

# CERN Theory Institute

*Perturbative higher-order effects at work at the LHC*

## Top Quark Physics with D-Dimensional Generalized Unitarity

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in collaboration with K. Melnikov



JOHNS HOPKINS  
UNIVERSITY

# Outline

- i.) NLO QCD corrections to  $t\bar{t}$  production and decay
- ii.) Top mass measurements at NLO QCD + [S. Biswas]
- iii.) NLO QCD corrections to  $t\bar{t} + \text{jet}$  production
  - [ JHEP 0908:049,2009 ],
  - [ arXiv: 1006.0910 [hep-ph] ],
  - [ arXiv: 1004.3284 [hep-ph] ]

# Is this really new?

## No and Yes.

Literature on hadronic top production beyond leading-order is rich:

- **stable top quarks:**

**Classic NLO QCD corrections:**

Beenakker, Dawson, Ellis, Frixione, Meng, Nason, v. Neerven, Schuler, Smith; Czakon, Mitov

**Threshold resummation & Coulomb corrections:**

Banfi, Bonciani, Catani, Czakon, Frixione, Kidonakis, Kiyo, Kühn, Laenen, Mangano, Mitov, Moch, Nason, Ridolfi, Steinhouse, Sterman, Uwer, Vogt

**Electroweak corrections:**

Beenakker, Bernreuther, Fuecker, Denner, Hollik, Kao, Kollar, Kühn, Ladinsky, Mertig, Moretti, Nolten, Ross, Sack, Scharf, Si, Uwer, Wackerlo, Yuan

**NNLO QCD contributions:**

Anastasiou, Aybat, Bonciani, Czakon, Ferroglia, Gehrmann, Körner, Langenfeld, Maitre, Merebashvili, Mitov, Moch, Rogal, Studerus, Uwer

- **decays of top quarks:**

**Study of non-factorizable corrections:**

Beenakker, Berends, Chapovsky, Fadin, Khoze, Martin, Melnikov, Yakovlev

**Factorizable correction to top decays:**

Czarnecki, Jezabek, Kühn; Bernreuther, Brandenburg, Si, Uwer

**Spin correlations:**

Mahlon, Parke; Bernreuther, Brandenburg, Si, Uwer

- **event generators:**

**MC@NLO:** Frixione, Webber; Laenen, Motylinski, Nason, White

**POWHEG:** Frixione, Nason, Oleari, Ridolfi

# Is this really new? No and Yes.

Only very recently:

NLO QCD corrections to  
top quark pair production and decay at hadron colliders

Bernreuther, S. (2010); Melnikov, S. (2009)

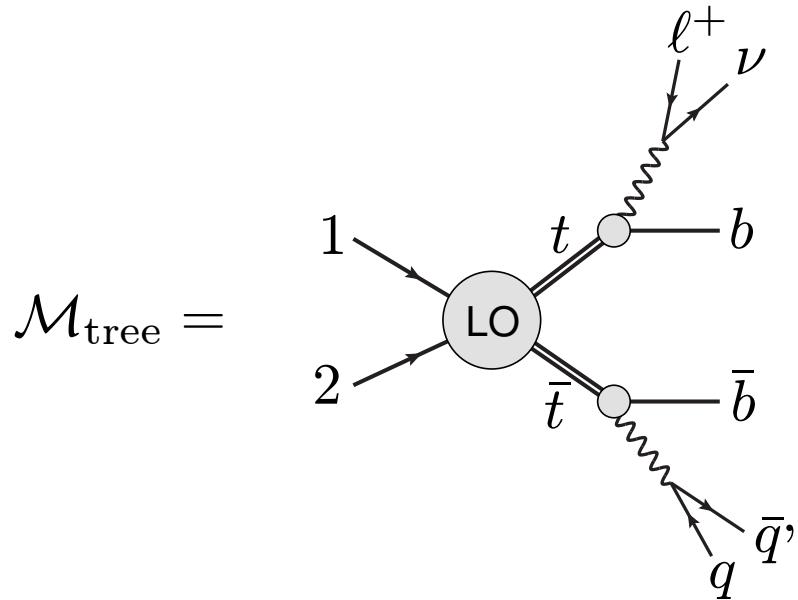
Top quark decays: leptonic or hadronic decays at NLO  
Narrow Width Approximation  $\Gamma_t/m_t \rightarrow 0$   
neglect non-factorizable corrections

Allows for:

- realistic description of the final state
- implementation of arbitrary detector cuts
- accounting for all spin correlations

# Our implementation

leading order:



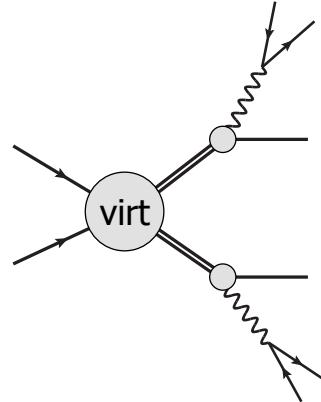
We calculate  
helicity amplitudes.

- Generate phase space of top quarks
- Generate phase space of decay particles
- $\bar{u}(p_t) \rightarrow \tilde{u}(p_t) = \mathcal{M}(t \rightarrow b\ell^+\nu) \frac{i(p_t + m_t)}{\sqrt{2m_t\Gamma_t}}$
- $\mathcal{M}_{\text{tree}} = \tilde{u}(p_t) \tilde{\mathcal{M}}(12 \rightarrow \bar{t}t) \tilde{v}(p_{\bar{t}}) + \mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)$

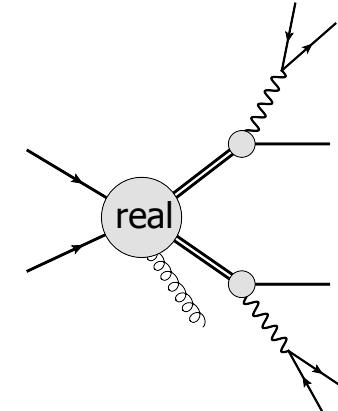
# Our implementation

Next-to-leading order:

Production



D-dimensional generalized unitarity  
+ OPP

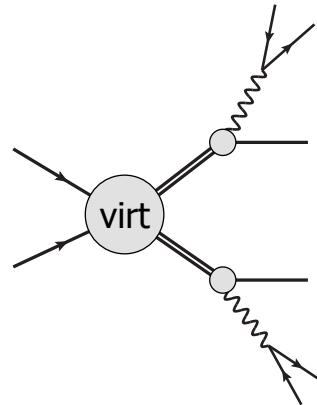


Dipole subtraction  
with alpha dependence

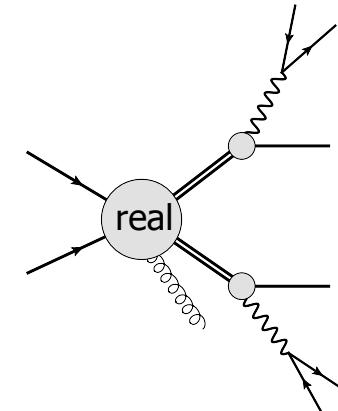
# Our implementation

Next-to-leading order:

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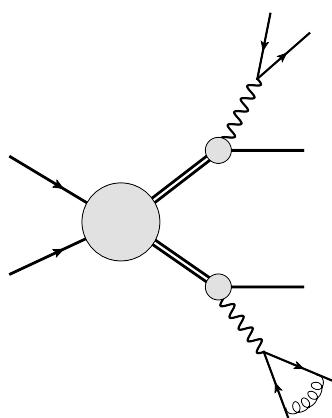
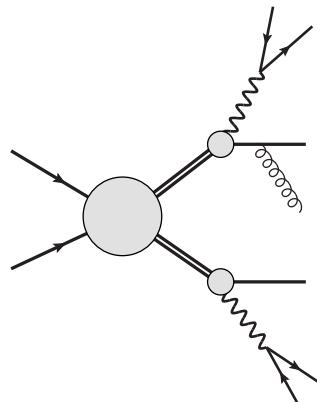


D-dimensional generalized unitarity  
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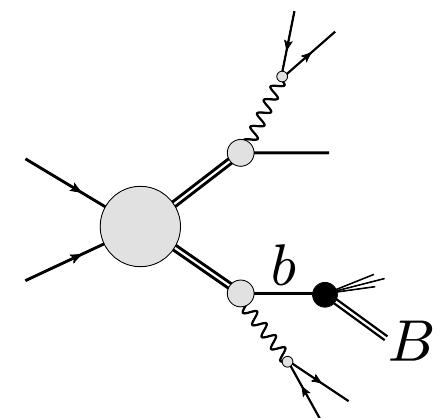


Dipole subtraction  
with alpha dependence

Decay



+ extra:



B-meson fragmentation

## How relevant is this?

- Measurement of the total  $t\bar{t}$  cross section

The total cross section is claimed to be measured with 5-10% accuracy

NLO QCD corrections: typically 10-30%

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NLO QCD corrections: typically 10-30%

**Note:** The total cross section is never measured in an experiment

$$\sigma_{\text{tot}} = \frac{N_{\text{obs}}}{\mathcal{L}} \cdot \frac{1}{A}$$

with  $A = \frac{\sigma_{\text{cuts}}}{\sigma_{\text{tot}}}$

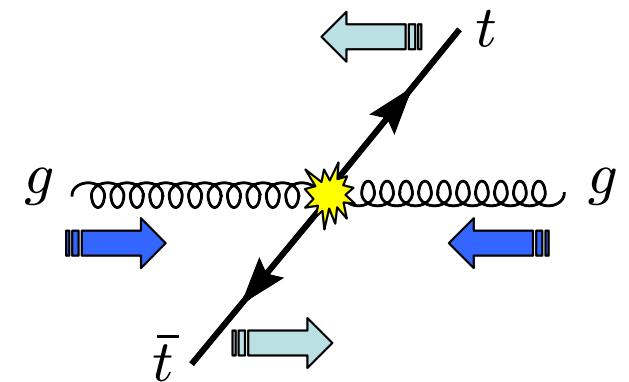
To claim that the total cross section has been measured with NLO accuracy, we need to calculate  $A$  at NLO QCD. Otherwise, we introduce potential biases.

# How relevant is this?

- Spin correlations in  $t\bar{t}$

[Parke,Mahlon]

[Bernreuther,Brandenburg,Si,Uwer]

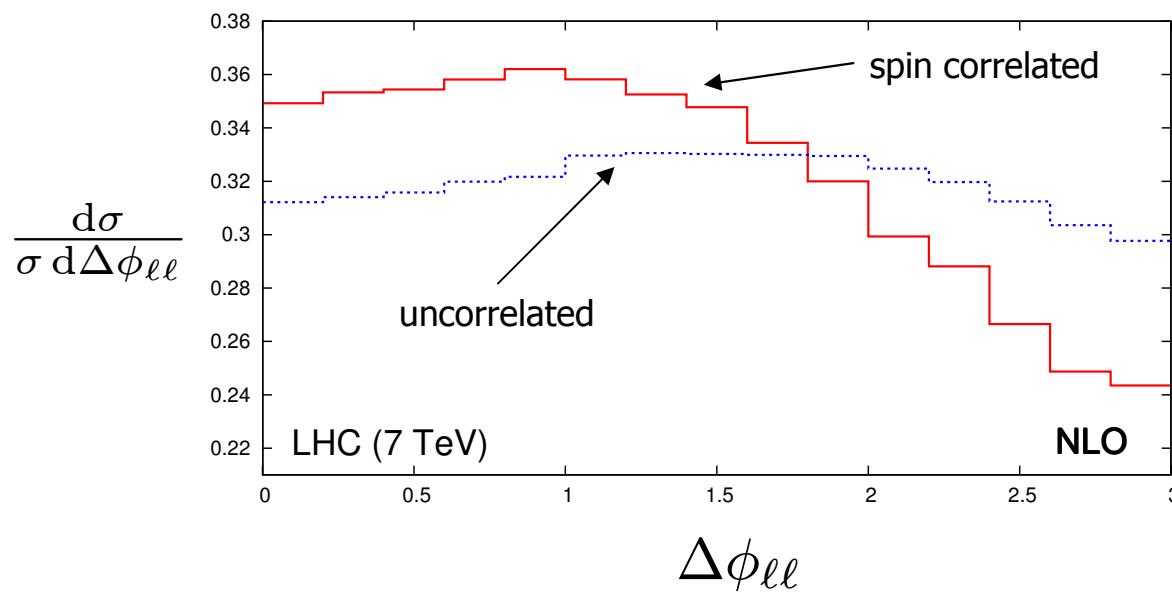
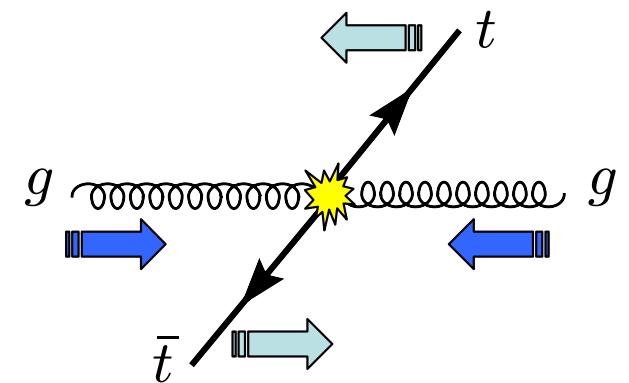


# How relevant is this?

- Spin correlations in  $t\bar{t}$

[Parke,Mahlon]

[Bernreuther,Brandenburg,Si,Uwer]



Cuts:

