HP2.3rd - GGI Florence

High Precision for Hard Processes at the LHC

Top Quark Physics
with
D-Dimensional Generalized Unitarity

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in collaboration with K. Melnikov

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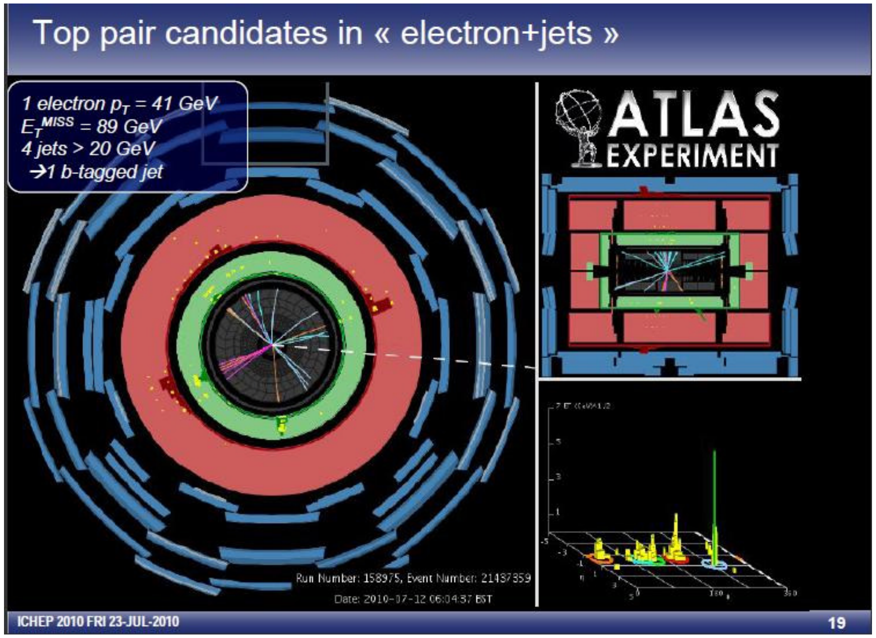
Top quark phenomenology

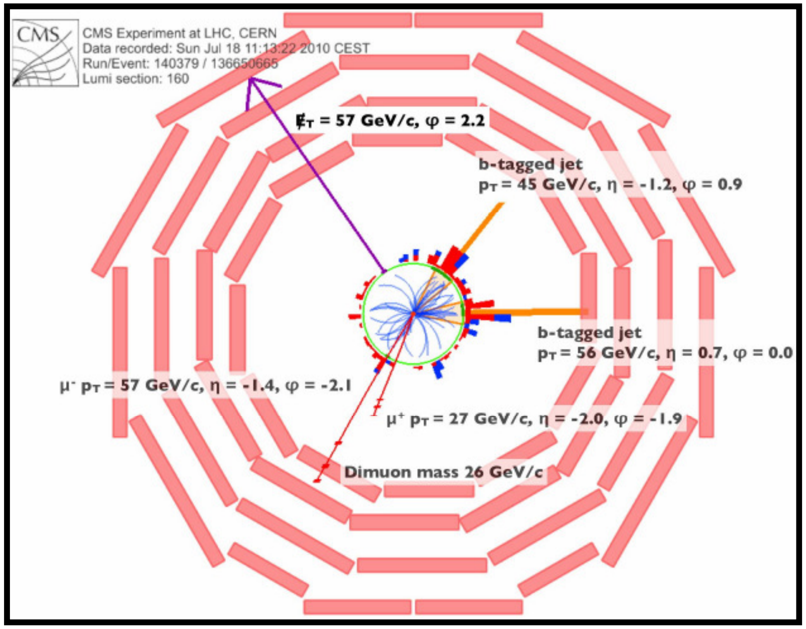


Top pair candidates in « electron+jets »

1 electron p_T = 41 GeV
E_T^{MISS} = 89 GeV
4 jets > 20 GeV
→1 b-tagged jet

Run Number: 158975, Event Number: 21437359
Date: 2010-07-12 06:04:37 BST

ICHEP 2010 FRI 23-JUL-2010 19



LHC (7 TeV) : $\sigma_{t\bar{t}} \approx 200\ \mathrm{pb}$

Tevatron : $\sigma_{t\bar{t}} \approx 7\ \mathrm{pb}$

→

$\approx 200\ \mathrm{k}$ events from
LHC (7 TeV) with 1 fb^{-1}

vs.

$\approx 30\ \mathrm{k}$ events from
Tevatron with 5 fb^{-1}

Outline

NLO QCD corrections to $t\bar{t}$ production and decay

- Calculation framework
- Top quark spin correlations
- Top quark mass measurements at NLO QCD + [S. Biswas]

[JHEP 0908:049, 2009],
[JHEP 1008:048, 2010]

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,Steinhause,Sterman,Uwer,Vogt
  Electroweak corrections:
  Beenakker,Bernreuther,Fuecker,Denner,Hollik,Kao,Kollar,Kühn,Ladinsky,Mertig,Moretti,Nolten,Ross,Sack,Scharf,Si,Uwer,Wackeroth,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, Si (2010); Melnikov, M.S. (2009)

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

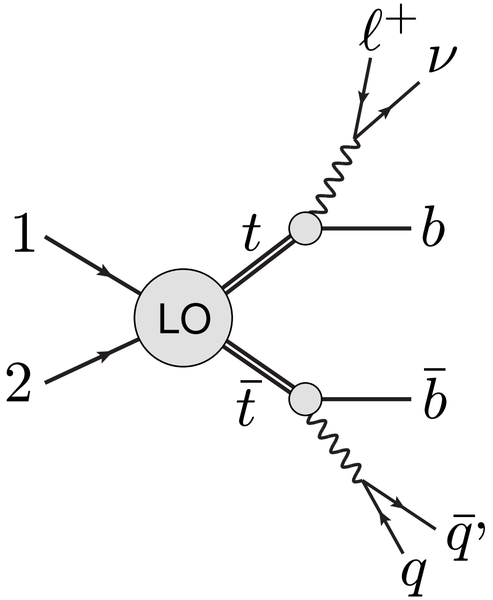
Allows for:

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

Our implementation

leading order:

$$\mathcal{M}_{\text{tree}} =$$



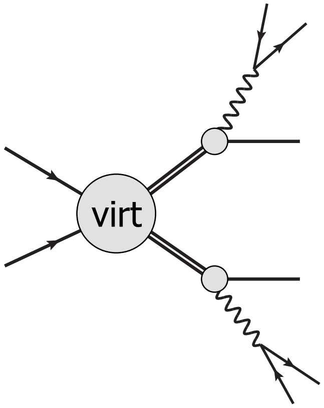
We calculate helicity amplitudes.

- Generate phase space of top quarks
- Generate phase space of decay particles
- $\bar{u}(p_t) \;\rightarrow\; \tilde{\bar{u}}(p_t) = \mathcal{M}(t \to b\ell^+\nu)\,\frac{\mathrm{i}(\not{p}_t + m_t)}{\sqrt{2m_t\Gamma_t}}$
- $\mathcal{M}_{\text{tree}} = \tilde{\bar{u}}(p_t)\,\tilde{\mathcal{M}}(12 \to \bar{t}t)\,\tilde{v}(p_{\bar{t}}) \quad + \mathcal{O}(\frac{\Gamma_t}{m_t})$

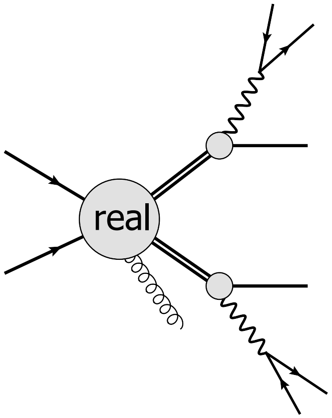
Our implementation

Next-to-leading order:

Production



D-dimensional generalized unitarity
+ OPP

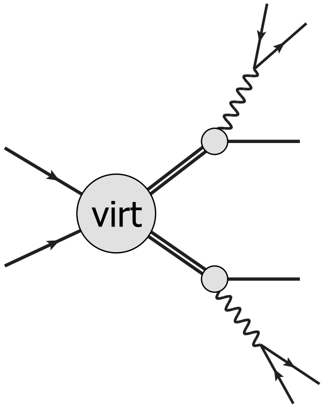


Dipole subtraction
with alpha dependence

Our implementation

Next-to-leading order:

Production



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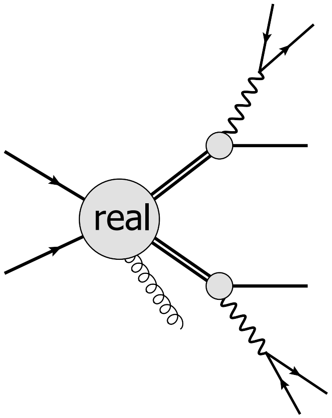

Dipole subtraction
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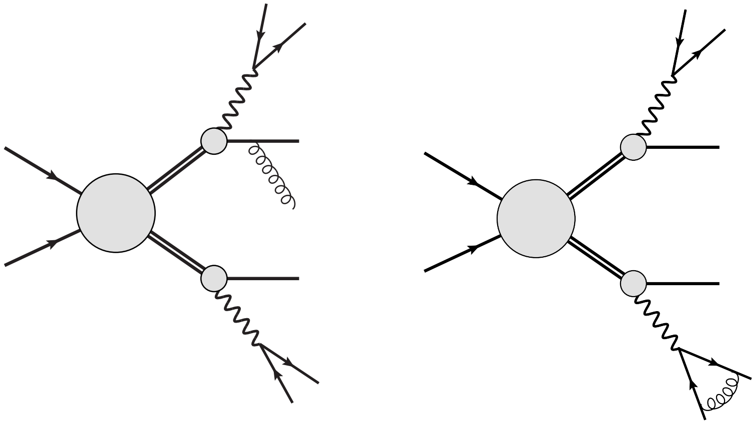
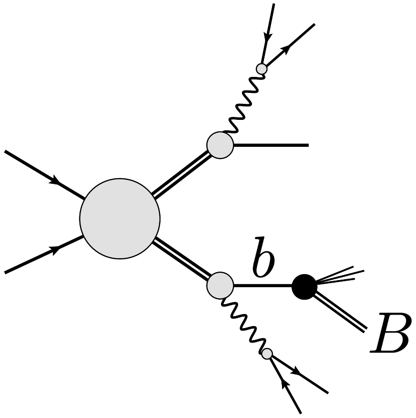
Decay



+ 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%

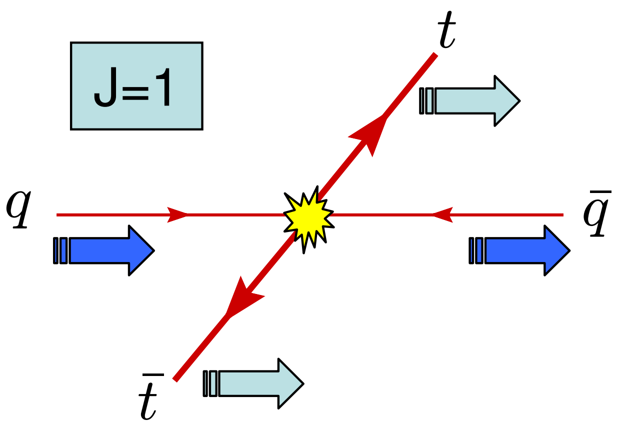
Note: The total cross section is never measured in an experiment

$$\boxed{\sigma_{\mathrm{tot}} = \frac{N_{\mathrm{obs}}}{\mathcal{L}} \cdot \frac{1}{A}} \qquad \text{with} \qquad A = \frac{\sigma_{\mathrm{cuts}}}{\sigma_{\mathrm{tot}}}$$

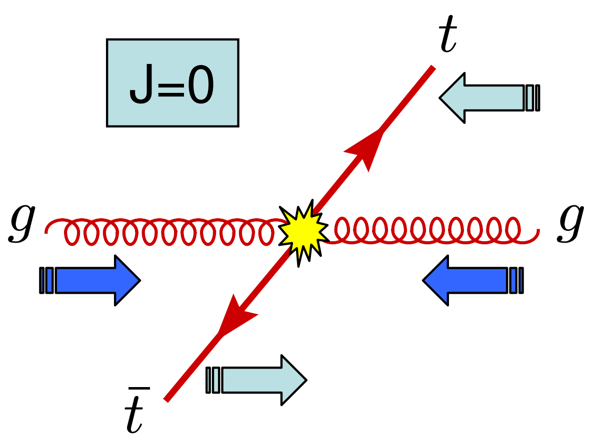
To claim that the total cross section has been measured with NLO accuracy, we need to calculate A at NLO QCD. Otherwise, we introduce potential biases.

• Top quark spin correlations

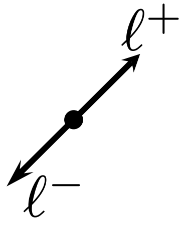
Spins of production and decay mechanism are interlocked



close to threshold:
S-wave production
(L=0)



⇨ leptons preferably anti-parallel



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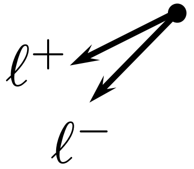

- Top quark spin correlations

These effects are only observable for top quarks

$$\frac{\text{spin-flip time}}{\text{life time}} \sim \frac{m_{\text{top}}}{\Lambda^2_{\text{QCD}}} \cdot \Gamma_{\text{top}}$$

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$$\frac{\text{spin-flip time}}{\text{life time}} \sim \frac{m_{\text{top}}}{\Lambda^2_{\text{QCD}}} \cdot \Gamma_{\text{top}}$$

So far, only one measurement exists:

$$\frac{1}{\sigma}\,\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\phi_i\,\mathrm{d}\cos\phi_j} = \frac{1}{4}\left(1 - C\cos\phi_i\cos\phi_j\right)$$

requires boost into top rest frames
and specification of a quantization axis

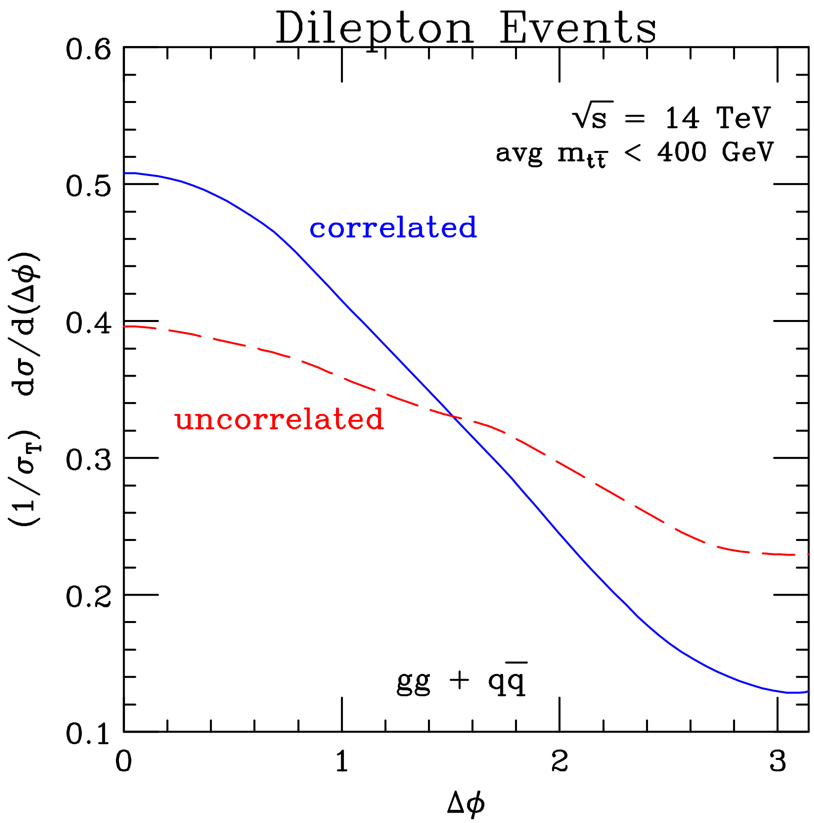
$C(\text{SM theory}) = 0.78$

[Bernreuther et..al.]

