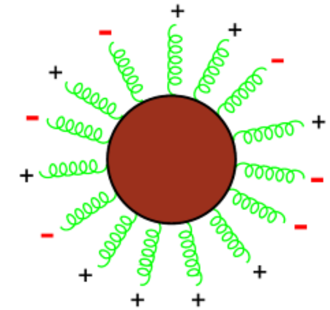

QCD and Monte Carlo

4. Modern Perturbative Techniques & Tools

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Universidad Simon Bolivar, Caracas, Venezuela

Fermilab-CERN Hadron Collider Physics Summer School

August 11-22, 2014, , Fermilab, Chicago

THE NLO REVOLUTION

Need for Higher Orders, High Multiplicity, Whish List

REVISITING GAUGE TREES

MHV, Complexify Momenta, BCFW

NLO CALCULATIONS

Feynman Diagrams, Integral Basis, OPP, Quad Cuts Exm

TOOLS FOR HIGHER ORDERS

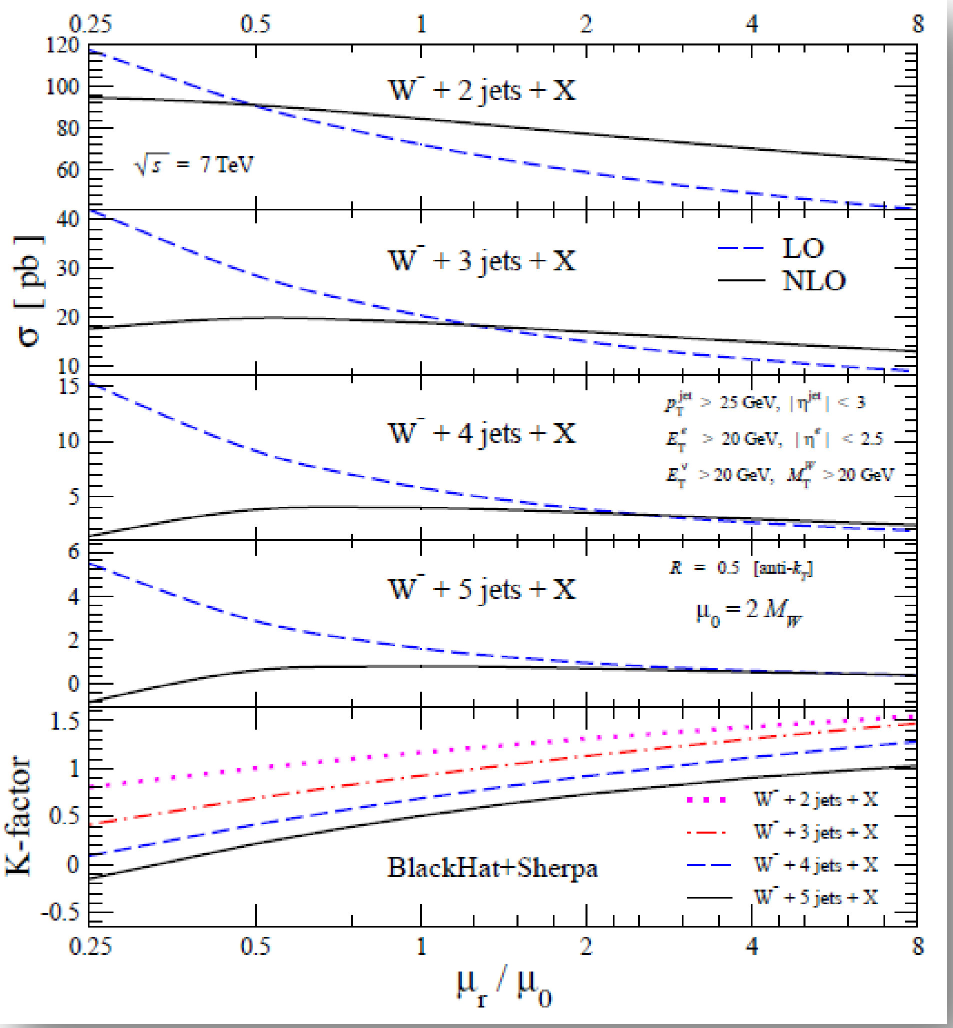
NLO, Automation, NLO Shower, NNLO

NLO More Important for Larger Jet Multiplicities

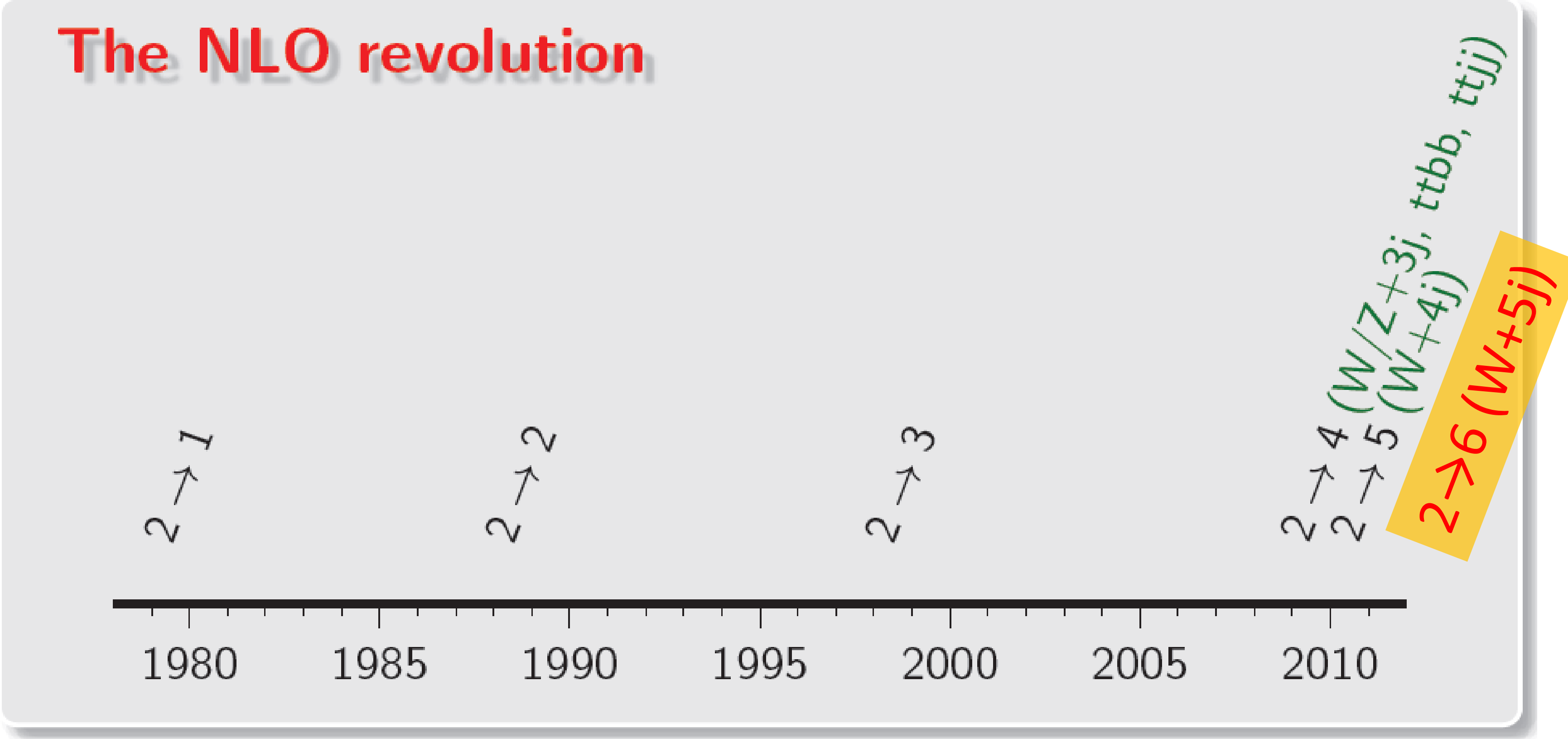
[Bern, Dixon, FFC, Hoeche, Ita, Kosower, Maitre, Ozeren arXiv:1304.1253]

W+ *n* Jet Production

- LO unphysical scale dependence is large
- It grows with jet multiplicity
- Even more, shapes of distributions modified by quantum corrections
- NLO scale uncertainty more stable over multiplicity of jets
- NLO gives first quantitative prediction for observables
- Precision QCD (down to few percent uncertaity) needs NNLO!



The NLO revolution



2009: NLO $W+3j$ [Rocket: Ellis, Melnikov & Zanderighi] [unitarity]
2009: NLO $W+3j$ [BlackHat: Berger et al] [unitarity]
2009: NLO $t\bar{t}b\bar{b}$ [Bredenstein et al] [traditional]
2009: NLO $t\bar{t}b\bar{b}$ [HELAC-NLO: Bevilacqua et al] [unitarity]
2009: NLO $q\bar{q} \to b\bar{b}b\bar{b}$ [Golem: Binoth et al] [traditional]
2010: NLO $t\bar{t}jj$ [HELAC-NLO: Bevilacqua et al] [unitarity]
2010: NLO $Z+3j$ [BlackHat: Berger et al] [unitarity]

2010: NLO $W+4j$ [BlackHat: Berger et al] [unitarity]

The Les Houches NLO Wish List Few Years ago

Status Les Houches 2009

$pp \to W\,W$ jet	Dittmaier/Kallweit/Uwer; Campbell/Ellis/Zanderighi
	Binoth/Guillet/Karg/Kauer/Sanguinetti
$pp \to Z\,Z$ jet	Binoth/Gleisberg/Karg/Kauer/Sanguinetti; Dittmaier/Kallweit
$pp \to t\bar{t}\,b\bar{b}$	Bredenstein/Denner/Dittmaier/Pozzorini;
	Bevilacqua/Czakon/Papadopoulos/Pittau/Worek
$pp \to t\bar{t} + 2$ jets	Bevilacqua/Czakon/Papadopoulos/Worek
$pp \to Z\,Z\,Z$	Lazopoulos/Melnikov/Petriello; Hankele/Zeppenfeld
$pp \to V\,V\,V$	Binoth/Ossola/Papadopoulos/Pittau; Zeppenfeld et al.
$pp \to V\,V\,b\bar{b}$	
$pp \to W\,\gamma$ jet	Campanario/Englert/Spannowsky/Zeppenfeld
$pp \to V\,V + 2$ jets	VBF: Bozzi/Jäger/Oleari/Zeppenfeld, VBFNLO coll.
$pp \to W + 3$ jets	BlackHat coll.; Ellis/Giele/Kunszt/Melnikov/Zanderighi *
$pp \to Z + 3$ jets	BlackHat collaboration
$pp \to b\bar{b}b\bar{b}$	Binoth/Greiner/Guffanti/Guillet/Reiter/Reuter

● done ● partial results * leading colour only

NNLO QCD+NLO EW wishlist

Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)

add a column here for current exp precision and that expected at 14 TeV

N. Glover, S. Dittmaier

Modern Wish List (2013) more challenging and thought out!

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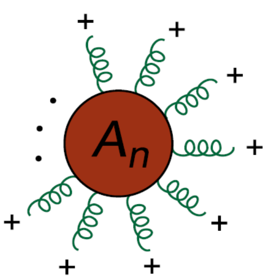
On-shell simplifications

- Calculated ON-SHELL, amplitudes much simpler than expected.

