Flavour TAGging &

Particle IDentification

FCC Physics Performance meeting
July 15, 2024

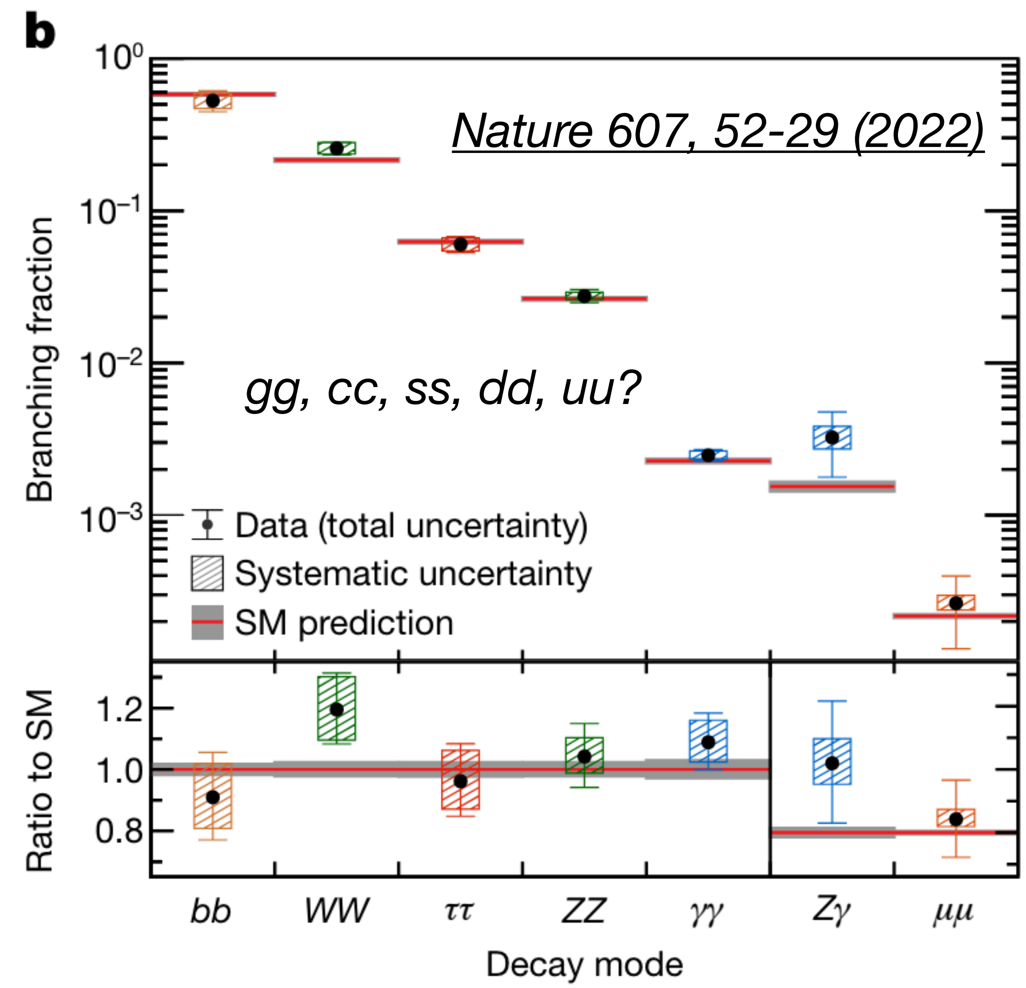
Andrea Sciandra
With help from V. Cavaliere & M. Selvaggi

Brookhaven National Laboratory

FUTURE CIRCULAR COLLIDER

Introduction & Motivation

- Flavor tagging: very powerful tool, *serving Physics purpose*
  - Key for e^+e^- program!
  - Access **Higgs**-boson properties, hardly accessible at the (HL-)LHC
    - Challenging decay modes like *cc*, *ss*, 1st generation fermions, *gg*?
  - Precise determination of **top**-quark properties - provided sufficient COM energy
    - Mass, width, Yukawa
  - **QCD**: strong coupling, hadronization modeling, tuning of MC, etc…



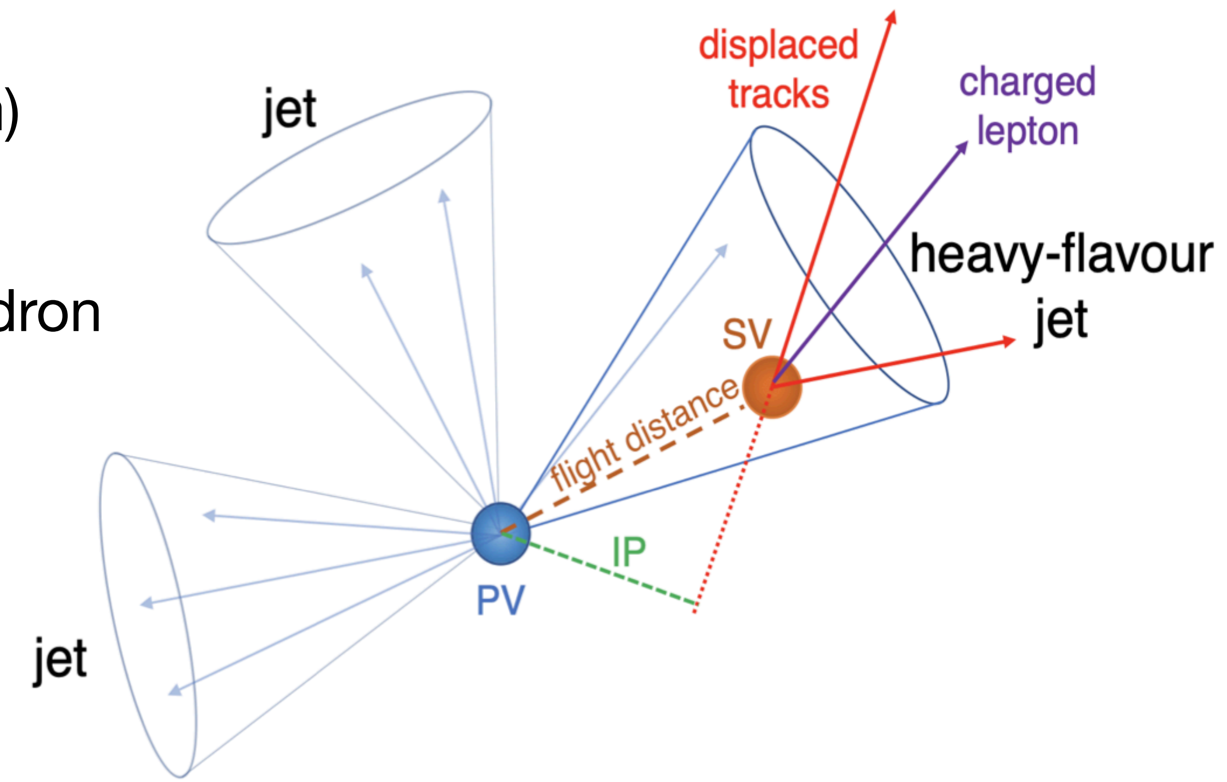
E_{CM} = 240 GeV [10.8 ab^{-1}, 4 IP]

Decay mode	Z(→LL)H(→jj) [%]	Z(→vv)H(→jj) [%]	Z(→jj)H(→jj) [%]	Combination
H→bb	0.55	0.24	0.20	0.15
H→cc	3.35	1.77	2.38	1.20
H→ss	280	93	296	80
H→gg	1.86	0.75	1.63	0.65

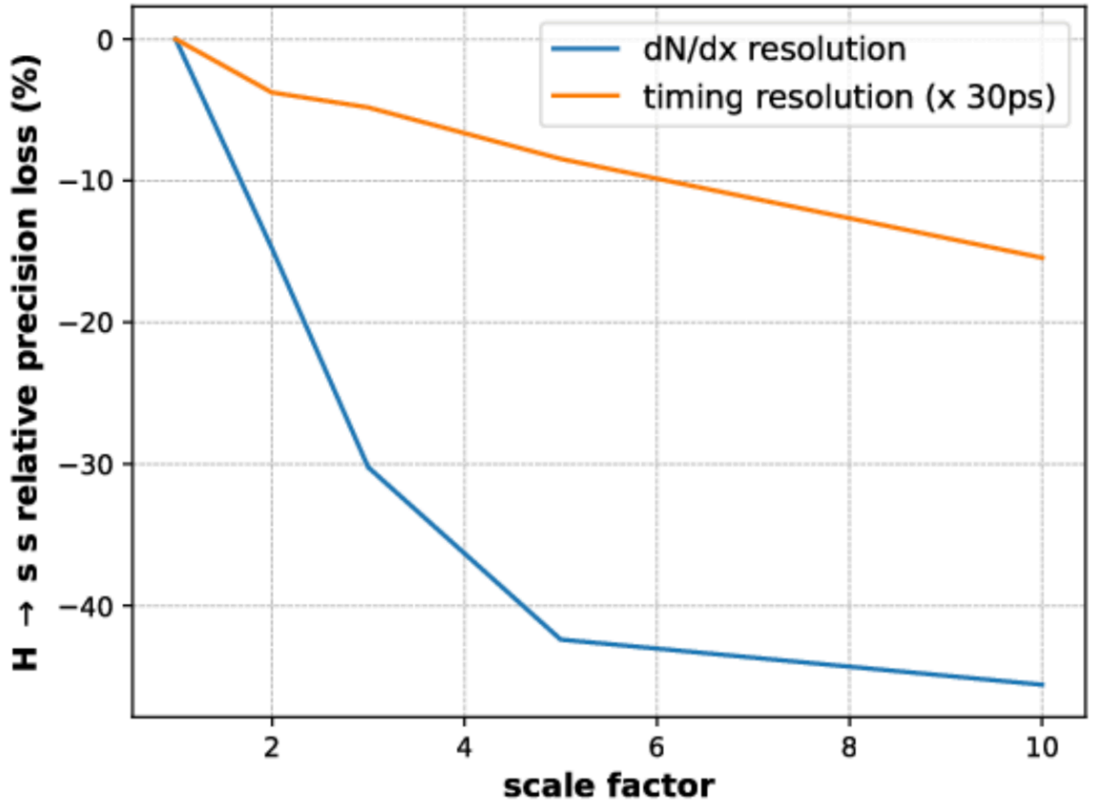
Loukas' Talk @FCC Week 2024

Flavor-Tagging Principles

- ***Bottom & charm*** tagging based on:
  - Large lifetime (~1/0.1 ps) & decay length (~500 μm)
  - Displaced vertices/tracks
    - Tertiary vertex for B hadrons decaying to C hadron
  - Relatively large invariant mass
  - Large track multiplicity (~5 charged particles on average)
  - Non-isolated charged leptons from semileptonic decays: 20(10)% in B(C)-hadrons decays

