FCC-ee ParticleNet Tagger & IDEA Detector Tracker

FCC PP meeting
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Thanks to Michele & Jan
for helpful discussions!

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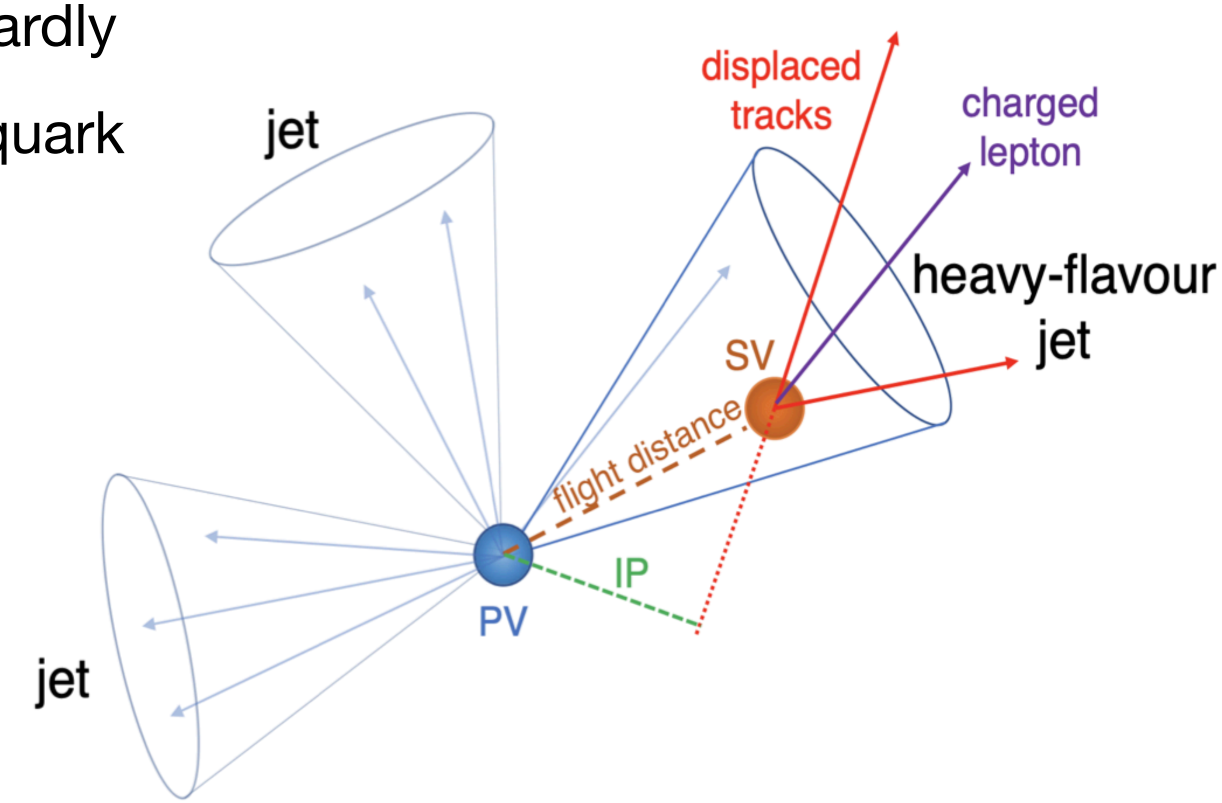
Introduction & Motivation

- Flavor tagging is key for e^+e^- program, in particular to access challenging Higgs-boson decay modes like *cc* & *ss* - hardly accessible at the LHC -, precise determination of top-quark properties, strong coupling, hadronization, etc…
- *Bottom* & *charm* tagging based on:
  - Large lifetime
  - Displaced vertices/tracks
  - Large track multiplicity
  - Non-isolated charged leptons
- *Strange* tagging, exploiting large Kaon content
  - Charged requiring K/π separation, neutral $K_S \to \pi\pi$, K_L
  - Benefitting from good PID
- Disclaimer: **focus on pixel/tracking systems & *b*/*c*-tagging** in the following



