very heavy quarks

Alexander Schmidt

Universität Hamburg

DER FORSCHUNG | DER LEHRE | DER BILDUNG

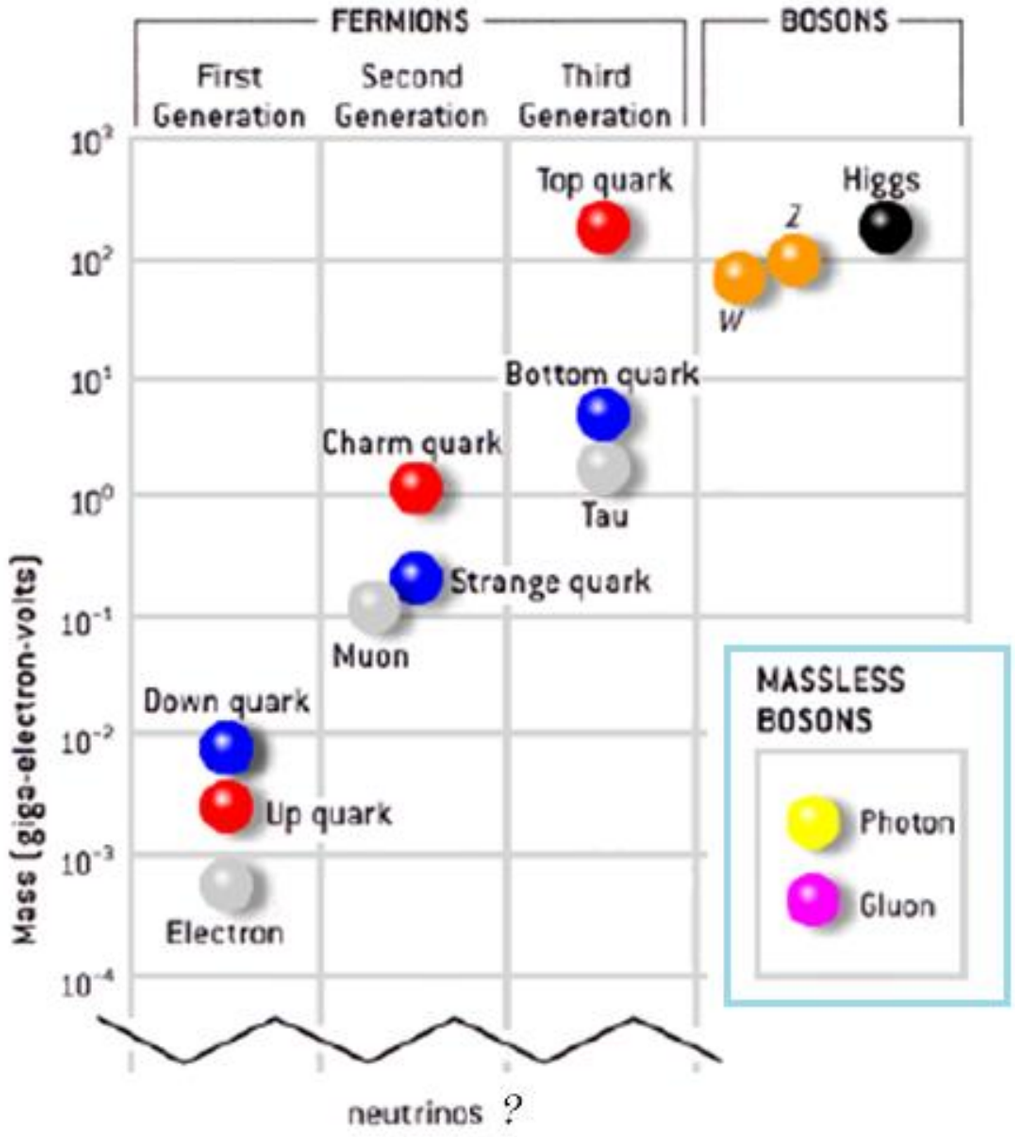
introduction

The Nobel Prize in Physics 2008

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Makoto Kobayashi

Toshihide Maskawa



model still incomplete:

- mass spectrum?
- mixing pattern?
- why 3 generations? Could be 4 or more!

fourth generation?

popular for many years:

- chiral fourth Fermion generation
- exact replication of three SM generations

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \quad \begin{pmatrix} t' \\ b' \end{pmatrix}_L$$

$$u_R, d_R, c_R, s_R, t_R, b_R, t'_R, b'_R$$

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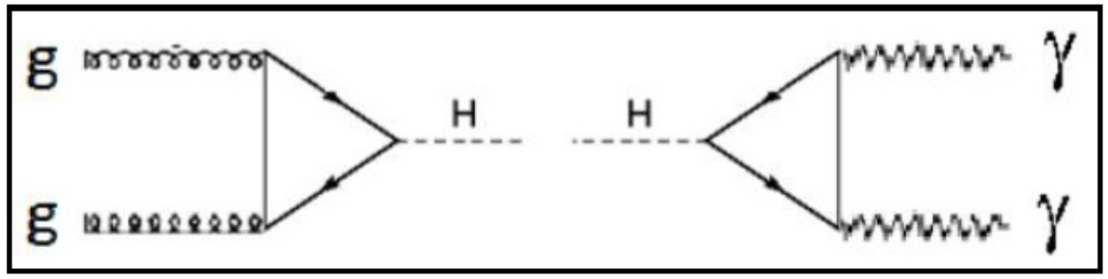
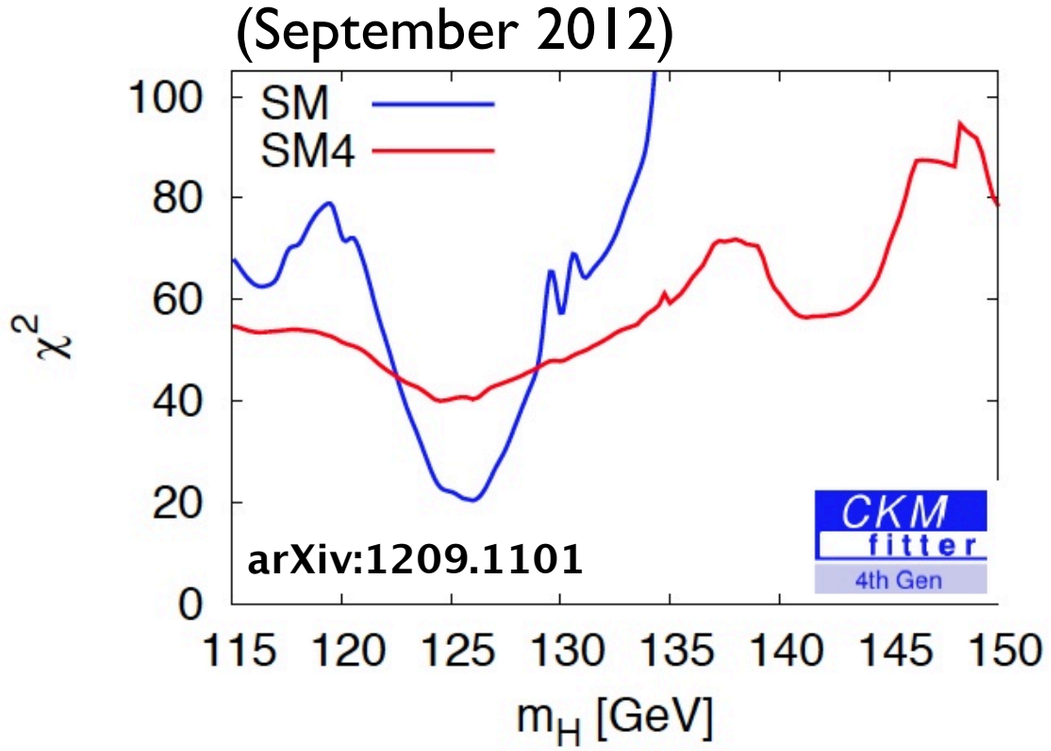
now ruled out!

- connection with Higgs through loops
- use CKMfitter for combined fit of SM parameters
- first thing after Higgs discovery...

➡SM4 ruled out at 5.3σ





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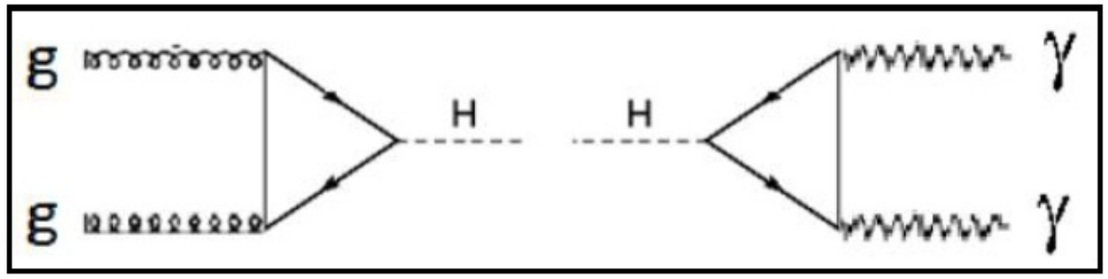
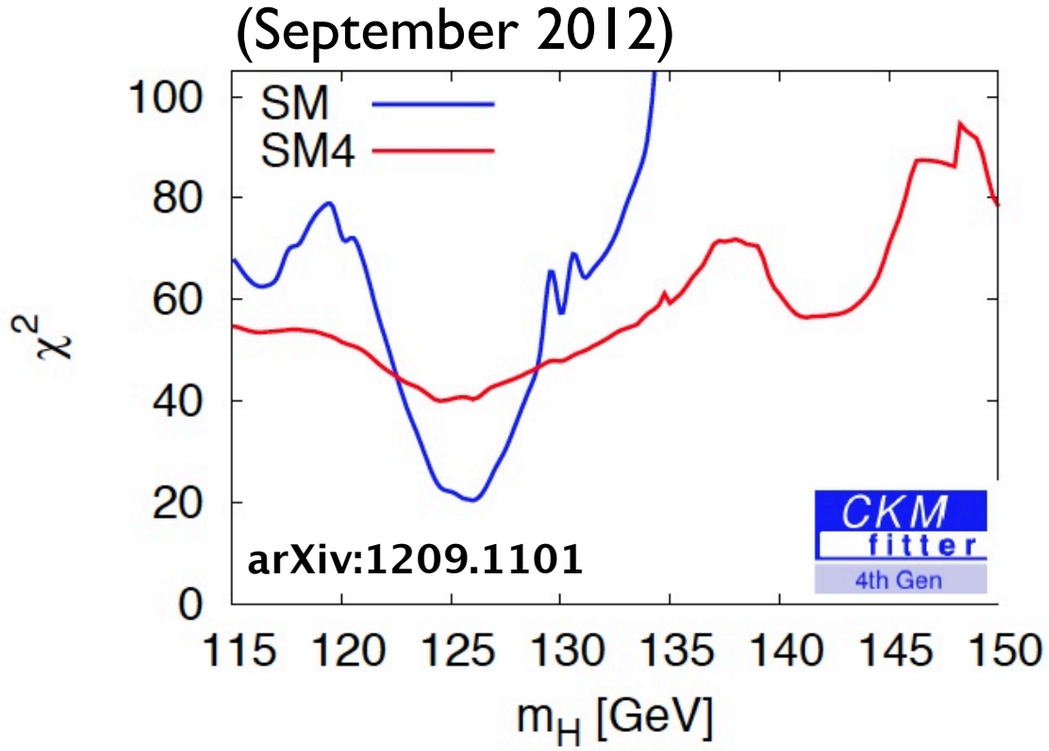




➡SM4 ruled out at 5.3σ

- small caveat: assumes minimal Higgs sector!

top partners !

popular new physics models (still on the market):

- extra dimensions: top partners appear as KK excitations of bulk fields
- composite Higgs models: top partners as excited resonances of the bound states
- little Higgs models: as partners of SM Fermions embedded in larger group representations (e.g. SO(10) / $SO(5)^2$....)
- various other models....

common feature:

vector-like quarks!

vector-like quarks

what are vector-like quarks:

- they are quarks: coloured, charged spin 1/2 particles

- no difference between chiralities: they couple to left- and right- handed charged currents (in the same way)

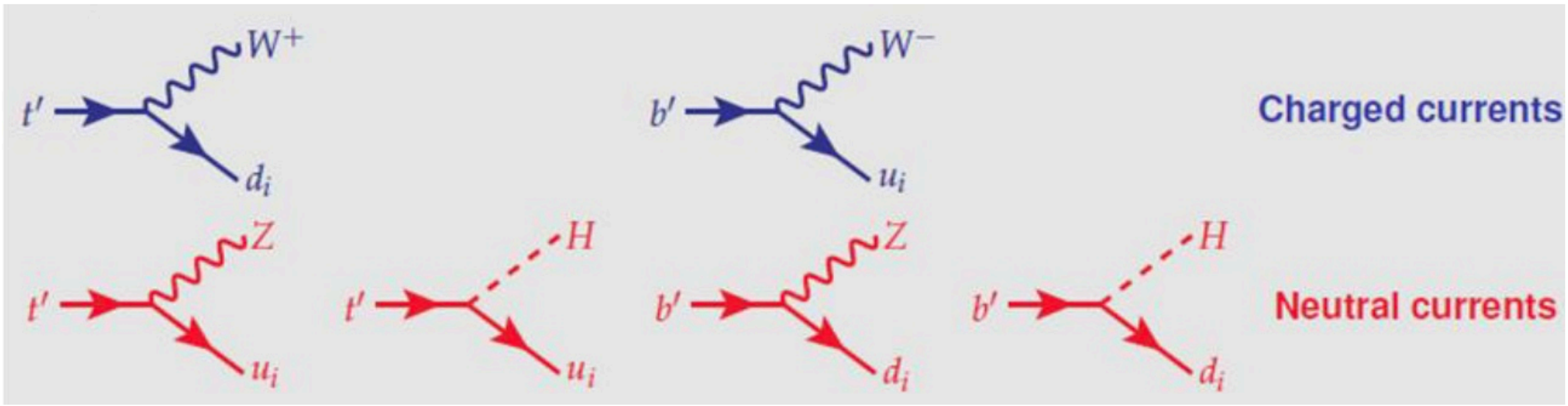
- remember that mass terms in the Lagrangian violate gauge invariance because left- and right- handed chiralities transform differently

➡ VL quarks can have mass terms without violating gauge invariance!

