Z' and W' bosons at the LHC

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UNIVERSITÉ Grenoble Alpes

Laboratoire de Physique Subatomique et de Cosmologie

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- Personnels
  - Total de 225 personnes + environ 50 stagiaires/an
  - 66 physiciens permanents (38 CNRS et 28 EC: 19 UJF + 9 INPG)
  - 84 ITA et 7 IATOS
  - Environ 35 Doctorants et 20-25 Postdoc/CDD/CCD
- Projets scientifiques
  - Quarks et leptons [ATLAS & ILC, (D0), UCN]
  - Théorie et phénoménologie
  - Astroparticules et cosmologie [AUGER,PLANCK,MIMAC, AMS-CREAM-LSST,Neutrino]
  - Physique hadronique et nucléaire [ALICE, (JLAB), Structure nucléaire]
  - Physique des Réacteurs
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Theory and Phenomenology

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- **Collider phenomenology**
  - Heavy quark production (D and B)
  - Gamma+Q in pp, pA and AA
- **Parton Distribution Functions (PDFs)**
- **Physics beyond the SM (BSM)**
  - SUSY, BSM-Higgs
  - DM
  - GUTs, W', Z'
  - Flavour physics, Family symmetries
- **Other**
  - Hadronic physics, neutrino interactions
  - Lattice QCD

Overview and Outline

- LHC phenomenology for G(221)=SU(2)xSU(2)xU(1) models:
  - Correlations help with the inverse problem! **arXiv: 1203.5314**
  - Resummation predictions, mass limits **arXiv: 1410.4692**
- AUGER: W', Z' effects not observable (with F. Montanet, M. Tartare from the AUGER group) **arXiv: 1401.6012**
- NLO QCD calculations in the POWHEG-BOX
  - Z'→t+tbar, calculation recently published **arXiv: 1511.08185**
  - W'→t+bbar, calculation soon completed
- PyR@TE: Public Python code to generate two-loop RGE's for general gauge theories (with F. Staub, A. Wingerter) **arXiv: 1309.7030**

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I. LHC phenomenology of general SU(2)xSU(2)xU(1) models

T. Jezo, M. Klasen, IS, PRD86(2012)035005, arXiv:1203.5314

Introduction

- Models with an extended gauge group predict new gauge bosons: Z', W'

- Simplest non-Abelian extension of SM: extra SU(2)

- Additional SU(2) factors appear in breaking of E_6, SO(10), ...

- $SU(2)_1 x SU(2)_2 x U(1)_X = G(221)$

- Symmetry breaking: G(221) → $SU(2)_L$ x $U(1)_Y$ → $U(1)_Q$

  - different ways to break symmetry

  - interesting LHC pheno

Breaking of G(221) symmetry

- Consider two types of Breaking Patterns (BP)
- Stage 1, at high scale u:
  - **BP-I**: $SU(2)_1 = SU(2)_L$, $SU(2)_2 \times U(1)_X \rightarrow U(1)_Y$
    - via a $SU(2)_2$-doublet of complex scalars $\phi \sim (1,2,1/2)$
    - via a $SU(2)_2$-triplet of scalars $\phi \sim (1,3,1)$
  - **BP-II**: $U(1)_X = U(1)_Y$, $SU(2)_1 \times SU(2)_2 \rightarrow SU(2)_L$
    - via a bidoublet $\phi \sim (2,2^*,0)$
- Stage 2, at EWSB scale v: $SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$

Charge assignments of G(221) models

BP	Model	$SU(2)_1$	$SU(2)_2$	$U(1)_X$
BP-I	Left-right (LR)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}, \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, $-\frac{1}{2}$ for leptons.
	Lepto-phobic (LP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, $Y_{\rm SM}$ for leptons.
	Hadro-phobic (HP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$Y_{\rm SM}$ for quarks, $-\frac{1}{2}$ for leptons.
	Fermio-phobic (FP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$		$Y_{\rm SM}$for quarks, $Y_{\rm SM}$ for leptons.
BP-II	Un-unified (UU)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$Y_{\rm SM}$ for quarks. $Y_{\rm SM}$ for leptons.
	Non-universal (NU)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{1^{\rm st},2^{\rm nd}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{1^{\rm st},2^{\rm nd}}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{3^{\rm rd}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{3^{\rm rd}}$	$Y_{\rm SM}$ for quarks. $Y_{\rm SM}$ for leptons.

$SU(2)_l = SU(2)_L$ (BP-I)

$U(1)_X = U(1)_Y$ (BP-II)

- Note that these models do not contain any new fermionic fields except for a potential ν_R
- Need two scalar multiplets for the symmetry breaking: ϕ (stage 1), H (stage 2)
- Some of the models might not be free of gauge anomalies and need a UV-completion.

Breaking of G(221) symmetry

BP – I $\quad \mathrm{SU(2)_1 \times SU(2)_2 \times U(1)_X}$ $\quad$ BP – II

$\mathrm{SU(2)_1 \equiv SU(2)_L}$ **Identification** $\mathrm{U(1)_X \equiv U(1)_Y}$

Doublet $\phi \sim (\mathbf{1}, \mathbf{2}, \frac{\mathbf{1}}{\mathbf{2}})$

Triplet $\phi \sim (\mathbf{1}, \mathbf{3}, \mathbf{1})$

Bi-doublet $\phi \sim (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{0})$

$\mathrm{SU(2)_2 \times U(1)_X}$ $\qquad$ $\mathrm{SU(2)_1 \times SU(2)_2}$

$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ u_{\rm D} \end{pmatrix}$ $\quad$ $\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ u_{\rm T} & 0 \end{pmatrix}$ $\quad$ **First Stage** $\quad$ $\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix}$

$\mathrm{U(1)_Y}$ $\qquad$ $\mathrm{SU(2)_L}$

$\mathrm{SU(2)_L \times U(1)_Y}$ $\quad$ **Second Stage** $\quad$ $\mathrm{SU(2)_L \times U(1)_Y}$

$H \sim (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{0})$ $\quad \langle H\rangle = \frac{v}{\sqrt{2}}\begin{pmatrix} c_\beta & 0 \\ 0 & s_\beta \end{pmatrix}$ $\qquad$ $H \sim (\mathbf{1}, \mathbf{2}, \frac{\mathbf{1}}{\mathbf{2}})$ $\quad \langle H\rangle = \frac{v}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \end{pmatrix}$

LR-D, LP-D, FP-D, HP-D $\quad$ LR-T, LP-T, FP-T, HP-T $\quad$ $\mathrm{U(1)_{e.m.}}$ $\quad$ UU, NU

Model-independent effective Lagrangian

$$\mathcal{L}_{\rm CC}^{W'} = \frac{g_W}{\sqrt{2}} \left[\bar{u}_i \gamma^\mu \left(\left(C_{q,L}^{W'} \right)_{ij} P_L + \left(C_{q,R}^{W'} \right)_{ij} P_R \right) d_j \right.$$

$$\left. + \bar{\nu}_i \gamma^\mu \left(\left(C_{\ell,L}^{W'} \right)_{ij} P_L + \left(C_{\ell,R}^{W'} \right)_{ij} P_R \right) e_j \right] W'_\mu + h.c.$$

$$\mathcal{L}_{\rm NC}^{Z'} = \frac{g_W}{c_{\theta_W}} \left[\sum_q \bar{q}_i \gamma^\mu \left(\left(C_{q,L}^{Z'} \right)_{ij} P_L + \left(C_{q,R}^{Z'} \right)_{ij} P_R \right) q_j \right.$$

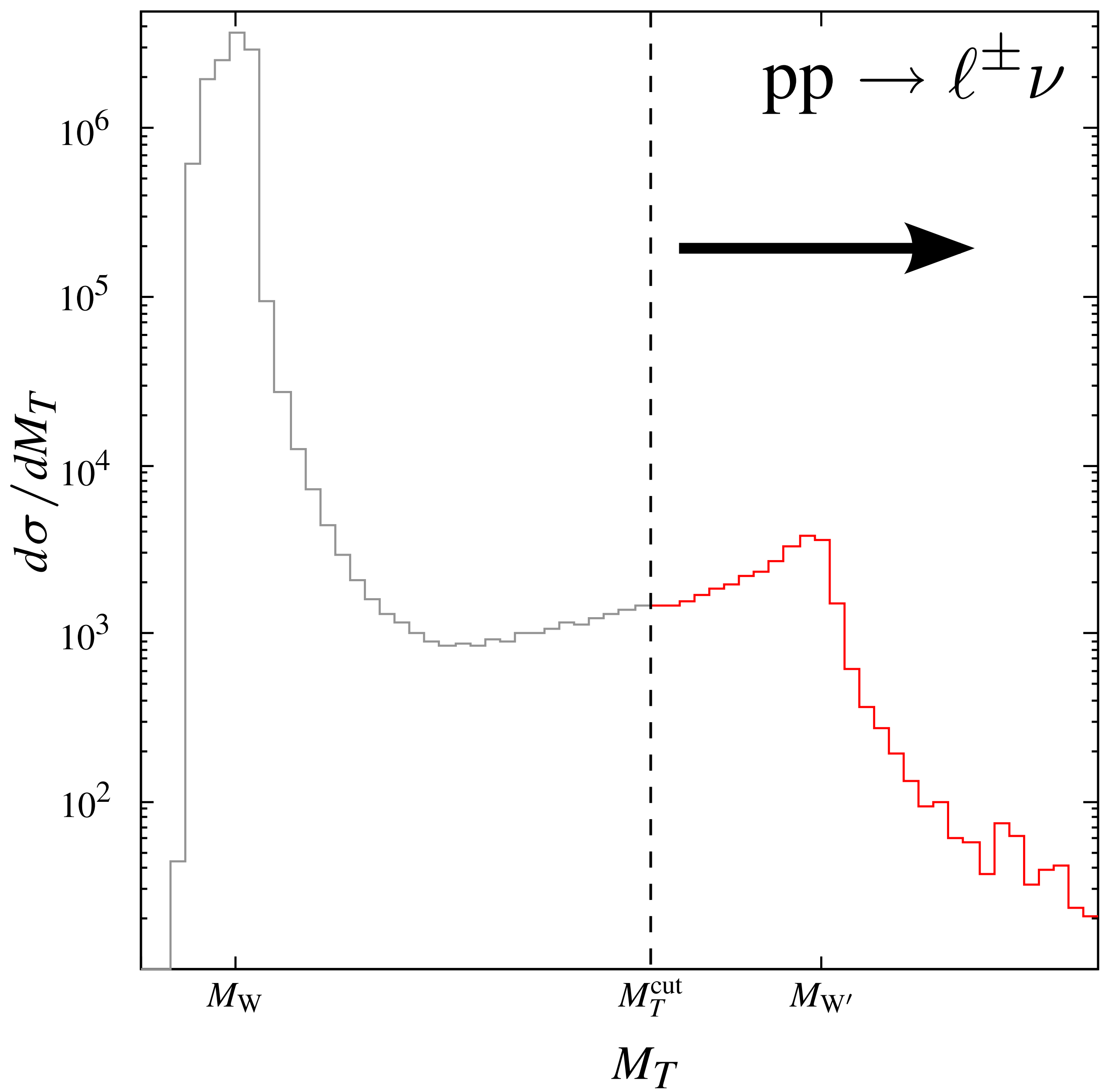
$$\left. + \sum_\ell \bar{\ell}_i \gamma^\mu \left(\left(C_{\ell,L}^{Z'} \right)_{ij} P_L + \left(C_{\ell,R}^{Z'} \right)_{ij} P_R \right) \ell_j \right] Z'_\mu + h.c.$$

Couplings C given in the different G(221) models

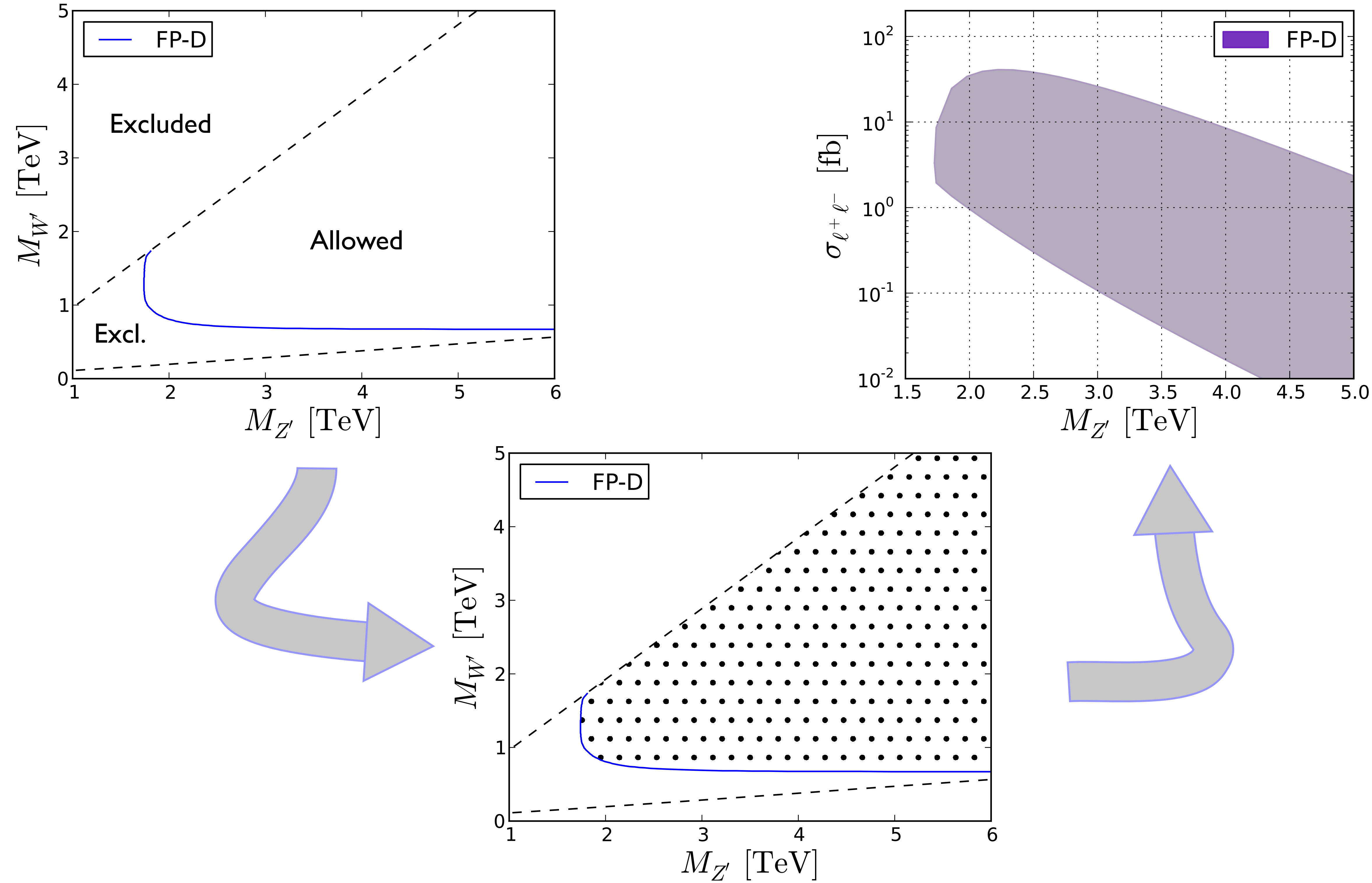
Collider Observables

- observable: $\sigma = \int_{M_{I(T)}^{cut}} \frac{d\sigma}{dM_{I(T)}}$ where $M_{I(T)}^{cut} = 0.75 M_{Z'(W')}$

