FCC-ee/TLEP Physics Workshop (TLEP7)
CERN, 19-21 June 2014

Rare top decays at TLEP

(~10 ^{6} ttbar at threshold + ~10 ab $^{-1}$ at 240 GeV)

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19 June 2014

Outline :

- **“inclusive” approach to rare top (exotic) decays:**
  a) study of top recoil system in top pairs
  b) excess in top total width

hard to conceive at hadronic colliders !

- **“exclusive” approach to rare top decays:**
  a) “measurable” SM rare top decays
  b) rare top decays measurable only in BSM

- **$e^+e^- \rightarrow t\,q$ (FCNC) at TLEP 240**

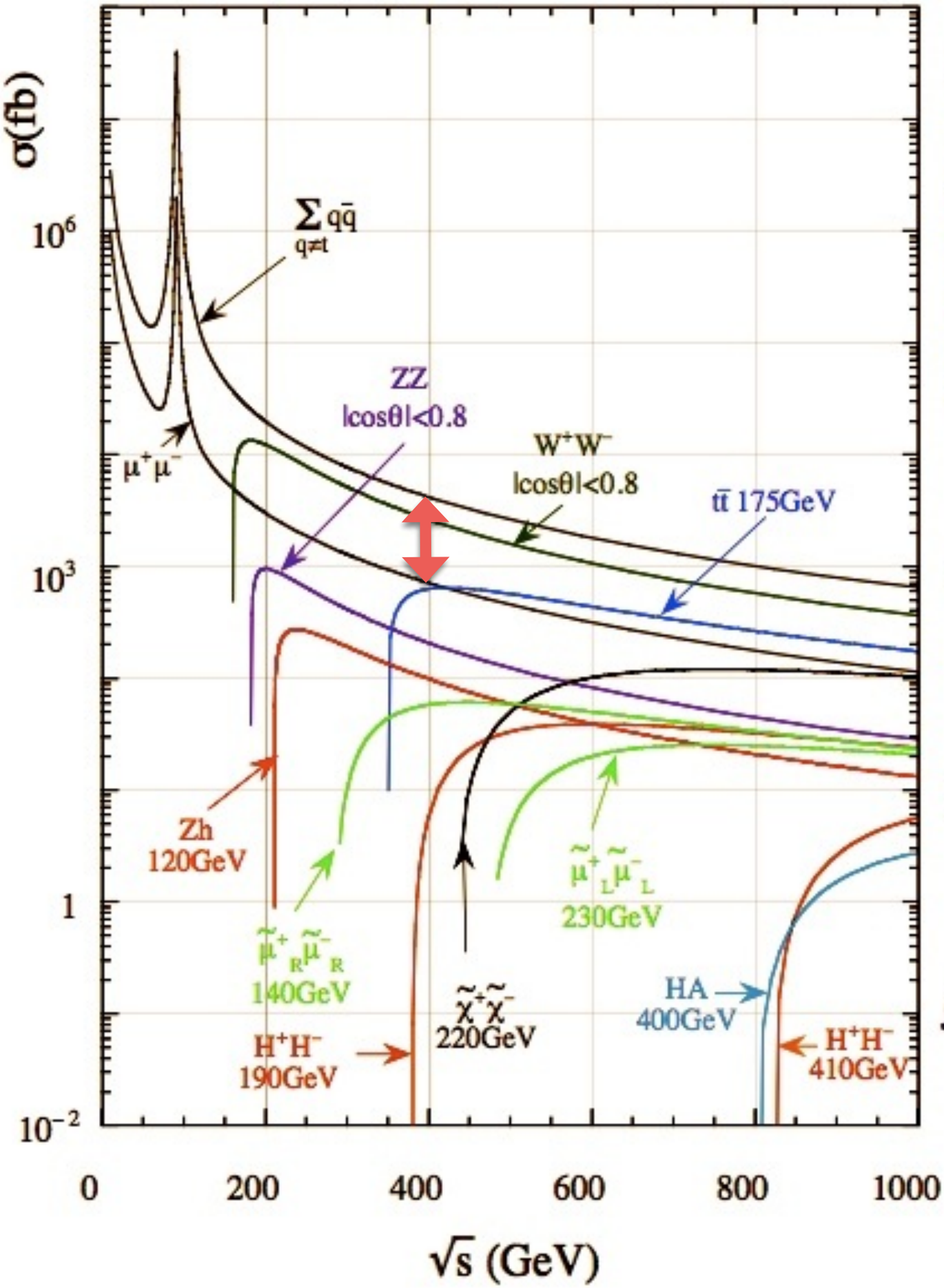
mainly a few thoughts not an exhaustive review !

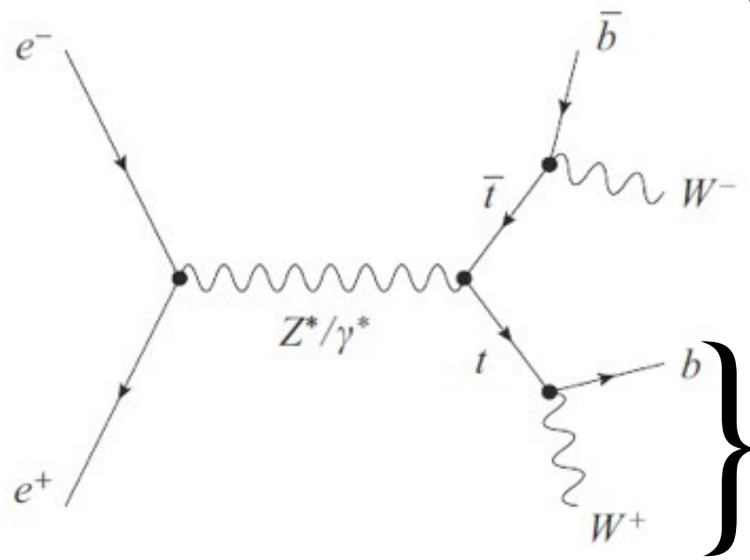
Main References

- **TLEP Physics Case arxiv:1308.6176; TLEPnth Workshop material, ILC TDR ’13**
- **Snowmass Studies 2013 (arxiv:1307.8265,1311.2028)**
- **AWLC14, Fermilab, 12-16 May 2014 http://www.linearcollider.org/awlc14/**

what makes unique e^+e^- environment wrt (larger N_{ev}) had collisions :

- democracy in σ's (all EW σ's !)
- accurate TH predictions
- clean EXP environment
- untriggered operation
- can detect and reconstruct "any" hadronic final state
- can detect what is invisible at LHC just because we do not know what to trigger on …

