A Simple-Minded Guess for the LHC: A Fourth Family

Not My Outline

- motivation
- constraints
- model building
- identify process
- signal to background

Mixed-up Outline

- identify process
- motivation
- signal to background
    - jet mass technique
    - initial state radiation
    - $t\bar{t}$, multijets, ...
    - favorite event generator
- constraints
- model building
    - bottom-up—effective operators

BH, JHEP 0703 (2007) 063
BH, JHEP 0608 (2006) 076

The process

- sequential fourth family with at least some CKM mixing
- fourth family quarks with mass ≈ 600 GeV

$$pp \to t'\overline{t'} \to W^+W^-b\bar{b}$$

or

$$pp \to b'\overline{b'} \to W^+W^-t\bar{t}$$

- since colored fermions are involved, cross sections are decent at the LHC

$$\sigma_{LO} \approx 900 \text{ fb}$$

$$\sigma_{NLO} \approx 1400 \text{ fb}$$

- why 600 GeV?

Quick and dirty motivation

- nature has a replication of families—the flavor problem
- we know the mass of a fourth family at which something special happens
- above a mass of ≈ 550 GeV, quark's coupling to the Goldstone bosons of electroweak symmetry breaking is strong
- brings together flavor physics and electroweak symmetry breaking
- this simple motivation is 27 years old! (Chanowitz, Furman and Hinchliffe 1979)

- strong interactions (rather than a Higgs) unitarize WW scattering
- what are the effective massive degrees of freedom?
- fermions rather than bosons
  - unconfined by new strong interaction—like old NJL model

- other theories have new vector-like fermions
- masses and decay modes much less constrained
  - flavor changing neutral currents

- how do we live without a light Higgs?
- basically some mass splitting shifts the T parameter in a similar way

- so just how likely is this picture?

- would involve some broken gauge dynamics that we don't have much handle on (although I say more about this later)
- would rule most of the currently studied theory space

theorist:

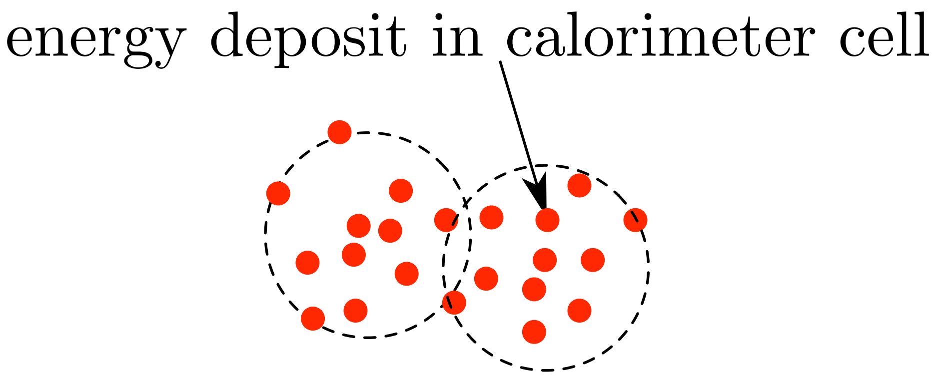
- "doesn't sound too likely"
- "I don't want to think about it"

experimentalist:

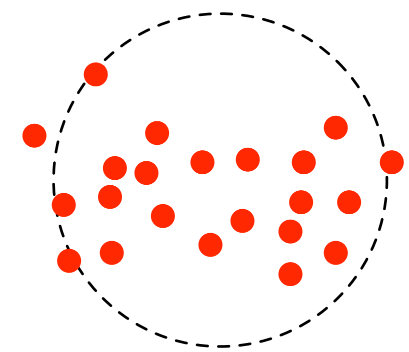
- "sounds like a best case scenario!"
- "exactly how do I look for it?"

Identifying energetic and isolated W's

- $W \to jj$ from single jet invariant mass



$p_1^\mu + p_2^\mu$



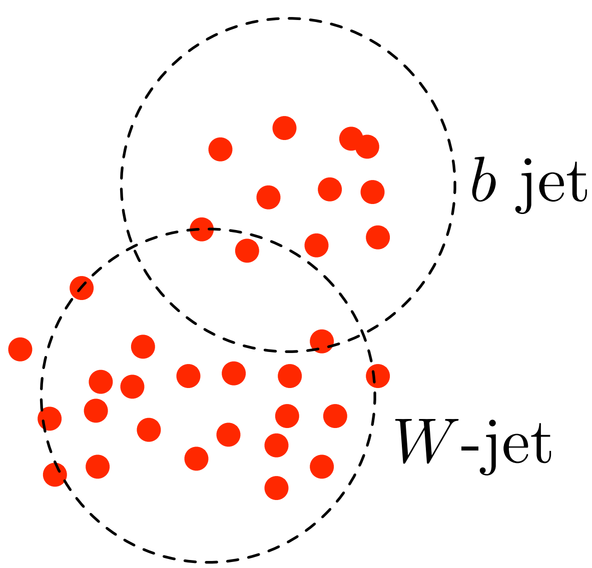
$\sum_i p_i^\mu$

J. M. Butterworth, B. E. Cox and J. R. Forshaw 2002

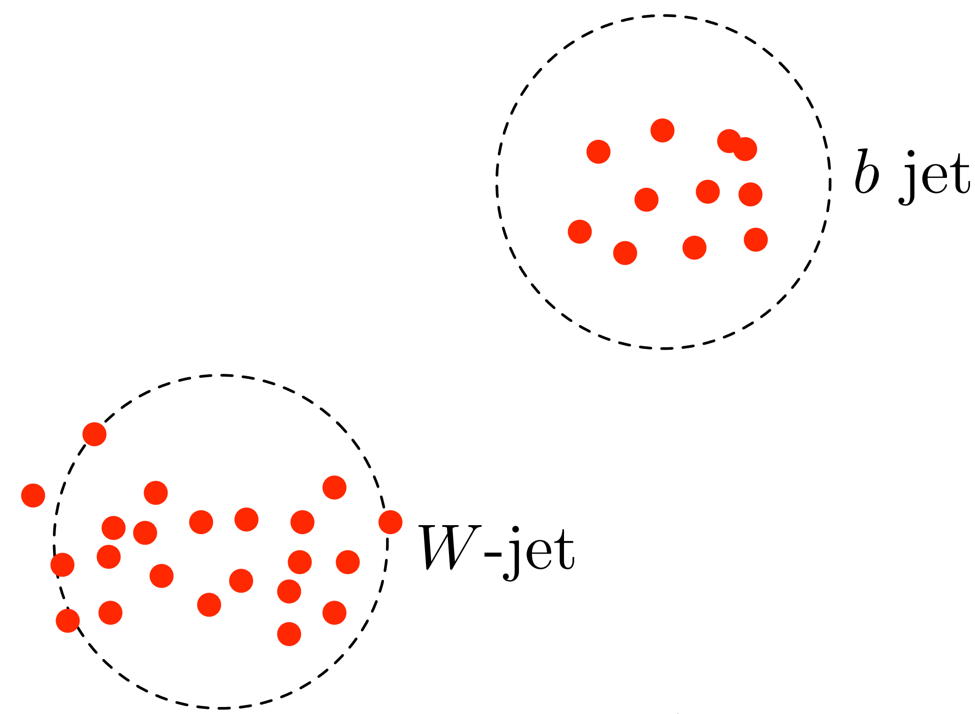
P. Savard 1997
I. Borjanovic et al. 2005

W. Skiba and D. Tucker-Smith 2007

- suppression of $t\bar{t}$ background

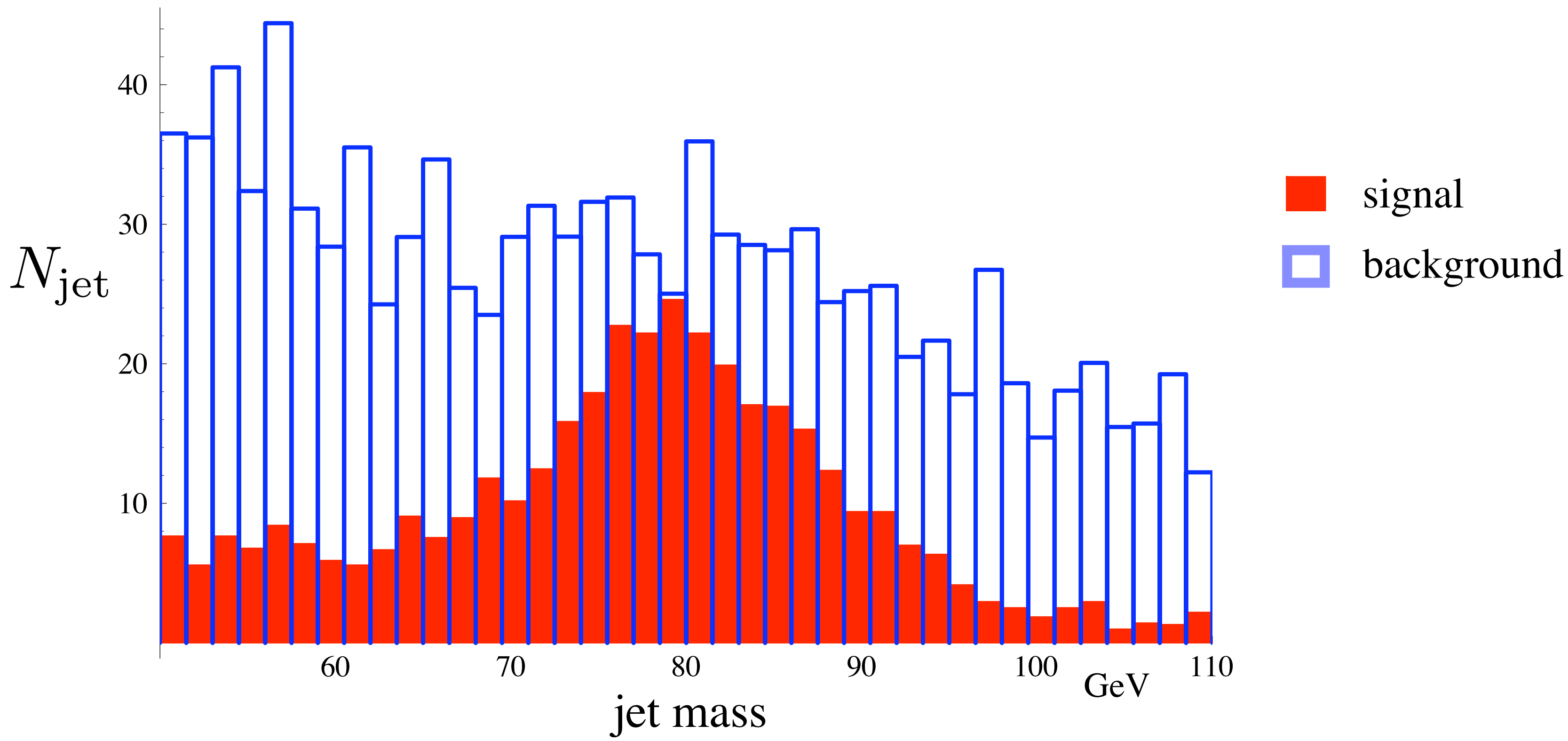


from boosted t



from t'

Sample jet mass plot



W-jet definition

- invariant mass of jet within ≈ 10 GeV of the peak
- peak can be experimentally determined—need not be exactly at M_W
    - "splash out" and "splash in" effects

Detector Simulation

- PGS4 with cone-based jet finder option

```
ATLAS                 ! parameter set name
81                    ! eta cells in calorimeter
63                    ! phi cells in calorimeter
0.1                   ! eta width of calorimeter cells  |eta| < 5
0.099733101           ! phi width of calorimeter cells
0.01                  ! electromagnetic calorimeter resolution  const
0.1                   ! electromagnetic calorimeter resolution * sqrt(E)
0.8                   ! hadronic calolrimeter resolution * sqrt(E)
0.2                   ! MET resolution
0.00                  ! calorimeter cell edge crack fraction
cone                  ! jet finding algorithm (cone or ktjet)
3.0                   ! calorimeter trigger cluster finding seed threshold (GeV)
0.5                   ! calorimeter trigger cluster finding shoulder threshold (GeV)
0.6                   ! calorimeter kt cluster finder cone size (delta R)
1.0                   ! outer radius of tracker (m)
2.0                   ! magnetic field (T)
0.000005              ! sagitta resolution (m)
0.98                  ! track finding efficiency
0.30                  ! minimum track pt (GeV/c)
2.5                   ! tracking eta coverage
3.0                   ! e/gamma eta coverage
2.4                   ! muon eta coverage
2.0                   ! tau eta coverage
```

- Brian Beare has been using Atlfast in the Athena framework and finding similar results

$$pp \to t'\overline{t'} \to W^+W^-b\bar{b}$$

Event Selection

- scalar p_T sum of 5 hardest objects $> \Lambda_{\rm top5}$
- one b-tag jet with $p_T > \Lambda_b$
- one W-jet

- choose $\Lambda_{\rm top5} = 2m_{t'}$ and $\Lambda_b = m_{t'}/3$
- for real data keep $\Lambda_{\rm top5}/\Lambda_b = 6$ and scan to optimize signal

b-tagging efficiencies

- account for large p_T's, where efficiencies worsen

  1/2 for b's

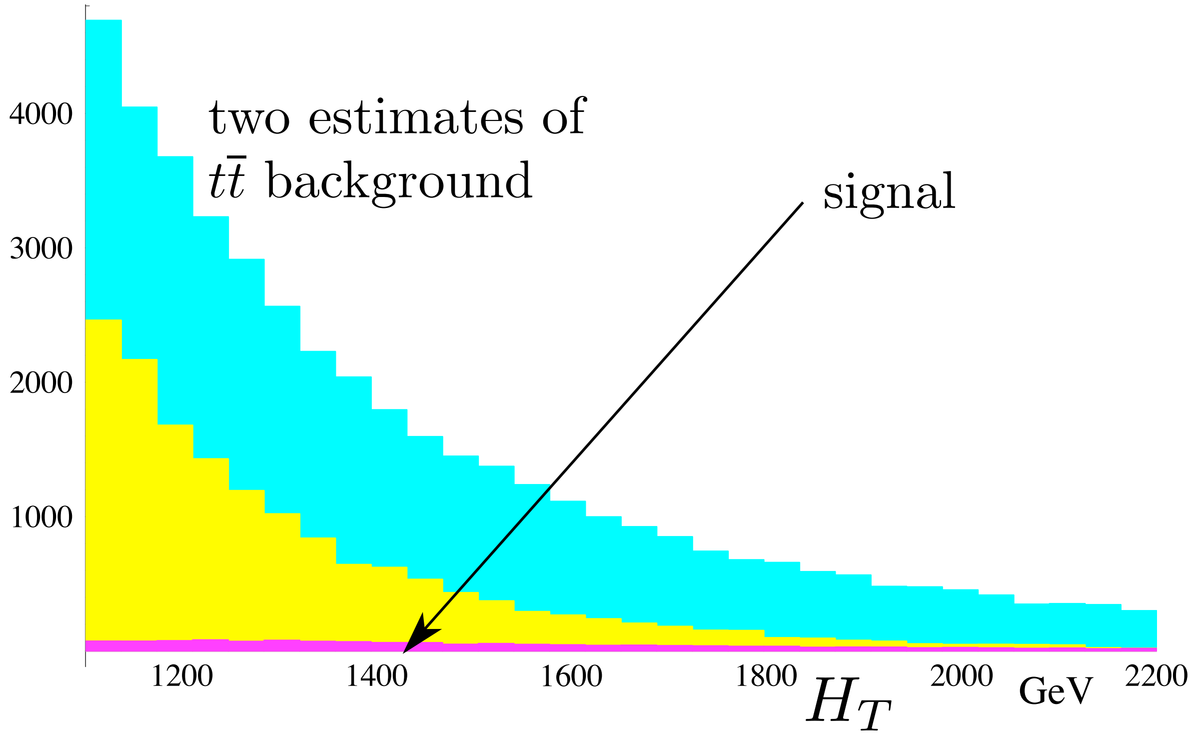
  1/10 for c's

  1/30 for light quarks and gluons

- assume to vanish for pseudorapidity $|\eta| > 2$

H_T *distribution*

- scalar p_T sum of everything in the event
- signal peaks at high $H_T \approx 2m_{t'}$
- why not just look for the signal bump on the tail?



