NLO pheno with MadGraph

Marco Zaro, CP3 - UCLouvain

in collaboration with

Rikkert Frederix, Stefano Frixione, Fabio Maltoni, Paolo Torrielli, Valentin Hirschi

& the MadGraph5 Team

Theory seminar @ FNAL

August 30th, 2012

aMC@NLO pheno with MadGraph

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Dawn of the precision LHC era

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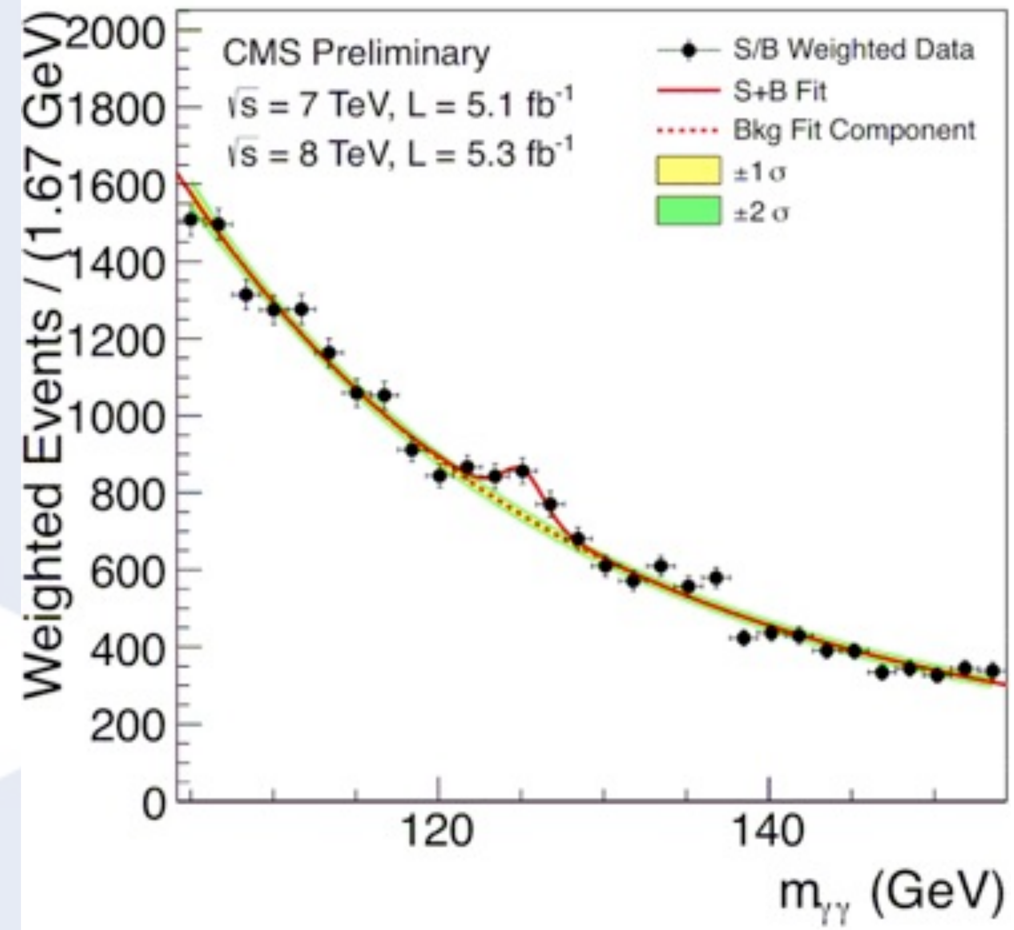
- July 4th: evidence for a new boson



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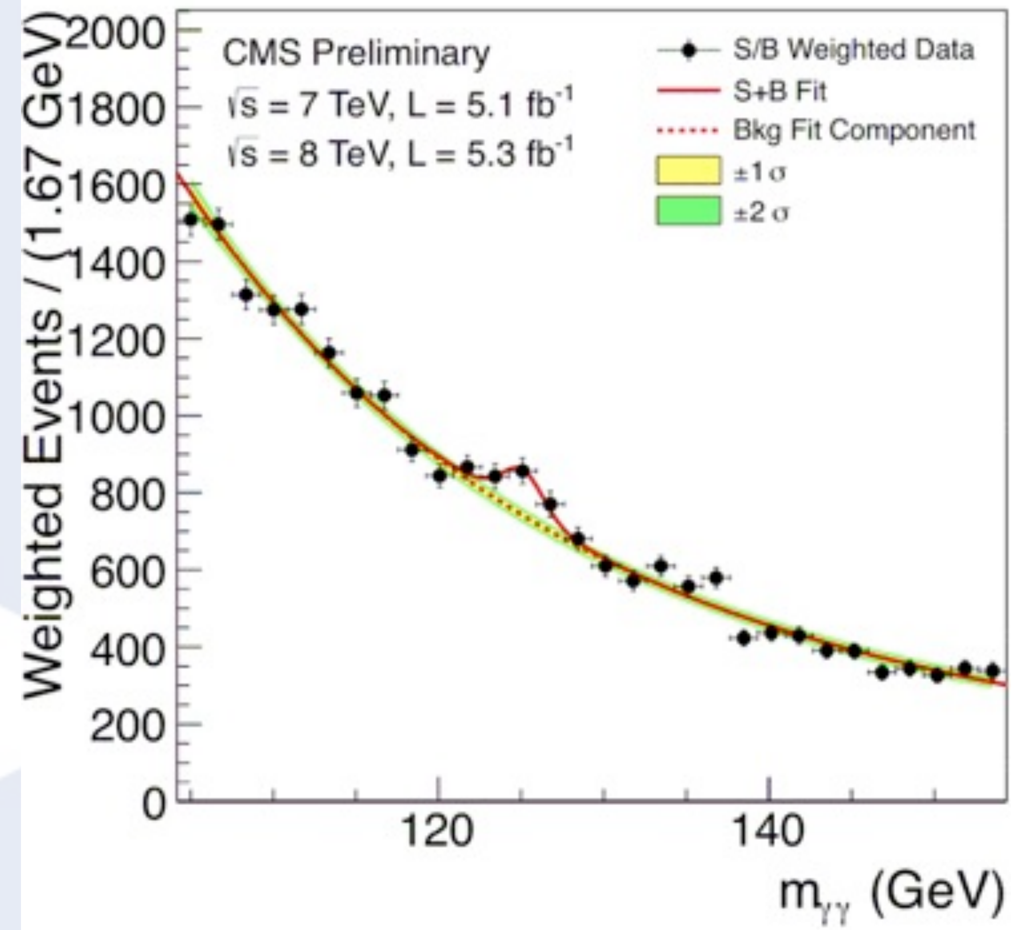

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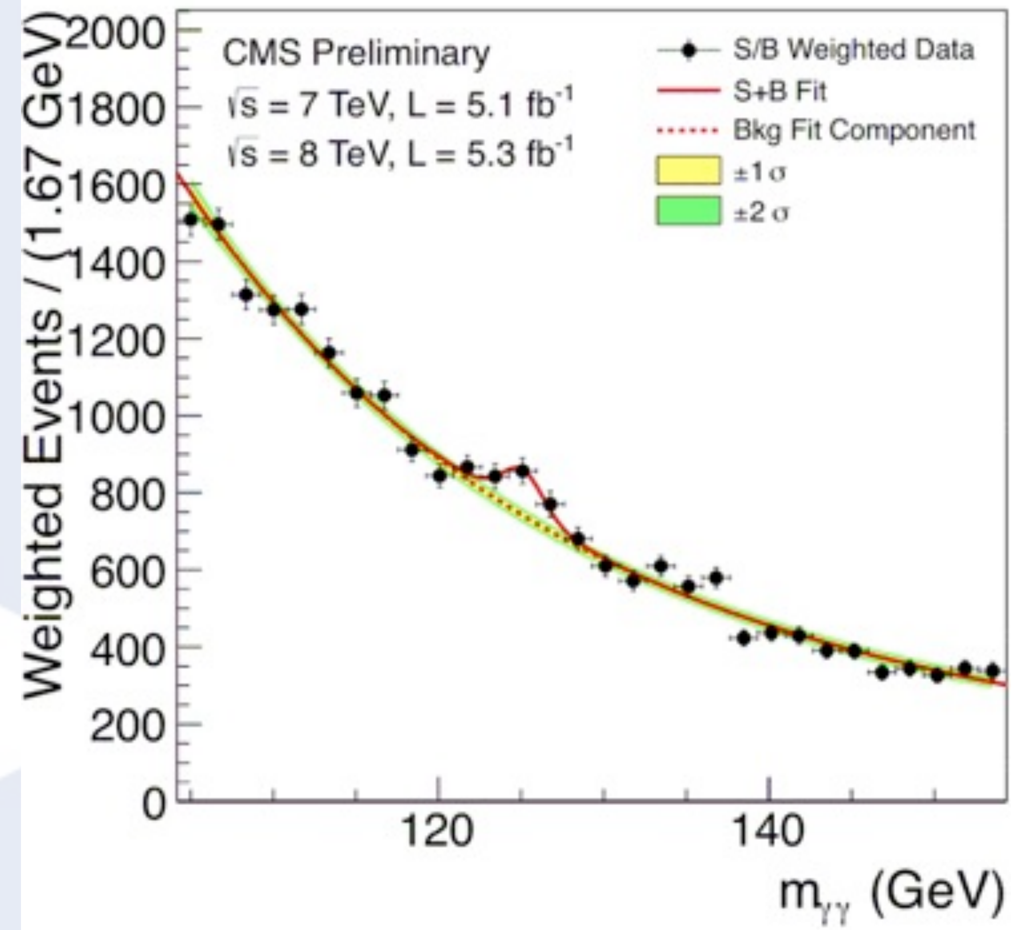

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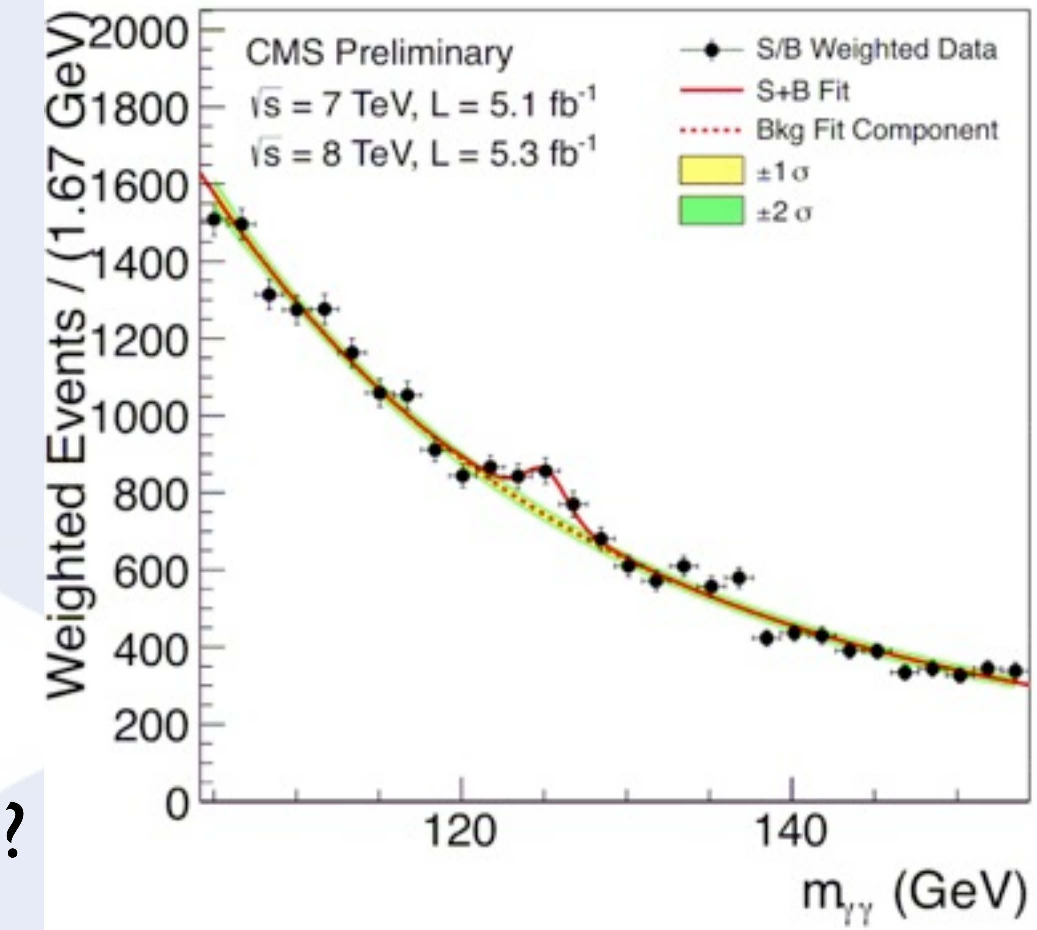

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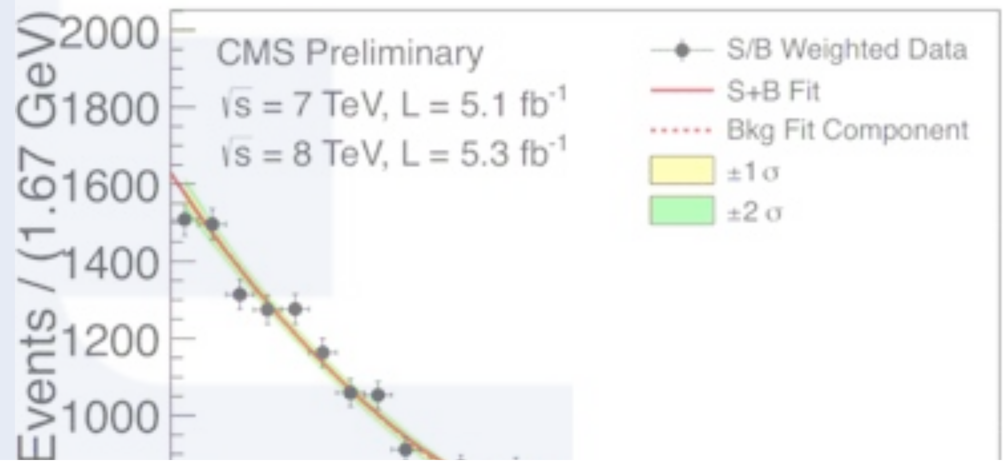

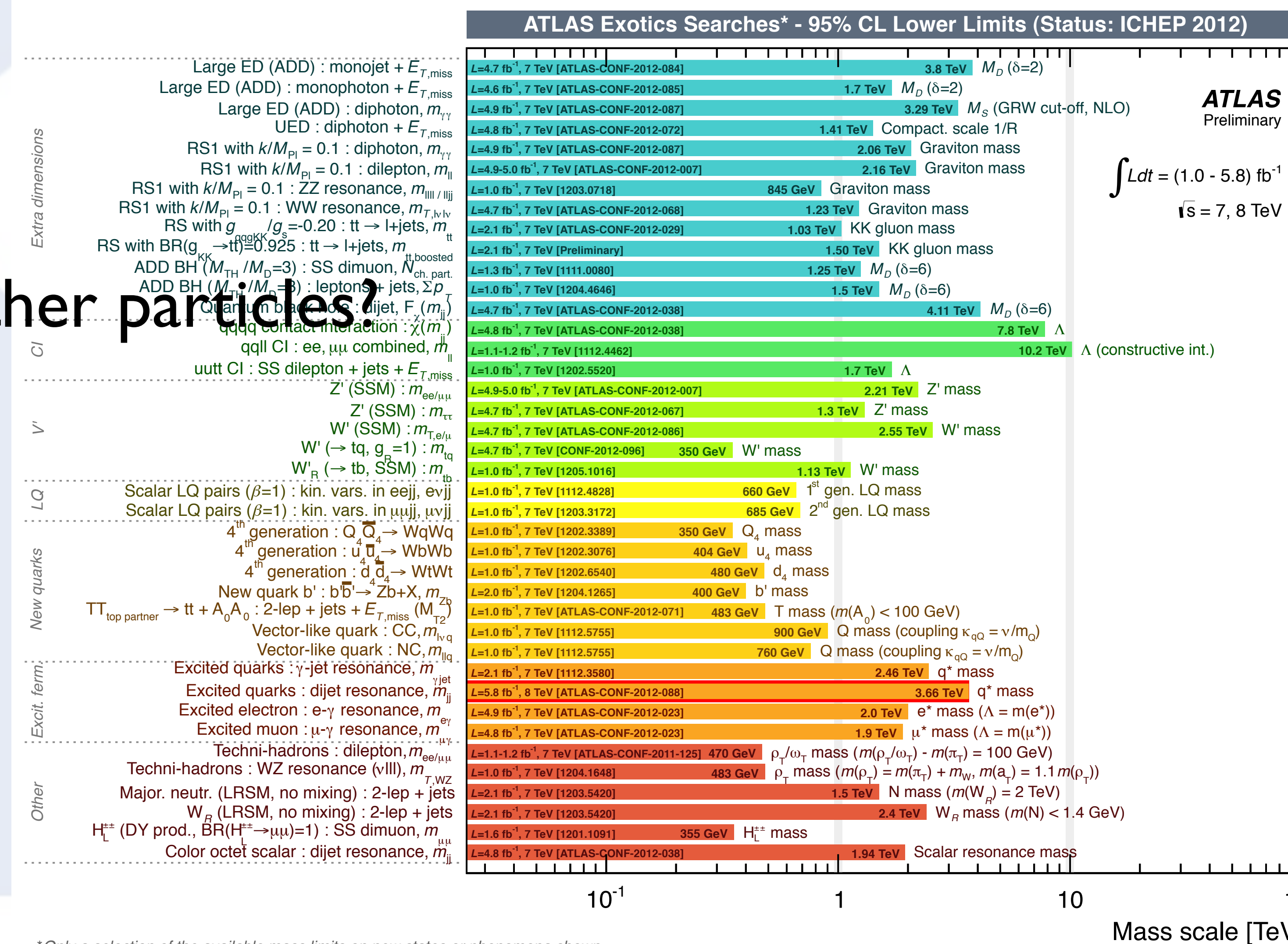

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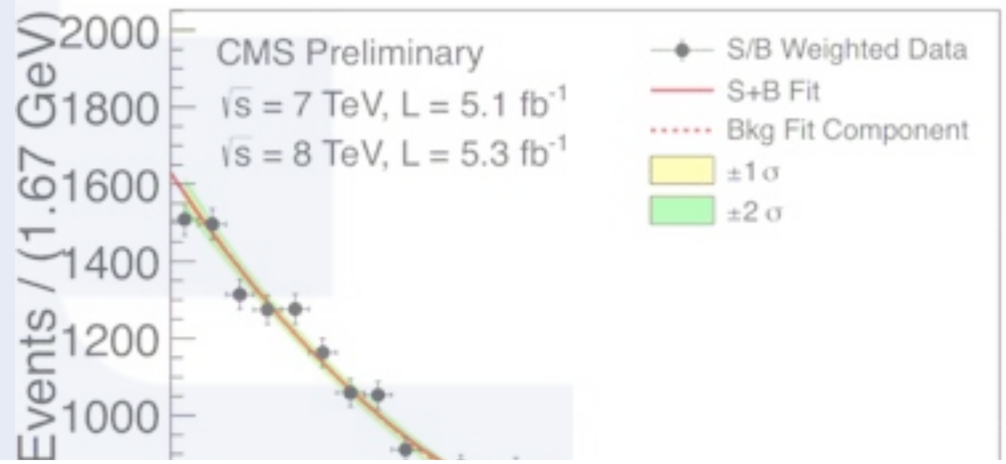