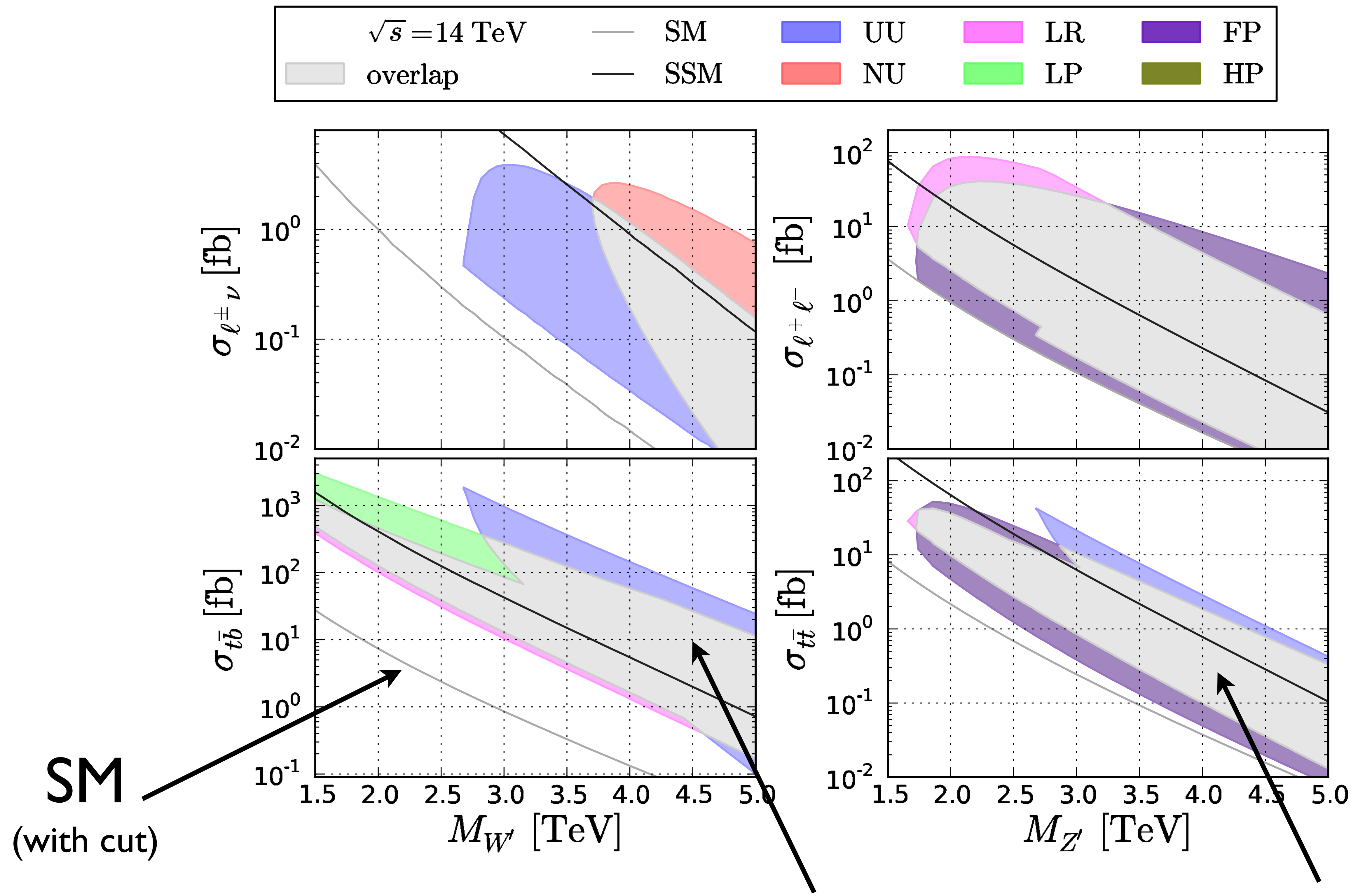
- M_I for $\ell^+\ell^-$, $t\bar{t}$ and $t\bar{b}$
  $M_I = \sqrt{p_3^2 + p_4^2}$
- M_T for $\ell^\pm\nu$
  $M_T = \sqrt{p_{T_W}^2 + M_W^2}$



From exclusion limits to cross section regions



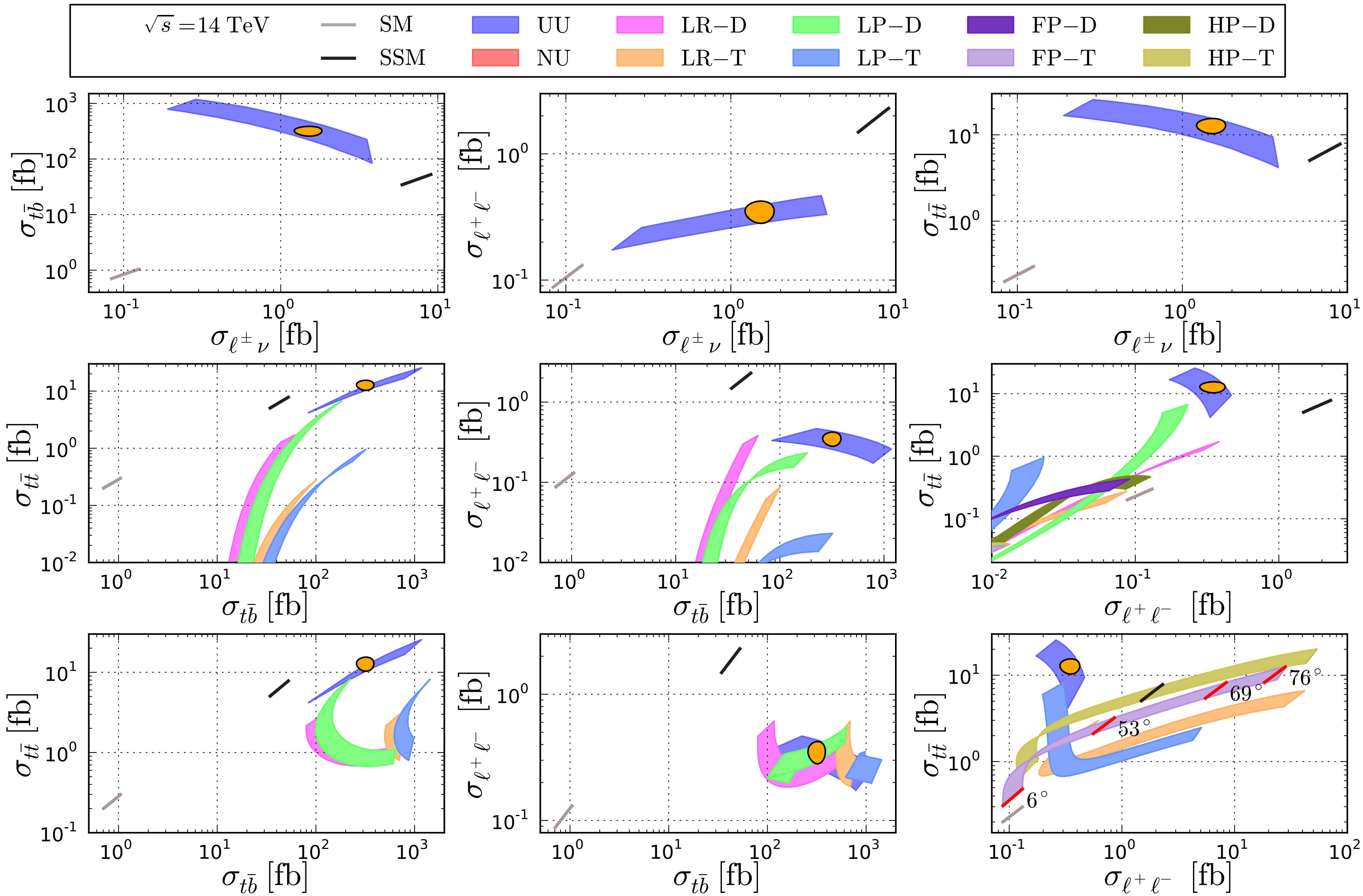
Cross section regions



Difficult to distinguish different G(221) models

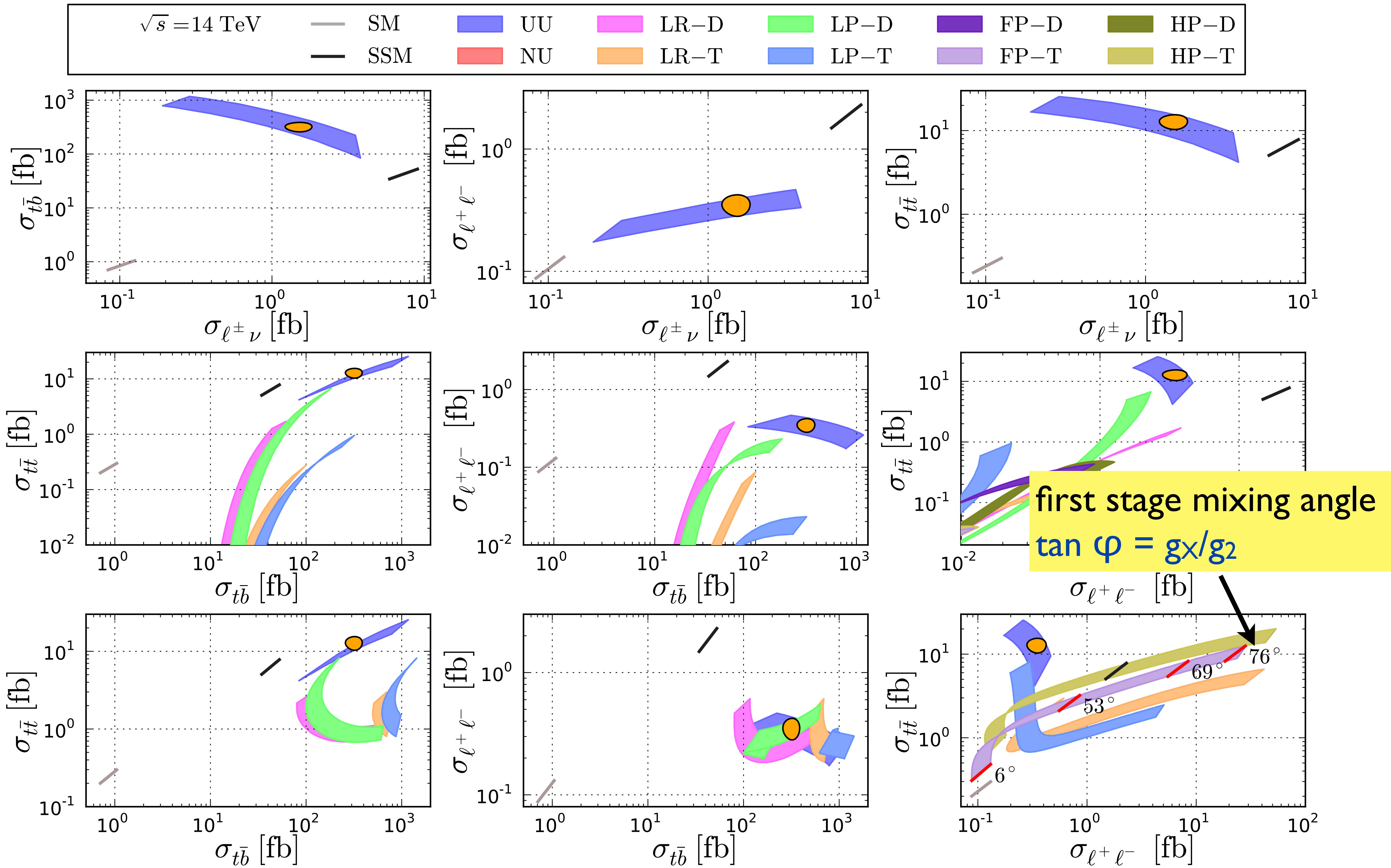
Cross section correlations

$M_{W'}=M_{Z'}=3\pm0.1$ TeV



Cross section correlations

$M_{W'} = M_{Z'} = 3 \pm 0.1$ TeV



Conclusions I

- Cross section predictions for G(221) models at LHC7
  - leading order with own implementation of W', Z' in PYTHIA
  - scan over allowed parameter space (from low energy observables)
- Correlations between different observables are **crucial** to distinguish G(221) models ("inverse problem")
- Future work:
  - Repeat/Update analysis at higher order
  - Generalize flavour structure of V' couplings to SM fermions
  - Ultimately needed: global analysis

NLO+NLL limits on Z' and W' gauge bosons

T. Jezo, M. Klasen, D. Lamprea, F. Lyonnet, IS, JHEP12(2014)092, arXiv:1410.4692

Introduction

- New heavy resonances W', Z' predicted in a variety of models: GUT, Extra dimension, Compositeness

- Collider limits:

  - SSM, String inspired Z', LR

  - Most stringent limits obtained in leptonic final states:

    - ca. 25 searches (each, ATLAS and CMS)
      ⇒ In SSM $M_{Z'} > 2.9$, $M_{W'} > 3.3$ TeV

  - Most of them obtained using **PYTHIA LO + PS** rescaled to NNLO with **FEWZ** or **ZWPROD**

    - No interference with SM W and Z bosons

Our approach

- Public code **RESUMMINO** already implements soft-gluon resummation for
  - Z', gaugino and slepton pair production
  - Added the W' → lν process
- Present QCD resummation predictions for
  - pp → W/W' → lν and pp → Z/Z' → ll
  - Include the interferences
  - Allow general couplings
- Compare our results with **our version of PYTHIA** which includes interferences and **FEWZ**

Theoretical Setup

PYTHIA (6.4.27) **LO+PS**:

- Implemented the full qq(‘) →Z’/W’ → ll (lν)
- Includes interferences with Z/W
- Automatic calculation of the total width
- SM like couplings:

$$\bar{\nu}_\ell \ell W'^+, \bar{\ell}\nu_\ell W'^- \sim \frac{g}{2\sqrt{2}}\gamma^\mu(V_\ell - A_\ell\gamma_5) \ ,$$
$$\bar{q}q' W'^\pm \sim \frac{g}{2\sqrt{2}} U_{\rm CKM}\gamma^\mu(V_q - A_q\gamma_5) \ .$$

FEWZ **LO, NLO, NNLO**:

- Fixed order, fully exclusive → arbitrary cuts
- Extrapolate SM predictions:
  - Fed with the W’ and Z’ properties from PYTHIA
  - Observables need to be rescaled by the proper combination of couplings (not always possible)
- No interferences

Theoretical Setup

RESUMMINO **NLO+NLL**:

- Our implementation of the W/W' and Z/Z' into leptons processes
- Resummation of the small p_T and production threshold regions
- Resums the large logarithms from soft gluon emission in these regions: $p_T \to 0, z \equiv Q^2/s \to 1$
- Matched to fixer order NLO calculation:
  $\sigma_{ab} = \sigma_{ab}^{(res.)} + \sigma_{ab}^{(f.o.)} - \sigma_{ab}^{(exp.)}$
- The code also allows for fixed order predictions: LO, NLO

Numerical Results

- Comparison of **RESUMMINO**, **PYTHIA** and **FEWZ** for various models at LHC14
    - SSM
    - G(221) models: Un-Unified (UU) and Generation Non-Universal (NU)
- In total 5 benchmark points with $M_{W'}$ = 4 TeV

Name	Model	$M_{W'}$ [TeV]	t	$\Gamma_{W'}$ [GeV]	$\Gamma_{W' \to \ell\nu}$ [GeV]
B_1	SSM	4	—	142.85	11.69
B_2	UU	4	0.7	237.15	5.73
B_3	UU	4	1.2	125.35	16.83
B_4	NU	4	0.7	217.80	23.85
B_5	NU	4	1.4	141.82	5.96

- MSTW 2008 PDFs at LO, NLO and NNLO including error sets at 68% C.L.