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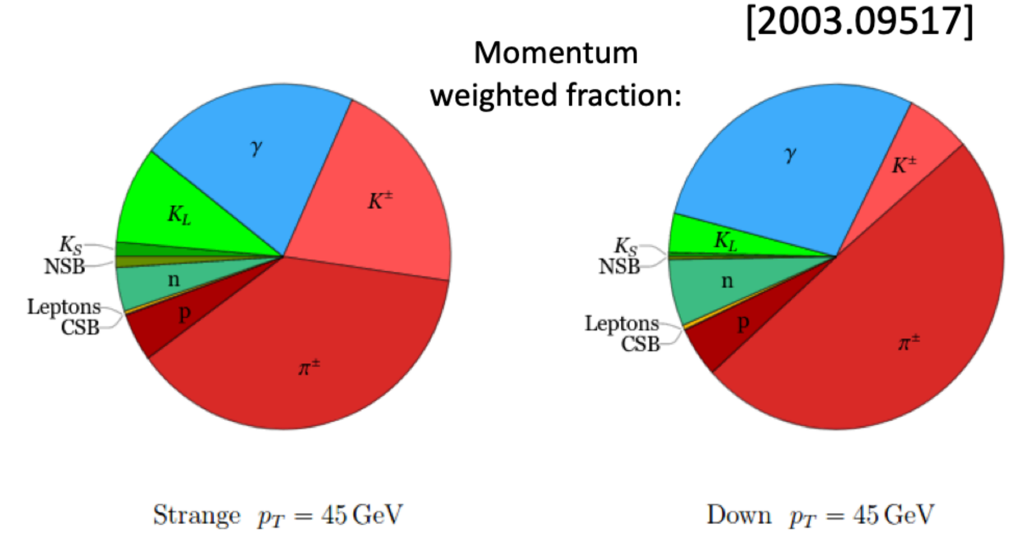
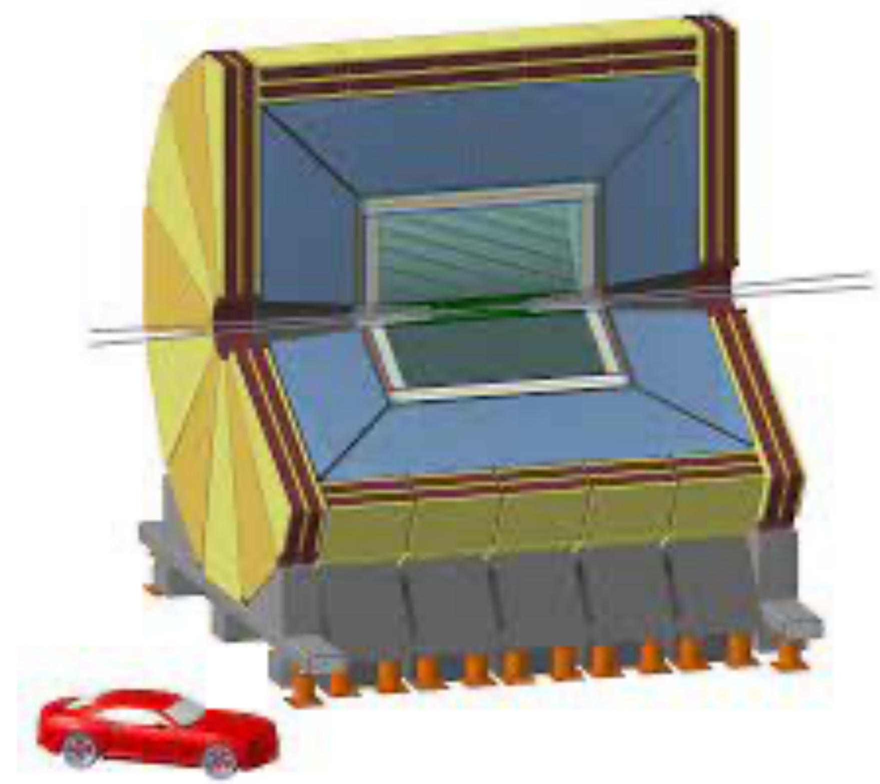
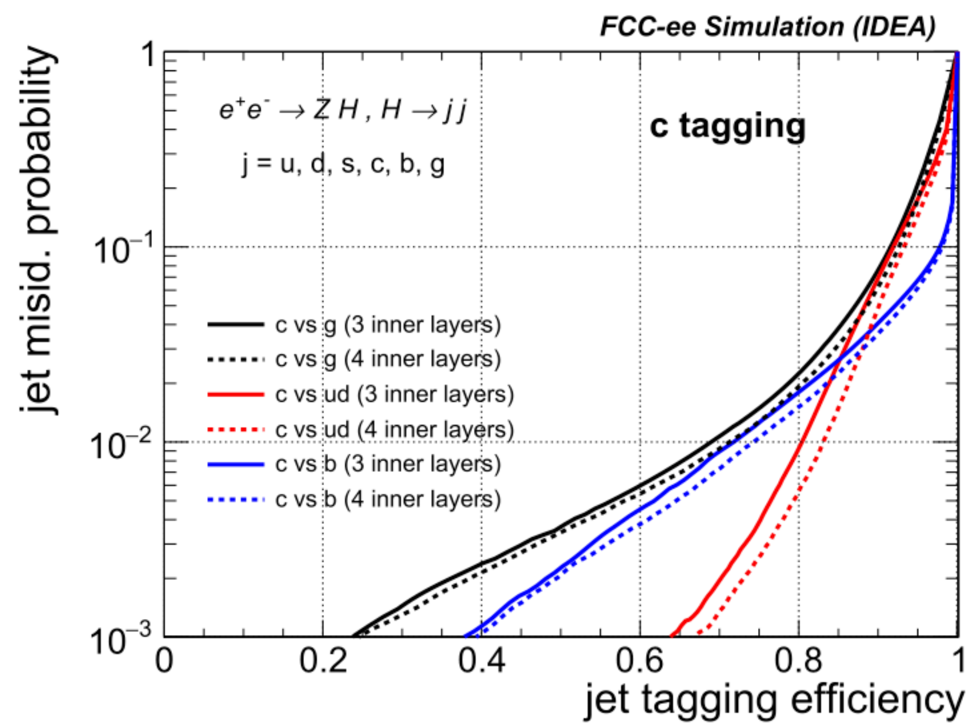


The IDEA Tracker as an Opportunity

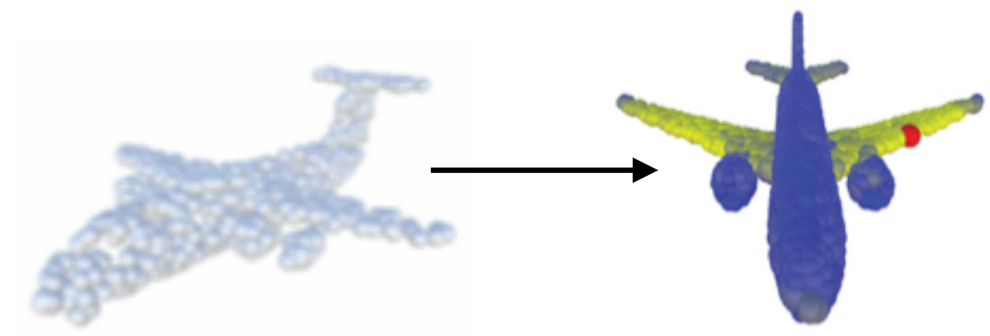


- Different possible detector scenarios, *tracker* particularly relevant to flavor-tagging
  - **Amount (e.g. n. of layers)** & **quality of material**
  - **Hit resolution**
  - PID capabilities: timing, energy loss (gas/silicon)
- Baseline IDEA detector as a well-established reference for detector-performance studies
  - Opportunity to access impact of detector configurations/ properties on physics performance
  - A lot already studied, see Eur. Phys. J. C 82, 646 (2022)
  - **-> Update and cross-check studies based on latest IDEA layout & complement detector-performance studies**
- Current IDEA pixel/tracking system -> beam pipe at 1cm, 4 VTXD layers: (1.2cm, 2cm, 3.15cm, 15cm)

