Signatures of new physics in final-states with top quarks at CMS

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Introduction

- New physics in final-states with top quarks at the LHC is predicted by various extensions of the Standard Model
  - Supersymmetric models, e.g. mSUGRA
  - Theories with neutral heavy resonances that predominantly decay into top quark pairs

- Aim: Study signatures of mSUGRA and neutral heavy resonances in final-states of $t\bar{t}$ pairs at CMS
  - Apply a standard event selection for $t\bar{t}$ events
  - Study signatures of mSUGRA in the selected events
  - Analyze visibility of neutral heavy resonances in the distribution of the reconstructed invariant $t\bar{t}$ mass

mSUGRA

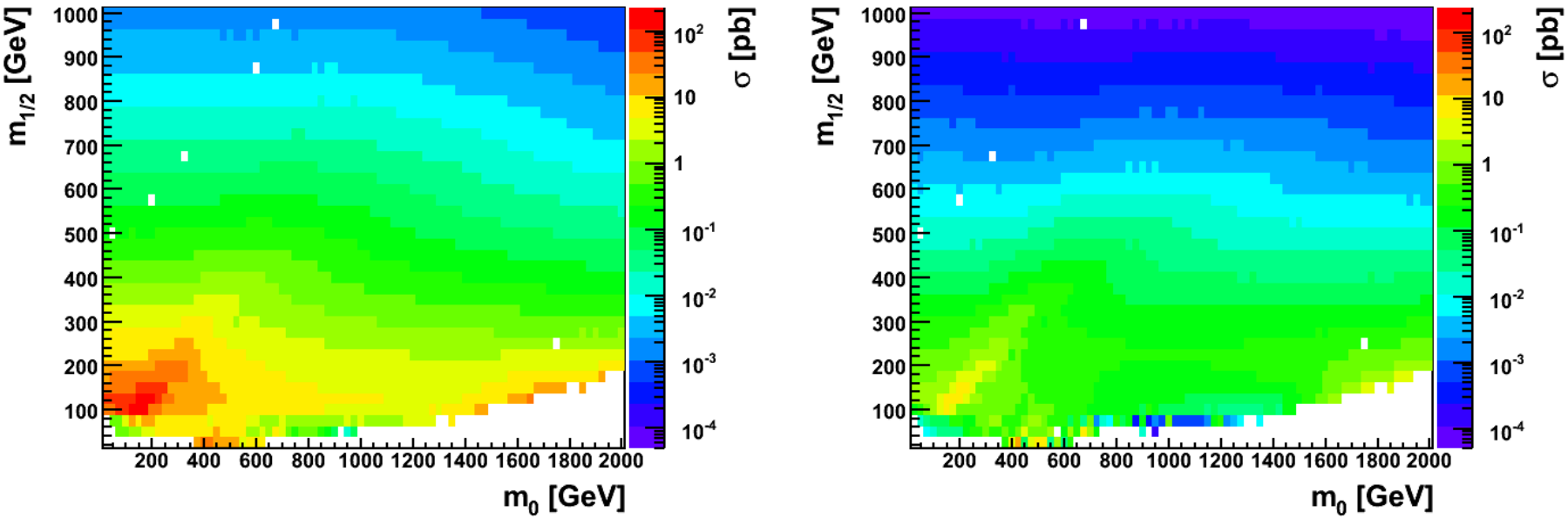


Figure: L.O. cross-section for inclusive top quark (left) and top quark pair (right) production from the decay of sparticles for $A_0 = 0$, $\tan\beta = 10$, sign $\mu = 1$.

- Larger cross-section for inclusive top quark than top quark pair production
  - Small production cross-section for H^0, A^0
  - Top quarks are mainly produced in different decay-branches

Point	$m_0[GeV]$	$m_{1/2}[GeV]$	$\tan\beta$	sign(μ)	A_0	σ(top)	σ(all)
LM1	60	250	10	+	0	6.68	42.83
LM2	185	350	35	+	0	1.76	7.46
LM3	**330**	**240**	**20**	**+**	**0**	**13.75**	**33.02**
LM4	210	285	10	+	0	4.85	19.34
LM5	230	360	10	+	0	1.54	6.20
LM6	85	400	10	+	0	0.81	4.09
LM8	500	300	10	+	-300	5.40	9.00
LM10	3000	500	10	+	0	0.03	0.55
HM1	180	850	10	+	0	0.01	0.05
HM2	350	800	35	+	0	0.01	0.07
HM3	700	800	10	+	0	0.01	0.05
HM4	1350	600	10	+	0	0.04	0.11

Table: L.O. cross-section for inclusive top quark production σ(top) from the decay of sparticles and total leading-order cross-section σ(all) for sparticle production in pb.