First stage mixing angle: t = tan φ = g_2/g_1

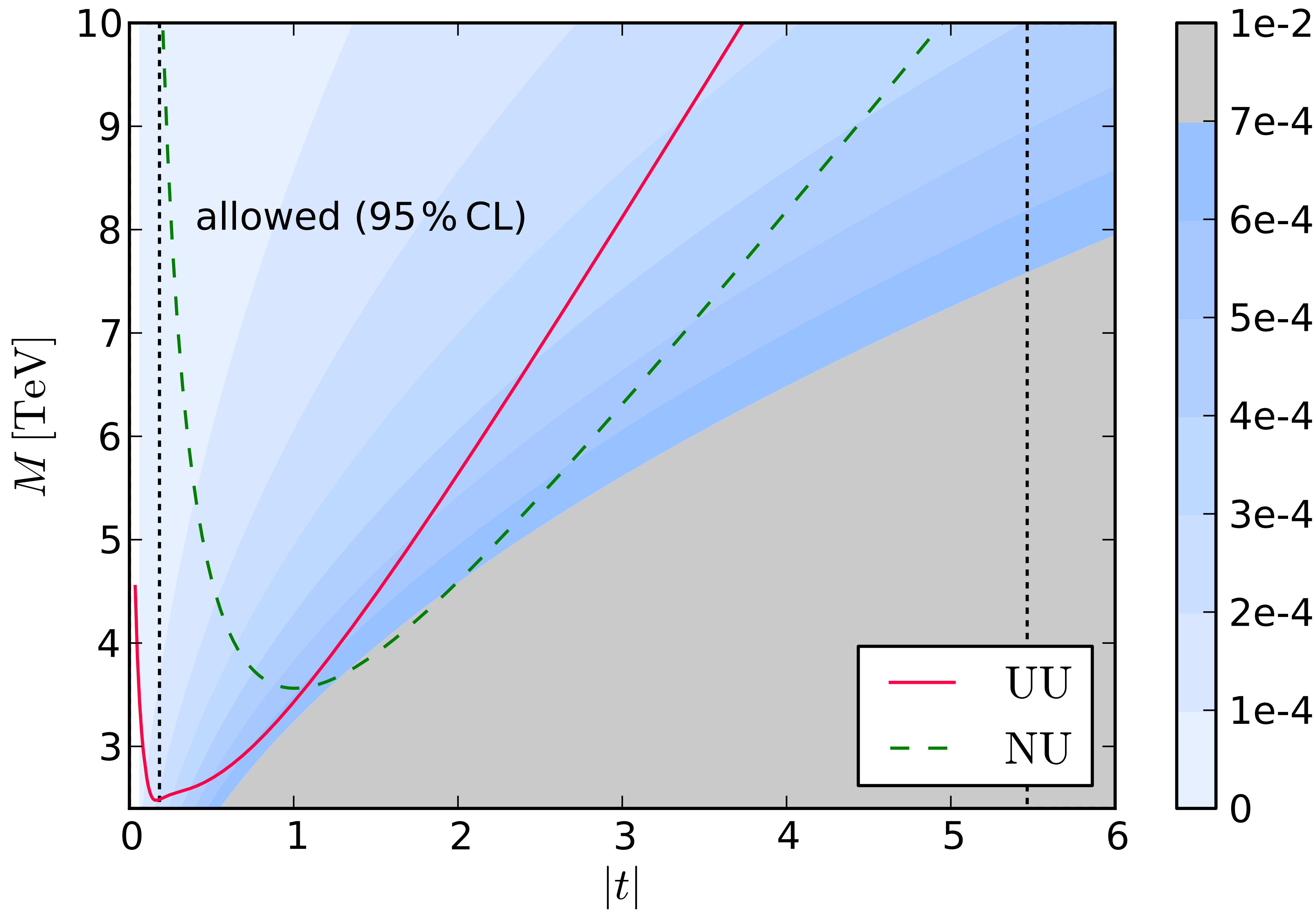


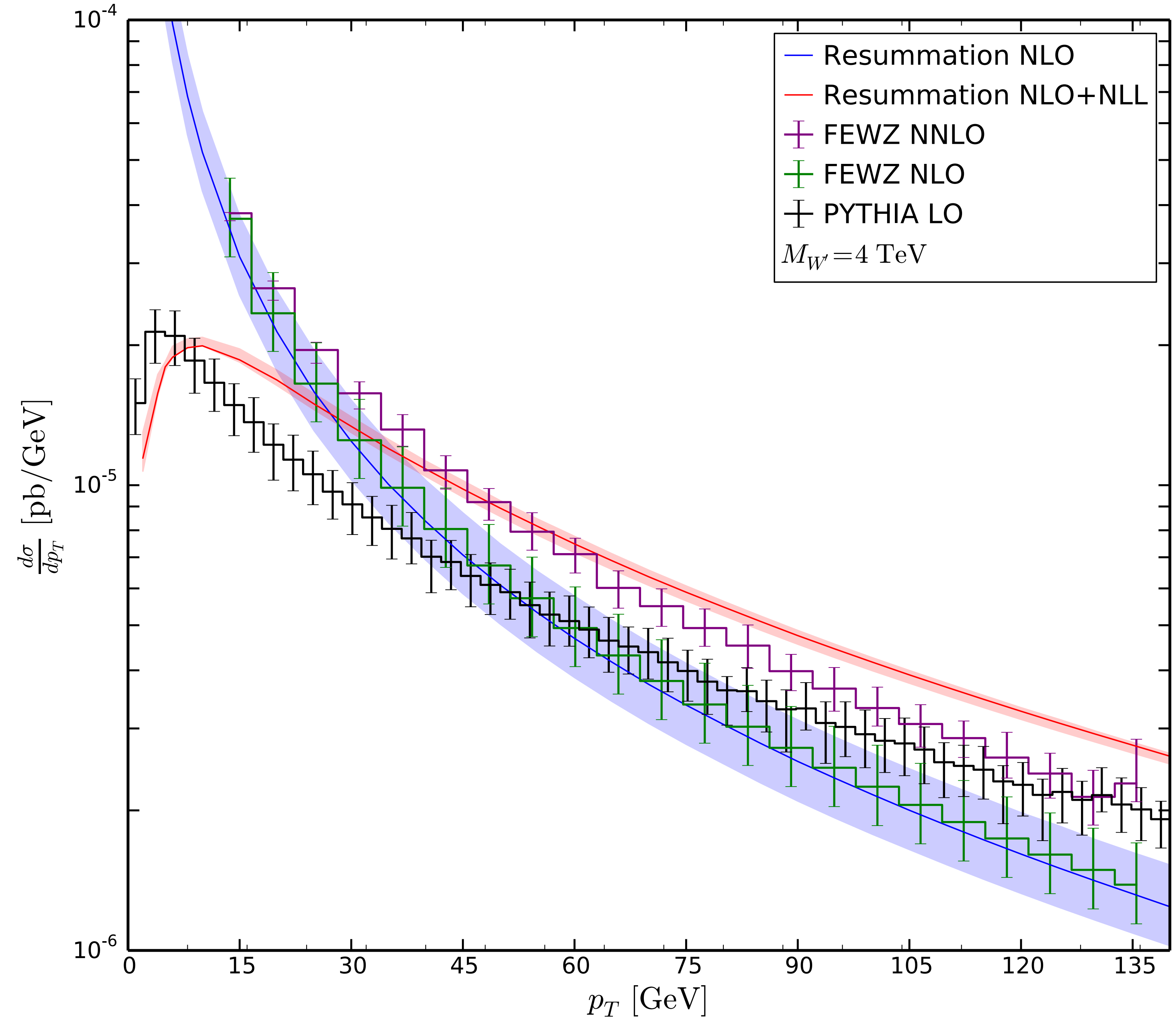
Figure 1. Exclusion limits for left-handed G(221) models. The red (full) and green (dashed) lines represent 95% confidence level contours of allowed regions in the UU and NU models. In regions outside the area bounded by dotted lines at least one of the gauge couplings becomes non-perturbative. Shaded contours represent values of $\epsilon(t, M_{V'})$.

Numerical Results

p_T spectrum:

- SSM
- W'$^{+}$ of 4 TEV
- $Q_{e+\nu}$>0.75 $M_{W'}$

to limit interferences and W contribution



Total cross section for the 5 benchmark points:

- at LO PYTHIA, FEWZ, RESUMMINO agree at ~1-2%
- at NLO FEWZ, RESUMMINO agree at ~1-2%

Total cross sections for the 5 benchmark points

Model	RESUMMINO LO	PYTHIA LO	RESUMMINO NLO	FEWZ NLO	RESUMMINO NLO+NLL	FEWZ NNLO
B_1	$1338.6^{-155.5}_{+186.7}$	$1333.0^{+188.9}_{-155.4}$	$1469.2^{+119.7}_{-134.7}$	$1492.9^{+74.7}_{-79.4}\pm^{+127.9}_{-89.2}$	$1411.2^{-88.7}_{-37.2}$	$1509.1^{+25.7}_{-34.5}\pm^{+146.9}_{-92.3}$
B_2	$799.2^{+92.5}_{-111.4}$	$799.6^{+112.2}_{-91.6}$	$874.6^{+73.8}_{-83.9}$	$893.5^{+44.7}_{-47.3}\pm^{+74.9}_{-52.0}$	$843.3^{-47.5}_{-26.0}$	$902.7^{+12.7}_{-18.4}\pm^{+86.5}_{-54.3}$
B_3	$1515.4^{+175.3}_{-213.6}$	$1520.0^{+214.9}_{-176.4}$	$1672.7^{+138.9}_{-156.2}$	$1689.2^{+85.5}_{-90.3}\pm^{+145.2}_{-101.4}$	$1605.7^{-99.7}_{-44.2}$	$1705.1^{+24.2}_{-35.3}\pm^{+168.1}_{-105.7}$
B_4	$3630.9^{+420.3}_{-506.5}$	$3636.9^{+504.5}_{-427.1}$	$3986.9^{+339.9}_{-375.4}$	$4053.5^{+203.3}_{-215.3}\pm^{+341.0}_{-236.9}$	$3841.5^{-214.4}_{-112.1}$	$4094.5^{+57.6}_{-83.7}\pm^{+394.3}_{-247.6}$
B_5	$351.2^{+41.1}_{-49.0}$	$349.6^{+48.9}_{-40.6}$	$385.2^{+31.3}_{-35.7}$	$388.9^{+19.6}_{-20.8}\pm^{+47.8}_{-33.4}$	$369.9^{-23.4}_{-10.2}$	$392.6^{+5.5}_{-8.1}\pm^{+38.5}_{-24.2}$

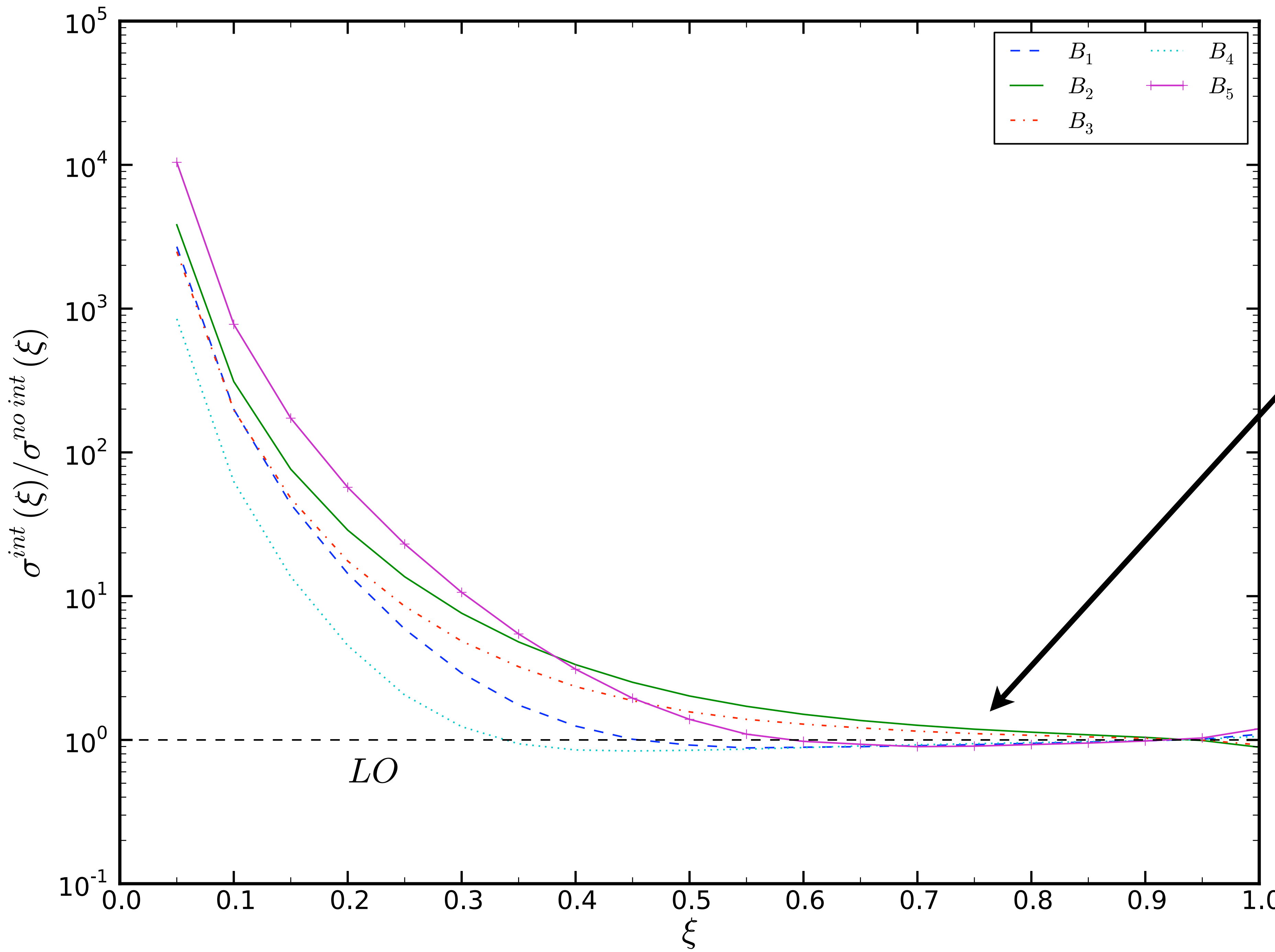
Table 4. Total cross section predictions for positively charged W' bosons decaying into a positron and a neutrino at LHC14 (in attobarns) for the benchmark points defined in table 3. Interference terms between W and W' gauge bosons and the pure SM contribution are neglected. The invariant mass of the lepton pair is restricted to $Q > 3M_{W'}/4$.

Model	PYTHIA w/o int.	PYTHIA w/ int.	RESUMMINO LO	RESUMMINO NLO	RESUMMINO NLO+NLL
B_1	$1333.0^{+188.9}_{-155.4}$	$1237.7^{+175.4}_{-145.5}$	$1241.7^{+147.6}_{-176.1}$	$1379.5^{+113.4}_{-121.1}$	$1313.3^{-92.3}_{-27.9}$
B_2	$799.6^{+112.2}_{-91.6}$	$953.2^{+128.1}_{-108.6}$	$949.0^{+107.6}_{-129.5}$	$1013.8^{+90.3}_{-105.7}$	$993.1^{-37.7}_{-40.0}$
B_3	$1520.0^{+214.9}_{-176.4}$	$1684.3^{+234.3}_{-194.4}$	$1676.9^{+193.5}_{-233.0}$	$1831.2^{+158.9}_{-177.3}$	$1775.6^{-86.7}_{-57.2}$
B_4	$3636.9^{+504.5}_{-427.1}$	$3418.0^{+478.2}_{-404.0}$	$3419.4^{+398.8}_{-481.6}$	$3781.1^{+318.5}_{-343.2}$	$3618.7^{-228.5}_{-90.3}$
B_5	$349.6^{+48.9}_{-40.6}$	$317.9^{+45.3}_{-37.8}$	$317.9^{+37.6}_{-45.8}$	$351.9^{+29.5}_{-32.9}$	$332.7^{-25.4}_{-9.0}$

Table 5. Same as table 4, but with interference terms now included.

Importance of the interference terms

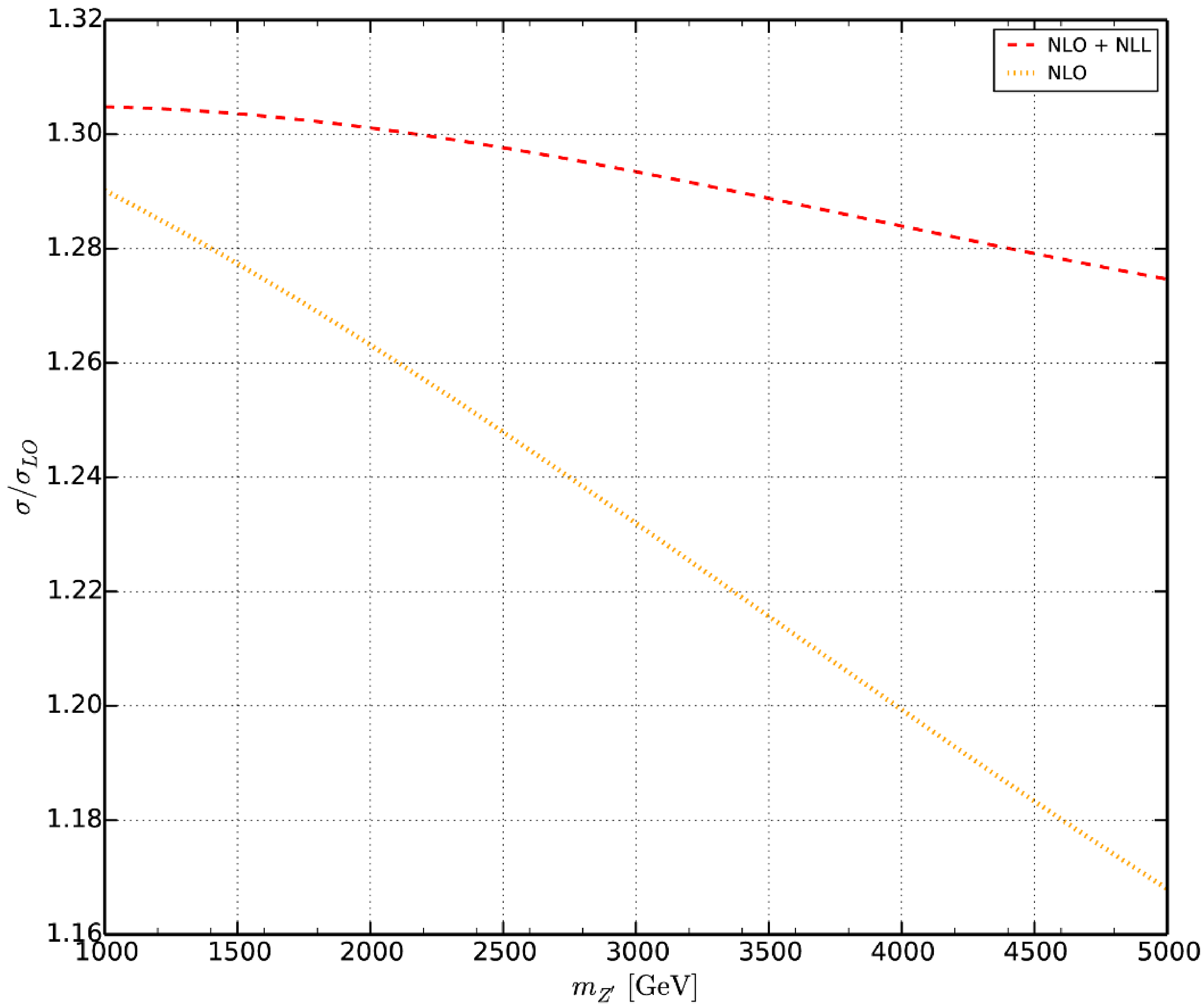
Ratio of the LO cross sections with and without interference as a function of the minimal invariant mass cut $Q_{e+\nu} > \xi\, M_{W'}$



interference terms still important here

Importance of the resummation

Ratio of Z' production cross sections at LHC14 at NLO and NLO+NLL over the LO cross section in the SSM vs $M_{Z'}$



With increasing mass the threshold effects become more and more important leading to a ~10% increase of the cross section at $M_{Z'}$ = 5 TeV.

