Jet flavor tagging & implications on ~~detector~~ requirements for FCC-ee tracker

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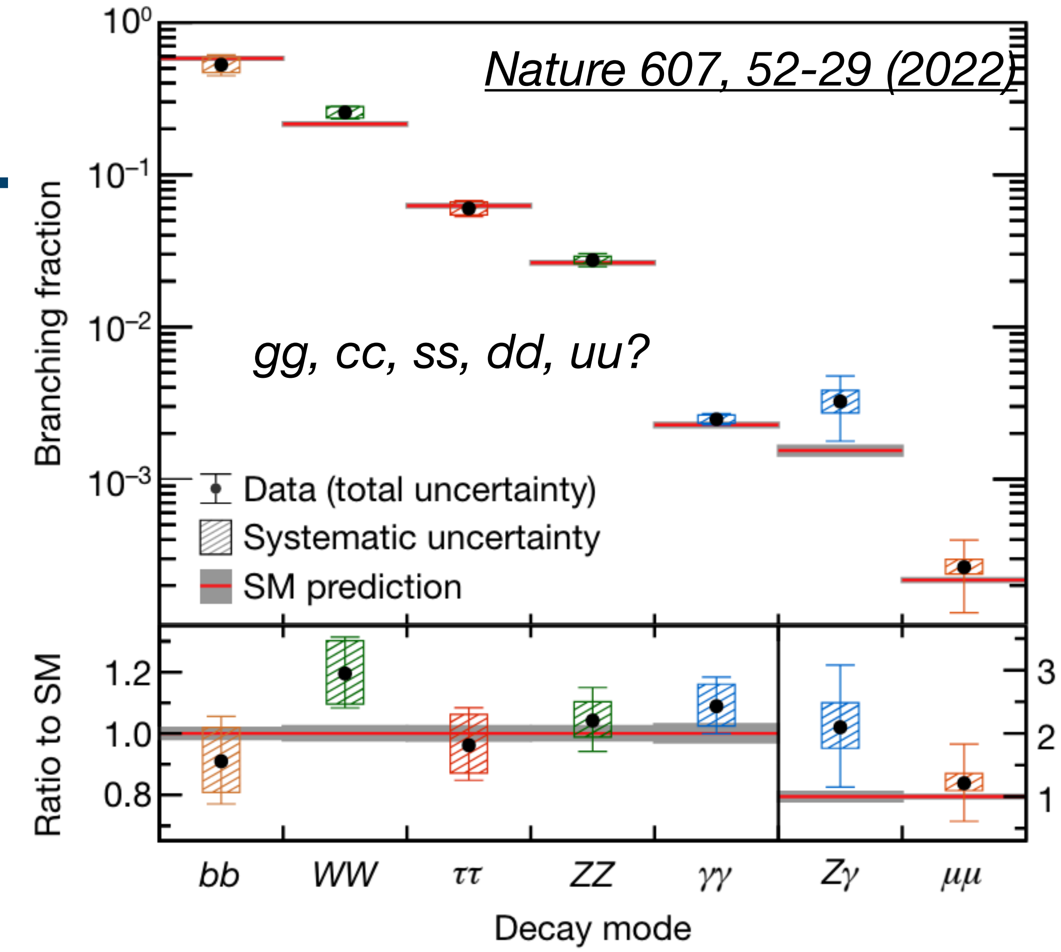
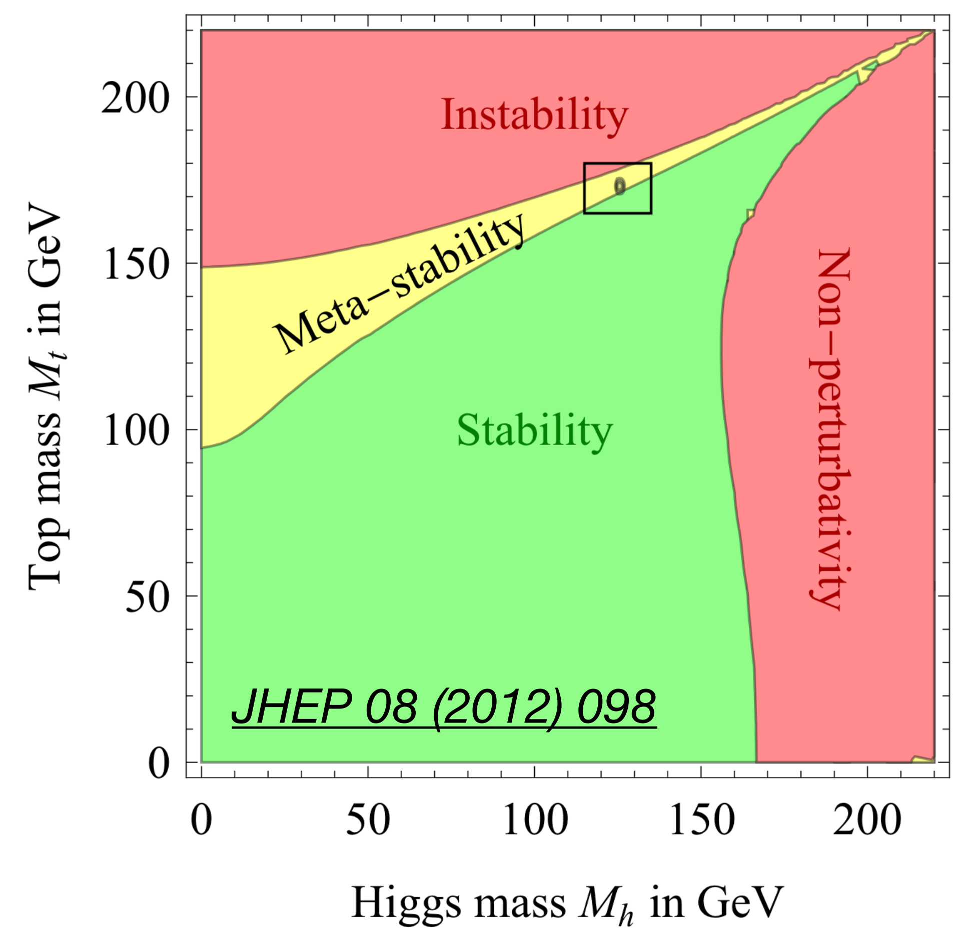
FUTURE CIRCULAR COLLIDER

Introduction & Motivation

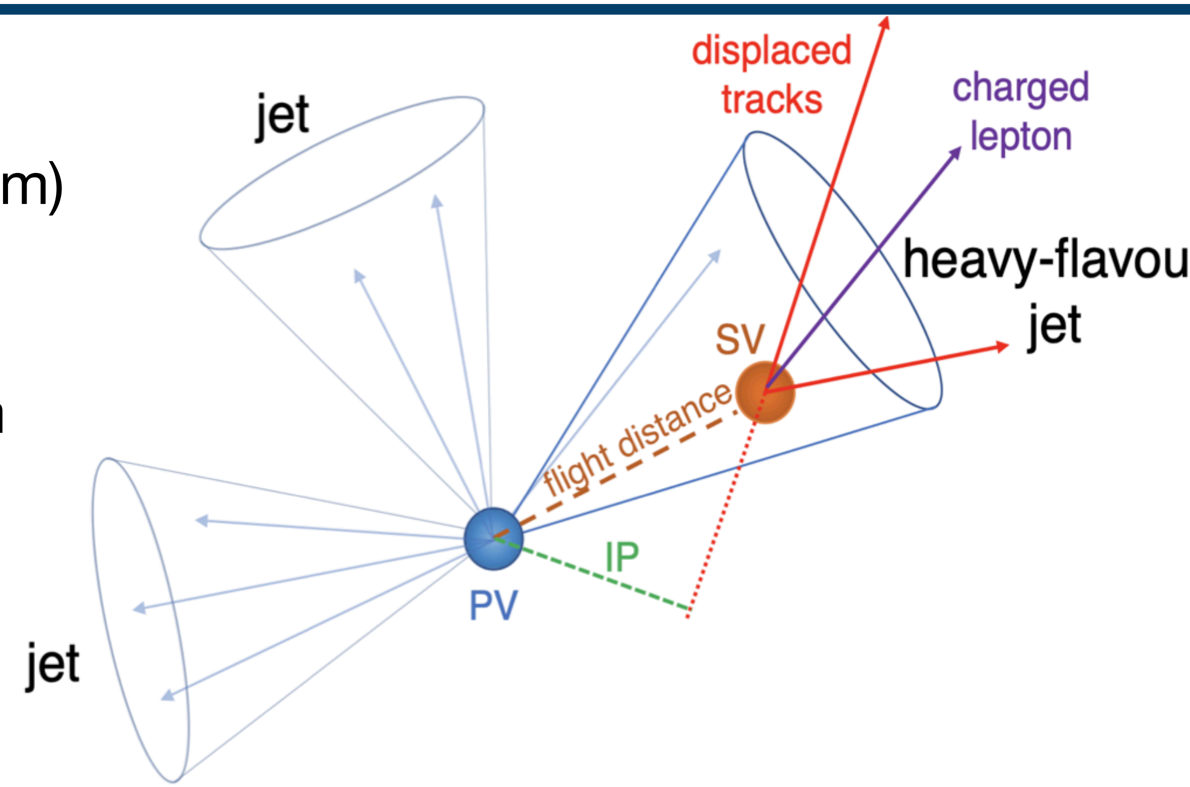
- Flavor tagging: very powerful tool, *serving Physics purpose*
  - Key for e+e- program!
  - Access **Higgs**-boson properties, hardly accessible at the (HL-)LHC
    - Challenging decay modes like *cc* and “impossible” hadronic decay modes: *gg*, *ss*, 1st generation quarks
  - Precise determination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





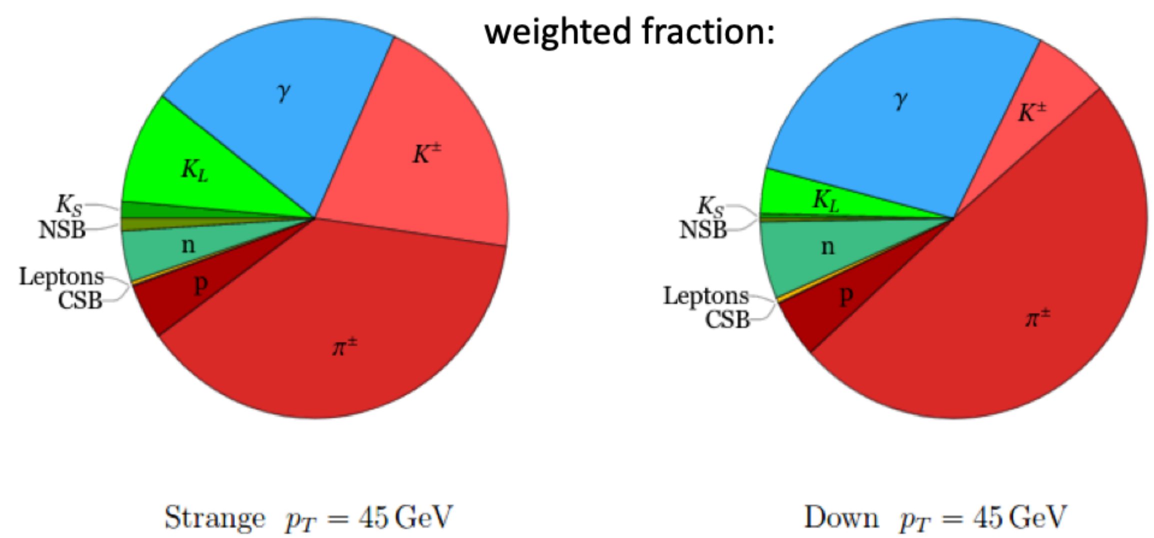
Flavor-Tagging Principles

- ***Bottom & charm*** tagging based on:
  - Large lifetime (~1/0.1 ps) & decay length (~50-500 μm)
  - Displaced vertices/tracks
    - Tertiary vertex for B hadrons decaying to "charm hadron" or "D hadron"
  - Relatively large invariant mass
  - Specific track multiplicity (~5 charged particles on average)
  - Non-isolated charged leptons from semileptonic decays: 20(10)% in B(C)-hadrons decays
  - Tracker needs: good spatial resolution, small material budget
- ***Strange*** tagging, exploiting large Kaon content
  - Charged requiring K/π separation, neutral $K_S \to \pi\pi$, K_L
  - Benefitting from good PID: timing detectors, Cherenkov detectors, charged energy loss (silicon/gas)



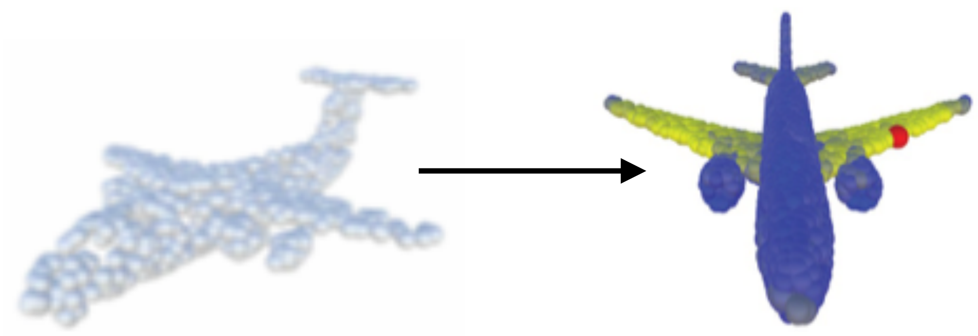
[2003.09517]

