Approaching a strong fourth family

- we are being pushed in this direction by the Tevatron
- $m_{b'} > 338$ GeV

Some statements (ghosts) from the past...

- “The fourth family is already ruled out”
- “There is something unnatural about a heavy fourth neutrino”
- “A fourth family sheds little light on electroweak symmetry breaking”
- “A fourth family sheds little light on the flavor puzzle”
- “A fourth family has no theoretical motivation”
- “We already know how to look for heavy quarks—just like tops”
- “A fourth family is just plain boring—both theoretically and experimentally”

sequential fourth family comes in one of two types

- LIGHT—masses just above current lower bounds
- HEAVY—masses closer to the upper bound from partial wave unitarity

- if a fourth family is discovered as LIGHT:

Who ordered THAT?

- if a fourth family is discovered as HEAVY:

So THAT is the way nature works!

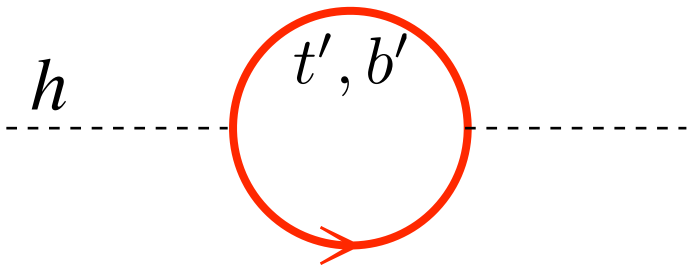
A LIGHT fourth family tries to co-exist with the Higgs

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

- Yukawa couplings $y_{q'}(\mu)$ also run quickly into trouble

- but perhaps Yukawa and Higgs couplings flow to UV fixed point [Hung, Xiong]

- more troublesome is direct contribution to Higgs mass



assume cutoff $\Lambda > m_{q'}$ →

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

HEAVY fourth family cannot co-exist with light Higgs

Higgs description loses meaning

- $m_{t',b'} \approx 600$ GeV close to the unitarity upper bound
- Goldstone bosons of electroweak symmetry breaking couple strongly to t', b', so strong interactions unitarize WW scattering

Higgs is no longer needed

- strong interactions can also be responsible for the Goldstone bosons
- a fermion condensate replaces the Higgs vev

- so where do quark and lepton masses come from?

$$\langle \overline{\Psi}\Psi \rangle = \Lambda_{ew}^3 \qquad \frac{1}{\Lambda_{fl}^2}\overline{\Psi}\Psi\overline{\psi}\psi \qquad m_\psi = \frac{\Lambda_{ew}^3}{\Lambda_{fl}^2}$$

what causes $\langle \overline{\Psi}\Psi \rangle = \Lambda_{ew}^3$?

- new strong UNBROKEN gauge interaction—technicolor

  or

- new strong BROKEN gauge interaction—similar to original NJL model

- for the latter we can identify Ψ with the fourth family

$$\frac{1}{\Lambda_{fl}^2}\overline{\Psi}\Psi\overline{\psi}\psi \qquad\qquad \frac{1}{{\Lambda'_{fl}}^2}\overline{\Psi}\Psi\overline{\Psi}\Psi$$

$$\Lambda_{fl} \gg \Lambda'_{fl} \approx \Lambda_{ew} \approx 1 \text{ TeV}$$

- flavor gauge interactions, partially broken at Λ_{fl}, with a remnant broken at Λ'_{fl}

Can a light Higgs be ruled out before a serious search starts?

How to tell a sequential quark from a vector quark?

vector-like quarks

- compatible with light Higgs, heavy Higgs or no Higgs
- sometimes motivated by theories of a light Higgs (perhaps composite)
- their masses are not constrained
- have nonstandard decays involving Z and H
- how best to distinguish them?

How will a sequential fourth family first start to show?

- assume for now that the dominant decay modes are

$$t' \to W^+ b \quad \text{and} \quad b' \to W^- t$$

- assume b-tagger not yet working

Early warning systems

- same sign leptons from $b'\overline{b'} \to W^+W^-W^+W^-b\bar{b}$
  - backgrounds are small, but so are the branching fractions
  - could also be a signal of other new physics
- excess of boosted and isolated W's
  - from both $b'\overline{b'} \to W^+W^-W^+W^-b\bar{b}$ and $t'\overline{t'} \to W^+W^-b\bar{b}$
  - focus on the hadronic decays that give "W-jets"
  - look for peak in jet invariant mass

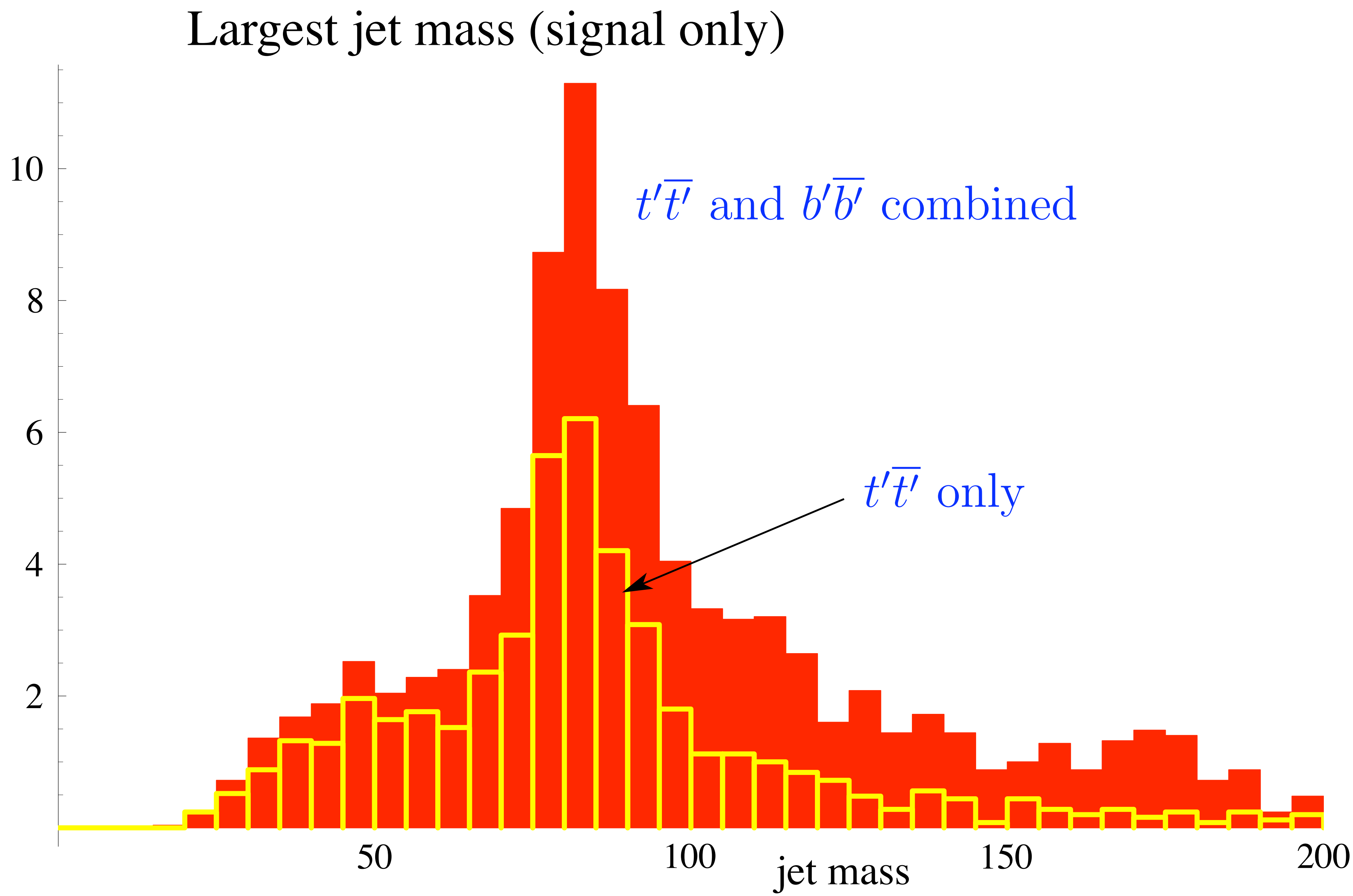
Simulation details

- Madgraph for signal
- Alpgen for backgrounds—$t\bar{t}$ + jets and W + jets
- Pythia tune D6 using CTEQ6L1
- PGS modified to use anti-k_T jet finding
- 1 fb^{-1} at $\sqrt{s} = 10$ TeV and 7 TeV
- $m_{q'} = 600$ and 450 GeV
- K factor of 1.5 for signal and $t\bar{t}$ + jets

a search for W-jets

- crucial to use jet finder with $R \approx 0.8$
  - $H_T > 2m_{q'}$ (or adjust H_T to maximize S/B)
  - three or more jets with $p_T > 100$ GeV
  - $L \equiv$[isolated lepton $p_T > 15$ GeV **or** missing $E_T > 200$ GeV]
- in each event find jet with largest jet mass
  - keep if isolated ($\Delta R > 1$ from other objects)
- form histogram of these jet masses

