Systematic Uncertainties from Synthetic Datasets

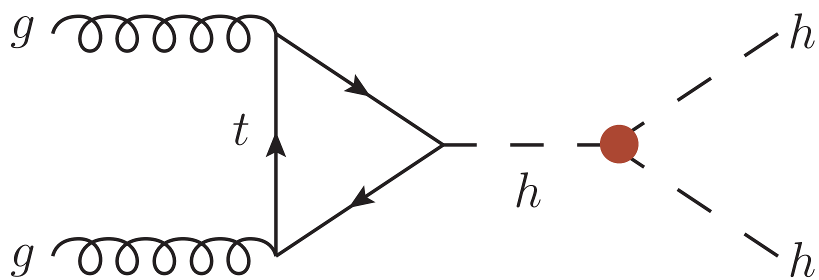
A case study with $HH \rightarrow 4b$

John Alison

Carnegie Mellon University

Motivation

Measuring the Higgs self-coupling λ major goal of the HL-LHC
Di-Higgs production most direct and most sensitivity way measure λ



(~3 / hour)

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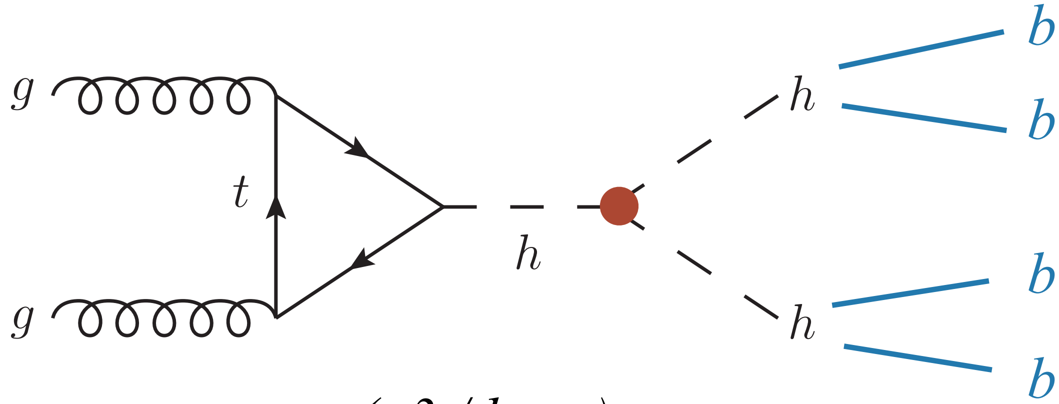

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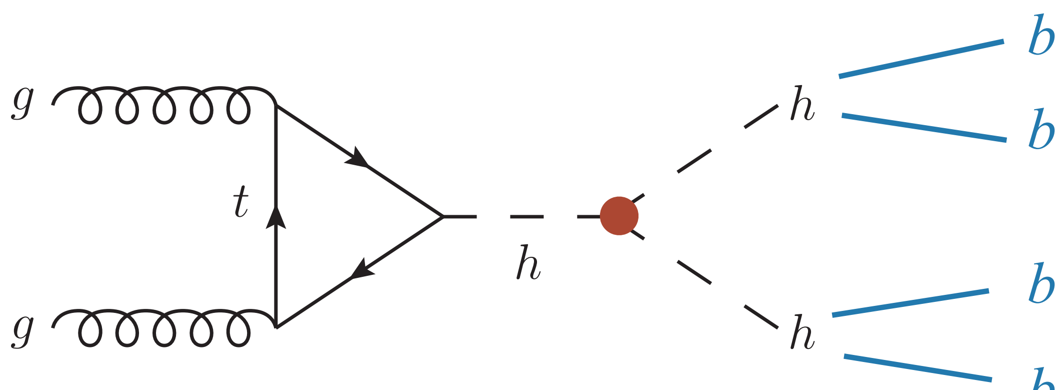

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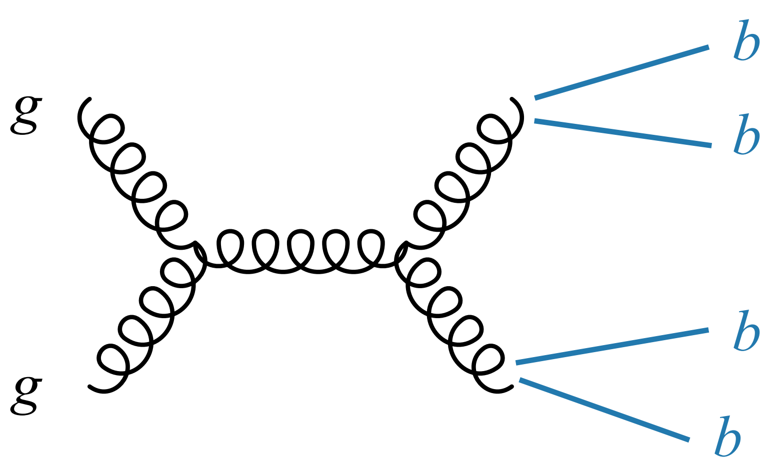
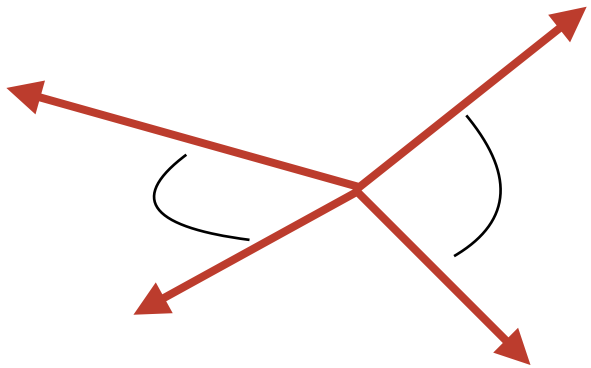


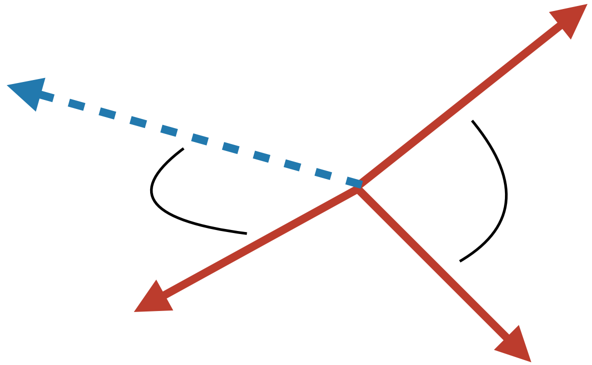
(~30,000 / hour)

Data Driven Background: *ABCD*

"4b"



"3b"



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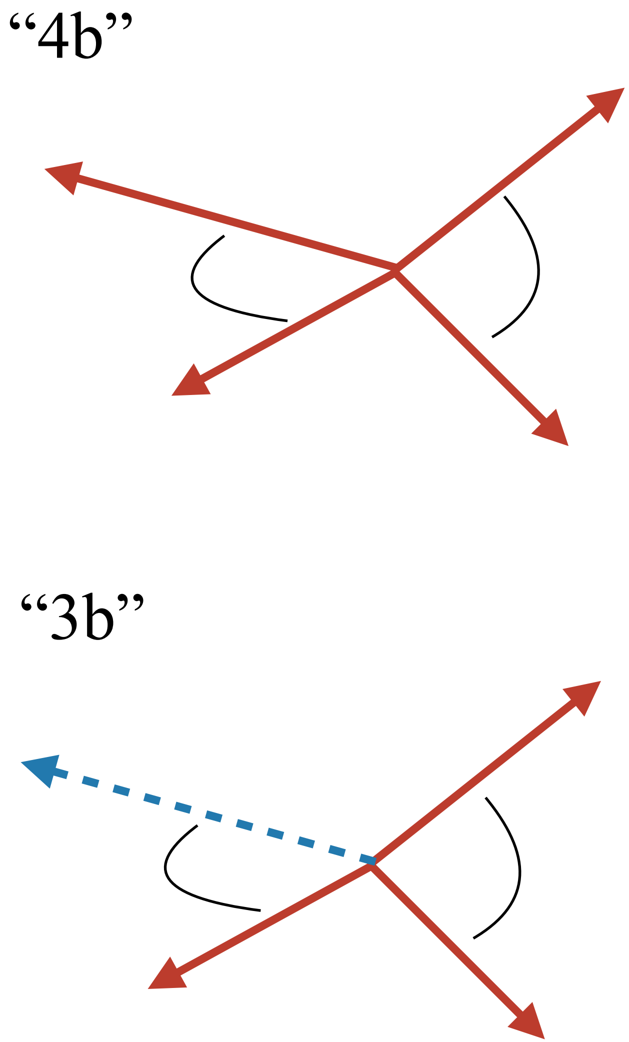

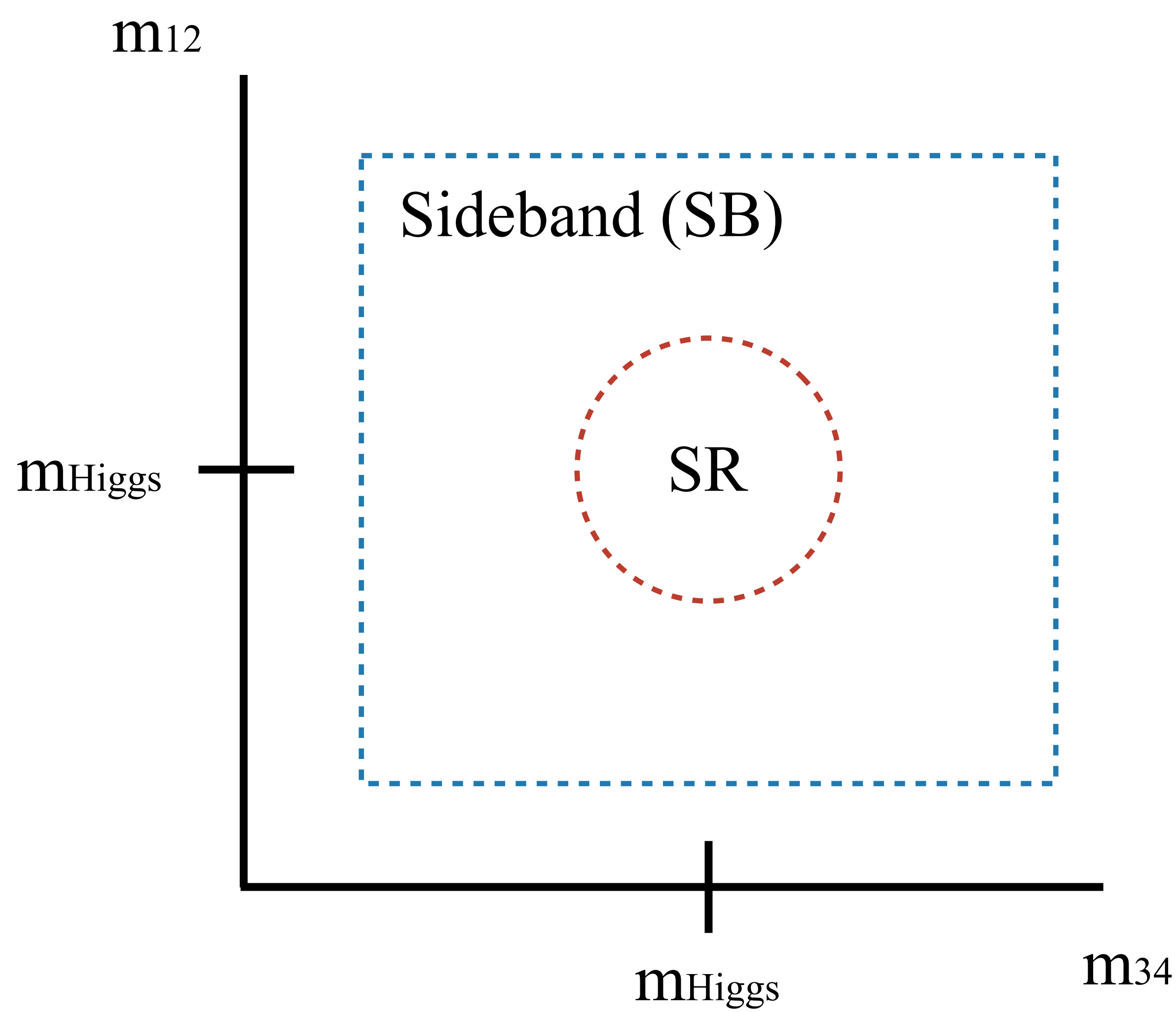

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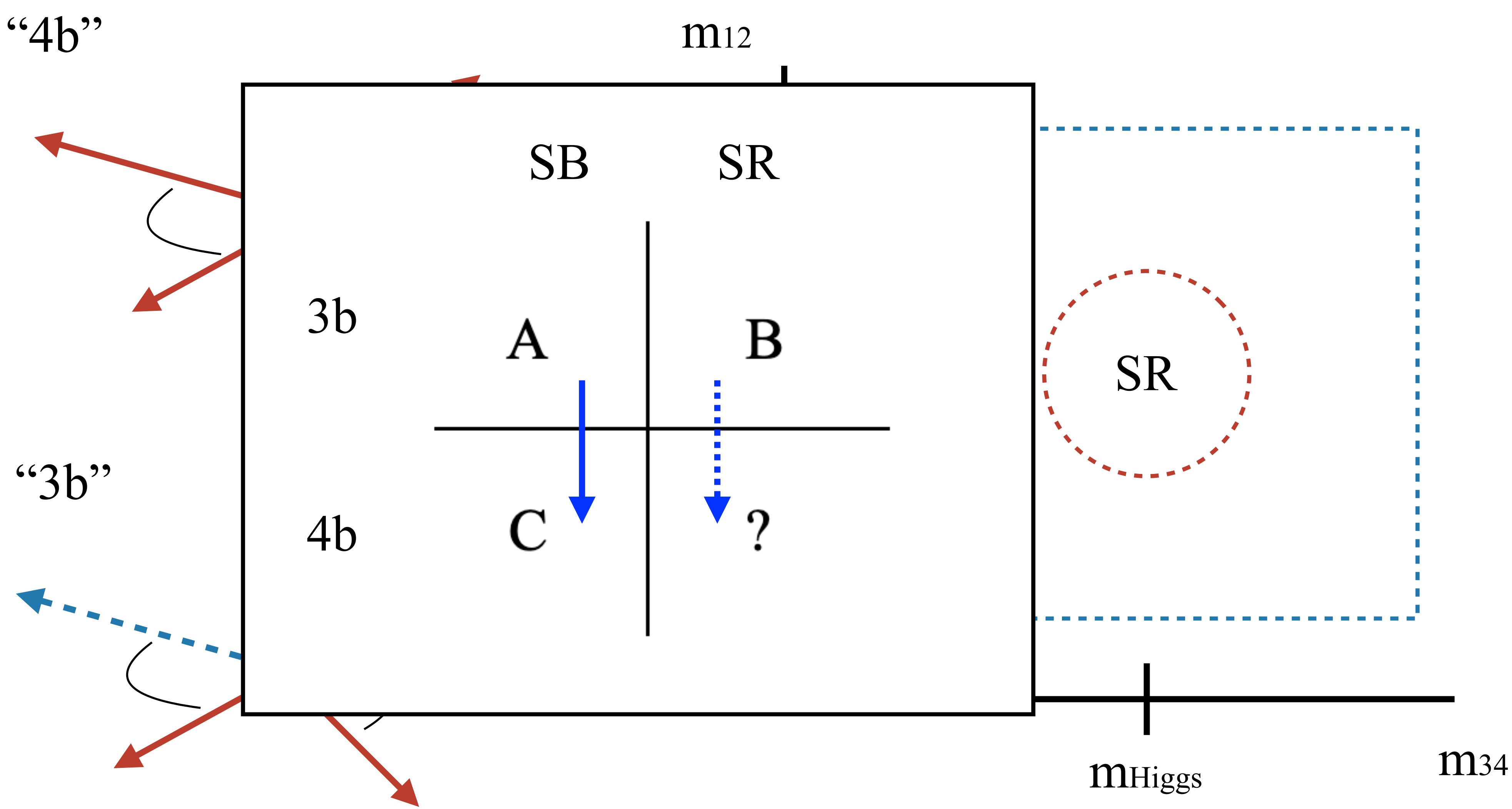
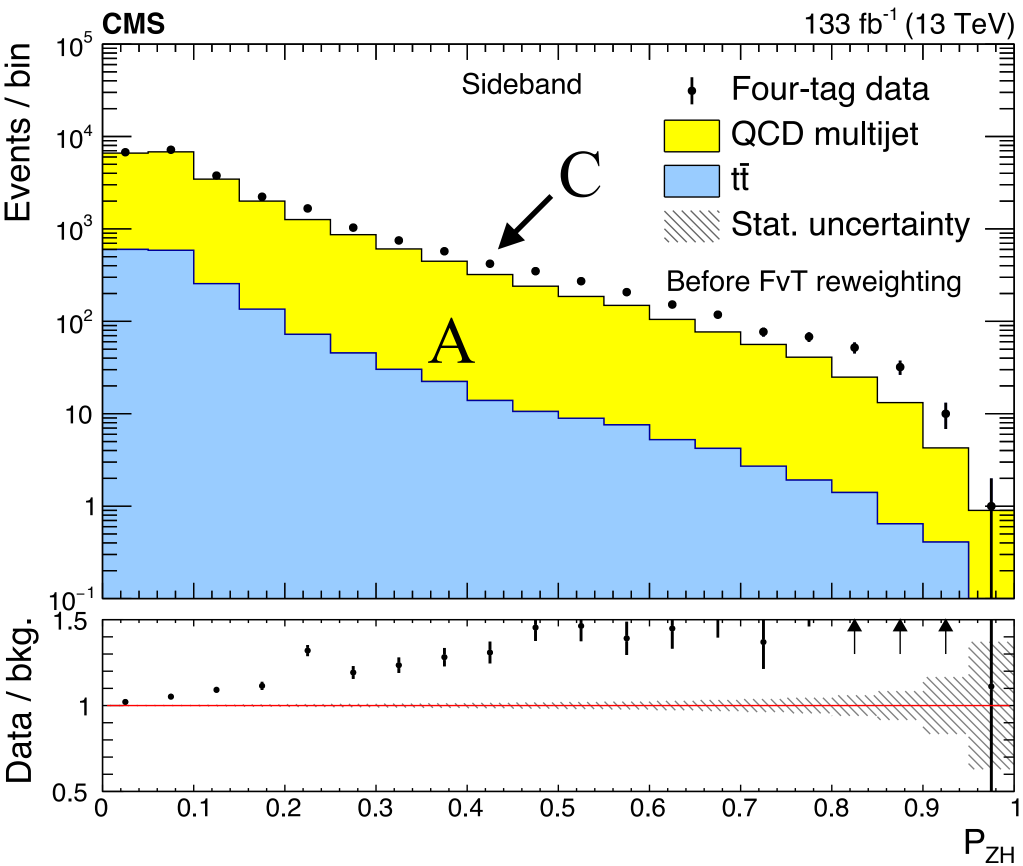
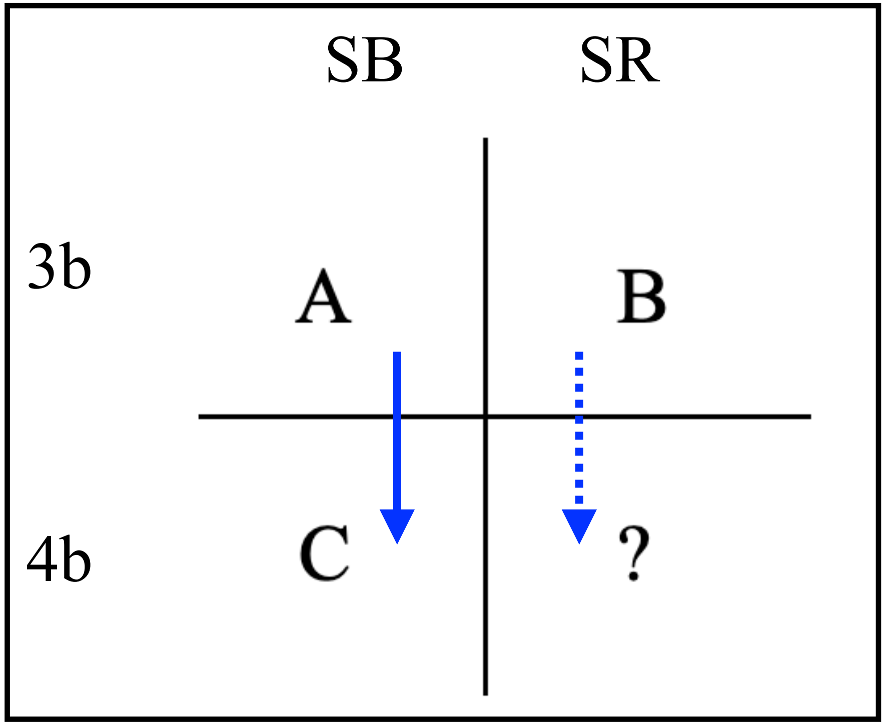