- not constrained through Higgs discovery

possible representations and decays

	SM	Singlets	Doublets	Triplets
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	(t') (b')	$\begin{pmatrix} X \\ t' \end{pmatrix}$ $\begin{pmatrix} t' \\ b' \end{pmatrix}$ $\begin{pmatrix} b' \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ t' \\ b' \end{pmatrix}$ $\begin{pmatrix} t' \\ b' \\ Y \end{pmatrix}$
$SU(2)_L$	2 and 1	1	2	3
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3 -1/3	7/6 1/6 -5/6	2/3 -1/3

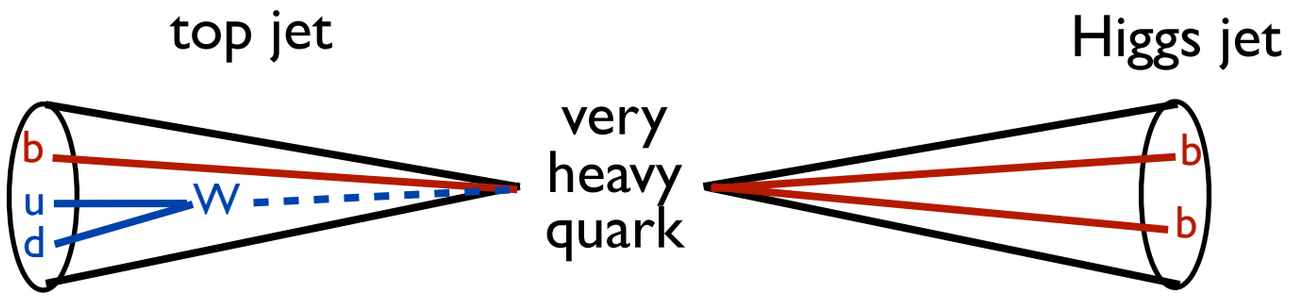


searching for VLQ

CMS-PAS-B2G-14-002

brand new result from CMS (1 week ago):

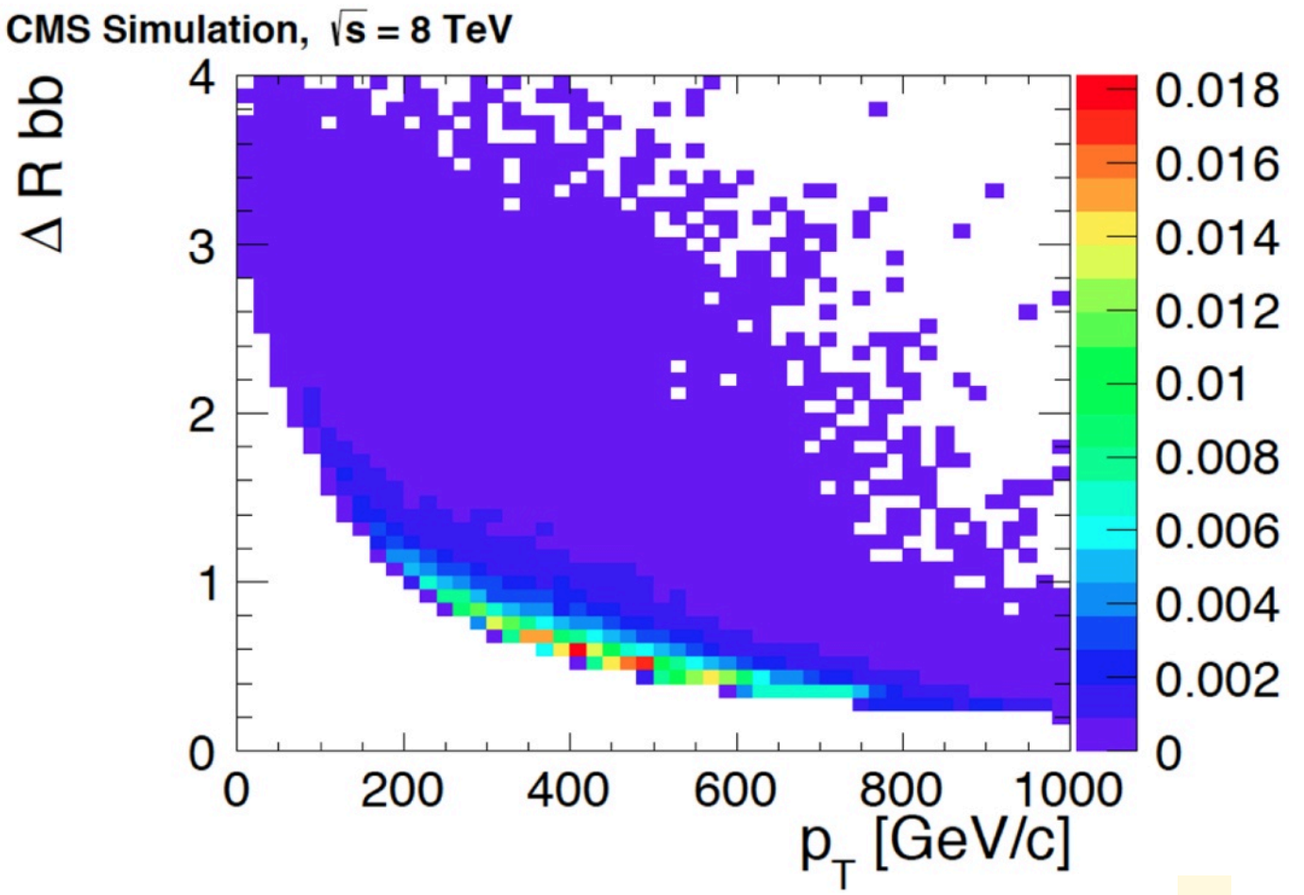
- searching for T' → tH in all-hadronic decay modes



- decay products can be very boosted → merged jets
- requires new methods to analyse jet substructure

keywords:

- top-jet-tagging
- Higgs-tagging (see backup slides)

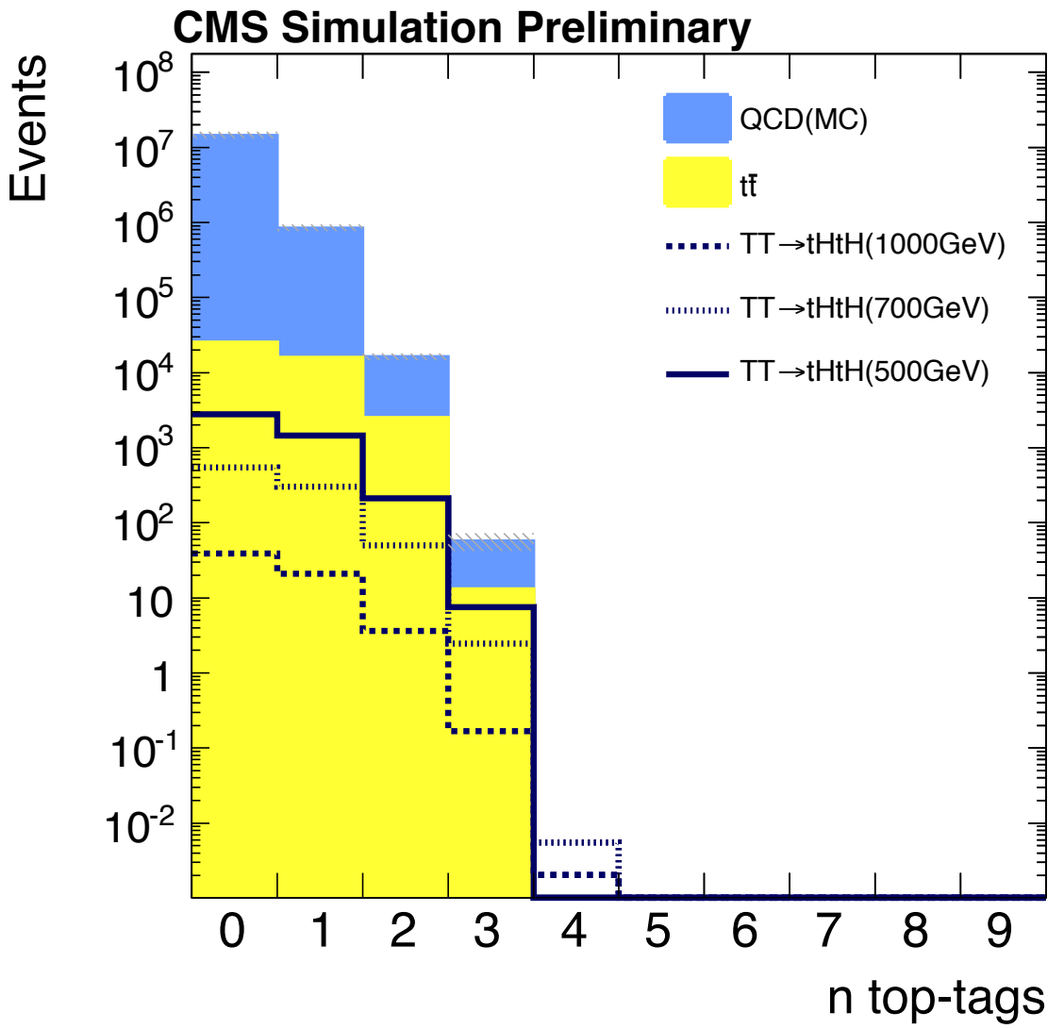


substructure methods

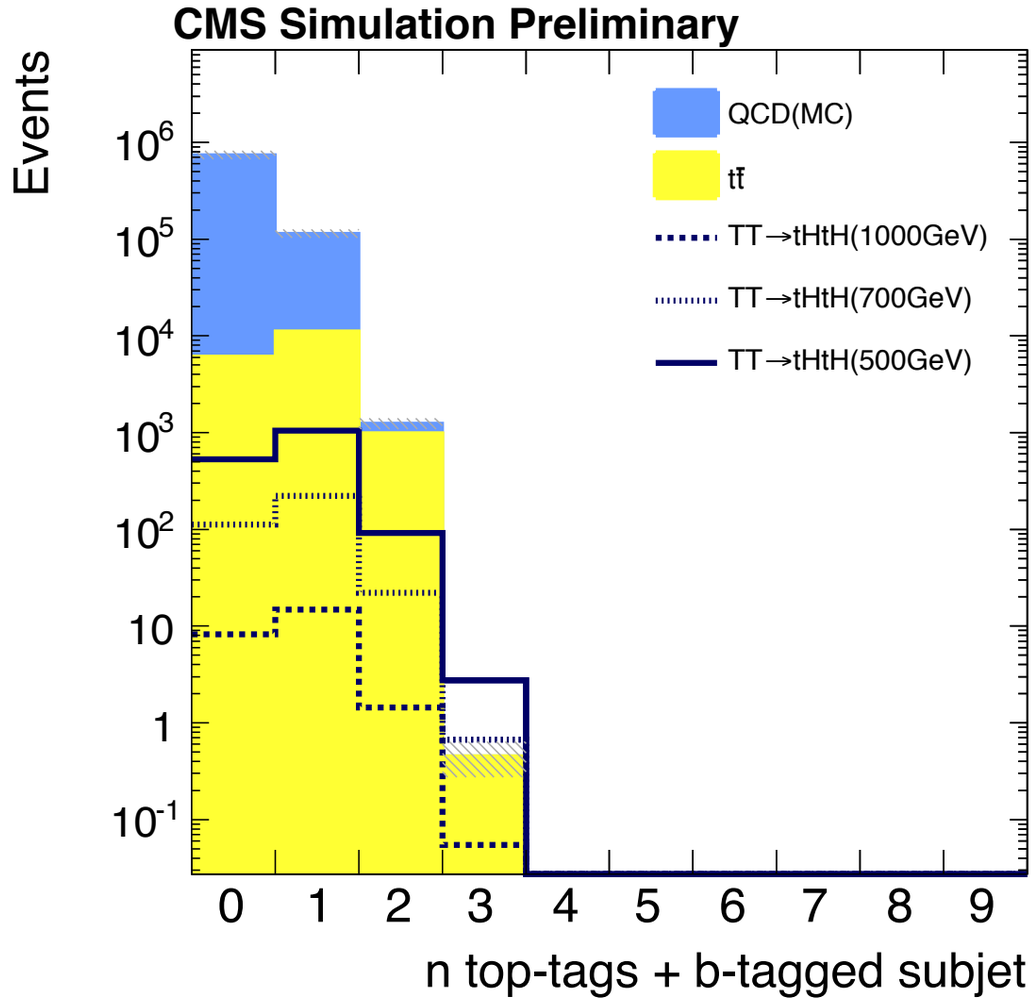
CMS-PAS-B2G-14-002

jet substructure analysis reduces QCD background:

#jets selected by the HEPTopTagger algorithm



#jets with a b-tagged subjet

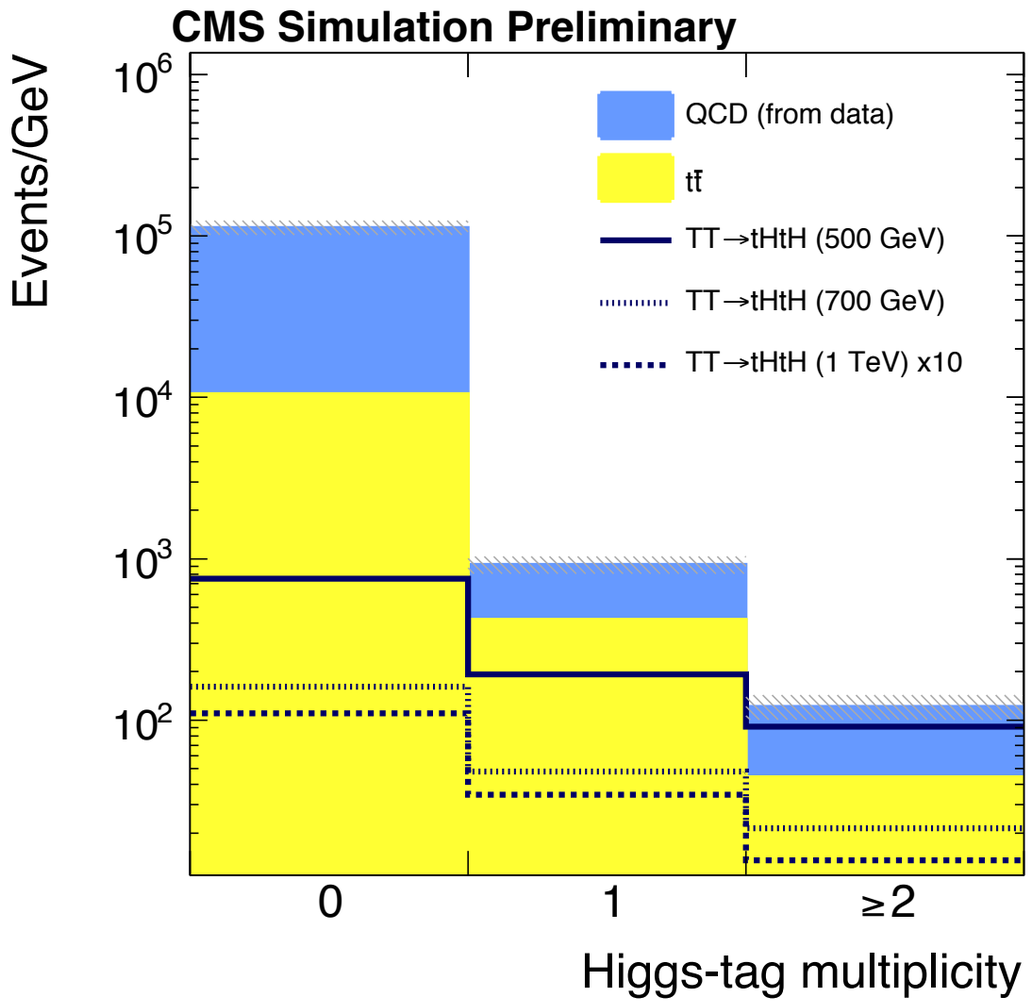


substructure methods

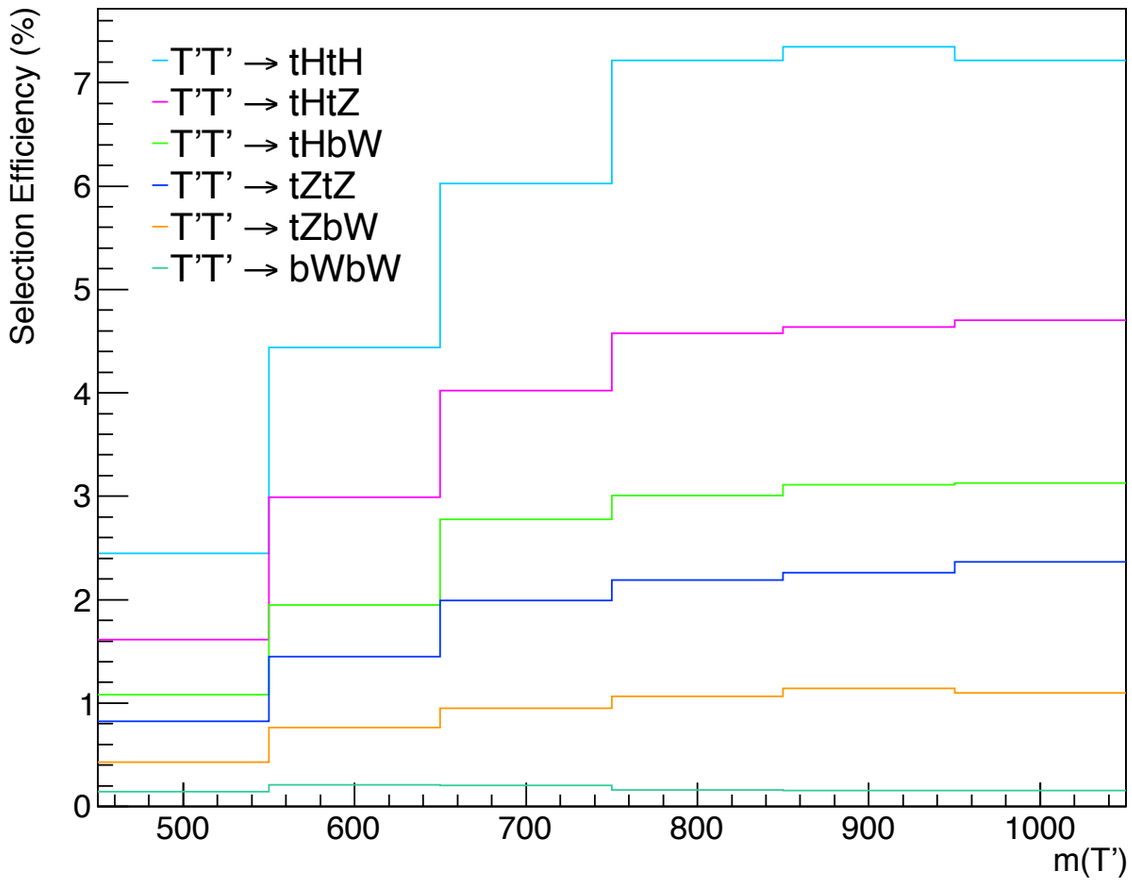
CMS-PAS-B2G-14-002

jet substructure analysis reduces QCD background (and top-background as well)

#jets selected by the Higgs-tagging algorithm



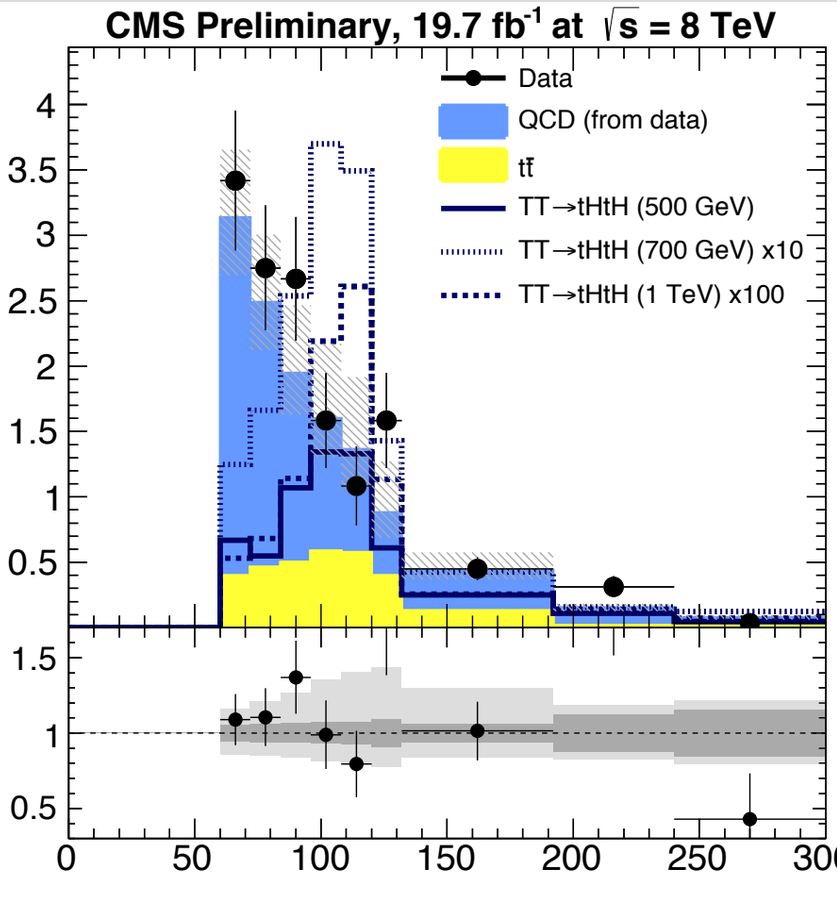
signal selection efficiency



increases for higher T' mases!

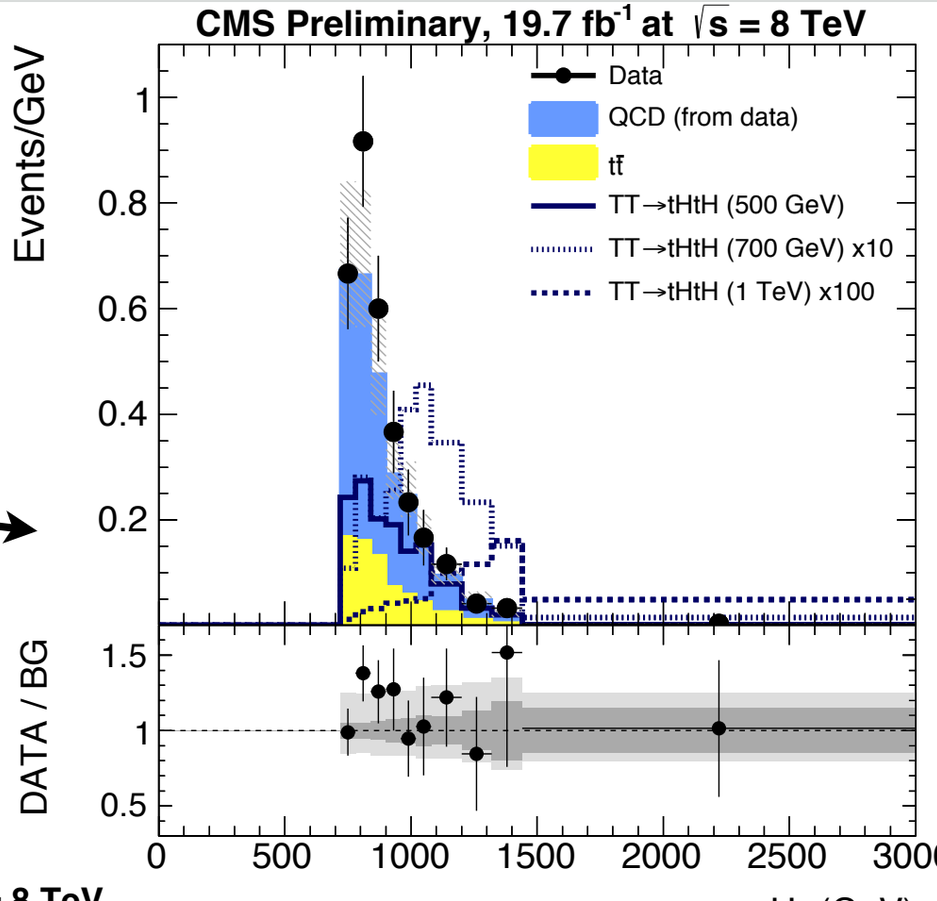
sensitive variables

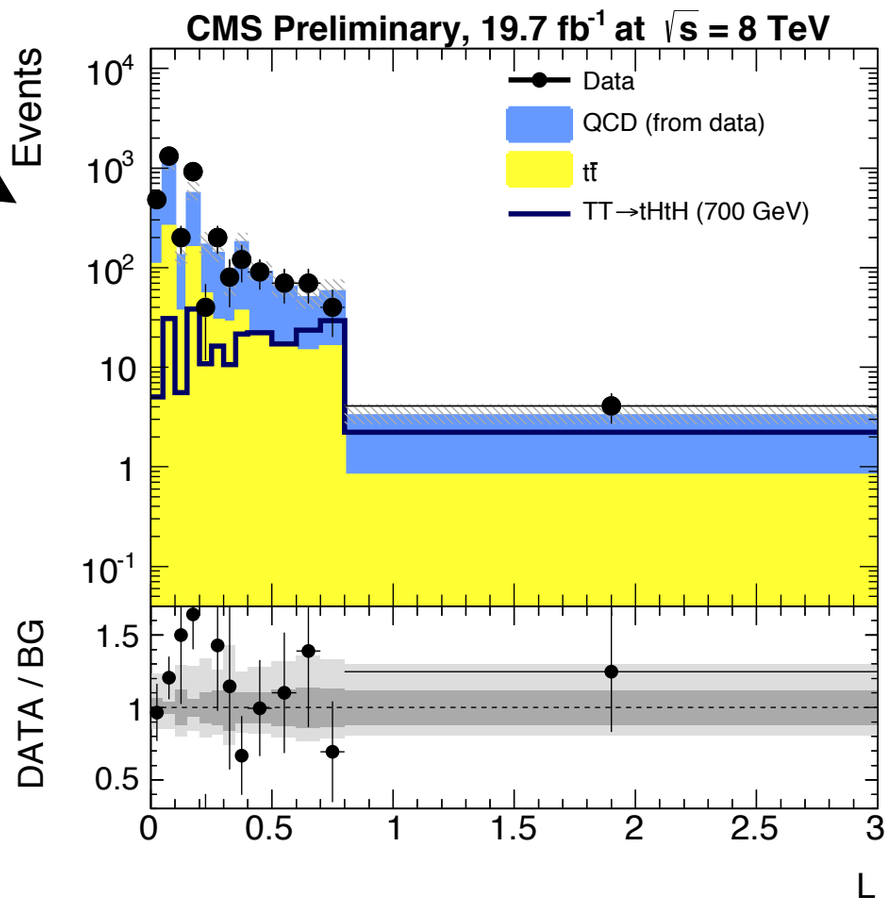
CMS-PAS-B2G-14-002



Higgs candidate mass

total transverse energy sum





- both combined into one discriminator
- enhancing sensitivity

background

CMS-PAS-B2G-14-002

top-quark background:

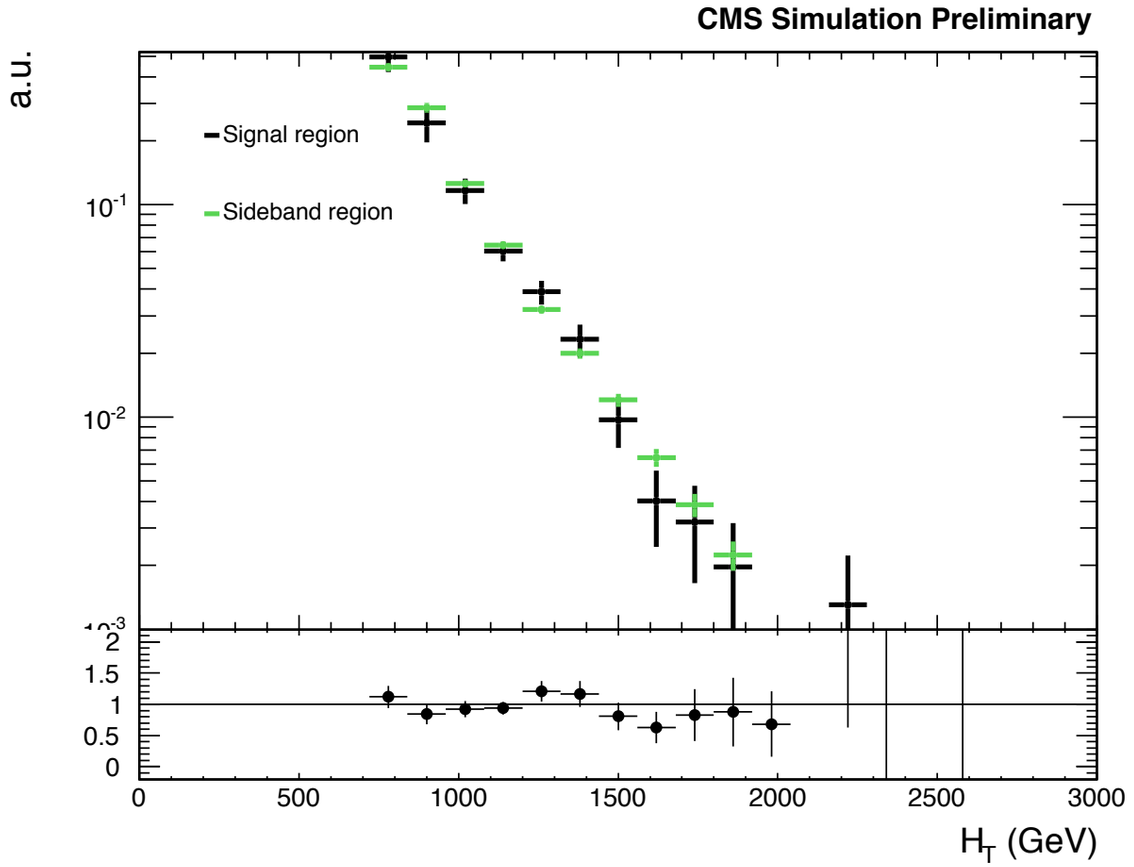
- rely on simulation (large uncertainties)

non-top QCD multijet background:

- derived from data
- "ABCD" method

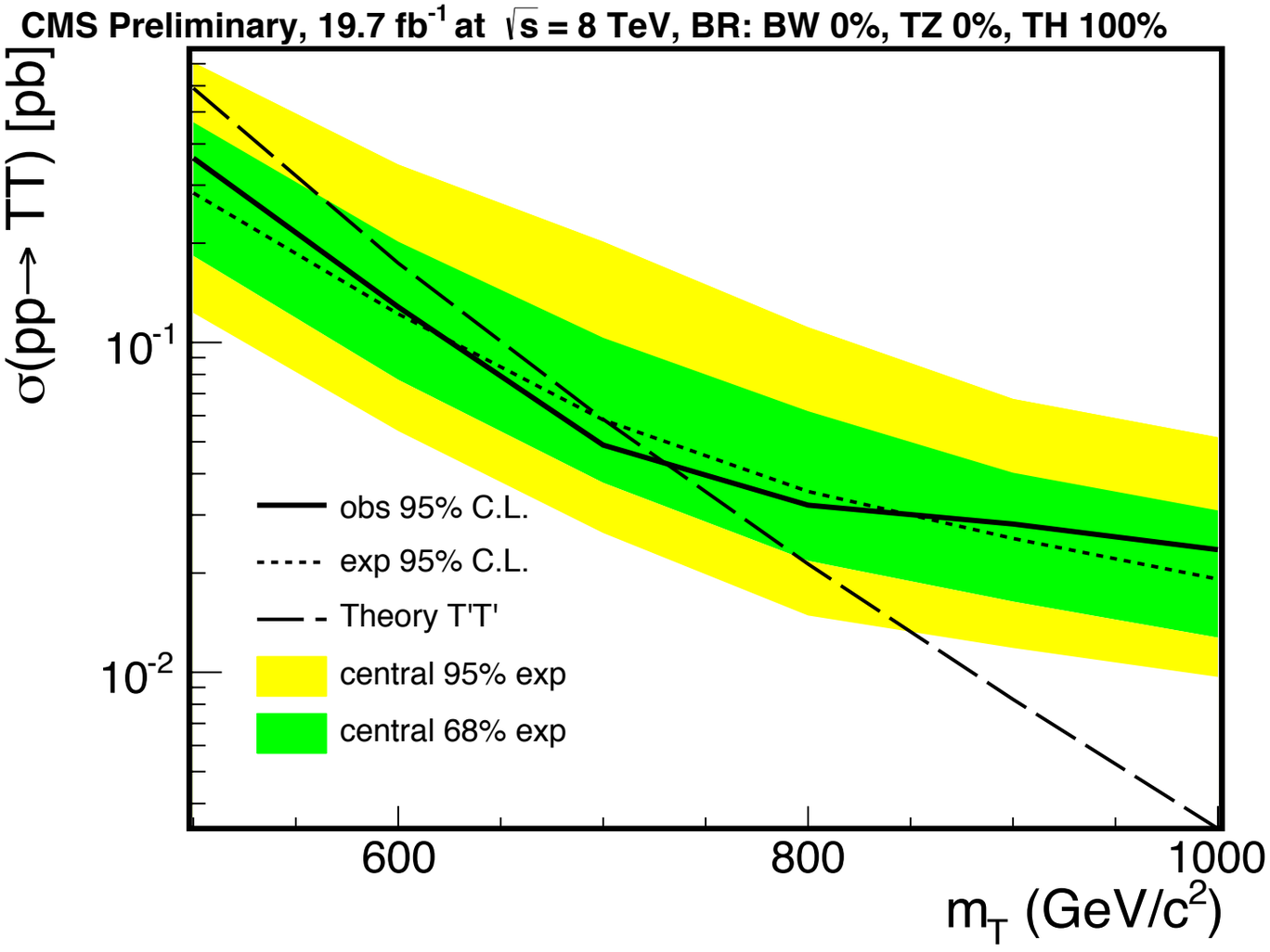
	Inv. H tag	H tag
Inv. top tag	A	B
top tag	C	D (Signal)

- substructure selection criteria can be inverted
- uncorrelated signal-depleted sideband regions
- allows to predict rate and shape of backgrounds



results

excluded T' production cross-section at 95% CL for BR(T'→tH)=100%:

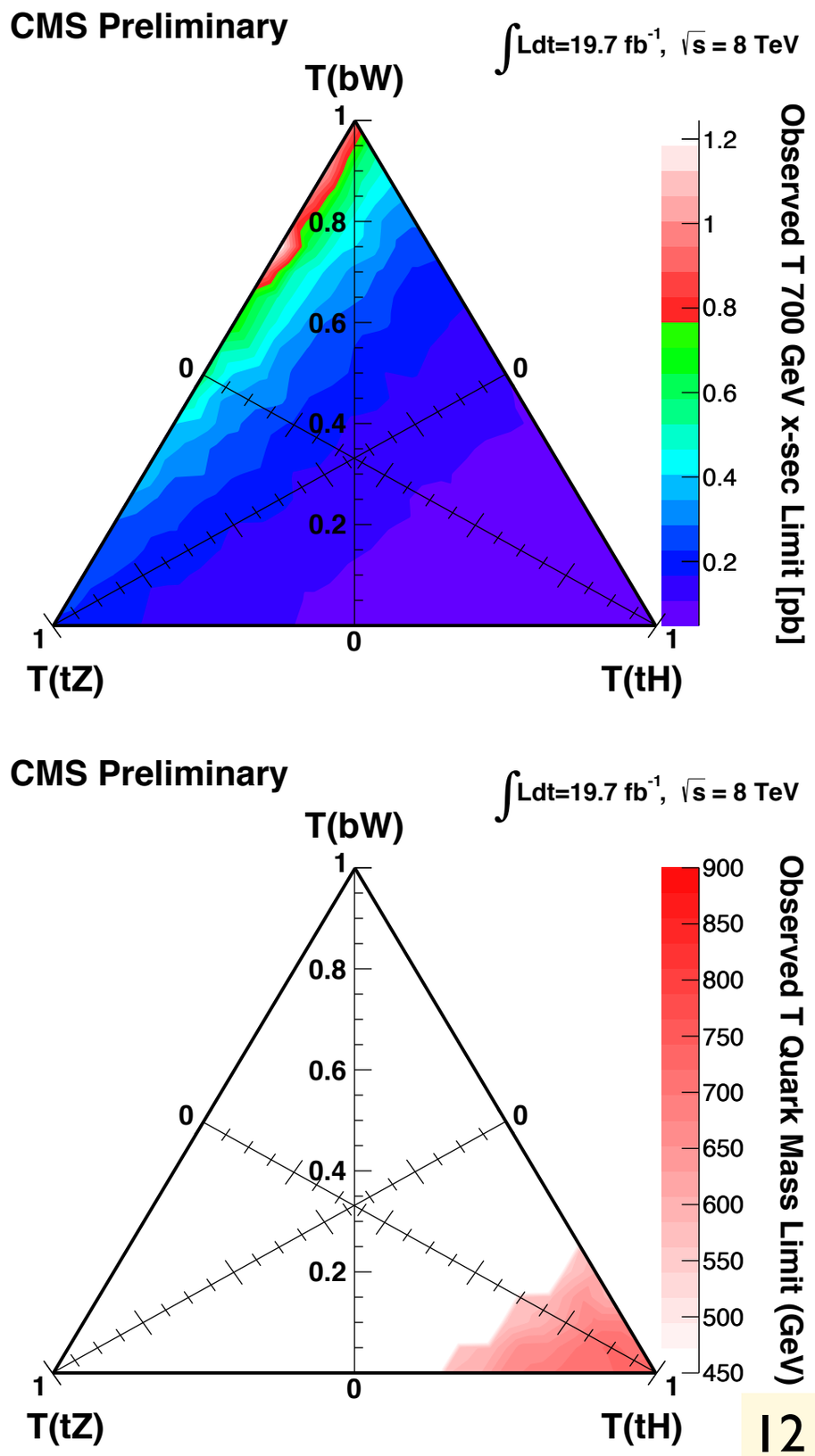


mass limit:

expected 701 GeV/c^2

observed 747 GeV/c^2

scanning other BR:

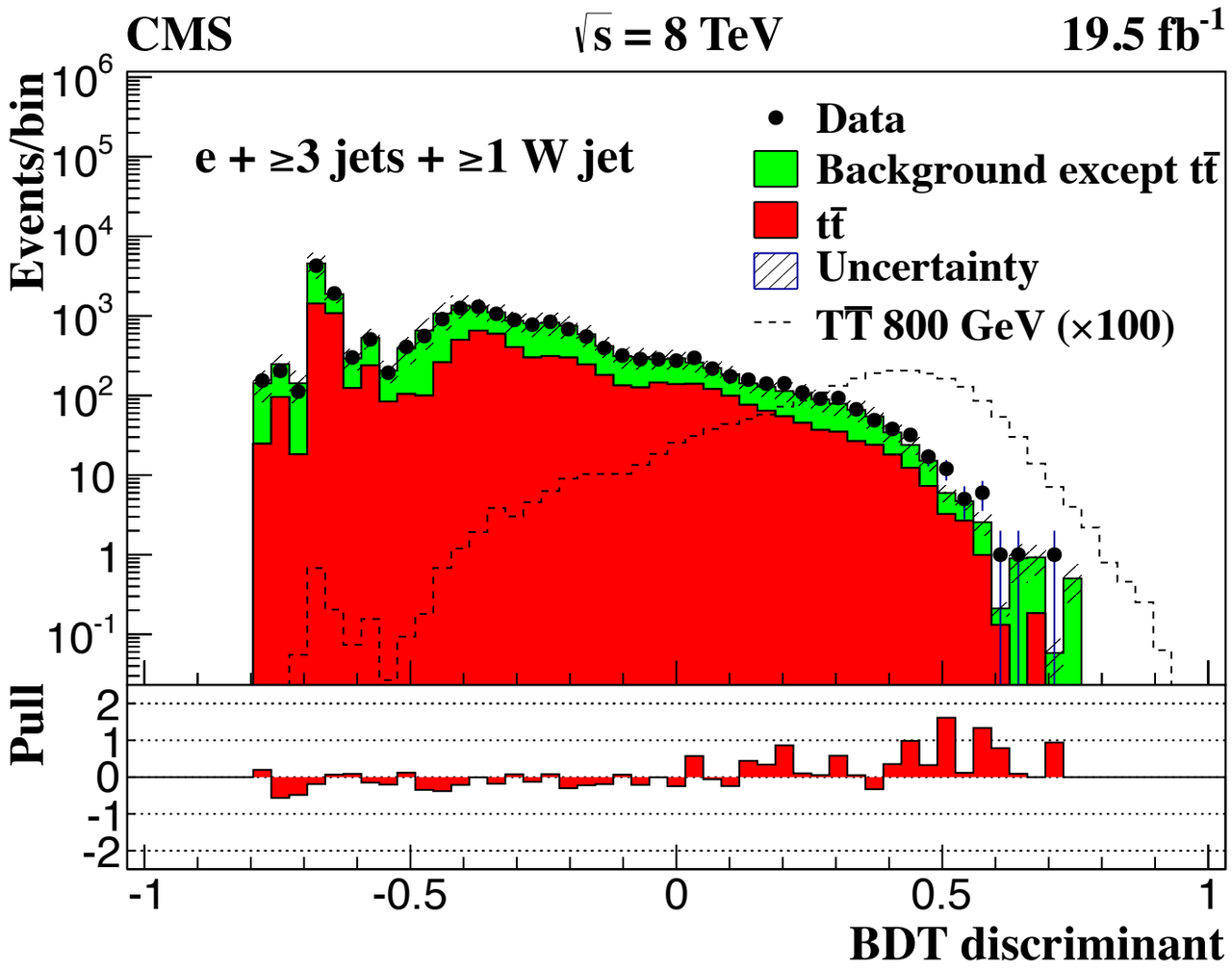


other analyses

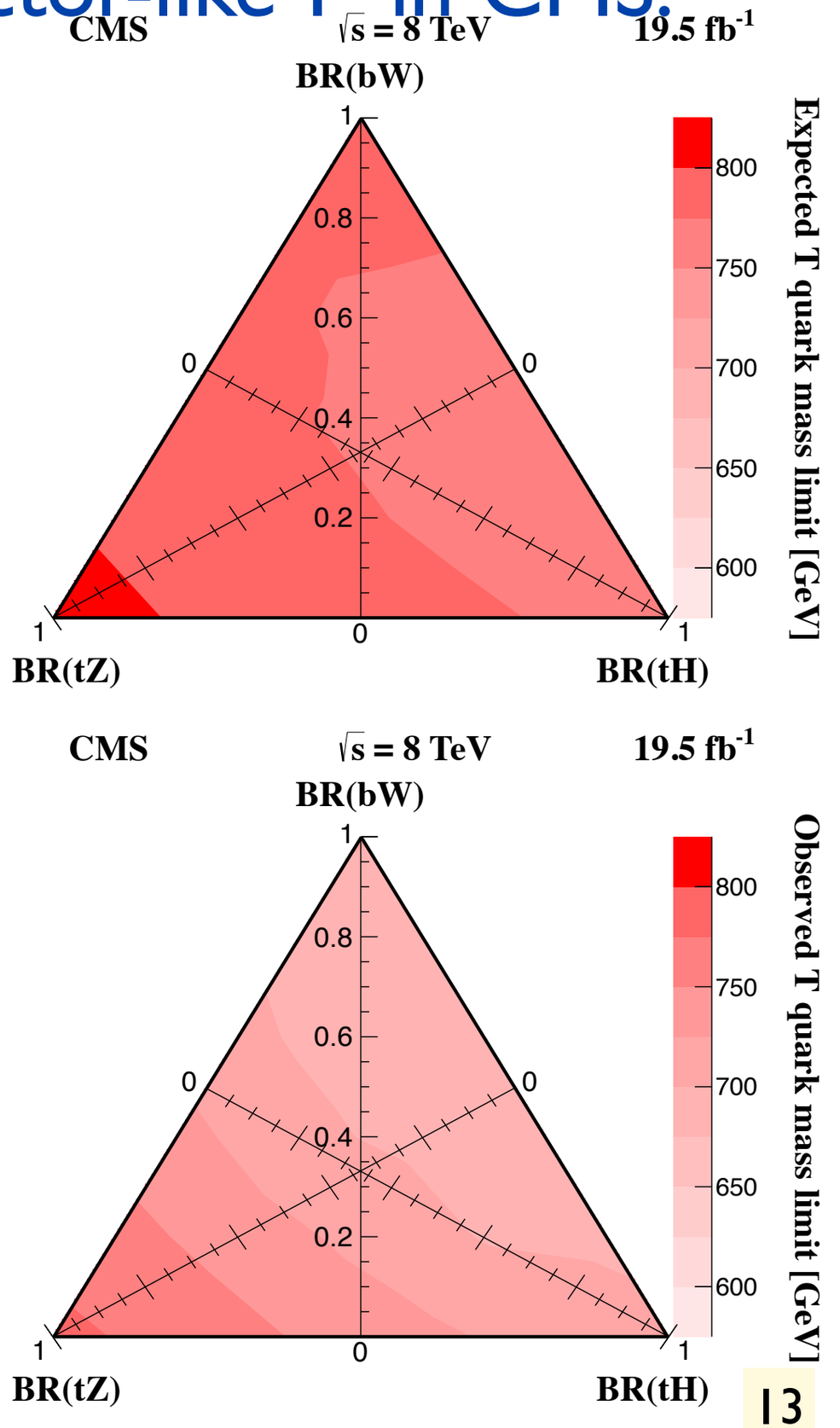
CMS-PAS-B2G-12-015

only one more public result on vector-like T' in CMS:

- using leptonic decays (sensitive to wide range of BR)
- tt, W-, Z- boson and Drell-Yan backgrounds, suppressed by boosted decision trees (BDT)