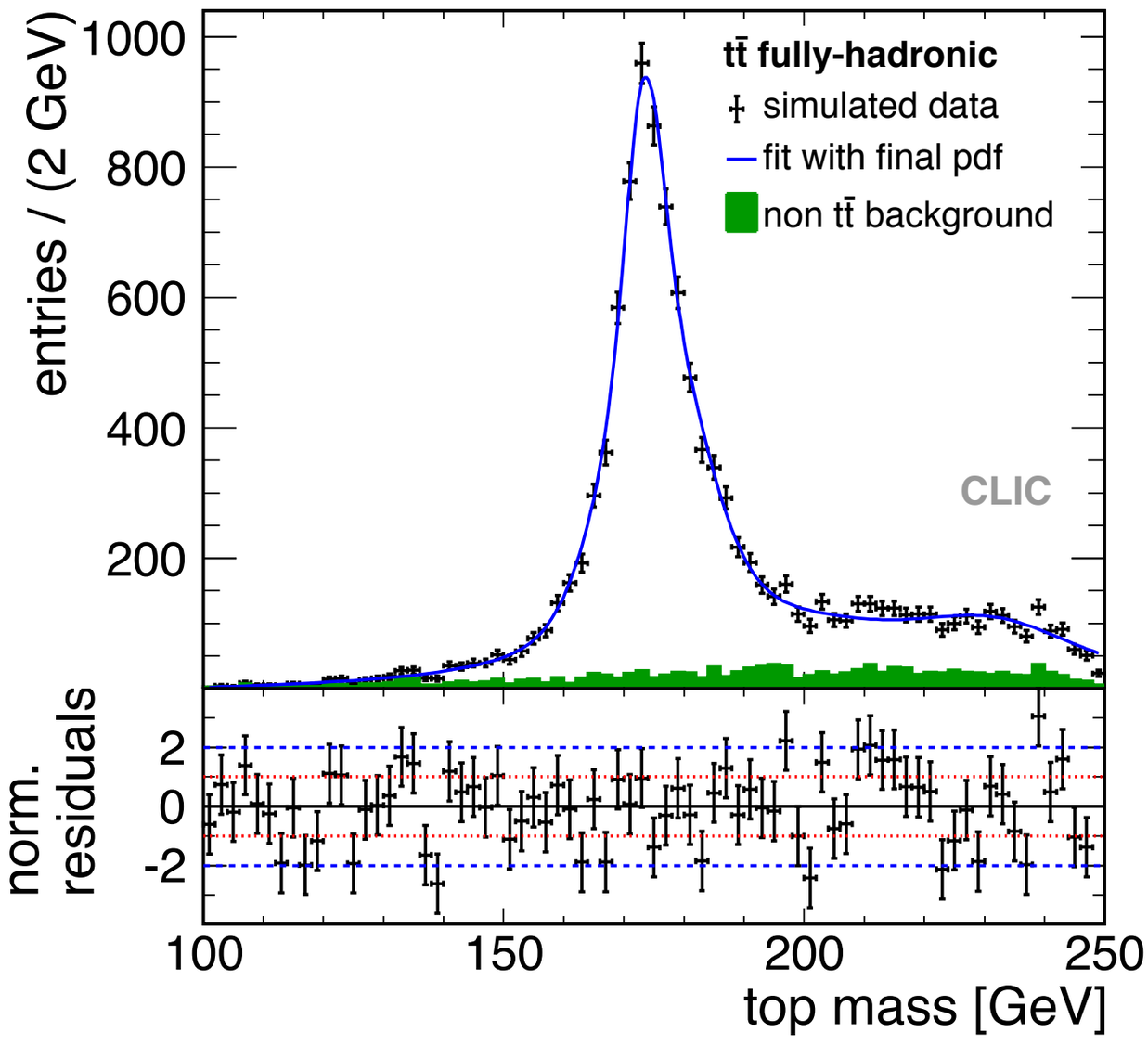


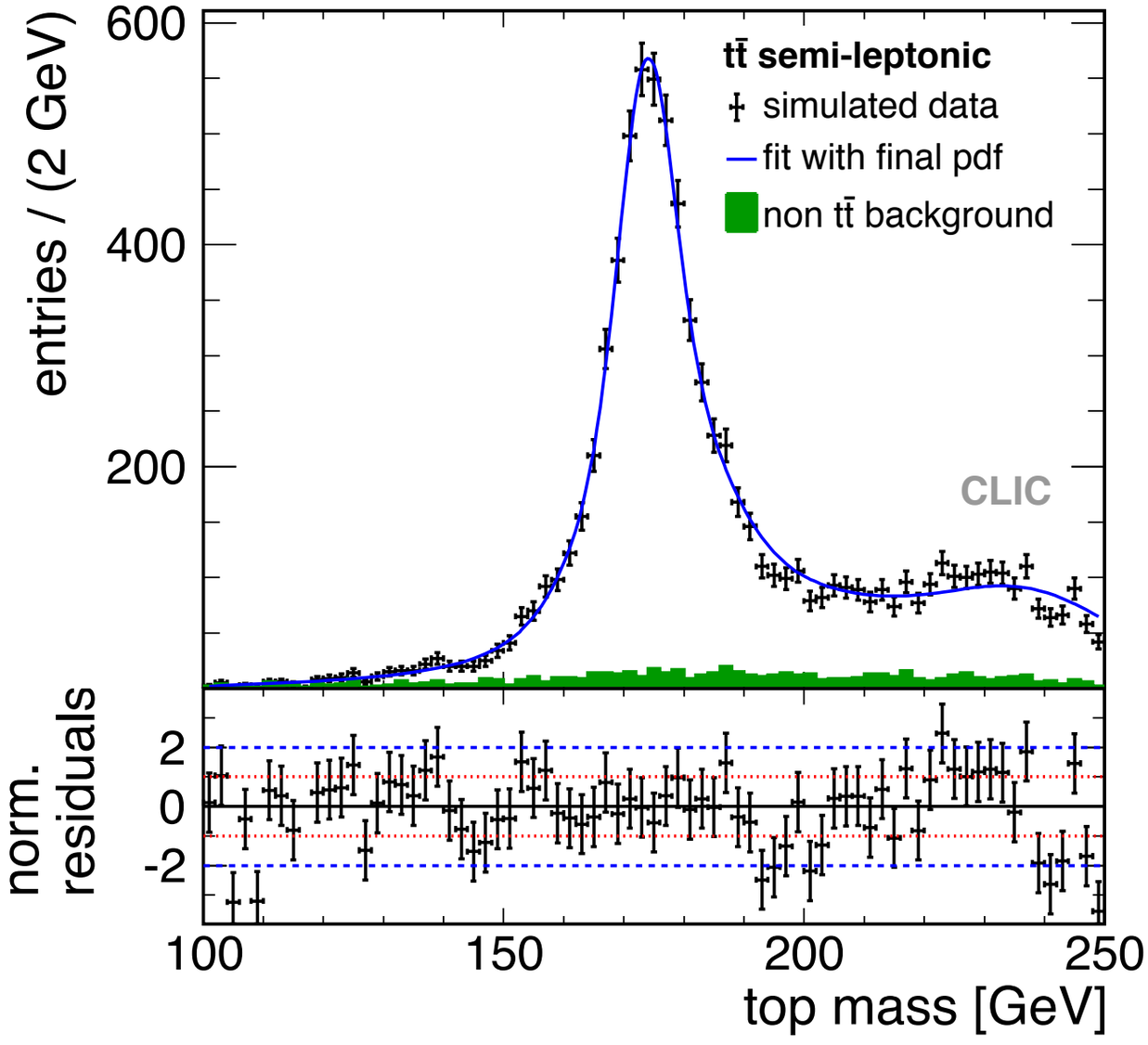


ttbar physics cleanness in e^+e^- collisions well represented by plots below (**green is background !**)

