Single Top Production in association with a Z-boson

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Outline

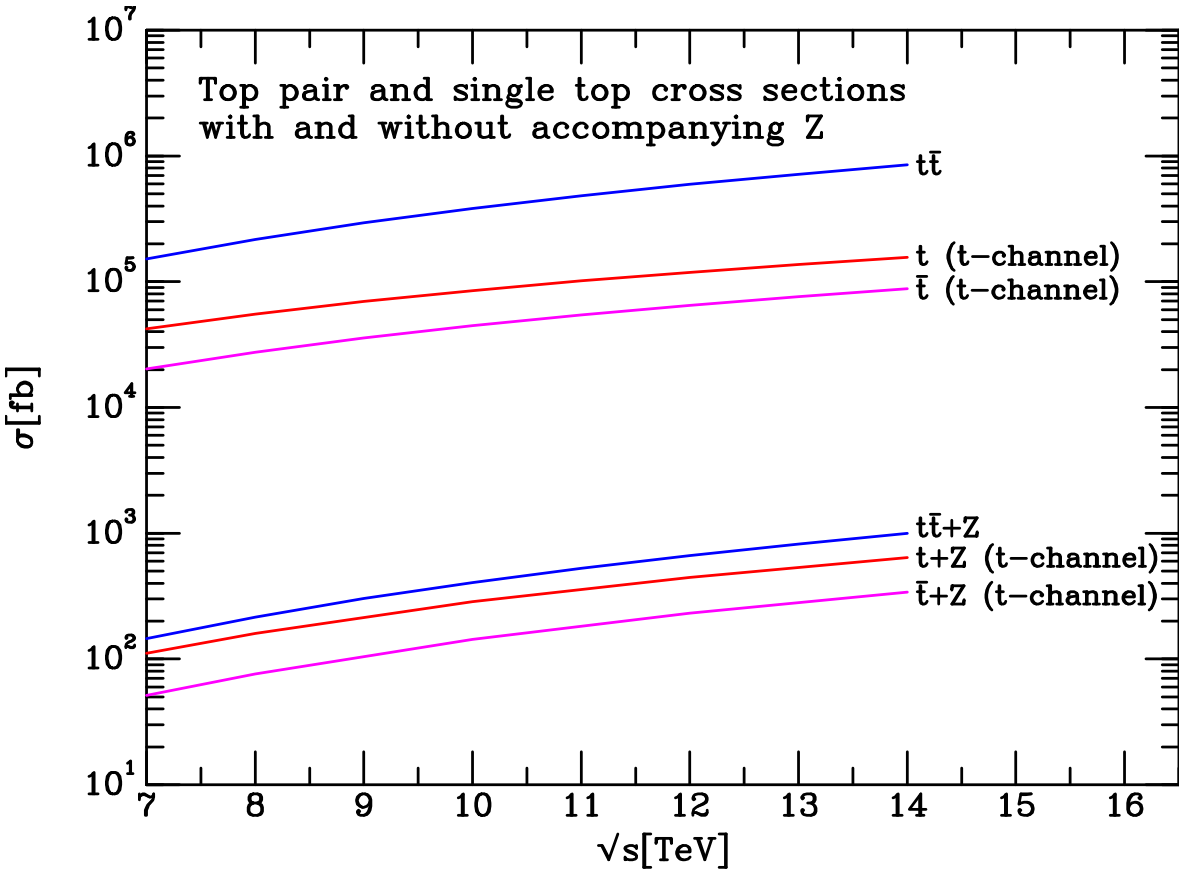
- Motivation
- Details of calculation
- Results
  - Production cross-sections
  - Jet-binned comparison with $t\bar{t}Z$
  - Background for FCNC searches
- Conclusions

Motivation

- The LHC is a **top factory** ($\sigma(t\bar{t}) \sim 10^3$pb) – high energies allow precision studies of top properties.
- E.g. top-Z coupling, top-Higgs coupling not well constrained.
- $t\bar{t}Z$ events already observed at LHC.
- **Single top + Z** production interesting on its own or as background to $t\bar{t}Z$.