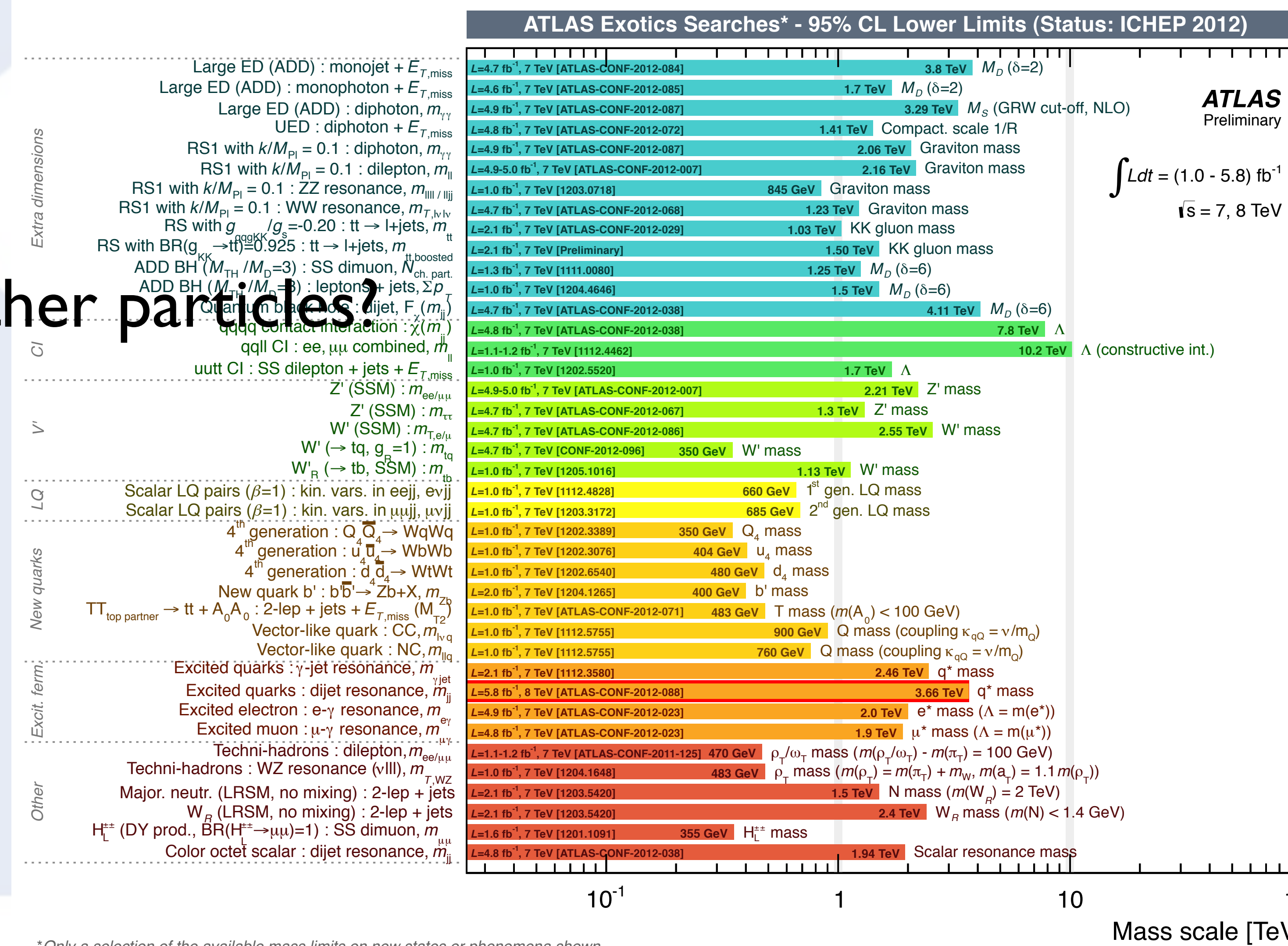

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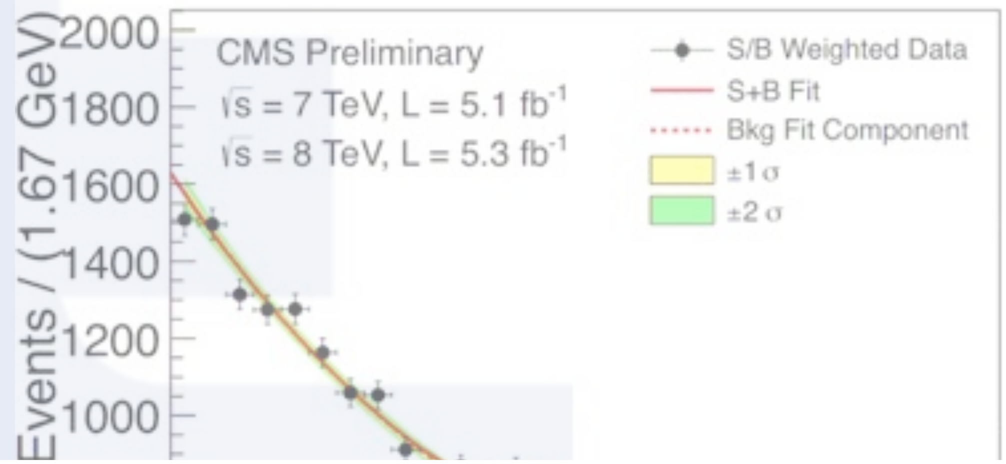

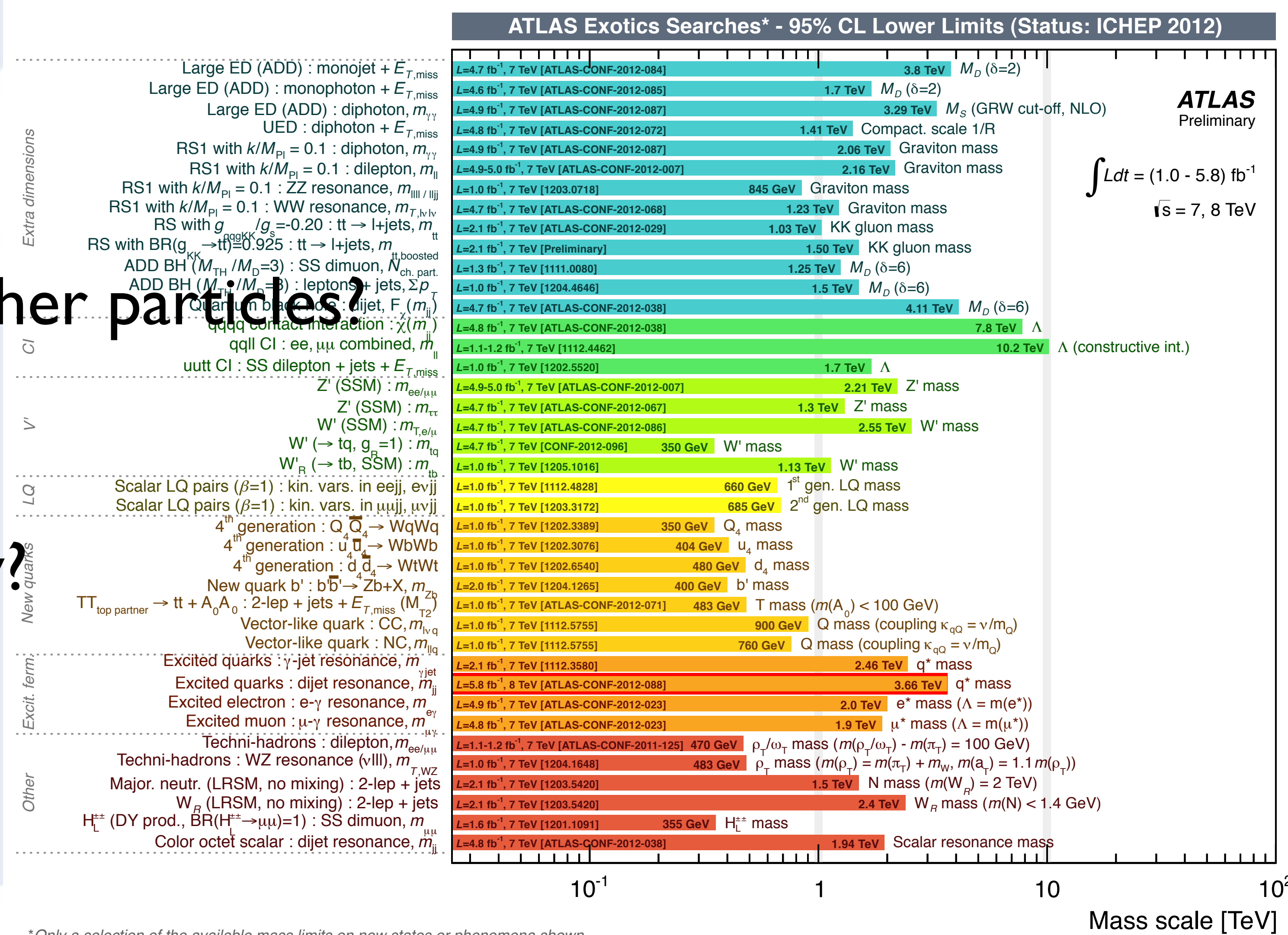

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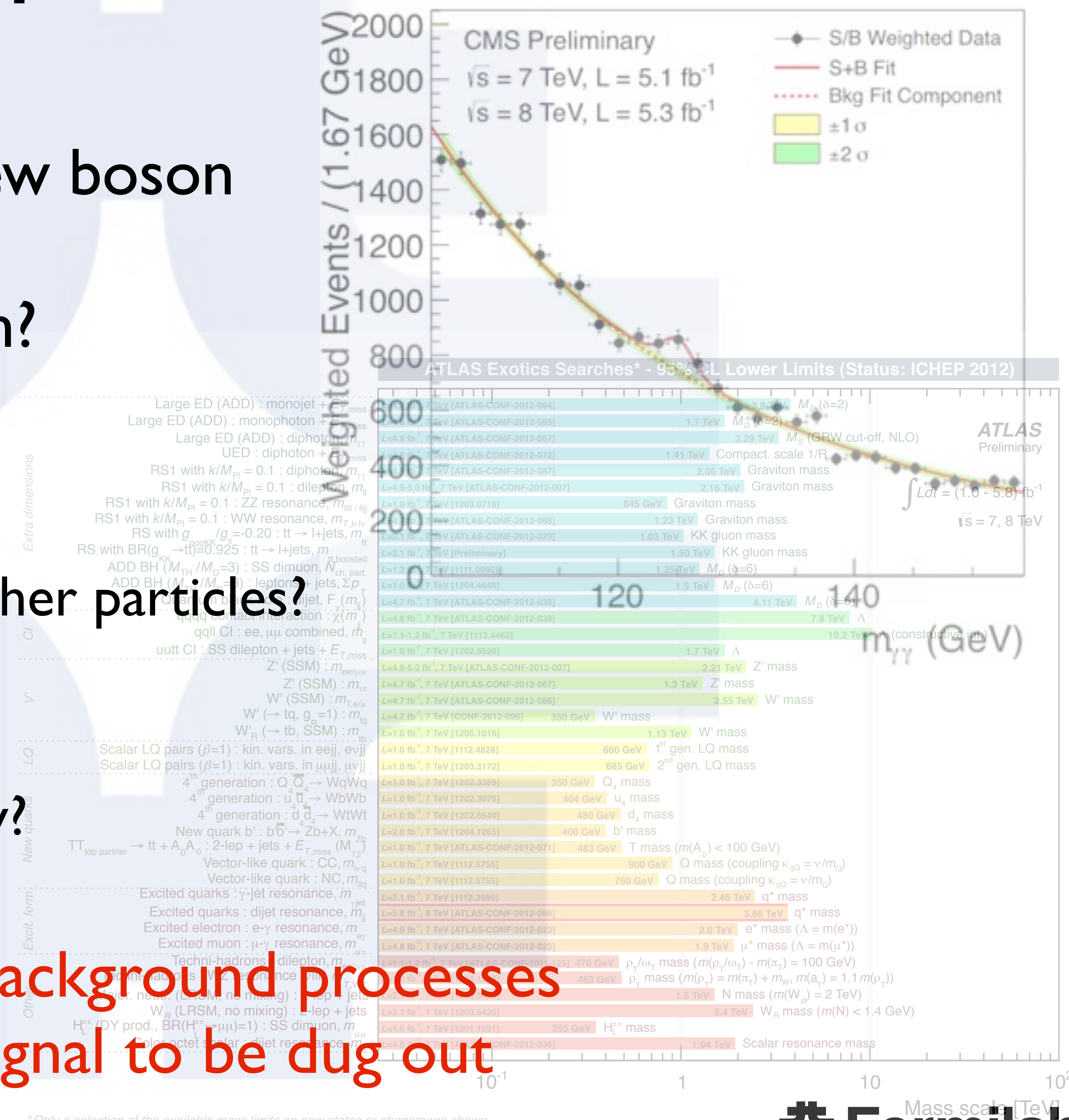

Lots of background processes
Tiny signal to be dug out

The exp'list request

The answer:

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If you give a man a fish, you feed him for a day. But if you give him a fishing rod, you feed him for a lifetime

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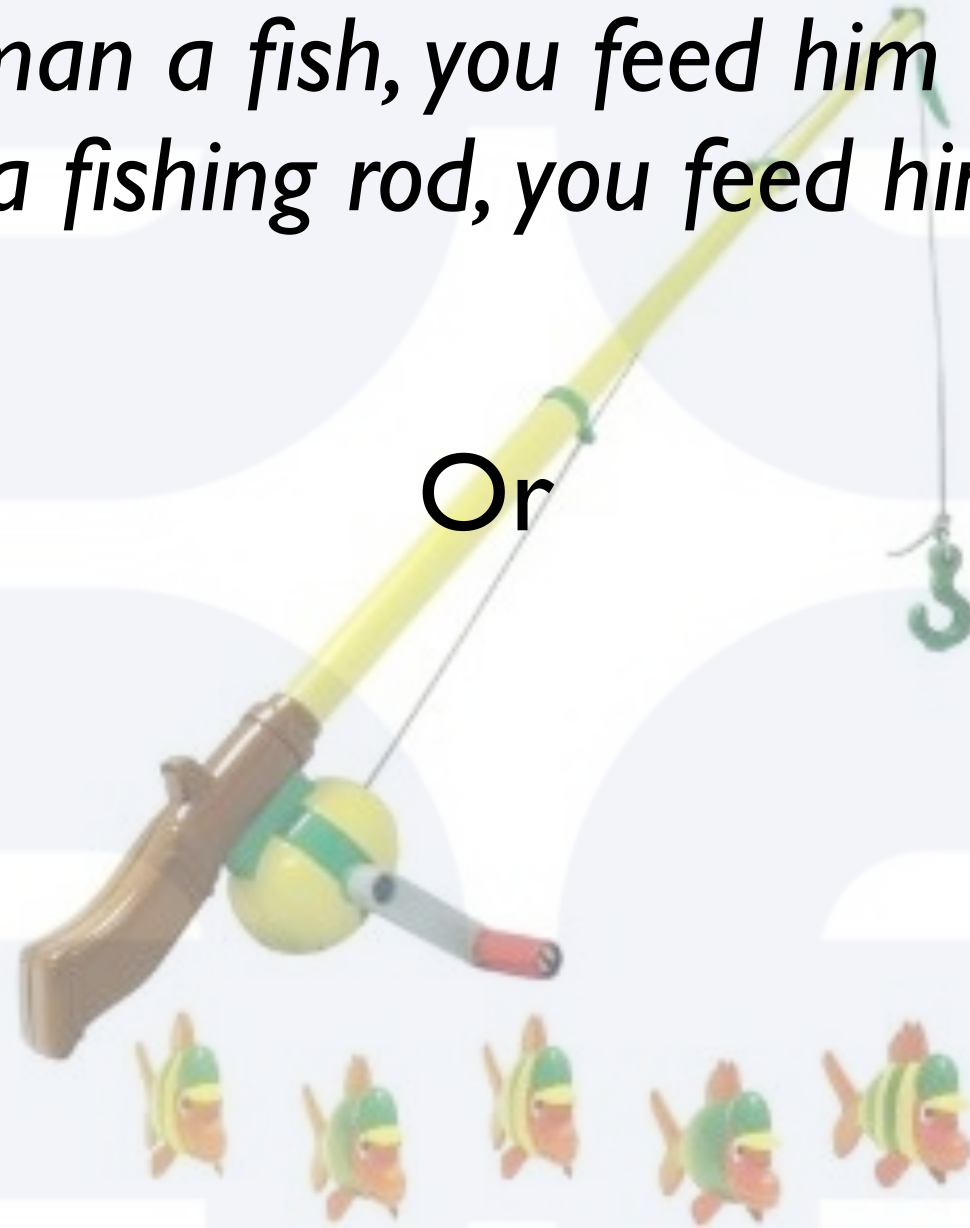

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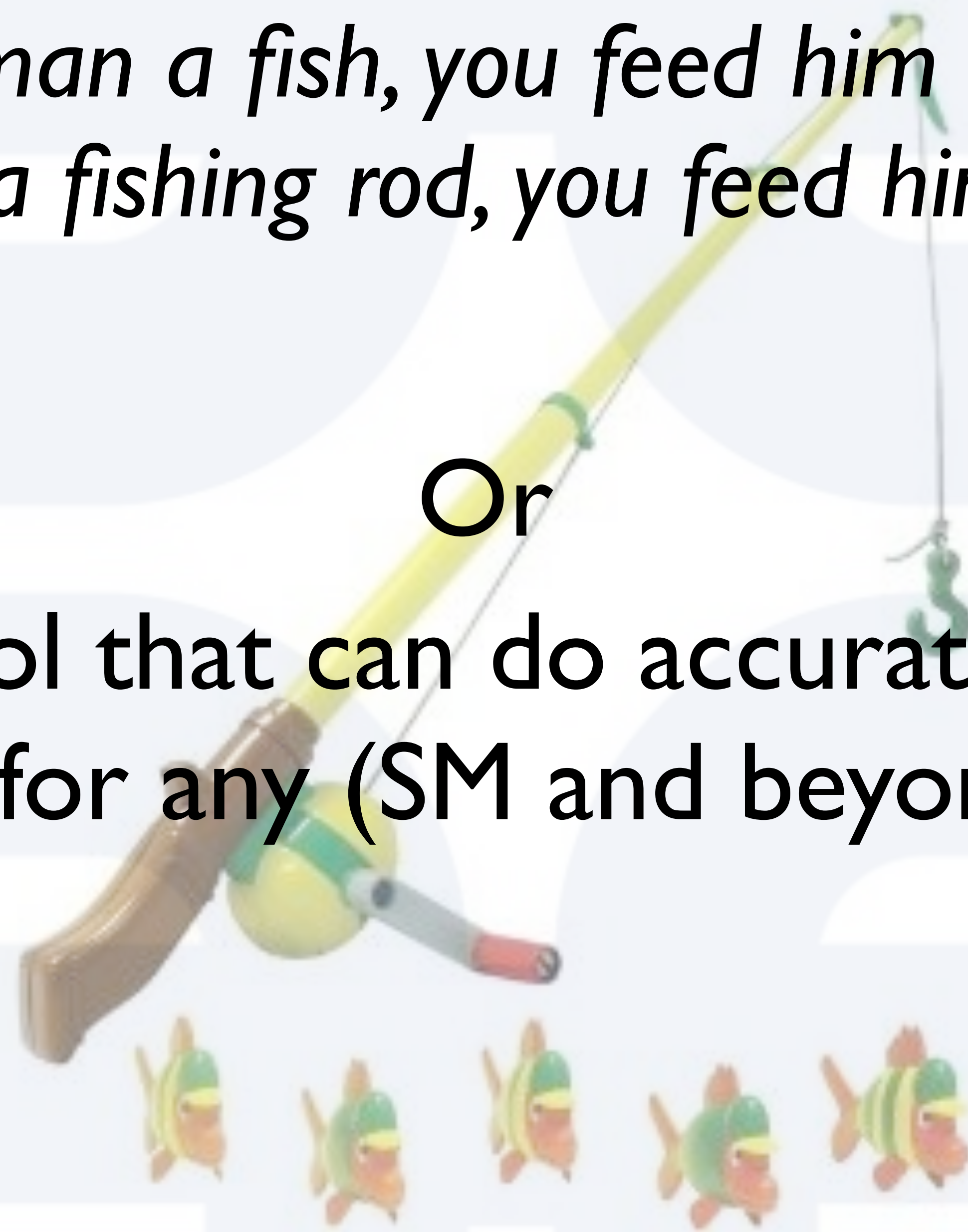
Or

Provide a tool that can do accurate and realistic simulations for any (SM and beyond) process...