fully hadronic and semi-leptonic top mass reconstruction

Seidel et al. 1303.3758





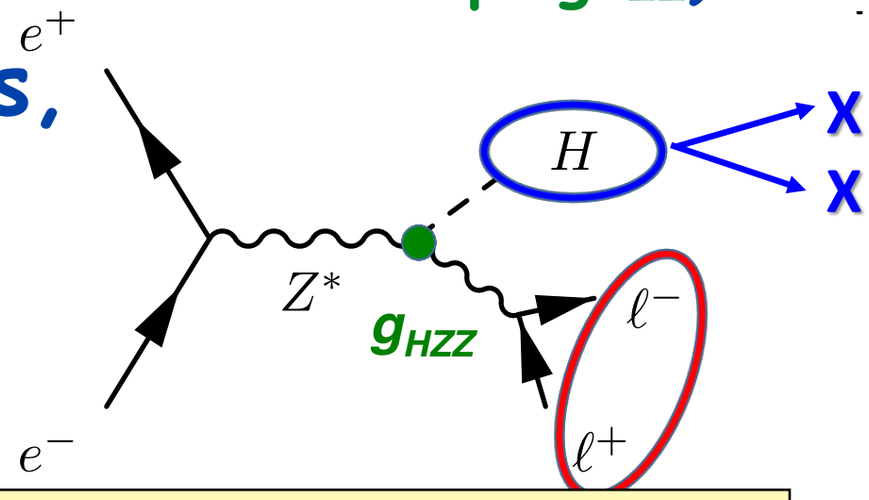
inclusive Higgs studies through Z recoil system

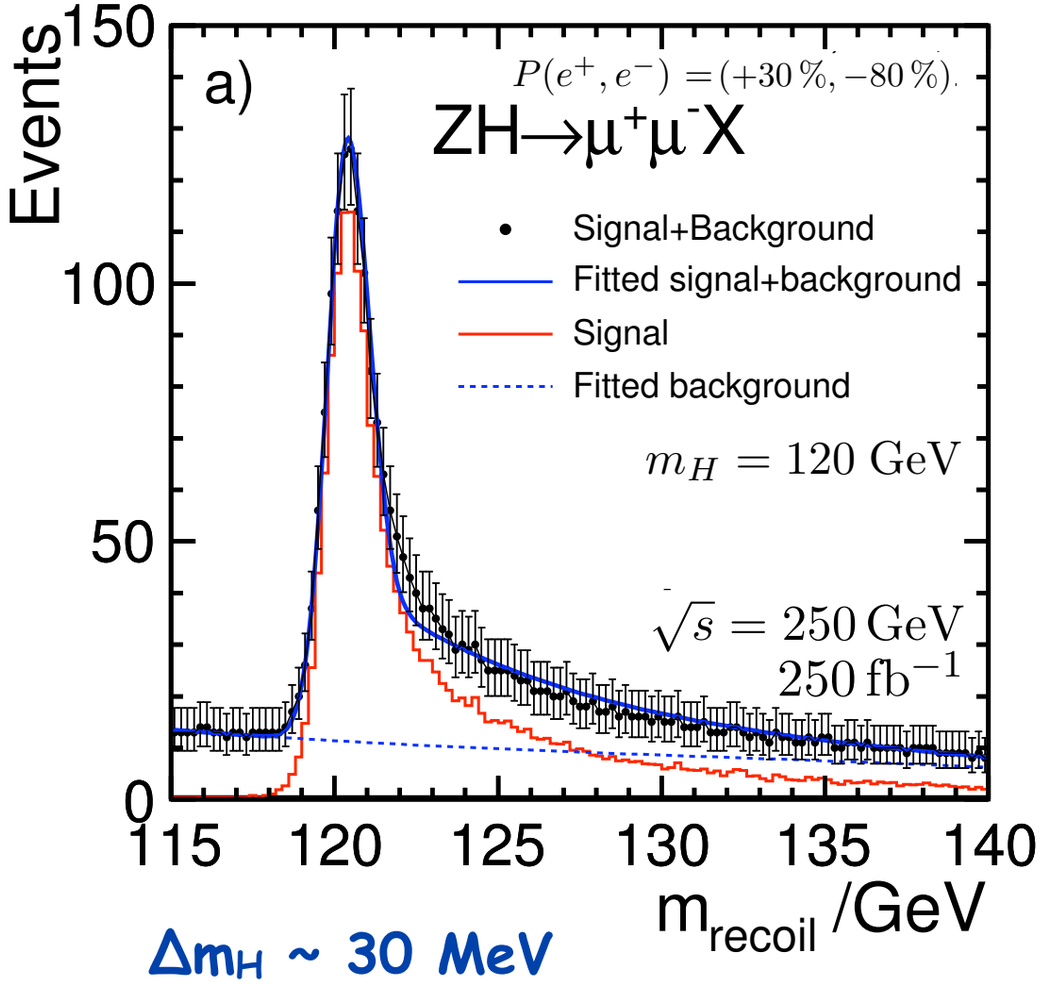
- HZ selected by just identifying Z decay products

  (→ absolute σ_{tot} (~g_{HZZ}^2) measurement → model indep. g_{HZZ})

- → direct access to **invisible** H decays, and **invisible-at-LHC** decays

  (H → cc, H → gg)





Δm_H ~ 30 MeV

could we extend this technique to top pairs in $e^+e^- \to t\bar{t}$ and make inclusive searches for exotic top final states by looking at recoil top system ?

heavy top mass allows decays into new BSM states

examples :

$$t \to H^+ b \to \tau \nu b$$

$$t \to H^+ s \to c \bar{s} s$$

still allowed beyond 2HDM type II

$t \to Z' c, Z' u$ (light neutral gauge bosons)

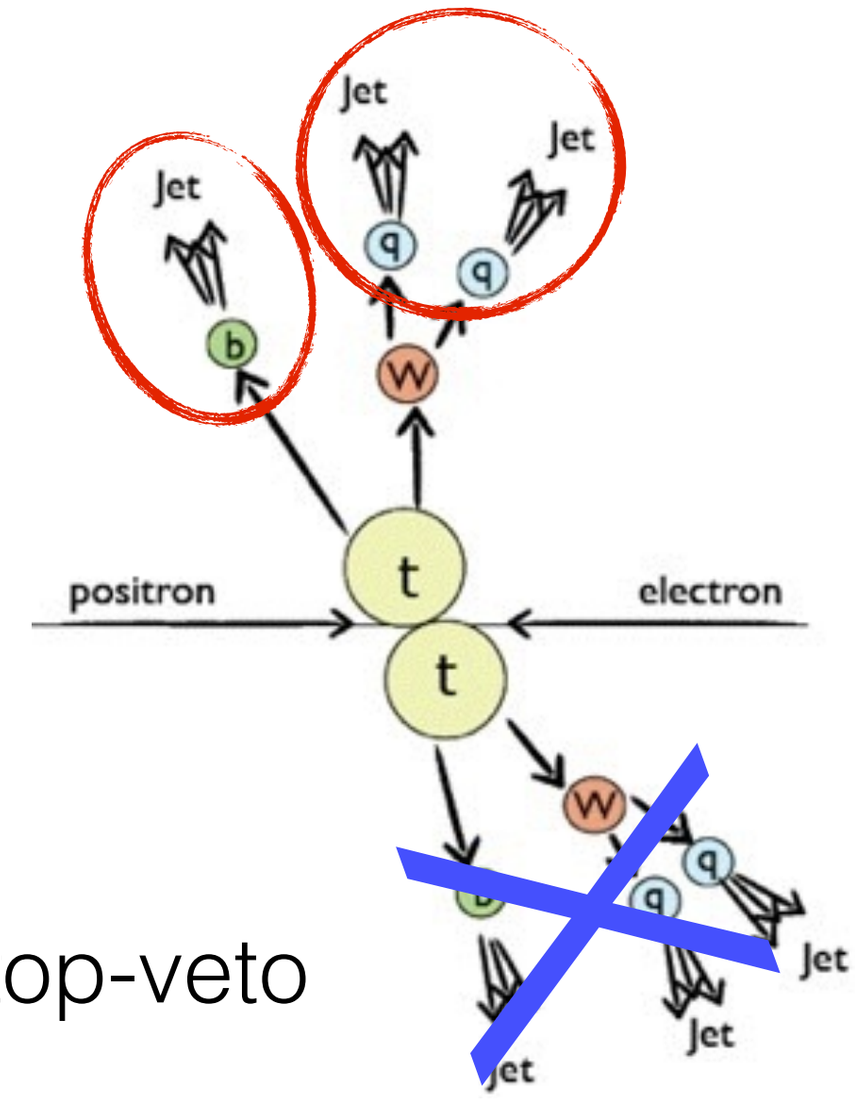
$t \to \chi\chi c, \quad \chi\chi u$ (dark matter)

