Collider phenomenology with aMC@NLO

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Leading order

- For many of the theory predictions needed in the searches for new physics leading order predictions are used
- The reasons for this are clear:
  - In many regions of phase-space they do a decent job, in particular for shapes of distributions
  - Parton showers and hadronizations models are tuned to data
  - **Many flexible lowest order (LO) tools are readily available**
- Unfortunately LO predictions describe total rates rather poorly

Need for NLO

- If we would have the same **flexible** tools available at NLO, the experimental analyses will benefit a various ways:
  - NLO predictions predict rates much more precisely
  - Reduced theoretical uncertainties due to meaningful scale dependence
  - Shapes are better described
  - Correct estimates for PDF uncertainties
  - Even data-driven analyses might benefit: smaller uncertainty due to interpolation from control region to signal region
- These accurate theoretical predictions are particularly needed for
  - searches of signal events in large backgrounds samples and
  - precise extraction of parameters (couplings etc.) when new physics signals have been found

NLO tools

- Flexible tools for NLO predictions do not exist:
  - MCFM *[Campbell & Ellis & Williams & ...]* has it available almost all relevant process for background studies at the Tevatron and LHC, but gives only fixed-order, parton-level results
  - MC@NLO *[Frixione & Webber & ...]* has matching to the parton shower to describe fully exclusive final states, but the list of available processes is relatively short
  - POWHEG BOX *[Nason et al.]* provides a framework to match any existing parton level NLO computation to a parton shower. However, the NLO computation is not automated and some work by the user is needed to implement a new process
- Idea: write an automatic tool that is flexible and allows for any process to be computed at NLO accuracy, including matching to the parton shower to produce events ready for hadronization (and detector simulation)

Why an automatic tool?

- To save time

  Less human time spending on computing matrix elements means more time available for physics and phenomenology.

- Robustness

  Modular code structure means that elements can be checked systematically and extensively once and for all. Trust can easily be build.

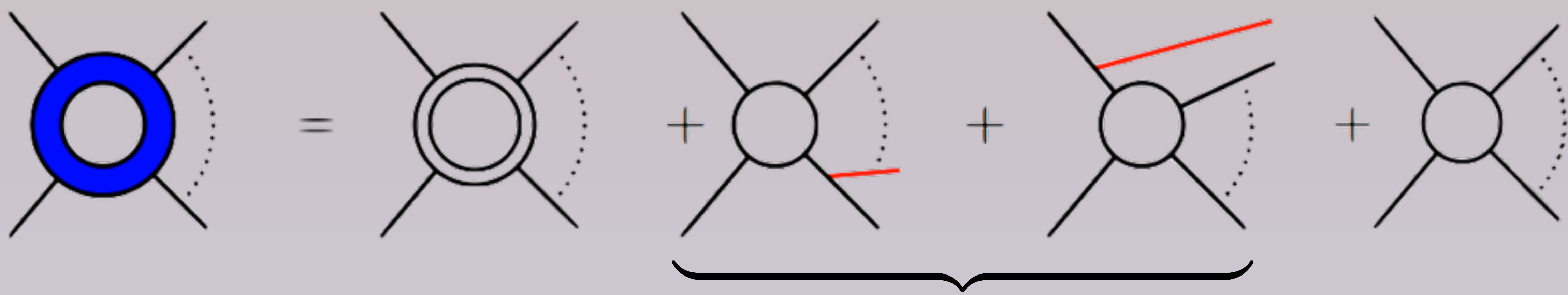
- Wide accessibility

  One framework for all. Available to everybody for an unlimited set of applications. Suitable for experimental collaborations.

Outline

- The rest of the talk will be about such a tool that is being developed
  - Real emission corrections and phase-space integration (including subtraction terms, ...) using MadFKS
  - Virtual corrections using MadLoop+CutTools
  - Matching with the shower: `aMC@NLO`
- Selected results

NLO contributions



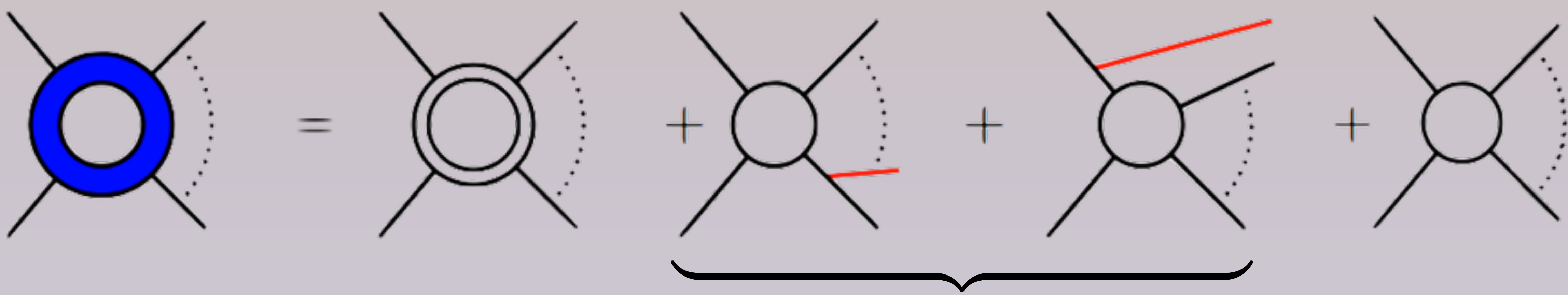
$$\sigma^{\mathrm{NLO}} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

'Virtual' or 'one-loop' NLO corrections

'Real emission' NLO corrections

'Born' or 'LO' contribution

NLO CONTRIBUTIONS



$$\sigma^{\rm NLO} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

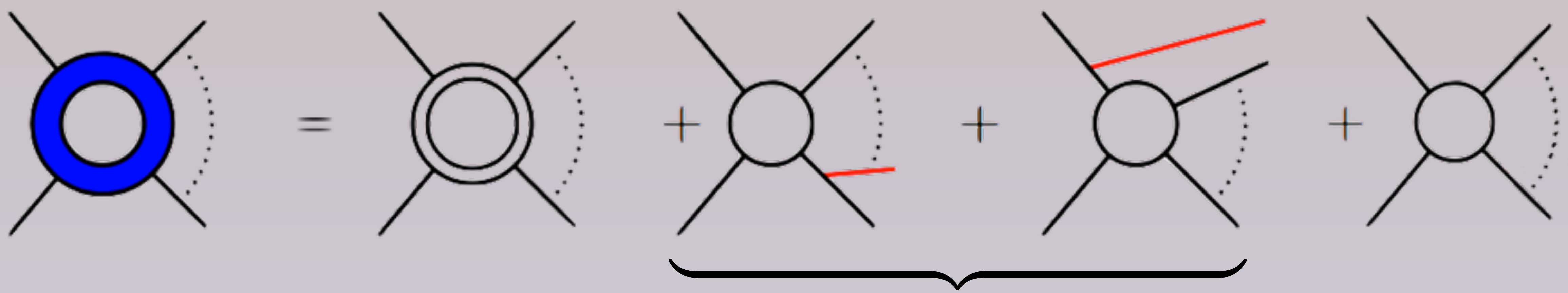
$$\sigma^{\rm NLO} = \int_{m+1}\left[d^{(4)}\sigma^R - d^{(4)}\sigma^A\right] + \int_m \left[d^{(4)}\sigma^B + \int_{\rm loop} d^{(d)}\sigma^V + \int_1 d^{(d)}\sigma^A\right]_{\epsilon=0}$$

MadFKS

RF, Frixione, Maltoni & Stelzer, arXiv:0908.4272

- Automatic generation of the Born and real emission matrix elements: tree level contributions, so readily available in MadGraph
- Subtraction terms to cancel IR singularities using the FKS formalism [*Frixione, Kunszt, Signer*]: process independent kernels times the Born amplitudes. Color-linked Borns available in MadGraph via the MadDipole [*RF, Greiner, Gehrmann*] package
- Efficient phase-space integration: written from scratch but using the same single-diagram enhanced techniques as in MadEvent
- Naive scaling of the number of subtraction terms is n^2 (as opposed to n^3 of CS dipoles). Can be greatly reduced by using symmetry of the matrix elements
- Overall management of symmetry factors, subprocess combination, generation of plots, etc.

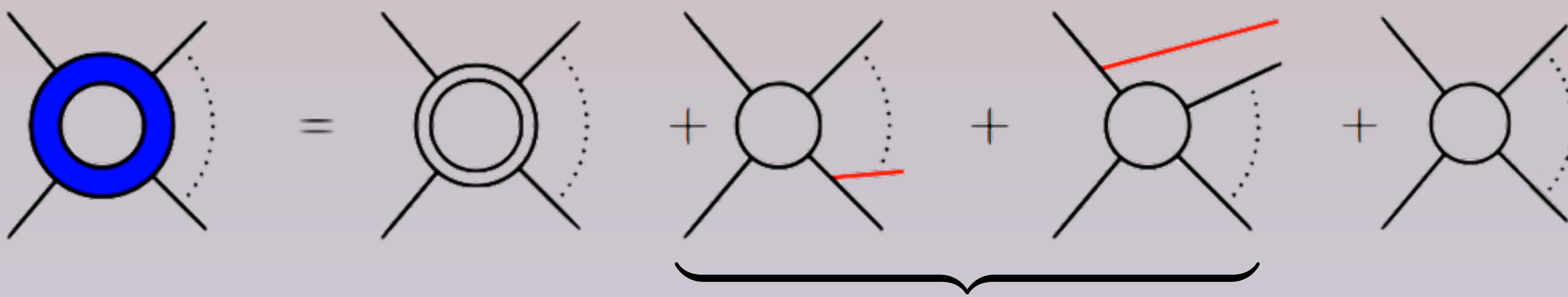
NLO contributions



$$\sigma^{\mathrm{NLO}} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

MadFKS

NLO contributions



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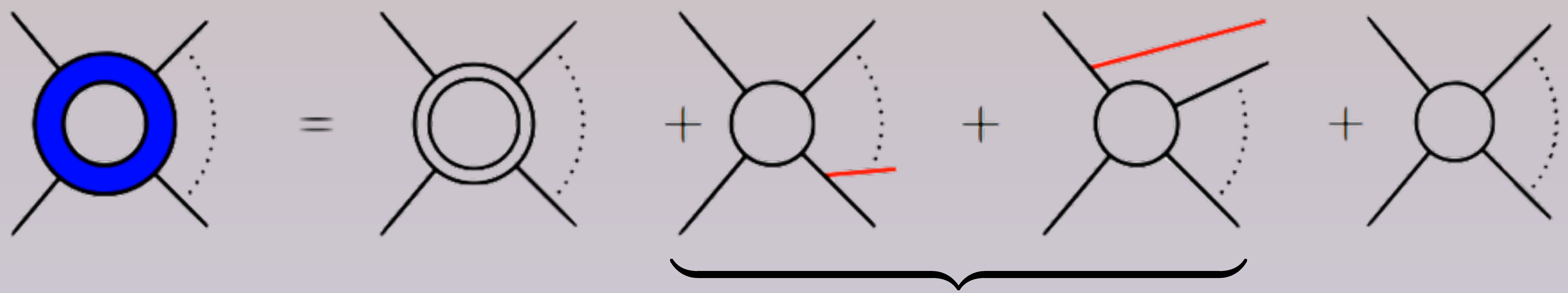
MadFKS

NLO contributions



$$\sigma^{\mathrm{NLO}} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

MadFKS

Full NLO

- Interface to link with the virtual corrections following the Binoth-Les Houches Accord
  - Standardized way to link MC codes to one-loop programs
- Unfortunately, no flexible one-loop programs readily available
  - BlackHat & Rocket are impressive (private) tools for multi-jet processes, but limited when massive particles appear
  - Golem is not (yet) in a shape that it can be used straight-forwardly. Nor is it a public tool.
  - Helac One-Loop is not public (and so complicated to use that not even all authors know how to run it...)
- We wrote our own using CutTools: MadLoop
  [*Hirschi, RF, Frixione, Garzelli, Maltoni & Pittau, arXiv:1103.0621*]

One-loop integrals

- Any one-loop diagram (or amplitude) can be expressed as a linear combination of scalar integrals (+ a remainder)
  - These scalar integrals are known (e.g. QCDLoop [*Ellis & Zanderighi*] and OneLOop [*Van Hameren*])
  - Only the coefficients in front of these integrals need to be determined
  - The OPP method (implemented in CutTools) is an efficient way to determine these coefficients numerically by sampling the integrand (which is provided by MadLoop) for various values of the loop momentum [*Ossola, Papadopoulos & Pittau*]
  - The remainder can be computed using tree-level diagrams, with some special vertices [*Draggiotis, Garzelli, Papadopoulos & Pittau*]
    - very similar to normal counter terms for the UV renormalization

MadLoop: local checks

$u\bar{u} \to W^+W^-b\bar{b}$	MadLoop	Ref. [33]
a_0	2.338047209268890E-008	2.338047130649064E-008
c_{-2}	-2.493920703542680E-007	-2.493916939359002E-007
c_{-1}	-4.885901939046758E-007	-4.885901774740355E-007
c_0	-2.775800623041098E-007	-2.775787767591390E-007
$gg \to W^+W^-b\bar{b}$		
a_0	1.549795815702494E-008	1.549794572435312E-008
c_{-2}	-2.686312747217639E-007	-2.686310592221201E-007
c_{-1}	-6.078687041491385E-007	-6.078682316434646E-007
c_0	-5.519004042667462E-007	-5.519004727276688E-007

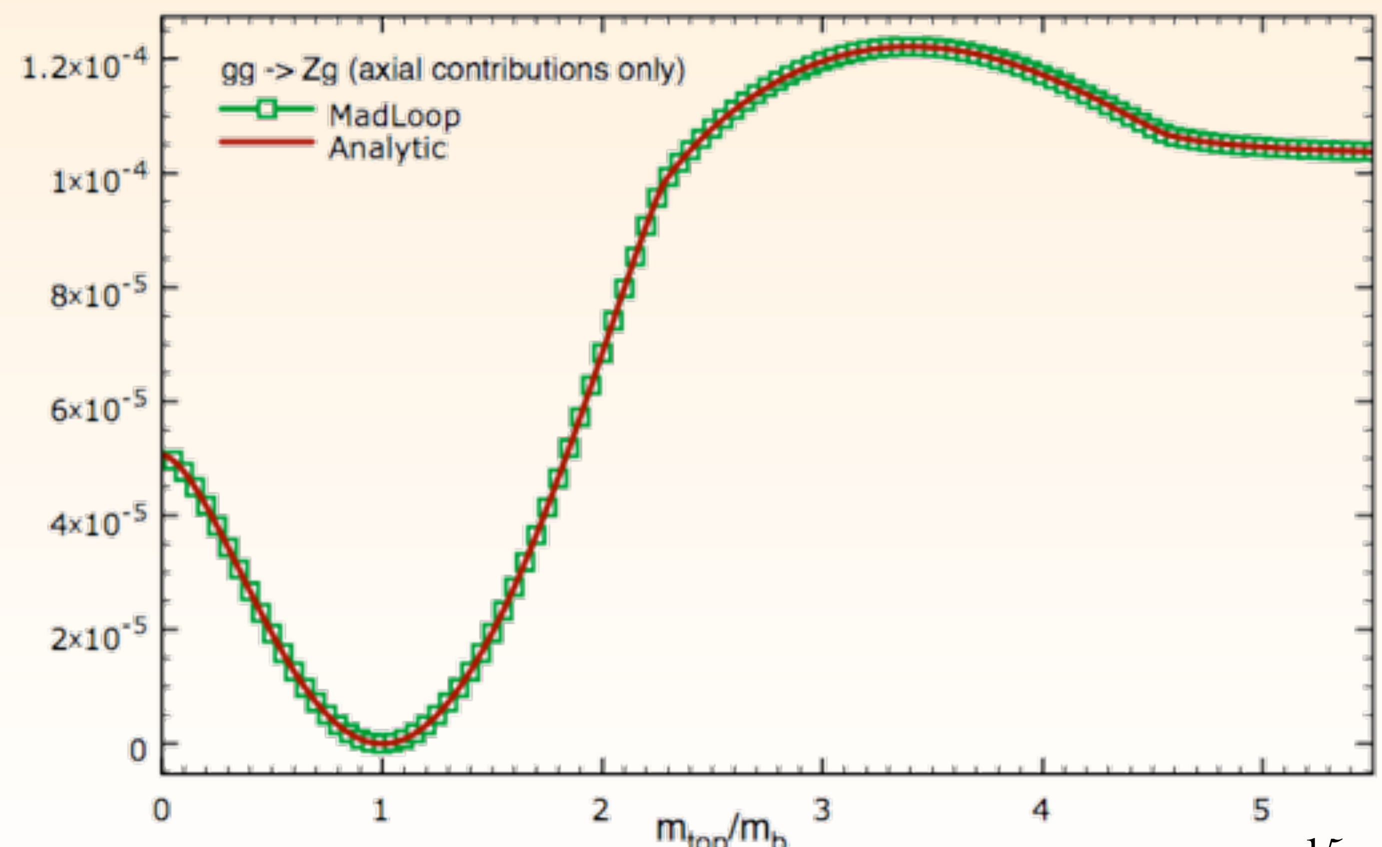
Ref. [33]: *A. van Hameren et al. arXiv:0903.4665*

~25 processes checked against known results (24 pages appendix of MadLoop paper, arXiv:1103.0621)

We believe the code is very robust - e.g., MadLoop helped to find mistakes in published NLO computations implementations (pp → Zjj, pp → W^+W^+jj)

The numerics are pin-point on analytical data, even with several mass scales.