ABCD Method Works





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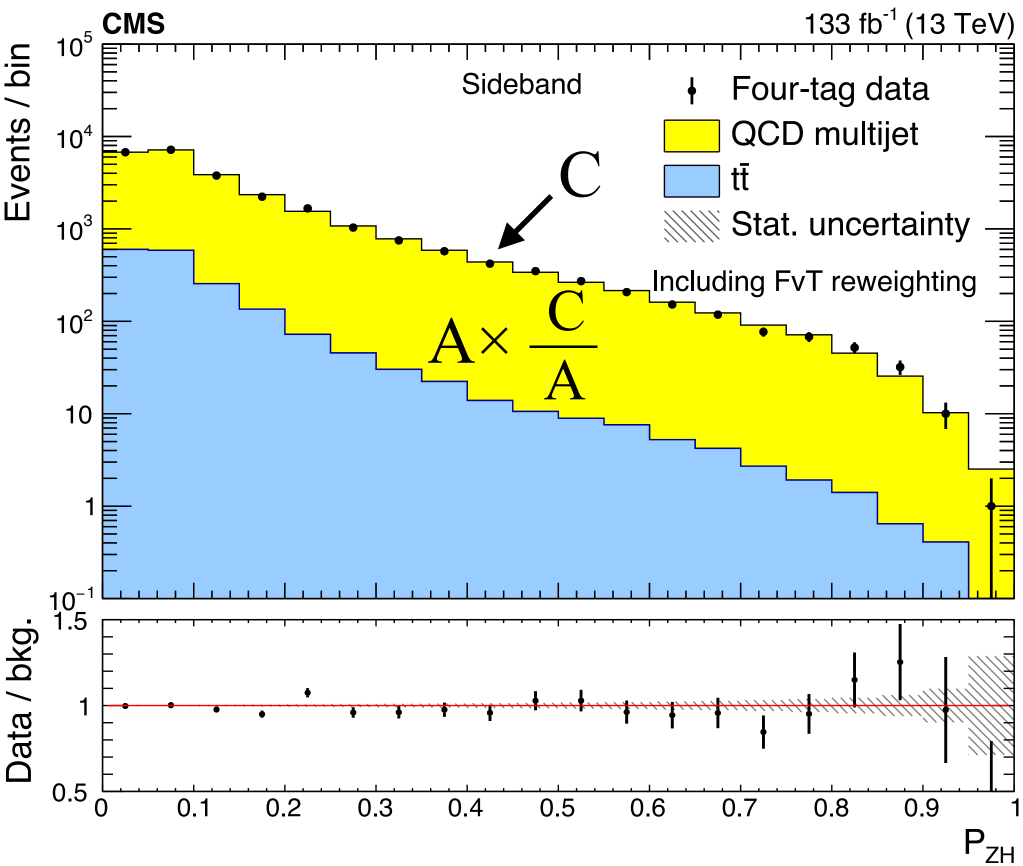

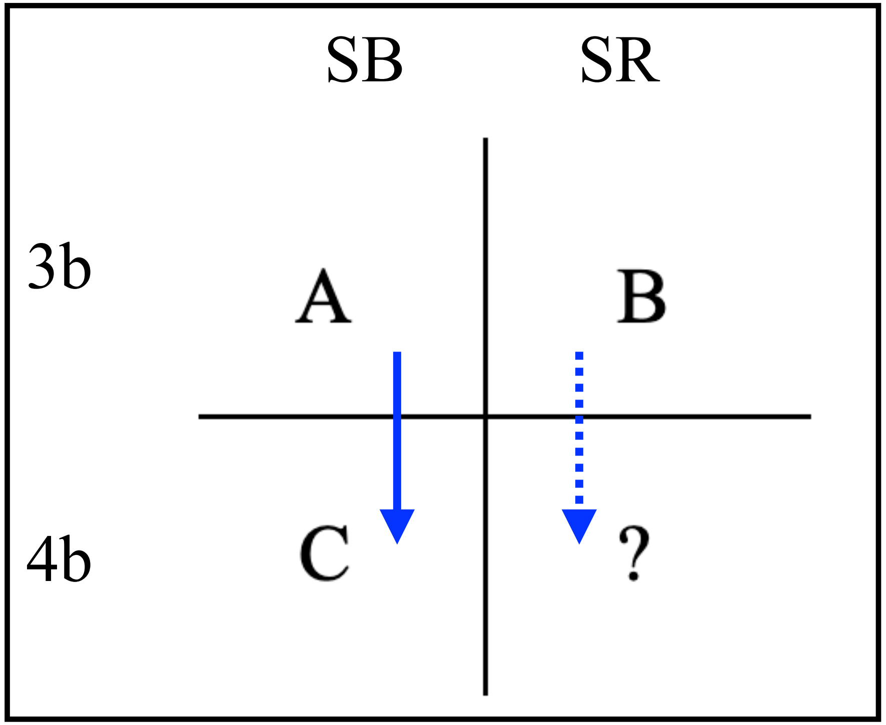

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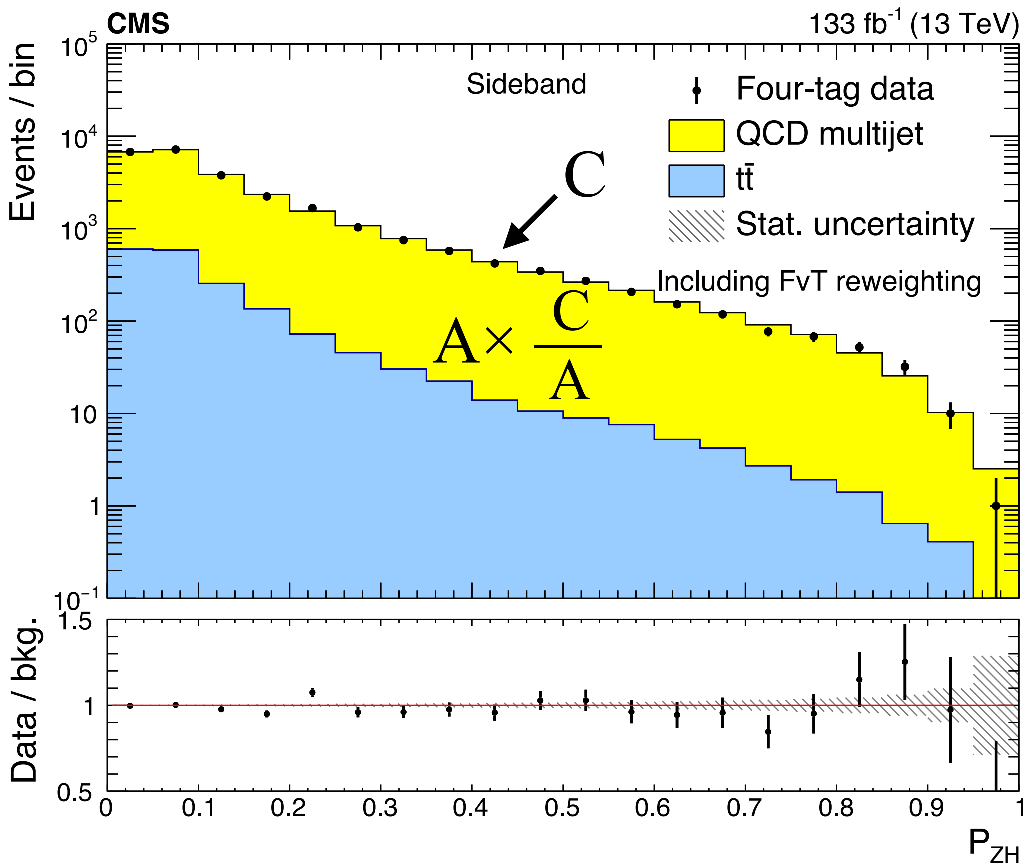

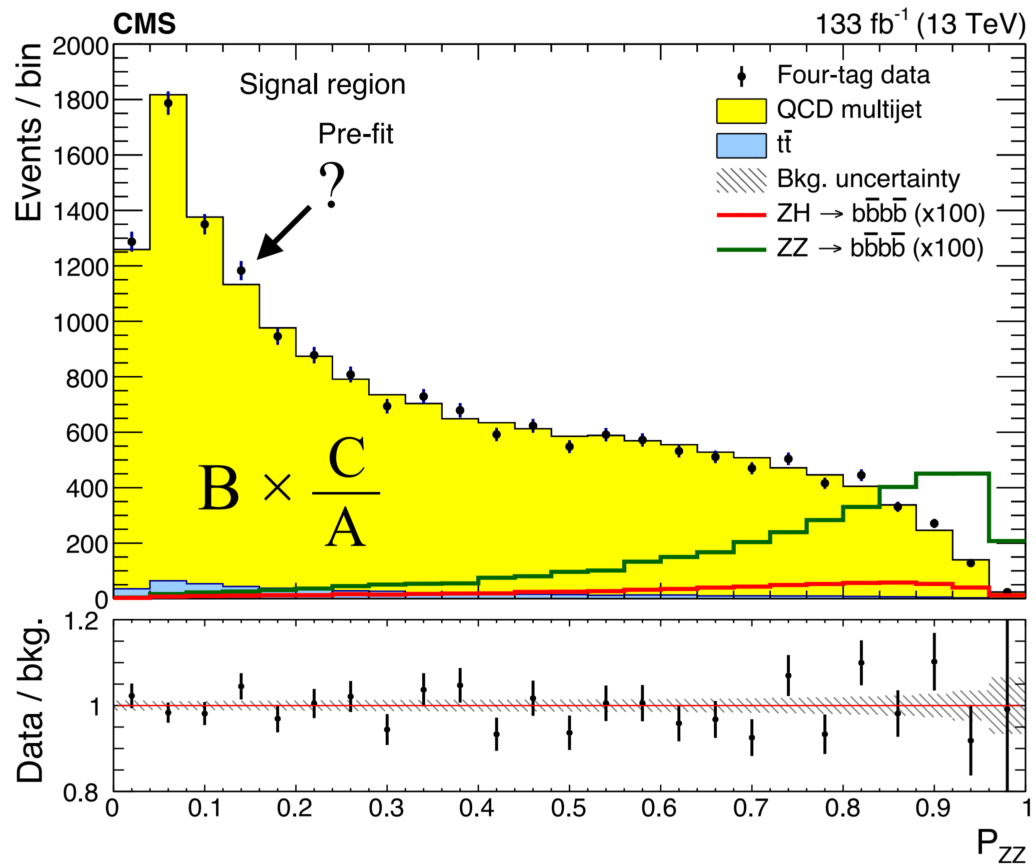

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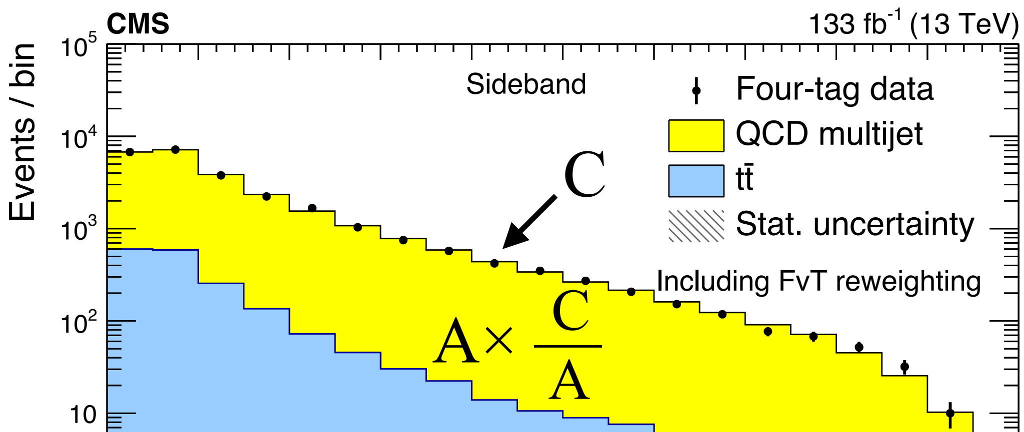
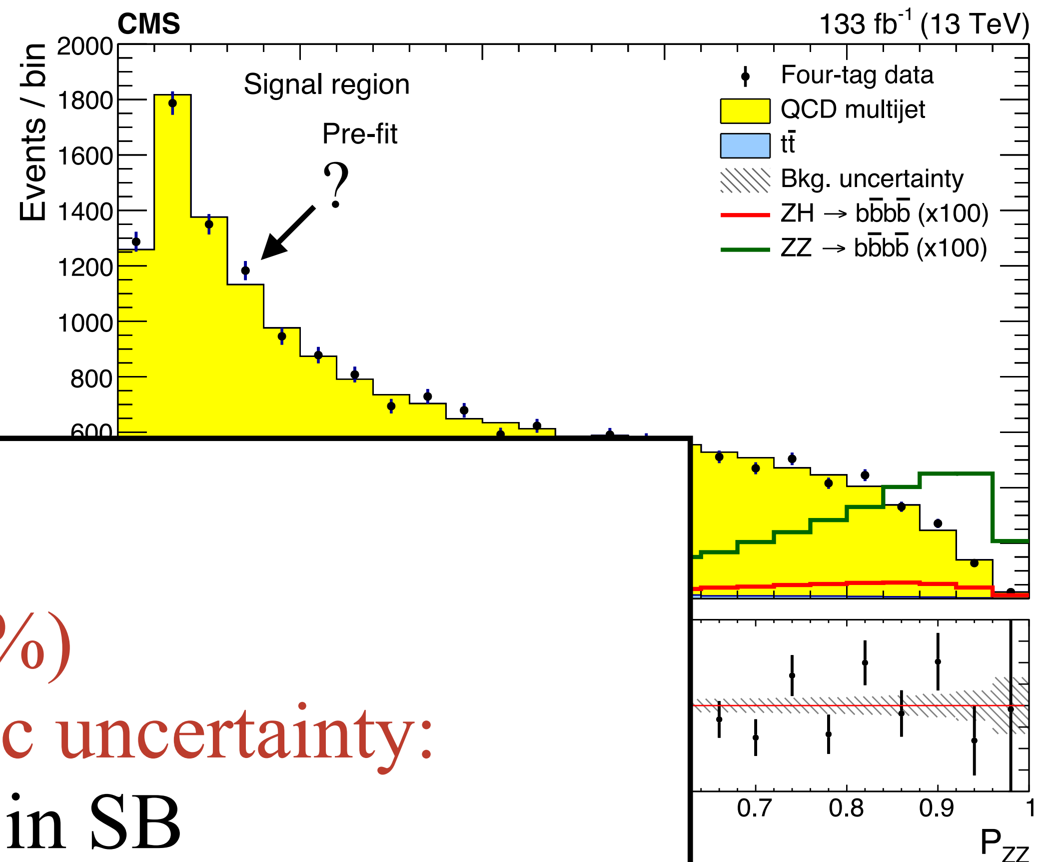




