Investigation of the top quark coupling to photons at the ATLAS detector

Measurement of the $t\bar{t}\gamma$ cross section and further prospects

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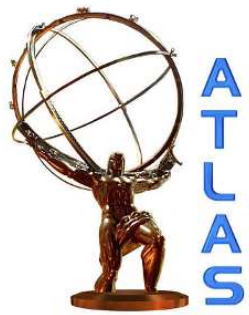
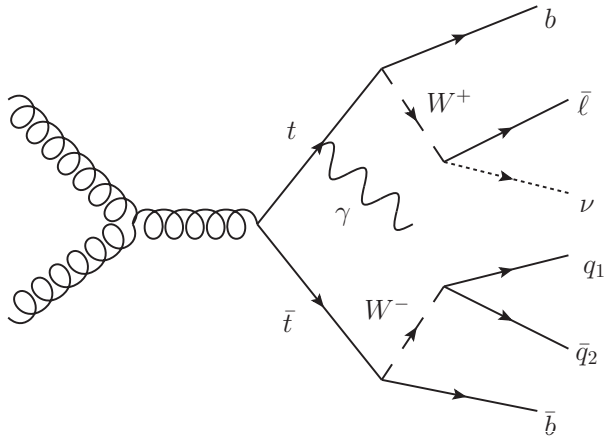


Top quark physics at the LHC

- Top quark discovery at Tevatron (Fermilab) in 1995
- Very high mass: $m_t = (172.9 \pm 0.6 \pm 0.9)\,\text{GeV}$
  $\Rightarrow$ plays a special role in EWSB (Large Higgs mass corrections, sensitive to New Physics)
- Many properties of the top quark not addressed since then
  - FCNC ($t \to Zc$, $t \to \gamma c$)
  - EW couplings (ttZ, $tt\gamma$)
  - Strong coupling ($t\bar{t} + g$)
  - Spin correlations
  - ...
- LHC is a "top quark factory": $\approx 850,000$ top quark pairs produced so far ($\sigma_{t\bar{t}} \approx 170\,\text{pb}$, $5\,\text{fb}^{-1}$ of data collected until end of 2011)

Radiative top quark processes (1)

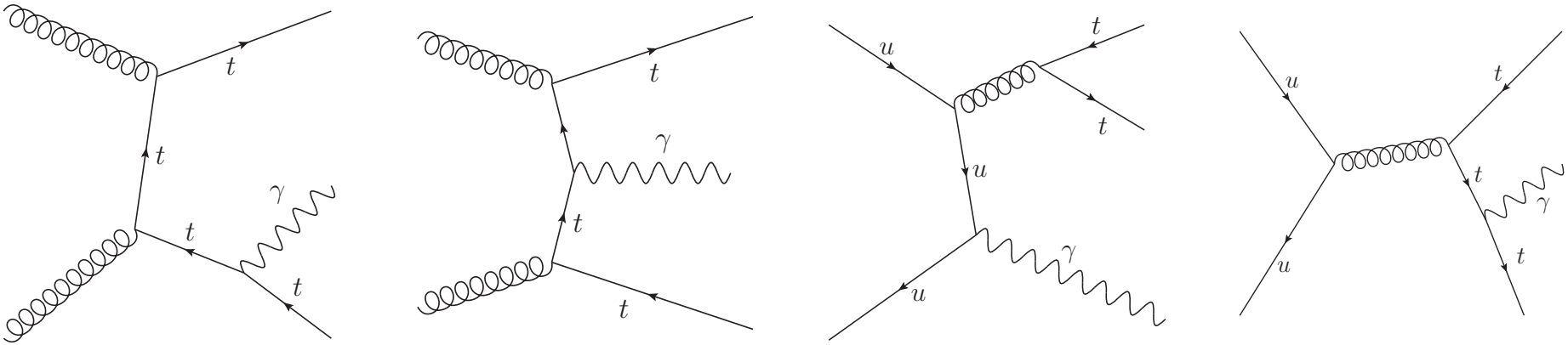
- **Pair production of top quarks** (semi-leptonic decay) with additional photon radiation