- For example: some tree level all-multiplicity gluon amplitudes can fit on a page:



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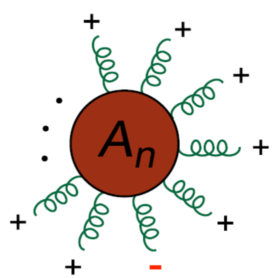

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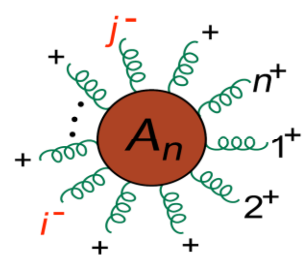
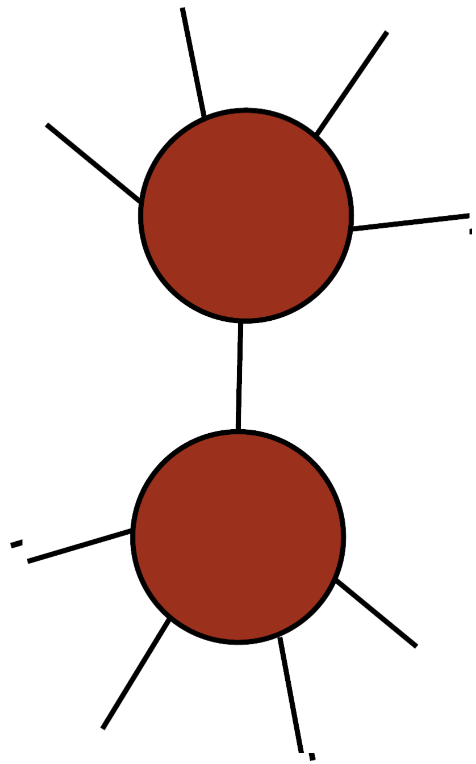


$$= \frac{\langle i\, j\rangle^4}{\langle 1\, 2\rangle\langle 2\, 3\rangle\cdots\langle n\, 1\rangle}$$

Park, Taylor

Factorization

How amplitudes "fall apart" into simpler ones in special limits

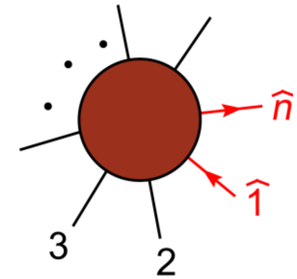


Explore limits in complex plane

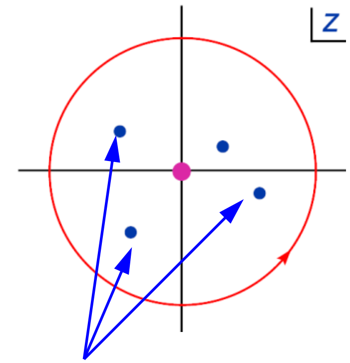
Britto, Cachazo, Feng, Witten, hep-th/0501052

Inject complex momentum at leg 1, remove it at leg *n*.

$$k_1(z) + k_n(z) = k_1 + k_n$$
$$k_1^2(z) = k_n^2(z) = 0$$
$$\Rightarrow \quad A(0) \rightarrow A(z)$$



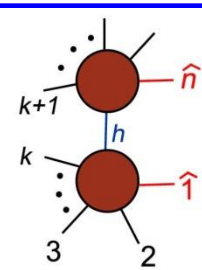
special limits ⇔ poles in *z*



Cauchy: If $A(\infty) = 0$ then

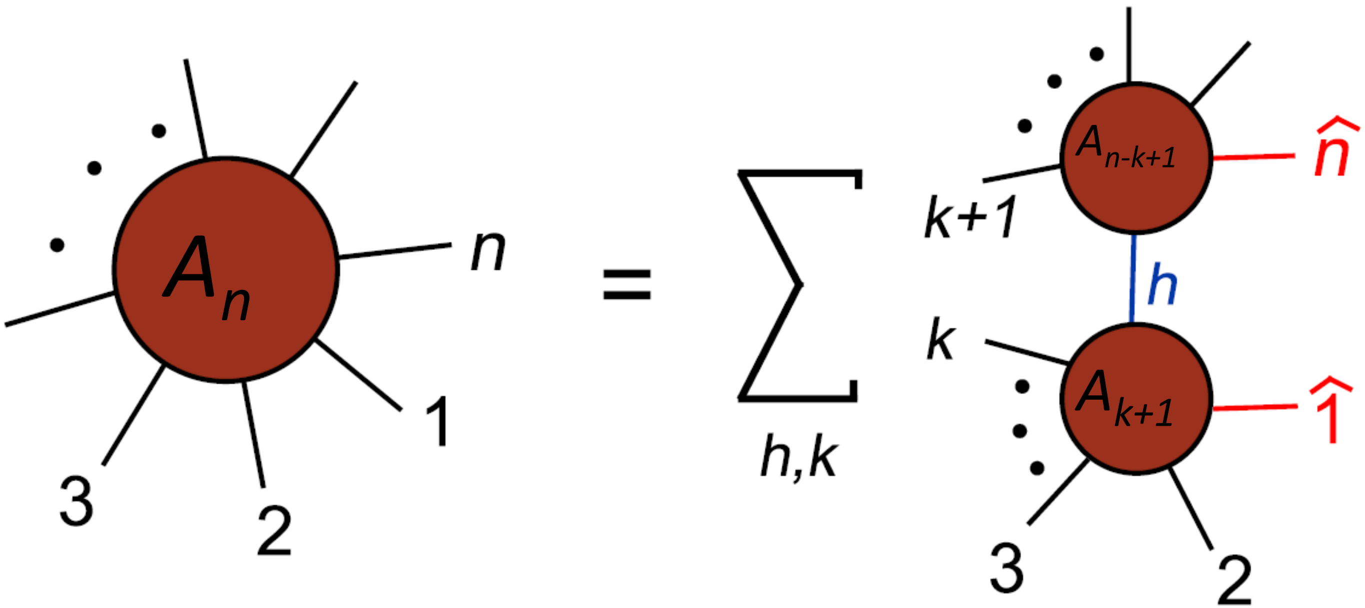
$$0 = \frac{1}{2\pi i} \oint dz \frac{A(z)}{z} = A(0) + \sum_k \mathrm{Res}\left[\frac{A(z)}{z}\right]\Big|_{z=z_k}$$

residue at z_k = [k^{th} factorization limit] =



→ BCFW (on-shell) recursion relations

Britto, Cachazo, Feng, hep-th/0412308



A_{k+1} and A_{n-k+1} are on-shell tree amplitudes with **fewer** legs, and with momenta shifted by a **complex** amount

Trees recycled into trees!

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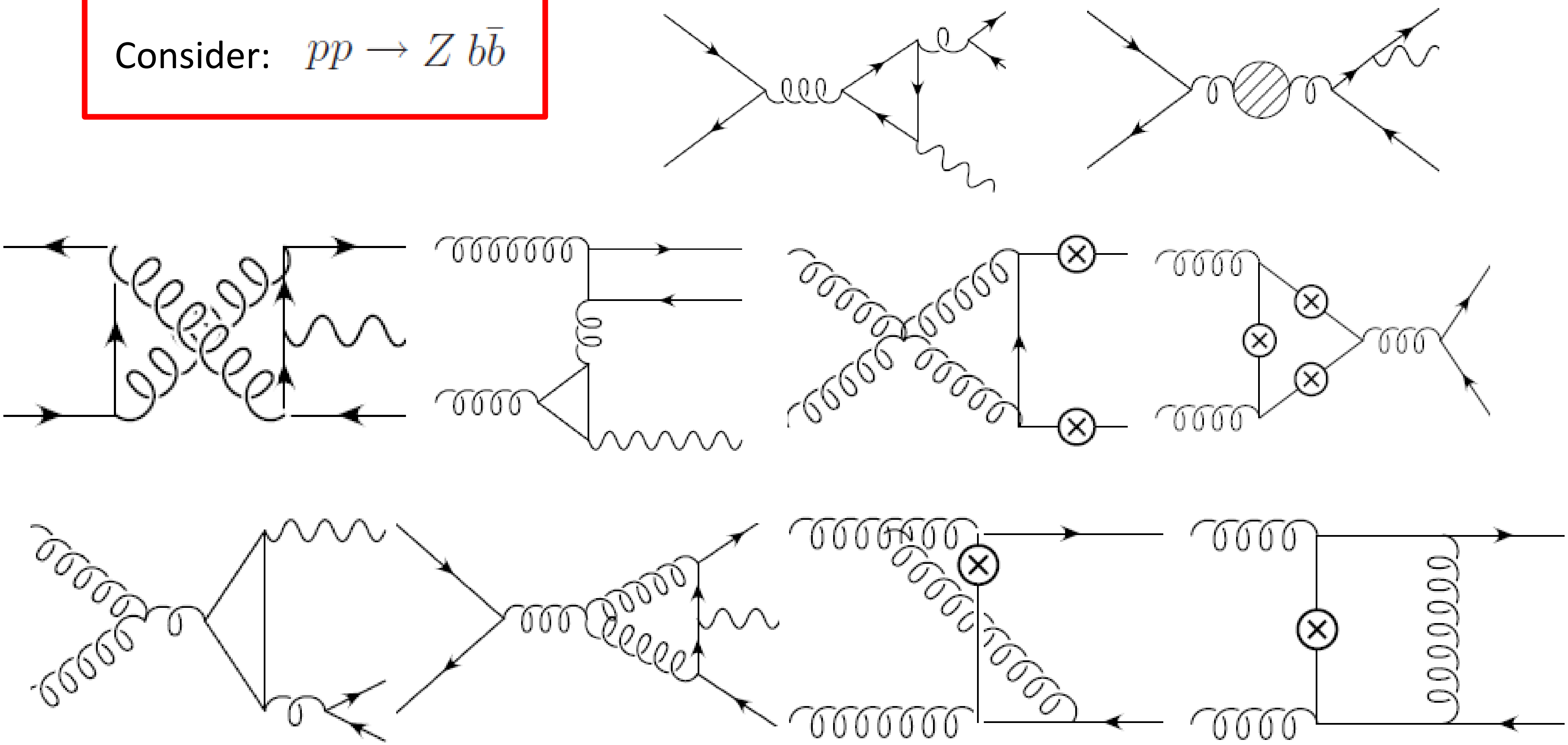
Feynman Diagrams

- Tool to compute amplitudes in Quantum Field Theories
- *Easy* to use
- In principle applies to all kind of processes and to all orders
- Tree level automation manageable (at least for up to 7/8 points in QCD)

- Complexity of calculations grow fast with number of legs and number of loops
- Introduces many non-physical degrees of freedom which cancel in final results
- Gauge invariance *hidden* in them

Loop Feynman Diagrams

Consider: $pp \to Z\, b\bar{b}$



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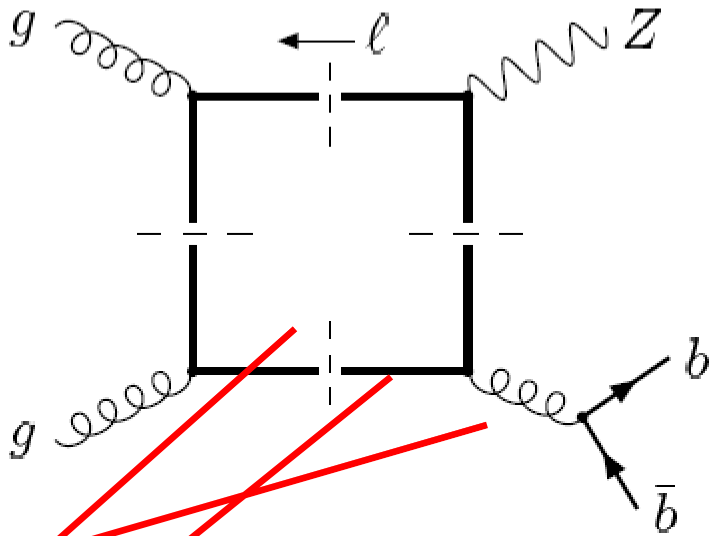
An Example…



