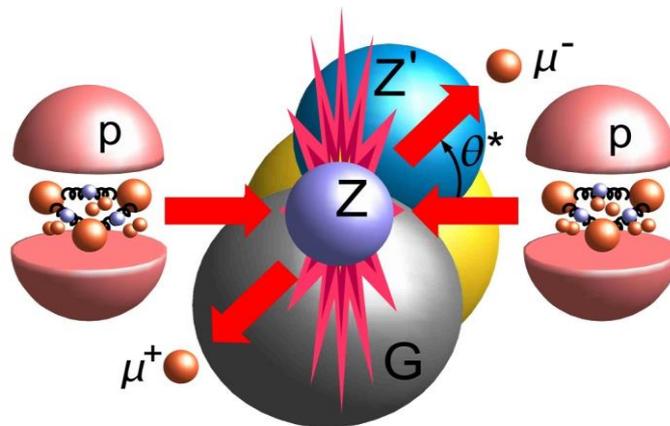


# 对撞机蒙特卡洛模拟： MadGraph

## 2021对撞机唯像学暑期学校



李强 北京大学物理学院技术物理系  
qliphy0@pku.edu.cn



# Caveats

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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/>

**MadGraph School Shanghai 2015**

MadGraph School on Collider Phenomenology

**November 23-27, T-D Lee Library, SJTU**



## Main generators:

Generator
<a href="#">Pythia6</a>
<a href="#">Pythia8</a>
<a href="#">MadGraph5_aMCatNLO</a>
<a href="#">POWHEG</a>
<a href="#">SherpaNLO</a>

Package
<a href="#">LHAPDF</a>

<a href="#">Photos</a>
<a href="#">EvtGen</a>
Particle Guns
<a href="#">Tauola++ and TauSpinner</a>

## Other generators which could be of interest:

Generator
<a href="#">Herwig6</a>
<a href="#">ThePEG</a> (for Herwig++)
<a href="#">ALPGEN</a>
<a href="#">MC@NLO</a>
<a href="#">gg2VV</a>
<a href="#">Phantom</a>
<a href="#">Hydjet</a>
<a href="#">Hydjet++</a>
<a href="#">Pyquen</a>
<a href="#">Cosmic Muon Generator</a>
<a href="#">ExHuME</a>
<a href="#">Pomwig</a>
<a href="#">BCVEGPY</a>
<a href="#">HARDCOL</a>
<a href="#">PHOJET</a>
<a href="#">Regge-Gribov Generators (EPOS, QGSJetII, Sibyll)</a>
<a href="#">CASCADE</a>
<a href="#">Herwig++</a>

Generator
<a href="#">CompHEP</a>
<a href="#">TopRex</a>
<a href="#">Charybdis</a>
<a href="#">EDDE</a>
<a href="#">HELAC</a>

# Outline

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- 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

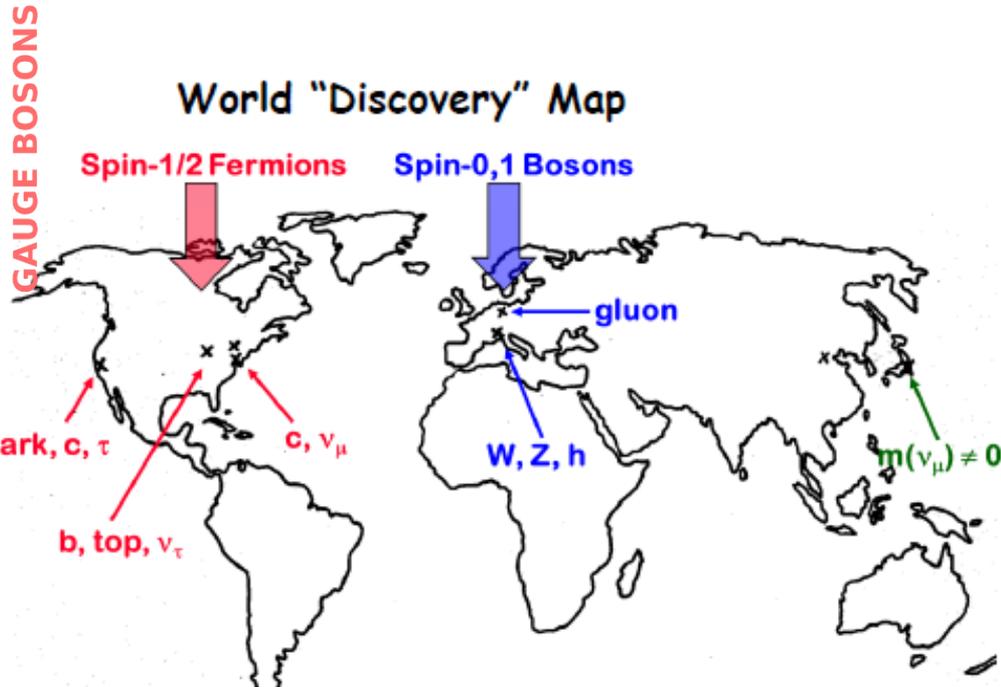


mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	$2/3$	$2/3$	$2/3$	0	0
spin →	$1/2$	$1/2$	$1/2$	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> Higgs boson
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson	

**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**



# QED vs QCD



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

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

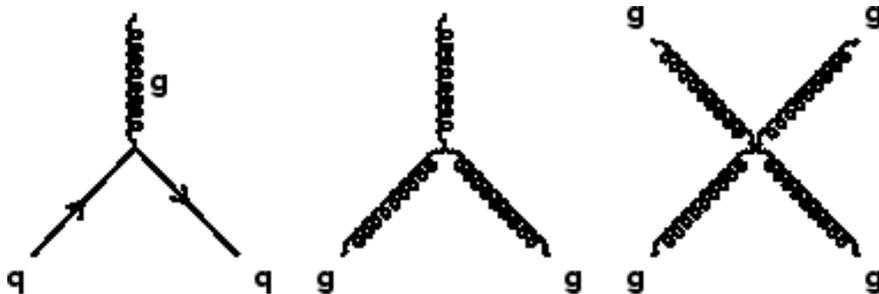
$$\alpha_{em} = \frac{e^2}{4\pi} \sim \frac{1}{137}$$

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

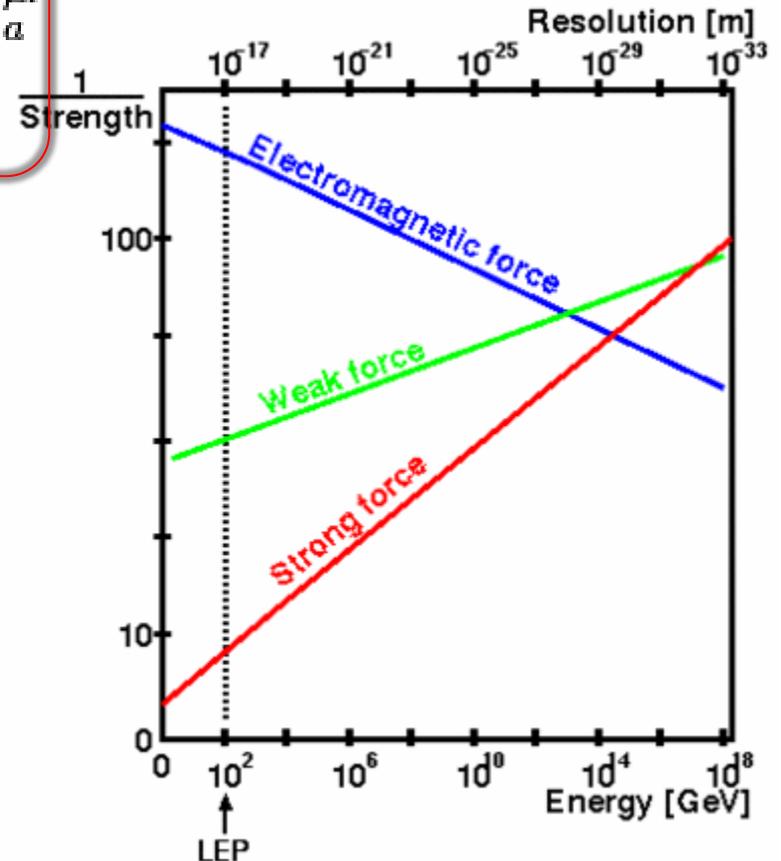
$$\mathcal{L}_{QCD} = \bar{\psi}_i (i(\gamma^\mu D_\mu)_{ij} - m \delta_{ij}) \psi_j - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}$$

$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf^{abc} A_\mu^b A_\nu^c,$$

**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



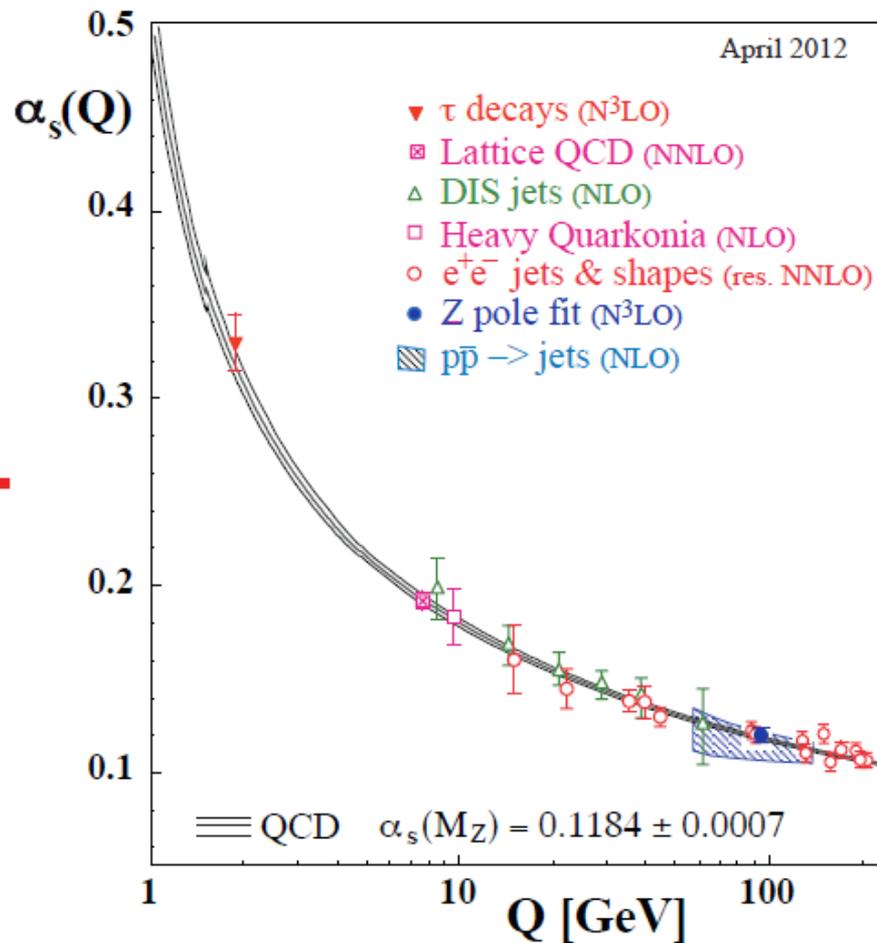
H. David Politzer  
Prize share: 1/3



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

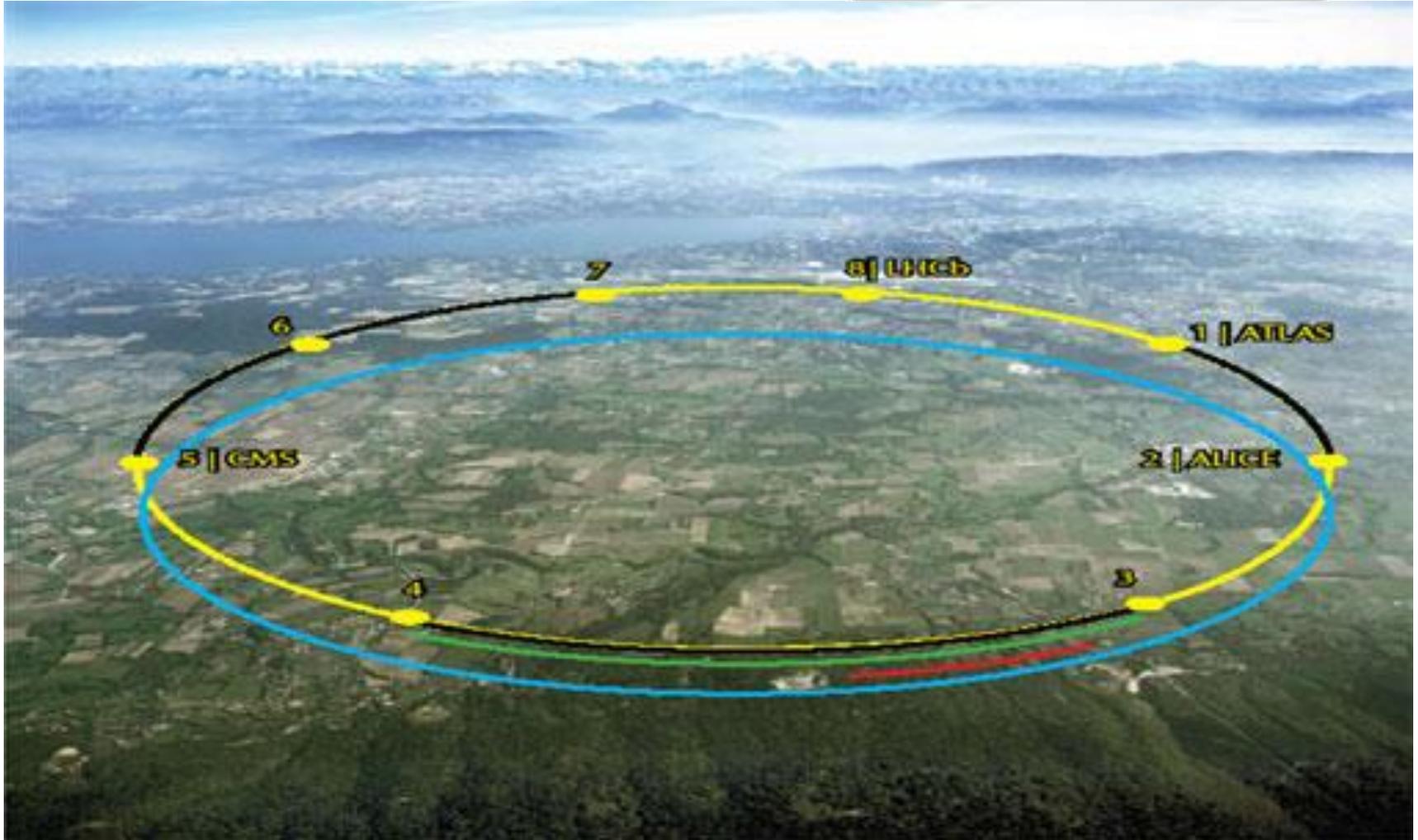
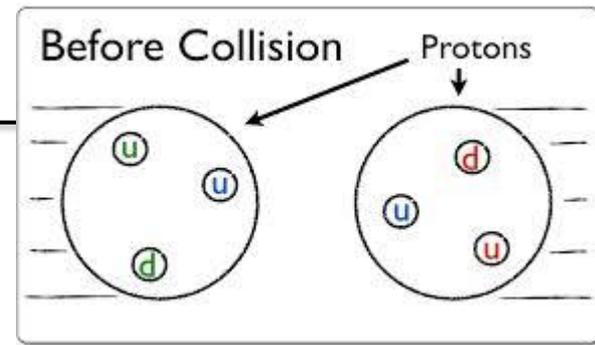
Asymptotic Freedom  
& Grand Unification?