Motivation

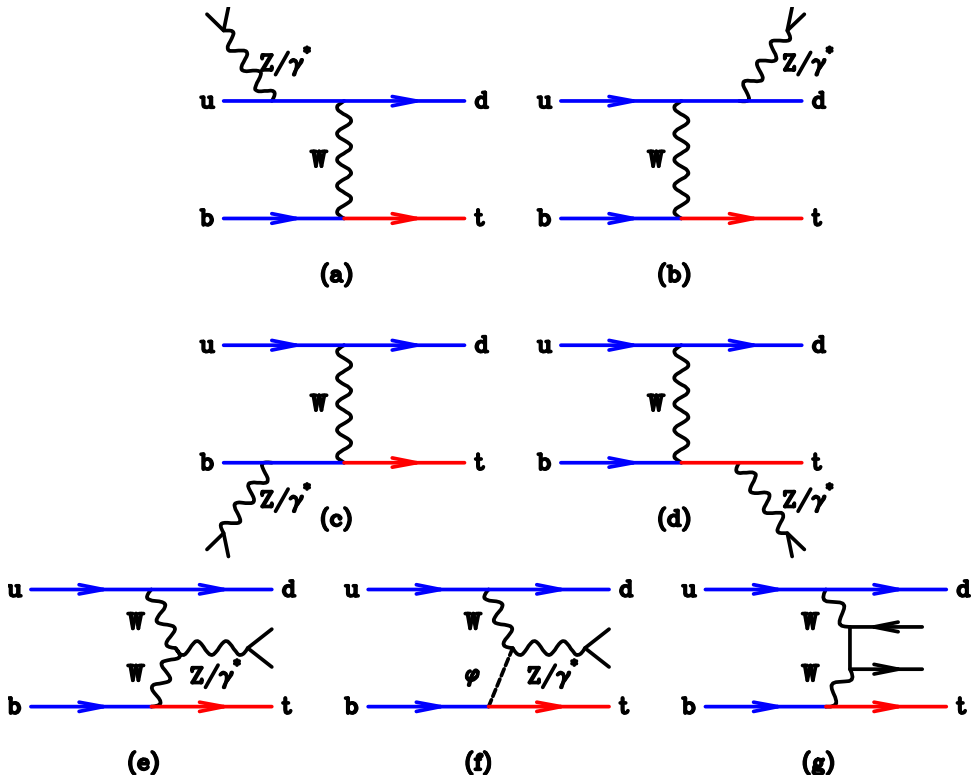
- t-channel single top production has initial state b
  $\Rightarrow$ pdf-suppressed.



- Phase space enhancement for tZ over $t\bar{t}Z$, leading to $\sigma(tZ + \bar{t}Z) \simeq \sigma(t\bar{t}Z)$.
- tZ events may already be recorded, so necessary to provide theoretical predictions.

Details of calculation - LO

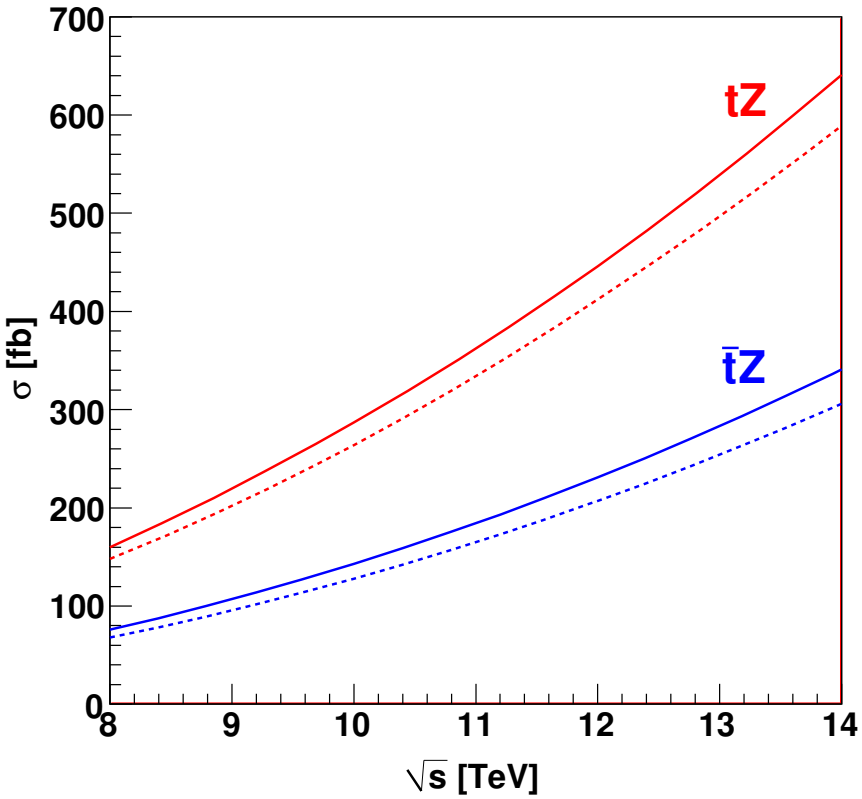
- Single top + Z production through $u + b \to d + t + Z$ (EW only).
- Charge conjugate for $\bar{t} + Z$ production.
- Easiest expressed in Feynman gauge.



