The Strong Case for New Flavor Interactions

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

Search for a fourth family

- focus on the use of the jet mass technique

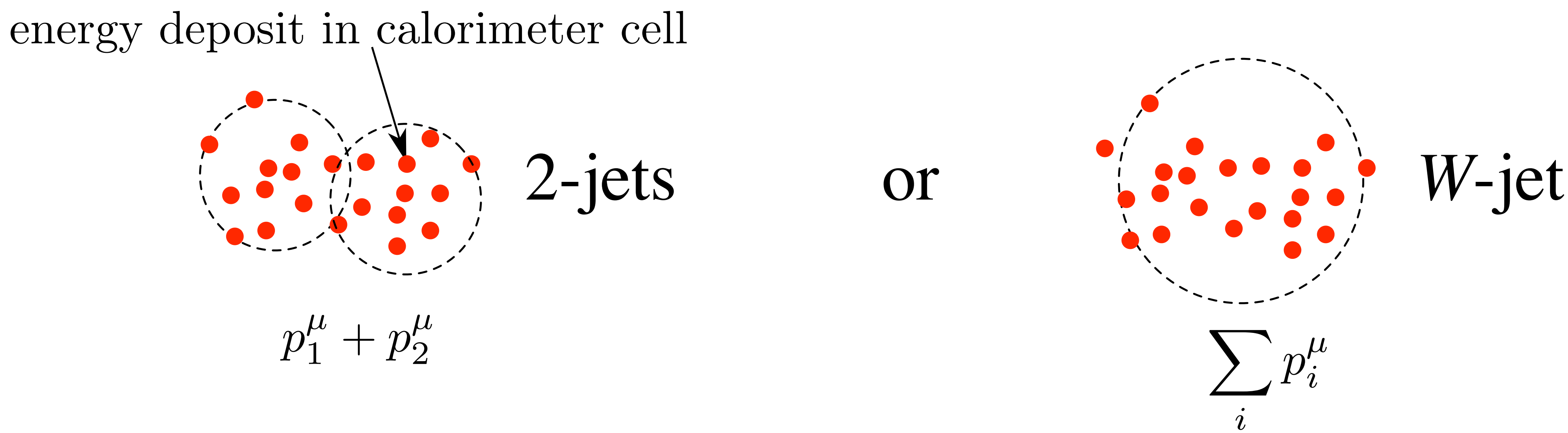
Implications of a fourth family

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

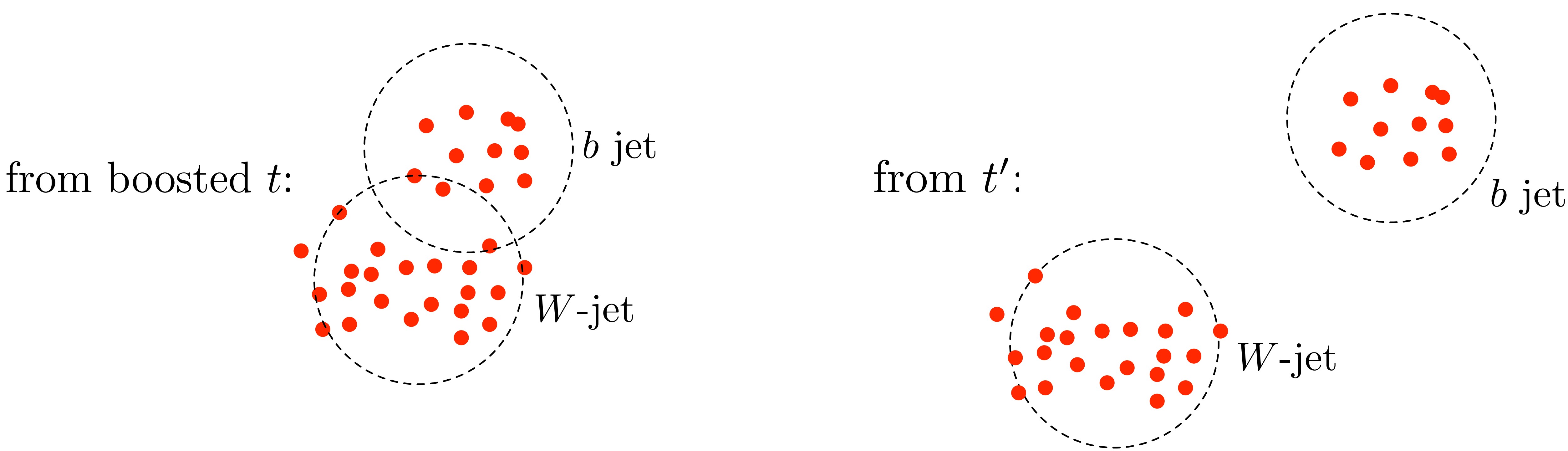
Motivation for a fourth family

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

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



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



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