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

# Collider



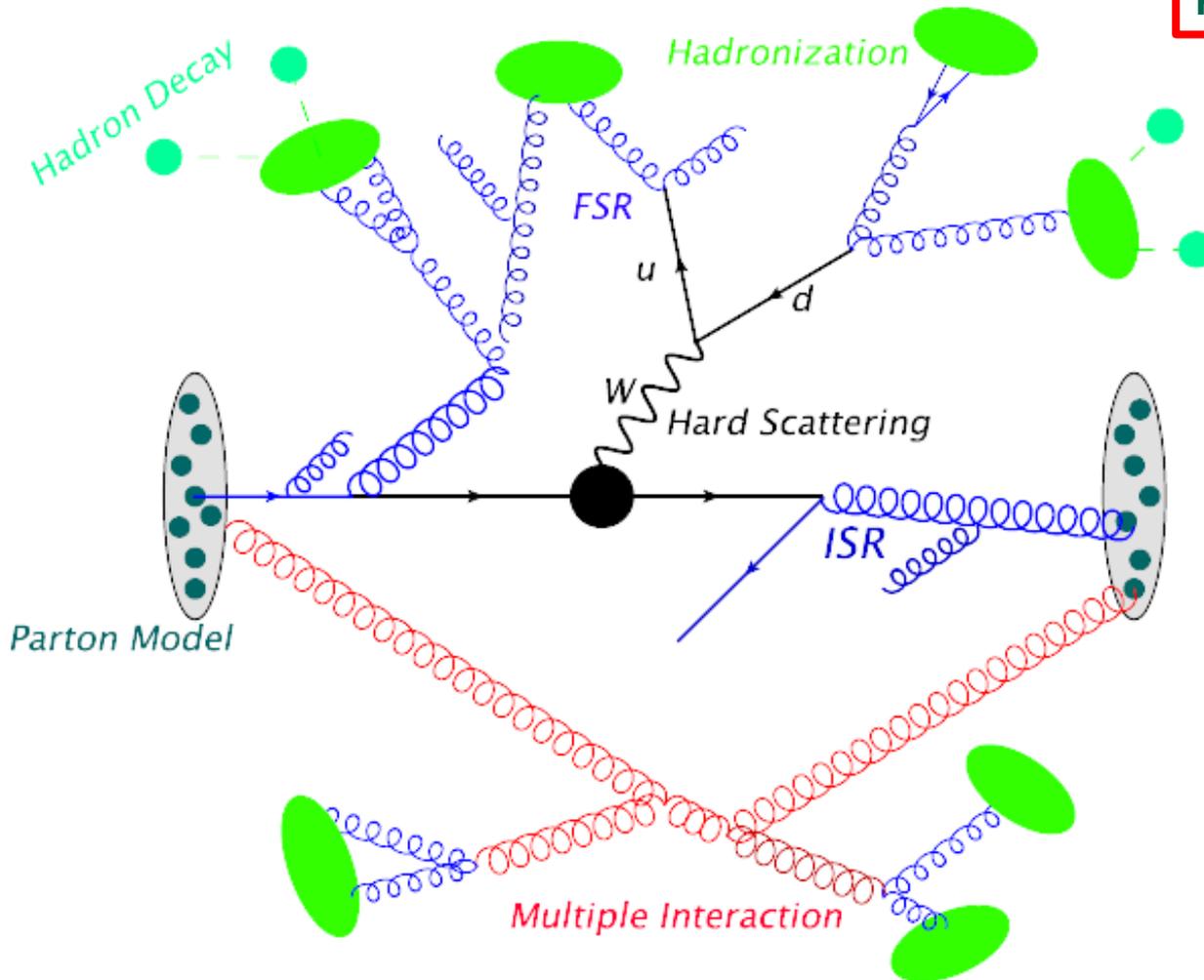
$1\text{ fm} \sim 5\text{ GeV}^{-1}$



# Anatomy of a LHC Collision



LHC collision: QCD machine



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

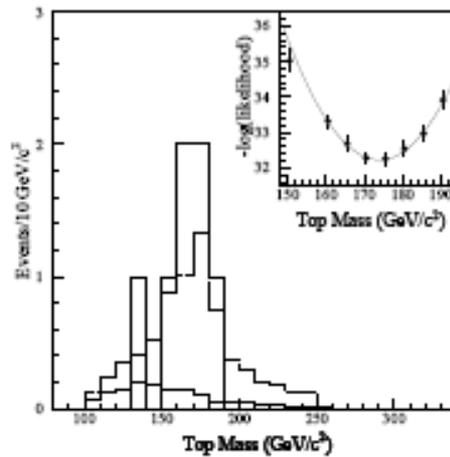
**QCD Machine**

**Factorization**

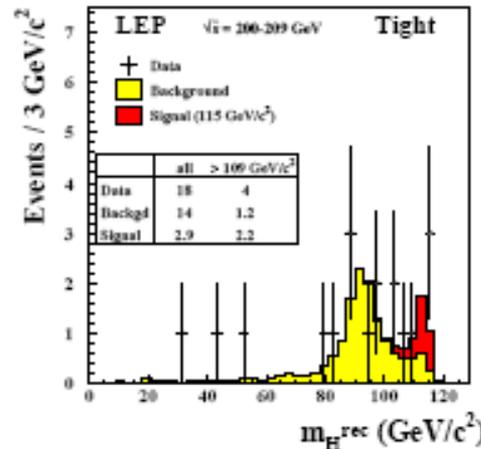
**Multi-level**

# Why Generators?

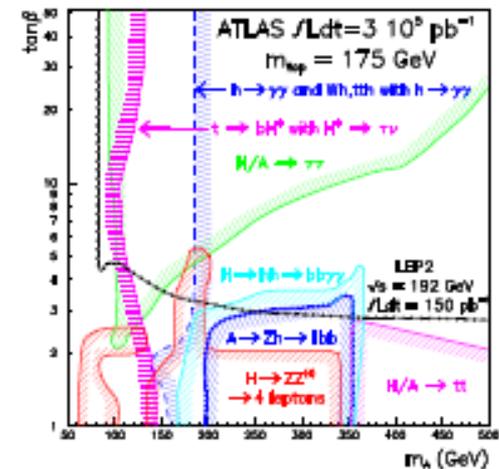
Torbjörn Sjöstrand



top discovery  
and mass  
determination



Higgs (non)  
discovery



Higgs and  
supersymmetry  
exploration

not feasible without generators

# PT and (pseudo-)Rapidity



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

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

$$p_T \equiv \sqrt{p_x^2 + p_y^2}$$

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

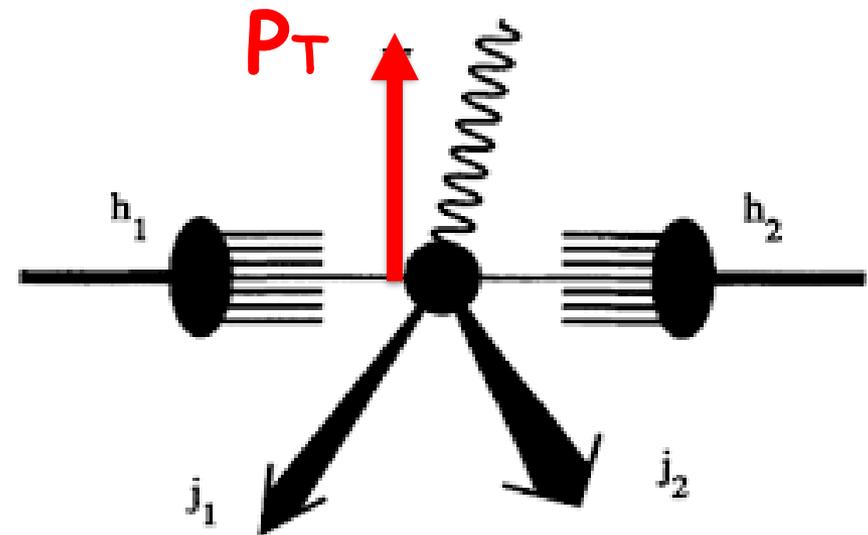
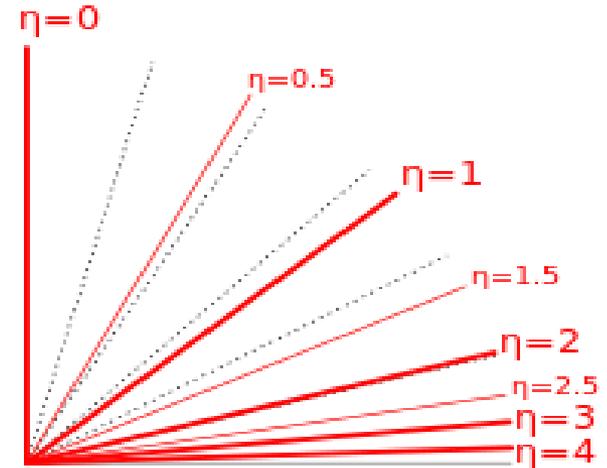
## Lorentz Invariant Distance

**LHC typical:**

**PT > 20-30 GeV**

**|η| < 2.5, 4.7**

**ΔR > 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  $\gamma = 1/\sqrt{1 - \beta^2}$ .

$$p'_{x,y} = p_{x,y}$$

$$p'_z = \gamma(p_z + \beta E)$$

$$E' = \gamma(E + \beta p_z)$$

$$p'^+ = \gamma(1 + \beta)p^+ = \sqrt{\frac{1 + \beta}{1 - \beta}} p^+ = k p^+$$

$$p'^- = \gamma(1 - \beta)p^- = \sqrt{\frac{1 - \beta}{1 + \beta}} p^- = \frac{p^-}{k}$$

$$y' = \frac{1}{2} \ln \frac{p'^+}{p'^-} = \frac{1}{2} \ln \frac{k p^+}{p^-/k} = y + \ln k$$

$$y'_2 - y'_1 = (y_2 + \ln k) - (y_1 + \ln k) = y_2 - y_1$$

# Pseudorapidity

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

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

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  $\eta$ .

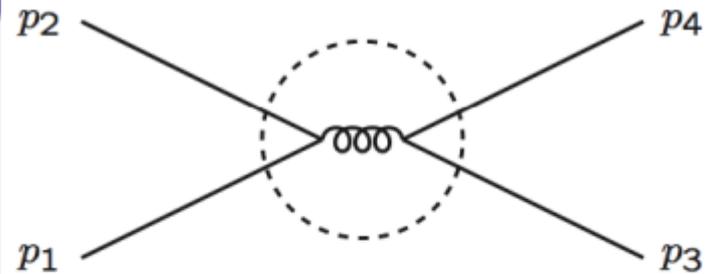
# Mandelstam variables

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

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$

$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$



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

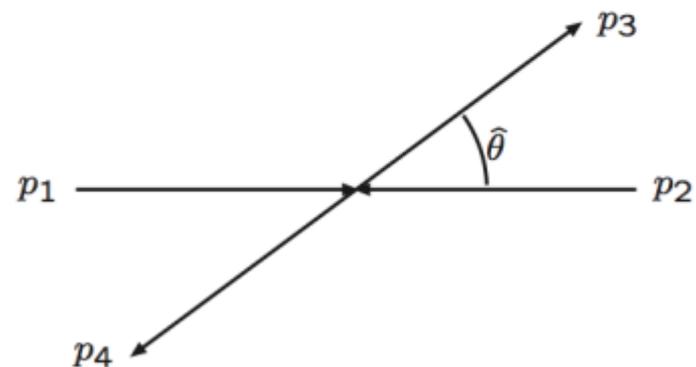
$$p_{1,2} = \frac{E_{\text{cm}}}{2} (1; 0, 0, \pm 1)$$

$$p_{3,4} = \frac{E_{\text{cm}}}{2} (1; \pm \sin \hat{\theta}, 0, \pm \cos \hat{\theta})$$

$$s = E_{\text{cm}}^2$$

$$t = -2p_1 p_3 = -\frac{s}{2} (1 - \cos \hat{\theta})$$

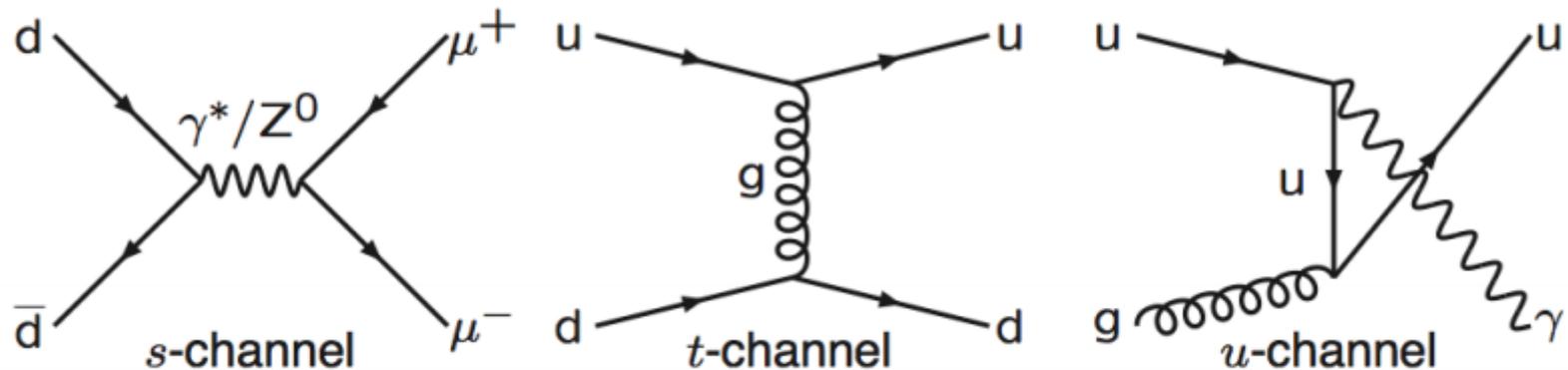
$$u = -2p_2 p_4 = -\frac{s}{2} (1 + \cos \hat{\theta})$$



$$s + t + u = 0$$

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

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



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

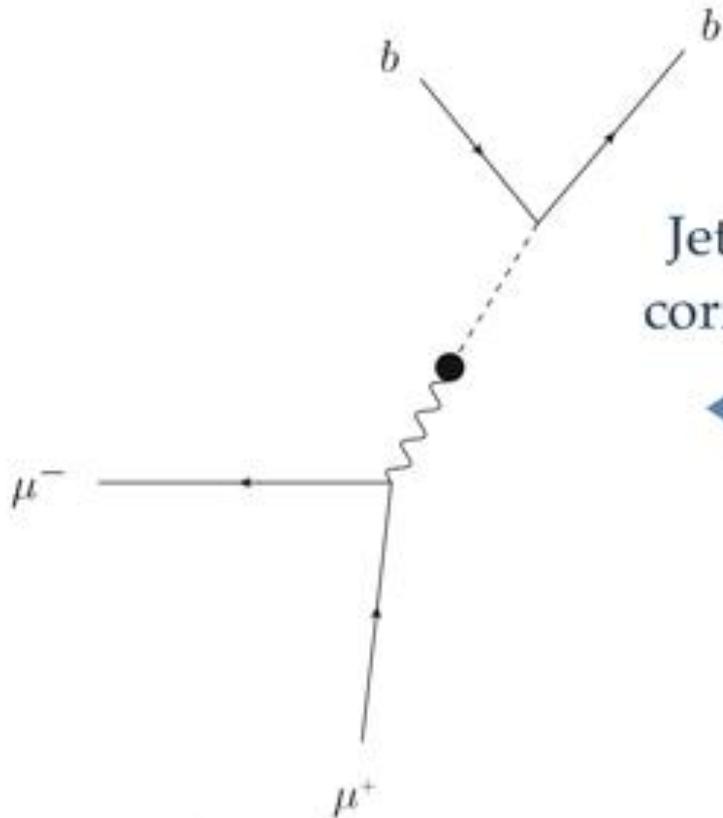
$$\frac{d\sigma(qq' \rightarrow qq')}{dt} = \frac{\pi}{s^2} \frac{4}{9} \alpha_s^2 \frac{s^2 + u^2}{t^2}$$

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

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

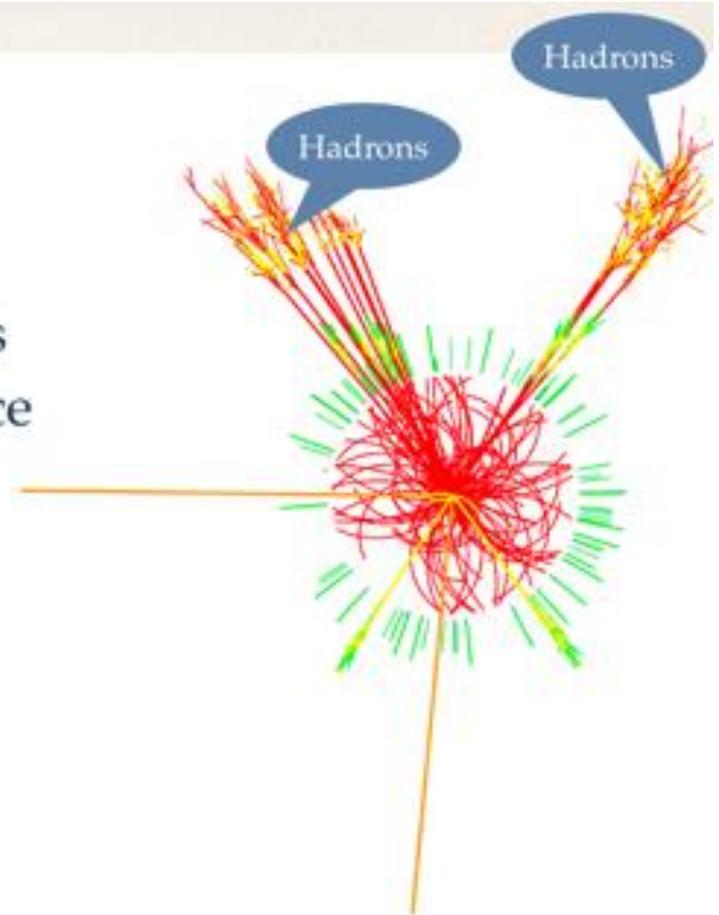
i.e. Rutherford scattering!

# Parton, Jet



What we calculate

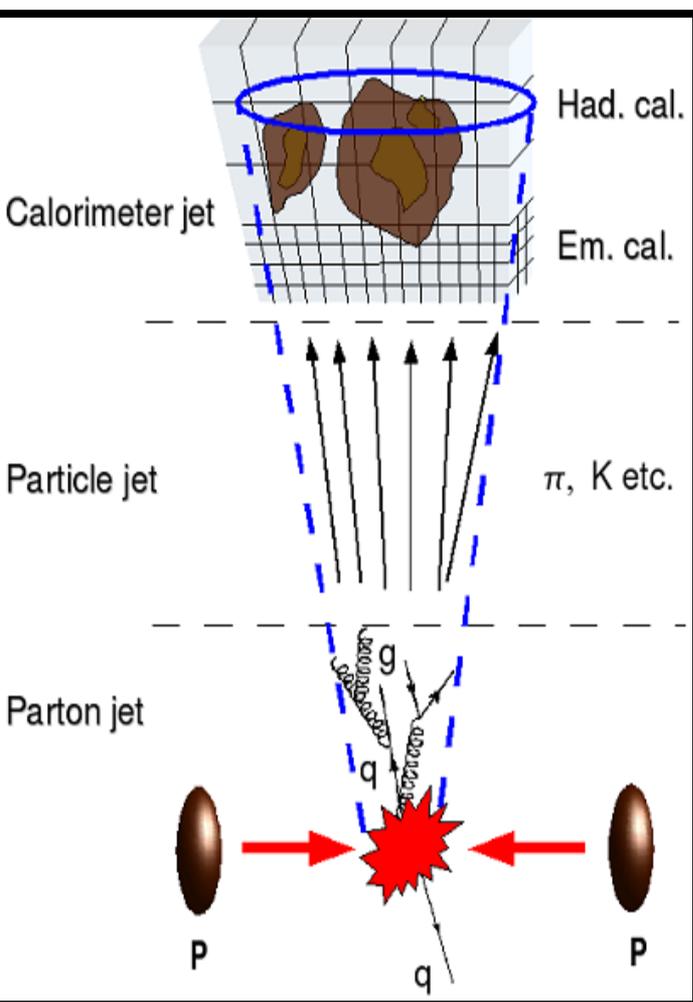
Jets make this  
correspondence



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

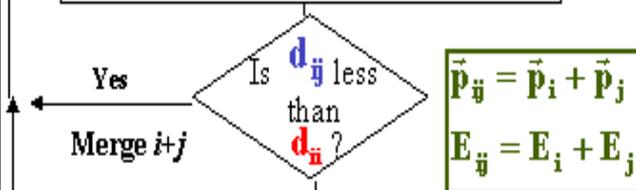
**Table 3:** Orders of magnitude of the event multiplicities  $N$  (charged + neutral) for various kinds of event. The  $e^+e^-$ , photoproduction, DIS and  $pp$  results have been estimated with Pythia 6.4[102, 100], LHC PbPb with Pythia + Hydjet [103] and RHIC has been deduced from [104]. Note that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



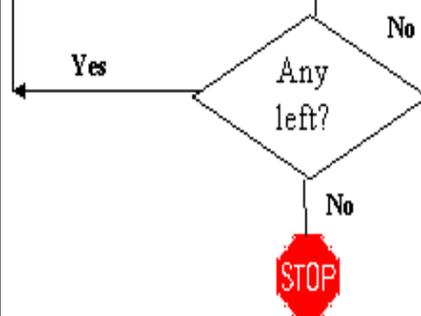
## K<sub>T</sub> Jet Algorithm

- Form preclusters out of seed towers  
cone with  $R = 0.4, R=0.7$  or  $R=1.0$

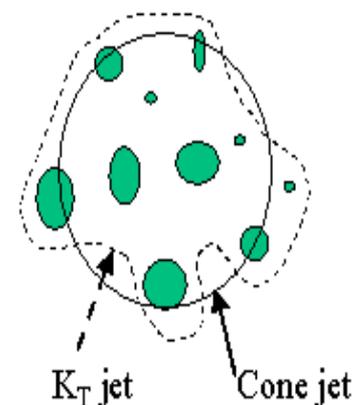
$$d_{ij} = \min(E_{T,i}^2, E_{T,j}^2) \frac{\Delta R_{ij}^2}{D^2} \quad d_{ii} = E_{T,i}^2$$



Move  $i$  to list of jets



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



All clusters with  $r < D$  are merged  
Clusters with  $r > D$  can be merged if  $\Delta E_T \gg 0$