Details of calculation - NLO

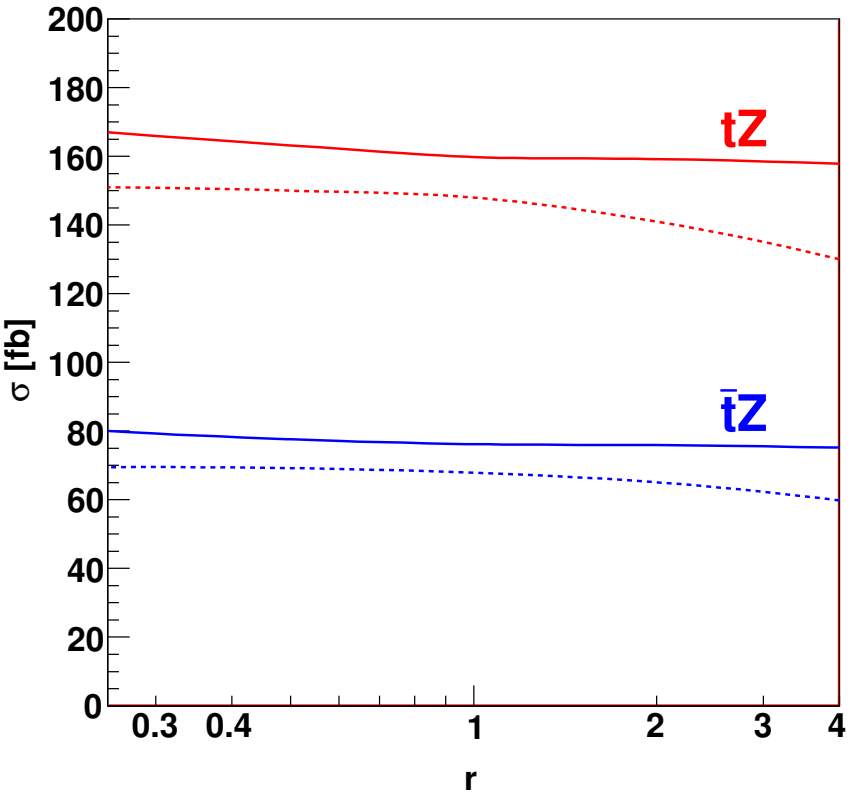
- Color structure means virtual gluons never connect two quark lines.
  $\rightarrow$ maximum 4-point integrals.
- These are calculated numerically using **tensor reduction scheme**.
- Good agreement with `GoSam` at level of matrix elements.
- Top quark decays included in NWA; LO only.

Results - Production cross-sections



- NLO corrections $\sim 10\%$.
- $\sigma(tZ)/\sigma(\bar{t}Z) \simeq 2$ due to pdf ratio $f_u/f_d \simeq 2$.
- $\sigma(tZ + \bar{t}Z) \sim 1$ pb at $\sqrt{s} = 14$ TeV.

Results - Production cross-sections



- Low scale dependence at both LO and NLO.
- Central scale $\mu = m_t$ and $\mu_R = r m_t$, $\mu_F = m_t / r$ with $r \in [1/4, 4]$.
- LO, NLO increases with increased μ_F and NLO decreases with μ_R.