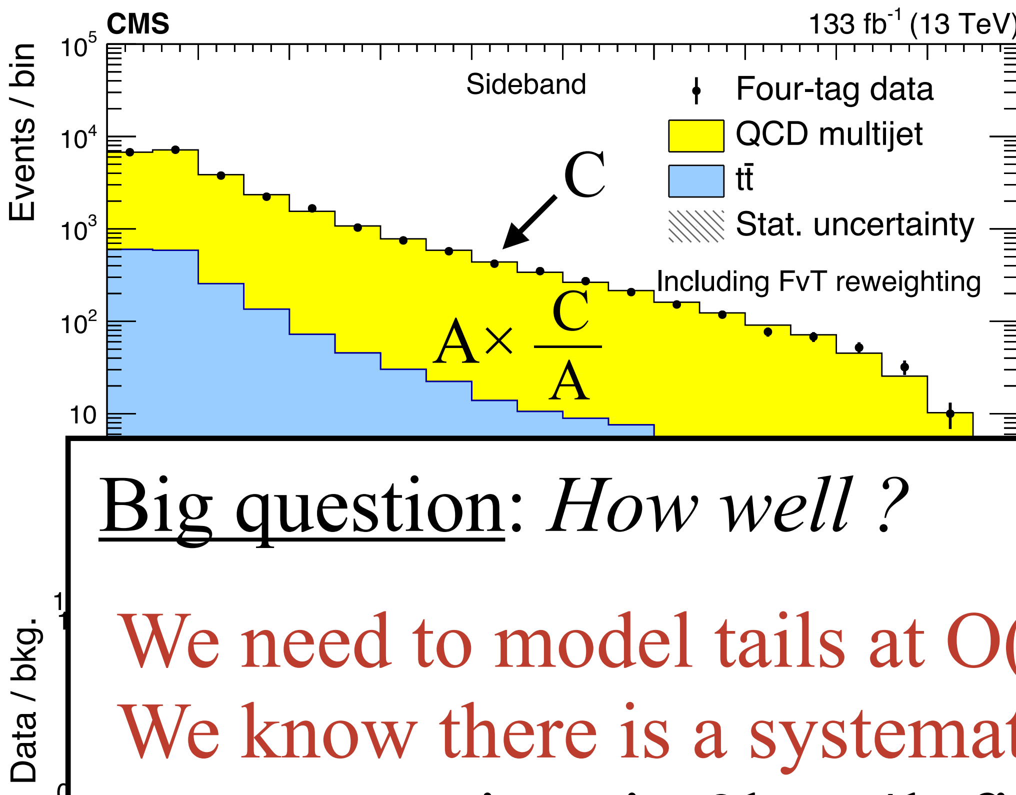
Big question: *How well ?*

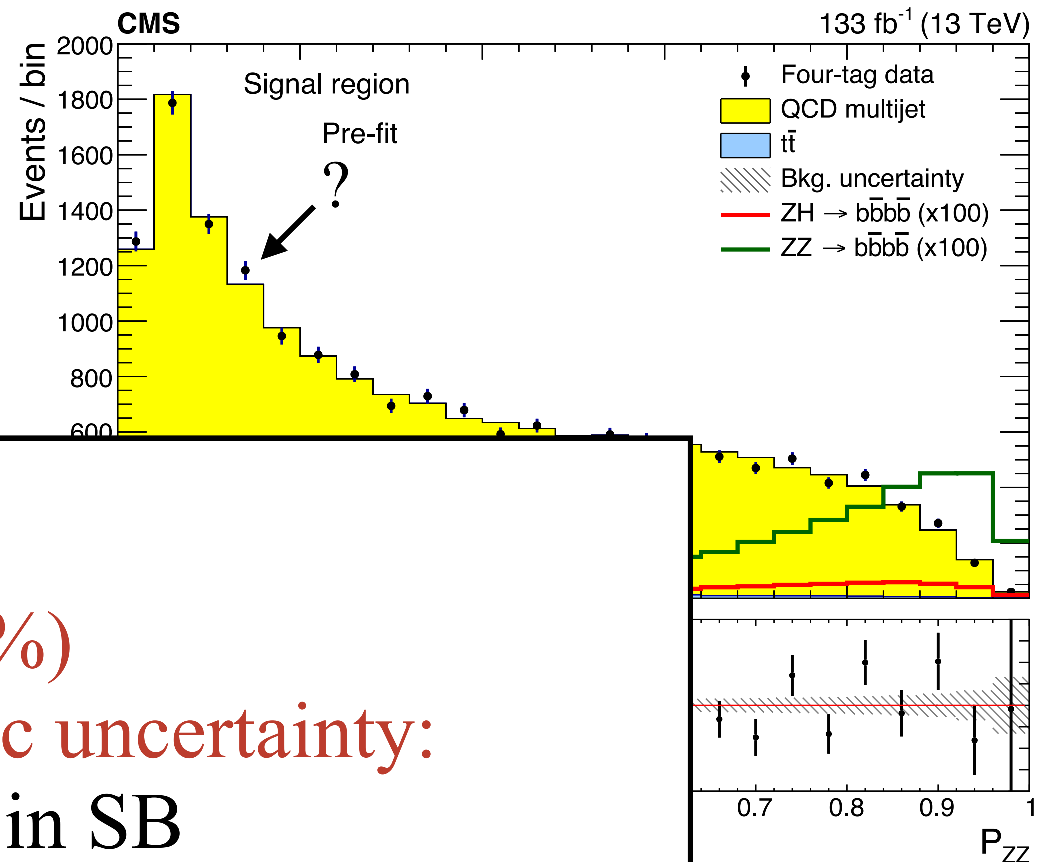
We need to model tails at O(%)

We know there is a systematic uncertainty:

- Uncertainty in 3b→4b fit in SB
- Extrapolation (domain shift) from CR→SR
- …

ABCD Method Works





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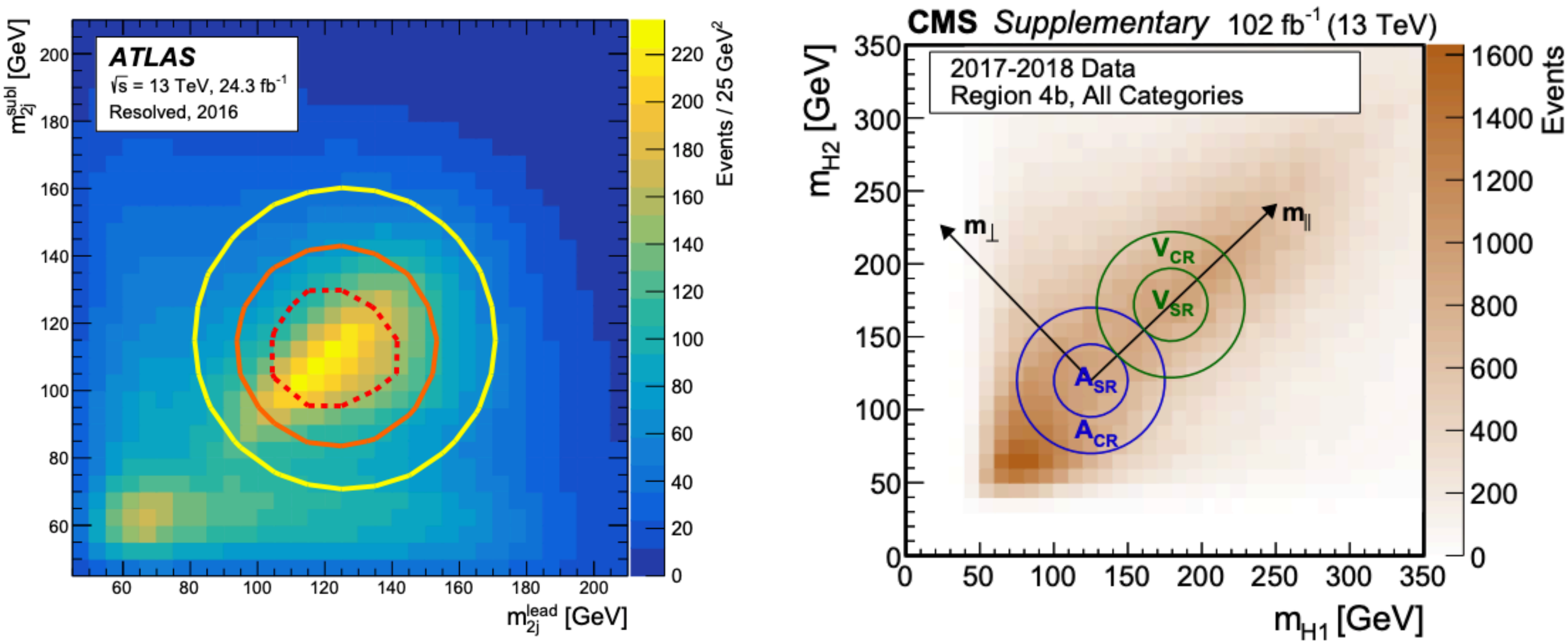
Rest of this talk is an idea for validating this uncertainty

Standard Solution: Validation Region

Strategy in previous 4b analyses:

Validated prediction in alternative signal-free region



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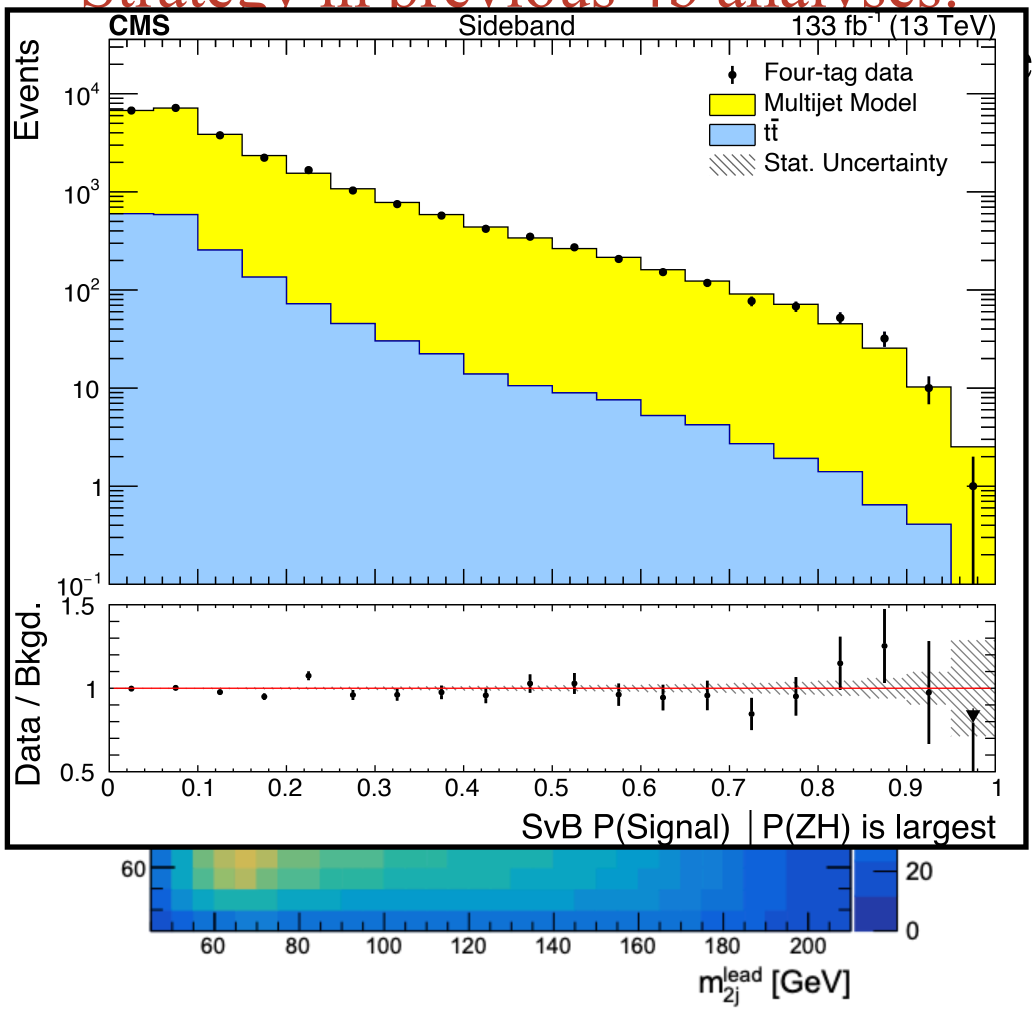

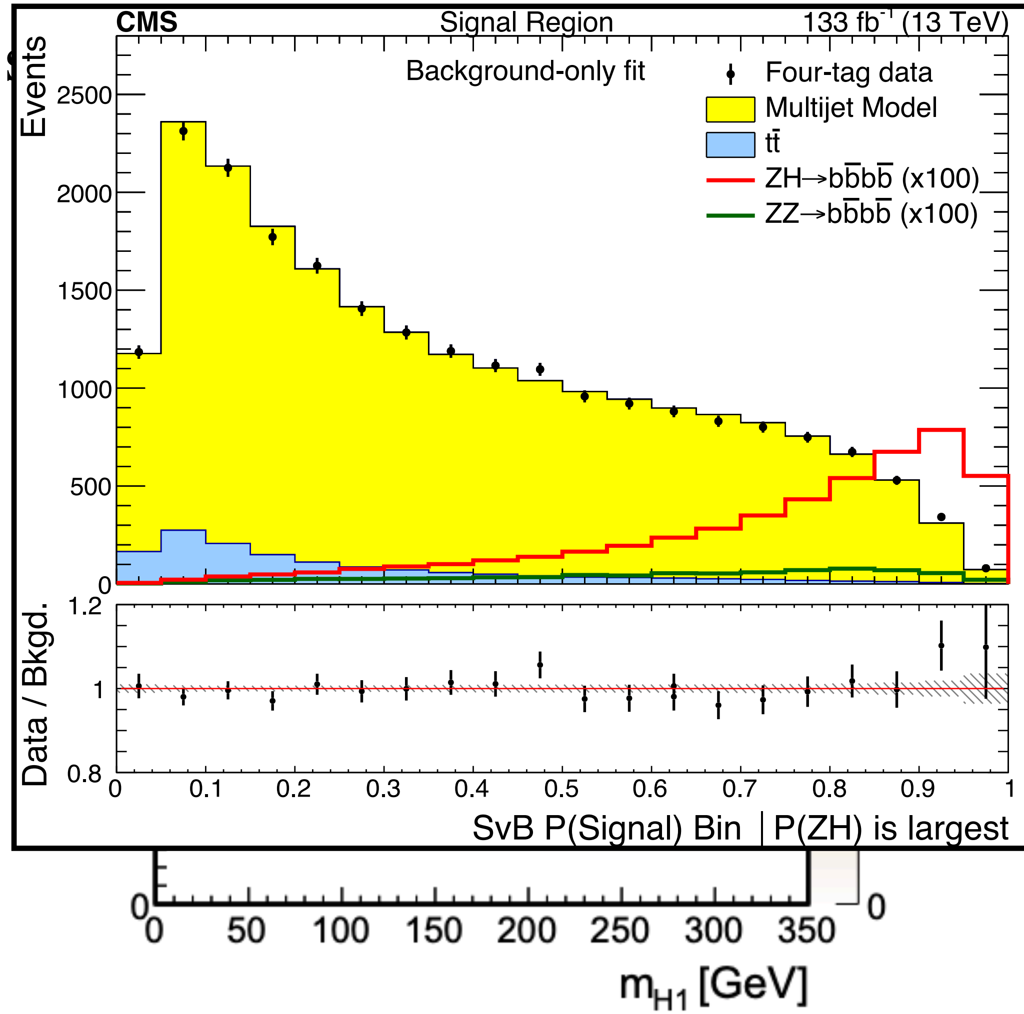

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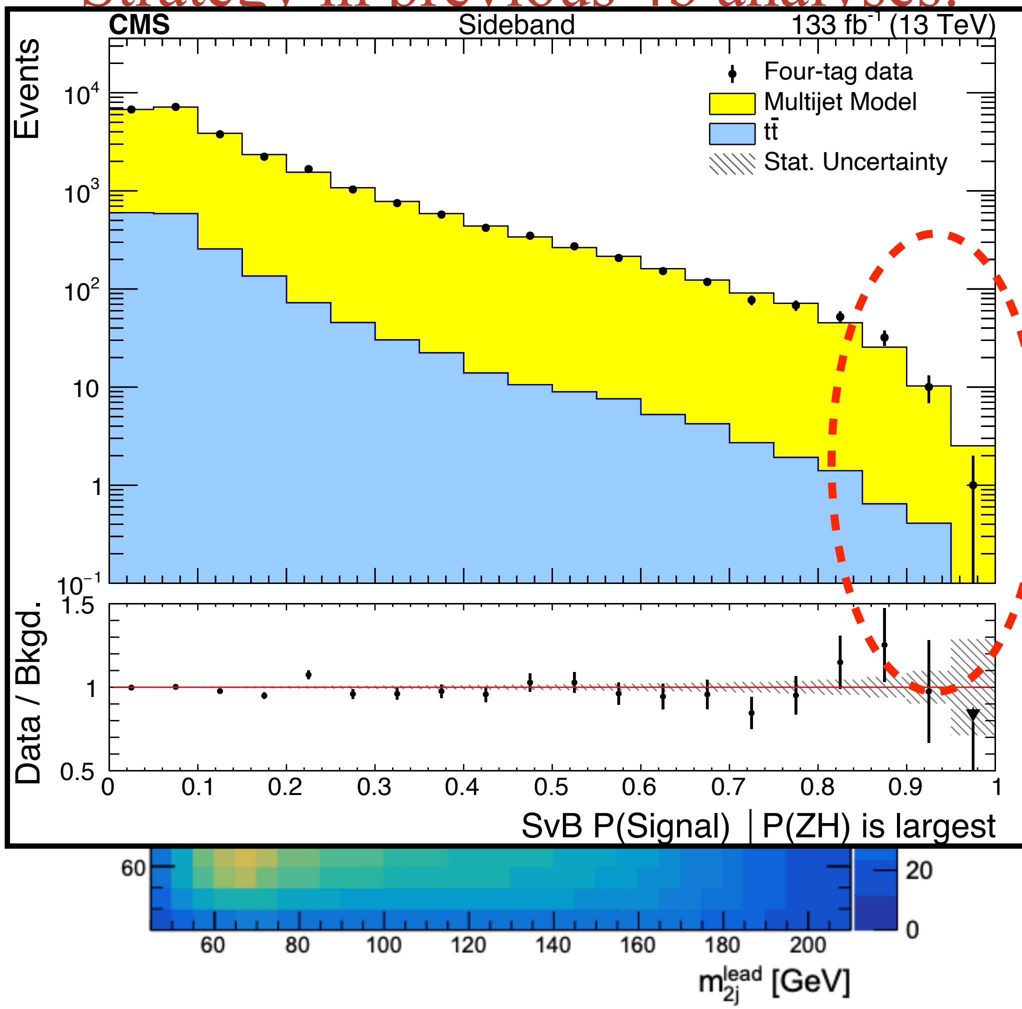

