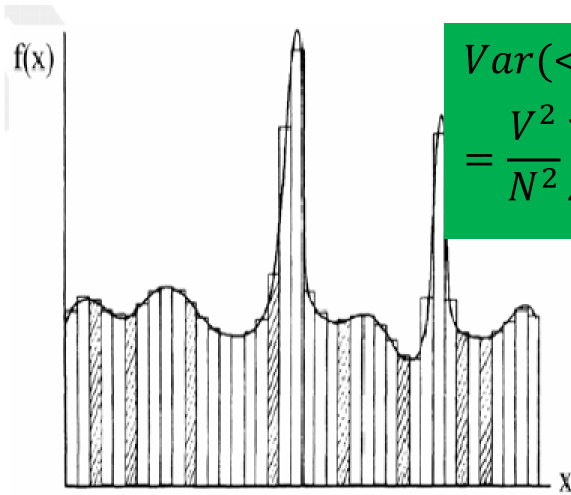
# MC Generator for LHC Experiments

Qiang Li 2019

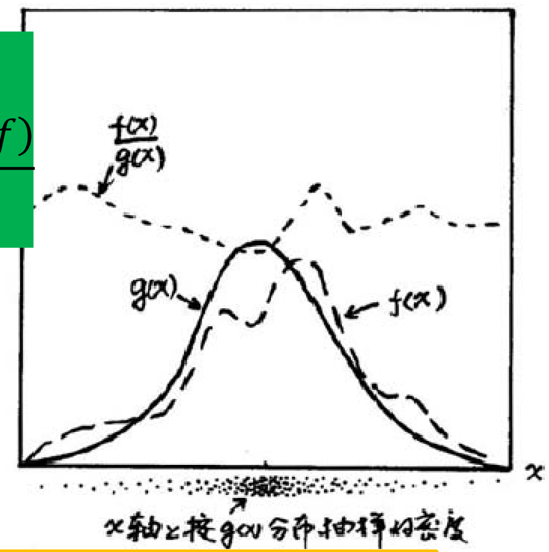
# 回顾:重要抽样法

简单抽样法积分近似度较差




$$Var(<f>) = \frac{V^2}{N^2}\sum_{1}^{N} Var(f) = V^2\frac{Var(f)}{N}$$

重要抽样法示意图




- 重要抽样法的原理起源于数学上的变量代换方法的思想，即：

$$\int_0^1 f(x)dx = \int_0^1 \frac{f(x)}{g(x)}g(x)dx = \int \frac{f(x)}{g(x)}dG(x)$$

- 此时随机点的选择不再是简单抽样法中的均匀选择，而是以分布函数G(x)分布的
- 这里g(x)称为偏倚分布密度函数。

# 回顾: Markov Chain

马尔可夫链，因安德烈·马尔可夫（A.A.Markov，1856－1922）得名，是指数学中具有马尔可夫性质的离散事件随机过程。该过程中，在给定当前知识或信息的情况下，**过去（即当前以前的历史状态）对于预测将来（即当前以后的未来状态）是无关的。**

在马尔可夫链的每一步，系统根据概率分布，可以从一个状态变到另一个状态，也可以保持当前状态。状态的改变叫做转移，与不同的状态改变相关的概率叫做**转移概率**。随机漫步就是马尔可夫链的例子

$X_1, X_2, X_3...$ 马尔可夫链（Markov Chain），描述了一种状态序列，其每个状态值取决于前面有限个状态。马尔可夫链是具有马尔可夫性质的随机变量的一个数列。这些变量的范围，即它们所有可能取值的集合，被称为"状态空间"，而 $X_n$ 的值则是在时间n的状态。如果 $X_{n+1}$ 对于过去状态的条件概率分布仅是 $X_n$ 的一个函数，则

$$P(X_{n+1} = x | X_1 = x_1, X_2 = x_2, ..., X_n = x_n) = P(X_{n+1} = x | X_n = x_n).$$

这里x为过程中的某个状态。上面这个恒等式可以被看作是马尔可夫性质。

# 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. MC Productions at LHC Experiment

# 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:

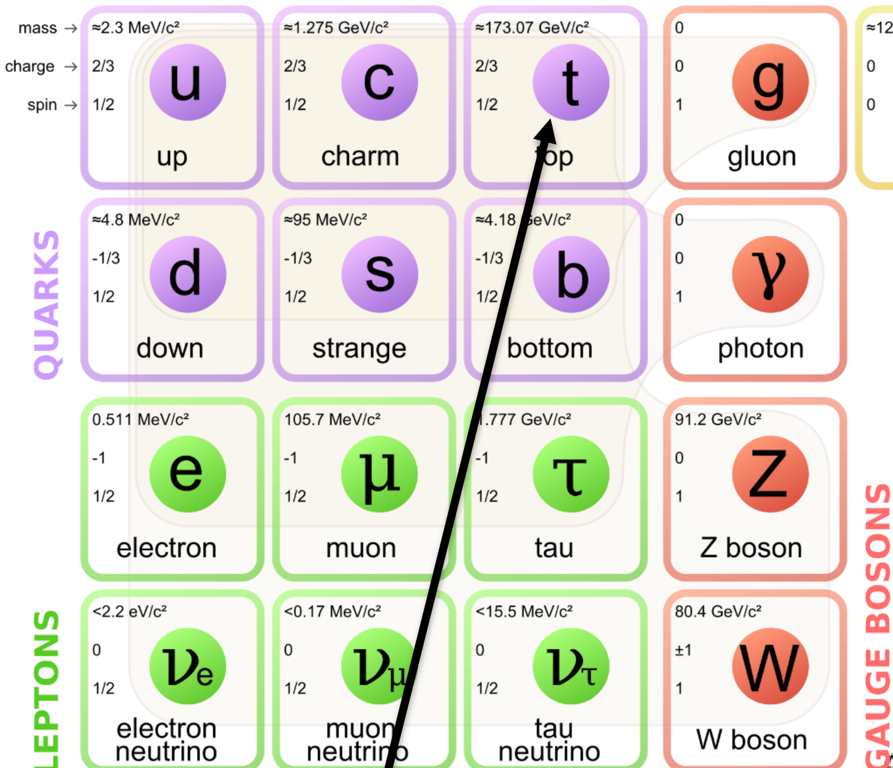
| Generator |
|---|
| Herwig6 |
| ThePEG (for Herwig++) |
| ALPGEN |
| MC@NLO |
| gg2VV |
| Phantom |
| Hydjet |
| Hydjet++ |
| Pyquen |
| Cosmic Muon Generator |
| ExHuME |
| Pomwig |
| BCVEGPY |
| HARDCOL |

| Generator |
|---|
| CompHEP |
| TopRex |
| Charybdis |
| EDDE |
| HELAC |

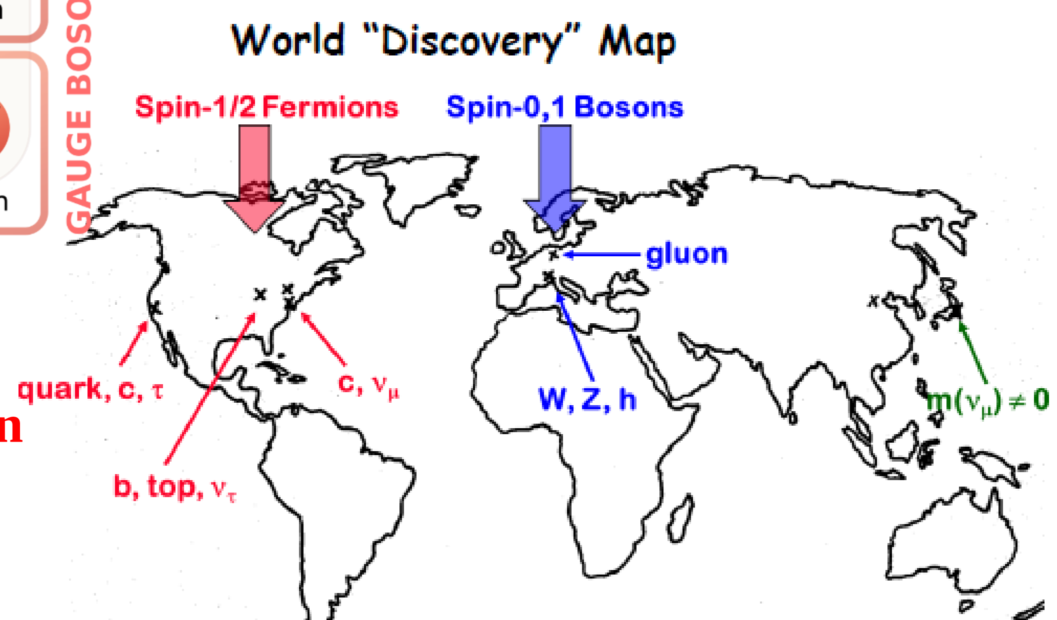
| |
|---|
| PHOJET |
| Regge-Gribov Generators (EPOS, QGSJetII, Sibyll) |
| CASCADE |
| Herwig++ |

# 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

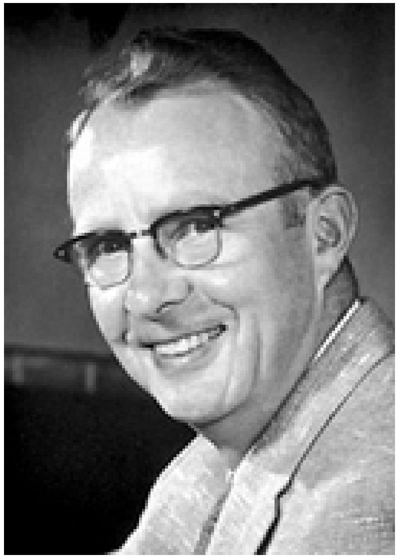
Richard P. Feynman

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

Murray Gell-Mann

Prize share: 1/1

强相互作用
夸克

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

丁肇中

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

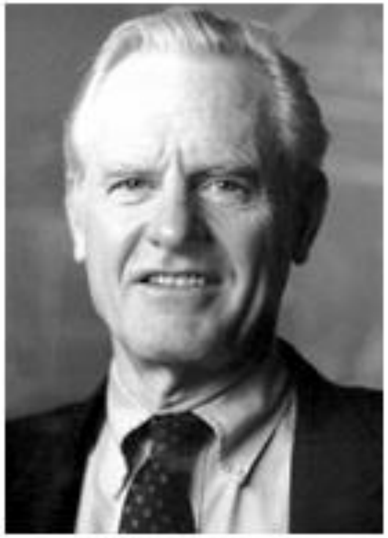
The Nobel Prize in Physics 1988 was awarded jointly to Leon M. Lederman, Melvin Schwartz and Jack Steinberger *"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"*.

# 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

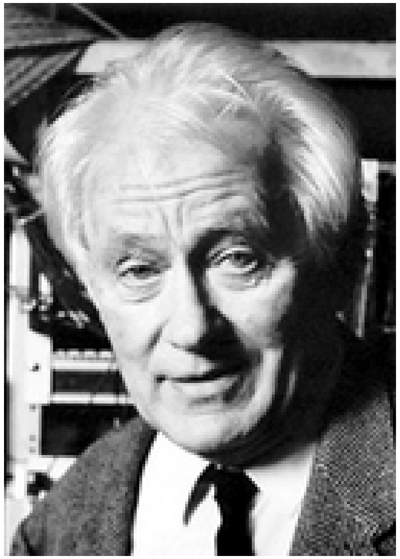
Photo: T. Nakashima

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

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**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

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

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

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

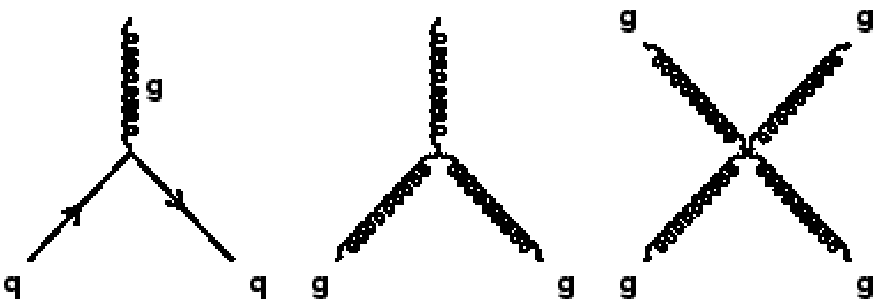
$$\alpha_{QCD}(100GeV) = \frac{g_{s^2}}{4\pi} \sim 0.13$$

$$\mathcal{L}_{\rm QCD} = \bar{\psi}_i \left( i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

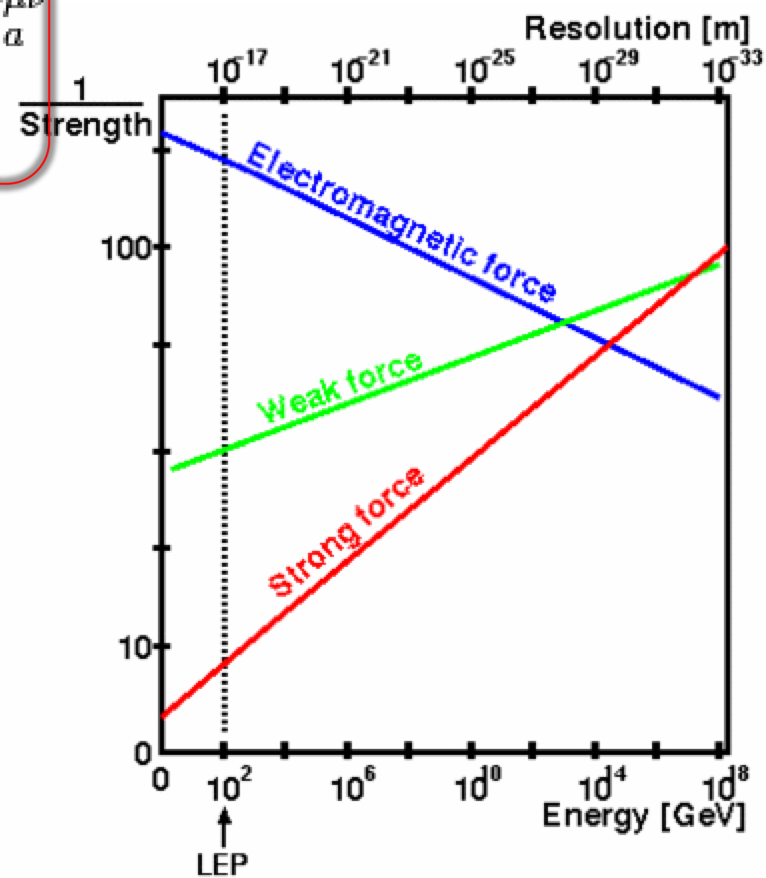
$$G^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu + g f^{abc} \mathcal{A}^b_\mu \mathcal{A}^c_\nu \,,$$

