V + HEAVY FLAVOR
(THEORY)

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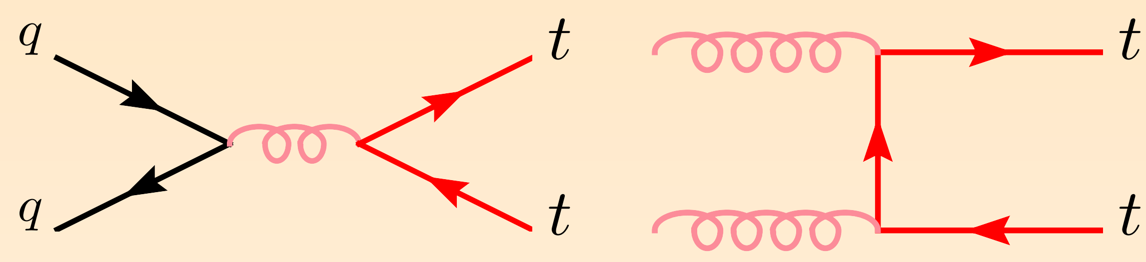
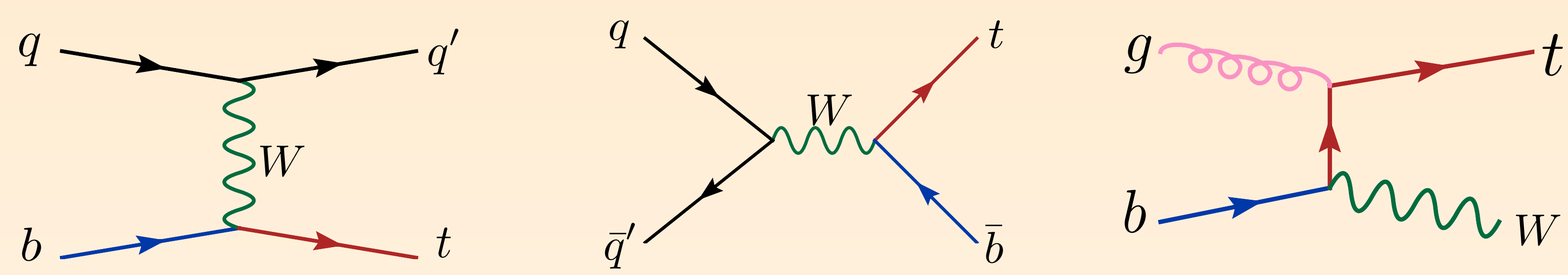
4th international workshop on Top Quark Physics, Sant Feliu de Guixols, Spain, Sep. 25-30, 2011

Background to tops

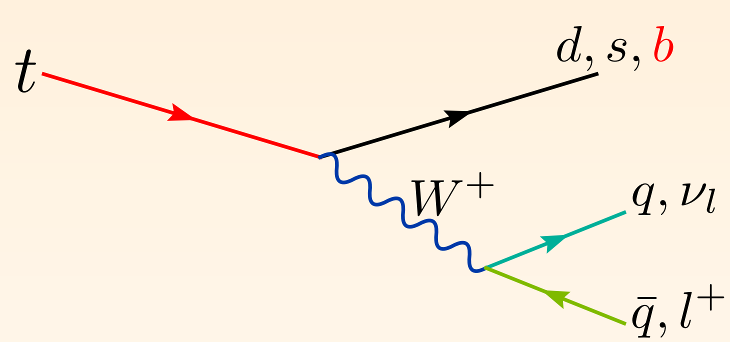
Top pair



Single top



Top decay

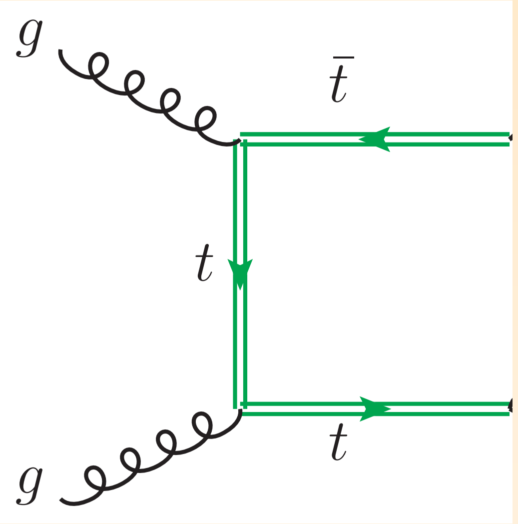


- The main backgrounds to top quark are W-bosons plus heavy jets
- The (ir)reducible backgrounds to top pair and single top production involve vector boson(s) plus heavy jets events

Outline

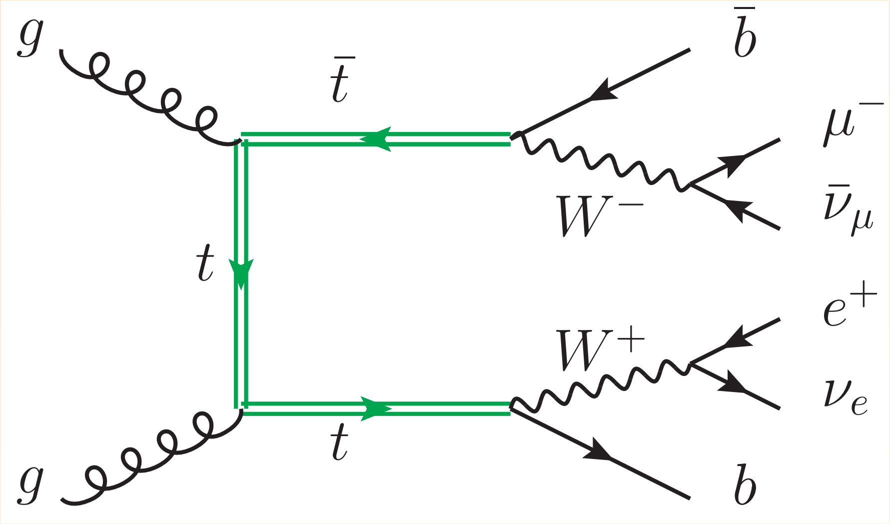
- The irreducible "background" to top pair production: WWbb at NLO
- 4 & 5 flavor scheme for W + heavy jets
- Wbb (and Zbb) matched to the parton shower

ON-SHELL TOP QUARKS



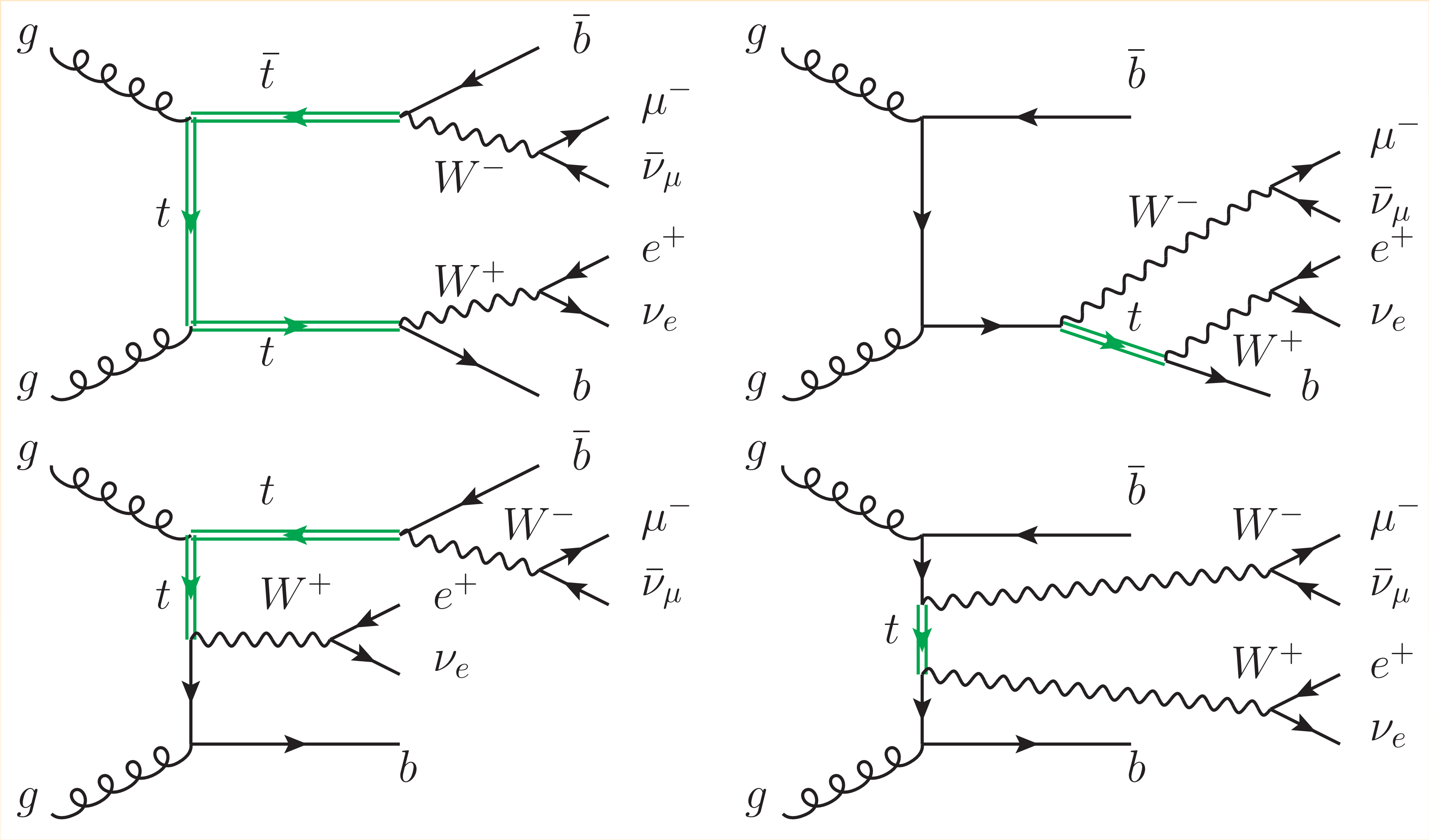
- Until recently all (exclusive) calculations beyond LO used the narrow width approximation for the top quark pair production: tops are assumed to be stable

