Electroweak top-quark pair hadroproduction in the presence of Z' bosons in POWHEG

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based on:
R. Bonciani, T. Jezo, M. Klasen, D. Lamprea, F. Lyonnet, I. Schienbein,
JHEP 1602 (2016) 141, arXiv: 1511.08185

<u>Outline</u>

Introduction

The calculation

Numerical results

Conclusions

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Introduction

Motivation pour Z' → t+tbar

- New heavy resonances Z' are predicted in a variety of models with extra U(1) or SU(2) symmetry, e.g.,
  - $E_6 \rightarrow SO(10) \times U(1)_\psi$, $SO(10) \rightarrow SU(5) \times U(1)_\chi$
  - LR symmetric models: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_Y$
  - G(221) models: $SU(3)_c \times SU(2)_1 \times SU(2)_2 \times U(1)_X$
- In many cases, the Z' can decay leptonically and the strongest constraints come from searches with leptonic final states [JHEP12(2014)092]
- Nevertheless, **final states with top quarks** are very interesting:
  - The heavy top quark may play a special role w.r.t. to EWSB and BSM physics which couples preferentially to the third generation or not to leptons
  - Even for models with couplings to leptons, the addition of top quark observables is important to distinguish between different BSM scenarios [PRD86(2012)035005]

This talk

- Here, we present our new calculation of NLO QCD corrections to EW top-pair production at the LHC in the presence of a Z' boson [arXiv:1511.08185]
  - Z' boson with general (flavour diagonal) couplings to SM fermions
  - Results are implemented in the POWHEG BOX MC event generator
  - Standard Model and new physics interference effects taken into account
  - QED singularities consistently subtracted
- Numerical results for the Sequential SM and a leptophobic TopColor model
  - SM and Z' total cross sections
  - Distributions: invariant mass, transverse momentum, azimuthal angle, rapidity of the top-quark pair

Leptophobic topcolor model

- New strong dynamics with $SU(3)_2$ symmetry coupling preferentially to the third generation while the original $SU(3)_1$ gauge group couples only to the 1st and 2nd generation; breaking $SU(3)_1 x SU(2)_2 \rightarrow SU(3)_c$
- Formation of top quark condensate generates large top mass
- To block the formation of a bottom quark condensate an additional $U(1)_2$ symmetry with associated Z' is introduced; $U(1)_1 x U(1)_2 \rightarrow U(1)_Y$
- Different couplings of the Z' to the three fermion generations define different variants of the model
- **Leptophobic TC model**: (model IV in hep-ph/9911288)
  - Z' couples only to 1st and 3rd generation
  - no significant coupling to leptons
  - experimentally accessible cross section at the LHC

Leptophobic topcolor model

- Three parameters (in addition to $M_{Z'}$):
  - Ratio of the two U(1) coupling constants: $\cot \Theta_H$
  - f_1: relative strength of the Z'-coupling to right-handed up-type quarks w.r.t. to the left-handed up-type quarks
  - f_2: same for down-type quarks

- $\cot \Theta_H$ should be large to enhance the condensation of top quarks but no bottom quarks

- The LO cross sections are usually computed using
  - a fixed small Z' width (which fixes $\cot \Theta_H$): $\Gamma_{Z'} = 1.2\% \ M_{Z'}$
  - $f_1=1$, $f_2=0$ (maximes the fraction of Z' bosons decaying into top pairs)

The calculation

Top-quark pair production

The partonic top-quark pair production cross section at NLO:

$$\sigma_{ab}(\mu_r) = \boxed{\sigma_{2;0}(\alpha_S^2)} + \sigma_{0;2}(\alpha^2) + \boxed{\sigma_{3;0}(\alpha_S^3)} + \sigma_{2;1}(\alpha_S^2\alpha) + \sigma_{1;2}(\alpha_S\alpha^2) + \sigma_{0;3}(\alpha^3)$$

- $\sigma_{2;0}$: SM QCD background
- $\sigma_{3;0}$: NLO QCD corrections to the SM background

- NLO known since the late 80ths — Nason, Dawson, Ellis '88/'89; Beenakker, Kuif, van Neerven, Smith '89; Bojak, Stratmann '03: polarized case
- NLO predictions for heavy quark correlations — Mangano, Nason, Ridolfi '92
- Spin correlations between t and tbar — Bernreuther, Brandenburg, Si, Uwer, '01/'04
- NNLO calculation recently completed — Czakon, Mitov '13: σ_{tot}; Czakon, Mitov '14: distributions

Top-quark pair production

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- $\sigma_{2;0}$: SM QCD background
- $\sigma_{3;0}$: NLO QCD corrections to the SM background
- $\sigma_{2;1}$: EW corrections to the QCD background

- Gauge invariant subset, no QCDxEW interferences from box diagrams — Beenakker,Denner,Hollik,Mertig,Sack,Wackeroth '94; Kao,Wackeroth '00: 2HDM
- Rest of EW corrections including Z-gluon interferences and corrections from real and virtual photons — Kühn,Scharf,Uwer, '06; Moretti,Nolten,Ross '06; Bernreuther,Fuecker,Si '06; Hollik,Kollar '08

Top-quark pair production

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Existing calculations including a Z' boson:

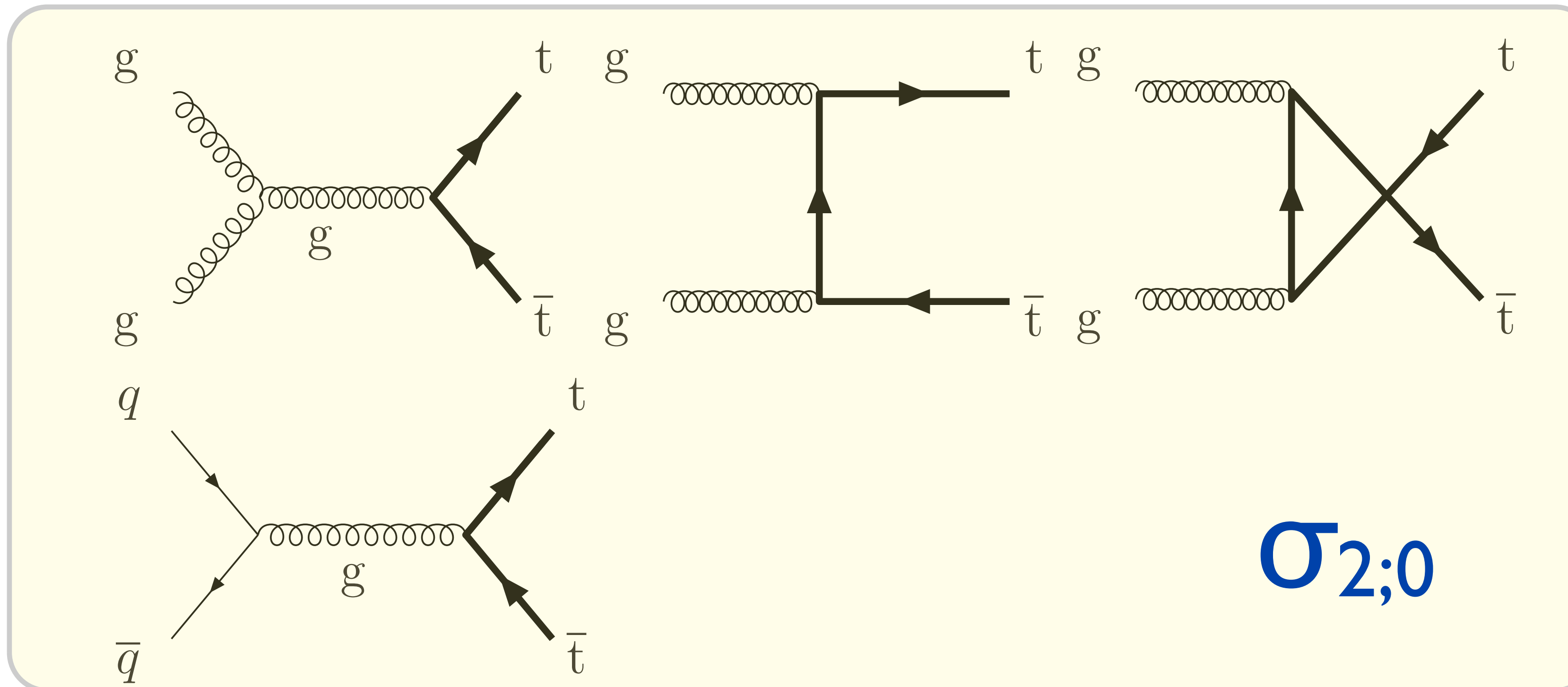
- Factorized approach (no SMxZ', no qg-channel with Z'), purely vector or axial vector or left or right couplings — Gao, C.S. Li, B.H. Li, Yuan, Zhu '10
- no SMxZ', includes: qg-channel, top-decay in NWA with spin correlations, Z' contribution to $\sigma_{2;1}$ (broad resonances) — Caola, Melnikov, Schulze '13

- **Our calculation**: includes: SMxZ' interferences, general couplings, QED contribution, POWHEG implementation, no top-decay, no Z' contribution to $\sigma_{2;1}$
  - $\sigma_{0;2}$: EW top-quark pair production — R. Bonciani, T. Jezo, M. Klasen, F. Lyonnet, IS: arXiv:1511.08185
  - $\sigma_{1;2}$: NLO QCD corrections to EW top-quark pair production

