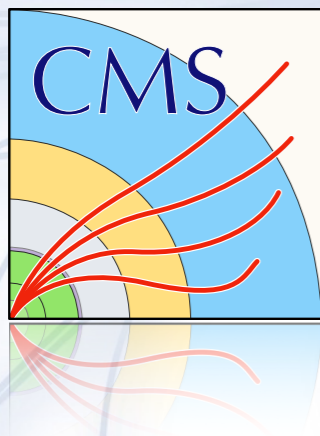


Searches for $t\bar{t}$ and $t\bar{b}$ resonances at CMS

Emanuele Usai on behalf of the CMS Collaboration



Universität Hamburg



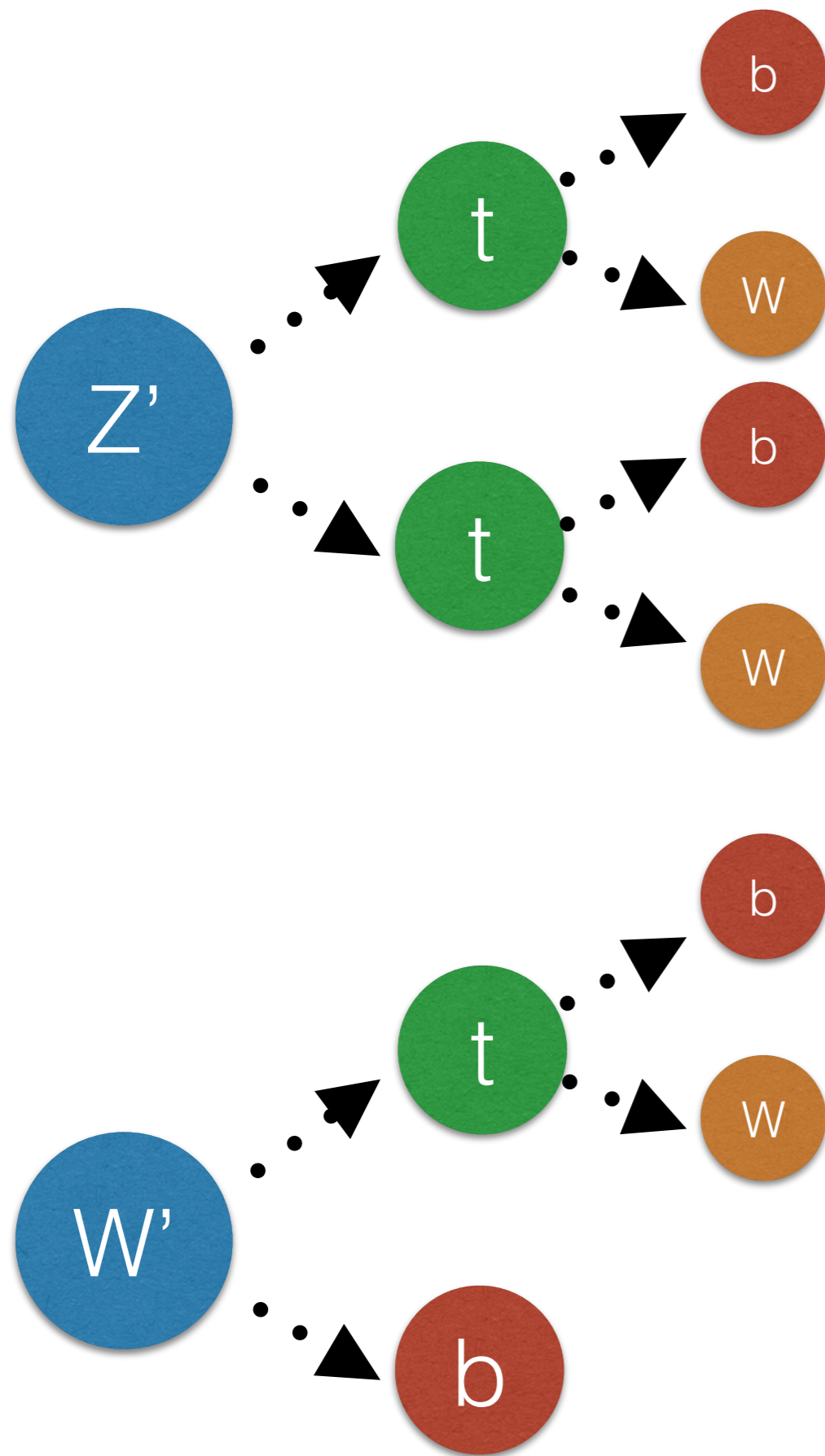
SUSY

2015

August 23-29

Lake Tahoe, California

The models



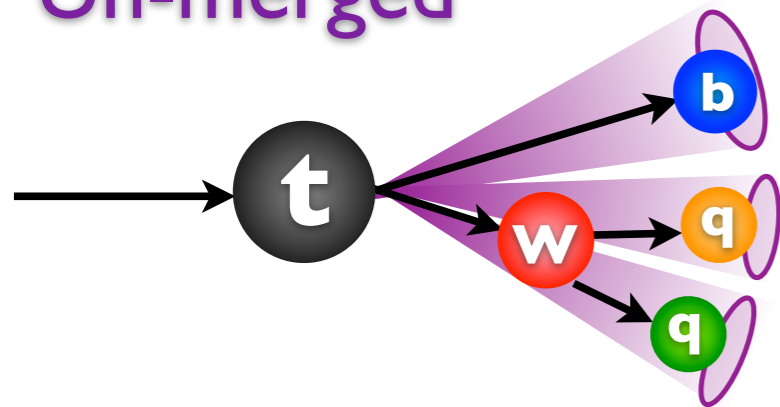
spin 1: Z-like resonance
Randall-Sundrum gluon

tt and tb resonances appear
in many BSM models
at the TeV mass range

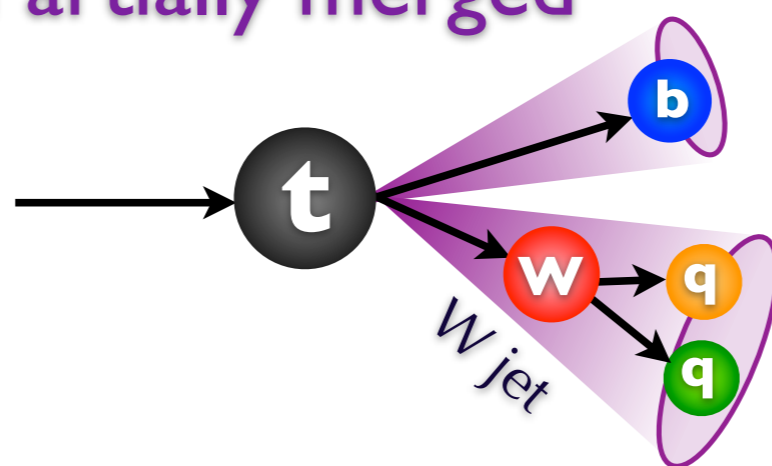
natural to probe connection to new
physics through the top quark

spin 1: W-like resonance
scanning over RH and LH
coupling fractions

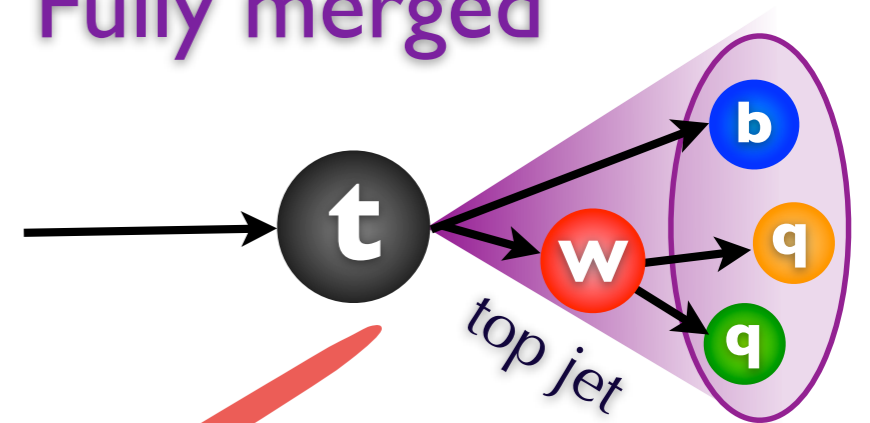
Un-merged



Partially merged



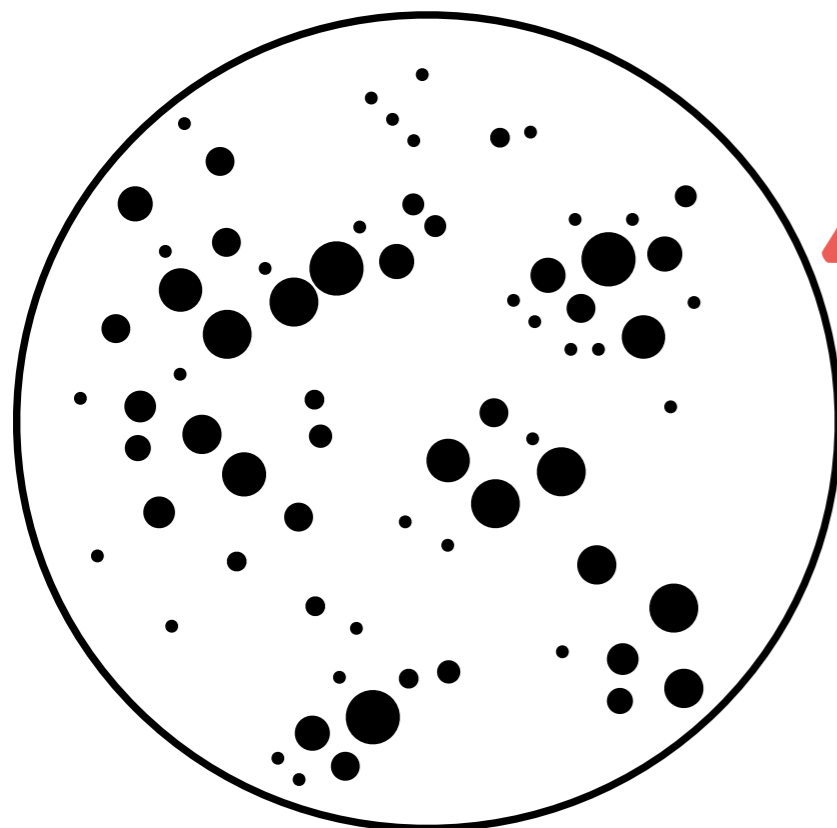
Fully merged



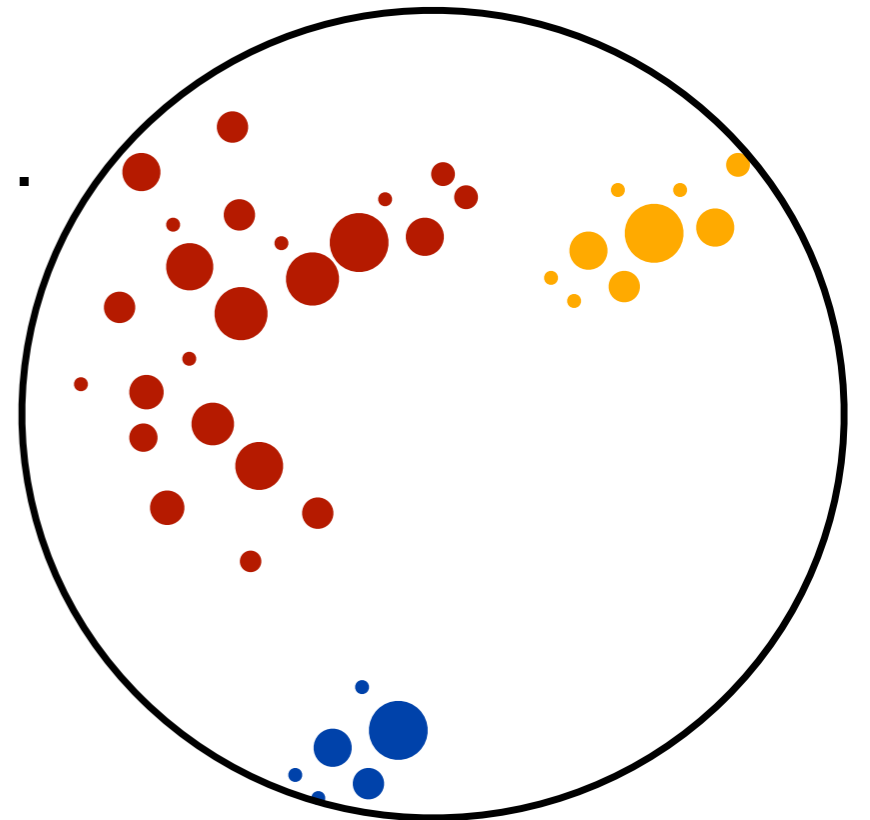
low p_T

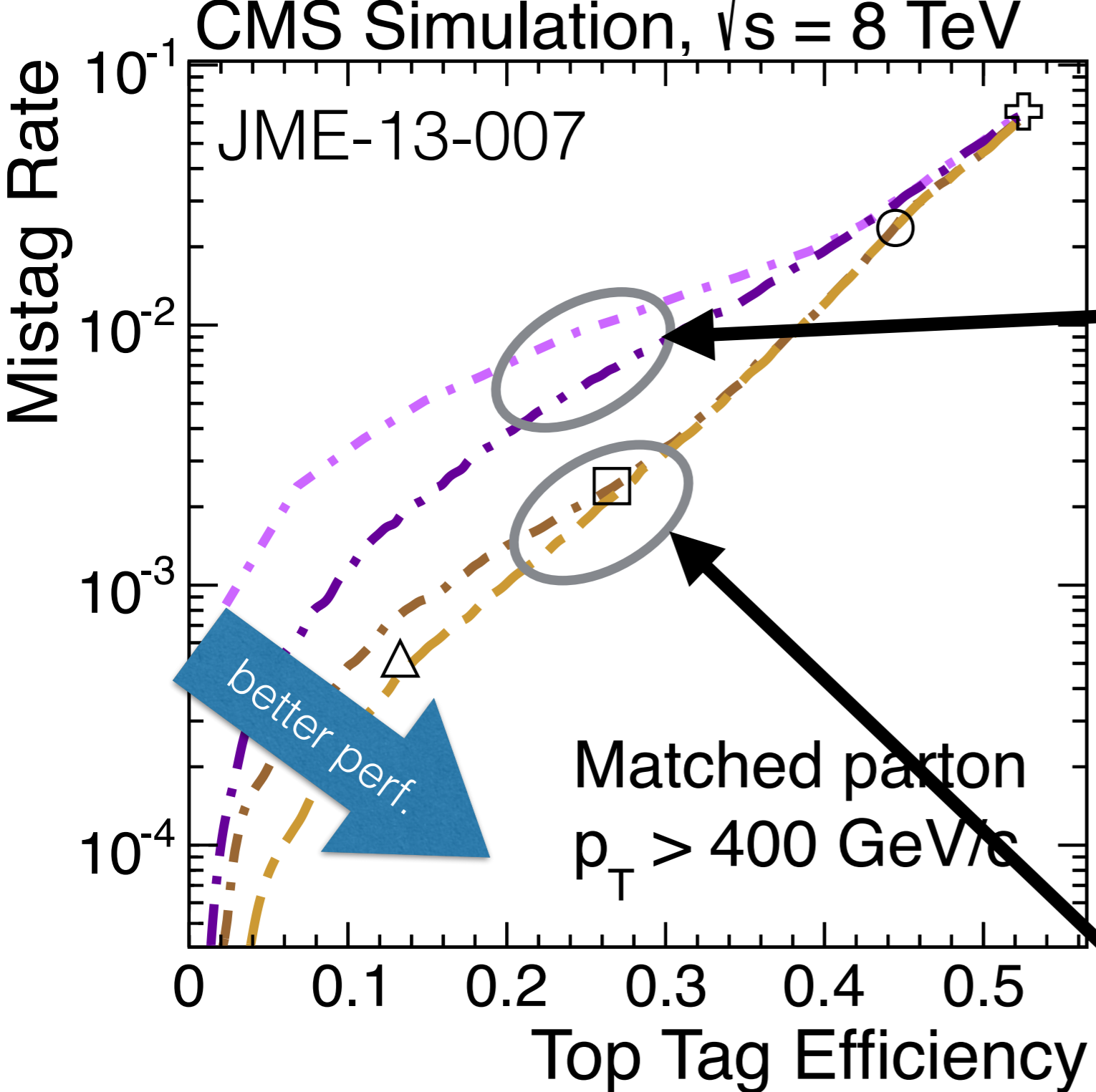
moderate p_T

high p_T



Top tagger



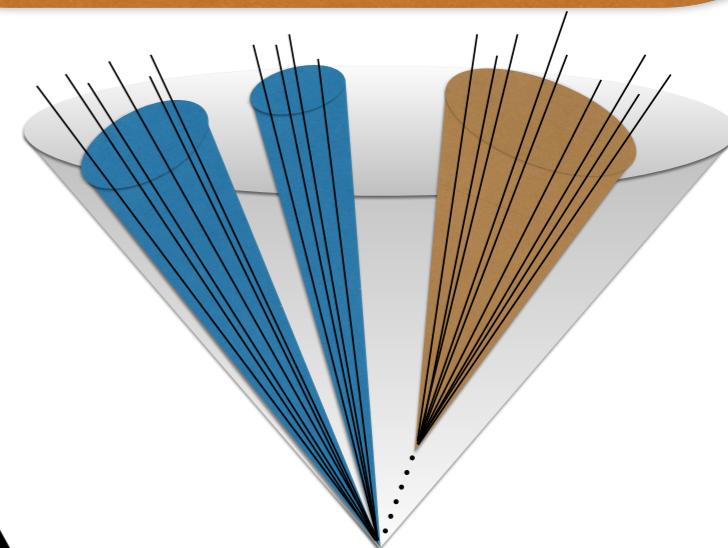


Tools

Top tag only



Top tag +
subjet b tag



--- HEP Top Tagger

--- HEP + τ_3/τ_2

--- HEP + sub. b-tag

--- HEP + τ_3/τ_2 + subjet b-tag

+ HEP WP0

○ HEP Comb. WP1

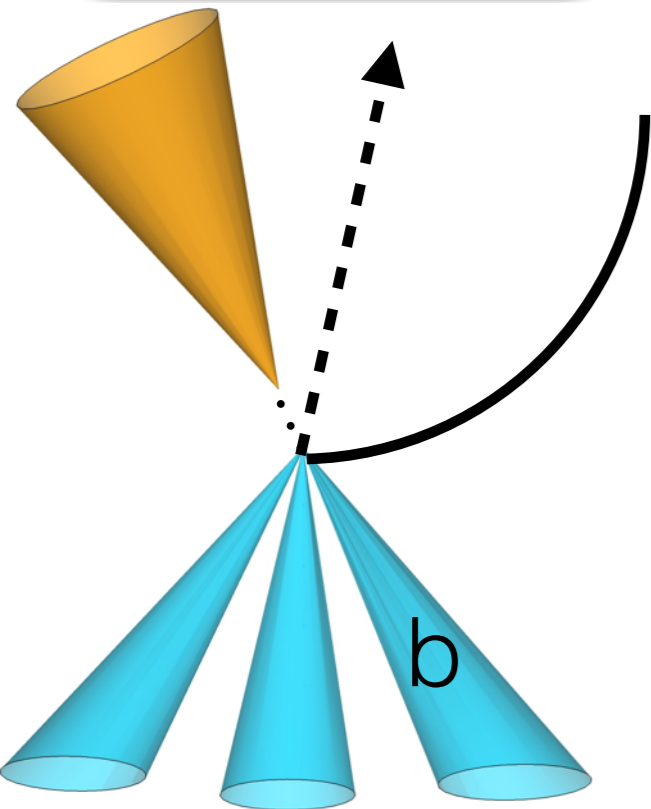
□ HEP Comb. WP2

△ HEP Comb. WP3

Analysis strategy top+antitop

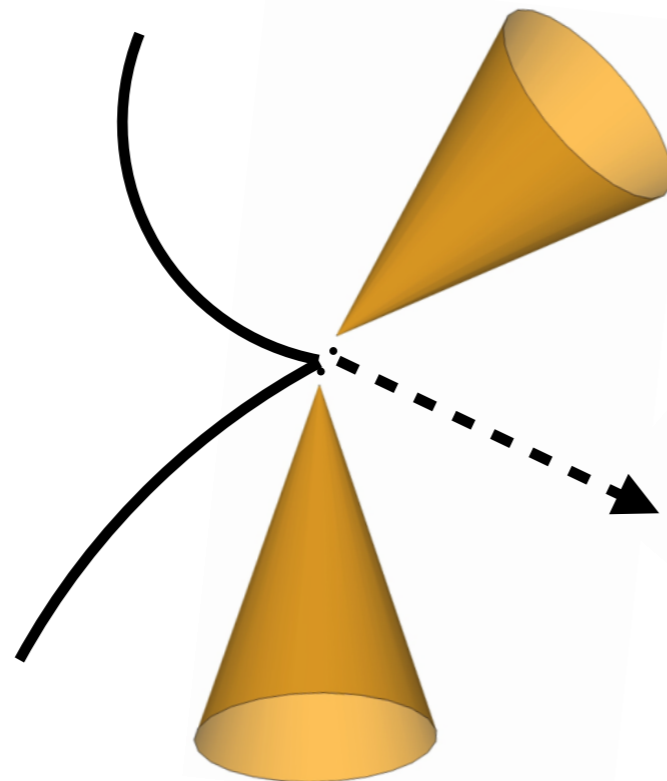
semileptonic
“resolved”

ideal for low
mass resonances



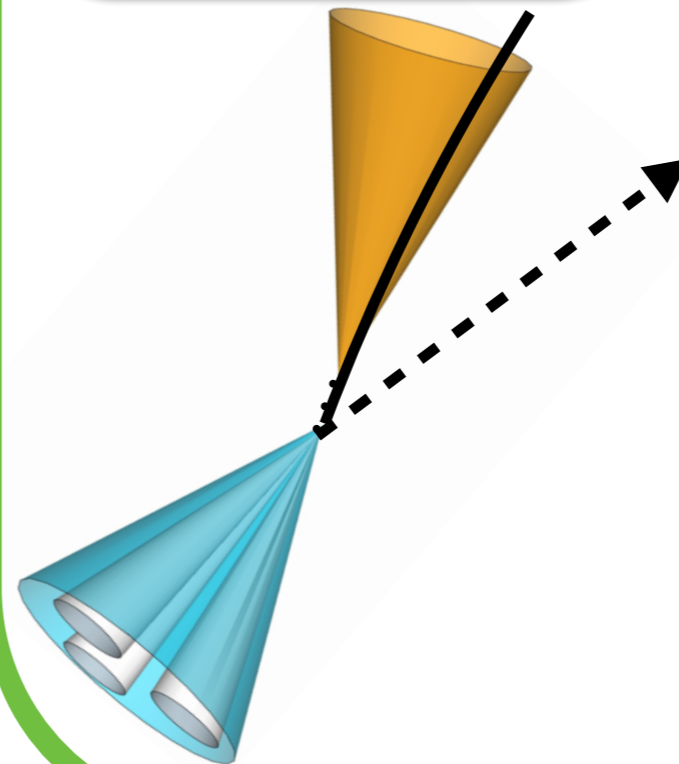
dileptonic

challenging
reconstruction



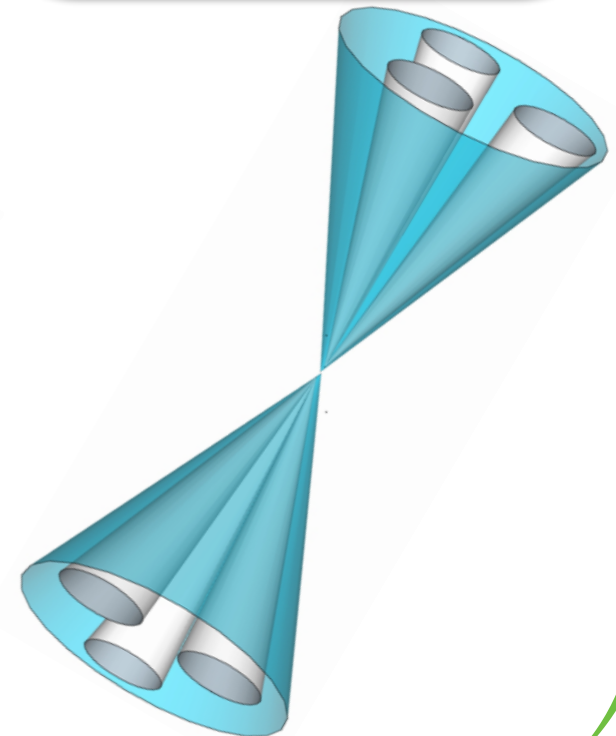
semileptonic
“boosted”

ideal for high
mass resonances



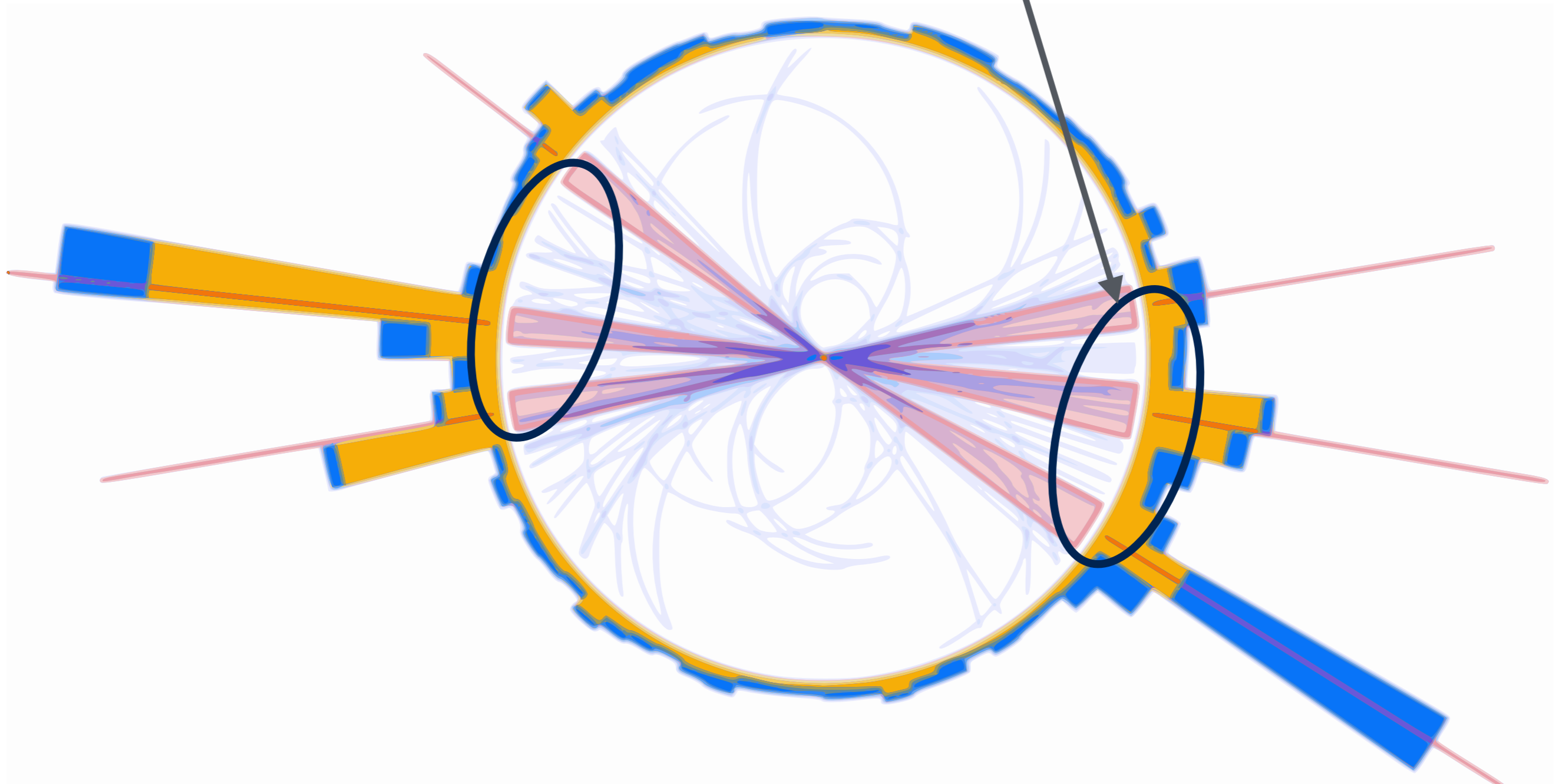
boosted
all hadronic

challenging final
state



all hadronic top+antitop

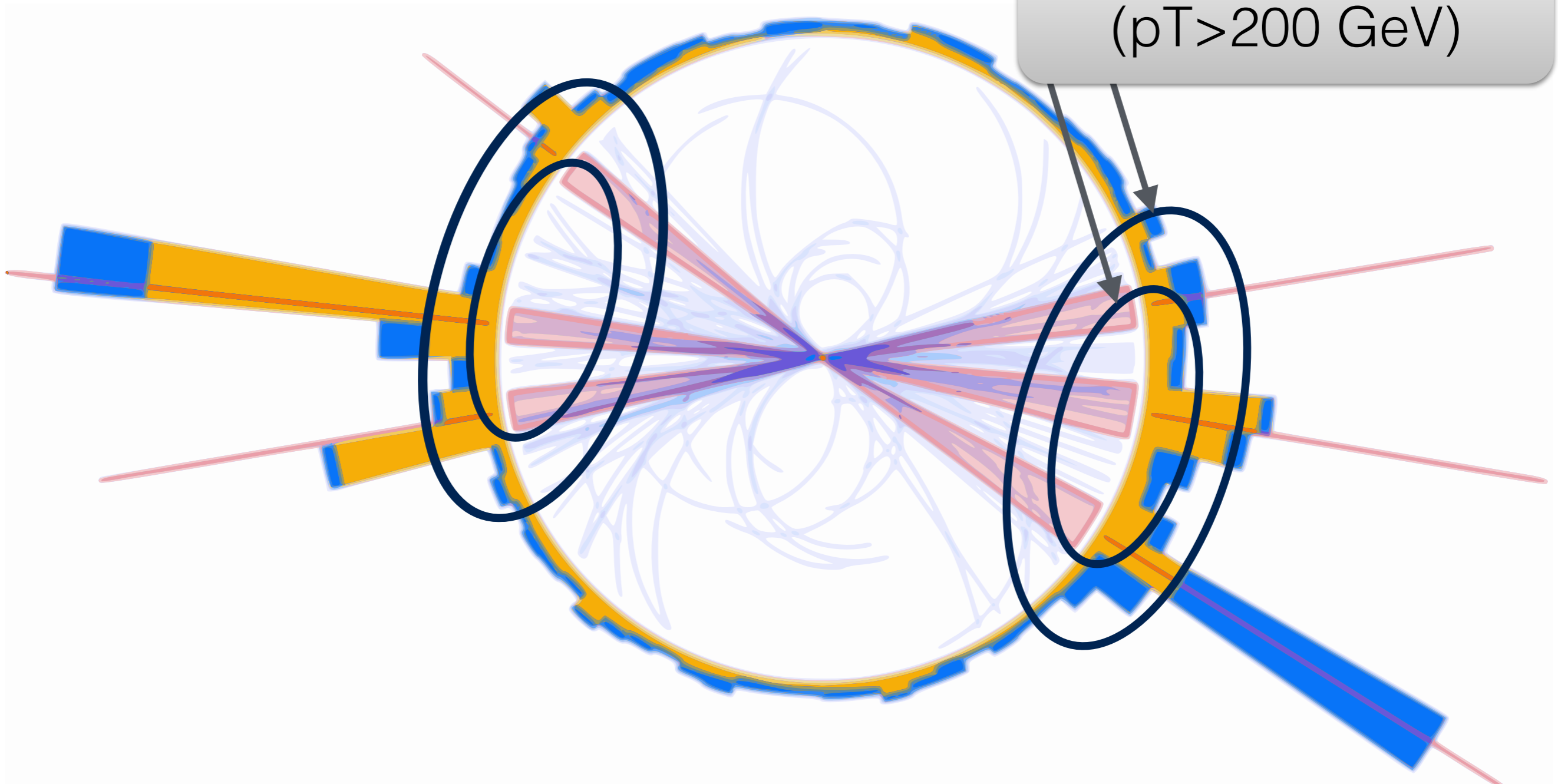
CMS Top Tagger
($p_T > 400$ GeV)