$C(\text{Tevatron}) = 0.32^{+0.55}_{-0.78}$

[CDF+D0, 4.3fb^{-1}]

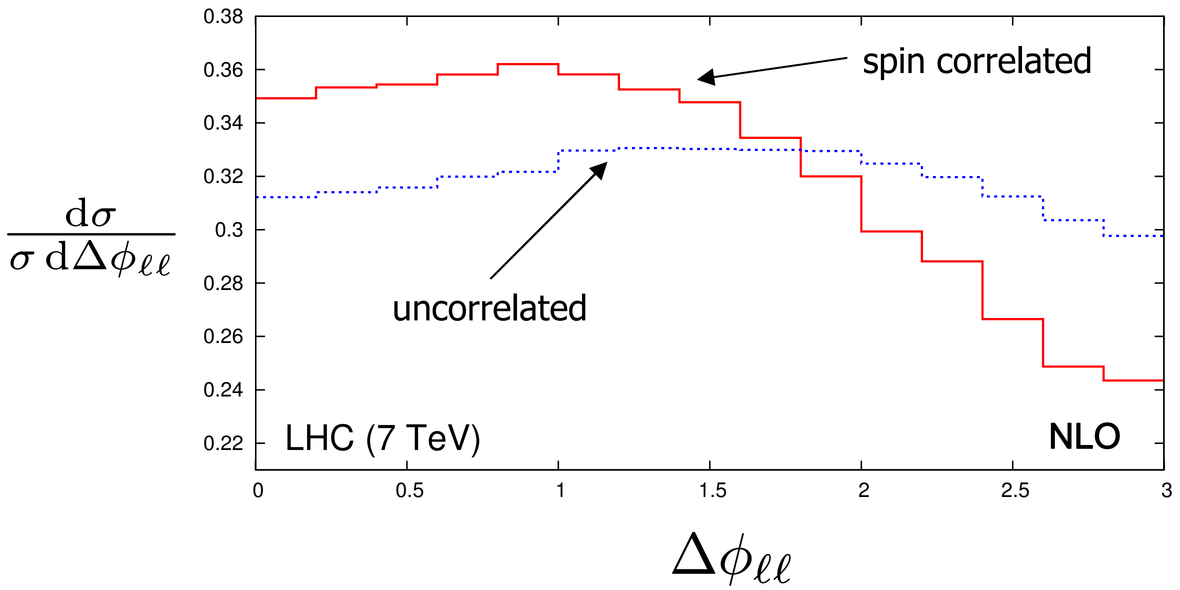
Mahlon, Parke: measure lepton opening angle with $m_{t\bar{t}} < 400$ GeV



$m_{t\bar{t}}$ is not an observable

Cut can be applied to the average, $<m_{t\bar{t}}>$

our suggestion: measure lepton opening angle
with special cuts on leptons



Cuts:

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

+ $m_{\ell\ell} < 100\mathrm{GeV}$
$p_{\mathrm{T},\ell} < 50\mathrm{GeV}$

advantage: clean observable,
simpler measurement

New ideas (under development):

define indicator r that is sensitive to spin correlations

$$r(\Phi) = \frac{|\mathcal{M}_{\rm corr}|^2}{|\mathcal{M}_{\rm corr}|^2 + |\mathcal{M}_{\rm unco}|^2}$$

Φ depends on neutrino momenta which are unobservable

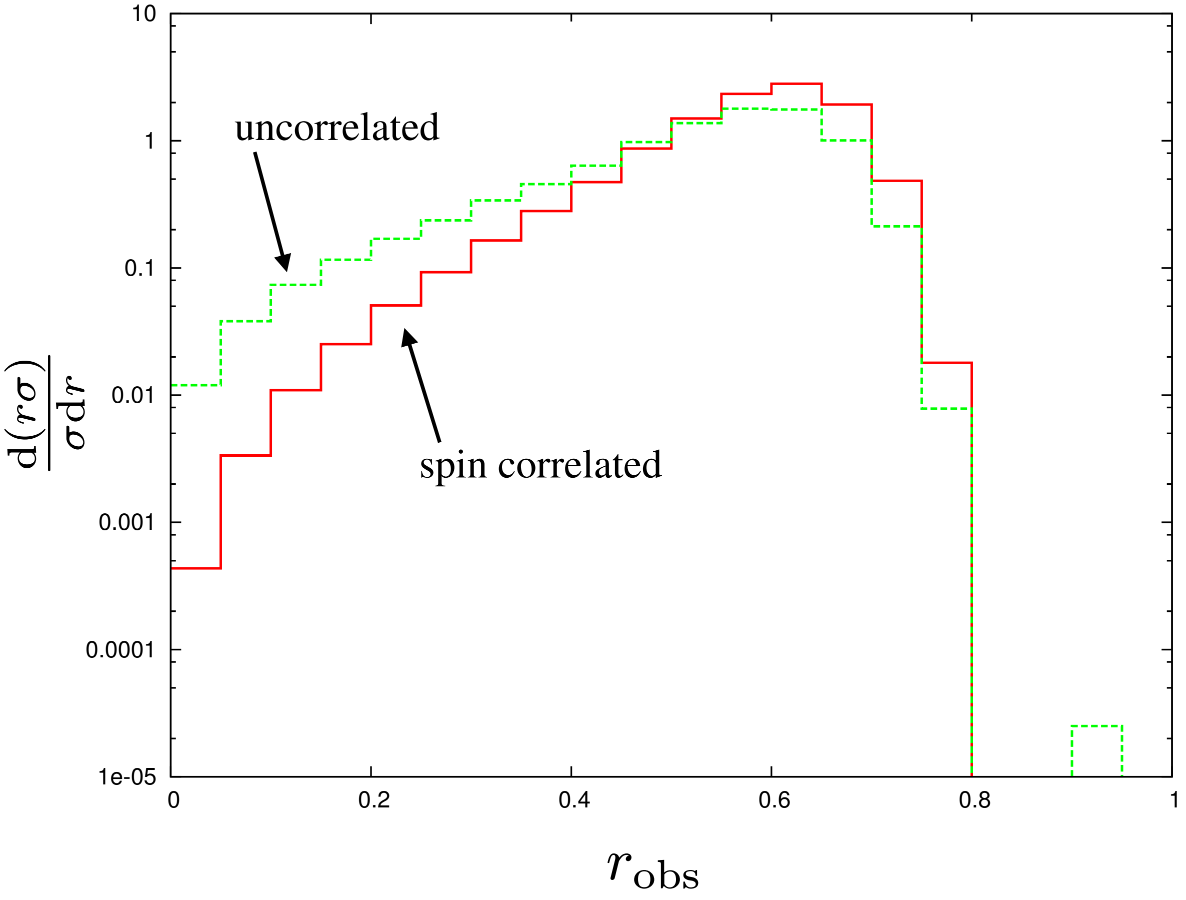
integration of $r(\Phi)$ over neutrino momenta yields up to 8 solutions

$$\boxed{r_{\rm obs} = \sum_i r(\Phi_i)}$$

→ we calculate $r_{\rm obs}$, weighted with the cross section for spin correlated and uncorrelated top quarks

preliminary LO result

LHC(10TeV) di-leptonic final state with standard acceptance cuts



we find similar results for the Tevatron

• Top quark mass measurement 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 studies were estimated by parton showers whose reliability at this level of precision is questionable.