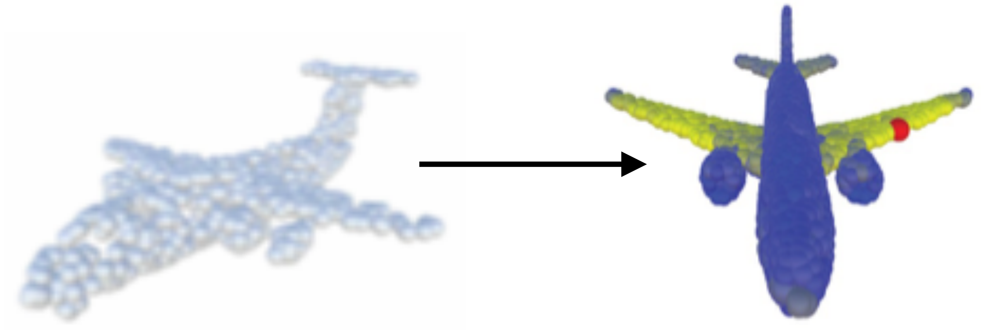


- ***Strange*** tagging
  - Exploiting enhanced Kaon fraction with large momentum share
  - Charged requiring K/π separation, neutral K_S->ππ, K_L
  - Benefitting from good PID: timing detectors, Cherenkov detectors, charged energy loss (silicon/gas)

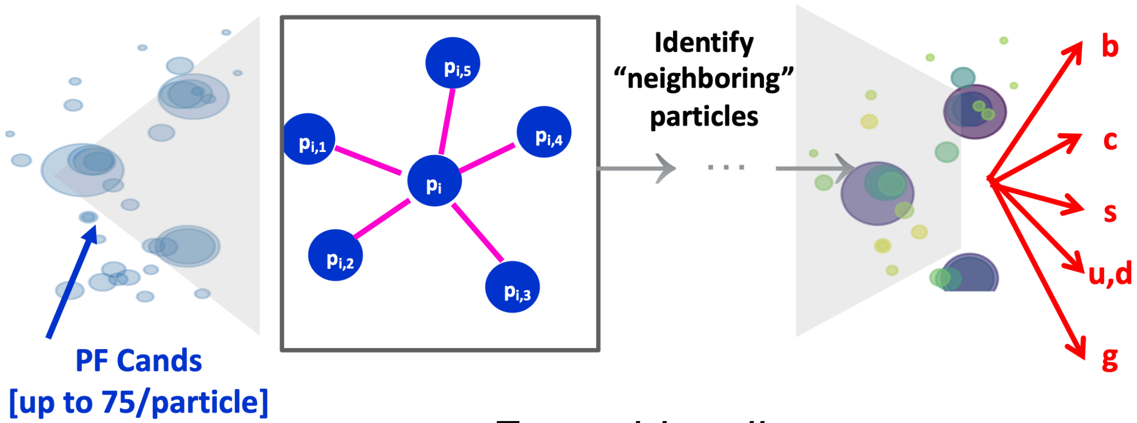


The ParticleNet Tagger

- Graph-based tagger, where each jet is treated as a “cone” of reconstructed particles traversing the detector
- Particle-flow (PF) principle: particle candidates are mutually exclusive and have lots of info associated with
  - E/p, position
  - Impact parameters, particle type
  - Timing
- Experiments at the LHC moving(ed…) towards particle-based jet tagging, exploiting the whole information directly related to PF candidates
  - Full info, reco (one day…) potential & det granularity
- Jets are unordered sets of particles with correlations & relationships. Graph-Neural-Network architecture for **ParticleNet**:
  - Identify properties of “particle cloud”, represented as a **graph**
  - Learn local structures -> move to global ones



From this article

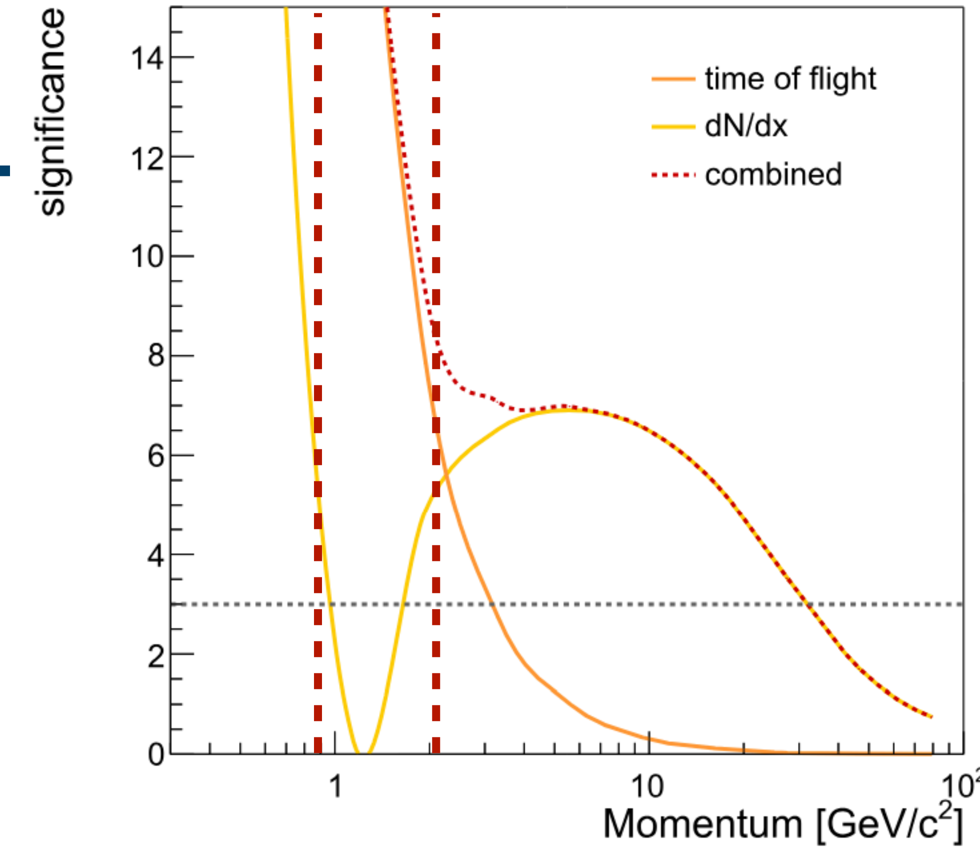


From this talk

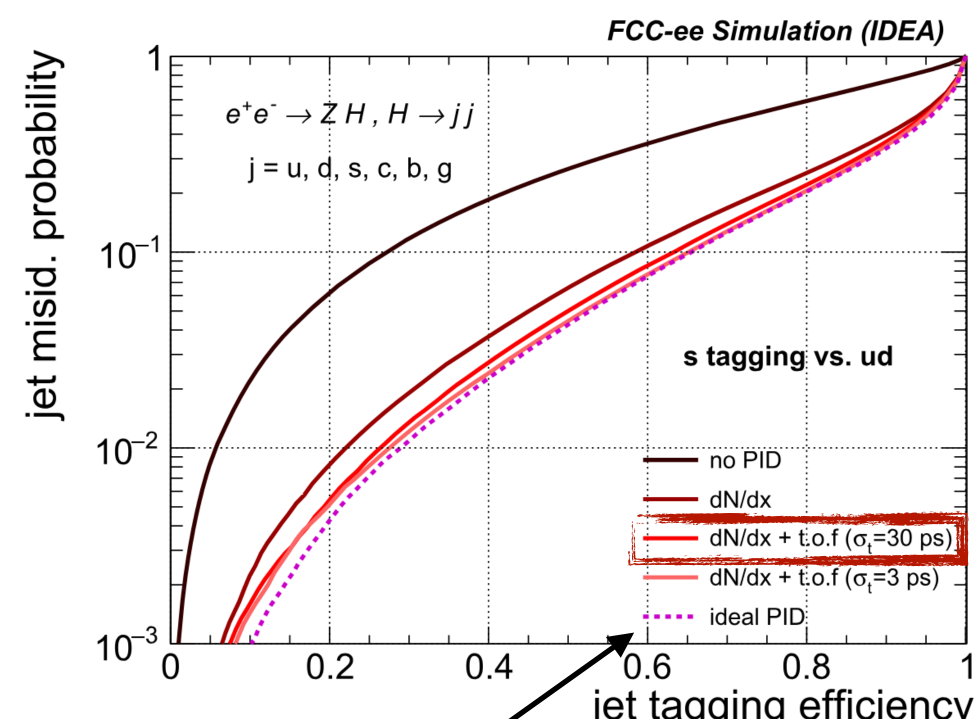
Flavour Tagging & PID

- Count number of primary ionization clusters along track path (dN/dx)
- ToF results in good K/π separation at low-momenta
- dN/dx brings most of the gain additional gain w/ TOF (30ps resolution)
  - Minor gains from better time precision (3ps)
  - **dN/dx + TOF (30ps) is ~as performant as a perfect PID!**

-> Updated & complementary PID performance studies on bottom, charm & strange tagging



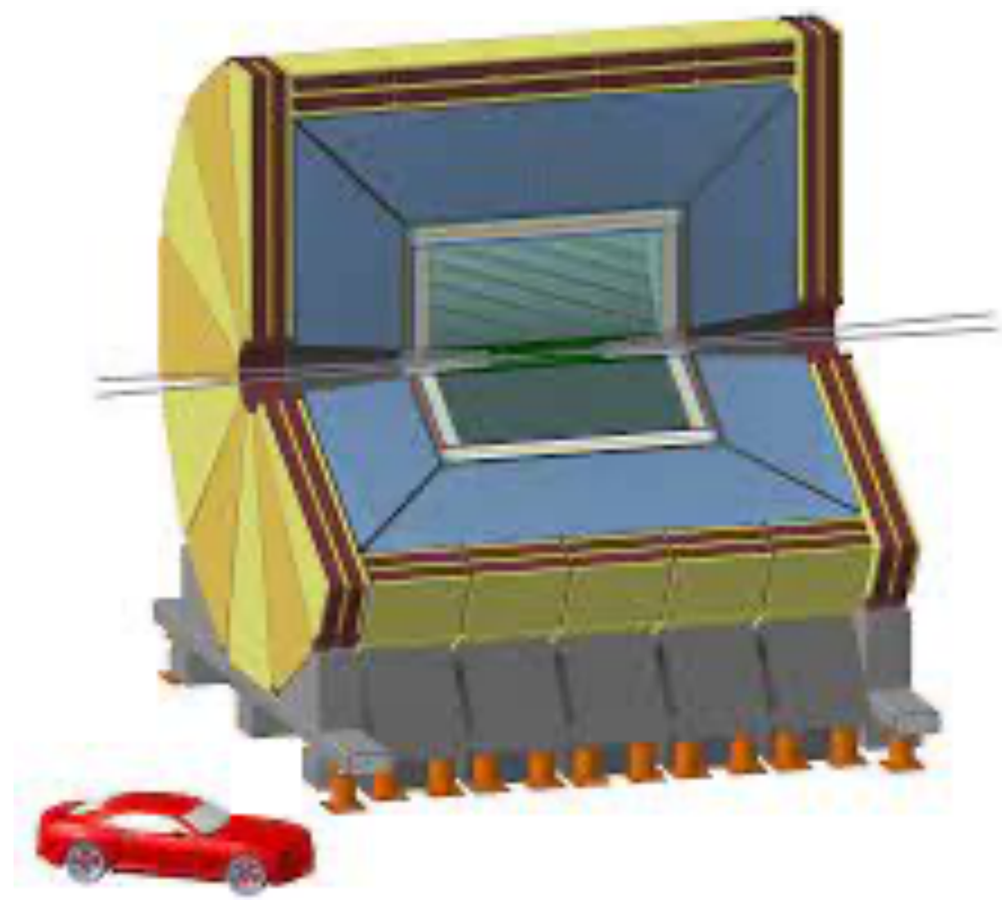
Eur. Phys. J. C 82, 646 (2022)