- $\sqrt{s} = 10$ TeV and 1 fb^{-1}
- $m_{q'} = 600$ GeV



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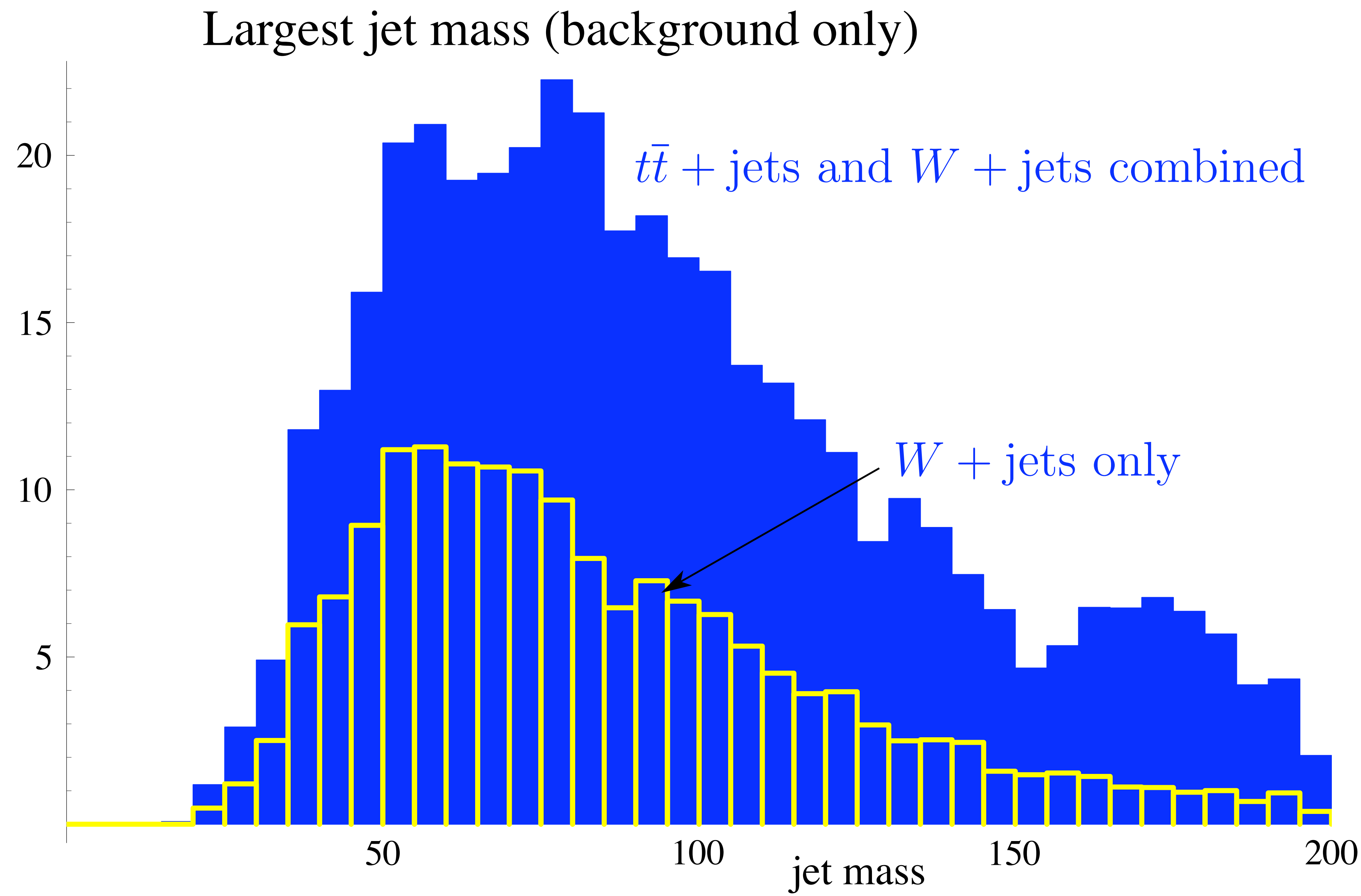

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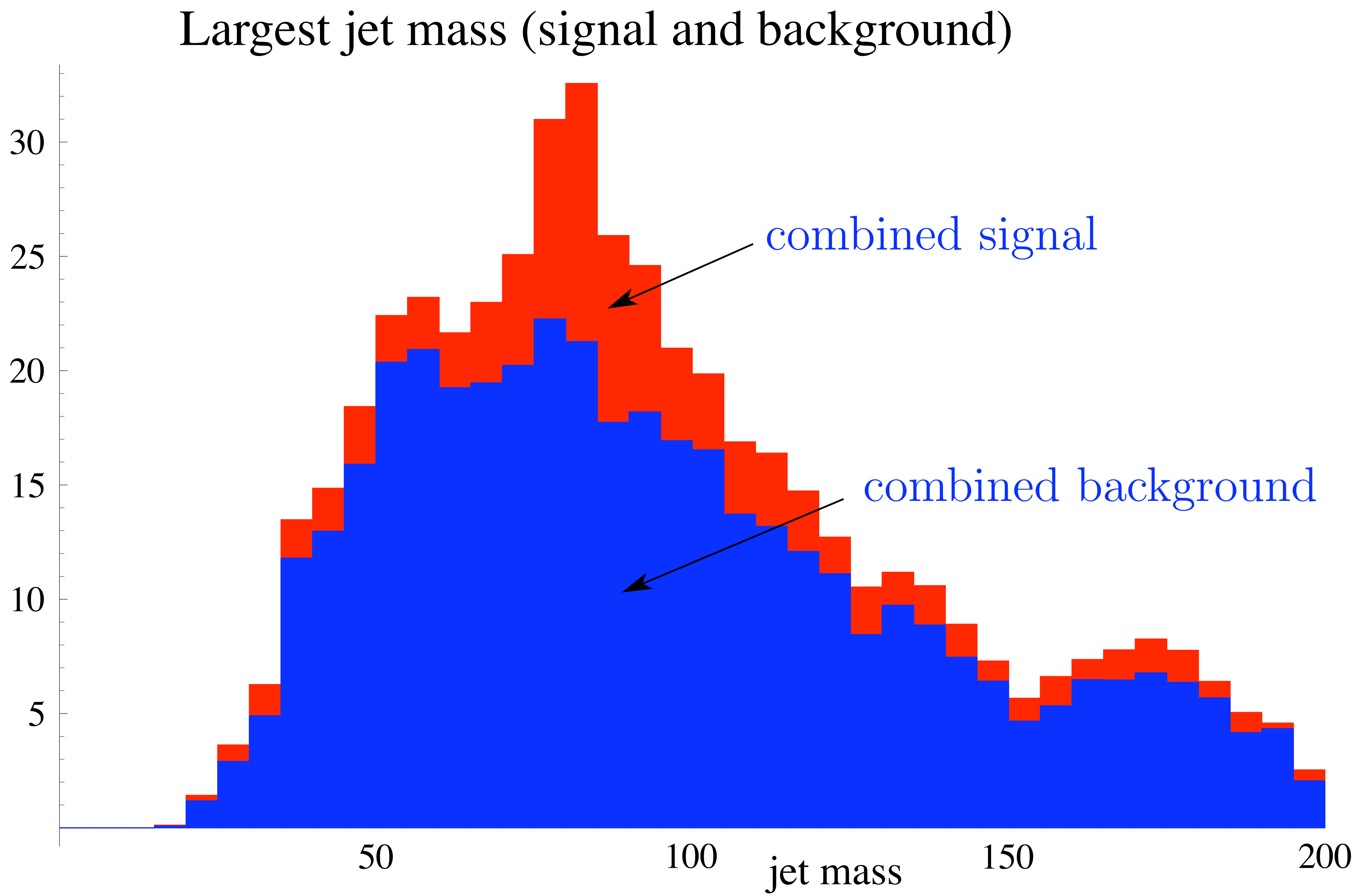
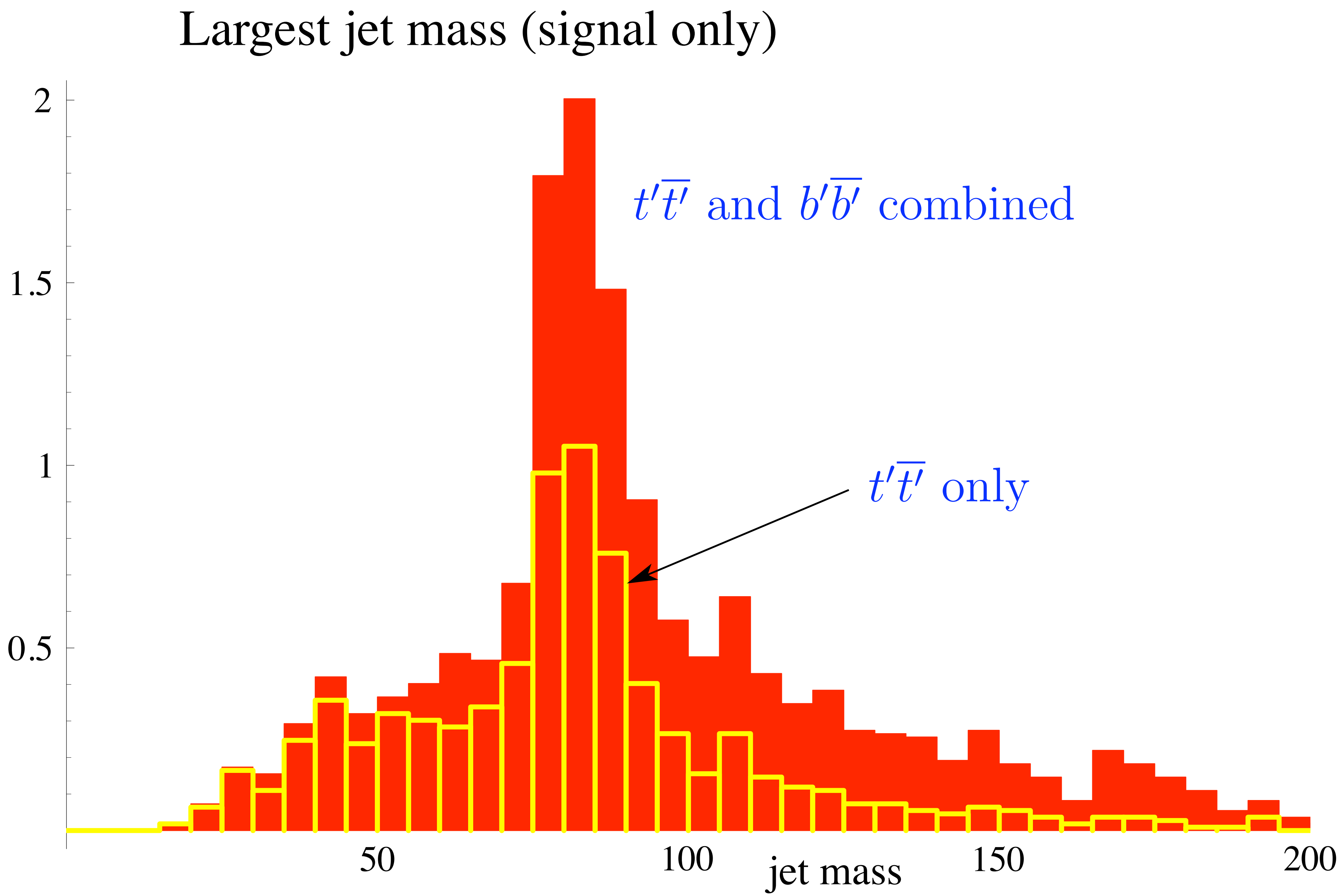