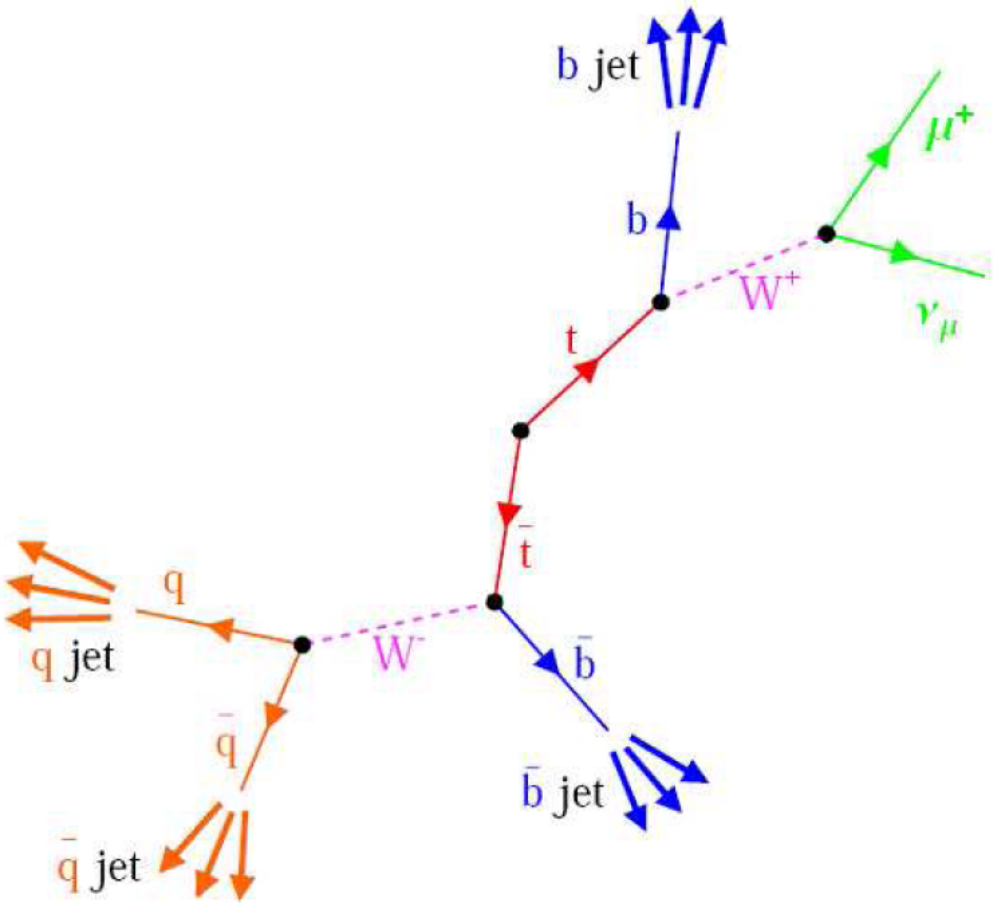
Theories with neutral heavy resonances

- Models with finite extra spatial dimensions:
  - At low energies: SM-particles are trapped to the four-dim. spacetime
  - At high energies: SM-particles can be excited to quantized states in the TeV range and appear as heavy resonances called Kaluza-Klein-particle (KK-particle)
  - E.g. Randall-Sundrum-model (RS-model)
- Models with (at least) one additional U(1)-gauge-symmetry
  - Add. U(1)-gauge-symmetry comes along with a new neutral gauge boson
  - E.g. in Grand Unification Theories, models with topcolor
- Cross-sections are model-dependent.

- Considered as Z' benachmark model: Z' model with
  - $m_{Z'} = 750$ GeV
  - $\sigma(Z' \rightarrow \text{semilep.}t\bar{t}) = 4.6$ pb
    (as in the topcolor model used as benchmark model at the Tevatron)
  - But with the same couplings to fermions as the SM Z-boson

Event selection

- Di-muonic $t\bar{t}$ decay-channel turns out not to be appropriate due to the small branching ratio and two neutrinos in the final-state
- Fully hadronic $t\bar{t}$ decay-channel is expected to suffer from a large background
- Choose semi-leptonic $t\bar{t}$ decay-channel with a muon in the final-state



Signature:

- One muon
- Missing E_T
- Two light jets
- Two b-jets

Background:

- Other $t\bar{t}$
- QCD
- V+Jets (including VV+Jets)

Muon selection:

- At least one 'good' muon with
  $p_T > 20$ GeV,
  $|\eta| < 2.1$ and
  $I_{rel} < 0.1$

- $I_{rel} = \frac{\sum_{tracker} p_T + \sum_{cal.} p_T}{p_T(\text{muon})}$,
  where p_T in tracker and E_T in calorimeter are summed in cone with $\Delta R = 0.3$ around muon.

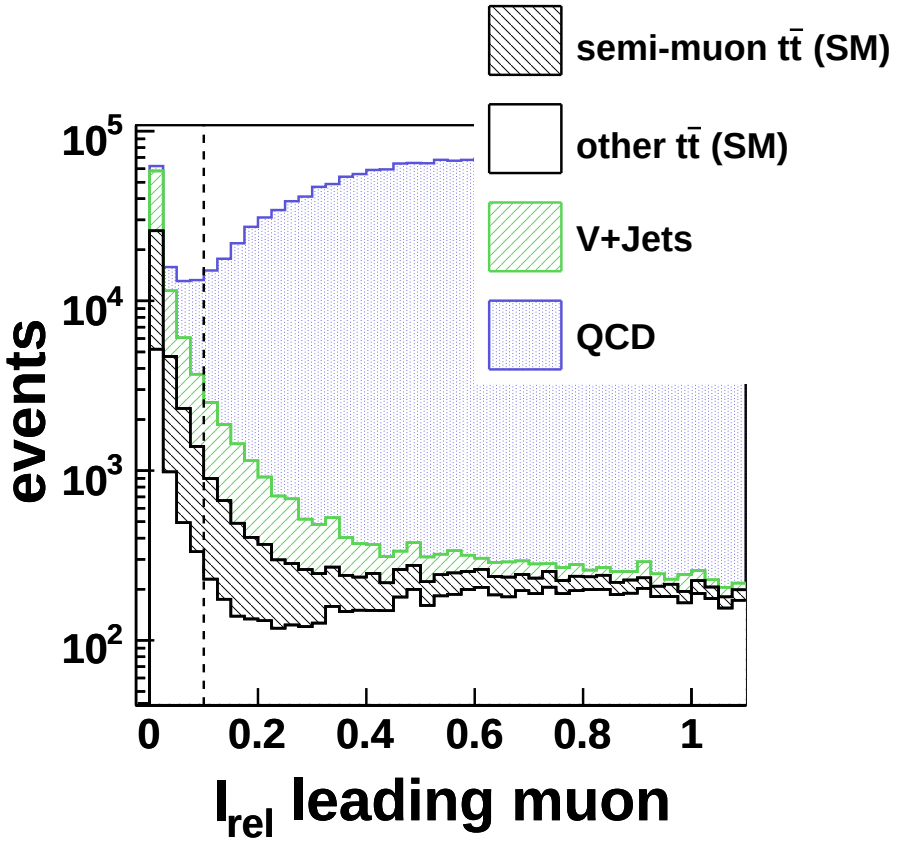
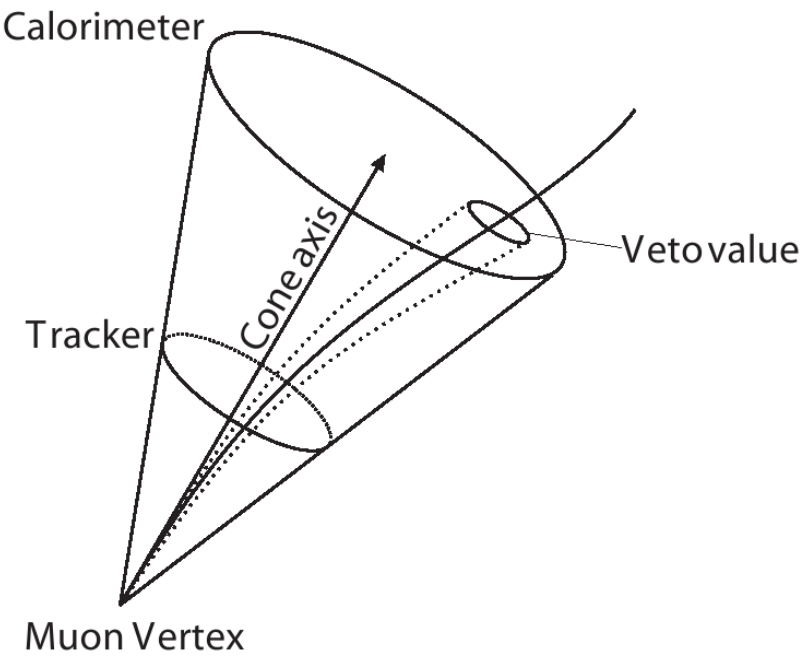