- t' mass reconstruction is essential
    - consider invariant mass of all W-b pairs
- pairs of plots: W-mass plot and t'-mass plot

Event Generators

- MC@NLO-Herwig comes the closest to correctly modeling the partonic scattering by including the one-loop amplitudes
- Alpgen accounts for more jets by incorporating higher order tree level amplitudes, and can be interfaced to either Herwig or Pythia
- stand-alone Pythia includes a more varied and possibly more advanced description of initial state radiation and the underlying event

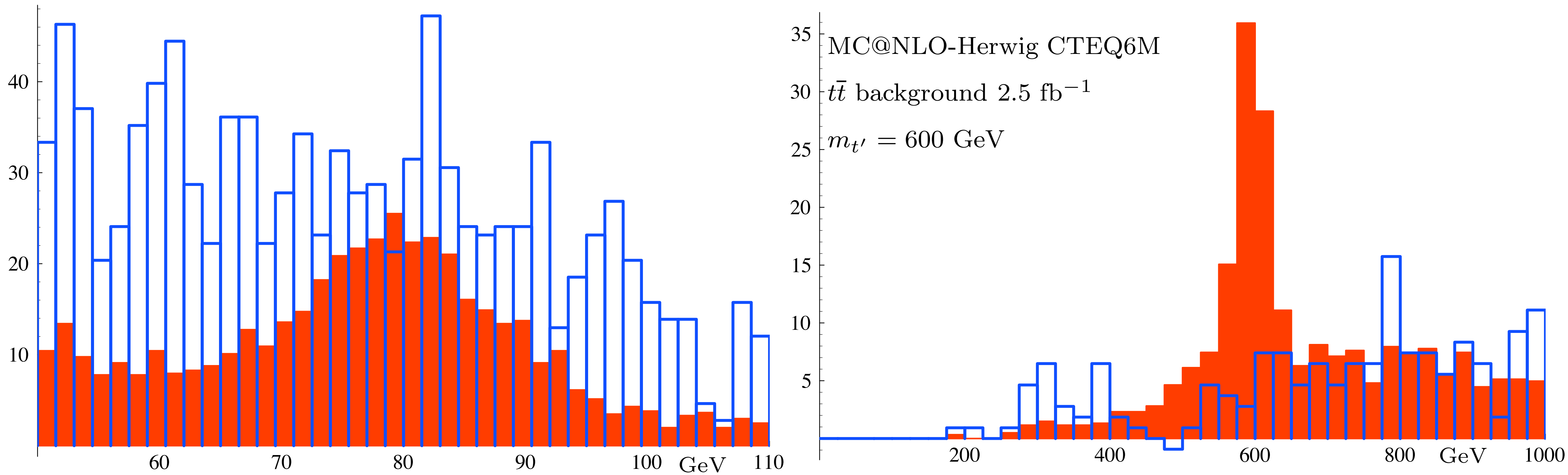
- in each case we use the same tools to calculate both signal and background

Backgrounds

- consider the $t\bar{t}$ irreducible background first
- then consider QCD multijet backgound
- dealing with this basically eliminates other backgrounds: $(W/Z) + \text{jets}$, $b\bar{b} + \text{jets}$, $(W/Z)b\bar{b}$, $(WW/ZZ/WZ) + \text{jets}$, and $(t/\bar{t})(\bar{b}/b)W$

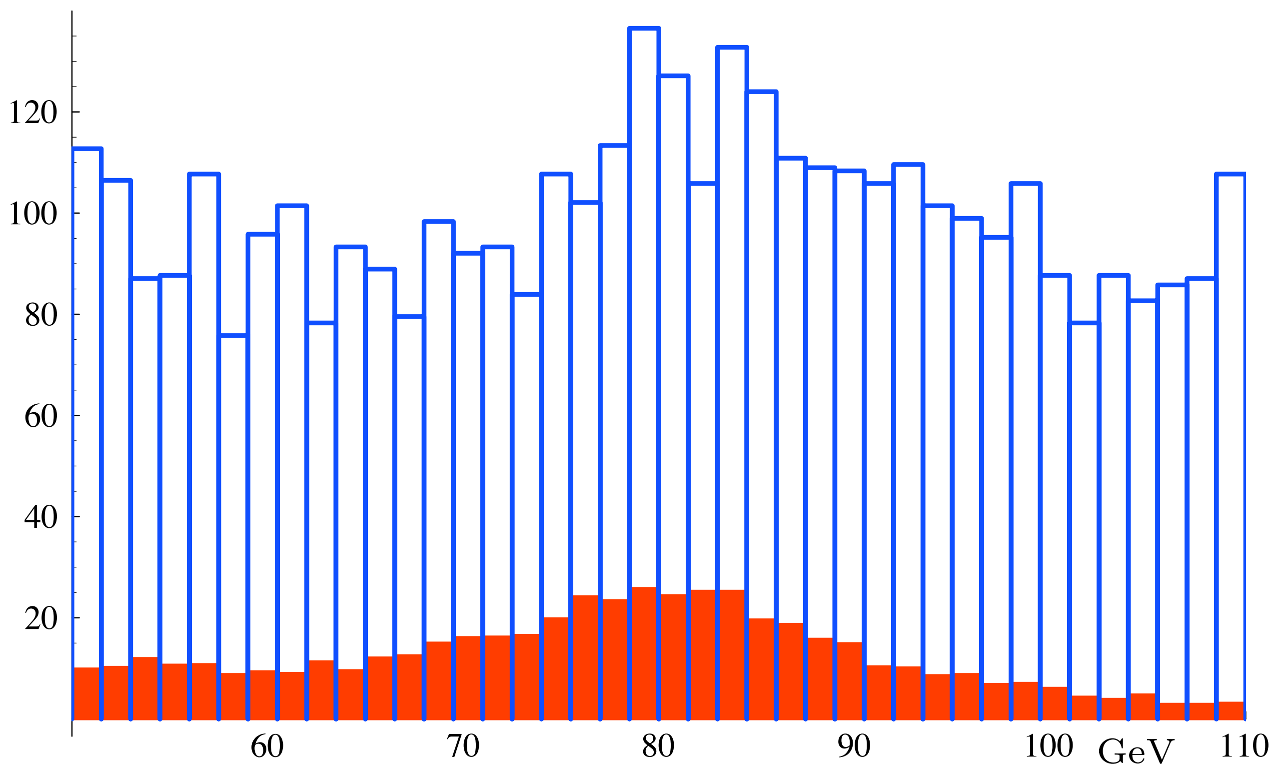
MC@NLO-Herwig

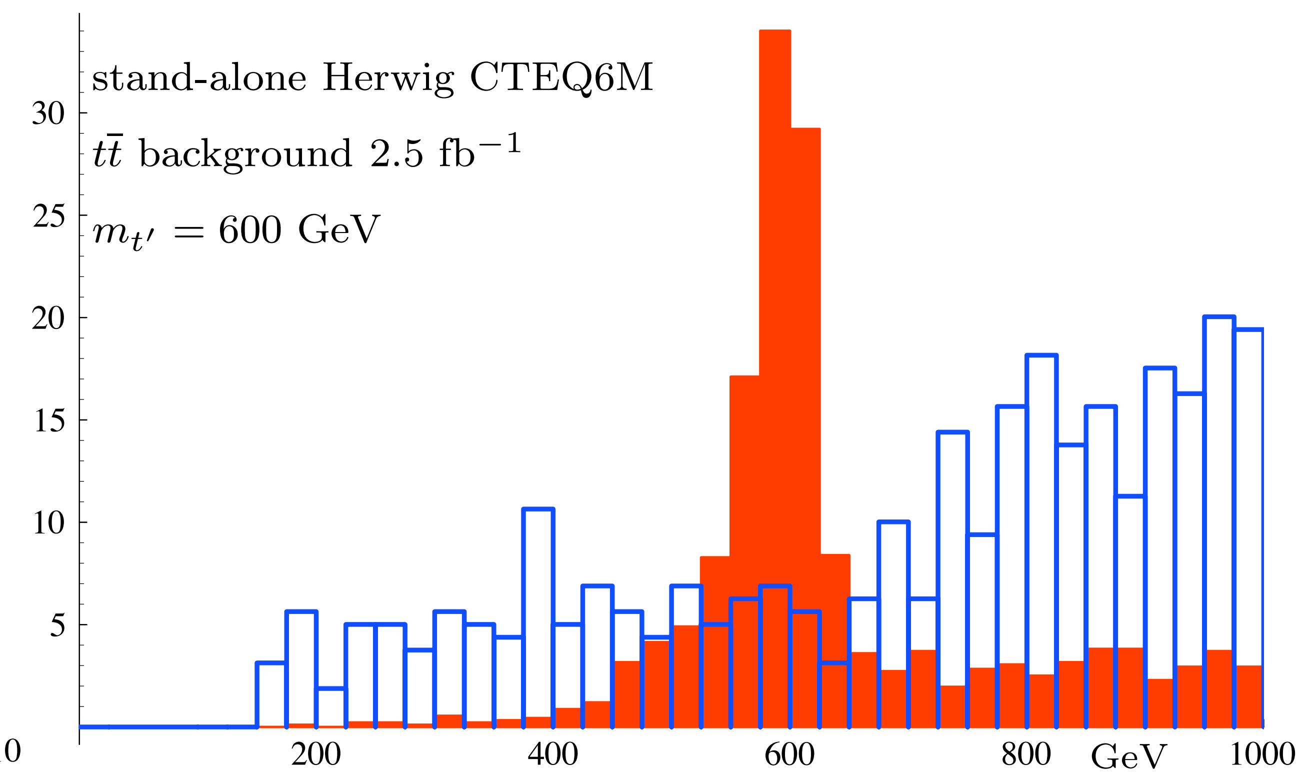
- good for getting absolute rates
- no description of fourth family
  - use $m_t = 600$ GeV and $t \to bW$ to model $t' \to bW$
- produces some negative weights ($\approx 15\%$)
- use CTEQ6M and scale to 2.5 fb^{-1}



stand-alone Herwig

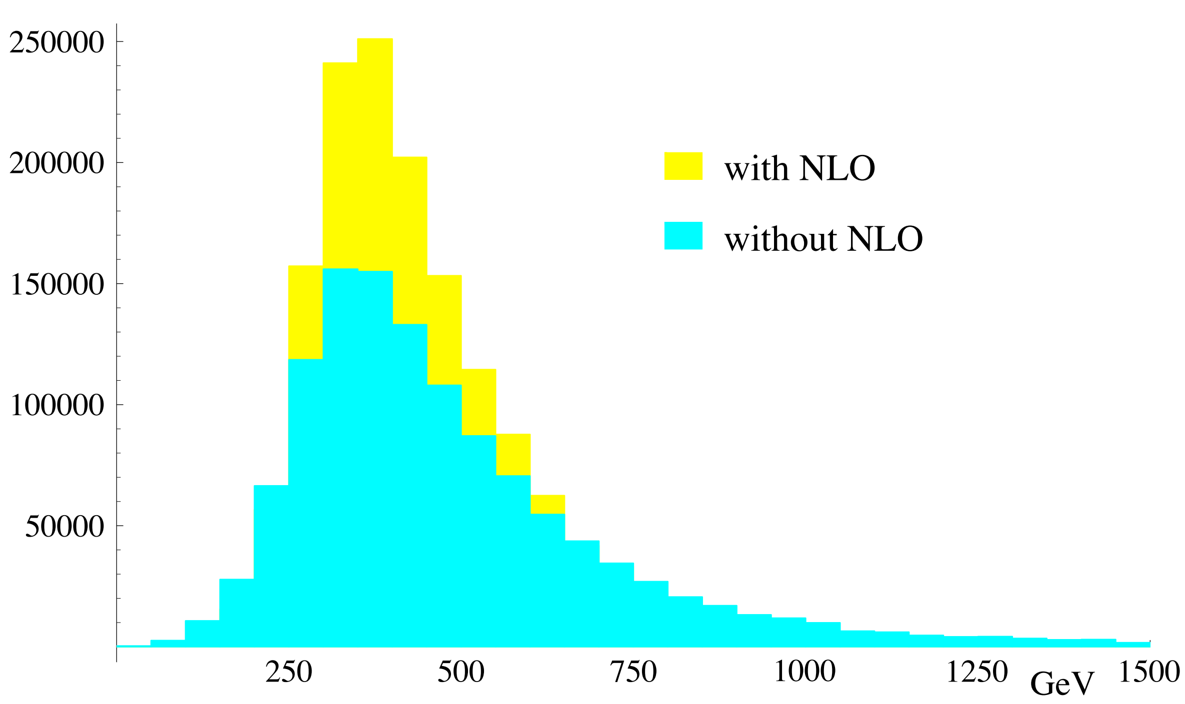
- increases background and decreases signal!