**Jet Shapes are more natural**

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

# Jet Algorithm

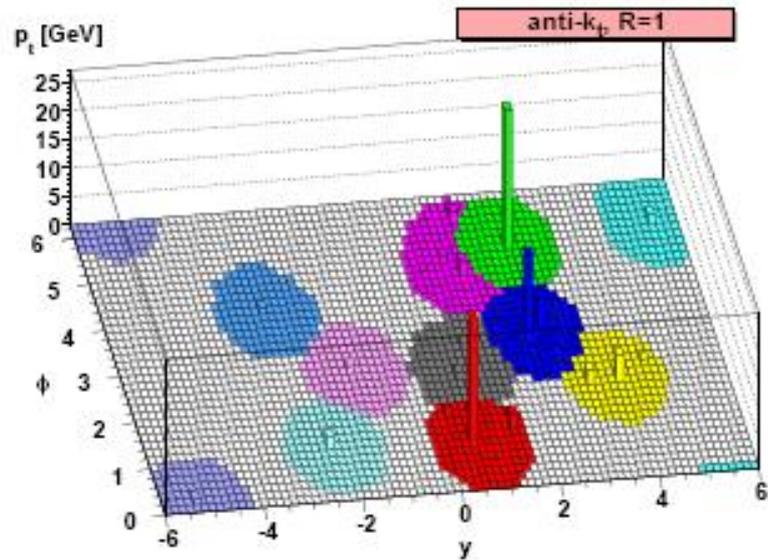
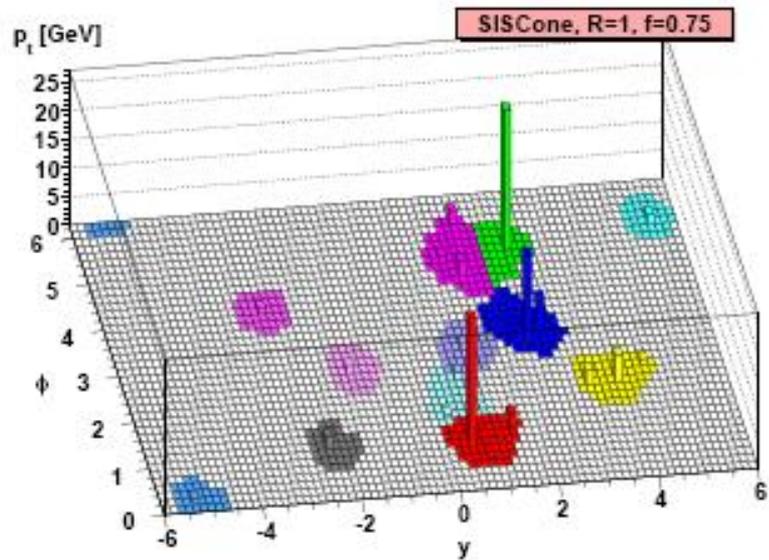
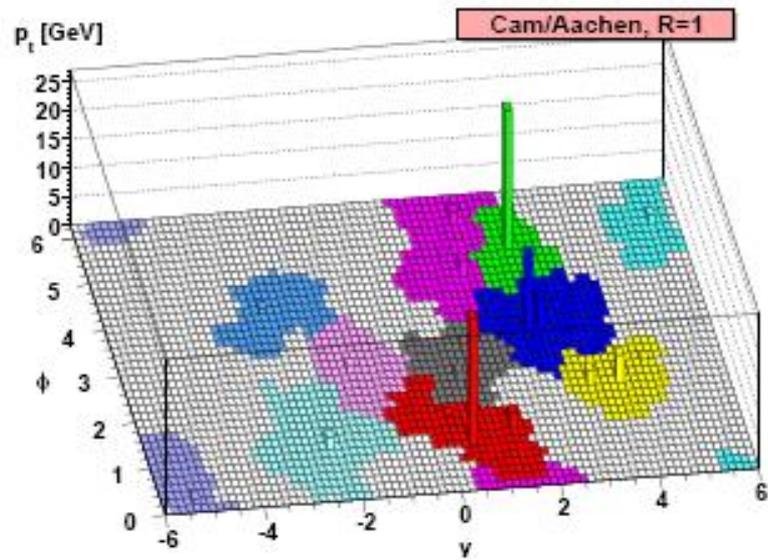
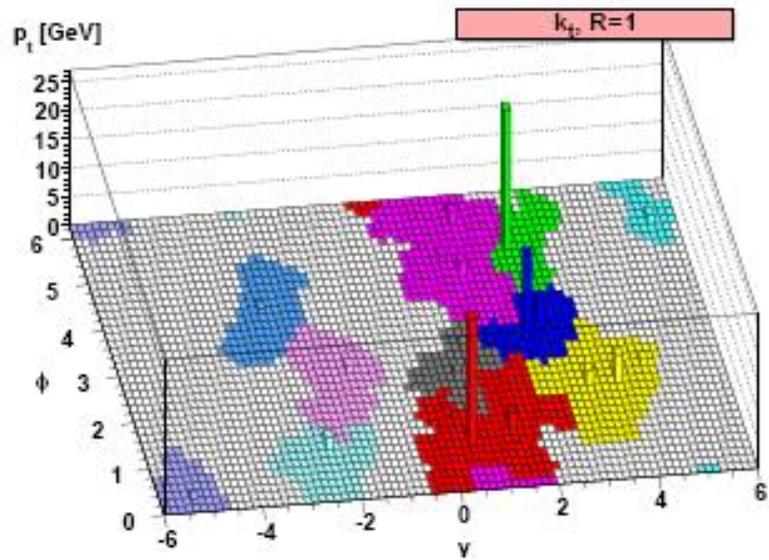


$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \quad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2,$$
$$d_{iB} = p_{ti}^{2p},$$

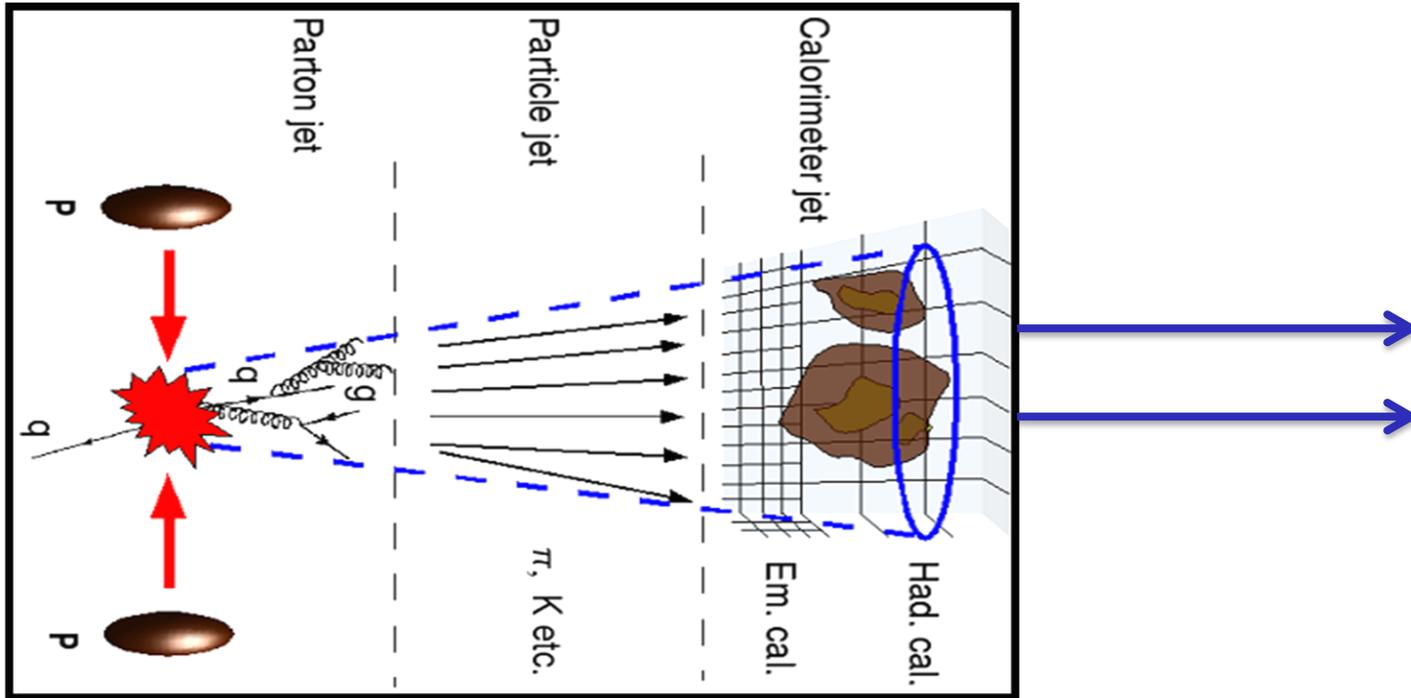
1. Work out all the  $d_{ij}$  and  $d_{iB}$  according to eq. (8).
2. Find the minimum of the  $d_{ij}$  and  $d_{iB}$ .
3. If it is a  $d_{ij}$ , recombine  $i$  and  $j$  into a single new particle and return to step 1.
4. Otherwise, if it is a  $d_{iB}$ , declare  $i$  to be a [final-state] jet,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

**$D = -1, 0, 1$**

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



# 4-momenta, hits/deposits, digitalize

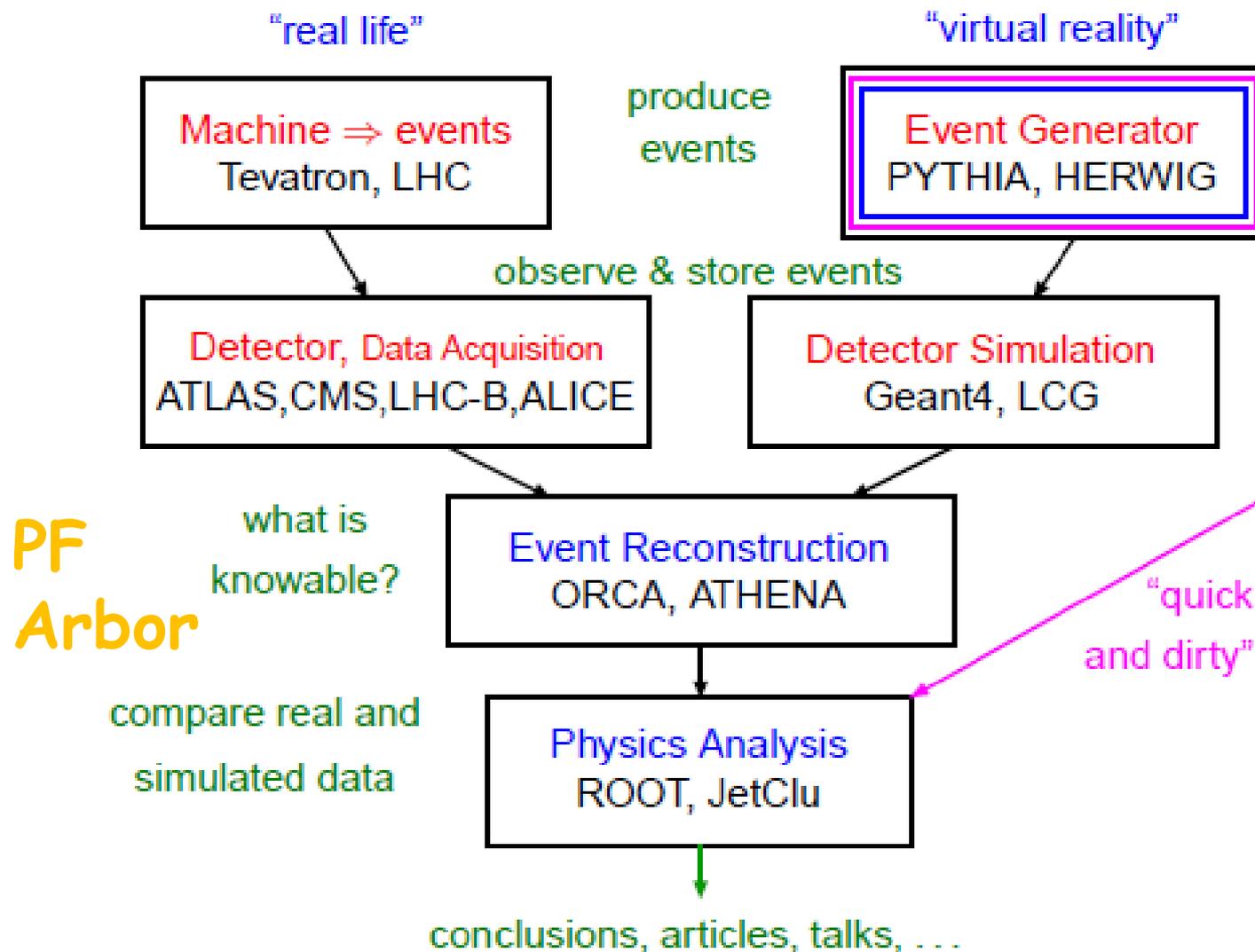


Your study can be cut at some level, depending on what you want

# Simulation at all levels



## Event Generator Position



# Generator Landscape

	General-Purpose	Specialized
Hard Processes	<b>HERWIG</b>  <b>PYTHIA</b>  <b>ISAJET</b>  <b>SHERPA</b>	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

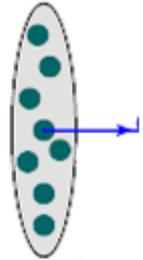
## parton interactions

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

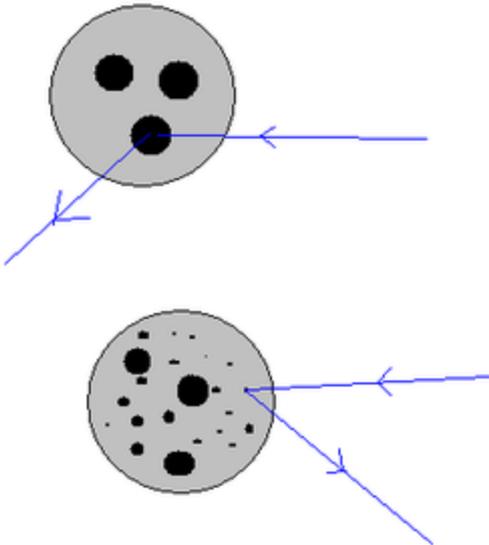
$x$  **is momentum fraction**

$\mu_F$  *is factorization scale*

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



Parton Model

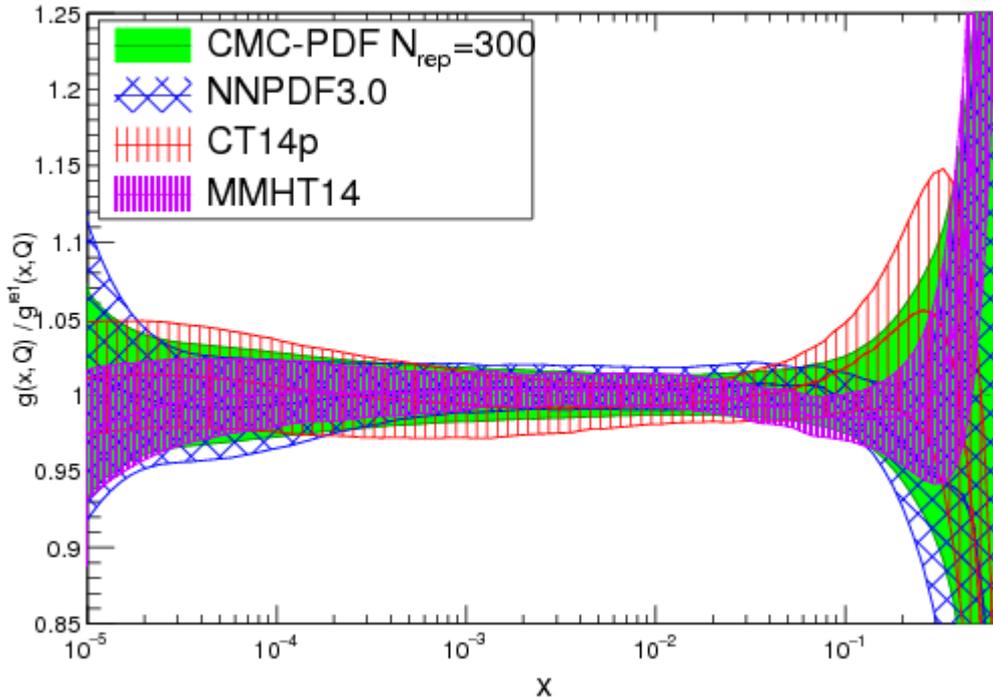


**The scattering particle only sees the valence partons. At higher energies, the scattering particles also detects the sea partons.**

# PDF and LHAPDF

## Many choices on the market

NNLO,  $\alpha_s=0.118$ ,  $Q = 100$  GeV



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**

**PDF4LHC**

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

## Recommendation for LHC cross section calculations

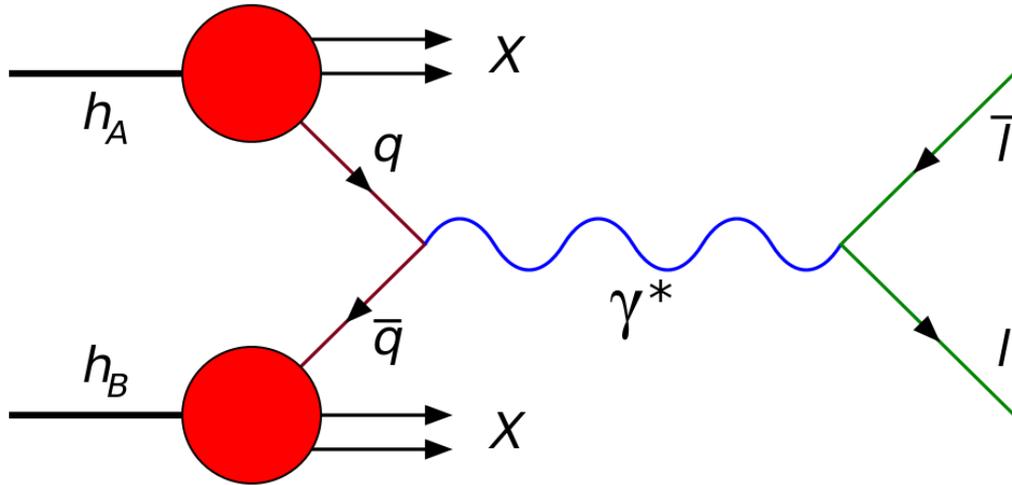
The LHC experiments are currently producing cross sections from the 7 TeV data, and thus need accurate predictions for these cross sections and their uncertainties at NLO and NNLO. Crucial to the predictions and their uncertainties are the parton distribution functions (PDFs) obtained from global fits 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+ $\alpha_s$  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**

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

**Factorization scale**

$\mu_F$

**Renormalization Scale**

$\mu_r$

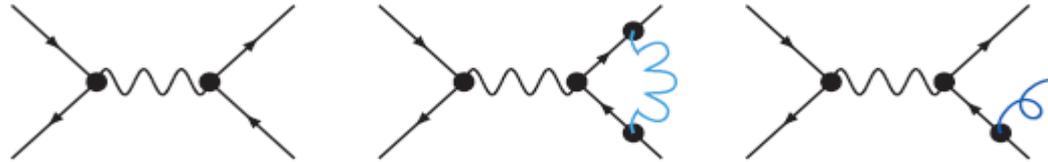
**Phase Space**

$d\Phi_f$

# Hard Scattering: Higher order



loops (virtual corrections) or legs (real corrections)



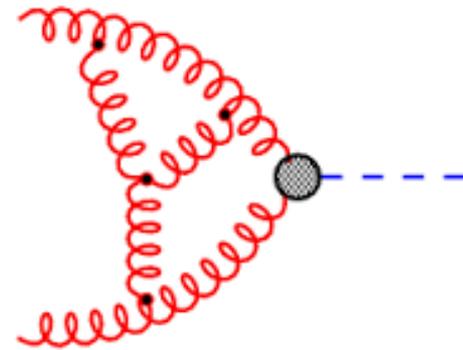
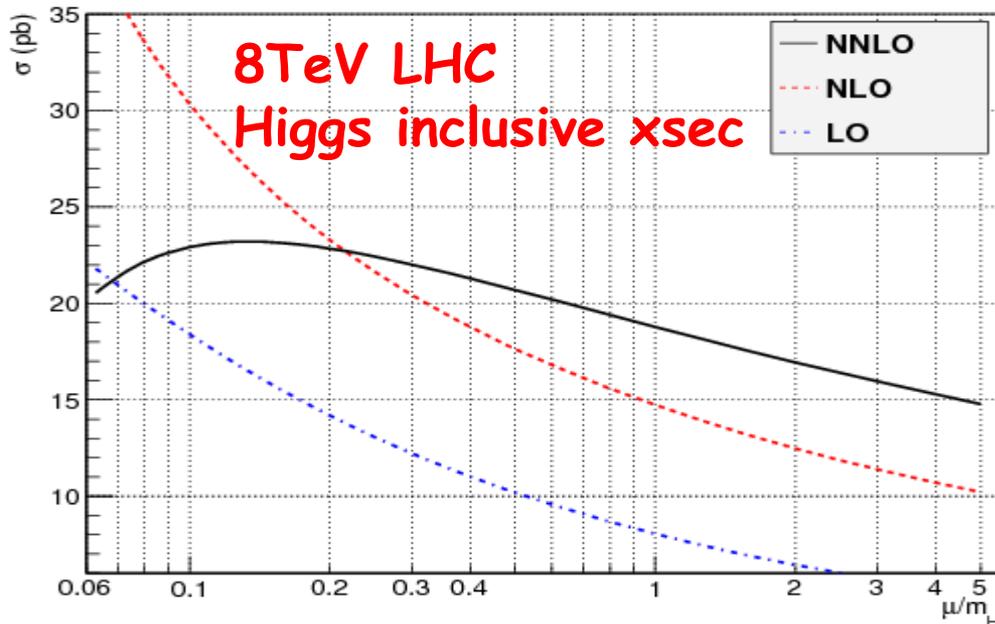
- effect: reducing the dependence on  $\mu_R$  &  $\mu_F$

(NLO first order allowing for meaningful estimate of uncertainties)

- additional difficulties when going NLO:

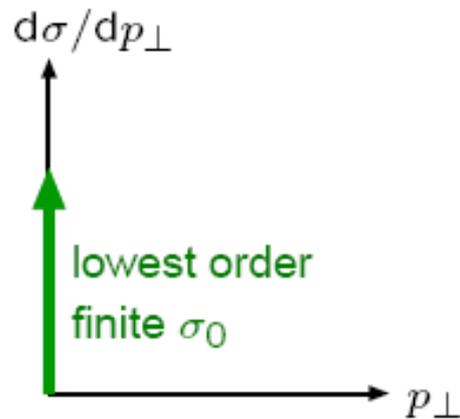
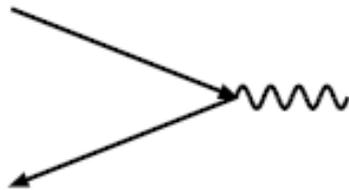
ultraviolet divergences in virtual correction

infrared divergences in real and virtual correction

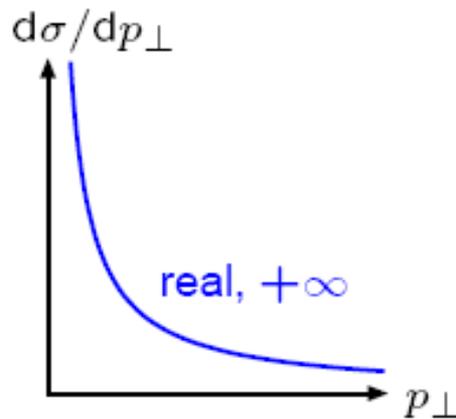
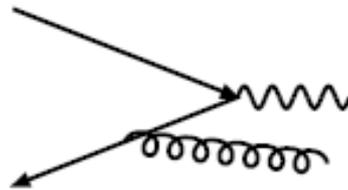


# Next-to-leading order (NLO) calculations

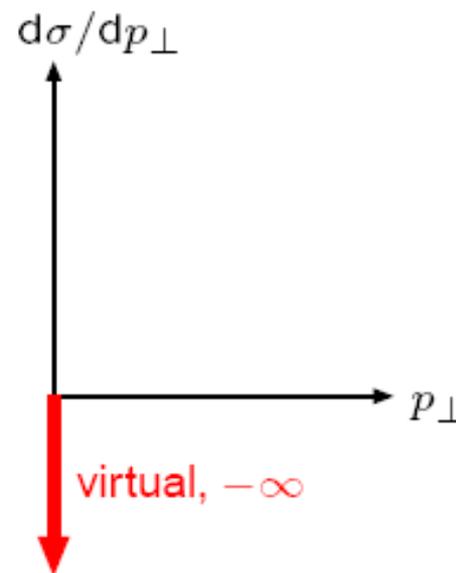
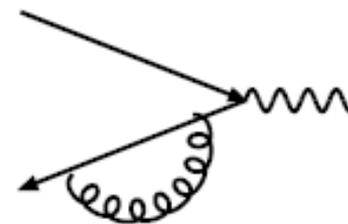
I. Lowest order,  
 $\mathcal{O}(\alpha_{em})$ :  
 $q\bar{q} \rightarrow Z^0$



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



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

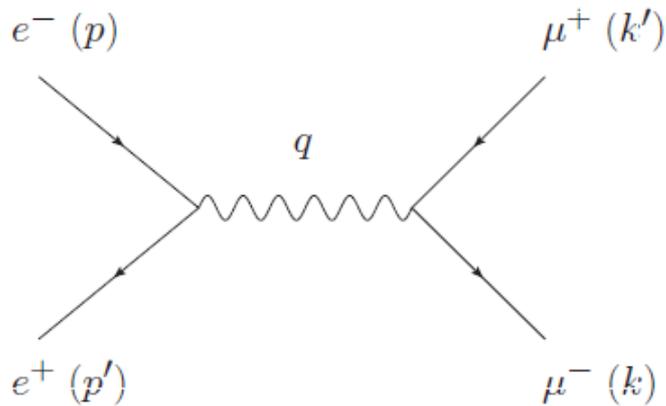


# Higher order Calculation is not easy



$pp \rightarrow W + 0 \text{ jet}$	1978	Altarelli, Ellis, Martinelli
$pp \rightarrow W + 1 \text{ jet}$	1989	Arnold, Ellis, Reno
$pp \rightarrow W + 2 \text{ jets}$	2002	Campbell, Ellis
$pp \rightarrow W + 3 \text{ jets}$	2009	BH+Sherpa Ellis, Melnikov, Zanderighi
$pp \rightarrow W + 4 \text{ jets}$	2010	BH+Sherpa
$pp \rightarrow W + 5 \text{ jets}$	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**

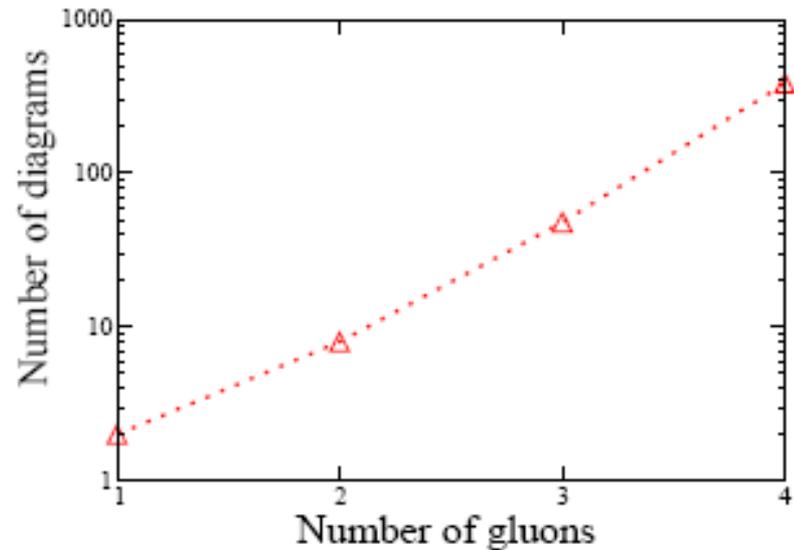
$$\frac{1}{2} \sum_s \frac{1}{2} \sum_{s'} \sum_r \sum_{r'} |\mathcal{M}|^2 = \frac{e^4}{4q^4} \text{Tr}[p'\gamma^\lambda p\gamma^\nu] \text{Tr}[k\gamma_\lambda k'\gamma_\nu] = \frac{8e^4}{q^4} [(p \cdot k)(p' \cdot k') + (p \cdot k')(p' \cdot k)]$$

**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  $e^+e^- \rightarrow q\bar{q} + ng$

$n$	#diags
0	1
1	2
2	8
3	48
4	384

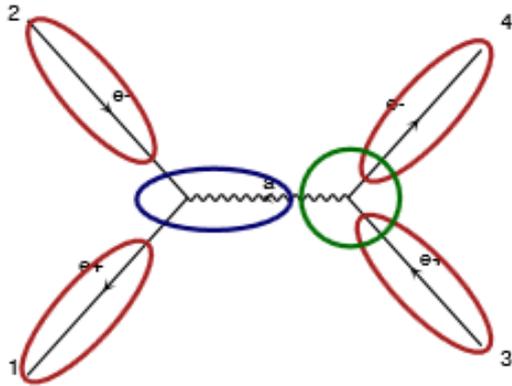


## Helicity Method, numerical way, sum over spin later:

$O(n)$

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

**Alwall**  
**2012**

Time for matrix element evaluation on a Sony Vaio TZ laptop

# $e^+ e^- \rightarrow \mu^+ \mu^- / Z$

```
matrix1.f
~/Desktop/MG5_aMC/MG5_aMC_v2_4_2/eemm/SubProcesses/P1_ILI

ENDDO
IF (XTOT.NE.0D0) THEN
  ANS=ANS*AMP2(SUBDIAG(1))/XTOT
ELSE
  ANS=0D0
ENDIF
ENDIF
ANS=ANS/DBLE(IDEN)

Print *, "-----"
Print *, "ZQQQ1", ANS*4.0
q12=2d0*(P(0,3)*P(0,4)-P(1,3)*P(1,4)-P(2,3)*P(2,4)-P(3,3)*P(3,4))
pa1=(P(0,1)*P(0,3)-P(1,1)*P(1,3)-P(2,1)*P(2,3)-P(3,1)*P(3,3))
pa2=(P(0,1)*P(0,4)-P(1,1)*P(1,4)-P(2,1)*P(2,4)-P(3,1)*P(3,4))
pb1=(P(0,2)*P(0,3)-P(1,2)*P(1,3)-P(2,2)*P(2,3)-P(3,2)*P(3,3))
pb2=(P(0,2)*P(0,4)-P(1,2)*P(1,4)-P(2,2)*P(2,4)-P(3,2)*P(3,4))
m12=32.d0*(pa1*pb2+pa2*pb1)/q12/q12*8.9937763771622652E-003
Print *, "ZQQQ2", m12, q12
Print *, "-----"

END

REAL*8 FUNCTION MATRIX1(P,NHEL,IC)

Generated by MadGraph5_aMC@NLO v. 2.4.2, 2016-06-10
By the MadGraph5_aMC@NLO Development Team
Visit launchpad.net/madgraph5 and amcatnlo.web.cern.ch

Returns amplitude squared summed/avg over colors
for the point with external lines W(0:6,NEXTERNAL)

Process: e+ e- > mu+ mu- WEIGHTED<=4 / z @1

IMPLICIT NONE

CONSTANTS

INTEGER NGRAPHS
PARAMETER (NGRAPHS=1)
INCLUDE 'genps.inc'
INCLUDE 'nexternal.inc'
```

```
qliphy@qliphy: ~/Desktop/MG5_aMC/MG5_aMC_v2_4_2/eemm
File Edit View Search Terminal Tabs Help
qili@lxplus754:~ x qliphy@qliphy: ~/Desktop/MG5_aMC/... x qliphy@qliphy: ~/Desktop/2021Spring...

-----
ZQQQ1 3.7068399004403285E-002
ZQQQ2 3.7068399573030188E-002 1000000.0000000000
-----
ZQQQ1 4.5792325502347950E-002
ZQQQ2 4.5792326204799318E-002 1000000.0000000000
-----
ZQQQ1 6.1071722536203209E-002
ZQQQ2 6.1071723473039609E-002 1000000.0000000000
-----
ZQQQ1 6.9937267682229867E-002
ZQQQ2 6.9937268755063287E-002 1000000.0000000000
-----
ZQQQ1 6.4424862883308329E-002
ZQQQ2 6.4424863871581681E-002 1000000.0000000000
-----
ZQQQ1 3.7744210521205065E-002
ZQQQ2 3.7744211100198870E-002 1000000.0000000000
-----
ZQQQ1 5.1131742520158230E-002
ZQQQ2 5.1131743304515941E-002 1000000.0000000000
-----
```

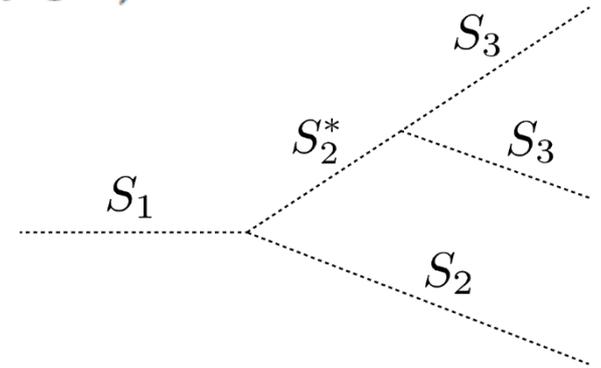
# Hard Scattering: Phase Space



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

**3n-4**

**+2 = 3n-2 dimension**



**An example of Phase space factorization**

**→ Recursive in numerical**

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

# MC Technique



$$I = \int_{x_1}^{x_2} dx f(x) = (x_2 - x_1) \langle f(x) \rangle \quad I \approx (x_2 - x_1) \frac{1}{N} \sum_{i=1}^N f(x_i)$$

**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



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

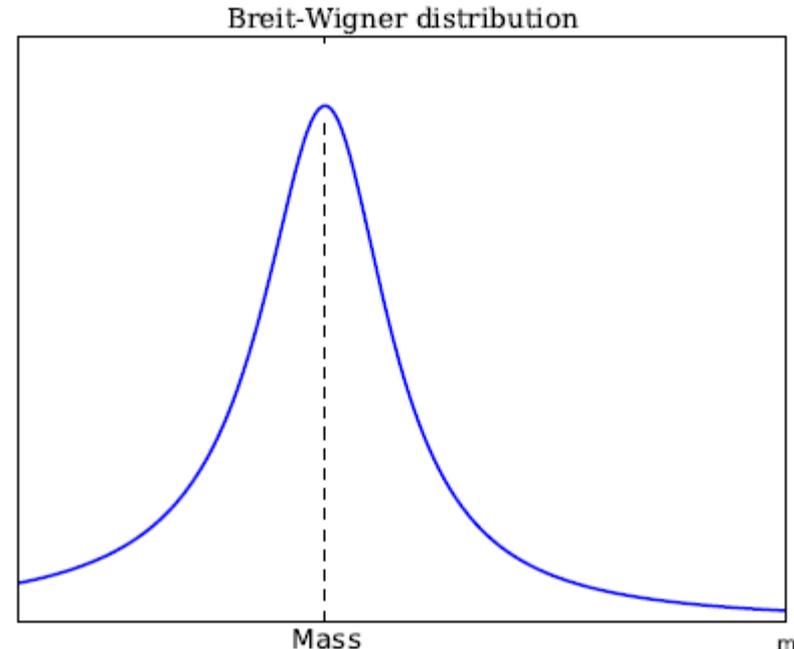
- **Good convergence for high dimension integrals**
- **We also got events randomly distributed**
- **$V_N$  should be small: importance sampling**

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

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



$$\begin{aligned} I &= \int_{\rho_{\min}}^{\rho_{\max}} d\rho \left| \frac{\partial m^2}{\partial \rho} \right| \frac{1}{(m^2 - M^2)^2 + M^2 \Gamma^2} \\ &= \frac{1}{M\Gamma} \int_{\rho_{\min}}^{\rho_{\max}} d\rho \end{aligned}$$



# Unweighting

---



**We often want events without weights as mother Nature produce**

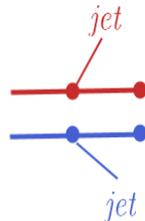
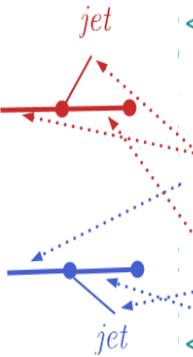
- 1. Monte Carlo integration and scanning are performed:  
N points are picked randomly**
- 2. The phase-space point which give the maximum weight,  
W<sub>max</sub> is stored**
- 3. ‘hit-or-miss’: go through randomly chosen phase-space  
points and compare the probability of each, given by  
W<sub>i</sub>/W<sub>max</sub> to a random number R in (0, 1).  
If W<sub>i</sub>/W<sub>max</sub> > R, we ‘accept’ the event, otherwise wereject  
it. This is done until we have collected the desired number  
of events, N<sub>events</sub>.**

# 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>
...

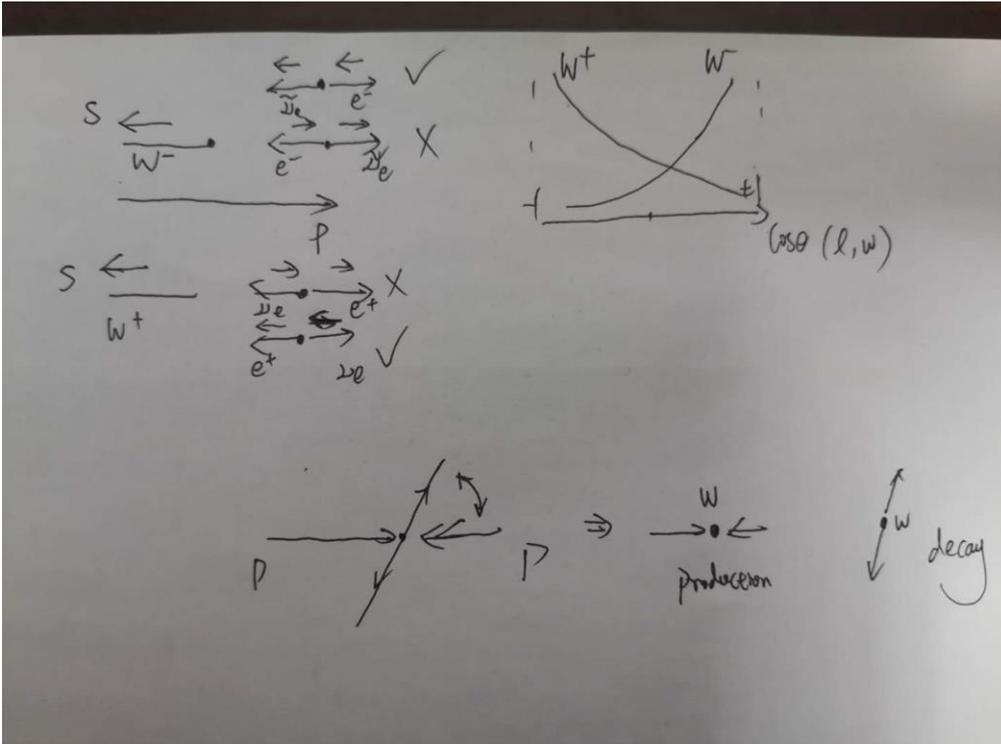
```



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

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

# W polarization



the  $W$  moves strictly along the beam axis, with no transverse momentum,  $p_T^W = 0$ . Suppose the  $W$  is moving in the direction of the initial-state quark, as opposed to the anti-quark. This is likely to be the case at the LHC, because the LHC is a  $pp$  machine and the quark distributions  $q(x)$  have a larger average momentum fraction  $x$  than the antiquark distributions  $\bar{q}(x)$ . Because the electroweak charged current is purely-left-handed, the quark must be left-handed and the anti-quark right-handed. (We assume massless quarks and leptons throughout this paper.) By angular momentum conservation, the spin of the  $W$  is 100% left-handed along its direction of motion, for either  $W^+$  or  $W^-$ , as shown in fig. 2. This effect is diluted some by anti-quarks that occasionally carry a larger  $x$  than the quarks with which they collide. However, the dilution is small at large rapidities, because the ratio  $q(x)/\bar{q}(x)$  increases rapidly as  $x \rightarrow 1$ .

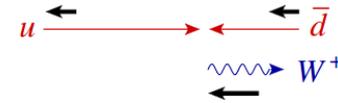


FIG. 2: When a  $W^+$  is produced at lowest order by  $u(x_1)\bar{d}(x_2) \rightarrow W^+$  with  $x_1 > x_2$ , it is 100% left-handed polarized along its direction of motion, which is along the beam axis in the quark direction. Thick (black) arrows represent spin vectors; the other arrows represent momentum vectors in the  $pp$  center-of-mass frame.

[1103.5445] Left-Handed W Bosons at the LHC (arxiv.org)

```
import model sm
generate p p > w+ w- , w+ > mu+ vm , w- > jj
Or
generate p p > w+ w- , w- > mu- vm~ , w+ > jj
output ppww
```

```
import model heft
generate p p > h > w+ w- , w+ > mu+ vm , w- > jj
```

```
import model RSgenerate p p > y > w+ w- , w+ >
mu+ vm , w- > jj
```

$p p > w^+ w^-, w^+ > \mu^+ \nu_\mu, w^- > q \bar{q}$

$p p > w^+ w^-, w^- > \mu^- \bar{\nu}_\mu, w^+ > q \bar{q}$

```
int f1w,f1wb,p1dwp,p1dwm,
int firstdwp=1;
int firstdwm=1;

TLorentzVector w;
TLorentzVector lep;
TLorentzVector neu;

//-----
for(int j=3; j<=nne; j++){
TRootLHEFParticle *ppw=(TRootLHEFParticle*) branchParticle-
>At(j-1);

ifw=(fabs(ppw->PID)-13)*(fabs(ppw->PID)-11);
if(ifw==0) {ptl=ppw->PT; etal=ppw->Eta; phil=ppw->Phi; el=ppw->E;
ifwb=(fabs(ppw->PID)-12)*(fabs(ppw->PID)-14);
if(ifwb==0) {ptv=ppw->PT; etav=ppw->Eta; phiv=ppw->Phi; ev=ppw->E;
}

lep.SetPtEtaPhiE(ptl,etal,phil,el);
neu.SetPtEtaPhiE(ptv,etav,phiv,ev);
w=lep+neu;
TVector3 v1 = w.Vect();
TLorentzVector lep_in_w(lep);
TVector3 wboost = -(w.BoostVector());
lep_in_w.Boost(wboost);
TVector3 v2 = lep_in_w.Vect();
double theta = v1.Angle(v2);