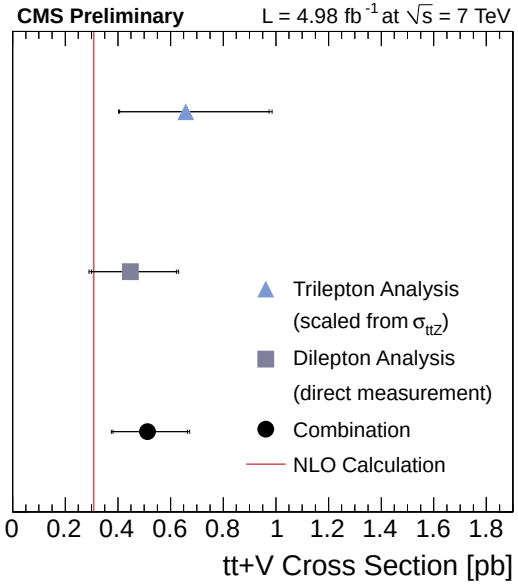
Total production cross-sections at $\sqrt{s} = 8$ TeV:

$\sigma_{\mathrm{LO}}(tZ) = 148$ fb, $\quad \sigma_{\mathrm{NLO}}(tZ) = 160^{+7}_{-2} \pm 11$ fb.

$\sigma_{\mathrm{LO}}(\bar{t}Z) = 68$ fb, $\quad \sigma_{\mathrm{NLO}}(\bar{t}Z) = 76^{+4}_{-1} \pm 5$ fb.

Agree with aMC@NLO

Comparison with $t\bar{t}Z$



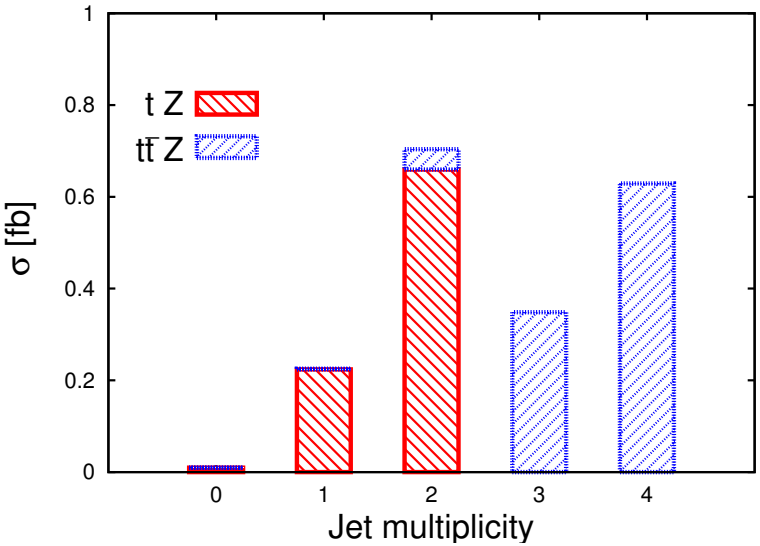
- 9 $t\bar{t}Z$ events seen by CMS, 1 by ATLAS, consistent with cross-section.
- Detection through leptonic decay of Z, semi-leptonic decay of one top, hadronic decay of other
  $\rightarrow$ signature of three charged leptons, missing energy, jets (4 @ LO).

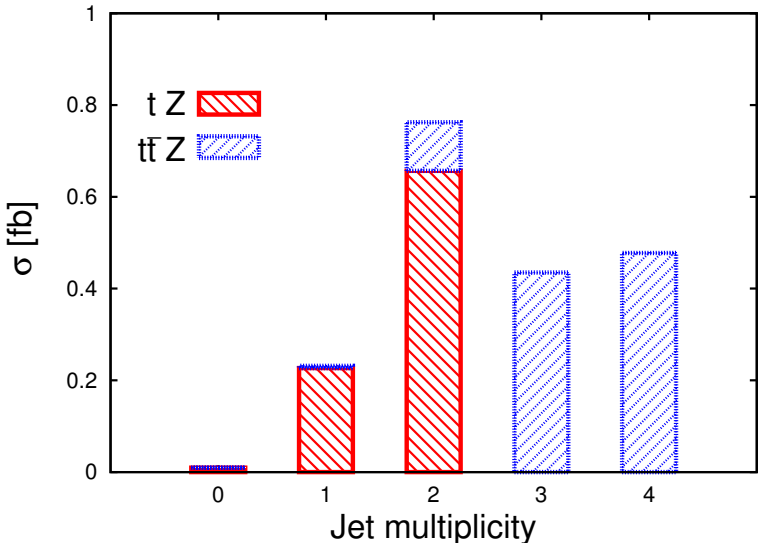
- In $t(\bar{t})Z$, leptonic decay of Z and semi-leptonic decay of top $\rightarrow$ three charged leptons, missing energy, jets (2 @ LO).
- **Two mutual backgrounds**.