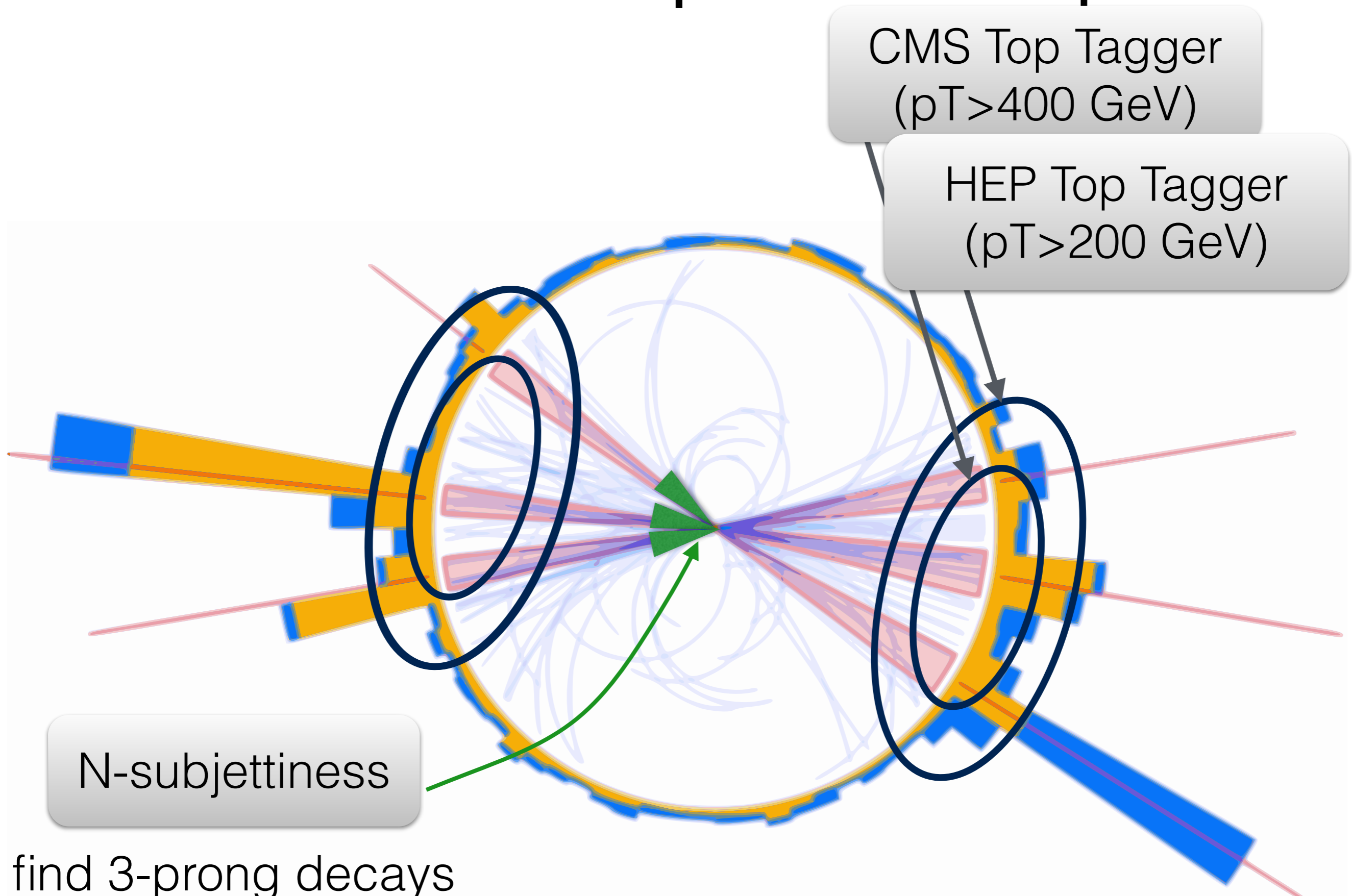
all hadronic top+antitop

CMS Top Tagger
($p_T > 400$ GeV)

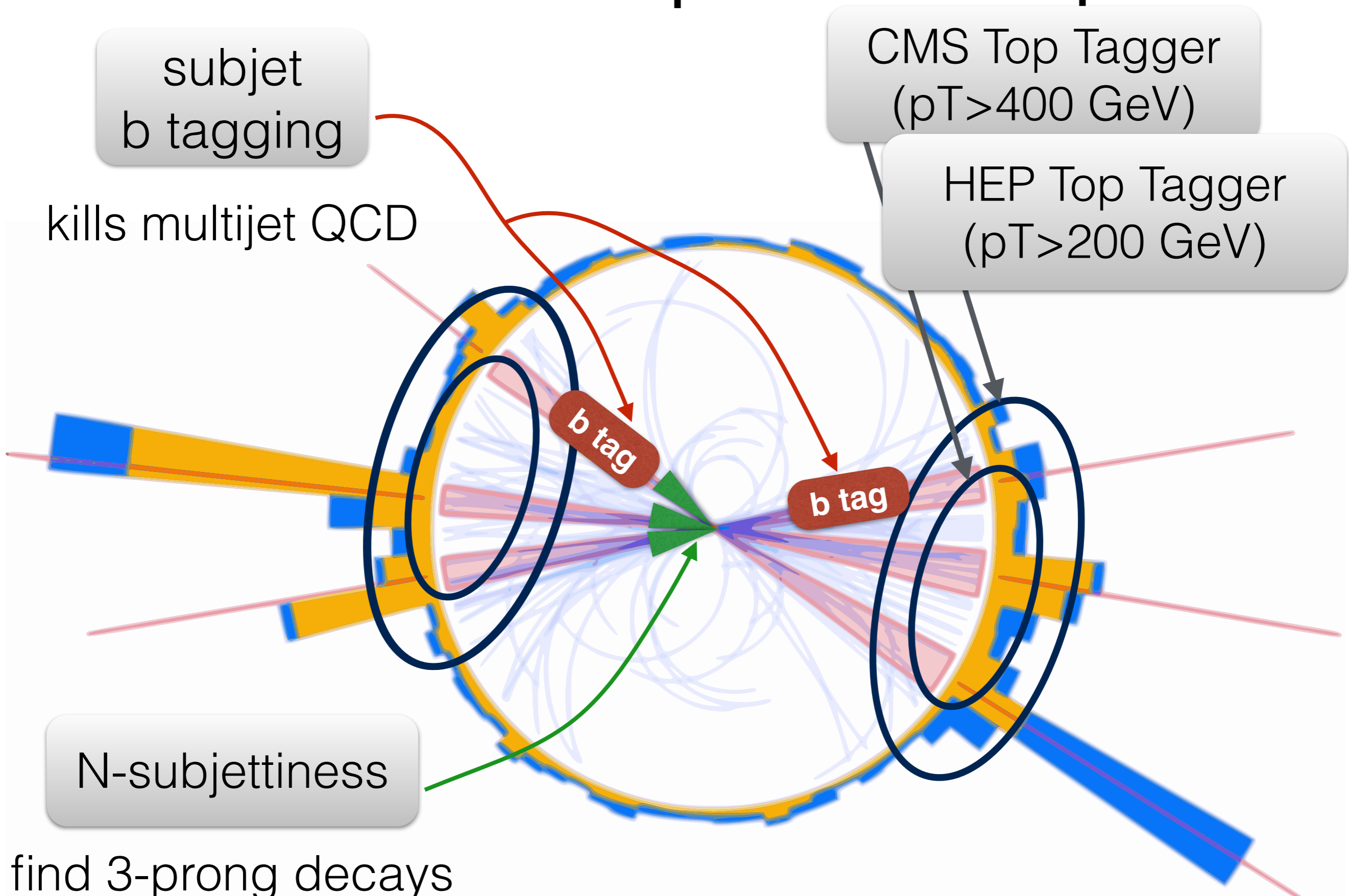
HEP Top Tagger
($p_T > 200$ GeV)



all hadronic top+antitop



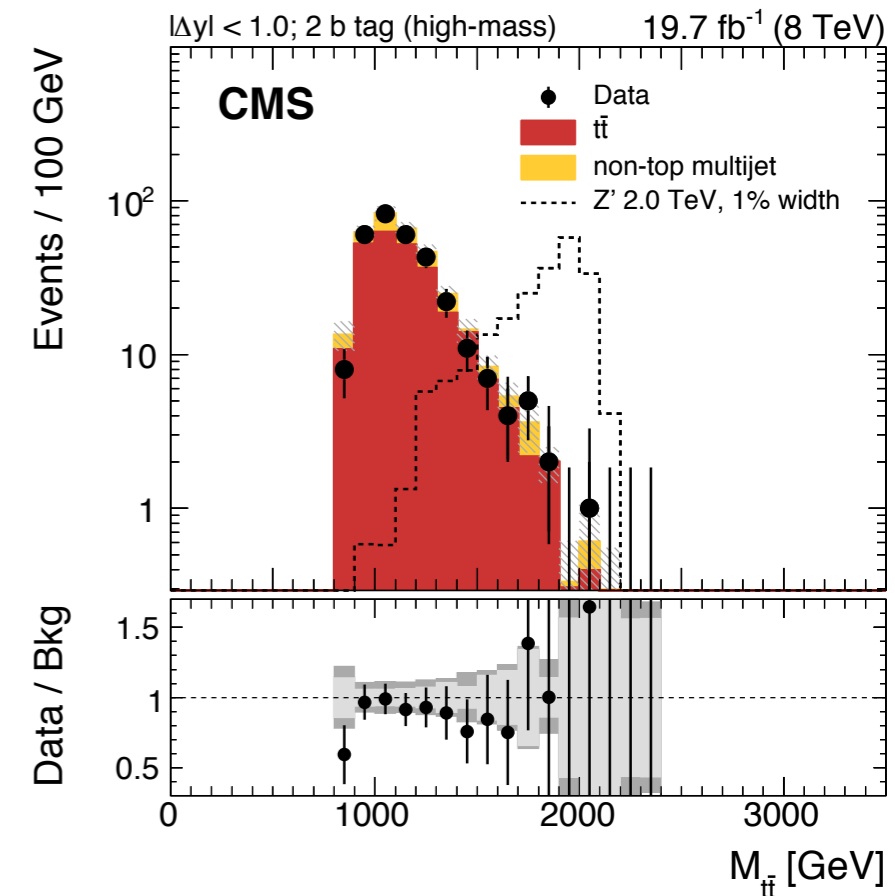
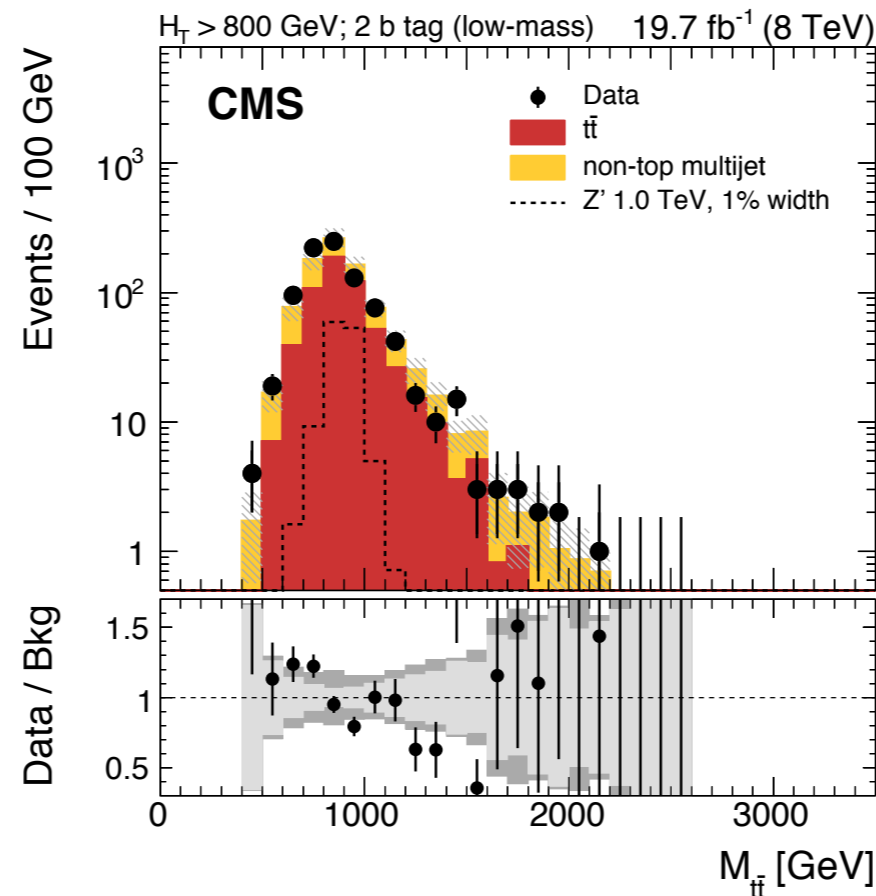
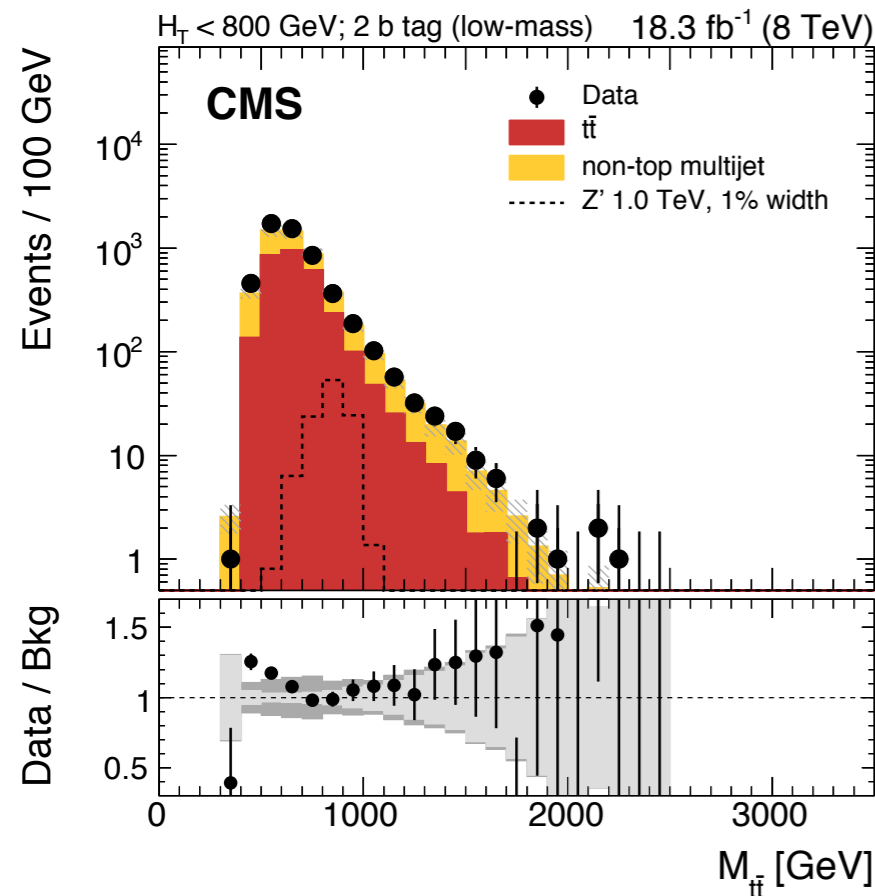
all hadronic top+antitop



2 b tags, HEP Tagger
HT<800 GeV

2 b tags, HEP Tagger
HT>800 GeV

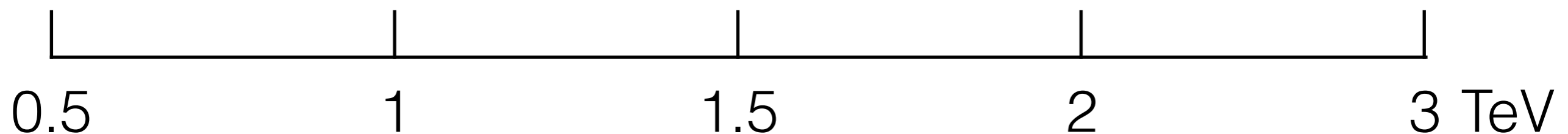
2 b tags, CMS Tagger
N-subjettiness cut



CMS Tagger

HEP Tagger - HT>800 GeV

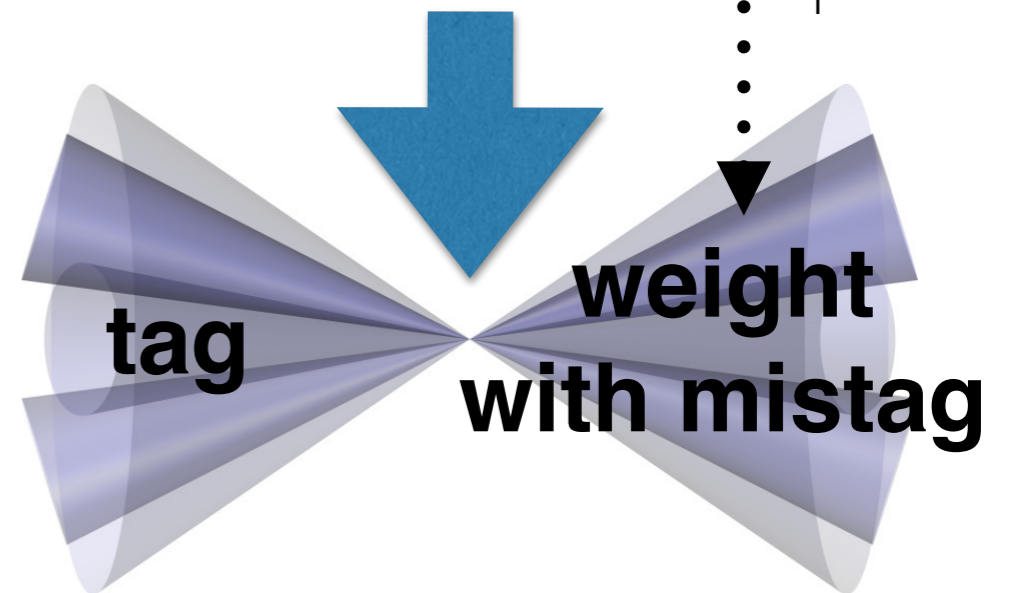
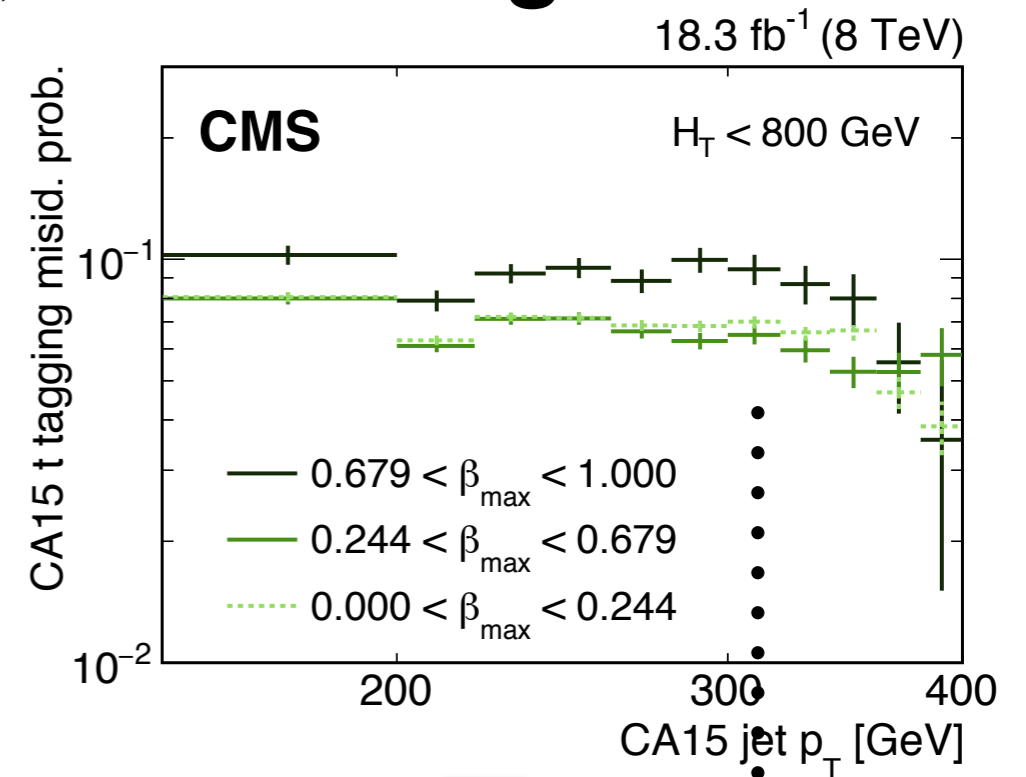
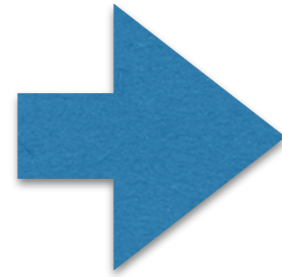
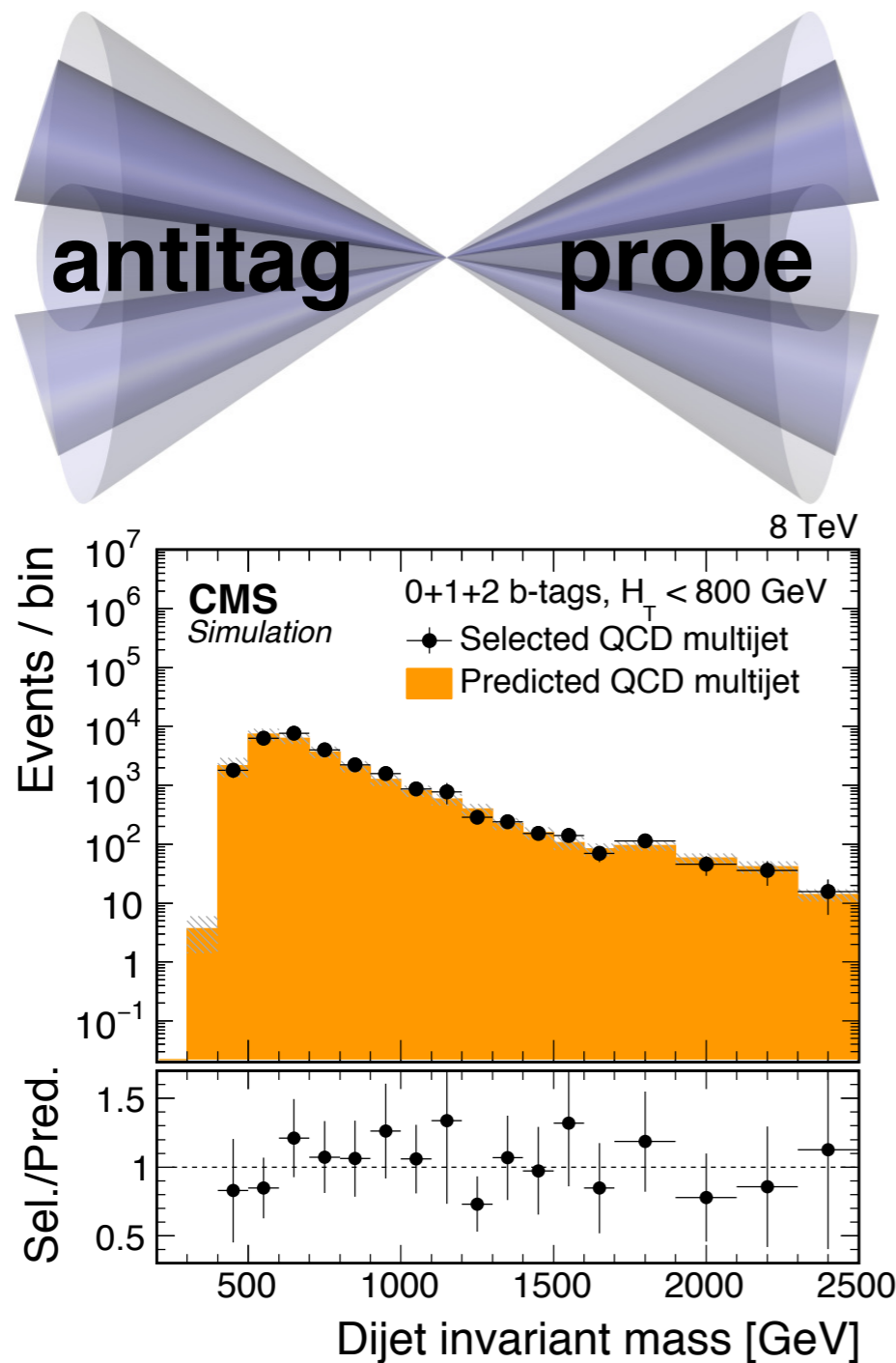
HEP Tagger - HT<800 GeV