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

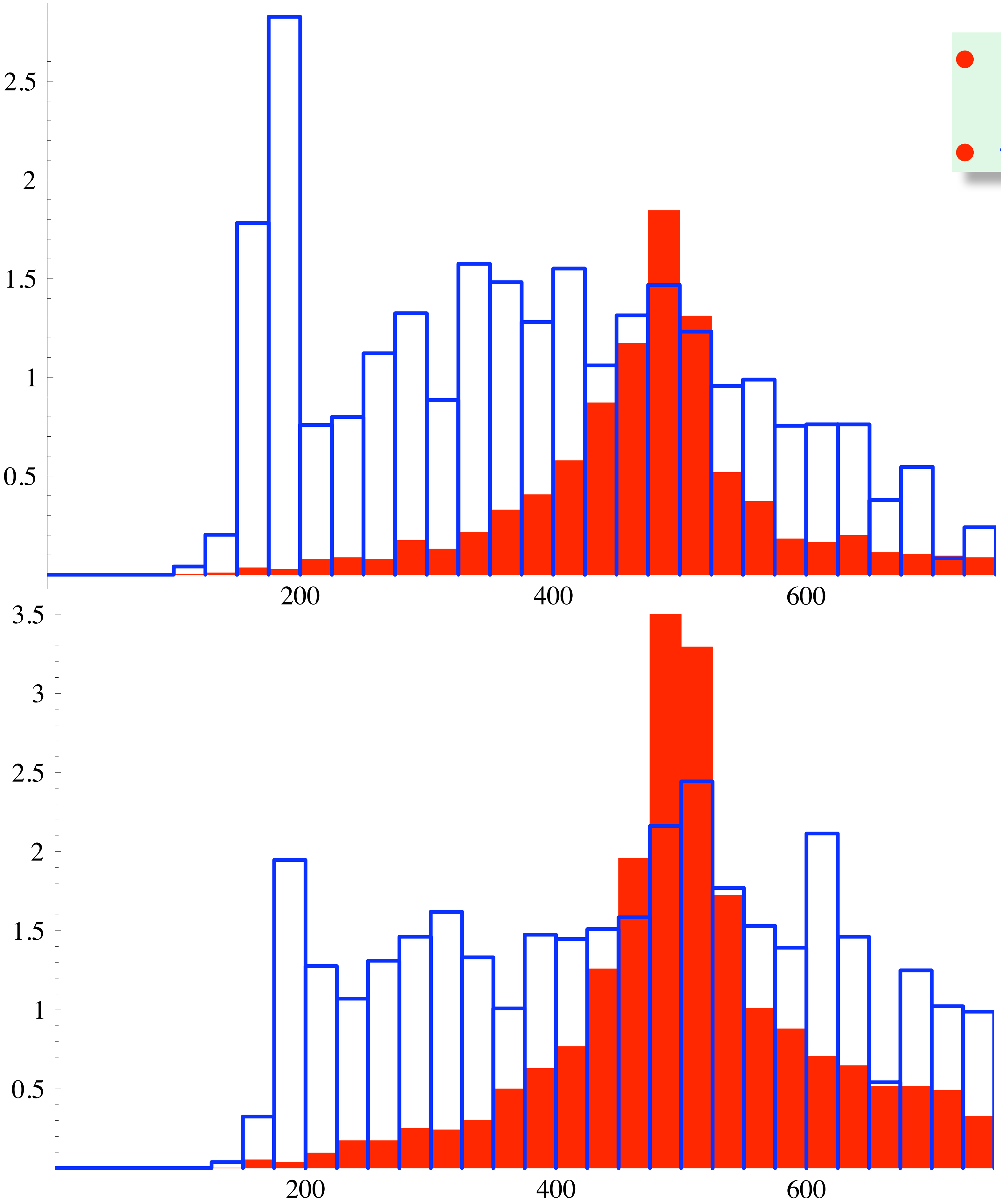
- isolated lepton with $p_T > 15$ GeV or missing $E_T > 100$ GeV
- three jets with $p_T > 60$ GeV, one with $p_T > 150$ GeV
- one "W-jet" with invariant mass $m_{\text{jet}} > 60$ GeV
- ΔR between ($p_T > 150$ jet) and (W-jet) less than 2.5
- take invariant mass of any two such objects

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)

compare the two methods

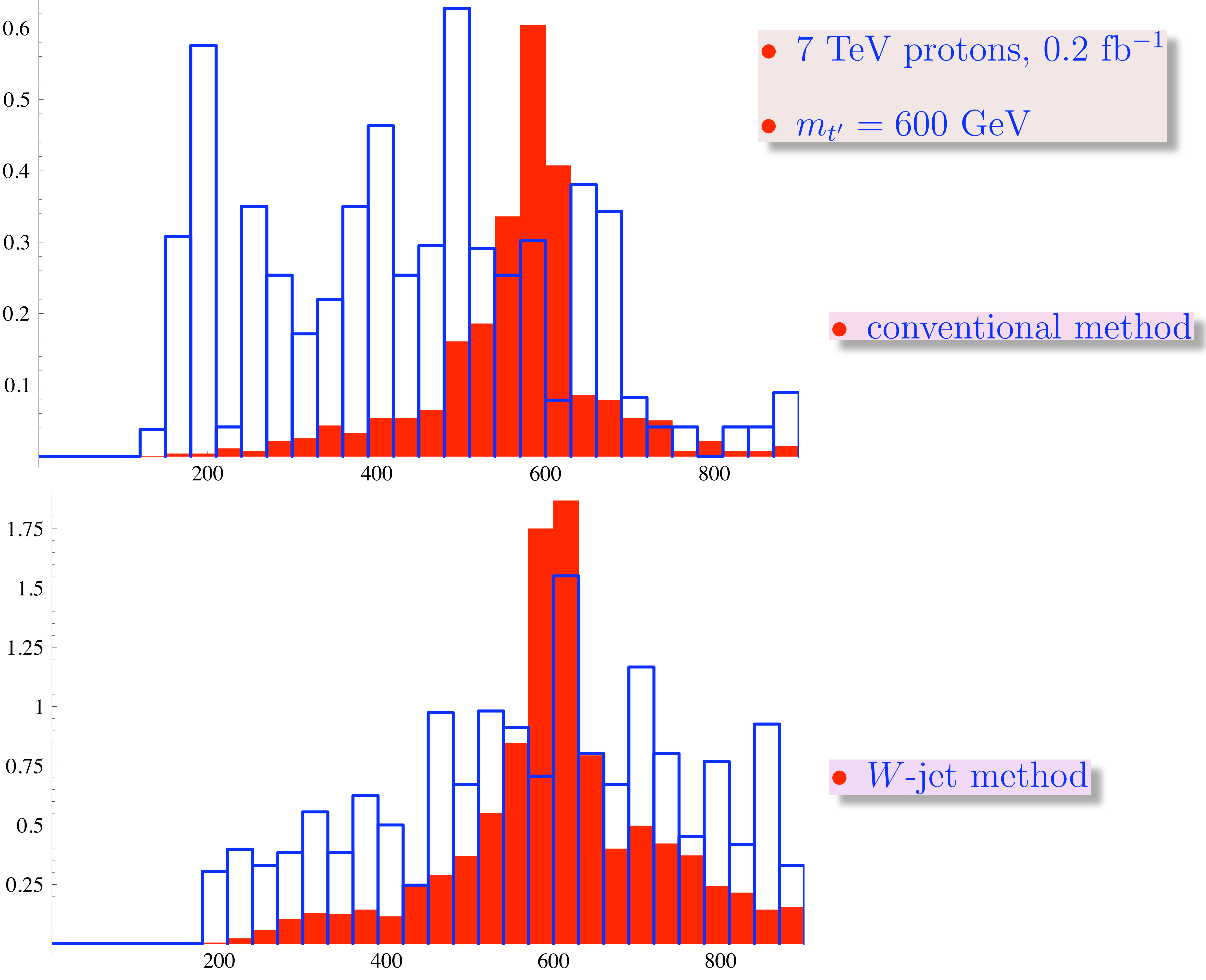
- $t'\bar{t}'$ signal vs $t\bar{t}$ background
- also take $H_T > 2m_{t'}$