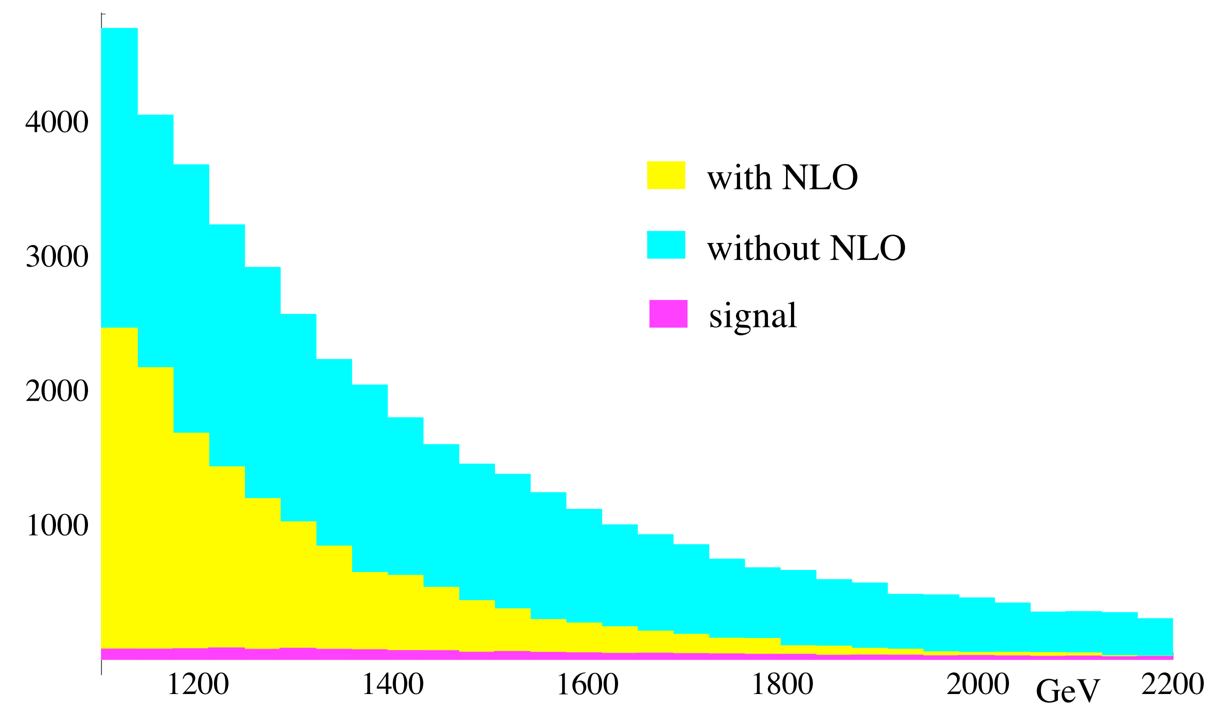




H_T *distribution*

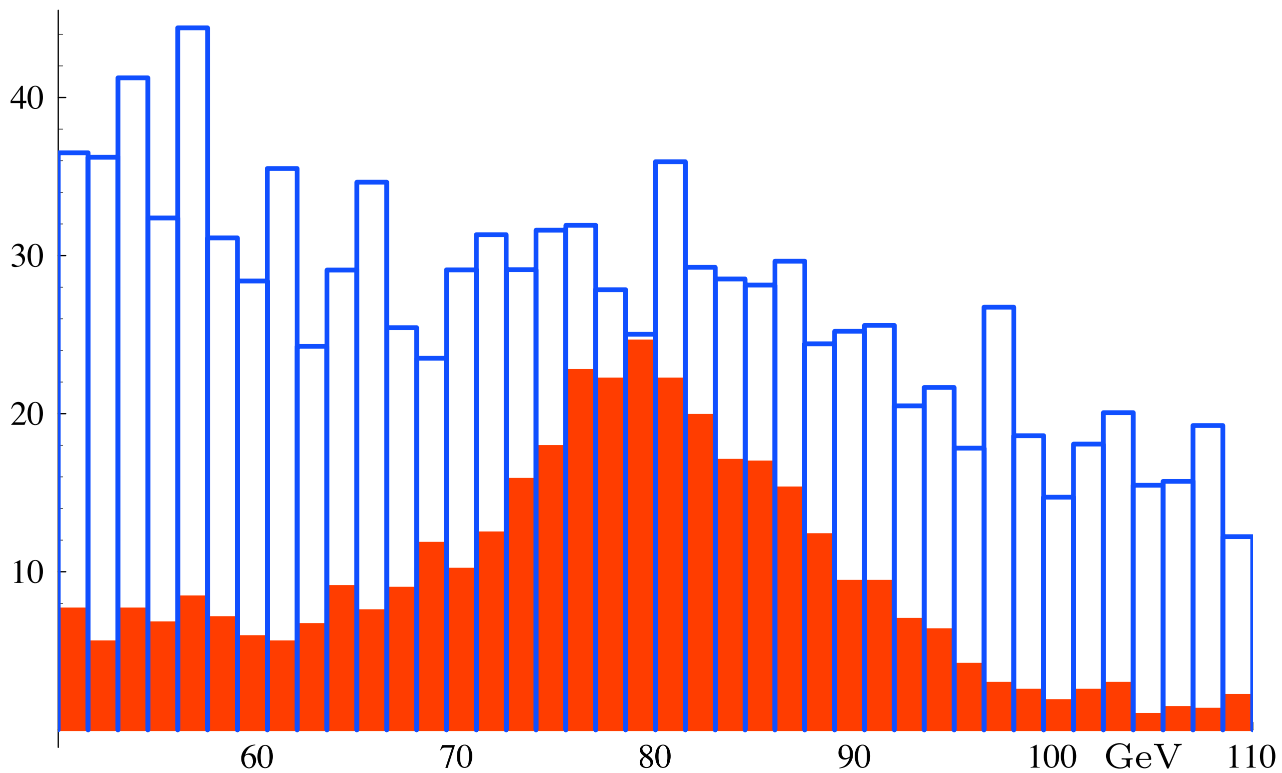
- seems that NLO suppresses the tail, in addition to giving the K-factor enhancement
- but what is stand-alone Herwig doing?

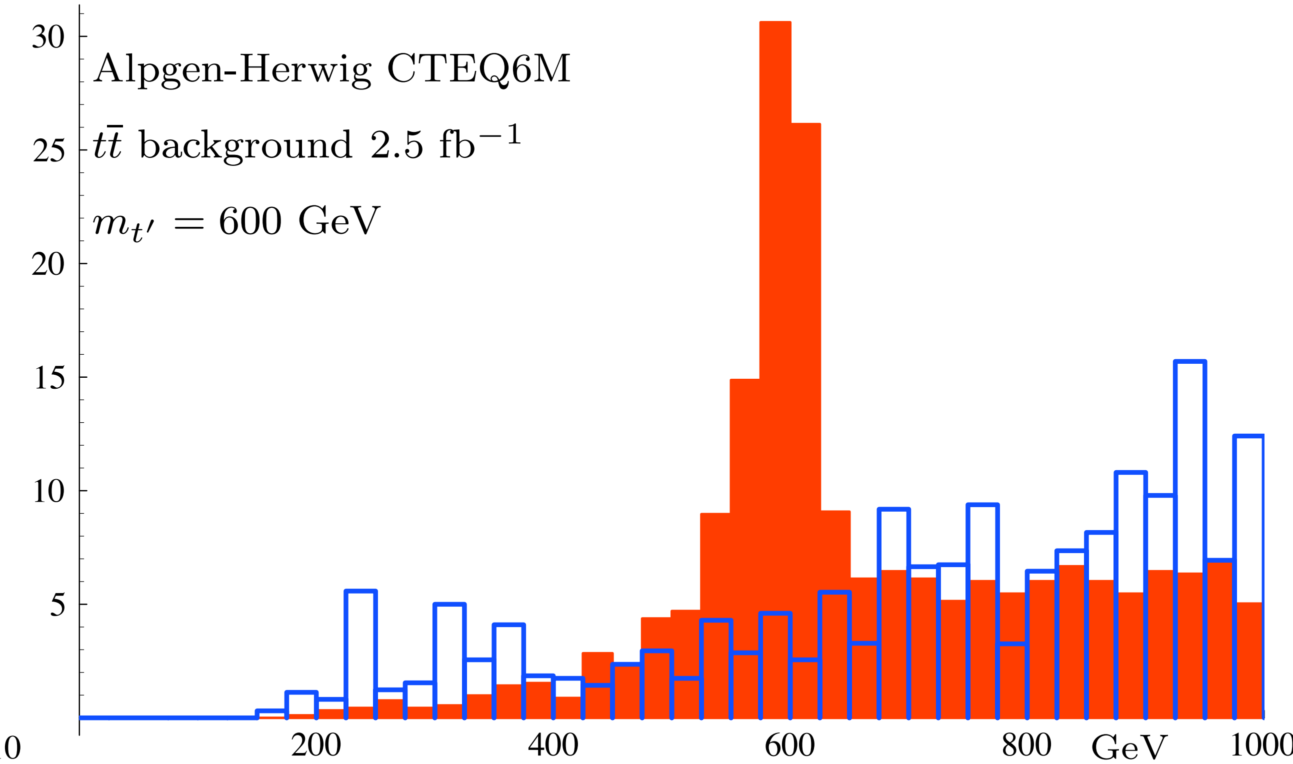




Alpgen-Herwig

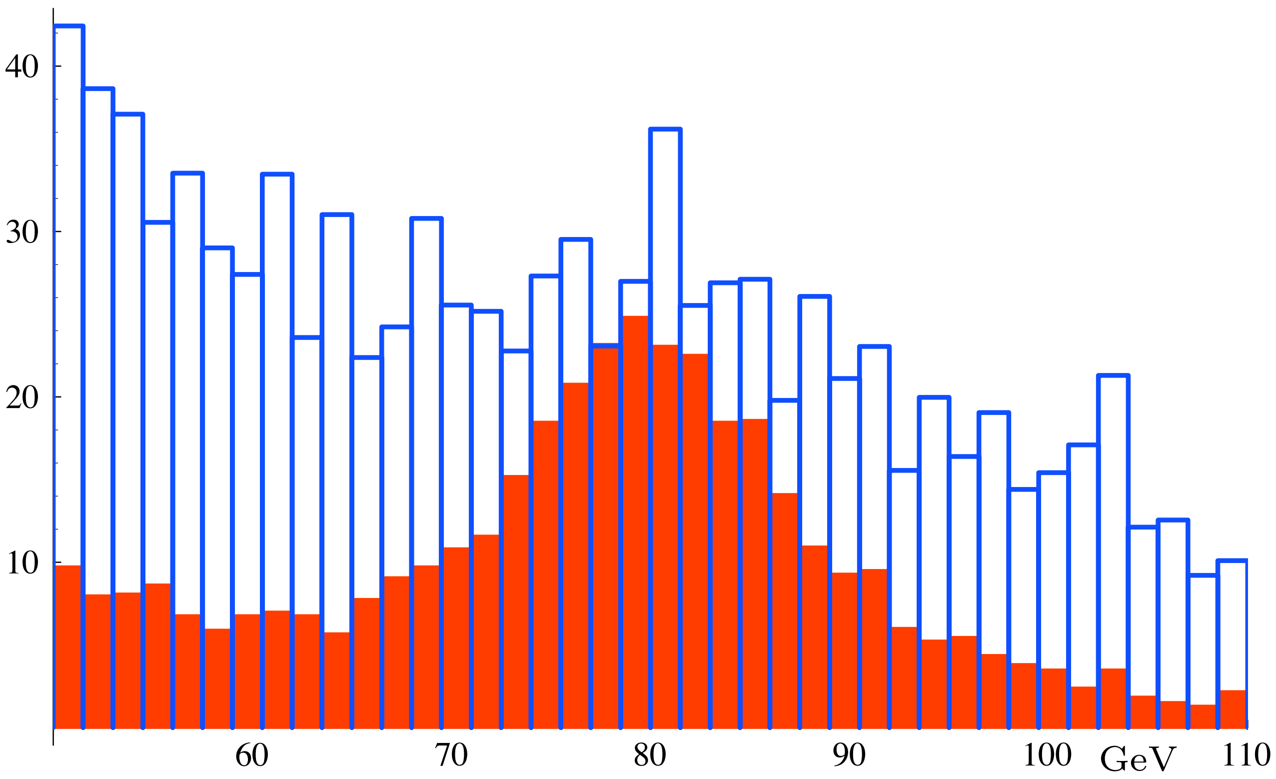
- choose $\sqrt{\hat{s}}/2$ as the renormalization scale—ignore K-factors
- generate samples involving $t\bar{t}+0$, $t\bar{t}+1$ and $t\bar{t}+2$ partons
- use MLM parton-jet matching scheme
- model t' decay the same way and use CTEQ6M again