**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

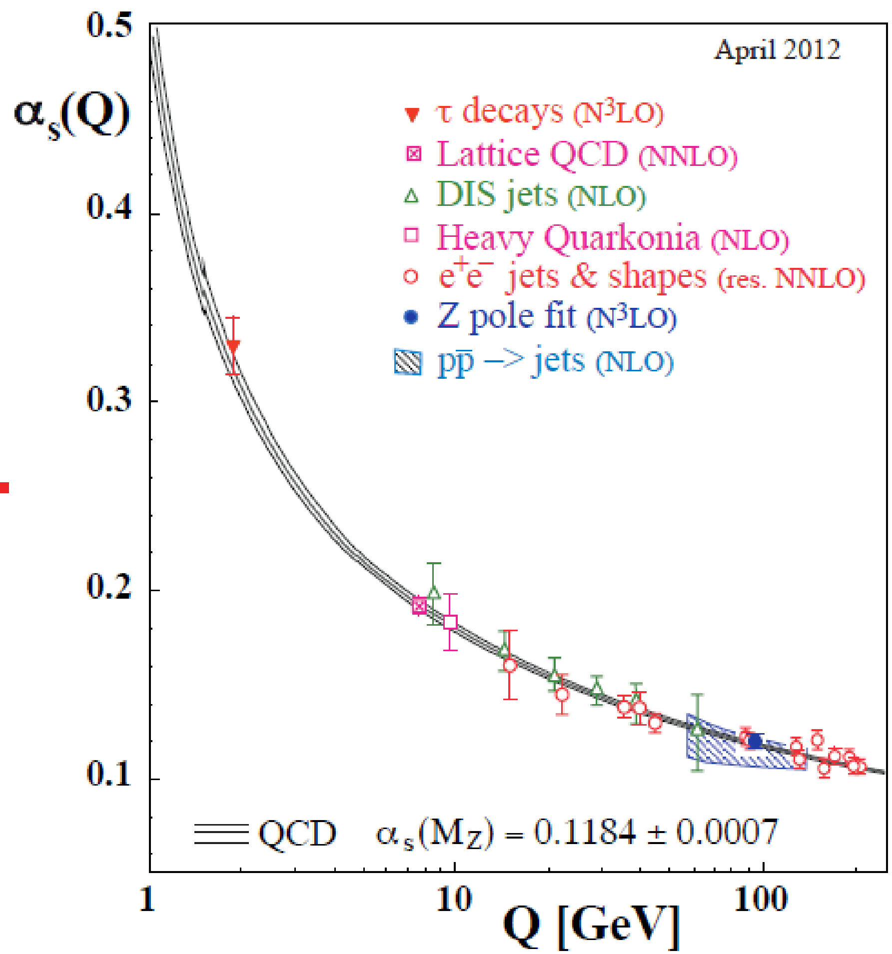
Prize share: 1/3

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



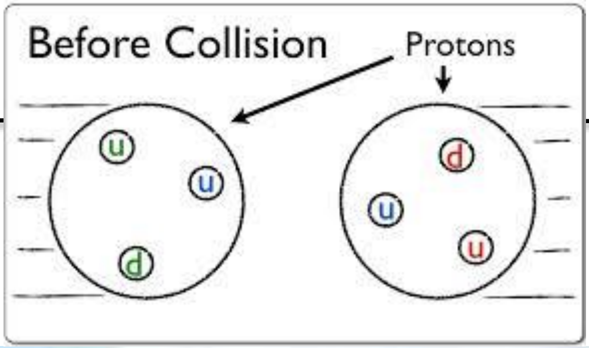

Asymptotic Freedom

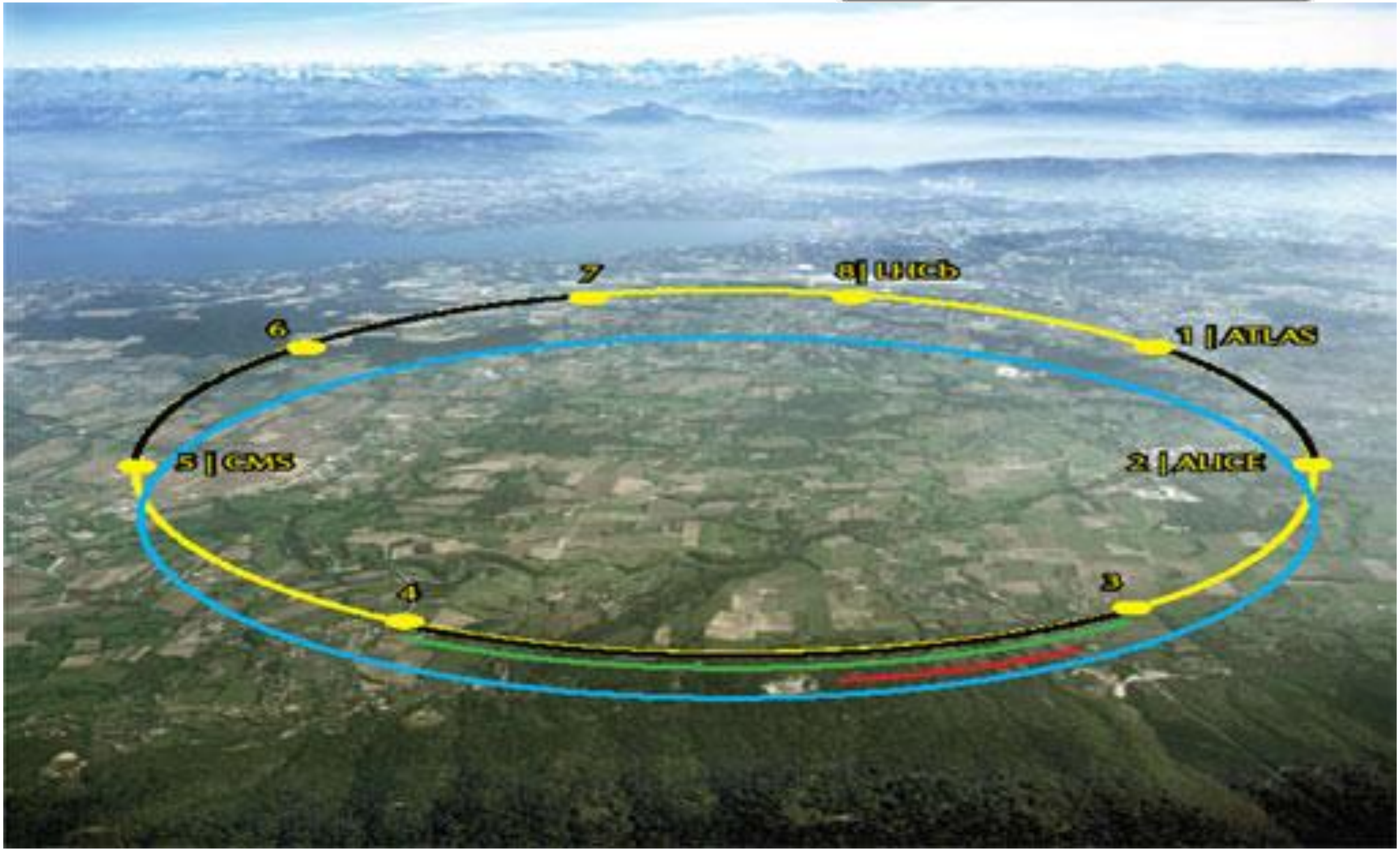
& Grand Unification?

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

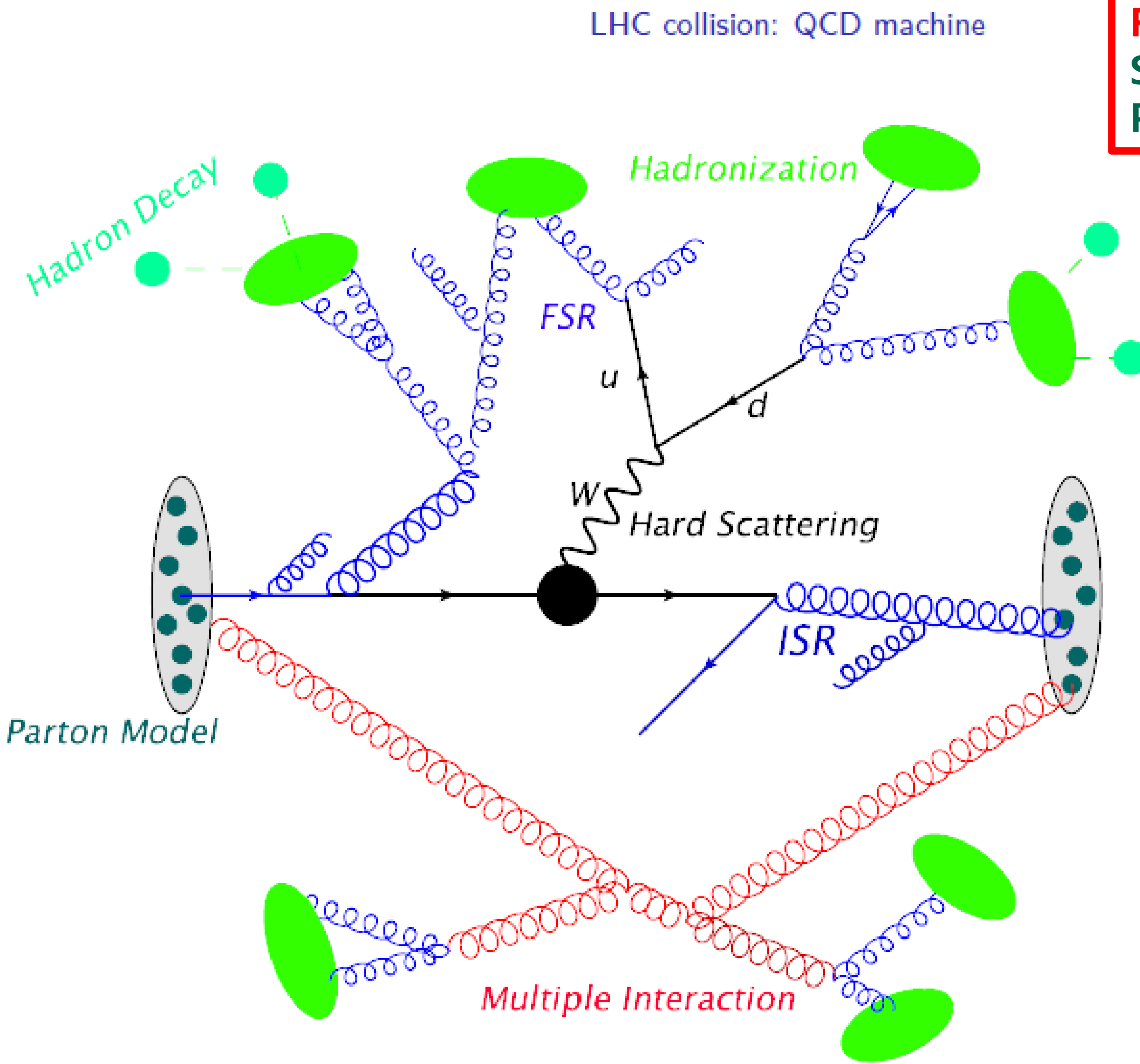
# Collider

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



# Anatomy of a LHC Collision



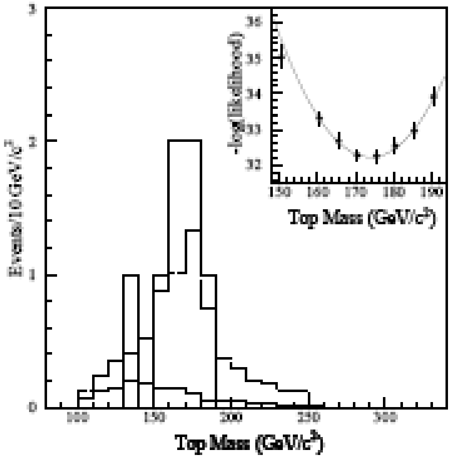

**Factorization Theorem:**
**Separate Short Distance Physics from Soft one**

**QCD Machine**

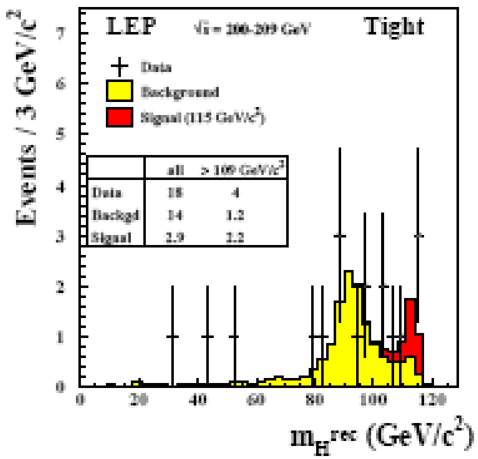
**Factorization**

**Multi-level**

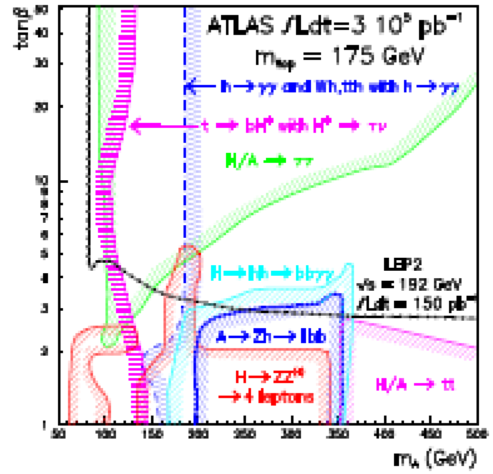
# Why Generators? Torbjörn Sjöstrand




top discovery and mass determination




Higgs (non) discovery




Higgs and supersymmetry exploration

not feasible without generators

# PT and (pseudo-)Rapidity

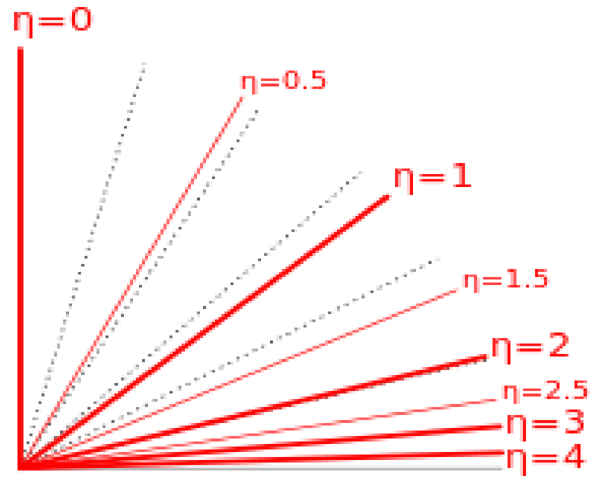
$$y \equiv \frac{1}{2}\ln\left(\frac{E+p_{\mathrm{L}}}{E-p_{\mathrm{L}}}\right)$$

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

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

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

**Lorentz Invariant Distance**

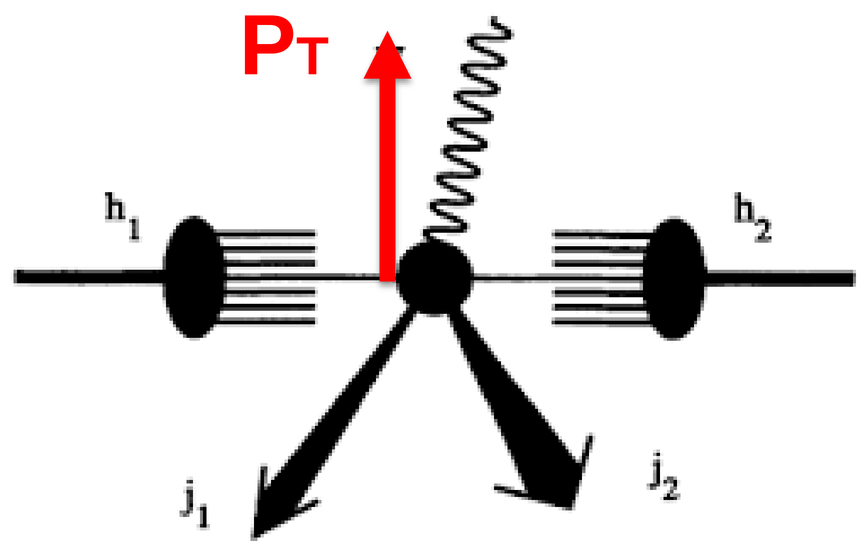



**LHC typical:**

**PT>20-30GeV**

**|η|<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 $\beta$, 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 $\eta$:

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

or

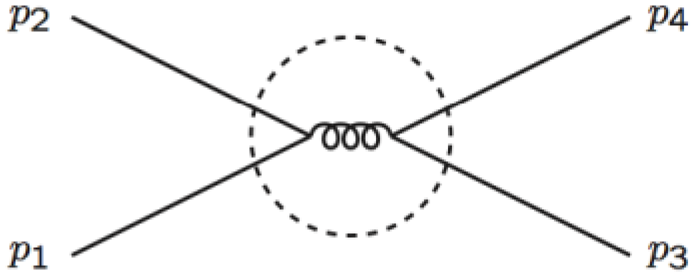
$$\begin{aligned} \eta &= \frac{1}{2} \ln \frac{\underline{p} + \underline{p} \cos\theta}{\underline{p} - \underline{p} \cos\theta} = \frac{1}{2} \ln \frac{1 + \cos\theta}{1 - \cos\theta} \\ &= \frac{1}{2} \ln \frac{2\cos^2\theta/2}{2\sin^2\theta/2} = \ln \frac{\cos\theta/2}{\sin\theta/2} = -\ln\tan\frac{\theta}{2}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

which thus only depends on polar angle.
$\eta$ 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 $\eta$.