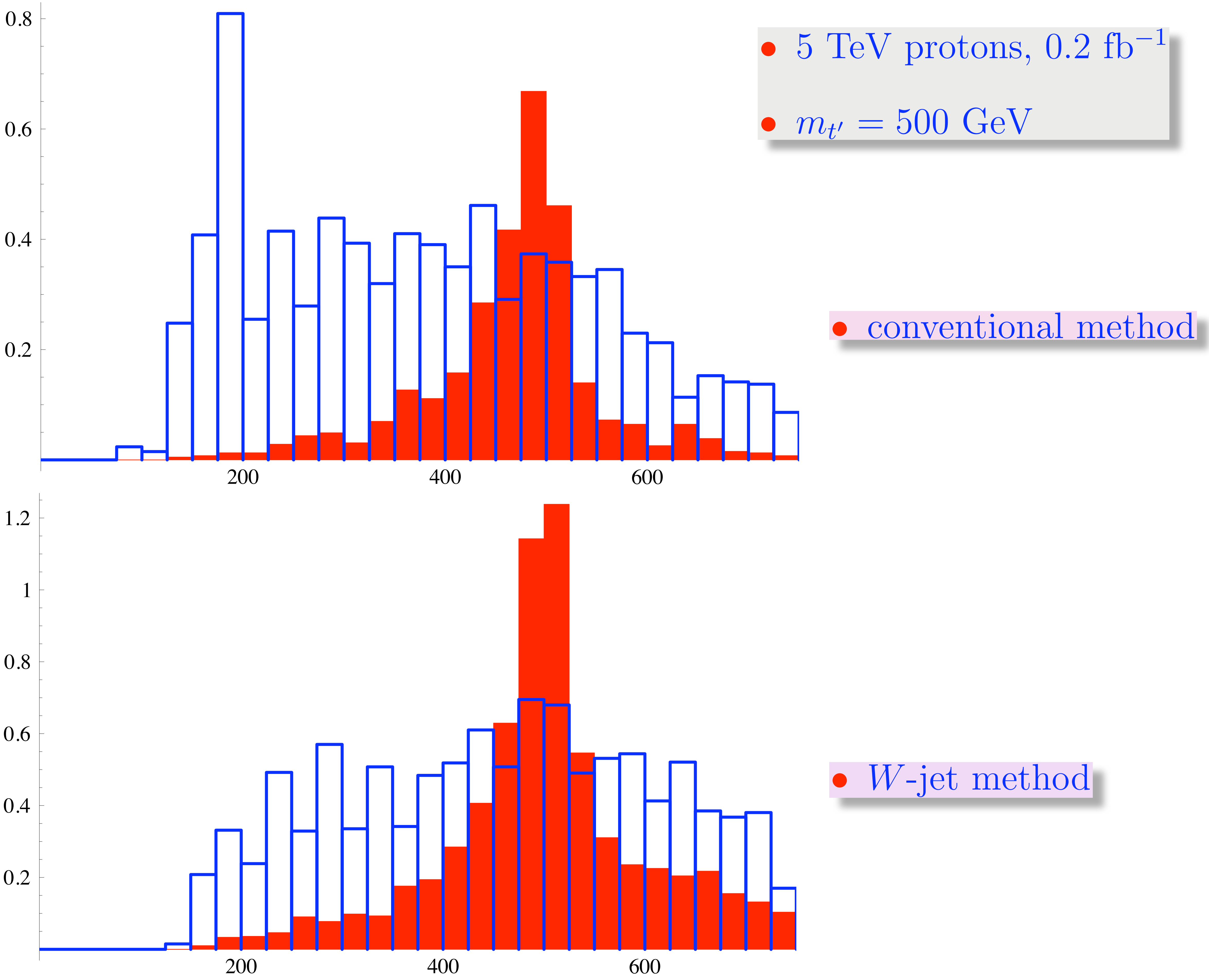
- 7 TeV protons, 0.2 fb^{-1}
- $m_{t'} = 500$ GeV