$$p_{T,\ell} > 20 \text{ GeV}$$

$$p_{T,\text{bjet}} > 25 \text{ GeV}$$

$$p_{T,\text{miss}} > 40 \text{ GeV}$$

$$\eta_\ell, \eta_{\text{bjet}} < 2.5$$

$$+ m_{\ell\ell} < 100 \text{ GeV}$$

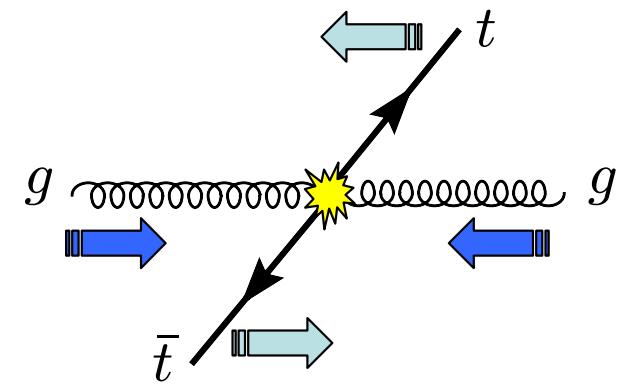
$$p_{T,\ell} < 50 \text{ GeV}$$

# How relevant is this?

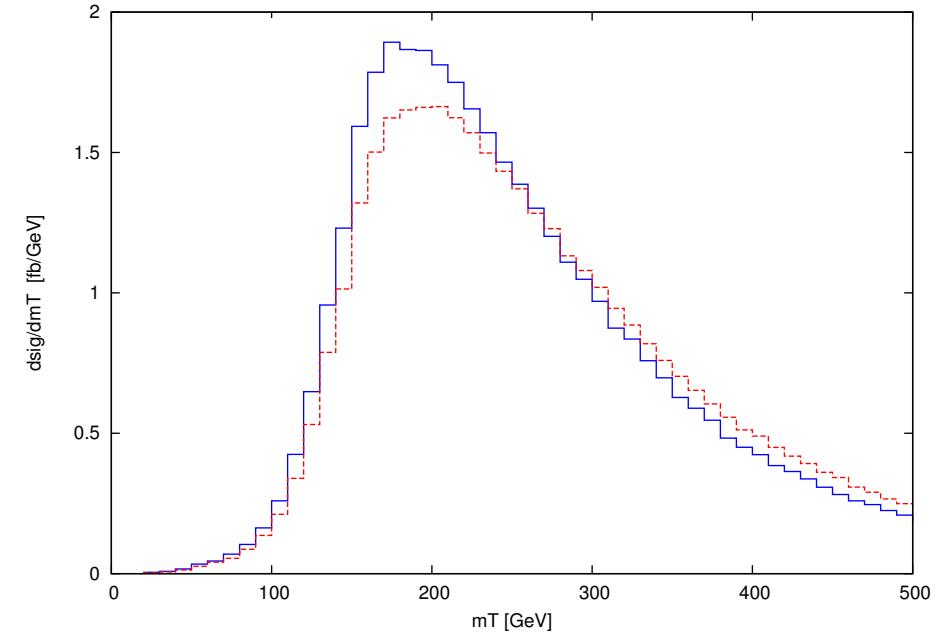
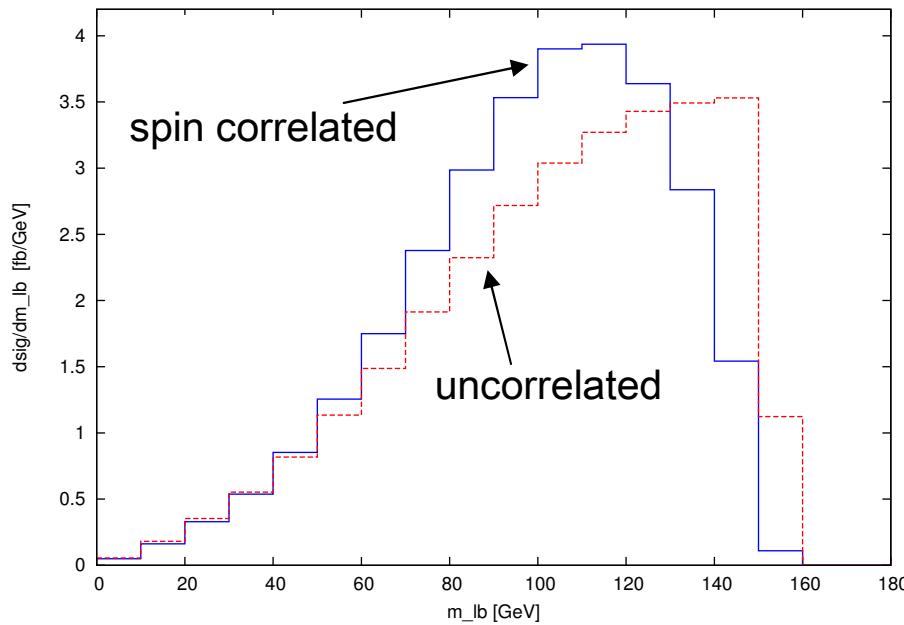
- Spin correlations in  $t\bar{t}$

[Parke,Mahlon]

[Bernreuther,Brandenburg,Si,Uwer]



Angle and invariant mass distributions are very sensitive to spin correlations



$$p_{T,bjet} > 25 \text{ GeV}, \quad p_{T,\ell} > 20 \text{ GeV}, \quad p_{T,miss} > 40 \text{ GeV}, \quad \eta_\ell, \eta_{bjet} < 2.5$$

## How relevant is this?

- Measurement of the top quark mass at the LHC

Target precision is about 1 GeV, dominated by systematics.

Clean measurements involve kinematics of top quark decay products.

So far, systematics of all those analysis were estimated by parton showers whose reliability at this level of precision is questionable.

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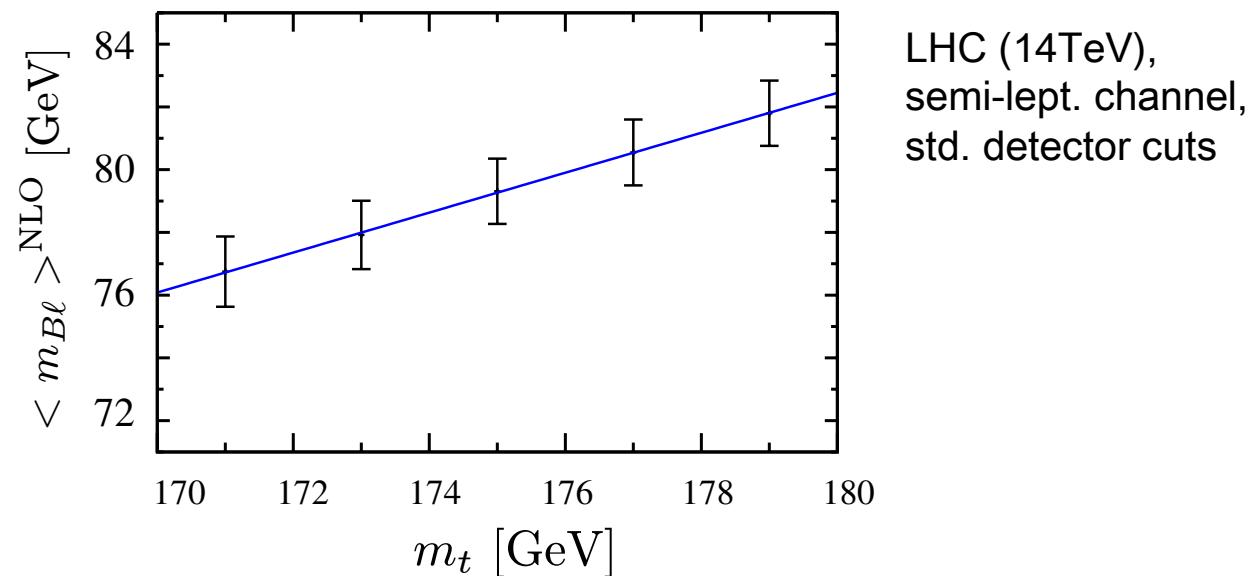
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So far, systematics of all those analysis were estimated by parton showers whose reliability at this level of precision is questionable.