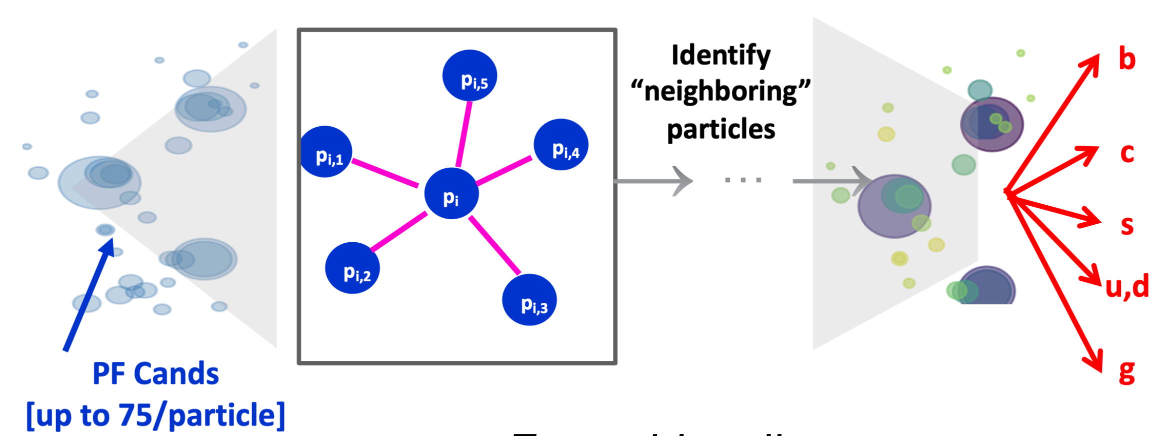


The ParticleNet Tagger

- 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



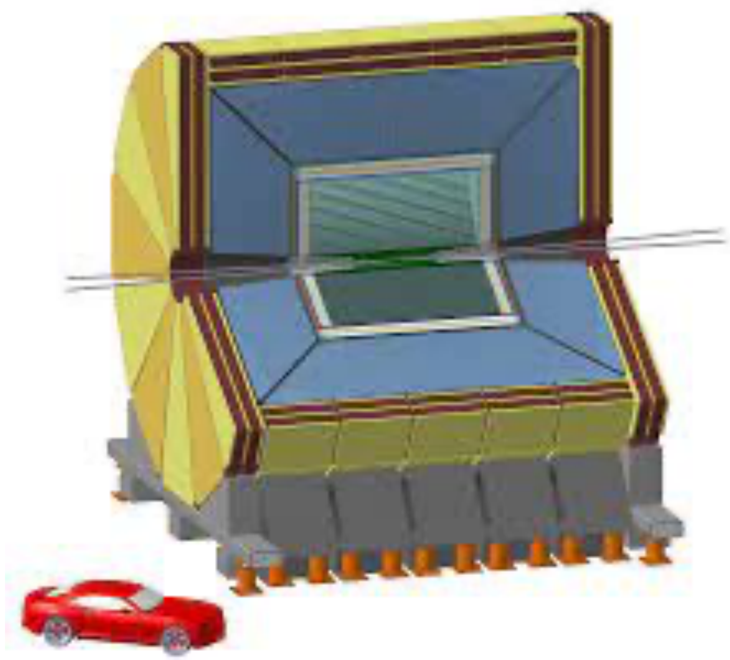
From this article



From this talk

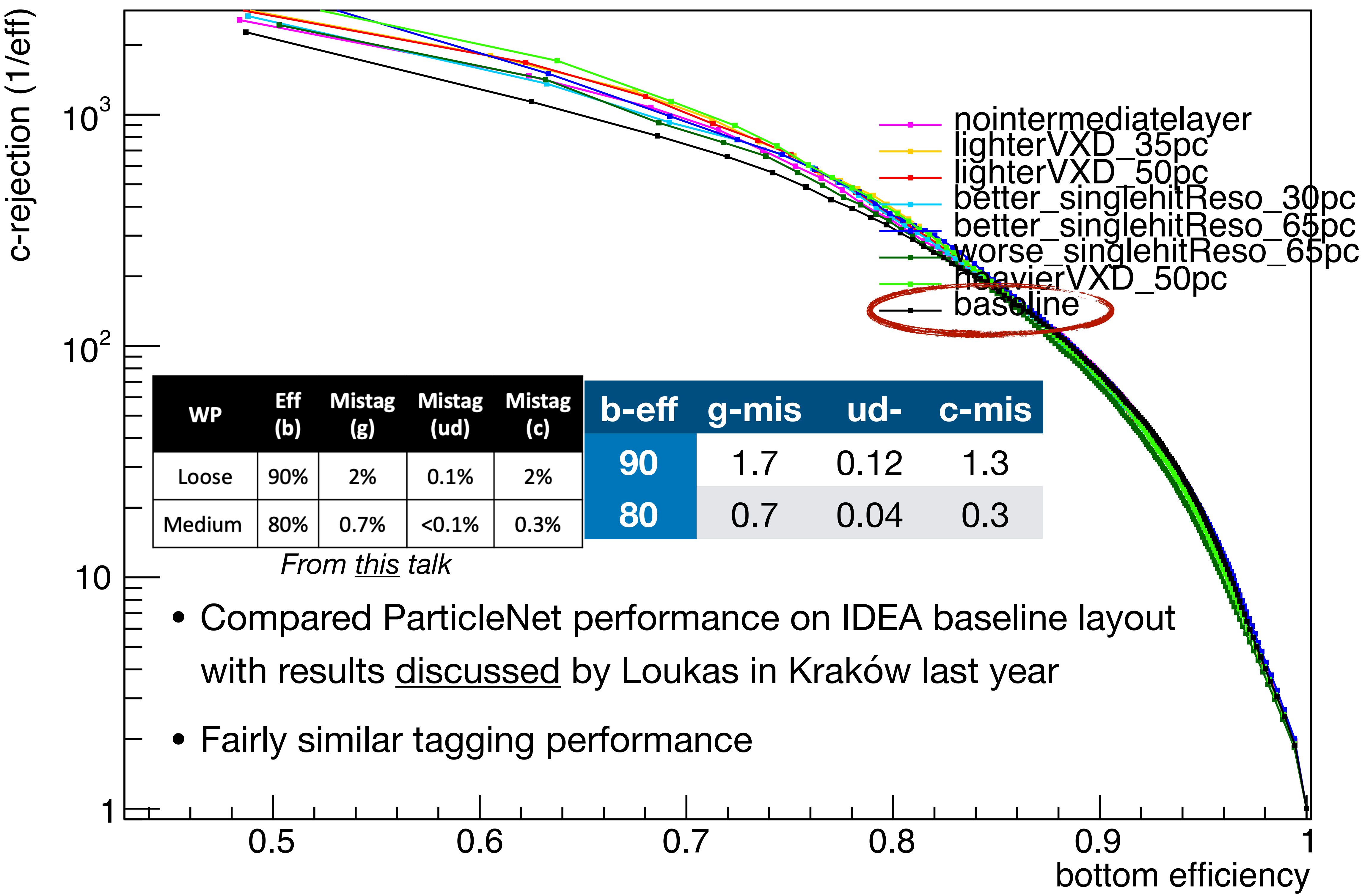
The IDEA for Tagger Studies & Setup

- Generate 5 jet flavors in *vvH* Higgs decay (*Whizard*)
  - *bb, cc, ss, qq(=uu,dd), gg* [*N.B. may add taus, split gluon, if/where useful*]
- Simulate through IDEA detector
  - Fast simulation (*Delphes*)
  - Several alternative trackers probed:
    - **w/o 2nd/4th innermost layer,**
    - **better/worse hit resolution,**
    - **lighter/heavier material.**



- 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
  - Used 200k jets per flavor (1M jets in total)

“Validation” of Training Setup



WP	Eff (b)	Mistag (g)	Mistag (ud)	Mistag (c)
Loose	90%	2%	0.1%	2%
Medium	80%	0.7%	<0.1%	0.3%

