ENP Collaboration Meeting,
INFN, Roma1, 19 May 2025

Bounding exotic top decays inclusively at FCC-ee (via ~10 ^{6} t tbar)

Barbara Mele (INFN Roma 1)

with G. Corcella and D. Sengupta

a few thoughts …
not an exhaustive discussion !

heavy top mass allows decays into new BSM states

just few 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)

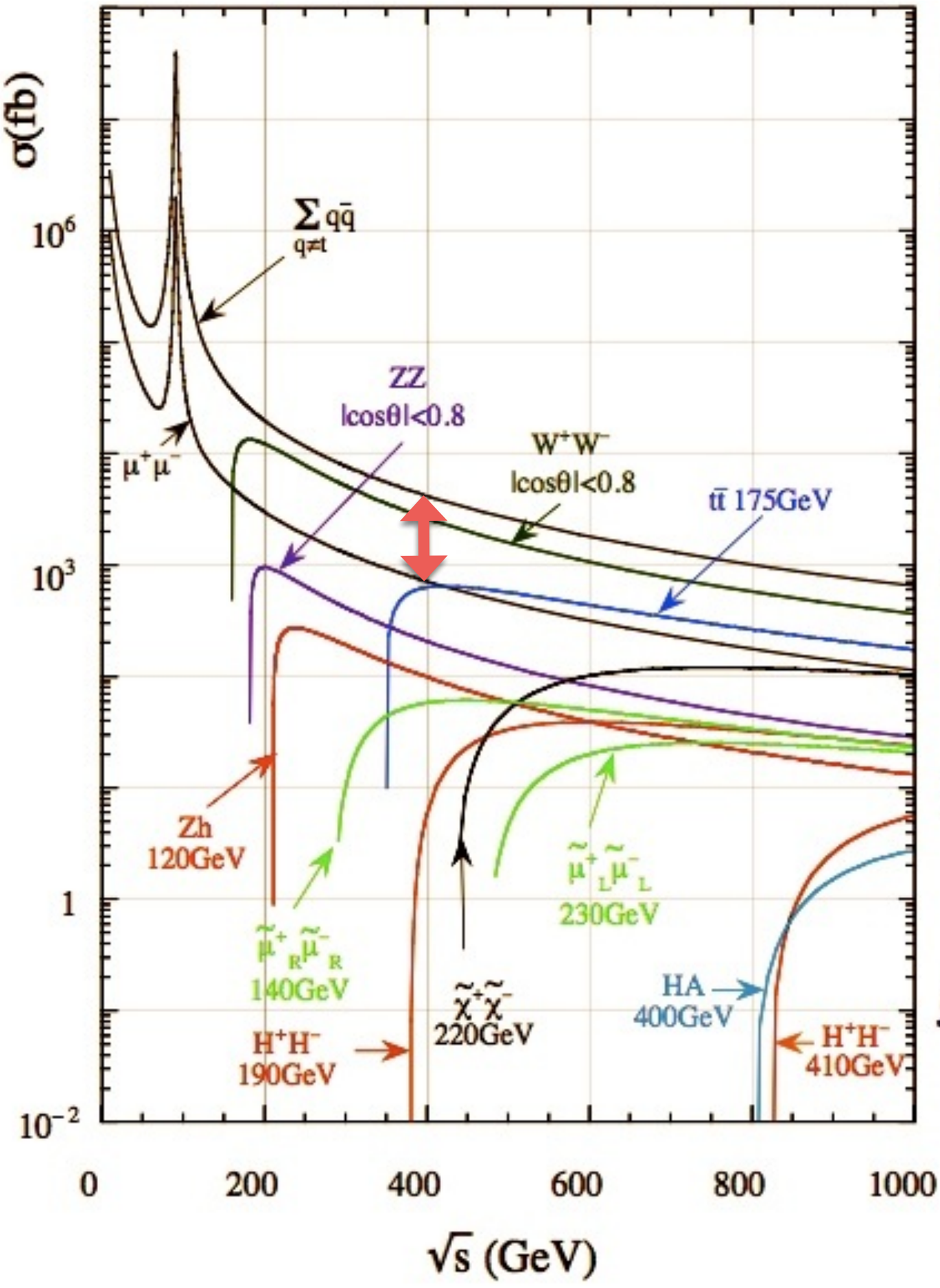
$$t \to n\ jets \neq bW \to bjj$$ (???)

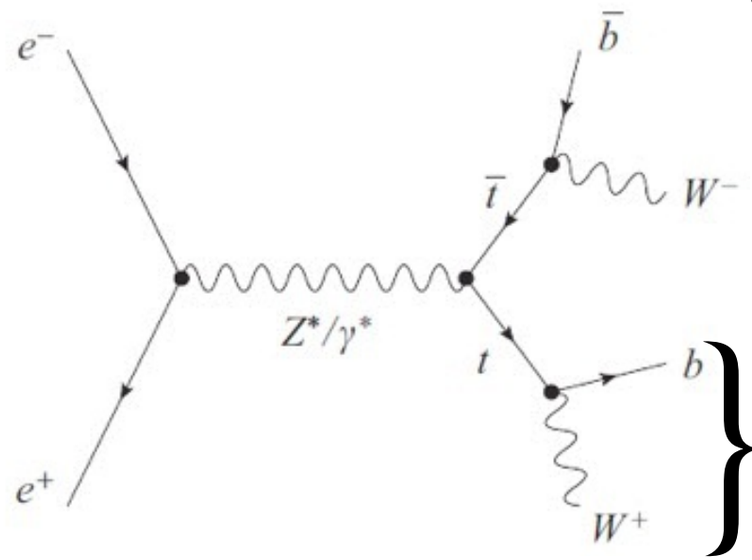
could have many different "unexpected" final states with unexpected kinematical features ...
can't find them at LHC [unless you make assumptions on what you are looking for] !

what about e^+e^- collider ?