Figure: I_{rel} of the leading isolated muon. The distributions are stacked.

'Good' muon:

- Global muon
- χ^2/ndf of global fit < 10
- Impact parameter for tracker fit < 2 mm
- Number of valid hits in tracker > 11
- Deposited energies in muon veto-cones:
  - In hcal. < 6 GeV
  - In ecal. < 4 GeV



Jet selection:

- At least four jets with $p_T > 30$ GeV and $|\eta| < 2.4$
- At least one jet is required to have a Bjet-discriminator larger than 3.
- Bjet-Discriminator: Significance of the impact parameter of the second track ("trackCountingHighEffBJetTags")

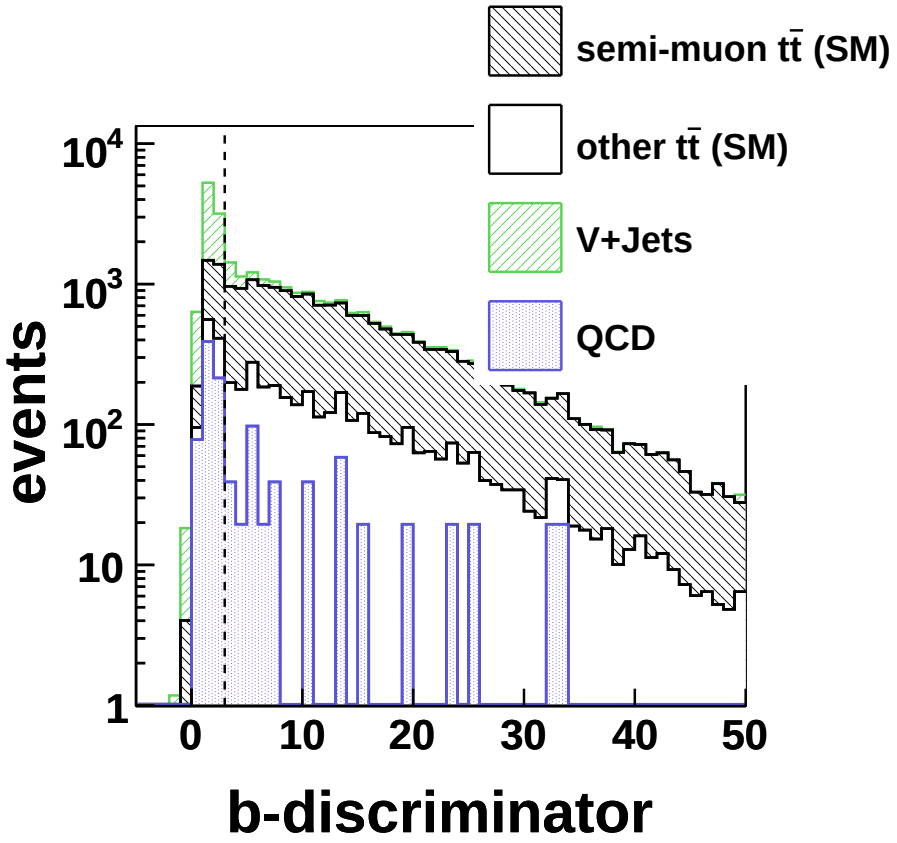


Figure: B-Discriminator for the jet with the highest value. The distributions are stacked.