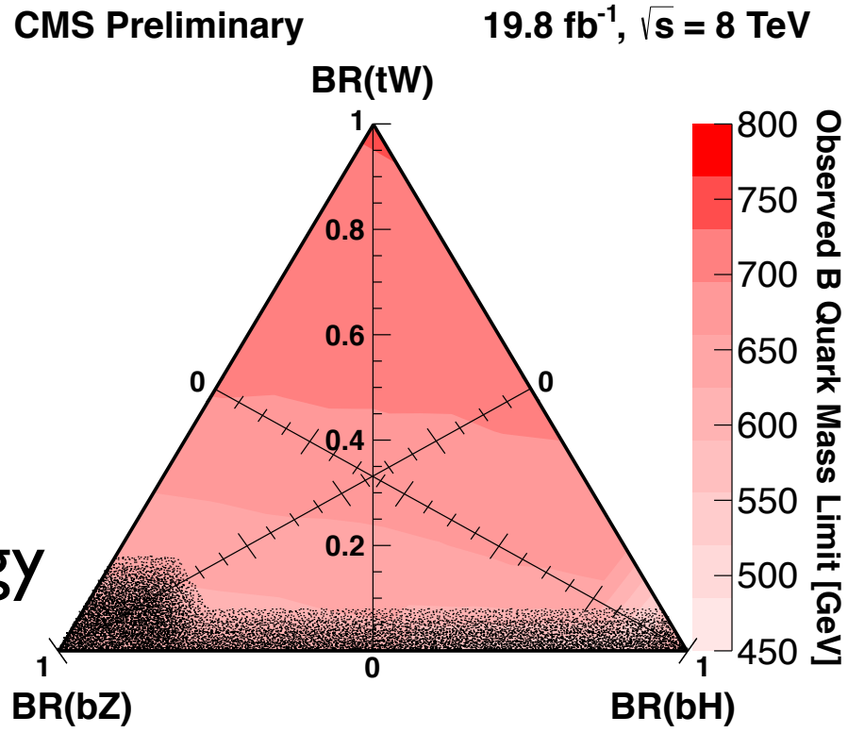
limits between 690 and 780 GeV/c^2 depending on BR



searches for B'

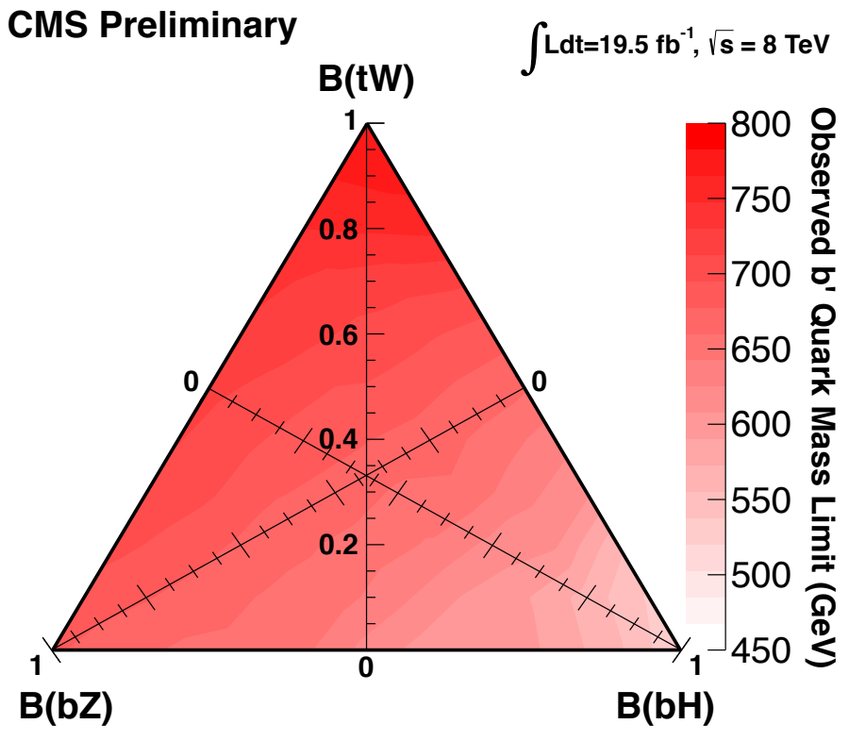
lepton+jets channel:

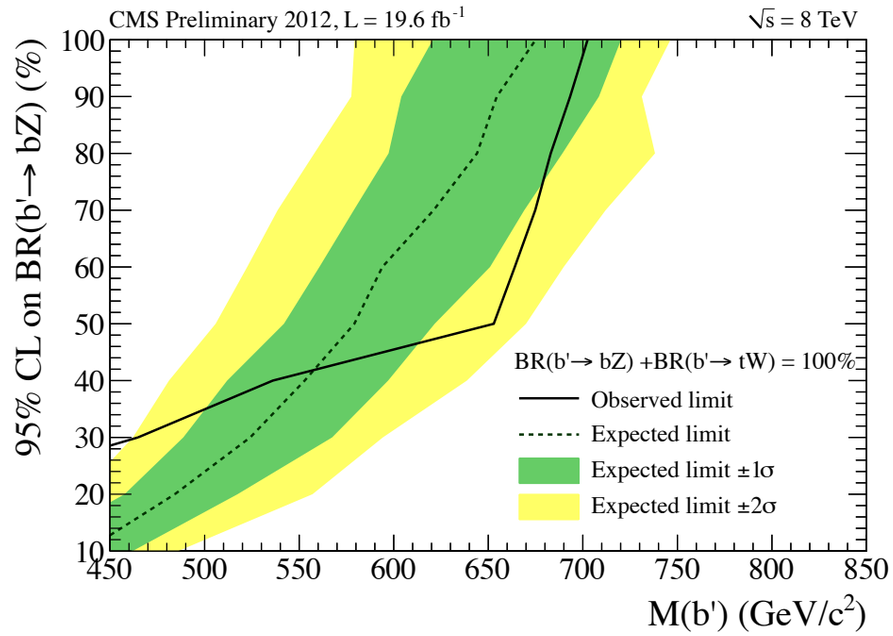
- sensitive to B'→tW
- electron or muon, four jets (one b-jet), missing energy



di-lepton + jets channel:

- sensitive to B'→bZ
- reconstruct Z resonance and b-tagged jets





three-lepton channel:

- similar to multilepton SUSY searches

all-hadronic:

- still in pipeline

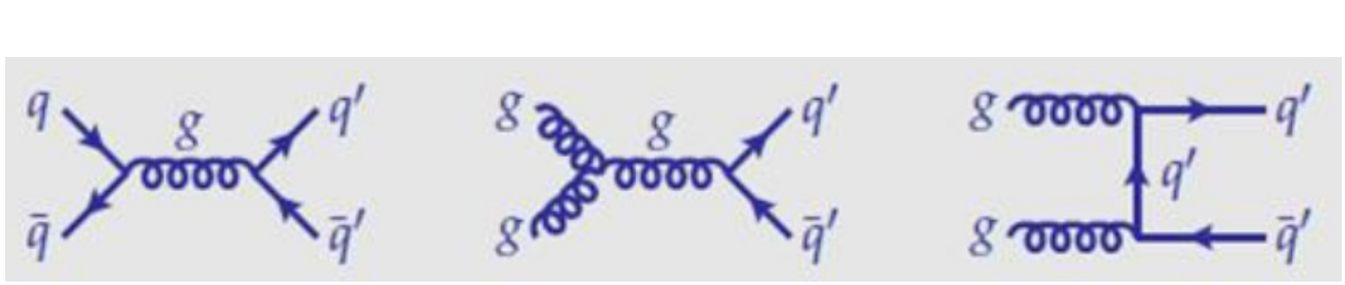
what next?

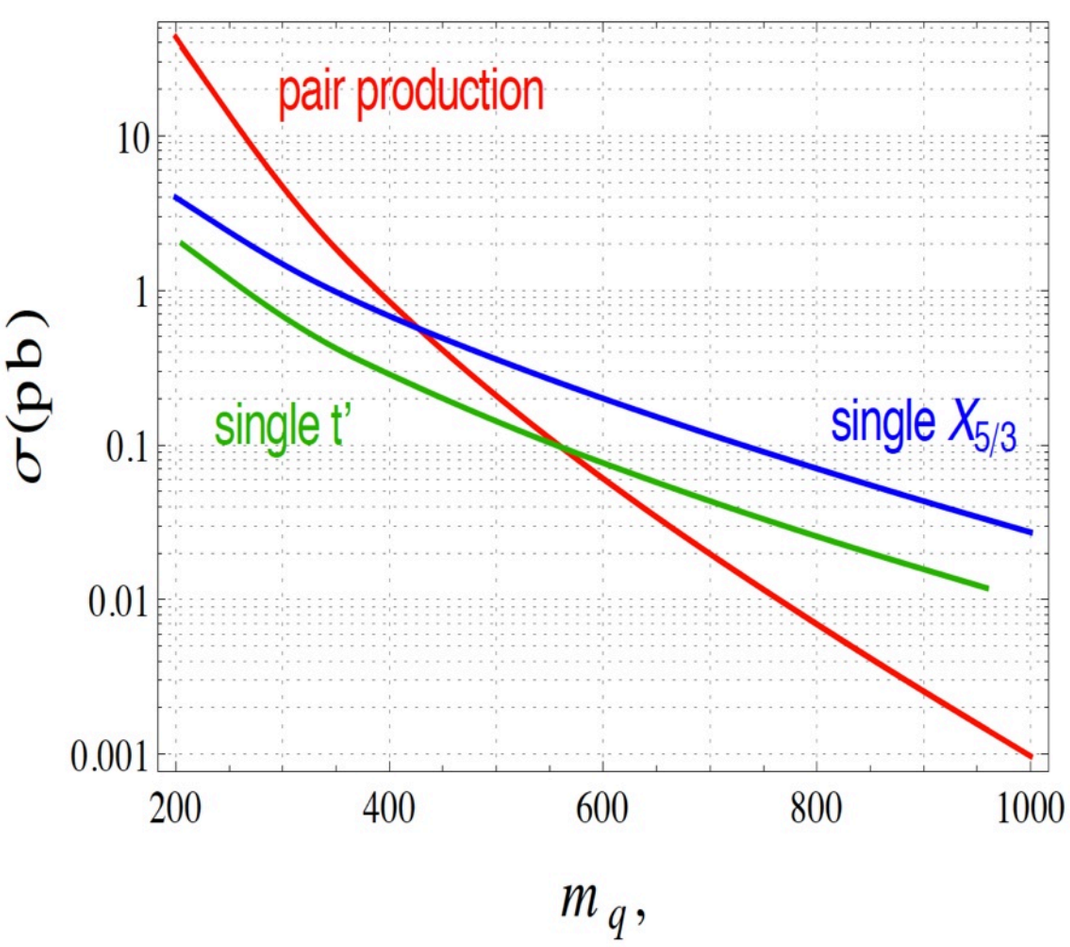
various other results still in the pipeline

- followed by a combination of everything
  (limits should then get close to ~900 GeV/c2)

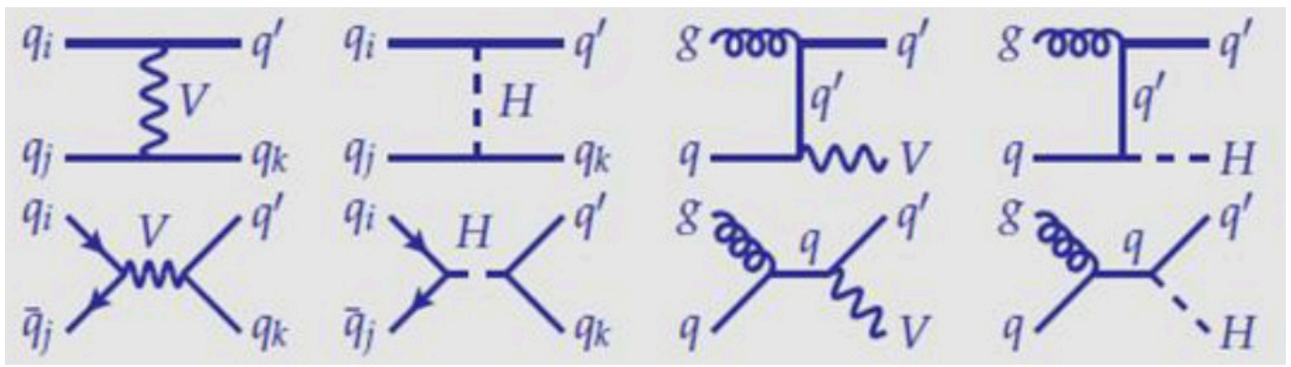
all the analyses assumed pair production of VLQ

- QCD cross-sections calculated to NNLO





- single production becoming more relevant as exclusion limits are pushed higher
- more difficult to access theoretically



Helmholtz Alliance

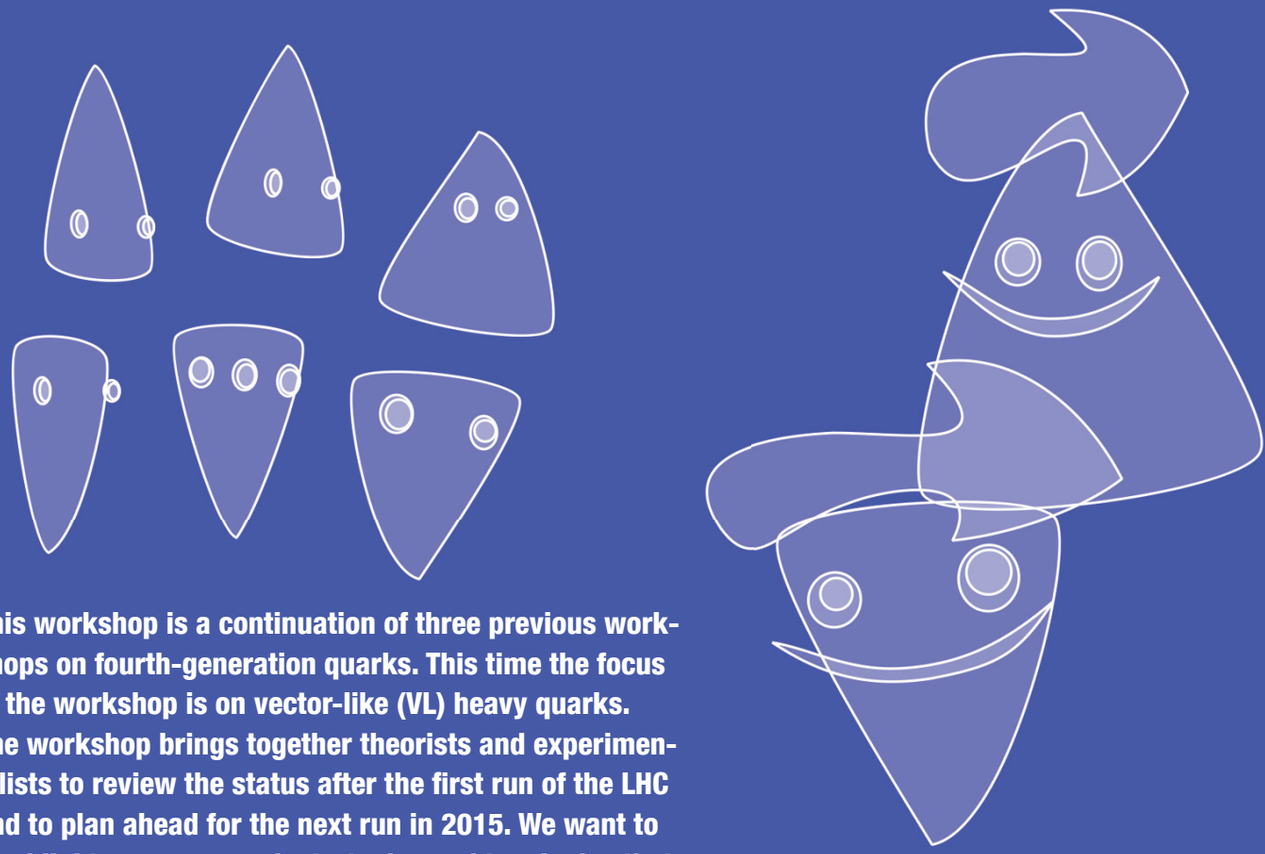
PHYSICS AT THE TERASCALE

Deutsches Elektronen-Synchrotron DESY +++ Karlsruher Institut für Technologie - Großforschungsbereich +++ Max-Planck-Institut für Physik München +++ Rheinisch-Westfälische Technische Hochschule Aachen +++ Humboldt-Universität zu Berlin +++ Rheinische Friedrich-Wilhelms-Universität Bonn +++ Technische Universität Dortmund +++ Technische Universität Dresden +++ Albert-Ludwigs-Universität Freiburg +++ Justus-Liebig-Universität Gießen +++ Georg-August-Universität Göttingen +++ Universität Hamburg +++ Ruprecht-Karls-Universität Heidelberg +++ Karlsruher Institut für Technologie - Universitätsbereich +++ Johannes Gutenberg-Universität Mainz +++ Ludwig-Maximilians-Universität München +++ Universität Regensburg +++ Universität Rostock +++ Universität Siegen +++ Julius-Maximilians-Universität Würzburg +++ Bergische Universität Wuppertal +++

Workshop on Vector-like Quarks 2014

15-16 September 2014

Hamburg University



This workshop is a continuation of three previous workshops on fourth-generation quarks. This time the focus of the workshop is on vector-like (VL) heavy quarks. The workshop brings together theorists and experimentalists to review the status after the first run of the LHC and to plan ahead for the next run in 2015. We want to shed light on new search strategies and topologies that may become relevant at higher energies.