//-----

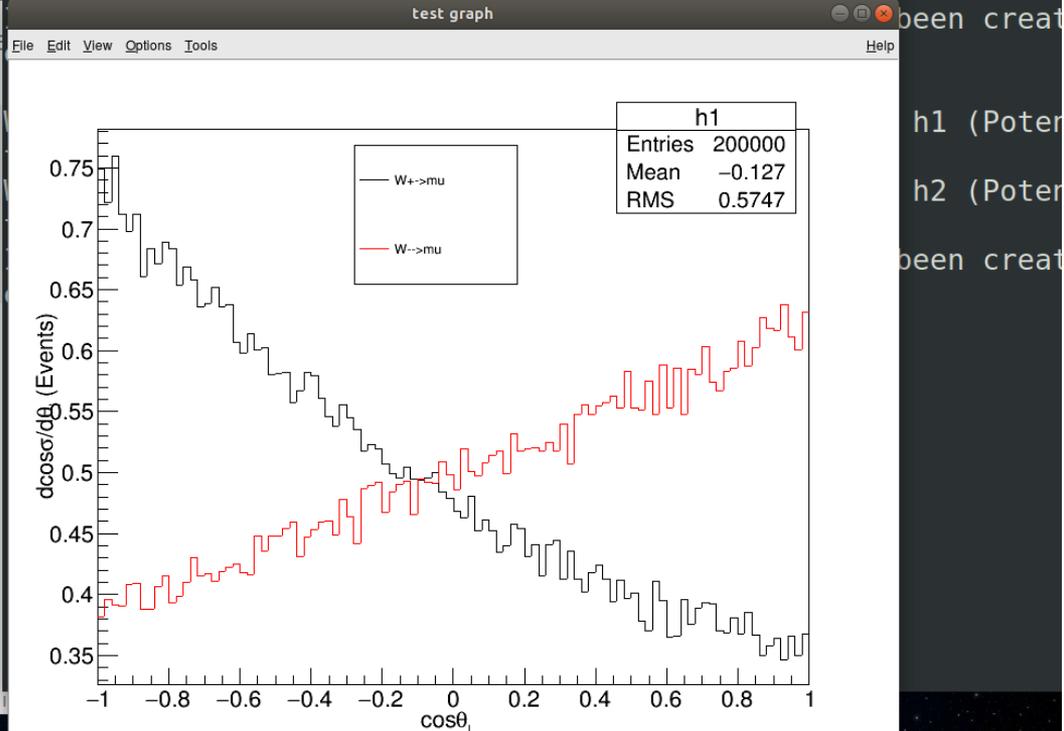
h1->Fill(cos(theta),nbin/(finx-inix)/float(numberOfEntries));

////*****
}

//((((((((((((((((((((((((((((((((((((((((((((((((((((((((((((
TChain chain2("LHEF");
chain2.Add("sm2.root");

// Create object of class EvDontTreeReader
C++ Tab Width: 8 Ln 59, Col 1
```

```
File Edit View Search Terminal Tabs Help
qili@lxplus754:~
qlyphy@qlyphy: ~/Desktop/2021Spring...
qlyphy@qlyphy: ~/Desktop/2021Spring...
1103.5445.pdf h sm2 y
1.jpg h.root sm2.root y.root
2.png Lecture2.pdf sm.root
angular.pdf ppbar test2.cpp
goldschmidt_poster.pdf sm WeakWW-1.pdf
qlyphy@qlyphy:~/Desktop/2021Spring/refs/Tutorial/Tutorial-WWa
angular$ root -l test2.cpp
root [0]
Processing test2.cpp...
```

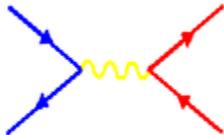




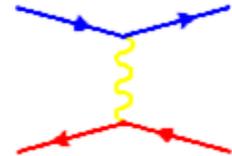
# Example: MG\_aMC@NLO



PP > Z LO & NLO



[The MadGraph5\\_aMC@NLO homepage](#)



[UCL UIUC Launchpad](#)  
by the [MG/ME Development team](#)

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[Register](#)

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[Database](#)

[Status](#)

[account\)](#)

[Wiki](#)

[Answers](#)

[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 lhpdf to lhpdf-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

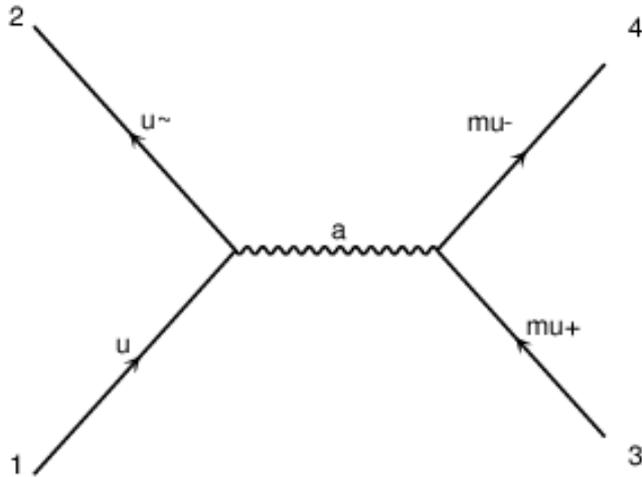


diagram 1

QCD=0, QED=2

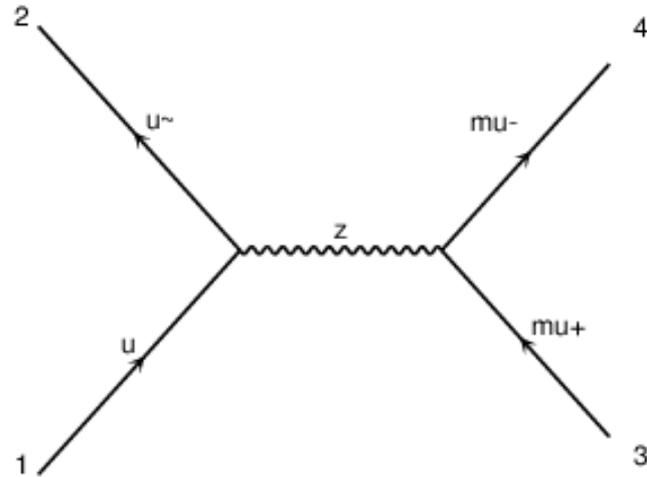


diagram 2

QCD=0, QED=2

**You can choose QCD or QED vertex number**



# Example: PP > Z LO & NLO



```
#####
```

```
## INFORMATION FOR MASS
```

## Parameter Card

```
#####
```

```
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
```

DAQ state		Run Number	LVL rate
Running	195658	41.222 kHz	

Data to Surface						
Sub-System	State	TRF	FED IN	Stream	Hz	
TRF	Running	4	4	4	ALCAPRO	35
CDC	Running	2	2	2	NanoDST	1.2
DAQ	Running	0	0	0	ALCAPHYSM	2
DOM	Running	0	0	0	RFCMON	4
OT	Running	6	6	6	ALCALUMP	2
ECAL	Running	24	24	24	PhysicsDST	2
ET	Running	12	12	12	A	2
		20	20	20	Calibration	472
		20	20	20	BeamCalibran	472
		20	20	20	Express	72
		2	2	2	A	5.5
		1	1	1	HITMON	20
		1	1	1	TrackerCalib	12
		1	1	1		0

```
)
```

# 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 = isedd ! 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 electron
```

```
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
```

```
nn23l01 = pdlabel ! PDF set
```

BW cutoff ( $M \pm bwcutoff * \Gamma$ )

```
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 = mml1 ! 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/qcliphy/Desktop/MG5\\_aMC\\_v2\\_1\\_2/LO-DY/index.html](/home/qcliphy/Desktop/MG5_aMC_v2_1_2/LO-DY/index.html)

PIXEL	Running	40	40	40	Express	69.919E+3	13.81	3.24
SCAL	Running	1	1	1	B	53.769E+3	10.48	3.07
TRACKER	Running	249	437	437	HLTMON	49.959E+3	9.51	3.34
					TrackerCalib	32.472E+3	15.36	0.24
					FaultyEvents	0.000E+0	0.00	0.00



JTC time: 07/06/12 05:45:02 Local time: Geneva 07:45, Los Angeles 22:45, Chicago 00:4

# 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  0.650000000000E+04  0.650000000000E+04  0  0  200400  200400  3  1
0.15075857952E+04  0.13200875619E+01  0.150760000000E+00  0
</init>
<event>
  5  0  0.1507600E+00  0.9150336E+02  0.7546771E-02  0.1299251E+00
    -2  -1  0  0  0  501  0.000000000000E+00  0.000000000000E+00  0.18656257017E+03  0.18656257017E+03  0.0
000000000000E+00  0.  1.
    2  -1  0  0  501  0  0.000000000000E+00  0.000000000000E+00  -0.11219916338E+02  0.11219916338E+02  0.0
000000000000E+00  0.  -1.
    23  2  1  2  0  0  0.000000000000E+00  0.000000000000E+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: $PP > Z \text{ LO \& NLO}$



```
<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
00000000000E+00 0. 1.
    -2 -1 0 0 0 501 0.00000000000E+00 0.00000000000E+00 -0.67242837278E+00 0.67242837278E+00 0.0
00000000000E+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 mumubar**

# Example: PP > Z LO & NLO



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

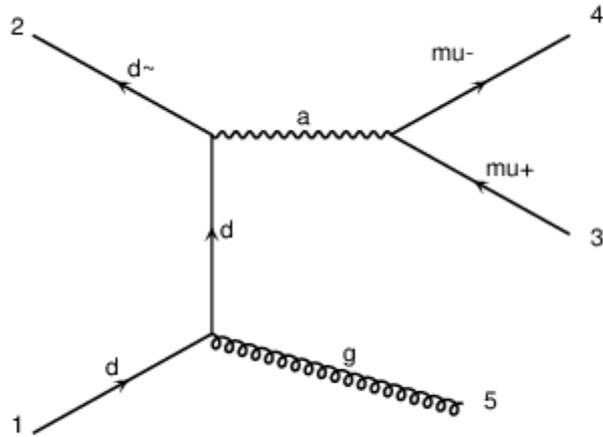
```
# Collider type and energy
#*****
1      = lpp1      ! beam 1 type (0 = no PDF)
1      = lpp2      ! beam 2 type (0 = no PDF)
6500   = ebeam1    ! beam 1 energy in GeV
6500   = ebeam2    ! beam 2 energy in GeV
#*****
# PDF choice: this automatically fixes also
#*****
nn23nlo = pdlabel    ! PDF set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

**NLO PDF for NLO, LO PDF for LO**

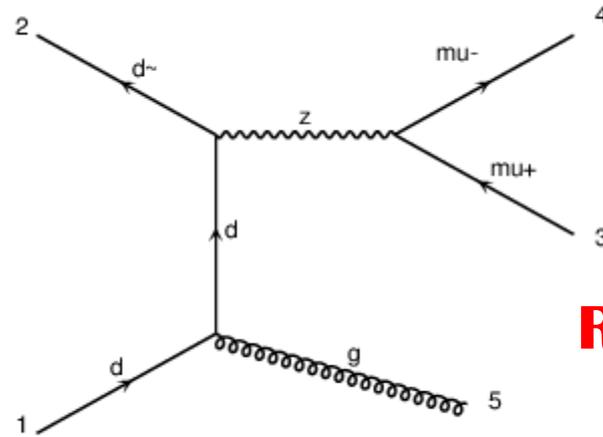
```
HERWIG6 = parton_shower
```

**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**

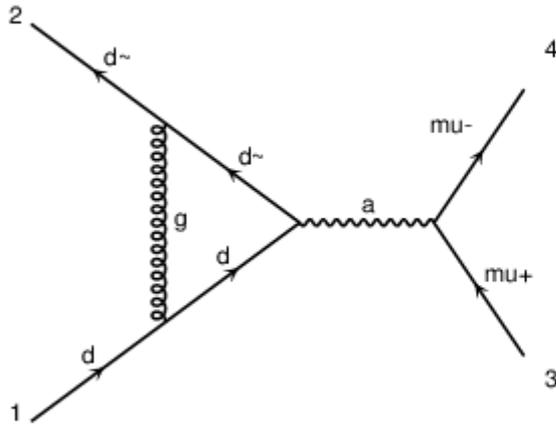


diagram 1 QCD=2, QED=2

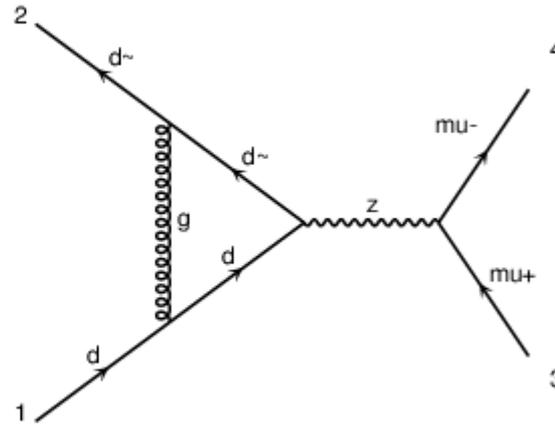


diagram 2 QCD=2, QED=2

**One Loop virtual**

# Example: $PP > Z$ LO & NLO



**Intermediate results:**

**Random seed: 34**

**Total cross-section:  $1.824e+03 \pm 2.9e+00$  pb**

**Total abs(cross-section):  $2.056e+03 \pm 2.6e+00$  pb**

**Summary:**

**Process  $p p > \mu^+ \mu^-$  [QCD]**

**Run at  $p$ - $p$  collider (6500 + 6500 GeV)**

**Total cross-section:  $1.824e+03 \pm 2.9e+00$  pb**

**Number of events generated: 10000**

**Parton shower to be used: HERWIG6**

**Fraction of negative weights: 0.06**

**Total running time : 1m 19s**

**K Factor:  $1824/1508 \sim 1.21$**

**$2.056 * (0.94 - 0.06) = 1.81$**

# Example: $PP > Z$ LO & NLO



Z/a* (50)	FEWZ 3.1	m(l) > 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



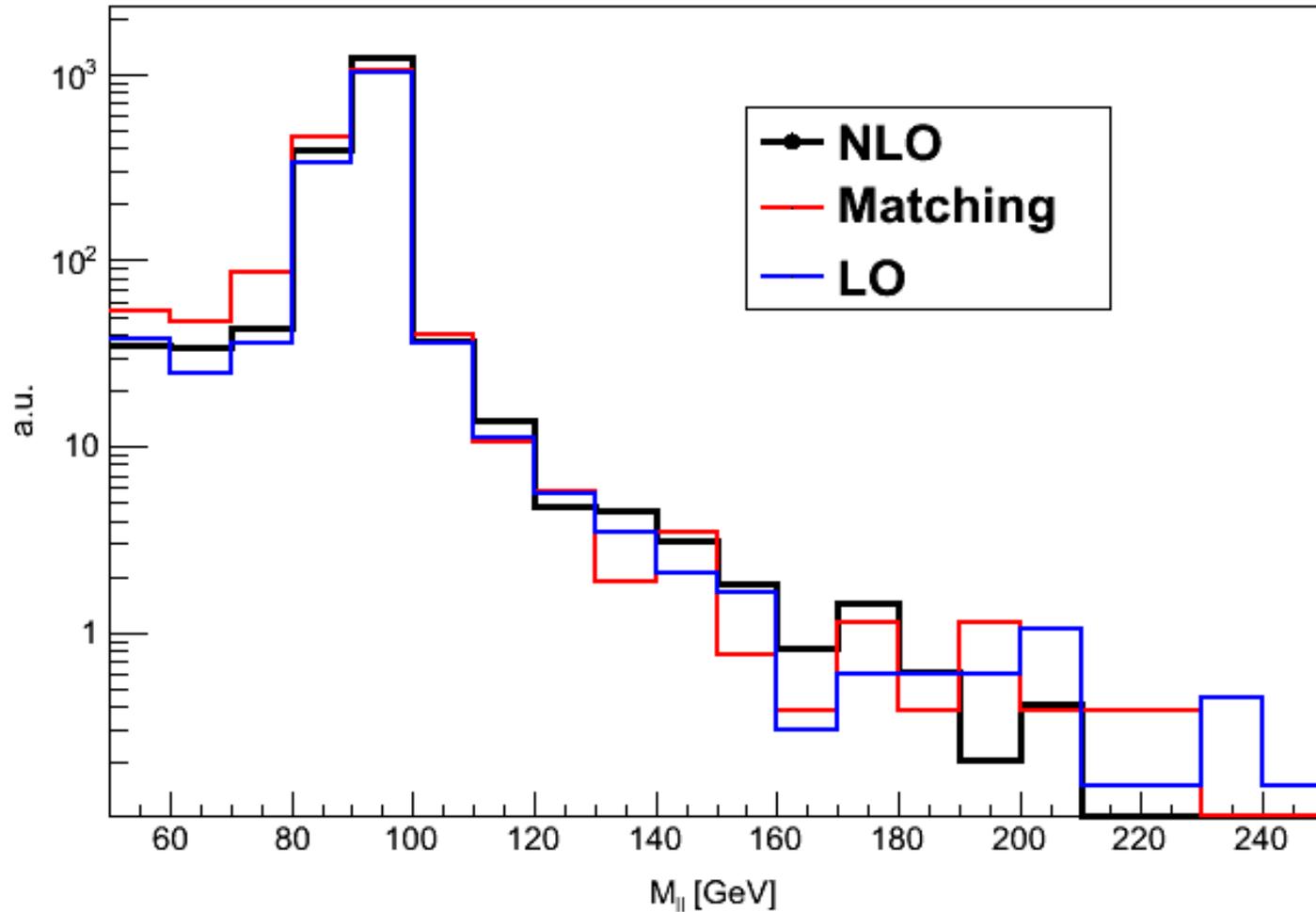
```
-rw-rw-r-- 1 qliphy qliphy 19704 Jul 25 15:59 run_02_tag_1_banner.txt
-rw-rw-r-- 1 qliphy qliphy 158832 Jul 25 15:59 alllogs_0.html
-rw-rw-r-- 1 qliphy qliphy 3426 Jul 25 15:59 res_0.txt
-rw-rw-r-- 1 qliphy qliphy 165095 Jul 25 16:00 alllogs_1.html
-rw-rw-r-- 1 qliphy qliphy 3426 Jul 25 16:00 res_1.txt
-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



$pp \rightarrow \mu^+\mu^-$  at 13TeV LHC



# Example: LO vs NLO vs Matching



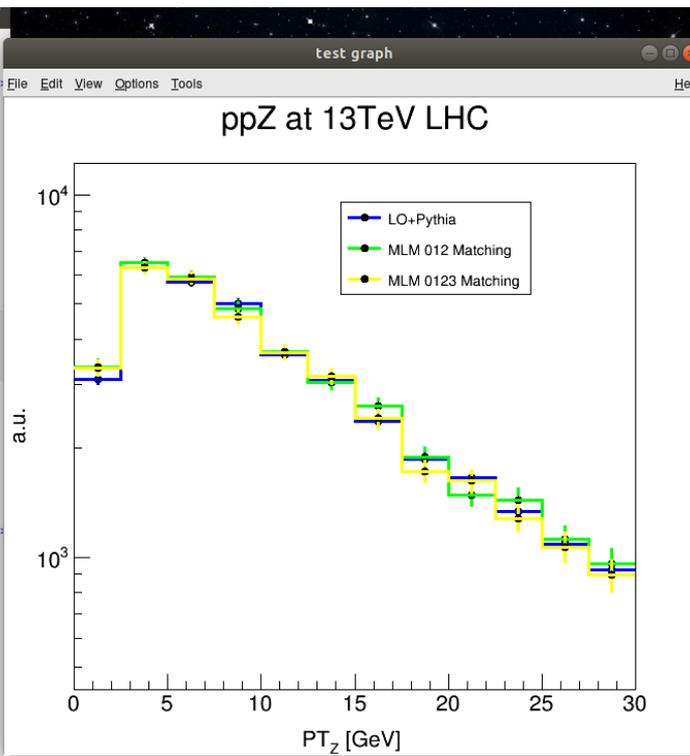
```

///
*****
J15.SetPtEtaPhiE(0.,0.,0.,0.);
treeReader5->ReadEntry(i);
TRootLHEFEvent *event5=(TRootLHEFEvent*)
ranchEvent5->At(0);
int np=event5->Nparticles;
for(int j=2; j<np; j++) {
  TRootLHEFParticle
particle15=(TRootLHEFParticle*) branchParticle5-
At(j);
  if(abs(particle15->PID)==23 ) {
    J15.SetPtEtaPhiE(particle15-
PT,particle15->Eta,particle15->Phi,particle15-
E);
  }
}
cout<<J15.Pt()<<endl;
h5->Fill(J15.Pt(), event5->Weight/10000.0);
///
*****

c1->SetLogy();

h2->SetTitle("ppZ at 13TeV LHC");
h2->GetXaxis()->SetTitle("PT_{Z} [GeV] ");
h2->GetYaxis()->SetTitle("a.u.");
h2->GetXaxis()->CenterTitle();
h2->GetYaxis()->CenterTitle();
h2->SetStats(kFALSE);

