Searches for Diboson Resonances at CMS

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on behalf of the CMS collaboration

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introduction and overview

reconstruction techniques

background estimation

results and outlook

This talk focuses on searches for resonances with mass > 1 TeV
See talk by Brian Pollack for searches for heavy Higgs (with mass < 1 TeV)

high mass resonances for **diboson resonances** are a staple of new physics searches

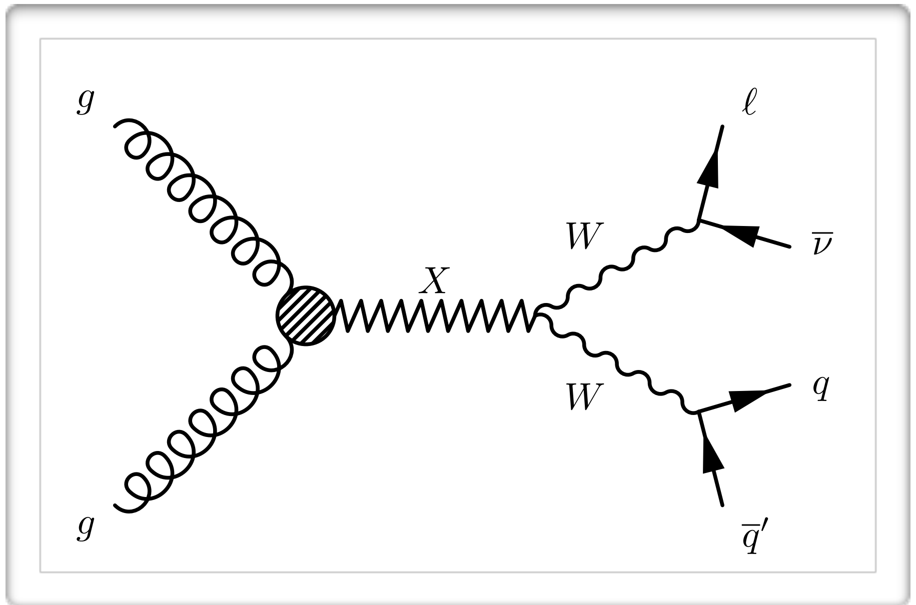
model interpretations…

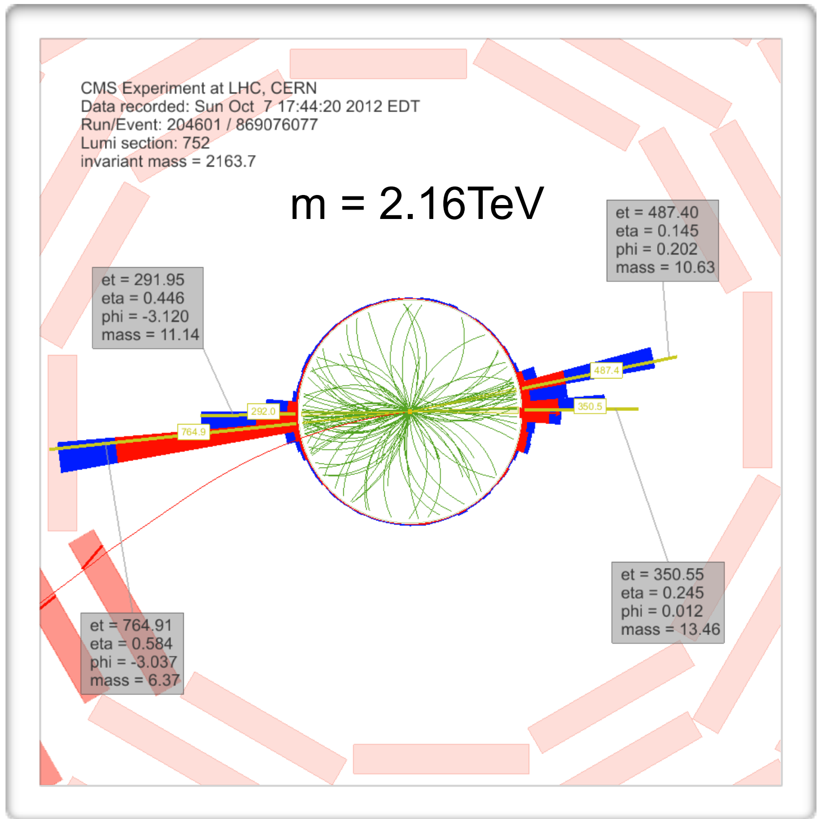
extra dimensional models

bulk scenario of RS models; heavy spin-2 graviton or spin-0 radion decaying mainly to W_L,Z_L, H

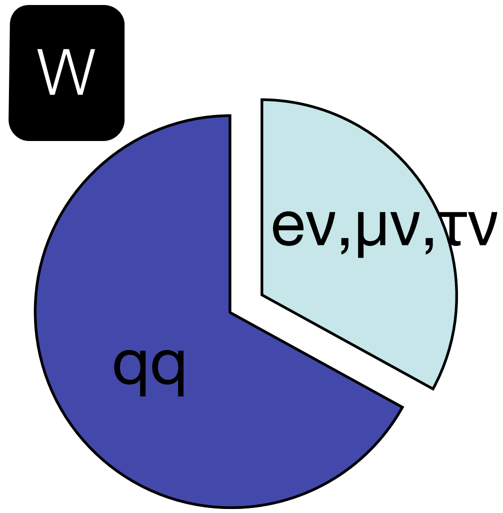
composite Higgs

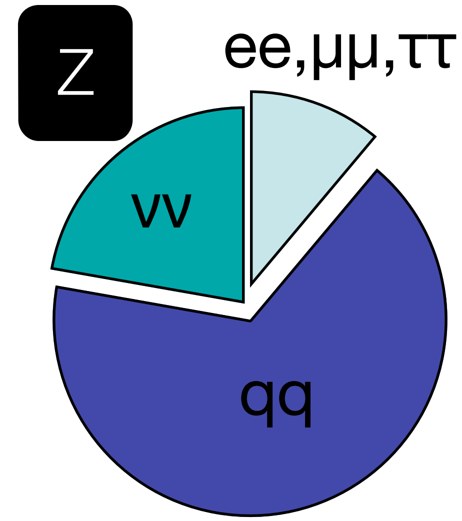
heavy vector triplet scenario; heavy spin-1 W’ or Z’ decaying mainly to to W_L,Z_L, H

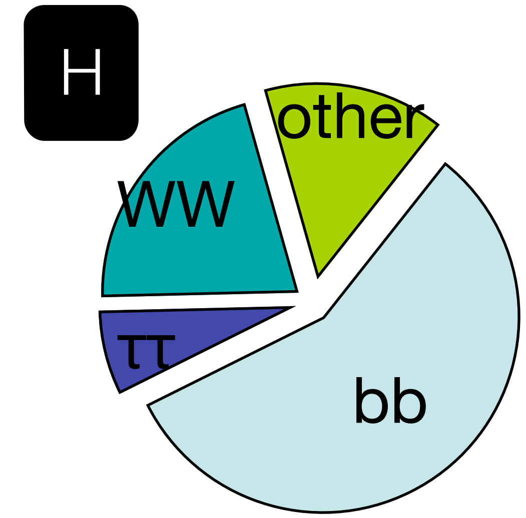




diboson final states



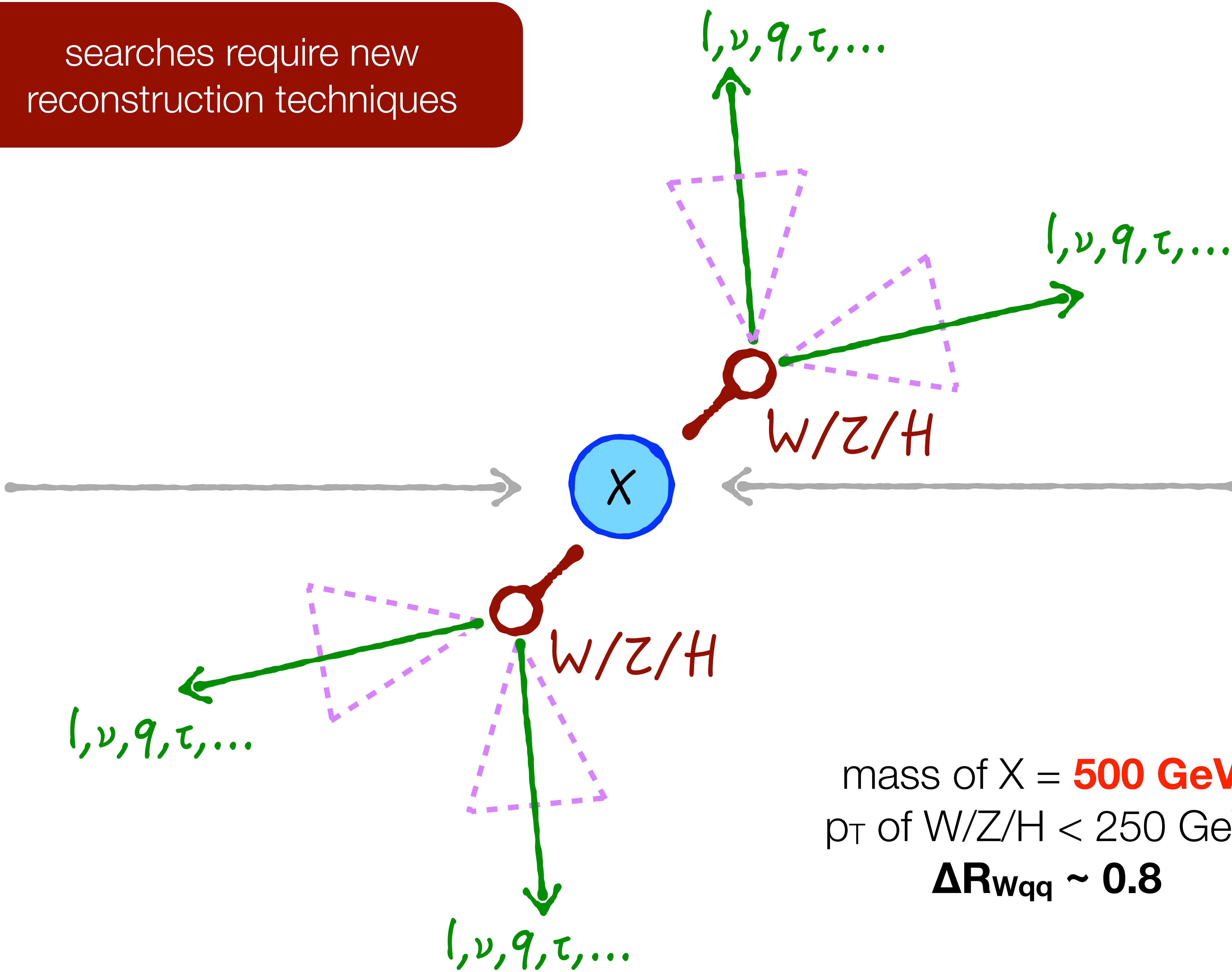




	W	Z	H
W	lν+qq, qq+qq	lν+qq, ll+qq qq+qq, lν+ll	lν+bb, qq+bb, qq+ττ, qq+WW(qqqq)
Z		ll+qq, qq+qq	qq+bb,qq+ττ, qq+WW(qqqq)
H			bb+bb

references: EXO-12-024, EXO-12-025, EXO-12-053, EXO-13-009, EXO-13-007, EXO-14-009, EXO-14-010

searches require new
reconstruction techniques

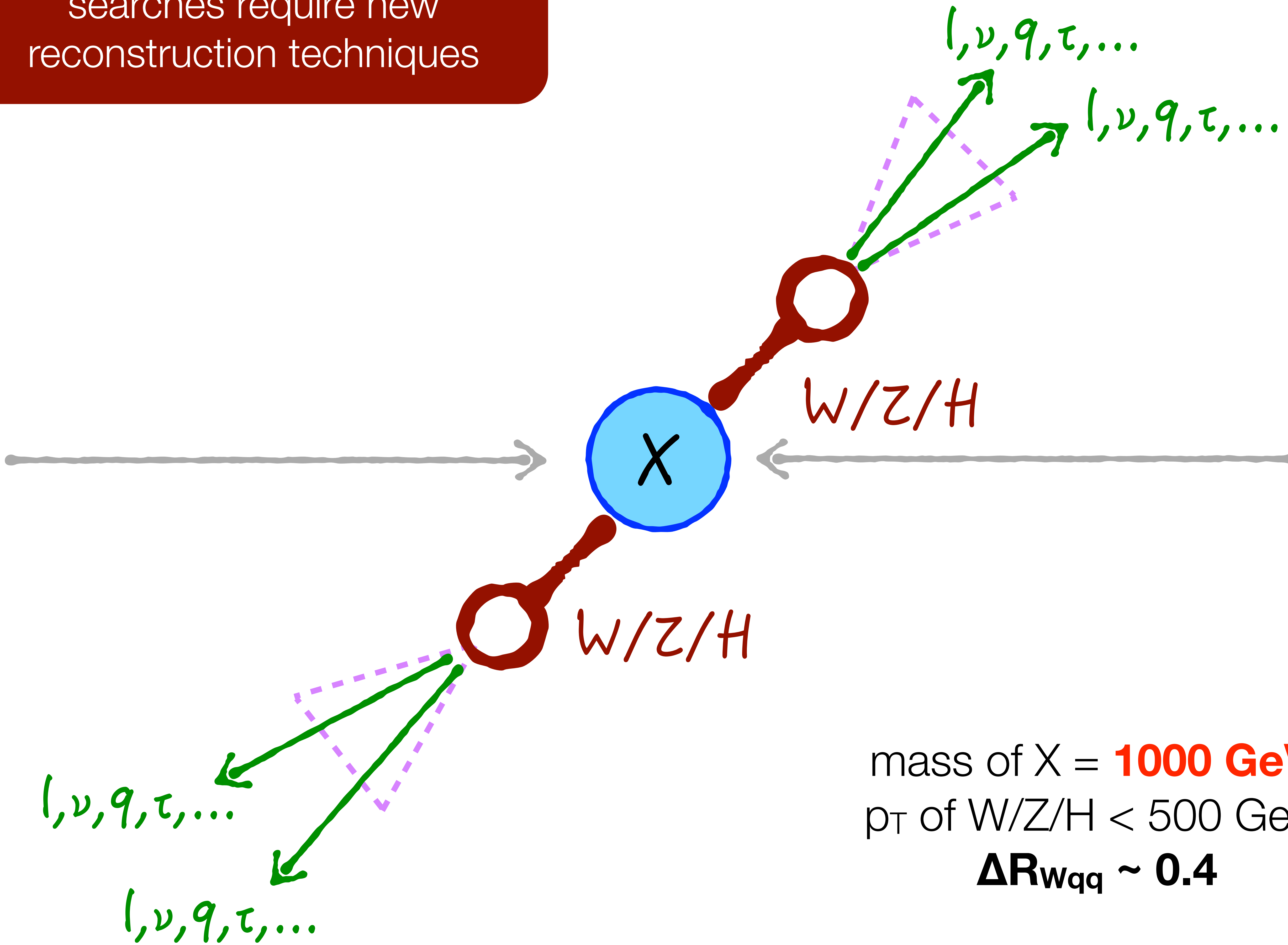


mass of X = **500 GeV**

p_T of W/Z/H < 250 GeV

ΔR_{Wqq} ~ 0.8

searches require new reconstruction techniques



mass of X = **1000 GeV**

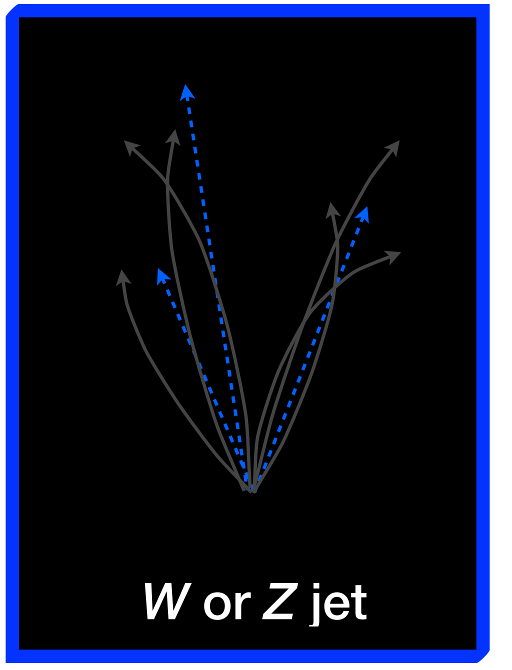
p_T of W/Z/H < 500 GeV

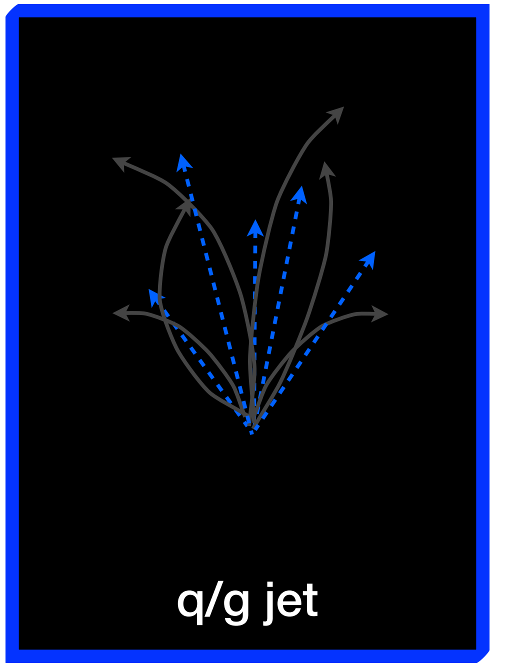
ΔR_{Wqq} ~ 0.4

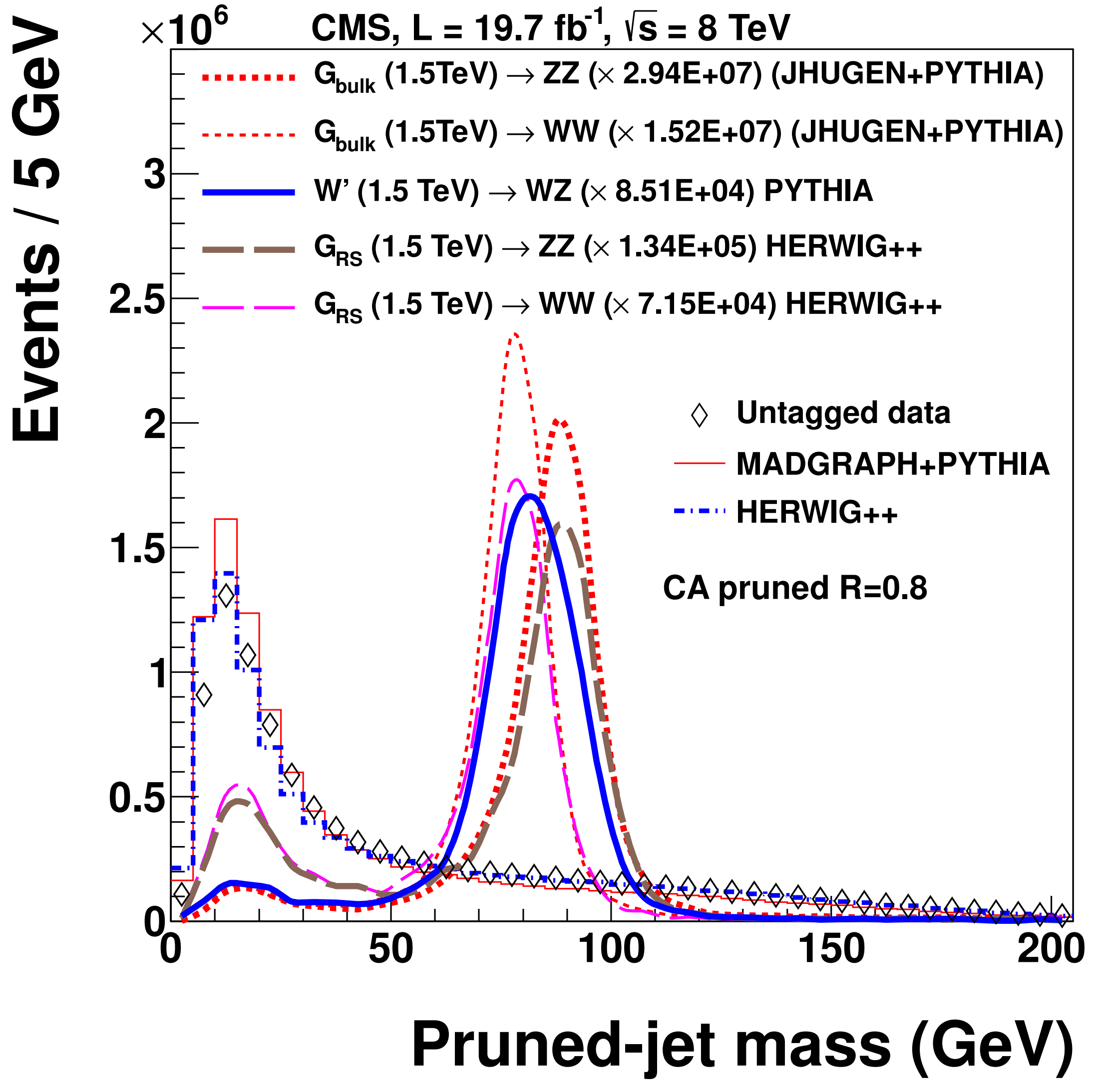
merged W/Z → qq

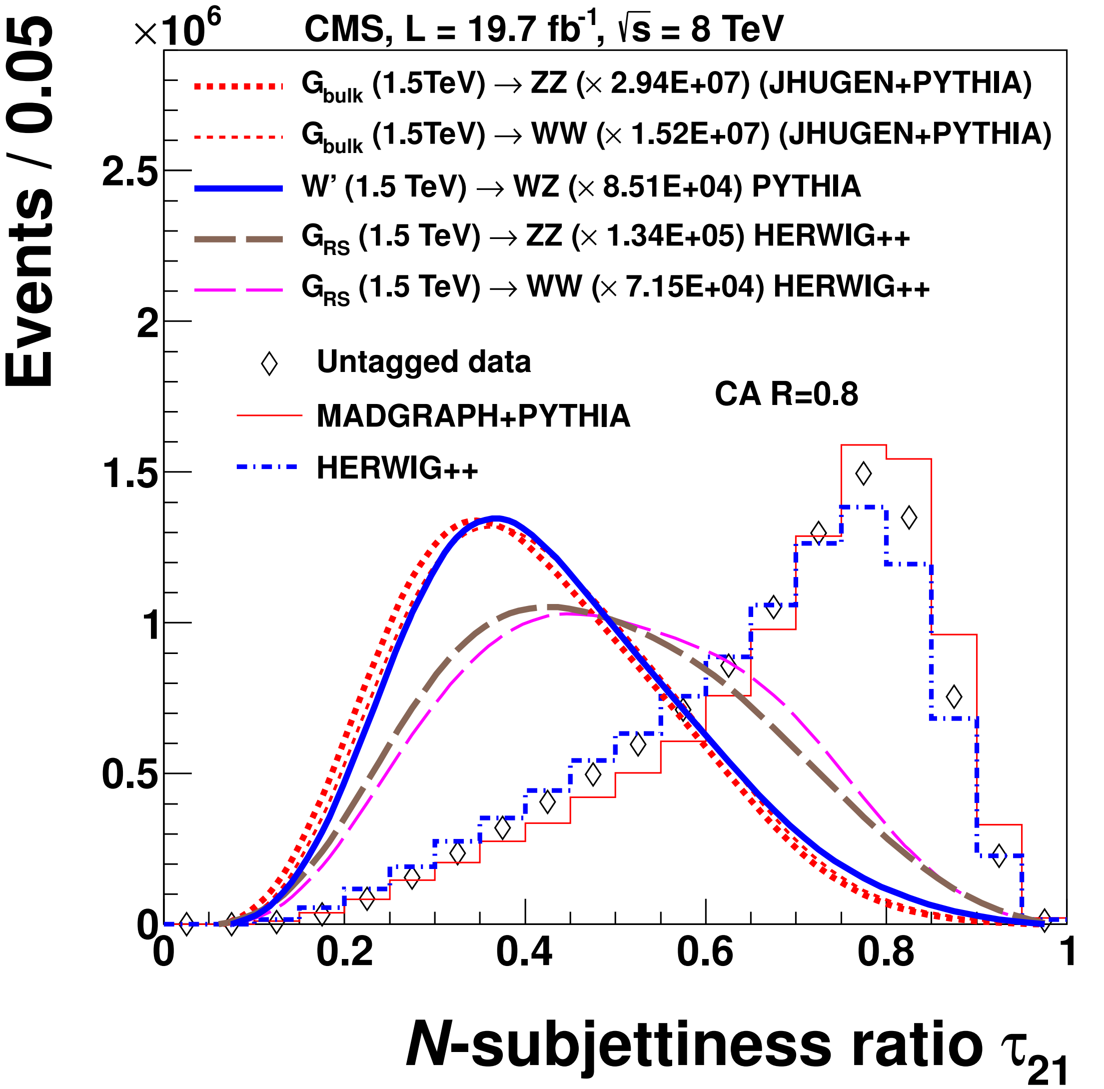
massive 2-prong jets:

W/Z tagging in CMS Run 1 uses CA8 jets with **pruned mass** (70-100 GeV) + **n-subjettiness τ_2/τ_1**



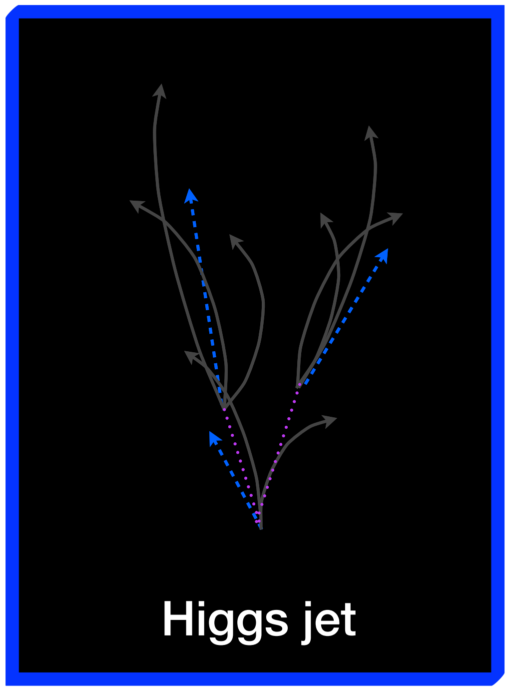


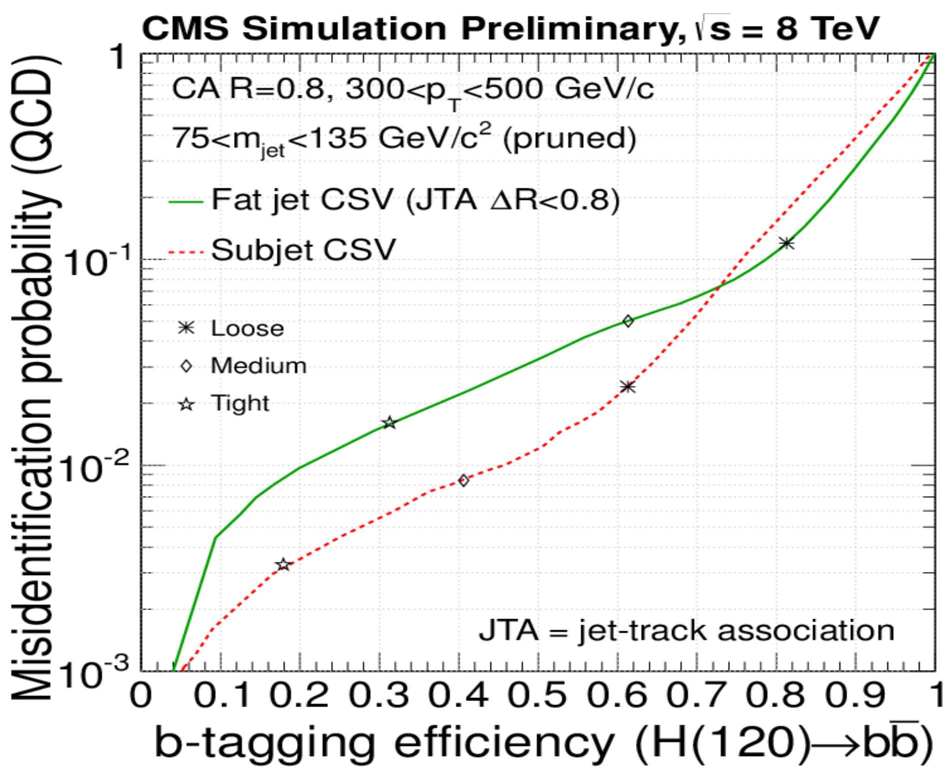


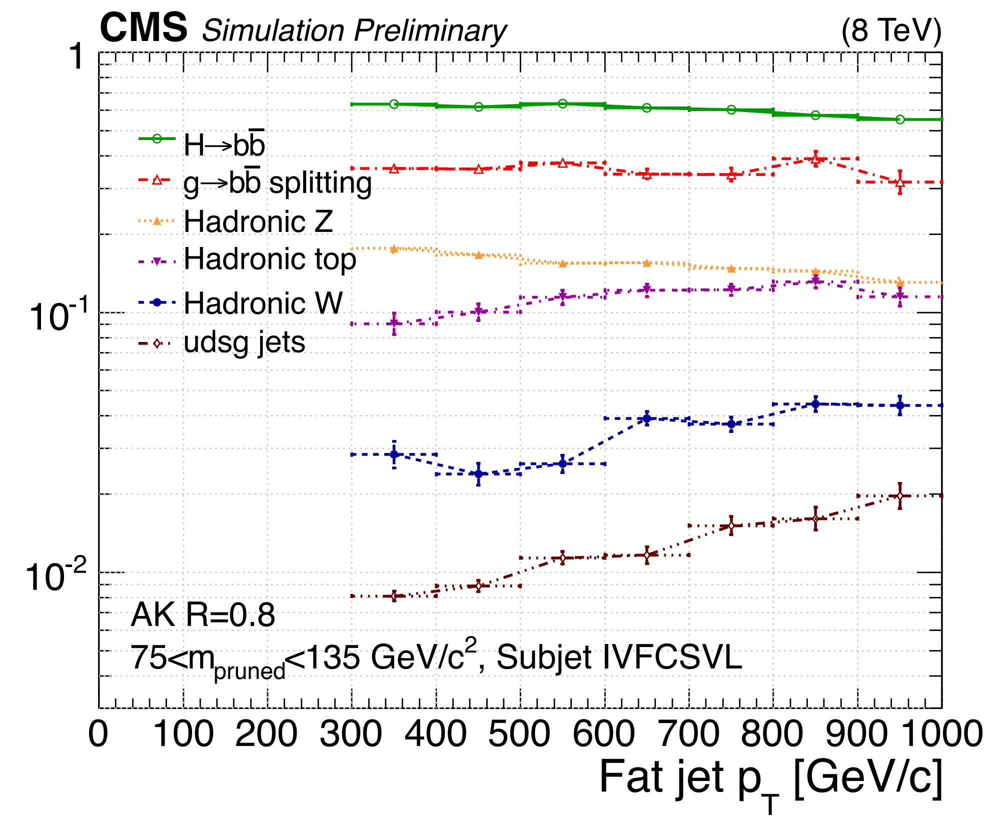


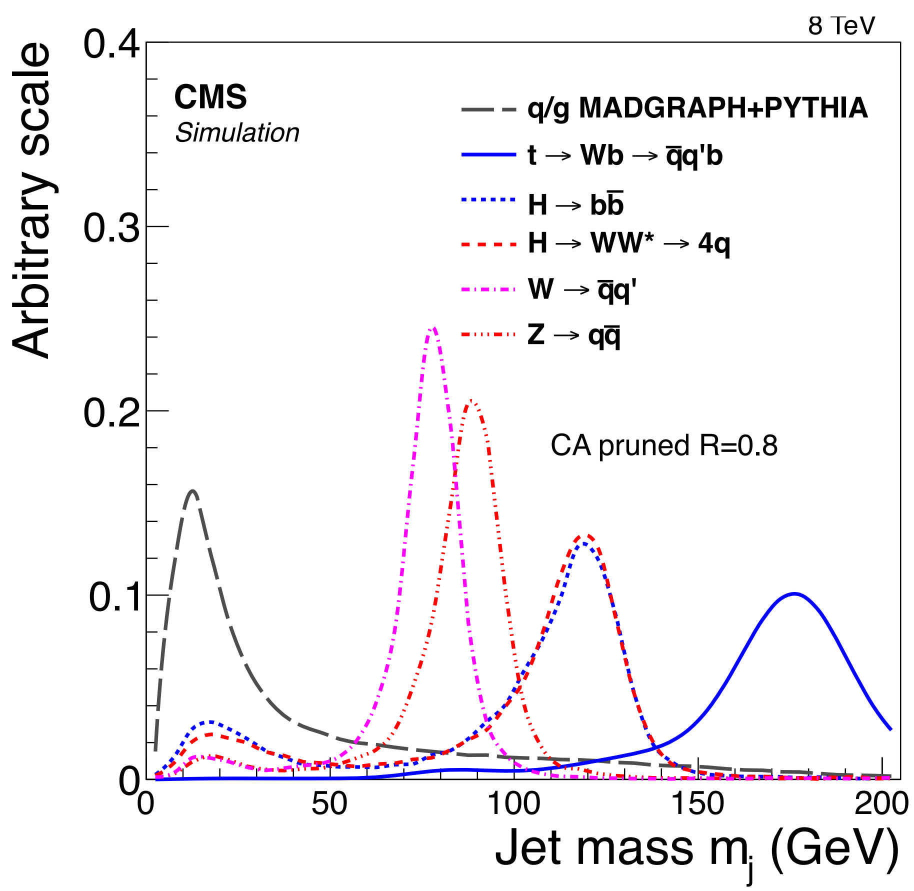
tagging efficiencies are polarization dependent!

merged Z/H → bb









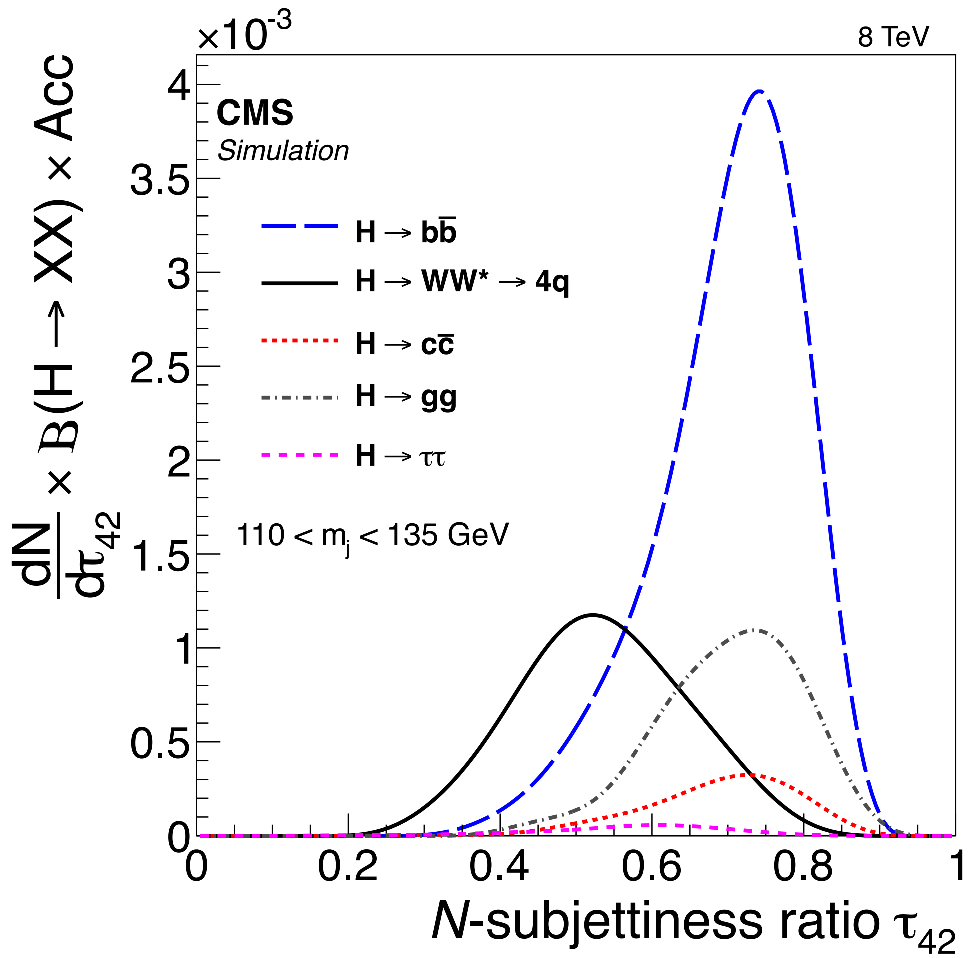
b tagging in boosted topologies:

subjet b-tagging methods developed by CMS in Run 1 for Higgs and Z tagging

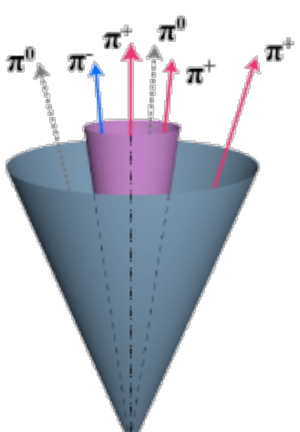
boosted Higgs mass robust for bb and WW, mass resolution sufficient to distinguish from W/Z/t jets

merged H → WW → qqqq

novel method for tagging HWW* using τ_4/τ_2

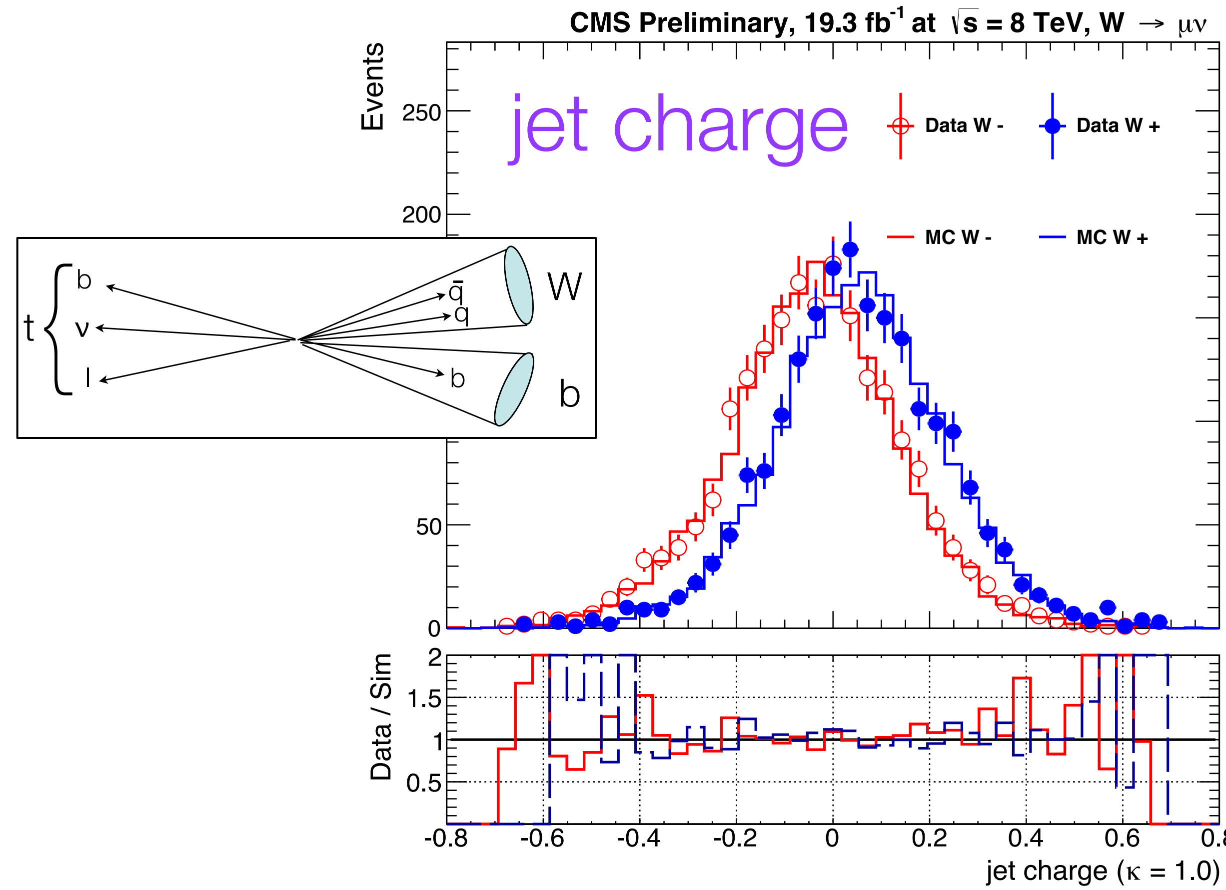


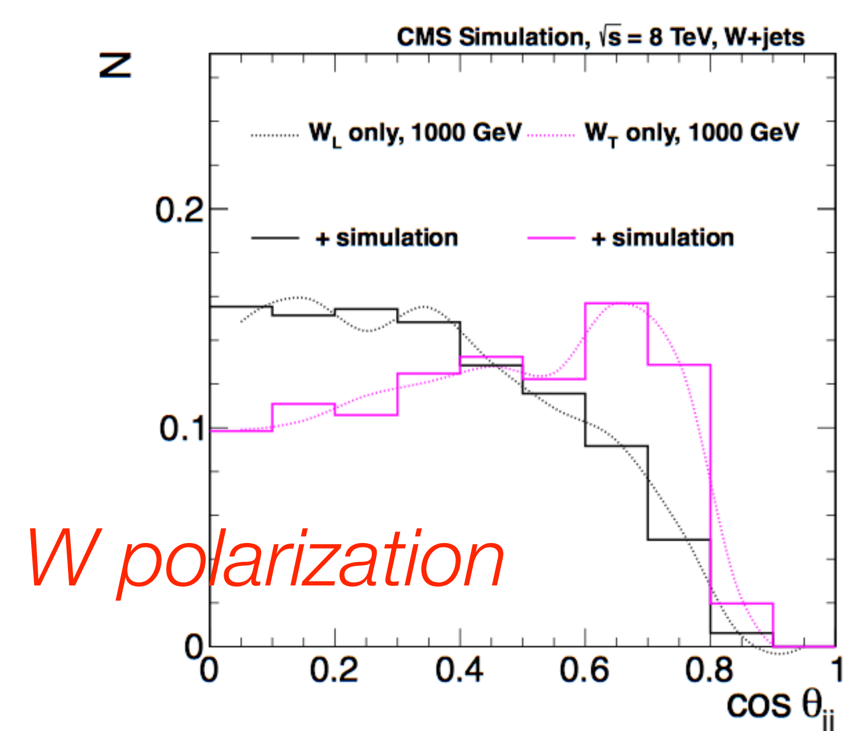
H → $\tau_h\tau_h$ tagging



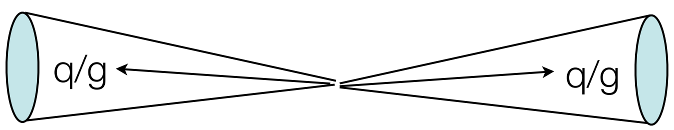
takes advantage of **subjet techniques** and a **mass drop criteria** in a fat jet to define inputs to traditional τ reconstruction techniques