Organising Committee:
Heiko Lacker (HU Berlin),
Alexander Schmidt (U Hamburg)
Thomas Schörner-Sadenius (DESY)

Contact: anacen@desy.de

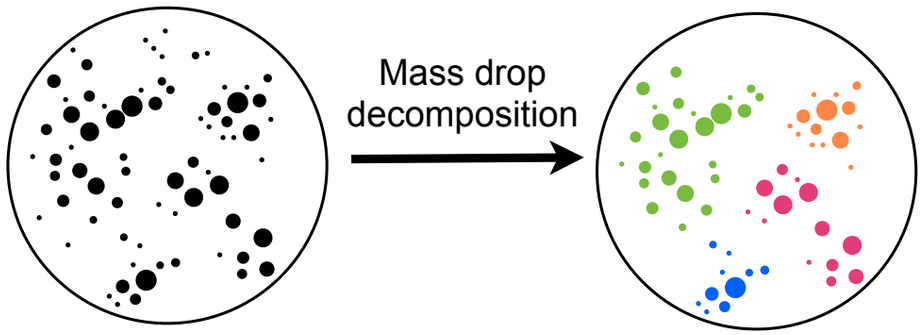
Registration fee: 20 Euros
Registration deadline: 1 September 2014

For more information and registration go to:
www.terascale.de/vlq2014

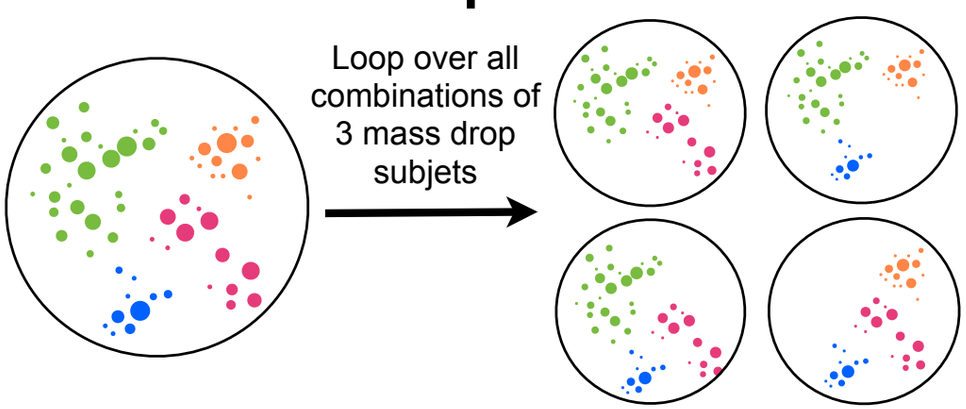
backup

HEP Top Tagger details

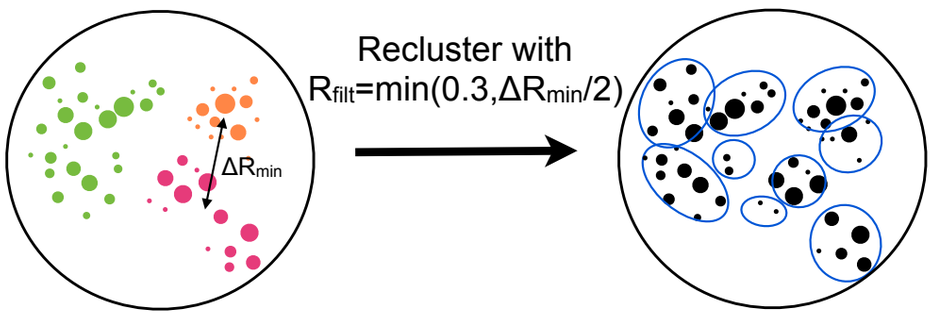
Step 1:



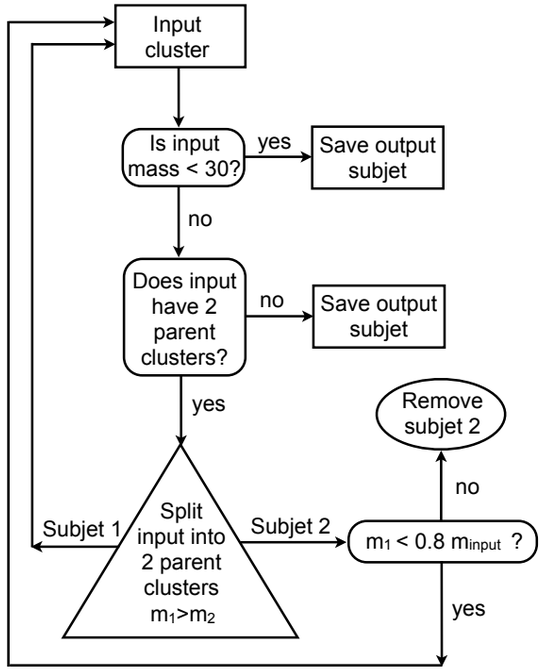
Step 2:



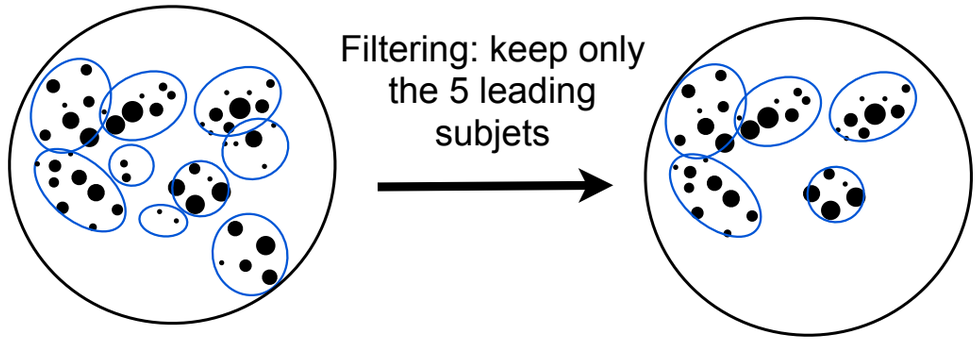
Step 3:



HEP Top Tagger
Mass drop decomposition

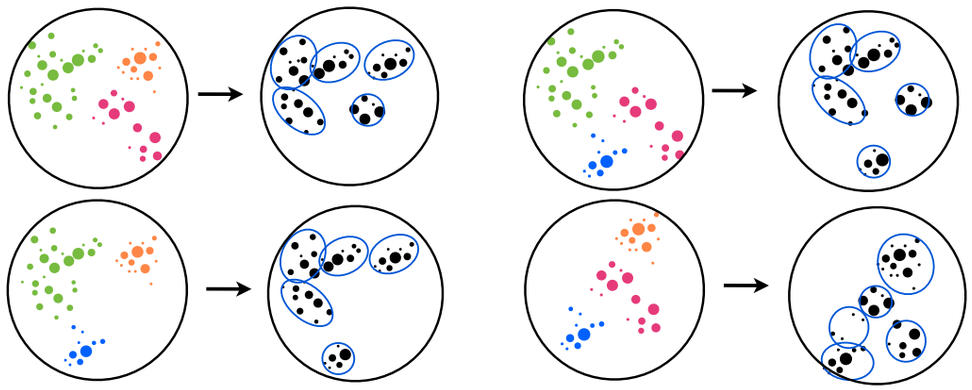


Step 4:

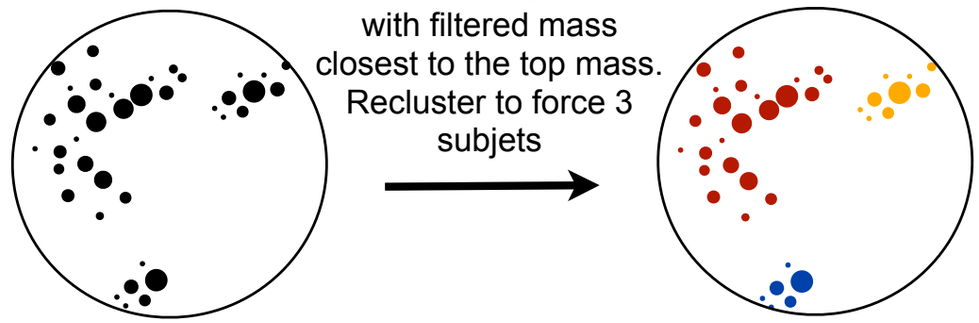


Step 5:

Repeat reclustering and filtering procedure for all combinations of 3 mass drop subjets



Step 6:



HEP Top Tagger - W mass selection

Bi-dimensional distribution based on the ratio of subjet pairwise masses

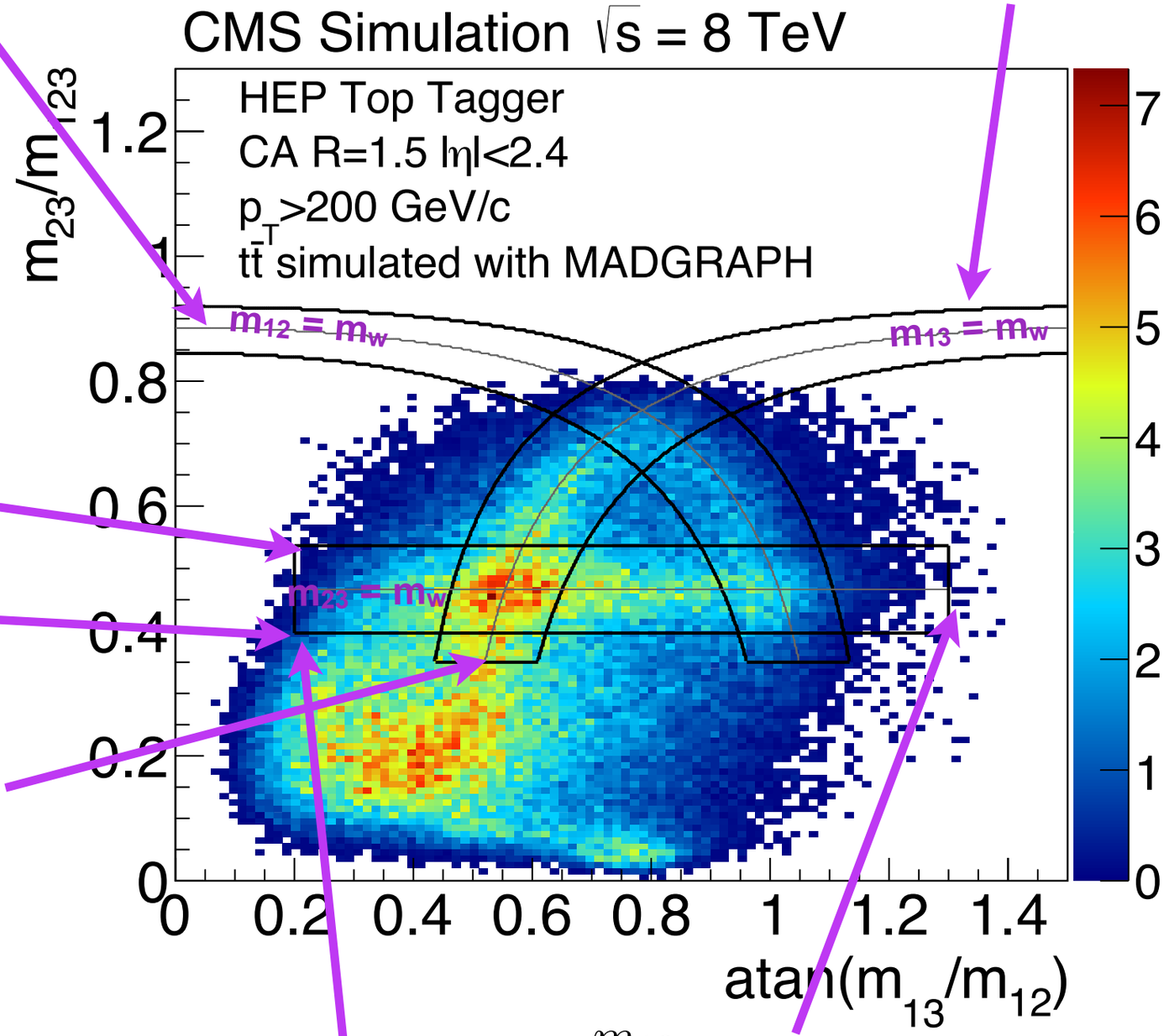
$$R^2_{\rm min}(1+(\frac{m_{12}}{m_{13}})^2) < 1-(\frac{m_{23}}{m_{123}})^2 < R^2_{\rm max}(1+(\frac{m_{12}}{m_{13}})^2) \quad R^2_{\rm min}(1+(\frac{m_{13}}{m_{12}})^2) < 1-(\frac{m_{23}}{m_{123}})^2 < R^2_{\rm max}(1+(\frac{m_{13}}{m_{12}})^2)$$

$$R_{\rm min} < \frac{m_{23}}{m_{123}} < R_{\rm max}$$

$$R_{\rm max} = (1+f_W)\times m_W/m_t$$

$$R_{\rm min} = (1-f_W)\times m_W/m_t$$

$$\frac{m_{23}}{m_{123}} > 0.35$$

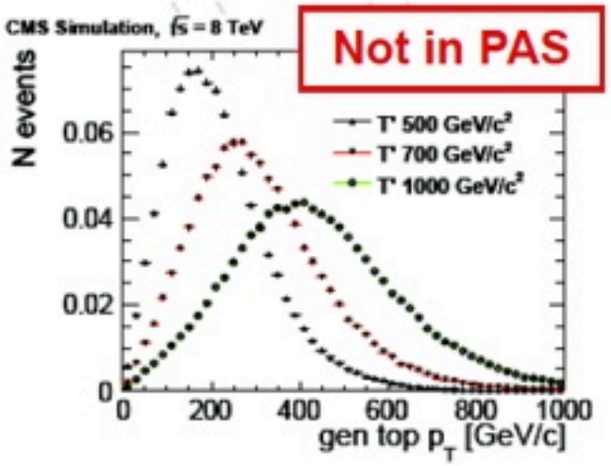


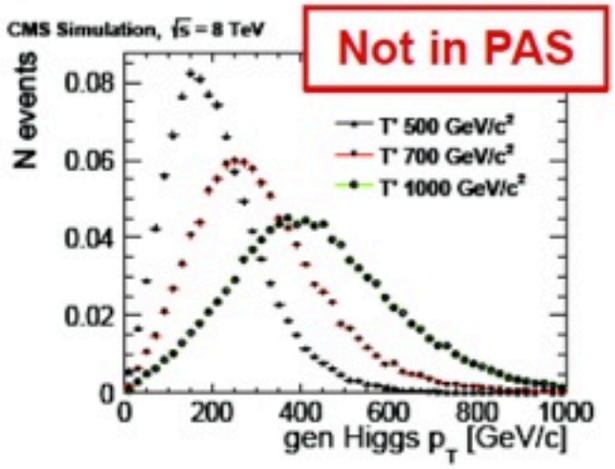
$$0.2 < \arctan\frac{m_{13}}{m_{12}} < 1.3$$

