

# Studies with aMC@NLO in ATLAS

S. Argyropoulos

DESY Hamburg

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# This talk

- what aMC@NLO **does**
- what aMC@NLO does **not** (yet)
- current status of the code
- ▶ (mainly) studies done in ATLAS

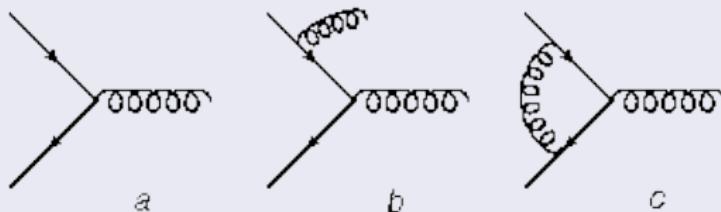
## aMC@NLO: **automatic** MC@NLO

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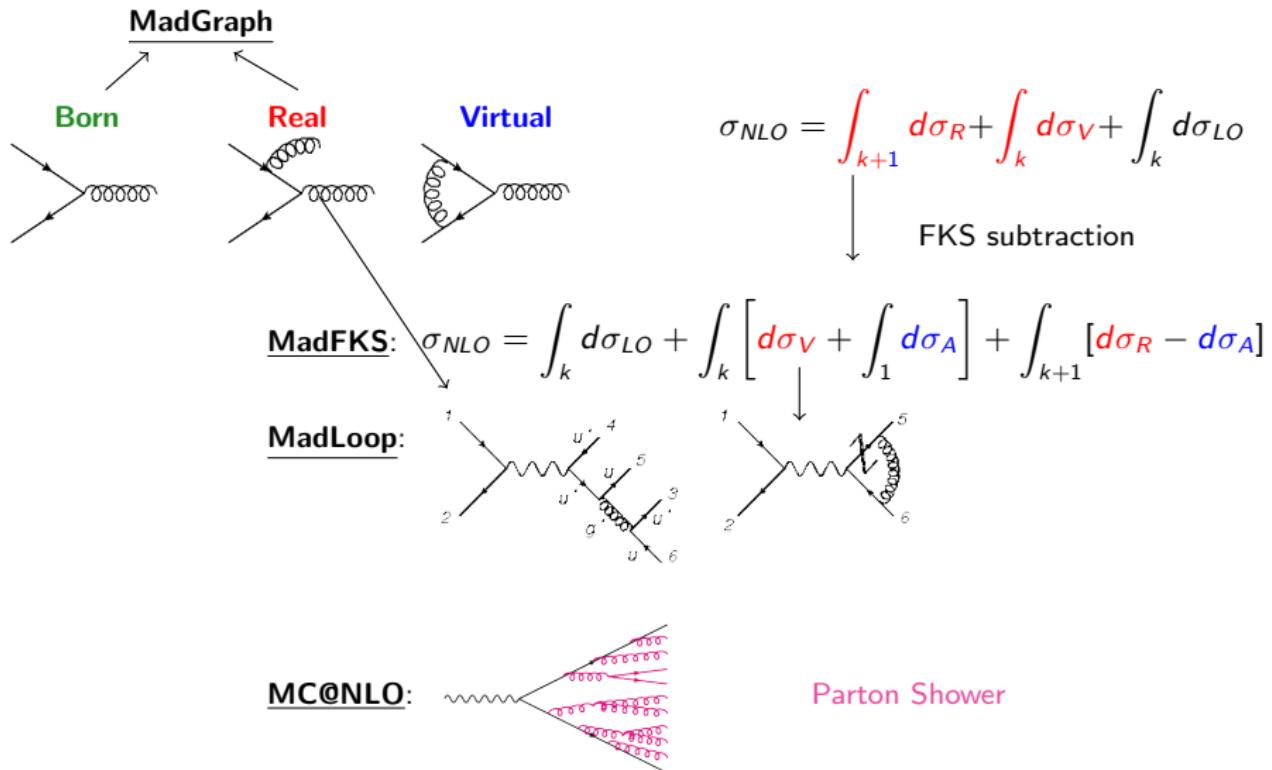
# NLO calculations

## NLO corrections



- NLO corrections to Born (a) amplitudes: Real (b) and Virtual (c)
- NLO needed to:
  - explain phenomena which are inaccessible to LO PT
  - predict absolute rates
  - reduce dependencies on unphysical scales
- **BUT** Real and Virtual corrections are divergent
  - $\int_k^\Lambda \frac{d^4 q}{q^4}$ , UV ( $\Lambda \rightarrow \infty$ ), IR ( $k \rightarrow 0$ ), collinear
- divergences should cancel or be absorbed in observables, which acquire a scale dependence

# The aMC@NLO framework



# aMC@NLO - what you get

- automatic generation of the color and helicity correlated Born amplitudes
- automation of the (FKS) subtraction procedure
- automatic determination of the subtraction terms for the parton-shower matching
- ✓ can *a priori* work for all SM processes
- ✓ can *a priori* be interfaced to any of the existing shower MC
- ✓ generate partonic final state including exact spin correlations, interference and off-shell effects with singly and doubly resonant diagrams
- ✓ automatic determination of scale and PDF uncertainties

# Scale and PDF uncertainties

A LO hard cross section can be written schematically:

$$d\sigma_{LO} = f_a(\mu_F) f_b(\mu_F) g_s^{2b}(\mu_R) |\tilde{\mathcal{M}}|^2 d\Phi$$