$t \to n\ jets \neq bW \to bjj$ (???)

in principle one can have many different final states with unexpected kinematical features …
can't find them at LHC unless you make assumptions on what you are looking for !

inclusive searches for exotic t decays through recoil system (e^+e^-)

large variety
of possible final states
➜ global analysis of the
recoil system with a top-veto



top-veto

a) define criteria to tag
a Wb/Wj system
as a (SM) top quark

b) look for events containing
a top-system with
a veto on a 2nd tag
(i.e. recoil system does not
pass the SM top-system
criteria)

c) full simulation needed to
assess sensitivity (<% σ ?)

d) get model independent
bounds on $BR(top)_{exotica}$!

- E_{cm} > 350 GeV

inclusive approach to exotic top decays (b)

(excess in top total width)

bounds on $\delta\,\Gamma_{top}$ can bound exotic decay widths

SM:

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}|V_{tb}|^2\left(1-\frac{m_W^2}{m_t^2}\right)^2\left(1+2\frac{m_W^2}{m_t^2}\right)\left[1-\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3}-\frac{5}{2}\right)\right]$$

+ (b → s,d)

$$\Gamma_t = 1.33\ \text{GeV} \qquad (m_t = 172.5\text{GeV})$$

top width measurement at hadron colliders :

combine $\mathcal{R} = \mathcal{B}(\mathrm{t}\to\mathrm{Wb})/\mathcal{B}(\mathrm{t}\to\mathrm{Wq})$ with t-channel single top σ :

$$\Gamma_{\mathrm{t}} = \frac{\sigma_{t\text{-ch.}}}{\mathcal{B}(\mathrm{t}\to\mathrm{Wb})}\cdot\frac{\Gamma(\mathrm{t}\to\mathrm{Wb})}{\sigma^{\text{theor.}}_{t\text{-ch.}}}$$

assuming SM ($\sum_{\mathrm{q}}\mathcal{B}(\mathrm{t}\to\mathrm{Wq}) = 1$) :

CMS 1404.2292

→ $\Gamma_{\mathrm{t}} = 1.36 \pm 0.02\,(\text{stat.})^{+0.14}_{-0.11}\,(\text{syst.})\,\text{GeV}$

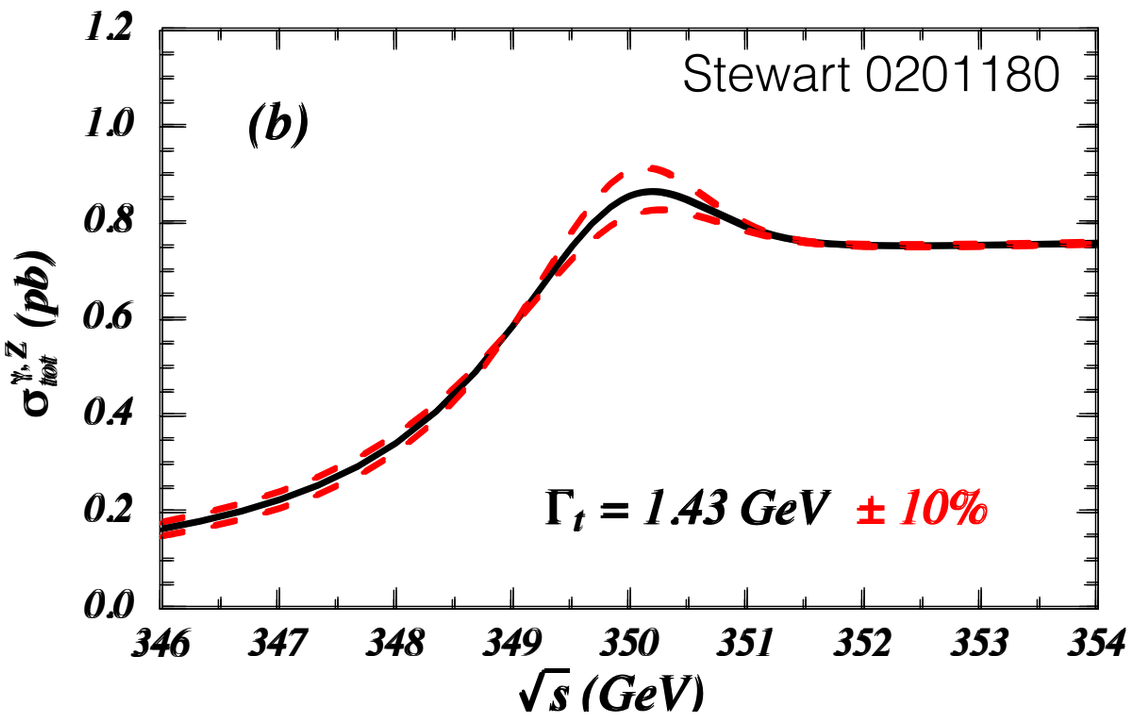
$\mathcal{R} = |V_{\mathrm{tb}}|^2$

$|V_{\mathrm{tb}}| = 1.007 \pm 0.016\,(\text{stat.+syst.})$

inclusive approach to exotic top decays (b)

(model independent) Γ_{top} measurement at 1% at TLEP

resonance cross section at threshold very sensitive to $\alpha_s,\ m_t,\ \Gamma_t$;
peak at $\sigma_{\rm res} \sim \alpha_s^3/(m_t\Gamma_t)$



	$m_{\rm top}$	$\Gamma_{\rm top}$	$\lambda_{\rm top}$
TLEP	**10 MeV**	**11 MeV**	**13%**
ILC	31 MeV	34 MeV	40%

