# $t\bar{t}H$ Theory Overview


Stefano Pozzorini

Zurich University

in collaboration with Stefan Guindon, Laura Reina, Chris Neu


$8^{\rm th}$ Workshop of LHC Higgs Cross Section Working Group
CERN, Geneva, 22 January 2015


FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

# Outline

1. $t\bar{t}H$ Signal
2. Backgrounds for $H \to b\bar{b}$
3. Backgrounds for $H \to \gamma\gamma$
4. Backgrounds for $H \to WW, ZZ, \tau\tau \to$ multi-leptons
5. Scale uncertainties in NLO matching & merging

# Theory Challenges in $t\bar{t}H$ searches

**Large multi-particle backgrounds** ($t\bar{t}+$jets, $t\bar{t}V+$jets, $t\bar{t}\gamma\gamma$, $VV+$jets)

- Key priority is precision for backgrounds
- NLO automation powerful but $2 \to 4$ CPU intensive

**NLO matching & merging crucial**

- *various* new methods (FxFx, MEPS@NLO, MINLO, UNLOPS,...)
- *various* automated tools (MG5_aMC@NLO, Sherpa, Minlo–PowHeg,...)

**Theory uncertainty estimates nontrivial**

- still limited experience in NLO matching+merging framework
- sophisticated analyses (data-driven extrapolations, reweighting, ...)

# Strategy of $t\bar{t}H$ subgroup

**New priorities $\leftrightarrow$ dominant sources of theory systematics**

- emphasis on backgrounds and NLO Monte Carlo methods
- close intereaction with ATLAS/CMS to identify theory priorities

**Goals and guiding principles**

- recommend state-of-the-art methodology and encourage use of *all* relevant tools
- support/coordinate NLO simulations in ATLAS/CMS
- understanding and assessment of theory uncertainties (choices and variations of renormalisation+factorisation+resummation+merging scales in multi-scale processes)

# Outline

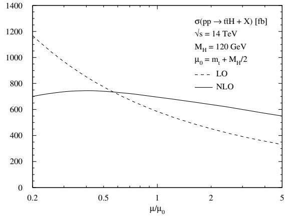
1. $t\bar{t}H$ Signal
2. Backgrounds for $H \to b\bar{b}$
3. Backgrounds for $H \to \gamma\gamma$
4. Backgrounds for $H \to WW, ZZ, \tau\tau \to$ multi-leptons
5. Scale uncertainties in NLO matching & merging

# NLO tools for $t\bar{t}H$ I

## NLO $t\bar{t}H$ cross section

[Beenakker et al '01; Reina, Dawson '01]

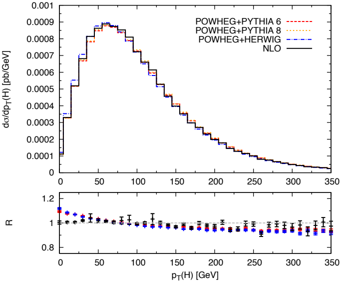
- moderate uncertainty (9% scale, 8% PDF+$\alpha_S$)
- sufficient for mid-term future




## Publicly available NLO+PS tools

- MG5_aMC@NLO (2011)
- Powhel samples (2011)
- Powheg Box [Jaeger et al, 1501.04498]
- Sherpa+OpenLoops or GoSam

$\sim 10\%$ uncertainty for inclusive observables, more if sensitive to jet radiation

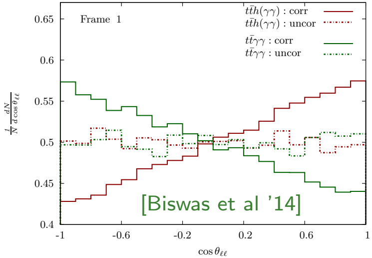


# NLO tools for $t\bar{t}H$ II

## Spin-correlated top decays in Powheg, MG5_aMC@NLO, Sherpa

- (NLO production)$\times$(LO decays)
- Breit–Wigner smearing
- spin correlations via $t\bar{t}H(+\mathrm{j})$ tree amplitudes

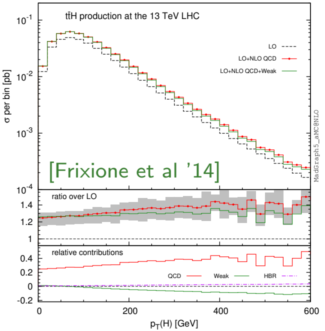
$\Rightarrow$ mandatory for signal and all backgrounds!