Reweight the cross section on an event-by-event basis by

$$R_i = \frac{f_a(x_{a,i}\mu'_F) f_b(x_{a,i}\mu'_F) g_s^{2b}(\mu'_R)}{f_a(x_{a,i}\mu_F) f_b(x_{a,i}\mu_F) g_s^{2b}(\mu_R)}$$

- separate the calculation of uncertainties from the calculation of the ME
- exact for ME, approximate for PS
- write a modified Les-Houches Event File containing the reweighting factors for each event
- ✓ automatic script to calculate the uncertainties

# aMC@NLO - Current status

- Status of showers
  - ✓ Herwig6, Pythia6Q
  - Pythia6pt, Pythia8, Herwig++
- Current limitations of MadLoop
  - no Born contributions containing 4-gluon vertices
  - no loops containing EW bosons
  - all Born contributions must factorize the same power of  $\alpha$  and  $\alpha_s$
  - no finite-width effects for particles appearing in loops
  - will all be solved with the interface to MadGraph5
- Processes studied by aMC@NLO team (<http://amcatnlo.cern.ch>)
  - $H/A t\bar{t}$
  - $W/Z/\gamma^* b\bar{b}$
  - 4 lepton
  - $Wj, Wjj$

# Outline

## 1 Introduction to aMC@NLO

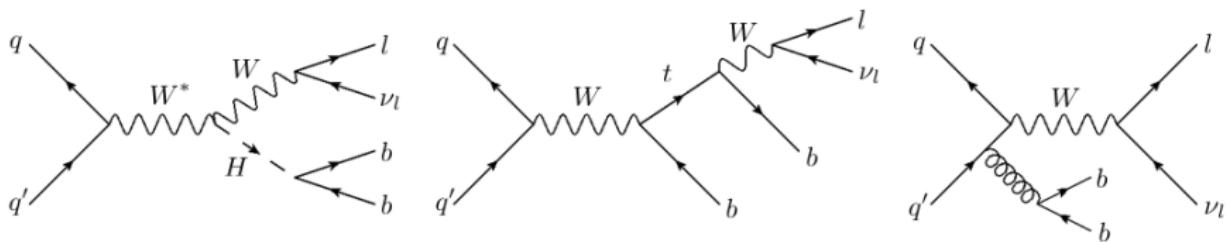
- A tiny bit of theory
- The aMC@NLO framework

## 2 Studies with aMC@NLO

- Motivation
- Consistency checks on  $Z/\gamma^* b\bar{b}$
- Generation of  $Wb\bar{b}$

# Why to study $Vb\bar{b}$ events

- Background for:
  - Single top/Top pair production
  - Higgsstrahlung
  - MSSM/2HDM:  $H/A b\bar{b} \rightarrow \tau^+ \tau^- b\bar{b}$  ( $Z b\bar{b}$ )
- Discrepancy with recent measurements
  - CDF (factor of 2.5-3.5)
  - ATLAS  $1.5\sigma$



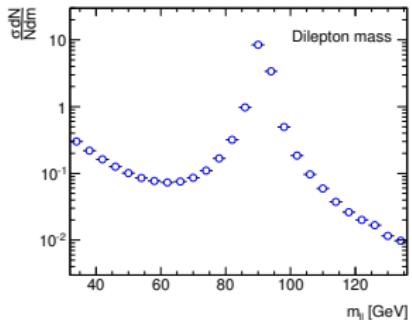
## Goal:

- check and benchmark **ATLAS software** against the aMC@NLO collaboration result [[arXiv:1106.6019v1](#)]
  - create a **standalone framework** for: reading LHEF, showering (Herwig6 C++ wrapper), jet clustering (FastJet) and writing ROOT output
- ✓ Good results for both cases

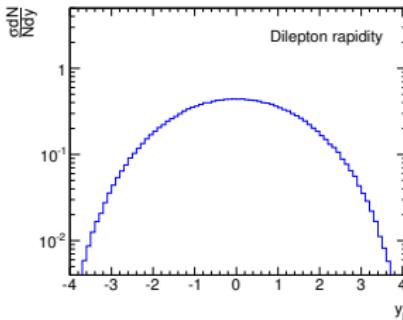
Analysis cuts:

- $m_{ll} > 30 \text{ GeV}$
- AntiKt5,  $p_T^j > 20 \text{ GeV}, |\eta_j| < 2.5$
- b jets defined by the presence of a b quark within  $\Delta R \leq 0.5$  from jet axis

