Fermi National Laboratory

LPC Seminar – May 30th 2013

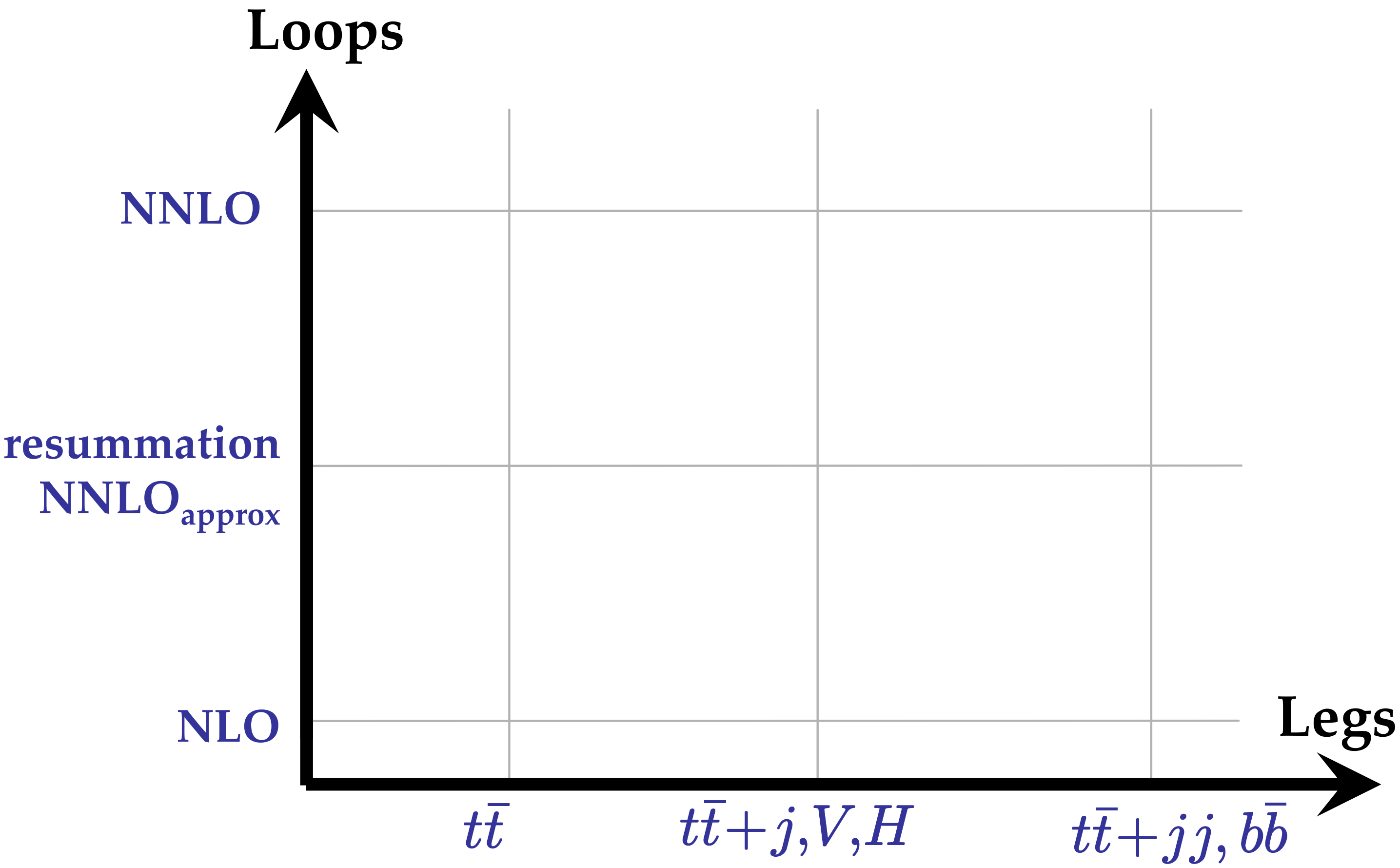
Associated top quark pair production at the LHC:

A new era in top quark physics

Markus Schulze

Argonne NATIONAL LABORATORY

Directions



Loops

NNLO

resummation
NNLO$_{\text{approx}}$

NLO

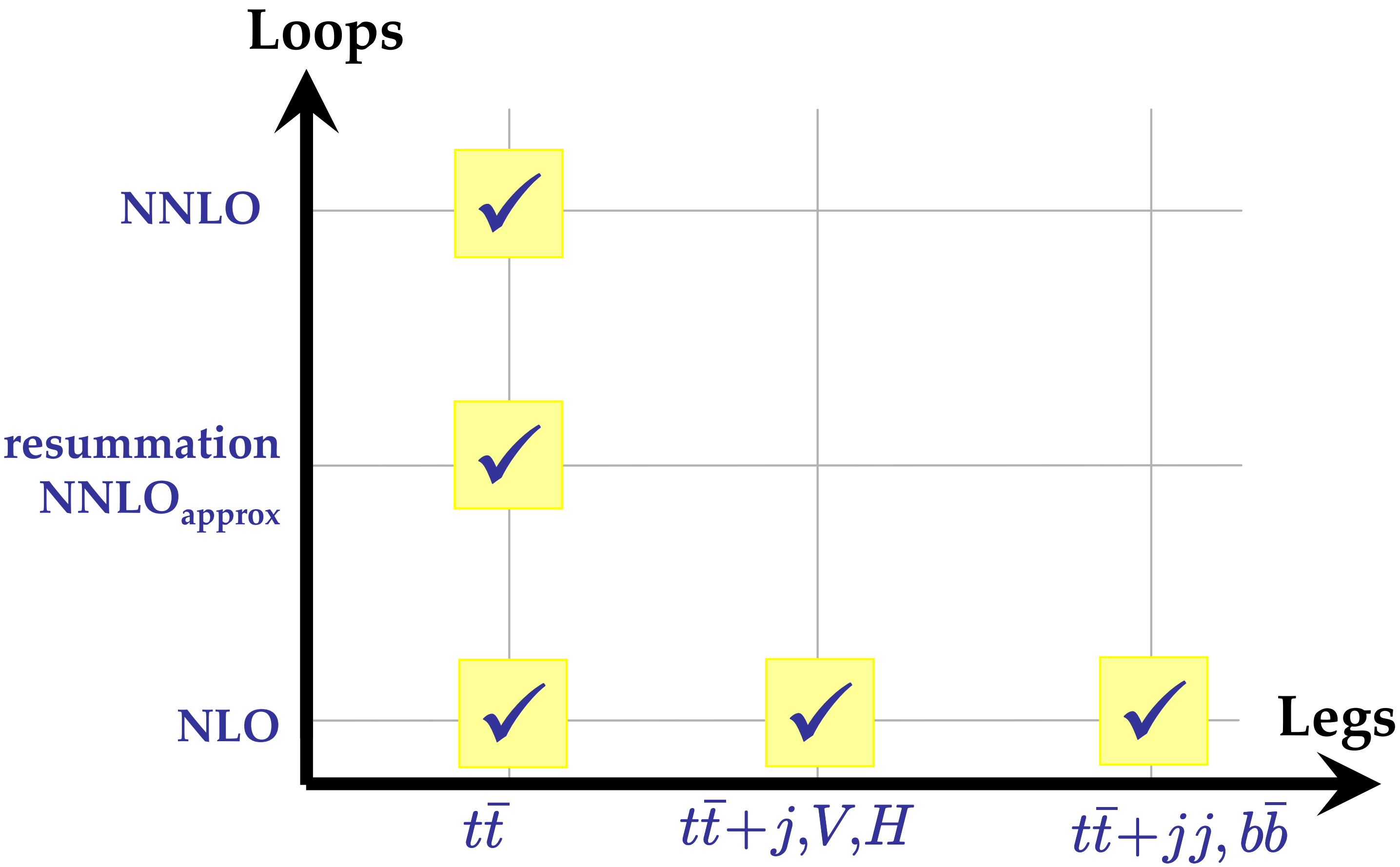
Legs

$t\bar{t}$

$t\bar{t}+j,V,H$

$t\bar{t}+jj,b\bar{b}$

Directions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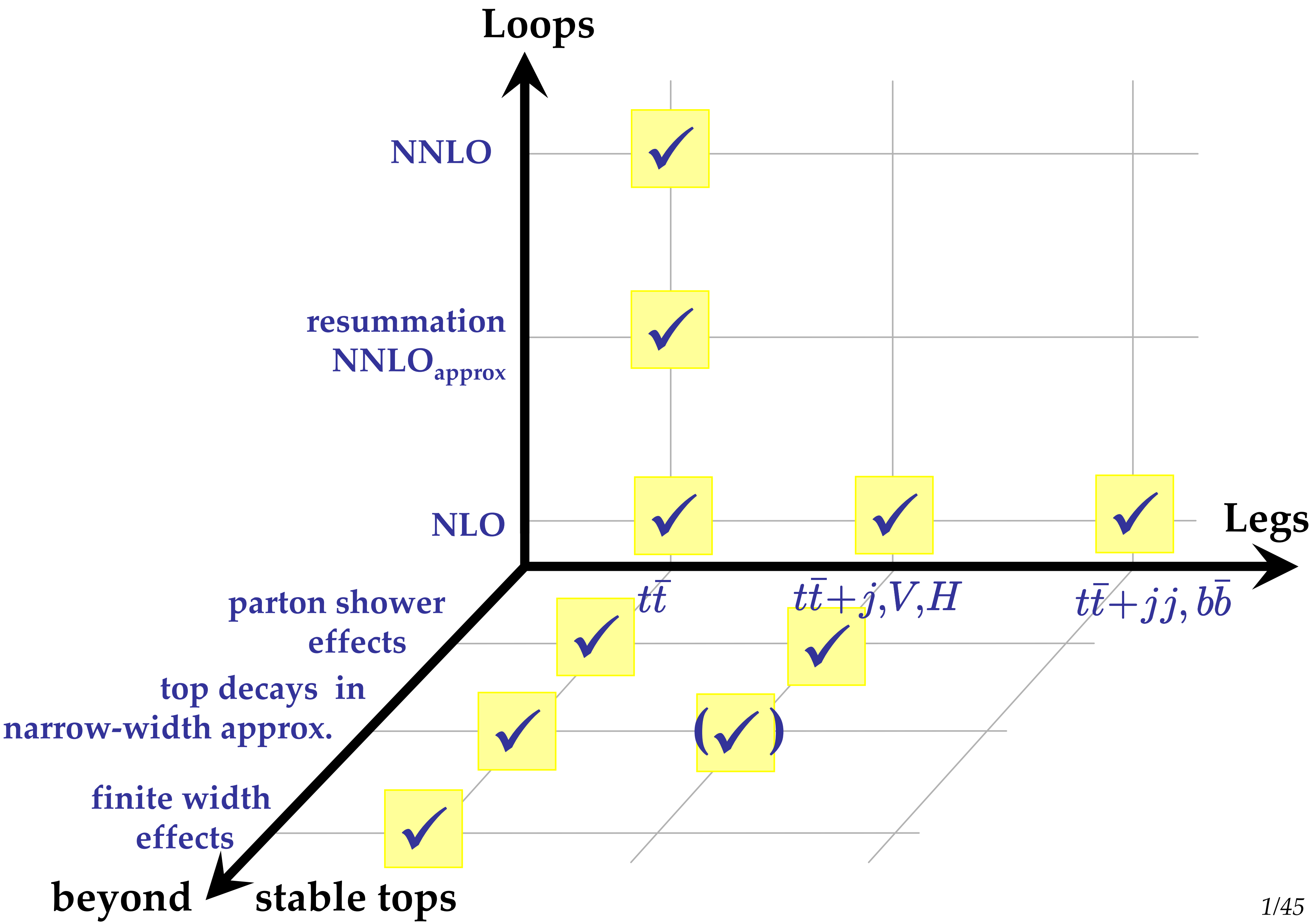

Loops

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$\mathrm{NNLO}_{\mathrm{approx}}$

NLO

Legs

$t\bar{t}$

$t\bar{t}+j, V, H$

$t\bar{t}+jj, b\bar{b}$

parton shower effects

top decays in narrow-width approx.

finite width effects

beyond stable tops

Associated top quark pair production

Outline:

I. **Most interesting signals**

II. **Theoretical description**

III. **Results**

Work with K. Melnikov, A. Scharf, R. Boughezal, R. Röntsch

Associated top quark pair production

“Associated top quark pair production“

Electroweak corner:

$t\,\bar{t} + \gamma$ $\qquad$ $t\,\bar{t} + H$

$t\,\bar{t} + Z$ $\qquad$ $t\,\bar{t} + W^{\pm}$

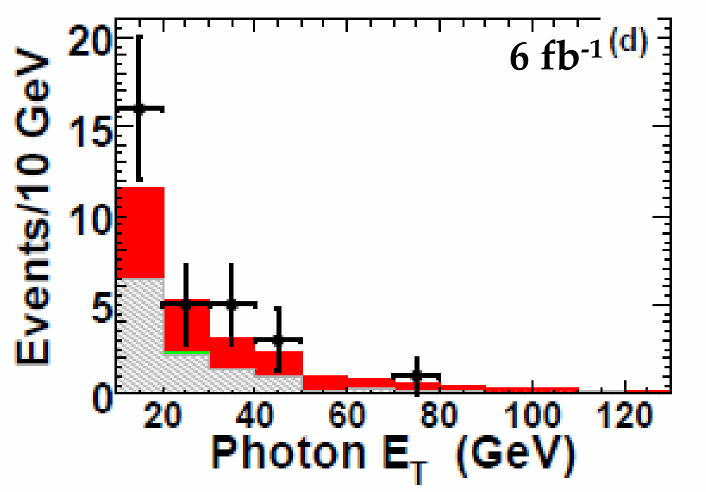
QCD corner: $\quad$ $t\,\bar{t} + \text{jets}$ $\qquad$ $t\bar{t}\,b\bar{b}$ $\qquad$ $t\bar{t}\,t\bar{t}$

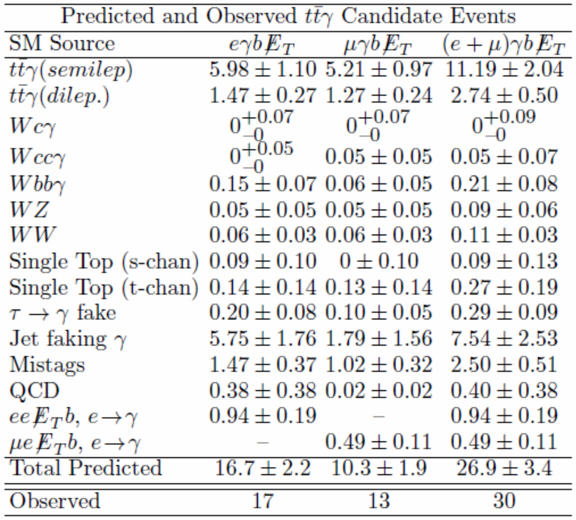
New Physics corner:

$$\begin{tikzcd}
 & t\,\bar{t} + \text{large}\ E_{\mathrm{T}}^{\mathrm{miss}} \arrow[dl] \arrow[d] \arrow[dr] & \\
\tilde{t}\,\tilde{t}^{*} \to t\,\bar{t} + \chi_o\bar{\chi}_o & t\,\bar{t} + Z(\to \nu\bar{\nu}) & T\,\bar{T} \to t\,\bar{t} + A_o\bar{A}_o
\end{tikzcd}$$

ttb+photon

CDF
Phys.Rev,D84:031104,2011

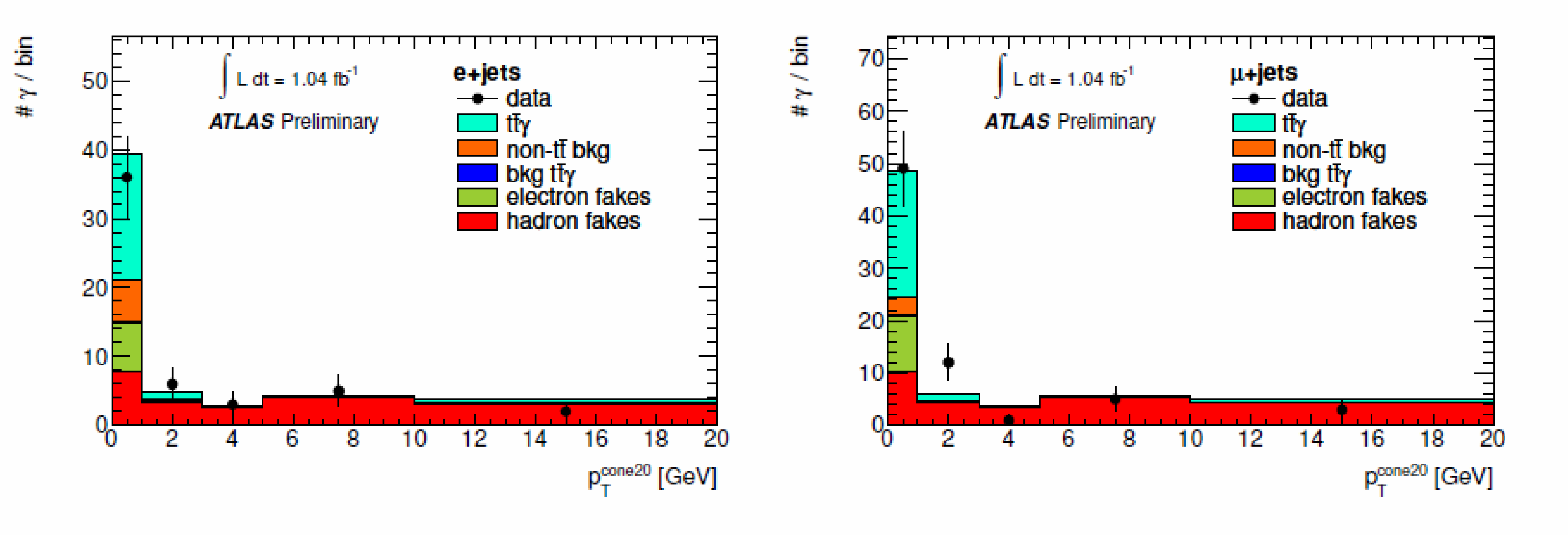




Predicted and Observed $t\bar{t}\gamma$ Candidate Events			
SM Source	$e\gamma b\not\!\!E_T$	$\mu\gamma b\not\!\!E_T$	$(e+\mu)\gamma b\not\!\!E_T$
$t\bar{t}\gamma(semilep)$	5.98 ± 1.10	5.21 ± 0.97	11.19 ± 2.04
$t\bar{t}\gamma(dilep.)$	1.47 ± 0.27	1.27 ± 0.24	2.74 ± 0.50
$Wc\gamma$	$0^{+0.07}_{-0}$	$0^{+0.07}_{-0}$	$0^{+0.09}_{-0}$
$Wcc\gamma$	$0^{+0.05}_{-0}$	0.05 ± 0.05	0.05 ± 0.07
$Wbb\gamma$	0.15 ± 0.07	0.06 ± 0.05	0.21 ± 0.08
WZ	0.05 ± 0.05	0.05 ± 0.05	0.09 ± 0.06
WW	0.06 ± 0.03	0.06 ± 0.03	0.11 ± 0.03
Single Top (s-chan)	0.09 ± 0.10	0 ± 0.10	0.09 ± 0.13
Single Top (t-chan)	0.14 ± 0.14	0.13 ± 0.14	0.27 ± 0.19
$\tau \rightarrow \gamma$ fake	0.20 ± 0.08	0.10 ± 0.05	0.29 ± 0.09
Jet faking γ	5.75 ± 1.76	1.79 ± 1.56	7.54 ± 2.53
Mistags	1.47 ± 0.37	1.02 ± 0.32	2.50 ± 0.51
QCD	0.38 ± 0.38	0.02 ± 0.02	0.40 ± 0.38
$ee\not\!\!E_T b$, $e \rightarrow \gamma$	0.94 ± 0.19	–	0.94 ± 0.19
$\mu e\not\!\!E_T b$, $e \rightarrow \gamma$	–	0.49 ± 0.11	0.49 ± 0.11
Total Predicted	16.7 ± 2.2	10.3 ± 1.9	26.9 ± 3.4
Observed	17	13	30