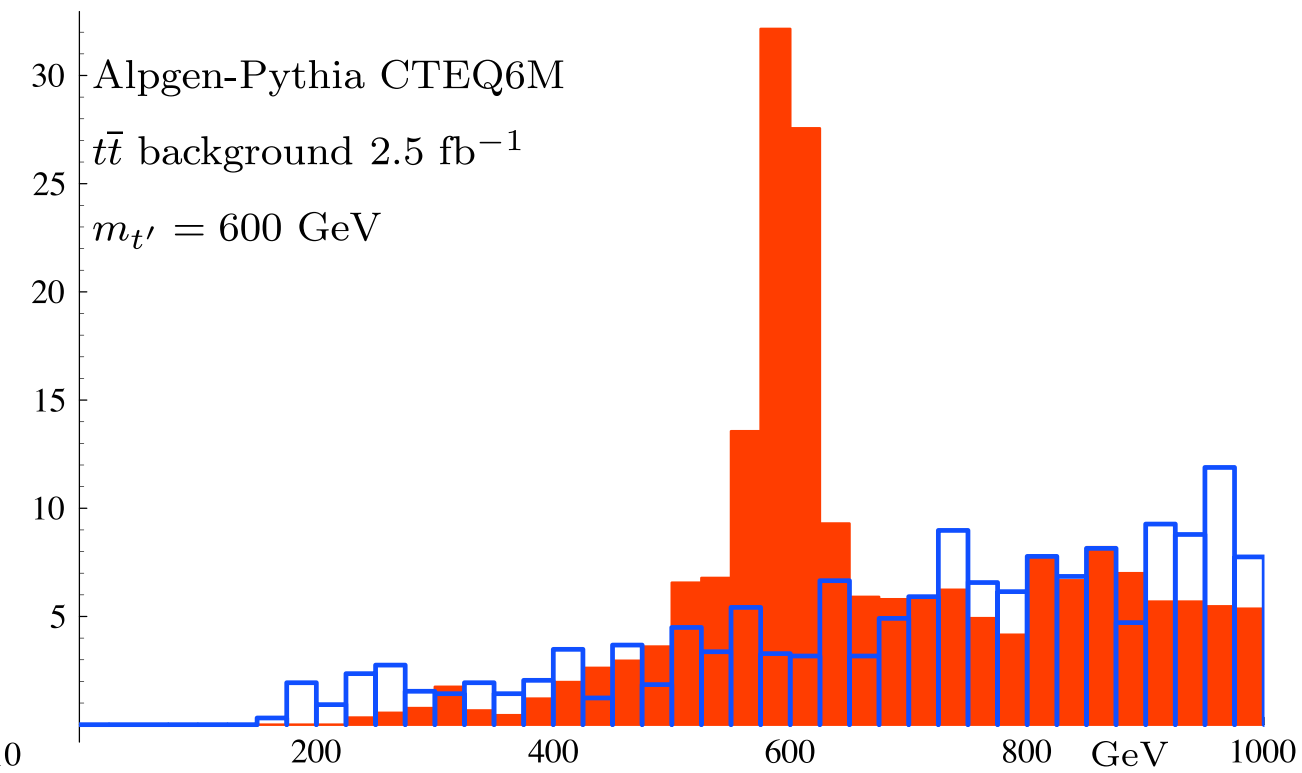




Alpgen-Pythia

- good agreement with Alpgen-Herwig and MC@NLO-Herwig

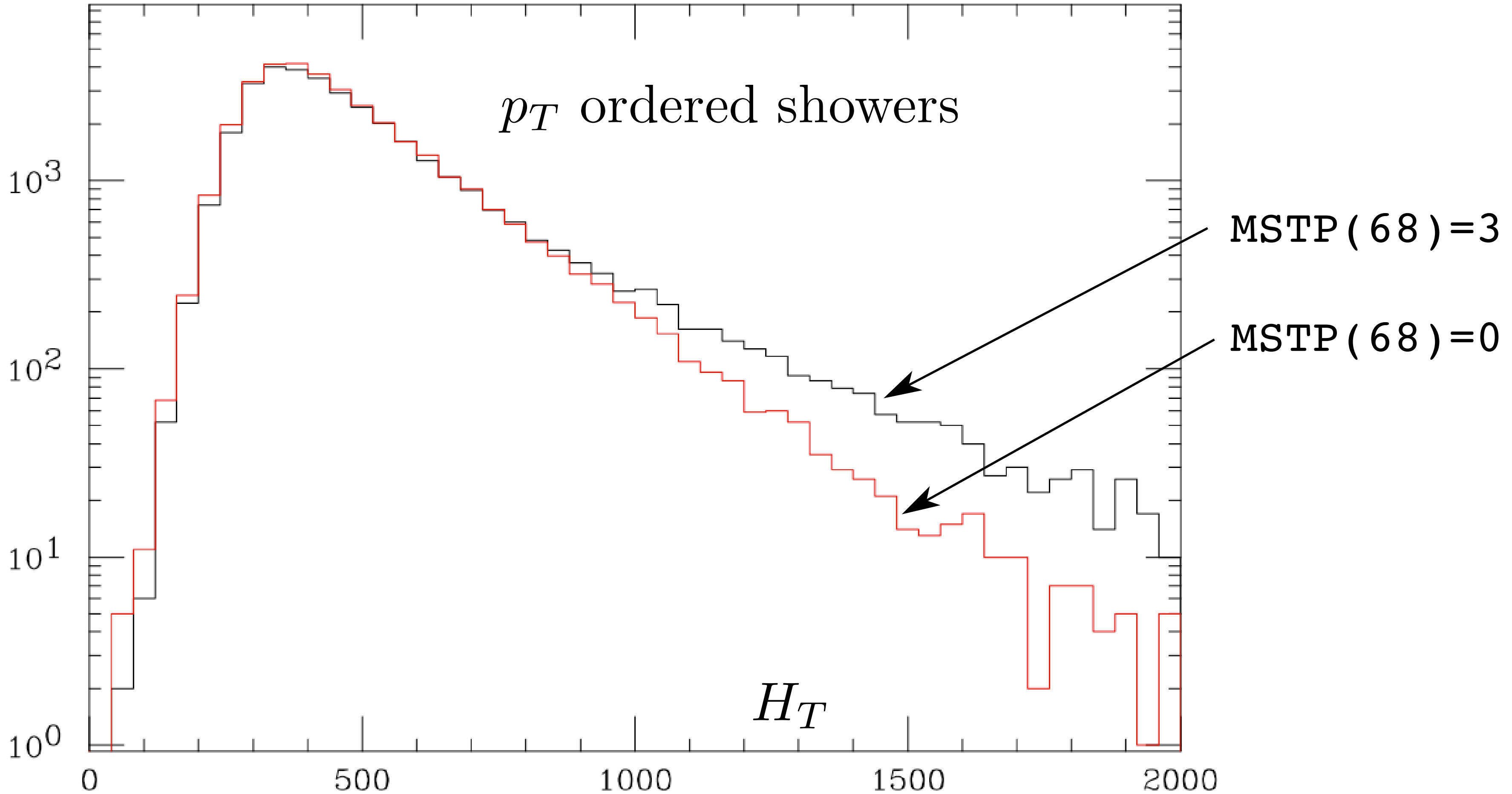




- results so far suggest that improved matrix elements tend to improve S/B
- what about stand-alone Pythia?

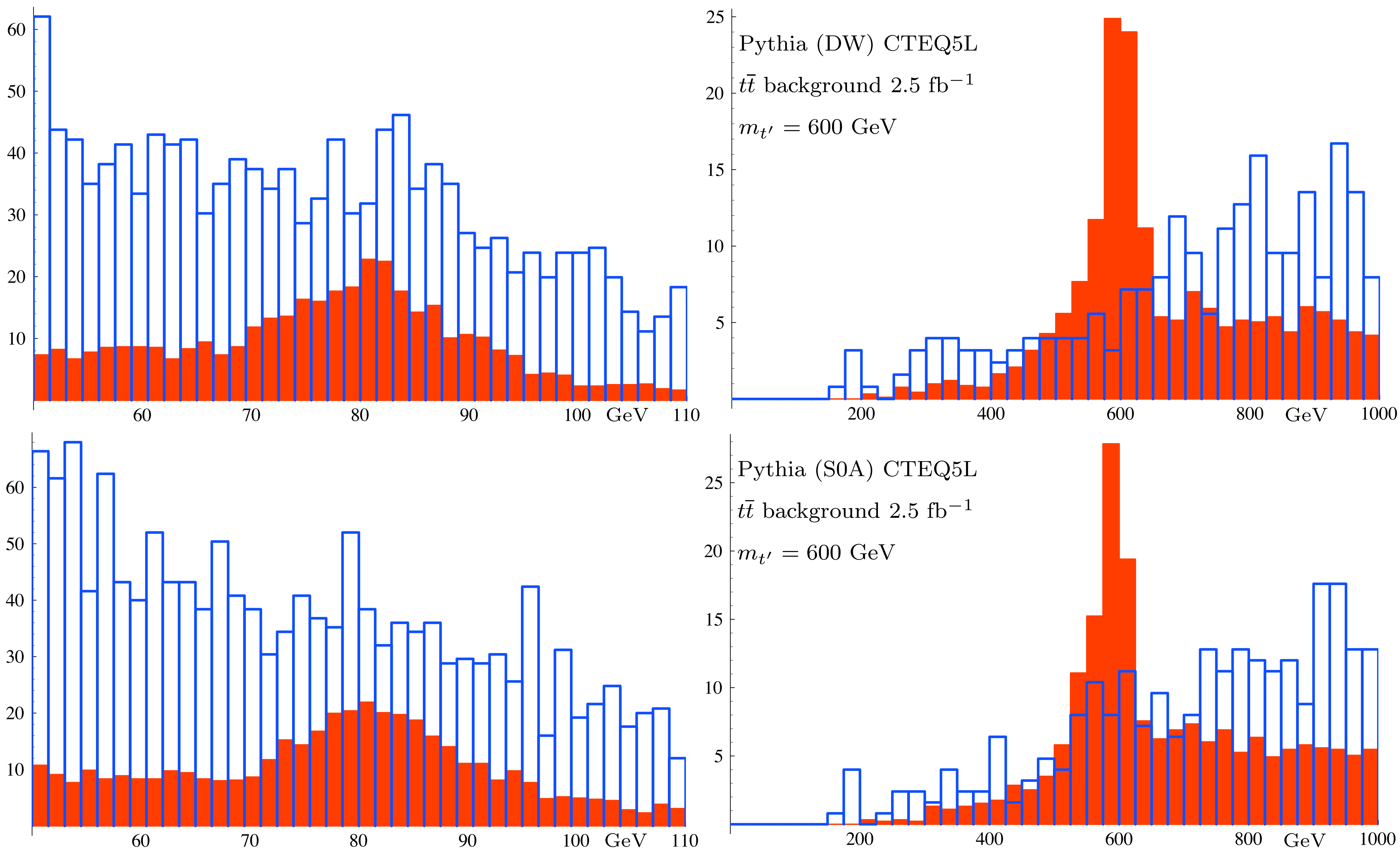
Stand-alone Pythia

- initial-state radiation becomes an issue
- models of underlying event
  (old with Q^2 ordered showers and new with p_T ordered showers)
- note that `MSTP(68)=3` is default ("power showers")
  - ISR has very high phase space cutoff in $t\bar{t}$ production
- `MSTP(68)=0` gives a phase space cutoff more in line with the hard process itself



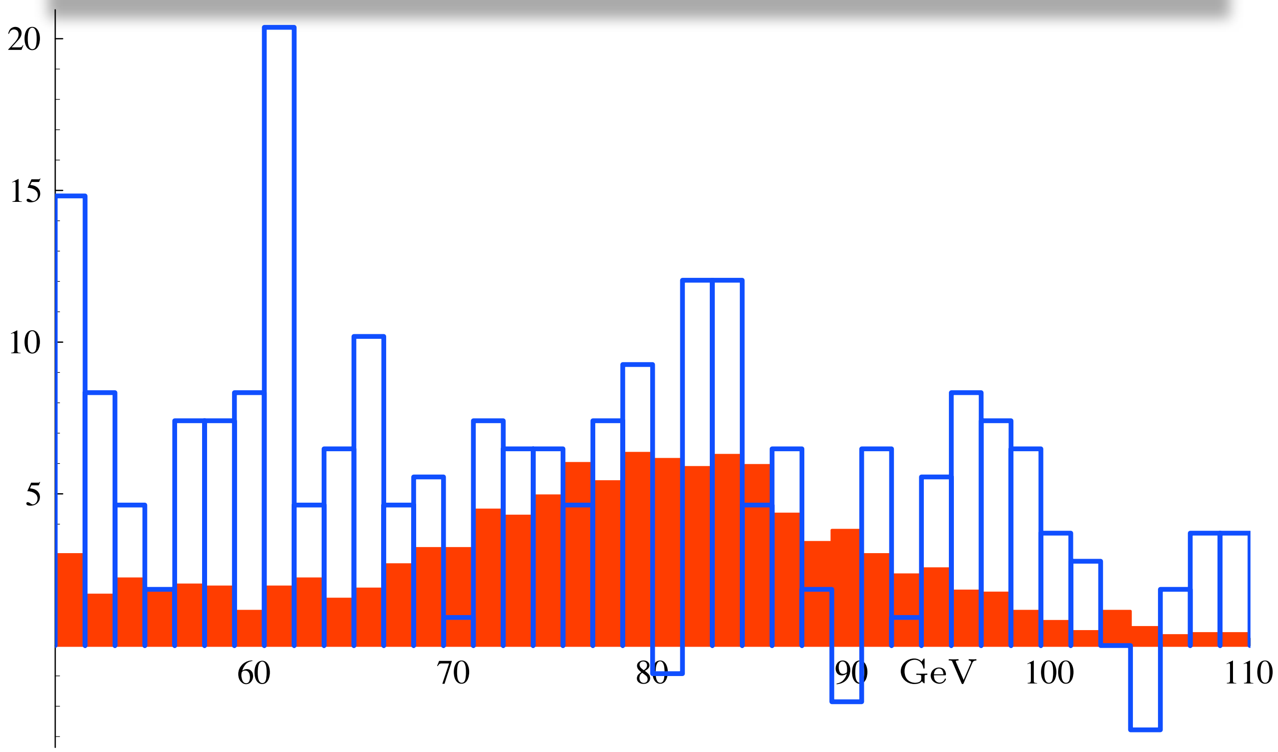
DW (R. Field) and S0A (Sandhoff-Skands) tunes

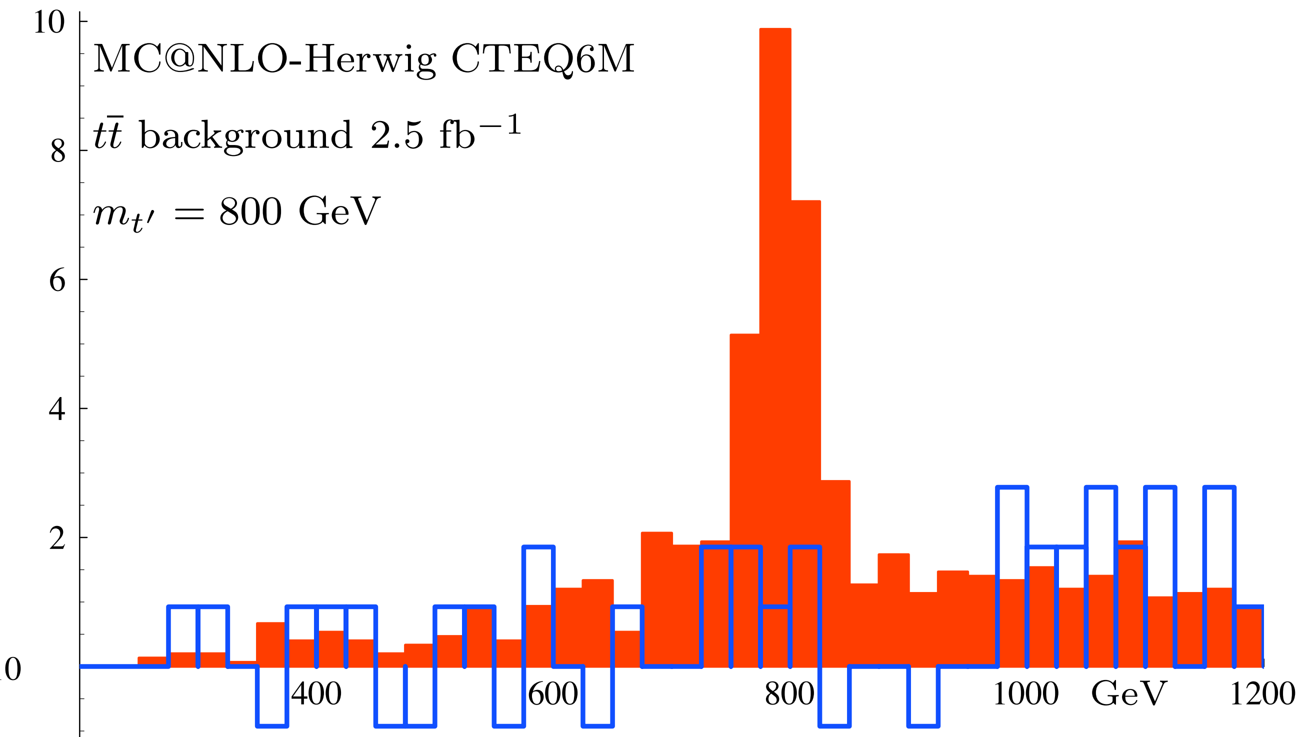
- both use CTEQ5L and share value of `PARP(90)`