# Mandelstam variables

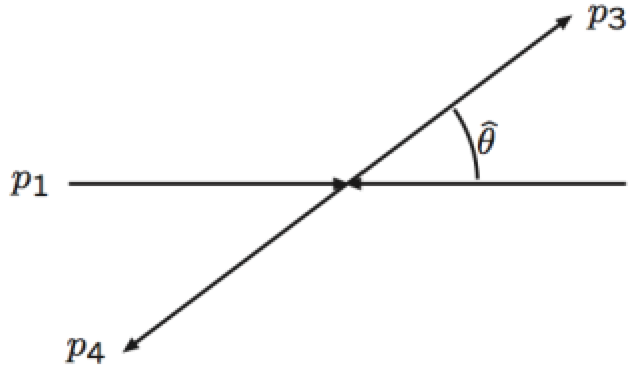
**For process $1 + 2 \to 3 + 4$**

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




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

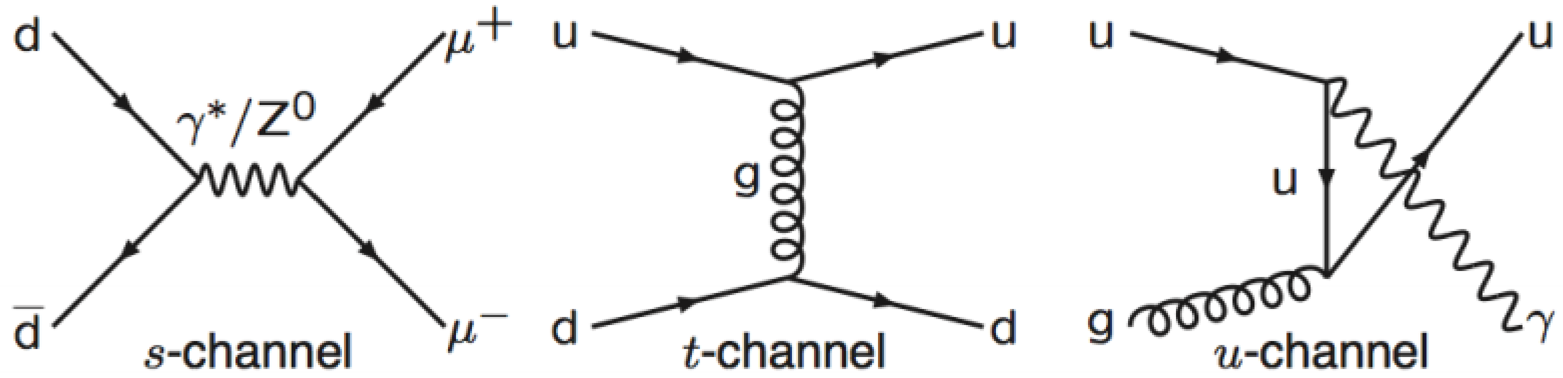
$$\begin{aligned} p_{1,2} &= \frac{E_{\rm cm}}{2}(1; 0, 0, \pm) \\ p_{3,4} &= \frac{E_{\rm cm}}{2}(1; \pm\sin\hat\theta, 0, \pm\cos\hat\theta) \\ s &= E_{\rm cm}^2 \\ t &= -2p_1p_3 = -\frac{s}{2}(1 - \cos\hat\theta) \\ u &= -2p_2p_4 = -\frac{s}{2}(1 + \cos\hat\theta) \end{aligned}$$




$$s + t + u = 0$$

# $s$-, $t$- and $u$-channel processes

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




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

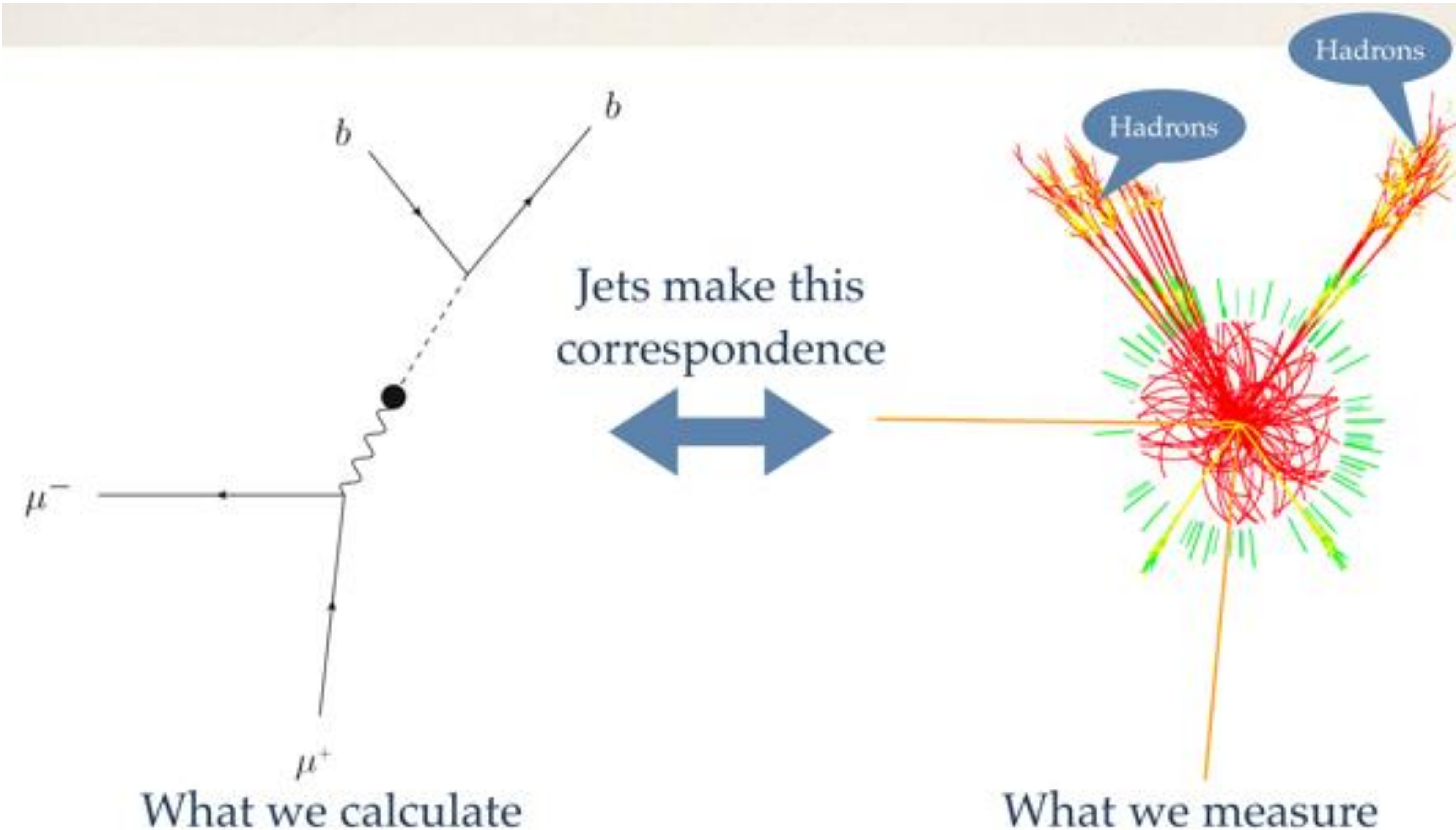
$$\frac{\mathrm{d}\sigma(\mathrm{qq}' \to \mathrm{qq}')}{\mathrm{d}t} = \frac{\pi}{s^2}\frac{4}{9}\alpha_\mathrm{s}^2\frac{s^2+u^2}{t^2}$$

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

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

i.e. Rutherford scattering!

# Parton, Jet

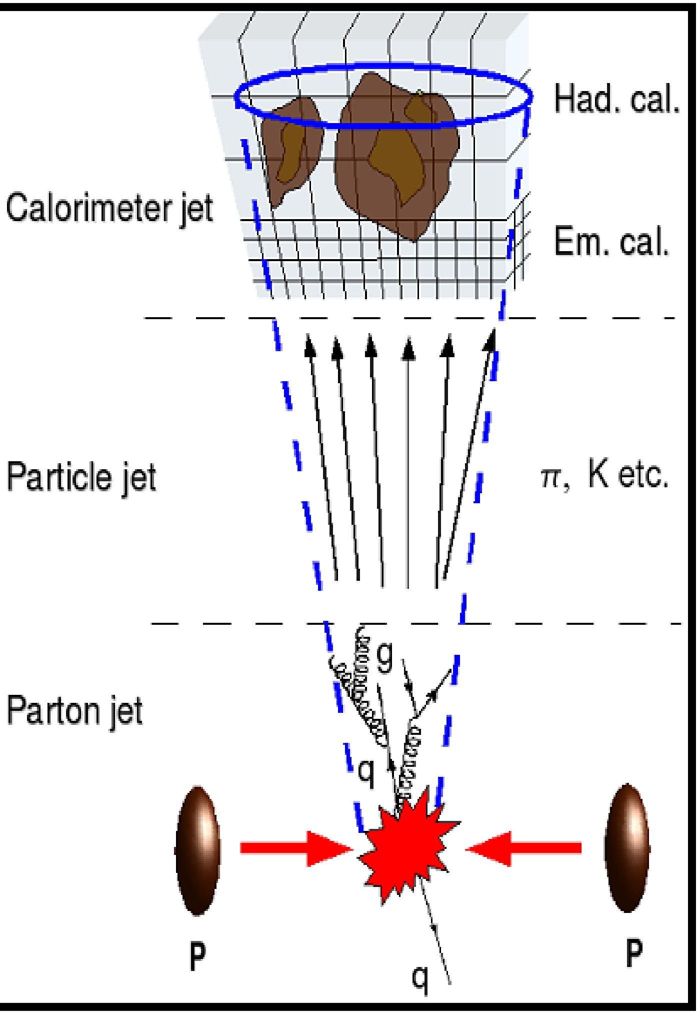


b
b
μ⁻
μ⁺
What we calculate
Jets make this correspondence
Hadrons
Hadrons
What we measure

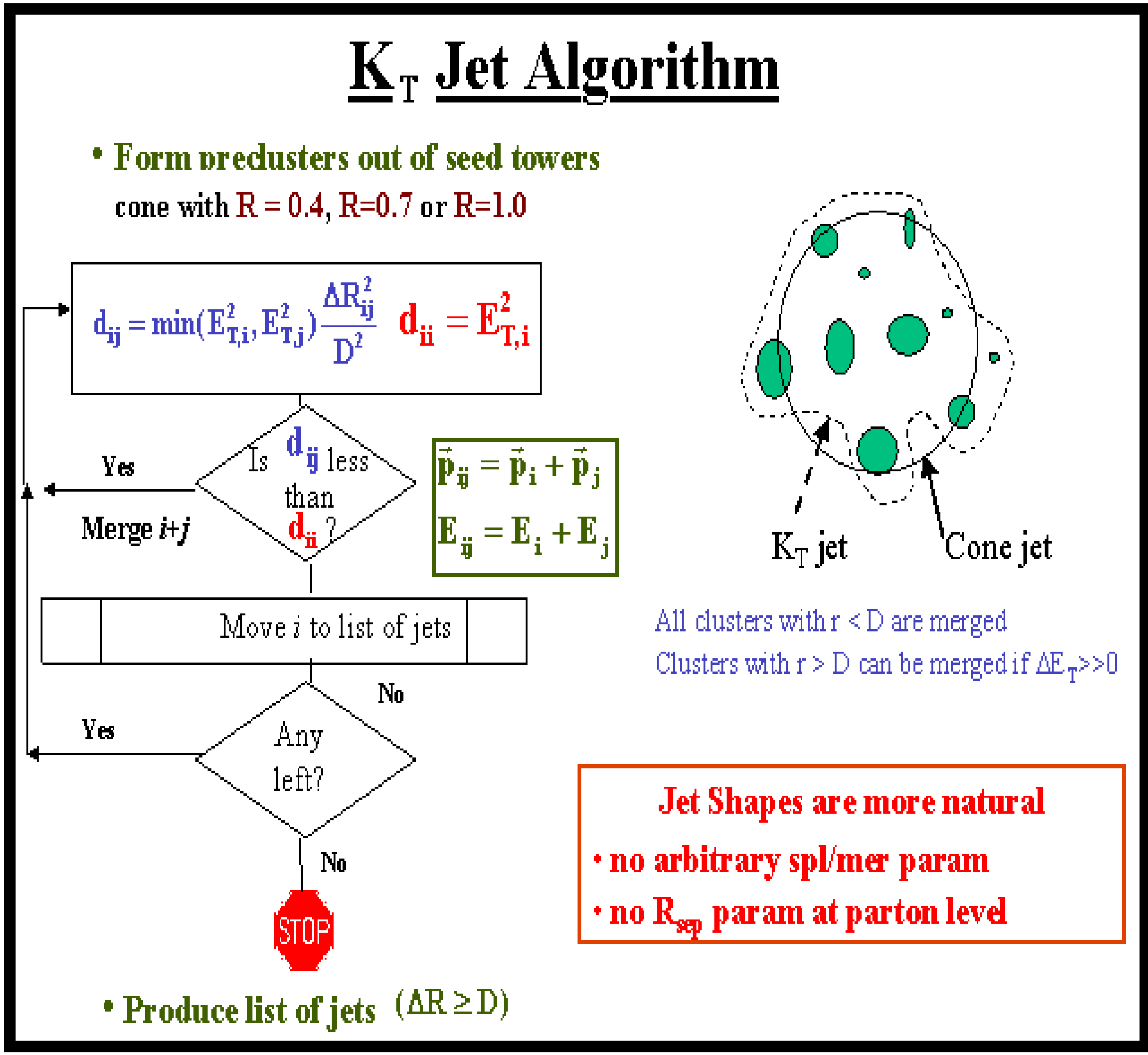
| Type of event | $N$ |
|---|---|
| $e^+e^- \to$ hadrons event on the $Z$ peak | 40 |
| HERA direct photoproduction (dijet) or DIS | 40 |
| HERA resolved photoproduction (dijet) | 60 |
| Tevatron ($\sqrt{s} = 1.96$ TeV) dijet event | 200 |
| LHC ($\sqrt{s} = 14$ TeV) dijet event | 400 |
| LHC low-luminosity 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



Had. cal.
Calorimeter jet
Em. cal.
Particle jet
π, K etc.
Parton jet
g
q
P
P
q

K_T Jet Algorithm
• Form preclusters out of seed towers
cone with R = 0.4, R=0.7 or R=1.0
$d_{ij} = \min(E_{T,i}^2, E_{T,j}^2)\frac{\Delta R_{ij}^2}{D^2}$
$d_{ii} = E_{T,i}^2$
Is $d_{ij}$ less than $d_{ii}$ ?
Yes
Merge i+j
$\vec{p}_{ij} = \vec{p}_i + \vec{p}_j$
$E_{ij} = E_i + E_j$
No
Move i to list of jets
Yes
Any left?
No
STOP
• Produce list of jets ($\Delta R \geq D$)
K_T jet
Cone jet
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