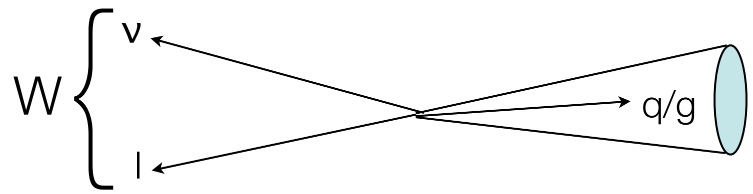
W/Z discrimination

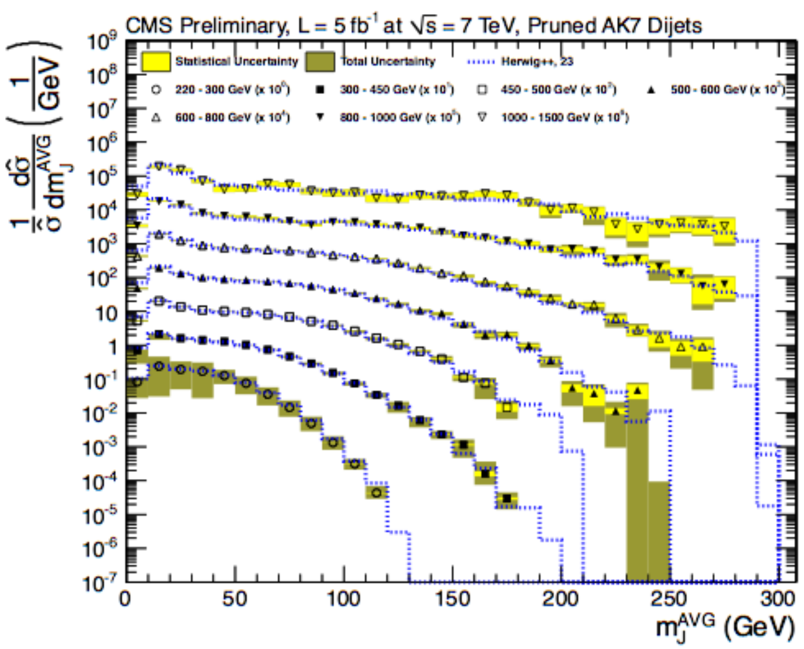


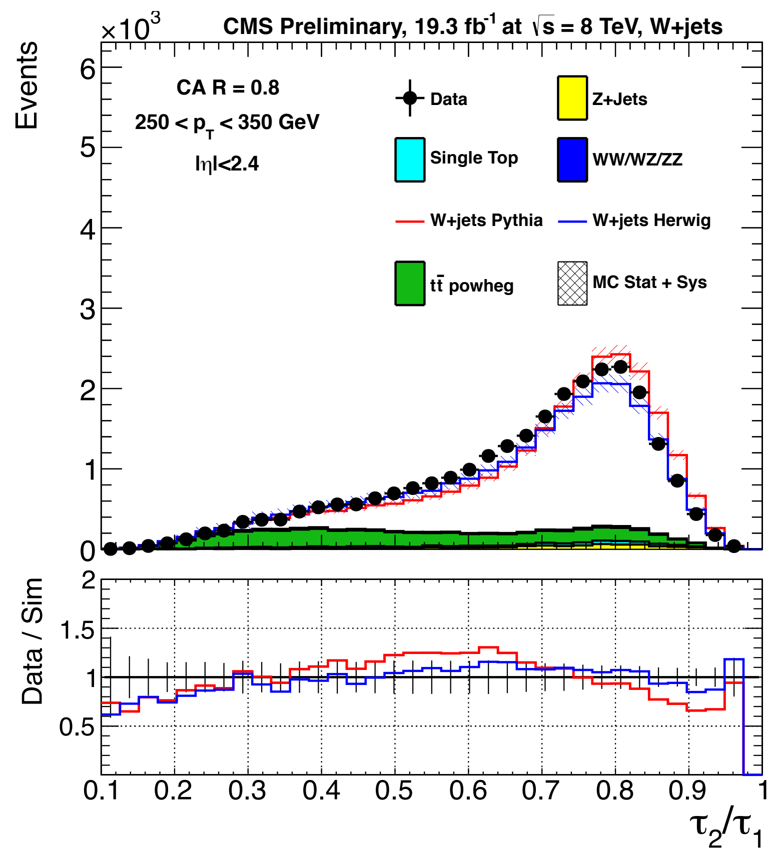


validation of QCD







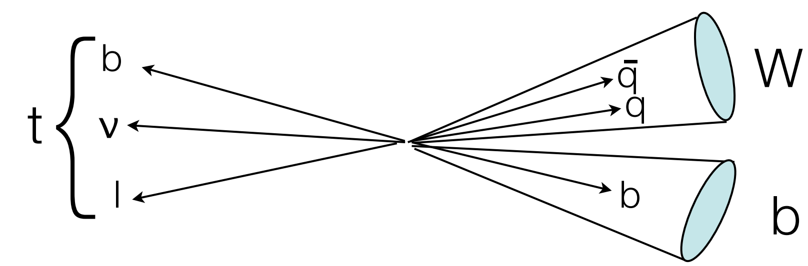


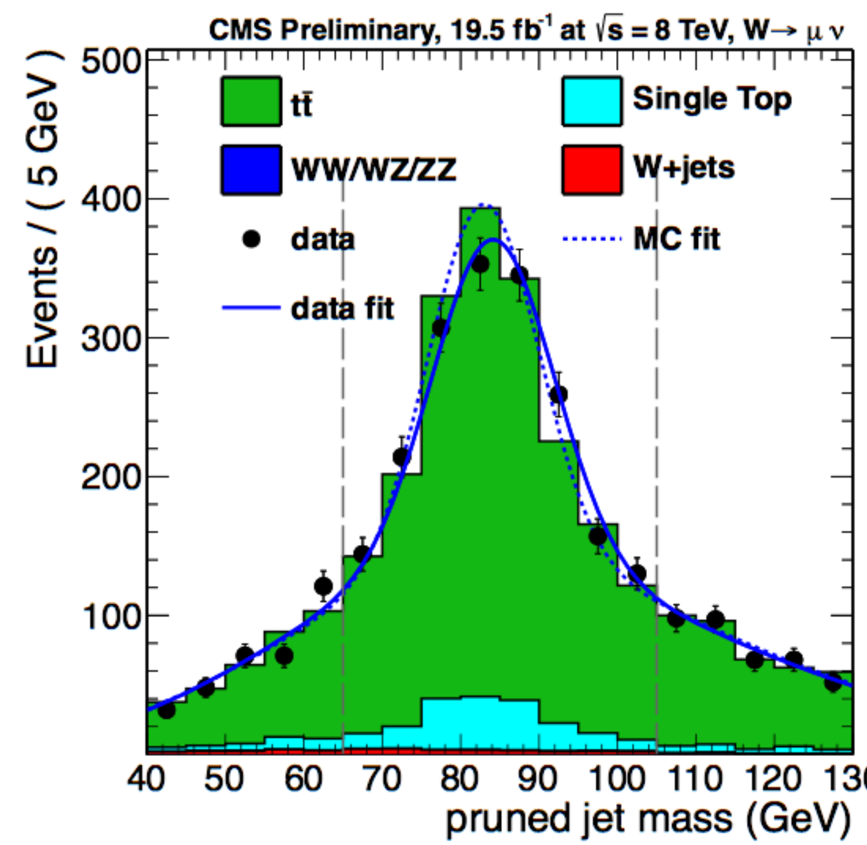
Extensive studies of substructure variables in many different topologies between data and MC

unfolded measurements are used to validate parton shower tunes

standard candles

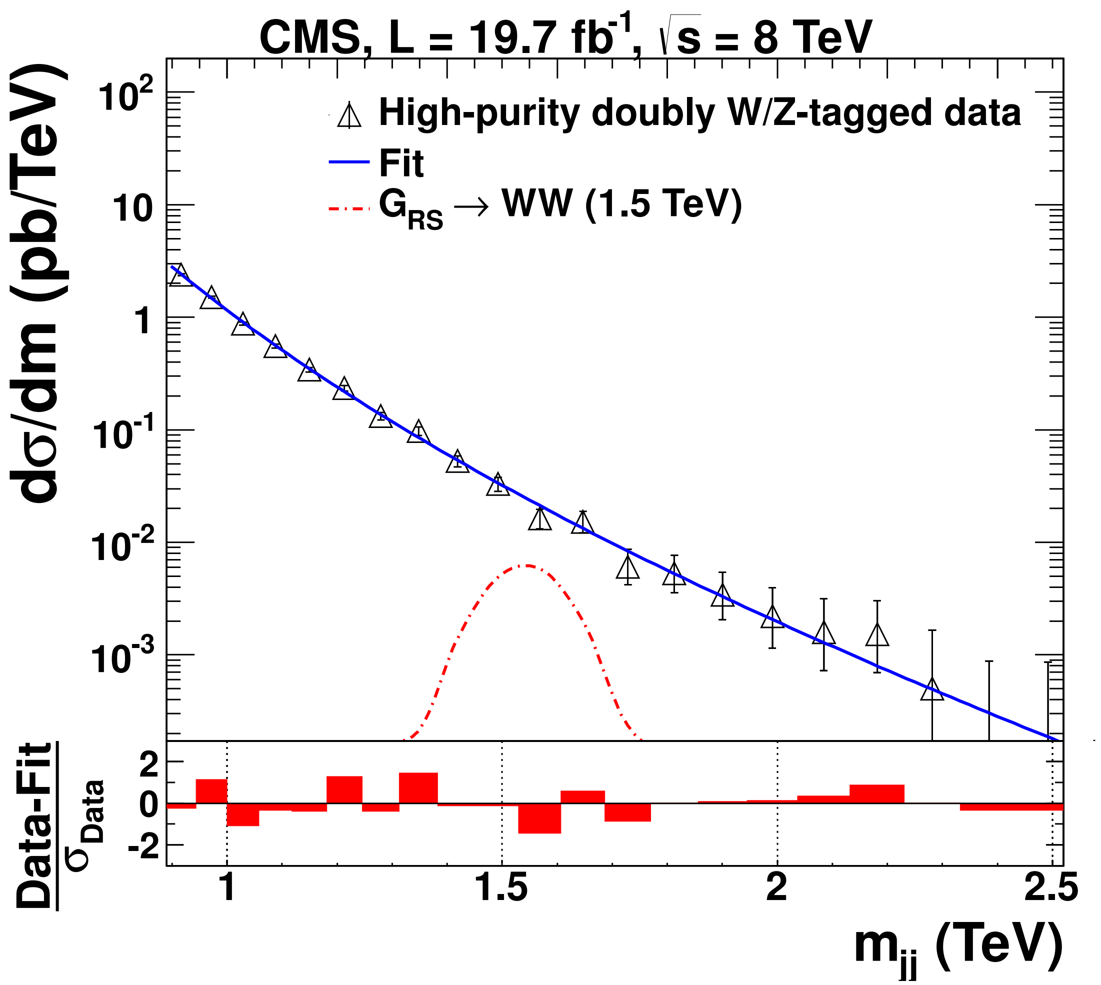
efficiency measurements using real boosted W jets in semi-leptonic tt

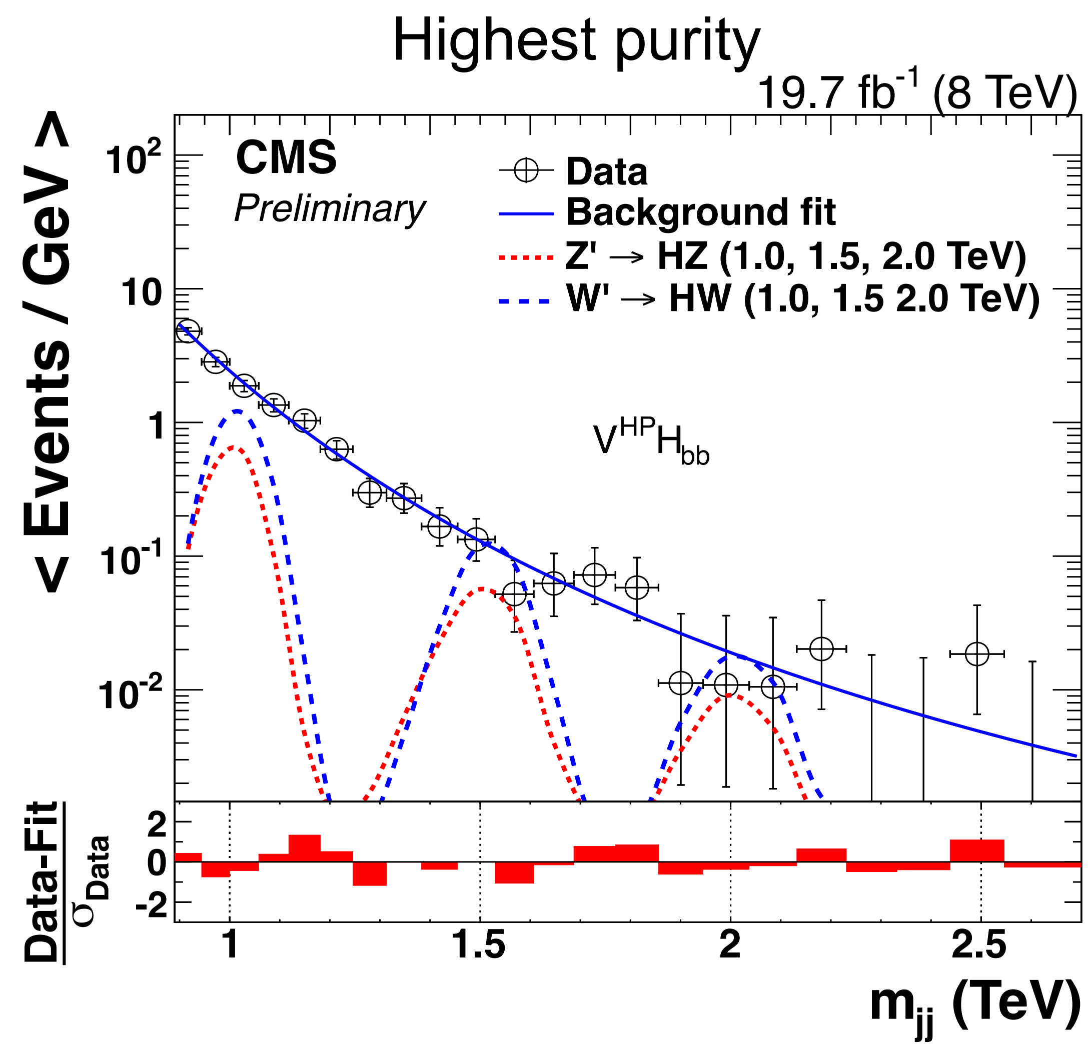




fully data driven backgrounds

Used for JJ (qqqq,qqbb,bbbb,qqqqqq,qqτhτh)



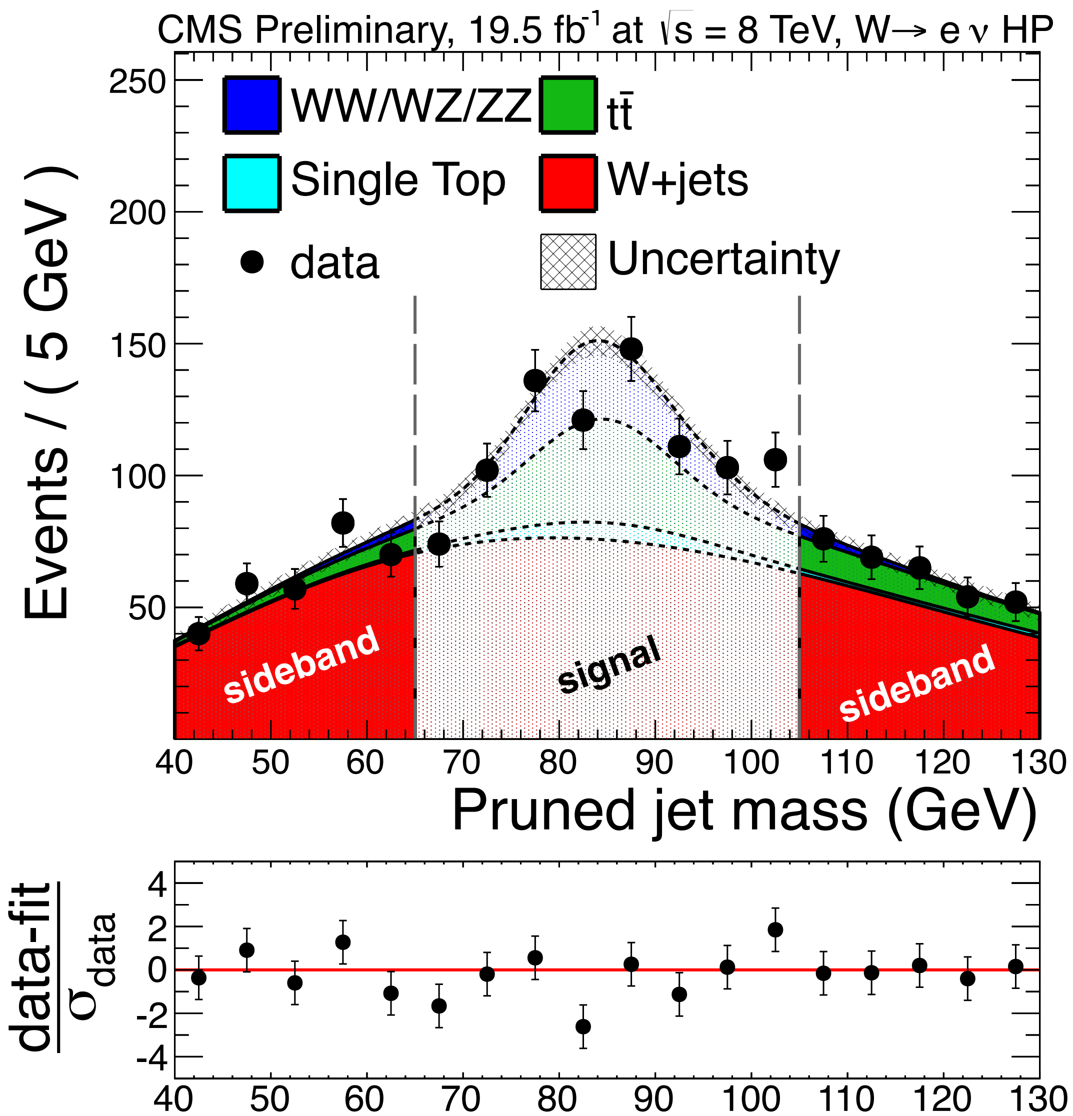


Assuming background has smooth shape, look for bump on top of background shape; simultaneous signal/background fit

no need for background simulation, but only relevant bump hunting on a smooth background (no kinematic/trigger turn-ons)

partially data driven backgrounds

Used for JJ (lvqq,llqq,qqτlτl/h)



Use sideband region to extrapolate into signal region

Rate and shape taken from background sideband; takes shape extrapolation and related uncertainties from the simulation

Closure tests performed in simulation and alternative data sidebands

fully MC estimated backgrounds

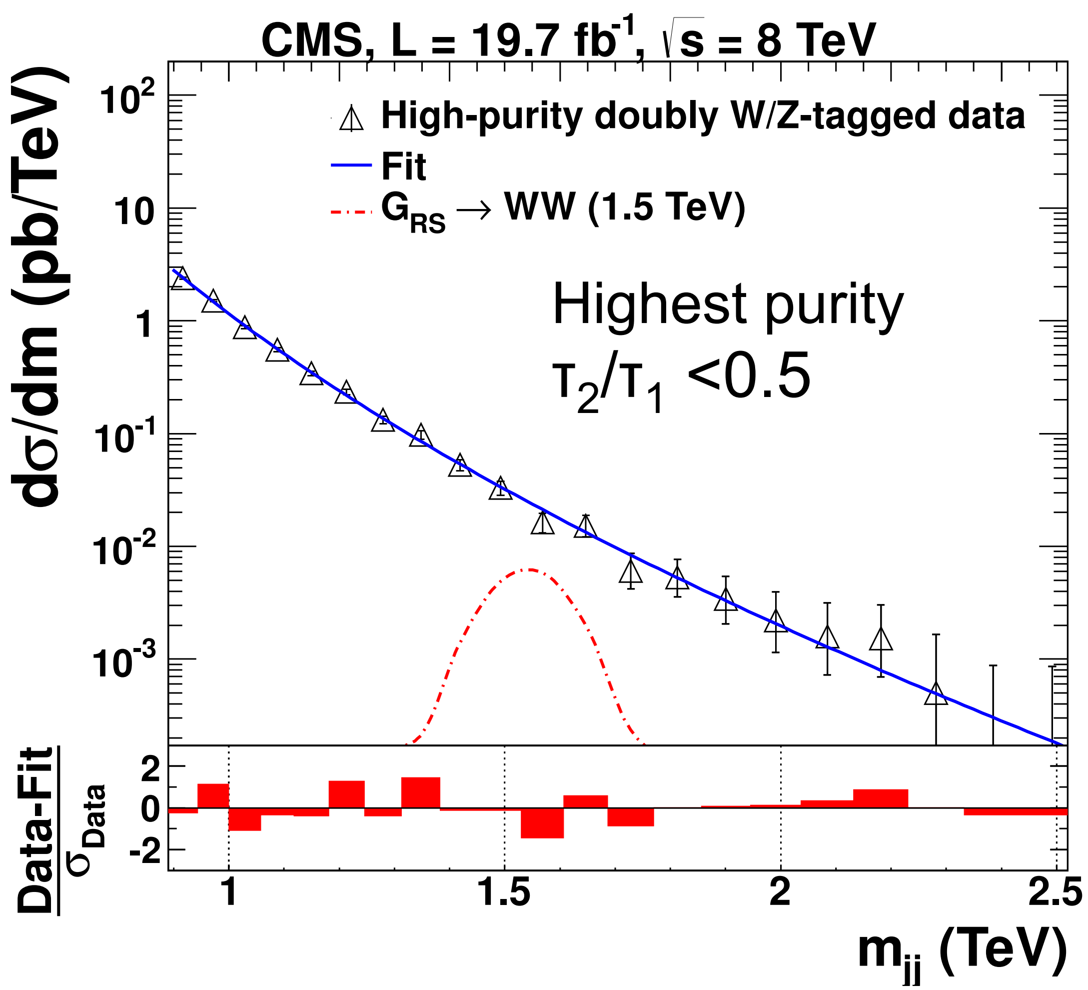
Used for smaller SM backgrounds, e.g. WZ → lllv search results