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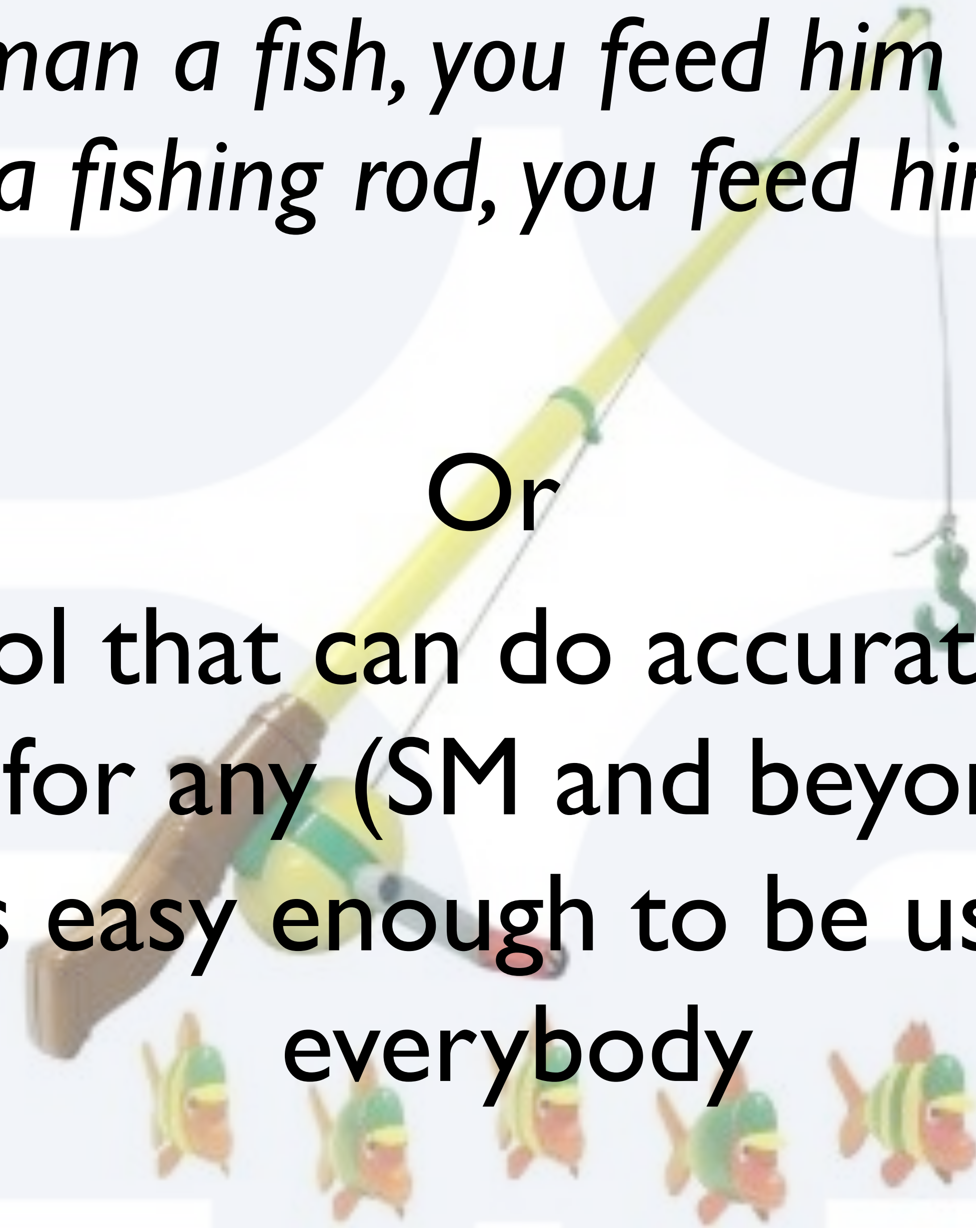

If you give a man a fish, you feed him for a day. But if you give him a fishing rod, you feed him for a lifetime

Or

Provide a tool that can do accurate and realistic simulations for any (SM and beyond) process...
...and which is easy enough to be used by (almost) everybody

Say it again?!?

- Accurate
  - Reliable prediction of total rates
  - Reliable assessment of uncertainties
- Realistic
  - That simulates what we actually see at experiments
- For any (SM and beyond) process
  - Automatic
  - Linkable to any model
- Easy to use

Accurate predictions at hadron colliders

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$$\sigma = \int dx_1 dx_2 f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2)\ \ \sigma_{ab}\left(x_1, x_2, \alpha_s(\mu_R^2)\right)$$

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- fit from data
- process independent

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Short distance (partonic) cross-section

- known order by order in pert. theory
- process dependent

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$$\sigma_{ab} = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \ldots$$

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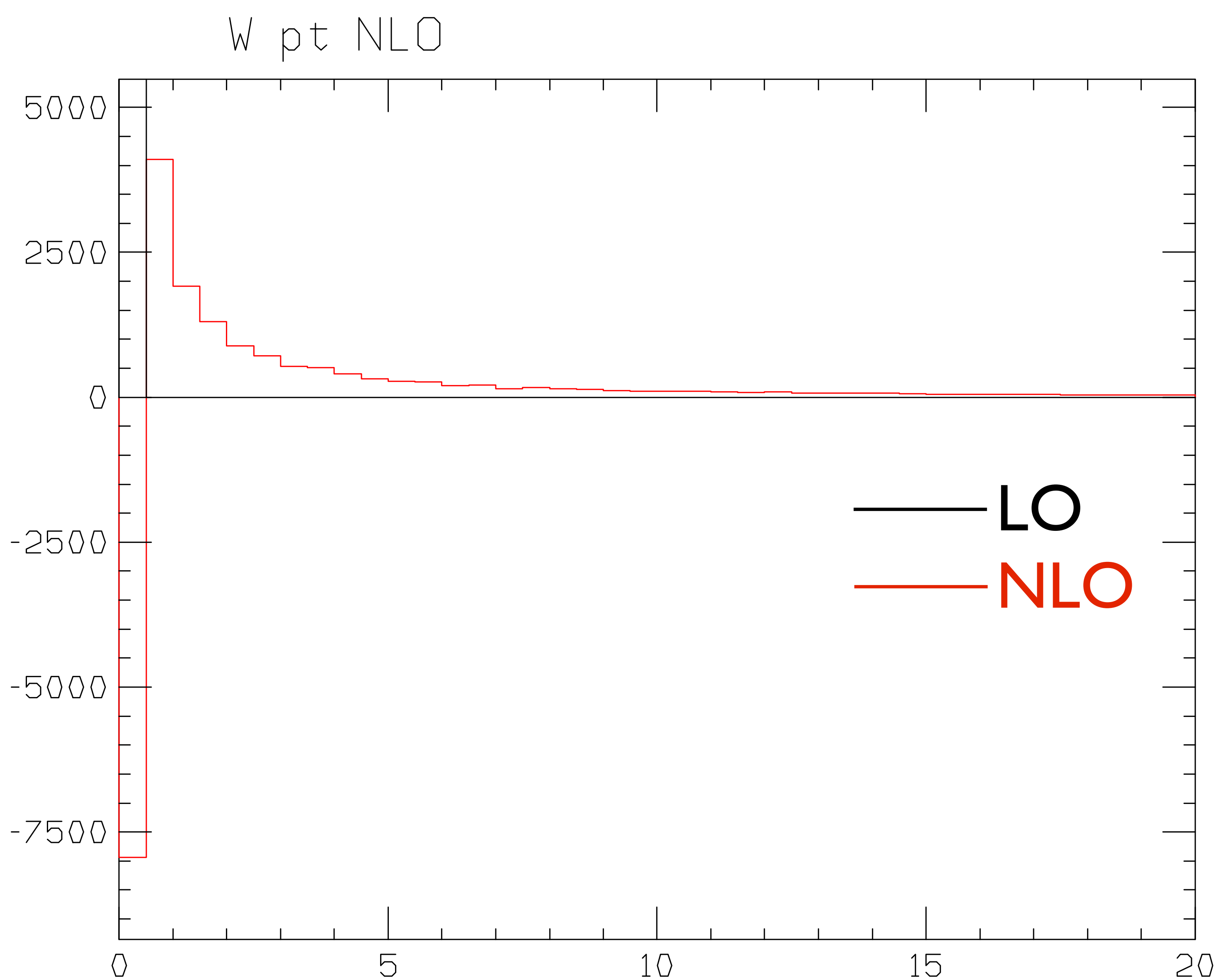
LO NLO NNLO

$$\sigma_{ab} = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \ldots$$

- Inclusion of higher orders improves data/theory agreement
- Inclusion of higher orders reduces TH errors
- NLO mandatory
  - Reliable predictions of rates and uncertainities
- Still not all observables are well behaved at fixed order

W boson pt



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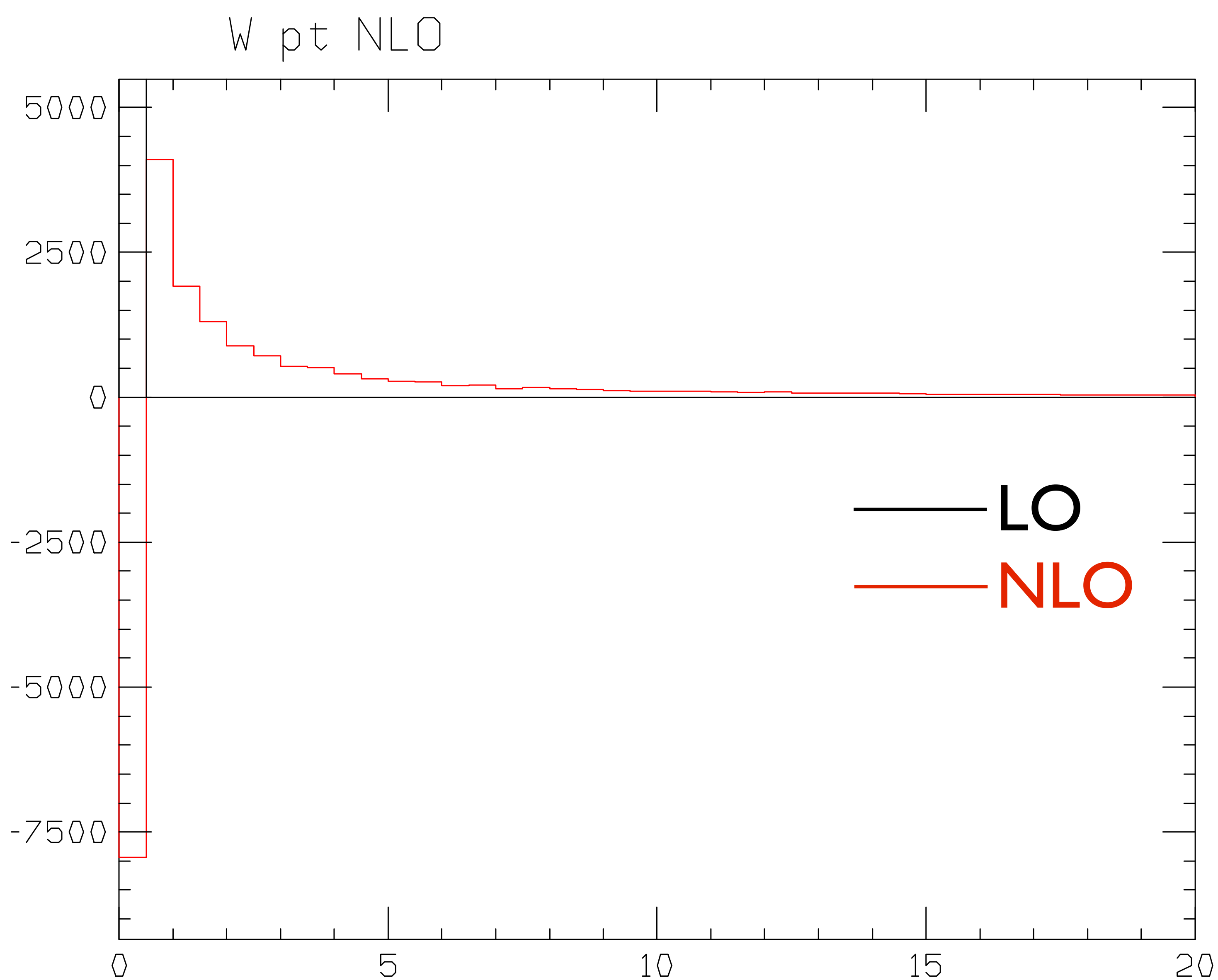

back on this later...

NLO: how to?

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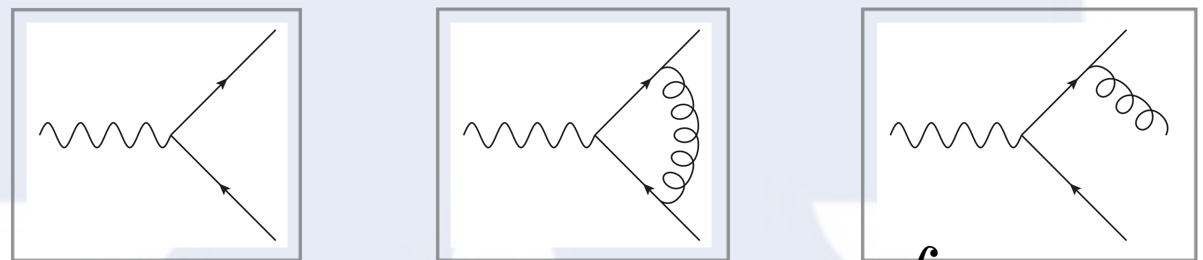

$$d\sigma^n_{NLO} = d\sigma^n_{LO} + d\sigma^n_V + \int d\Phi_1 \, d\sigma^{n+1}_R$$

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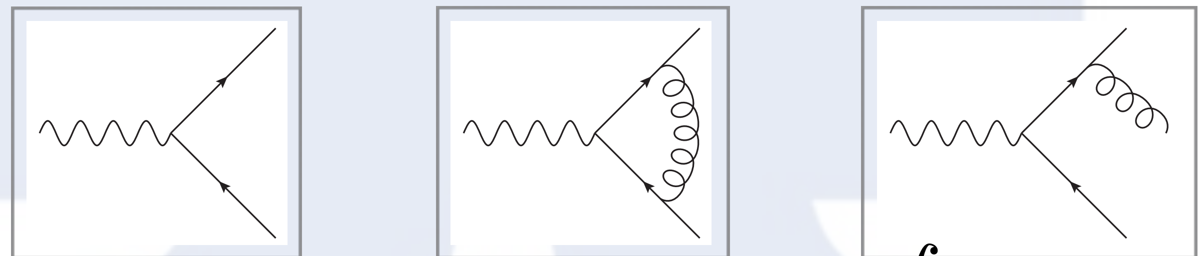

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  - Need to cancel them before numerical integration (in D=4)

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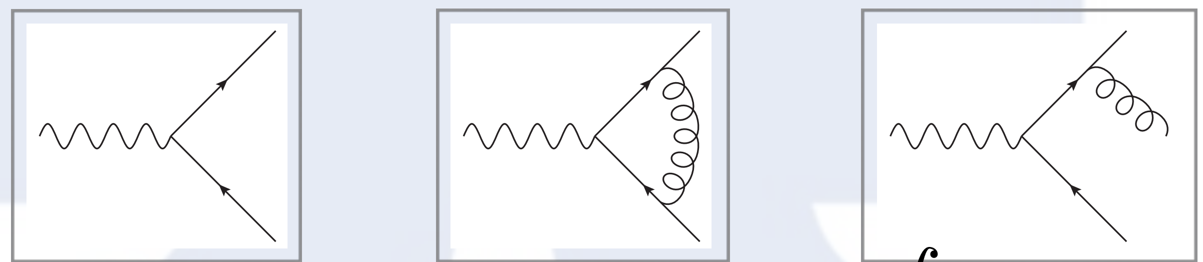

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- Warning! Real emission ME is divergent!
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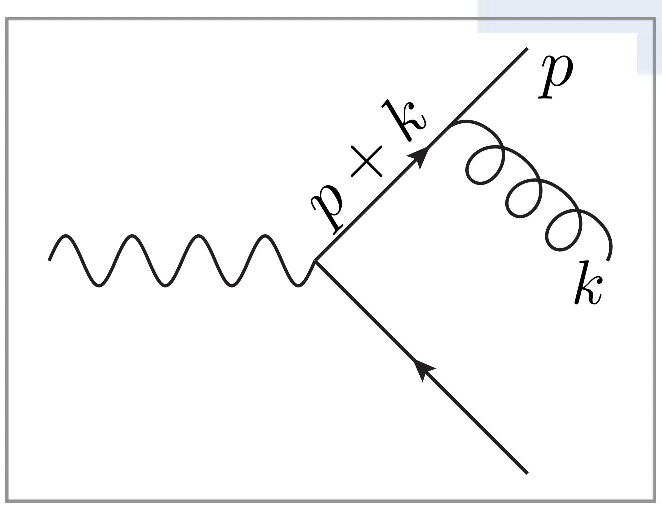
  - Need to cancel them before numerical integration (in D=4)
- Structure of divergences is universal:



$$(p+k)^2 = 2E_pE_k(1-\cos\theta_{pk})$$

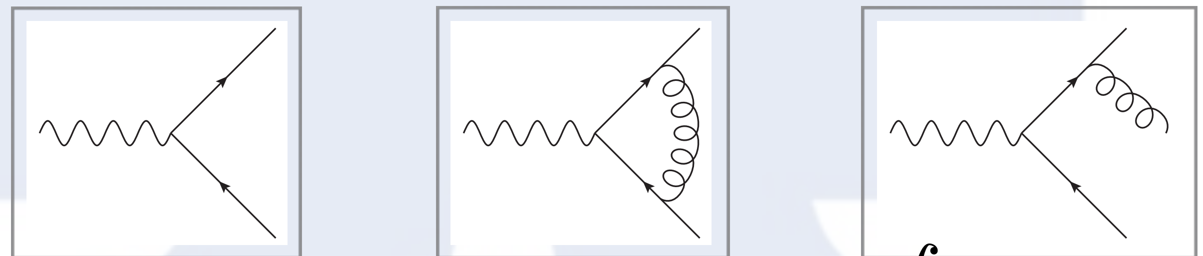
- Collinear singularity:

$$\lim_{p//k} |M_{n+1}|^2 \simeq |M_n|^2 \; P^{AP}(z)$$

- Soft singularity:

$$\lim_{k\to 0} |M_{n+1}|^2 \simeq \sum_{ij} |M_n^{ij}|^2 \frac{p_i p_j}{p_i k \; p_j k}$$

NLO: how to?