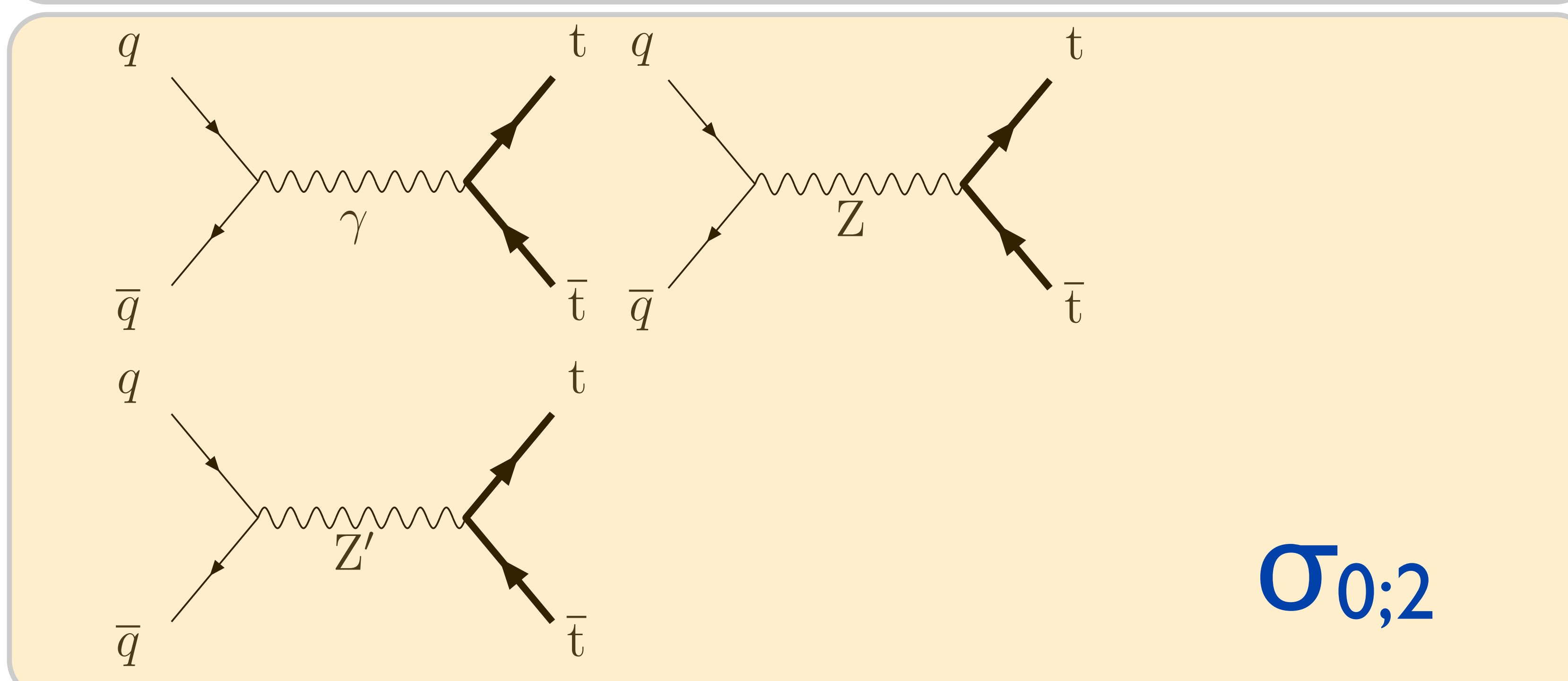
- $\sigma_{0;3}$: negligible

LO subprocesses: $\sigma_{2;0}$ and $\sigma_{0;2}$

- $\hat{\sigma}^{\mathrm{LO}} = \hat{\sigma}_S^{\mathrm{LO}}(\alpha_S^2) + \hat{\sigma}_W^{\mathrm{LO}}(\alpha_W^2)$
- SM
  - gg, $\mathcal{O}(\alpha_S^2)$:
  - $q\bar{q}$, $\mathcal{O}(\alpha_S^2)$:



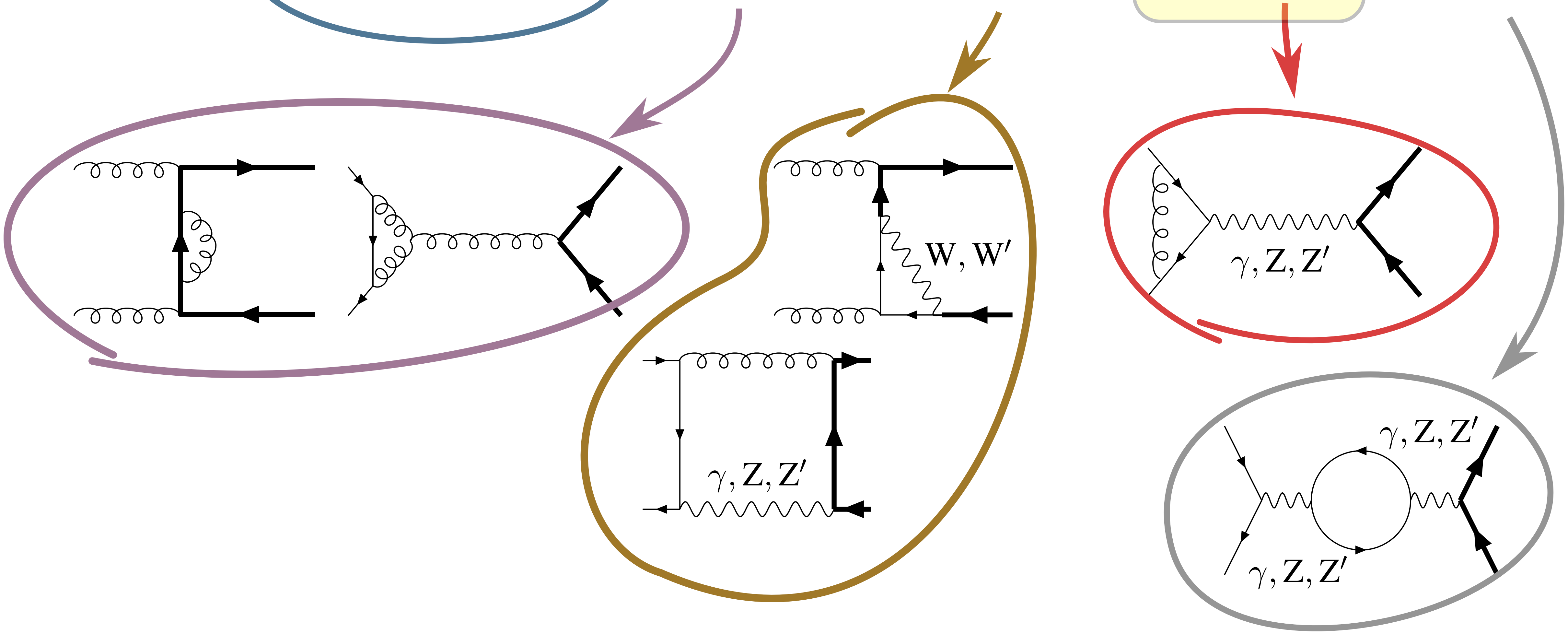
  - $q\bar{q}$, $\mathcal{O}(\alpha_W^2)$:
- beyond SM
  - $q\bar{q}$, $\mathcal{O}(\alpha_W^2)$:



NLO virtual

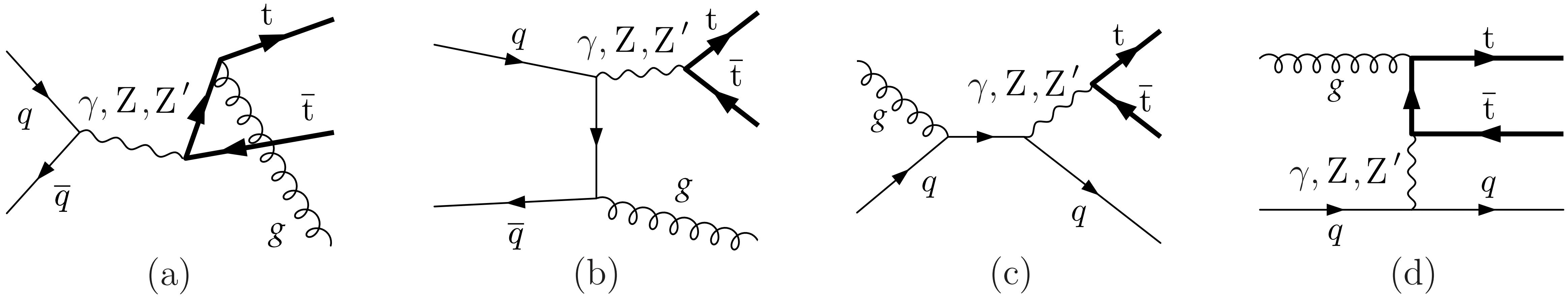
LO

- $\hat{\sigma}^{\text{NLO}} = \hat{\sigma}(\alpha_S^2) + \hat{\sigma}(\alpha_W^2) + \hat{\sigma}(\alpha_S^3) + \hat{\sigma}(\alpha_S^2\alpha_W) + \hat{\sigma}(\alpha_S\alpha_W^2) + \hat{\sigma}(\alpha_W^3)$