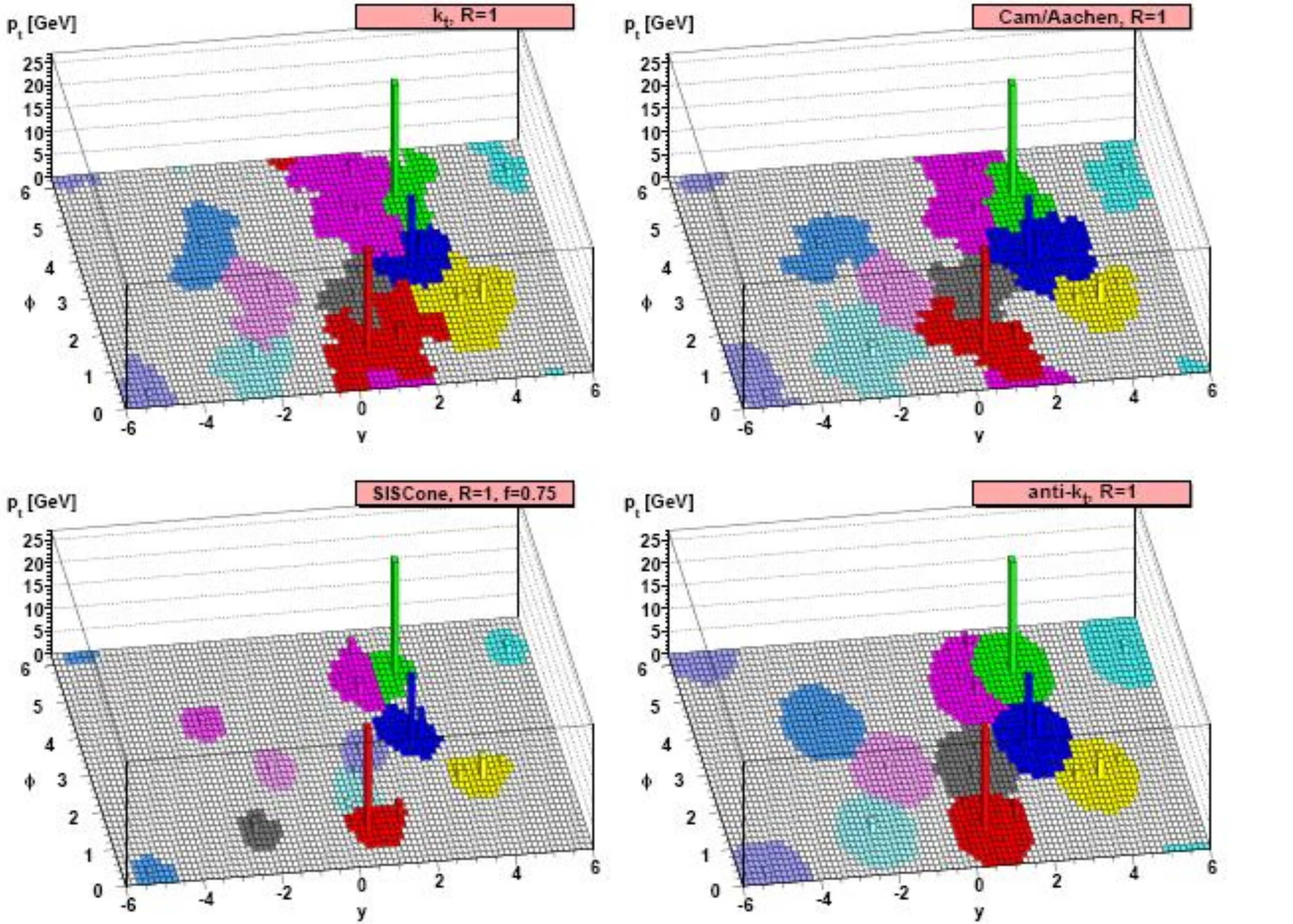
# Jet Algorithm

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

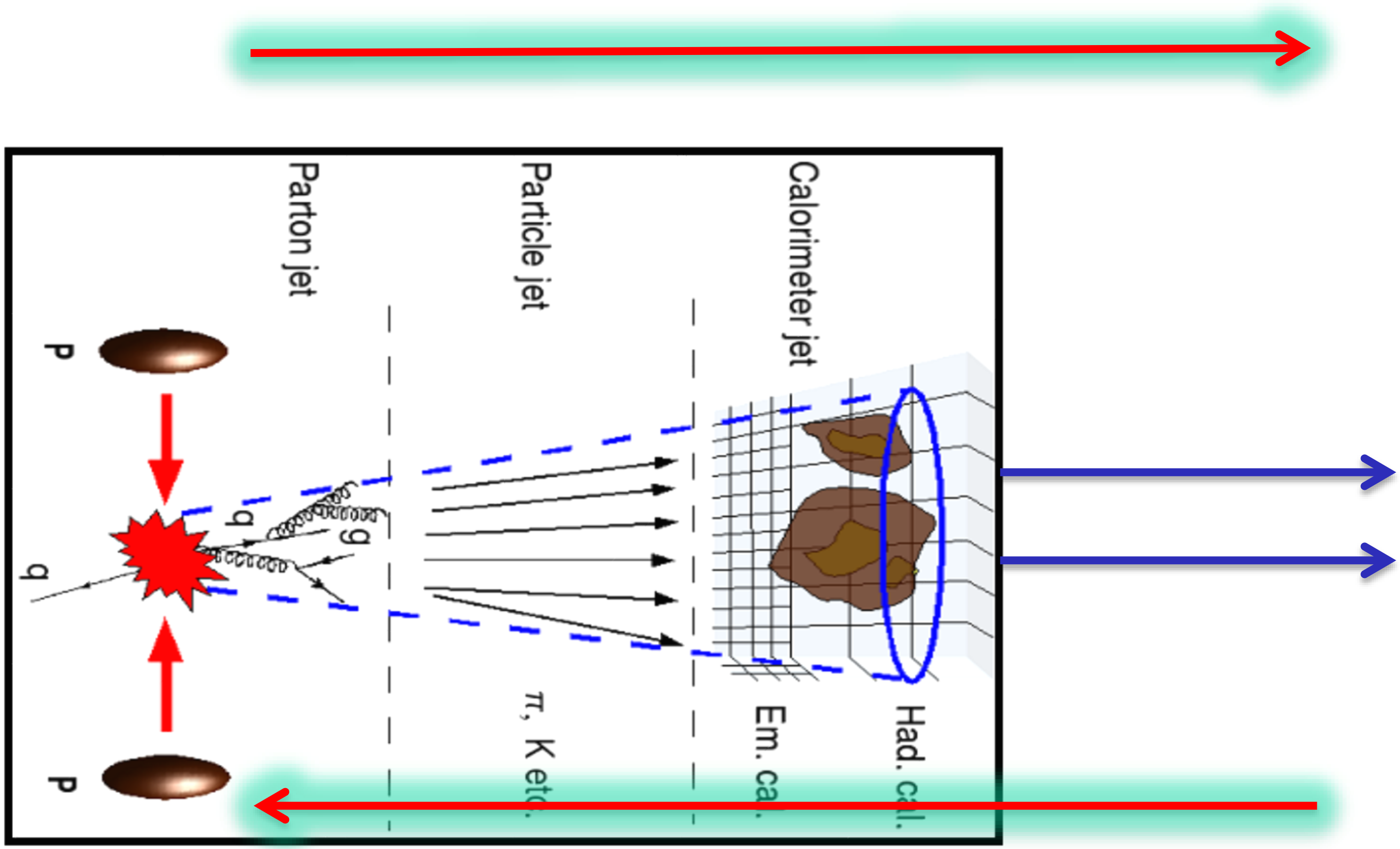
1. Work out all the $d_{ij}$ and $d_{iB}$ according to eq. (8).
2. Find the minimum of the $d_{ij}$ and $d_{iB}$.
3. If it is a $d_{ij}$, recombine $i$ and $j$ into a single new particle and return to step 1.
4. Otherwise, if it is a $d_{iB}$, declare $i$ to be a [final-state] jet, and remove it from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

**P=-1 ,0 ,1**

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

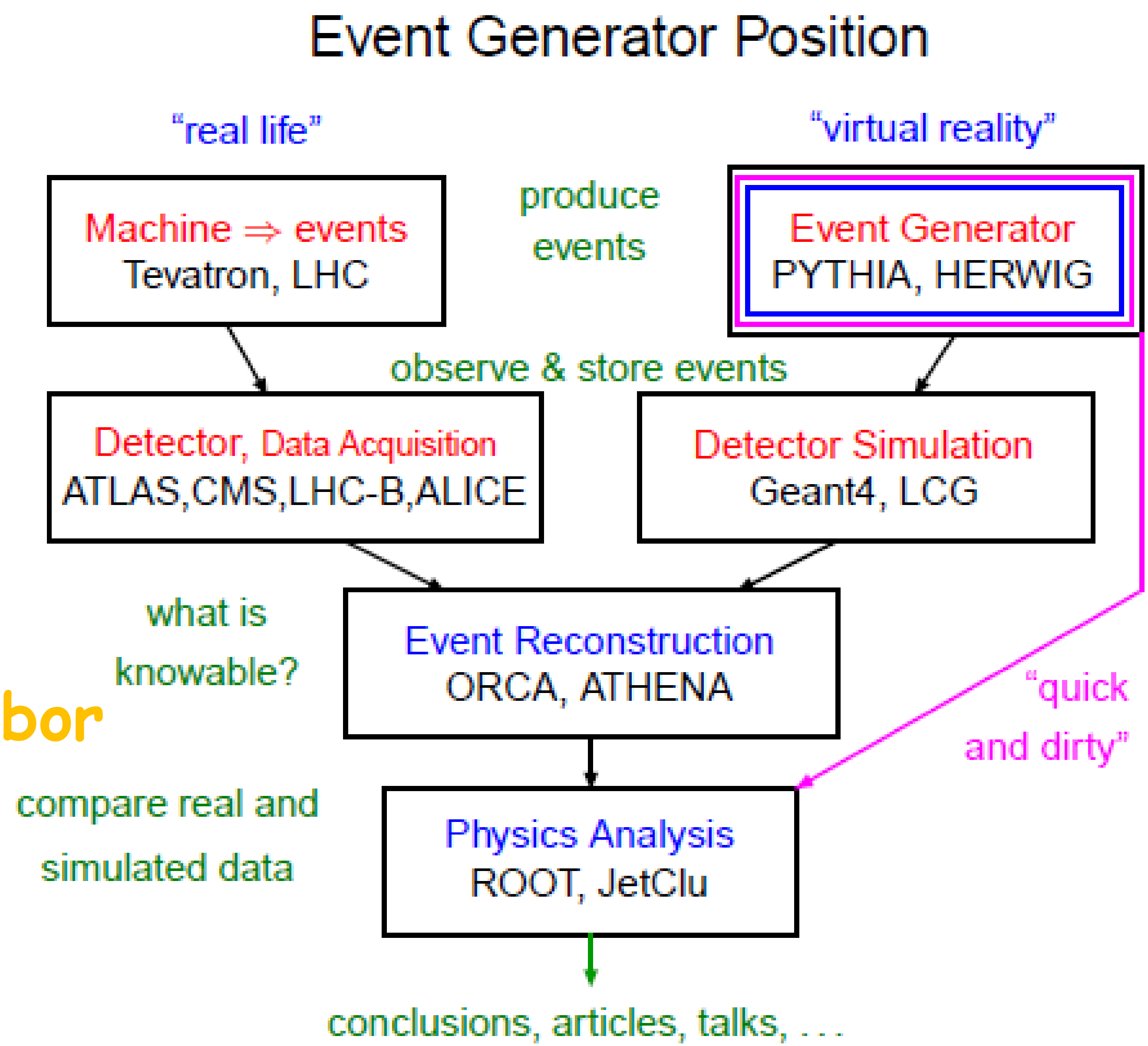

k_t, R=1
Cam/Aachen, R=1
SISCone, R=1, f=0.75
anti-k_t, R=1
p_t [GeV]
φ
y

# 4-momenta, hits/deposits, digitalize




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

# Simulation at all levels



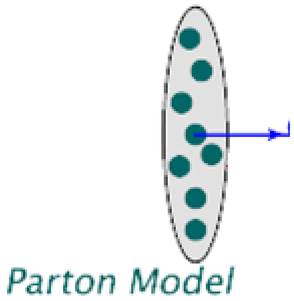

PF
Arbor

# Generator Landscape

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

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

# Parton Distribution Function



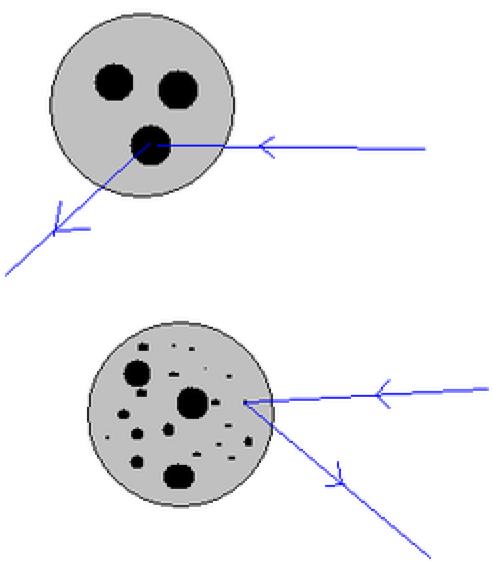

**parton interactions**

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

$x$ **is momentum fraction**

$\mu_F$ *is factorization scale*

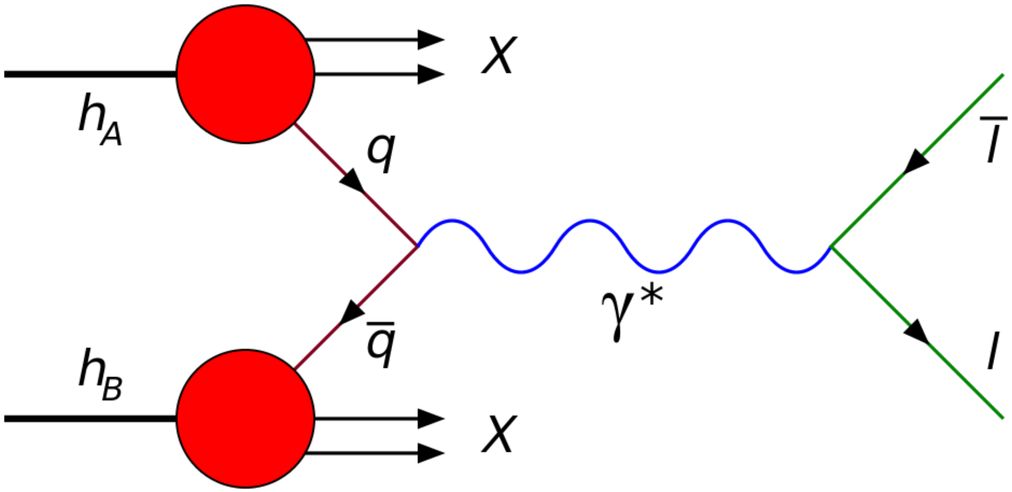
**Non-perturbative functions, from global fit**



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

# Hard Scattering:

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




**LO: Born term**

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

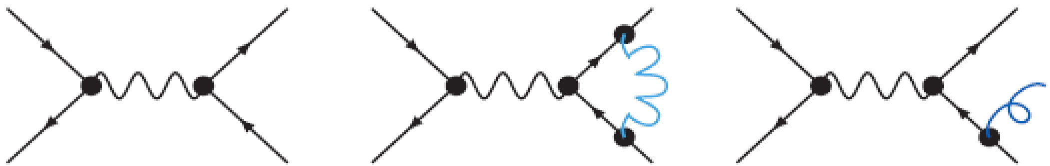
**Factorization scale** $\mu_F$

**Renormalization Scale** $\mu_r$

**Phase Space** $d\Phi_f$

# Hard Scattering:  Higher order

loops (virtual corrections) or legs (real corrections)