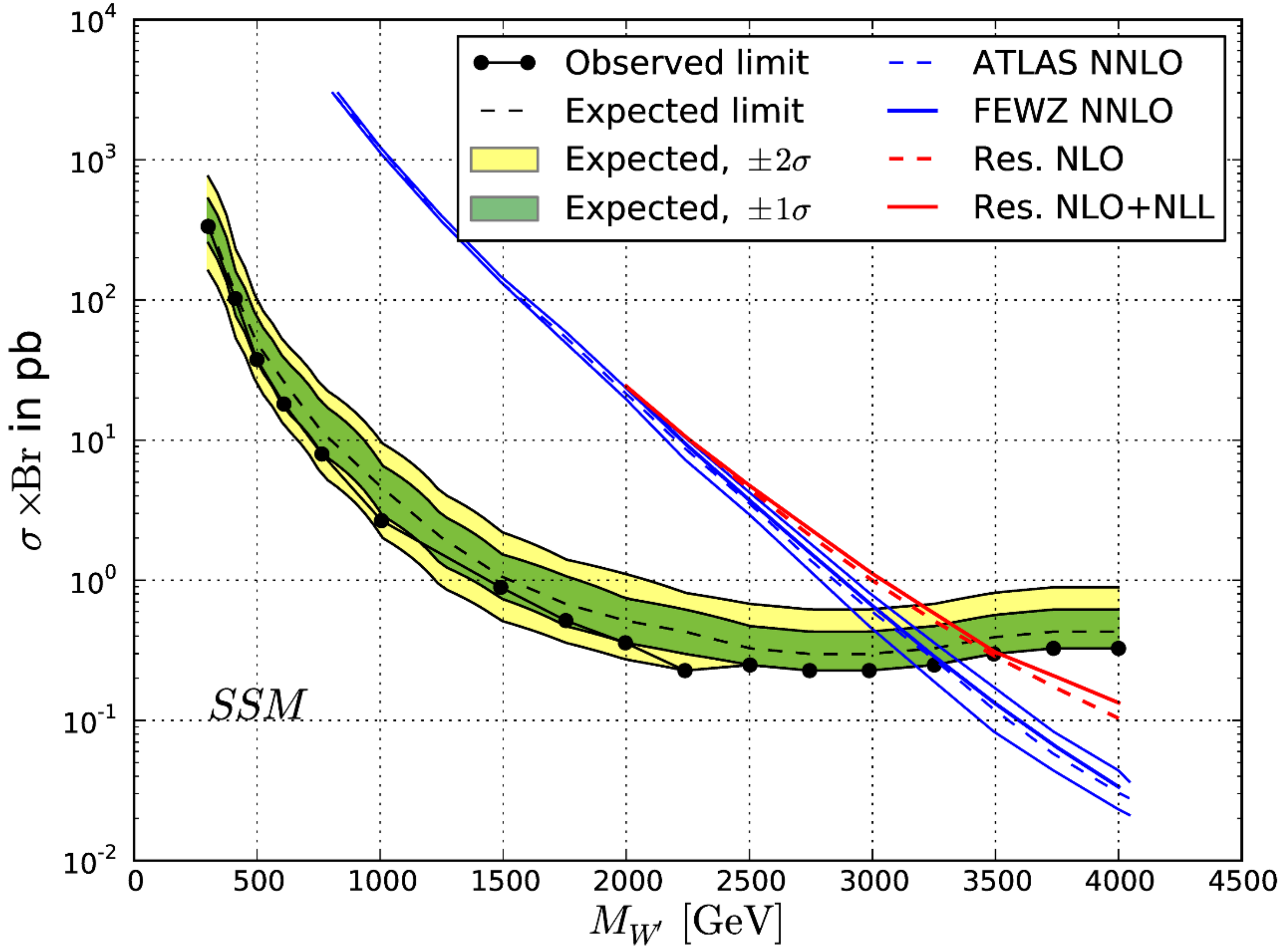
Gauge boson mass limits in general SM extensions

- Experimental searches by ATLAS and CMS for W' and Z' bosons in the SSM using data from LHC8 ⇒ Limits on $M_{W'}$ and $M_{Z'}$
- We have performed a reanalysis using our NLO+NLL predictions
- Results in the SSM, UU and NU models

Gauge boson mass limits: ATLAS-W' - SSM

Reanalysis of the ATLAS results at LHC8, 20.3 fb^{-1} [arXiv:1407.7494]

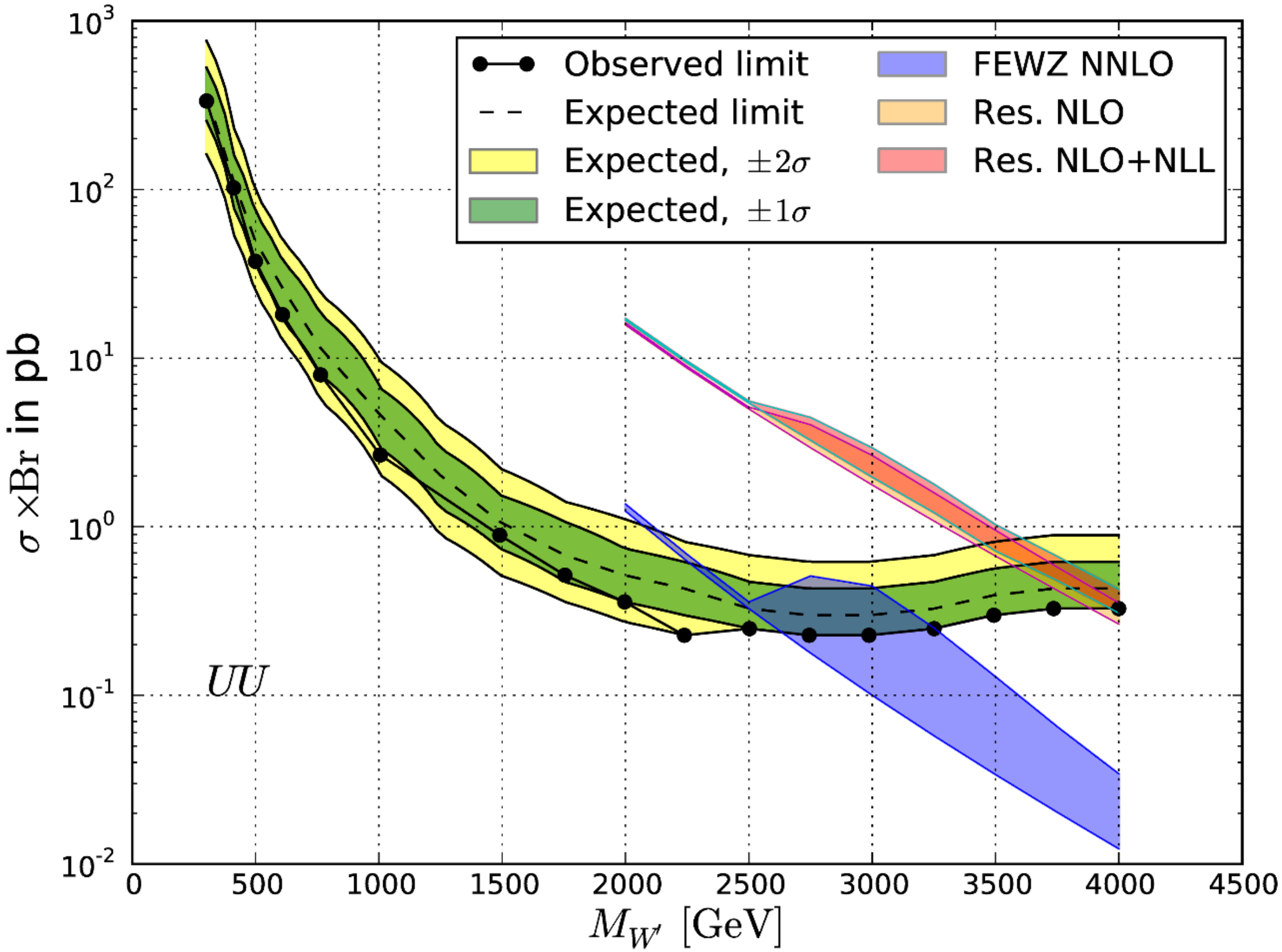
- **PYTHIA LO+PS**, $W^+ + W^-$ with $Q>0.4\ M_{W'}$
- Rescaled to NNLO with ZWPROD ⇒ No interference terms
- SSM: $M_{W'} > 3.24$ TeV



Our result:
$M_{W'}^{Res} = 3.5$ TeV

Gauge boson mass limits: ATLAS-W'and Z'- UU

Reanalysis of the ATLAS results at LHC8, 20.3 fb^{-1} [arXiv:1407.7494]



Our result:

$M_{W'}^{Res} > 3.9 - 4$ TeV

Note: UU-model

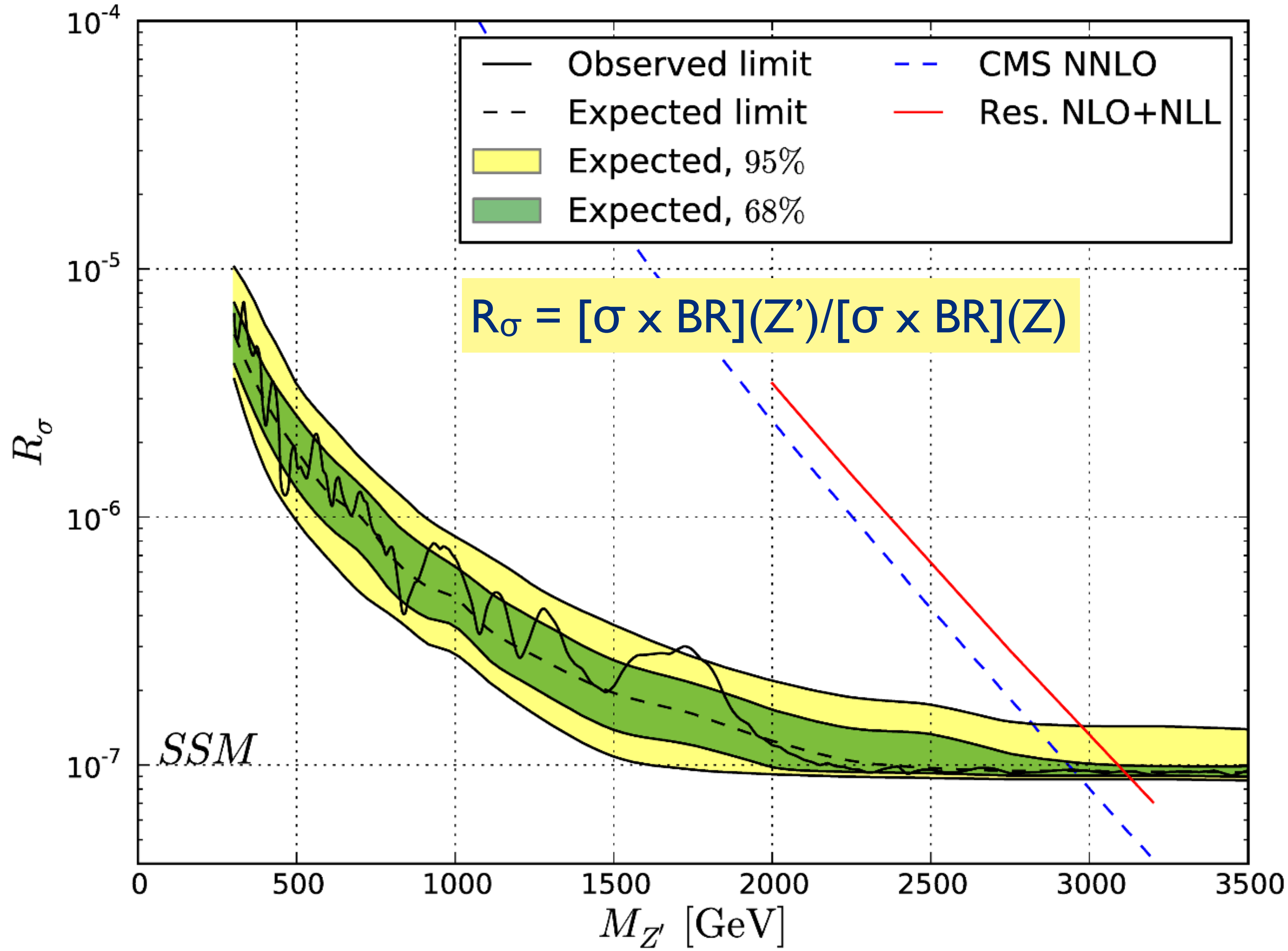
$M_{Z'} = M_{W'} + O(v^2/u^2)$

- (Res. NLO+NLL)/(Res. NLO) ≃1.2
- Large interference effects

Gauge boson mass limits: CMS Z' - SSM

Reanalysis of the CMS results at LHC8, 20.6 fb^{-1} [CMS-PAS-EXO-12-061]

- **PYTHIA LO+PS**
- Rescaled to NNLO with ZWPROD ⇒ No interference terms
- **SSM**: $0.6\, M_{Z'} < Q < 1.4\, M_{Z'} \Rightarrow M_{Z'} > 2.96$ TeV



Our result:

$M_{Z'}^{Res}$ = 3.2 TeV

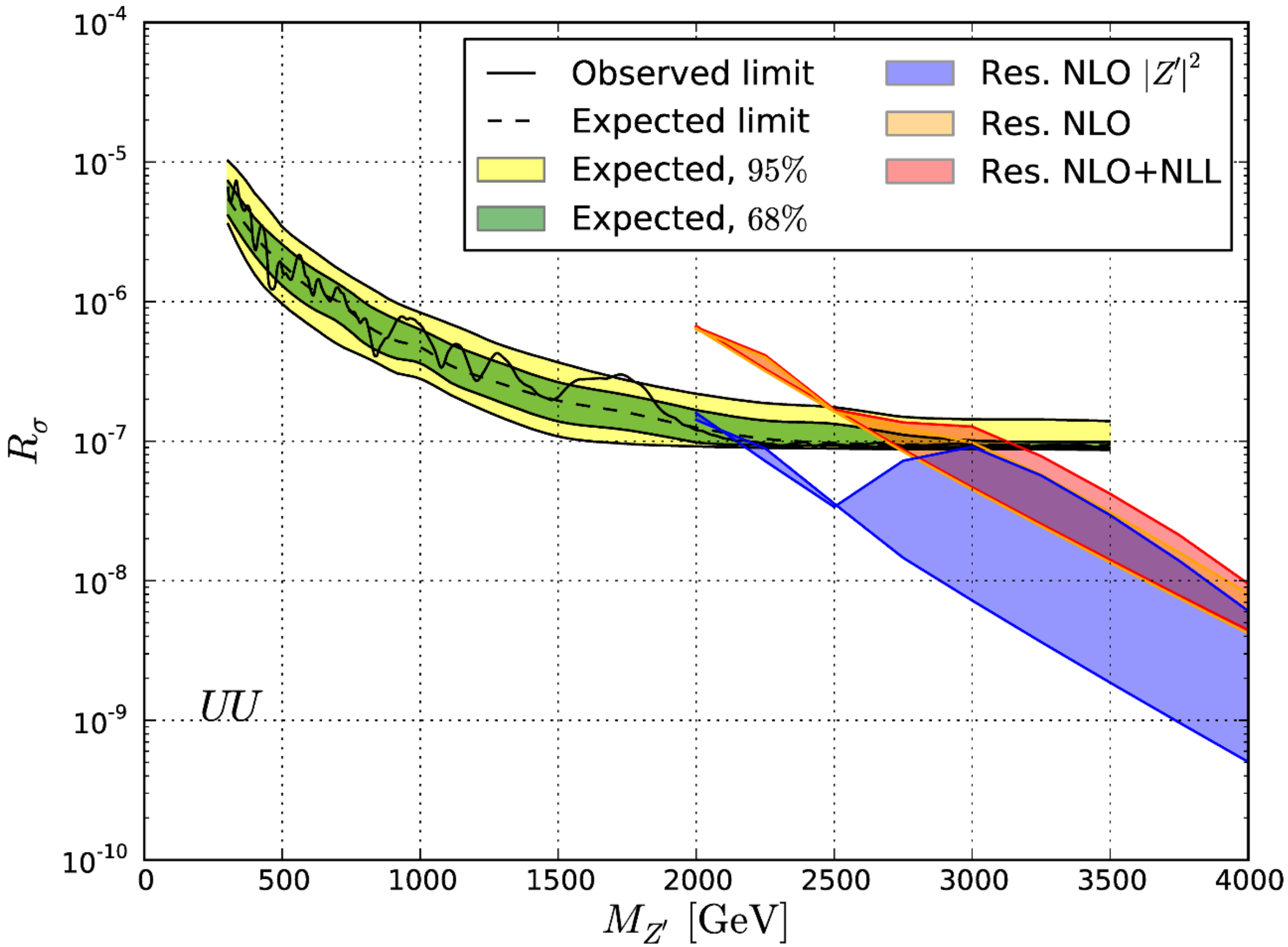
Large interferences

Gauge boson mass limits: CMS Z' - UU

Reanalysis of the CMS results at LHC8, 20.6 fb^{-1} [CMS-PAS-EXO-12-061]

- **PYTHIA LO+PS**
- Rescaled to NNLO with ZWPROD ⇒ No interference terms
- $0.6\ M_{Z'} < Q < 1.4\ M_{Z'}$

$R_\sigma = [\sigma \times BR](Z')/[\sigma \times BR](Z)$



Our result:

$M_{Z'}^{Res}$ = 2.8 - 3.2 TeV

$M_{W'} = M_{Z'} + O(v^2/u^2)$

previous limits:

2.5 TeV

Summary of mass limits

Model	New gauge boson	Previous mass limit [TeV]	New mass limit [TeV]
SSM	W'	3.27–3.28	3.5
SSM	Z'	2.90–2.96	3.2
UU	W'	2.48	3.9–4.0
UU	Z'	2.48	2.8–3.2
NU	W'	3.56	(3.5)
NU	Z'	3.56	(3.3)

Table: Previously obtained exclusion limits, using ATLAS and CMS data for the SSM as well as low-energy and precision data for the UU and NU models, and new exclusion limits, including all interference effects and NLO+NLL corrections, for W' and Z' gauge bosons.

Conclusions II

- Comparison of W', Z' production at LO, NLO, NNLO, NLO+NLL
- Our implementation: **RESUMMINO NLO+NLL** is available
- Recast the ATLAS and CMS analyses using LHC8 data and extracted new mass limits in the SSM and G(221) models
- Interference terms can be very large in some models and impact strongly the exclusion limits
- Approaching the threshold region with higher masses ⇒ Resummation needed

EW top pair production at the LHC with Z' bosons to NLO QCD in POWHEG

R. Bonciani, T. Jezo, M. Klasen, F. Lyonnet, IS, JHEP(2016), arXiv:1511.08185

Motivation for 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 $SU(3)_1 \times SU(2)_2 \rightarrow SU(3)_c$
- 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; $U(1)_1 \times U(1)_2 \rightarrow U(1)_Y$
- 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

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

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

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

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

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

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

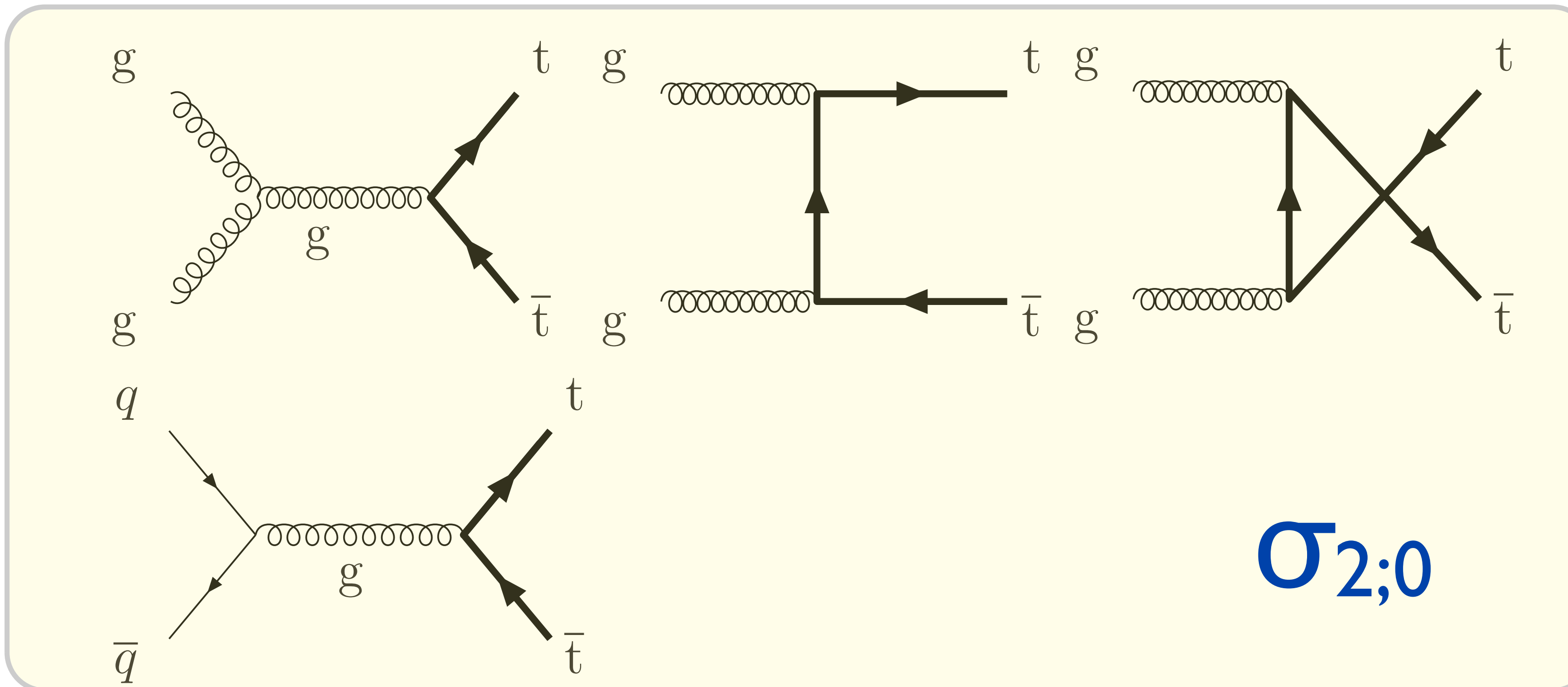
- $\sigma_{0;3}$: negligible

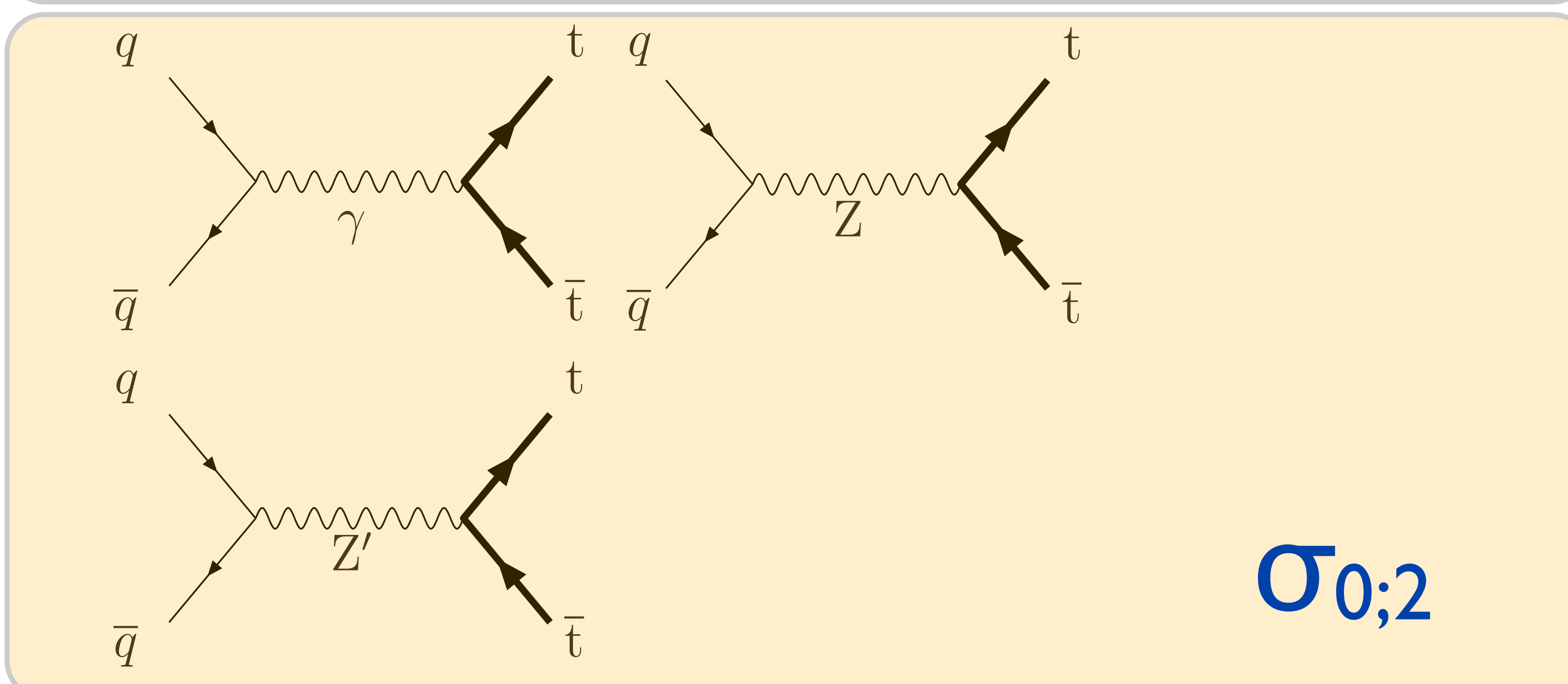
LO subprocesses: $\sigma_{2;0}$ and $\sigma_{0;2}$

- $\hat{\sigma}^{\mathrm{LO}} = \hat{\sigma}_S^{\mathrm{LO}}(\alpha_S^2) + \hat{\sigma}_W^{\mathrm{LO}}(\alpha_W^2)$

- SM
  - gg, $\mathcal{O}(\alpha_S^2)$:
  - $q\overline{q}$, $\mathcal{O}(\alpha_S^2)$:
  - $q\overline{q}$, $\mathcal{O}(\alpha_W^2)$:

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

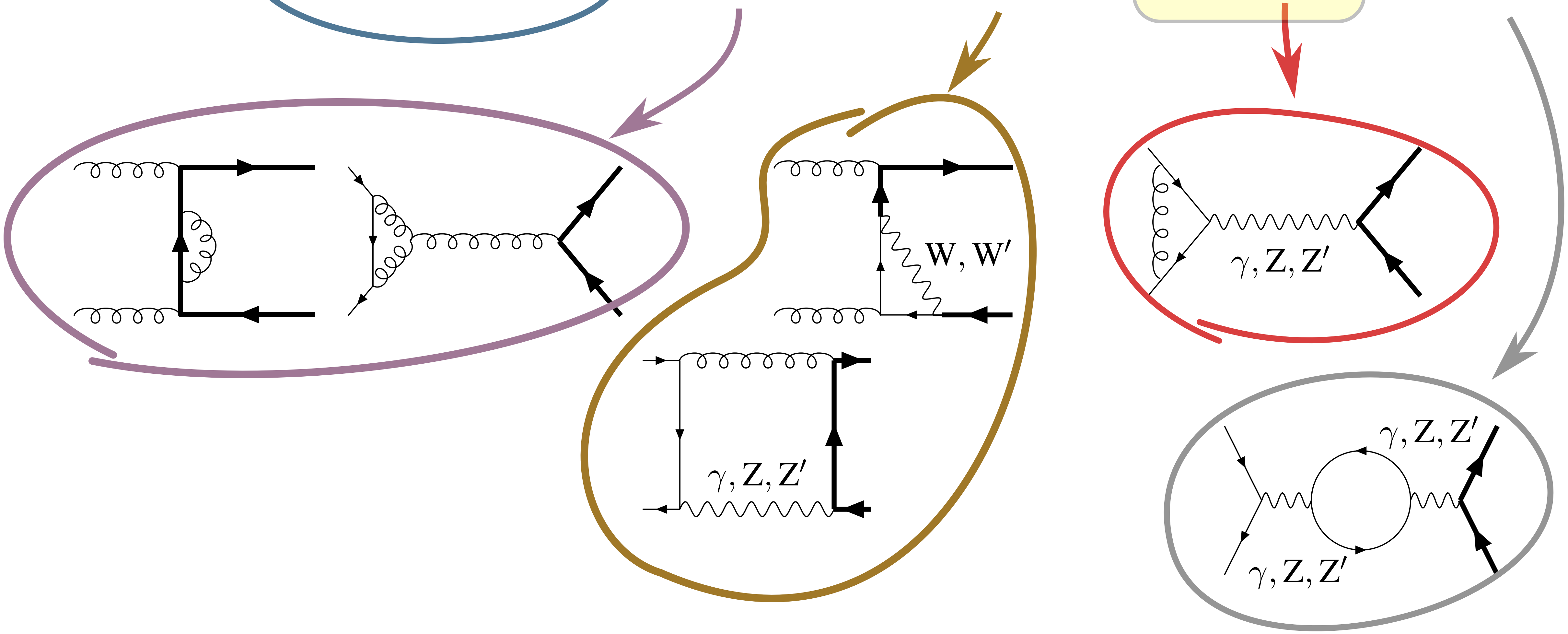




NLO virtual

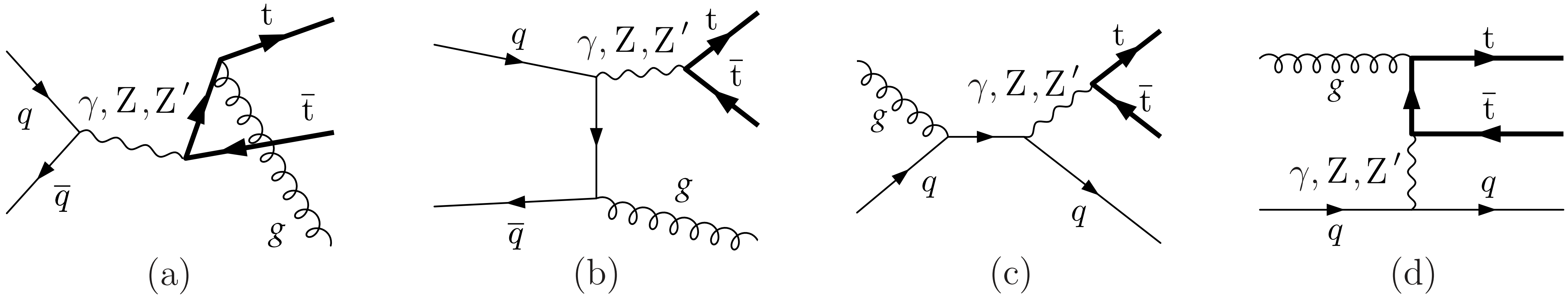
LO

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



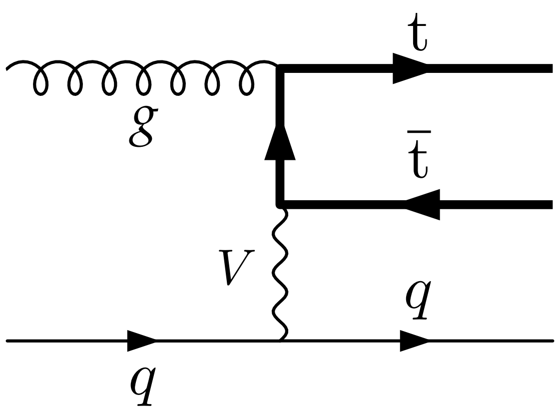
- $\mathcal{O}(\alpha_S^3)$ not affected by the presence of Z′
- we calculate $\mathcal{O}(\alpha_S\alpha_W^2)$