## Towards NLO EW corrections

- weak corrections to $t\bar{t}H$ in MG5_aMC@NLO
  $-10\%$ at high-$p_{\mathrm{T}}$
- $2 \to 2,3,4$ NLO EW automation in OpenLoops [1412.5157] and Recola [1411.0916]

$\Rightarrow$ relevant for signal *and* backgrounds at high $p_{\mathrm{T}}$

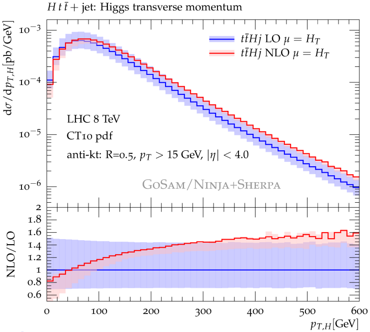


# NLO tools for $t\bar{t}H$ III

## Towards NLO merging for $t\bar{t}H + 0,1$ jets

- parton-level $t\bar{t}Hj$ SHERPA+GOSAM [Deurzen et al, '13]
- SHERPA and MG5_AMC@NLO support NLO merging

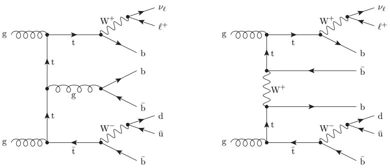
⇒ more reliable prediction *and* uncertainty for extra jet activity (impact on $t\bar{t}H$ analysis?)




## Off-shell+EW effects in $pp \to \ell\nu + 2j + 4b$ at LO [Denner at al, 1412.5290]

- tiny $t\bar{t}H$ signal–background interference
- $t\bar{t}b\bar{b}$ QCD bckg receives $+16\%$ EW cont and $-8\%$ QCD–EW interference!
- extra $+12\%$ from off-shell top decays

⇒ calls for detailed off-shell studies at NLO



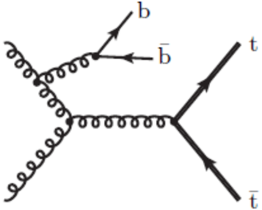
# Outline

1. $t\bar{t}H$ Signal
2. Backgrounds for $H \to b\bar{b}$
3. Backgrounds for $H \to \gamma\gamma$
4. Backgrounds for $H \to WW, ZZ, \tau\tau \to$ multi-leptons
5. Scale uncertainties in NLO matching & merging

# Irreducible $t\bar{t}b\bar{b}$ background

**NLO** $t\bar{t}b\bar{b}$ [Bredenstein et al '09/'10; Bevilacqua et al '09];

- $t\bar{t}b\bar{b}$ dominates $t\bar{t}H(b\bar{b})$ systematics
- NLO reduces uncertainty from 80% to 20–30%




**NLO+PS** $t\bar{t}b\bar{b}$ **5F scheme** $(m_b = 0)$ with POWHEL [Garzelli et al '13/'14]

- $t\bar{t}b\bar{b}$ **MEs cannot describe collinear** $g \to b\bar{b}$ **splittings**

$\Rightarrow$ *inclusive* $t\bar{t}$+b-jets simulation requires NLO merging $t\bar{t} + 0, 1, 2$ jets

**NLO+PS** $t\bar{t}b\bar{b}$ **4F scheme** $(m_b > 0)$ with SHERPA+OPENLOOPS [Cascioli et al '13]

- $t\bar{t}b\bar{b}$ **MEs cover full b-quark phase space**

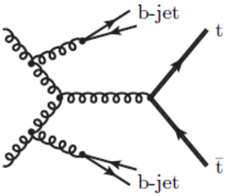
$\Rightarrow$ inclusive $t\bar{t}$+b-jets simulation possible