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 …

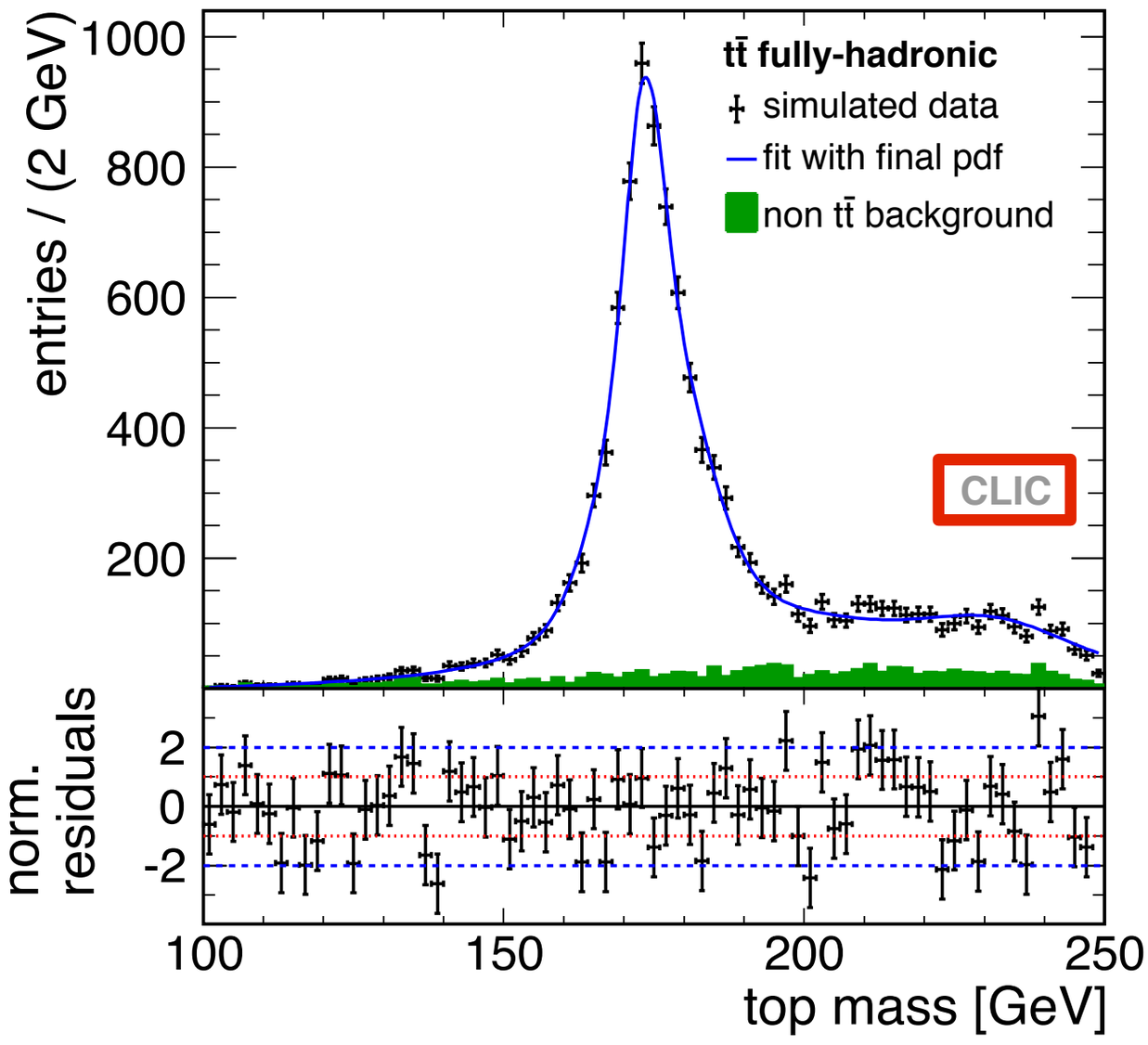


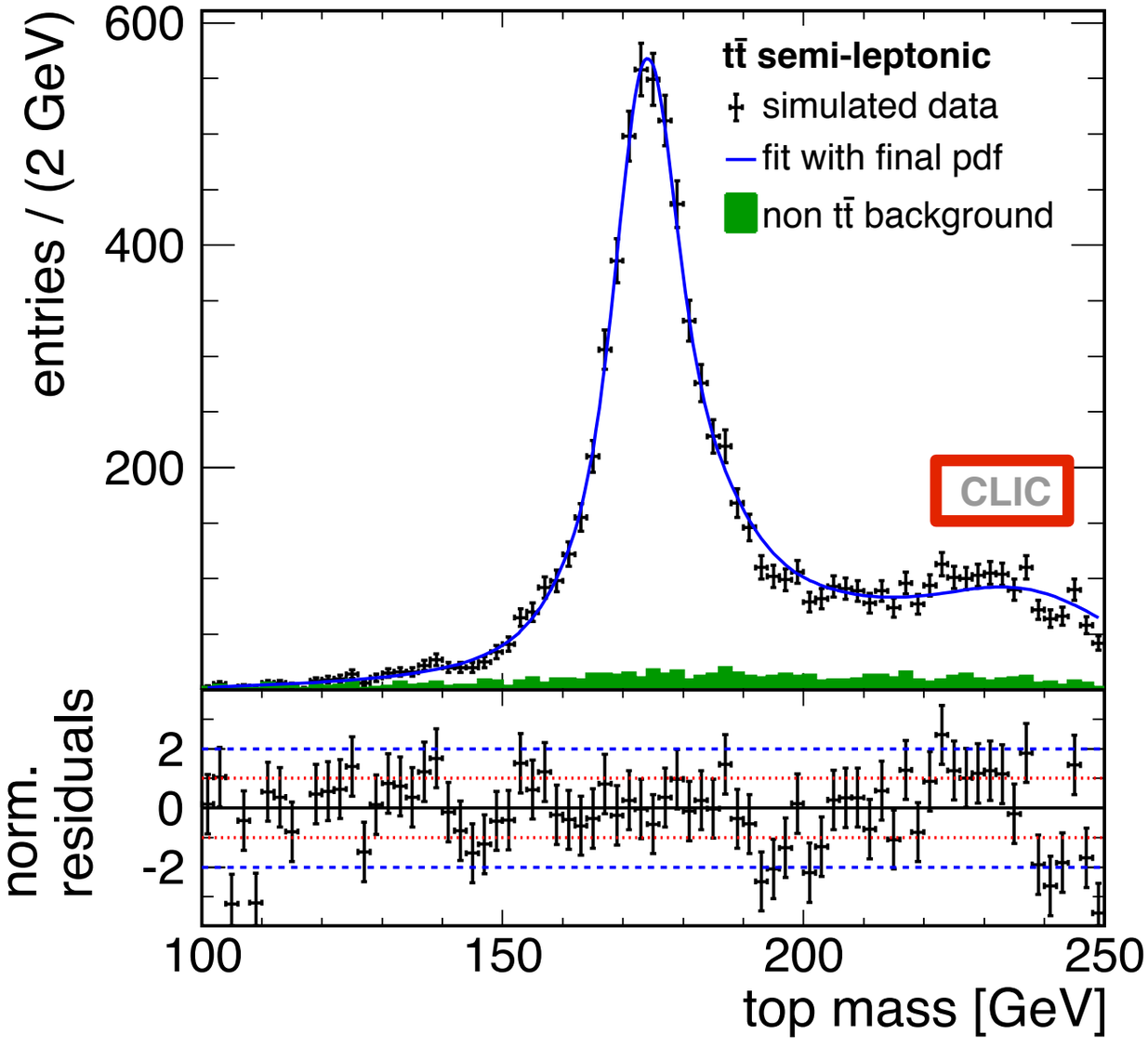


ttbar physics cleanness in e^+e^- collisions well represented by plots below (**green is background !**)

fully hadronic and semi-leptonic top mass reconstruction

Seidel et al. 1303.3758





two different approaches to rare top decays

"exclusive" approach **(two examples)**

@ "measurable" SM rare top decays ➜ $t \to s\,W$

(BR ~ 10^{-3})