ttb+photon

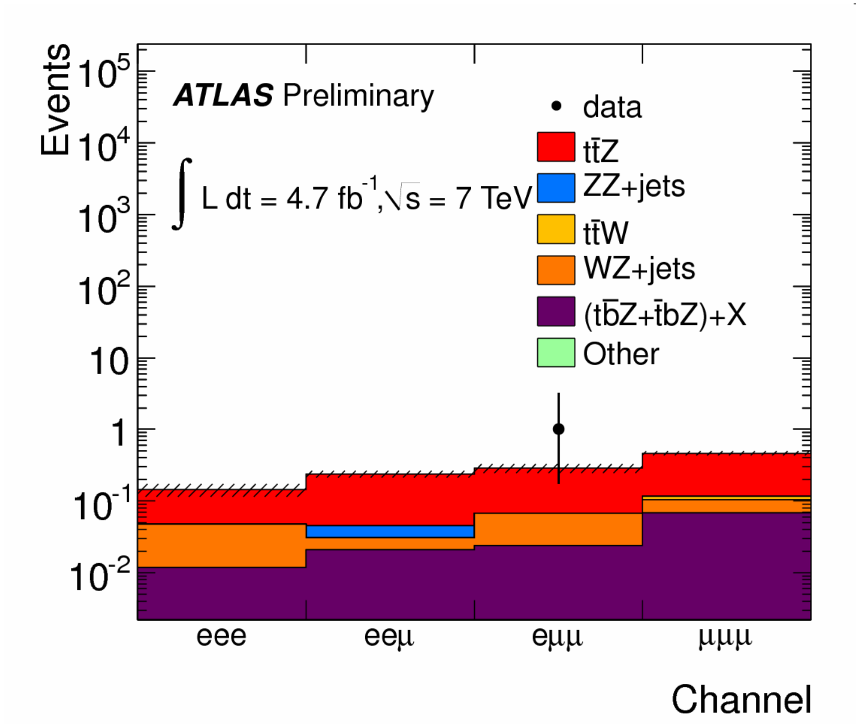
ATLAS-CONF-2011-153

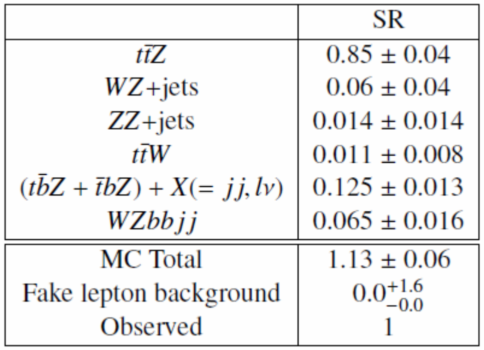


Updated analyses in preparation

ttb+Z,W

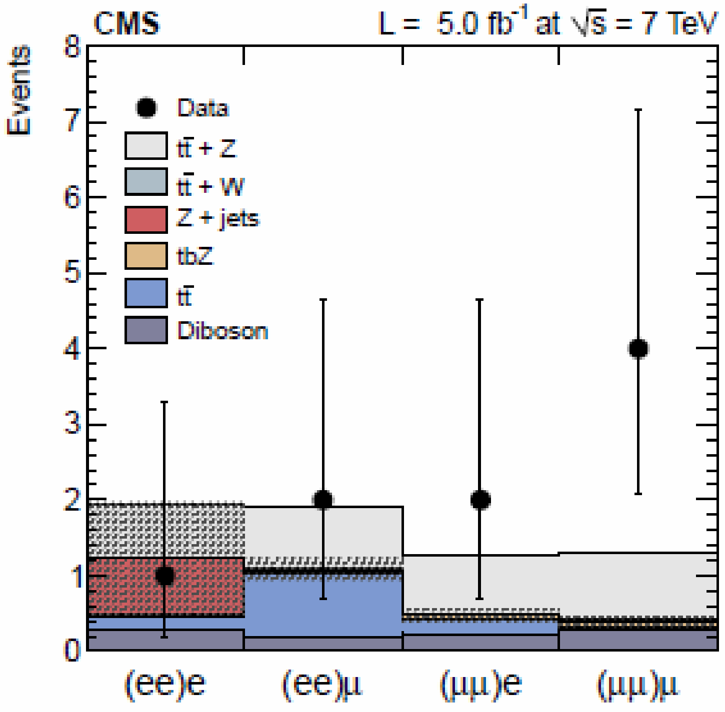
ATLAS-CONF-2012-126





	SR
$t\bar{t}Z$	0.85 ± 0.04
WZ+jets	0.06 ± 0.04
ZZ+jets	0.014 ± 0.014
$t\bar{t}W$	0.011 ± 0.008
$(t\bar{b}Z + \bar{t}bZ) + X(= jj, l\nu)$	0.125 ± 0.013
$WZbbjj$	0.065 ± 0.016
MC Total	1.13 ± 0.06
Fake lepton background	$0.0^{+1.6}_{-0.0}$
Observed	1

CMS-TOP-12-014



$$\sigma_{t\bar{t}V} = 0.43^{+0.17}_{-0.15}\,(\text{stat.})\ {}^{+0.09}_{-0.07}\,(\text{syst.})\,\text{pb}.$$

ttb+H

Associated top quark pair production

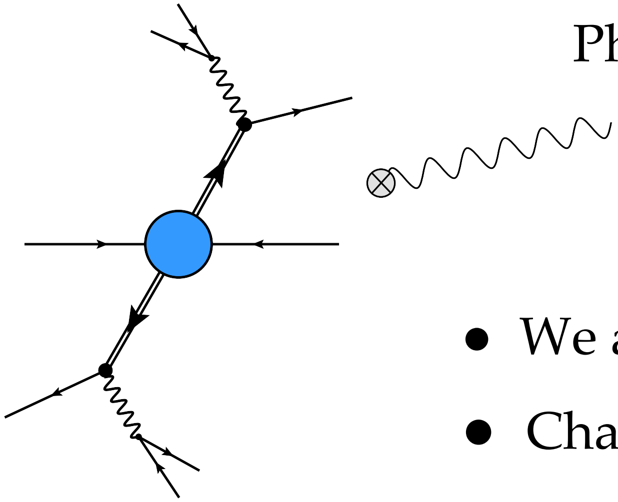
- Current event samples of the SM processes *ttb+V,H* are small
- Strictly speaking, none of these processes have been *observed* at the Tevatron nor at the LHC
- These processes are important for *direct* measurements of electroweak couplings of the top quark or as background to BSM searches

The LHC will produce sufficiently large event samples and will allow us to explore these channels for the first time.

This is why I call it a “new era“ in top quark physics.

Associated top quark pair production

$$pp \to t\bar{t} + \gamma$$



Photon couples to all charged particles.

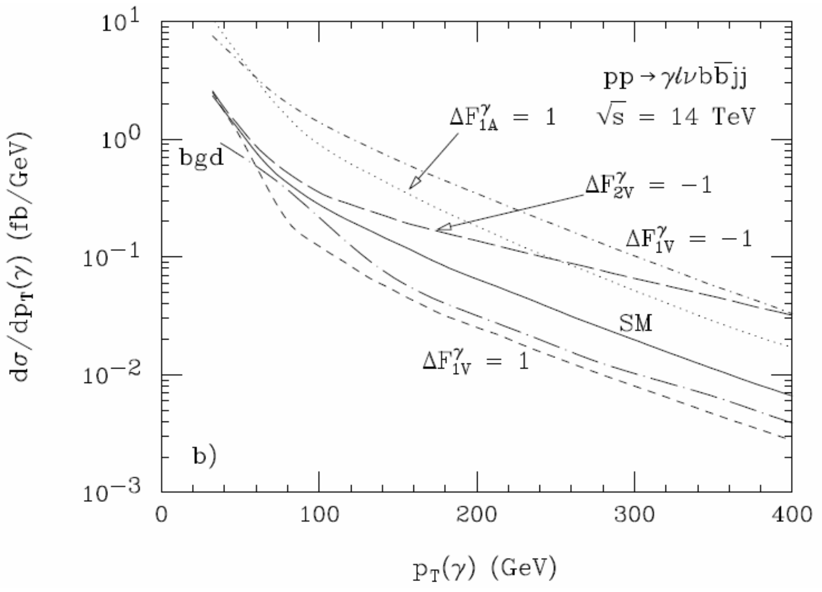
- We are interested in the correlation $\sigma_{t\bar{t}\gamma}(|Q^2_{\mathrm{top}}|)$.
- Charge measurement is mainly a counting experiment.

  → NLO normalization is important.

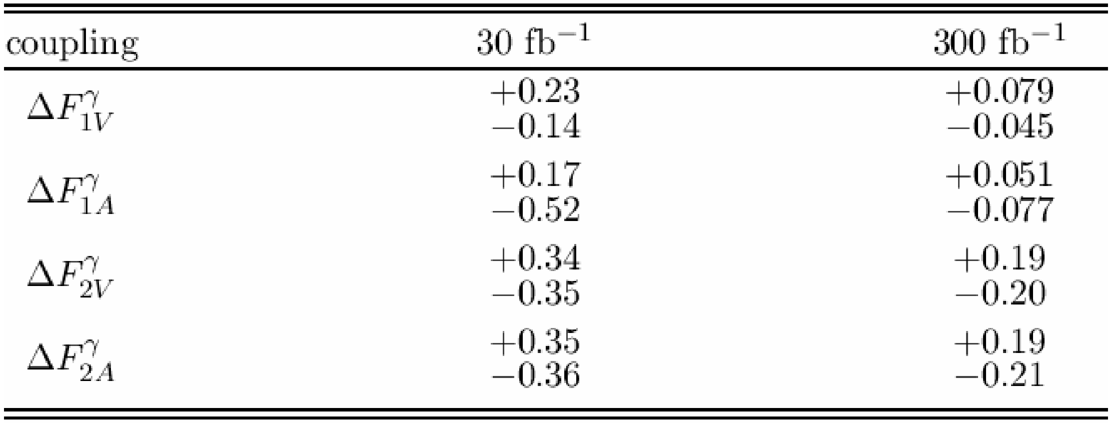
Associated top quark pair production

$$pp \to t\bar{t} + \gamma$$

$$\Gamma_\mu^{t\bar{t}\gamma} \sim \gamma_\mu \left(F_{1,V} + \gamma_5 F_{1,A}\right) + \sigma_{\mu\nu} \frac{q^\nu}{2m_t} \left(\mathrm{i}F_{2,V} + \gamma_5 F_{2,A}\right)$$



2004/05 [Baur,Juste,Orr,Rainwater]:



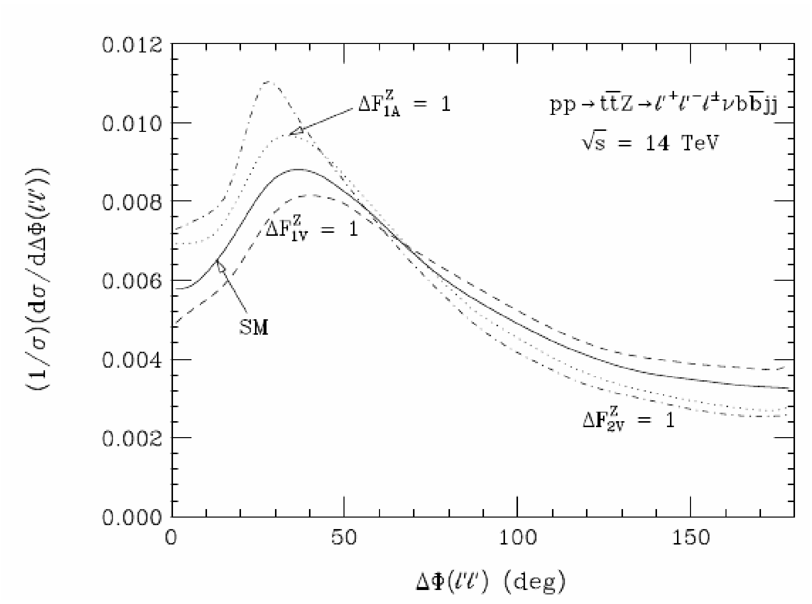
coupling	30 fb^{-1}	300 fb^{-1}
ΔF_{1V}^γ	$+0.23$ -0.14	$+0.079$ -0.045
ΔF_{1A}^γ	$+0.17$ -0.52	$+0.051$ -0.077
ΔF_{2V}^γ	$+0.34$ -0.35	$+0.19$ -0.20
ΔF_{2A}^γ	$+0.35$ -0.36	$+0.19$ -0.21

Associated top quark pair production

$$pp \to t\bar{t} + Z$$

$$\Gamma_\mu^{t\bar{t}Z} \sim \gamma_\mu \left(F_{1,V} + \gamma_5 F_{1,A}\right) + \sigma_{\mu\nu}\frac{q^\nu}{2m_t}\left(\mathrm{i}F_{2,V} + \gamma_5 F_{2,A}\right)$$

$\Delta\phi(\ell^+,\ell^-)$ from $Z \to \ell^+\ell^-$ is a good analyzer



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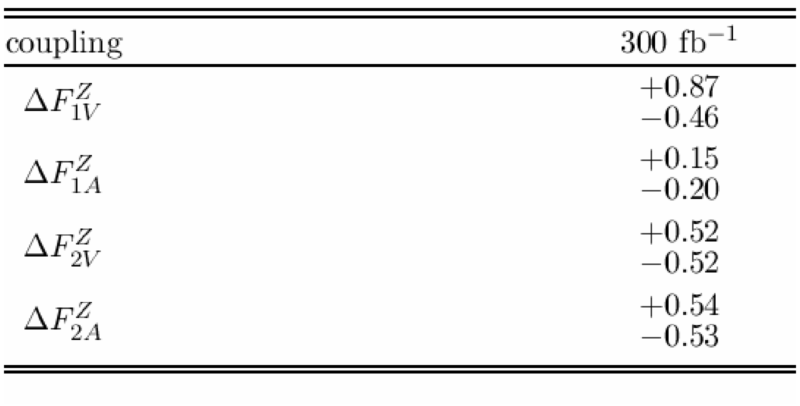


coupling	300 fb^{-1}
ΔF^Z_{1V}	$^{+0.87}_{-0.46}$
ΔF^Z_{1A}	$^{+0.15}_{-0.20}$
ΔF^Z_{2V}	$^{+0.52}_{-0.52}$
ΔF^Z_{2A}	$^{+0.54}_{-0.53}$

Associated top quark pair production

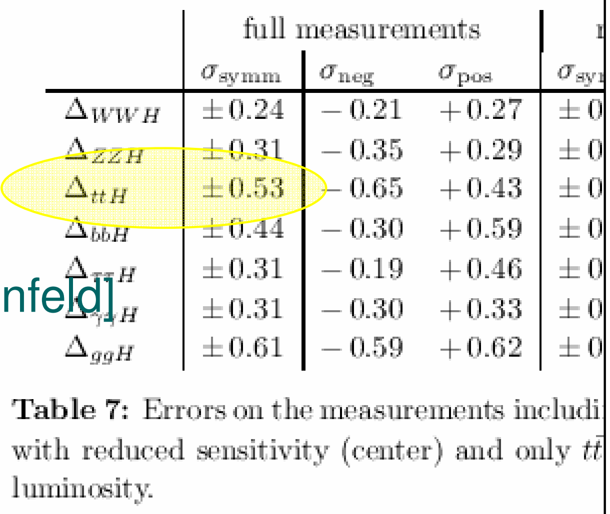
$$pp \to t\bar{t} + H$$

$\sigma_{t\bar{t}+H} \sim y_t^2$: allows a direct measurement of y_t

can be compared to y_t from gg→H which is sensitive to NP

extensively studied:

1999: [Dawson,Juste,Reina,Wackeroth]
2002: [Belyaev,Reina], [Maltoni,Rainwater,Willenbrock]
2004: [Duehrssen,Heinemayer,Logan,Rainwater,Weiglein,Zeppenfeld]
2009: [Duehrssen,Lafaye,Plehn,Rauch,Zerwas]
2012: [Peskin]
+ others



	full measurements			
	$\sigma_{\rm symm}$	$\sigma_{\rm neg}$	$\sigma_{\rm pos}$	$\sigma_{\rm sy}$
Δ_{WWH}	± 0.24	-0.21	$+0.27$	± 0
Δ_{ZZH}	± 0.31	-0.35	$+0.29$	± 0
Δ_{ttH}	± 0.53	-0.65	$+0.43$	± 0
Δ_{bbH}	± 0.44	-0.30	$+0.59$	± 0
$\Delta_{\tau\tau H}$	± 0.31	-0.19	$+0.46$	± 0
$\Delta_{\gamma\gamma H}$	± 0.31	-0.30	$+0.33$	± 0
Δ_{ggH}	± 0.61	-0.59	$+0.62$	± 0

Table 7: Errors on the measurements includi
with reduced sensitivity (center) and only $t\bar{t}$
luminosity.