"Ideal" PID from MC truth record

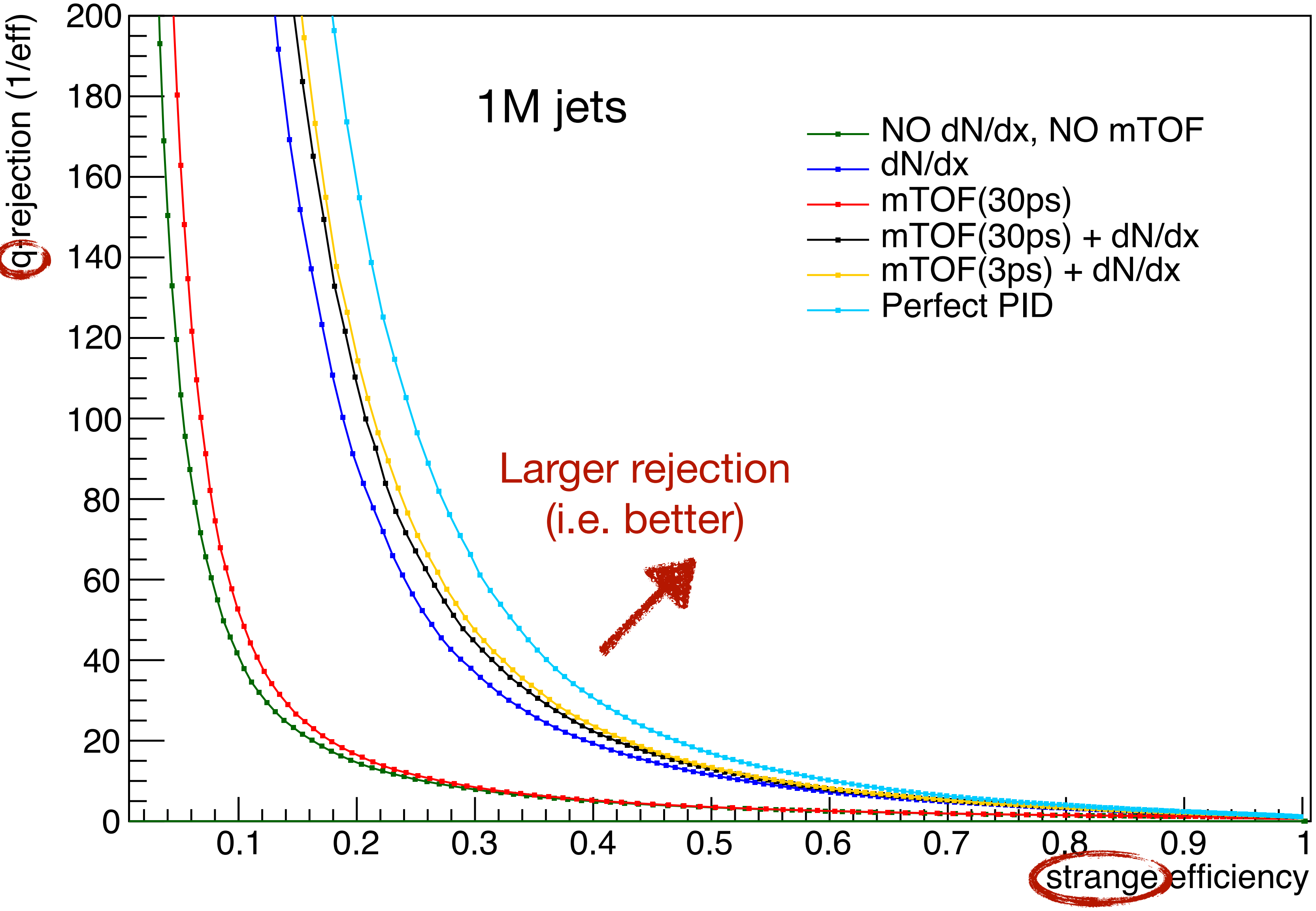
The IDEA for Tagger Studies & Setup

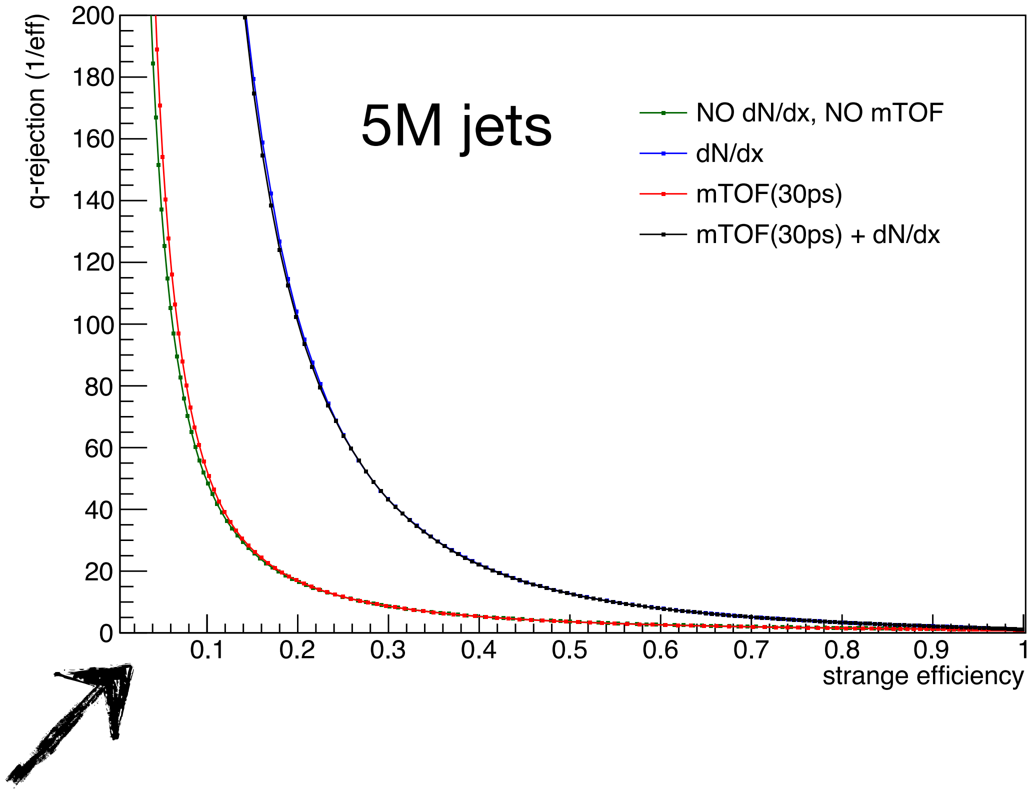
- Generate 5 jet flavors in *vvH* Higgs decay (*Whizard*)
  - *bb, cc, ss, qq(=uu,dd), gg*
- Simulate through IDEA detector fast simulation (*Delphes*)
  - Different PID configurations studied:
    - **no PID**,
    - **TOF only** (not evaluated before),
    - **dN/dx only**,
    - **IDEA** (dN/dx+TOF(30ps)),
    - dN/dx+TOF(**3ps**),
    - **Ideal PID**, charged hadrons PDG ID from truth MC record.



- Process key4hep files to get ntuples, *inputs to flavor-tagger* trainings
- Perform trainings (on GPUs) for different tracker scenarios & evaluate gain/ drop in tagging performance
- These **steps** (simulate->process->retrain->evaluate) are **repeated for each single detector-configuration variation**
  - Exploited 200k/1M jets per flavor (1/5M jets in total), depending on training