Momentum weighted fraction:



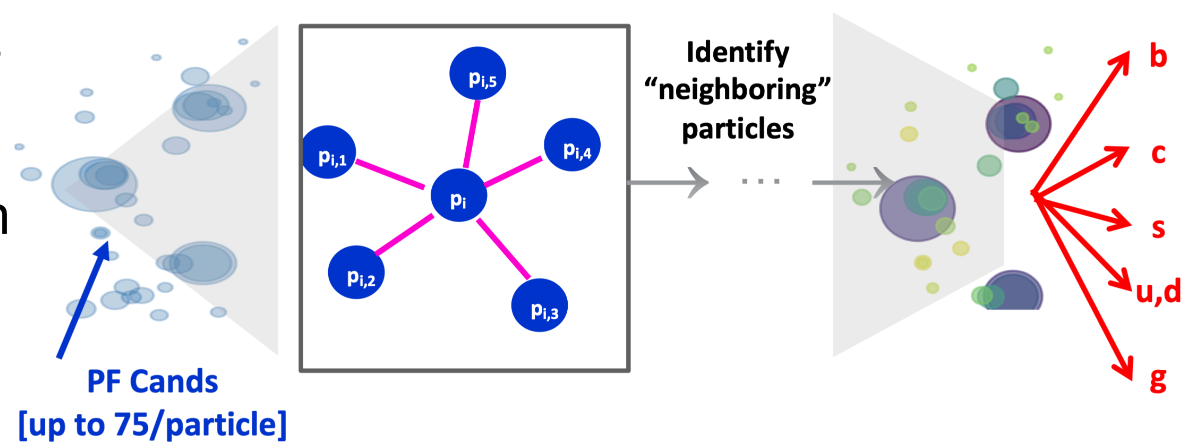
The ParticleNet Tagger

- 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
- kT jet-reconstruction algorithms to reco jets: unordered sets of particles with correlations & relationships. Graph-Neural-Network architecture for ParticleNet:
  - Identify properties of “particle cloud”, represented as a **graph**
  - Each particle: **node** of the graph; connections between particles: the **edges**
  - Learn local structures -> move to more global ones



From this article

[O(50) properties/particle] x [~50-100 particles/jet] ~O(1000) inputs/jet

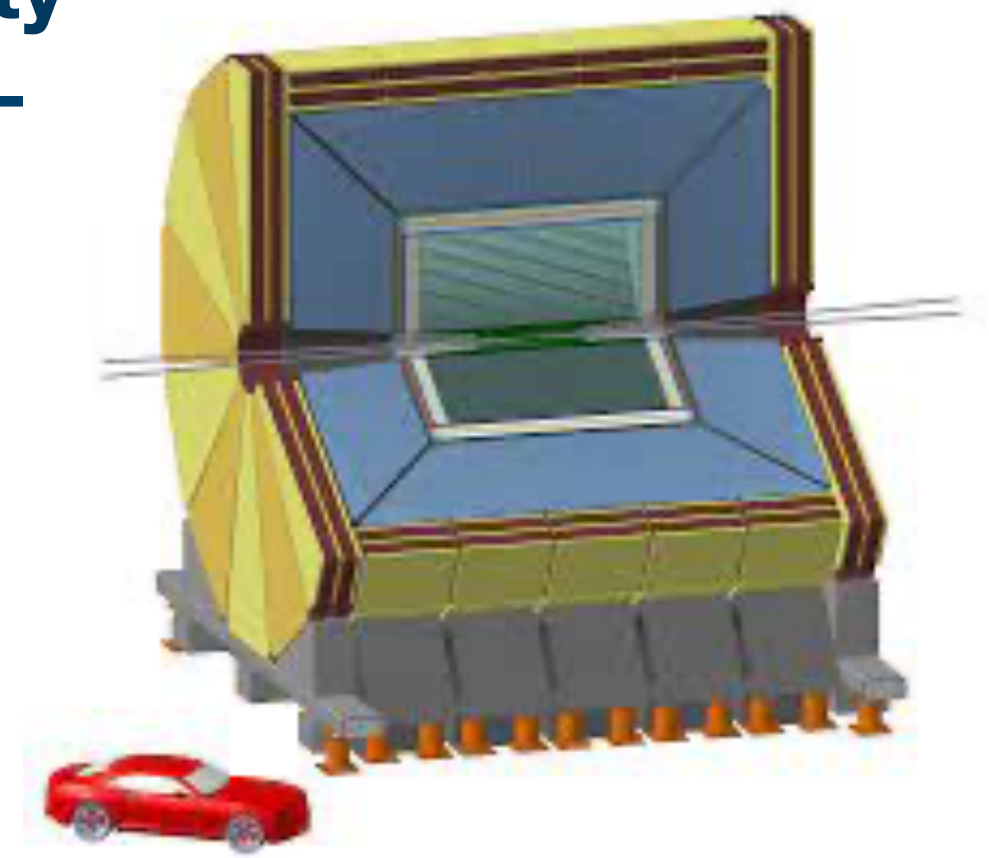


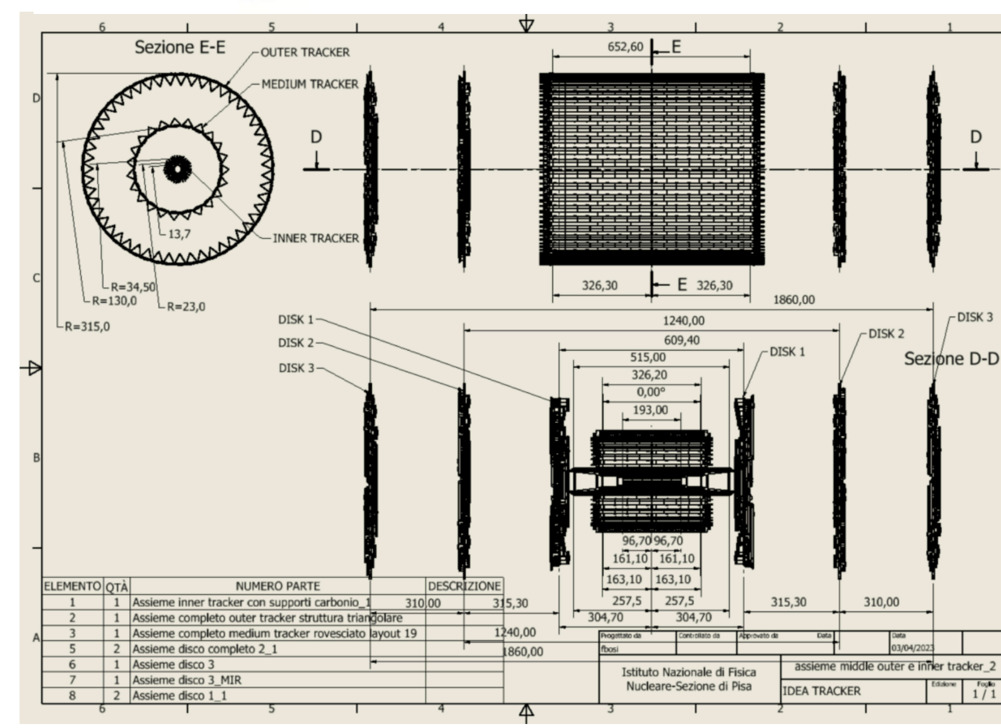
Full List of Input Variables

Variable	Description
Kinematics	
$E_{\text{const}}/E_{\text{jet}}$	energy of the jet constituent divided by the jet energy
θ_{rel}	polar angle of the constituent with respect to the jet momentum
ϕ_{rel}	azimuthal angle of the constituent with respect to the jet momentum
Displacement	
d_{xy}	transverse impact parameter of the track
d_z	longitudinal impact parameter of the track
SIP_{2D}	signed 2D impact parameter of the track
$\text{SIP}_{\text{2D}}/\sigma_{\text{2D}}$	signed 2D impact parameter significance of the track
SIP_{3D}	signed 3D impact parameter of the track
$\text{SIP}_{\text{3D}}/\sigma_{\text{3D}}$	signed 3D impact parameter significance of the track
d_{3D}	jet track distance at their point of closest approach
$d_{\text{3D}}/\sigma_{d_{\text{3D}}}$	jet track distance significance at their point of closest approach
C_{ij}	covariance matrix of the track parameters
Identification	
q	electric charge of the particle
$m_{\text{t.o.f.}}$	mass calculated from time-of-flight
dN/dx	number of primary ionisation clusters along track
`isMuon`	if the particle is identified as a muon
`isElectron`	if the particle is identified as an electron
`isPhoton`	if the particle is identified as a photon
`isChargedHadron`	if the particle is identified as a charged hadron
`isNeutralHadron`	if the particle is identified as a neutral hadron

The (IDEA) Tracker as an Opportunity

- Different possible detector scenarios, *tracker* particularly relevant to flavour-tagging
    - **Amount (e.g. n. of layers)** & **quality of material**
    - **Hit resolution** & **barrel proximity**
    - **PID capabilities**: timing, energy loss (gas/silicon)
- Baseline IDEA detector as a well-established reference for detector-performance studies
    - Opportunity to access impact of detector configurations/ properties on physics performance
    - A lot already studied in the past [Eur. Phys. J. C 82, 646 (2022)]
    - **New studies based on latest detector layouts performed for final Feasibility Study Report**
- Current IDEA pixel/tracking system:
    - beam pipe at 1cm, **3 *innermost* silicon barrel layers**: 1.2cm, 2cm, 3.15cm
    - **PID**: cluster-counting (dN/dx) + 30ps ToF system