Martinez, Miguel 0207315

- TLEP Physics Case arxiv:1308.6176

bounds on $\delta\Gamma_{top}$ can probe inclusively rare decays for $BR_{exotic} \geq$ few % at TLEP

exclusive approach :
a) measurable SM rare top decays

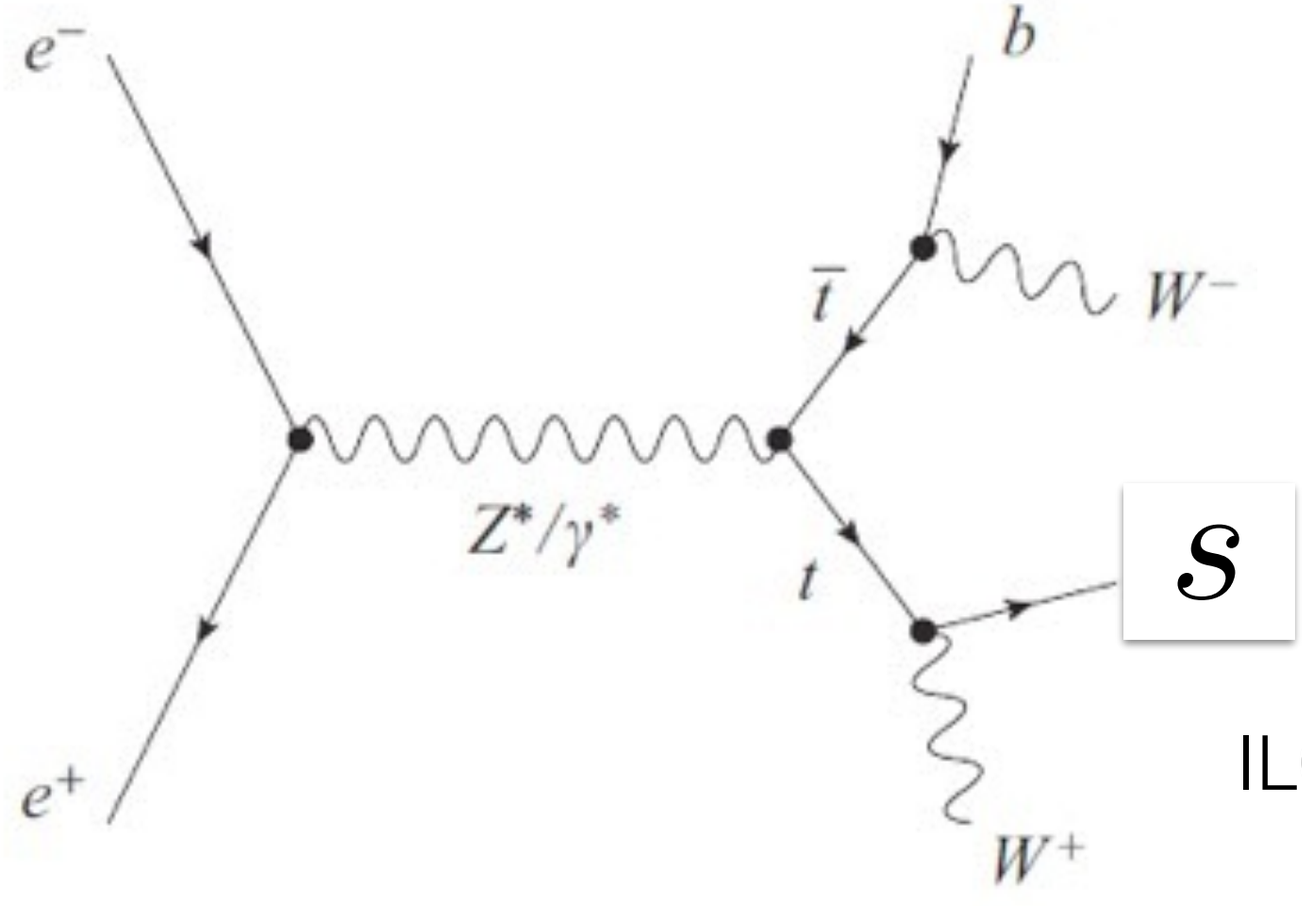
$$t \to s\, W$$

$BR(t \to s\, W) \sim 2 \times 10^{-3}$ direct observation of tsW coupl.

can also probe anomalous interac.s of type (b->s):

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + h.c.$$

needs discriminants to suppress dominant $t \to bW$



with 10^6 $\bar{t}t$ pairs

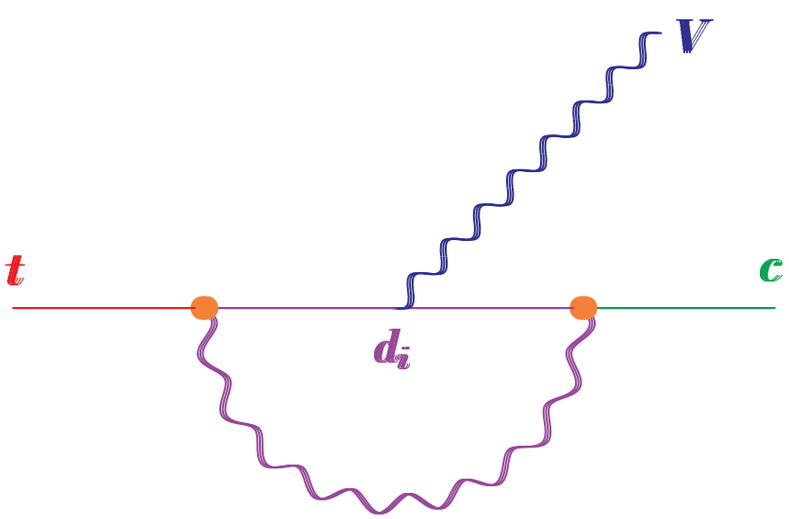
$\Rightarrow\ 4\ 10^3\ \ t \to sW$

ILC sensitive to $BR(t \to s\, W) \sim 10^{-3}$

(Diaz-Cruz et al 0712.3782)

exclusive approach :

b) rare top decays measurable only in BSM frameworks



FCNC top decays in the SM

GIM-suppressed by $(\frac{m_b}{M_W})^4$

$\mathrm{BR}(t \to c\gamma) \simeq 5 \times 10^{-14}$ $\quad$ $\mathrm{BR}(t \to u\gamma) \simeq 4 \times 10^{-16}$

$\mathrm{BR}(t \to cg) \simeq 5 \times 10^{-12}$ $\quad$ $\mathrm{BR}(t \to ug) \simeq 4 \times 10^{-14}$

$\mathrm{BR}(t \to cZ) \simeq 1 \times 10^{-14}$ $\quad$ $\mathrm{BR}(t \to uZ) \simeq 8 \times 10^{-17}$

$\mathrm{BR}(t \to ch) \simeq 3 \times 10^{-15}$ $\quad$ $\mathrm{BR}(t \to uh) \simeq 2 \times 10^{-17}$

$$(t \to ux)/(t \to cx) \simeq |V_{ub}/V_{cb}|^2 \simeq 0.008$$

(Aguilar-Saavedra hep-ph/0409342)

New Physics models can hugely enhance predictions !
Different models predict different pattern of enhancements

	2HDM	MSSM	RS
$t \to cZ$	$\lesssim 10^{-6}$	$\lesssim 10^{-7}$	$\lesssim 10^{-5}$
$t \to c\gamma$	$\lesssim 10^{-7}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$
$t \to cg$	$\lesssim 10^{-5}$	$\lesssim 10^{-7}$	$\lesssim 10^{-10}$
$t \to ch$	$\lesssim 10^{-2}$	$\lesssim 10^{-5}$	$\lesssim 10^{-4}$