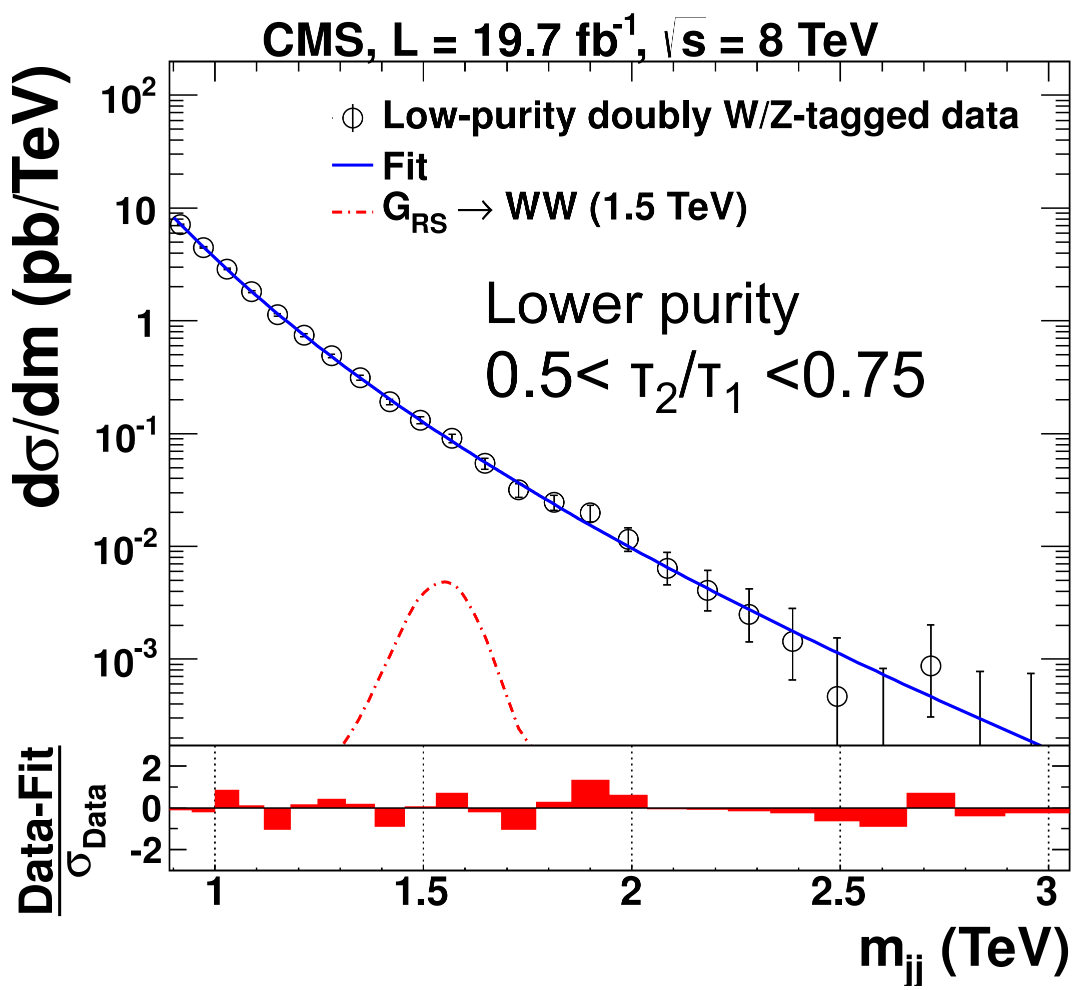
V V

V H

H H

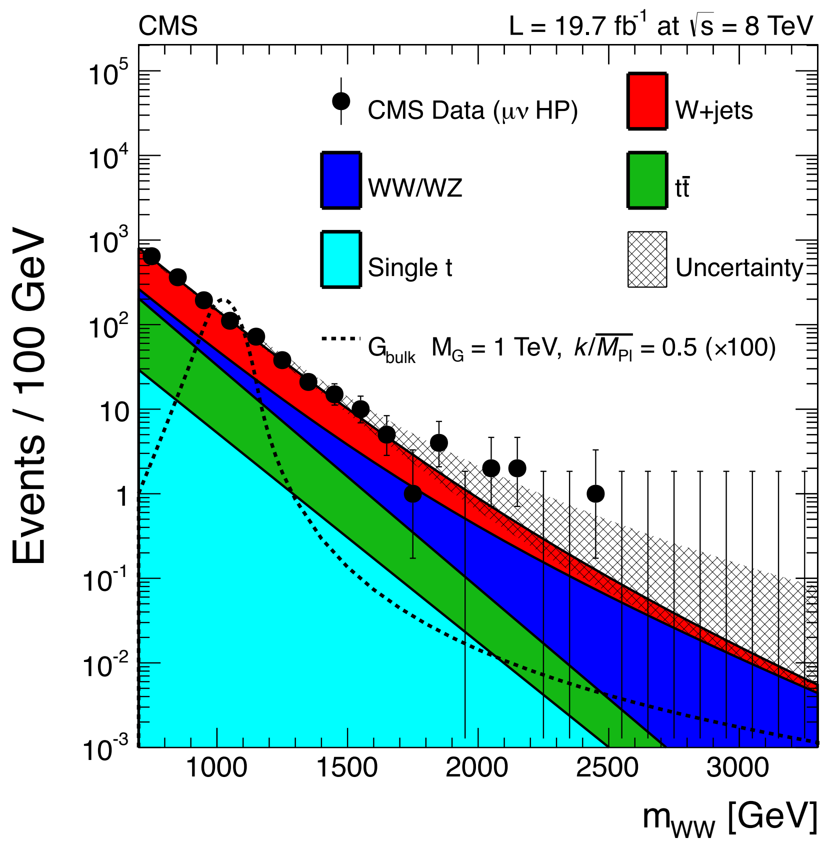
analysis split into high and low purity regions