@ rare top decays **measurable only in BSM**

➜ $t \to c\,\gamma\,(Z, g, H)$ **($BR_{SM} < 10^{-12}$)**

"inclusive" approach to (exotic) decays

a) excess in **top total width**

b) study of ***top recoil system*** in top pairs

proposal for e^+e^- collisions

➜ hard to conceive at hadron colliders !

here we focus on :

inclusive approaches to exotic top decays

inclusive approach (a) →→ THEORY

[excess in top total width: Γ_{top}-$\Gamma_{top}^{(SM)}$]

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 most recent N³LO QCD determination (SM):

$$\Gamma_t^{\text{tot}} = 1.3120^{+0.0194}_{-0.0192}\ \text{GeV}$$ (2404.11133)

[uncertainty in top total width Γ_{top}] ⟶ $\Delta\Gamma_{top}$ (TH) ~ 1.5 %

inclusive approach (a) →→ MEASUREMENTS

PRESENT → top width measurement at hadron colliders :

assuming SM ($\sum_q \mathcal{B}(t \to Wq) = 1$)

***t*-quark DECAY WIDTH** [PDG 2024]

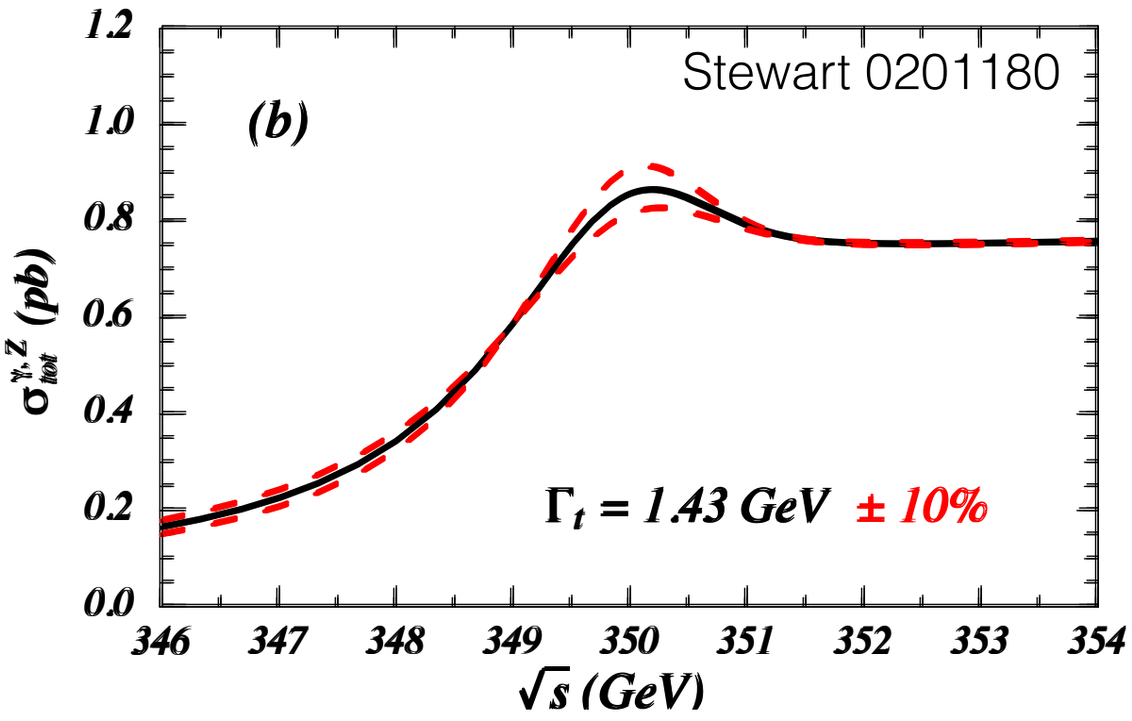
VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
→ **$1.42^{+0.19}_{-0.15}$ OUR AVERAGE**		Error includes scale factor of 1.4.			
$1.76 \pm 0.33^{+0.79}_{-0.68}$		[1] AABOUD	18AZ	ATLS	$\ell + \not{E}_T + \geq 4$j (≥ 1 b)
$1.36 \pm 0.02^{+0.14}_{-0.11}$		[2] KHACHATRY...	14E	CMS	$\ell\ell + \not{E}_T$ +2-4jets (0-2b-tag)
$2.00^{+0.47}_{-0.43}$		[3] ABAZOV	12T	D0	$\Gamma(t \to bW)/\mathrm{B}(t \to bW)$

$\Delta\Gamma_{top}$ (exp) ~ 200 MeV ~ 13%

inclusive approach (a) →→ FCC-ee

(model independent) Γ_{top} measurement at ~3% at FCC-ee

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



$\Delta\Gamma_{top}$ ~ 45 MeV at FCC-ee

[by 0.2 ab^{-1} around tt threshold]

- FCC CDR, vol. 2

bounds on $\delta\,\Gamma_{top}$ can probe inclusively rare decays with $BR_{exotic} \geq$ few % at FCC-ee