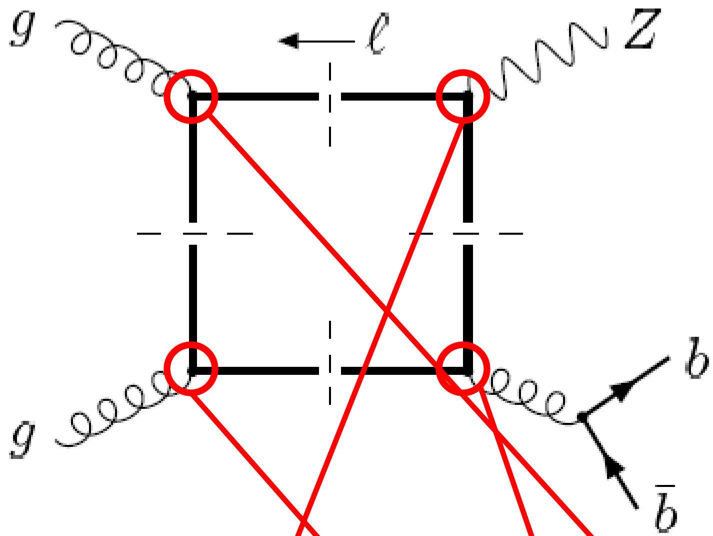
Not including couplings, polarization vectors, factors of "*i*", etc

$$\mathcal{A} \propto \frac{1}{m_{b\bar{b}}^2}\int \frac{d^d l}{(2\pi)^d}\frac{1}{[l^2-m_t^2][(l+q_1)^2-m_t^2][(l+q_1+q_2)^2-m_t^2][(l-p_Z)^2-m_t^2]}$$

$$Tr\Big[(\not{l} + m_t)\gamma_\rho(g_V^t + g_A^t\gamma_5)(\not{l} + \not{p}_Z + m_t)\gamma_\mu$$

$$(\not{l} + \not{q}_1 + \not{q}_2 + m_t)\gamma_\nu(\not{l} + \not{q}_1 + m_t)\gamma_\lambda\Big]$$

An Example…



Vertices

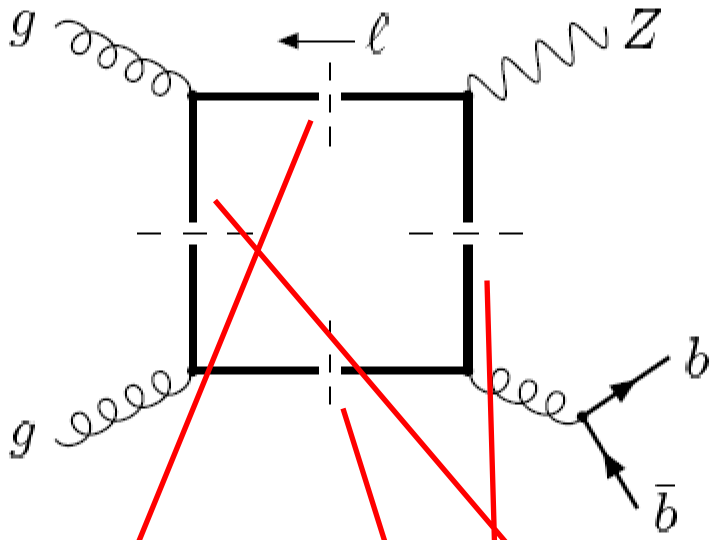
Not including couplings, polarization vectors, factors of "*i*", etc

$$\mathcal{A} \propto \frac{1}{m_{b\bar{b}}^2} \int \frac{d^d l}{(2\pi)^d} \frac{1}{[l^2 - m_t^2][(l+q_1)^2 - m_t^2][(l+q_1+q_2)^2 - m_t^2][(l-p_Z)^2 - m_t^2]}$$

$$Tr\Big[(\not{l} + m_t)\gamma_\rho(g_V^t + g_A^t\gamma_5)(\not{l} + \not{p}_Z + m_t)\gamma_\mu$$

$$(\not{l} + \not{q}_1 + \not{q}_2 + m_t)\gamma_\nu(\not{l} + \not{q}_1 + m_t)\gamma_\lambda\Big]$$

An Example…



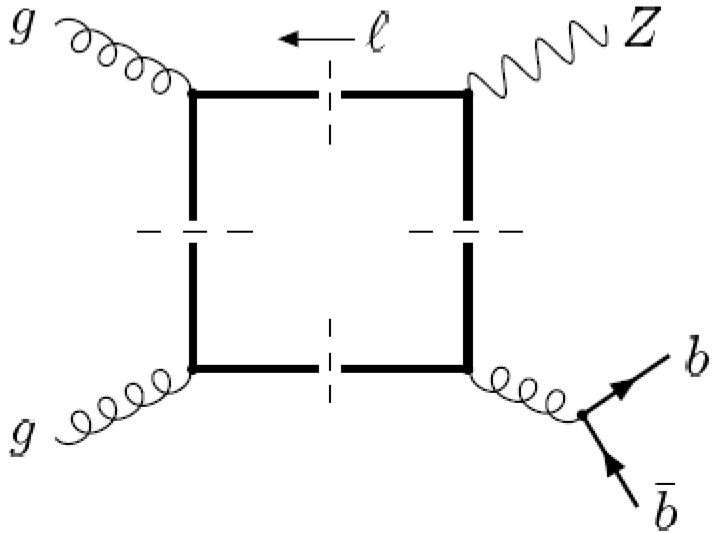
Propagators

Not including couplings, polarization vectors, factors of "*i*", etc

$$\mathcal{A} \propto \frac{1}{m_{b\bar{b}}^2} \int \frac{d^d l}{(2\pi)^d} \frac{1}{[l^2 - m_t^2][(l+q_1)^2 - m_t^2][(l+q_1+q_2)^2 - m_t^2][(l-p_Z)^2 - m_t^2]}$$

$$Tr\Big[(\not{l} + m_t)\gamma_\rho(g_V^t + g_A^t\gamma_5)(\not{l} + \not{p}_Z + m_t)\gamma_\mu$$

$$(\not{l} + \not{q}_1 + \not{q}_2 + m_t)\gamma_\nu(\not{l} + \not{q}_1 + m_t)\gamma_\lambda\Big]$$



$$\mathcal{A} \propto \frac{1}{m_{b\bar{b}}^2} \int \frac{d^d l}{(2\pi)^d} \frac{1}{[l^2 - m_t^2][(l+q_1)^2 - m_t^2][(l+q_1+q_2)^2 - m_t^2][(l-p_Z)^2 - m_t^2]}$$

$$Tr\Big[(\not{l} + m_t)\gamma_\rho(g_V^t + g_A^t\gamma_5)(\not{l} + \not{p}_Z + m_t)\gamma_\mu$$

This indeed is a complicated expression!

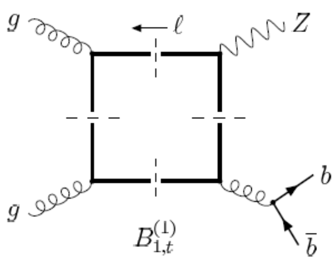
$$(\not{l} + \not{q}_1 + \not{q}_2 + m_t)\gamma_\nu(\not{l} + \not{q}_1 + m_t)\gamma_\lambda\Big]$$

You have to deal with Trace Technology and solve many integrals like this one:

$$\int \frac{d^d l}{(2\pi)^d} \frac{l^{\mu_1} l^{\mu_2} l^{\mu_3} l^{\mu_4}}{[l^2 - m_t^2][(l+q_1)^2 - m_t^2][(l+q_1+q_2)^2 - m_t^2][(l-p_Z)^2 - m_t^2]}$$

$$\equiv D4(q_1, q_2, -p_Z + q_1 + q_2, m_t, m_t, m_t, m_t)$$

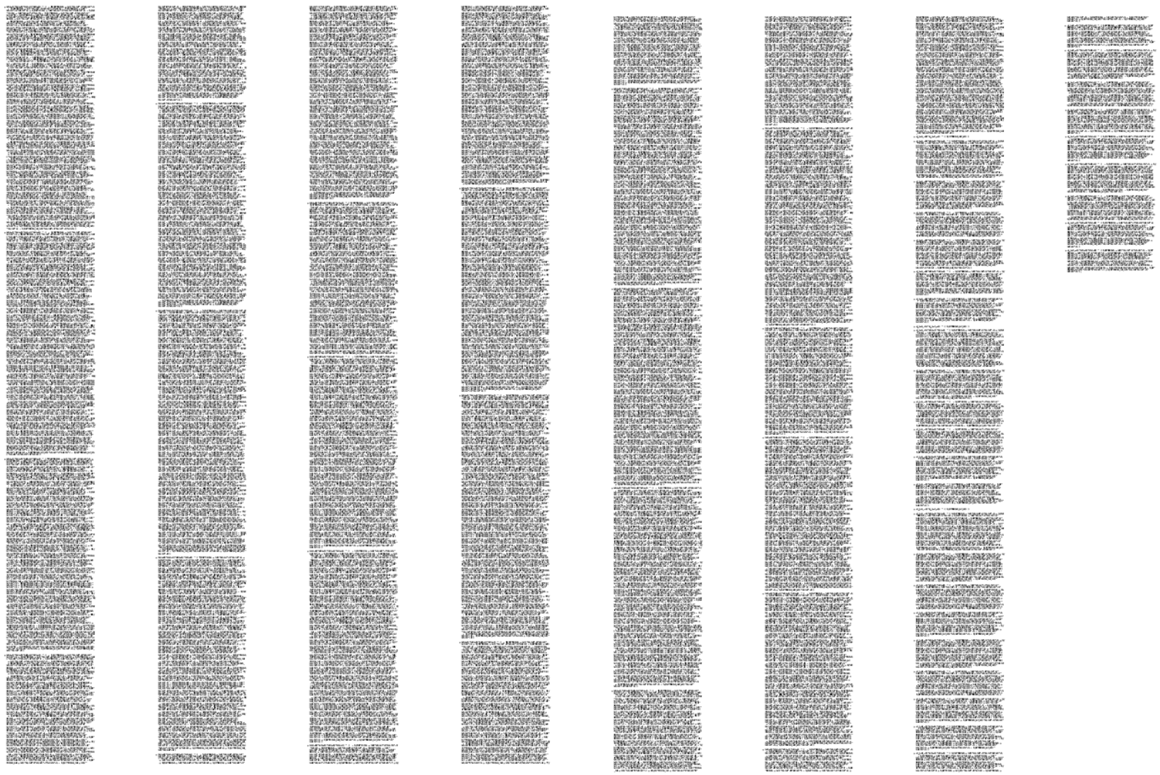
Tensor Integrals:
The Passarino-Veltman Reduction