One example:

average invariant mass  
of lepton and B-meson

⇒ uncertainty of 1.5 GeV  
is feasible with  $20 \text{ fb}^{-1}$



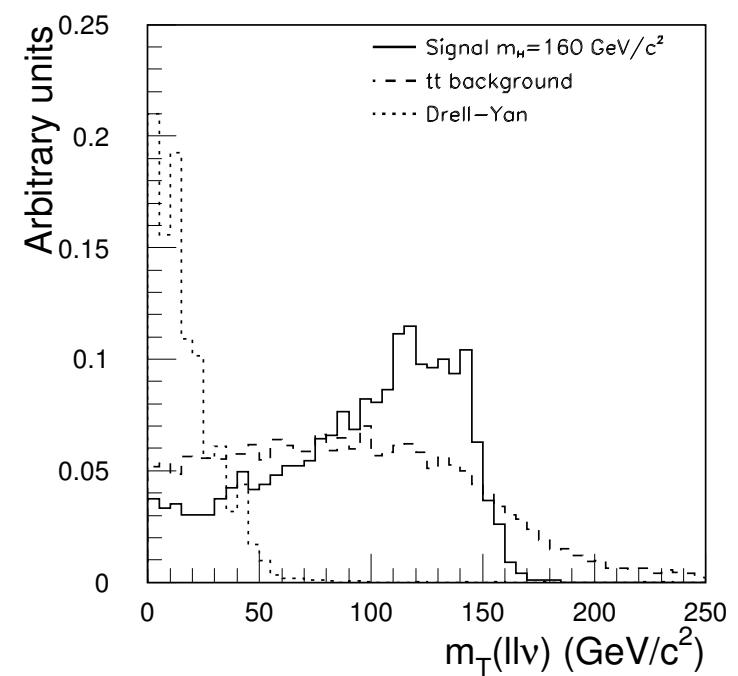
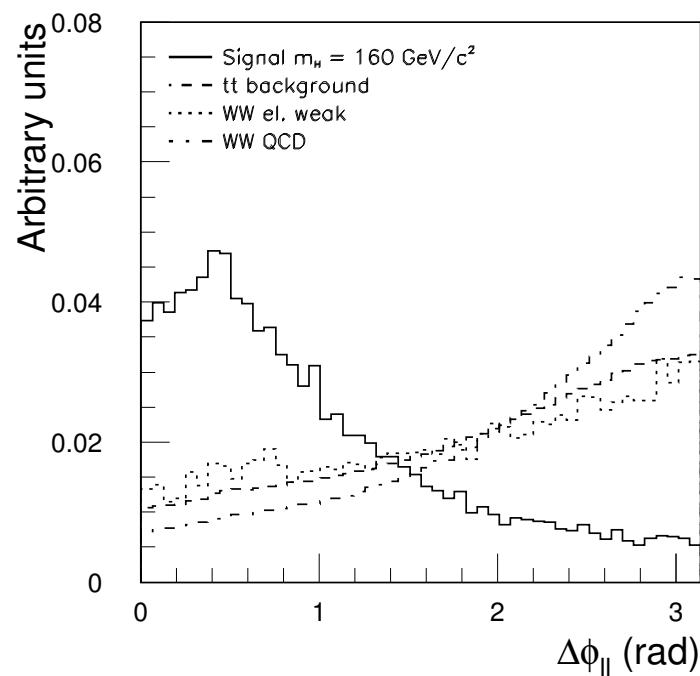
$t\bar{t}$  + jet

Process:  $t\bar{t}$  + jet

Major background for Higgs  $\rightarrow$  WW in VBF

$t\bar{t} + X$  comprises 2/3 of all backgrounds (80% from  $t\bar{t}$  + jet)

ATLAS:



## Process: $t\bar{t}$ + jet

LHC:  
 $(\mu = m_t)$

$\sigma_{\text{NLO}} = 376.2 \pm 0.6 \text{ pb}$  Dittmaier,Uwer,Weinzierl (2007)

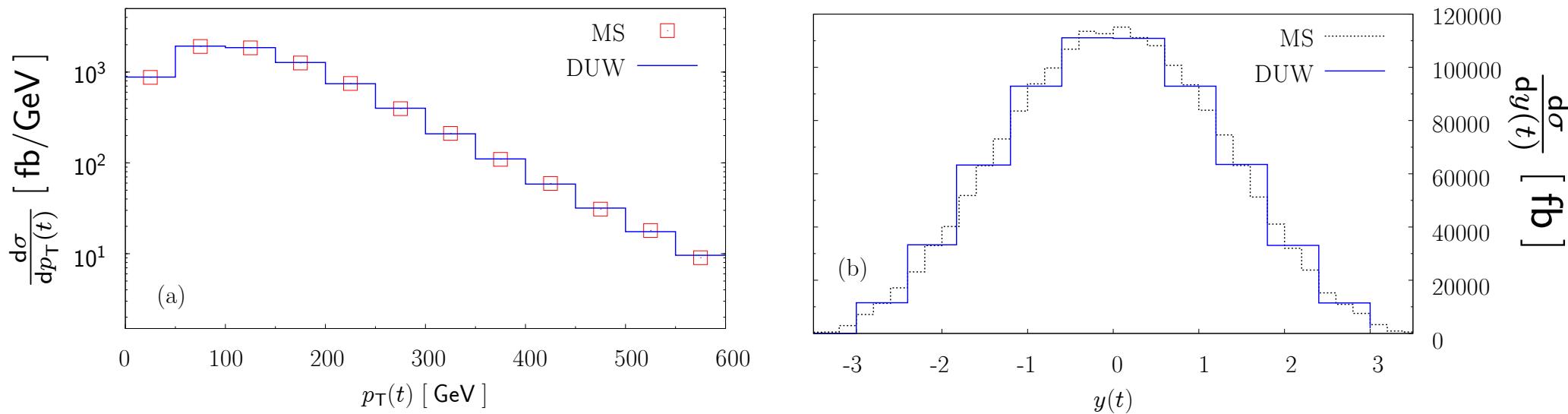
$\sigma_{\text{NLO}} = 376.6 \pm 0.6 \text{ pb}$  Bevilacqua,Czakon,Papadopoulos,Worek (2010)

$\sigma_{\text{NLO}} = 375.8 \pm 1.0 \text{ pb}$  Melnikov,S. (2010)

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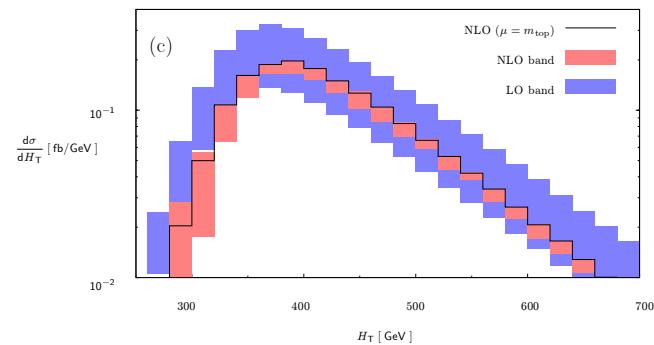
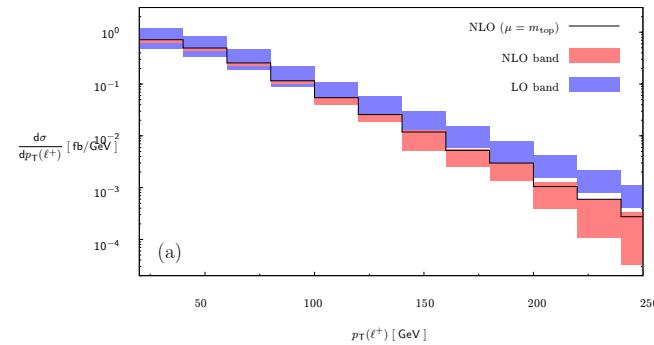
Cross check with DUW (stable top quarks):