Background estimation

- Tail of the distributions not well modeled in MC simulations
- Reduce theoretical systematic uncertainties

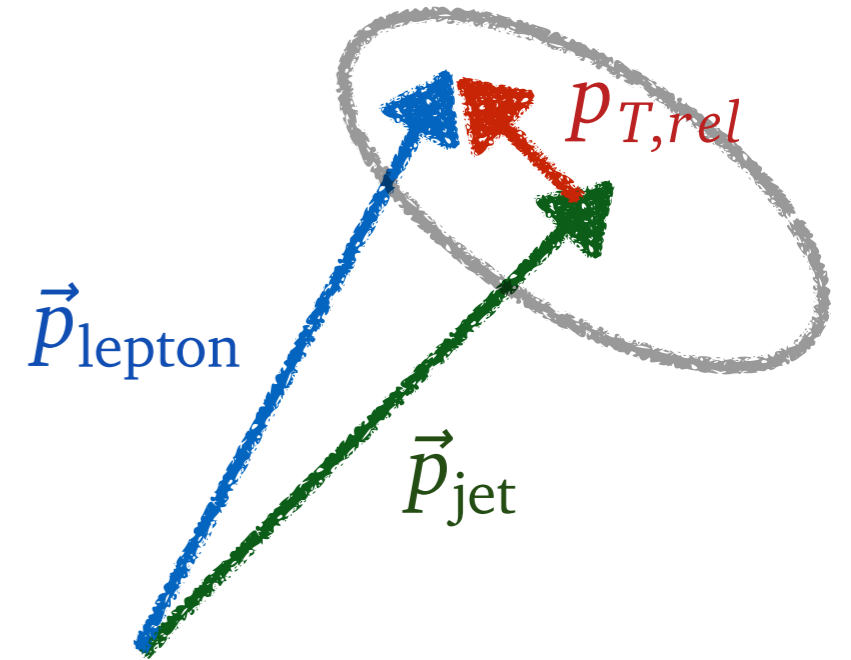
Example $Z' \rightarrow t\bar{t}$ all hadronic, **QCD background**



top+antitop: boosted semileptonic

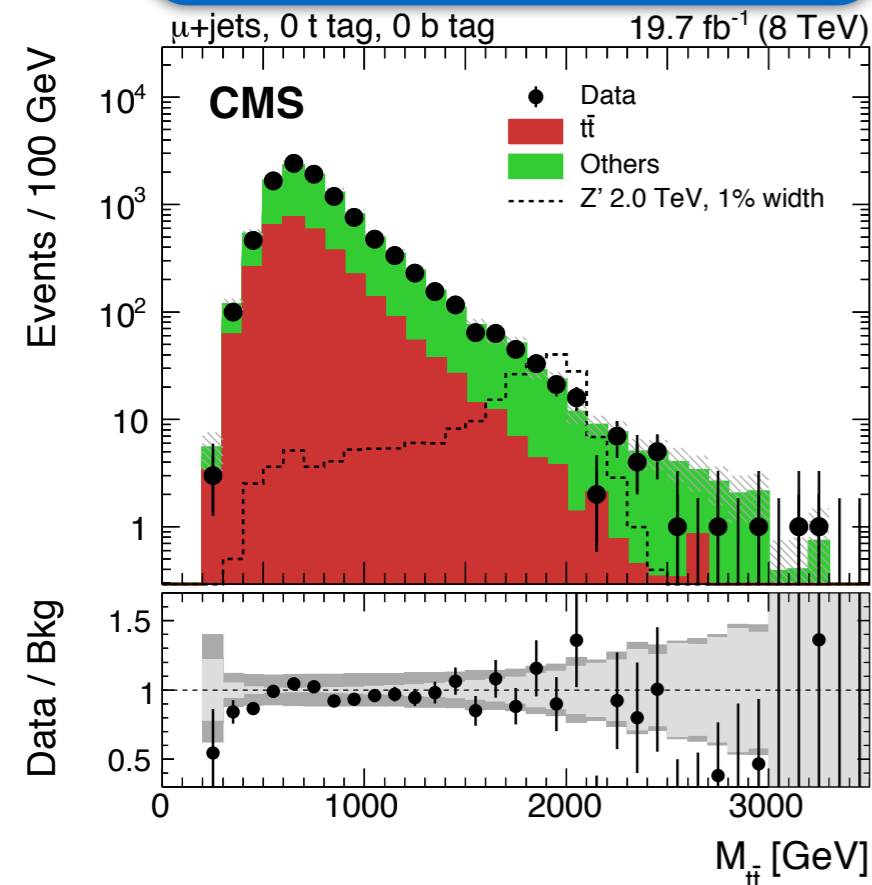
- 1 non isolated e or mu, missing ET
- at least two jets, $p_T > 150, 50$ GeV
- $p_{T,rel}$: recover non isolated leptons
- categories with CMSTopTag and b tag
- Chi squared: choose best combination

$$\chi^2 = \left[\frac{M_{top}^{lep} - \bar{m}_{top}^{lep}}{\sigma_M^{lep}} \right]^2 + \left[\frac{M_{top}^{had} - \bar{m}_{top}^{had}}{\sigma_M^{had}} \right]^2$$

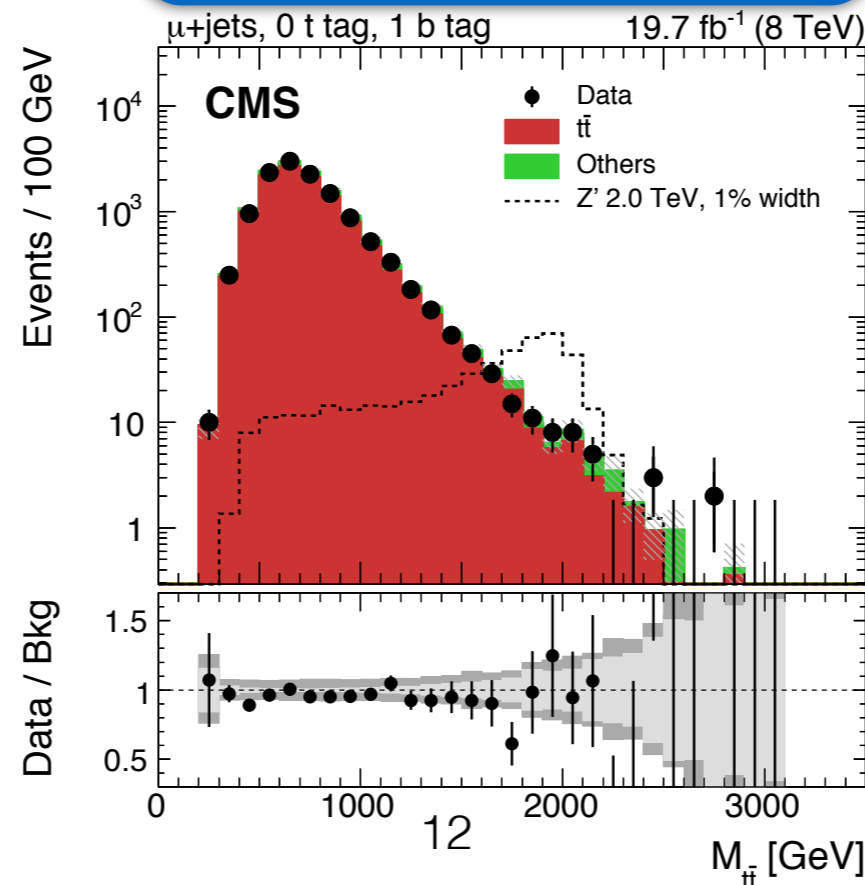


arxiv:1506.03062v1

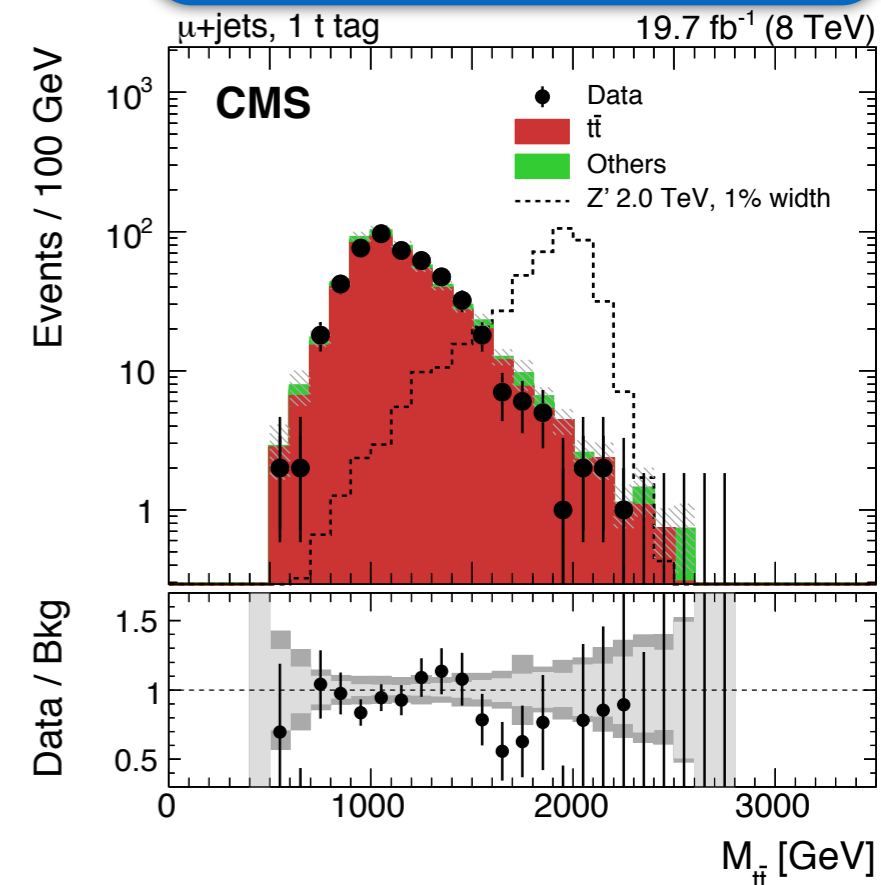
0 b tag, 0 top tag



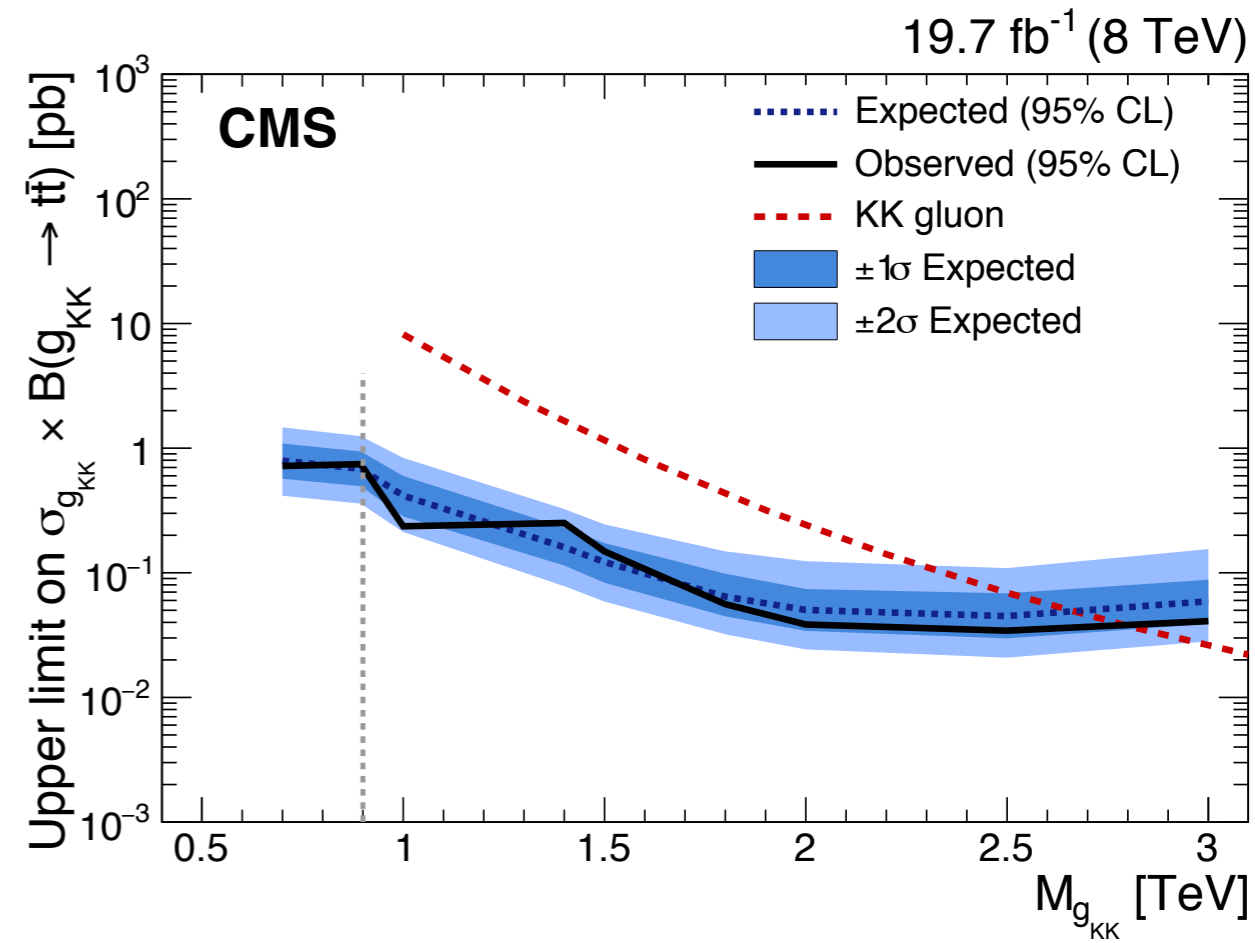
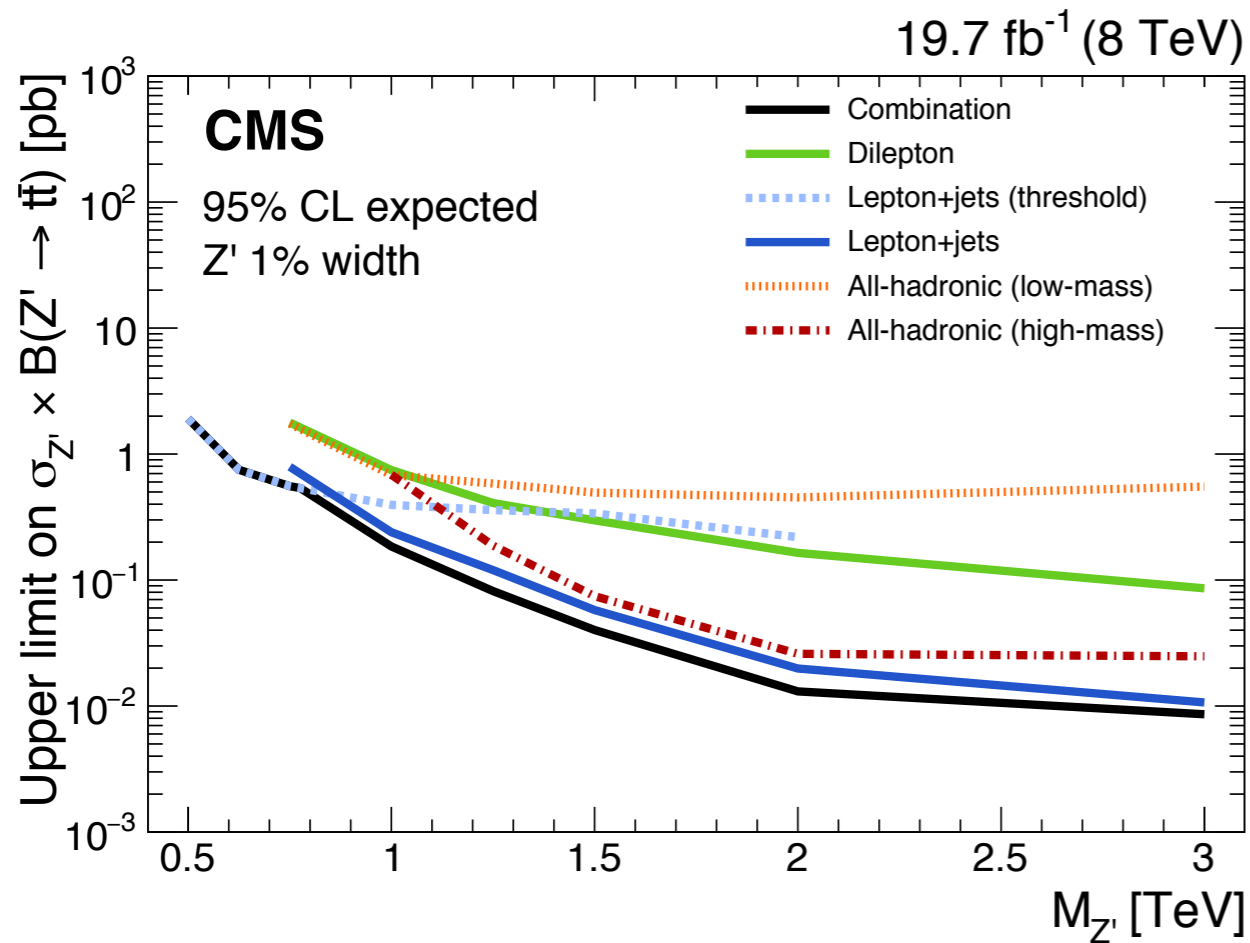
1 b tag, 0 top tag



1 top tag



Results: top+antitop

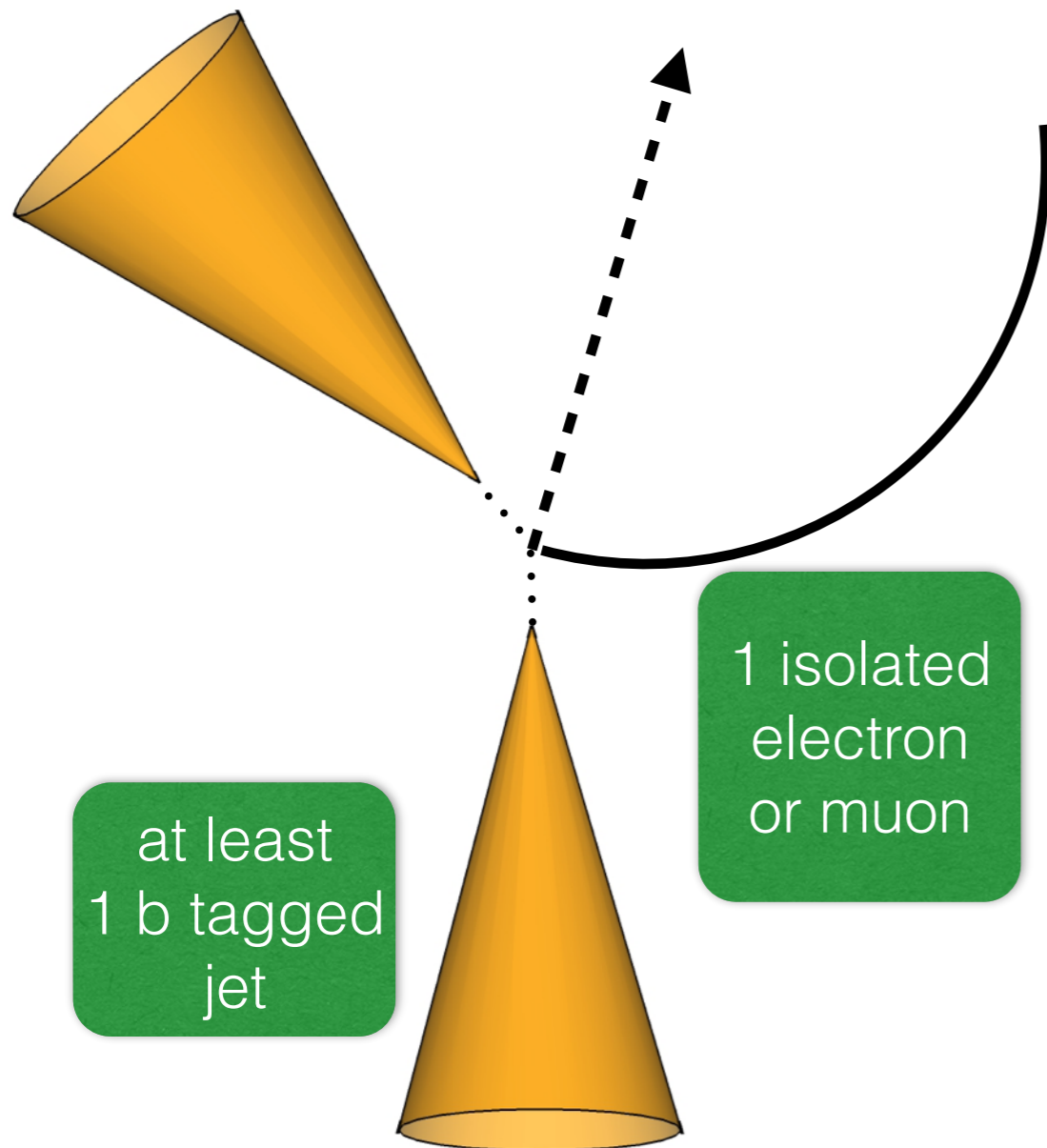


arxiv:1506.03062v1

	Mass limit [TeV]							
	Dilepton channel		Lepton+jets channel		All-hadronic channels		Combined	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
$Z', \Gamma_{Z'} / M_{Z'} = 1.2\%$	1.4	1.5	2.2	2.3	2.1	2.1	2.4	2.4
$Z', \Gamma_{Z'} / M_{Z'} = 10\%$	2.1	2.2	2.7	2.8	2.5	2.5	2.8	2.9
RS KK gluon	1.8	2.0	2.5 ¹³	2.5	2.4	2.3	2.7	2.8

