EXPLORING BOOSTED TOP QUARK DECAYS USING RUN 3 DATA COLLECTED BY THE CMS EXPERIMENT

— **Johanna Matthiesen**[1], Johannes Haller[1], Roman Kogler[2], Daniel Savoiu[1] —

[1]Universität Hamburg - [2]DESY, Hamburg

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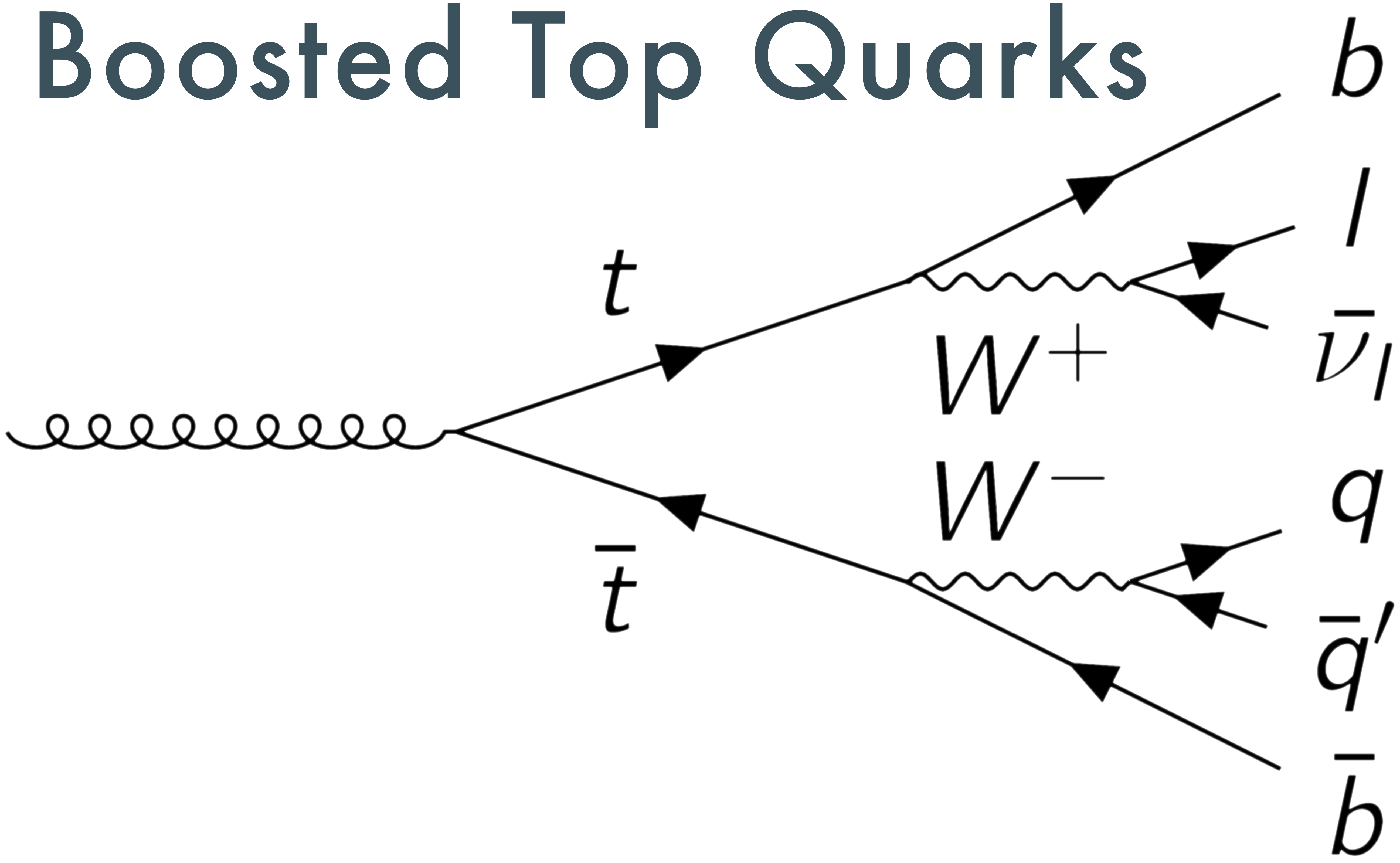
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

FSP CMS
Erforschung von
Universum und Materie

Boosted Top Quarks



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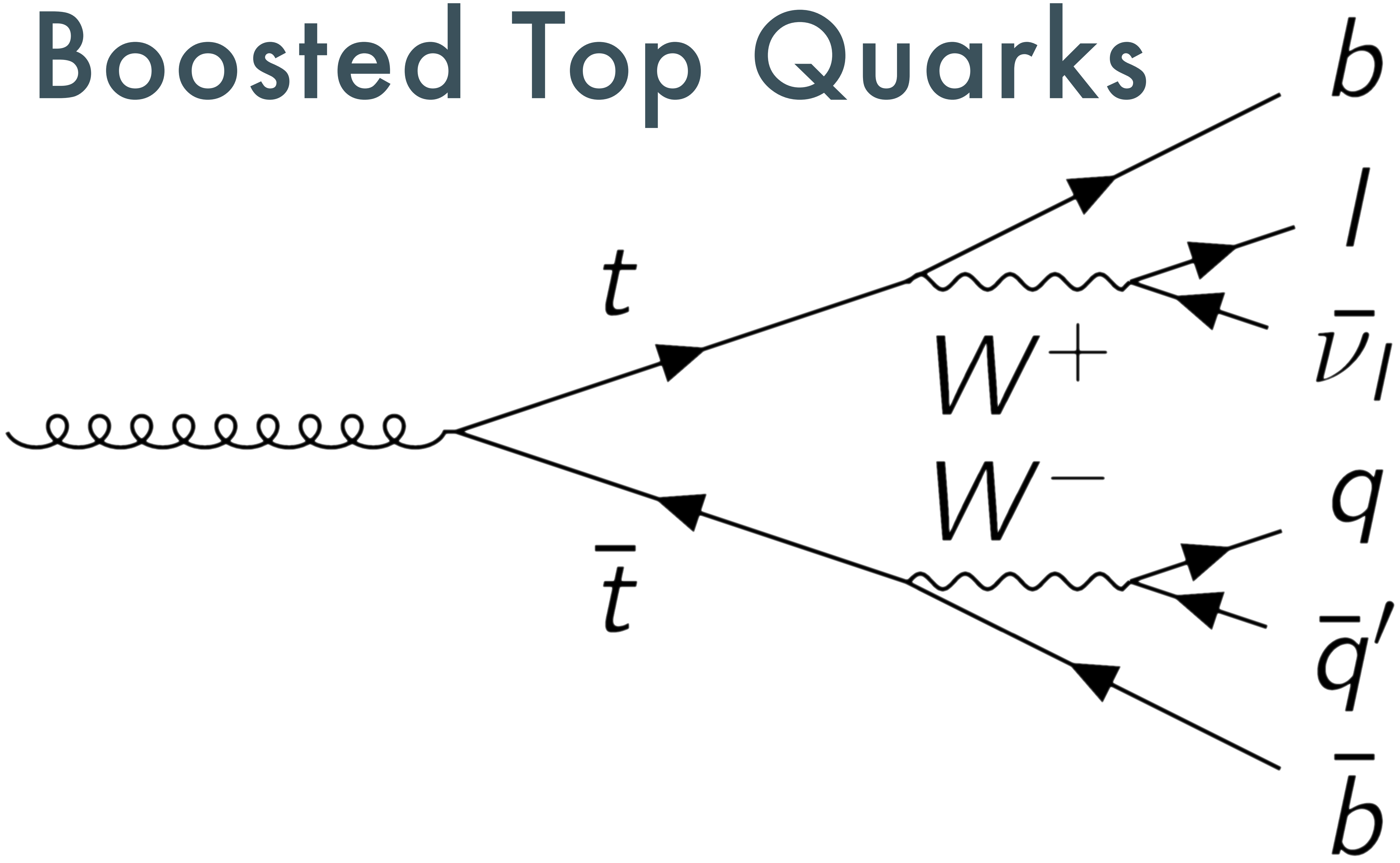

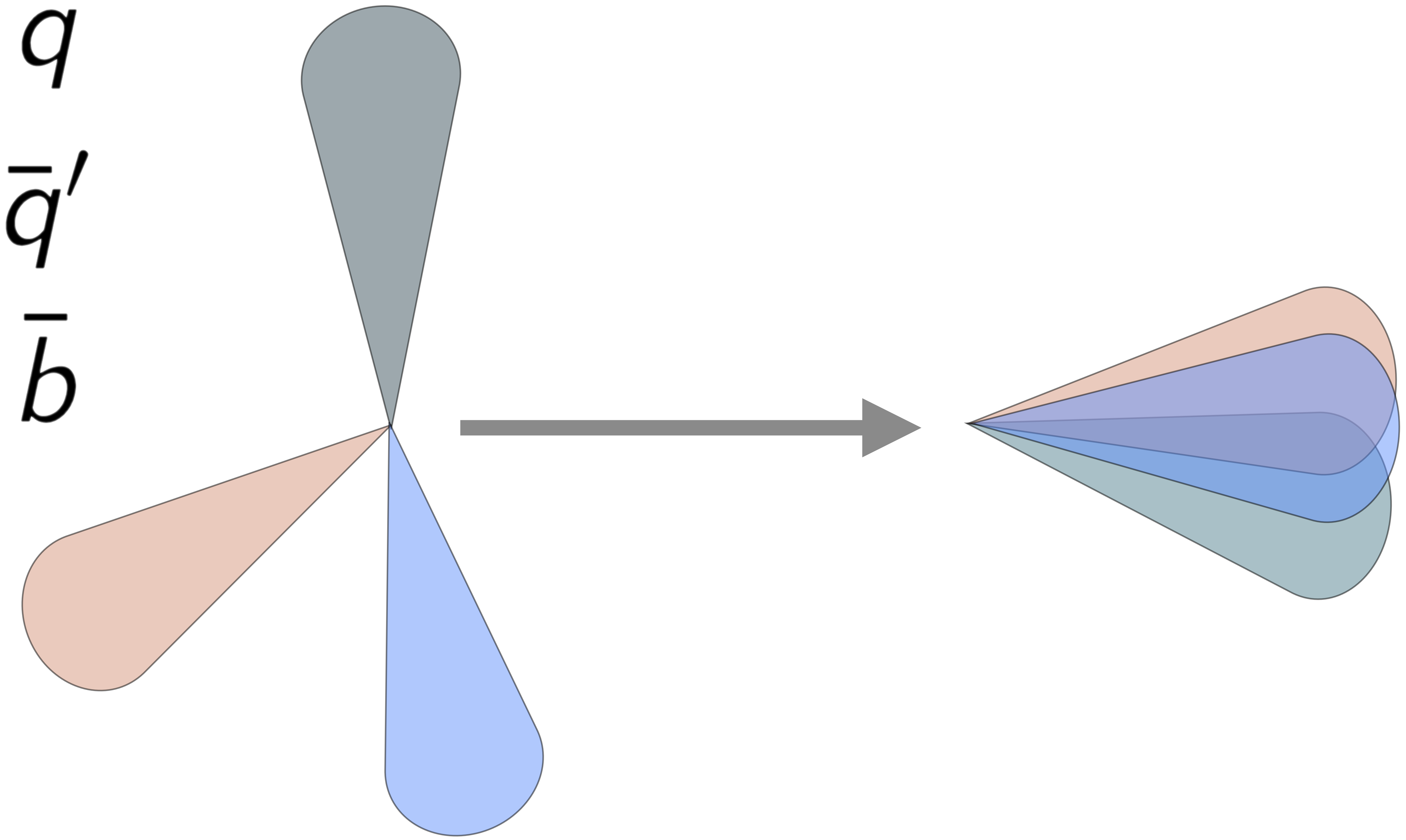

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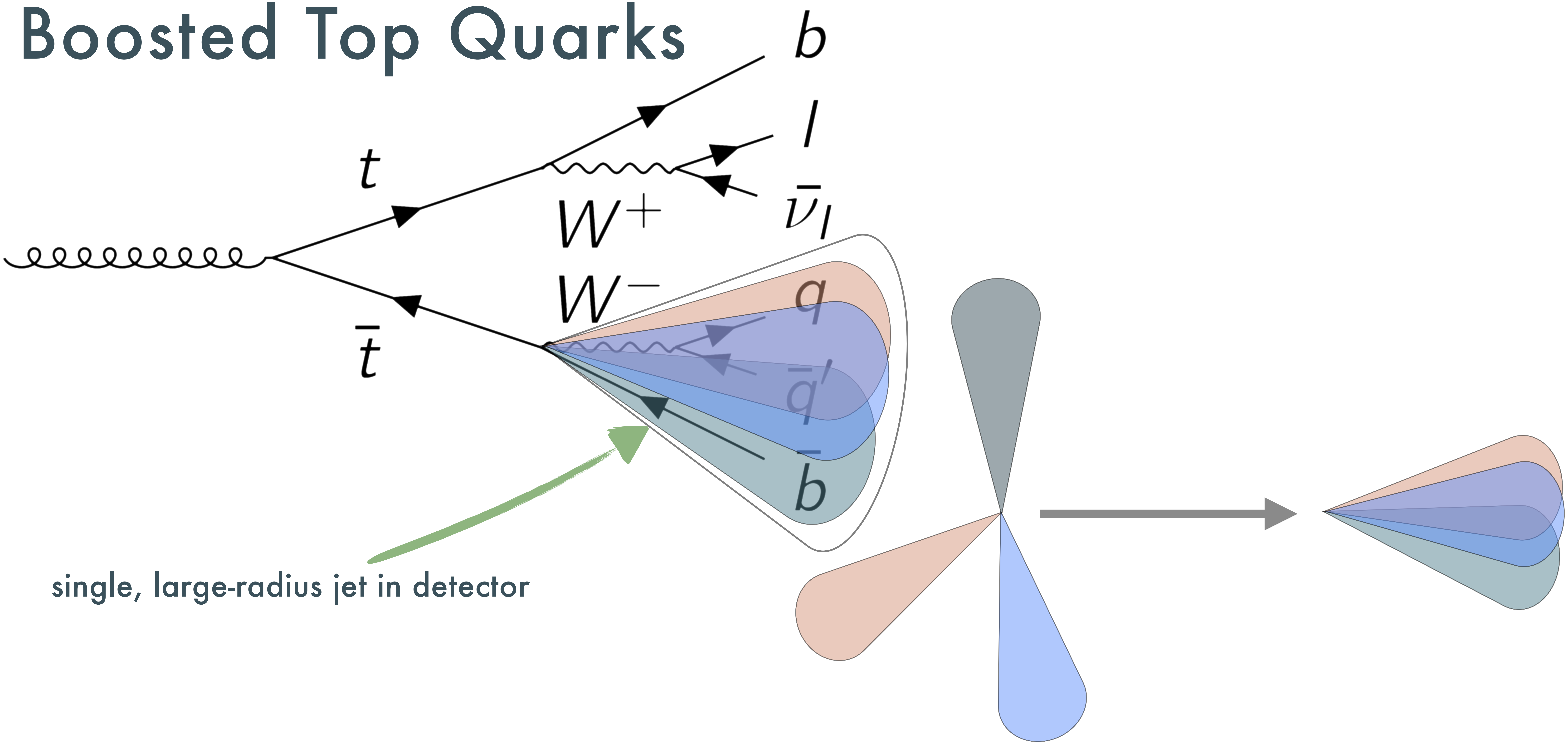
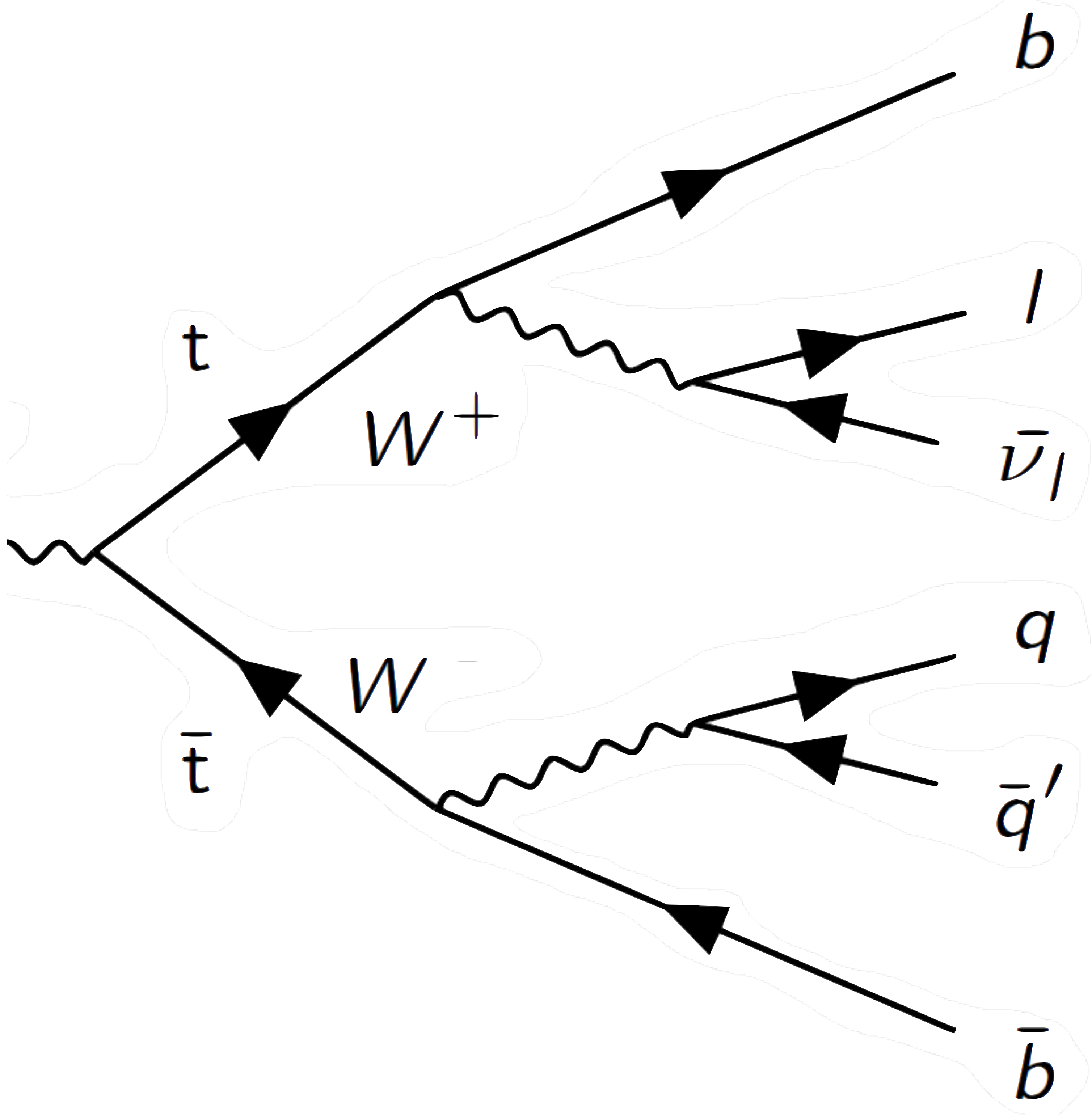


single, large-radius jet in detector

Boosted Top Quarks

— in BSM signals —



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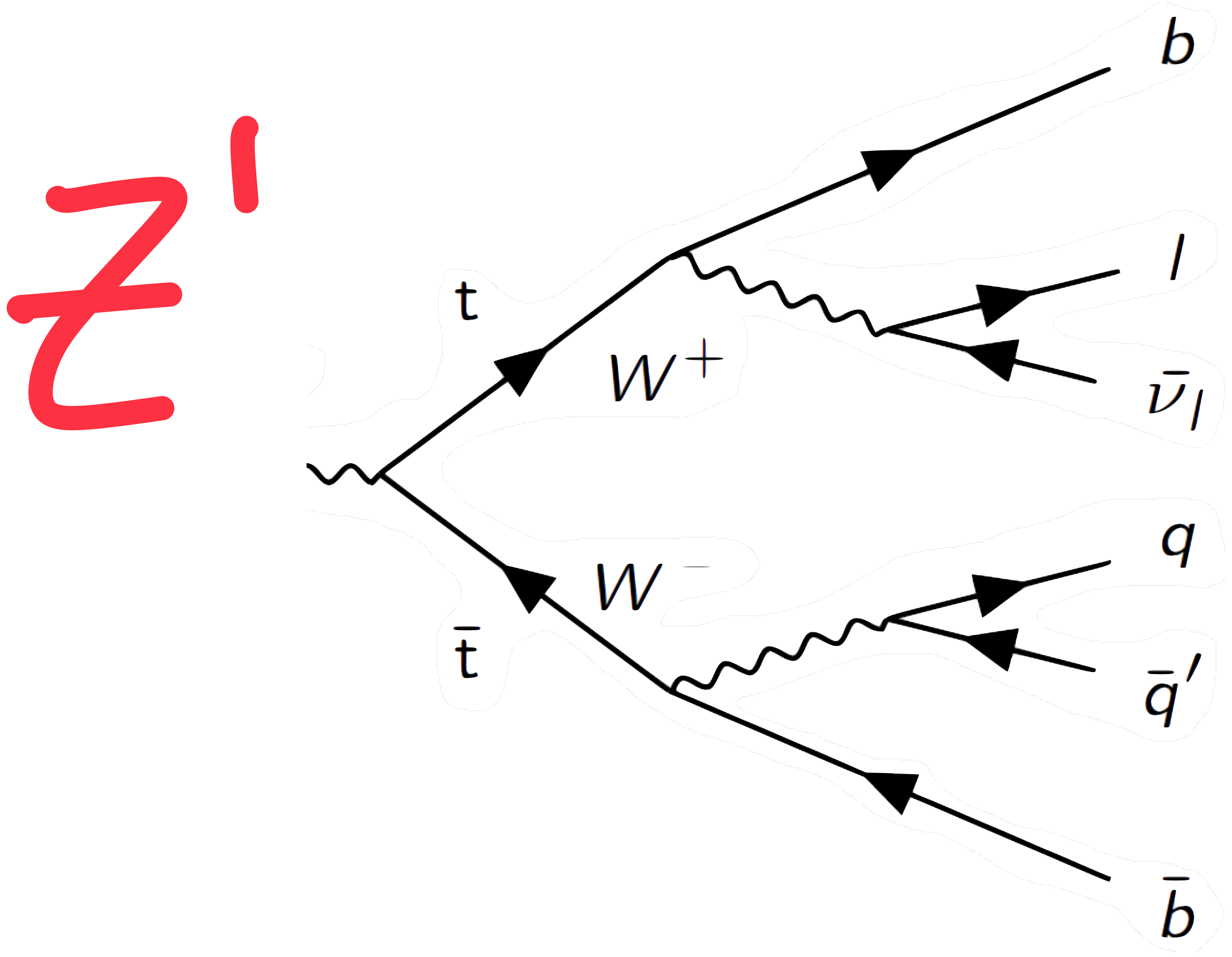
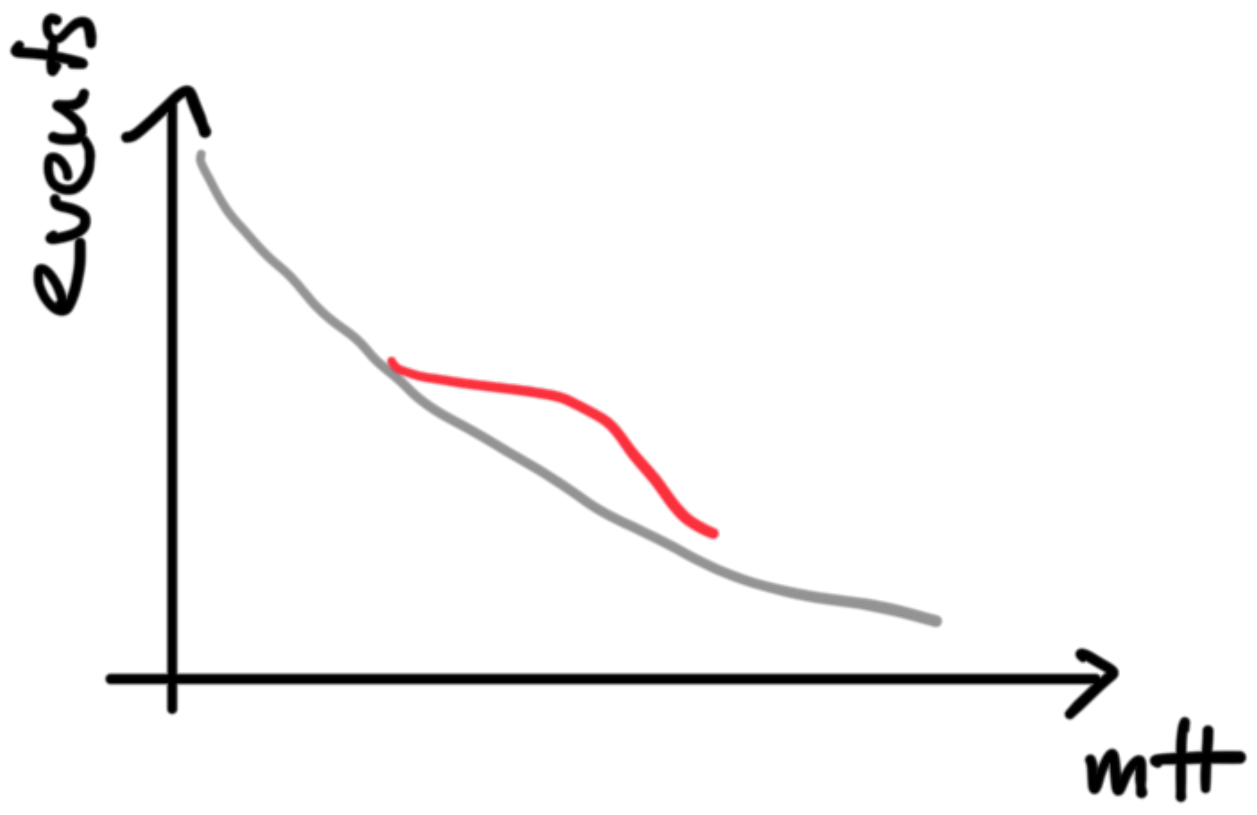
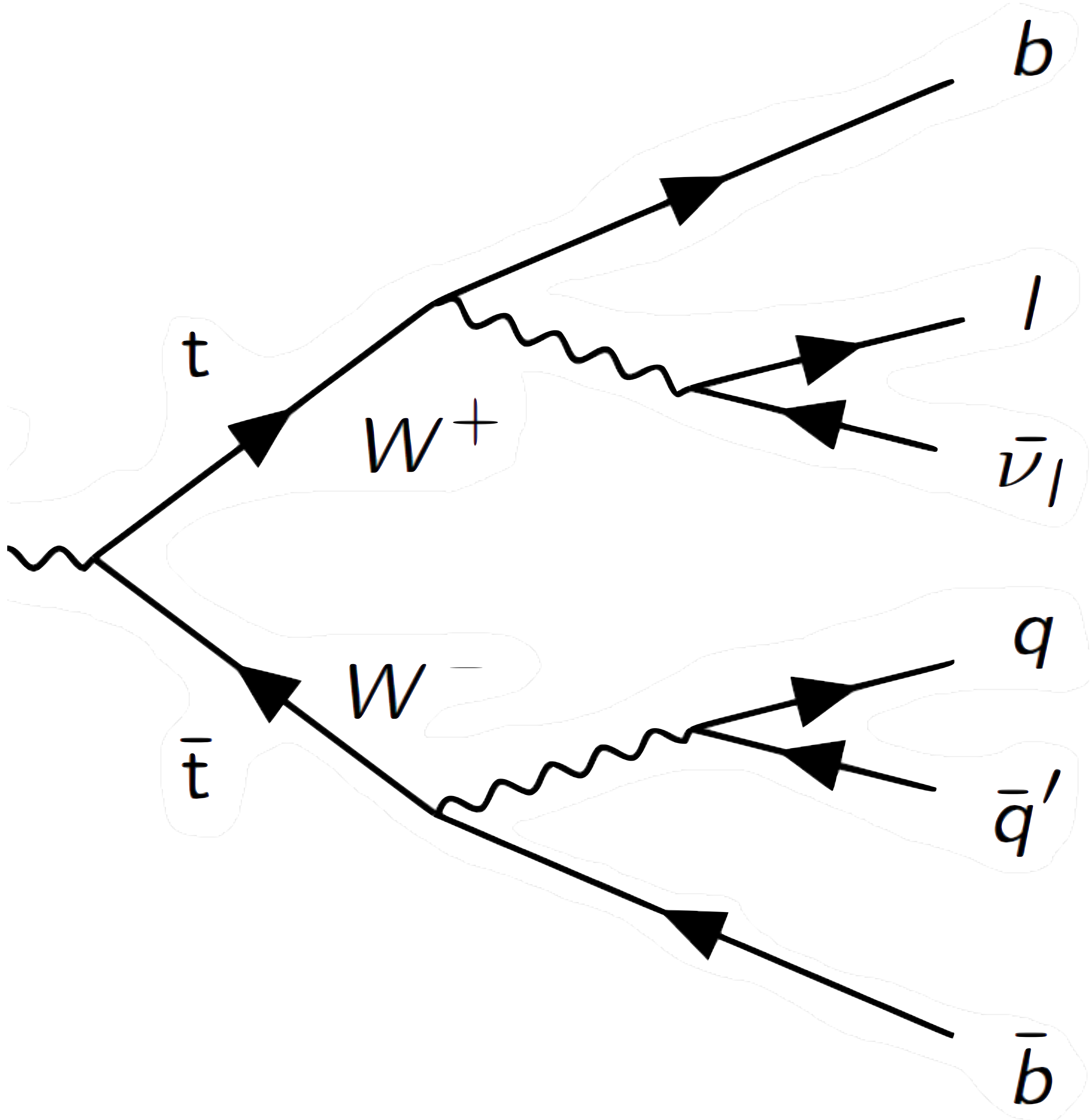


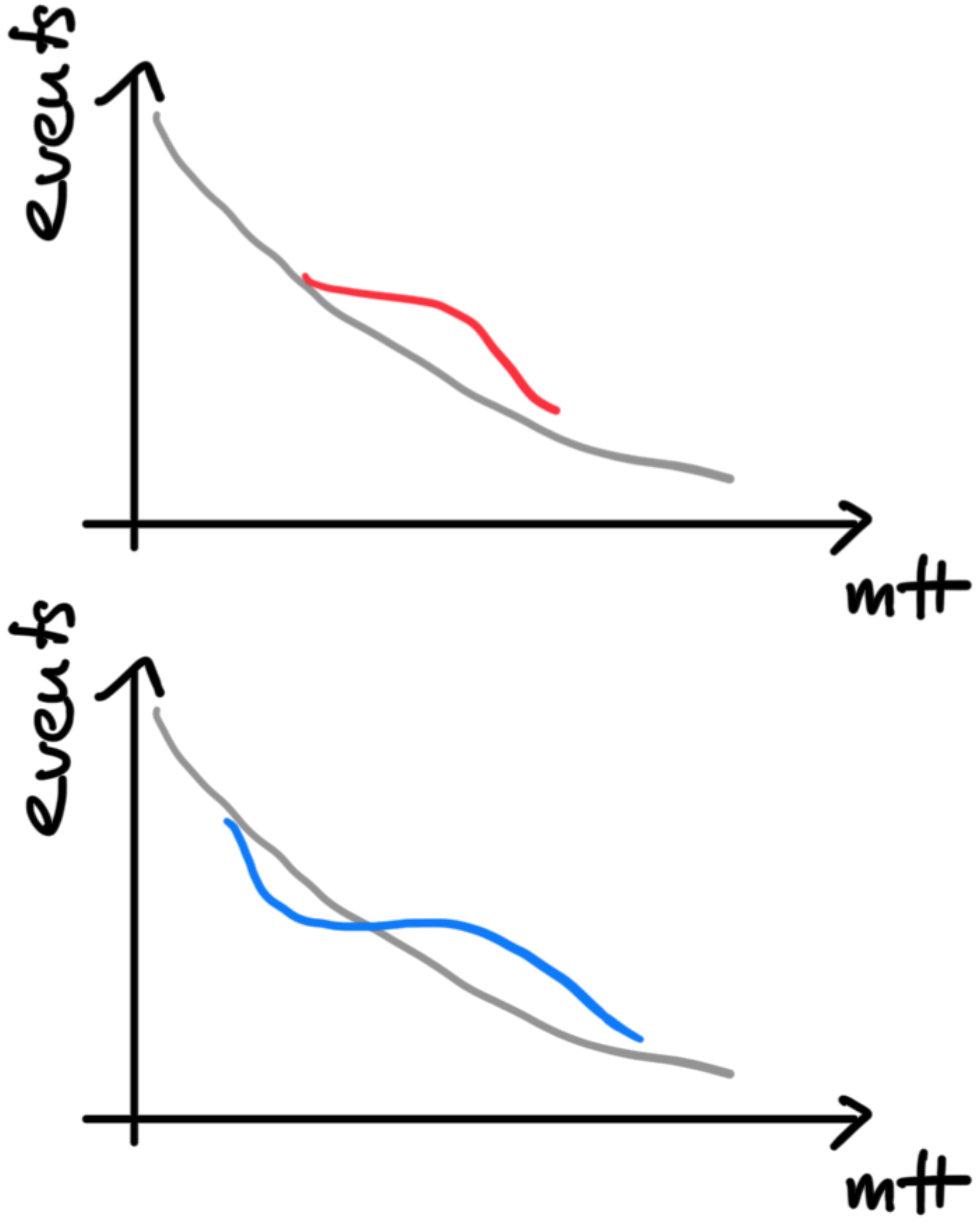


Boosted Top Quarks

— in BSM signals —

A/H Z'





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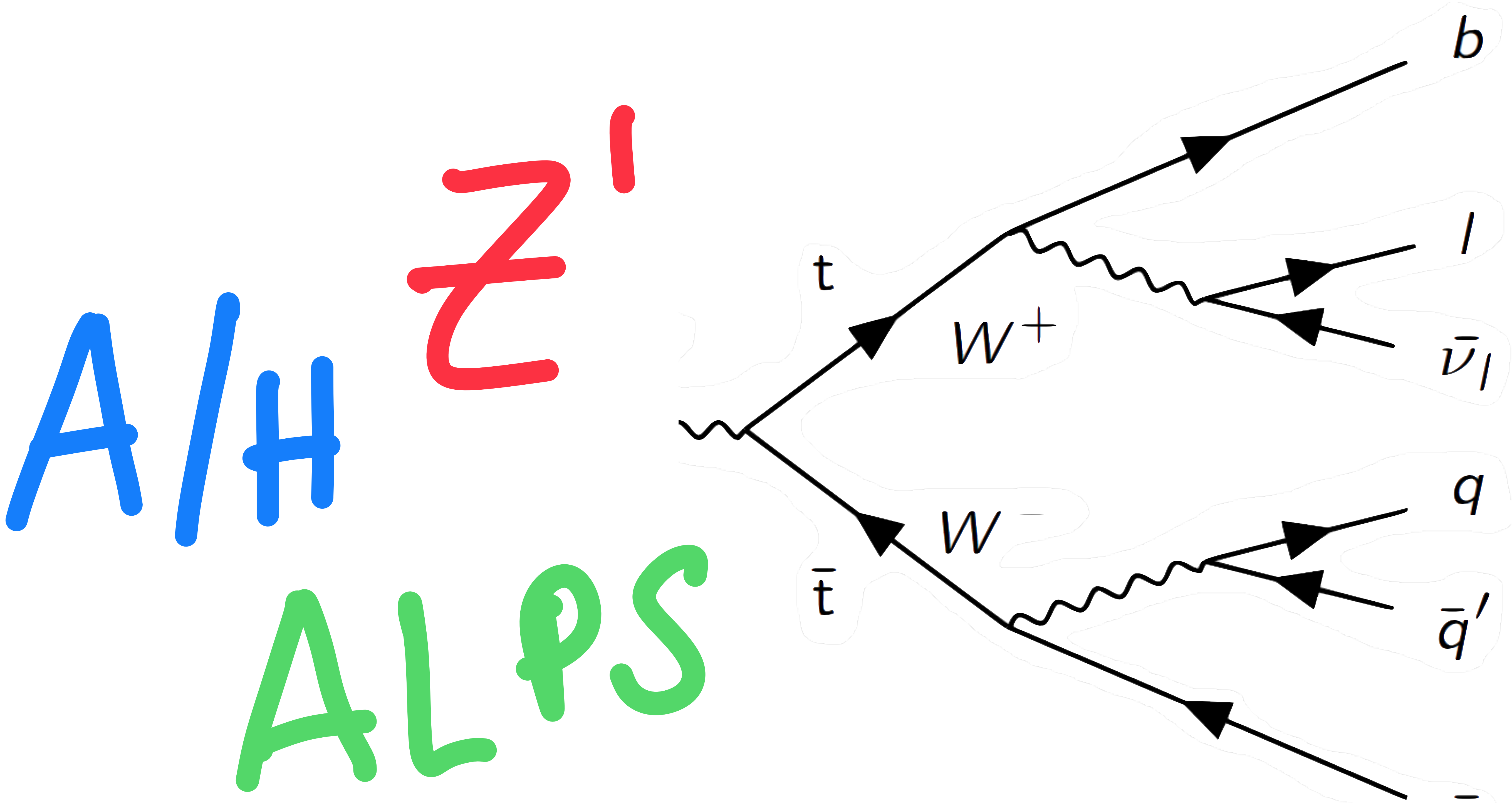
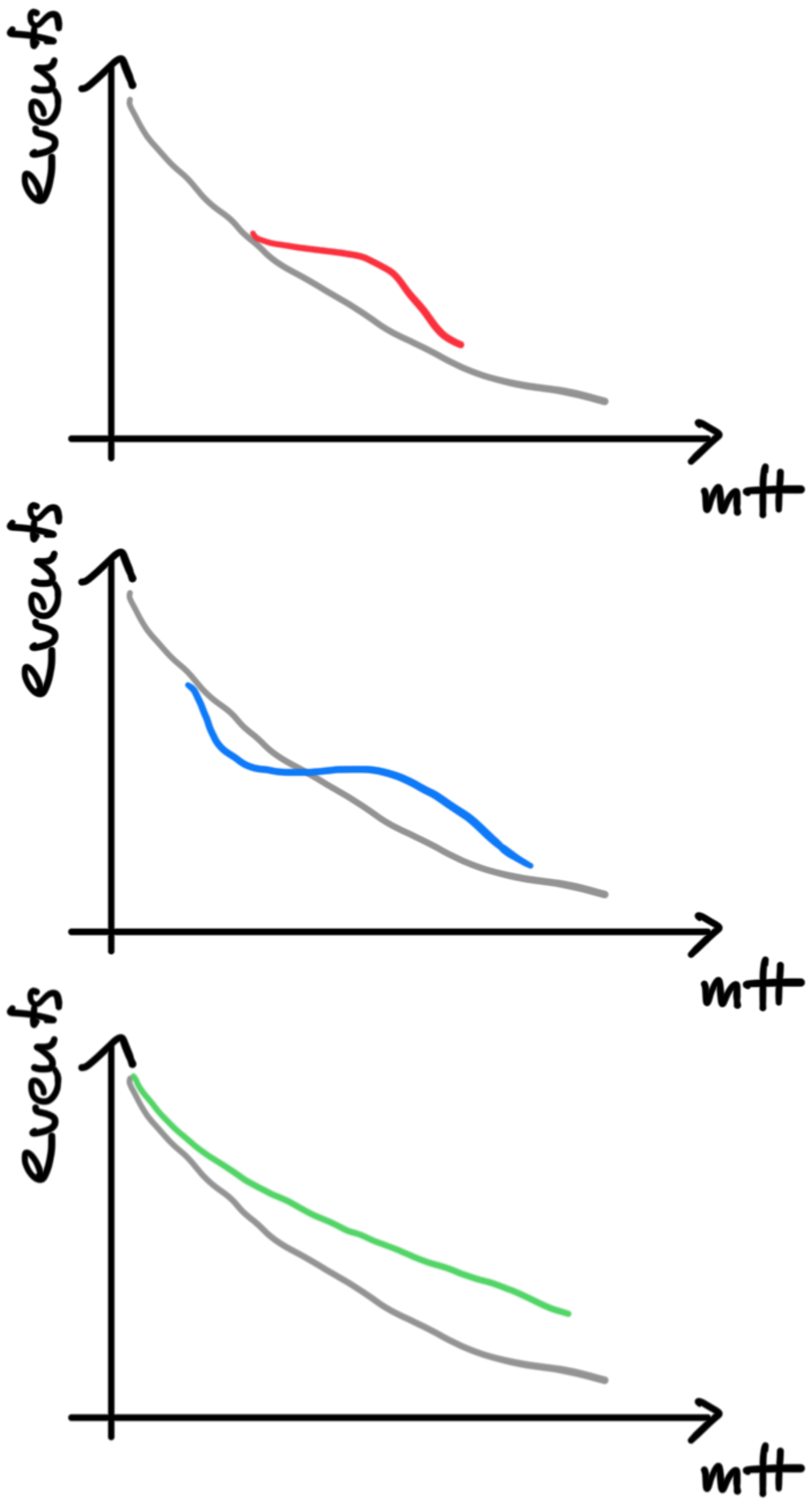
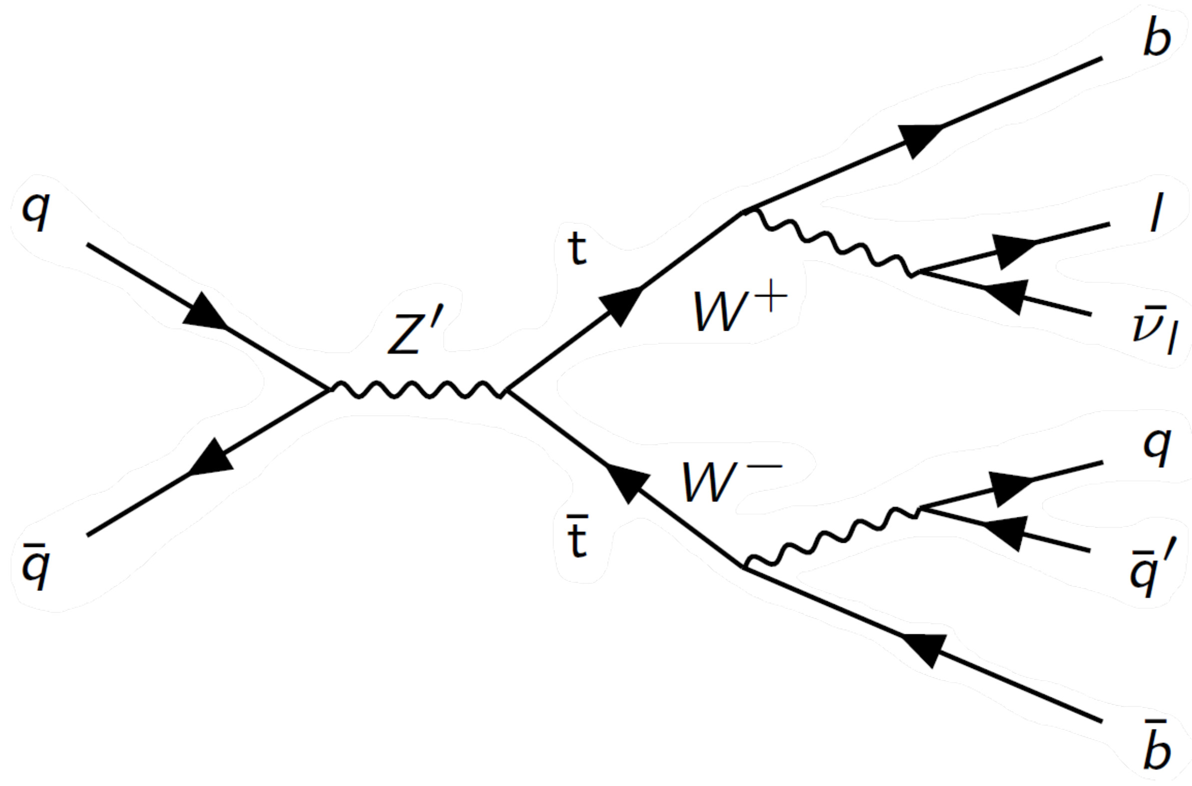