Comparison with $t\bar{t}Z$ - Jet multiplicity

- Lepton cuts: $p_{T,l} > 20$ GeV, $|\eta_l| < 2.5$, $p_{T,\mathrm{miss}} > 20$ GeV.
- Jets: $p_{T,j} > 20$ GeV, and three setups:
  - $|\eta_j| < 3.5$, $\Delta R = 0.4$ (I)
  - $|\eta_j| < 2.0$, $\Delta R = 0.4$ (II)
  - $|\eta_j| < 3.5$, $\Delta R = 0.7$ (III)
- Width of jet $\rightarrow$ **small effect** in tZ: one jet forward, other central.
- Bigger effect in $t\bar{t}Z$: lower jet bins increase with ΔR.

At LO, jet multiplicity is good way of discriminating between $t(\bar{t})Z$ and $t\bar{t}Z$.

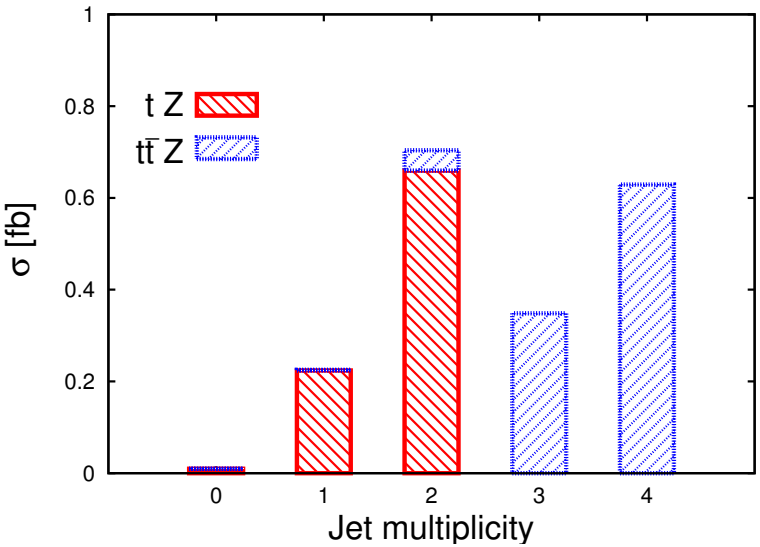


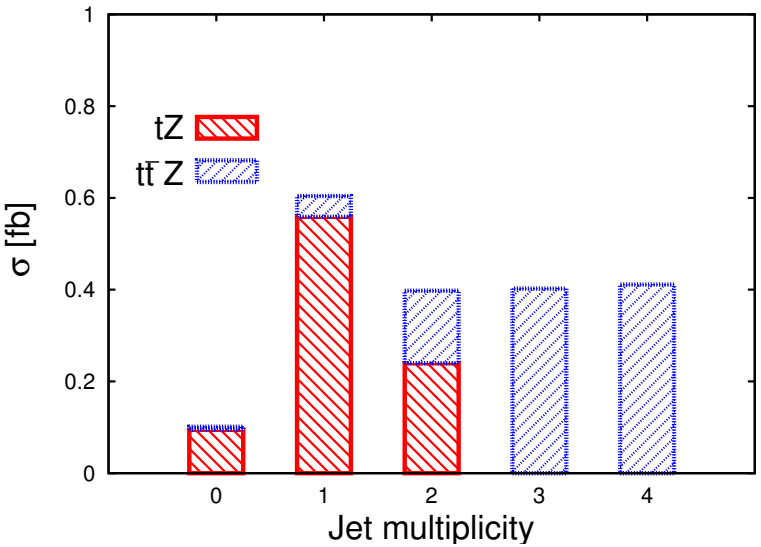


Comparison with $t\bar{t}Z$ - Jet multiplicity

Requiring jets be more central:

- **Big effect** in tZ
  forward jet excluded $\rightarrow$ 2-jet bin smaller, 1-jet bin dominates.
- Also big effect on $t\bar{t}Z$ $\rightarrow$ lower bins become populated.