Analytic computation via an implementation of the formulae found in a paper by *J.J. van der Bij & N. Glover*



MadLoop: Integrated results

- Errors are the MC integration uncertainty only
- Cuts on jets, γ*/Z decay products and photons, but no cuts on b quarks (their mass regulates the IR singularities)
- Efficient handling of exceptional phase-space points: their uncertainty always at least two orders of magnitude smaller than the integration uncertainty
- Running time: two weeks on ~150 node cluster leading to rather small integration uncertainties
- MadFKS+MadLoop results are fully differential in the final states (but only parton-level)

	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

Matching to a parton shower

- To get fully exclusive predictions at NLO (ready to be passed to a hadronization model) we have to match the parton level results to a parton shower
- There is a severe problem of double counting:
  - Real emission from the NLO and PS should be counted only once
  - Virtual corrections in the NLO and the Sudakov should not overlap
- The MC@NLO method *[Frixione & Webber]* removes this double counting explicitly by introducing MC counter terms
  - MC counter terms are process independent kernels (but do depend on the parton shower used) times the Born amplitudes

AUTOMATIC MC@NLO

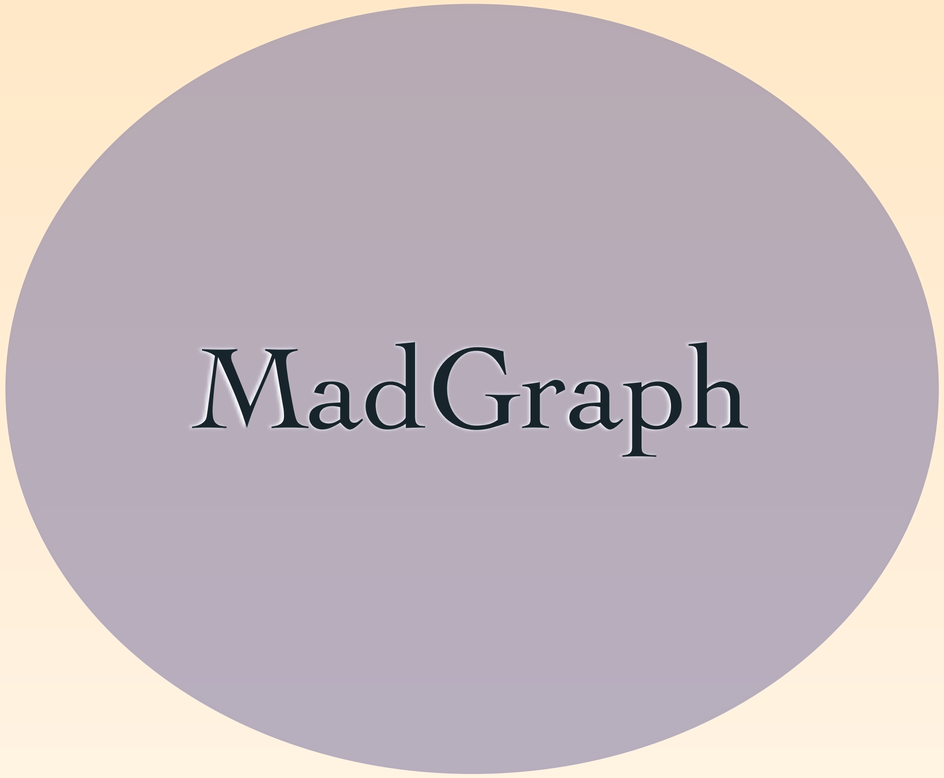
[*Torrielli, RF & Frixione (to appear)*]

$$d\sigma^{(\mathbb{H})}_{\mathrm{MC@NLO}} = d\phi_{n+1}\Big(\mathcal{M}^{(r)}(\phi_{n+1}) - \mathcal{M}^{(\mathsf{MC})}(\phi_{n+1})\Big)$$

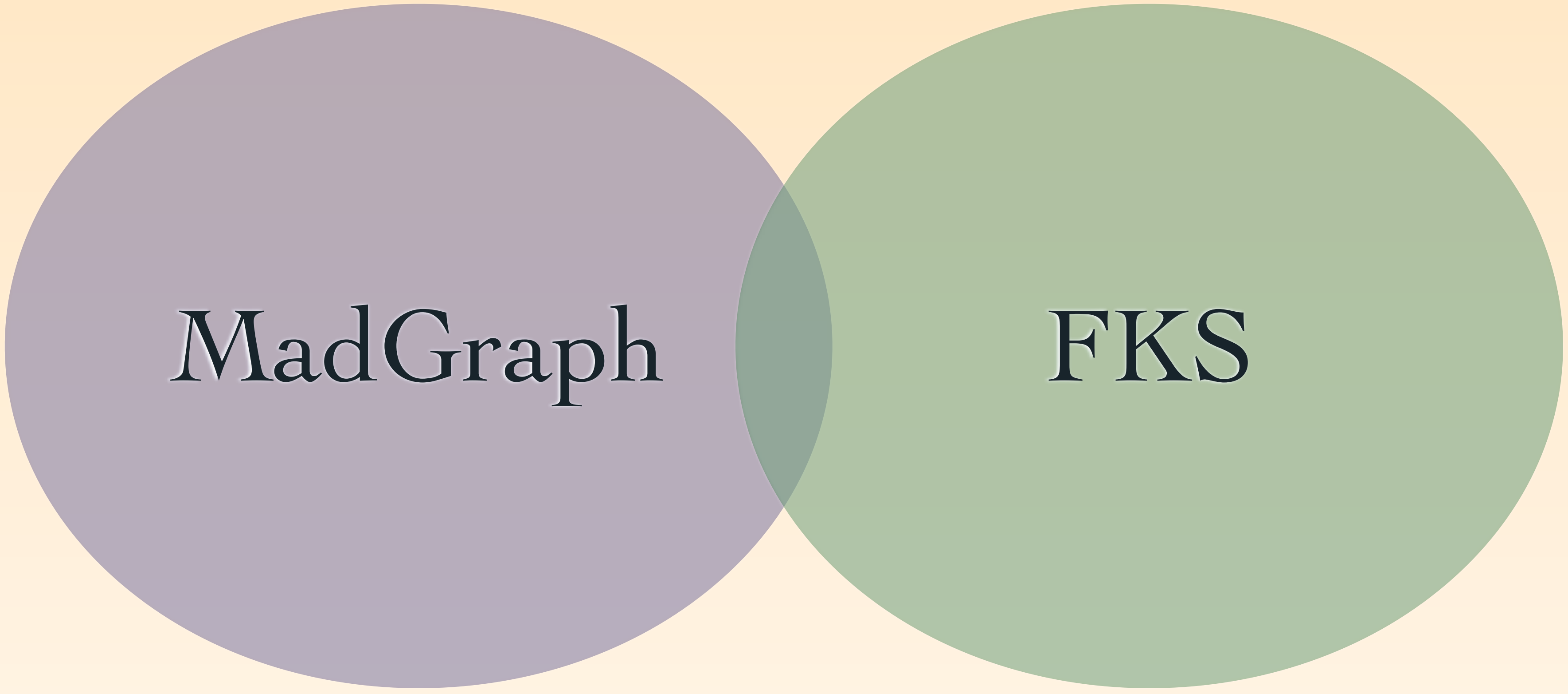
$$d\sigma^{(\mathbb{S})}_{\mathrm{MC@NLO}} = \int_{+1} d\phi_{n+1}\Big(\mathcal{M}^{(b+v+rem)}(\phi_n) - \mathcal{M}^{(c.t.)}(\phi_{n+1}) + \mathcal{M}^{(\mathsf{MC})}(\phi_{n+1})\Big)$$

- In black: pure NLO (MadFKS and MadLoop+CutTools)
- In red: MC counter terms have been implemented for Herwig6, Pythia and Herwig++ (but only fully tested for Herwig6)
    - FKS subtraction is based on a collinear picture, so are the MC counter terms: branching structure is for free
    - Automatic determination of color partners
    - Automatic computation of leading-color matrix elements
    - Works also when MC-ing over helicities

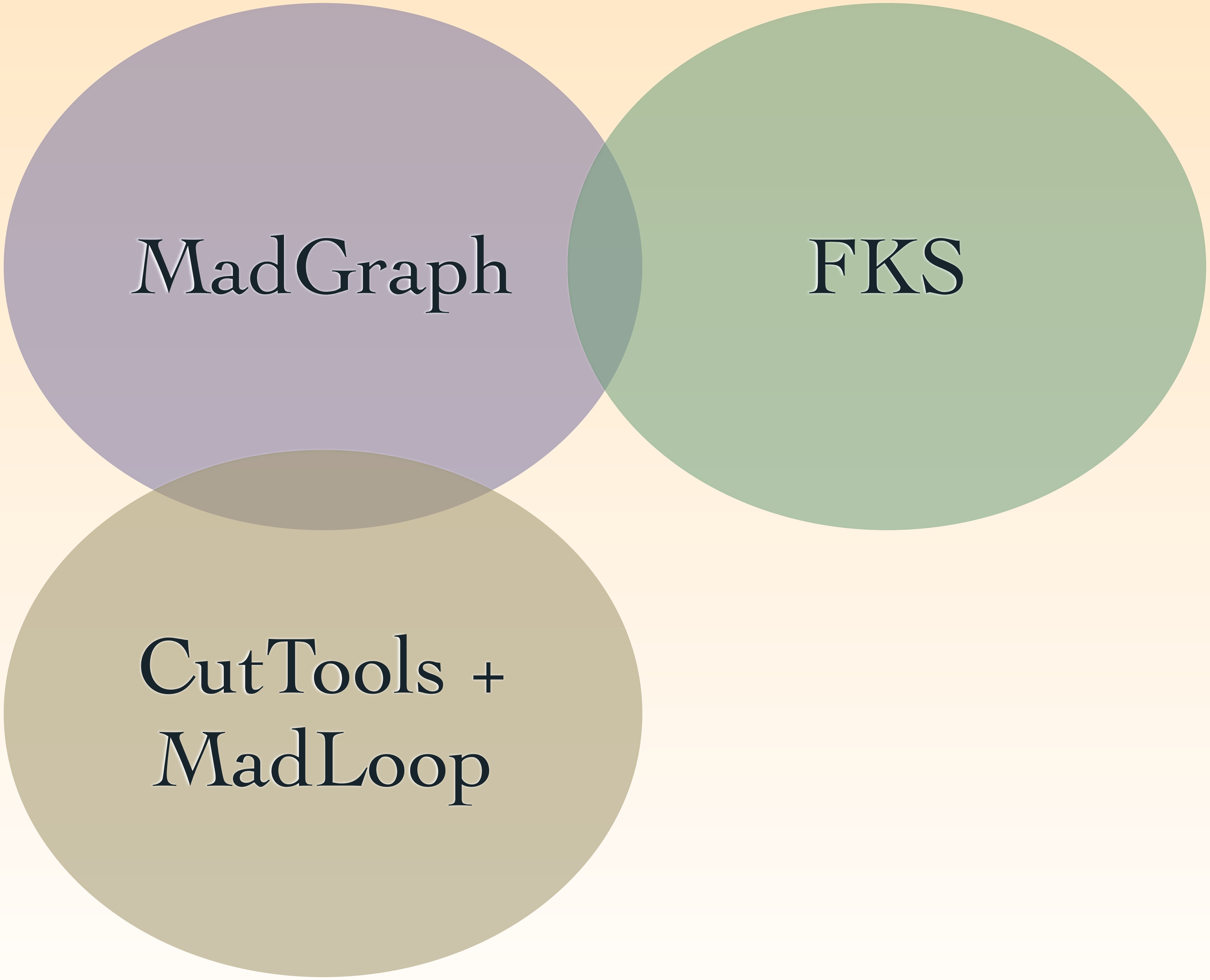
The aMC@NLO code



The aMC@NLO code



The aMC@NLO code



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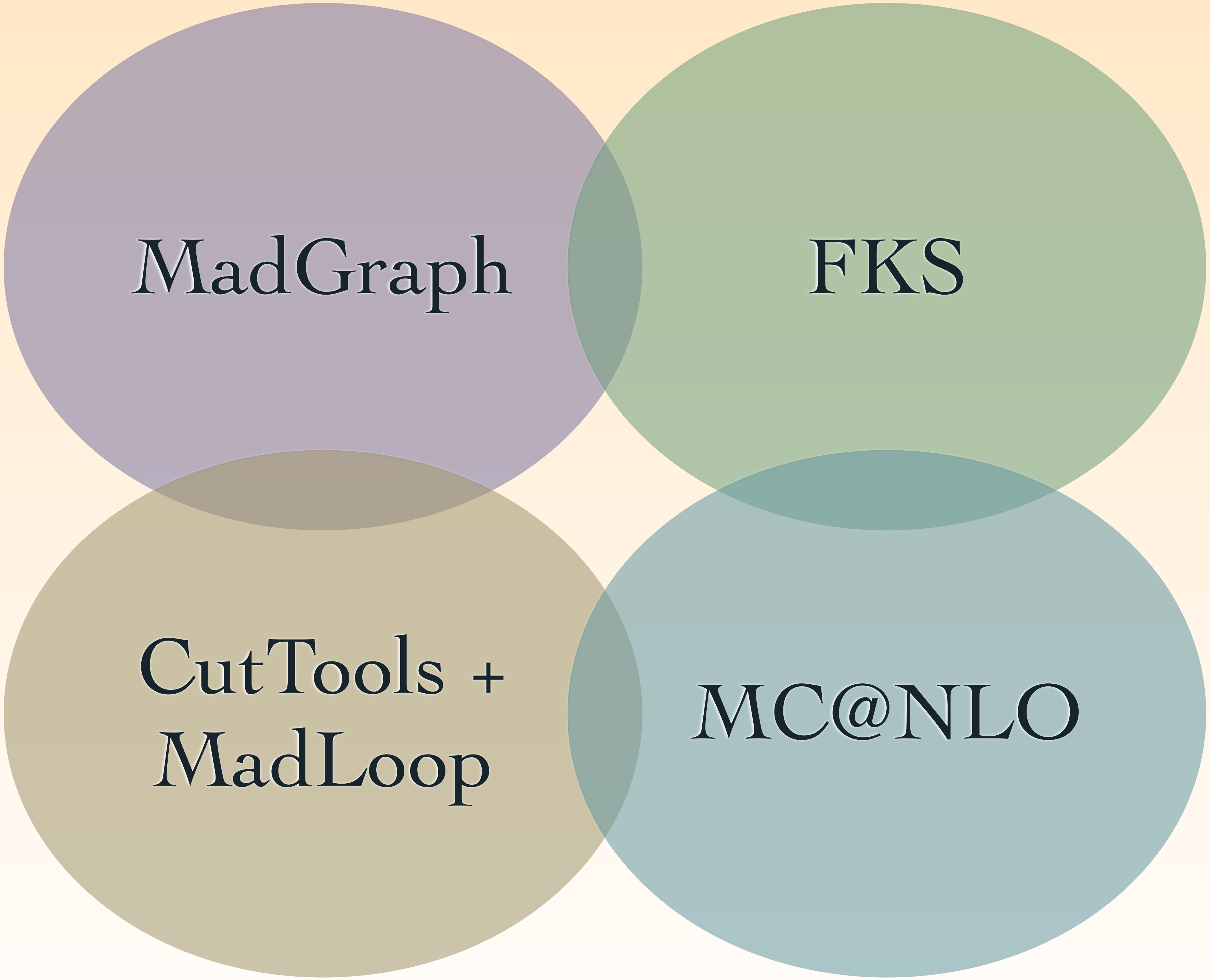
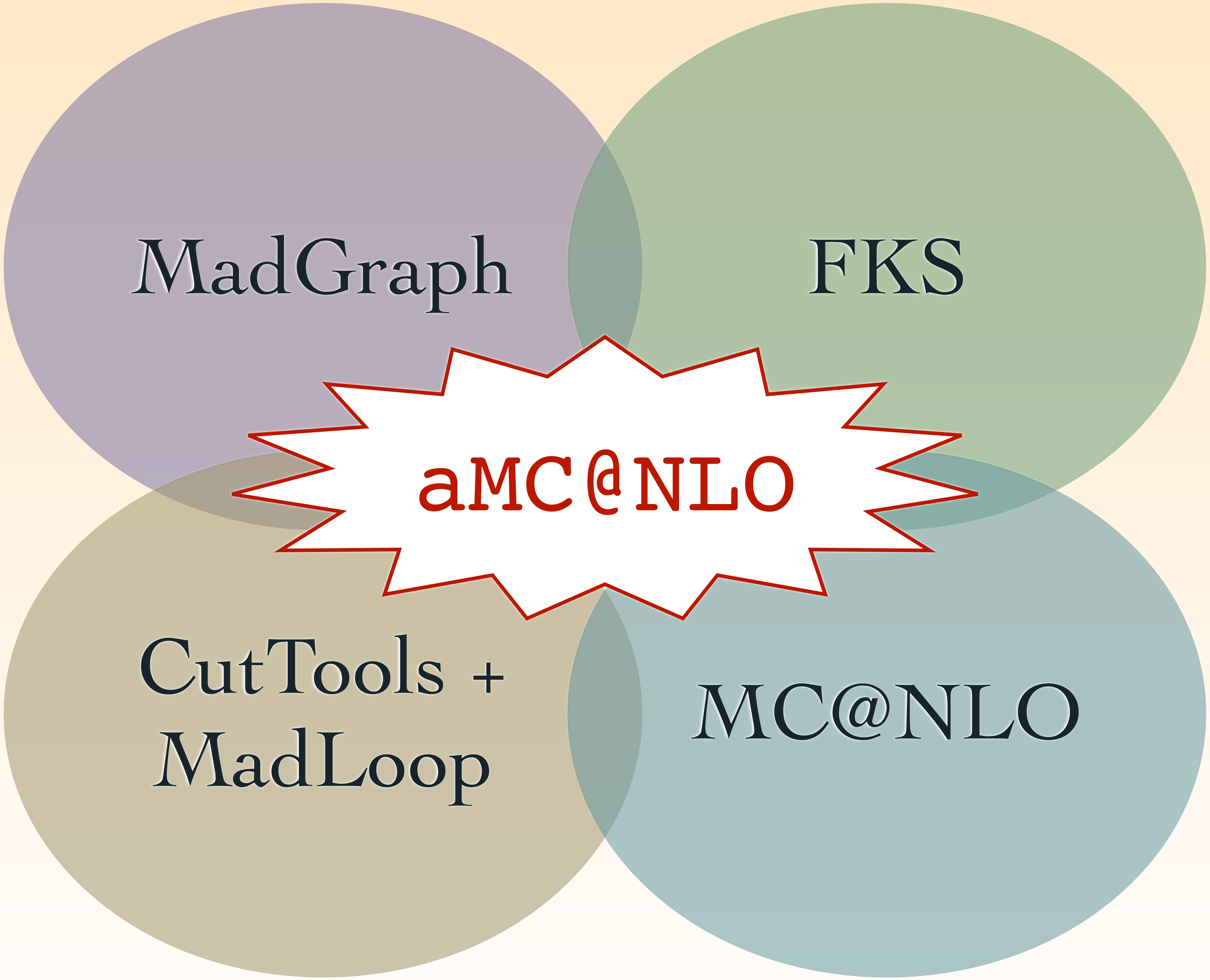