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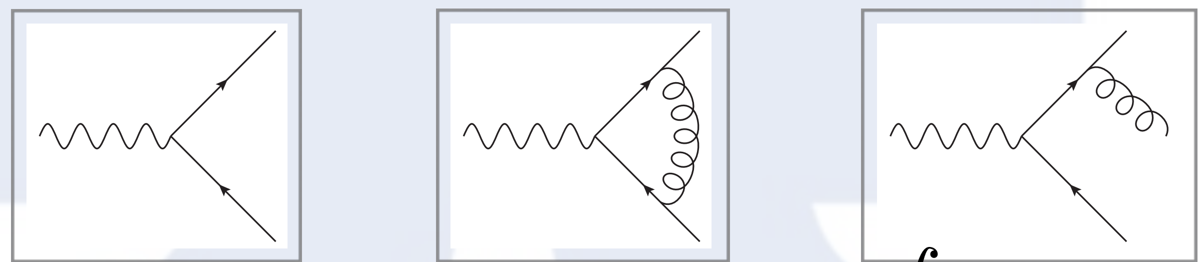

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- Add local counterterms in the singular regions and subtract its integrated finite part (poles will cancels against the virtuals)
- The *n* and *n+1* body integral now are perfectly finite in 4 dimension
  - Can be integrated numerically

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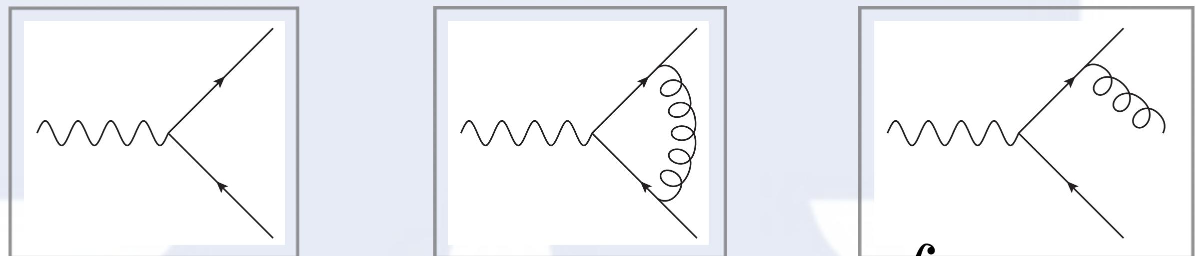

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How to do this in an efficient way?

The FKS subtraction

Frixione, Kunszt, Signer, arXiv:hep-ph/9512328

- Soft/collinear singularities arise in many PS regions
- Find parton pairs *i, j* that can give collinear singularities
- Split the phase space into regions with one collinear sing
  - Soft singularities are split into the collinear ones

$$|M|^2 = \sum_{ij} S_{ij} \, |M|^2 = \sum_{ij} |M|^2_{ij} \qquad \sum S_{ij} = 1$$

$$S_{ij} \to 1 \text{ if } k_i \cdot k_j \to 0 \qquad S_{ij} \to 0 \text{ if } k_{m \neq i} \cdot k_{n \neq j} \to 0$$

- Integrate them independently
  - Parallelize integration
  - Choose ad-hoc phase space parameterization
- Advantages:
  - # of contributions ~ n^2
  - Exploit symmetries: 3 contributions for g g > ng

What about loops?

- Several methods/tools to compute loop amplitudes are available
  - Generalized unitarity (BlackHat, Rocket)

    Bern, Dixon, Dunbar, Kosower, hep-ph/9403226 + ...
    Ellis, Giele, Kunszt 0708.2398, +Melnikov 0806.3467
  - Integrand reduction (CutTools, Samurai)

    Ossola, Papadopolulos, Pittau, hep-ph/0609007, del Aguila, Pittau, hep-ph/0404120
    Mastrolia, Ossola, Reiter, Tramontano, 1006.0710
  - Tensor reduction (Golem)

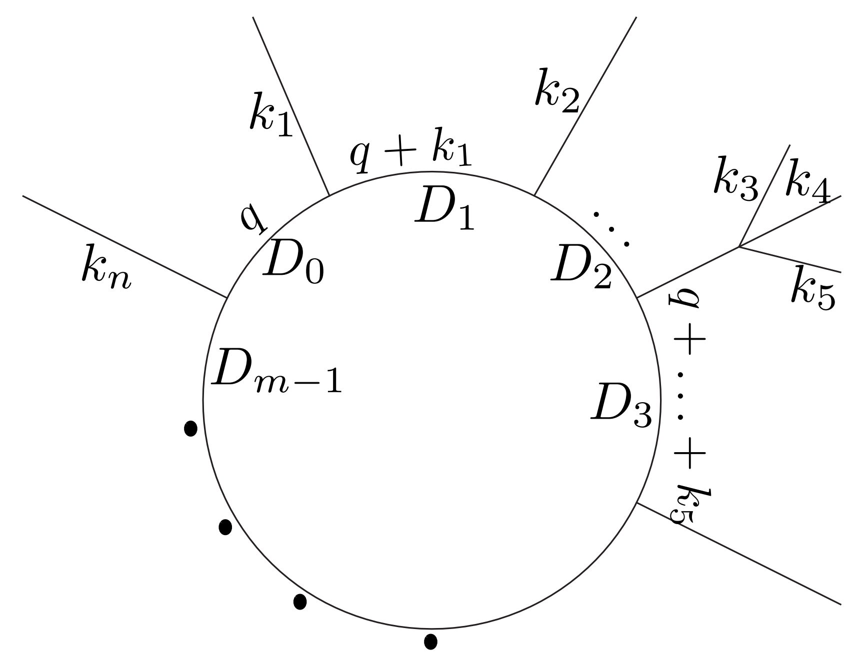
    Passarino, Veltman, 1979; Denner, Dittmaier, hep-ph/0509141
    Binoth, Guillet, Heinrivh, Pilon, Reiter 0810.0092

The OPP Method

Ossola, Papadopoulos, Pittau, arXiv:hep-ph/0609007 & arXiv:0711.3596

- Passarino & Veltman reduction:
  - Write the amplitude at the integral level as linear combination of 1-...-4-point scalar integrals

$$
\begin{aligned}
A(q) &= \sum_{i_0<i_1<i_2<i_3}^{m-1} d(i_0 i_1 i_2 i_3) D_0(i_0 i_1 i_2 i_3) \\
&+ \sum_{i_0<i_1<i_2}^{m-1} c(i_0 i_1 i_2) C_0(i_0 i_1 i_2) \\
&+ \sum_{i_0<i_1}^{m-1} b(i_0 i_1) B_0(i_0 i_1) \\
&+ \sum_{i_0}^{m-1} a(i_0) A_0(i_0) \\
&+ R
\end{aligned}
$$



  - Do this at the integrand level

The OPP Method

Ossola, Papadopoulos, Pittau, arXiv:hep-ph/0609007 & arXiv:0711.3596

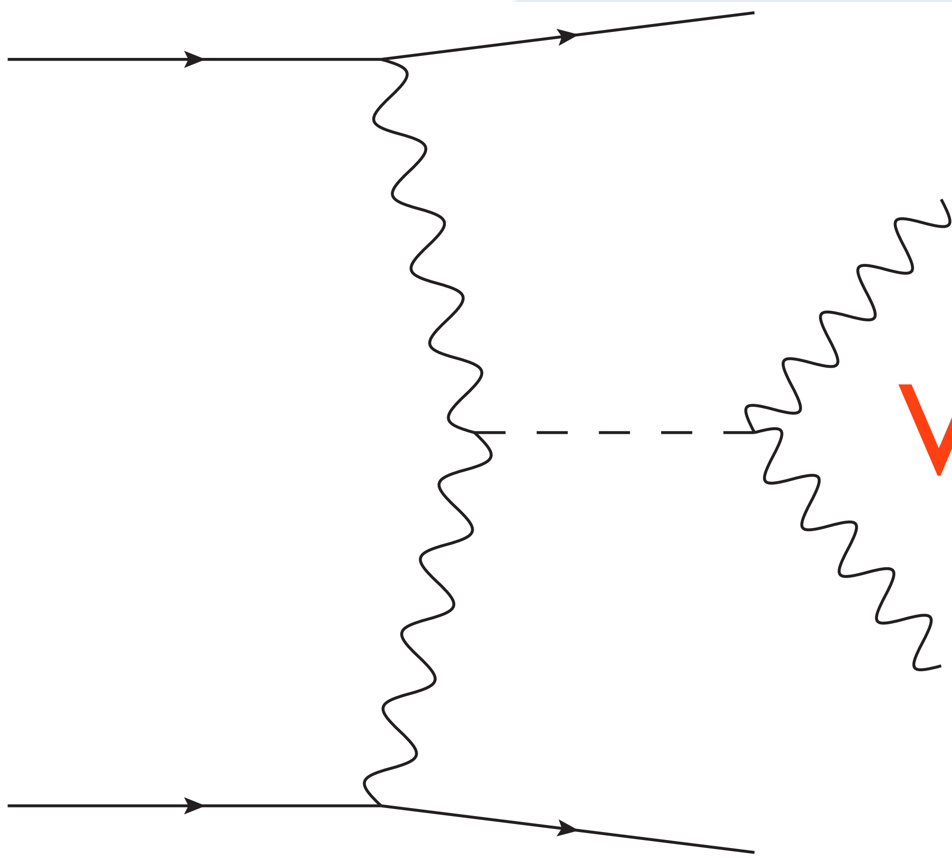
$$A(\bar{q}) = \frac{N(q)}{D_0 D_1 \cdots D_{m-1}} \quad N(q) = \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0i_1i_2i_3) + \tilde{d}(q;i_0i_1i_2i_3)\right] \prod_{i\neq i_0,i_1,i_2,i_3}^{m-1} D_i$$
$$+ \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0i_1i_2) + \tilde{c}(q;i_0i_1i_2)\right] \prod_{i\neq i_0,i_1,i_2}^{m-1} D_i$$
$$+ \sum_{i_0<i_1}^{m-1} \left[b(i_0i_1) + \tilde{b}(q;i_0i_1)\right] \prod_{i\neq i_0,i_1}^{m-1} D_i$$
$$+ \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q;i_0)\right] \prod_{i\neq i_0}^{m-1} D_i$$
$$+ \tilde{P}(q) \prod_{i}^{m-1} D_i \,.$$

- Sample the numerator at complex values of the loop momenta in order to reconstruct the *a,b,c,d* coefficients and part of the rational terms (R1)
- Use CutTools: fed with the loop numerator outputs the coefficients of the scalar integrals and CC rational terms (R1)
- Add R2-rational terms/UV counterterms (process-independent)

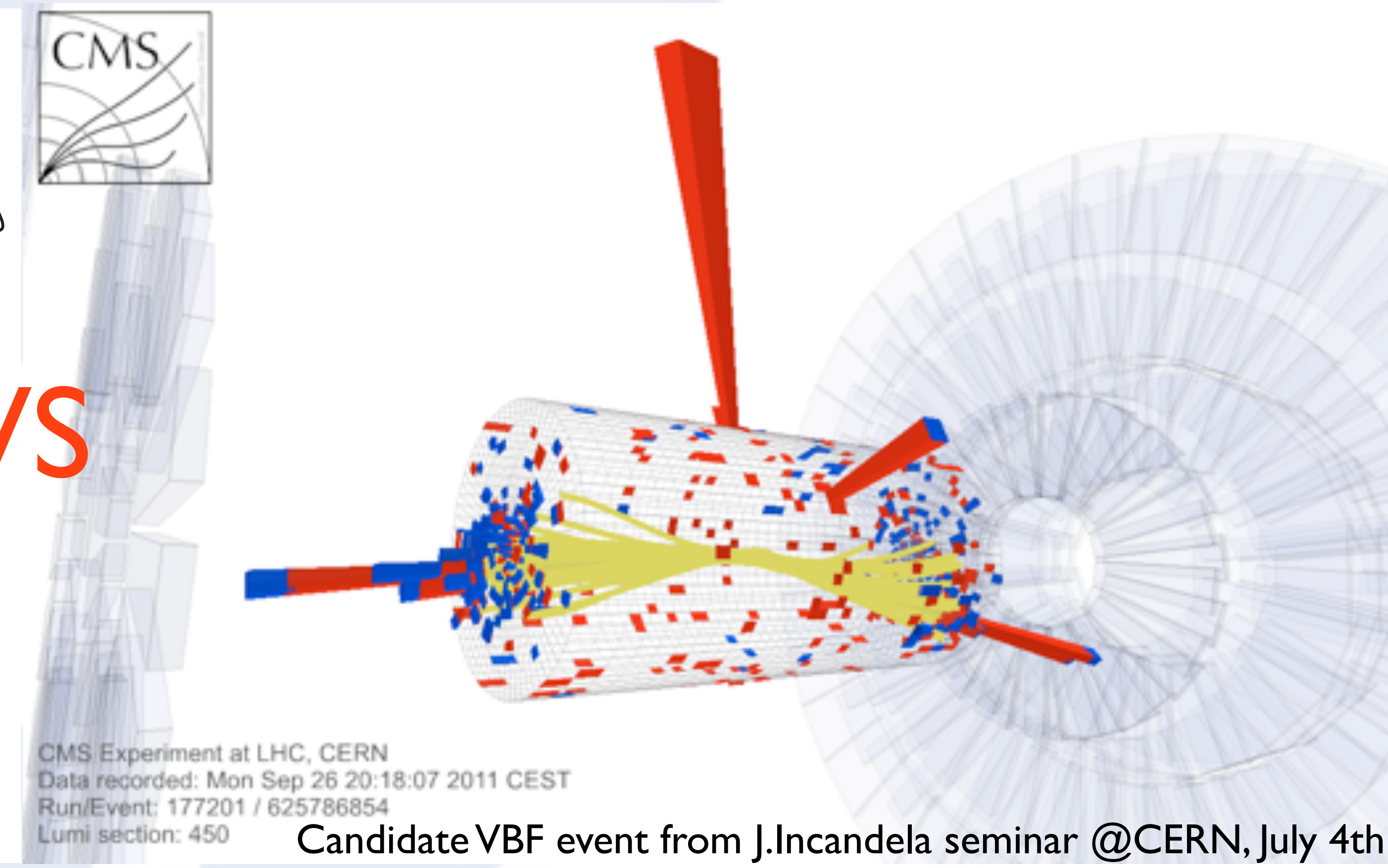
Realistic predictions at hadron colliders

E. Hopper, *Rooms by the sea* 1951

Realistic predictions at hadron colliders



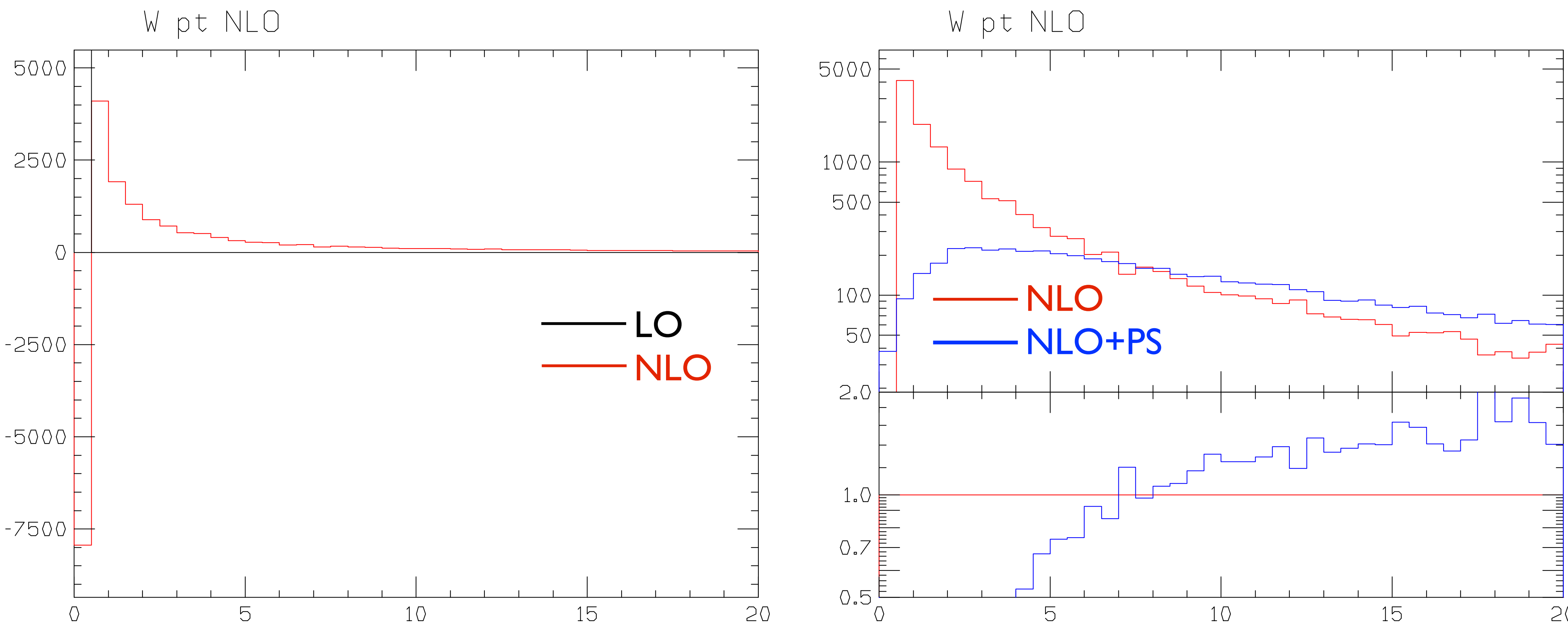
VS



Candidate VBF event from J.Incandela seminar @CERN, July 4th

- Parton level does not catch all the complexity that we see
- Matching to shower/hadronization MC needed
  - This also cures fixed orders ill-behaved observables