- conventional method

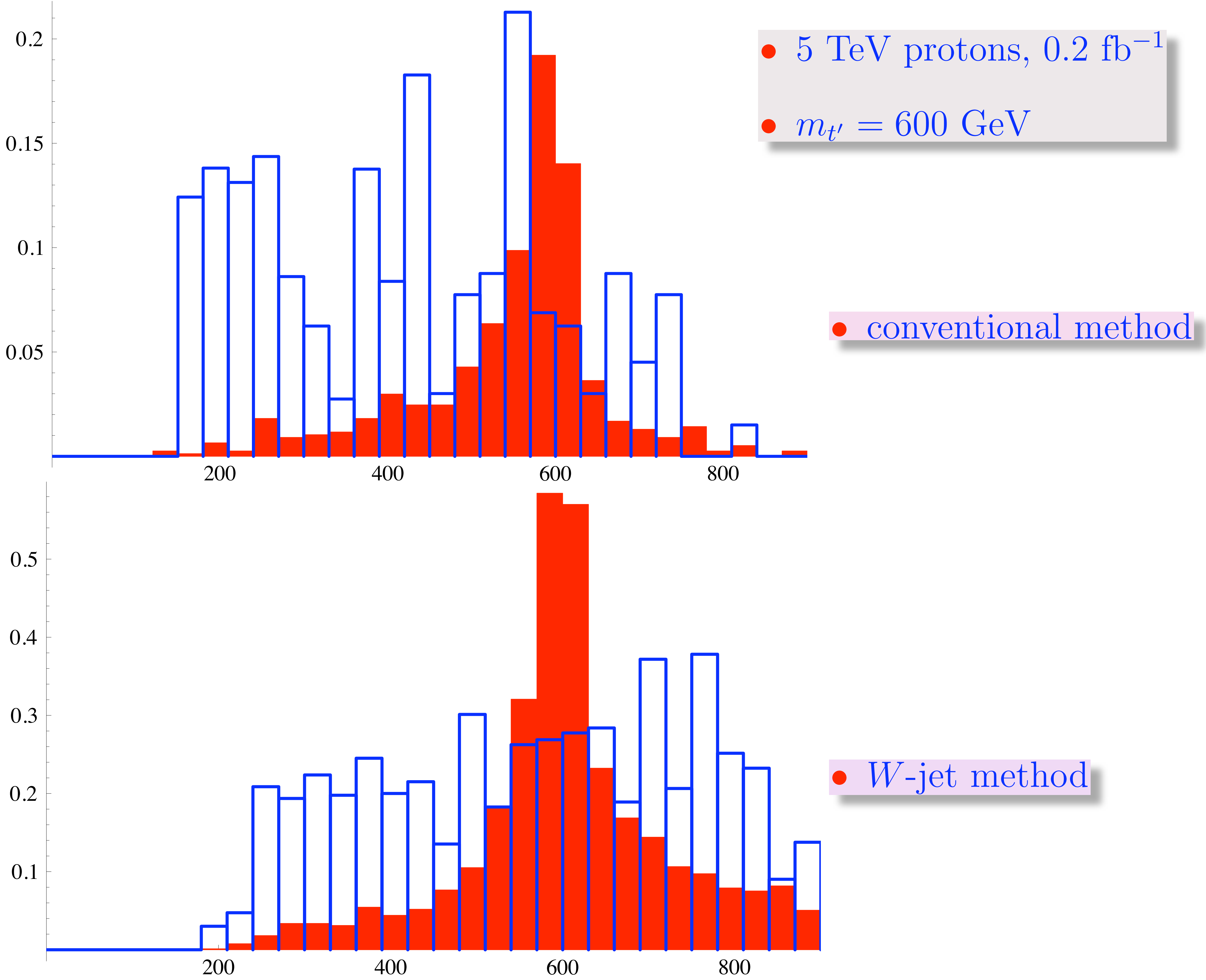
- W-jet method



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

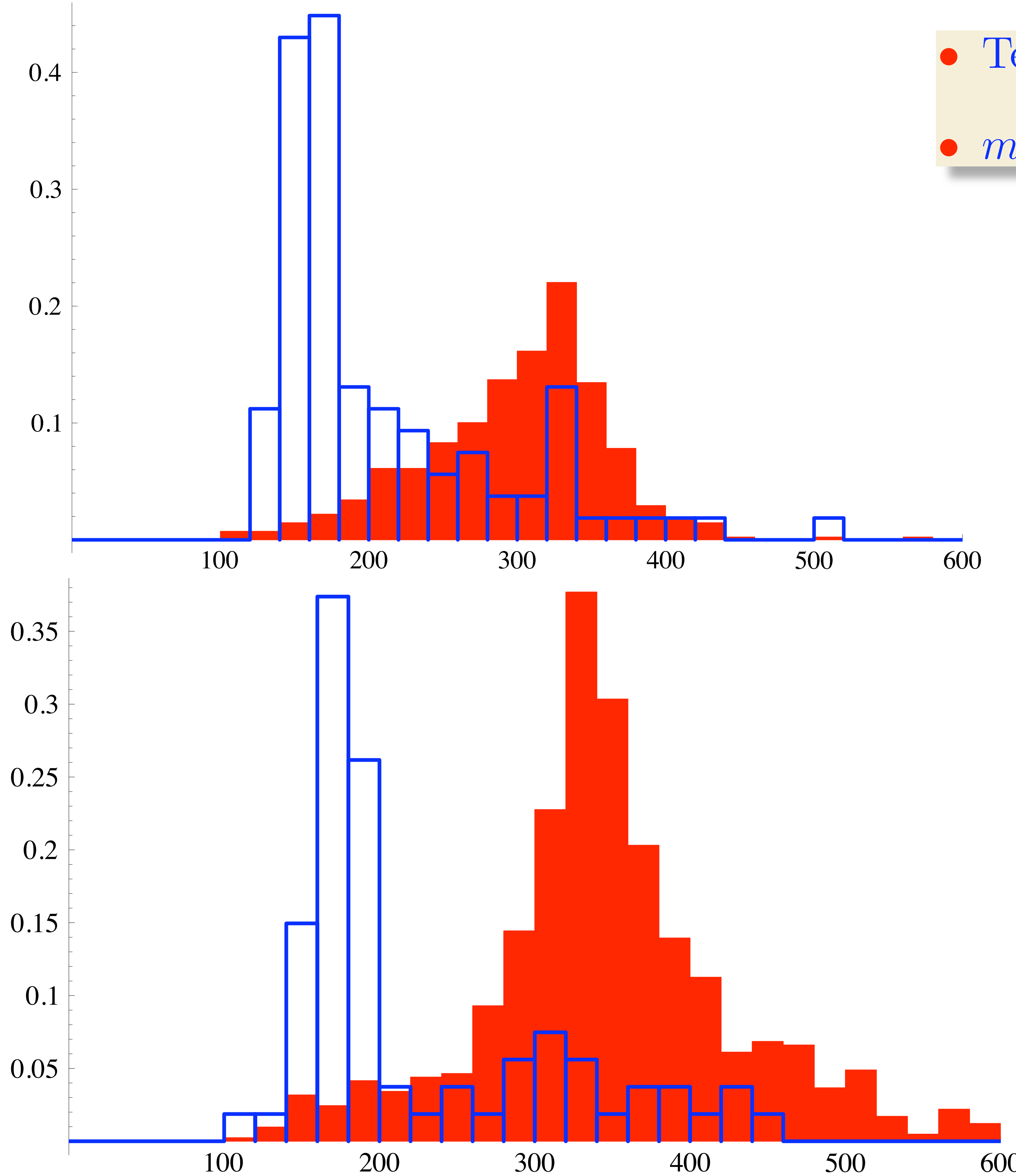


0.8
0.6
0.4
0.2
200
400
600
5 TeV protons, 0.2 fb^{-1}
$m_{t'} = 500$ GeV
conventional method
1.2
1
0.8
0.6
0.4
0.2
200
400
600
W-jet method



5 TeV protons, 0.2 fb^{-1}
$m_{t'} = 600$ GeV
conventional method
W-jet method
0.2
0.15
0.1
0.05
200
400
600
800
0.5
0.4
0.3
0.2
0.1
200
400
600
800