Signatures of new physcis

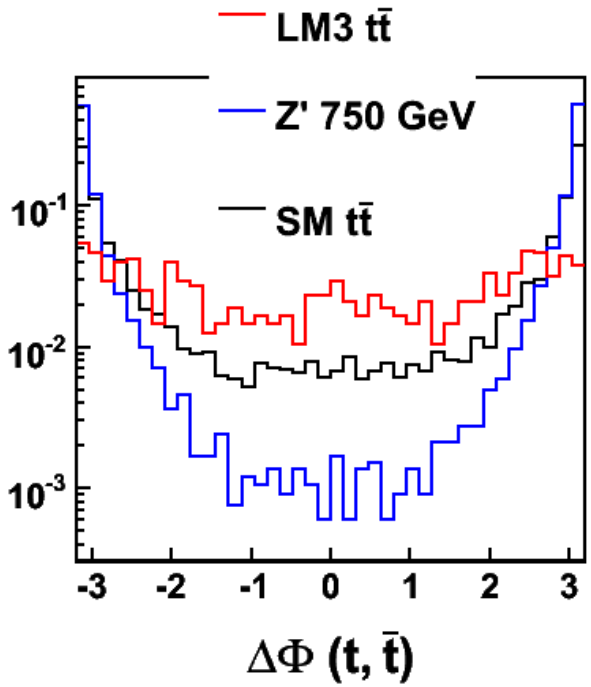


Figure: Azimuthal angle ϕ between the top and the anti-top quark on generator level. All distributions are normalized to unit area.

Model-independent search difficult because

- Just a few $t\bar{t}$ events among the selected LM3 events
- Variables like E_T^{miss}, HT, MT, ... are not sensitive to differences between considered Z' model and SM

$\Longrightarrow$ Split analysis:

- Signatures of mSUGRA
- Reconstrcution of Z'