Jet multiplicity - NLO corrections

Situation is worstened at NLO: radiation opens 3-jet bin.

Jet multiplicity		0	1	2	≥ 3
$\Delta R = 0.4, \lvert\eta_j\rvert < 3.5$ (I)	LO	0.01	0.33	1.05	-
	NLO	0.01	0.24	0.59	0.69
$\Delta R = 0.4, \lvert\eta_j\rvert < 2$ (II)	LO	0.14	0.86	0.40	-
	NLO	0.12	0.67	0.53	0.21
$\Delta R = 0.7, \lvert\eta_j\rvert < 3.5$ (III)	LO	0.01	0.34	1.05	-
	NLO	0.01	0.24	0.66	0.61

(in fb)

- Looking at (I) $\Rightarrow$ third jet is hard: almost half of cross-section in 3-jet bin.
- Radiation migrates events to higher bins $\rightarrow$ decrease in 1-, 2-jet bins.
- Compare (III): smaller 3-jet bin, larger 2-jet bin $\leftarrow$ NLO radiated gluon clustered with LO jet.
- In (II): 1- and 2-jet bins dominate.

Radiation smears cross-section over jets.

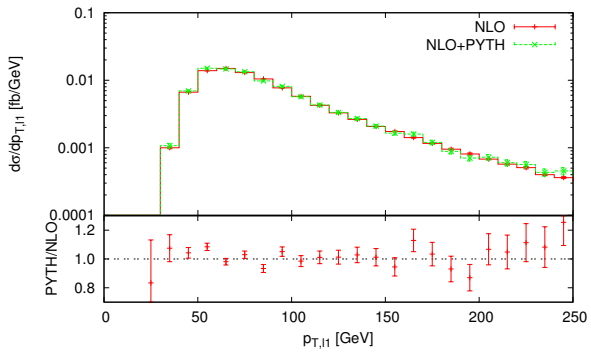
Jet multiplicity - Parton showering

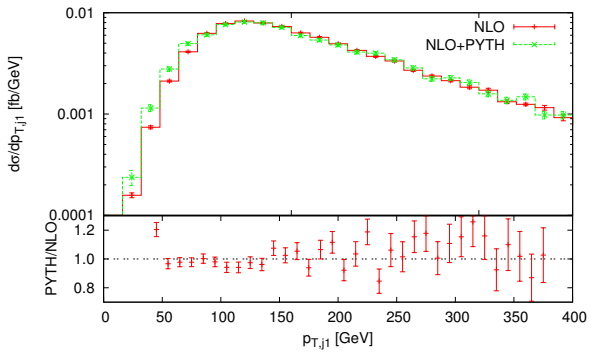
What about parton showering ?

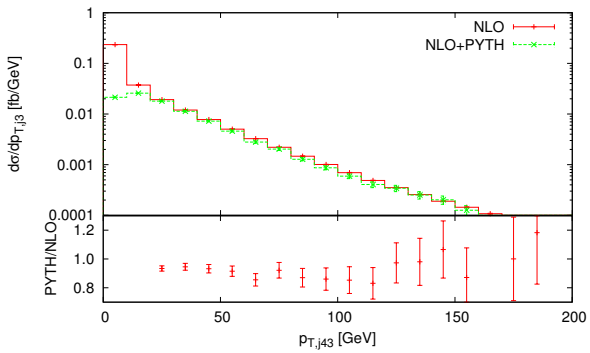
- $t(\bar{t})Z$ production implemented in POWHEG.