Snowmass Top Quark Working Group Report 1311.2028

Present LHC bounds from $t\bar{t} \xrightarrow{\text{FCNC}} (Z/\gamma/g/h+j)(Wb)$
plus single-top anomalous production $qg \to t(Z/\gamma/H)$

Process	Br Limit	Search	Dataset
$t \to Zq$	5×10^{-4}	CMS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	19.7 fb^{-1}, 8 TeV
$t \to Zq$	7.3×10^{-3}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	2.1 fb^{-1}, 7 TeV
$t \to gu$	3.1×10^{-5}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV
$t \to gc$	1.6×10^{-4}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV
$t \to \gamma u$	1.6×10^{-4}	CMS $qg \to t\gamma \to Wb\gamma$	19.1 fb^{-1}, 8 TeV
$t \to \gamma c$	1.8×10^{-3}	CMS $qg \to t\gamma \to Wb\gamma$	19.1 fb^{-1}, 8 TeV
$t \to hq$	7.9×10^{-3}	ATLAS $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	20 fb^{-1}, 8 TeV
$t \to hq$	5.6×10^{-3}	CMS $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	19.5 fb^{-1}, 8 TeV

single-top production more sensitive to u-type vertex

most general effective Lagrangian for FC tqV(H) interactions with terms up to dim 5

$$
\begin{aligned}
-\mathcal{L}^{\text{eff}} = & \frac{g}{2c_W} X_{qt}\, \bar{q}\gamma_\mu(x_{qt}^L P_L + x_{qt}^R P_R) t Z^\mu + \frac{g}{2c_W} \kappa_{qt}\, \bar{q}(\kappa_{qt}^v + \kappa_{qt}^a\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t} t Z^\mu \\
& + e\lambda_{qt}\, \bar{q}(\lambda_{qt}^v + \lambda_{qt}^a\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t} t A^\mu + g_s\zeta_{qt}\, \bar{q}(\zeta_{tq}^v + \zeta_{qt}^a\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t} T^a q G^{a\mu} \\
& + \frac{g}{2\sqrt{2}} g_{qt}\, \bar{q}(g_{qt}^v + g_{qt}^a\gamma_5) t H + \text{H.c.}\,,
\end{aligned}
$$

$\sigma_{\mu\nu}$ terms grow with V^μ momentum q^{nu}

$$
\left.
\begin{aligned}
\text{Br}(t \to qZ)_\gamma &= 0.472\, X_{qt}^2\,, \\
\text{Br}(t \to qZ)_\sigma &= 0.367\, \kappa_{qt}^2\,,
\end{aligned}
\right\}
\quad > 5 \times 10^{-4} \Rightarrow X_{qt} < 0.033 \;\; \Rightarrow \kappa_{qt} < 0.037
$$

$$
\text{Br}(t \to q\gamma) = 0.428\, \lambda_{qt}^2\,, \qquad > 2 \times 10^{-3} \Rightarrow \lambda_{qt} < 0.065
$$

$$
\text{Br}(t \to qg) = 7.93\, \zeta_{qt}^2\,, \qquad > 2 \times 10^{-4}
$$

$$
\text{Br}(t \to qH) = 3.88 \times 10^{-2}\, g_{qt}^2 > 6 \times 10^{-3}
$$

LHC

(Aguilar-Saavedra hep-ph/0409342)

bounds on tqZ and $tq\gamma$

ILC versus full LHC

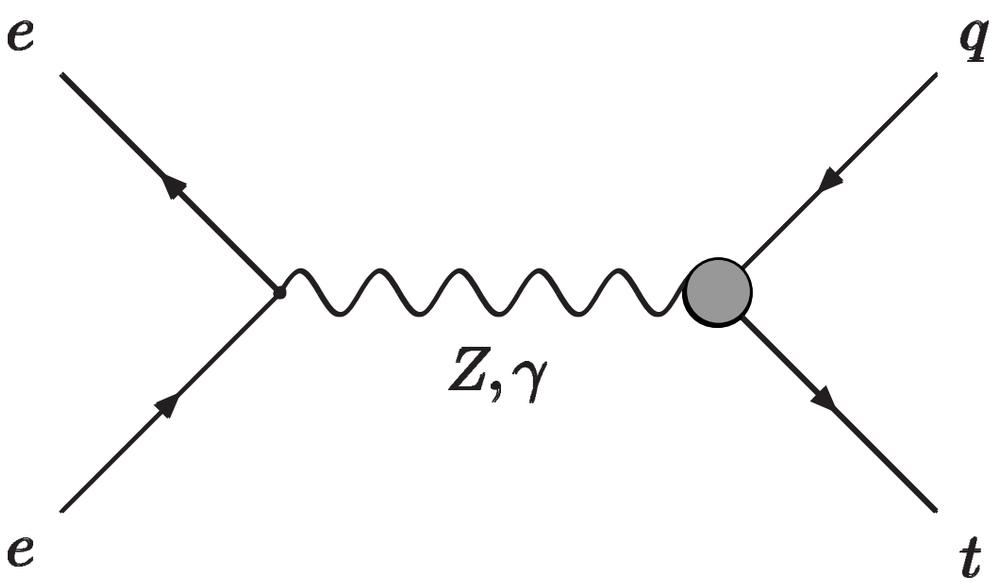
Process	Br Limit	Search	Dataset
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV
$t \to Zq$	$5\,(2) \times 10^{-4}$ *	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 250 GeV
$t \to Zq$	$1.5\,(1.1) \times 10^{-4\,(-5)}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV
$t \to Zq$	$1.6\,(1.7) \times 10^{-3}$	ILC $t\bar{t}$, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV
$t \to \gamma q$	8×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	300 fb^{-1}, 14 TeV
$t \to \gamma q$	2.5×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	3000 fb^{-1}, 14 TeV
$t \to \gamma q$	6×10^{-5} *	ILC single top	500 fb^{-1}, 250 GeV
$t \to \gamma q$	6.4×10^{-6}	ILC single top	500 fb^{-1}, 500 GeV
$t \to \gamma q$	1.0×10^{-4}	ILC $t\bar{t}$	500 fb^{-1}, 500 GeV

$\sigma_{\mu\nu}$ terms grow with V^μ momentum q^{mu} * extrapolated

$\Rightarrow$ $e^+e^- \to \gamma, Z(q^\mu) \to tq$ at ILC, most sensitive one!