one example:

average invariant mass of B-meson and lepton

J/Psi decay mode allows for very precise measurements already with 20 fb^{-1}

⇨ calculate $<m_{B\ell}>$ as a function of m_{top}

parton show studies neglect $t\bar{t}$ production process

$$<m_{B\ell}>_{\rm Herwig} = 0.61 m_{\rm top} - 25.31 {\rm GeV}$$

$$<m_{B\ell}>_{\rm Pythia} = 0.59 m_{\rm top} - 24.11 {\rm GeV}$$

$$<m_{B\ell}>_{\rm NLO} = 0.60 m_{\rm top} - 26.7 {\rm GeV}$$

deviations in slope lead to $\approx 3{\rm GeV}$ uncertainty

uncertanties from scale variations comparable to expected experimental errors

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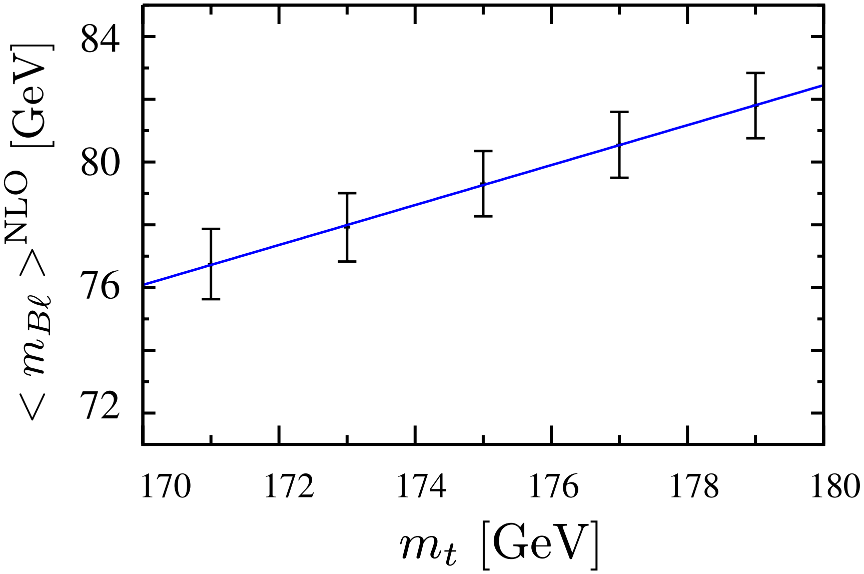
complete NLO study of $pp \to t\bar{t} \to b\bar{b}\ell\nu jj$



$$<m_{B\ell}>^{\text{prod}}_{\text{NLO}} = 0.64 m_{\text{top}} - 32.12\text{GeV}$$

$\Rightarrow$ uncertainty of 1.5 GeV on m_{top}

Summary

- NLO QCD corrections to $t\bar{t}$ production and decay
  - important contributions have been neglected in the past
  - realistic description of the final state incl. spin correlations is crucial for a precise understanding
  - allows for new improved studies of
    e.g. top mass measurement or spin correlations

- I left out:

  NLO QCD corrections to $t\bar{t} + \mathrm{jet}$ production

Extras

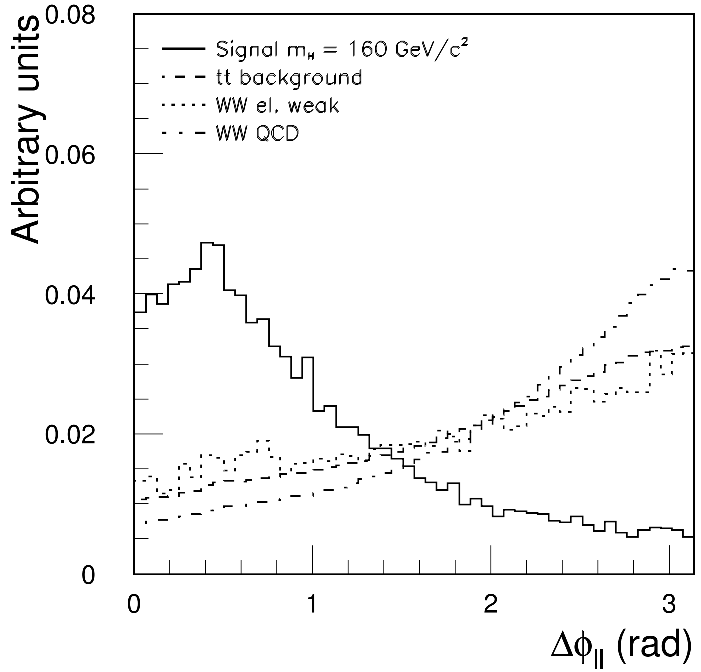
$t\bar{t}$ + jet

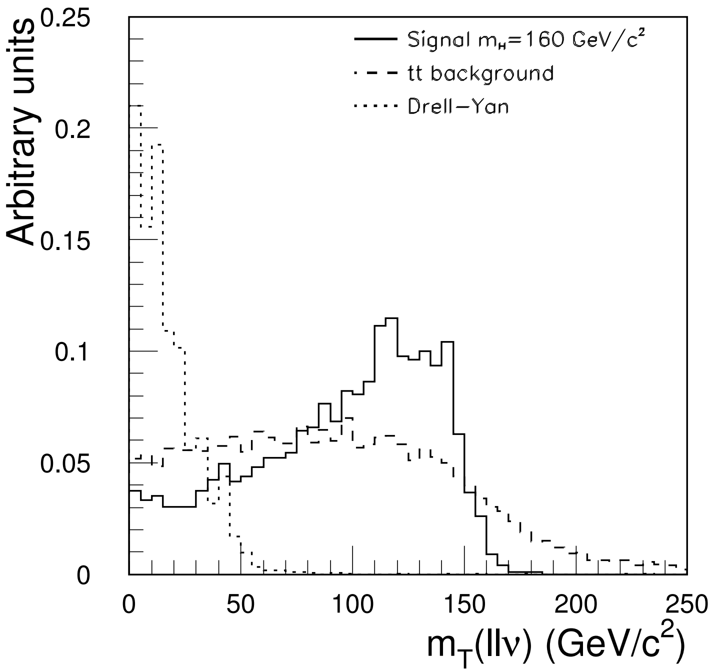
Process: $t\bar{t}$ + jet

Major background for Higgs → WW in VBF

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

ATLAS:

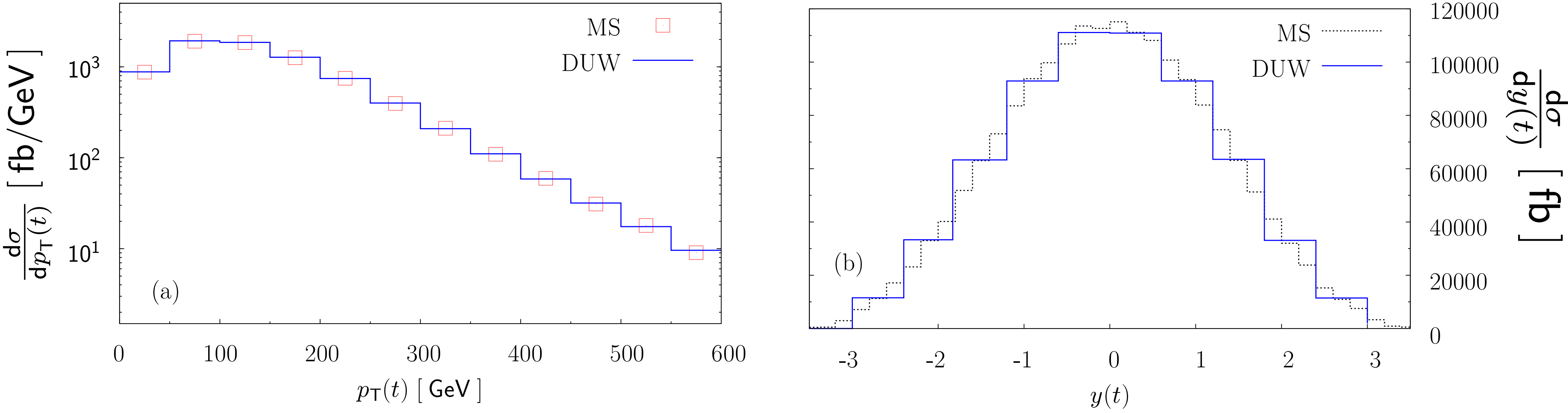




Process: $t\bar{t}$ + jet

LHC: $(\mu = m_t)$	$\sigma_{\rm NLO} = 376.2 \pm 0.6$ pb	Dittmaier,Uwer,Weinzierl (2007)
	$\sigma_{\rm NLO} = 376.6 \pm 0.6$ pb	Bevilacqua,Czakon,Papadopoulos,Worek (2010)
	$\sigma_{\rm NLO} = 375.8 \pm 1.0$ pb	Melnikov,S. (2010)