  public release soon

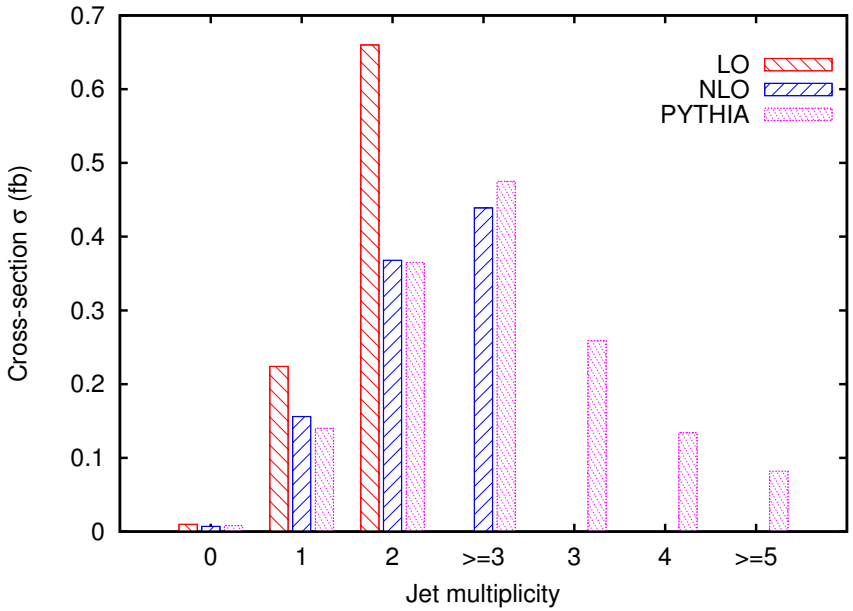
- Parton showering with PYTHIA: no QED radiation or hadronization.
- Showering behaves as expected:
  - small effect for lepton distributions;
  - larger effect for jet distributions;
  - removes low-p_T divergences in third jet.

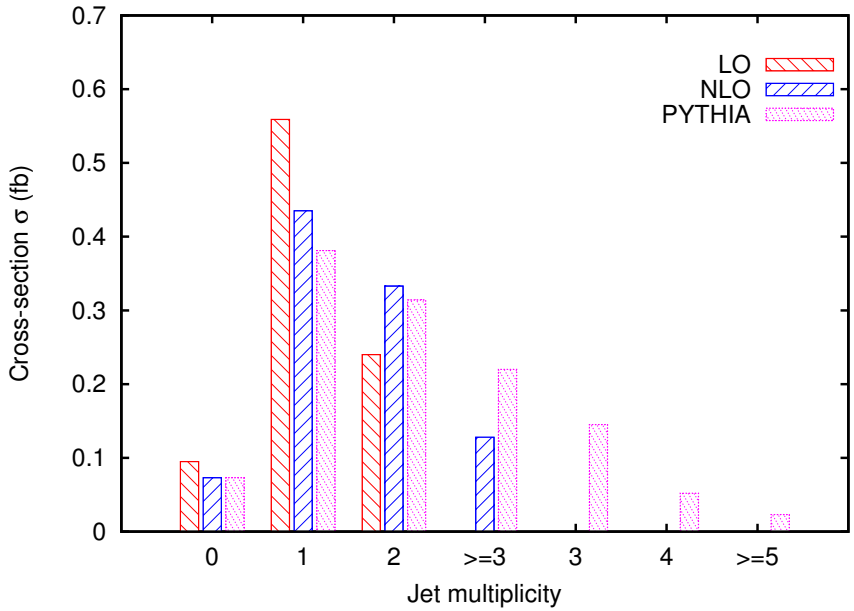






Jet multiplicity - parton showering





- Small ($\sim \mathcal{O}(10\%)$) corrections to jet-binned cross-sections for (I), (III).
- 4- and 5-jet bins make up about 20% of total cross-section: **main bins for $t\bar{t}Z$ searches**
- Requiring more central jets (II) $\Rightarrow$ larger effect, esp. in 3-jet bin.

Background to FCNC top-decay searches

- FCNC top-decays CKM-suppressed.
- Best search from CMS constrains $\mathcal{B}(t \to Zq) < 0.24\%$ in $t\bar{t}$ production in 5.0 fb^{-1} of data at $\sqrt{s} = 7$ TeV.
- SM (semi-leptonic) decay of other top $\to$ same final state as $t(\bar{t})Z$.
- The $t(\bar{t})Z$ background **not taken into account** in CMS analysis.