TLEP studies for FCNC single top in progress →

$$e^+e^- \to \gamma, Z(q^\mu) \to tq$$



Han and Hewett 9811237

Bar-Shalom, Wudka 9905407

Aguilar-Saavedra, Riemann 0102197

(at LEP2 and ILC)

main background from W j j

E= 240 GeV ***(max cross section and large lumi at TLEP)***

versus

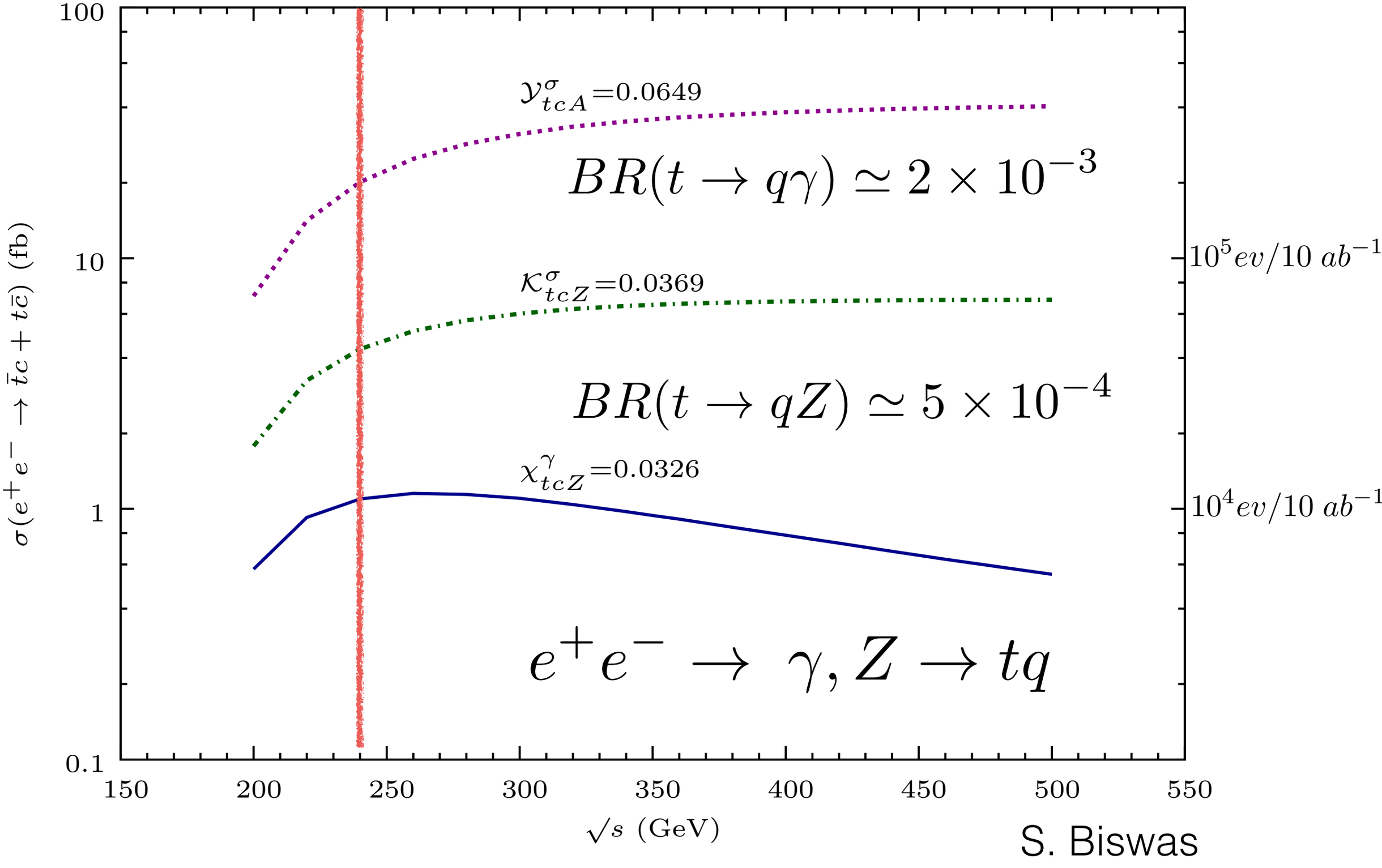
E= 500 GeV **(lower bckgd and more sensitive to $\sigma_{\mu\nu}$ terms)**

$$-\mathcal{L} = \frac{g_W}{2c_W} X_{tq}\, \bar{t}\gamma_\mu (x_{tq}^L P_L + x_{tq}^R P_R) q Z^\mu + \frac{g_W}{2c_W}\, \kappa_{tq}\, \bar{t}(\kappa_{tq}^v - \kappa_{tq}^a \gamma_5) \frac{i\sigma_{\mu\nu} q^\nu}{m_t} q Z^\mu$$
$$+ e\, \lambda_{tq}\, \bar{t}(\lambda_{tq}^v - \lambda_{tq}^a \gamma_5) \frac{i\sigma_{\mu\nu} q^\nu}{m_t} q A^\mu \,,$$

Updated analysis at TLEP 240 in progress

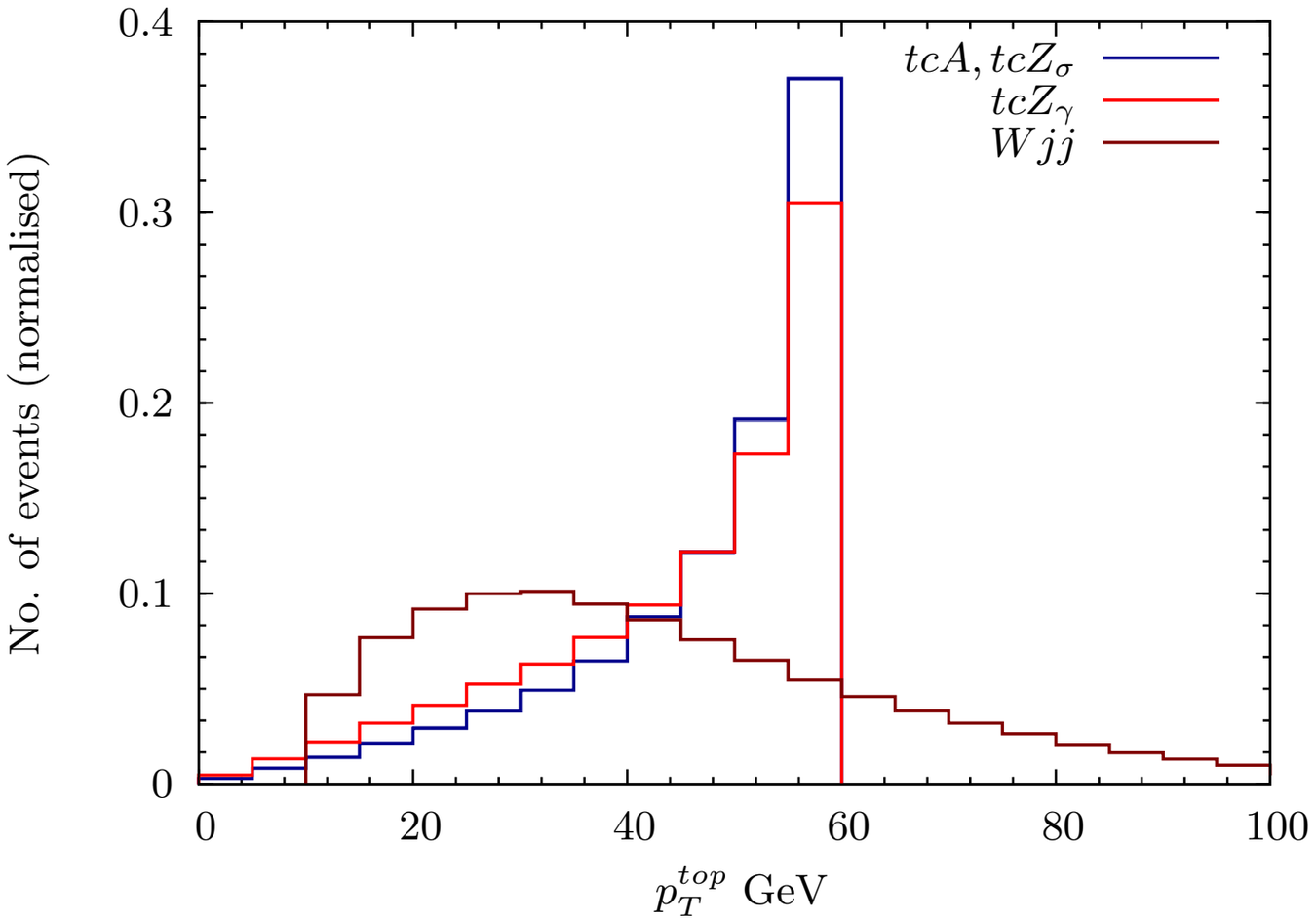
(Azzi, Biswas, Margaroli, BM)