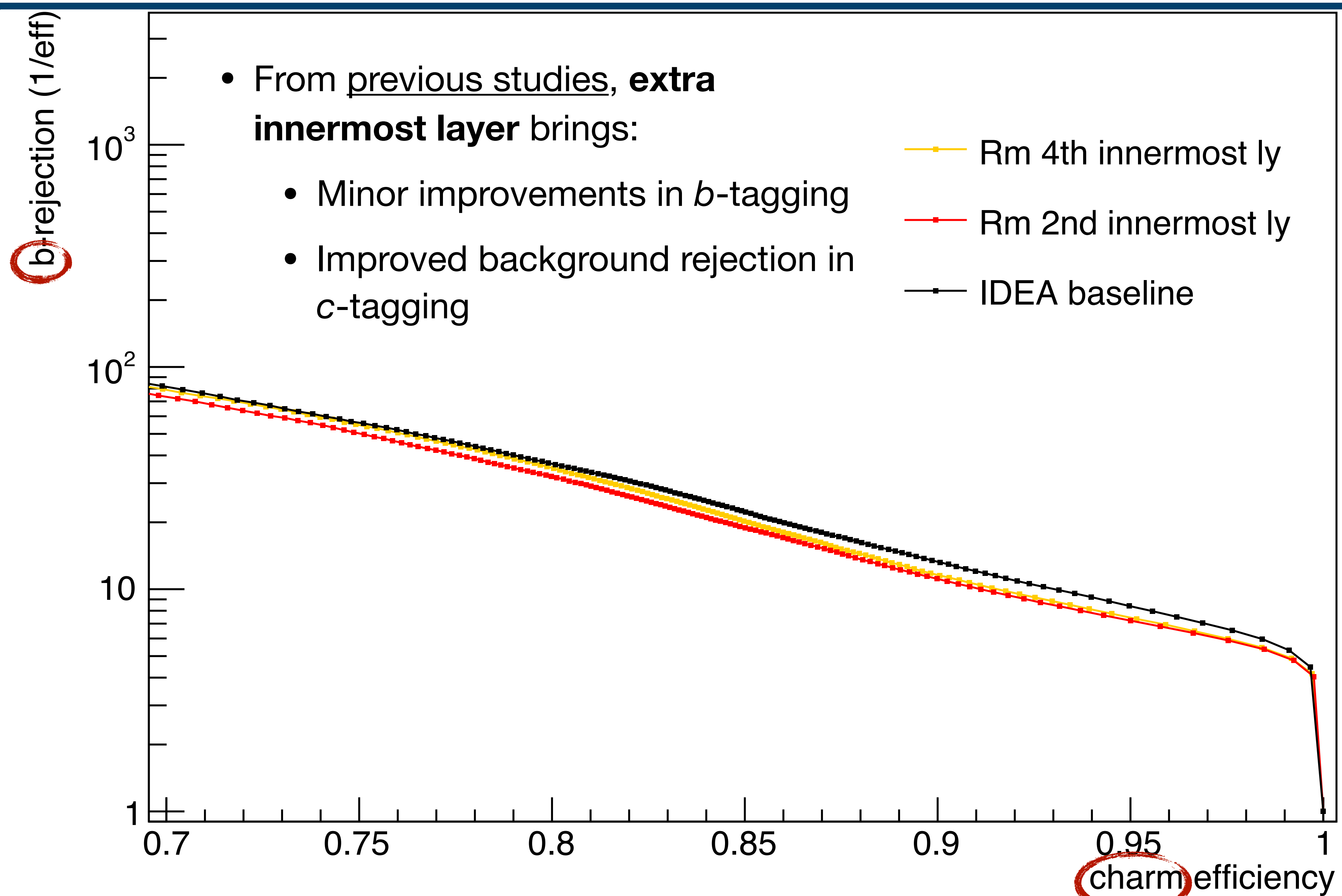




Latest IDEA tracker layout from F. Palla's talk

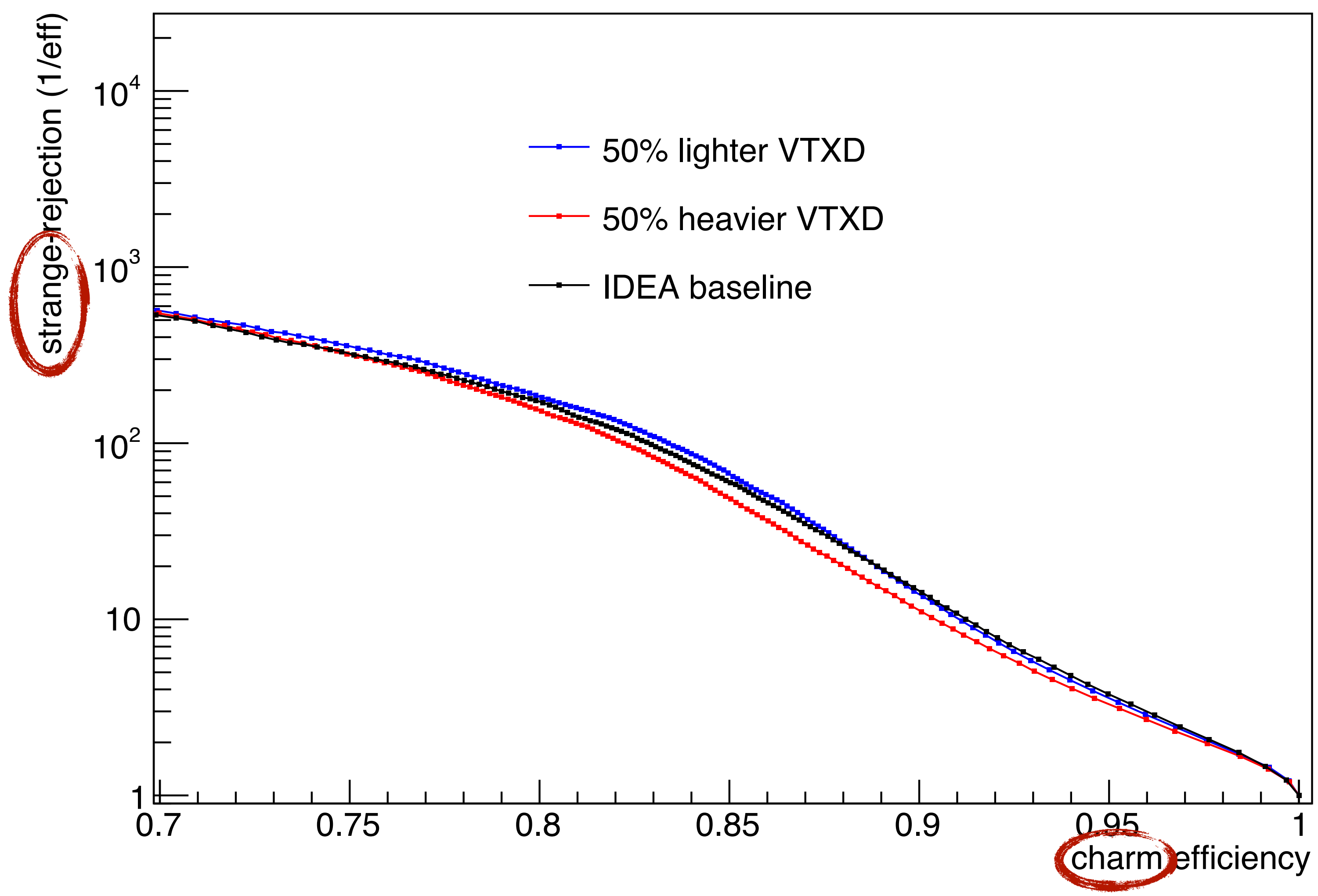
Charm Tagging & Number of Pixel Layers

- From previous studies, **extra innermost layer** brings:
  - Minor improvements in *b*-tagging
  - Improved background rejection in *c*-tagging



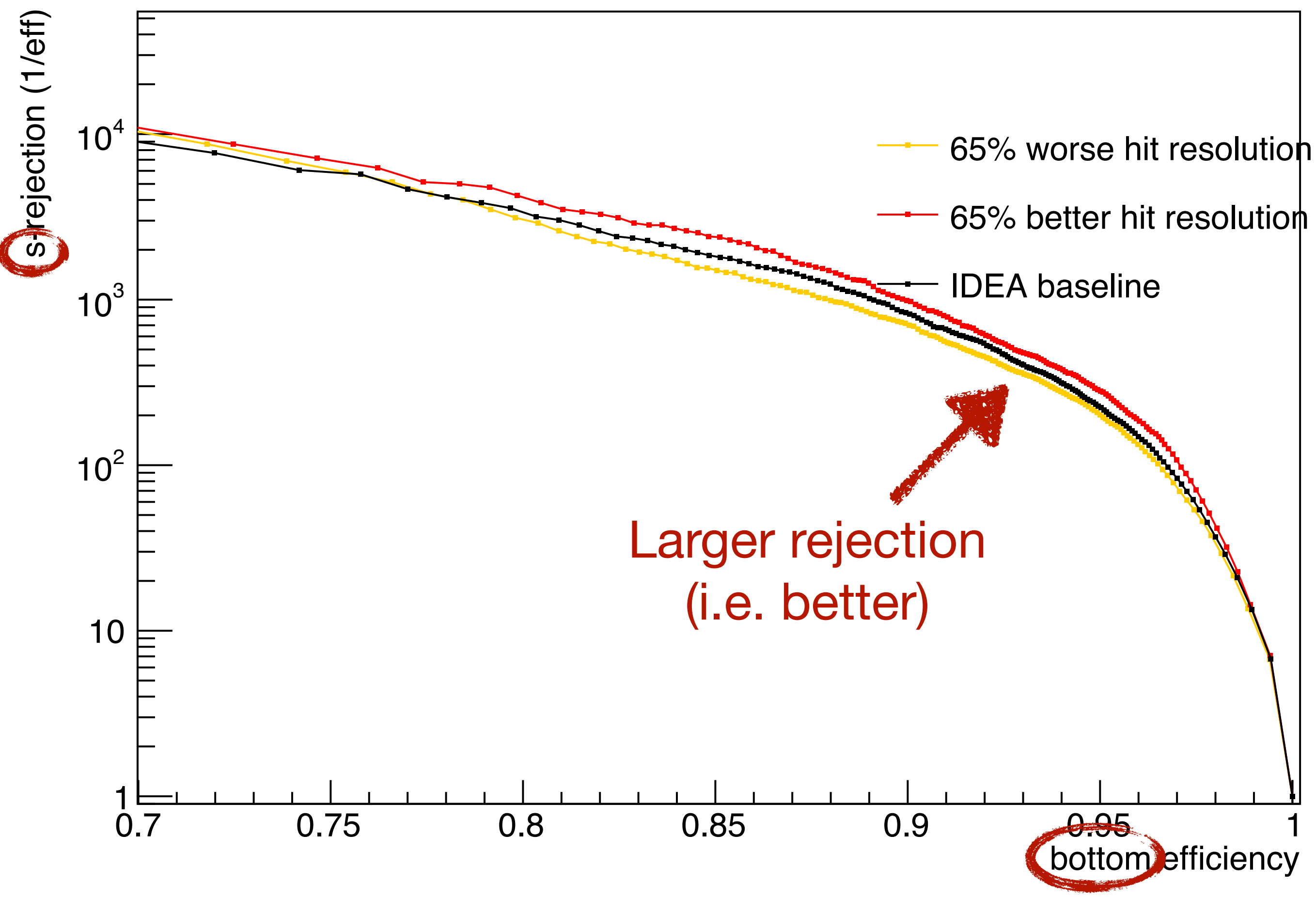
- Assuming innermost layer at 1.2cm, **removal of intermediate layers** (*2 and 15cm*):
  - Minor effects on *b*-tagging - *picture may change at high momentum*
  - Visible effects on *c*-tagging
    - Similar patterns in strange, light & gluon rejection
- **Charm tagging definitely sensitive to number of pixel layers!**

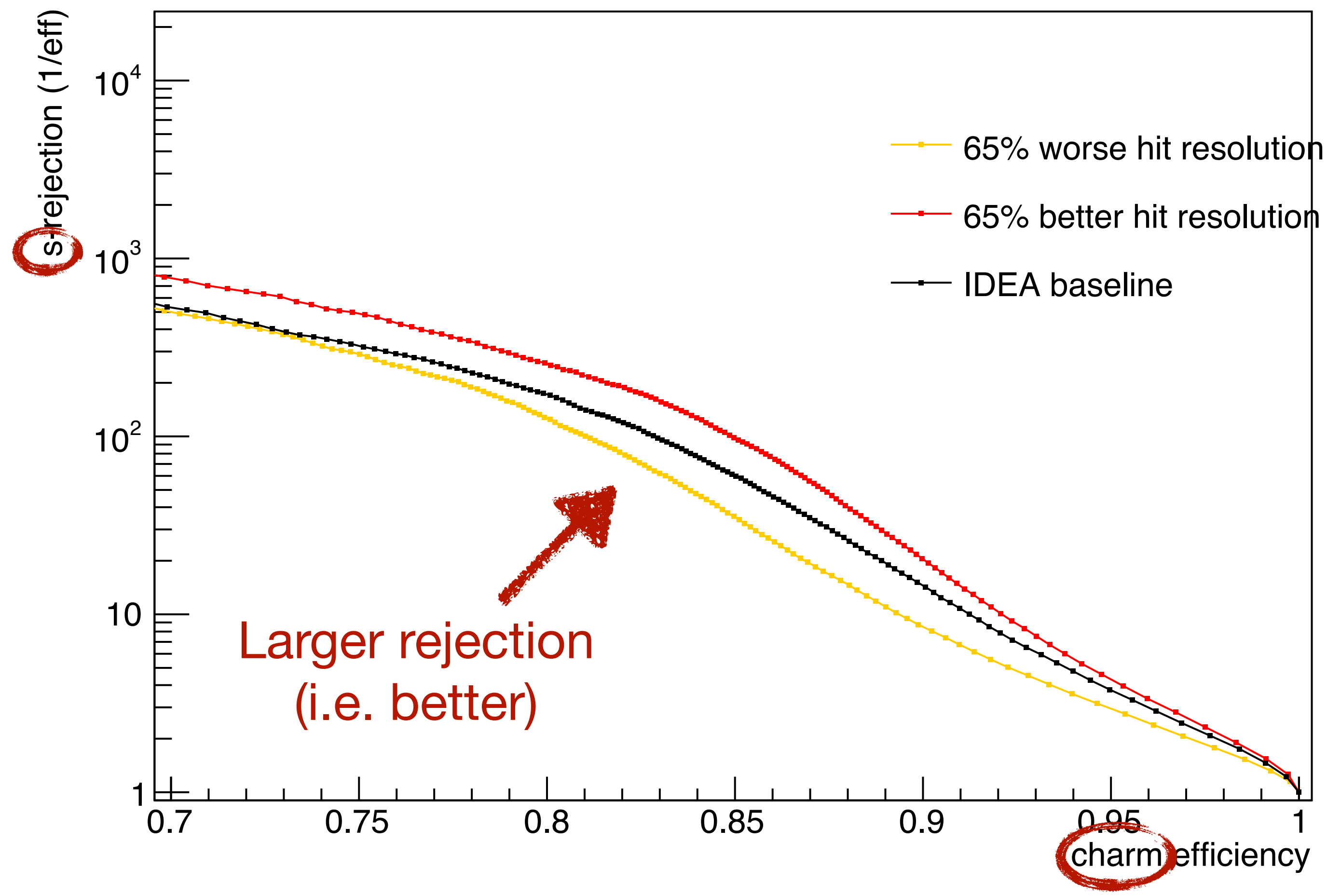
Pixel-Detector Material Budget



- May add many extra vertex layers, but eventually material (and real!) budget come into play
- Studied impact from ±50% relative variations in the radiation length for all of the vertex layers
- Asymmetric impact observed for *c*-tagging - minor on *b*-tagging:
  - Do not gain much from lighter vertex detector
  - **Can loose in performance with more/heavier material though!**
- For large increase of beam-pipe material budget the impact of material in first vertex-detector layer is not very significant