The aMC@NLO code



http://amcatnlo.cern.ch

Selection of results

- Published results:
  - (pseudo-)scalar Higgs production in association with a top-antitop pair [*RF, Frixione, Hirschi, Maltoni, Pittau & Torrielli, arXiv:1104.5613*]
  - Vector boson production in association with a bottom-antibottom pair [*RF, Frixione, Hirschi, Maltoni, Pittau & Torrielli, arXiv:1106.6019*]
- (Very) preliminary unpublished results:
  - 4 charged lepton production
  - W+2j production

PP → HTT/ATT

- Top pair production in association with a (pseudo-)scalar Higgs boson
- Three scenarios

  I) scalar Higgs H, with $m_H = 120$ GeV

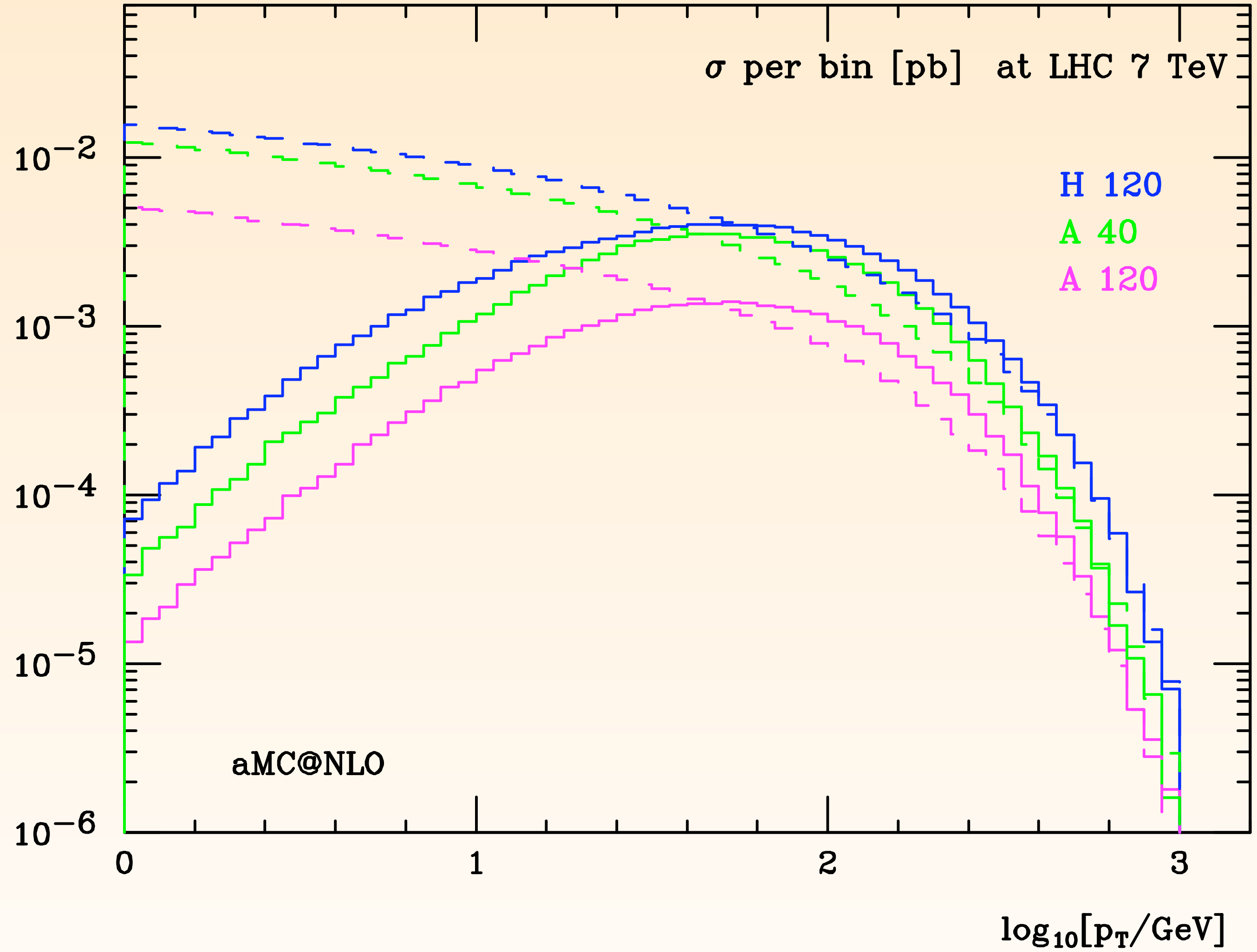
  II) pseudo-scalar Higgs A, with $m_A = 120$ GeV

  III) pseudo-scalar Higgs A, with $m_A = 40$ GeV
- SM-like Yukawa coupling, $y_t/\sqrt{2}=m_t/v$
- Renormalization and factorization scales $\mu_F = \mu_R = \left(m_T^t m_T^{\bar{t}} m_T^{H/A}\right)^{\frac{1}{3}}$ with $m_T = \sqrt{m^2 + p_T^2}$ and $m_t^{pole} = m_t^{\overline{MS}} = 172.5$ GeV
- Note: first time that pp → ttA has been computed beyond LO

Impact of the shower

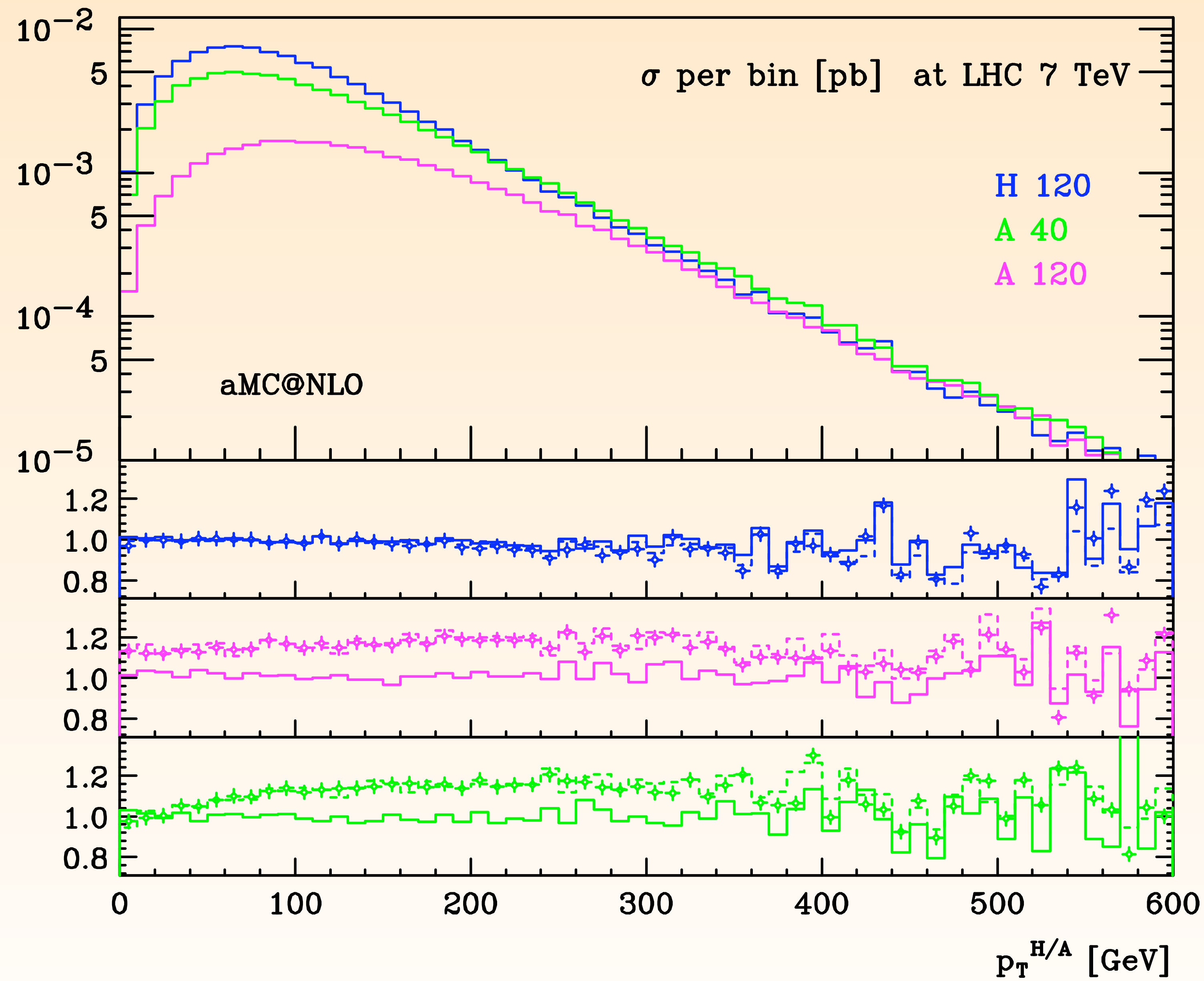
- Three particle transverse momentum, p_T(H/A t tbar), is obviously sensitive to the impact of the parton shower
- Infrared sensitive observable at the pure-NLO level for $p_T \rightarrow 0$
- aMC@NLO displays the usual Sudakov suppression
- At large p_T's the two descriptions coincide in shape and rate

Dashed: NLO, Solid: aMC@NLO



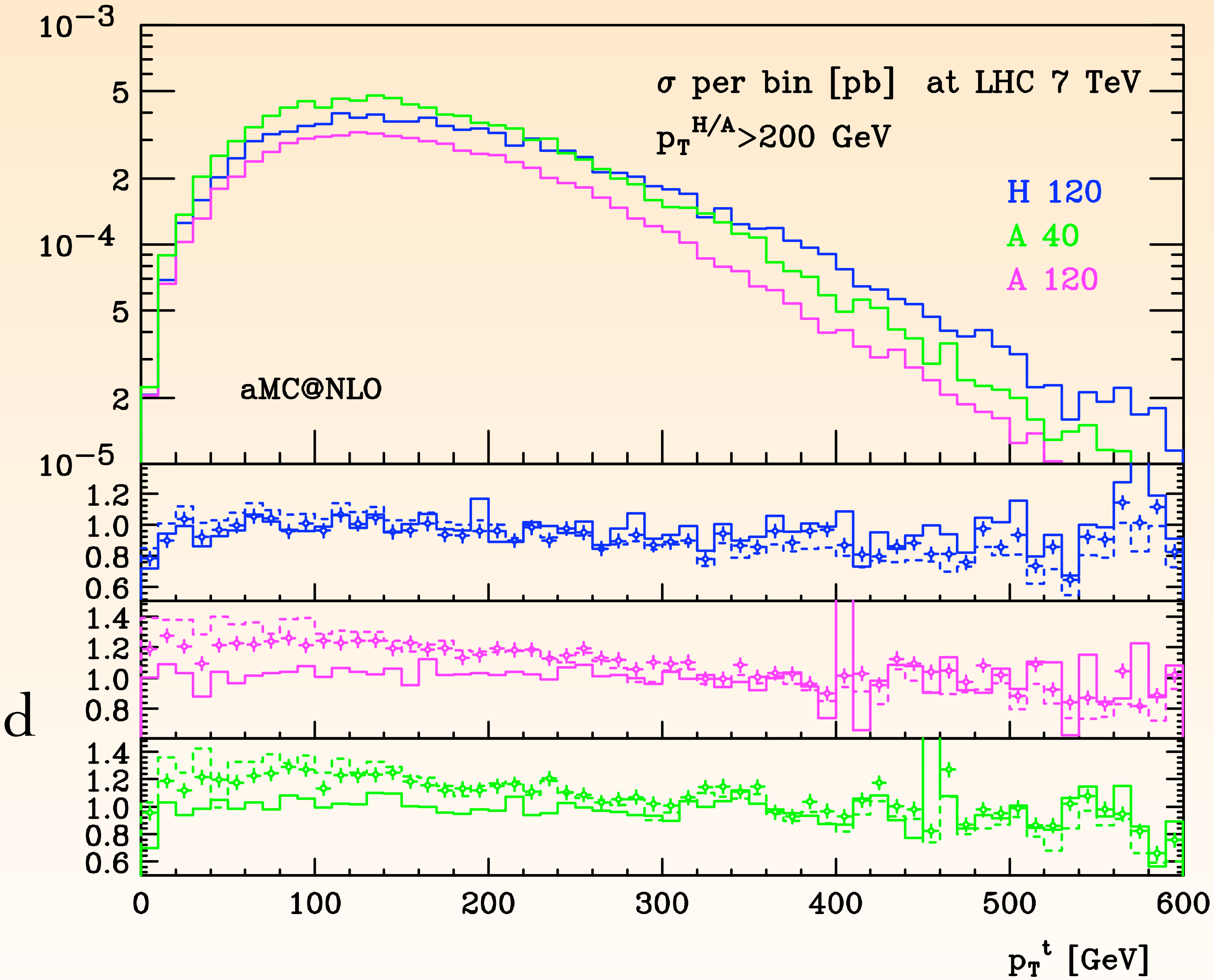
Higgs p_T

- Transverse momentum of the Higgs boson
- Lower panels show the ratio with LO (dotted), NLO (solid) and aMC@LO (crosses)
- Corrections are small and fairly constant
- At large p_T, scalar and pseudo-scalar production coincide: boosted Higgs scenario [*Butterworth et al., Plehn et al.*] should work equally well for pseudo-scalar Higgs



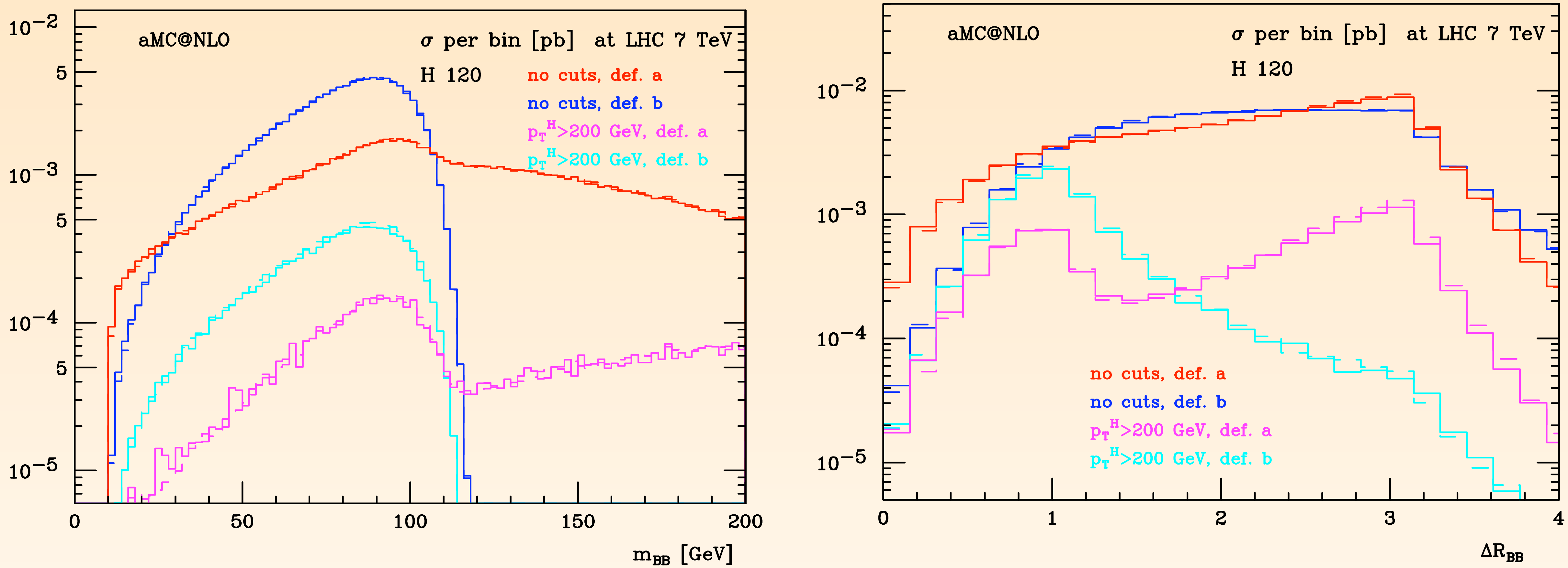
Boosted Higgs

- Boosted Higgs: $p_T^{H/A} > 200$ GeV
- Transverse momentum of the top quark
- Corrections compared to (MC@)LO are significant and cannot be approximated by a constant K-factor