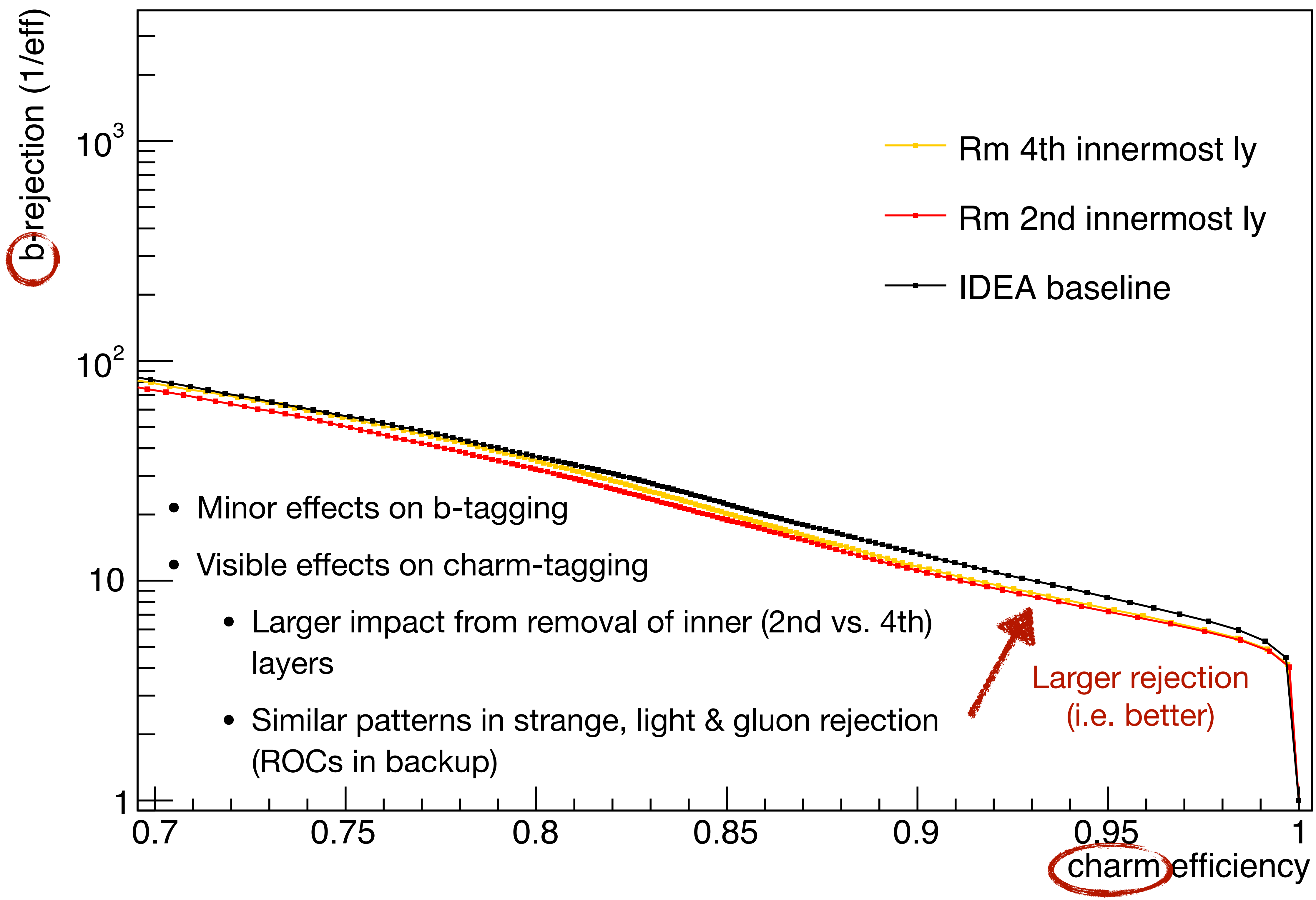
From this talk

b-eff	g-mis	ud-	c-mis
90	1.7	0.12	1.3
80	0.7	0.04	0.3

- Compared ParticleNet performance on IDEA baseline layout with results discussed by Loukas in Kraków last year
- Fairly similar tagging performance

Number of Pixel Layers