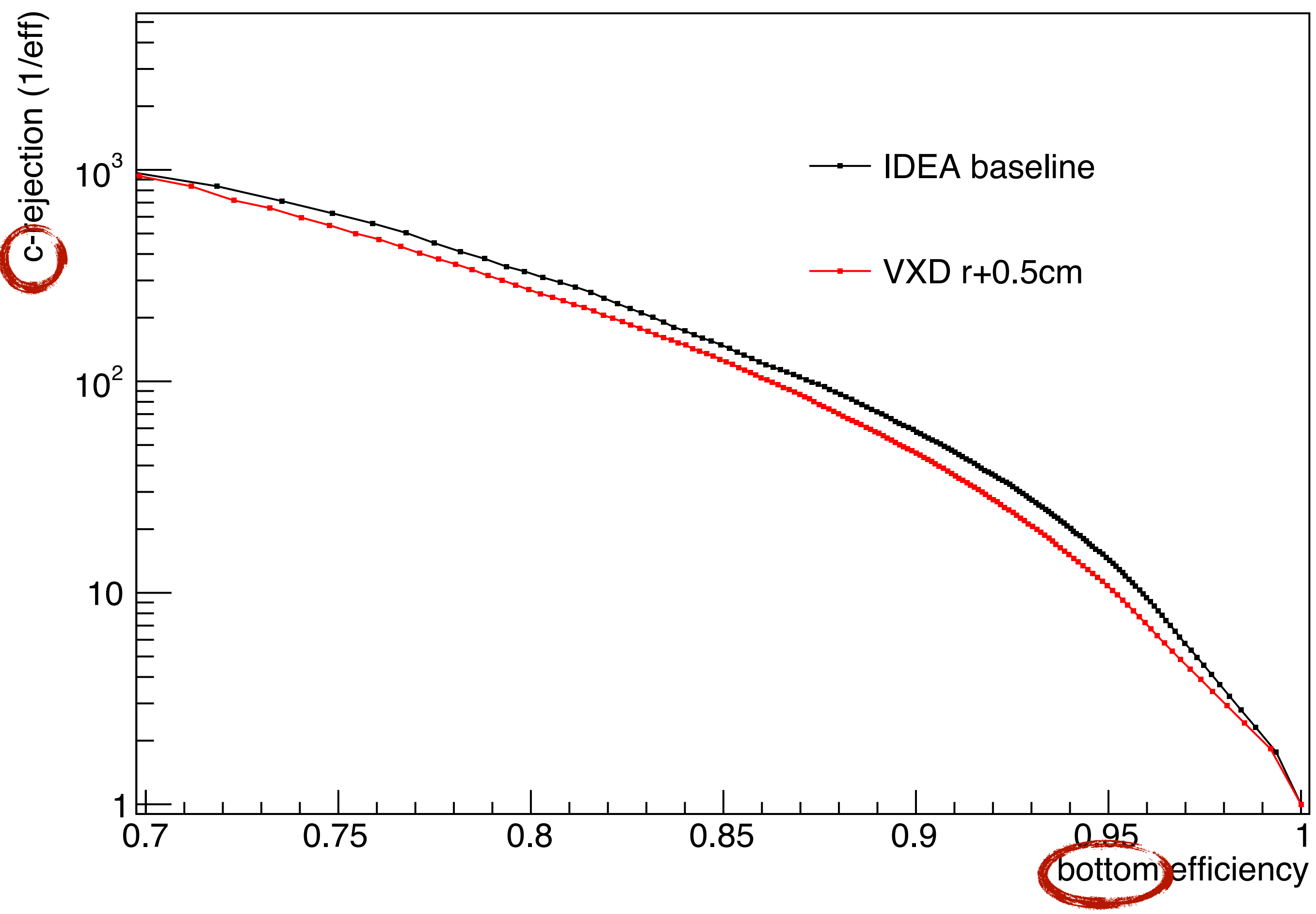
Bottom/Charm Tagging & Single-Point Resolution

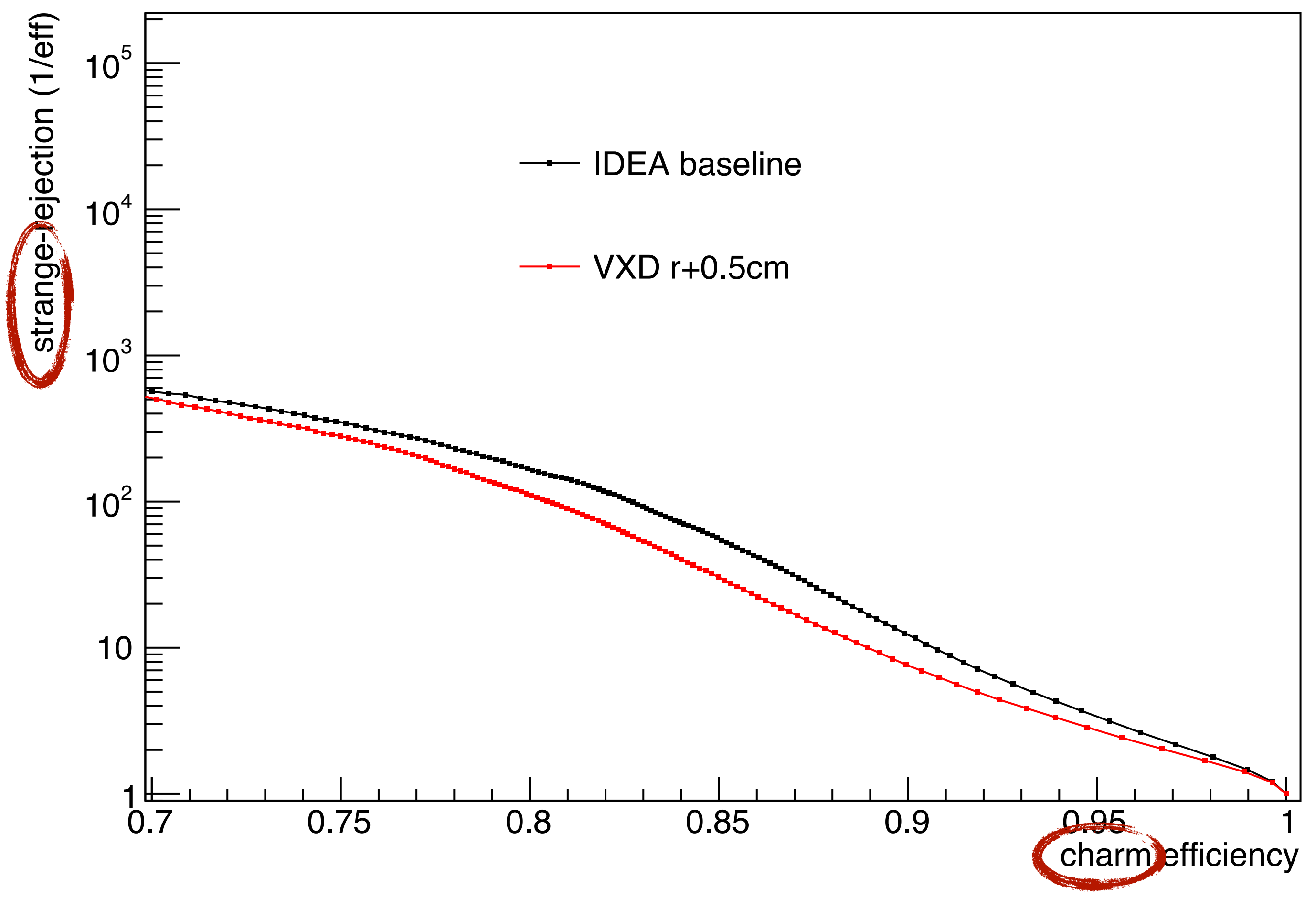




- Visible effects on *b*-tagging
- More significant effects on *c*-tagging
  - Fairly symmetric impact on rejection of all flavors
  - **Crucial role of single-point resolution** (*nominal: 3μm with 25x25μm^2 inner barrel pitch*) in rejection of major backgrounds for charm

Pixel-Detector Proximity to Interaction Point



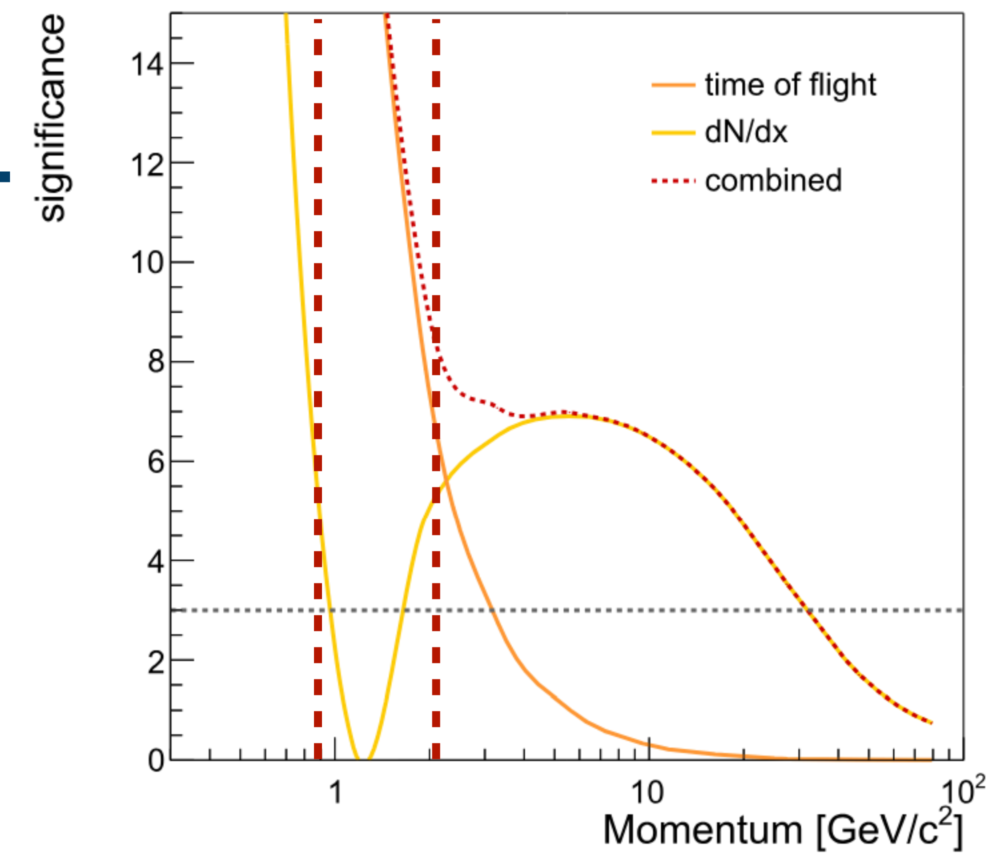


- Studied impact of **shifting VTXD barrel layers 0.5cm away from beam pipe**
- **Significant impact on bottom and charm tagging**, coming from worsening in impact-parameter resolution