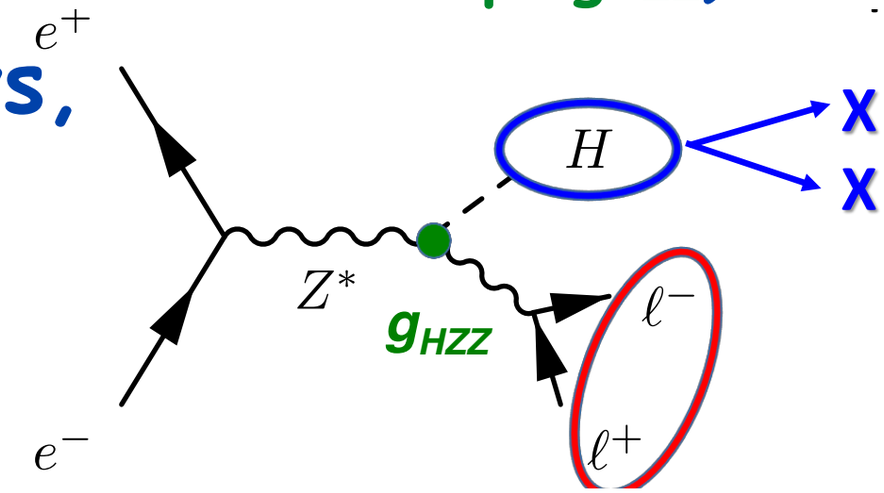
one further inclusive approach

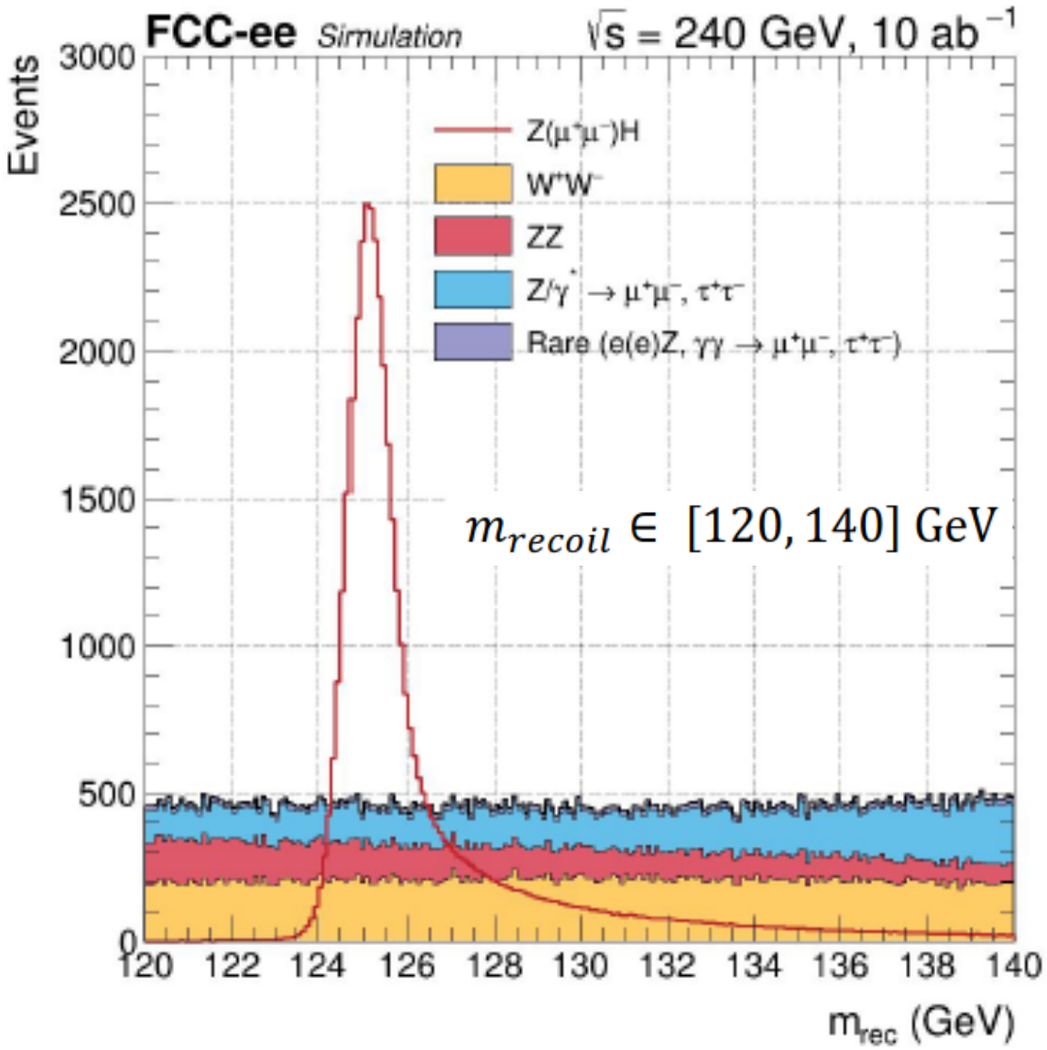
inclusive Higgs studies through Z recoil system [LHC]

- 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,ss H → gg)

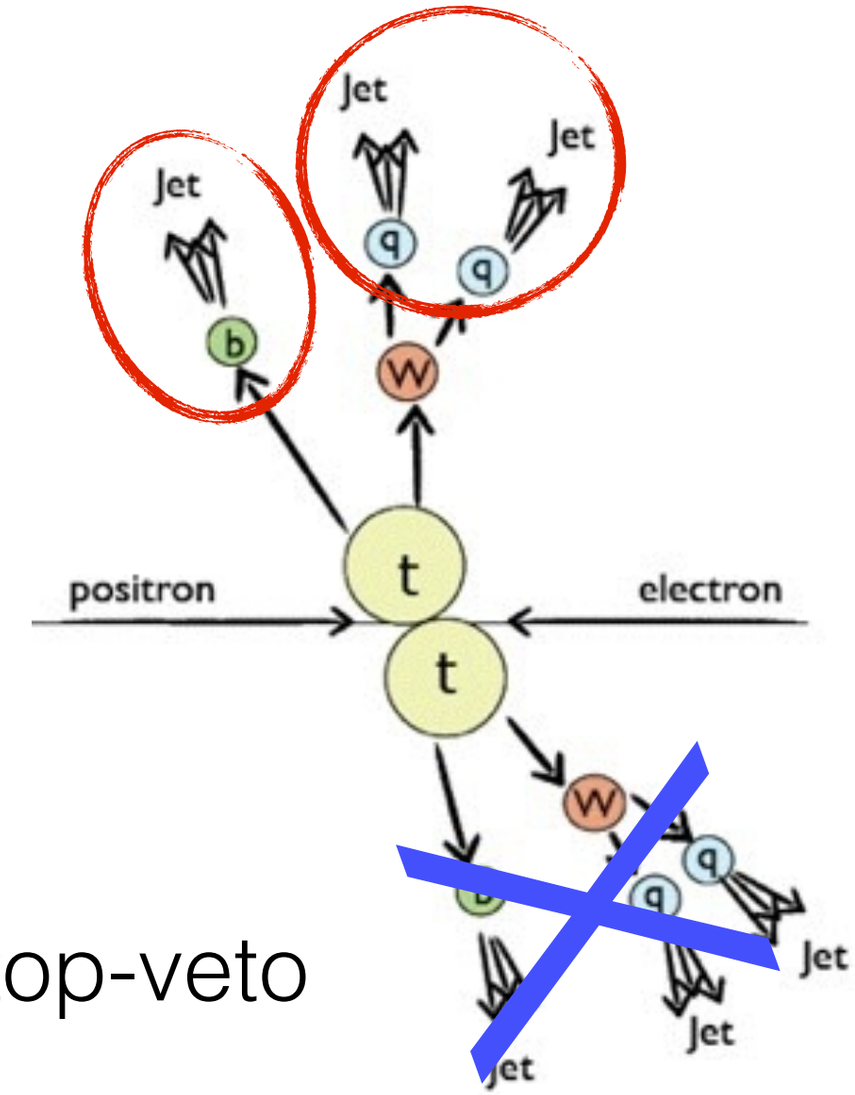




could we extend this technique to top pairs in $e^+e^- \to t\bar{t}$ and make inclusive searches for exotic top final states by looking at top recoil system ???

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
one top-system with
a veto on a 2nd tagged top
(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} ~ 365 GeV

how good can be this strategy depends on
how efficiently we are able to simulate
the real SM top pair production !

any SM tt event badly reconstructed
(where only one top passes the tagging request)
contributes in principle to a fake "exotic top width"

actual general strategy ???