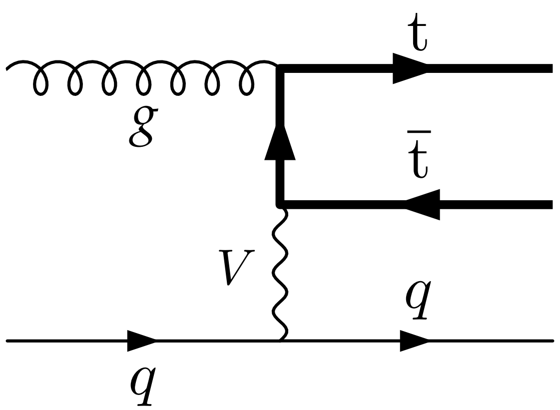
- $\mathcal{O}(\alpha_S^3)$ not affected by the presence of Z′
- we calculate $\mathcal{O}(\alpha_S\alpha_W^2)$

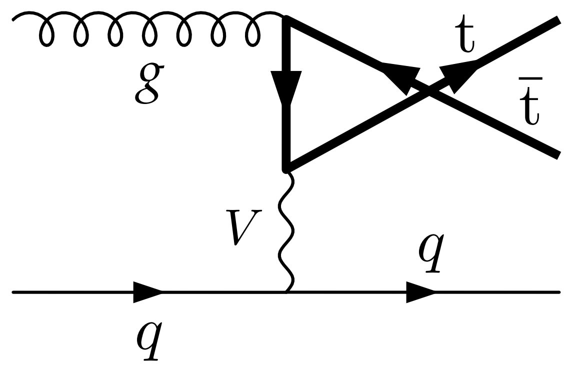
NLO real corrections

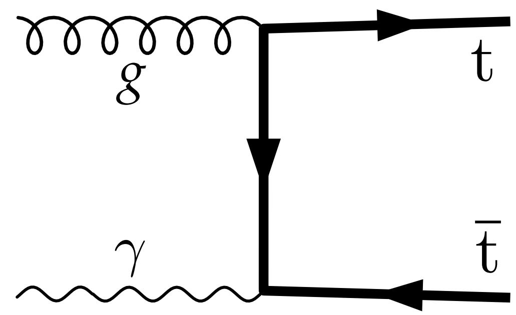


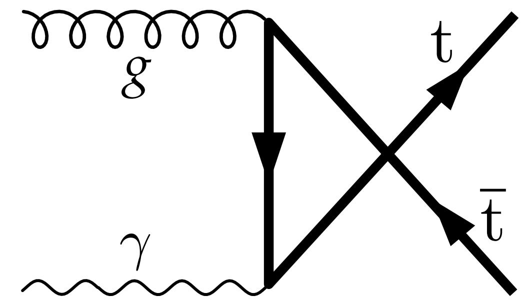
- interferences of real and real diagrams
- new channel as compared to tree-level and 1-loop diagrams
- no loops, no UV divergences
- IR divergences, after integration over 1 particle phase space
  - soft (S) divergences: radiation of a soft gluon (a), (b)
  - initial state collinear (ISC) divergences: (b), (d)
  - no final state collinear (FSC) divergences

QED contribution









- The gq-channel has an initial state C-div. associated to a photon propagator
- For the mass factorization procedure need to introduce a photon PDF and have to include photon-initiated subprocesses
- Counting the photon PDF as $O(\alpha)$ the LO gγ-channel contributes to $\sigma_{1;2}(\alpha_s\alpha^2)$
- This channel turns out to be numerically important

Shower Monte Carlo's (SMCs) at NLO QCD

- SMCs@LO
  - automatically generate low angle radiation via PS
  - simulates hadronization, decay of unstable hadrons
  - resums contributions in near collinear regions to all orders
  - lack accuracy

- SMCs@NLO: non-trivial
  - PS generates higher-order contributions in collinear regions
  - NLO QCD already contains those contributions
  - application of PS on NLO QCD would lead to overcounting

- PS and NLO QCD calculation need to be matched
  - MC@NLO: SMC dependent, can lead to events with negative weights
  - POWHEG: SMC independent, only positive weighted events

MC@NLO: hep-ph/0305252 ; POWHEG: arXiv:0707.3088

POWHEG Box implementation

User input:

- List of all flavour structures of tree level (Born, Real) processes
- Born phase space
- Born amplitude squared, Color-correlated Born amplitude, Spin-correlated Born amplitude
- Finite part of the virtual amplitude
- Real amplitude squared

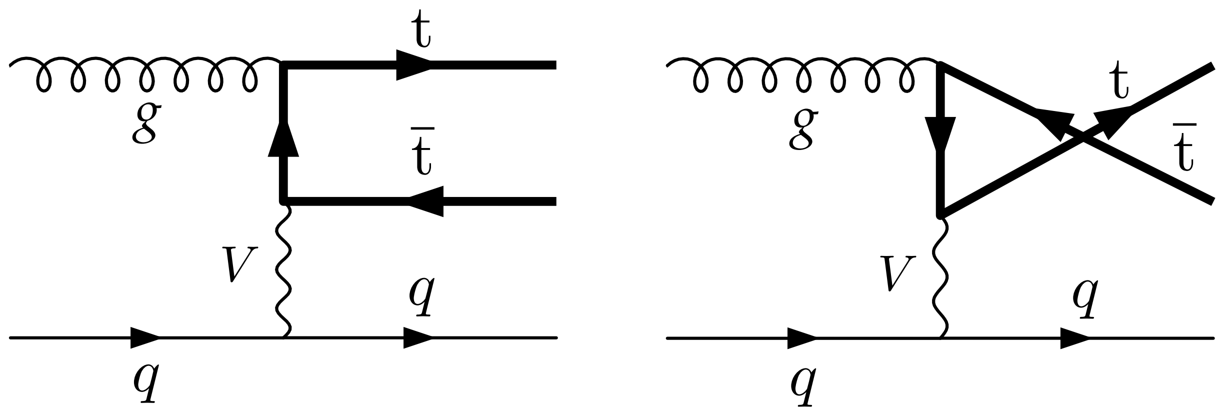
POWHEG Box:

S. Alio, P. Nason, C. Oleari, E. Re:arXiv:1002.2581

- Finds all the singular regions
- Constructs the soft and collinear counter terms
- Builds the collinear remnants (i.e. the finite part after the subtractions)
- Generates the events with Born kinematics (including the virtual corrections)
- Generates the hardest emission of the PS

POWHEG Box implementation

QED contribution:



- The diagrams above involve photon-initiated underlying Born diagrams, preceded by a splitting of a quark into a photon
- The corresponding QED singularities were so far not treated properly in POWHEG (only the singular emission of final state photons had been implemented in version 2 of POWHEG BOX)
- We therefore
  - replaced the POWHEG subtraction for the $q \to g+q$ splitting by a similar procedure for the QED $q \to \gamma+q$ splitting
  - enabled the POWHEG flag for real photon emission (which then allows for the automatic factorization of the QED singularity and the use of photon PDFs)
  - implemented the photon-initiated Born structures