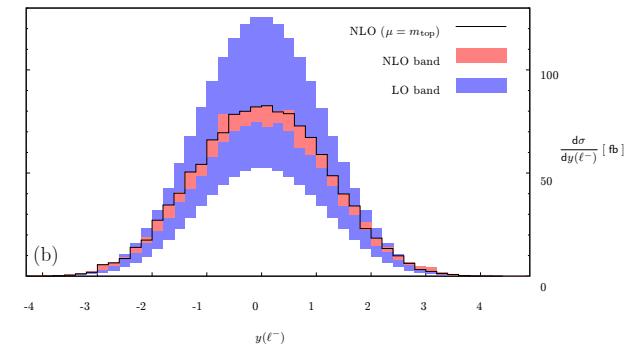
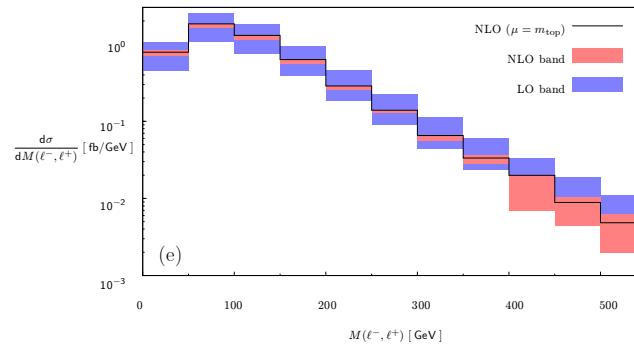
# Process: $t\bar{t}$ + jet

We include LO decays into leptons and jets:

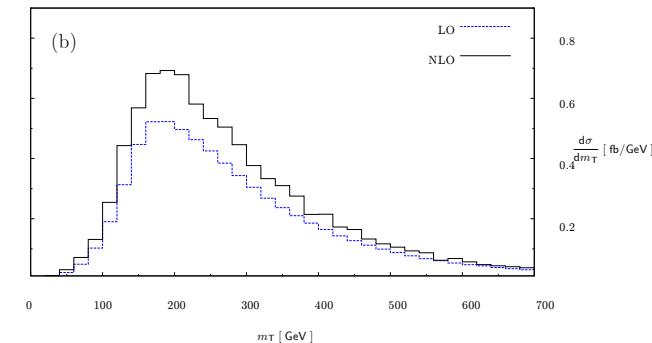
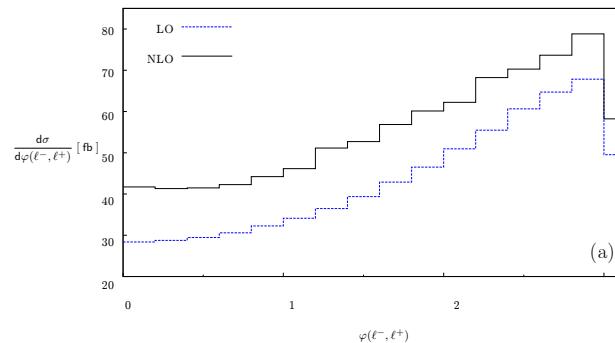
Tevatron:  
(semi-lept.)



LHC, signal:  
(7 TeV, di-lept.)



LHC, VBF bkgrd.:  
(14 TeV, di-lept.)