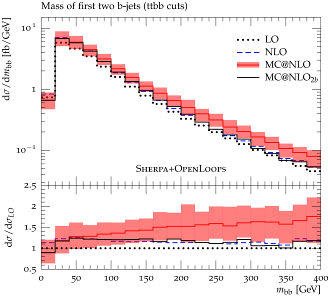
# S–MC@NLO $t\bar{t}b\bar{b}$ 4F scheme [Cascioli et al '13]

## Good perturbative stability but unexpected MC@NLO enhancement

| | $ttb$ | $ttbb$ | $ttbb\,(m_{bb} > 100)$ |
|---|---|---|---|
| $\sigma_{\rm LO}$[fb] | $2644^{+71\%+14\%}_{-38\%-11\%}$ | $463.3^{+66\%+15\%}_{-36\%-12\%}$ | $123.4^{+63\%+17\%}_{-35\%-13\%}$ |
| $\sigma_{\rm NLO}$[fb] | $3296^{+34\%+5.6\%}_{-25\%-4.2\%}$ | $560^{+29\%+5.4\%}_{-24\%-4.8\%}$ | $141.8^{+26\%+6.5\%}_{-22\%-4.6\%}$ |
| $\sigma_{\rm NLO}/\sigma_{\rm LO}$ | 1.25 | 1.21 | 1.15 |
| $\sigma_{\rm MC@NLO}$[fb] | $3313^{+32\%+3.9\%}_{-25\%-2.9\%}$ | $600^{+24\%+2.0\%}_{-22\%-2.1\%}$ | $181^{+20\%+8.1\%}_{-20\%-6.0\%}$ |
| $\sigma_{\rm MC@NLO}/\sigma_{\rm NLO}$ | 1.01 | 1.07 | 1.28 |

## Large enhancement (~30%) in Higgs region from double $g \to b\bar{b}$ splittings




⇒ understand PS and matching systematics!!

# $t\bar{t}+$ jets background and merging at NLO

**NLO $t\bar{t}+2$ jets** [Bevilacqua, Czakon, Papadopoulos, Worek '10/'11]

- reduces uncertainty from 80% to 15%

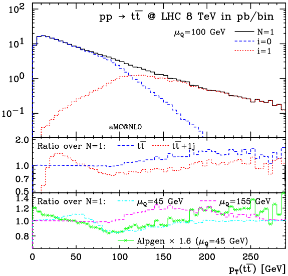
**NLO merging** (FxFx, MEPS@NLO, UNLOPS, . . . )

| | |
|---|---|
| 0-jet | NLO+PS $t\bar{t}$ |
| 1-jet | NLO+PS $t\bar{t}+1$ j |
| . . . | . . . |
| $\geq n$ jets | NLO+PS $t\bar{t}+n$ j |

- NLO and log accuracy for $0, 1, \ldots n$ jets
- separated via $k_{\mathrm{T}}$-algo at merging scale $Q_{\mathrm{cut}}$
- smooth PS–MEs transition $\leftrightarrow$ MEs with PS-like scale and Sudakov FFs

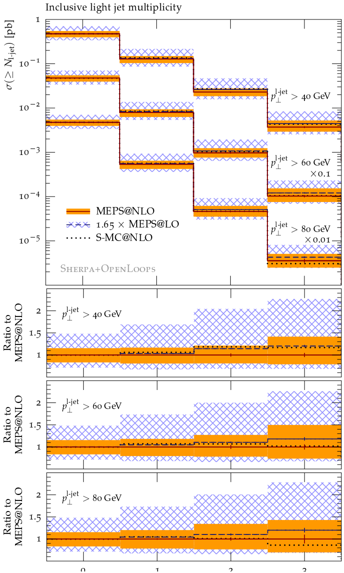
**NLO merging for $t\bar{t}+0, 1$ jets**