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

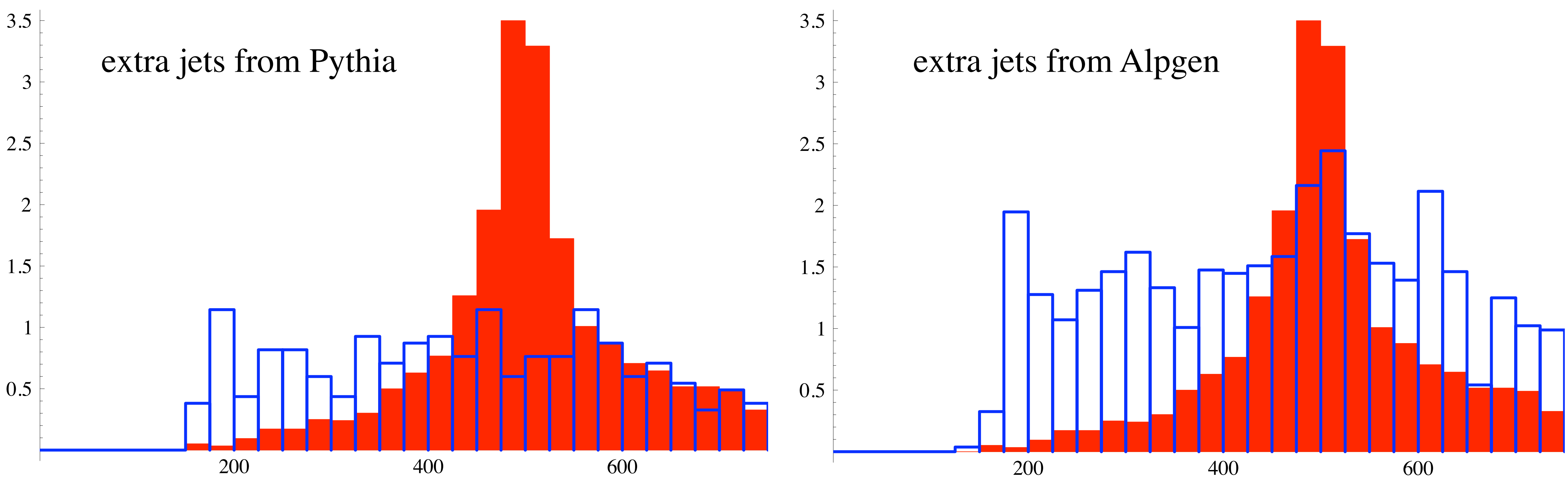


- conventional method

- 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 $p_{T\text{min}} = 50$ GeV
- otherwise $t\bar{t}$ background can be underestimated

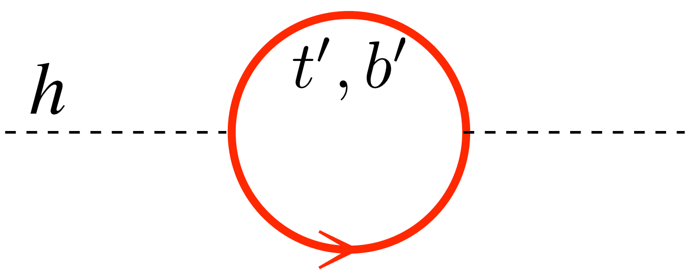


- not clear that S/B can be improved using jet substructure

Fourth family and the Higgs

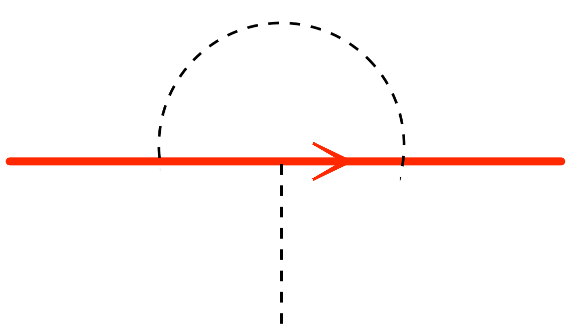
- modifies running of quartic Higgs coupling: $d\lambda/dt \propto \lambda y_{q'}^2 - y_{q'}^4 + \ldots$
- smaller range of m_h allowed to keep λ finite and positive at 1 TeV

- more dramatic is direct contribution to Higgs mass



assume cutoff $\Lambda > m_{q'}$ $\longrightarrow$ $\delta m_h^2 \approx \left[\frac{m_{q'}}{400 \text{ GeV}}\right]^2 \Lambda^2$

- to keep Higgs light, the new physics has to sit on top of the fourth family
- e.g. supersymmetry with $m_{\tilde{q}'} \approx m_{q'}$



- 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]

- for $m_{t',b'} \approx$ 600-700 GeV the Higgs loses meaning completely
- Goldstone bosons of electroweak symmetry breaking couple strongly to t', b'
- strong interactions unitarize WW scattering
- $\langle\phi\rangle$ is replaced by $\langle\overline{t}'t'\rangle$, $\langle\overline{b}'b'\rangle$, $\langle\overline{\nu}'\nu'\rangle$, $\langle\overline{\tau}'\tau'\rangle$
- ΔT from light Higgs is replaced by effects $\propto (m_{t'} - m_{b'})^2$, $(m_{\nu'} - m_{\tau'})^2$

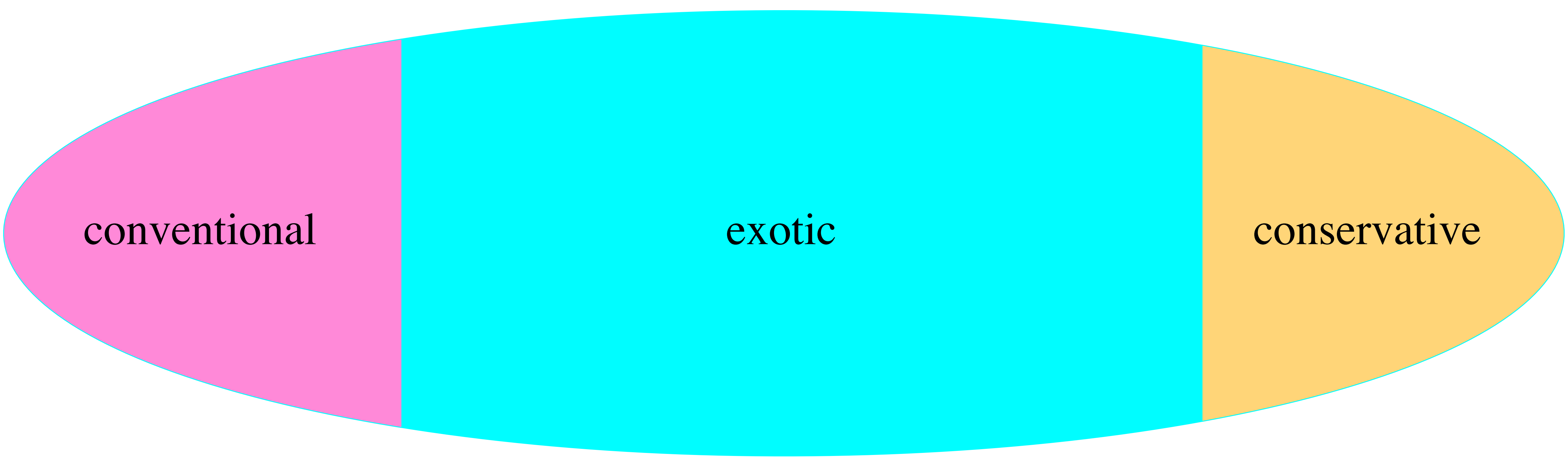
the underlying physics?

- 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?