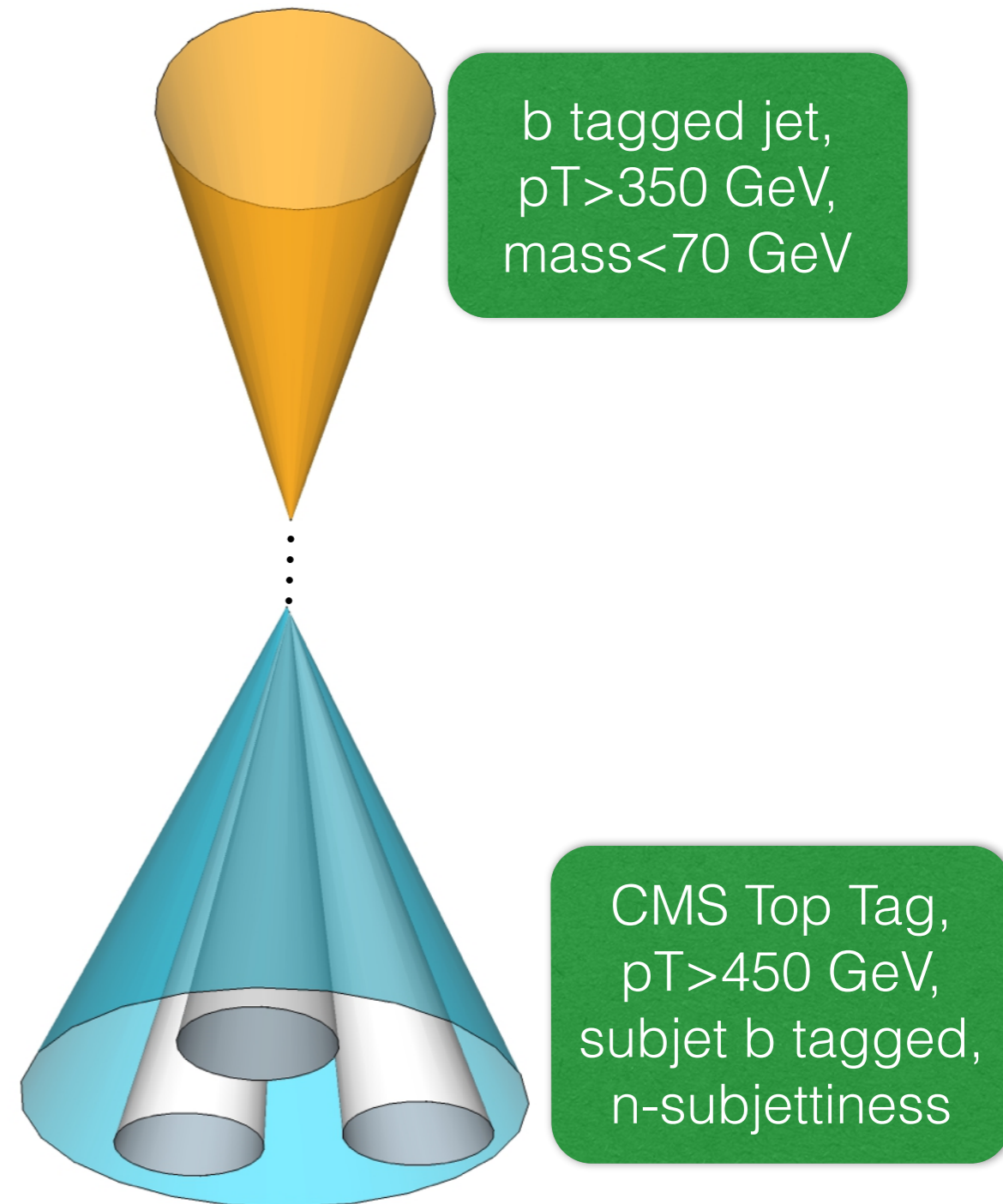
Analysis strategy top+b

lepton+jets channel

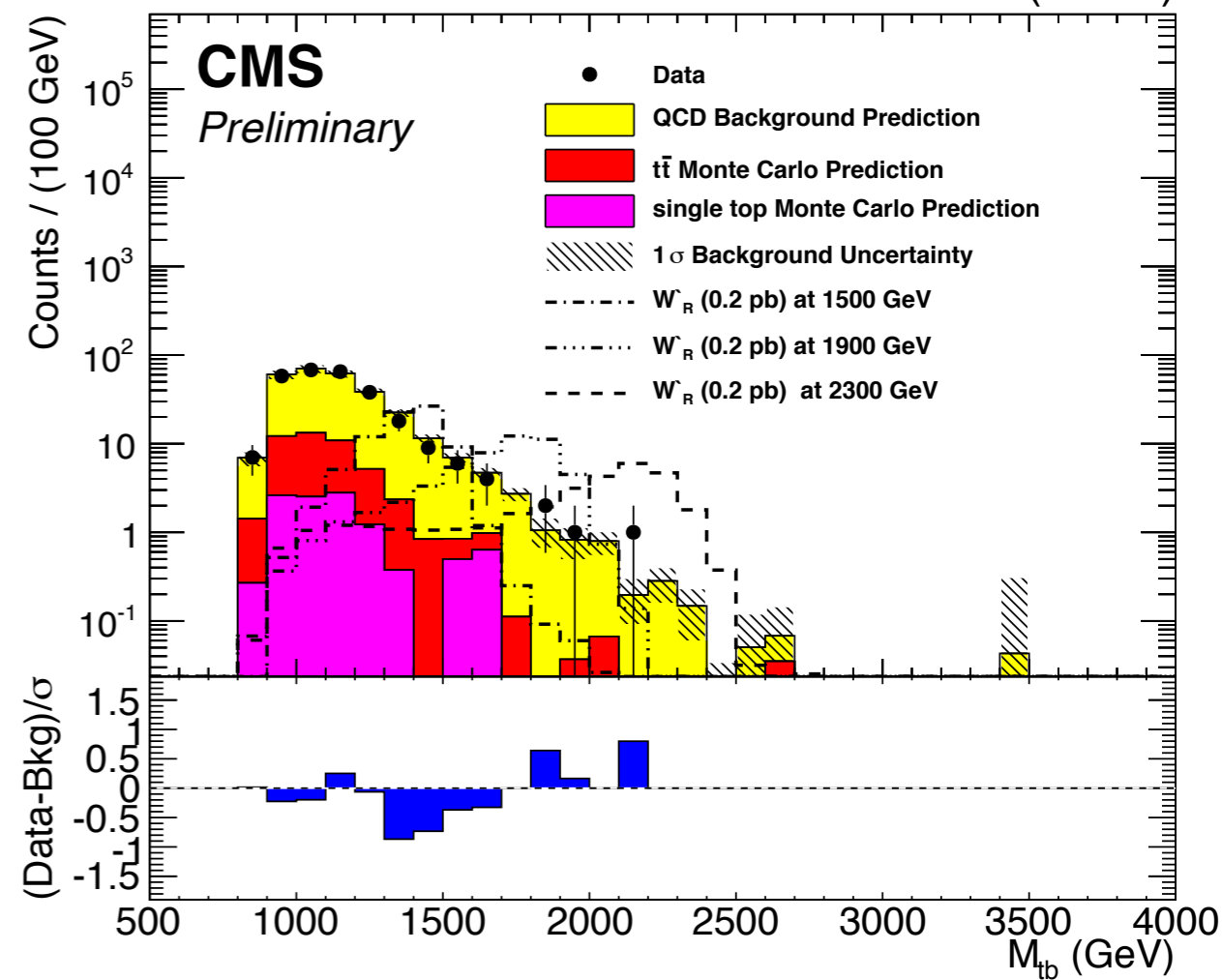
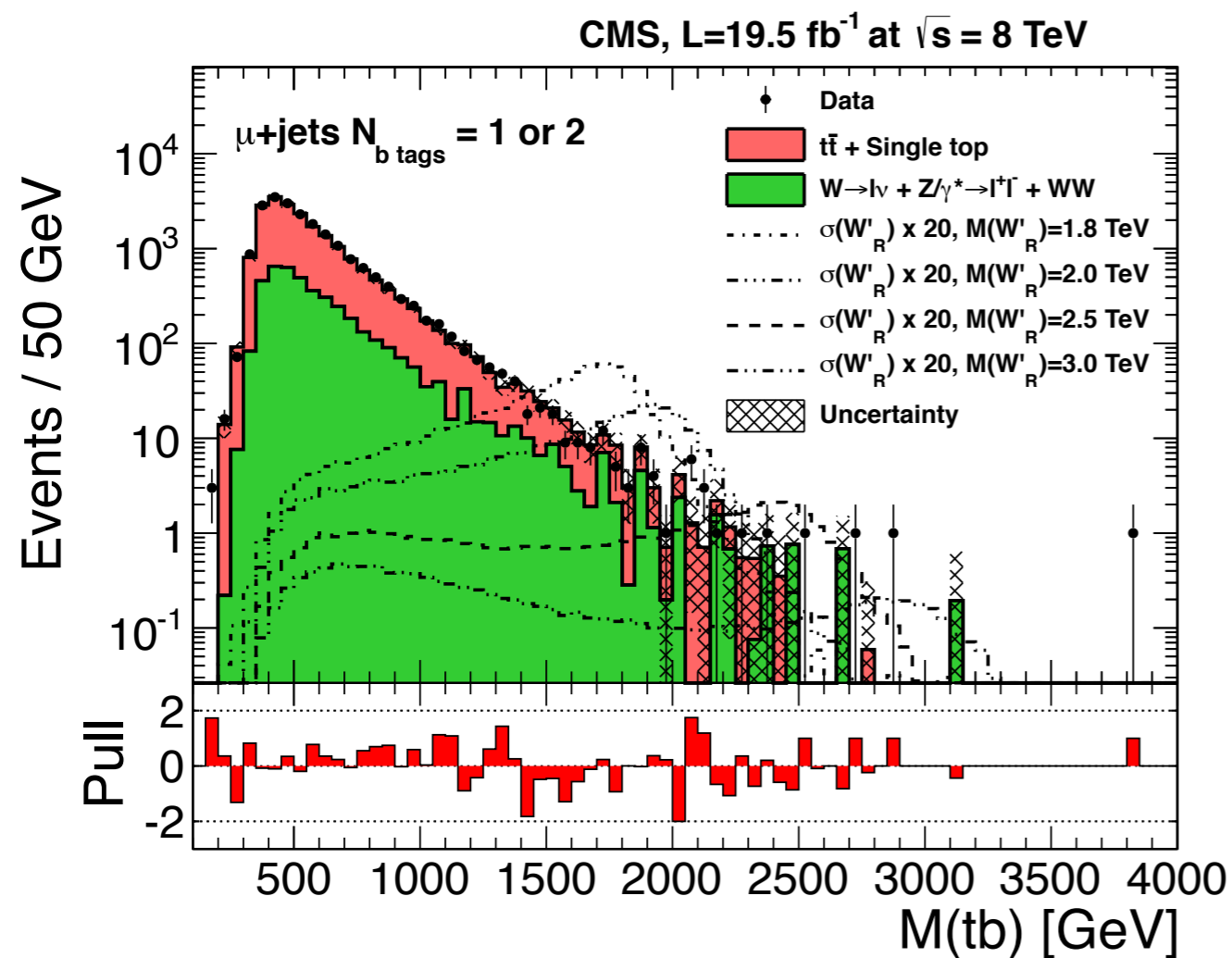
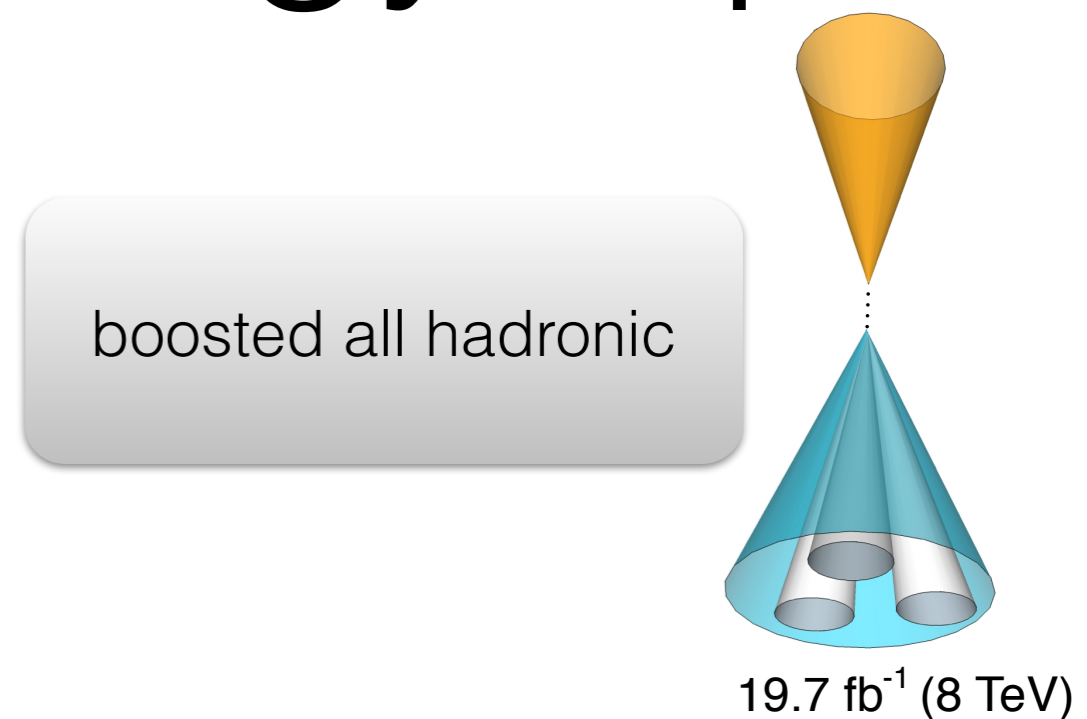
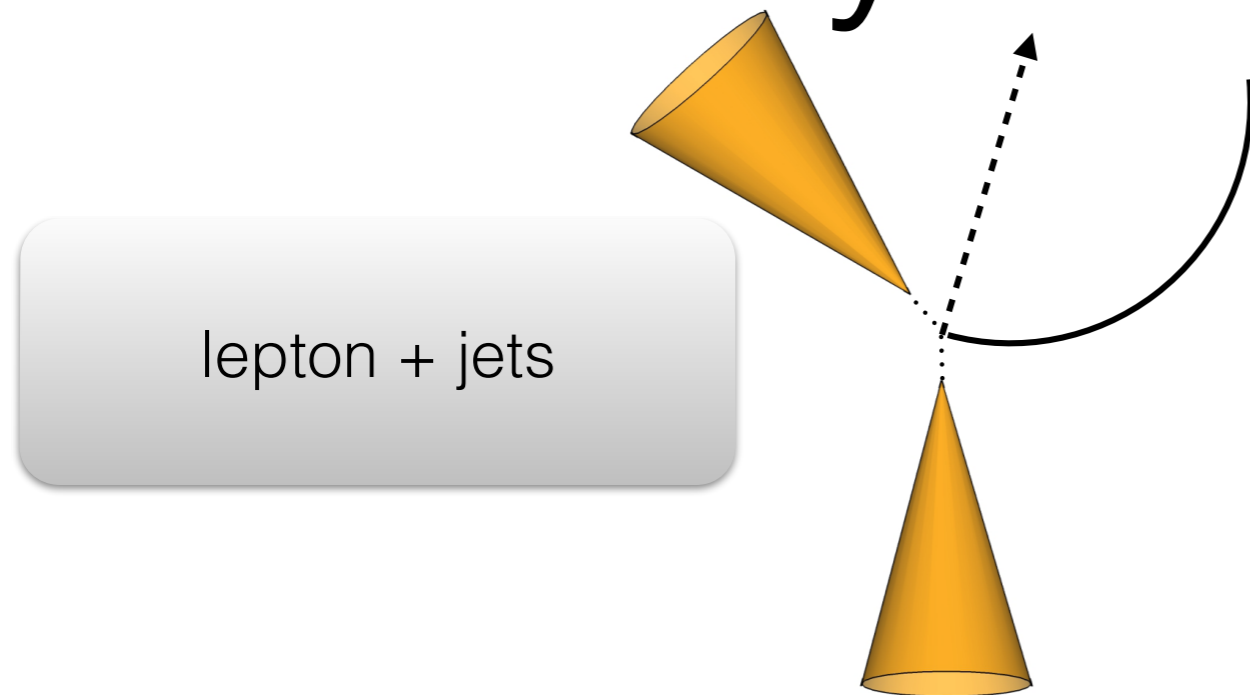


Top mass reconstructed as
lepton + neutrino + "best" jet
($p_T > 85$ GeV, $130 < \text{mass} < 210$ GeV)