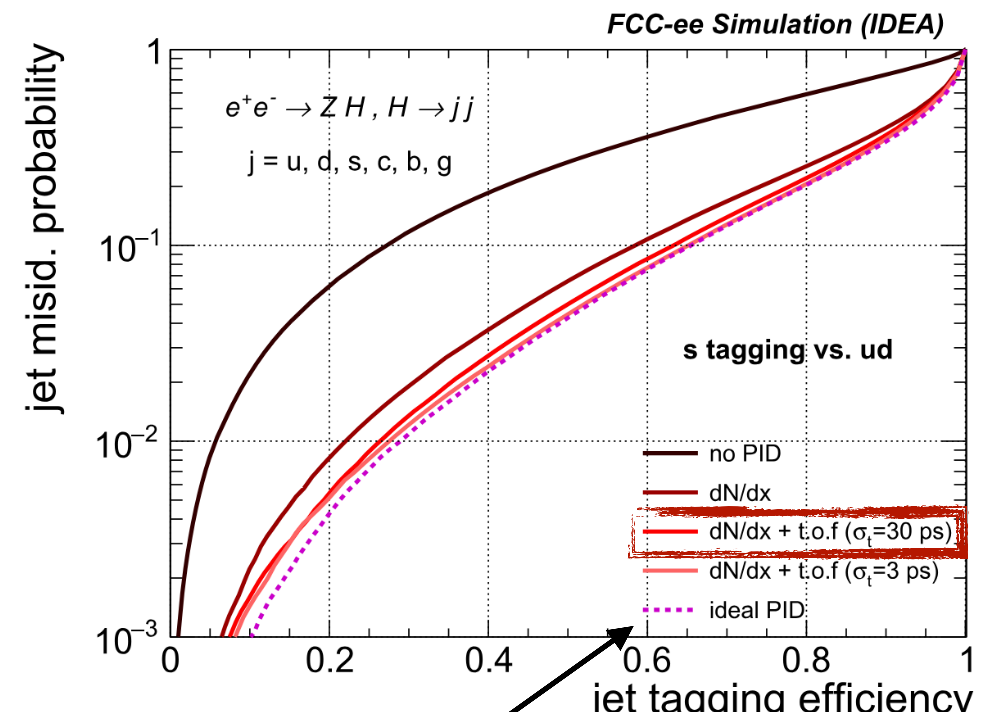
Flavour Tagging & PID

- 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 follow

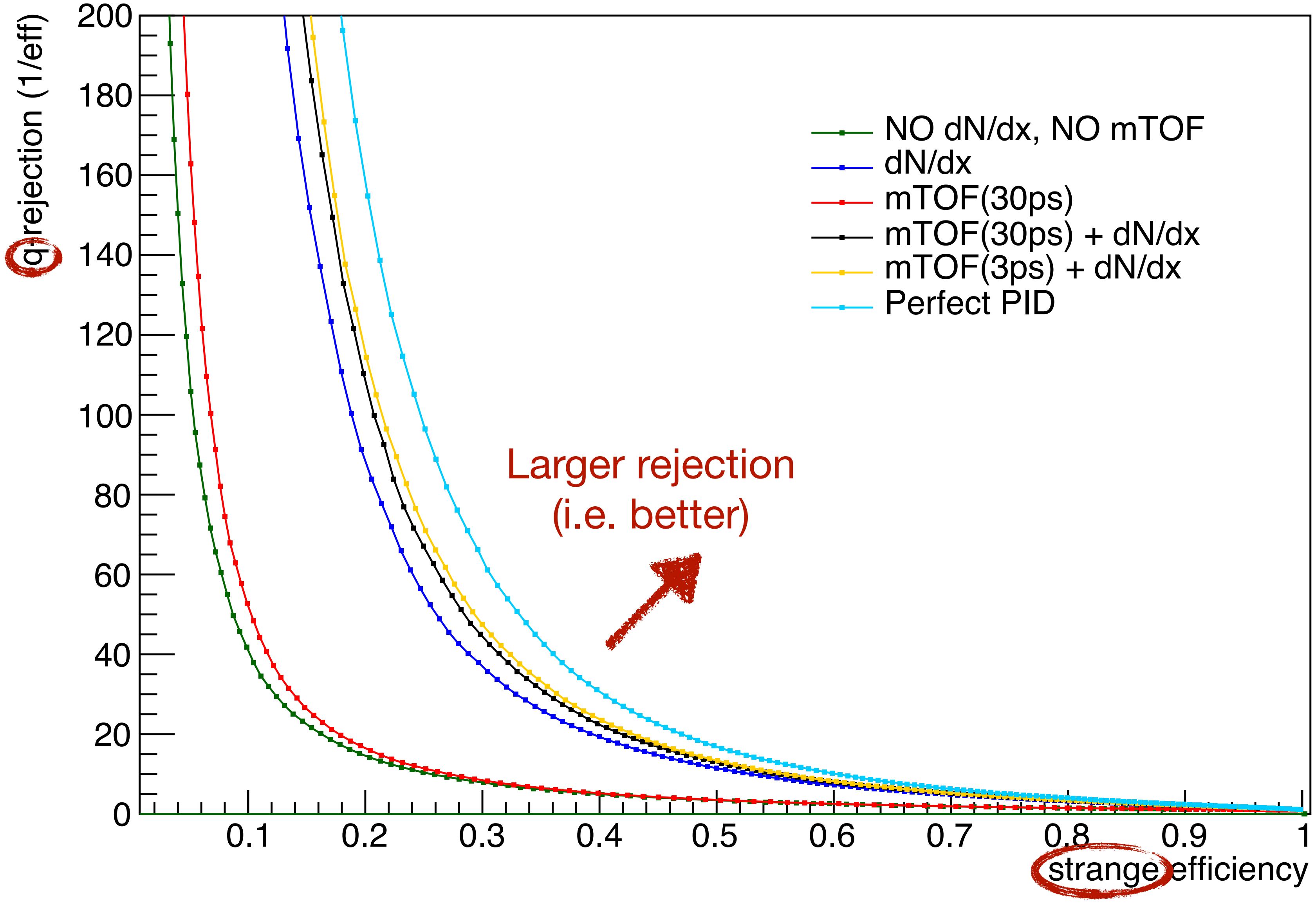


Eur. Phys. J. C 82, 646 (2022)