Validation

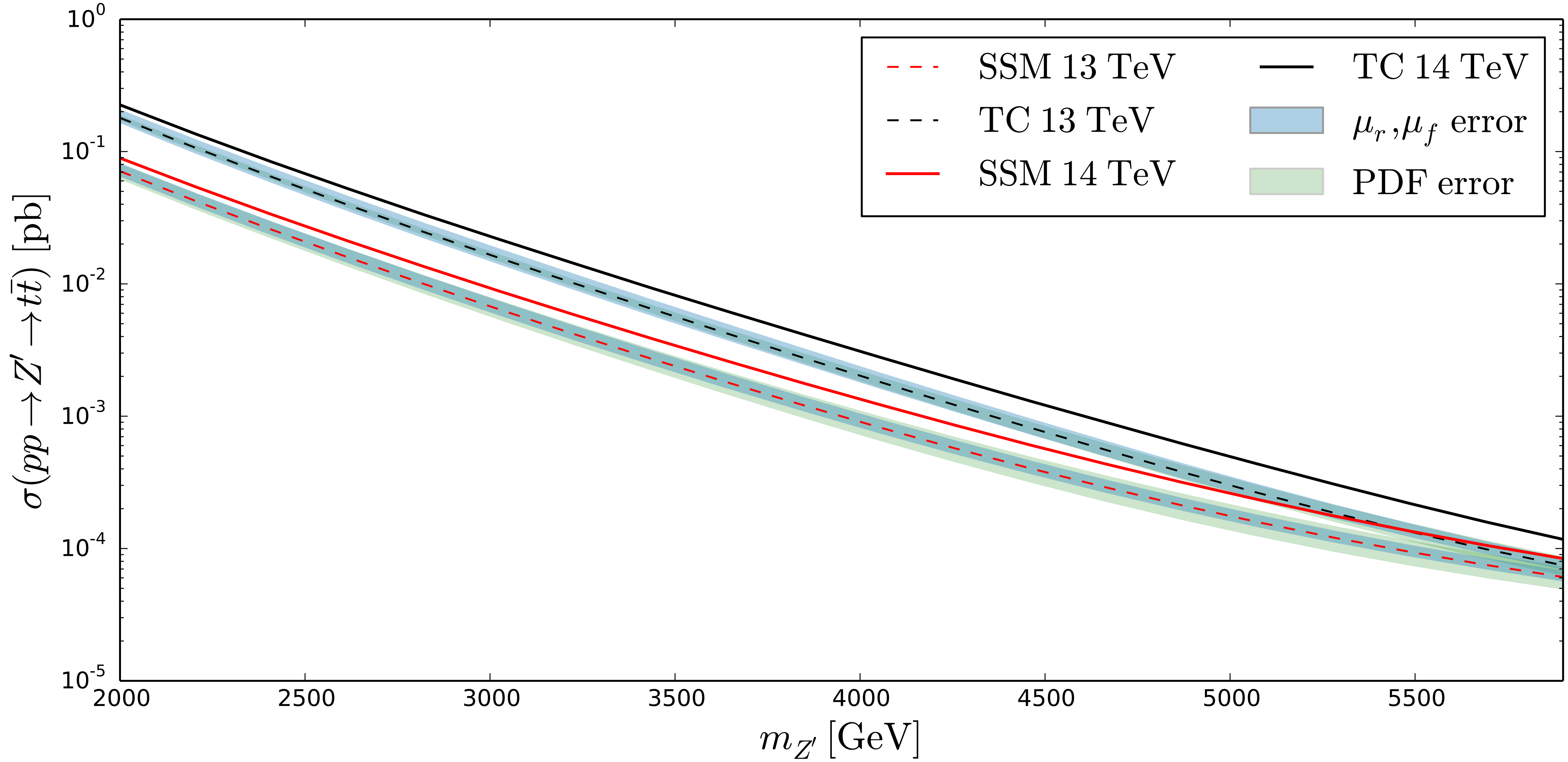
- Our implementation of EW top pair production with Z' contributions has been added to the list of POWHEG processes under the name: *PBZp*
- Our SM Born, Real amplitudes in agreement with MadGraph5_aMC@NLO
- $1/\varepsilon$ expansion of our virtual matrix elements checked against GoSam
- For the full calculation: UV and IR divergences cancel
- Checked completeness relations for color- and spin-correlated Born amplitudes
- Did the automated POWHEG checks for the kinematic limits of the real emission amplitudes
- For the q-qbar process in the SM: total hadronic cross section in agreement with MadGraph5_aMC@NLO (which does not allow for a proper treatment of the QED divergence in the gq subprocess)
- Agreement with Gao et al within 2% if we reduce our calculation to their setup [no SMxZ', no gq-channel, purely vector or purely axial-vector couplings]
- Agreement with the K-factors of Caola et al if we remove the SMxZ' interferences and the factorizable QCD corrections to the top quark decay

Numerical results

Numerical results: Input

- With our **POWHEG** implementation **PBZp** at LO and NLO coupled to the PS and hadronization procedure in **PYTHIA 8**
- Results for LHC13 (total cross sections also at LHC14)
- NNPDF23_nlo_as0118_qed PDFs (including a photon PDF)
- central scale choice: $\mu_R^2 = \mu_F^2 = \text{shat}$
  (applies also to the SM channels where no $M_{Z'}$ present)
- Models:
  - SSM: $\Gamma/M_{Z'} = 3.2\%$
  - leptophobic TopColor (LPTC): $\Gamma/M_{Z'} = 1.2\%, f_1=1, f_2=0$

Resonant-only Z'-boson production at NLO

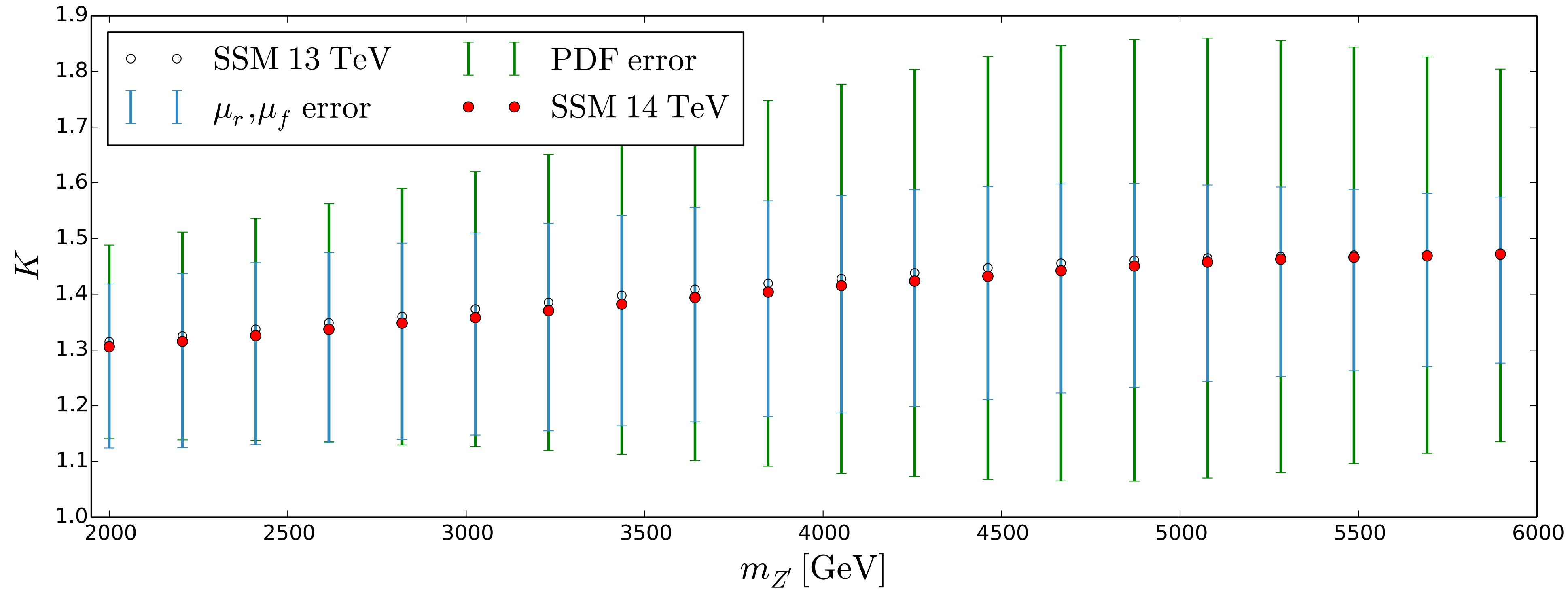


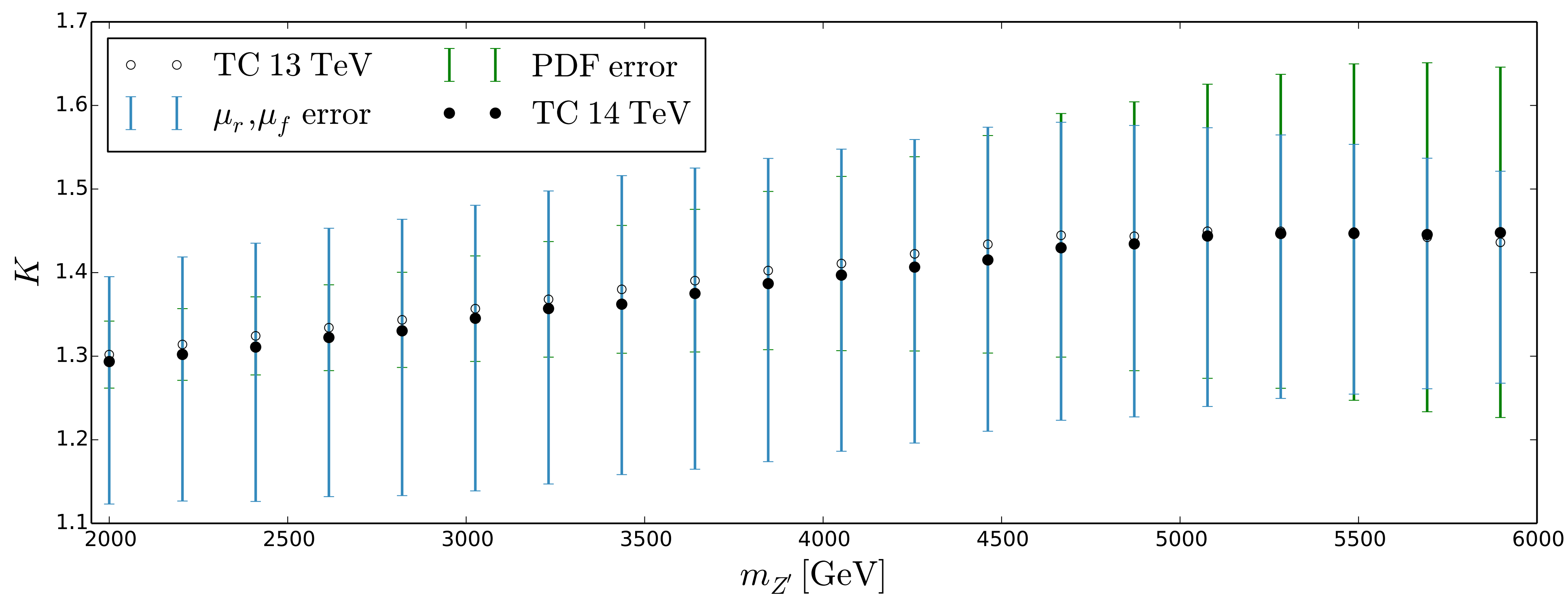
- SSM (lower curves):
  - For Lint = 100 fb^{-1}, LHC13: number of expected events 10^4 ($M_{Z'}$=2 TeV) ... 10 ($M_{Z'}$=6 TeV)
  - Uncertainties range from 15% - 35%
    Interestingly, the PDF uncertainty dominates over entire $M_{Z'}$ range shown
- LPTC model: Uncertainties range from 15% - 20%. Scale uncertainty dominates for $M_{Z'}$ < 5 TeV