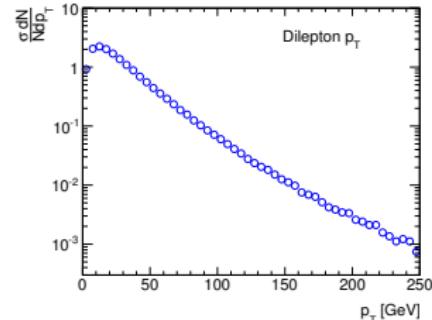
# Sample of results



Dilepton invariant mass

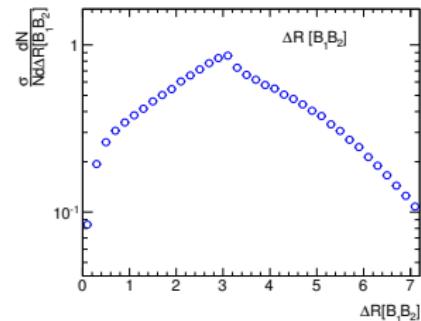
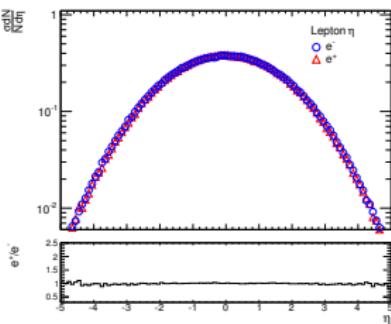
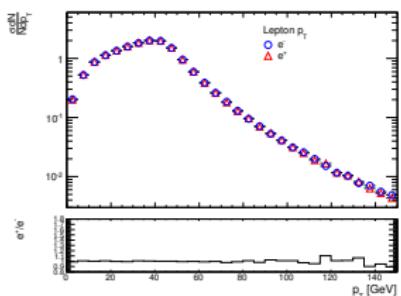


Dilepton rapidity



Dilepton  $p_T$

# Sample of results



# aMC@NLO production settings in ATLAS

- PDFset: CT10
- $m_t = 172.5$  GeV
- $m_b = 4.75$  GeV (values used in CT10)  
should be varied over  $4.5 \leq m_b[\text{GeV}] \leq 5$
- Other particle masses,  $V_{CKM}$  from PDG2010
- EW parameters  $\alpha, \sin \theta_W, G_F, m_W, m_Z$  are **correlated**
  - $G_F, m_W, m_Z$  set to PDG2010 values
  - $\alpha, \sin \theta_W$  calculated from tree-level EW relations

$$\begin{aligned}\sin^2 \theta_W &= 1 - \frac{m_W^2}{m_Z^2} \\ \alpha(m_Z) &= \frac{\sqrt{2} m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right) G_F}{\pi}\end{aligned}$$

# $Wb\bar{b}$ generation

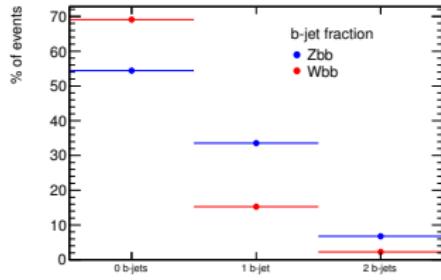
Parameter	1106.6019v1	MC11
$m_b$ [GeV]	4.5	4.75
PDF	MSTW2008NLO	CT10
Leptons	$e, \mu$	$e, \mu, \tau$
Jet algorithm	AntiKt5	AntiKt4
CKM	diagonal	PDG2010
$m_W$ [GeV]	80.419	80.399
$\alpha_{EW}^{-1}(m_Z)$	132.50698	132.348905
$G_F [10^{-5} \text{ GeV}^{-2}]$	1.16639	1.16637
$\Gamma_W$ [GeV]	2.0476	2.085
$\alpha_s^{MS}(m_Z)$	0.114904	0.118
Jet cuts	20 GeV	25 GeV
	$ \eta_j  < 2.5$	$ y_j  < 2.1$

$$\mu_R = \mu_F = \sqrt{m_{l\nu}^2 + p_T^2(l\nu) + \frac{m_b^2 + p_T^2(c)}{2} + \frac{m_b^2 + p_T^2(\bar{b})}{2}}$$

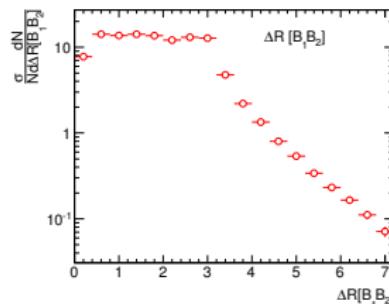
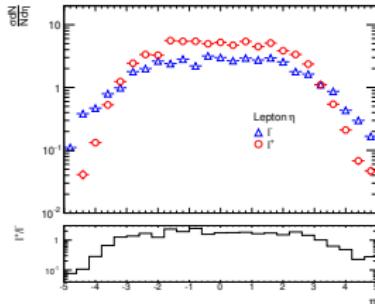
## Results:

- MC11:  $\sigma_{NLO} = (112.144 \pm 0.064)\text{pb}$ ,  $\sigma_{LO} = (46.098 \pm 0.007)\text{pb}$ ,  $K = 2.43$
- 1106.6019v1:  $\sigma_{NLO} = 38.9 \text{ pb}$ ,  $\sigma_{LO} = 19.4 \text{ pb}$ ,  $K = 2.01$

# Results

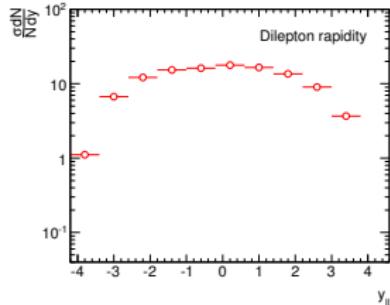
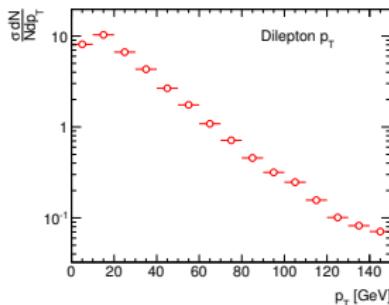
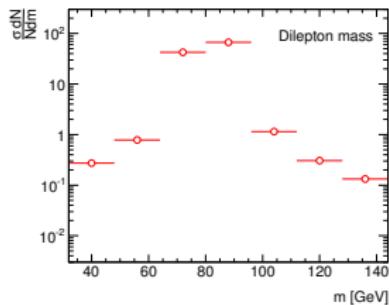