When applying this procedure to our tensor integral of interest:

$$D4(q_1, q_2, -p_Z + q_1 + q_2, m_t, m_t, m_t, m_t)$$

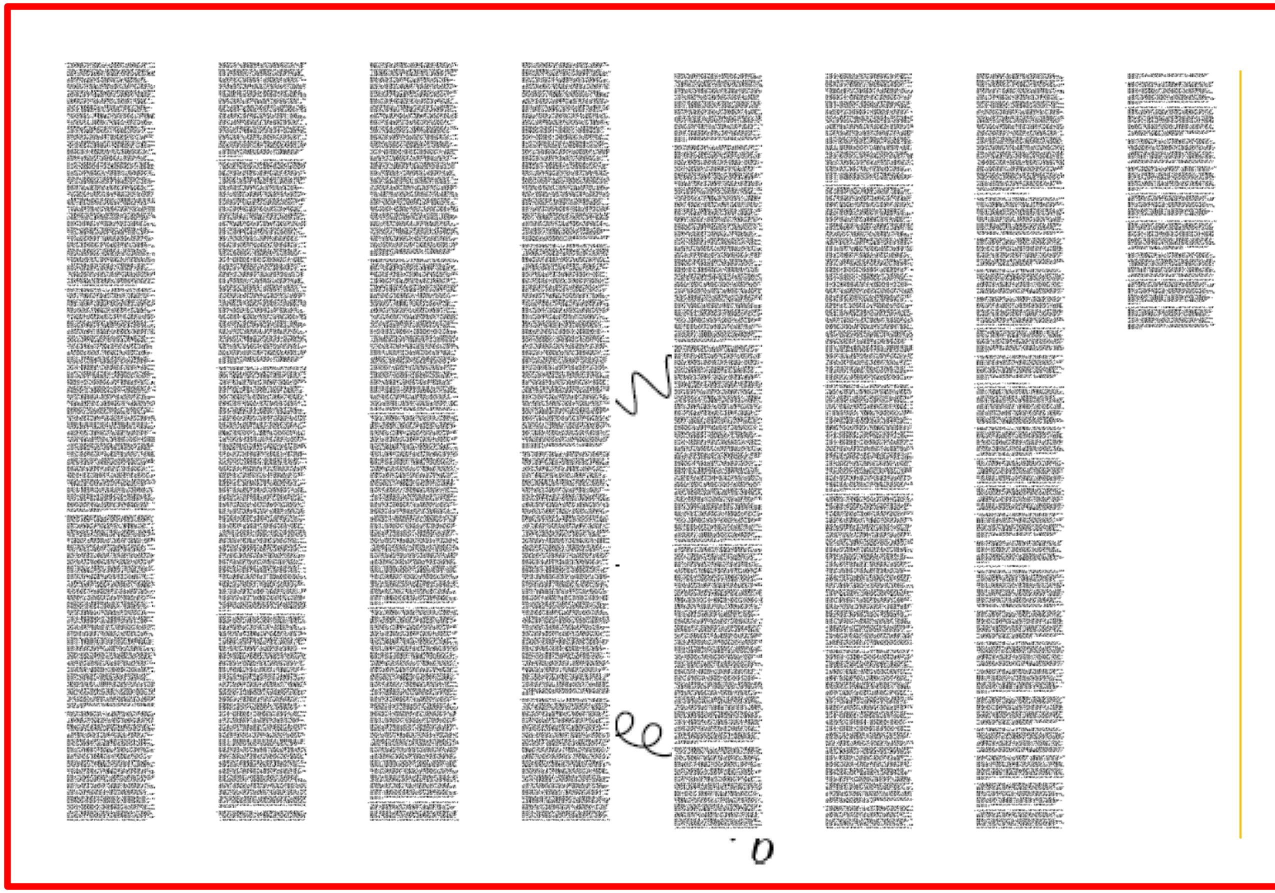
We find that ONLY the coefficient of the corresponding scalar box looks like:



Which is not only large and computer intensive, but suffers from strong numerical instabilities over PS!

And this is only a piece of a single tensor integral that appears in a single Feyman diagram…

This is the coefficient of the box scalar diagram of one of the integrals in the amplitude…



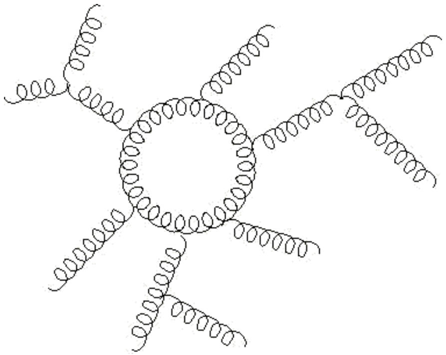
$$\mathcal{A} \propto \frac{1}{m_{b\bar{b}}^2}\int \frac{d^dl}{(2\pi)^d}\frac{1}{[l^2-m_t^2][(l+q_1)^2-m_t^2][(l+q_1+q_2)^2-m_t^2][(l-p_Z)^2-m_t^2]}$$

$$Tr\Big[(\not{l} + m_t)\gamma_\rho(g_V^t+g_A^t\gamma_5)(\not{l}+\not{p}_Z+m_t)\gamma_\mu$$

$$(\not{l}+\not{q}_1+\not{q}_2+m_t)\gamma_\nu(\not{l}+\not{q}_1+m_t)\gamma_\lambda\Big]$$

But, it gets worse! With the number of legs...

- Consider scattering of pure gluon QCD:



6 gluons → **~10,000** diagrams

7 gluons → **~150,000** diagrams

8 gluons → ~ 3,000,000 diagrams

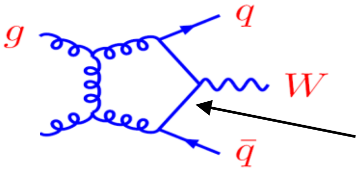
Gauge dependant quantities, large cancellations between terms

Each one of them having an exponentially growing complexity!

- A Factorial growth in the number of terms, particularly bad for large number of partons.

Are there alternative ways to this Feynman diagrams MESS?!

Think off-shell, work on-shell!



$E^2 - \vec{p}^2 \neq m^2$

- Vertices and propagators involve unphysical gauge-dependent off-shell states.

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

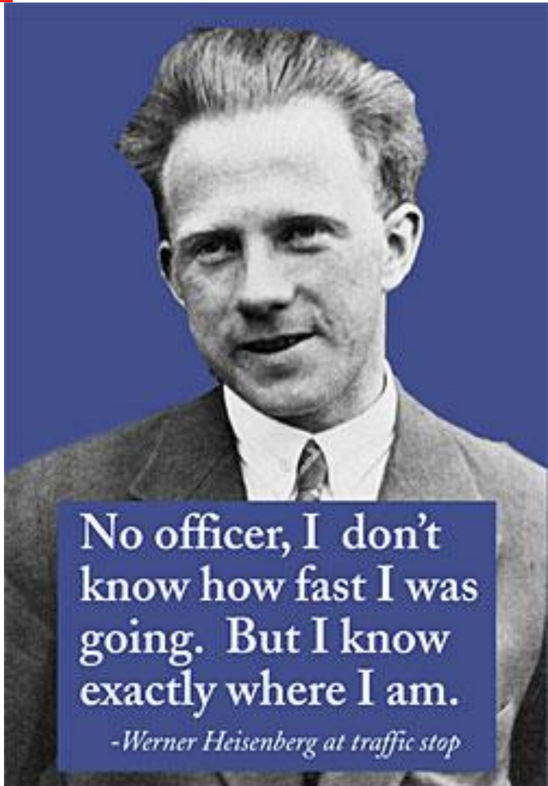
Would like to reconstruct amplitude using only on-shell information.

- Feynman diagram loops have to be off-shell because they encode the uncertainty principle.

Fact: Off-shellness is essential for getting the correct answer.

- Keep particles on-shell in intermediate steps of calculation, not in final results.

Bern, Dixon, Dunbar, Kosower



The result: one-loop basis.

See Bern, Dixon, Dunbar, Kosower, hep-ph/9212308.

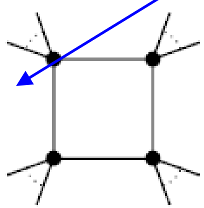
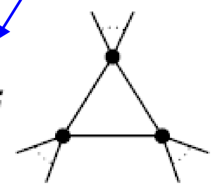
All external momenta in *D=4*, loop momenta in *D=4-2ε* (dimensional regularization)

Rational part

Cut part

Process dependent D=4 rational integral coefficients

$$A = R + C$$

$$C = \sum_i b_i$$  $$+ \sum_i c_i$$  $$+ \sum_i d_i$$ 

- Cut Part from unitarity cuts in 4 dimensions
- Rational part from on-shell recurrence relations

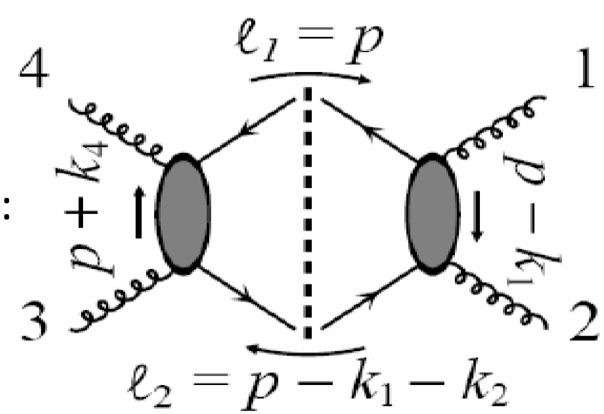
Unitarity: an on-shell method of calculation.

Bern, Dixon, Kosower

$$-i(T - T^\dagger) = T^\dagger T\,.$$

Cutting loops = sewing trees:

Sewing:

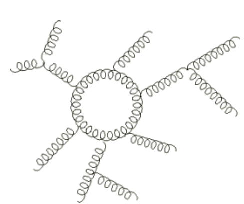


$$\text{Im}\, T^{1-\text{loop}} = \sum_{j\in B} c_j\, \text{Cut}\, \mathcal{I}_j\,.$$

Cutting: 2x $\dfrac{i}{p^2 + i\varepsilon} \longrightarrow 2\pi\, \delta^{(+)}(p^2)$

Equation:

$$\sum_{j\in B} c_j\, \text{Cut}\, \mathcal{I}_j = \int \frac{dp^4}{(2\pi)^4} 2\pi\delta^{(+)}(\ell_1^2 - m^2) 2\pi\delta^{(+)}(\ell_2^2 - m^2)$$
$$A_4^{\text{tree}}(-\ell_1, 1, 2, \ell_2) A_4^{\text{tree}}(-\ell_2, 3, 4, \ell_1)\,.$$

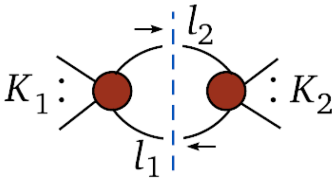
And NOT: $A = \int \dfrac{dp^4}{(2\pi)^4} \sum_{\text{Number of diags.}}$ 

Generalized Unitarity: isolate the leading discontinuity.