```



```

file:///home/qliphy/.cache/fr-qkizIA/unweighted_events.lhe
Muon Collider Collabo... My Drive - Google Drive PKU HEP - Indico The Science a
define j = g u c d s u~ c~ d~ s~
define l+ = e+ mu+
define l- = e- mu-
define vl = ve vm vt
define vl~ = ve- vm- vt-
generate p p > z
add process p p > z j
add process p p > z j j QED=1
add process p p > z j j j QED=1
output ppzmlm0123
</MG5ProcCard>
<MGProcCard>
*****
# MadGraph/MadEvent
# http://madgraph.hep.uiuc.edu
# proc_card.dat
*****
# This Files is generated by MADGRAPH 5
#
# WARNING: This Files is generated for MADEVENT (compatibility
# This files is NOT a valid MG4 proc_card.dat
# Running this in MG4 will NEVER reproduce the result c
#
#*****
# Process(es) requested : mg2 input
#*****
# Begin PROCESS # This is TAG. Do not modify this line
p p > z #Process
# Be careful the coupling are here in MG5 convention
end coup # End the couplings input

```

```

qliphy:~/Desktop/2021Spring/refs/Tutorial/Tutorial1b-ppz
lo-pythia lo.root mlm mlm0123 mlm0123.root nlo Note-PPZ test2.C ZJets
qliphy@qliphy:~/Desktop/2021Spring/refs/Tutorial/Tutorial1b-ppz$ vi test2.C
qliphy@qliphy:~/Desktop/2021Spring/refs/Tutorial/Tutorial1b-ppz$ root -l test2.C
root [0]
Processing test2.C...
Info in <TCanvas::Print>; file PTZ.png has been created

```

[1606.05864] Measurement of the transverse momentum spectra of weak vector bosons produced in proton-proton collisions at  $\sqrt{s} = 8$  TeV ([arxiv.org](https://arxiv.org/abs/1606.05864))

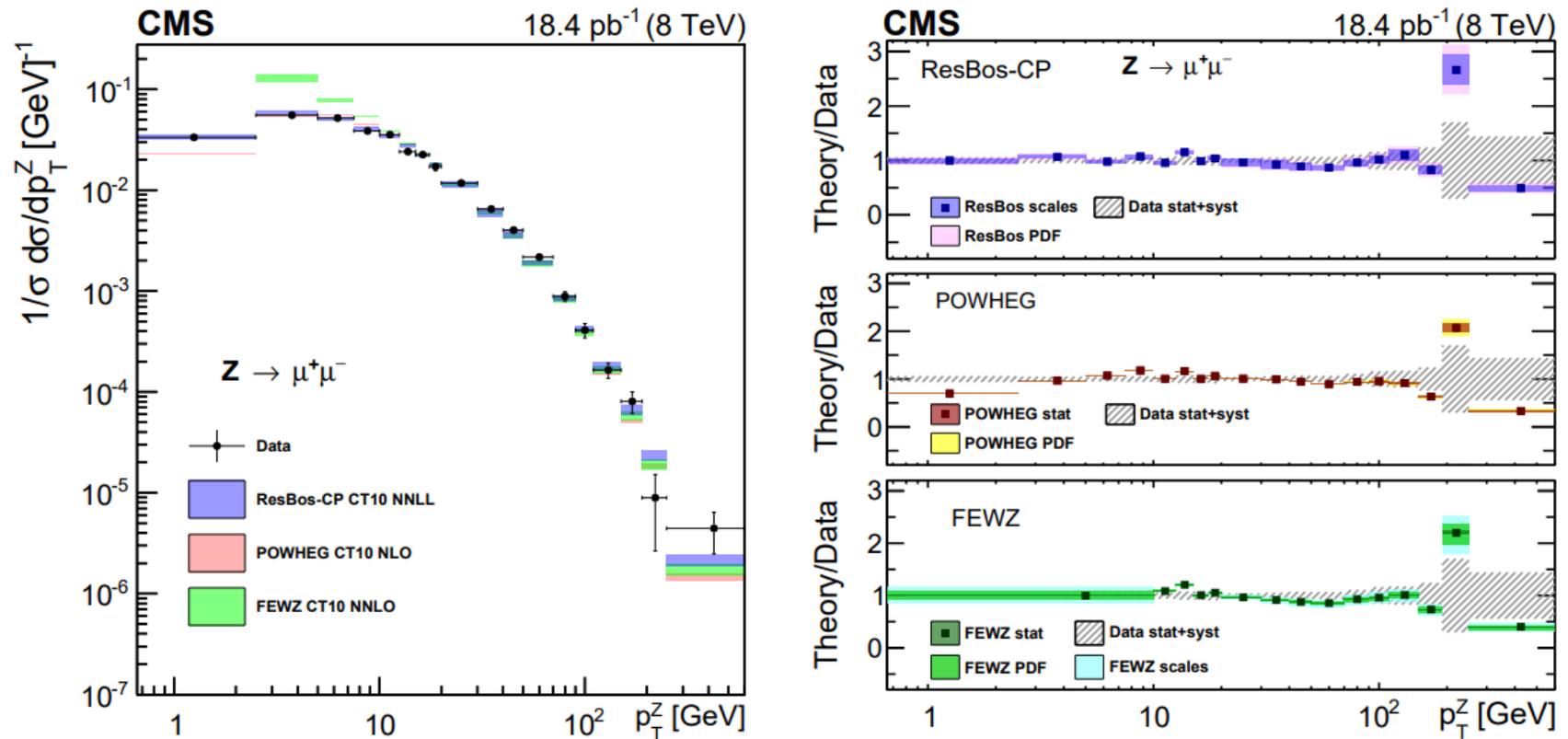
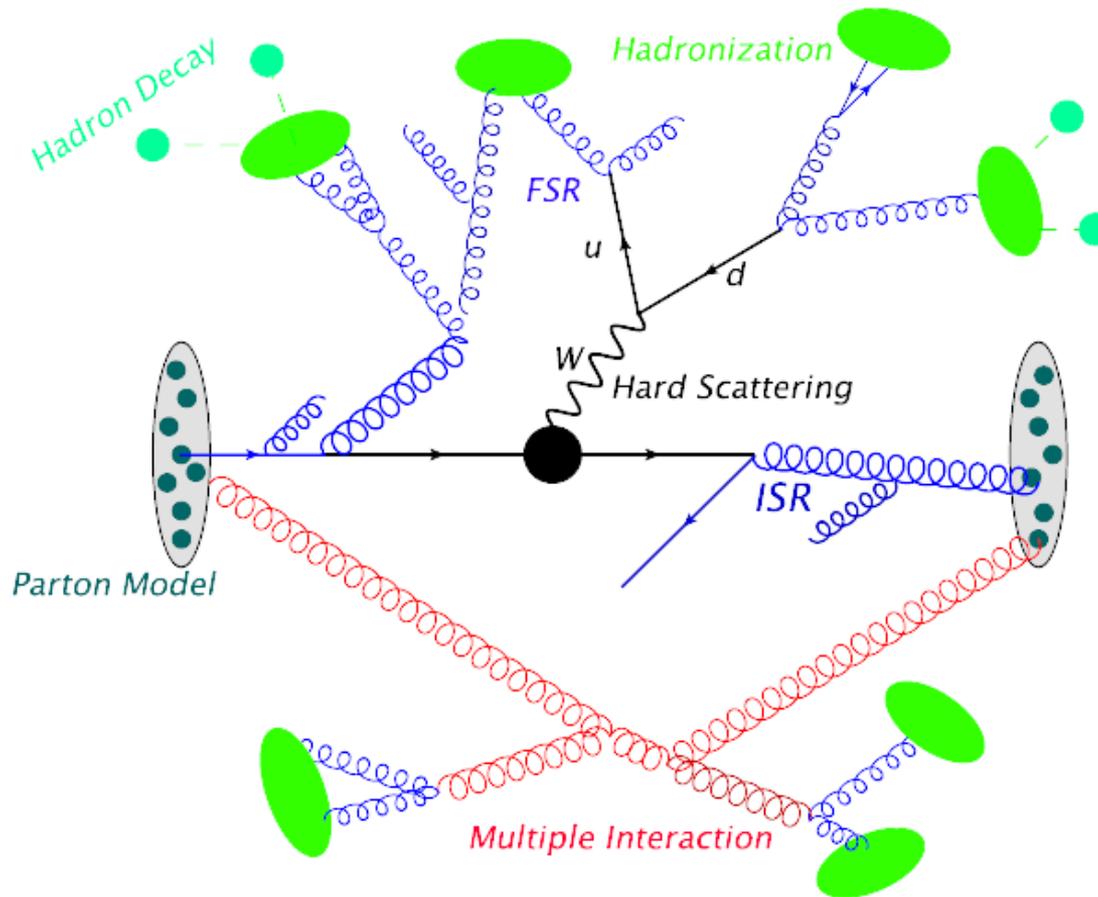


Figure 5: Comparison of the normalized dimuon differential transverse momentum distribution from data (solid symbols) with different theoretical predictions. The right panels show the ratios of theory predictions to the data. The RESBOS-CP version with scale and PDF variation is used for comparison.

# Anatomy of a LHC Collision

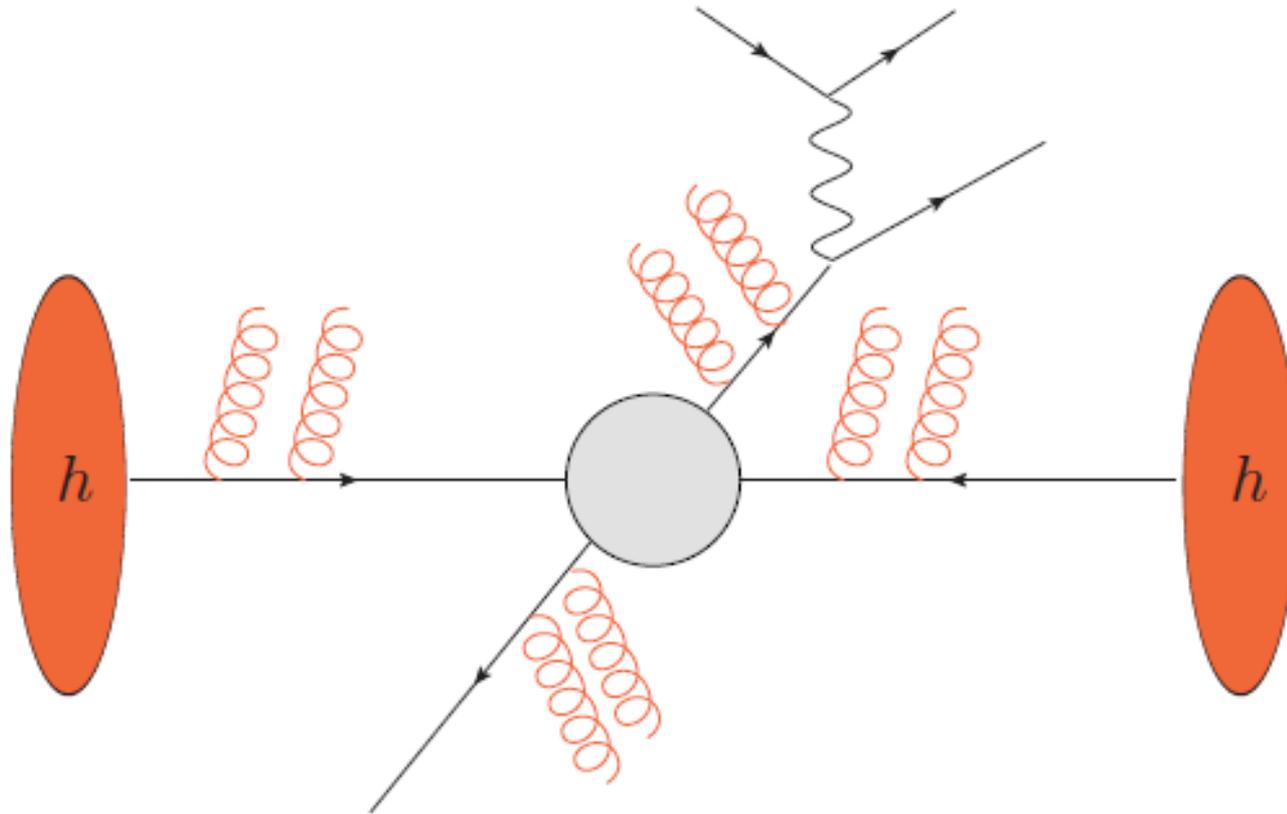


LHC collision: QCD machine



**Only hard scattering  
by now**

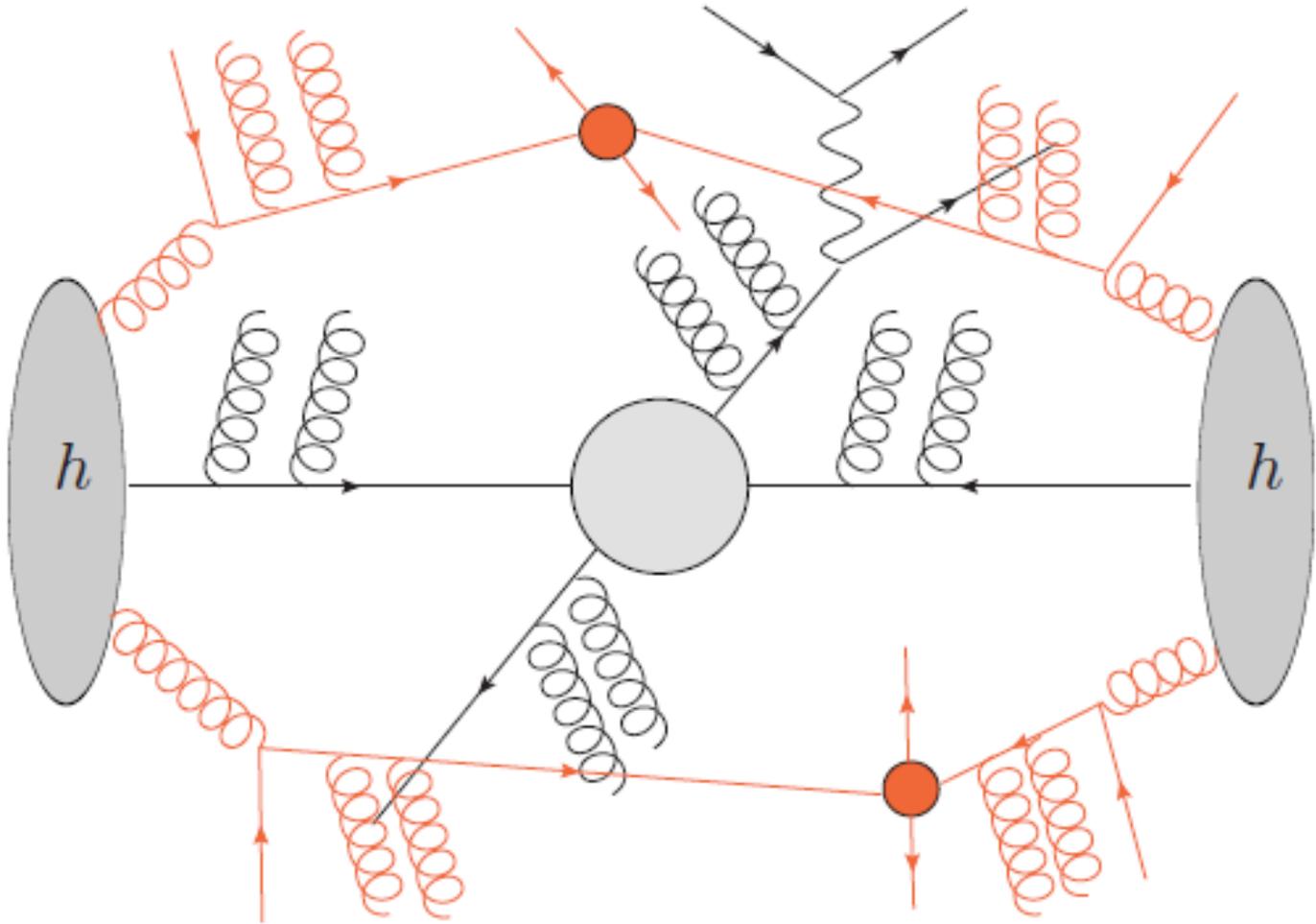
# Parton Shower



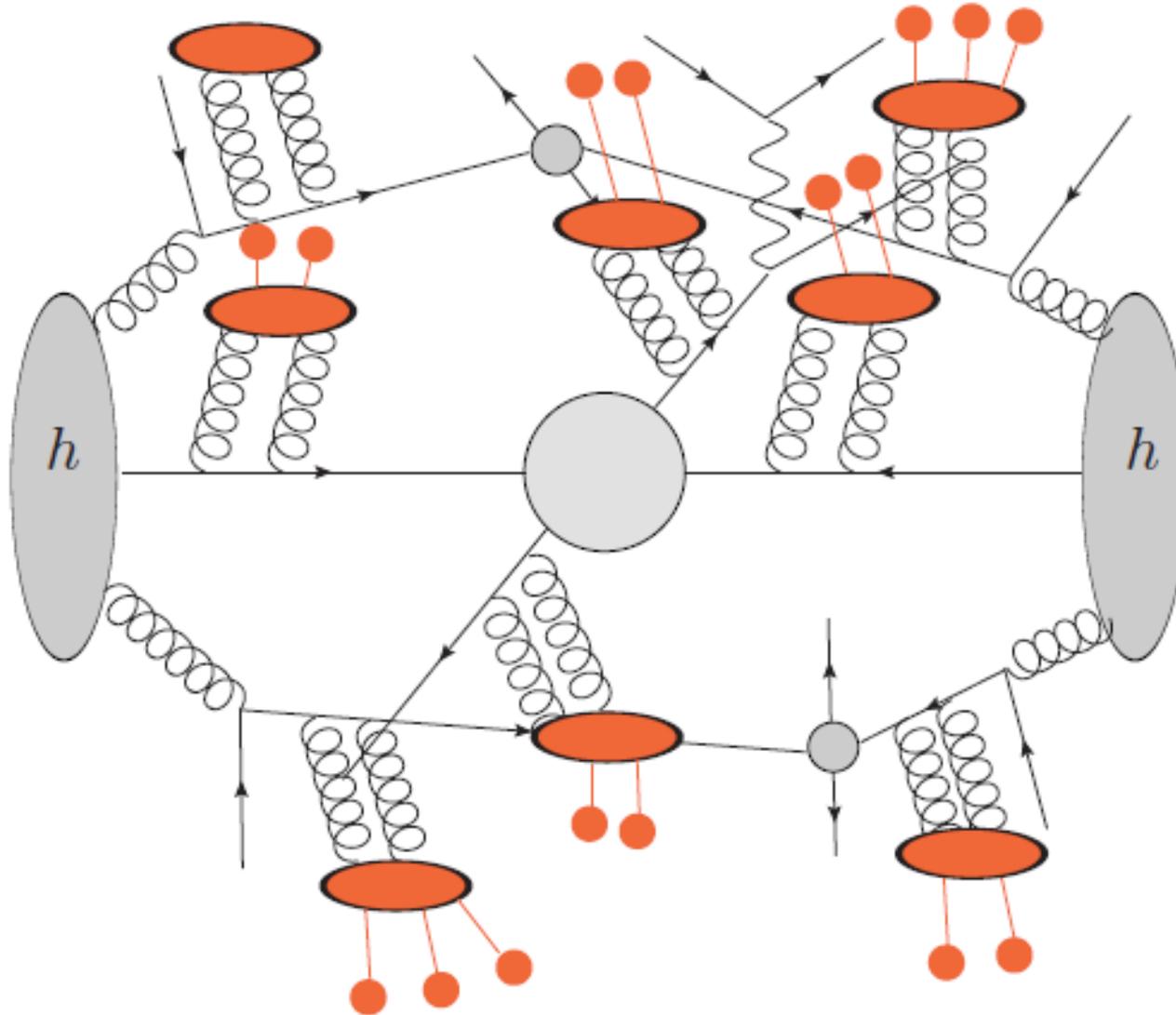
We will see a TeV quark/gluon splits all the way down to low scale