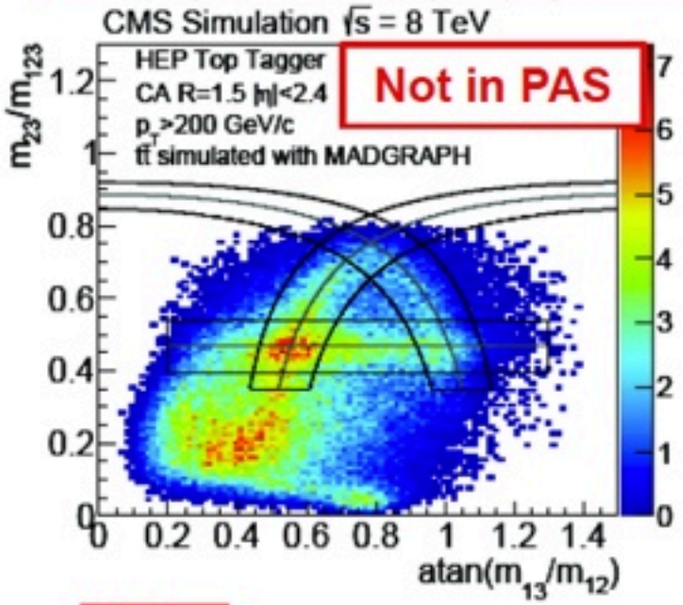
Details in JME-13-007

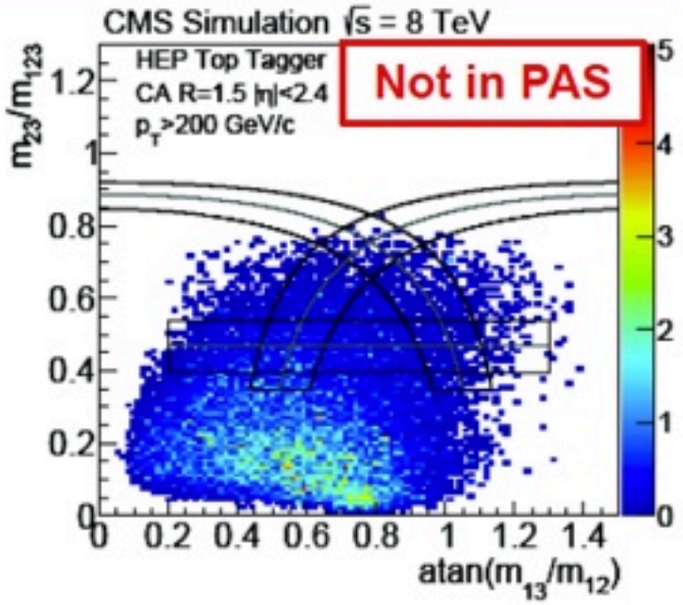
HEPTopTagger

HEPTopTagger optimal for **moderately boosted jets** with p_T of ~ 200 GeV due to large jet cone ($\Delta R = 1.5$)









More detail in backup

HEPTopTagger Algorithm

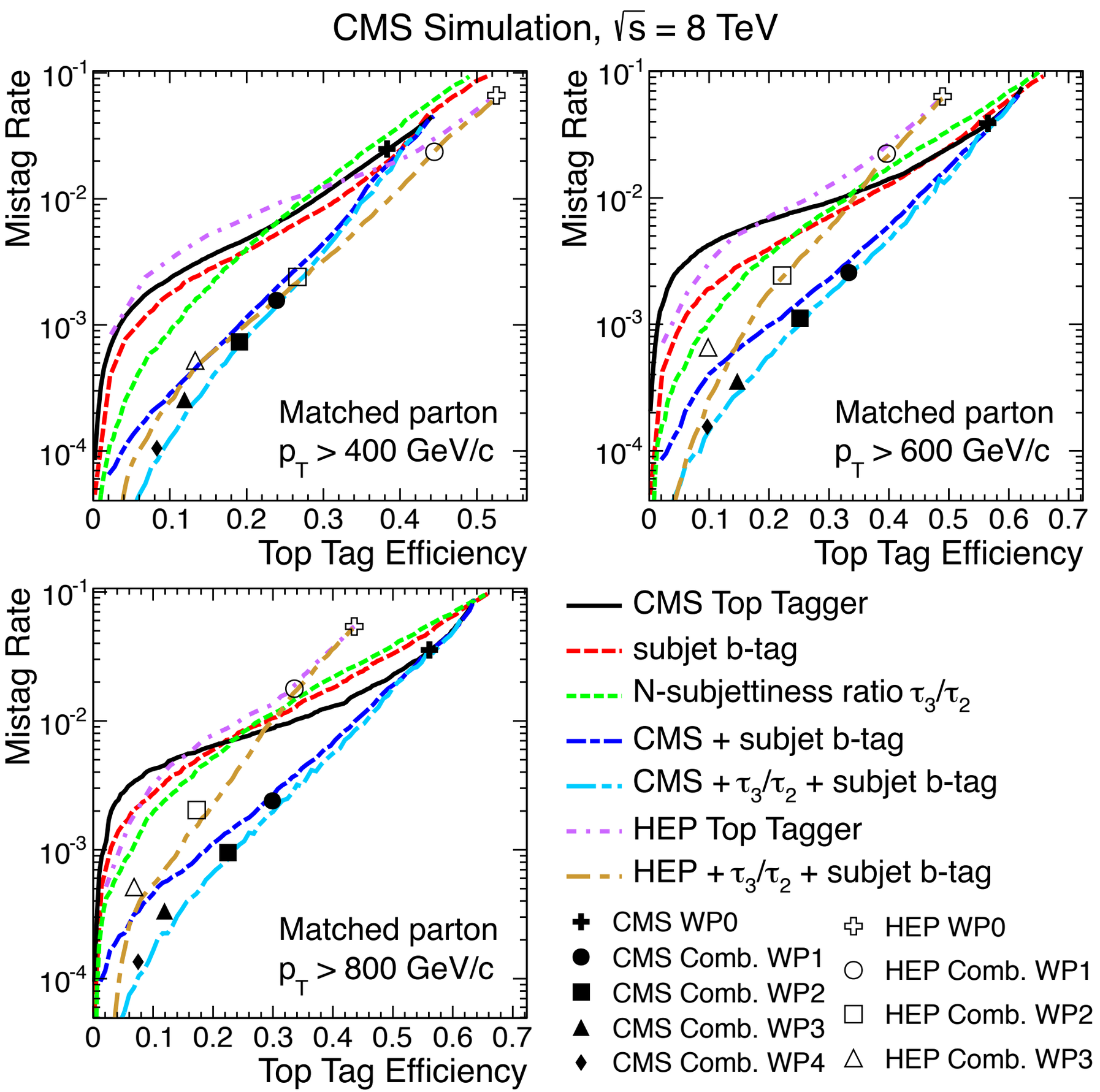
1. Subjet definition using filtering algorithm and mass drop requirement

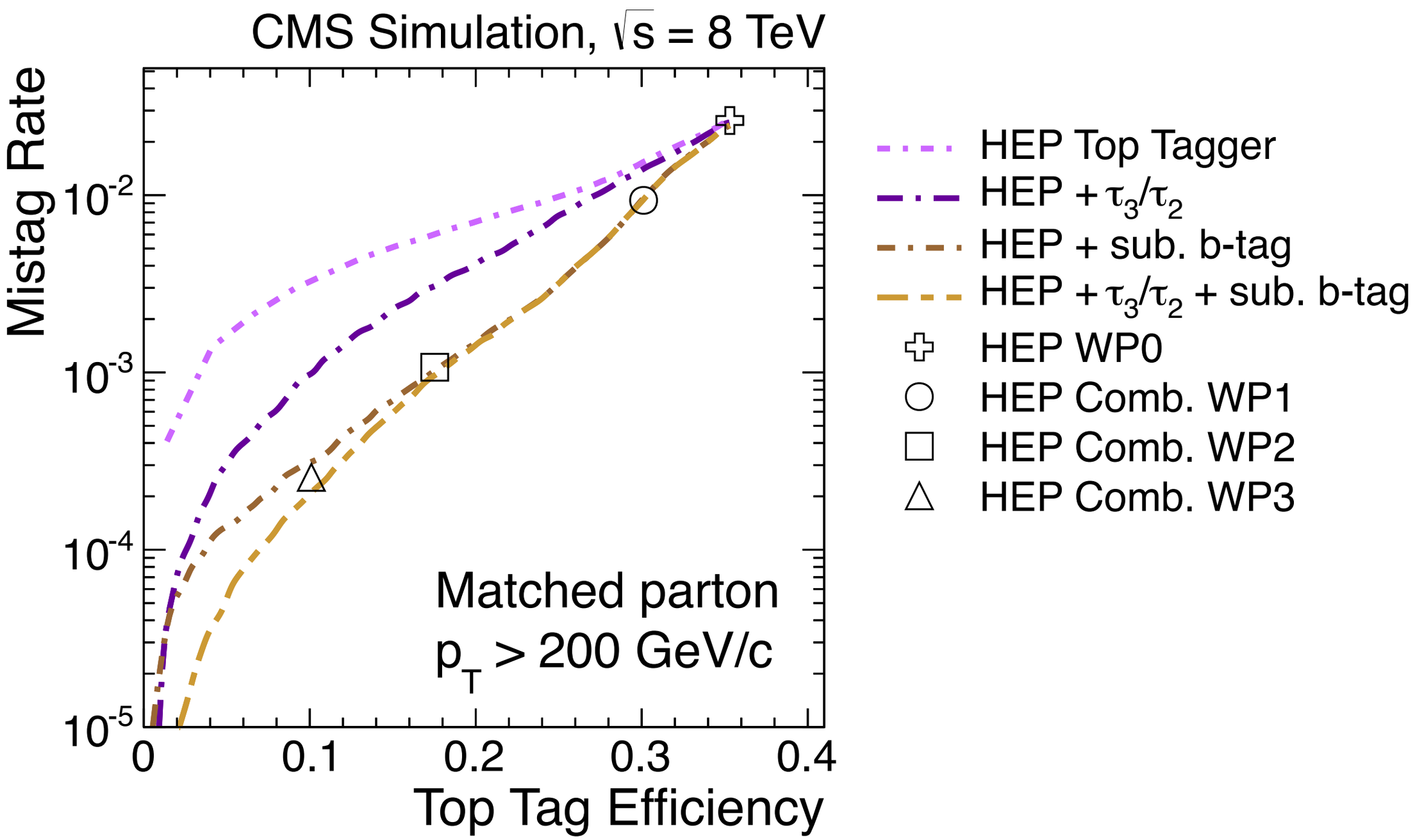
2. Using combination of three subjets which results in **jet mass closest to top mass**

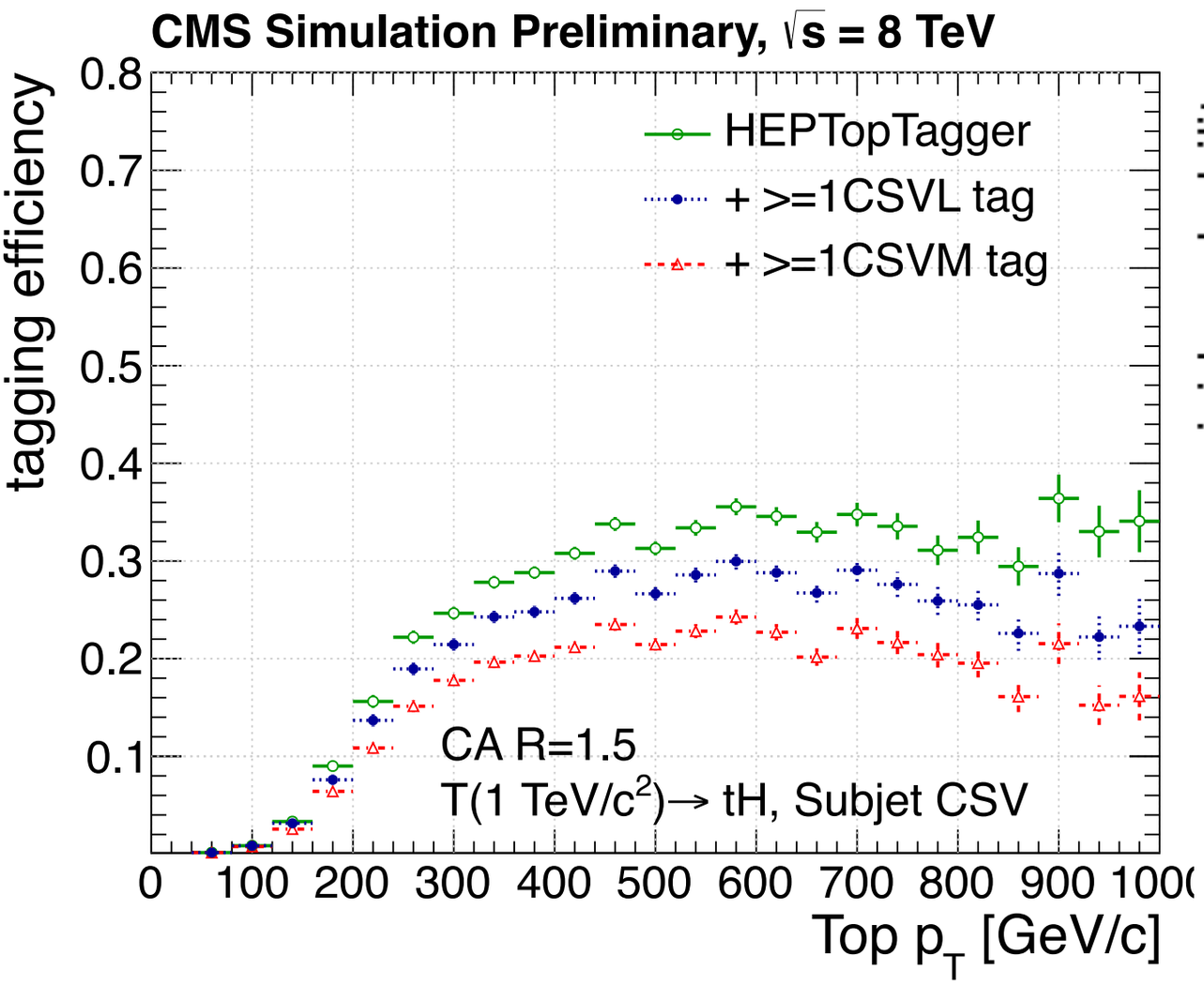
3. **top mass** selection on $\mathbf{m_{123}}$