Caution: unconventional opinions ahead

Theory Space



Most Conventional

Higgs

- part of our culture
- perturbative

but 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'

- 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

Most Conservative

- what do we know for sure?
- gauged theories of fermions exist in nature
- dynamical symmetry breaking and mass formation occurs through strongly interacting gauge theories (QCD)

- consider standard model with Higgs removed
- $SU(2) \times U(1)$ gauge symmetry still does not survive
- QCD $\Rightarrow$ $\langle \bar{q} q \rangle \neq 0$ $\Rightarrow$ W's and Z receive mass (too low of course)

- no problem with high energy unitarity
- $M_W \ll M_{\text{Planck}}$—what hierarchy problem?
- (chiral) gauge symmetries suffer from dynamical symmetry breaking in nature

broken gauge interactions

- theory of flavor
- electroweak symmetry breaking
- gauge anomalies
- top mass

theory of flavor

- broken gauge interactions can connect different families and have the effect of feeding mass down from heavy to light
- to do this, scales of flavor physics range from a TeV to ≈ 1000 TeV
  - also accounts for light neutrino masses
  - $\phi\phi\nu_L\nu_L$ is replaced by a six fermion operator

- new scales are inversely related to mass of fermions to which that physics couples
- new physics has little (big) impact on lightest (heaviest) fermions

EWSB

- heaviest fermions are 4th family: $\langle \overline{t'}t' \rangle$ $\langle \overline{b'}b' \rangle$ $\langle \overline{\nu}'\nu' \rangle$ $\langle \overline{\tau}'\tau' \rangle \Rightarrow$ EWSB
- lightest remnant of flavor interactions plays some role in generating these condensates
- "extended technicolor" without the technicolor

gauge anomalies

- can arise if e.g. a new massive gauge boson X couples to fourth family
- 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

top mass

- 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

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

- due to its form, custodial sym. breaking and $Zb\bar{b}$ corrections are suppressed
- if both third and fourth family quarks feel a 'walking type interaction', then suitable enhancement is expected
- points again to a remnant flavor interaction—the X boson

main point

- Yukawa couplings → decouples theory of flavor from electroweak symmetry breaking
- no elementary scalar → flavor problem becomes integrated with EWSB

- our fascination with the Higgs keeps us from considering a more exciting prospect at the LHC—the discovery of new flavor physics

the X

- X couples equally strongly to all members of the third family
- thus distinctive decay mode $X \to \tau^+\tau^-$
- different from KK excitations of gluons for example

- doesn't couple to light quarks (unlike typical Z')
- X is produced through its coupling to the b quark

$$\begin{array}{rcll} b\bar{b} & \to & X & (\approx 2/3 \text{ of cross section}) \\ g(b \text{ or } \bar{b}) & \to & Xg(b \text{ or } \bar{b}) & (\approx 1/4 \text{ of cross section}) \\ gg & \to & Xb\bar{b} & \\ q(b \text{ or } \bar{b}) & \to & Xq(b \text{ or } \bar{b}) & (q = \text{light quark}) \end{array}$$

- X is probably a broad resonance (also unlike a typical Z')