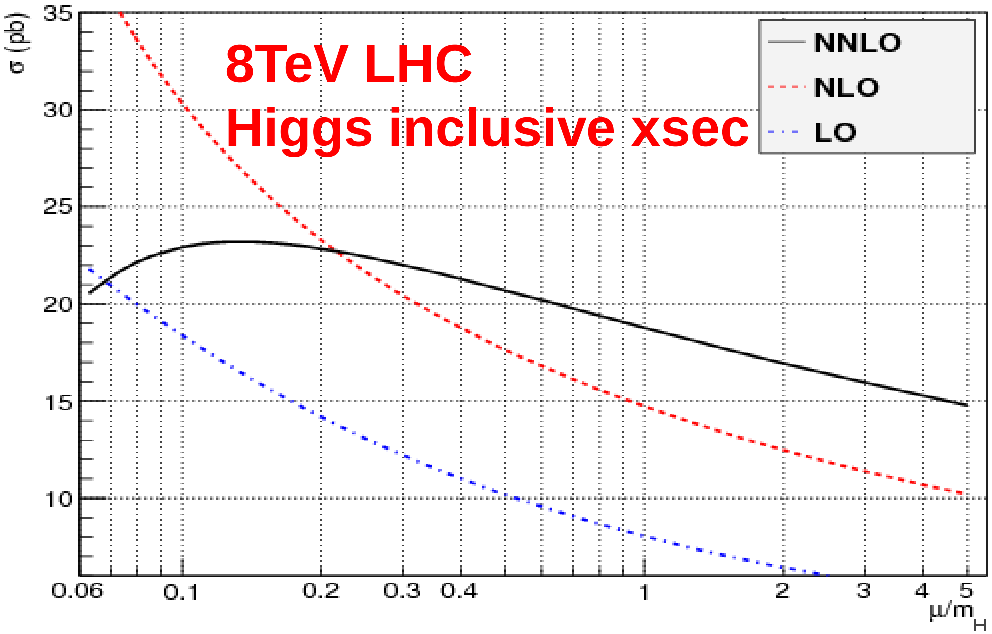
- effect: reducing the dependence on $\mu_R$ & $\mu_F$

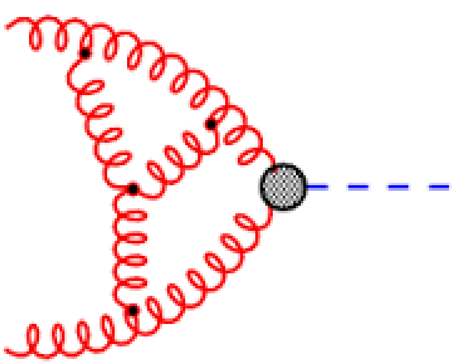
(NLO first order allowing for meaningful estimate of uncertainties)

- additional difficulties when going NLO:

ultraviolet divergences in virtual correction

infrared divergences in real and virtual correction



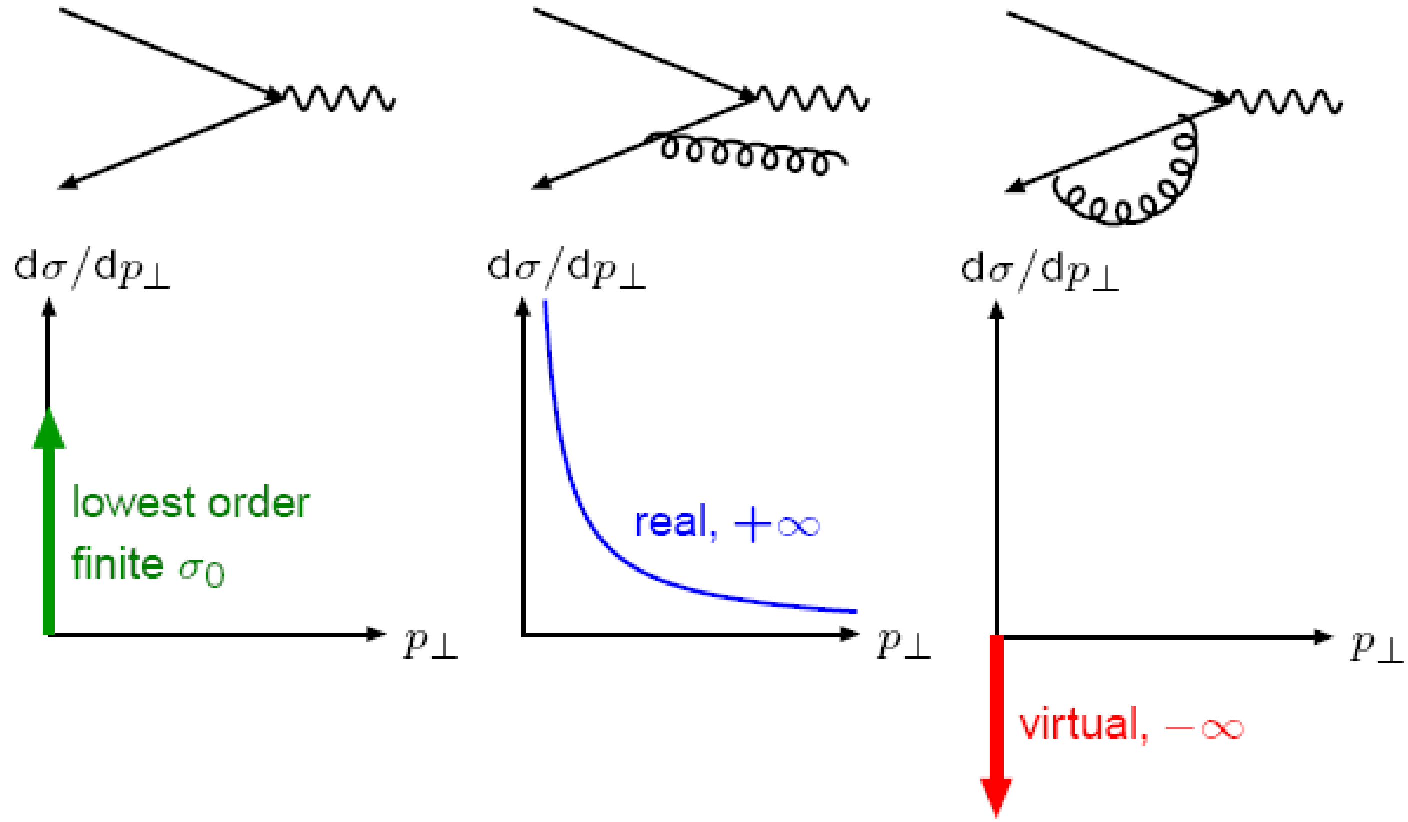



# Next-to-leading order (NLO) calculations

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

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

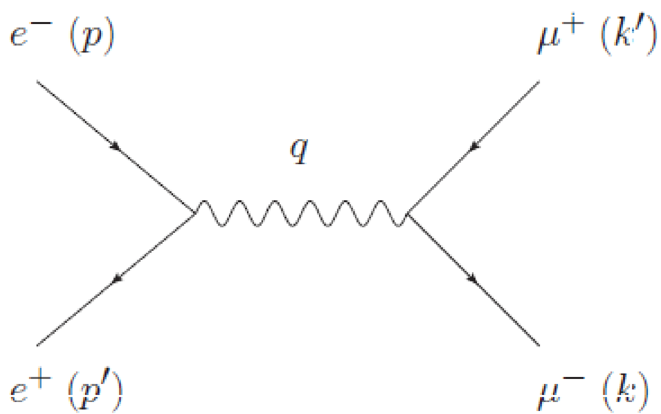
III. First-order virtual,
$\mathcal{O}(\alpha_{em}\alpha_s)$:
$q\bar{q} \to Z^0$ with loops



# 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<br>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**

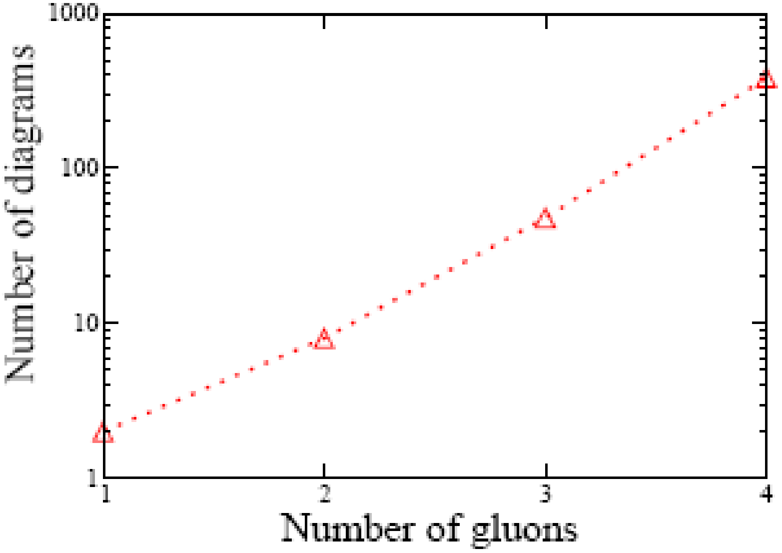
$$\frac{1}{2}\sum_s \frac{1}{2}\sum_{s'}\sum_r\sum_{r'}|\mathcal{M}|^2 = \frac{e^4}{4q^4}\mathrm{Tr}[\not{p}'\gamma^\lambda\not{p}\gamma^\nu]\mathrm{Tr}[\not{k}\gamma_\lambda\not{k}'\gamma_\nu] = \frac{8e^4}{q^4}\left[(p\cdot k)(p'\cdot k') + (p\cdot k')(p'\cdot k)\right]$$

**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 | $\#_{\text{diags}}$ |
|---|---|
| 0 | 1 |
| 1 | 2 |
| 2 | 8 |
| 3 | 48 |
| 4 | 384 |



# HELAS

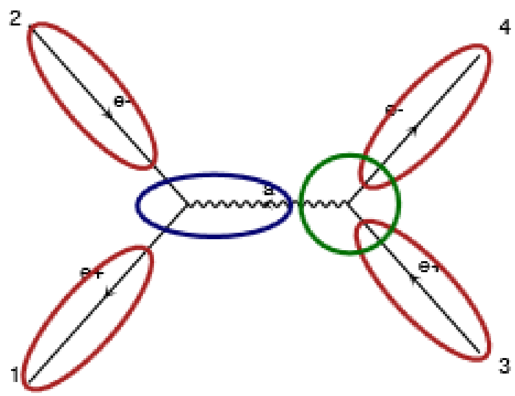
[MURAYAMA, WATANABE, HAGIWARA, 1992]

## 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 $\mu s$ | 27 $\mu s$ |
| $u\bar{u} \to d\bar{d}gg$ | 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 $\mu s$ | 83 $\mu s$ |
| $u\bar{u} \to d\bar{d}d\bar{d}g$ | 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**

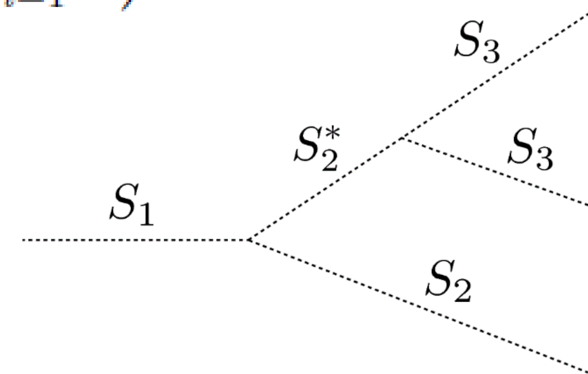
# Hard Scattering: Phase Space

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

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

**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

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

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

**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**

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

# Unweighting

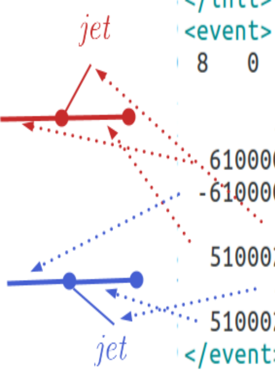
We often want events without weights as mother Nature produce

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

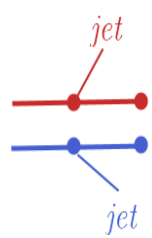
2. The phase-space point which give the maximum weight, Wmax is stored

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>
...
```



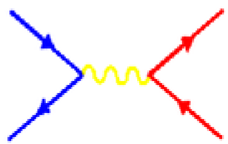

Weight: $\frac{13.448\ pb}{\#events}$

Mass Array:
$[[800\ GeV, 500\ GeV], [800\ GeV, 500\ GeV]]$

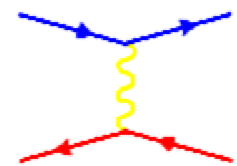
# Example: MG_aMC@NLO

## PP > Z LO & NLO

madgraph.phys.ucl.ac.be

The MadGraph5_aMC@NLO homepage



UCL UIUC Launchpad

by the MG/ME Development team

Generate Process | Register | Tools | My Database | Cluster Status | Downloads (needs account) | Wiki | Answers | Bug reports

Generate processes online using MadGraph5_aMC@NLO

# Example: PP > Z LO & NLO

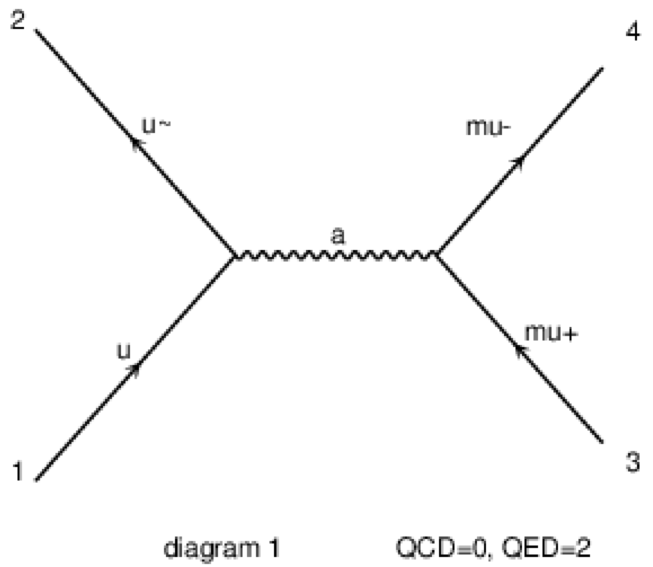
qliphy@qiangqiang: ~/Desktop/MG5_aMC_v2_3_0

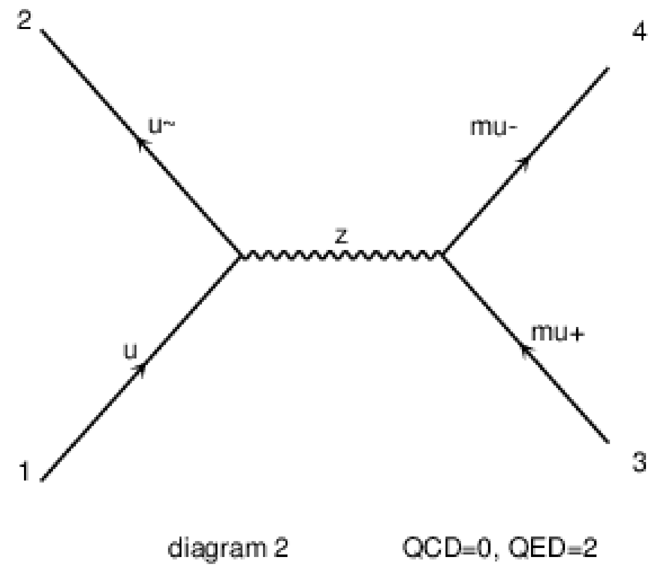
```
*         VERSION 2.3.0                    2015-07-01           *
*                                                               *
*    The MadGraph5_aMC@NLO Development Team - Find us at        *
*    https://server06.fynu.ucl.ac.be/projects/madgraph          *
*                             and                               *
*            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]
```

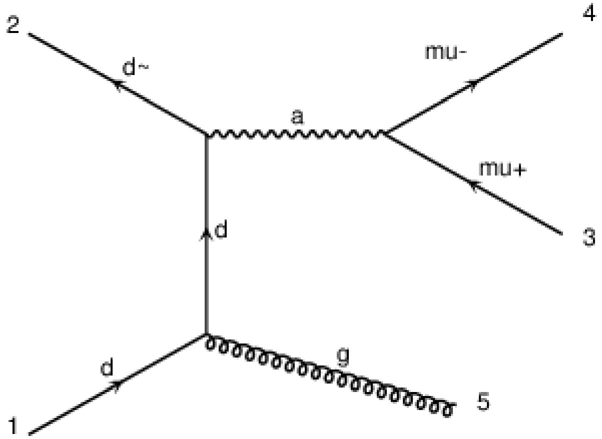
```
# Collider type and energy
#*****************************************
1     = lpp1     ! beam 1 type (0 = no PDF)
1     = lpp2     ! beam 2 type (0 = no PDF)
6500     = ebeam1   ! beam 1 energy in GeV
6500     = ebeam2   ! beam 2 energy in GeV
#*****************************************
# PDF choice: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