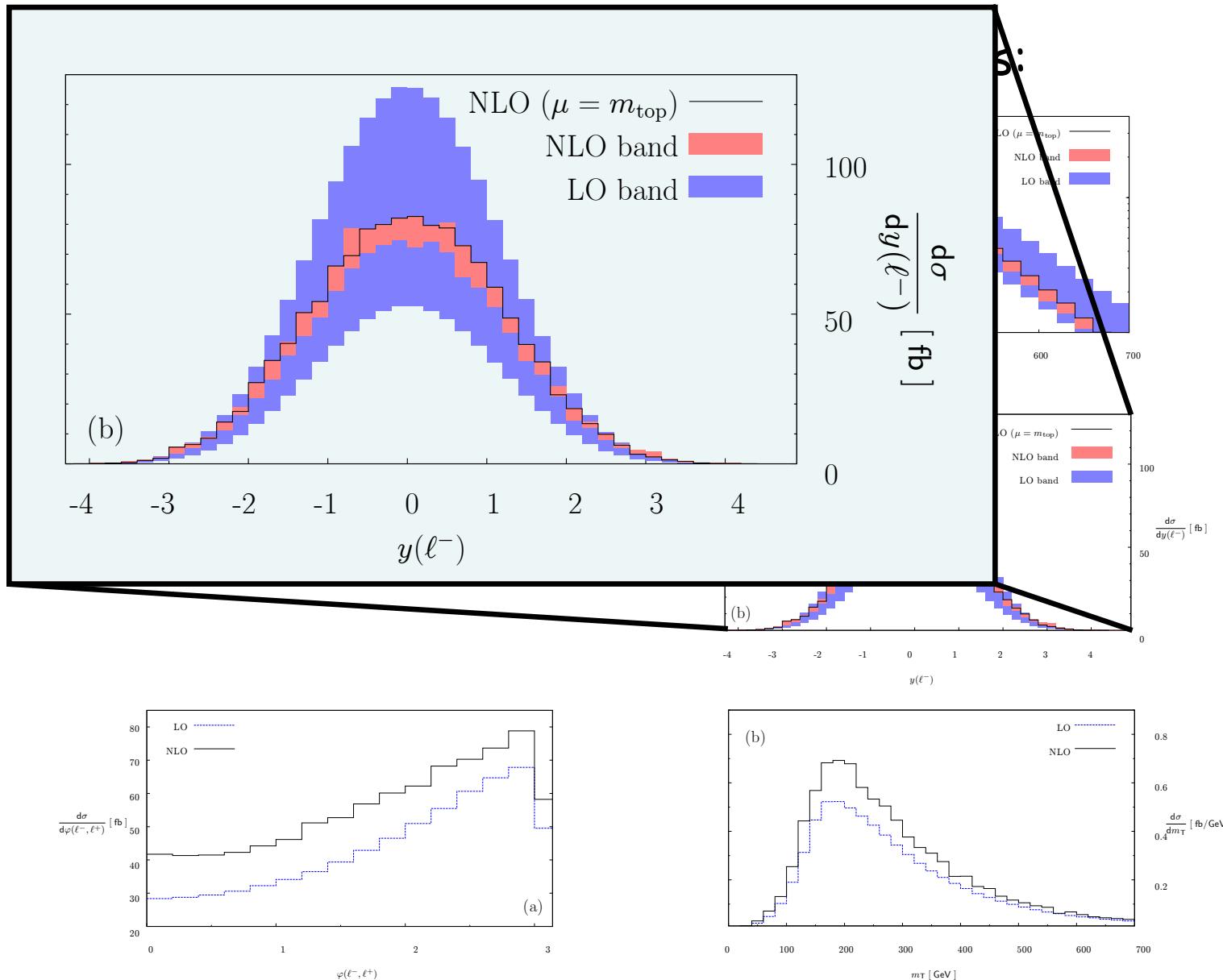


# Process: $t\bar{t} + \text{jet}$

Tevatron:  
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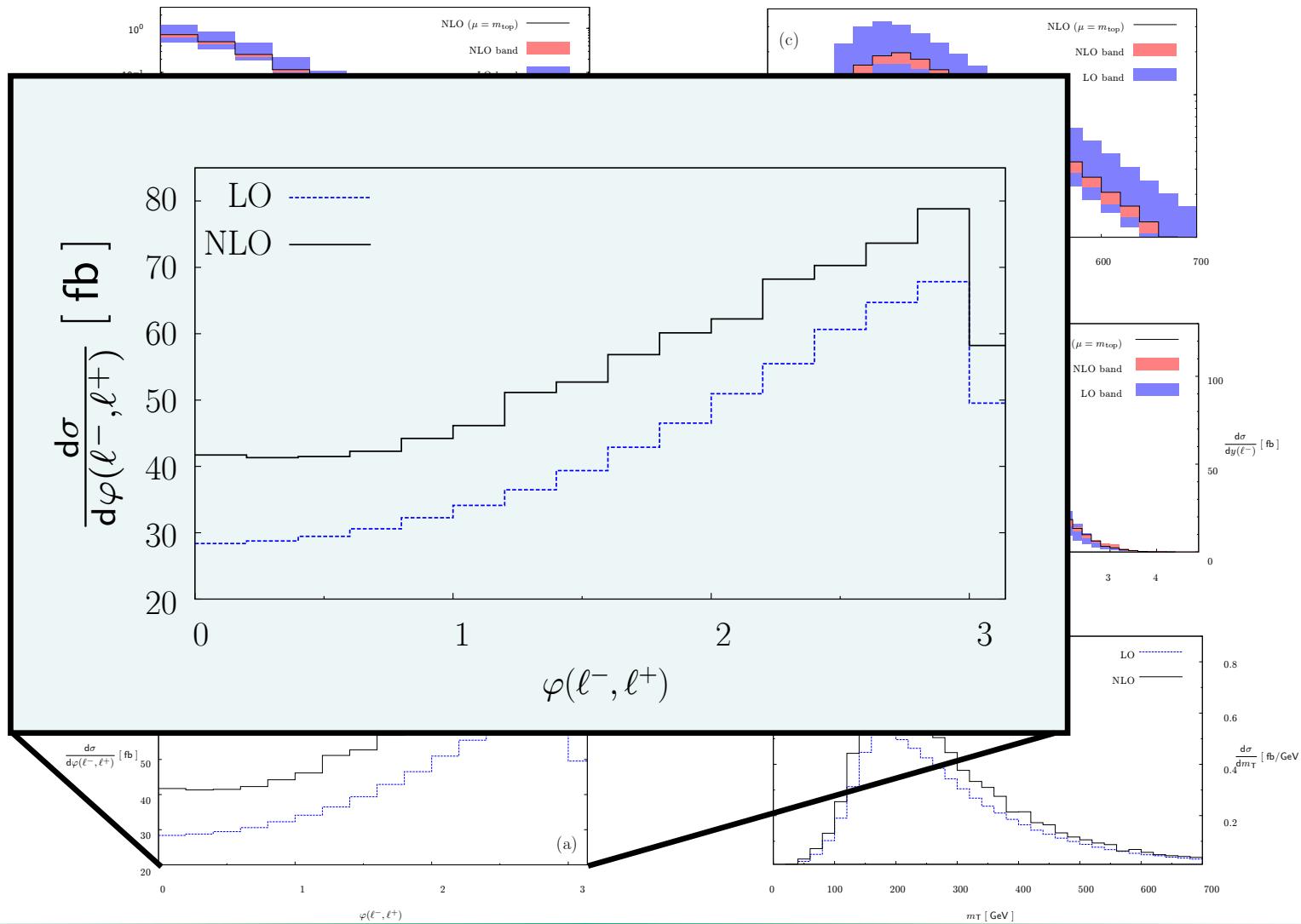
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Process:  $t\bar{t}$  + jet

Forward-Backward Asymmetry  
at Tevatron

[Kühn,Rodrigo]

$$A_{t\bar{t}} = \begin{cases} 0\% & \text{LO} \\ +5\% \pm 2\% & \text{NLO} \end{cases}$$

CDF:  
(2.3 fb<sup>-1</sup>)

$$A_{t\bar{t}}^{\text{exp}} = +19\% \pm 8\%$$

# Process: $t\bar{t}$ + jet

## Forward-Backward Asymmetry at Tevatron

[Kühn,Rodrigo]

$$A_{t\bar{t}} = \begin{cases} 0\% & \text{LO} \\ +5\% \pm 2\% & \text{NLO} \end{cases}$$

CDF:  $A_{t\bar{t}}^{\text{exp}} = +19\% \pm 8\%$   
(2.3  $\text{fb}^{-1}$ )

$$A_{t\bar{t}+\text{jet}}(p_{\perp\text{jet}} > 30\text{GeV}) = \begin{cases} -8.3\% \pm 0.1\% & \text{LO} \\ -2.3\% \pm 0.5\% & \text{NLO} \end{cases}$$

in agreement  
with DUW

$$A_{\ell^+\ell^-+\text{jet}}(p_{\perp\text{jet}} > 20\text{GeV}) = \begin{cases} -5.1\% \pm 0.1\% & \text{LO} \\ -0.5\% \pm 0.7\% & \text{NLO} \end{cases}$$

## Process: $t\bar{t}$ + jet

Runtime

Virtual corrections:  $gg \rightarrow t\bar{t}g$        $5000\text{min}/0.65\text{Mevents} = 460\text{msec/event}$

( Intel Xeon 2.8GHz,  
events after cuts,  
incl. QuadPrec stabilization )

Real corrections:  $gg \rightarrow t\bar{t}gg$        $2400\text{min}/7\text{Mevents} = 21\text{msec/event}$

( Intel Xeon 2.8GHz,  
events after cuts,  
incl. Dipoles  $\alpha=10^{-2}$  )

with a handful of quad-core processors  $\Rightarrow$  distributions in 4 days

DW:  $\approx 10\times$  faster for virtual corrections.

However, we compare a mostly analytic reduction with a fully numerical approach.

# Summary

- NLO QCD corrections to  $t\bar{t}$  production and decay
  - D-dimensional generalized unitarity + OPP
  - realistic description of the final state incl. spin correlations
- NLO QCD corrections to  $t\bar{t} + \text{jet}$  production
  - method works well for a complex process
  - realistic final state is important for discrimination of background to Higgs signal in VBF
  - strong reduction of the asymmetry, even for leptons in the decay

# Extras

## Sabine Lammers (U-Indiana, D0)

comparison of different MC generators with D0 data for Z+jet (Run II, 1fb-1 )

Performance by	Z+jet normalization	Z+jet angles	Z+jet pt
MCFM NLO	✓	✓	✓
Alpgen/MLM + Pythia			✓
Alpgen/MLM + Herwig			✓
Sherpa/CKKW		✓	
HERWIG			
PYTHIA			