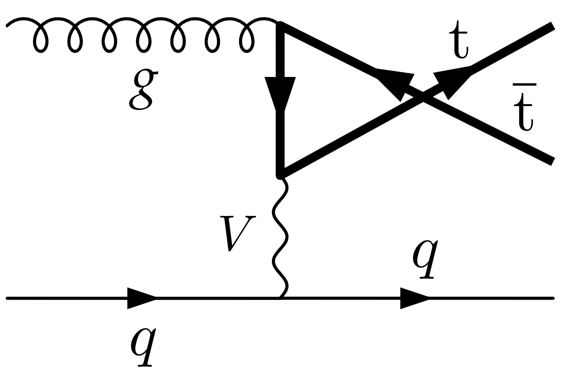
NLO real corrections

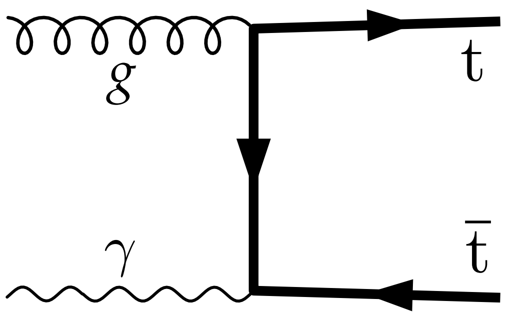


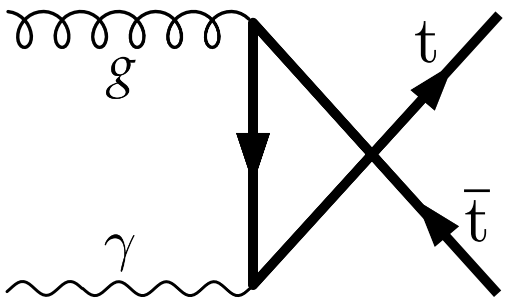
- interferences of real and real diagrams
- new channel as compared to tree-level and 1-loop diagrams
- no loops, no UV divergences
- IR divergences, after integration over 1 particle phase space
    - soft (S) divergences: radiation of a soft gluon (a), (b)
    - initial state collinear (ISC) divergences: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

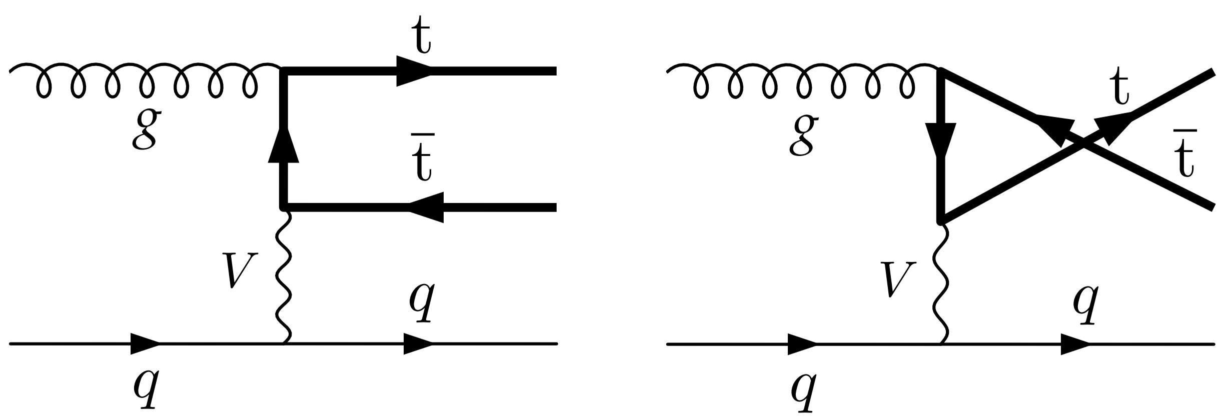
POWHEG Box:

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

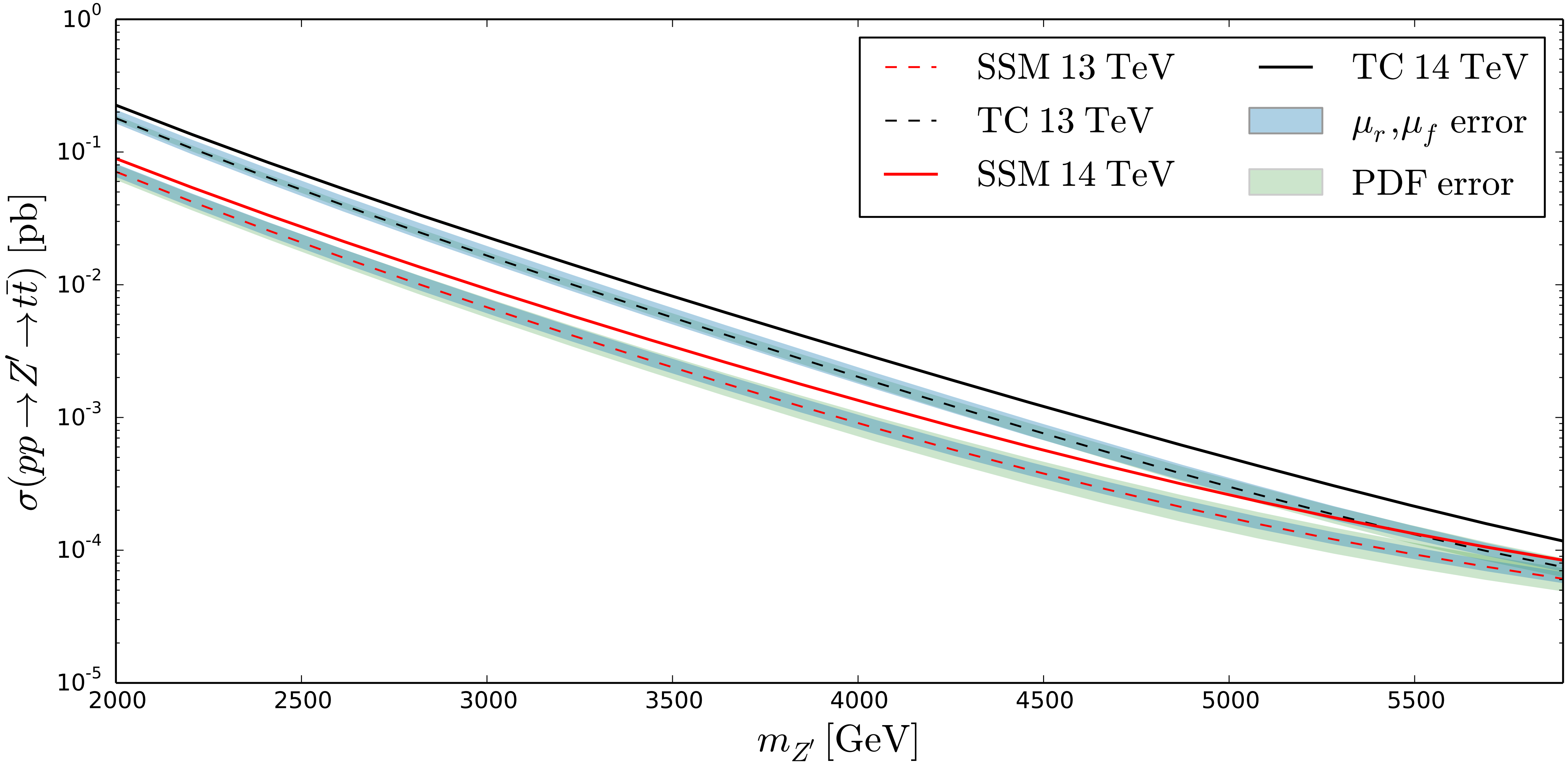
- Our implementation of EW top pair production with Z' contributions has been added to the list of POWHEG processes under the name: *PBZp*
- Our SM Born, Real amplitudes in agreement with MadGraph5_aMC@NLO
- $1/\varepsilon$ expansion of our virtual matrix elements checked against GoSam
- For the full 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

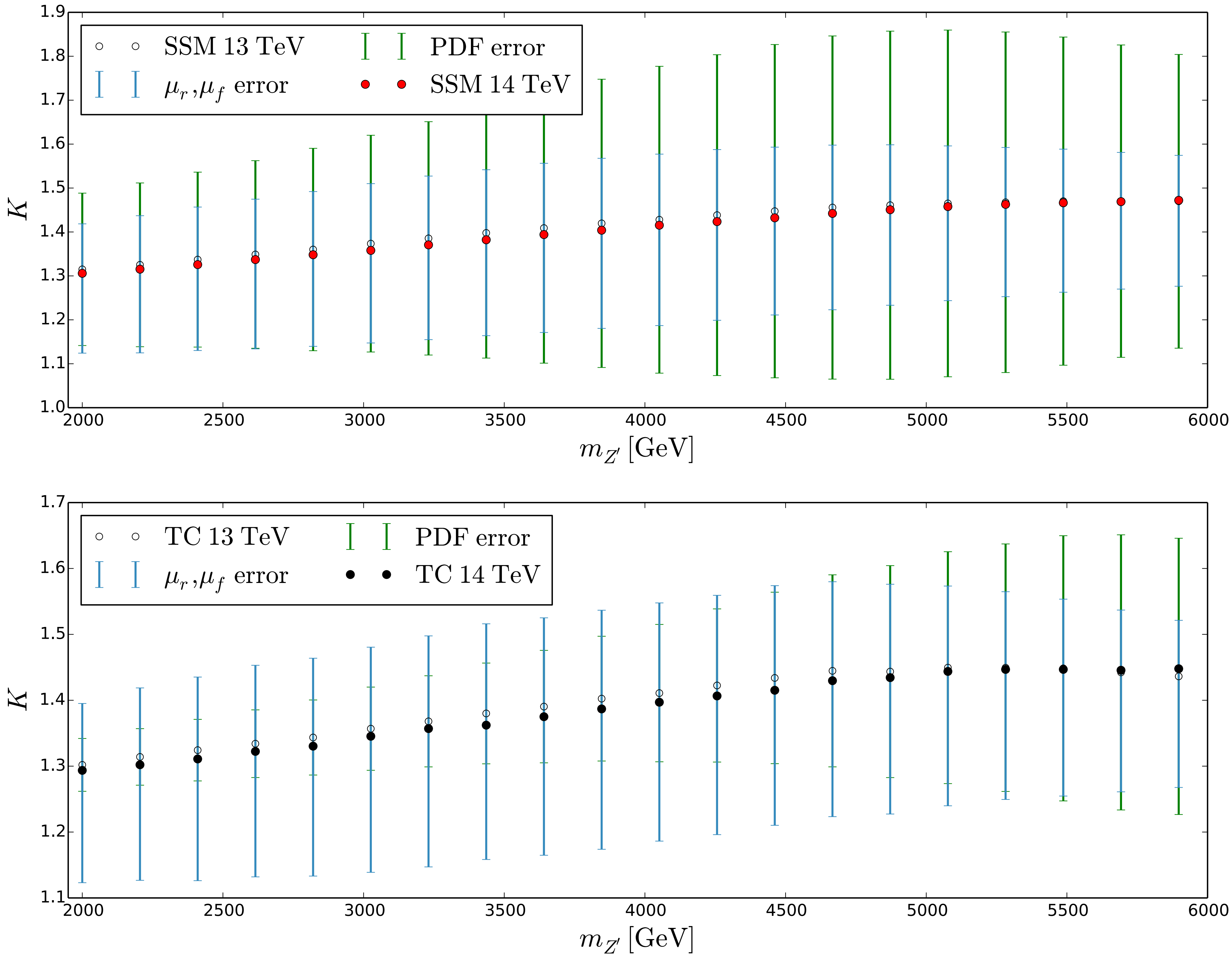


- SSM (lower curves):
  - For Lint = 100 fb^{-1}, LHC13: number of expected events 10^4 ($M_{Z'}$=2 TeV) ... 10 ($M_{Z'}$=6 TeV)
  - Uncertainties range from 15% - 35%
    Interestingly, the PDF uncertainty dominates over entire $M_{Z'}$ range shown
- LPTC model: Uncertainties range from 15% - 20%. Scale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

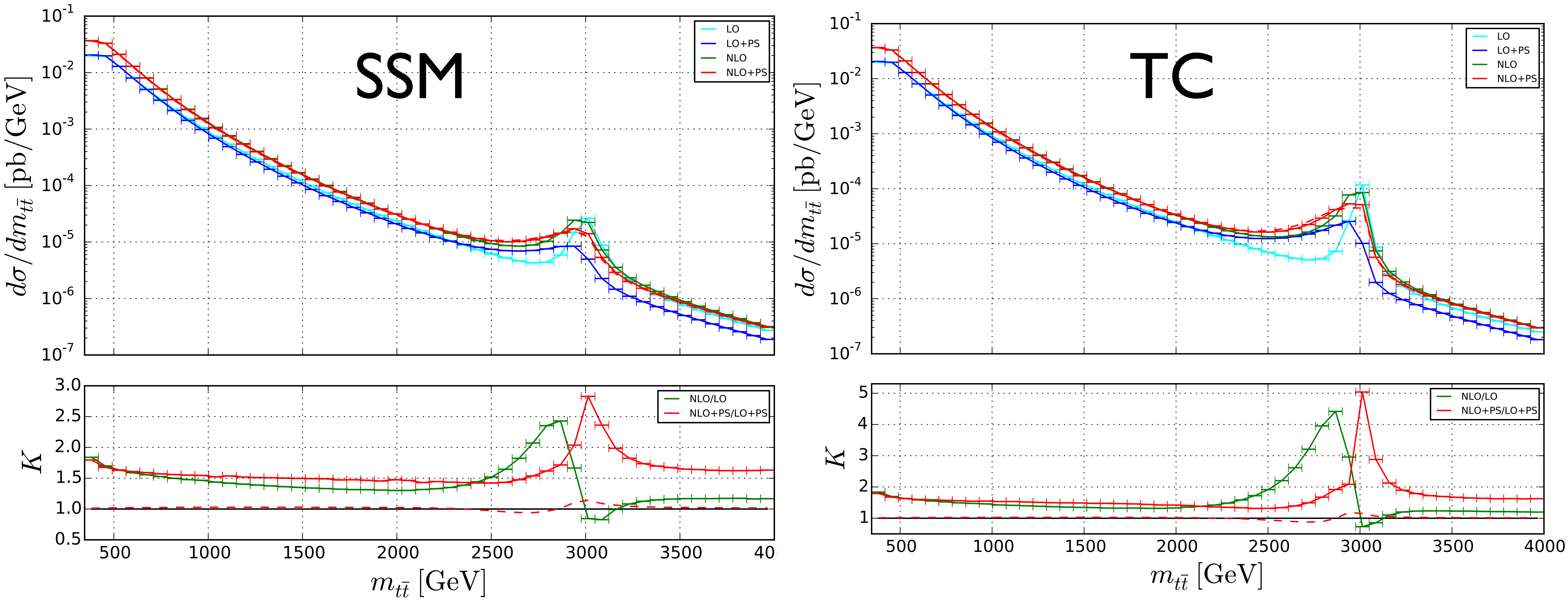
Resonant-only Z'-boson production at NLO

The K-factor ranges from 1.3 to 1.45.