LHC (14TeV), 30 fb^{-1}; M_H=120 GeV

LHC(14 TeV), 300fb^{-1}; δy_t(ttH)≈ ± 15%

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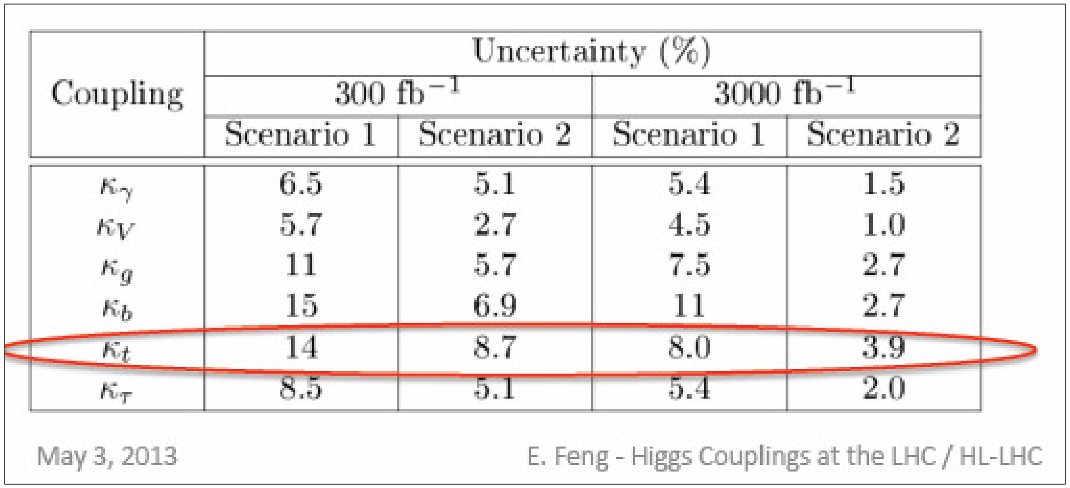


Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

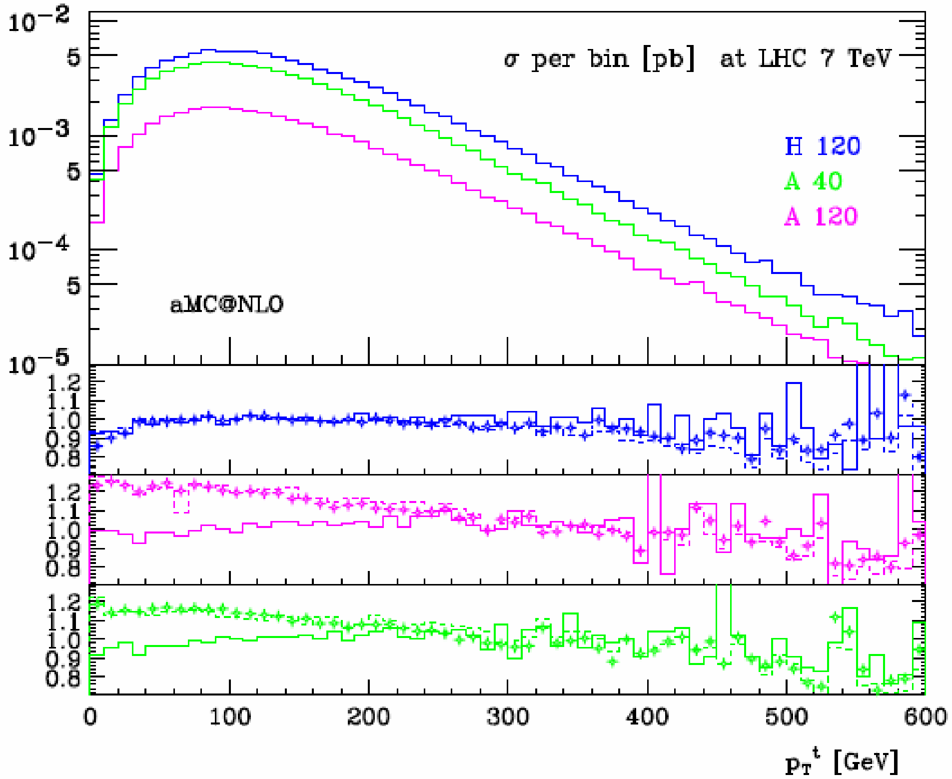
May 3, 2013

E. Feng - Higgs Couplings at the LHC / HL-LHC

Associated top quark pair production

$$pp \to t\bar{t} + H$$

Open questions: Is it possible to measure CP properties in this process?



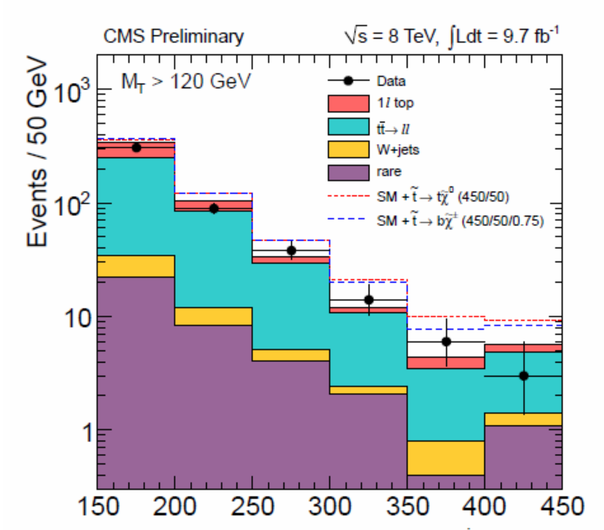
[Frederix,Frixione,Hirschi,
Maltoni,Pittau,Torielli]

Associated top quark pair production

$$pp \to t\bar{t} + \text{large}\ E_{\mathrm{T}}^{\mathrm{miss}}$$

$$t\,\bar{t} + Z(\to \nu\bar{\nu}) \qquad \tilde{t}\,\tilde{t}^{*} \to t\,\bar{t} + \chi_o\bar{\chi}_o \qquad \tilde{b}\,\tilde{b}^{*} \to t\,\bar{t} + \chi_1^{+}\chi_1^{-}$$

$$\tilde{g}\tilde{g} \to t\bar{t}\,t\bar{t} + \chi_o\bar{\chi}_o \qquad T\,\bar{T} \to t\,\bar{t} + A_o\bar{A}_o \qquad t\,\bar{t} \to b\,c\mu^{-}\,W^{+}b \qquad \dots$$



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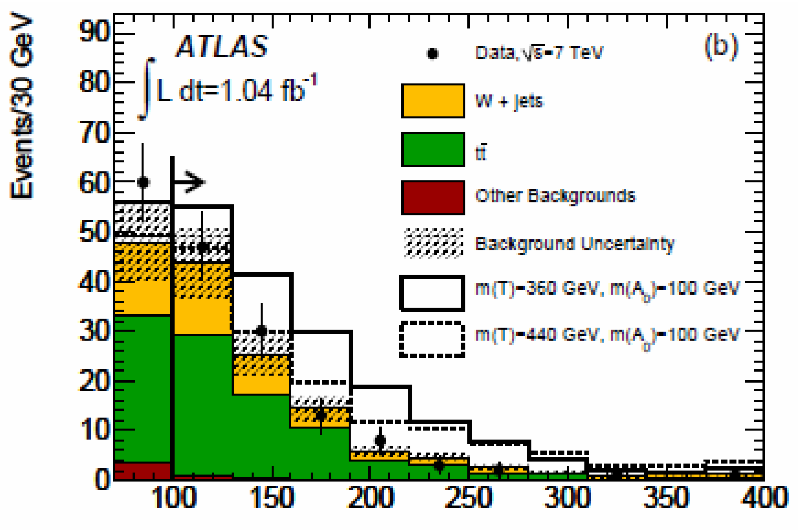

ATLAS, Phys. Rev. Lett. 108 (2012) 041805

Open questions:

How robust are LO studies against higher order corrections?

How reliable are existing exclusion limits?

What are the optimal variables to determine mass, spin, ... ?

Theoretical predictions

Theoretical predictions

We want to realistically describe the hadronic production of a top quark pair in association with (let‘s say) a photon/jet or large ETmiss at NLO QCD.

$pp \to t\bar{t} + \gamma \to b\bar{b}\; \ell\nu\; jj + \gamma$ is a $2 \to 7$ process

$pp \to \tilde{t}\tilde{t}^* \to t\bar{t}\,\chi_o\bar{\chi}_o \to b\bar{b}\; \ell\nu\; jj\chi_o\bar{\chi}_o$ is a $2 \to 8$ process

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$pp \to \tilde{t}\tilde{t}^* \to t\bar{t}\,\chi_o\bar{\chi}_o \to b\bar{b}\,\ell\nu\,jj\chi_o\bar{\chi}_o$ is a 2 → 8 process

What is important?

- decays of all unstable particles:
  realistic final state
- spin correlations:
  acceptances
- photon radiation in decay:
  large contribution
- NLO corrections in production & decay:
  normalization, scale dependence,
  leading soft/collinear emissions

What can be approximated?

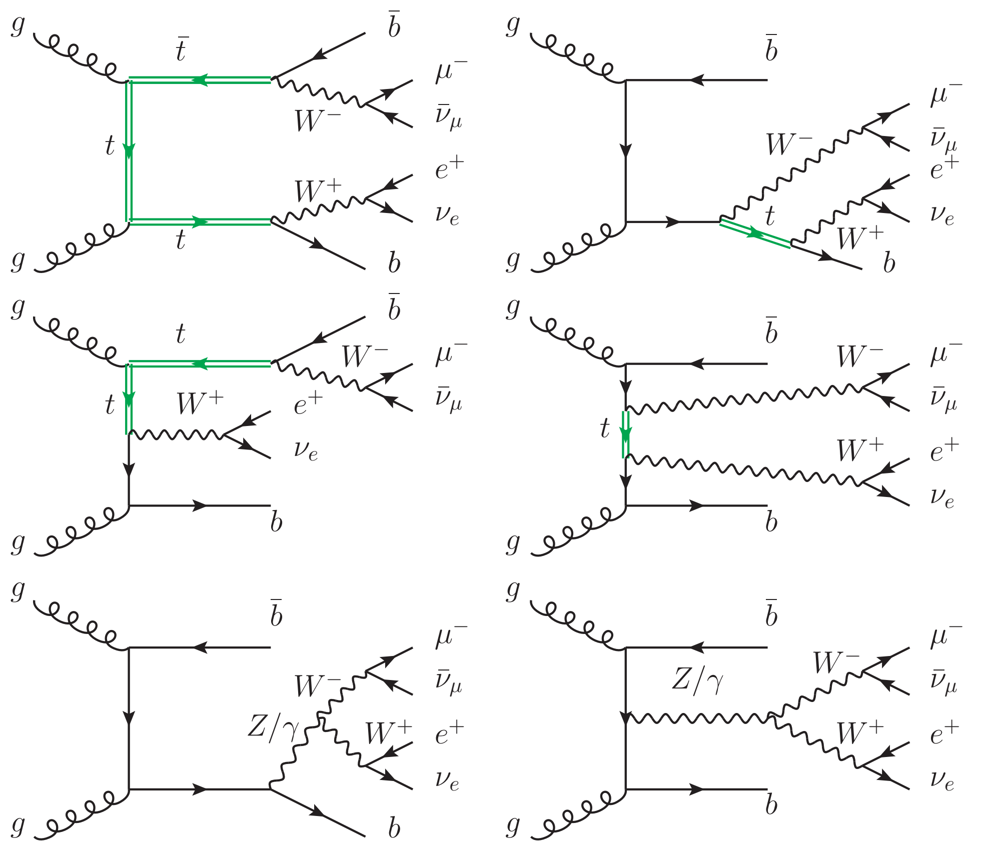
- largely off-shell top quarks, W's:
  neglect non-resonant contributions
  $\Rightarrow$ *apply narrow width approximation*
  valid up to $\mathcal{O}(\Gamma/m)$
- neglect shower effects and higher order threshold corrections:
  observables under consideration
  should not be very sensitive

None of the current automated NLO tools include decays at NLO.

Theoretical predictions

Beyond the Narrow-width approximation

[Bevilacqua,Czakon,vHameren,Papadopoulos,Worek], [Denner,Dittmaier,Kallweit,Pozzorini]



Theoretical predictions

Quality of the
Narrow-width approximation

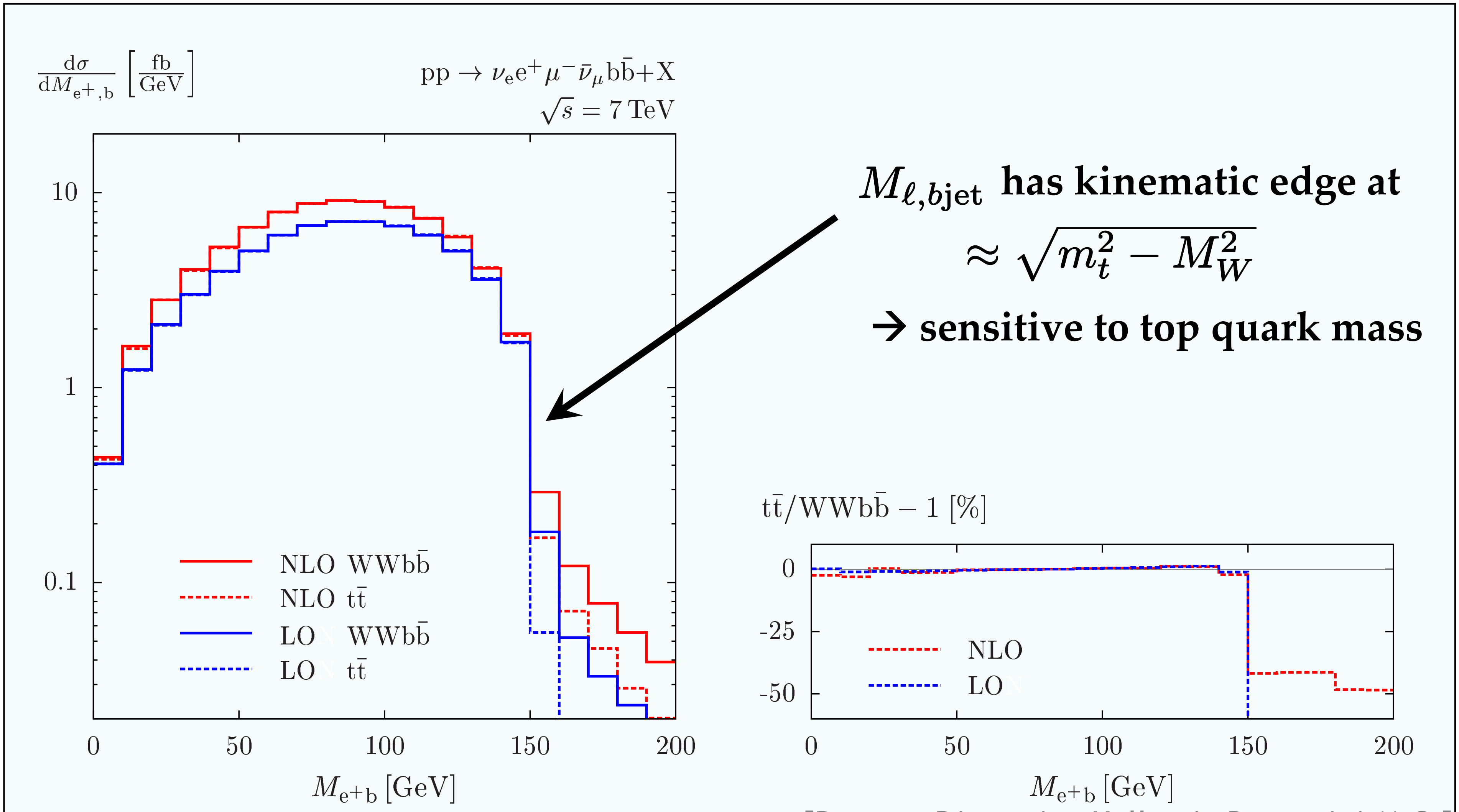
Tuned benchmark comparison

[Denner,Dittmaier,Kallweit,Pozzorini,M.S.]

Collider	$\sqrt{s}$ [TeV]	approx.	$\sigma_{t\bar{t}}$ [fb]	σ_{WWbb} [fb]	$\sigma_{t\bar{t}}/\sigma_{WWbb} - 1$
Tevatron	1.96	LO	$44.691(8)^{+19.81}_{-12.58}$	$44.310(3)^{+19.68}_{-12.49}$	$+0.861(19)\%$
		NLO	$42.16(3)^{+0.00}_{-2.91}$	$41.75(5)^{+0.00}_{-2.63}$	$+0.98(14)\%$
LHC	7	LO	$659.5(1)^{+261.8}_{-173.1}$	$662.35(4)^{+263.4}_{-174.1}$	$-0.431(16)\%$
		NLO	$837(2)^{+42}_{-87}$	$840(2)^{+41}_{-87}$	$-0.41(31)\%$

Theoretical predictions

Narrow-width approximation



$M_{\ell,\mathrm{bjet}}$ **has kinematic edge at**

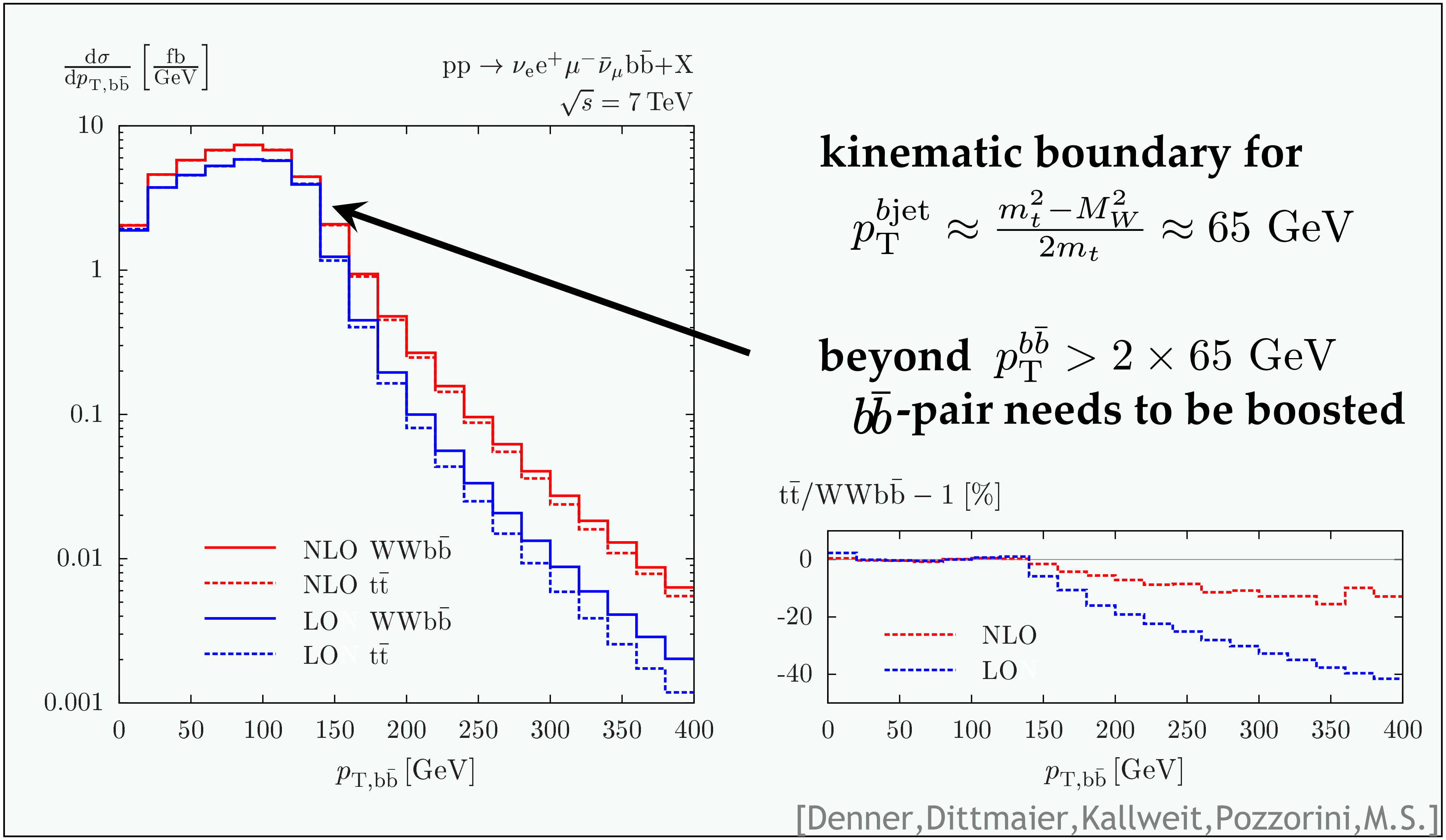
$$\approx \sqrt{m_t^2 - M_W^2}$$

→ sensitive to top quark mass

[Denner,Dittmaier,Kallweit,Pozzorini,M.S.]

Theoretical predictions

Narrow-width approximation



kinematic boundary for

$$p_T^{bjet} \approx \frac{m_t^2 - M_W^2}{2m_t} \approx 65 \text{ GeV}$$

beyond $p_T^{b\bar{b}} > 2 \times 65$ GeV

$b\bar{b}$**-pair needs to be boosted**

[Denner,Dittmaier,Kallweit,Pozzorini,M.S.]

Theoretical predictions

- Narrow width approximation works excellent in most parts of phase space.
- This gives us confidence for treating tops on-shell in processes that are more complicated.