- $\sqrt{s} = 7$ TeV and 1 fb^{-1}
- $m_{q'} = 600$ GeV



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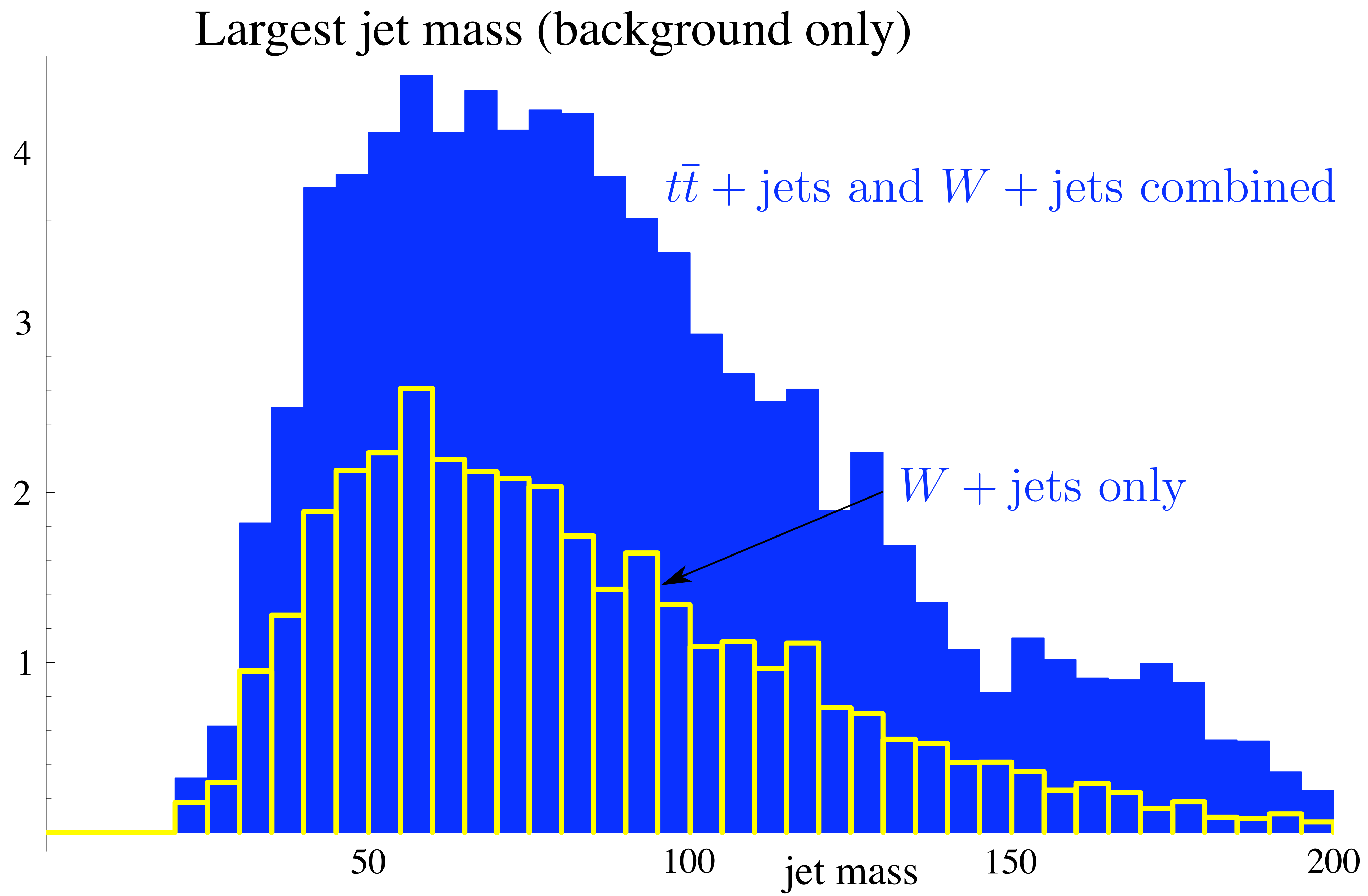

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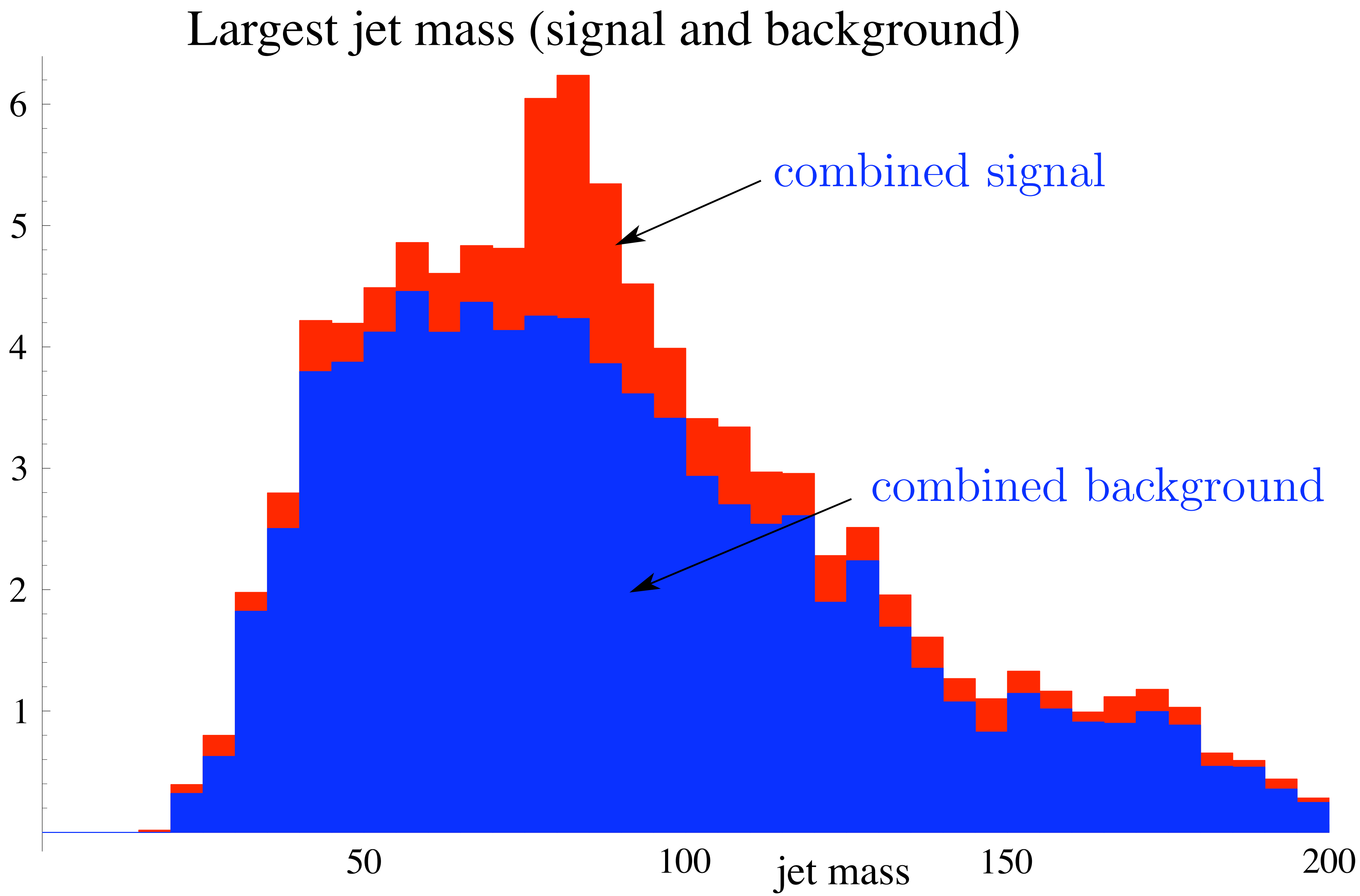
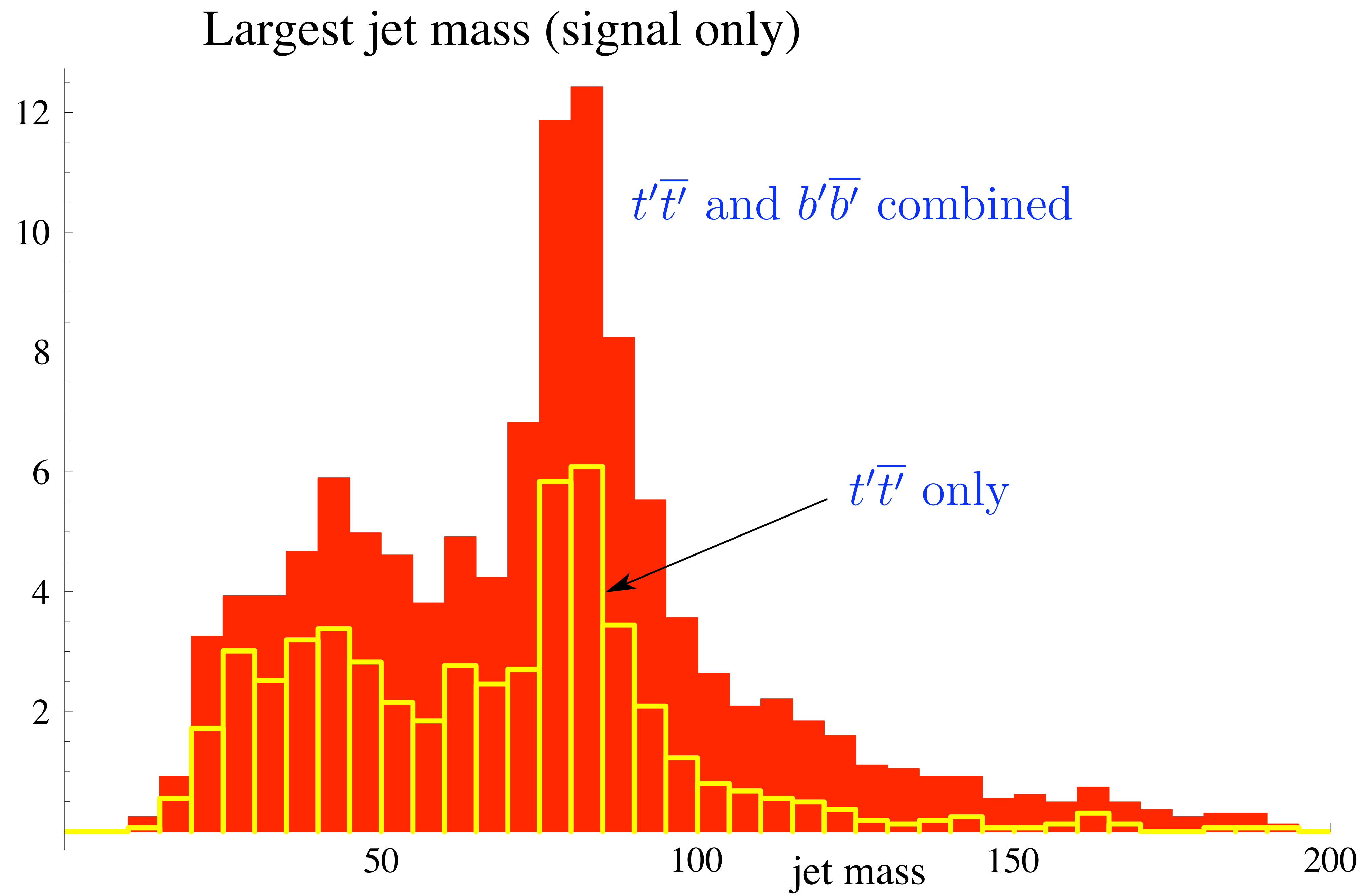