Strange Tagging & Light Rejection

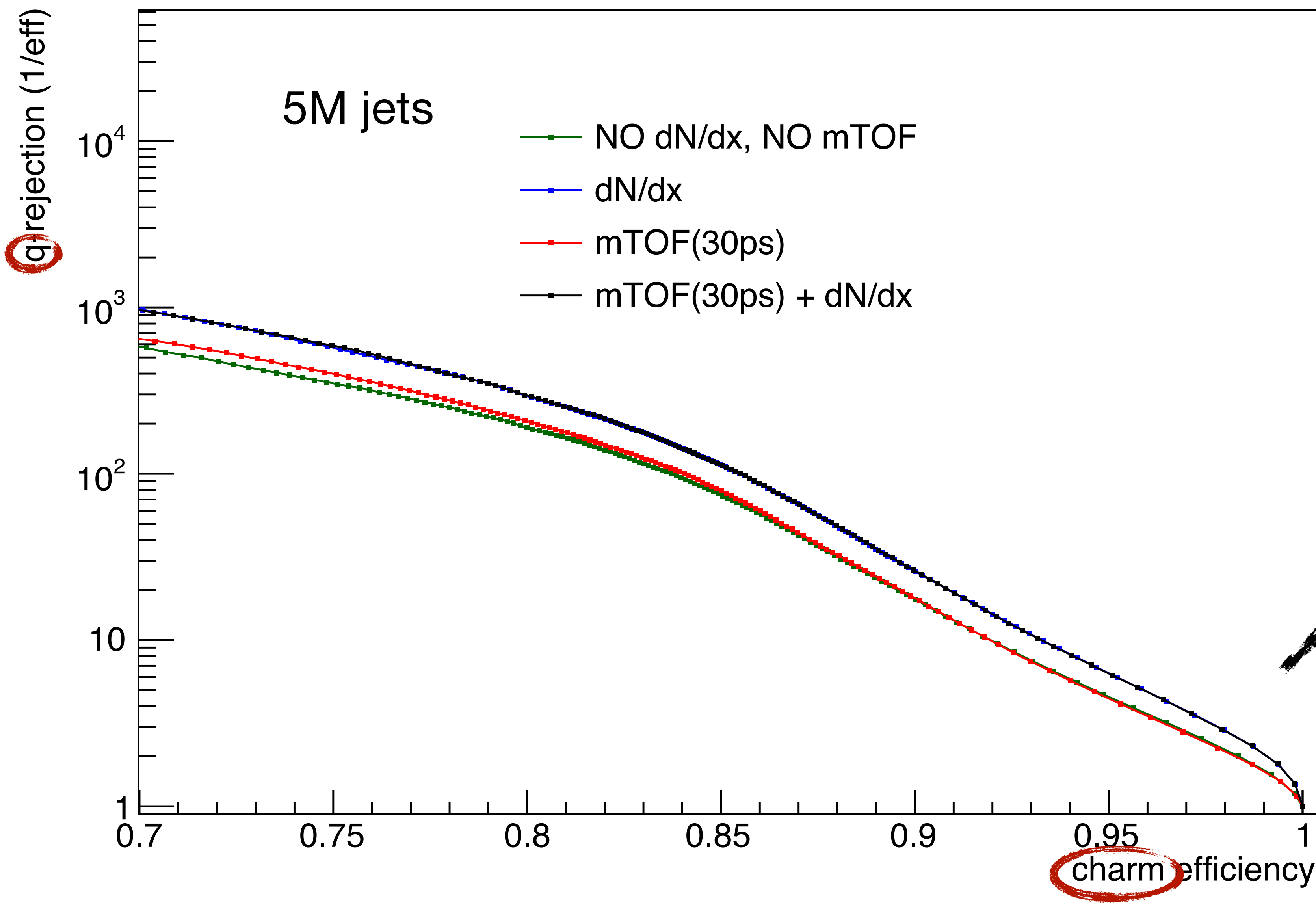


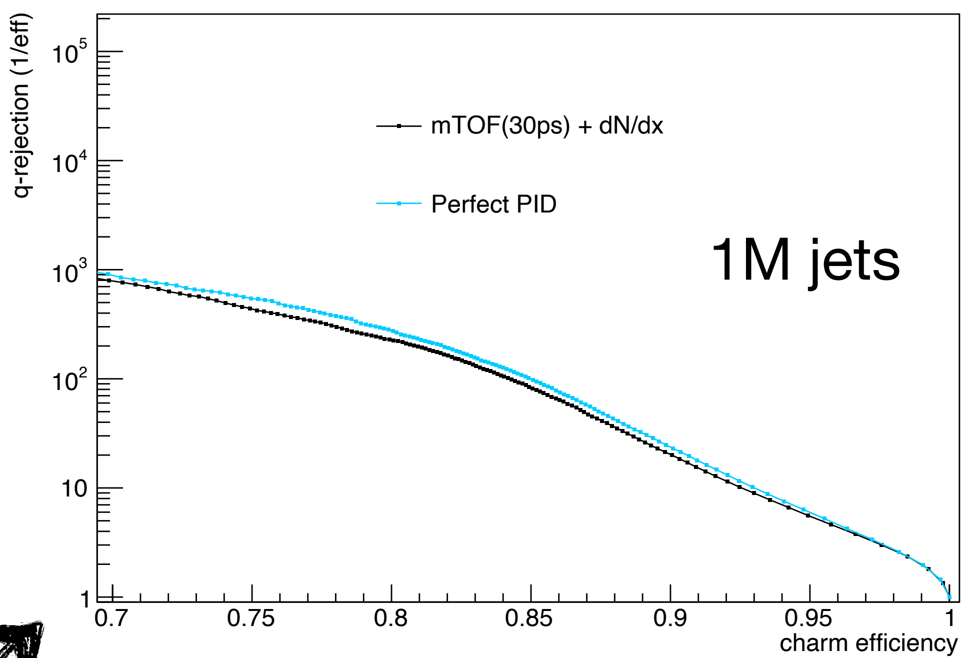


N.B. impact of TOF becomes "more"~negligible when training on x5 larger stats!

- **Most of achievable gain from PID confirmed to come from dN/dx**
- Very **limited impact of TOF** mass measurement (even with dream resolution) on strange tagging
  - Benchmark: 60% efficiency -> light rejection 2.5 (mTOF) vs. 7.5 (dN/dx) vs. 8 (dN/dx+mTOF)
- Ideal PID shows visible enhancement, especially at low efficiency
  - Benchmark: 60% efficiency -> light rejection 8 (dN/dx+mTOF) vs. 10.5 (+truth MC PID)

Charm Tagging & Light Rejection

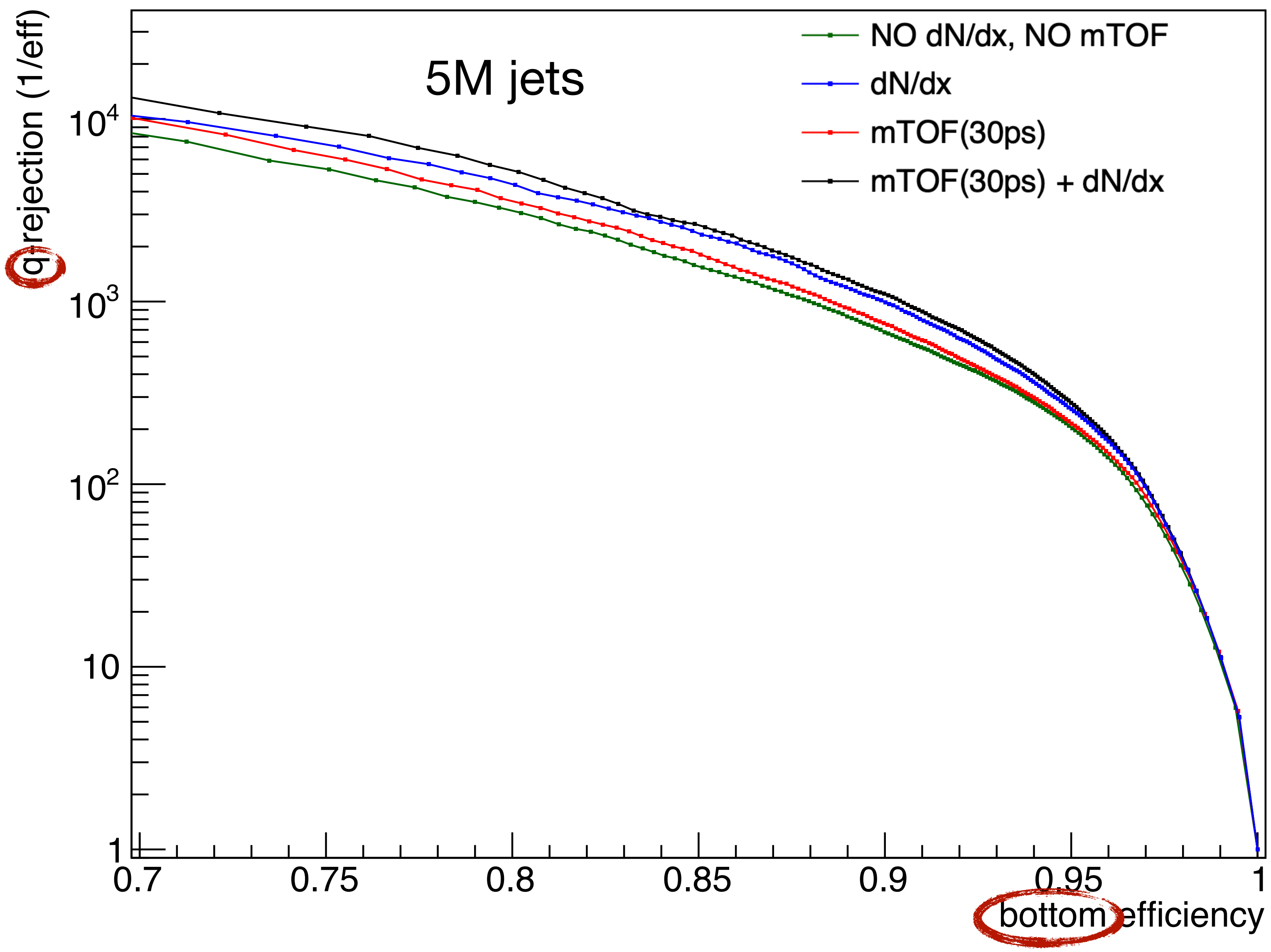


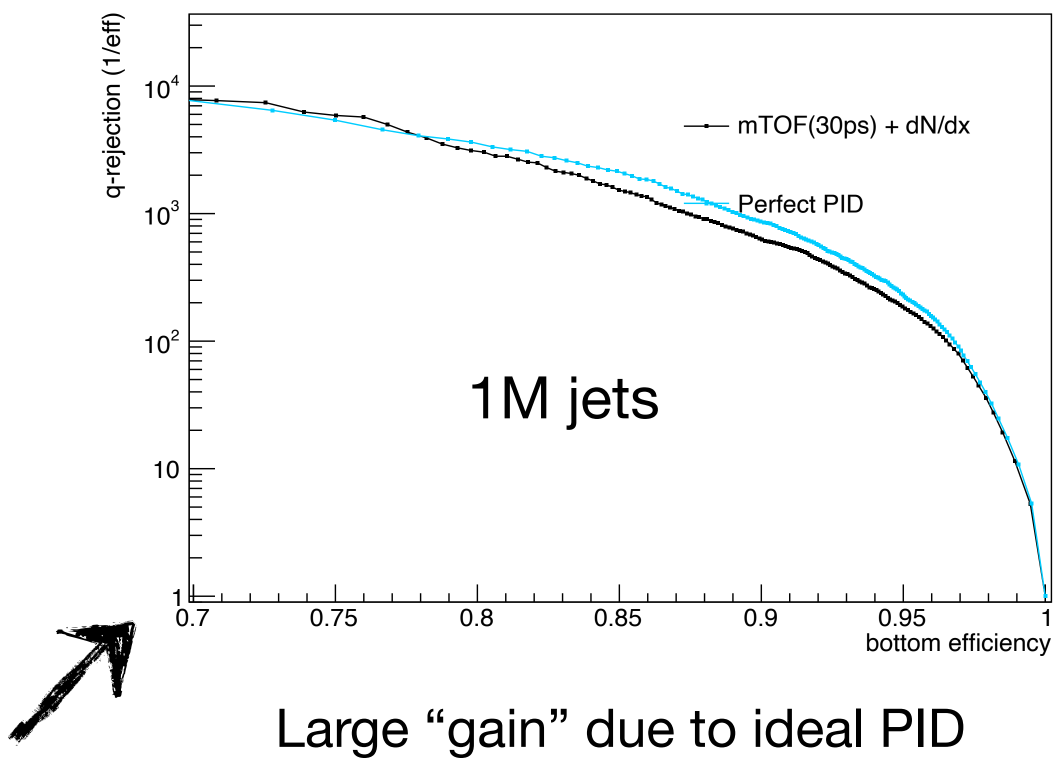


“Enhancement” due to ideal PID, significant but smaller than relative gain from dN/dx itself

- **dN/dx dominates** again, as expected from kinematic regime of *ZH* events
- **Visible** contribution from **TOF, in absence of dN/dx**