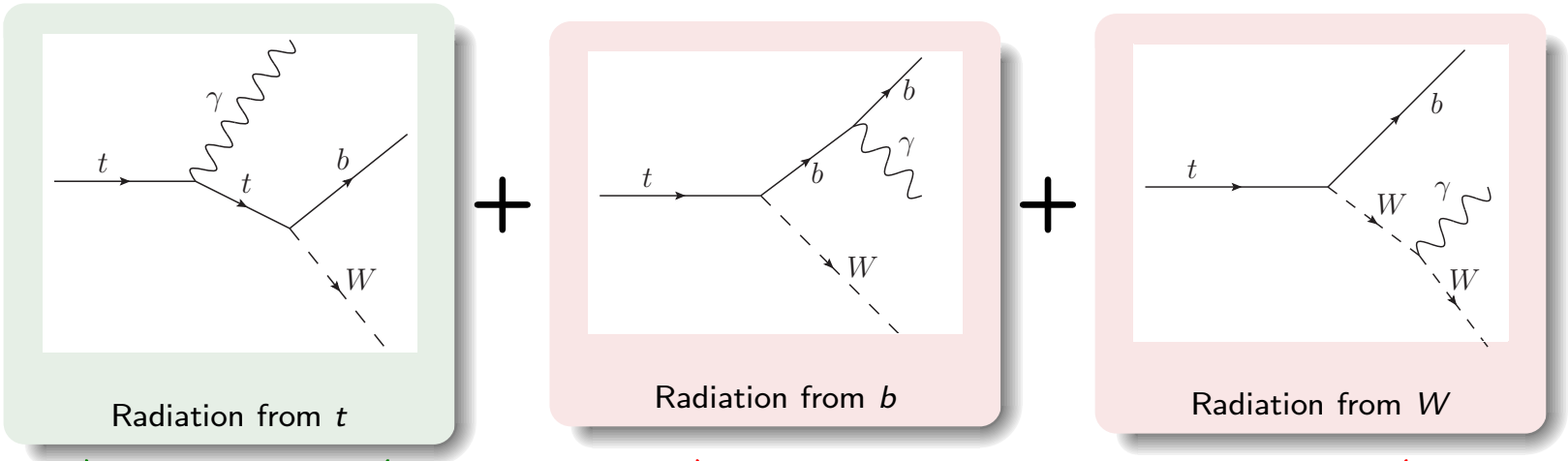
- Final goal: determination of the photon coupling to the top quark
  - Test of the SM predictions: Is the strength/structure of photon coupling as predicted?
  - Is the top quark a point-like Dirac particle? Inner structure (dipole moments)?
- First step: total $t\bar{t}\gamma$ cross section

Radiative top quark processes (2)

- Radiative top quark production



- Radiative top quark decay



$t\bar{t}\gamma$ cross section measurement at ATLAS

- Conference note recently published [1]
  - Univ. of Siegen and Göttingen involved
  - **First LHC result!**
- Data from March until June 2011 ($1.04\,\mathrm{fb}^{-1}$) @7 TeV
- Signal Monte Carlo generated with WHIZARD 1.93
- Background modeled with a large variety of different MC generators
  - MC@NLO: $t\bar{t}$ (largest background), single top
  - ALPGEN: Z+jets, W+jets, diboson
  - AcerMC: Several systematic studies (e. g. ISR/FSR)
- All MC samples are interfaced to HERWIG (except AcerMC: $\rightarrow$ PYTHIA)

WHIZARD $t\bar{t}\gamma$ signal MC (1)

- WHIZARD 1.93 (validated within ATLAS in 2010 against MadGraph/MadEvent)
- 7-particle final state produced (semi- and dileptonic)
  $\Rightarrow pp(\rightarrow t\bar{t}(\gamma)) \rightarrow \ell\nu j_1 j_2 b\bar{b}\gamma$ and $pp(\rightarrow t\bar{t}(\gamma)) \rightarrow \ell\nu\ell\nu b\bar{b}\gamma$)
  - Inclusive cross section (no explicit top quarks as intermediate states)
  - Full matrix element calculation down to a low energy scale
  - Takes into account all interference terms
- MC cross section: $\sigma_{t\bar{t}\gamma} = 840\,\text{fb}$
- 500k events produced with full detector simulation (corresponds to $\int L\,dt = 600\,\text{fb}^{-1}$)
- Parton showering/hadronisation: HERWIG
- Additional photon radiation modelled with PHOTOS