Off-shell effects



- However, top quarks decay, so the better LO diagram is this one
- In fact, there are quite a few more diagrams of the same order...

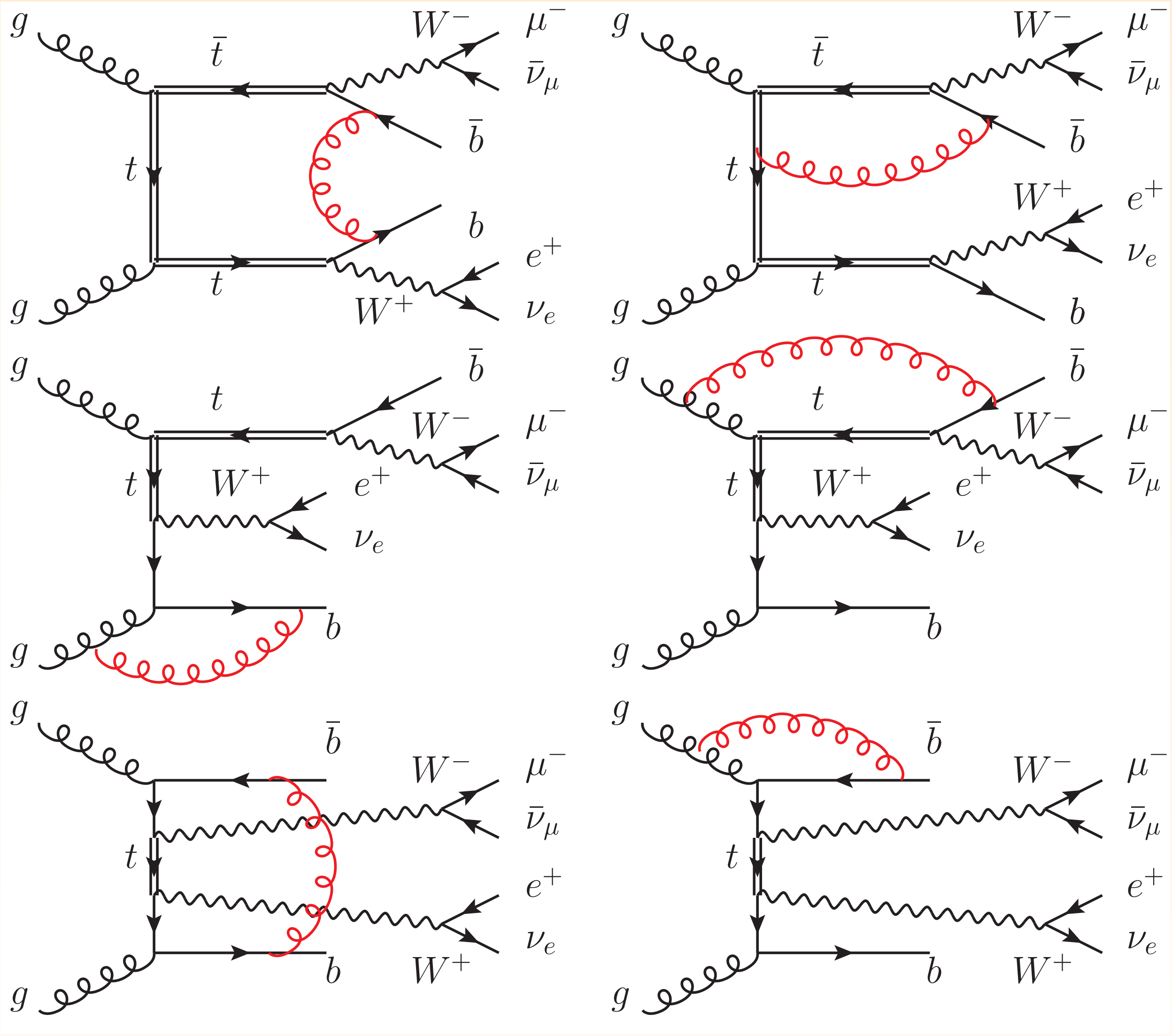
Not only Top Pairs...



- Gauge invariance guides us to include also single-resonant and non-resonant production
- There is interference between the diagrams above