TTH DECAYED

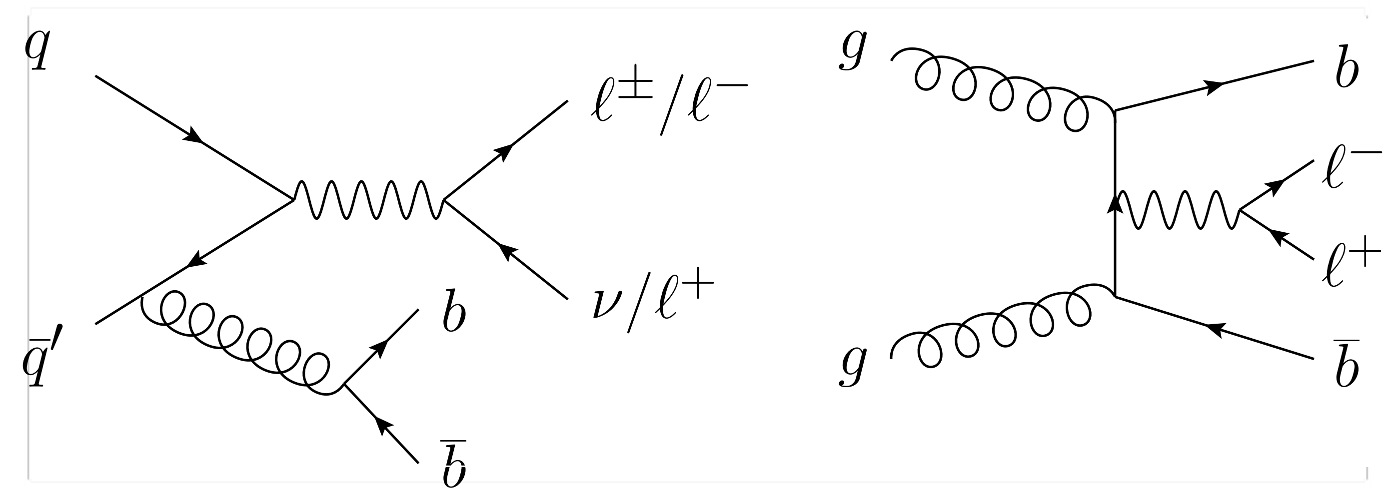
Dashed: aMC@LO, Solid: aMC@NLO



- Two definitions of the B hadron pair in these plots (assuming 100% b-tagging efficiency)
  - a) hardest pair in the event
  - b) decay products of the Higgs (uses MC truth)
- A cut on the p_T of the Higgs improves the selection of B hadrons from the Higgs decay

pp → Wbb/Zbb

- Background to pp → HW/HZ, H → bb
- 4 Flavor scheme calculations
  - Massive b quarks
  - No initial state b quarks
  - Born is finite: no generation cuts are needed



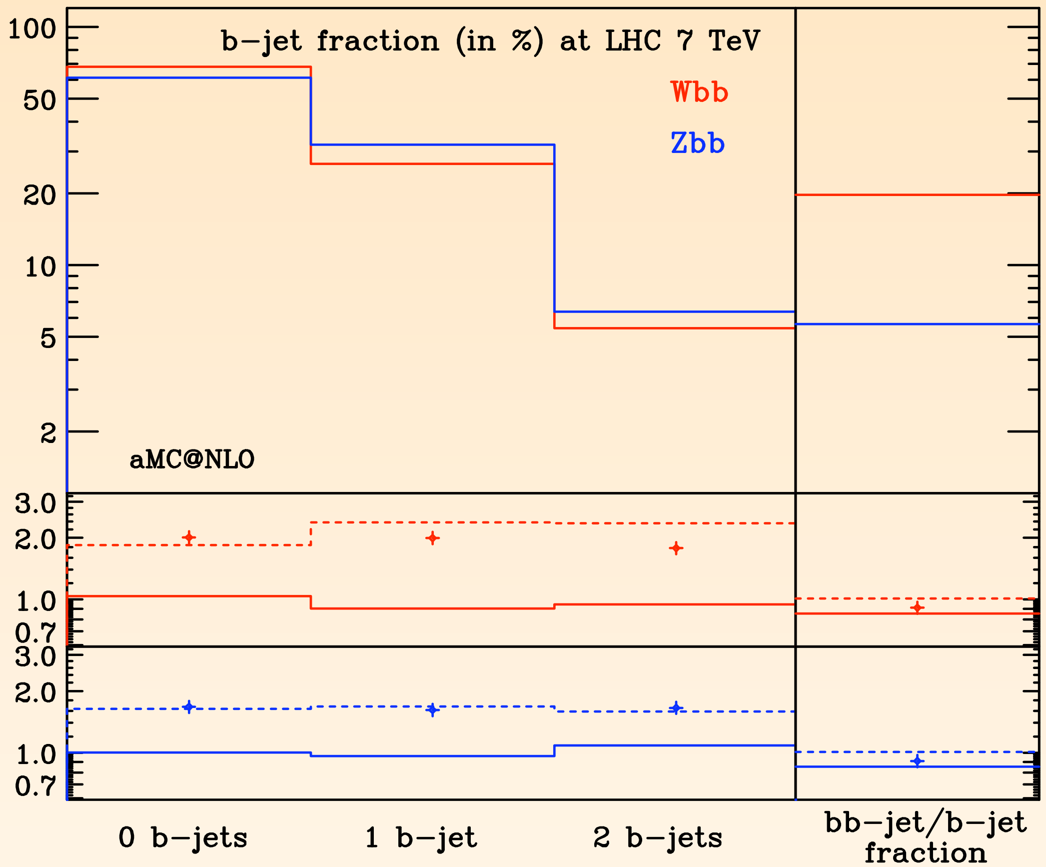
- At LO, Wbb is purely qq induced, while Zbb has also contributions from gg initial states
- Cross sections for Zbb and Wbb are similar at LHC 7 TeV

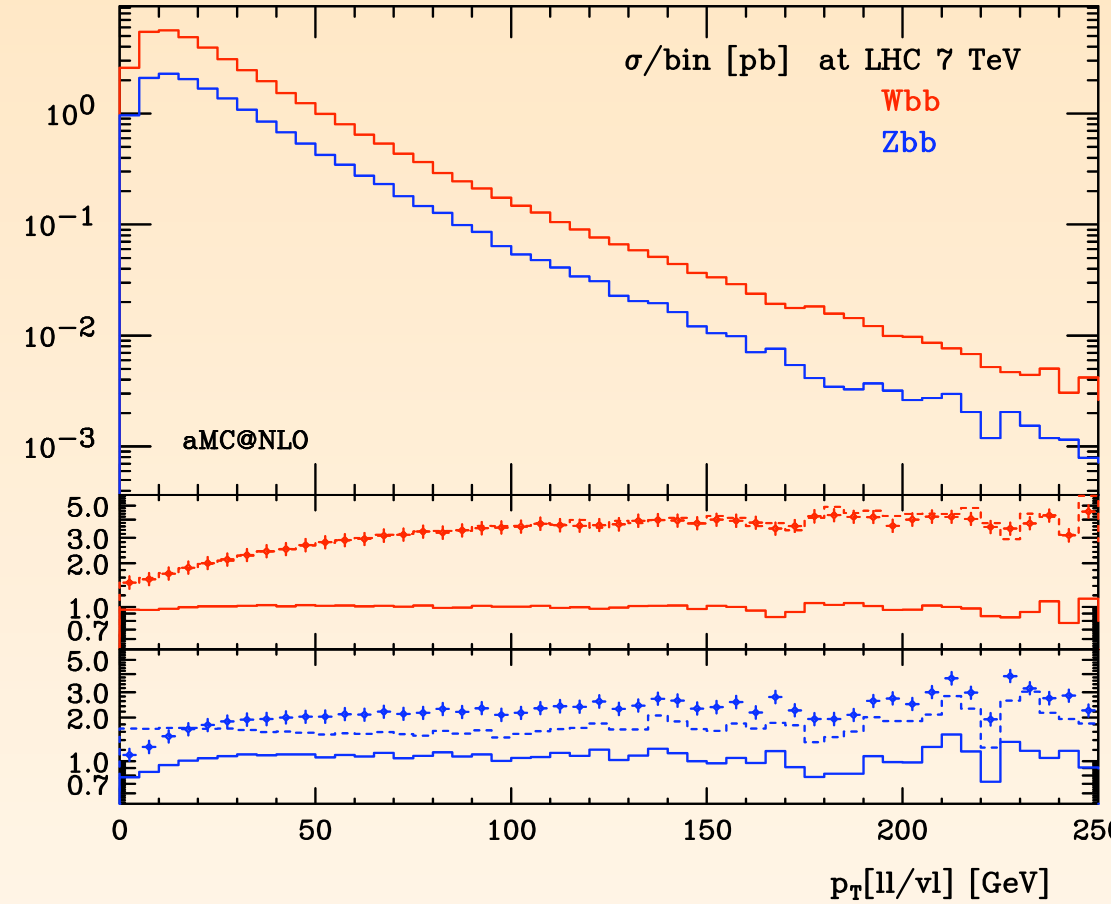
[RF, Frixione, Hirschi, Maltoni, Pittau & Torrielli, arXiv:1106.6019]

	Cross section (pb)					
	Tevatron $\sqrt{s}$ =1.96 TeV			LHC $\sqrt{s}$ =7 TeV		
	LO	NLO	K factor	LO	NLO	K factor
$\ell\nu b\bar{b}$	4.63	8.04	1.74	19.4	38.9	2.01
$\ell^+\ell^- b\bar{b}$	0.860	1.509	1.75	9.66	16.1	1.67

$$\mu_F^2 = \mu_R^2 = m_{\ell\ell'}^2 + p_T^2(\ell\ell') + \frac{m_b^2 + p_T^2(b)}{2} + \frac{m_b^2 + p_T^2(\bar{b})}{2}$$

pp → Wbb/Zbb

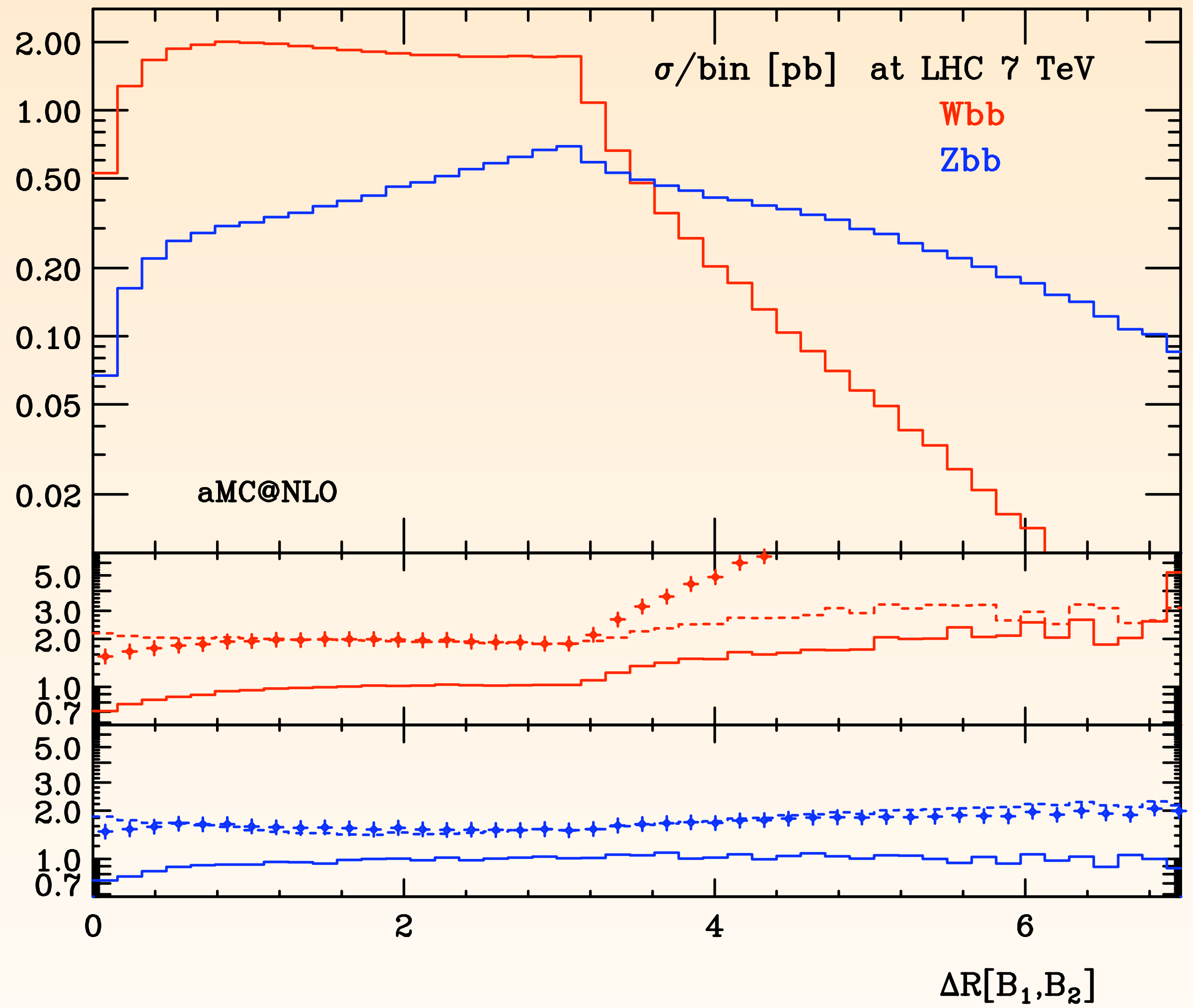




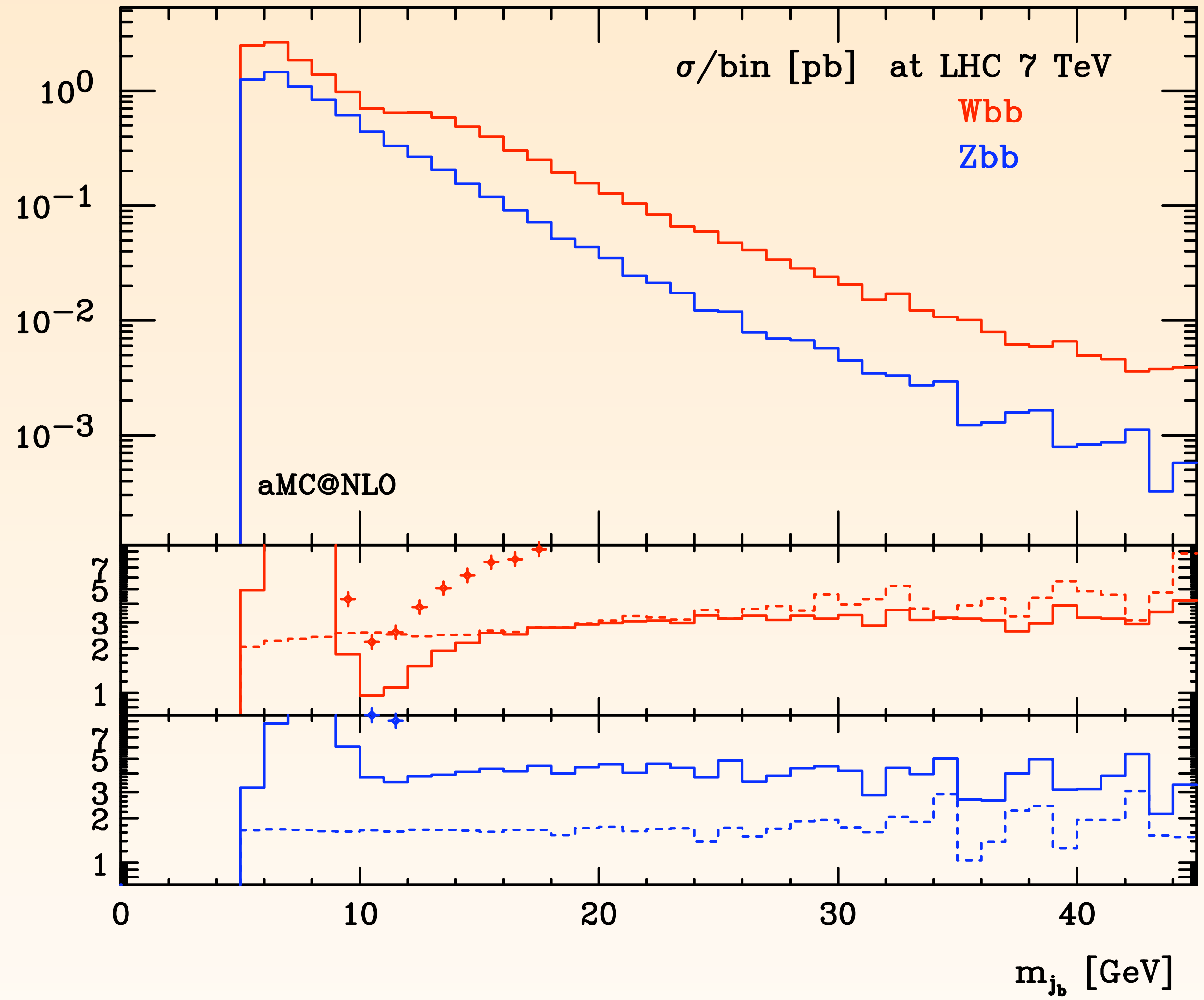
- In Wbb, ~20% of b-jets are bb-jets; for Zbb only ~6%
  - Jets defined with anti-k_T and R=0.5, with $p_T(j)$>20 GeV and $|\eta|$<2.5
- Lower panels show the ratio of aMC@NLO with LO (crosses), NLO (solid) and aMC@LO (dotted)
- NLO and aMC@NLO very similar and consistent

pp → Wbb/Zbb

Distance between B-mesons (no cuts)