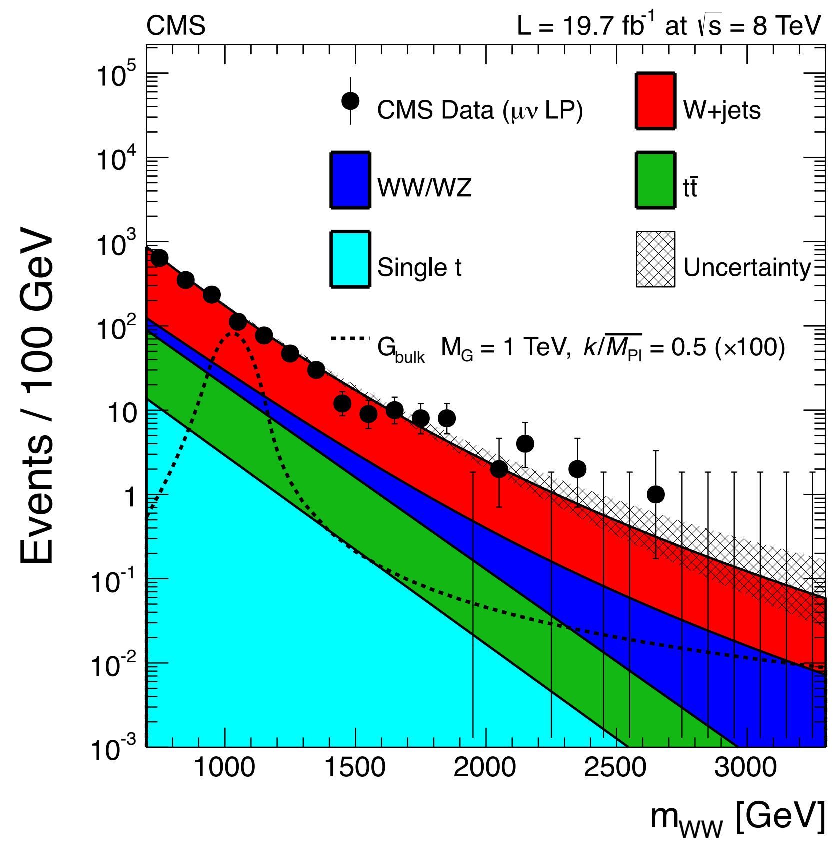


1.3σ effect at 1.8 TeV

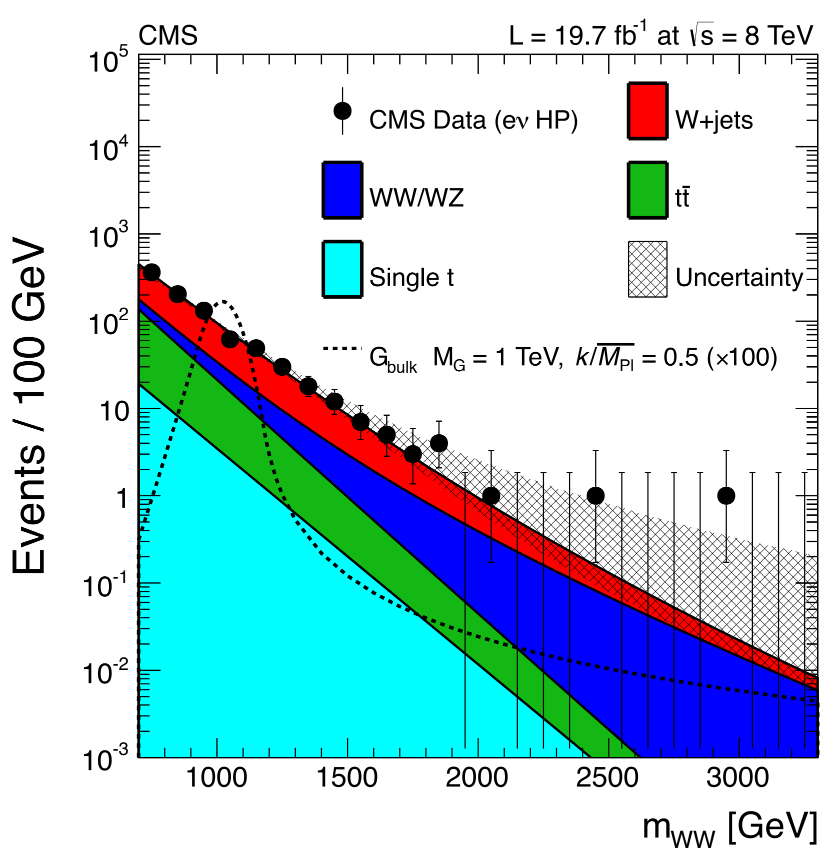
μ channel high purity



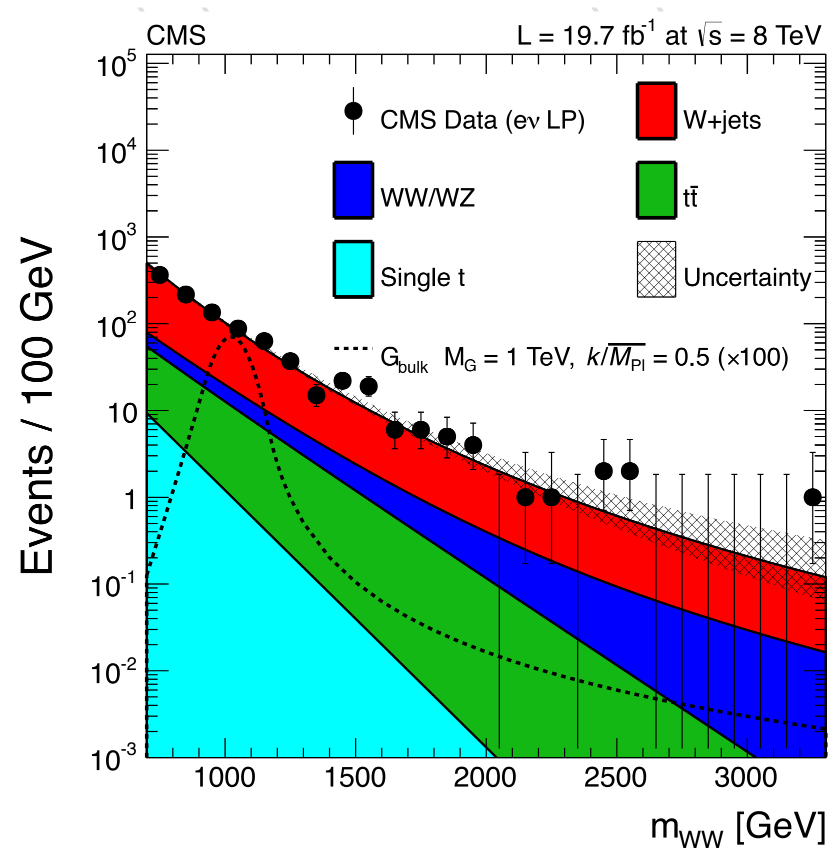
μ channel low purity



e channel high purity



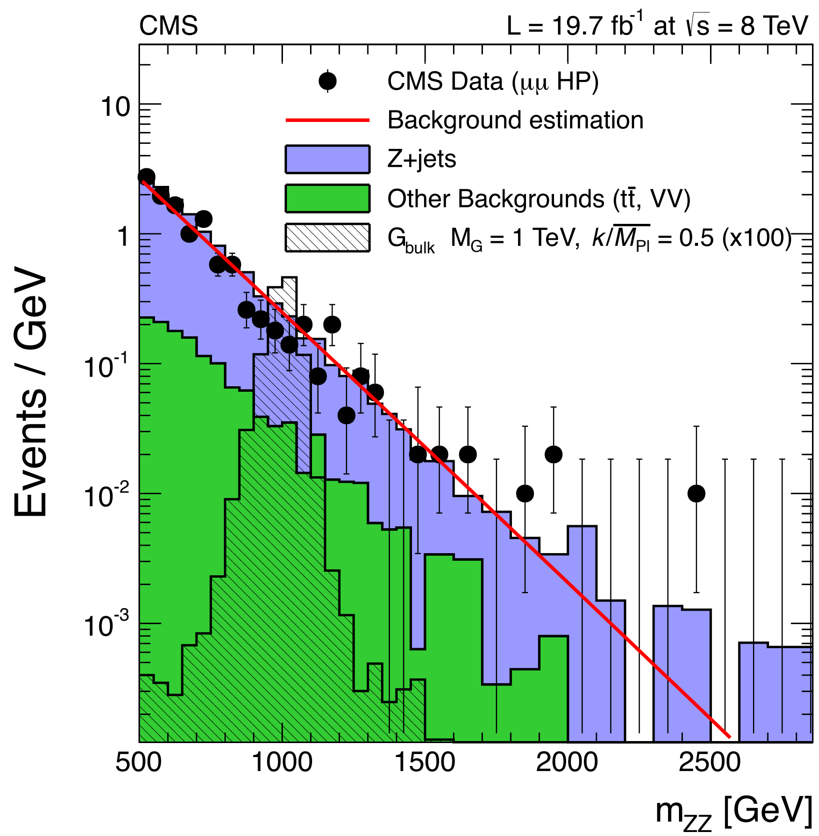
e channel low purity

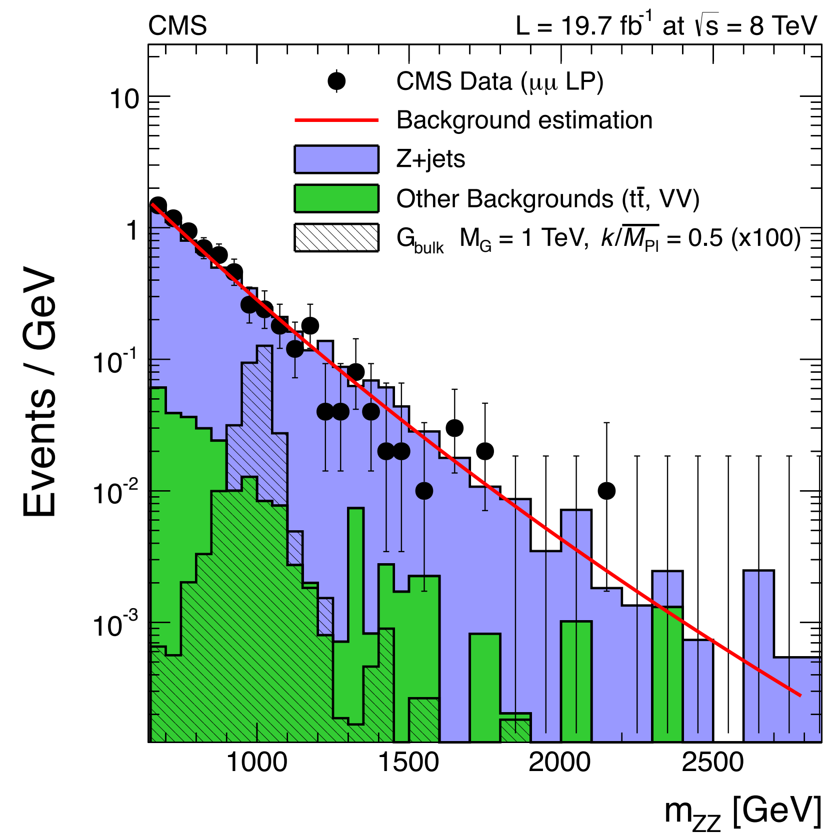


V V → llqq

EXO-13-009

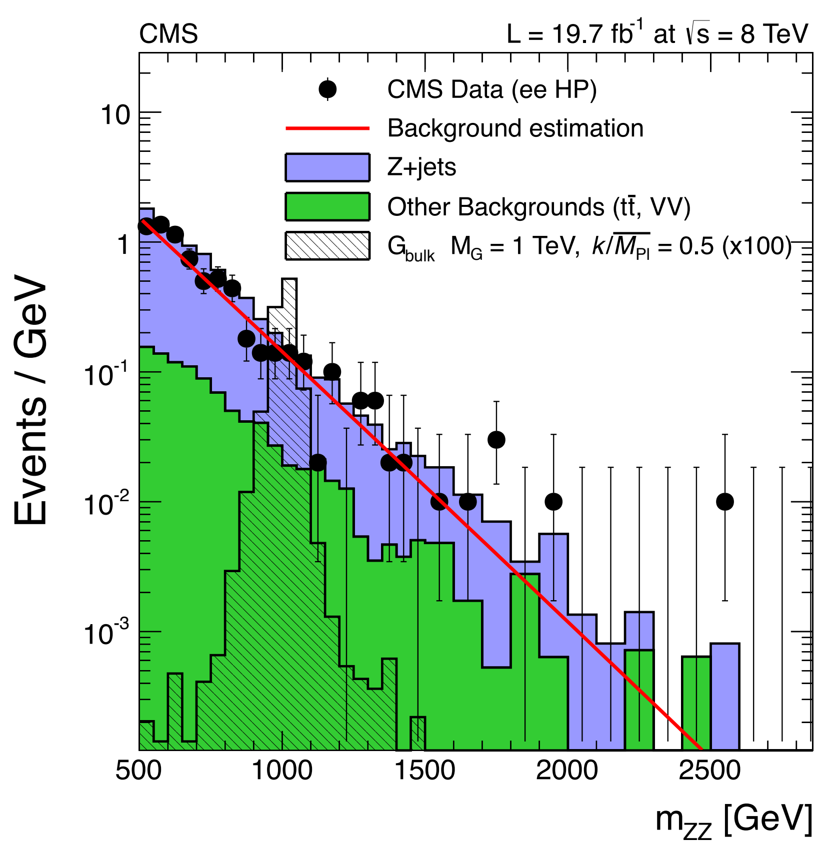
μμ channel high purity

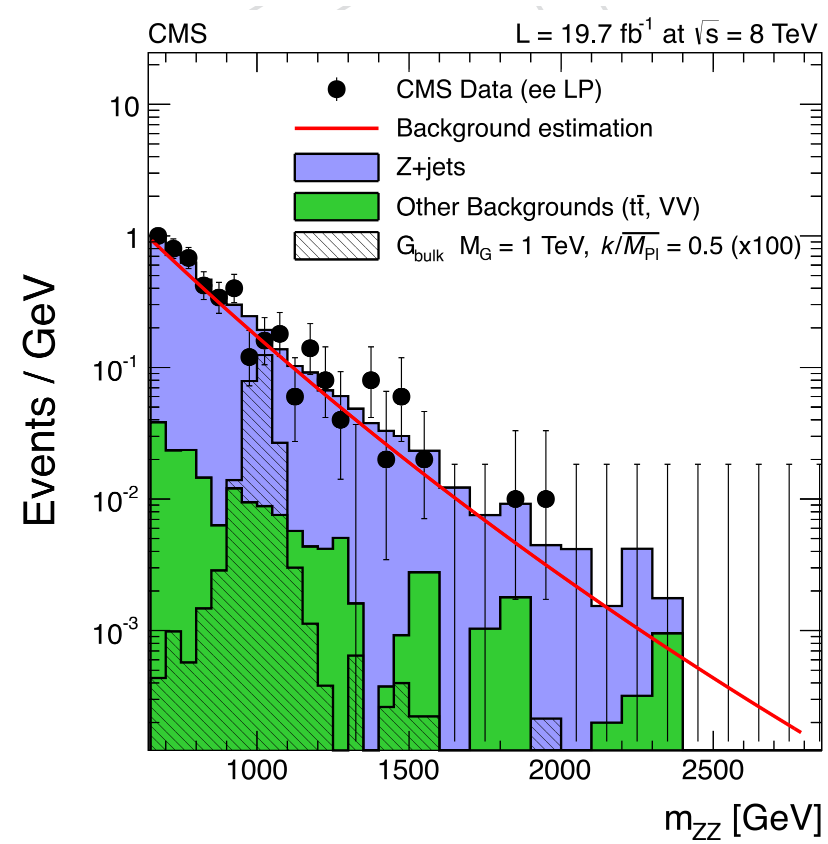




μμ channel low purity

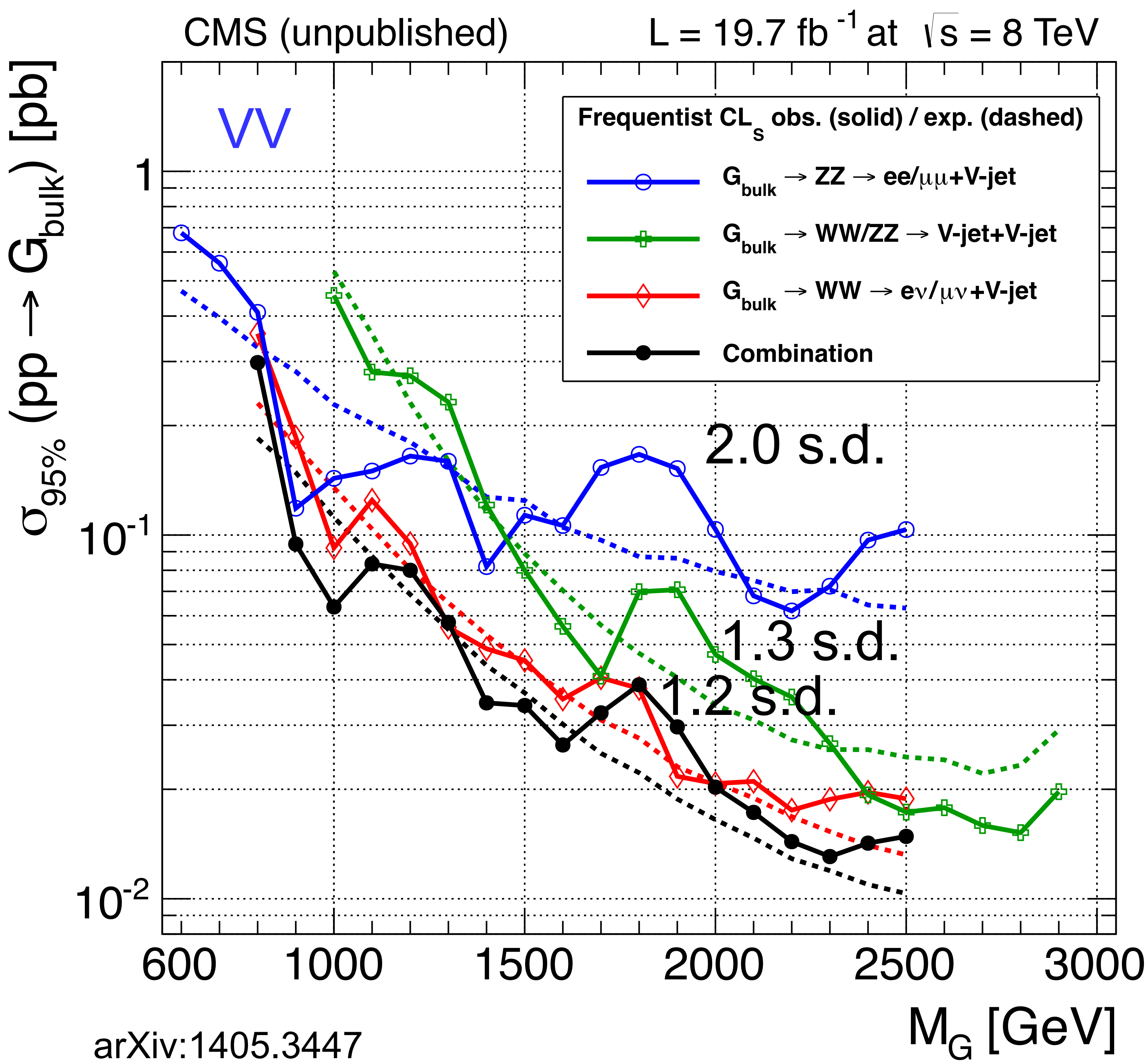
ee channel high purity





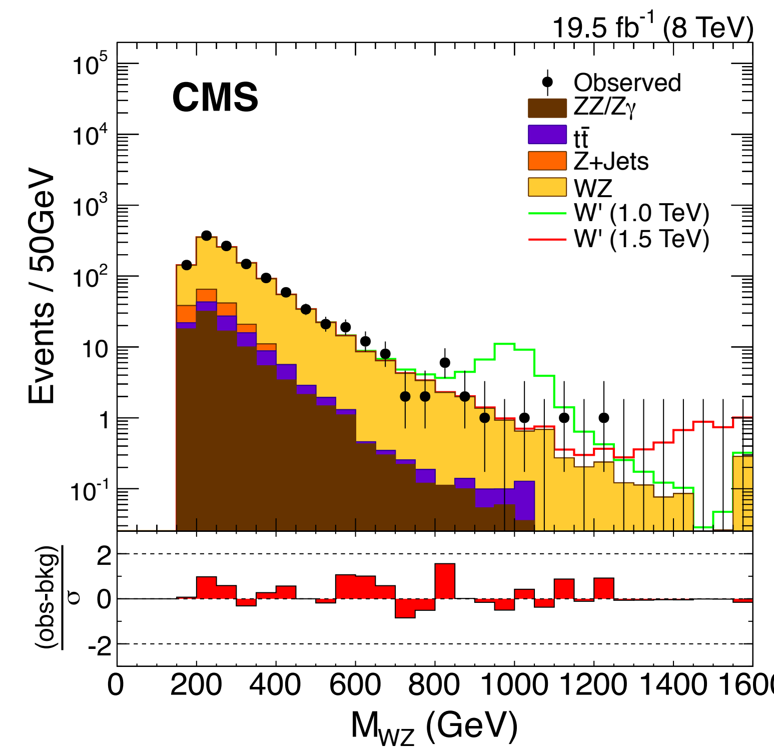
ee channel low purity

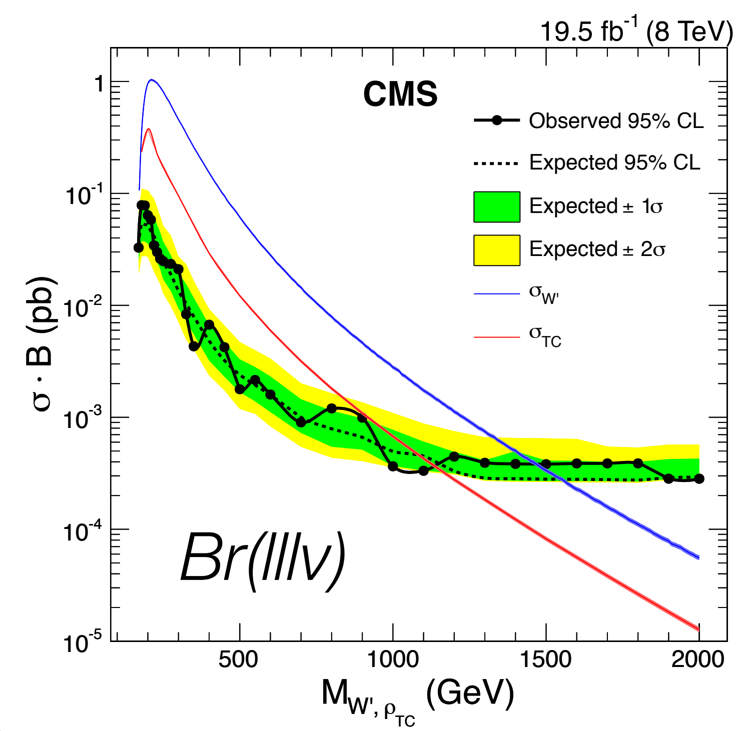
VV upper limits



arXiv:1405.3447

WZ → lllν

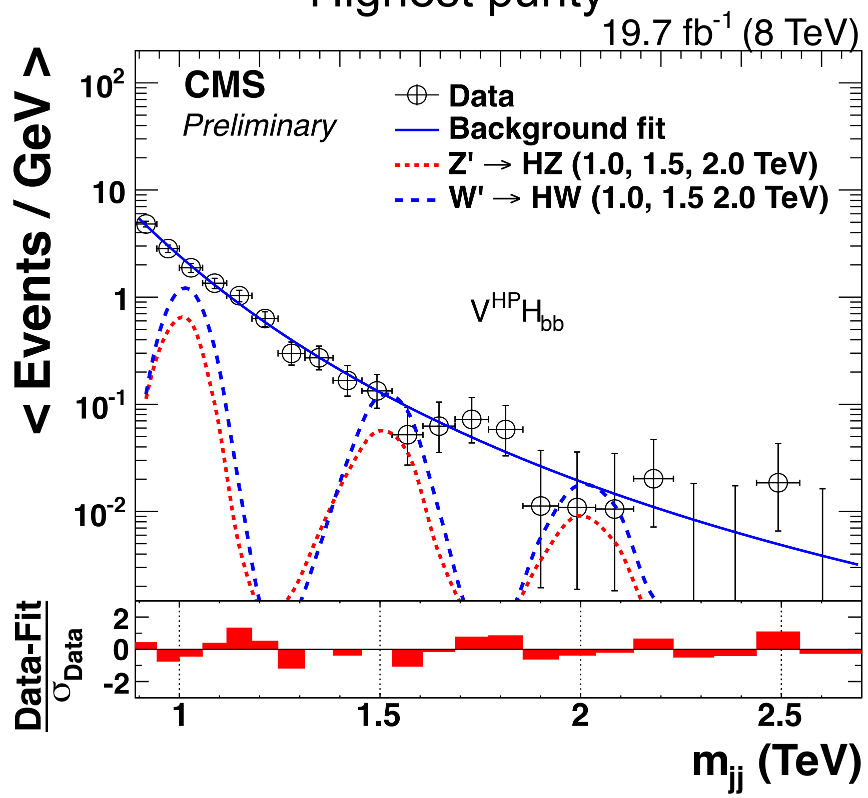




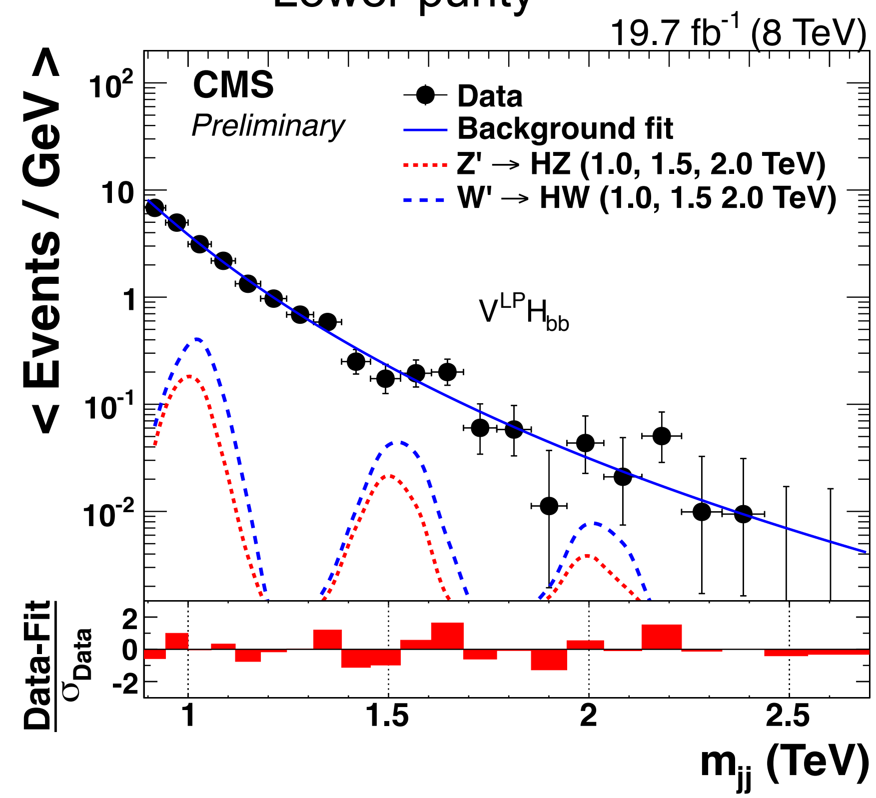
VH → qqbb, 6q

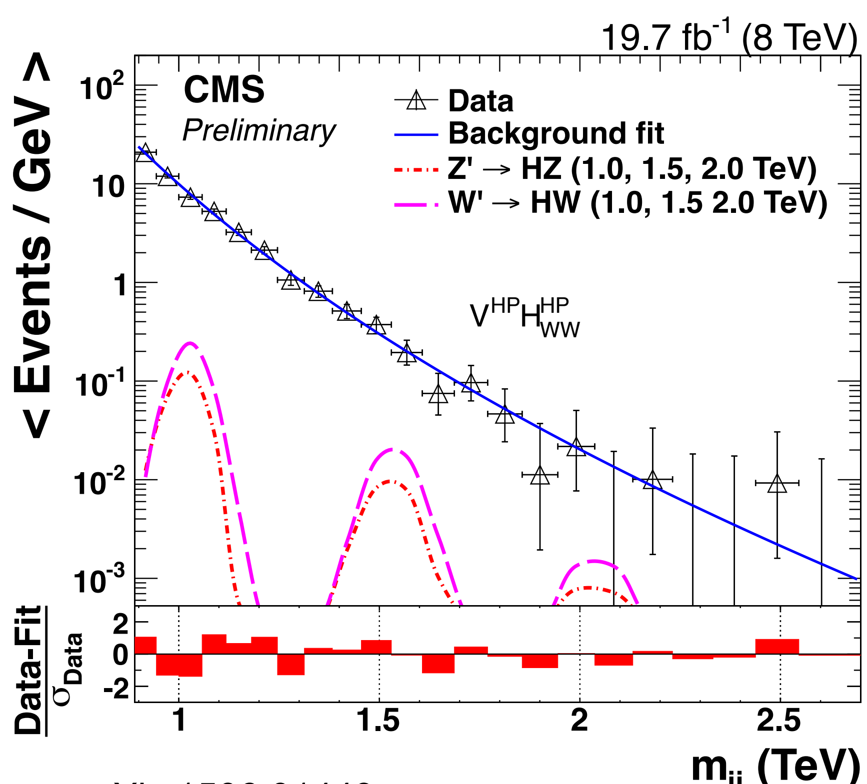
W/Z+H → qqbb

Highest purity



Lower purity



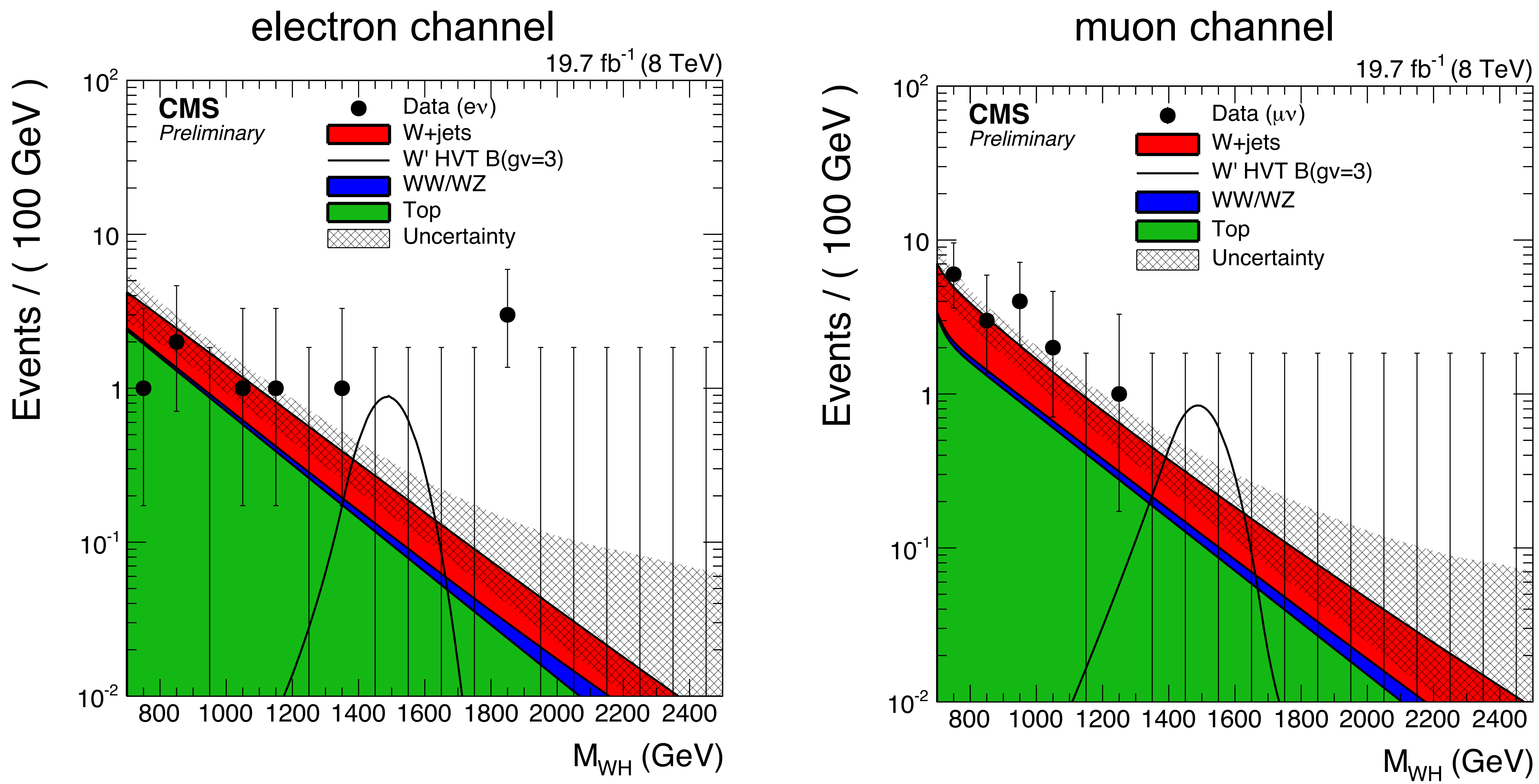


arXiv:1506.01443

VH → VWW → 6q

(also $V^{HP}H_{LP}$, $V^{LP}H_{HP}$ categories)

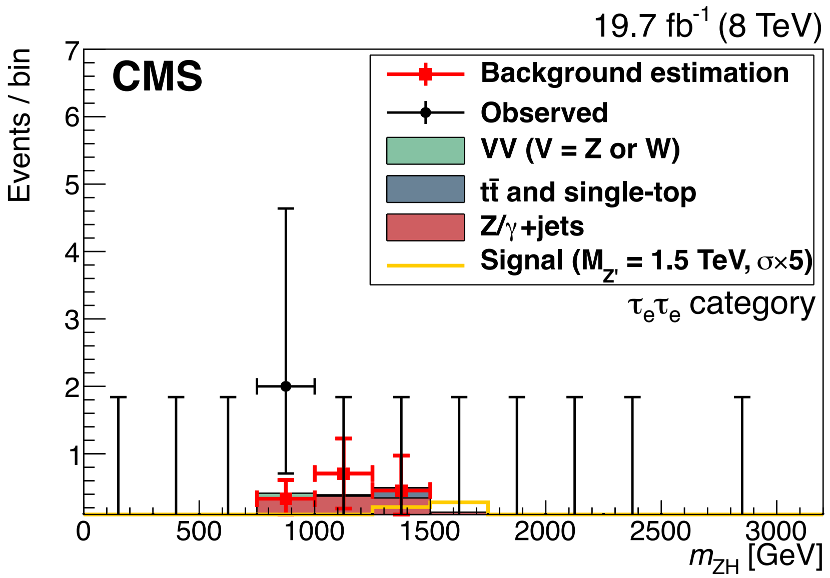
WH → lvbb


electron channel
19.7 fb-1 (8 TeV)
CMS
Preliminary
Data (eν)
W+jets
W' HVT B(gv=3)
WW/WZ
Top
Uncertainty
Events / (100 GeV)
MWH (GeV)
muon channel
19.7 fb-1 (8 TeV)
CMS
Preliminary
Data (μν)
W+jets
W' HVT B(gv=3)
WW/WZ
Top
Uncertainty
Events / (100 GeV)
MWH (GeV)

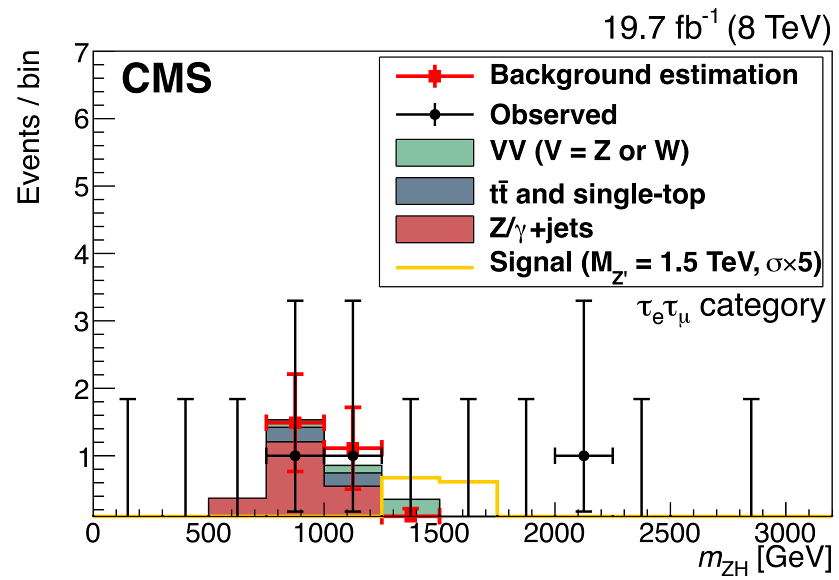
$ZH \rightarrow qq\tau\tau$

all τ modes are covered!