NLO PDF for NLO, LO PDF for LO

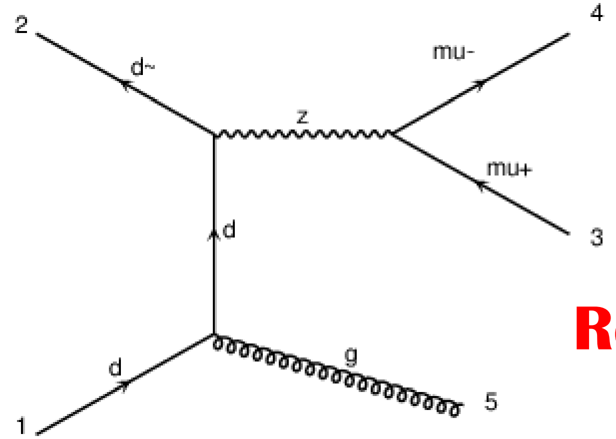
```
HERWIG6    = parton_shower
```

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**

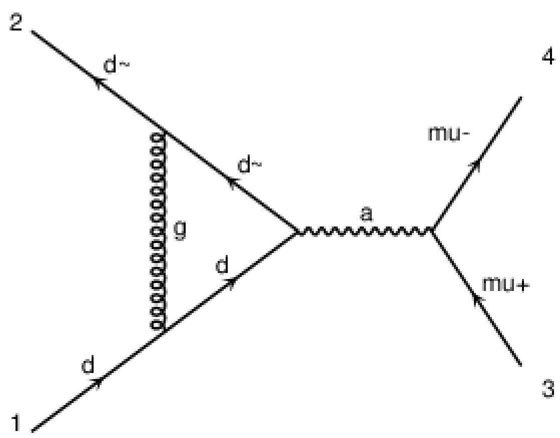



diagram 1 QCD=2, QED=2

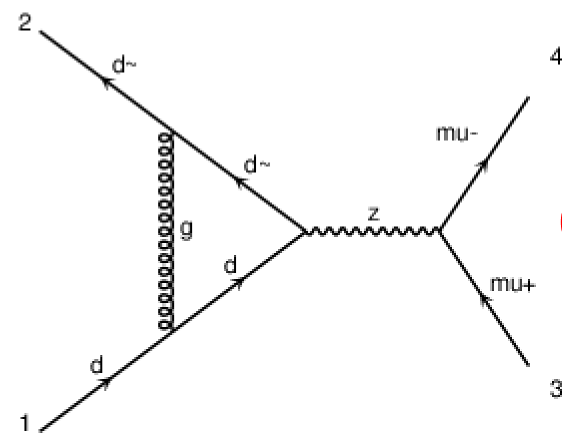



diagram 2 QCD=2, QED=2

**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>
```

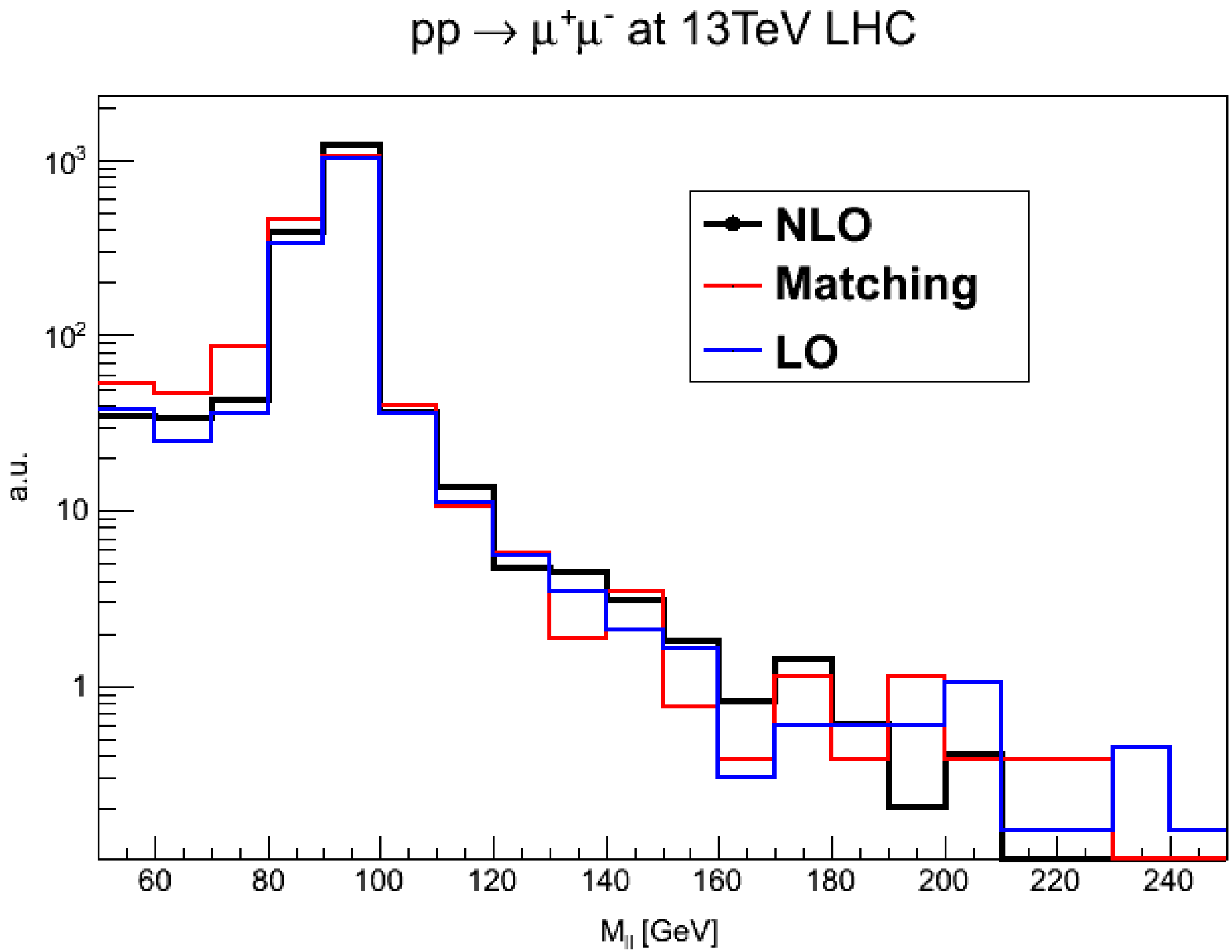
**NLO events:    negative weight**

# Example: PP > Z LO & NLO

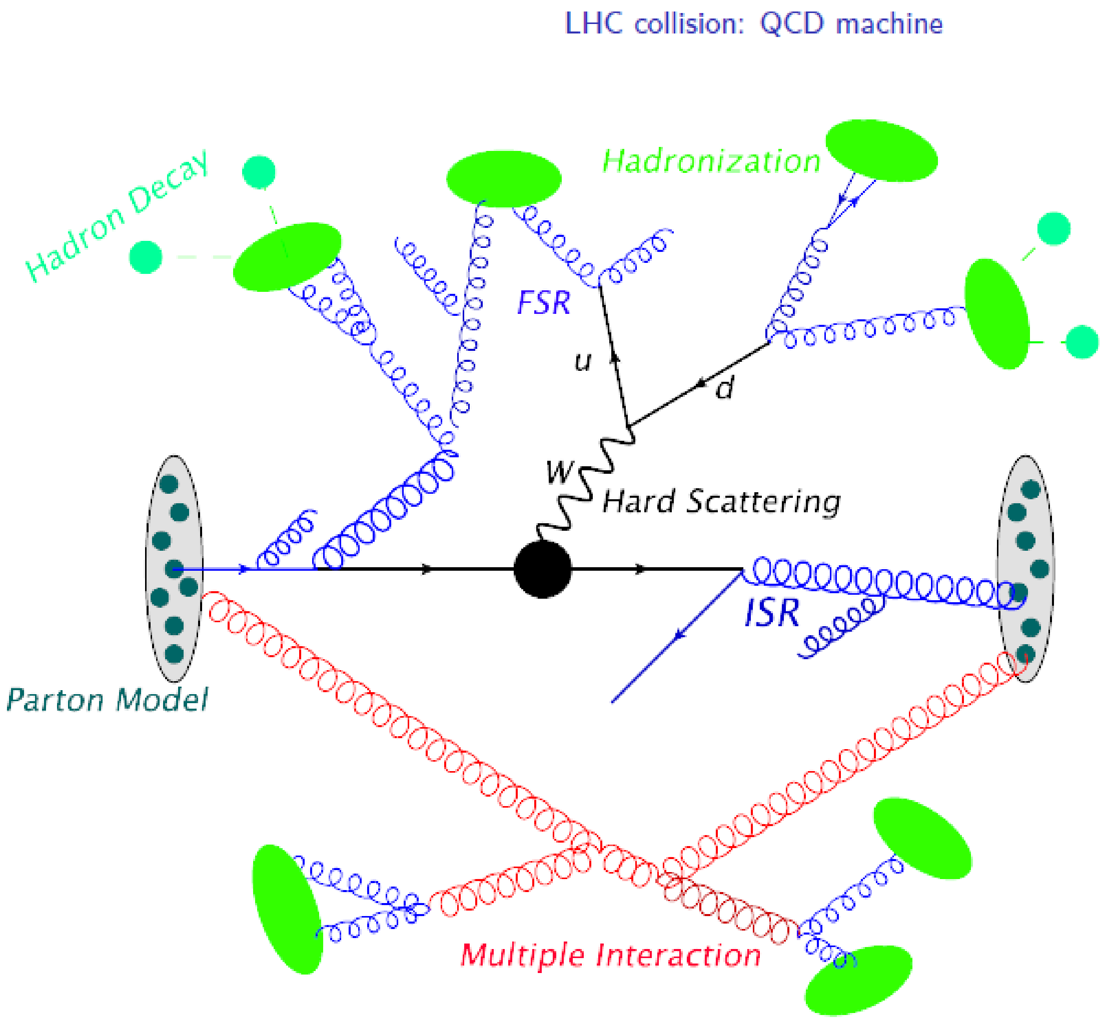
```
-rw-rw-r-- 1 qliphy qliphy     19704 Jul 25 15:59 run_02_tag_1_banner.txt
-rw-rw-r-- 1 qliphy qliphy    158832 Jul 25 15:59 alllogs_0.html
-rw-rw-r-- 1 qliphy qliphy      3426 Jul 25 15:59 res_0.txt
-rw-rw-r-- 1 qliphy qliphy    165095 Jul 25 16:00 alllogs_1.html
-rw-rw-r-- 1 qliphy qliphy      3426 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