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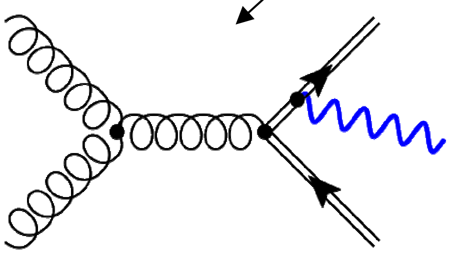
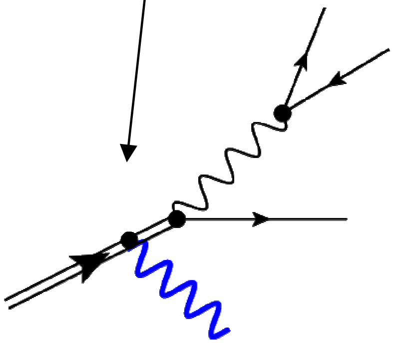
Narrow width approximation separates production from decay process

→ we can distinguish QCD corrections in production and decay
as well as photon radiation in production and in decay

Master formula: $d\sigma \overset{\text{NWA}}{=} \boxed{d\sigma_{t\bar{t}\gamma}} \cdot d\mathcal{B}_{t\bar{t}} + d\sigma_{t\bar{t}} \cdot \boxed{d\mathcal{B}_{t\bar{t}\gamma}}$



„radiation in production“



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expand in α_{s} up to $\mathcal{O}(\alpha_s^3)$:

$$\mathrm{d}\sigma^{\delta\mathrm{NLO}} = \mathrm{d}\sigma_{t\bar{t}\gamma}^{\delta\mathrm{NLO}} \cdot \mathrm{d}\mathcal{B}_{t\bar{t}}^{\mathrm{LO}} + \mathrm{d}\sigma_{t\bar{t}\gamma}^{\mathrm{LO}} \cdot \mathrm{d}\mathcal{B}_{t\bar{t}}^{\delta\mathrm{NLO}}$$

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expand in α_{s} up to $\mathcal{O}(\alpha_s^3)$:

$$\begin{aligned}\mathrm{d}\sigma^{\delta\mathrm{NLO}} = {} & \mathrm{d}\sigma^{\delta\mathrm{NLO}}_{t\bar{t}\gamma} \cdot \mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t\bar{t}} + \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}\gamma} \cdot \mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t\bar{t}} \\ & + \mathrm{d}\sigma^{\delta\mathrm{NLO}}_{t\bar{t}} \cdot \mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t\bar{t}\gamma} + \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}} \cdot \mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t\bar{t}\gamma}\end{aligned}$$

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Master formula: $\mathrm{d}\sigma^{\mathrm{NWA}} = \mathrm{d}\sigma \quad \mathrm{d}\mathcal{B}_{t\bar{t}} + \mathrm{d}\sigma_{t\bar{t}} \cdot \mathrm{d}\mathcal{B}_{t\bar{t}\gamma}$

$$\mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t\gamma}\,\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}} + \mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t}\,\mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{\bar{t}\gamma} + \mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t\gamma}\,\mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{\bar{t}} + \mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t}\,\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}\gamma}$$

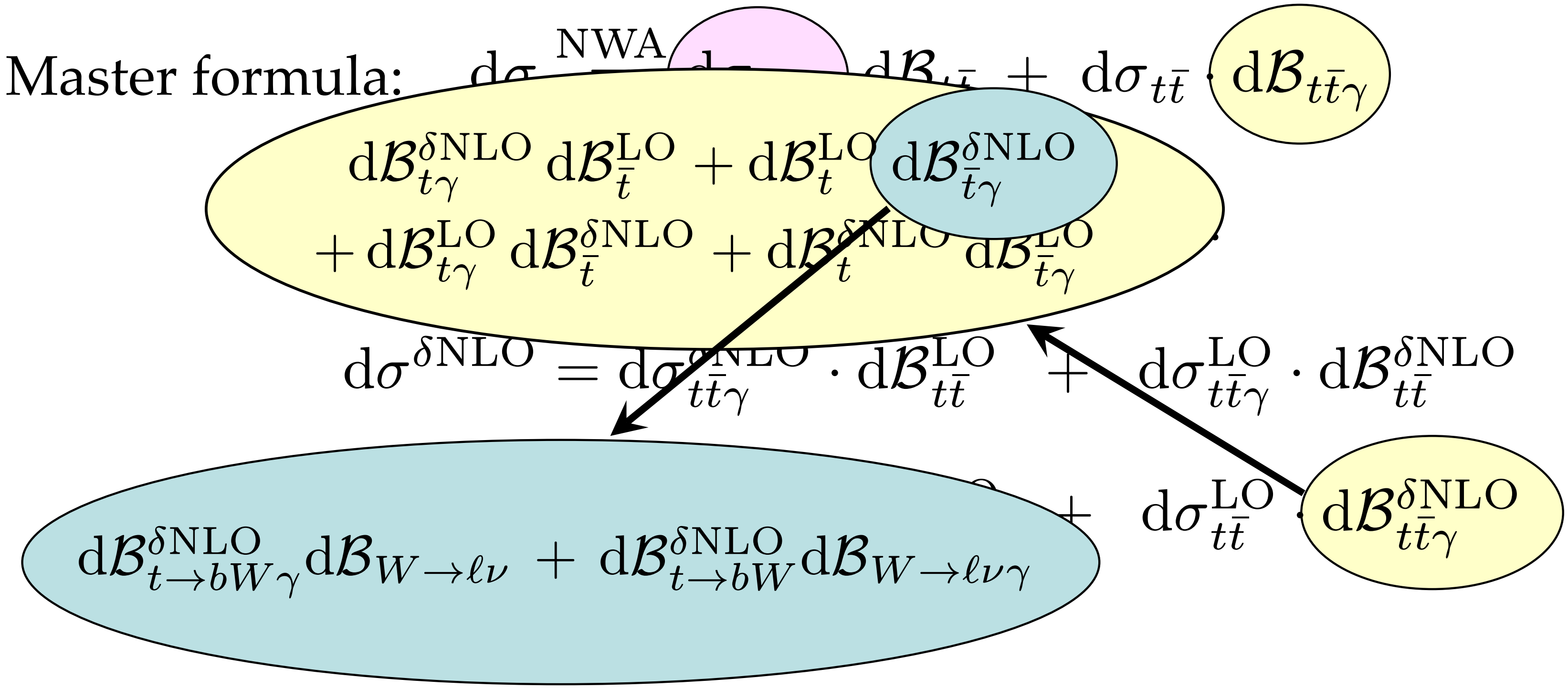
$$\mathrm{d}\sigma^{\delta\mathrm{NLO}} = \mathrm{d}\sigma^{\delta\mathrm{NLO}}_{t\bar{t}\gamma} \cdot \mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t\bar{t}} + \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}\gamma} \cdot \mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t\bar{t}} + \mathrm{d}\sigma^{\delta\mathrm{NLO}}_{t\bar{t}} \cdot \mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t\bar{t}\gamma} + \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}} \cdot \mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t\bar{t}\gamma}$$

Theoretical predictions

- Narrow width approximation works excellent in most parts of phase space.
- This gives us confidence for treating tops on-shell in processes that are more complicated.

Narrow width approximation separates production from decay process

→ we can distinguish QCD corrections in production and decay
as well as photon radiation in production and in decay



Master formula: $\mathrm{d}\sigma^{\mathrm{NWA}} = \mathrm{d}\sigma \quad \mathrm{d}\mathcal{B}_{t\bar{t}} + \mathrm{d}\sigma_{t\bar{t}} \cdot \mathrm{d}\mathcal{B}_{t\bar{t}\gamma}$

$$\mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t\gamma}\,\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}} + \mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t}\,\mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{\bar{t}\gamma} + \mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t\gamma}\,\mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{\bar{t}} + \mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t}\,\mathrm{d}\mathcal{B}^{\mathrm{LO}}_{\bar{t}\gamma}$$

$$\mathrm{d}\sigma^{\delta\mathrm{NLO}} = \mathrm{d}\sigma^{\delta\mathrm{NLO}}_{t\bar{t}\gamma} \cdot \mathrm{d}\mathcal{B}^{\mathrm{LO}}_{t\bar{t}} + \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}\gamma} \cdot \mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t\bar{t}}$$

$$+ \ \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}} \cdot \mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t\bar{t}\gamma}$$

$$\mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t\to bW\gamma}\,\mathrm{d}\mathcal{B}_{W\to\ell\nu} + \mathrm{d}\mathcal{B}^{\delta\mathrm{NLO}}_{t\to bW}\,\mathrm{d}\mathcal{B}_{W\to\ell\nu\gamma}$$

Theoretical predictions

Reconstructing a one-loop amplitude
from tree level graphs

Theoretical predictions

Reconstructing a one-loop amplitude
from tree level graphs

optical theorem (unitarity)

$$\sigma_{\mathrm{tot}} = \frac{4\pi}{k}\psi(\theta=0)$$

$$S^\dagger S = 1 \;\leftrightarrow\; \mathrm{i}(T^\dagger - T) = T^\dagger T$$

$$\mathrm{Im}\left(A^{\text{1-loop}}\right) \sim \int \mathrm{d}\Pi\, |A^{\mathrm{tree}}|^2$$

master integral basis

$$A^{\text{1-loop}} = \sum_j c_j \cdot I_j$$

I_j : master integrals

c_j : process-dependent integral coefficients

$$\int \mathrm{d}\Pi\, |A^{\mathrm{tree}}|^2 \sim \sum_j c_j\, \mathrm{Im}\left(I_j\right)$$

Theoretical predictions

The algorithm combines several different developments
in quantum field theory:

- **color ordering**: [Bern,Dixon,Kosower,1994]
  one-loop QCD amplitudes can be decomposed into
  color-stripped, gauge invariant sub amplitudes with ordered external legs

- **OPP tensor integral reduction**: [Ossola,Papadopoulos,Pittau,2006]
  integral reduction at the integrand level

- **interface of above with generalized unitarity**: [Ellis,Giele,Kunszt,2008]
  integral coefficients can be expressed in terms of tree amplitudes
  with complex on-shell momenta in 4 dimensions.

- **formulation of *D*-dimensional generalized unitarity for numerical implementations**: [Ellis,Giele,Kunszt,Melnikov,2009]
  fully general approach to calculate one-loop amplitudes in QFT

Theoretical predictions

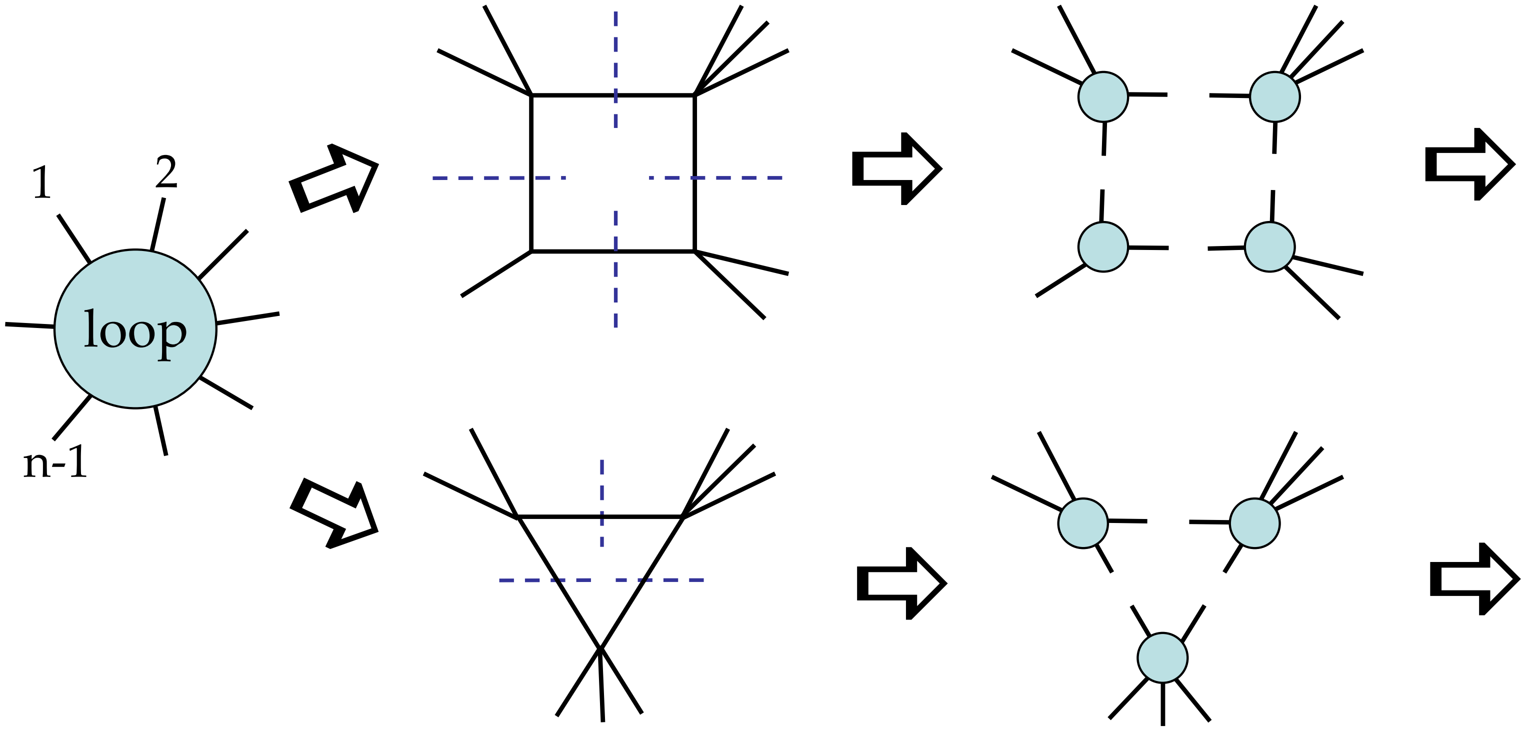
Reconstructing a one-loop amplitude
from tree level graphs

particle ordering:

cutting: $\frac{1}{\ell^2-m^2+i} \to \delta(\ell^2-m^2)$

factorization into trees: $\Pi_i \mathcal{M}_i(\ell_i, \{p\})$

mapping onto integral coefficients



$$c_4^{ijkl} \cdot \int \frac{\mathrm{d}^D \ell}{2\pi} \frac{1}{D_i D_j D_k D_l}$$

$$c_3^{ijk} \cdot \int \frac{\mathrm{d}^D \ell}{2\pi} \frac{1}{D_i D_j D_k}$$

Theoretical predictions

Virtues of this approach

- Basic ingredients are tree currents in D dimensions with complex momenta
- Works for any renormalizable QFT in a process independent way
- Only physical degrees of freedom enter the reduction
- Good scaling with large number of external legs, numerical stability is not a major problem

Theoretical predictions

Virtues of this approach

- Basic ingredients are tree currents in D dimensions with complex momenta
- Works for any renormalizable QFT in a process independent way
- Only physical degrees of freedom enter the reduction
- Good scaling with large number of external legs,
  numerical stability is not a major problem
- Implemented in the program TOPAZ

$pp \to t\bar{t} \to b\ell^+\nu\bar{b}jj$	[Melnikov,M.S.]	
$pp \to t\bar{t} + j \to b\ell^+\nu\bar{b}jjj$	[Melnikov,Scharf,M.S.]	
$pp \to t\bar{t} + \gamma \to b\ell^+\nu\bar{b}jj\gamma$	[Melnikov,Scharf,M.S.]	
$gg \to WW + j \to \ell^+\nu\ell^-\bar{\nu} + j$	[Melia,Melnikov,Röntsch,M.S.,Zanderighi]	
$pp \to Z' \to t\bar{t} \to b\ell^+\nu\bar{b}jj$	[Caola,Melnikov,M.S.]	
$pp \to \tilde{t}\tilde{t}^* \to t\bar{t}\,\chi_o\bar{\chi}_o \to b\bar{b}\;\ell\nu\;jj\chi_o\bar{\chi}_o$	[Boughezal,M.S.]	
$pp \to T\bar{T} \to t\bar{t}\,A_o\bar{A}_o \to b\bar{b}\;\ell\nu\;jjA_o\bar{A}_o$	[Boughezal,M.S.]	(coming soon)
$pp \to t\bar{t} + Z \to b\ell^+\nu\bar{b}jj\ell^+\ell^-$	[Röntsch,M.S.]	(coming soon)

Results

Results

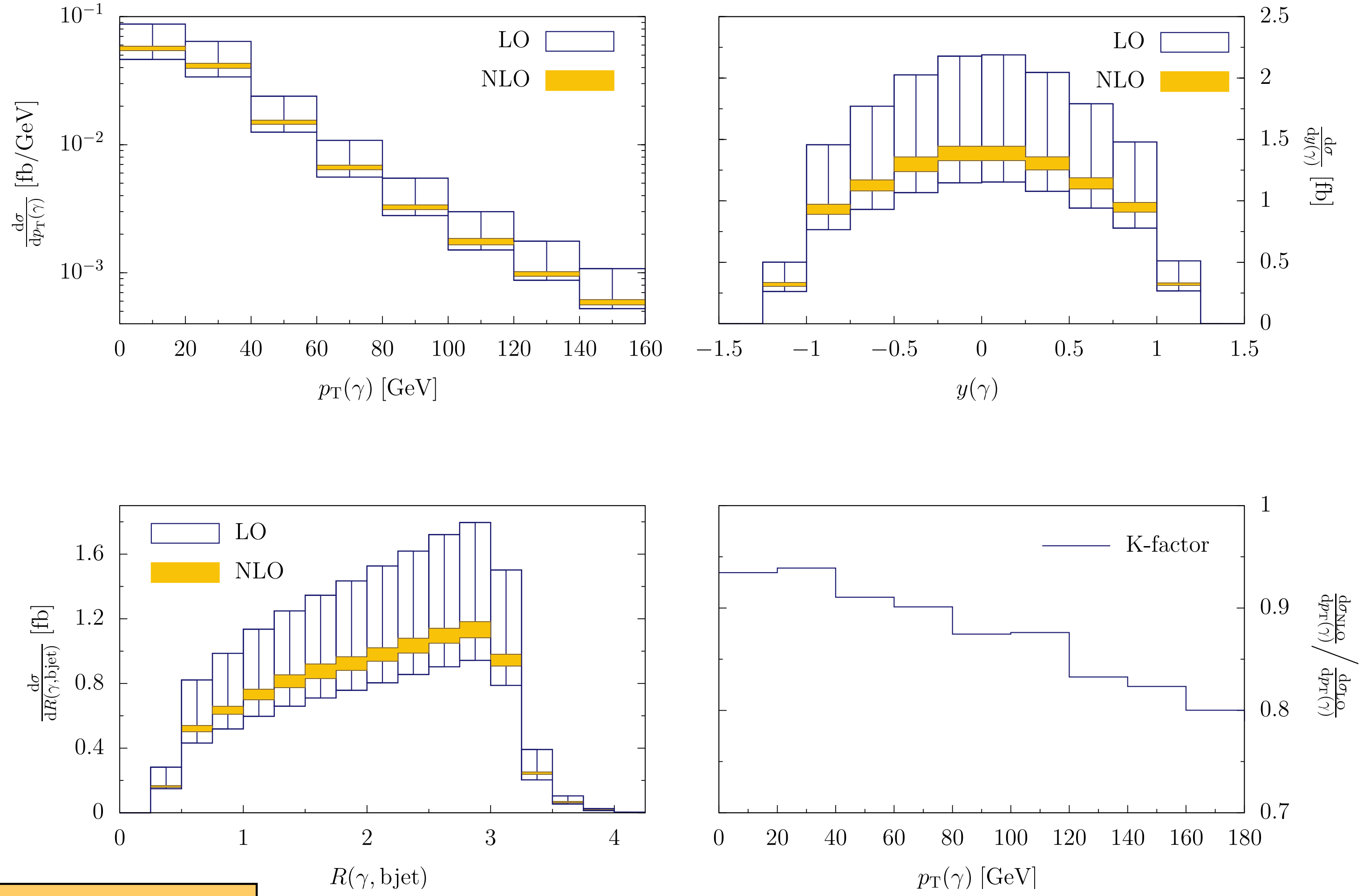
$$t\bar{t} + \gamma$$

K. Melnikov, A. Scharf, M.S.

Phys.Rev. D83 (2011) 074013

$t\bar{t}$+photon

$$p\bar{p}(1.96\mathrm{TeV}) \rightarrow t\bar{t} + \gamma \rightarrow b\bar{b}\;\ell\nu\;jj + \gamma$$



$$\boxed{\sigma^{\mathrm{NLO}}_{t\bar{t}\gamma} = 2.64\ \mathrm{fb}} \xrightarrow[\times \text{efficiencies} \times 4]{\mathcal{L}_{\mathrm{int}} = 6.0\ \mathrm{fb}^{-1}} 14 \pm 1 \text{ events} \quad \text{vs.} \quad \textbf{CDF:}\ 14 \pm 3 \text{ events}$$