Signatures of mSUGRA

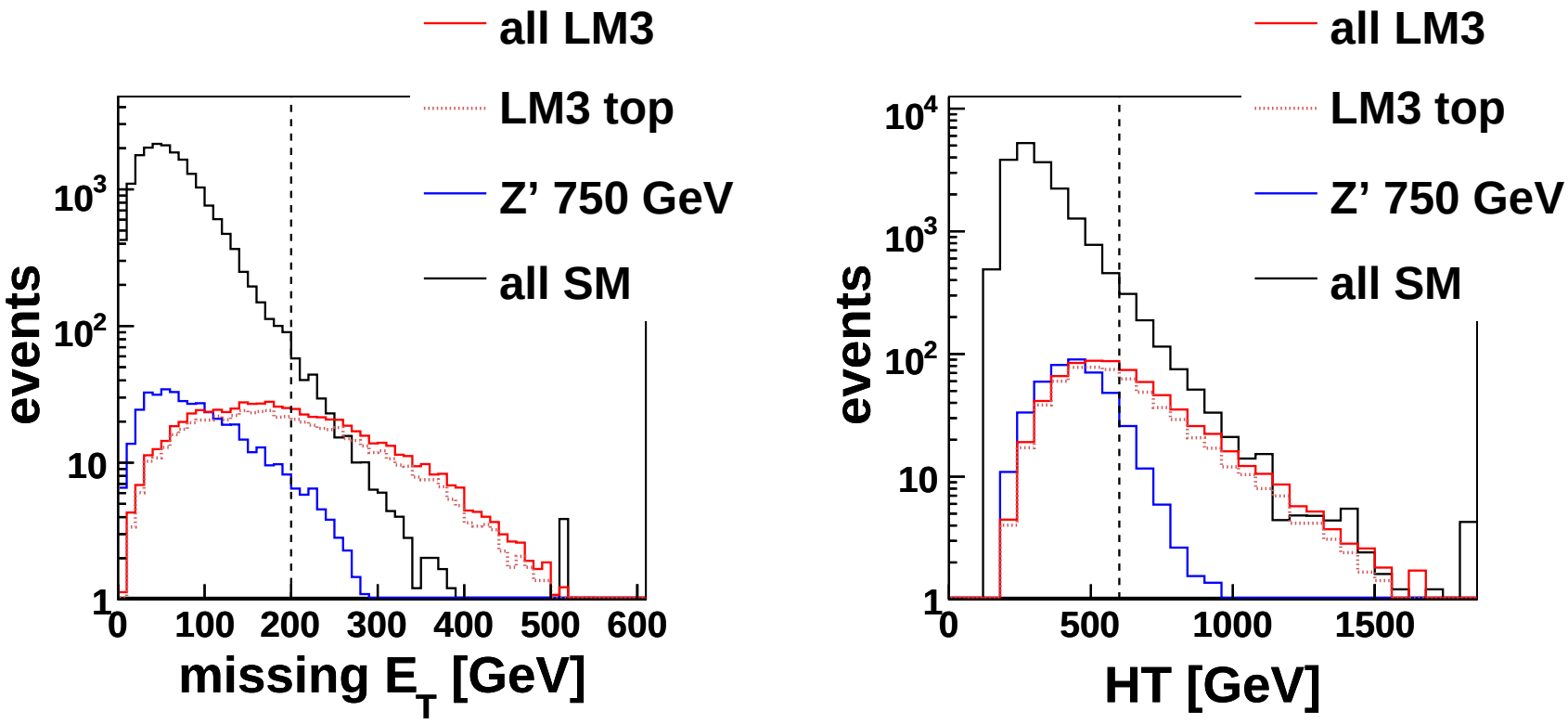


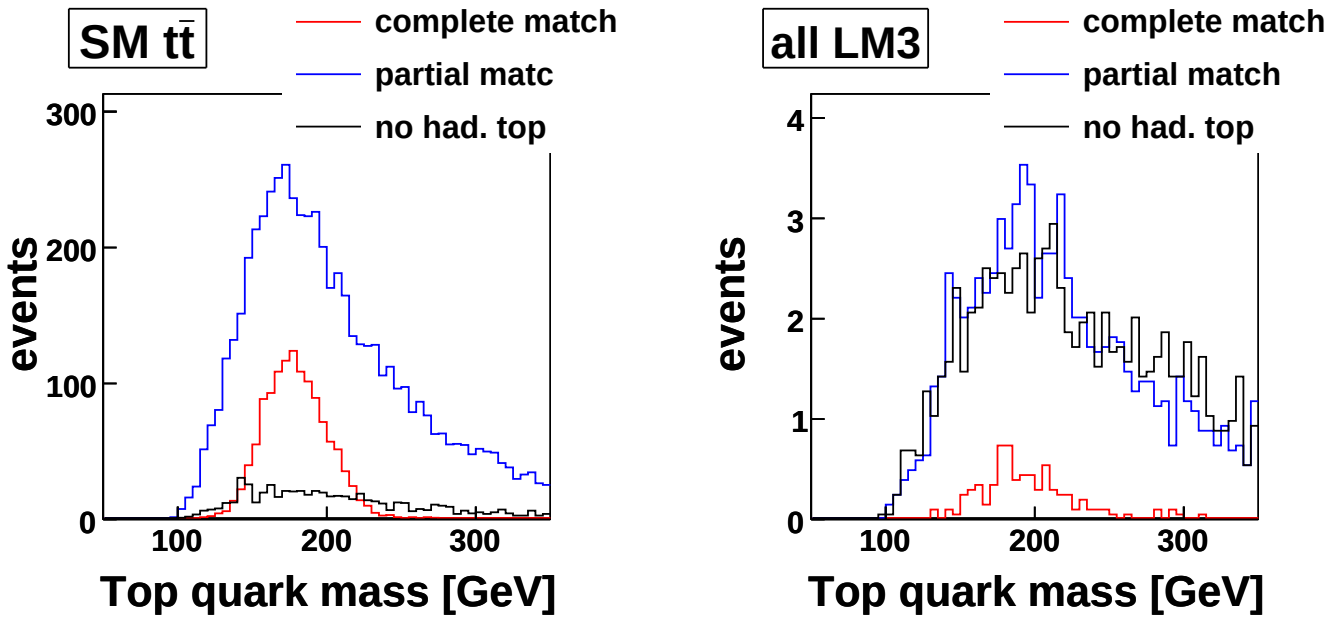
Figure: Missing E_T and $\mathrm{HT} = \sum_i^4 E_T(\mathrm{jet}_i)$ for a center of mass energy of $\sqrt{s} = 10$ TeV and an integrated luminosity of $L = 1$ fb^{-1}. The distributions are stacked.

- Signatures of mSUGRA LM3 is quantified by the significance $S = \frac{N_{\mathrm{BSM}}}{\sqrt{N_{\mathrm{BSM}}+N_{\mathrm{SM}}}}$.

variable	cut value	S of LM3	cut value	S of Z' 750 GeV
E_T^{miss}	200	13.50	0	3.21
HT	540	10.02	480	4.44
MT	810	11.04	540	4.82
N_{jets}	6	7.66	0	3.21
N_{leptons}	2	5.24	0	3.21

Table: Sensitivity of variables to differences between the SM, the mSUGRA LM3 scenario and the considerd a Z' model for a center of mass energy of $\sqrt{s} = 10$ TeV and an integrated luminosity of $L = 1$ fb^{-1}. For each variable the cut value that results in the largest significance S is calculated.

- Just a few $t\bar{t}$ events among the selected LM3 events, but 86% of the selected LM3 events contain at least one top quark.
  - Reconstruction of one top quark might allow to distinguish between mSUGRA scenarios like LM3 and LM8 and other mSUGRA scenarios,
  - Simple kinematic method turns out to be difficult due to the large jet multiplicity



Reconstruction of neutral heavy resonances

Kinematic Fit:

- 'Input':
  Leading four jets,
  leading isolated muon,
  E_T^{miss} as start-value for p^{μ}
- Constraints: Masses of W^+, W^-, t, $\bar{t}$
- χ^2-probability > 0.05
- Provides better results than the geometric method used

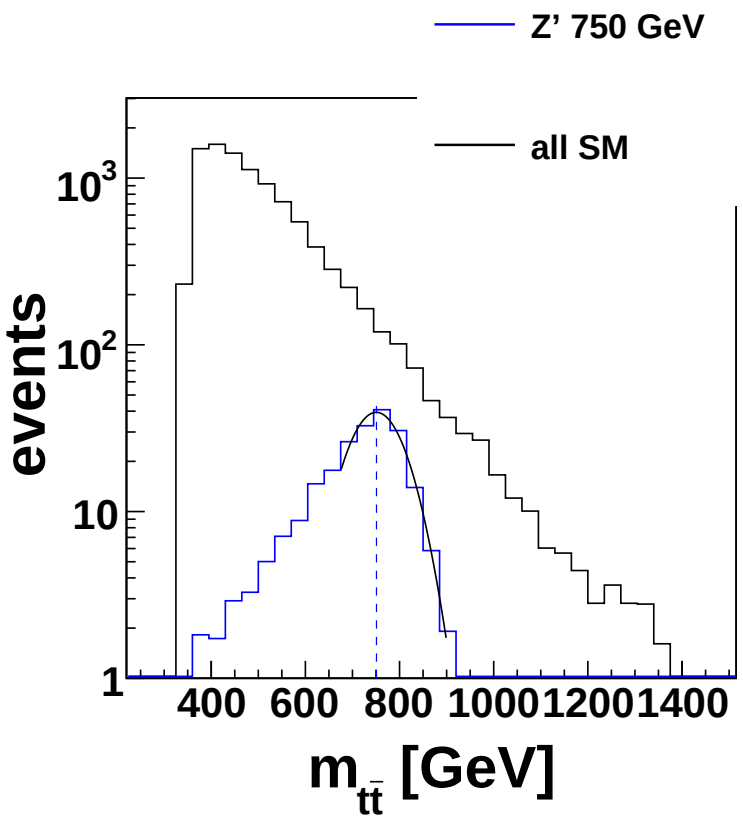


Figure: Invariant $t\bar{t}$ mass reconstructed with the kinematic fit after the event selection.