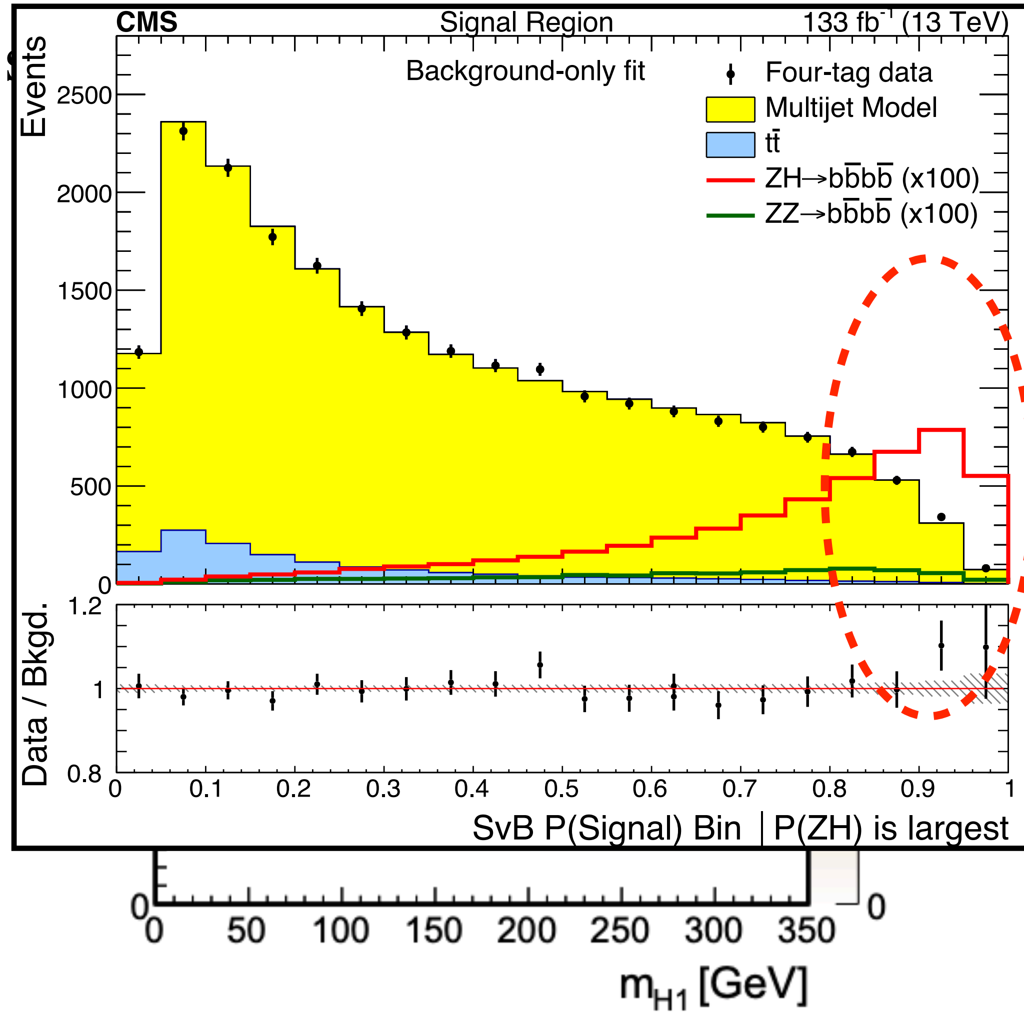

Aside: Solution with Optimal Transport

BACKGROUND MODELING FOR DOUBLE HIGGS BOSON PRODUCTION: DENSITY RATIOS AND OPTIMAL TRANSPORT

BY TUDOR MANOLE[a], PATRICK BRYANT[d], JOHN ALISON[e], MIKAEL KUUSELA[b], AND LARRY WASSERMAN[c]

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Department of Physics and NSF AI Planning Institute for Data-Driven Discovery in Physics, Carnegie Mellon University
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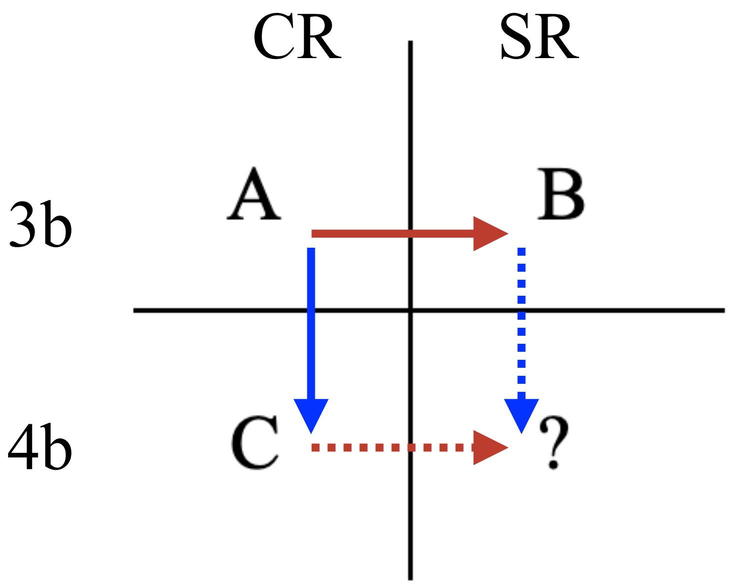
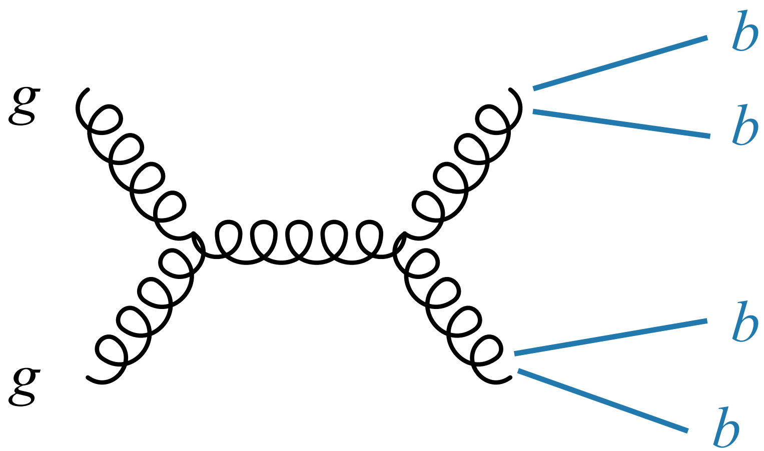
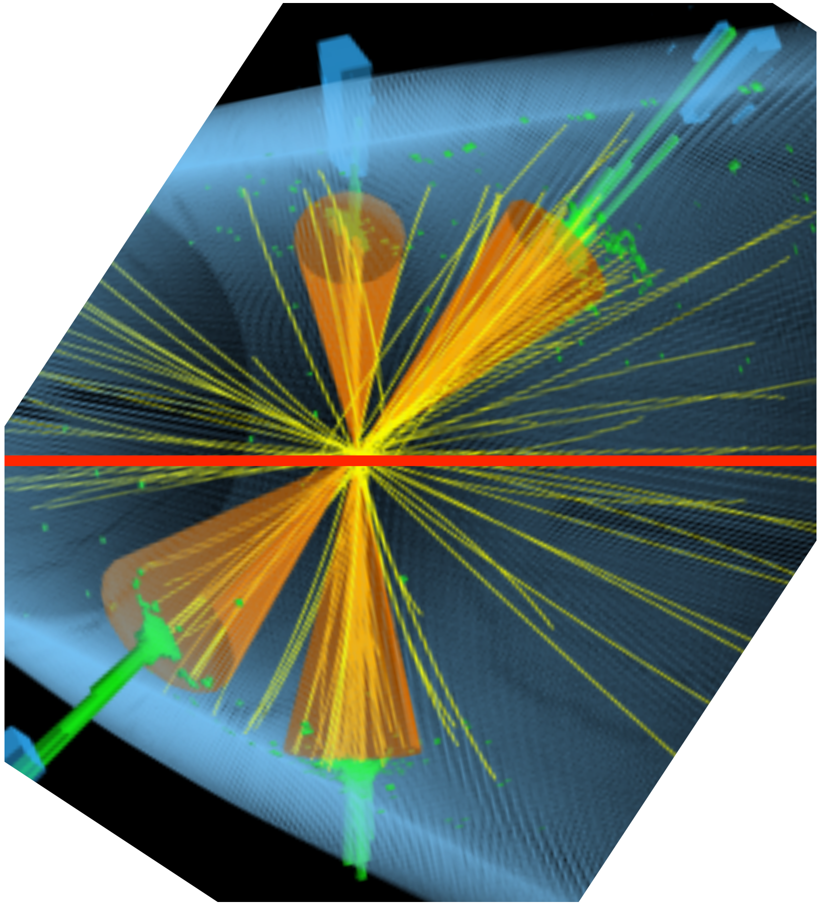


arXiv:2208.02807

Synthetic Datasets: Event Mixing





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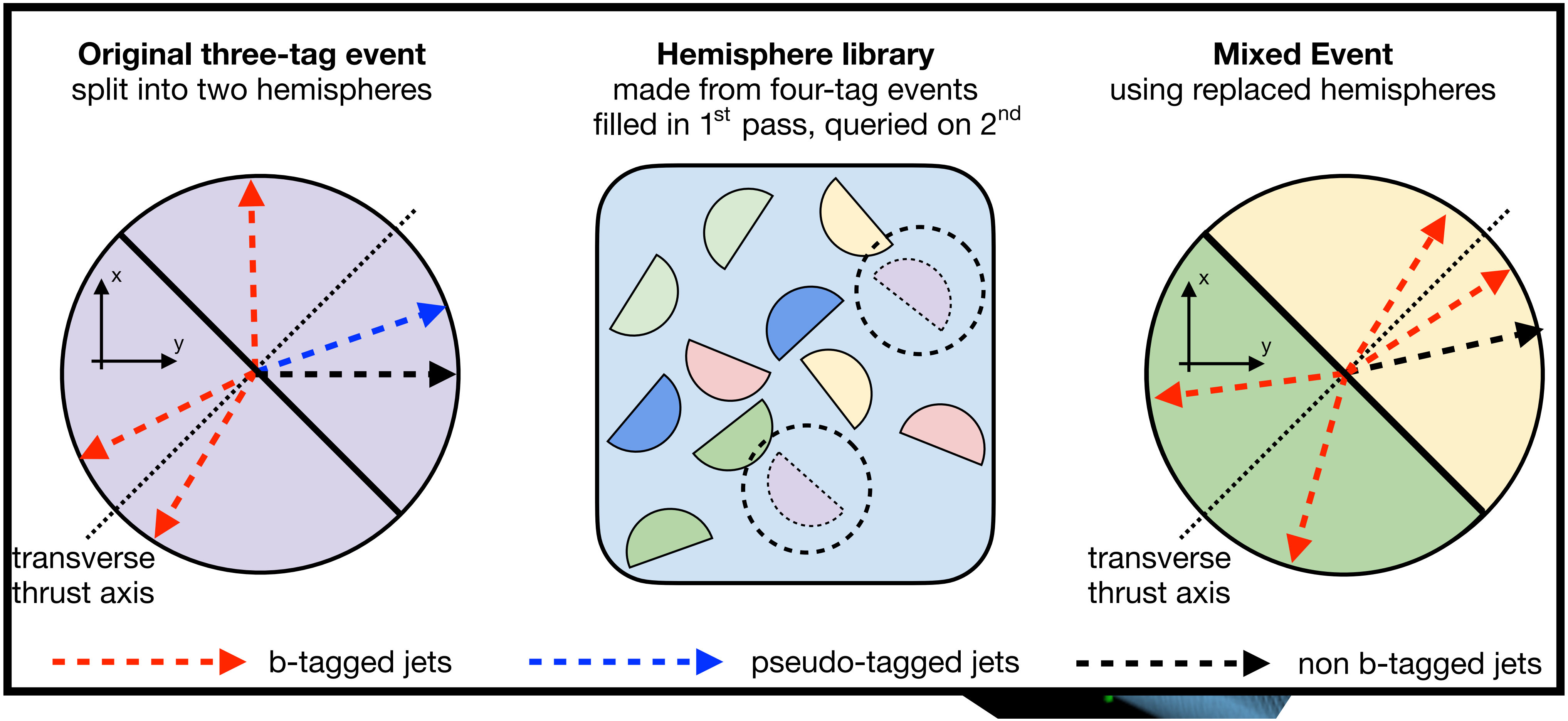

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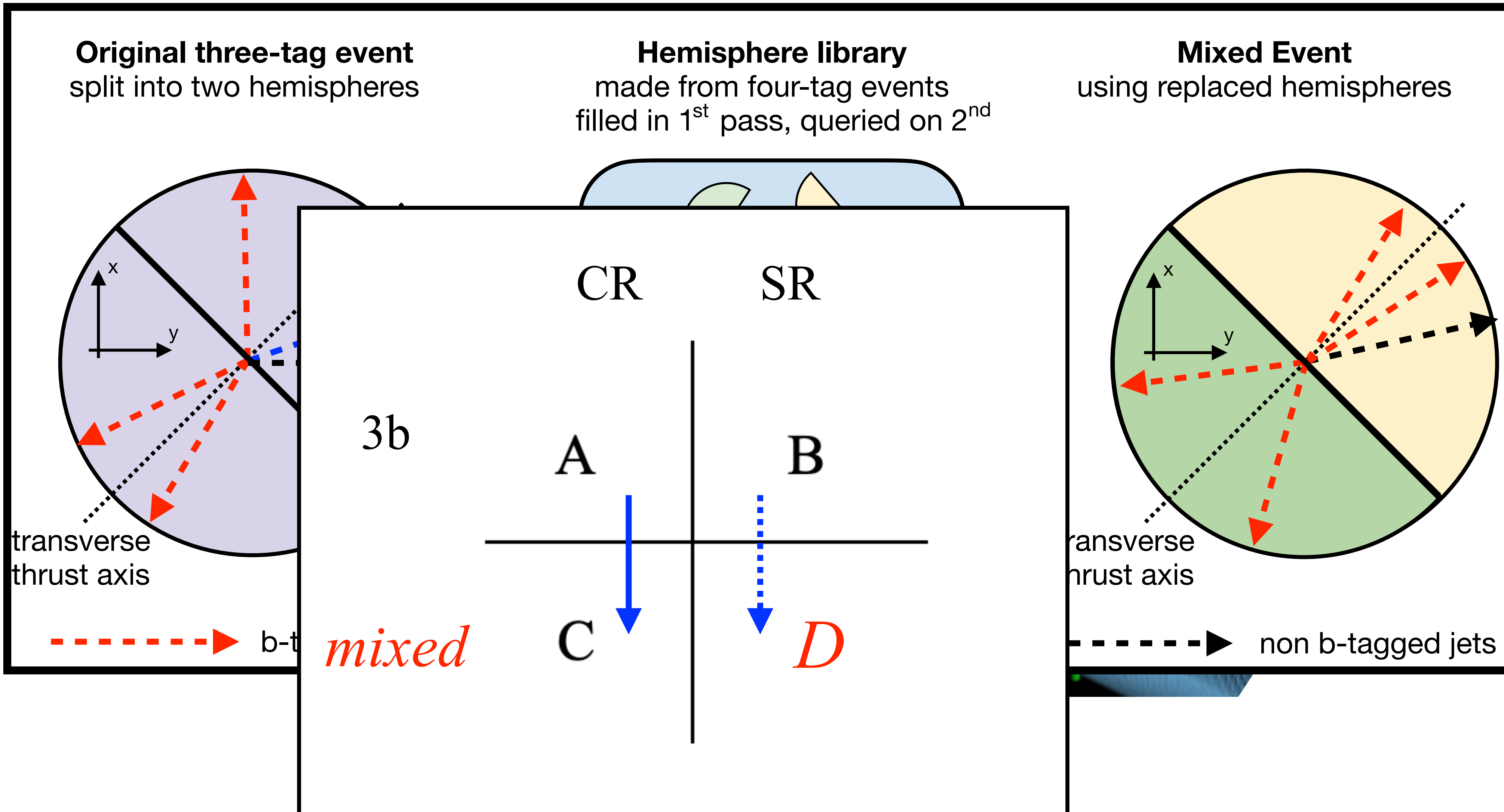
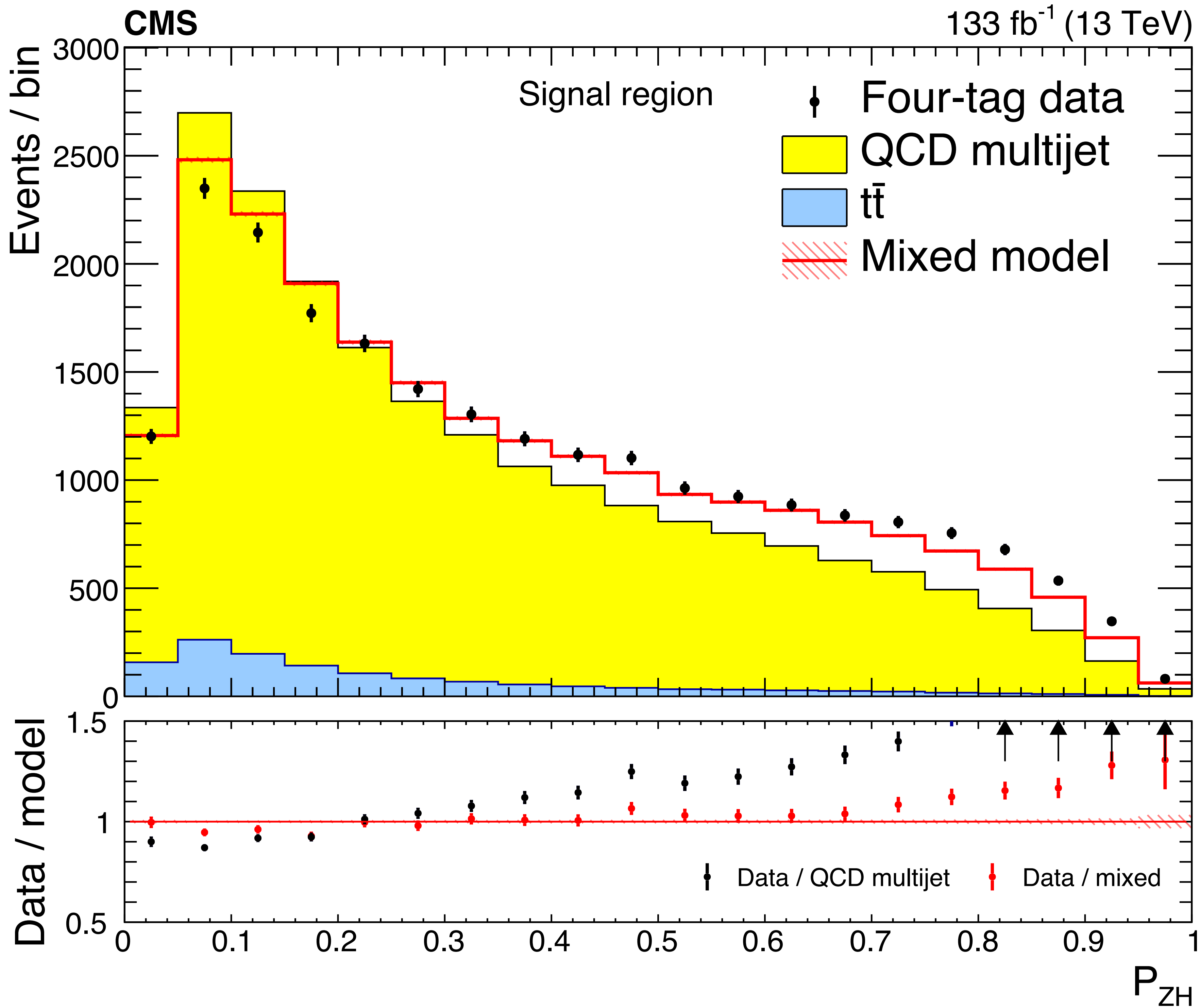
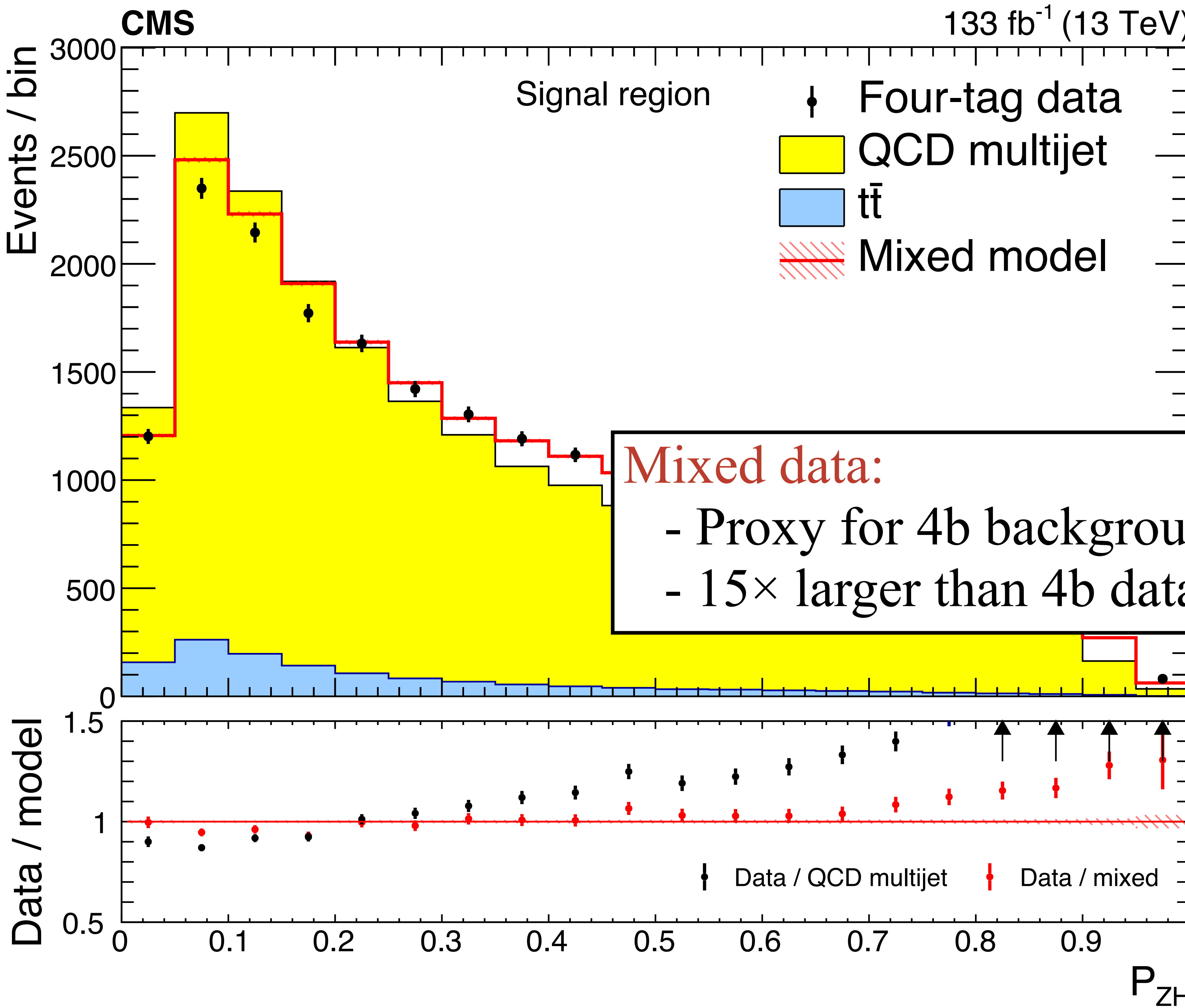