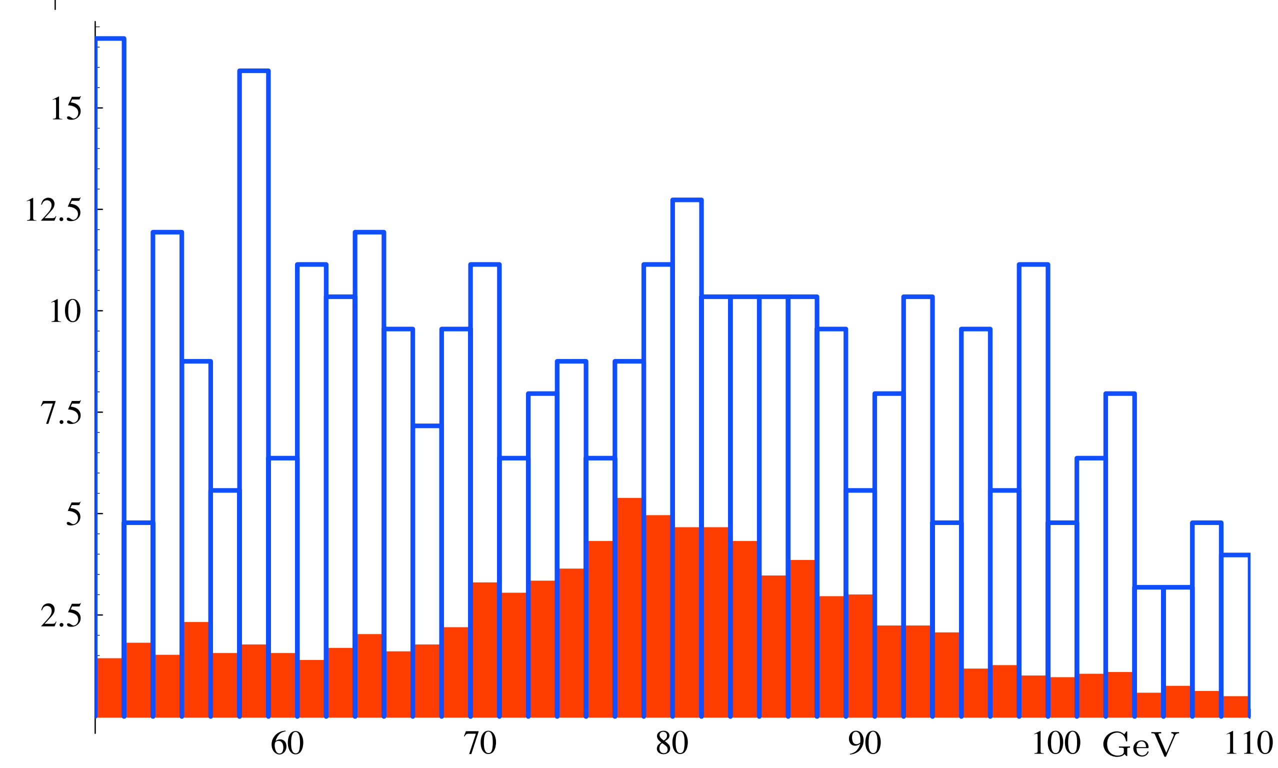


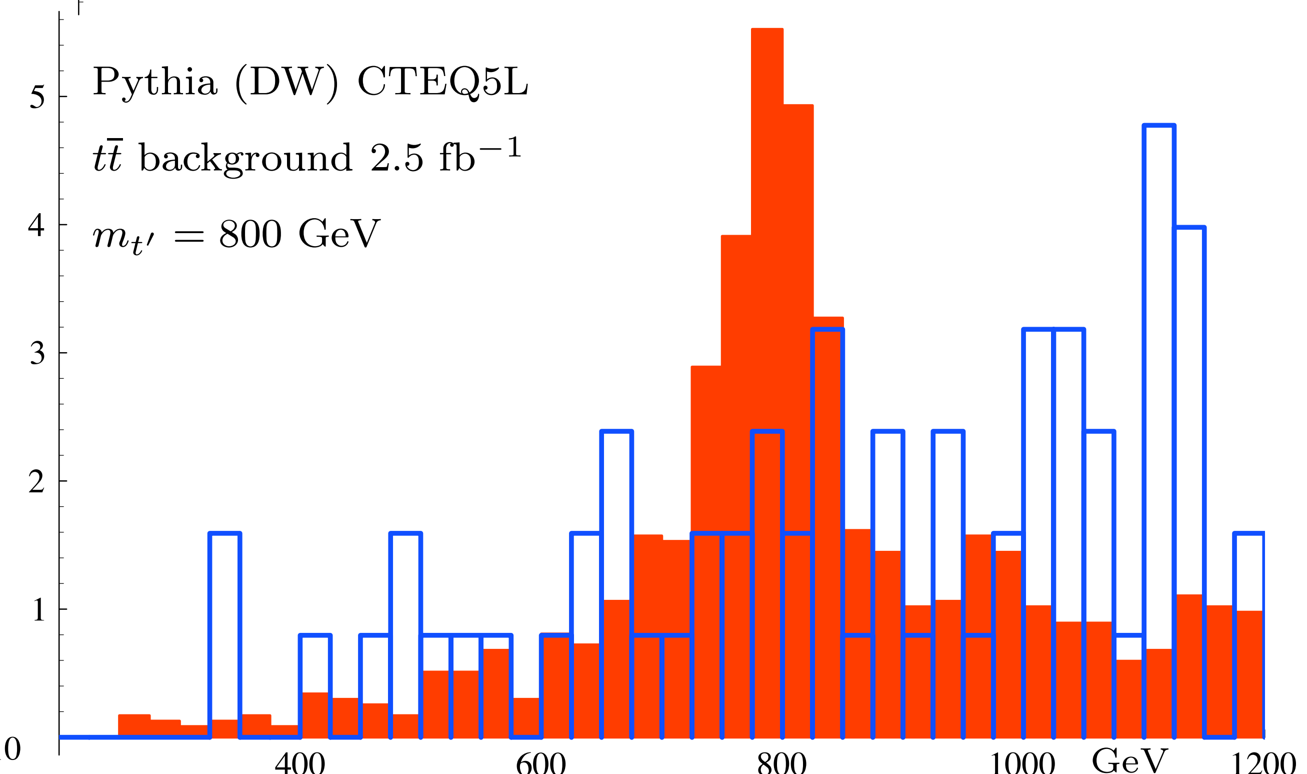
$m_{t'} = 800\ GeV$

- increase Λ_{top5} and Λ_b by 4/3
- MC@NLO-Herwig and Pythia(DW)



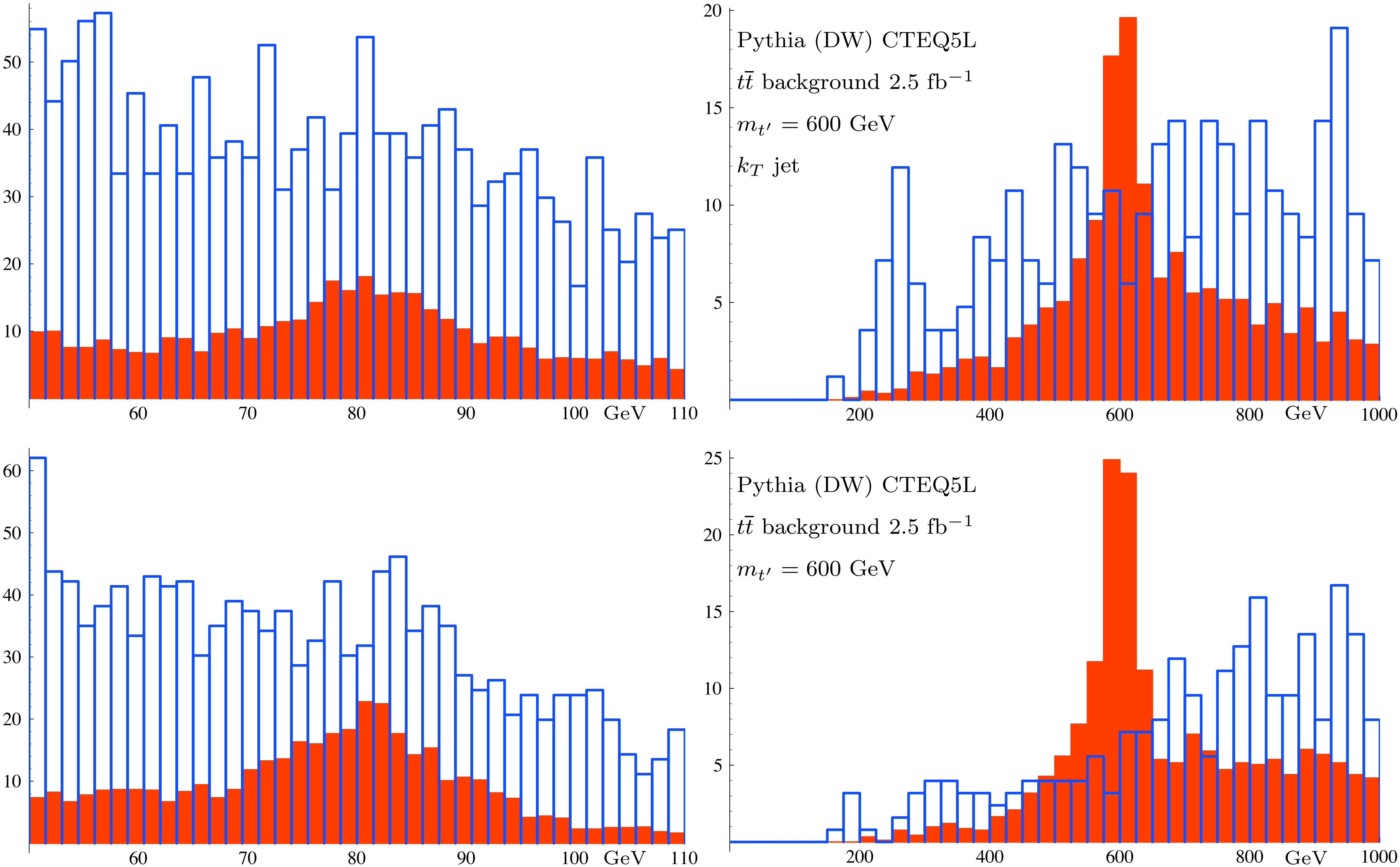






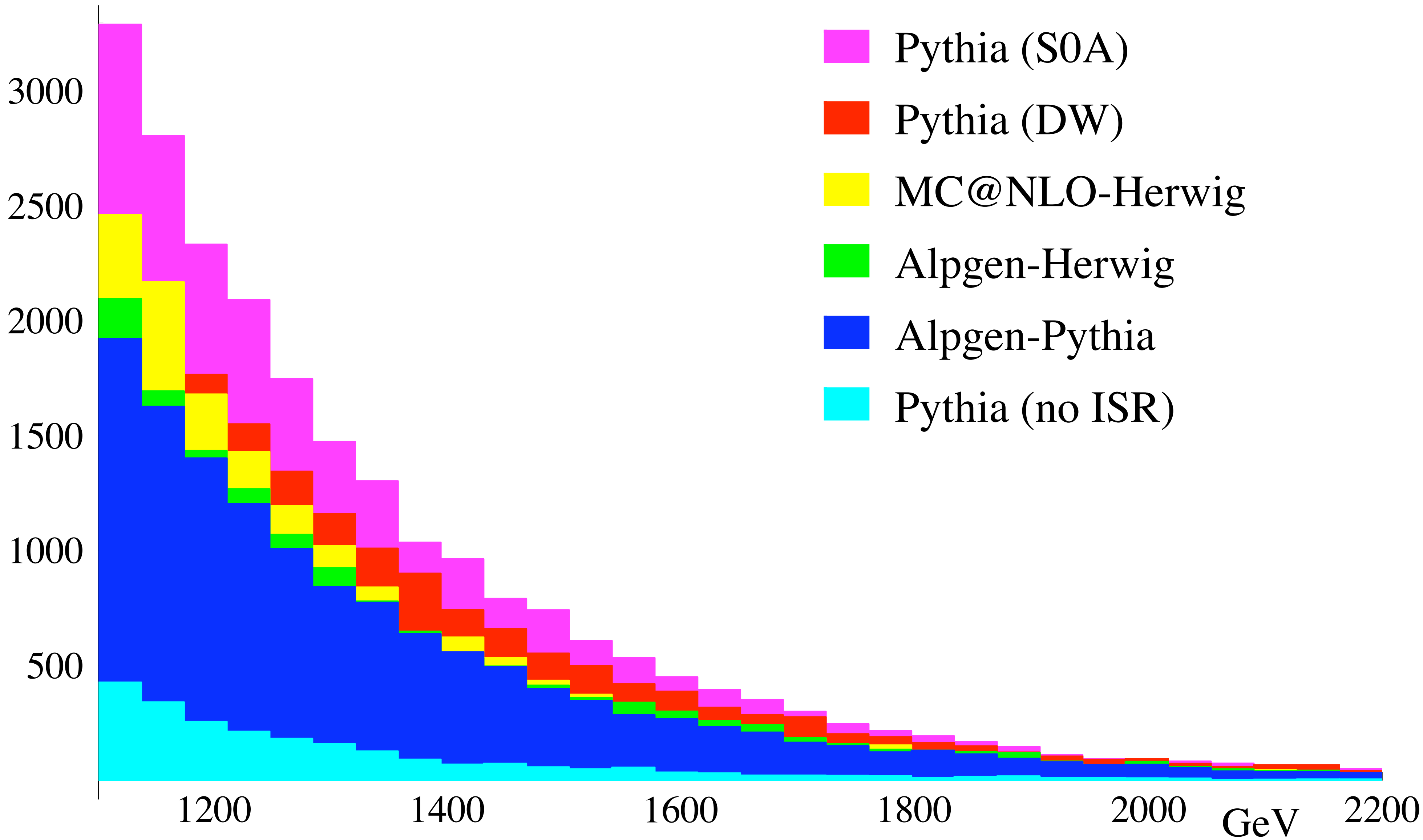
k_T jet vs. cone jet finder

- Pythia(DW)