(LO: 16±5 events)

$t\bar{t}$+photon

Forward-backward asymmetry in $t\bar{t}\gamma$

$$\boxed{A_{\rm FB} = \frac{N(y_t{>}0) - N(y_t{<}0)}{N(y_t{>}0) + N(y_t{<}0)}}$$

- $t\bar{t}$ asymmetry appears only at NLO QCD [Kühn,Rodrigo]

  Theory prediction $A_{\rm FB}(t\bar{t}) = 5\%$ in tension with measurement (2σ)

- $t\bar{t}+\gamma$ asymmetry appears already at LO

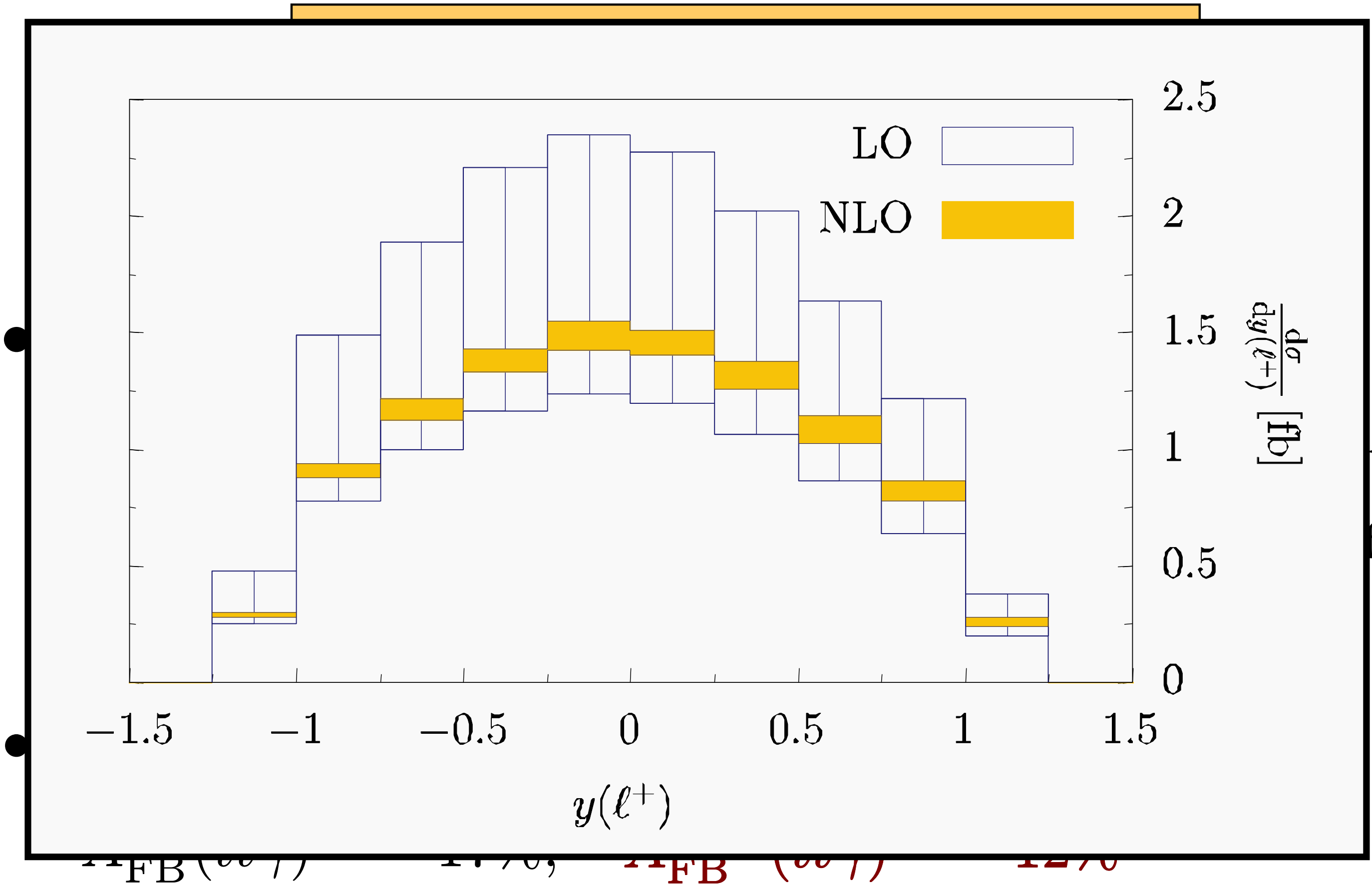
  $A^{\rm LO}_{\rm FB}(t\bar{t}\gamma) = -17\%$, $\quad A^{\rm NLO}_{\rm FB}(t\bar{t}\gamma) = -12\%$ (stable tops)

The 5% reduction at NLO can be understood [Melnikov,MS : $t\bar{t}$ +jet]

Similar effect for $t\bar{t}$+jet: $A^{\rm LO}_{\rm FB}(t\bar{t}{\rm jet}) = -8\%$, $A^{\rm NLO}_{\rm FB}(t\bar{t}{\rm jet}) = -2\%$

$t\bar{t}$+photon

Forward-backward asymmetry in $t\bar{t}\gamma$



[Kühn,Rodrigo]

urement (2σ)

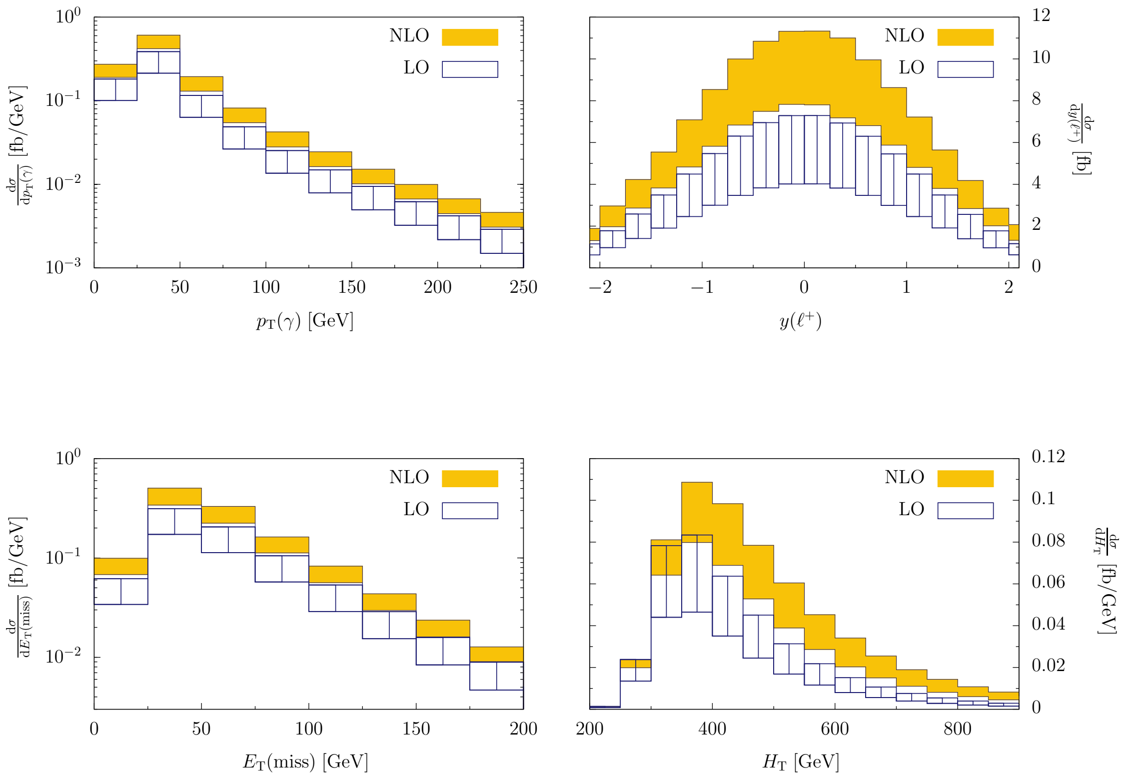
for robustness

The 5% reduction at NLO can be understood [Melnikov,MS : $t\bar{t}$ +jet]

Similar effect for $t\bar{t}$+jet: $A_{\rm FB}^{\rm LO}(t\bar{t}{\rm jet}) = -8\%,\ A_{\rm FB}^{\rm NLO}(t\bar{t}{\rm jet}) = -2\%$

Results: ttb+photon

$$pp(7\mathrm{TeV}) \to t\bar{t} + \gamma \to b\bar{b}\,\ell\nu\,jj + \gamma$$

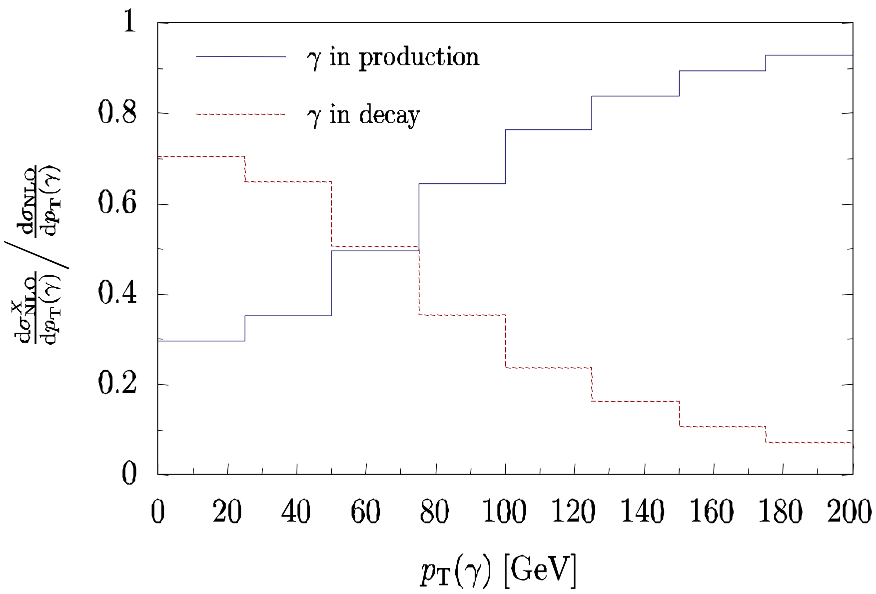


$$\sigma^{\mathrm{LO}}_{t\bar{t}\gamma} = 15.6 \pm 4.6\ \mathrm{fb} \qquad \sigma^{\mathrm{NLO}}_{t\bar{t}\gamma} = 26.8 \pm 5.0\ \mathrm{fb}$$

Large K-factor; almost no reduction of scale dependence

(qg, $\bar{q}g$ channels open up only at NLO)

Results: ttb+photon

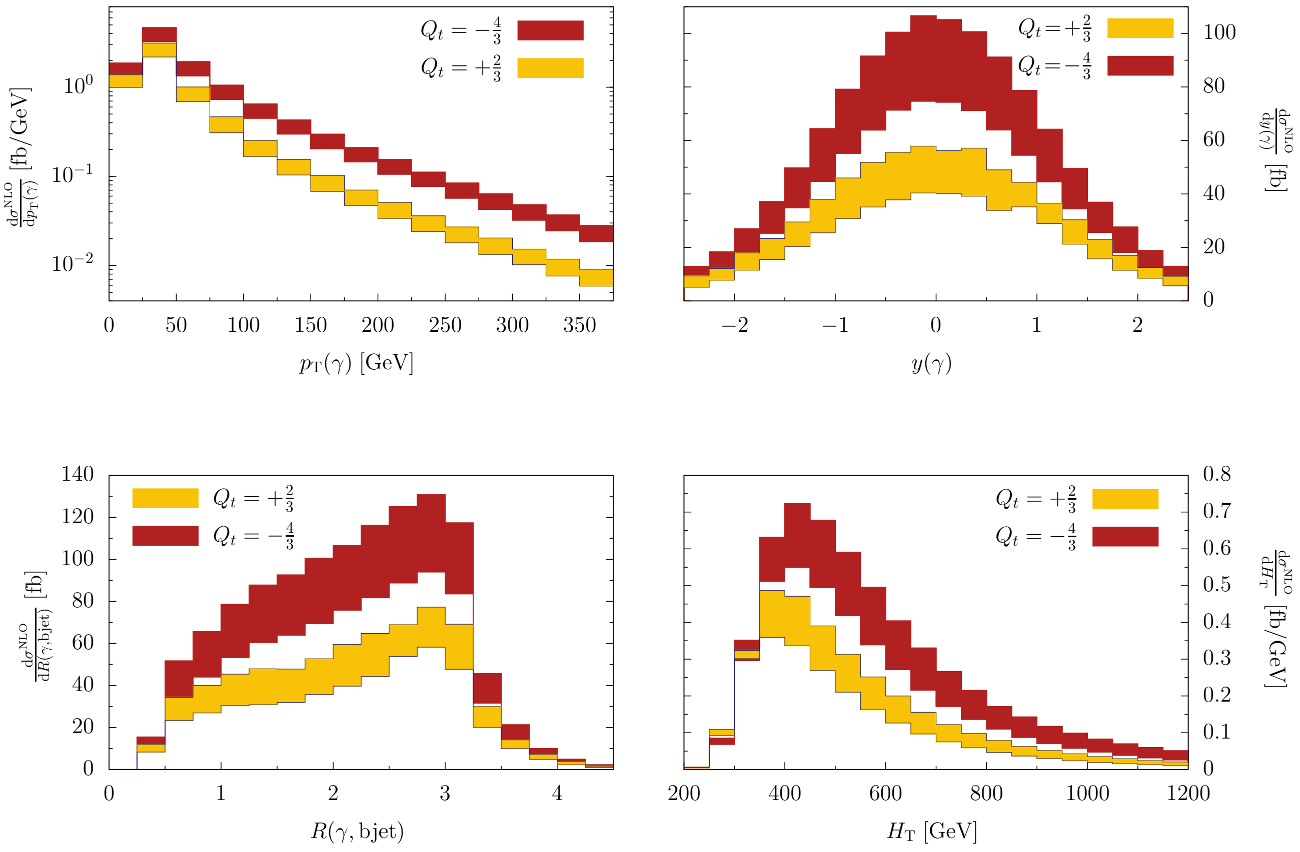


Most of the photons with $p_T^\gamma < 50$ GeV are radiated in the top quark decay.

Inclusion of radiative top quark decay is crucial.

Results: ttb+photon

Exotic top quarks



$$\sigma^{\mathrm{NLO}}_{t\bar{t}\gamma} = 138 \text{ fb} \xrightarrow{Q_t = \frac{2}{3} \to -\frac{4}{3}} \sigma^{\mathrm{NLO}}_{t\bar{t}\gamma} = 243 \text{ fb}$$

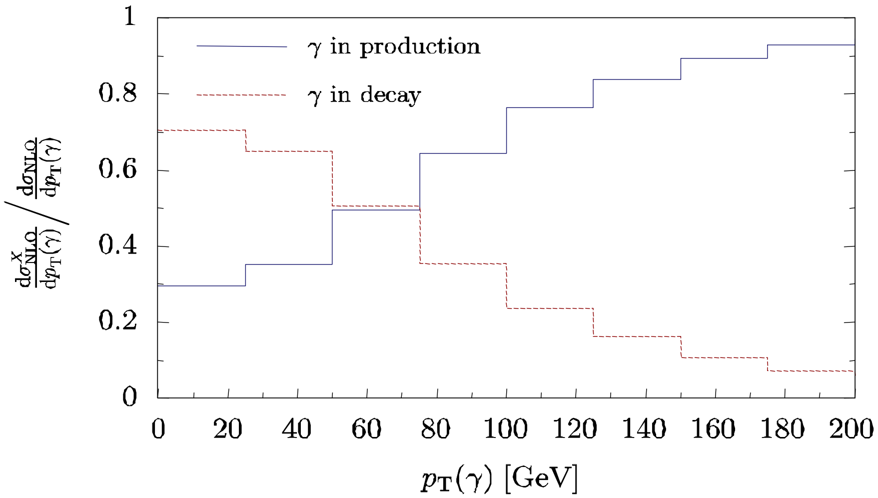
Naive expectation of Q_t^2 scaling fails.