However, we can not calculate  $2 \rightarrow n_j$  with  $n \sim 8-10$

# Multiple Interactions



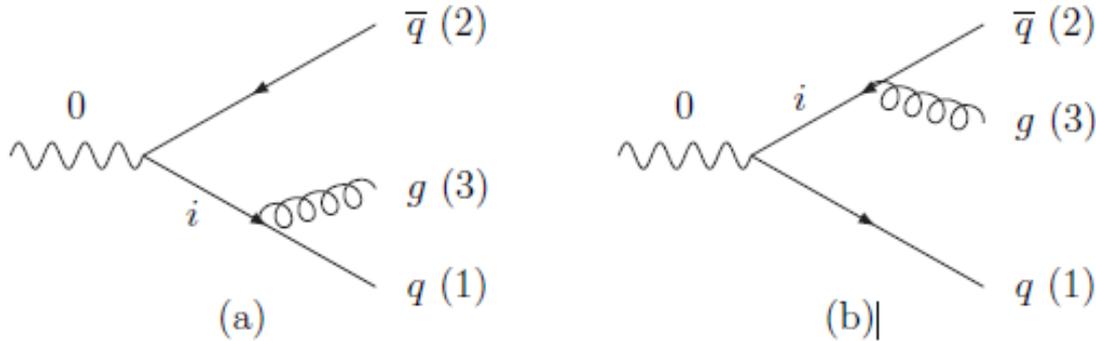
# Hadronization and Decay



# A bit about PS



$$e^+e^- \rightarrow \gamma^*/Z^0 \rightarrow q\bar{q}.$$



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

$$E_q = zE_i \text{ and } E_g = (1-z)E_i$$

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

$$x_2 \rightarrow 1.$$

**1,3 collinear**

**Factorization  
Universal  
Incoherent**

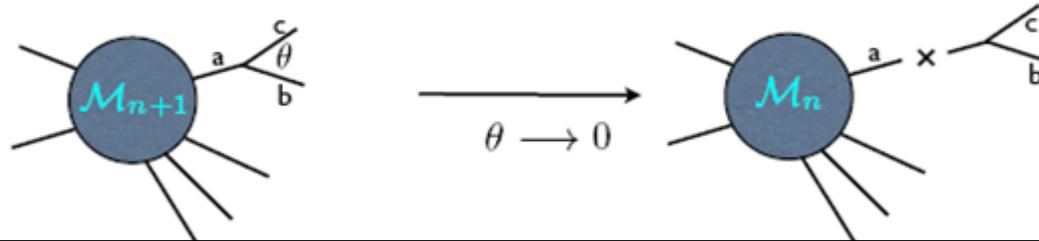
$$1 - x_2 = \frac{m_{13}^2}{E_{\text{cm}}^2} = \frac{Q^2}{E_{\text{cm}}^2} \implies dx_2 = \frac{dQ^2}{E_{\text{cm}}^2}$$

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

$$x_3 \approx 1 - z$$

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

# A bit about PS



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

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

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

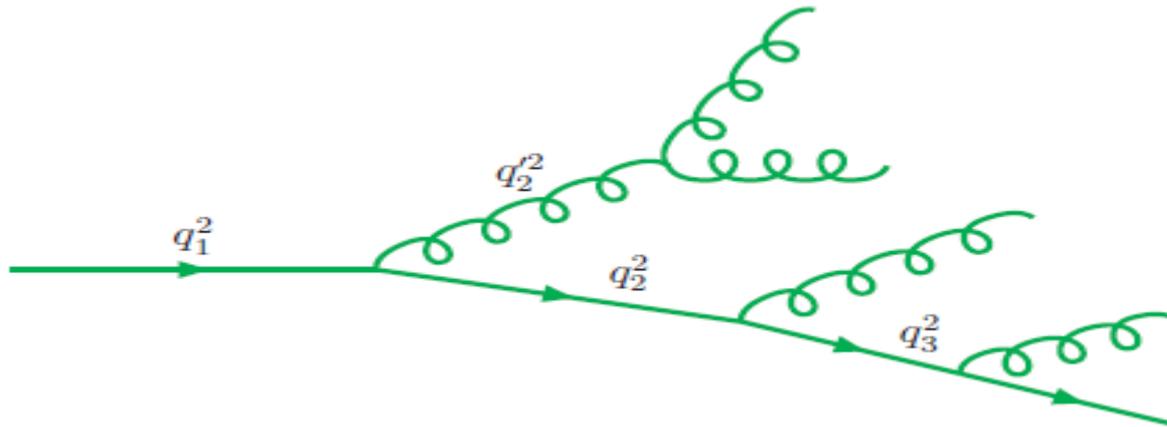
$$P_{g \rightarrow q\bar{q}} = \frac{n_f}{2} (z^2 + (1-z)^2) \quad (n_f = \text{no. of quark flavours})$$

**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  $t$ :

$$\Delta(Q^2, t) = \prod_k \left[ 1 - \sum_{bc} \frac{dt_k}{t_k} \int dz \frac{d\phi}{2\pi} \frac{\alpha_s}{2\pi} P_{a \rightarrow bc}(z) \right] =$$
$$\exp \left[ - \sum_{bc} \int_t^{Q^2} \frac{dt'}{t'} dz \frac{d\phi}{2\pi} \frac{\alpha_s}{2\pi} P_{a \rightarrow bc}(z) \right] = \exp \left[ - \int_t^{Q^2} dp(t') \right].$$

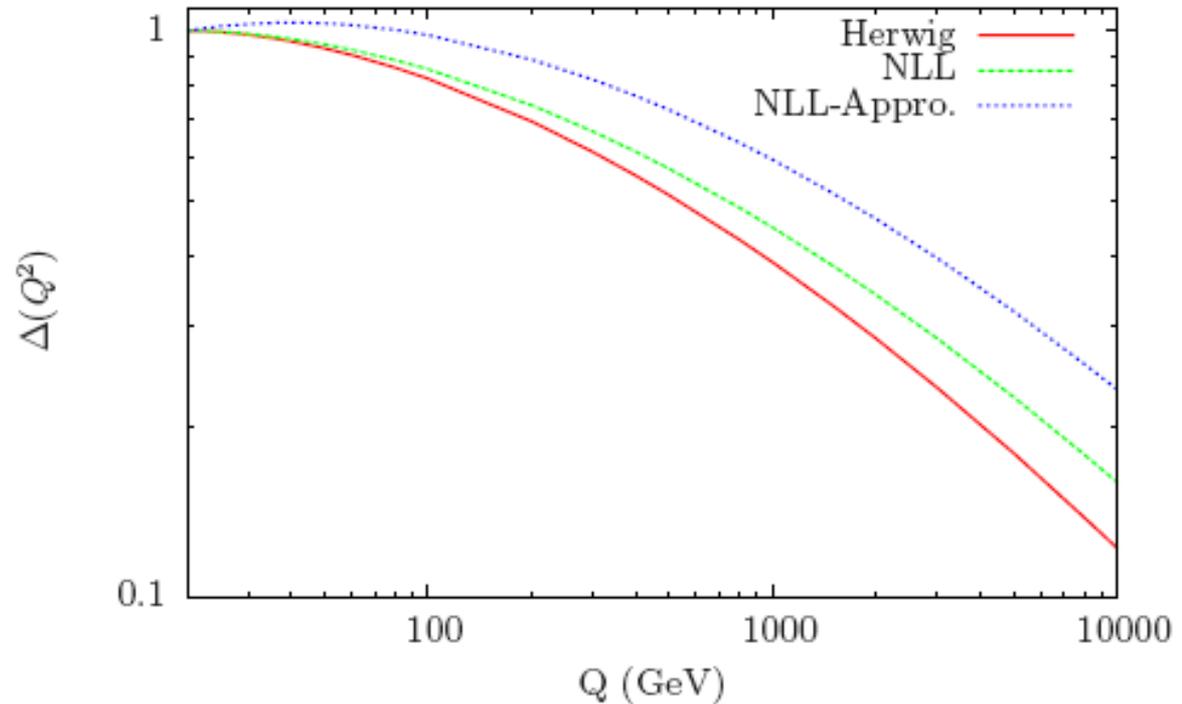
- ▶  $\Delta(Q^2, t)$  is the Sudakov form factor.
- ▶ Property:  $\Delta(A, B) = \Delta(A, C)\Delta(C, B)$ .

**Sudakov Factor**

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

Quark Sudakov,  $Q_0 = \sqrt{t_0} = 10 \text{ GeV}$

A TeV  
quark has  
large  
probability  
to split



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

$$\Delta_{a \rightarrow bc}(Q) = \exp \left\{ - \int_{Q_1=2\sqrt{t_0}}^Q dq \Gamma_{a \rightarrow bc}(q, Q) \right\} \quad \Gamma_{q \rightarrow qg} = \frac{2C_F}{\pi} \frac{\alpha_S(q)}{q} \left( \ln \frac{Q}{q} - \frac{3}{4} \right)$$

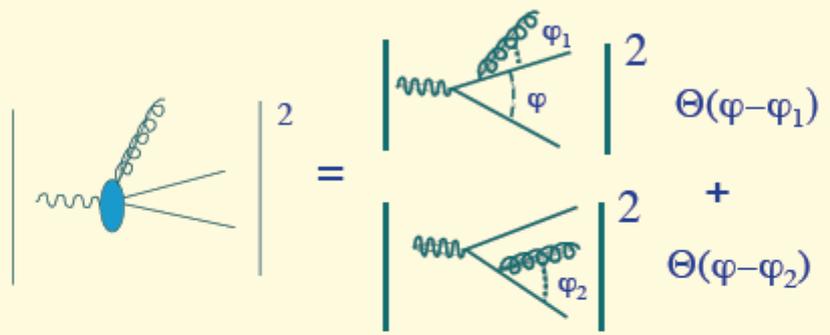
# A bit about PS



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

Angular ordering  
(slide by M. Mangano)

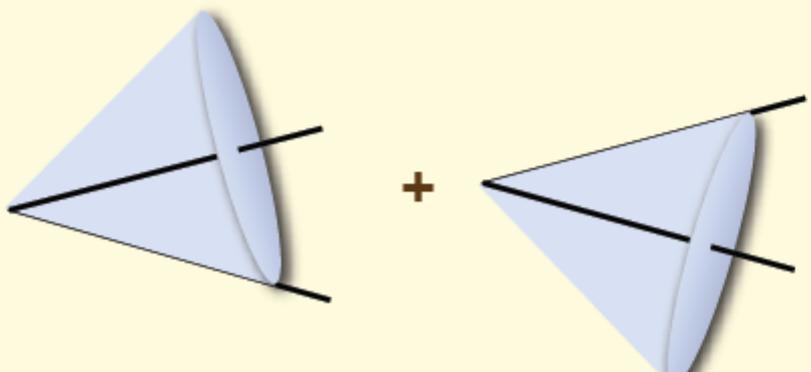
## Angular ordering



**Soft limit:  $E_3 \rightarrow 0$  i.e.  $z \rightarrow 1$**   
**Not like in collinear limit,**  
**There will be interference**

**Fortunately, we can**  
**implement the effects by**  
**angular ordering**

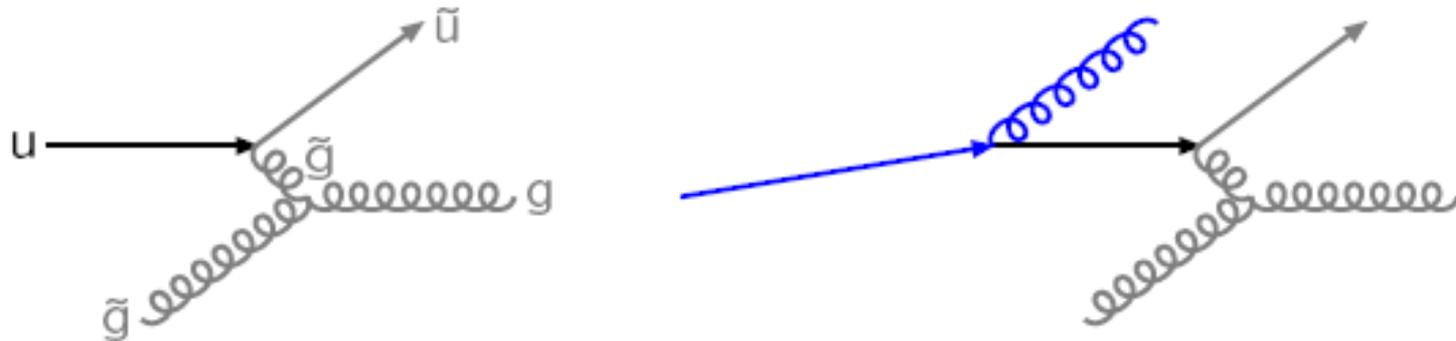
Radiation inside the cones is allowed, and described by the eikonal probability, radiation outside the cones is suppressed and averages to 0 when integrated over the full azimuth



# A bit about PS



## ISR Involves PDF



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

$$\frac{df_b(x, Q^2)}{dt} = \sum_a \int_x^1 \frac{dz}{z} f_a(x', Q^2) \frac{\alpha_S}{2\pi} P_{a \rightarrow bc}(z)$$

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

$$d\mathcal{P}_b = \frac{df_b}{f_b} = |dt| \sum_a \int dz \frac{x' f_a(x', t)}{x f_b(x, t)} \frac{\alpha_S}{2\pi} P_{a \rightarrow bc}(z)$$

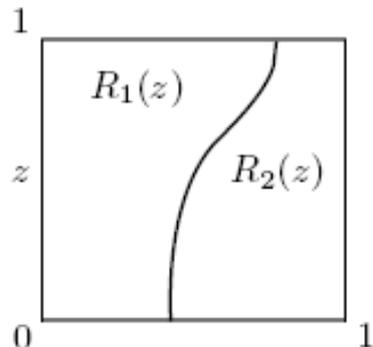
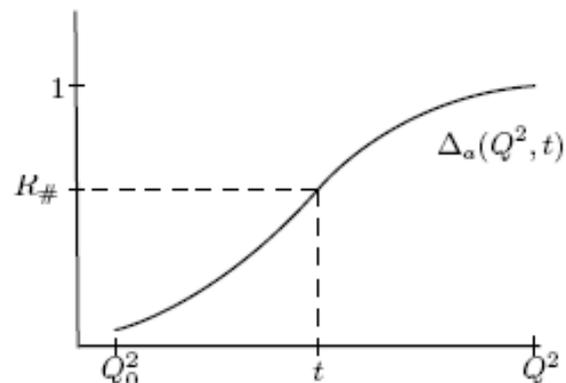
then solve for *decreasing*  $t$ , i.e. backwards in time,  
starting at high  $Q^2$  and moving towards lower,  
with Sudakov form factor  $\exp(-\int d\mathcal{P}_b)$

# 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  $P_{a \rightarrow bc}(z)$ . 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  $Q_0^2 \sim 1 \text{ GeV}$ .
- ▶ Put partons on shell and hadronize.

# 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  $PT_G$ .
- **$G + 2, 3j$** : 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?

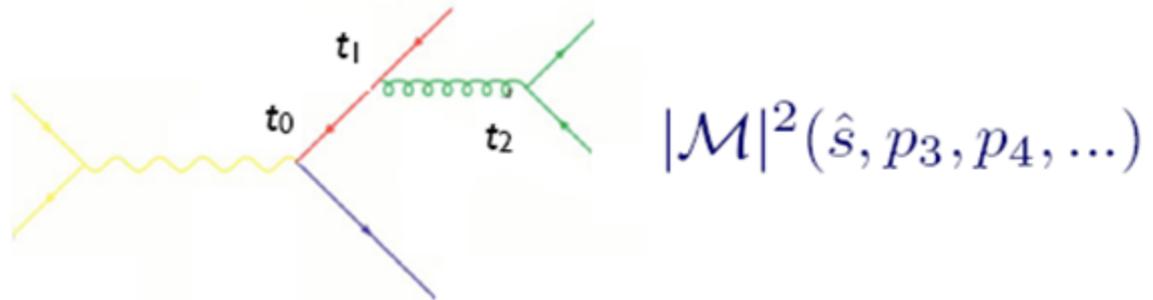
# ME+PS Matching: MLM, CKKW

---



- 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-weighting.  
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.

## Mimic PS history



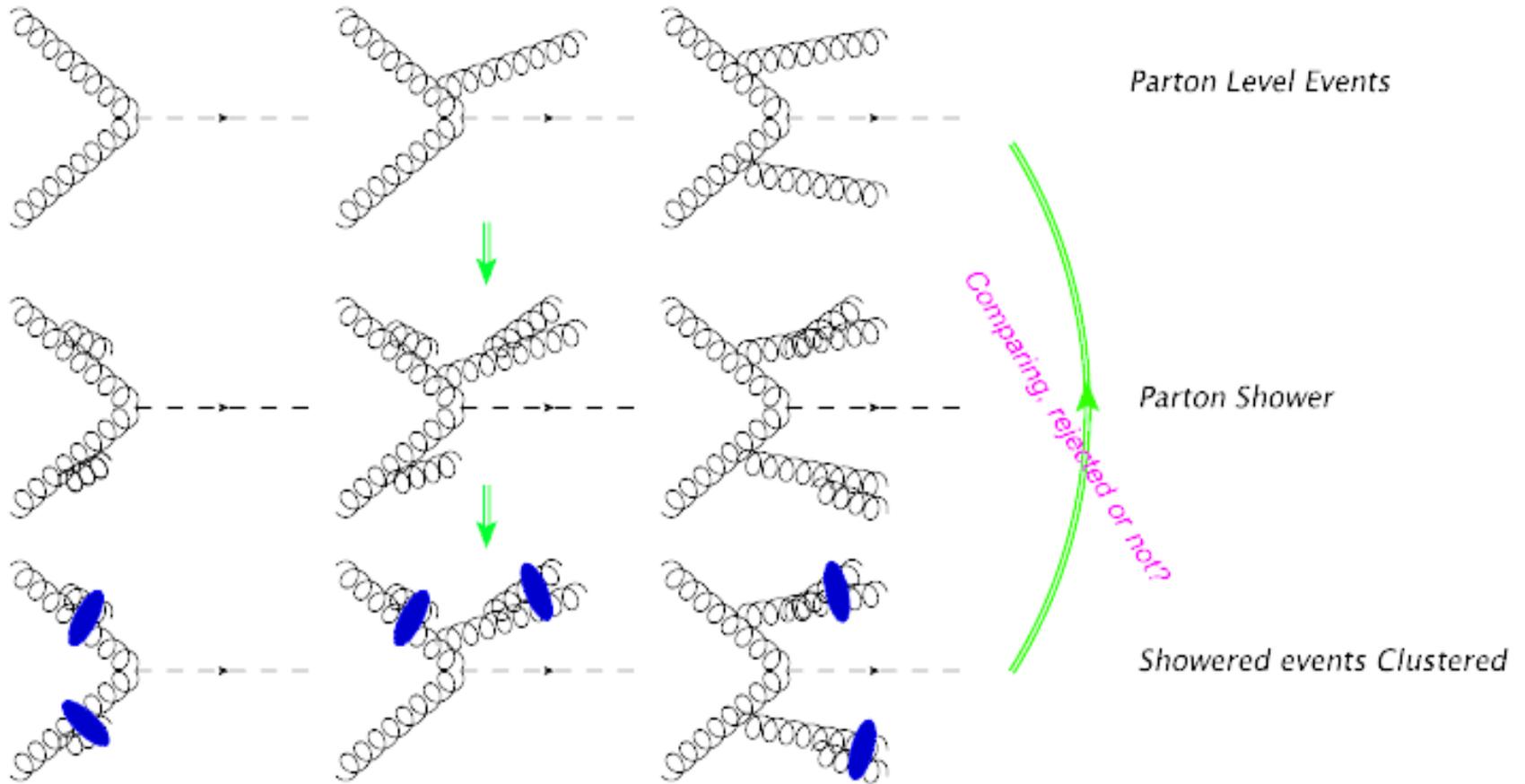
- To get an equivalent treatment of the corresponding matrix element, do as follows:

1. Cluster the event using some clustering algorithm  
- this gives us a corresponding “parton shower history”
2. Reweight  $\alpha_s$  in each clustering vertex with the clustering scale

$$|\mathcal{M}|^2 \rightarrow |\mathcal{M}|^2 \frac{\alpha_s(t_1)}{\alpha_s(t_0)} \frac{\alpha_s(t_2)}{\alpha_s(t_0)}$$

3. Use some algorithm to apply the equivalent Sudakov suppression  $(\Delta_q(t_{\text{cut}}, t_0))^2 \Delta_g(t_2, t_1) (\Delta_q(\text{cut}, t_2))^2$