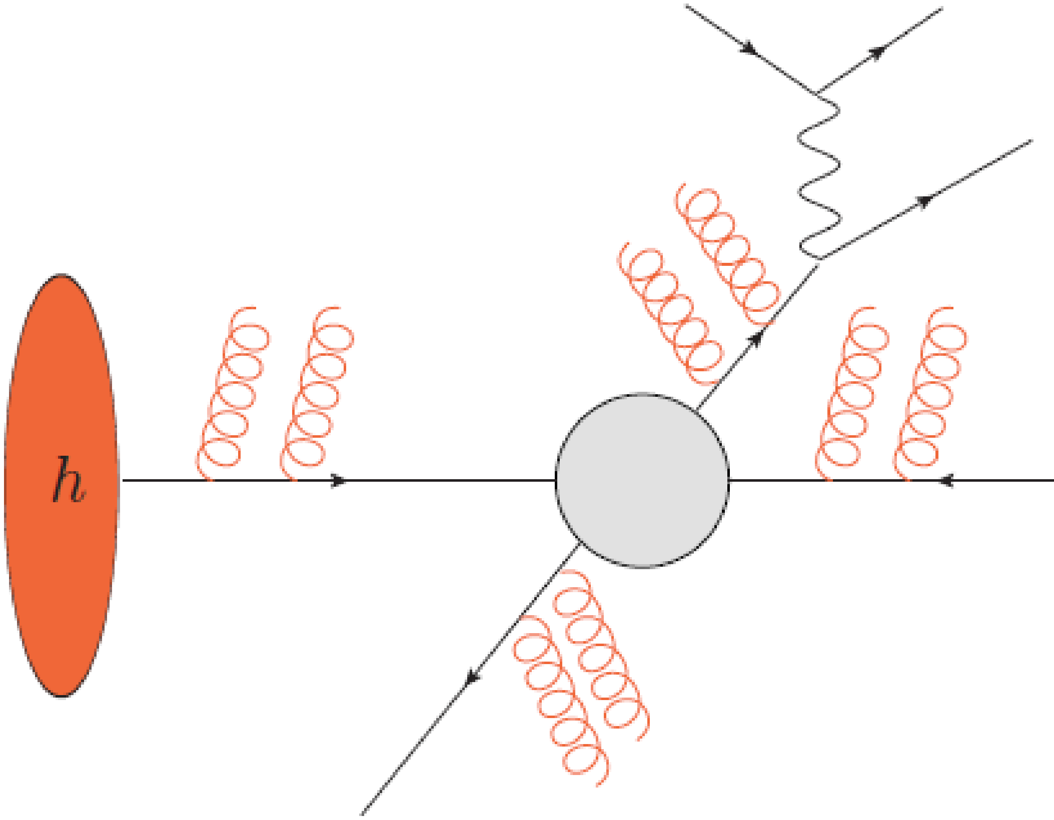


# Anatomy of a LHC Collision




**Only hard scattering by now**

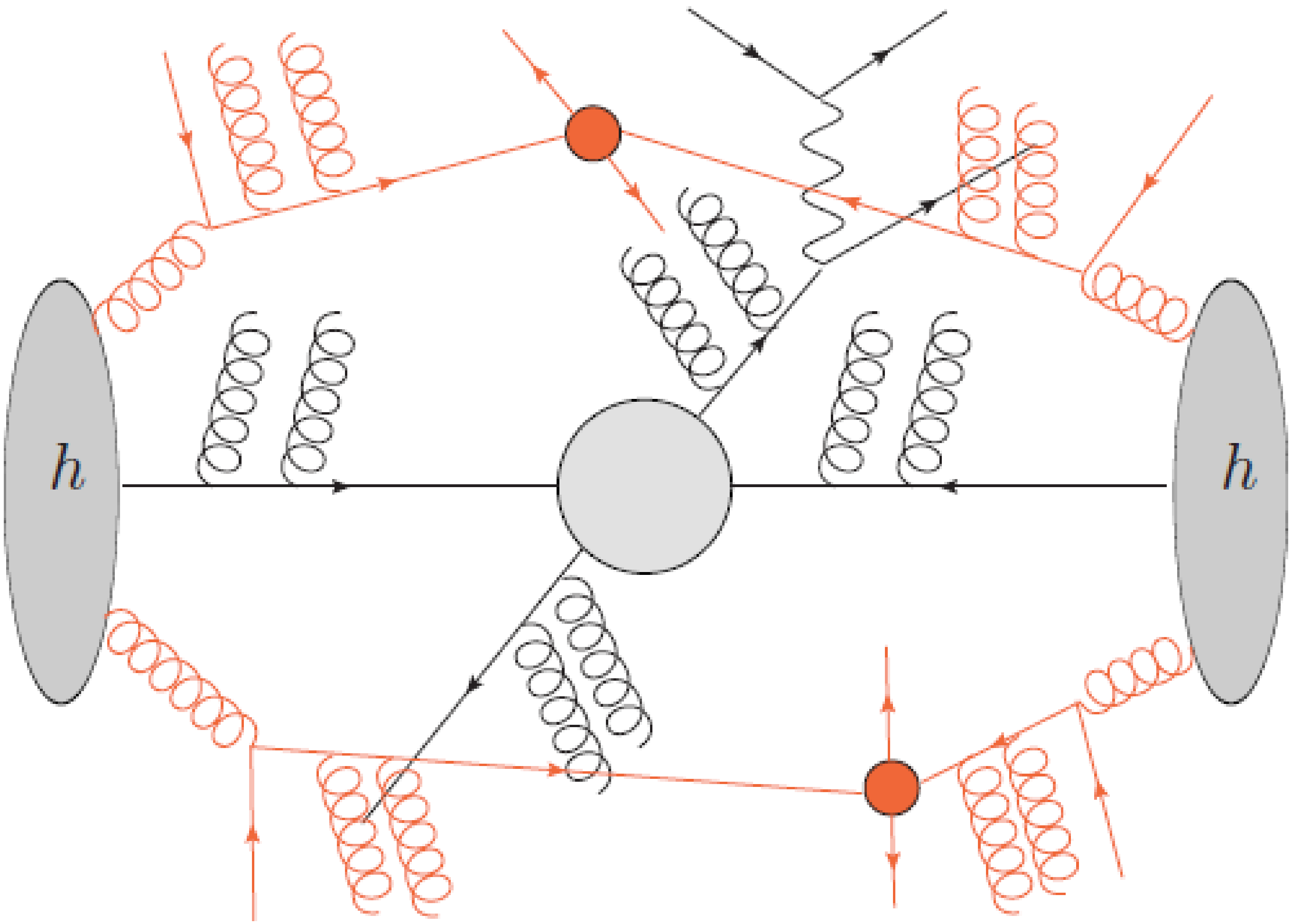
# Parton Shower



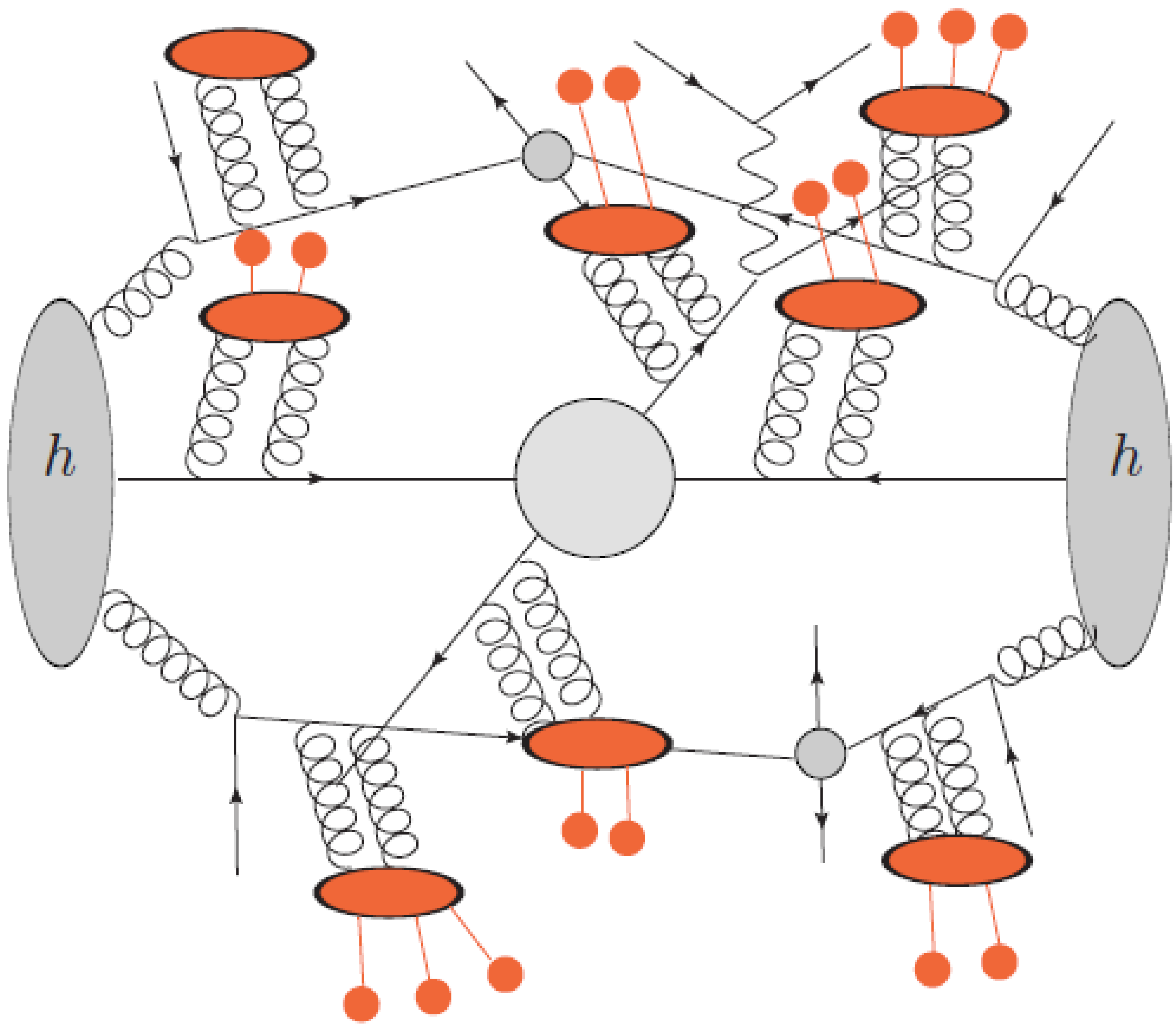

We will see a TeV quark/gluon splits all the way down to low scale

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

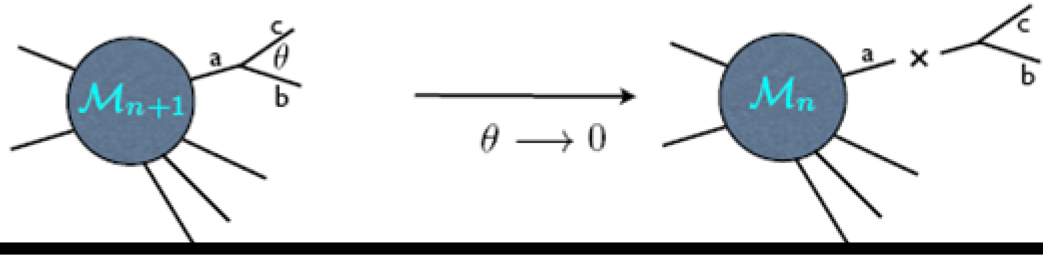
# Multiple Interactions



# Hadronization and Decay



# A bit about PS




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

where

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

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

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

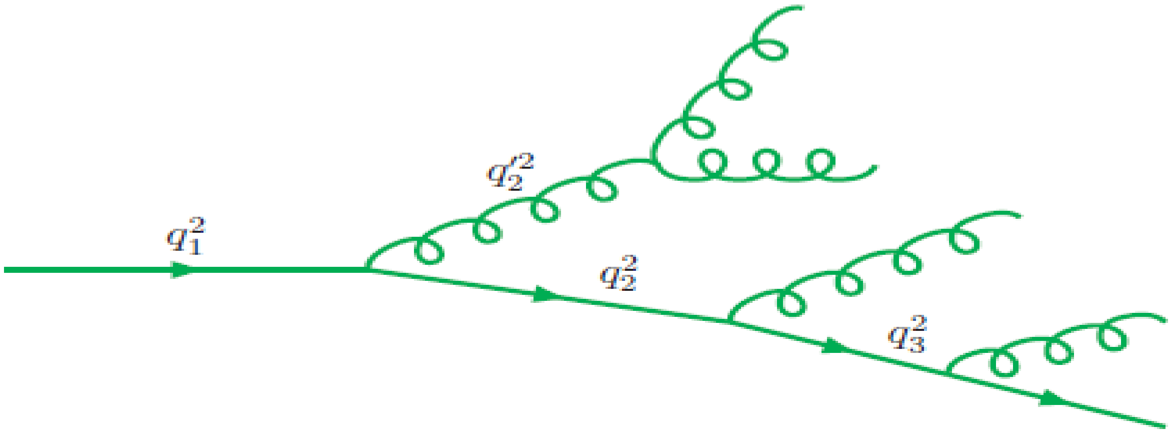
**DGLAP function**

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 $t$:

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

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

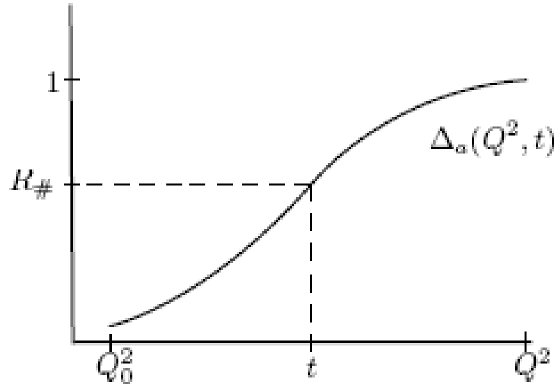
- $\Delta(Q^2, t)$ is the Sudakov form factor.
- Property: $\Delta(A, B) = \Delta(A, C)\Delta(C, B)$.

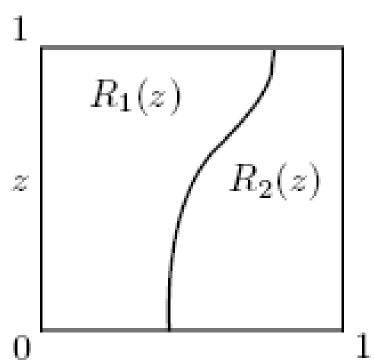
**Sudakov Factor**

# 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 $\phi$ (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: $t = (p_b)^2_\perp$.

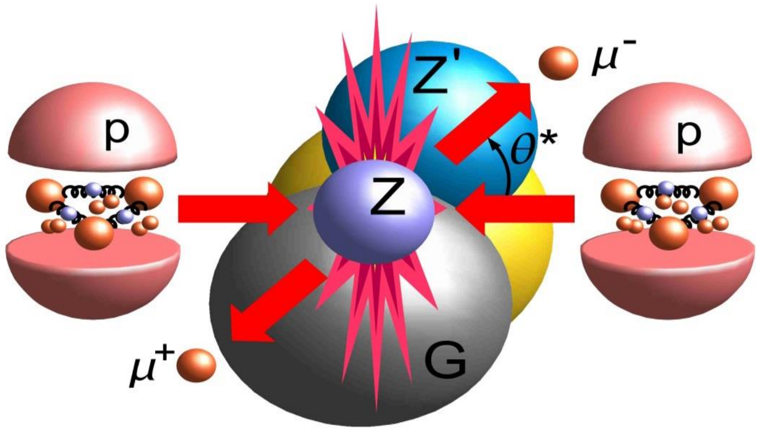
Simpler variables, but decreasing angles not guaranteed: PYTHIA has to reject the events that don't respect the angular ordering (though this is not completely equivalent to ordering in angle).

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.

# CMS MC Simulation Overview




– **Hard process/Matrix Element generation**:
  Desired process up to parton level
  using perturbative QCD

– **Parton Shower/Hadronization**:
  QCD and QED emissions down to a low scale,
  and produces hadrons from QCD partons

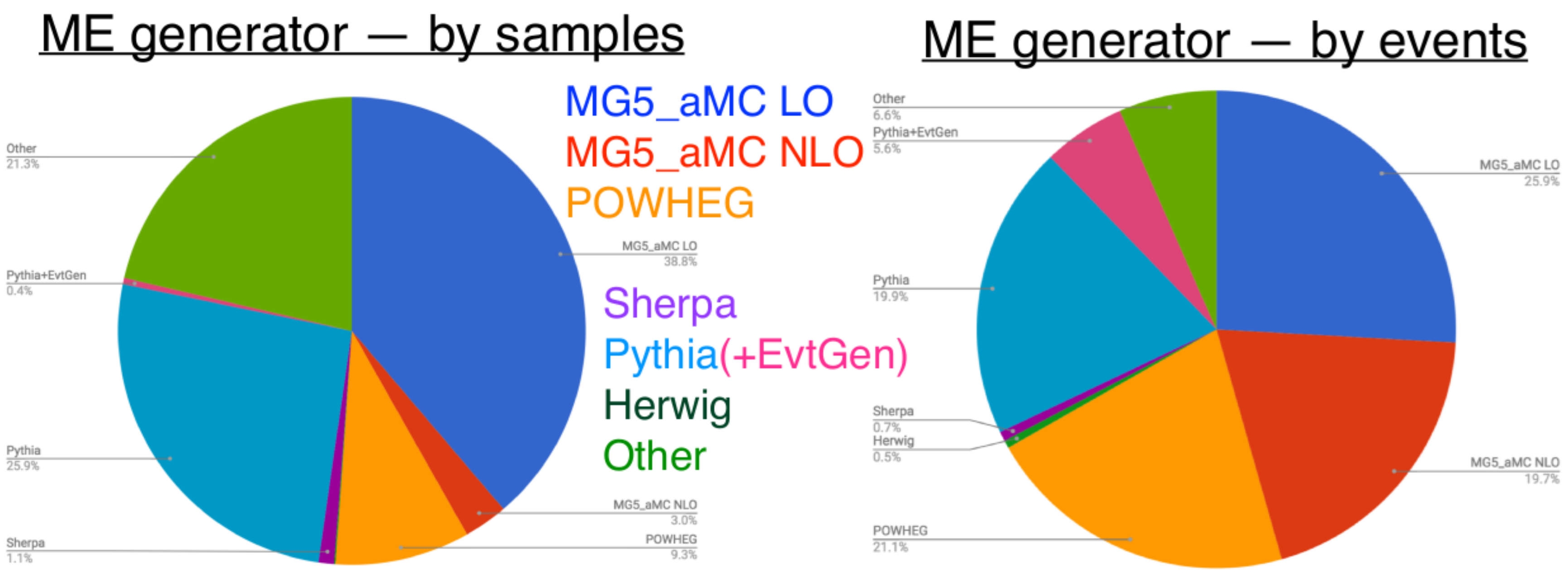
– *Multiple Parton Interaction*

– *Detector Simulation and Digitization*:
  Detailed Geant4 simulation of the interactions of the outgoing particles with the CMS detector, followed by simulation of detector electronics and creation of simulated raw data

– *Reconstruction*:
  Reconstruction of simulated raw data into higher level physics objects
  To a good approximation, identical code as runs on real data