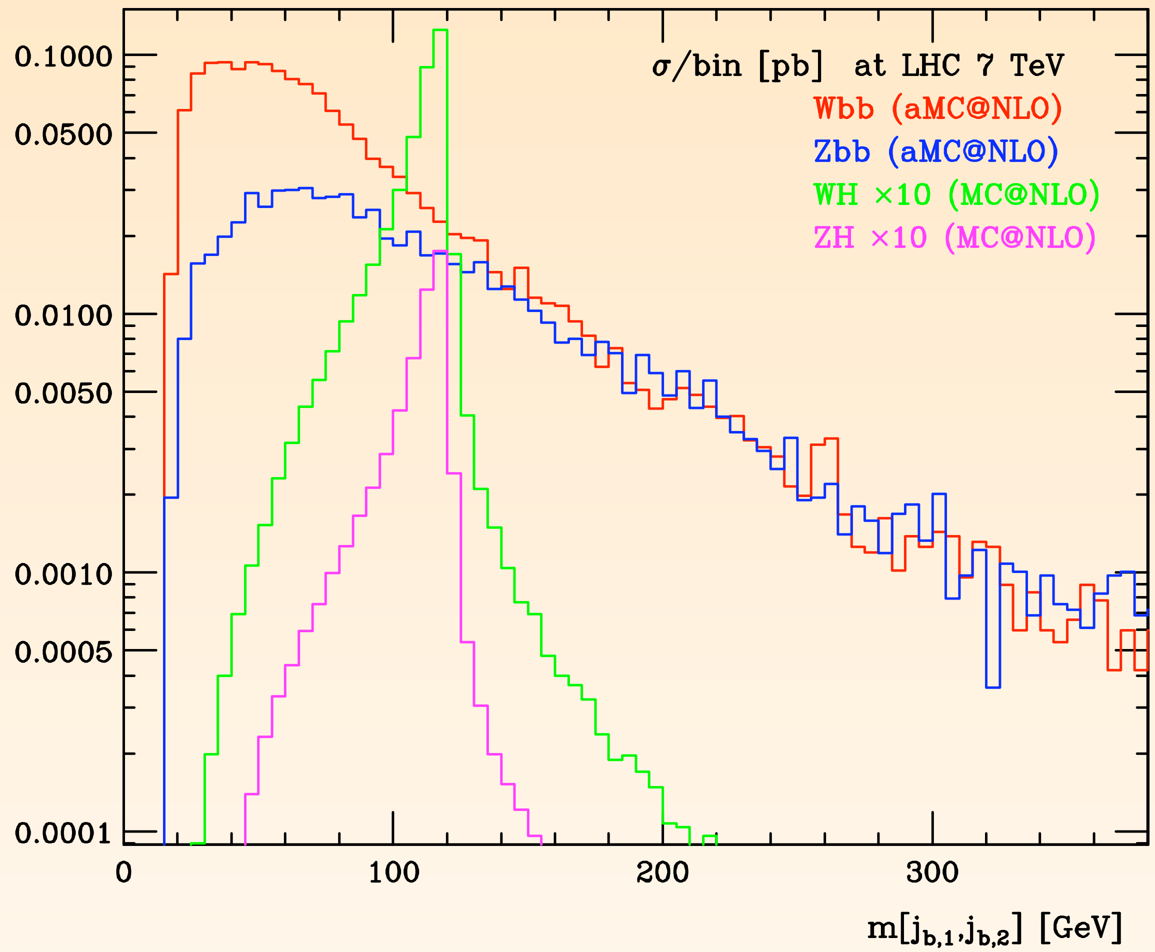


b-jet mass



- For some observables NLO effects are large and/or parton showering has large effects

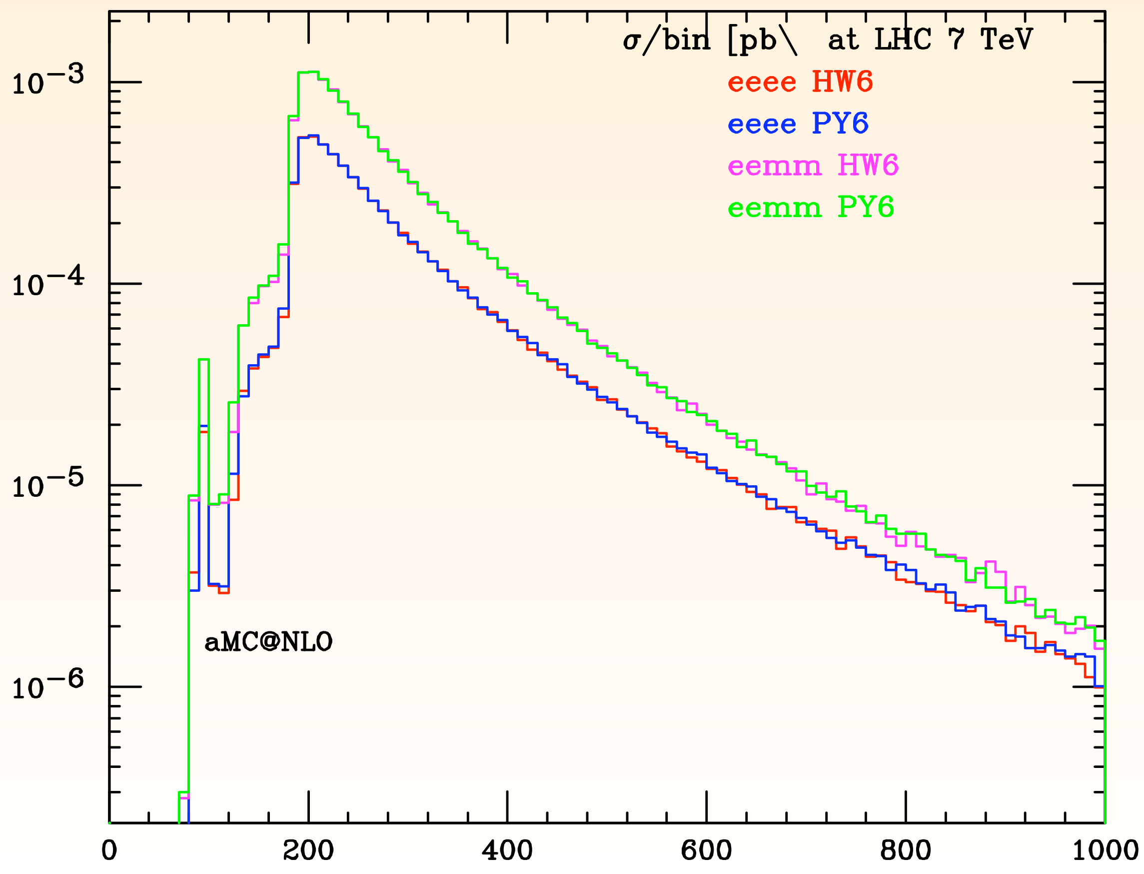
Signal + background

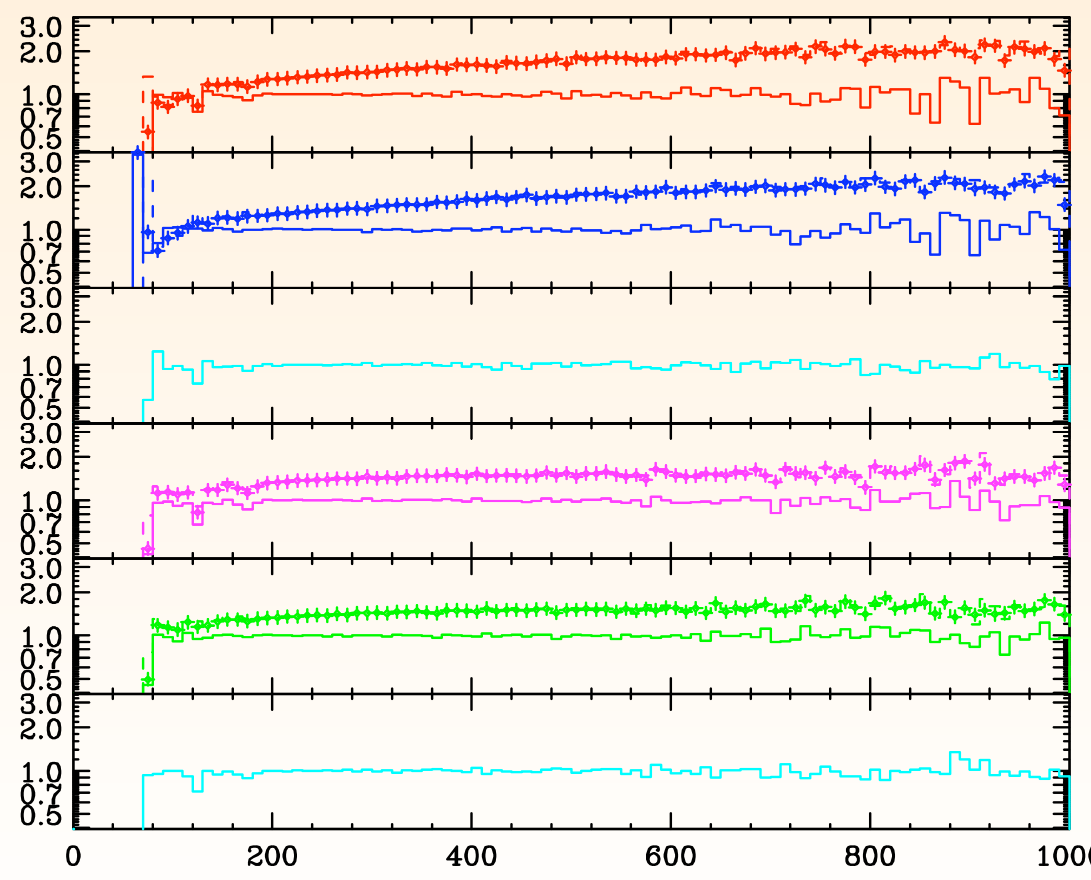


- Using (a)MC@NLO both signal and background for Vector boson production in association with a Higgs boson (where the Higgs decays to b anti-b) can be produced at the same NLO accuracy, including showering and hadronization effects

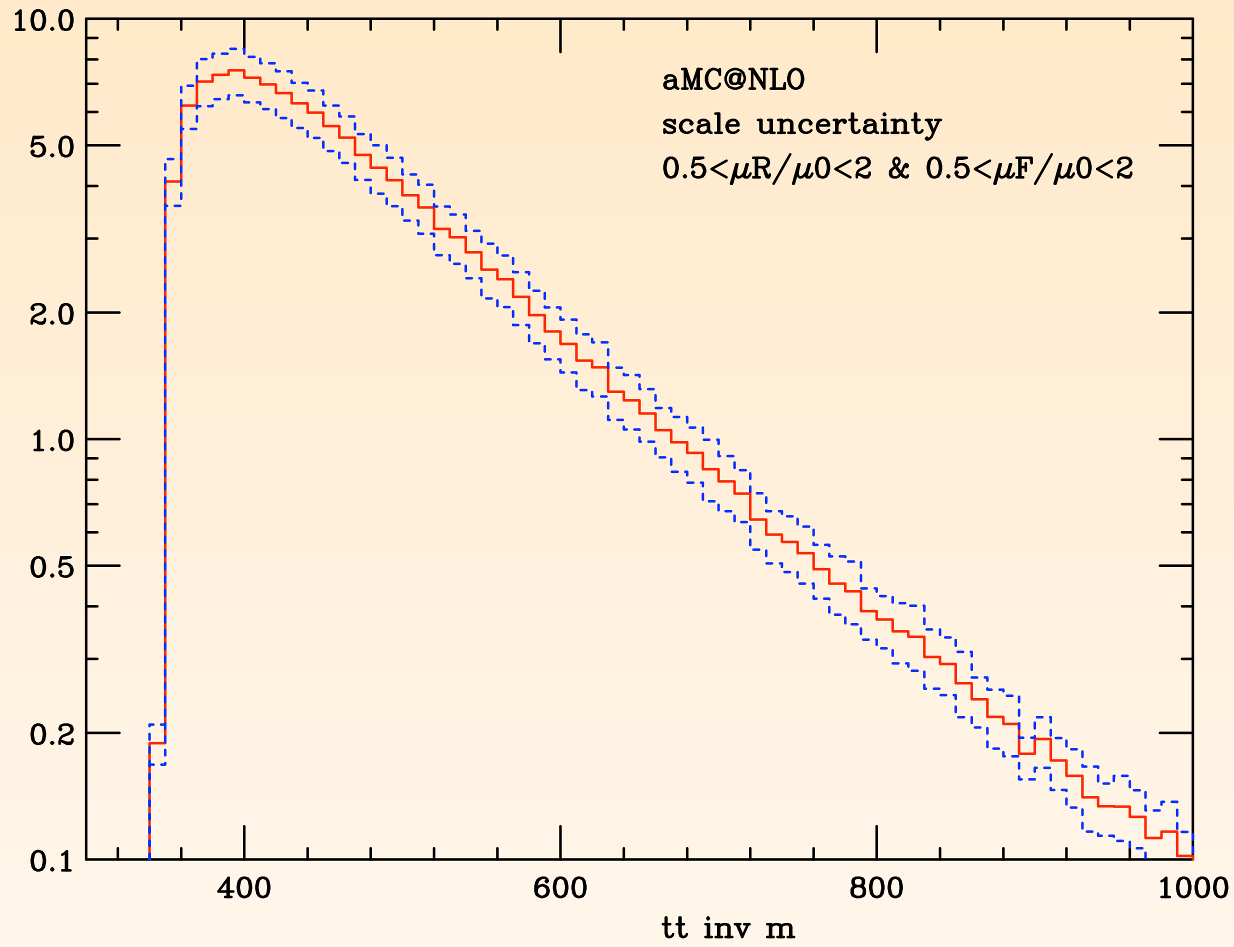
PP → ZZ → 4L

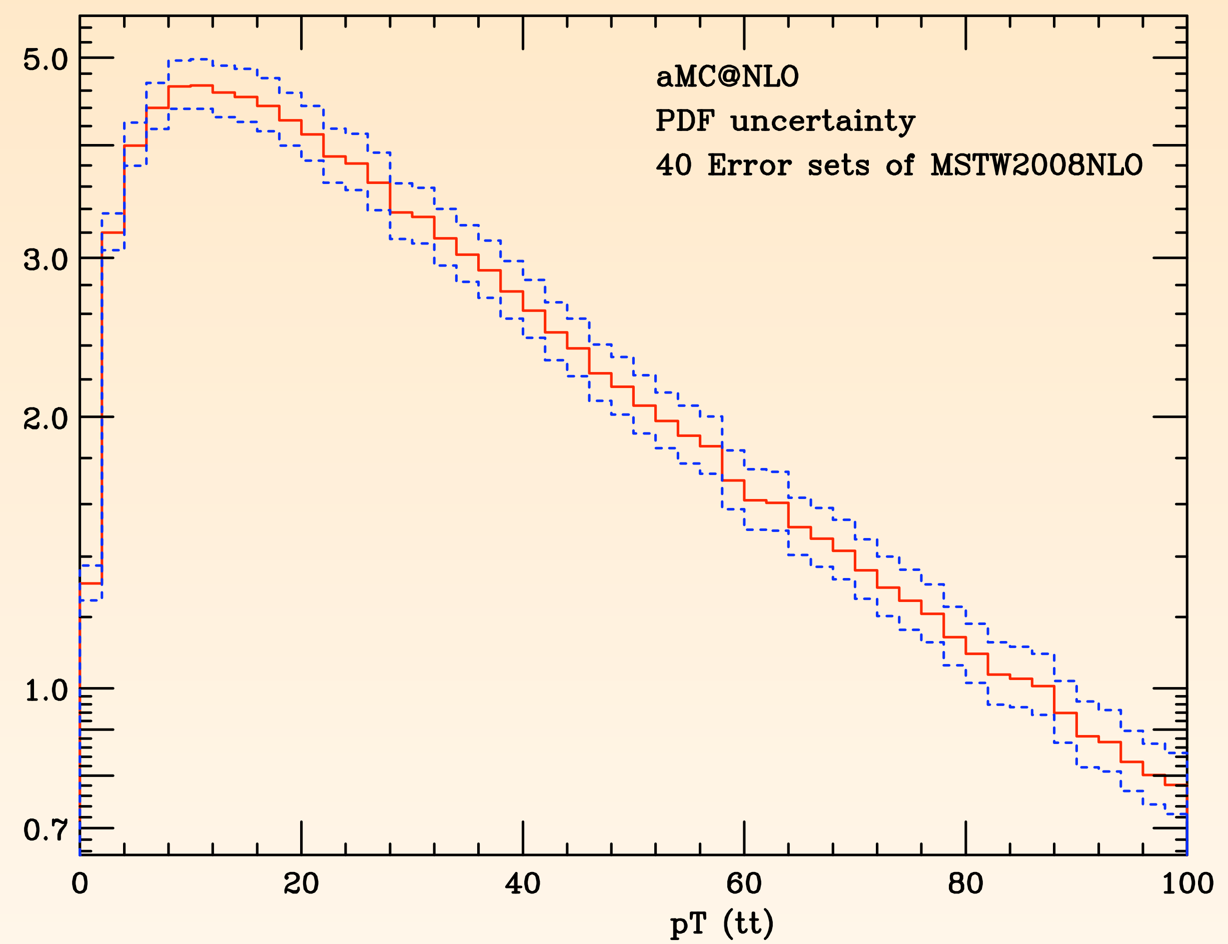
- Important background to heavy Higgs bosons
- NLO calculation includes Z/γ^* interference and single-resonant contributions, but no gg-induced (α_s^2) contributions
- First results using aMC@NLO with Pythia
- extremely stable predictions