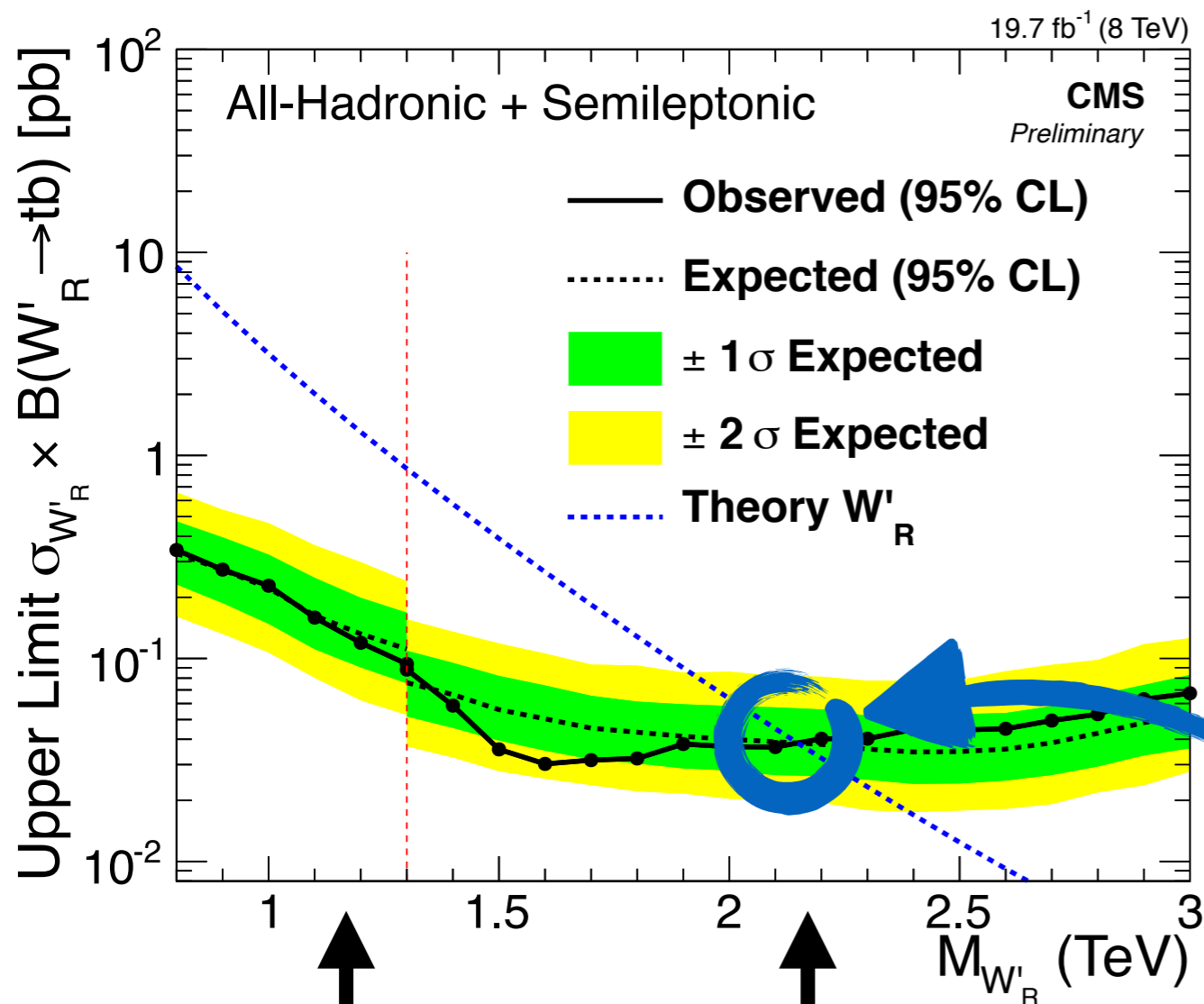
boosted all hadronic



Analysis strategy top+b



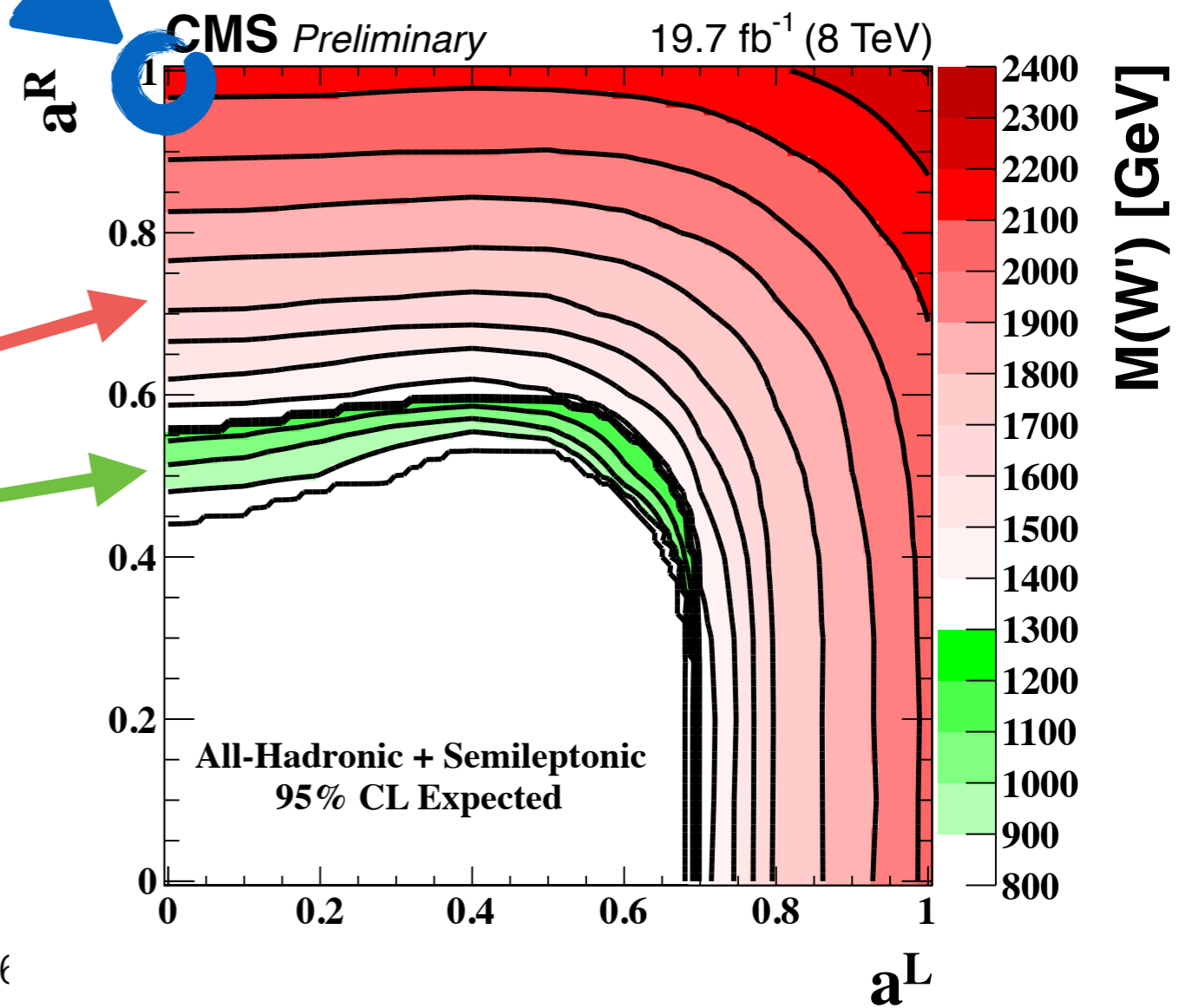
Results: top+b



Scan over LH and RH couplings

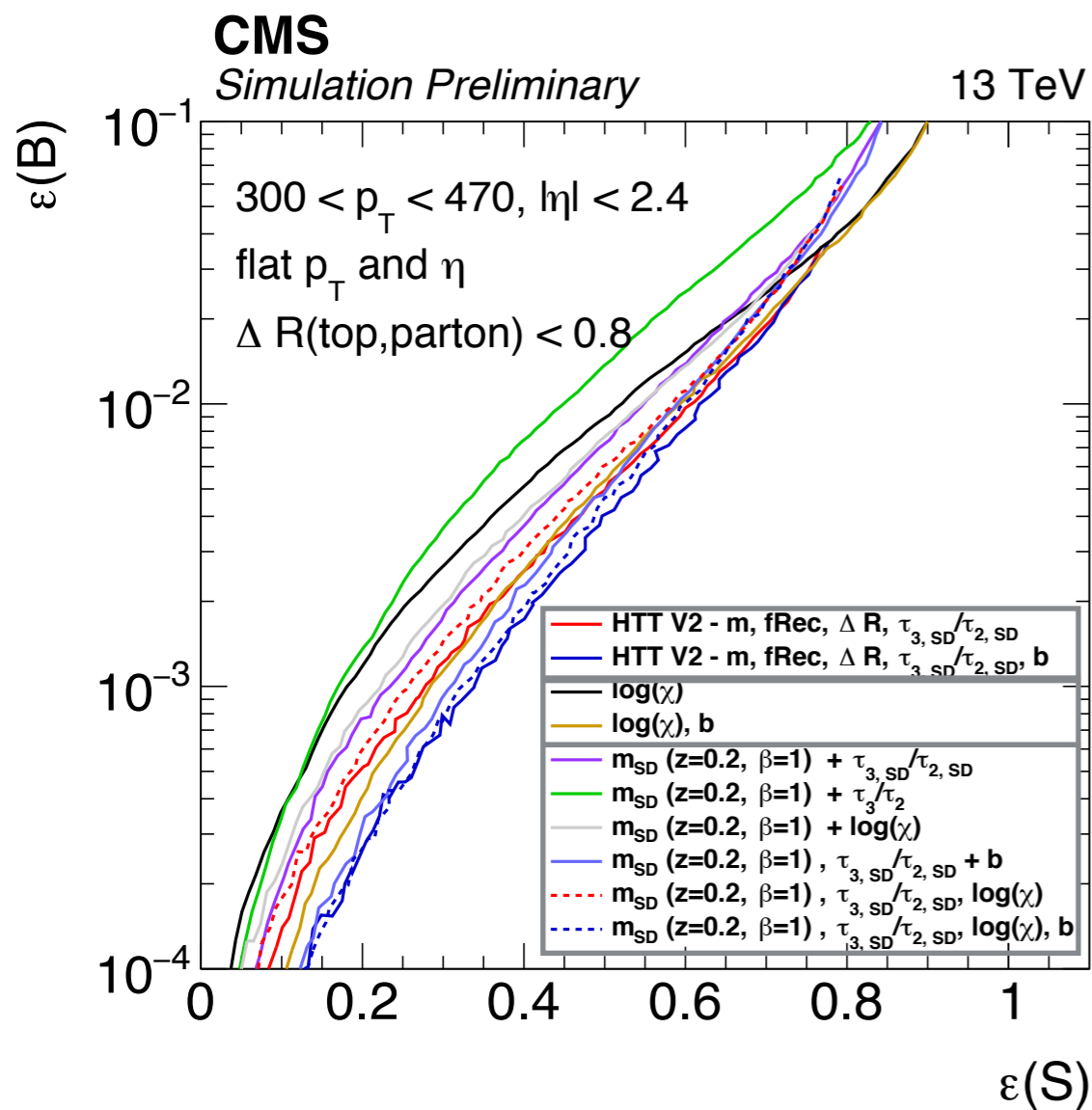
leptonic + hadronic

leptonic only



13 TeV outlook

Improved tools



HEPTopTagger
using CA $R=1.5$

Shower deconstruction
similar to ME methods

Soft-drop mass tagger
using AK $R=0.8$

high level trigger based on
jet substructure

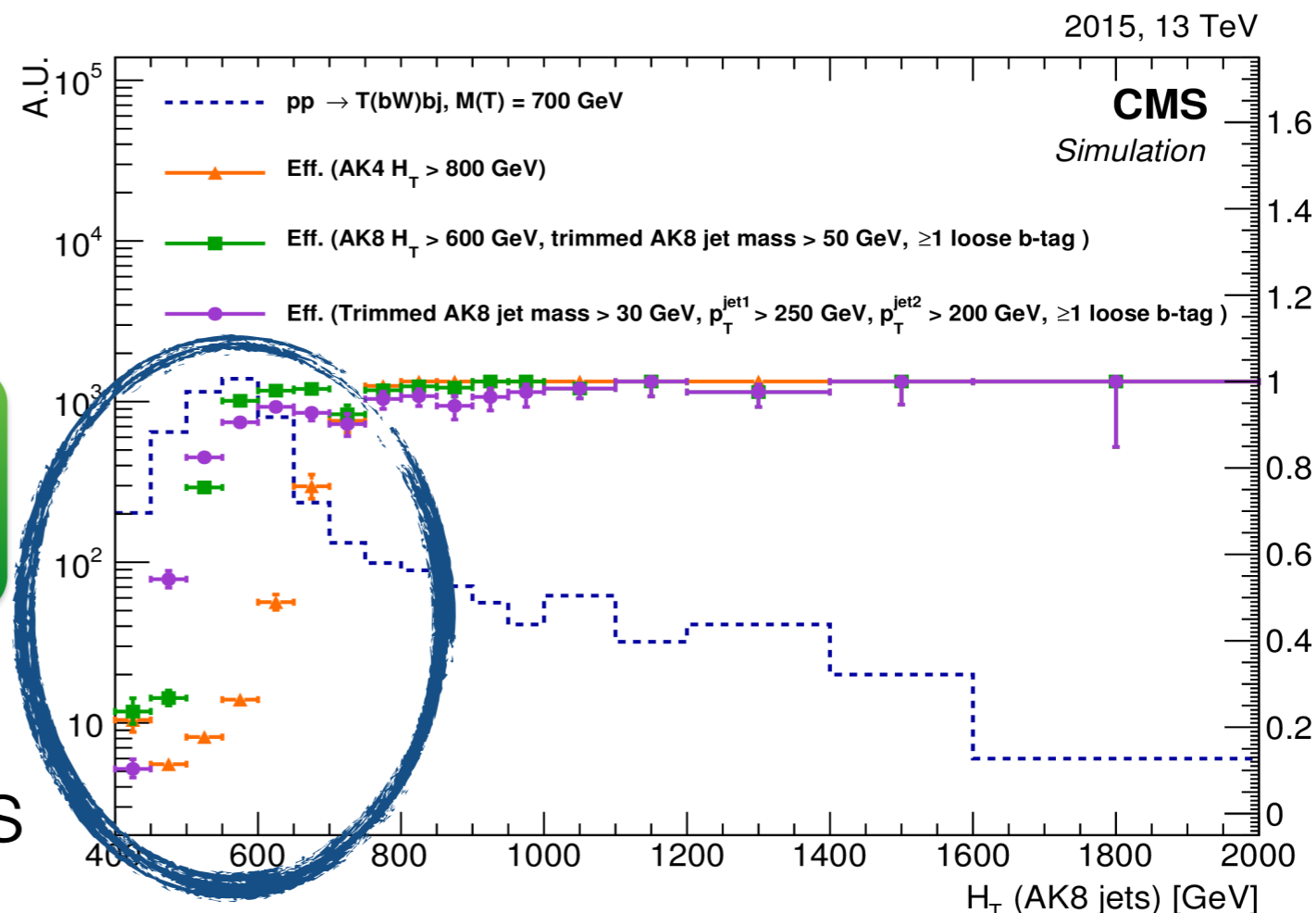
base HT
trigger

AK8+HT
trim. mass
btag

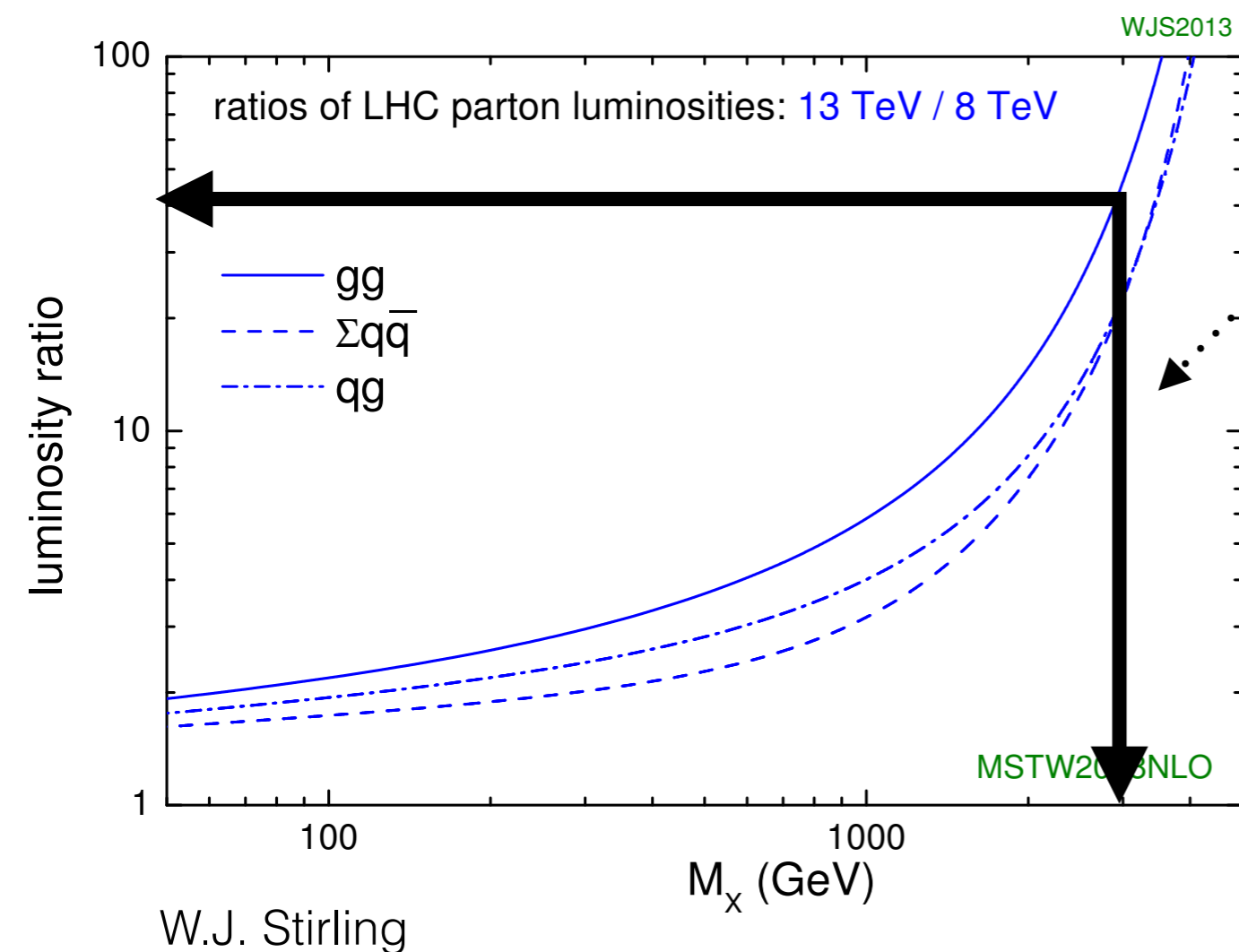
2xAK8+HT
trim. mass
btag

performance gain

for low mass all-had searches



Strategy for searches



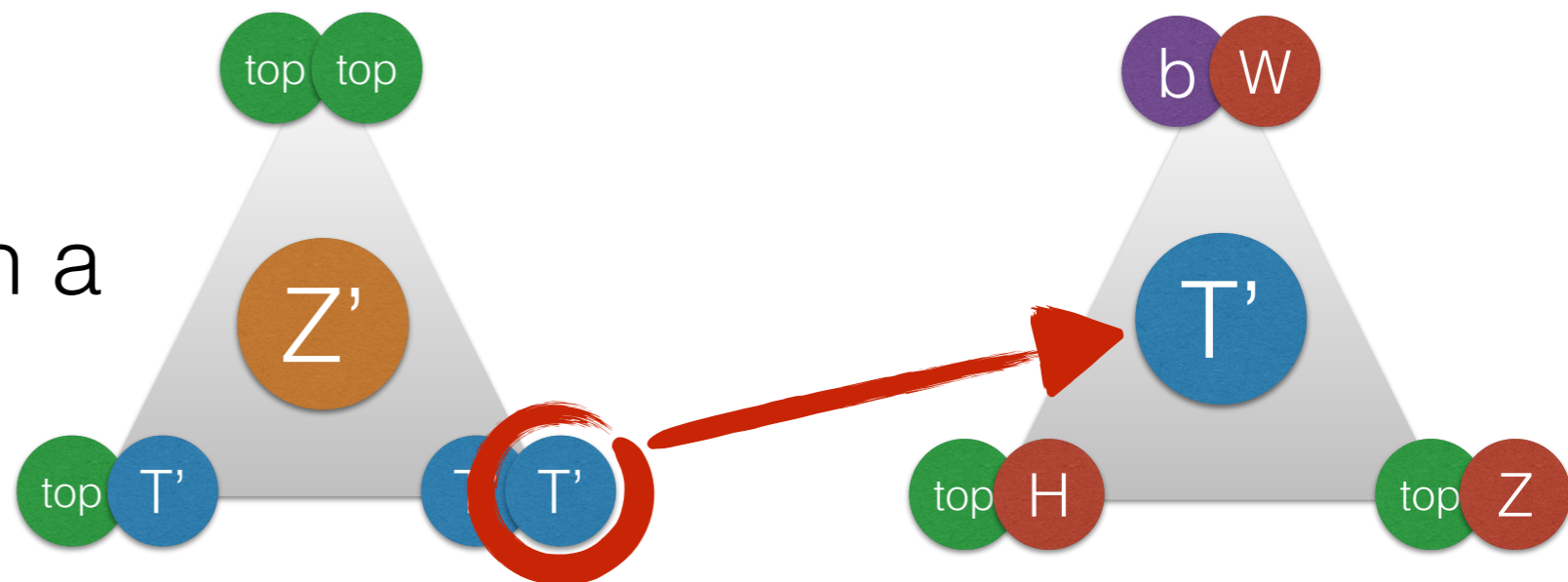
parton luminosities give
big boost to cross section
of multi TeV resonances

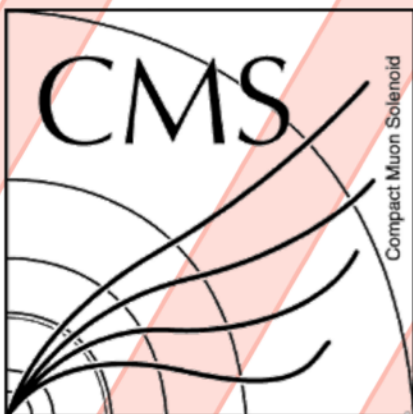
these analyses are sensitive
to high masses with few fb^{-1}
of 13 TeV data

NOTE: this affects backgrounds too

New ideas:

what if the Z' can decay in a
vector-like T' ?





CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 07:25:11 2015 CEST
Run/Event: 251562 / 111132974
Lumi section: 122
Orbit/Crossing: 31722792 / 2253

Subjet 4,
et = 133 GeV
eta = -0.47
phi = -1.56

Subjet 1,
et = 275 GeV
eta = 2.08
phi = 1.94

Subjet 5,
et = 402 GeV
eta = -0.86
phi = -1.44

Subjet 2,
et = 49 GeV
eta = 1.64
phi = 1.64

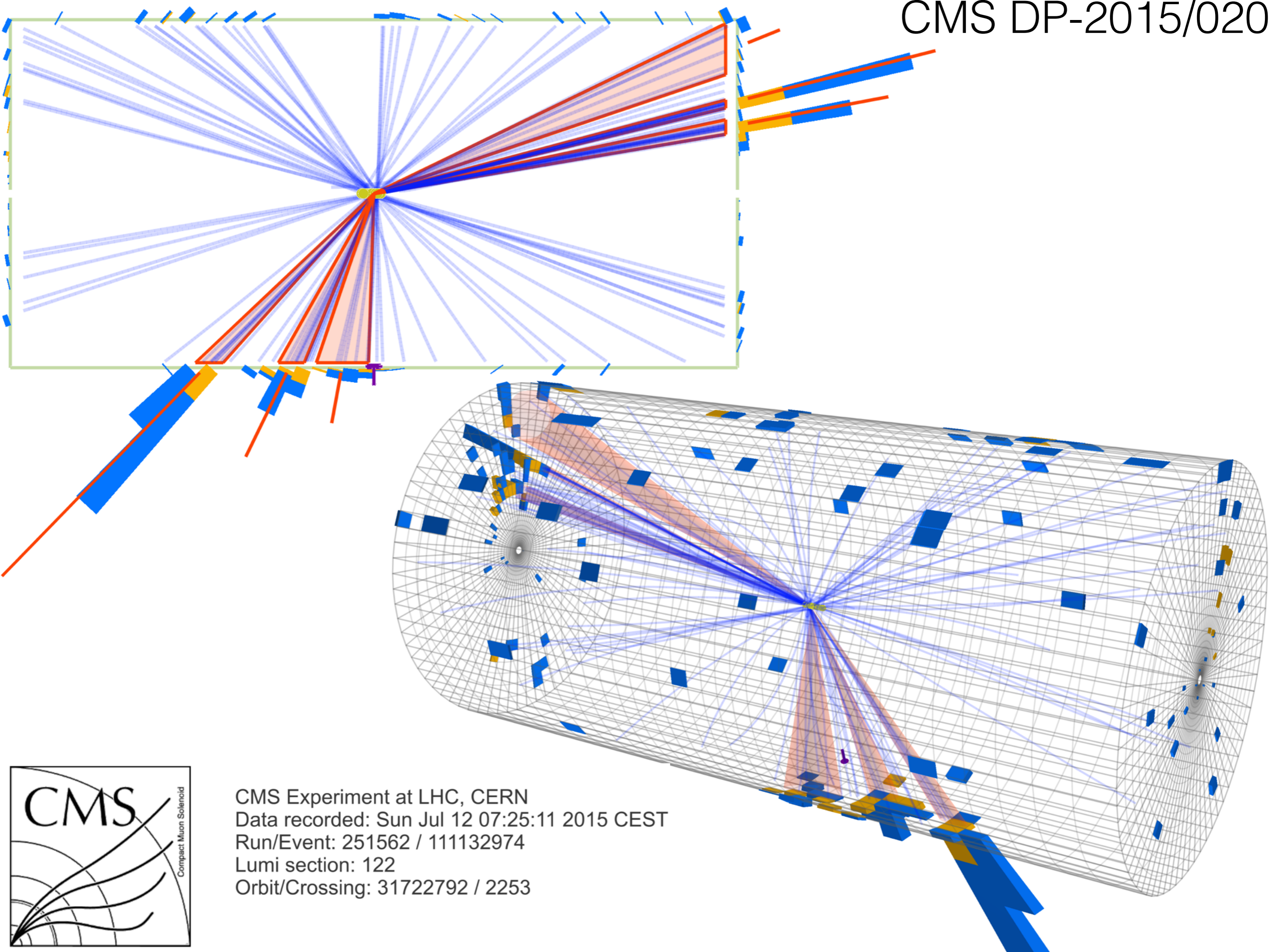
Subjet 3,
et = 203 GeV
eta = 2.37
phi = 1.48

Top jet candidate 1
pt = 488 GeV
eta = 2.22
phi = 1.74
mass = 176 GeV

Top jet candidate 2,
pt = 613 GeV
eta = -0.70
phi = -1.46
mass = 177 GeV

Subjet 6,
et = 73 GeV
eta = -0.18
phi = -1.30

ttbar event candidate



CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 07:25:11 2015 CEST
Run/Event: 251562 / 111132974
Lumi section: 122
Orbit/Crossing: 31722792 / 2253

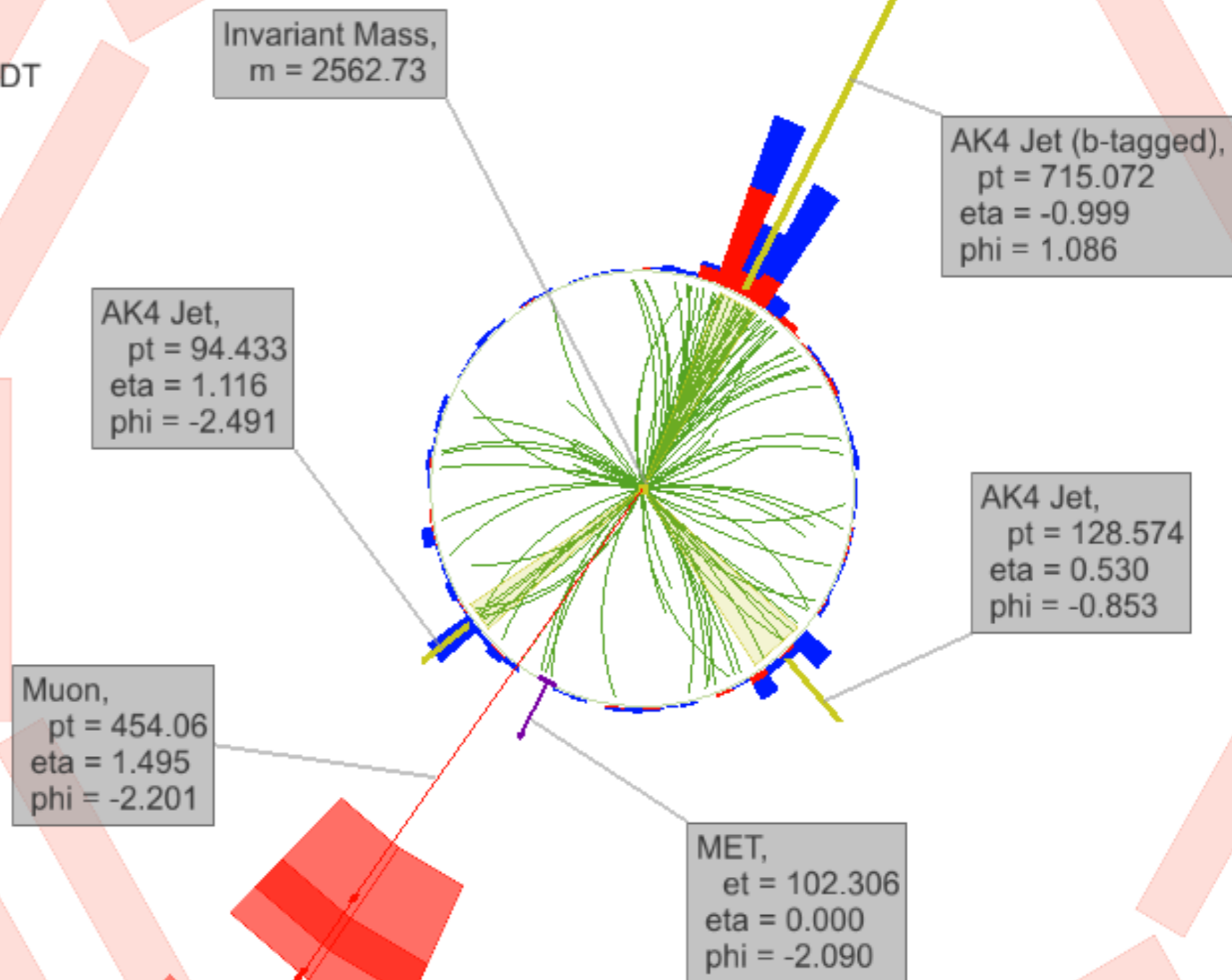
CMS

Compact Muon Solenoid



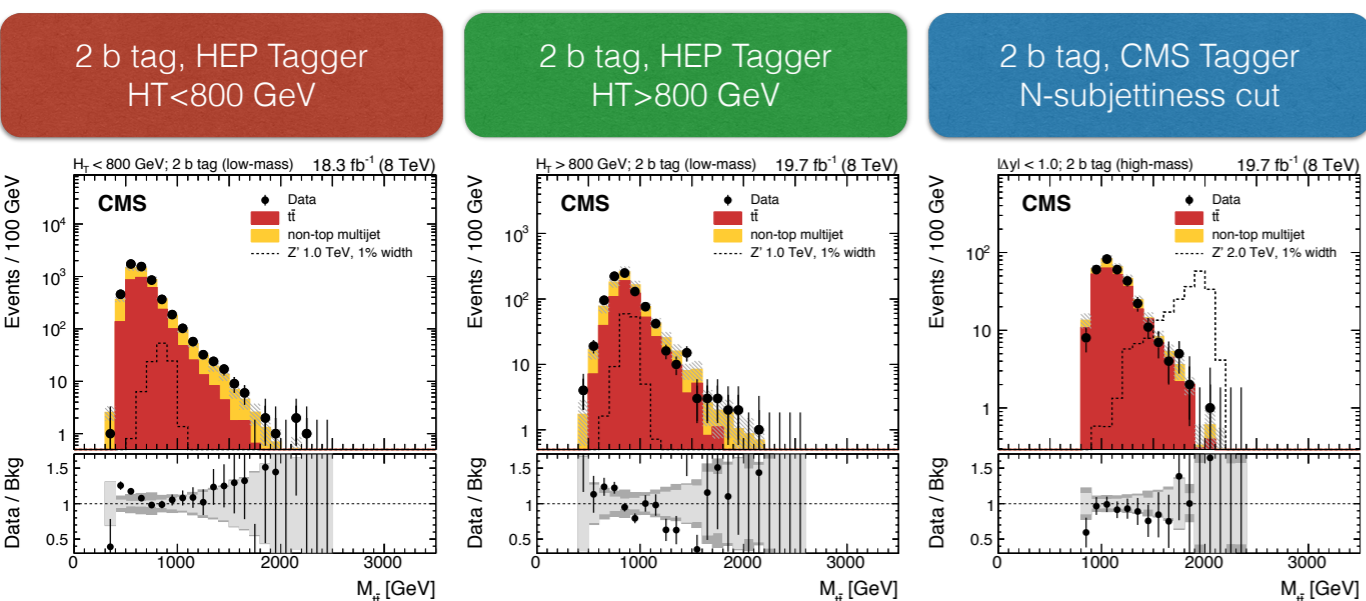
top+b event candidate

CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 02:10:08 2015 CDT
Run/Event: 251562 / 348224693
Lumi section: 392

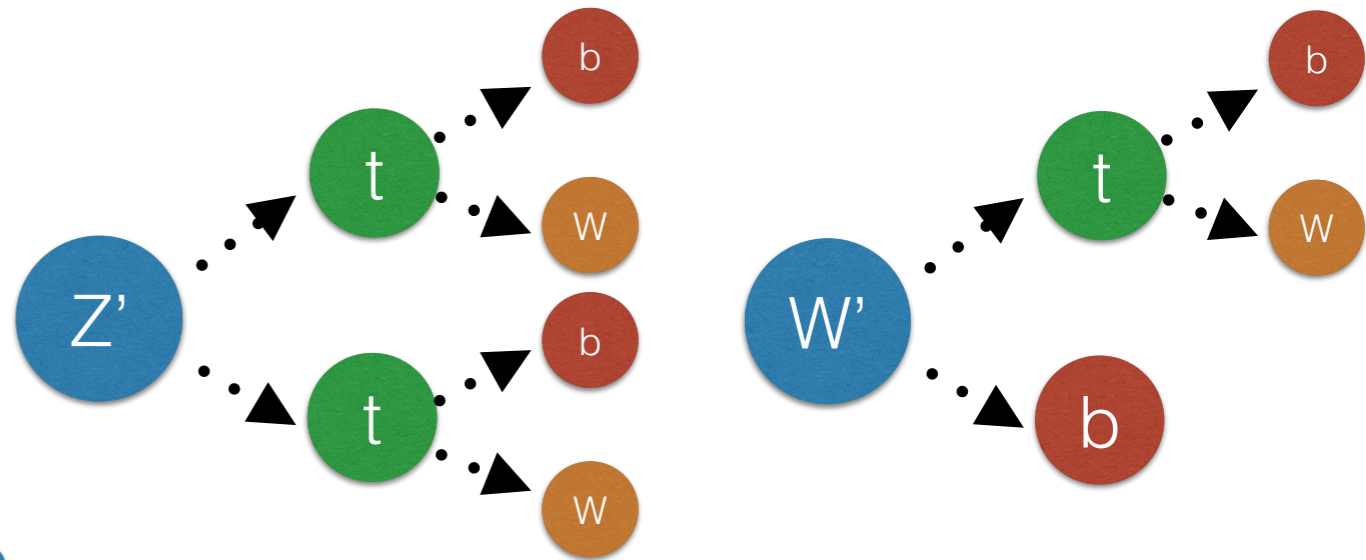
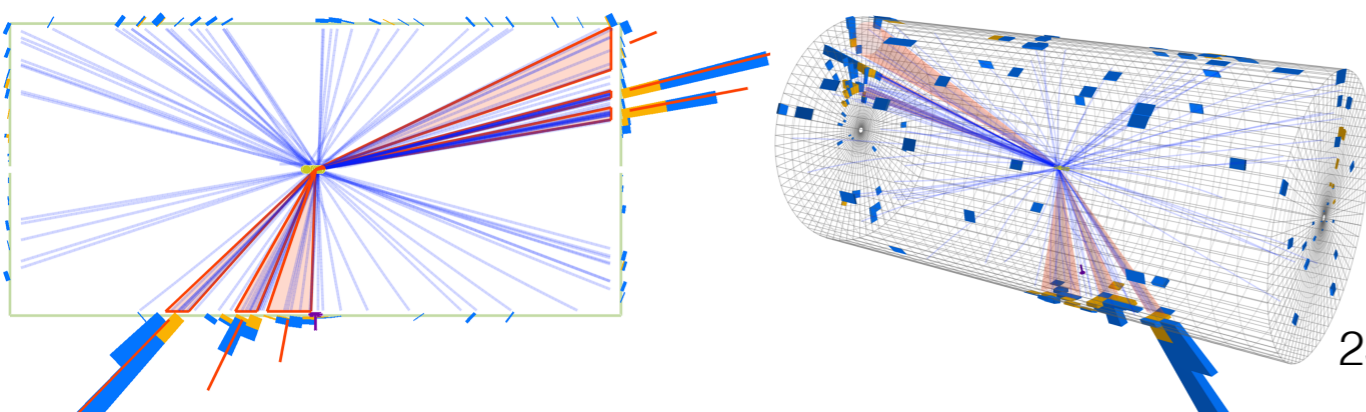


Conclusions

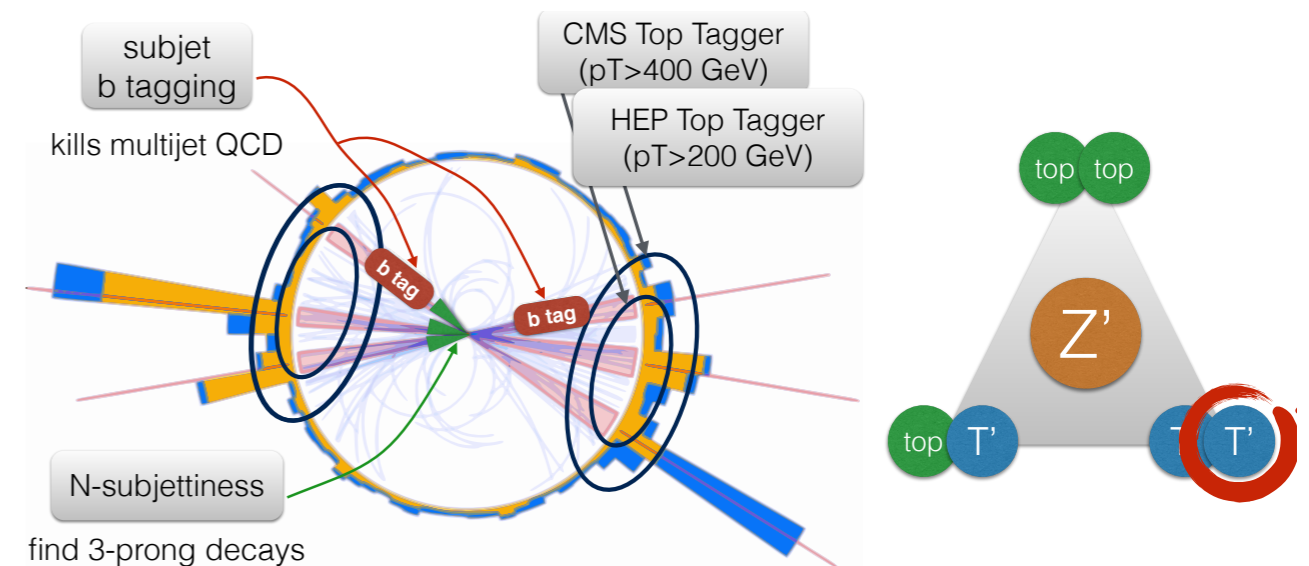
$t\bar{t}$ and $t\bar{b}$ resonances
natural probe to new physics



improved reconstruction
tools and new ideas



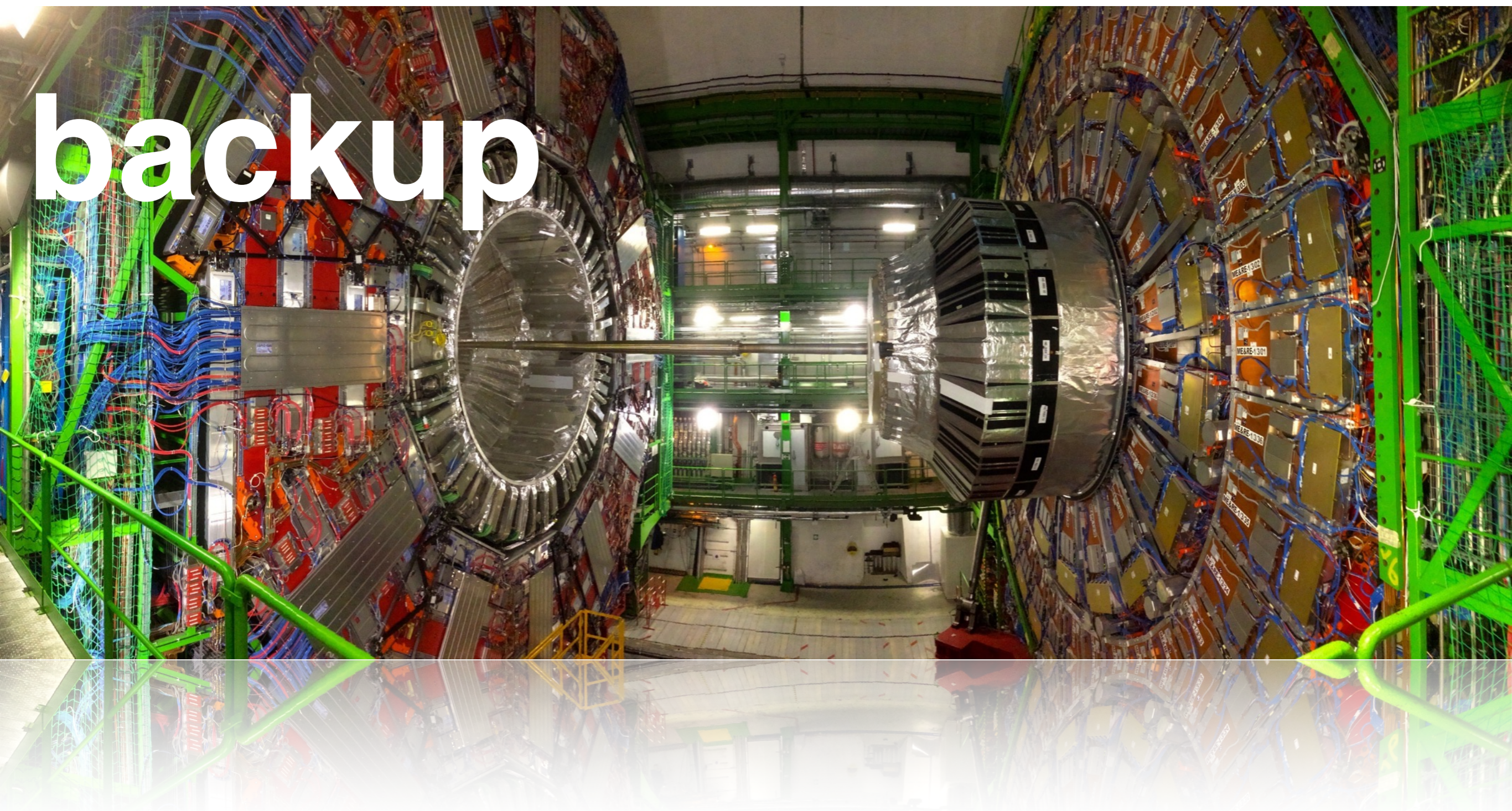
using 8 TeV data no evidence
up to ~ 2.9 (2.15) TeV for Z' (W')