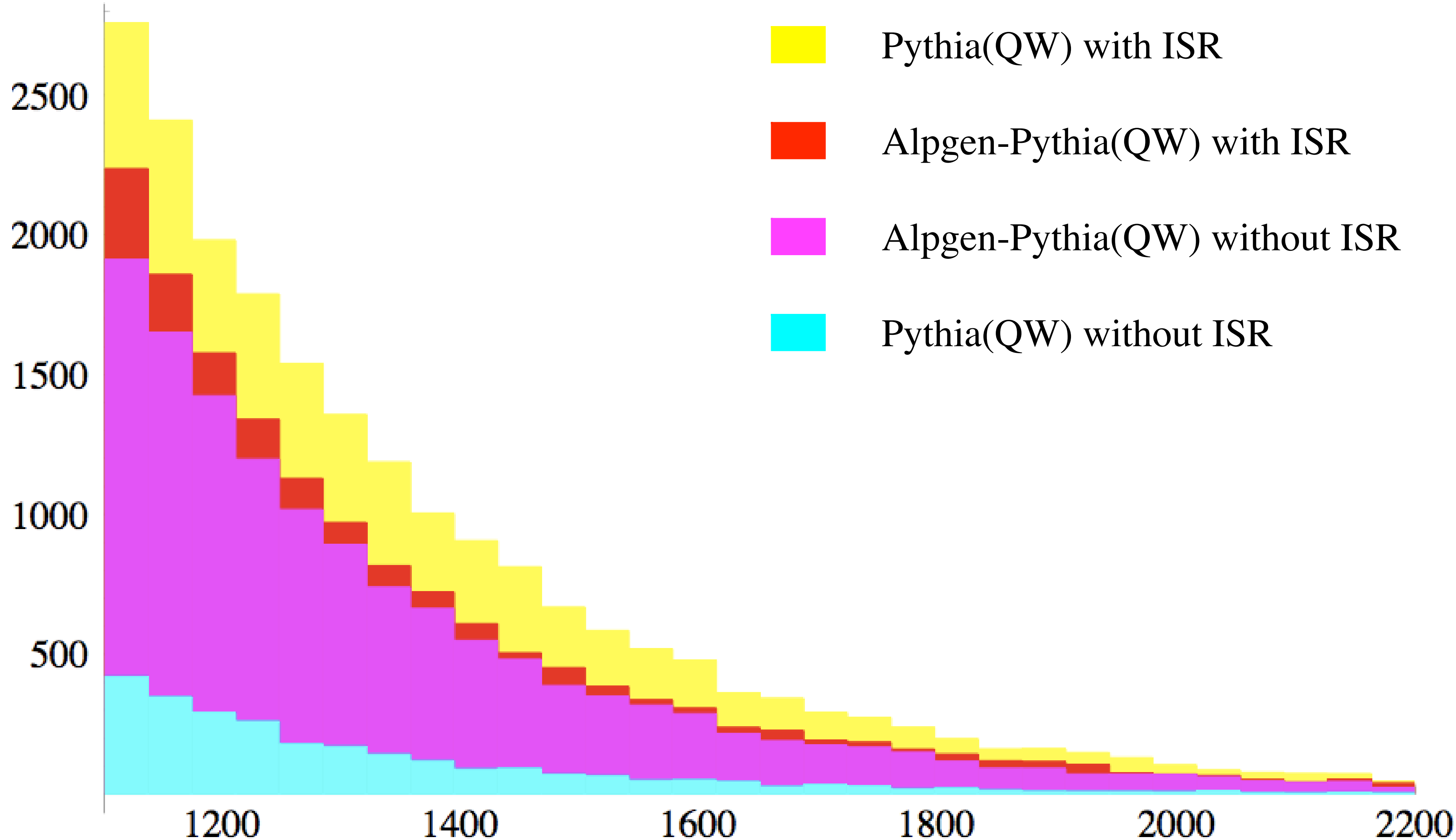
H_T *tails—measure of background*

- power showers and stand-alone Herwig not included
- note sensitivity to initial state radiation



more H_T tails

- standardize on tune QW and CTEQ6.1
- compare Alpgen-Pythia with stand-alone Pythia



- Alpgen removes sensitivity to ISR

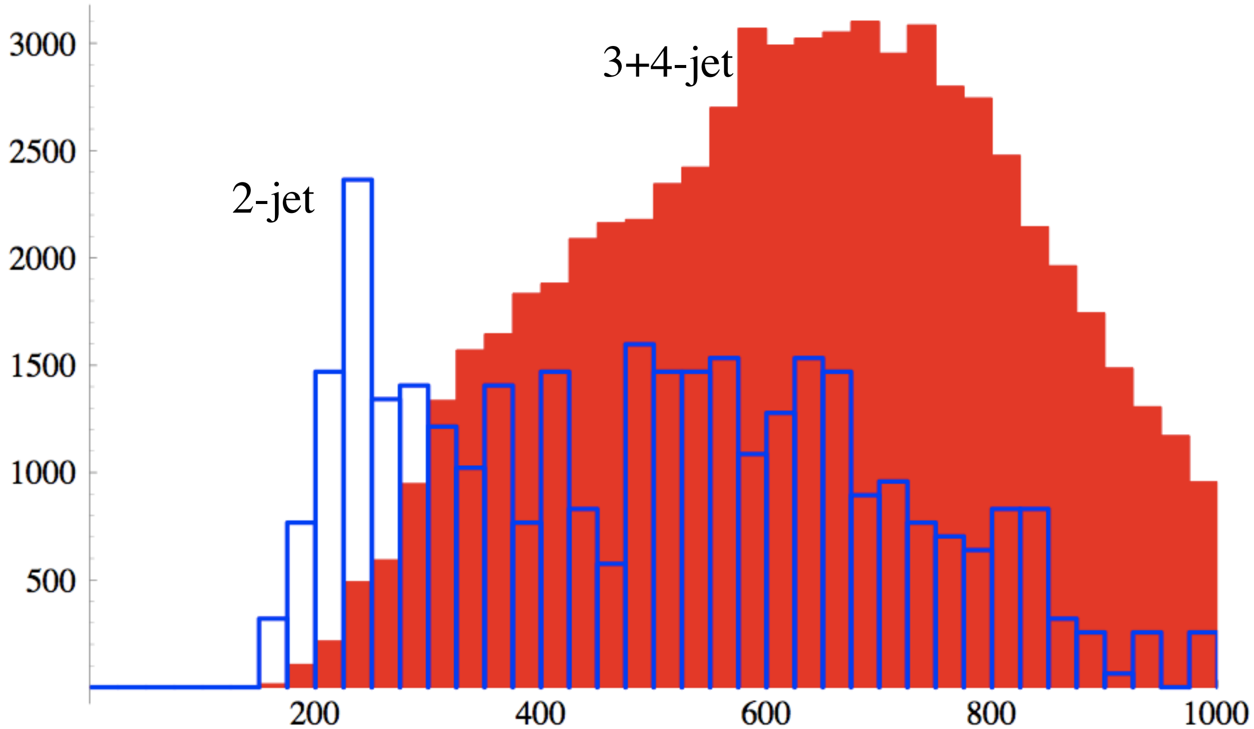
QCD multijet background

- problem is that the cross section is enormous and only a tiny fraction survives in the signal region—how to generate enough events?

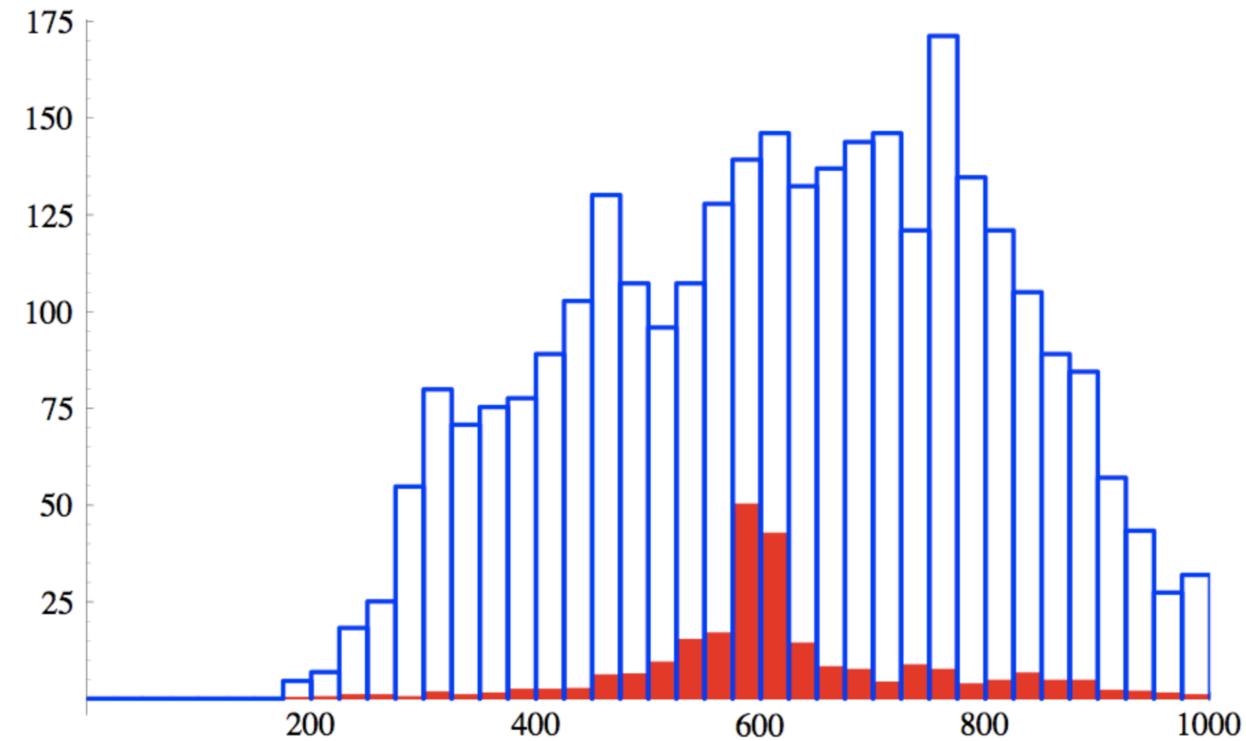
- use Alpgen to "divide and conquer"
- generate 2, 3, and 4-jet samples, with relative sizes determined by a p_T^{min}
  - 3-jet sample dominates 2-jet sample (in signal region) if p_T^{min} is not too large
  - cross sections are smaller if p_T^{min} is large
- compromise by choosing $p_T^{min} = 200$ GeV

- 2-jet sample still has enormous cross section
- remove b-tag to generate enough events, and then compare to the $3 + 4$ jet samples
- then only keep $3 + 4$ jet samples with b-tag, times a correction factor

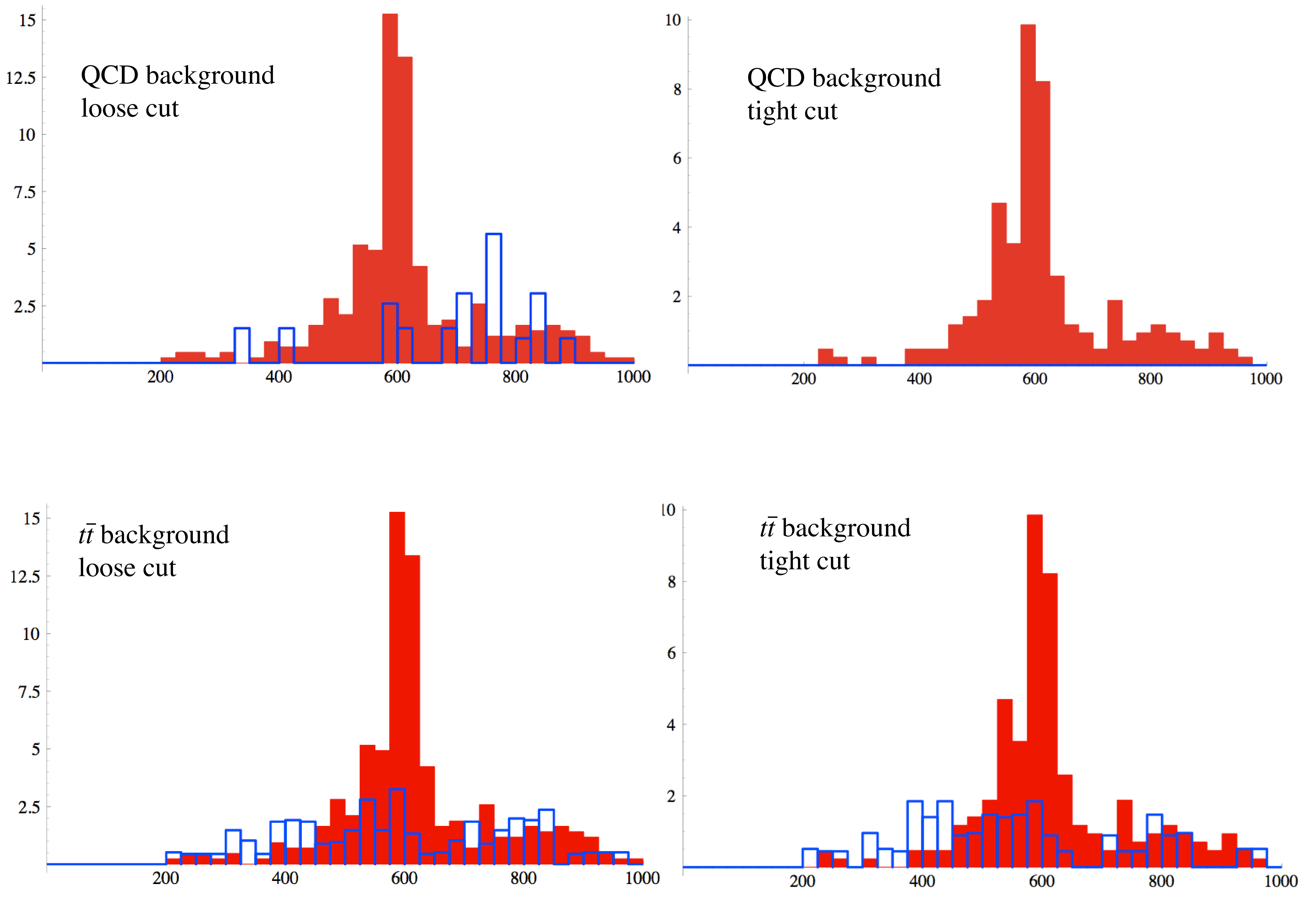
backgrounds without b-tags



signal and background with b-tags



- have added $\Delta R < 2.5$ between W and b, but clearly need to improve S/B
- look for the leptonic decay of the other W in the signal events
- consider a loose cut and a tight cut
  - (isolated electron or muon) or ($>$ 200 GeV missing energy)
  - (isolated electron or muon) and ($>$ 50 GeV missing energy)



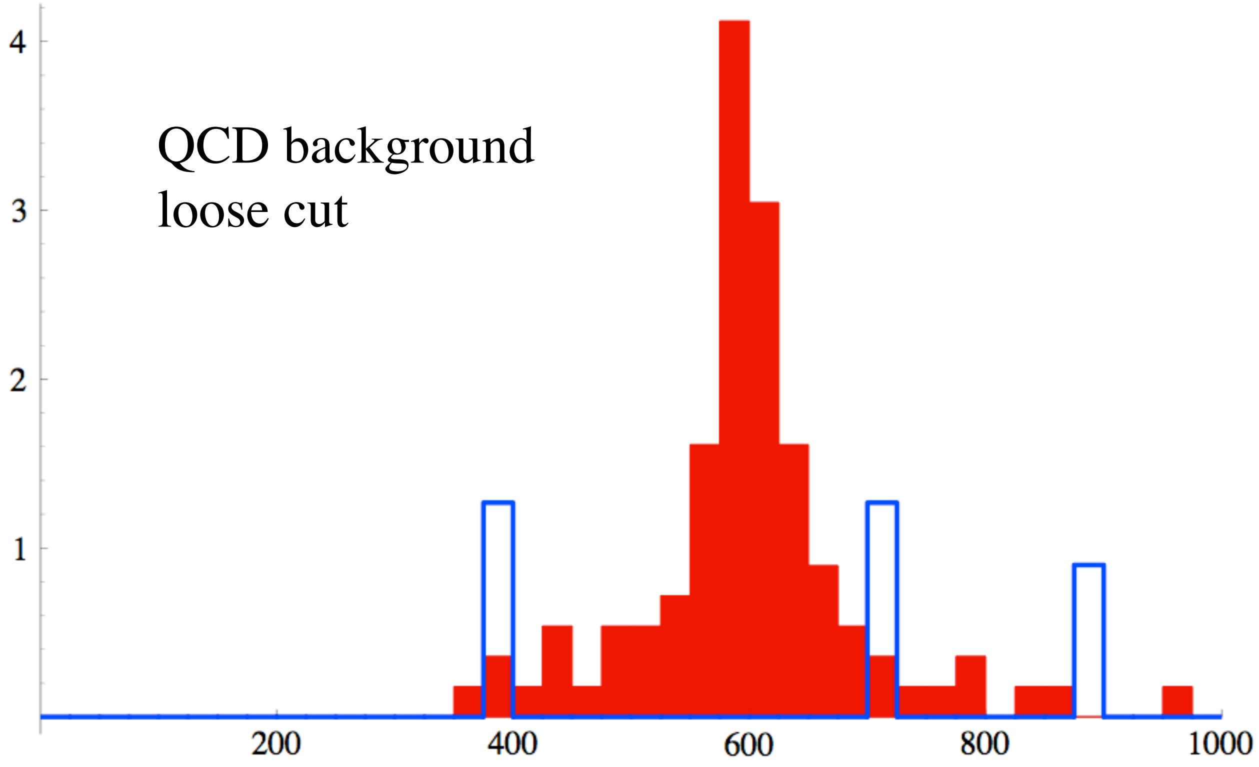
- Alpgen-Pythia with tune QW and everything scaled to 4 fb^{-1}