- take a SM tt fully simulated sample
- require kinematically robust (→ hadronic) tag for first top
- put a veto on top-like had+lep tag on second top
- measure how much is left out of the SM tt sample
- sensitivity to Γ_{top} excess is connected to that !
  [a Γ_{top} excess can hide inside SM tt reco inefficiencies]

a comment :

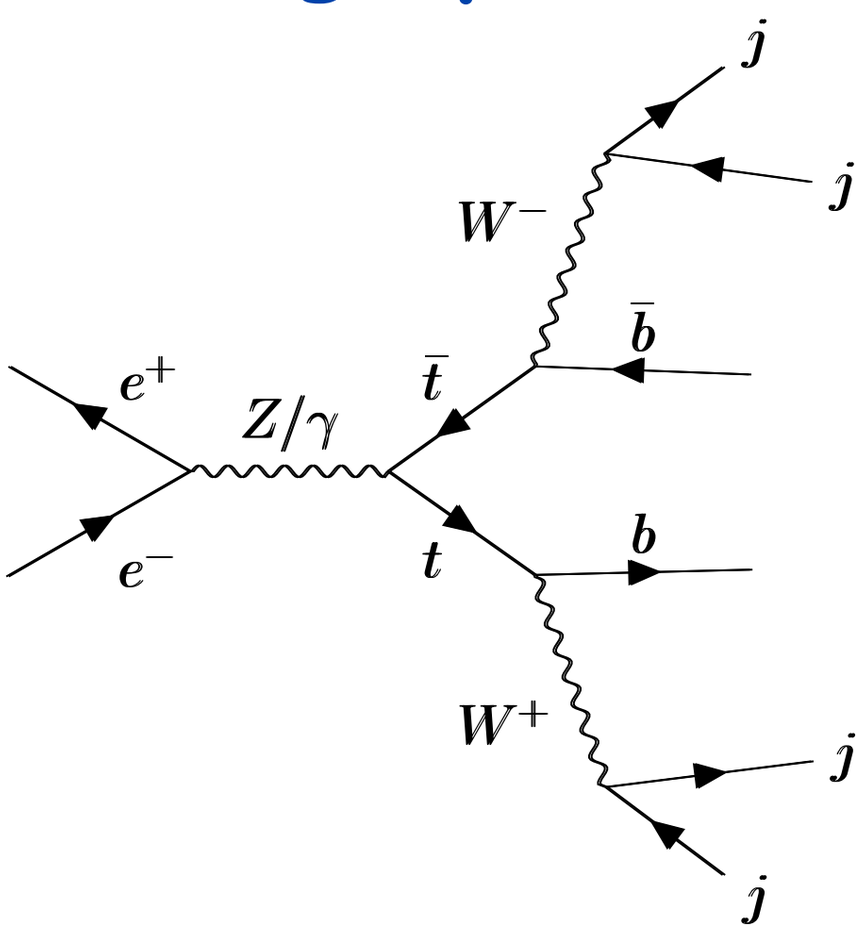
actually events will be in general so clean
that in the real exp sample
it would be feasible to look
into the "unrecognized" tt events
and scrutinize what is inside the second top
➜ going beyond inclusive approach...

"unrecognized" tt ➜ only single tag passed

a realistic study would need detailed detector characteristics !

G. Corcella, BM, D. Sengupta

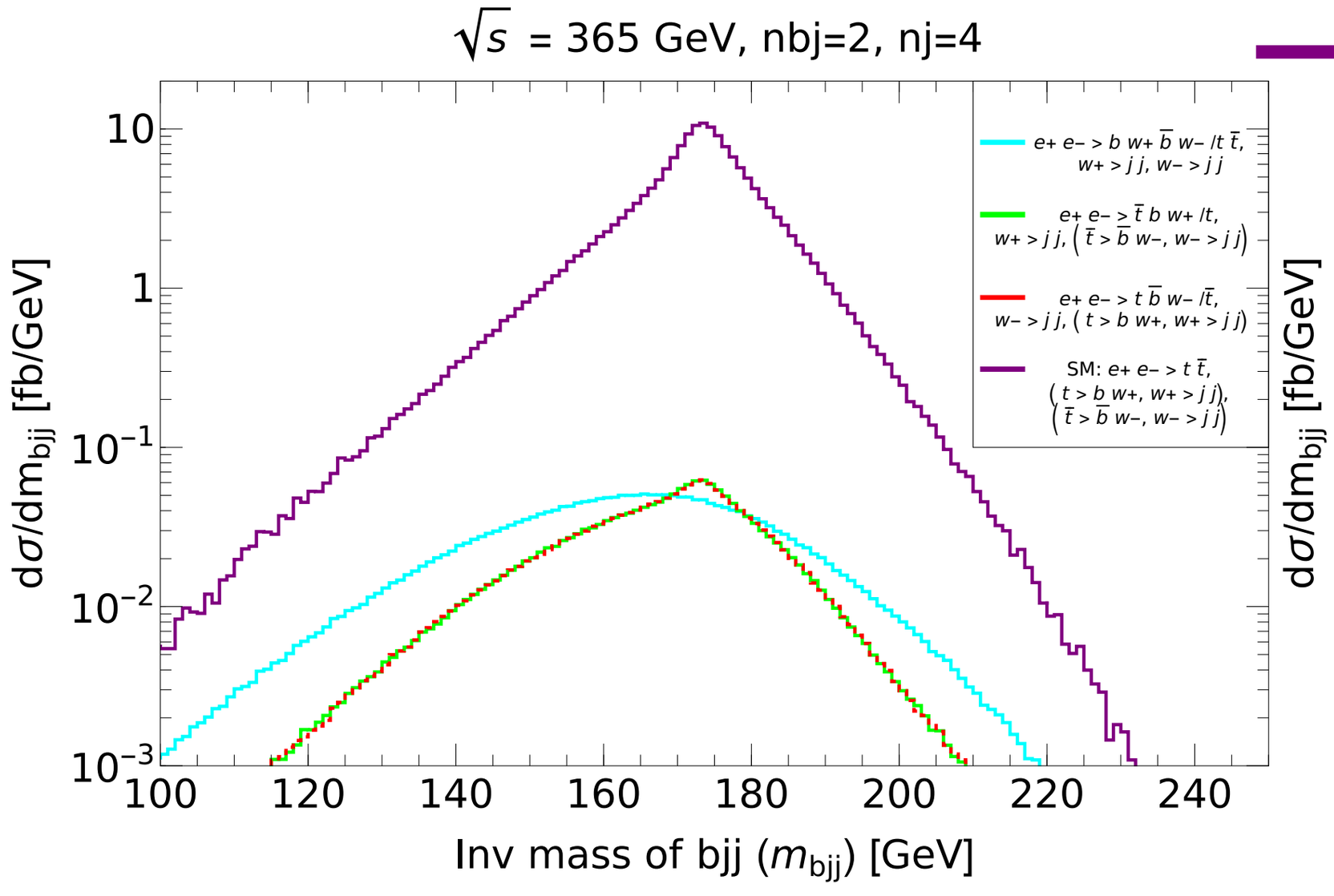
we started by estimating how efficiently
one can reconstruct SM tt events
from a "theoretical" Monte Carlo sample
(Madgraph5 followed by Pythia8)