- $\sqrt{s} = 7$ TeV and 1 fb^{-1}
- $m_{q'} = 450$ GeV



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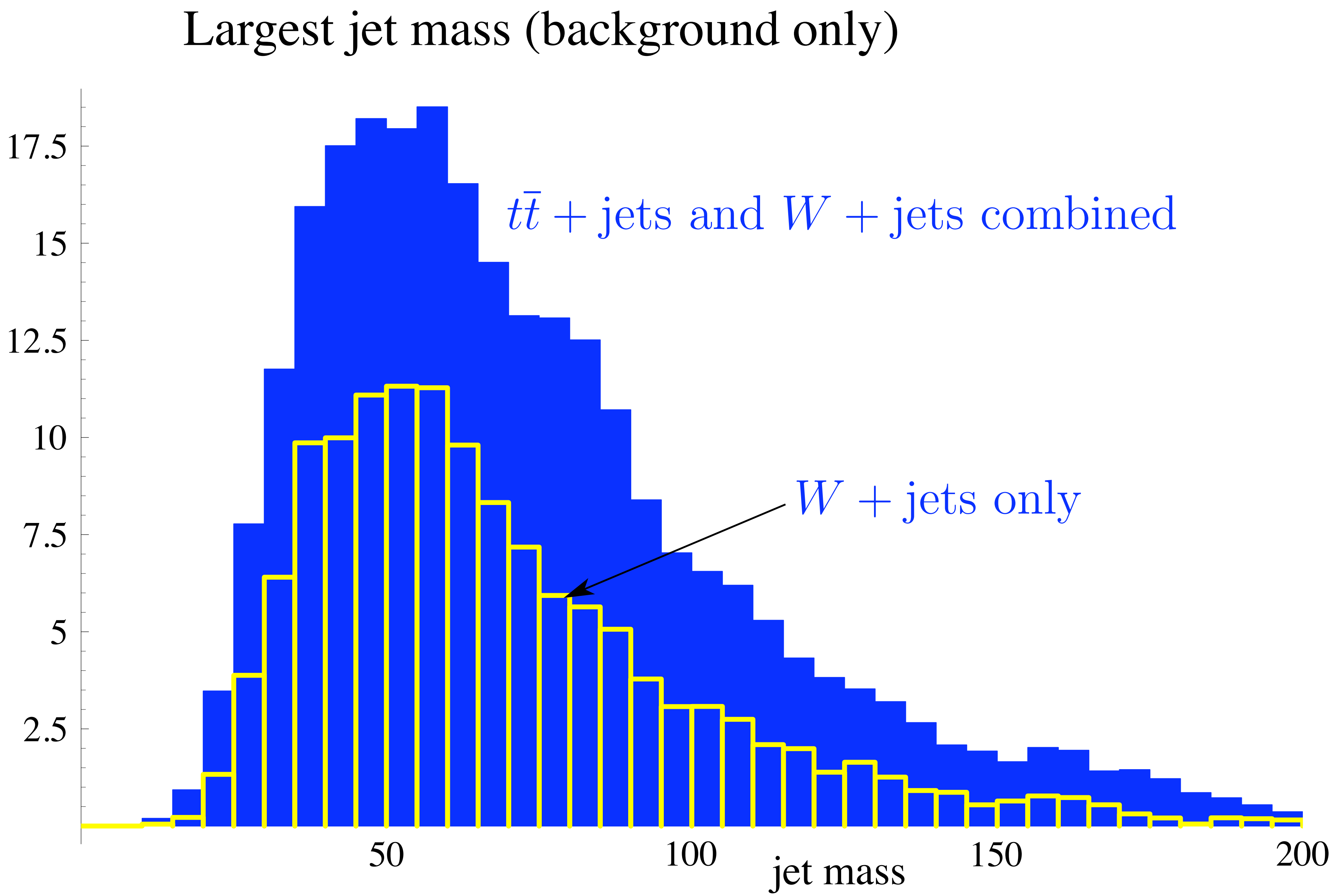

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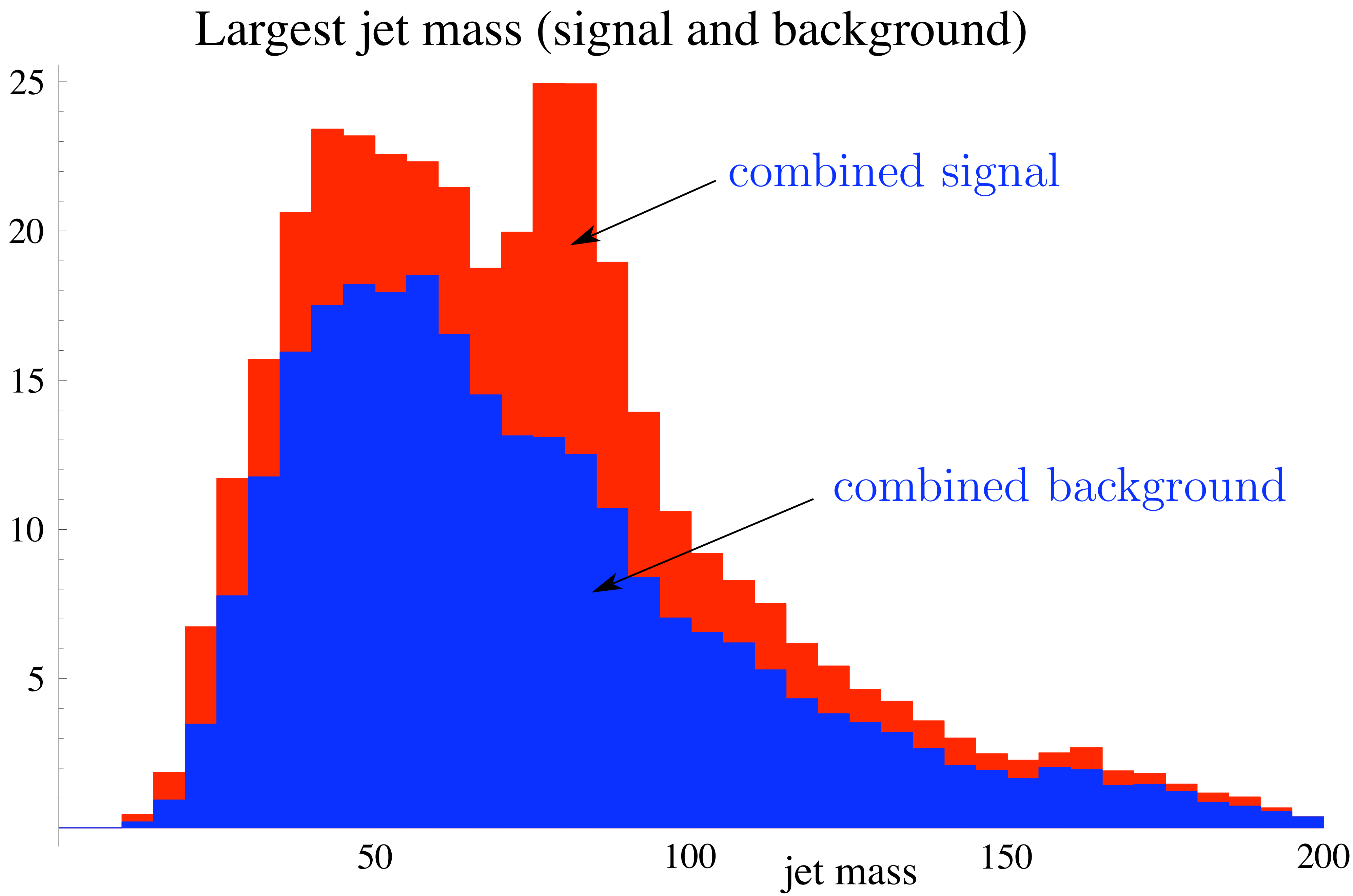
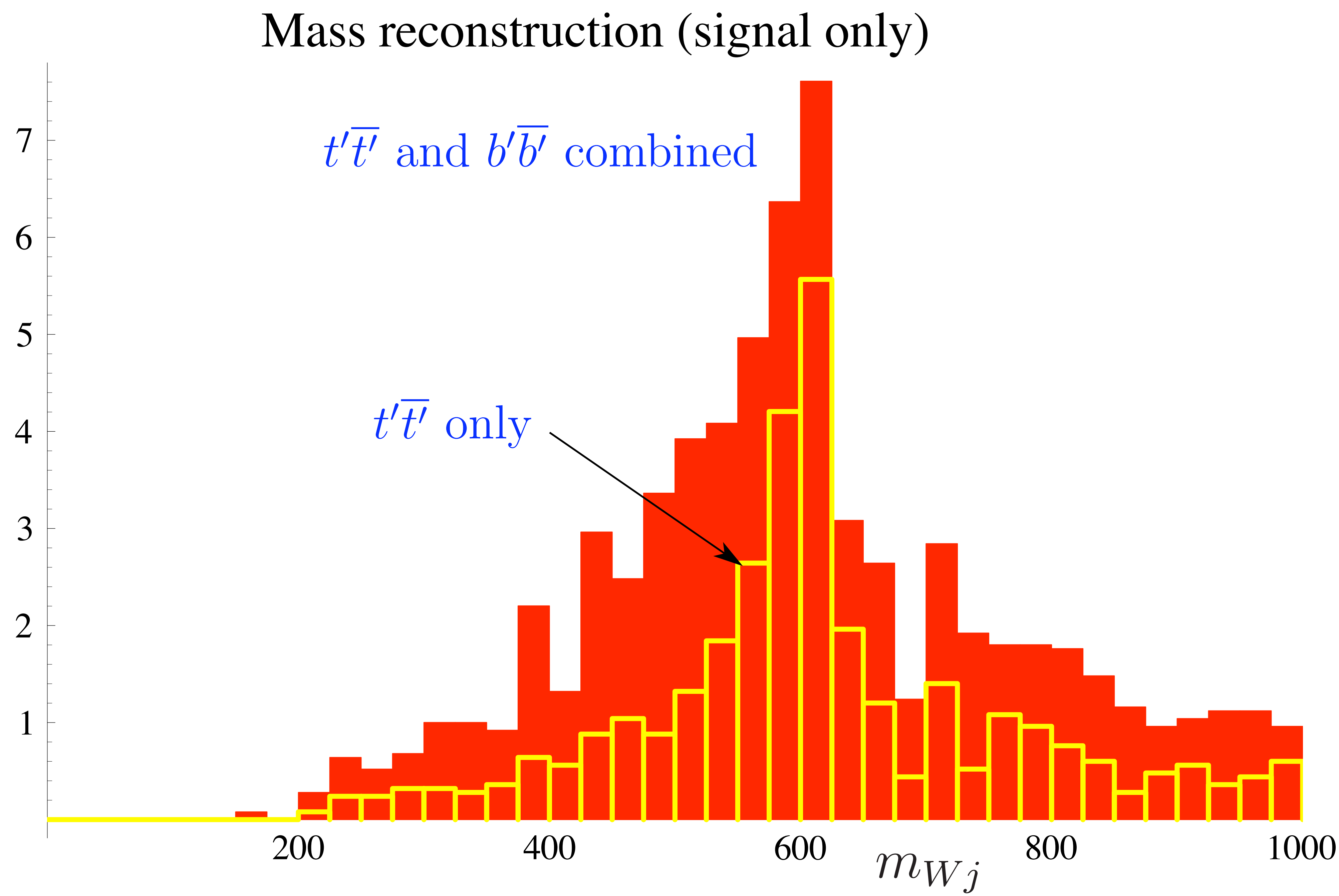