- FxFx with MADGRAPH5/AMC@NLO [Frederix, Frixione '12]
- MEPS@NLO with SHERPA+GOSAM [Höche et al '13]



# MEPS@NLO for $t\bar{t} + 0, 1, 2$ jets (Sherpa+OpenLoops)

[Höche, Krauss, Maierhöfer, S. P. , Schönherr, Siegert '14]




## Consistency with LO merging and NLO+PS

- decent (10–20%) mutual agreement

## Reduction of $\mu_R, \mu_F, \mu_Q$ variations

| $N_{\text{light-jet}} \geq$ | 0 | 1 | 2 |
|---|---|---|---|
| LO | 48% | 65% | 80% |
| NLO | 17% | 20% | 20–30% |

## Merging scale choice and dependence

- $Q_{\text{cut}} = 30 \pm 10$ GeV and $\ll 10\%$ dependence

$\Rightarrow$ NLO precision for $t\bar{t} + 0, 1, 2$ jets

## Next steps

- improve CPU performance (ongoing)
- consolidate understanding of theory uncertainty
- combination with $t\bar{t}b\bar{b}$

# Outline

1. $t\bar{t}H$ Signal
2. Backgrounds for $H \to b\bar{b}$
3. Backgrounds for $H \to \gamma\gamma$
4. Backgrounds for $H \to WW, ZZ, \tau\tau \to$ multi-leptons
5. Scale uncertainties in NLO matching & merging

# Relevant backgrounds and existing predictions

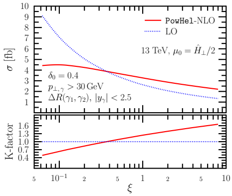
## Relevant backgrounds

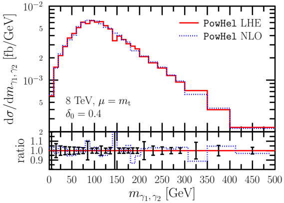
- $t\bar{t}+1,2\gamma$, single-top$+1,2\gamma$, jets$+1,2\gamma$
- $H$+jets with $H\to\gamma\gamma$ and HF jets

## NLO+PS for $t\bar{t}\gamma$ and $t\bar{t}\gamma\gamma$ with POWHEL [Kardos, Trocsanyi '14]

(available also in MG5_MC@NLO and SHERPA+OPENLOOPS)

- $K \simeq 1.25$ and 14% NLO scale uncertainty ($\mu = H_{\mathrm{T}}/2$)
- mild MC effects for inclusive observables

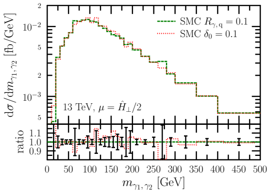



## Isolation of hard photons (POWHEL)

- realistic cone isolation at NLO+PS level
- loose Frixione isolation at generation-cut level

$\Rightarrow$ avoid fragmentation component



# Some open issues in $t\bar{t}$+photons

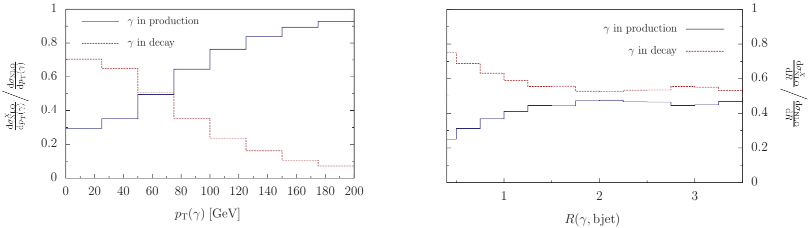
## Production of $t\bar{t}$+multiple photons

- ATLAS/CMS requires sample with $N_\gamma$=1,2
- photons from matrix elements and/or shower

$\Rightarrow$ requires merging of $t\bar{t} + 0, 1, 2\,\gamma$

## Radiative top decays [hep-ph/0604120]

- $t\bar{t}\gamma$ at NLO including radiative top decays ($t \to b\ell^+\nu + \gamma$) [Melnikov, Schulze '11]