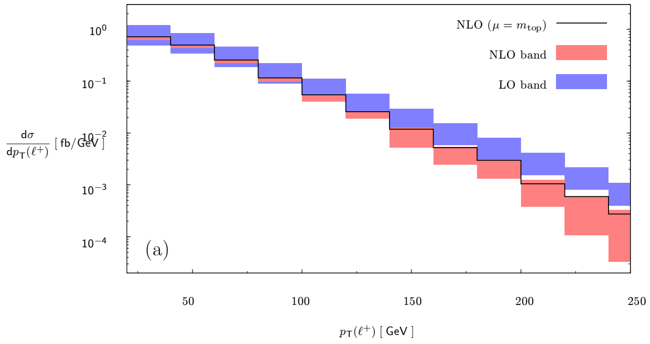
Cross check with DUW (stable top quarks):

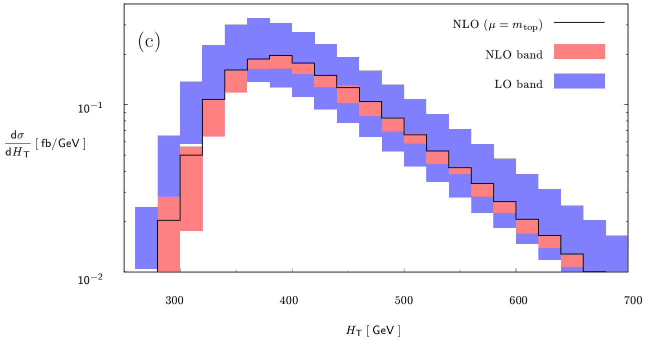


Process: $t\bar{t}$ + jet

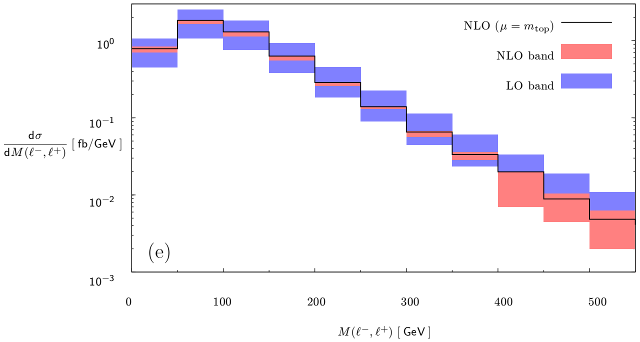
We include LO decays into leptons and jets:

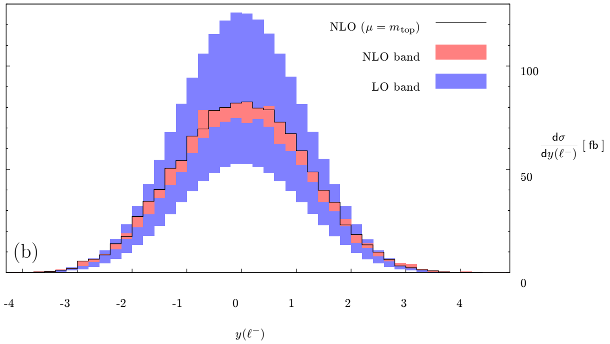
Tevatron:
(semi-lept.)



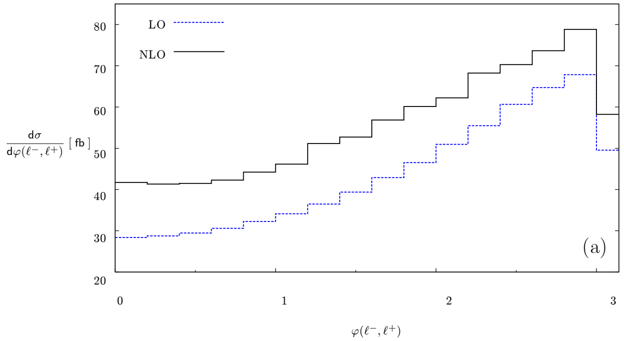


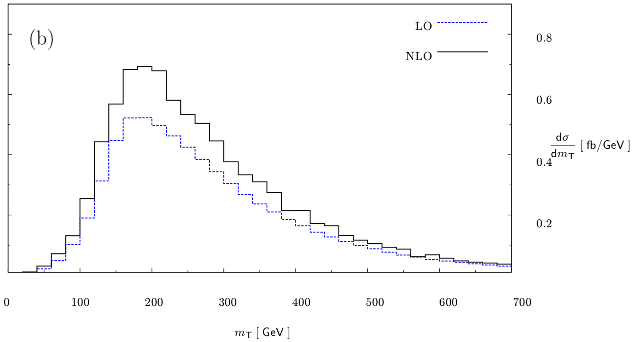
LHC, signal:
(7 TeV, di-lept.)