Background to FCNC top-decay searches

		S_T cuts (ab)	b-tag cuts (ab)
Zt	σ_{LO}	33.3	14.3
	σ_{NLO}	52.0	24.5
$Z\bar{t}$	σ_{LO}	17.5	7.71
	σ_{NLO}	26.2	12.5

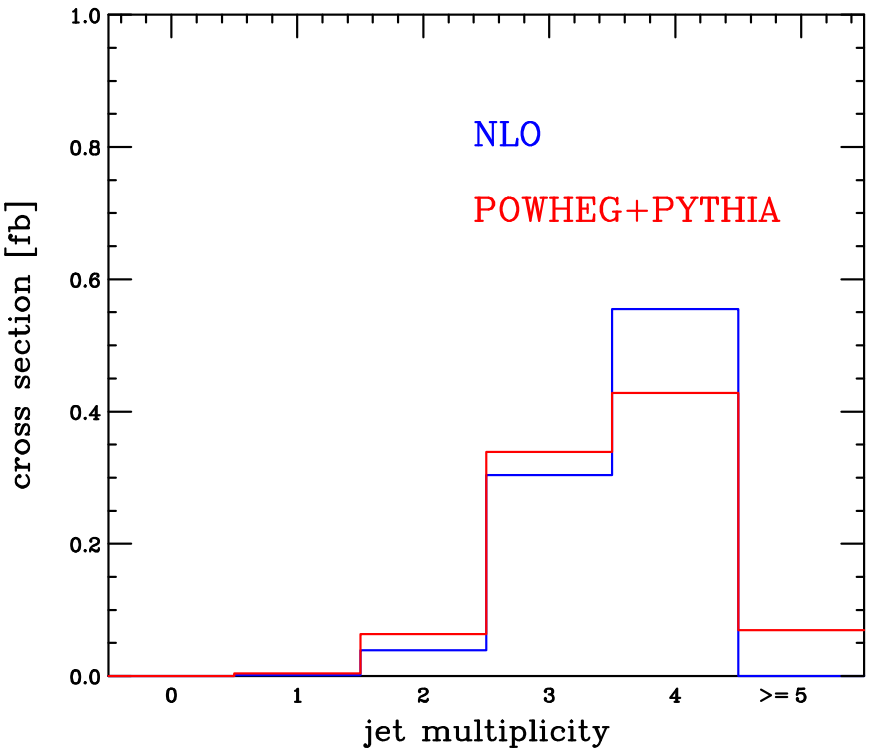
- Larger k-factors (1.5 for S_T cuts, 1.7 for b-tag cuts) – extra jet at NLO helps satisfy jet requirements.
- $(0.052 + 0.026) \times 4 \times 5 = 1.6\ tZ + \bar{t}Z$ events using S_T cuts $\leftrightarrow$ 16.2 background events expected (13.6 from $WZjj$)
- $(0.025 + 0.013) \times 4 \times 5 = 0.74\ tZ + \bar{t}Z$ events using b-tag cuts $\leftrightarrow$ 0.83 background events expected
- **This is dominant background using b-tag cuts.**

Conclusions

- Hadroproduction of $t(\bar{t})Z$ calculated to NLO.
- Production rates of this process competetive with $t\bar{t}Z$.
- Distinguishing between these processes challenging, **even in regions of high jet multiplicity.**
- Unconsidered background to FCNC top decays – may be **dominant** background.
- Code available as part of `MCFMv6.6`.
- `POWHEG` release soon.

Backup I: Showering in $t\bar{t}Z$

LO $t\bar{t}Z$ in POWHEG + showering



- Cross-section in 4-jet bin **decrease**; migrates to 3- and 5-jet (incl.) bins.
- Lower jet bins unaffected.
- $\sim$ 20% effect.

Backup slides II: FCNC cuts

Cuts from CMS:

- $p_{T,l} > 20$ GeV, $|\eta_l| < 2.5$, $p_{T,\mathrm{miss}} > 20$ GeV.
- $p_{T,j} > 30$ GeV, $|\eta_j| < 2.4$
- $60\mathrm{GeV} < m_{ll} < 120$ GeV
- Lepton isolation: ratio of sum of p_T of jets, leptons within $\Delta R = 0.3$ of lepton ¡ 0.125 (0.1) $\times p_{T,l}$ for lepton from Z (W).
- "S_T" cuts:
  - At least two jets, as above
  - S_T = Sum of all p_T ¡ 250 GeV
  - $100\mathrm{GeV} < m_{Zj}, m_{Wb} < 250$ GeV
- "b-tag" cuts:
  - At least two jets, one b-tagged.
  - $|m_{Zj} - m_t| < 25$ GeV; $|m_{Wb} - m_t| < 35$ GeV