WHIZARD $t\bar{t}\gamma$ signal MC (1)

- WHIZARD phase space cuts (to avoid soft and collinear divergencies)
  - Photon $p_T > 8\,\text{GeV}$
  - Transverse momenta of all other particles $p_T > 10\,\text{GeV}$
  - Invariant mass cuts: $m_{\text{inv}} > 5\,\text{GeV}$ for all pairs of massless particles (photons, leptons, light quarks, incoming gluons)
- Running PDF factorisation scale (WHIZARD: $\mu_F = \sqrt{\hat{s}}$)
- Fixed renormalisation scale: $\mu_R = 2m_t$
  - WHIZARD 1.93: Only setting of strong coupling constant possible $\Rightarrow g_s = 1.1607$
  - Corresponds to 5-flavour leading-log and $\Lambda_{\text{QCD}} = 170\,\text{MeV}$
  - Setting renorm. scale directly via μ_R possible in WHIZARD 2

Event selection

- Two different channels (e and μ) considered
  $\Rightarrow$ optimised for semi-leptonic $t\bar{t}$ event selection
- Event selection based on standard ATLAS $t\bar{t}$ selection + additional photon requirement
  - Exactly one isolated electron(muon) with $p_{\mathrm{T}} > 25(20)\,\mathrm{GeV}$
  - μ channel: $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}(W) > 60\,\mathrm{GeV}$ and $E_{\mathrm{T}}^{\mathrm{miss}} > 20\,\mathrm{GeV}$
  - e channel: $E_{\mathrm{T}}^{\mathrm{miss}} > 35\,\mathrm{GeV}$ and $m_{\mathrm{T}}(W) > 25\,\mathrm{GeV}$
  - at least 4 jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$
  - at least 1 of the jets identified as a b-jet
- At least 1 isolated well-identified photon with $p_{\mathrm{T}} > 15\,\mathrm{GeV}$
- Further requirements
  - Jets overlapping with a selected photons removed
  - Events removed where still a jet overlapping with a selected photon
  - e channel: events removed where
    $86\,\mathrm{GeV} \leq m_{\mathrm{inv}}(e,\gamma) \leq 96\,\mathrm{GeV}$ ($e \rightarrow \gamma$ fakes)

