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] —

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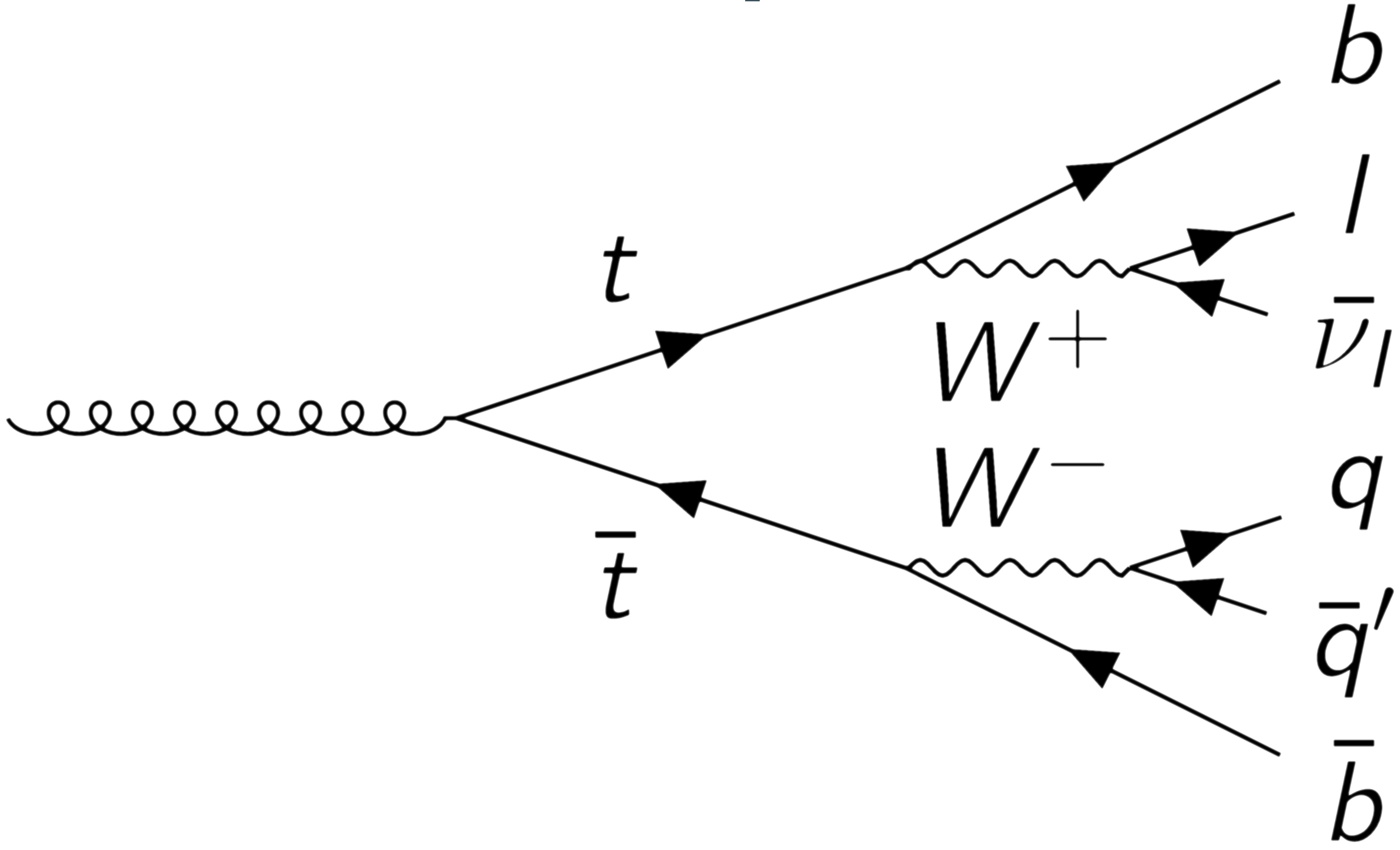
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

FSP CMS
Erforschung von
Universum und Materie

Boosted Top Quarks



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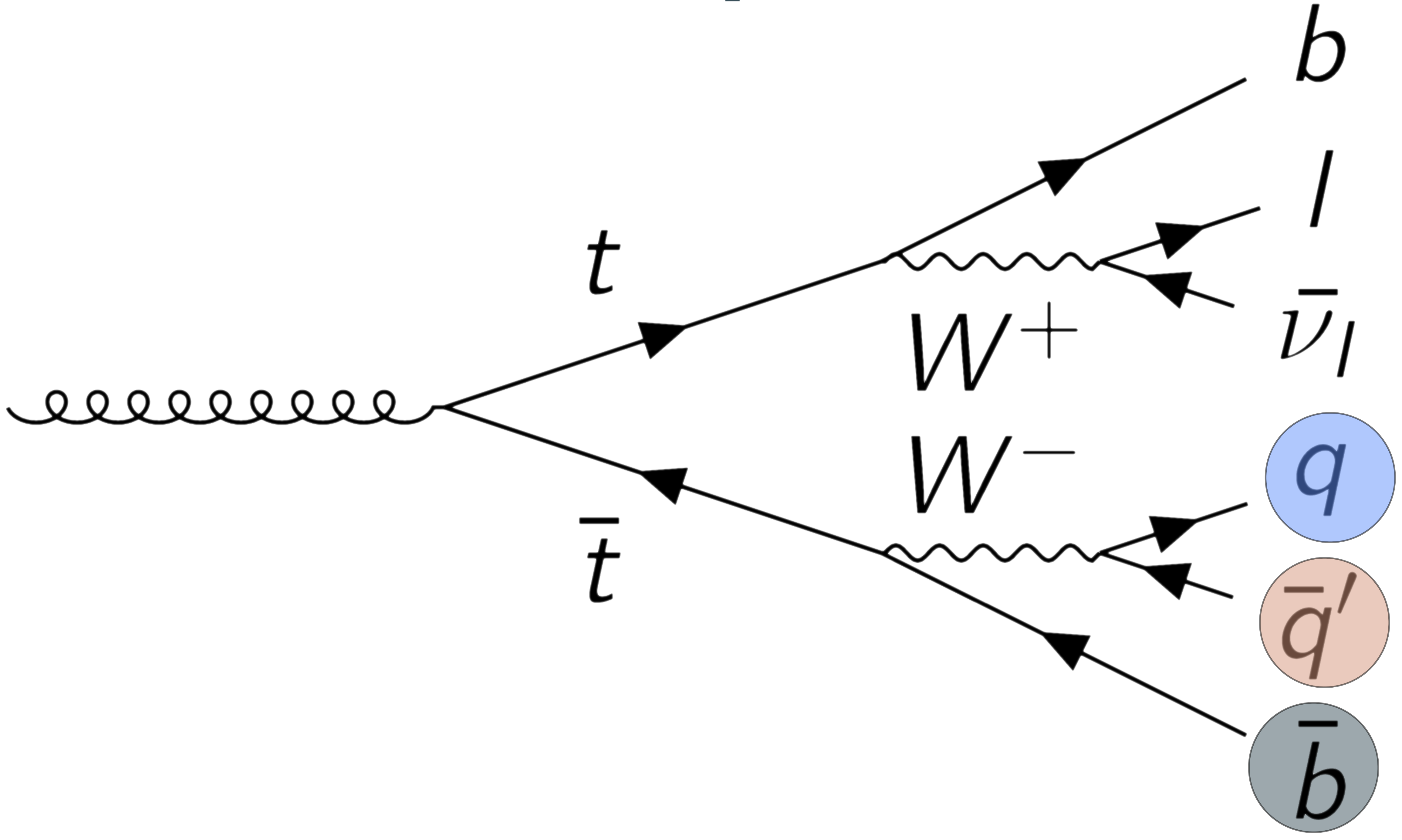

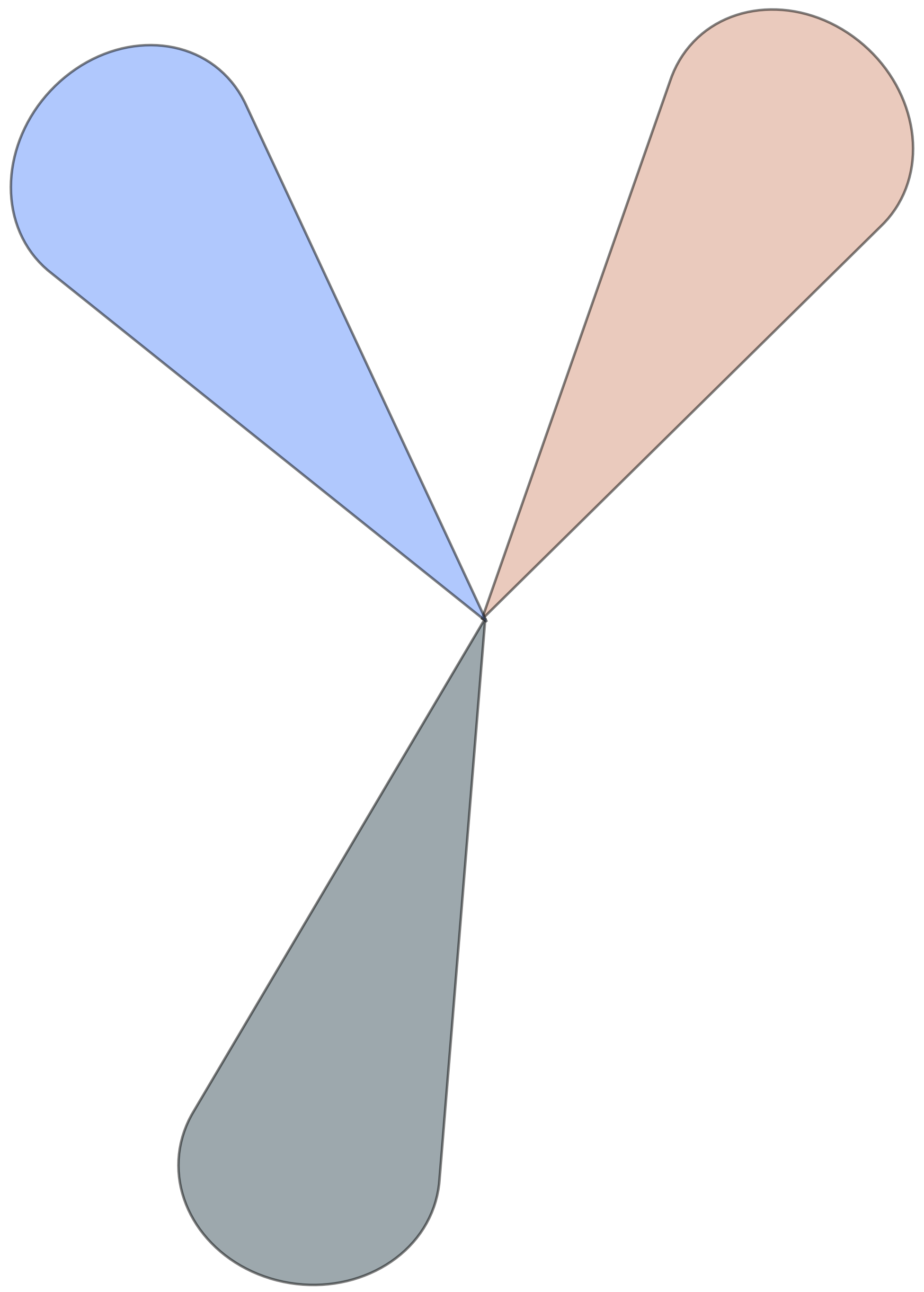

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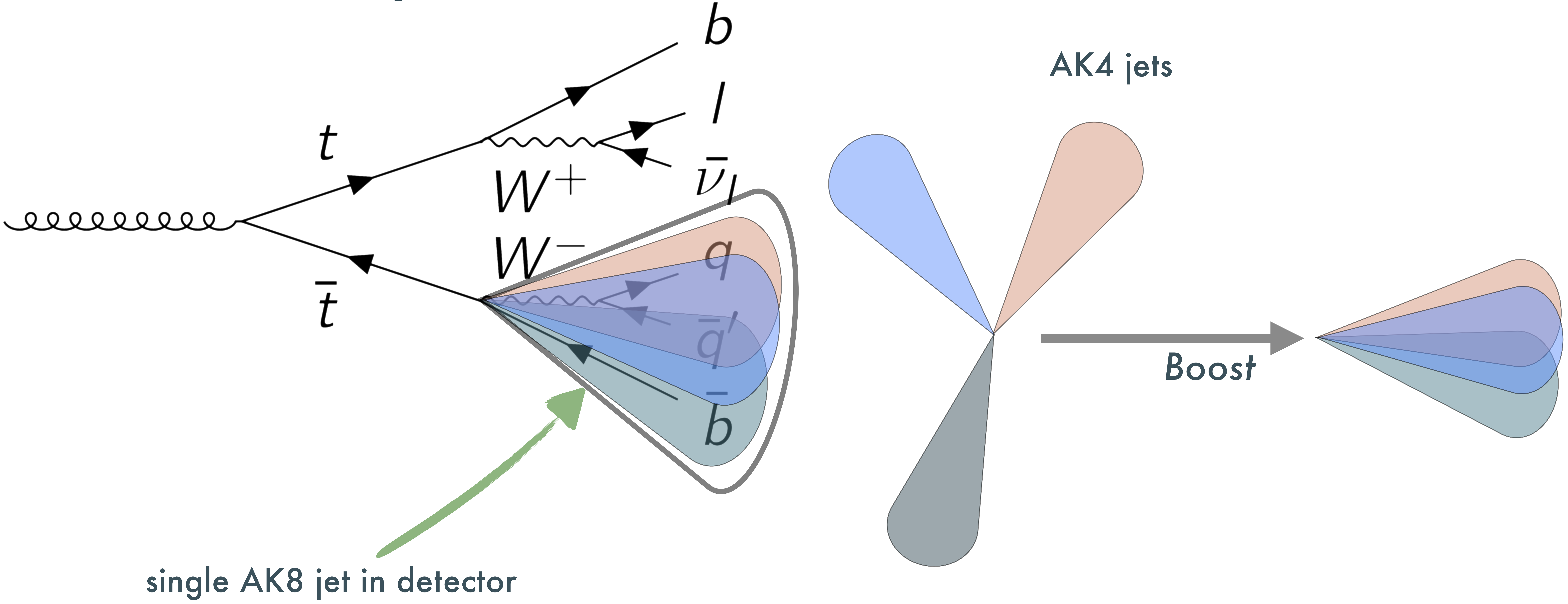
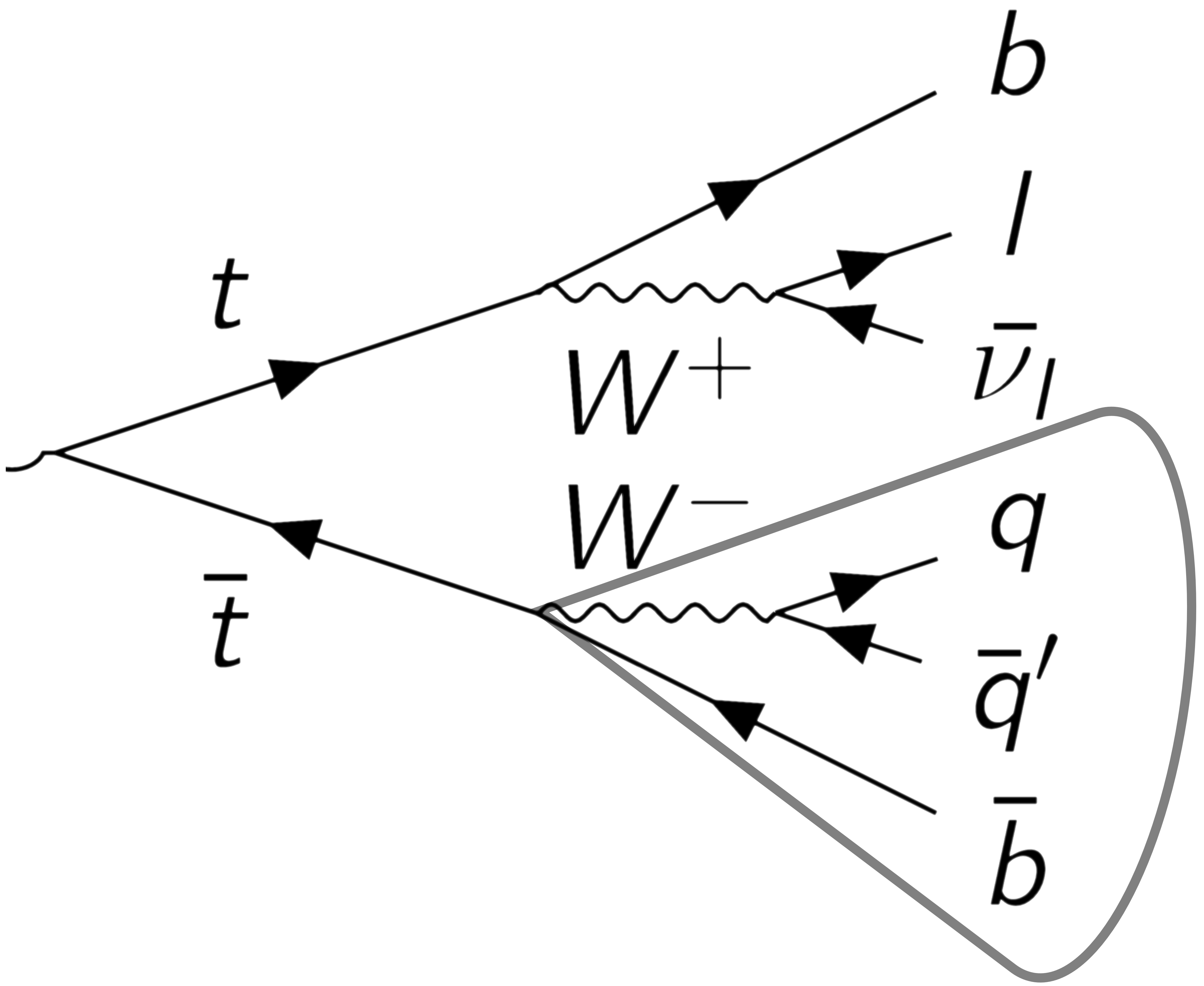


Boosted Top Quarks

— in BSM signals —



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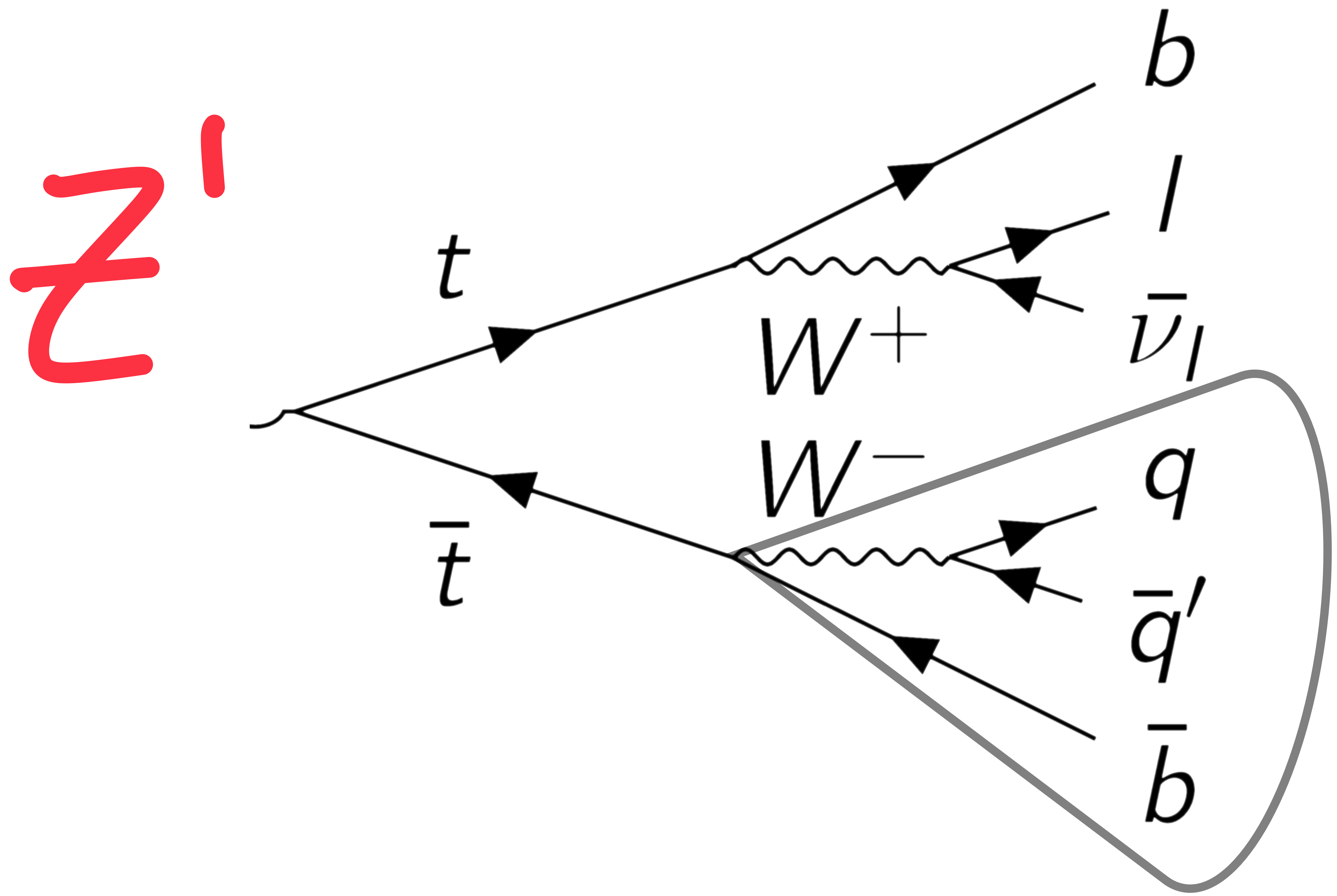

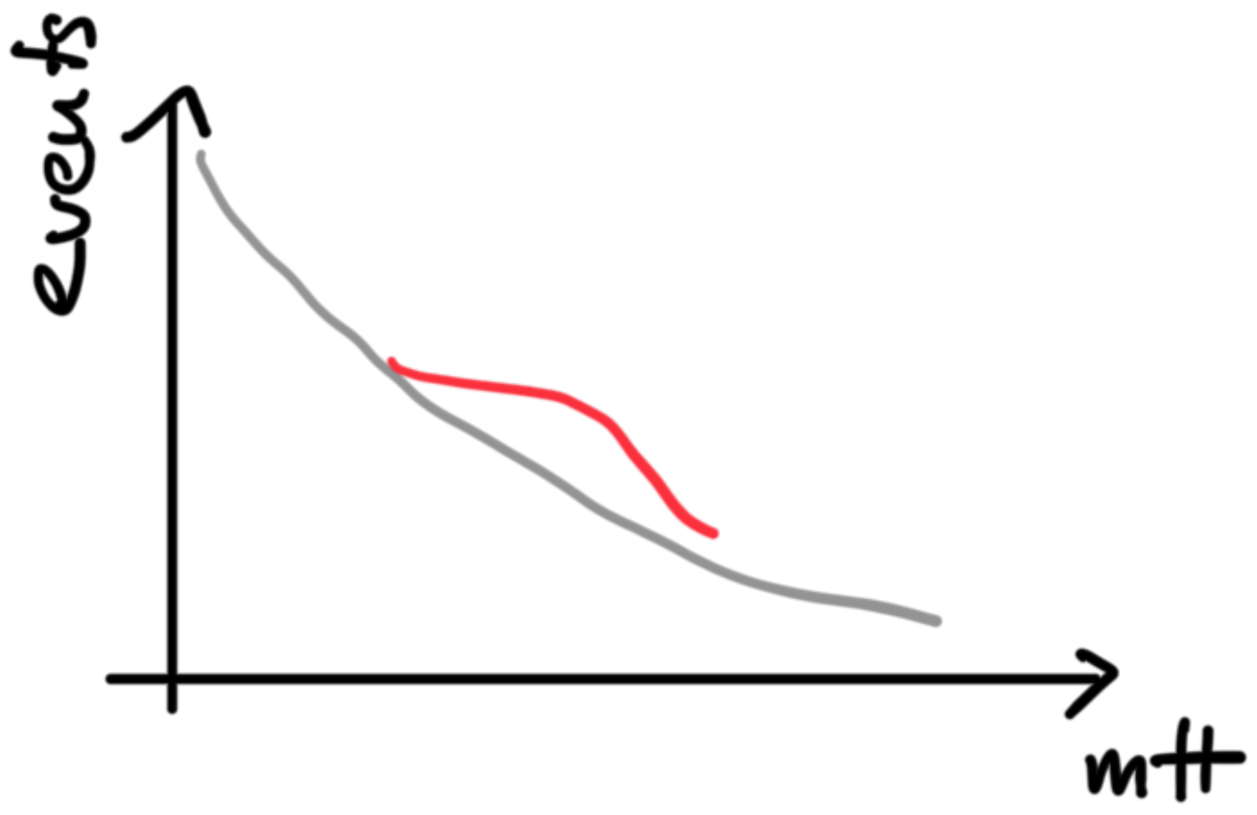

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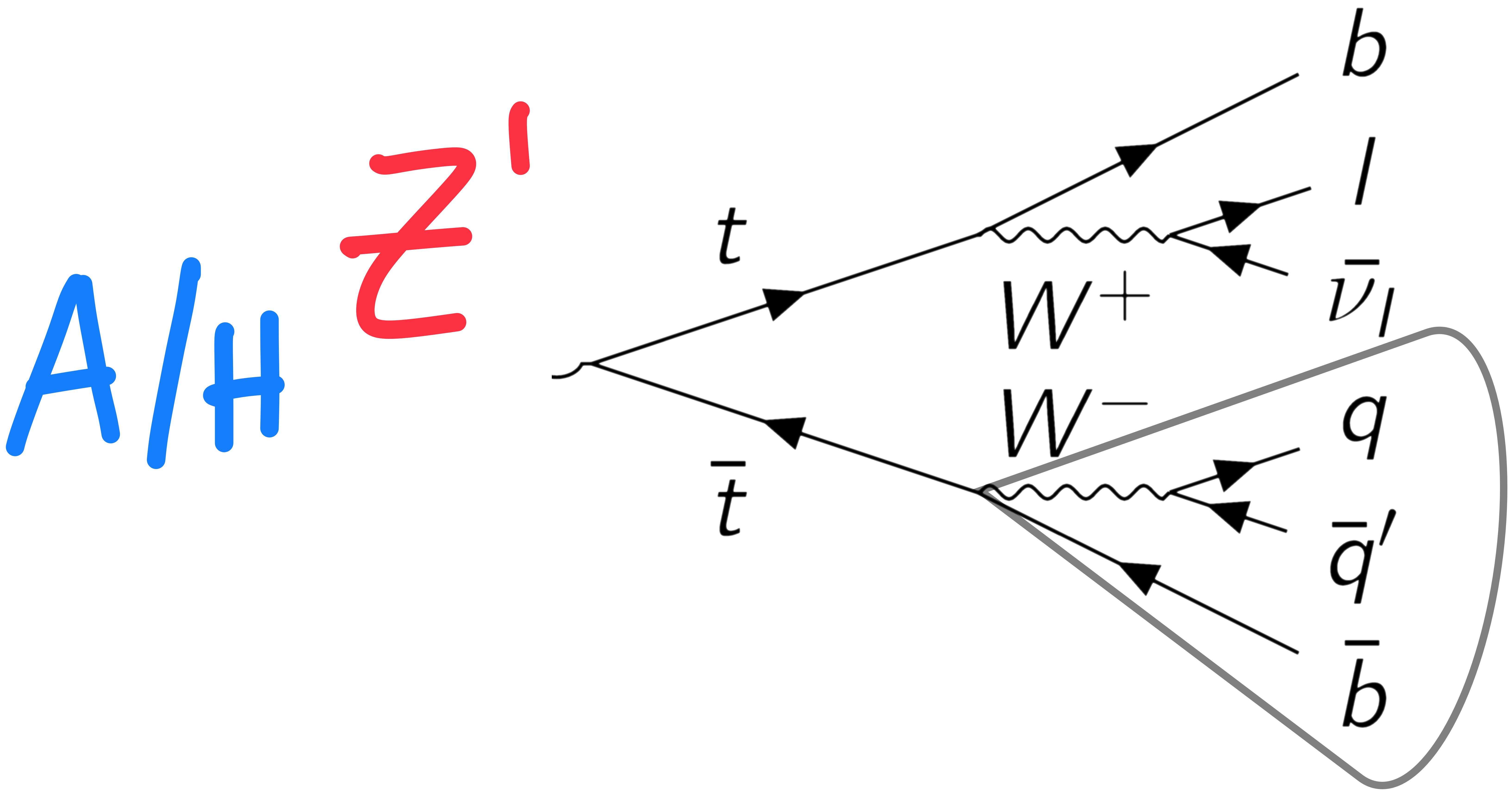

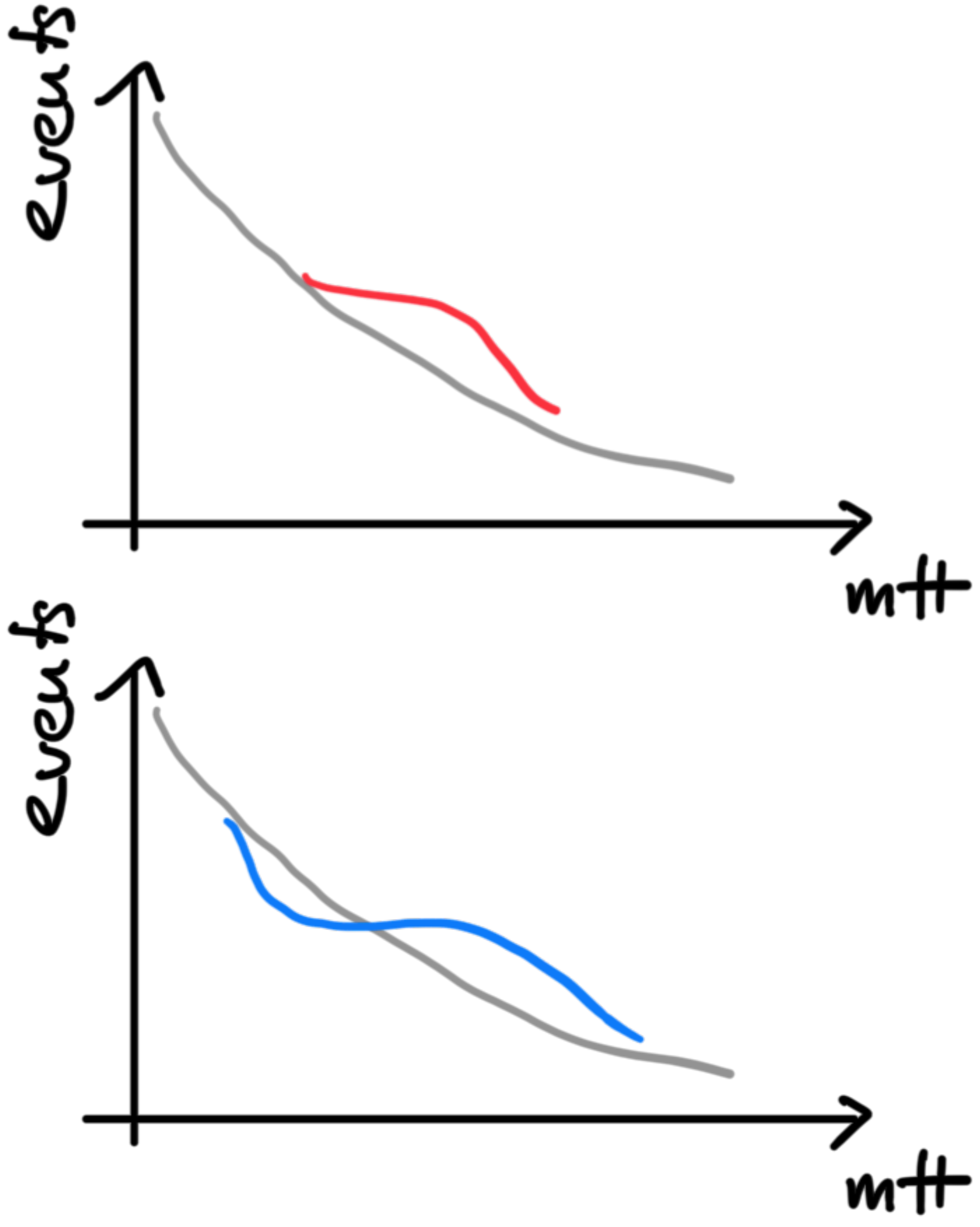

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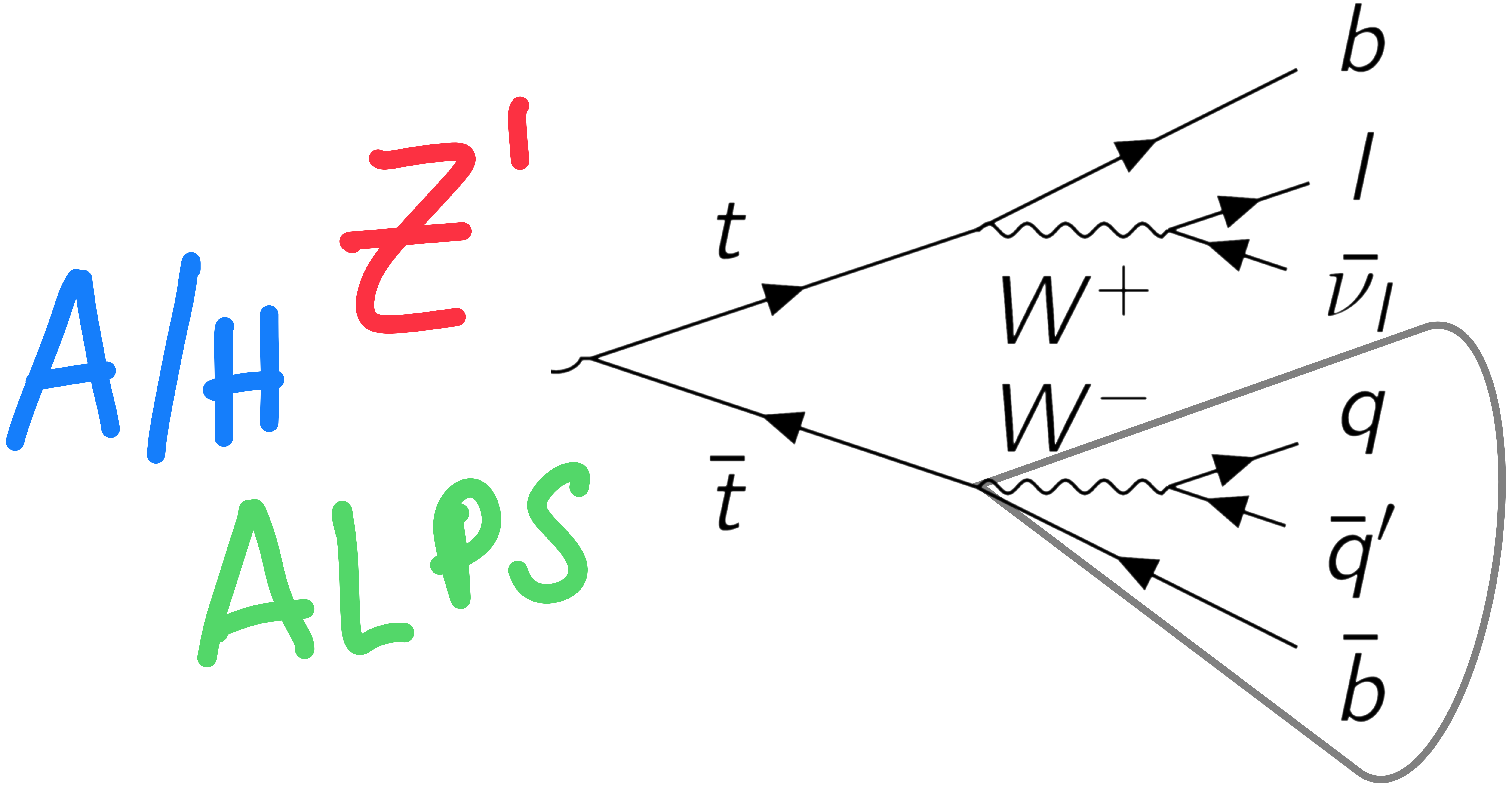

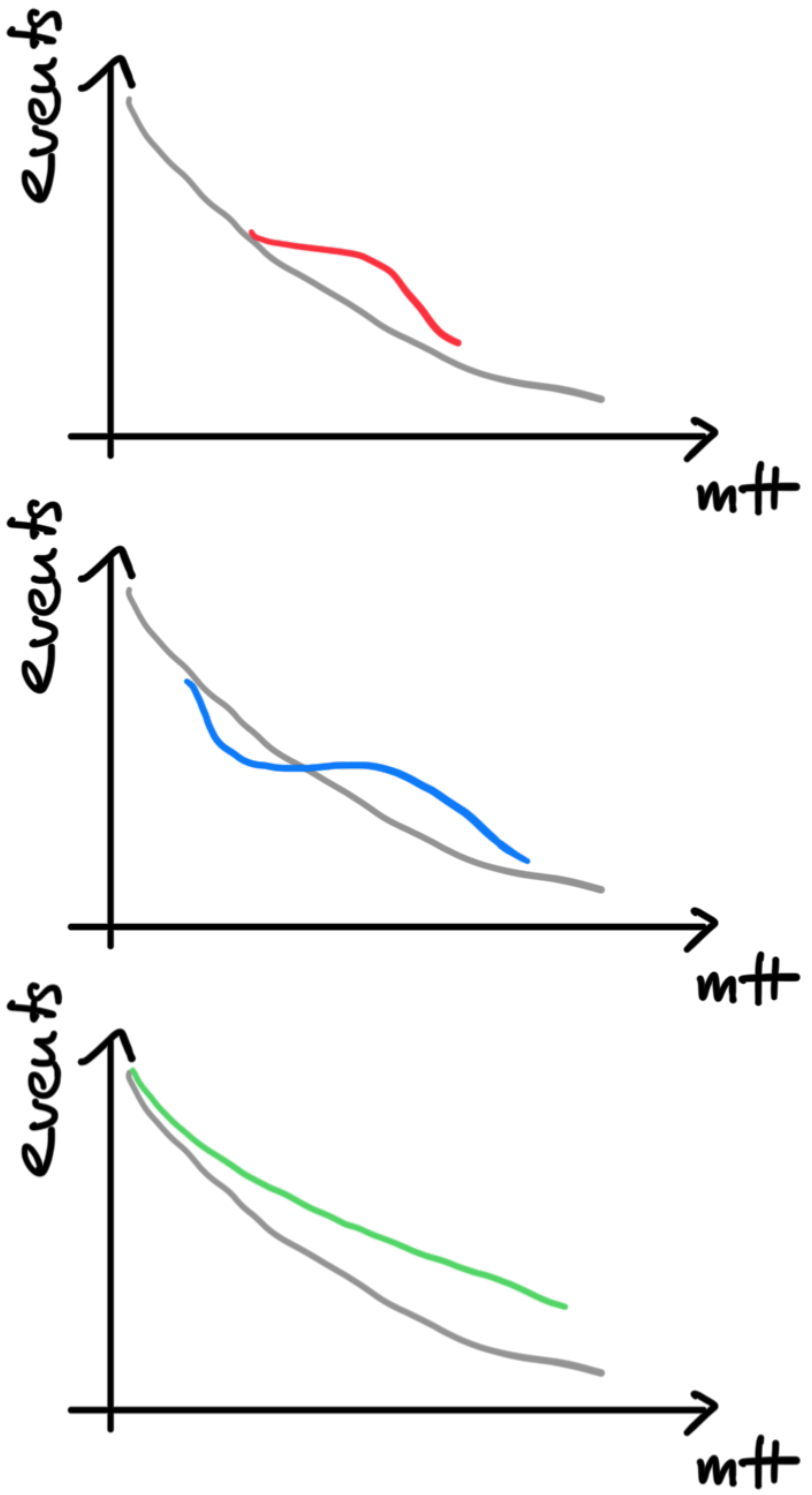

Identifying Boosted Top Quarks

— 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-2025-010

N-subjettiness

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

JHEP 1103:015,2011 - arXiv:1011.2268

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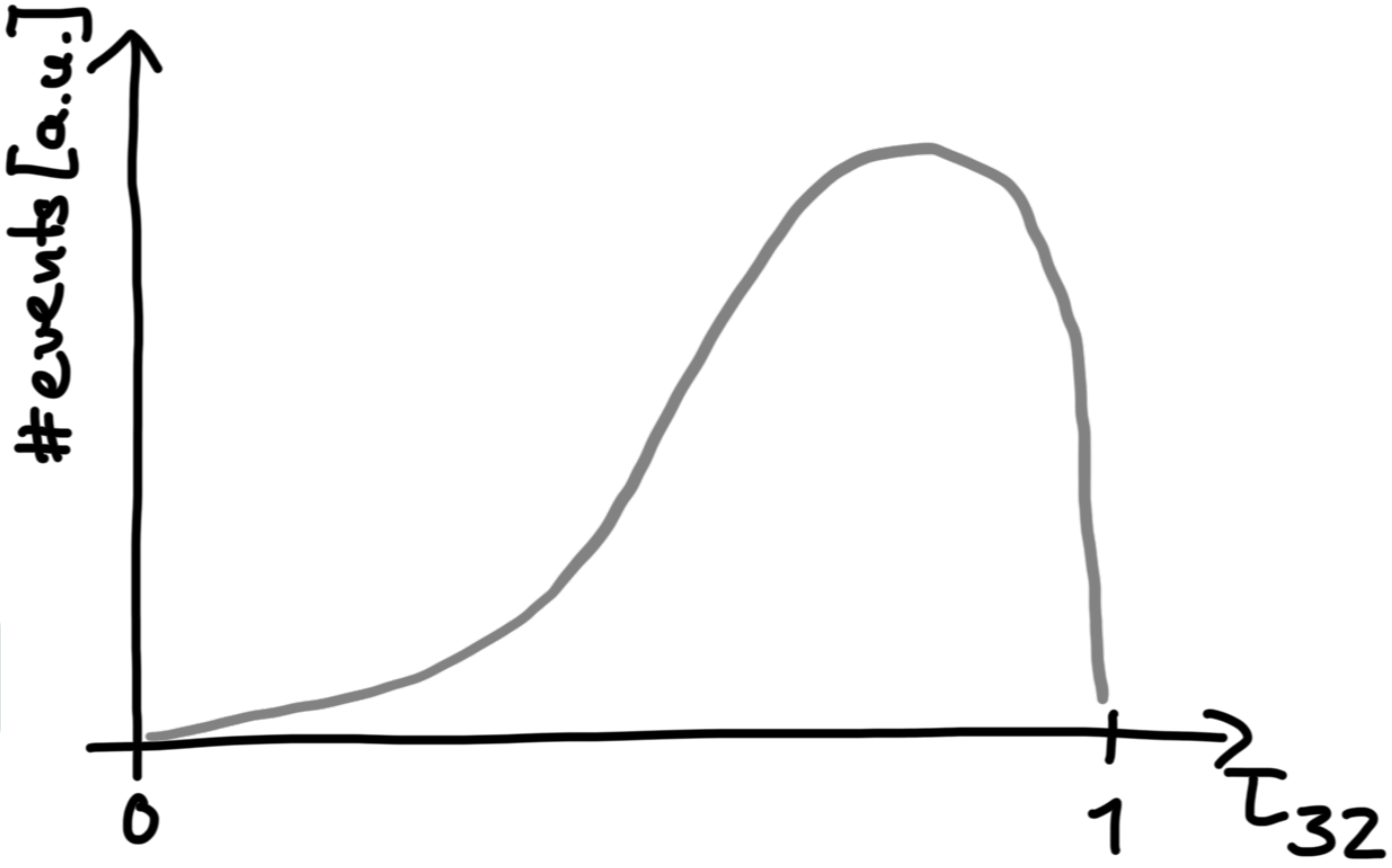
$$\tau_{32} := \tau_3/\tau_2$$



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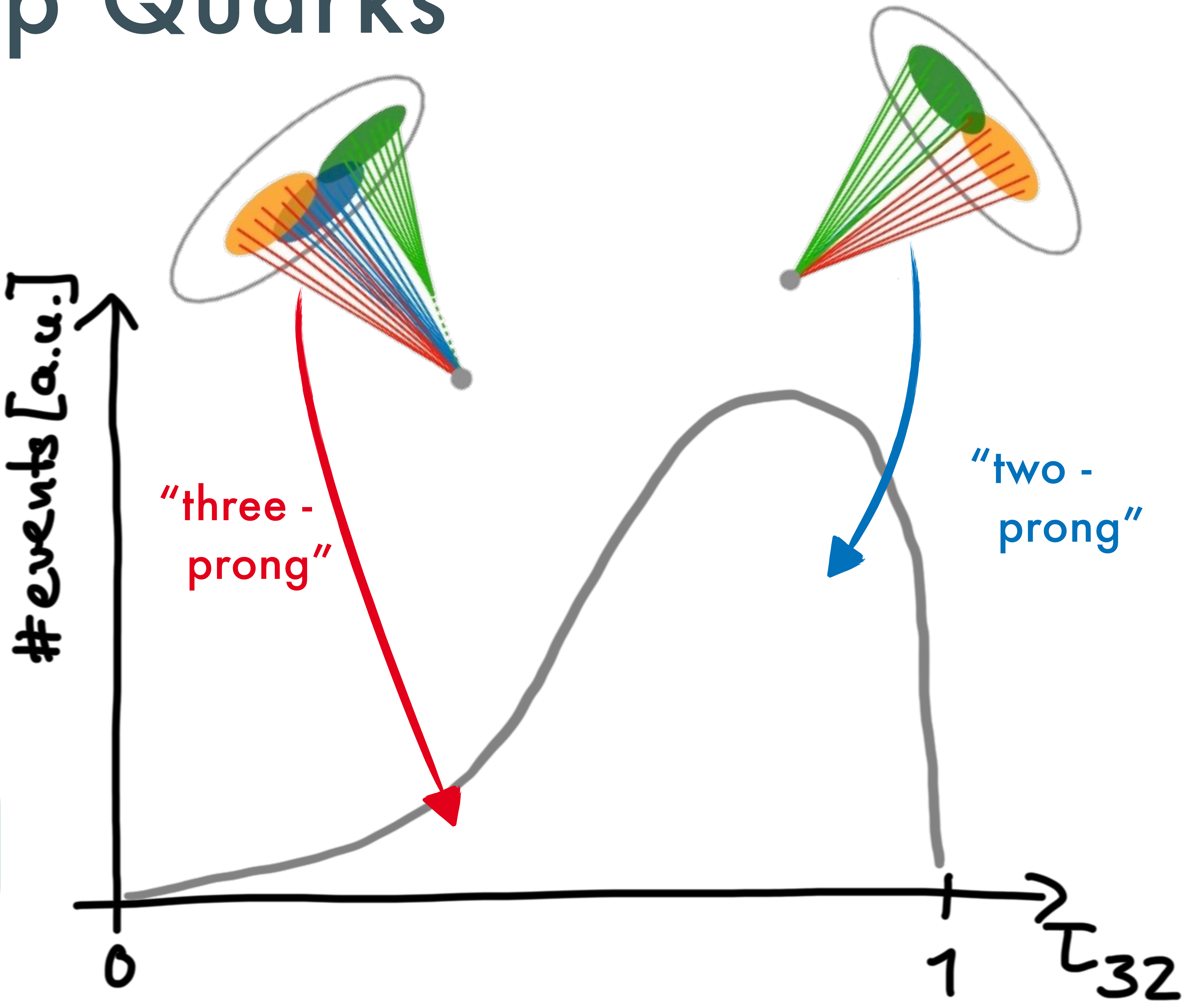

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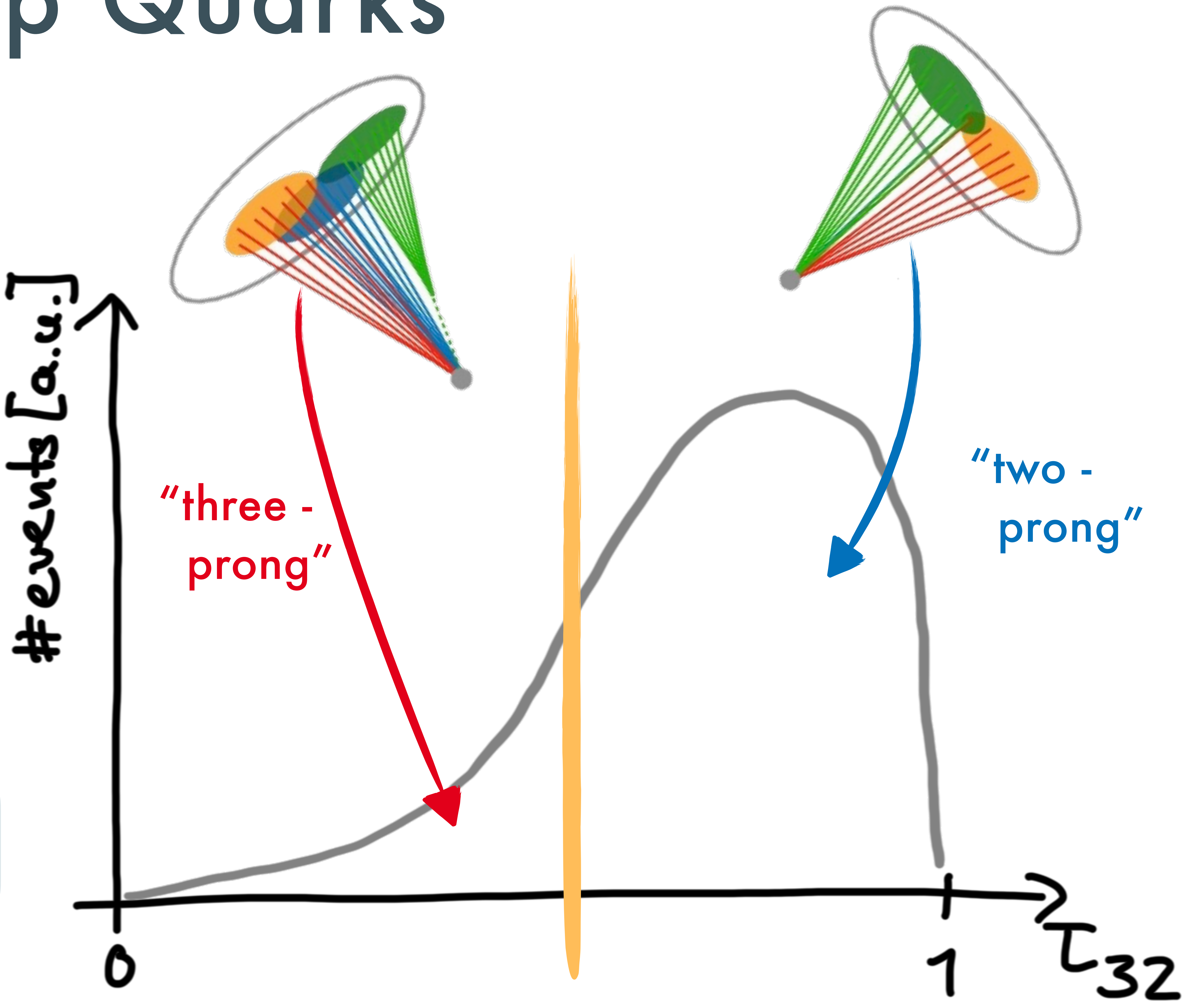
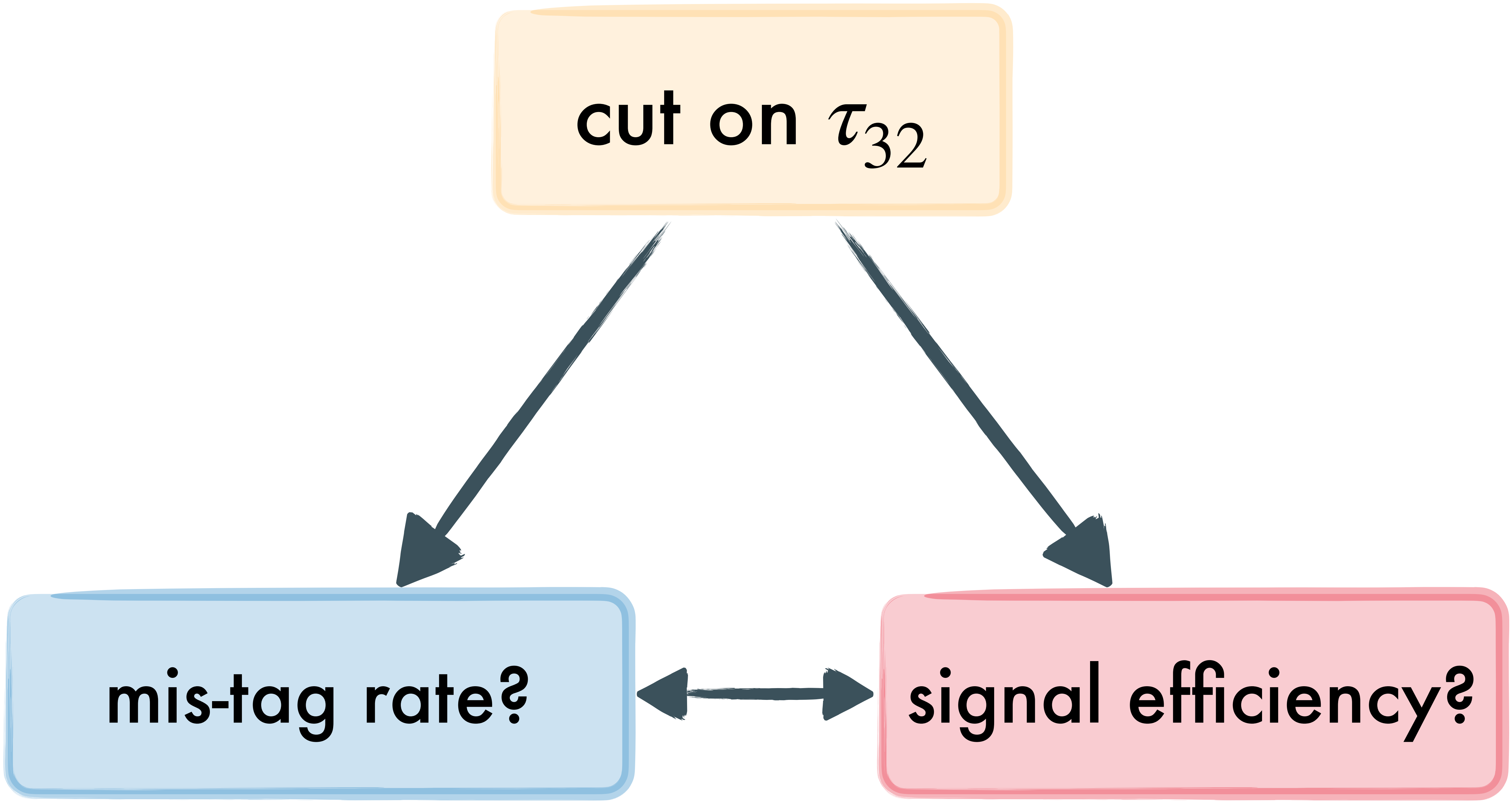


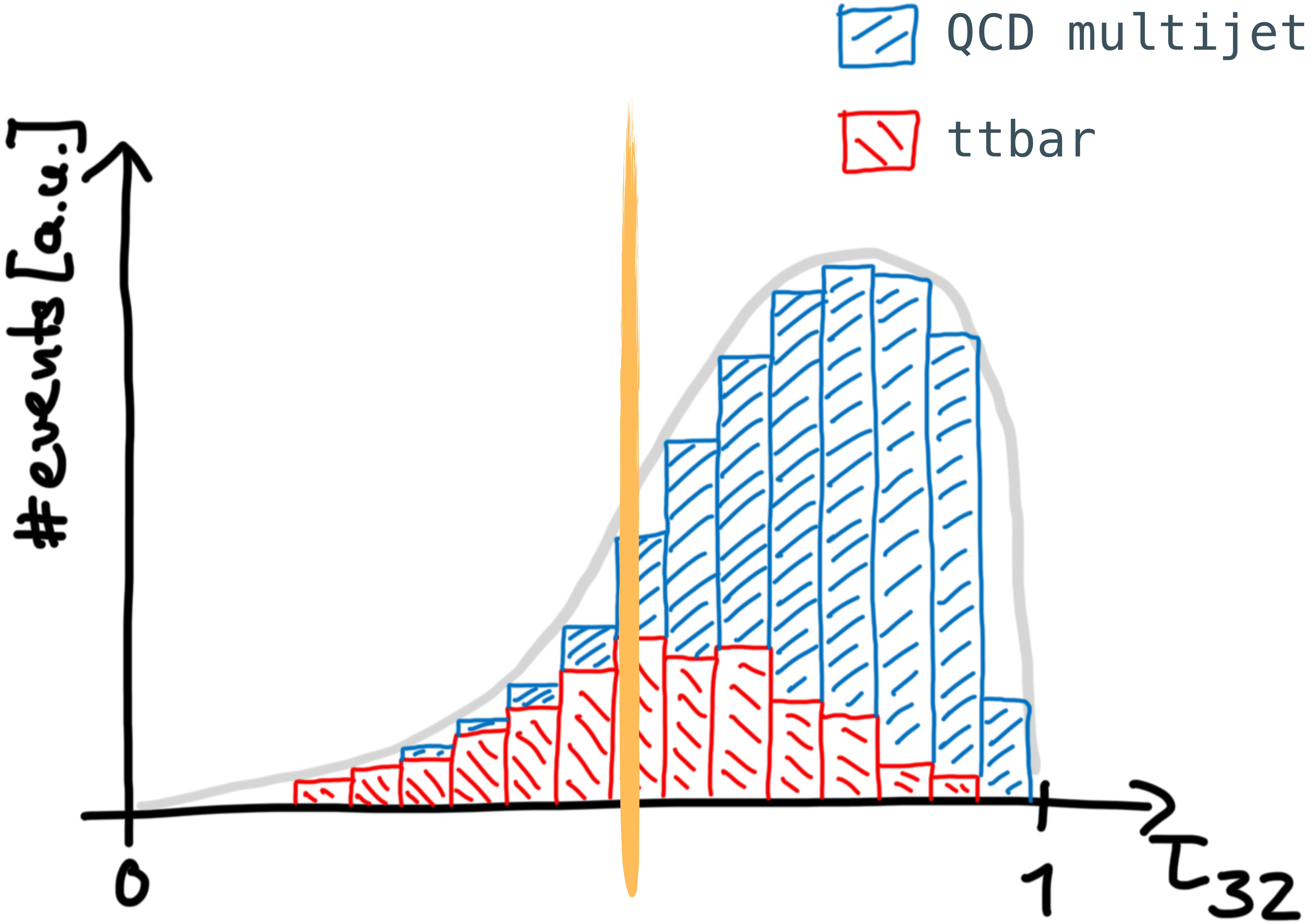
Separating Signal From Background

cut on τ_{32}

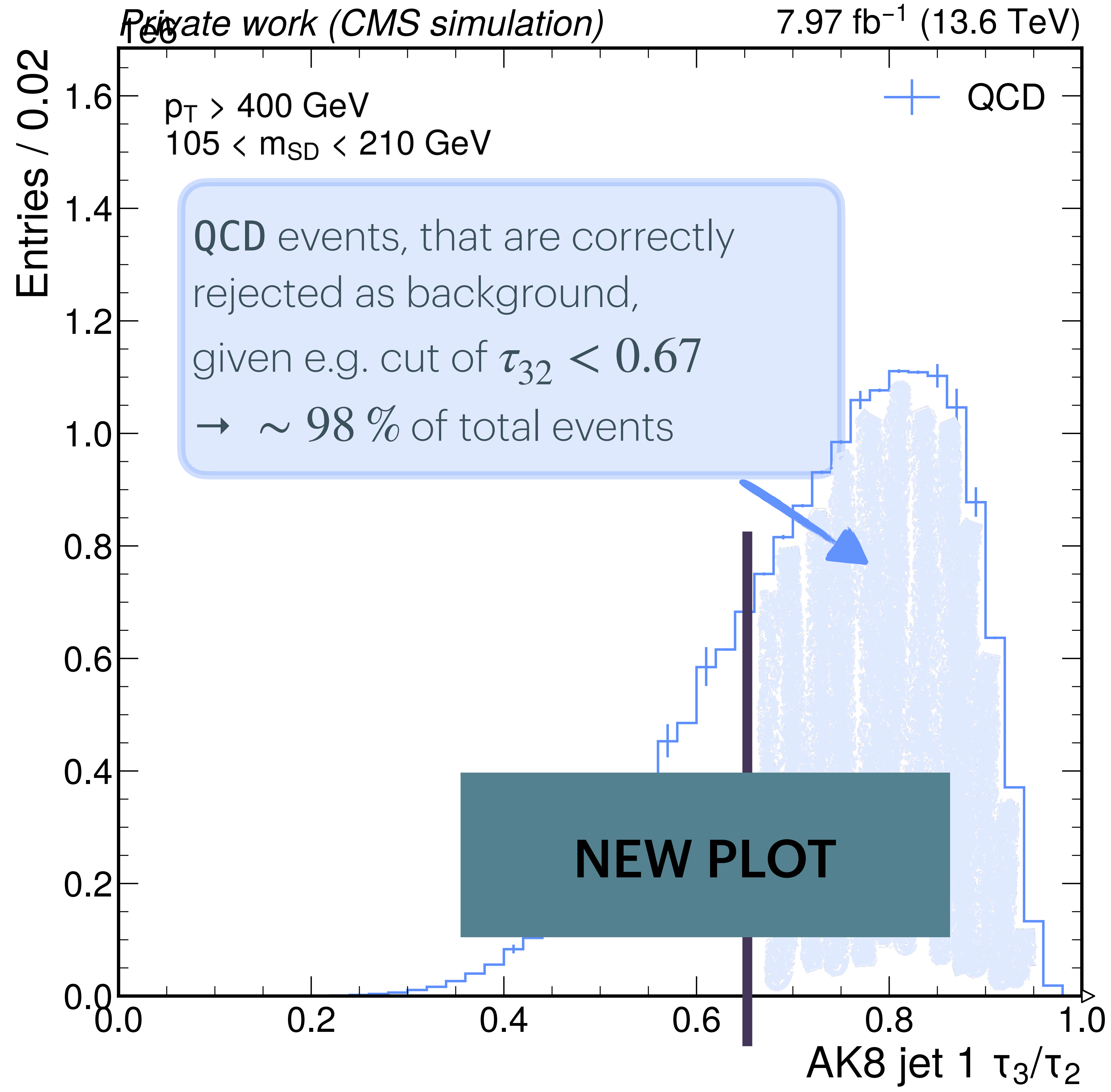
mis-tag rate? ⟷ signal efficiency?

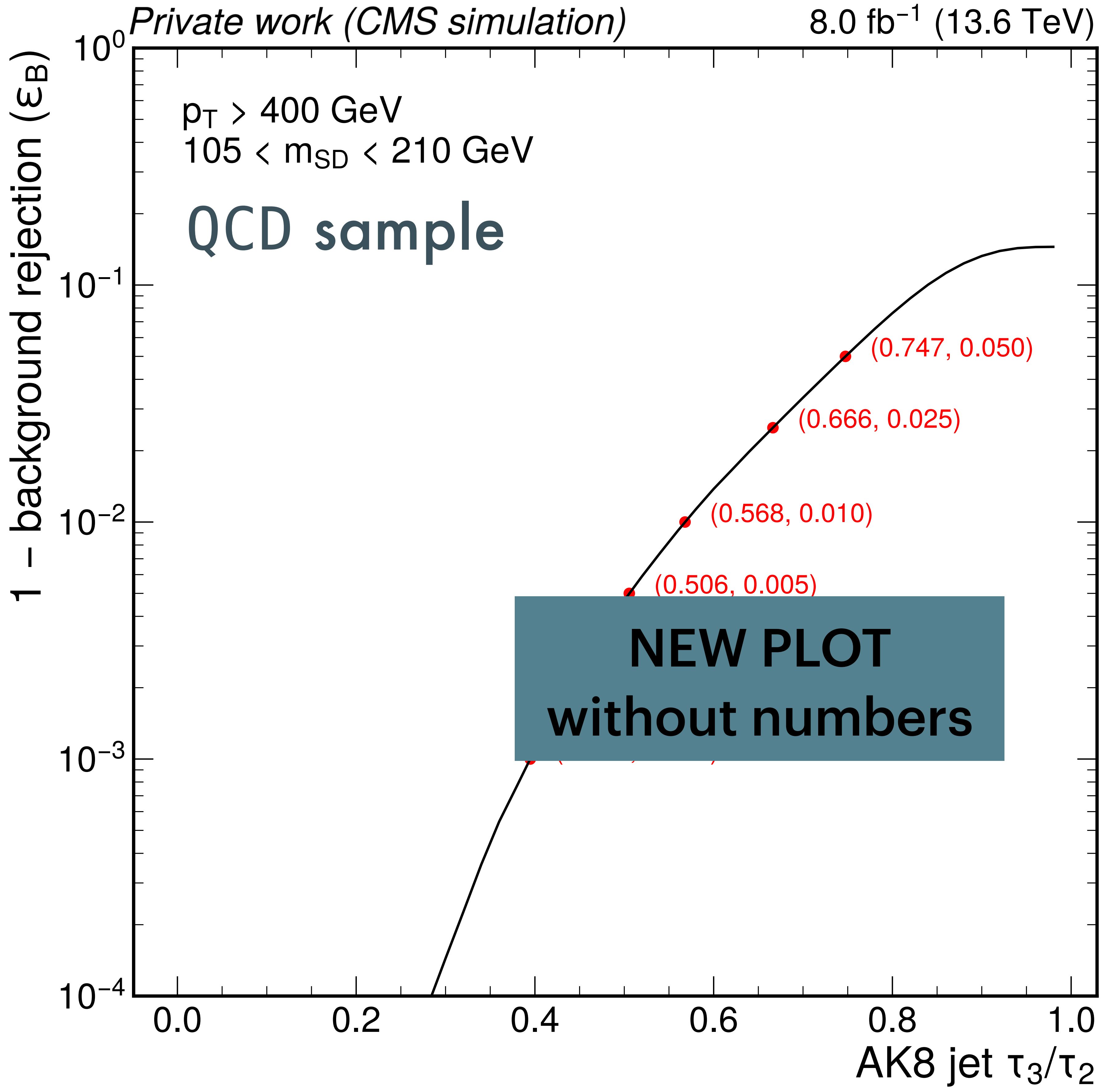
Separating Signal From Background





Mis-Tag Rate

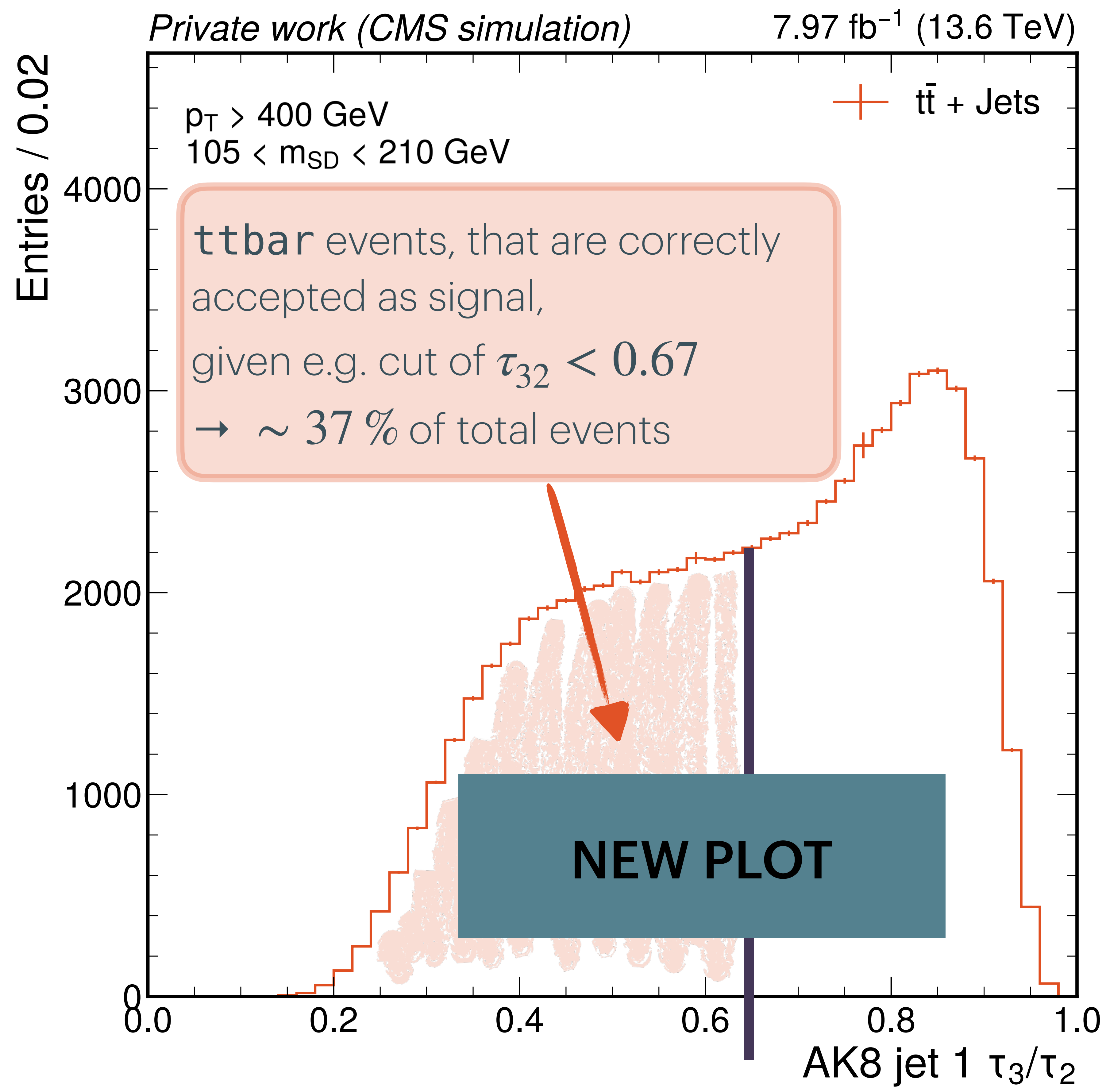


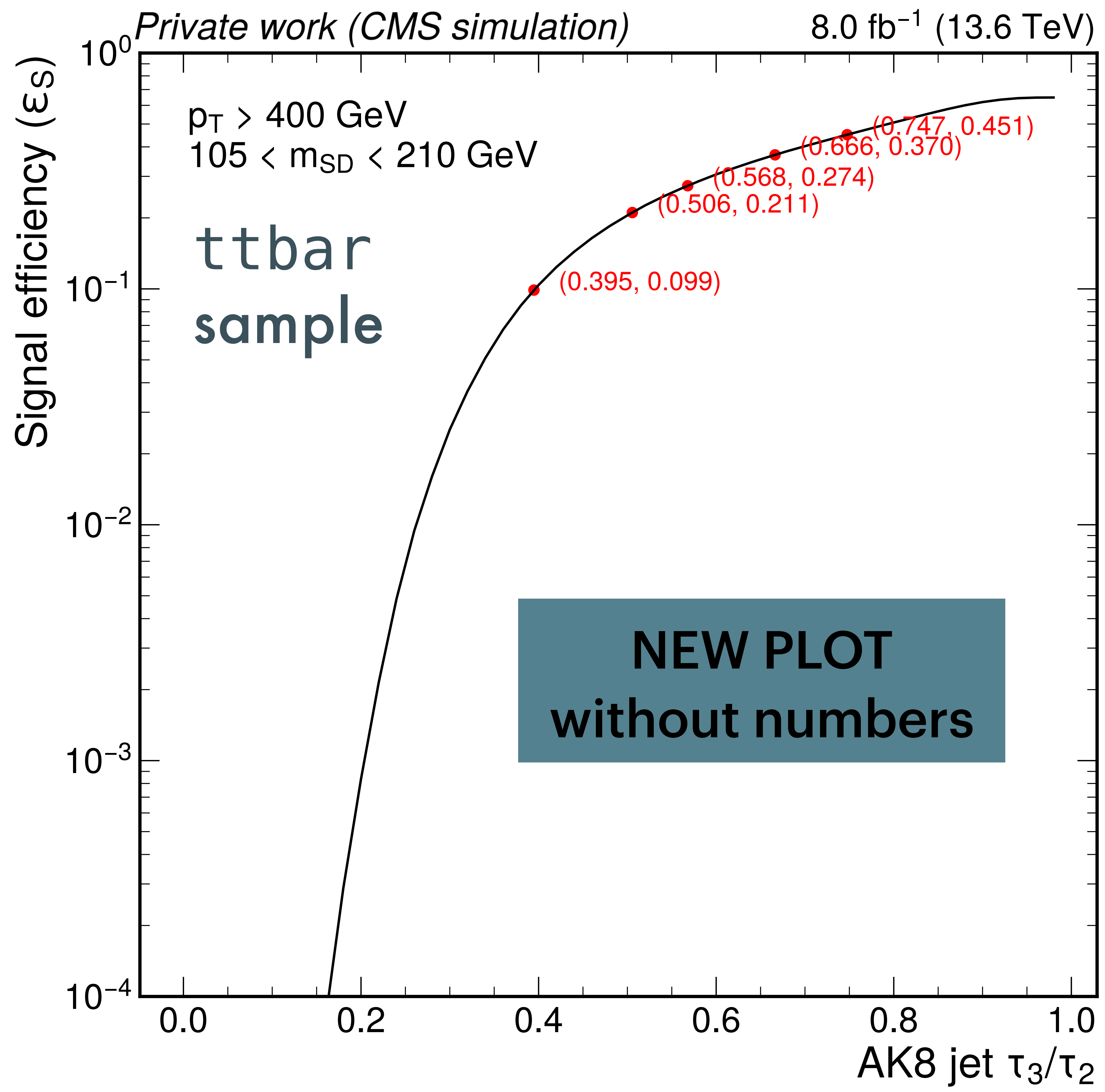


$$\frac{\text{number of QCD events with a FatJet passing selection AND (incorrectly) tagged as a top jet given the } \tau_{32} \text{ cut}}{\text{total number of events in QCD dataset}}$$

-

Signal Efficiency

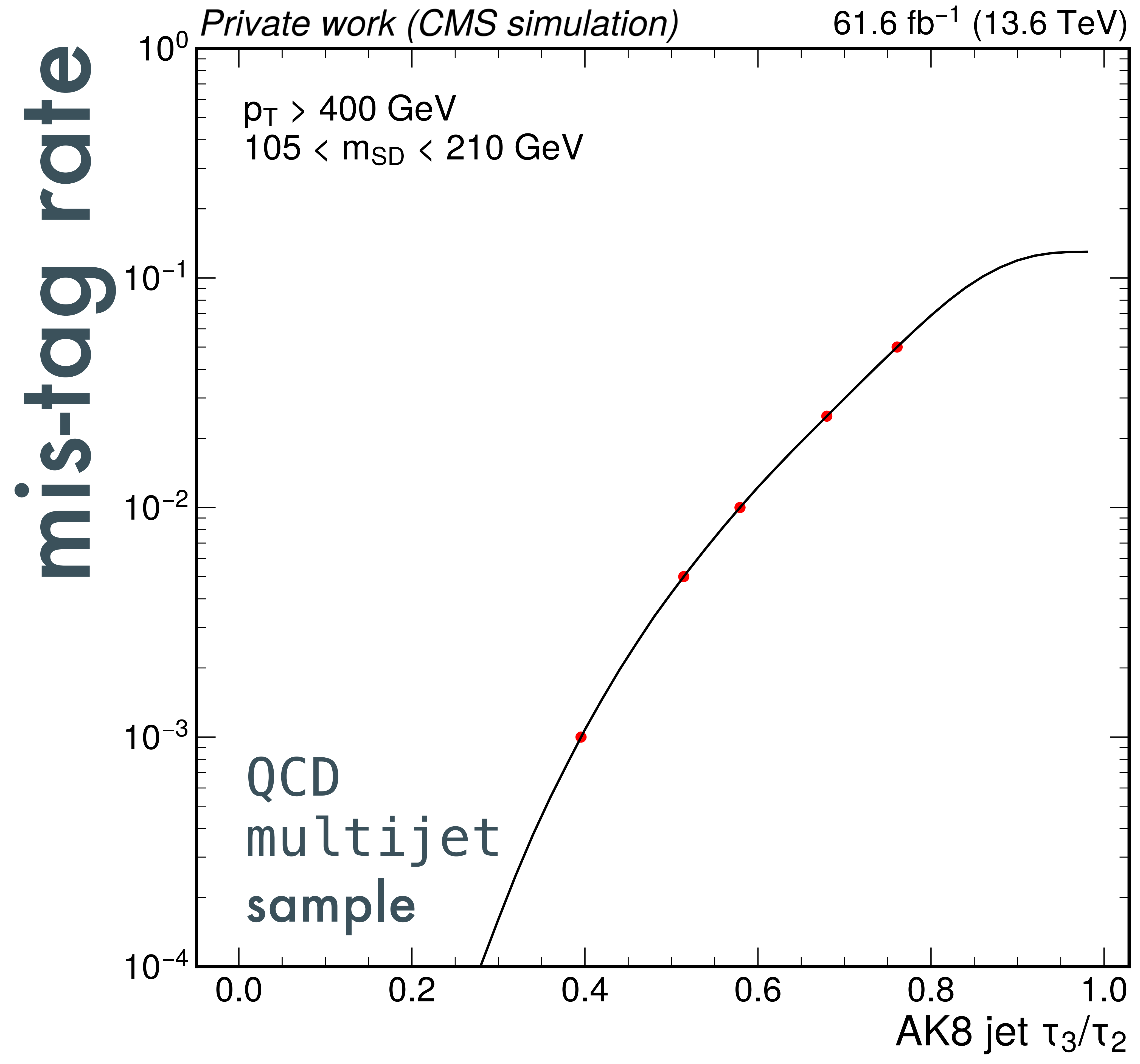




$$\frac{\text{number of ttbar events with a FatJet passing selection AND (correctly) tagged as a top jet given the } \tau_{32} \text{ cut}}{\text{total number of events in ttbar dataset}}$$

-

Working Points in One Slide



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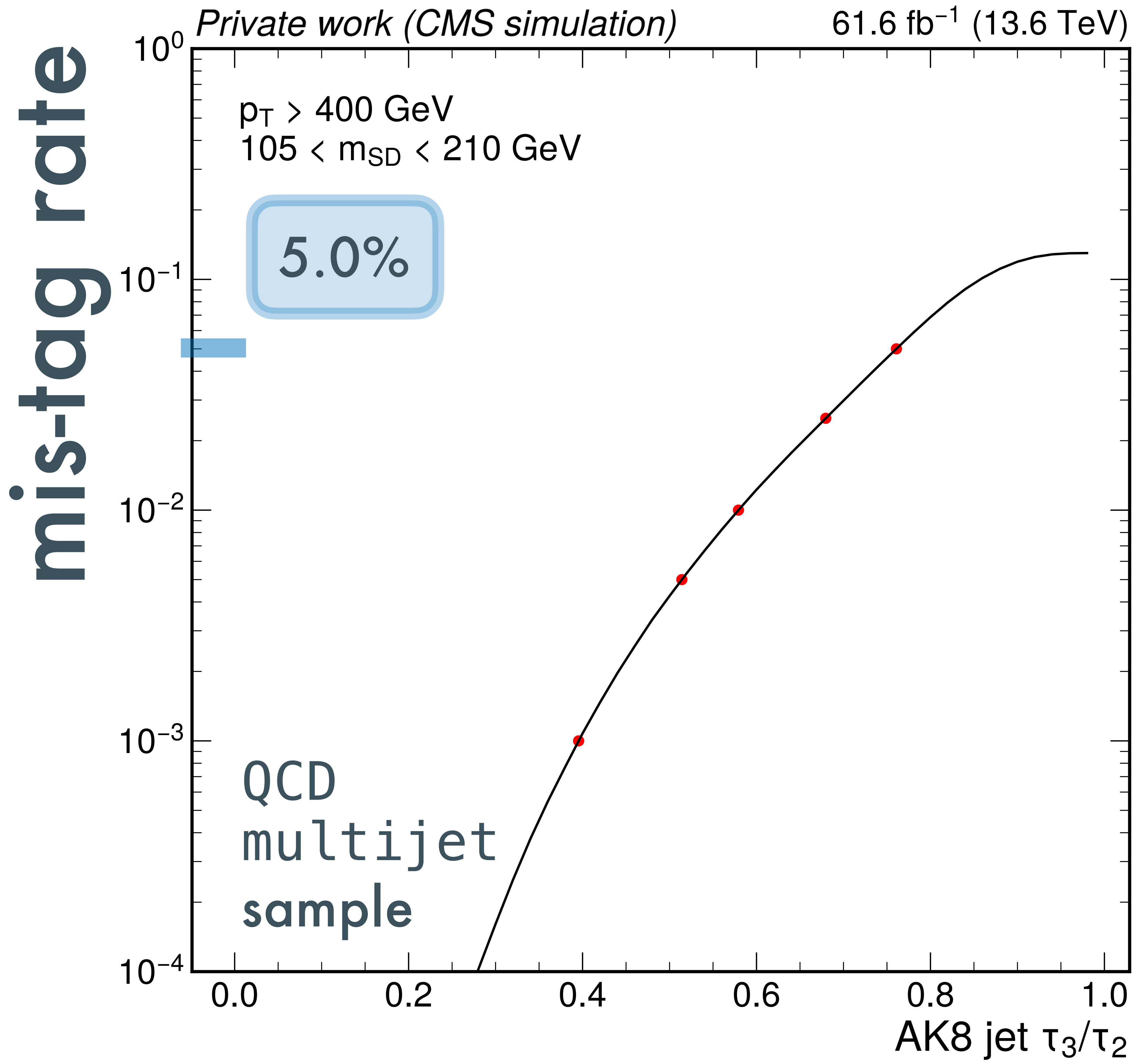

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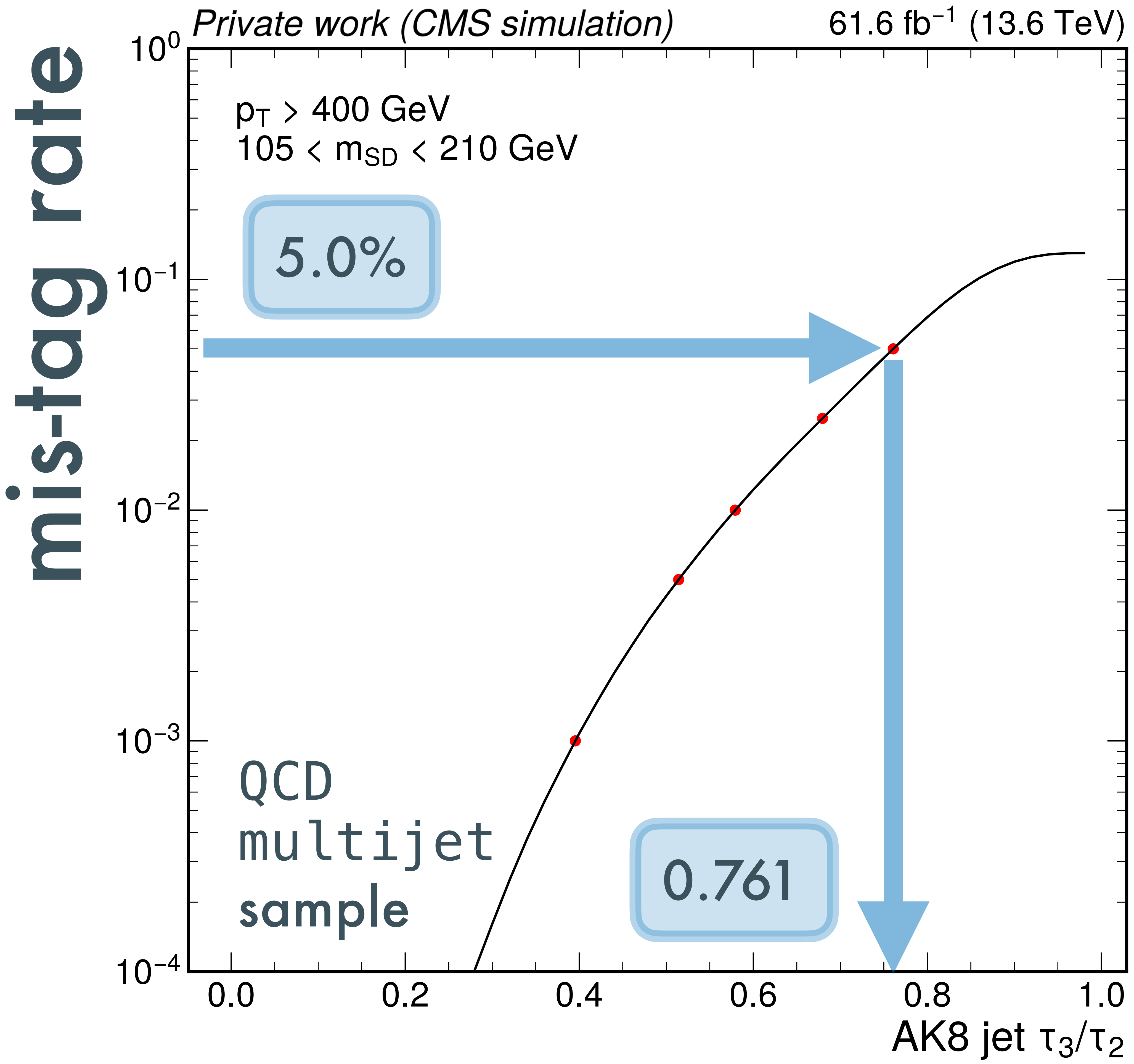

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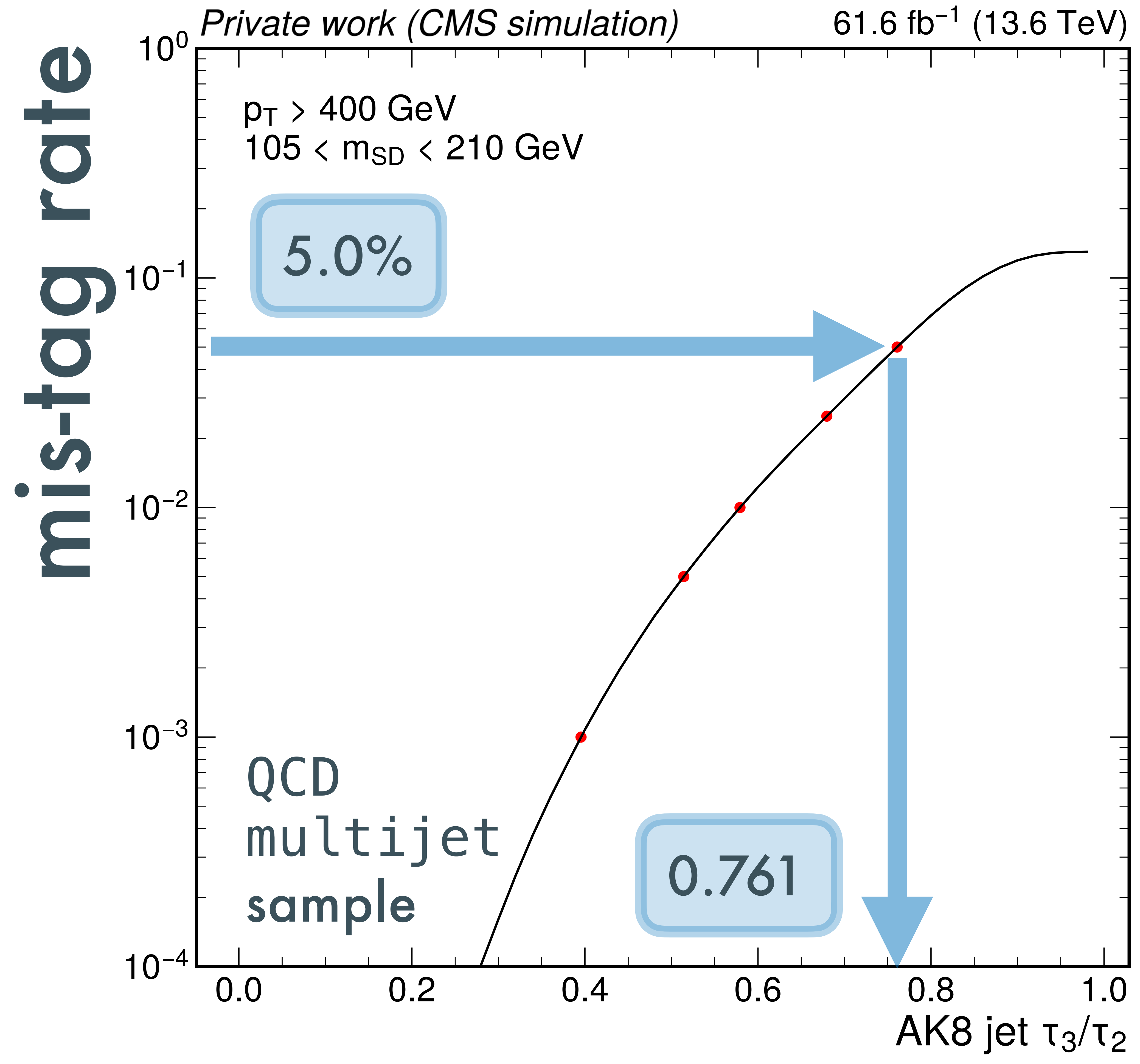

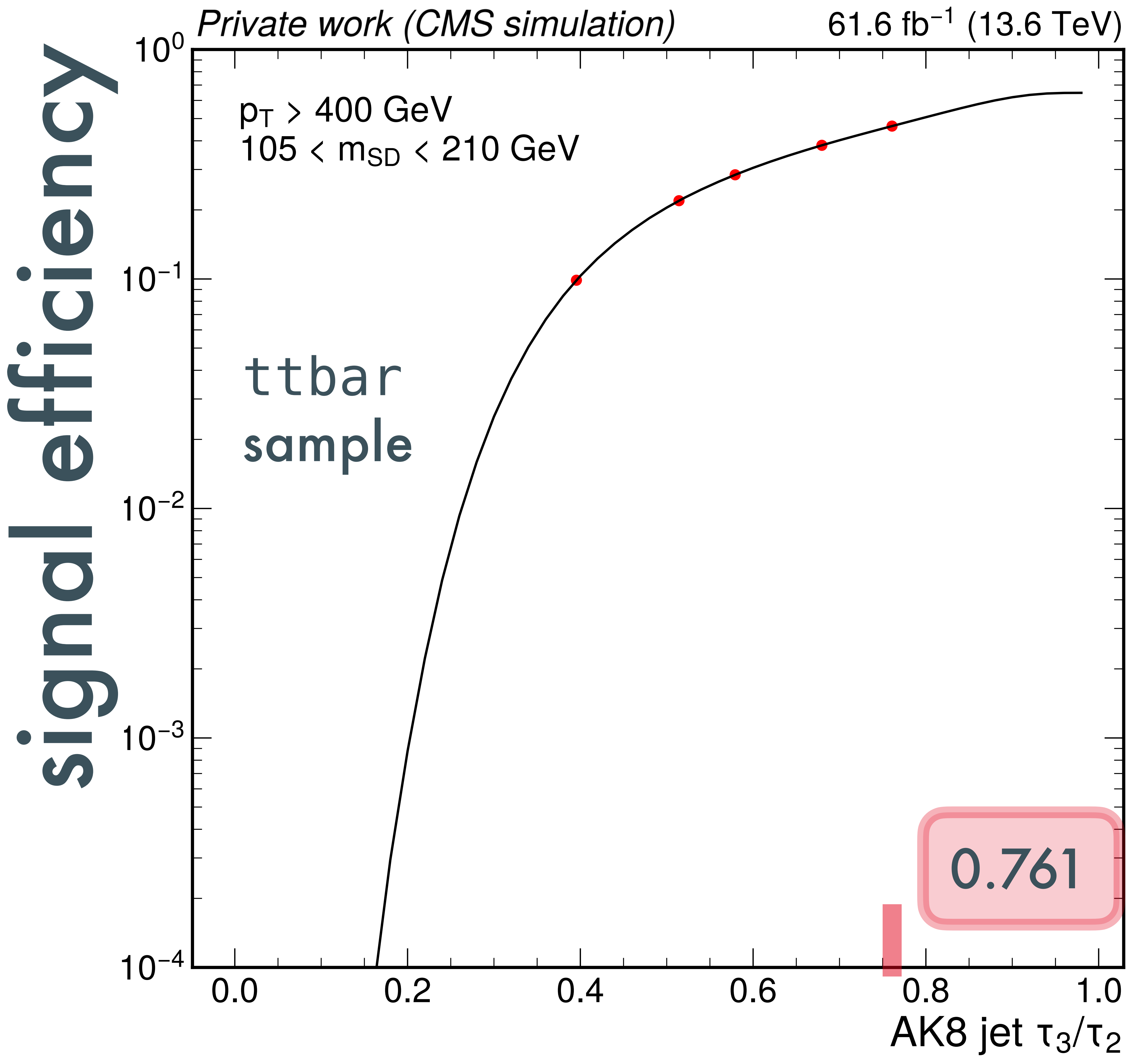

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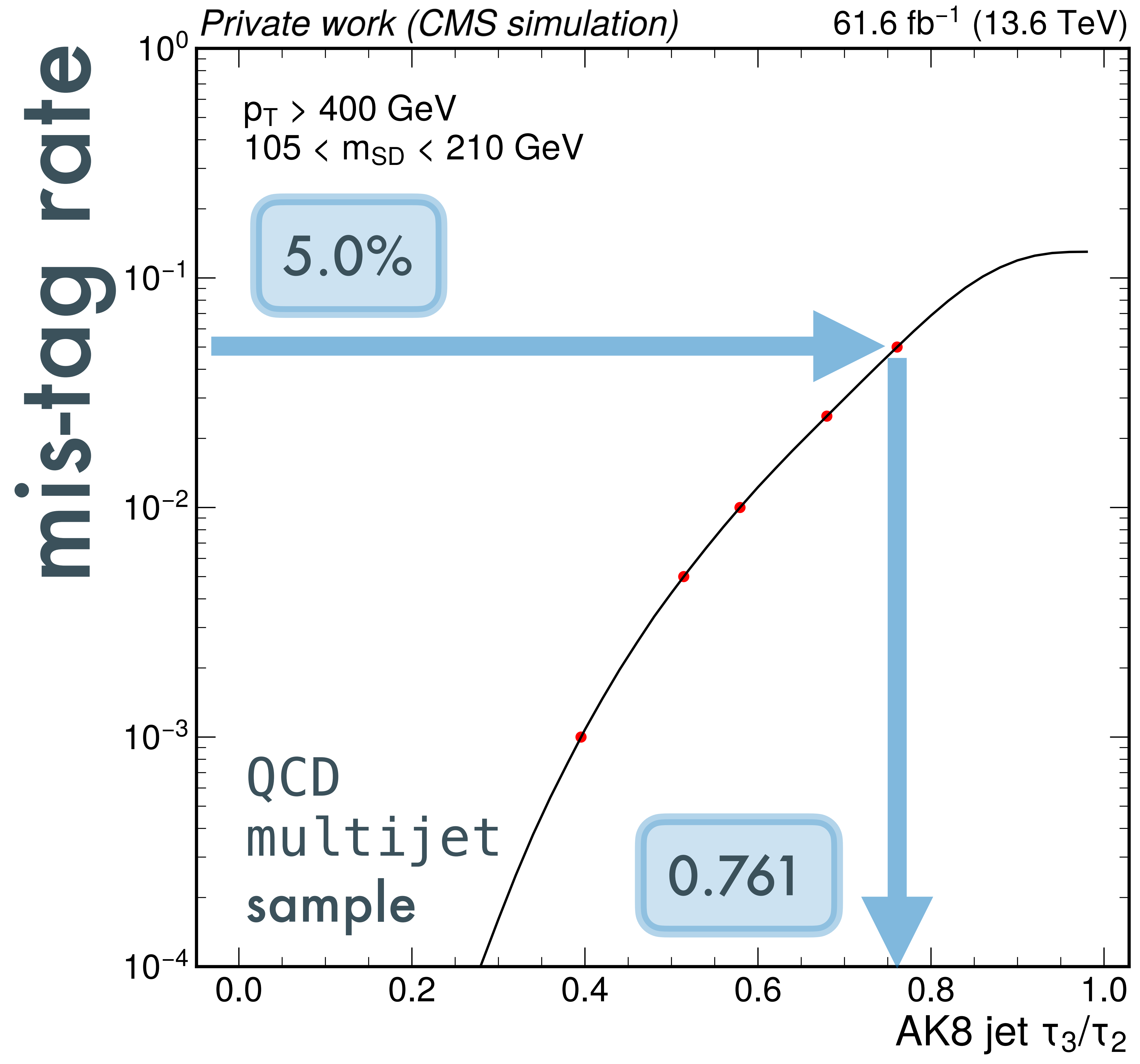
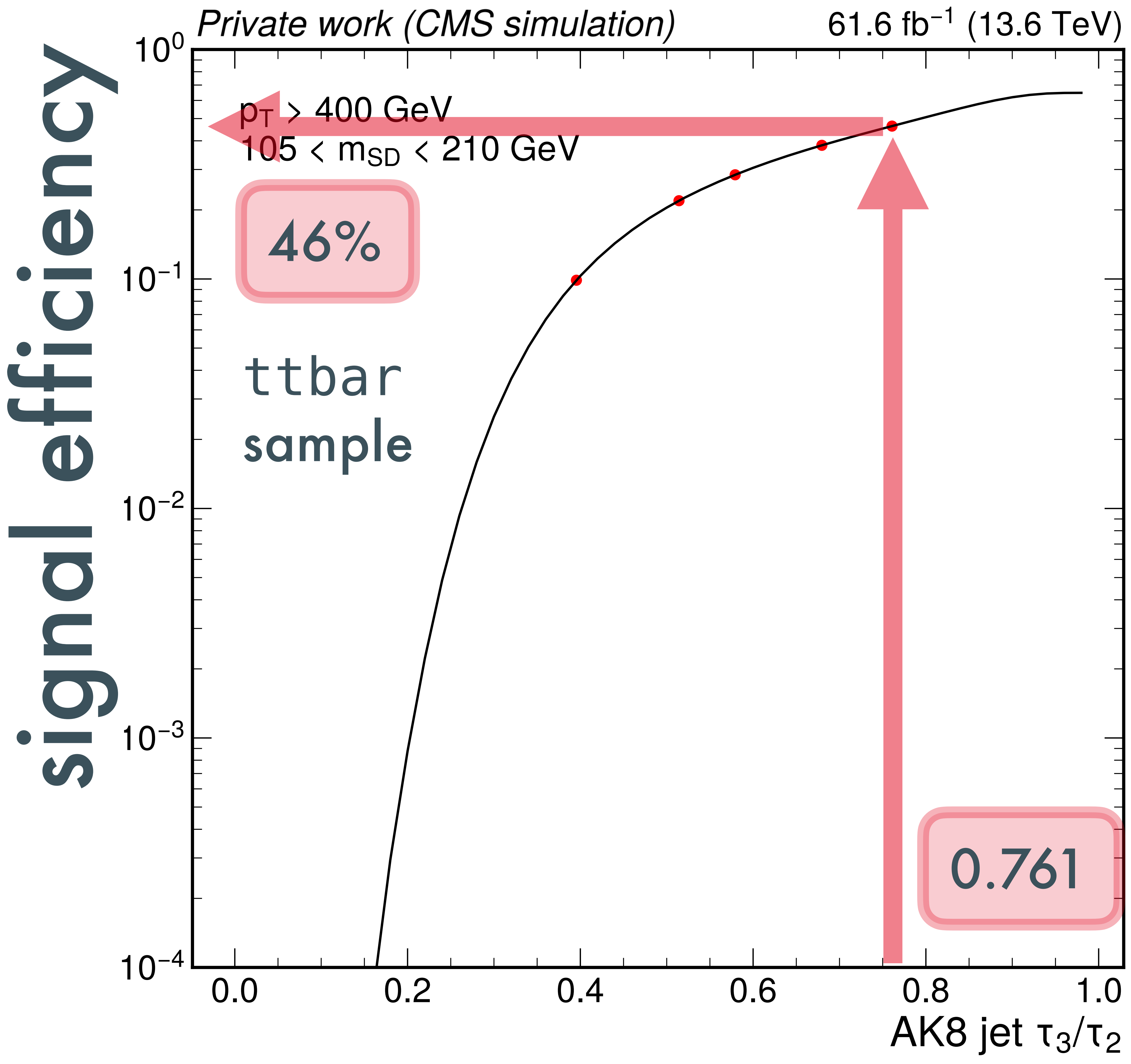
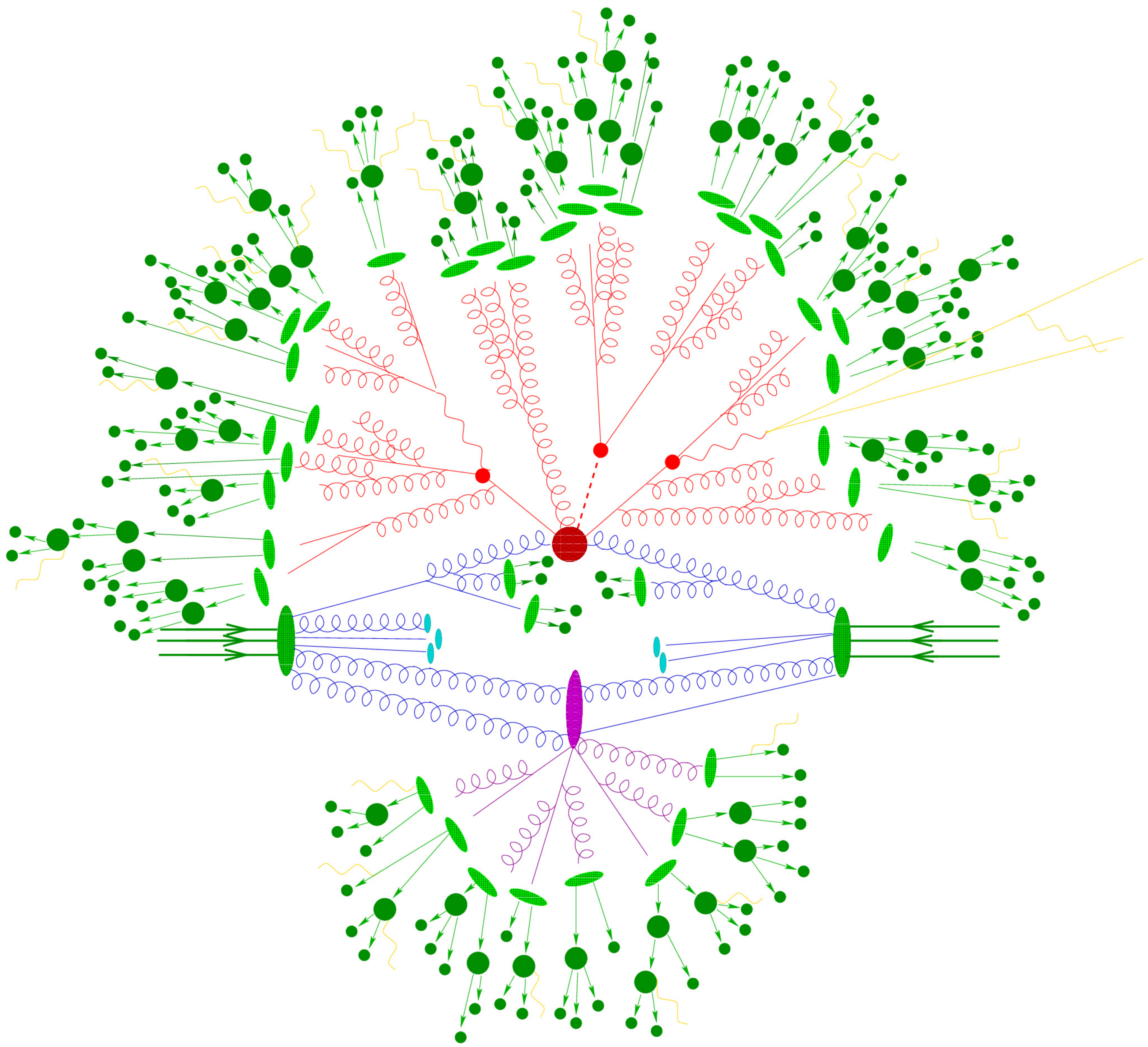
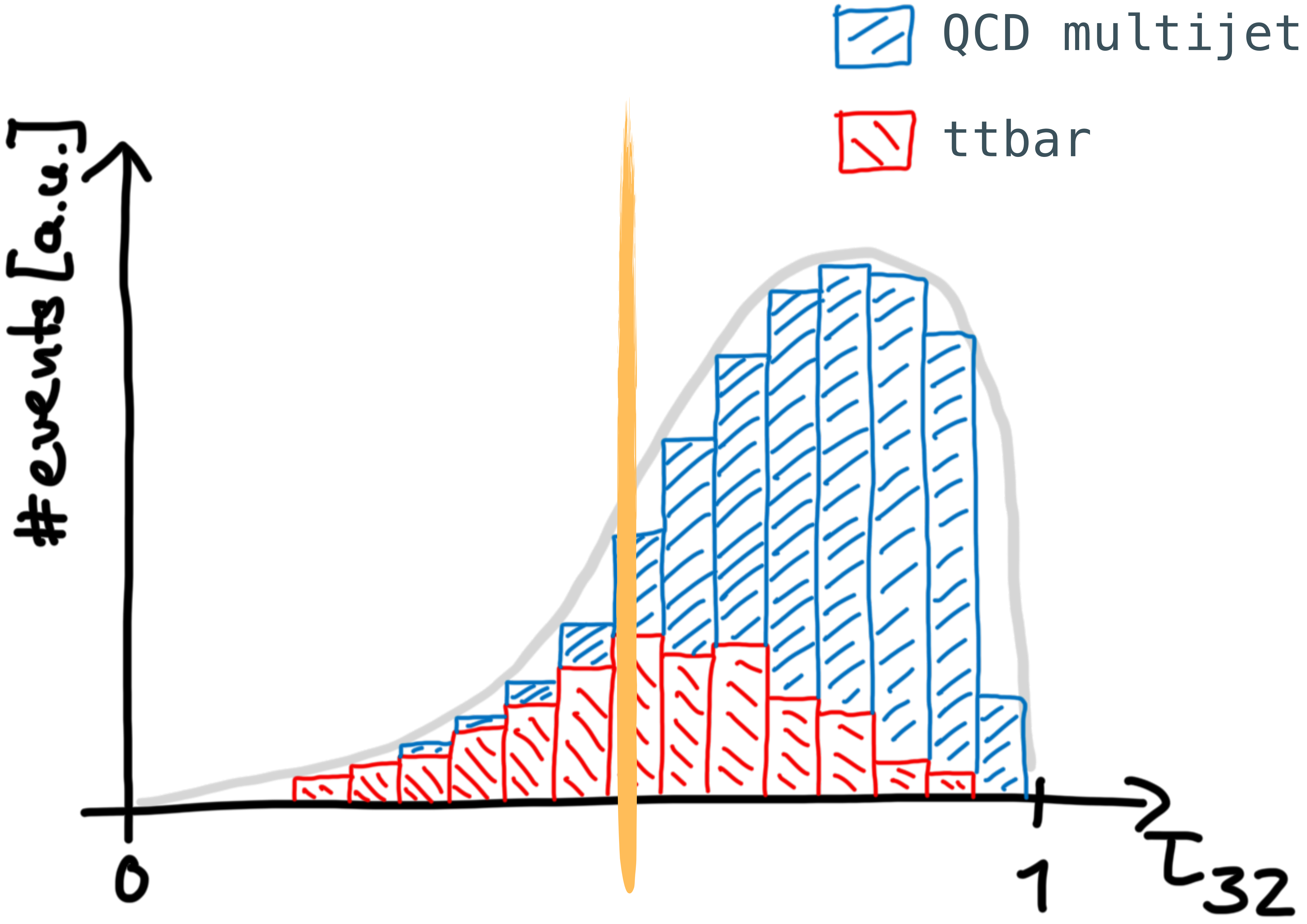




Jet Substructure in Recorded Data





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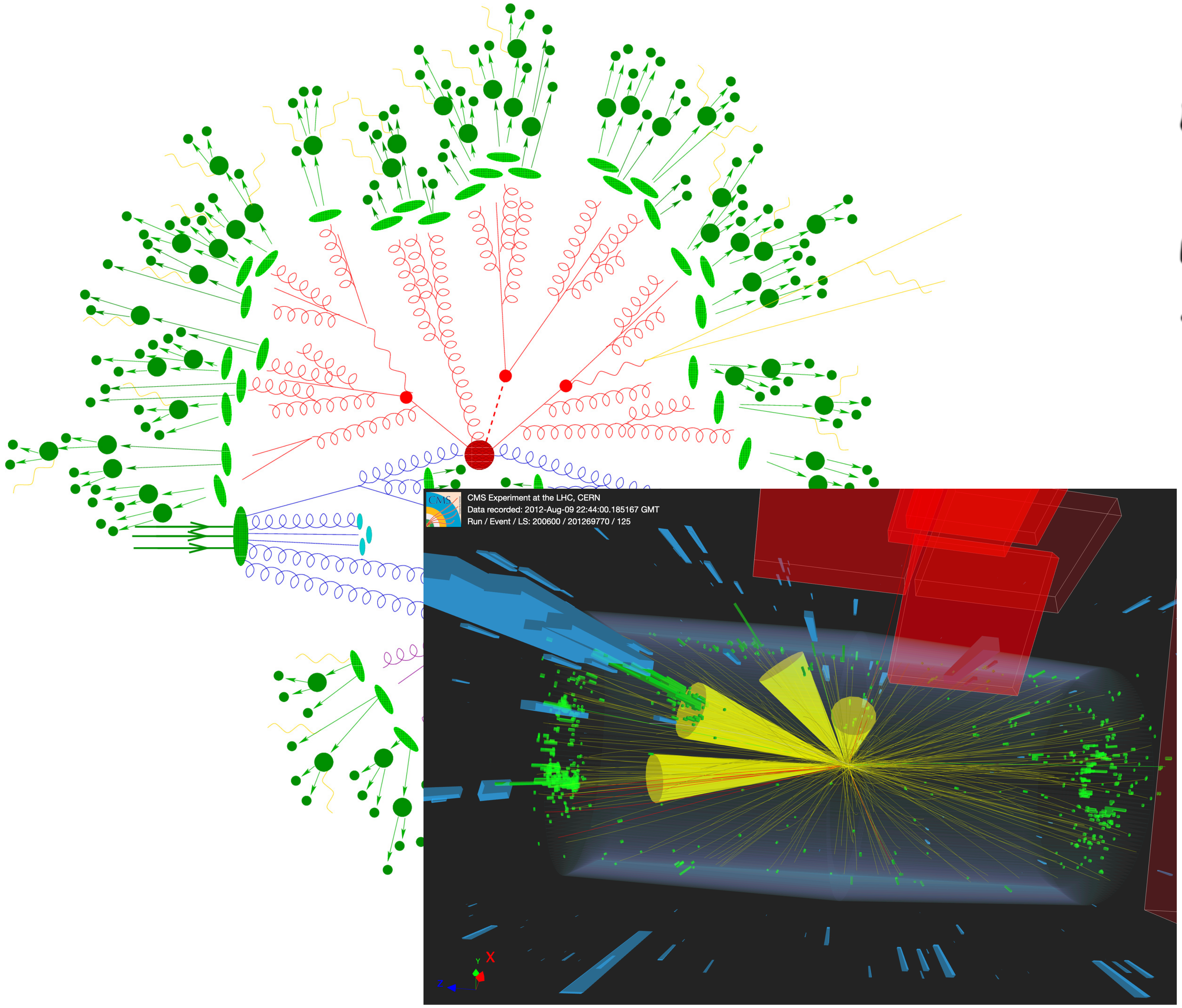
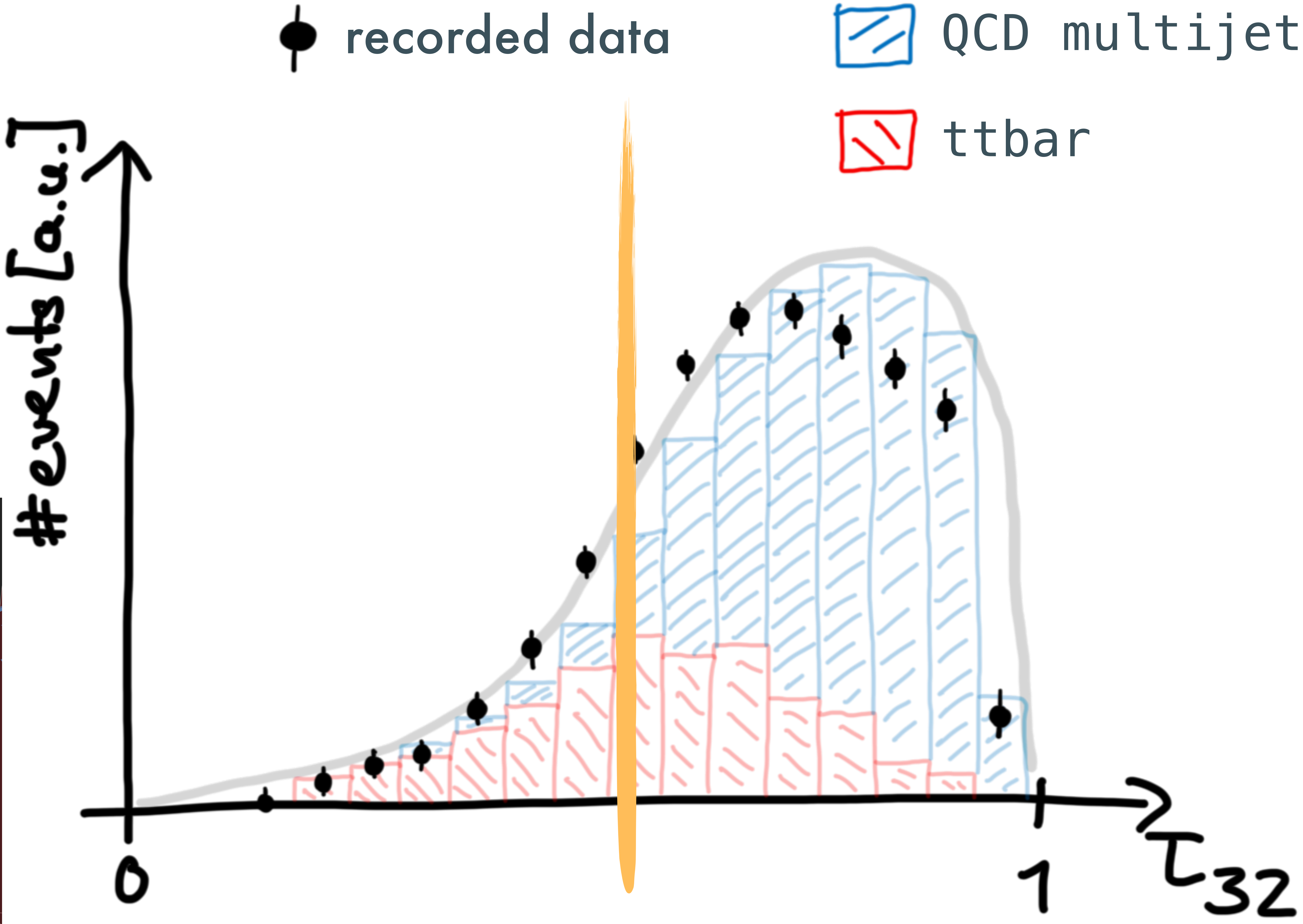
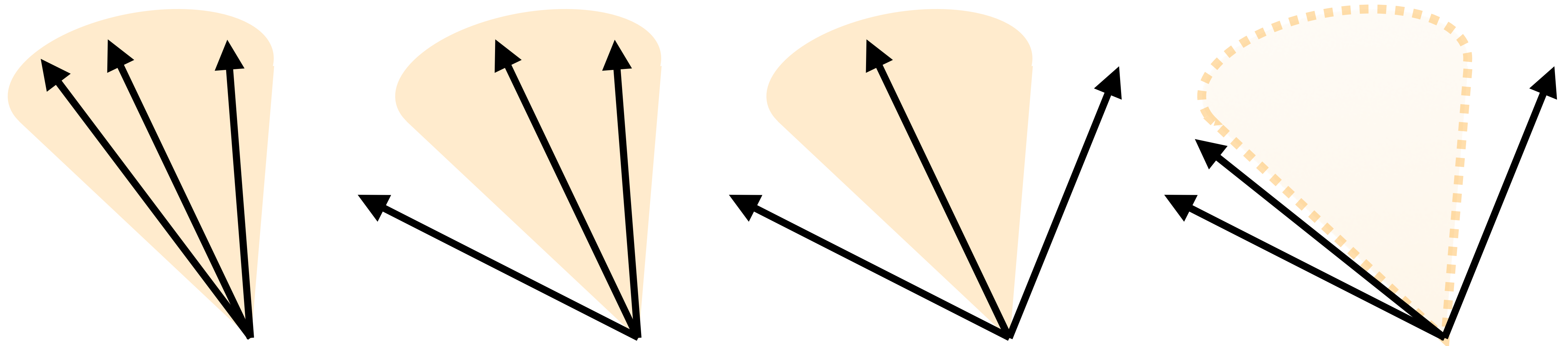




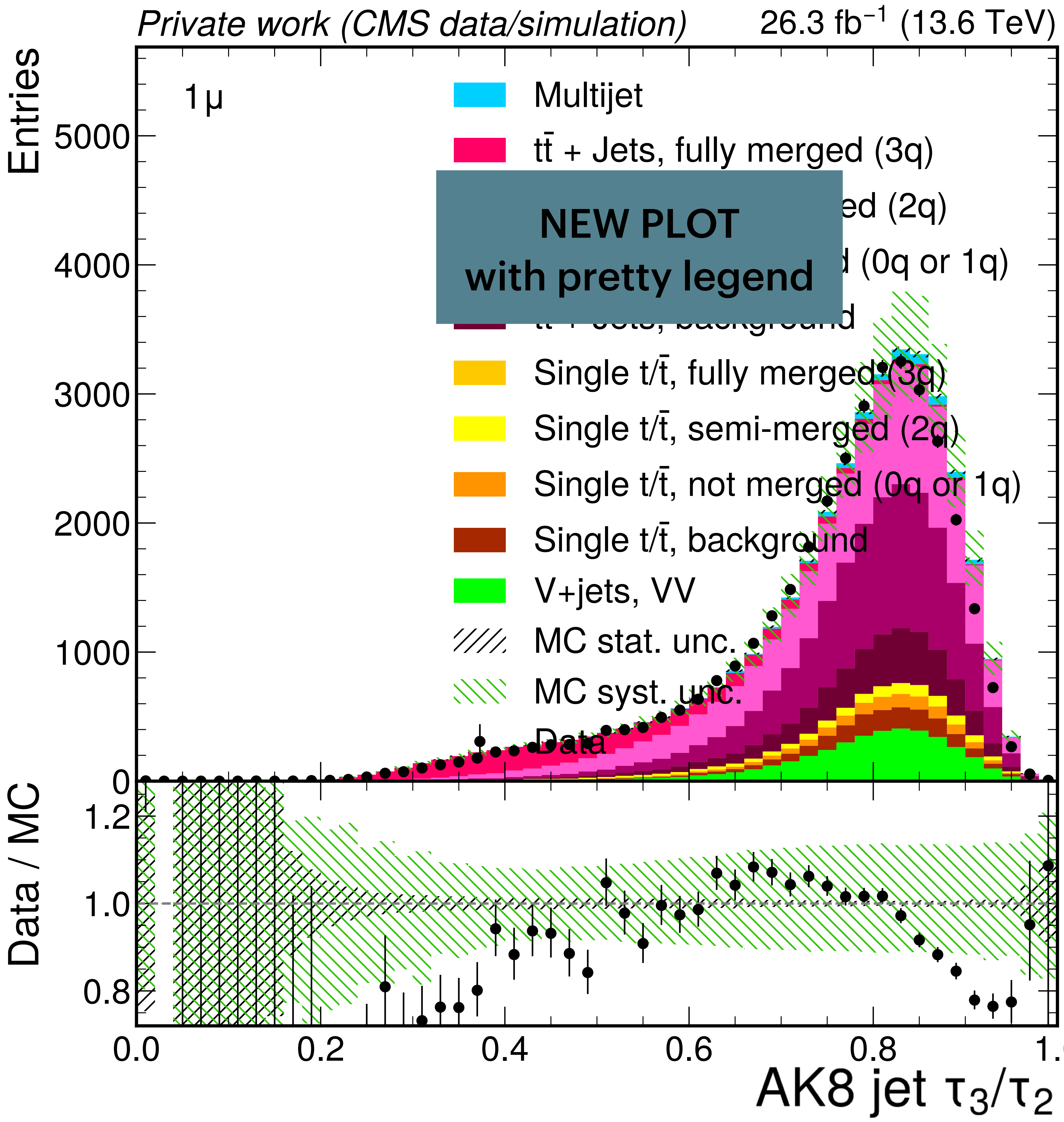
Scale Factors

— 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

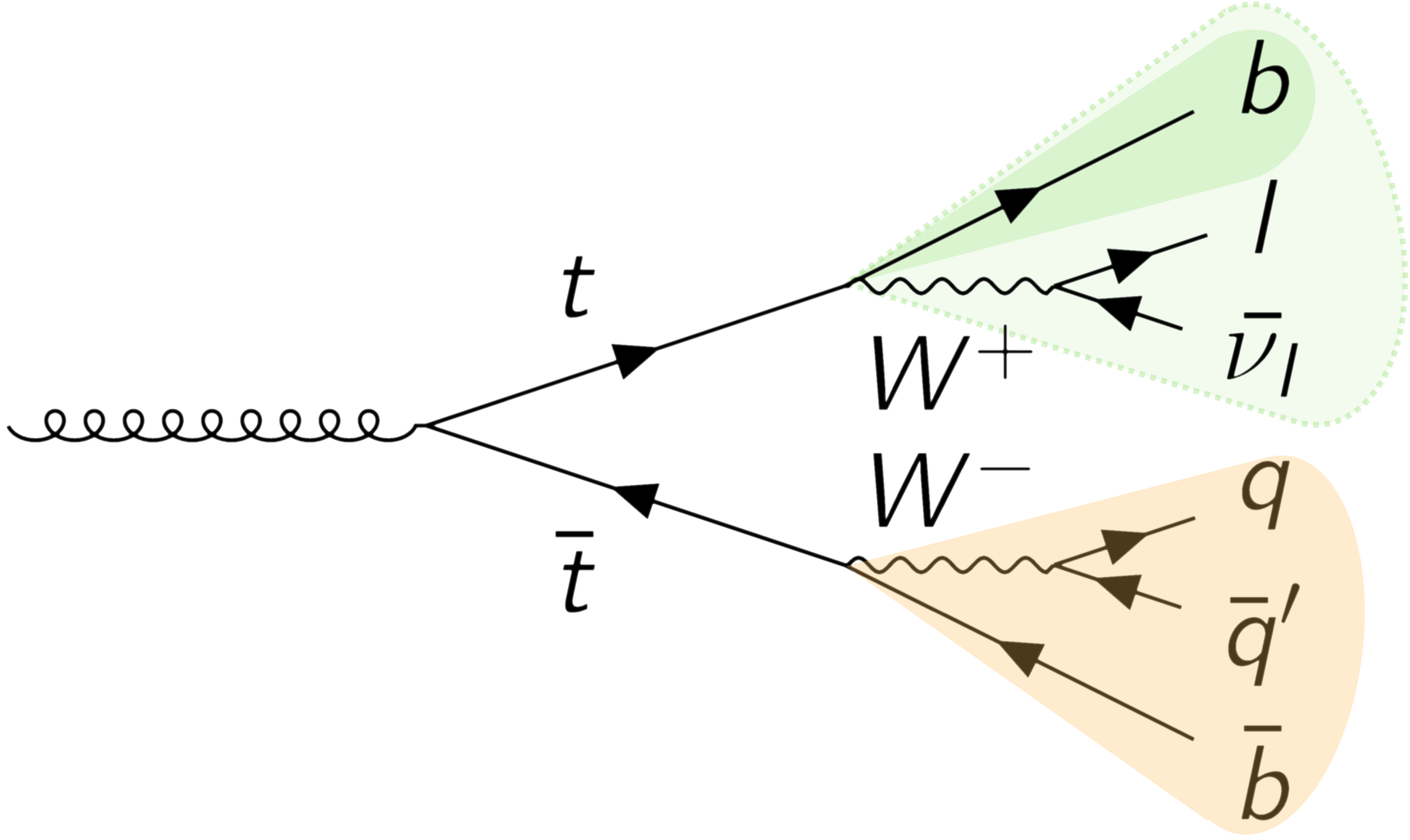


3q   2q   0o1q   background



NEW PLOT with pretty legend

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



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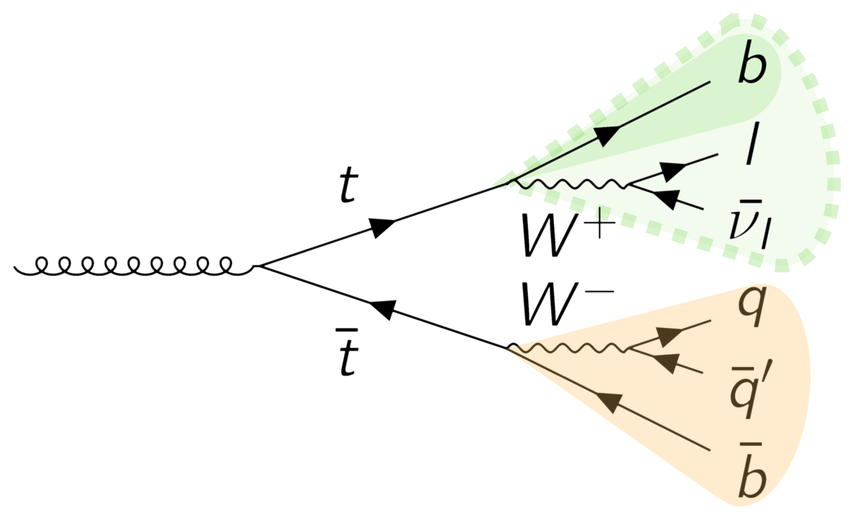
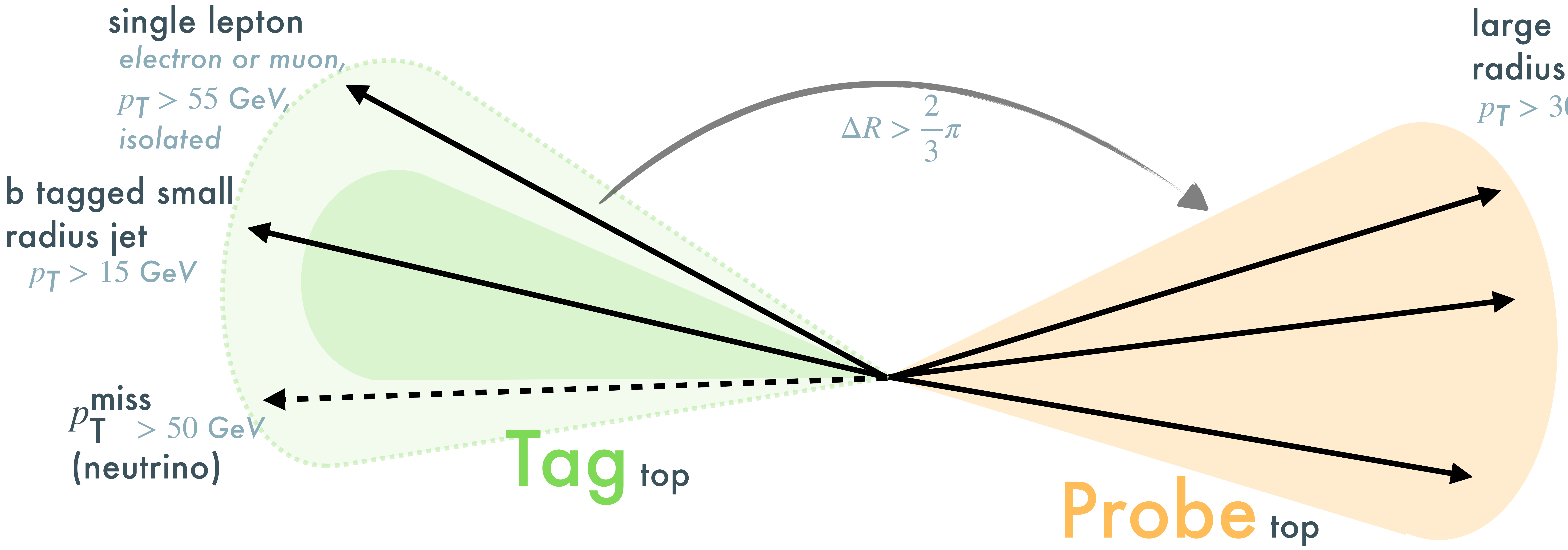
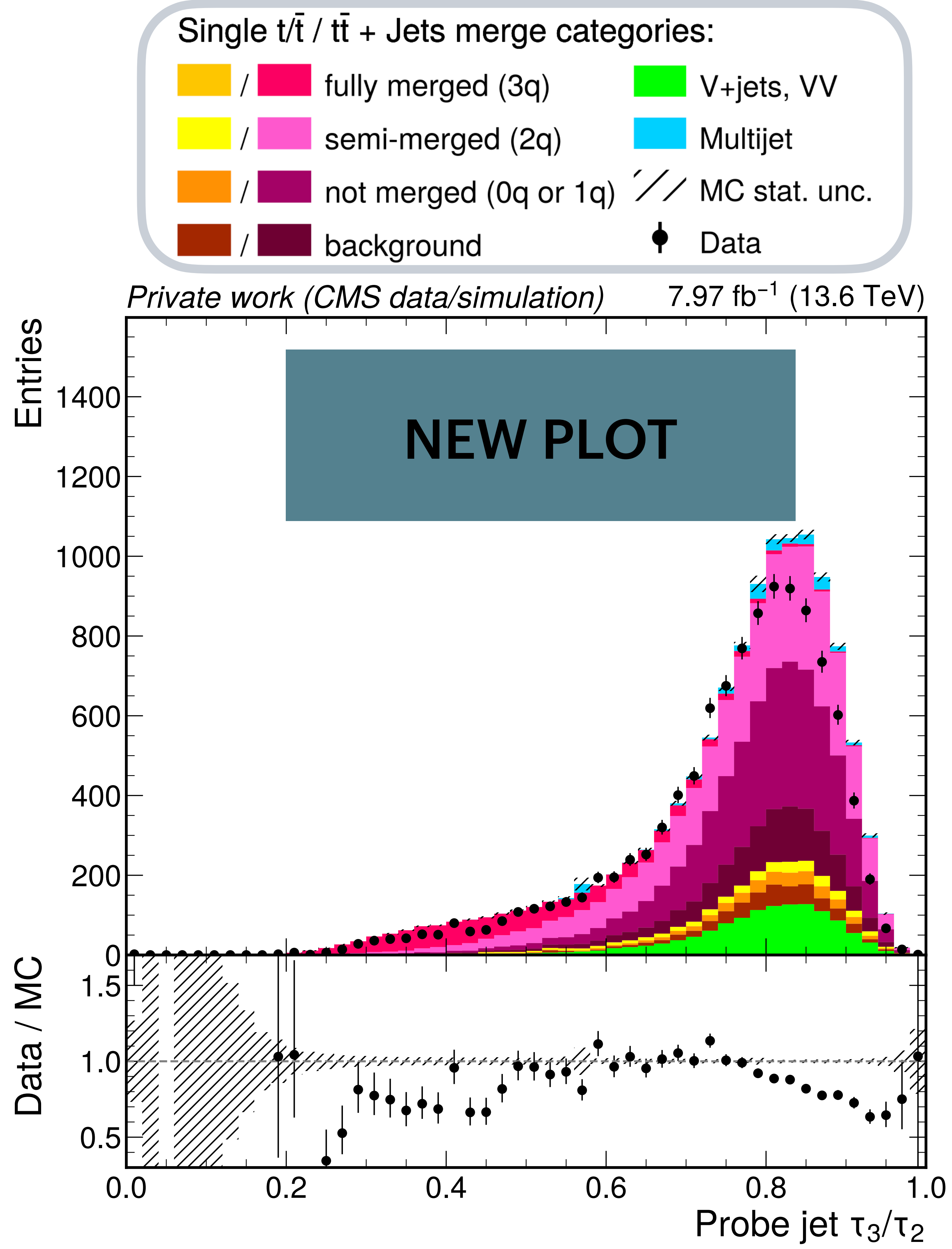


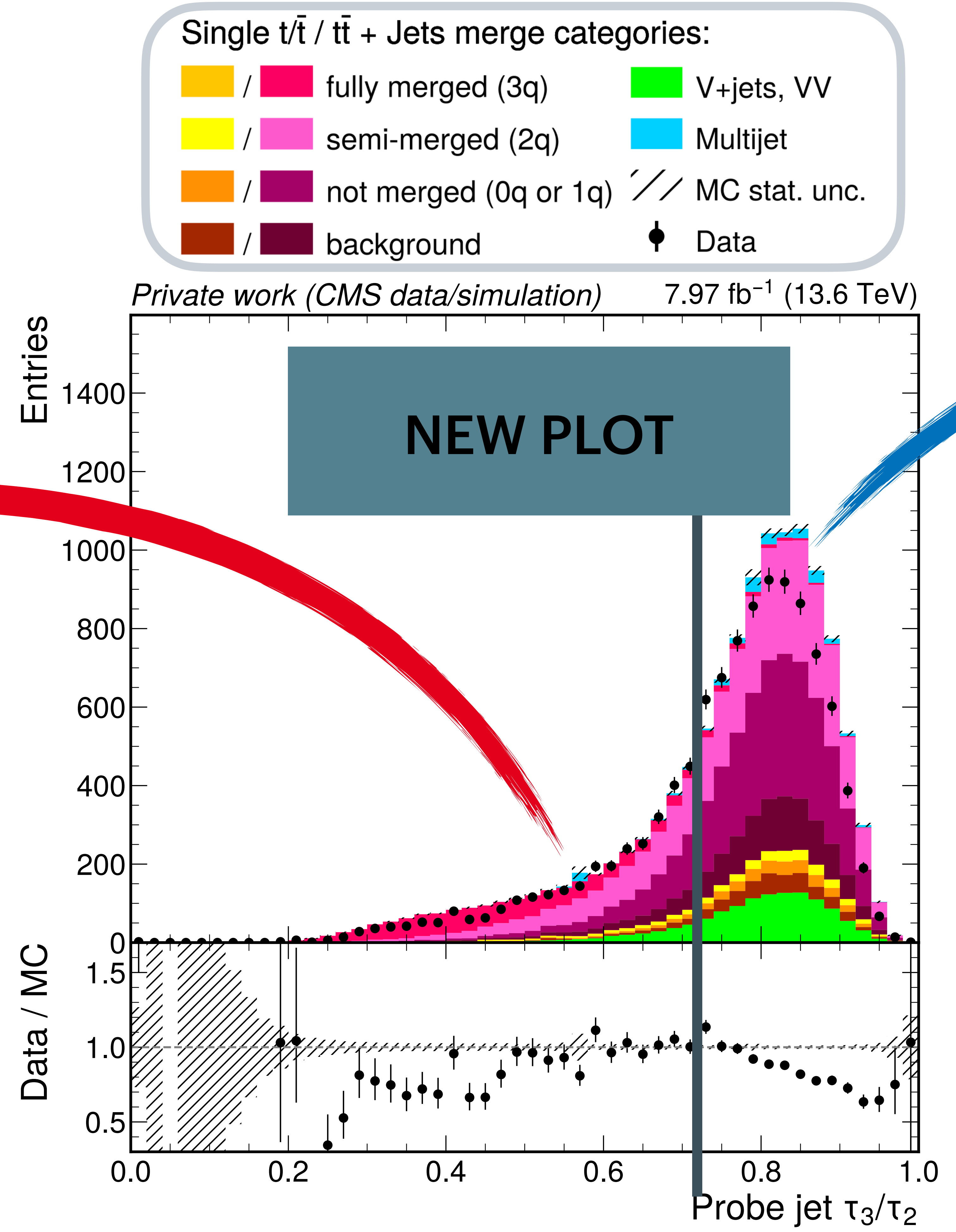


Probe Jet: τ_{32}



Probe Jet: τ_{32}

passing
τ_{32} cut



failing
τ_{32} cut

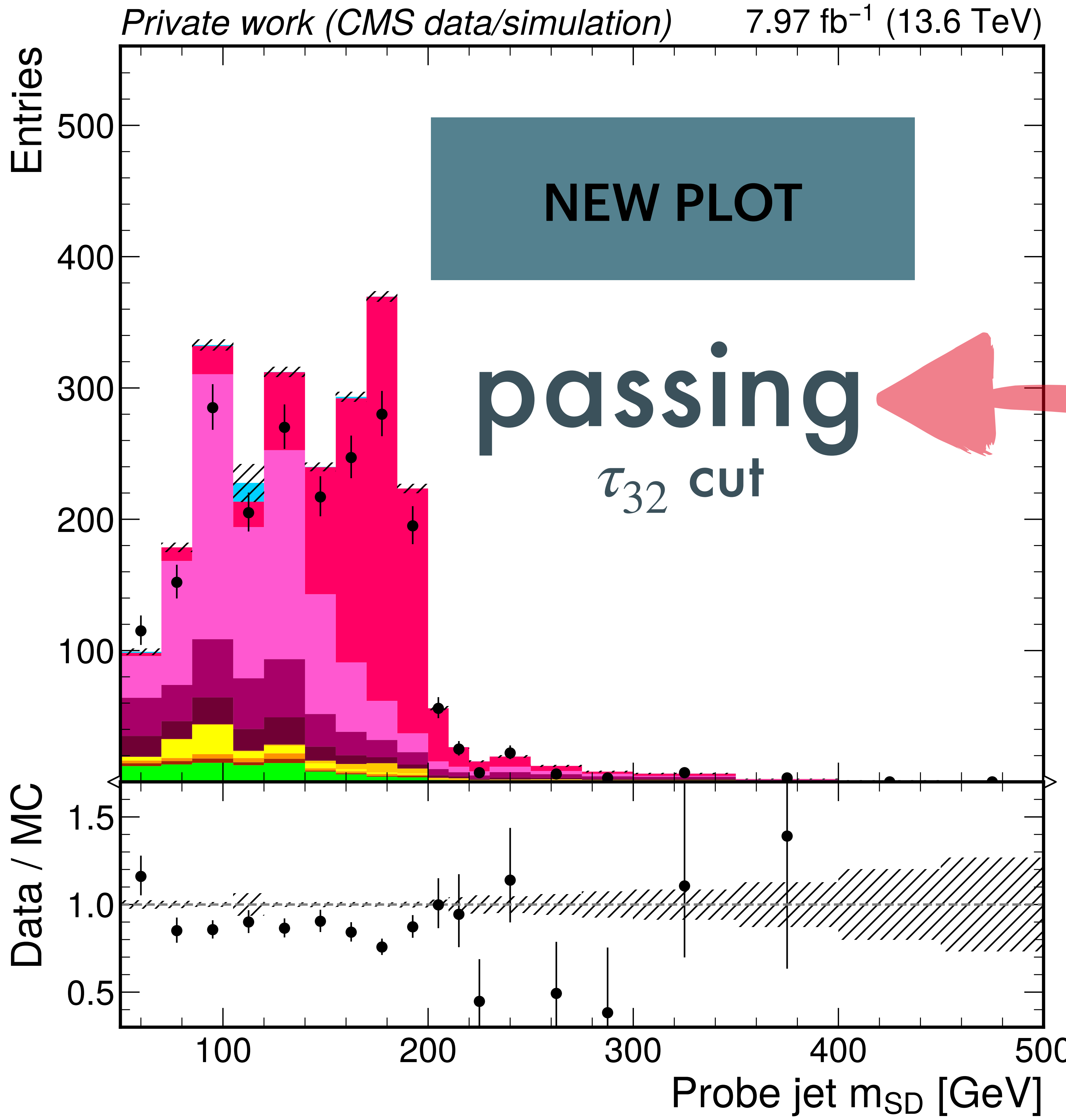
Probe Jet: τ_{32} and m_{SD}

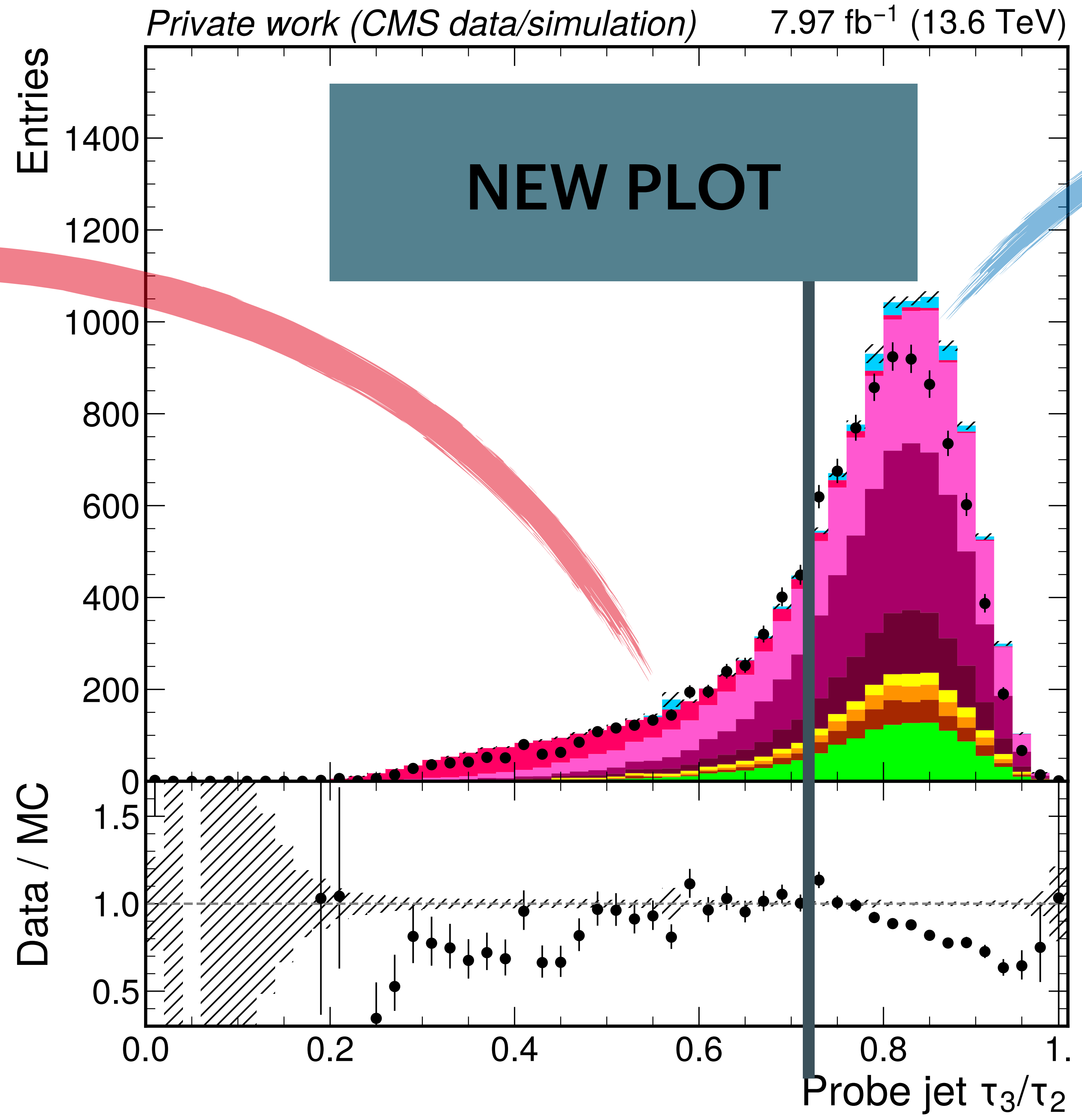
soft drop criterion $\frac{\min(p_{T1}, p_{T,2})}{p_{T1} + p_{T2}} > z_{\mathrm{cut}} \cdot \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$

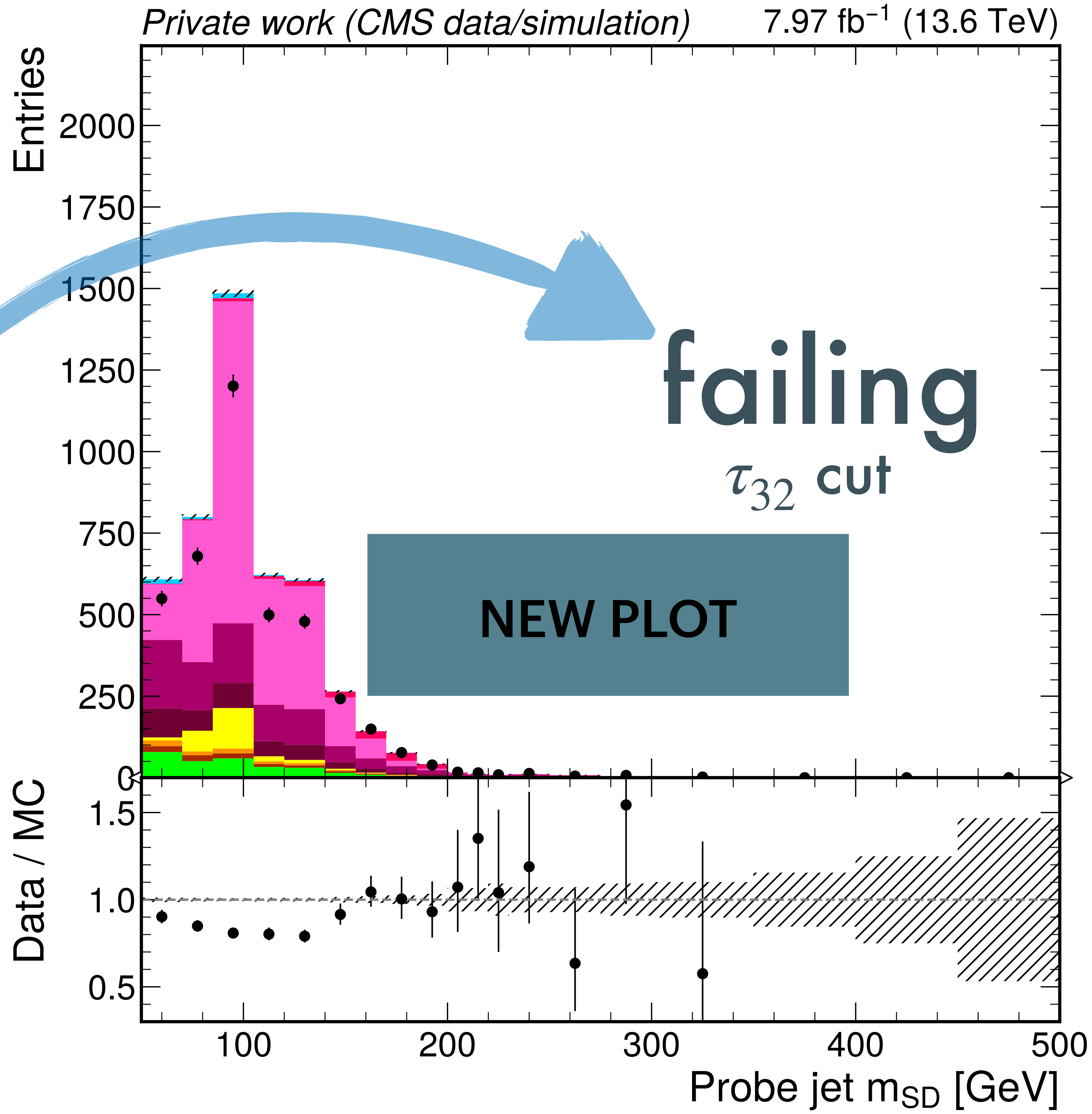
JHEP 1405 (2014) 146 - arXiv:1402.2657

Single t/$\bar{t}$ / t$\bar{t}$ + Jets merge categories:

- / fully merged (3q)
- / semi-merged (2q)
- / not merged (0q or 1q)
- / background
- V+jets, VV
- Multijet
- MC stat. unc.
- Data



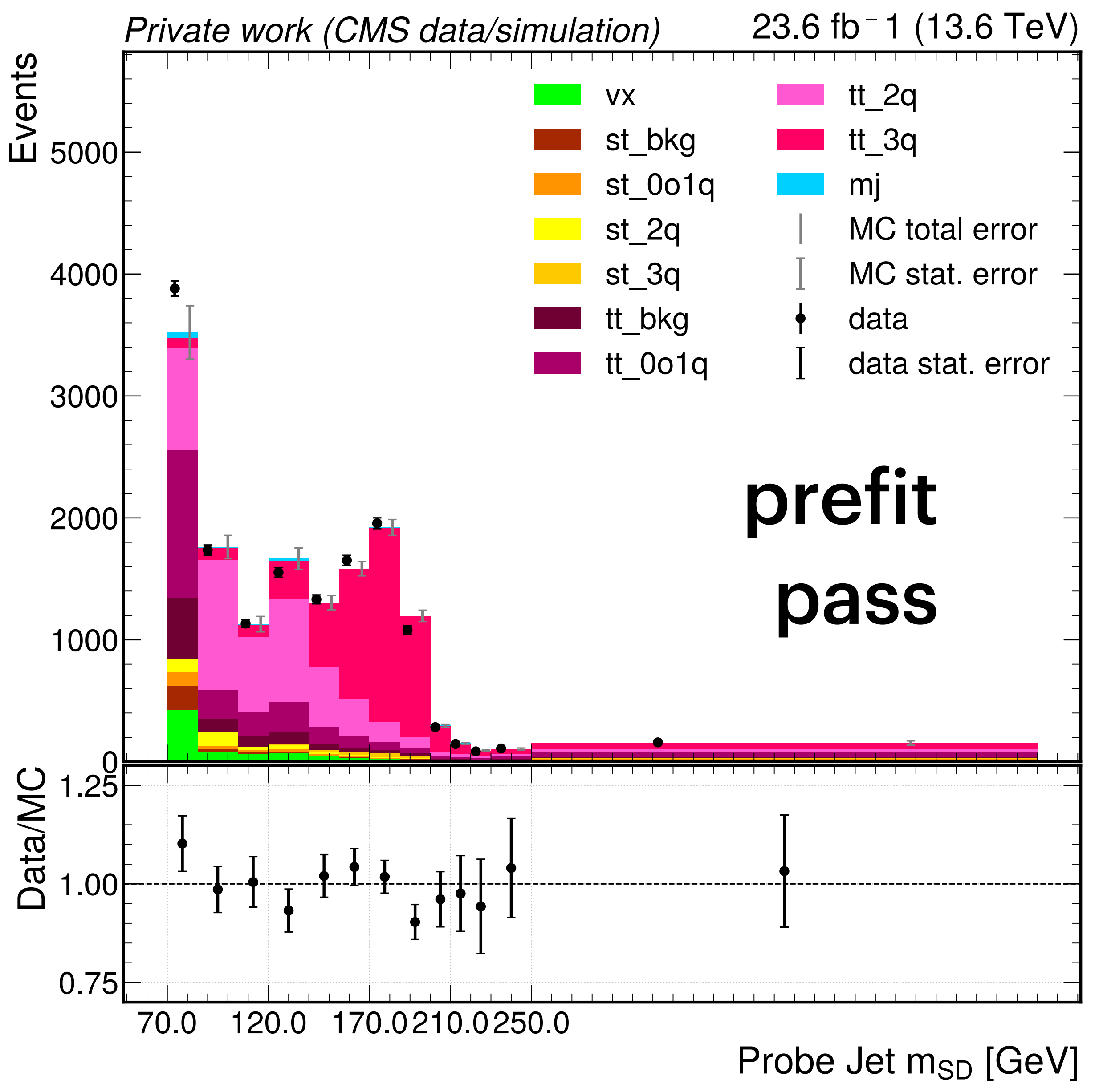


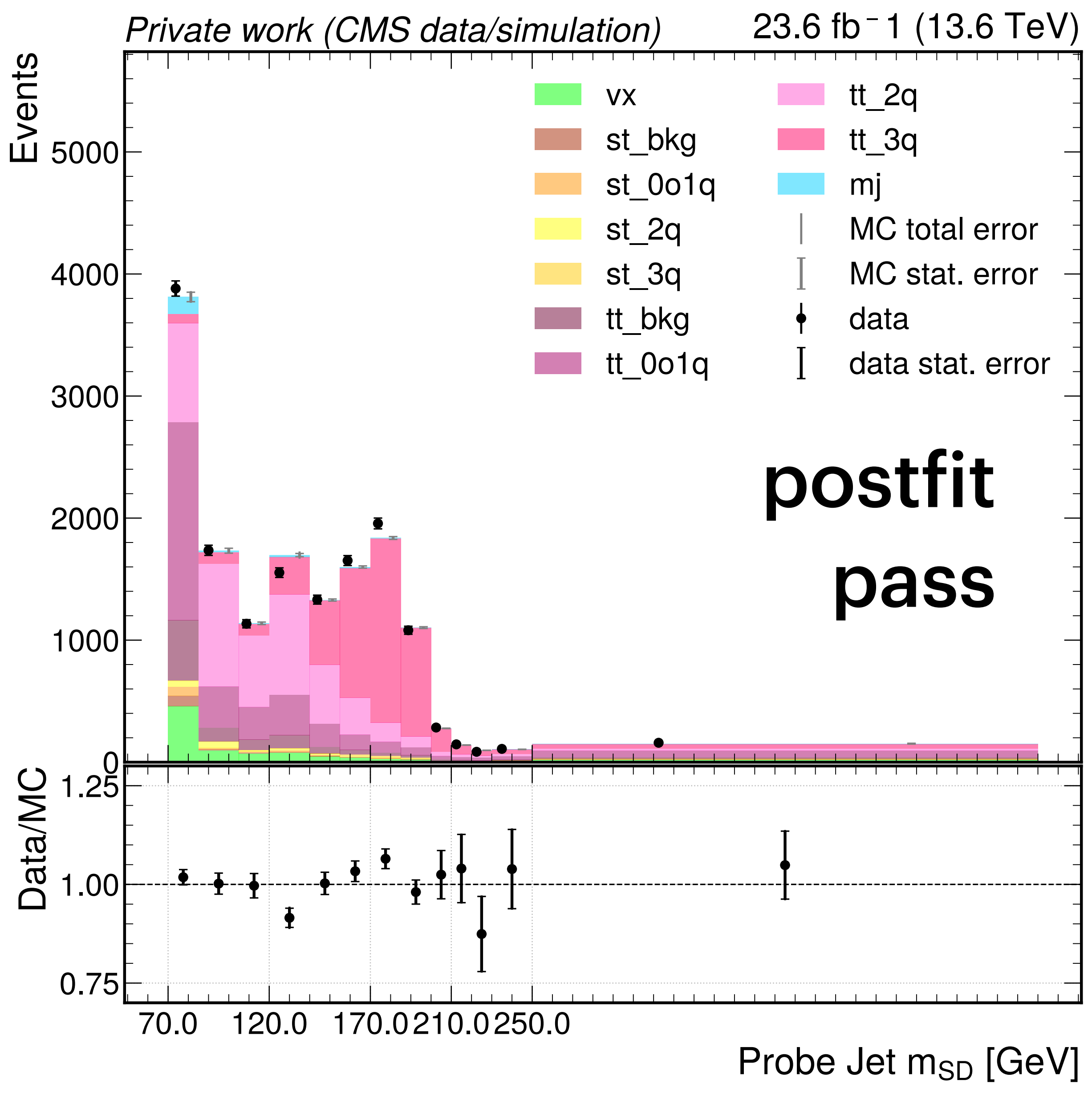


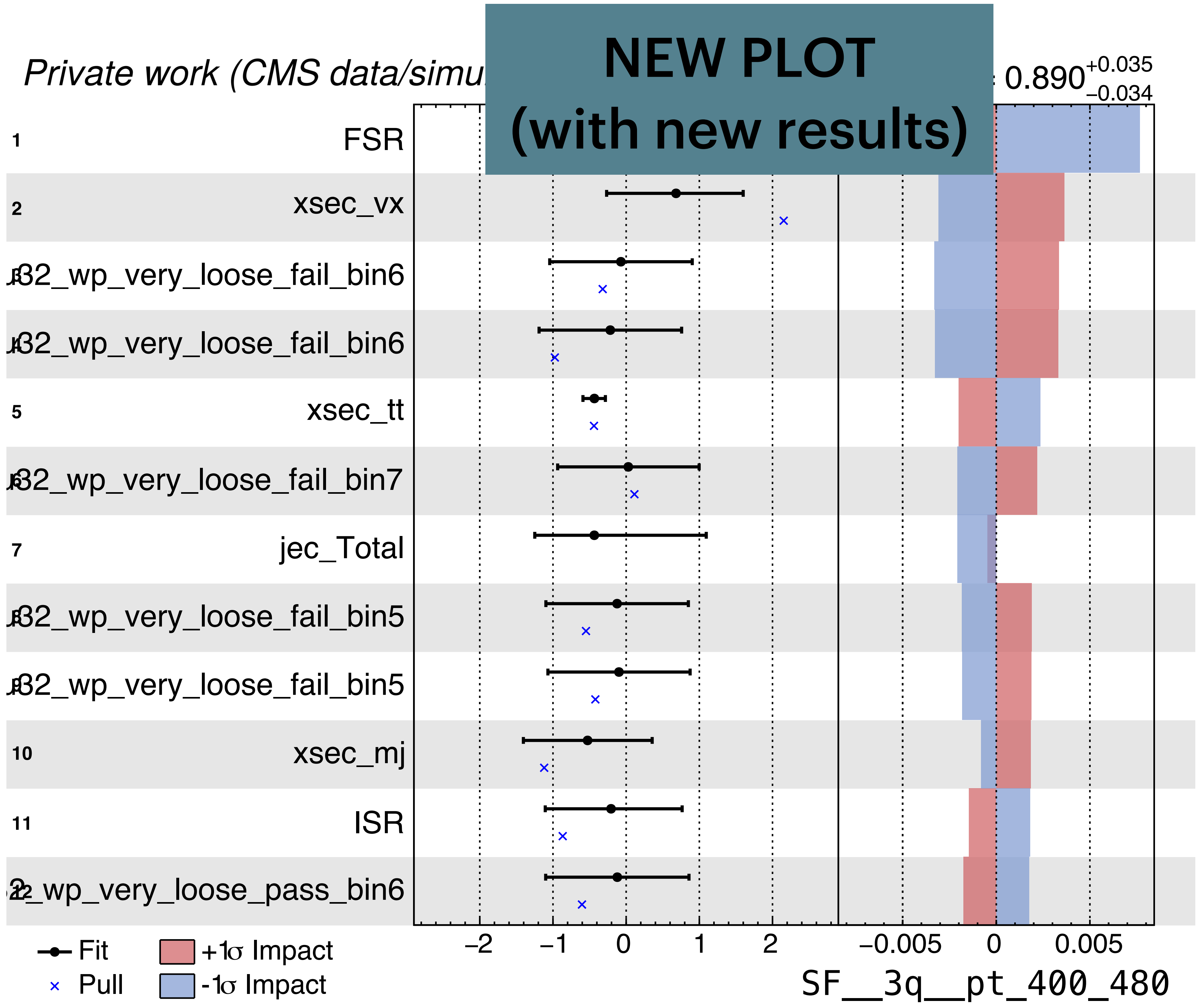
SF Derivation

— 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, FSR largest impact







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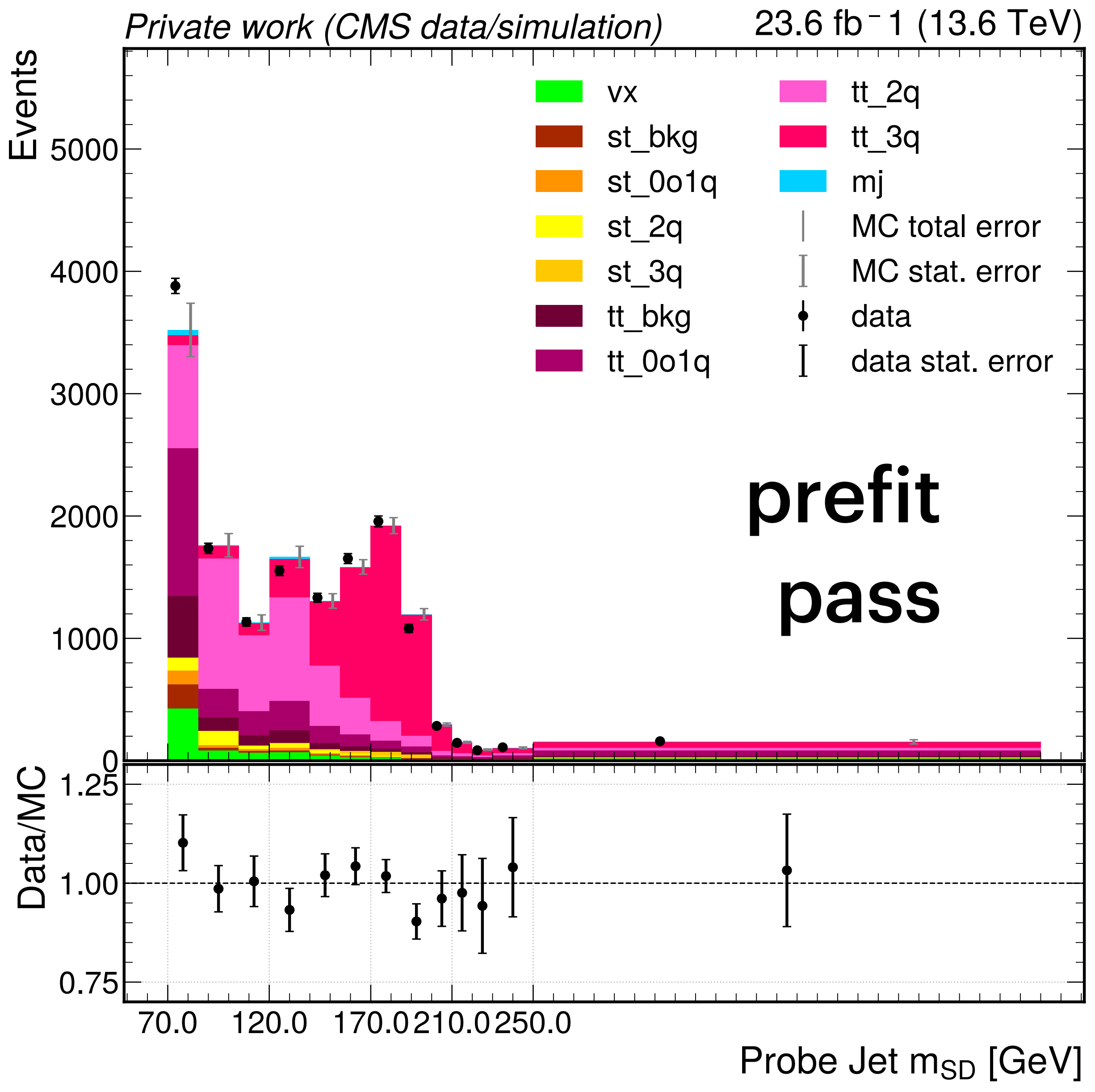
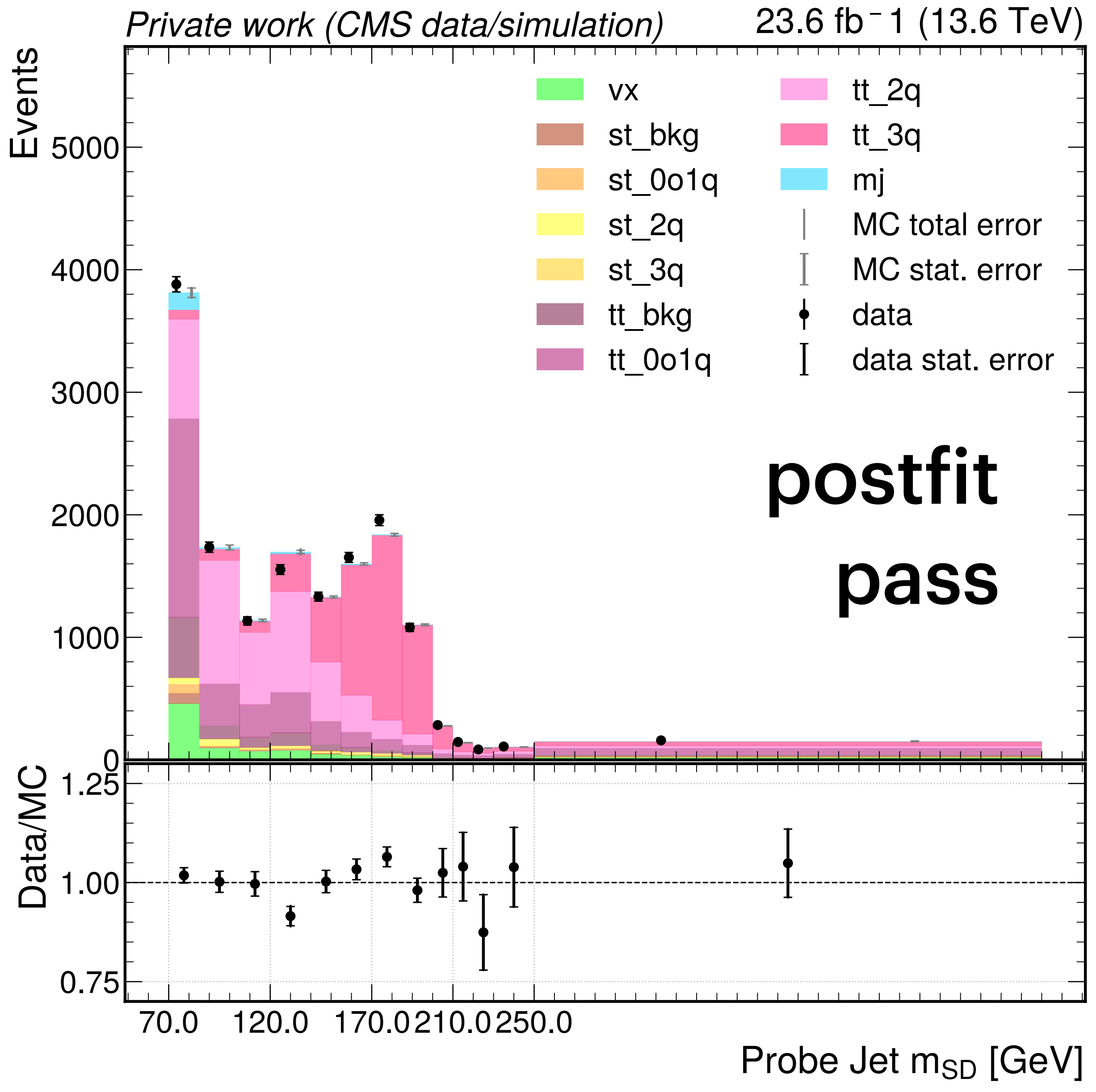
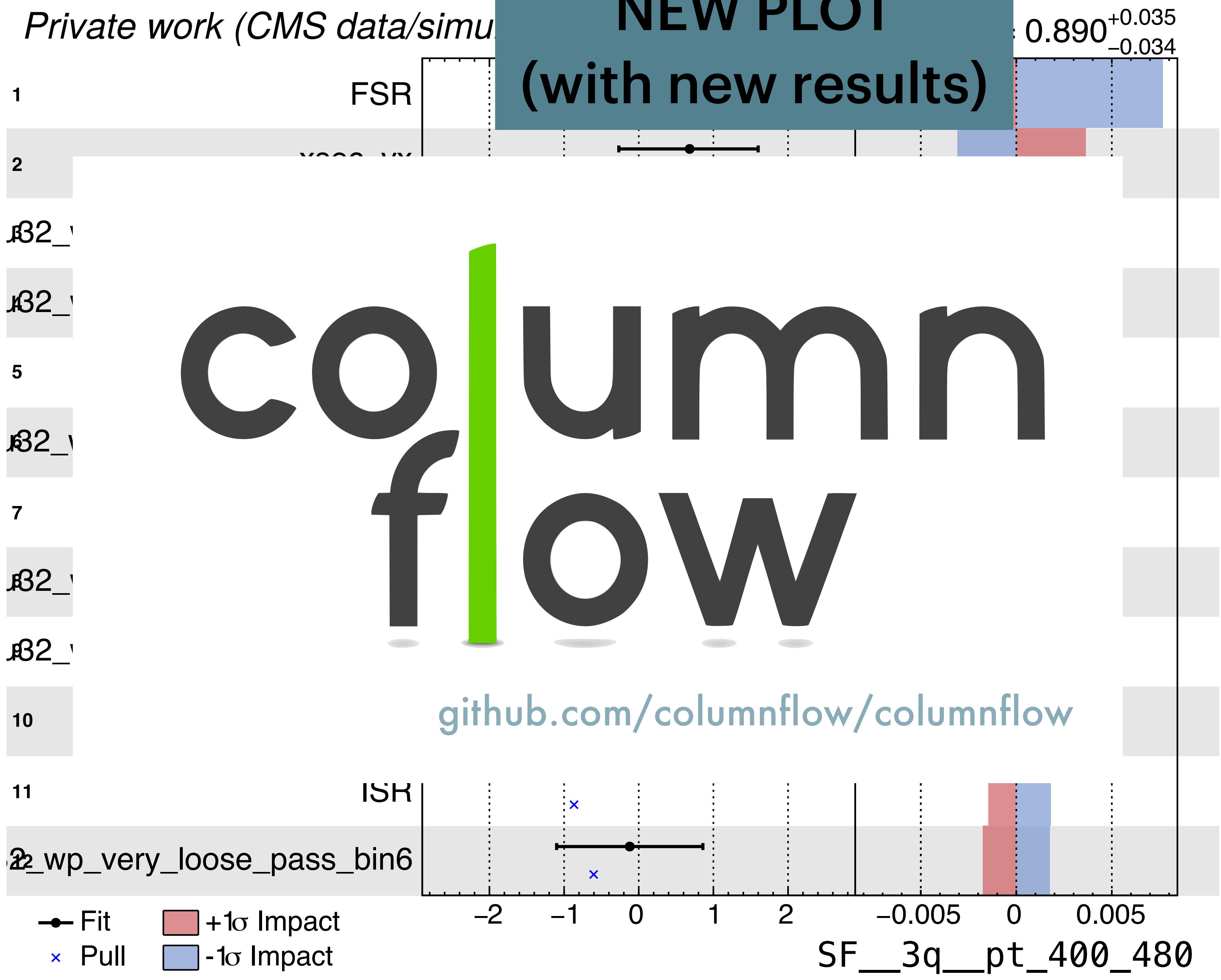
Quick and automated derivation of SF essential to be used in analyses.



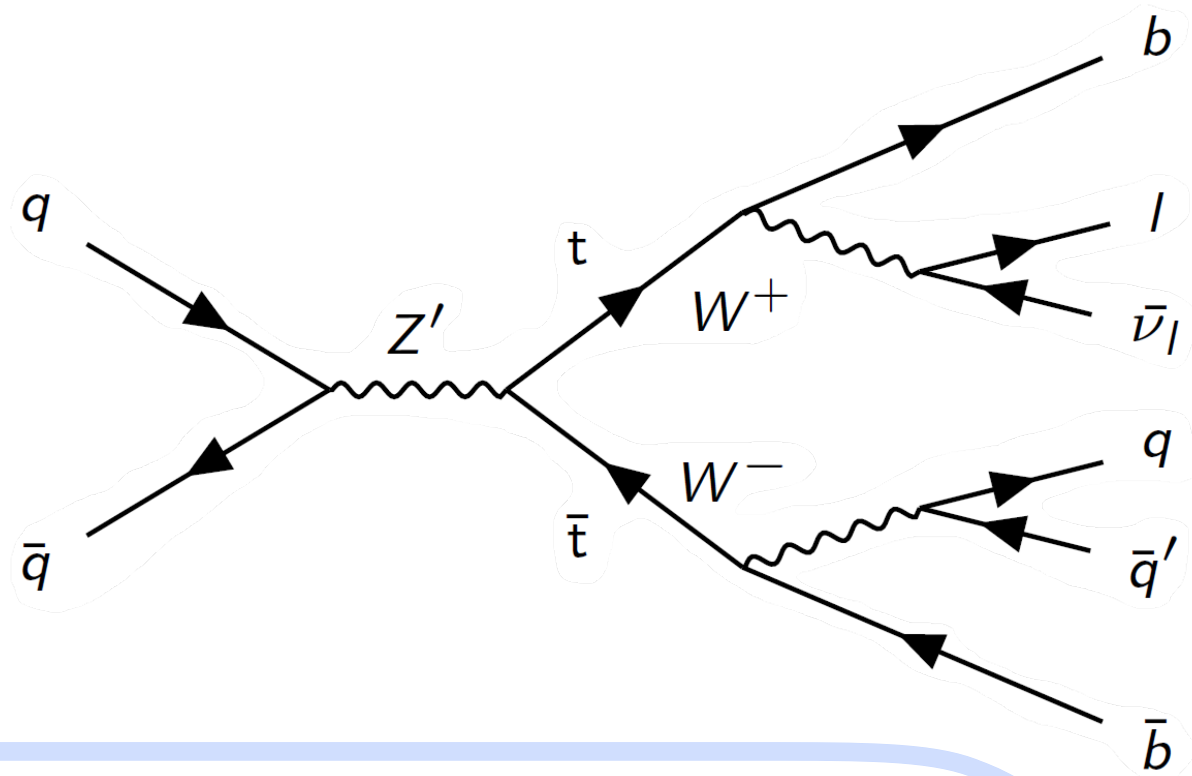


NEW PLOT (with new results)



Analysis Strategy

— searching for Z' bosons —



I. Selection

$t\bar{t}$ events with lepton+jets final state objects

II. Reconstruction

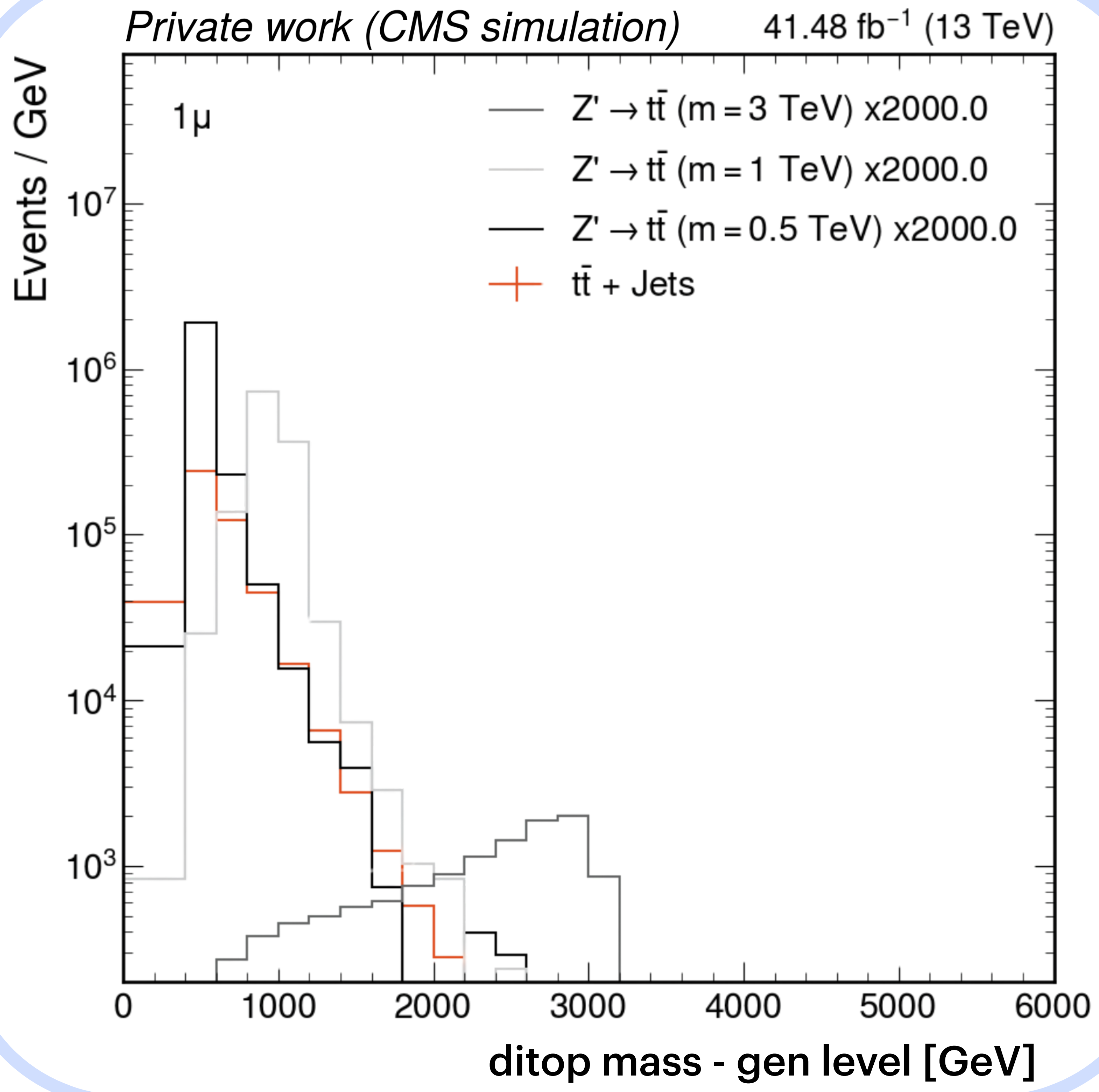
kinematics of the $t\bar{t}$ system

III. Event Classification

using machine learning

IV. Statistical Analysis

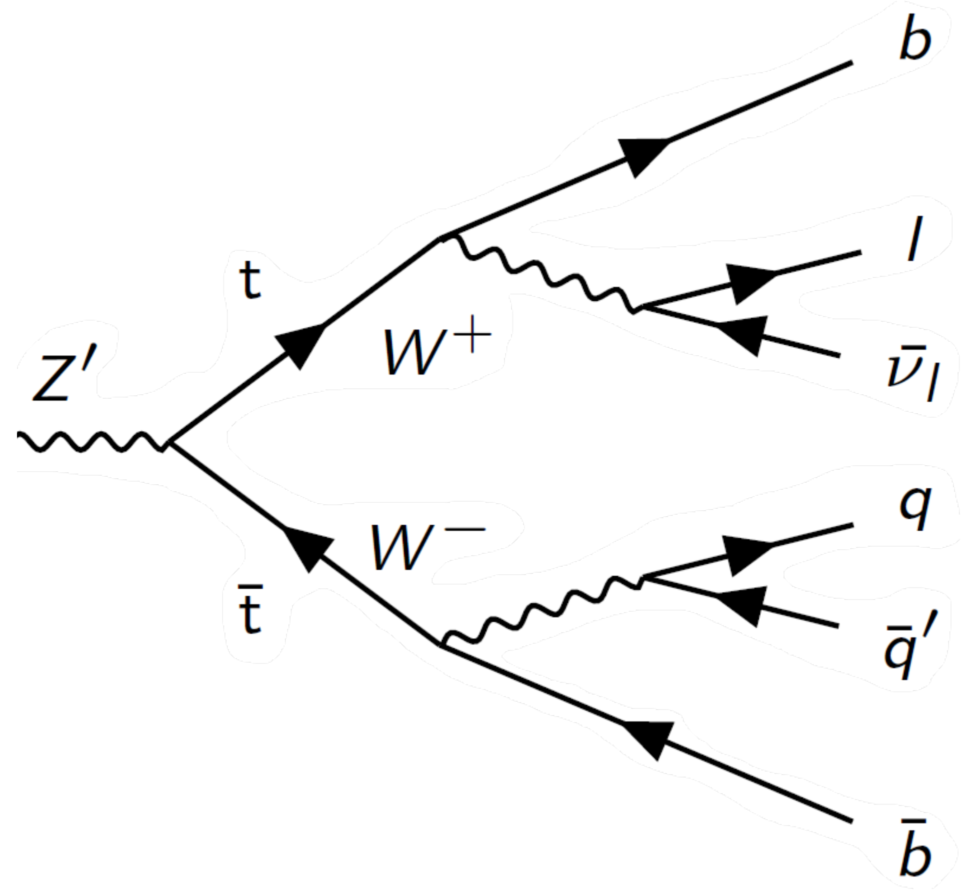
bump hunt or set limits



Search for New Physics Effects ...

calibrate events/objects

select events



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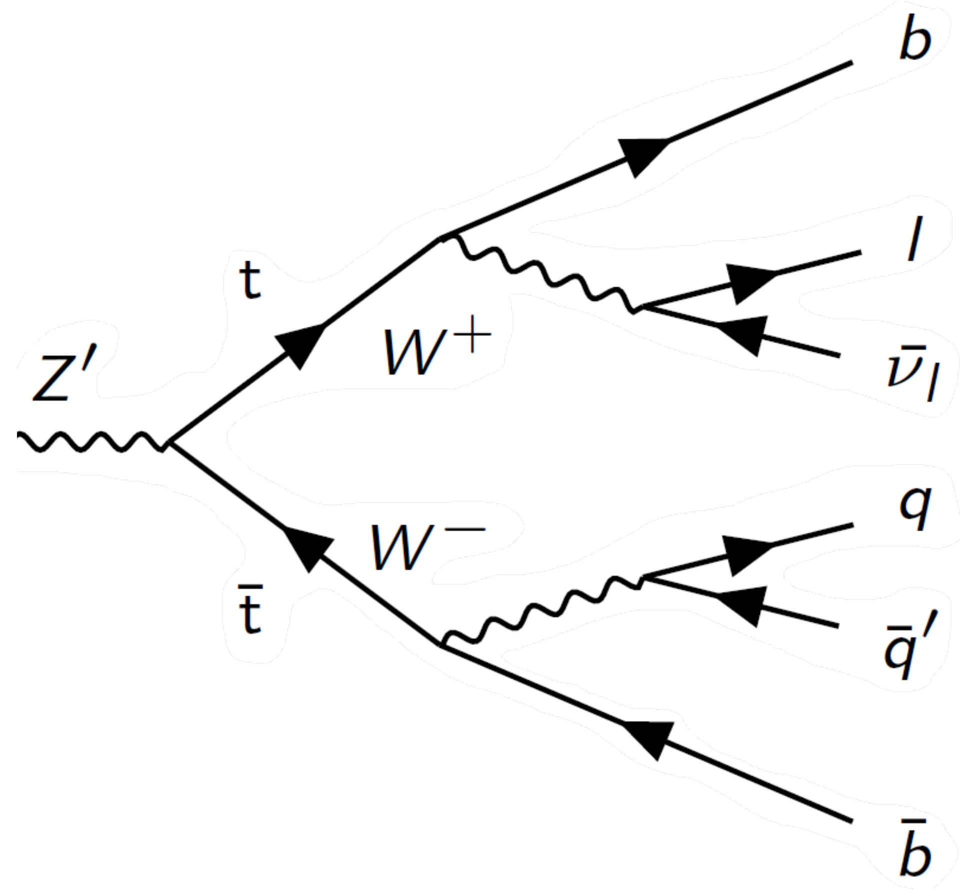


AK8 jet present?

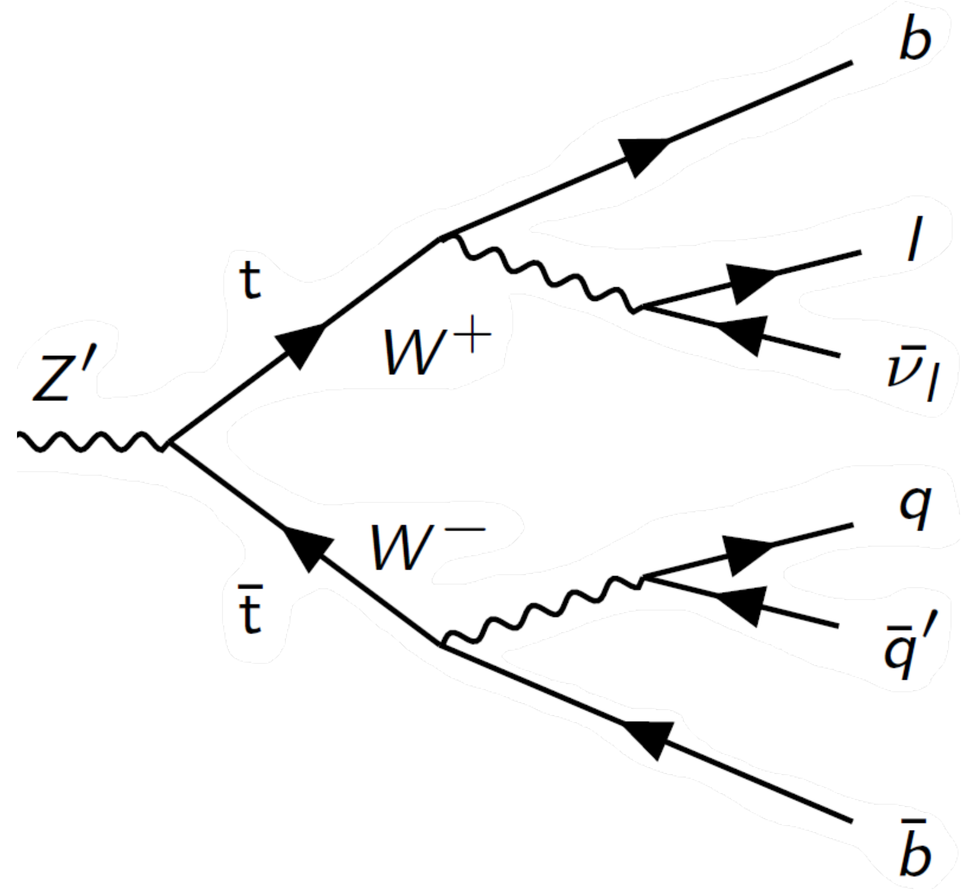
✓

boosted reconstruction

Search for New Physics Effects …

calibrate events/objects

select events



AK8 jet present?

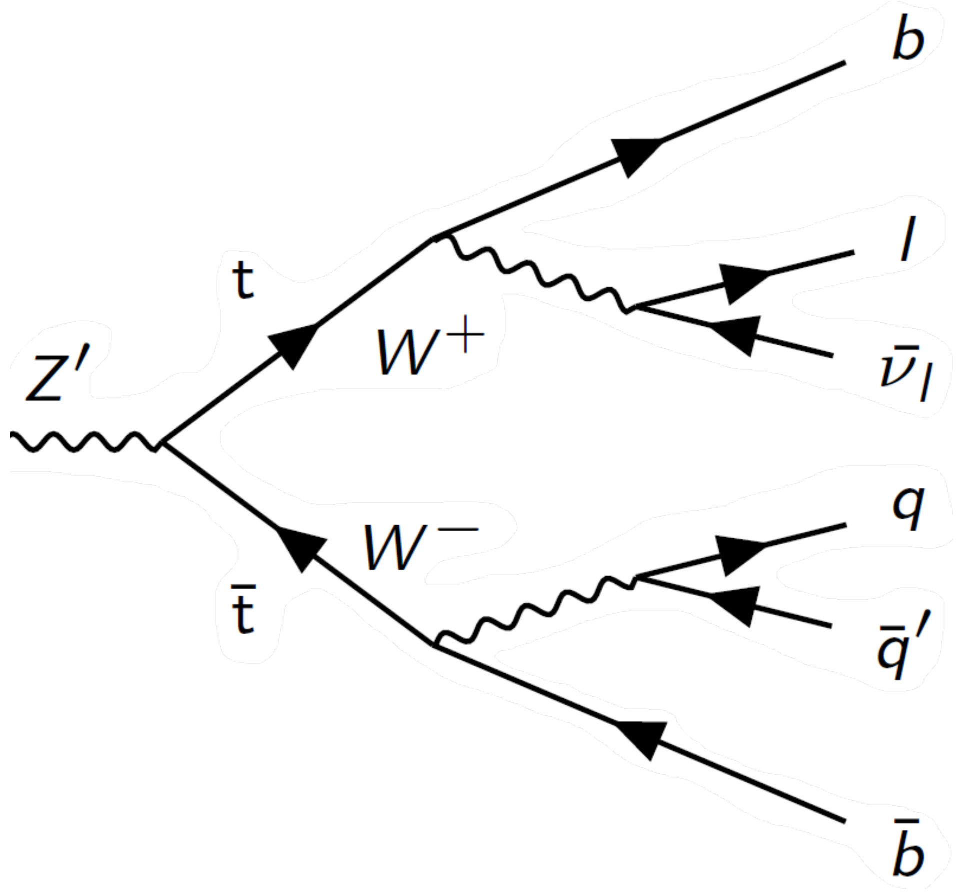
resolved reconstruction

boosted reconstruction

Search for New Physics Effects ...

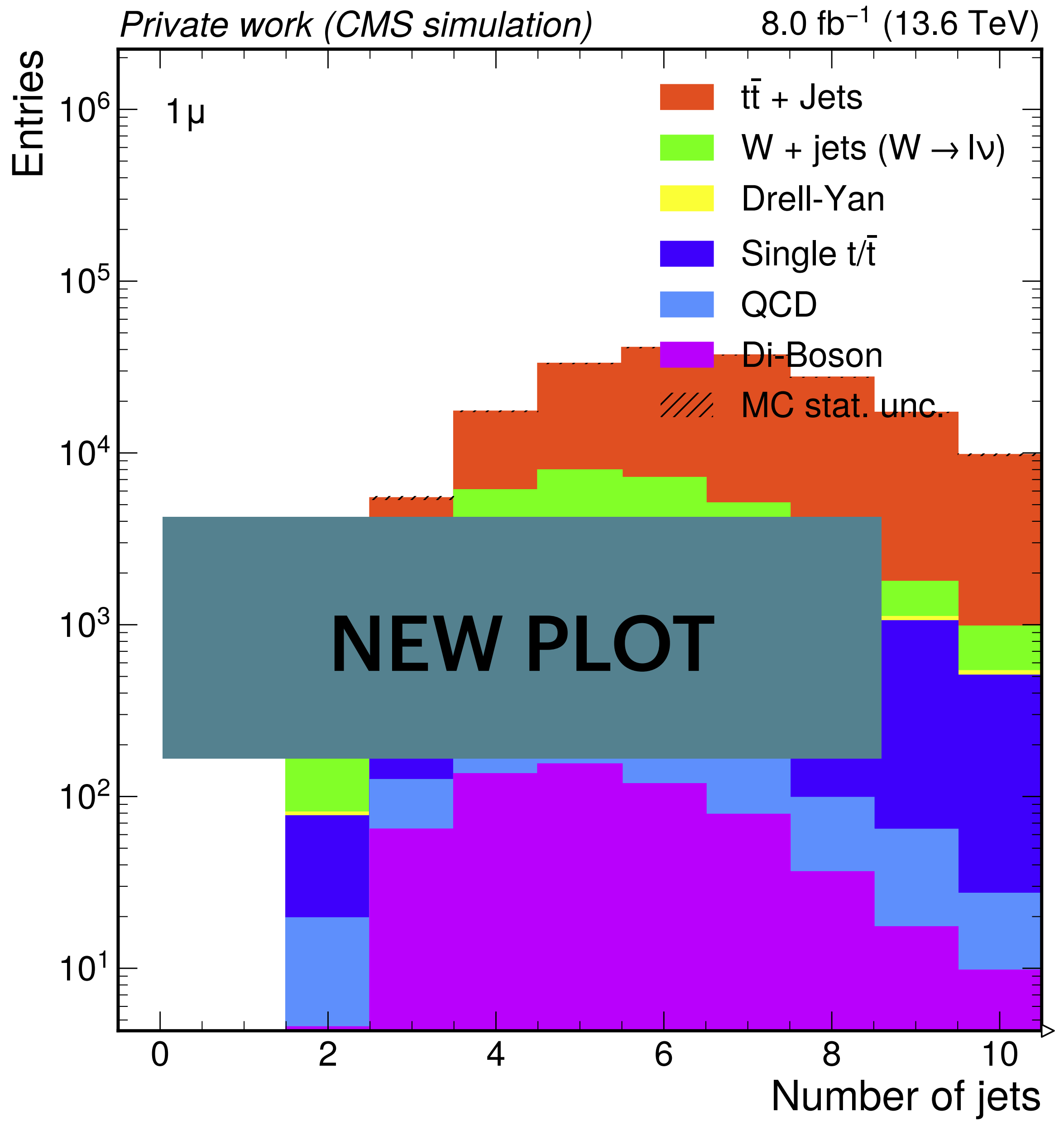
calibrate events/objects

select events



AK8 jet present?

resolved reconstruction

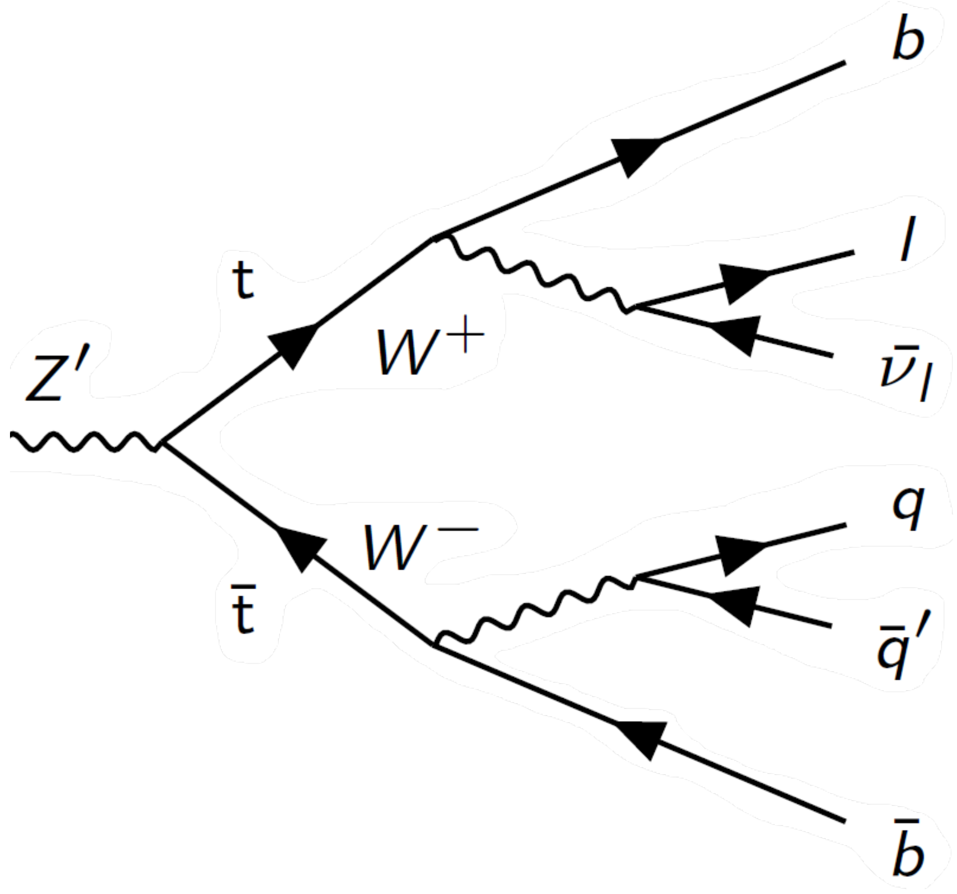


boosted reconstruction

Search for New Physics Effects …

calibrate events/objects

select events



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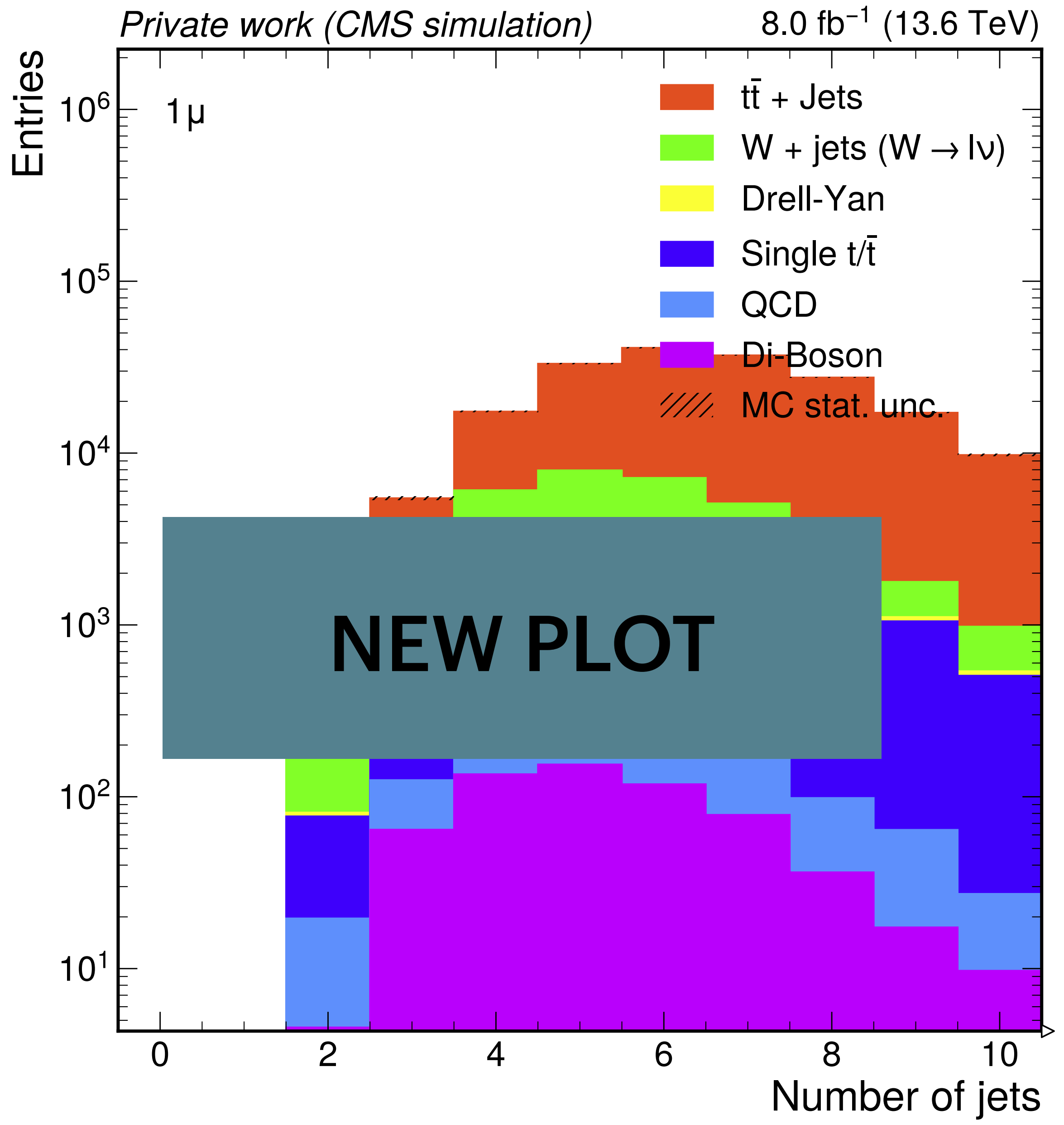


boosted reconstruction

choose best jet combination 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

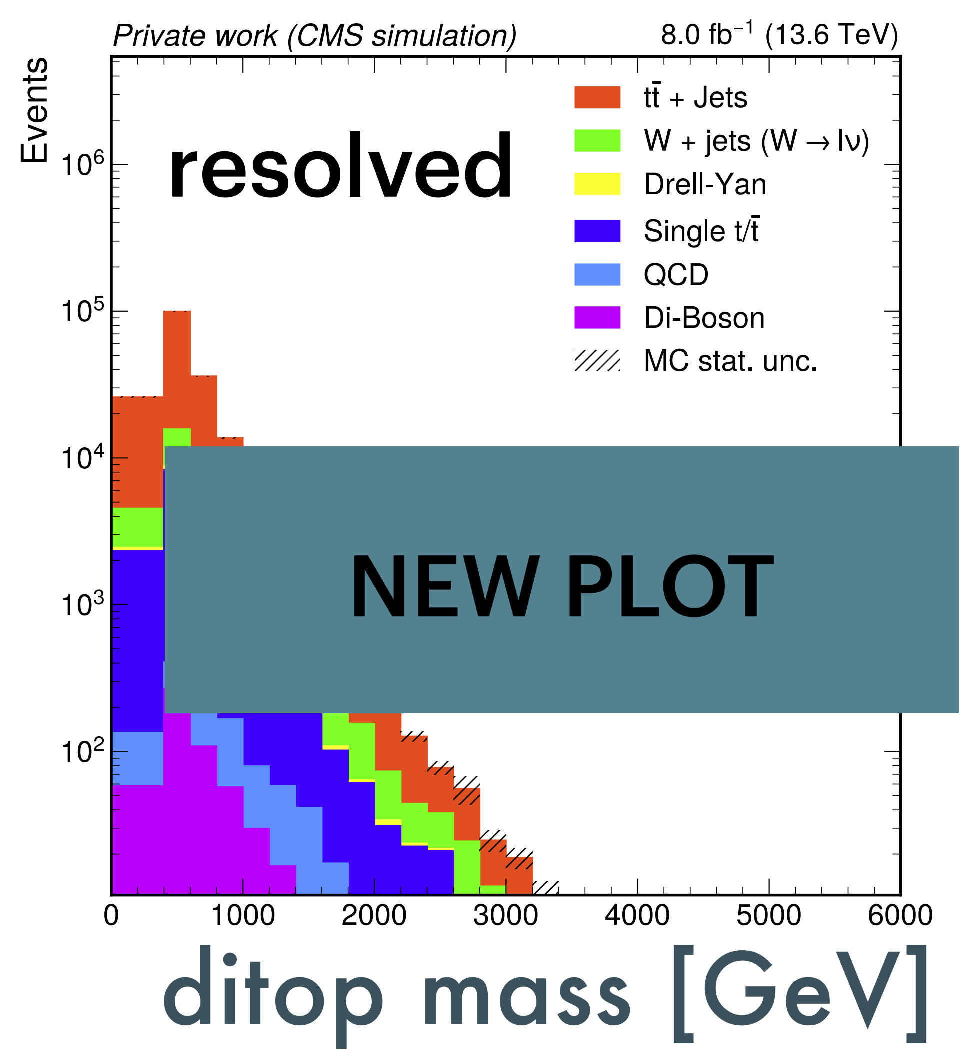
NEW PLOT

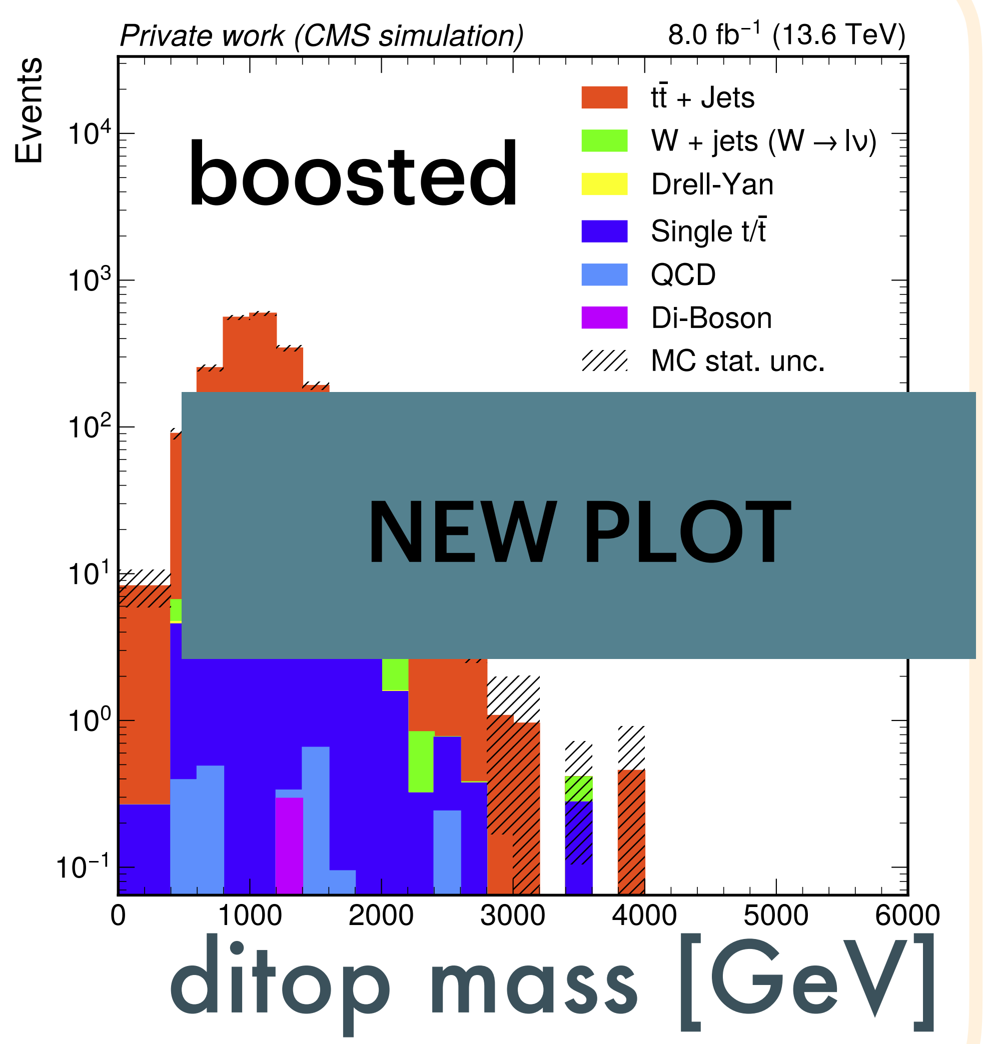
$\chi^2 < 30$

NEW PLOT

... In the Ditop Mass Spectrum

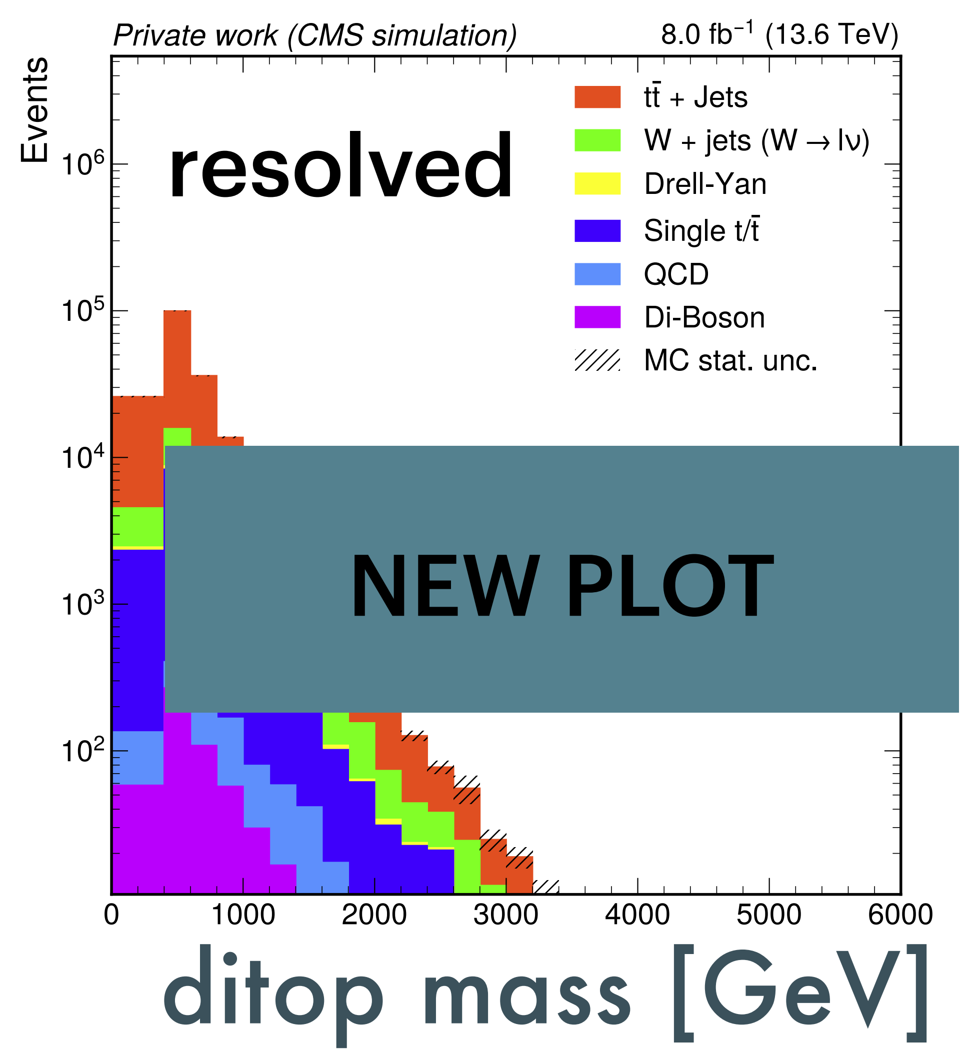
$\chi^2 < 30$

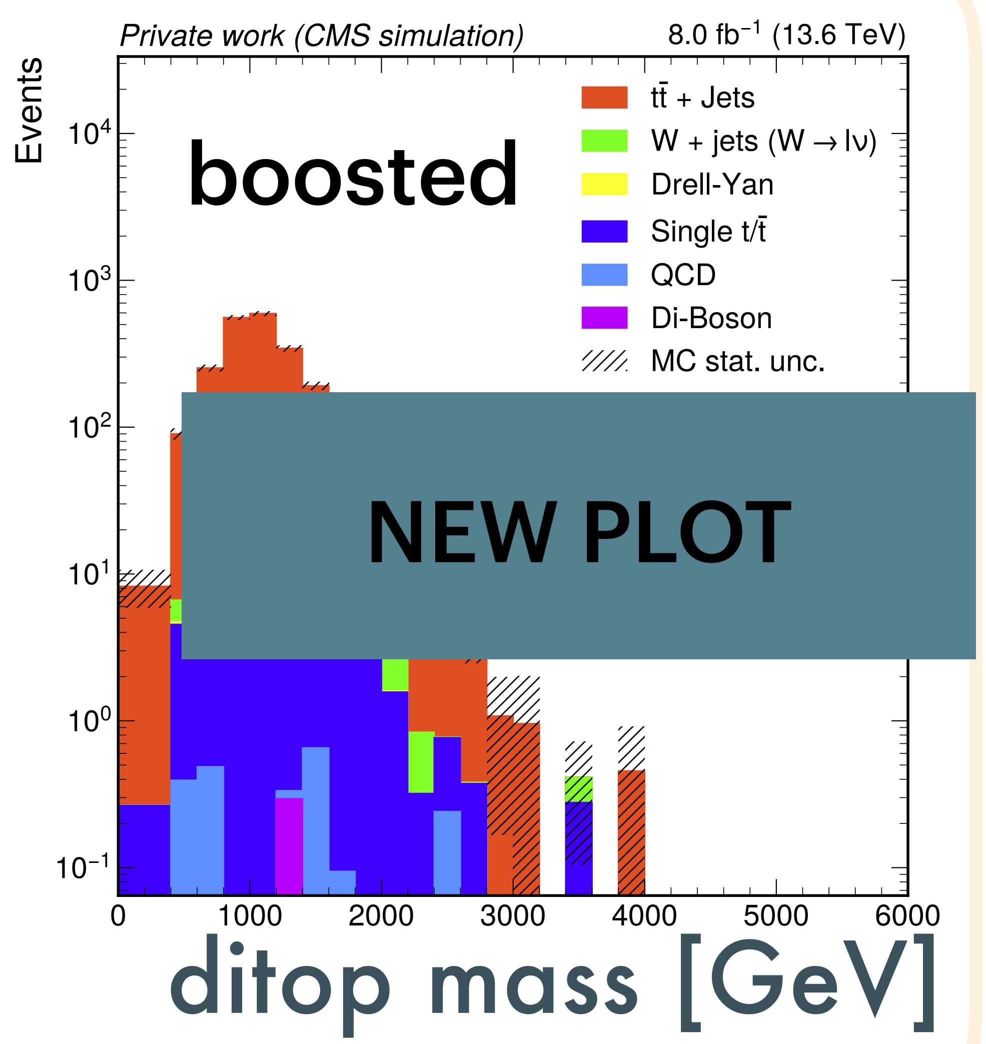




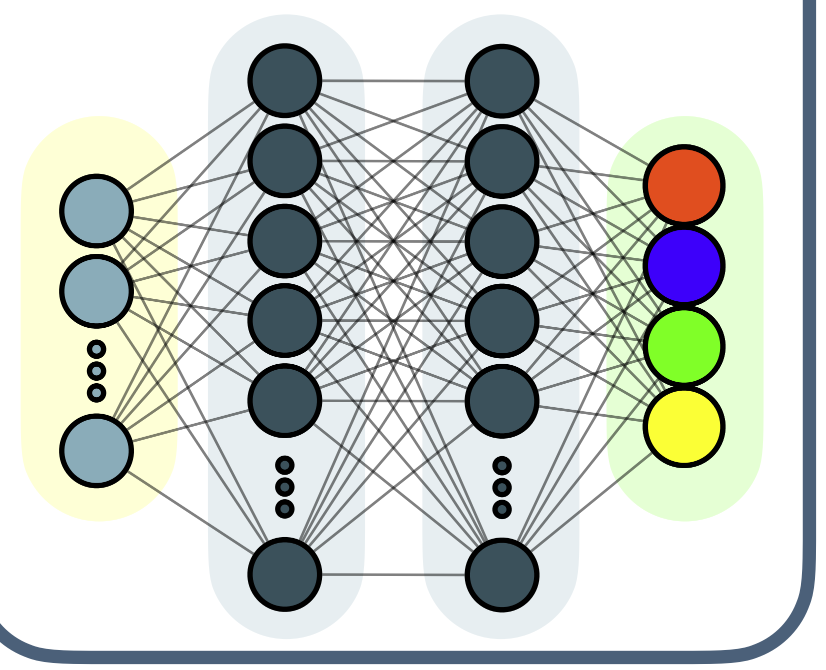
… In the Ditop Mass Spectrum

$\chi^2 < 30$





DNN for event classification



selected events

... In the Ditop Mass Spectrum

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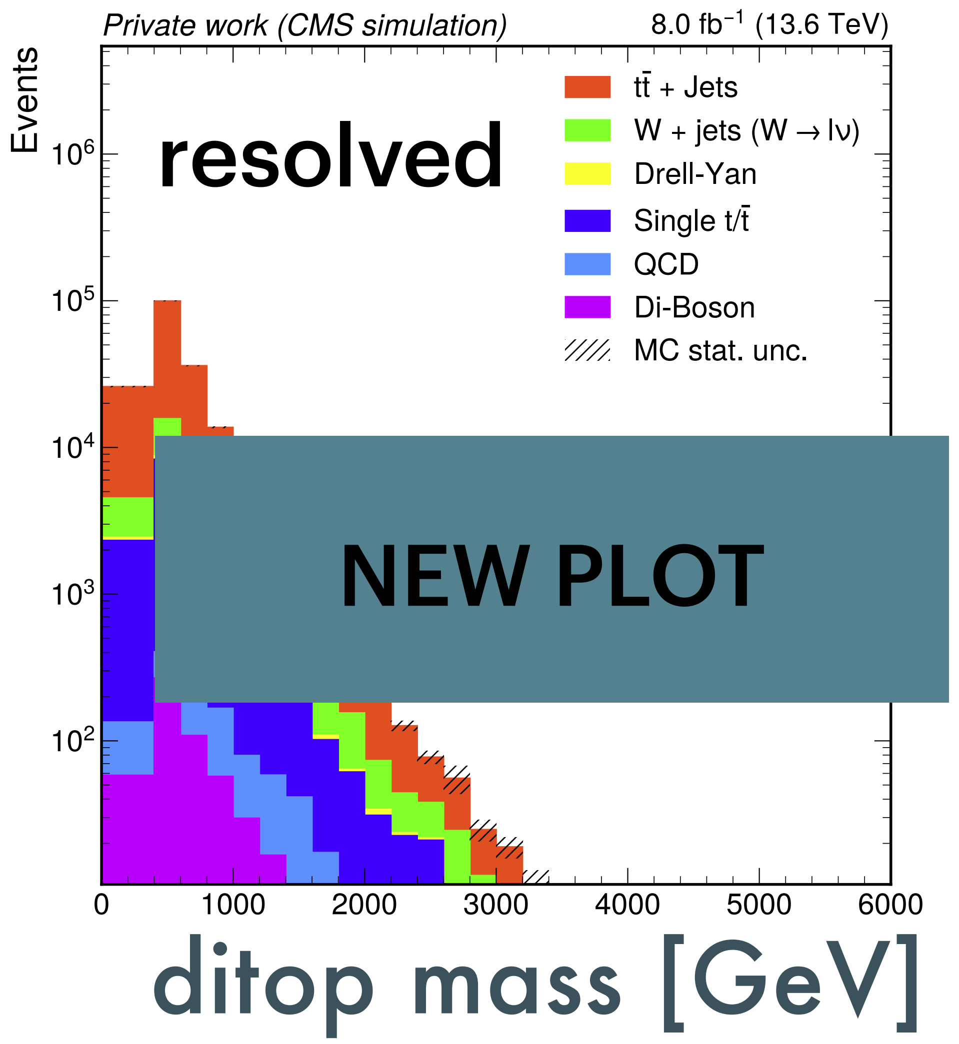

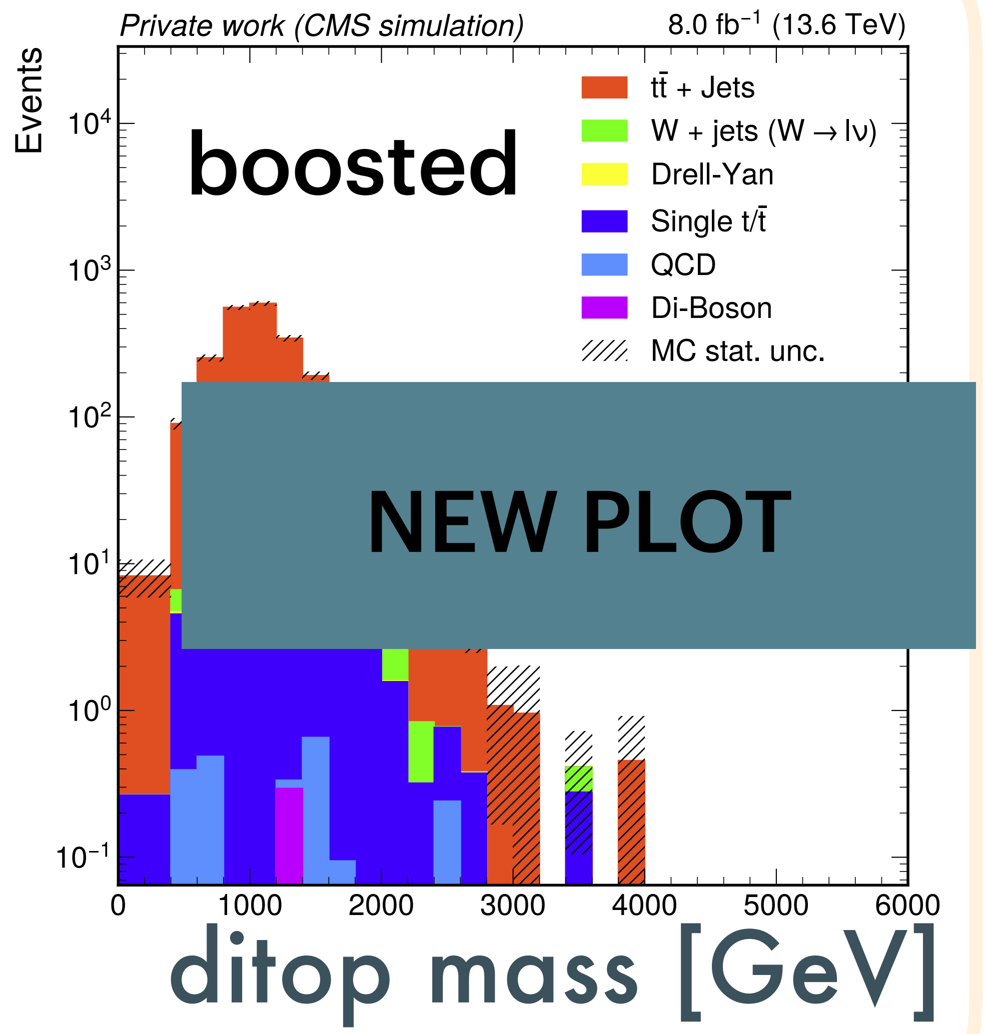

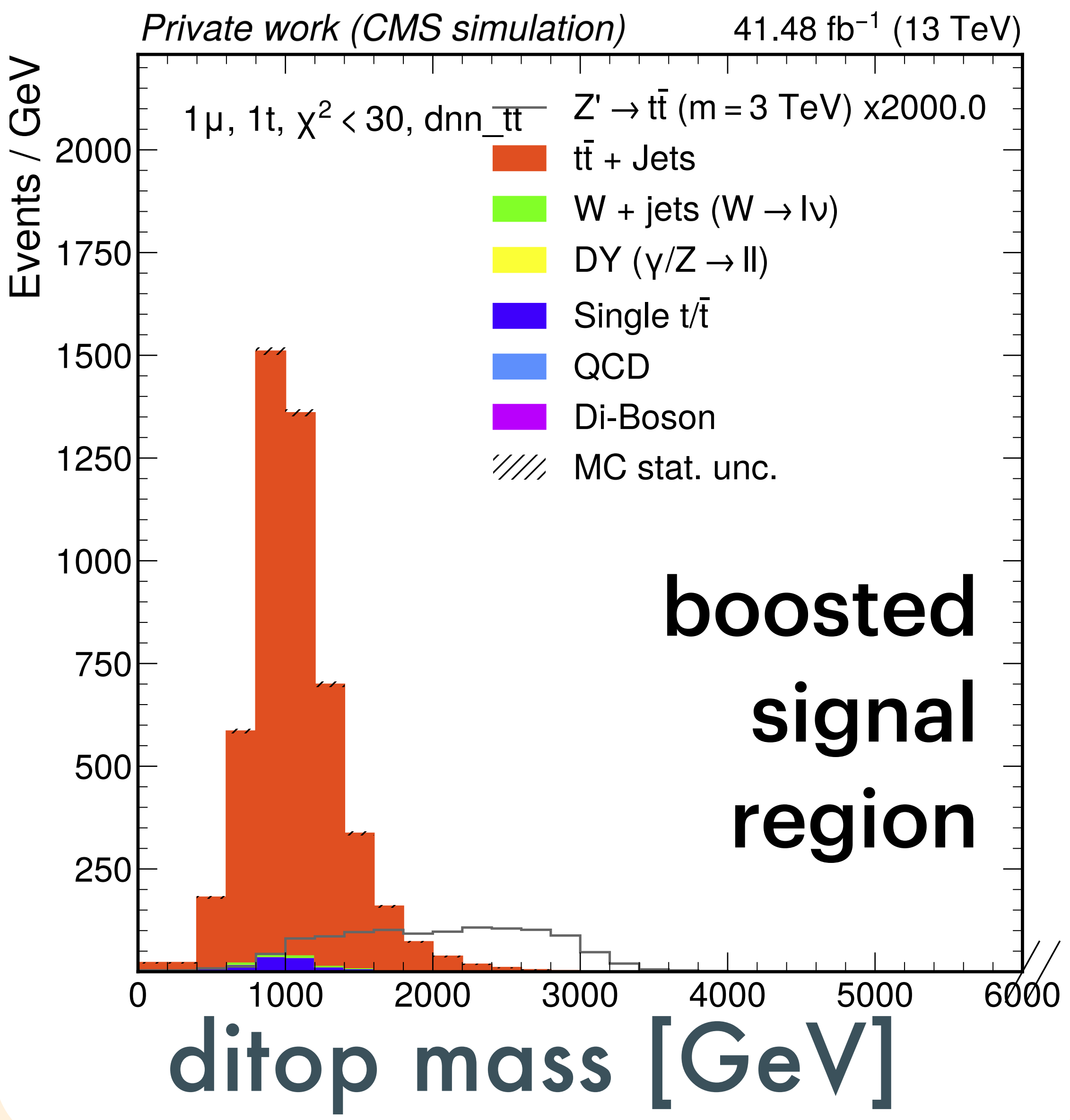

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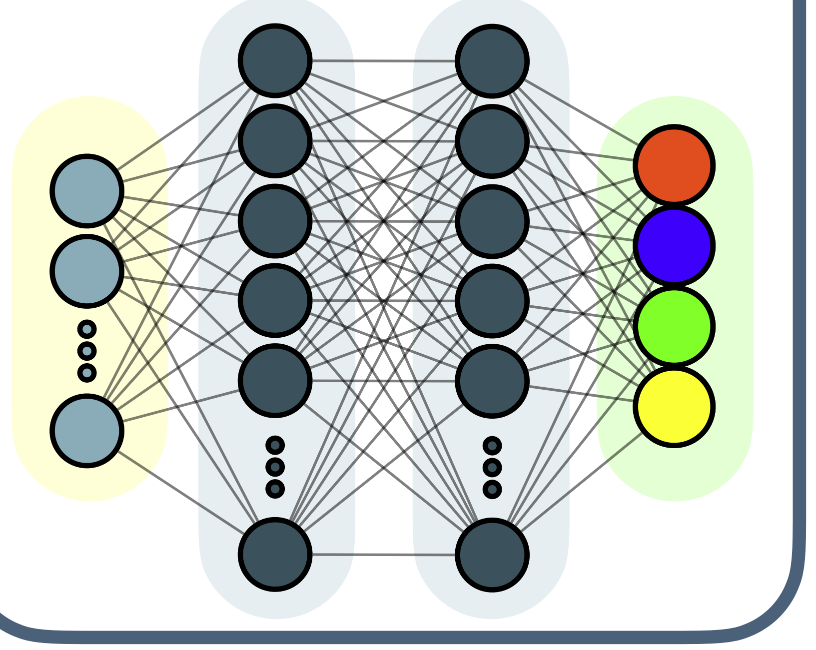
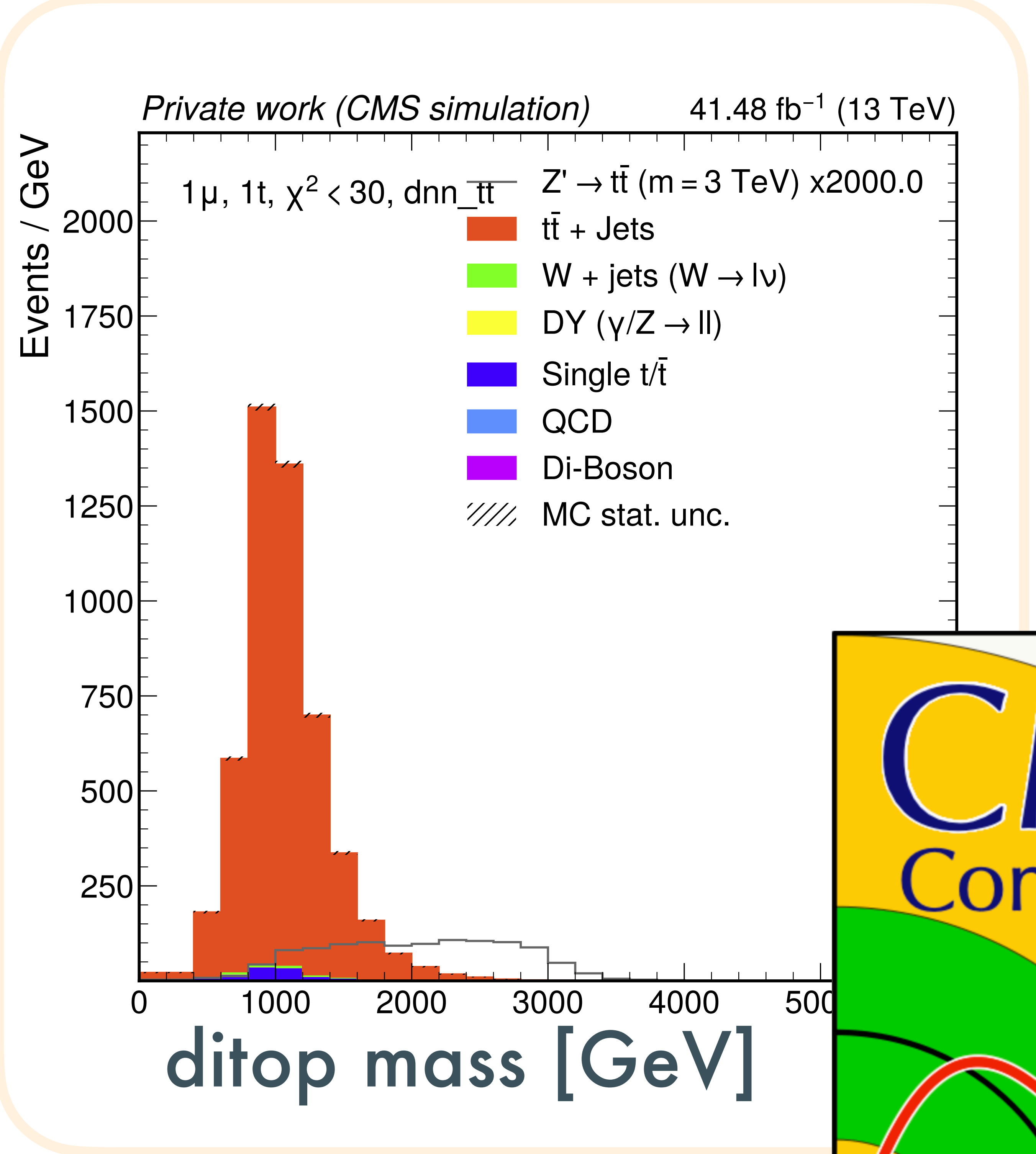
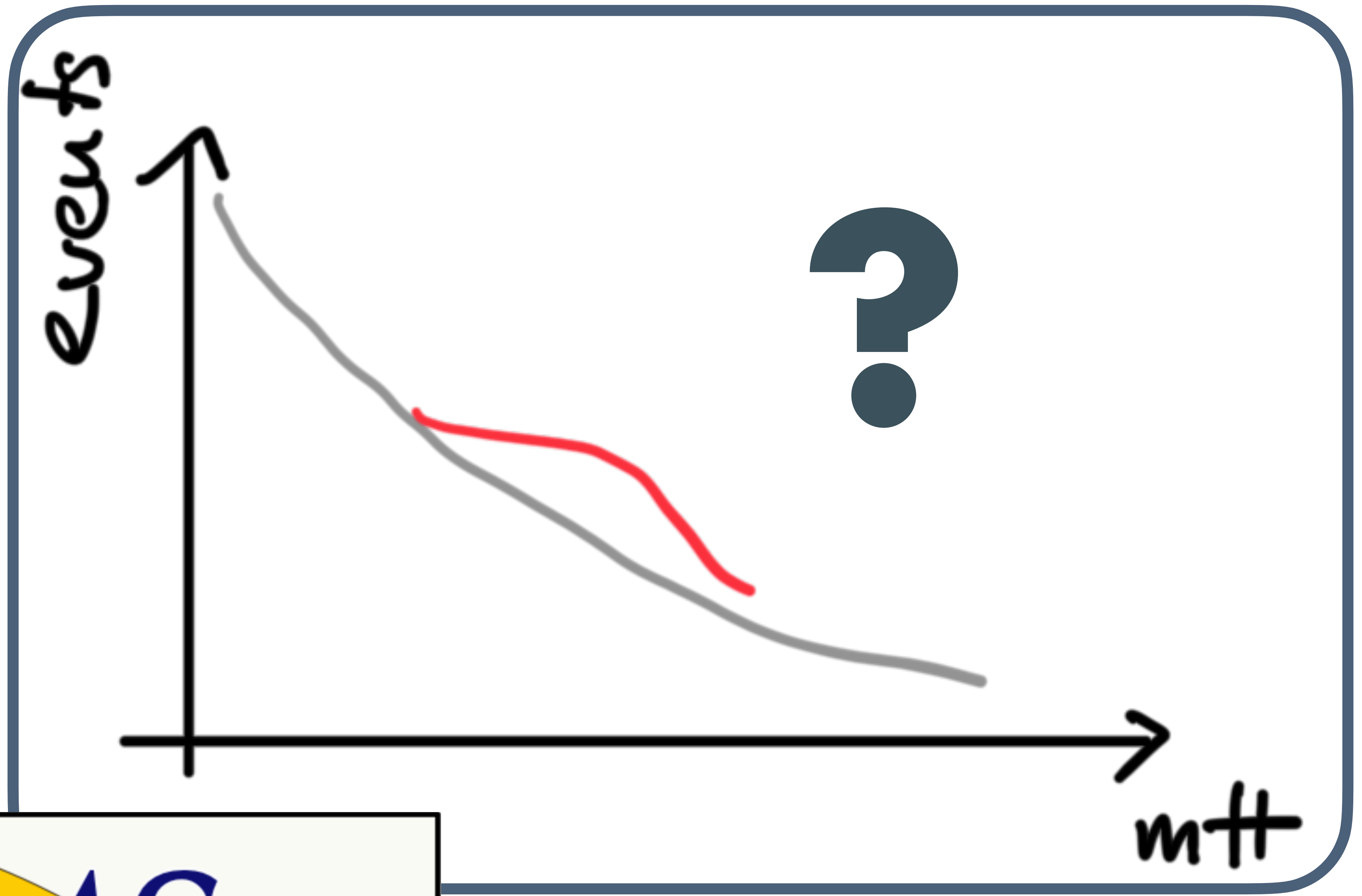


selected events

Statistical Analysis

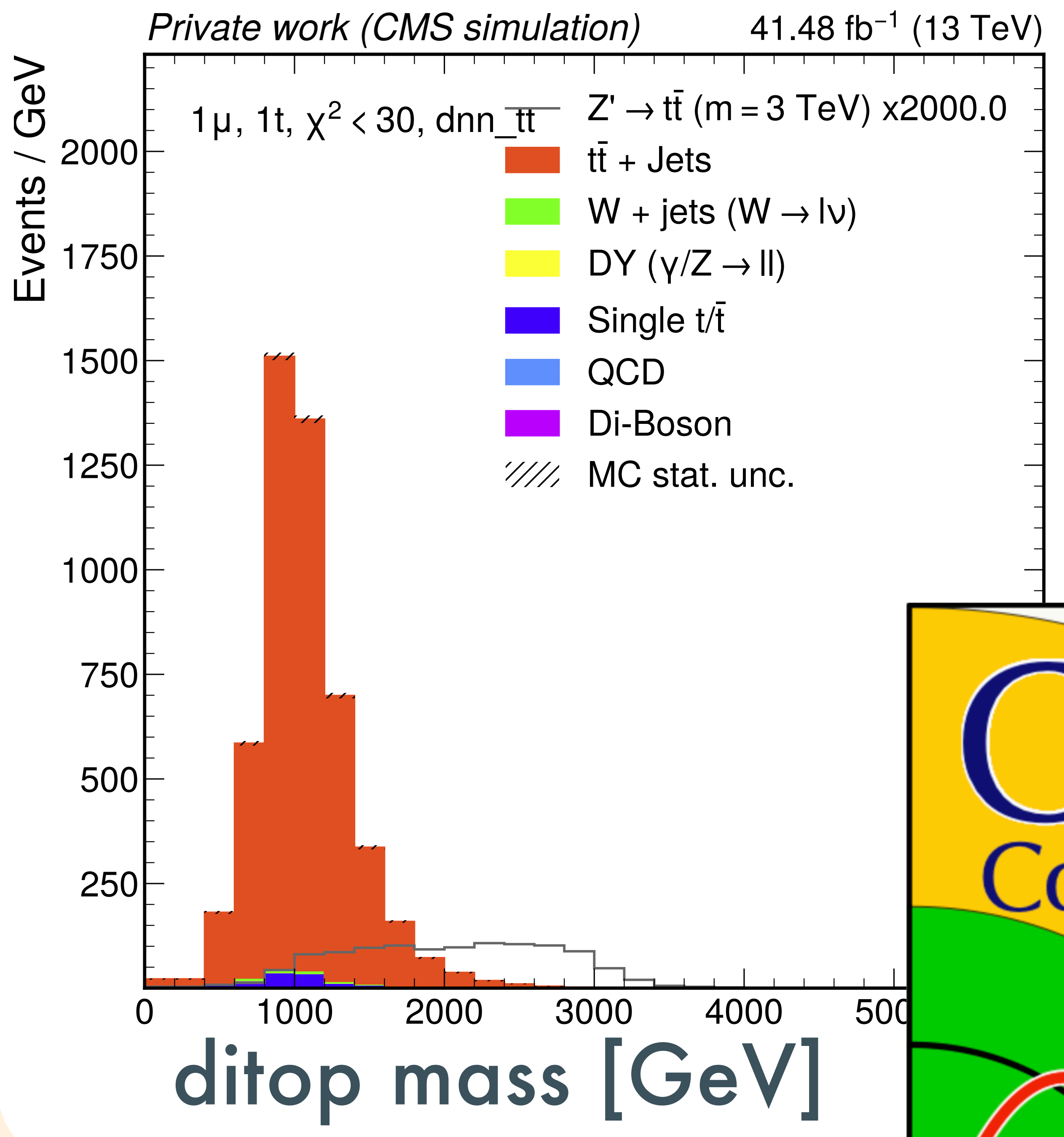


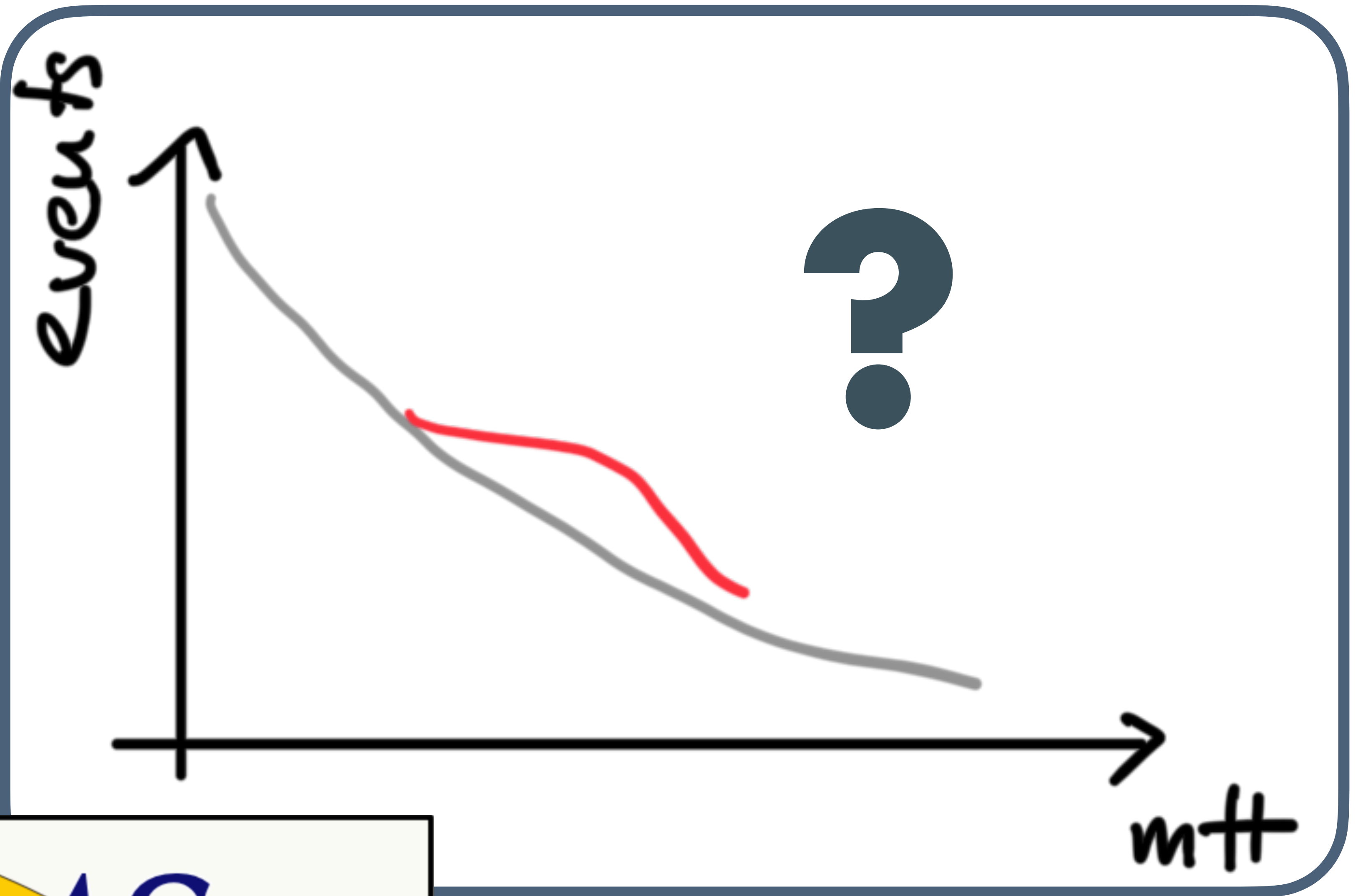


CMS Combine

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

Statistical Analysis

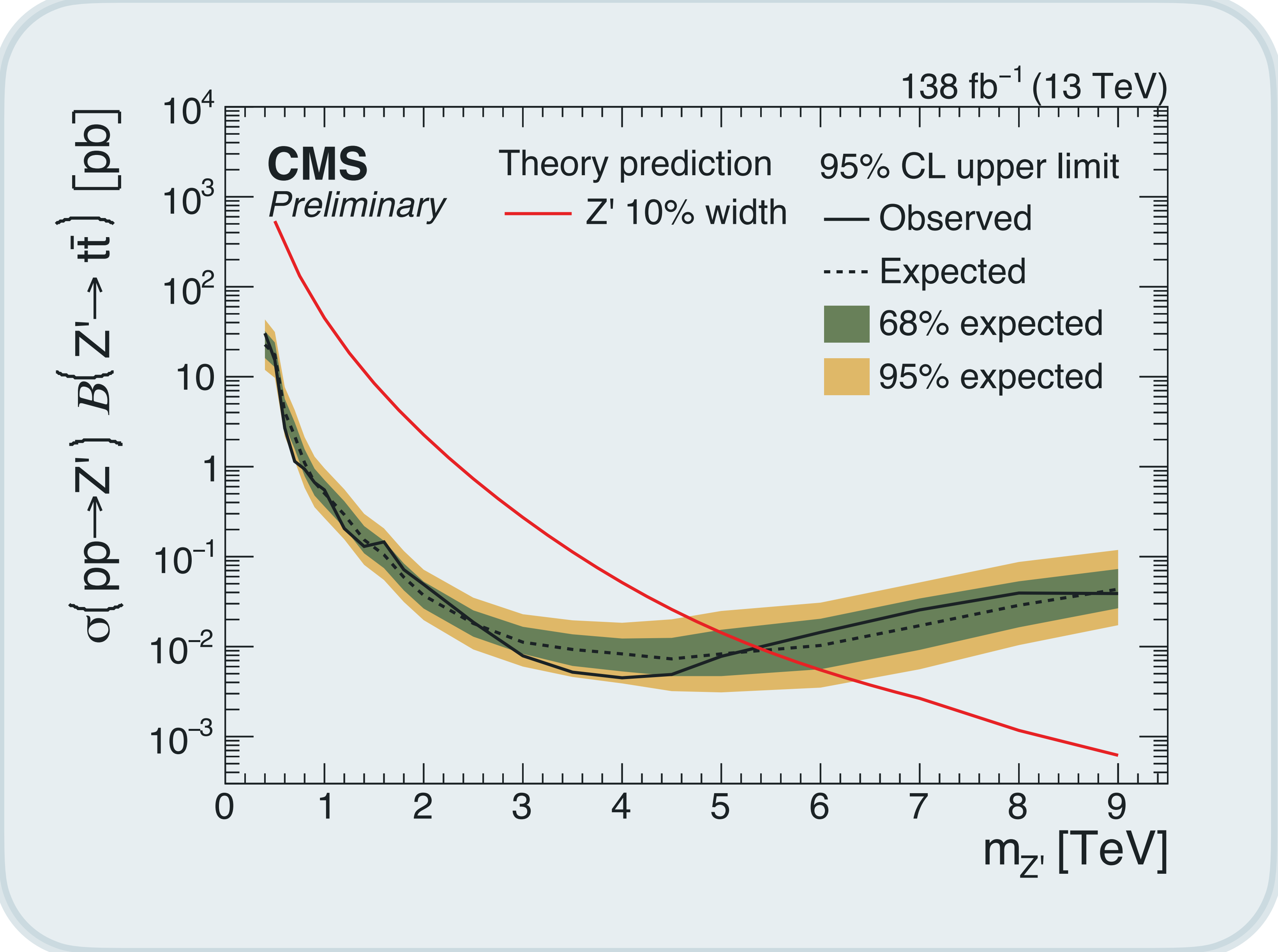




CMS Combine

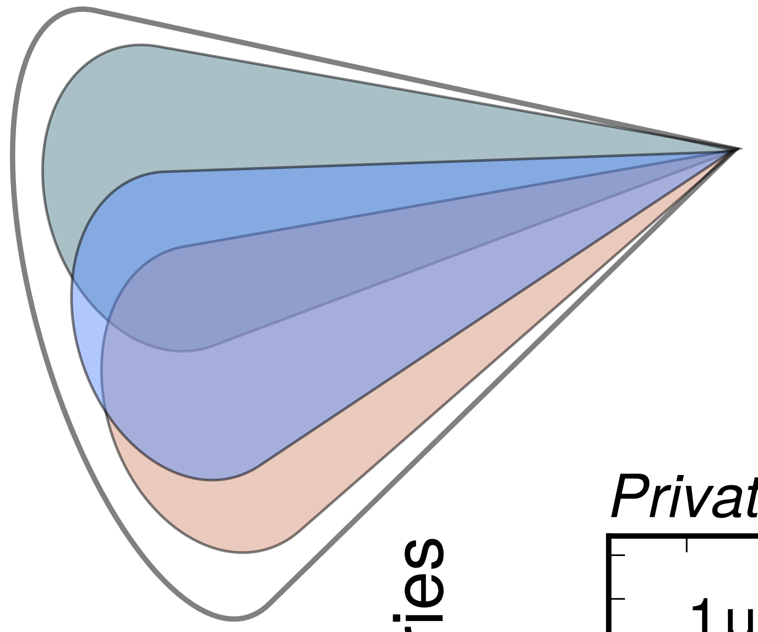
Comput.Softw.Big Sci. 8 (2024) 1, 19 - arXiv:2404.06614

CMS-PAS-B2G-22-006

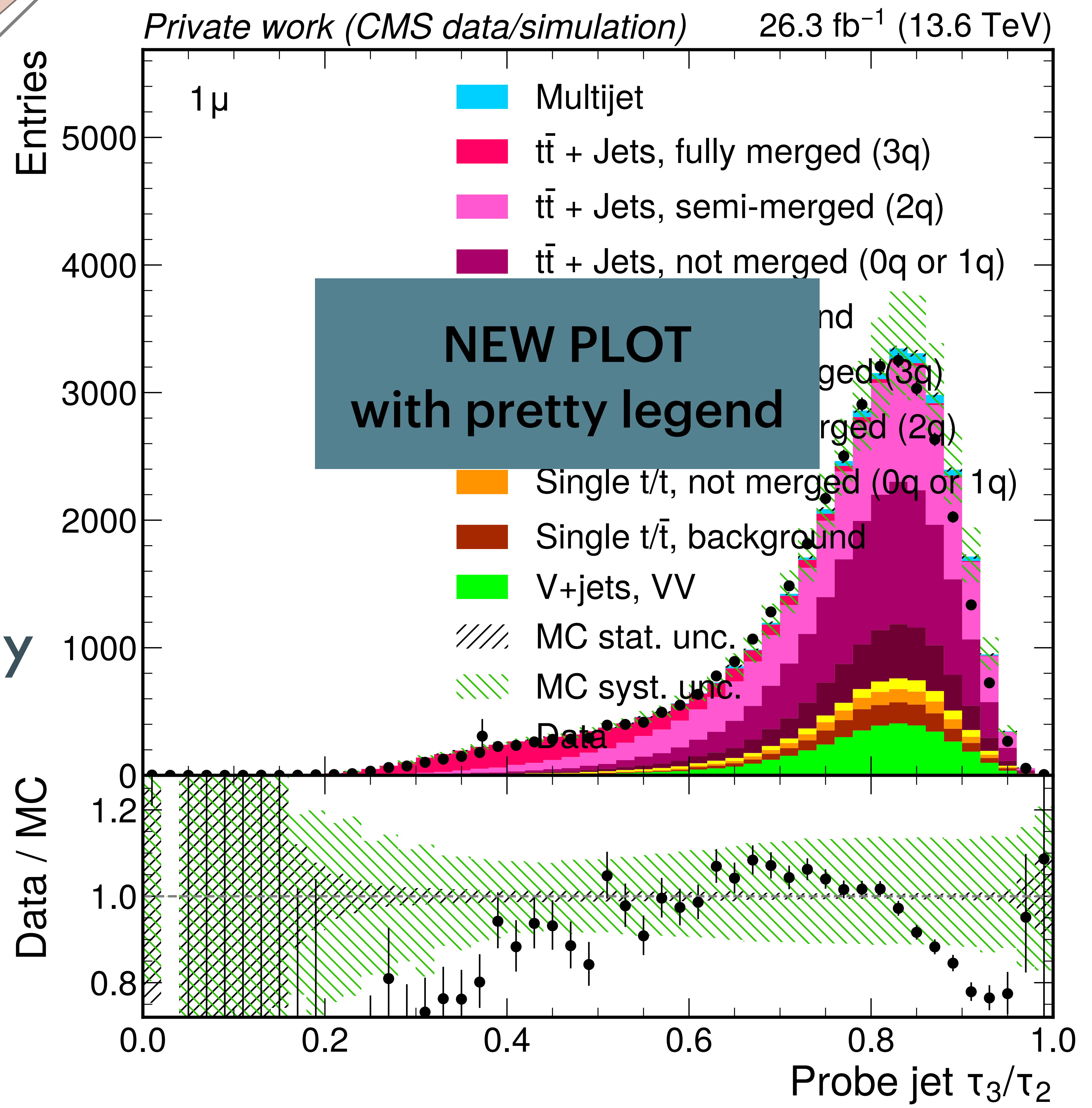


improve limits found in Run 2 analysis

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 public under CMS-PAS-B2G-22-006
  - Run 3 search to use more data and improved analysis strategy
- **cut based top tagging algorithm** using jet substructure and soft drop mass as baseline for top tagging
  - derived working points and scale factors

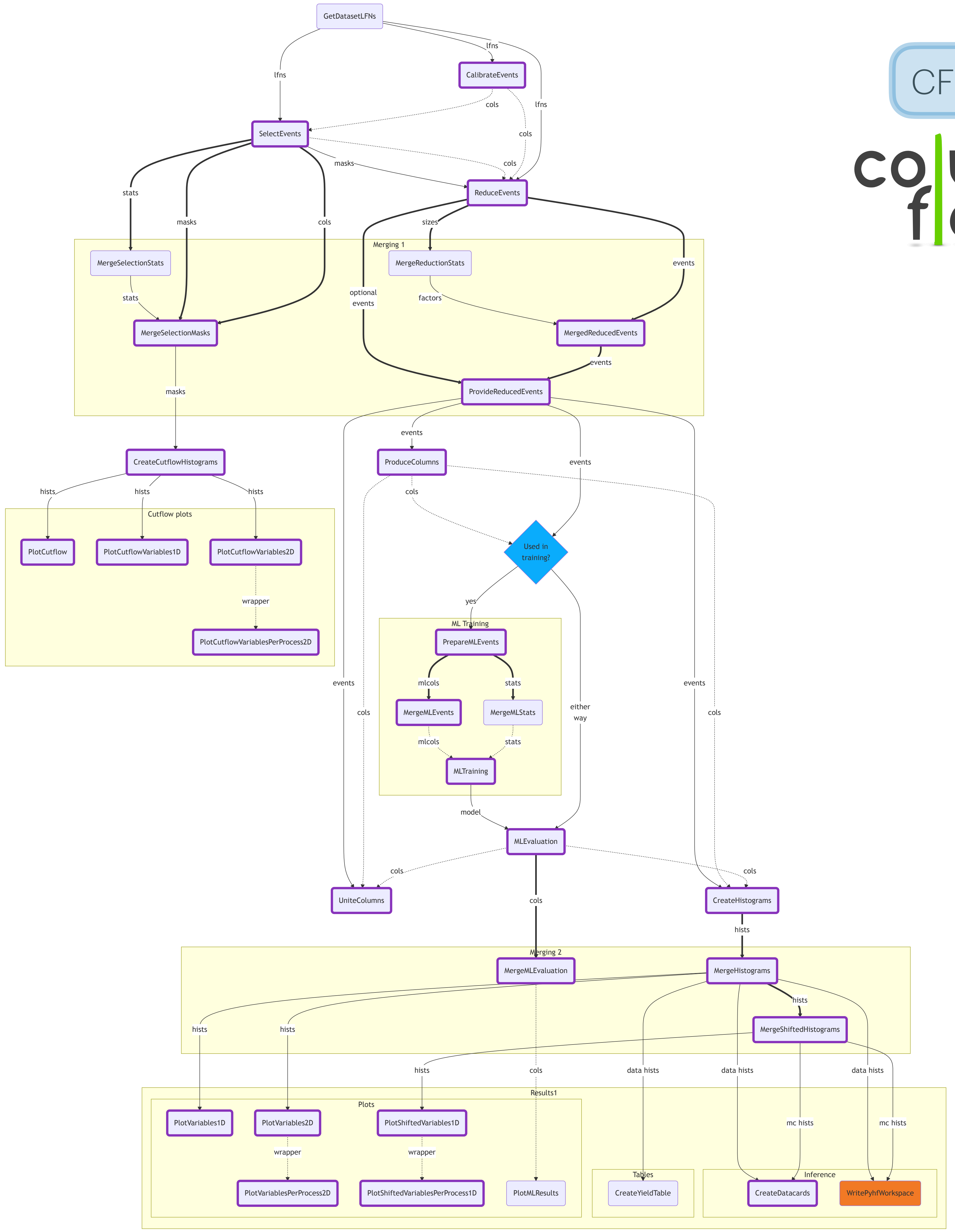


BACKUP

New Framework for Run 3

— columnar-based analysis with columnflow (CF) —

- 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



CF repo

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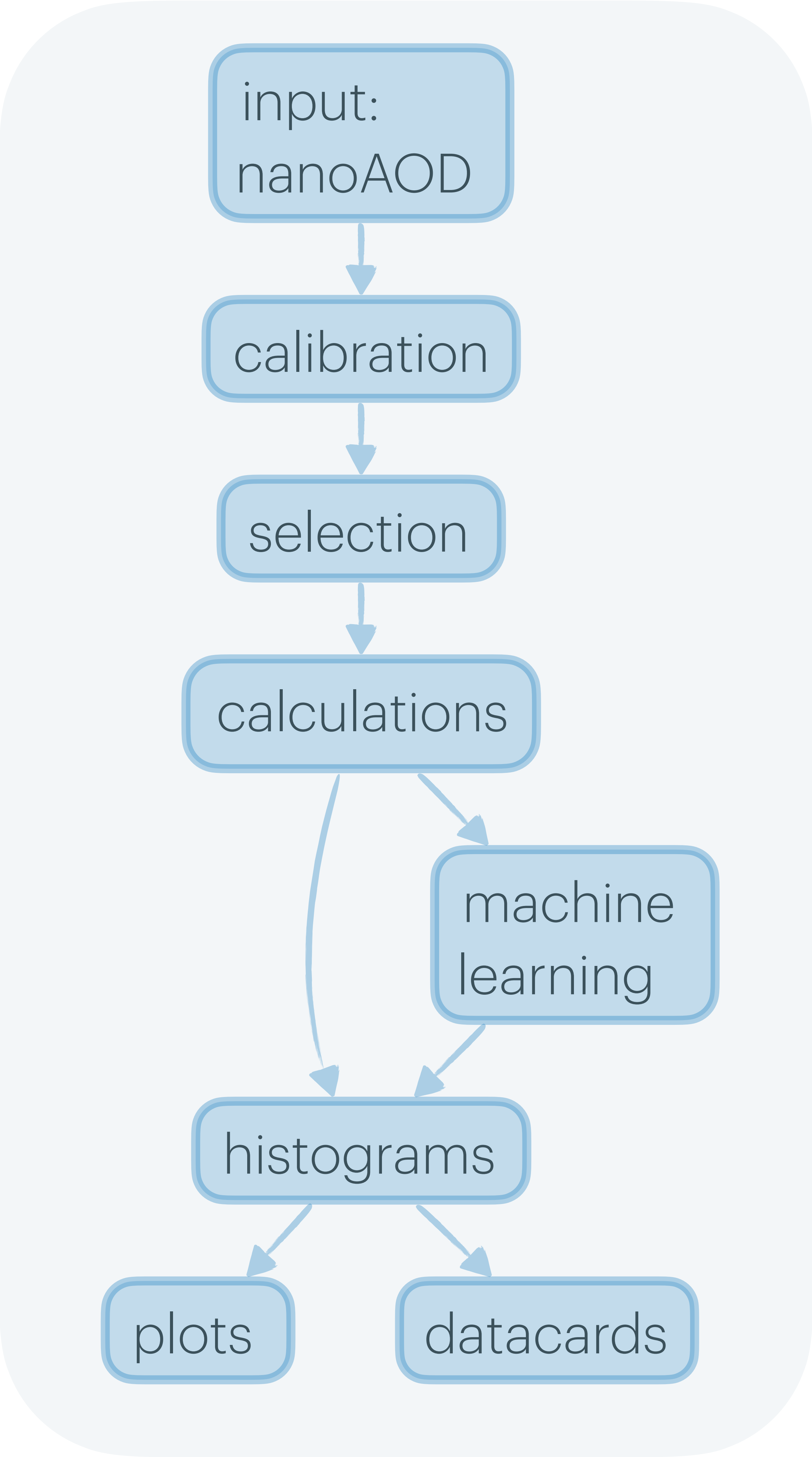


CF repo

columnflow

Procedure and Selection

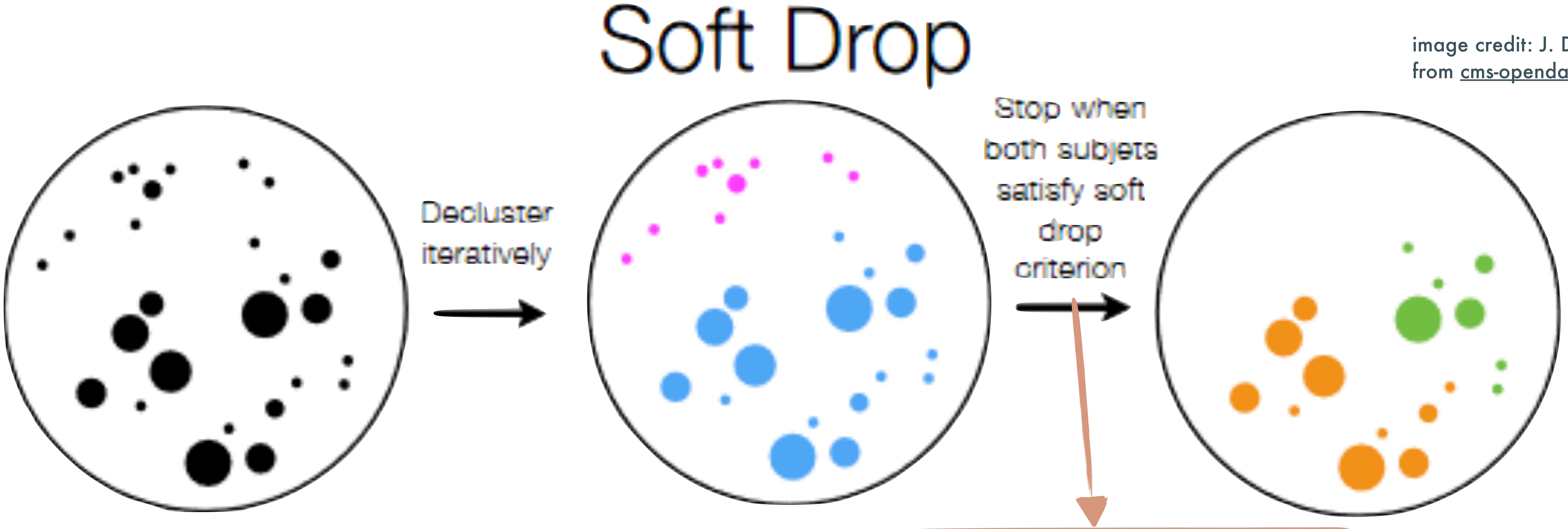
— for WP derivation —

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
  - $|\eta| < 2.4$
  - $p_\mathrm{T} > 400$ GeV
    → boosted regime
  - in `ttbar` sample to determine signal efficiency:
    uniquely matched to parton-level top quark
  - additional softdrop mass constraint:
    $105 < m_\mathrm{SD} < 210$ GeV
    → window around top mass

m_{SD} Of FatJets

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



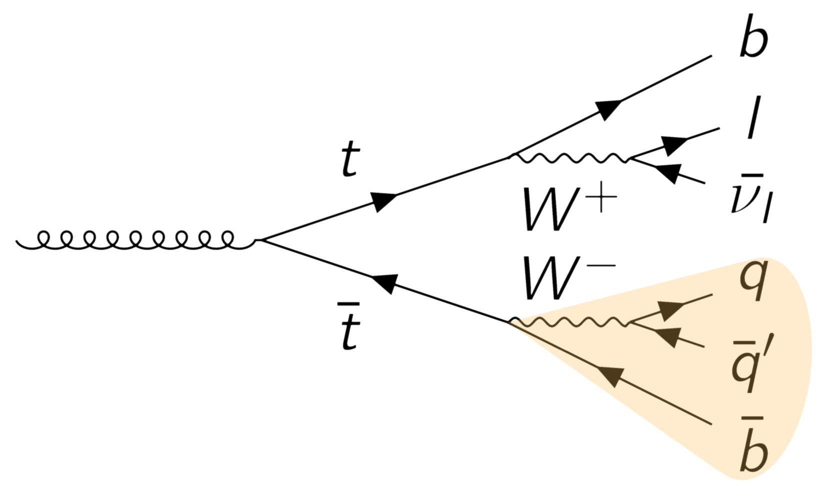
$$\frac{\min(p_{T1}, p_{T,2})}{p_{T1} + p_{T2}} > z_{cut} \cdot \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

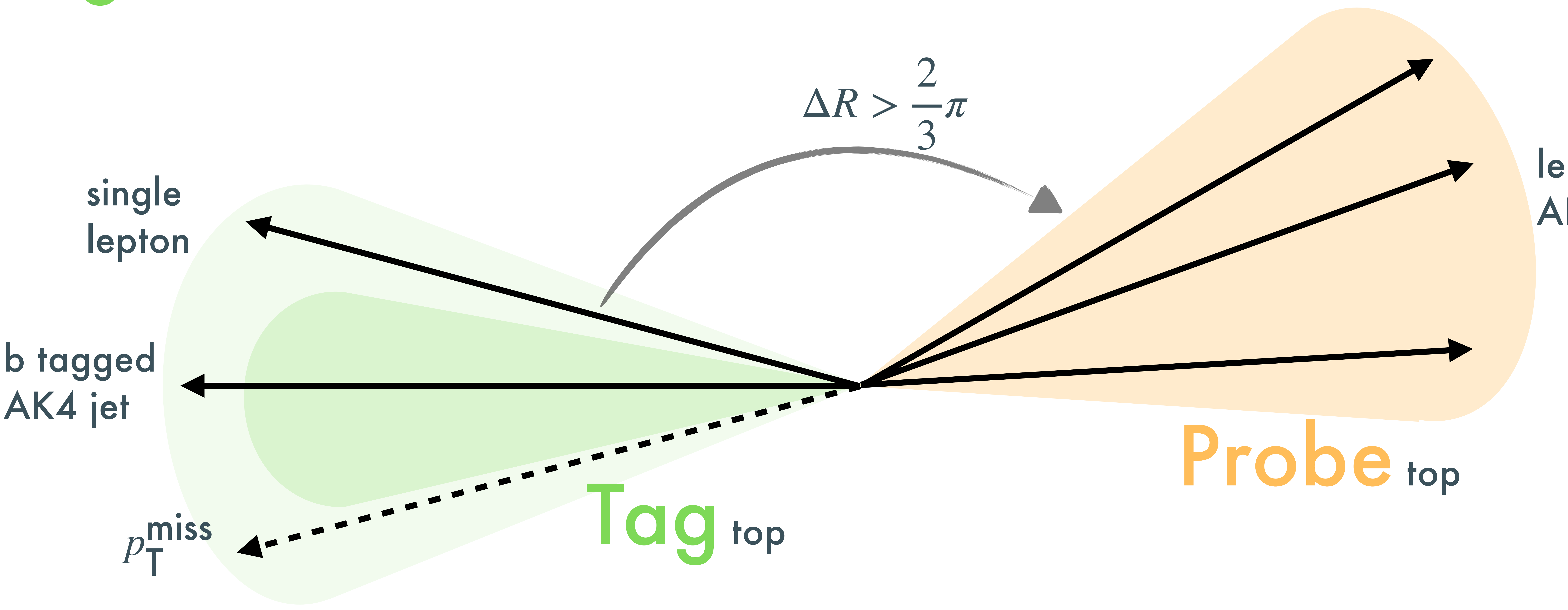
$\beta = 0$

$z_{cut} = 0.1$

→ 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

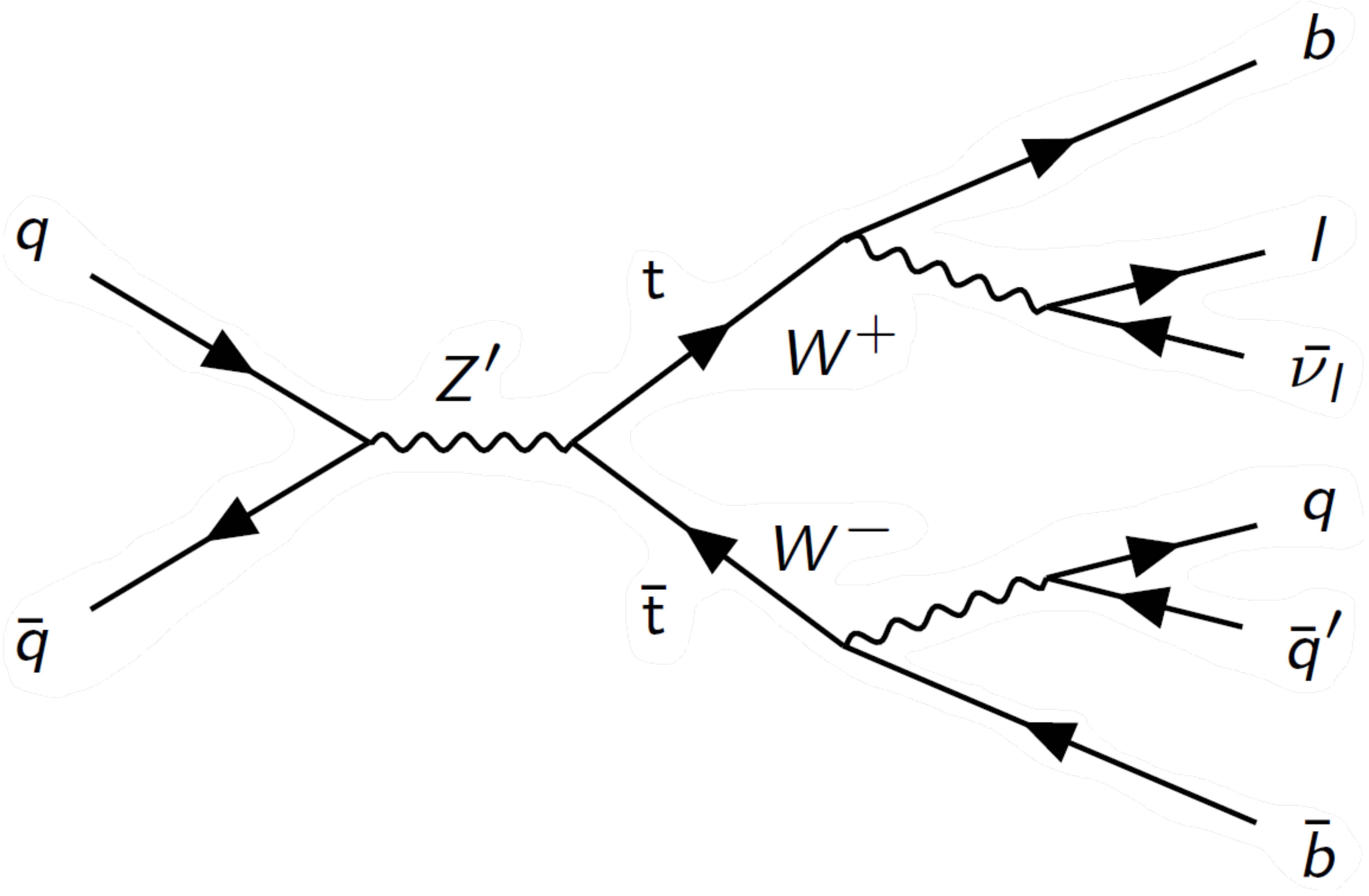
- $p_T^{miss} > 50$ GeV
- $p_T(W_{lep}) > 150$ GeV

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

Baseline Selection

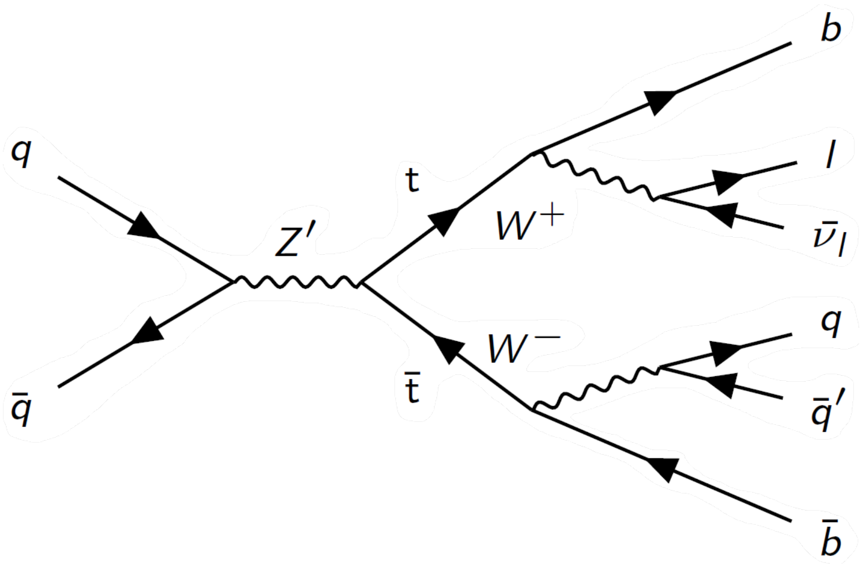
— in numbers —

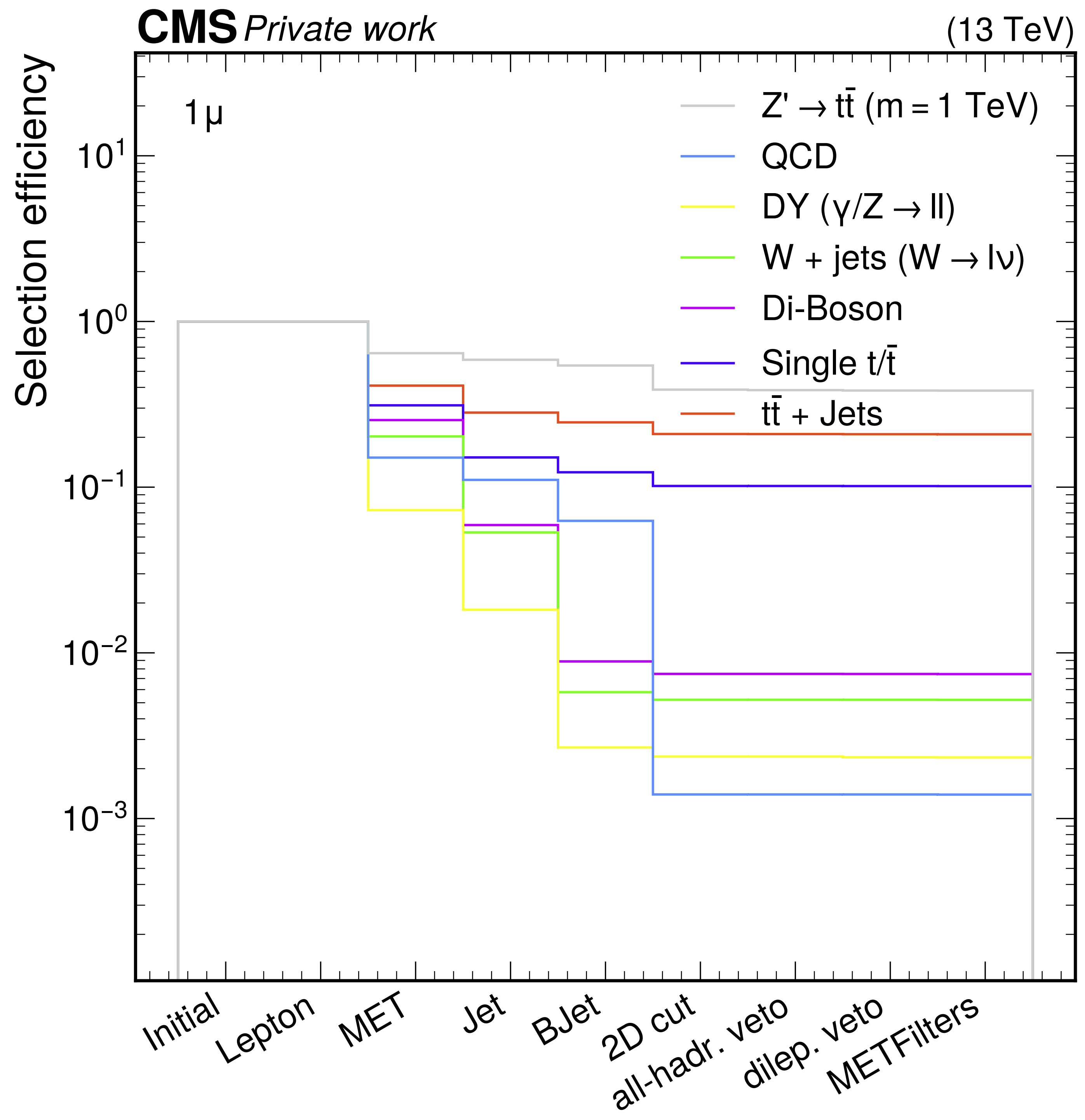
muon/electron channel



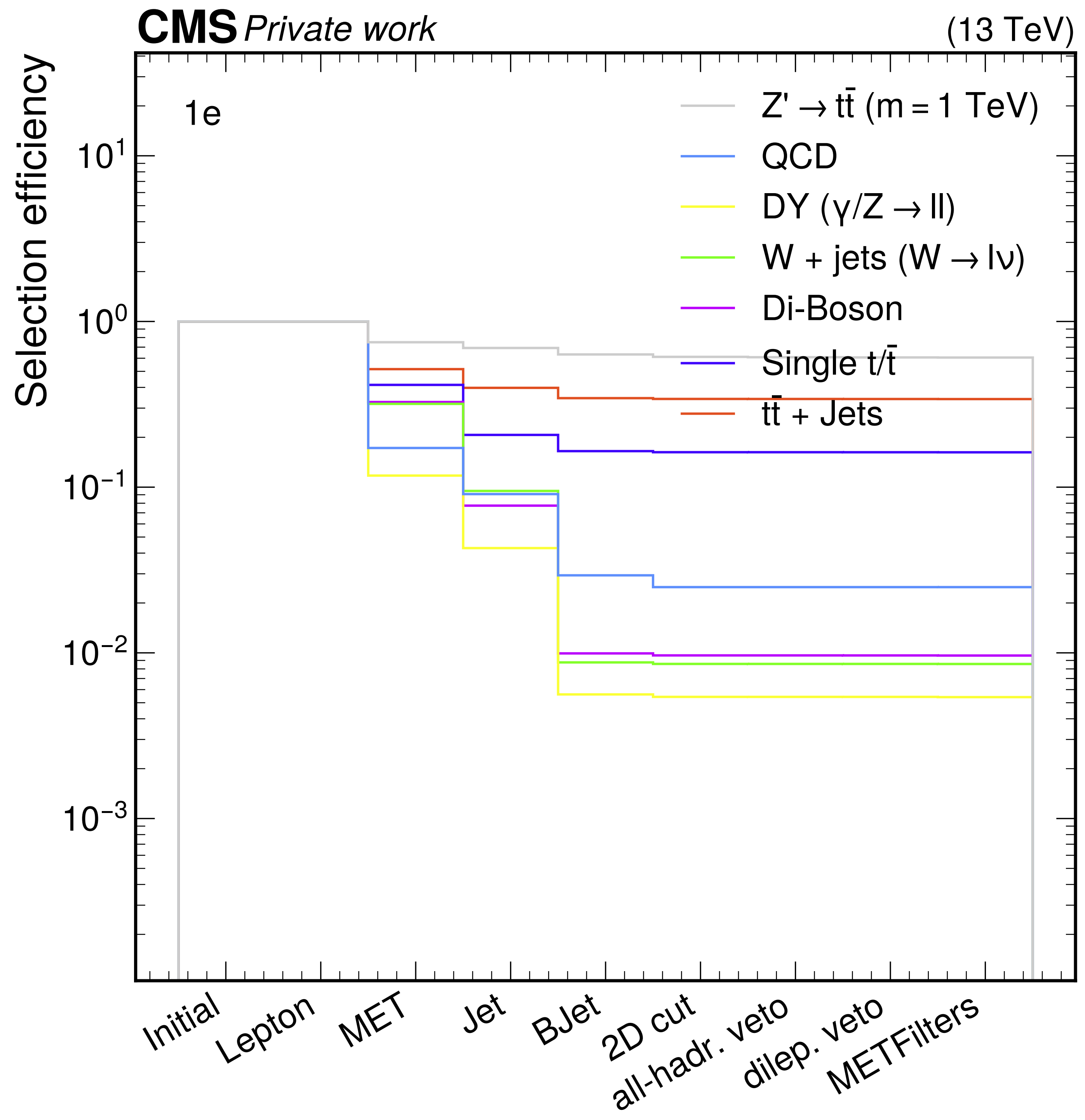
- lepton selection:
  - single muon/electron trigger
  - low p_T: $30/35 < p_T < 55/120$ GeV and isolation
  - high p_T: $p_T > 55/120$ GeV and 2D isolation
  - $|\eta^{\mu/e}| < 2.4$
- $p_T^{miss} > 70/60$ GeV
- at least two jets with $|\eta| < 2.5$ and:
  - $p_T^{jet1} > 50/50$ GeV
  - $p_T^{jet2}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

Selection Efficiencies

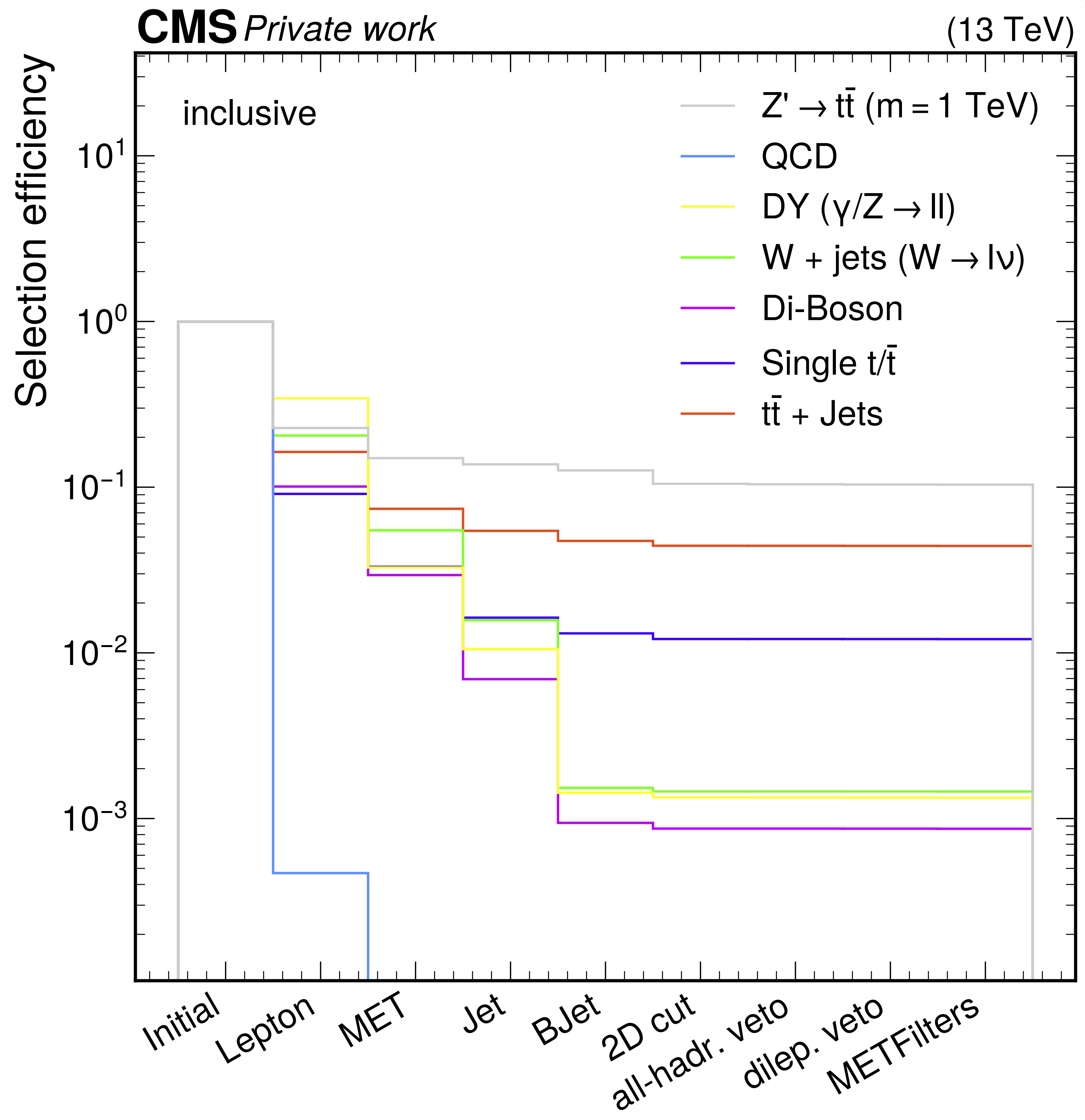




muon channel



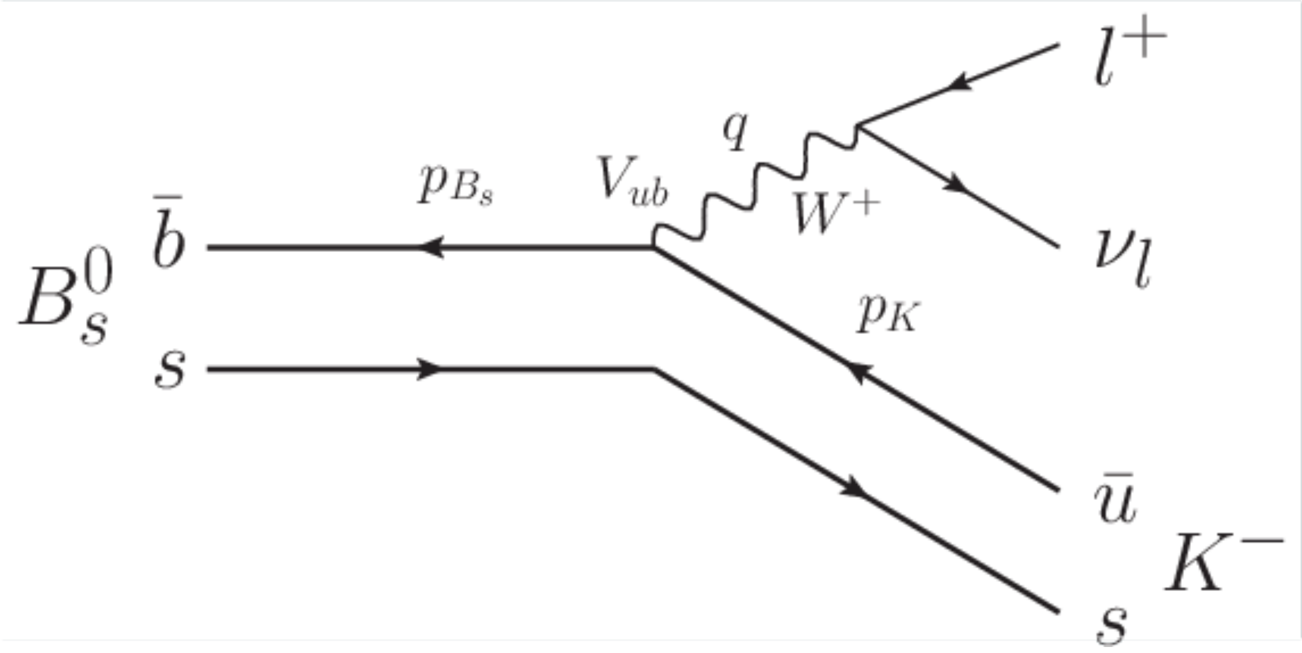
electron channel



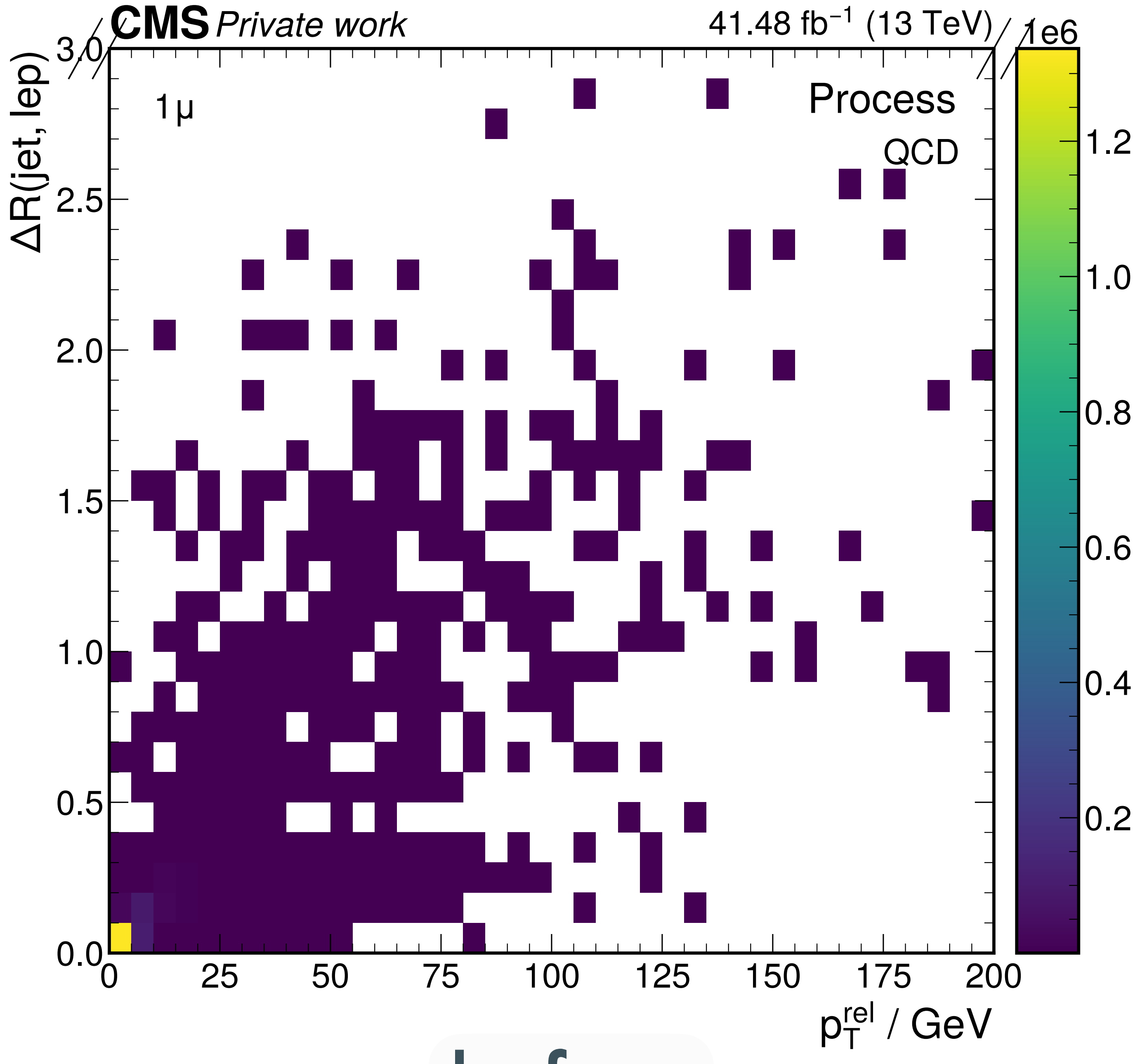
inclusive channel

Jet-Lepton 2D Cut

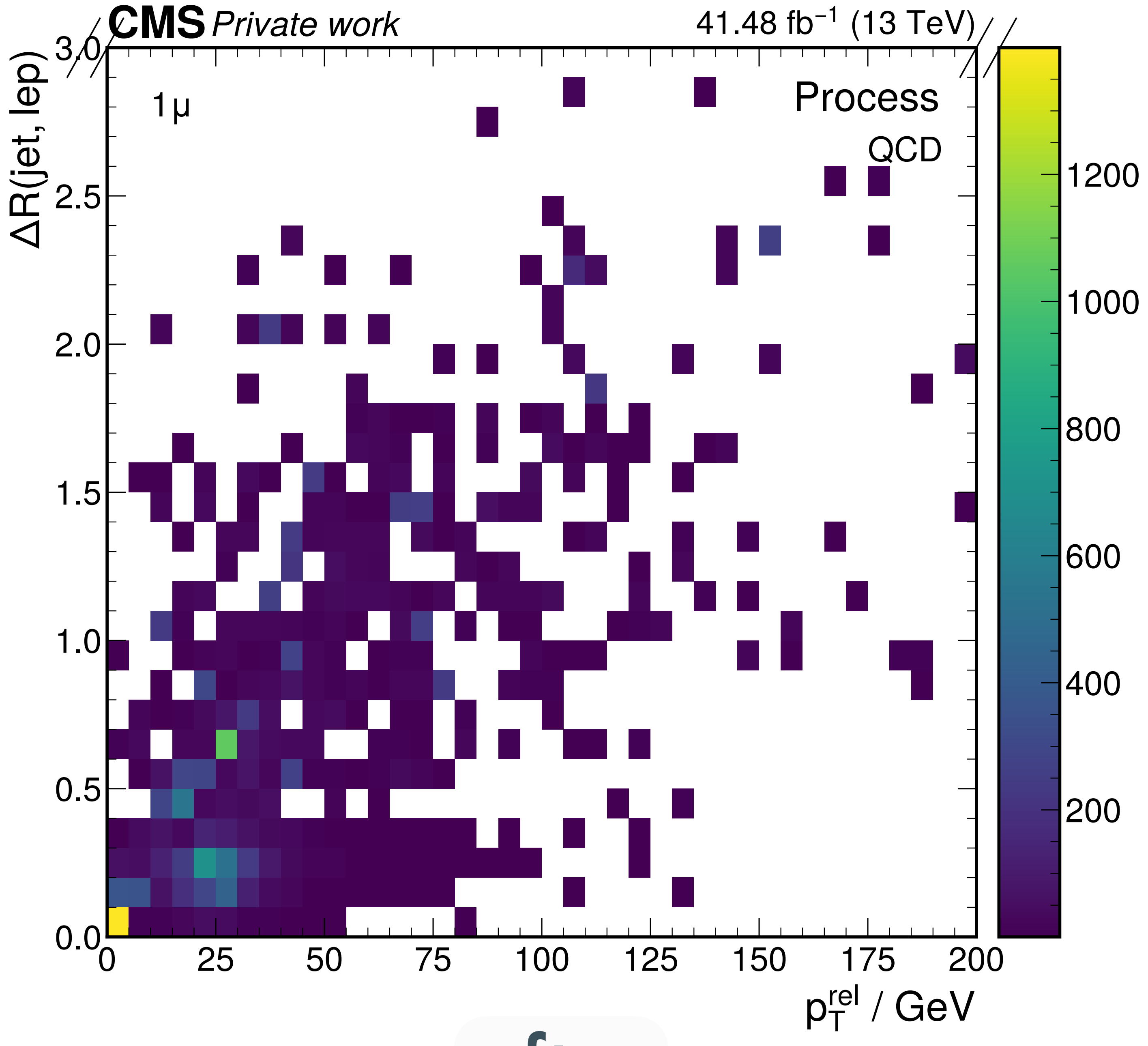
— filtering leptonic B meson decays —



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

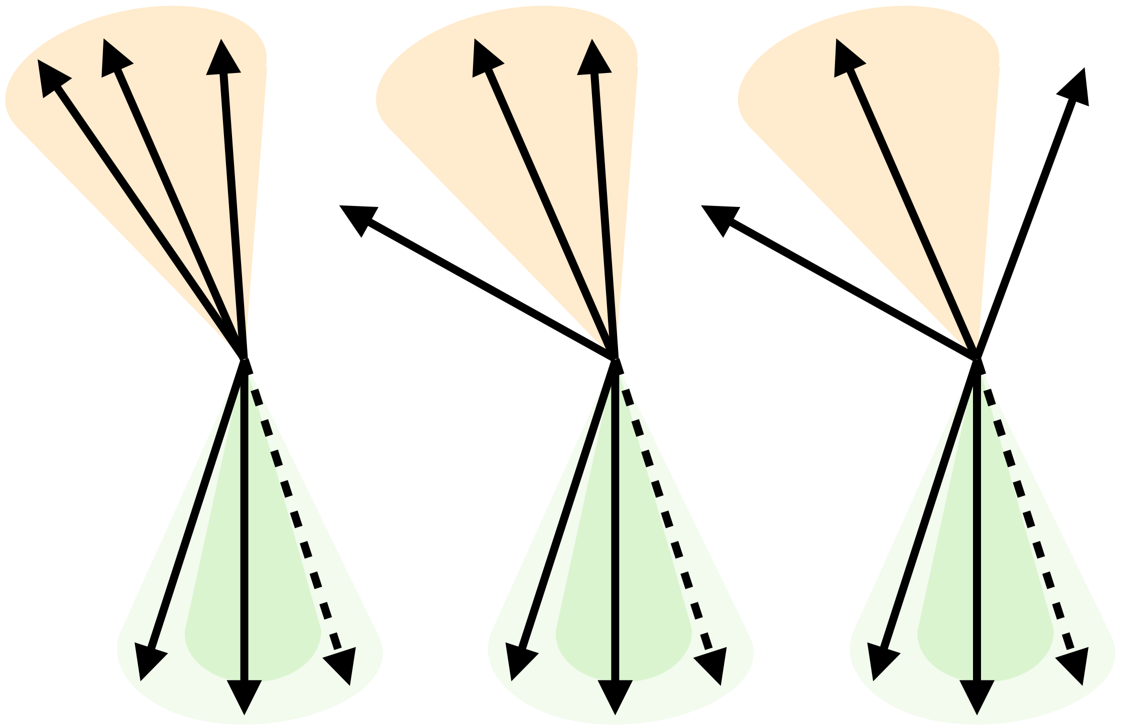
Combine Physics Model

- 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

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

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



```
SF__3q/2q/0o1q__22__pt_300_400
SF__3q/2q/0o1q__22__pt_400_480
SF__3q/2q/0o1q__22__pt_480_600
SF__3q/2q/0o1q__22__pt_600_inf
```

→ 12 scale factors

Main Uncertainities

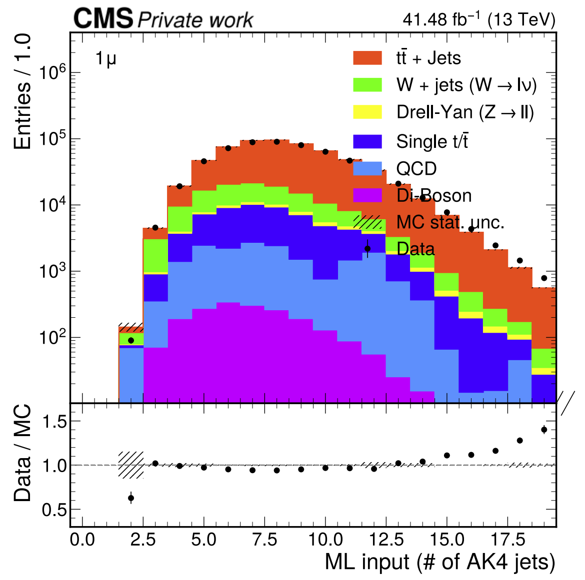
— in Run 2 —

- 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

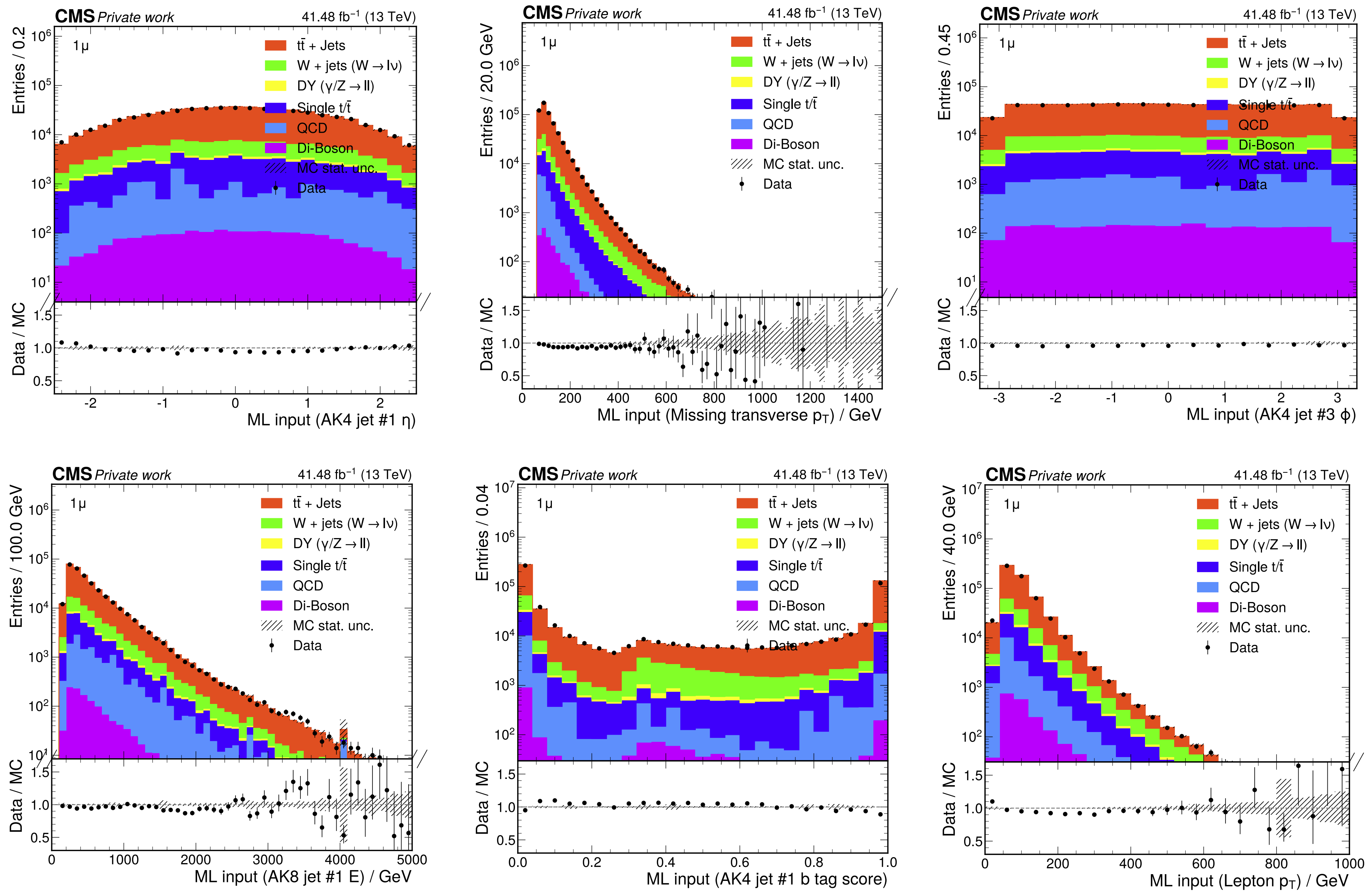
DNN for Event Classification

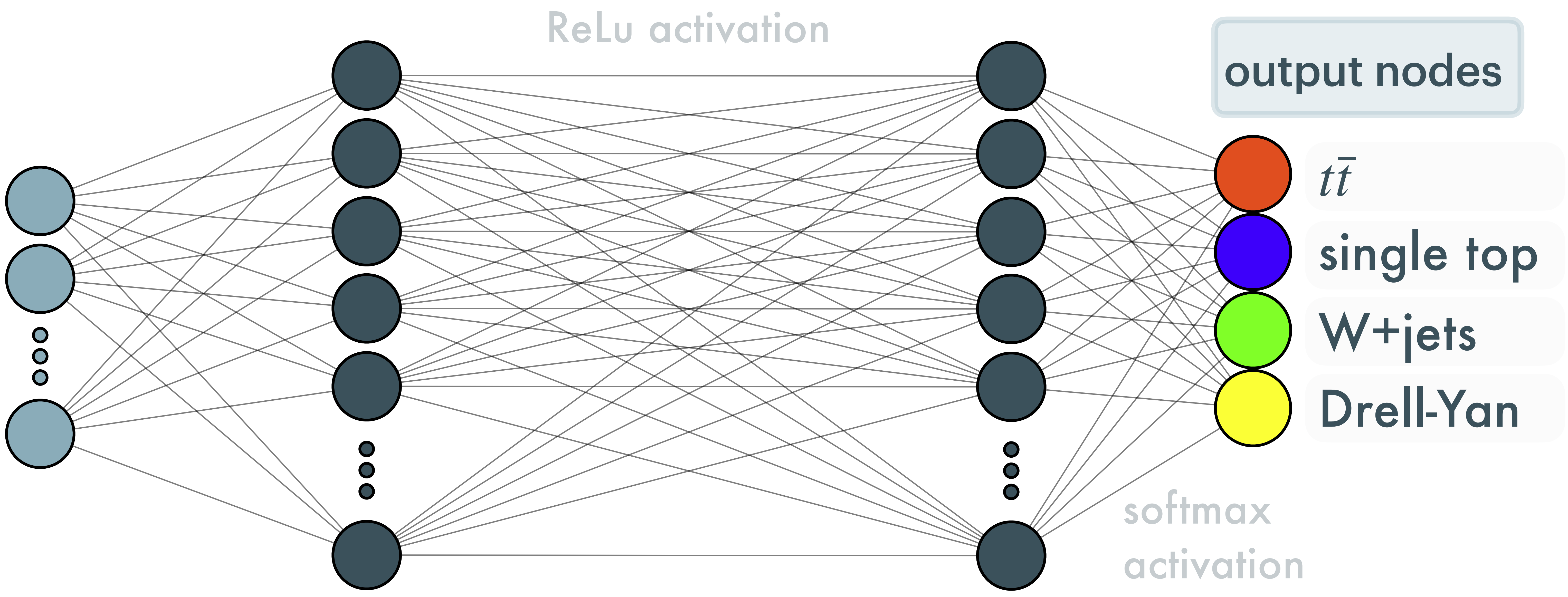
— network architecture —



59 input features:

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





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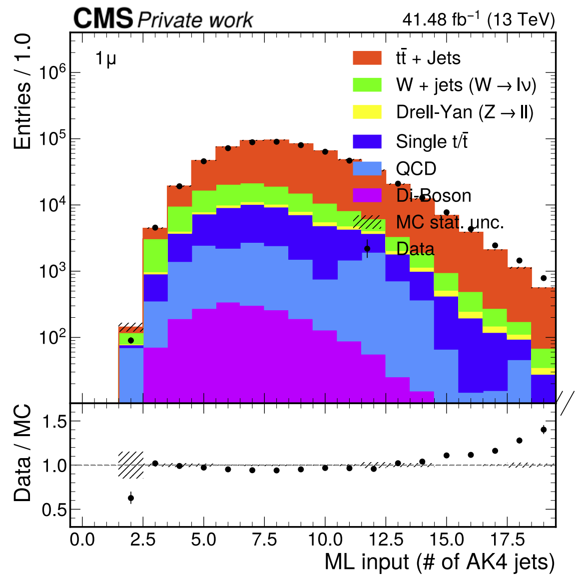

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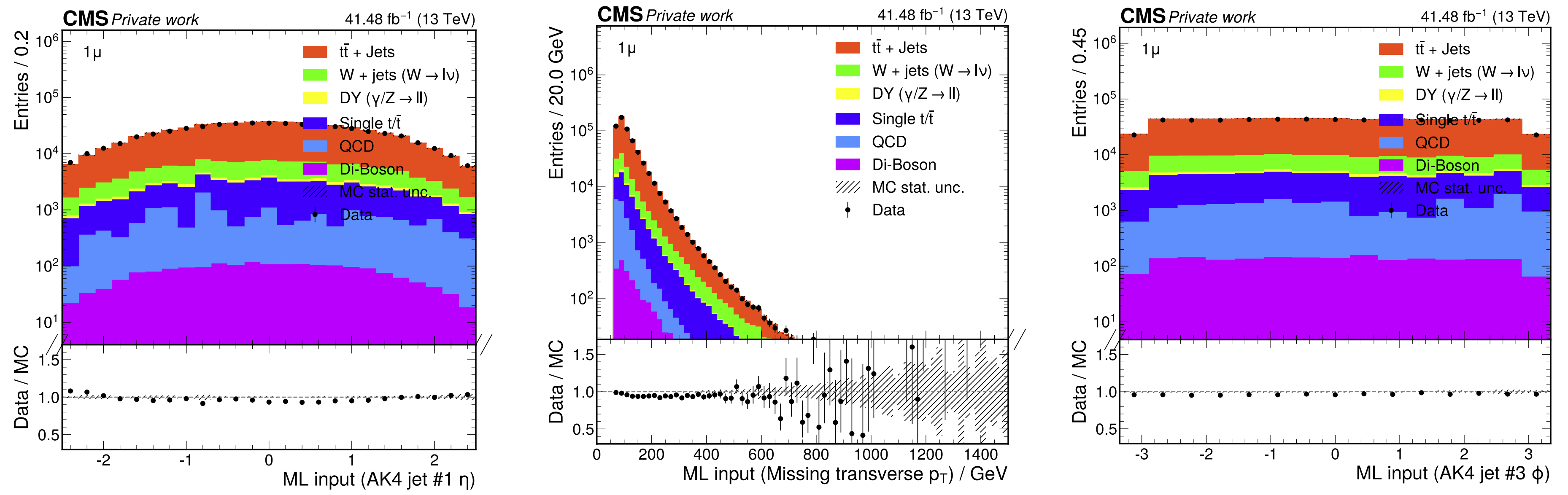

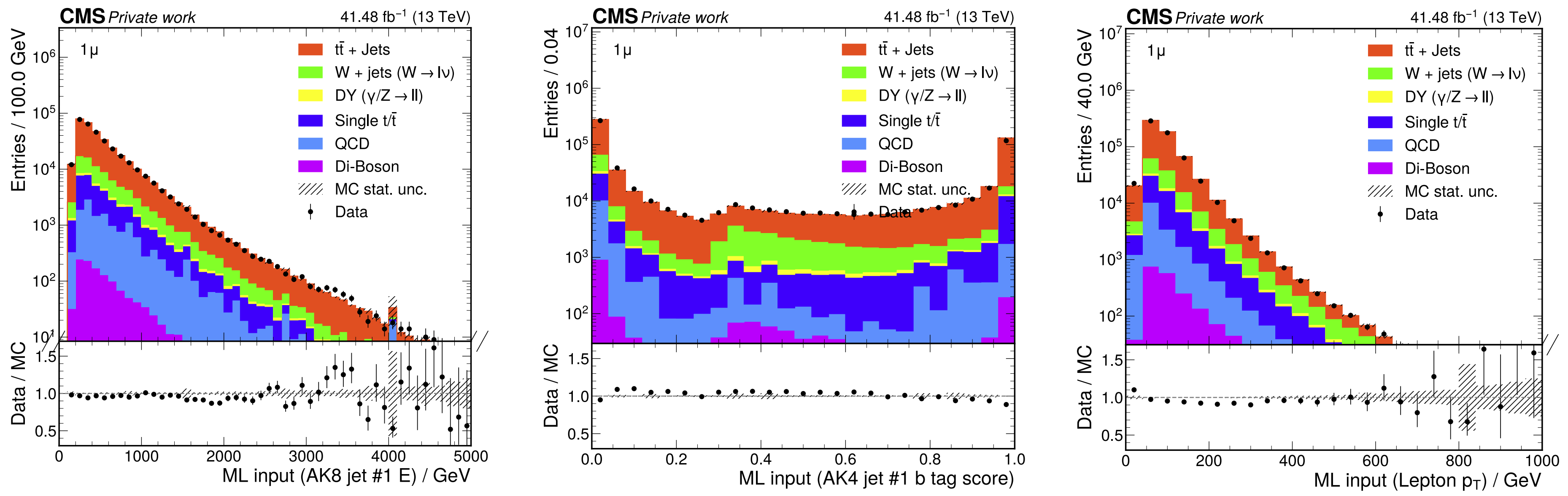

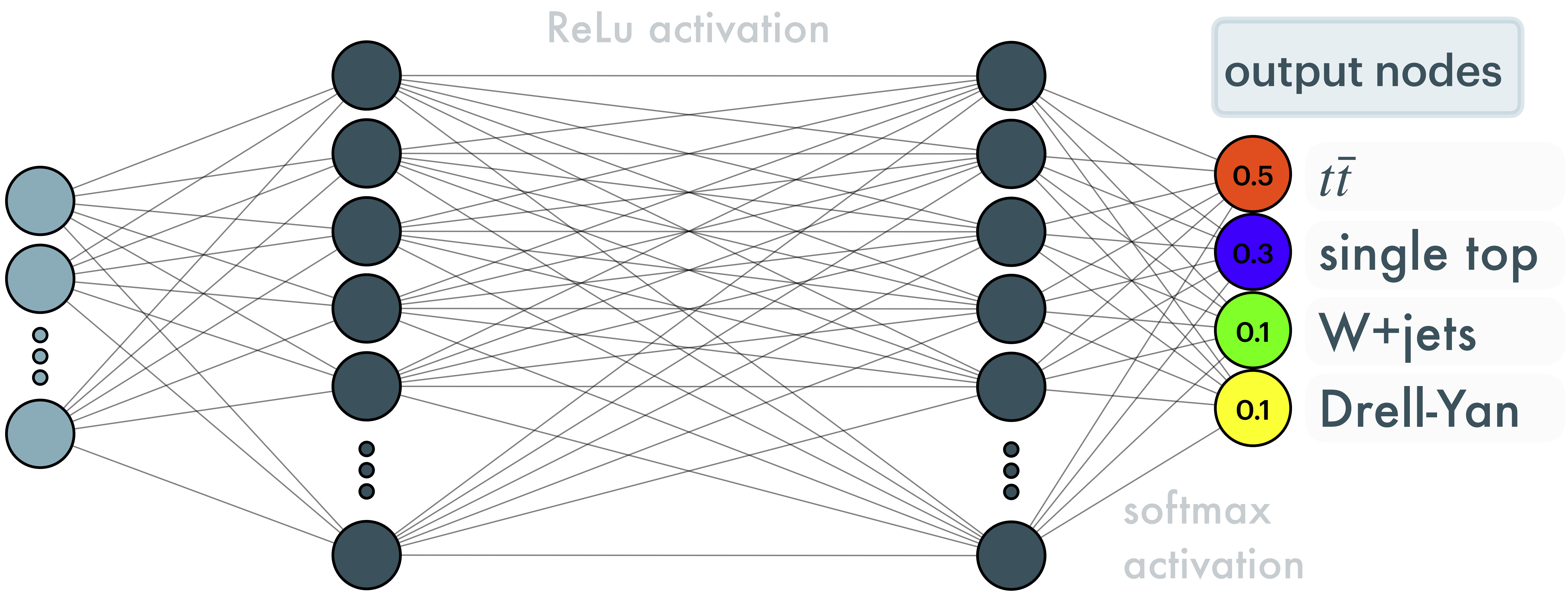

DNN Parameter

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