reconstruct the heavy quark mass

- three jets only with $p_T > 150$ GeV, labelled J_W, J_1, J_2
- J_W is "W-jet" with m_{jet} within 12 GeV of M_W
- $L \equiv$[isolated lepton $p_T > 15$ GeV **or** missing $E_T > 200$ GeV]
- L is $\Delta R > 1$ away from J_W, J_1, J_2
- consider all possible ways of assigning objects to $[J_W, J_1, J_2, L]$
- in each case take invariant mass of $[J_W, J_1]$

- $\sqrt{s} = 10$ TeV and 1 fb^{-1}
- $m_{q'} = 600$ GeV



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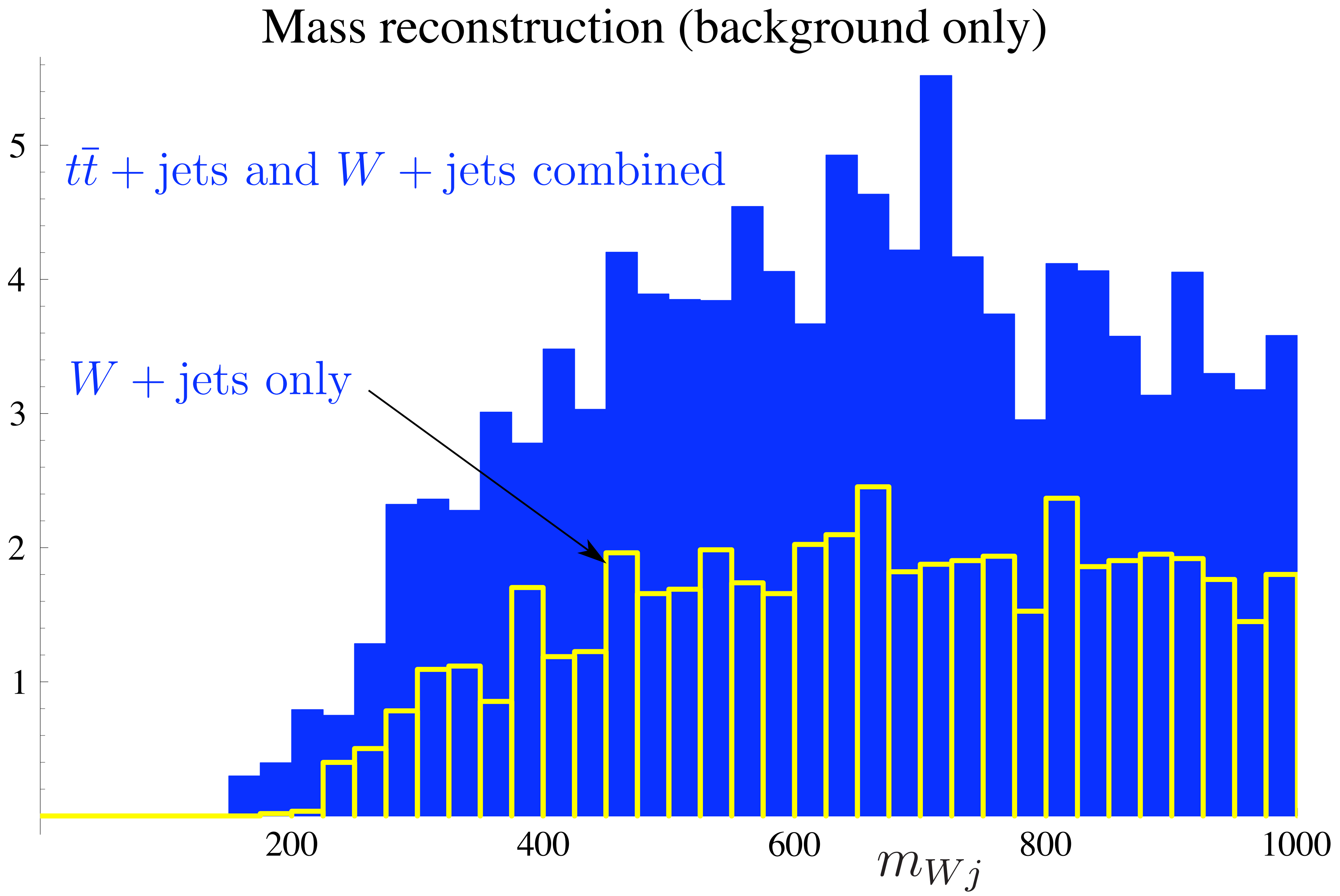

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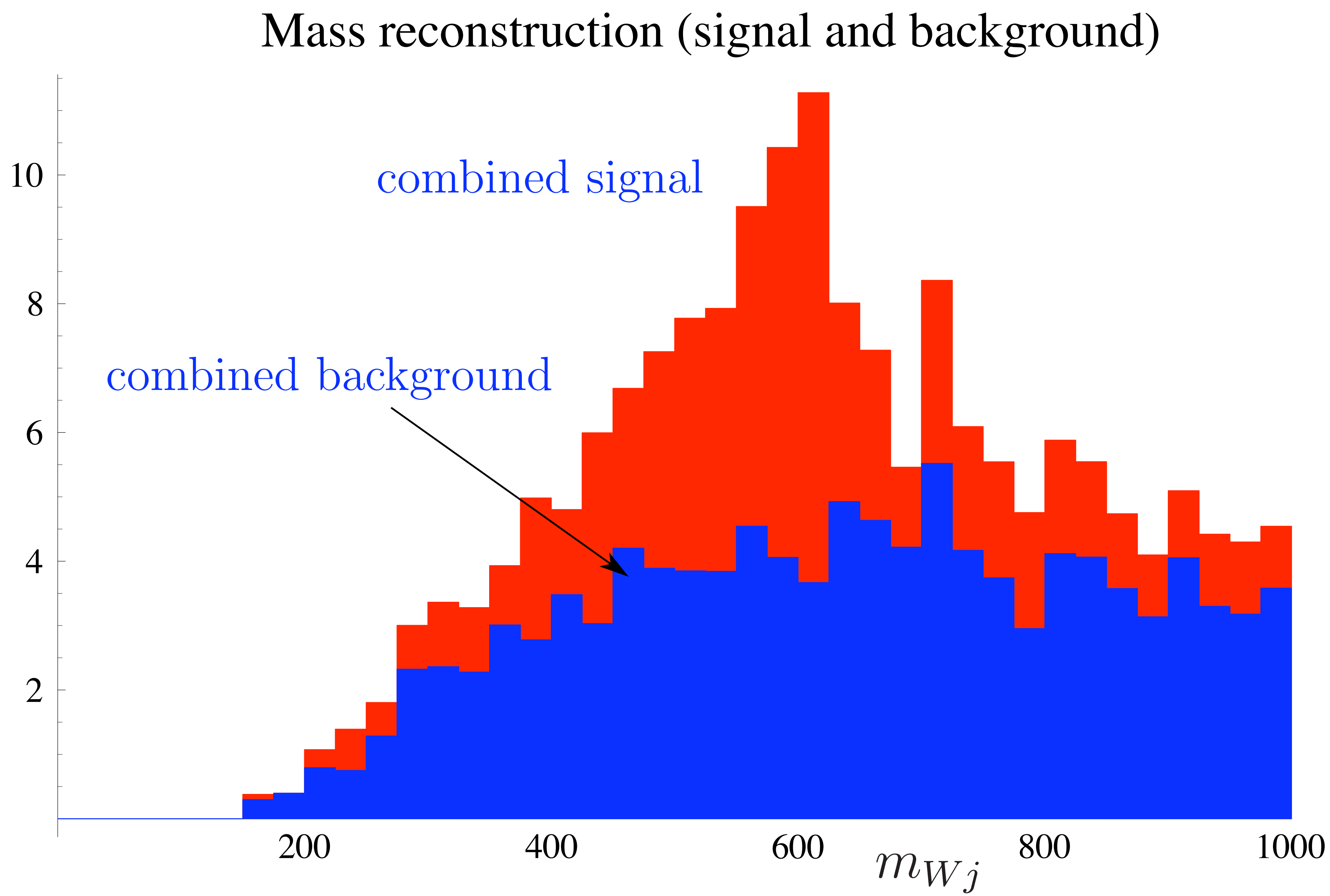