Fraction of b jets

b hardon  $\Delta R$ Lepton  $\eta$ 

- more b jets reconstructed in  $Zb\bar{b}$
- more bb jets in  $Wb\bar{b}$
- ▶ AntiKt5,  $p_T > 20$  GeV,  $|\eta| < 2.5$  in  $Zb\bar{b}$ , AntiKt4,  $p_T > 25$  GeV,  $|y| < 2.1$  in  $Wb\bar{b}$  in our calculation

# Results



# Conclusions and Prospects

- ✓ Standalone/ATLAS showers validated
- ✓ MadLoop optimized for batch computing
- ✓ Started using aMC@NLO in ATLAS
  - ➡ Set up the GRID interface
  - ➡ Awaiting for Pythia8 and HERWIG++ interfaces
  - ➡ Awaiting for MadGraph5

## Thanks

Many thanks to the GDR organization comitee for the invitation, the UniGe ATLAS group (where this work was carried out) and to Stefano Frixione, Rikkert Frederix and Valentin Hirschi for many fruitful discussions

# Backup Slides

## LO vs NLO

Consider observable  $\mathcal{O}$  evaluated at FO in PT:

$$\mathcal{O}\left(\frac{Q^2}{\mu^2} = 1, \alpha_s(Q^2)\right) = \mathcal{O}_1 \alpha_s + \mathcal{O}_2 \alpha_s^2 + \dots$$

Including the running coupling

$$\alpha_s(Q^2) = \alpha_s(\mu^2) - b_1 \ln \frac{Q^2}{\mu^2} \alpha_s^2(\mu^2) + \dots$$

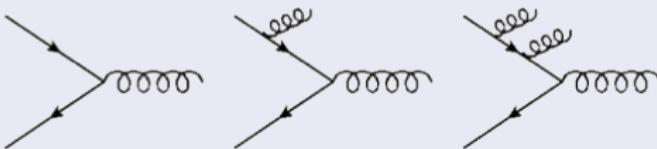
one has:

$$\mathcal{O}(\alpha_s(Q^2)) = \mathcal{O}_1 \alpha_s(\mu^2) + \left( \mathcal{O}_2 - \mathcal{O}_1 b_1 \ln \frac{Q^2}{\mu^2} \right) \alpha_s^2(\mu^2) + \dots$$

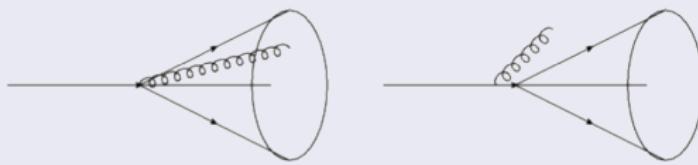
LO can give no control over the absolute normalizations

# Merging ME with PS

## Double Counting



## Matrix Element Corrections



- separate PS in 2 regions with jet measure
- use PS in soft region/ME in hard region
- MLM, CKKW, CKKW-L

## NLOPS

- first emission from ME (NLO)
- additional emissions from PS
- MC@NLO, POWHEG

# Monte Carlo principles

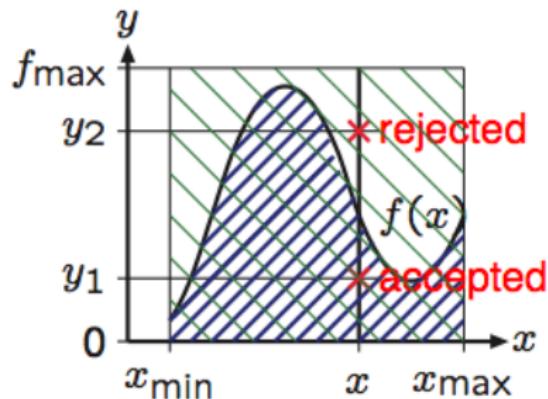
## Mean Value Theorem + Law of Large Numbers

$$\sigma = \int_0^1 dx \frac{d\sigma}{dx} = \left\langle \frac{d\sigma}{dx} \right\rangle \approx \frac{1}{N} \sum_{i=1}^N \frac{d\sigma}{dx} \Big|_i$$

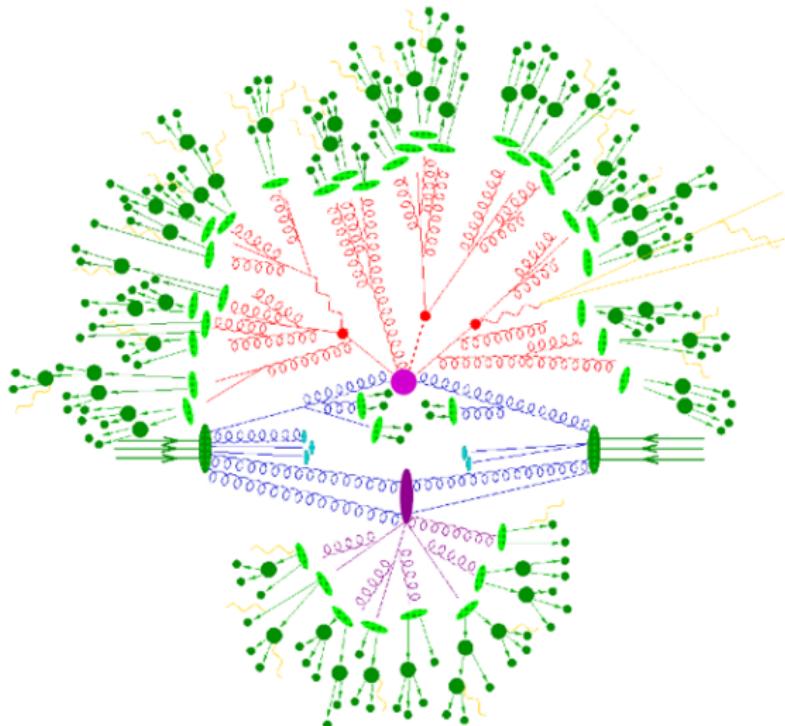
- $\frac{d\sigma}{dx} \Big|_i$ : event weight
- Hit-and-Miss technique:  