**IN CMS Jargon: LHE –> GEN–> SIM–> DIGI–> RECO**

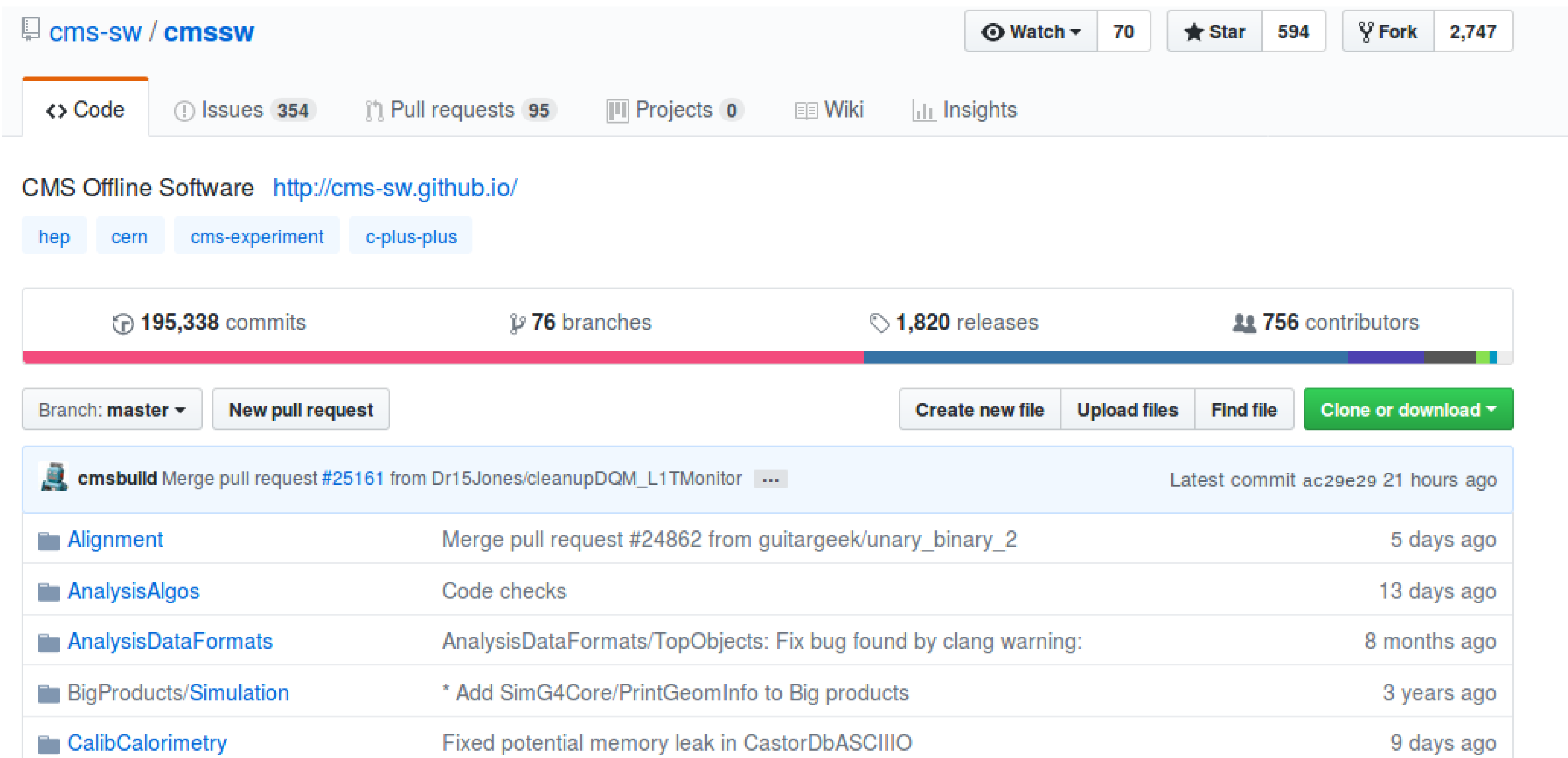
# Generator Usage in CMS




***Approximate and based on 2016 MC campaign***

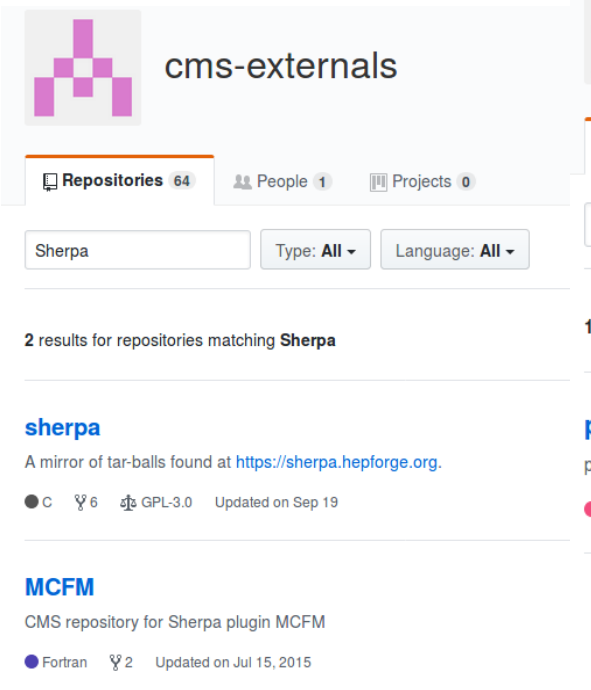
# CMS Software

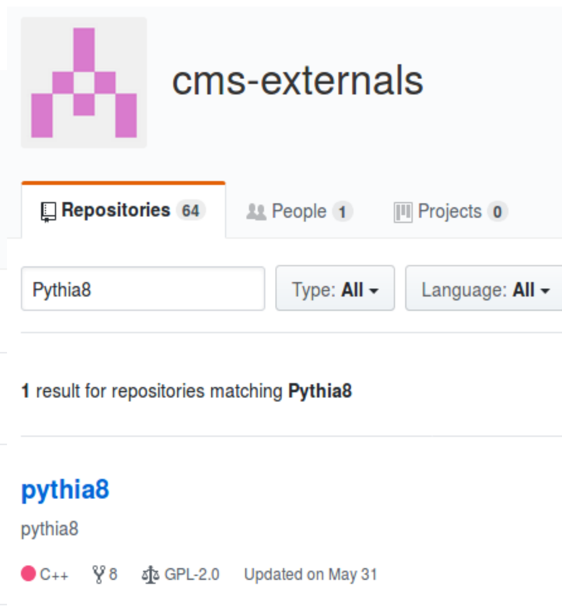
- **Main CMS software application: CMSSW**
  – Modular C++ application used for event generation, detector simulation, reconstruction, and analysis
- **Configuration of CMSSW runs steered with python configuration files**
- **Input and output with ROOT-based Event Data Model (EDM) files**
  – Storing run-, lumi-section-(23s periods for real data), or event-level data products



# CMS Software

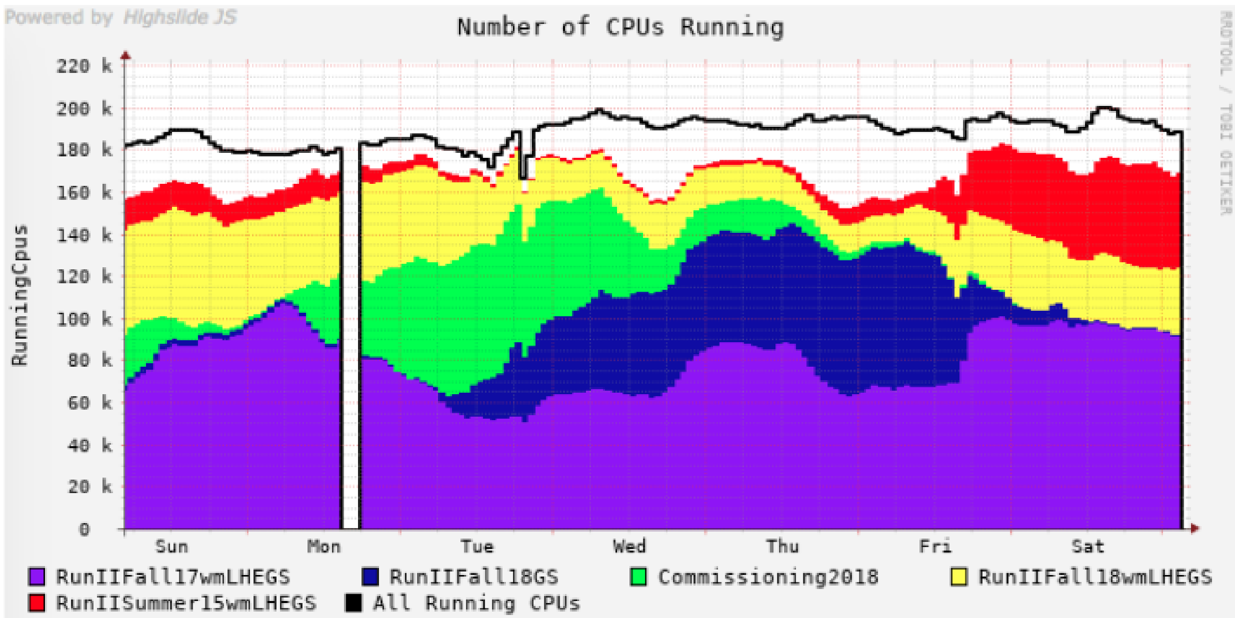
- **CMSSW links directly to many externals**
  - Either an indirect dependency or is directly called from within CMSSW
  - ***Compiled with the same common libraries***, as CMSSW and packaged together with a given release
  - From either a tarball from the author's website, GENSER, or a cms-managed github mirror




**CMSSW software and externals are made available on worker nodes through CVMFS – a network file system based on HTTP**

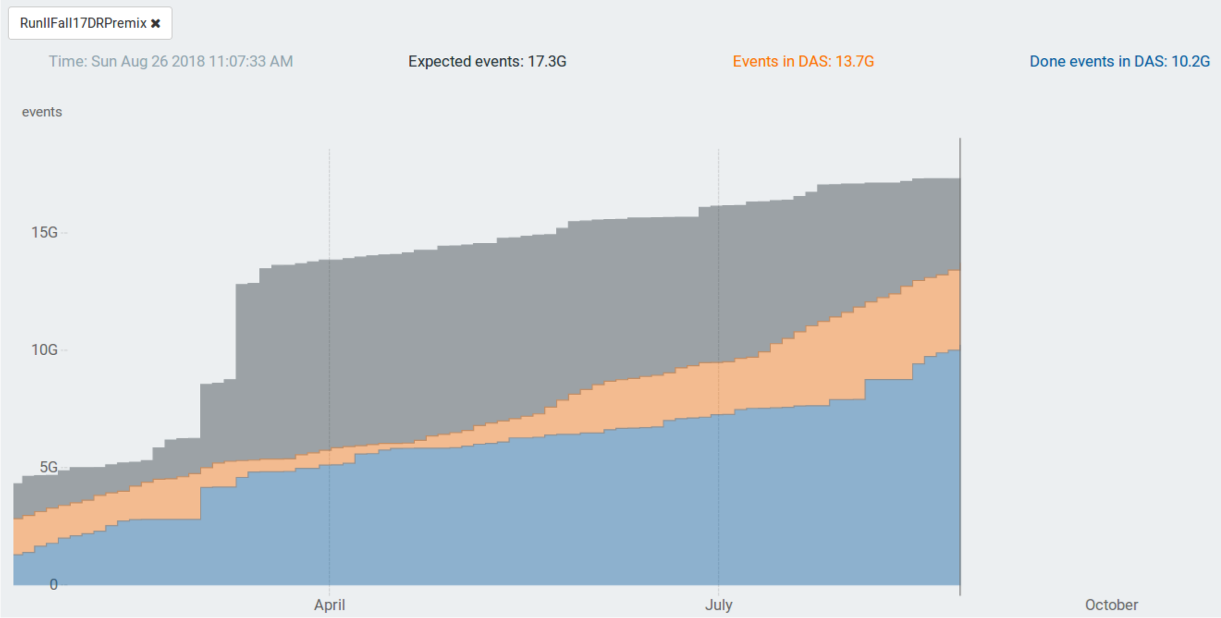
# CMS MC Production Status




| | Max | Avegage | Min | Current |
|---|---|---|---|---|
| All Running Cpus | 200852 | 184808 | 0 | 0 |
| RunIIFall17wmLHEGS | 107174 | 77841 | 0 | 0 |
| RunIIFall18GS | 67541 | 25083 | 0 | 0 |
| Commissioning2018 | 66891 | 19301 | 0 | 0 |
| RunIIFall18wmLHEGS | 54306 | 28947 | 0 | 0 |
| RunIISummer15wmLHEGS | 49421 | 13149 | 0 | 0 |

- Major Campaigns sharing the computing resources

# CMS MC Production Status




**Multi-leg LO**

- up to ~10s/gen-evt
- ~50% matching efficiency -> 20s/full-sim-evt

**Multi-leg NLO**

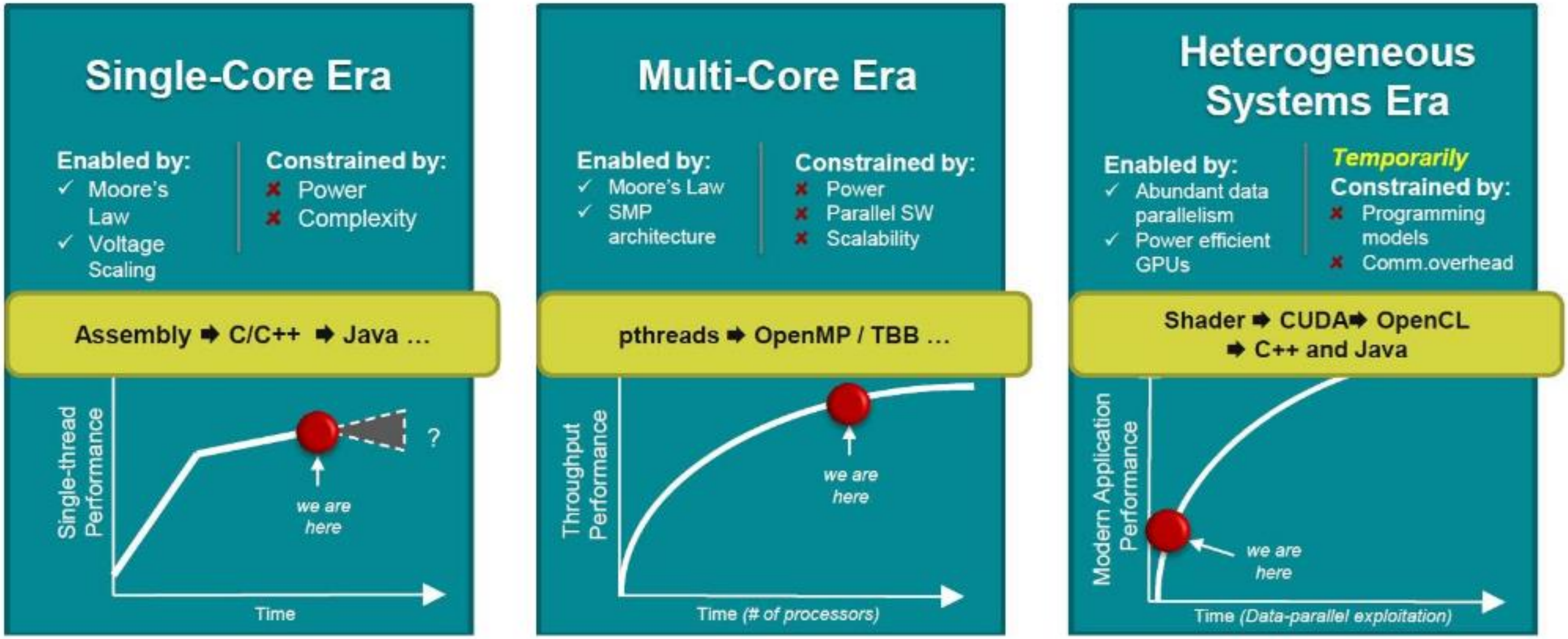
- up to ~30s/gen-evt
- ~30% matching efficiency -> 100s/full- sim-evt

**Taking 2017 as an example:**
**15 B (+ some other production ~ 20 B) in 8 months**

- **GEN-SIM-DIGI-RECO** ~85 sec/evt
- **60k cores** (~1/3 of the CMS production power)

- Large fraction of negative weights of up to ~40% -> larger samples!

# **The Future :** Heterogeneous Architecture




https://opensourceforu.com/2016/12/how-heterogeneous-systems-evolved-and-the-challenges-going-forward/

**The computing available in 2026 will be heterogeneous and highly concurrent.** **d**ifferent types of compute units and interconnects