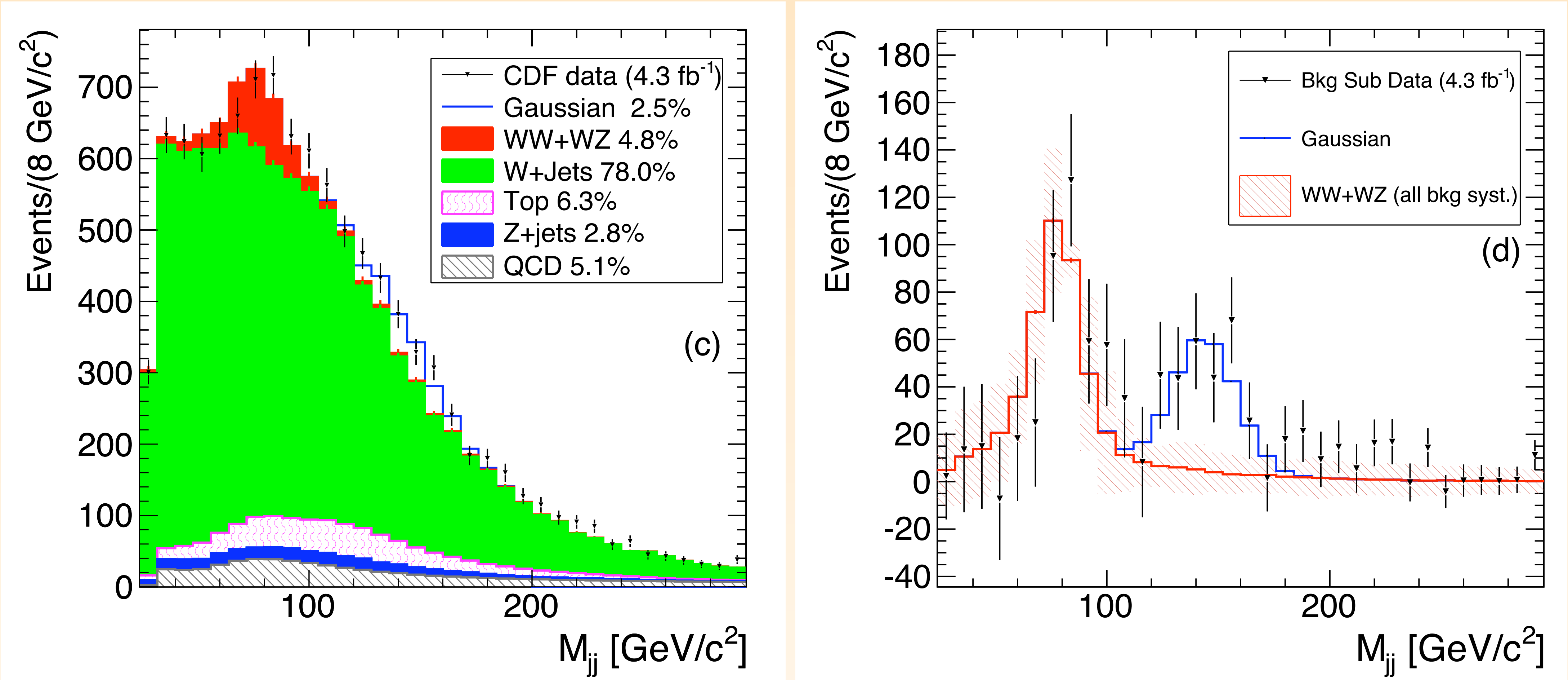
Scale & PDF uncertainties





- Any short-distance cross section can be written as a linear combination of scale and PDF dependent terms, with coefficients independent of both scales and PDFs.
- Therefore, saving these coefficients in the event file allows for a posterior evaluation of scale and PDF uncertainties, by evaluating their dependence event-by-event, without needing to rerun the generation of the events

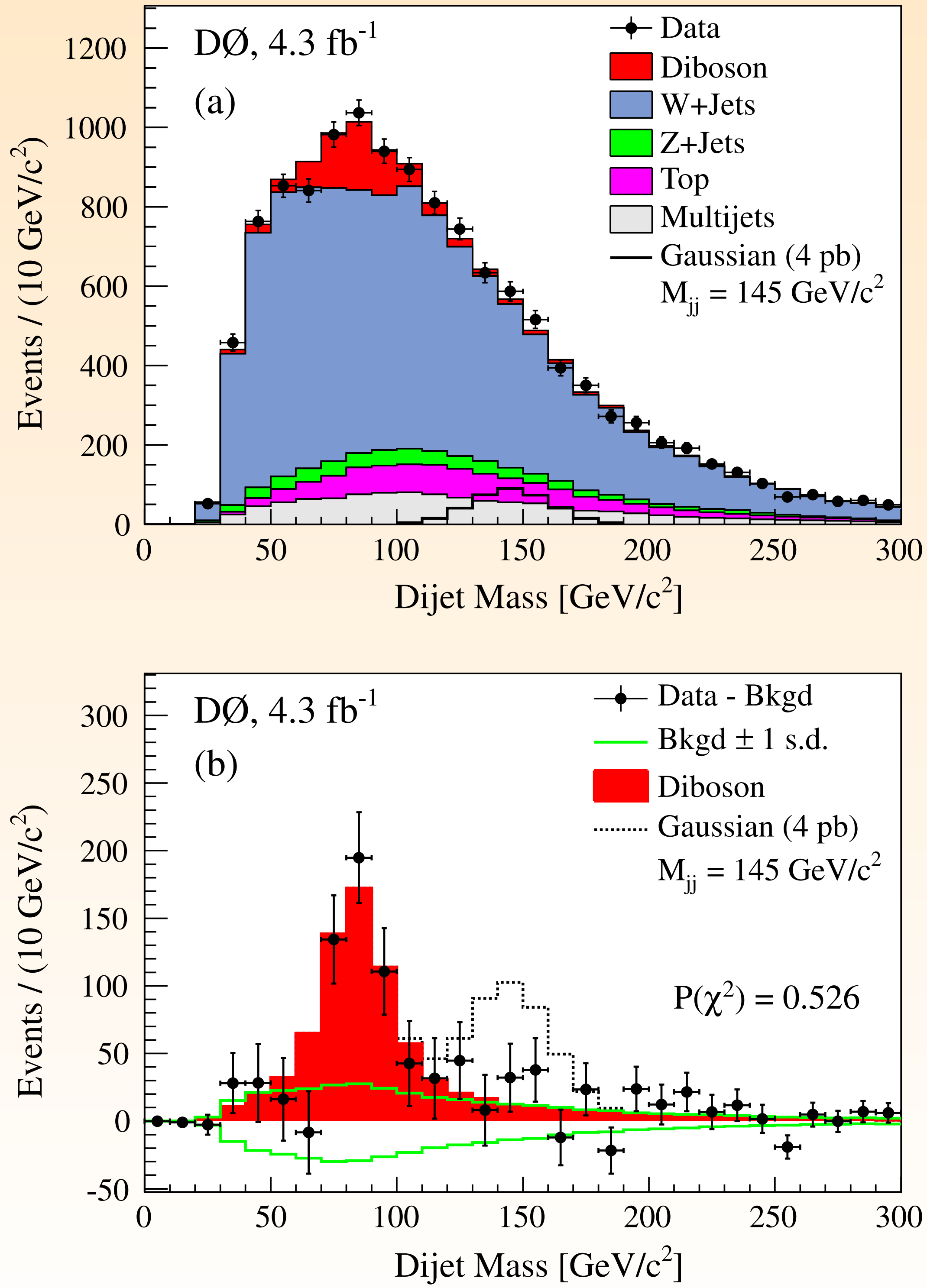
Wjj at CDF



- In April CDF reported an excess of events with 3.2 standard deviation significance in the dijet invariant mass distribution (with invariant mass 130-160 GeV) for Wjj events
- The update in June (using 7.3 fb^{-1} of data) increased significance of the excess to 4.1 standard deviations

Response...

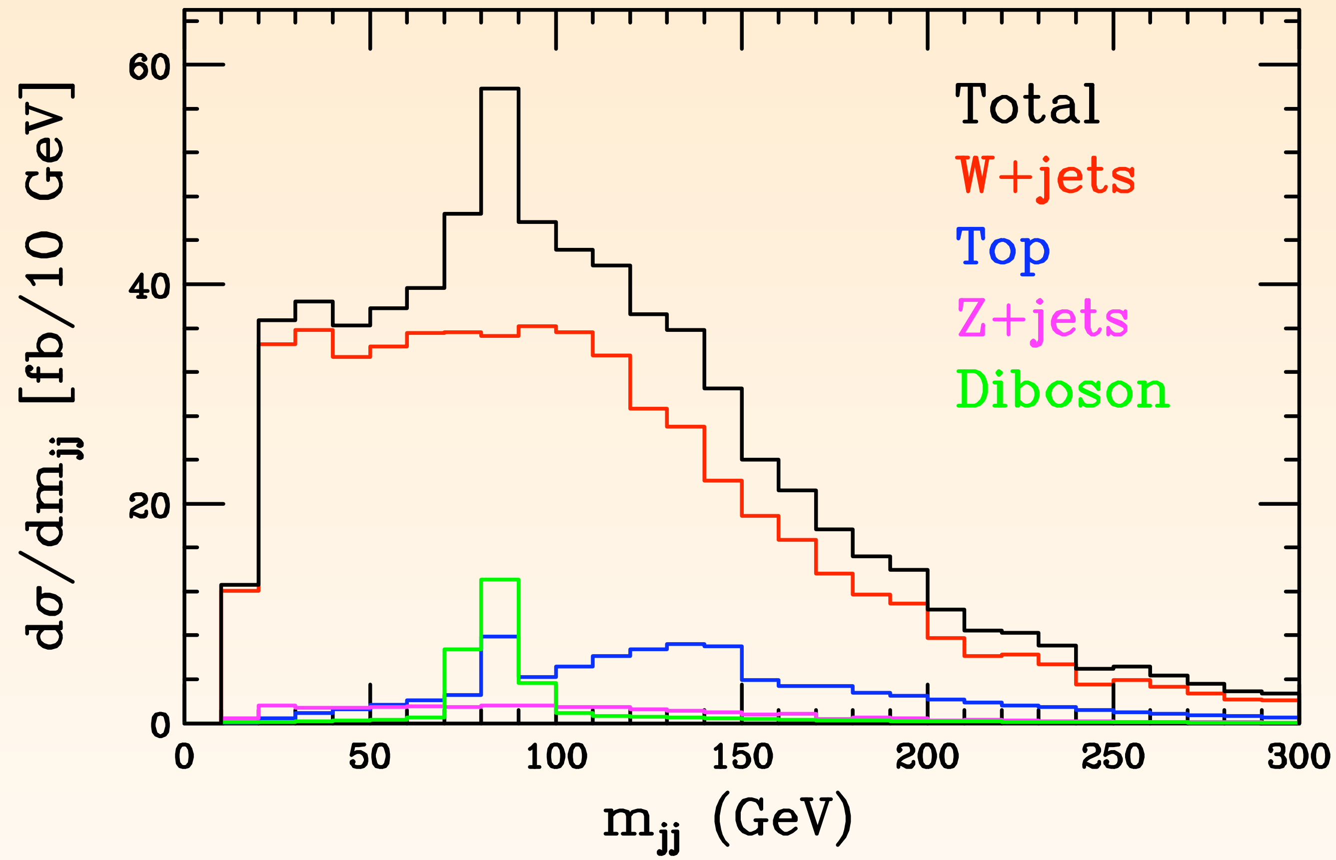
- By now more than 60 papers have appeared trying to explain this excess by introducing BSM physics
- 2 papers tried to explain the results within the SM (by addressing issues in the top quark sector)
- CDF's results are not confirmed by DØ



NLO effects

- Both CDF and DØ estimates their backgrounds using LO SMC programs (Alpgen+Pythia & Sherpa) normalized to (N)NLO or to the data

- J. Campbell, A. Martin & C. Williams have looked at the same distribution at parton level to study the impact of NLO corrections on differential distributions

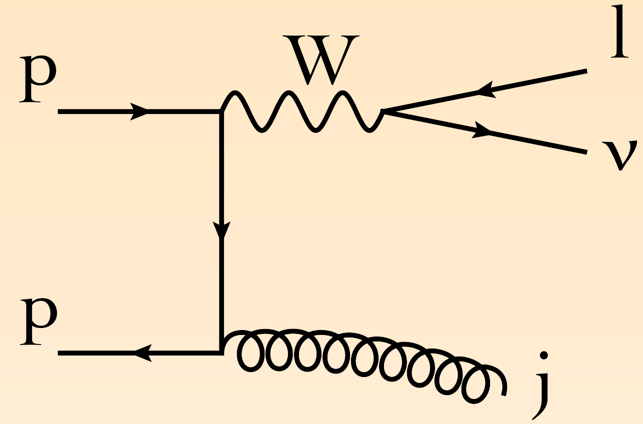


- Using the newly developed tool, aMC@NLO, we would like to address the main background, W+2j, at the NLOwPS level to see how well LOwPS or fixed order NLO describe this distribution

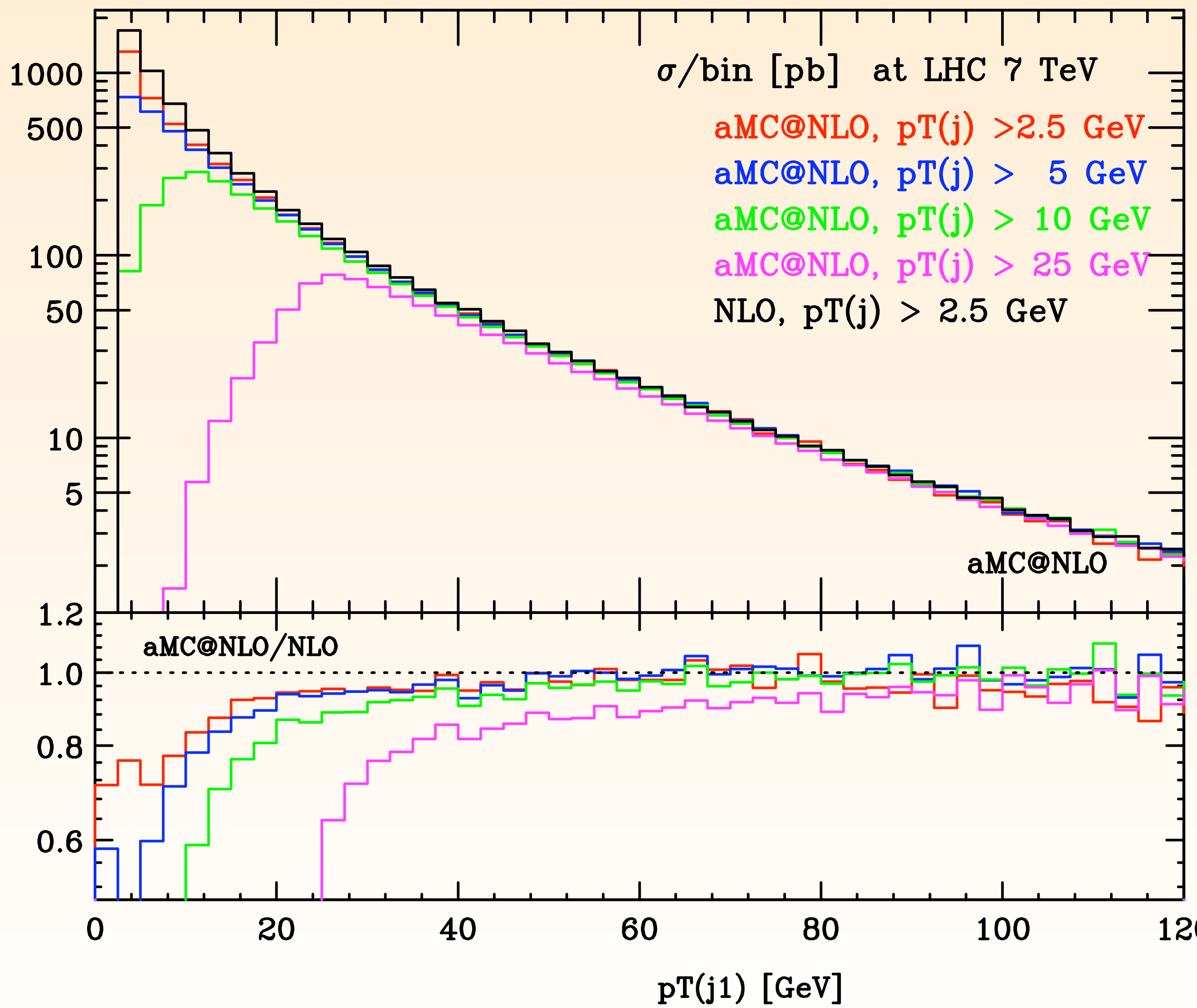
Computational challenge

- This is the first time that such a process with so many scales and possible (IR) divergences is matched to a parton shower at NLO accuracy
- Start with W+1j production to validate processes which need cuts at the matrix-element level
- To check the insensitivity to this cut:
  - generate a couple of event samples with different cuts and show that the distributions after analysis cuts are statistically equivalent

PP → WJ



- For W+1j the easiest cut would be in on the p_T of the W boson
- However, for validation purposes it is more appropriate to apply this cut on the jet instead (because that is what we'll be doing in W+2j). Same at LO, but different at NLO



- Different cuts at generation level yield the same distributions at analysis level if the analysis level cut is 3-4 times larger