CMS
133 fb^{-1} (13 TeV)
Signal region
Four-tag data
QCD multijet
$t\bar{t}$
Mixed model
Events / bin
Data / model
Data / QCD multijet
Data / mixed
P_{ZH}



Mixed data:

- Proxy for 4b background
- 15× larger than 4b dataset

Systematics with Mixed Data

Consider three sources of potential systematic uncertainty

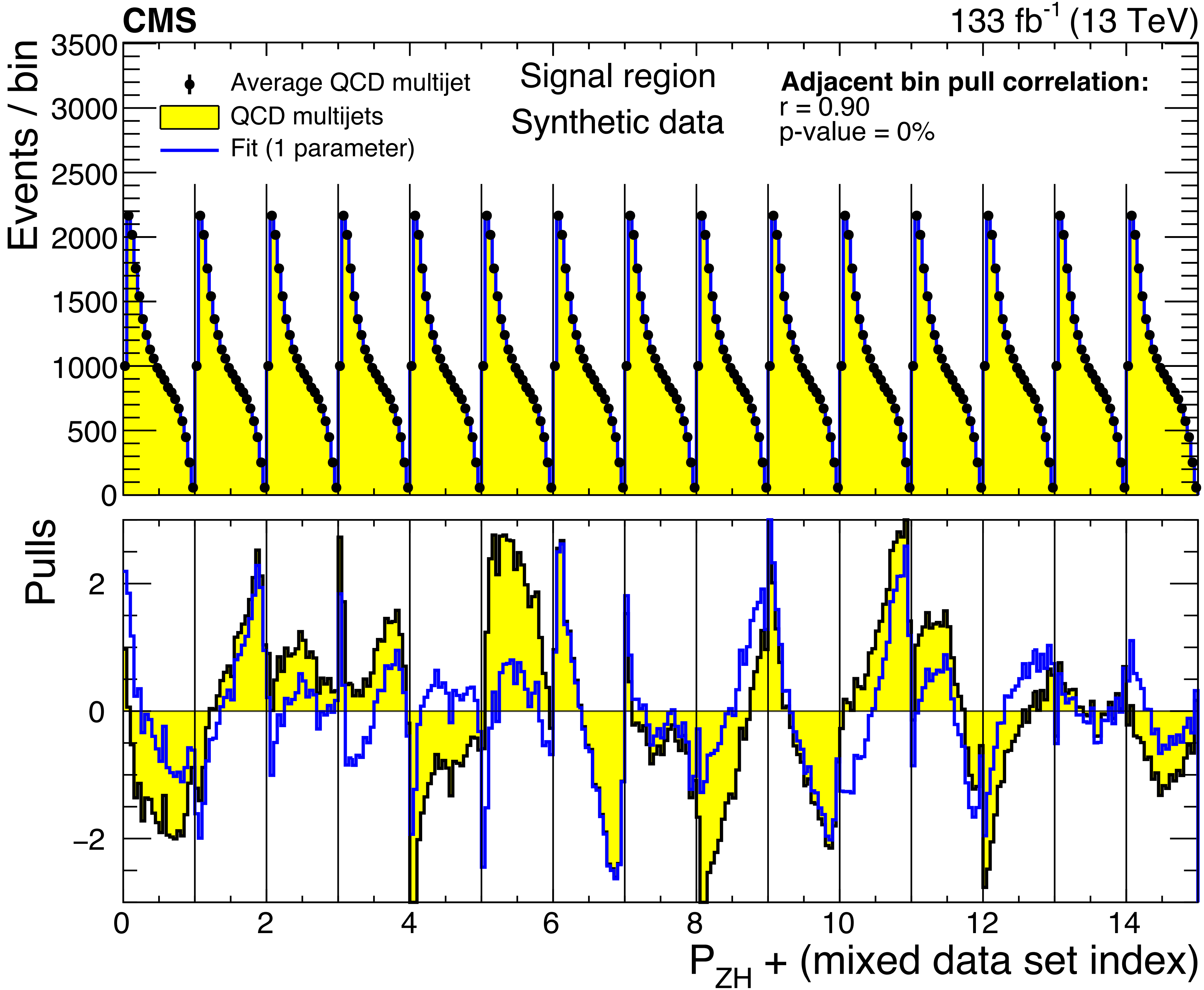
Variance: Arises from multi-variate classifier fit finite dataset CR

Bias: Assumption that density ratio measured in CR is same as SR

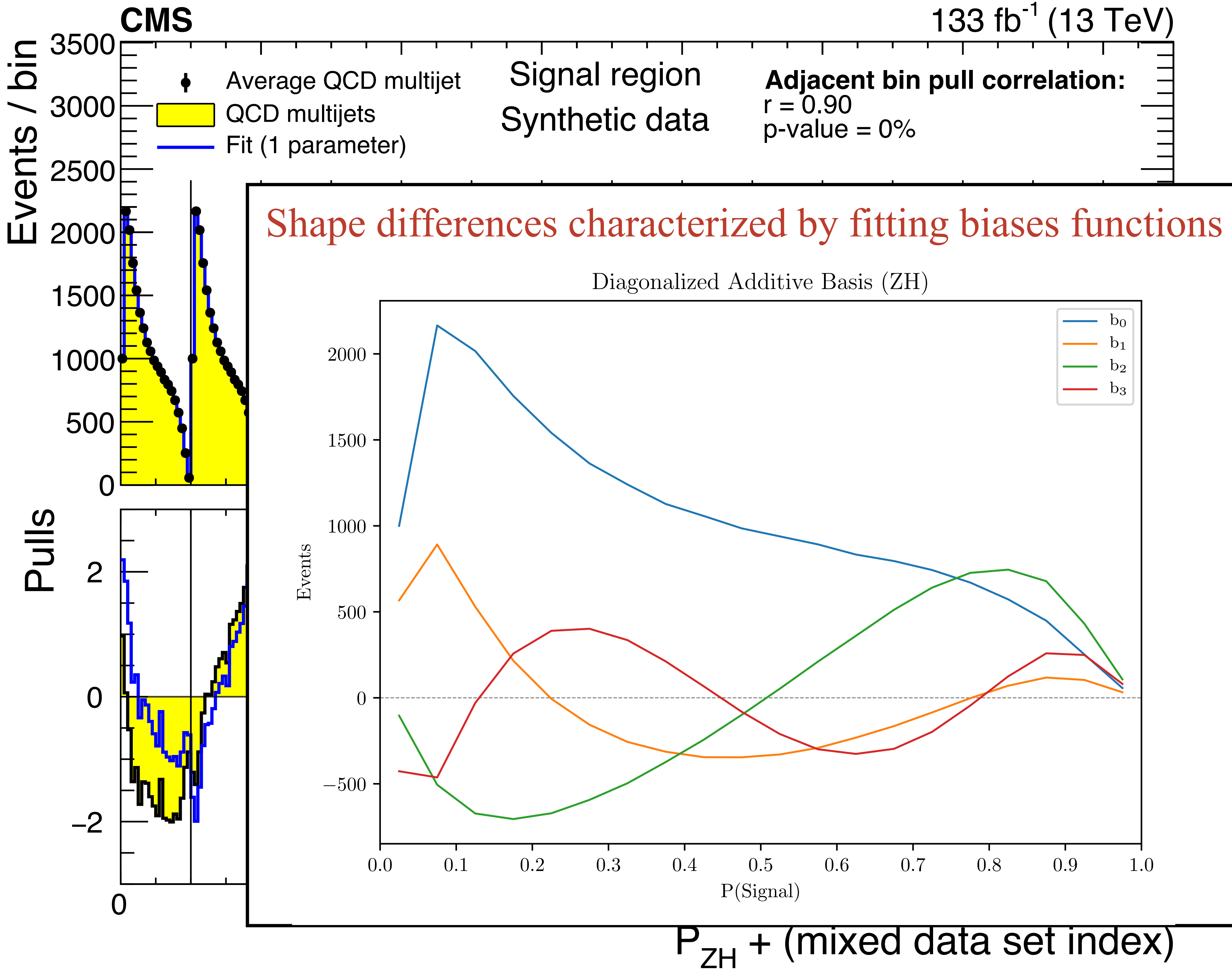
Spurious Signal Can misspecification of the background model look like a signal under the null hypothesis ?

(See backup)

Assumptions rigorously defined for stats audience: arXiv:2208.02807



CMS
133 fb-1 (13 TeV)
Events / bin
Average QCD multijet
QCD multijets
Fit (1 parameter)
Signal region
Synthetic data
Adjacent bin pull correlation:
r = 0.90
p-value = 0%
Pulls
P_ZH + (mixed data set index)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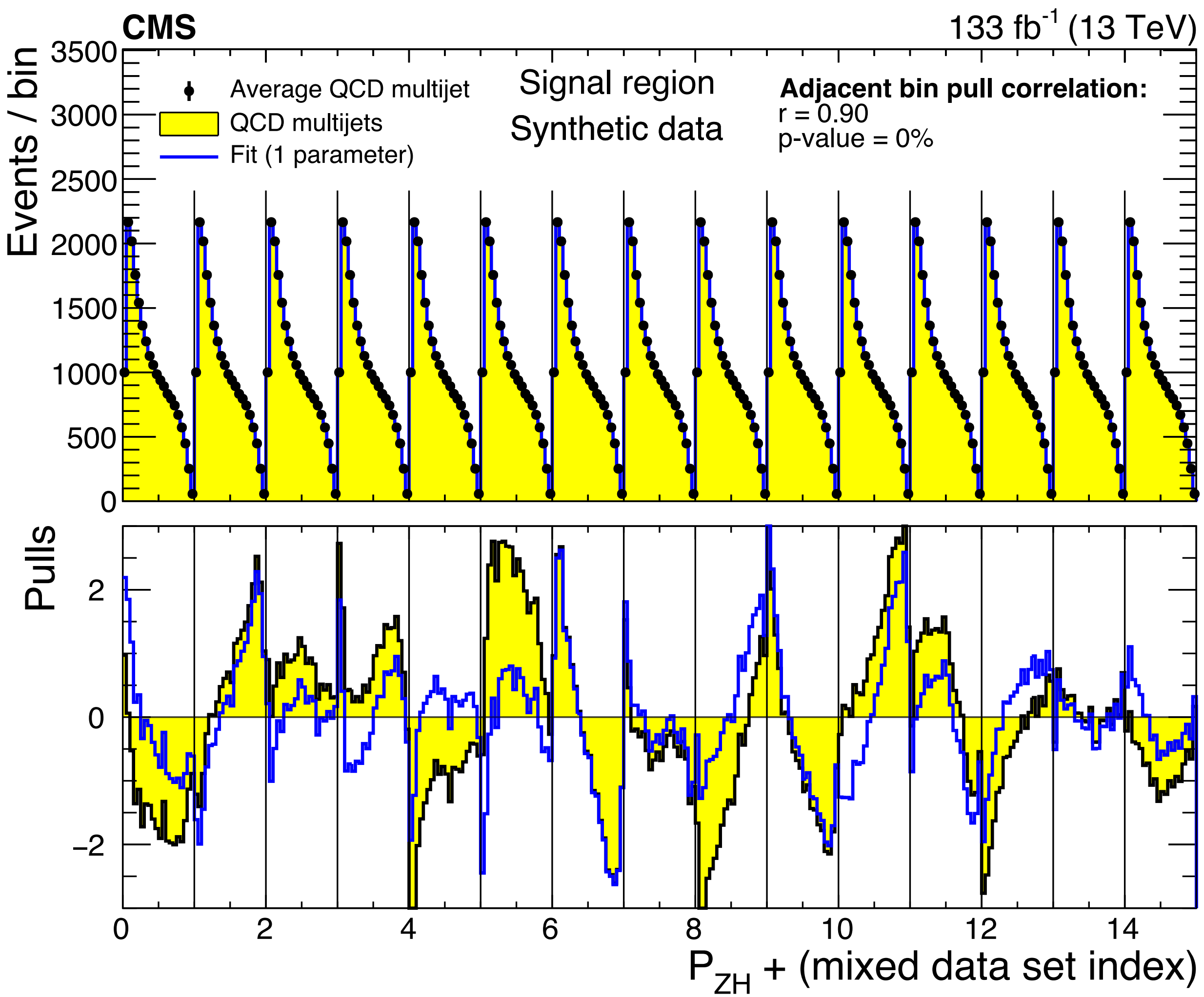
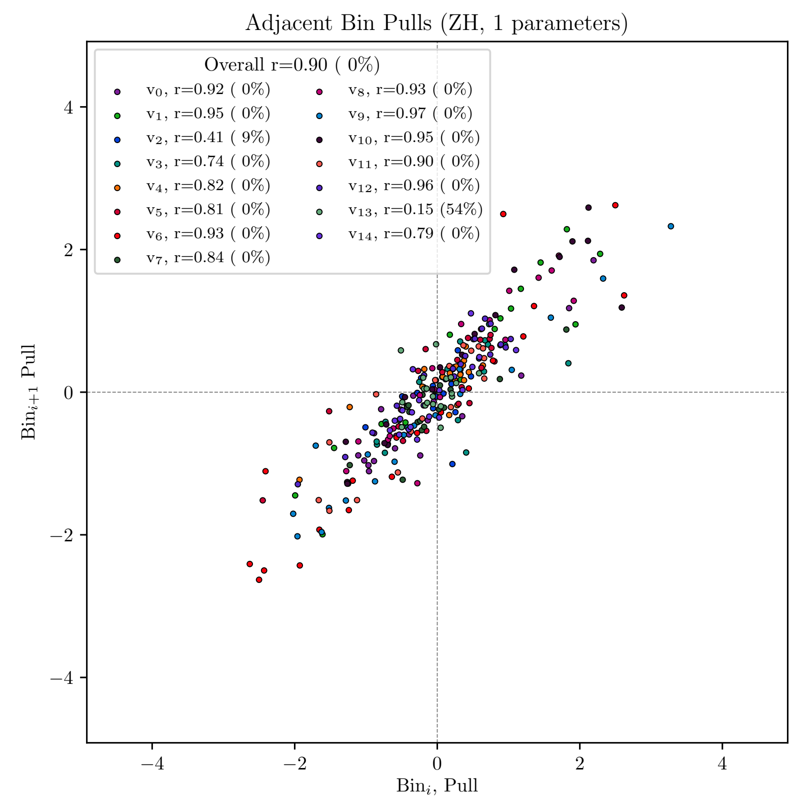
Pulls
Shape differences characterized by fitting biases functions
Diagonalized Additive Basis (ZH)
Events
b0
b1
b2
b3
P(Signal)
P_ZH + (mixed data set index)