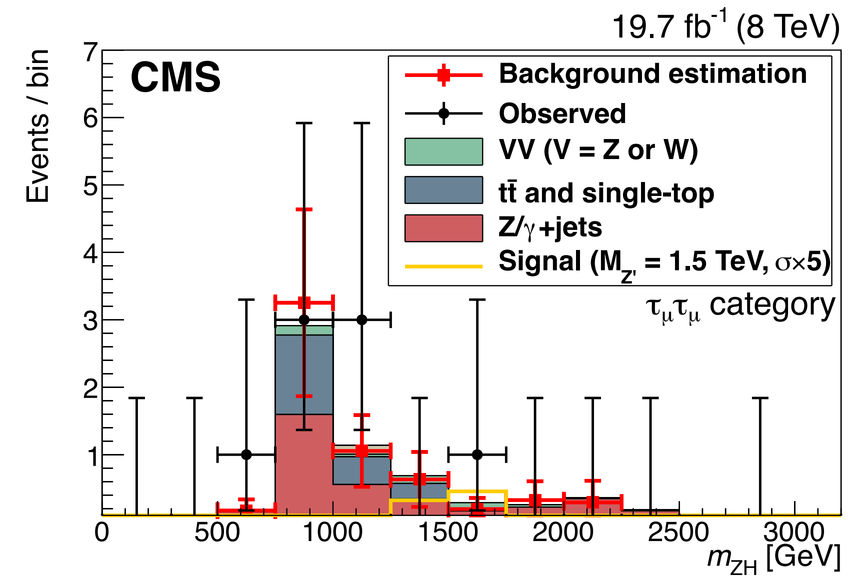
$\tau_e\tau_e$

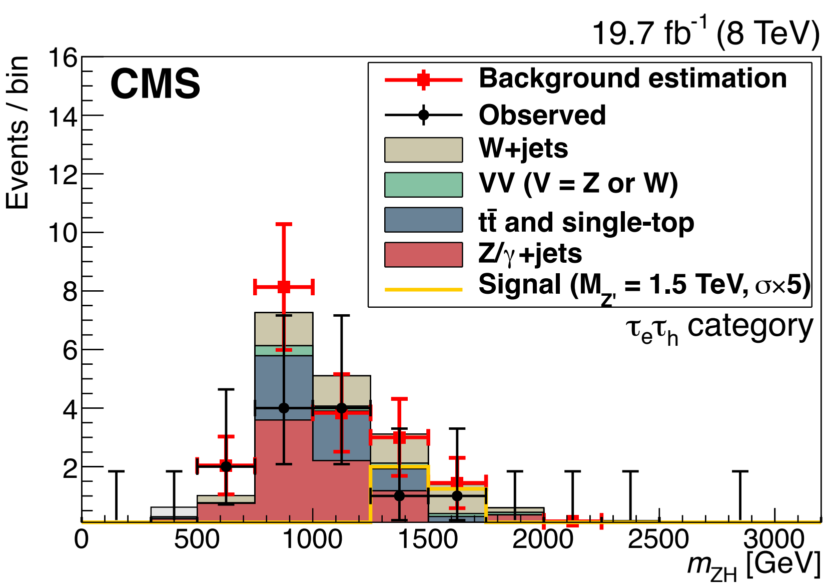


$\tau_e\tau_\mu$

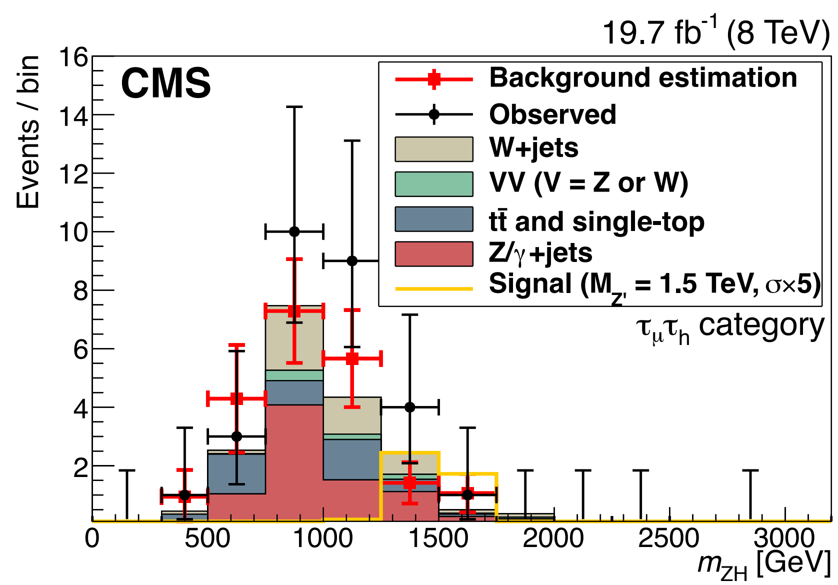


$\tau_\mu\tau_\mu$

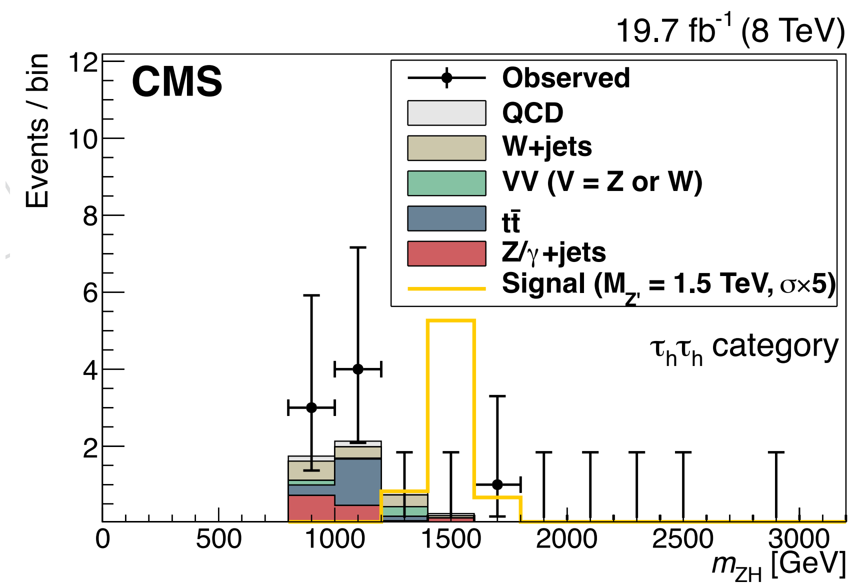




$\tau_e\tau_h$



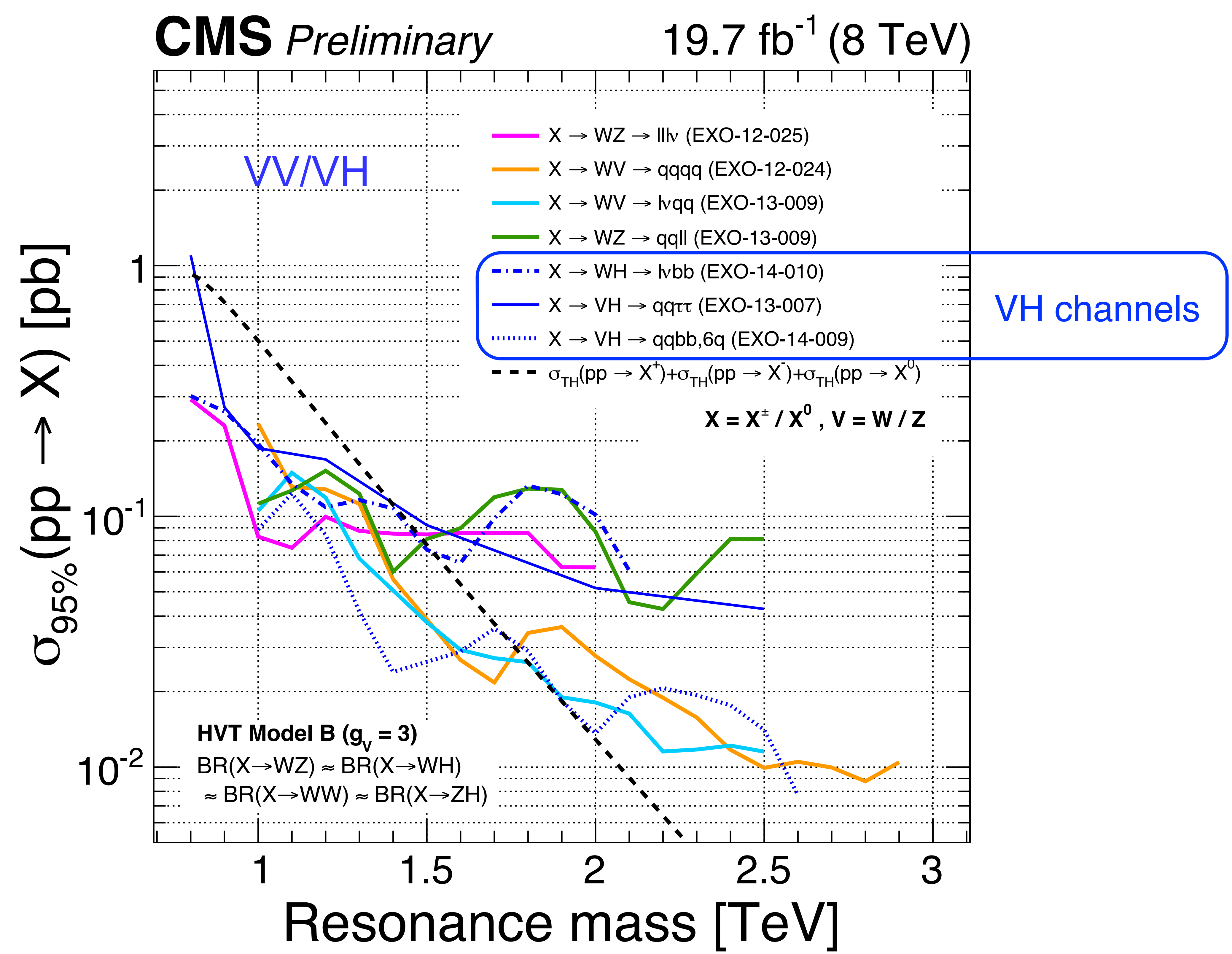
$\tau_\mu\tau_h$



$\tau_h\tau_h$

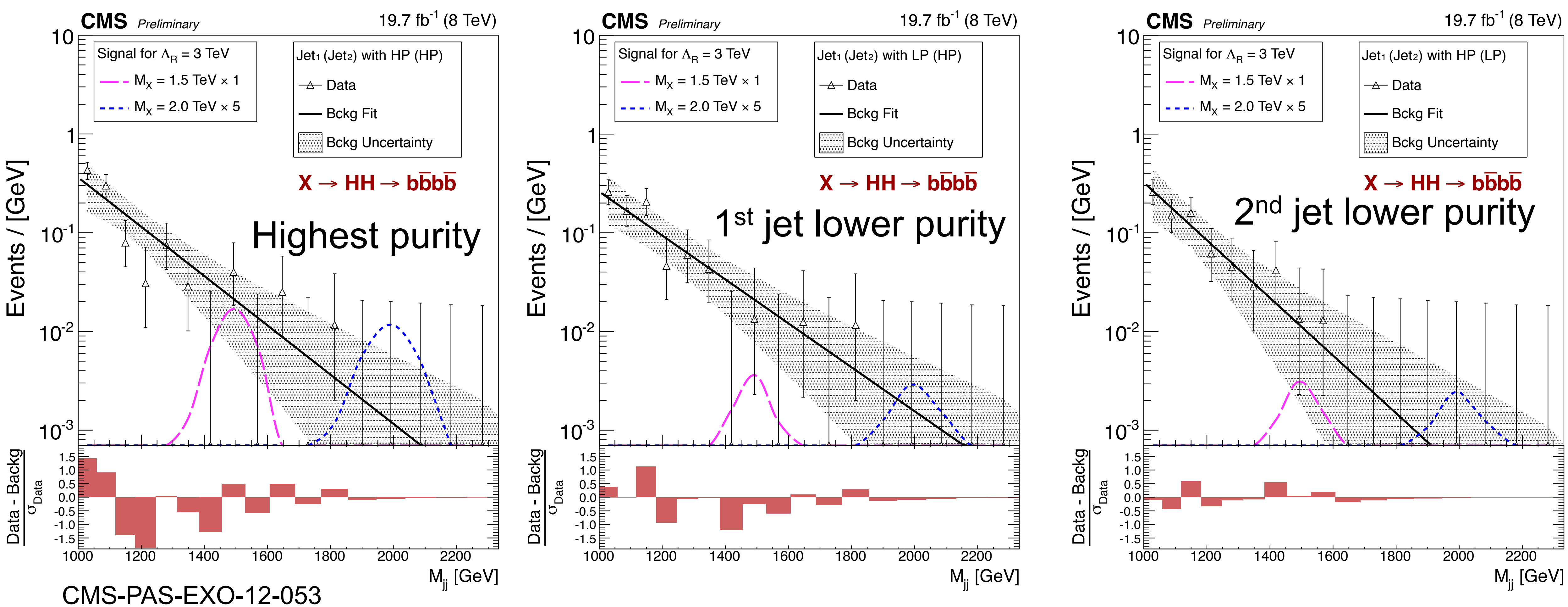
VH upper limits

N.B. different signal model, heavy vector triplet



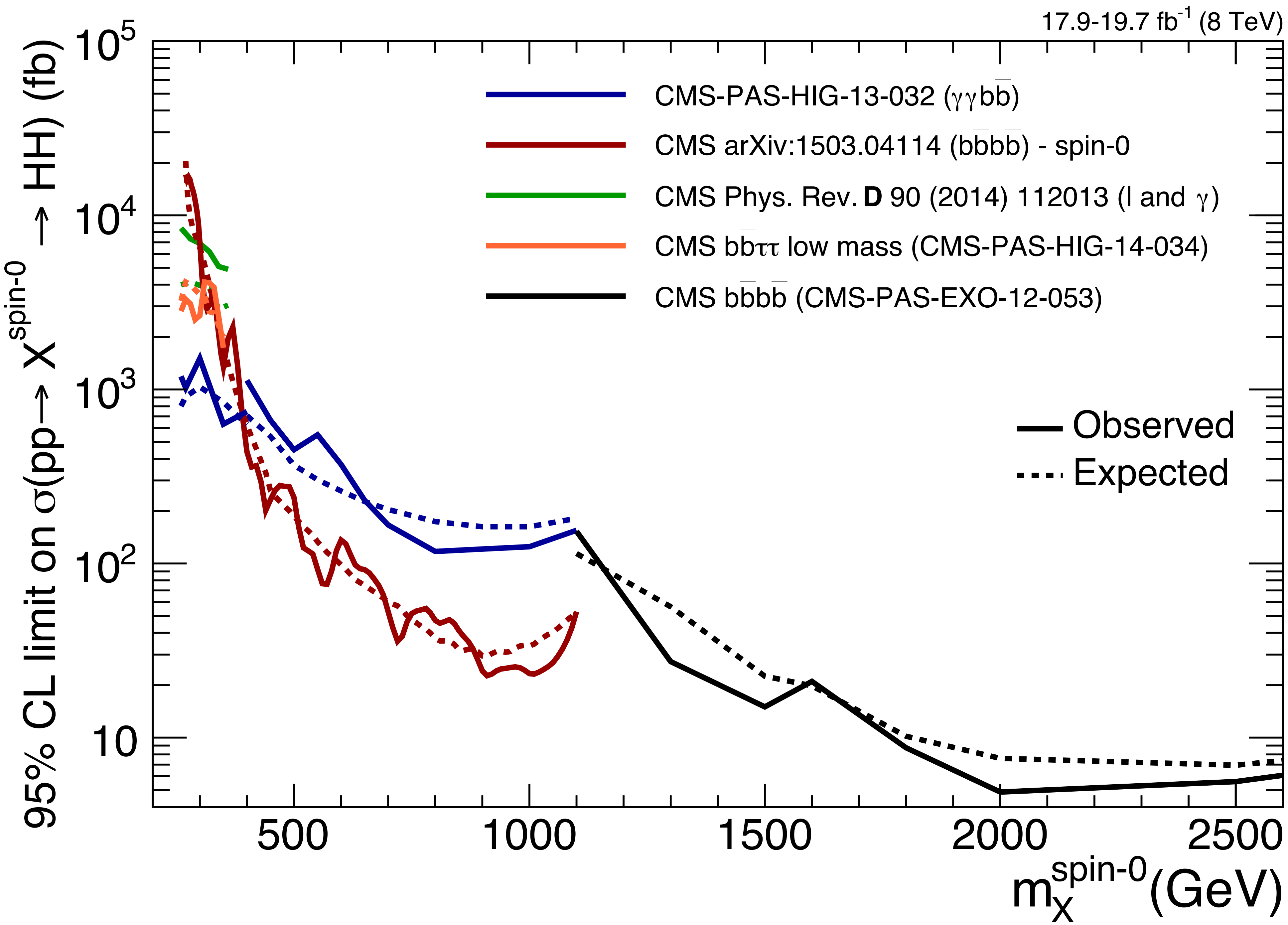
HH → bbbb

analysis split into high and low τ_2/τ_1 purity regions



subjet b-tagging based on 3 highest subjets or 2 fat jet b tags

HH → bbbb



N.B. boosted regime taking over > ~1 TeV

conclusions and outlook

rich program of diboson searches at CMS
- broad searches for VV, VH and HH

common techniques used amongst various different analyses
- many analyses use jet substructure techniques and subjet b-tagging to identify highly boosted W,Z,H
- similar jet substructure background techniques across the analyses

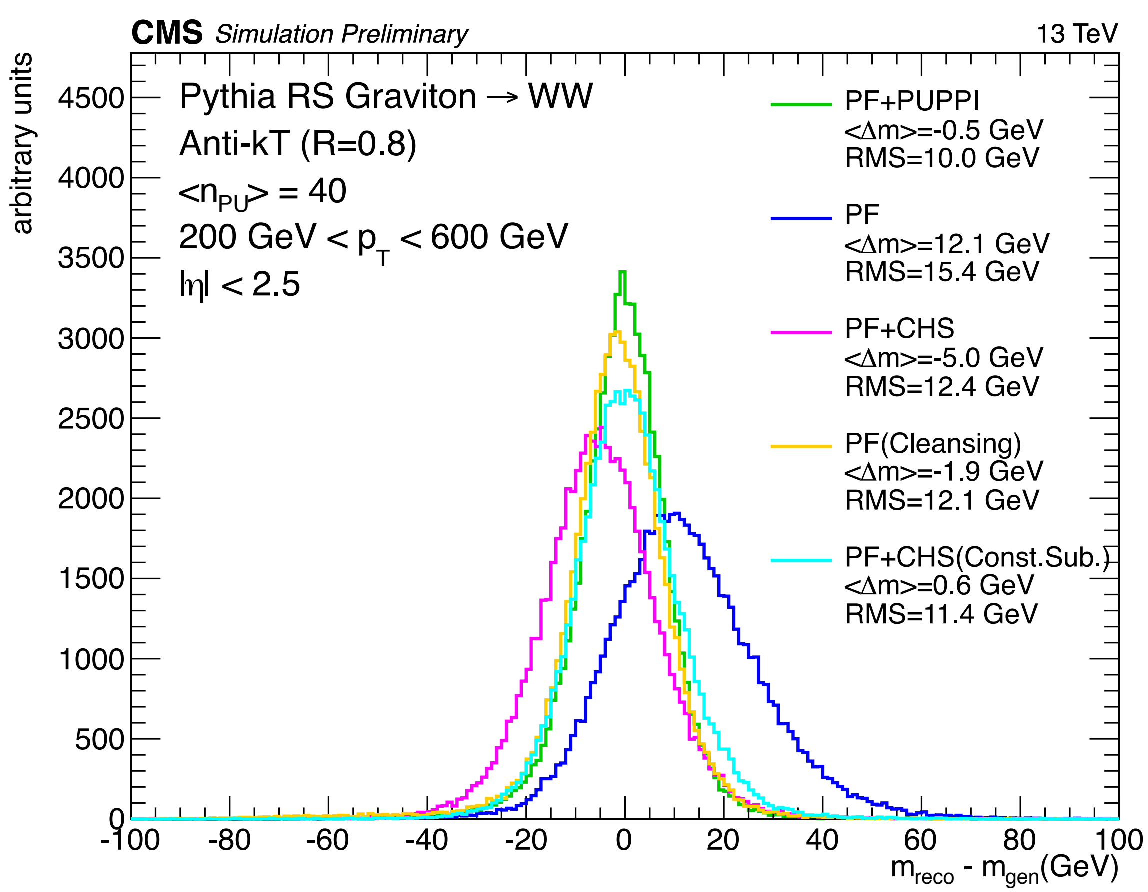
	W	Z	H
W	lv+qq, qq+qq	lv+qq, ll+qq qq+qq, lv+ll	lv+bb, qq+bb, qq+ττ, qq+WW(qqqq)
Z		ll+qq, qq+qq	qq+bb,qq+ττ, qq+WW(qqqq)
H			bb+bb

conclusions and outlook

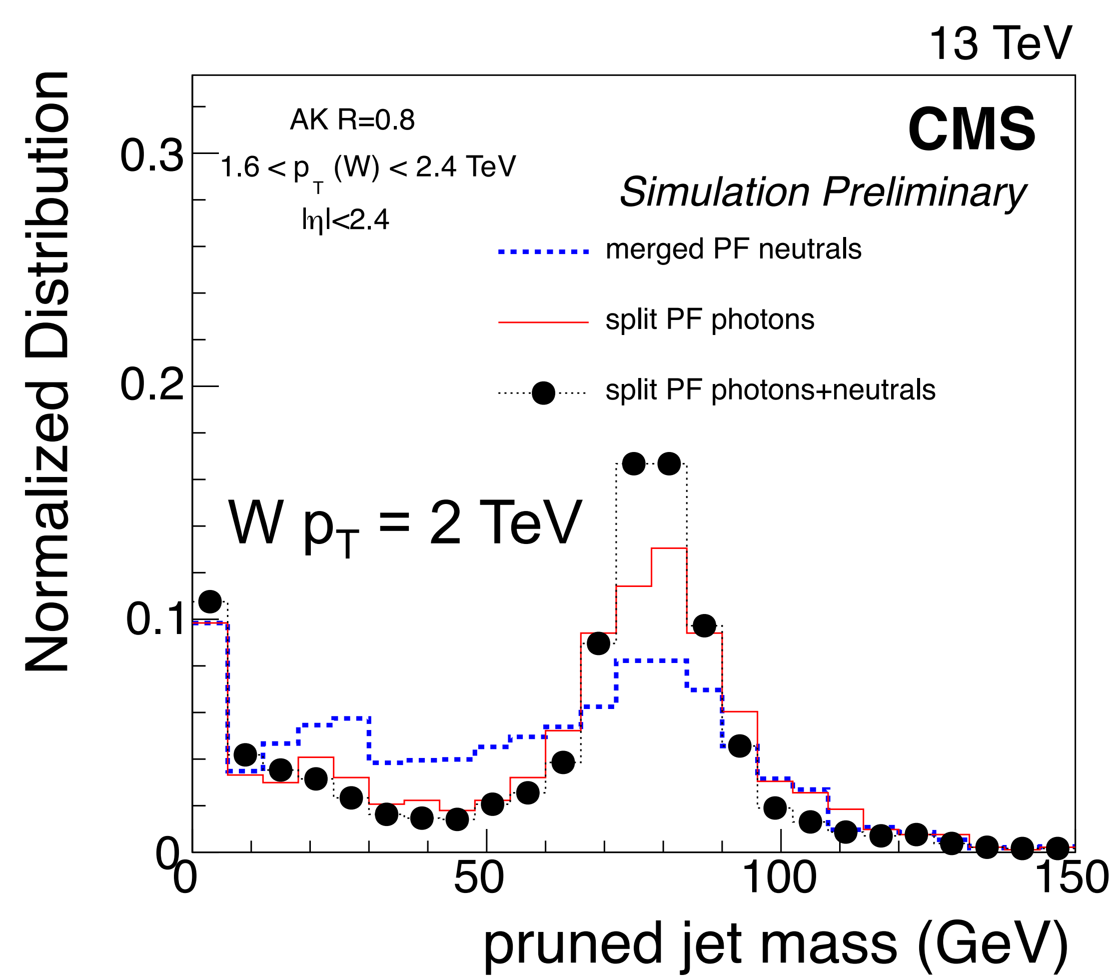
Some mild excesses to keep an eye on for Run 2!