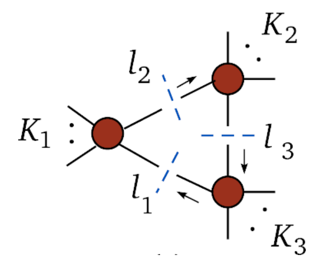
Cutting: n x $$\frac{i}{p^2 + i\varepsilon} \longrightarrow 2\pi\,\delta^{(+)}(p^2)$$

More cuts, more trees, less algebra:

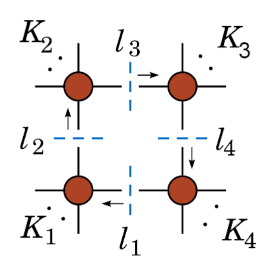
- Two-particle cut: product of trees contains subset of box-, triangle- and bubble-integrals. (Bern, Dixon, Kosower, Dunbar)



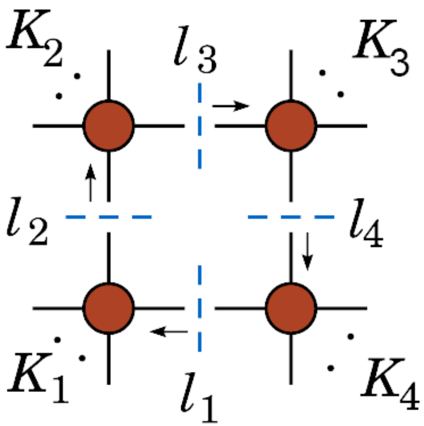
- Triple-cut: product of three trees contains triangle- and box-integrals. (Bern, Dixon, Kosower)



- Quadruple-cut: read out single box coefficient. (Britto, Cachazo, Feng)



Boxes: the simplest cuts



Berger, Bern, Dixon, FFC, Forde,Ita, Kosower, Maitre arXiv:0803.4180; Risager arXiv:0804.3310.

$$d_i = \frac{1}{2}\sum_{\sigma=\pm} d_i^\sigma ,$$

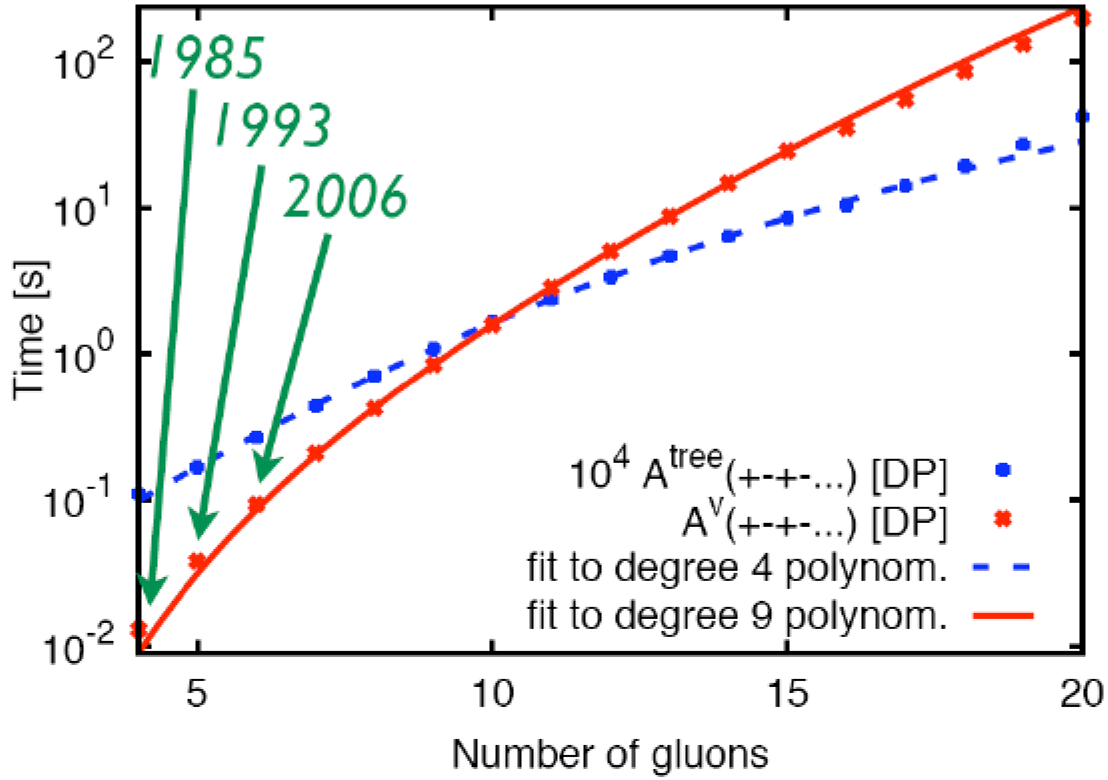
$$d_i^\sigma = A^{\rm tree}_{(1)} A^{\rm tree}_{(2)} A^{\rm tree}_{(3)} A^{\rm tree}_{(4)}\Big|_{l_i=l_i^{(\sigma)}}$$

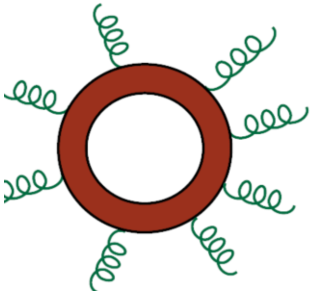
$$(l_1^{(\pm)})^\mu = \frac{\langle 1^\mp|\, \not{K}_2 \not{K}_3 \not{K}_4 \gamma^\mu \,|1^\pm\rangle}{2\,\langle 1^\mp|\, \not{K}_2 \not{K}_4 \,|1^\pm\rangle} , \qquad (l_2^{(\pm)})^\mu = -\frac{\langle 1^\mp|\, \gamma^\mu \not{K}_2 \not{K}_3 \not{K}_4 \,|1^\pm\rangle}{2\,\langle 1^\mp|\, \not{K}_2 \not{K}_4 \,|1^\pm\rangle} ,$$

$$(l_3^{(\pm)})^\mu = \frac{\langle 1^\mp|\, \not{K}_2 \gamma^\mu \not{K}_3 \not{K}_4 \,|1^\pm\rangle}{2\,\langle 1^\mp|\, \not{K}_2 \not{K}_4 \,|1^\pm\rangle} , \qquad (l_4^{(\pm)})^\mu = -\frac{\langle 1^\mp|\, \not{K}_2 \not{K}_3 \gamma^\mu \not{K}_4 \,|1^\pm\rangle}{2\,\langle 1^\mp|\, \not{K}_2 \not{K}_4 \,|1^\pm\rangle} .$$

Un-physical (=spurious) singularities from parameterization.
Have to cancel eventually: role of rational term R.

A Powerful Technique!





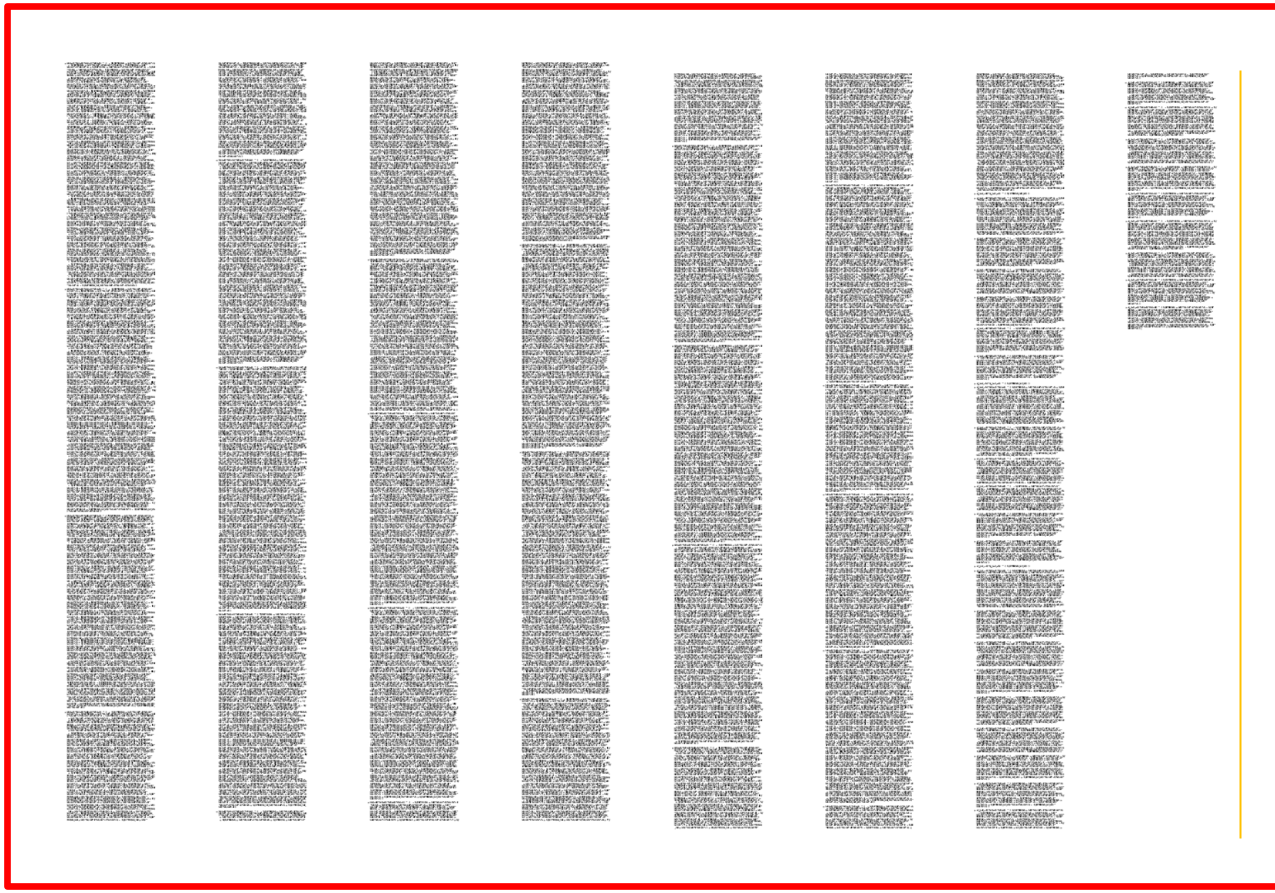
[Giele, Zanderighi arXiv:0806.2152]

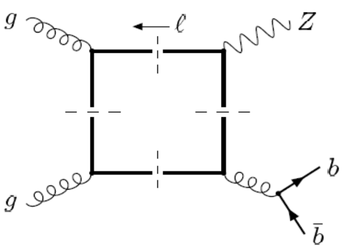
BUT STILL VERY COMPUTER INTENSIVE

[BlackHat + Sherpa]

NTUPLES: STORE THE MORE INFORMATION YOU CAN DURING YOUR COMPUTATION!

This is the coefficient of the box scalar diagram of one of the integrals in the amplitude…



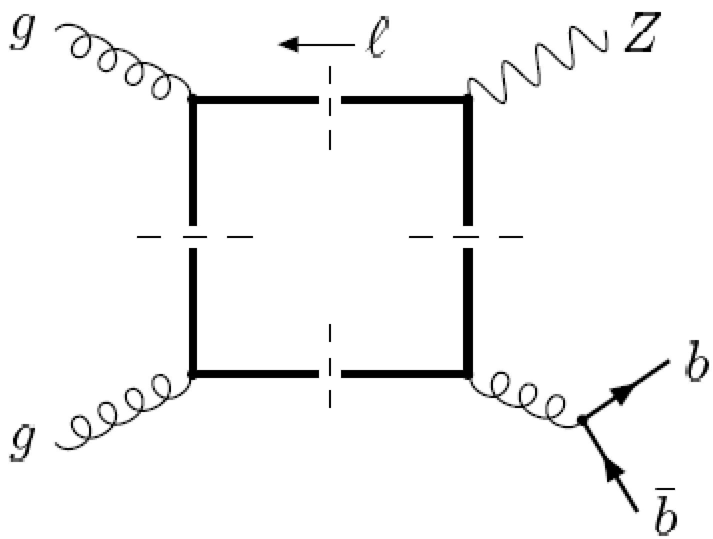


$$\mathcal{A} \propto \frac{1}{m_{b\bar{b}}^2} \int \frac{d^d l}{(2\pi)^d} \frac{1}{[l^2 - m_t^2][(l+q_1)^2 - m_t^2][(l+q_1+q_2)^2 - m_t^2][(l-p_Z)^2 - m_t^2]}$$

$$Tr\Big[(\not{l} + m_t)\gamma_\rho(g_V^t + g_A^t\gamma_5)(\not{l} + \not{p}_Z + m_t)\gamma_\mu$$

$$(\not{l} + \not{q}_1 + \not{q}_2 + m_t)\gamma_\nu(\not{l} + \not{q}_1 + m_t)\gamma_\lambda\Big]$$

Now, use unitarity! The Quad Cut!