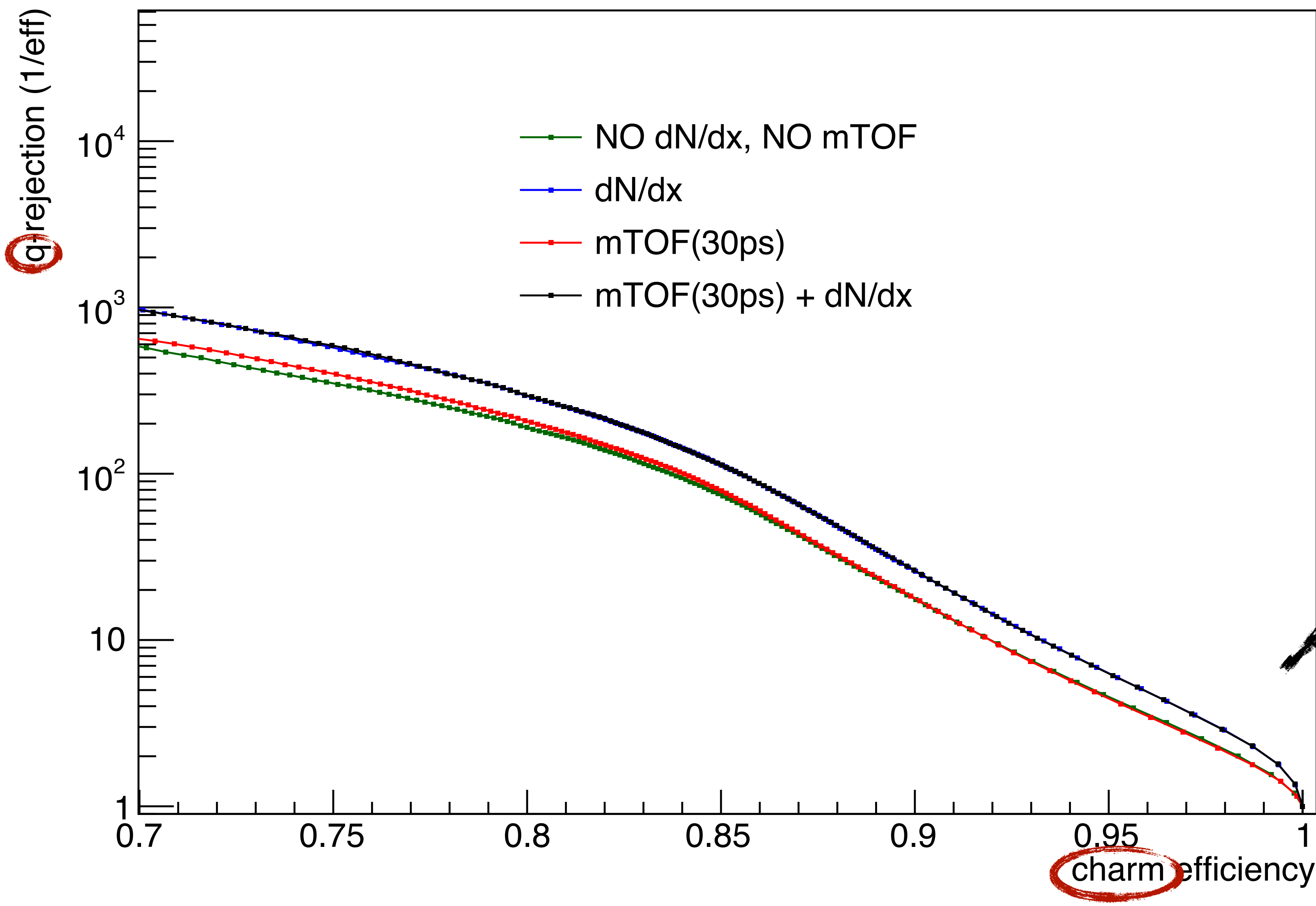
"Ideal" PID from *MC truth record*

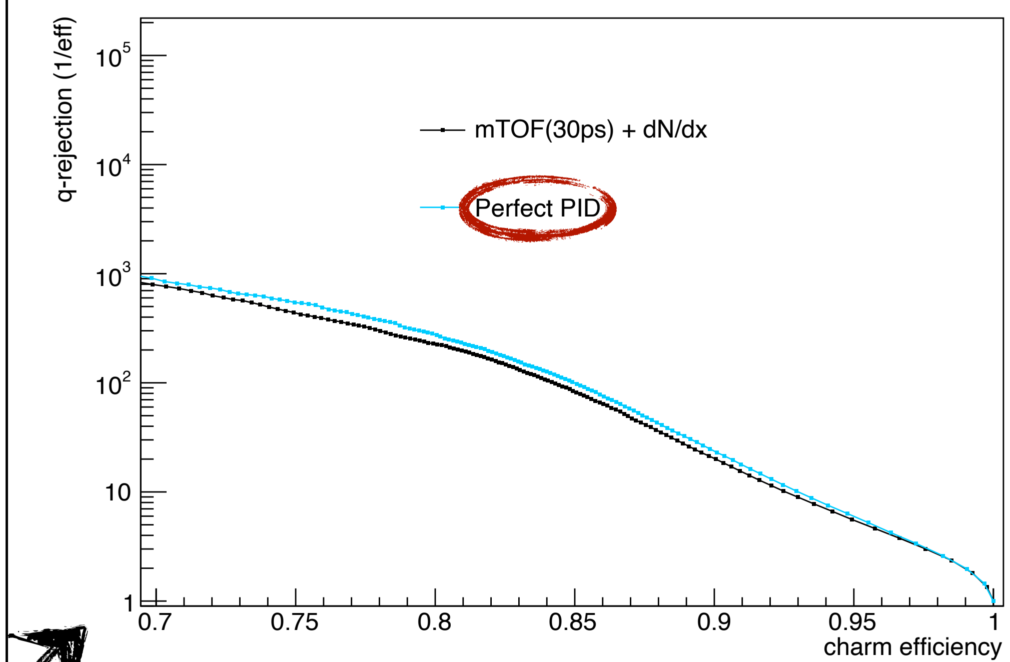
Strange Tagging & Light Rejection



- **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

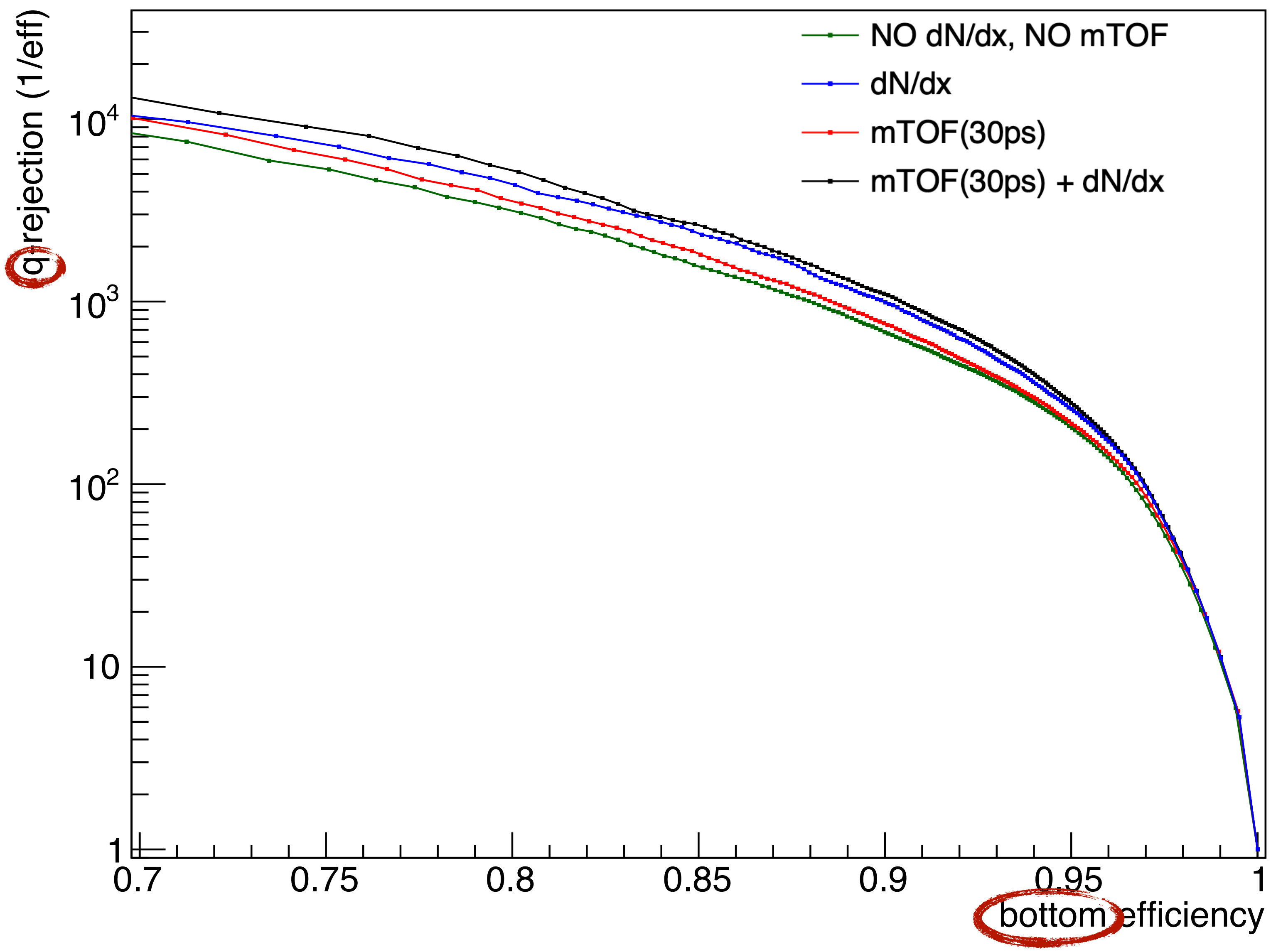


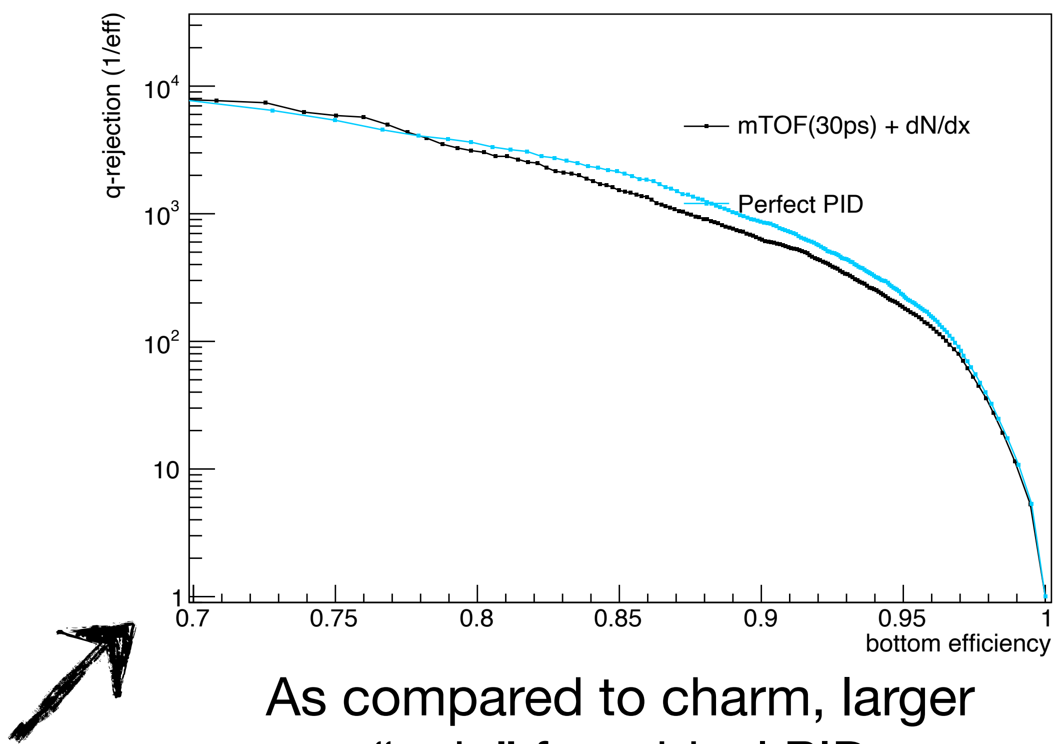


"Enhancement" due to ideal PID, significant but smaller than relative gain from dN/dx itself

- **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

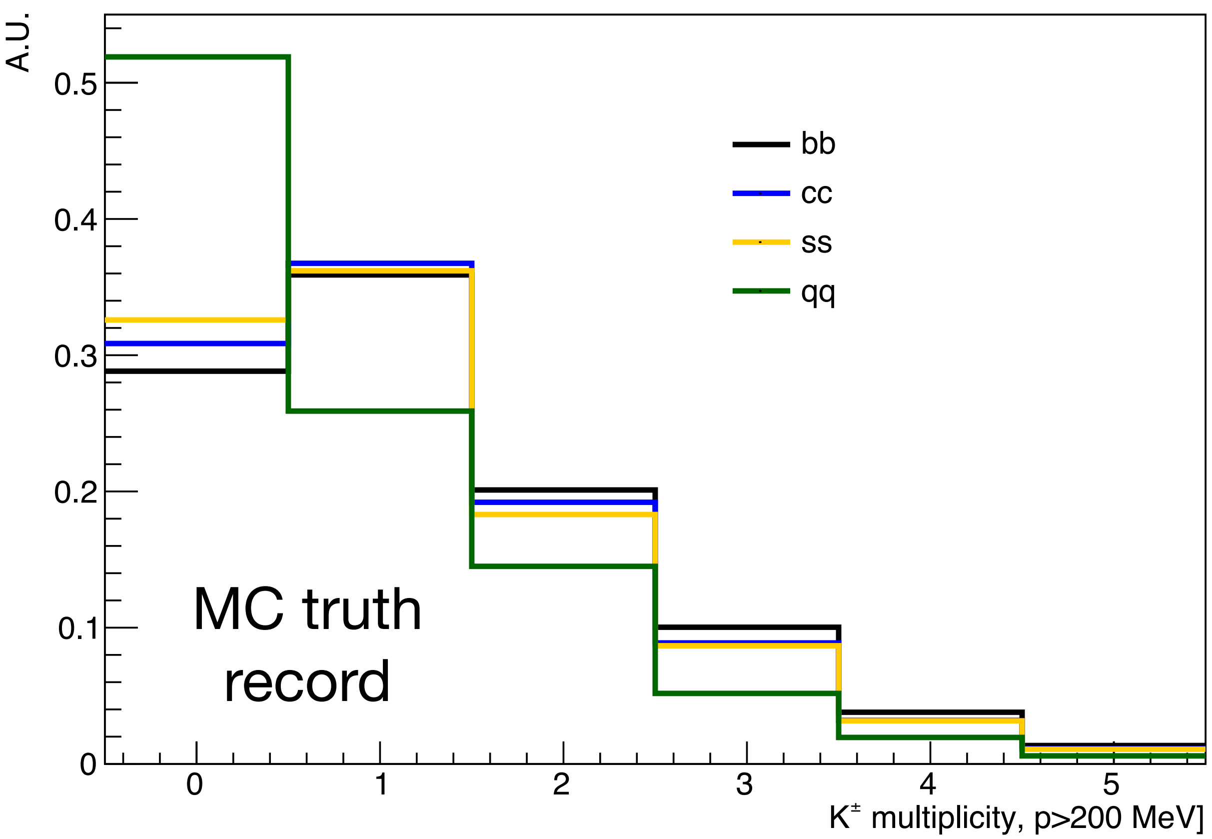


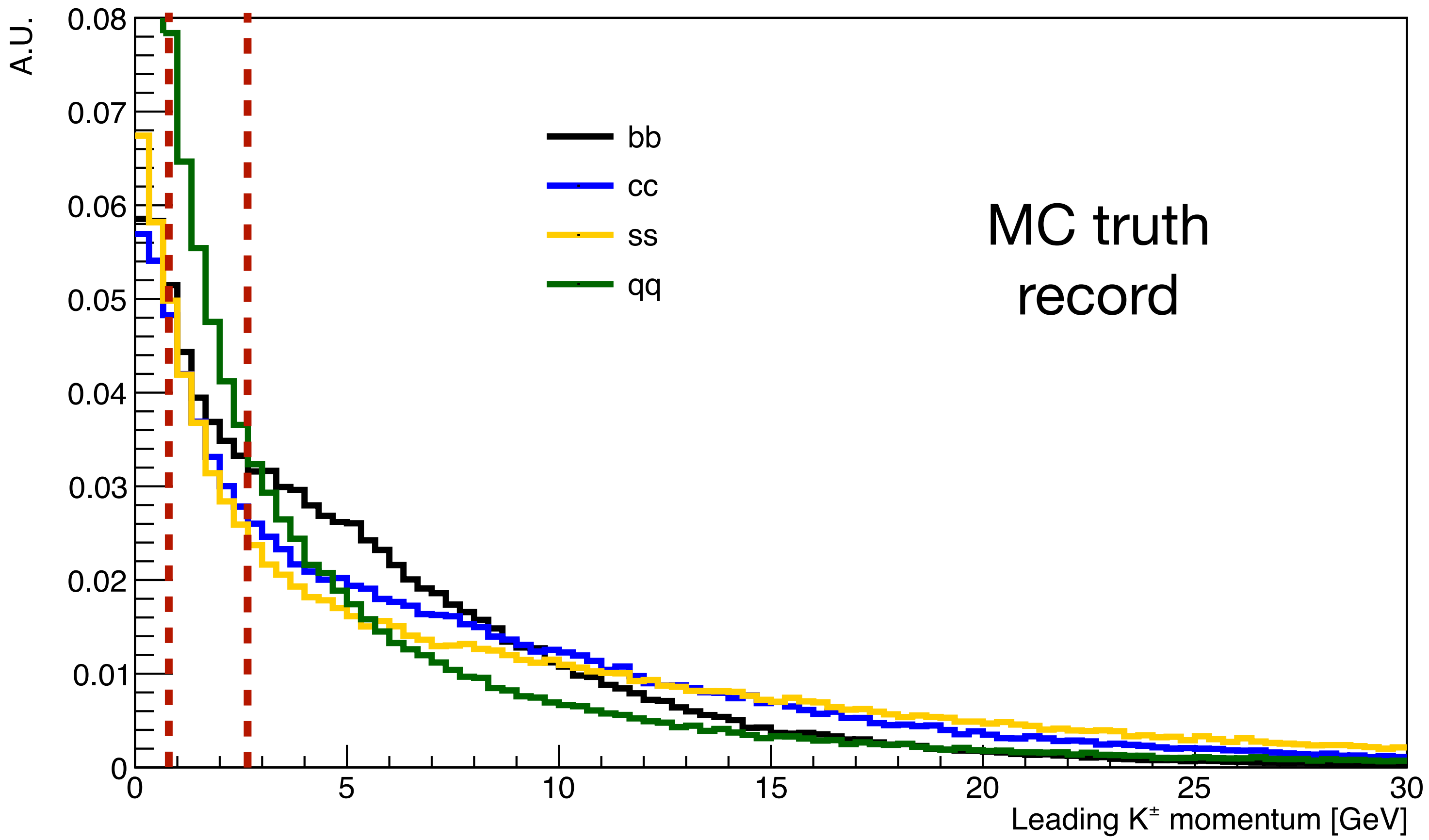


As compared to charm, larger "gain" from ideal PID

- 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

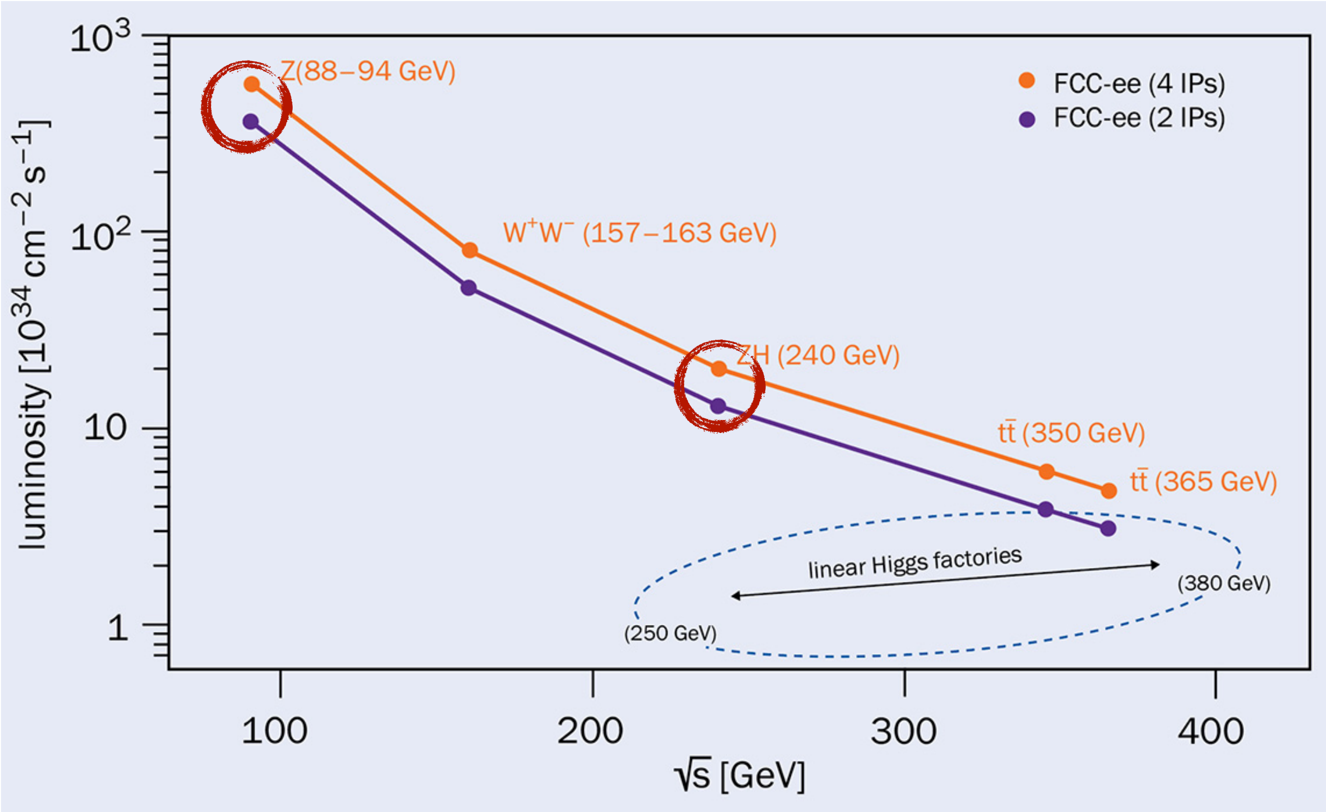




- Similar ***K*± multiplicity** for *b*, *c* & *s* jets, much smaller in light jets
- Hierarchy of TOF impact on light rejection for *b*, *c* & *s*-tagging reflected by spectra of leading $K^{\pm}$ in jet
- Generally, **harder spectrum in strange jets**, more evident for leading charged hadrons