Run 2 will be present new challenges for diboson searches
higher pileup and boost, CMS is prepared!

Pileup Per Particle Id (PUPPI)
keeps substructure observables robust in high pileup environments



Particle flow improvements keep substructure robust at very high pT

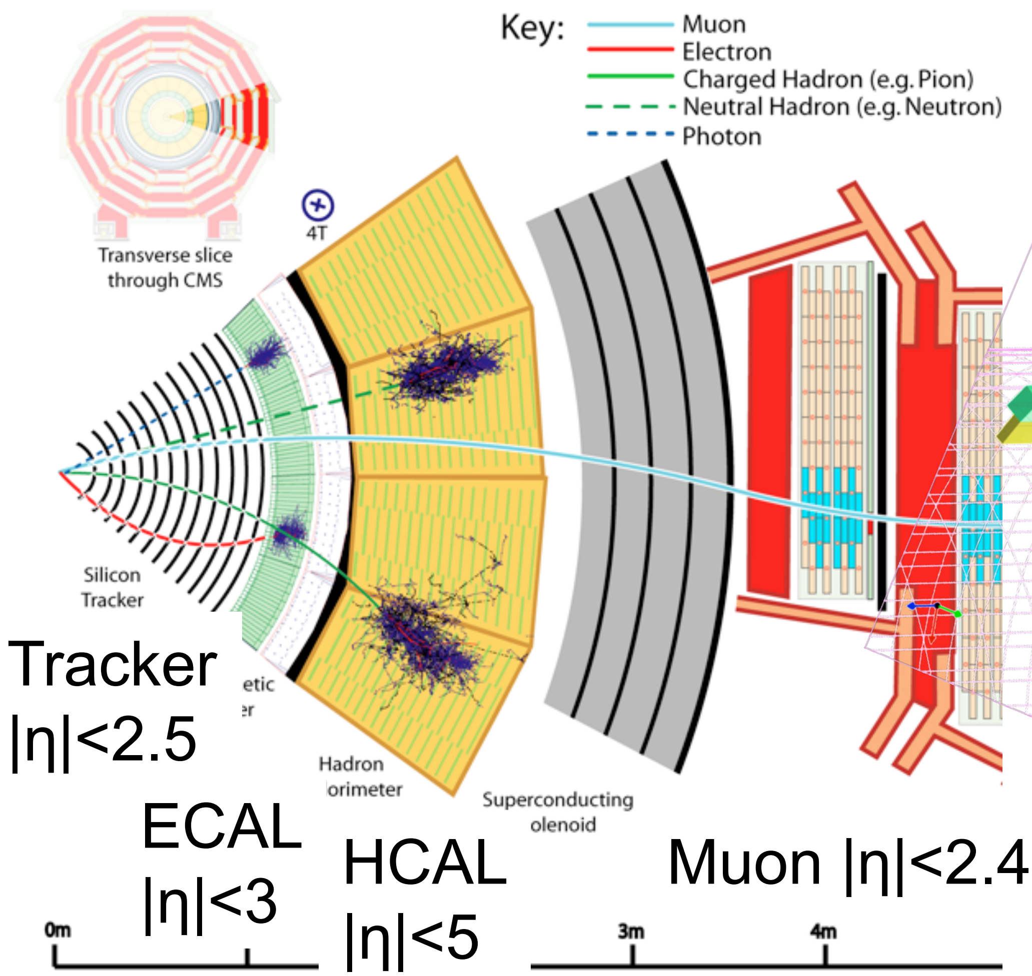


backup

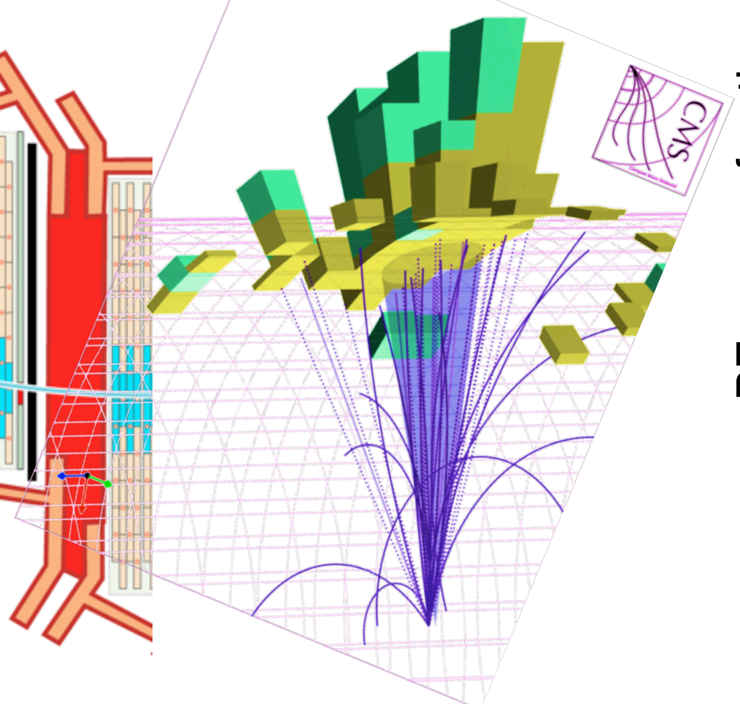
CMS jet reconstruction in a nutshell

Andreas Hinzmann

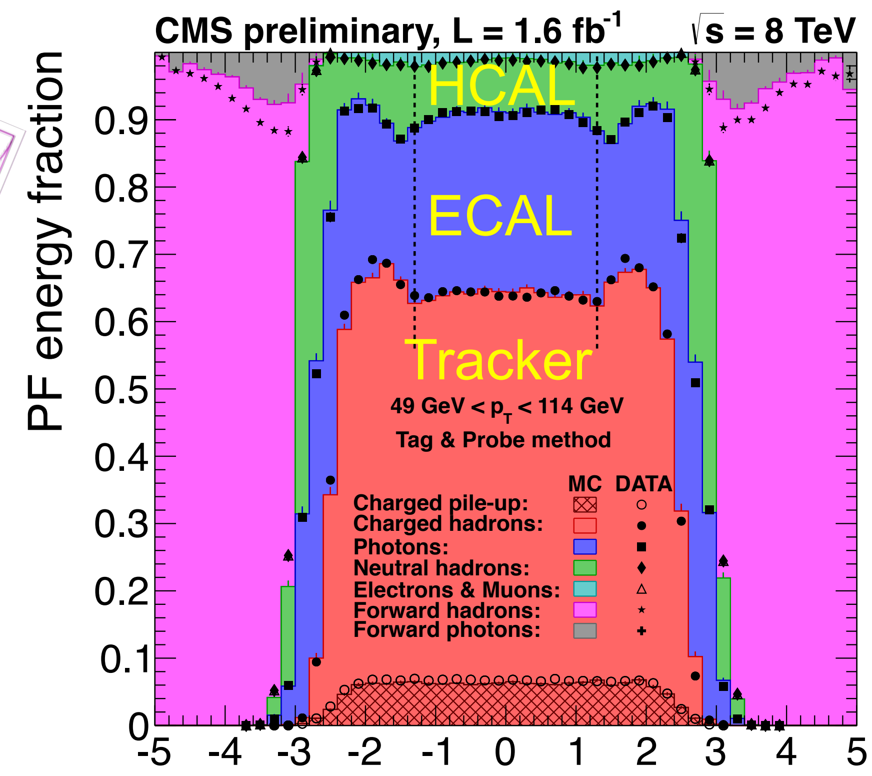
Particle flow reconstruction



Jet clustering (anti-k_T or CA)



Jet energy fractions



CMS-DP-2012/012

Particle Flow algorithm benefits from sub-detectors with best spatial+energy resolution

Detector	p_T-resolution	η/Φ-segmentation
Tracker	0.6% (0.2 GeV) – 5% (500 GeV)	0.002 x 0.003 (first pixel layer)
ECAL	1% (20 GeV) – 0.4% (500 GeV)	0.017 x 0.017 (barrel)
HCAL	30% (30 GeV) – 5% (500 GeV)	0.087 x 0.087 (barrel)

pT,Y,ϕ + tracking

mass

4-vector sum of jet constituents

highly sensitive to soft QCD and pileup; **grooming** can be used to mitigate these dependencies

shapes

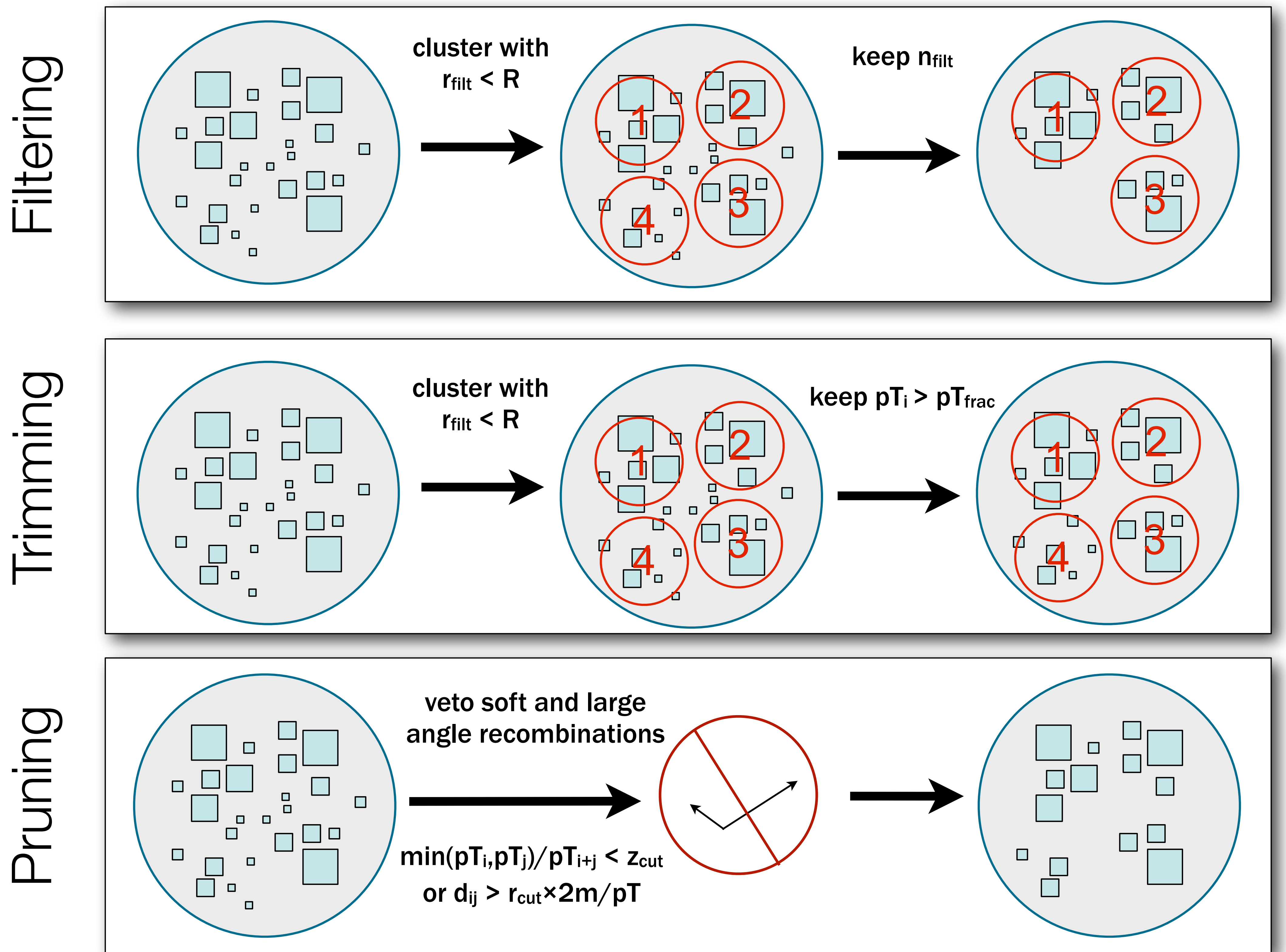
several classes: declustering/reclustering, generalized jet shapes and energy flow, statistical interpretation (Qjets), jet charge

algorithms

some combination of cuts on mass, shapes, tracking

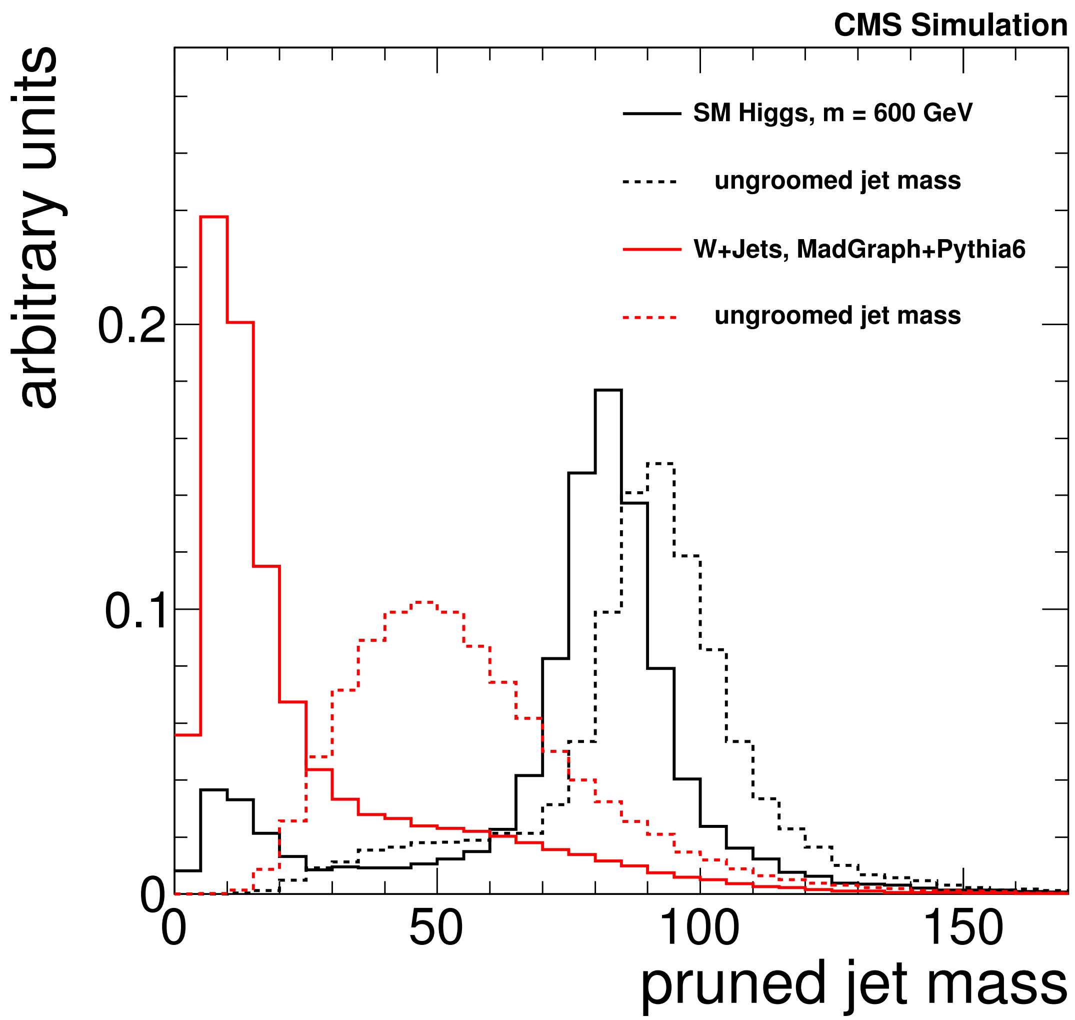
most typical in **top tagging**

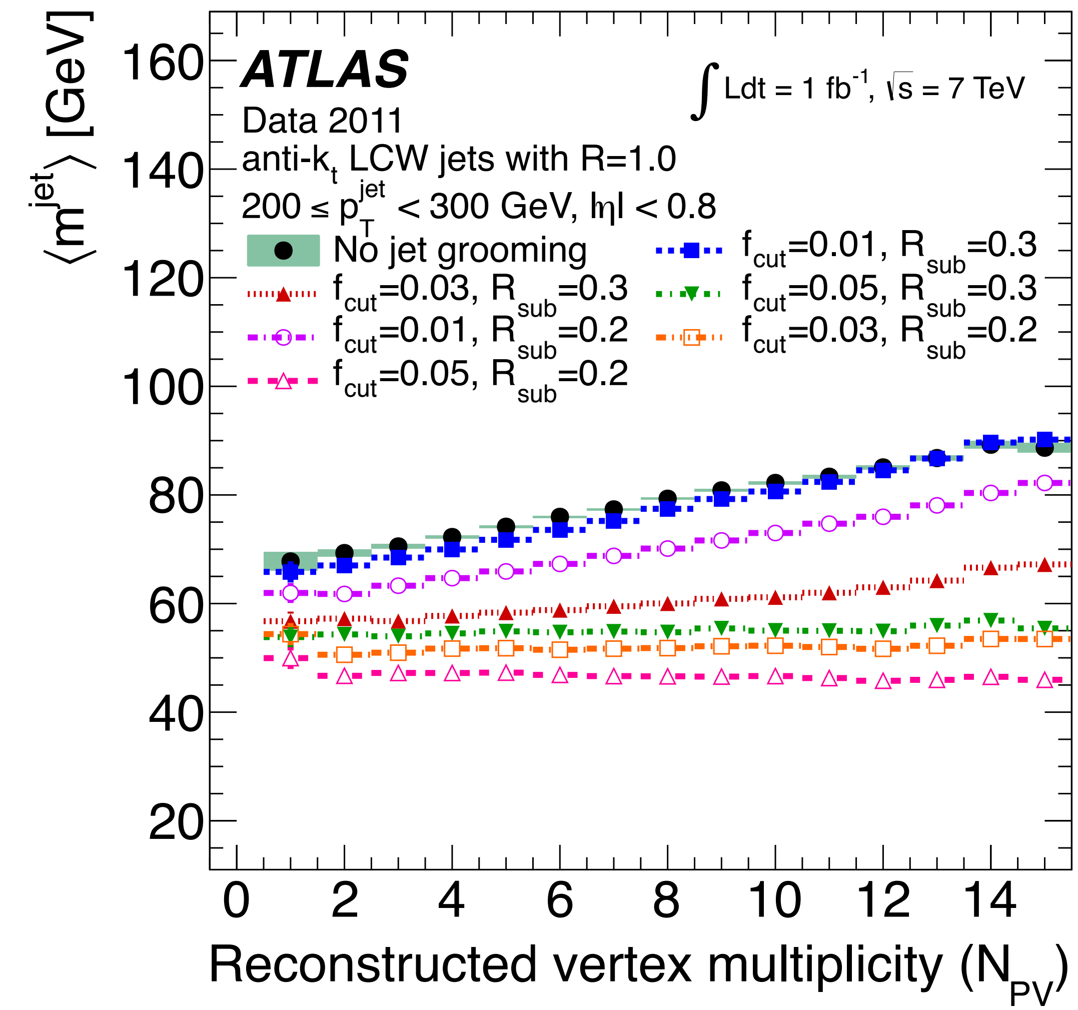
arXiv:0802.2470
arXiv:0912.1342
arXiv:0903.5081



groomed mass

CMS-PAS-HIG-13-008
JHEP 1309 (2013) 076





Grooming tends to push the jet mass scale of the **background to lower values** while **preserving the hard scale of the heavy resonance**

Grooming techniques are also vital in **reducing the pileup dependence** of the jet mass

Declustering and reclustering

For modern sequential recombination jet algorithms, the jet has a history — a series of 2-to-1 combinations

examples: **mass drop** - (m_{sj1}/m) , $\sqrt{d_{12}}$ - first splitting scale of kT algorithm

Generalized jet shapes

some simple questions: *How wide is a jet? How prong-y is a jet? How asymmetric is a jet? How stable is a jet?*

N-subjettiness (τ_N) [1], how consistent a jet is with having N subjets, ratios are typically used, e.g. τ_2/τ_1 for W-jets, τ_3/τ_2 for top jets

energy correlation functions [2], axis-less version of N-subjettiness

Qjets [3], Exploiting the "quantum" nature of jets

jet charge [4], an oldy but a goody

jet width; pT_D; r-cores; planar flow...