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

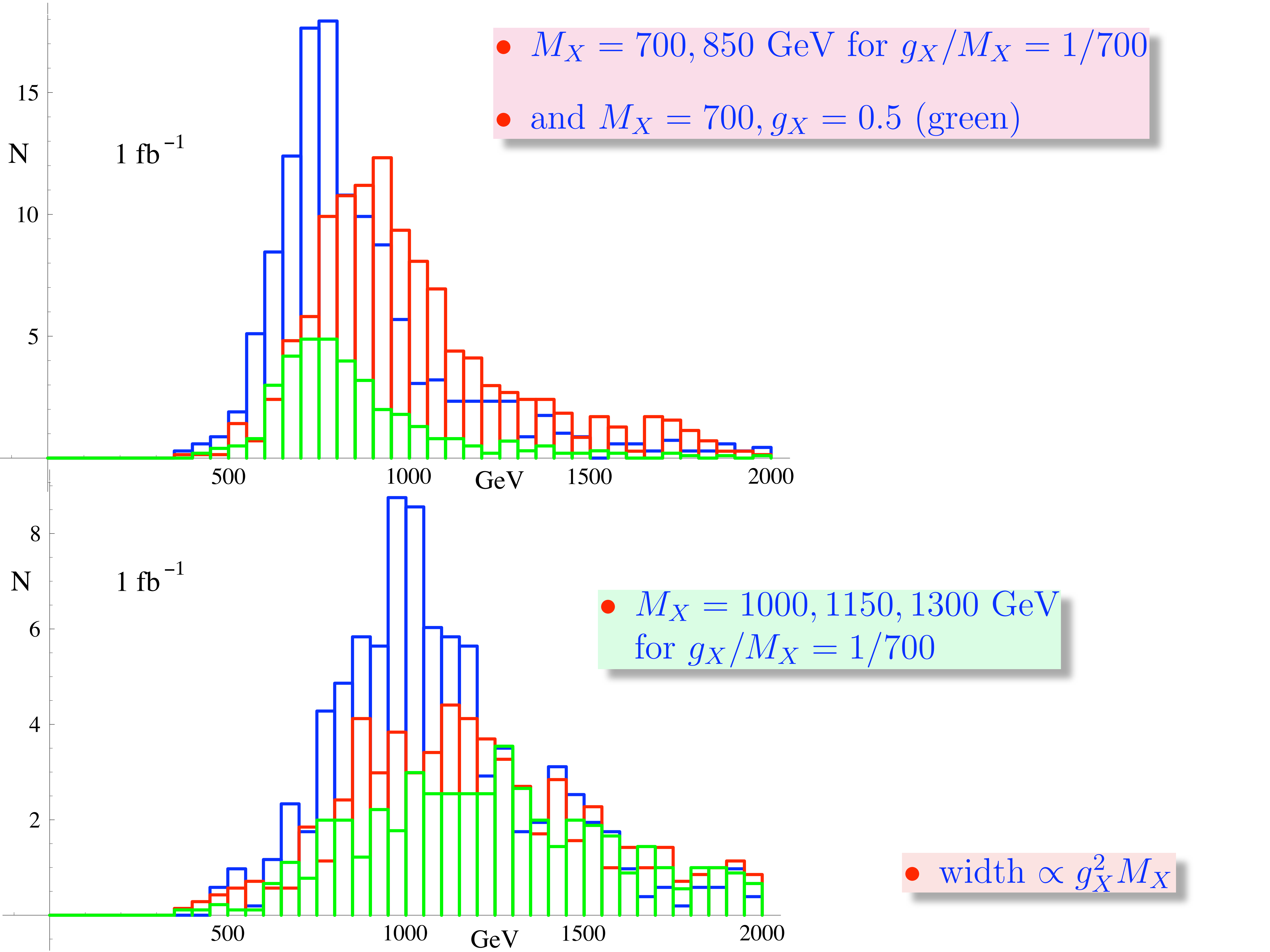
Mass reconstruction

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

- 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 $1/\sqrt{x_+x_-}$

Cuts

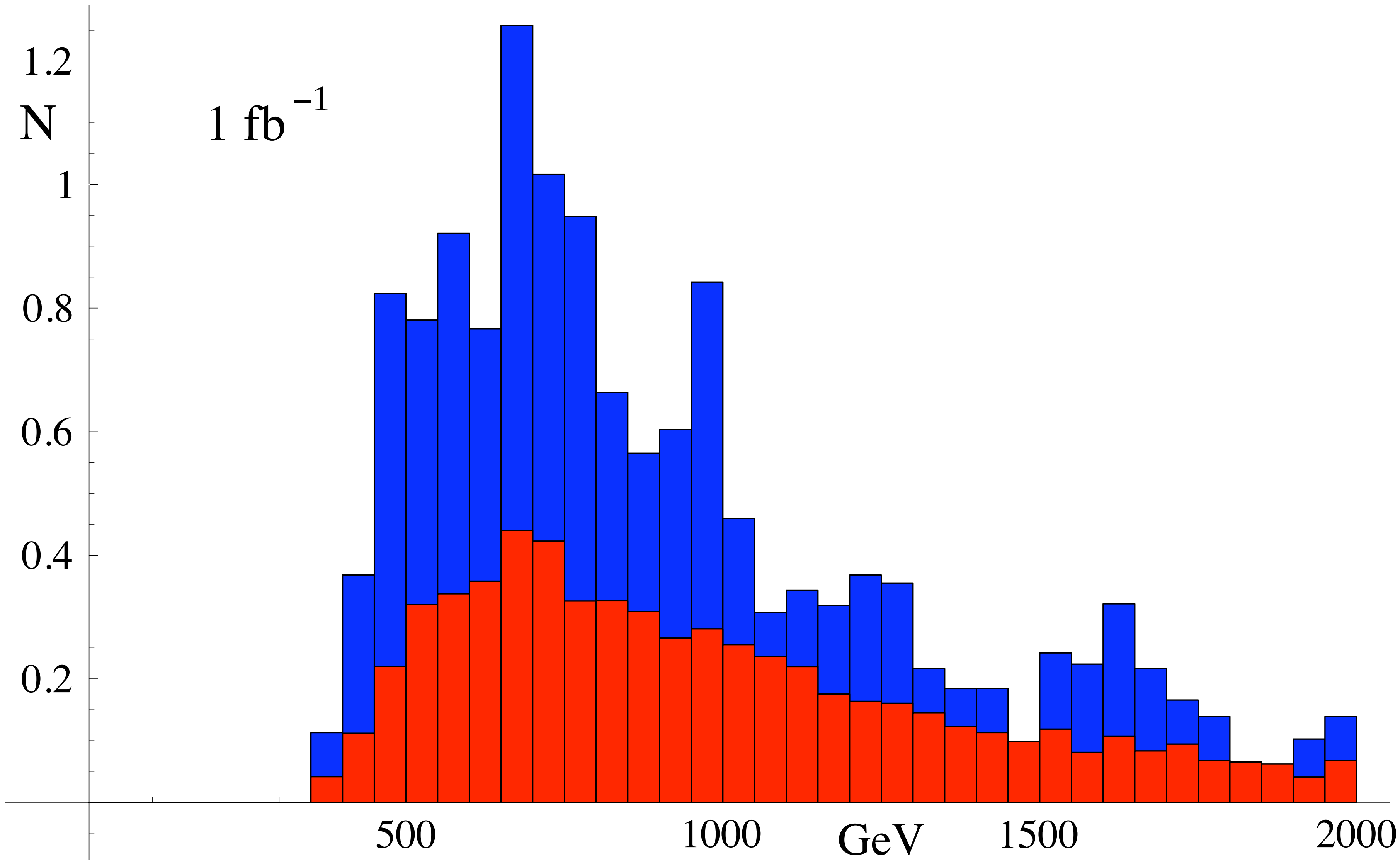
- at least one pair of oppositely charged leptons, including τ-tagged jets, each with $p_T > 60$ GeV, with invariant mass > 300 GeV
- missing energy $\not{p}_T > 60$ GeV
- $H_T > 700$ GeV
- not more than one non-b-tag jet with $p_T > 60$ GeV



• $M_X = 700, 850$ GeV for $g_X/M_X = 1/700$
• and $M_X = 700, g_X = 0.5$ (green)
N
1 fb^{-1}
15
10
5
500
1000
GeV
1500
2000
8
6
4
2
N
1 fb^{-1}
• $M_X = 1000, 1150, 1300$ GeV
for $g_X/M_X = 1/700$
• width $\propto g_X^2 M_X$
500
1000
GeV
1500
2000

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%



Summary

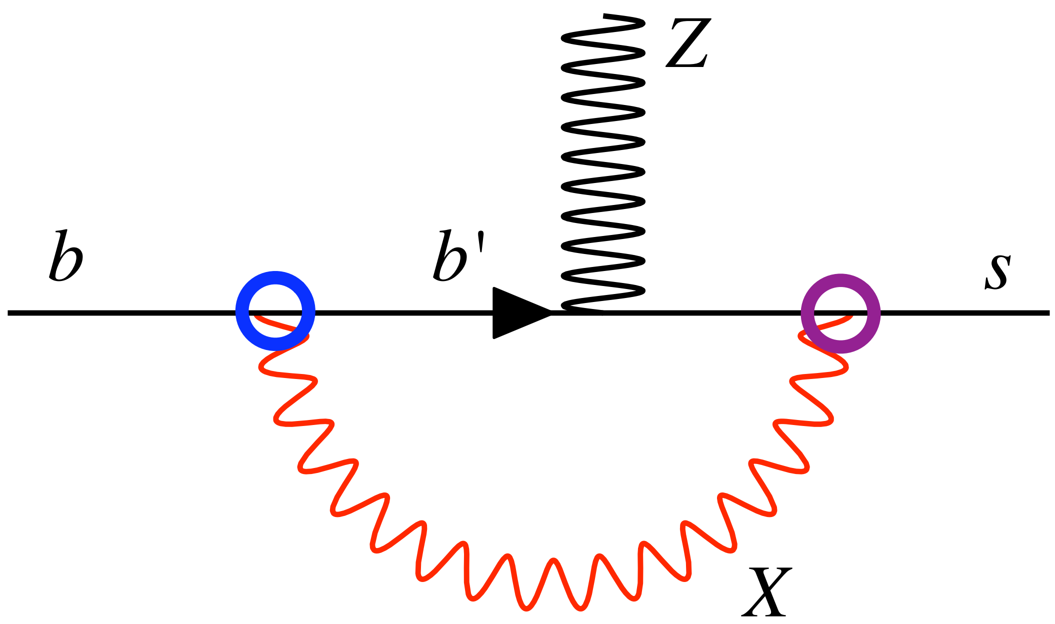
- a fourth family is easy to find—just how easy?
- discovery could decrease the motivation for Higgs searches
- instead it may focus attention on new flavor physics