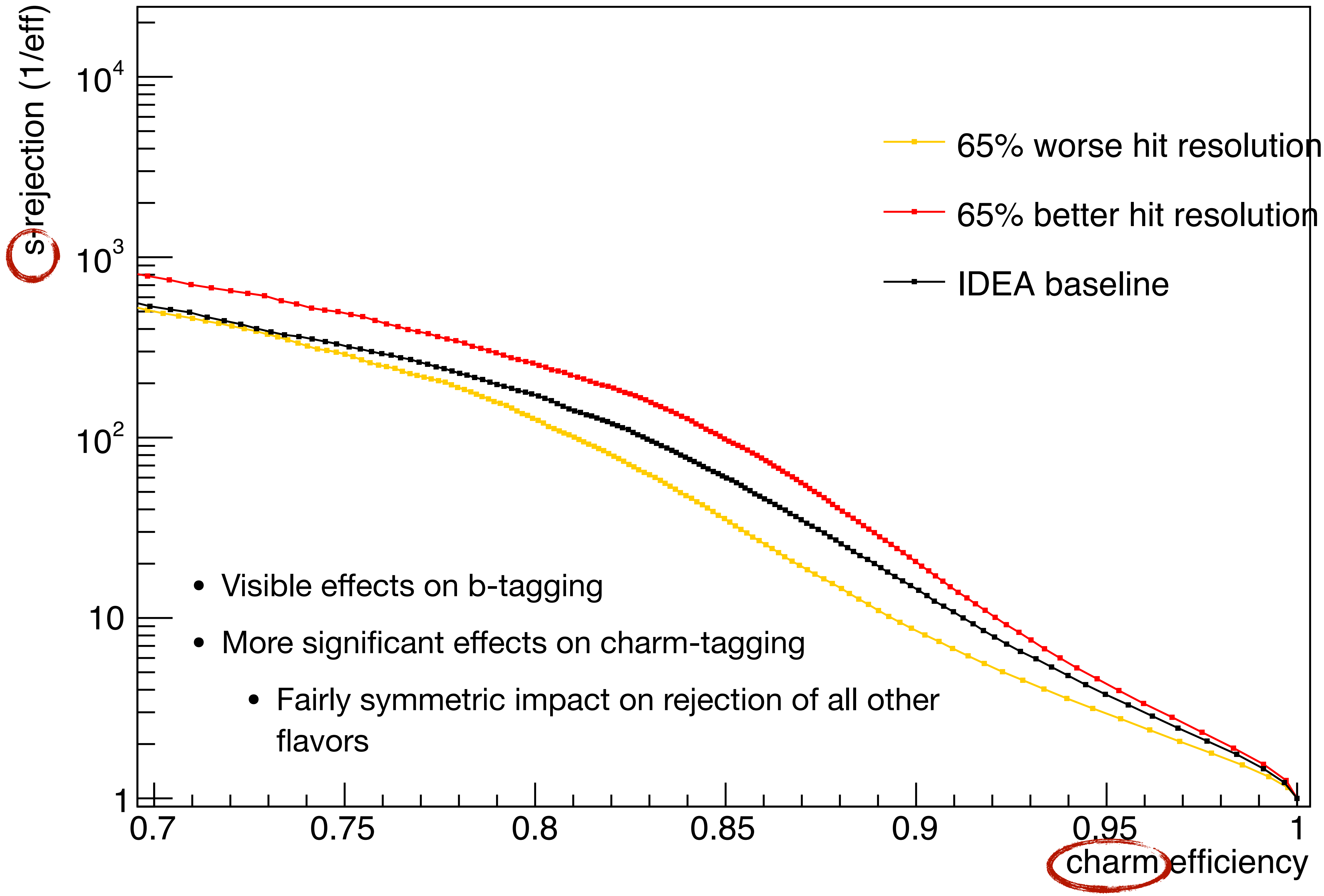
Number of Pixel Layers



- Minor effects on b-tagging
- Visible effects on charm-tagging
  - Larger impact from removal of inner (2nd vs. 4th) layers
  - Similar patterns in strange, light & gluon rejection (ROCs in backup)