Quantifying Variance

Compare each of the background predictions to the average





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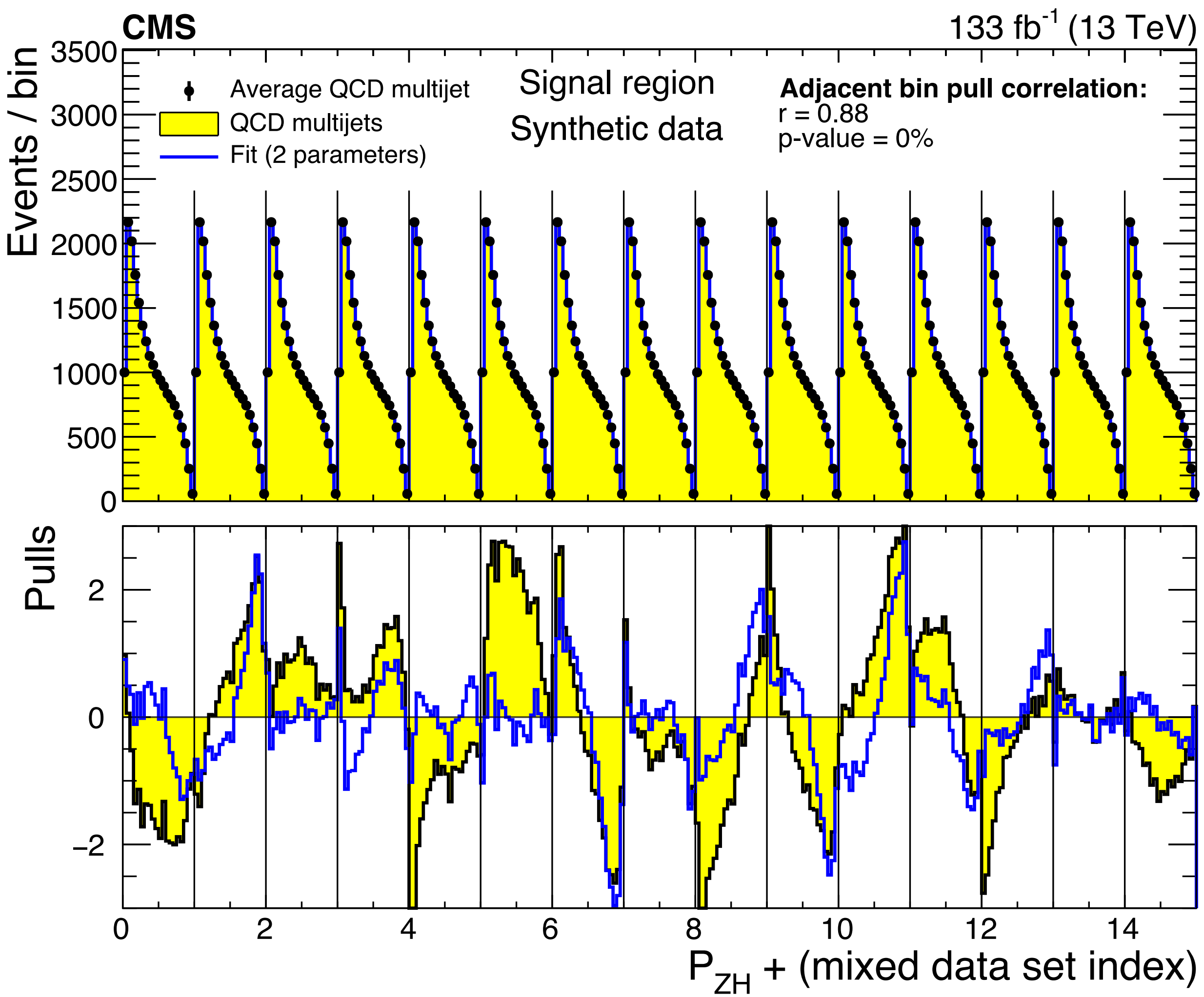

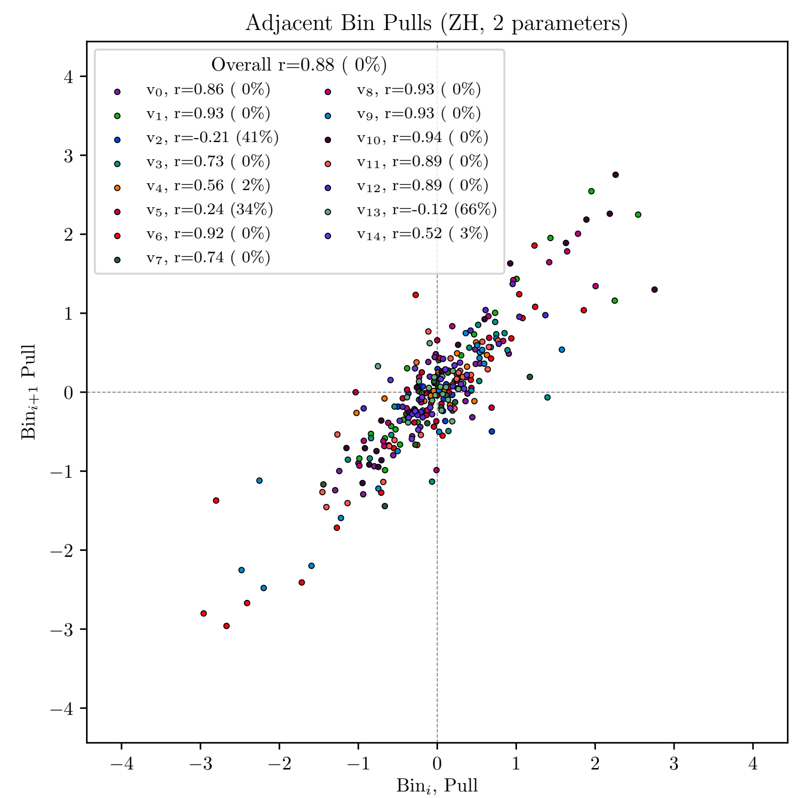

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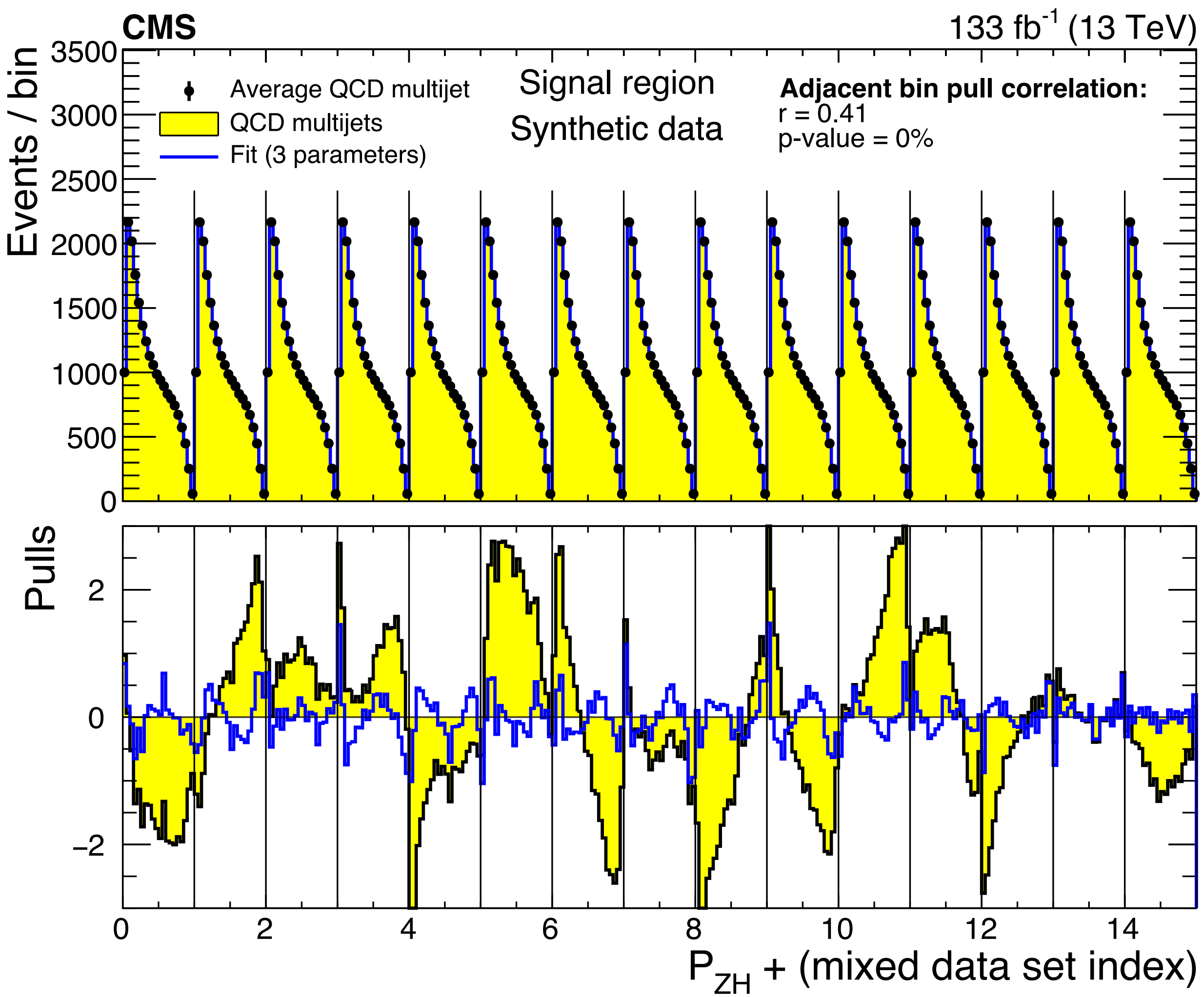

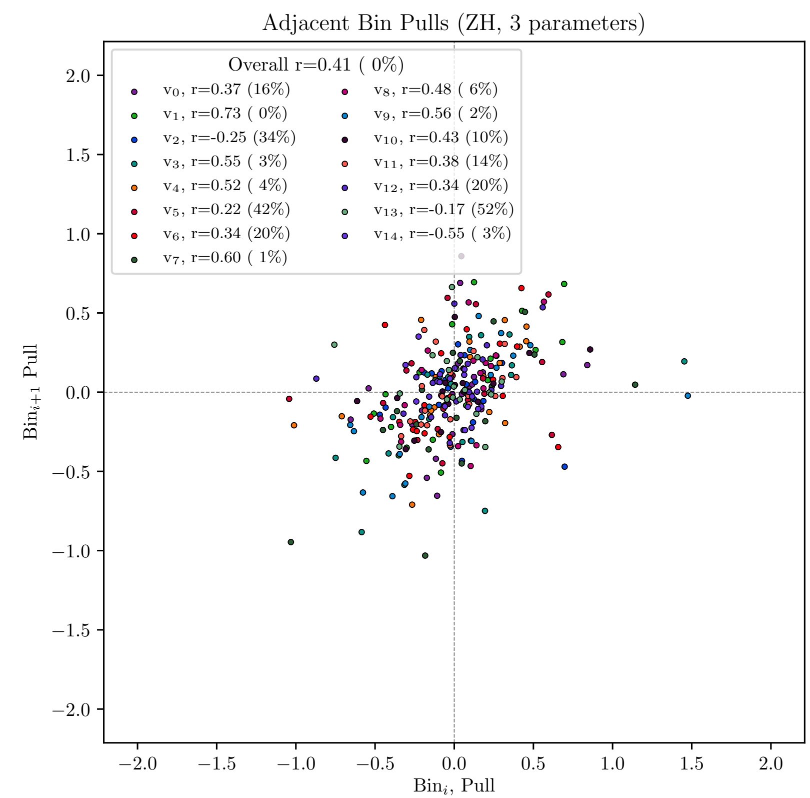

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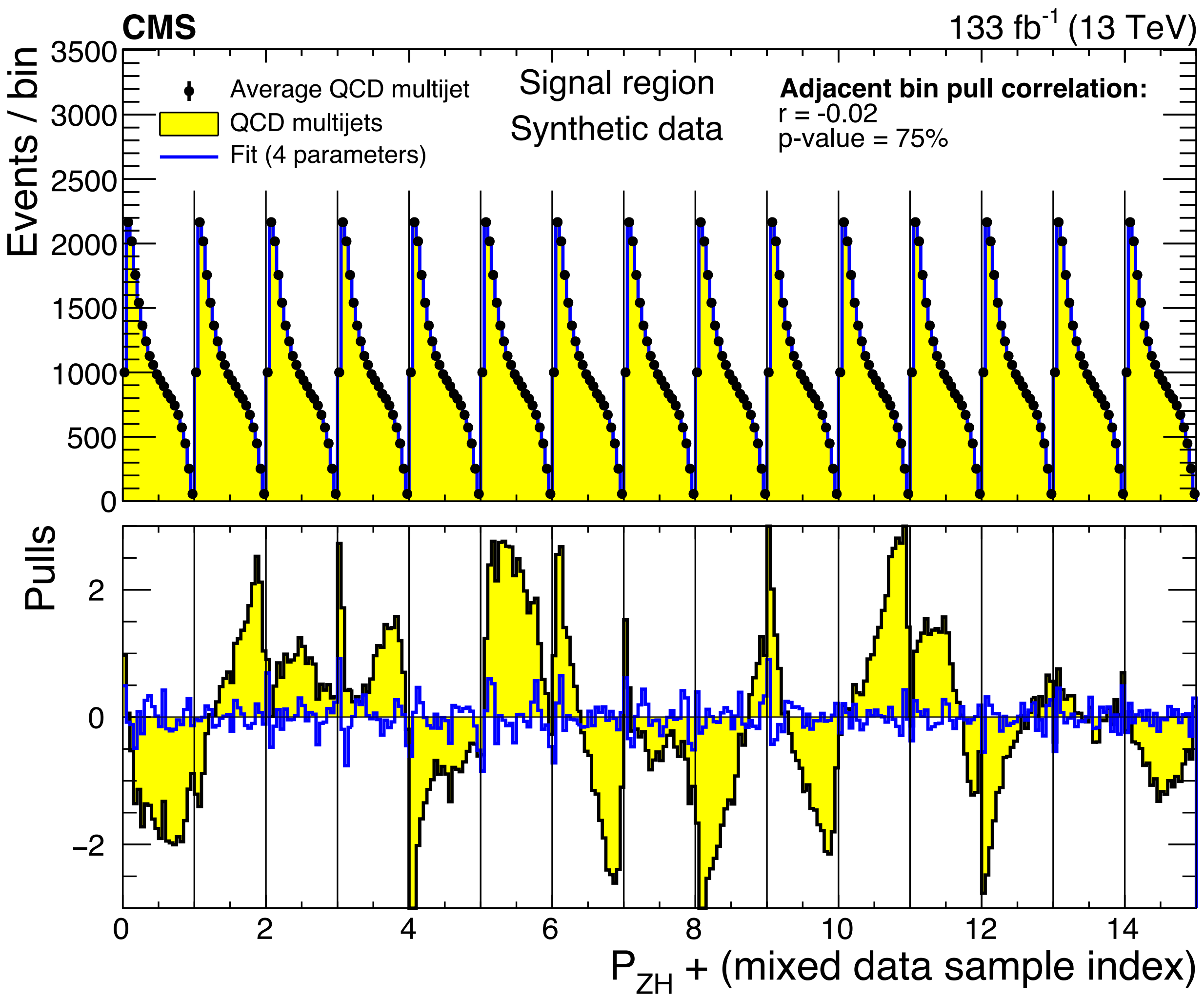
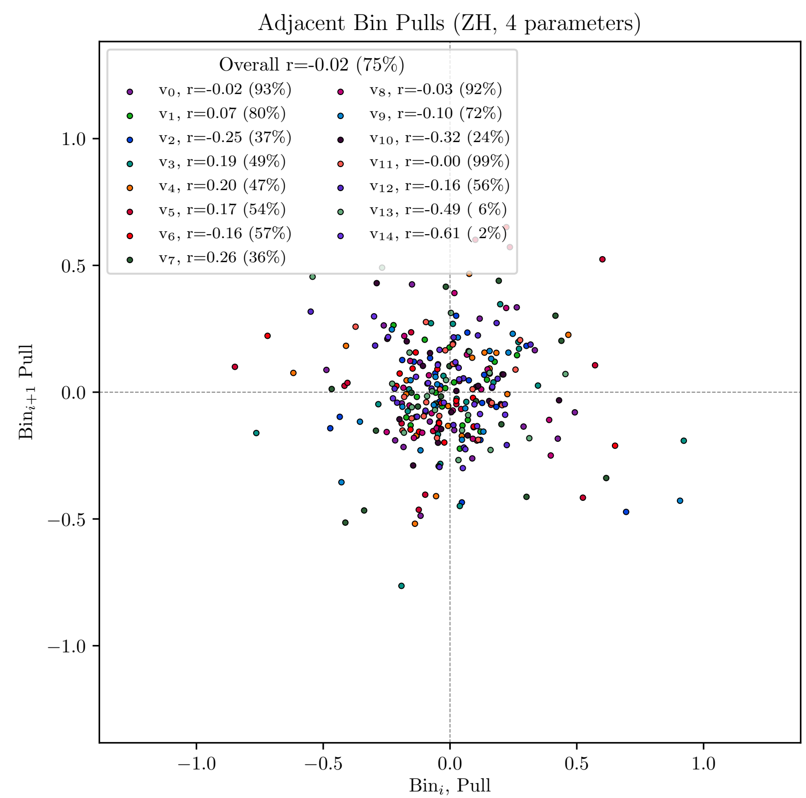
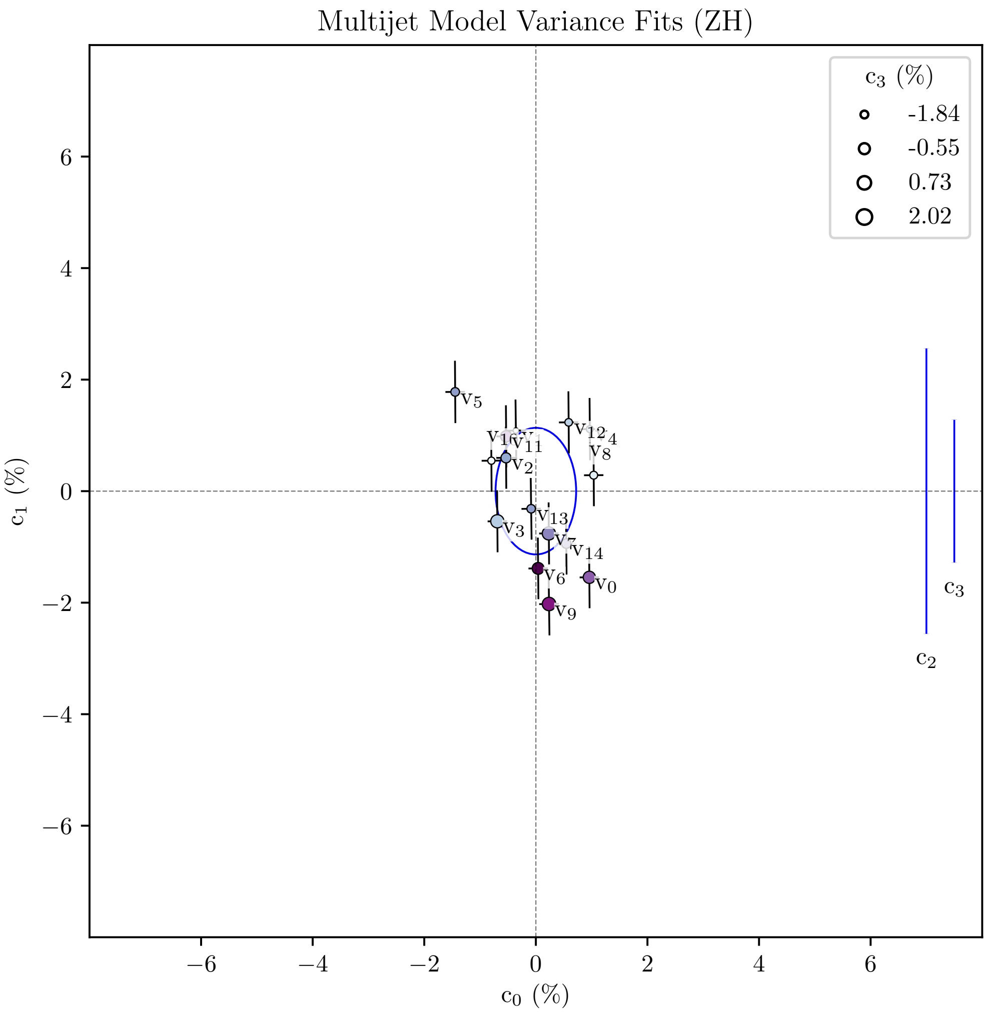
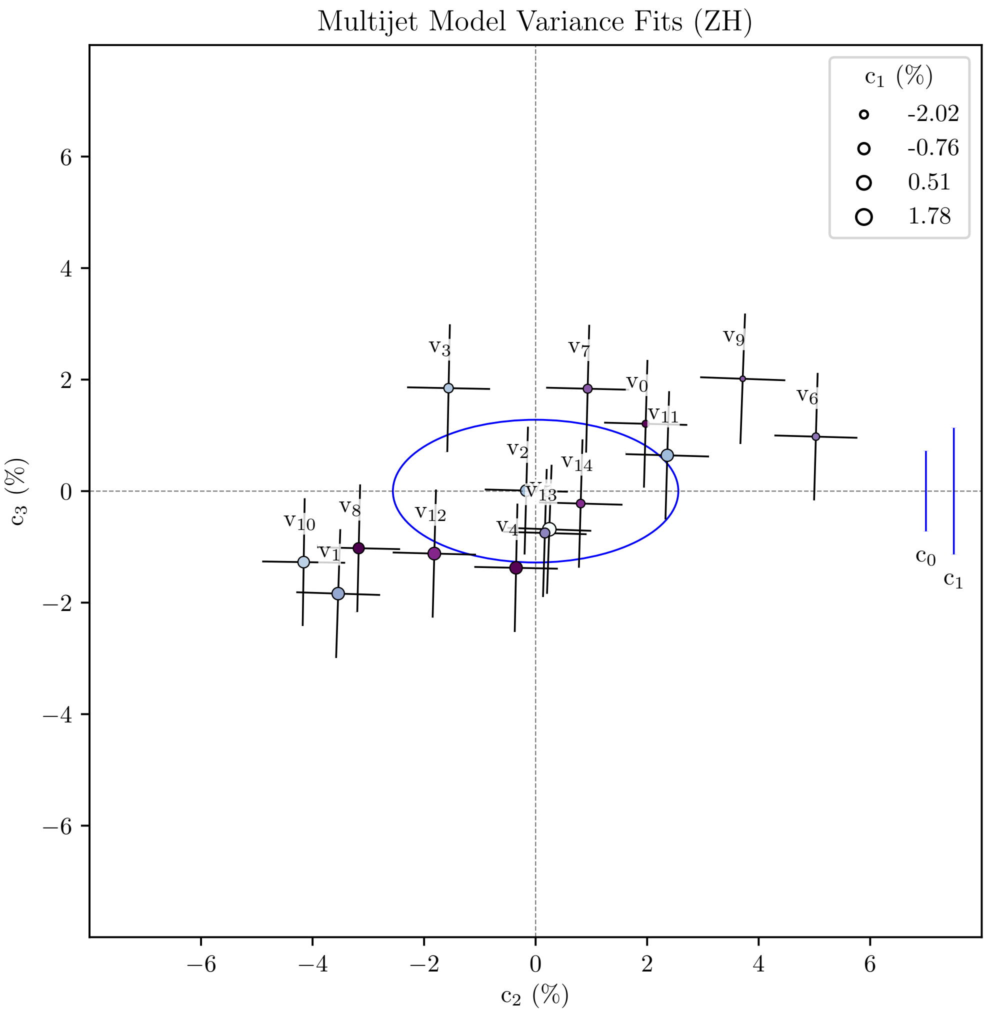