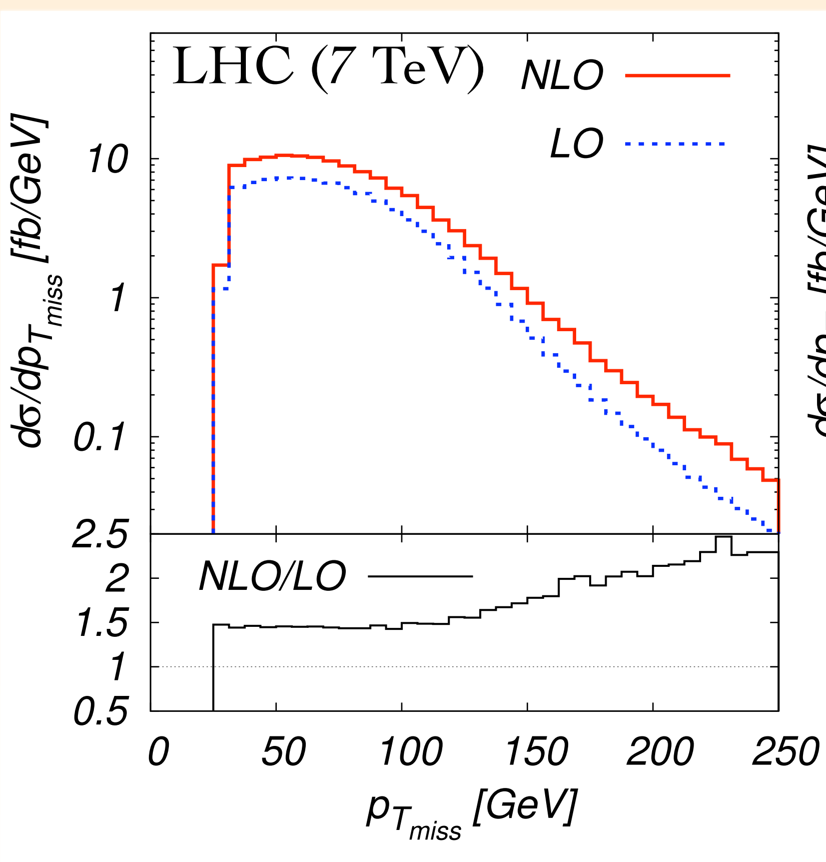
WWbb at NLO

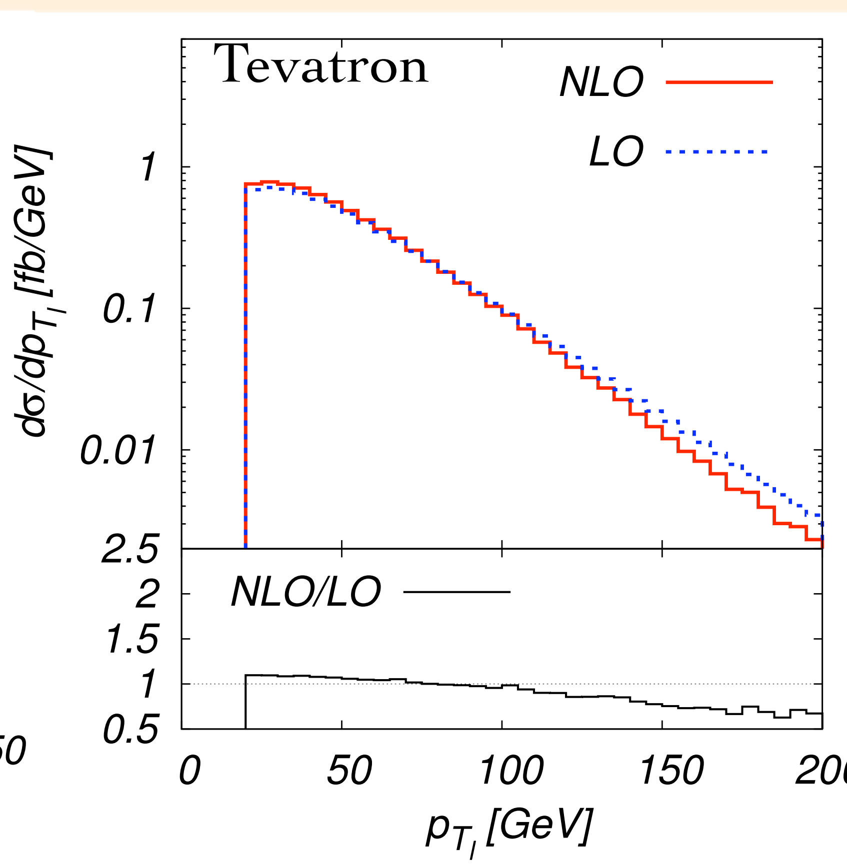
- Recently, the full NLO computations to the WWbb process were calculated by two independent groups
  Denner et al.; Bevilacqua et al.
- Consistent description of top pair production and irreducible backgrounds
- Particularly important when cuts require tops to be off-shell
- Matrix element-level calculation; matching to the parton shower not (yet) available

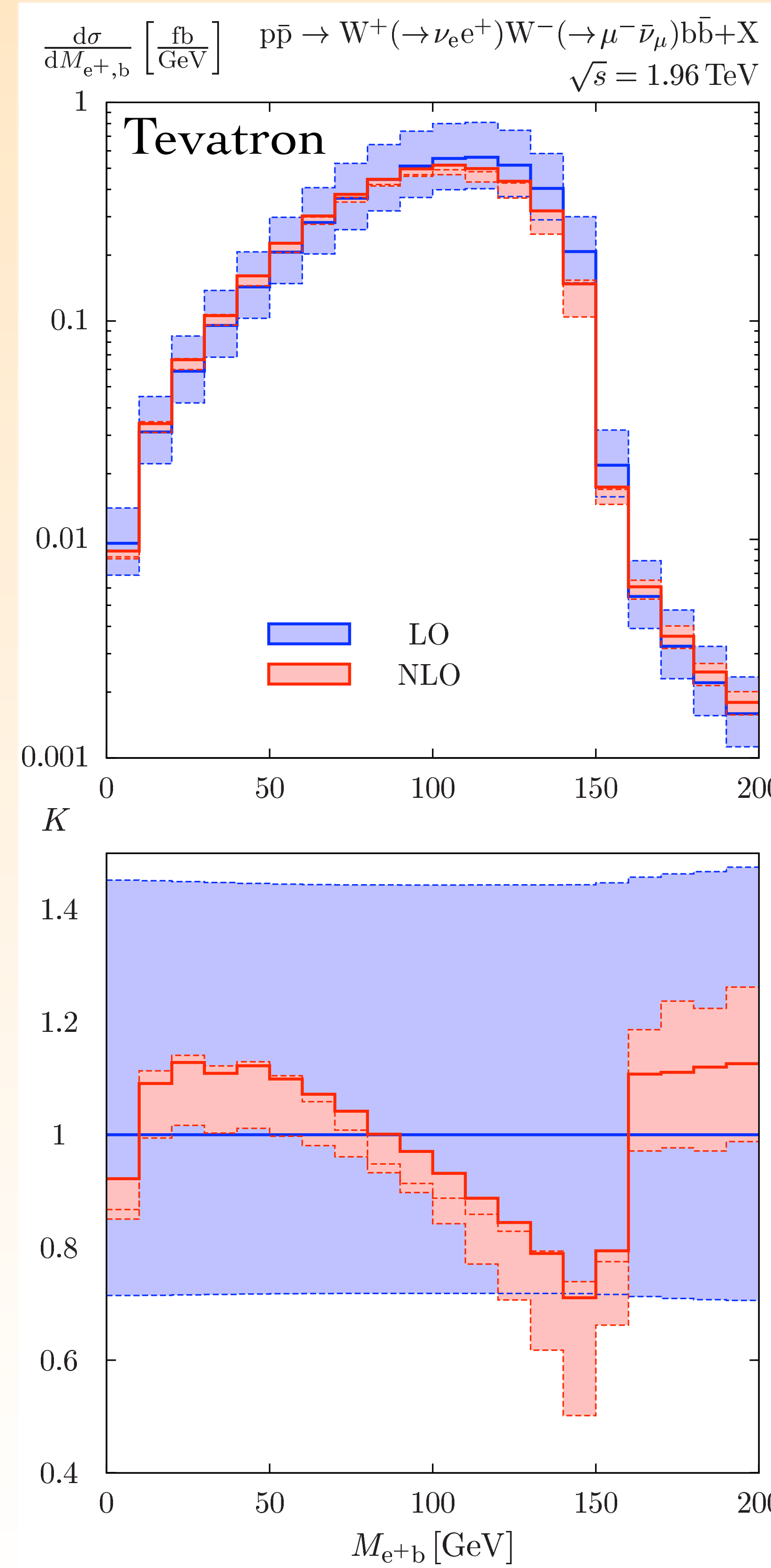


No constant 'K-factor'

- Corrections are small for most observables
- Compared the LO WWbb production, the NLO corrections are **not** an overall change in normalization

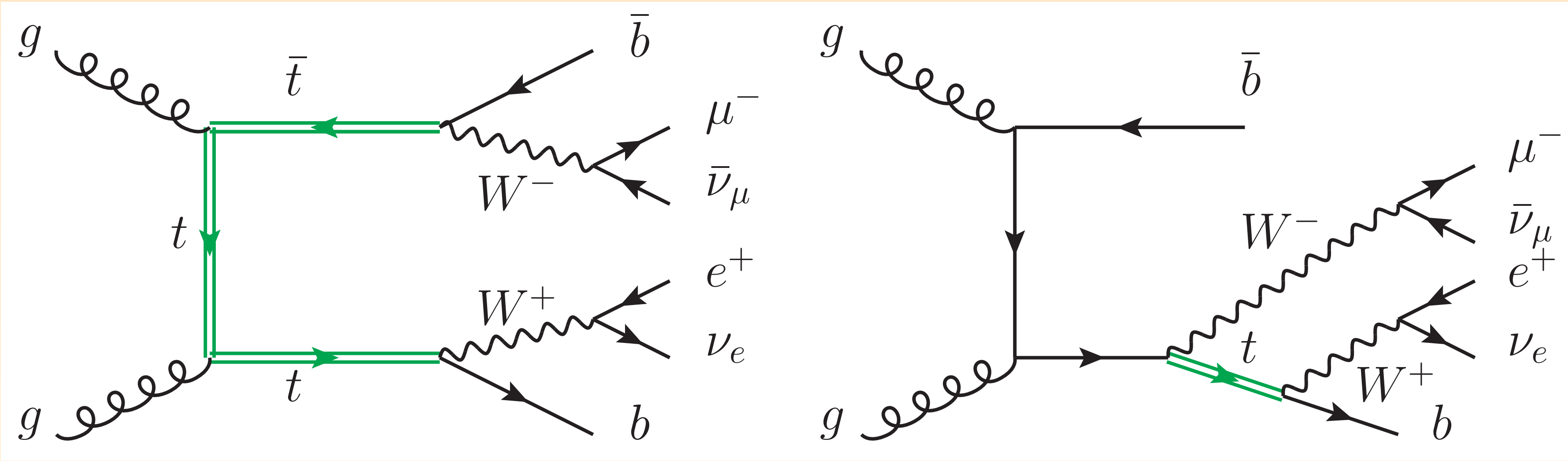






Denner et al.; Bevilacqua et al.