"theoretical" ➜ not including detector effects

focus on tt ➜ bjj bjj

tiny physical bckgrs ! (tt → 4j+2b)



e+ e− > b w+ $\bar{b}$ w− /t $\bar{t}$, w+ > j j, w− > j j

e+ e− > $\bar{t}$ b w+ /t, w+ > j j, ($\bar{t}$ > $\bar{b}$ w−, w− > j j)

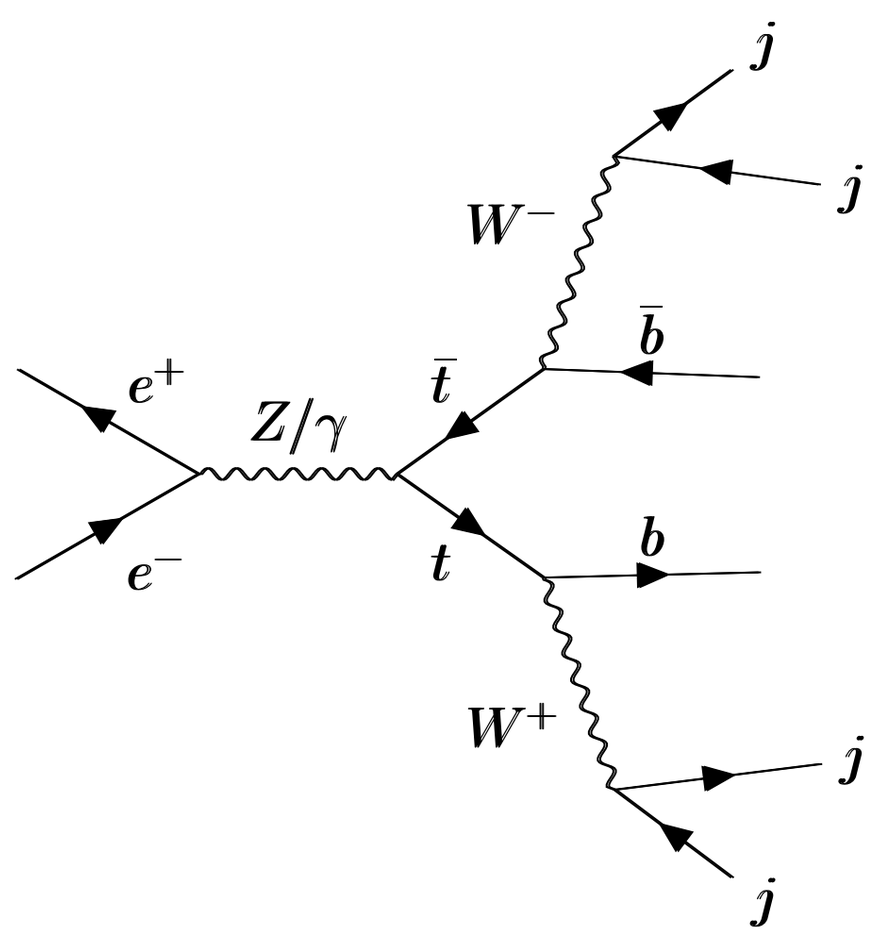
e+ e− > t $\bar{b}$ w− /$\bar{t}$, w− > j j, (t > b w+, w+ > j j)

SM: e+ e− > t $\bar{t}$, (t > b w+, w+ > j j), ($\bar{t}$ > $\bar{b}$ w−, w− > j j)

- jets are clustered using ee k_T (Durham) algorithm, embedded in Fastjet, requiring exactly 6 jets

- ~ 98% of events match the 2b+4j flavour composition

how to match properly light jets to the right top system in m_{bjj} ?

