$t\bar{t}$ + isolated photon production at NLO accuracy matched with PS

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Higgs boson has been discovered

one of the two best channels
Higgs boson has been discovered

- $m_H \ [\text{GeV}] = 125.09 \pm 0.21_{\text{stat}} \pm 0.11_{\text{scale}} \pm 0.02_{\text{other}} \pm 0.01_{\text{theo}}$
  (CMS + ATLAS Run 1: $\gamma\gamma + 4\text{ lepton})$
- $\Gamma_H \ [\text{MeV}] = 1.7^{+7.7}_{-1.8} \ (\text{CMS}), < 23 \ (95\%, \text{ATLAS})$
- $\sigma/\sigma_{\text{SM}} = 1.00 \pm 0.13 \ (\text{ATLAS})$
- All measured properties are consistent with SM expectations within experimental uncertainties
  - spin zero
  - parity +
  - couples to masses of $W$ and $Z$ (with $c_V=1$ within experimental uncertainty)
- Prime task at LHC: to measure its couplings (could signal BSM physics)
- $y_t$ cannot be measured in $H \rightarrow tT$ decay ($m_t > m_H$)
How to measure $y_+^t$?

- $H \rightarrow yy$ is sensitive to $y_+^t$ through t-quark loop, but rates are small and W loop also contributes.

- $gg \rightarrow H$ is sensitive to $y_+^t$ through t-quark loop if only SM model particles contribute (so far xsec is consistent with SM).

- $gg \rightarrow H$ is sensitive to BSM physics if $y_+^t$ is measured separately.
y_{t} can be measured in pp → tTH through many decay channels (all very difficult):

- **hadrons with single lepton:** \( t \rightarrow b l \nu, \bar{t} \rightarrow \bar{b}jj, H \rightarrow b\bar{b} \)
- **hadrons with dilepton:** \( t \rightarrow b l \nu, \bar{t} \rightarrow \bar{b}l \nu, H \rightarrow b\bar{b} \)
- **hadrons with hadronic tau:** \( t \rightarrow b l \nu, \bar{t} \rightarrow \bar{b}jj, H \rightarrow \tau_{h}^{+}\tau_{h}^{-} \)
- **diphoton with lepton:** \( t \rightarrow b l \nu, \bar{t} \rightarrow \bar{b}jj, H \rightarrow \gamma\gamma \)
- **diphoton with hadrons:** \( t \rightarrow bjj, \bar{t} \rightarrow \bar{b}jj, H \rightarrow \gamma\gamma \)
- **same sign dilepton:** \( t \rightarrow bjj, \bar{t} \rightarrow \bar{b}jj, H \rightarrow l\nu l[\nu] \)
- **3 leptons with di, trilepton:** \( t \rightarrow b l \nu, \bar{t} \rightarrow \bar{b}jj, H \rightarrow l[\nu]l[\nu] \)
- **4 lepton with di, trilepton:** \( t \rightarrow b l \nu, \bar{t} \rightarrow \bar{b}l[\nu], H \rightarrow l[\nu]l[\nu] \)
\\( \text{tTH hadroproduction} \)

- \( y_t \) can be measured in \( pp \rightarrow \text{tTH} \) through many decay channels (all very difficult):
  - hadrons with single lepton: \( t \rightarrow b l \nu, \bar{t} \rightarrow \bar{b}jj, H \rightarrow b \bar{b} \)
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  - diphoton with lepton: \( t \rightarrow b l \nu, \bar{t} \rightarrow \bar{b}jj, H \rightarrow \gamma \gamma \)
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the photons have to be isolated
Isolated photons in the final state

... are cumbersome theoretically

two contributions:

\[ \sigma = \sigma_d + \sigma_f \]

Origin of the fragmentation contribution is a light quark - photon singularity absorbed into the fragmentation function \( D_q^\gamma(z, \mu^2) \)

photon fragmentation is not known well
Fragmentation function
Fragmentation function

- cannot be computed in perturbation theory, only its evolution
- suppressed by isolation, hard to extract

Can we avoid it?
Fragmentation function

• cannot be computed in perturbation theory, only its evolution
• suppressed by isolation, hard to extract
  Can we avoid it?
• yes: isolate photon from partons with cone radius decreasing as parton energy inside the cone decreases (smooth isolation of Frixione):

$$\sum_{i \in \text{trks}} E_{\perp, \Theta} (\delta_0 - \Delta R(\gamma, i)) \leq \epsilon_\gamma E_{\perp, \gamma} \left( \frac{1 - \cos \Delta R(\gamma, i)}{1 - \cos \delta_0} \right)^{n_\gamma}$$
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- but experimenters prefer cone of fixed radius with reduced hadronic activity inside the cone:

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E_{\perp, \text{had}} = \sum_{i \in \text{tracks}} E_{\perp, i} \Theta (R_\gamma - R(p_\gamma, p_i)) < E_{\perp, \text{had}}^{\max}
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  \]
Generate events with loose smooth photon generation isolation (i.e. small $\delta_{0}^{\text{gen}}$) using the POWHEG method

[Kardos and Trócsányi, arXiv: 1406.2324]
RESULT of PowHel:

Les Houches file of Born and Born+1st radiation events (LHE) ready for processing with SMC followed by almost arbitrary experimental analysis
Physical predictions do not depend on the generation isolation...