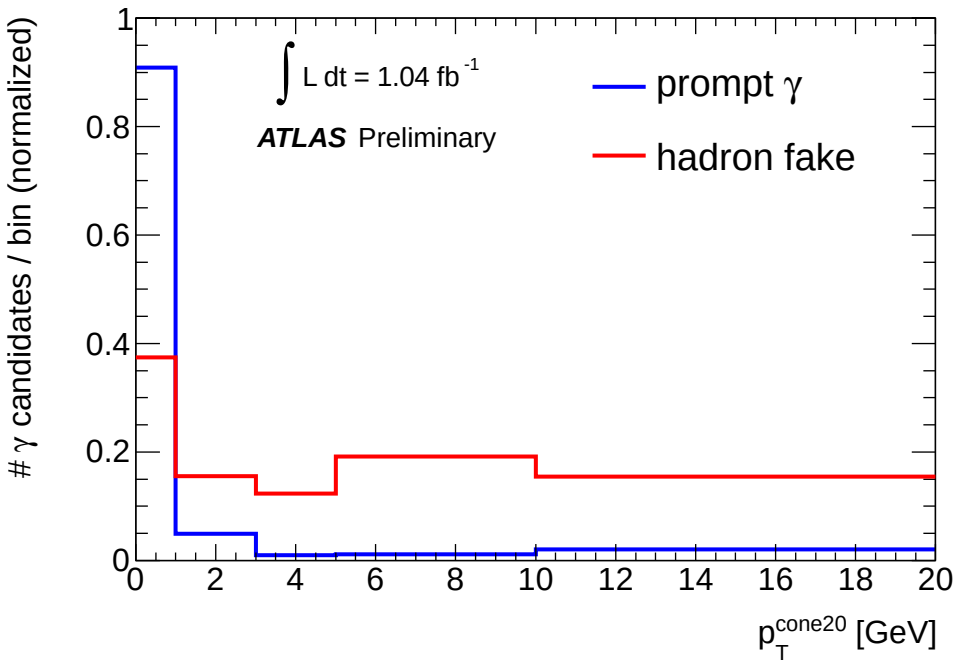
Signal overlap with MC@NLO

- Also "approximated" $t\bar{t}\gamma$ events generated in MC@NLO $t\bar{t}$ by PHOTOS/HERWIG
- signal overlap has to be removed (double-counting)
- Remove all MC@NLO events with a photon radiated from the top quarks or their direct decay products (ℓ, q, b, W) (applying WHIZARD phase space cuts)
- Still a small fraction of MC@NLO $t\bar{t}\gamma$ events survives event selection:
  - Radiation from leptons
  - Radiation from light quarks before showering/hadronisation (bremsstrahlung)

Analysis strategy (1)

- Based on template fit method
- Uses photon isolation as discrimant
  - $p_{\mathrm{T}}^{\mathrm{cone20}}$: Scalar sum of p_{T} of tracks within a cone of $R \leq 0.2$ around the photon
- Two kinds of photons:
  - **Prompt photons**: "Real" photons radiated from hard processes ($t\bar{t}\gamma$, $Z \rightarrow \ell\ell\gamma$, ...)
    $\rightarrow$ usually well isolated
  - **Hadron fakes**: Photons radiated during jet fragmentation/hadronisation (e.g. π^0 decays) $\rightarrow$ usually less isolated (emission collinear to particles of hadron jet)
- Third source of photon background: electrons misidentified as photons (**e $\rightarrow \gamma$ fakes**)
  - Estimated from $Z \rightarrow ee$ events

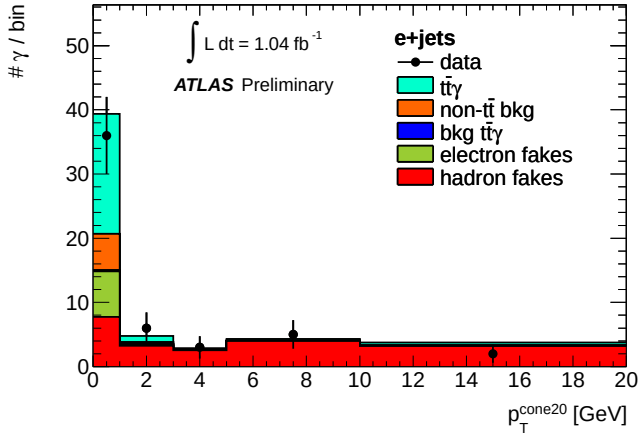
Analysis strategy (2)

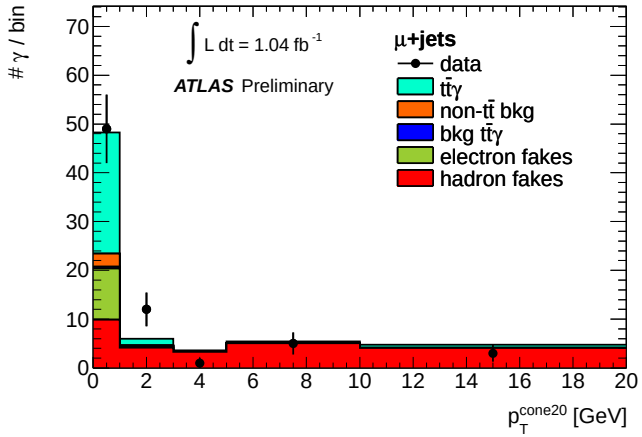


- Two templates: prompt photons (including signal) more isolated than hadron fakes
- Signal template: Taken from $Z \rightarrow ee$ electrons (isolation spectrum very similar to that of prompt photons)
- Background template: Inverting photon selection cuts in hadron enriched data stream (jet triggers)

Result

- 51(70) event candidates in the $e(\mu)$ channel
- MC signal expectation: 22(28) $t\bar{t}\gamma$ events
- Combined template fit for both lepton channels
- Main systematic uncertainties
  - ISR/FSR (16%)
  - Photon ident. efficiency (17%)
  - jet energy scale (14%)