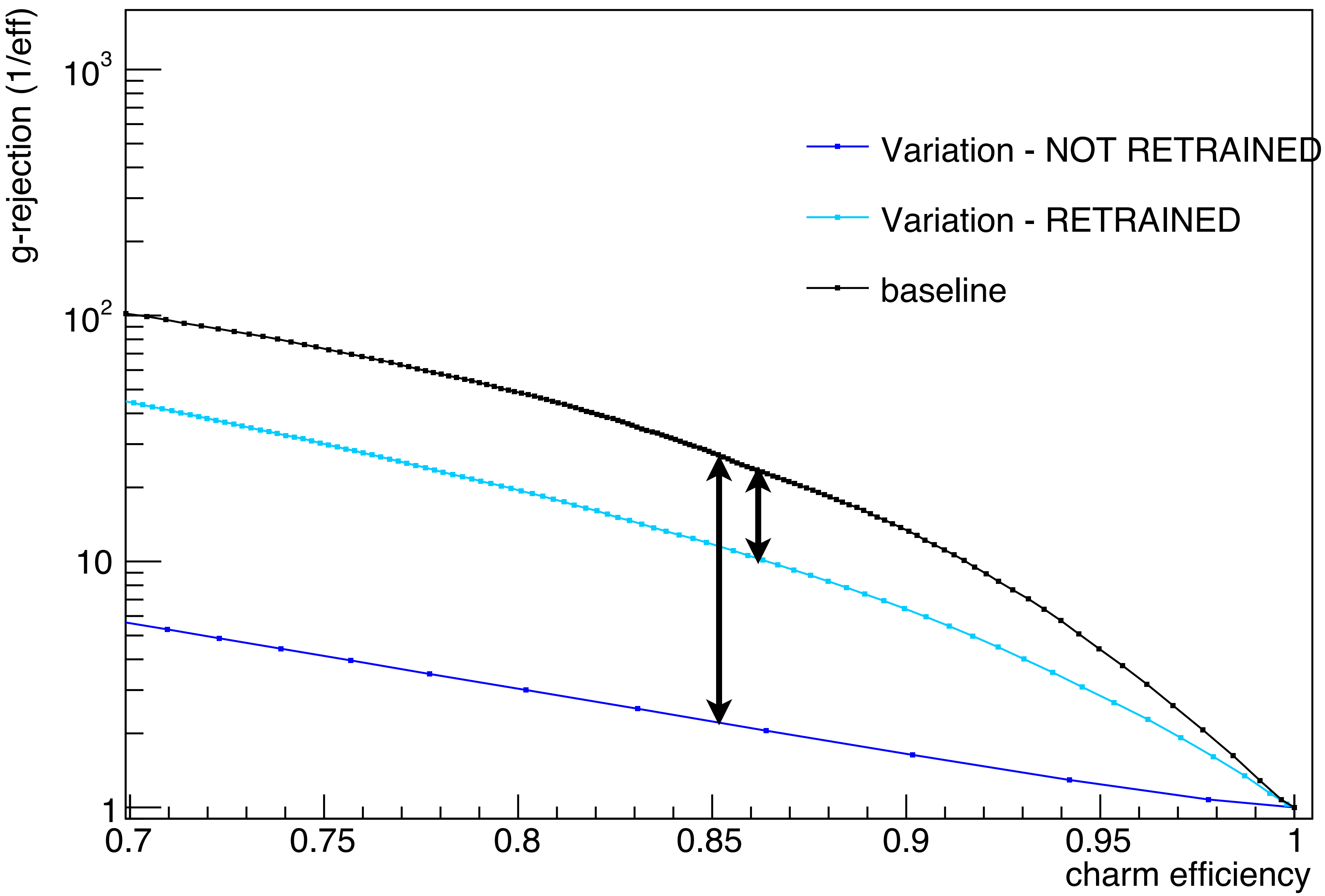
Conclusion & Plans

- **Significant effects observed in efficiency(rejection) at fixed rejection(efficiency) for different silicon and particle-identification detector properties**
  - Re-training against each configuration allows for partial performance recovery or significant improvement
- **Physics**, not the tagger performance per se, **should drive detector requirements**
  - **Propagated** largest tagger-performance variations **through Higgs coupling analyses**, see detailed studies in **Iza's talk**
- Tagger plans for the near future…
  - Characterize interplay between reconstruction (e.g. particle-flow candidate selection, reconstruction optimizations, etc…) in **full simulation** & tagger performance - Delphes performance is very optimistic!
  - Possibility to include **vertex information**, see Franco's talk
  - **Up- vs. Down** discrimination starts to seem possible thanks to jet charge, see Michele's talk
  - Calibration (Z pole → ZH threshold extrapolation)



BACKUP

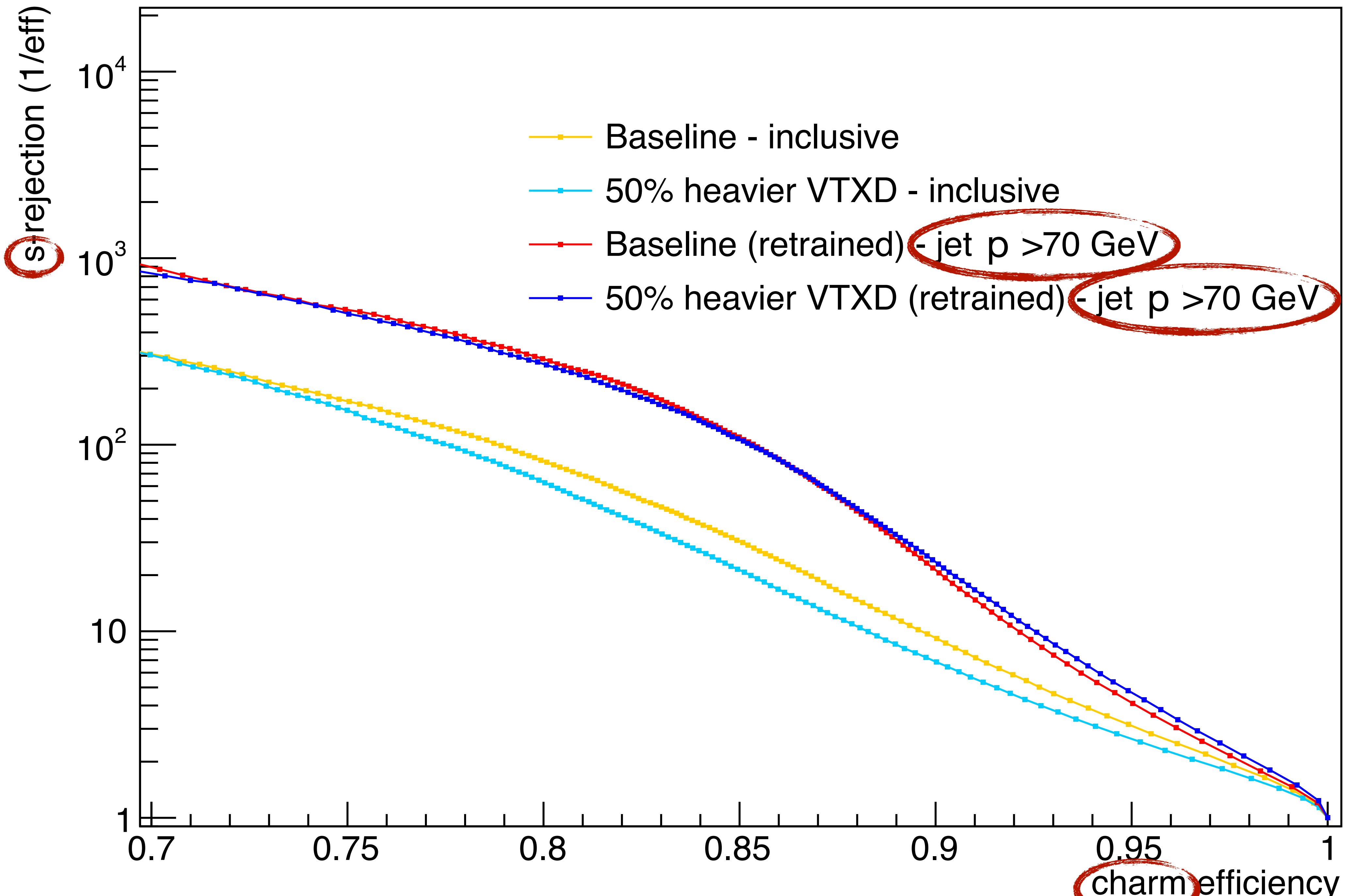
Why is Retraining Necessary?



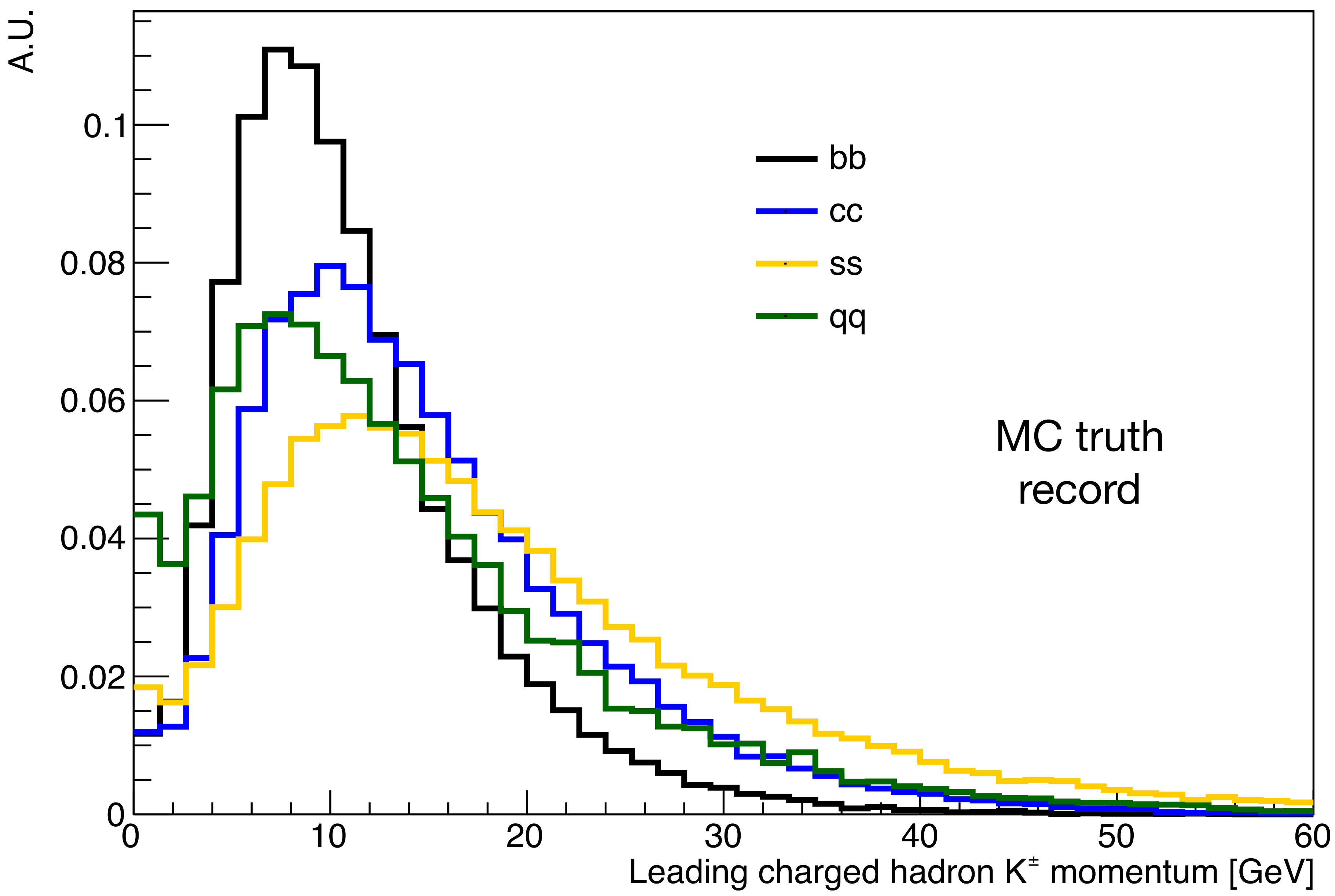
- Obviously, given a detector configuration, ParticleNet would be trained against it
- Re-training allows recovering of (a significant) part of drop in performance
  - **Need re-training for fair & meaningful performance assessment of each point in the detector-configuration space**