Resonant-only Z'-boson production at NLO

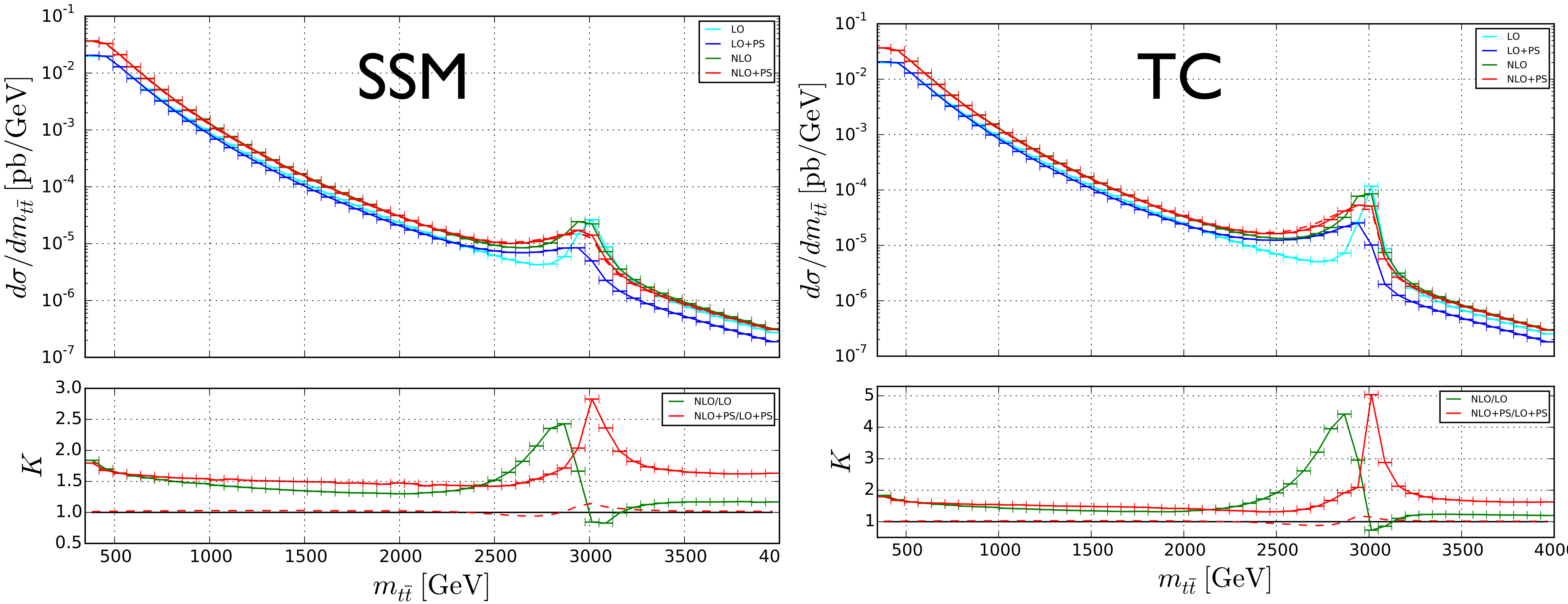
The K-factor ranges from 1.3 to 1.45.

Not entirely mass-independent even for resonant only Z'-boson production!