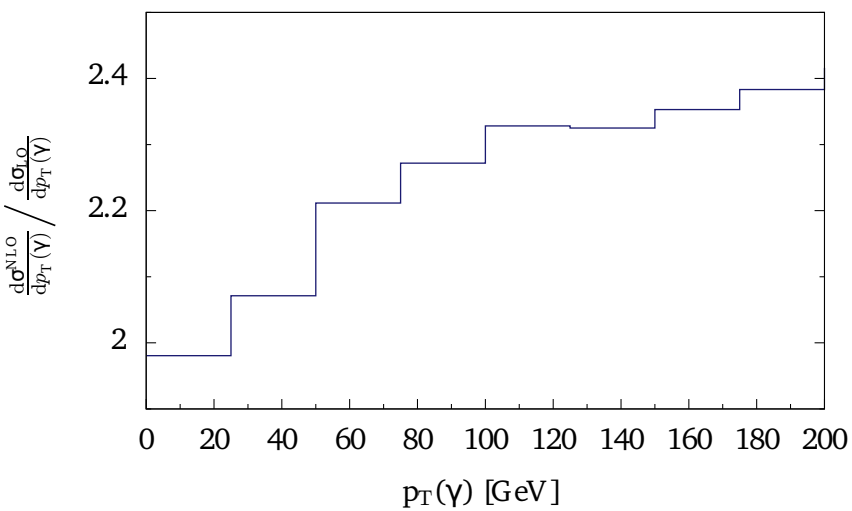
ATLAS result for $t\bar{t}\gamma \times$ BR cross section

$$\sigma_{t\bar{t}\gamma} = 2.0 \pm 0.5(\text{stat.}) \pm 0.7(\text{syst.}) \pm 0.1(\text{lumi.})\,\text{pb}$$

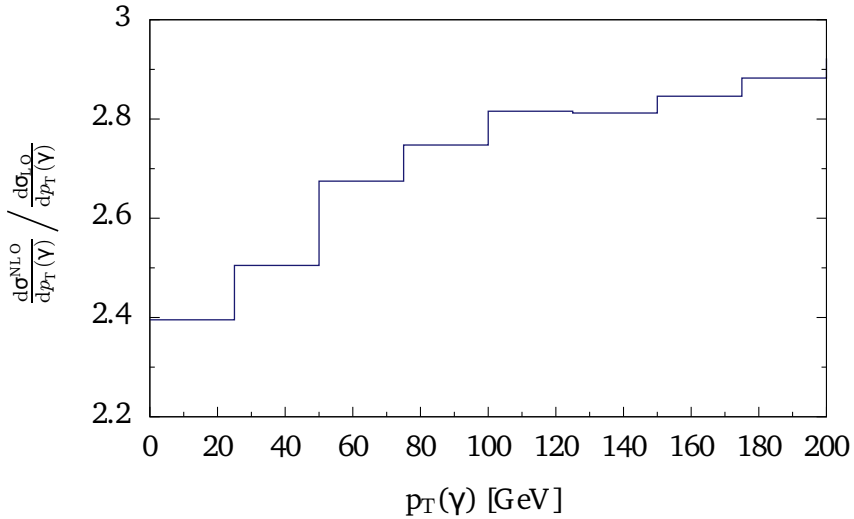
CDF result (Tevatron, $\sqrt{s} = 1.96$ TeV): $\sigma_{t\bar{t}\gamma} = 170 \pm 30$ fb

$t\bar{t}\gamma$ NLO calculations (k-factor)

- $t\bar{t}\gamma$ cross section at NLO calculated by A. Scharf et al. [3]
- Paper: Calculations for 14 TeV
  $\rightarrow$ 7 TeV: private communications
- Generally: $t\bar{t}\gamma$ has a large k-factor
- k-factor strongly depending on energy scale!
  - Difficulty: Running μ_F in WHIZARD signal samples
  - Ad-hoc suolution: Take average of two μ_R scenarios
    ($k(\mu_R = m_t) = 2.85$ and $k(\mu_R = 2m_t) = 2.11$)
    $\Rightarrow \langle k \rangle = 2.55 \pm 0.50 \Rightarrow \boldsymbol{\sigma_{\text{theor.}} = 2.1 \pm 0.4}$ pb



k-factor for $\mu_R = m_t$



k-factor for $\mu_R = 2m_t$

Measurement of top-photon couplings (1)