MASSLESS B-QUARKS

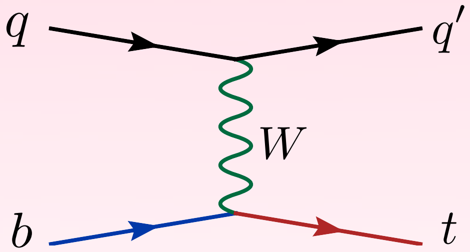
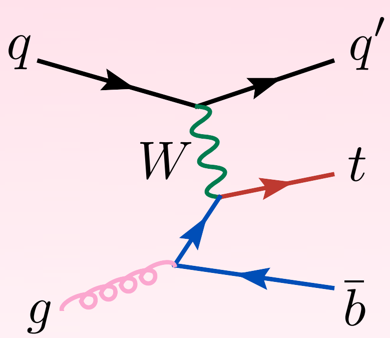
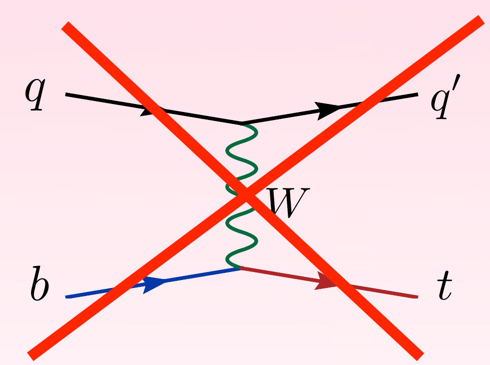
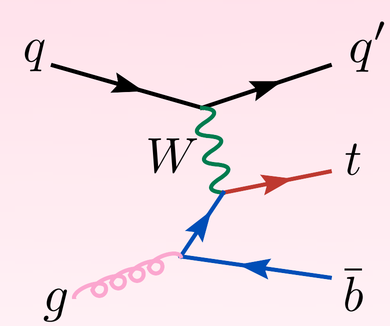


Top pair production

Looks like single top production (Wt-channel, 4-flavor scheme) but it isn't really...

- However, b quarks are considered to be massless: need to put cuts on them to make this process finite
  - This calculation cannot be used to predict the rate when one b-quark is too far forward/soft to be observed

4- & 5-flavor schemes

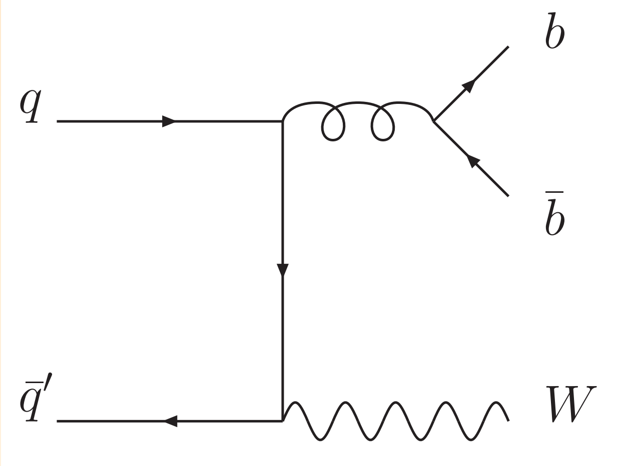
5 flavor scheme	4 flavor scheme
massless b	massive b
PDF includes initial state b quarks	No b quarks in PDF
Log[m_b/μ_F] resummed in PDF	Finite terms correctly included
Simpler calculation	More involved prediction
 leading order  (contribution to) NLO	 Does not exist  (part of) leading order
Descriptions are equivalent when including all orders in perturbation theory	

W-boson + b jets

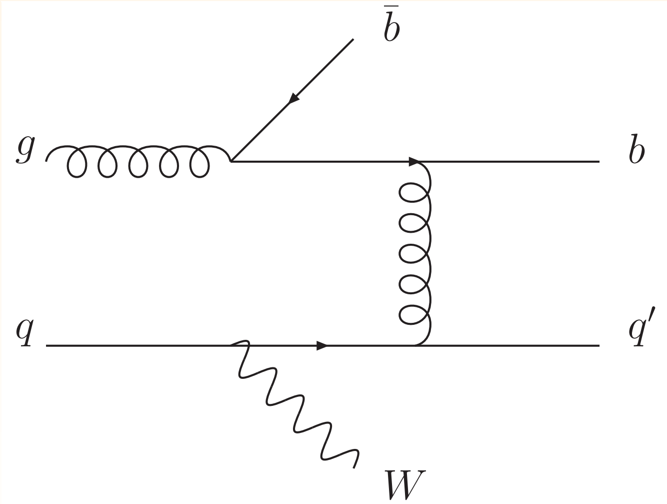
- For single top it is straight-forward to understand the two prescriptions
- It is more involved when trying to describe W-boson plus b-jets
- Each of the following need a separate description, e.g.
  - W+1 jets with 1 b tag (inclusive or exclusive)
  - W+2 jets with 1 b tag (inclusive or exclusive)
  - W+2 jets with 2 b tags (inclusive or exclusive)
  - W+bb-jet (inclusive or exclusive)
    [bb-jet is a jet containing two b-quarks]

4-FLAVOR SCHEME

1. W+1 jets with 1 b tag (inclusive or exclusive)
2. W+2 jets with 1 b tag (inclusive or exclusive)
3. W+2 jets with 2 b tags (inclusive or exclusive)
4. W+bb-jet (inclusive or exclusive)

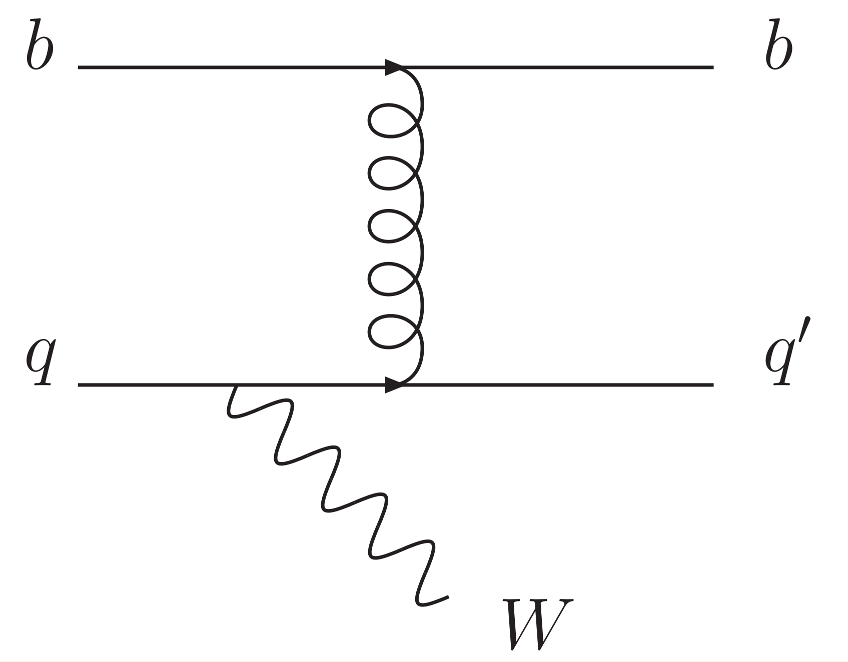


- All of them are described by this process in the 4-flavor scheme
  - finite process (IR singularities regularized by the bottom mass)
  - known at NLO (even matched to parton shower)
- "W+2jets with 1 b tag (inclusive)" is also (better?) described by:
  - Only known at LO, therefore already included in NLO description of the diagram above



5-flavor scheme

- When requiring 2 b tags or a bb-jet, the same diagrams as in the 4-flavor scheme are appropriate here as well (in principle with a massless b-quark)
- When requiring only 1 b tag, there is a better description with initial state b-quarks
  - Smaller uncertainties compared to 4-flavor scheme for observables that are not sensitive to very soft/forward b quarks
  - NLO study to combine the two approaches in one consistent description for W+1,2 jets with (at least) 1 b tag [*Caola et al. arXiv:1107.3714*]