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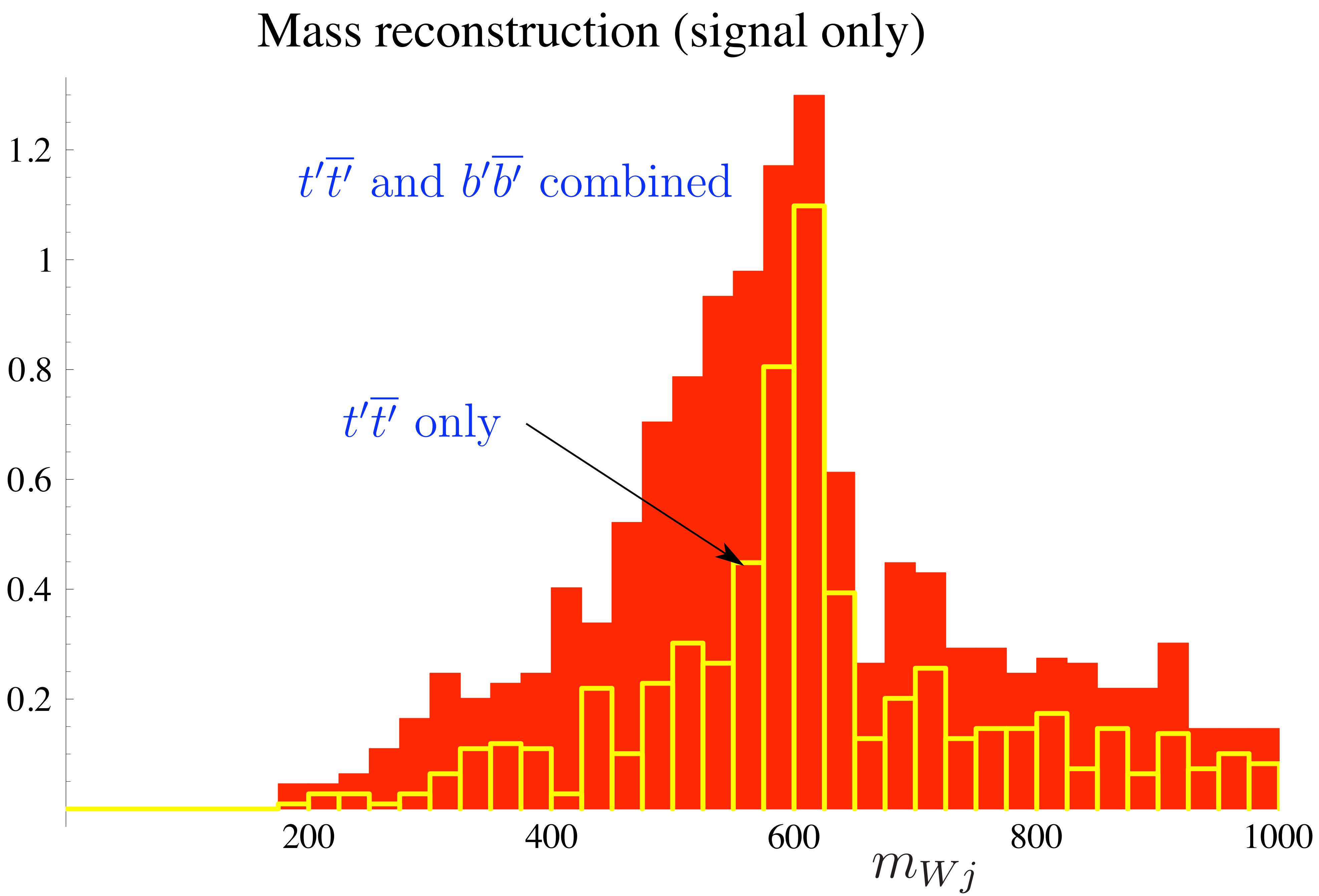

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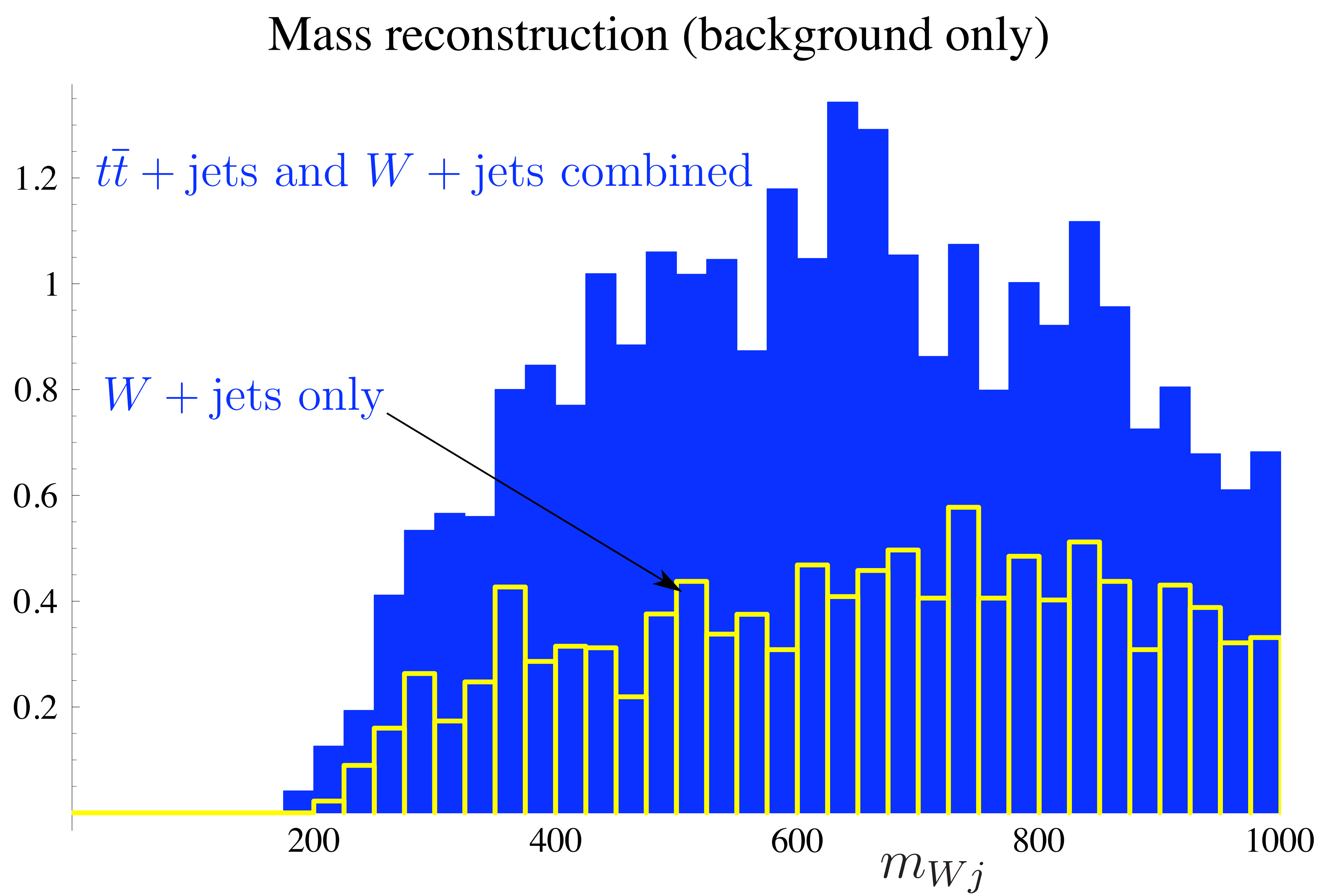

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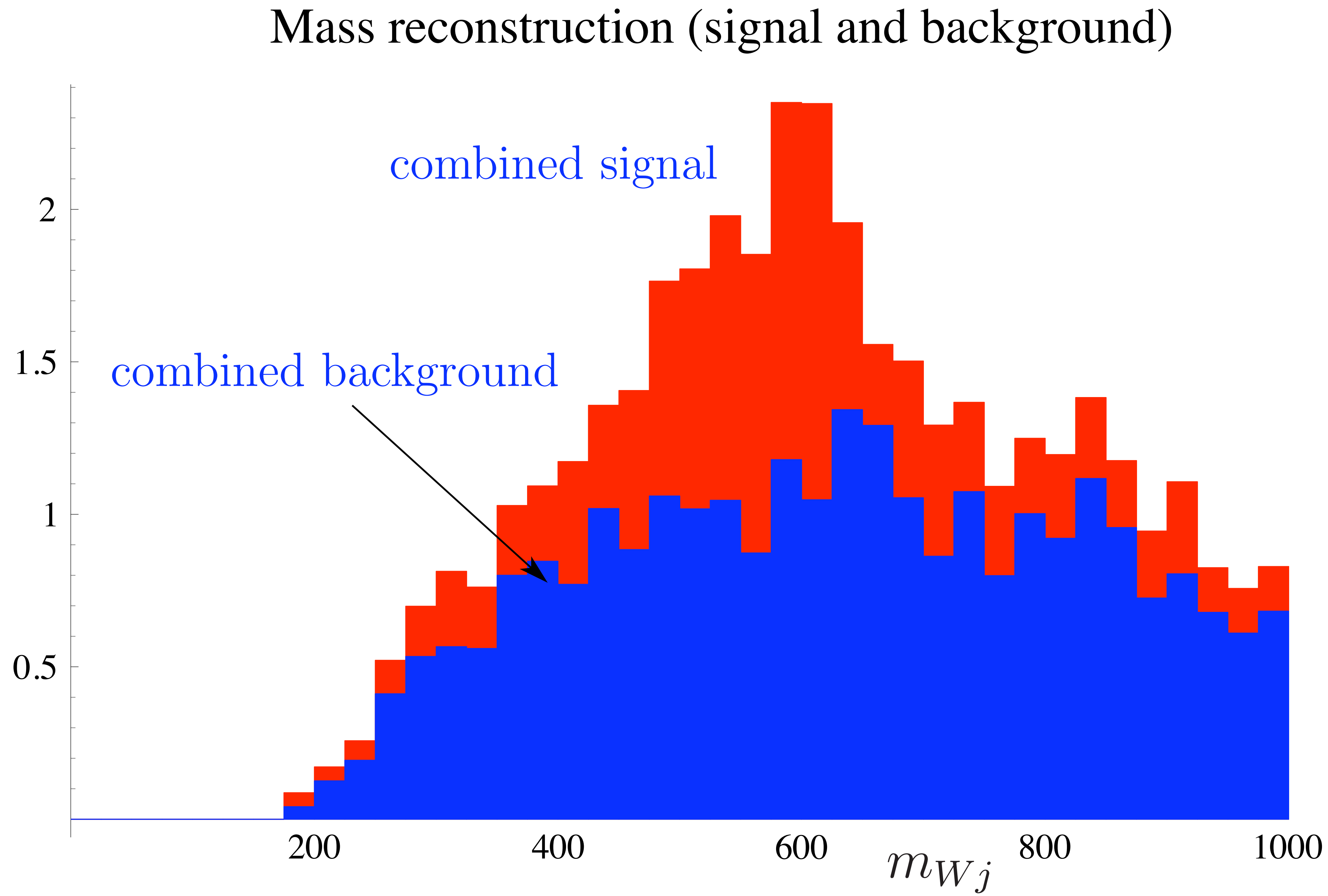