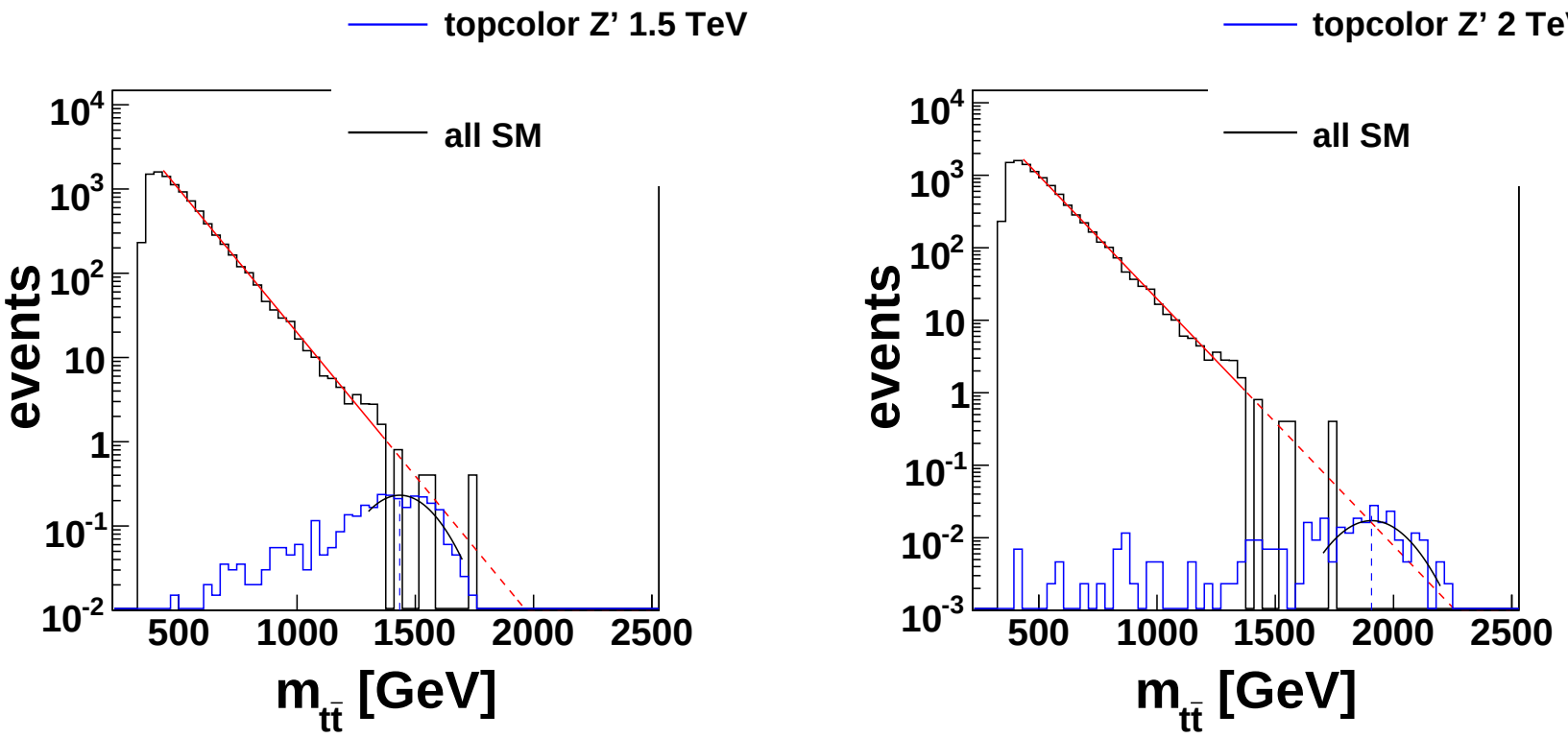


Figure: Invariant $t\bar{t}$ mass reconstructed with the kinematic fit for a center of mass energy of $\sqrt{s} = 10$ TeV and an integrated luminosity of $L = 1$ fb^{-1} after the event selection.

- Signatures of Z' models is quantified by the significance $S = \frac{N_{Z'}}{\sqrt{N_{BSM}+N_{Z'}}}$.

model		significance	signal-over-background
topcolor Z'	750 GeV	4.95	0.13
Z'	1000 GeV	2.62	0.26
Z'	1250 GeV	1.19	0.29
Z'	1500 GeV	0.62	0.21
Z'	2000 GeV	0.16	0.49
RS KK-gluon	1000 GeV	9.13 ± 0.44	1.17 ± 0.08
	1500 GeV	2.96 ± 0.05	1.39 ± 0.03
	2000 GeV	0.69 ± 0.03	3.69 ± 0.69

Table: Significance and signal-over-background ratio for the considered topcolor and RS models after the event selection for a center of mass energy of $\sqrt{s} = 10$ TeV and an integrated luminosity of $L = 1$ fb^{-1}.