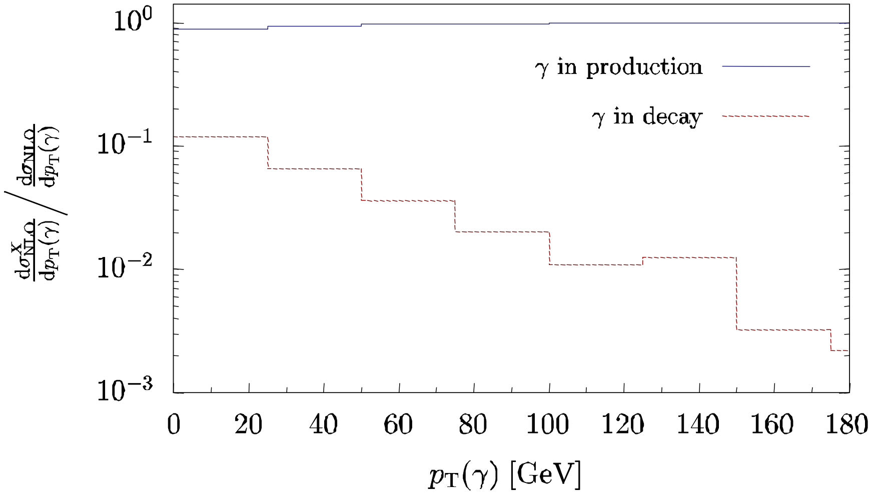
$t\bar{t}$+photon

A) Choose cuts to enhance Q_t^2 dependence

Inspired by U.Baur et.al.: suppress radiative top decays [Baur,Buice,Orr]

$$m_T(b\ell\gamma; E_T^{\text{miss}}) > 180\ \text{GeV}, \qquad m_T(\ell\gamma; E_T^{\text{miss}}) > 90\ \text{GeV},$$
$$160\,\text{GeV} < m(bjj) < 180\ \text{GeV},\ 70\,\text{GeV} < m(j,j) < 90\ \text{GeV}$$





$t\bar{t}$+photon

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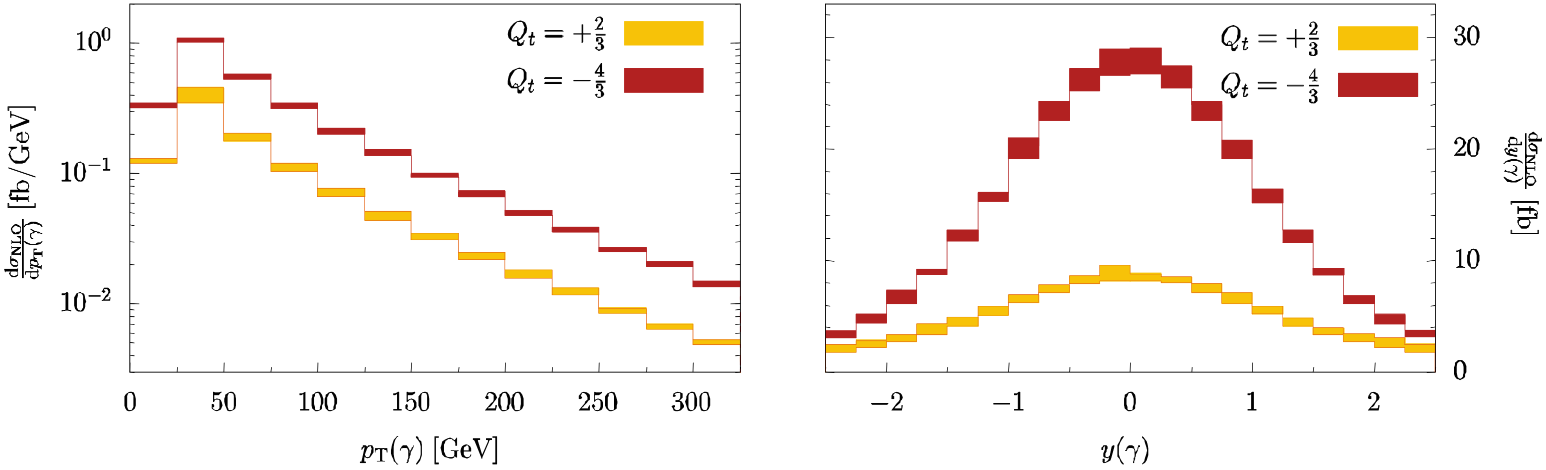
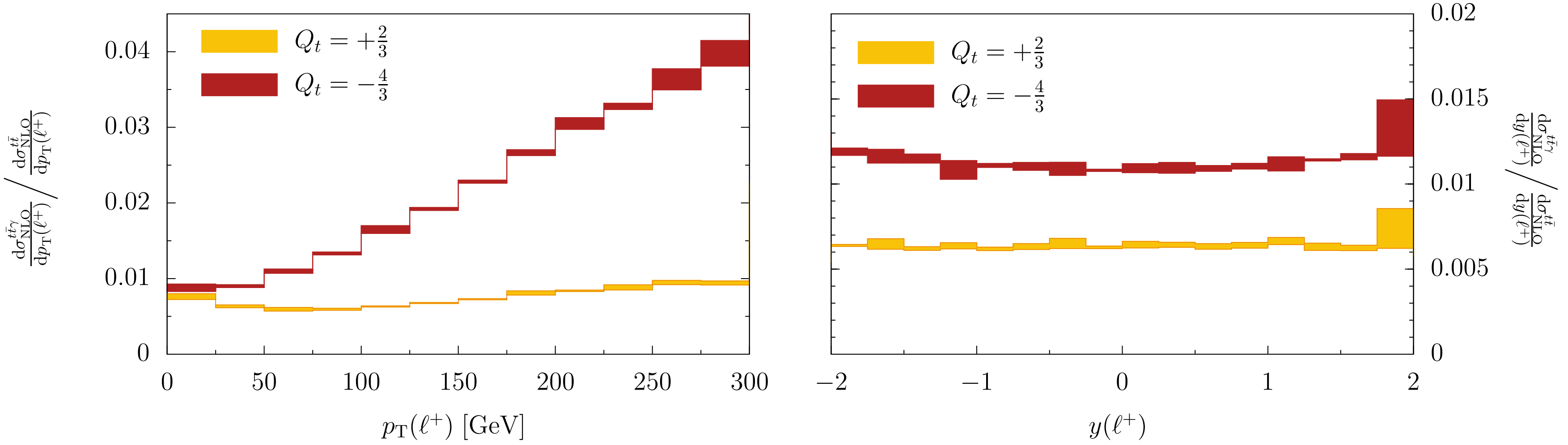


$$\sigma_{t\bar{t}\gamma}^{\mathrm{NLO}} = 26.7^{+1.3}_{-2.3}\ \mathrm{fb}$$

improved scaling with Q_t but significantly smaller cross section

$t\bar{t}$+photon

B) Ratio of cross sections $\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}}$



$$\frac{\sigma^{Q_t=2/3}_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}} = \begin{cases} 5.66^{+0.03}_{-0.02} \times 10^{-3}, & \text{LO;} \\ 6.33^{+0.26}_{-0.14} \times 10^{-3}, & \text{NLO,} \end{cases} \qquad \frac{\sigma^{Q_t=-4/3}_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}} = \begin{cases} 10.4^{+0.2}_{-0.2} \times 10^{-3}, & \text{LO;} \\ 11.2^{+0.3}_{-0.2} \times 10^{-3}, & \text{NLO.} \end{cases}$$

- Ratios are significantly more stable against NLO corrections
- Small scale uncertainties
- Experimental uncertainties cancel

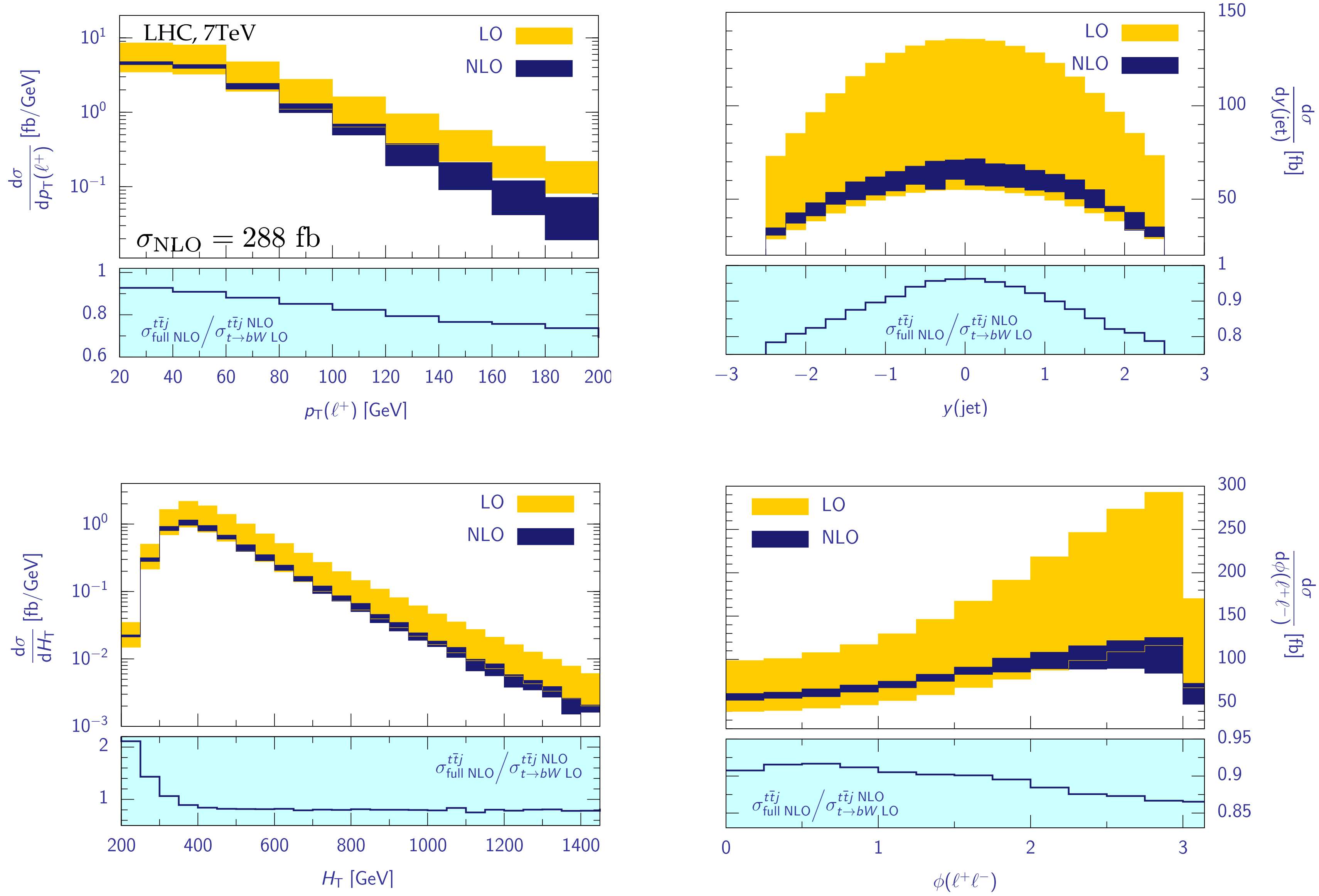
Results

$t\bar{t} + \mathrm{jet}$

K.Melnikov, M.S. Nucl.Phys.B840 (2010)

K.Melnikov, A. Scharf, M.S. Phys.Rev.D85 (2012)

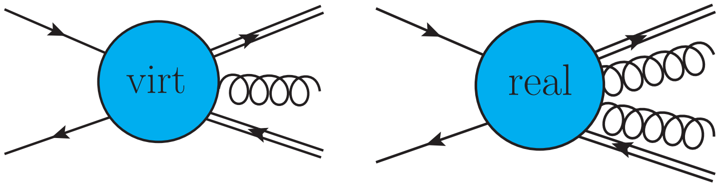
Results: ttbar+jet



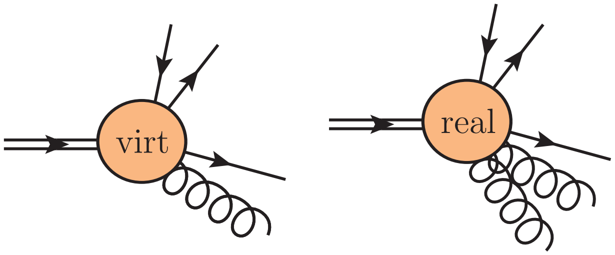
Results: ttbar+jet

$$
\begin{aligned}
\mathrm{d}\sigma^{\mathrm{NLO}}_{t\bar{t}+1j} = \Gamma^{-2}_{t,\mathrm{tot}}\Big(&\mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}+1j}\mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}} + \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}}\mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}+1j} + \overbrace{\left(\mathrm{d}\sigma^{\mathrm{virt}}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\mathrm{real}}_{t\bar{t}+2j}\right)\mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}}}^{(a)} \\
&+ \underbrace{\mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}}\left(\mathrm{d}\Gamma^{\mathrm{virt}}_{t\bar{t}+1j} + \mathrm{d}\Gamma^{\mathrm{real}}_{t\bar{t}+2j}\right)}_{(b)} + \underbrace{\mathrm{d}\sigma^{\mathrm{real}}_{t\bar{t}+1j}\mathrm{d}\Gamma^{\mathrm{real}}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\mathrm{virt}}_{t\bar{t}}\mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}+1j}\mathrm{d}\Gamma^{\mathrm{virt}}_{t\bar{t}}}_{(c)}\Big).
\end{aligned}
$$

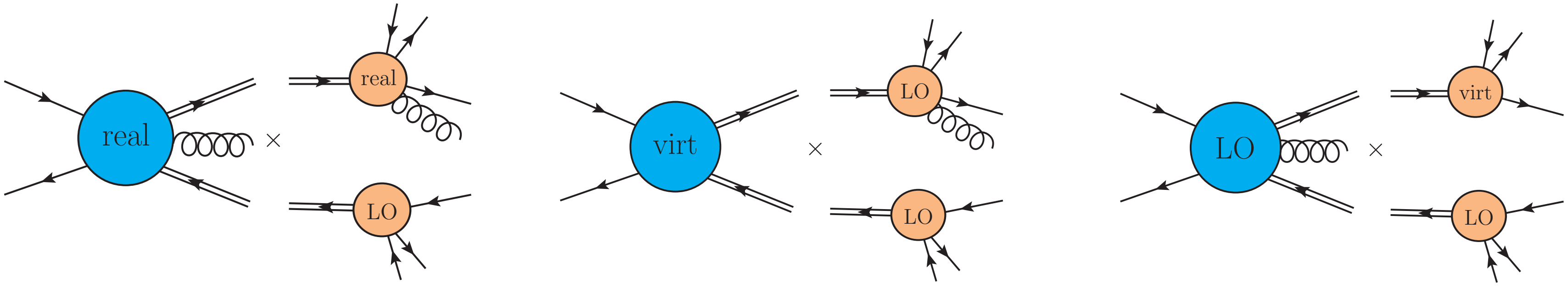
(a)



(b)



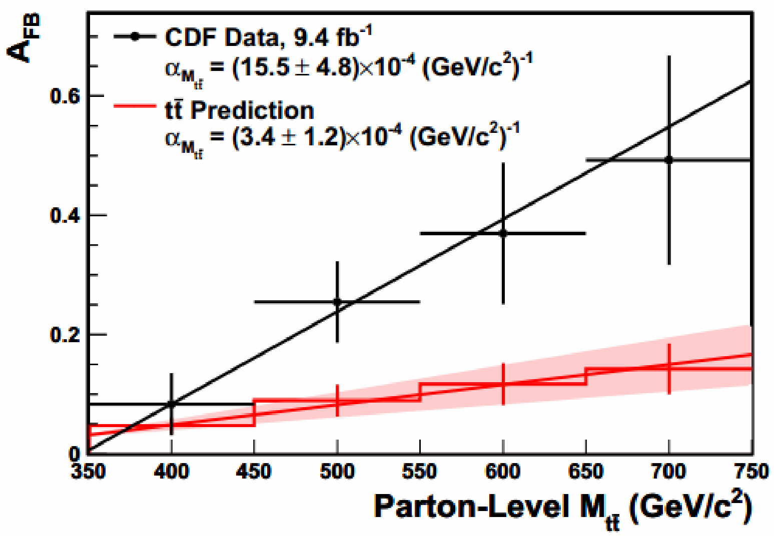
(c)



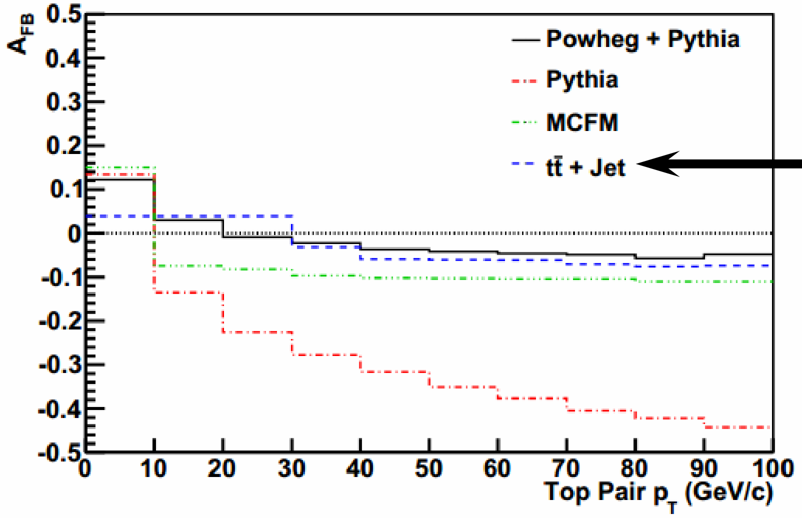
Results: ttbar+jet

Measurement of the top quark forward-backward production asymmetry and its dependence on event kinematic properties

CDF, arXiv:1211.1003 [hep-ex]



(b)



K.Melnikov, A. Scharf, M.S.

Results

$$t\bar{t} + \mathrm{large}\, E_{\mathrm{T}}^{\mathrm{miss}}$$

R. Boughezal, M.S.

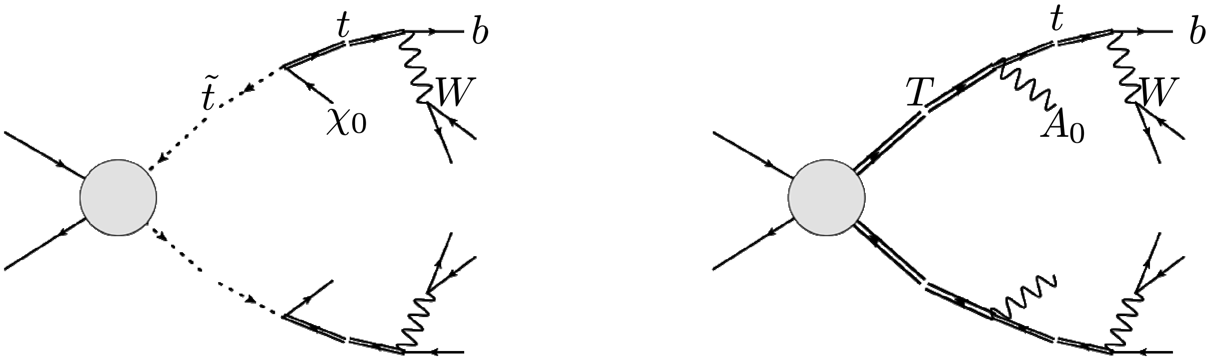
arXiv: 1212.0898 , PRL xxx

Results: ttbar + ETmiss

We consider two scenarios:

$pp \to \tilde{t}\tilde{t}^* \to t\bar{t} + \chi_0\bar{\chi}_0$ (aka *direct* stop production)

$pp \to T\bar{T} \to t\bar{t} + A_0\bar{A}_0$ (littlest Higgs, UED,...)



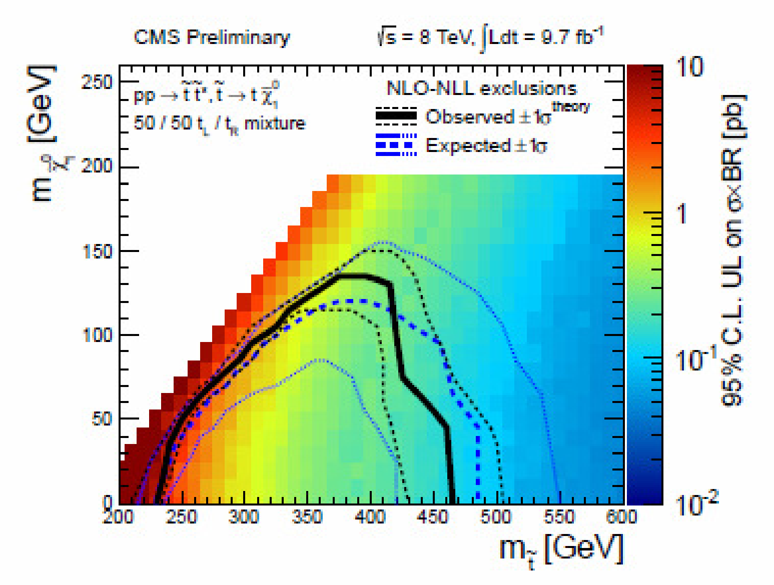
3-stage decay chain: $\tilde{t} \to \chi_0 + t$

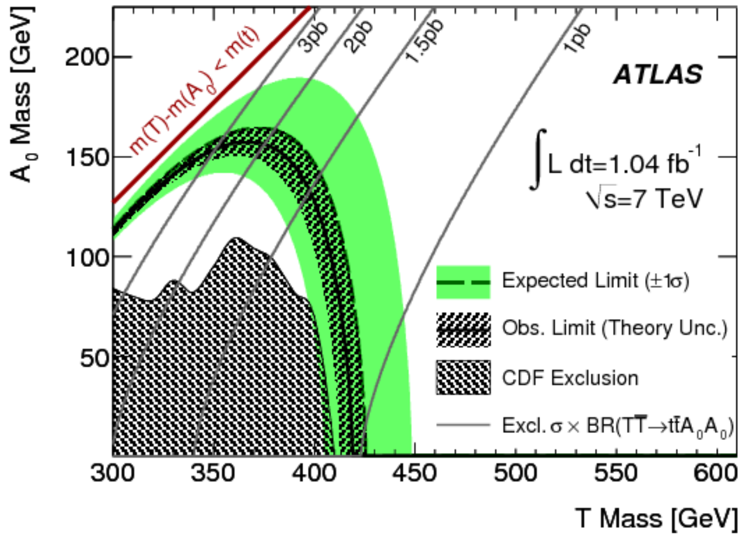
$t \to b + W$

$W \to f\bar{f}'$

Results: ttbar + ETmiss

Dedicated searches





Existing analyses use LO signal modelling times const. K-factor for stable (s)tops.