From Unitarity, our coefficient can be obtained from:

Loop integral frozen!

$$\rightarrow \quad \sum_{\ell=\ell_\pm} (\ell^2 - m_t^2)\left((\ell+q_1)^2 - m_t^2\right)\left((\ell+q_1+q_2)^2 - m_t^2\right)\left((\ell+p_Z)^2 - m_t^2\right) \cdot \mathcal{A}\Big|_\ell$$

Where the sum is over the two solutions of the (*simple*) algebraic on-shell conditions

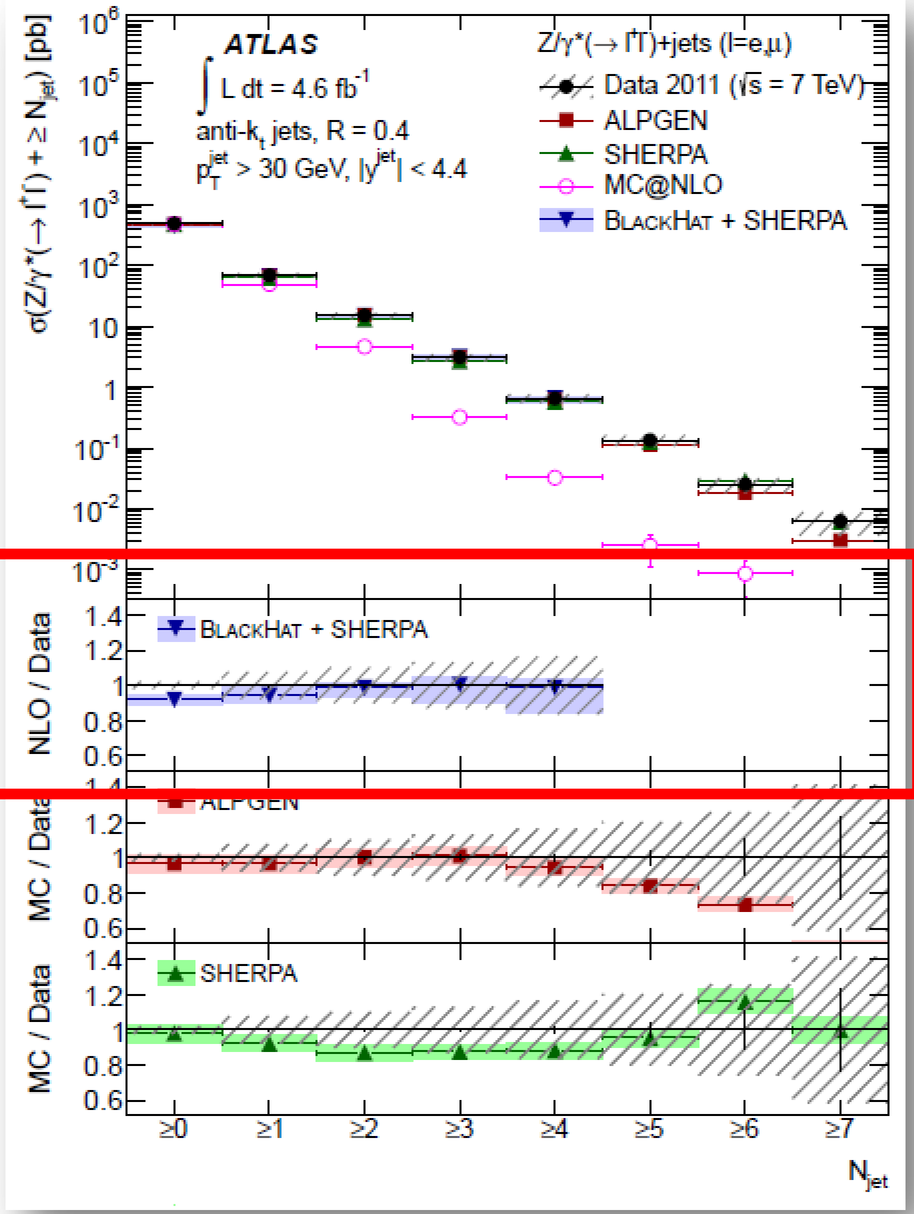
$$\{\ell \mid \ell^2 = m_t^2,\ \ (\ell+q_1)^2 = m_t^2,\ \ (\ell+q_1+q_2)^2 = m_t^2,\ \ (\ell+p_Z)^2 = m_t^2\}$$

¡¡¡!!!

On-Shell Techniques in action @ LHC!

Z+Jets at the LHC

→ 4.6 fb^{-1}
→ Inclusive cross section for each multiplicity
→Good agreement with NLO results
→ Good statistical error control for six jet events
→ Electron/muon channel shown



These calculations made within an automated framework (BlackHat+SHERPA) based on On-Shell/Unitarity techniques!
Experimentalist with access to NTuples

arXiv:1304.7098 [hep-ex]

THE NLO REVOLUTION

Need for Higher Orders, High Multiplicity, Whish List

REVISITING GAUGE TREES

MHV, Complexify Momenta, BCFW

NLO CALCULATIONS

Feynman Diagrams, Integral Basis, OPP, Quad Cuts Exm

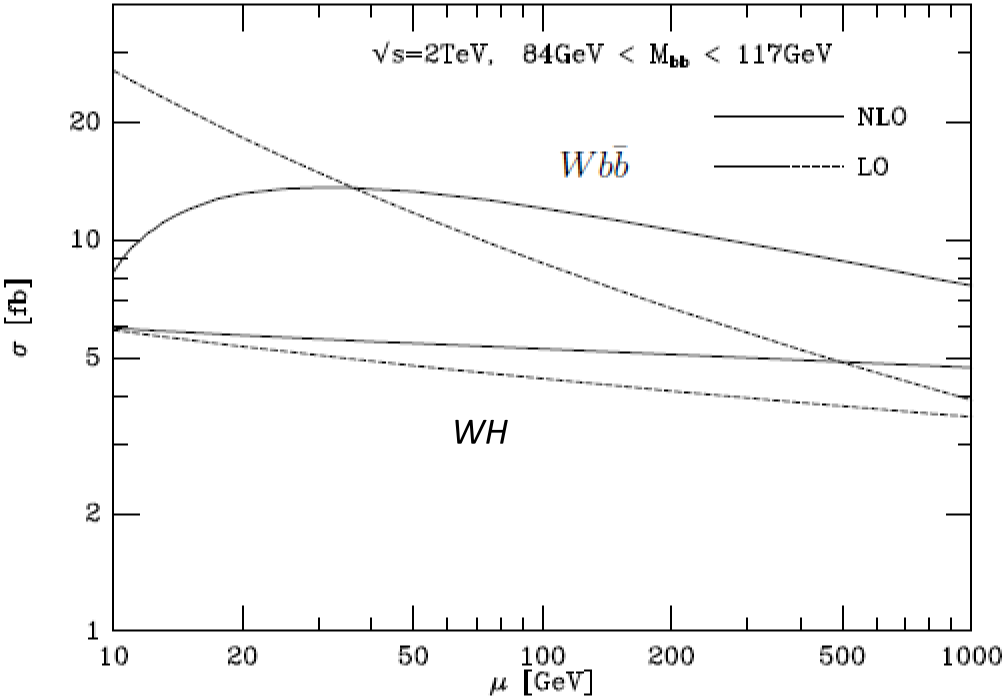
TOOLS FOR HIGHER ORDERS

NLO, Automation, NLO Shower, NNLO

MCFM v1

John Campbell, Keith Ellis

→ FORTRAN based Parton Level NLO Montecarlo
→ First released in 2000, with a compilation of analytically computed NLO QCD corrections
→ Originally included a handful of processes (W/Z production, W/Z+jet, W/Z+bb, Weak Vector Boson Pairs and Higgstrahlung processes)
→ Meant to make available important calculations to the larger experimental and theory community
→ Easy access to multiple observables



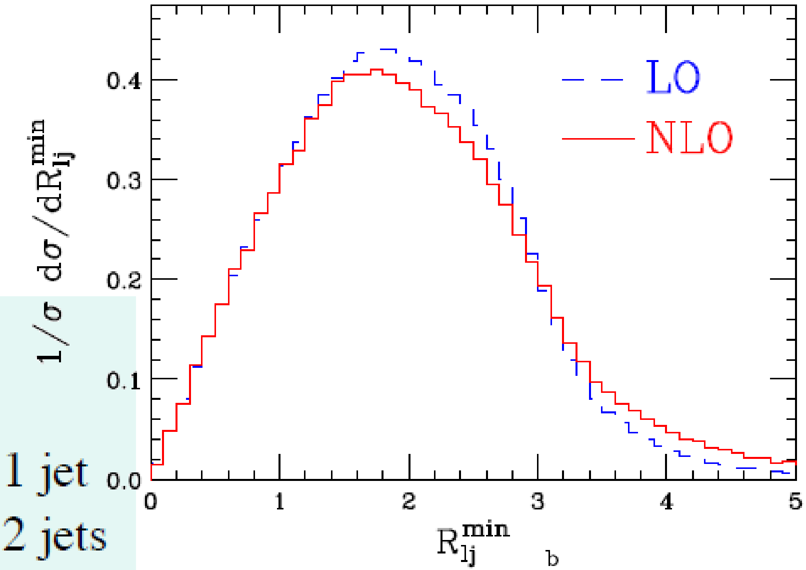
MCFM v6.8

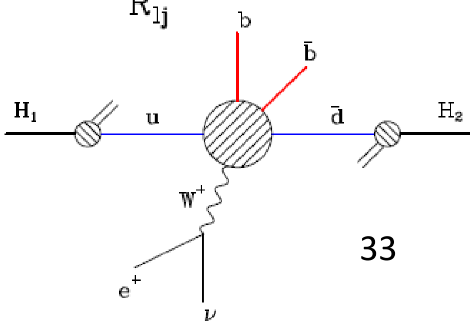
John Campbell, Keith Ellis, Ciaran Williams

→ Widely used by experimental collaborations and theorist
→ Leading in analytical computations of state of the art calculations
→ Large amount of procceses included. Still analytical *handmade* calculations

http://mcfm.fnal.gov/
arXiv:1208.0566 [hep-ph], arXiv:1107.5569 [hep-ph], arXiv:1105.0020 [hep-ph], arXiv:1011.6647 [hep-ph] …

- pp → W/Z
- pp → W+Z, WW, ZZ
- pp → W/Z + 1 jet
- pp → W/Z +2 jets
- pp → t W
- pp → tX (s&t channel)
- pp → tt
- pp → W/Z+H
- pp (gg) → H
- pp→(gg) → H + 1 jet
- pp→(gg) → H + 2 jets
- pp(VV) → H +2 jets
- pp → W/Z +b , W+c
- pp → W/Z +bb