- Extension of the SM photon vertex structure ($-ie\gamma^\mu$):

$$\begin{aligned} -i\Gamma_\mu^{tt\gamma} &= e\gamma_\mu \left(F_{1V}^\gamma(k^2) + F_{1A}^\gamma(k^2)\gamma_5\right) \\ &+ \frac{e}{2m_t}\sigma_{\mu\nu}\left(q+\bar{q}\right)^\nu \left[iF_{2V}^\gamma(k^2) + F_{2A}^\gamma(k^2)\gamma_5\right] \end{aligned}$$

Factor	Interpretation	SM value
F_{1V}^γ	electric charge	$-2e/3$
F_{1A}^γ	axial-vectorial coupling	0
F_{2V}^γ	anomalous magnetic form factor	0
F_{2A}^γ	electric dipole form factor	0

- Electric charge: exotic top quark model with $F_{1V}^\gamma = 4e/3$ at more than 5σ [2]
- F_{1A}^γ: Only contribution to off-shell photons $\Rightarrow$ no contribution in LO calculations
- Tensor couplings constrained by experimental results:

$$-0.2 \leq F_{2V}^\gamma(0) \leq 0.5 \qquad |F_{2A}^\gamma| < 4.5$$

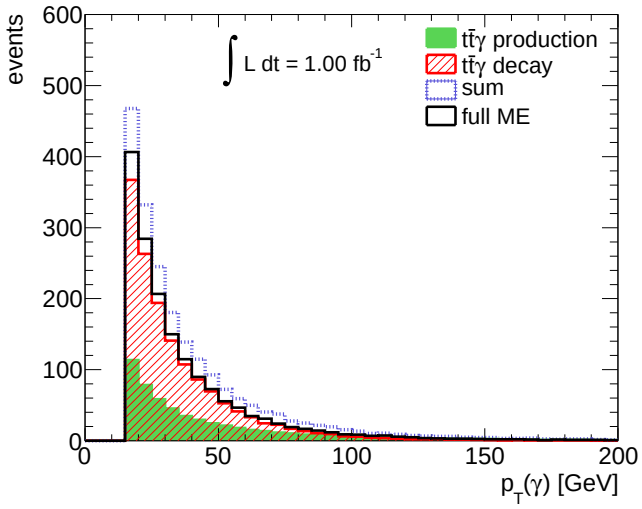
Measurement of top-photon couplings (2)

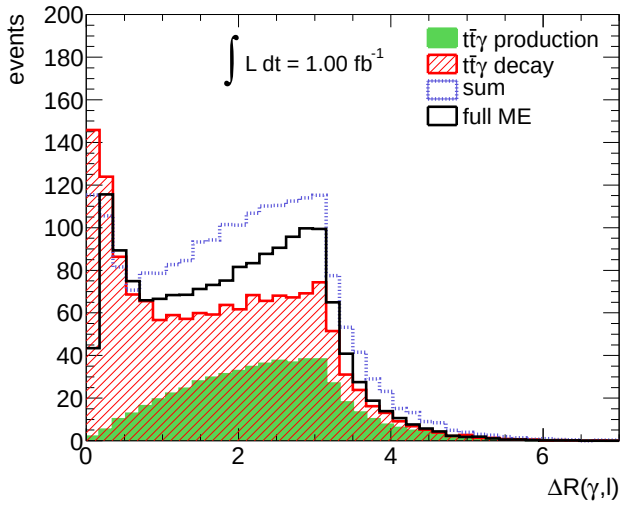
- $t\bar{t}\gamma$ cross section: very first step on testing the SM
- Next step: Direct measurement of the $t\gamma$ vertex structure
  - WHIZARD 2.0.5 contains a model for varying vectorial/axial-vectorial tensor couplings (`SM_anom_top.mdl`)
- In experiment: cannot distinguish uniquely between $t\gamma$ and other couplings (interference)
  - WHIZARD 2: Factorisation of processes possible ($t\bar{t}$: "narrow width approximation")
  - Create two samples