“early” analyses: very sensitive
to high mass with few fb^{-1}



Thanks for the attention



120, 40 GeV -> leading and subleading

W+jets scale factor -> 0 btag selection

ttbar scale factor -> geq 2 btag, 400<m<750

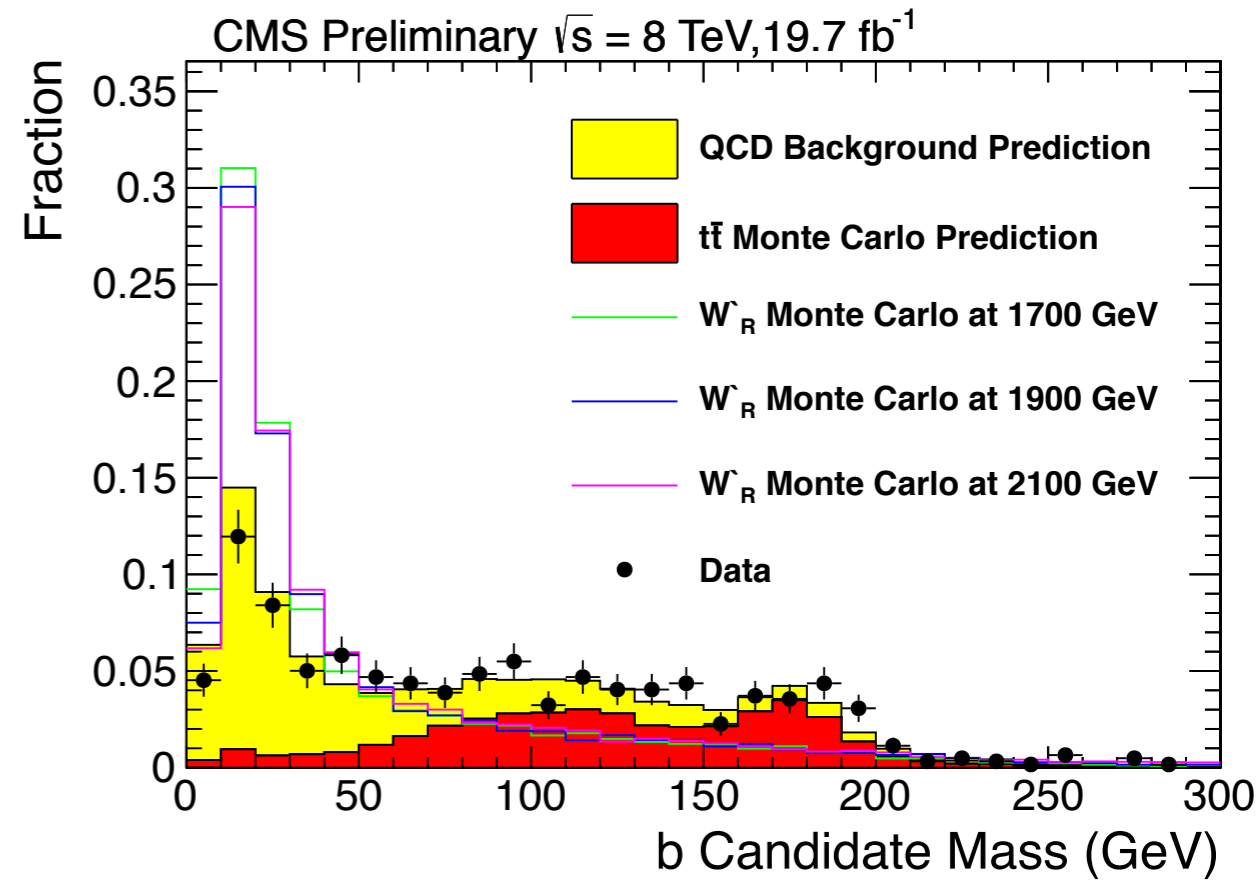
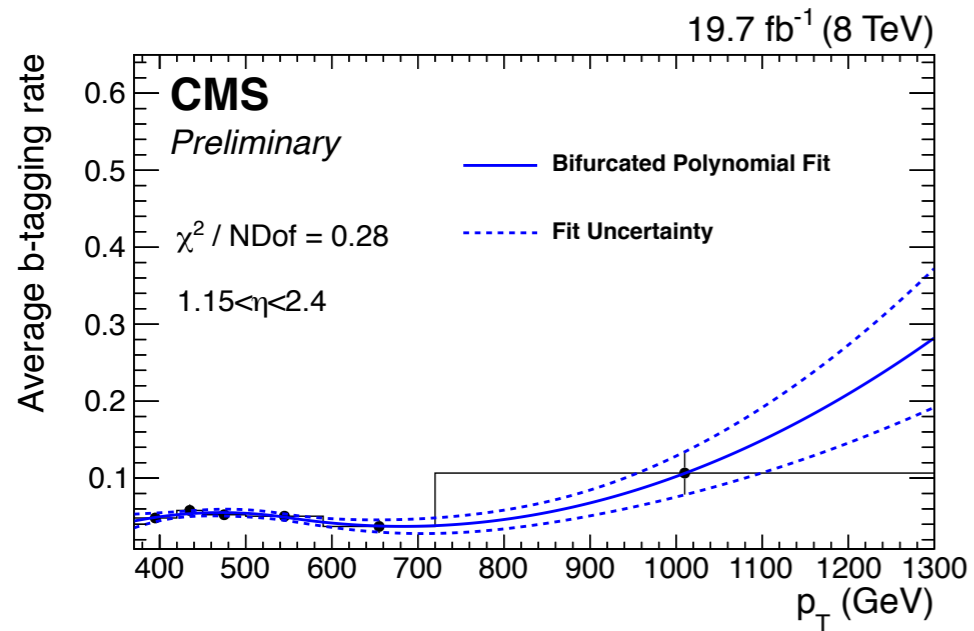
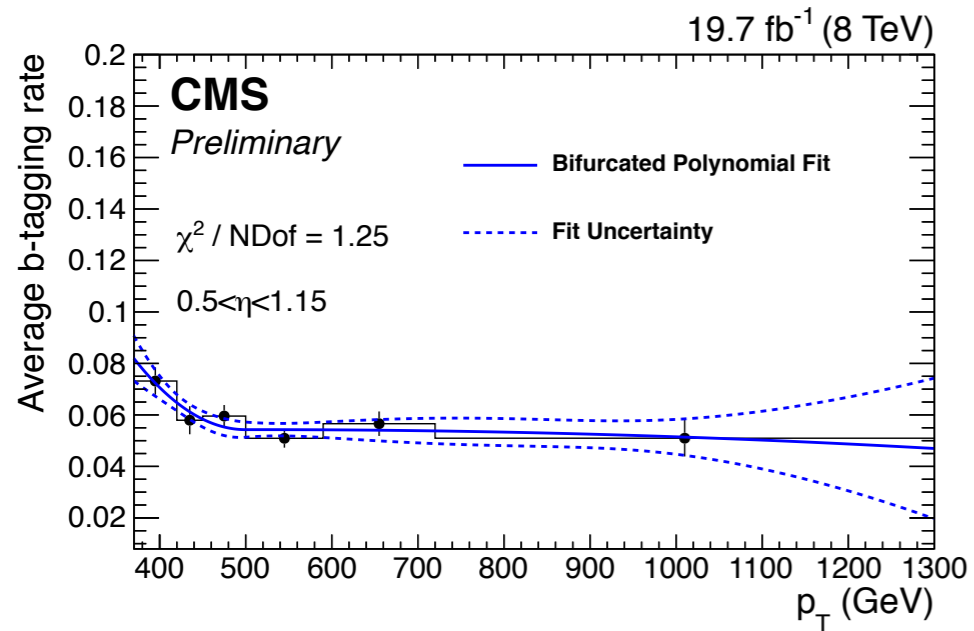
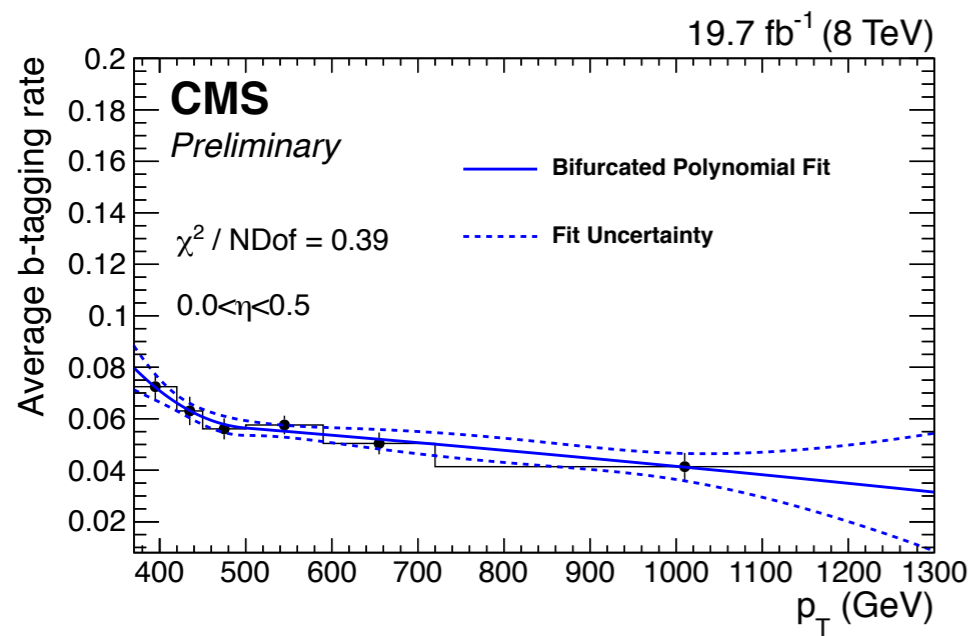
$$\mathcal{L} = \frac{V_{fifj}}{2\sqrt{2}} g_w \bar{f}_i \gamma_\mu (a_{fifj}^R (1 + \gamma^5) + a_{fifj}^L (1 - \gamma^5)) W'^\mu f_j + \text{h.c.},$$

$$\begin{aligned} \sigma &= \sigma_{\text{SM}} + a_{\text{ud}}^L a_{\text{tb}}^L (\sigma_L - \sigma_R - \sigma_{\text{SM}}) \\ &+ \left(\left(a_{\text{ud}}^L a_{\text{tb}}^L \right)^2 + \left(a_{\text{ud}}^R a_{\text{tb}}^R \right)^2 \right) \sigma_R \\ &+ \frac{1}{2} \left(\left(a_{\text{ud}}^L a_{\text{tb}}^R \right)^2 + \left(a_{\text{ud}}^R a_{\text{tb}}^L \right)^2 \right) (\sigma_{\text{LR}} - \sigma_L - \sigma_R). \end{aligned}$$

- **Jet Mass** $140 \text{ GeV} < m_{\text{jet}} < 250 \text{ GeV}$ - The mass of the CA jet is required to be consistent with the top quark mass.
- **Number of Subjets** $N_{\text{subjets}} > 2$ - The number of subjets found by the algorithm must be at least 3.
- **Minimum Pairwise Mass** $m_{\text{min}} > 50 \text{ GeV}$ - The three highest p_T subjets are taken pairwise, and each pair's invariant mass is calculated. m_{min} is the mass of the pair with the lowest invariant mass. The minimum pairwise mass must be close to the W boson mass.

$$d_0 = \sum_i p_{T_i} R_0$$

$$\tau_N = \frac{1}{d_0} \sum_i p_{T_i} \min\{\Delta R_{1,i}, \Delta R_{2,i}, \dots, \Delta R_{N,i}\}$$



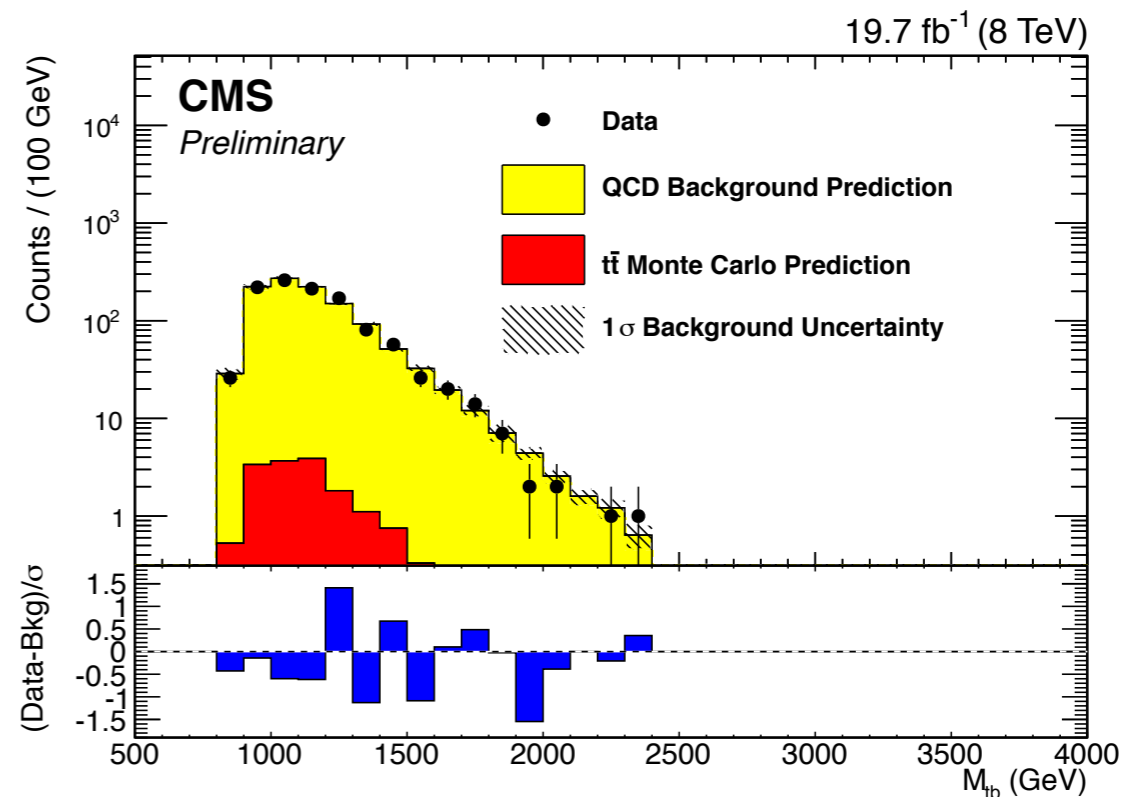
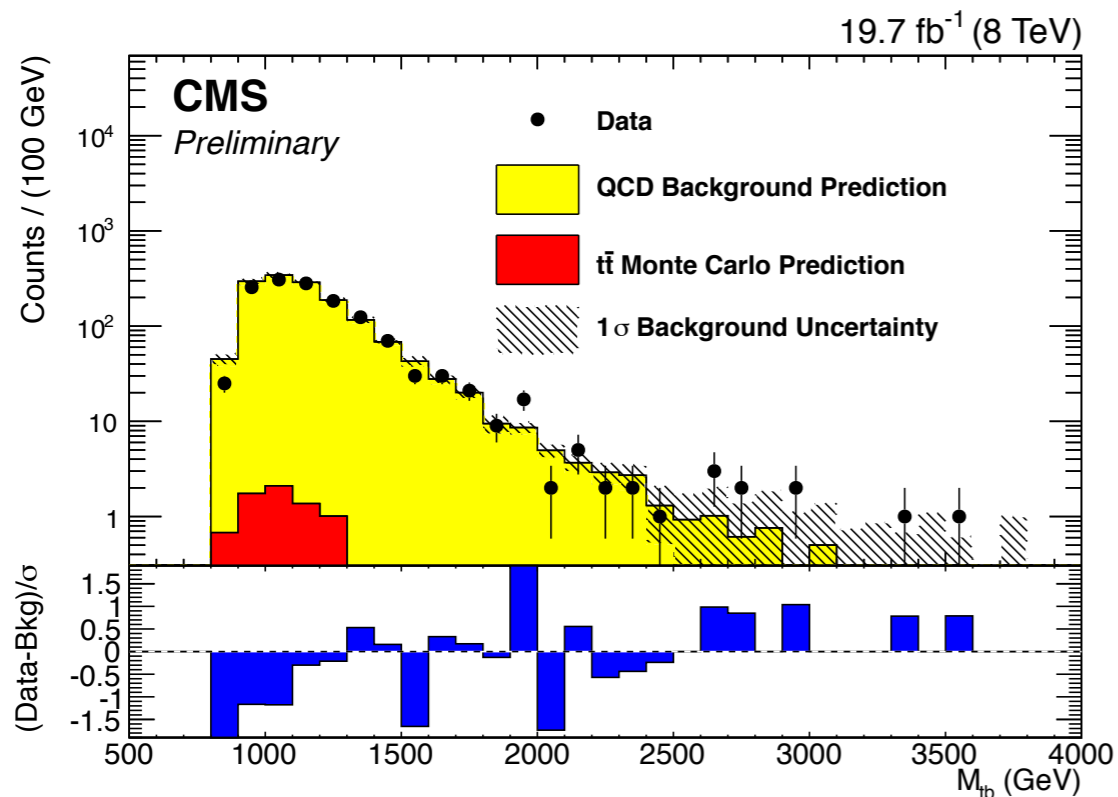
$$140 < m_{\text{jet}} < 250 \text{ GeV}$$

$$N_{\text{subjects}} \leq 2$$

$$SJ_{\text{CSVMAX}} \geq 0.679$$


- Jet Mass $140 \text{ GeV} < m_{\text{jet}} < 250 \text{ GeV}$
- Number of Subjets $N_{\text{subjets}} > 2$
- Minimum Pairwise Mass $m_{\text{min}} \leq 50 \text{ GeV}$
- N-subjettiness $\tau_3/\tau_2 \geq 0.55$
- Subject b-Tagging $SJ_{\text{CSVMAX}} \geq 0.679$

- Jet Mass $140 \text{ GeV} < m_{\text{jet}} < 250 \text{ GeV}$
- Number of Subjets $N_{\text{subjets}} > 2$
- Minimum Pairwise Mass $m_{\text{min}} > 50 \text{ GeV}$
- N-subjettiness $\tau_3/\tau_2 < 0.55$
- Subject b-Tagging $SJ_{\text{CSVMAX}} \leq 0.679$

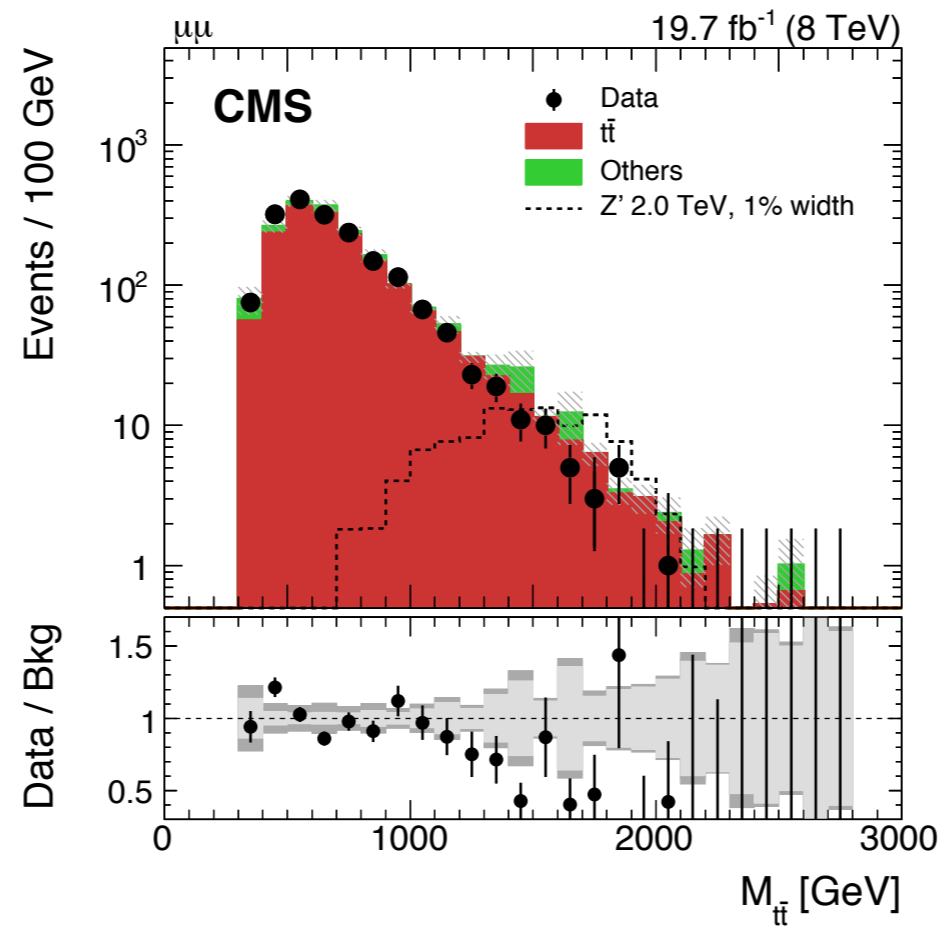
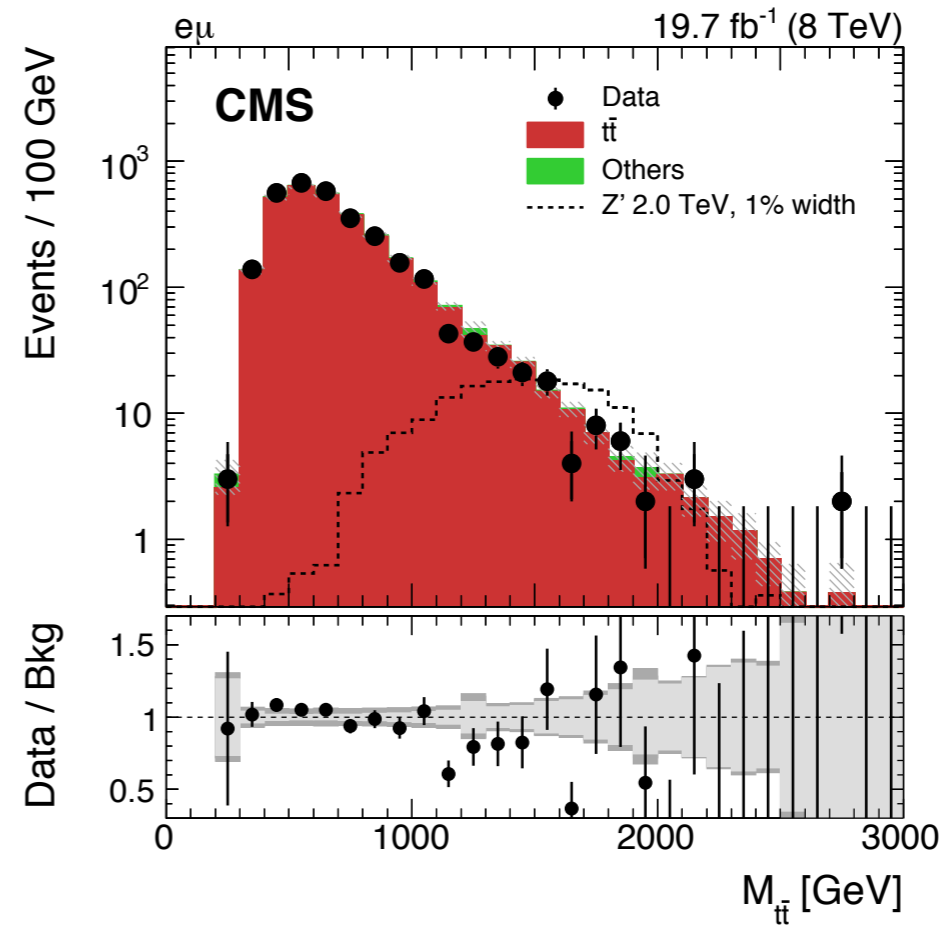
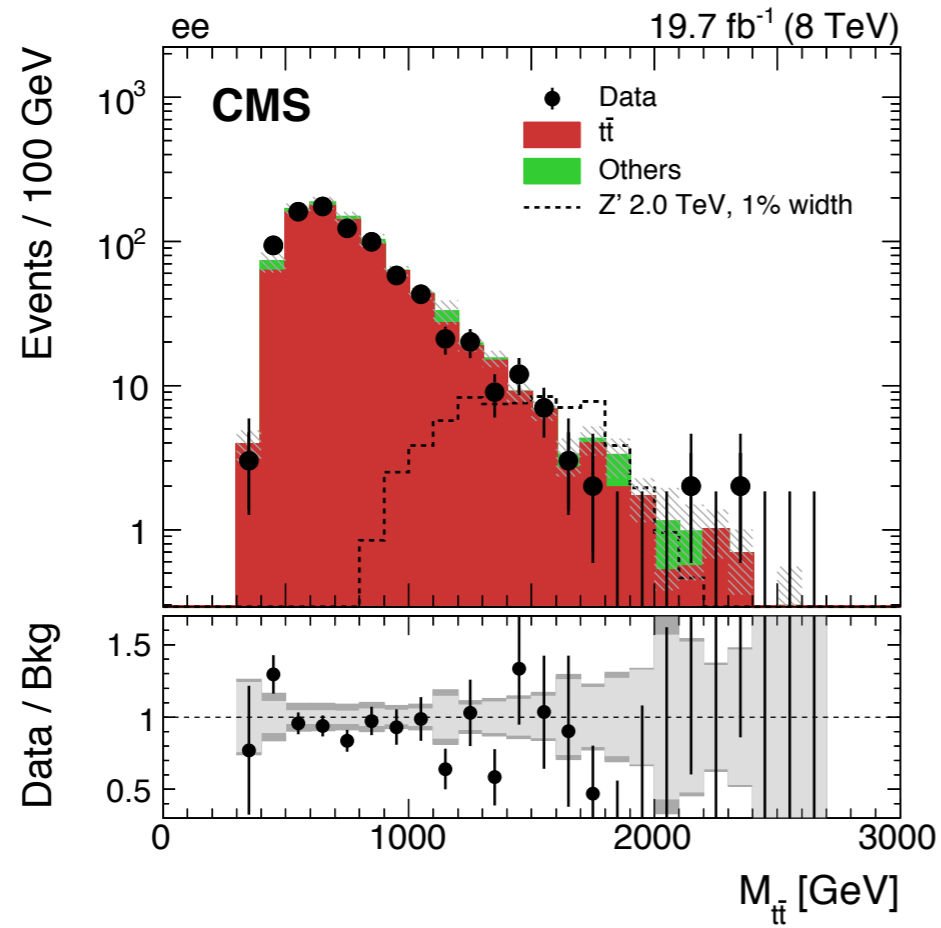


dilepton

- ❑ Two oppositely charged leptons:
 - $\mu\mu$: $p_{T1} > 45$ GeV in $|\eta| < 2.1$, $p_{T2} > 20$ GeV in $|\eta| < 2.4$
 - ee : $p_{T1} > 85$ GeV, $p_{T2} > 20$ GeV in $|\eta| < 2.5$
 - $e\mu$: $p_{T\mu} > 45$ GeV in $|\eta| < 2.1$, $p_{Te} > 20$ GeV in $|\eta| < 2.5$
- ❑ In $\mu\mu$ and ee channels: $M_{ll} > 12$ GeV, and Z-mass veto on $76 \text{ GeV} < M_{ll} < 106$
- ❑ At least two jets with $p_{T1} > 100$ and $p_{T2} > 50$ GeV in $|\eta| < 2.5$
- ❑ If $\Delta R(l, \text{closest jet}) < 0.5$, then $p_{T, \text{rel}}(l, \text{closest jet}) > 15 \text{ GeV}$
- ❑ In $\mu\mu$ and ee channels: $E_T^{\text{miss}} > 30$ GeV
- ❑ ≥ 1 CSVM or ≥ 2 CSVL b-tagged jet within $|\eta| < 2.4$

 The background $\sim 90\%$ dominated by irreducible $t\bar{t}$ background after these selections

- ❑ Further selection cuts to reduce $t\bar{t}$ background:
 $\Delta R(l_1, \text{jet}) < 1.2$ and $\Delta R(l_2, \text{jet}) < 1.5$
- ❑ Mass variable: reconstructed from 4-momenta of two leading leptons, two leading jets and E_T^{miss} . Total p_z of the two neutrinos set to 0.
- ❑ Define background region using the nominal selection, except:
 - $\Delta R(l_2, \text{jet}) > 1.5$
 - $> 90\%$ dominated by $t\bar{t}$
 - Negligible signal contamination ($< 0.1\%$ for 2 TeV signal)



semileptonic

- $= 1 \mu (e)$ with $p_T > 45 (35) \text{ GeV}$, $|\eta| < 2.1 (2.5)$
- ≥ 1 jet with $p_T > 150 \text{ GeV}$, $|\eta| < 2.4$
- ≥ 2 jets with $p_T > 50 \text{ GeV}$, $|\eta| < 2.4$
- $\cancel{E}_T > 50 \text{ GeV}$
- $H_T^{\text{lep}} \equiv \cancel{E}_T + p_T^\ell > 150 \text{ GeV}$
- lepton 2D-cut:
$$\Delta R_{\min}(\ell, j) > 0.5 \text{ OR } p_{T,\text{rel}}(\ell, j) > 25 \text{ GeV}$$
- (electron-only) triangular cuts
$$|\Delta\phi(x, \cancel{E}_T) - 1.5| < \frac{1.5}{75 \text{ GeV}} \cancel{E}_T \quad (x = e, j1)$$
- veto on events with > 1 CA8 top-tagged jet

$$\chi^2 = \left[\frac{M_{\text{top}}^{\text{lep}} - \bar{m}_{\text{top}}^{\text{lep}}}{\sigma_M^{\text{lep}}} \right]^2 + \left[\frac{M_{\text{top}}^{\text{had}} - \bar{m}_{\text{top}}^{\text{had}}}{\sigma_M^{\text{had}}} \right]^2$$