$$\int_{x_{\min}}^{x_{\max}} = f_{\max}(x_{\max} - x_{\min}) \frac{N_{hit}}{N_{try}}$$
- Unweighting: accept with probability:  

$$\frac{(d\sigma/dx)_i}{(d\sigma/dx)_{\max}}$$
  
 Efficiency:  $\frac{(d\sigma/dx)_{ave}}{(d\sigma/dx)_{\max}}$



# Event generators



- Hard Scattering (ME)
- Parton Shower
- Hadronization
- Decays
- Multiple Parton Interactions

## MC@NLO vs POWHEG

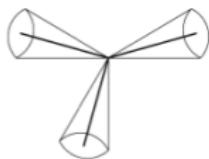
$$\begin{aligned}\langle \mathcal{O} \rangle_{NLOPS} &= \int d\Phi_n \bar{B}(\Phi_n) \left\{ \mathcal{O}(\Phi_n) \Delta_{t_0} + \int d\Phi_r \mathcal{O}(\Phi_n, \Phi_r) \Delta_t \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} \right\} \\ &+ \int d\Phi_{n+1} \mathcal{O}(\Phi_{n+1}) [R(\Phi_{n+1}) - R^s(\Phi_{n+1})]\end{aligned}$$

with

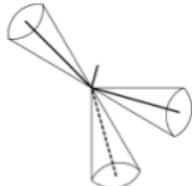
$$\Delta_t = \exp \left[ - \int d\Phi'_r \frac{R(\Phi_n, \Phi'_r)}{B(\Phi_n)} \theta(t' - t) \right]$$

- $\bar{B}(\Phi_n) d\Phi_n$ :  $\mathbb{S}$  event
- $R(\Phi_{n+1}) - R^s(\Phi_{n+1})$ :  $\mathbb{H}$  event
- $R(\Phi_{n+1}) - R^s(\Phi_{n+1})$  can be negative in MC@NLO
- in POWHEG:  $R^s(\Phi_{n+1}) = R(\Phi_{n+1})F(\Phi_{n+1})$  with  $0 \leq F(\Phi_{n+1}) \leq 1$  and  $F(\Phi_{n+1}) \rightarrow 1$  in the soft and collinear limit. Thus  $R(\Phi_{n+1}) - R^s(\Phi_{n+1}) = R(\Phi_{n+1})[1 - F(\Phi_{n+1})] \geq 0$
- Differences can arise at NNLO

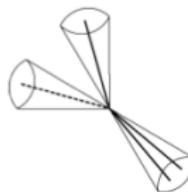
# The MLM matching scheme



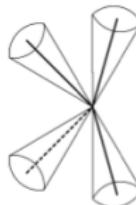
- 3 jets with ME partons
- Matched



- 2 jets with ME partons
- 1 jet from parton shower
- Not matched

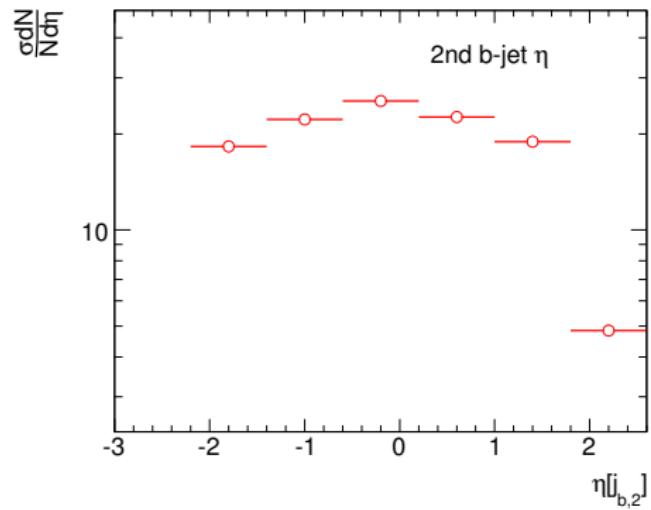
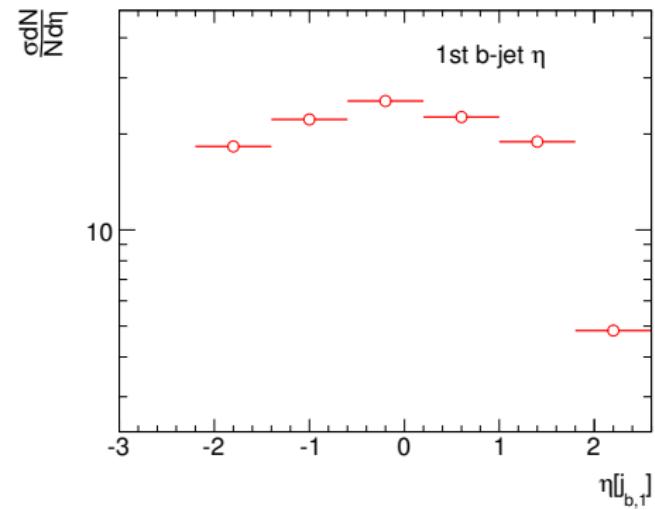