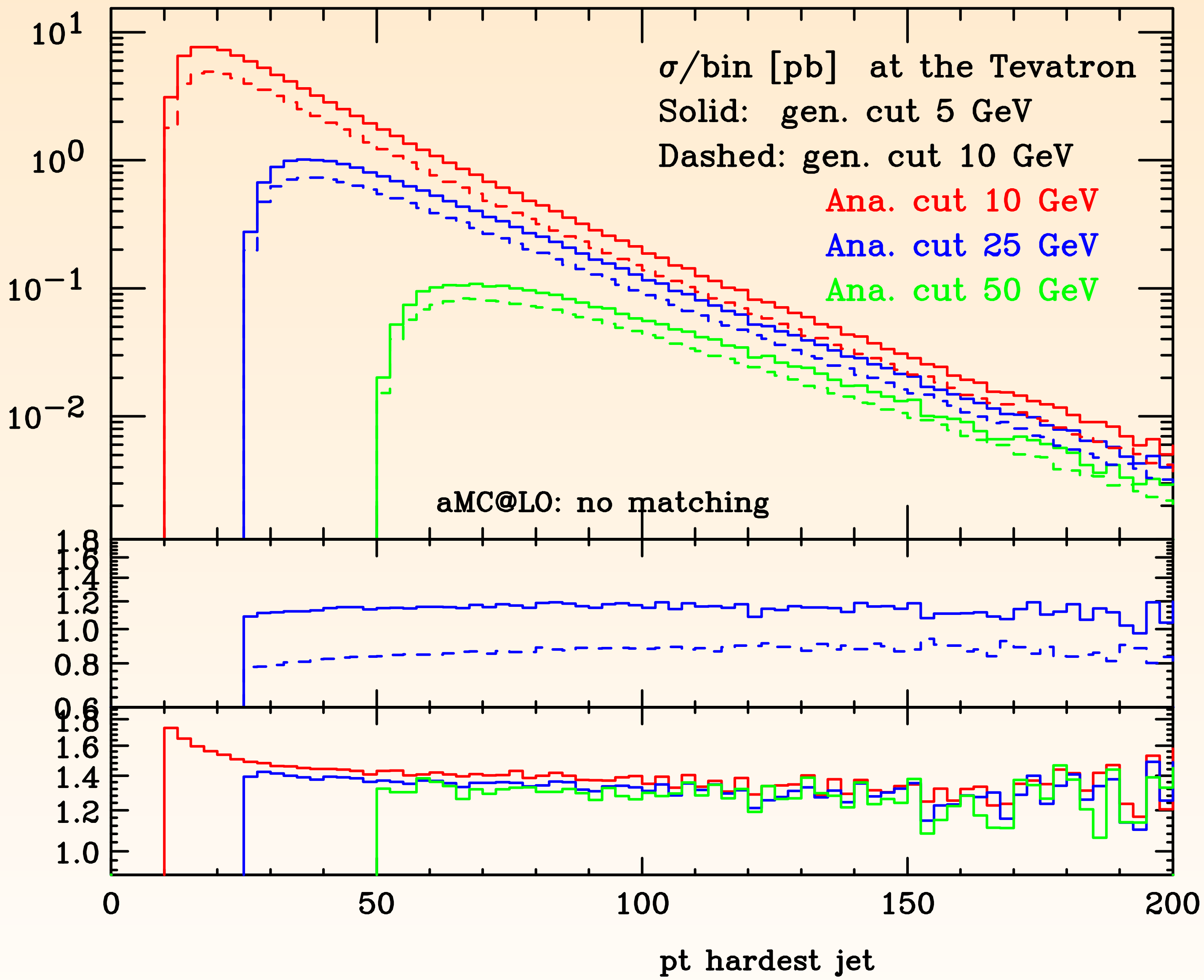
pp → Wjj
Set-up

- Two event samples with 5 GeV and 10 GeV p_T cuts on the jets at generation level, respectively, each with 10 million unweighted events
- Renormalization and factorization scales equal to $\mu_R = \mu_F = H_T/2$

$$2\mu_R = 2\mu_F = H_T = \sqrt{(p_{T,l\nu}^2 + m_{l\nu}^2)} + \sum |p_{T,i}|$$

  where sum is over the 2 or 3 partons (and the matrix element level)
- Jets are defined with anti-k_T and R=0.4
- MSTW2008(N)LO PDF set for the (N)LO predictions (with $\alpha_s(m_Z)$ from PDF set using (2)1-loop running)
- m_W = 80.419 GeV,
  G_F = 1.16639 · 10^{-5} GeV^{-2},
  α^{-1} = 132.507,
  Γ_W = 2.0476 GeV

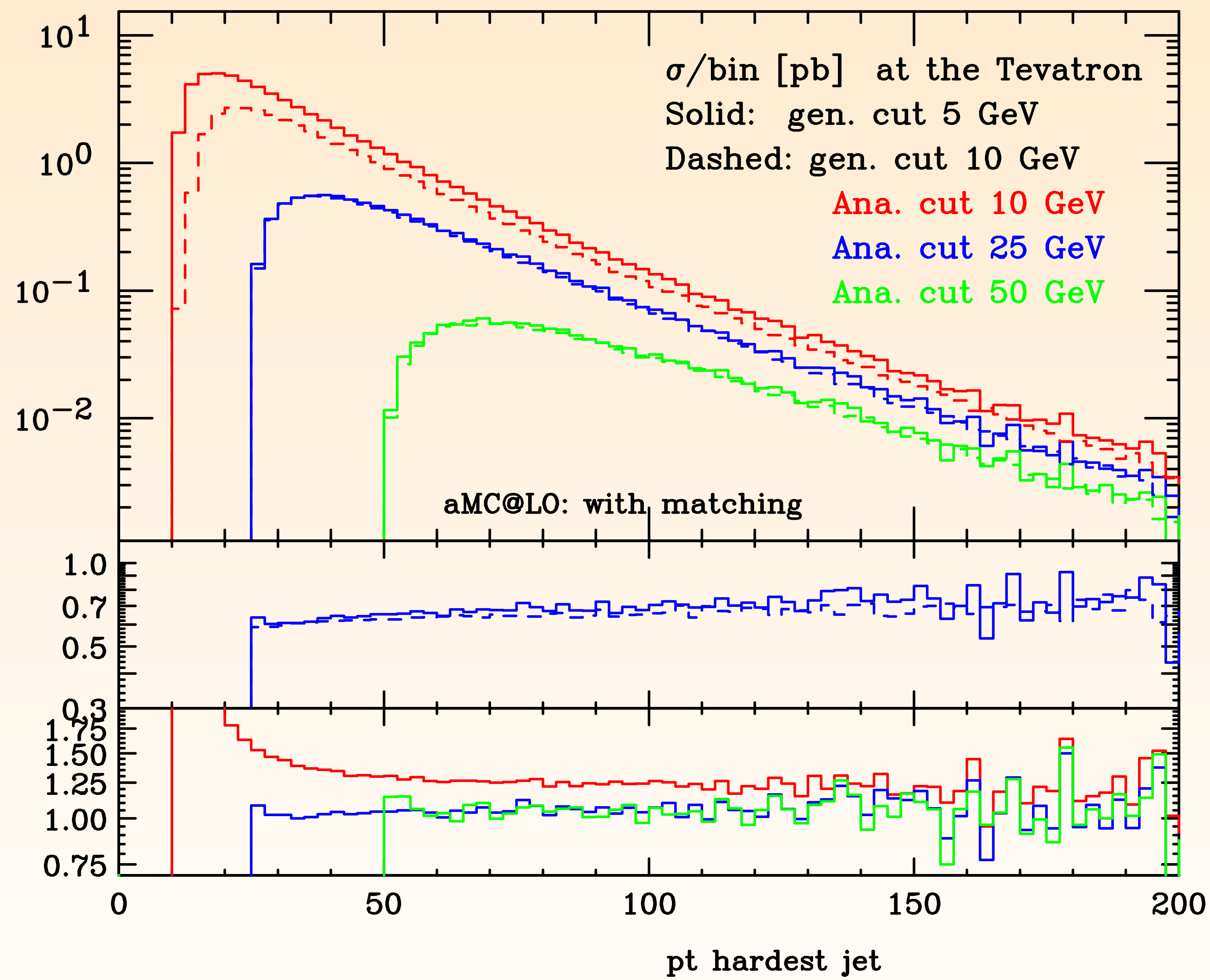
PP → WJJ
Leading Order



- The two generation-level cuts do not lead to the same distributions at the analysis level...
- Middle plot is the ratio with the fixed order
- Lower plot is the ratio of the two generation level cuts
- There is a possible double counting from jets from matrix elements and jets from parton shower: should apply a matching prescription

PP → WJJ LO WITH MATCHING

- Apply MLM matching prescription
  - The two partons (generation level) should match the two hardest jets (before hadronization), i.e., $\Delta R < 1.5\ R_{jet}$ and α_s reweighting according to "most-likely parton shower history"
- The two generation level cuts now agree. However, the overall normalization has not yet been fully understood

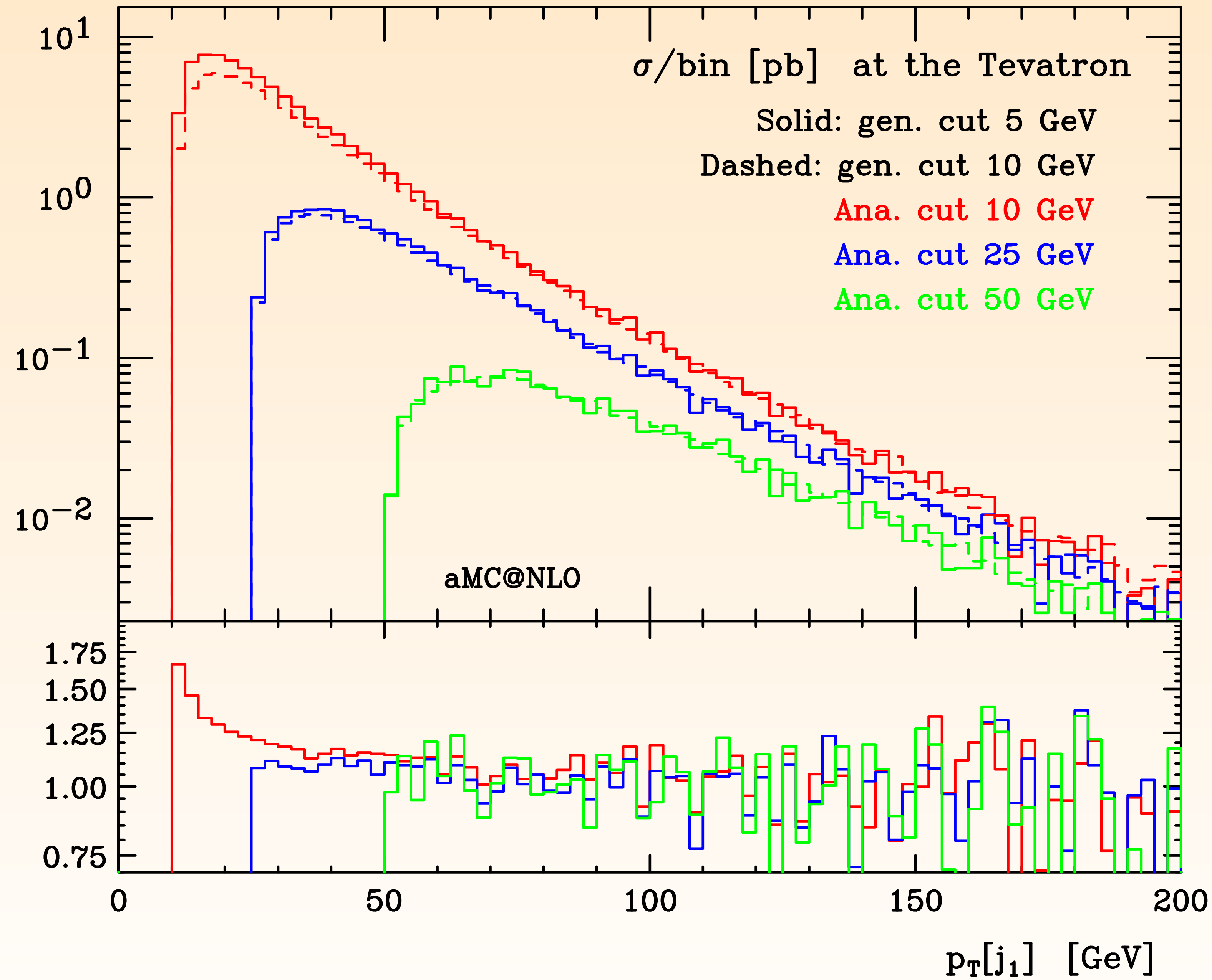


pp → Wjj
no MLM matching at NLO

- There is no need for a MLM or CKKW matching prescription when already matching with MC@NLO:
  - **The first emission from the PS is already properly matched with the real-emission matrix elements**
  - Another hard jet from the PS is very unlikely (in particular at the Tevatron)

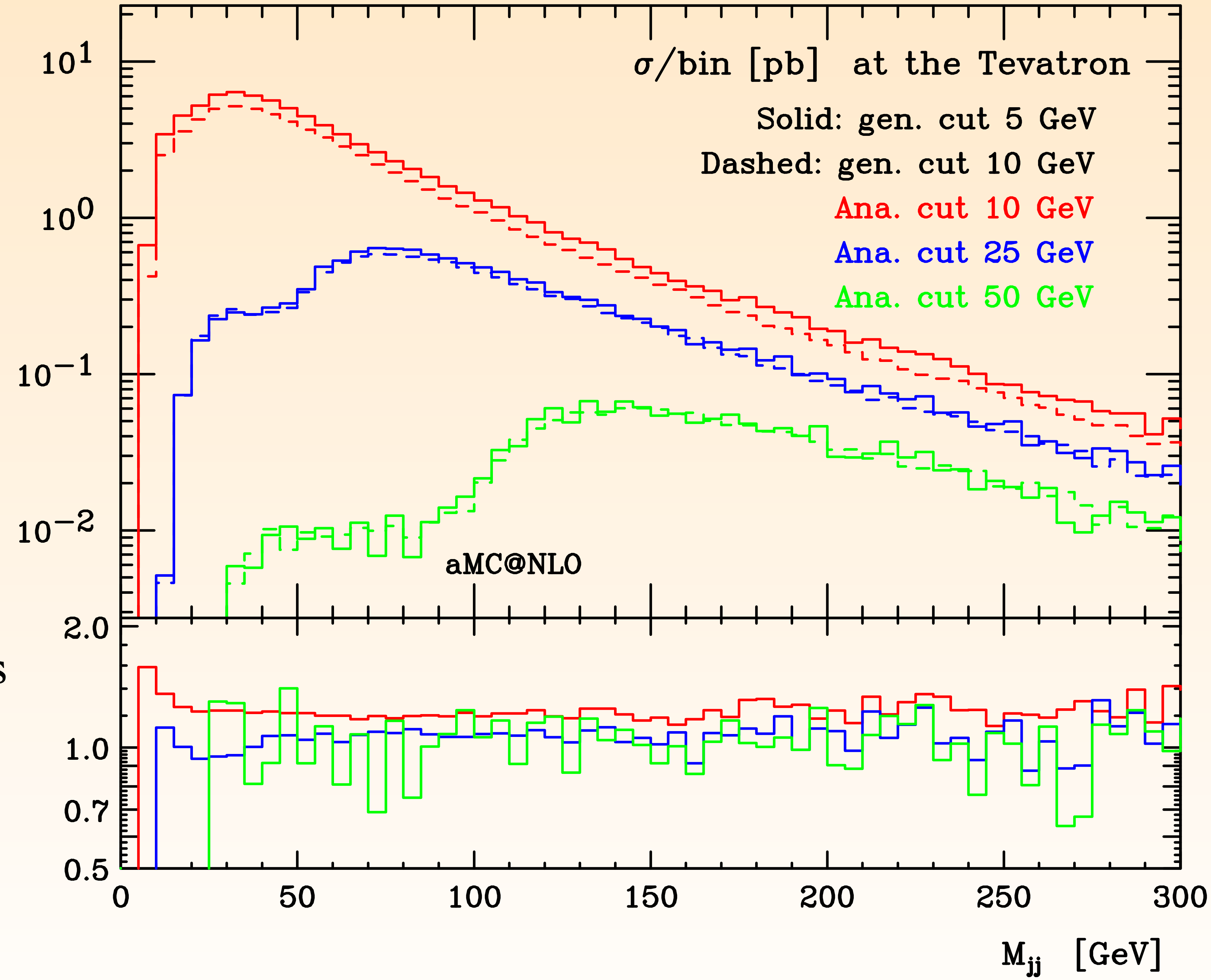
PP → WJJ Validation

- The two generation level cuts agree for high enough momenta (or harder analysis cuts)
- Middle plot shows ratio of NLO (solid), LO (dotted) and LOwPS (dashed) over aMC@NLO
- Good agreement with (N)LO, slight difference in shape
- Tails have low statistics, in particular for the 5 GeV generation cuts