Pixel
Hit Resolution

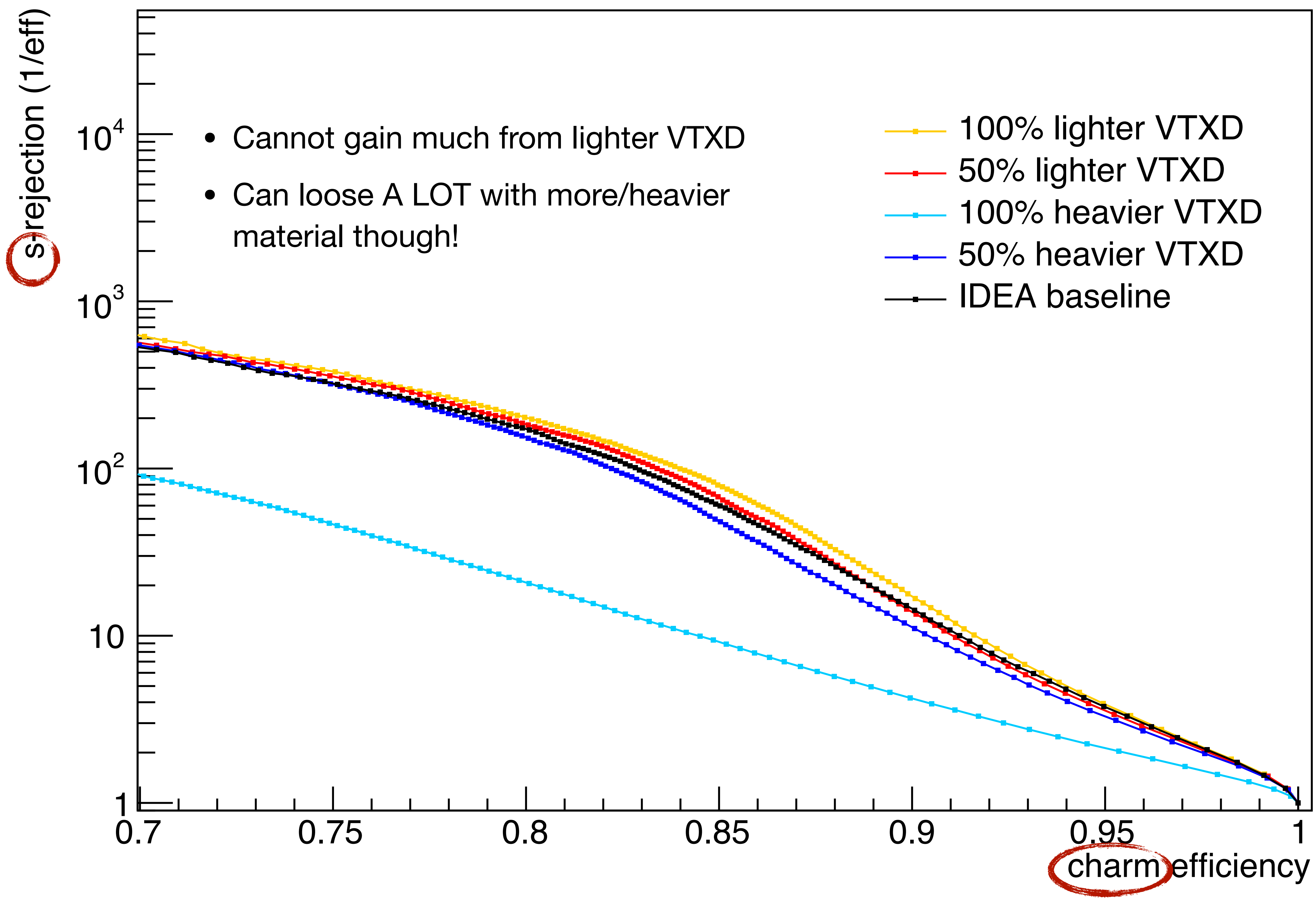
Pixel Hit Resolution



- Visible effects on b-tagging
- More significant effects on charm-tagging
  - Fairly symmetric impact on rejection of all other flavors