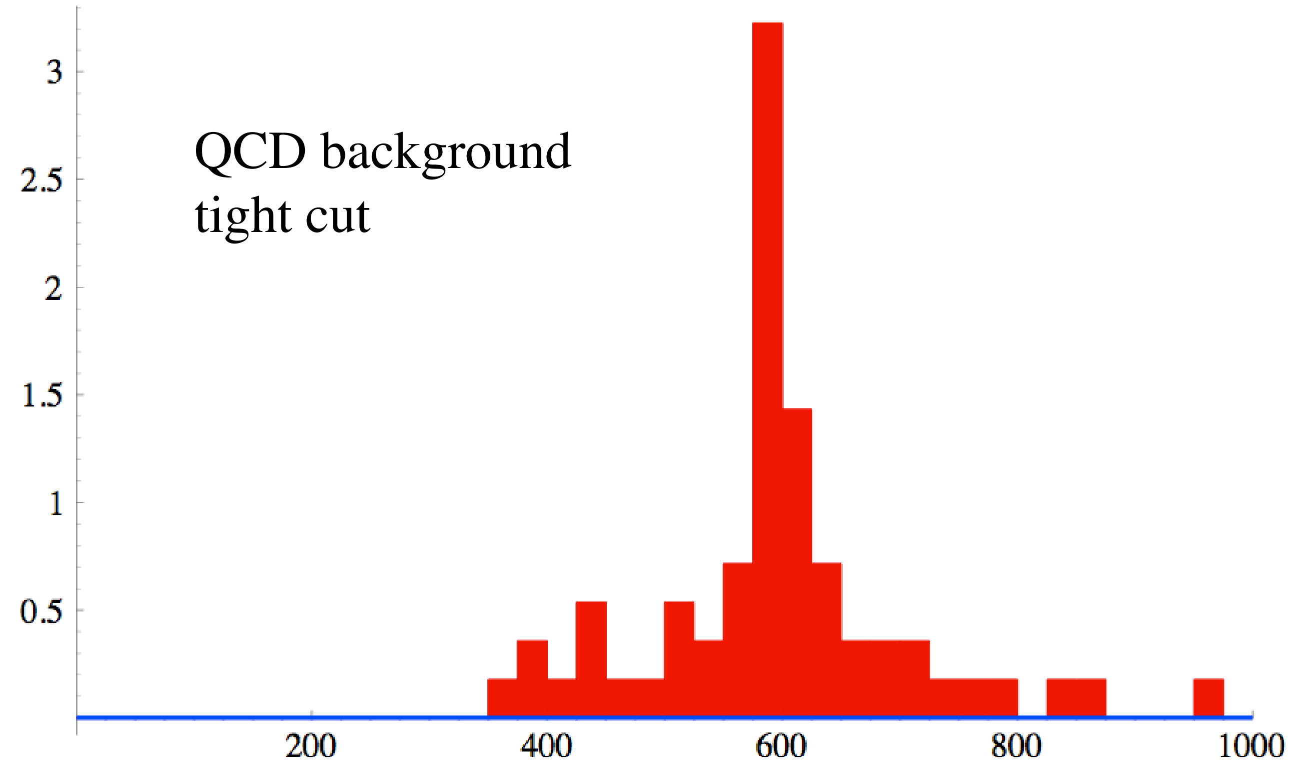
$pp \to b'\overline{b'} \to W^+W^-t\bar{t}$

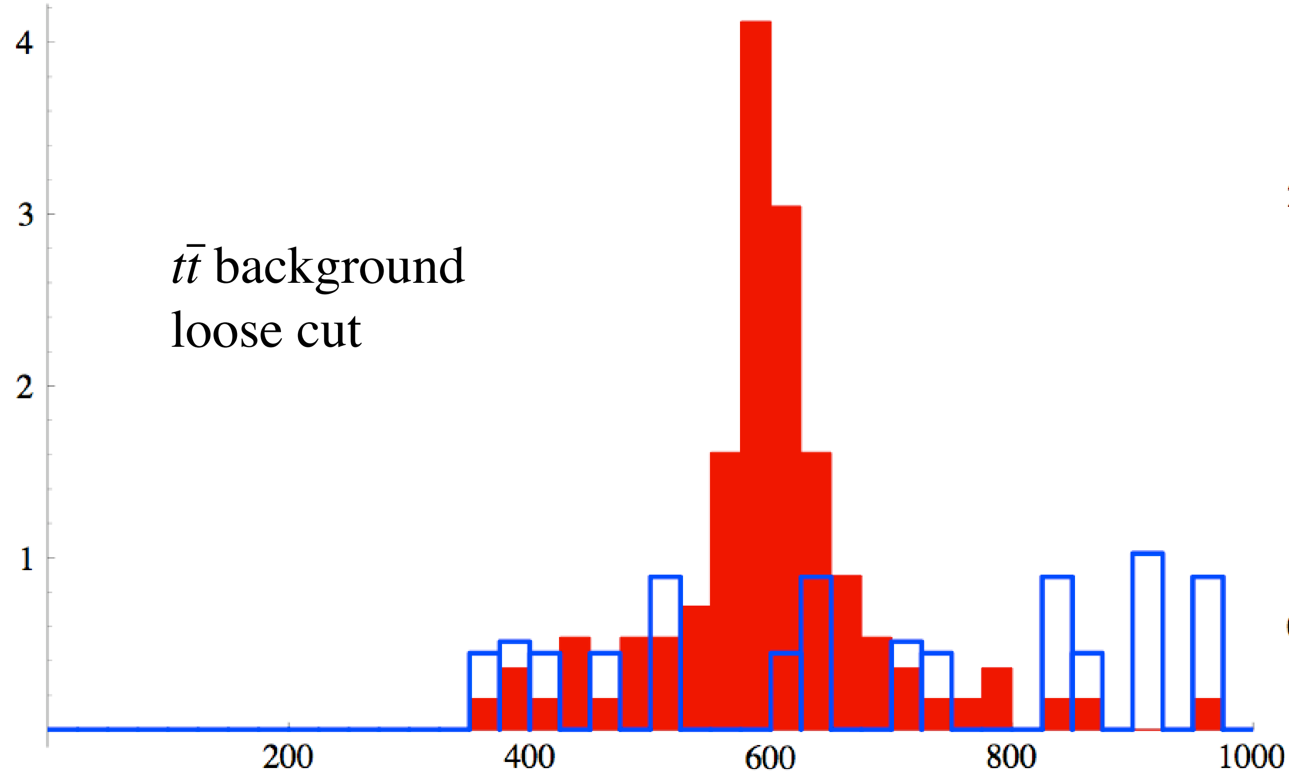
- use jet masses to identify both the t and the W
- problem is that a single cone size is not optimal for either
- choose cone size 0.8
  - W-jet: $75 < m_{\rm jet} < 95$
  - t-jet: $150 < m_{\rm jet} < 200$

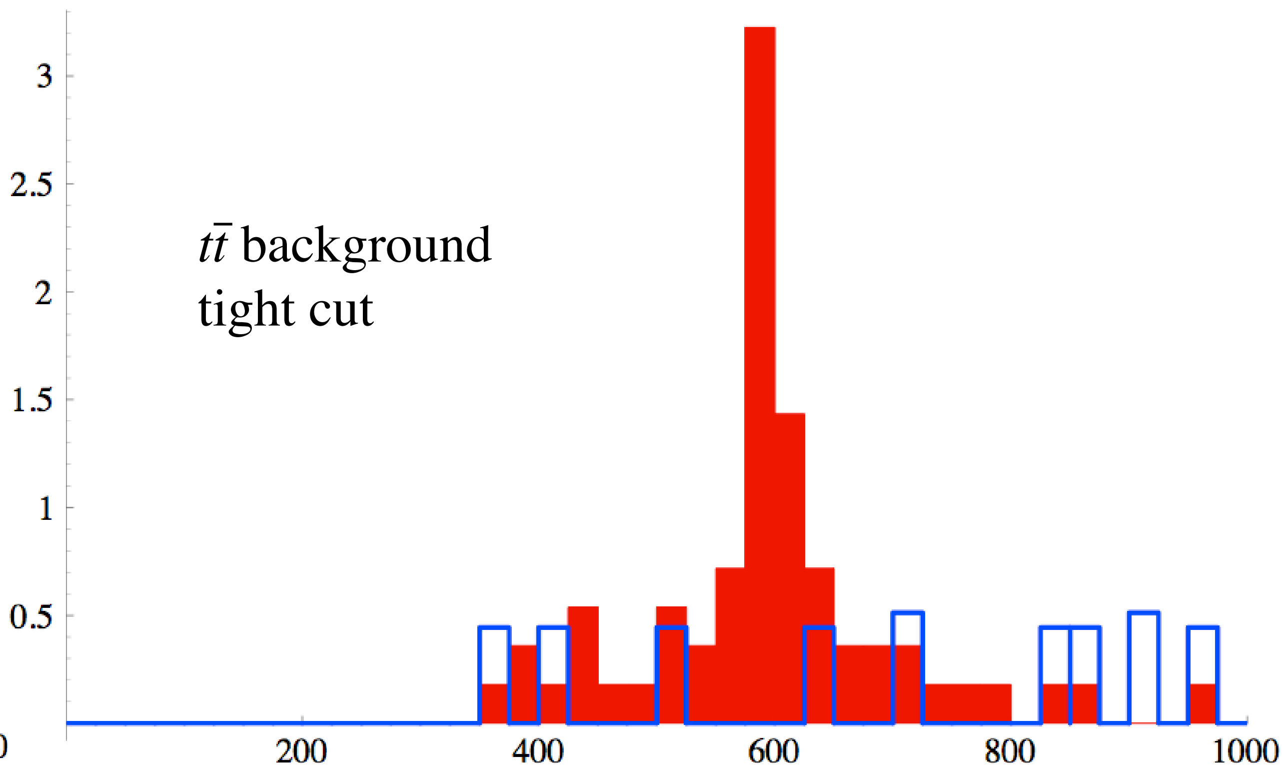
- choose $\Delta R < 2$ constraint between W and t jets
- once again estimate background contribution from 2-jet sample

- discovery of this process would take a little longer









- Alpgen-Pythia with tune QW and everything scaled to 4 fb^{-1}

Mass constraints on a fourth family

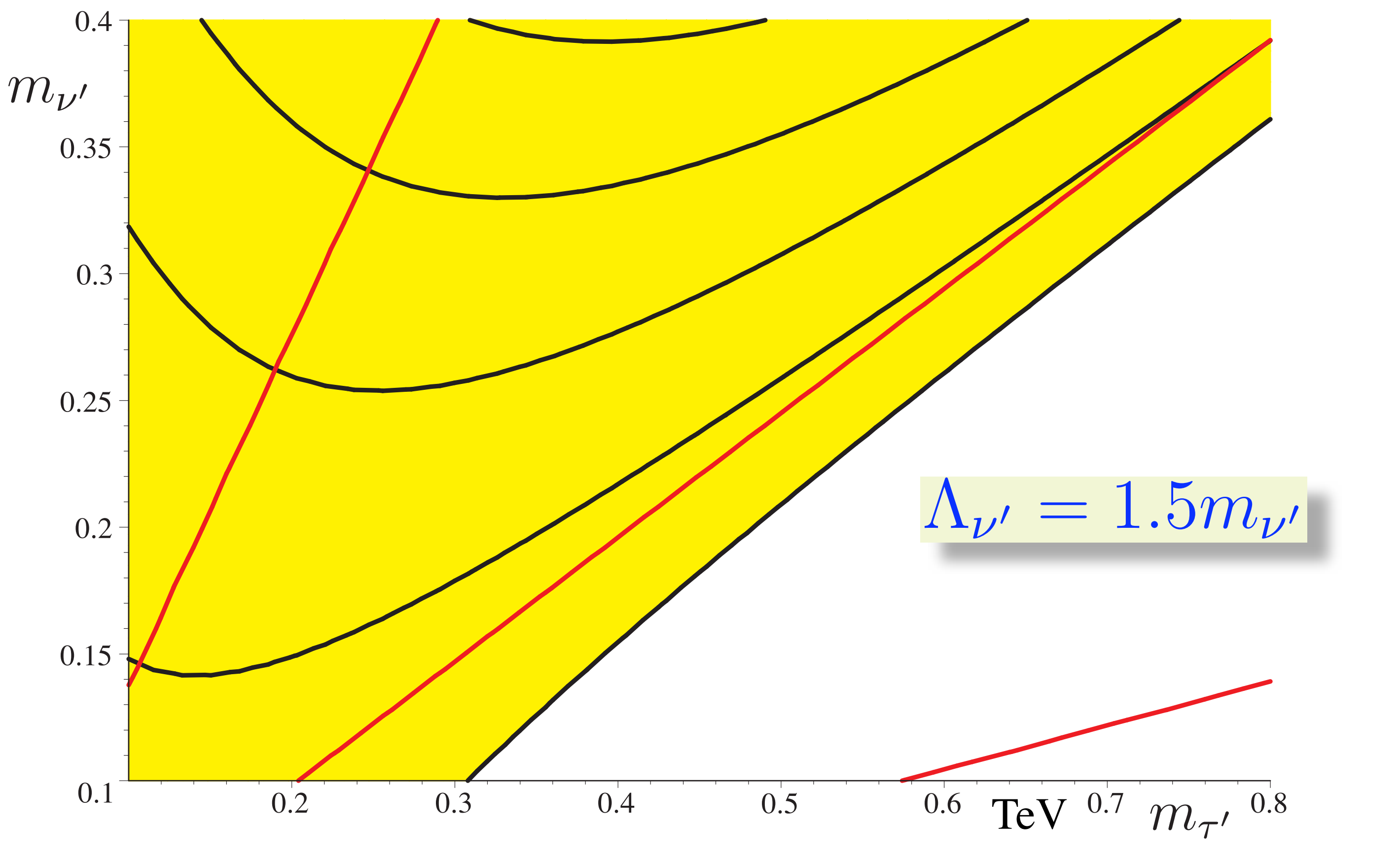
$$0.25 \lesssim \Delta T \lesssim 0.55 \text{ at } 68\% \text{ CL}$$