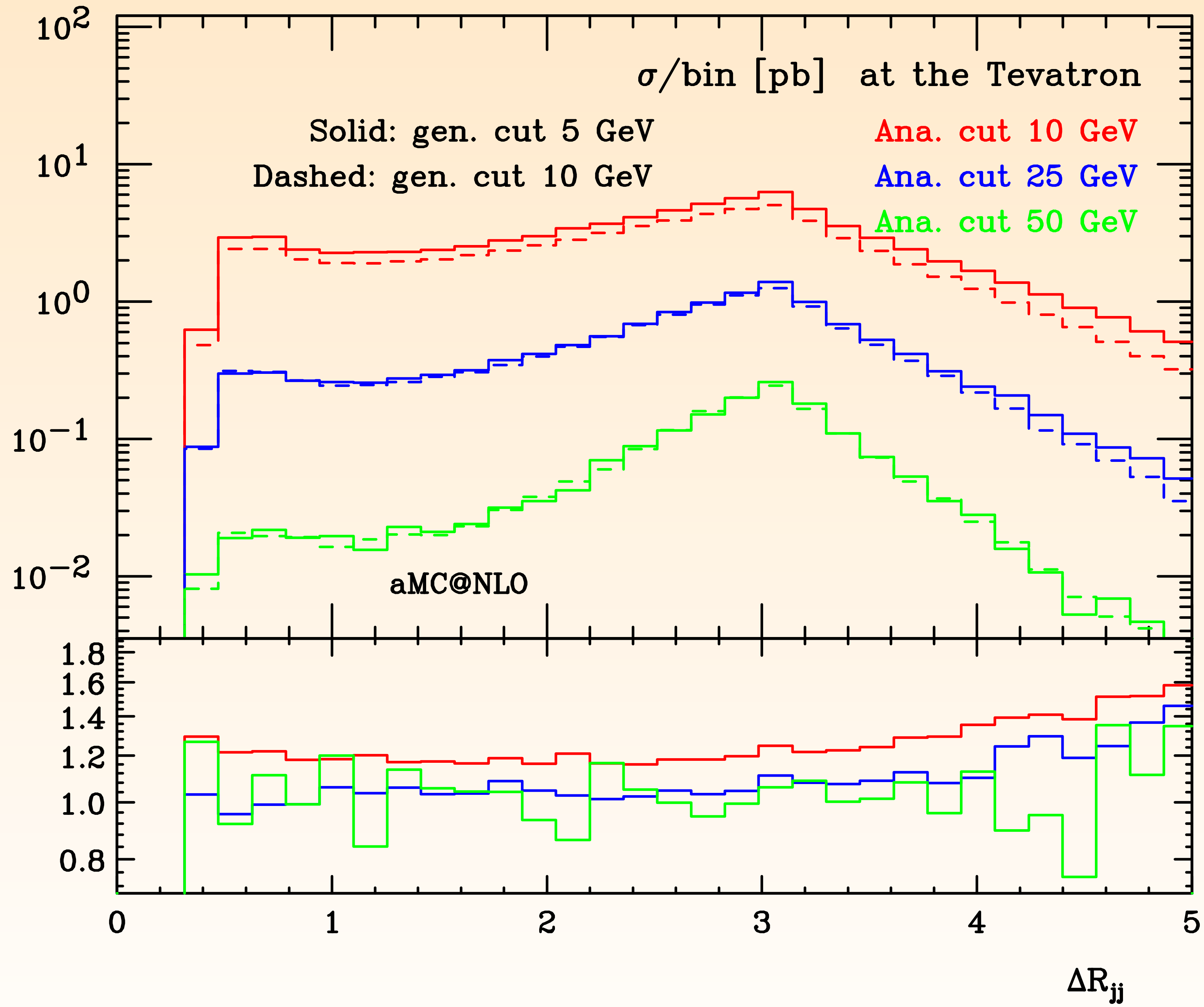


PP → WJJ Validation - II

- Dijet invariant mass
- For analysis cuts larger than 25 GeV the two event samples coincide (except for the very low mass region)
- For smaller analysis cuts the bias is flat in this distribution



pp → Wjj Validation - III



- Distance between the jets
- A small bias remains at 25 GeV analysis in the tail of the distribution, but reduced a lot from lower cuts analysis cuts
  - 5 GeV sample probably ok, 10 GeV gen. cut is a bit too hard
- Of all distributions we have looked at, this one shows the largest bias due to generation cut

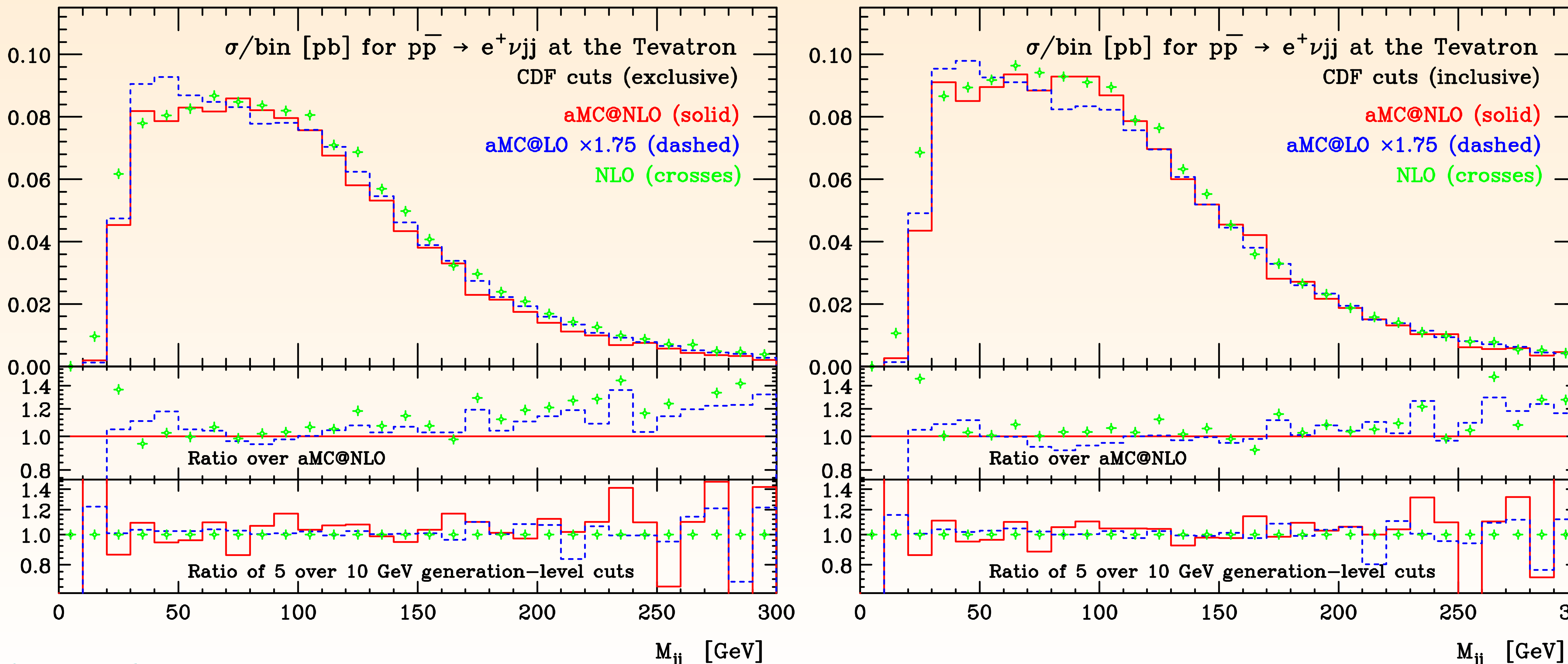
PP → WJJ CDF/DØ ANALYSIS CUTS

- minimal transverse energy for the lepton: $E_T(l) > 20$ GeV;
- maximal pseudo rapidity for the lepton: $|\eta(l)| < 1$;
- minimal missing transverse energy: $\not{E}_T > 25$ GeV;
- minimal transverse W-boson mass: $M_T(l\nu_l) > 30$ GeV;
- jet definition: JetClu algorithm with 0.75 overlap and $R = 0.4$;
- minimal transverse jet energy: $E_T(j) > 30$ GeV;
- maximal jet pseudo rapidity: $|\eta(j)| < 2.4$;
- minimal jet pair transverse momentum: $p_T(j_1 j_2) > 40$ GeV;
- minimal jet-lepton separation: $\Delta R(lj) > 0.52$;
- minimal jet-missing energy separation: $\Delta\phi(\not{E}_T j) > 0.4$;
- hardest jets close in pseudorapidity: $|\Delta\eta(j_1 j_2)| < 2.5$;
- jet veto: no third jet with $E_T(j) > 30$ GeV and $|\eta(j)| < 2.4$;
- lepton isolation: transverse hadronic energy smaller than 10% of the lepton transverse energy in a cone of $R = 0.4$ around the lepton.

- To slightly simplify the analysis, the MC truth is used to assign the lepton to the W-boson decay
- Only W^+ events (simply a factor 2)
- No underlying event

$p\bar{p} \rightarrow Wjj$
Dijet invariant mass

- Dijet invariant mass with/without jet veto
- This is the distribution in which CDF found an excess of events around 130-160 GeV
- No differences in shape between the 5 and 10 GeV generation level cuts
- No sign of enhancement over (N)LO or LOwPS in the mass range 130-160 GeV



Future improvements

- The MadLoop code is being rewritten in MadGraph v5. This will:
  - remove the limitations presented on the previous slide
  - make it faster:
    - Recycling of tree-structures attached to the loops
    - Identify identical contributions (e.g. massless fermion loops of different flavors)
    - Call CutTools not per diagram, but per set of diagrams with the same loop kinematics
    - Use recursion relations (will mostly help the real-emission corrections)
    - Even more efficient mapping of integrand to integration channels
  - allow for the automatic generation of UV renormalization and remainder vertices using FeynRules [*Christensen, Duhr et al.*] for BSM physics

Future plans

- Validate the MC counter terms for Herwig++ and Pythia (FSR)
- Move the code to MadGraph v5: much more efficient and removes (minor) limitations from MadLoop
- Merge predictions using various multiplicity matrix elements at NLO into one consistent, all-inclusive event sample
- Make the use of the code public for specific processes by running on the website, http://amcatnlo.cern.ch
- Make the code public

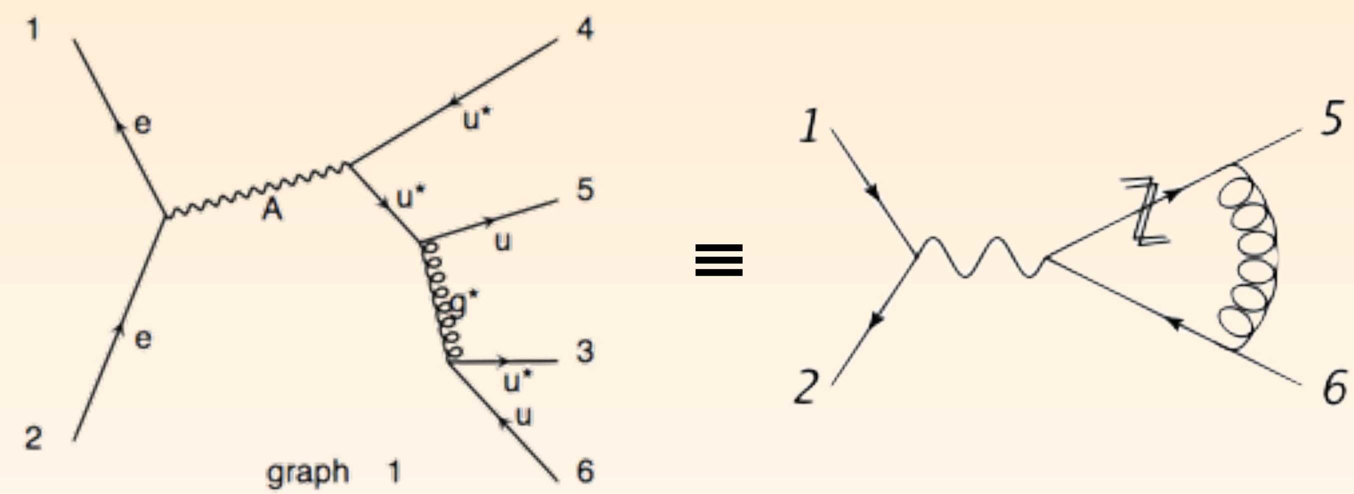
Conclusions

- Flexible, automatic event generators at NLO accuracy will become publicly available for analyses very soon
- First completely automatic NLO events within the MadGraph framework have been produced using `aMC@NLO`, matching MadFKS with MadLoop+CutTools to the Herwig6 and Pythia6 showers using the MC@NLO method
- Have a look at our website!, http://amcatnlo.cern.ch/, where we will make available soon:
  - more NLO event samples to be showered by the user
  - On-line running of validated aMC@NLO code for specific processes
  - Phase-space point checking for virtuals using MadLoop

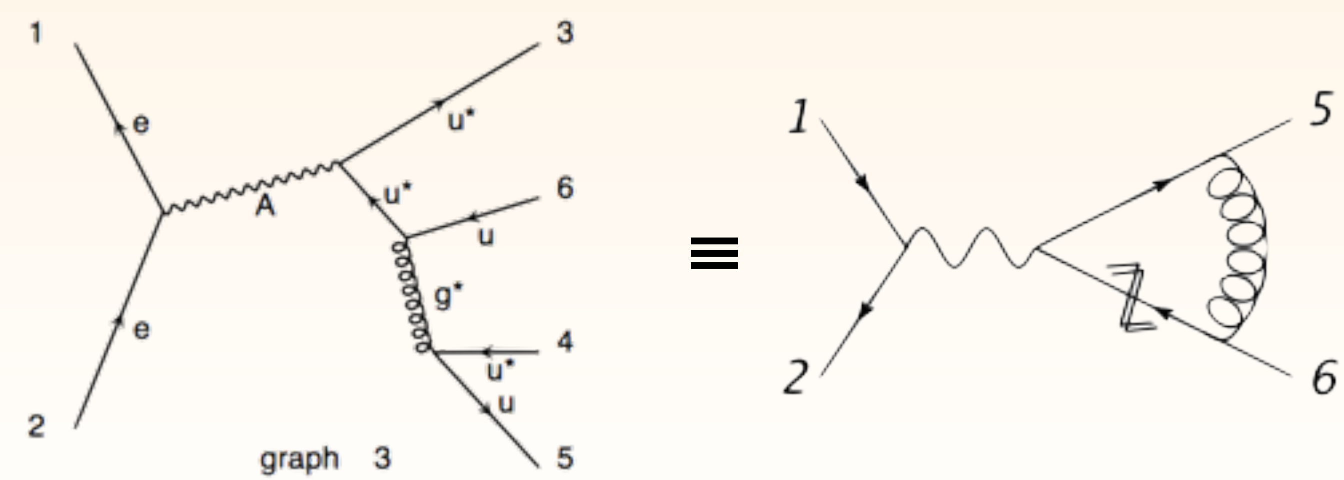
Backup

L-cut diagrams

- Instead of writing a new code to generate loop diagrams, we use the existing, well-tested MadGraph code to generate tree-level diagrams
- A loop diagrams with the loop cut open has to extra external particles. Consider $e^+e^- \rightarrow$ u* ubar* u ubar (loop particles are denoted with a star). MadGraph will generate 8 L-cut diagrams. Here are two of them:
  - All diagrams with two extra particles are generated and the ones that are needed are filtered out
  - Each diagram gets an unique tag: any mirror and/or cyclic permutations of tags of diagrams already in the set are taken out
  - Additional filter to eliminate tadpoles and bubbles attached to external lines



$\text{Diag}_{\,1} = [u^*(6)g^*(5)u^*(A)]$



$\text{Diag}_{\,3} = [u^*(A)u^*(6)g^*(5)]$

MadLoop: Exceptional PS points

- There are (almost) always phase-space points for which the numerical reduction to determine the coefficients in front of the scalar integrals does not work due to numerical instabilities
- CutTools has build-in routines to determine if a phase-space point is exceptional or not
  - By sending $m_i^2 \to m_i^2 + M^2$ CT has an independent reconstruction of the numerator and can check if both match
  - CT can ask MadLoop to evalutate the integrand at a given loop momentum and check if the result is close enough to the one from the reconstructed integrand
- Using quadruple precision numerics in the reduction helps, but not always

MadLoop: Exceptional PS points

- When CutTools assigns a phase-space point to be unstable, MadLoop tries to cure it
  - Check if the Ward Identity holds at a satisfactory level
  - Shift the phase-space point by rescaling one of the components of the 3-momenta (for all particles), e.g. $k_i^3 = (1+\lambda_\pm)k_i^3$, and adjusting the energy components to keep the point on-shell
    - Provide an estimate of the virtual of the original phase-space point (with uncertainty) $V_{\lambda=0}^{FIN} = \left|\mathcal{A}_{\lambda=0}^{born}\right|^2 (c \pm \Delta)$ where

$$c = \frac{1}{2}\left(v_{\lambda_+}^{FIN} + v_{\lambda_-}^{FIN}\right) \qquad \Delta = \left|v_{\lambda_+}^{FIN} - v_{\lambda_-}^{FIN}\right| \qquad v_{\lambda_\pm}^{FIN} = \frac{V_{\lambda_\pm}^{FIN}}{|\mathcal{A}_{\lambda=0}^{born}|^2}$$

  - If all shifts fail (very rarely) use the median of the results of the last 100 stable points and the median absolute deviation (MAD (!)) to determine the associated uncertainty

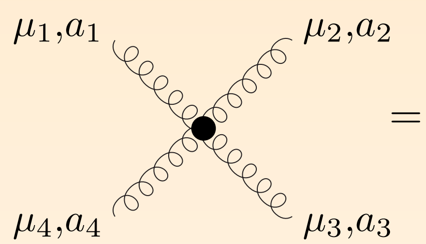
MadLoop

Hirschi, RF, Frixione, Garzelli, Maltoni & Pittau, arXiv:1103.0621

- Generation of the loop diagrams
  - Generate "L-cut diagrams" and select a non-redundant set
  - Compute color factors to interfere virtual amplitude with the Born
  - Provide the numerators of the loop integrals that need to be passed to CutTools
  - Perform sanity checks (Double pole, Ward identity, ...)
- Performing the phase-space integration
  - MadFKS provides the momenta (and helicity)
  - CutTools determines the coefficient in front of the scalar integrals (times the scalar integral) numerically
  - Compute the remainder (and UV-renormalization)
  - Handle possible "exceptional phase-space points"

MadLoop: limitations

- Of course, there are some limitations on what the code cannot do yet...
  - No four-gluon vertex at the Born level: the special vertex to compute the remainder is too complicated to implement in MadGraph v4



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

  - If EW bosons appear in the loops, the reduction by CutTools might not work
  - No finite-width effects for massive particles also appearing in the loops
  - All Born contributions must factorize the same power of all coupling orders