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

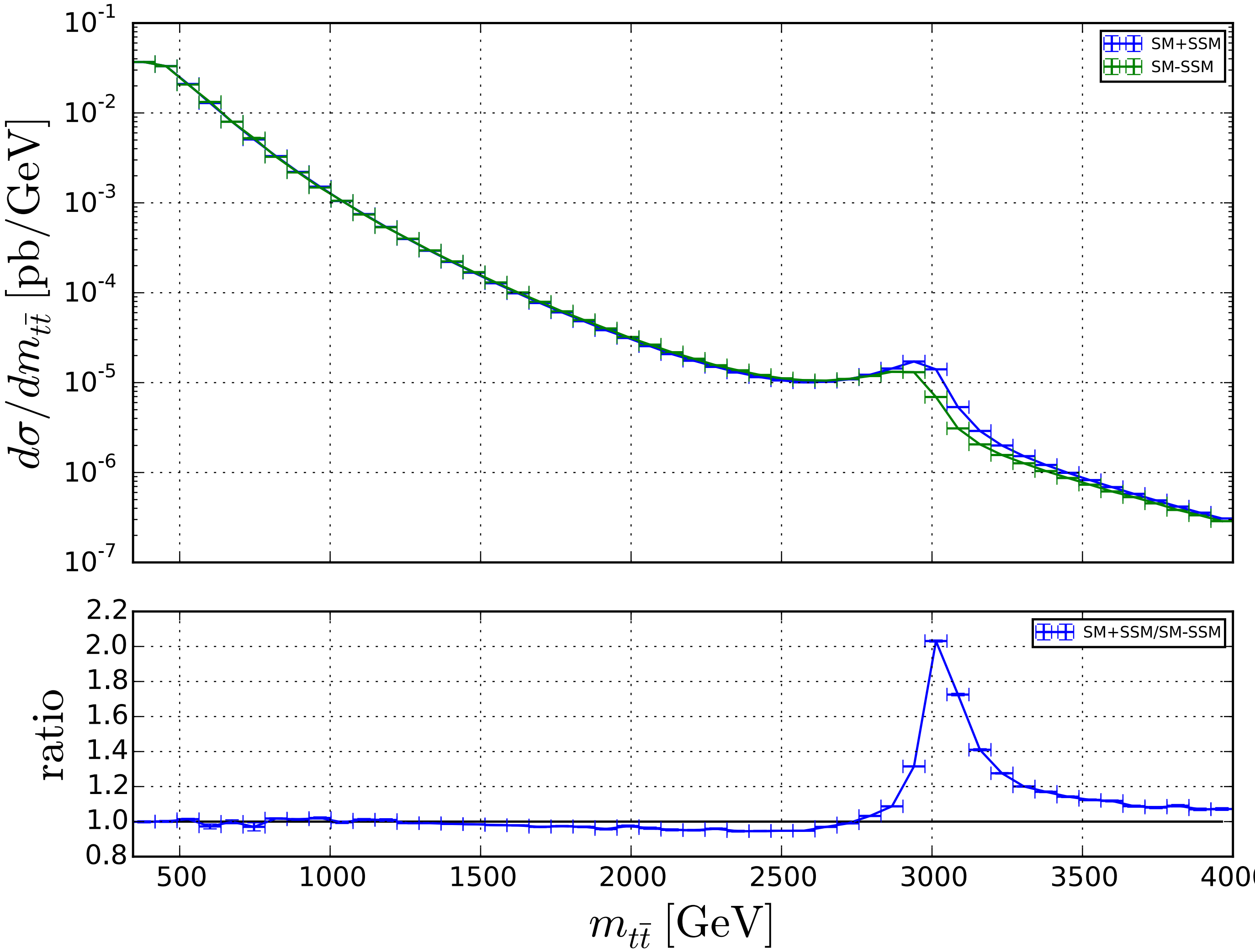


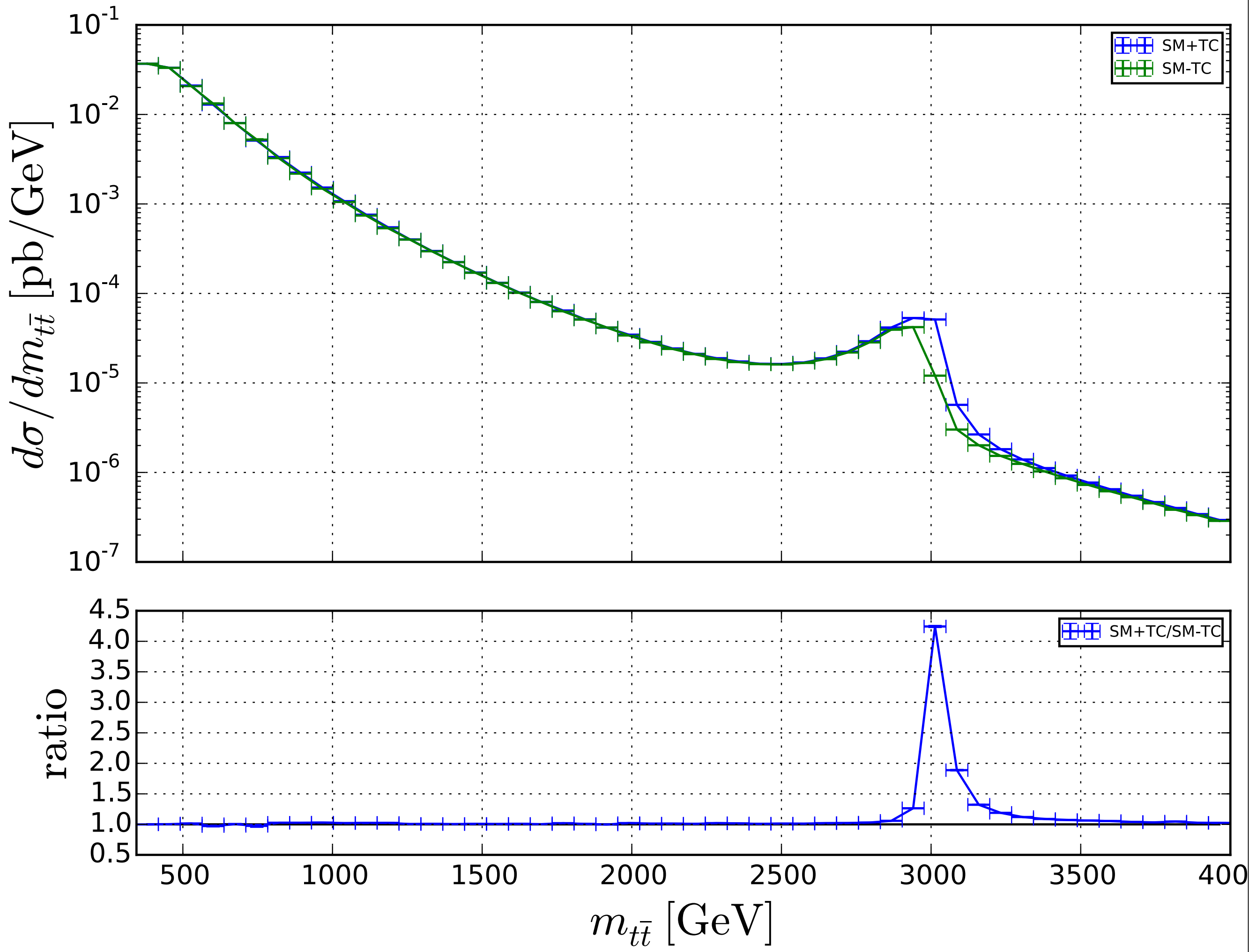
Invariant mass distributions for $M_{Z'}$=3 TeV



- 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

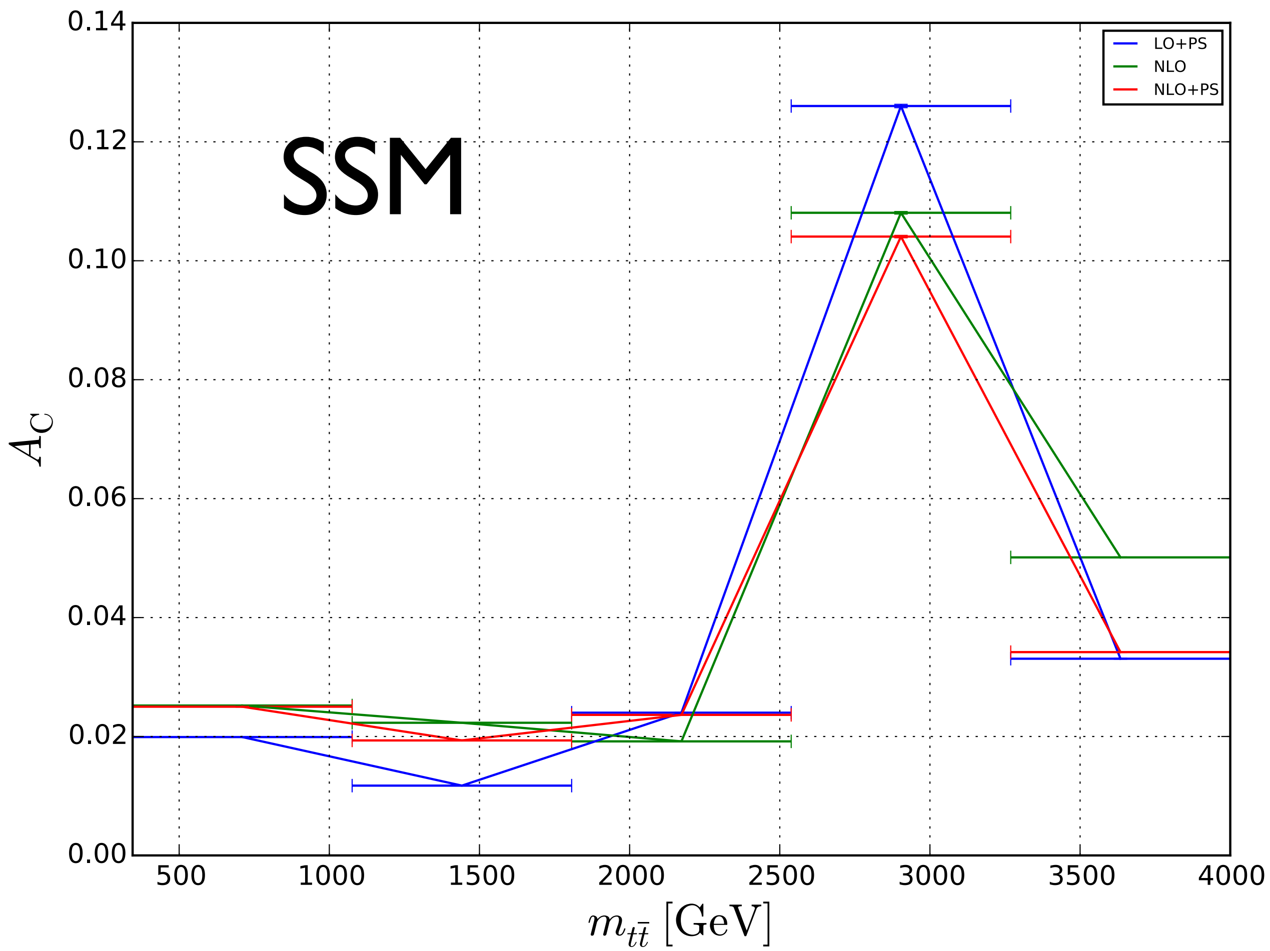
Effect of interferences

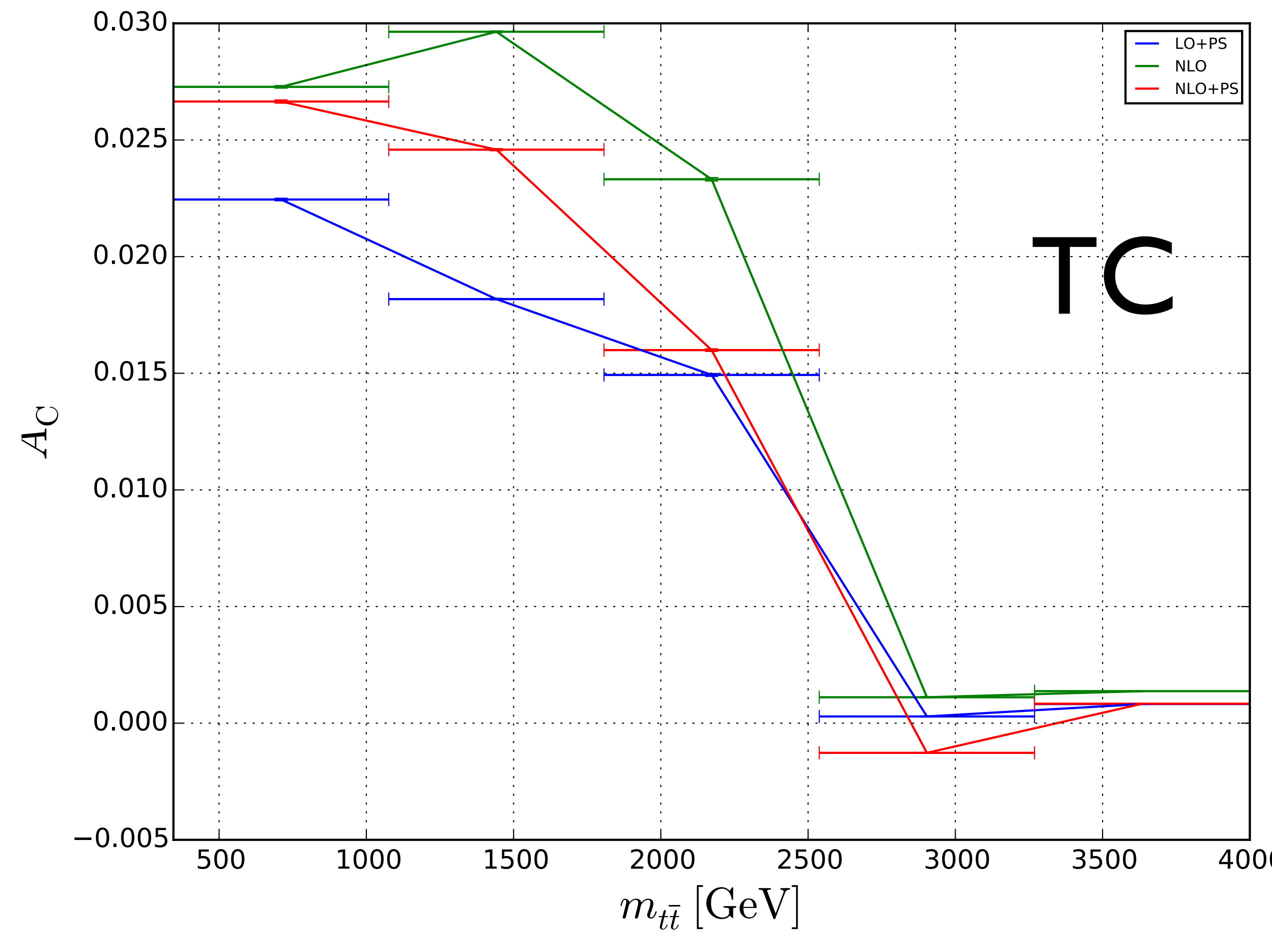




- Blue curves: without interference terms
- Green curves: with interference terms
  Shifts resonance peak to smaller masses
- Ratio = Blue curve/Green curve
  Predictions without interferences overestimate the true signal by a factor of >2

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 III

- 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

ATLAS and CMS searches for new spin one bosons (W’, Z’) at the LHC using data from the pp runs in 2010 and 2011 at 7 TeV and the pp run in 2012 at 8 TeV