W boson pt (cont'd)



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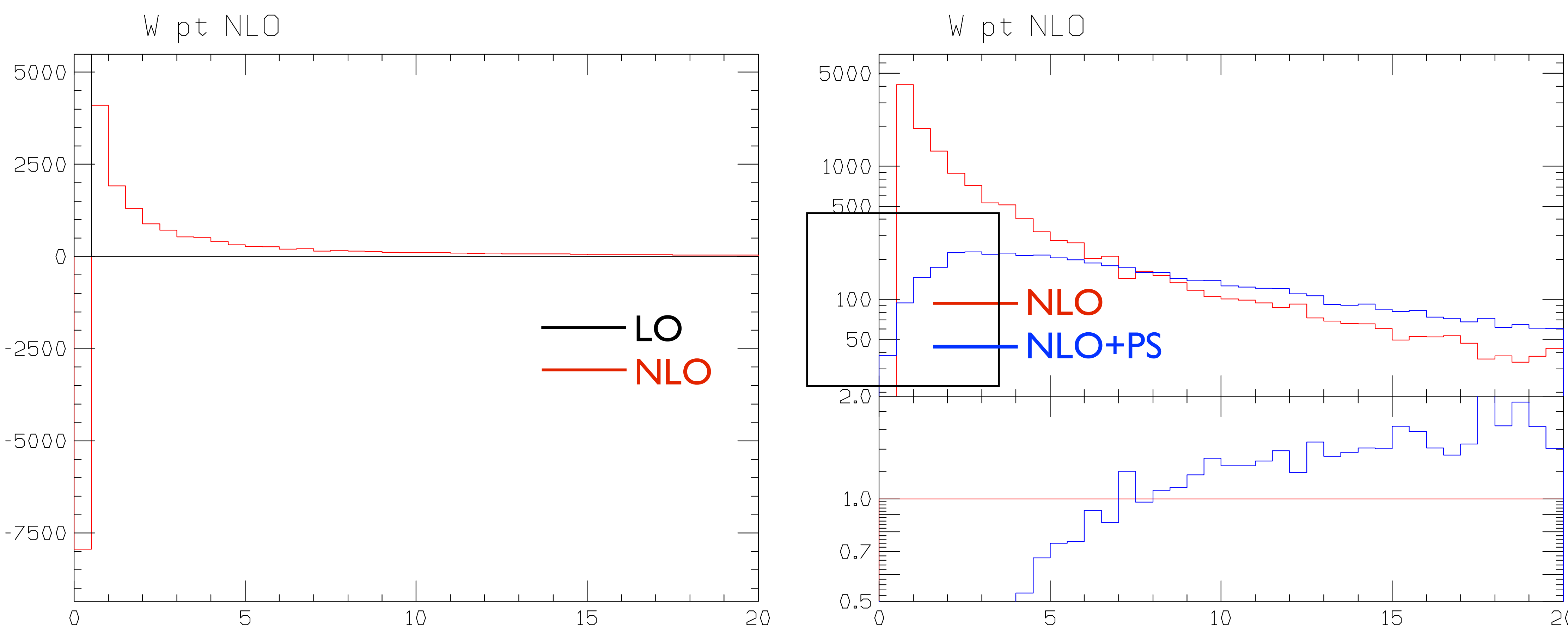

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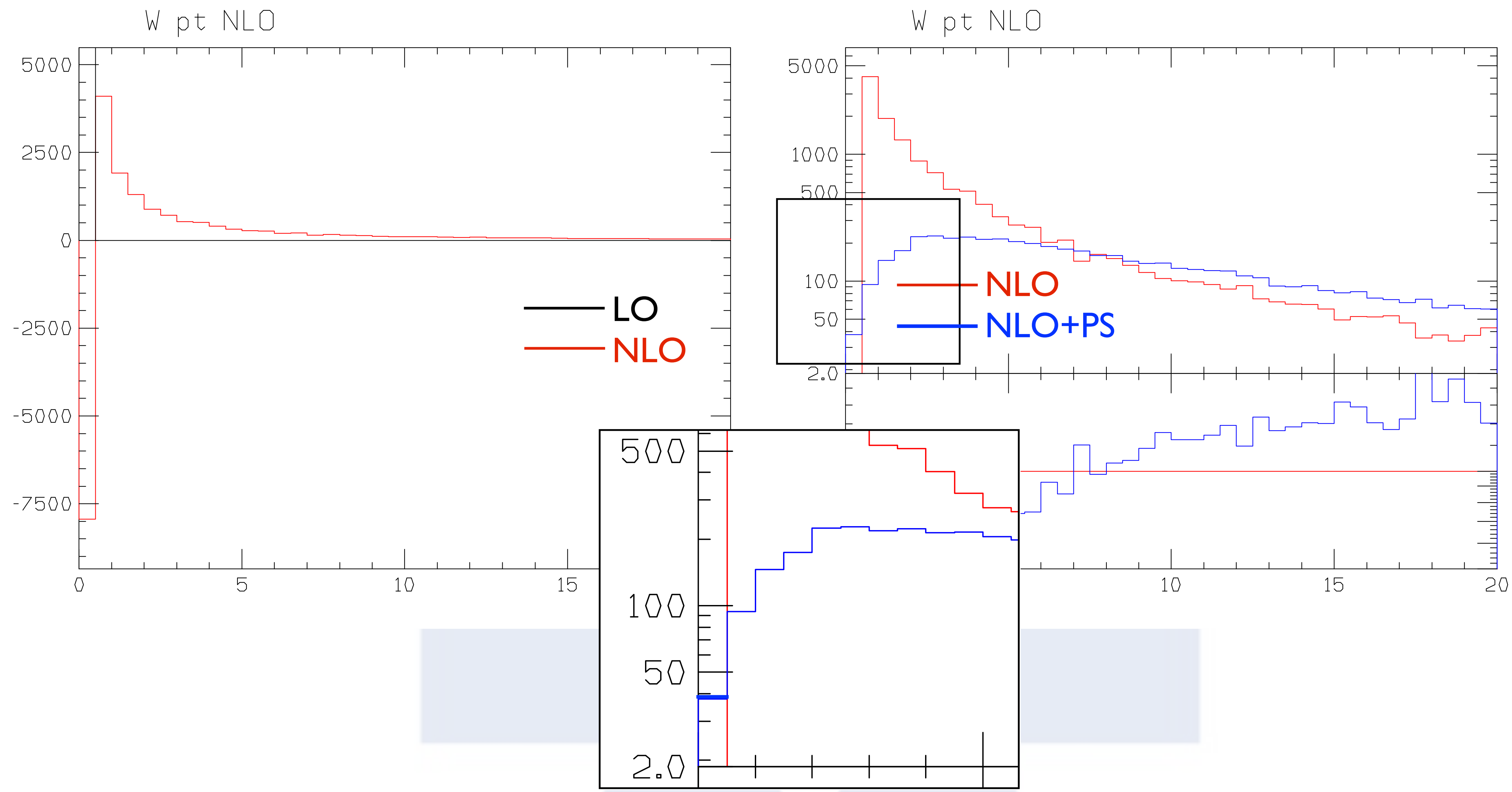

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$$\frac{d\sigma_{\text{``}MC@NLO\text{''}}}{dO} = \left[\int d\Phi_n (B+V)\right] I^n_{MC}(O) + \left[\int d\Phi_{n+1} R\right] I^{n+1}_{MC}(O)$$

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- One must avoid double counting the exact real/virtual MEs with the approximated ones from the Sudakov

MC@NLO:

Frixione, Weber, arXiv:hep-ph/0204244

- Add MC counterterms in the cross-section computation

$$\frac{d\sigma_{\text{“}MC@NLO\text{”}}}{dO} = \left[\int d\Phi_n (B + V + \int d\Phi_1 MC)\right] I^n_{MC}(O) + \left[\int d\Phi_{n+1}(R - MC)\right] I^{n+1}_{MC}(O)$$

  - The “shower operator” is related to *MC* as

$$I^k_{MC} = \Delta + \Delta d\Phi_1 \frac{MC}{B} + \dots \qquad \Delta = \exp\left[-\int d\Phi_1 \frac{MC}{B}\right]$$

  - So, NLO normalization of the total cross-section is kept
  - *MC* acts as a local soft/collinear counterterm
    - Suitable for numerical integration
  - Can generated unweighted (up to sign) events
  - *MC* is PS dependent

$$MC = J \frac{1}{t_{MC}} \frac{\alpha_s}{2\pi} P(z^{MC}) B$$

Automation

Automation

- Time for coding/debugging a new process@NLO: O(1) year
- Trade time spent for coding/debugging with time to do real physics
- Once building blocks are tested, results are almost “correct by definition”
- Automatic tools can be used as black-boxes. No need of knowing what the tool is actually doing for you

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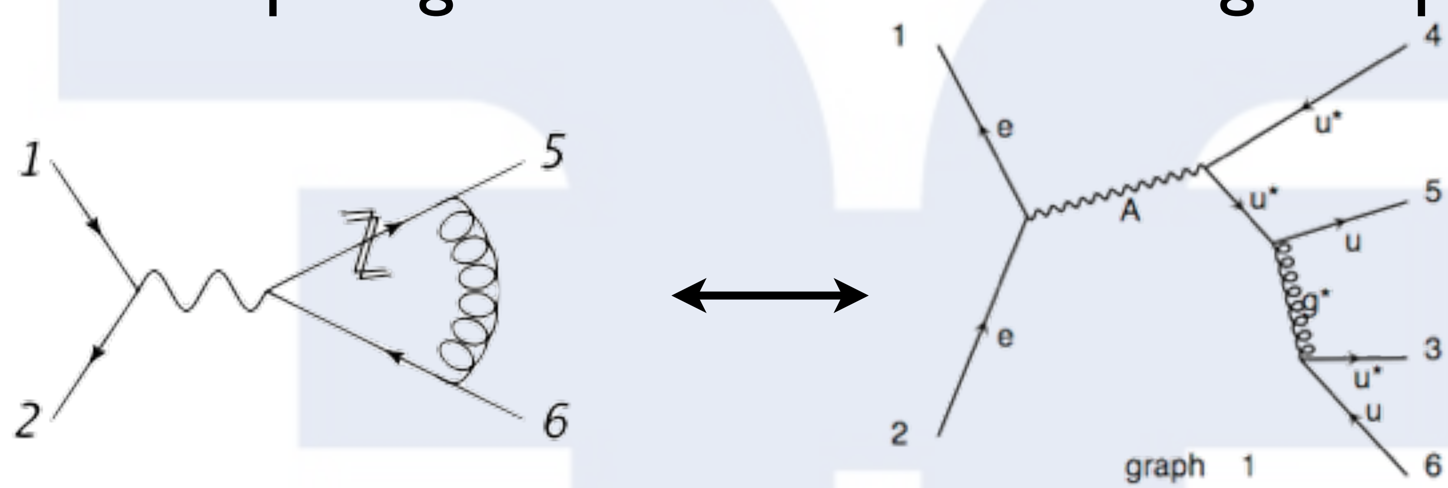

Automation with MadGraph

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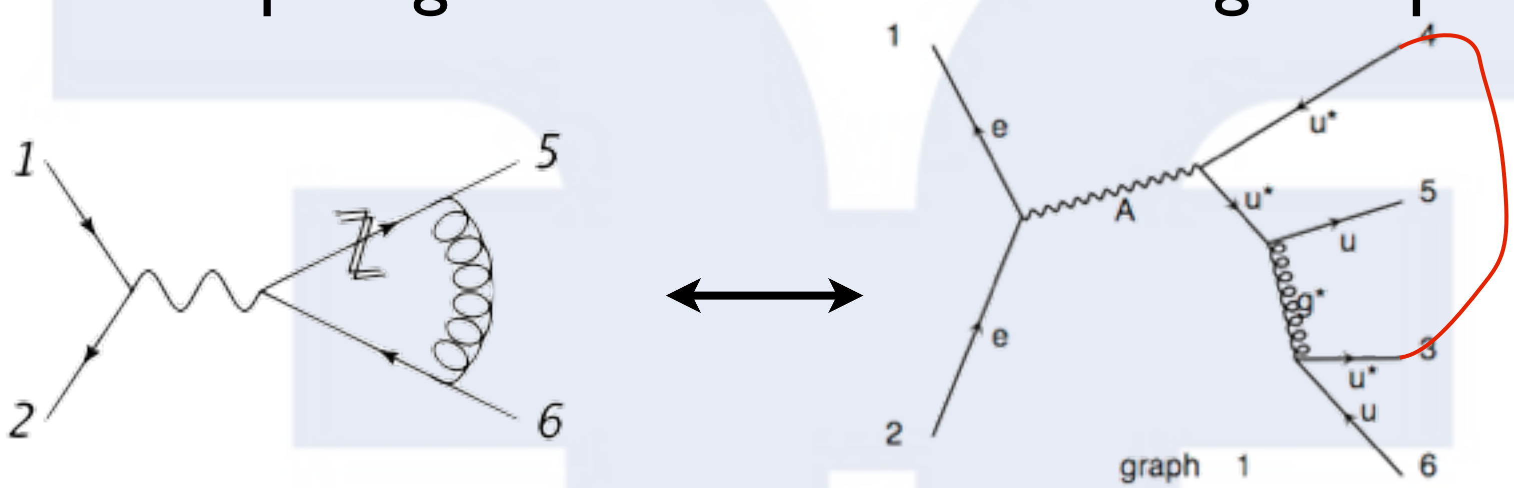

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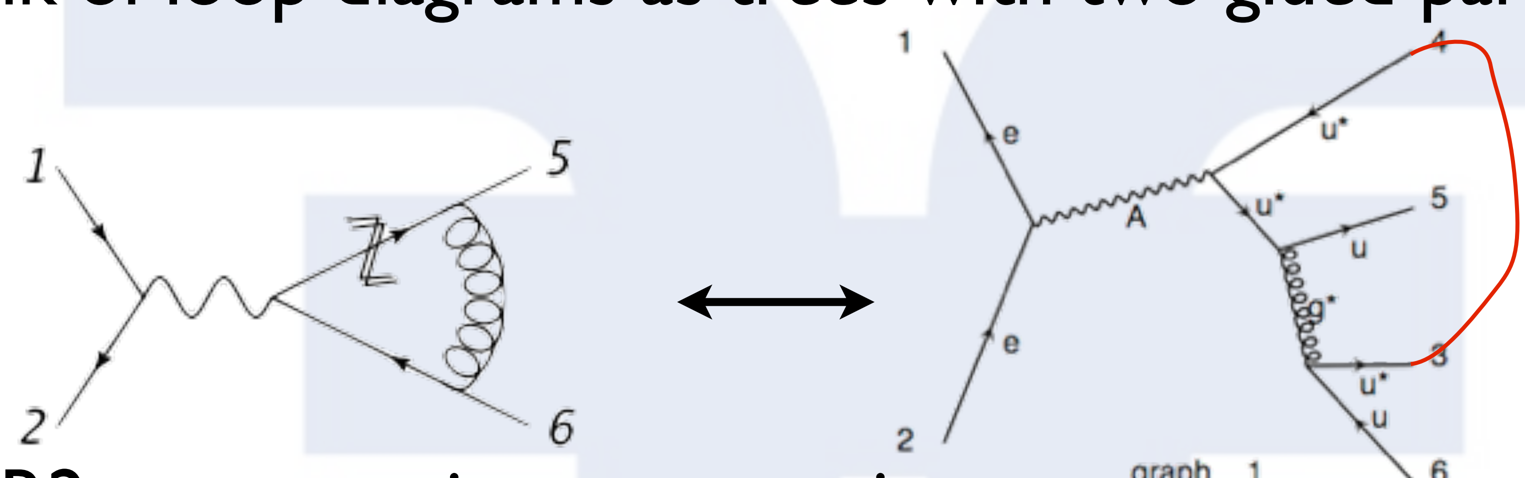

    - UV/R2 terms are just new vertices

MadLoop & MadFKS

Hirschi, et al. arXiv:1103.0621

Frederix, Frixione, Maltoni, Stelzer, arXiv:0908.4272

MadLoop & MadFKS

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  - Computes the loop numerator for any given amplitude and feeds it to CutTools
  - Adds R2/UV counterterms (coded as new vertices)