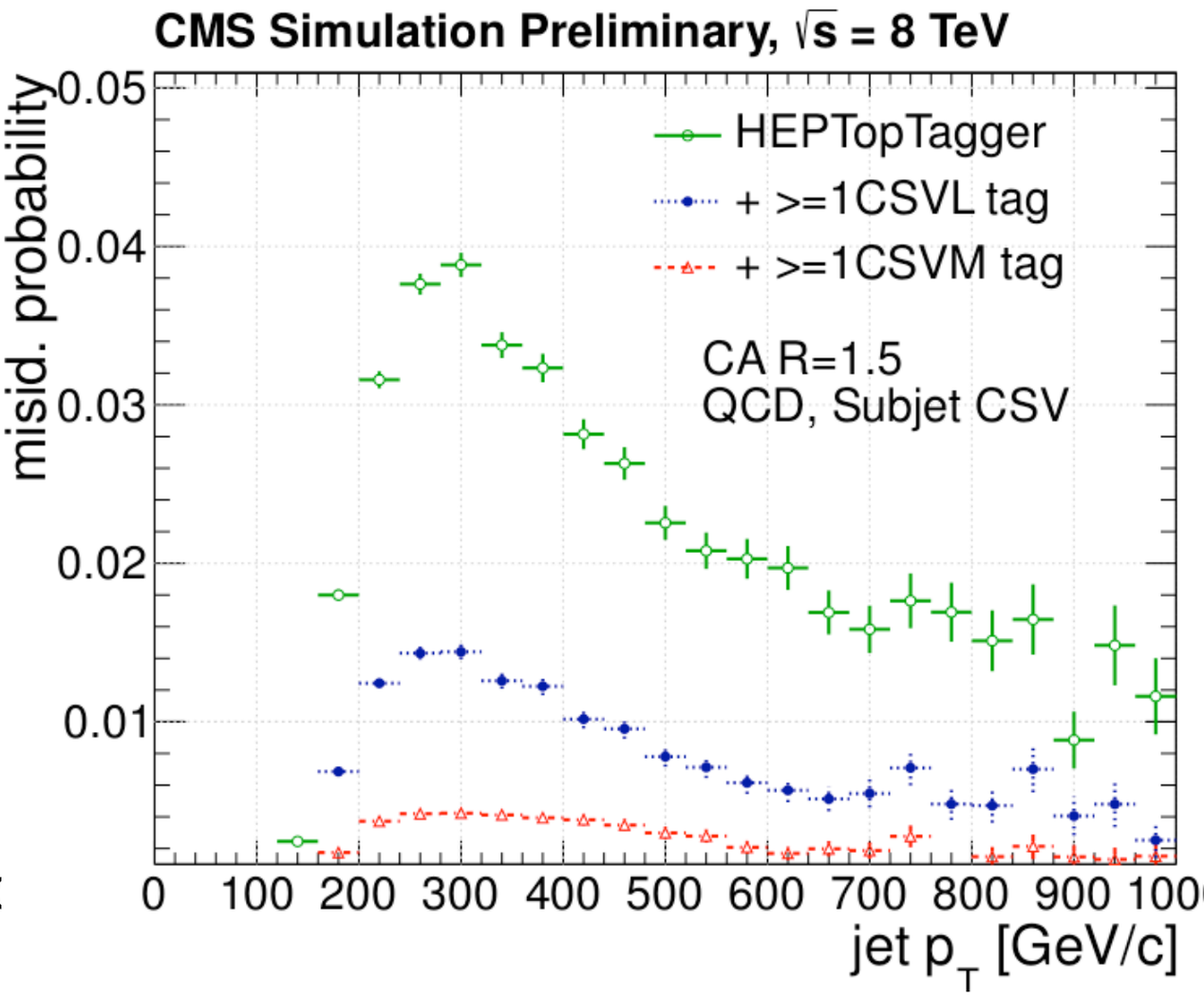
4. **W mass** selection on $\mathbf{m_{12}}$, $\mathbf{m_{13}}$, or $\mathbf{m_{23}}$

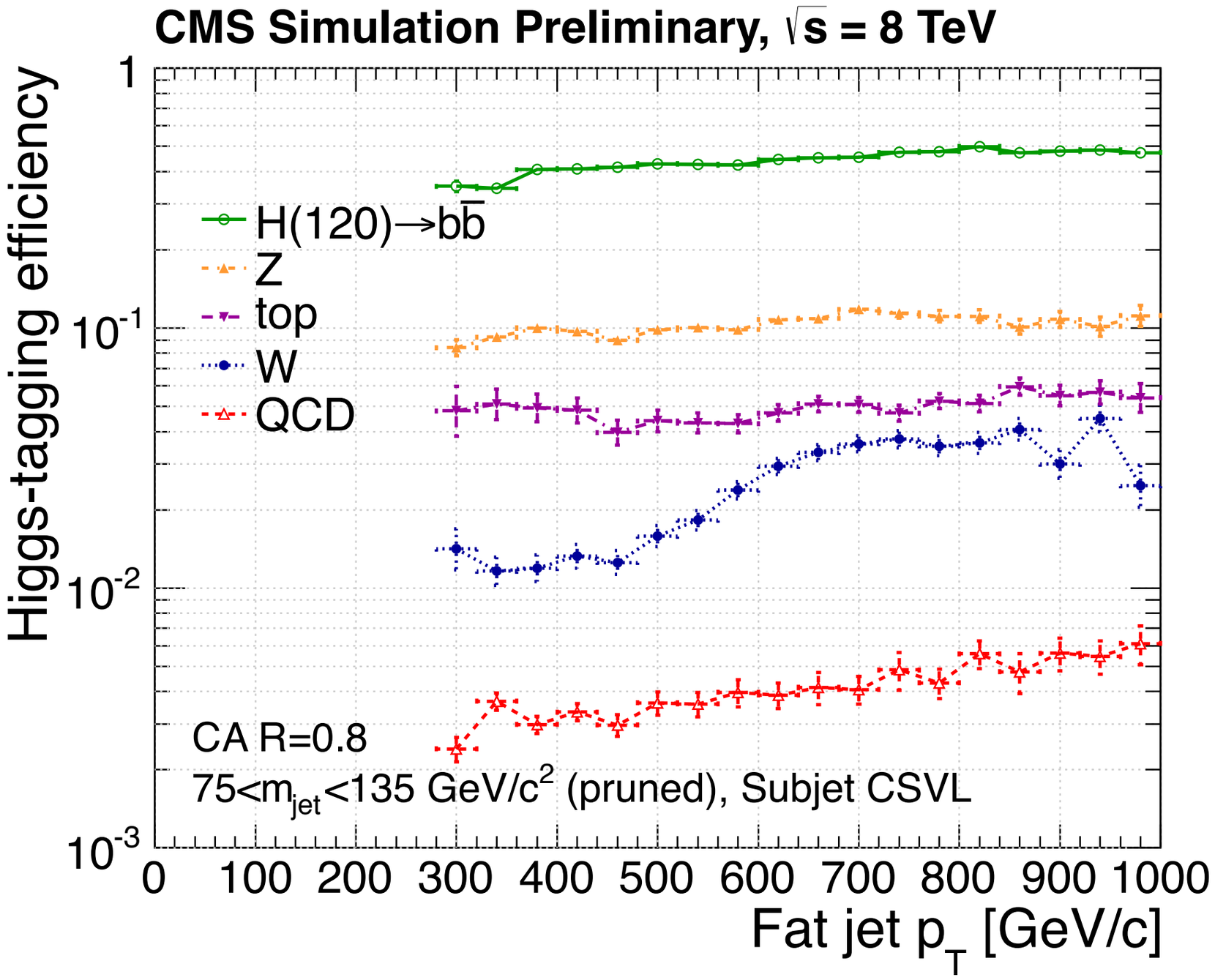
→ **A-shaped region**

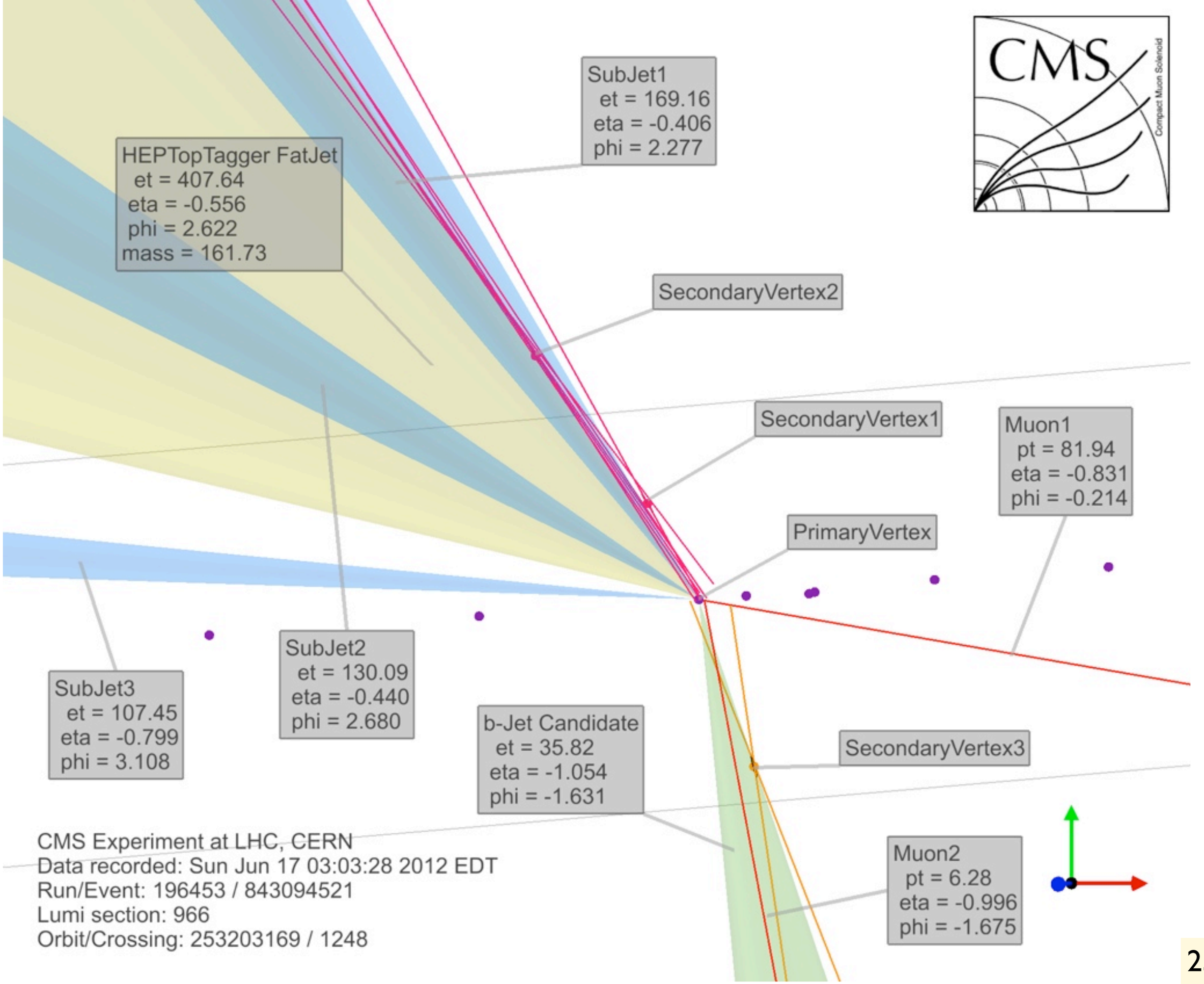

CMS Simulation, √s = 8 TeV
Mistag Rate
Top Tag Efficiency
Matched parton
p_T > 400 GeV/c
Matched parton
p_T > 600 GeV/c
Matched parton
p_T > 800 GeV/c
CMS Top Tagger
subjet b-tag
N-subjettiness ratio τ3/τ2
CMS + subjet b-tag
CMS + τ3/τ2 + subjet b-tag
HEP Top Tagger
HEP + τ3/τ2 + subjet b-tag
CMS WP0
CMS Comb. WP1
CMS Comb. WP2
CMS Comb. WP3
CMS Comb. WP4
HEP WP0
HEP Comb. WP1
HEP Comb. WP2
HEP Comb. WP3


CMS Simulation, √s = 8 TeV
Mistag Rate
10^-2
10^-3
10^-4
10^-5
0
0.1
0.2
0.3
0.4
Top Tag Efficiency
Matched parton
p_T > 200 GeV/c
HEP Top Tagger
HEP + τ3/τ2
HEP + sub. b-tag
HEP + τ3/τ2 + sub. b-tag
HEP WP0
HEP Comb. WP1
HEP Comb. WP2
HEP Comb. WP3


CMS Simulation Preliminary, √s = 8 TeV
tagging efficiency
HEPTopTagger
+ >=1CSVL tag
+ >=1CSVM tag
CA R=1.5
T(1 TeV/c²)→ tH, Subjet CSV
Top p_T [GeV/c]


CMS Simulation Preliminary, √s = 8 TeV
misid. probability
HEPTopTagger
+ >=1CSVL tag
+ >=1CSVM tag
CA R=1.5
QCD, Subjet CSV
jet p_T [GeV/c]


CMS Simulation Preliminary, √s = 8 TeV
Higgs-tagging efficiency
1
10^-1
10^-2
10^-3
H(120)→bb̄
Z
top
W
QCD
CA R=0.8
75<m_jet<135 GeV/c^2 (pruned), Subjet CSVL
0 100 200 300 400 500 600 700 800 900 1000
Fat jet p_T [GeV/c]


SubJet1
et = 169.16
eta = -0.406
phi = 2.277
HEPTopTagger FatJet
et = 407.64
eta = -0.556
phi = 2.622
mass = 161.73
SecondaryVertex2
SecondaryVertex1
Muon1
pt = 81.94
eta = -0.831
phi = -0.214
PrimaryVertex
SubJet3
et = 107.45
eta = -0.799
phi = 3.108
SubJet2
et = 130.09
eta = -0.440
phi = 2.680
b-Jet Candidate
et = 35.82
eta = -1.054
phi = -1.631
SecondaryVertex3
Muon2
pt = 6.28
eta = -0.996
phi = -1.675
CMS Experiment at LHC, CERN
Data recorded: Sun Jun 17 03:03:28 2012 EDT
Run/Event: 196453 / 843094521
Lumi section: 966
Orbit/Crossing: 253203169 / 1248