Search for Heavy Z Like Boson

— analysis overview—



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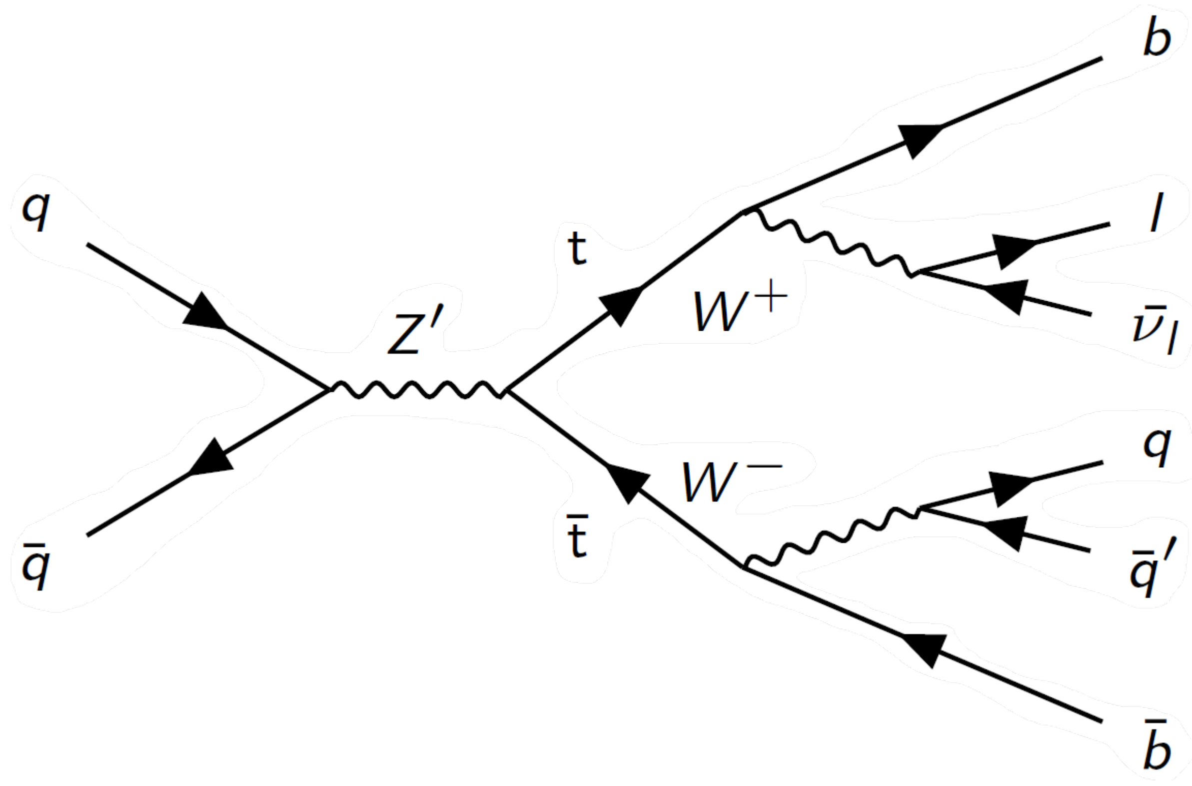

I. Selection

II. Reconstruction

III. Event Classification

IV. Statistical Analysis

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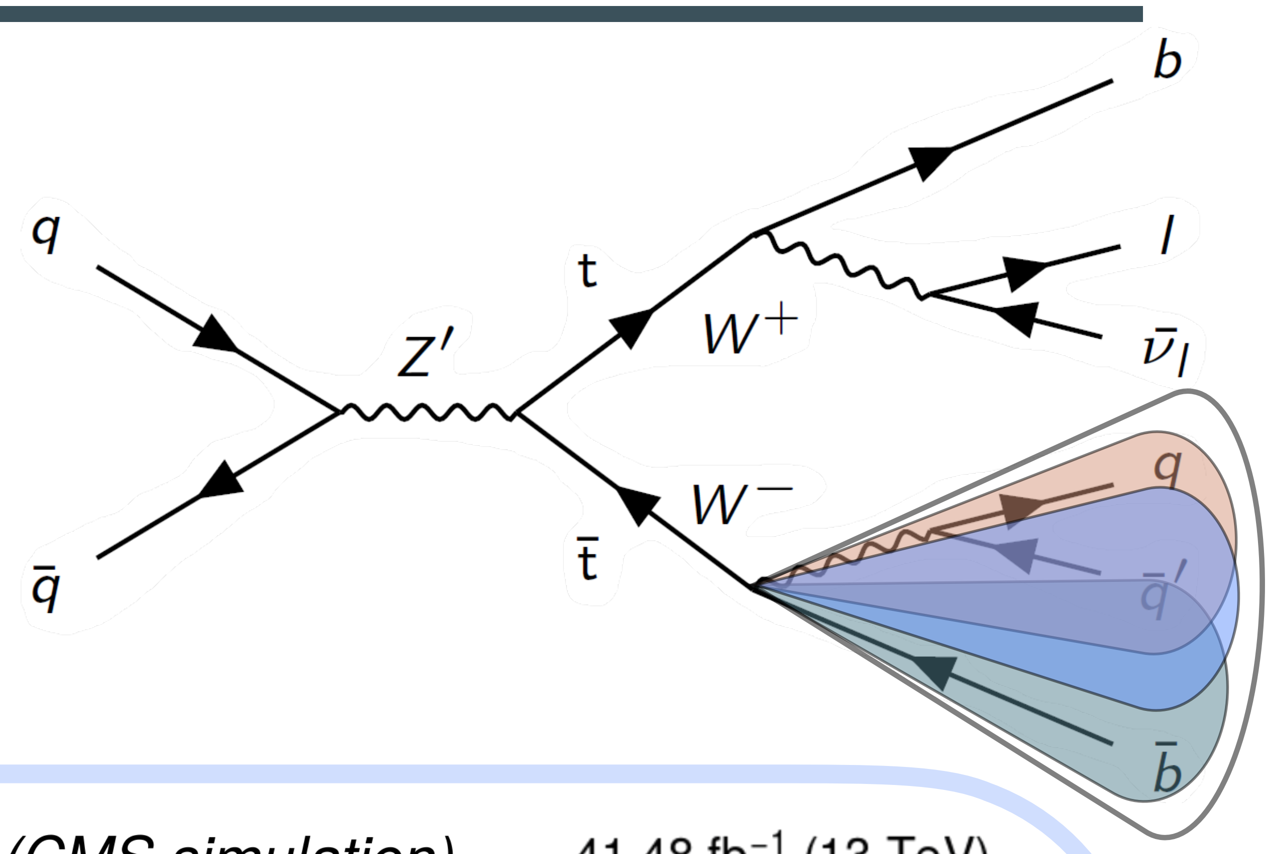

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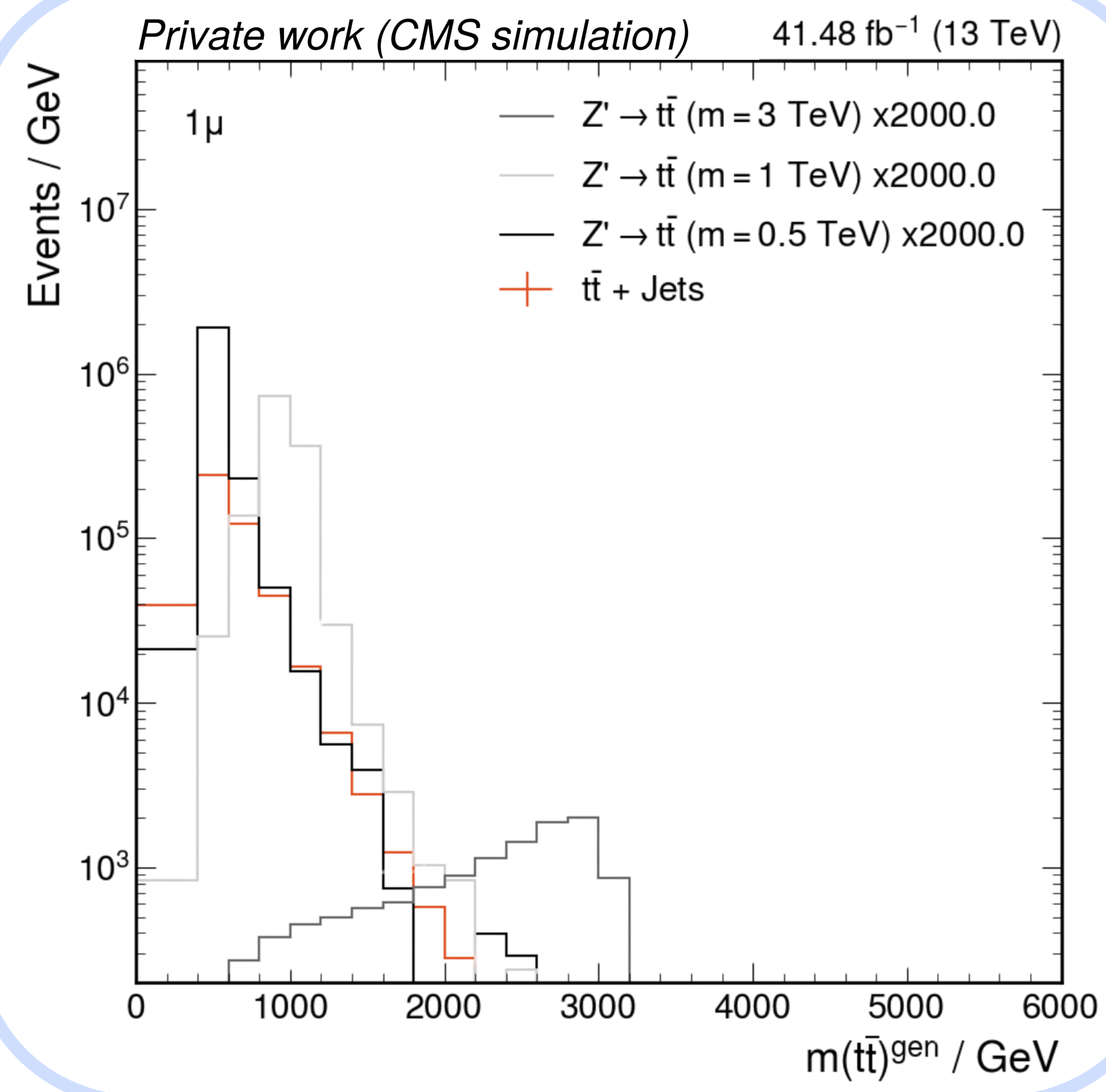

Identifying Boosted Top Quarks

— in CMS—

- different approaches to top tagging:
  - **machine learning** algorithms
    DeepAK8, ParticleNet, ...
    JINST 15 (2020) P06005 CMS-DP-2020-002
  - **cut based** using jet substructure techniques
    N-subjettiness ratio (τ_{32}) & soft drop mass (m_{SD})
    CMS-DP-2020-025

N-subjettiness

$$\tau_N = \frac{1}{d_0} \sum_k p_{\mathrm{T},k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k})$$

JHEP 1103:015,2011 - arXiv:1011.2268

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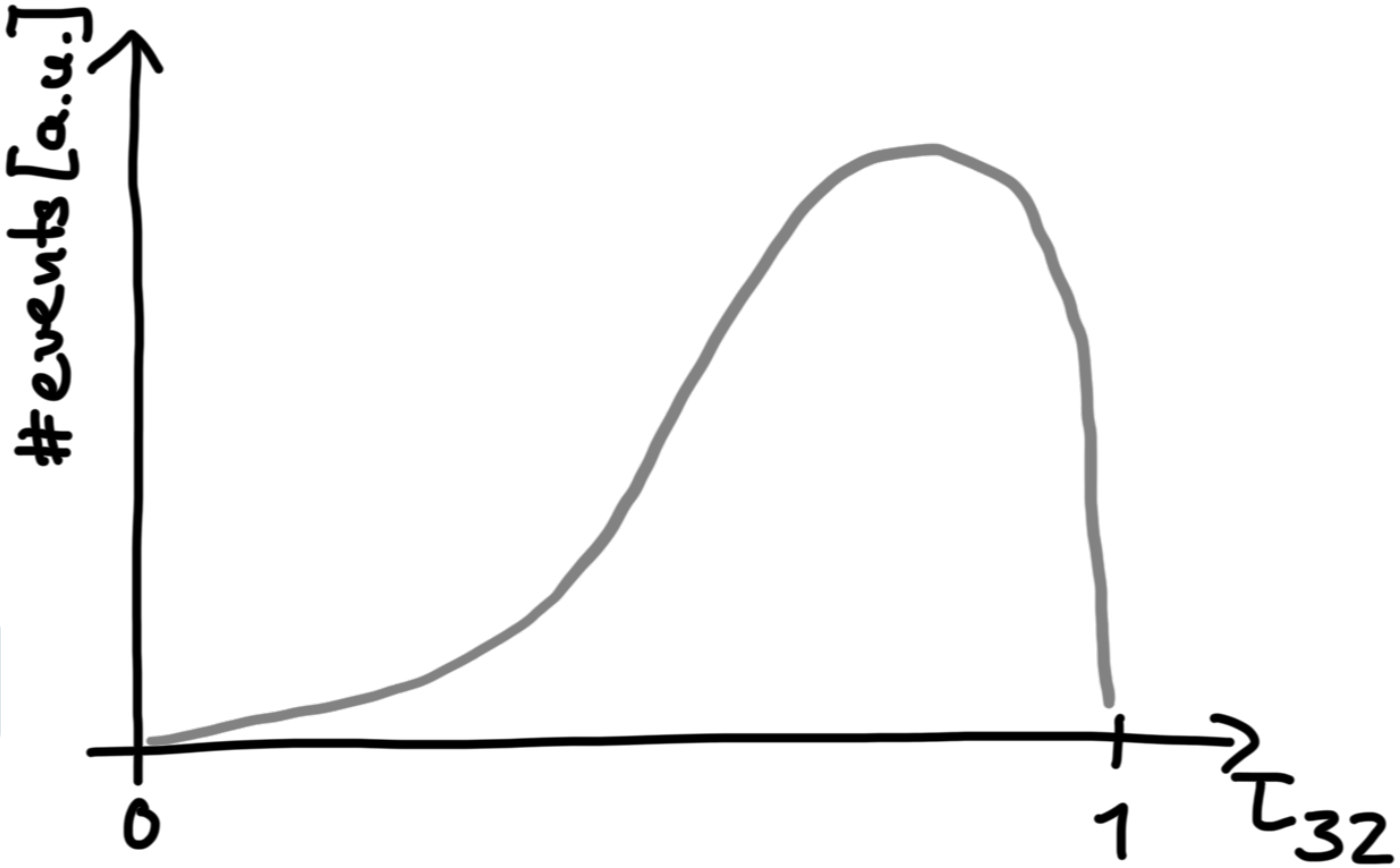

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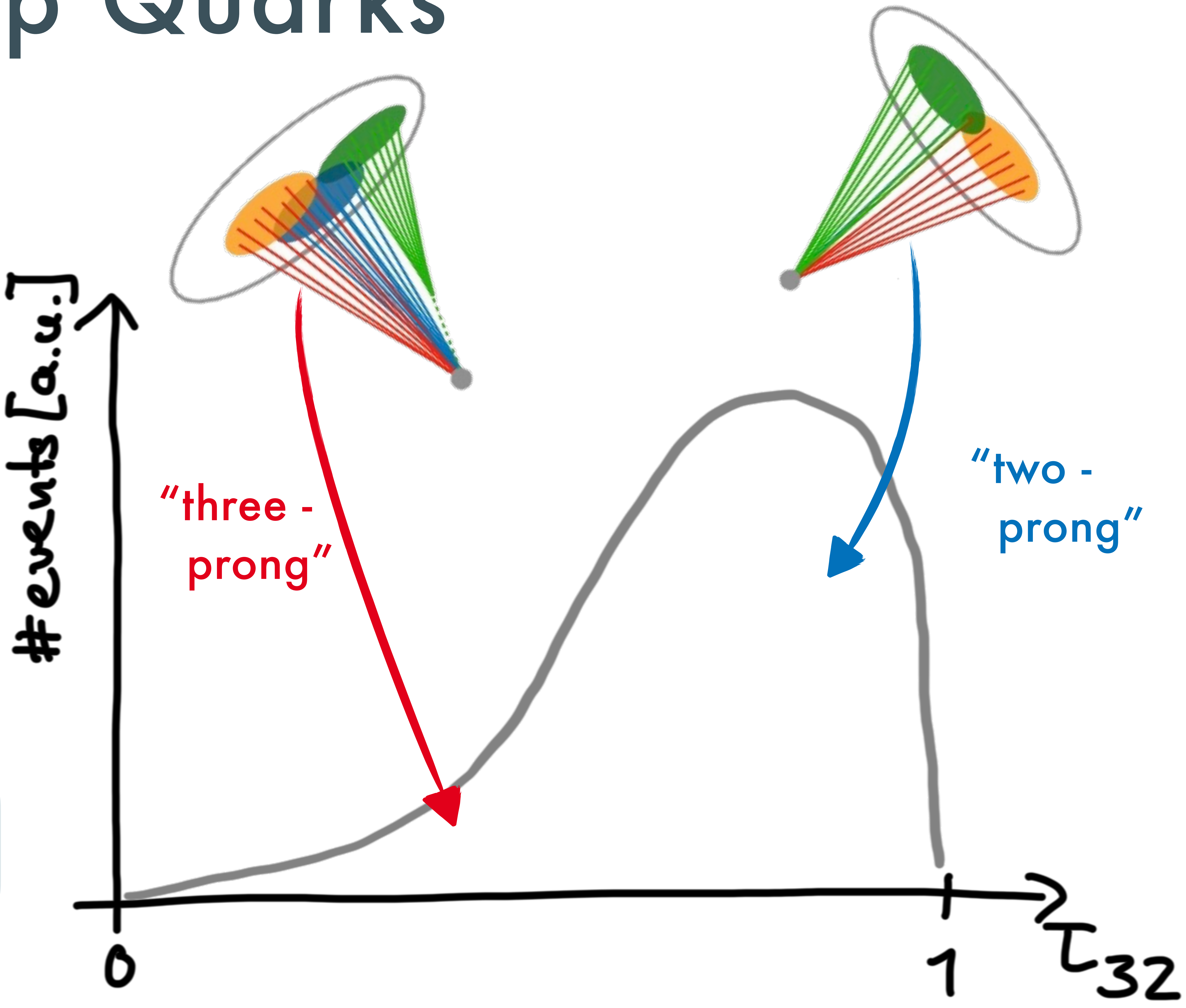

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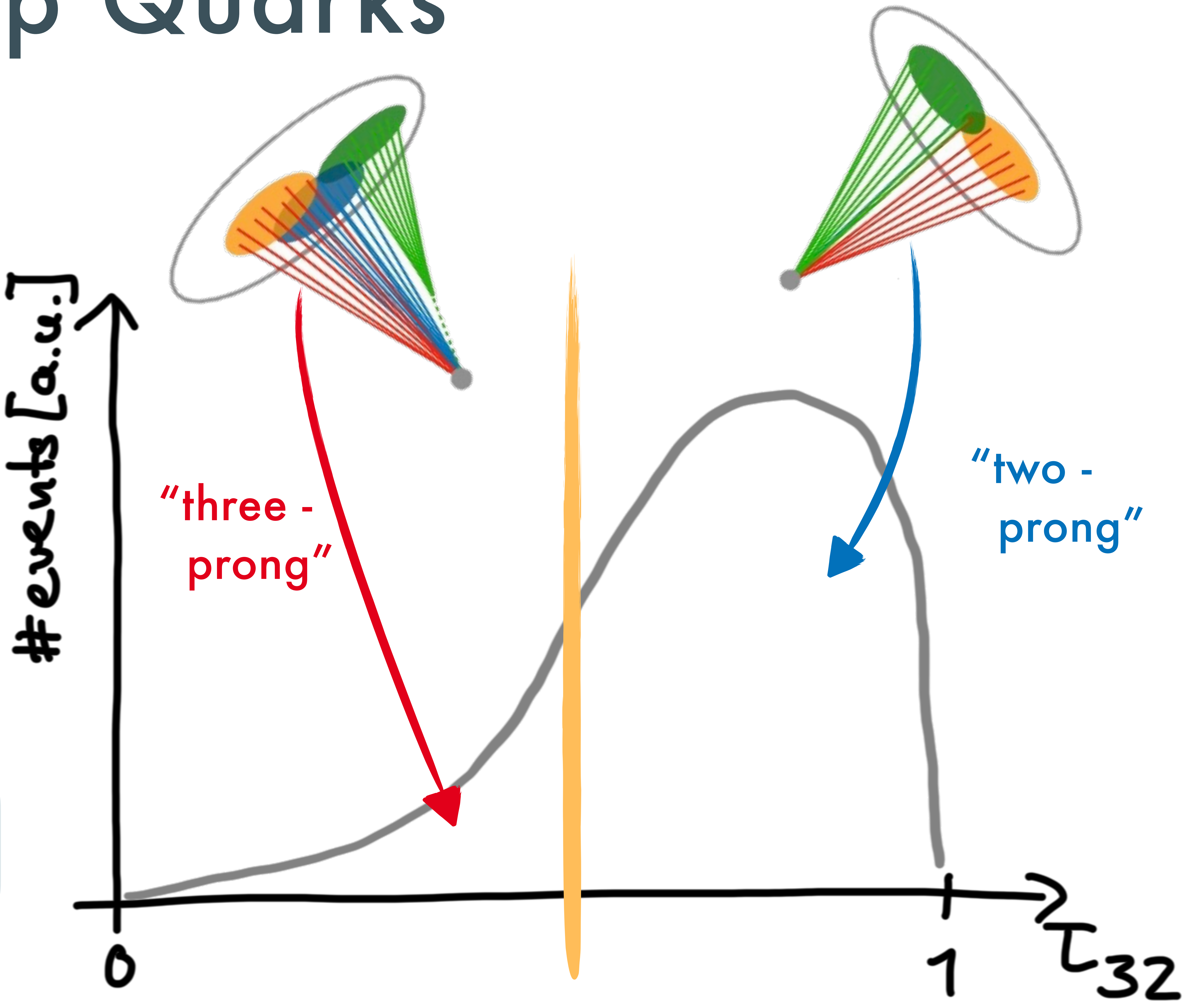
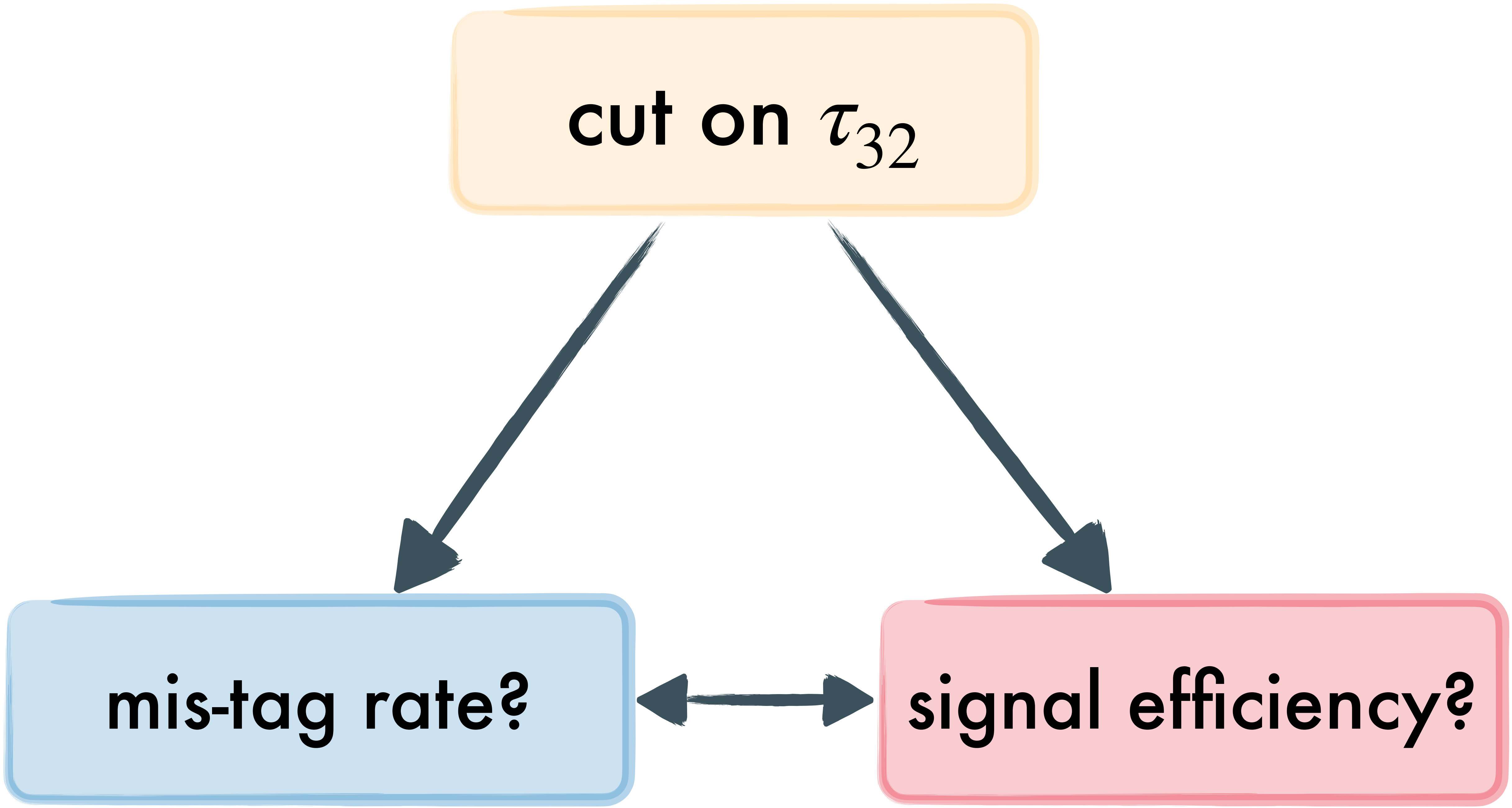


Classifying the Cut on τ_{32}



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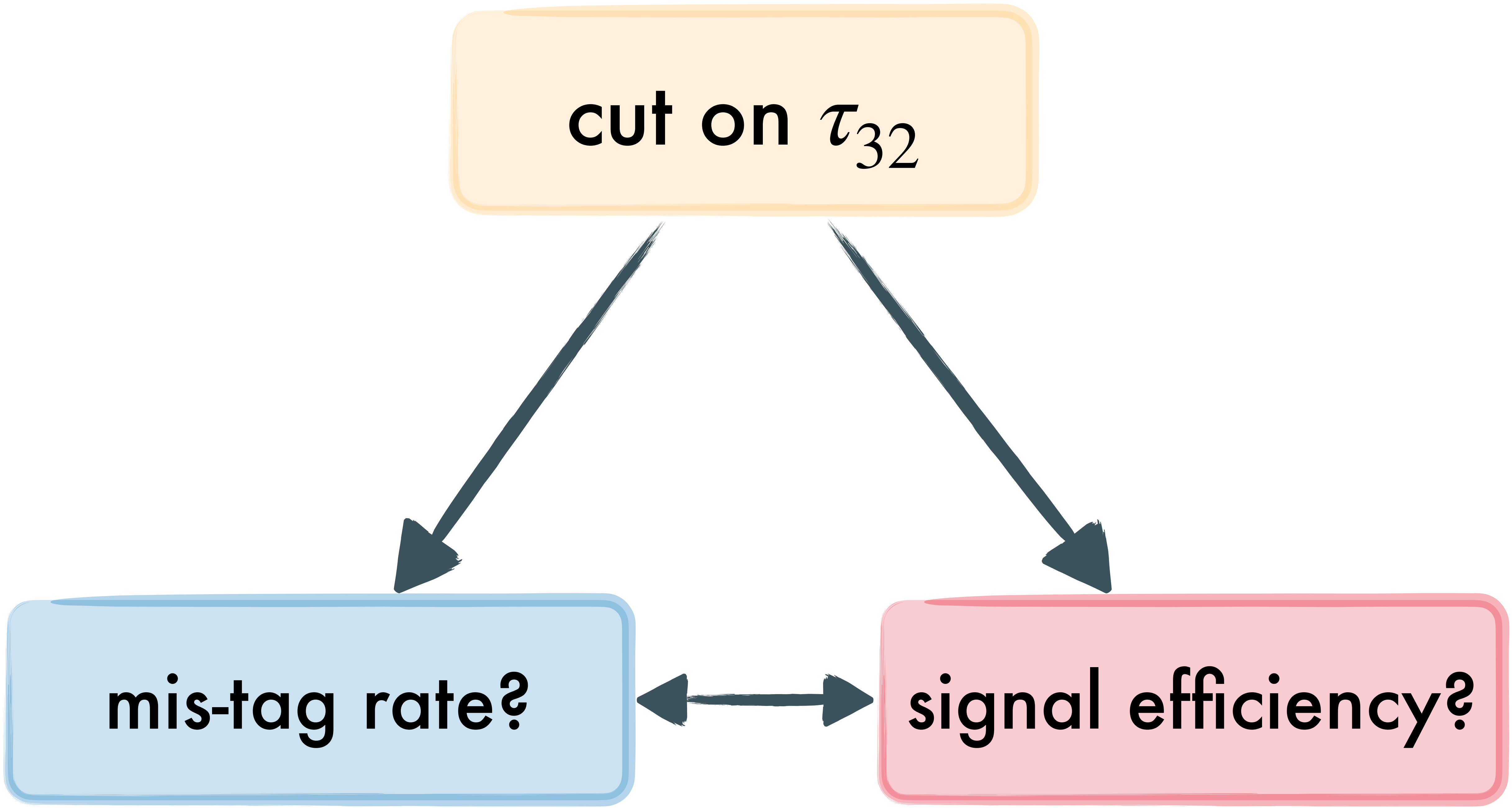
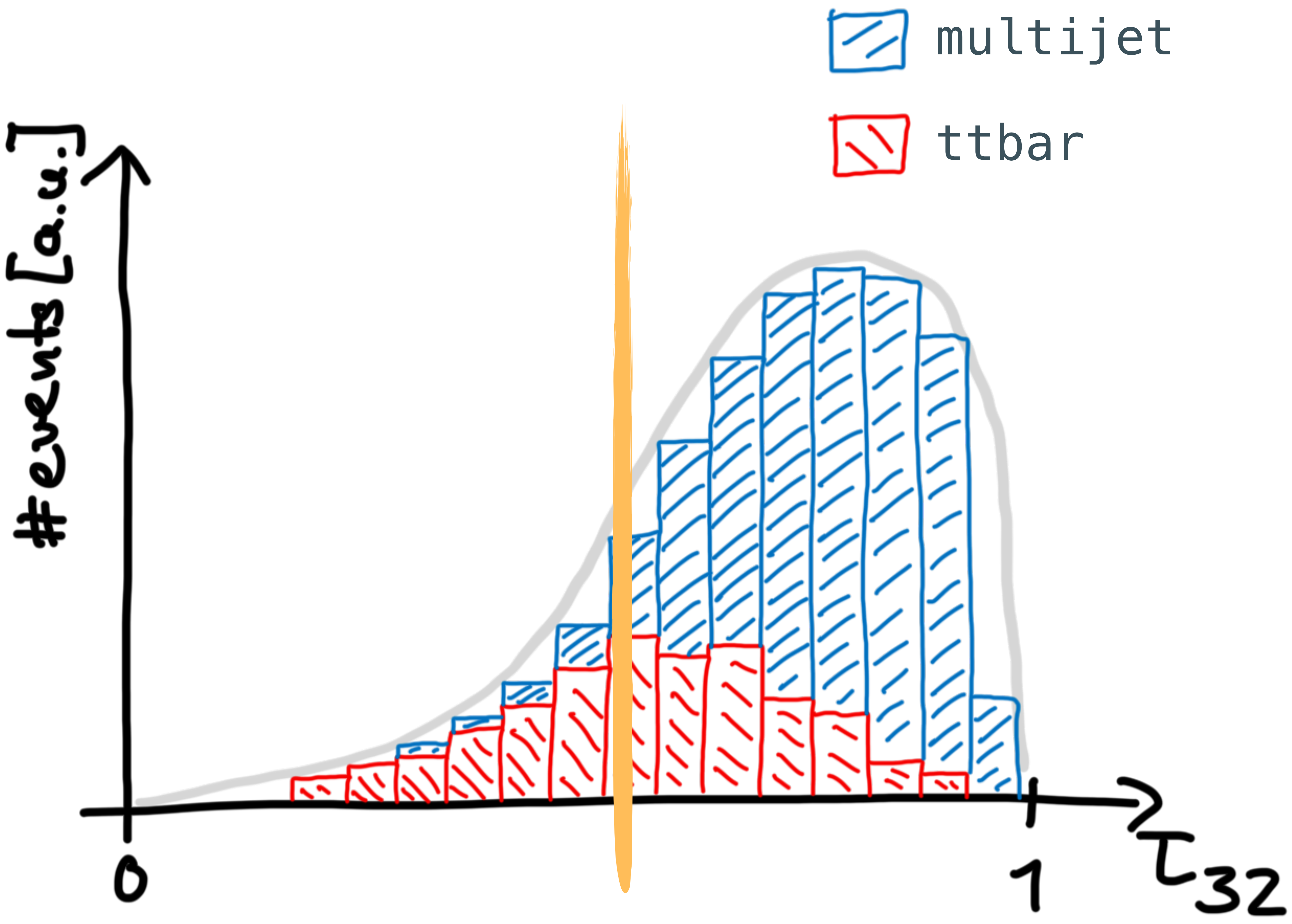
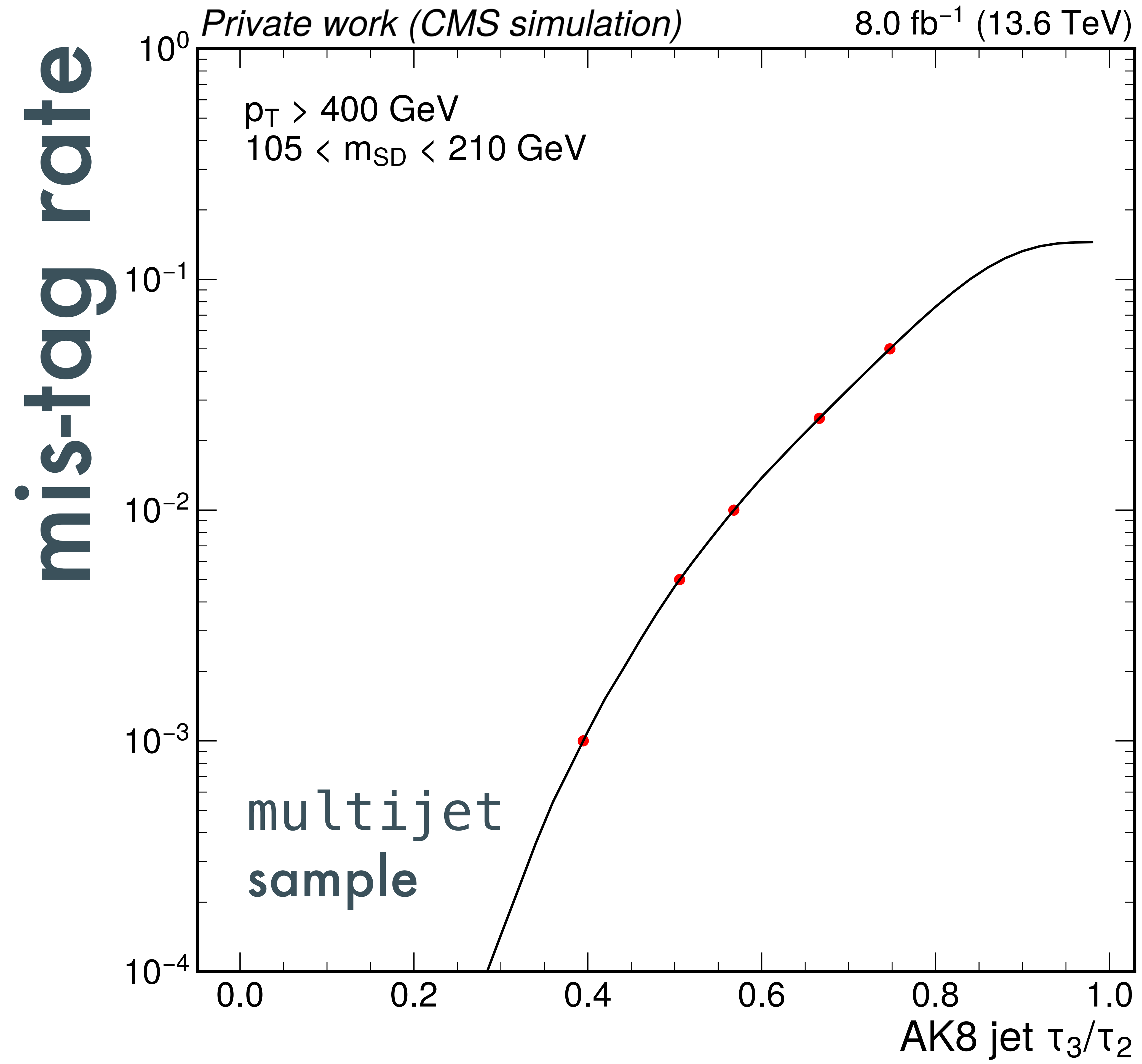




Working Points in One Slide



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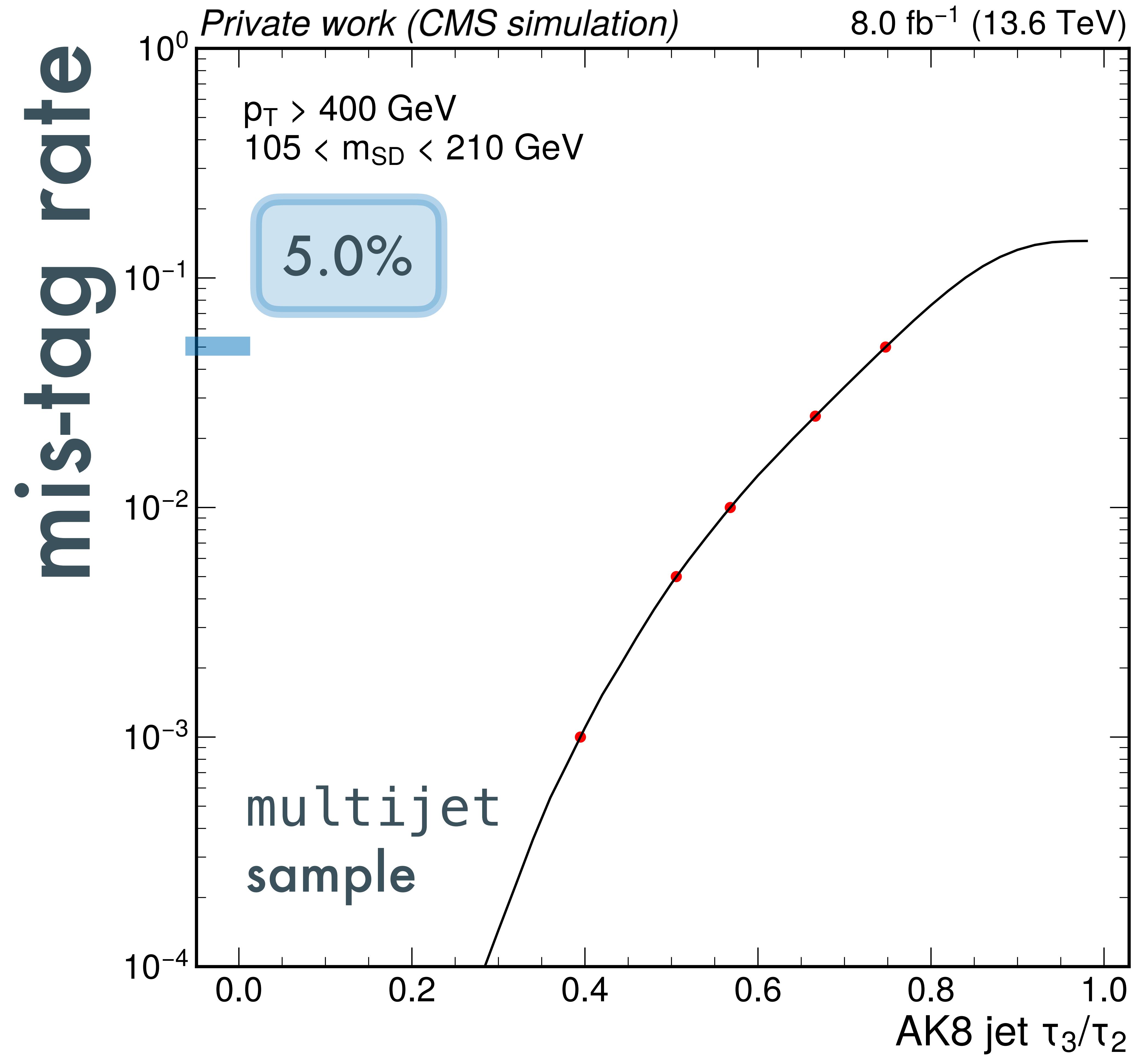

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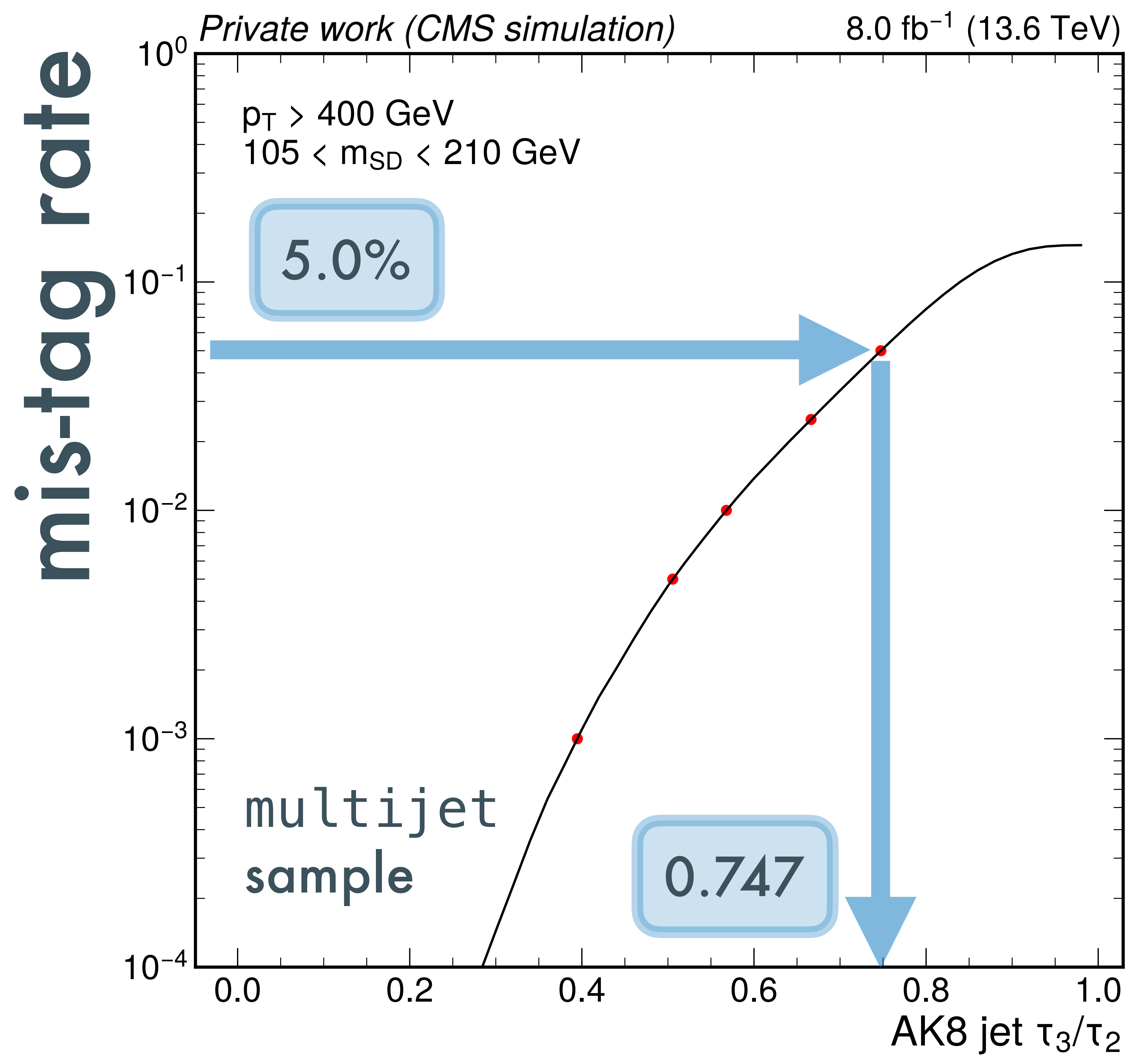

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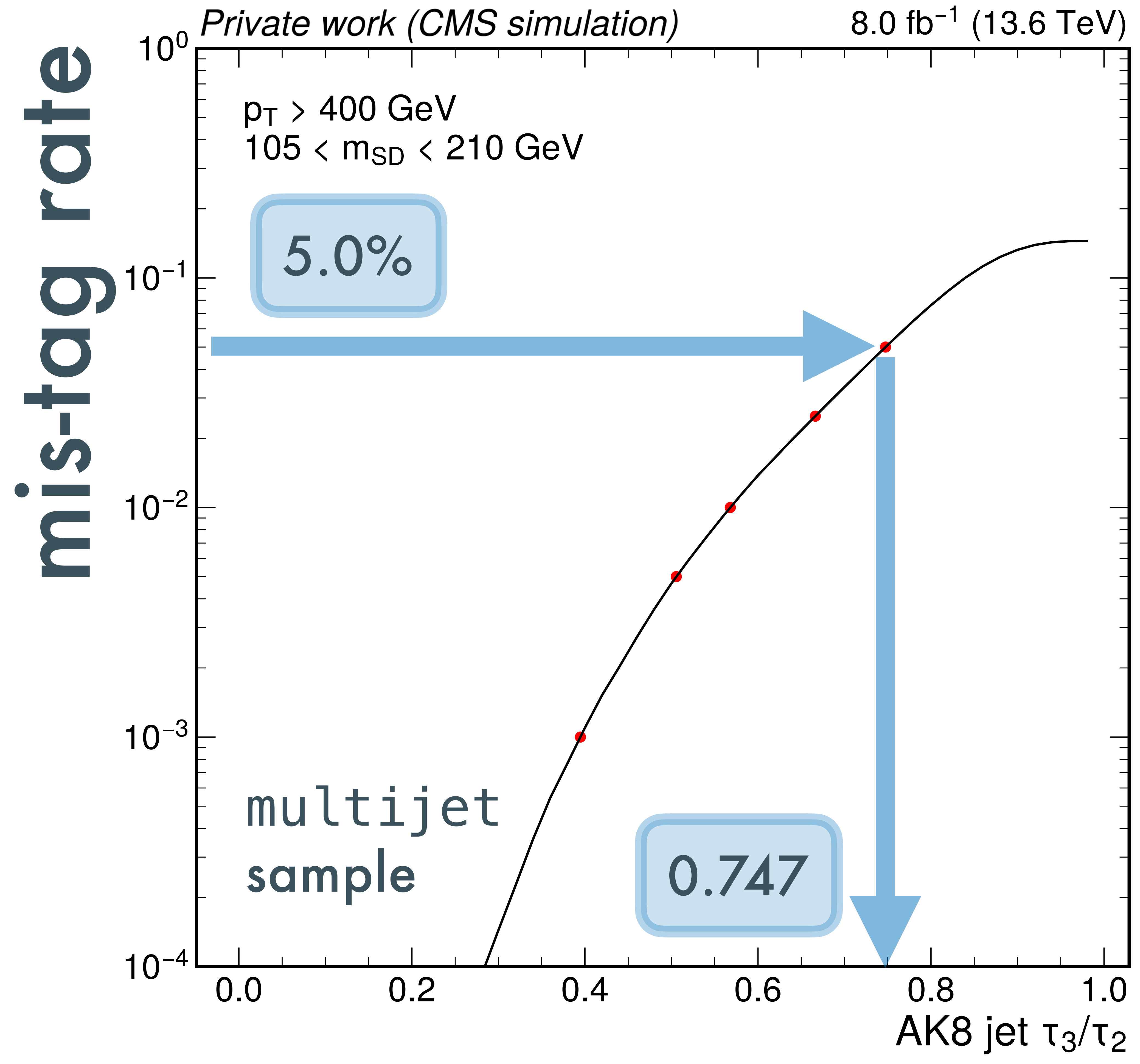

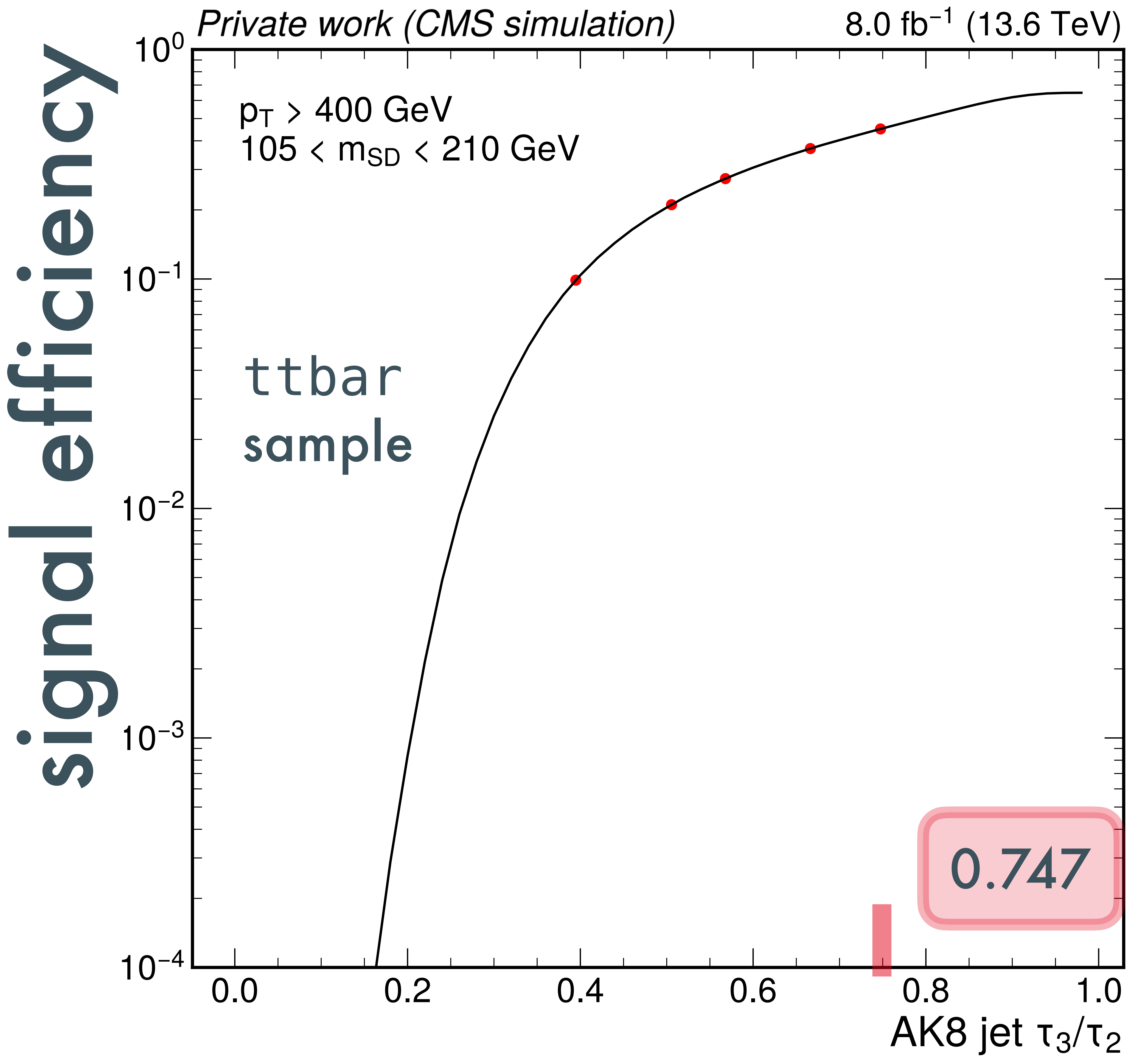

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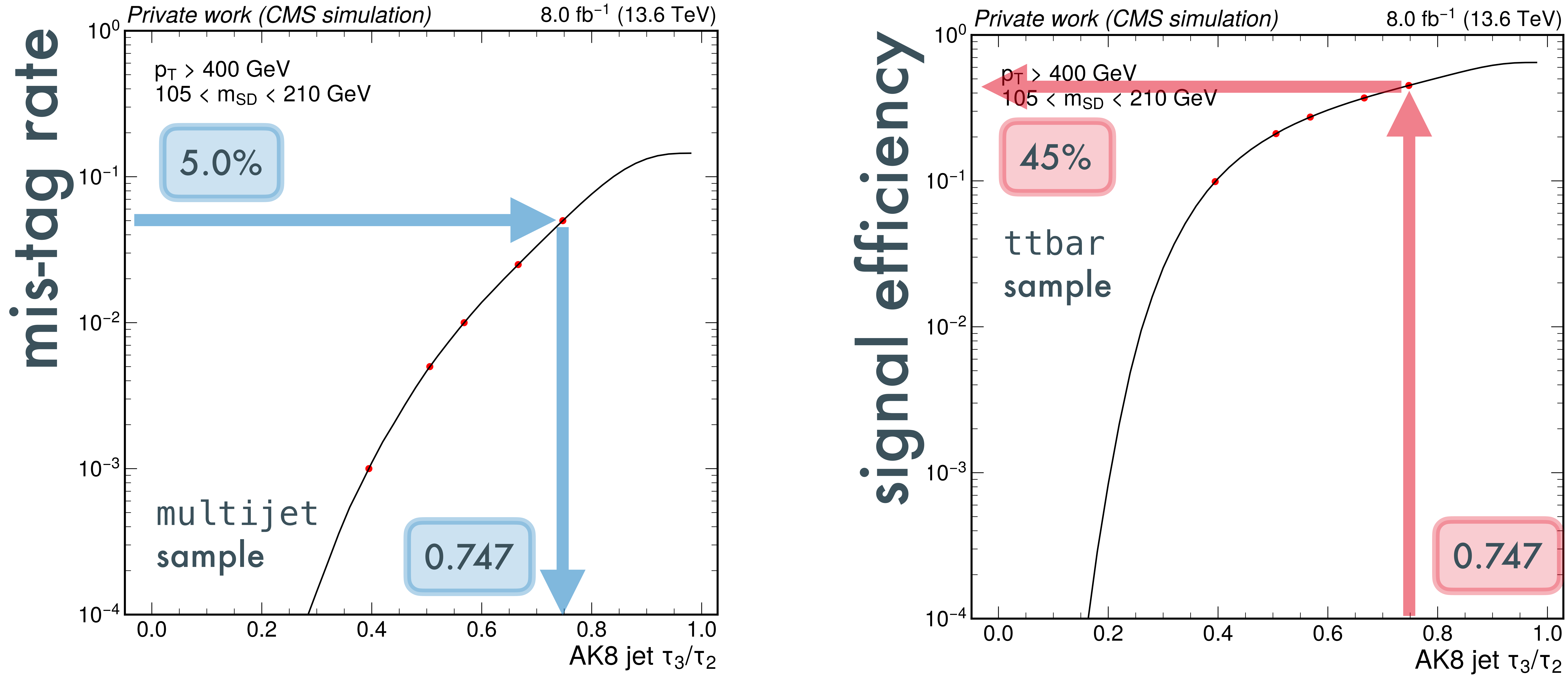

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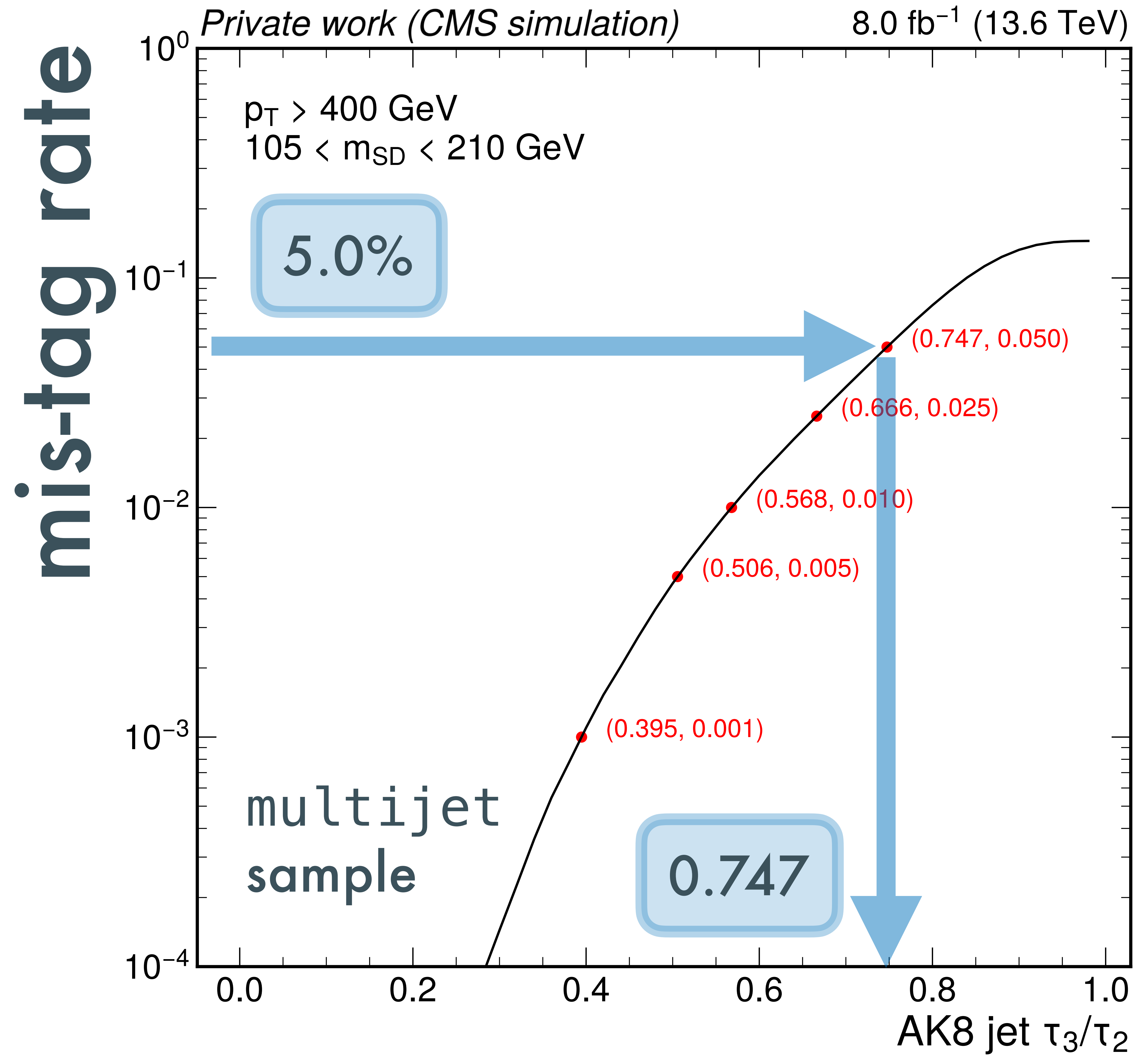
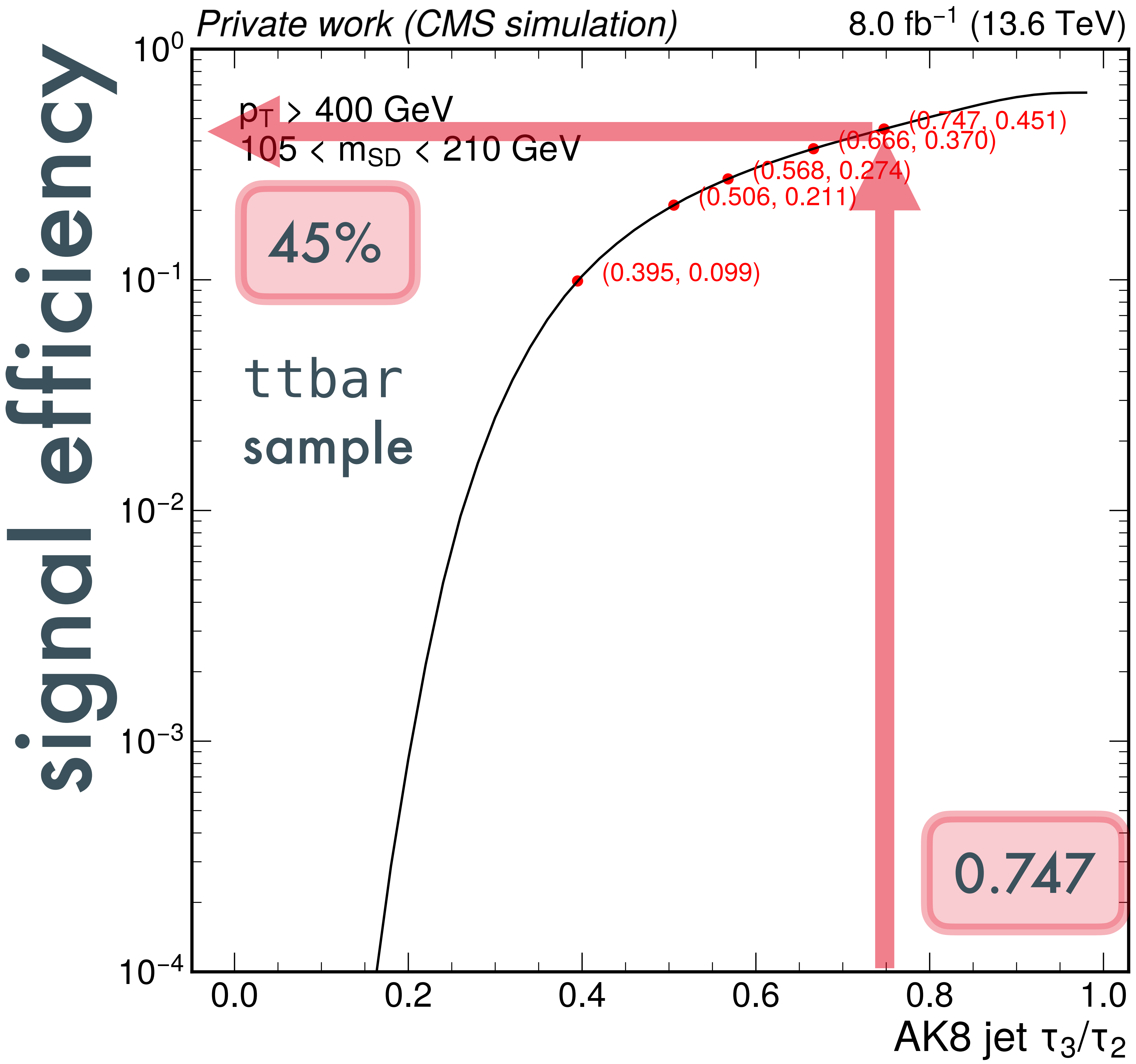
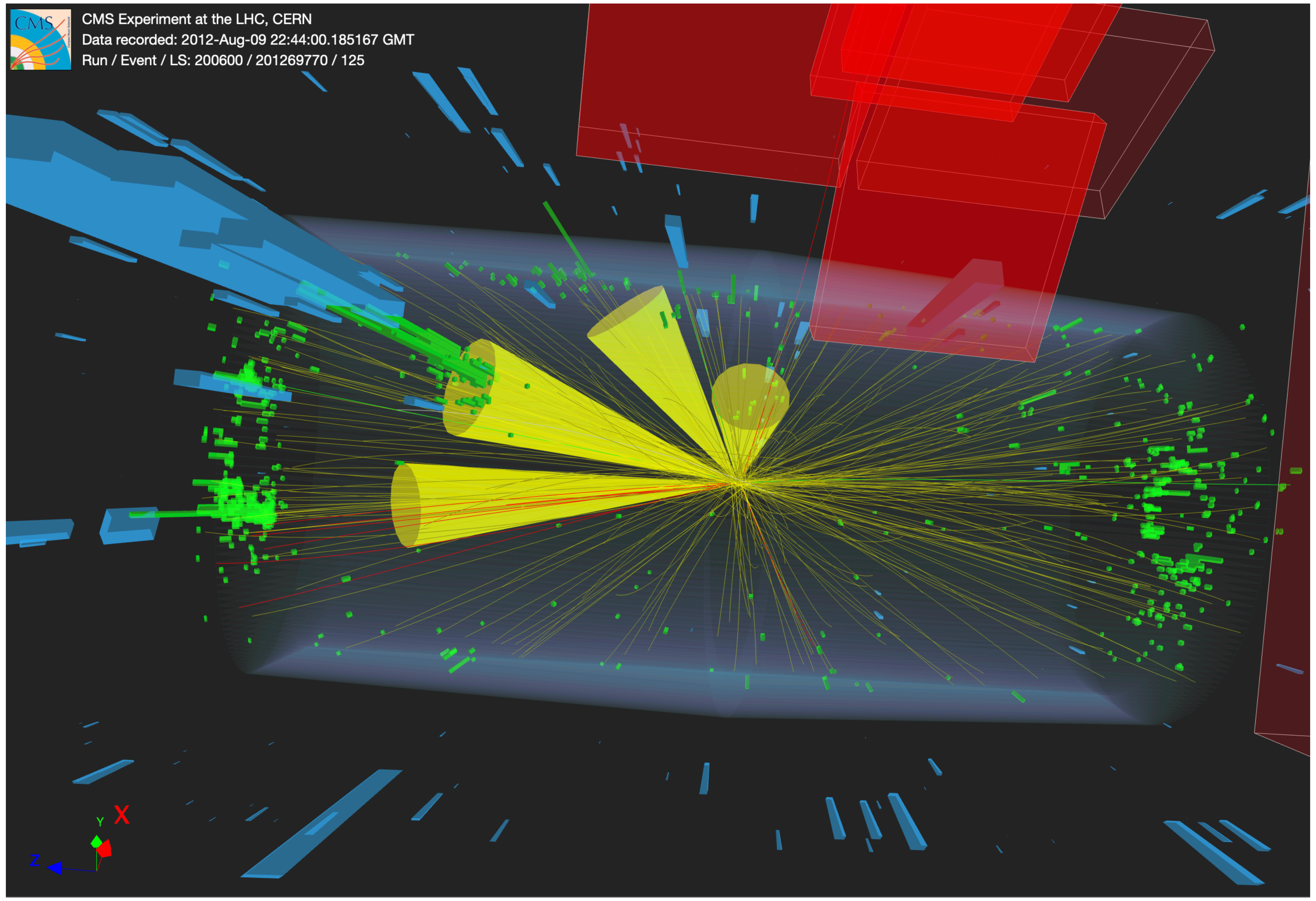
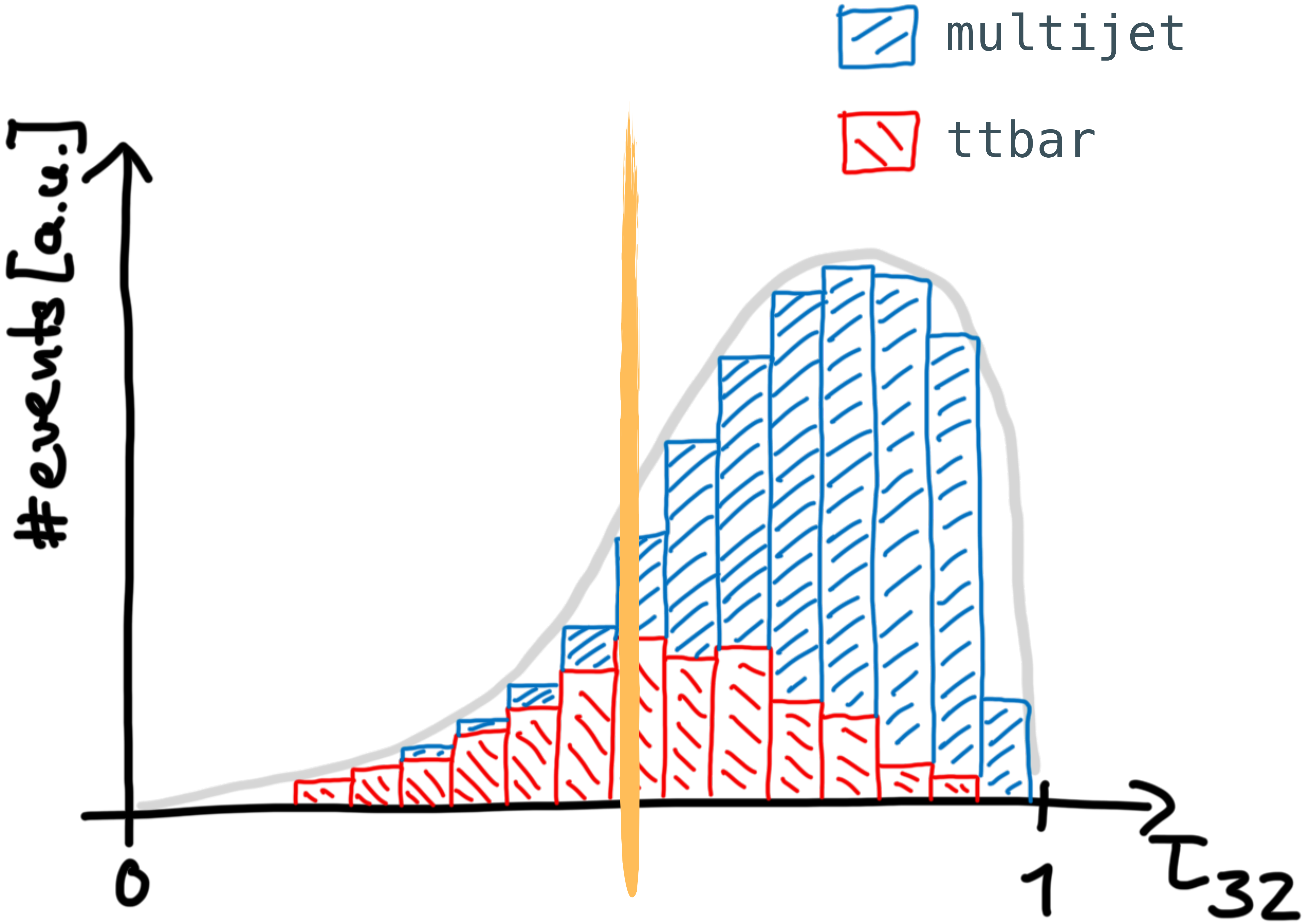




Jet Substructure in Recorded Data





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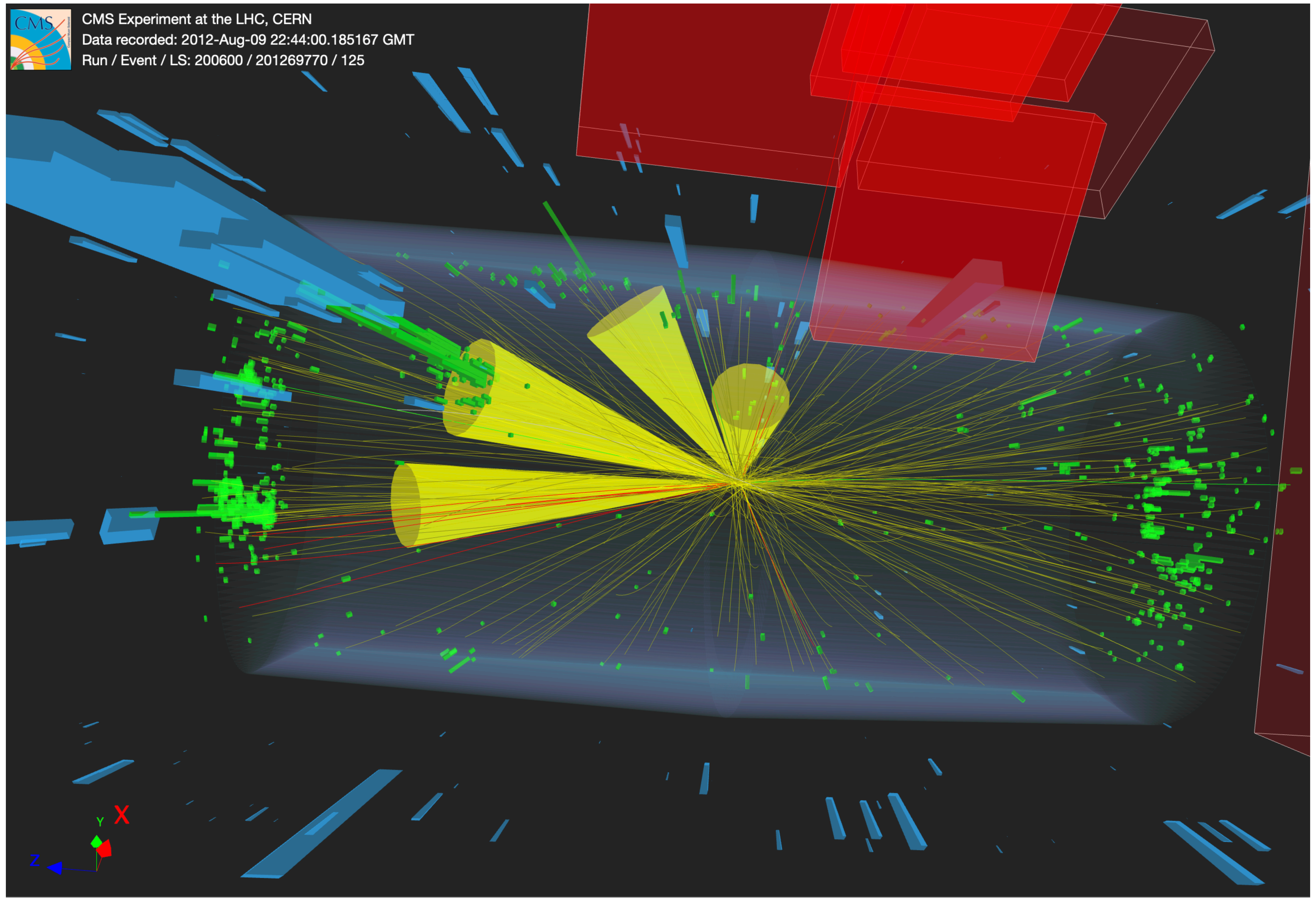
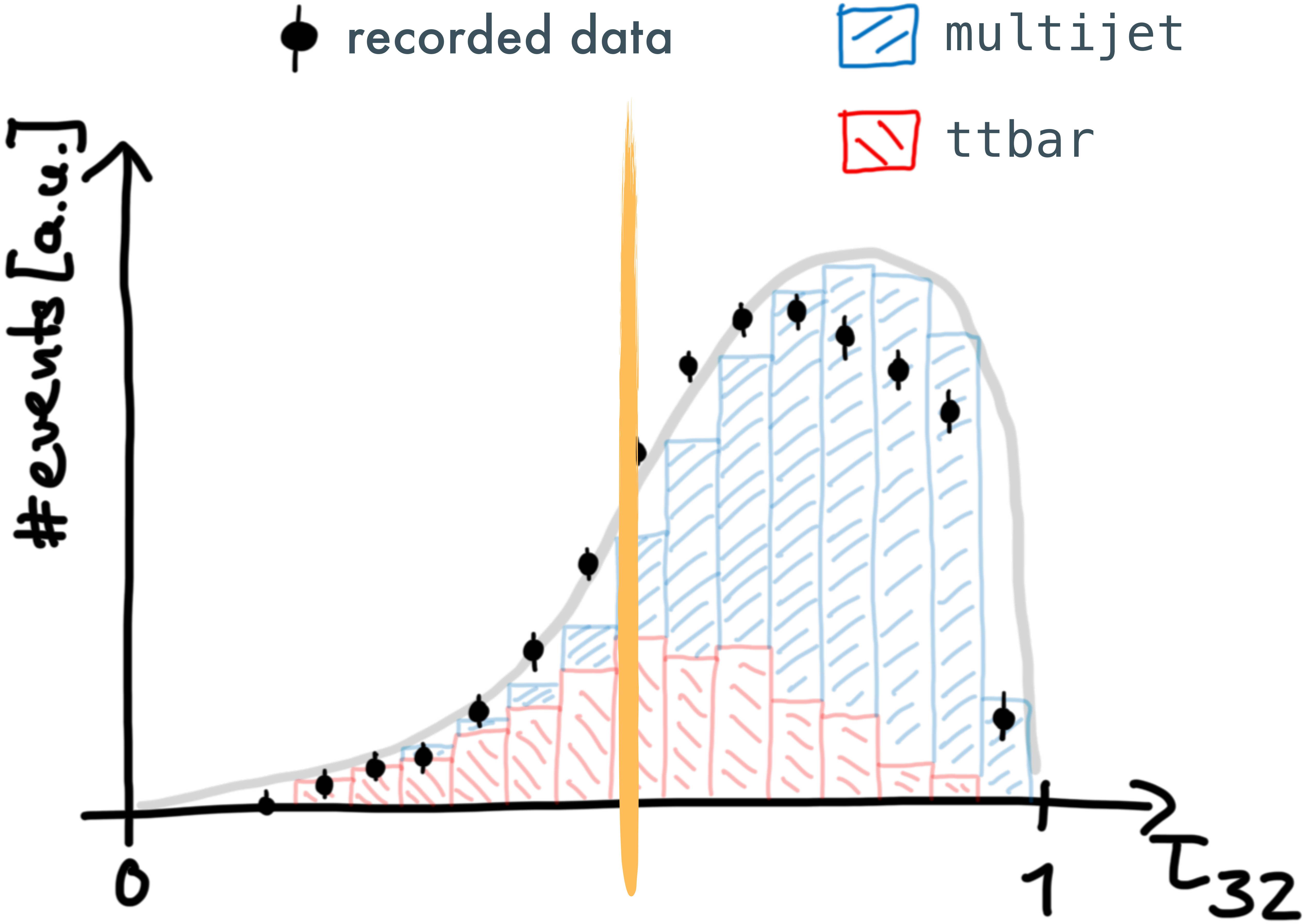
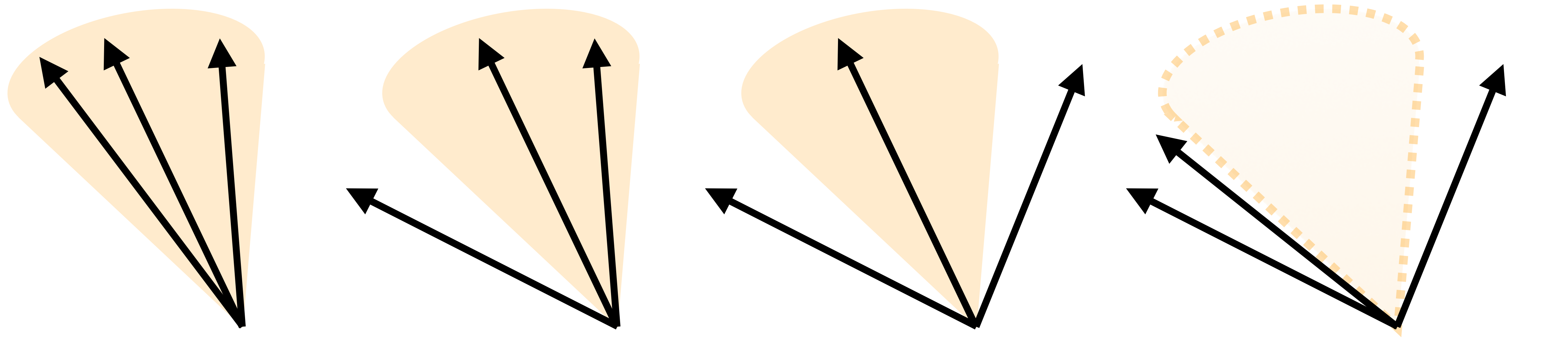


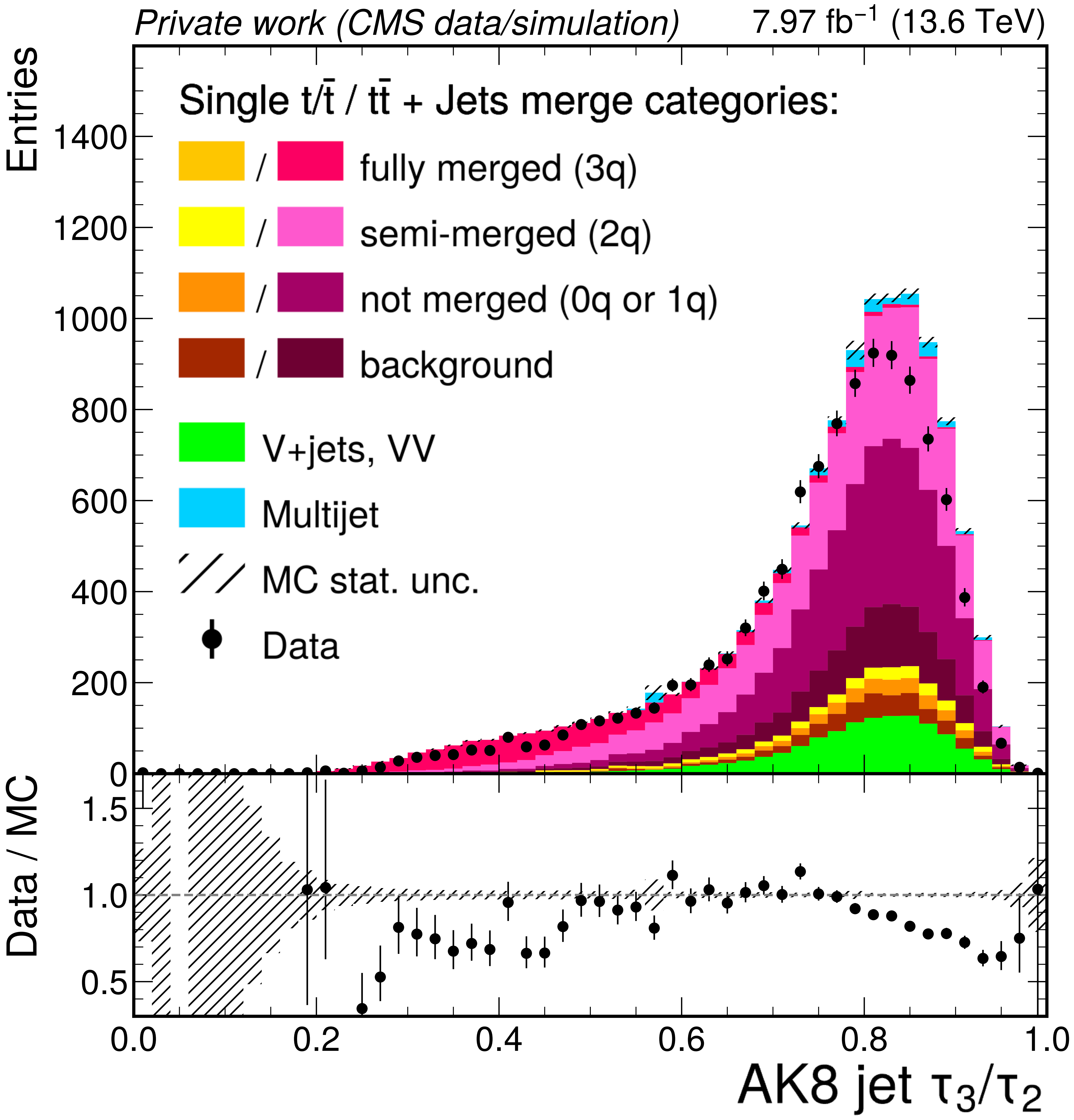


Scale Factors

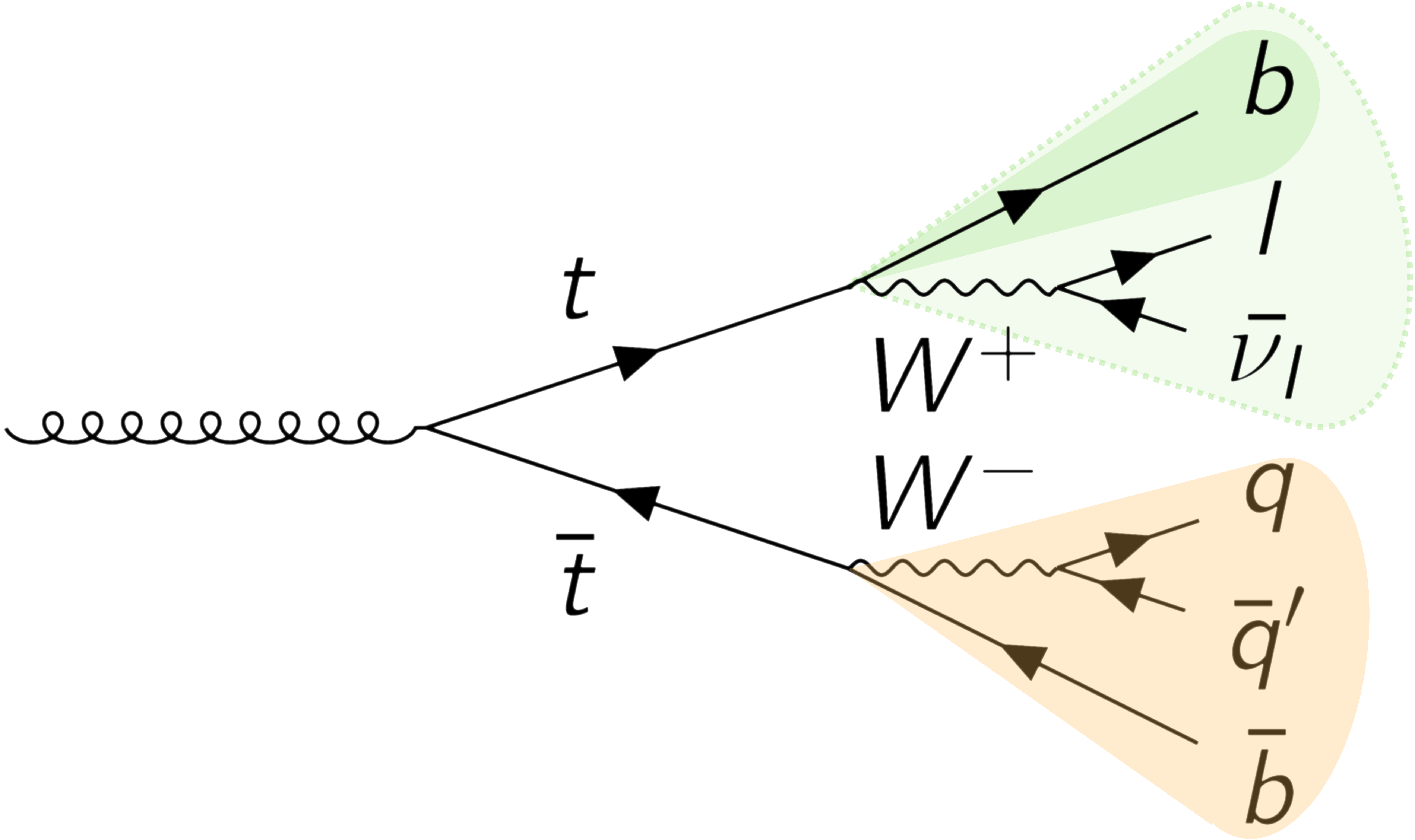
— to correct MC simulation —

- derive correction factors for each
  - data taking era
  - working point
  - p_T bin of large-radius jet (AK8 jet)
  - merge scenario of top quark decay products





Tag and Probe Method With $t\bar{t}$ Pairs



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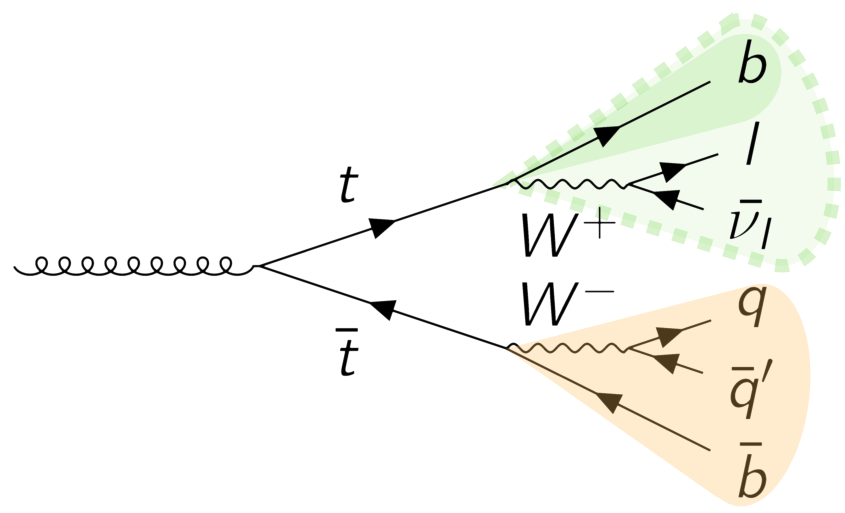
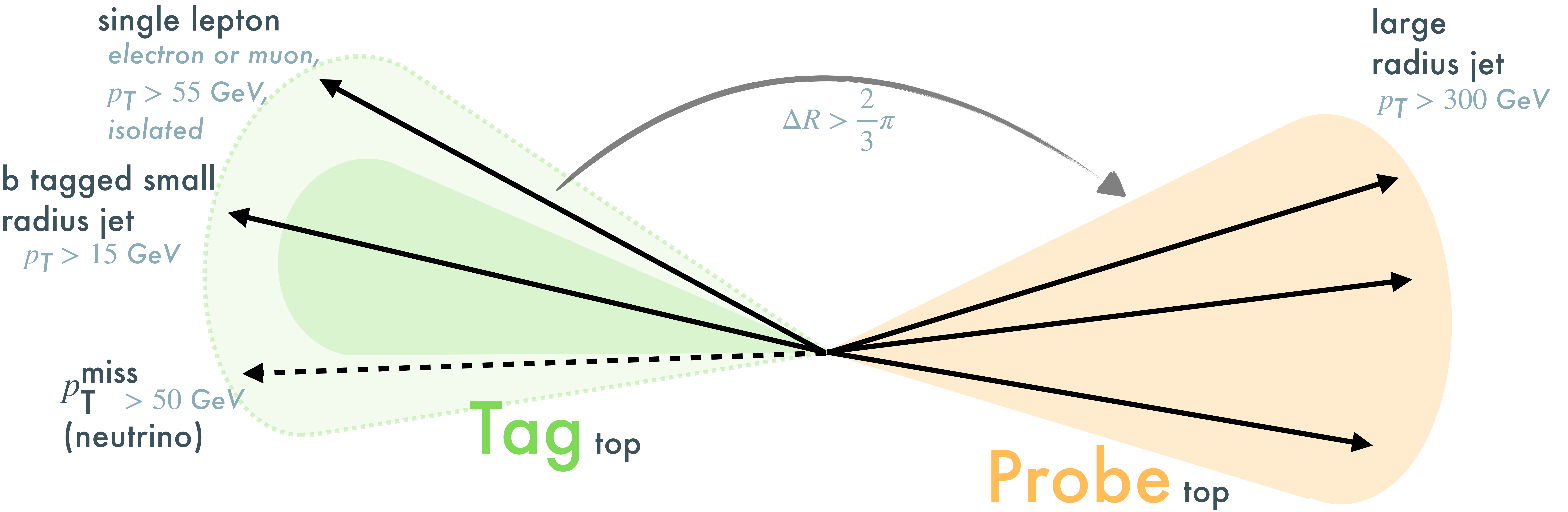
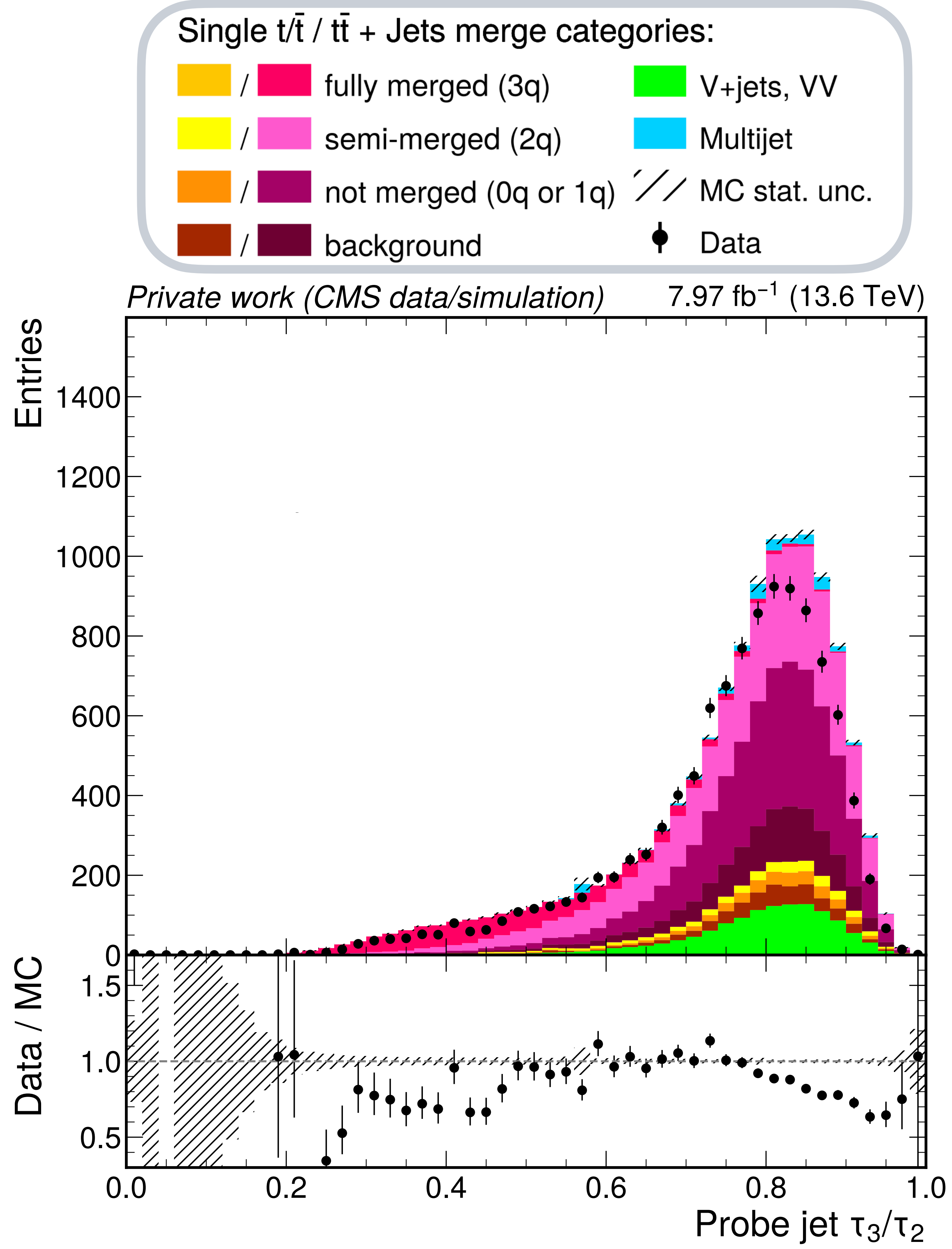


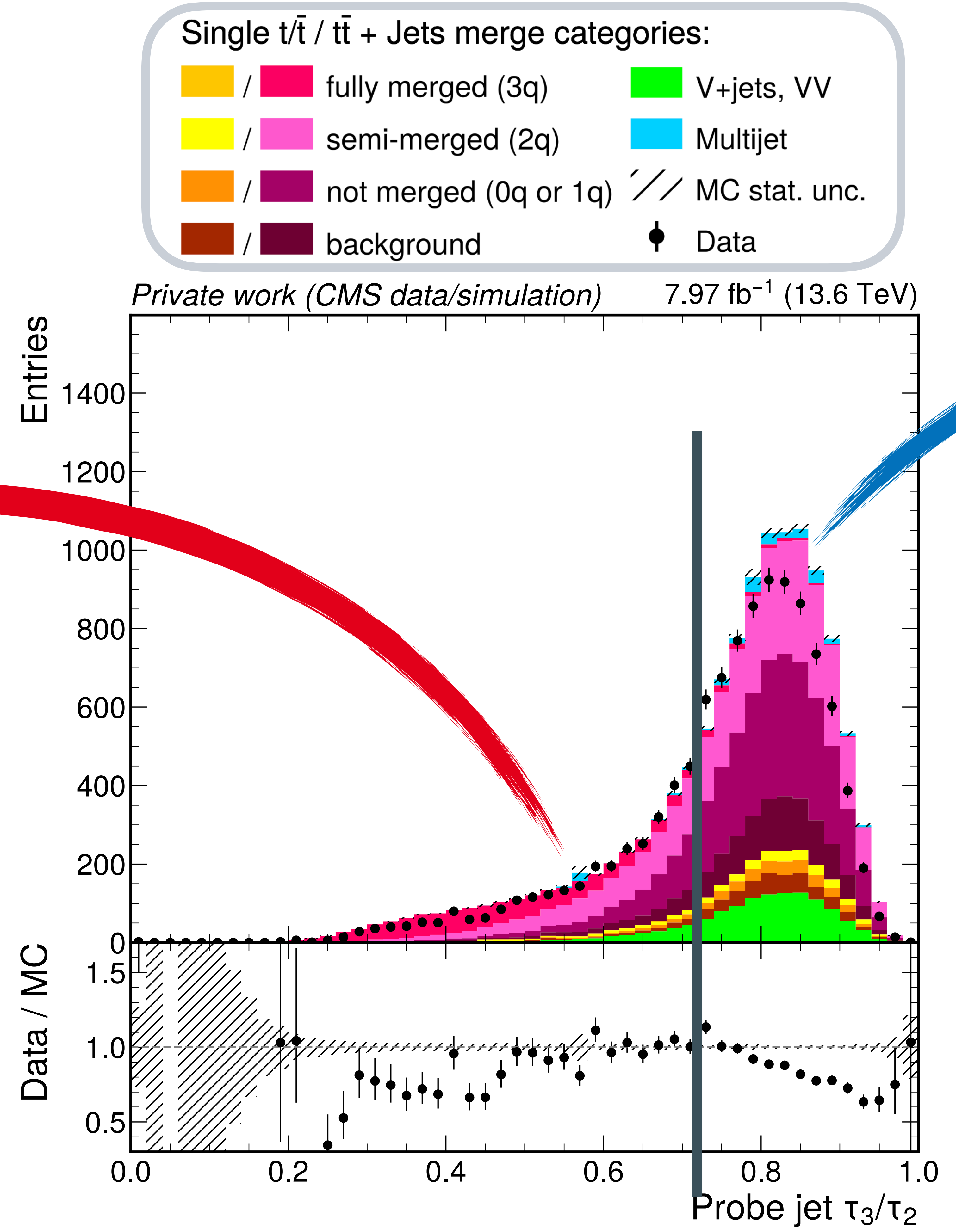


Probe Jet: τ_{32}



Probe Jet: τ_{32}

pass



fail

Probe Jet: τ_{32} and m_{SD}

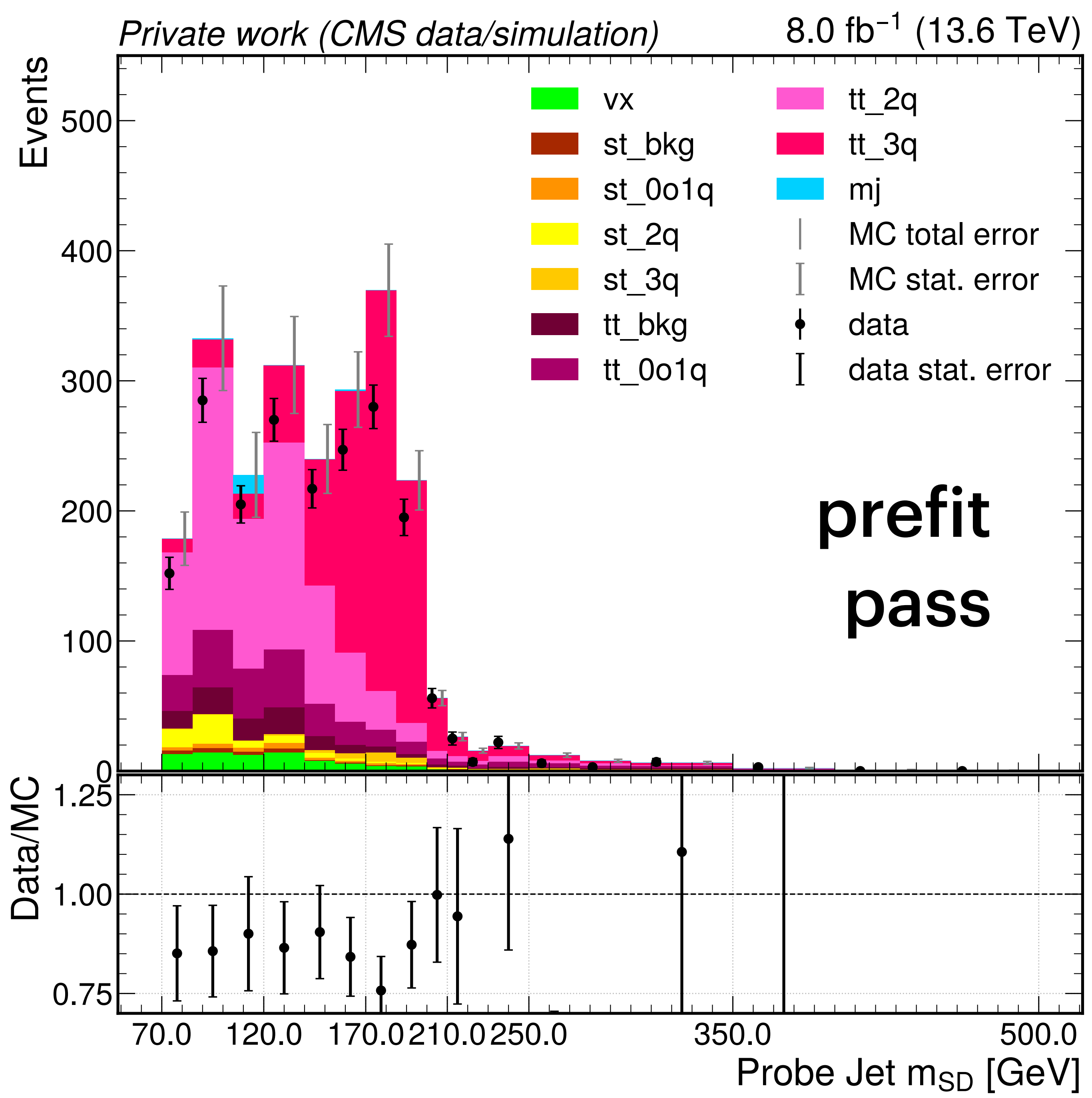
soft drop criterion $\frac{\min(p_{T1}, p_{T,2})}{p_{T1} + p_{T2}} > z_{cut} \cdot \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$

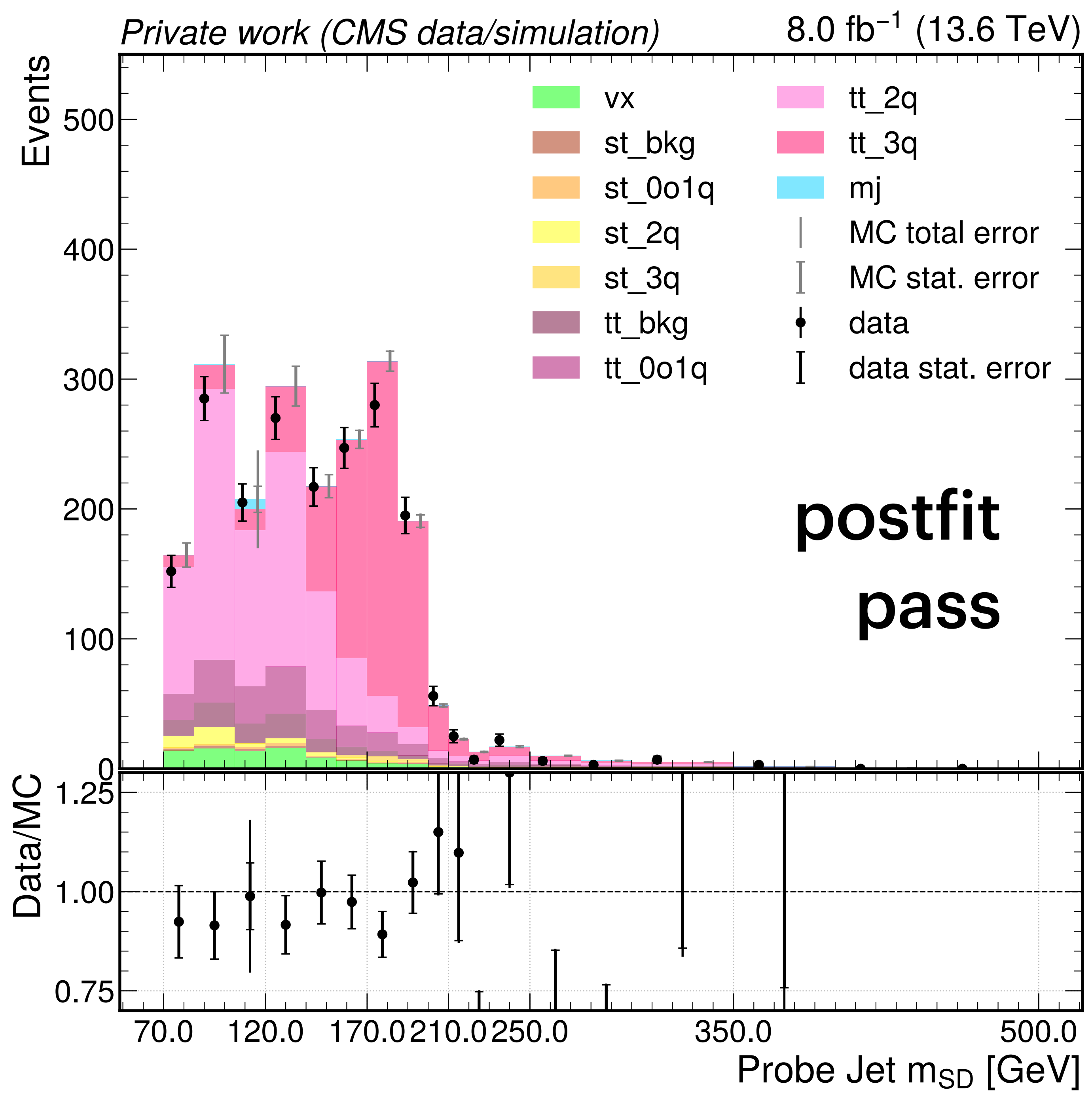
JHEP 1405 (2014) 146 - arXiv:1402.2657

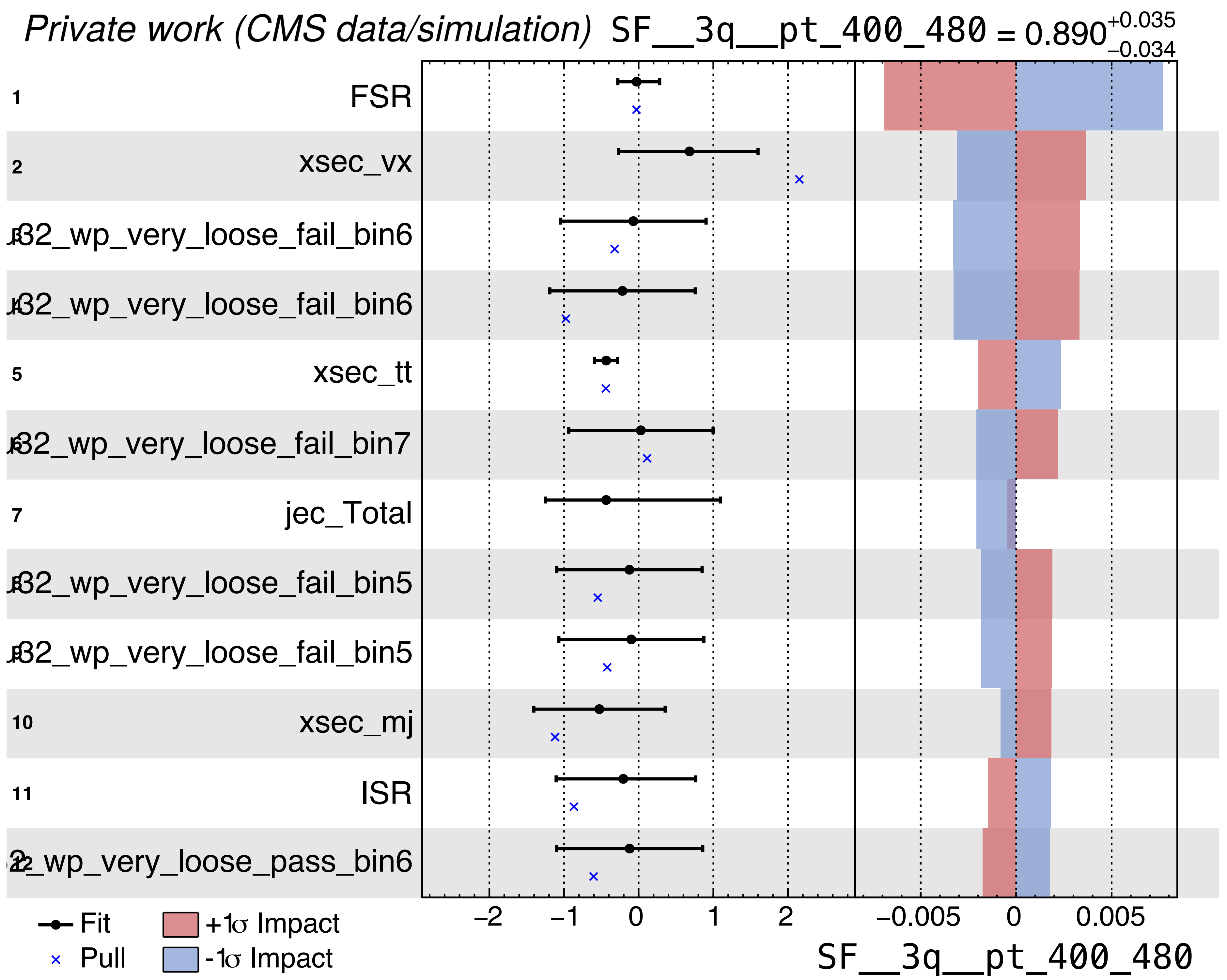
SF Derivation

— simultaneous fit for merge categories and p_T of probe jet —

- constraint: $N_{\text{total}} = N_{\text{pass}} + N_{\text{fail}} = \text{const}$
- syst. uncertainties considered, jet energy corrections largest







SF Derivation

— simultaneous fit for merge categories and p_T of probe jet —

Quick and automated derivation of SF essential to be used in analyses.

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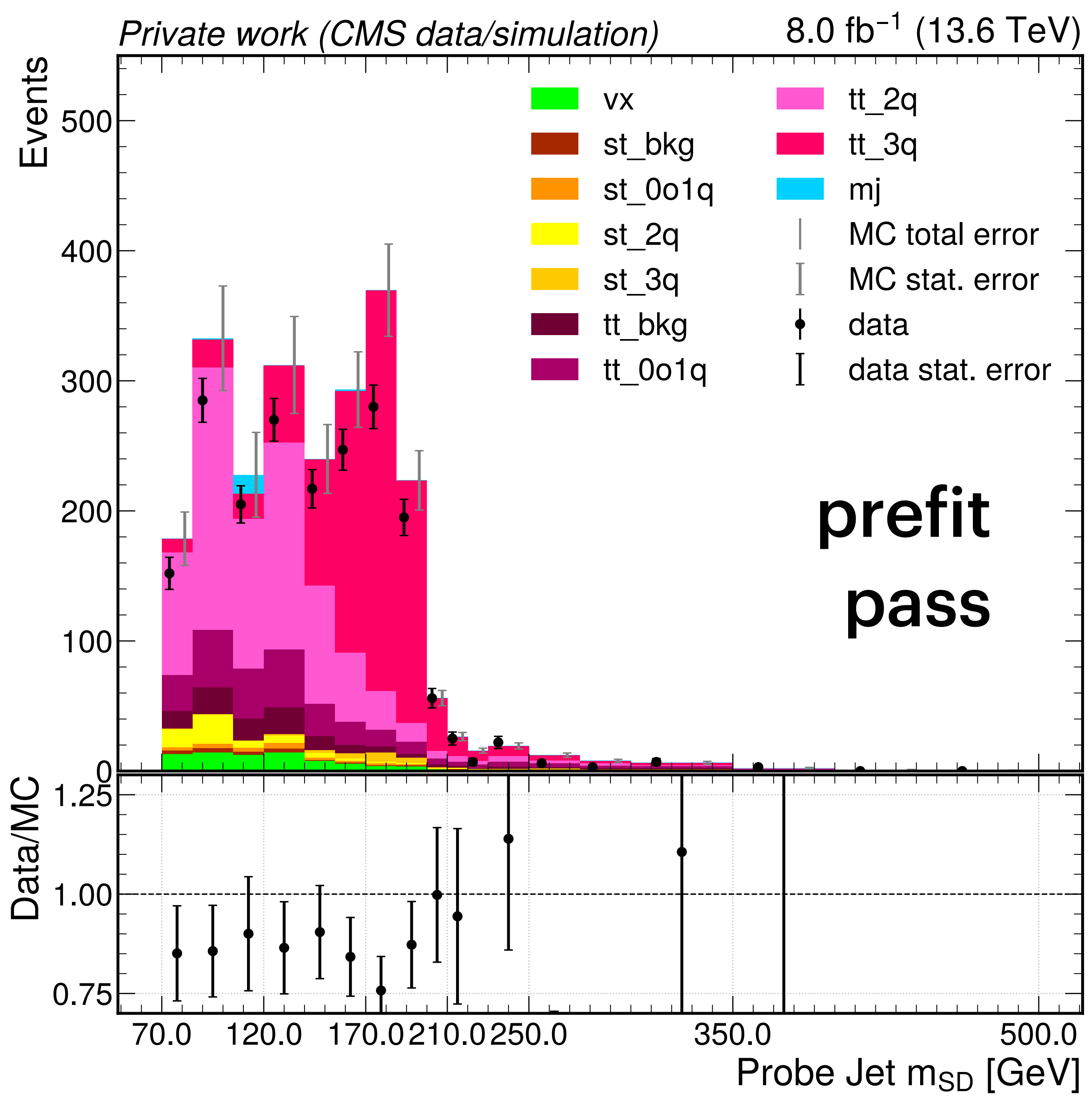
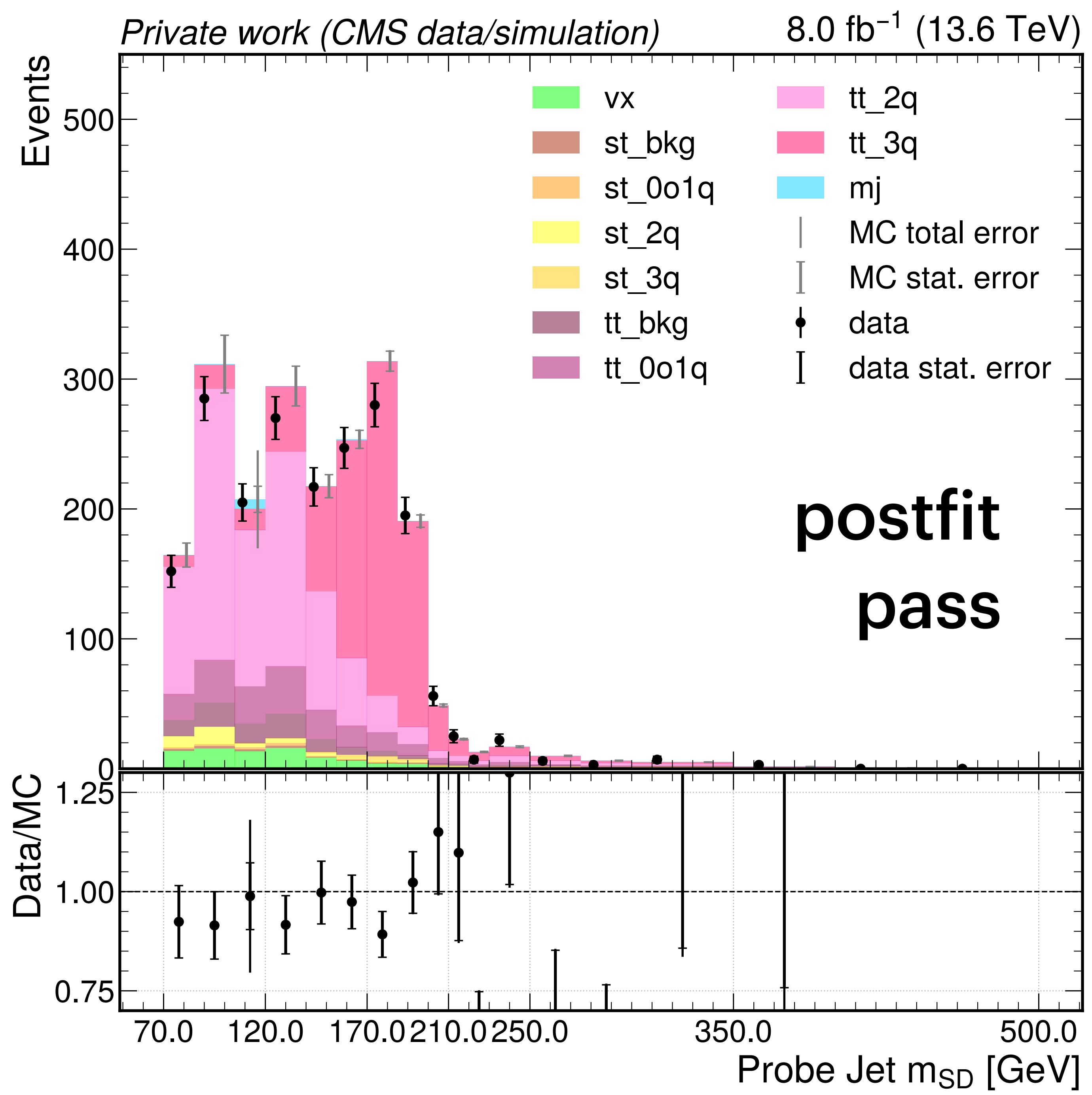
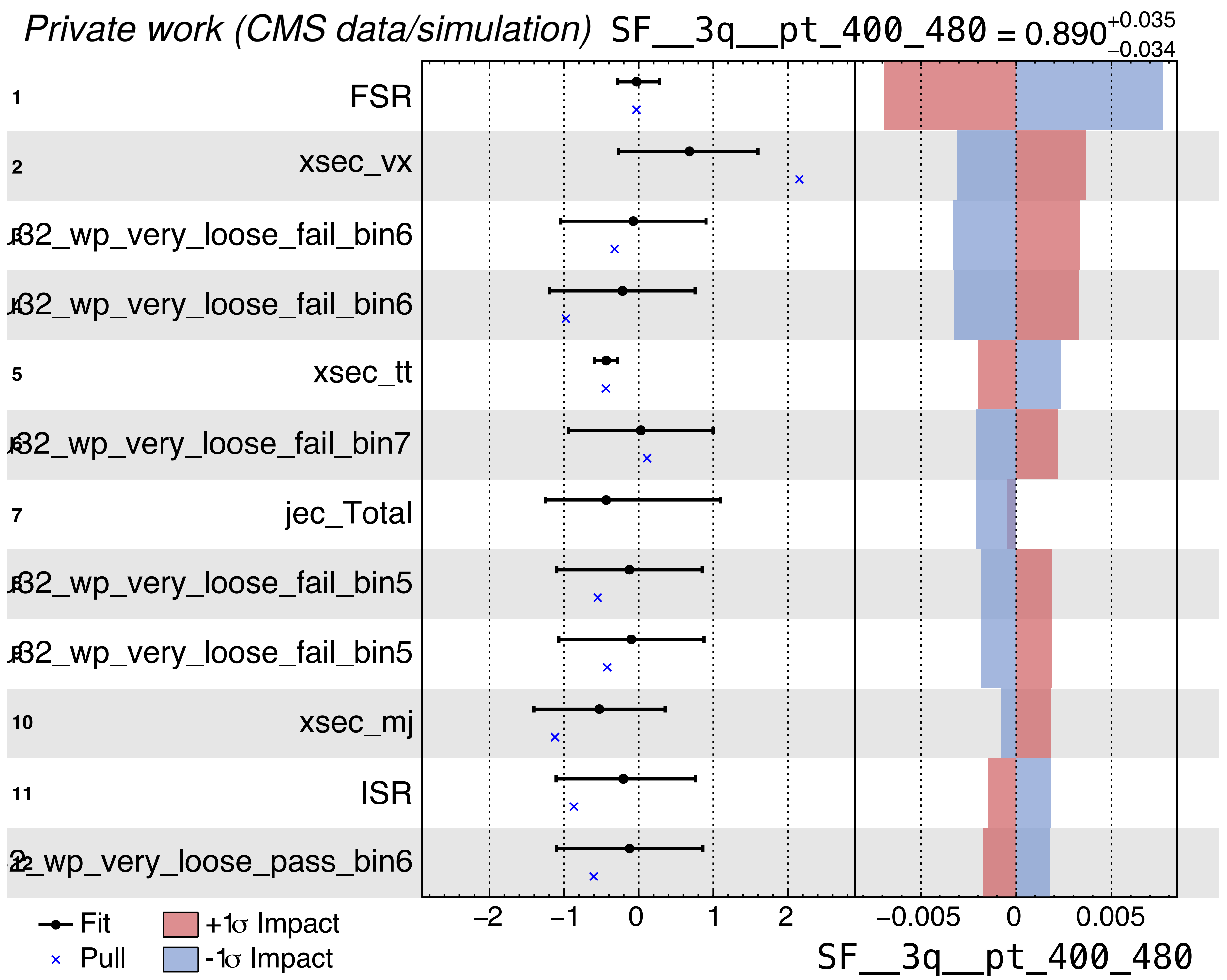


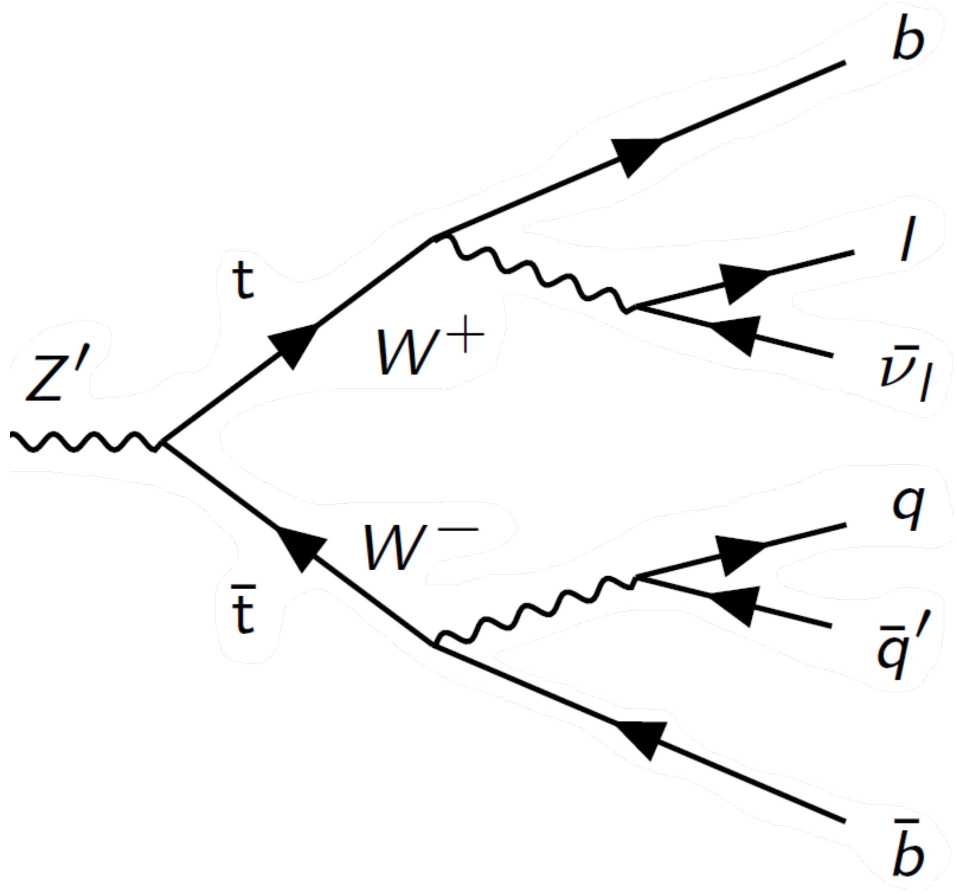




Search for New Physics Effects ...

calibrate events/objects

select events



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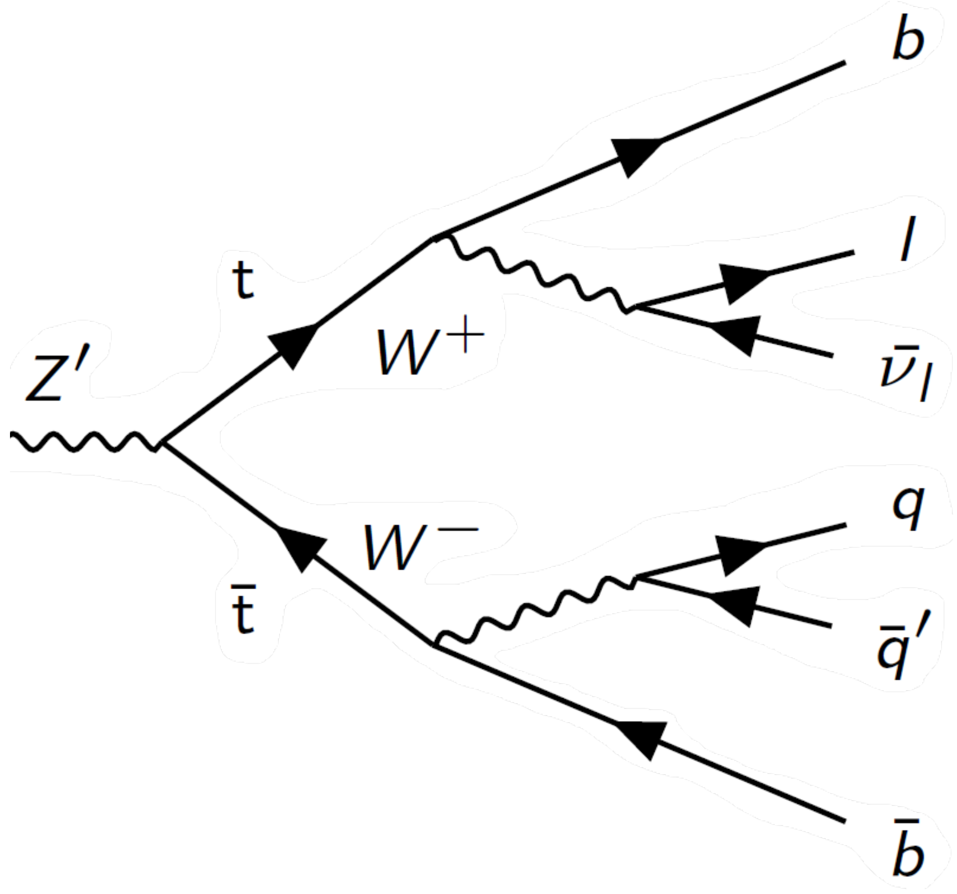

?

boosted reconstruction

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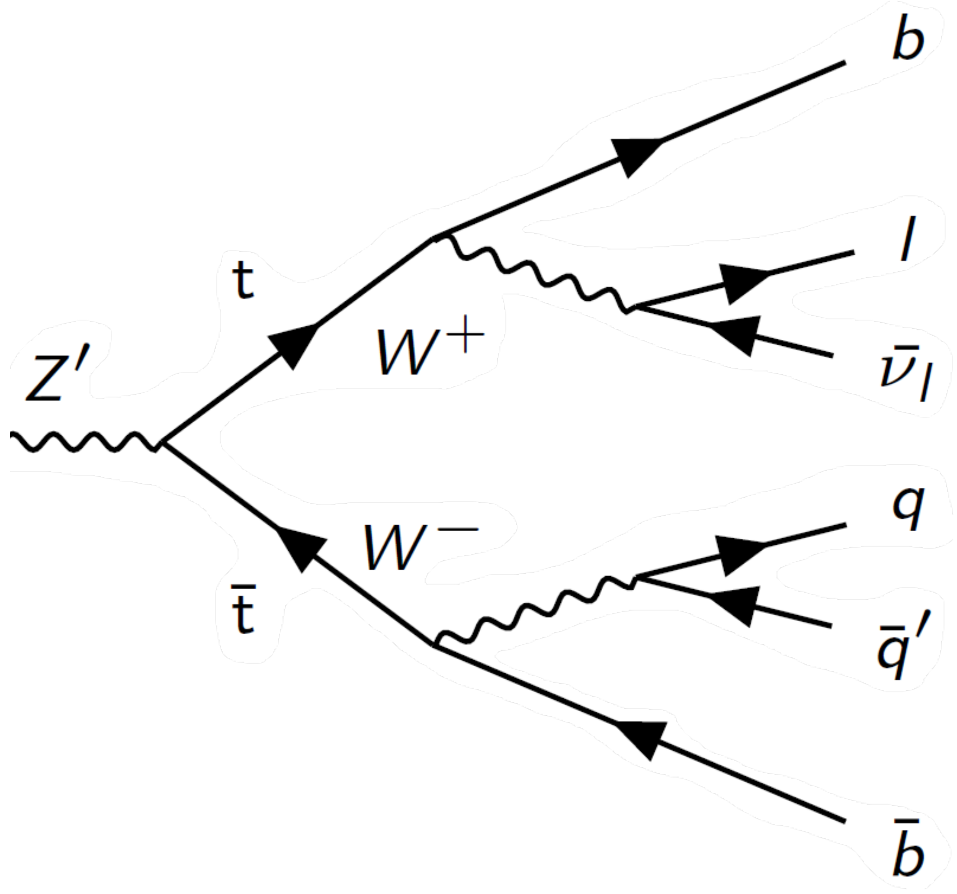

?

resolved reconstruction

boosted reconstruction

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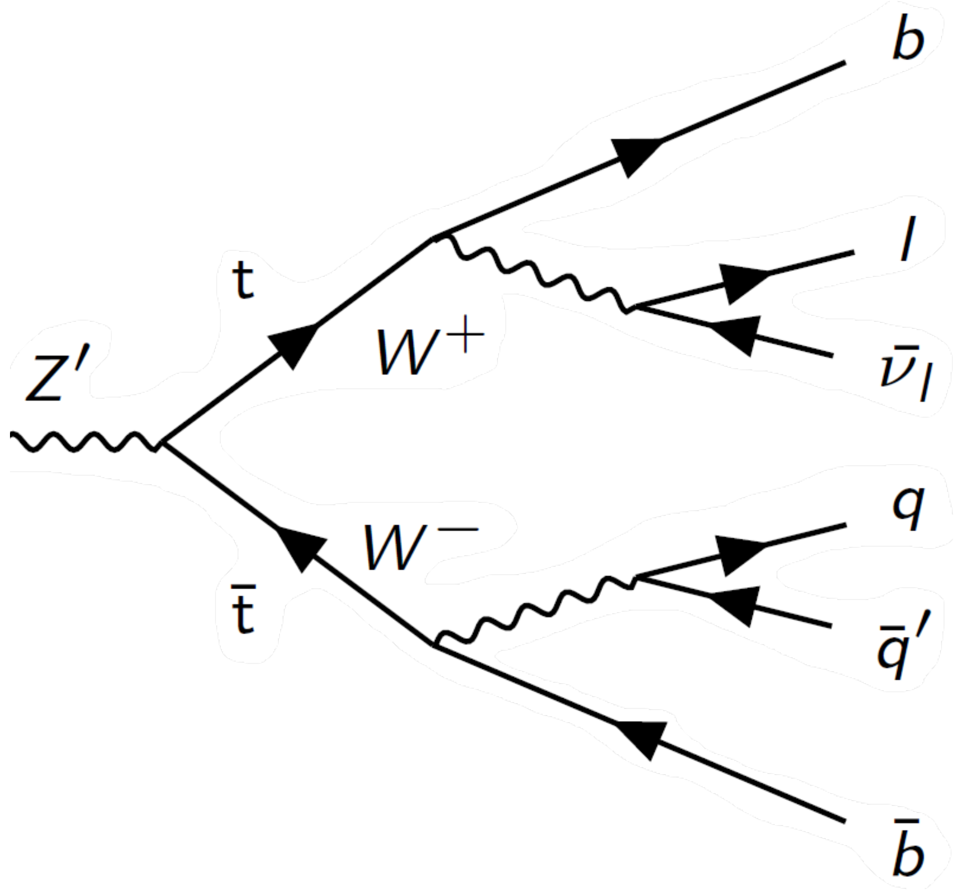

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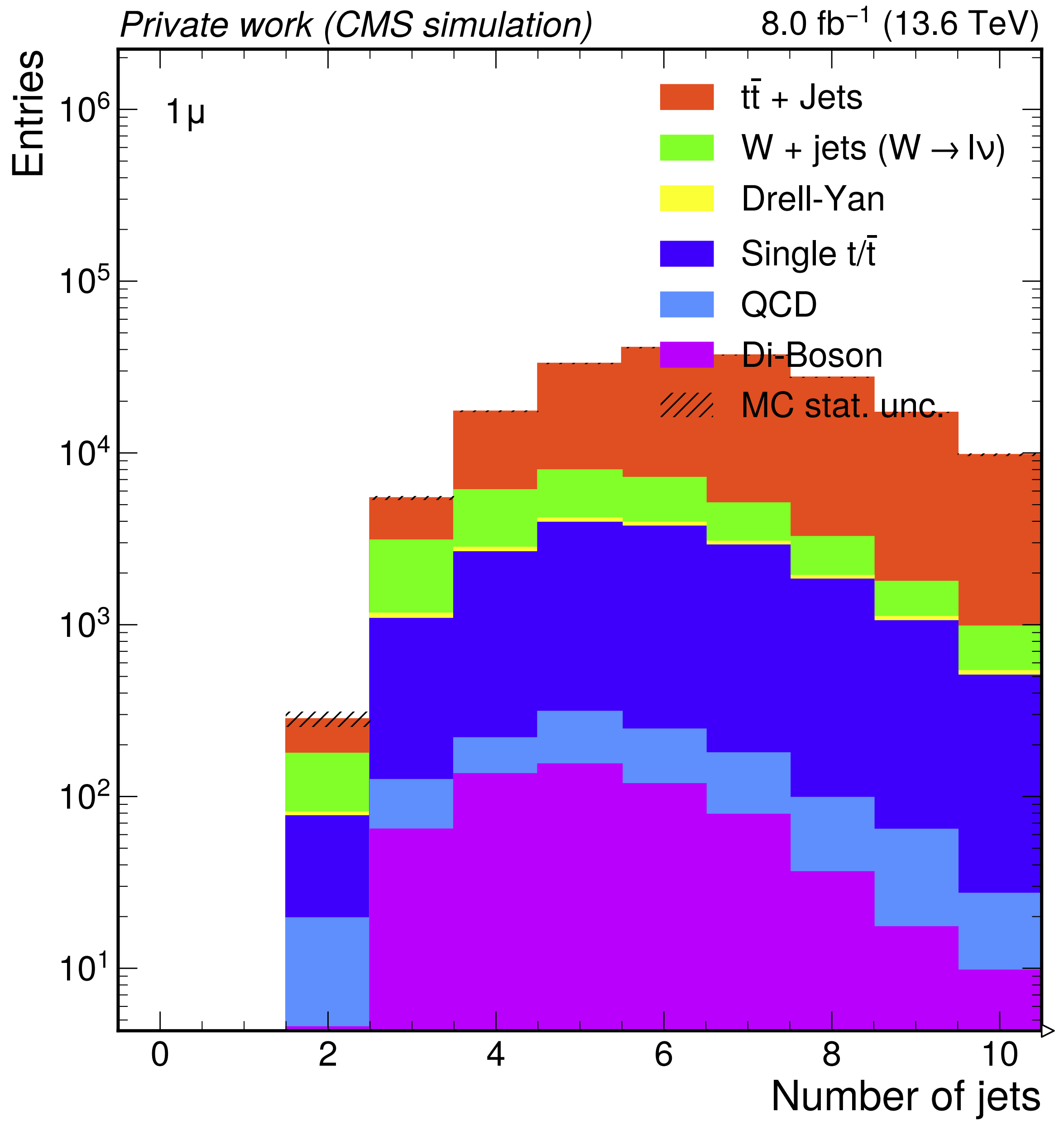

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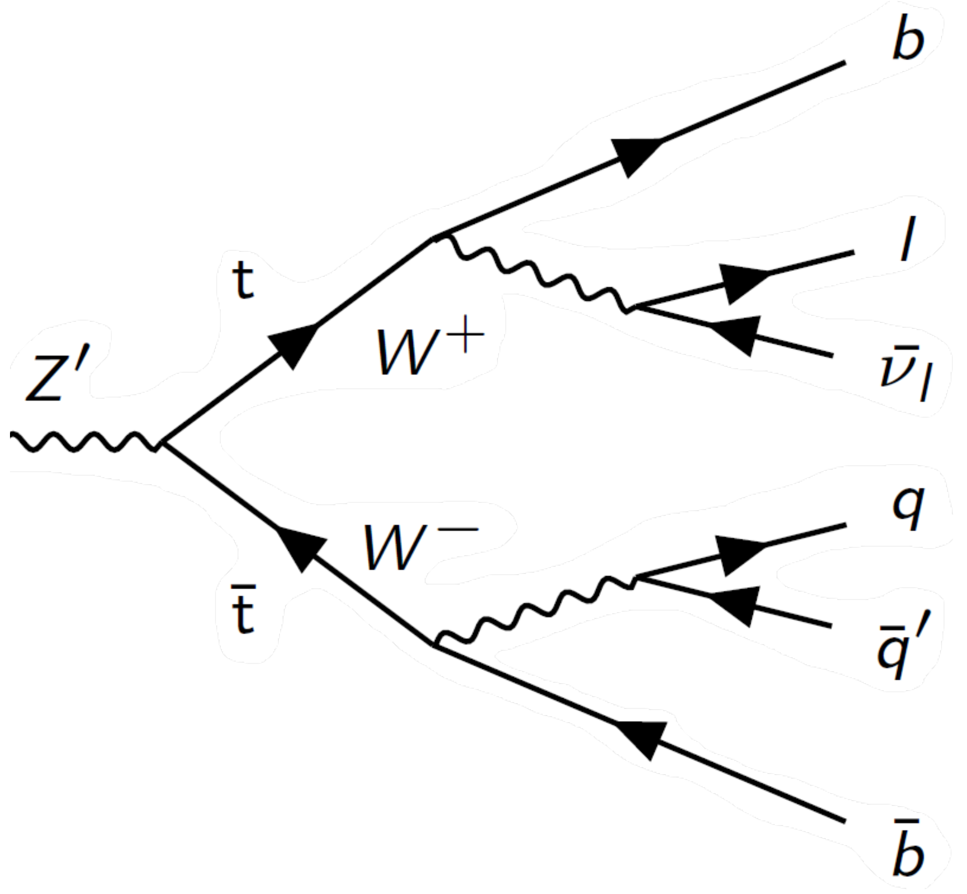

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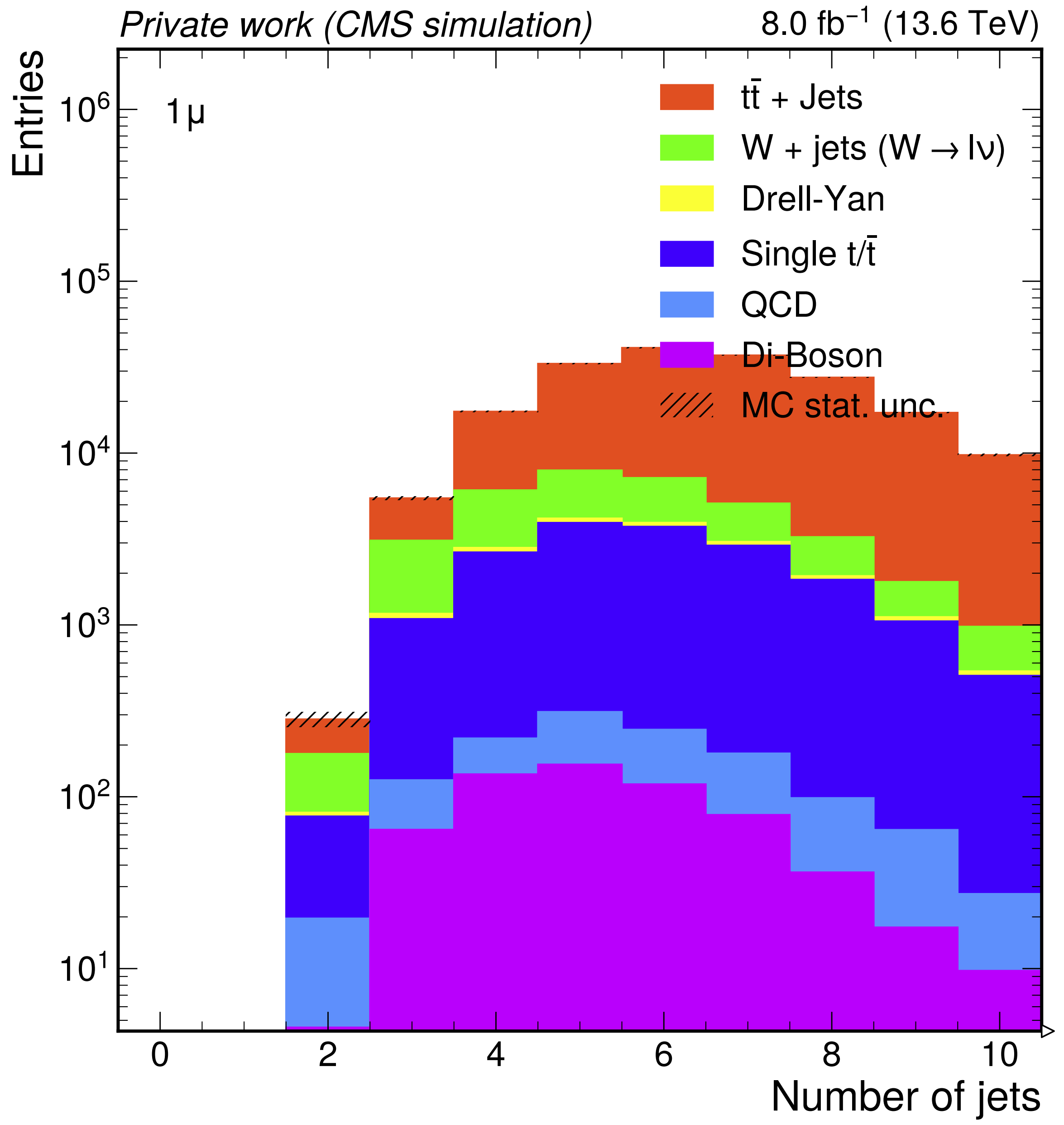


boosted reconstruction

choose best hypothesis per event

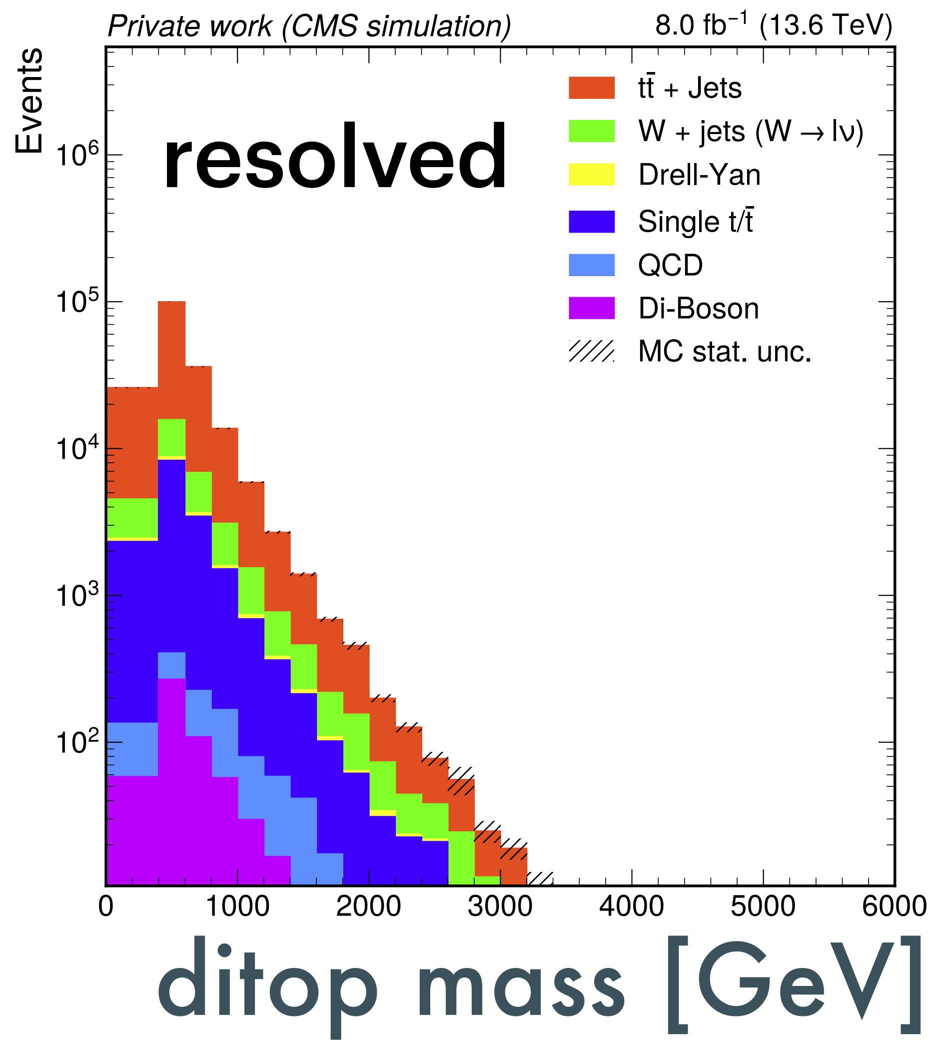
$$\chi^2 = \left(\frac{m_{\text{lep}} - \bar{m}_{\text{lep}}}{\sigma_{\bar{m}_{\text{lep}}}}\right)^2 + \left(\frac{m_{\text{had}} - \bar{m}_{\text{had}}}{\sigma_{\bar{m}_{\text{had}}}}\right)^2$$

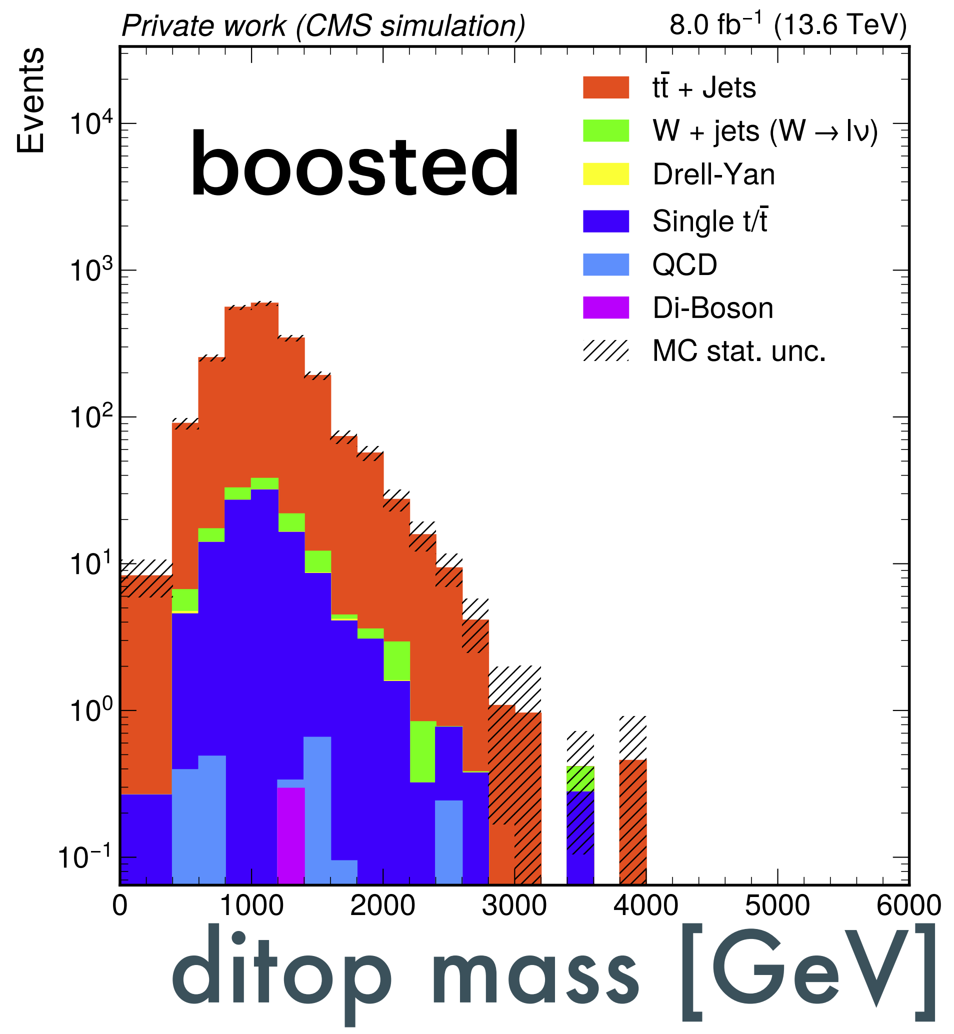
… In the Ditop Mass Spectrum

best
hypo-
thesis

... In the Ditop Mass Spectrum

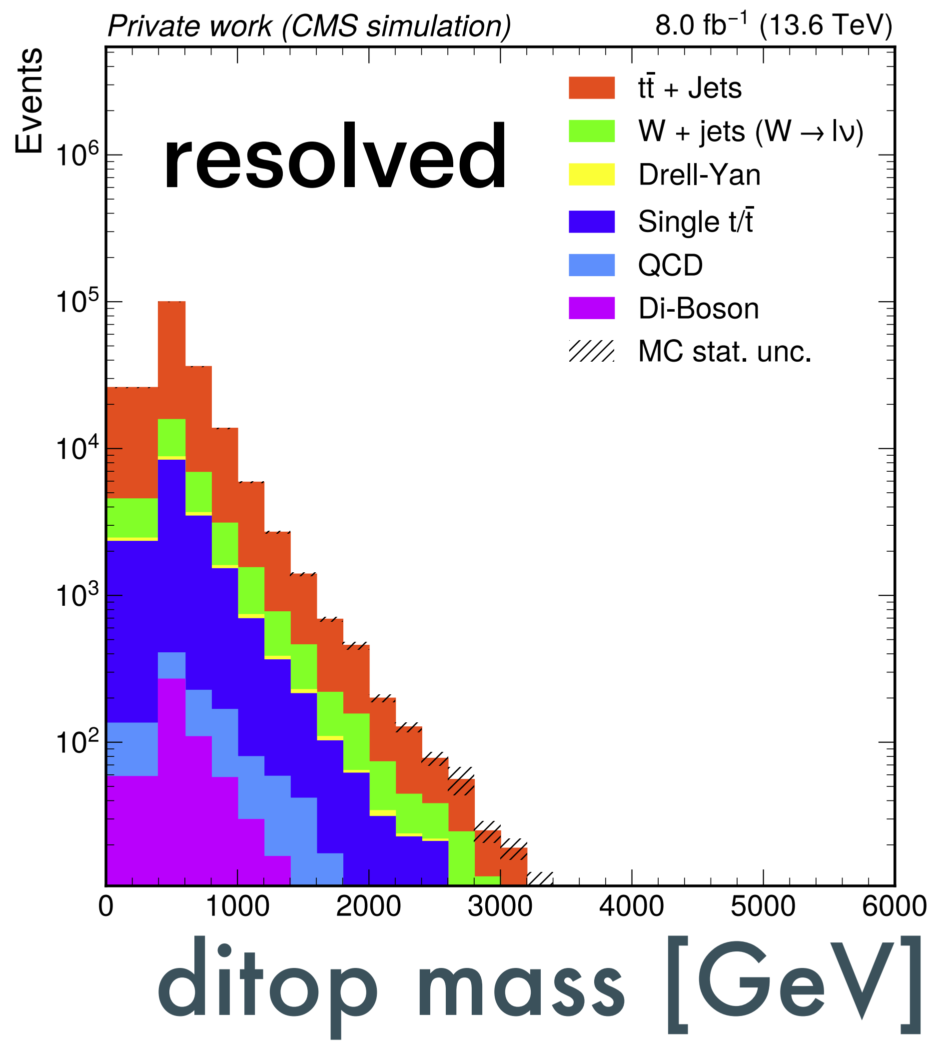
best hypo-thesis

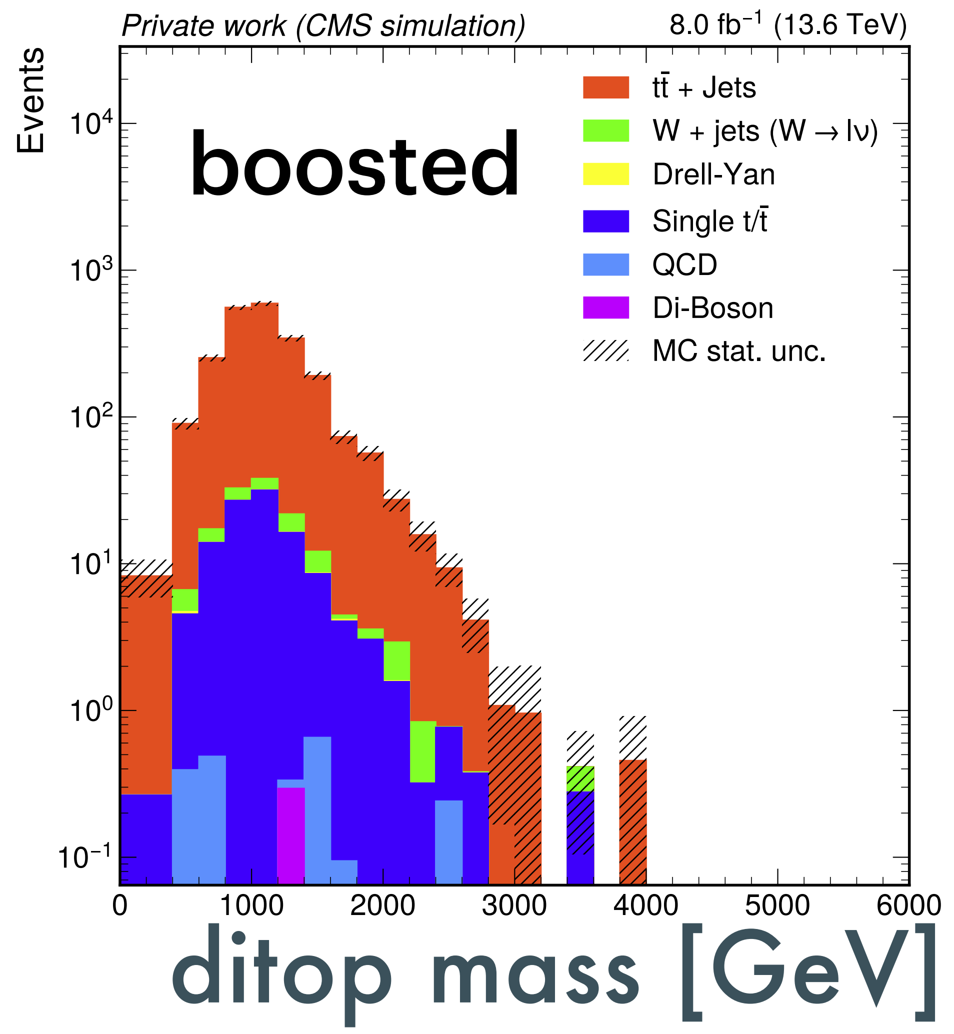




… In the Ditop Mass Spectrum

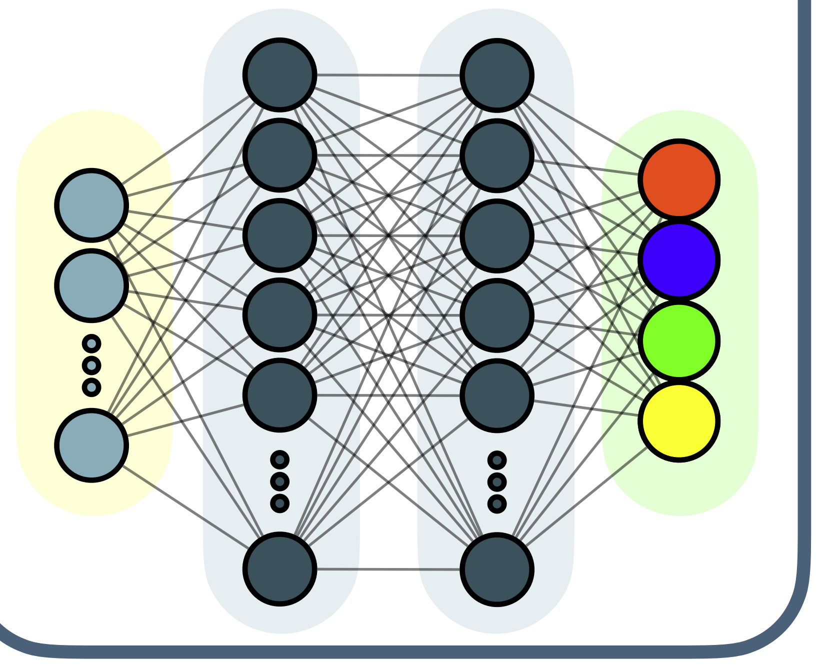
best hypo-thesis





selected events

DNN for event classification



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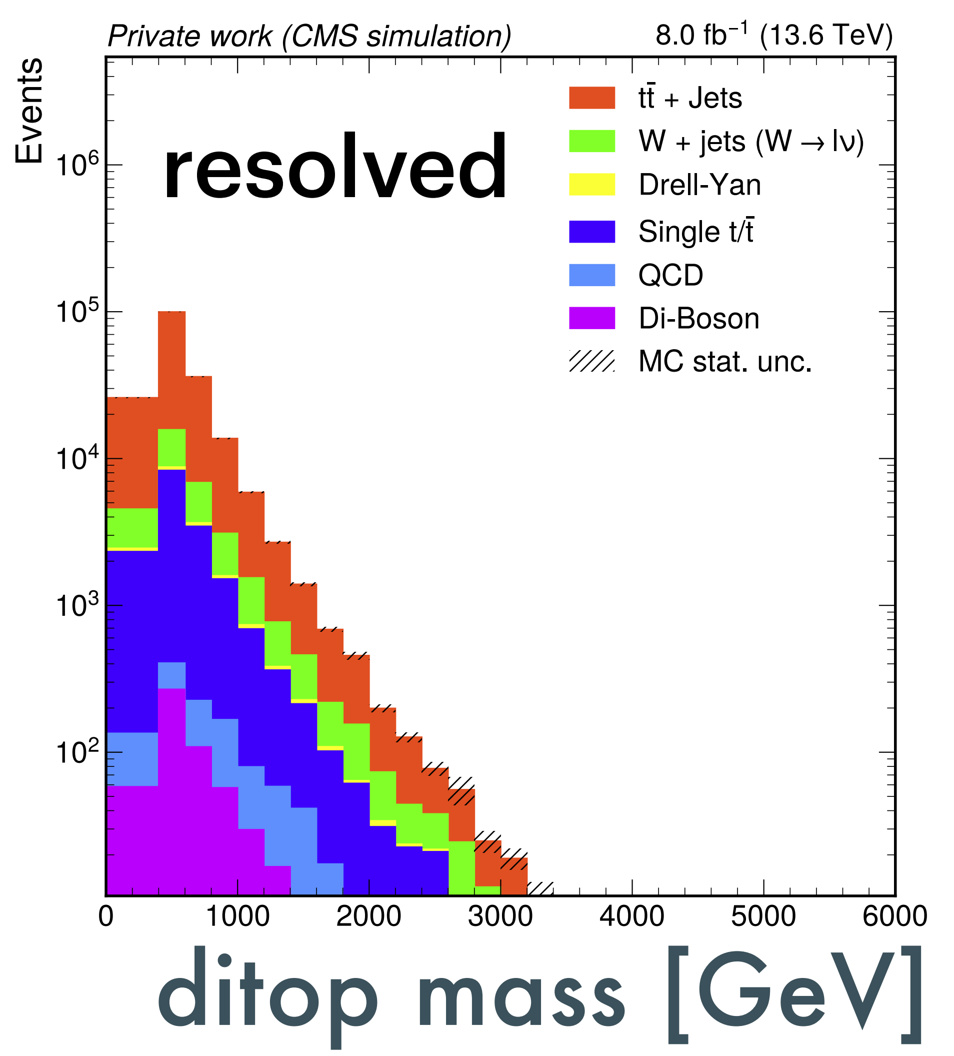
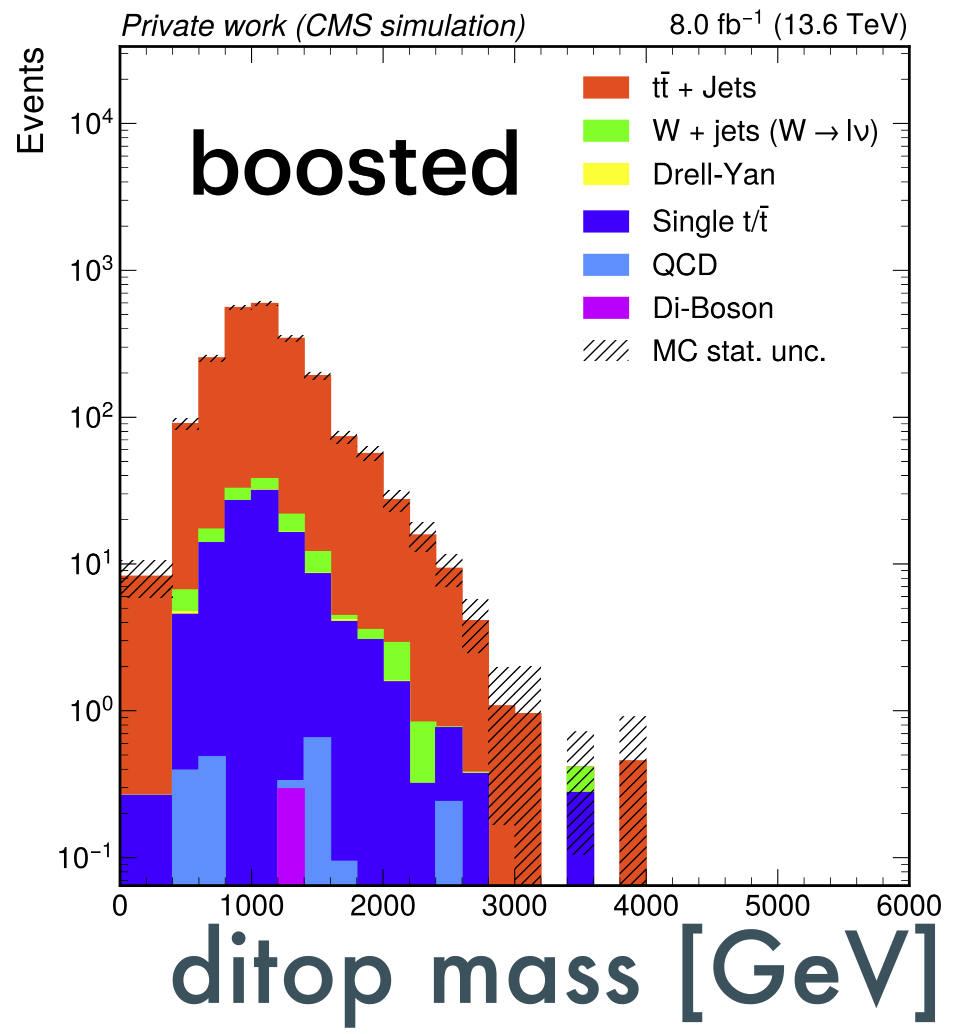
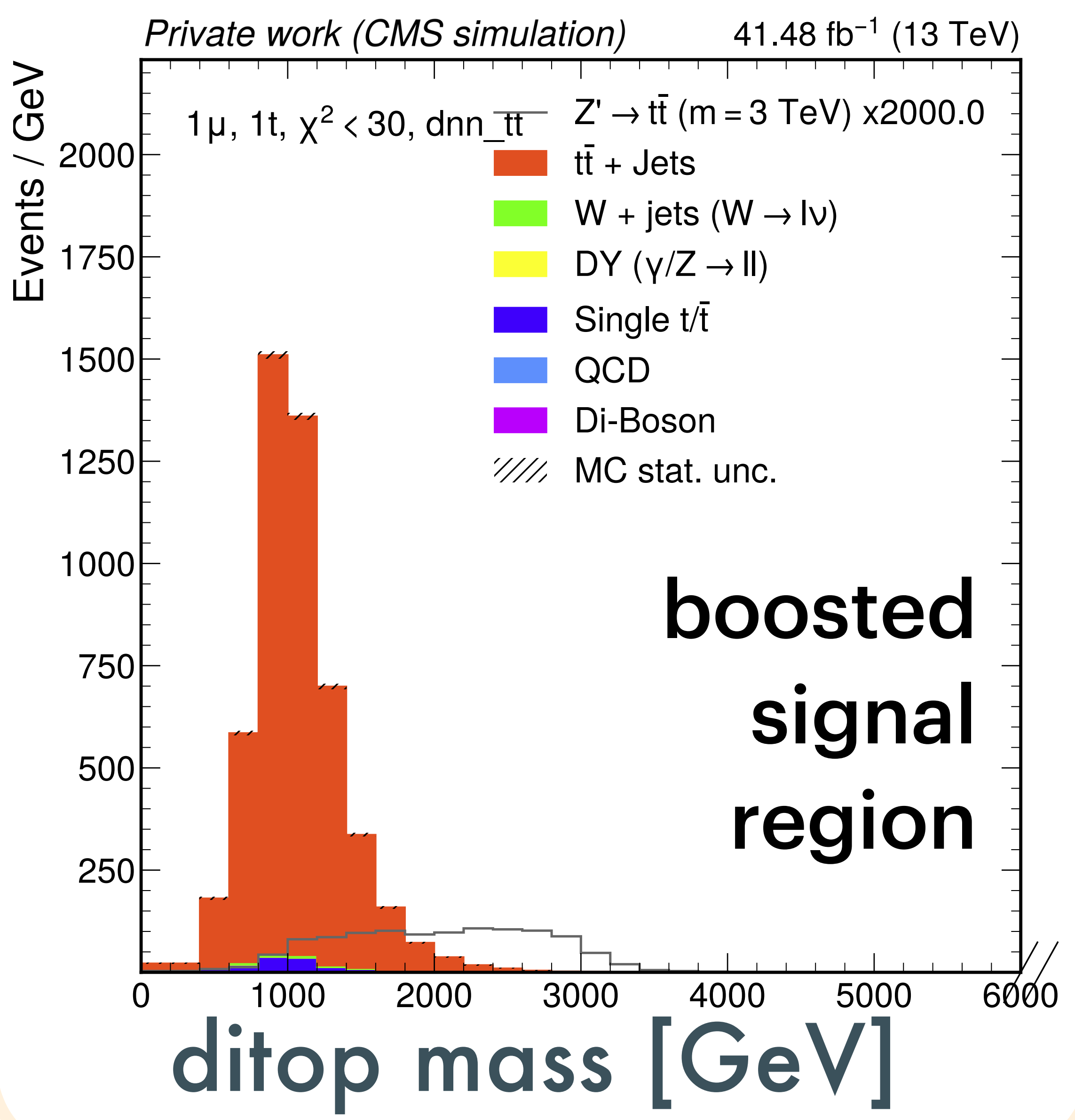
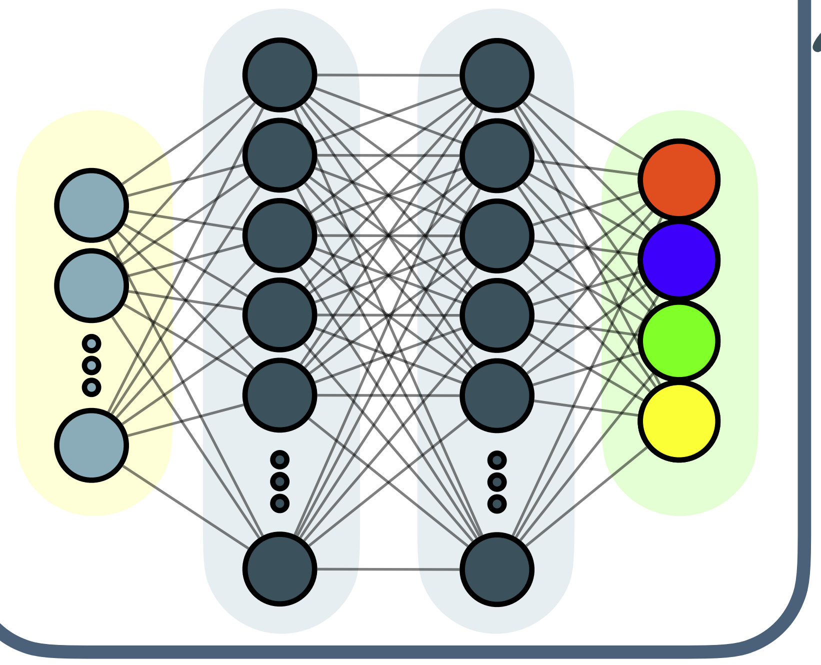




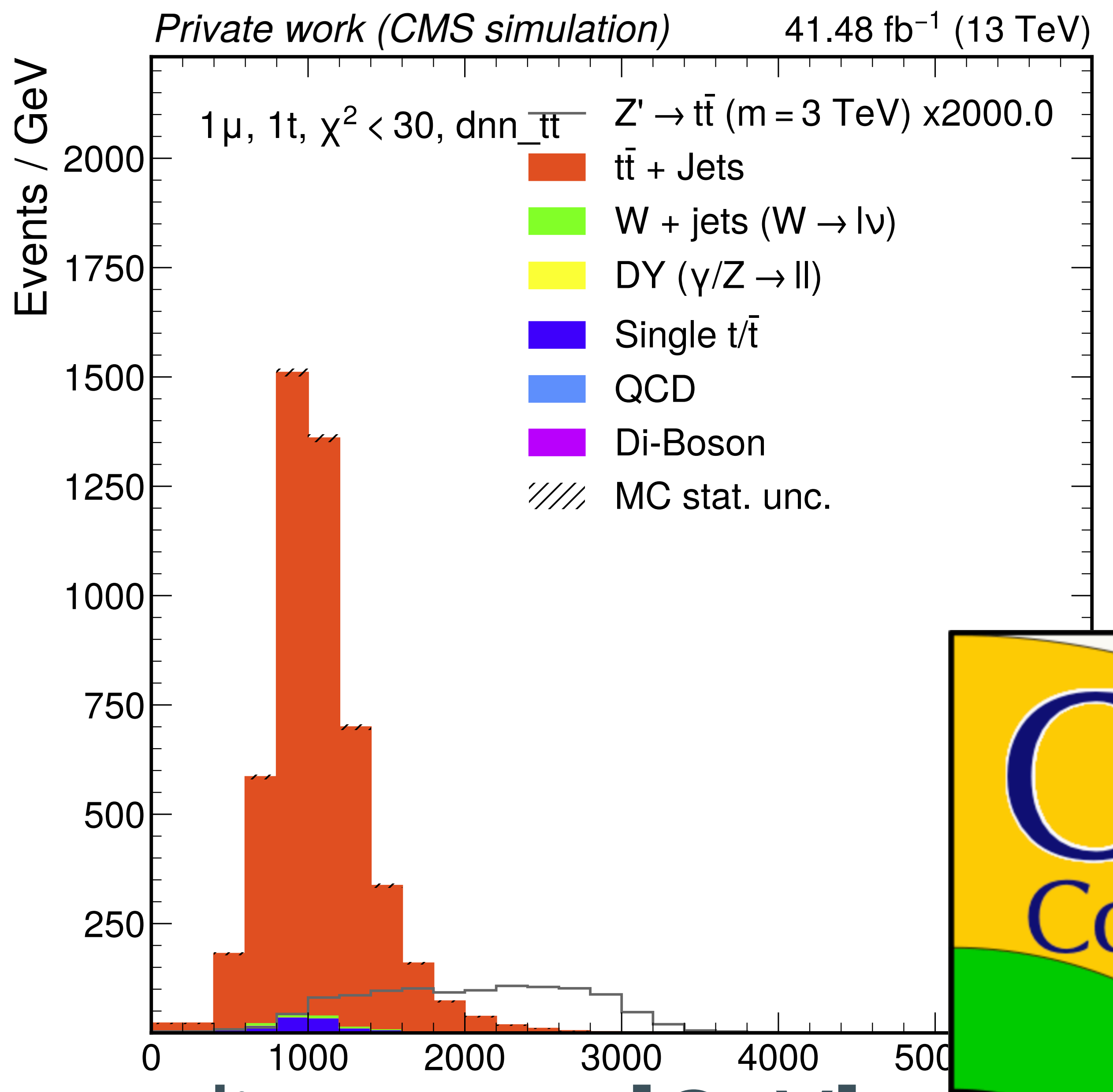


DNN for event classification

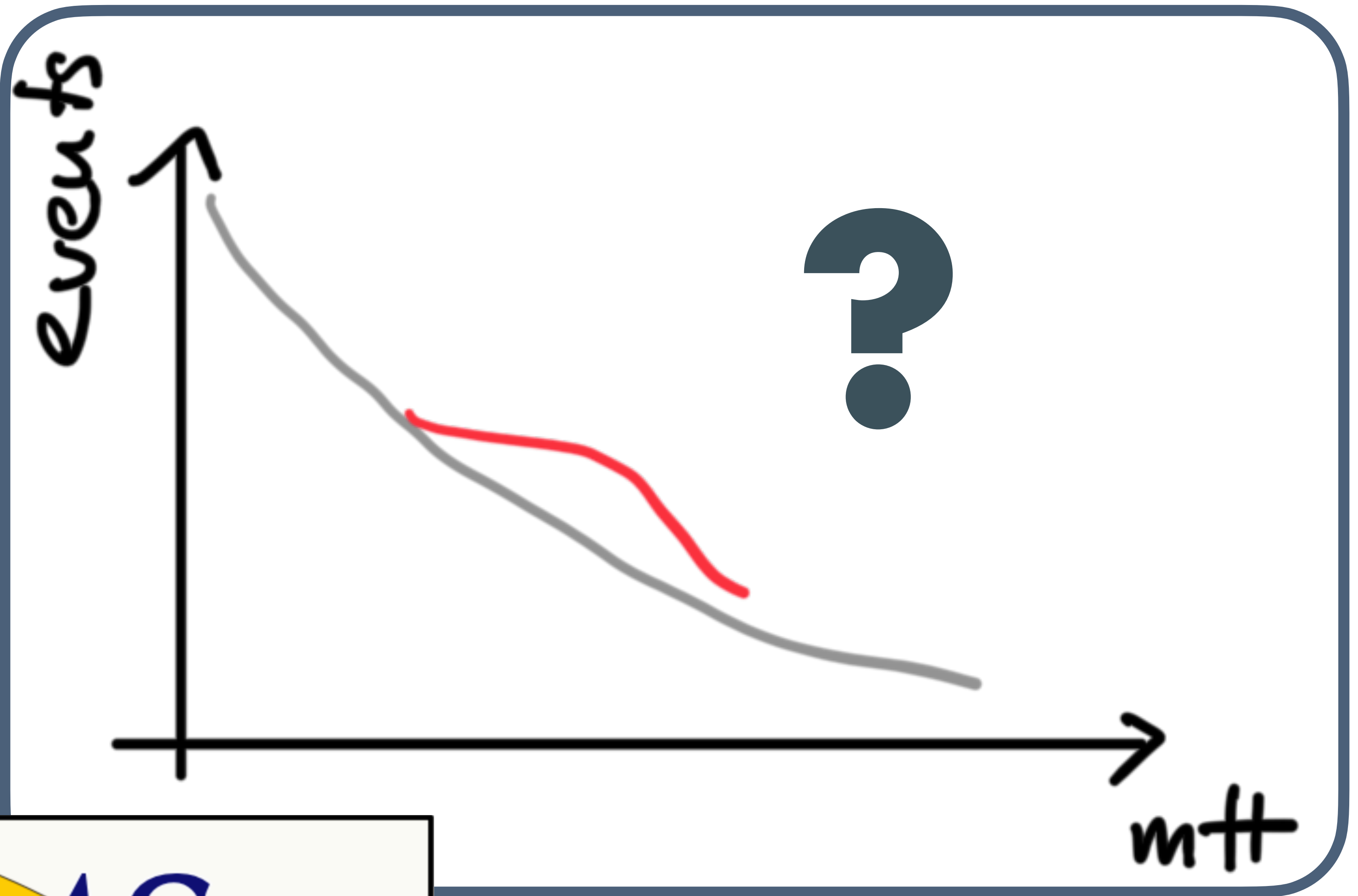


selected events

Statistical Analysis



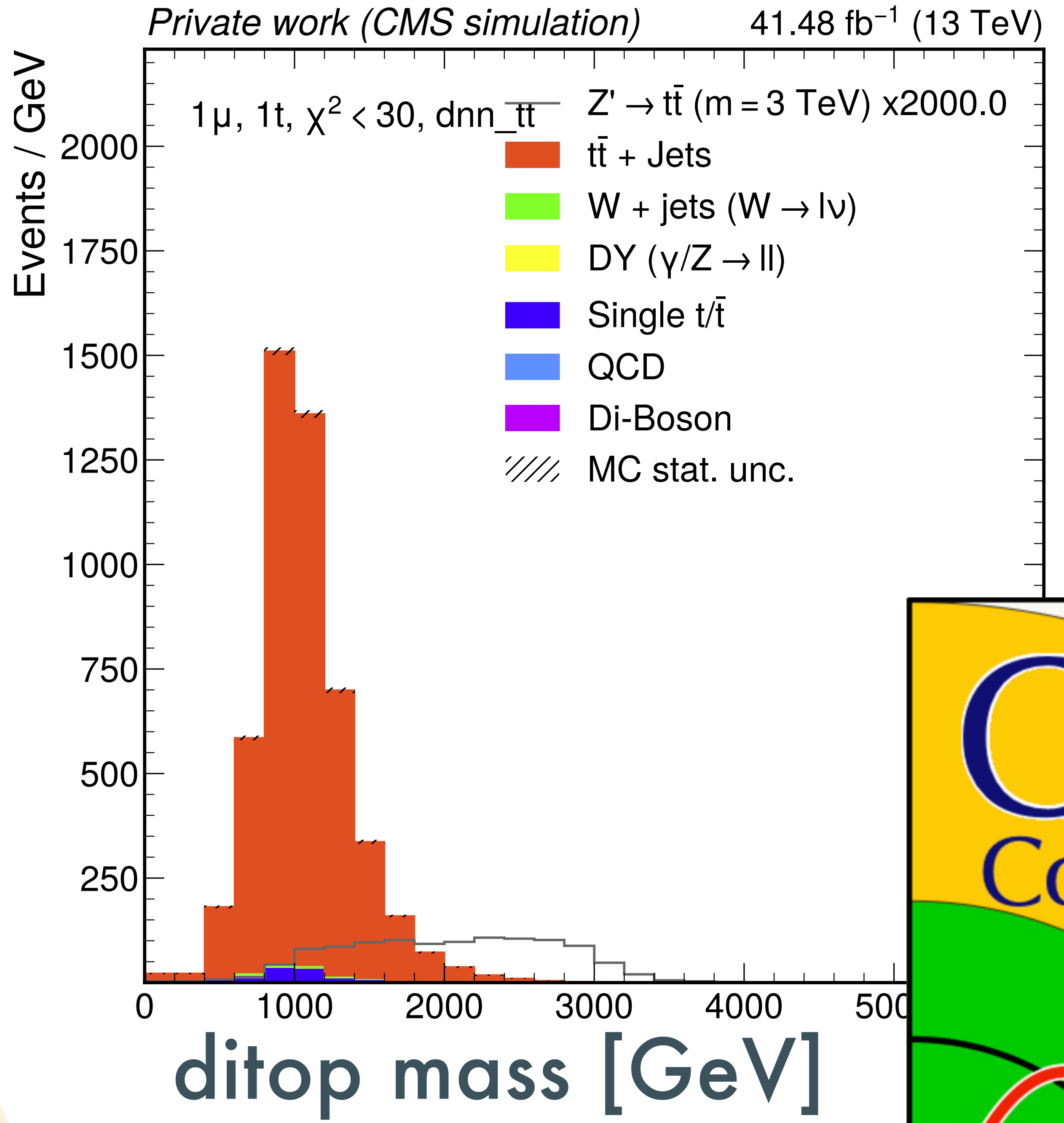
ditop mass [GeV]

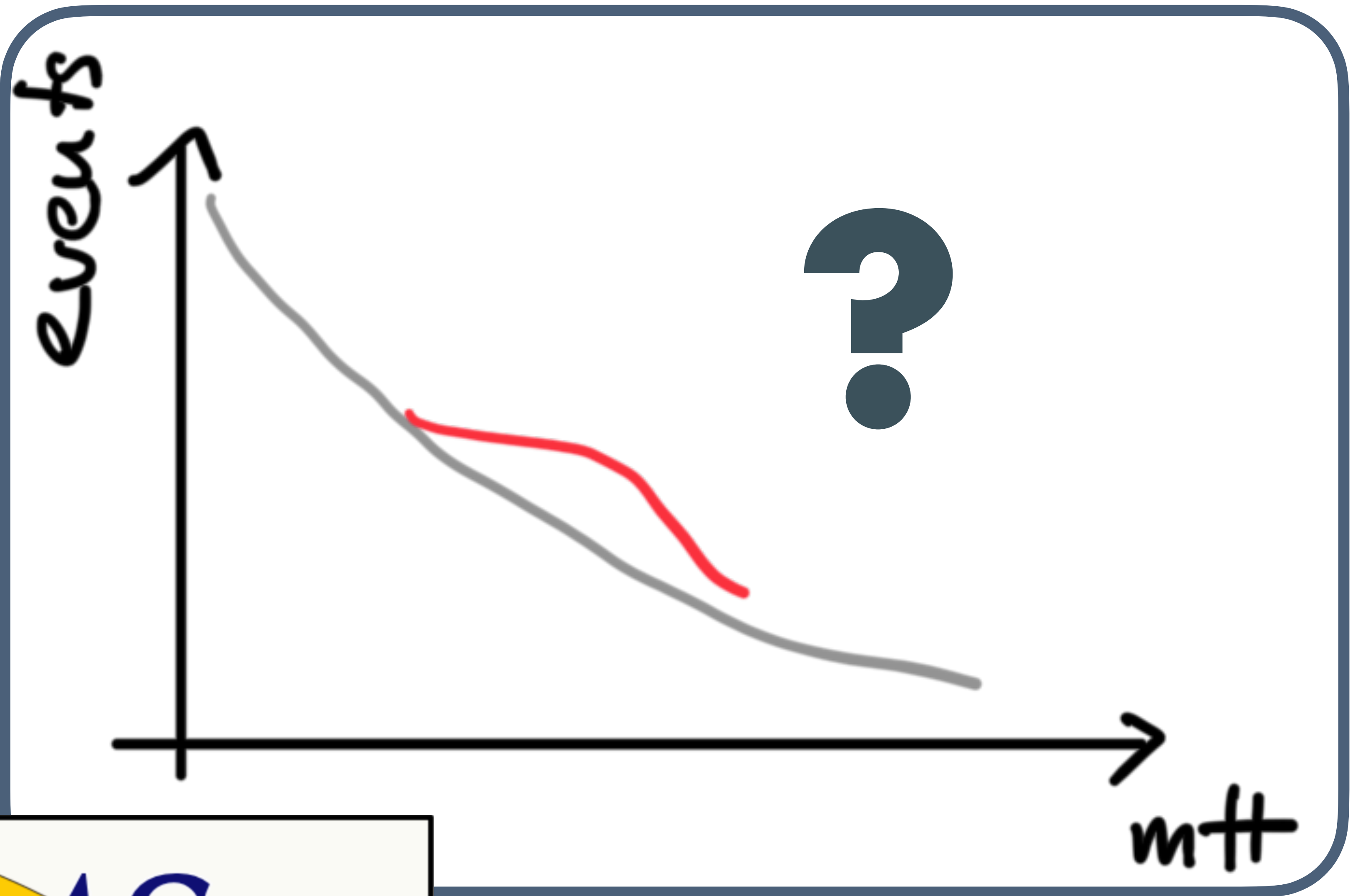


CMS Combine

Comput.Softw.Big Sci. 8 (2024) 1, 19 - arXiv:2404.06614

Statistical Analysis

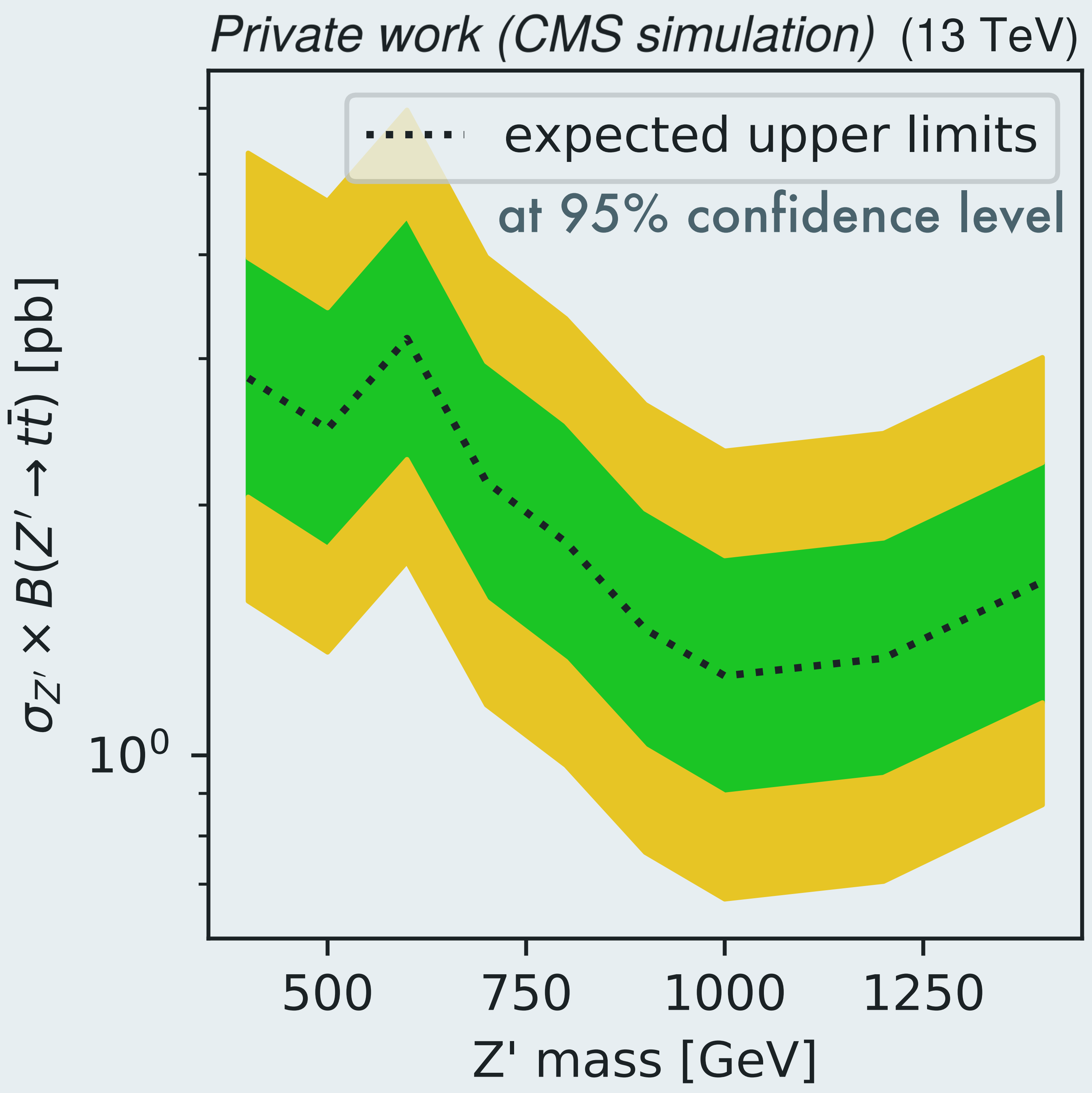




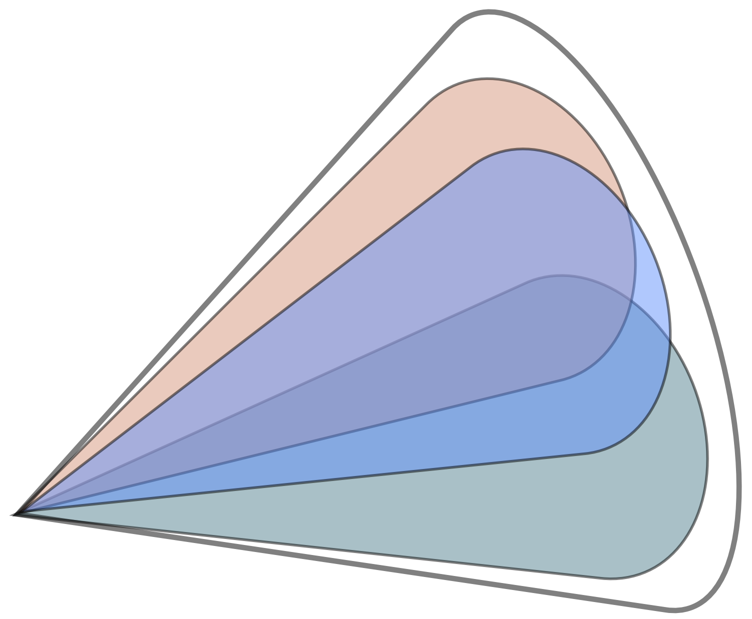
CMS Combine

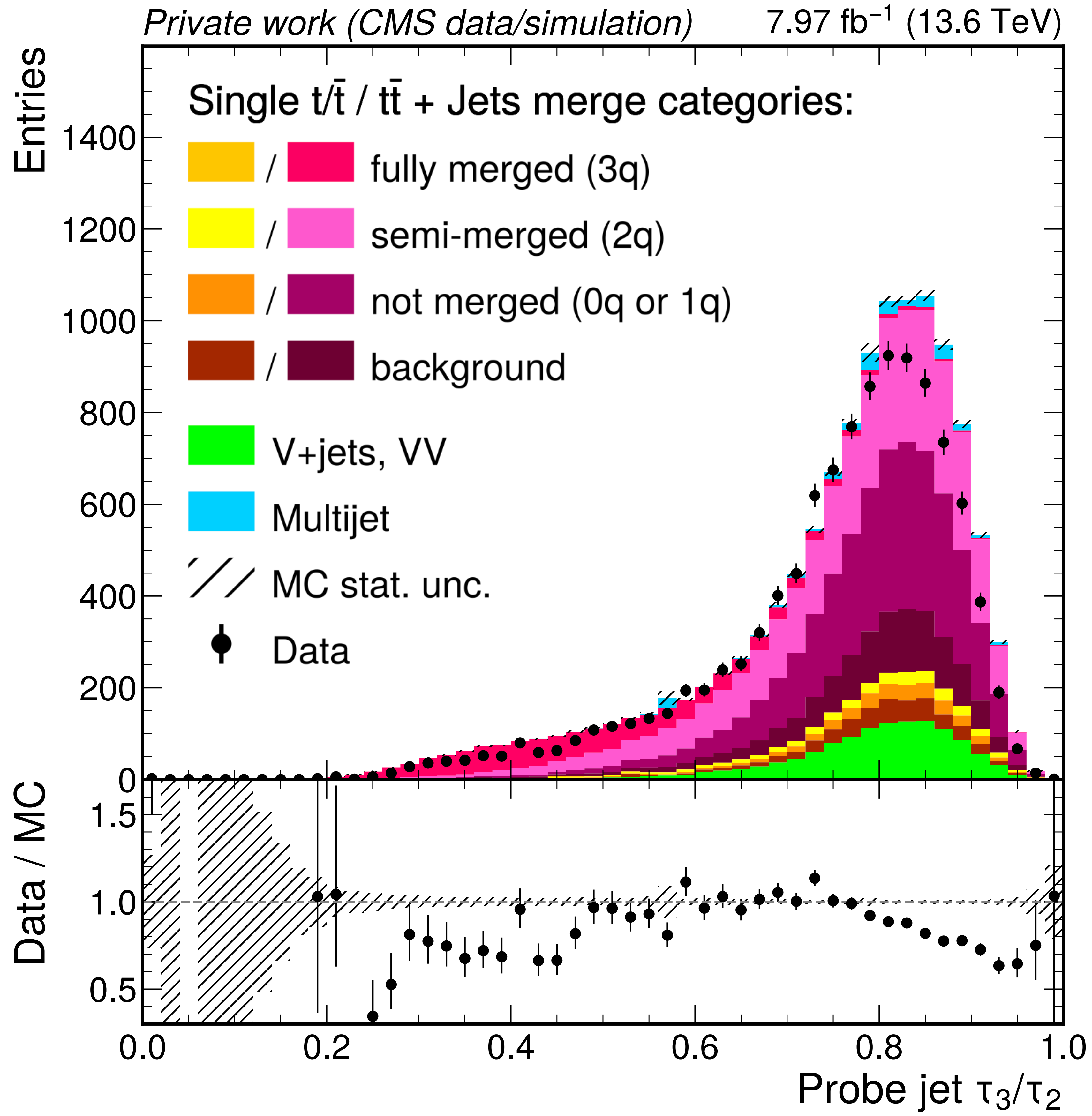
Comput.Softw.Big Sci. 8 (2024) 1, 19 - arXiv:2404.06614

for illustration:



Summary





- identification of boosted objects essential step in many analyses
- **boosted top quarks** as potential window to BSM physics
  here: heavy Z/Higgs bosons, non resonant $t\bar{t}$ production
  - Run 2 search expected to be published very soon
  - Run 3 search setup to look into new data
- understand **cut based top tagging algorithm**
  using jet substructure and soft drop mass
  - derived working points and scale factors

Summary

github.com/columnflow/columnflow

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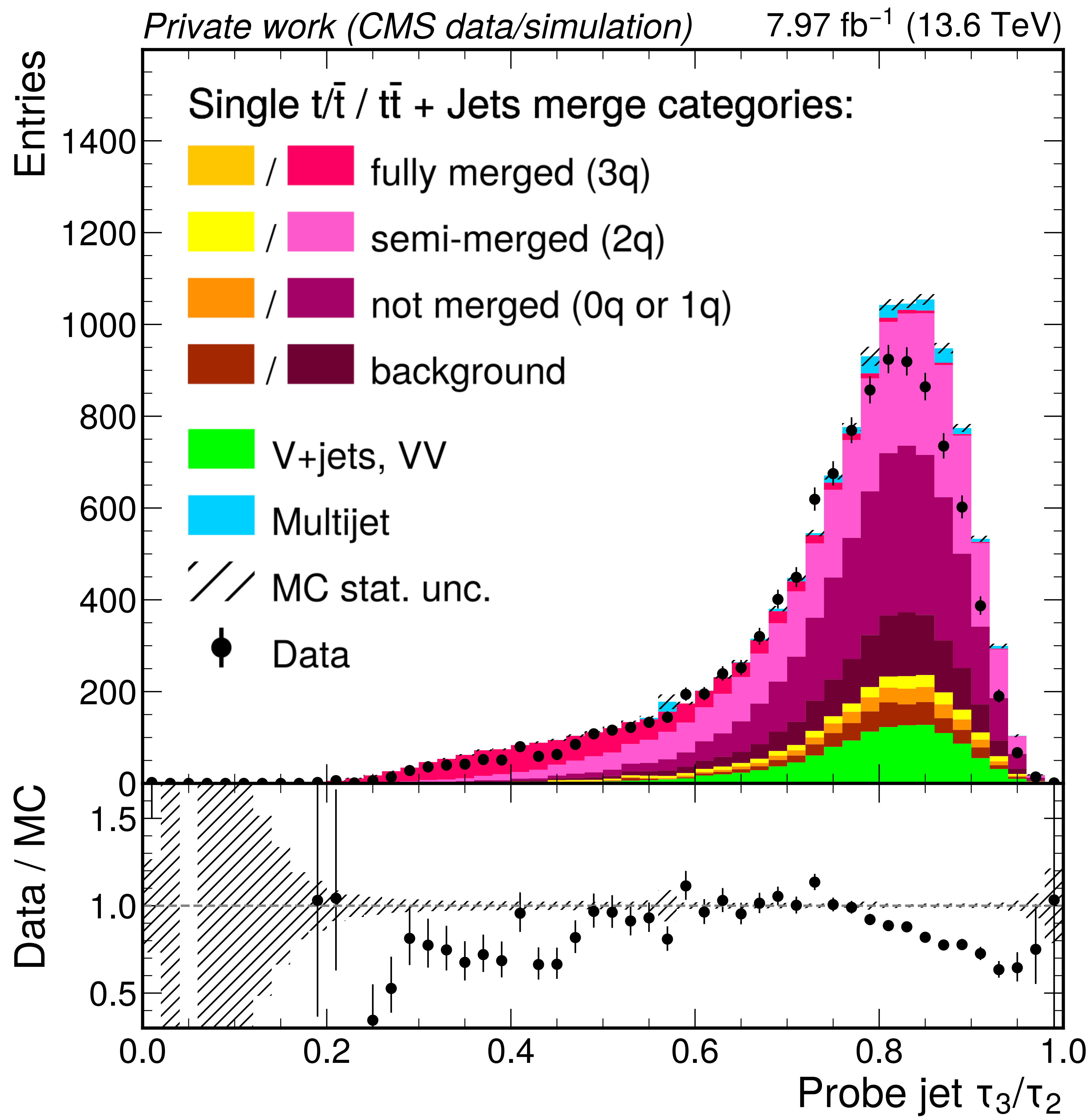


Stay tuned!

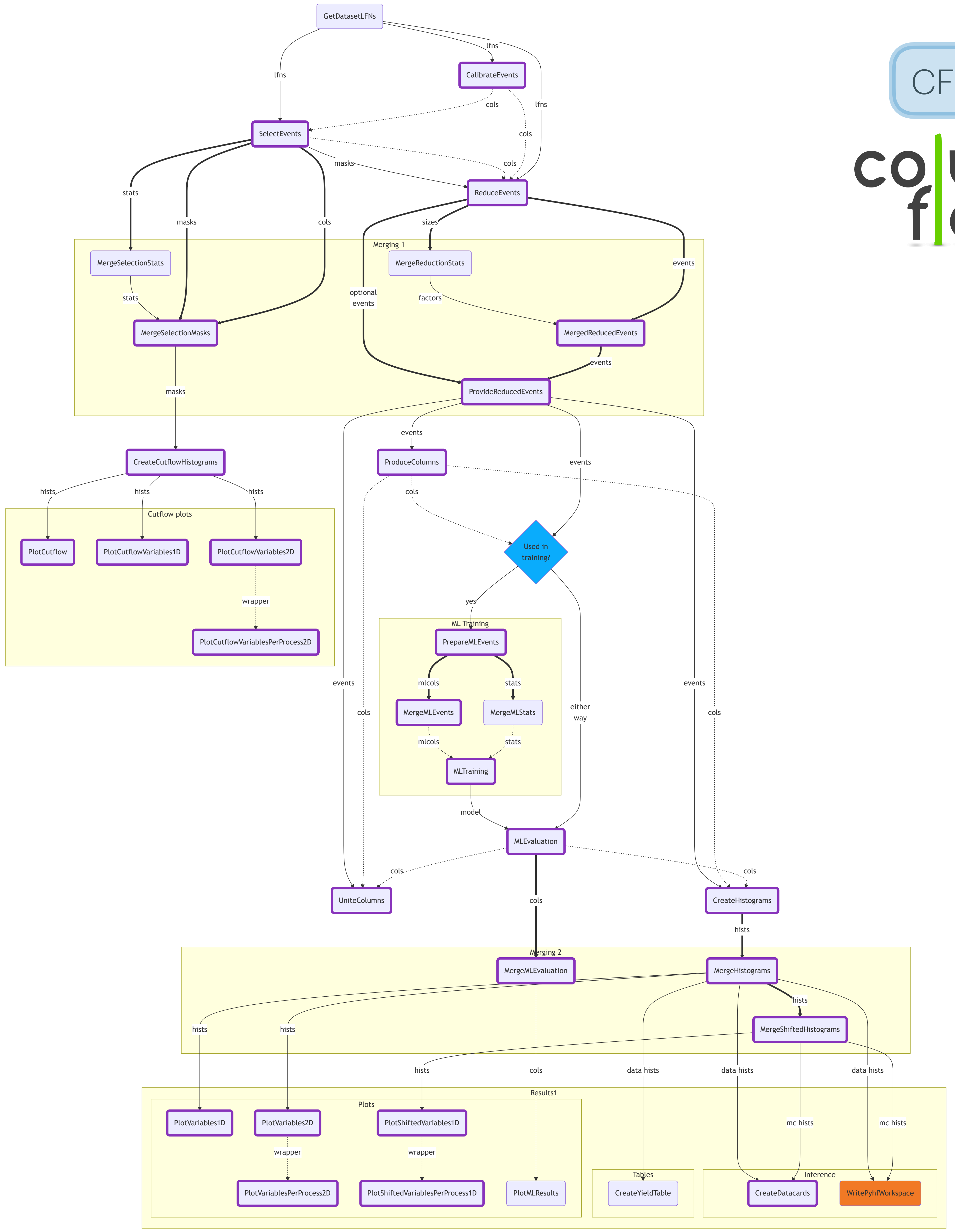
BACKUP

New Framework for Run 3

— columnar-based analysis with columnflow (CF) —

CF repo

- new framework in development in CMS
- advantages:
  - columnar analysis
  - fully orchestrated with intermediate outputs
  - Python-based
- single command triggers complete workflow
  - very quick turnaround time



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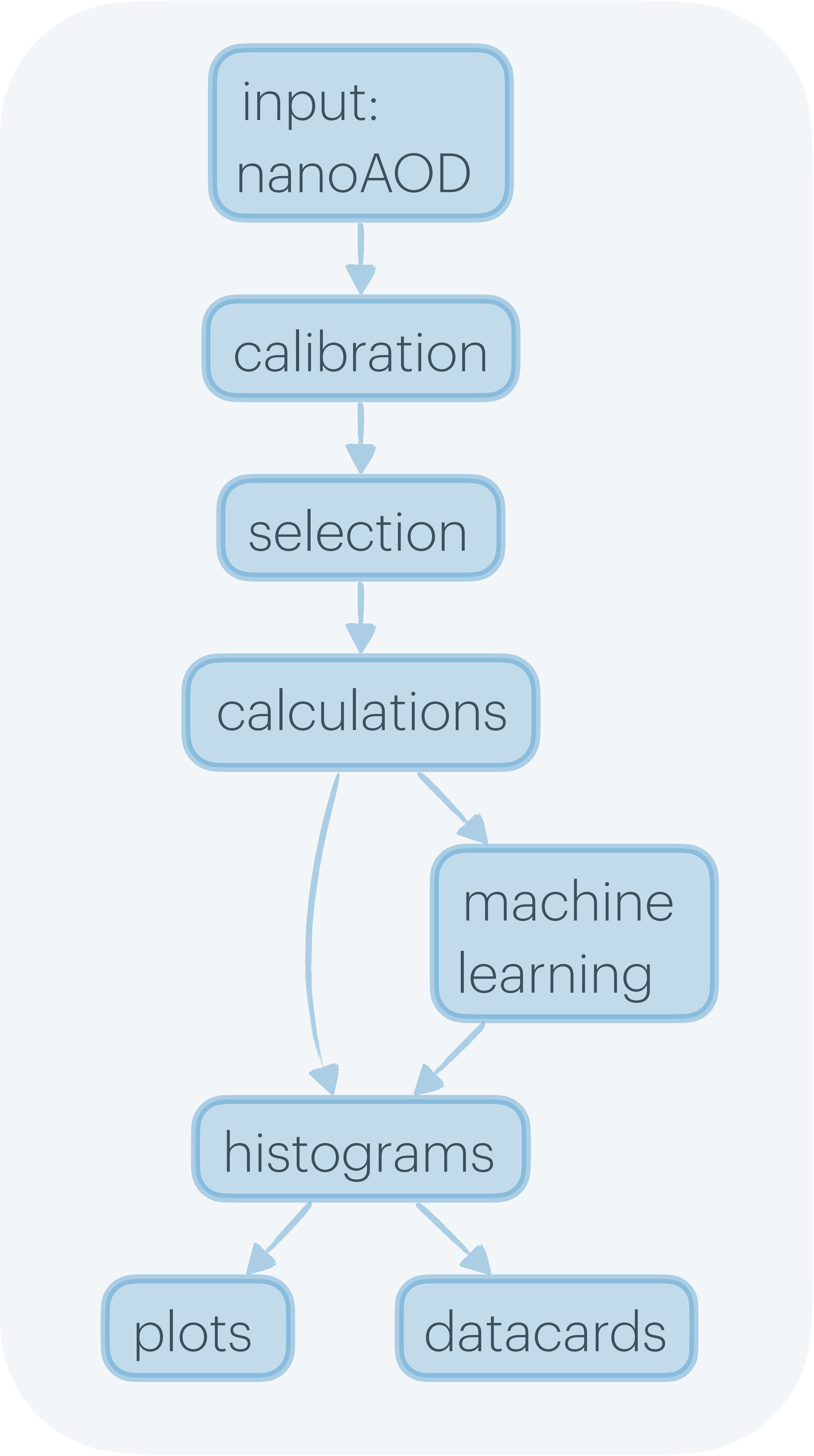


CF repo

column flow

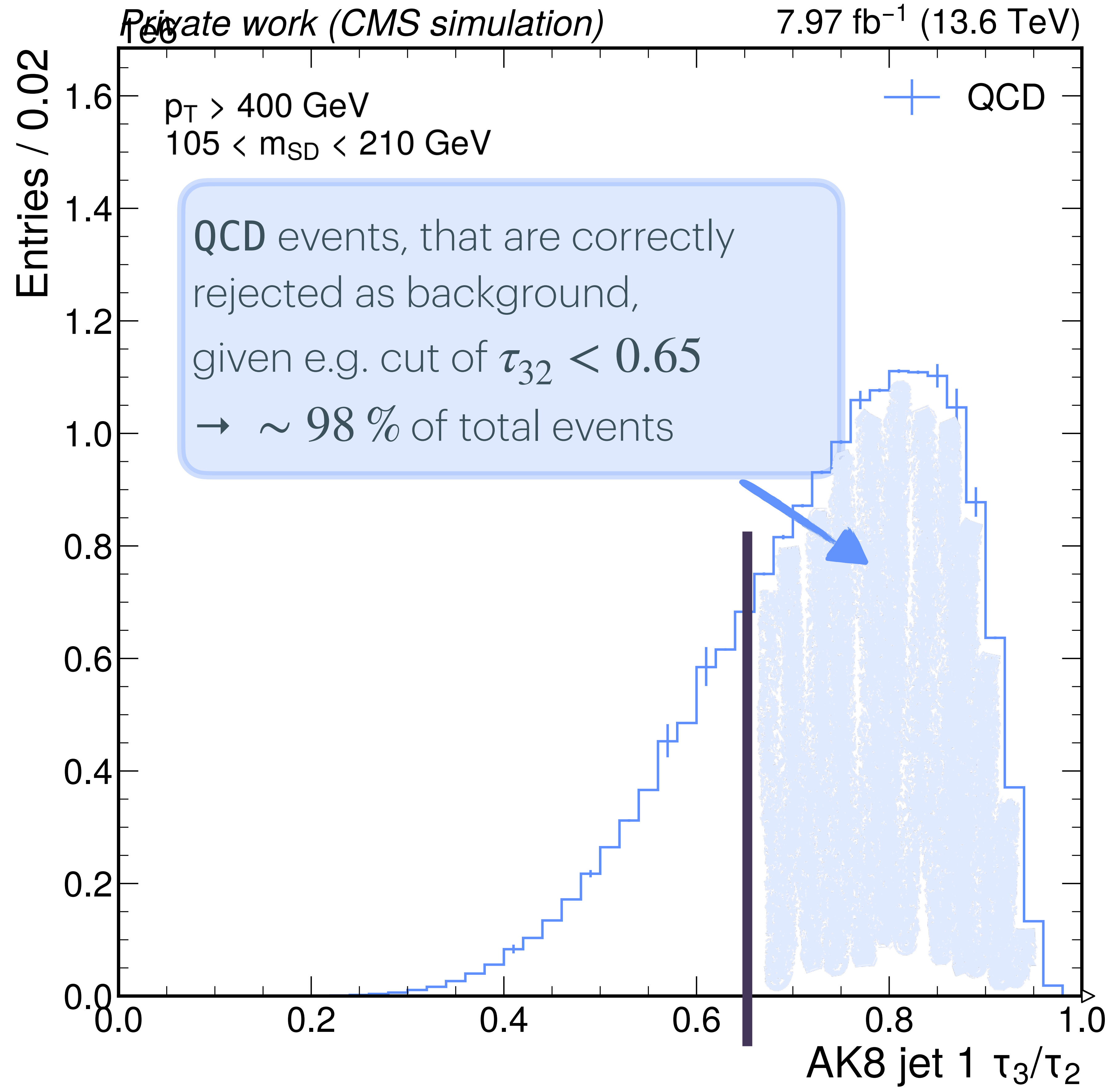
Procedure and Selection

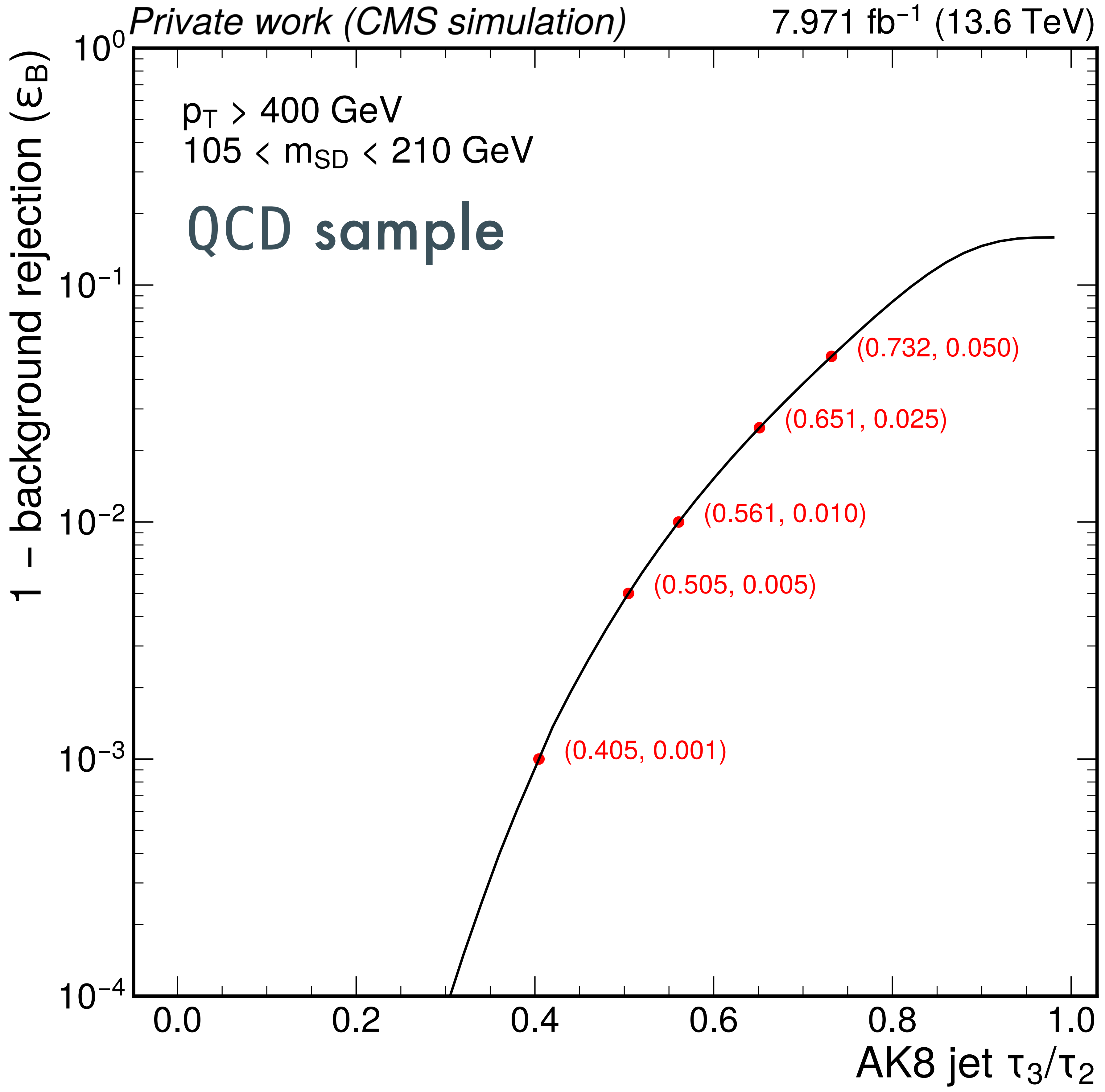
— for WP derivation —

1. Set mis-tag rates defining the WP:
   0.1% → `very tight`
   0.5% → `tight`
   1.0% → `medium`
   2.5% → `loose`
   5.0% → `very loose`
2. Plot mis-tag rate and determine cut values on τ_{32}
3. Plot signal efficiency and determine signal efficiency for these cut values/WP

- select FatJet (AK8 jet) with
  - $|\eta| < 2.4$
  - $p_T > 400$ GeV
    → boosted regime
  - in `ttbar` sample to determine signal efficiency:
    uniquely matched to parton-level top quark
  - additional softdrop mass constraint:
    $105 < m_{SD} < 210$ GeV
    → window around top mass

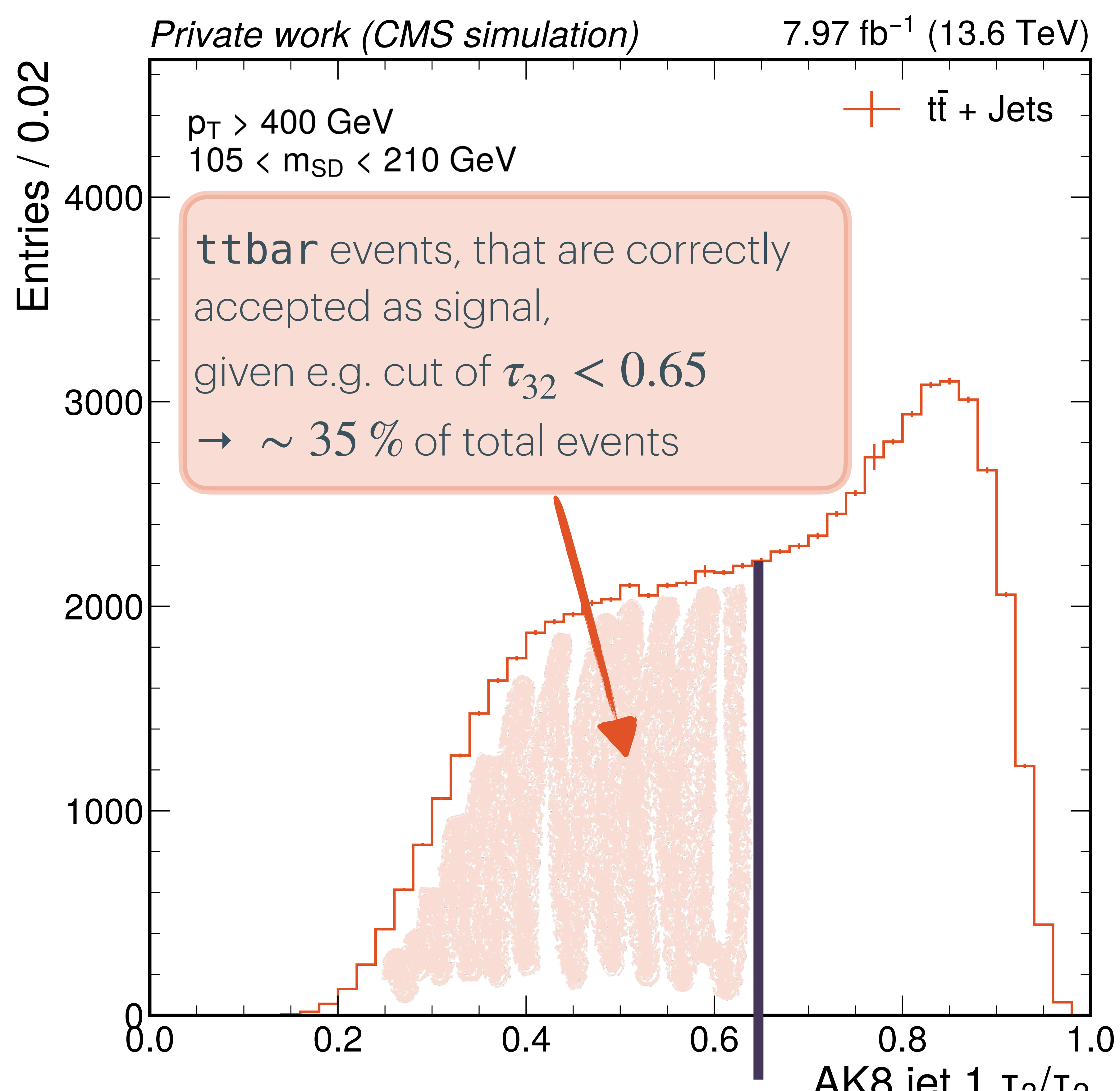
Mis-Tag Rate

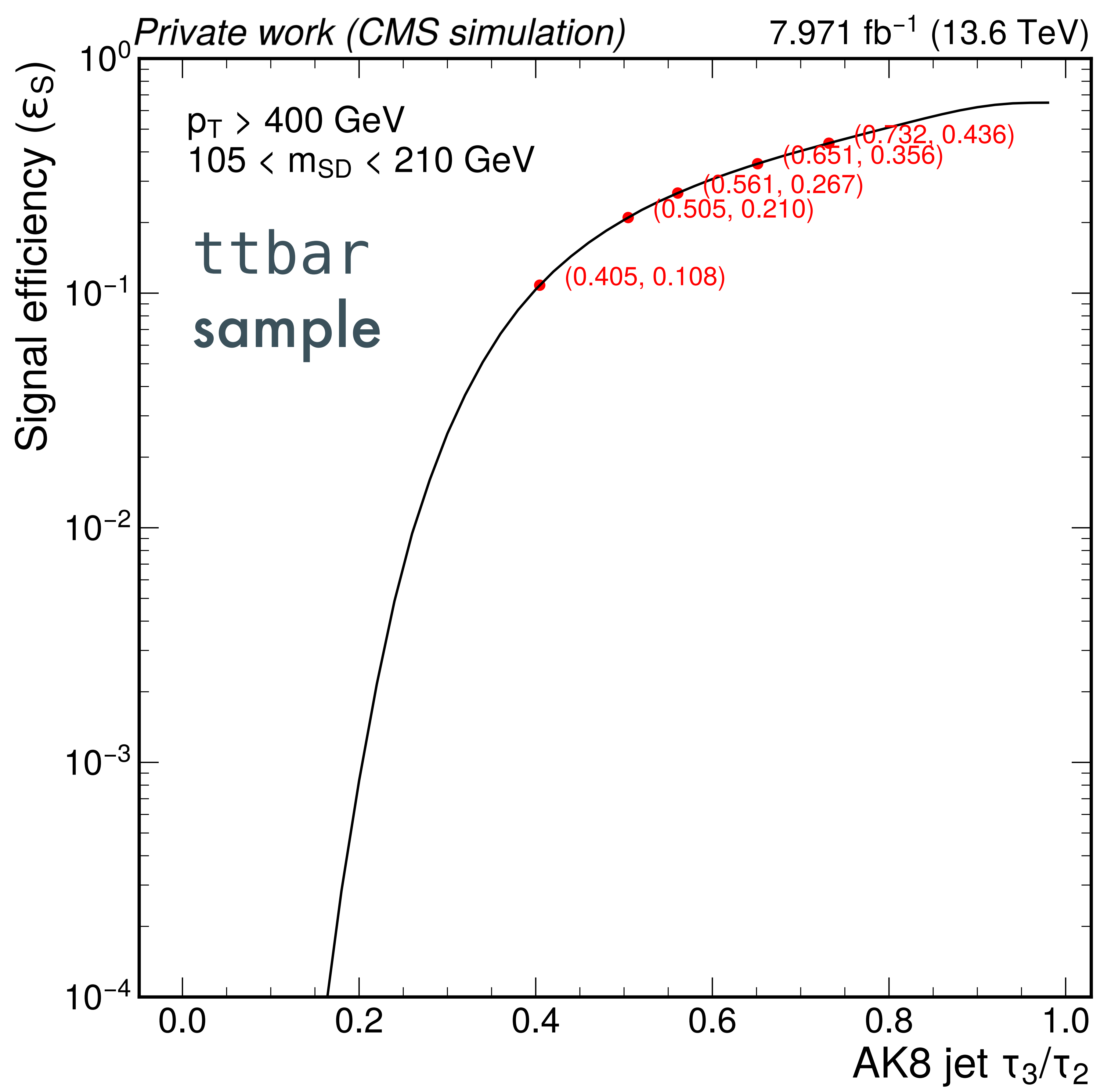




$$\frac{\text{number of QCD events with a FatJet passing selection AND (incorrectly) tagged as a top jet given the } \tau_{32} \text{ cut}}{\text{total number of events in QCD dataset}}$$

Signal Efficiency





$$\frac{\text{number of ttbar events with a FatJet passing selection AND (correctly) tagged as a top jet given the } \tau_{32} \text{ cut}}{\text{total number of events in ttbar dataset}}$$

m_{SD} Of FatJets

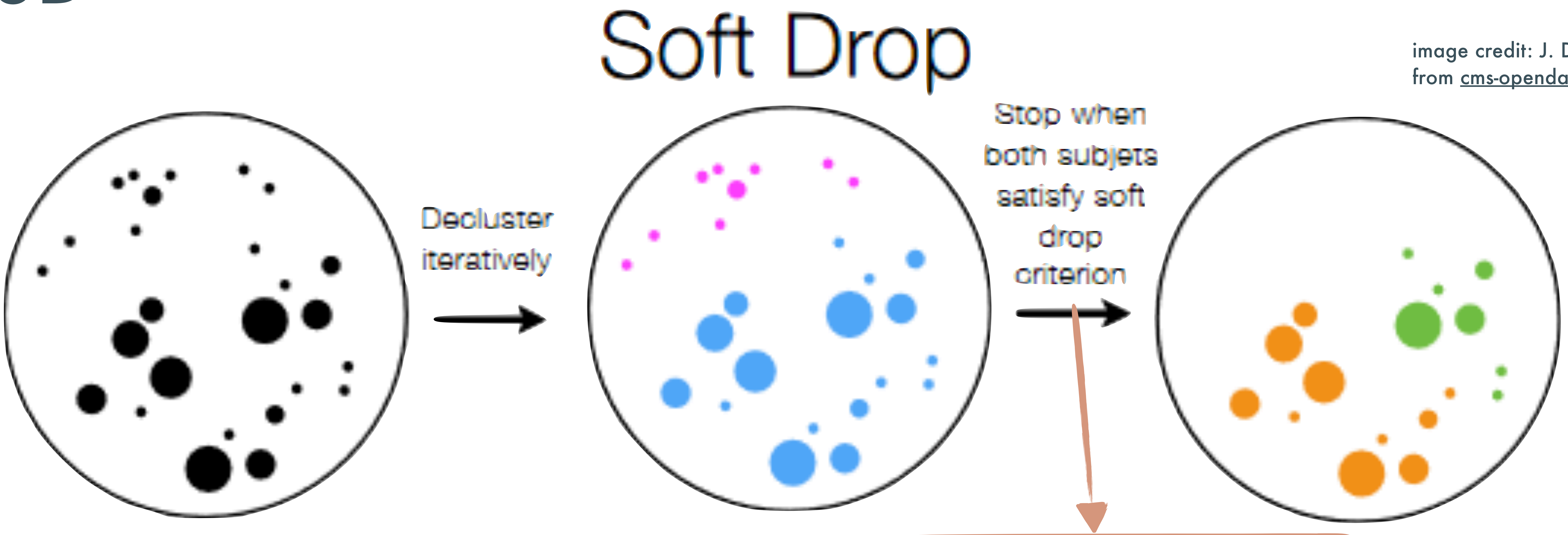
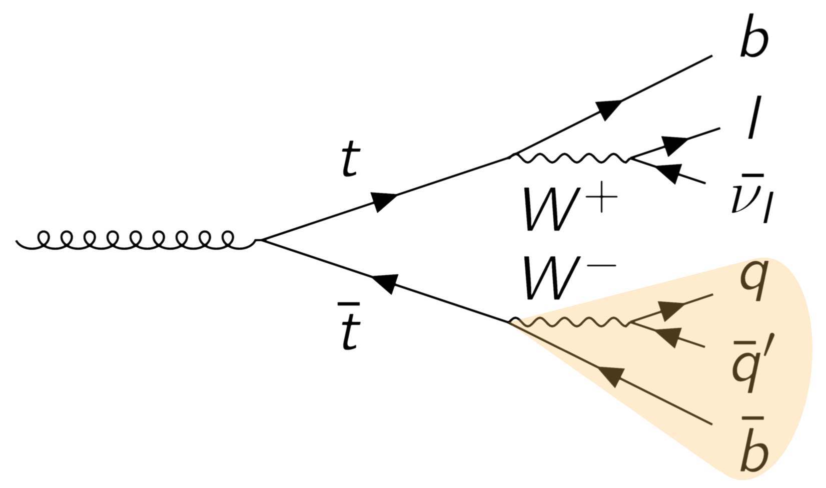


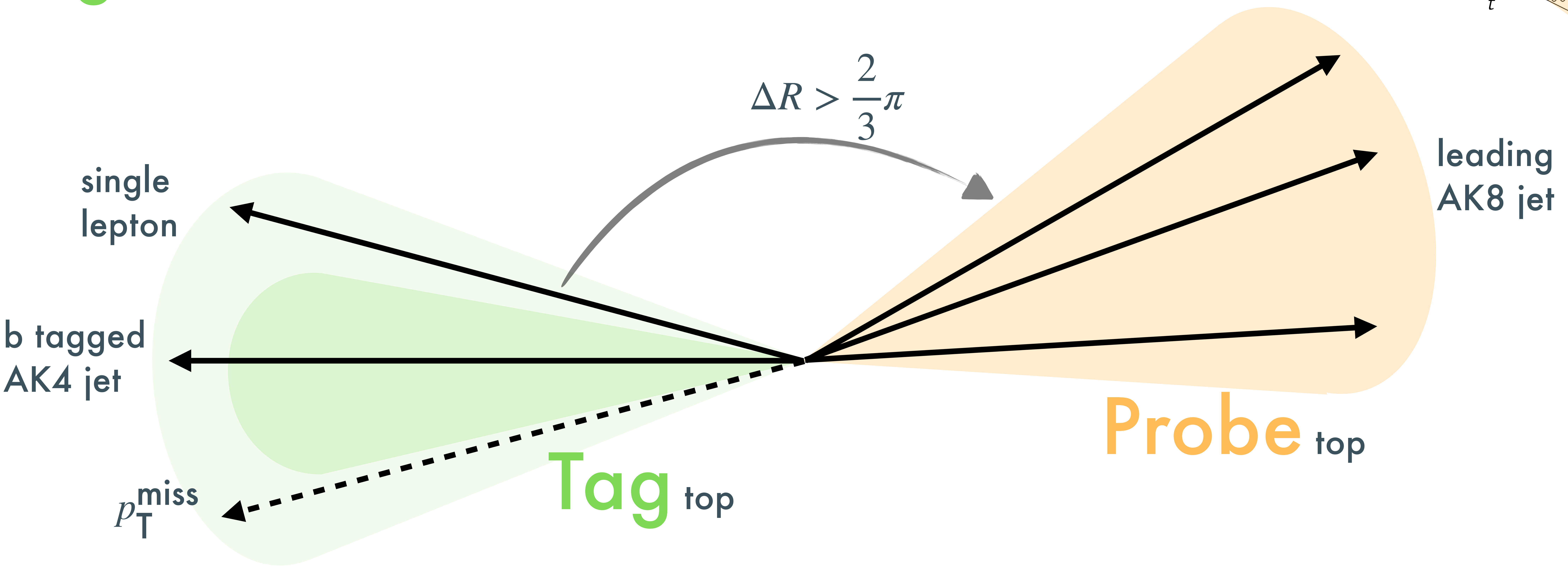
image credit: J. Dolen
from cms-opendata-workshop

$$\frac{\min(p_{T1}, p_{T,2})}{p_{T1} + p_{T2}} > z_{cut} \cdot \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

→ fails for wide-angle soft radiation

Tag and Probe Method With $t\bar{t}$ Pairs





- single lepton
- $p_{T,\,lep} > 55$ GeV

- b-tagged AK4 jet close to lepton
- $p_{T,\,AK4} > 15$ GeV

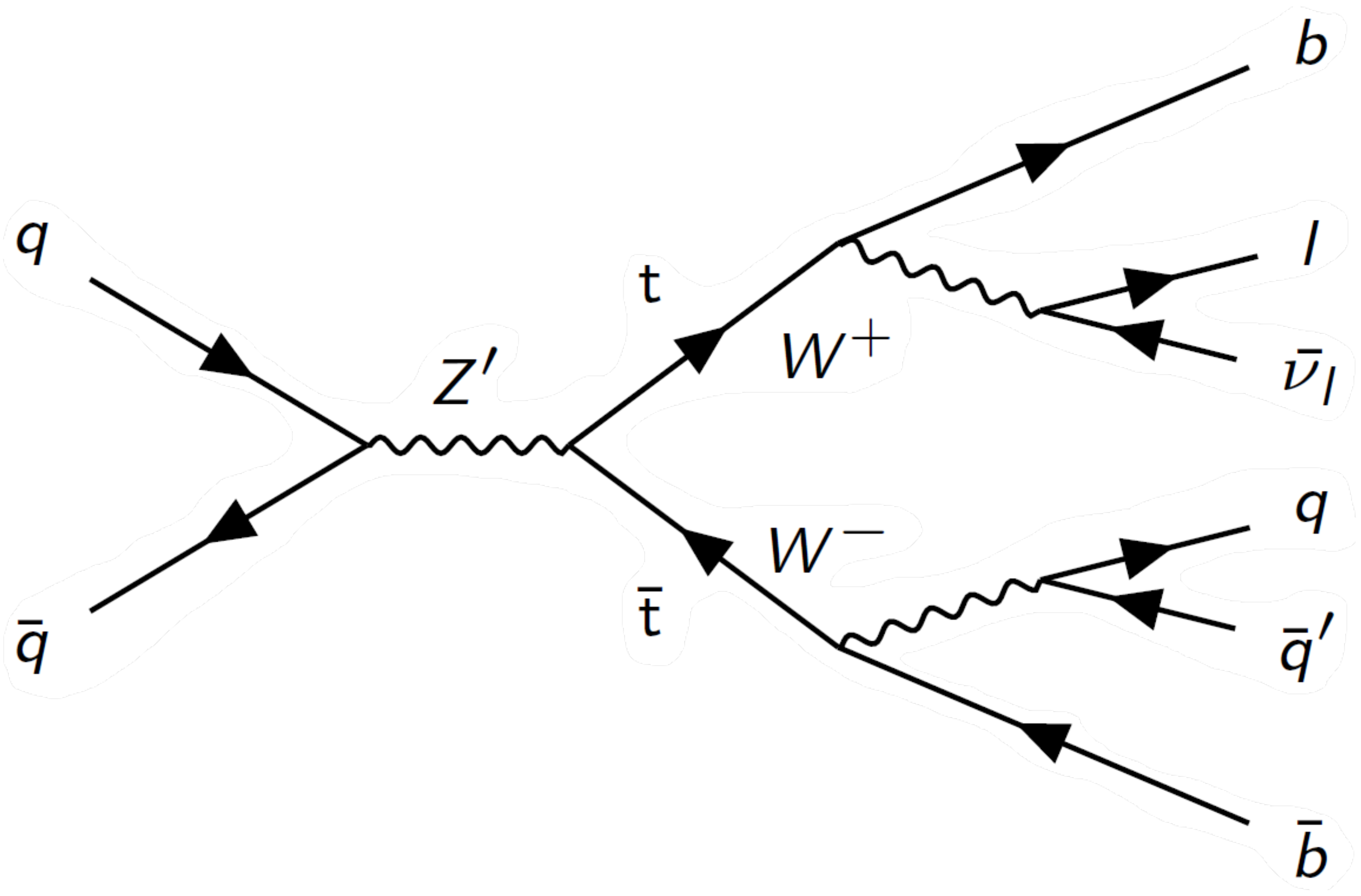
- $p_T^{miss} > 50$ GeV
- $p_T(W_{lep}) > 150$ GeV

- $p_{T,\,AK8} > 300$ GeV
- jet-lepton 2D isolation

Baseline Selection

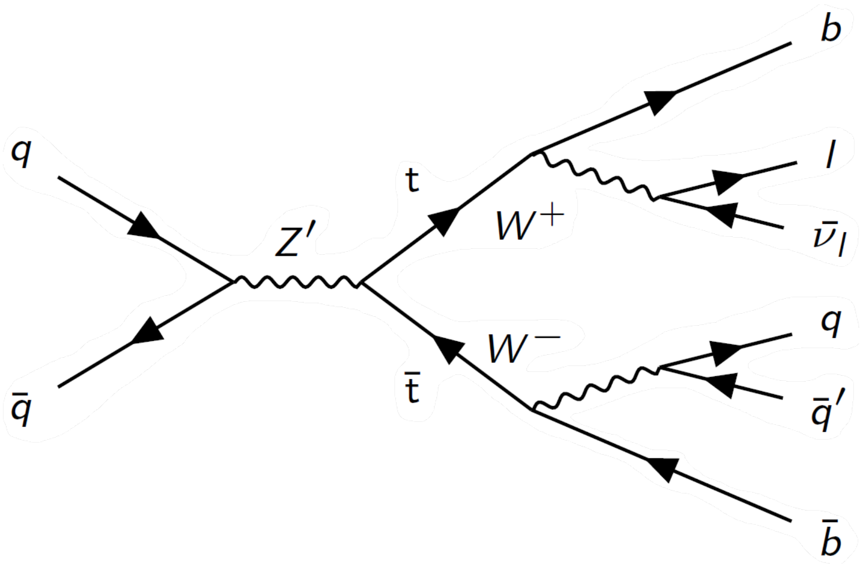
— in numbers —

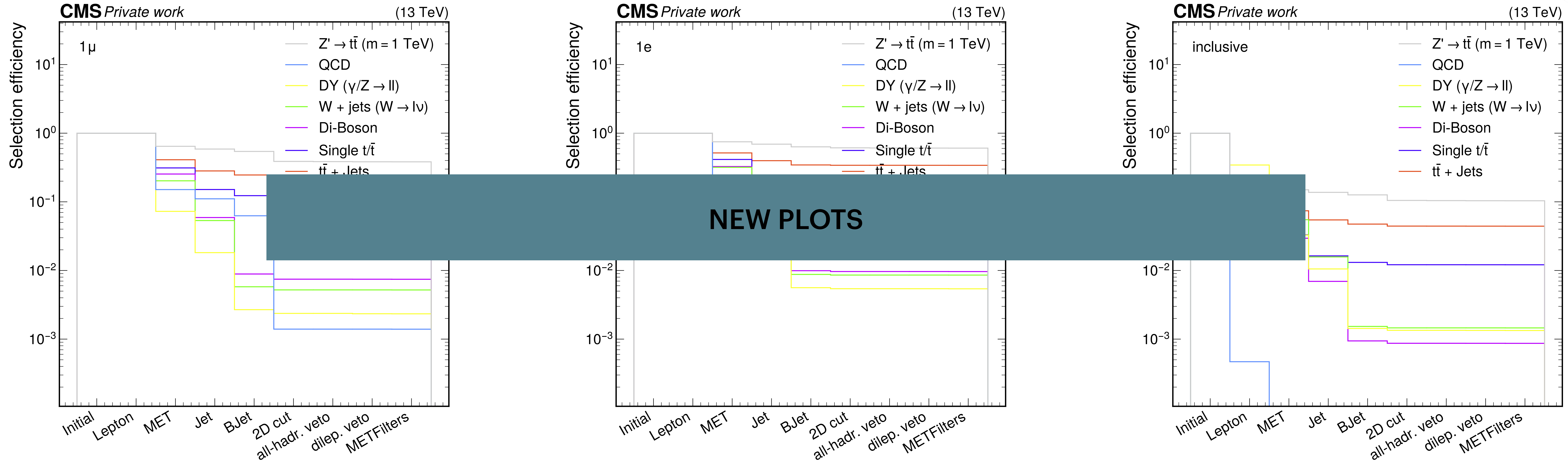
muon/electron channel



- lepton selection:
  - single muon/electron trigger
  - low p_T: $30/35 < p_T < 55/120$ GeV and isolation
  - high p_T: $p_T > 55/120$ GeV and 2D isolation
  - $|\eta^{\mu/e}| < 2.4$
- $p_T^{miss} > 70/60$ GeV
- at least two jets with $|\eta| < 2.5$ and:
  - $p_T^{jet1} > 50/50$ GeV
  - $p_T^{jet2} > 50/40$ GeV
  - at least one b-tagged jet

Selection Efficiencies





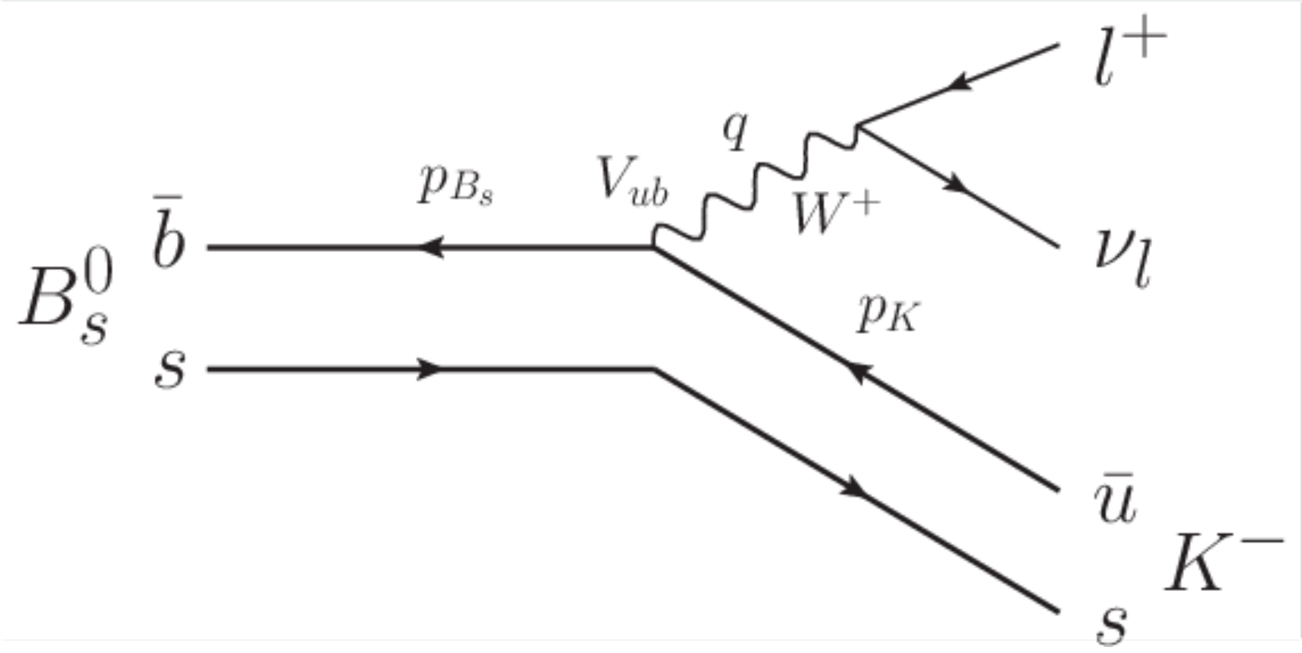
muon channel

electron channel

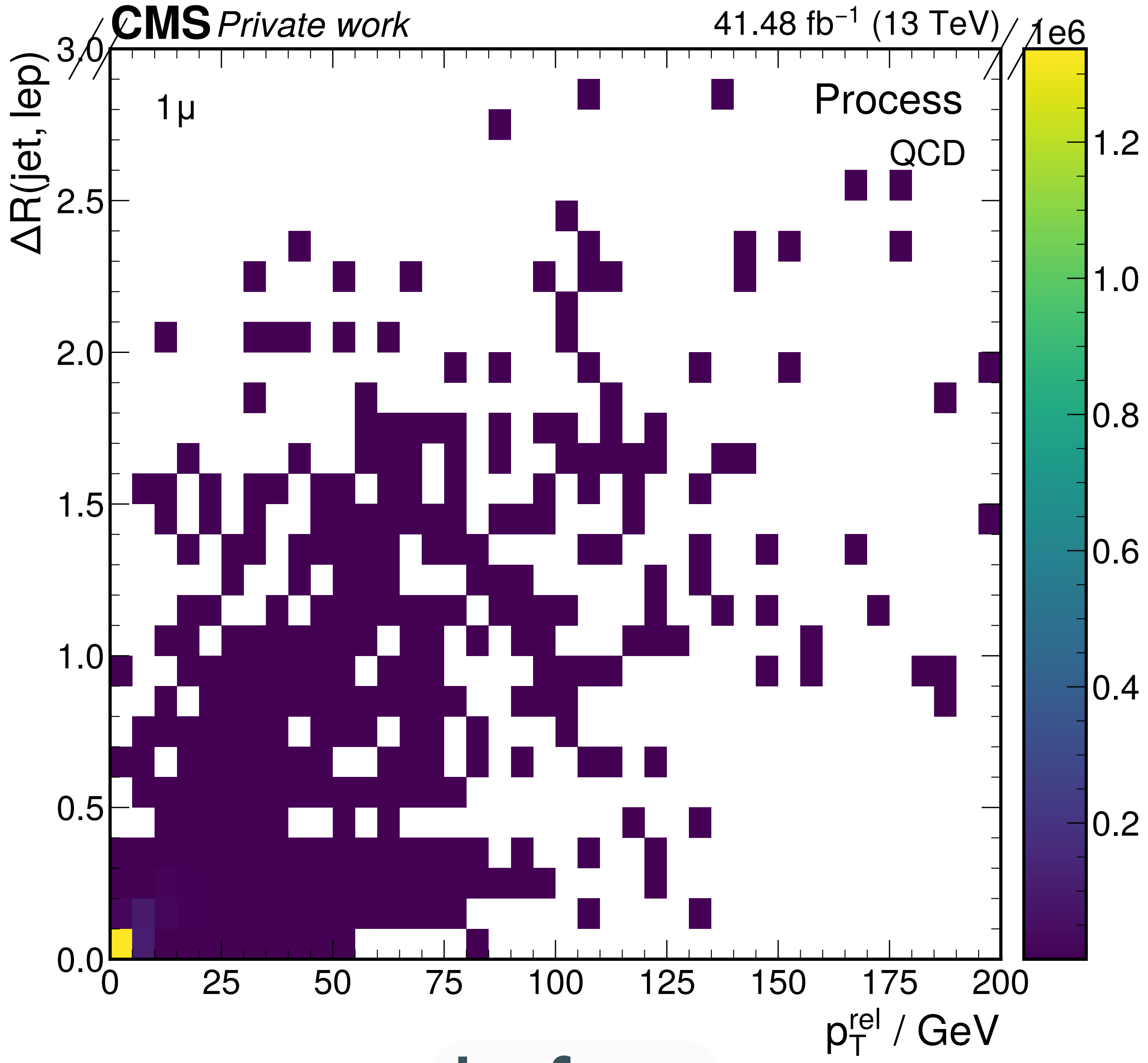
inclusive channel

Jet-Lepton 2D Cut

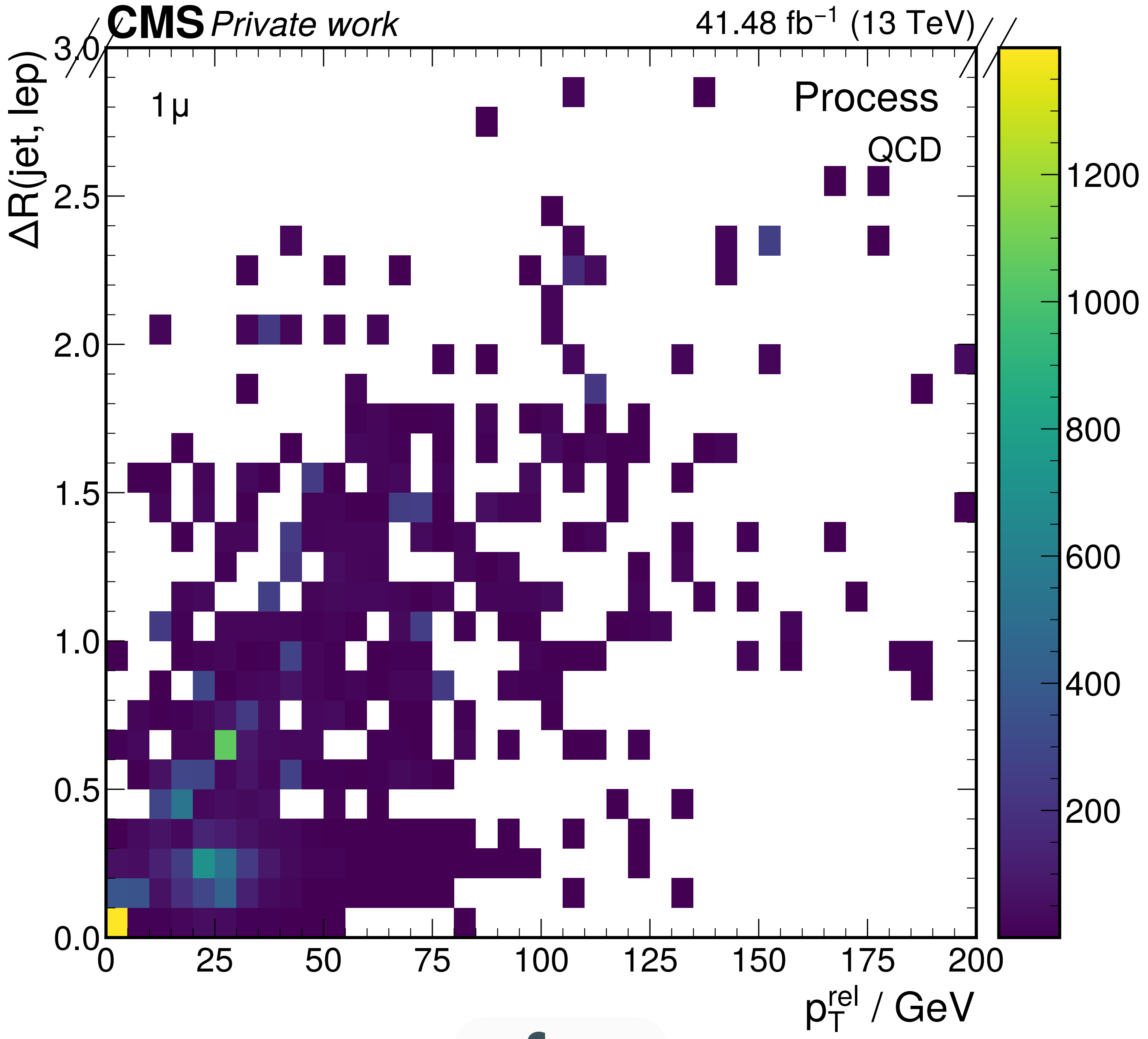
— filtering leptonic B meson decays —



$$\Delta R_{\text{min}}(\text{lep, jet}) > 0.4 \text{ or } p_{\text{T, lep}}(\text{lep, jet}) > 25 \text{ GeV}$$



before



after

- note different color scale!
- 2D cut only in high p_T regime of lepton
  - contribution of low p_T contributions in first bin
- reduces QCD background

Merge Category Algorithm

— process_ids producer—

Process	Decay mode	# of merged quarks	Subprocess
tt	semi-leptonic	3	tt_3q
		2	tt_2q
		1 or 0	tt_1o0q
	dileptonic or fully hadronic	any	tt_bkg
st	hadronic	3	st_3q
		2	st_2q
		1 or 0	st_1o0q

Process	Top decay	Assoc. W decay	# of merged quarks	Subprocess
st_tW	leptonic	hadronic	3	st_bkg*
			2	st_2q
			1 or 0	st_1o0q
st_tW	leptonic	leptonic	any	st_bkg
st_other	leptonic	--	any	st_bkg

process ID set per event from gen level info:

1. Check if st or tt.
2. Check if bkg:
   no probejet
   OR top decay merged into probejet not hadronic
   OR associated b quark and both associated W decay products merge into probejet
3. Check if 3q or 2q:
   not bkg
   AND exactly 3/2 quarks merged into probejet
4. Check if 0o1q:
   not bkg
   AND 0 or 1 quarks are merged into probejet

Combine Physics Model

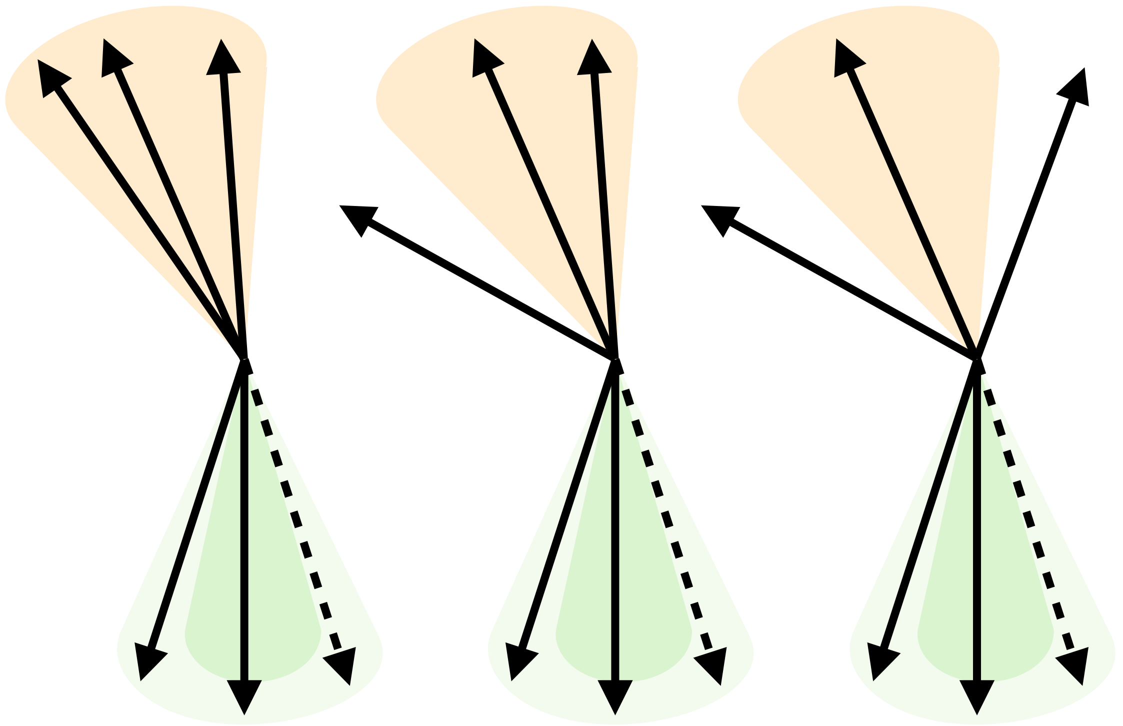
- with seesaw condition, keeping N_{total} constant
- SF_{pass} as parameter-of-interest, determining SF_{fail}

- one fit per combination of year/era and WP
  - simultaneous fit for merge categories and p_T bins of probe jet:

Seesaw Condition

$$N_{\text{total}} = N_{\text{pass}} + N_{\text{fail}} = \text{const}$$

$$SF_{\text{fail}} = (1 - SF_{\text{pass}}) \cdot \frac{N_{\text{pass}}^{\text{prefit}}}{N_{\text{fail}}^{\text{prefit}}} + 1$$



$$\left.\begin{array}{l}\texttt{SF\_\_3q/2q/0o1q\_\_22\_\_pt\_300\_400}\\ \texttt{SF\_\_3q/2q/0o1q\_\_22\_\_pt\_400\_480}\\ \texttt{SF\_\_3q/2q/0o1q\_\_22\_\_pt\_480\_600}\\ \texttt{SF\_\_3q/2q/0o1q\_\_22\_\_pt\_600\_inf}\end{array}\right\} \rightarrow \text{12 scale factors}$$

Main Uncertainities

— in Run 2 —

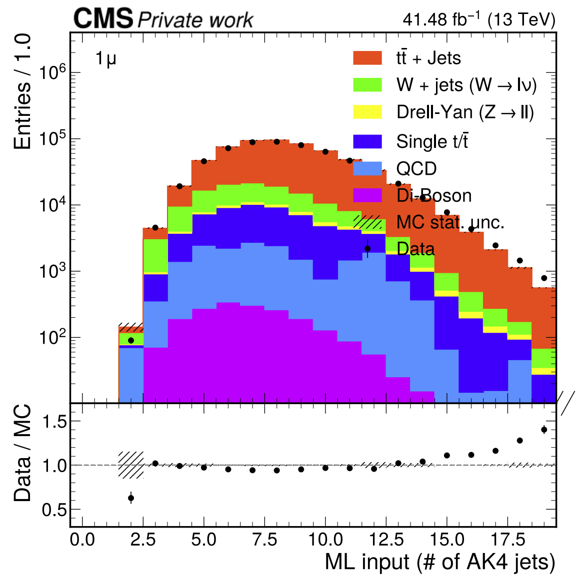
- checked Run 2 impacts ([JMAR Meeting 06.06.23]) and wrote down five highest for each SF in each pT bin:
  - `FSR q2qgMuR/g2ggMuR/x2xgMuR` — available in Nano as `PSWeight`, not split (single NP)
  - `xsec tt/st/mj/vx` — already used in v8 fit
  - `scale tt/st` — available in Nano as `LHEScaleWeight`
  - `toppt B` — available
  - `JES` — all unc. sources available from central json
  - `PU` — available (`minbias_xs`)
  - `btagging` — to be investigated

Impacts

— Text —

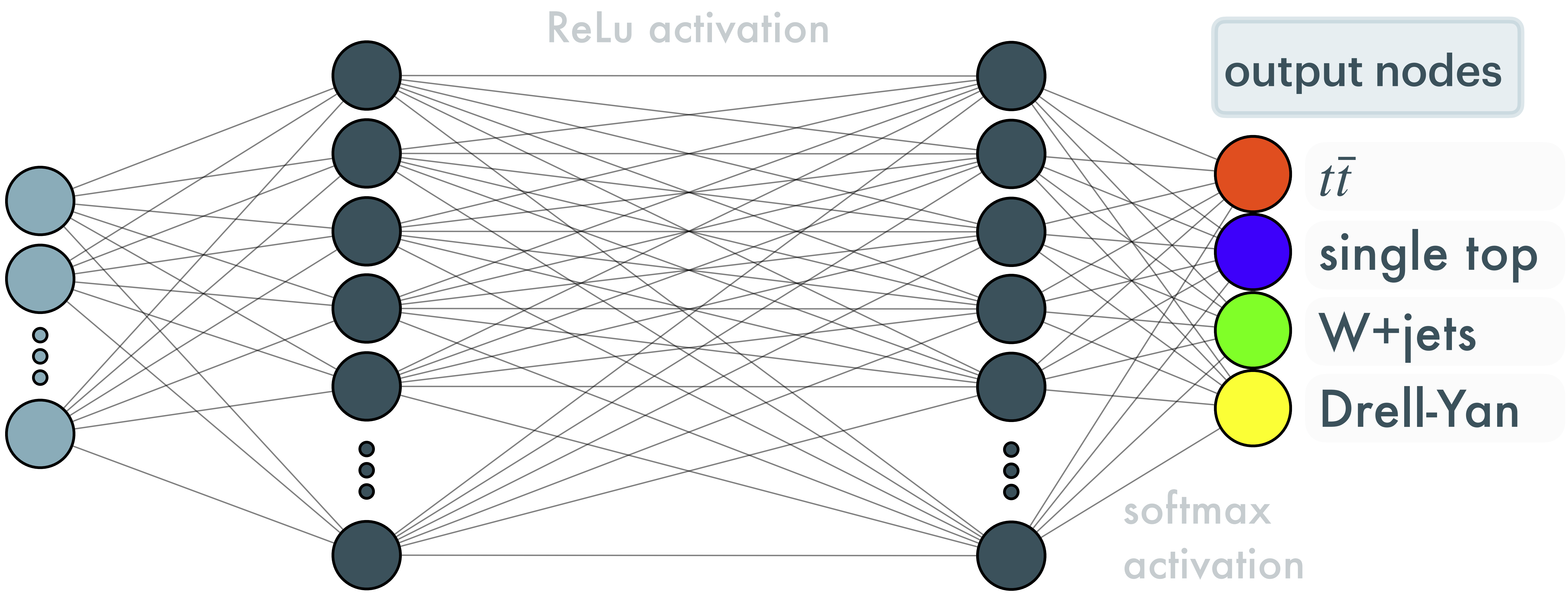
DNN for Event Classification

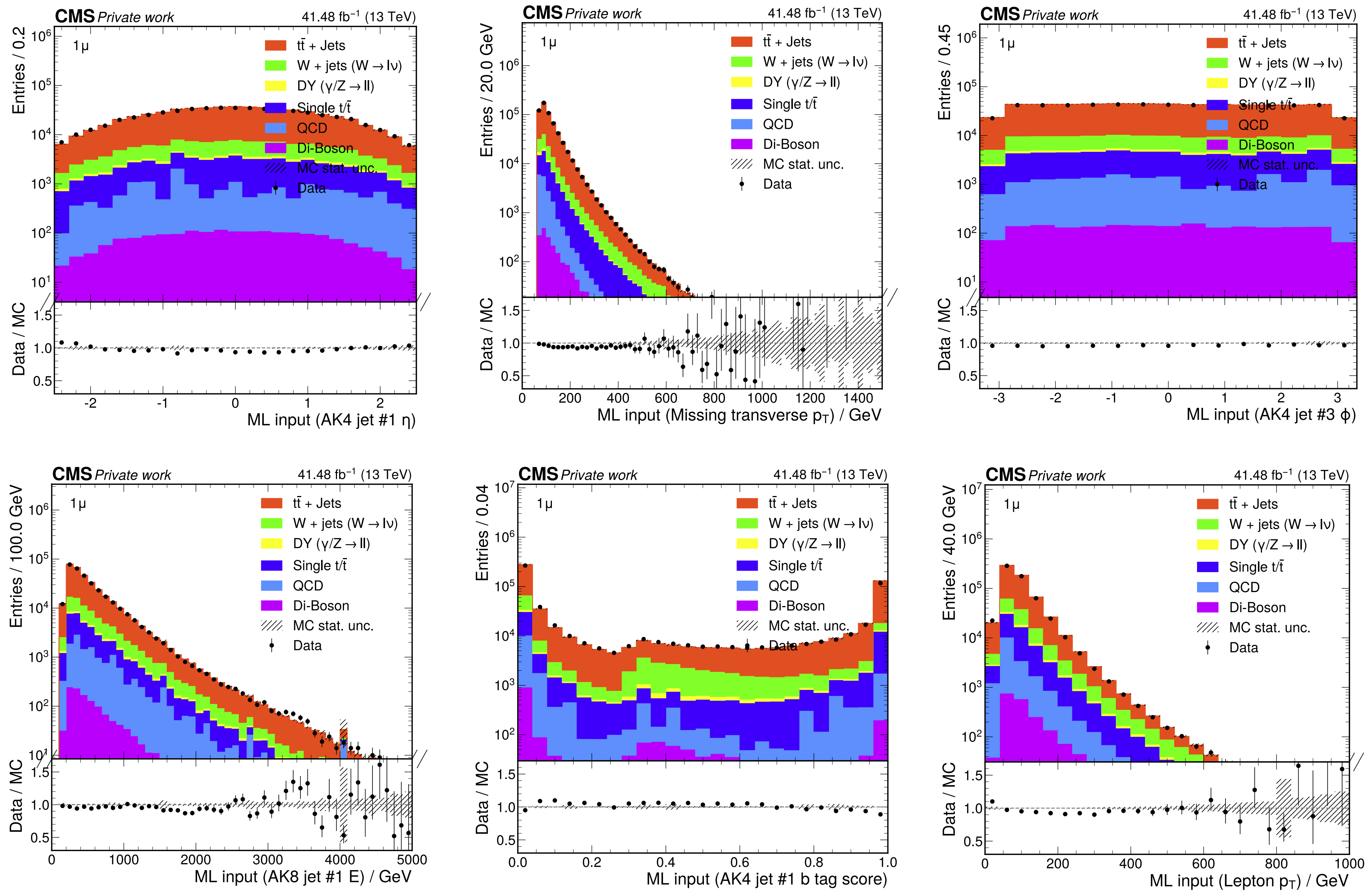
— network architecture —



59 input features:

- jet multiplicities
- kinematic properties of objects (MET, jets, lepton)





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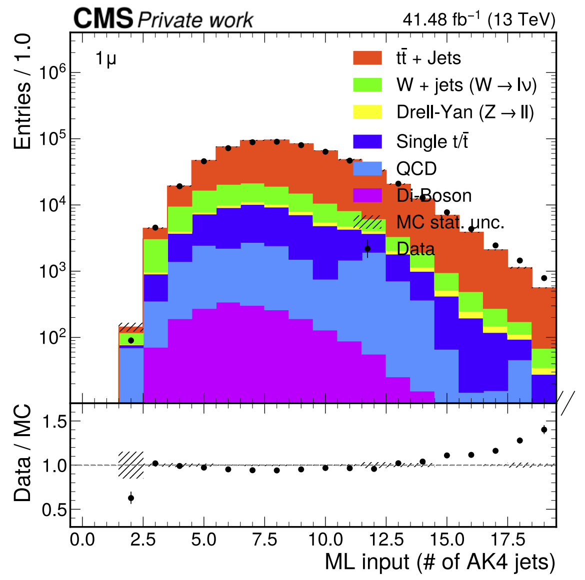

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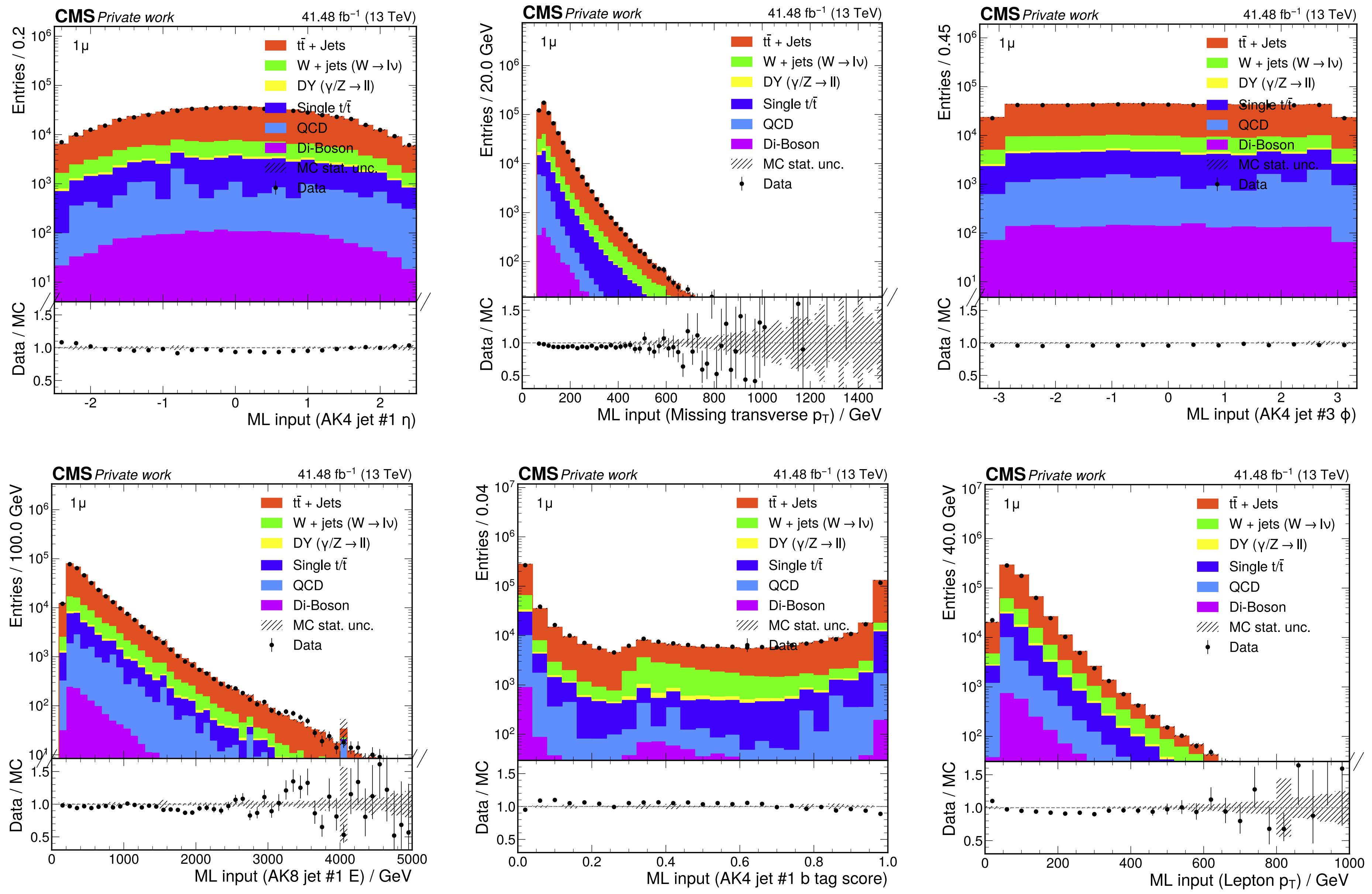

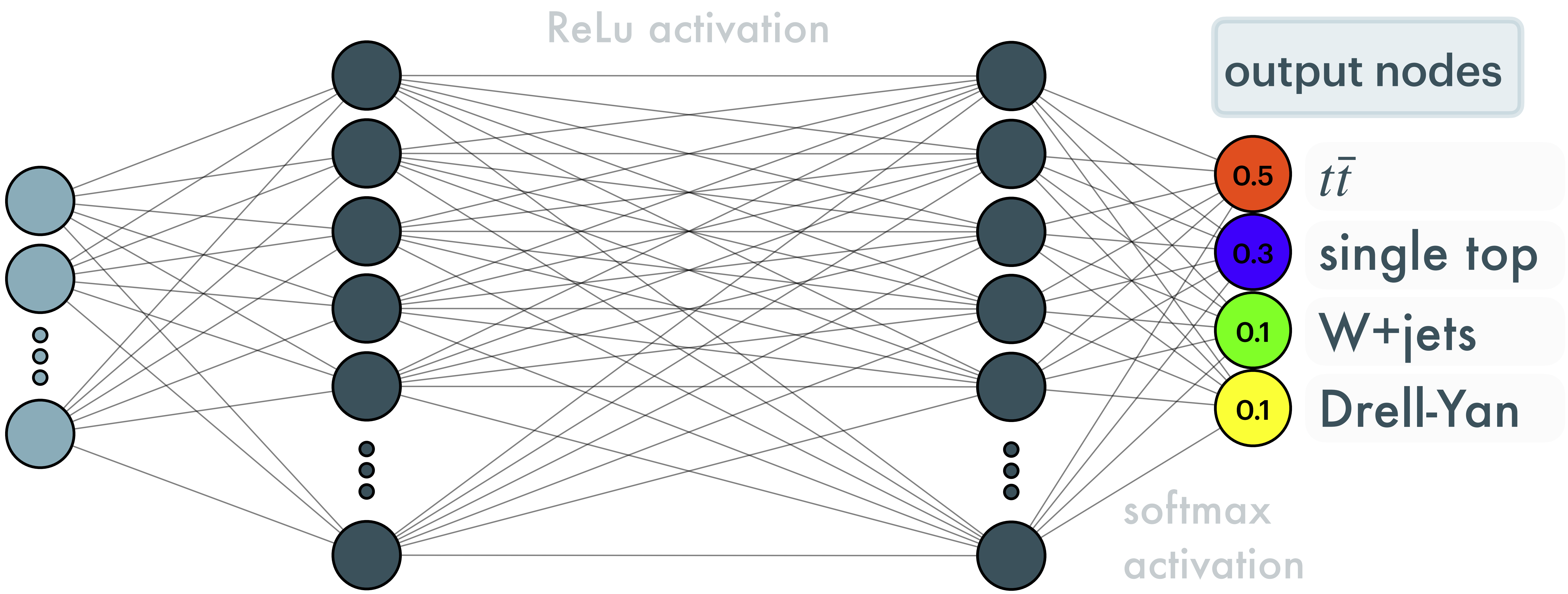

DNN Parameter

59 input features

jet multiplicity	5 AK4 jets	3 AK8 jets	lepton	MET
N_{AK4}	E	E	E	p_{T}
N_{AK8}	p_{T}	p_{T}	p_{T}	ϕ
	η	η	η	
	ϕ	ϕ	ϕ	
	mass	softdrop mass		
	b-tag score	τ_{21}		
		τ_{32}		

model hyperparameters

- AdamOptimizer
- ReLu activation for hidden layers
- softmax activation for output layers
- batchsize = 32768
- drop out rate = 0.5
- epochs $\leq$ 500
- folds = 5
- learning rate = 0.0005
- validation fraction = 0.25