Pixel-Detector Material Budget at High(er) Momentum

- As expected, **impact of multiple Coulomb interactions on performance becomes insignificant at high momentum**
  - Relevant for potential *differential measurements & higher center-of-mass points*
- Need retraining on kinematic sub-phase-space to observe recovery



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

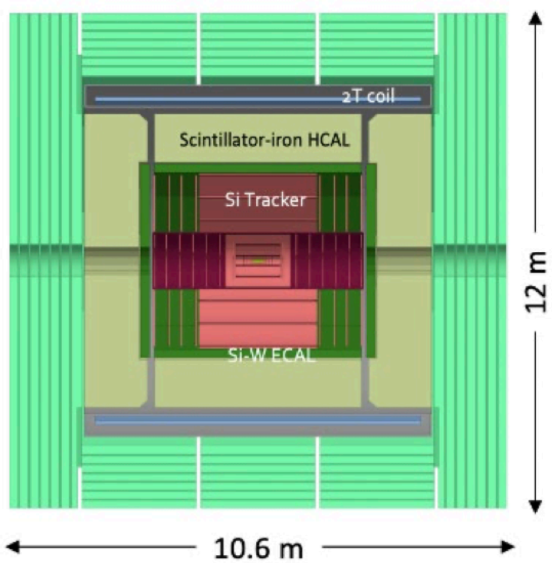


- Momentum of charged Kaons, when leading charged hadron in jet
- **Significantly higher jet momentum fraction in strange jets**

Current Detector Concepts

From Marc-André's talk

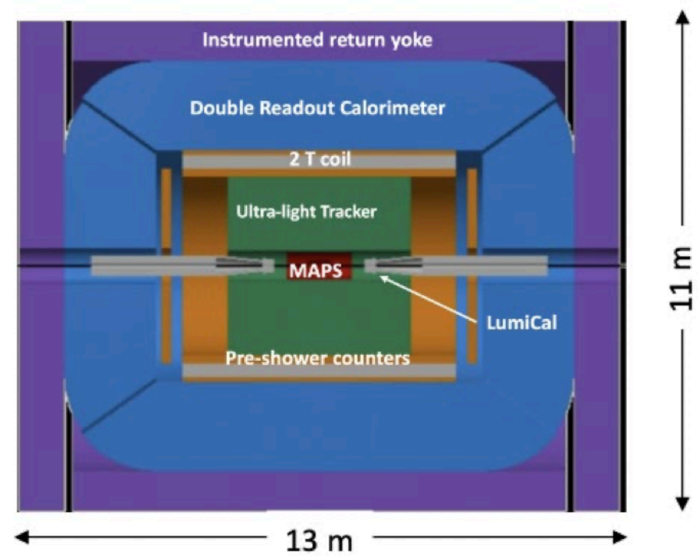
CLD



- 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)?
  - …

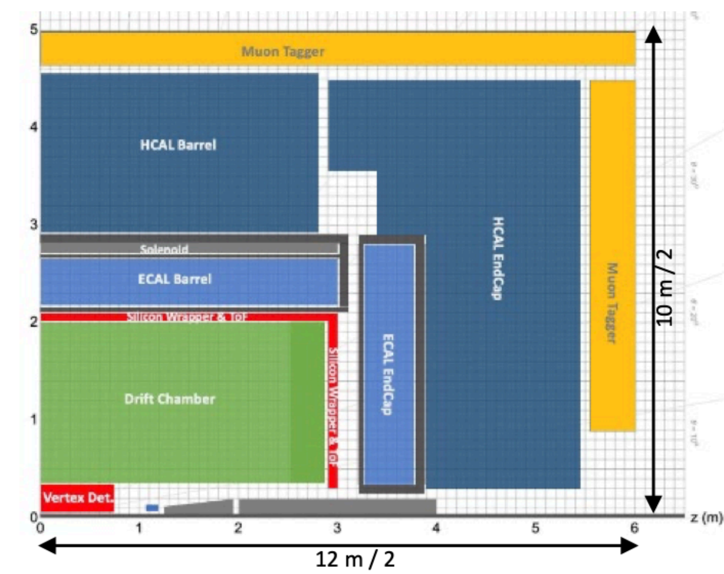
CDR

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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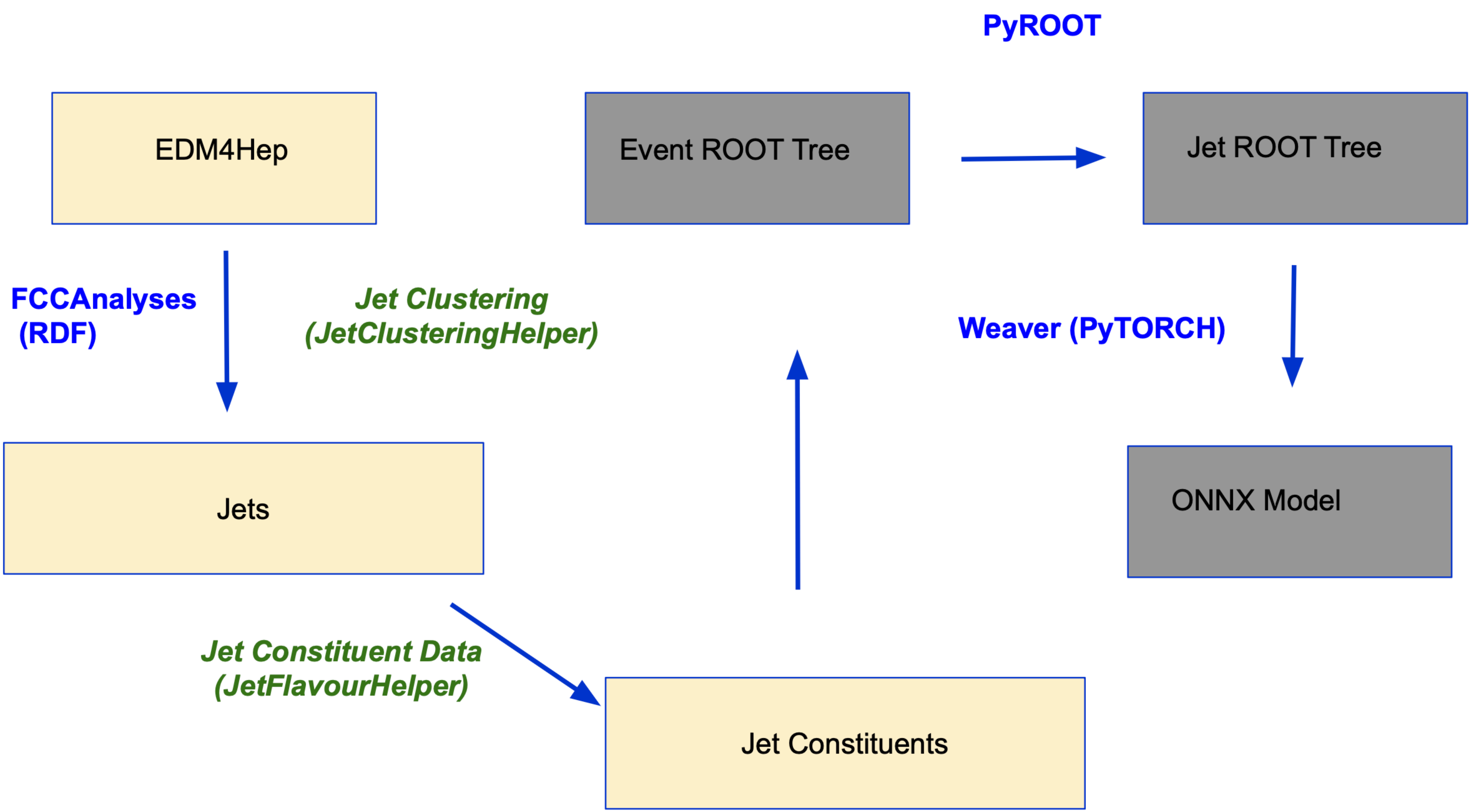
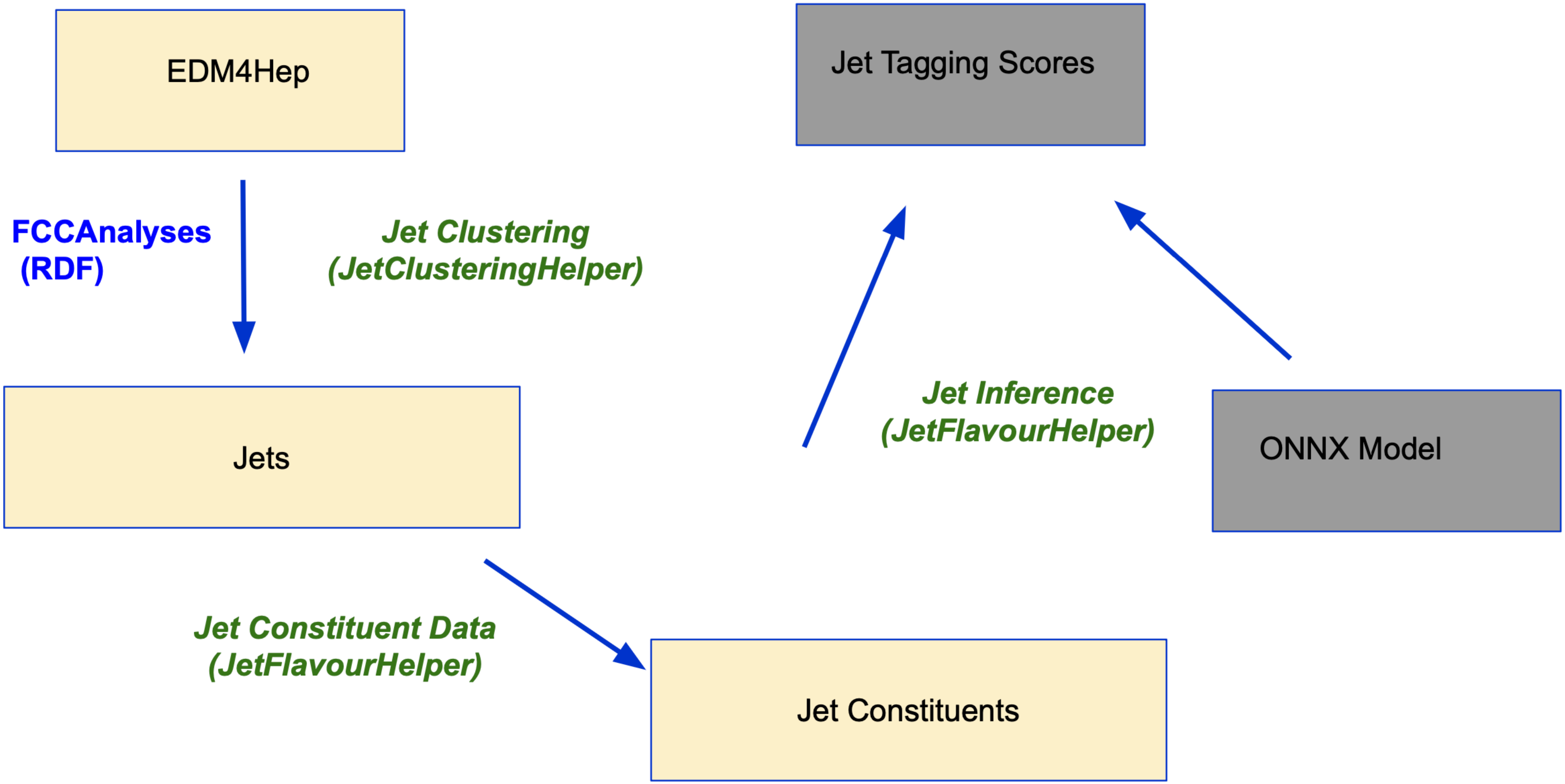
Training the Model



Inference


EDM4Hep
FCCAnalyses
(RDF)
Jet Clustering
(JetClusteringHelper)
Jets
Jet Constituent Data
(JetFlavourHelper)
Jet Constituents
Jet Tagging Scores
Jet Inference
(JetFlavourHelper)
ONNX Model