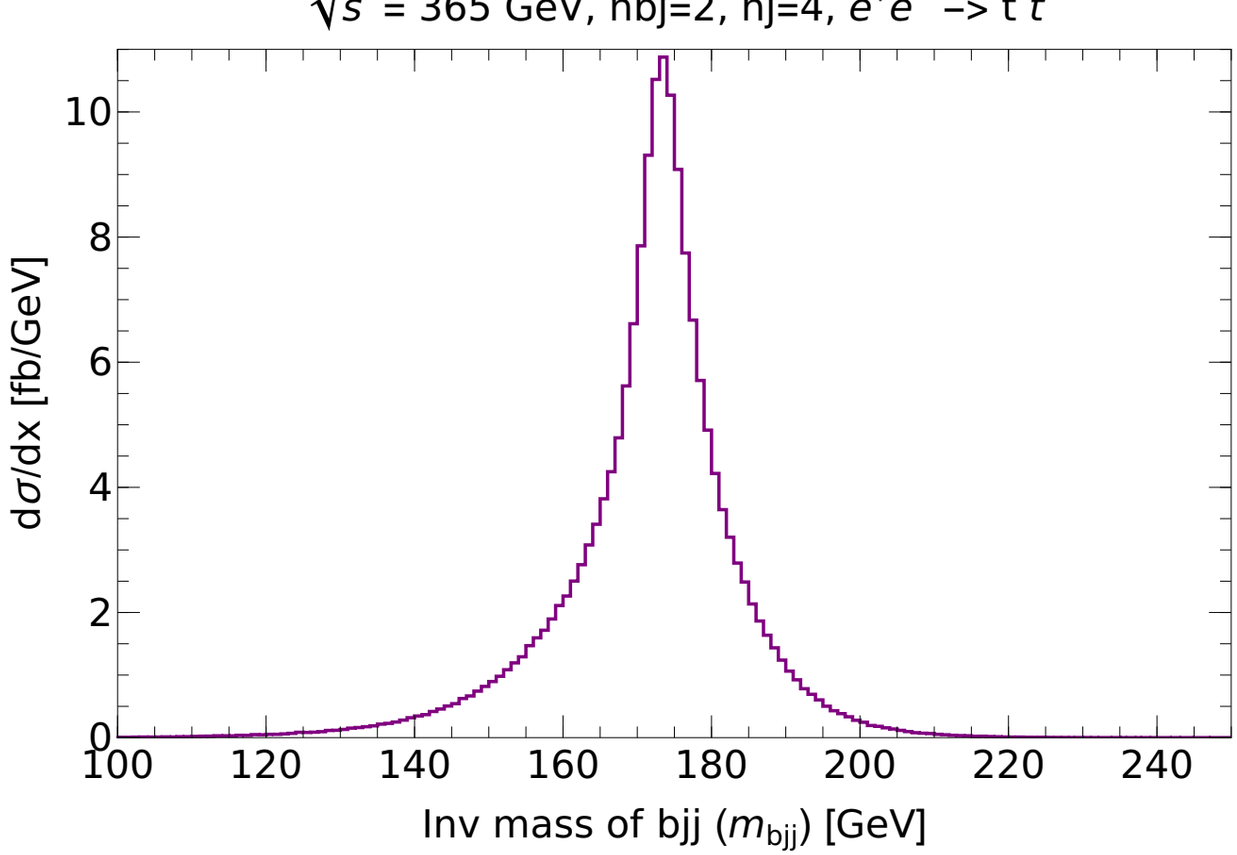


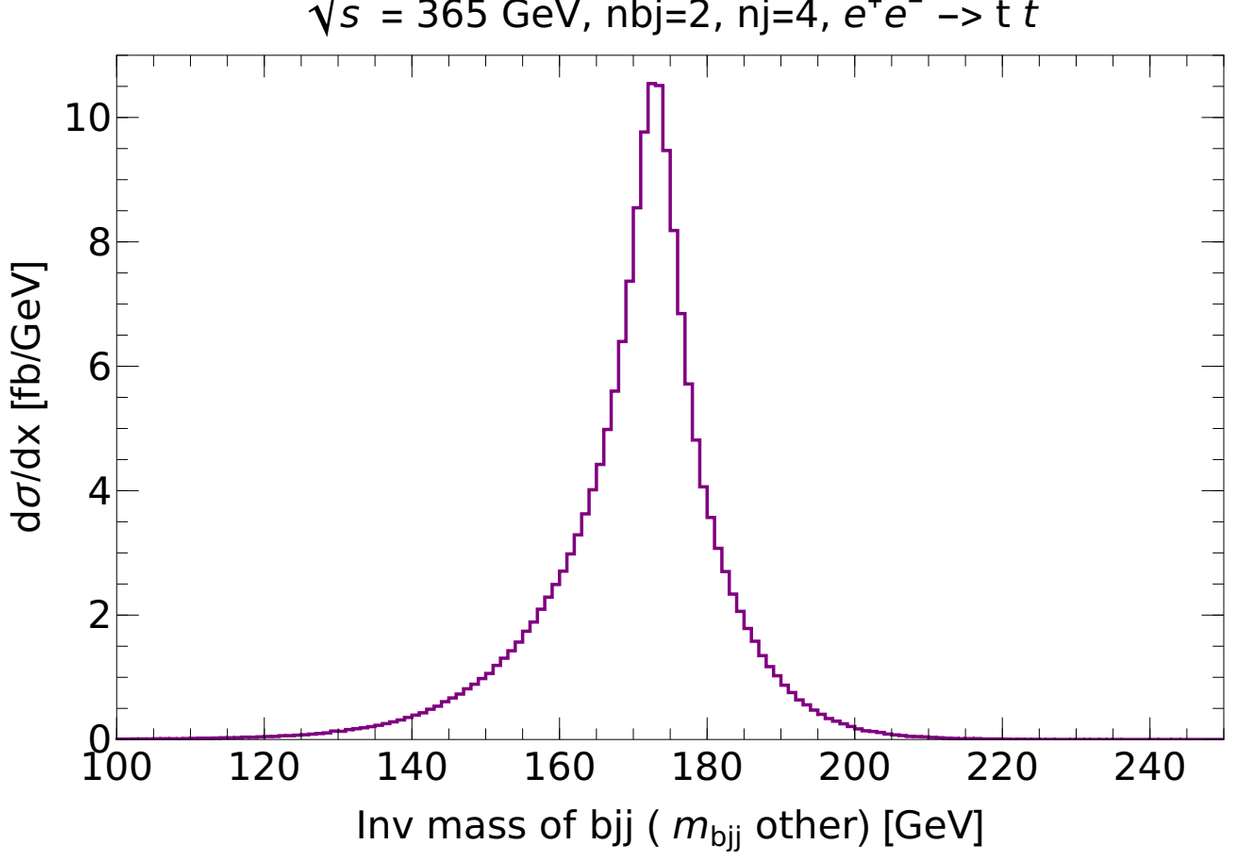
matching properly light jets+b to the right top system in m_{bjj}

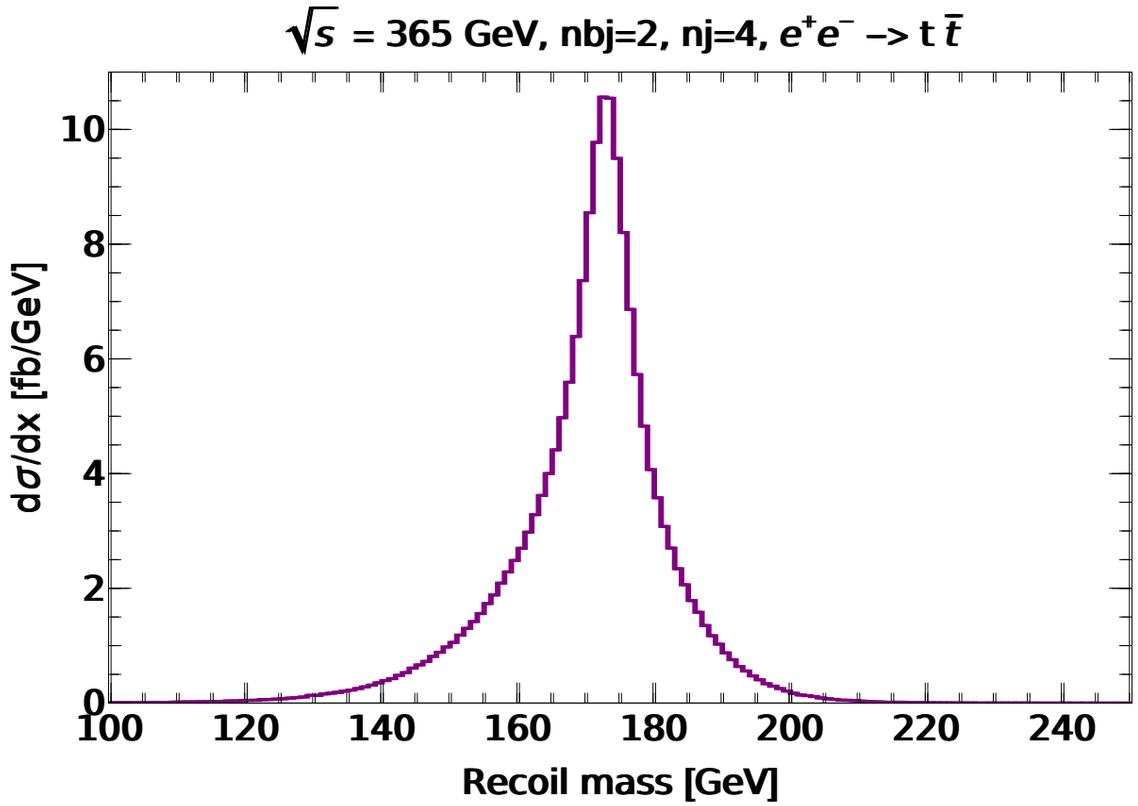
by minimazing :