- photons from top decays dominate up to $p_T(\gamma) \lesssim 60\,\text{GeV}$ (smooth isolation, $R_{\gamma i} > 0.4$)

$\Rightarrow$ requires detailed studies for $t\bar{t} + 2\gamma$

# Outline

1. $t\bar{t}H$ Signal
2. Backgrounds for $H \to b\bar{b}$
3. Backgrounds for $H \to \gamma\gamma$
4. Backgrounds for $H \to WW, ZZ, \tau\tau \to$ multi-leptons
5. Scale uncertainties in NLO matching & merging

# Need of accurate Monte Carlo predictions

**$t\bar{t}V$+jets with $V = W, Z/\gamma*$** (dominant MC systematics)

- enters signal through extra jet emissions
- requires precise MC for $t\bar{t}W + 0, 1, 2$ jets (same signature as $t\bar{t}H(H \to WW \to \ell\nu jj)$!
- $t\bar{t} + Z/\gamma(\to \ell^+\ell^-)$ requires off-shell effects down to small $m_{\ell\ell}$

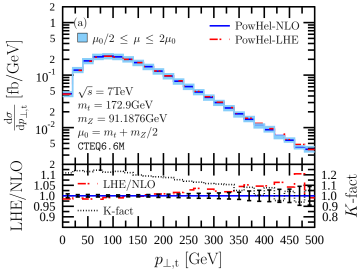
**$VV$+jets** (subdominant MC systematics)

- requires inclusive sample with NLO precision up to 2 jets
- HF jets crucial (genuine $VVb\bar{b}$ component and light-jet mistags)
- mainly $WZ \to 3\ell$ but also $ZZ \to 4\ell$

# Existing predictions and ongoing studies

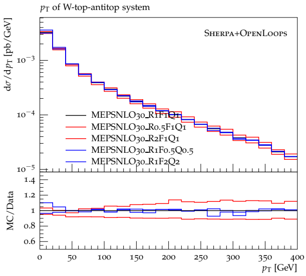
## NLO+PS $t\bar{t}V$ with POWHEL [Garzelli et al '12]

- $t\bar{t} + W^{\pm}/Z$ with NWA uncorrelated decays
- $K = 1.1$–$1.35$
- mild NLO uncertainties (10% scale, 8% PDFs)




## Ongoing SHERPA+OPENLOOPS and MG5_aMC@NLO studies

- $t\bar{t}V + 0, 1$ jets NLO merging
- $t\bar{t}\ell^+\ell^-$ with off-shell $Z/\gamma \to \ell^+\ell^-$ possible
- $WZ + 0, 1, 2$ jets possible (but HF-jets tricky)



# Outline

# Scale dependencies in NLO matching and merging

## Prescriptions for scale choices and variations

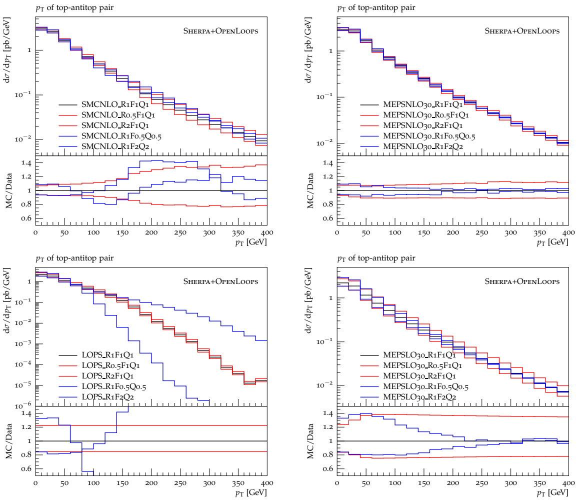
- basis for definition of *intrinsic* precision of NLO Monte Carlo
- matching ($\mu_Q$) and merging ($Q_{\rm cut}$) involve two technical scales; no widely accepted prescription for their choice and variation ($Q_{\rm cut}$ debate)!