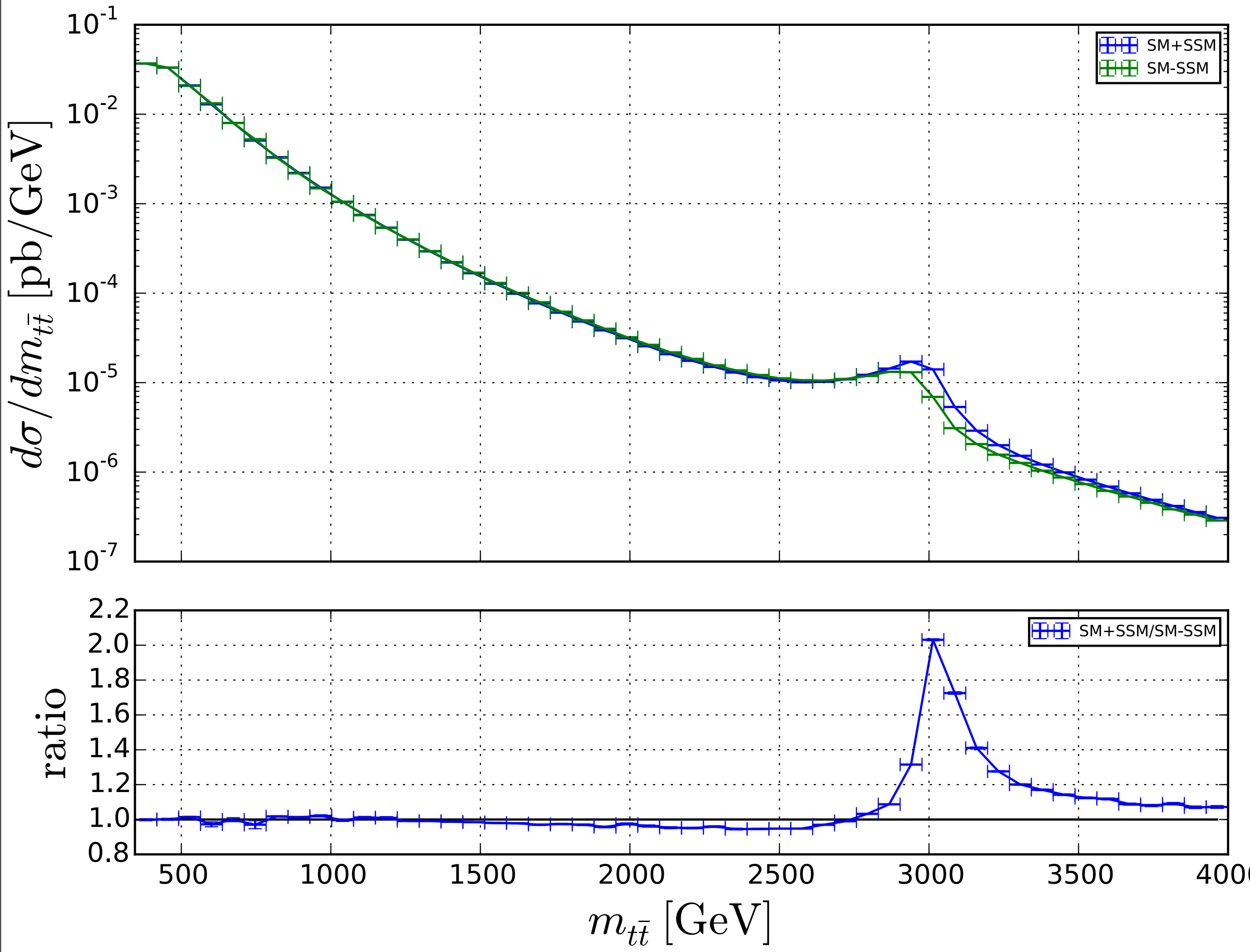


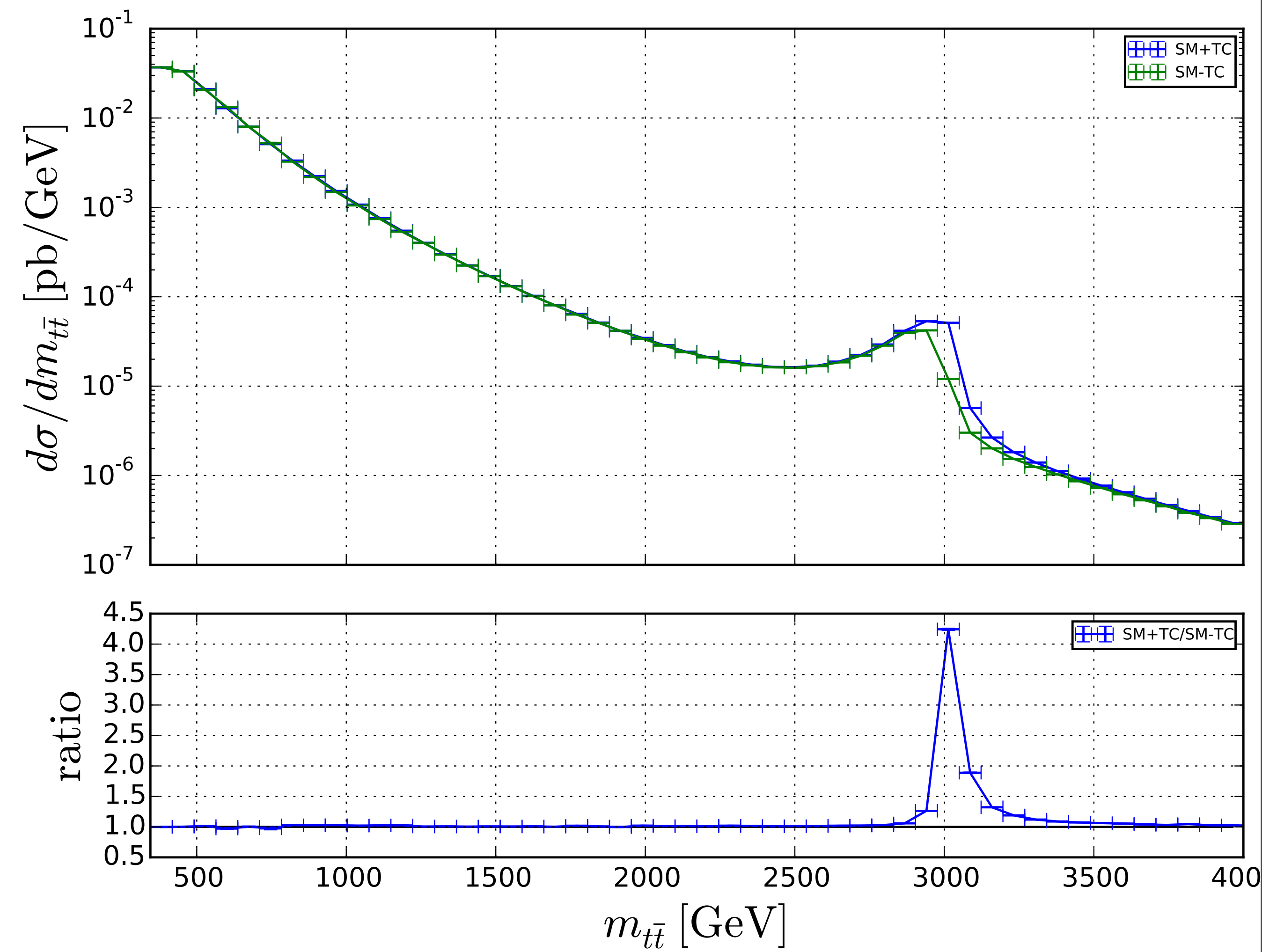
Invariant mass distributions for $M_{Z'}$=3 TeV



- Steeply falling spectra from 10^{-2} to 10^{-7} pb/GeV
- TC resonance peak about an order of magnitude larger (for the chosen couplings)
- K-factors highly dependent on invariant mass region
(position of resonance peak shifted to lower masses at NLO compared to LO due to radiation)
- Red dashed line: ratio of result obtained with PYTHIA over HERWIG as parton shower

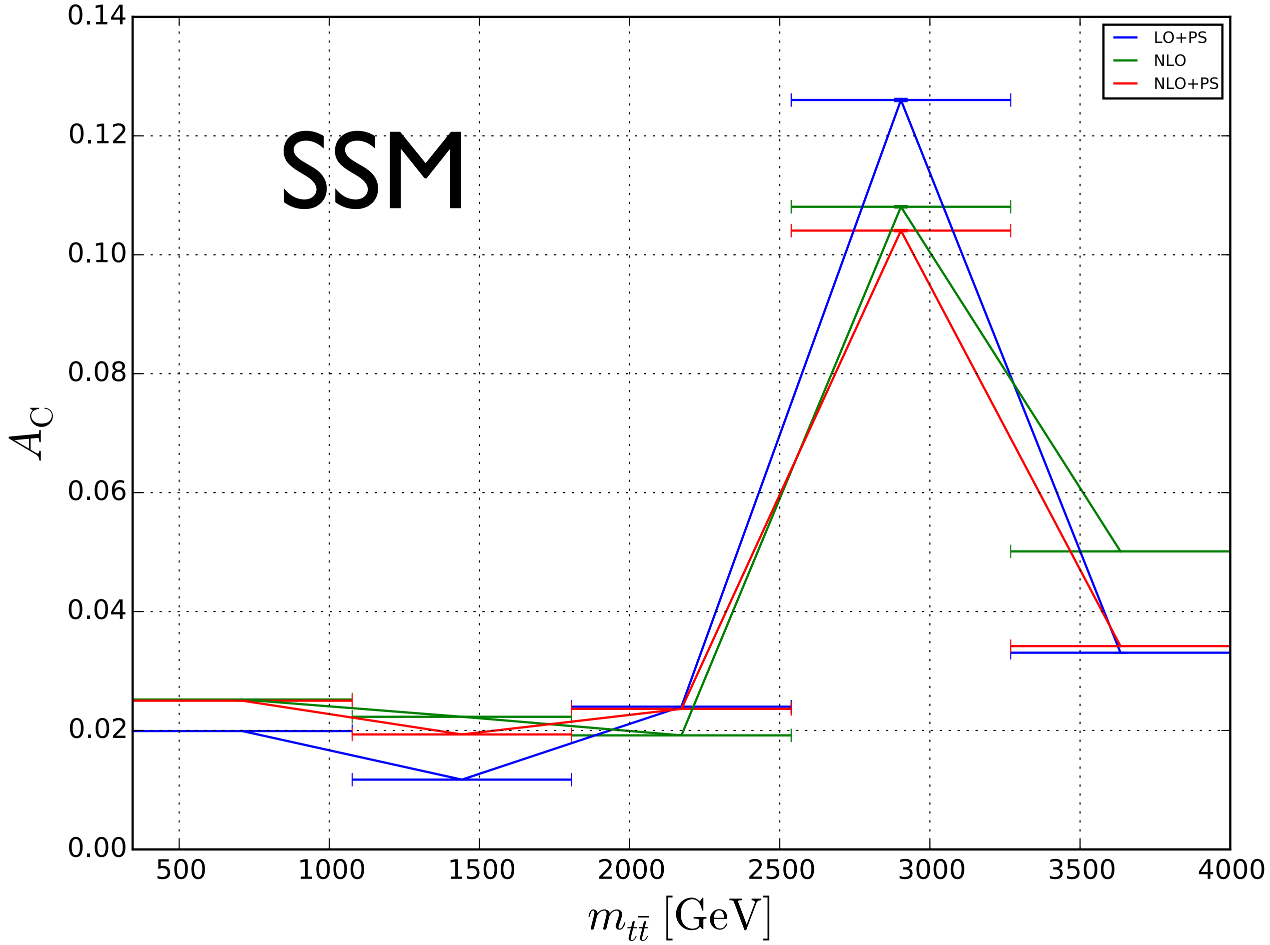
Effect of interferences

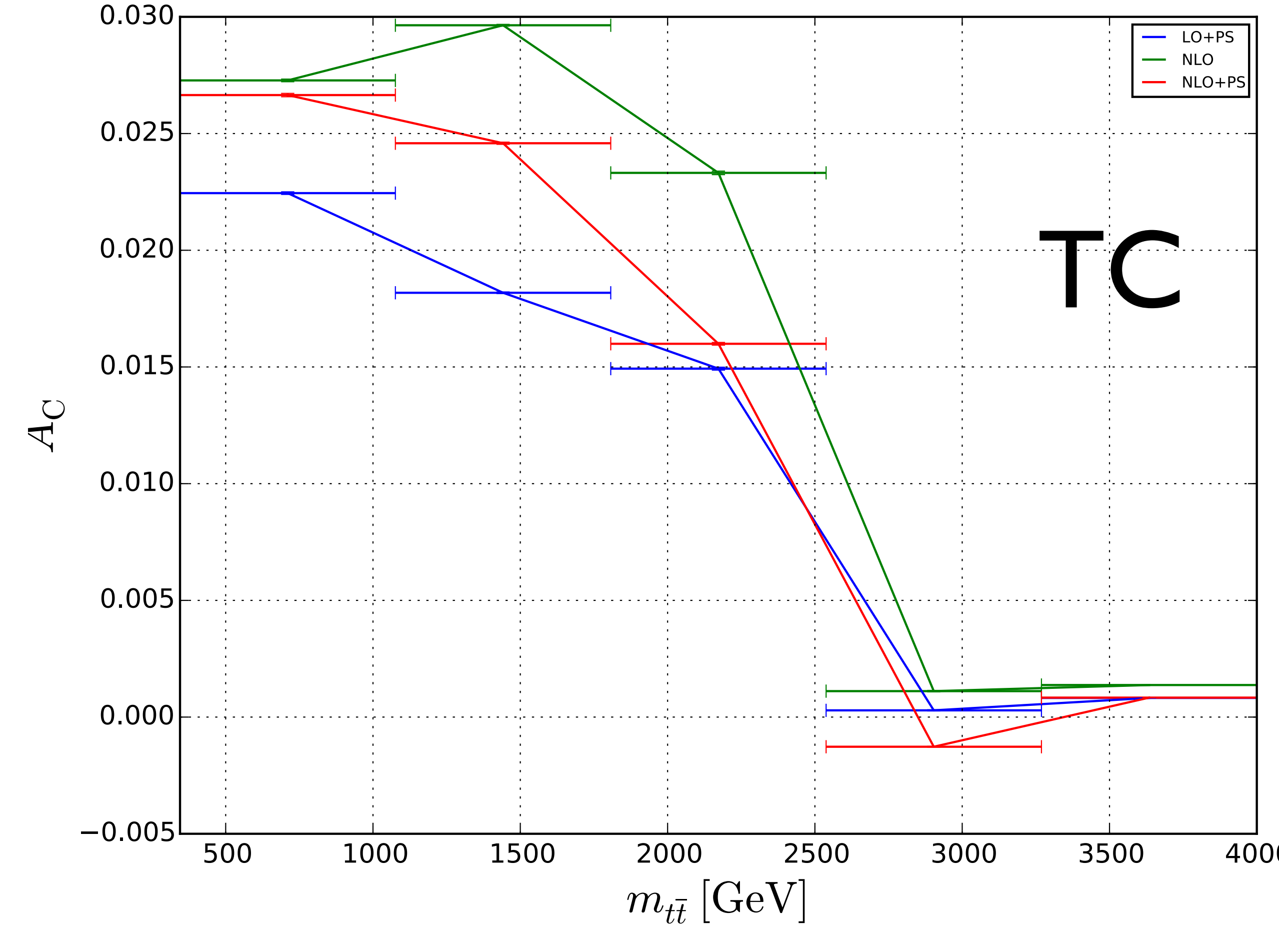




- Blue curves: without interference terms
- Green curves: with interference terms
  Shifts resonance peak to smaller masses
- Ratio = Blue curve/Green curve
  Predictions without interferences overestimate the true signal by a factor of >2