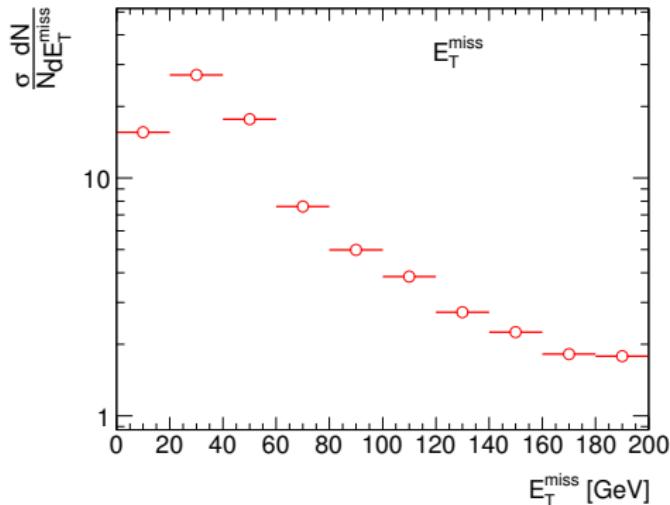
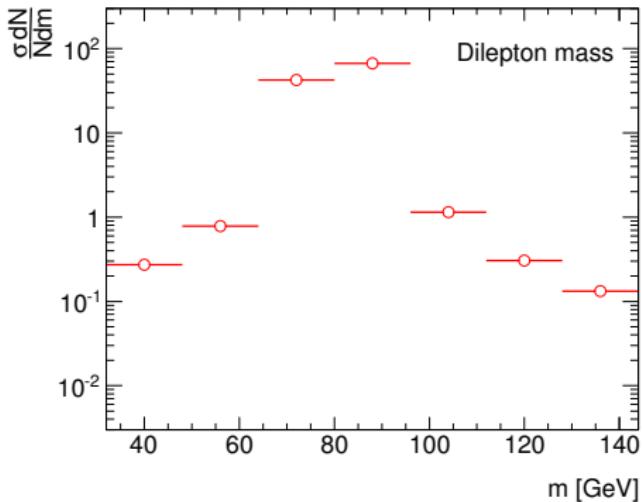
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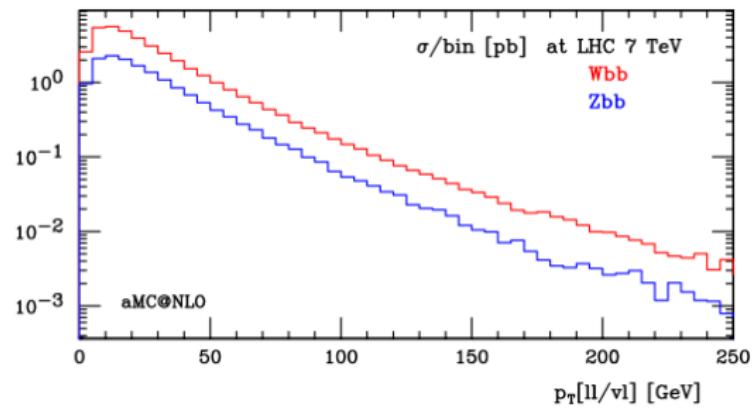
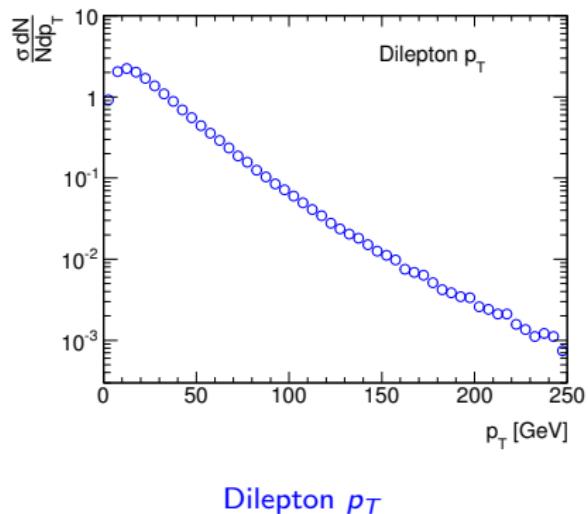


- 3 jets with ME partons
- 1 jet from parton shower
- Not matched

- $p_T^{parton} > p_T^{\min} \leq E_{T,jet}^{\min}$
- $\Delta R_{part-part} > \Delta R_{cut} \leq \Delta R_{jet}$
- converge for:  
 $p_T^{\min} \rightarrow 0, \Delta R_{cut} \rightarrow 0$