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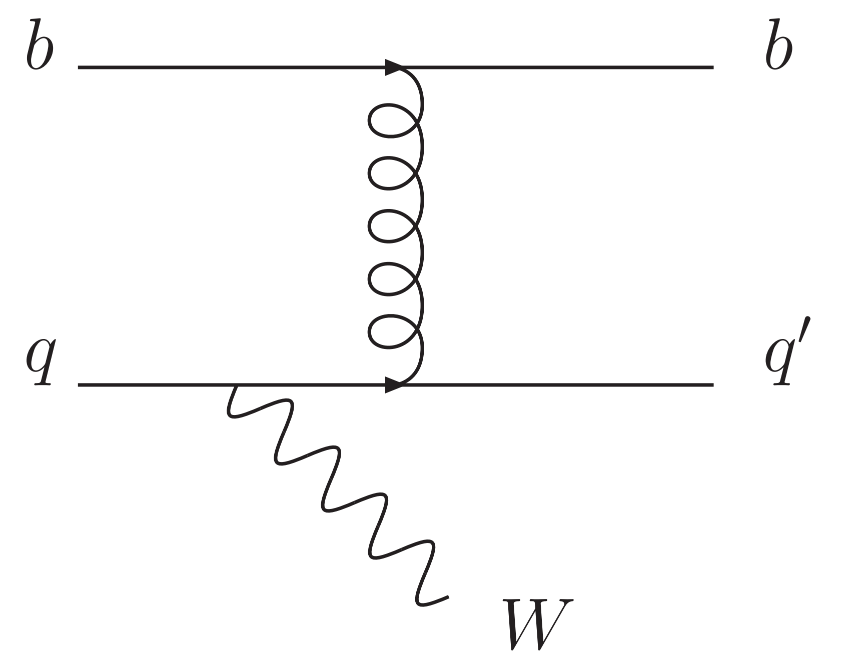

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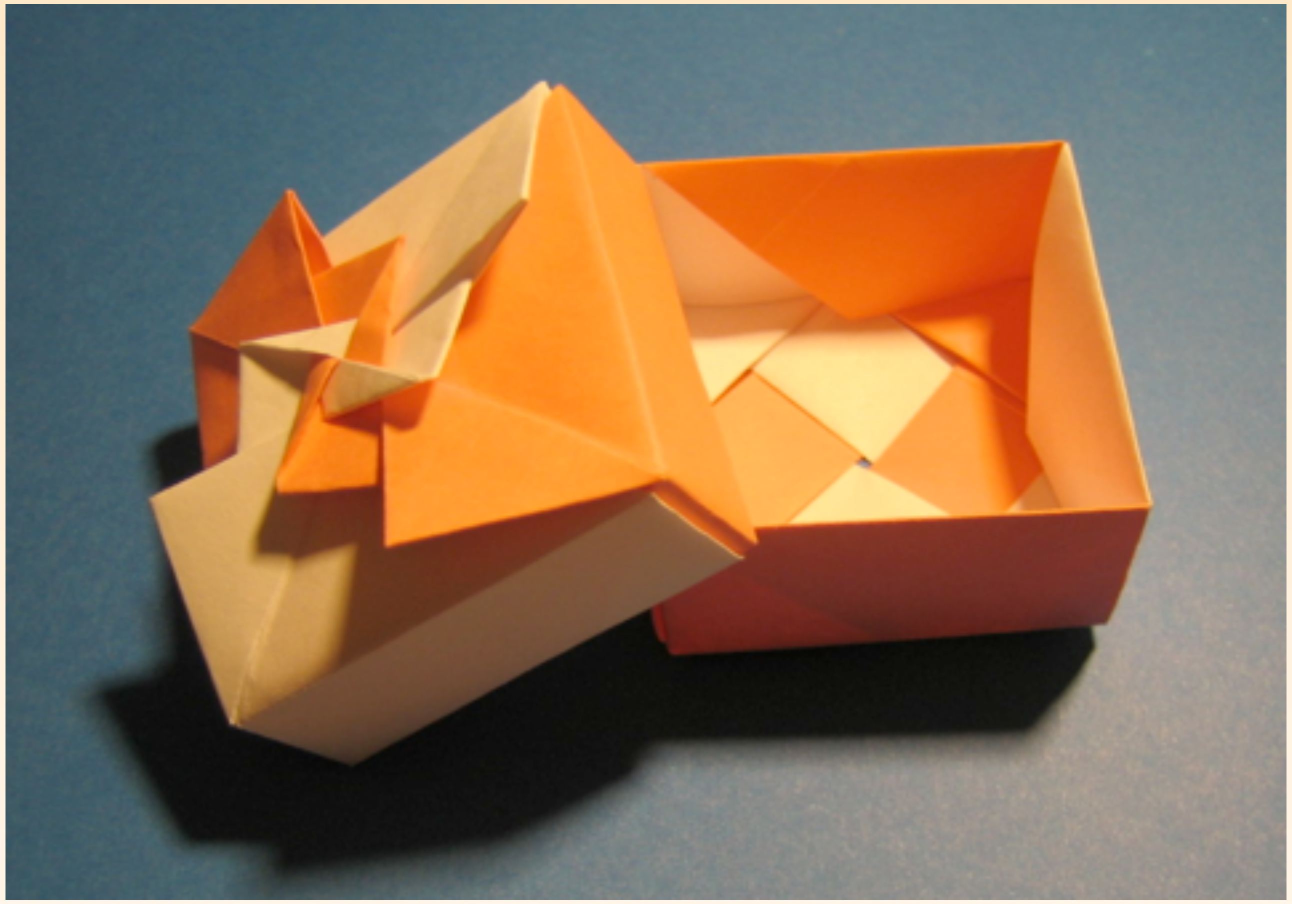
  - NLO study to combine the two approaches in one consistent description for W+1,2 jets with (at least) 1 b tag [*Caola et al. arXiv:1107.3714*]
- 4-flavor scheme calculation is simpler in the sense that "one fits all"
  - NLO matched to parton shower in POWHEG and aMC@NLO

POWHEG BOX



[*Nason, Oleari, Alioli, Re, ...*]

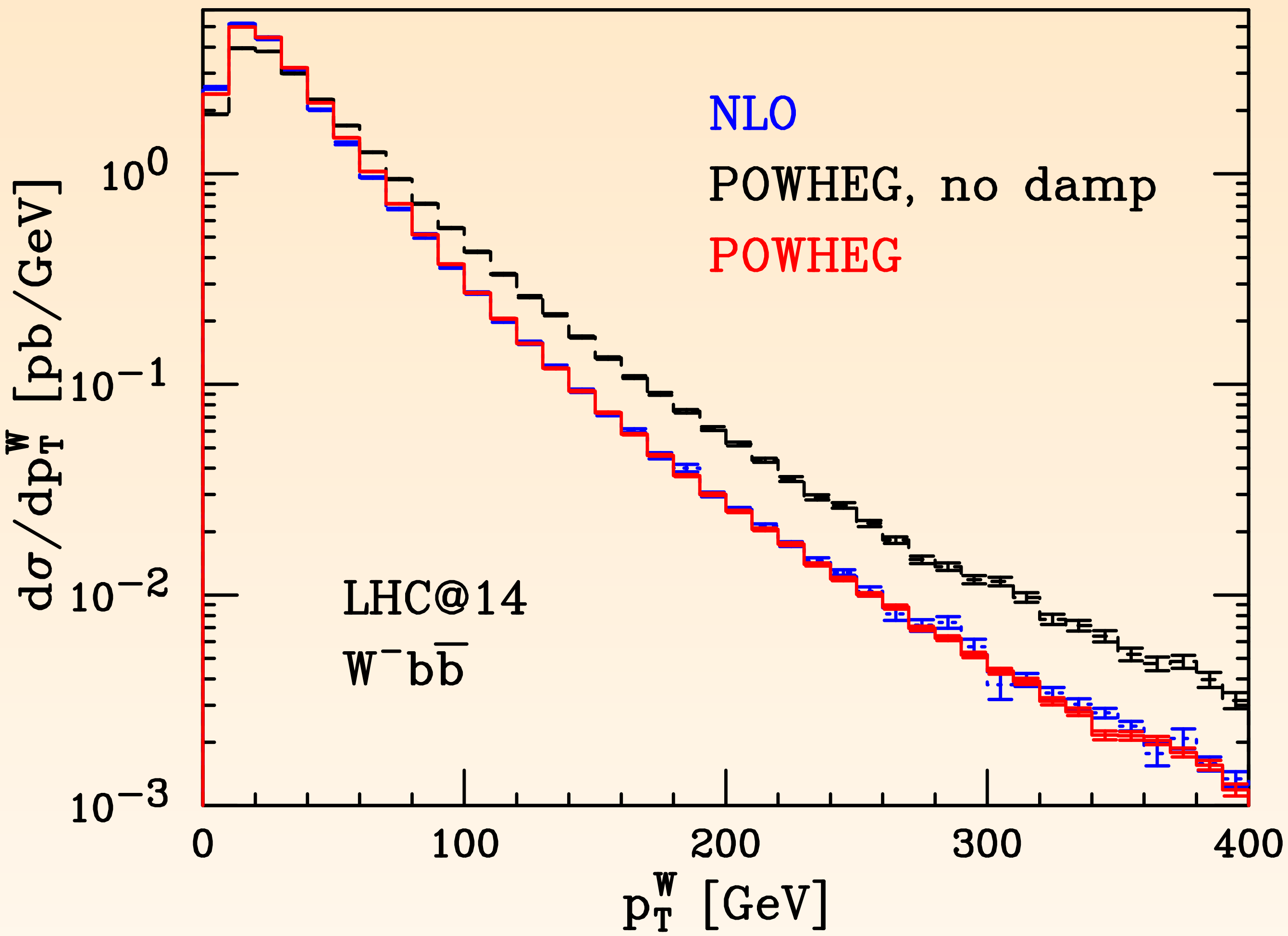
- Framework to convert any existing NLO computation to a matched NLOwPS prediction
- Can match to any (pT-ordered) parton shower
- Implementation of a new process requires some manual intervention
- Needs "perturbative tuning" for some processes
- Wbb process readily available [*Oleari & Reina, arXiv:1105.4488*]