- W -mass constraint to reconstruct neutrino p_z
 - χ^2 params measured in MC with gaussian fits
 - if event contains a CA8 top-tagged jet
 → hadronic top = top-tagged jet
 - test all possible jet assignments
 → keep only hypothesis with minimum χ^2
-

>> final selection and categorization

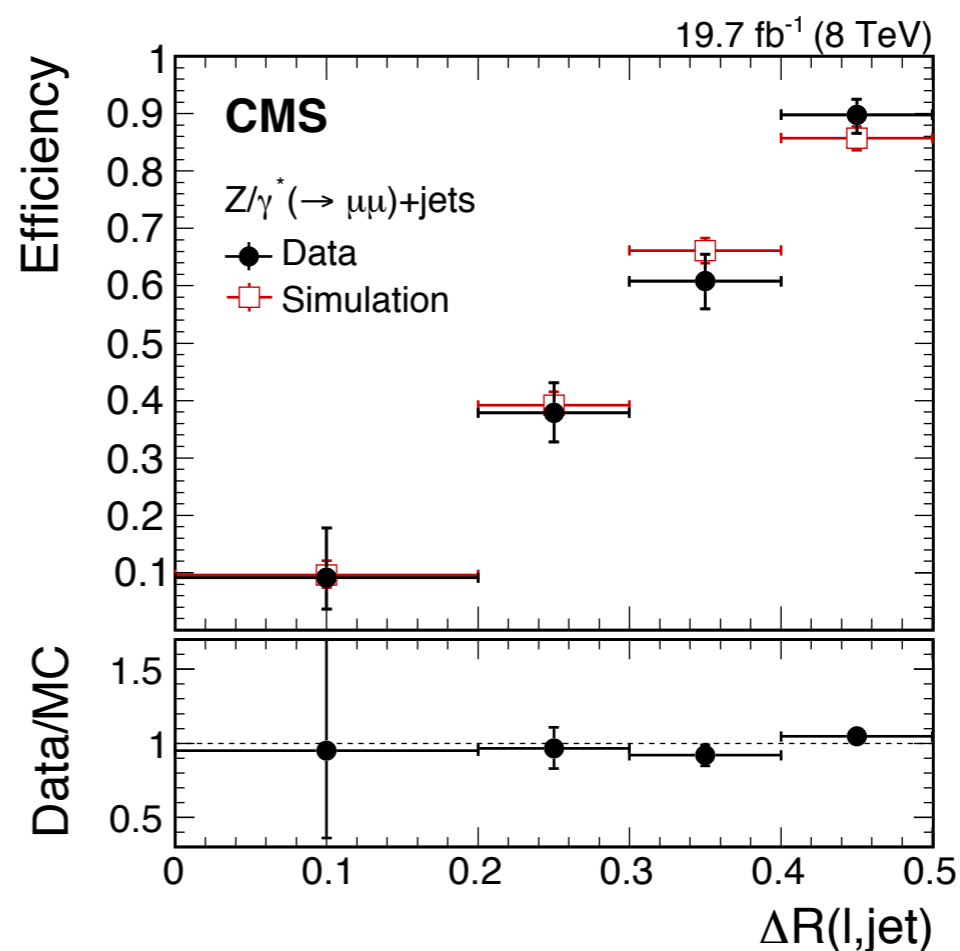
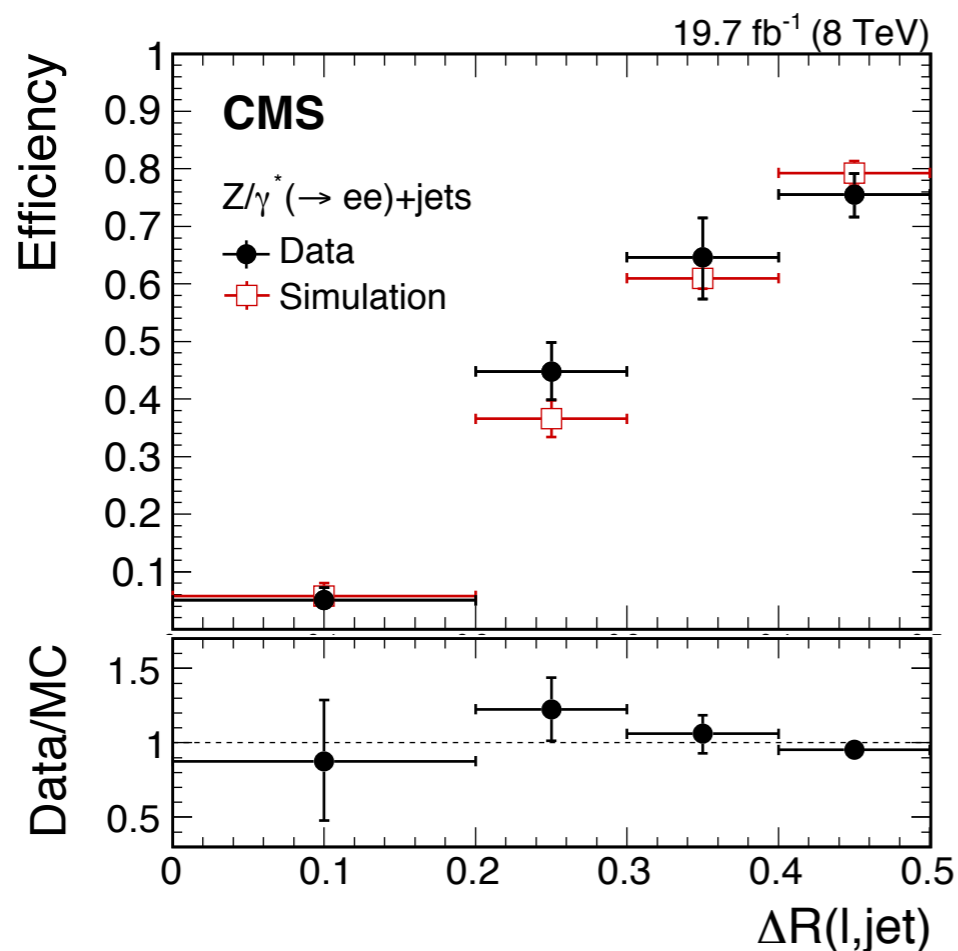
- $p_T^{\text{top-lep}} > 140 \text{ GeV}$ (electron only) & $\chi_{\text{min}}^2 < 50$
- 3 categories (chosen based on exp. limits)
 - ▶ 0-toptag + 0-btag
 - ▶ 0-toptag + 1-btag
 - ▶ 1-toptag

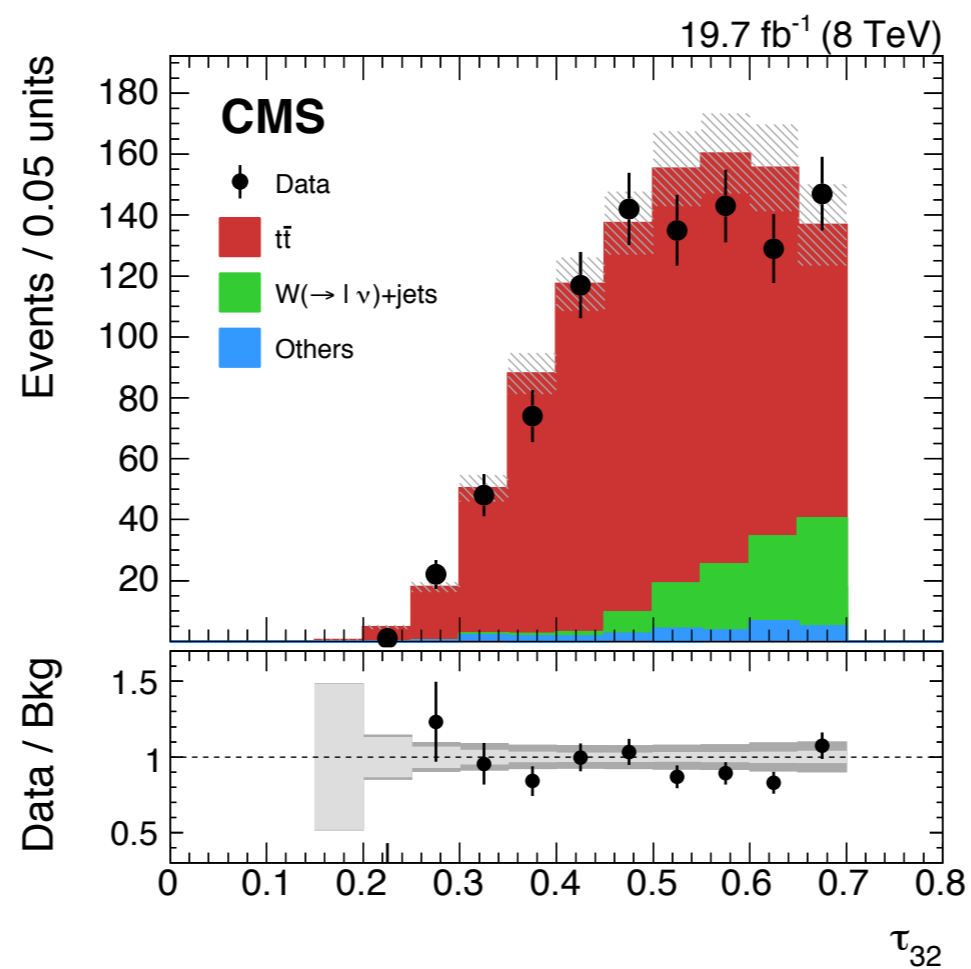
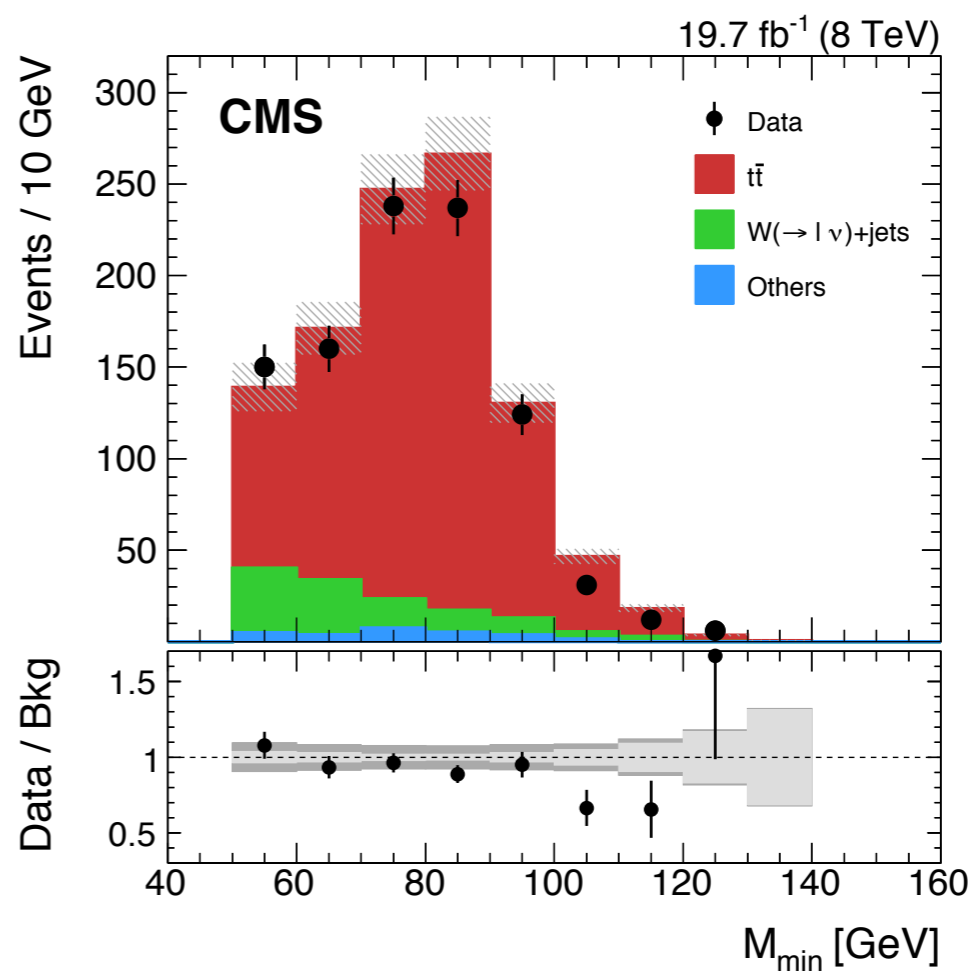
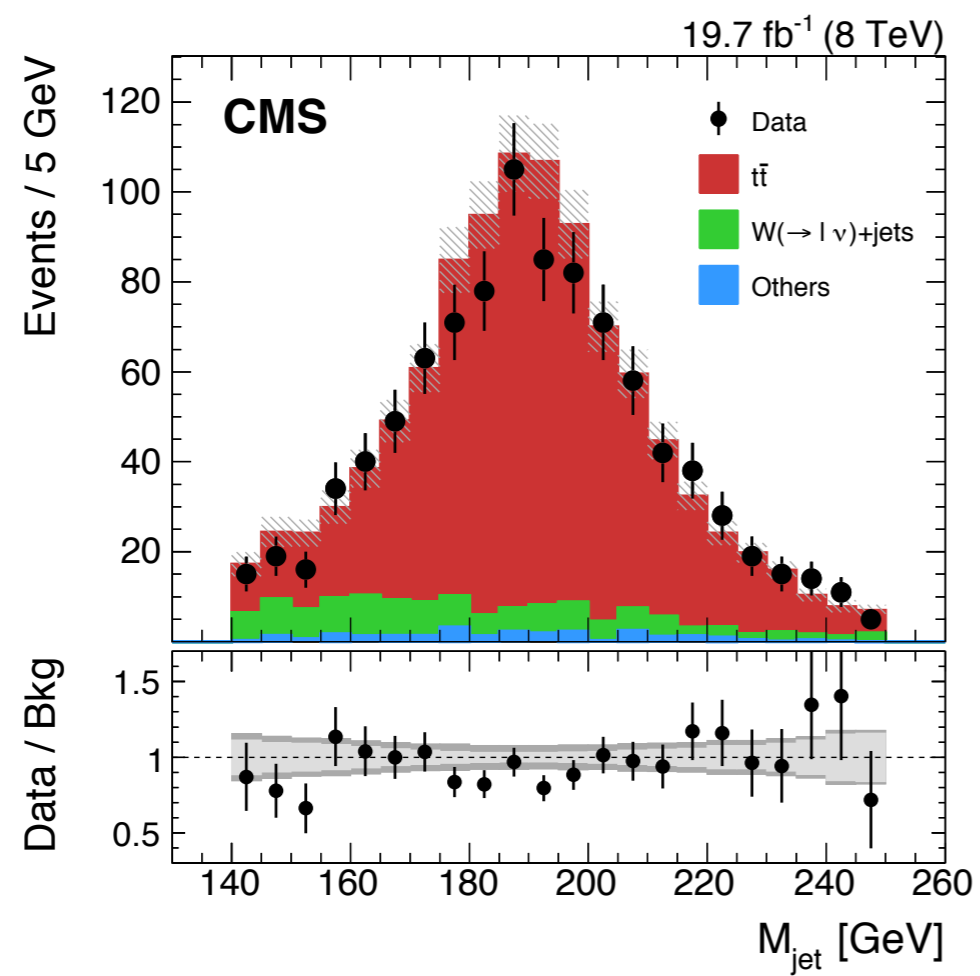
- lepton 2D-cut $\equiv \Delta R(\ell, j) > 0.5$ OR $p_{T,\text{rel}}(\ell, j) > 25$ GeV
- efficiency measured with **Tag-n-Probe** method in $Z \rightarrow \ell\ell$ control sample

Control sample selection:

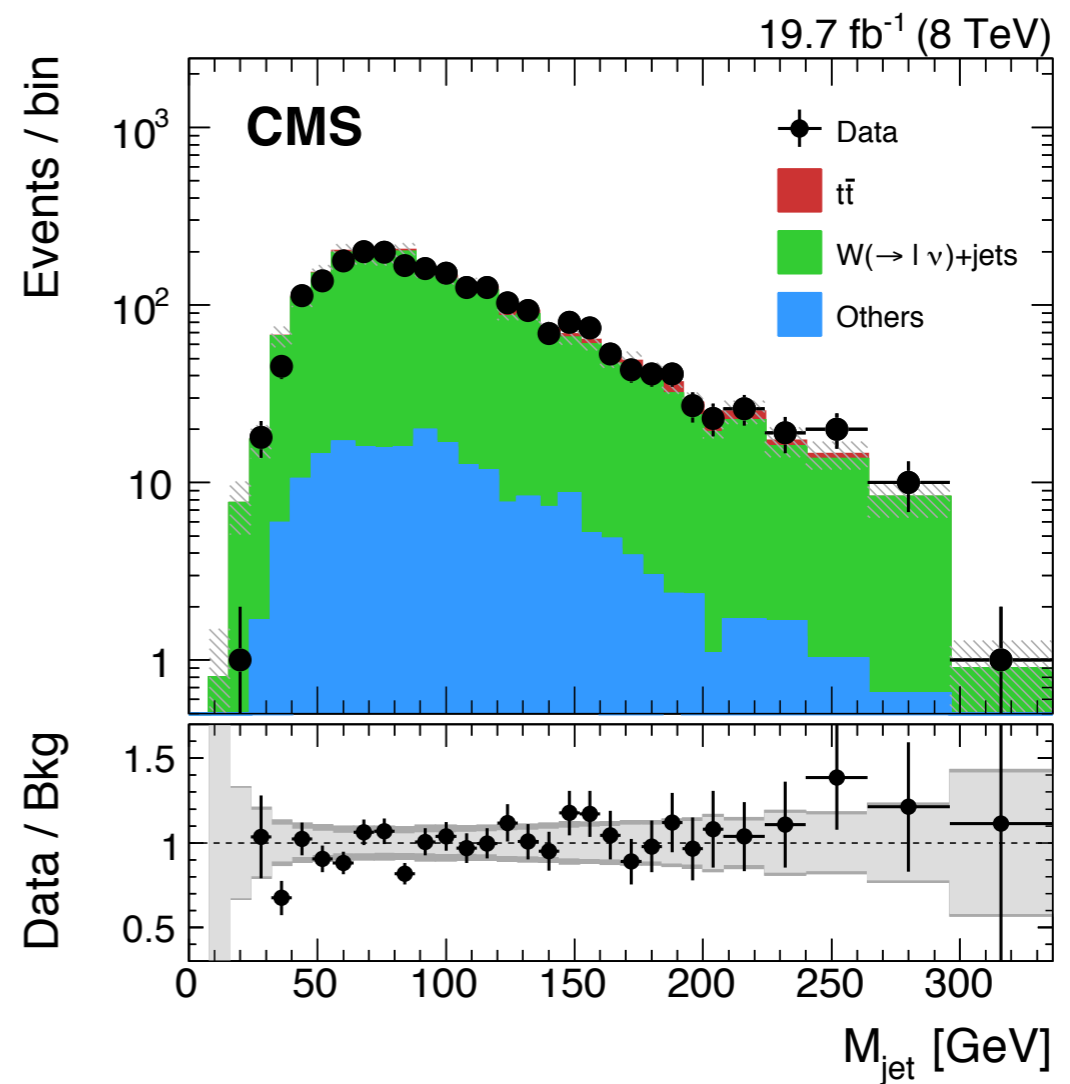
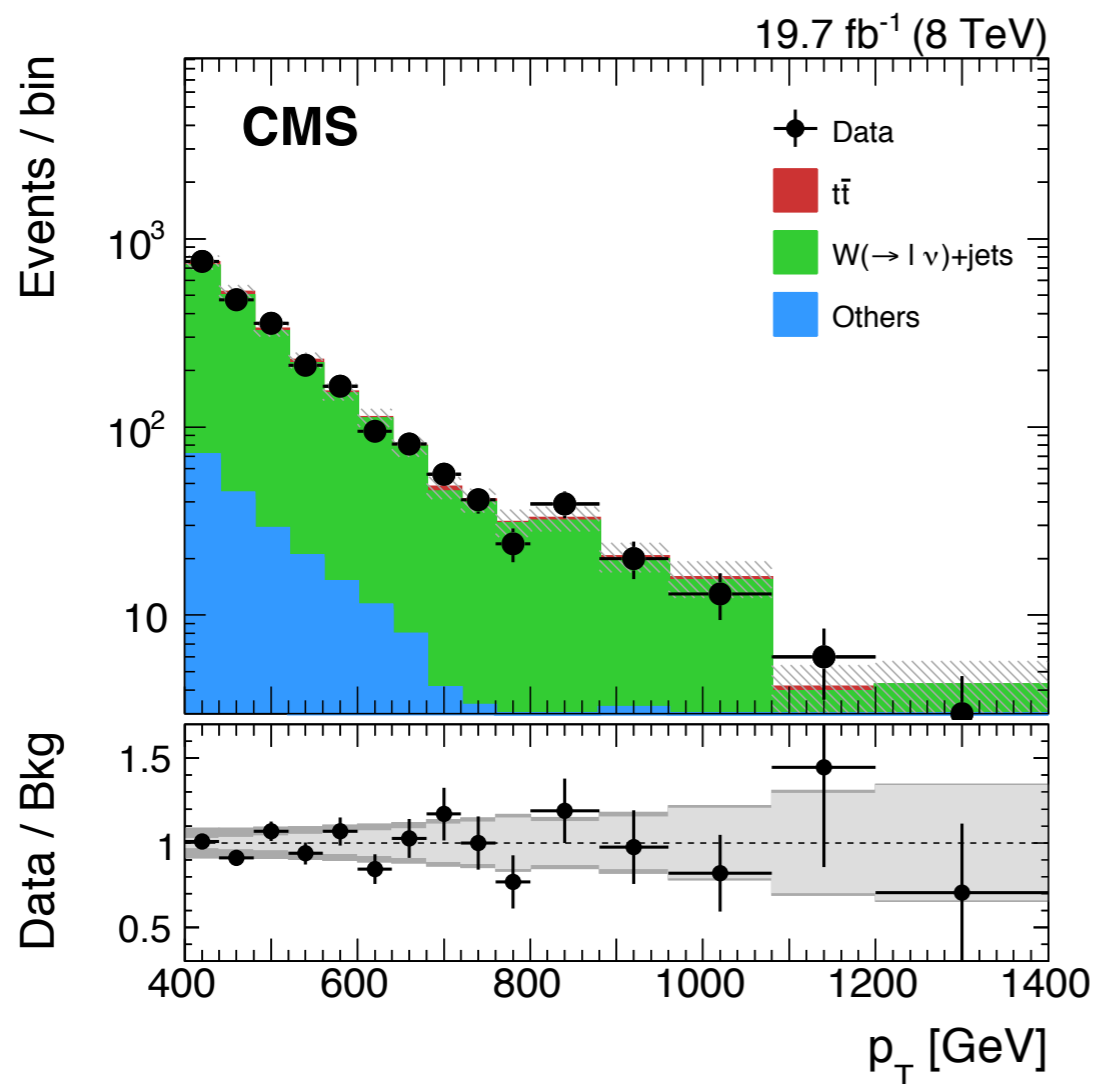
- 2 OSSF leptons in the Z mass peak
- same jet kinematics of ℓ +jets analysis
- efficiency in Data and MC measured in low- ΔR region ($\Delta R < 0.5$)

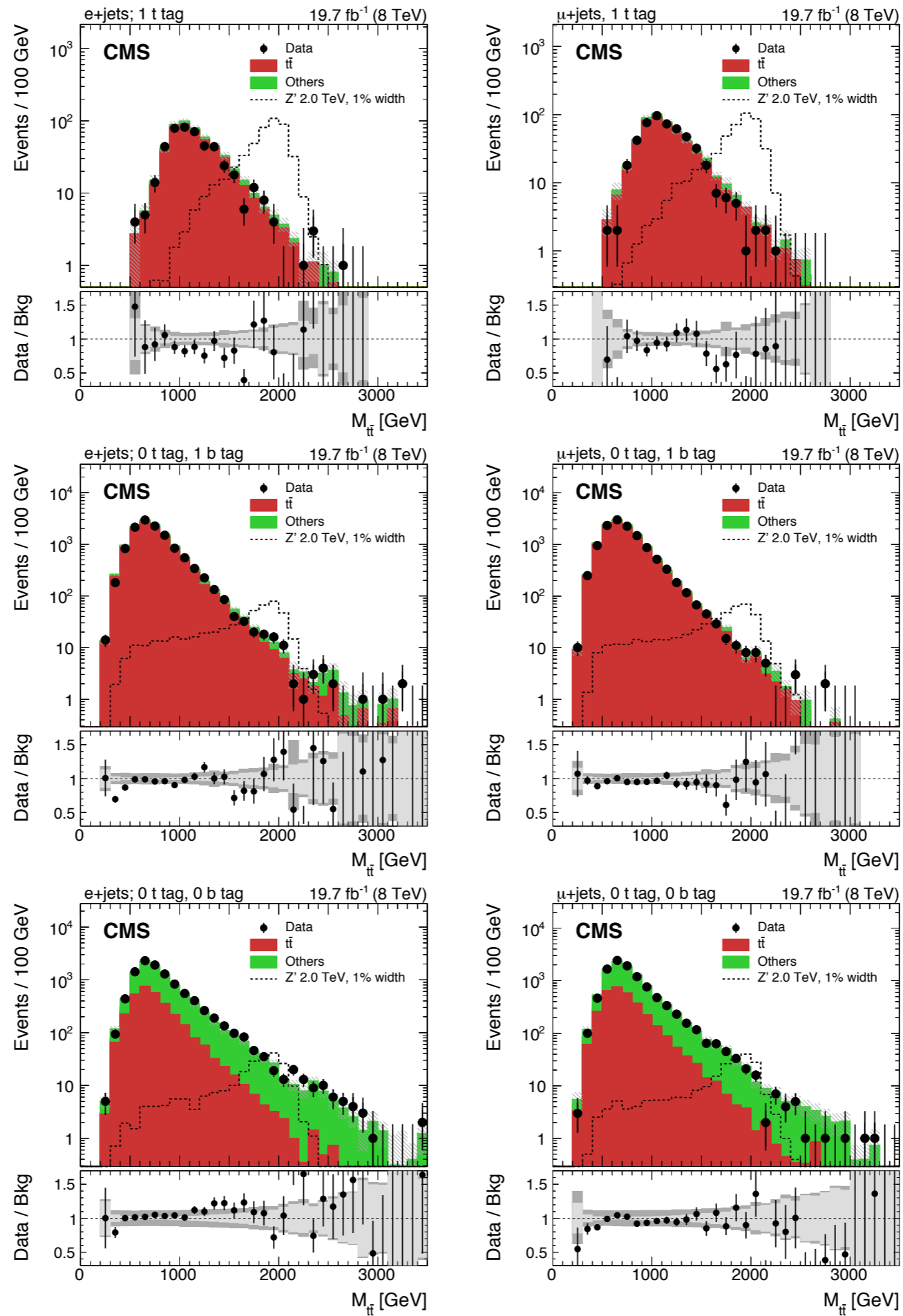
>> good agreement for Data and MC effs; no correction applied to MC;