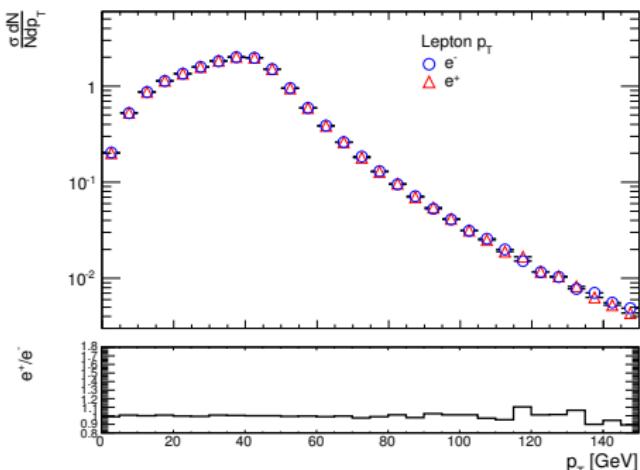
Results from  $Wb\bar{b}$ 

Results from  $Wb\bar{b}$ 

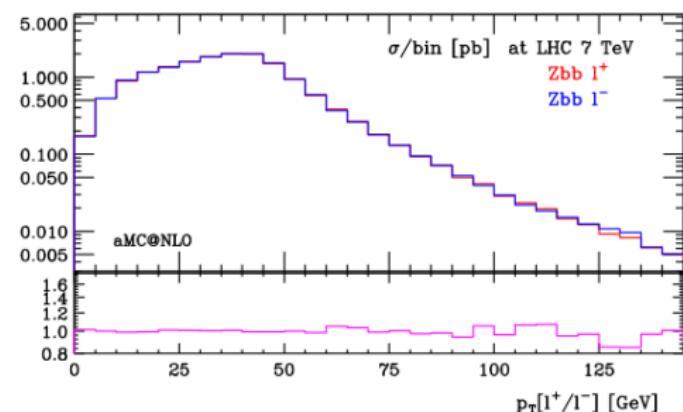
Results for  $Z/\gamma^* b\bar{b}$ 

1106.6019v1

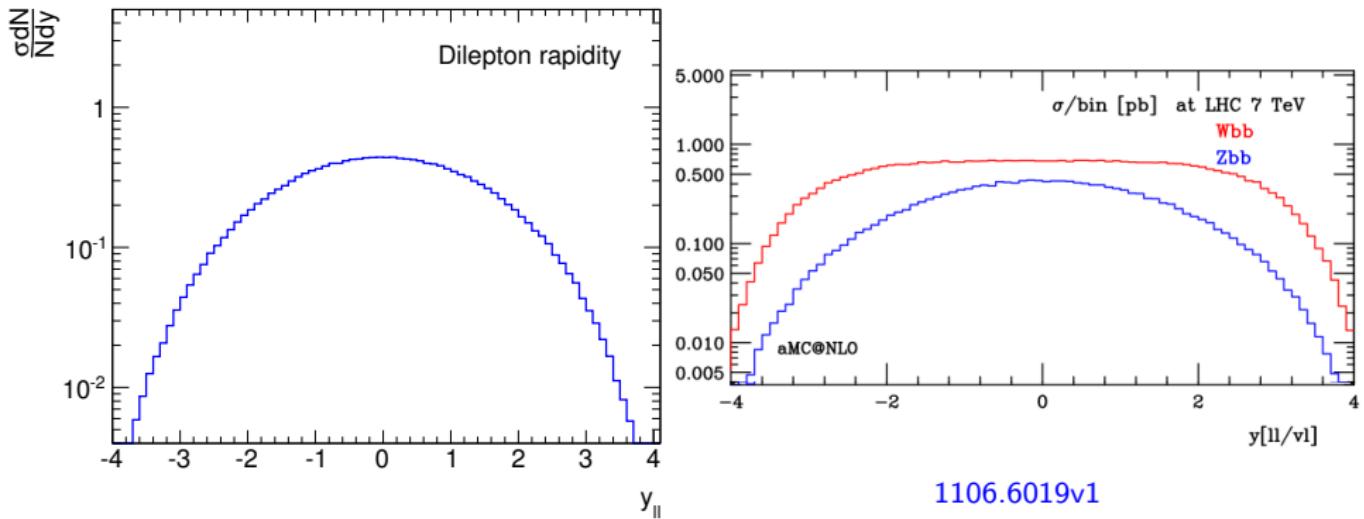
# Results for $Z/\gamma^* b\bar{b}$



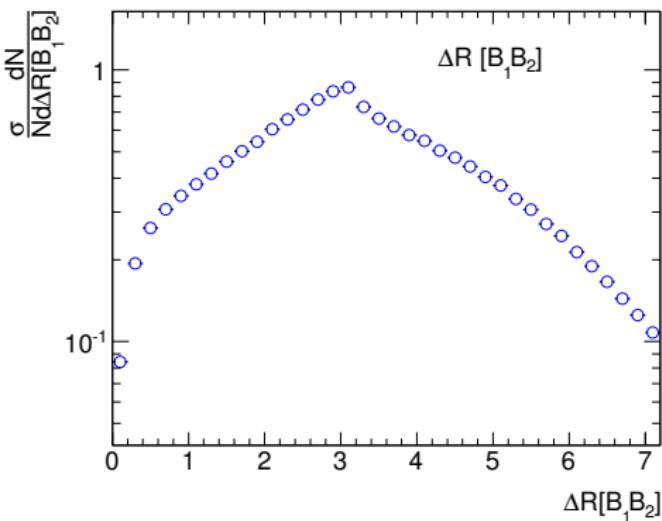
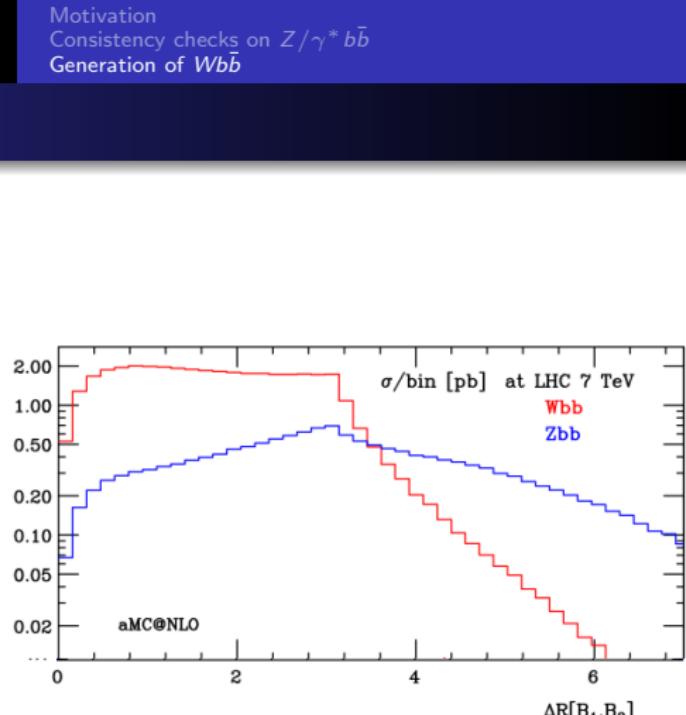
Our result



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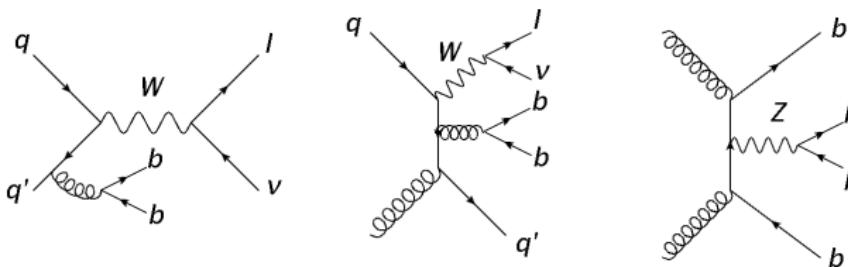
Results for  $Z/\gamma^* b\bar{b}$ 

Our result

Results from  $Z/\gamma^* b\bar{b}$ Our result  $Z/\gamma^* b\bar{b}$ 