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

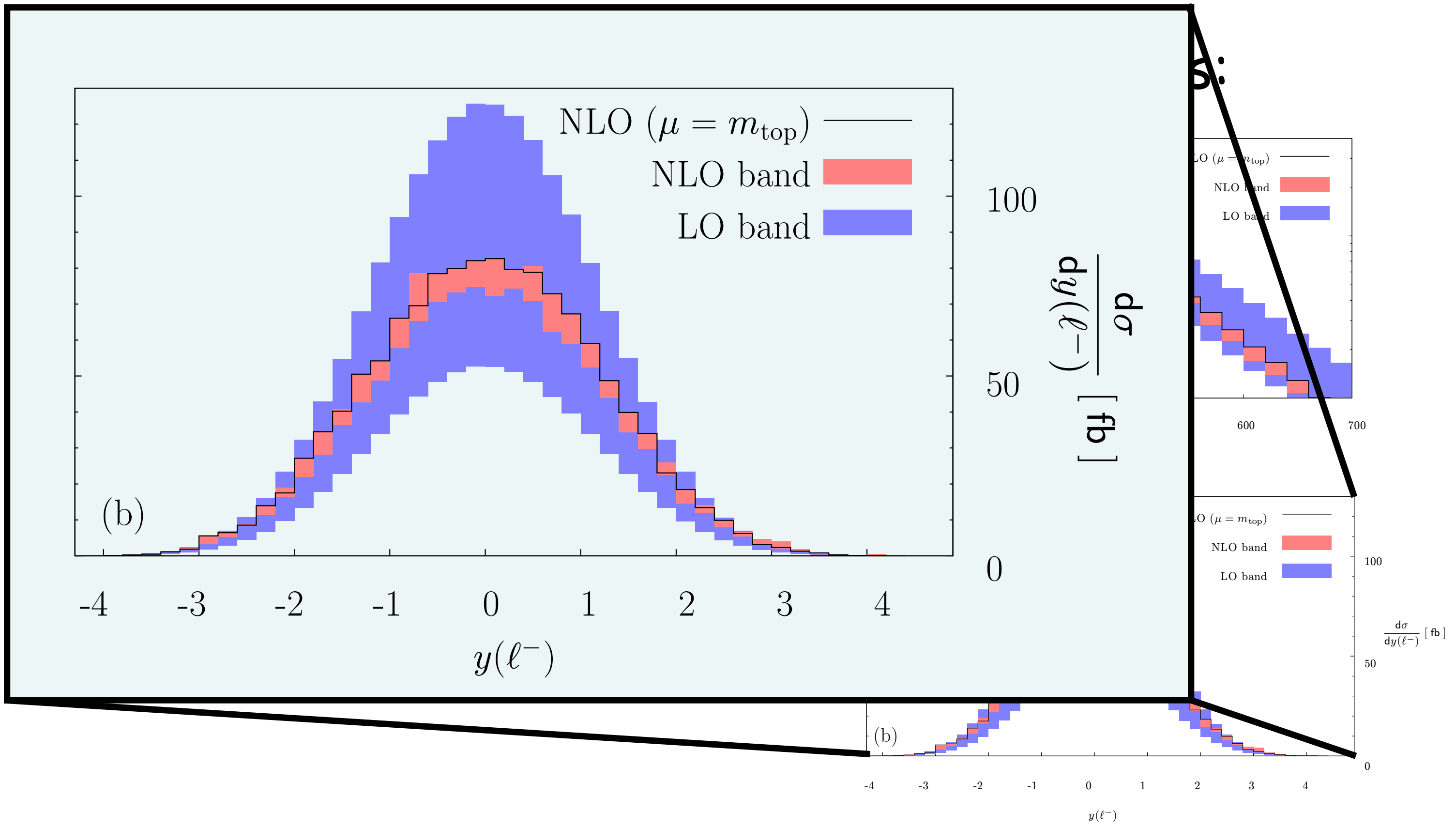




Process: $t\bar{t}$ + jet

Tevatron:
(semi-lept.)

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



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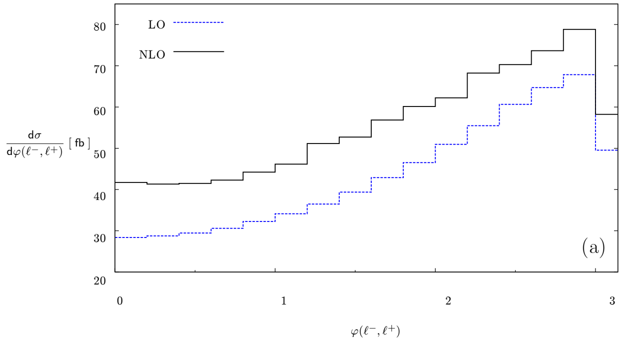

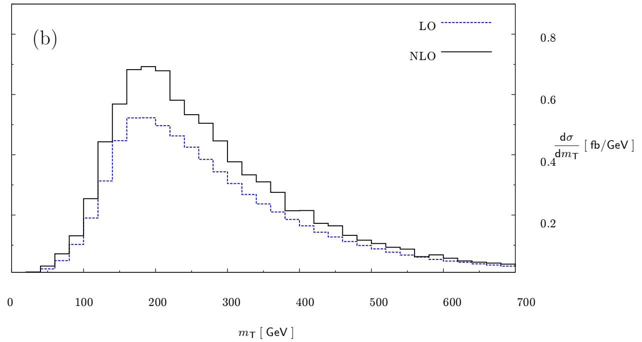

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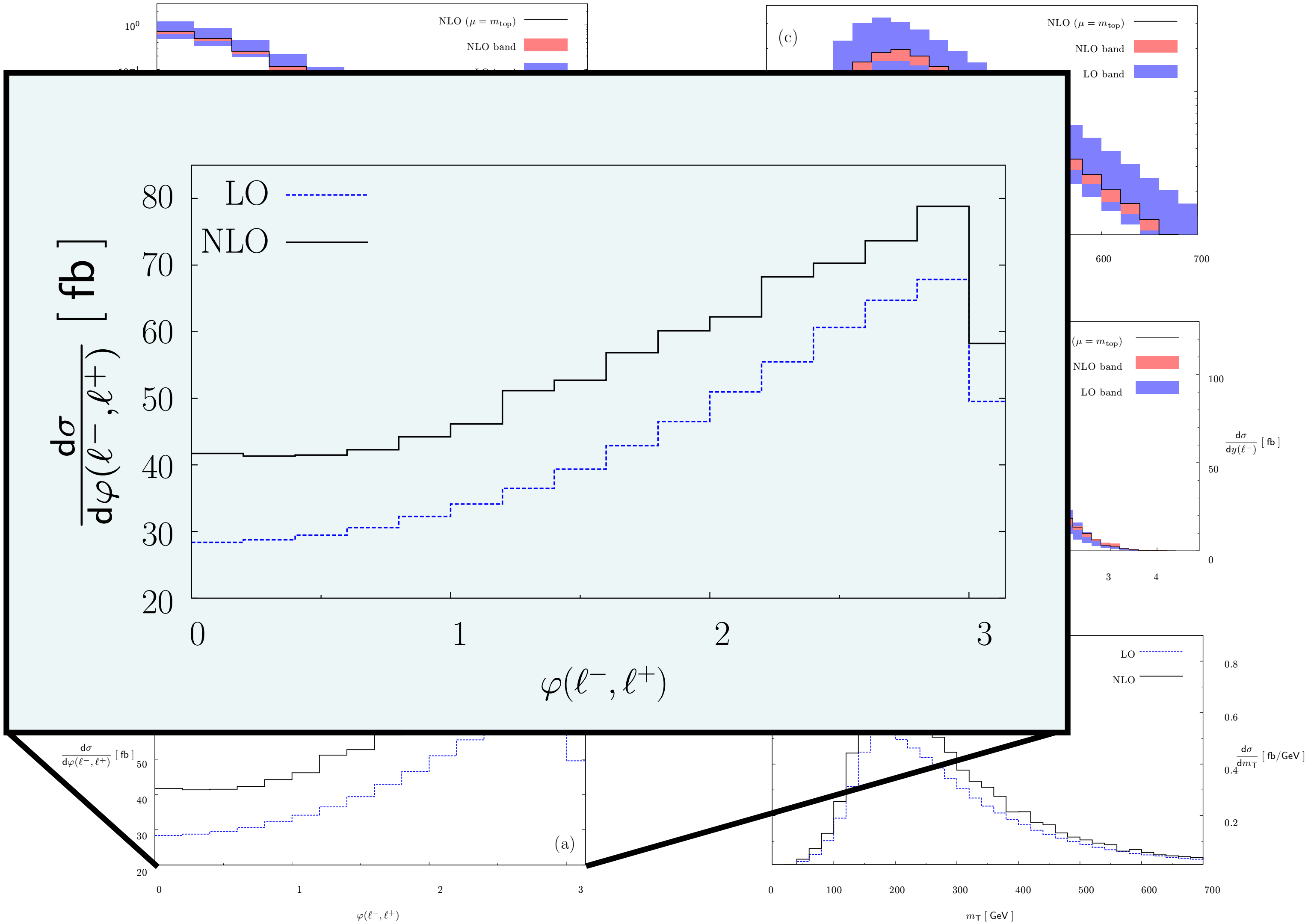

Process: $t\bar{t}$ + jet

Forward-Backward Asymmetry
at the Tevatron

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

[Kühn,Rodrigo]

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

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

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[Kühn,Rodrigo]