# Benefits of NLO matching and merging (top-pair $p_T$ in $t\bar{t} + 0, 1$ jets)

NLO

⟶

LO




matching ⟶ merging

$\mu_R = \xi\, m_t$

- renorm. scale

$\mu_Q = \mu_F = \xi\, m_t$

- factorisation scale
- resummation scale

**NLO merging**

- $10\%$ accuracy over whole spectrum!
- error estimate more realistic!

# Choice and variation of merging scale $Q_{\text{cut}}$?!

## Virtue of small $Q_{\text{cut}}$

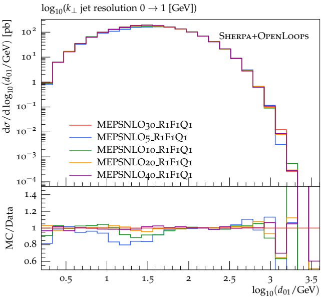
- NLO accuracy over whole $p_{\text{T}}$ spectrum of experimentally resolved jets

## Formal problem at (very) small $Q_{\text{cut}}$ [Hamilton, Nason, Oleari, Zanderighi '12]

- when $Q_{\text{cut}}$ approaches Sudakov peak, i.e. $\alpha_S \log^2(Q_{\text{cut}}/Q_{\text{hard}}) \sim 1$

$\Rightarrow$ fake subleading logs generates $\alpha_S^{1.5}$ uncertainty

$\Rightarrow$ Optimal $Q_{\text{cut}}$ choice? Uncertainty?




## Proposal (quantitative recipe)

- consider jet-$k_{\text{T}}$ dist $\Rightarrow$ max $Q_{\text{cut}}$ sensitivity
- push $Q_{\text{cut}}$ down to Sudakov region
- take *local* $Q_{\text{cut}}$ dependence as uncertainty estimate
- stop before you exceed NLO scale dependence

## Example: MEPS@LO for $t\bar{t} + 0, 1$ jets

- $Q_{\text{cut}} = 40 \ldots 5$ GeV $\Rightarrow$ less than 10% uncertainty for $Q_{\text{cut}} \geq 10\,\text{GeV}$

# Summary and Outlook

## New $t\bar{t}H$ priorities and activities

- emphasis on backgrounds and NLO matching+merging
- lot of exchange between theory ↔ ATLAS/CMS

## Next meetings and activities

- start $tH$ meetings (soon)
- focus $t\bar{t}H$ activities on "top priorities" and new meetings to survey TH and ATLAS/CMS progress
- theory requiremets from new Run2 analyses (fat jets, MEM, ...)?

## Guarantee coherence of MC simulations

- tool comparisons based on standard setup (coming soon)
- theory agreement on uncertainty estimates
- detailed recommendations for ATLAS/CMS

# Recommendations and Priorities

# Theory priorities and recommendations (loose selection) I

## $t\bar{t}H$ signal

- NLO merging of $ttH + 0, 1$ jets
- NLO decays for top and Higgs

## $H \to b\bar{b}$ backgrounds

- use 4F NLO+PS for $t\bar{t} + b$-jets; study systematics of $g \to b\bar{b}$ shower splittings
- use NLO merging for $t\bar{t} + 0, 1(2)$ jets
- combination of 4F $t\bar{t}b\bar{b}$ & $t\bar{t}+$ jets
- sound prescription for resummation/merging scale uncertainties
- NLO+PS for $t\bar{t} + c$-jets
- EW contributions and EW–QCD interferences

## $H \to \gamma\gamma$ backgrounds

- use NLO+PS tools for $t\bar{t}$+photons
- merging of $t\bar{t} + 0, 1, 2\,\gamma$ and radiative top decays

# Theory priorities and recommendations (loose selection) II

$H \to WW, ZZ, \tau\tau \to$ **multi-lepton backgrounds**

- NLO merging for $t\bar{t}W + 0, 1(2)$ jets
- NLO merging for $t\bar{t}Z/\gamma + 0, 1$ jets with off-shell $Z/\gamma \to \ell^+\ell^-$ (also from top decays)
- NLO predictions for $WZ + b/c$-jets

see more details at:
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGTthMeetingsSummary