The Conservative Case for a Fourth Family and New Strong Flavor Interactions

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- "A fourth family has no theoretical motivation"
- "A fourth family is just plain boring—both theoretically and experimentally"

PDG, 2008

An extra generation of ordinary fermions is excluded at the 6 σ level on the basis of the S parameter alone, corresponding to $N_F = 2.71 \pm 0.22$ for the number of families. This result assumes that there are no new contributions to T or U and therefore that any new families are degenerate. This restriction can be relaxed by allowing T to vary as well, since $T > 0$ is expected from a non-degenerate extra family. Fixing $S = 2/3\pi$, the global fit favors a fourth family contribution to T of 0.232 ± 0.045. However, the quality of the fit deteriorates ($\Delta\chi^2 = 6.8$ relative to the SM fit with M_H fixed to the same value of 117 GeV) so that this tuned T scenario is also disfavored (roughly at the 99% CL). A more detailed analysis is required if the extra neutrino (or the extra down-type quark) is close to its direct mass limit [218]. This can drive S to small or even negative values but at the expense of too-large contributions to T. These results are in agreement with a fit to the number of light neutrinos, $N_\nu = 2.986 \pm 0.007$ (which favors a larger value for $\alpha_s(M_Z) = 0.1237 \pm 0.0021$ mainly from R_ℓ and τ_τ, as well as a very low M_H). However, the S parameter fits are valid even for a very heavy fourth family neutrino.

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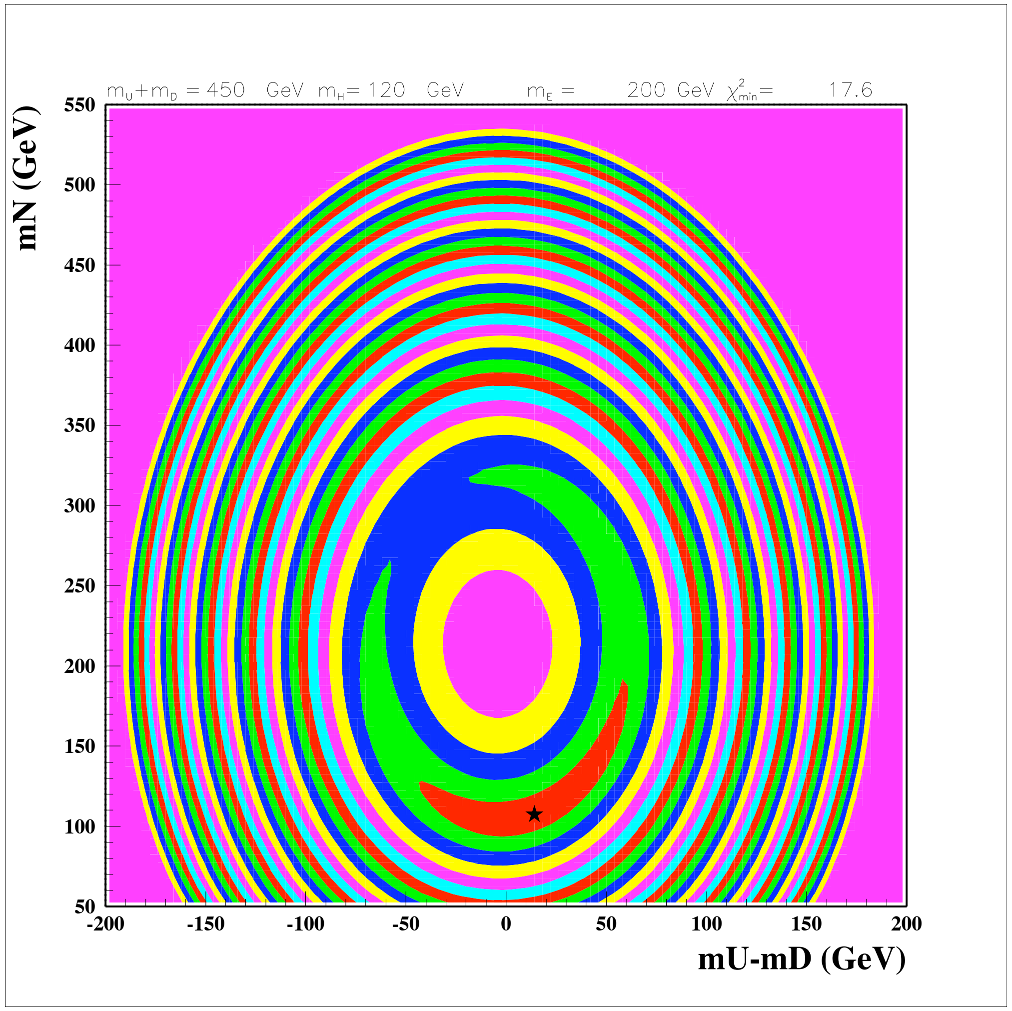
- compare to talk given by M. Vysotsky at *Beyond the 3SM generation at the LHC era Workshop*, CERN, Sept. 4-5.
  - update of M. Maltoni, V. A. Novikov, L. B. Okun, A. N. Rozanov, and M. I. Vysotsky, Phys. Lett. B476 (2000) 107

Vysotsky, 2008

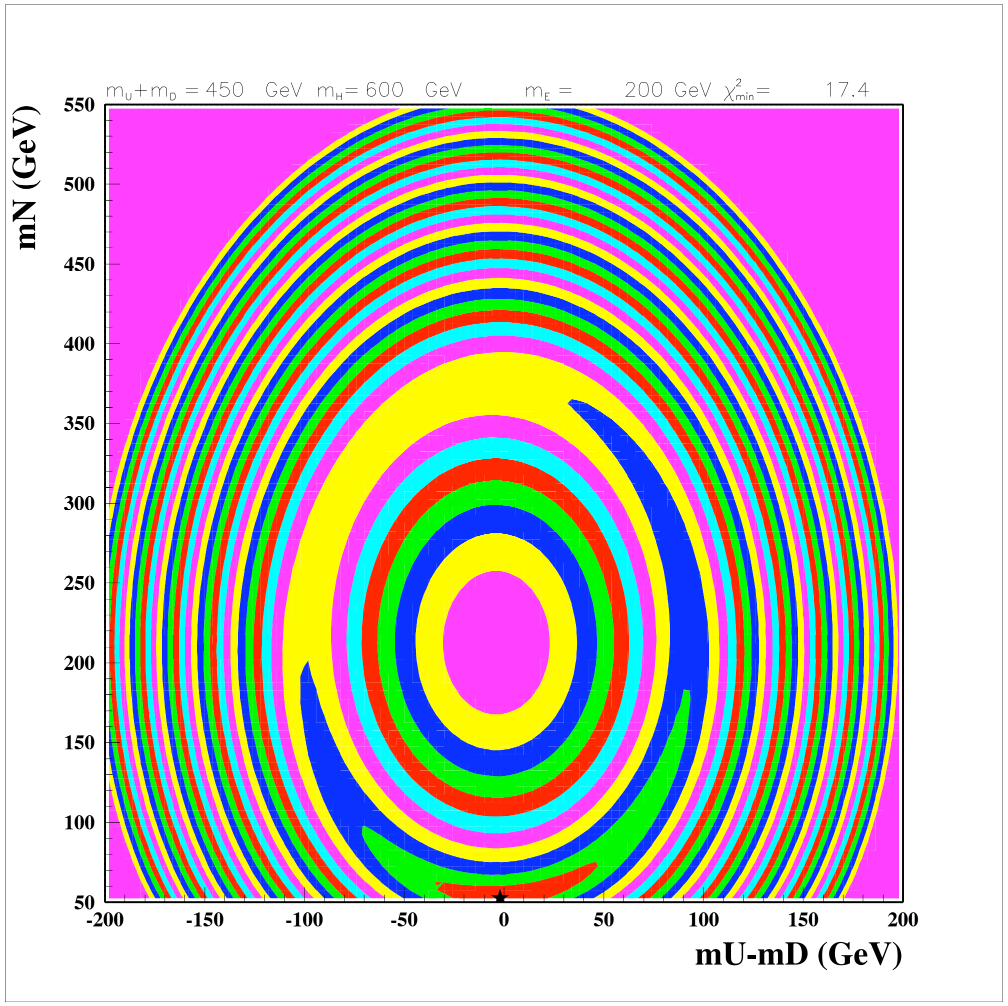
4 generation with 120 GeV higgs



$m_E = 200$GeV, $m_U + m_D = 450$ GeV, $\chi^2/d.o.f. = 17.6/11$, the quality of fit is the same as in SM.

Vysotsky, 2008

4 generation with 600 GeV higgs



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Vysotsky, 2008

(picking off his slides)

- The quality of fit for one extra generation is the same as that for SM for certain values of new particle masses;
- In case of 4^{th} generation the upper bound on higgs mass from SM fit is removed;

The example of unsuccessful application of S, T, U to 4^{th} generation :
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- but even the Russian analysis makes assumptions that can be relaxed
    - BH, PRD54(1996)721
- see also Kribs, Plehn, Spannowsky, Tait, PRD76(2007)075016

Outline

Search for a fourth family

- focus on the use of the jet mass technique

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Implications of a fourth family

- may change our view of the Higgs—points to additional physics

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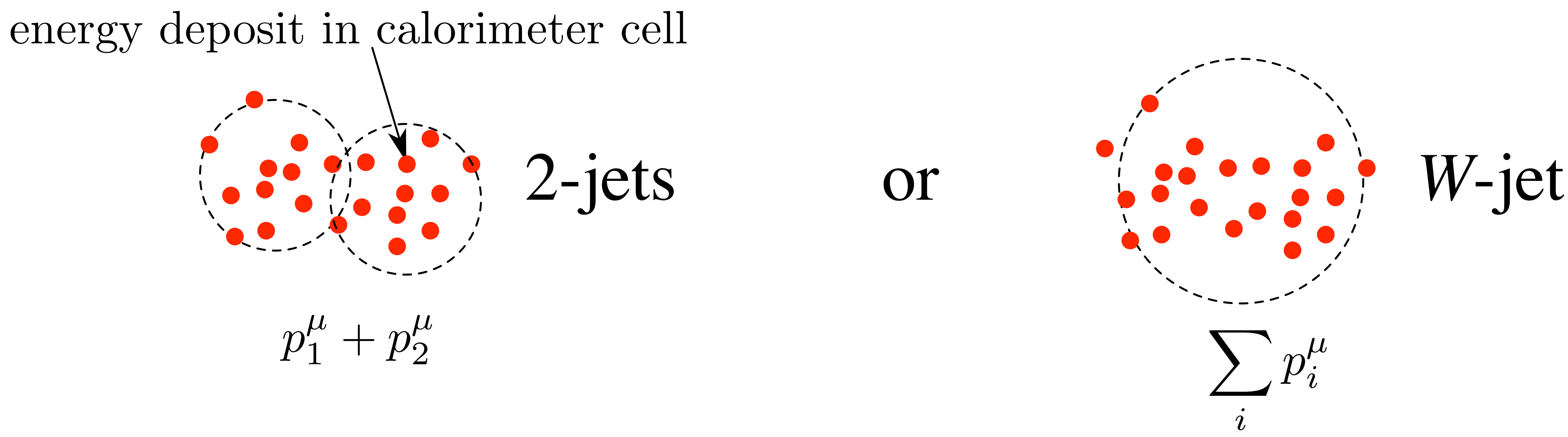
Motivation for a fourth family

- a conservative point of view for new physics
- new flavor interactions, EWSB, top mass etc.—how do the pieces fit?
- another LHC search
- return to S and T

jet mass technique for $t' \to Wq \to (W\text{-}jet)(q\text{-}jet)$



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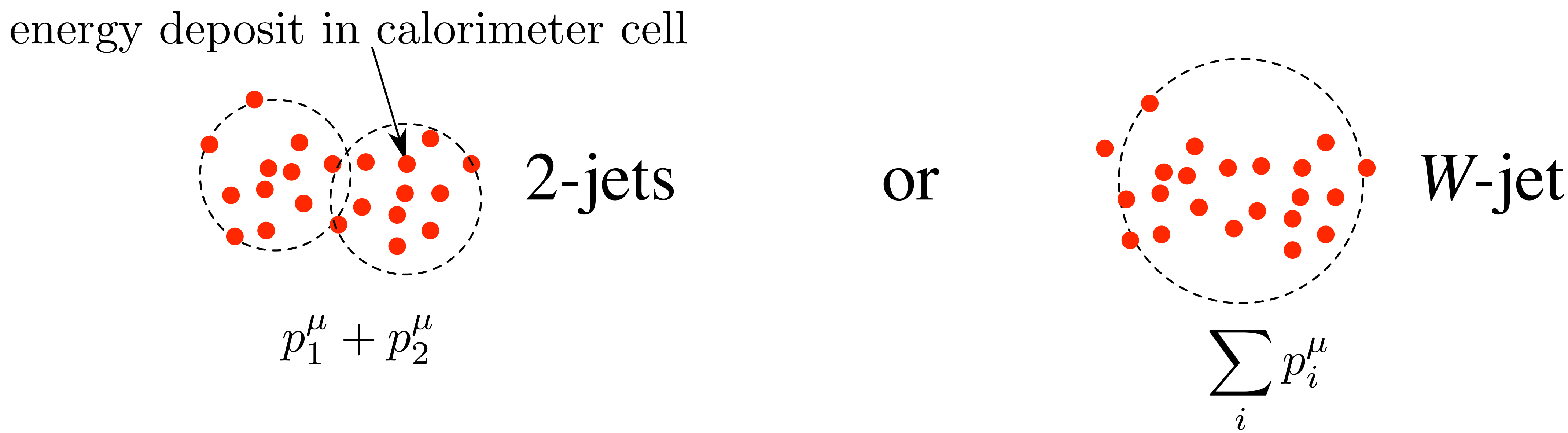
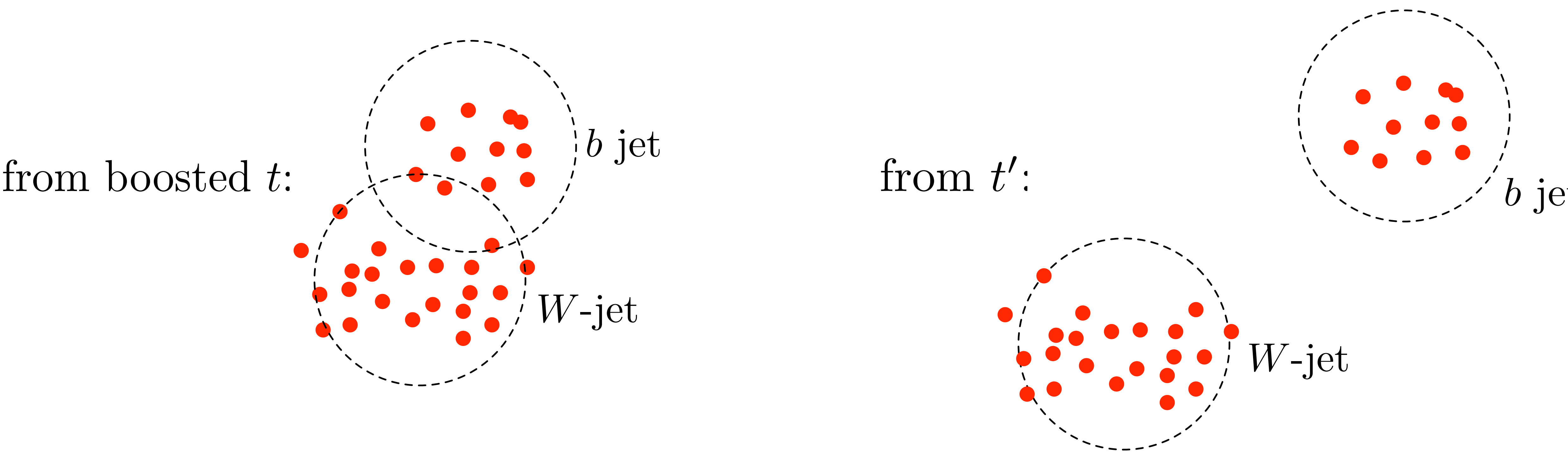
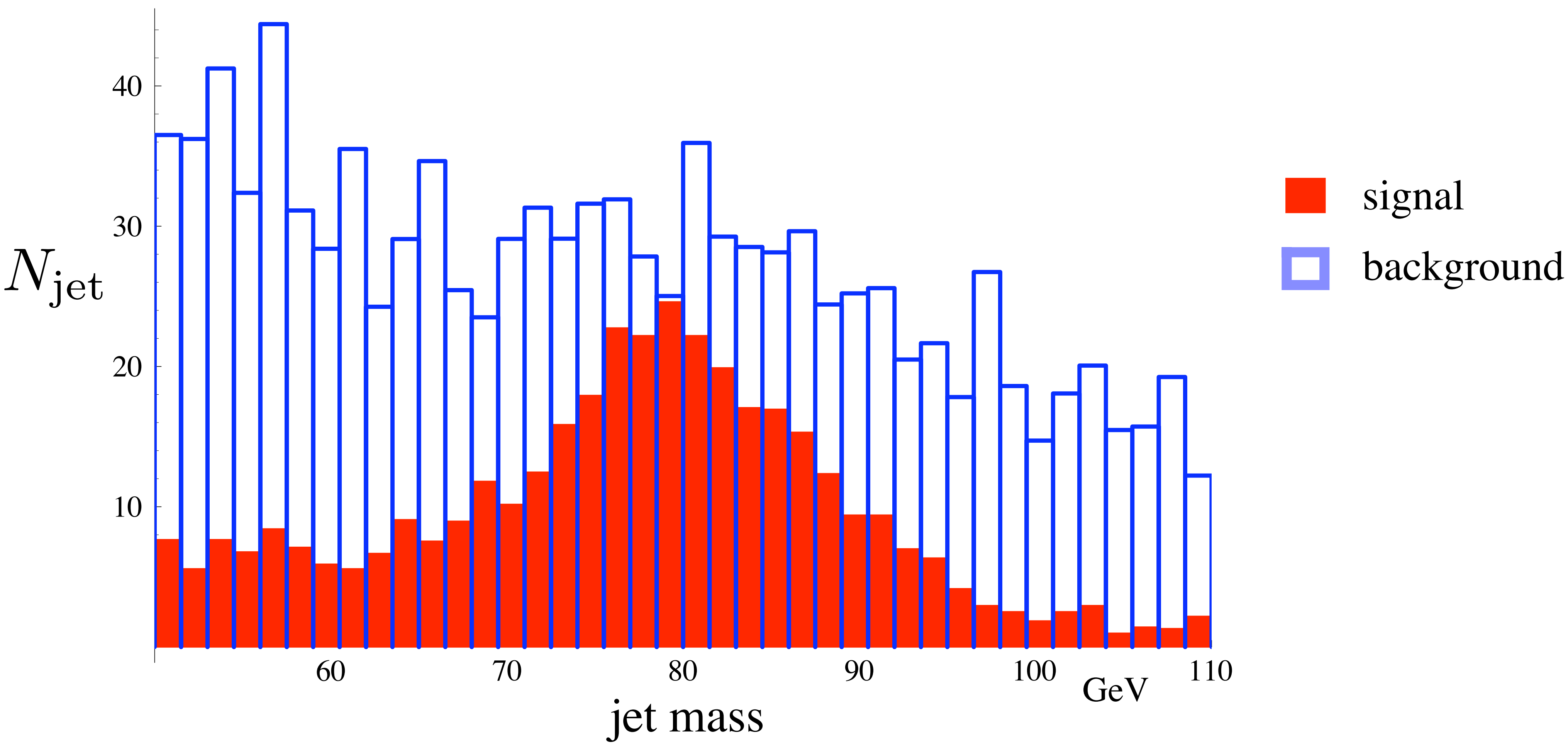


relative suppression of $t\bar{t}$ *background*



Sample jet mass plot



$$t'\overline{t}' \longrightarrow W^+W^-q\overline{q} \longrightarrow (\ell\overline{\nu})(W\text{-jet})q\overline{q}$$

$$t'\overline{t}' \to W^+W^-q\overline{q} \to (\ell\overline{\nu})(W\text{-jet})q\overline{q}$$

method based on jet mass technique (without b-tag)

- isolated lepton with $p_T > 15$ GeV or missing $E_T > 100$ GeV
- three jets with $p_T > 60$ GeV, one with $p_T > 150$ GeV
- one "W-jet" with invariant mass $m_{\rm jet} > 60$ GeV
- ΔR between ($p_T > 150$ jet) and (W-jet) less than 2.5
- take invariant mass of any two such objects

standard method (without b-tag)

- isolated lepton with $p_T > 15$ GeV
- missing $E_T > 20$ GeV
- four jets with $p_T > 40$ GeV, two with $p_T > 100$ GeV (use smaller cone)
- reconstruct p_ν such that combined with p_ℓ reconstructs M_W
- find the pair of jets whose invariant mass comes closest to M_W (reject if greater than 200 GeV)
- make remaining jet assignments to minimize the difference between the two reconstructed t' masses (reject if greater than 150 GeV)

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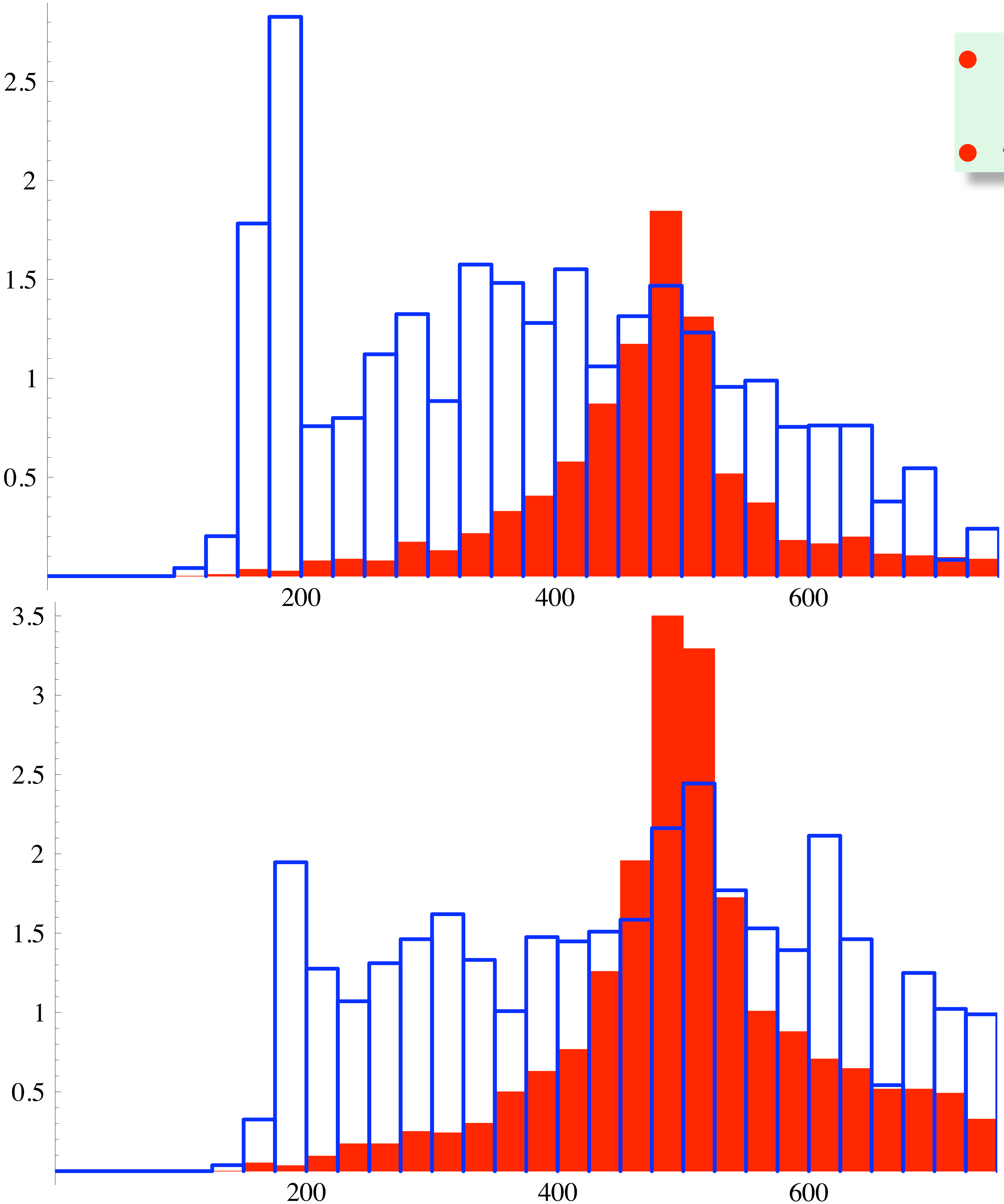
compare the two methods

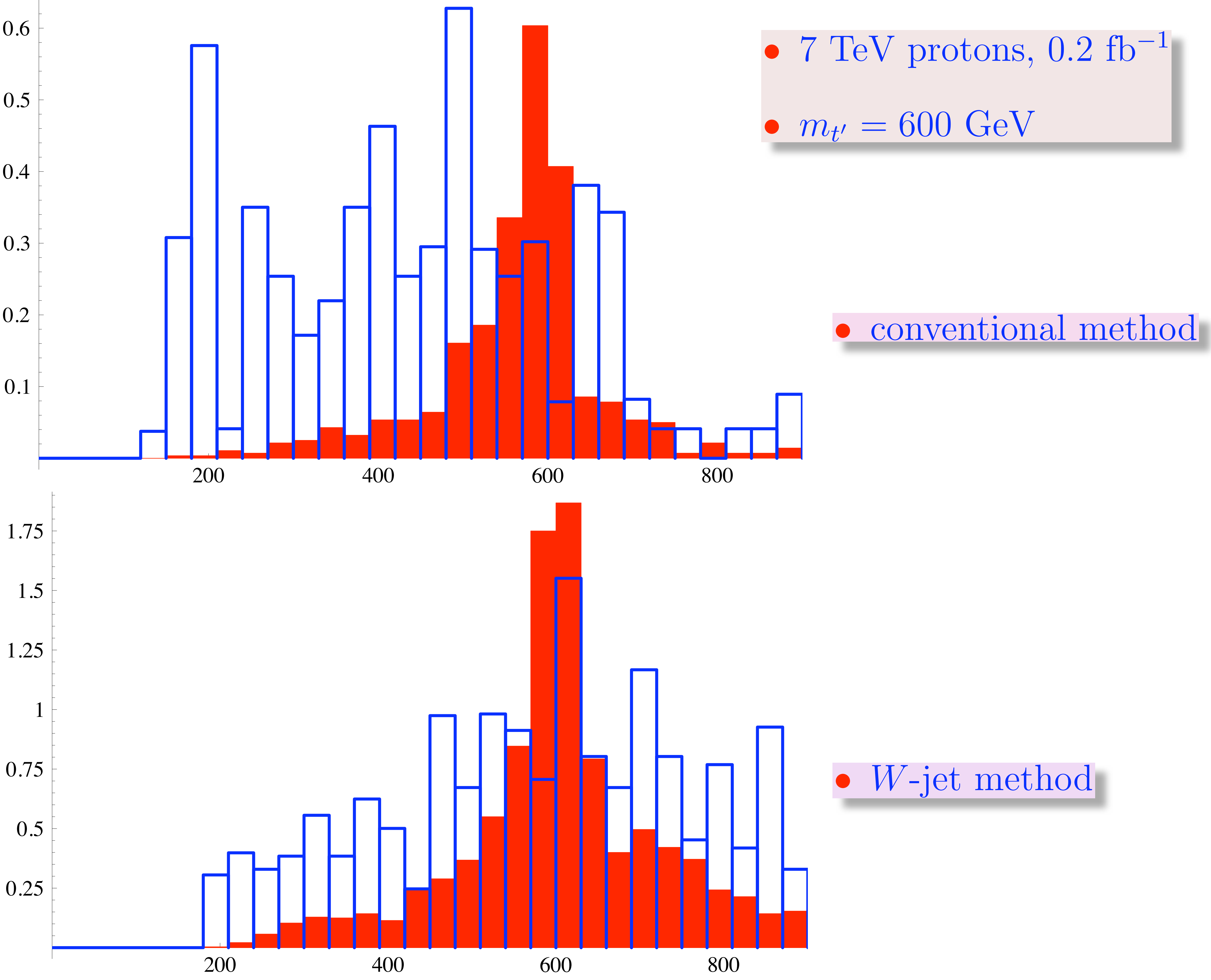
- $t'\bar{t}'$ signal vs $t\bar{t}$ background
- also take $H_T > 2m_{t'}$



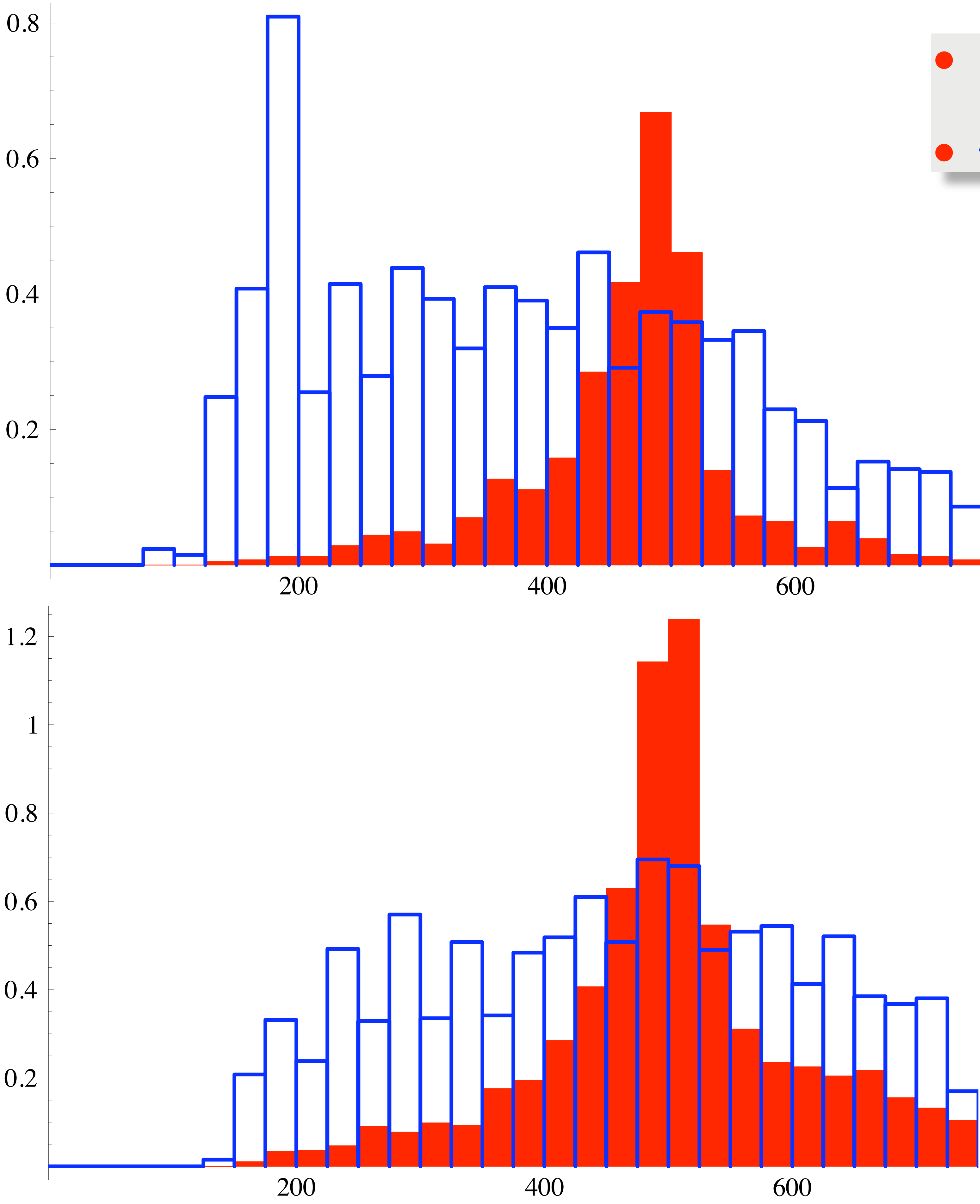
- 7 TeV protons, 0.2 fb^{-1}
- $m_{t'} = 500$ GeV

- conventional method

- W-jet method



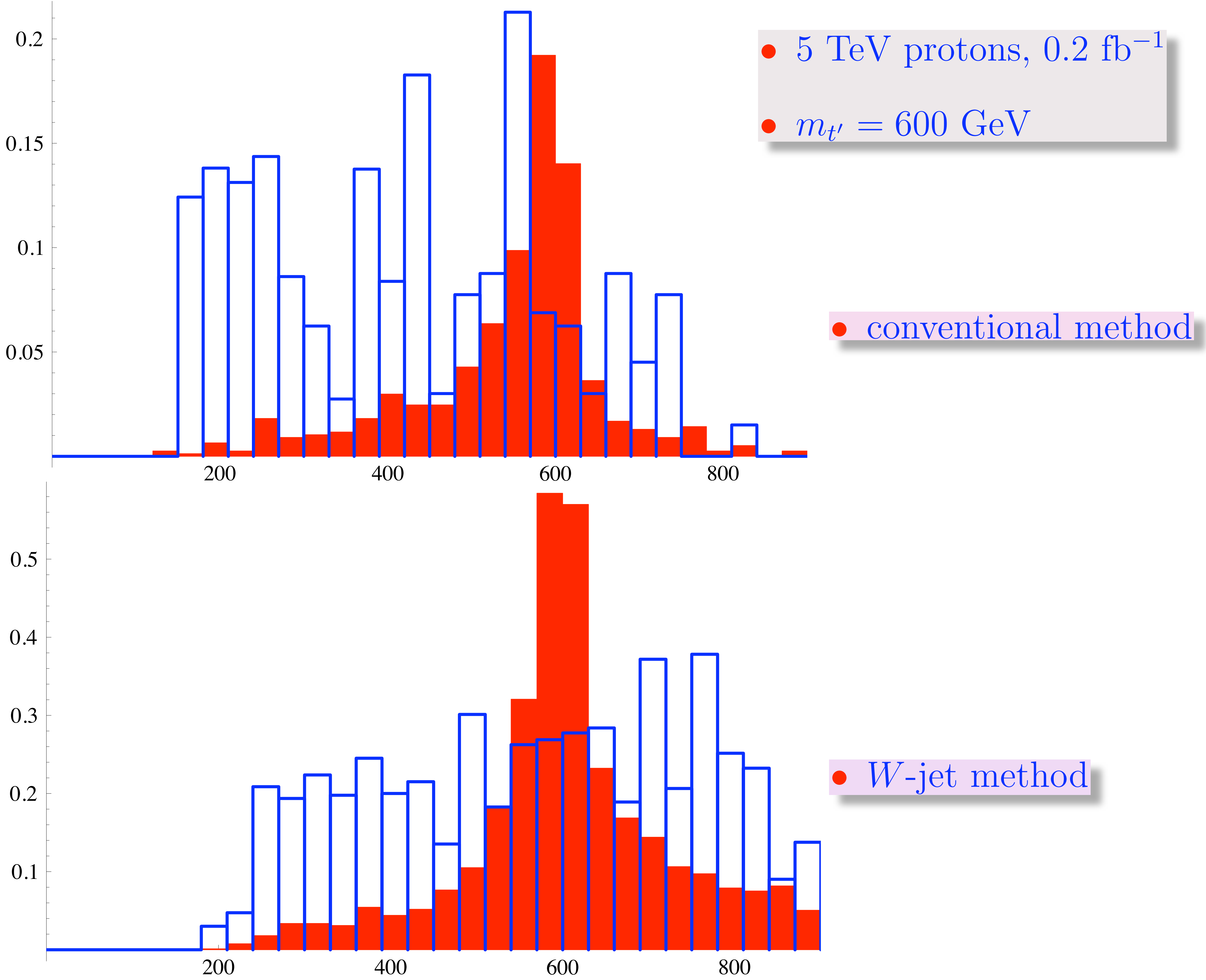
7 TeV protons, 0.2 fb^{-1}
$m_{t'} = 600$ GeV
conventional method
W-jet method
0.1
0.2
0.3
0.4
0.5
0.6
200
400
600
800
0.25
0.5
0.75
1
1.25
1.5
1.75
200
400
600
800



- 5 TeV protons, 0.2 fb^{-1}
- $m_{t'} = 500$ GeV

- conventional method

- W-jet method



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conventional method
W-jet method
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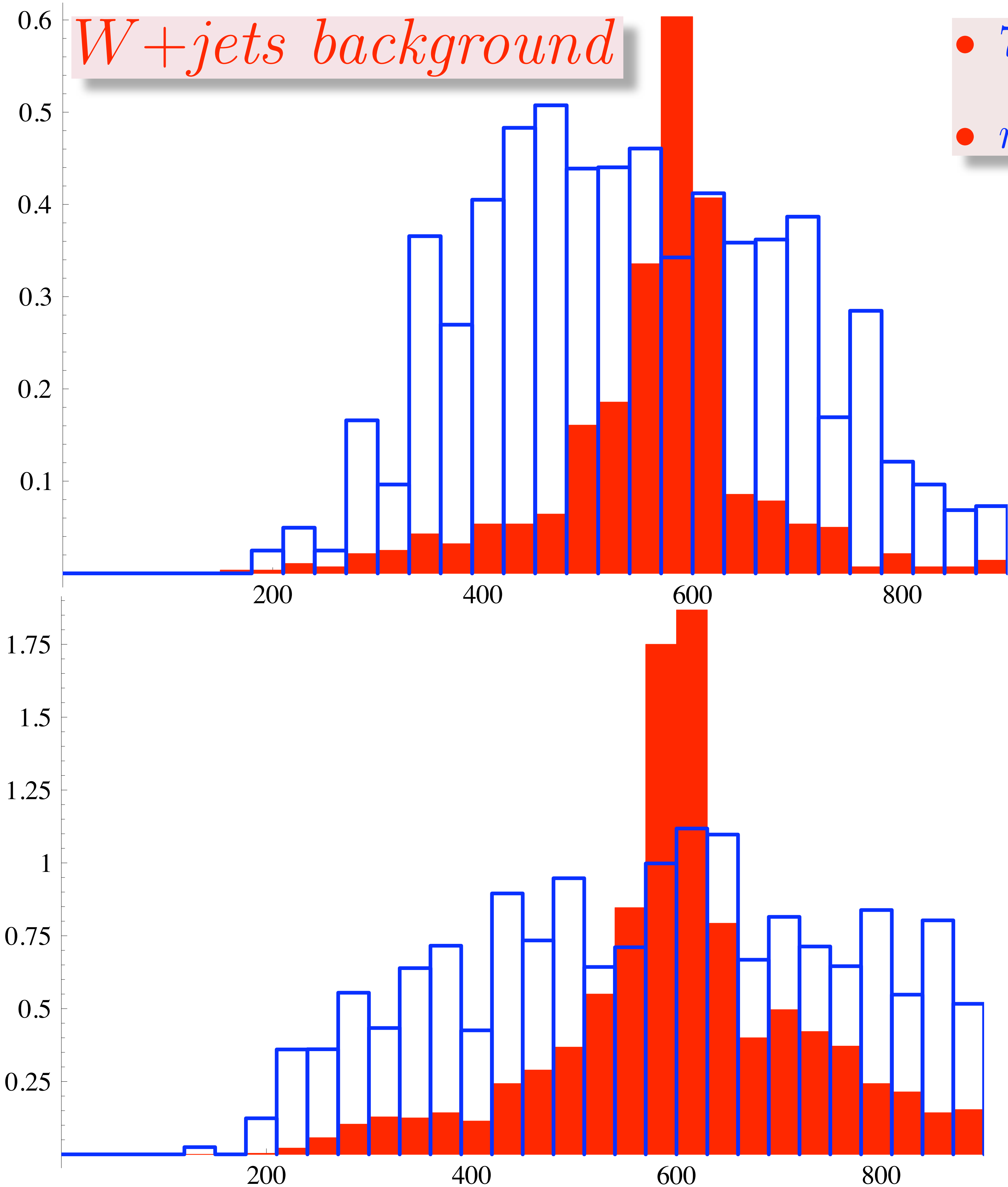
0.3
0.2
0.1



- 7 TeV protons, 0.2 fb^{-1}
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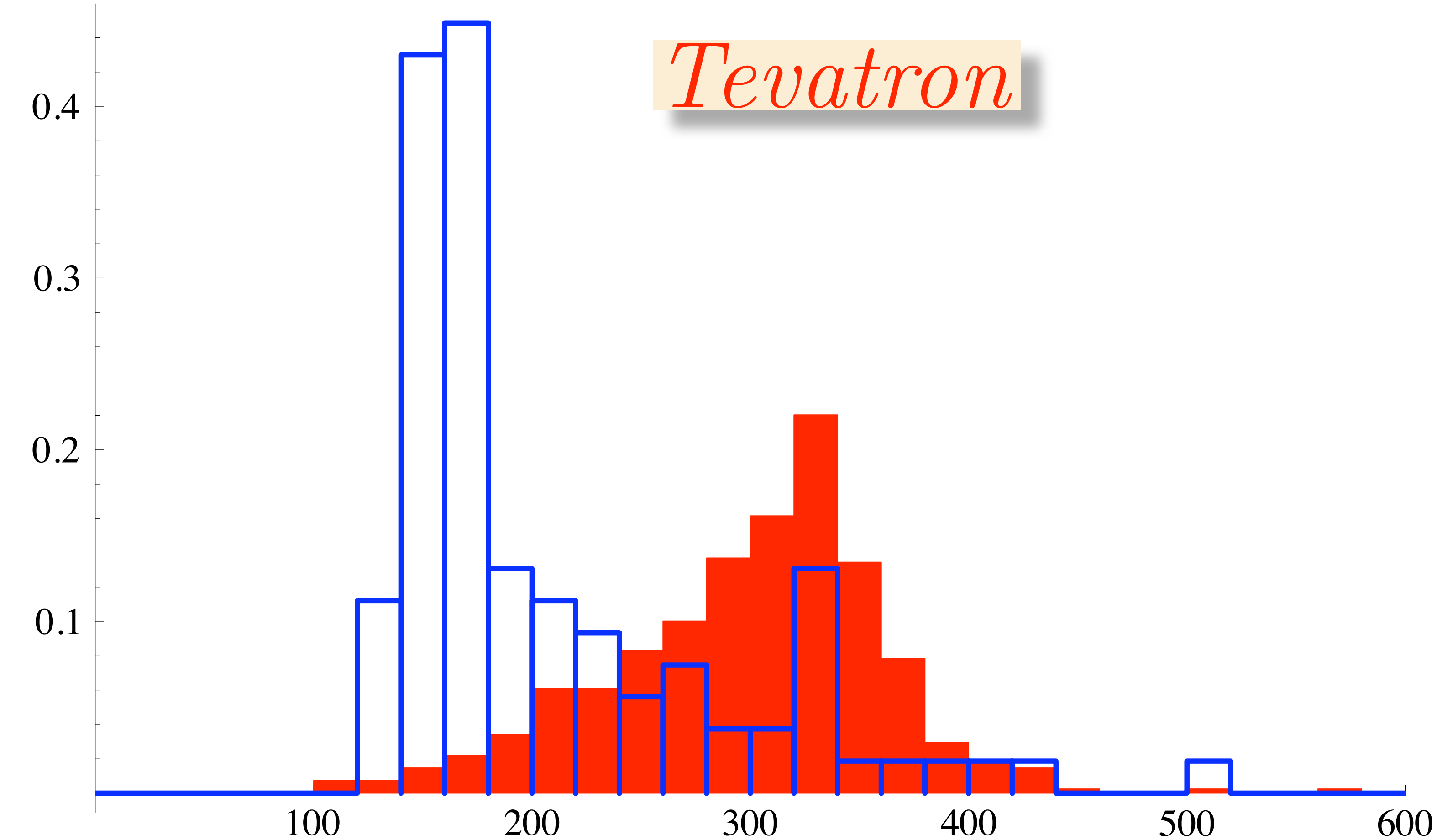
- conventional method

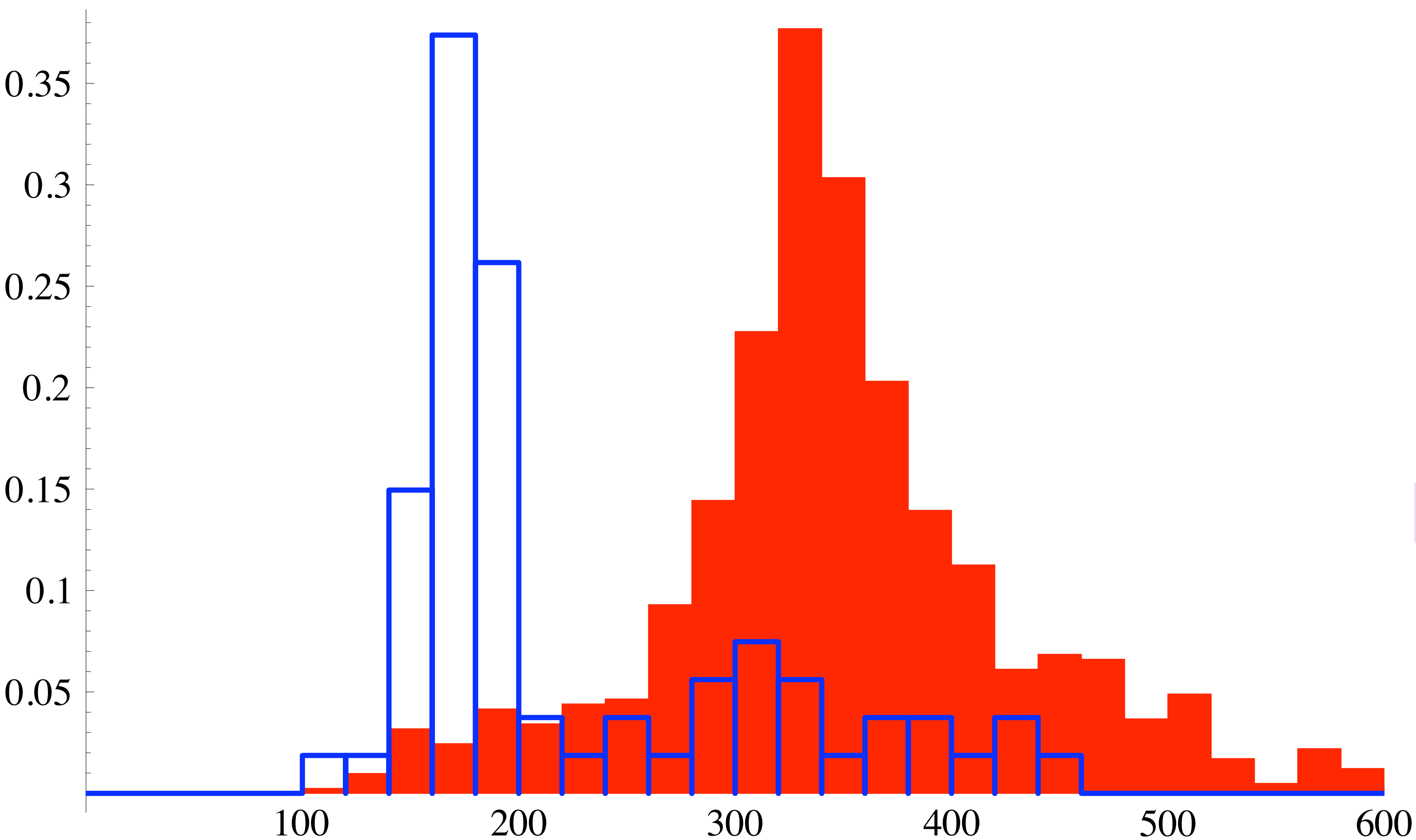
- W-jet method

Tevatron

- 1 TeV $p\bar{p}$, 4 fb^{-1}
- $m_{t'} = 350$ GeV



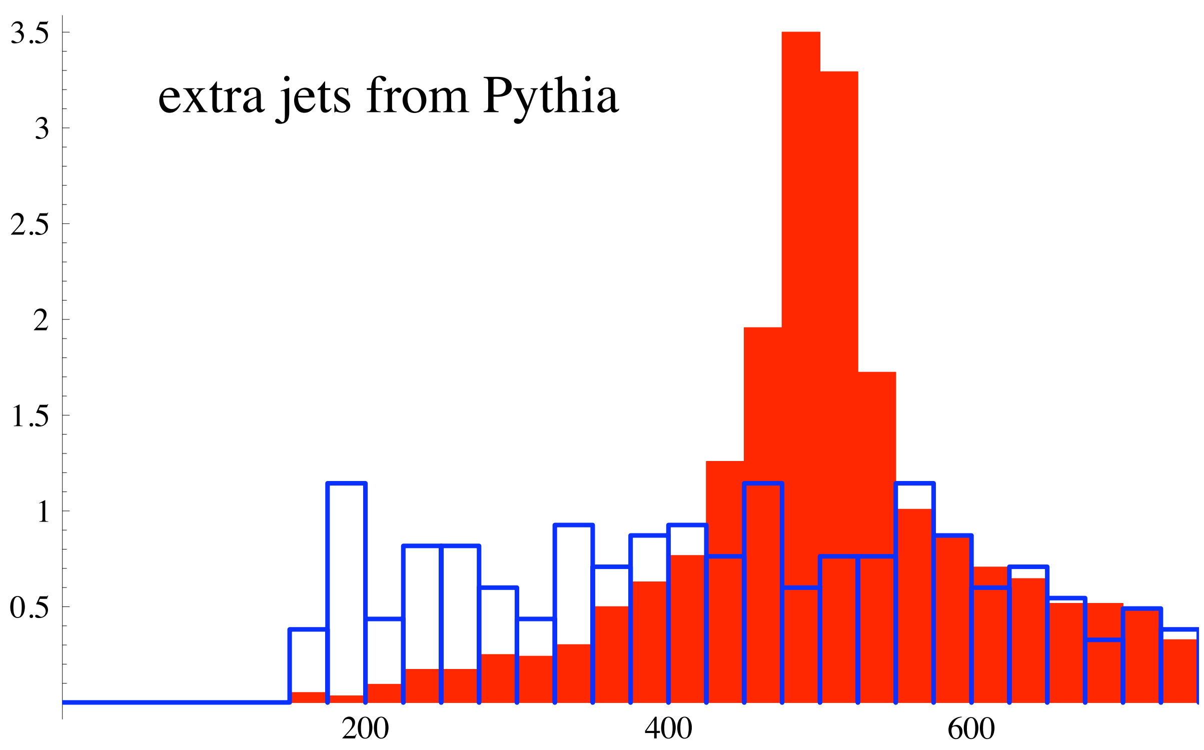
- conventional method

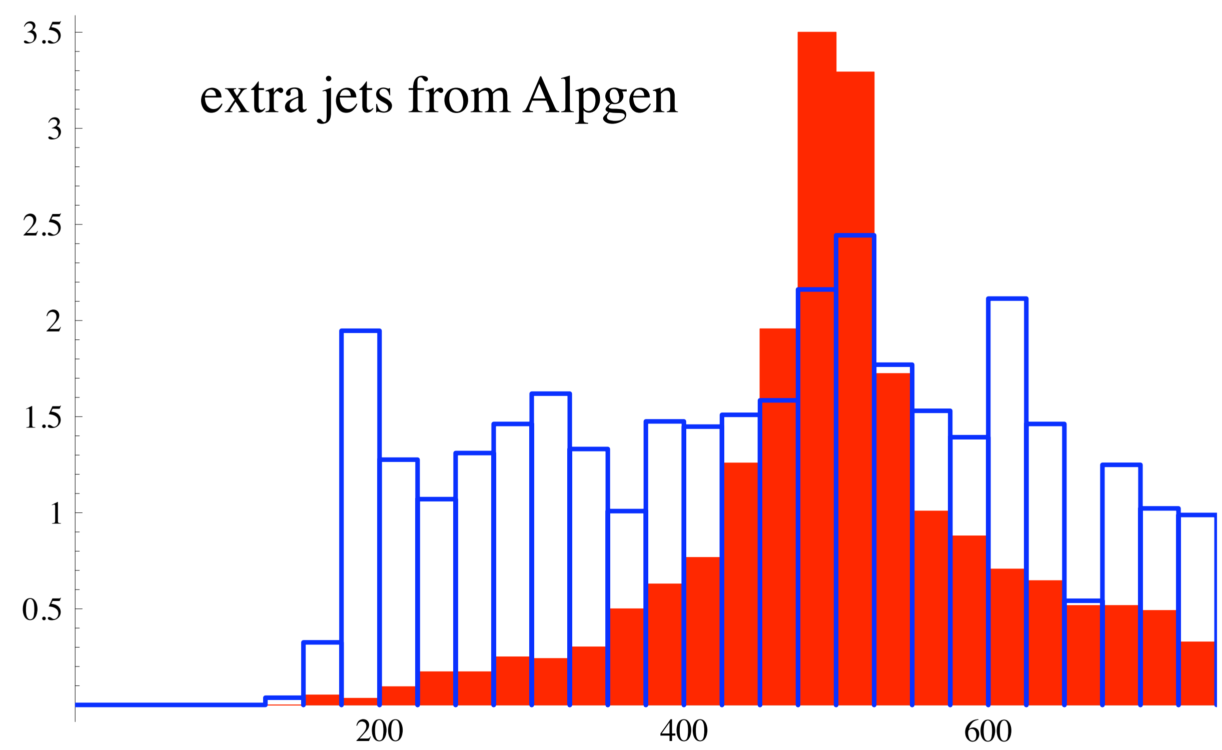


- *W*-jet method

- Alpgen-Pythia for background
- MadEvent-Pythia for signal
- CTEQ6L1 PDF with Pythia tune D6T
- PGS4 with ATLAS parameters

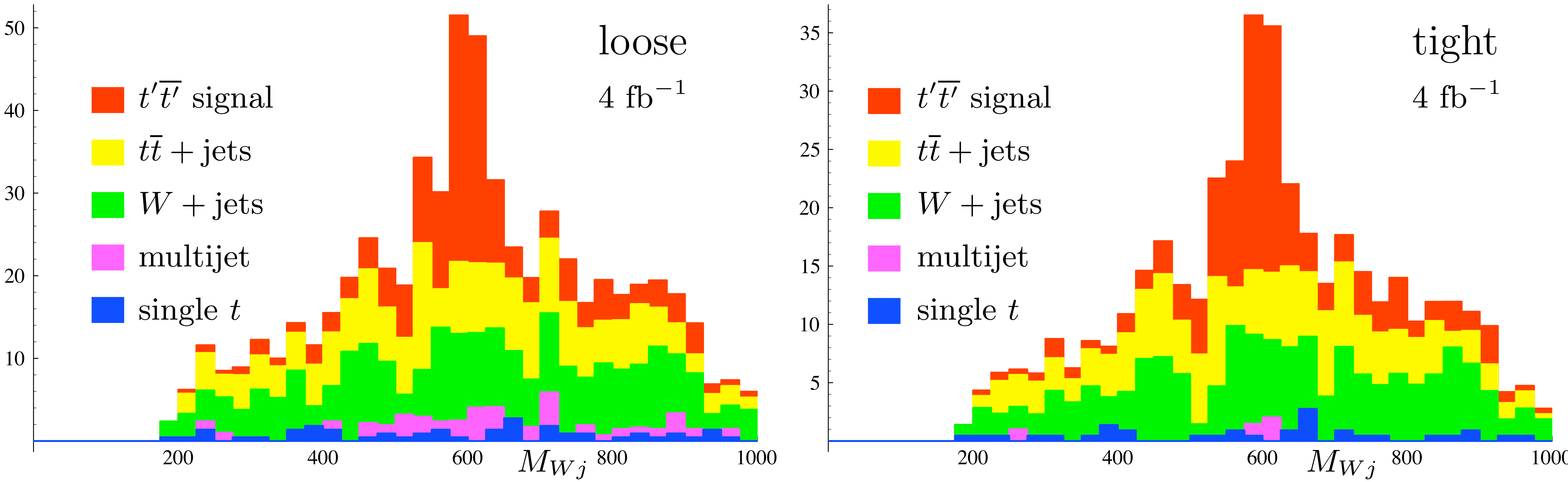
- Alpgen generates 0, 1, and 2 extra hard jet samples with $p_{T\min} = 50$ GeV
- otherwise $t\bar{t}$ background can be underestimated





- not clear that S/B can be improved using jet substructure

• without b tag



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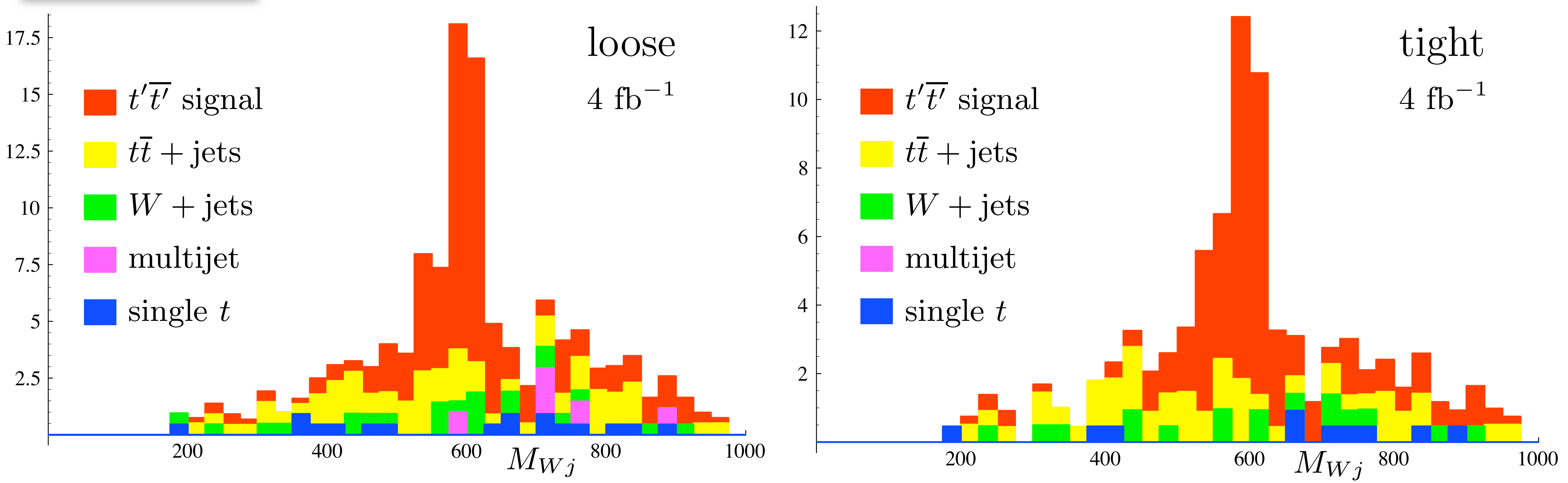

Fourth family and the Higgs

- modifies running of quartic Higgs coupling: $d\lambda/dt \propto \lambda y_{q'}^2 - y_{q'}^4 + \ldots$
- smaller range of m_h allowed to keep λ finite and positive at 1 TeV

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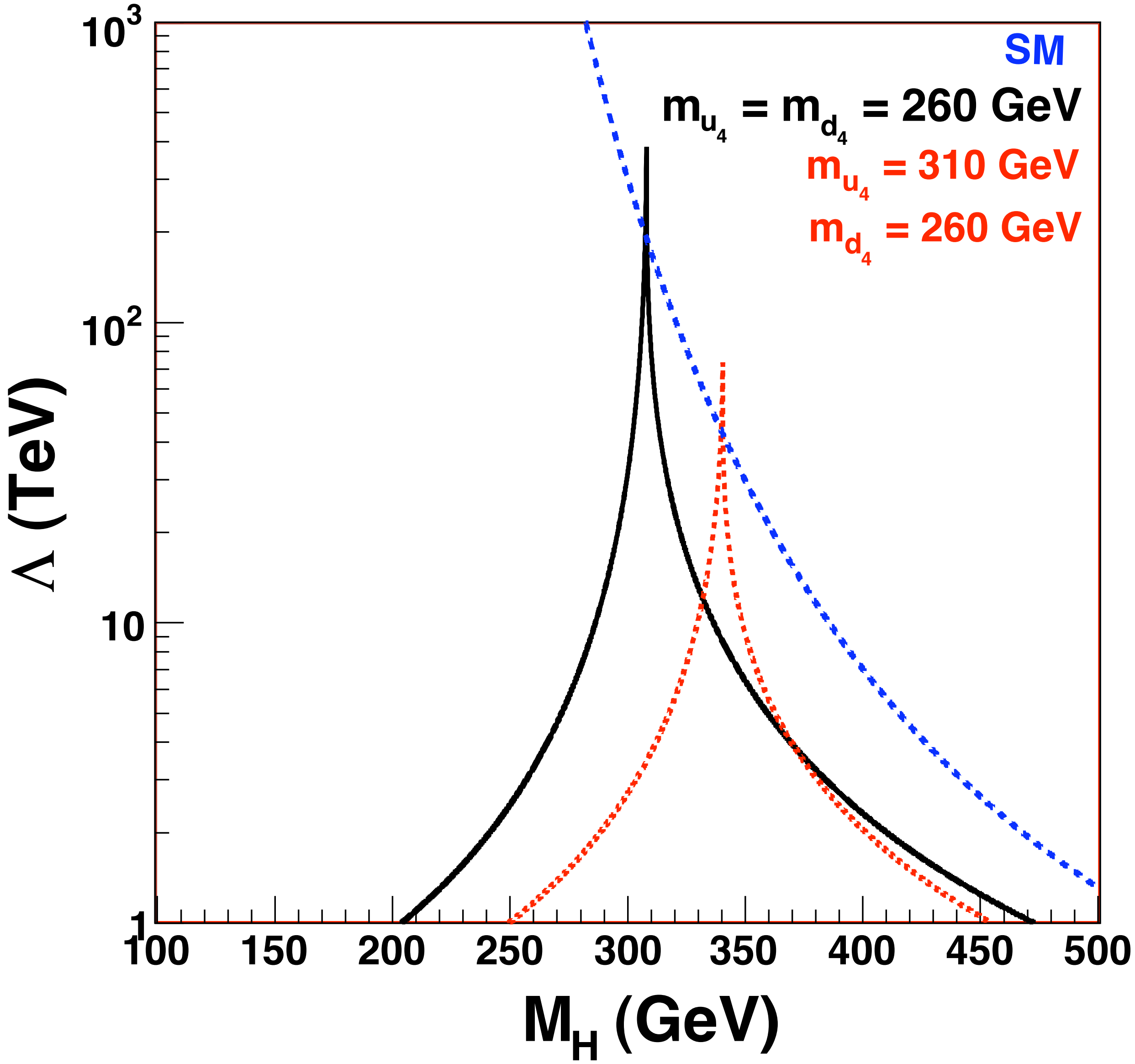
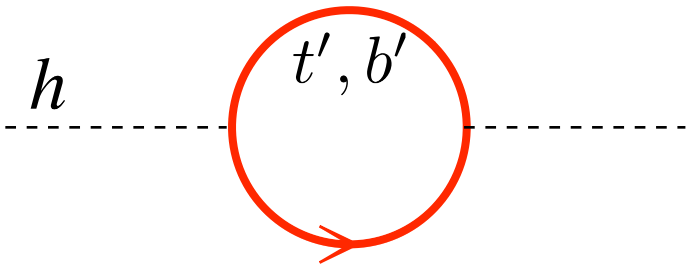
- even for the smallest possible masses (from Kribs et. al.) ...



- more dramatic is direct contribution to Higgs mass



assume cutoff $\Lambda > m_{q'}$

$$\delta m_h^2 \approx \left[\frac{m_{q'}}{400\ \mathrm{GeV}}\right]^2 \Lambda^2$$

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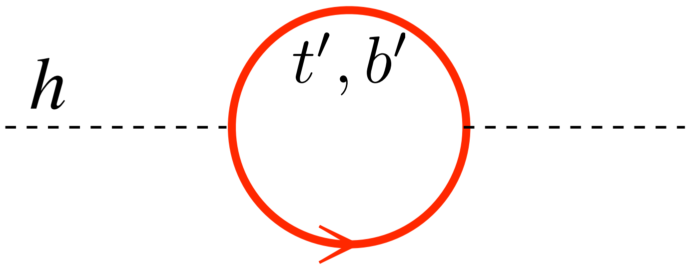

assume cutoff $\Lambda > m_{q'}$ $\longrightarrow$

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- e.g. supersymmetry with $m_{\tilde{q}'} \approx m_{q'}$

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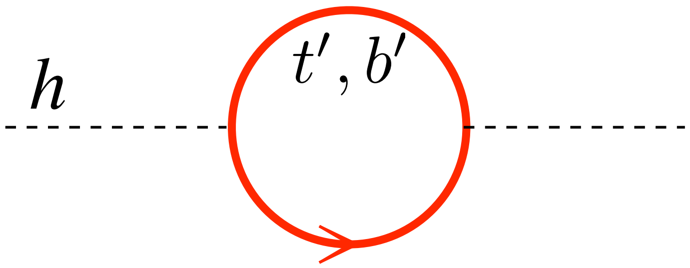

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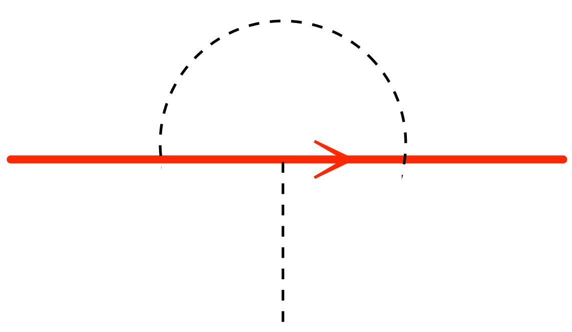

- but even in SUSY the Yukawa couplings $y_{q'}(\mu)$ run quickly
- again, strong interactions are not far away unless even more new physics is added Murdock, Nandi, Tavartkiladze

bite the bullet, cut out the Higgs

from wikipedia:

Bite the bullet is a phrase that generally refers to the acceptance of the consequences of a hard choice.[1] It is derived historically from the practice of having a patient clench a bullet in his or her teeth as a way to cope with the extreme pain of a surgical procedure without anesthetic.[2][3]

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- Goldstone bosons of electroweak symmetry breaking couple strongly to t', b'
- strong interactions unitarize WW scattering
- $\langle\phi\rangle$ is replaced by $\langle\bar{t}'t'\rangle$, $\langle\bar{b}'b'\rangle$, $\langle\bar{\nu}'\nu'\rangle$, $\langle\bar{\tau}'\tau'\rangle$
- ΔT from light Higgs is replaced by effects $\propto (m_{t'} - m_{b'})^2$, $(m_{\nu'} - m_{\tau'})^2$

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the underlying physics?

- fourth family does not feel a new confining force (CKM mixing)
- if a new strong gauge interaction, then it must be broken

before 4th family discovery, why consider such a thing?

The conservative case

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The conservative case

why the Higgs is not conservative

- elementary scalar fields go beyond what we know
- scalar mass is unstable and unnatural
- another layer is needed—but still 'little hierarchy problem'

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why the Higgs is not conservative

- elementary scalar fields go beyond what we know
- scalar mass is unstable and unnatural
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- again, supersymmetry goes beyond what we know
- no consensus on susy breaking (nonperturbative?)
- parameters (lots) replace understanding of mass and flavor
- fine-tuning problems still linger

A conservative start

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- dynamical symmetry breaking and mass formation occurs through strongly interacting gauge theories (QCD)

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- but EWSB and flavor physics are missing

pass EWSB, go directly to flavor

- broken gauge interactions can play central role
- can connect different families and have the effect of feeding mass down from heavy to light

$$\frac{1}{\Lambda^2}\overline{\Psi}\Psi\overline{\psi}\psi \quad \Rightarrow \quad \psi \text{ mass}$$

- to do this, scales of flavor physics range from a TeV to ≈ 1000 TeV

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EWSB—what produces $\langle\overline{\Psi}\Psi\rangle$?

- unbroken gauge interaction $\rightarrow$ technicolor
- broken gauge interaction $\rightarrow$ lightest remnant of flavor interaction

$$\frac{1}{\Lambda'^2}\overline{\Psi}\Psi\overline{\Psi}\Psi \quad \Rightarrow \quad \langle\overline{t'}t'\rangle, \langle\overline{b'}b'\rangle, \langle\overline{\nu}'\nu'\rangle, \langle\overline{\tau}'\tau'\rangle \quad \Rightarrow \quad \text{EWSB}$$

proceed sideways

- consider a new massive gauge boson X coupling to all fourth family members the same way (remnant of a sideways gauge symmetry)
- not so fast—gauge anomalies
- canceled by having equal and opposite couplings to the third and fourth families
- any approximate symmetry between third and fourth families must be dynamically broken

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view from the top

- there is a tension between the need for an approximate custodial symmetry and the top mass
- need separation of scales
  - approximate custodial symmetry is a property of 1 TeV dynamics
  - the top mass is a reflection of $SU(2)_R$ breaking at a higher scale
- so how is the $SU(2)_R$ breaking communicated to the top mass?

- consider an operator that can arise from $SU(2)_L \times U(1)$ preserving physics

$$\frac{1}{\Lambda^2}\bar{b}'_L b'_R \bar{t}_L t_R \quad \Rightarrow \quad t \text{ mass}$$

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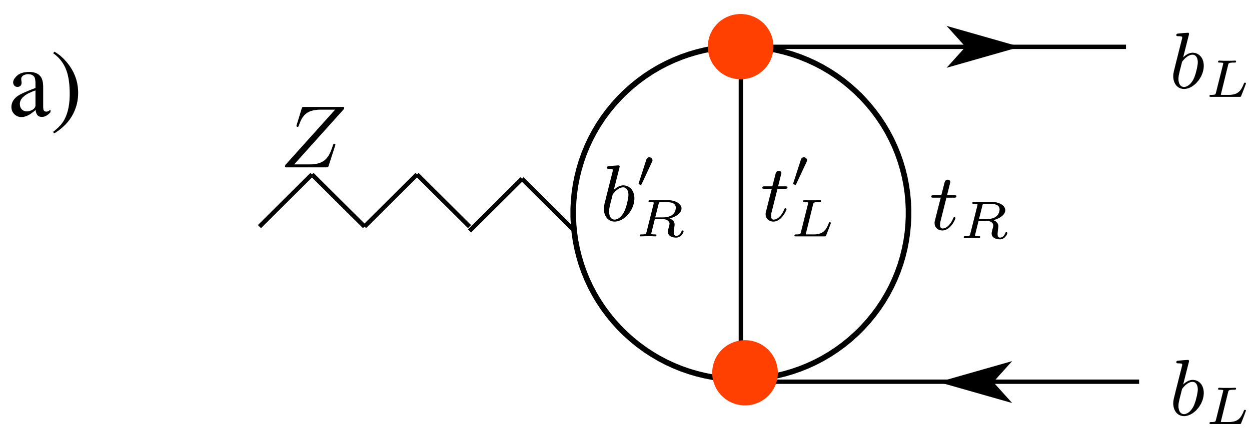
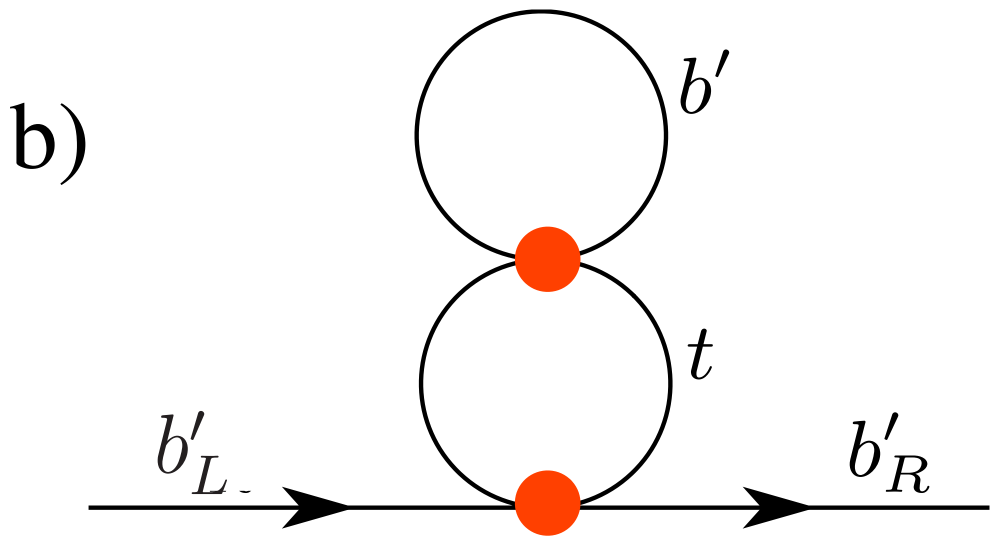
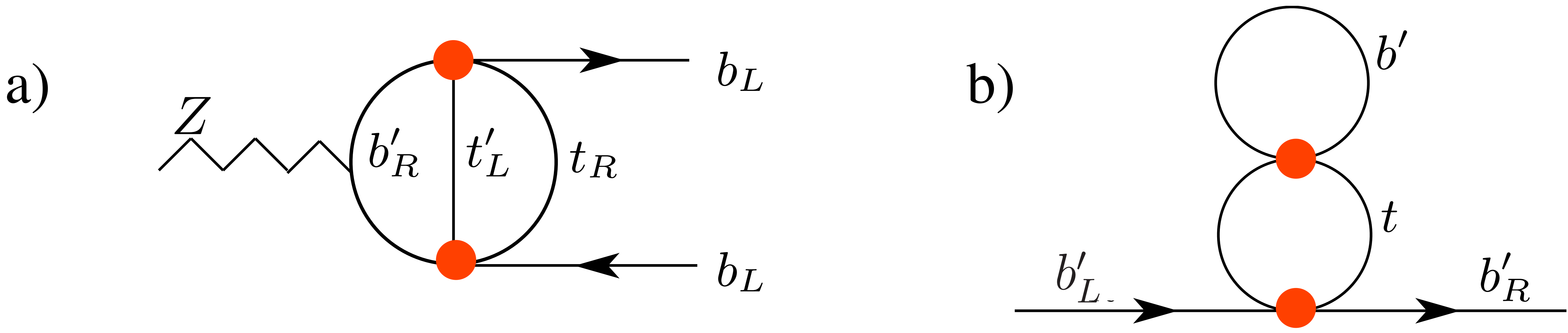




- consider an operator that can arise from $SU(2)_L \times U(1)$ preserving physics

$$\frac{1}{\Lambda^2}\bar{b}'_L b'_R \bar{t}_L t_R \quad \Rightarrow \quad t \text{ mass}$$

- due to its form, custodial sym. breaking and $Zb\bar{b}$ corrections are suppressed



- leads to $m_{b'} > m_{t'}$
- if **both** third and fourth family quarks feel a 'walking type interaction', then can get suitable enhancement of t mass operator
- points again to a remnant flavor interaction—the X boson

the X

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\begin{aligned}
b\bar{b} &\rightarrow X && (\approx 2/3 \text{ of cross section}) \\
g(b \text{ or } \bar{b}) &\rightarrow X g(b \text{ or } \bar{b}) && (\approx 1/4 \text{ of cross section}) \\
gg &\rightarrow X b\bar{b} && \\
q(b \text{ or } \bar{b}) &\rightarrow X q(b \text{ or } \bar{b}) && (q = \text{light quark})
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- X is probably a broad resonance (also unlike a typical Z')

$$\Gamma_X \approx g_X^2 \left[\frac{M_X}{500 \text{ GeV}} \right] 60 \text{ GeV}$$

Mass reconstruction

$$X \to \tau^+\tau^-$$

- boosted τ decay—visible and missing components are collinear
- visible components $\vec{p}_+$ and $\vec{p}_-$ carry fractions x_+ and x_-—can be determined
- X invariant mass determined by the four-vectors p_+ and p_- is scaled up by $1/\sqrt{x_+x_-}$

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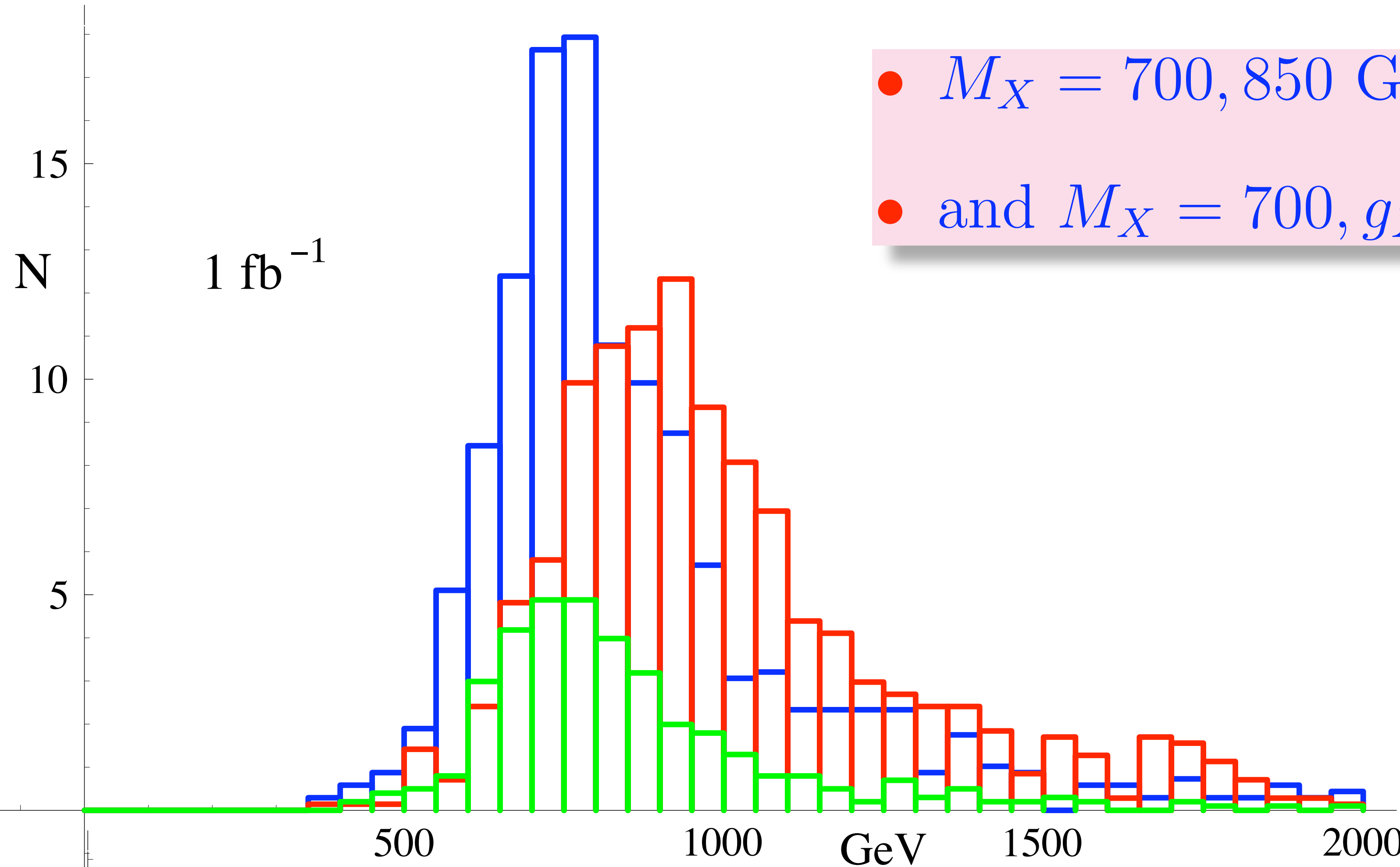
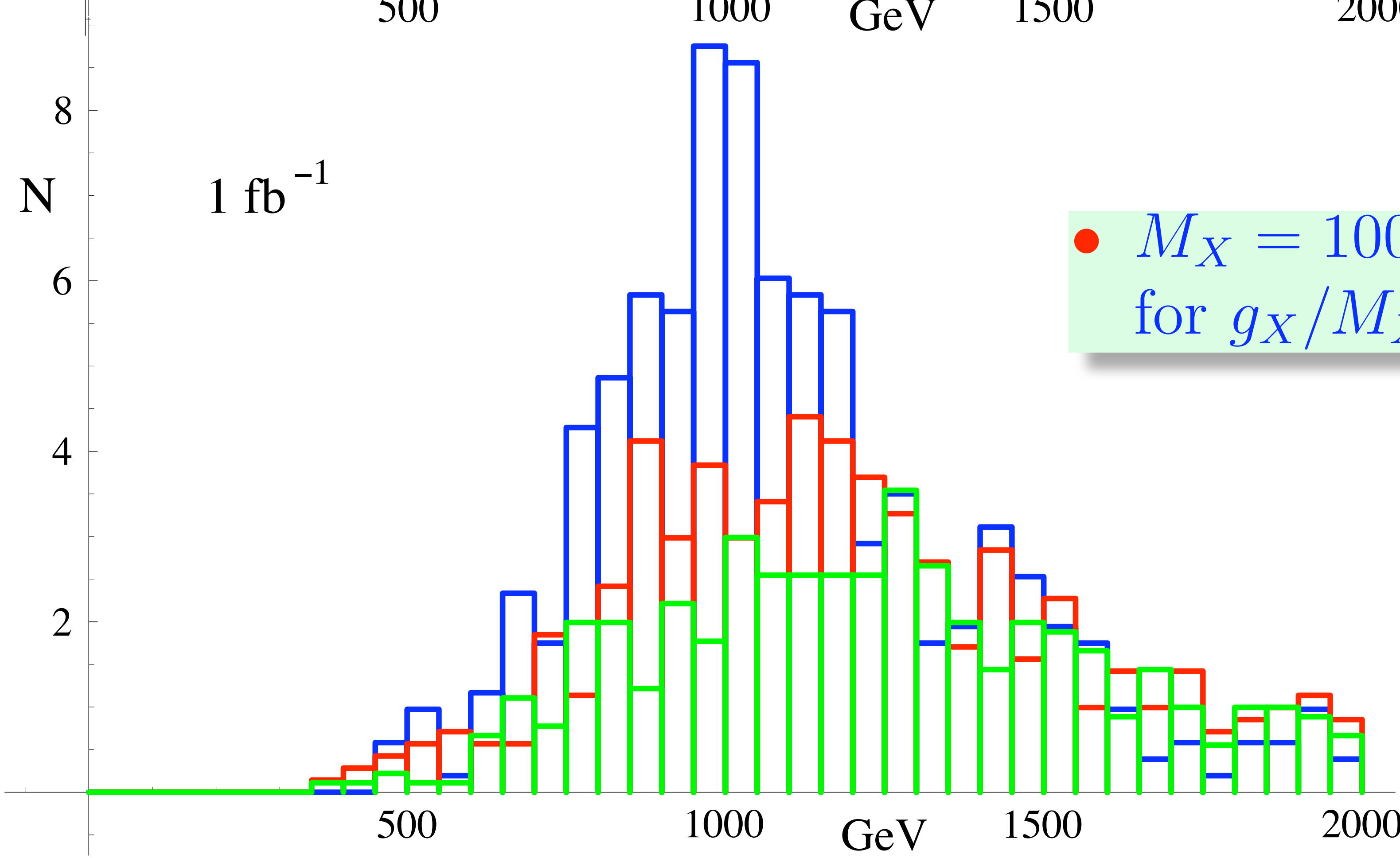
Cuts

- at least one pair of oppositely charged leptons, including τ-tagged jets, each with $p_T > 60$ GeV, with invariant mass > 300 GeV
- missing energy $\not{p}_T > 60$ GeV
- $H_T > 700$ GeV
- not more than one non-b-tag jet with $p_T > 60$ GeV



- $M_X = 700, 850$ GeV for $g_X/M_X = 1/700$
- and $M_X = 700, g_X = 0.5$ (green)

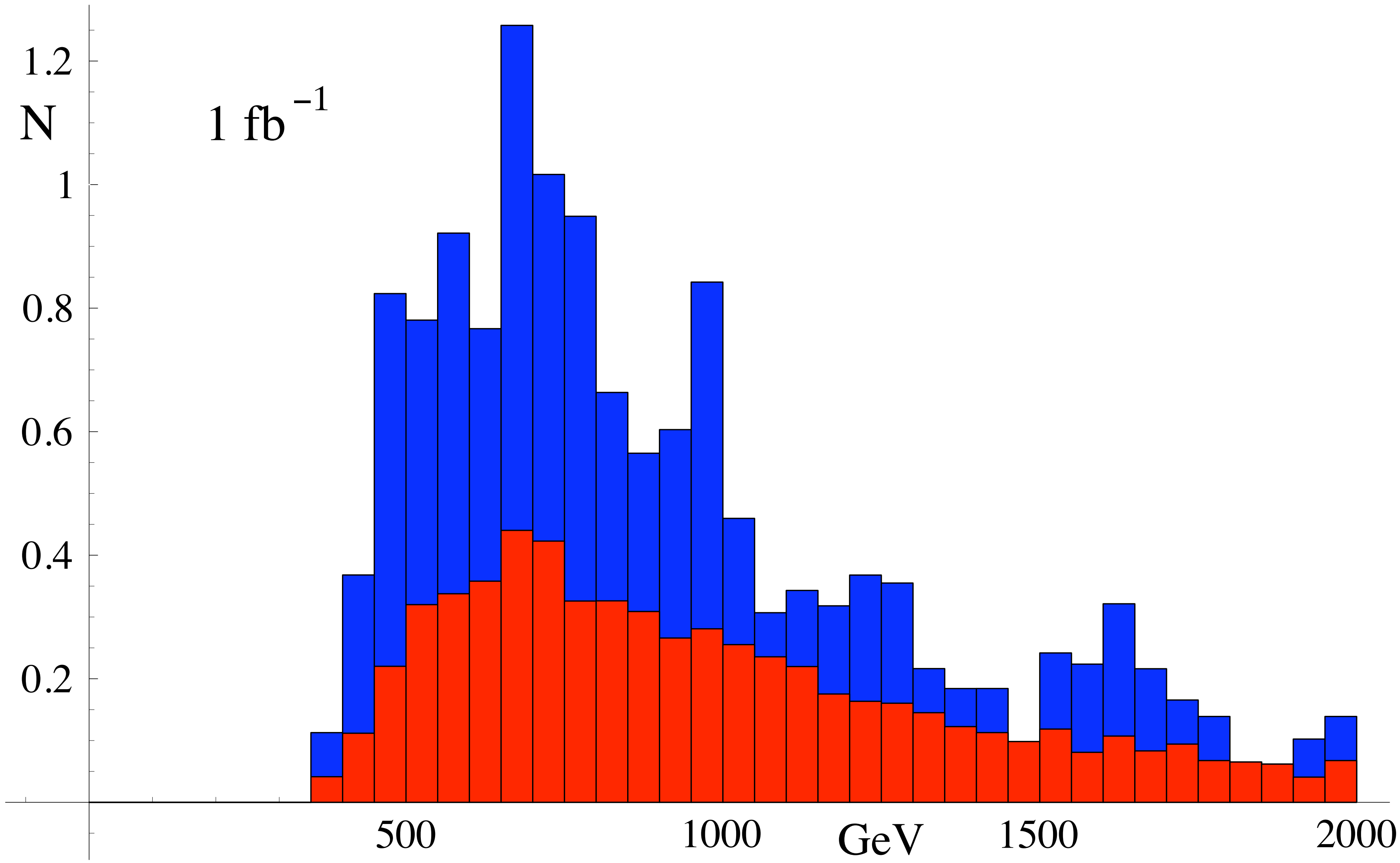


- $M_X = 1000, 1150, 1300$ GeV for $g_X/M_X = 1/700$

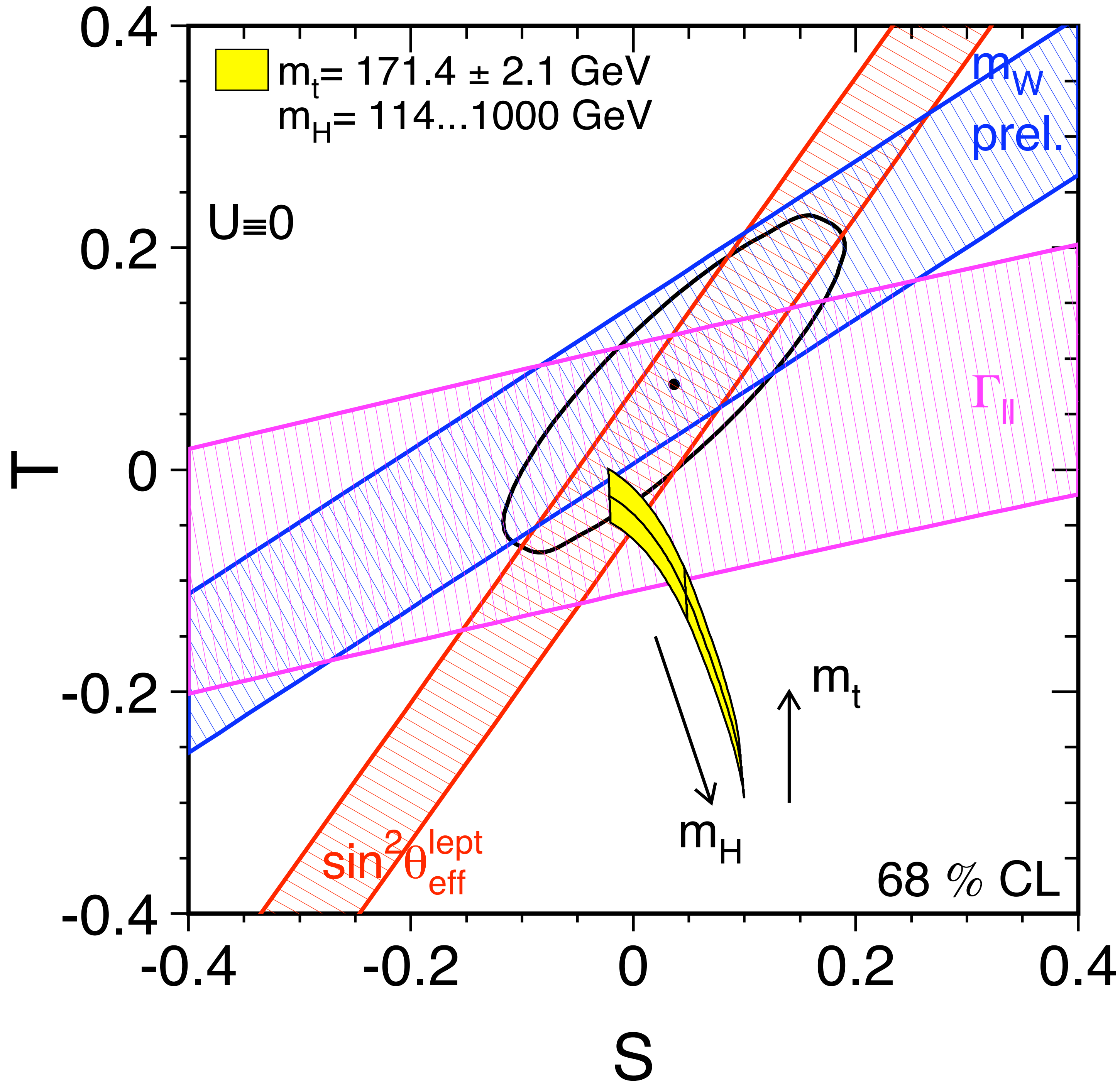
- width $\propto g_X^2 M_X$

main backgrounds

- $t\bar{t}$+jets (blue) with both top quarks decaying semileptonically
- W+jets (red) with W to decaying leptonically
  - take a τ fake rate of 1%



return to S and T



S and T from the fourth lepton sector

- depends on the form of the neutrino mass:
  - purely Dirac mass
  - Dirac mass plus Majorana mass for ν'_R
  - purely Majorana mass (no ν'_R)

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} usually considered (first two)

} BH, PRD54(1996)721 (third)

- ν_R's are not expected since it is more natural for $\langle\nu_R\nu_R\rangle \approx (1000\ \mathrm{TeV})^3$
- pure Majorana mass is dynamical and thus falls off in the ultraviolet

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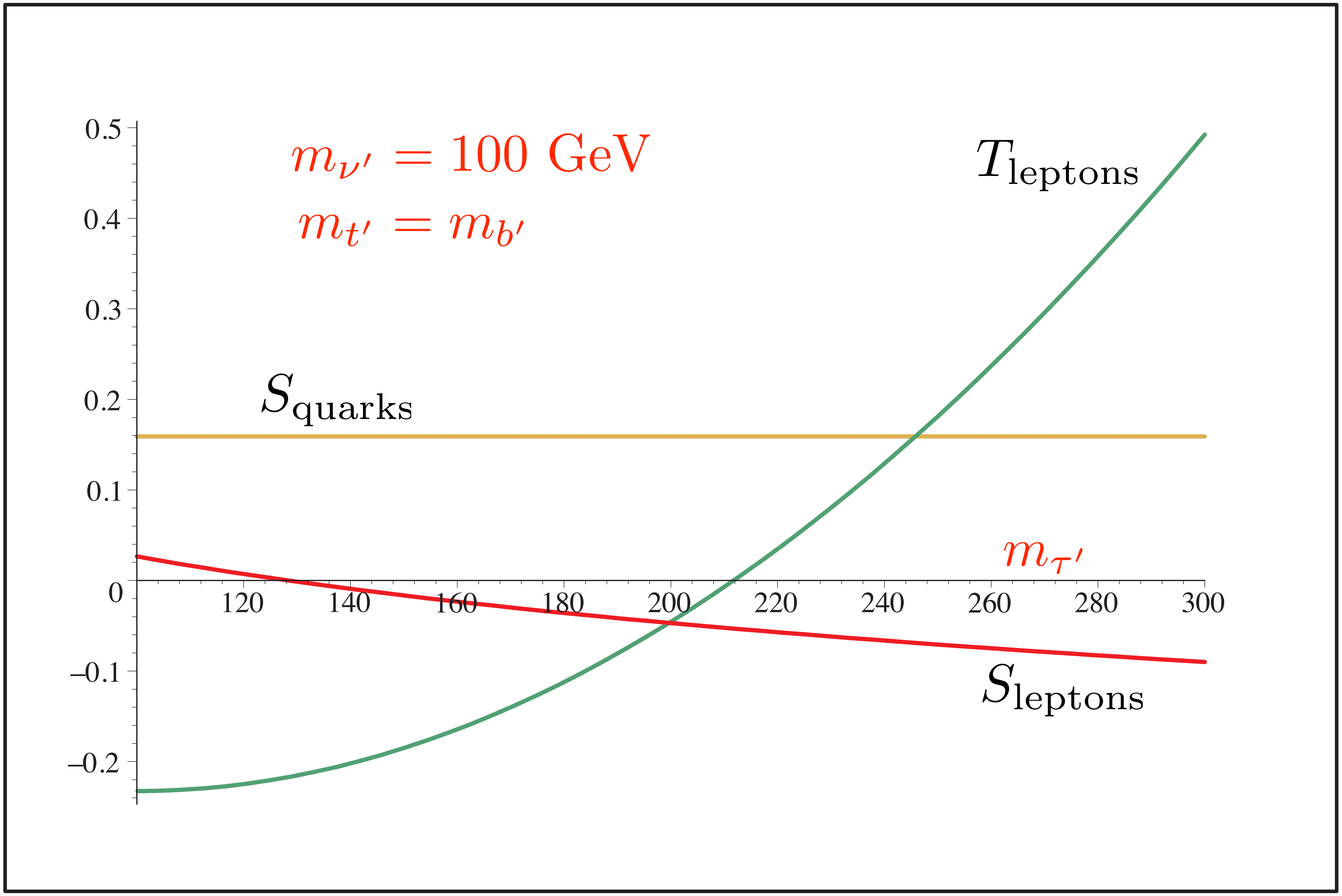
$$
\begin{aligned}
S_{\text{leptons}} &\approx \frac{1}{6\pi} - \frac{1}{3\pi}\ln\left(\frac{m_{\tau'}}{m_{\nu'}}\right) - \frac{1}{12\pi} \\
\alpha f^2 T_{\text{leptons}} &\approx \frac{1}{12\pi^2}(m_{\tau'} - m_{\nu'})^2 - \frac{m_{\nu'}^2}{4\pi^2}\ln\left(\frac{\Lambda_{\nu'}}{m_{\nu'}}\right)
\end{aligned}
$$

- $\Lambda_{\nu'}$ characterizes the ultraviolet fall-off of the mass function



$m_{\nu'} = 100$ GeV
$m_{t'} = m_{b'}$
T_{leptons}
S_{quarks}
$m_{\tau'}$
S_{leptons}
0.5
0.4
0.3
0.2
0.1
0
–0.1
–0.2
120
140
160
180
200
220
240
260
280
300

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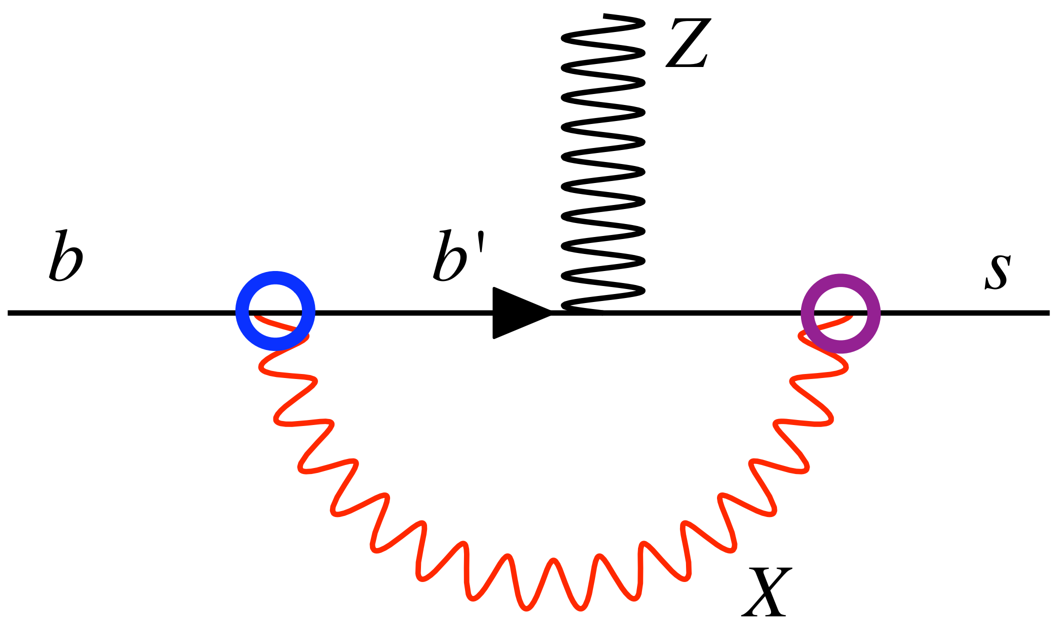
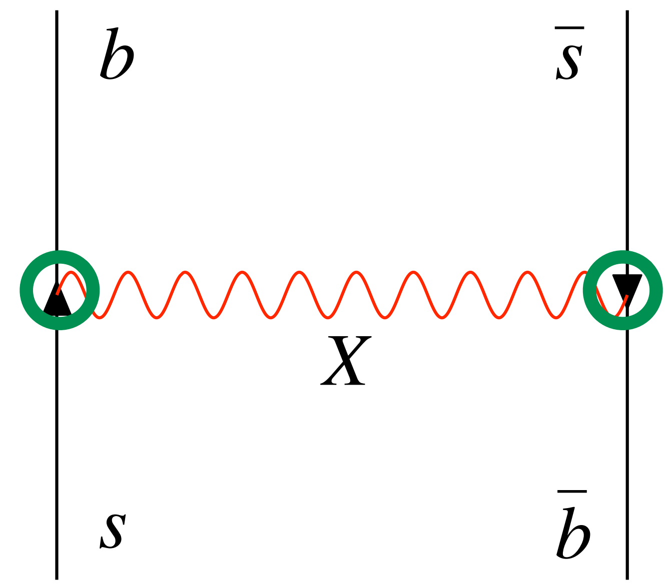
- even though there may be new strong interactions, a conservative point of view can still lead to "predictions"

New source of CPV in $b - s$ mixing





- vertex factors due to small mass mixing effects in the down sector (already must be smaller than CKM mixings)
- right handed couplings present
- independent mixing suppression factors

What does a 'potentially' complete model look like?

$$U_A(1) \times U_S(2) \times SU_{PS}(4) \times SU_L(2) \times SU_R(2)$$

$$(+, 2, 4, 2, 1)$$

$$(-, 2, 4, 1, 2)$$

$$(-, \overline{2}, 4, 2, 1)$$

$$(+, \overline{2}, 4, 1, 2)$$

- all possible global symmetries are gauged—but variations of this gauge symmetry is also be possible