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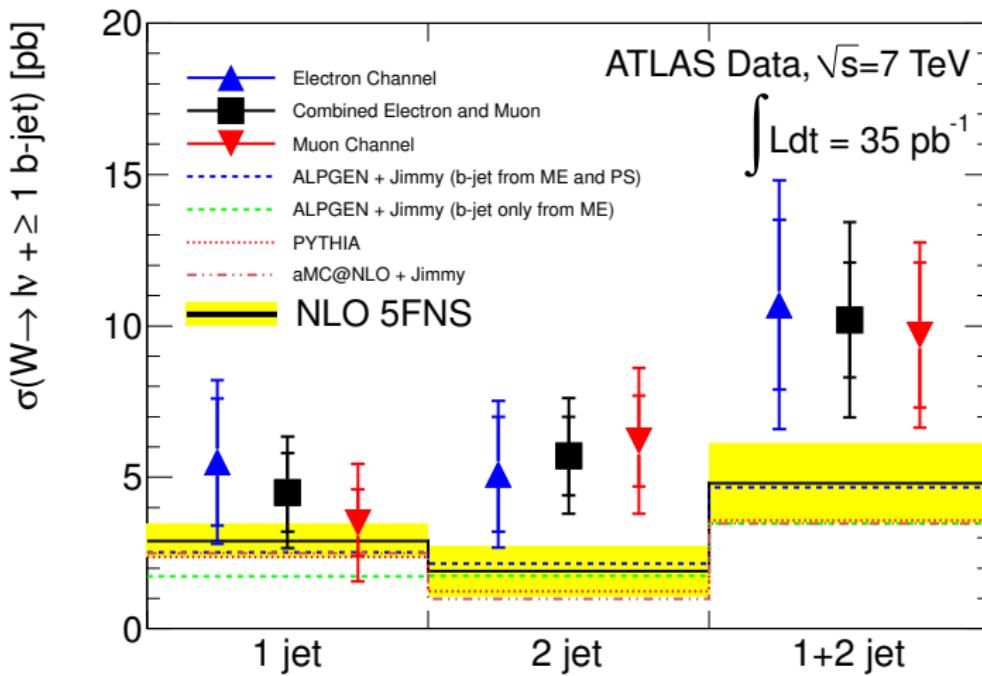
# Why $Wb\bar{b}$ differs from $Zb\bar{b}$



Differences between  $Zb\bar{b}$  and  $Wb\bar{b}$  can be explained if we consider

- different production mechanisms, new channels opening at NLO
- initial state  $\Rightarrow$  surplus of positive charge
- different parton luminosities for the 2 processes

## Comparison with ATLAS data - an exercise



- Normalization:  $\sigma_{1+2} = 68.9263 \text{ pb}$ ,  $\sigma_1 = 43.2172 \text{ pb}$