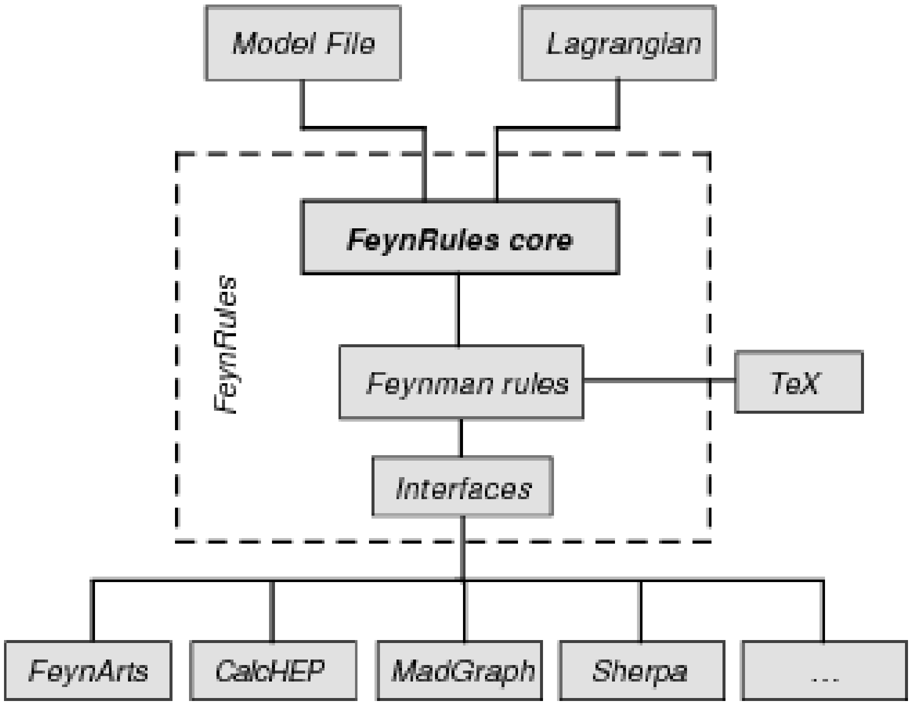
The ATLAS Collaboration



Also shown in Figures 3, 4, and 5 are particle-level expectations from PYTHIA, ALPGEN and SHERPA simulations as well as a calculation using MCFM v5.8 [35]. PYTHIA is LO, while ALPGEN and SHERPA match higher multiplicity matrix elements to a leading-logarithmic parton shower; these predictions have been normalised to the NNLO inclusive W production cross section. The version

arXiv:1012.5382

BSM implementations



FeynRules-> UFO/ALOHA-> MG

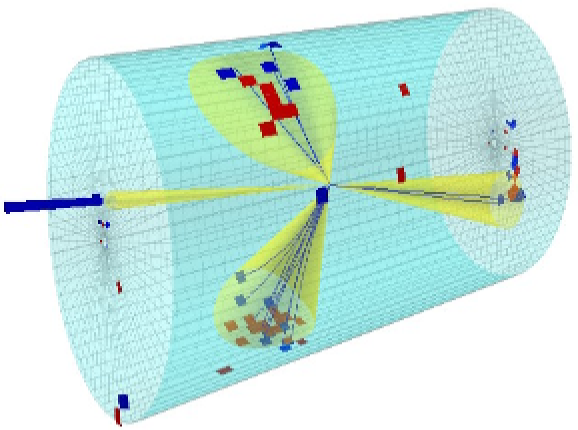
A Mathematica package to calculate Feynman rules

FeynRules is a Mathematica® package that allows the calculation of Feynman rules in momentum space for *any* QFT physics model. The user needs to provide FeynRules with the minimal information required to describe the new model, contained in the so-called model-file. This information is then used to calculate the set of Feynman rules associated with the Lagrangian. The Feynman rules calculated by the code can then be used to implement the new physics model into other existing tools, such as MC generators. This is done via a set of interfaces which are developed together and maintained by the corresponding MC authors.

Detector Fast Simulations

- **Delphes** is a **modular framework** that simulates the response of a multipurpose detector

- **Includes**:
  - pile-up
  - charged particle **propagation** in magnetic field
  - electromagnetic and hadronic **calorimeters**
  - **muon** system



- **Provides**:
  - leptons (electrons and muons)
  - photons
  - jets and missing transverse energy (particle-flow)
  - taus and b's

Running Delphes with STDHEP (XDR) input files:

```
./DelphesSTDHEP cards/delphes_card_CMS.tcl delphes_output.root input.hep
```

arXiv:1307.6346

Delphes CMS Card

Muon efficiency

```
##########################
# Muon tracking efficiency
##########################

module Efficiency MuonTrackingEfficiency {
  set InputArray ParticlePropagator/muons
  set OutputArray muons

  # set EfficiencyFormula {efficiency formula as a function of eta and pt}

  # tracking efficiency formula for muons
  set EfficiencyFormula {                                                    (pt <= 0.1)   * (0.00) + \
                                           (abs(eta) <= 1.5) * (pt > 0.1   && pt <= 1.0)   * (0.75) + \
                                           (abs(eta) <= 1.5) * (pt > 1.0)                  * (0.99) + \
                         (abs(eta) > 1.5 && abs(eta) <= 2.5) * (pt > 0.1   && pt <= 1.0)   * (0.70) + \
                         (abs(eta) > 1.5 && abs(eta) <= 2.5) * (pt > 1.0)                  * (0.98) + \
                         (abs(eta) > 2.5)                                                  * (0.00)}
}
```