[1] Thaler, Van Tilburg, JHEP 1103:015,2011
[2] Larkoski, Salam, Thaler, arXiv:1305.0007
[3] Ellis et al., PRL 108, 182003 (2012)
[4] Krohn et al., Phys. Rev. Lett. 110 (2013) 21200

example: N-subjettiness

J. Thaler, K. Van Tilburg, arXiv:1011.2268

generalizing subjets…

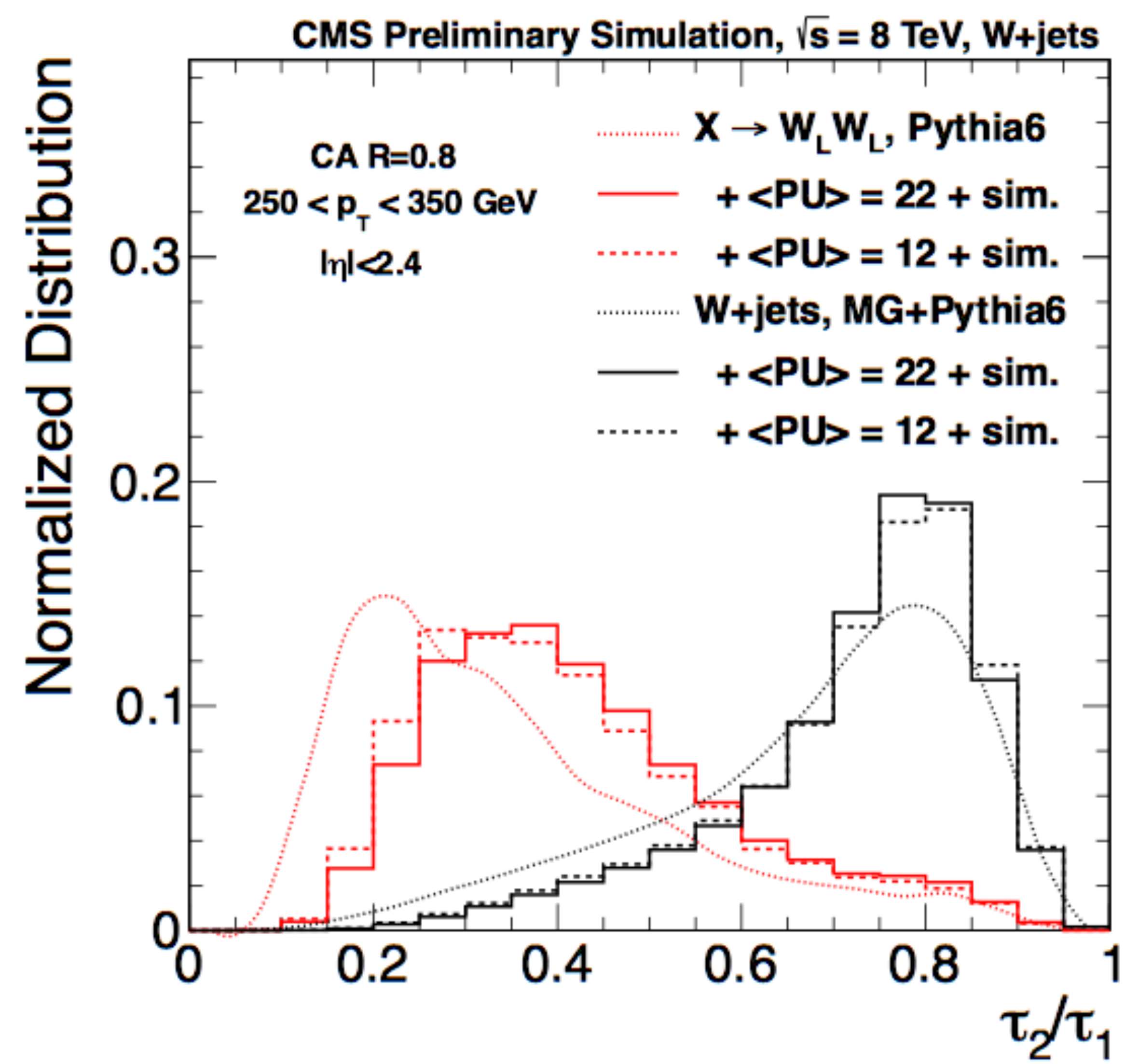
N-subjettiness: a measure of how consistent a jet is with having N subjets, τ_N

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\left\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right\}$$

As $\tau_N \rightarrow 0$, jet is more consistent with having N subjets

e.g. $\tau 2 \rightarrow 0$, more like a W jet
e.g. $\tau 1 \rightarrow 0$, more like a quark jet

Ratios are typically used:
τ_2/τ_1 for separating **W jets** from **quark and gluon jets**

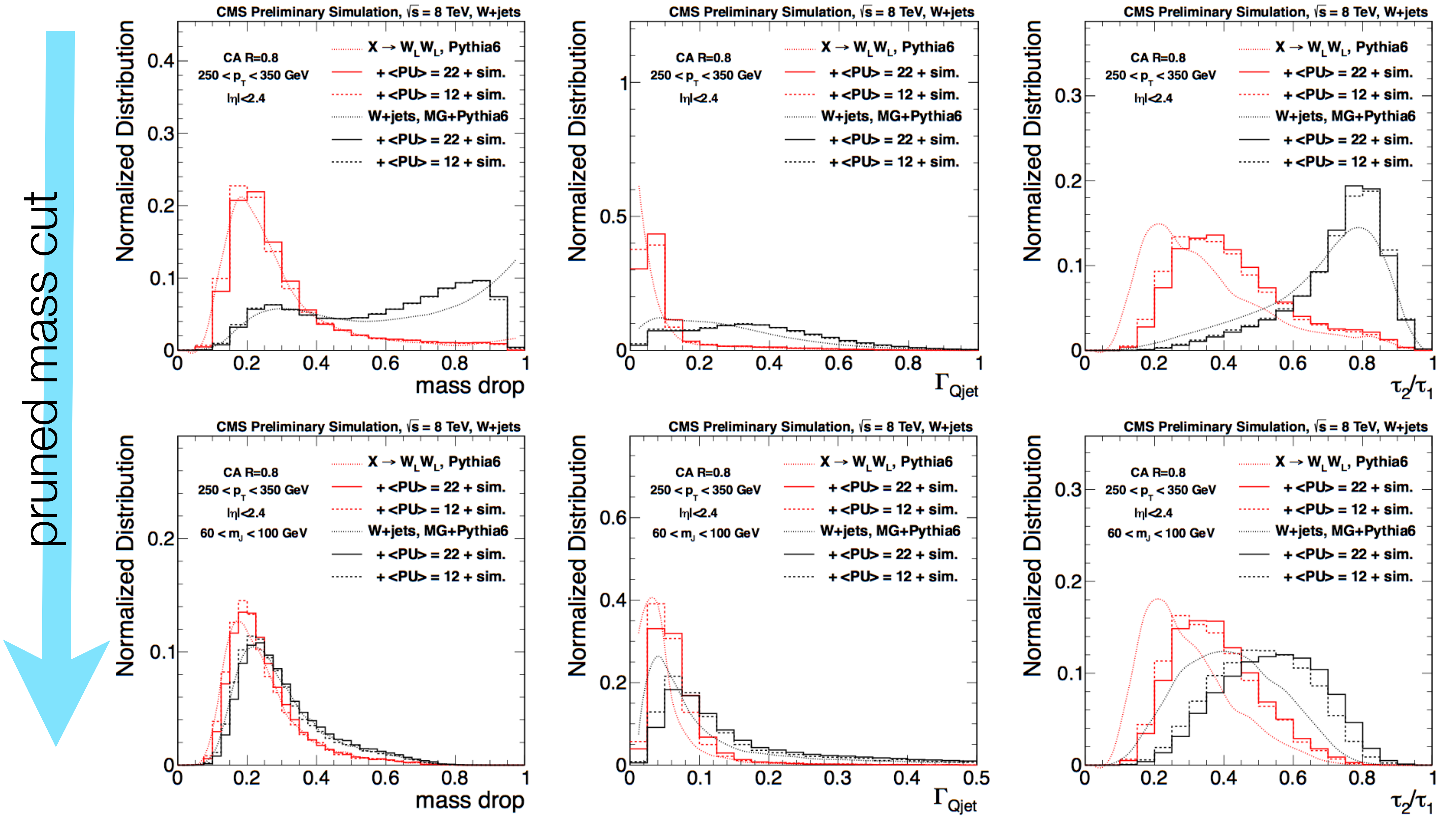


shapes for boosted objects

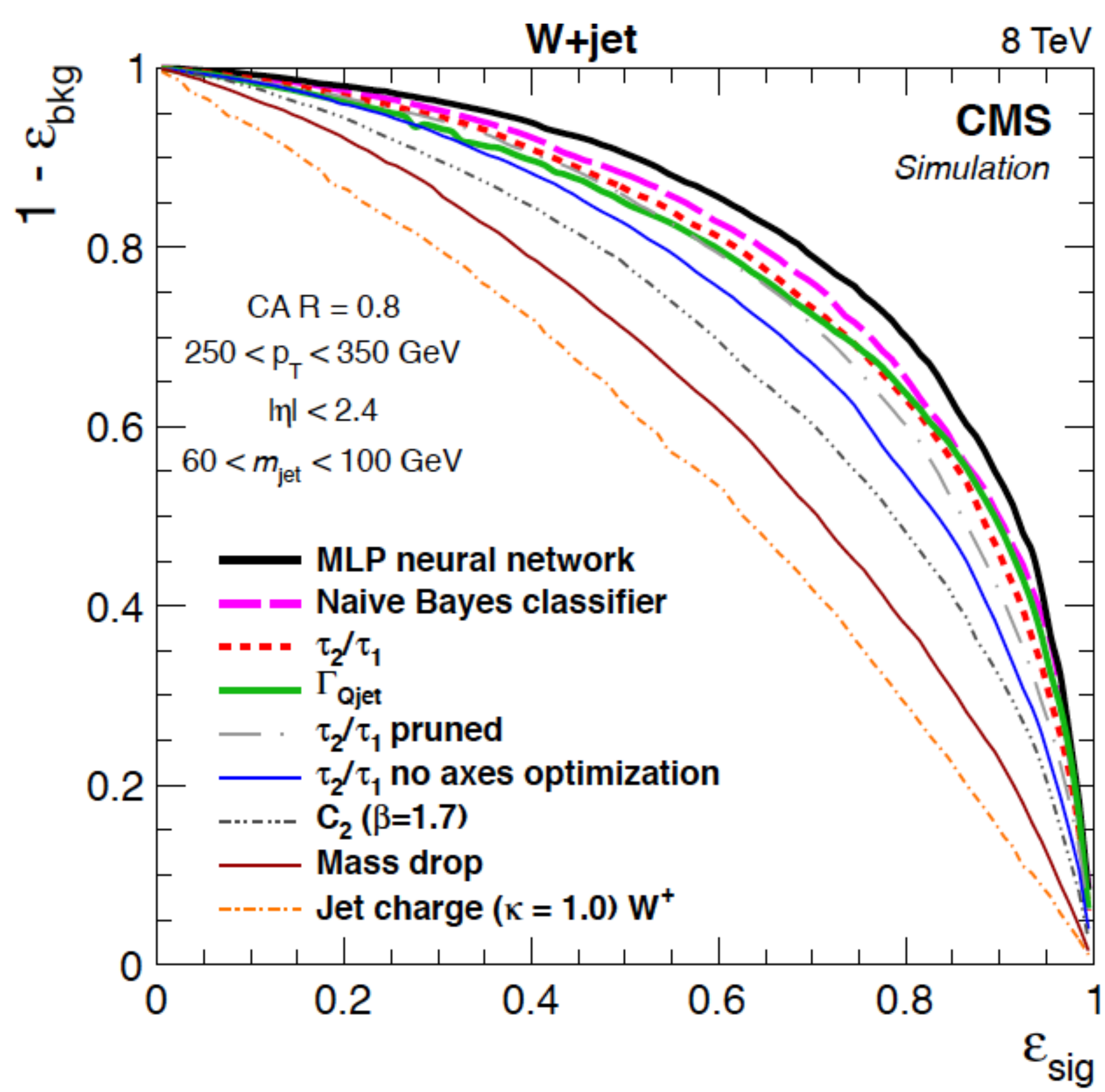
beware the correlations!

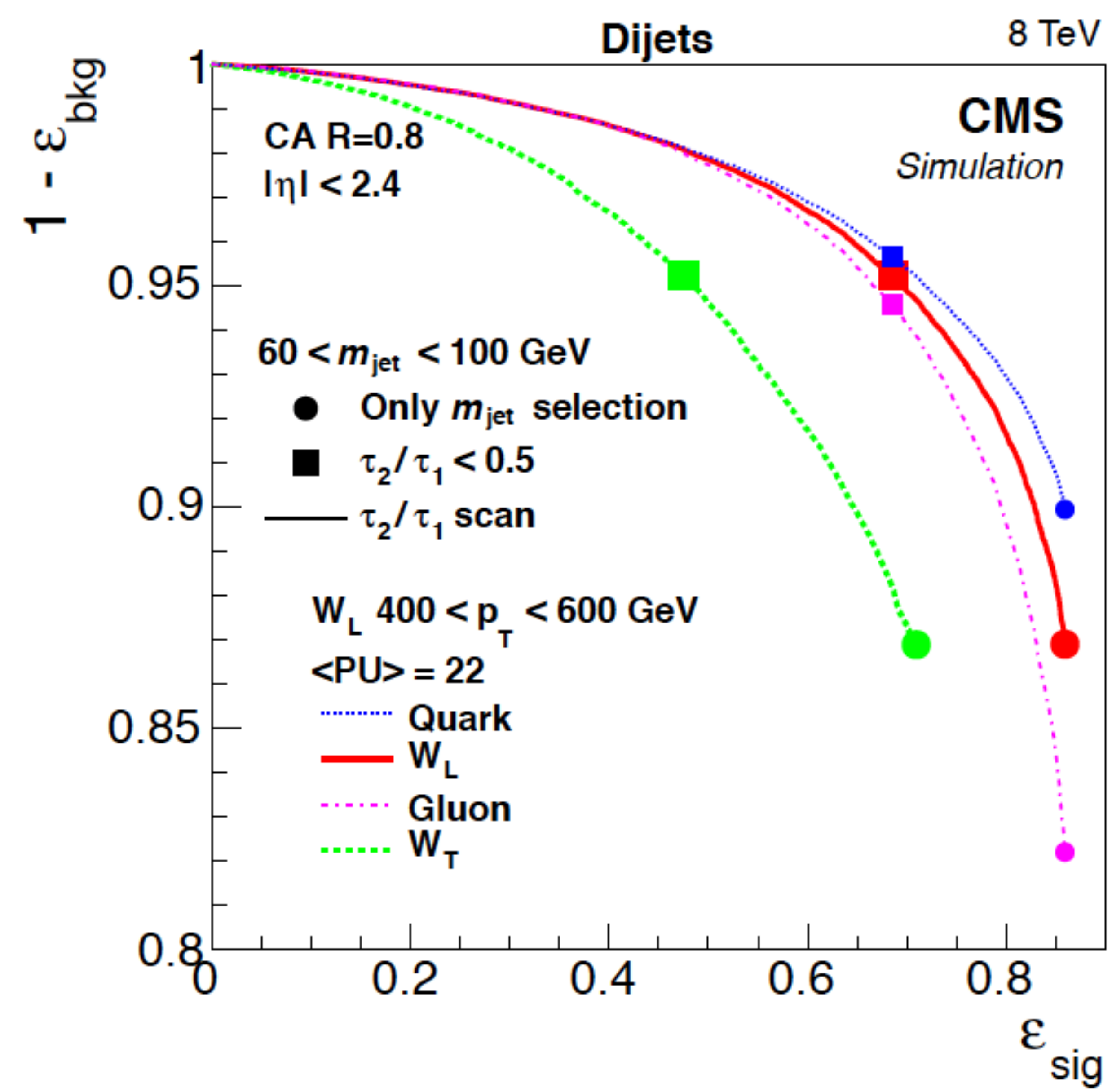
CMS PAS JME-13-006

mass drop | Qjet volatility | τ_2/τ_1



W tagger optimization

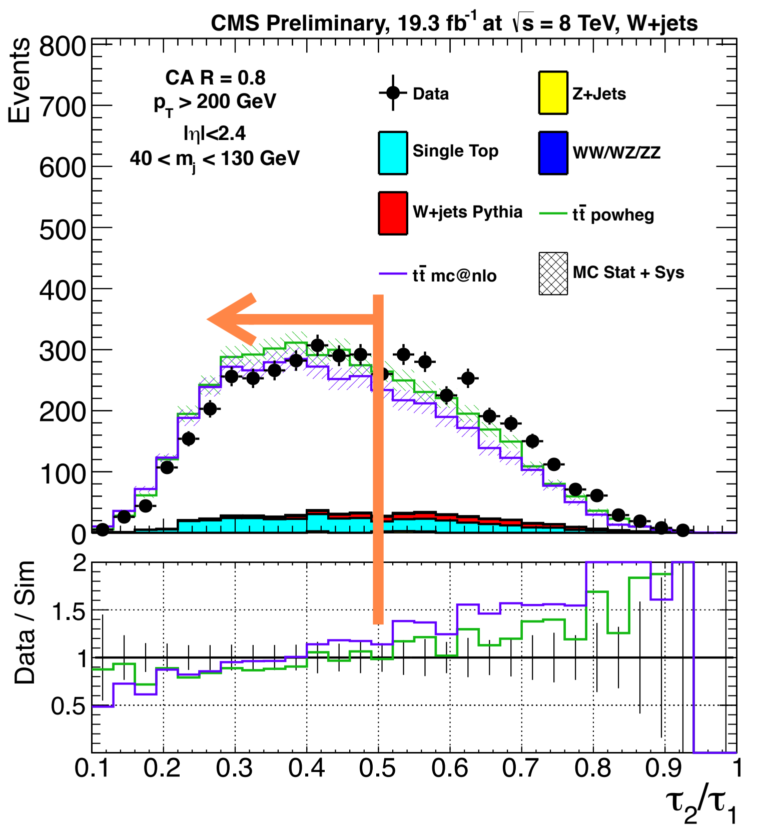


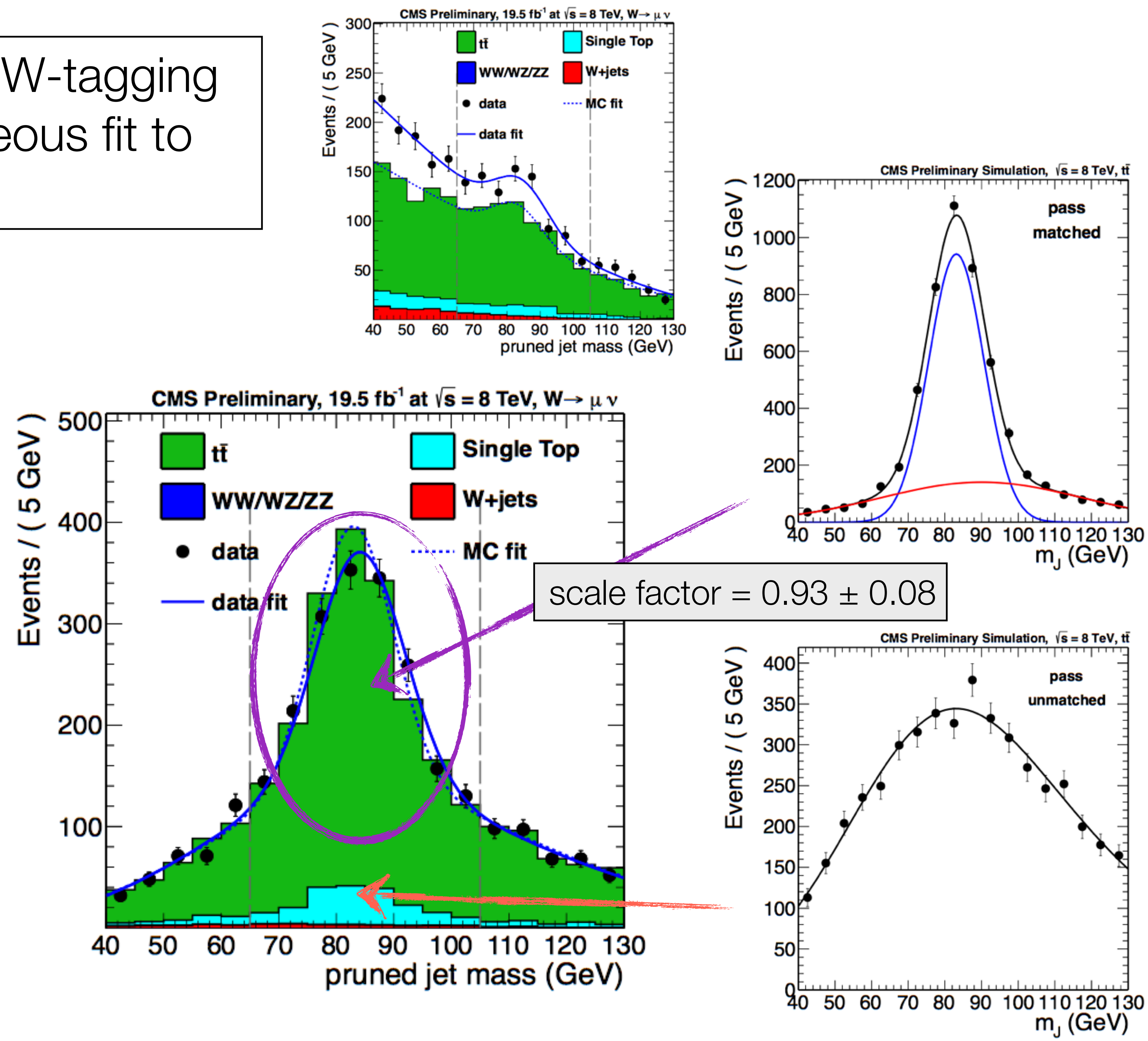


Tagger	BR(W/Z/H→xx)	Efficiency (W/Z/H)	Mistag rate (q/g-jets)
W/Z(qq)-tagger	70% / 68%	35%	1.2%
H(bb)-tagger	57%	35%	0.5%
H(WW→qqqq)-tagger	10%	35%	1.5%
H(ττ)-tagger	6%	35%	0.03%

data-driven methods

Data-driven estimation of W-tagging scale factors via simultaneous fit to pass/fail samples





mean (MC) = 83.2 ± 0.3 GeV
mean (data) = 84.4 ± 0.4 GeV
σ (MC) = 7.1 ± 0.4 GeV
σ (data) = 7.4 ± 0.6 GeV