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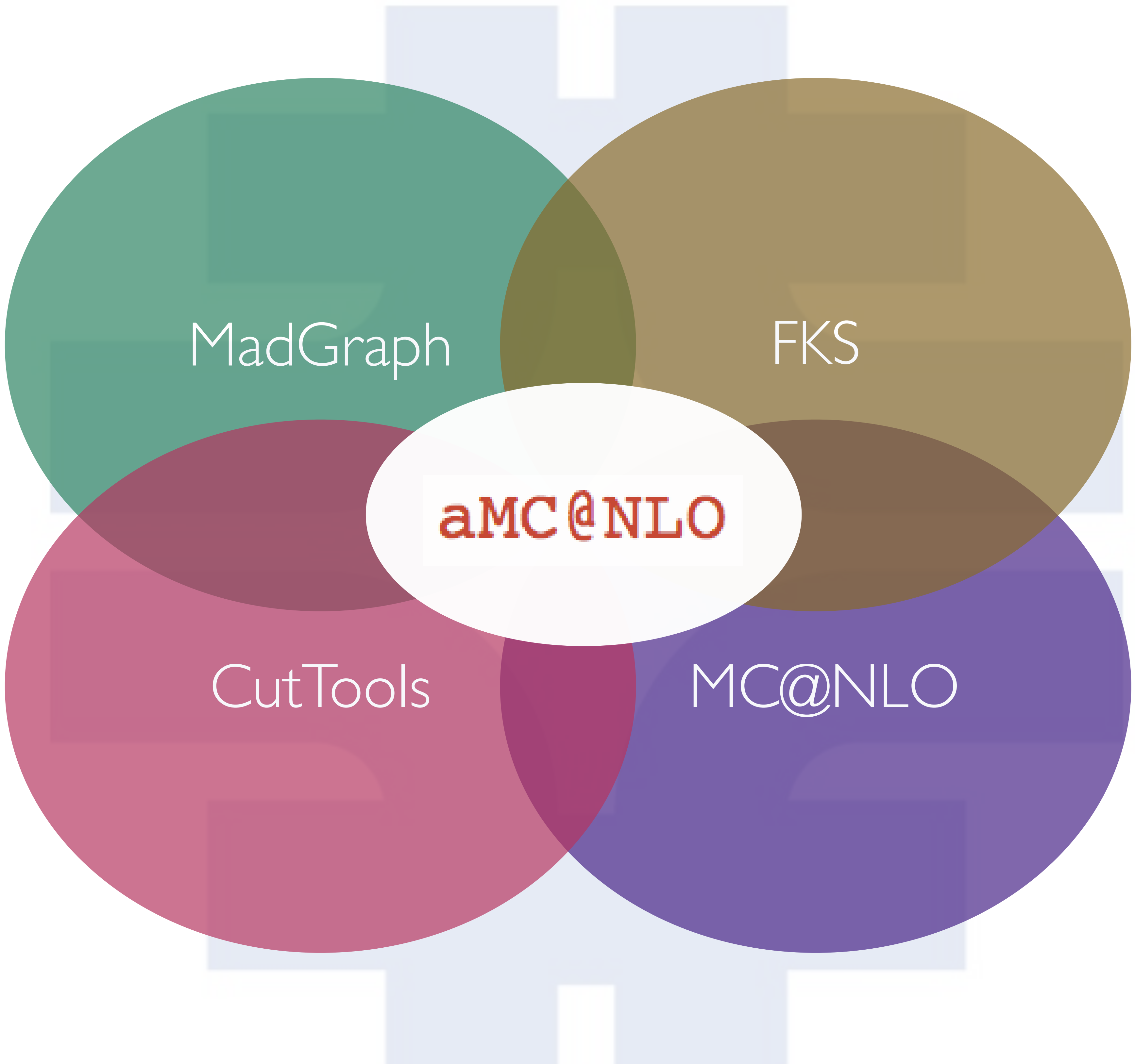
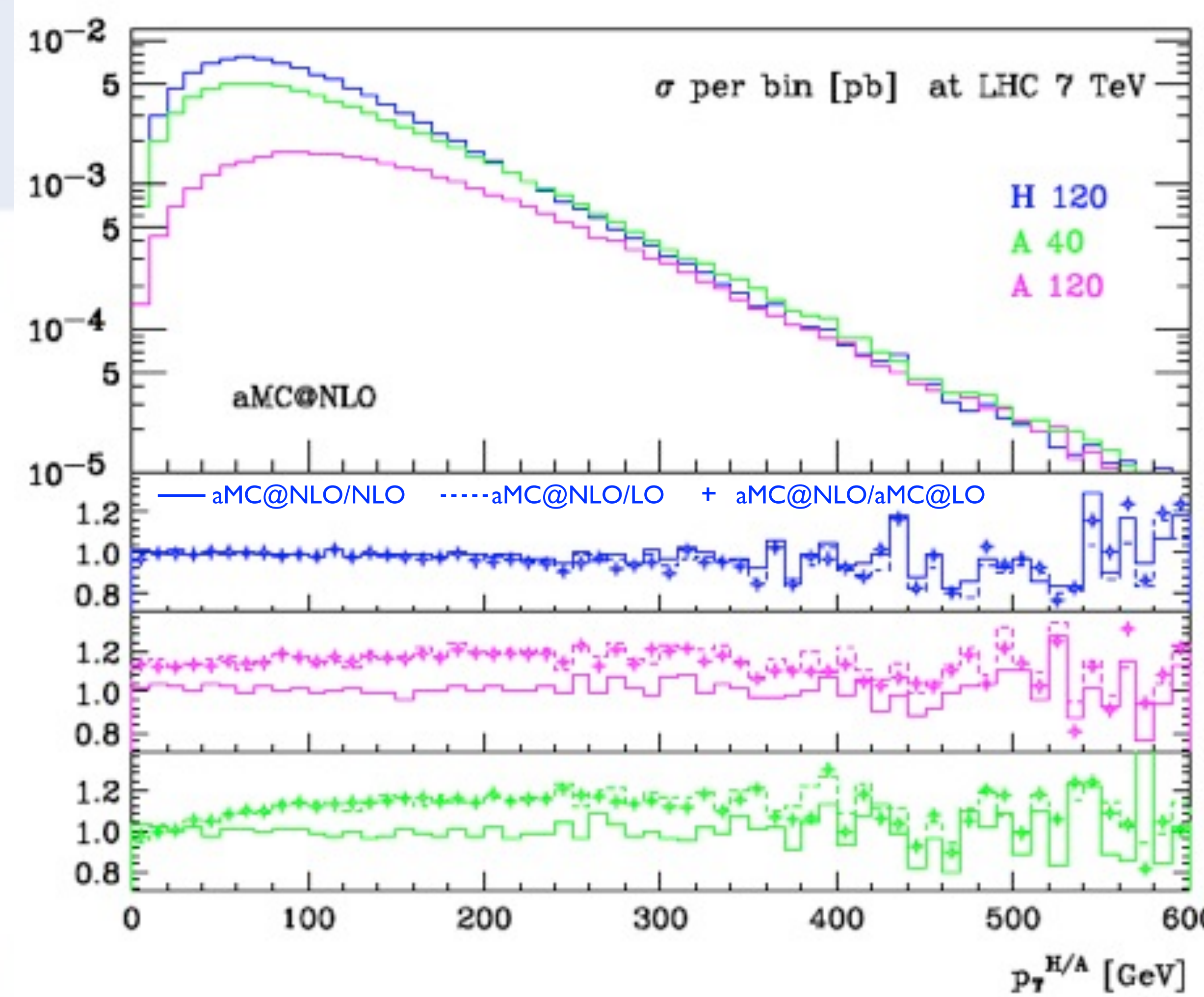
- MadLoop:
  - Computes the loop numerator for any given amplitude and feeds it to CutTools
  - Adds R2/UV counterterms (coded as new vertices)
- MadFKS:
  - Computes the real and born MEs and counterterms (color- and spin-linked borns)
  - Links the virtuals from MadLoop or via BLHA
  - Organizes the integration of n and n+1 body cross-section
  - Generates events to be showered


MadGraph
FKS
aMC@NLO
CutTools
MC@NLO

Physics results with MG4

Physics results with MG4

- ttH/ttA, arXiv:1104.5613



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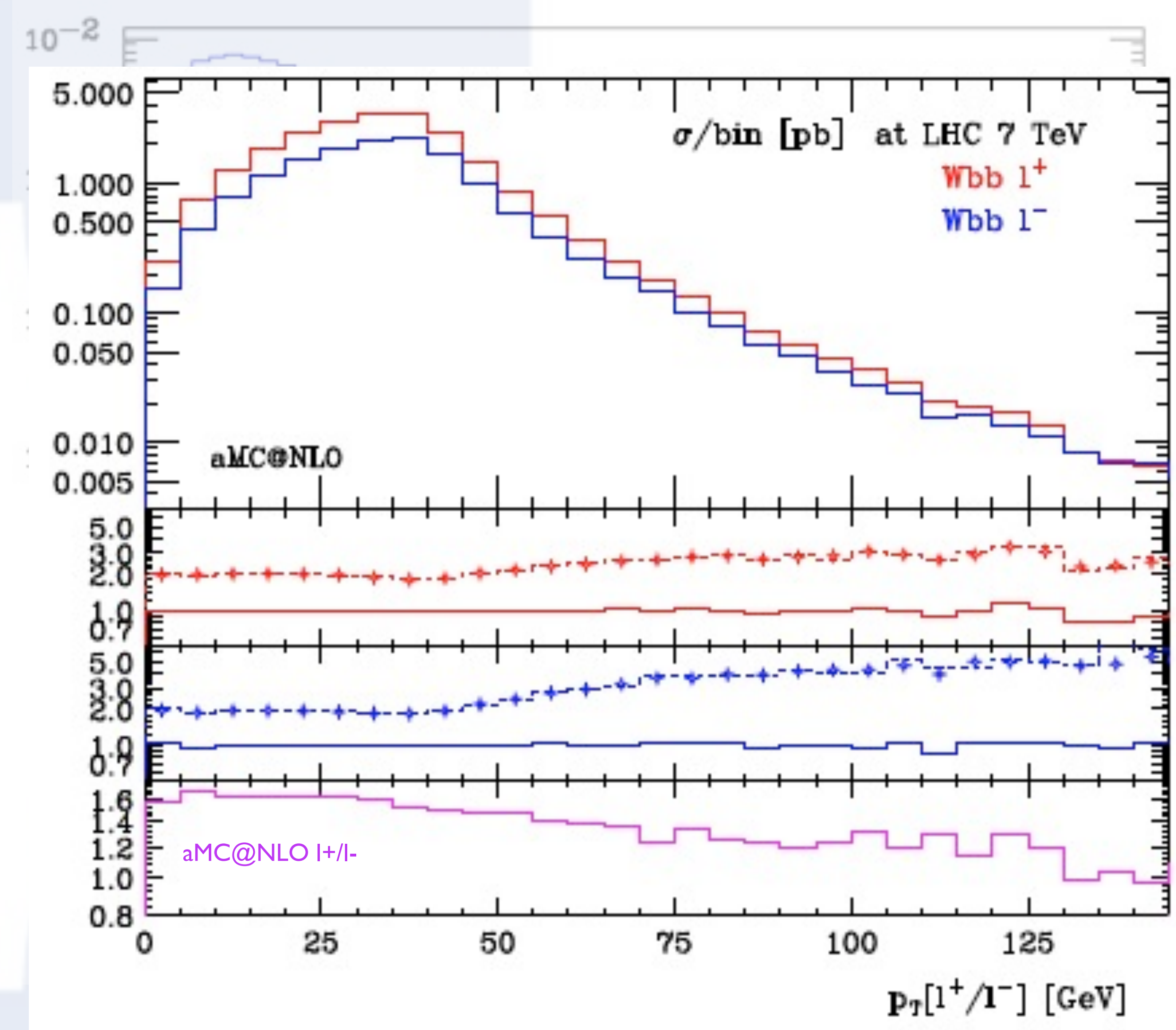

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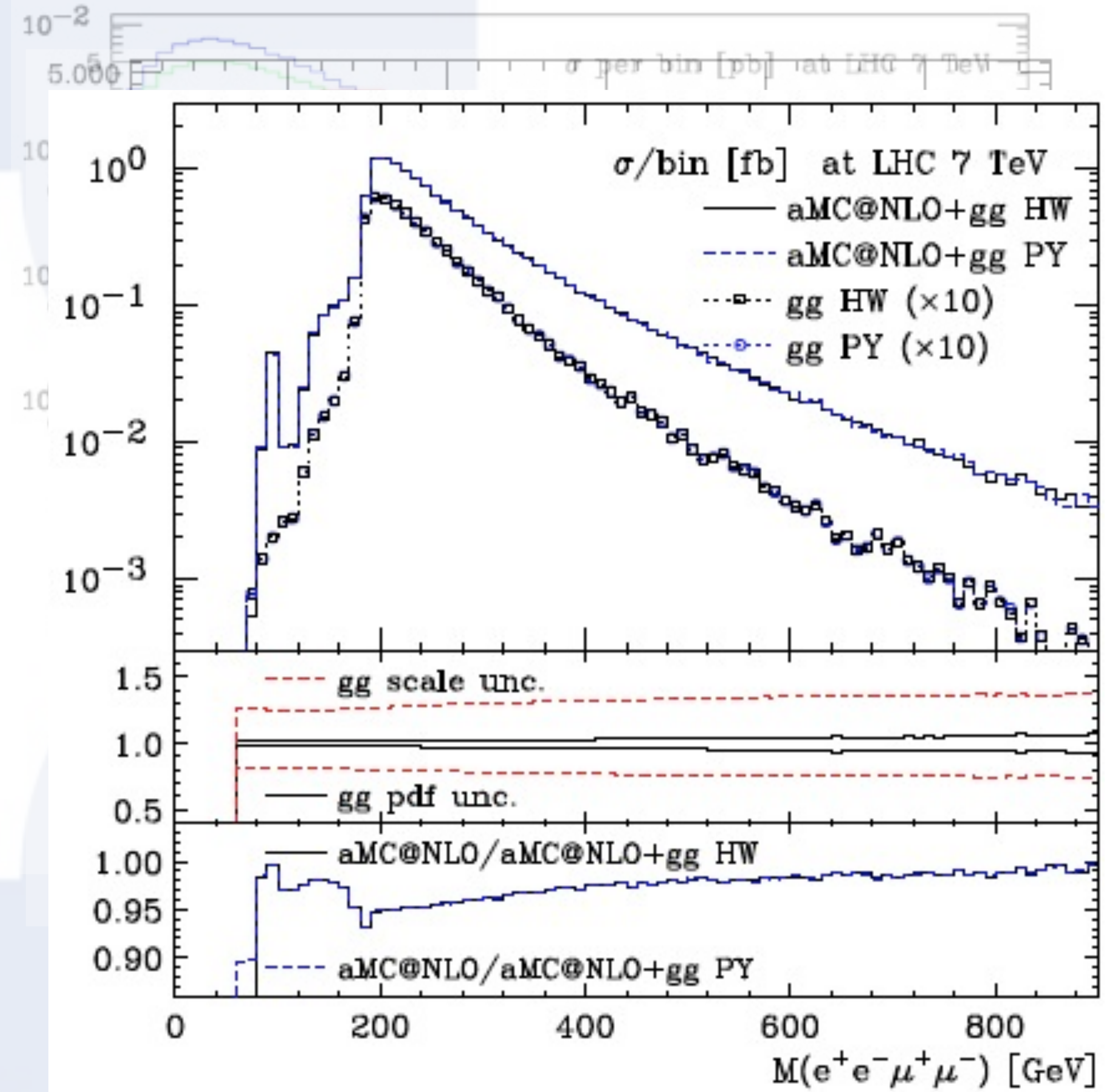
  - Added Pythia counterterms



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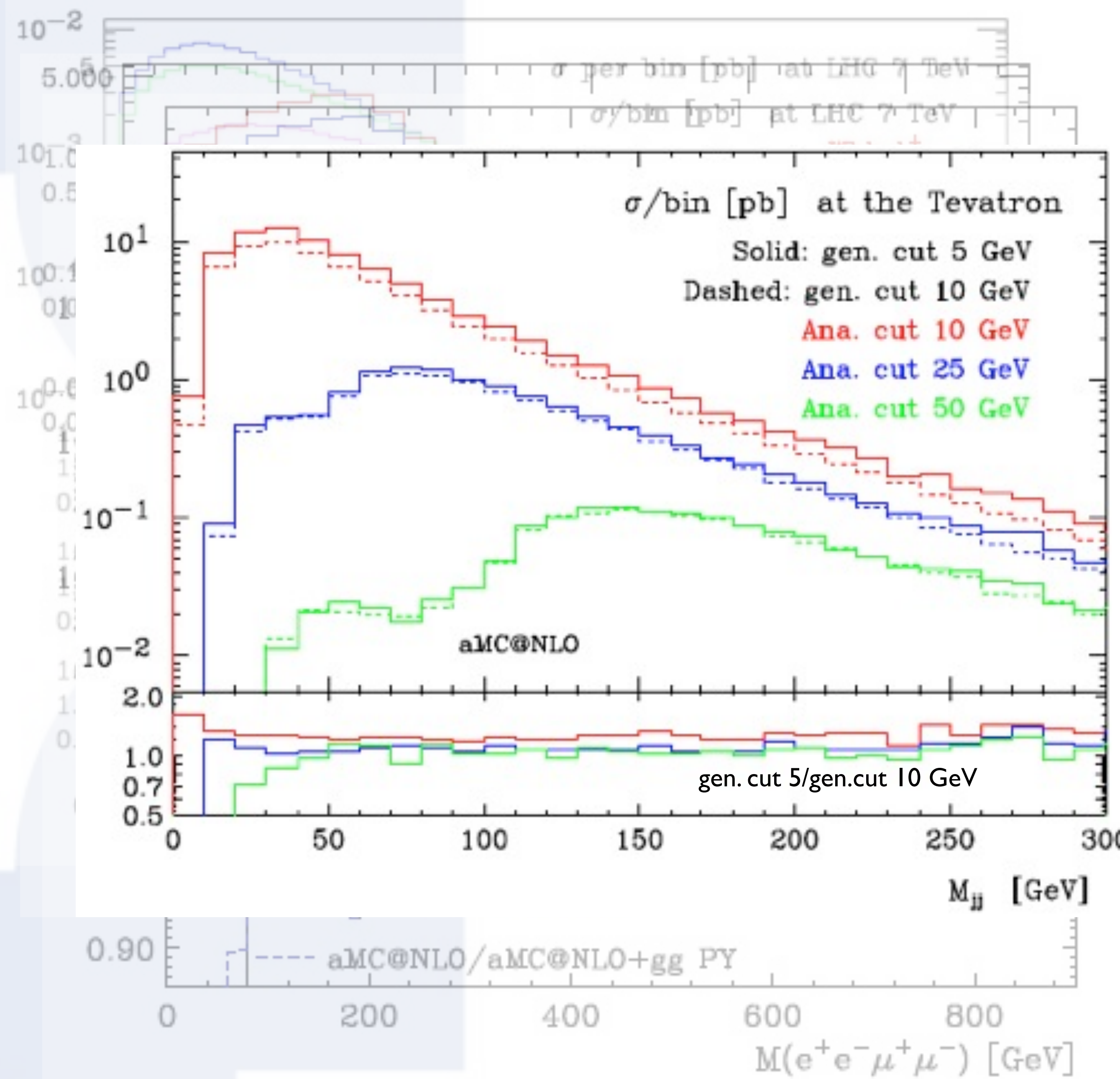

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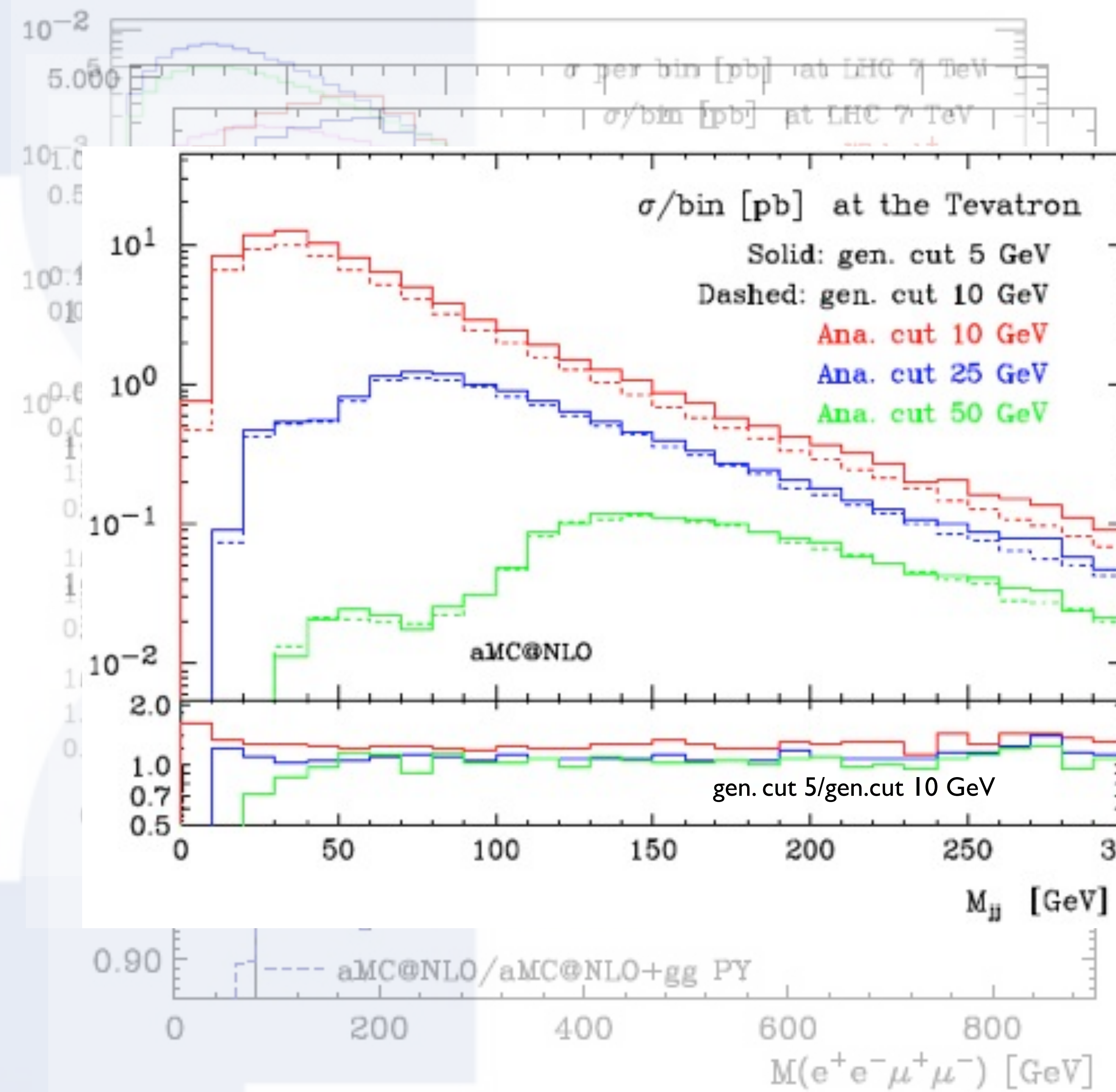

What happened in 2012?