Reference	$\sqrt{S}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	Mode	Limits [TeV]	Comments
ATLAS:					
PLB701(2011)50 [18]	7	0.036	$W' \to \ell\nu$	$M_{W'} > 1.49$	SSM
PLB705(2011)28 [19]	7	1.04	$W' \to \ell\nu$	$M_{W'} > 2.15$	SSM
EPJC72(2012)2241 [20]	7	4.7	$W' \to \ell\nu$	$M_{W'} > 2.55$	SSM
ATLAS-CONF-2014-017 [21]	8	20.3	$W' \to \ell\nu$	$M_{W'} > \mathbf{3.27}$	SSM
JHEP09(2014)037 [22]	8	20.3	$W' \to \ell\nu$	$M_{W'} > 3.24$	SSM
PRD85(2012)112012 [23]	7	1.02	$W' \to WZ \to \ell\nu\ell'\ell'$	$\sigma\times$Br	
PRL109(2012)081801 [24]	7	1.04	$W' \to tb \to \ell\nu jj$	$M_{W'_R} > 1.13$	LR Model
EPJC72(2012)2056 [25]	7	2.1	$W'_R \to \ell N \to \ell\ell jj$	$(M_{W'_R}, M_N)$ exclusions	LR Model
PRD87(2013)112006 [26]	7	4.7	$W' \to WZ \to \ell\nu jj$	$M_{W'} > 0.95$	
JHEP01(2013)29 [27]	7	4.8	$W' \to jj$	$M_{W'} > 1.68$	
ATLAS-CONF-2013-050 [28]	8	14	$W' \to tb \to \ell\nu bb$	$M_{W'_L} > 1.74$, $M_{W'_R} > 1.84$	LR Model
CERN-PH-EP-2014-147 [29]	8	20.3	$W' \to jj$	$M_{W'} > 2.45$	SSM
PLB737(2014)223 [30]	8	20.3	$W' \to WZ \to \ell\nu\ell'\ell'$	$M_{W'} > 1.52$	
CERN-PH-EP-2014-152 [31]	8	20.3	$W' \to tb \to qqbb$	$M_{W'_L} > 1.68$, $M_{W'_R} > 1.76$	LR Model
PLB700(2011)163 [32]	7	0.04	$Z' \to \ell\ell$	$M_{Z'} > 1.048$	SSM
PRL107(2011)272002 [33]	7	1.08-1.21	$Z' \to \ell\ell$	$M_{Z'} > 1.83$	SSM
JHEP11(2012)138 [34]	7	4.9	$Z' \to \ell\ell$	$M_{Z'} > 2.22$	SSM
CERN-PH-EP-2014-053 [35]	8	20.3-20.5	$Z' \to \ell\ell$	$M_{Z'} > \mathbf{2.90}$	SSM
EPJC72(2012)2083 [36]	7	2.05	$Z' \to tt$	$\sigma\times$Br	
PRD87(2013)052002 [37]	7	4.6	$\ell\ell\ell$	$\sigma^{\text{vis.}}$	
PLB719(2013)242 [38]	7	4.6	$Z' \to \tau\tau$	$M_{Z'} > 1.4$	SSM
PRD88(2013)012004 [39]	7	4.7	$Z' \to tt$	$\sigma\times$Br	Narrow Z'
JHEP01(2013)116 [40]	7	4.7	$Z' \to tt$	$\sigma\times$Br	
ATLAS-CONF-2013-052 [41]	8	14	$Z' \to tt$	$\sigma\times$Br	Narrow Z'
ATLAS-CONF-2013-066 [42]	8	19.5	$Z' \to \tau\tau$	$M_{Z'} > 1.9$	SSM
CMS:					
PLB698(2011)21 [43]	7	0.036	$W' \to e\nu_e$	$M_{W'} > 1.36$	SSM
PLB701(2011)160 [44]	7	0.036	$W' \to \mu\nu_\mu$	$M_{W'} > 1.4$	SSM
JHEP08(2012)023 [45]	7	5	$W' \to \ell\nu$	$M_{W'_L} > 2.43$-2.63, $M_{W'_R} > 2.5$	LR Model
PRD87(2013)072005 [46]	7-8	5-3.7	$W' \to \ell\nu$	$M_{W'} > 2.9$	SSM
CERN-PH-EP-2014-176 [47]	8	19.7	$W' \to \ell\nu$	$M_{W'} > \mathbf{3.28}$	SSM
PLB704(2011)123 [48]	7	1	$W' \to jj$	$M_{W'} > 1.51$	SSM
PRL109(2012)261802 [49]	7	5	$W'_R \to \ell N$	$(M_{W'_R}, M_N)$ exclusions	LR Model
PRL109(2012)141801 [50]	7	5	$W' \to WZ \to 3\ell\nu$	$M_{W'} > 1.143$	SSM
JHEP02(2013)036 [51]	7	5	$W' \to WZ \to \ell\ell jj$	$M_{W'} > 0.94$	SSM
PLB723(2013)280 [52]	7	5	$W' \to WZ \to 4j$	$\sigma\times$Br	SSM
PLB718(2013)1229 [53]	7	5	$W' \to tb \to \ell\nu bb$	$M_{W'_L} > 1.51$, $M_{W'_R} > 1.85$	LR Model
PLB717(2012)351 [54]	7	5	$W' \to ttj$	$M_{W'_R} > 0.84$	LR Model
CMS-PAS-EXO-12-025 [55]	8	19.5	$W' \to WZ$	$M_{W'} > 1.47$	SSM
CERN-PH-EP-2014-161 [56]	8	19.7	$W'_R \to \ell N$	$(M_{W'_R}, M_N)$ exclusions	LR Model
JHEP08(2014)173 [57]	8	19.7	$W' \to WZ \to jjX$	$M_{W'} > 1.7$	SSM
JHEP05(2011)093 [58]	7	0.04	$Z' \to \ell\ell$	$M_{Z'} > 1.14$	SSM
PLB714(2012)158 [59]	7	5	$Z' \to \ell\ell$	$M_{Z'} > 2.33$	SSM
PLB720(2013)63 [60]	7-8	5.3-4.1	$Z' \to \ell\ell$	$M_{Z'} > 2.59$	SSM
CMS-PAS-EXO-12-061 [61]	8	19.6-20.6	$Z' \to \ell\ell$	$M_{Z'} > \mathbf{2.96}$	SSM
PLB716(2012)82 [62]	7	4.9	$Z' \to \tau\tau$	$M_{Z'} > 1.4$	SSM
JHEP09(2012)029 [63]	7	5	$Z' \to tt$	$\sigma\times$Br	
JHEP01(2013)013 [64]	7	5	$Z', W' \to jjX$, $Z' \to bb$	$M_{W'} > 1.92$, $M_{Z'} > 1.47$	SSM
PRD87(2013)114015 [65]	8	4	$Z', W' \to jj$	$M_{W'} > 1.73$, $M_{Z'} > 1.62$	
CMS-PAS-EXO-12-059 [66]	8	19.6	$Z', W' \to jj$	$M_{W'} > 2.29$, $M_{Z'} > 1.68$	SSM
CMS-PAS-EXO-12-023 [67]	8	19.6	$Z' \to bb$	$M_{Z'} > 1.68$	SSM

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)
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)
~366fb	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)
~5fb	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)
~12fb	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)

~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

Order	Processes	Model	σ [pb]	σ [pb] $(m_{t\bar{t}} > \frac{3}{4} m_{Z'})$
	$\ldots gg \to t\bar{t}$		473.93(7)	0.15202(2)
	$\ldots gg + qg \to t\bar{t} + q$		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)
	$\ldots \to \gamma/Z \to t\bar{t}$	SM	0.5794(1)	0.00017174(5)
	$\ldots + qg \to \gamma/Z + q \to t\bar{t} + q$	SM	4.176(2)	0.001250(6)
	$\ldots \to Z' \to t\bar{t}$	SSM	0.0050385(8)	0.0044848(7)
	$\ldots \to \gamma/Z/Z' \to t\bar{t}$	SSM	0.35892(7)	0.0043464(7)
	$\ldots \to \gamma/Z/Z' \to t\bar{t}$	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)

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

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

For LO uses the NNPDF23_lo_as0119_qed PDF set

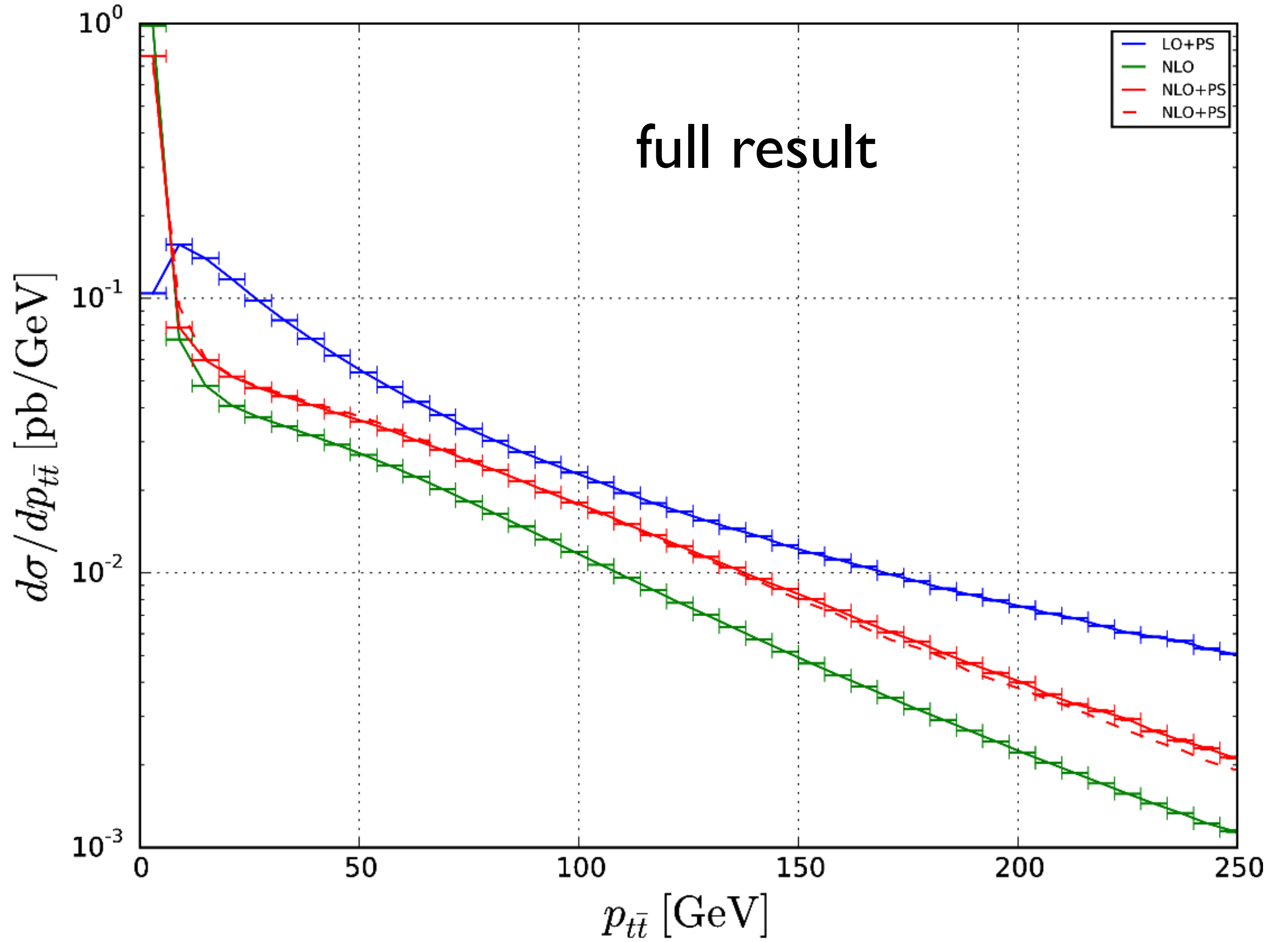
	Order	Processes	Model	σ [pb]	σ [pb] $(m_{t\bar{t}} > \frac{3}{4} m_{Z'})$
large K-factor (qg-channel!)	LO	$q\bar{q}/gg \to t\bar{t}$		473.93(7)	0.15202(2)
	NLO	$q\bar{q}/gg + qg \to t\bar{t} + q$		1261.0(2)	0.45255(7)
	LO	$\gamma g + g\gamma \to t\bar{t}$		4.8701(8)	0.0049727(6)
	LO	$\gamma g + g\gamma \to t\bar{t}$ (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)
K~1.56	NLO	$q\bar{q} \to \gamma/Z \to t\bar{t}$	SM	0.5794(1)	0.00017174(5)
proper subtr.	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~1.58	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~1.56	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)

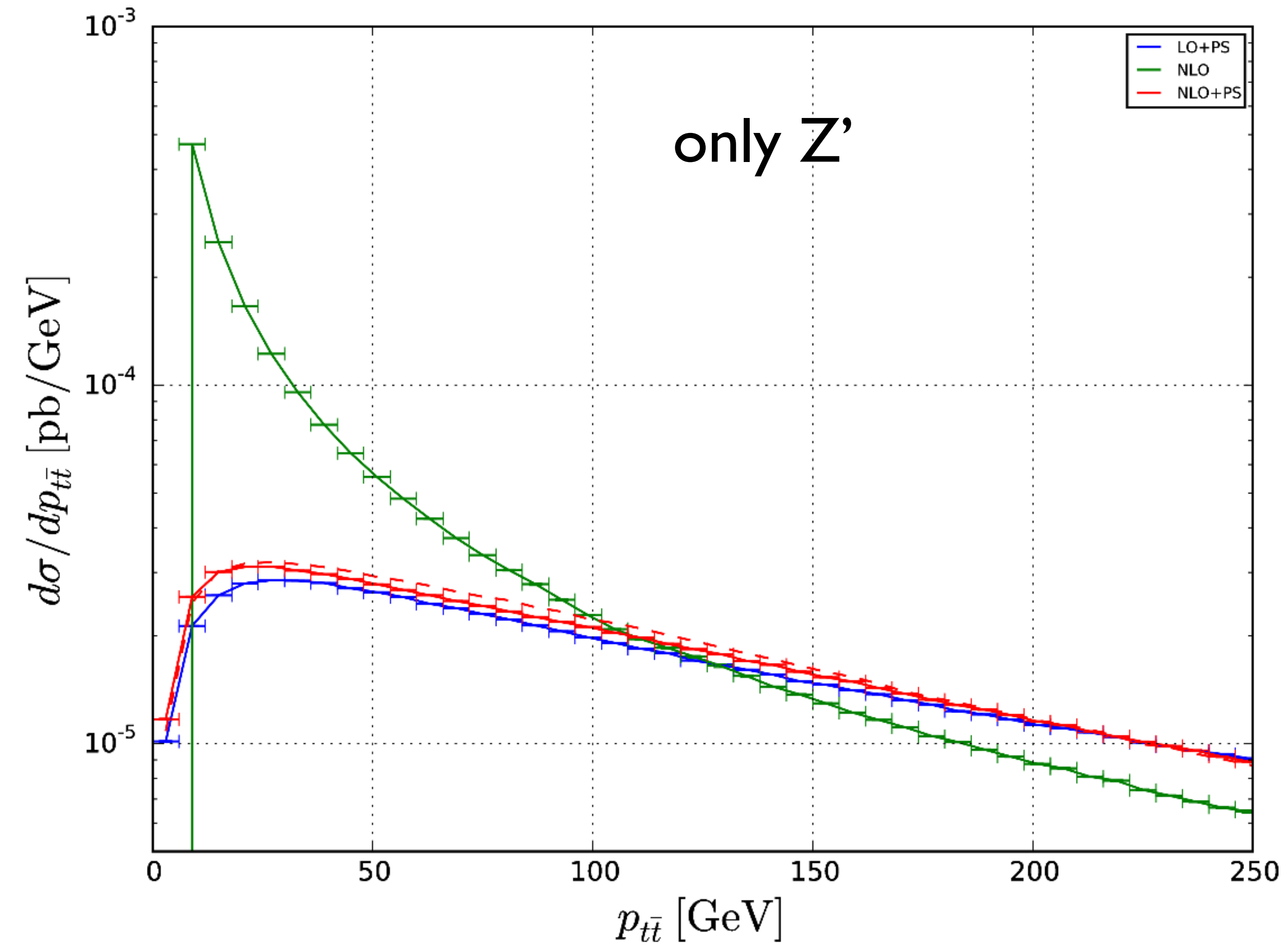
Total cross sections for $M_{Z'}$ = 3 TeV

For LO uses the NNPDF23_lo_as0119_qed PDF set

K	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)

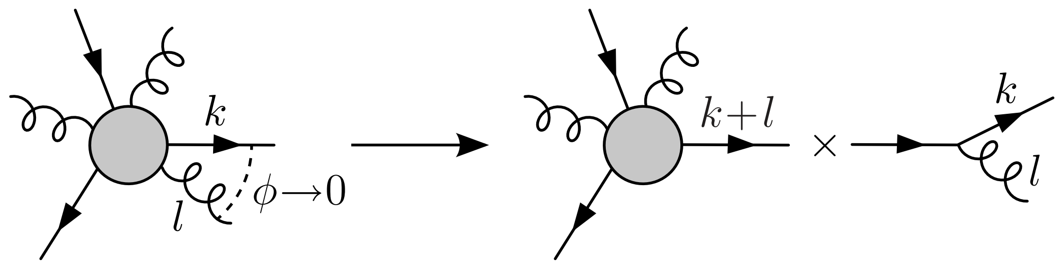
Transverse momentum distributions





- 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)

Collinear factorization and Parton Shower (PS)



$$|\mathcal{M}_{n+1}|^2 \to |\mathcal{M}_n|^2 d\Phi_n \times \frac{\alpha_S}{2\pi}\frac{dt}{t}P_{q,qg}(z)dz\frac{d\phi}{2\pi}$$

- t vanishes in the collinear limit, z momentum fraction, ϕ azimuthal angle
- $P_{q,qg}(z)$ Altarelli-Parisi splitting for $q \to qg$

- can be applied recursively
- n-splittings naively corresponds to real corrections at N^{n}LO
- virtual contributions taken account via Sudakov form factors

$$dP = \frac{\alpha_S}{2\pi}\frac{dt}{t}\int\frac{d\phi}{2\pi}\int P_{i,jl}(z)dz$$

- dP probability of $i \to jl$ splitting in $[t, t+dt]$
- $1 - dP$ probability of no radiation equivalent to virtual contributions

- automatable and process independent: Parton shower (`Pythia`, `Herwig`)
- equivalent to leading log resummation