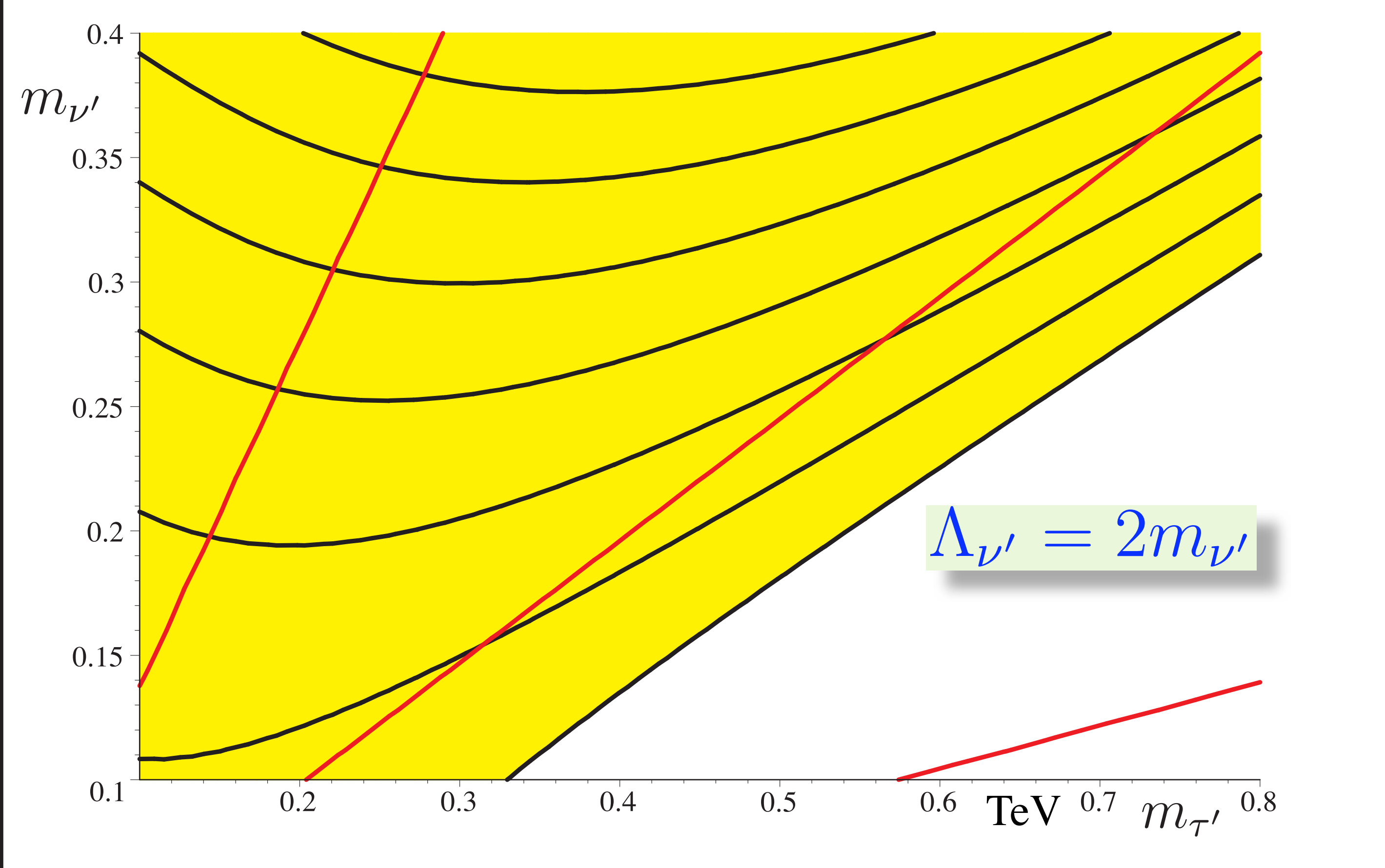
$$-0.2 \lesssim \Delta S \lesssim 0.11 \text{ at } 68\% \text{ CL}$$

- pick the lepton masses $m_{\nu'}$ and $m_{\tau'}$, and then adjust $m_{t'}$ and $m_{b'}$ to satisfy constraints
  - for what region in $m_{\nu'}$-$m_{\tau'}$ space is this possible?
  - to what extent are fine-tuned cancellations needed between quarks and leptons?

- use constituent quark type approximation (with $f = 246$ GeV)

$$\begin{aligned}
S &= \frac{7}{12\pi} - \frac{1}{3\pi}\ln(\frac{m_{\tau'}}{m_{\nu'}}) \\
\alpha f^2 T &= \frac{1}{16\pi^2}(3g(m_{t'}, m_{b'}) + g(m_{\nu'}, m_{\tau'})) - \frac{m_{\nu'}^2}{4\pi^2}\ln(\frac{\Lambda_{\nu'}}{m_{\nu'}}) \\
g(m_1, m_2) &= m_1^2 + m_2^2 - \frac{4m_1^2 m_2^2}{m_1^2 - m_2^2}\ln(\frac{m_1}{m_2})
\end{aligned}$$





black contours: T

- lower edge: leptons provide all of $T = 0.55$
- contributions from leptons decrease by $\Delta T = -1$ on successive contours (quark contributions $\Delta T = 1$)
- $\Delta T = 1$ corresponds to 130 GeV quark mass splitting

red contours: S

- from lower to upper: $S = 0$, $S = 0.11$ and $S = 0.22$

- plausible that:

  $m_{\nu'} \approx$ 150-300 GeV

  $m_{\tau'} \approx$ 400-600 GeV

effective dynamics

- chiral symmetry breaking but not confinement—NJL model is appropriate

$$\frac{g^2}{\Lambda^2}(\overline{q}'_L q'_R)(\overline{q}'_R q'_L)$$

$$v^2 = f^2 \approx \frac{3m_{q'}^2}{4\pi^2} \ln \frac{\Lambda^2}{m_{q'}^2}$$

- gives our estimate for $m_{q'}$

theory of flavor is nearby

- effective 4-fermion operators must play a role in feeding mass down to the lighter quarks and leptons

model building with a fourth family?

- here a bottom up approach
- study approximate symmetries—provides handle

BH, Chris Hill, among others, long ago...

the main issue: t mass

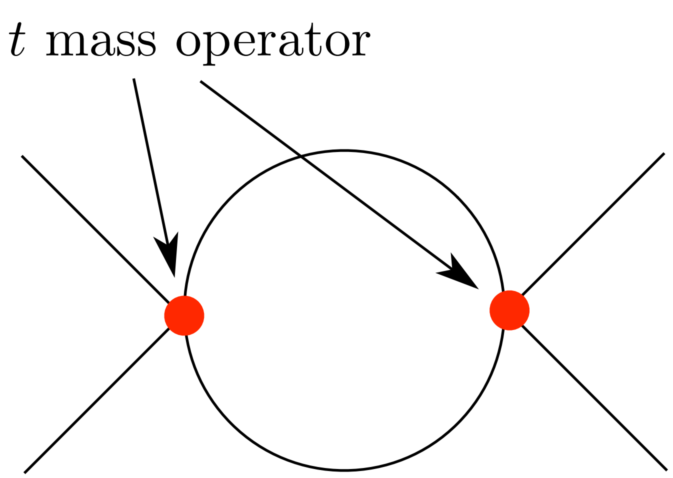
- approximate symmetries on (q'_L, q'_R, q_L, q_R) with $q' = (t', b')$ and $q = (t, b)$

  $\mathcal{Q}$: $(+,-,-,+)$ and $\tilde{\mathcal{Q}}$: $(+,-,+,-)$

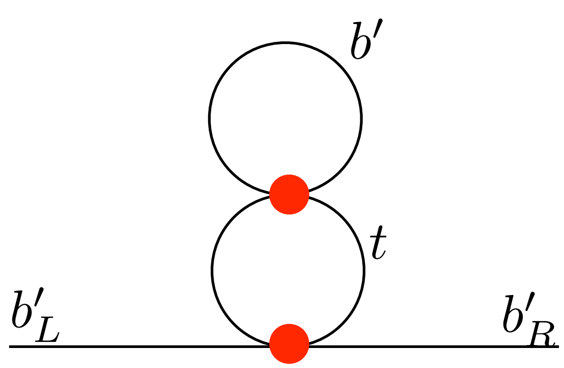
1) $\bar{t}'_L t'_R \bar{t}'_R t'_L \quad \bar{b}'_L b'_R \bar{b}'_R b'_L$ (allowed by both symmetries)
   - t' and b' masses
   - due to gauge exchange
2) $\bar{t}'_L t'_R \bar{t}_R t_L \quad \bar{b}'_L b'_R \bar{b}_R b_L$ (only allowed to the extent that $\mathcal{Q}$ is broken)
   - in ETC type models these are generated by gauge exchange
   - related gauge exchanges gave dangerous operators
   - t mass in tension with t'-b' mass splitting and $Zb\bar{b}$ corrections
3) $\bar{b}'_L b'_R \bar{t}_L t_R \quad \bar{t}'_L t'_R \bar{b}_L b_R$ (only allowed to the extent that $\tilde{\mathcal{Q}}$ is broken)
   - t mass
   - this dynamics must badly break $\mathrm{SU}(2)_R$

dangerous operators?

- they are $\tilde{Q}$ neutral whereas t mass operator $\overline{q}'_L b'_R \overline{q}_L t_R$ is not
- must insert twice in a loop
  - $\overline{q}'_L b'_R \overline{b}'_R q'_L \longrightarrow t'$-$b'$ mass splitting
  - $\overline{q}_L b'_R \overline{b}'_R q_L \longrightarrow$ corrects $Zb\overline{b}$ vertex
- thus can achieve extra suppression by powers of $m_t/m_{t'}$ and loop factor



- the t mass operator also feeds back on the b' mass
- this is the origin of the prediction $m_{b'} > m_{t'}$



leptons?

- story for τ' and τ is similar to story for b' and b
- may assume right-handed neutrinos have flavor scale masses
- ν_{Le}, $\nu_{L\mu}$, $\nu_{L\tau}$ masses
  - there is also a large zoo of six fermion operators that can contribute to these masses
  - they are naturally in the sub-eV range
- $\nu'_{L\tau}$ mass comes from $\ell'_L\ell'_L(\ell'_L\ell'_L)^\dagger$
- $\nu_{L\tau}$ mass—this is very different than the t mass
  - there is no $\mathcal{Q}$-invariant 4-fermion operator that can feed mass to $\nu_{L\tau}$
  - need $\mathcal{Q}$-violating operator $\ell'_L\ell'_L(\ell_L\ell_L)^\dagger$—thus $\mathcal{Q}$ must be very good symmetry in the neutrino sector

- the nearby theory of flavor also includes neutrinos

Summary

- a sequential fourth family wrapped up with electroweak symmetry breaking is a predictive scenario
- the process $pp \to t'\overline{t'} \to W^+W^-b\bar{b}$ is most promising
- jet mass technique is a promising way to identify W's and enhance S/B
- what about the heavy leptons? ILC?

- improved matrix elements from MC@NLO and Alpgen give results that are in agreement (and encouraging for S/B)
- Alpgen reduces sensitivity to initial state radiation
- why not develop tunes after incorporating the matrix elements?
- main issue is multijet background—and the faking of leptons and missing energy

what would we learn?

- no elementary scalar—no associated fine tunings
- nature invokes dynamics at the scale it is needed
- theory of flavor is nearby

fragment of 2009 LHC press release

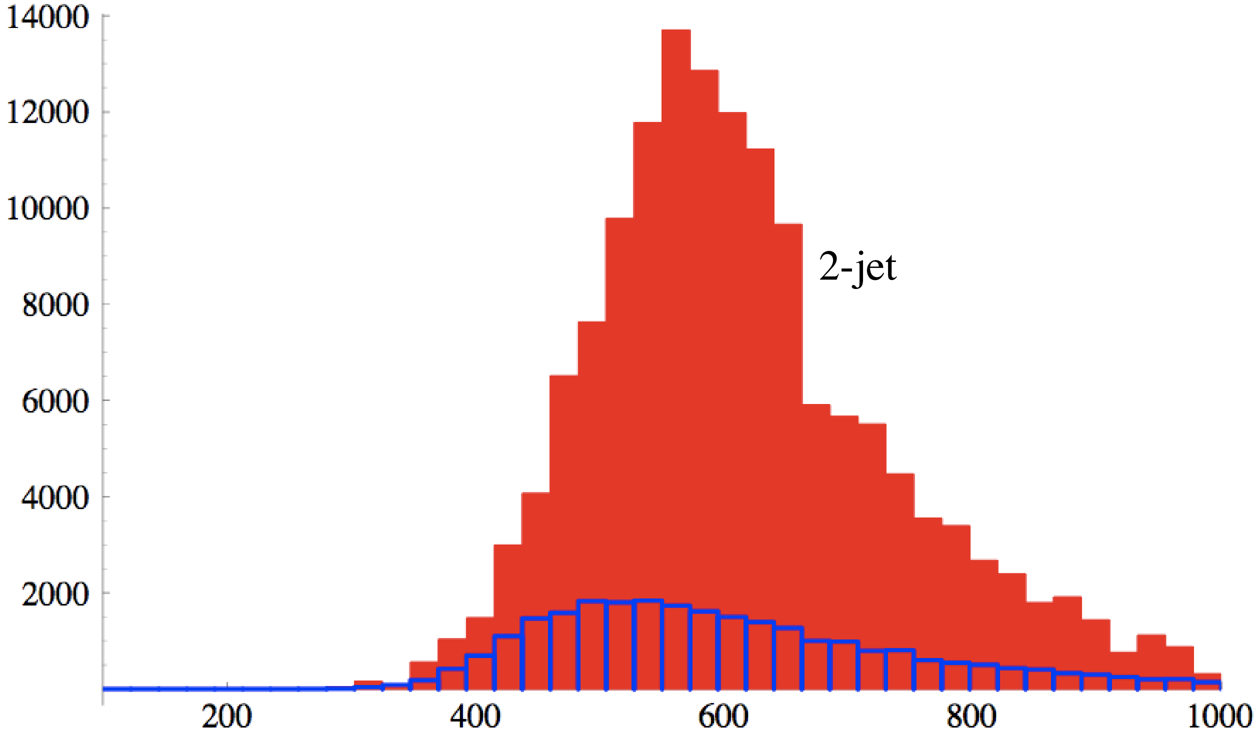
- "For decades theorists have sought a description of EWSB that is somehow perturbative, ..."

innocent questions

- do perturbative theories offer anything more than a "parameterization of our ignorance"?
- are they the precursor to anthropic reasoning?

backup

p_T distribution of "t-jets" in background



replace "t-jets" with $p_T > 400$ GeV jets