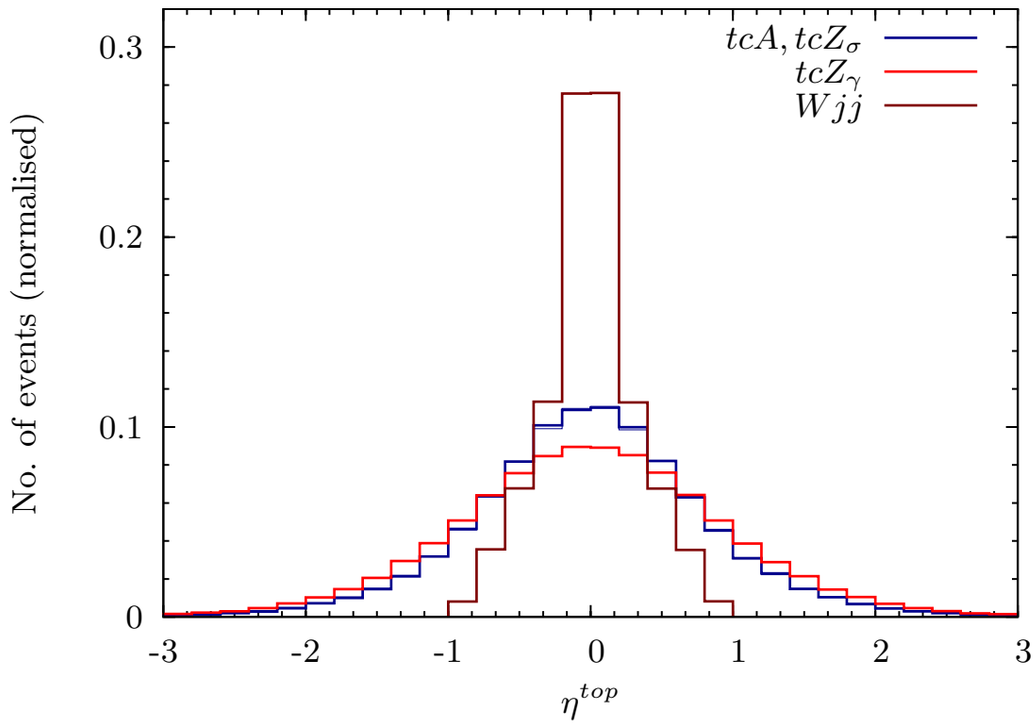
maximum allowed σ's by presents bounds on BR(top)^{FCNC}

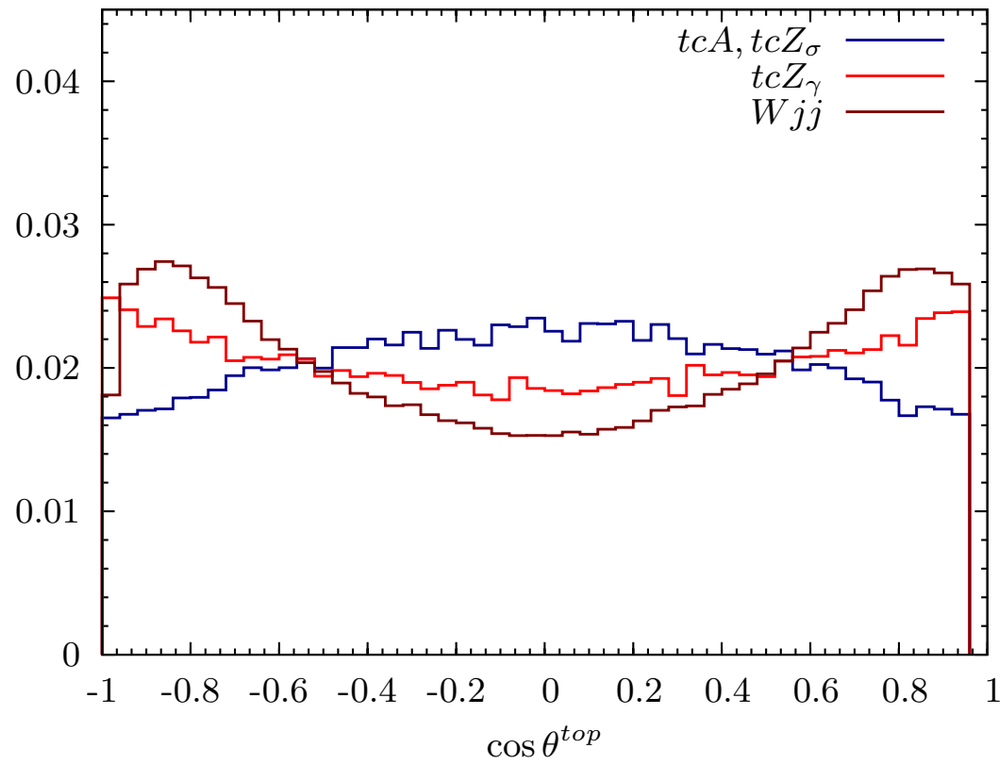


S. Biswas

signal vs Wjj bckgr : normalized distributions





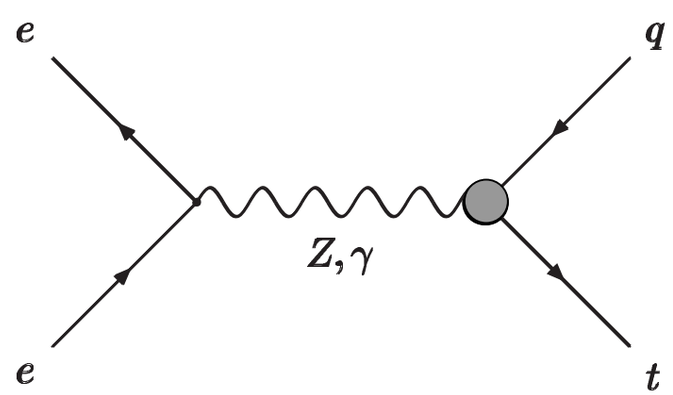


$\sqrt{S} = 240GeV$

Madgraph5

$p_T^j > 10GeV$

$\Delta R(jj) > 0.4$



disentangling photon from Z vertex can require looking at top FCNC decays at tt threshold

S. Biswas

Outlook

- ever since its discovery, the top quark has never been produced and studied in such a clean environment as the one expected in e^+e^- collisions

- e^+e^- collisions will almost allow to trace back top-quark final states on an event-by-event basis

- this will open the opportunity to look at details of top production and kinematics that is unthinkable in hadron collisions
(relevant strategies mostly still to be developed …)

- rare top decays is one of the (many) top physics chapters that would widely benefit from such spectacularly clean environment