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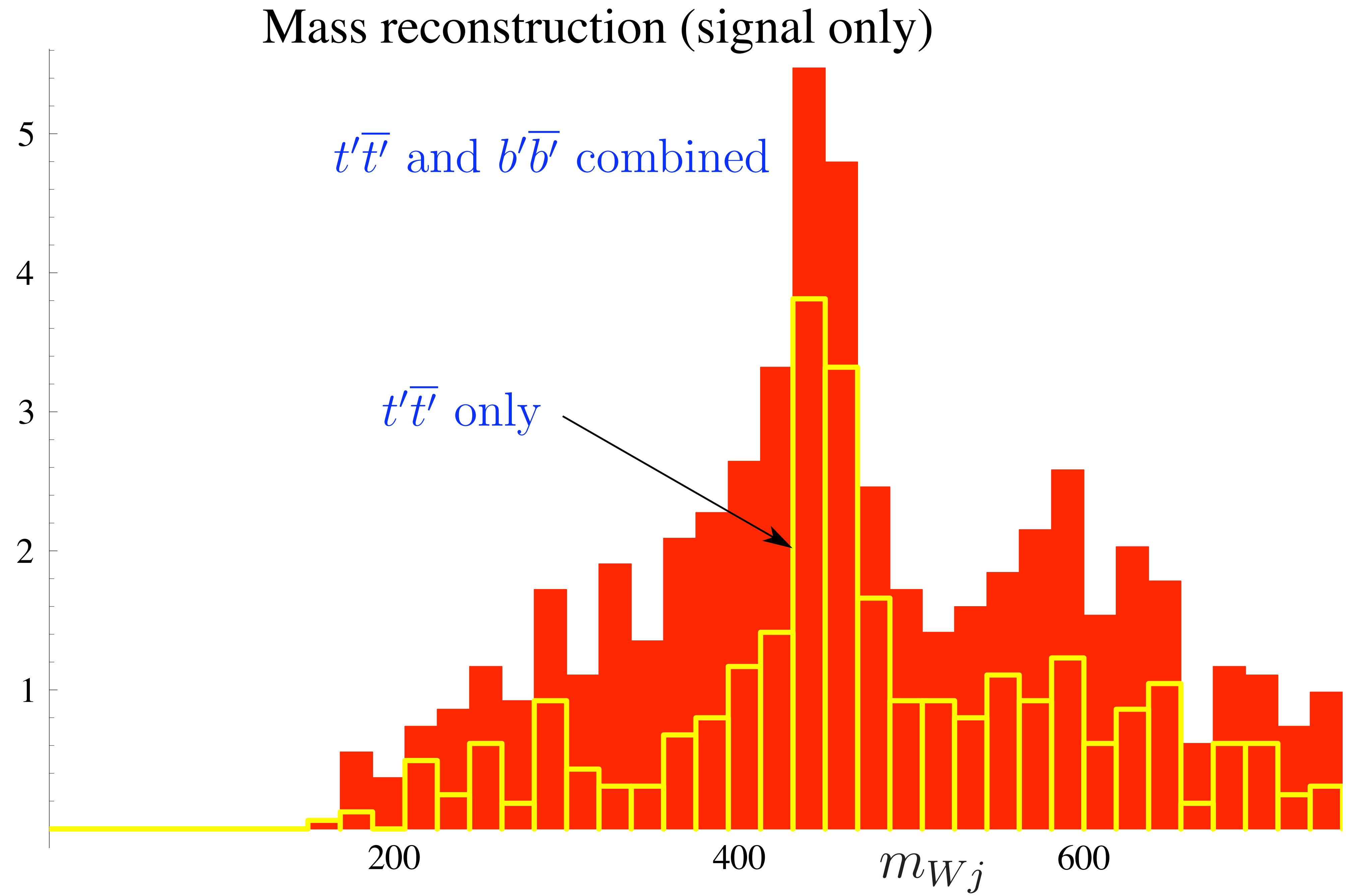

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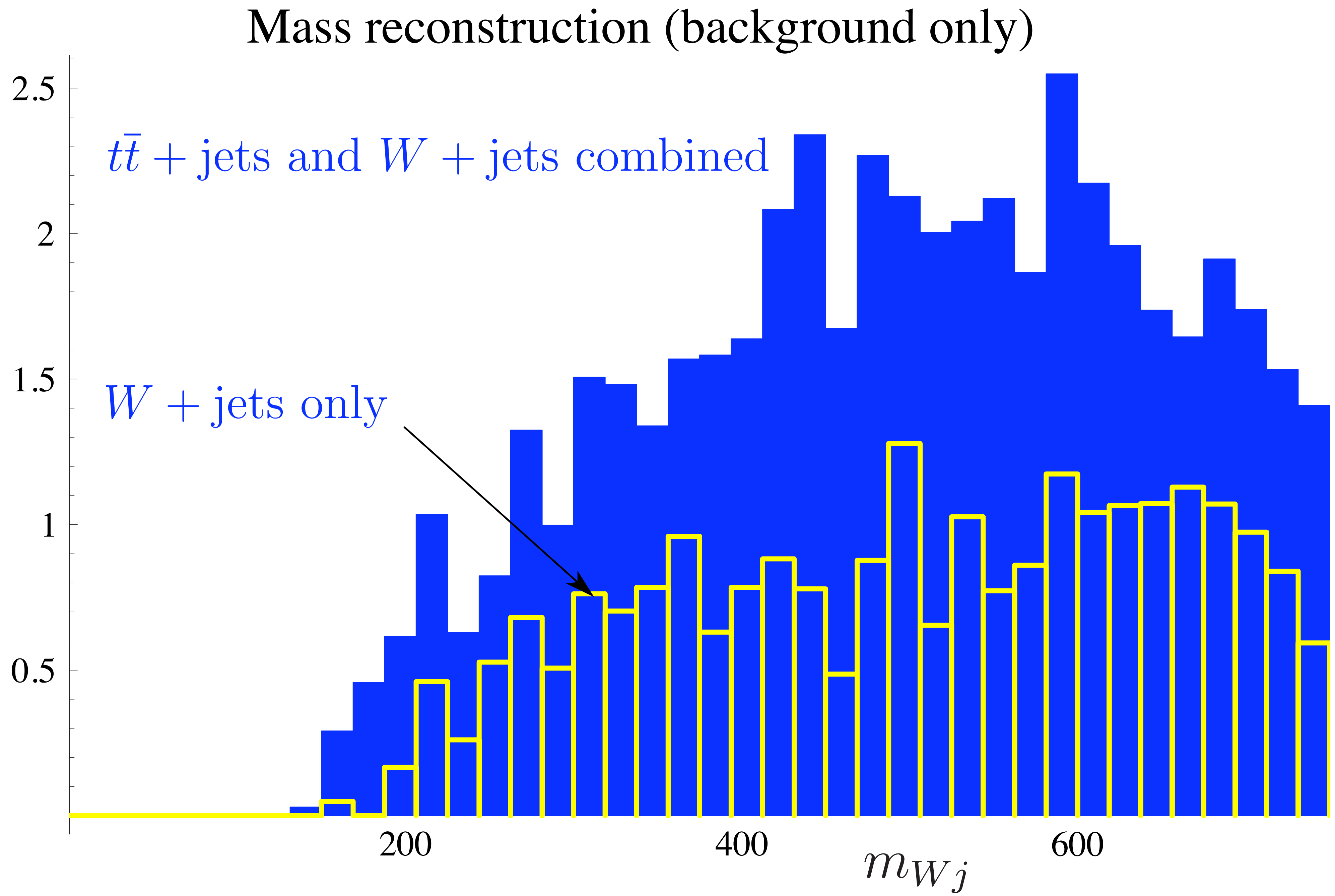