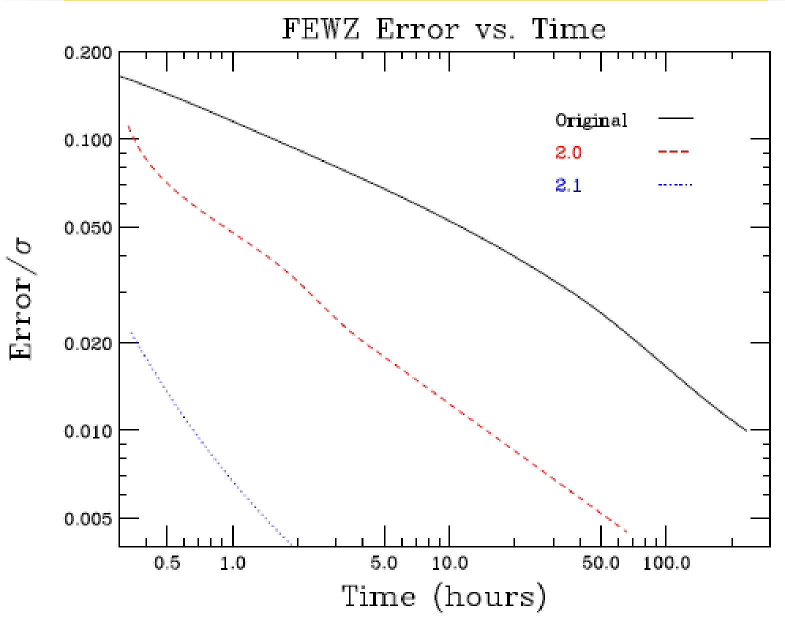
and more…

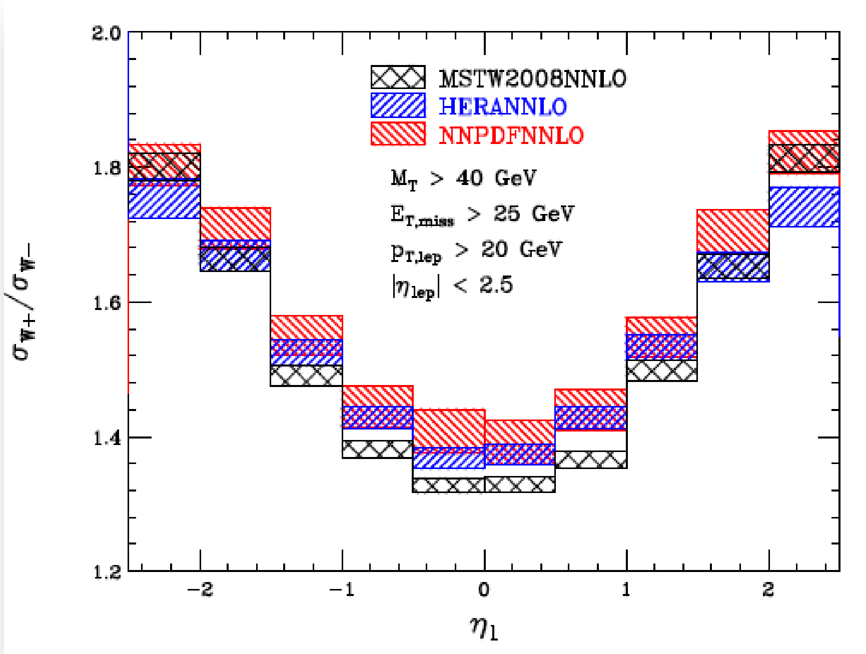
FEWZ v3

→ Parton Level Montecarlo of fully exclusive NNLO QCD calculation of W/Z production (including decaying products)
→ Reference for Drell-Yan studies at Hadron Colliders
→ Important recent improvements on convergence of numerical integration for observables

Frank Petriello, Seth Quackenbush, Ryan Gavin, Ye Li

http://gate.hep.anl.gov/fpetriello/FEWZ.html
arXiv:1208.5967 [hep-ph], arXiv:1201.5896 [hep-ph]
arXiv:1011.3540 [hep-ph] …





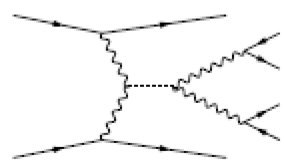
Recently Catani, Cieri, Ferrara, de Florian and Grazzini have presented a similar/alternative code **DYNNLO** (see for example arXiv:0903.2120 [hep-ph]) **http://theory.fi.infn.it/grazzini/dy.html**

VBFNLO v2.7.0

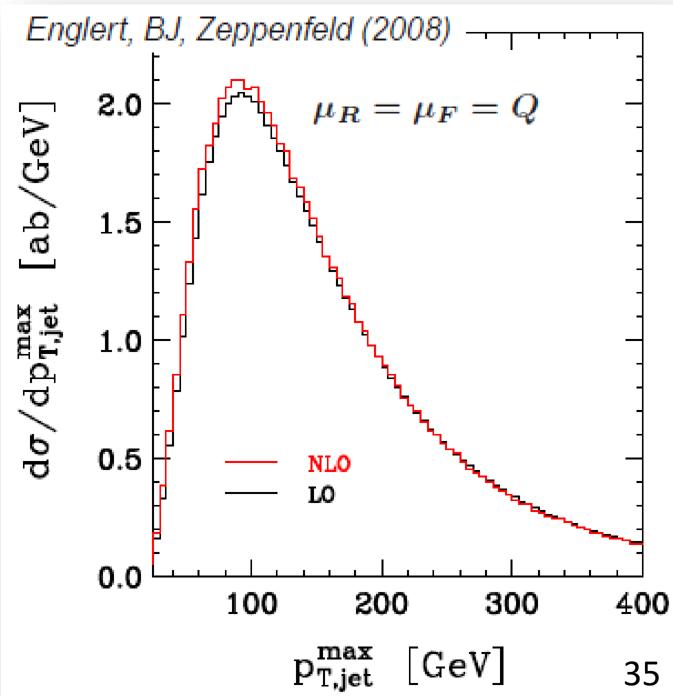
Arnold, Bellm, Bozzi, Campanario, Englert, Feigl, Frank, Figy, Jäger, Kerner, Kubocz, Oleari, Palmer, Rauch, Rzehak, Schissler, Schlimpert, Spannowsky, Zeppenfeld

→Flexible Parton Level Montecarlo at NLO-QCD
→ Meant for processes with EW bosons
→ Includes calculations for CP-odd and CP-even Higgs boson production

http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb/
arXiv:1404.3940 [hep-ph], arXiv:1207.4975 [hep-ph]
arXiv:1107.3149 [hep-ph] arXiv:1106.4009 [hep-ph] …



EW $VVjj$ production



it can simulate:

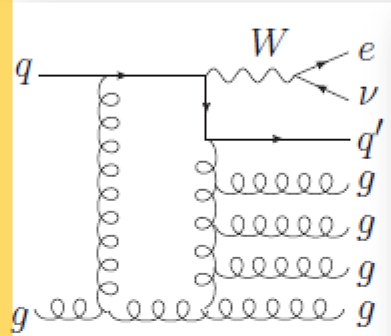
- various weak vector boson fusion processes
- double and triple weak boson production processes
- double weak boson production processes in association with a hard jet
- Higgs production via gluon fusion in association with two jets

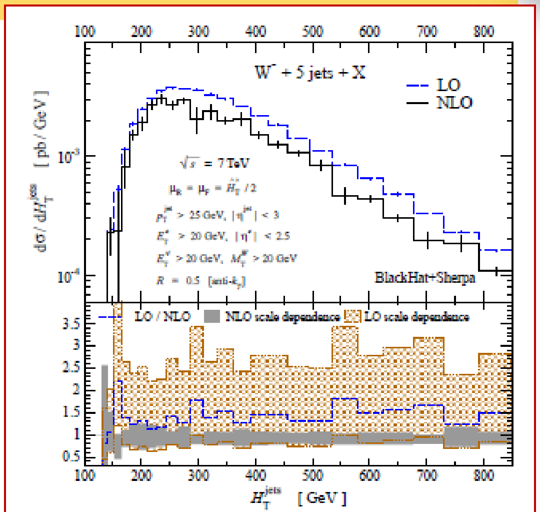
BlackHat + SHERPA

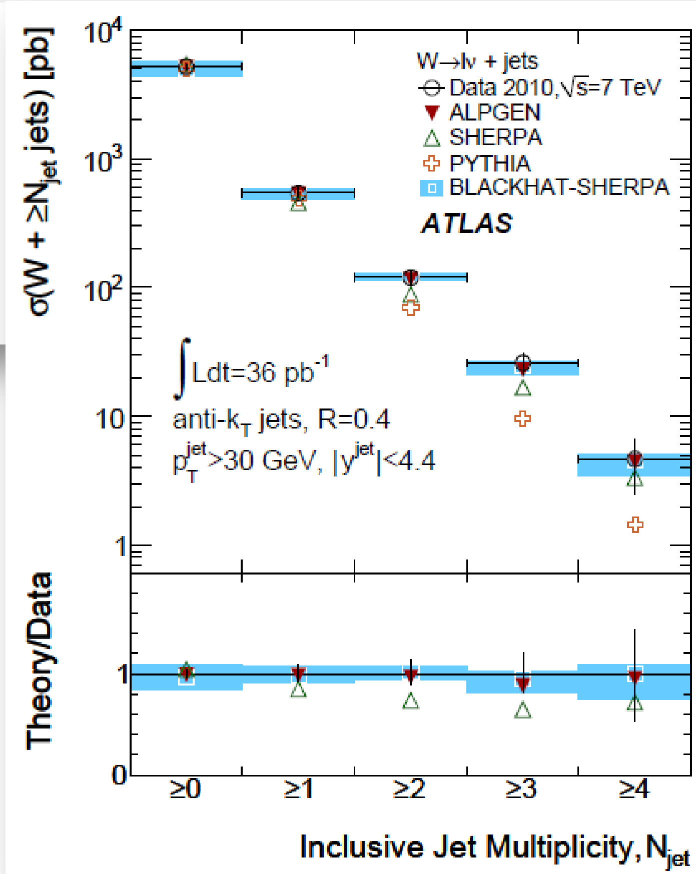
→Automated implementation of on-shell and unitarity techniques to NLO QCD computations
→ Focus on state of the art processes with large amount of jets (V+1,2,3,4,5 jets, pure QCD 2,3,4 jet production)
→ Access to calculations through **NTUPLES**: Flexible to allow user defined scale variations, change of PDFs, extract any IR safe observable, etc

Bern, Dixon, FFC, Hoeche, Ita, Kosower, Maitre

http://blackhat.hepforge.org/ (private release, ntuples available) http://sherpa.hepforge.org/trac/wiki
arXiv:1304.1253 [hep-ph], arXiv:1206.6064 [hep-ph], arXiv:1112.3940 [hep-ph], arXiv:1108.2229 [hep-ph] …







BHS NTUPLES in BRIEF

arXiv:1310.7439 [hep-ph]

- Files containing
  - Kinematic Information
  - Information needed to change factorization and renormalization scales and PDFs
  - Information for multiple jet algorithms (different R's, f-parameters, etc)
- Publically available
  - C++ library to read and handle them
- W/Z+0,1,2,3,4(,5) jets at the LHC
  - Already used by LHC's collaborations!

arXiv:1310.7439 [hep-ph]