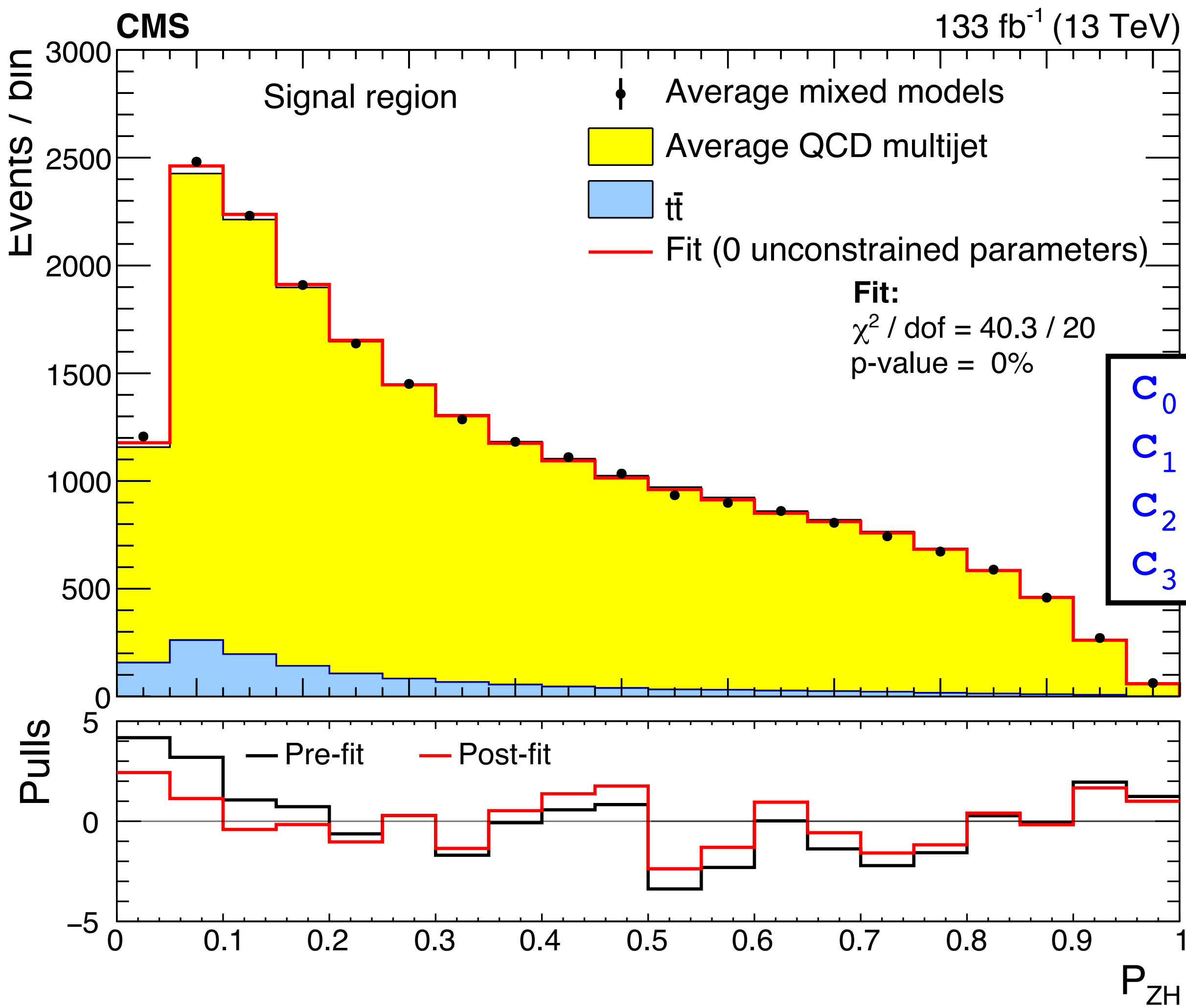
Variance Uncertainties





Extrapolation Uncertainty

Compare average background predictions to observed yield in (mixed-data) signal region



c_0 = 0.1% : 0.4σ
c_1 = 3.2% : 4.8σ
c_2 =−1.3% : 1.4σ
c_3 = 0.3% : 0.3σ

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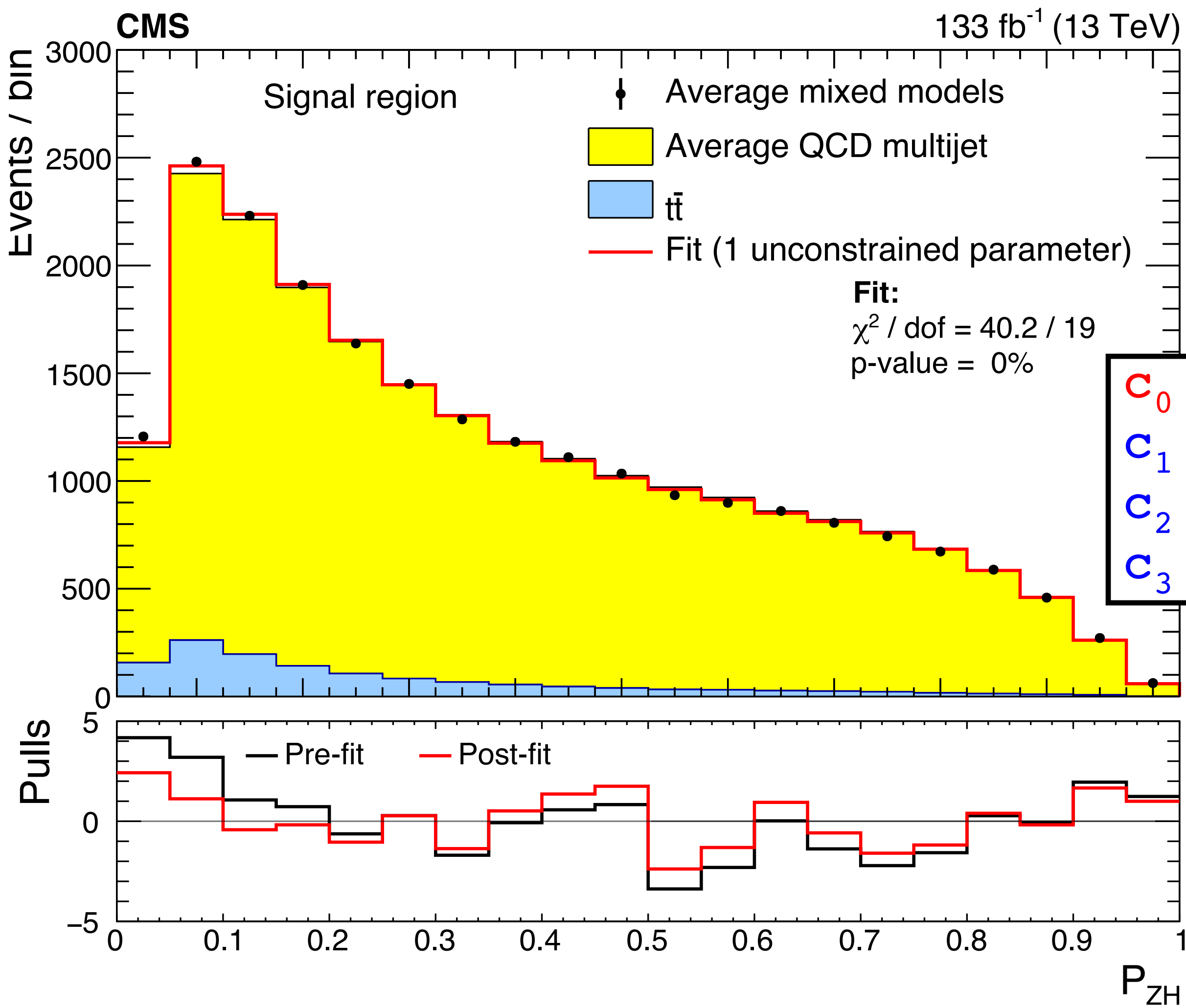

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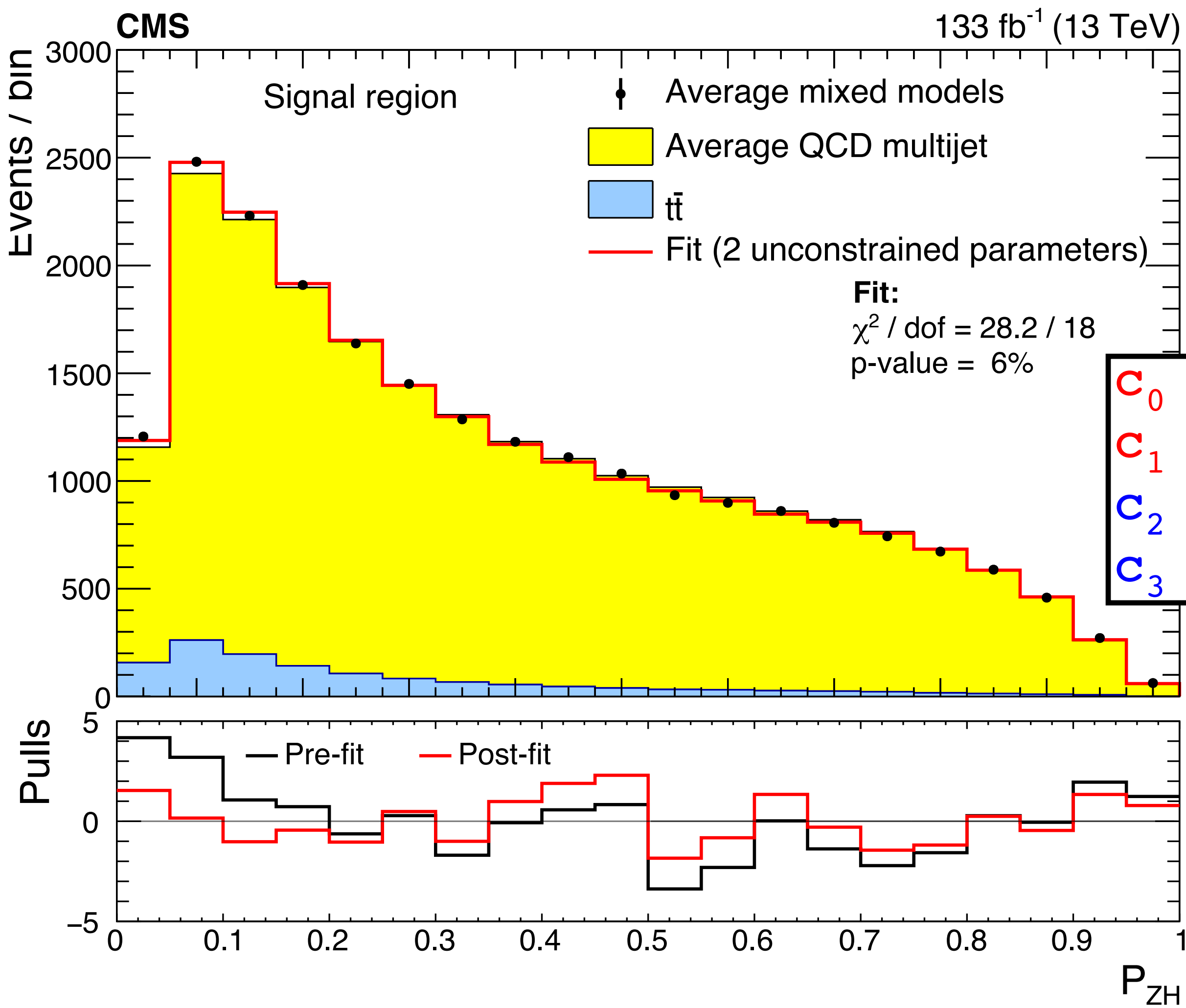
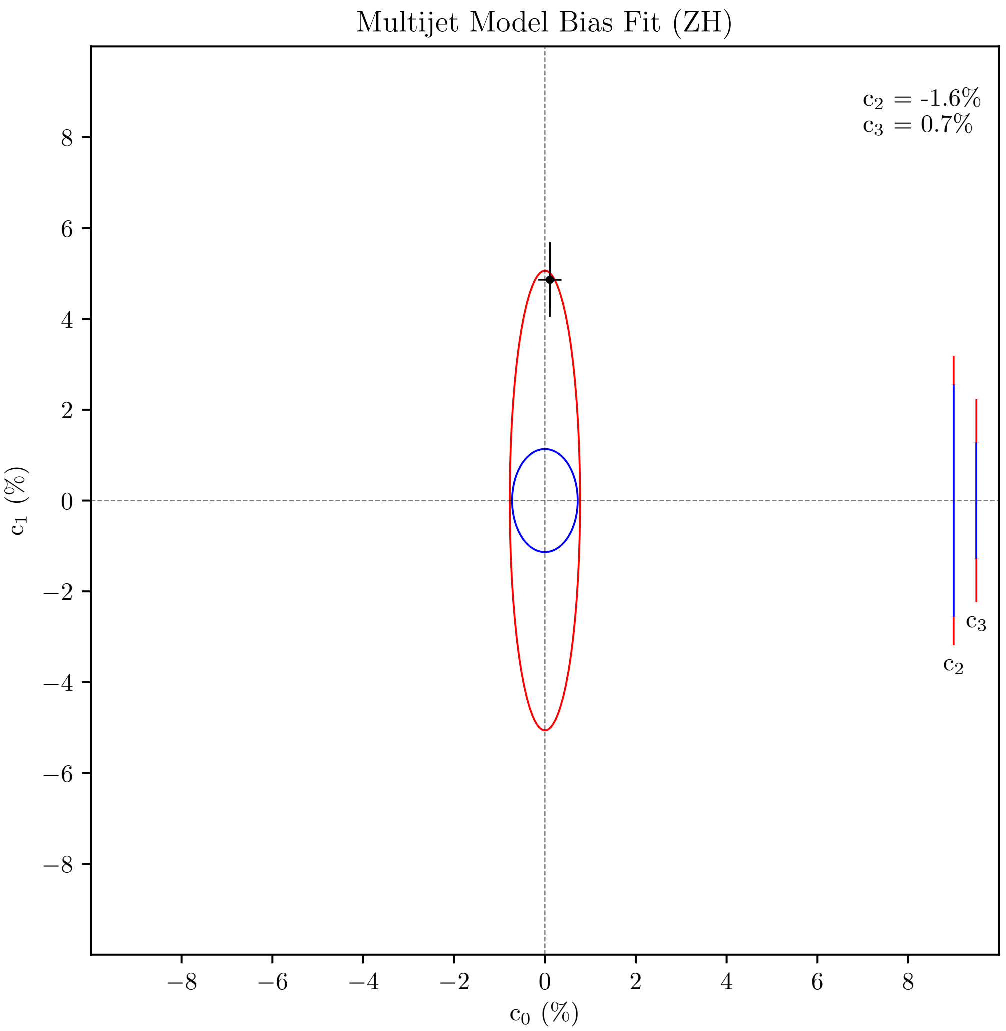
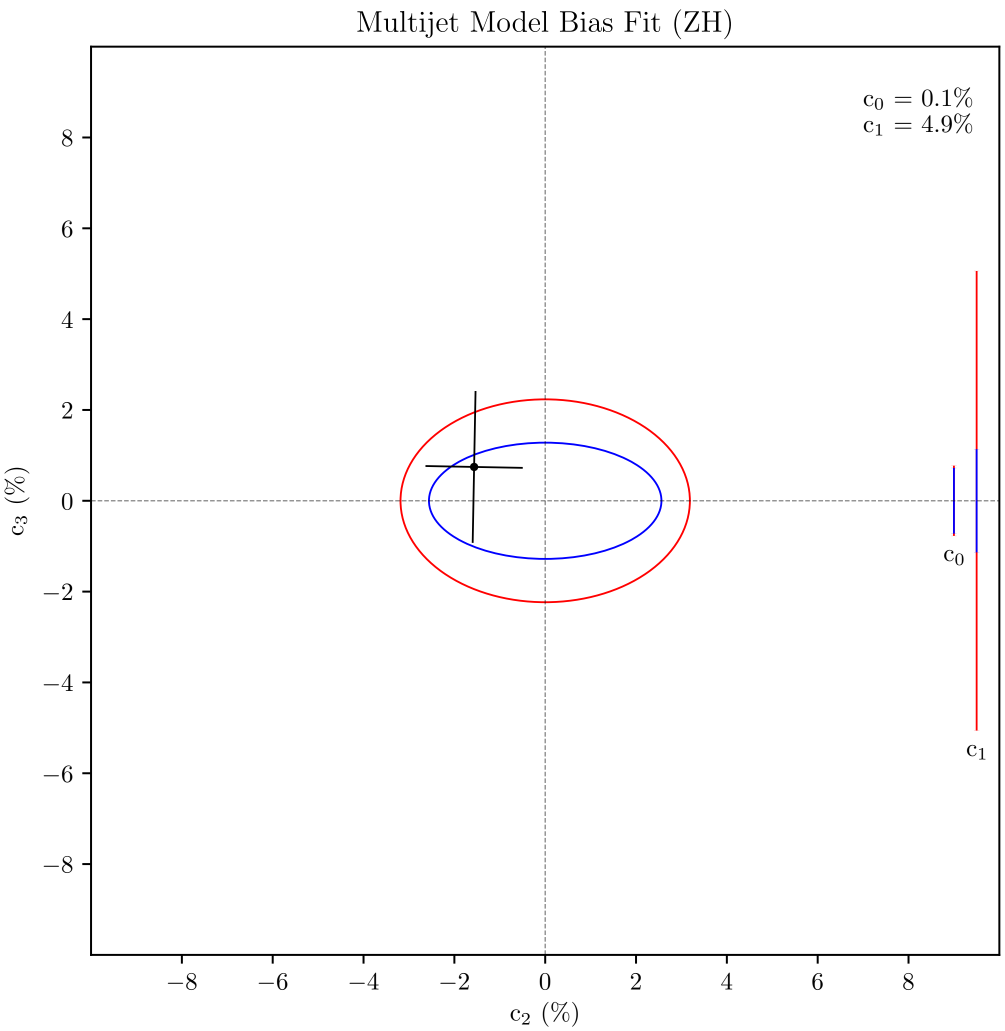