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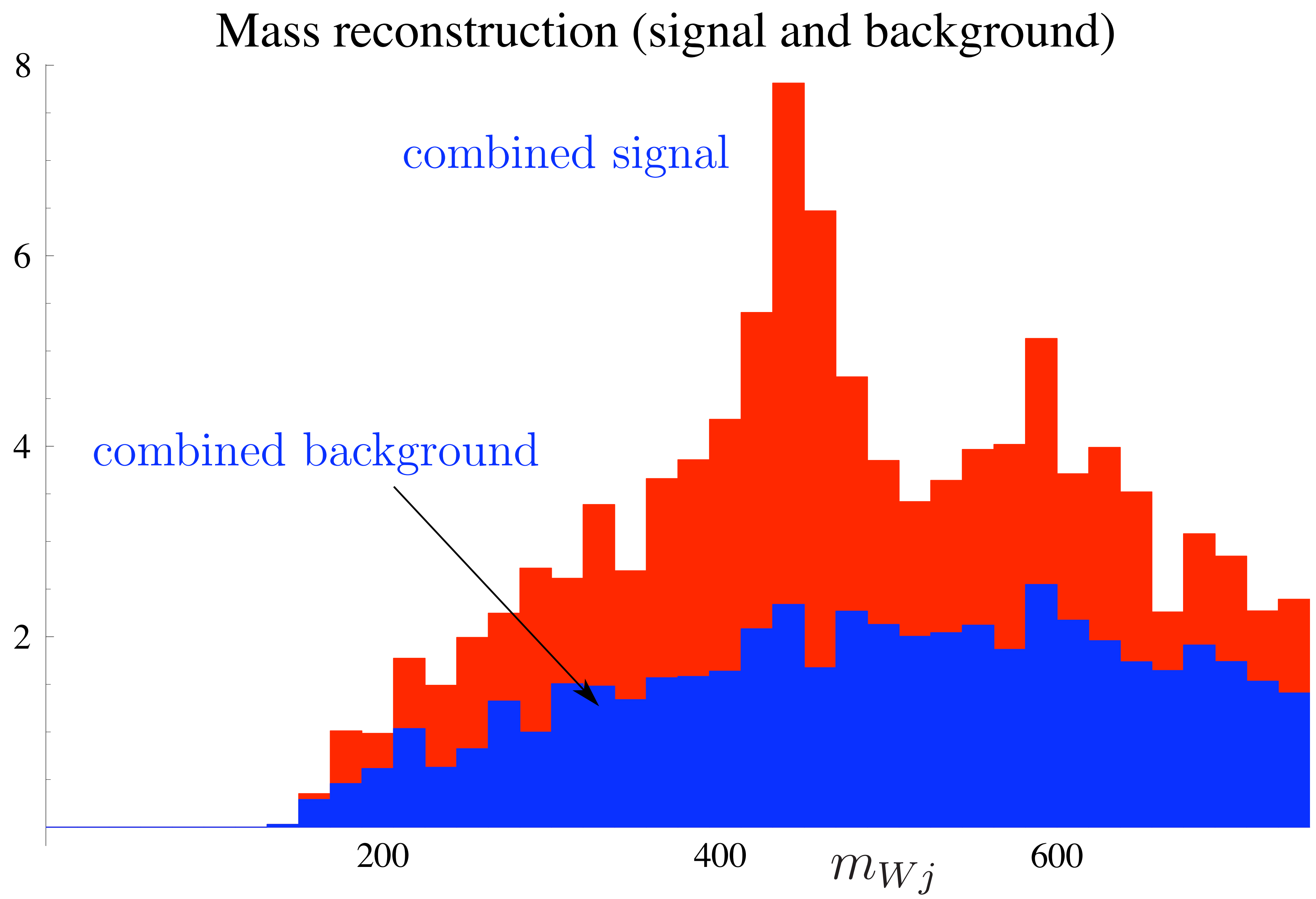


How to distinguish sequential from vector quarks?

- vector doublet of quarks $Q = (T, B)$ most closely resembles $q' = (t', b')$

$$\mathcal{L}_{\text{mixing}} = Y_t \overline{Q}_L t_R \tilde{\phi} + Y_b \overline{Q}_L b_R \phi + hc$$

$$T \to W^+ b,\ Zt,\ Ht$$

$$B \to W^- t,\ Zb,\ Hb$$

- proportions of $W : Z : H$ produced are $\approx 1 : 1/2 : 1/2$
- true also for other varieties of vector quarks and top partners

Production of $\ell^\pm\ell^\pm$ vs production of $Z \to \ell^+\ell^-$

- Event selection for $\ell^\pm\ell^\pm$
  - $H_T > 1$ TeV, 2 isolated same-sign leptons
    $\not{E} > 50$ GeV and $M(\ell^\pm\ell^\pm) > 100$ GeV
- Event selection for $Z \to \ell^+\ell^-$
  - $H_T > 1$ TeV, [2 isolated leptons and $\not{E} > 100$ GeV] or [3 isolated leptons]
    $M(e^\pm e^\mp)$ or $M(\mu^\pm\mu^\mp)$ within 4 GeV of the M_Z
- count signal events for $\sqrt{s} = 10$ GeV and 1 fb^{-1} and $m_{q'} = 600$ GeV

	$\ell^\pm\ell^\pm$	$Z \to \ell^+\ell^-$
sequential quarks	6	0.5
vector quarks	0 to 6	6
WZ + jets	0	1.5

- thus can distinguish sequential quarks from vector quarks at roughly the time that new same sign leptons are found!

Neutrinos

- why is the fourth neutrino so different?
- does a large mass for ν'_τ mean a Dirac mass?

- right-handed neutrinos may not even be present
- in particular, no gauge symmetry protects them from a much larger mass

- consider the origin of mass for a heavy 4th family
  —a new strong interaction couples to all members of the family
- the fourth neutrino can also receive dynamical mass
  —this can be a purely Majorana mass for $\nu'_{L\tau}$

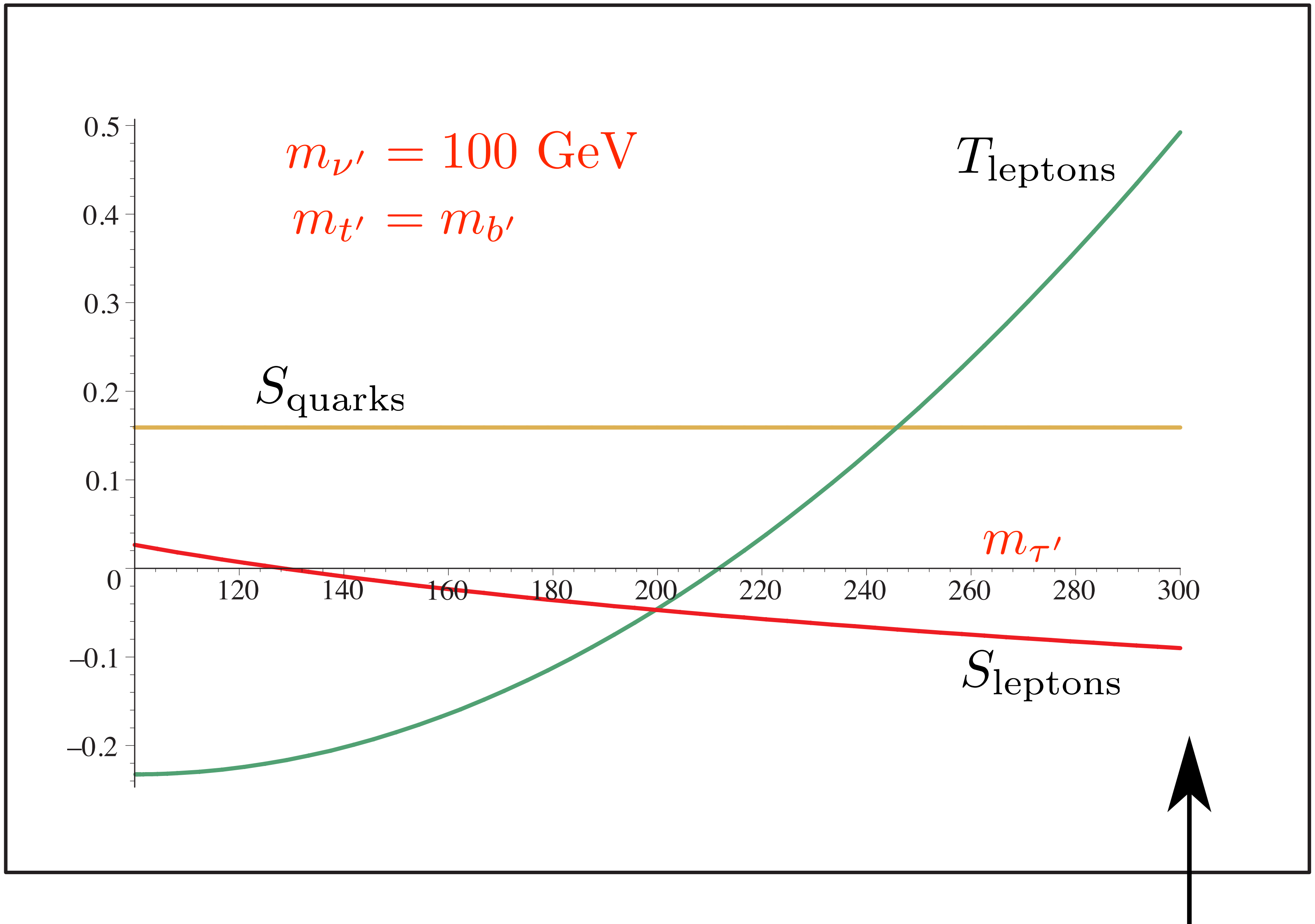
- a 4th neutrino mass similar to the other 4th family members is not unnatural
- the real question is why the other neutrinos are so light

Electroweak corrections from Majorana ν'_τ

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

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

BH 1996



Light neutrinos vs light leptons

- key is that light neutrinos are purely left handed
  - 4-fermion vs. 6-fermion operators

$$\frac{1}{\Lambda_{fl}^2}\overline{\tau'}_L\tau'_R\overline{e}_R e_L \qquad \frac{1}{\Lambda_{fl}^5}\overline{\tau'}_R\tau'_L\overline{\tau'}_R\tau'_L\nu_{Le}\nu_{Le}$$

$$\Lambda_{fl}\approx 200\text{ TeV and }\langle\overline{\tau'}_L\tau'_R\rangle\approx(300\text{ GeV})^3$$

$$\Rightarrow m_e\approx 0.7\text{ MeV and } m_\nu\approx 0.002\text{ eV}$$

- 6-fermion operators can result upon integrating out the heavy ν_R's
- consistent for the ν_R masses to be similar to Λ_{fl}
- contrast to standard see-saw

Flavor (gauge) symmetries

- a dangerous operator could feed down mass from $\nu'_{L\tau}$ to the light neutrinos

$$\overline{\nu'}_{L\tau}\overline{\nu'}_{L\tau}\nu_L\nu_L$$

- (fourth family lepton number) − (third family lepton number) symmetry
- this could be a remnant flavor gauge symmetry, broken e.g. by the $\nu'_{\tau L}$ mass

$$\overline{t'}_L t'_R \bar{t}_R t_L \qquad \overline{b'}_L b'_R \bar{b}_R b_L$$

$$\overline{b'}_L b'_R \bar{t}_L t_R \qquad \overline{t'}_L t'_R \bar{b}_L b_R$$

t'_L	t'_R	b'_L	b'_R
+	−	+	−
t_L	t_R	b_L	b_R
−	+	−	+

- (fourth family axial quark number) − (third family axial quark number)
- allows the t mass operator to be large without upsetting $Zb\bar{b}$ coupling

So why is a fourth (strong) family interesting?

A) Quite easy to find or rule out

B) Would have deep implications if found

1) Bring an end to the "Era of the Higgs"

2) Cause the focus of the LHC to suddenly shift

3) Cause the focus of theorists to suddenly shift

- new strong dynamics shows up where it is needed
- serious blow to anthropic thinking
- return of naturalness