# Multi-leg Matrix Element Matching



# Example: $PP \rightarrow Z+0,1,2$ 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 fall fragmentation cuts = 0.52890 *****
```

Cross section (pb): 1790.4565567581010

**Cross-section : 3799 +- 8.8 pb**

**Nb of events : 10000**

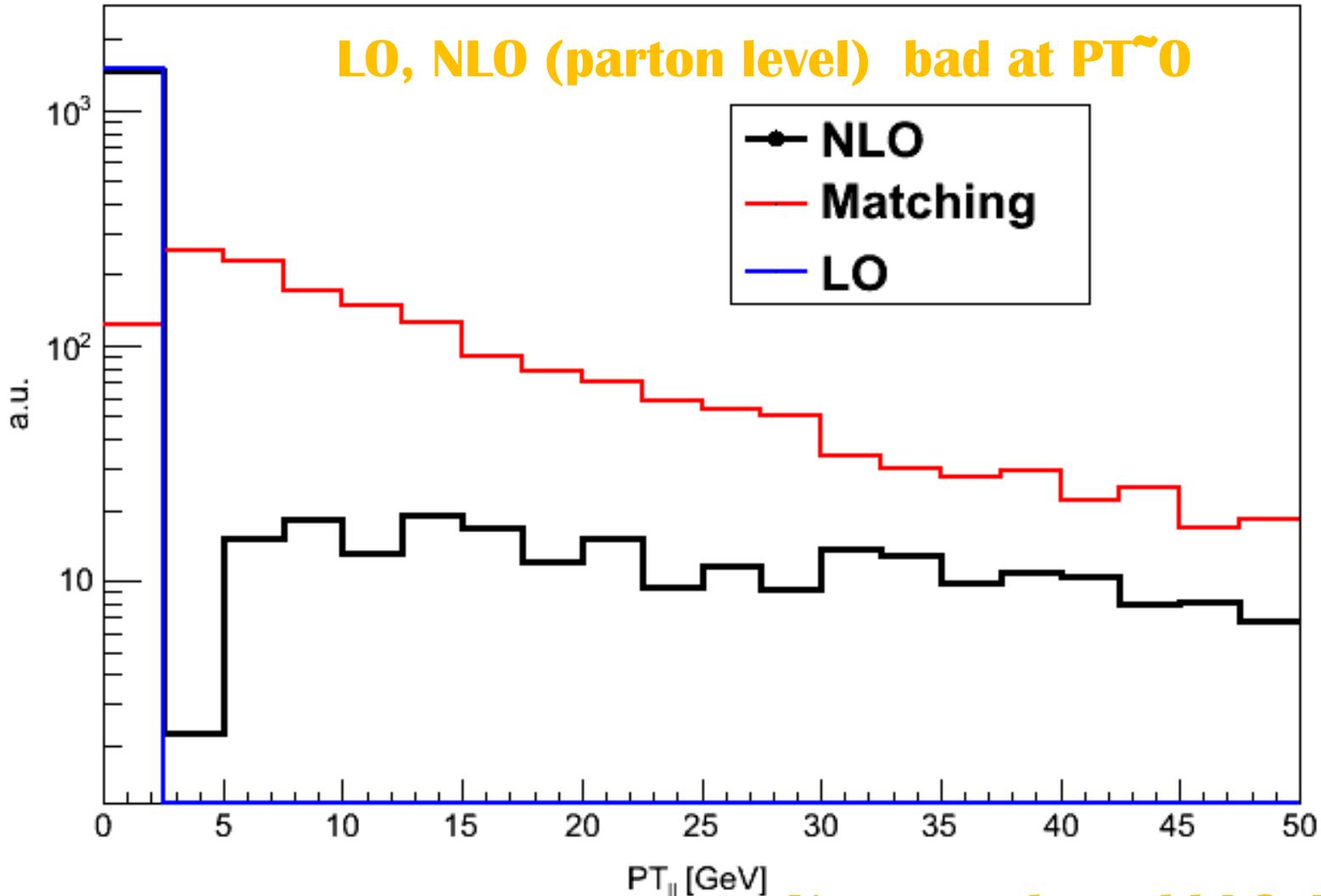
**Matched Cross-section : 1790 +- 19.41 pb**

**Nb of events after Matching : 4711**

# Example: LO vs NLO vs Matching



$pp \rightarrow \mu^+\mu^-$  at 13TeV LHC



**You can also add LO+Pythia**

# NLO+PS Matching: MC@NLO, POWHEG



**NLO has one additional parton emission**

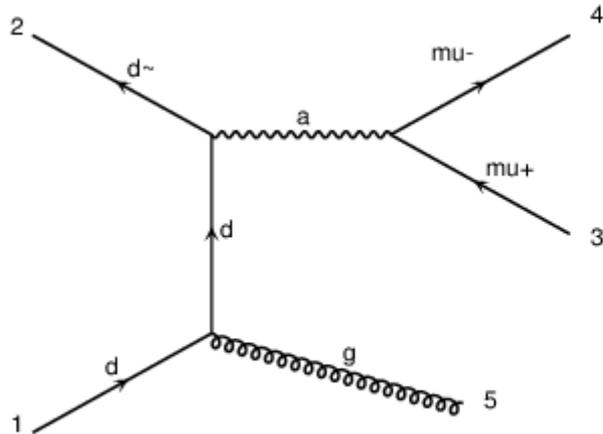
**NLO has higher accurate xsec**

**PS generate 1 or more emissions**

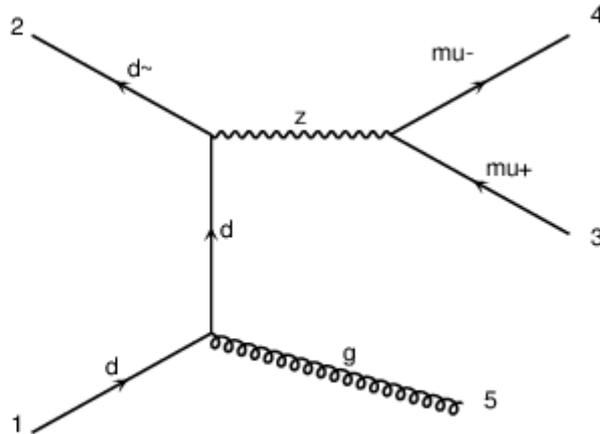
**To avoid double counting, needs to be very careful**

**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](https://doi.org/10.1088/1126-6708/2007/11/070)

e-Print: [arXiv:0709.2092](https://arxiv.org/abs/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](https://doi.org/10.1088/1126-6708/2003/08/007)

e-Print: [hep-ph/0305252](https://arxiv.org/abs/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](https://doi.org/10.1088/1126-6708/2002/06/029)

e-Print: [hep-ph/0204244](https://arxiv.org/abs/hep-ph/0204244) | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

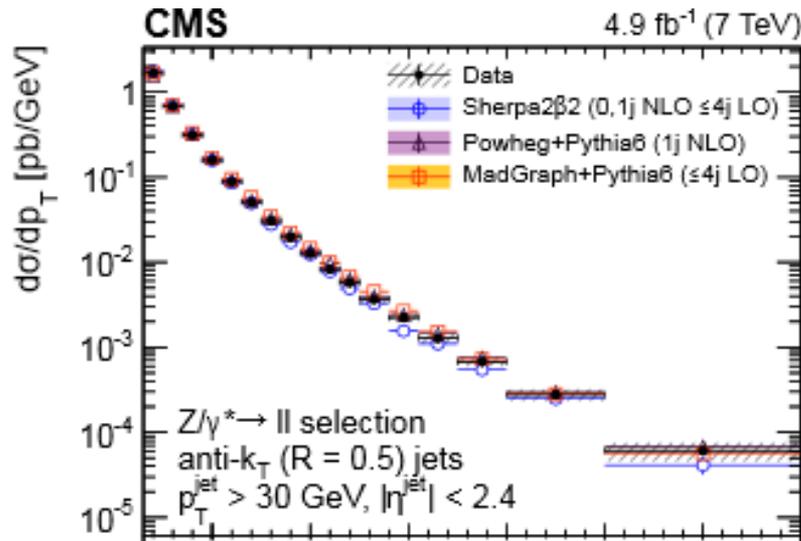
[ADS Abstract Service](#); [CERN Library Record](#); [JHEP Electronic Journal Server](#)

[详细记录](#) - [Cited by 1438 records](#) **1000+**

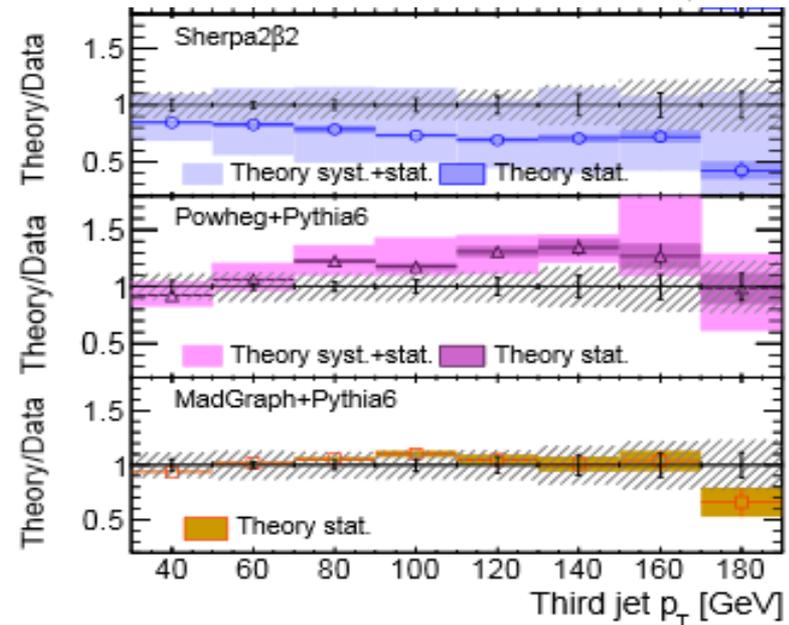
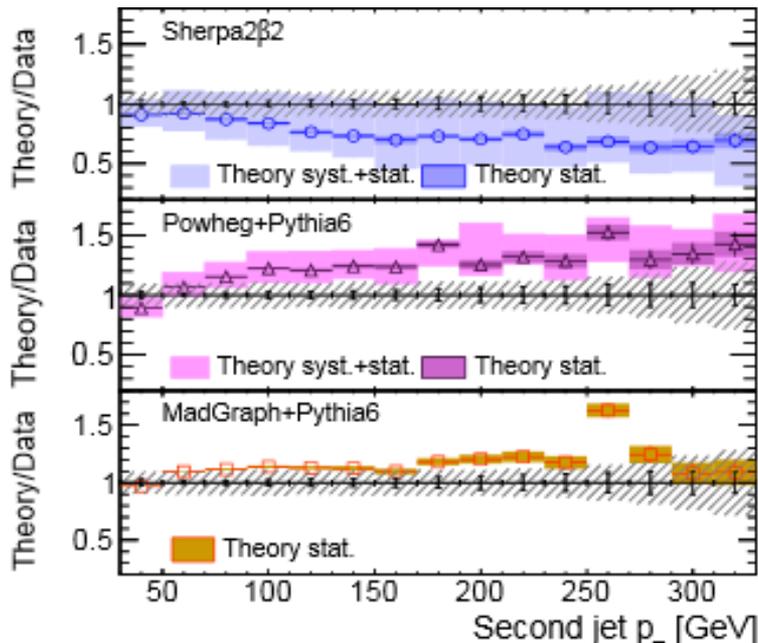
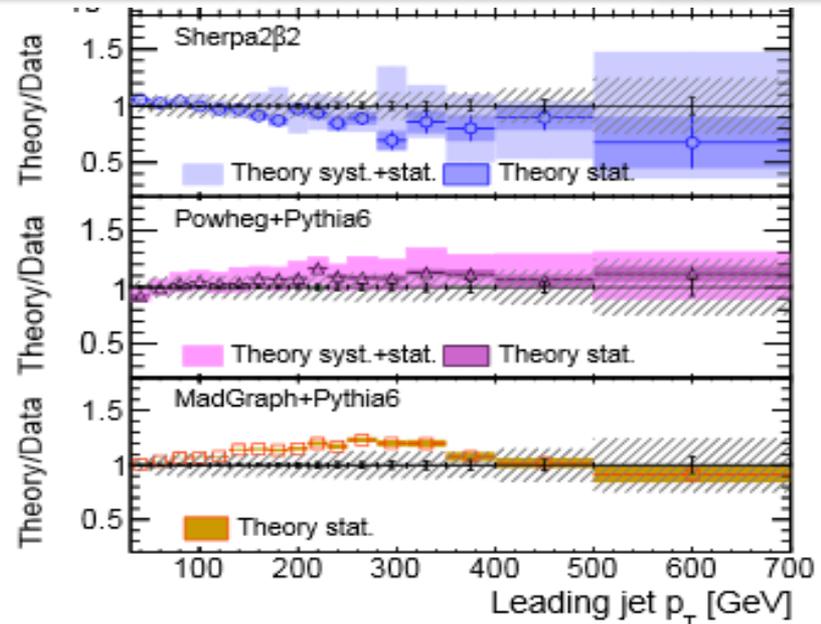
**Until**  
**2014/03/12**

# Experimental Usage

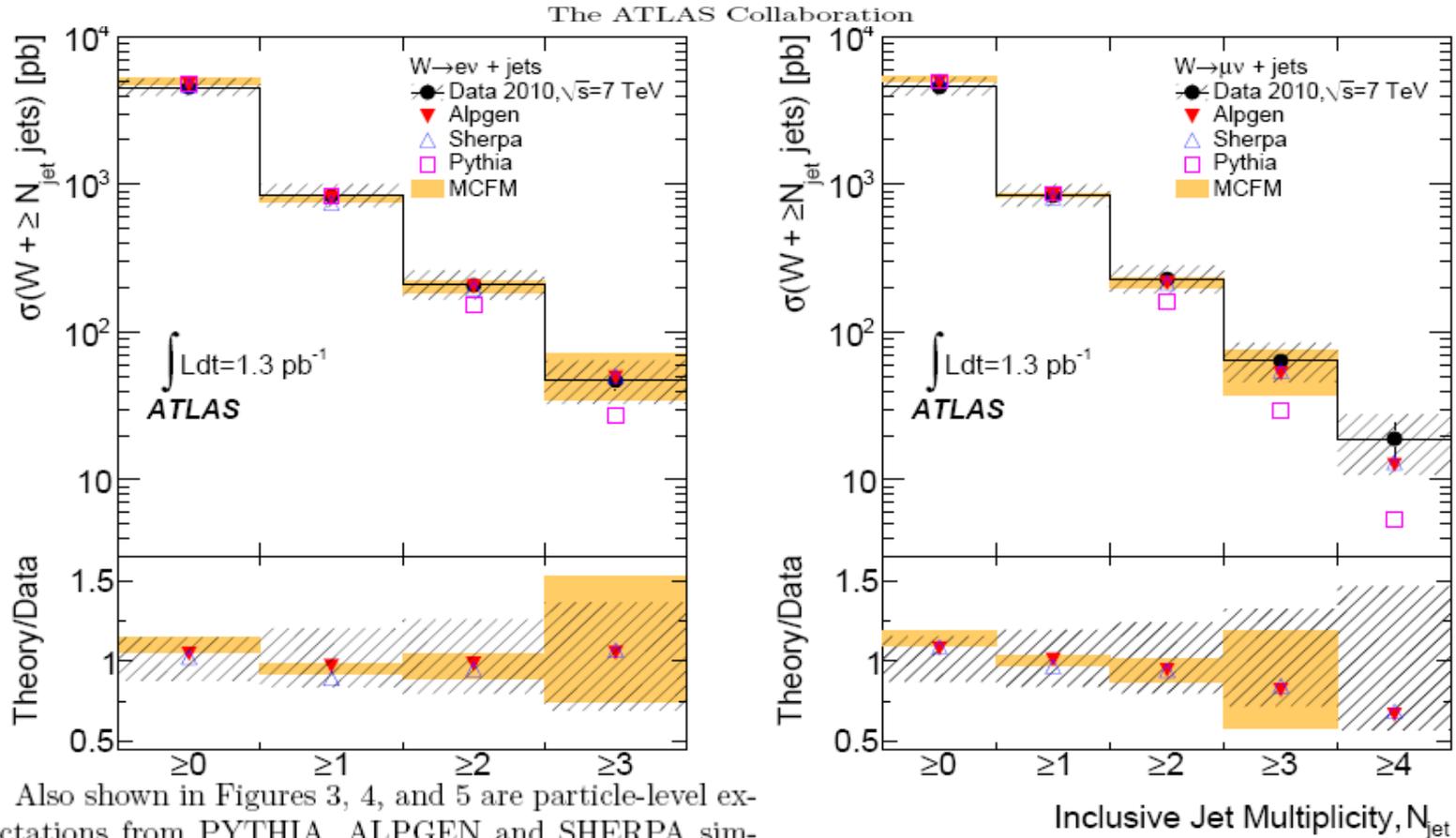
## CMS 7TeV Z+Jets



[arXiv:1408.3104](https://arxiv.org/abs/1408.3104)

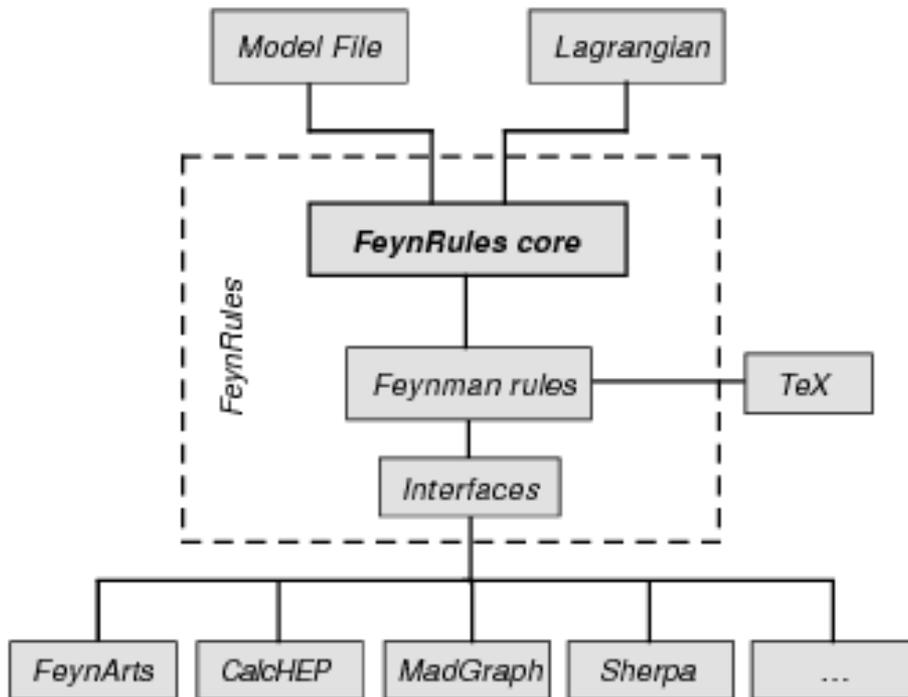


Measurement of the production cross section for W-bosons in association with jets in  $pp$  collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector



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

# BSM implementations



**FeynRules->  
UFO/ALOHA->  
MG**

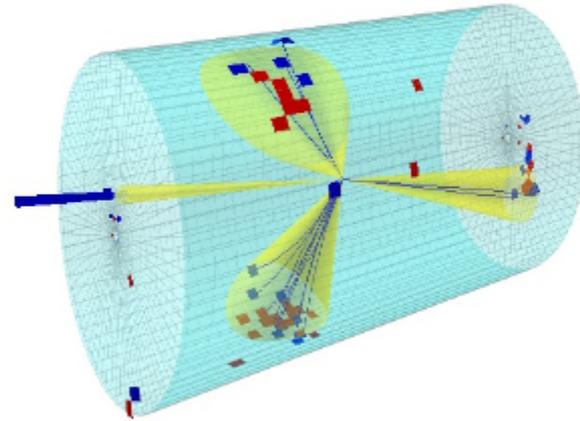
## A Mathematica package to calculate Feynman rules

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 tracking efficiency  
#####
```

## Muon 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) }  
}
```

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

## Muon momentum smearing

```
  # 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) }  
}
```

```
# 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
```

## geometry

```
}
```

## 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

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

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

All are important for Tune!

Pythia6 Z2\*, Herwig 4C ...