Pixel-Detector
Material Budget

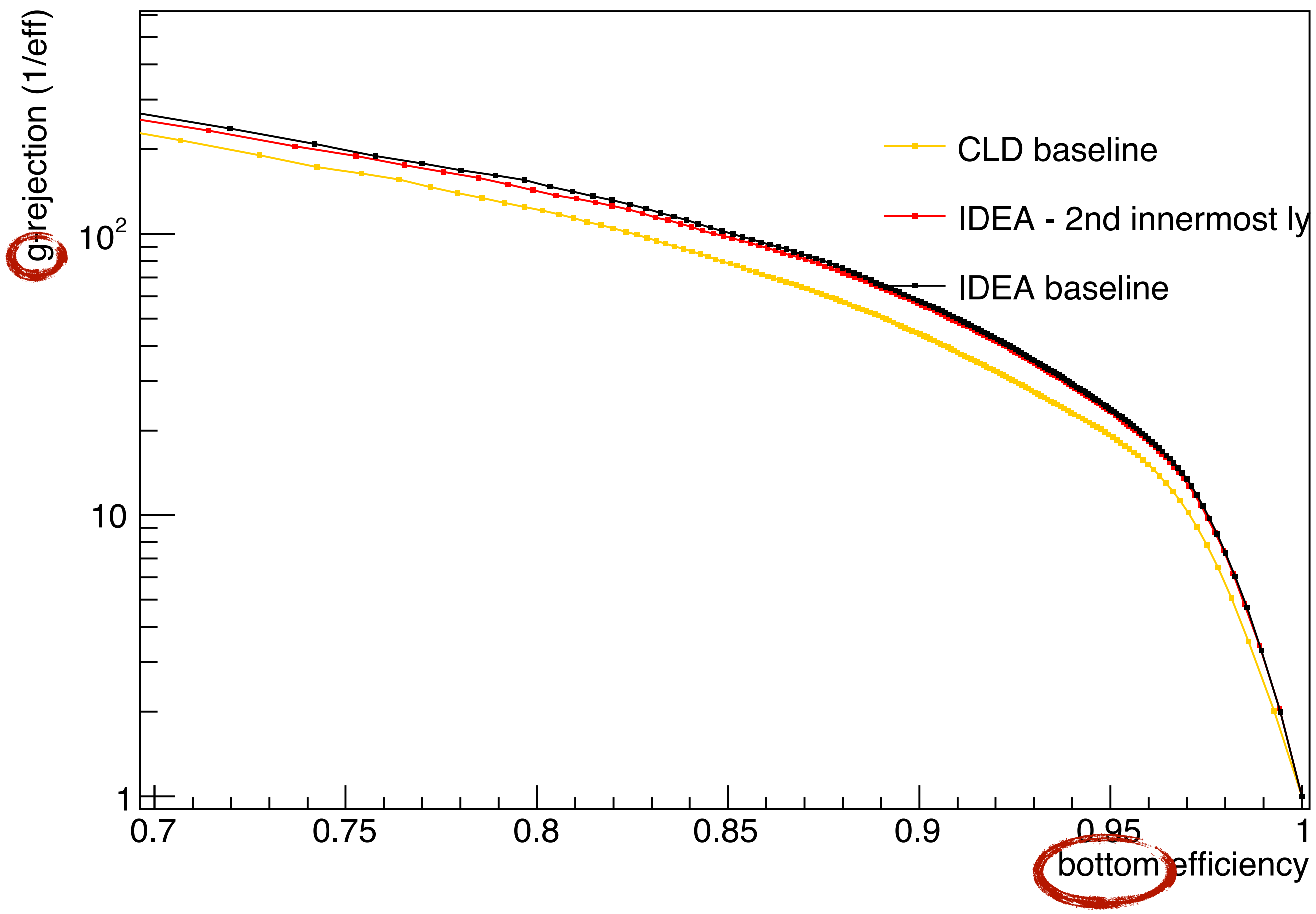
Pixel-Detector Material Budget

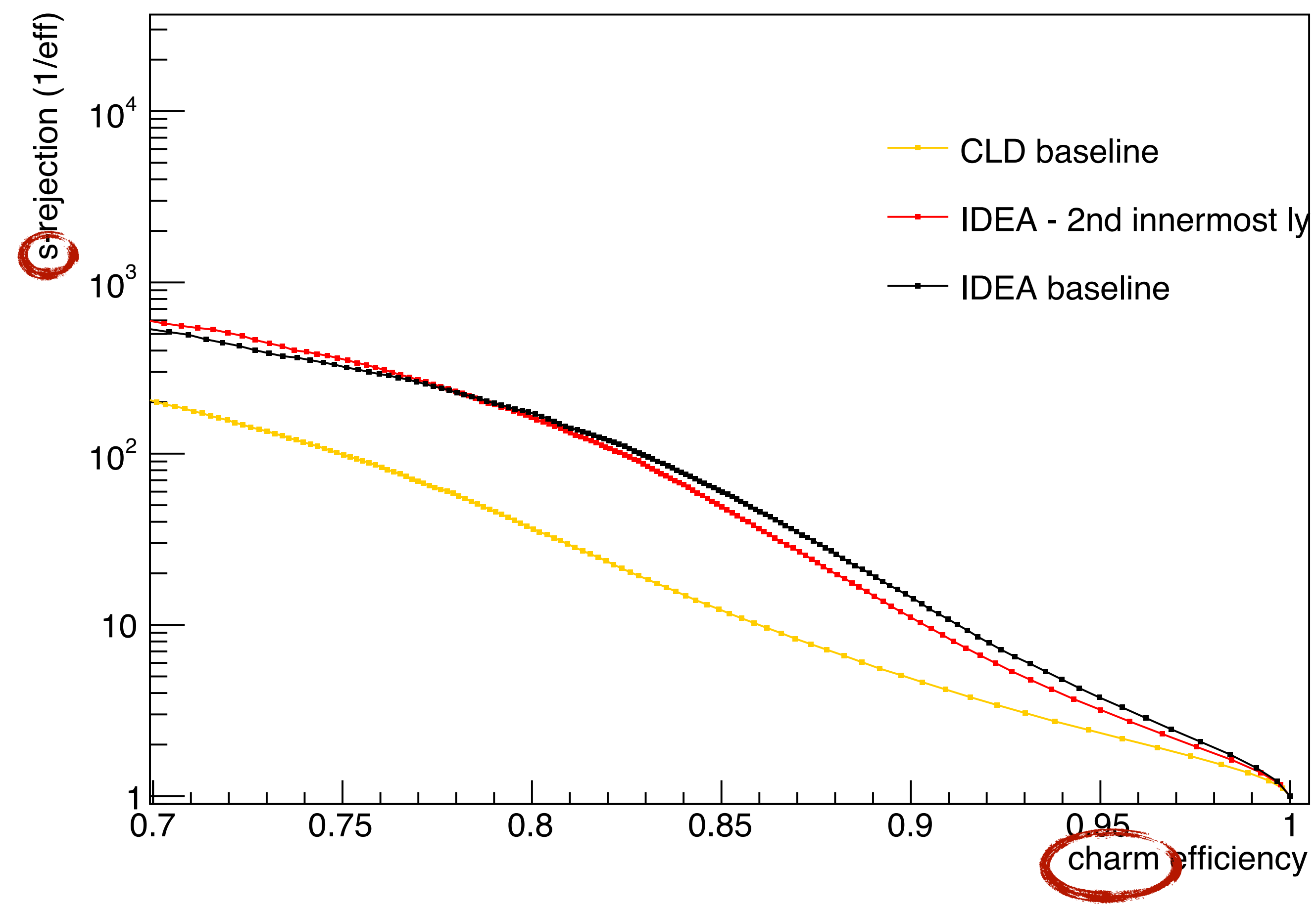


Bonus: CLD Fast Simulation

CLD vs. IDEA

- **CLD**: BP at 1cm too, full Si vtx+tracker: **3(vs. 4) VTXD layers & innermost at 1.8(vs.1.2)cm**
- **No powerful PID**
  - **Alike IDEA**'s ultra light drift chamber





- Fruitful optimization of detector design: pays off!
- How optimistic are we with Delphes benchmarks?