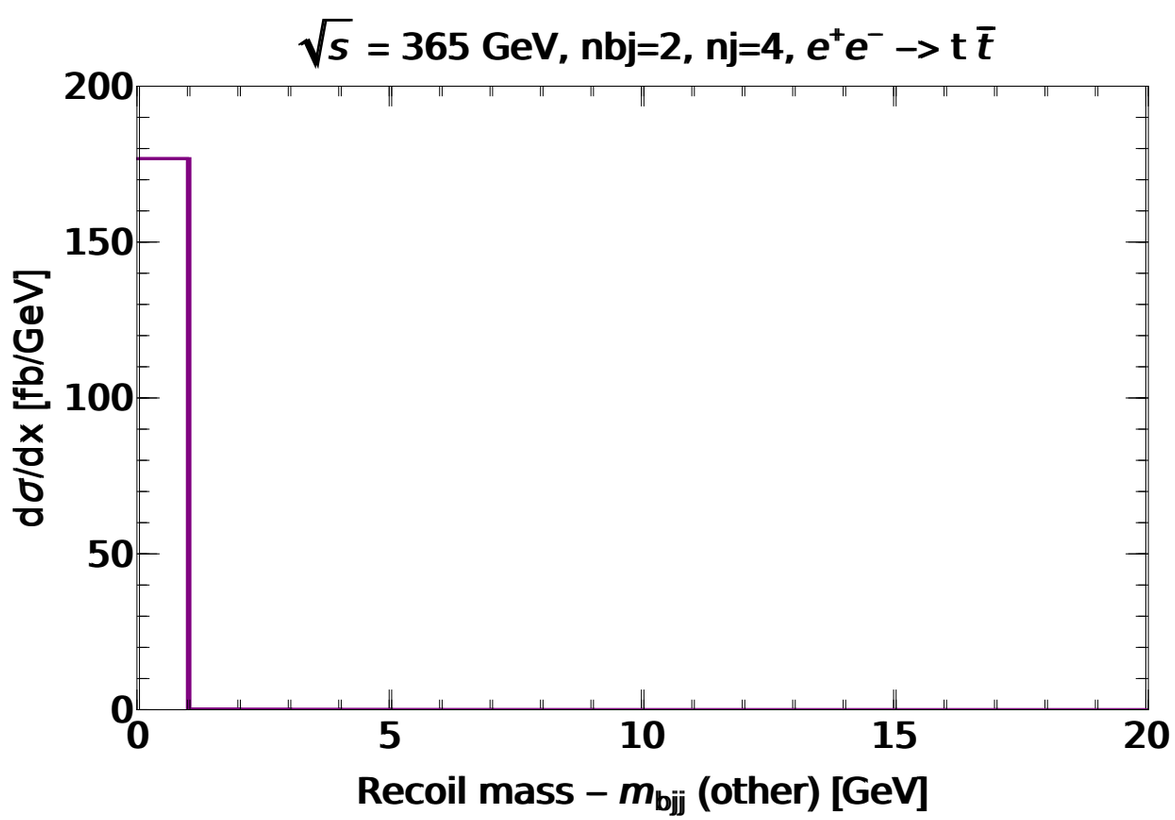
$$\chi^2 = (m_{jj} - m_w)^2 + (m_{bjj} - m_{top})^2 + (m_{recoil} - m_{top})^2$$

$$m^2_{recoil} = s + m^2_t - 2 \times E_t \times \sqrt{s}$$









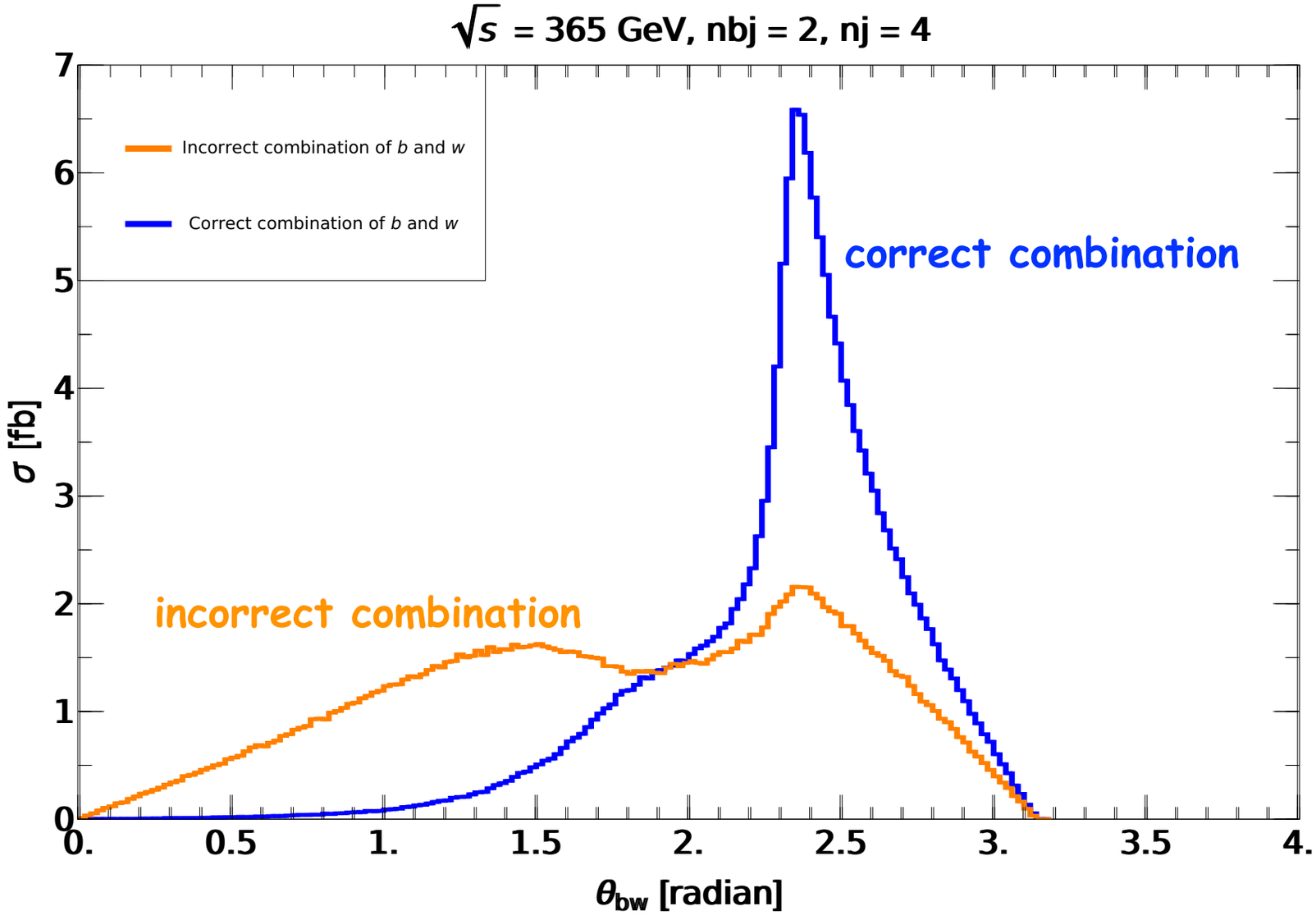
97.85% events have exactly 2 b-jet and 4 light jets

97.34% events have two top quarks with m_{bjj} between $m_{top} \pm 50$ GeV

→ ~ 0.5% accuracy in SM top system reconstruction

→ bound on BR_{exotic}

angular distance between b-jet and $W^{\pm}$



adding this structure to the X^2 minimization does not affect the result in a sensitive way !

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