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

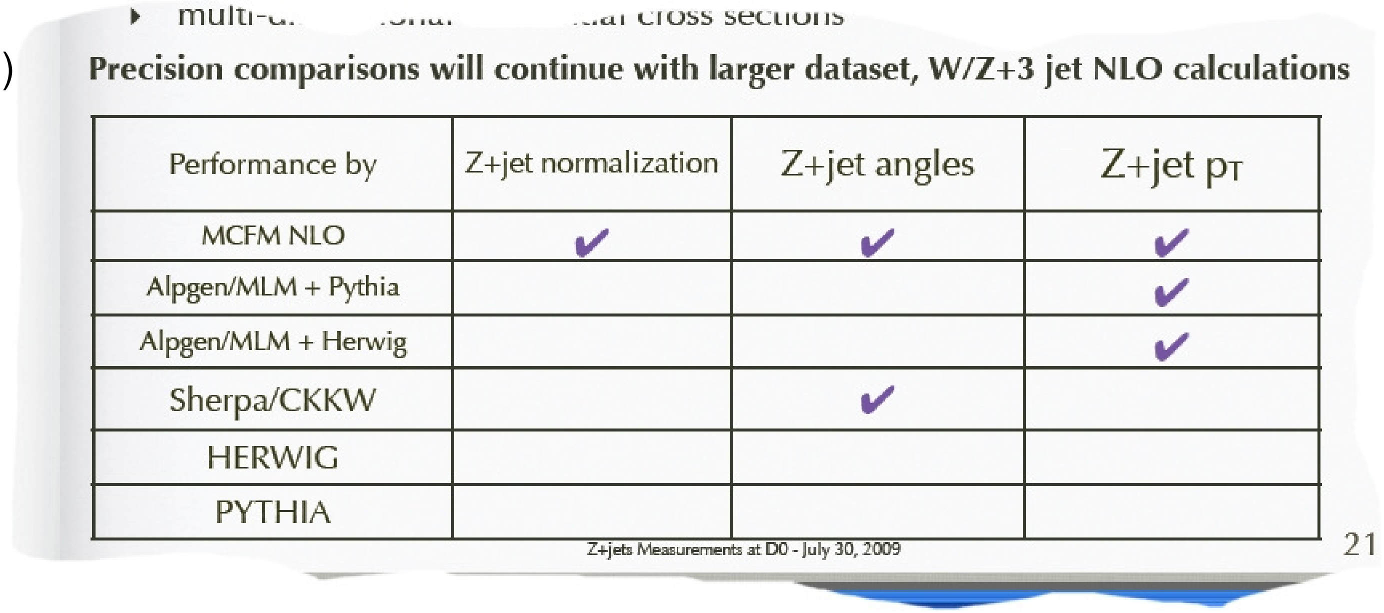
$$A_{t\bar{t}+\mathrm{jet}}(p_{\perp\mathrm{jet}} > 30\mathrm{GeV}) = \begin{cases} -8.3\% \pm 0.1\% & \text{LO} \\ -2.3\% \pm 0.5\% & \text{NLO} \end{cases}$$

in agreement with DUW

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

Sabine Lammers (U-Indiana, D0)

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



- multi-d onal ial cross sections

Precision comparisons will continue with larger dataset, W/Z+3 jet NLO calculations

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

Z+jets Measurements at D0 - July 30, 2009

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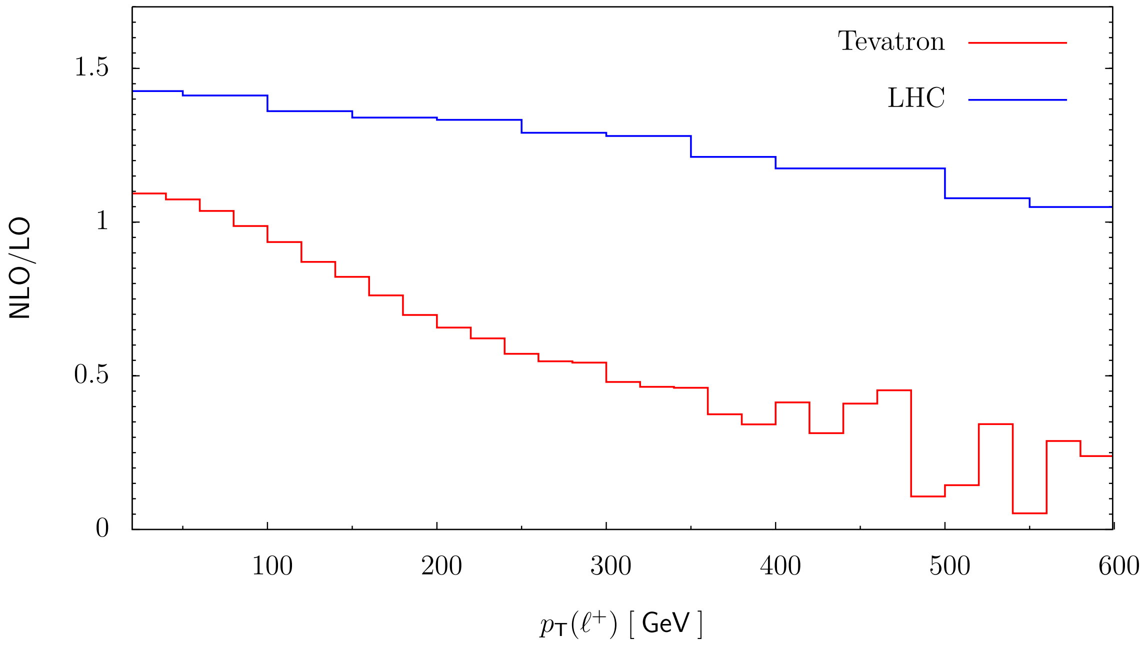
→ If precise measurements are available, NLO describes data best.