PERTURBATIVE TUNING

- Using the default way of incorporating the Wbb in POWHEG leads to an enormous enhancement of the W-p_T distribution compared to fixed order computations

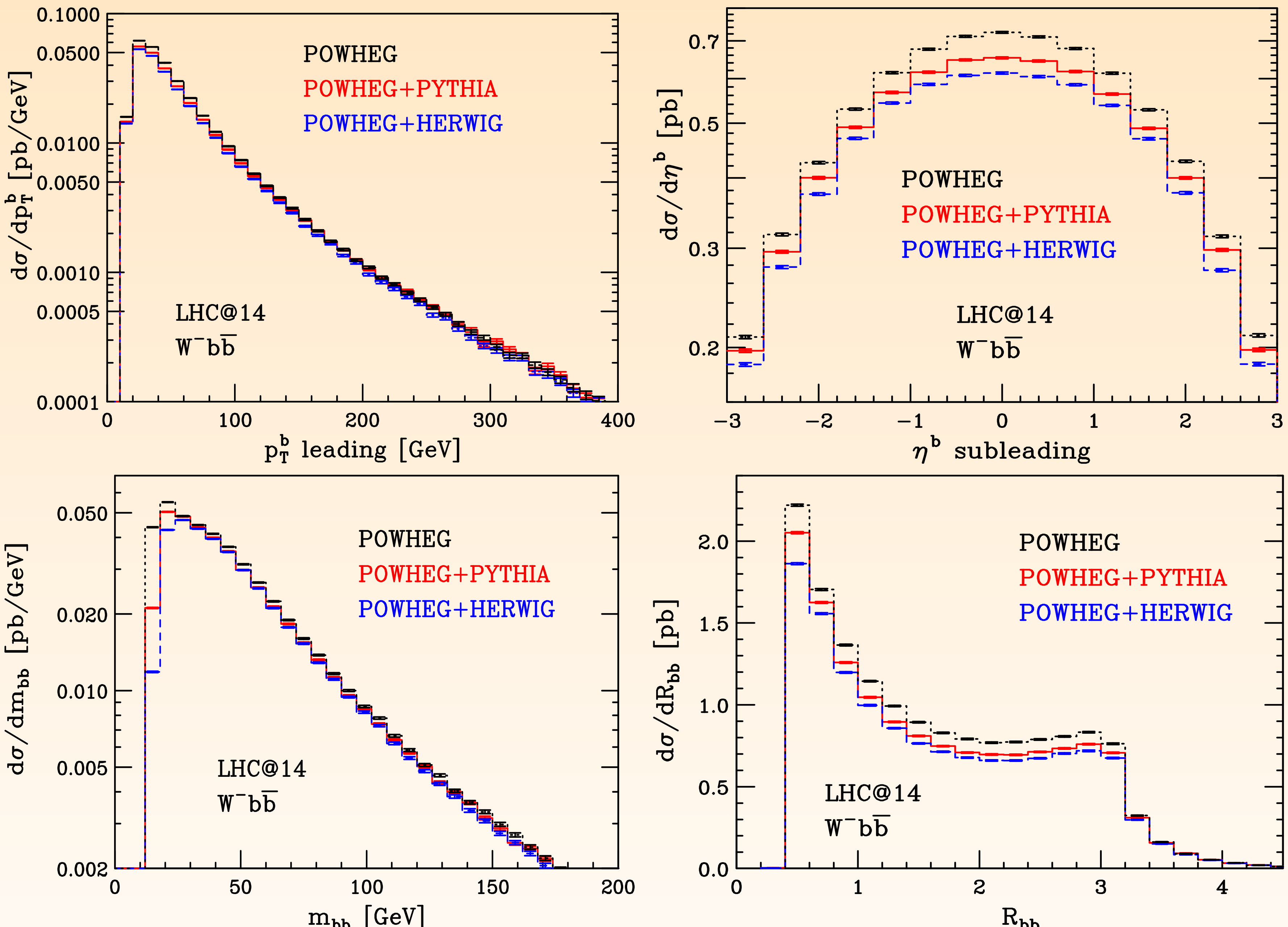
- Due to radiation from the bottom quarks that is exponentiated in the Sudakov factor

[*Oleari & Reina, arXiv:1105.4488*]



- Need to introduce a damping function that removes this radiation from the exponent
  - can be tuned to agree with fixed order NLO

Powheg results for Wbb



$$p_T^b > 15 \text{ GeV}, \quad |\eta^b| < 3, \quad p_T^j > 15 \text{ GeV}, \quad |y^j| < 3,$$

$$p_T^l > 15 \text{ GeV}, \quad |\eta^l| < 3, \quad \not{E}_T > 15 \text{ GeV}.$$

[*Oleari & Reina, arXiv:1105.4488*]

- With the tuning, corrections from the parton shower are small

aMC@NLO

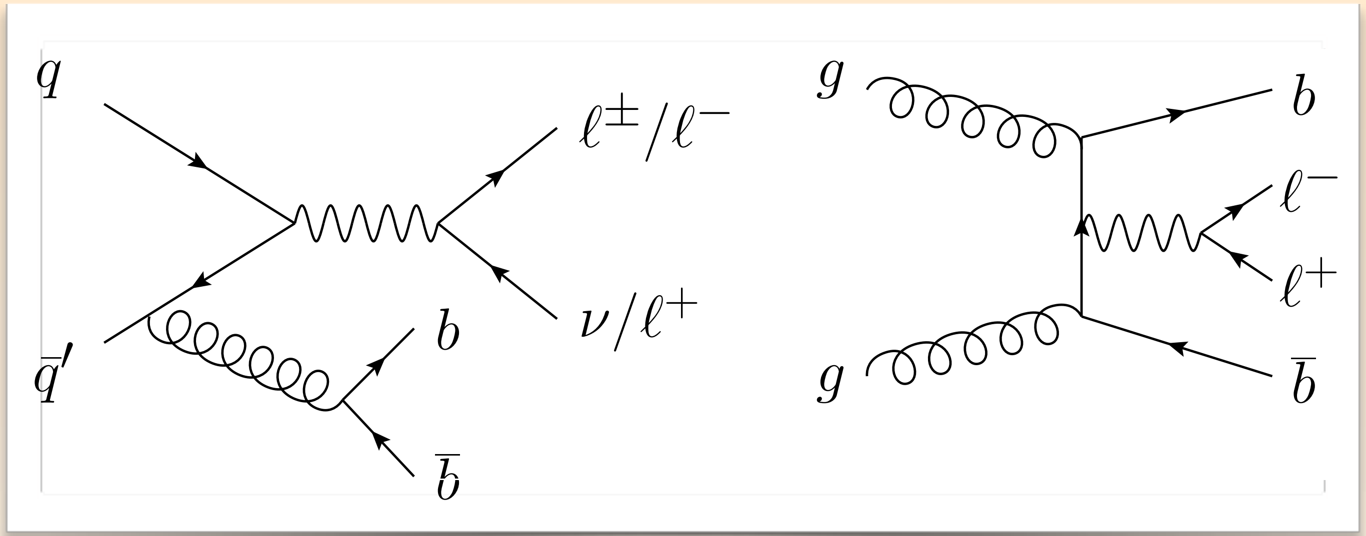
[RF, Frixione, Hirschi, Maltoni, Pittau & Torrielli]