Data-driven extension

- The only fundamental difference between top quarks pairs originating from a Z' decay and those produced in the SM is the production mechanism:

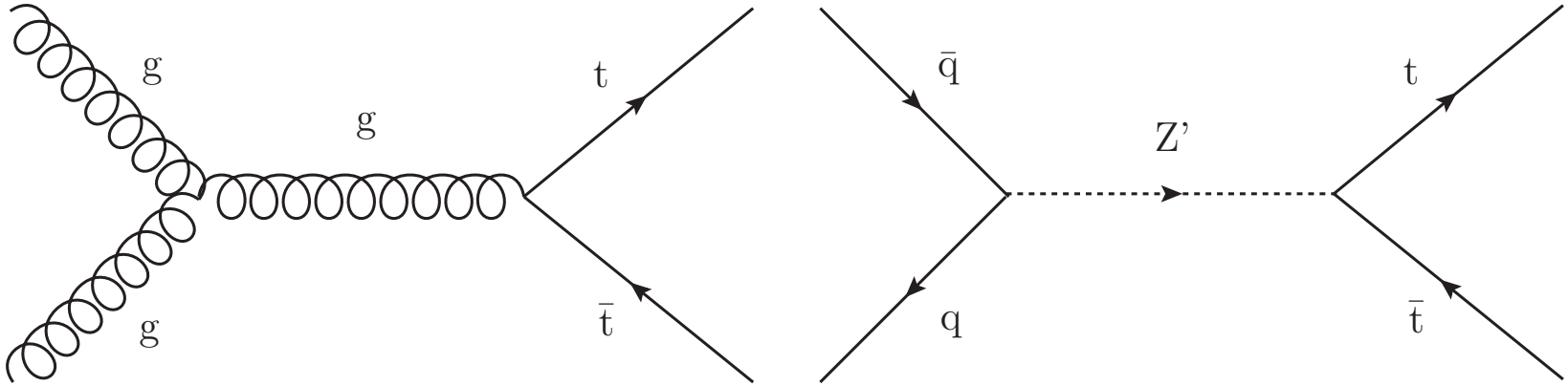


Figure: Feynman-diagram for the main process of top quark pair production in the SM (left) and from the decay of the considered Z' (right).

- Partonic center of mass energy in both processes:
  $\hat{s} = x_1 x_2 s$ with the center of mass energy $\sqrt{s}$ and the parton momentum fractions x_1 and x_2
- A given invariant mass does contrain $x_1 \cdot x_2$, but not $\frac{x_1}{x_2}$
- x_1 and x_2 might be likely to be more different in one of the both processes than in the other
- Parton momentum fractions are given by
  - $x_1 = \frac{m_T}{\sqrt{s}}(\exp(+y_t) + \exp(+y_{\bar{t}}))$,
  - $x_2 = \frac{m_T}{\sqrt{s}}(\exp(-y_t) + \exp(-y_{\bar{t}}))$.

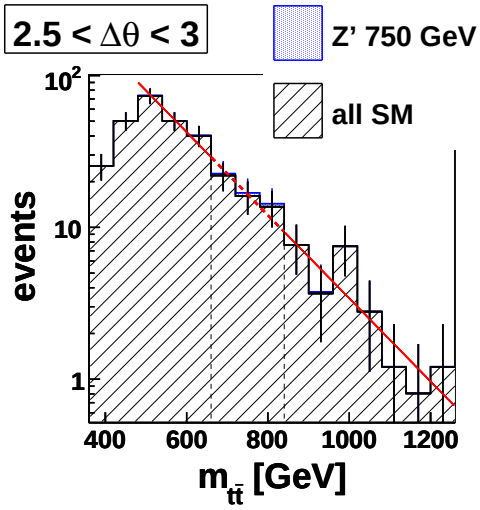
$\Longrightarrow$ Variables directly connected to the ratio $\frac{x_1}{x_2}$

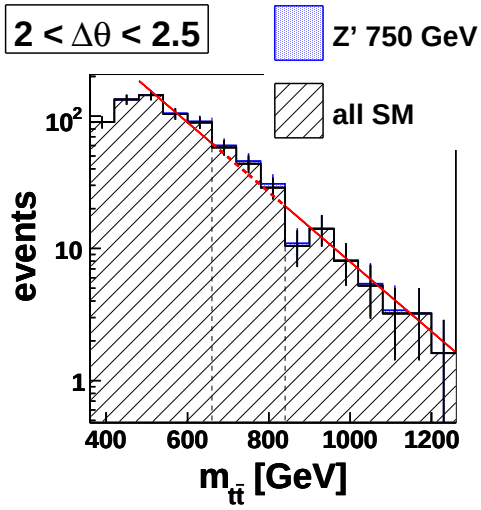
- might be sensitive to differences in the production mechanisms,
- are not correlated to the invariant$t\bar{t}$ mass.

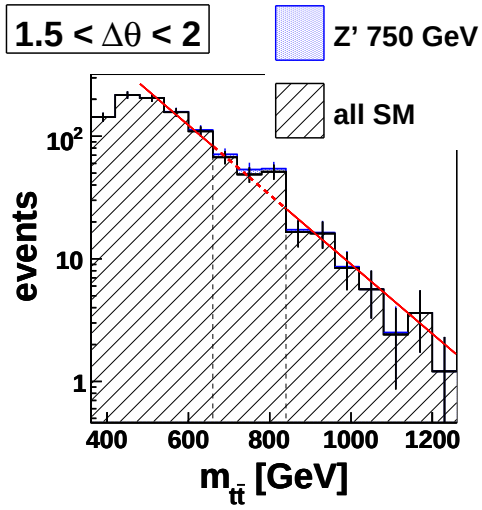
- Consider $\theta_{t\bar{t}} = |\theta_t - \theta_{\bar{t}}|$, $\Delta y = |y_t - y_{\bar{t}}|$ and $Y = |y_t + y_{\bar{t}}|$ in bins of the reconstructed $t\bar{t}$ mass
  - Applying a cut on $\theta_{t\bar{t}} \leq 1.5$ or $\Delta y \leq 1.5$ increases the significance
  - Among $\theta_{t\bar{t}}$, Δy and Y, the latter seems to be most independent from the invariant $t\bar{t}$