Charge asymmetry A_c





$$A_c = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

- Charge asymmetry known to be quite sensitive to distinguish different models
- At the resonance: **A_c = 11±1%** (SSM) **vs ±0.1%** (TC)
- Far below resonance: **A_c = 2.5±0.5%** (SSM and TC)

Conclusions

Conclusions

- Presented a new calculation of NLO QCD corrections to EW top-pair production at the LHC in the presence of a Z' boson
  - Z' boson with general (flavour diagonal) couplings to SM fermions
  - Results implemented in the POWHEG BOX MC event generator; called **PBZp**
  - Standard Model and new physics interference effects taken into account.
    They are non-negligible in particular for the invariant mass distribution.
  - QED singularities consistently subtracted. This contribution has a large impact.
- Showed numerical results for the Sequential SM and a leptophobic TopColor model
  - SM and Z' total cross sections
  - Distributions: invariant mass, transverse momentum, azimuthal angle, rapidity of the top-quark pair
  - Charge asymmetry promising to distinguish between models
- Similar calculation for the W' → tb case hopefully soon completed

Backup slides

Total cross sections for $M_{Z'}$ = 3 TeV

For LO uses the NNPDF23_lo_as0119_qed PDF set

pure QCD

photon ind.
factor 1/100

pure EW
factor 1/1000

Order	Processes	Model	σ [pb]	σ [pb] ($m_{t\bar{t}} > \frac{3}{4} m_{Z'}$)
LO	$q\bar{q}/gg \to t\bar{t}$		473.93(7)	0.15202(2)
NLO	$q\bar{q}/gg + qg \to t\bar{t} + q$		1261.0(2)	0.45255(7)
LO	$\gamma g + g\gamma \to t\bar{t}$		4.8701(8)	0.0049727(6)
LO	$\gamma g + g\gamma \to t\bar{t}$ (NLO α_s and PDFs)		5.1891(8)	0.004661(6)
LO	$q\bar{q} \to \gamma/Z \to t\bar{t}$	SM	0.36620(7)	0.00017135(3)
NLO	$q\bar{q} \to \gamma/Z \to t\bar{t}$	SM	0.5794(1)	0.00017174(5)
NLO	$q\bar{q} + qg \to \gamma/Z + q \to t\bar{t} + q$	SM	4.176(2)	0.001250(6)
LO	$q\bar{q} \to Z' \to t\bar{t}$	SSM	0.0050385(8)	0.0044848(7)
LO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	SSM	0.35892(7)	0.0043464(7)
NLO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	SSM	0.5676(1)	0.005155(3)
NLO	$q\bar{q} + qg \to \gamma/Z/Z' + q \to t\bar{t} + q$	SSM	4.172(2)	0.007456(9)
LO	$q\bar{q} \to Z' \to t\bar{t}$	TC	0.012175(2)	0.011647(2)
LO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	TC	0.38647(7)	0.011984(2)
NLO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	TC	0.6081(2)	0.01468(1)
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NLO	$q\bar{q} + qg \to \gamma/Z/Z' + q \to t\bar{t} + q$	SSM	4.172(2)	0.007456(9)
LO	$q\bar{q} \to Z' \to t\bar{t}$	TC	0.012175(2)	0.011647(2)
LO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	TC	0.38647(7)	0.011984(2)
NLO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	TC	0.6081(2)	0.01468(1)
NLO	$q\bar{q} + qg \to \gamma/Z/Z' + q \to t\bar{t} + q$	TC	4.202(2)	0.01002(1)

~366fb

interference: -4% for SSM

interference: +2% for TC

Total cross sections for $M_{Z'}$ = 3 TeV

For LO uses the NNPDF23_lo_as0119_qed PDF set

cut reduces bgd by more than three orders of mag.

cut reduces signal by only about 10%;
still signal only 3% to 8% of QCD background
→ additional cuts needed

Order	Processes	Model	σ [pb]	σ [pb] $(m_{t\bar{t}} > \frac{3}{4} m_{Z'})$
	$gg \to t\bar{t}$		473.93(7)	0.15202(2)
	$gg + qg \to t\bar{t} + q$		1261.0(2)	0.45255(7)
LO	$\gamma g + g\gamma \to t\bar{t}$		4.8701(8)	0.0049727(6)
LO	$\gamma g + g\gamma \to t\bar{t}$ (NLO α_s and PDFs)		5.1891(8)	0.004661(6)
LO	$q\bar{q} \to \gamma/Z \to t\bar{t}$	SM	0.36620(7)	0.00017135(3)
	$\to \gamma/Z \to t\bar{t}$	SM	0.5794(1)	0.00017174(5)
	$+ qg \to \gamma/Z + q \to t\bar{t} + q$	SM	4.176(2)	0.001250(6)
	$\to Z' \to t\bar{t}$	SSM	0.0050385(8)	0.0044848(7)
	$\to \gamma/Z/Z' \to t\bar{t}$	SSM	0.35892(7)	0.0043464(7)
	$\to \gamma/Z/Z' \to t\bar{t}$	SSM	0.5676(1)	0.005155(3)
NLO	$q\bar{q} + qg \to \gamma/Z/Z' + q \to t\bar{t} + q$	SSM	4.172(2)	0.007456(9)
LO	$q\bar{q} \to Z' \to t\bar{t}$	TC	0.012175(2)	0.011647(2)
LO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	TC	0.38647(7)	0.011984(2)
NLO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	TC	0.6081(2)	0.01468(1)
NLO	$q\bar{q} + qg \to \gamma/Z/Z' + q \to t\bar{t} + q$	TC	4.202(2)	0.01002(1)

Total cross sections for $M_{Z'}$ = 3 TeV

For LO uses the NNPDF23_lo_as0119_qed PDF set

Order	Processes	Model	σ [pb]	σ [pb] $(m_{t\bar{t}} > \frac{3}{4} m_{Z'})$
LO	$q\bar{q}/gg \to t\bar{t}$		473.93(7)	0.15202(2)
NLO	$q\bar{q}/gg + qg \to t\bar{t} + q$		1261.0(2)	0.45255(7)
LO	$\gamma g + g\gamma \to t\bar{t}$		4.8701(8)	0.0049727(6)
LO	$\gamma g + g\gamma \to t\bar{t}$ (NLO α_s and PDFs)		5.1891(8)	0.004661(6)
LO	$q\bar{q} \to \gamma/Z \to t\bar{t}$	SM	0.36620(7)	0.00017135(3)
NLO	$q\bar{q} \to \gamma/Z \to t\bar{t}$	SM	0.5794(1)	0.00017174(5)
NLO	$q\bar{q} + qg \to \gamma/Z + q \to t\bar{t} + q$	SM	4.176(2)	0.001250(6)
LO	$q\bar{q} \to Z' \to t\bar{t}$	SSM	0.0050385(8)	0.0044848(7)
LO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	SSM	0.35892(7)	0.0043464(7)
NLO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	SSM	0.5676(1)	0.005155(3)
NLO	$q\bar{q} + qg \to \gamma/Z/Z' + q \to t\bar{t} + q$	SSM	4.172(2)	0.007456(9)
LO	$q\bar{q} \to Z' \to t\bar{t}$	TC	0.012175(2)	0.011647(2)
LO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	TC	0.38647(7)	0.011984(2)
NLO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	TC	0.6081(2)	0.01468(1)
NLO	$q\bar{q} + qg \to \gamma/Z/Z' + q \to t\bar{t} + q$	TC	4.202(2)	0.01002(1)

large K-factor (qg-channel!)

K~1.56

proper subtr.