Bottom Tagging & Light Rejection

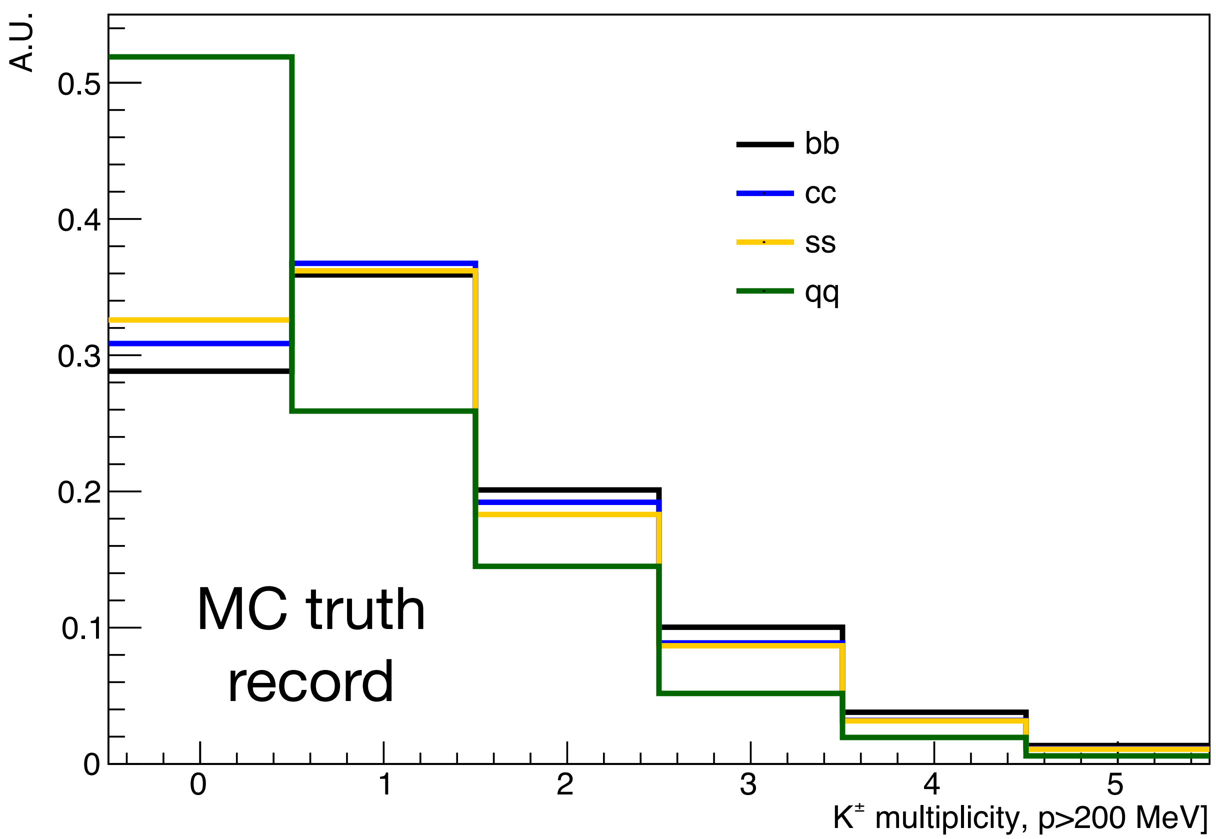


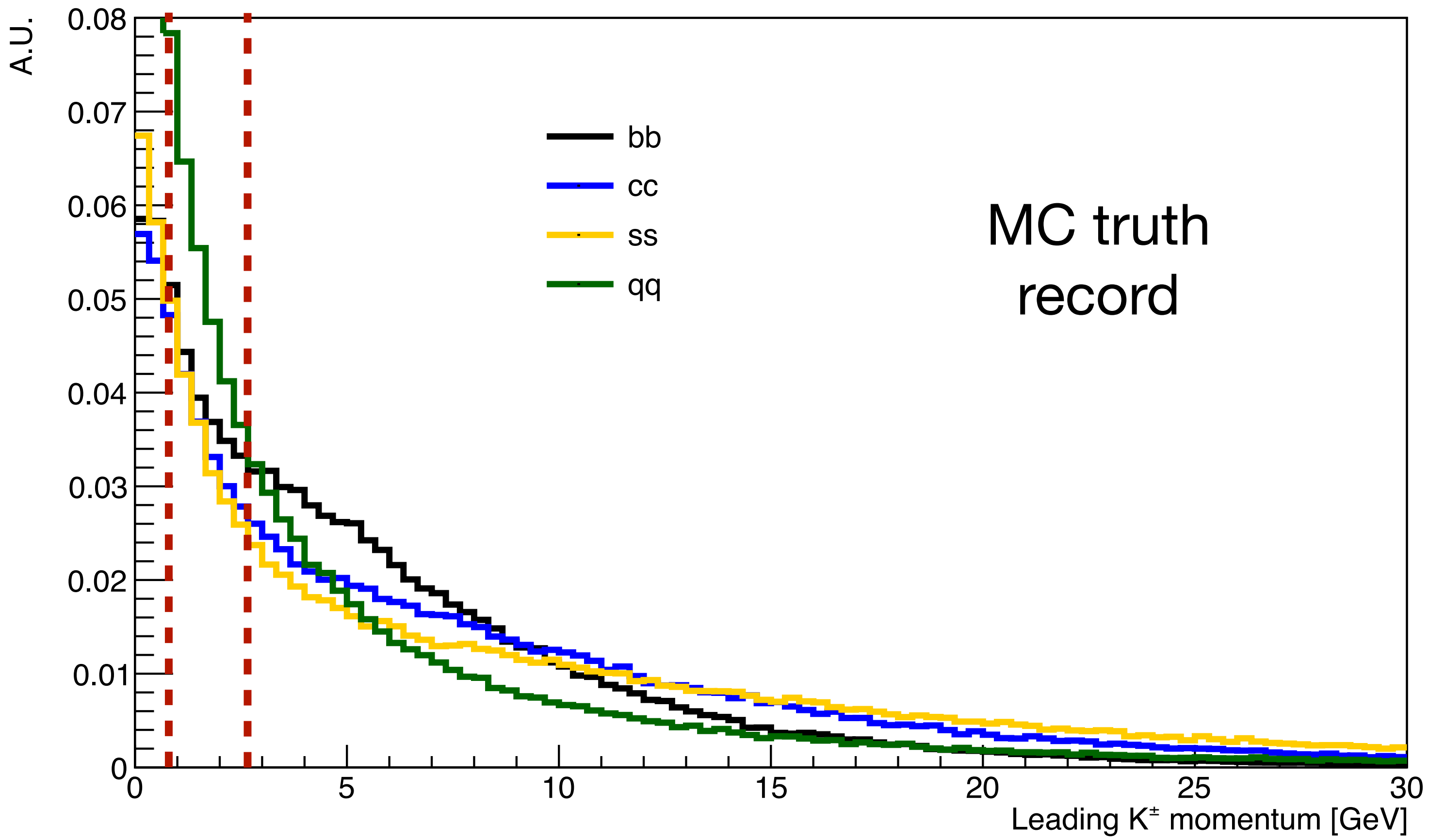


Large "gain" due to ideal PID

- Most of PID gain from dN/dx, but…
- **Significant contribution from TOF, with and without dN/dx!**
    - Benchmark: 80% efficiency -> light rejection 4400 (dN/dx) vs. 5100 (dN/dx+mTOF)

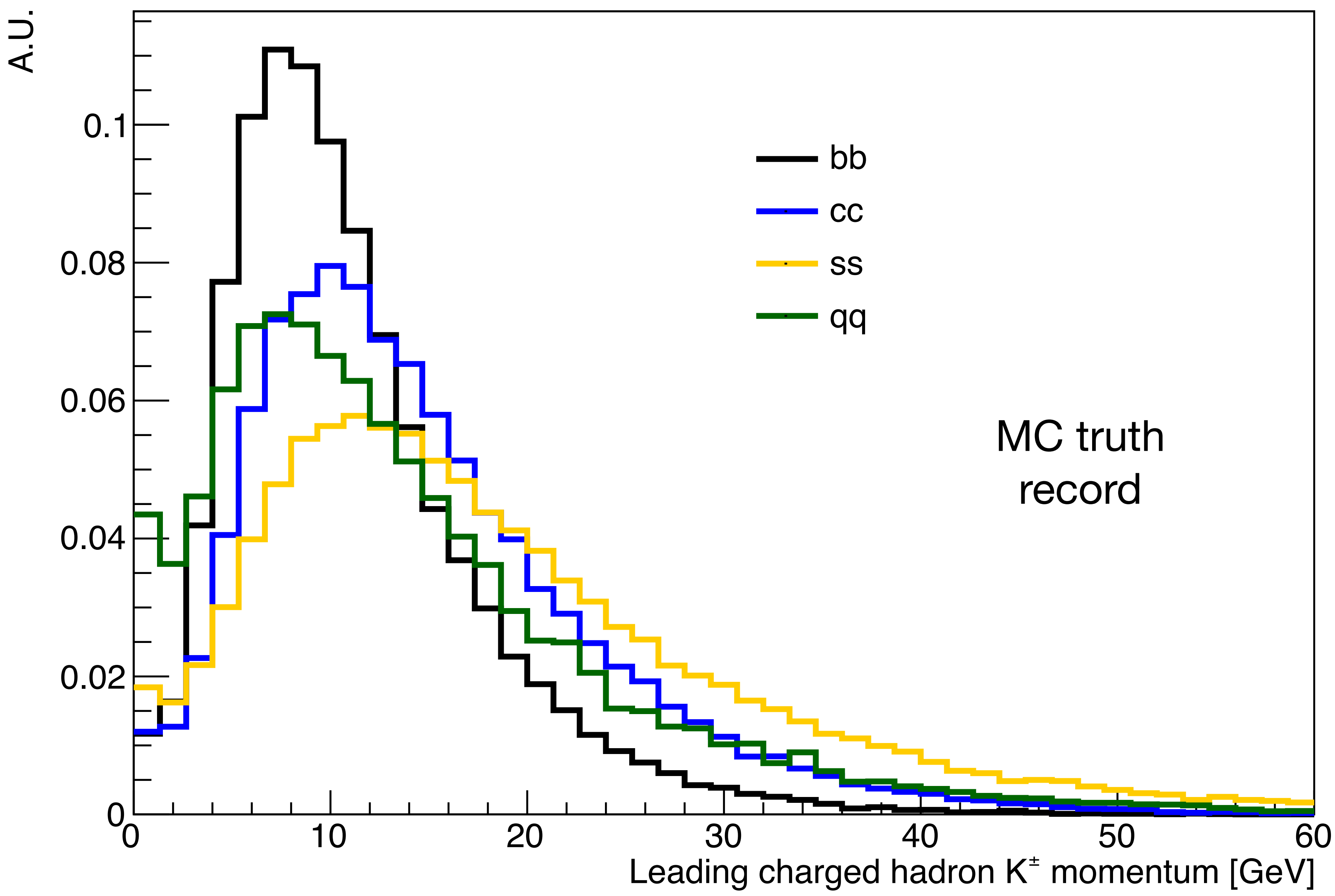
Multiplicity of $K^{\pm}$ & Leading $K^{\pm}$ Momentum





- Similar ***K*± multiplicity** for *b*, *c* & *s* jets, much smaller in light jets
- Hierarchy of TOF impact on light rejection for *b*, *c* & *s*-tagging reflected by spectra of leading $K^{\pm}$ in jet
- Generally, **harder spectrum in strange jets**, more evident for leading charged hadrons