Open questions:

How robust are LO studies against higher order corrections?

What are the effects of spin correlations at higher orders?

How reliable are existing exclusion limits?

Results: ttbar + ETmiss

- There are publicly available codes for stop or T` pair production
  which calculate the *total cross section* at NLO QCD (+ higher order terms).
  Stops and T are assumed to be *stable*. [Prospino,Hathor]

- **TOPAZ** includes NLO QCD corrections to the production process and
  the full decay chain including all spin correlations.
  All couplings for e.g. stop-chi-top, T-A_0-top can be freely chosen.

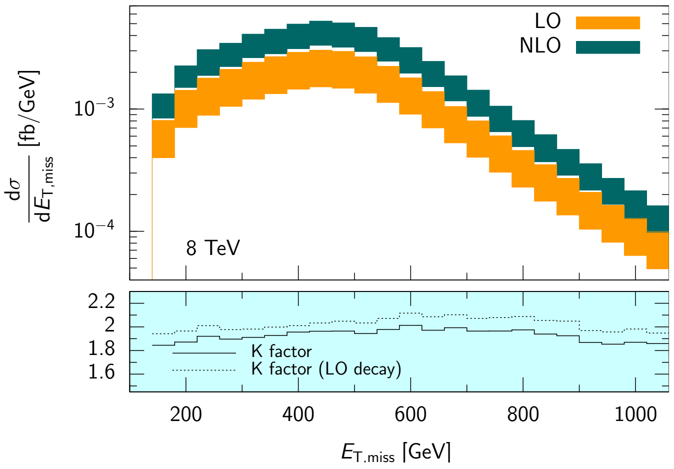
- We assume that the decay width is not too large and the NWA is applicable.

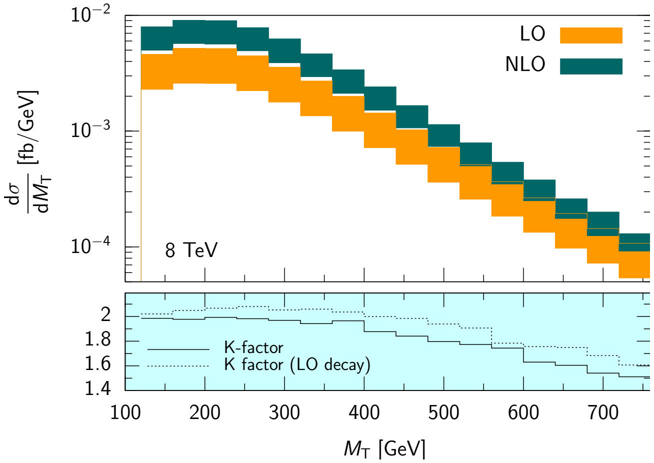
Results: ttbar + ETmiss

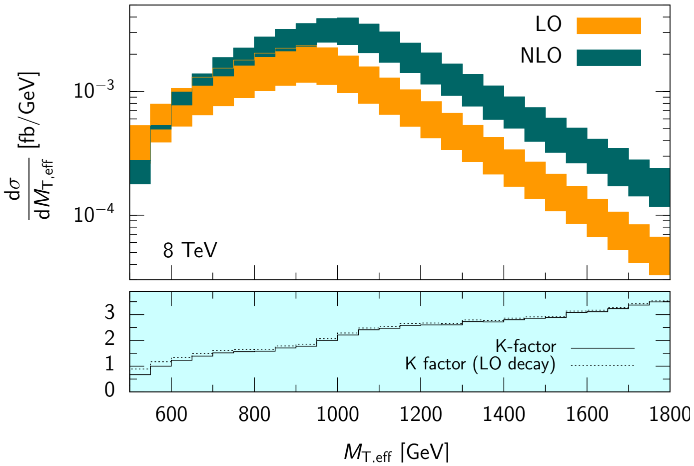
Scenario I: $m_{\tilde{t}} = 500\ \text{GeV}$ $m_{\chi_0} = 100\ \text{GeV}$ lept+jets channel

selection cuts: $p_{\mathrm{T}}^{\ell} > 20\ \text{GeV}$ $|y^{\ell}| < 2.5$ $p_{\mathrm{T}}^{\text{jet}} > 30\ \text{GeV}$ $|y^{\text{jet}}| < 2.5$

$p_{\mathrm{T}}^{\text{miss}} > 150\ \text{GeV}$







$$\sigma_{\mathrm{LO}} = 0.9\ \text{fb} \qquad \sigma_{\mathrm{NLO}} = 1.77\ \text{fb} \qquad (\sigma_{\mathrm{NLO}}^{14\mathrm{TeV}} = 14.0\ \text{fb})$$

$$A_{\mathrm{LO}} = \frac{\sigma_{\text{cuts}}^{\mathrm{LO}}}{\sigma_{\text{no cuts}}^{\mathrm{LO}}} = 0.20 \qquad A_{\mathrm{NLO}} = \frac{\sigma_{\text{cuts}}^{\mathrm{NLO}}}{\sigma_{\text{no cuts}}^{\mathrm{NLO}}} = 0.29$$

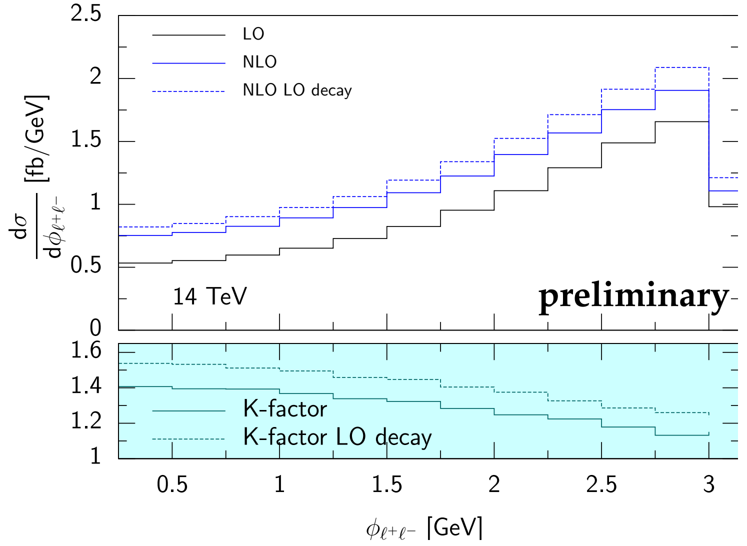
Effect of spin correlations: $A_{\mathrm{LO}}^{\text{no spin corr}} = 0.24$

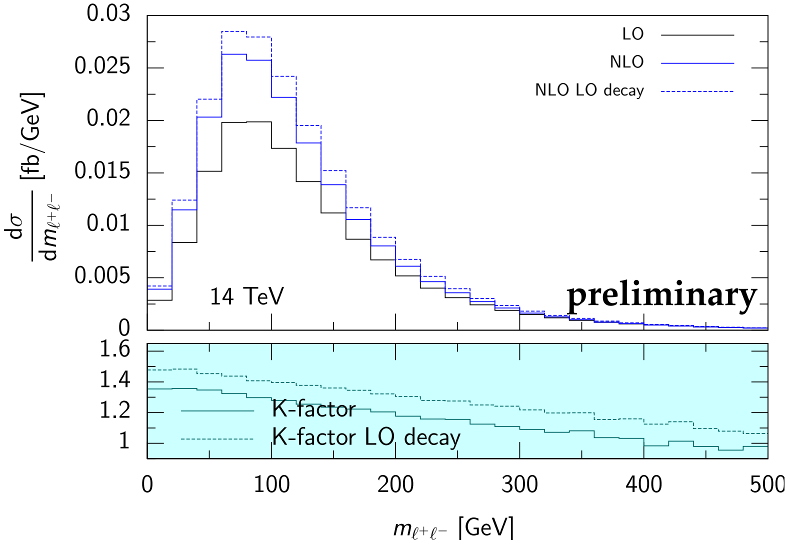
Results: ttbar + ETmiss

Scenario I: $m_{\tilde{t}} = 500$ GeV $m_{\chi_0} = 100$ GeV di-lept. channel

selection cuts: $p_T^\ell > 20$ GeV $|y^\ell| < 2.5$ $p_T^{\text{jet}} > 30$ GeV $|y^{\text{jet}}| < 2.5$

$p_T^{\text{miss}} > 150$ GeV





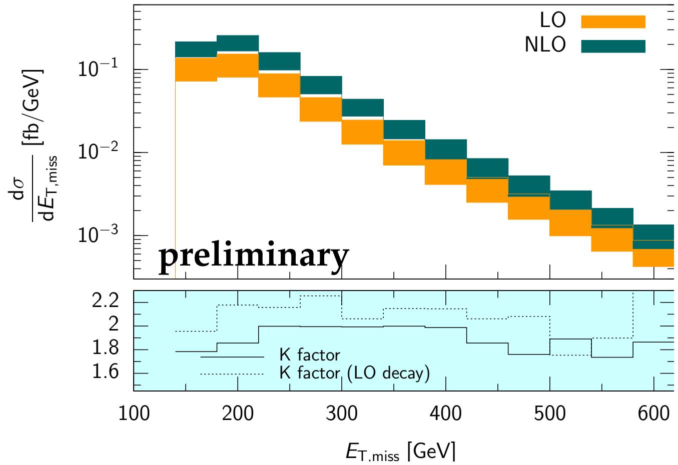
$\sigma_{\text{LO}} = 3.0$ fb $\sigma_{\text{NLO}} = 3.8$ fb

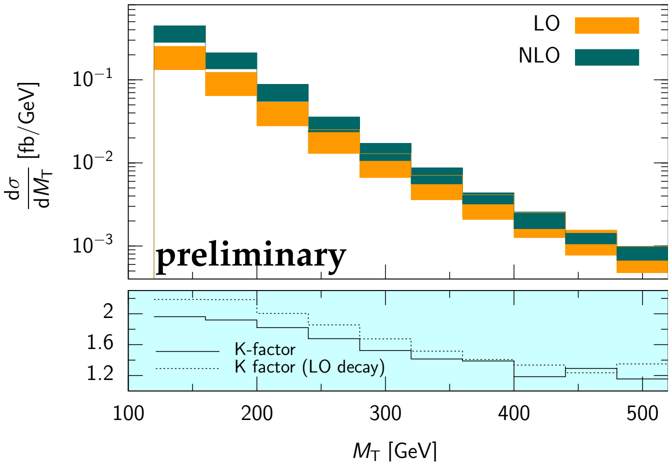
$$A_{\text{LO}} = \frac{\sigma^{\text{LO}}_{\text{cuts}}}{\sigma^{\text{LO}}_{\text{no cuts}}} = 0.50 \qquad A_{\text{NLO}} = \frac{\sigma^{\text{NLO}}_{\text{cuts}}}{\sigma^{\text{NLO}}_{\text{no cuts}}} = 0.47$$

Results: ttbar + ETmiss

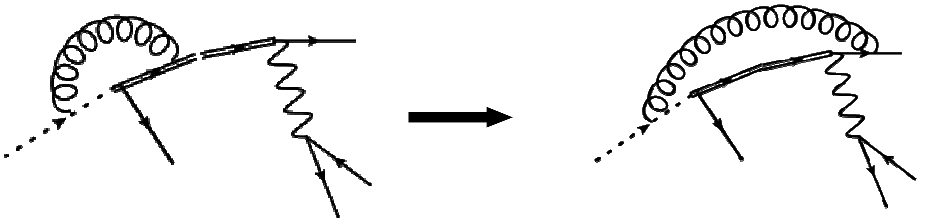
Scenario II: $m_{\tilde{t}} = 250\ \mathrm{GeV}$ $m_{\chi_0} = 50\ \mathrm{GeV}$ lept+jets channel

$$\sigma_{\mathrm{LO}} = 13.8\ \mathrm{fb} \quad \sigma_{\mathrm{NLO}} = 26.1\ \mathrm{fb}$$





- Close to the kinematic edge $m_{\tilde{t},T} \approx m_t + m_{\chi_0,A_0}$ the top quarks can be significantly off-shell. Might require extension of our calculation:
  3-stage decay → 2-stage decay



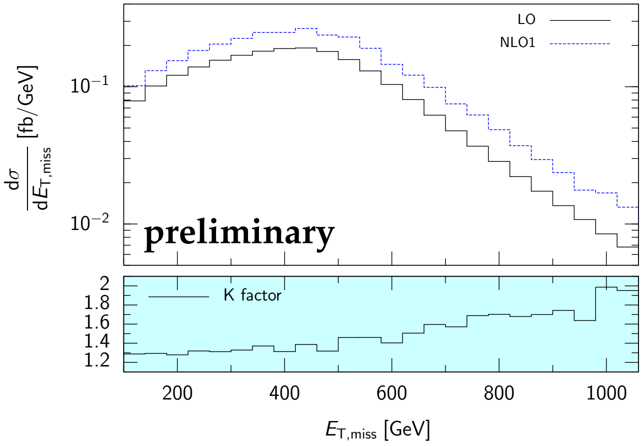
$$\frac{1}{m_t \Gamma_t} \qquad \frac{1}{p_t^2 - m_t^2 + \mathrm{i}\Gamma_t m_t}$$

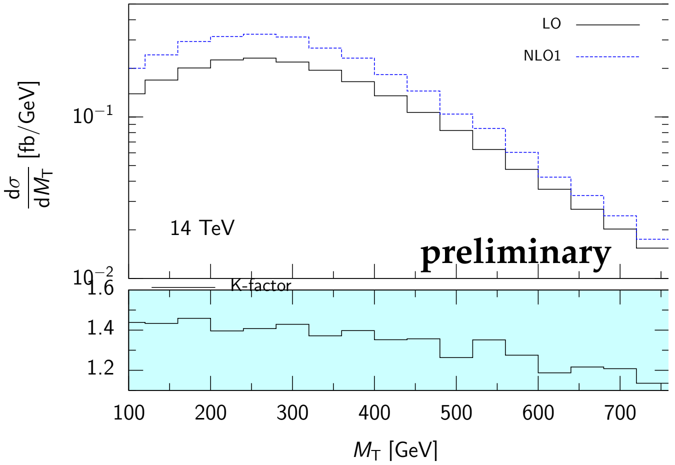
Results: ttbar + ETmiss

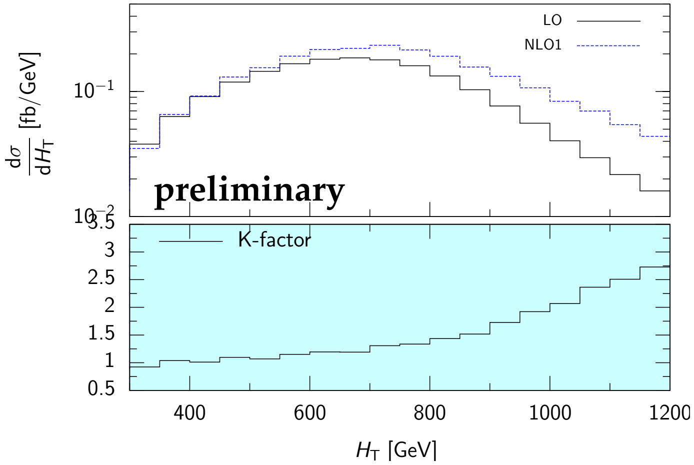
Scenario III: $m_T = 500\ \mathrm{GeV}$ $m_{A_0} = 50\ \mathrm{GeV}$ lept+jets channel

selection cuts: $p_T^\ell > 20\ \mathrm{GeV}$ $|y^\ell| < 2.5$ $p_T^{\mathrm{jet}} > 20\ \mathrm{GeV}$ $|y^{\mathrm{jet}}| < 2.5$

$p_T^{\mathrm{miss}} > 20\ \mathrm{GeV}$







$$\sigma_{\mathrm{LO}} = 91.4\ \mathrm{fb} \qquad \sigma_{\mathrm{NLO}} = 131\ \mathrm{fb}$$

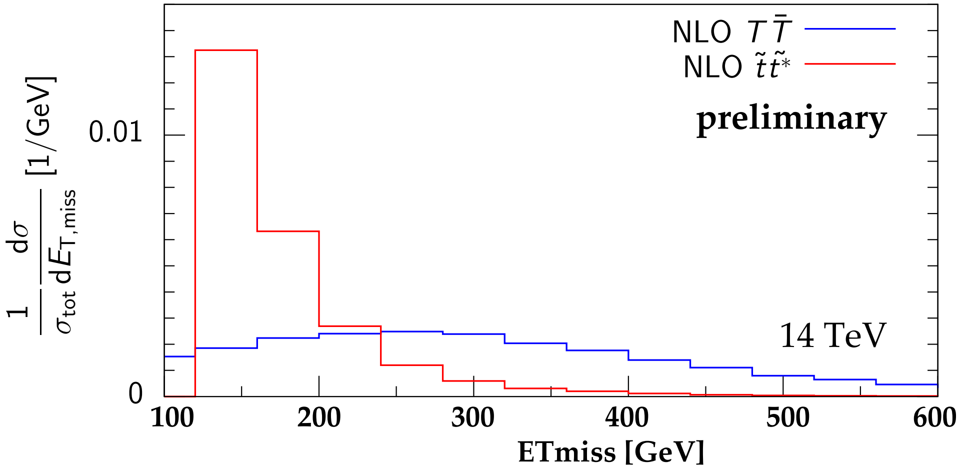
$$A_{\mathrm{LO}} = \frac{\sigma^{\mathrm{LO}}_{\mathrm{cuts}}}{\sigma^{\mathrm{LO}}_{\mathrm{no\ cuts}}} = 0.40 \qquad A_{\mathrm{NLO}} = \frac{\sigma^{\mathrm{NLO}}_{\mathrm{cuts}}}{\sigma^{\mathrm{NLO}}_{\mathrm{no\ cuts}}} = 0.46$$

Results: ttbar + ETmiss

Shape comparisons

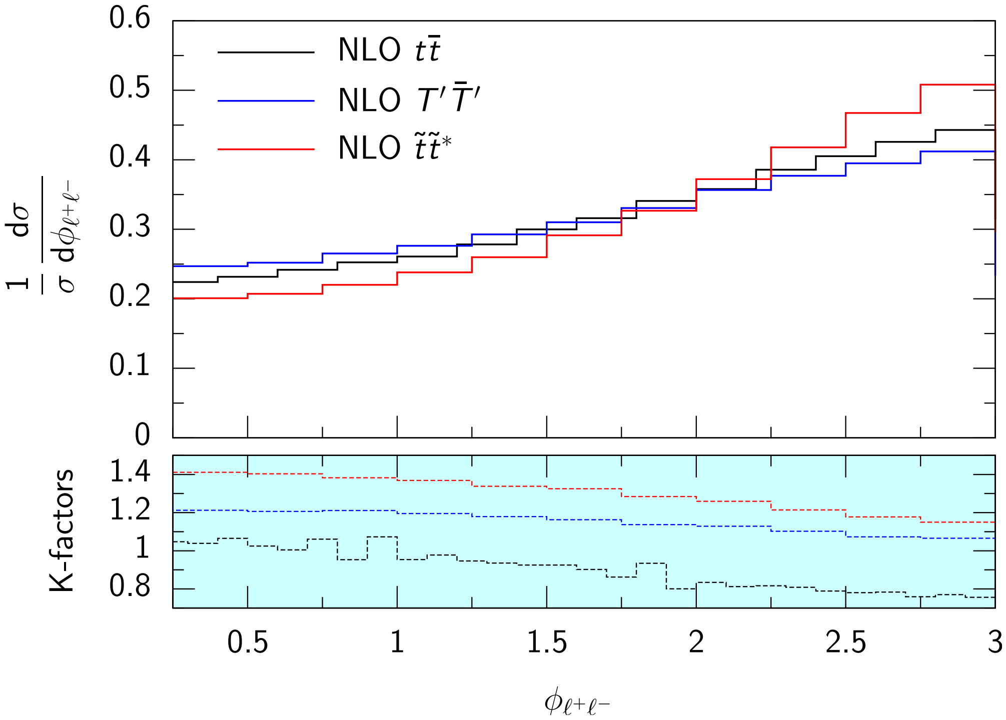
$$\sigma_{\mathrm{NLO}}^{\tilde{t}\tilde{t}^*} = 114\ \mathrm{fb} \qquad (250/50)\ \mathrm{GeV}$$

$$\sigma_{\mathrm{NLO}}^{TT'} = 131\ \mathrm{fb} \qquad (500/50)\ \mathrm{GeV}$$



Results: ttbar + ETmiss

Shape comparisons



Associated top quark pair production

CONCLUSIONS

- The study of associated top quark pair production at the LHC is the beginning of a new era in top quark physics.
- A good understanding of the SM processes *ttbar+V, H* is crucial for direct measurements of the top quark electroweak couplings.
- *ttbar*+large missing ET is a signal in many extensions of the SM. Description of a realistic final state at NLO QCD impacts K-factors and acceptances significantly.
- **TOPAZ** incorporates several top quark processes incl. full decay chains and spin correlations at NLO QCD.