BHSntuples (publicly) Available

Process	n-tuple file sets
$W^{\pm}(\to e^{\pm}\overset{(-)}{\nu}) + 0, 1, 2$ jets	B001, I001, R001, V001
$W^{\pm}(\to e^{\pm}\overset{(-)}{\nu}) + 3$ jets	B001, I001, R001, V001–V002
$W^{-}(\to e^{-}\bar{\nu}) + 4$ jets	B001, I001, R001, V001
$W^{+}(\to e^{+}\nu) + 4$ jets	B001, I001, R001–R005, V001
$Z(\to e^{+}e^{-}) + 0, 1, 2$ jets	B001, I001, R001, V001
$Z(\to e^{+}e^{-}) + 3$ jets	B001, I001, R001, V001–V002
$Z(\to e^{+}e^{-}) + 4$ jets	B001, I001–I003, R001–R006, V001–V006
n jets $(n = 1, 2, 3, 4)$	B001, I001, R001, V001

Which you can access/download from:

From the web:

https://blackhat.hepforge.org/trac/wiki/Availability

From CASTOR:

/castor/cern.ch/d/dmaitre/BHSNtuples/PROCESS/ENERGY/PART

From the LHC Grid:

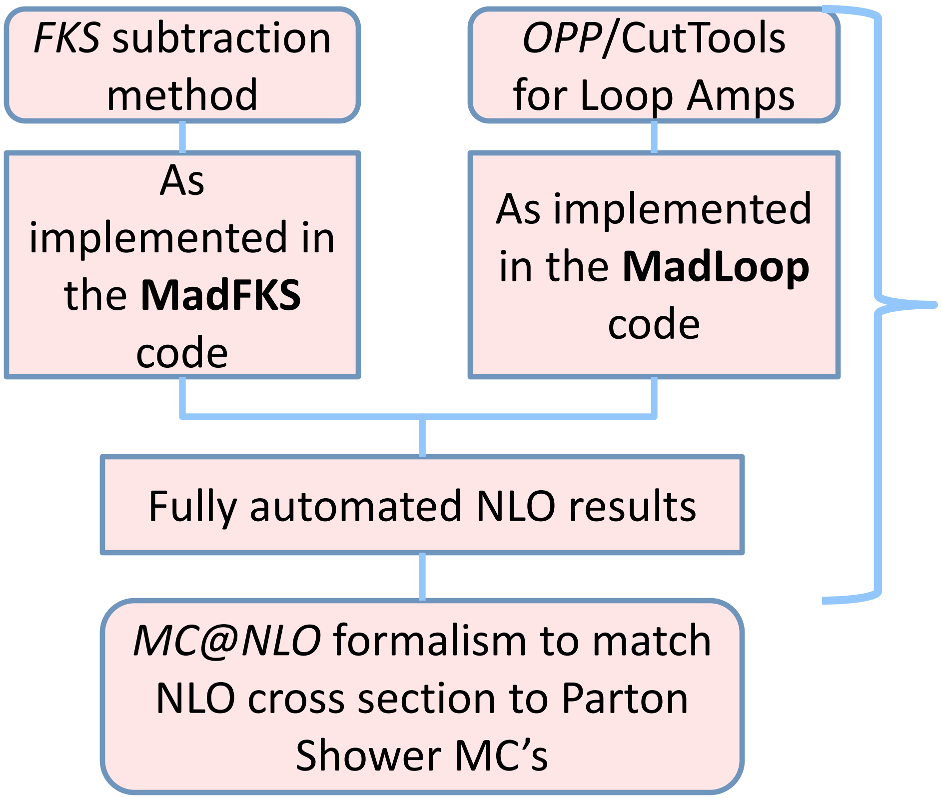
/grid/pheno/BHSNtuples/PROCESS/ENERGY/PART

The MadGraph5_aMC@NLO Framework

→ Collaborative Project for public automated MC tools for event generators with NLO precision for the LHC (built around MadGraph). Handles QCD (LO/NLO) and BSM (LO)

Alwall, Artoisenet, Frederix, Frixione, Fuks, Hirschi, Maltoni, Mattelaer, Pittau, Serret, Stelzer, Torrielli, Zaro

http://amcatnlo.web.cern.ch/ arXiv:1405.0301 [hep-ph], arXiv:1110.5502 [hep-ph] …



NLO all in *one go*…

	Process	μ	n_{lf}	Cross section (pb) LO	NLO
a.1	$pp \to t\bar{t}$	m_{top}	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp \to tj$	m_{top}	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp \to tjj$	m_{top}	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp \to t\bar{b}j$	$m_{top}/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp \to t\bar{b}jj$	$m_{top}/4$	4	8.195 ± 0.002	8.91 ± 0.01
b.1	$pp \to (W^+ \to)e^+\nu_e$	m_W	5	5072.5 ± 2.9	6146.2 ± 9.8
b.2	$pp \to (W^+ \to)e^+\nu_e\, j$	m_W	5	828.4 ± 0.8	1065.3 ± 1.8
b.3	$pp \to (W^+ \to)e^+\nu_e\, jj$	m_W	5	298.8 ± 0.4	300.3 ± 0.6
b.4	$pp \to (\gamma^*/Z \to)e^+e^-$	m_Z	5	1007.0 ± 0.1	1170.0 ± 2.4
b.5	$pp \to (\gamma^*/Z \to)e^+e^-\, j$	m_Z	5	156.11 ± 0.03	203.0 ± 0.2
b.6	$pp \to (\gamma^*/Z \to)e^+e^-\, jj$	m_Z	5	54.24 ± 0.02	56.69 ± 0.07
c.1	$pp \to (W^+ \to)e^+\nu_e b\bar{b}$	$m_W + 2m_b$	4	11.557 ± 0.005	22.95 ± 0.07
c.2	$pp \to (W^+ \to)e^+\nu_e t\bar{t}$	$m_W + 2m_{top}$	5	0.009415 ± 0.000003	0.01159 ± 0.00001
c.3	$pp \to (\gamma^*/Z \to)e^+e^- b\bar{b}$	$m_Z + 2m_b$	4	9.459 ± 0.004	15.31 ± 0.03
c.4	$pp \to (\gamma^*/Z \to)e^+e^- t\bar{t}$	$m_Z + 2m_{top}$	5	0.0035131 ± 0.0000004	0.004876 ± 0.000002
c.5	$pp \to \gamma t\bar{t}$	$2m_{top}$	5	0.2906 ± 0.0001	0.4169 ± 0.0003
d.1	$pp \to W^+W^-$	$2m_W$	4	29.976 ± 0.004	43.92 ± 0.03
d.2	$pp \to W^+W^-\, j$	$2m_W$	4	11.613 ± 0.002	15.174 ± 0.008
d.3	$pp \to W^+W^+\, jj$	$2m_W$	4	0.07048 ± 0.00004	0.1377 ± 0.0005
e.1	$pp \to HW^+$	$m_W + m_H$	5	0.3428 ± 0.0003	0.4455 ± 0.0003
e.2	$pp \to HW^+\, j$	$m_W + m_H$	5	0.1223 ± 0.0001	0.1501 ± 0.0002
e.3	$pp \to HZ$	$m_Z + m_H$	5	0.2781 ± 0.0001	0.3659 ± 0.0002
e.4	$pp \to HZ\, j$	$m_Z + m_H$	5	0.0988 ± 0.0001	0.1237 ± 0.0001
e.5	$pp \to Ht\bar{t}$	$m_{top} + m_H$	5	0.08896 ± 0.00001	0.09869 ± 0.00003
e.6	$pp \to Hb\bar{b}$	$m_b + m_H$	4	0.16510 ± 0.00009	0.2099 ± 0.0006
e.7	$pp \to Hjj$	m_H	5	1.104 ± 0.002	1.036 ± 0.002

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http://amcatnlo.web.cern.ch/ arXiv:1405.0301 [hep-ph], arXiv:1110.5502 [hep-ph] …

FKS subtraction method

As implemented in the **MadFKS** code

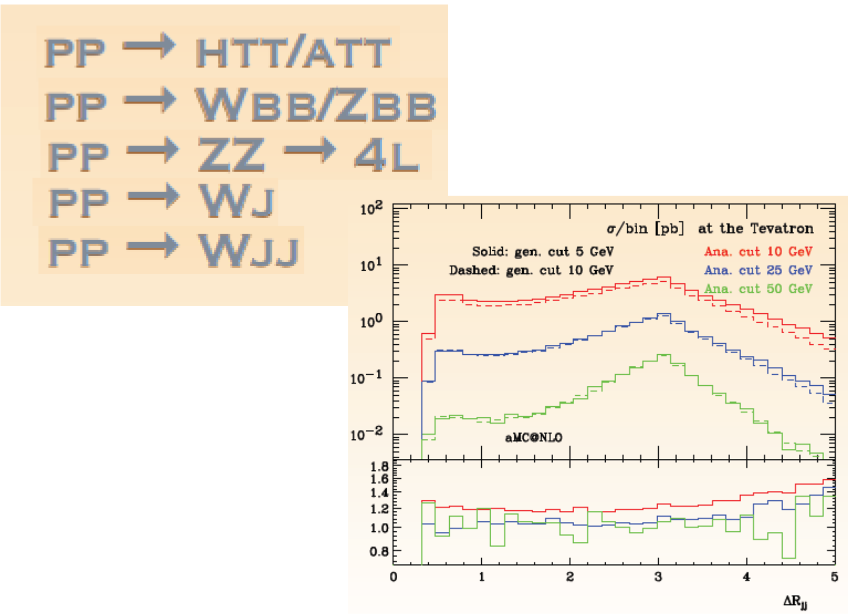
OPP/CutTools for Loop Amps

As implemented in the **MadLoop** code

Fully automated NLO results

MC@NLO formalism to match NLO cross section to Parton Shower MC's

NLO+PS also all in *one go…*



Similar frameworks with the **POWHEG BOX** and **SHERPA** !!! The later already includes matching of loop ME's for several jet multiplicities (see arXiv:1207.5030 [hep-ph])

And much (much) more…

→ **HRes** (de Florian, Ferrera, Grazzini, Tommasini) *NNLO and NNLL gg fusion production of Higgs (with decay modes!)*

→ **NLOJET++** (Nagy) *C++ library to compute jet cross sections in lepton colliders, DIS and hadron colliders*

→ **FastNLO** (Kluge, Rabbertz, Wobisch) *provides computer codes and tables of pre-computed perturbative coefficients for various observables at hadron colliders*

→ **The PHOX family** (Aurenche, Binoth, Fontannaz, Guillet, Heinrich, Pilon, Werlen) *provides NLO corrections to processes involving Photons, hadrons and jets*

→ …

→ **GoSam** (Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano) *Public package for general QCD & EW 1-loop amps SM & BSM*

→ **CompHEP** (Boos, Bunichev, Dubinin, Dudko, Edneral, Ilyin, Kryukov, Savrin, Semenov, Shertsnev) *Public package for automated LO computations from Lagrangians to final distributions (Built it QED, SM, Fermi, MSSM, SUGRA, …)*

→ **SAMURAI** (Mastrolia, Ossola, Reiter, Tramontano) *Automated implementation to compute loop multi-leg amplitudes within the D-dimensional Unitarity approach*

→ **CutTools** (Pittau) *Automated approach to loop amps/integrals using OPP algorithm*

→ …

CHECK OUT http://www.hepforge.org/downloads/ for a large amount of available programs for High Energy Physics!

Summary

- Our tools for full description of LHC events have proven to perform well
- Still continue improvement of our QCD understanding will be needed to tackle new (precision) challenges at the new LHC run
- We are living an exciting time in particle physics, and your work will contribute to the progress of our understanding of nature at the high-energy frontier