Leading Charged Hadron $K^{\pm}$ Momentum



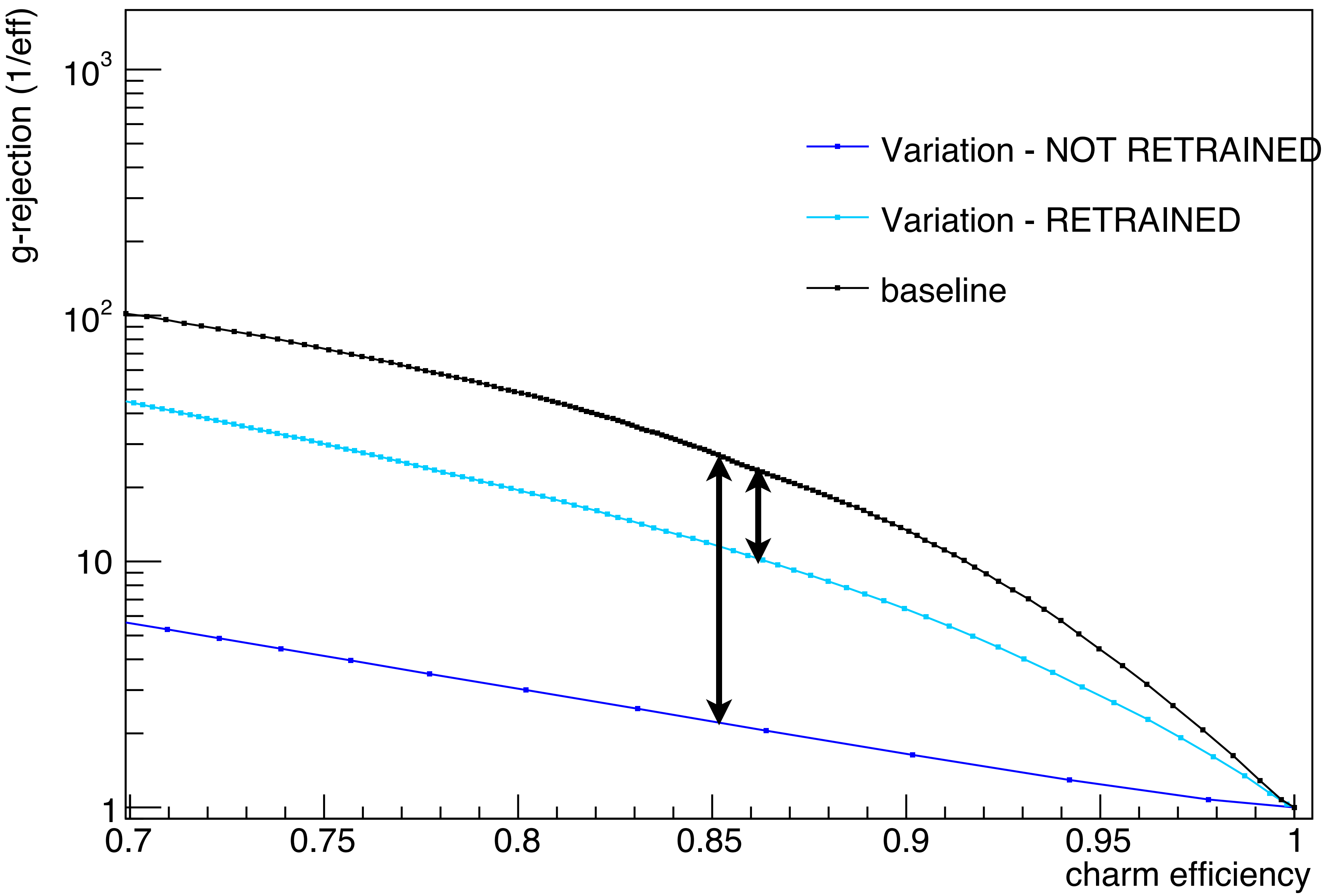
- Momentum of charged Kaons, when leading charged hadron in jet
- **Significantly higher jet momentum fraction in strange jets**

Conclusion & Plans

- Significant degradation observed in efficiency(rejection) at fixed rejection(efficiency), when dropping PID information
  - Given kinematic regime, **dN/dx dominates** PID performance enhancements across the board
- **Significant effects in bottom- and charm-tagging as well!**
  - Impact of TOF measurement larger in *b*-tagging, where larger fraction of $K^{\pm}$ populate dN/dx dip momentum range
  - Focused on light rejection, where effects are more significant, more ROC curves are in backup for the record
- Working on documentation of these and previous (link1 link2 link3) detector variation studies in a FCC note
  - Including impact on Higgs (all-hadronic and invisible *ZH*) analyses

BACKUP

Why is Retraining Necessary?



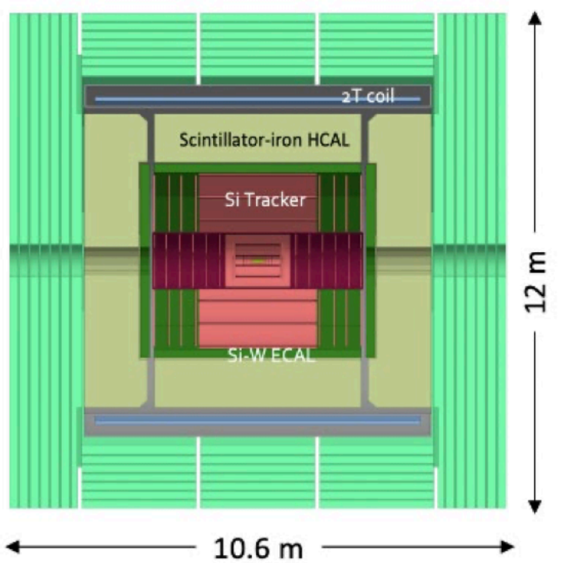
- Obviously, given a detector configuration, ParticleNet would be trained against it
- Re-training allows recovering of (a significant) part of drop in performance
  - **Need re-training for fair & meaningful performance assessment of each point in the detector-configuration space**

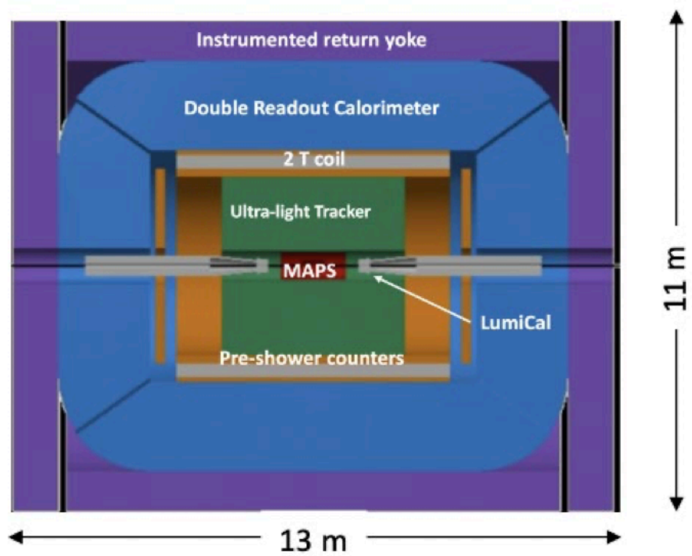
Current Detector Concepts

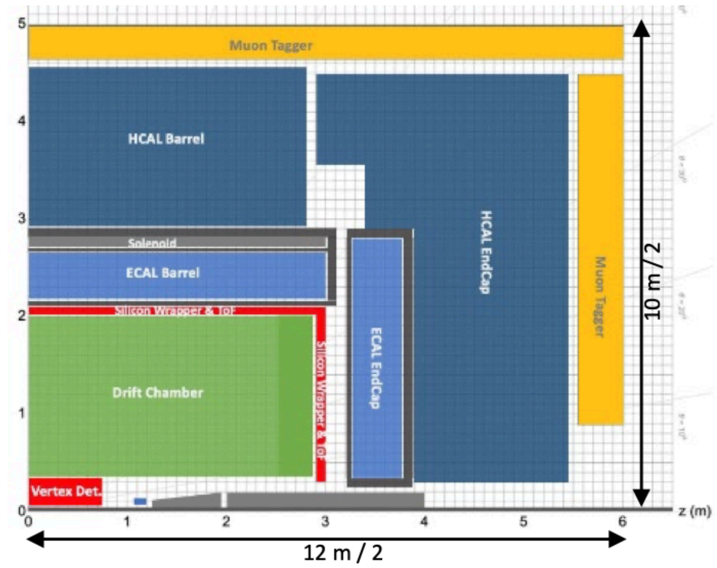
Current Detector Concepts

From Marc-André's talk

CLD	IDEA	ALLEGRO







CLD

- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

IDEA

- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber with powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

ALLEGRO

- The "new kid on the block"
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

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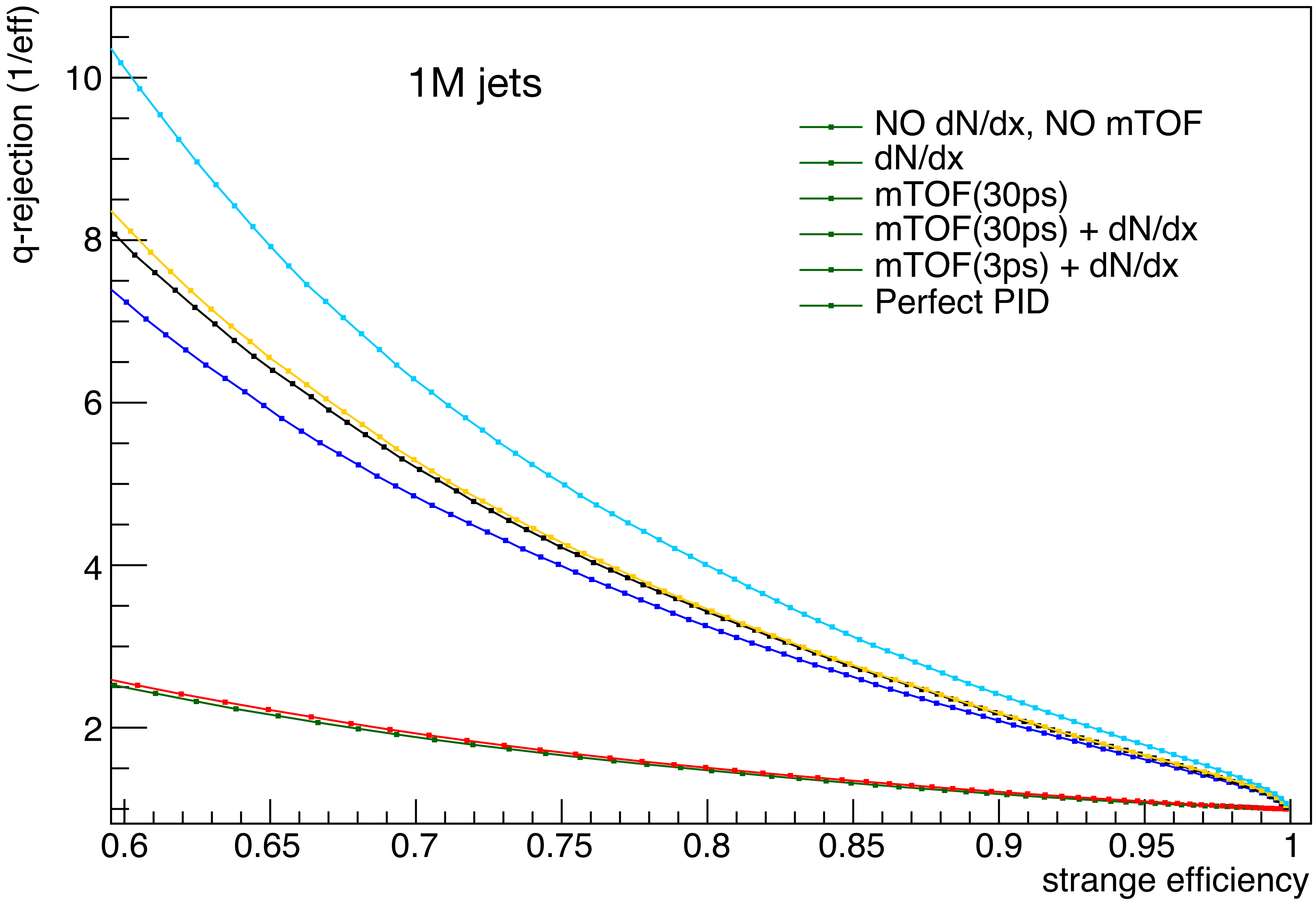
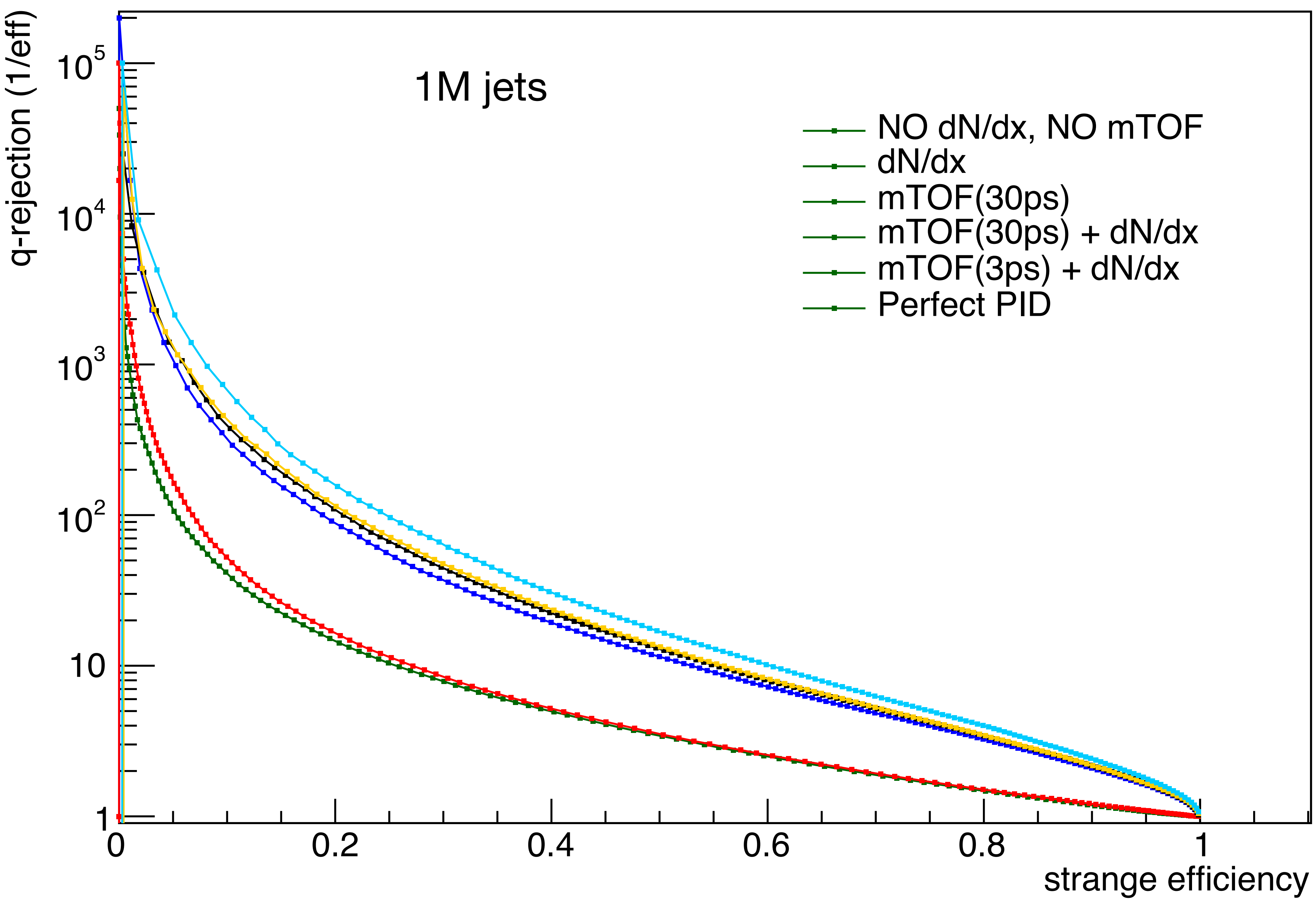
Strange Tagging

Strange Tagging & Light Rejection (Zoomed)

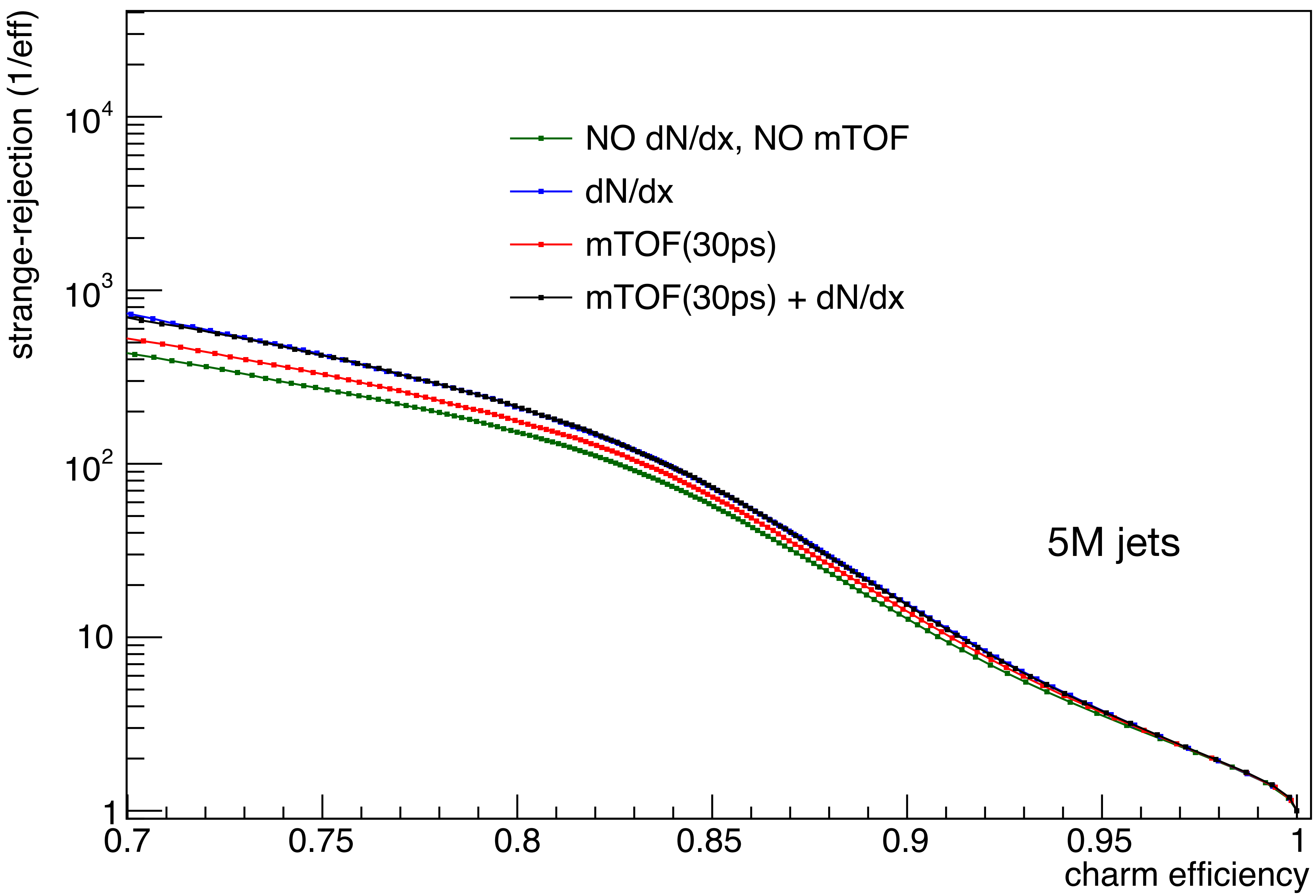


Strange Tagging & Light Rejection (logY)

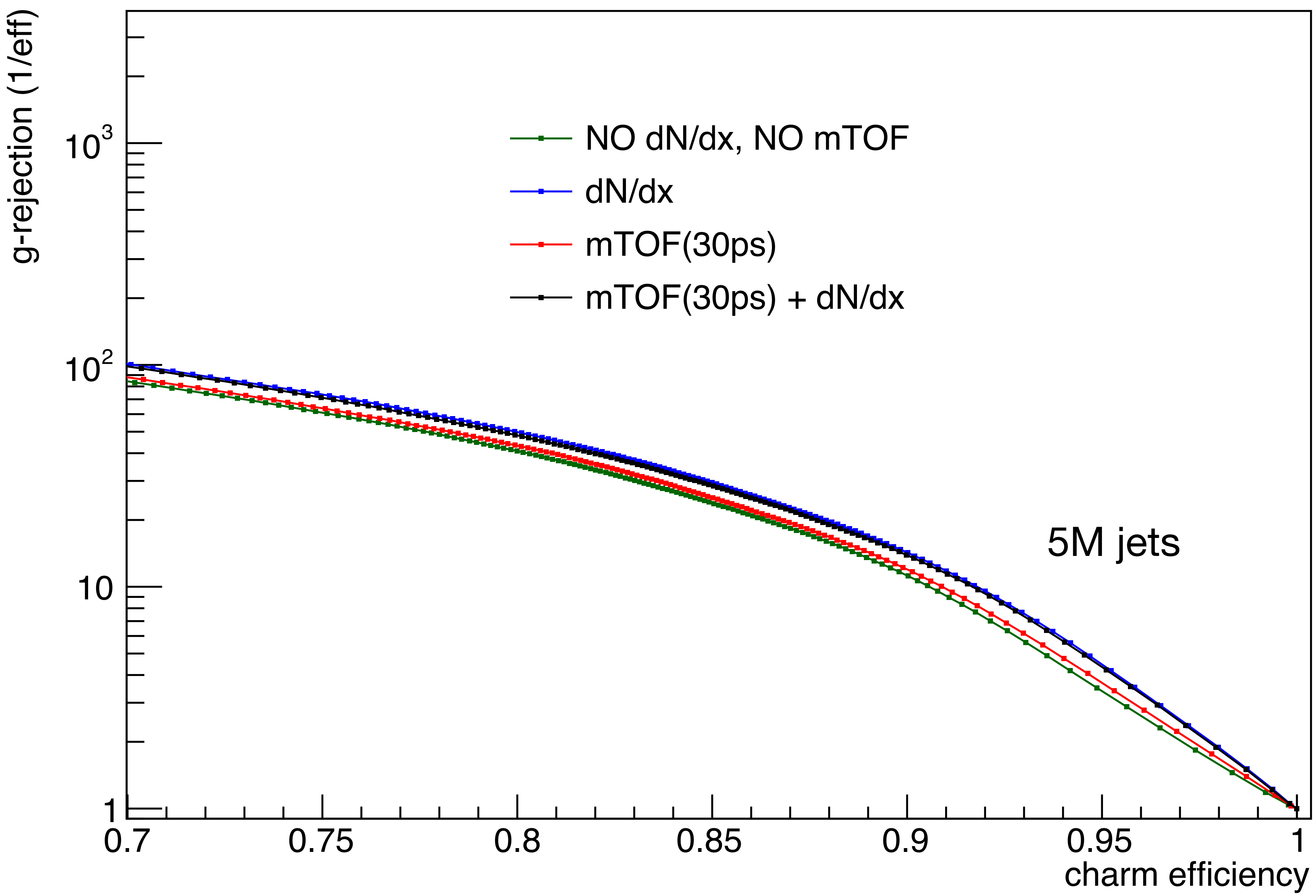


Charm Tagging

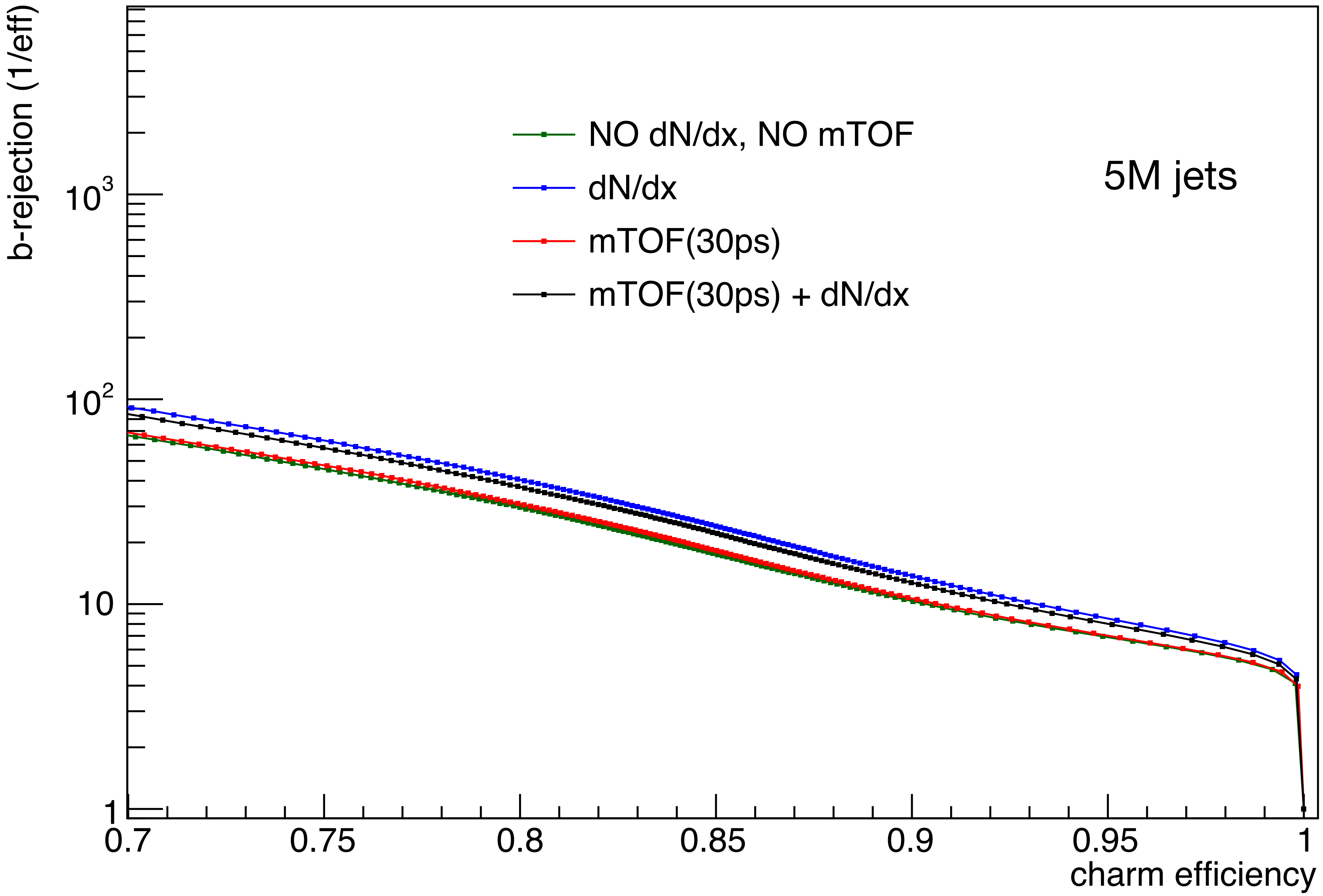
Charm Tagging & Strange Rejection



Charm Tagging & Gluon Rejection

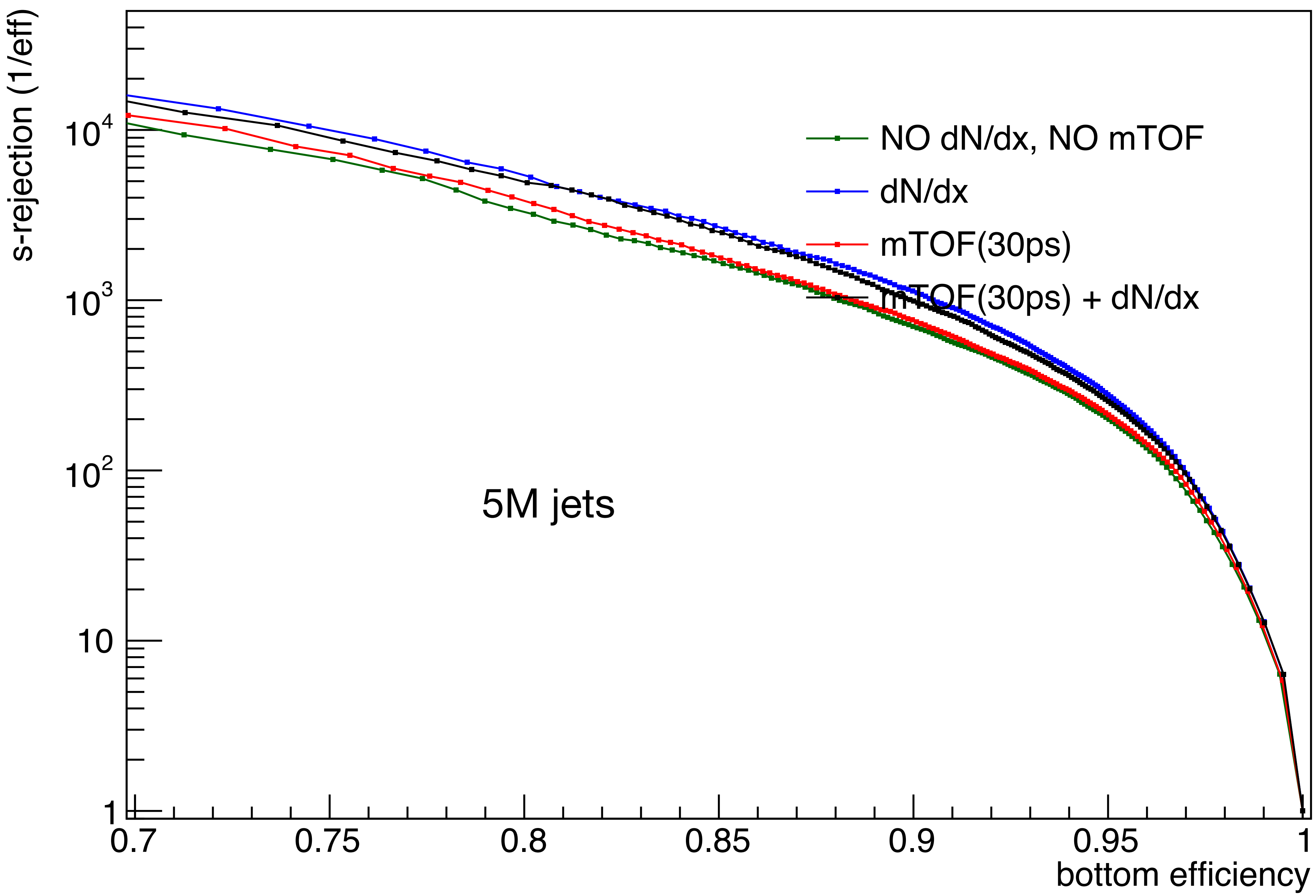


Charm Tagging & Bottom Rejection

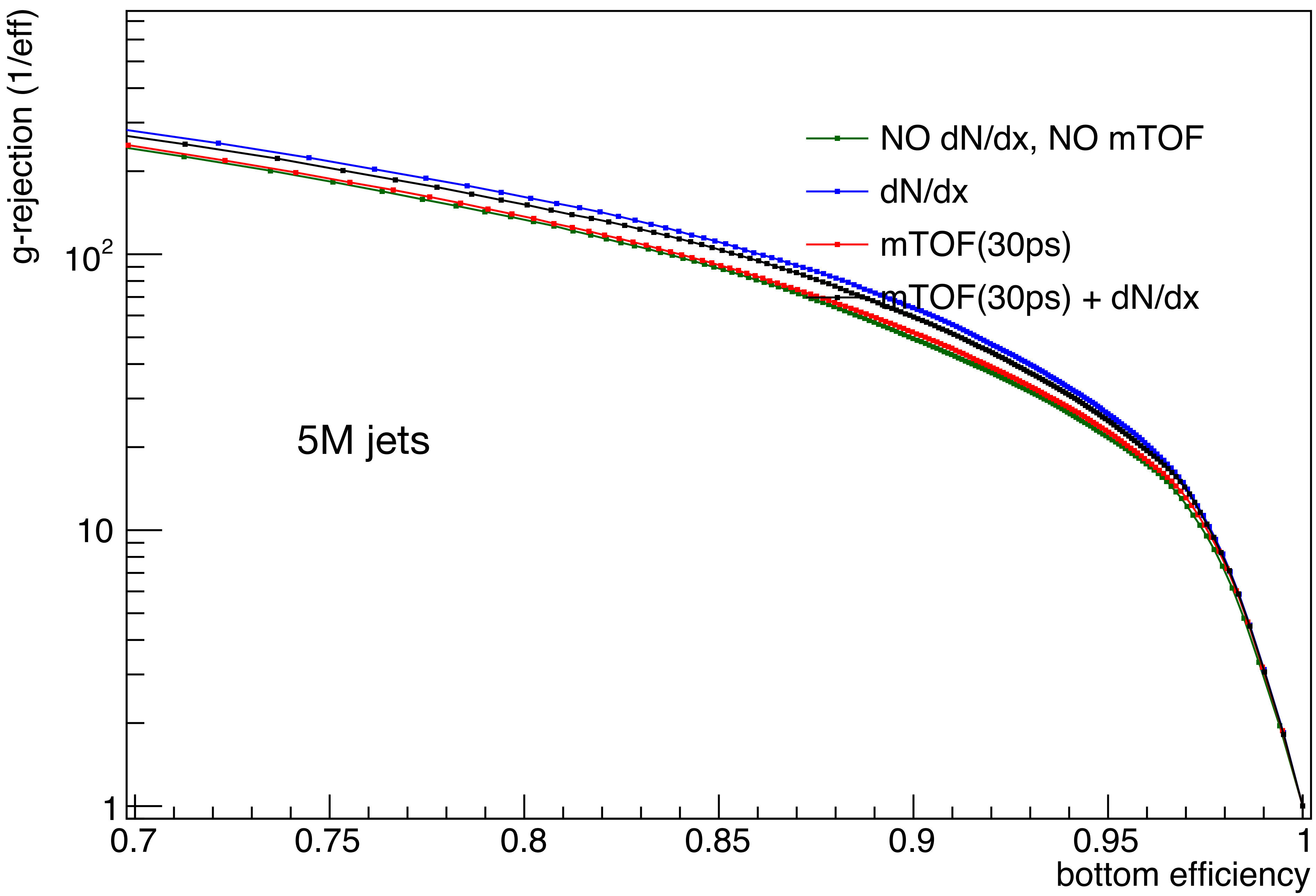


Bottom Tagging

Bottom Tagging & Strange Rejection



Bottom Tagging & Gluon Rejection



Bottom Tagging & Charm Rejection