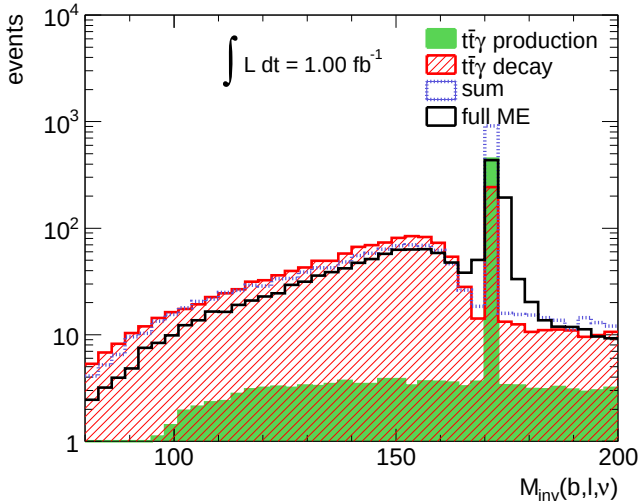
    $pp \to t\bar{t}\gamma \Rightarrow t \to b\ell\nu\ (t \to bq\bar{q}')$

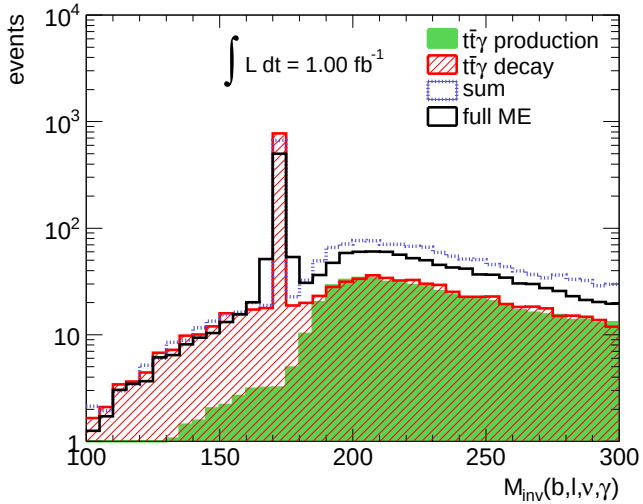
    $pp \to t\bar{t} \Rightarrow t \to b\ell\nu\gamma\ (t \to bq\bar{q}'\gamma)$
  - $\sigma_{\text{fac.}} = 800\,\text{fb}$ (vs. $\sigma_{\text{full ME}} = 640\,\text{fb}$)
- Find phase space regions enhanced by $t\gamma$ couplings from factorisation

Measurement of top-photon couplings (3)









- In general: agreement full ME↔factorisation
- photon p_T spectrum: Slightly harder for $t\bar{t}\gamma$ production
- $\Delta R(\ell, \gamma)$: Enhanced $tt\gamma$ coupling for $\Delta R \gtrsim 1.0$
- Inv. top mass also good discriminant **on 4-vector level**
  - Reconstructed top mass distributrions will strongly be smeared out!

Summary

- LHC is a top quark factory: Many yet unknown properties can be measured there
- ATLAS: first LHC result for $t\bar{t}\gamma$ cross section:

$$\sigma_{t\bar{t}\gamma} = 2.0 \pm 0.5(\text{stat.}) \pm 0.7(\text{syst.}) \pm 0.1(\text{lumi.})\,\text{pb}$$

- $t\bar{t}\gamma$ inclusive signal MC sample: 7-particle final state with WHIZARD 1.93
- Preliminary NLO k factor: 2.55 ± 0.50 (A. Scharf et al.)
- Prospects for the future: Determination of/setting limits on (anomalous) $tt\gamma$ couplings
  - Derive phase space cuts to enhance $tt\gamma$ coupling (WHIZARD 2: factorisation)
  - `SM_anom_top.mdl`: Variation of vectorial/axial-vectorial $tt\gamma$ tensor couplings

References

[1] The ATLAS Collaboration. *Measurement of the inclusive $t\bar{t}\gamma$ cross section at $\sqrt{s} = 7$ TeV with the ATLAS detector*. ATLAS-CONF-2011-153.

[2] The ATLAS Collaboration. *Measurement of the top quark charge in pp collisions at $\sqrt{s} = 7$ TeV in the ATLAS experiment*. ATLAS-CONF-2011-141.

[3] K. Melnikov, M. Schulze and A. Scharf. *QCD corrections to top quark pair production in association with a photon at hadron colliders*. Phys. Rev. D **83** (2011) 074013. [arXiv:1102.1967 [hep-ph]].