Limitations with MG4

- Identification of FKS i/j pair hardcoded and based on particles identities rather than on interactions
  - Difficult to generalize to new models or non-QCD perturbations
- No finite width effects in the loops
- 4glu R2 too much complicated to be implemented in Fortran
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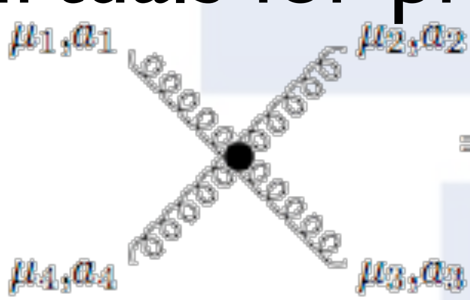

$$= -\frac{i g^4 N_{col}}{96\pi^2} \sum_{P(234)} \Big\{ \Big[\frac{\delta_{a_1a_2}\delta_{a_3a_4} + \delta_{a_1a_3}\delta_{a_4a_2} + \delta_{a_1a_4}\delta_{a_2a_3}}{N_{col}} + 4Tr(t^{a_1}t^{a_3}t^{a_2}t^{a_4} + t^{a_1}t^{a_4}t^{a_2}t^{a_3})(3+\lambda_{HV}) - Tr(\{t^{a_1}t^{a_2}\}\{t^{a_3}t^{a_4}\})(5+2\lambda_{HV}) \Big] g_{\mu_1\mu_2}g_{\mu_3\mu_4} + 12\frac{N_f}{N_{col}} Tr(t^{a_1}t^{a_2}t^{a_3}t^{a_4}) \Big(\frac{5}{3} g_{\mu_1\mu_3}g_{\mu_2\mu_4} - g_{\mu_1\mu_2}g_{\mu_3\mu_4} - g_{\mu_2\mu_3}g_{\mu_1\mu_4} \Big) \Big\}$$

From MG4 to MG5

- MadGraph completely rewritten in Python
  - Modern coding language
  - Modular/Object oriented structure
  - Unit/Acceptance/Parallel tests to test the code behaviour
  - New diagram generation algorithms
    - Code generation time drastically reduced
  - Possibility to reuse common part of diagrams
    - Running time improvement
  - Any model can be loaded via the FR/UFO interface
  - Possibility do define vertices with arbitrary # of legs and color structures

From MG4 to MG5

Process	MadGraph 4	MadGraph 5	Subprocesses	Diagrams
$pp \to jjj$	29.0 s	25.8 s	34	307
$pp \to jjl^+l^-$	341 s	103 s	108	1216
$pp \to jjje^+e^-$	1150 s	134 s	141	9012
$u\bar{u} \to e^+e^-e^+e^-e^+e^-$	772 s	242 s	1	3474
$gg \to ggggg$	2788 s	1050 s	1	7245
$pp \to jj(W^+ \to l^+\nu_l)$	146 s	25.7 s	82	304
$pp \to t\bar{t}$+full decays	5640 s	15.7 s	27	45
$pp \to \tilde{q}/\tilde{g}\,\tilde{q}/\tilde{g}$	222 s	107 s	313	475
7 particle decay chain	383 s	13.9 s	1	6
$gg \to (\tilde{g} \to u\bar{u}\tilde{\chi}^0_1)(\tilde{g} \to u\bar{u}\tilde{\chi}^0_1)$	70 s	13.9 s	1	48
$pp \to (\tilde{g} \to jj\tilde{\chi}^0_1)(\tilde{g} \to jj\tilde{\chi}^0_1)$	—	251 s	144	11008

- MadGraph c
  - Modern cc
  - Modular/C
  - Unit/Accep
  - New diagr
    - Code gene
  - Possibility to reuse common part of diagrams
    - Running time improvement
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Generation of 10,000 unweighted events
Computer: Sony Vaio TZ laptop / *128-core cluster

Process	Subproc. dirs.		Channels		Directory size		Event gen. time	
	MG 4	MG 5	MG 4	MG 5	MG 4	MG 5	MG 4	MG 5
$pp \to W^+j$	6	2	12	4	79 MB	35 MB	3:15 min	1:55 min
$pp \to W^+jj$	41	4	138	24	438 MB	64 MB	9:15 min	4:19 min
$pp \to W^+jjj$	73	5	1164	120	842 MB	110 MB	21:41 min*	8:14 min*
$pp \to W^+jjjj$	296	7	15029	609	3.8 GB	352 MB	2:54 h*	46:50 min*
$pp \to W^+jjjjj$	-	8	-	2976	-	1.5 GB	-	11:39 h*
$pp \to l^+l^-j$	12	2	48	8	149 MB	44 MB	21:46 min	3:00 min
$pp \to l^+l^-jj$	54	4	586	48	612 MB	83 MB	2:40 h	11:52 min
$pp \to l^+l^-jjj$	86	5	5408	240	1.2 GB	151 MB	49:18 min*	16:38 min*
$pp \to l^+l^-jjjj$	235	7	65472	1218	5.3 GB	662 MB	7:16 h*	2:45 h*
$pp \to t\bar{t}$	3	2	5	3	49 MB	39 MB	2:39 min	1:55 min
$pp \to t\bar{t}j$	7	3	45	17	97 MB	56 MB	10:24 min	3:52 min
$pp \to t\bar{t}jj$	22	5	417	103	274 MB	98 MB	1:50 h	32:37 min
$pp \to t\bar{t}jjj$	34	6	3816	545	620 MB	209 MB	2:45 h*	23:15 min*

aMC@NLO with MG5: tackling the old limitations

aMC@NLO with MG5: tackling the old limitations

Limitations in v4

- Identification of FKS i/j pair hardcoded and based on particles identities rather than on interactions
  - Difficult to generalize to new models or non-QCD perturbations
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  - Virtuals for processes with 4glu vertices incomplete
- No finite width effects in the loops

Improvements in v5

- Splitting of legs based on the interactions in the model, and on perturbation type (QCD, QED...)
  - Fully model independent, possibility to extend to non-QCD perturbation
- 4glu R2 available, treated as sum of different color/Lorentz structures
  - Any virtual ME can be generated
- Complex-mass scheme soon available

aMC@NLO with MG5: further improvements

MadFKS

- Drastic speed improvement on code-generation (~ 15 mins for pp > 3j)
- More compact code structure, sum/MC over different real emissions
    - Reduced number of channels for multichannel integration (real > born), possibility to use real MEs not based on Feynman diagrams

aMC@NLO with MG5: further improvements

MadLoop

- Speed improvements:
  - Recycle trees used in different diagrams
  - Call CutTools after helicity sum
  - Ongoing inclusion of open-loops techniques (expected time improvements ~ 10)
  - Support to complex masses
  - Loop-induced processes available
  - Multiprecision support

aMC@NLO with MG5: further improvements

MadLoop

- Speed improvements:
  - Re
  - Ca
  - O
    tin
  - Su
  - Lo
  - Mu

1-loop process	Generation time (MG5@NLO)	Generation time (MadLoop v4)	Output size[1] (MG5@NLO)	Output size[1] (MadLoop v4)	Compilation time (MG5@NLO)	Compilation time (MadLoop v4)	Running time[2] (MG5@NLO)	Running time[2] (MadLoop v4)
d d~ > u u~	3.5 s	5.378 s	68 Kb	268 Kb	0.8 s	2.996 s	2.2 ms	9.4 ms
d d~ > d d~ g	17.8 s	104.8 s	228 Kb	1.7 Mb	2.4 s	19.181 s	125 ms	0.74 s
d d~ > d d~ u u~	36.7 s	2094 s	372 Kb	3.3 Mb	4.1 s	45.02 s	291 ms	2.34 s
g g > g g	13.5 s	×	372 Kb	×	1.9 s	×	212 ms	×
g g > g g g	3 min 23s	×	180 Kb	×	15.7 s	×	10.2 s	×
g g > h h	4 s	×	28 Kb	×	0.5 s	×	44 ms	×
g g > g h h	11.4 s	×	64 Kb	×	1.0 s	×	1.16 s	×

[2] : Of the equivalent matrix.f file.

[4] : Per PS points, Color / Helicity summed amplitude.

MG5@NLO = ♦, MadLoop (v4) = ♦

Table from Valentin Hirschi

Going BSM

Going BSM

FR: Christiansen, Duhr, arXiv:0806.4194
UFO: Degrande et al. arXiv:1108.2040
ALOHA: Mattelaer et al. arXiv:1108.2041

- The FeynRules/UFO/ALOHA interface provides a straight way to use any model, starting from the Lagrangian
- FR extracts the Feynman rules from the Lagrangian
- UFO creates a Python module that can be linked to any ME generator (e.g. MadGraph)
  - Particles
  - Parameters
  - Vertices
  - Lorentz structures
- ALOHA writes the HELAS wavefunctions
  - Output available in c++, Fortran, Python

FR/UFO/ALOHA developments

- Automatic R2/UV from FR
- Feynman gauge
- HELAS amplitudes with complex masses
- HELAS amplitudes in multiple precision
- Spin 3/2
- ...

Ongoing projects

Ongoing projects: production + decay

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- How to deal with unstable final state particles (e.g. top) @NLO?

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  - Generate full process with only stable particles (p p > l+l- v v~ b b~)
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    - Needs special treatment of intermediate resonances (e.g. cpx mass)
    - Computationally very expensive
    - Only needed when background is enhanced or when aiming at very high precision

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Anything in between?

Spin correlations made easy: the DECAY package

Artoisenet, Frederix, Rietkerk

Spin correlations made easy: the DECAY package

Artoisenet, Frederix, Rietkerk

- Wish-list:
  - For a given event sample (LO or MC@NLO), include the decay of any final state particle
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- Solution:
  - Read event
  - Generate decay kinematics
  - Reweight the event with ratio $|M_{P+D}|^2 / |M_P|^2$
  - Or do secondary unweighting
    - Generate many decay configurations until $|M_{P+D}|^2 / |M_P|^2 > \mathrm{Rand}()\ \max\left(|\mathrm{M_{P+D}}|^2 / |\mathrm{M_P}|^2\right)$

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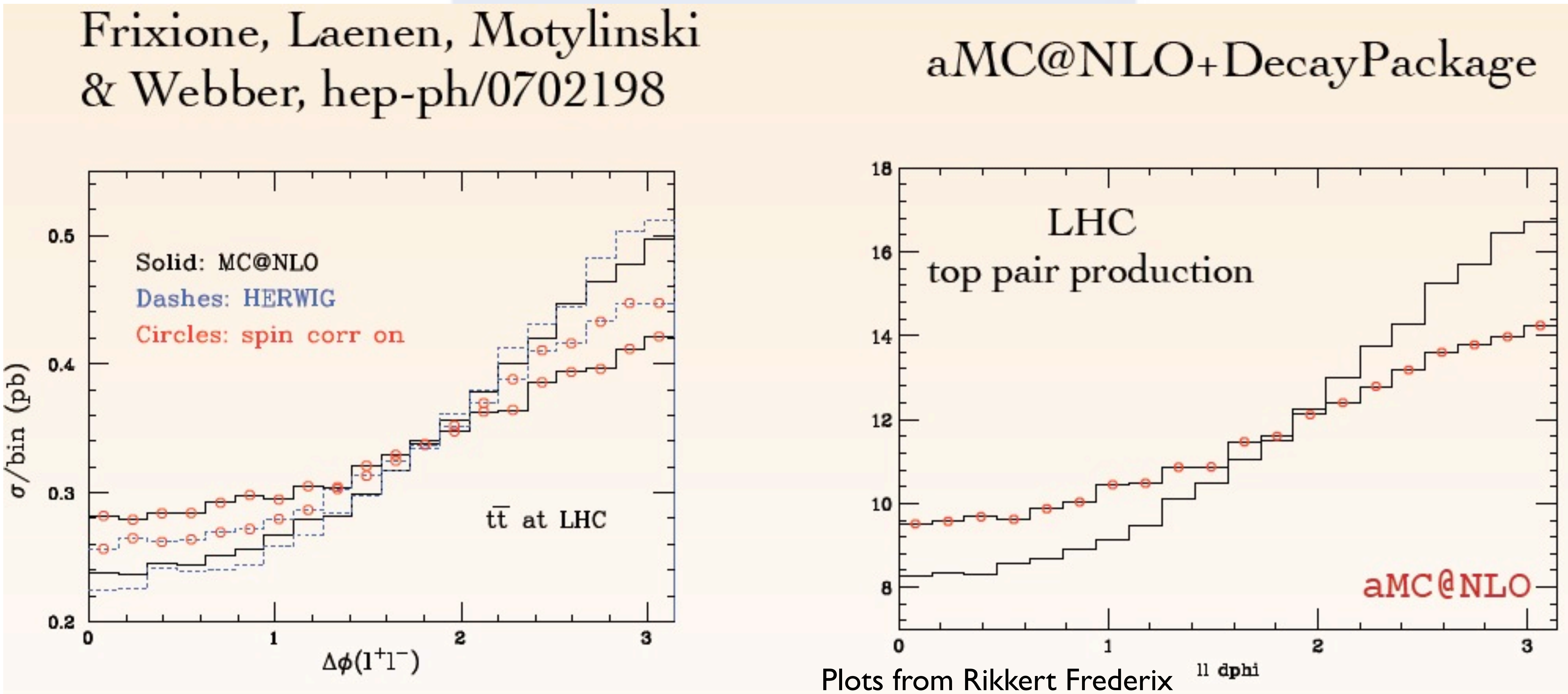
- This has already been done for t t~ and singletop

Frixione, Leanen, Motylinski, Webber, arXiv:hep-ph/0702198

Spin correlations made easy: the DECAY package

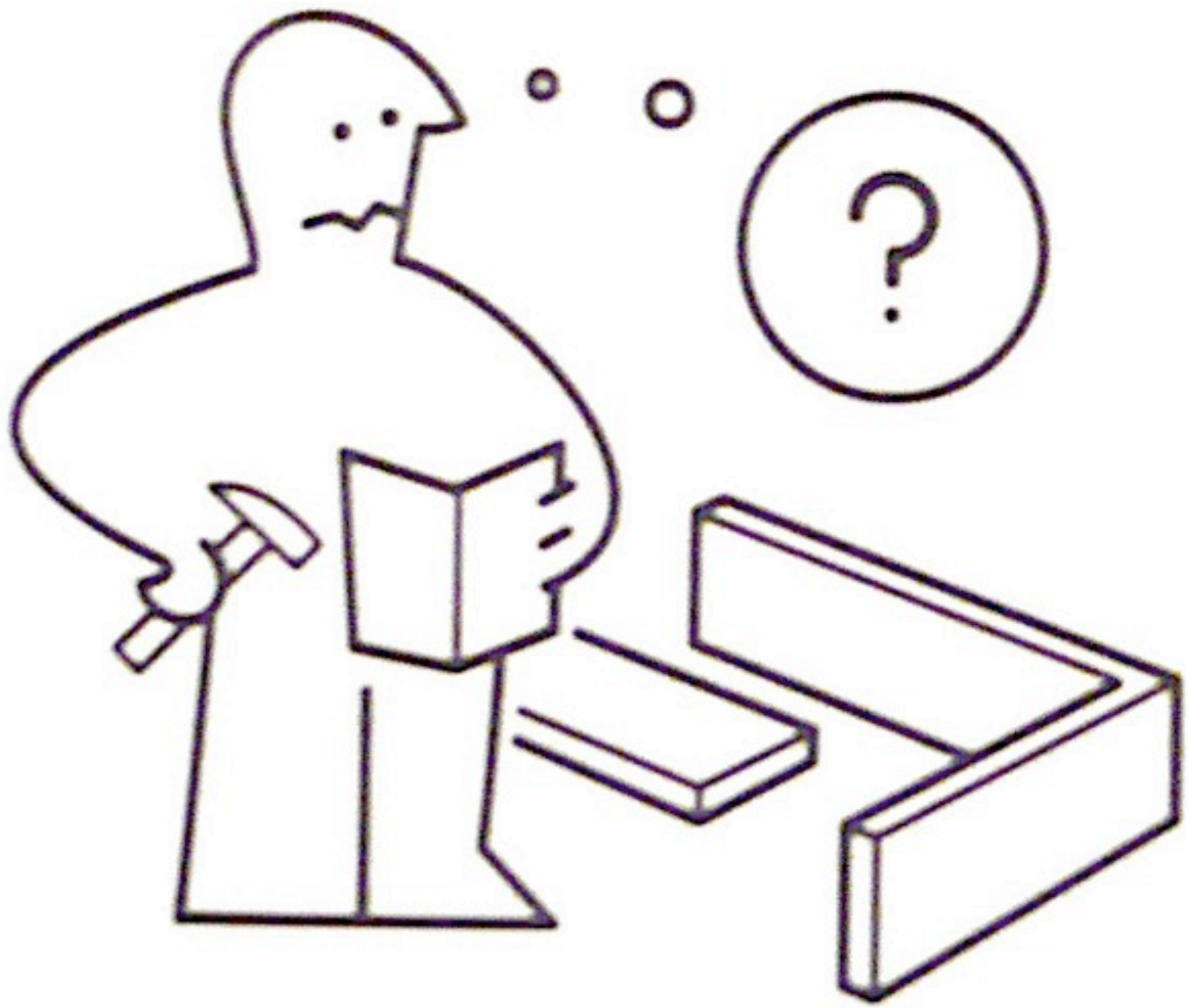
- How to deal with MC@NLO events?
- Spin correlations usually have tiny effects on observables
  - Include them at tree level
- For H (n+1 body) events, use decayed real-emission matrix-element
- For S (n body) events, use decaysed born matrix-element
- This guarantees NLO accuracy for observables related to production (e.g. top pt)
- This includes all spin correlation for observables related to production + decay (apart non-factorizable ones)