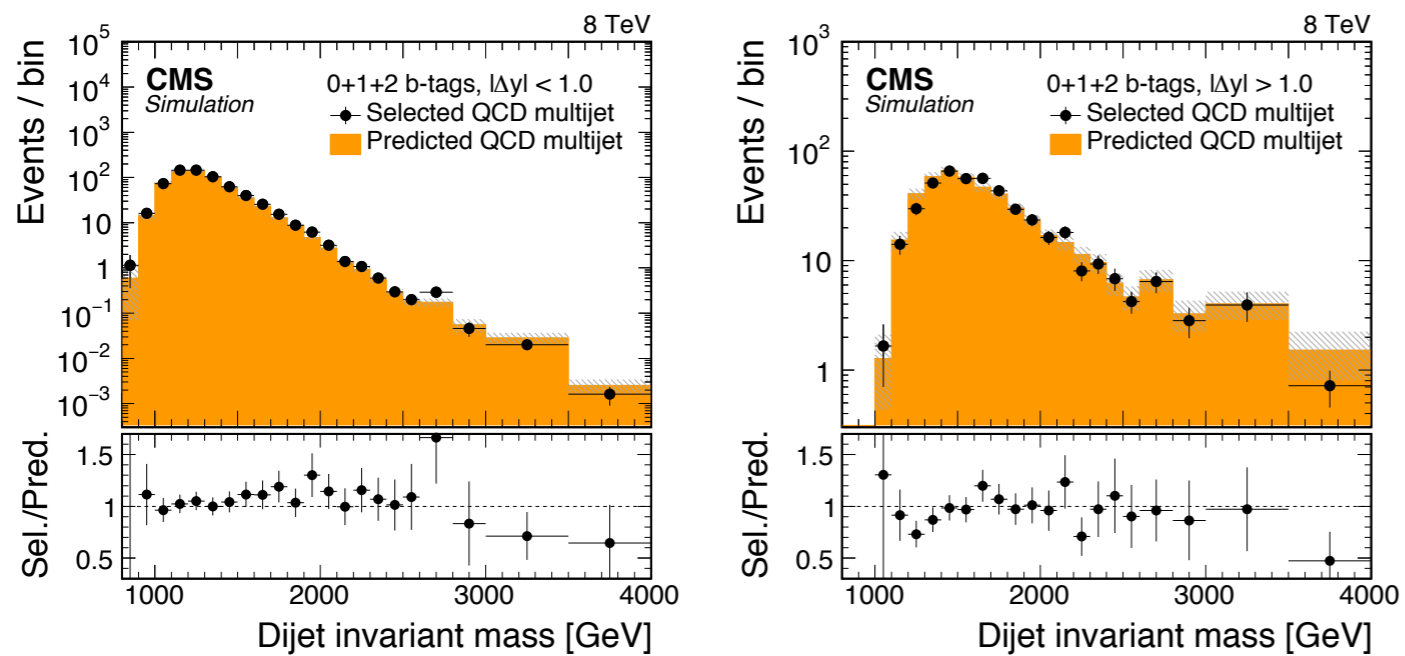
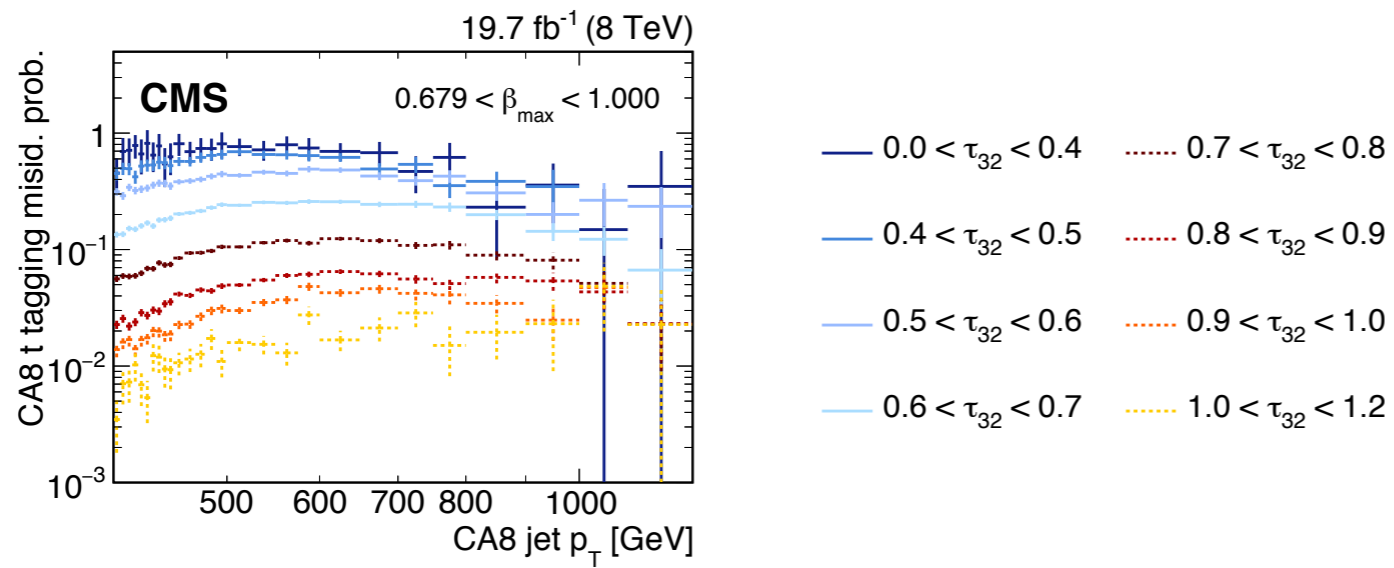
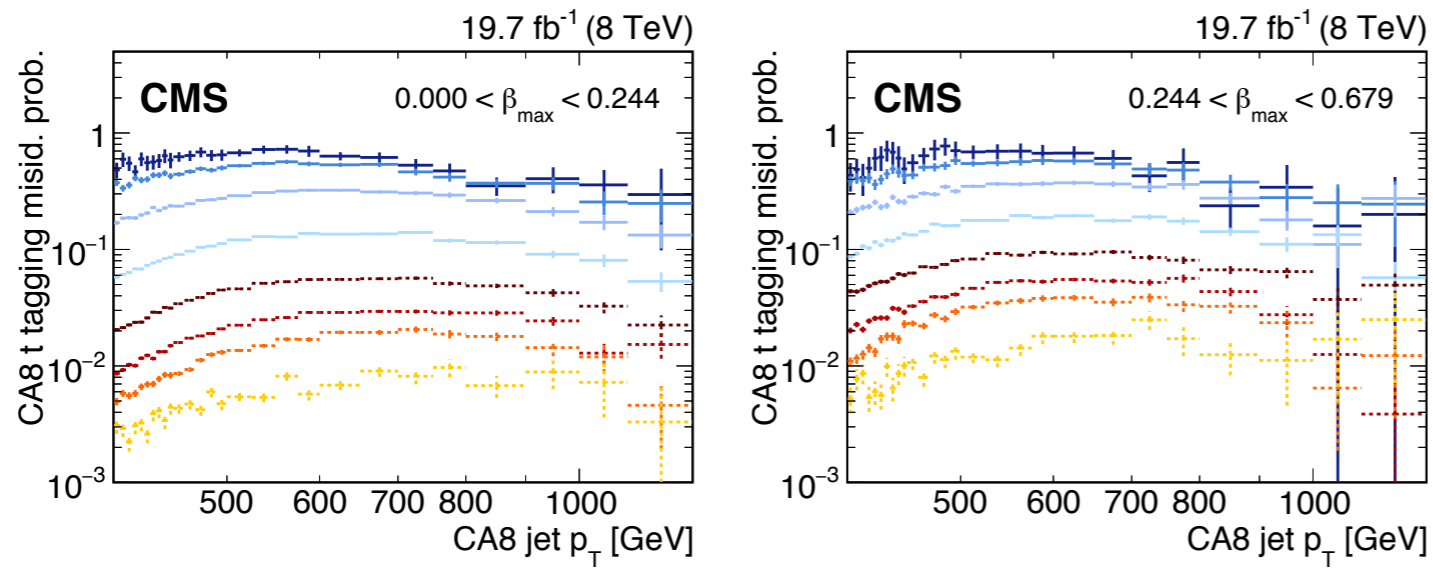


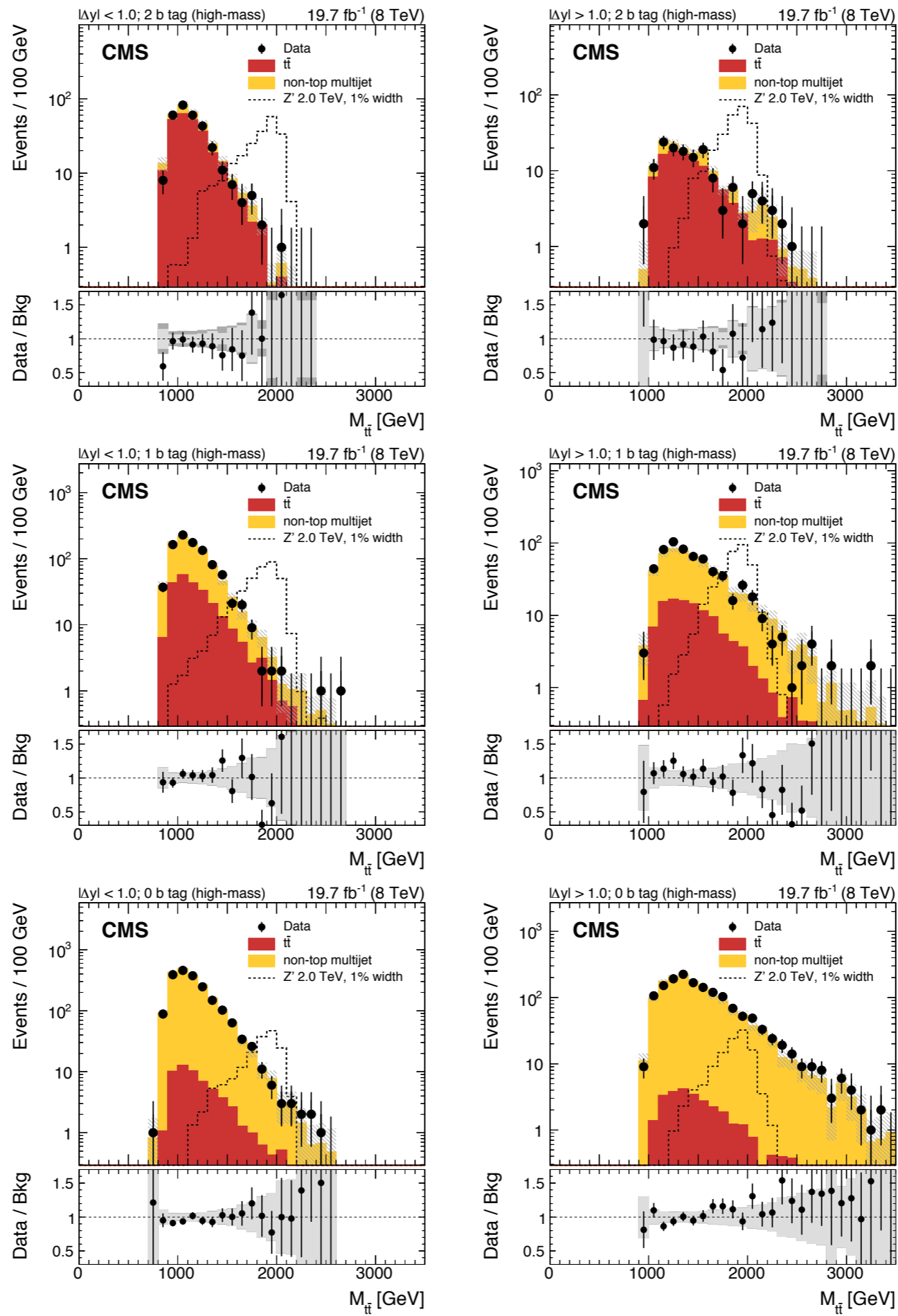


- W +jets \rightarrow main non-top bkg of the analysis
- control sample selection:
 - ▶ similar kinematics of the main analysis
 - ▶ inverted χ^2 cut ($\chi^2_{\text{lep}} > 50$)
 - ▶ veto on CSVL jets to suppress $t\bar{t}$
- measured flat Data/MC SF due to low stats:





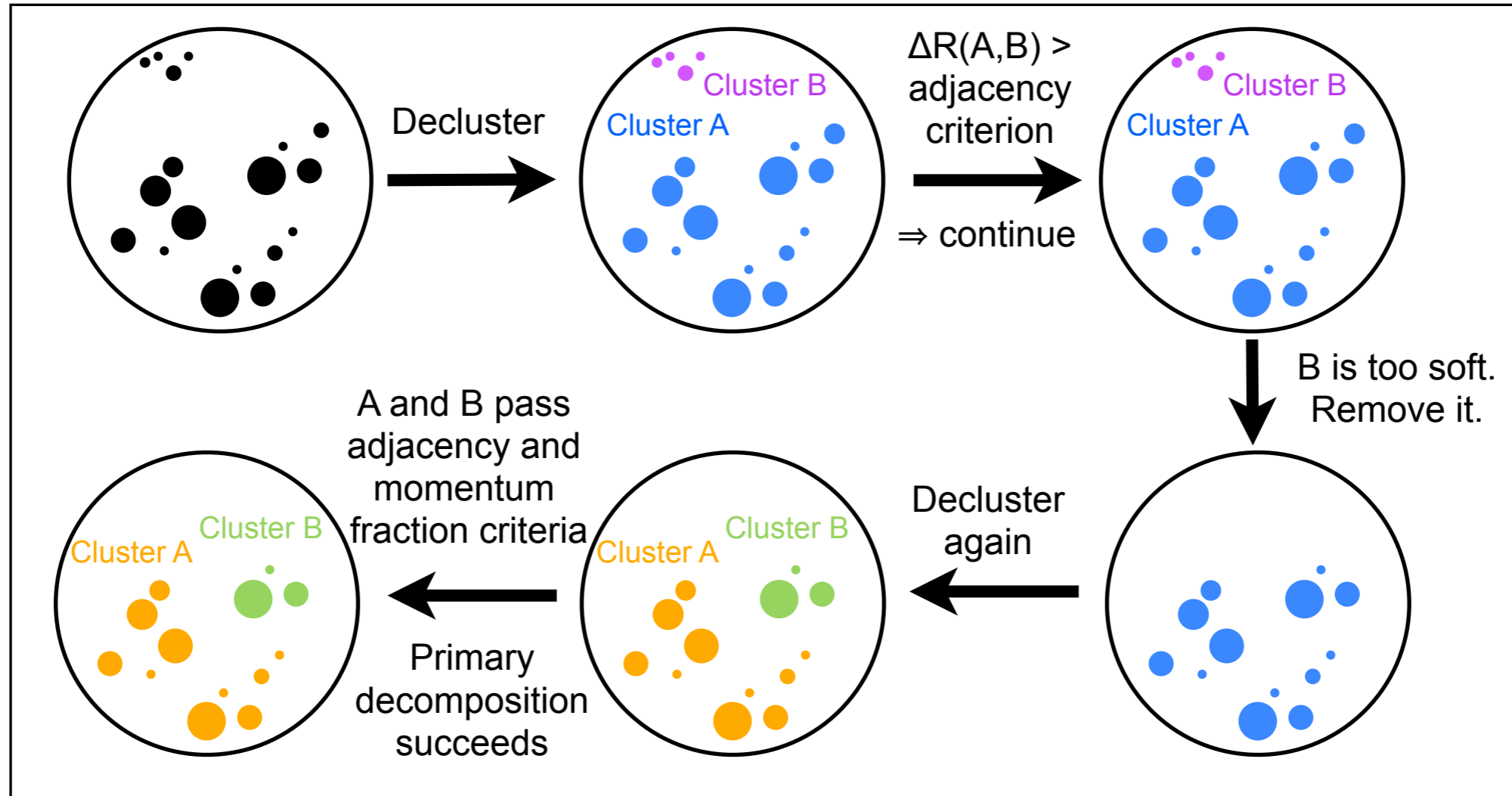




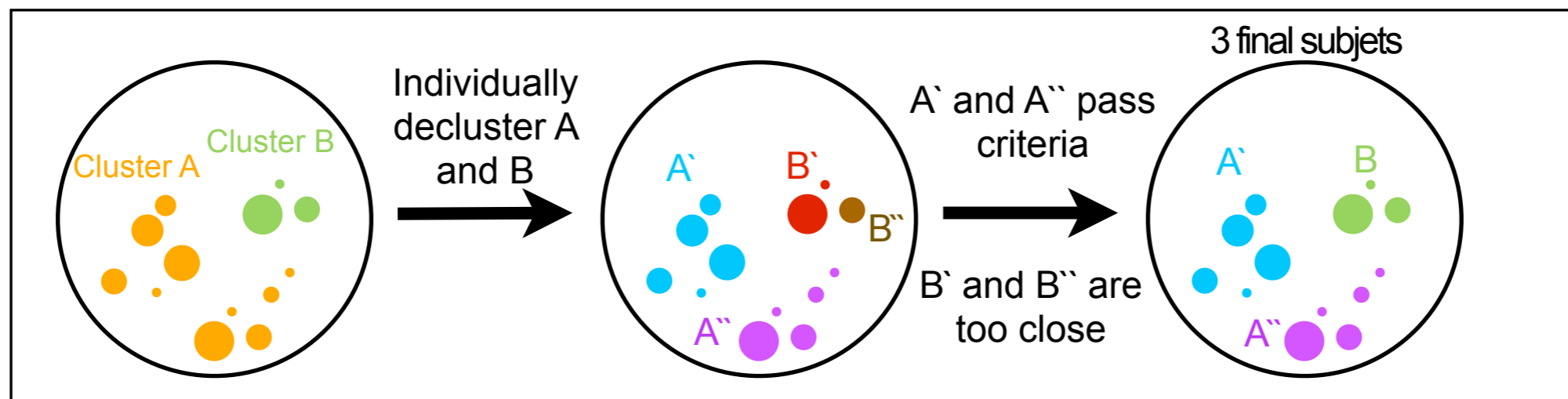
Source of uncertainty	Prior uncertainty	2ℓ	ℓ +jets	Had. channel high-mass	Had. channel low-mass
Integrated luminosity	2.6%	\oplus	\oplus	\oplus	\oplus
$t\bar{t}$ cross section	15%	\oplus	\oplus	\oplus	\oplus
Single top quark cross section	23%	\oplus	\oplus		
Diboson cross section	20%	\oplus	\oplus		
Z+jets cross section	50%	\oplus	\oplus		
W+jets (light flavor) cross section	9%		\odot		
W+jets (heavy flavor) cross section	23%		\odot		
Electron+jet trigger	1%		\odot		
H_T trigger	2%			\oplus	\oplus
Four-jet trigger	$\pm 1\sigma(p_T)$				\odot
Single-electron trigger	$\pm 1\sigma(p_T, \eta)$	\odot			
Single-muon trigger and id	$\pm 1\sigma(p_T, \eta)$	\oplus	\oplus		
Electron ID	$\pm 1\sigma(p_T, \eta)$	\oplus	\oplus		
Jet energy scale	$\pm 1\sigma(p_T, \eta)$	\oplus	\oplus	\oplus	\oplus
Jet energy resolution	$\pm 1\sigma(\eta)$	\oplus	\oplus	\oplus	\oplus
Pileup uncertainty	$\pm 1\sigma$	\oplus	\oplus	\oplus	\oplus
b tagging efficiency ^(†)	$\pm 1\sigma(p_T, \eta)$	\oplus	\oplus		\oplus
b tagging mistag rate ^(†)	$\pm 1\sigma(p_T, \eta)$	\oplus	\oplus		\oplus
CA8 subjet b tagging	unconstrained			\odot	
CA8 t tagged jet efficiency	unconstrained		\oplus	\oplus	
CA8 t-tagged jet mistag	$\pm 25\%$		\odot		
CA15 t-tagged jet efficiency	$\pm 1\sigma(p_T, \eta)$				\odot
QCD multijet background	sideband			\odot	\odot
PDF uncertainty	$\pm 1\sigma$	\oplus	\oplus	\oplus	\oplus
$t\bar{t}$ ren. and fact. scales	$4Q^2$ and $0.25Q^2$	\oplus	\oplus	\oplus	\oplus
W+jets ren. and fact. scales	$4Q^2$ and $0.25Q^2$		\odot		
W+jets matching scale μ	2μ and 0.5μ		\odot		
MC statistical uncertainty		\odot	\odot	\odot	\odot

^(†) AK5 and CA15 subjects

Primary decomposition

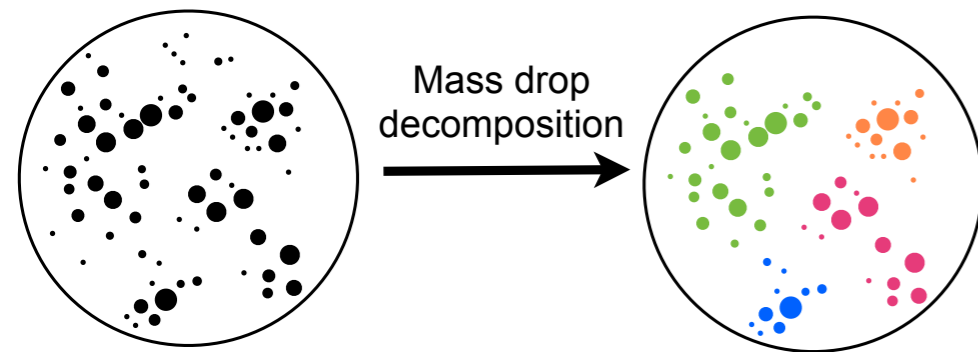


Secondary decomposition

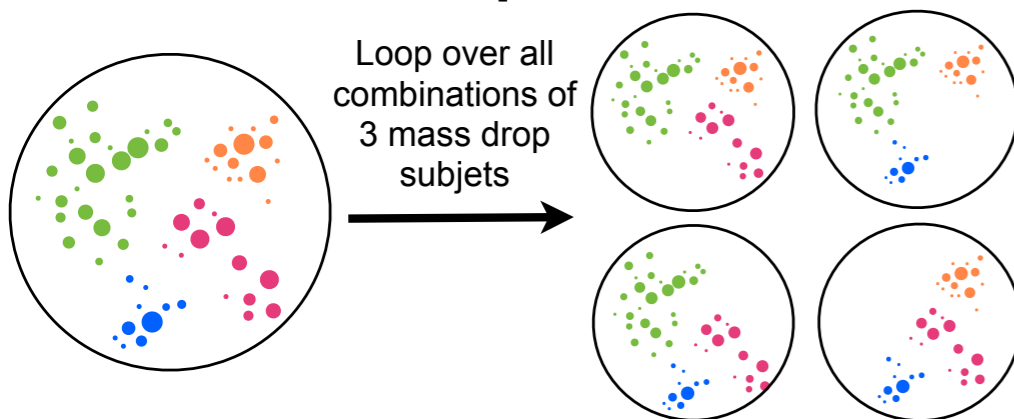


HEP Top Tagger details

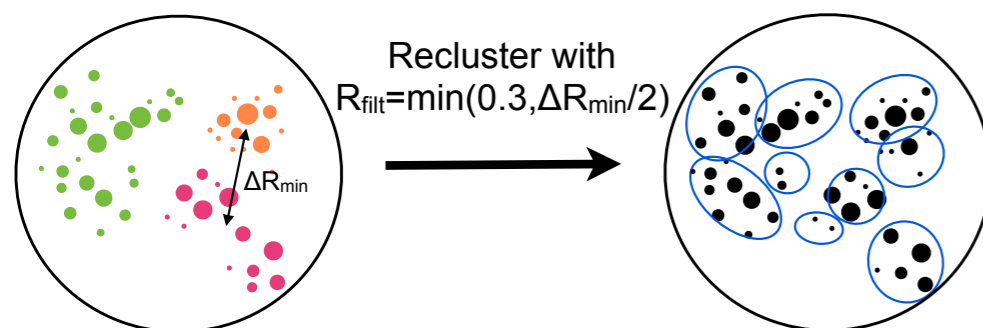
Step 1:



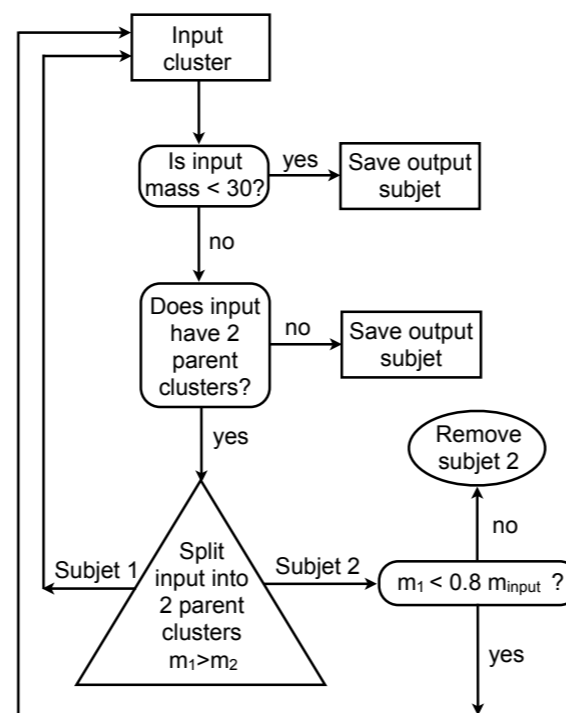
Step 2:



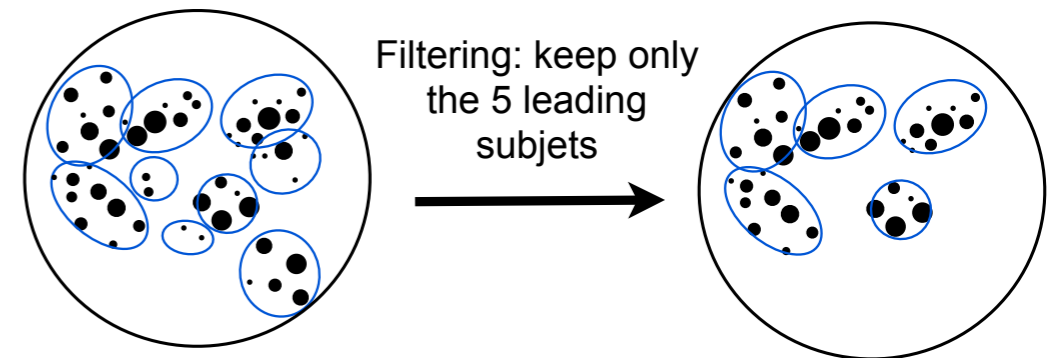
Step 3:



HEP Top Tagger Mass drop decomposition

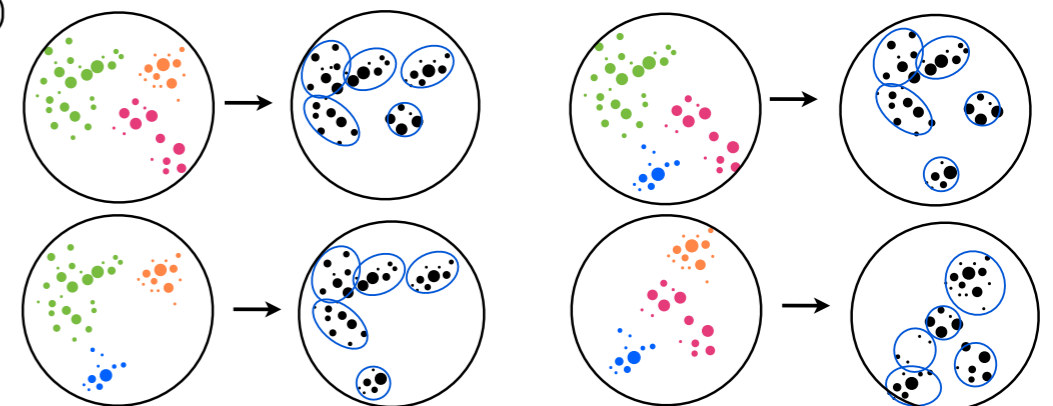


Step 4:

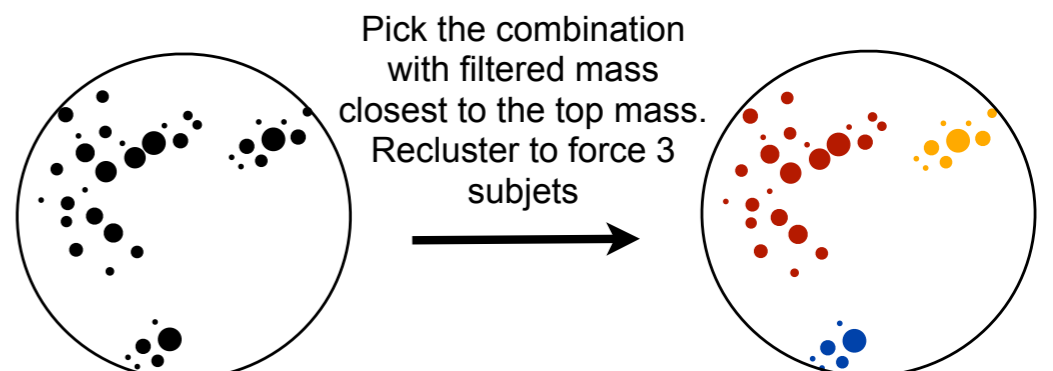


Step 5:

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



Step 6:



HEP Top Tagger - W mass selection

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

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