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

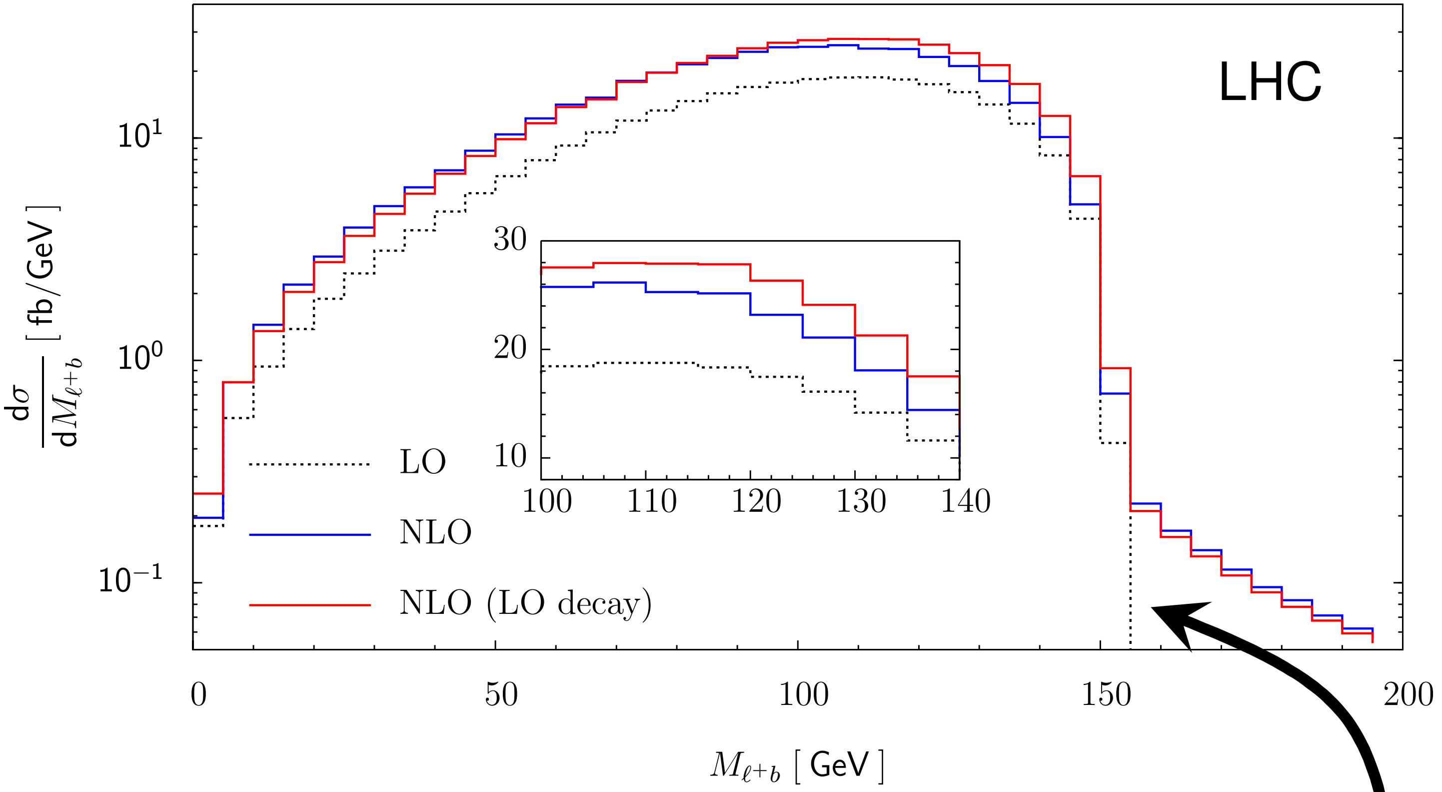
TEV → $\mathcal{O}$(1000) events

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

K - factor



invariant mass of lepton and b-jet



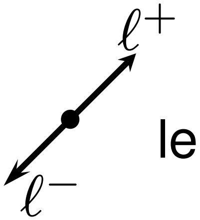
- boundary is top mass dependent
- spin studies for BSM particles
- NLO induces a tail

$$\max(M_{\ell+b}^2) = m_{\text{top}}^2 - m_W^2$$

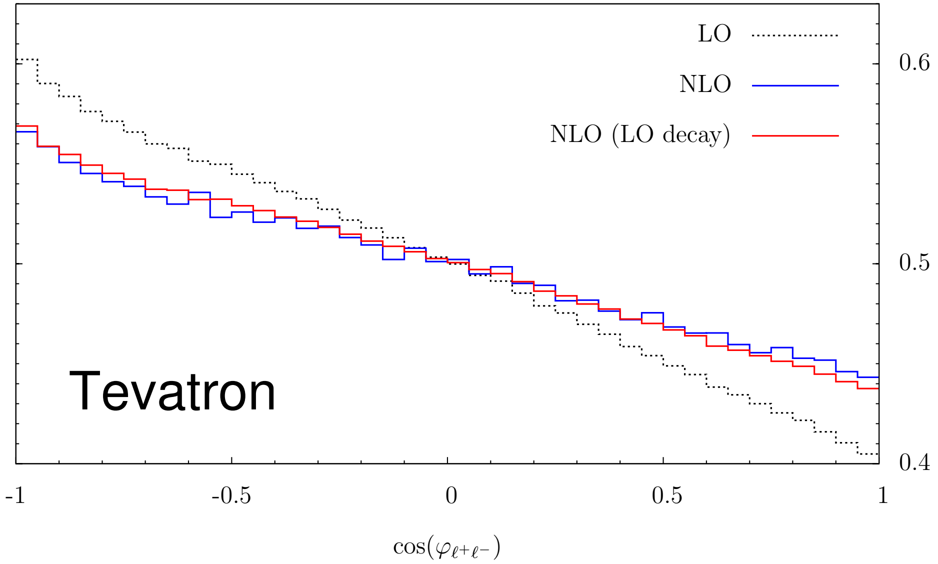
typical observable:

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

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



leptons preferably anti-parallel



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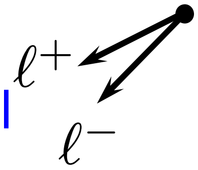
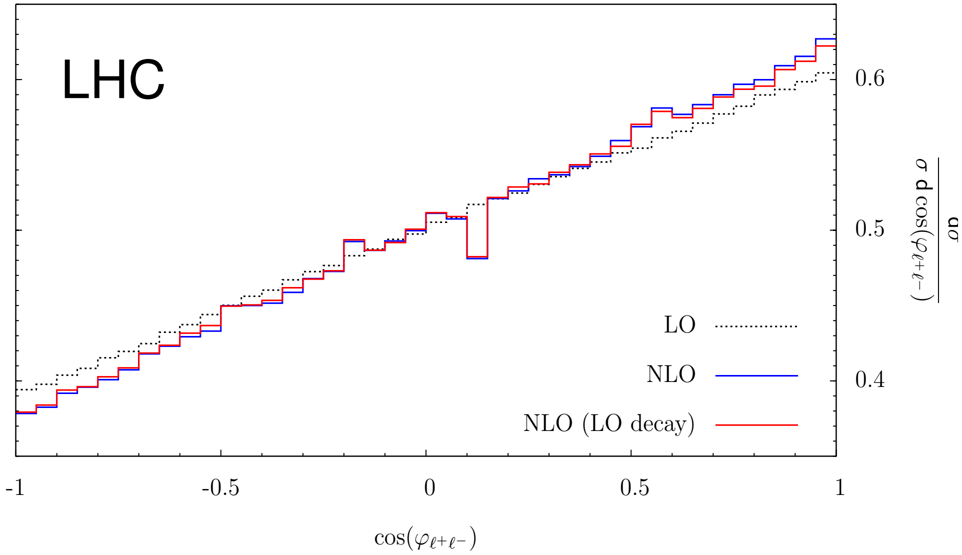


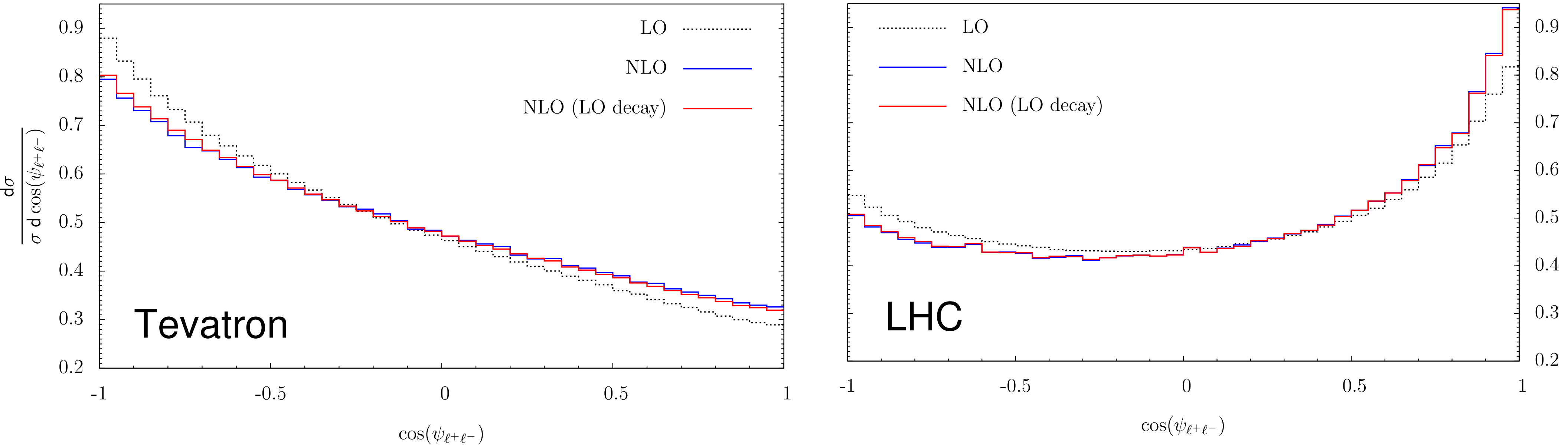


- substantial angular correlations, even at NLO
- NLO effects at Tevatron are significant

simpler observable:

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

$\psi_{\ell^+\ell^-}$: 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

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

Runtime

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

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

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

DUW: ≈ 10x faster for virtual corrections.

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