Z+jets Measurements at D0 - July 30, 2009

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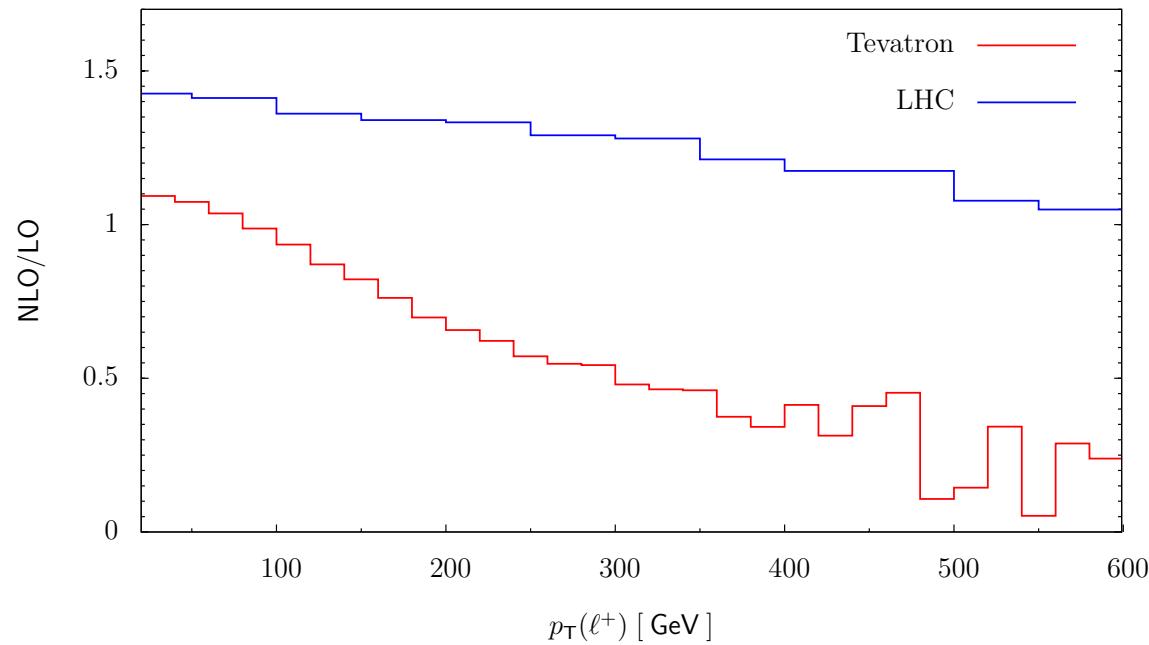
→ If precise measurements are available, NLO describes data best.

$Z + \text{jet}$  at Tevatron  $\sim t\bar{t}$  at LHC

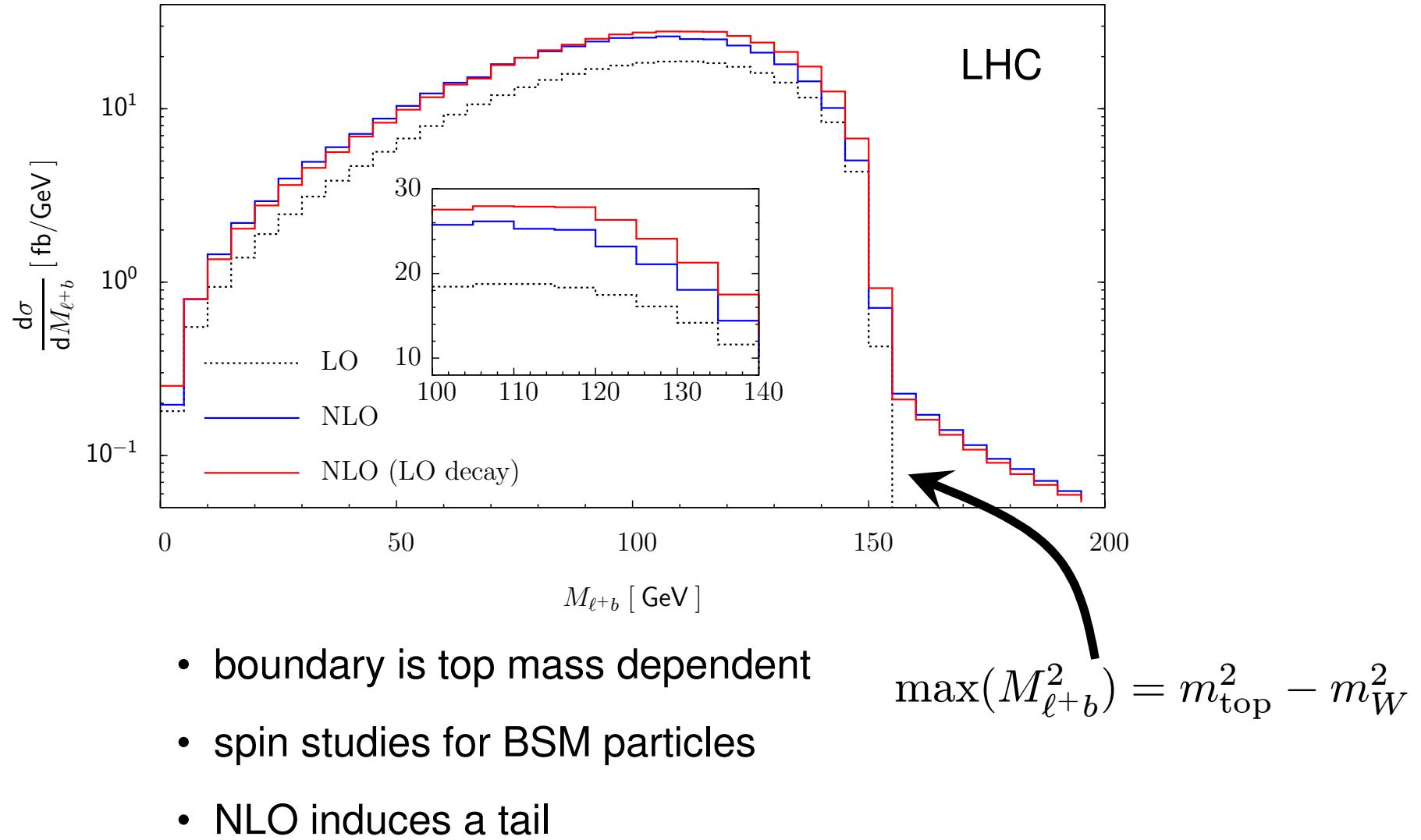
TEV  $\rightarrow \mathcal{O}(1000)$  events