- **Completely automatic tool to generate events at NLO accuracy** matched to a parton shower using the MC@NLO formalism
- Build on the MadGraph framework:
  "If you know how to run MadGraph, you know how to run `aMC@NLO` *as well"*
- Matching implemented for Herwig6, pythia6 and herwig++

- Website: http://amcatnlo.cern.ch
  - Validated NLO event samples for Wbb and Zbb available for download (to be showered with herwig6)
  - Single phase-space point check (for virtual) available later this week
- Will become publicly available soon

pp → Wbb/Zbb with aMC@NLO

- Background to top pair production and 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

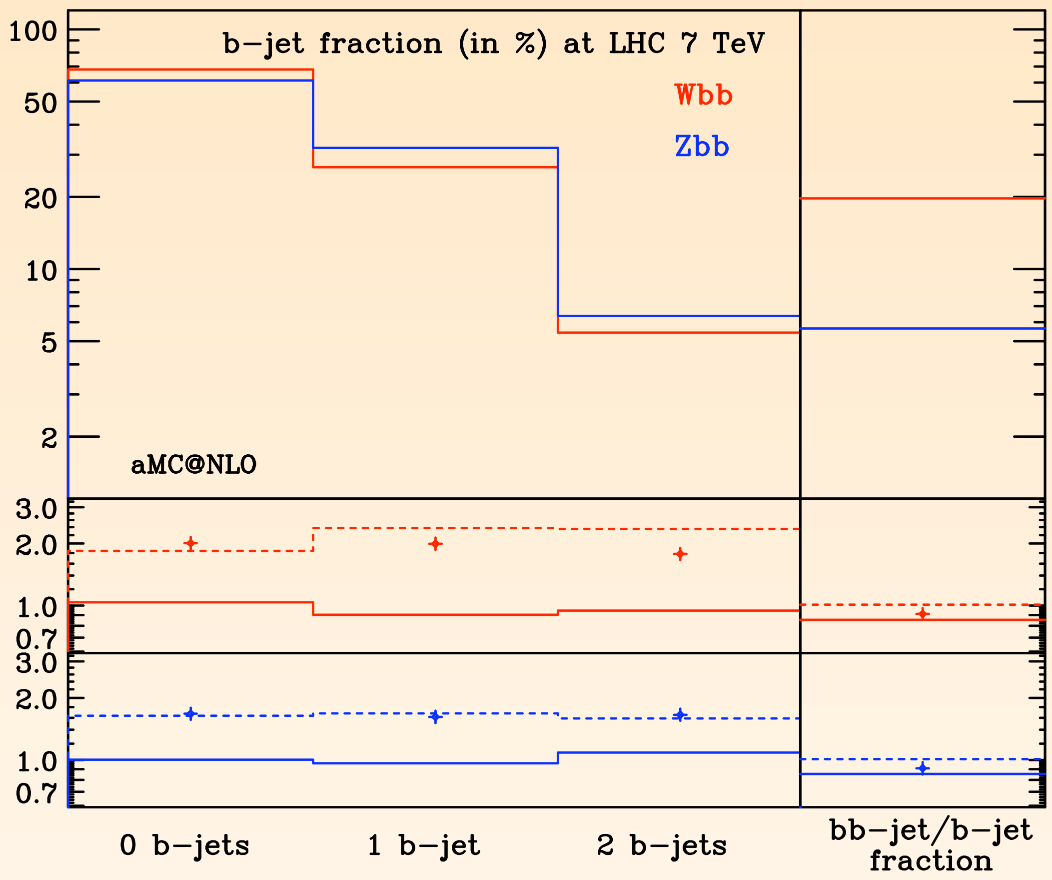
- Cross sections for Zbb and Wbb are similar at LHC 7 TeV

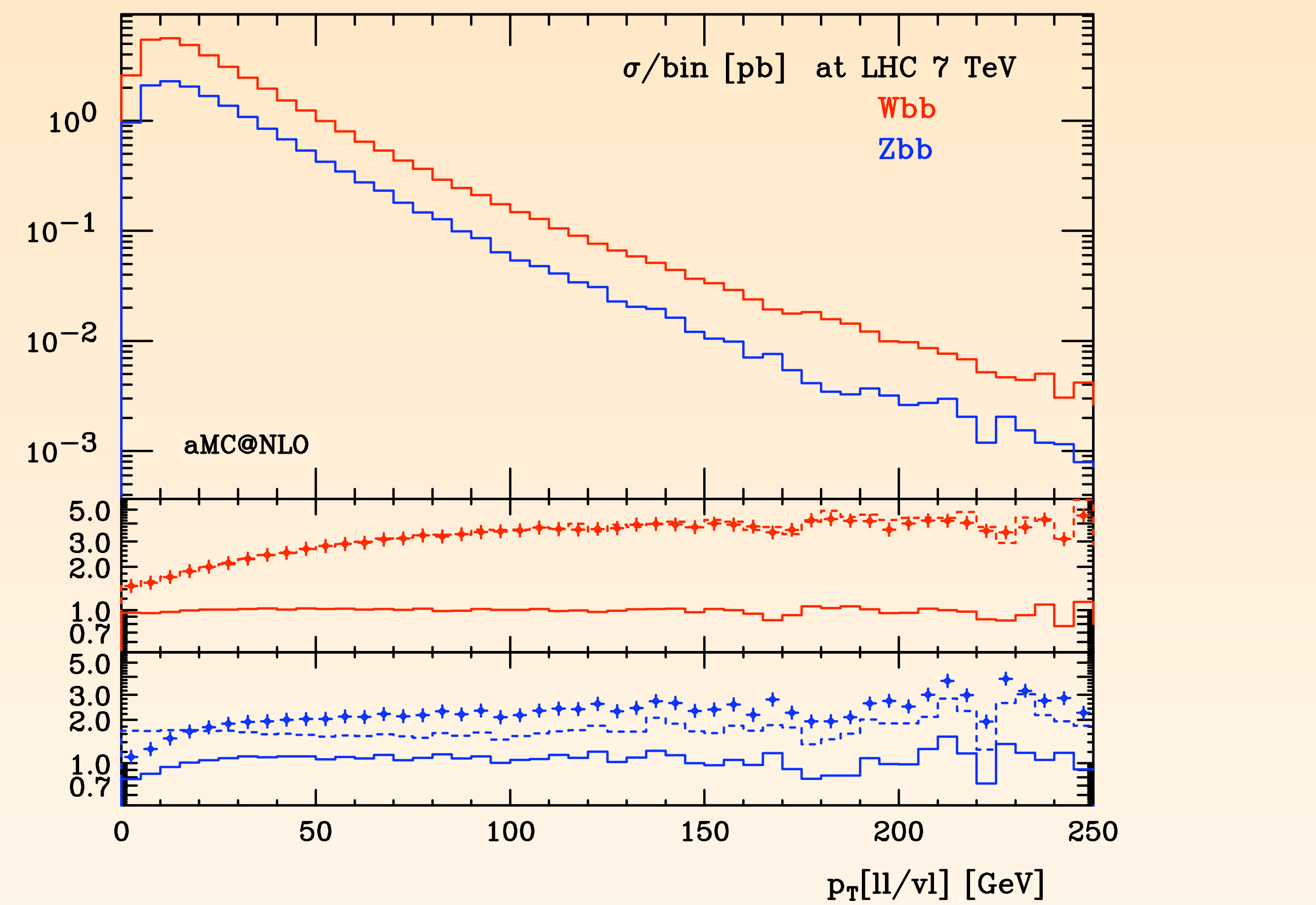
[*RF, Frixione, Hirschi, Maltoni, Pittau & Torrielli, arXiv:1106.6019*]