... if it is small enough
with sufficiently loose generation isolation the fragmentation can be neglected within the expected uncertainty of matched NLO+PS predictions if the photon is harder than the accompanying jets

[Kardos and Trócsányi, arXiv: 1406.2324]
Check method with Wy production

good description of ATLAS data if radiated photon is harder than accompanying jets

POWHEG (+MiNLO): [Barze et al: 1408.5766]

fragmentation is modeled by interleaved QCD+QED shower
The method is general

$tTyy$ hadroproduction at NLO and matched to PS

[Kardos and Trócsányi, arXiv: 1408.0278]
Choice of scales

We use the dynamical scale $\mu_{\text{dyn}} = H_T/2$, where $H_T$ is the scalar sum of transverse masses of final-state particles present in the underlying Born event.

![Graph showing $\sigma$ and K-factor vs. $\xi$]
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With this scale:

✓ the K factor is moderate, implying good convergence

✓ $\sigma_{\text{LO}} = 2.6$ fb, $\sigma_{\text{NLO}} = 3.3$ fb

$K = 1.24$ (@ 13 TeV with cuts)

scale dependence:

LO: $^{+30\%}_{-27\%}$, NLO: $^{+14\%}_{-13\%}$, largest if $\mu_R = \mu_F = \mu_{\text{dyn}}$
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Scale dependence:

- LO: $+30\%-27\%$
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Combine with:

$tTH$ hadroproduction at NLO and matched to PS

pp → t̅T (H→γγ) signal over
pp → t̅T γγ background

obtained with HEPTopTagger, CT10NLO, PYTHIA-6.4.25

signal: \( \mu_R = \mu_F = m_t + m_H/2 = (172.5 + 62.5) \) GeV

background: \( \mu_R = \mu_F = H_T/2 \)
Conclusions

- POWHEG method offers a simple way for generating almost inclusive sample of pre-showered events with (loosely isolated) photons.
- Predictions for hadroproduction of $W\gamma$ final states agree with ATLAS data if the photon is harder than the accompanying jet(s).
- Predictions presented for hadroproduction of $t\bar{t}\gamma$ and $t\bar{t}\gamma\gamma$ final states at NLO accuracy (and matched with PS).
- Effects of PS are small.
- Events are available on request or at [http://grid.kfki.hu/twiki/bin/view/DbTheory/](http://grid.kfki.hu/twiki/bin/view/DbTheory/)
Processes available in PowHel

✓ tt
✓ tt + Z 1111.0610, 1111.1444,
✓ tt + W 1208.2665,
✓ tt + H/A 1108.0387,
✓ tt + j 1101.2672,
✓ WWbB 1405.5659,
✓ tt + bb 1303.6291, 1408.0266
✓ tt, W + γ 1406.2324
✓ tt + γγ 1408.0278]
The end
Extra slides
HEPTopTagger

- Jet reconstruction using all the hadronic tracks with the C/A algorithm with $R = 1.5$ using FastJet
- Only those jets were considered for which $p_\perp > 200$ GeV and $|y| < 5$
- The t-quark candidate subjets were looked for in the jet-mass range of 150–200 GeV
- We selected that particular subjet as a t-quark jet for which the jet mass was the closest to $m_t$
Selection cuts for $t\bar{t}TH$ signal

- Two hard photons in central region with $p_{\perp, \gamma} > 30$ GeV and $|y_{\gamma}| < 2.5$.
- The photons are isolated from each other: $\Delta R(\gamma_1, \gamma_2) > 0.4$.
- Jet clustering on all the hadronic tracks with the anti-$k_\perp$ algorithm as implemented in FastJet with $R = 0.4$ and $p_{\perp, j} > 30$ GeV. Photons are isolated from these jets by $\Delta R(\gamma, j) > 0.4$ measured in the rapidity-azimuthal angle plane.
- Both of the hard photons are isolated from the top jet obtained by top tagging and from the three subjets of the top jet by $\Delta R(\gamma, j) > 0.4$ measured on the rapidity-azimuthal angle plane.
- One hard lepton in the central region with $p_{\perp} > 30$ GeV and $|y_l| < 2.5$, without distinction between leptons and antileptons.
- The lepton is isolated from both the jets and the photons with $\Delta R(l, i) > 0.4$, $i \in \{\gamma, j\}$ measured on the rapidity-azimuthal angle plane.
- Around photons the minimal hadronic activity in a cone of $R = 0.4$ is $E_{\text{max}} = 3$ GeV.