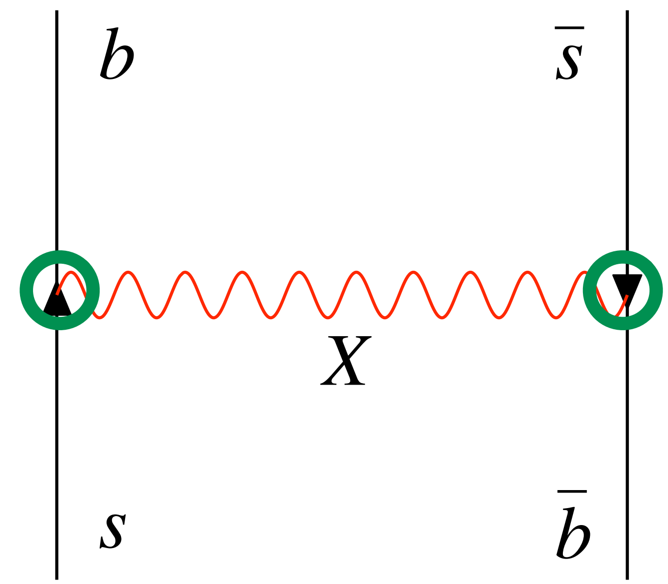
- minimal joining of EWSB and flavor physics
  $\Rightarrow$ fourth family in the 600-700 GeV range

- a minimal remnant of flavor gauge interactions—the X boson
  $\Rightarrow$ can be produced through coupling to b
  $\Rightarrow$ can decay through coupling to τ

- presently much attention on the conventional and the exotic
- what about the most conservative?

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

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)

} usually considered

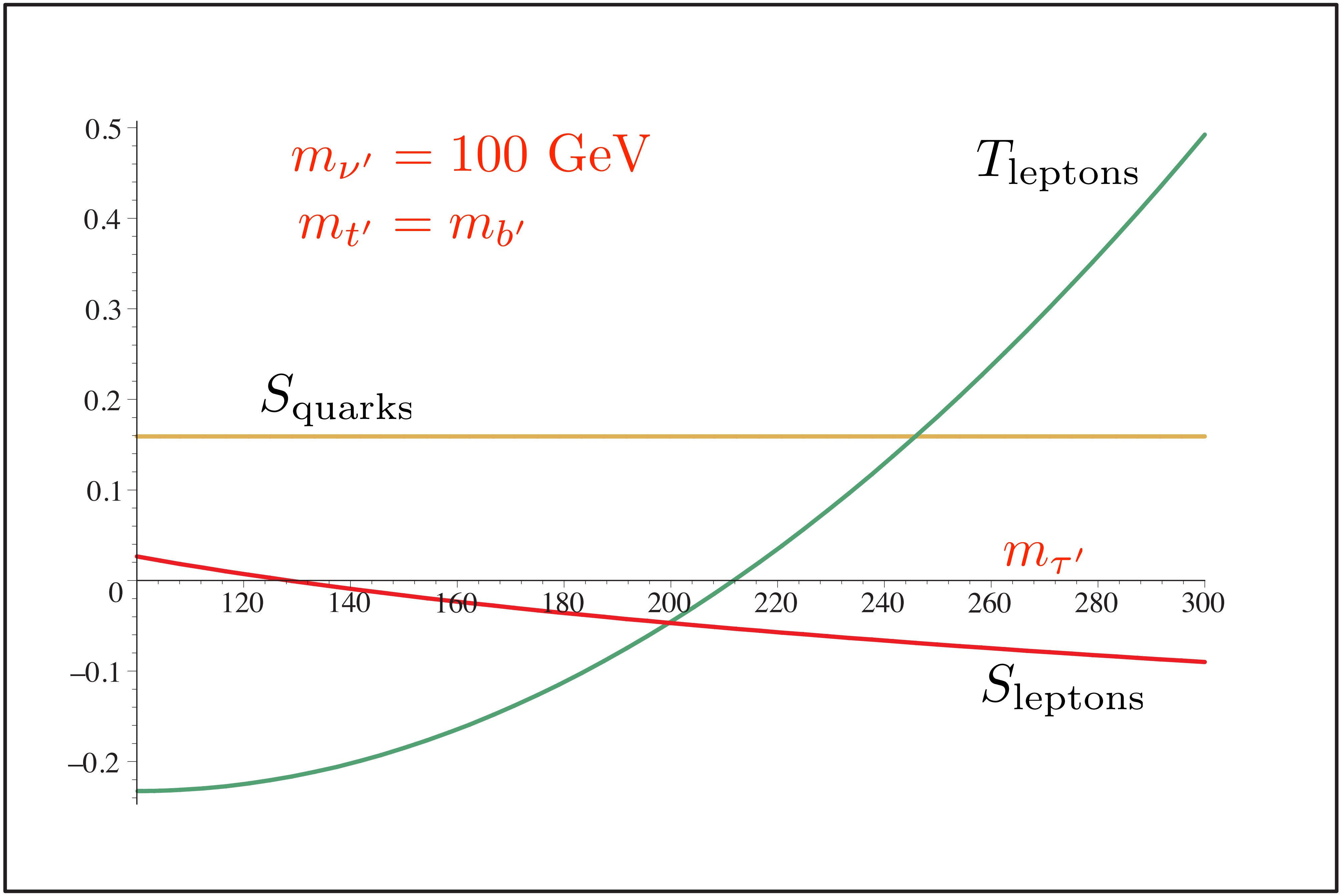
} BH, PRD54(1996)721

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

$$S_{\text{leptons}} \approx \frac{1}{6\pi} - \frac{1}{3\pi} \ln\left(\frac{m_{\tau'}}{m_{\nu'}}\right) - \frac{1}{12\pi}$$

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

- $\Lambda_{\nu'}$ 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