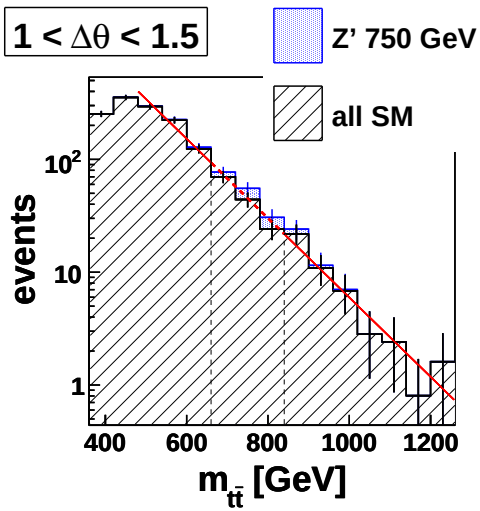
- Consider the distribution of the reconstructed invariant $t\bar{t}$ mass in bins of $\theta_{t\bar{t}} = |\theta_t - \theta_{\bar{t}}|$, $\Delta y = |y_t - y_{\bar{t}}|$ and $Y = |y_t + y_{\bar{t}}|$
  - $\theta_{t\bar{t}}$ is most suggestive for a data-drive extension of a Z' search

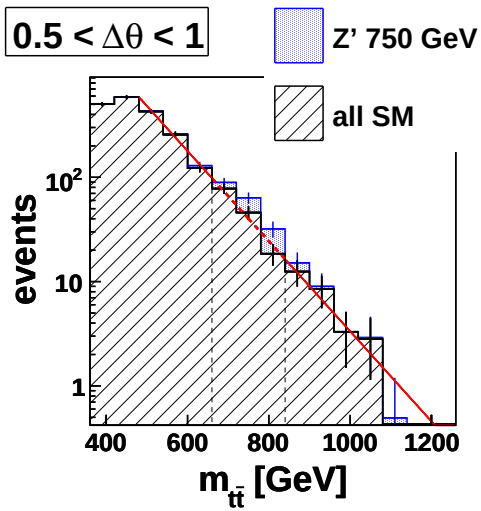
$\Longrightarrow$ Consider the distribution of the reconstructed invariant $t\bar{t}$ mass in different bins of $\theta_{t\bar{t}}$ and extract the background from two control regions in the signal region

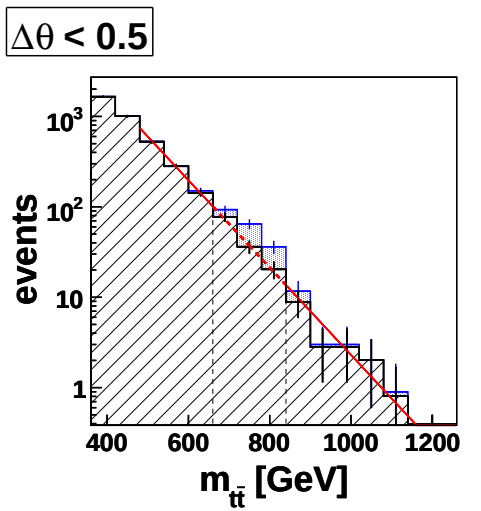

2.5 < Δθ < 3
Z' 750 GeV
all SM
events
$m_{t\bar{t}}$ [GeV]


2 < Δθ < 2.5
Z' 750 GeV
all SM
events
$m_{t\bar{t}}$ [GeV]


1.5 < Δθ < 2
Z' 750 GeV
all SM
events
$m_{t\bar{t}}$ [GeV]


1 < Δθ < 1.5
Z' 750 GeV
all SM
events
$m_{t\bar{t}}$ [GeV]


0.5 < Δθ < 1
Z' 750 GeV
all SM
events
$m_{t\bar{t}}$ [GeV]


Δθ < 0.5
events
$m_{t\bar{t}}$ [GeV]

bin	$\theta_{t\bar{t}}$	$N_{\text{background}}$	N_{expected}	N_{signal}	N_{excess}
1	0.0 - 0.5	134 ± 12	131 ± 9	61 ± 8	$64 + 17(-16)$
2	0.5 - 1.0	142 ± 12	137 ± 10	43 ± 7	$48 + 17(-16)$
3	1.0 - 1.5	138 ± 12	$147 + 12(-11)$	25 ± 5	$10 + 17(-15)$
4	1.5 - 2.0	167 ± 12	147 ± 12	12 ± 3	$2 + 16(-15)$
5	2.0 - 2,5	131 ± 11	$114 + 11(-10)$	6 ± 3	$5 + 14(-13)$
6	2.5 - 3.0	52 ± 7	$60 + 8(-7)$	2 ± 1	$1 + 9(-8)$

Table: Number of observed and expected background events, signal events and excess in the signal region after the event selection for a center of mass energy of $\sqrt{s} = 10$ TeV and an integrated luminosity of $L = 1$ fb^{-1}

Data-driven extension is

- More independent of simulated data, but
- Results in a lower siginificance and
- Depends on the production mechansim of the Z', which depends on the Z' model

Summary and outlook

- Event Selection and reconstruction with a kinematic fit results in a signal-over-background ratio of $R = \frac{N_{\text{all SM}}}{N_{\text{BSM}}} = 3.95$ and would allow to perform further studies of top quarks in the SM
- Scenarios like mSUGRA LM3 may already be observed after a standard selection for events containing a semi-leptonically decaying $t\bar{t}$ pair with a muon in the final-state
- A model-independet search for mSUGRA LM3 and neutral heavy resonances turns out to be difficult due to the small number of selected $t\bar{t}$ events in mSUGRA.

- The reconstruction of one top quark in mSUGRA might allow to distinguish between different types of mSUGRA scenarios, but turns out to be difficult due to the large jet multiplicity. (Rather than the number of reconstructed top quarks the multiplicity of b-jets might allow to distinguish between scenarios.)

- Neutral heavy resonances may be reonstructed with a kinematic fit up to masses of $m_{Z'} = 1.5$ TeV

- The topcolor Z' with $m_{Z'} = 750$ GeV and the RS KK-gluon $m_{KK} = 1$ TeV may be observed at CMS. Neutral heavy resonances with higher masses might be observed after a larger integrated luminosity.