Validation



Plots from Rikkert Frederix

User friendliness

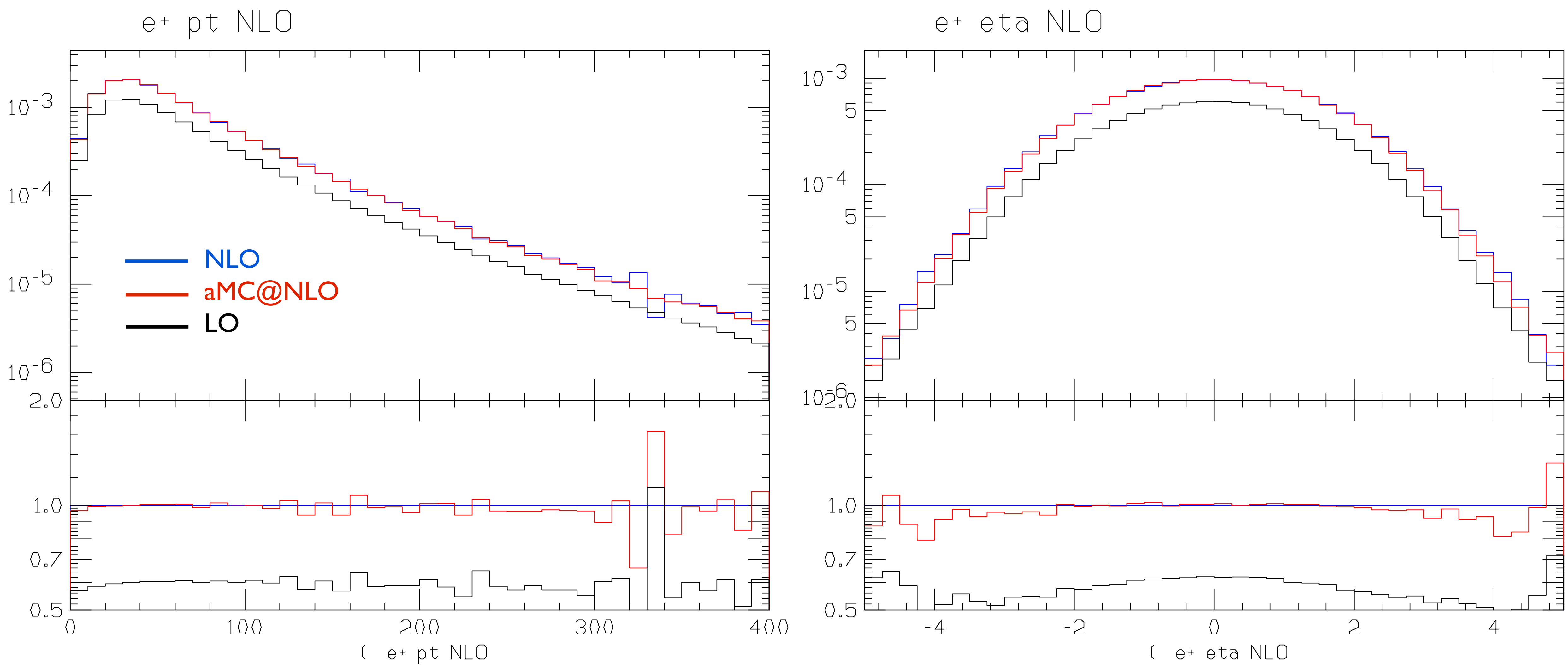


Just a bunch of commands...

```
./bin/mg5
> generate p p > t t~ w+ [QCD]
> output myppttw
> quit
cd myppttw
./bin/compile_amcatnlo.sh
./bin/run_amcatnlo.sh
```

There we go!

e+ from W decay



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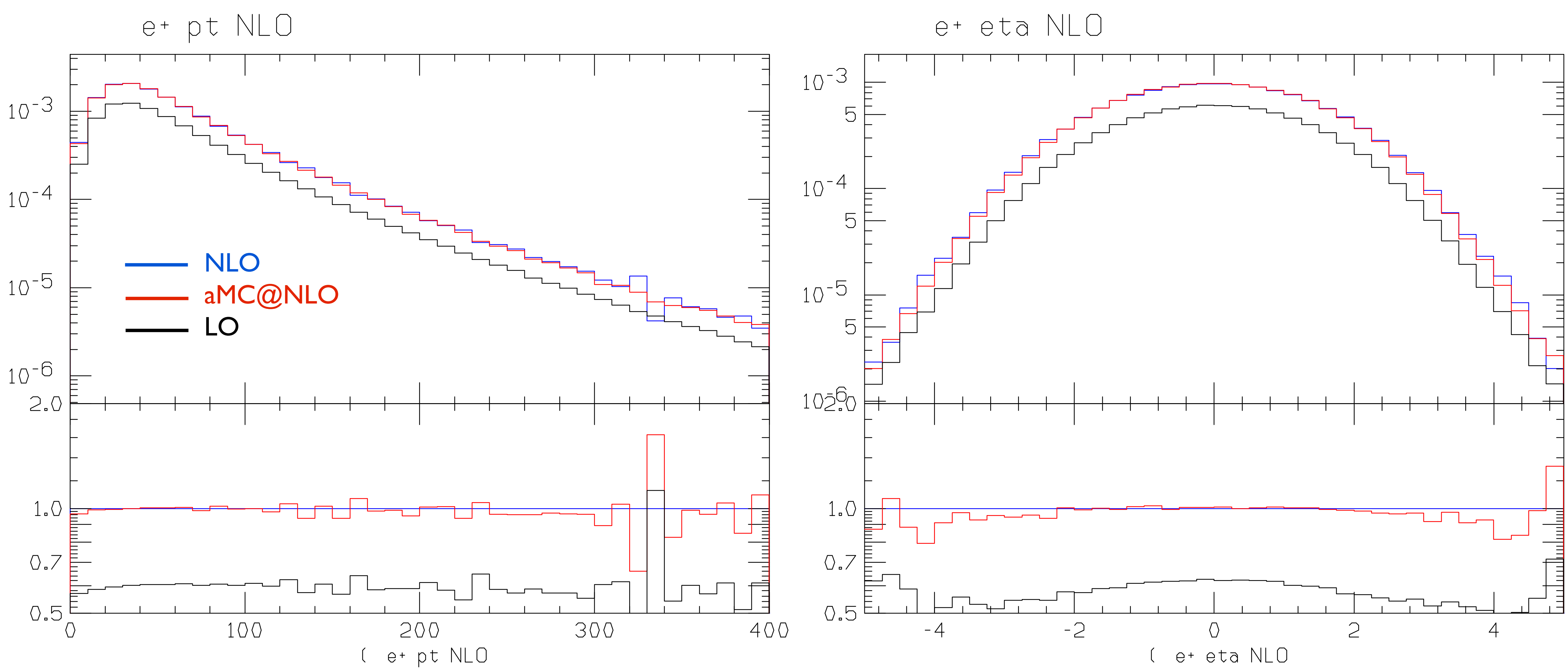


Integration/event generation and analyse made between yesterday and this morning!

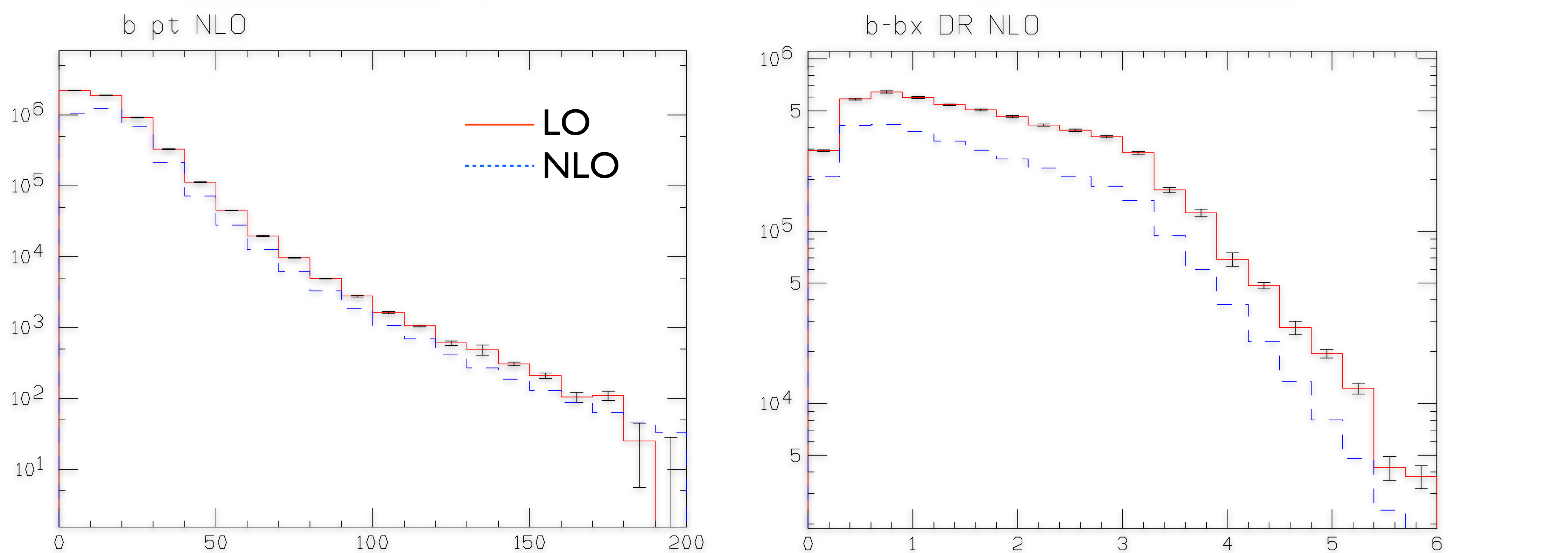
Conclusions

- Realistic and accurate predictions needed for LHC precision physics
- Powerful and generic techniques for NLO computation available
- MC@NLO formalism allows NLO+PS
- Automatic MC@NLO will carry on all this automatically
- Ready for BSM physics
- Decay package to handle unstable particles
- Code publicly available soon
- Stay tuned on http://amcatnlo.cern.ch!

Parton level results

bbj@NLO

- Virtuals from Dittmaier, Weinzerl, Uwer (arXiv:0810.0452)
  - validated against MadLoop5
- 4 flavour scheme (and PDF)
- Kt algo for jets, R=0.5, pt > 20 GeV
- K factor ~ 2



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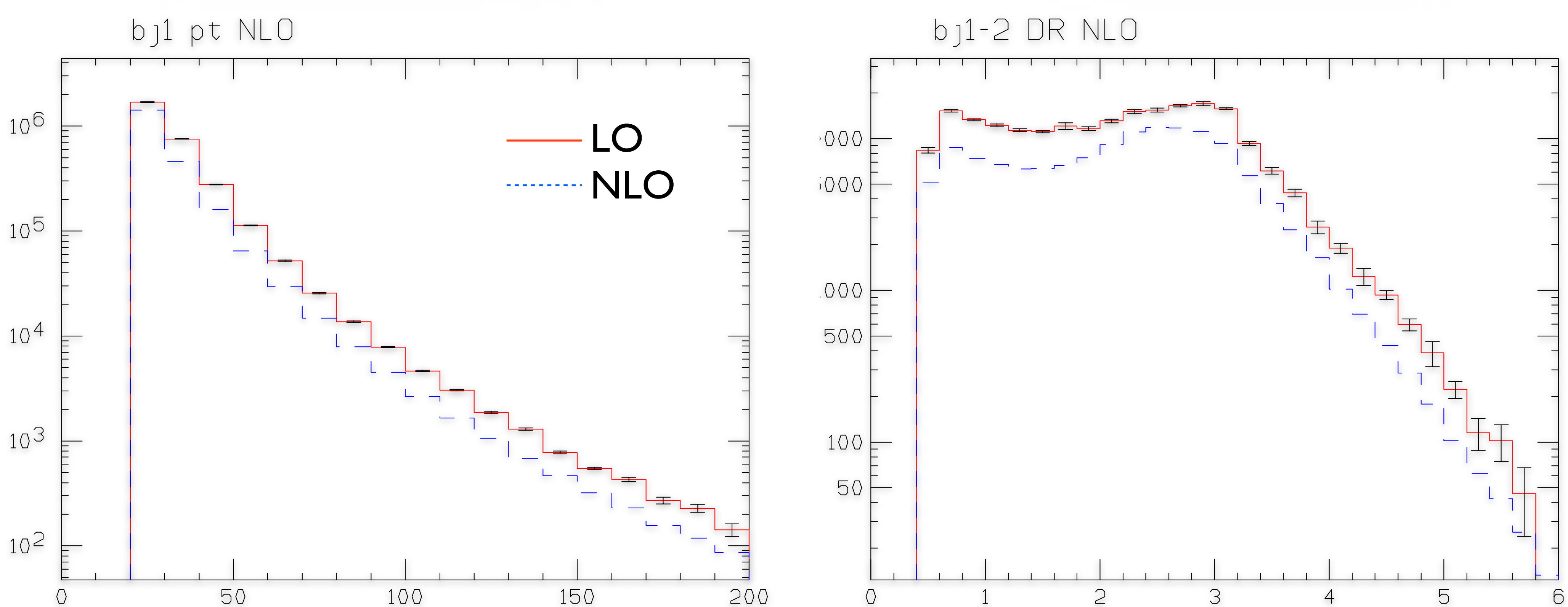
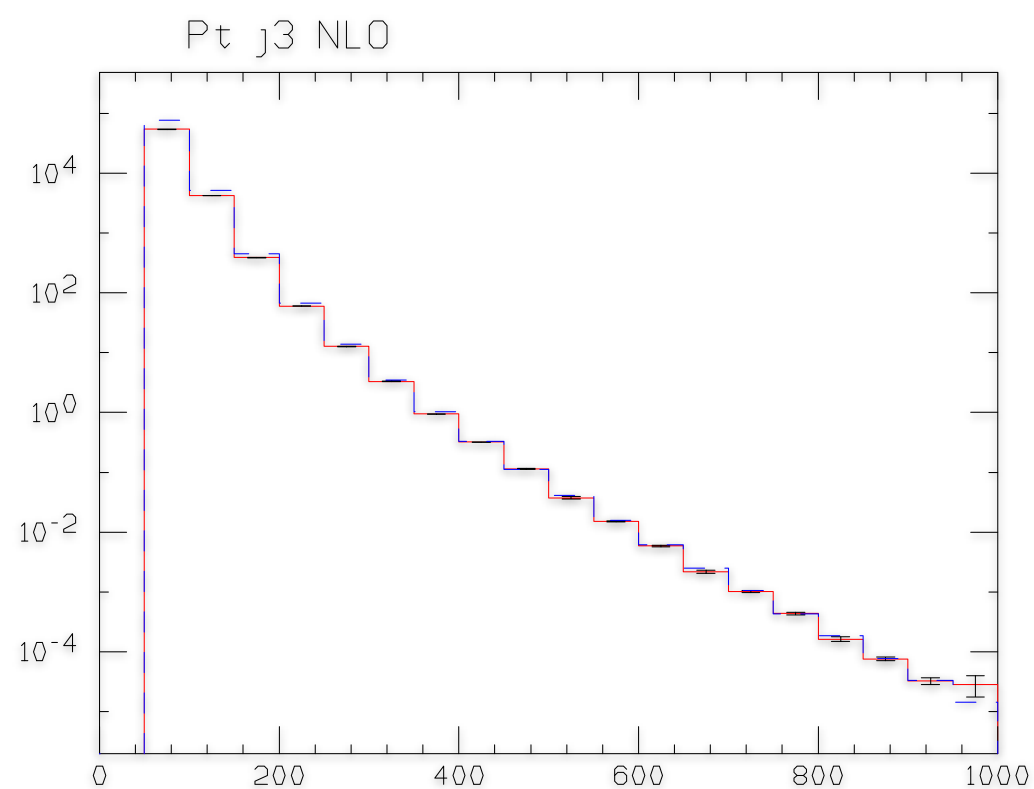
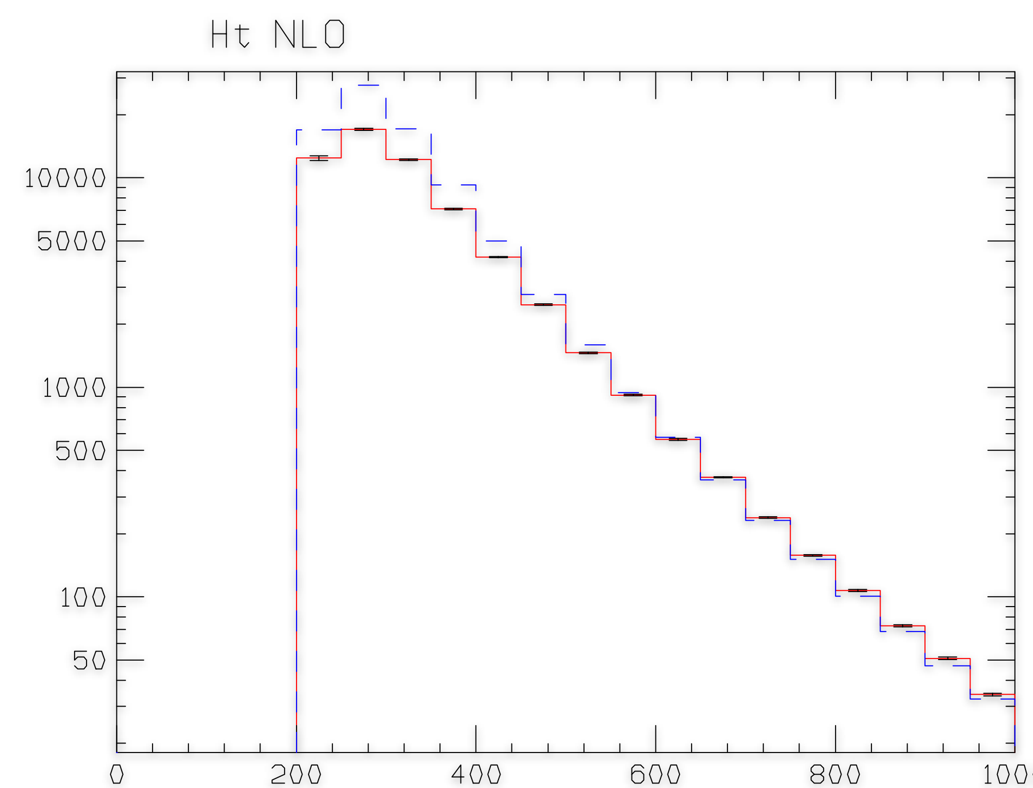


3 jets production@NLO

- Virtuals from NGluon (Badger, Biedermann, Uwer, arXiv:1011.2900) via MadFKS BLHA interface
- Validated against numbers in arXiv:1112.3940 (BlackHat coll.)
- anti-kt, R=0.4, pt leading (others) > 80 (60) GeV





- Code for 4 jets ready

Wbj@NLO

- Whole code from aMC@NLO
- 5 flavour scheme (j can be b)
  - Need to impose special cuts in order to have finite cross-section
    - Ask for >2 jets, at least one containing a b, but not bb