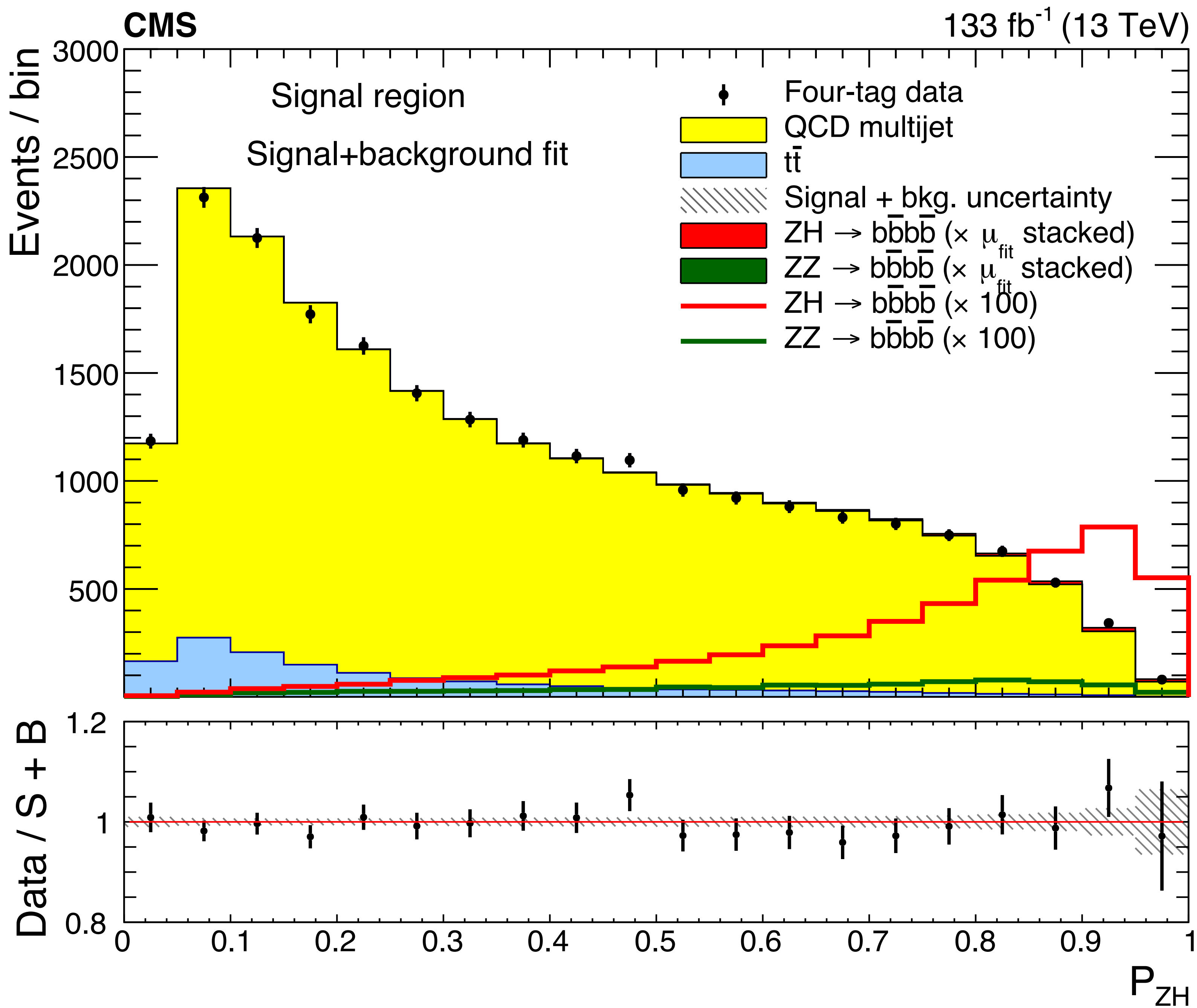
$c_0 = 0.1\% : 0.4\sigma$
$c_1 = 4.9\% : 5.9\sigma$
$c_2 = -1.3\% : 1.4\sigma$
$c_3 = 0.3\% : 0.3\sigma$

Bias Uncertainties





Analysis of 4b Signal Region



Conclusions

Data-driven background ubiquitous in particle physics

Require assumptions w/large hard-to-quantify systematic uncertainties

Synthetic datasets can provide more principled assessment of systematics
  Believe synthetic datasets will be increasing important in future

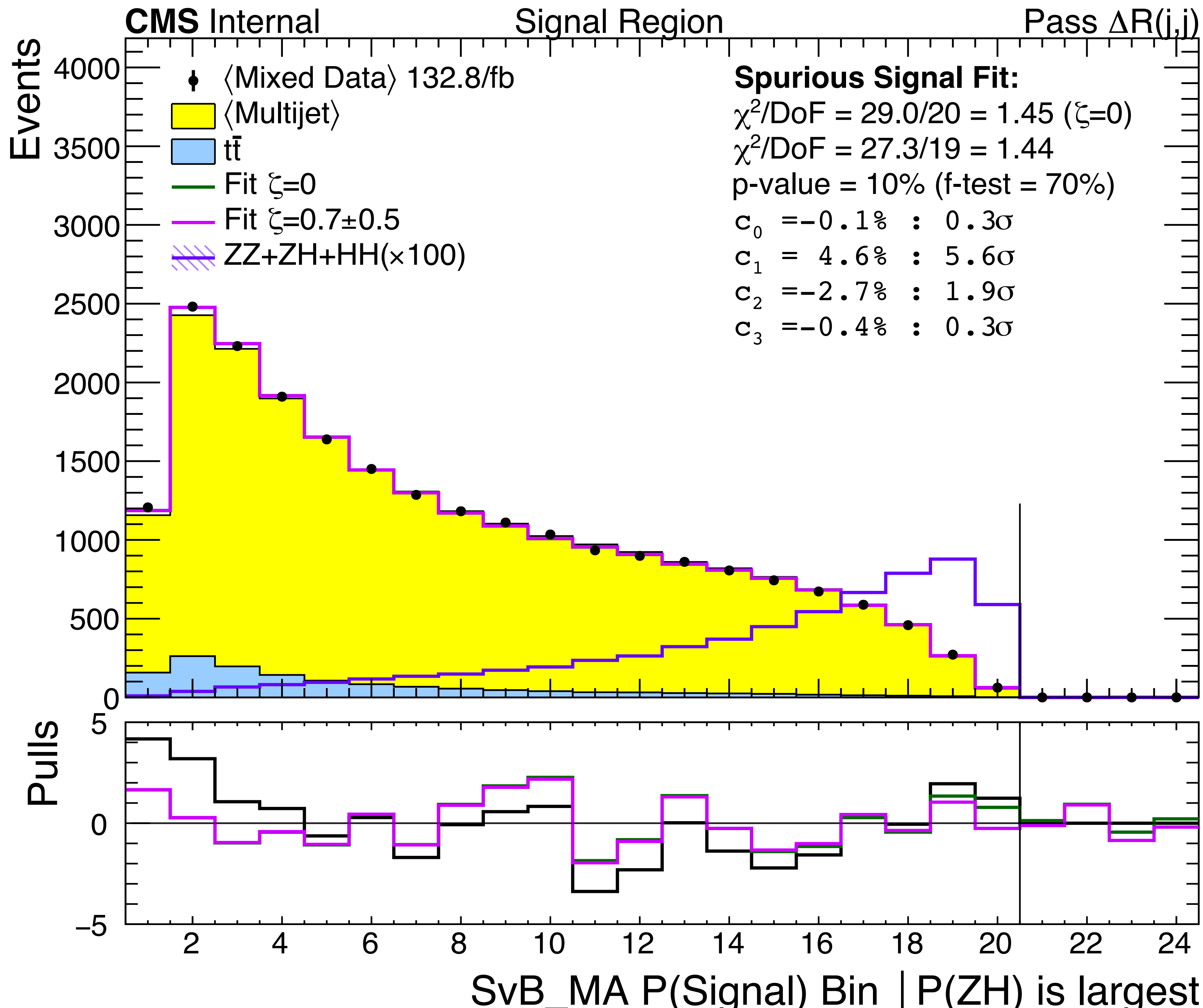
Case study in search for HH→4b more details: arXiv:2403.20241

Believe concept can be generalized beyond HH and high-energy physics

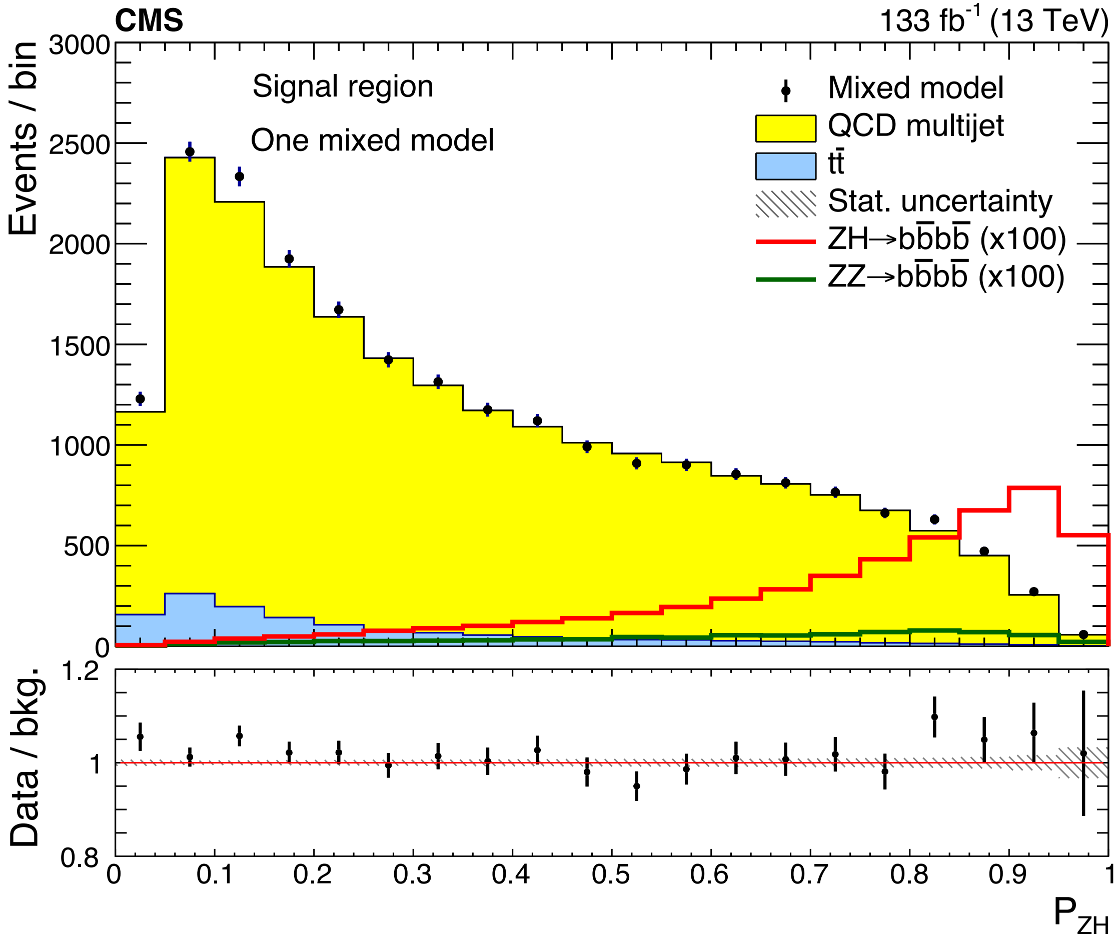
Future directions:
- Reduce variance by k-folding
- Correct bias, take smaller uncertainty
- Larger higher fidelity synthetic datasets

Backup

Spurious Signal



Mixed data: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$t\bar{t}$
Stat. uncertainty
ZH→$b\bar{b}b\bar{b}$ (x100)
ZZ→$b\bar{b}b\bar{b}$ (x100)
Data / bkg.
P_{ZH}

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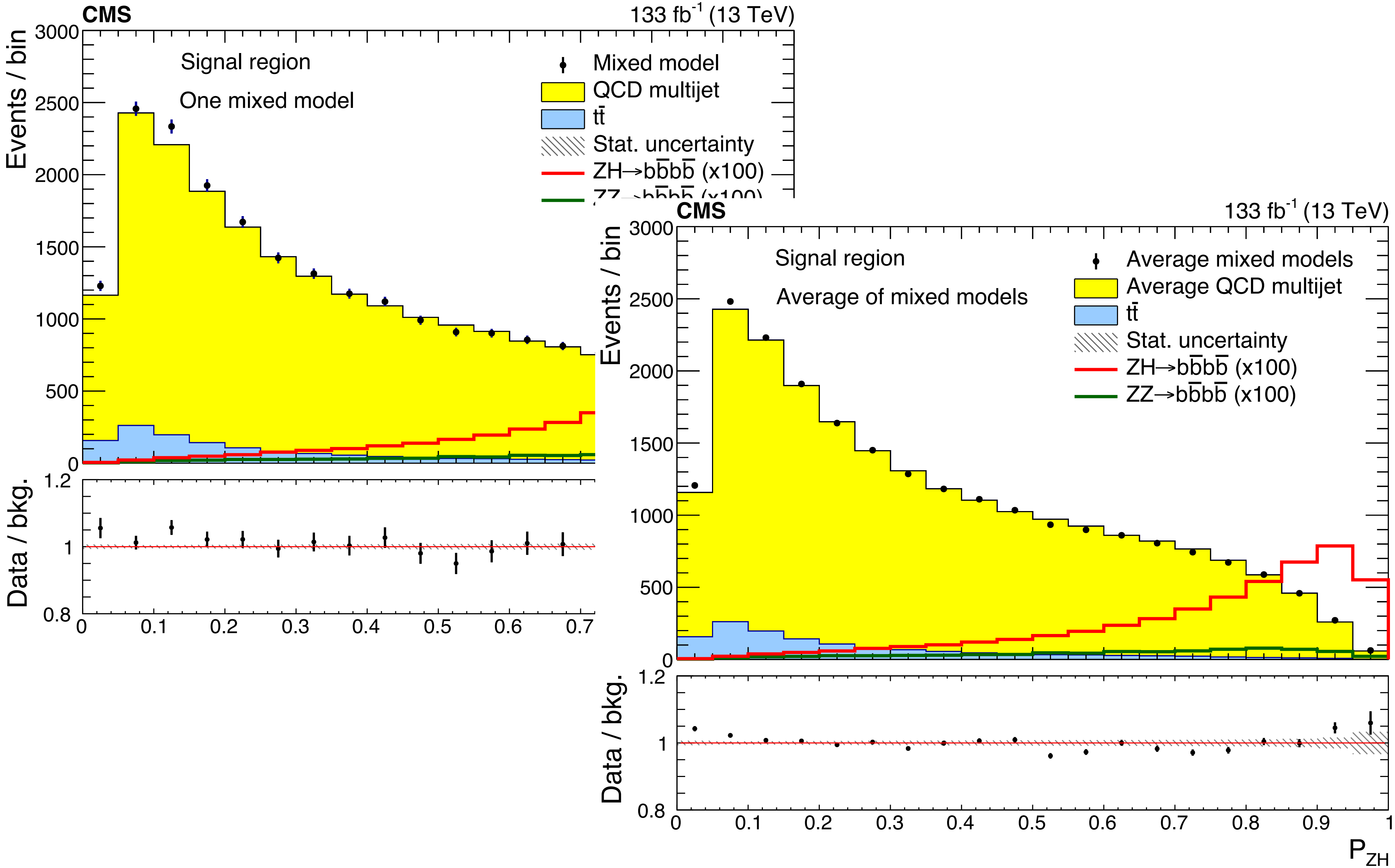

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Events / bin
Data / bkg.
CMS
133 fb^{-1} (13 TeV)
Signal region
Average of mixed models
Average mixed models
Average QCD multijet
$t\bar{t}$
Stat. uncertainty
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Events / bin
Data / bkg.
P_{ZH}