	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

pp → Wbb/Zbb

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



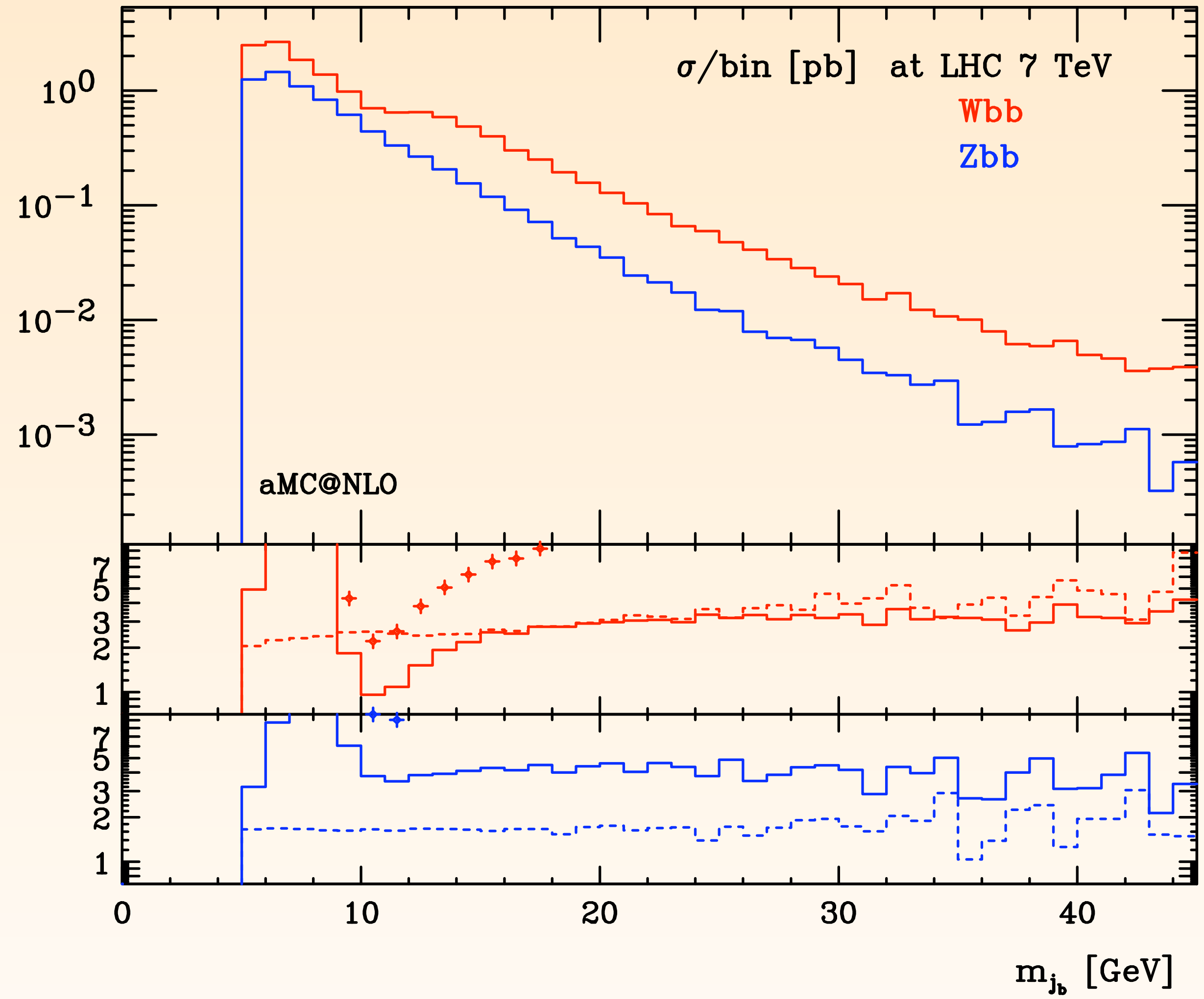


- In Wbb, ~20% of b-jets are bb-jets; for Zbb only ~6%
  - Jets defined with anti-k_T and R=0.5, with p_T(j)>20 GeV and |η|<2.5
- Lower panels show the ratio of aMC@NLO with LO (crosses), NLO (solid) and LOwPS (dotted)
- NLO and aMC@NLO very similar and consistent

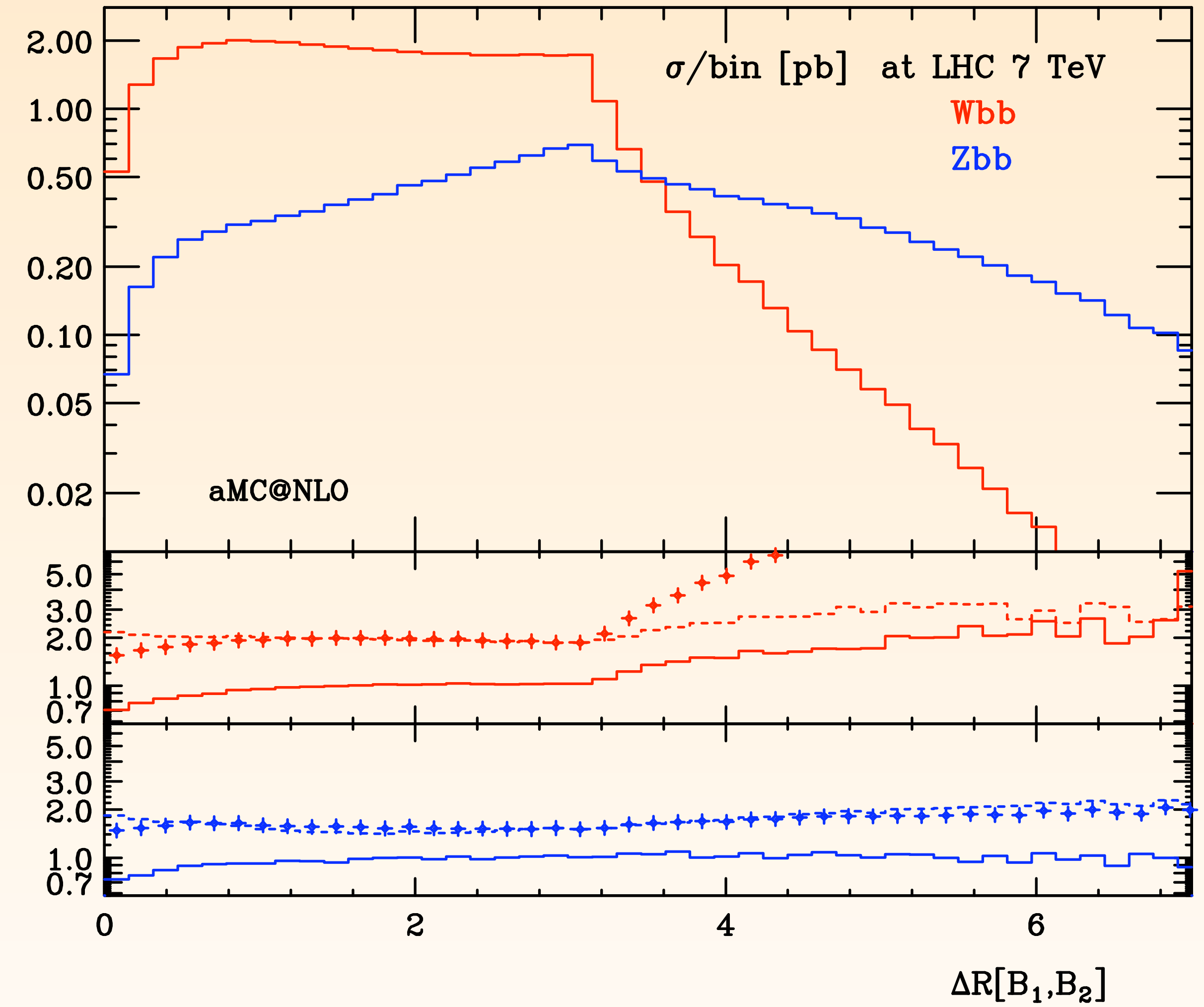
pp → Wbb/Zbb

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

b-jet mass



Distance between B-mesons (no cuts)



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

Conclusions

- NLO computation to WWbb can be used to describe (irreducible) background to top pair production consistently with signal, but not as a description of top pair, single top and non-resonant contributions as a background to another process (e.g. gg → H → W^+W^-)
  - Need this process with massive b quarks: consistent description of top pair and Wt-associated predictions
  - Need this process matched to the parton shower
- For W+jets+b-tags two descriptions exist (4 or 5 flavor schemes) that are equivalent when including all orders in perturbation theory
  - 4 flavor scheme description simpler for most observables; when requiring only 1 b tag, 5 flavor scheme has smaller uncertainty when inclusive to very soft/forward b-quarks
  - NLO Wbb has been matched to the parton shower using POWHEG and `aMC@NLO` (which has also Zbb)