K~1.58

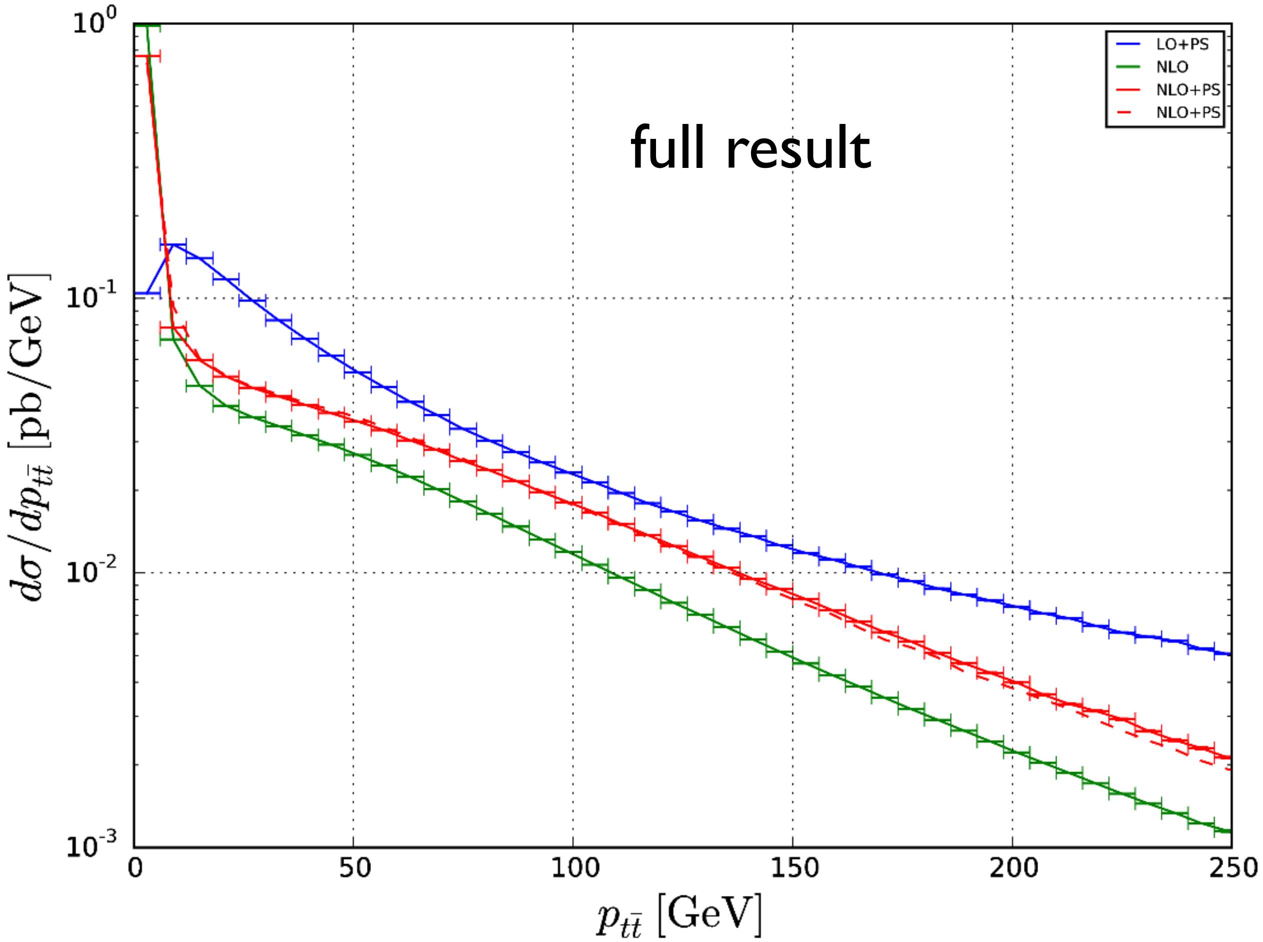
K~1.56

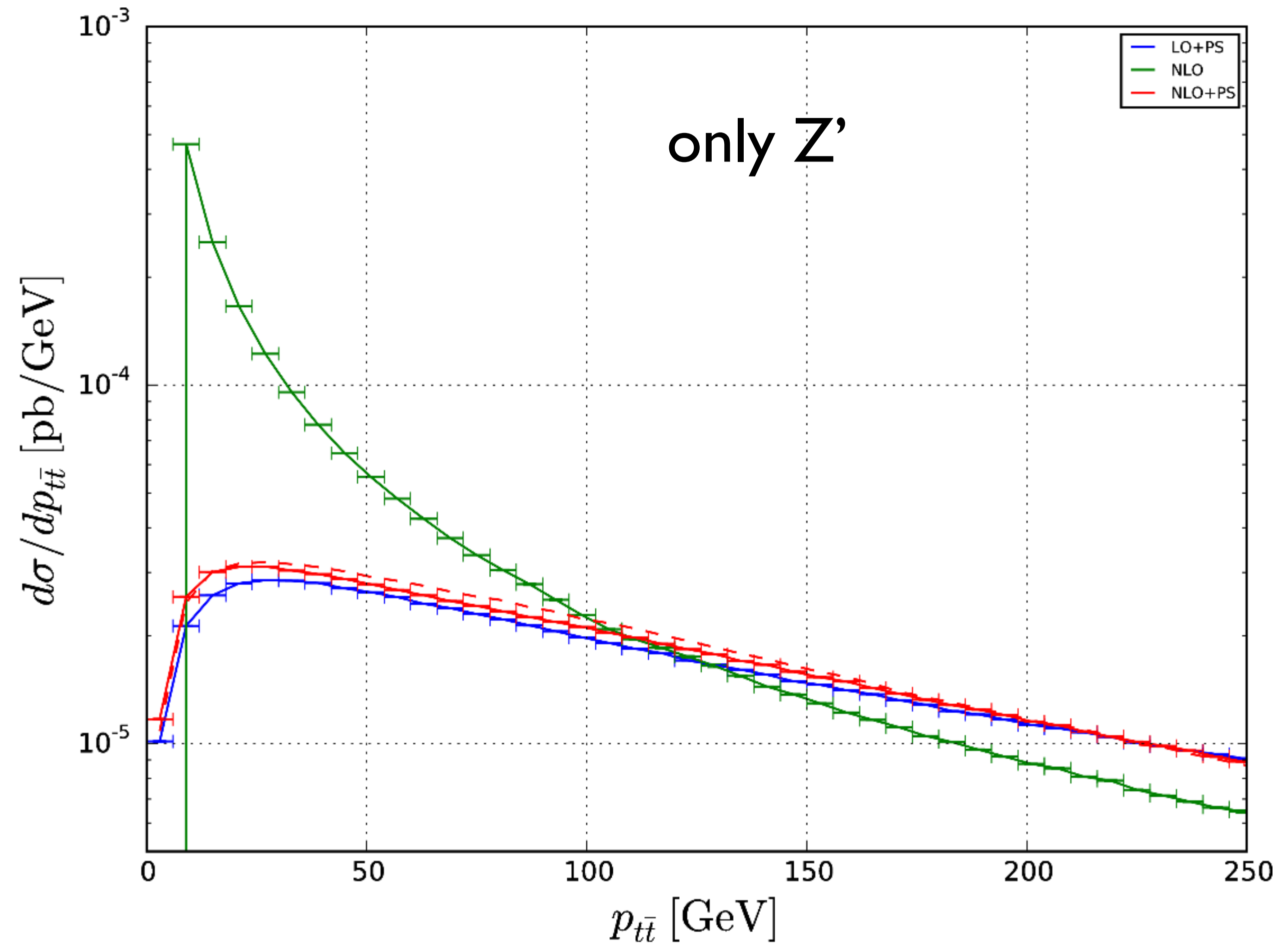
Total cross sections for $M_{Z'}$ = 3 TeV

For LO uses the NNPDF23_lo_as0119_qed PDF set

	Order	Processes	Model	σ [pb]	σ [pb] ($m_{t\bar{t}} > \frac{3}{4} m_{Z'}$)
	LO	$q\bar{q}/gg \to t\bar{t}$		473.93(7)	0.15202(2)
K~3	NLO	$q\bar{q}/gg + qg \to t\bar{t} + q$		1261.0(2)	0.45255(7)
	LO	$\gamma g + g\gamma \to t\bar{t}$		4.8701(8)	0.0049727(6)
	LO	$\gamma g + g\gamma \to t\bar{t}$ (NLO α_s and PDFs)		5.1891(8)	0.004661(6)
	LO	$q\bar{q} \to \gamma/Z \to t\bar{t}$	SM	0.36620(7)	0.00017135(3)
K~1	NLO	$q\bar{q} \to \gamma/Z \to t\bar{t}$	SM	0.5794(1)	0.00017174(5)
	NLO	$q\bar{q} + qg \to \gamma/Z + q \to t\bar{t} + q$	SM	4.176(2)	0.001250(6)
	LO	$q\bar{q} \to Z' \to t\bar{t}$	SSM	0.0050385(8)	0.0044848(7)
	LO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	SSM	0.35892(7)	0.0043464(7)
K~1.19	NLO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	SSM	0.5676(1)	0.005155(3)
	NLO	$q\bar{q} + qg \to \gamma/Z/Z' + q \to t\bar{t} + q$	SSM	4.172(2)	0.007456(9)
	LO	$q\bar{q} \to Z' \to t\bar{t}$	TC	0.012175(2)	0.011647(2)
	LO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	TC	0.38647(7)	0.011984(2)
K~1.23	NLO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	TC	0.6081(2)	0.01468(1)
	NLO	$q\bar{q} + qg \to \gamma/Z/Z' + q \to t\bar{t} + q$	TC	4.202(2)	0.01002(1)

Transverse momentum distributions





- Transverse momentum distributions particularly sensitive to soft parton radiation and the associated resummation in NLO+PS MCs
- Fixed NLO calculations (green) diverge at small transverse momentum.
- Physical turnover only at NLO+PS (red) or LO+PS (blue) level
- Red dashed line: result obtained with the HERWIG 6 PS (instead of PYTHIA 8)