Extras

Extras

$$t\bar{t} + \gamma$$

CDF 5.6 fb^{-1} (2011): recent measurement

1) identify W-boson charge through lepton charge
2) pair b-jet with W-boson (topfitter with mt,mW input)
3) measure b-jet charge (JetCharge Algorithm)

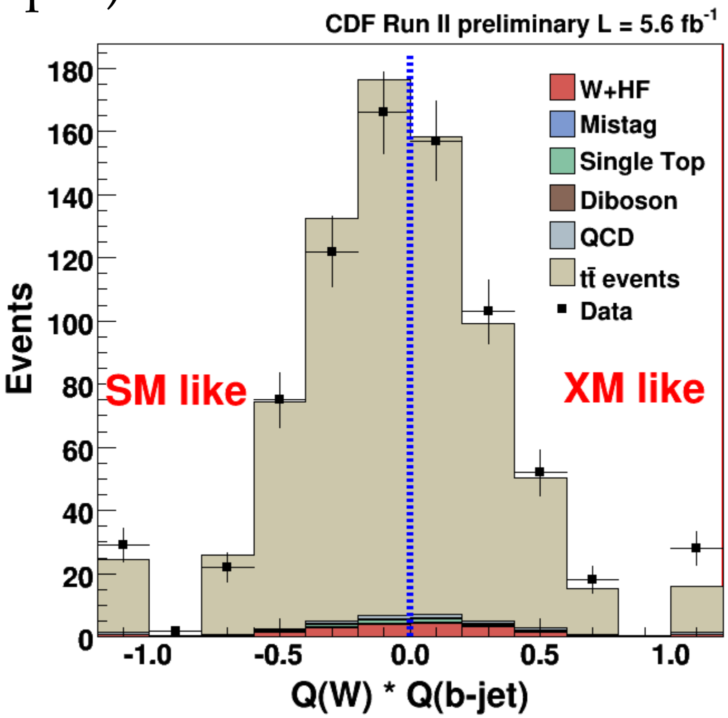
assign:

SM top quark charge $\leftrightarrow\ Q(W)\cdot Q(\text{bjet}) < 0$

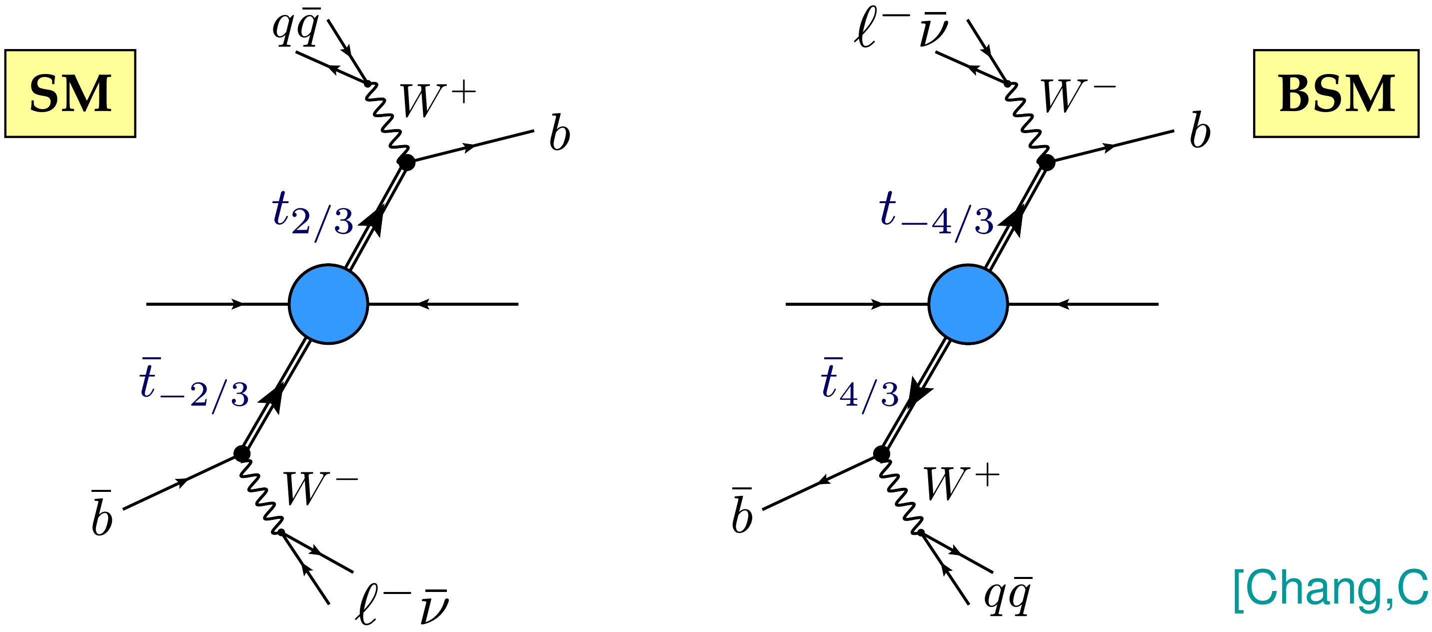
XM top quark charge $\leftrightarrow\ Q(W)\cdot Q(\text{bjet}) > 0$

result: 416 SM events vs. 358 XM events

$\Rightarrow$ Exclusion of XM hypothesis with 95% C.L.



Extras



[Chang,Chang,Ma]

$\begin{pmatrix} \mathrm{Q}_{4u} \\ \mathrm{Q}_{4d} \end{pmatrix}_{\mathrm{R}}$ with el.charges -1/3 and -4/3 **+** mixing $b_{\mathrm{R}} - (Q_{4u})_{\mathrm{R}}$ **+** $m_{Q_{4u}} = 172$ GeV, $m_{t_{2/3}} \geq 356$ GeV

✓ electroweak precision tests, ✓ Tevatron searches, ✓ LHC searches

Results: **Tevatron**

Our observable:

$$\begin{array}{rr} p_{\mathrm{T}}^{\ell} > 20\ \mathrm{GeV} & |y^{\ell}| < 1.1 \\ p_{\mathrm{T}}^{\gamma} > 10\ \mathrm{GeV} & |y^{\gamma}| < 1.1 \\ p_{\mathrm{T}}^{\mathrm{jet}} > 15\ \mathrm{GeV} & |y^{\mathrm{jet}}| < 2 \\ p_{\mathrm{T}}^{\mathrm{miss}} > 20\ \mathrm{GeV} & H_{\mathrm{T}} > 200\ \mathrm{GeV} \\ \Delta R(j,j) > 0.4 & \Delta R(\ell/j,\gamma) > 0.4 \end{array}$$

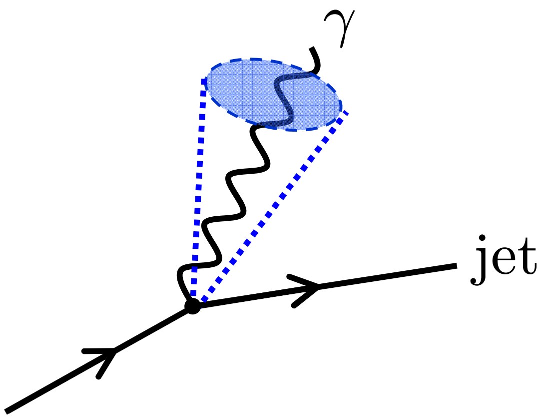
matches analysis by

CDF ExoTiC

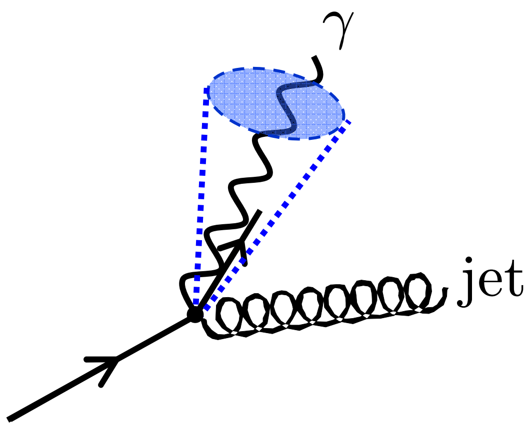
Photon isolation in pQCD:

fragmentation functions or some clever separation cuts

example:
$\Delta R(\gamma, \text{jet}) > \delta_{\text{sep}}$



works at LO



fails to reject collinear singularity

Results: **Tevatron**

Our observable:

$$\begin{array}{ll} p_{\mathrm{T}}^{\ell} > 20\ \mathrm{GeV} & |y^{\ell}| < 1.1 \\ p_{\mathrm{T}}^{\gamma} > 10\ \mathrm{GeV} & |y^{\gamma}| < 1.1 \\ p_{\mathrm{T}}^{\mathrm{jet}} > 15\ \mathrm{GeV} & |y^{\mathrm{jet}}| < 2 \\ p_{\mathrm{T}}^{\mathrm{miss}} > 20\ \mathrm{GeV} & H_{\mathrm{T}} > 200\ \mathrm{GeV} \\ \Delta R(j,j) > 0.4 & \Delta R(\ell/j,\gamma) > 0.4 \end{array}$$

matches analysis by

ExoTiC

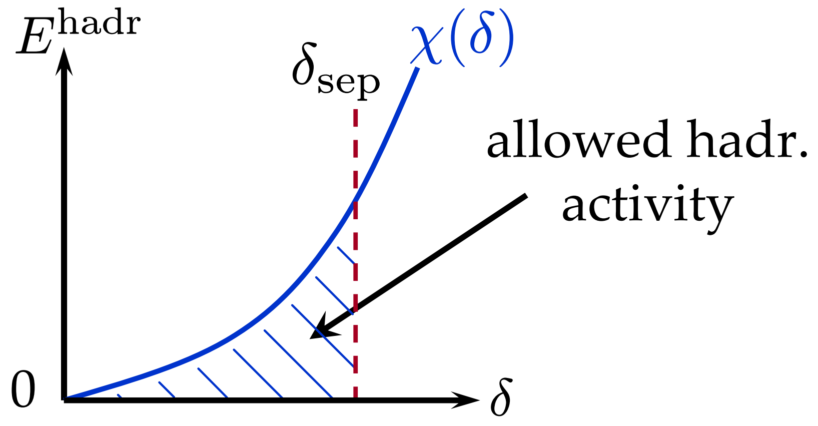
Photon isolation in pQCD:

fragmentation functions or some clever separation cuts

Frixione‘s isolation:

$$\sum_i E_i\, \theta(\delta - R_{i\gamma}) \leq \chi(\delta, E_\gamma)$$

$$\forall \delta \leq \delta_{\mathrm{sep}}$$



Extras

$t\bar{t} + \text{jet}$

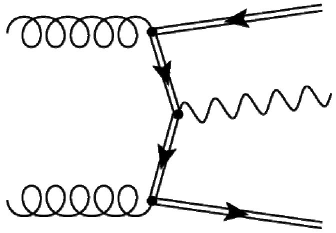
$$\mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}+1j} = \Gamma^{-2}_{t,\mathrm{tot}} \left[\mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}+1j} \mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}} + \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}} \mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}+1j} \right]$$

$$\begin{aligned}\mathrm{d}\sigma^{\delta\mathrm{NLO}}_{t\bar{t}+1j} = \Gamma^{-2}_{t,\mathrm{tot}} \Big[& \overbrace{\left(\mathrm{d}\sigma^{\mathrm{virt}}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\mathrm{real}}_{t\bar{t}+2j}\right)\mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}}}^{\text{production}} + \overbrace{\mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}}\left(\mathrm{d}\Gamma^{\mathrm{virt}}_{t\bar{t}+1j} + \mathrm{d}\Gamma^{\mathrm{real}}_{t\bar{t}+2j}\right)}^{\text{decay}} \\ & + \underbrace{\mathrm{d}\sigma^{\mathrm{real}}_{t\bar{t}+1j}\mathrm{d}\Gamma^{\mathrm{real}}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\mathrm{virt}}_{t\bar{t}}\mathrm{d}\Gamma^{\mathrm{LO}}_{t\bar{t}+1j} + \mathrm{d}\sigma^{\mathrm{LO}}_{t\bar{t}+1j}\mathrm{d}\Gamma^{\mathrm{virt}}_{t\bar{t}}}_{\text{mixed}} \Big].\end{aligned}$$

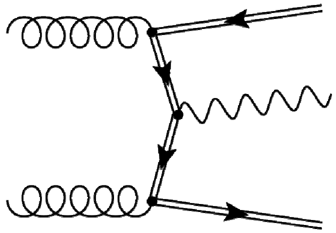
$$\sigma^{\mathrm{LO}}_{t\bar{t}+\mathrm{jet}} = 350^{+215}_{-123}\ \mathrm{fb} = 317(\mathrm{prod})\ +\ 33(\mathrm{decay})\ \mathrm{fb}$$

$$\sigma^{\mathrm{NLO}}_{t\bar{t}+\mathrm{jet}} = 288^{+46}_{-18}\ \mathrm{fb} = 323(\mathrm{prod})\ +\ 40.5(\mathrm{decay})\ -\ 75.5(\mathrm{mixed})\ \mathrm{fb}$$

Cross sections at NLO QCD for the LHC (14 TeV)

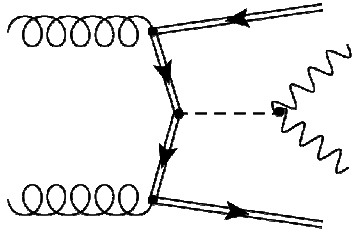


$$\sigma_{t\bar{t}+\gamma} = 3 \text{ pb}$$



$$\sigma_{t\bar{t}+Z} = 1.1 \text{ pb}$$

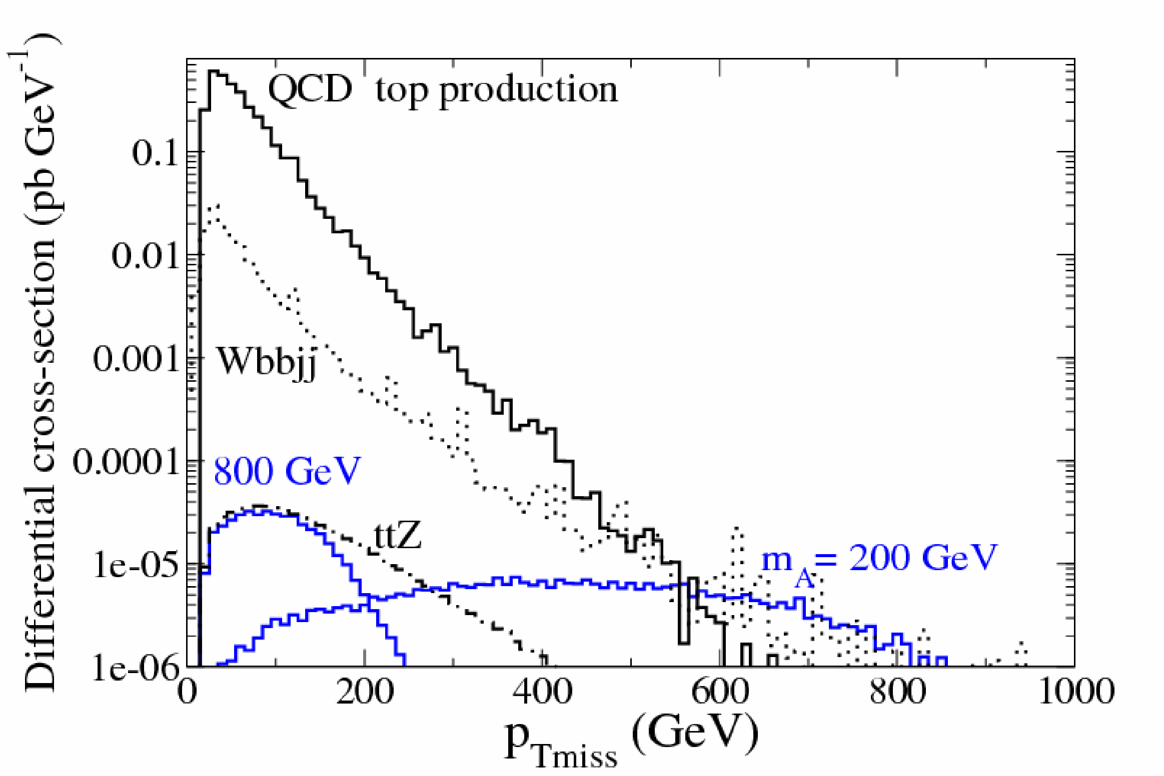
→ after branchings: $\sim \mathcal{O}(1\,\text{fb})$



$$\sigma_{t\bar{t}H}(m_H = 125\,\text{GeV}) = 611 \text{ fb} \;\pm 9\%(\text{scale}) \;\pm 9\%(\text{PDFs})$$

→ after branchings: $\sim \mathcal{O}(5\,\text{fb})$

Extras



Top Quark Pair plus Large Missing Energy at the LHC
Tao Han (Wisconsin U., Madison & Santa Barbara, KITP) , Rakhi Mahbubani (Santa Barbara, KITP & Ferm
Devin G.E. Walker (Santa Barbara, KITP & UC, Berkeley &LBL, Berkeley) ,
Lian-Tao Wang (Santa Barbara, KITP & Princeton U.)

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