LHC  $\rightarrow \mathcal{O}(10000)$  events already with 1/fb

## K - factor



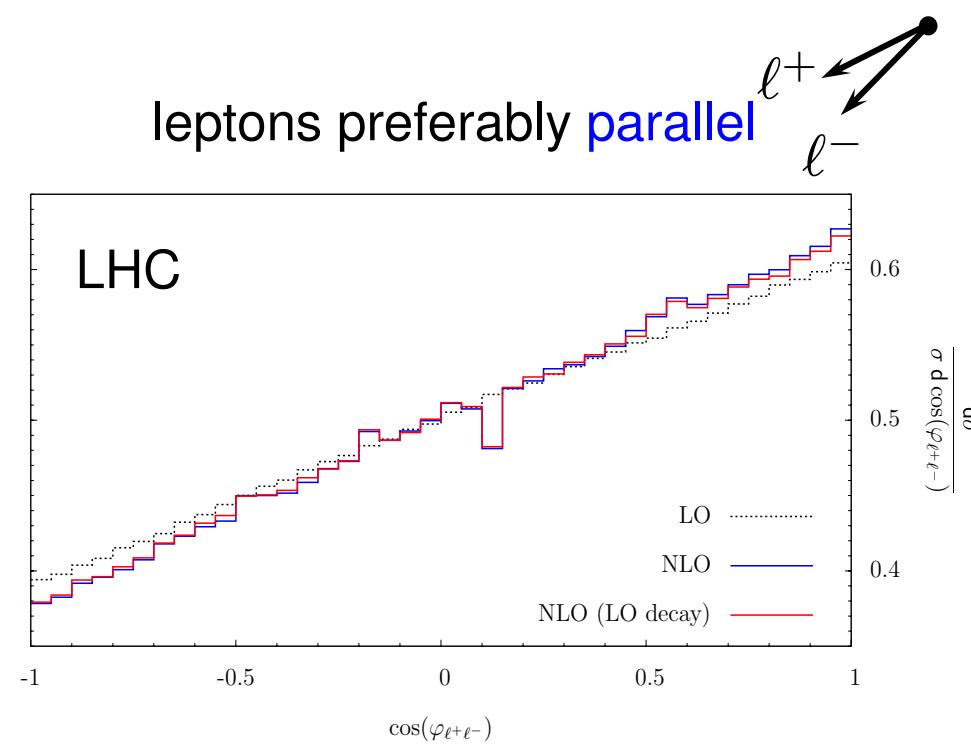
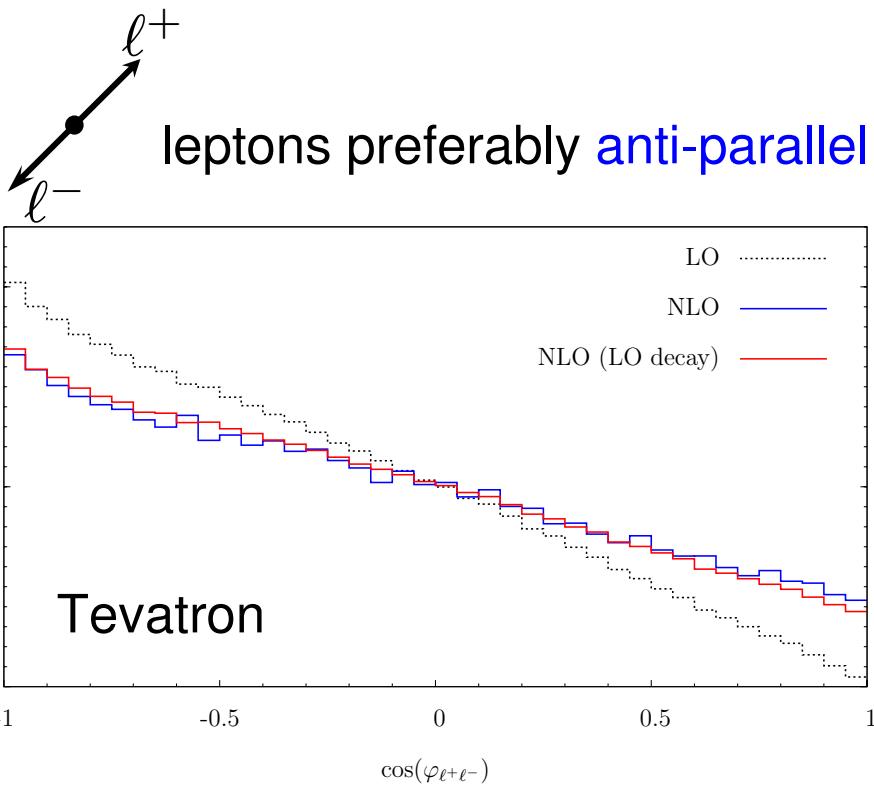
## invariant mass of lepton and b-jet



*typical observable:*

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos(\varphi_{\ell^+ \ell^-})}$$

$\varphi_{\ell^+ \ell^-}$ : angle between the directions of flight of leptons in the corresponding ***top rest frame***

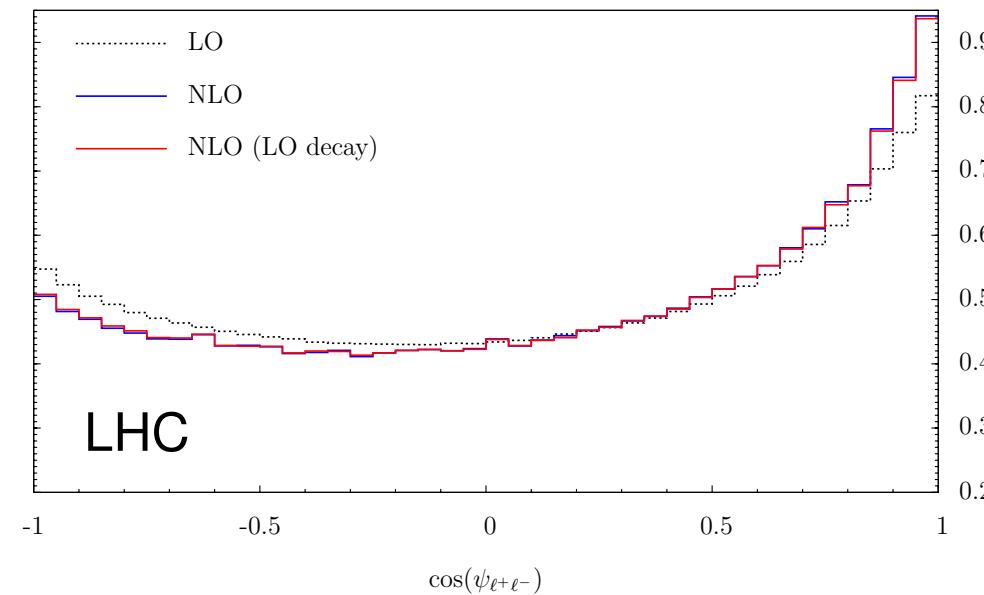
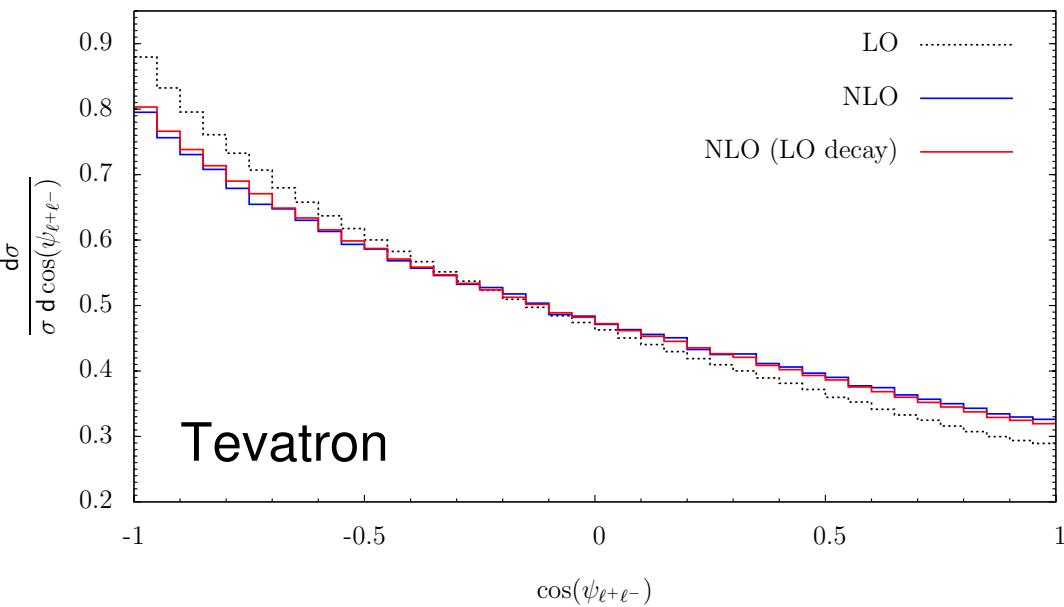


- substantial angular correlations, even at NLO
- NLO effects at Tevatron are significant

simpler observable:

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos(\psi_{\ell^+\ell^-})}$$

$\psi_{\ell^+\ell^-}$ : opening angle of the leptons in the  
***laboratory frame***



- top quark rest frames need not to be reconstructed
- angular correlations remain, stronger NLO effects at LHC