Muon momentum smearing

```
module MomentumSmearing MuonMomentumSmearing {
  set InputArray MuonTrackingEfficiency/muons
  set OutputArray muons

  # set ResolutionFormula {resolution formula as a function of eta and pt}

  # resolution formula for muons
  set ResolutionFormula {                  (abs(eta) <= 0.5) * (pt > 0.1   && pt <= 5.0)   * (0.02) + \
                                           (abs(eta) <= 0.5) * (pt > 5.0   && pt <= 1.0e2) * (0.015) + \
                                           (abs(eta) <= 0.5) * (pt > 1.0e2 && pt <= 2.0e2) * (0.03) + \
                                           (abs(eta) <= 0.5) * (pt > 2.0e2)                * (0.05 + pt*1.e-4) + \
                         (abs(eta) > 0.5 && abs(eta) <= 1.5) * (pt > 0.1   && pt <= 5.0)   * (0.03) + \
                         (abs(eta) > 0.5 && abs(eta) <= 1.5) * (pt > 5.0   && pt <= 1.0e2) * (0.02) + \
                         (abs(eta) > 0.5 && abs(eta) <= 1.5) * (pt > 1.0e2 && pt <= 2.0e2) * (0.04) + \
                         (abs(eta) > 0.5 && abs(eta) <= 1.5) * (pt > 2.0e2)                * (0.05 + pt*1.e-4) + \
                         (abs(eta) > 1.5 && abs(eta) <= 2.5) * (pt > 0.1   && pt <= 5.0)   * (0.04) + \
                         (abs(eta) > 1.5 && abs(eta) <= 2.5) * (pt > 5.0   && pt <= 1.0e2) * (0.035) + \
                         (abs(eta) > 1.5 && abs(eta) <= 2.5) * (pt > 1.0e2 && pt <= 2.0e2) * (0.05) + \
                         (abs(eta) > 1.5 && abs(eta) <= 2.5) * (pt > 2.0e2)                * (0.05 + pt*1.e-4)}
}
```

geometry

```
# radius of the magnetic field coverage, in m
set Radius 1.29
# half-length of the magnetic field coverage,
set HalfLength 3.00

# magnetic field
set Bz 3.8
```

MPI

Multi-Parton-Interaction

Double Parton Scattering

Underlying Event:
everything but the hard interaction including showers & hadronization
soft & hard remnant-remnant interactions

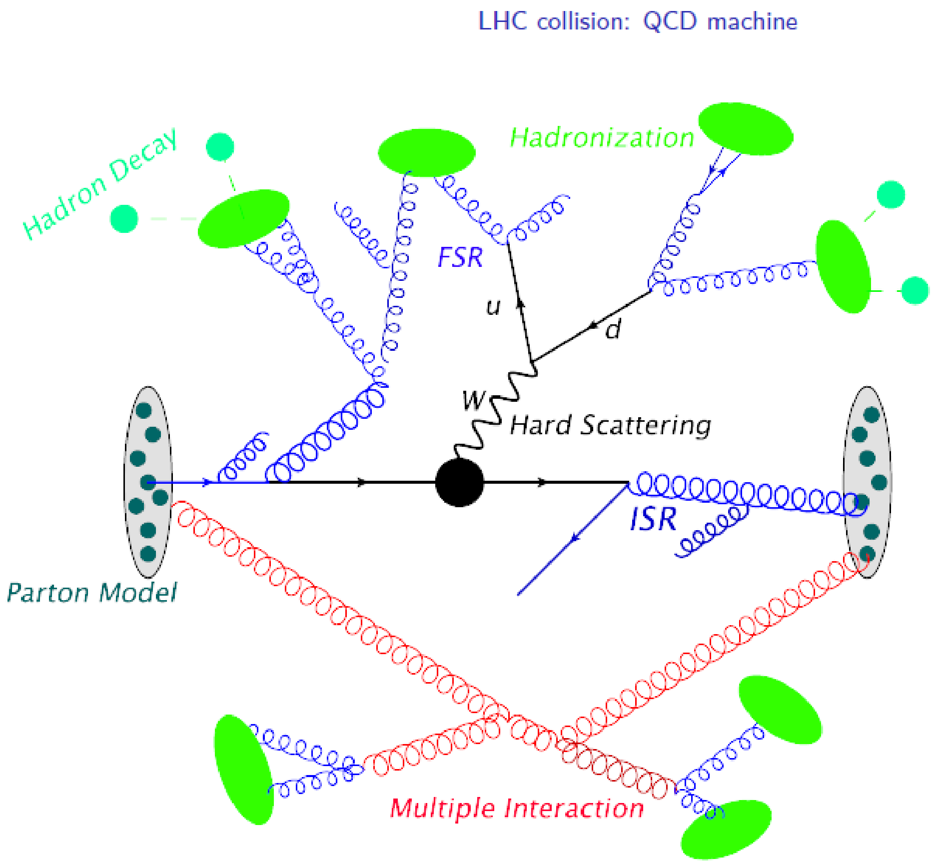
Minimum-bias: inclusive inelastic, non-diffractive events
Note in Exp, minimum-bias means more, including PileUp

$$\sigma_{\rm tot}(s) = \sigma_{\rm el}(s) + \sigma_{\rm inel}(s)$$

$$\sigma_{\rm inel}(s) = \sigma_{\rm SD}(s) + \sigma_{\rm DD}(s) + \sigma_{\rm CD}(s) + \sigma_{\rm ND}(s)$$

All are important for Tune!
Pythia6 Z2*, Herwig 4C ….

Summary



In practical,
We don't have
4-momenta

From Outside
to inside,
We need
Reconstruction.

Prof. Run's lecture