Conclusion & Plans

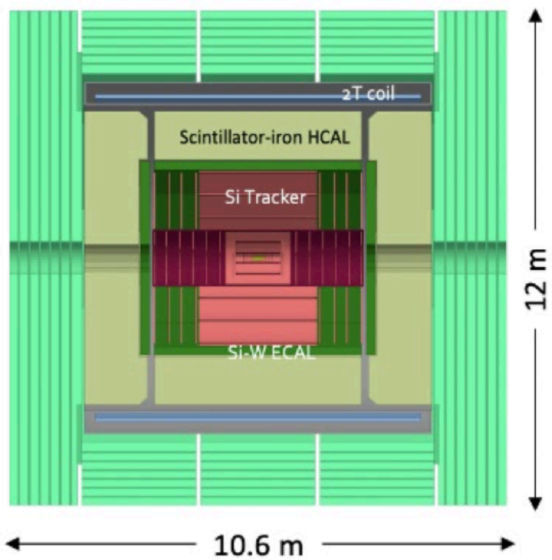
- **Significant effects observed in efficiency(rejection) at fixed rejection(efficiency) for different (IDEA) VTXD properties**
  - Re-training against each configuration allows for partial performance recovering
  - Some effects are non-trivial
- In near future, **may expand studies** beyond “simple” changes in silicon vertex detector
  - Material-budget interplay between beam pipe & first silicon layer
  - **PID & timing studies** possible with setup in place
- For the “farther” future… characterize interplay between reco (e.g. PF candidate selection, reco optimizations, etc…) in full simulation & ParticleNet tagger performance
- **Propagating tagger-performance changes through Higgs coupling analyses**
  - More details in Iza’s talk at US FCC Workshop next week
- Independently of flavor taggers: performing studies of ***H->invisible*** **sensitivity as a function of calorimetry properties** (E resolution, granularity, etc…) - see Diallo’s talk next week
- In general: looking forward to feedback on these studies
  - **Need to focus on most sought-after answers to make sure they will be available by this Summer** (final-report constraints)

BACKUP

Current Detector Concepts

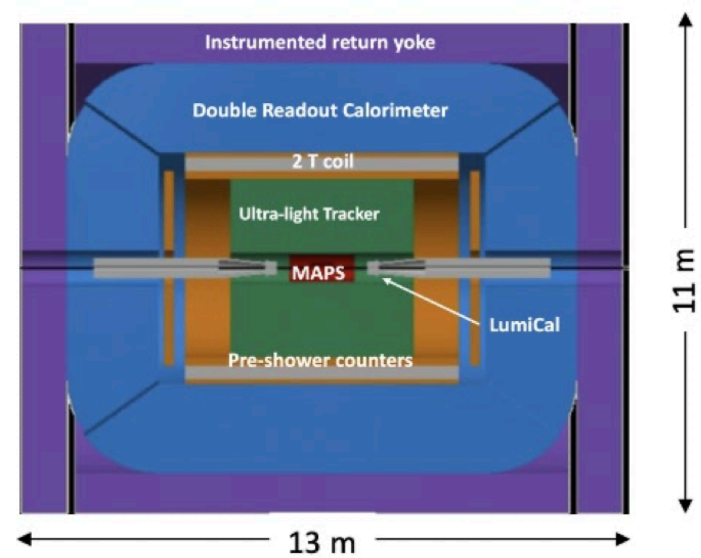
From this talk

CLD

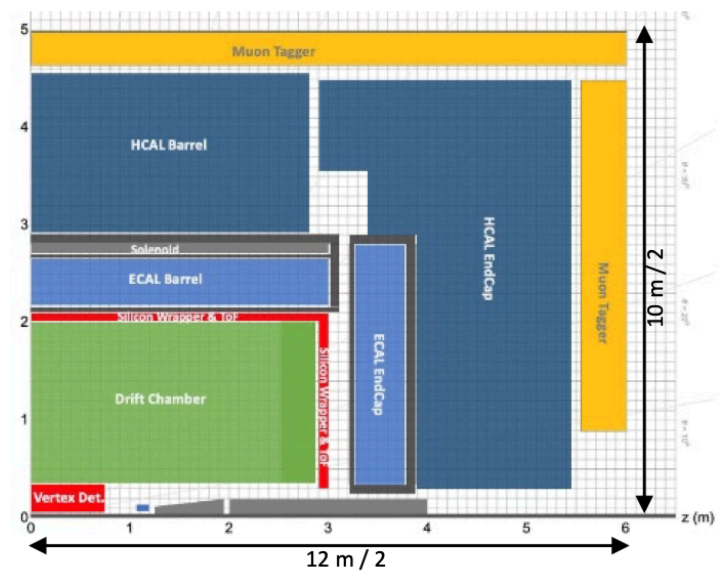


CDR

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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Delphes cards

IDEA Delphes card - Details

```
# barrel  name       zmin    zmax    r        w (m)      X0        n_meas  th_up (rad) th_down (rad)    reso_up (m)    reso_down (m)   flag

1 PIPE -100 100 0.01 0.00235 0.35276 0 0 0 0 0 0
1 VTXLOW -0.0965 0.0965 0.012 0.00028 0.0937 2 0 1.5708 3e-06 3e-06 1
1 VTXLOW -0.1609 0.1609 0.02 0.00028 0.0937 2 0 1.5708 3e-06 3e-06 1
1 VTXLOW -0.2575 0.2575 0.031525 0.00028 0.0937 2 0 1.5708 3e-06 3e-06 1
1 VTXLOW -0.1609 0.1609 0.15 0.00028 0.0937 2 0 1.5708 3e-06 3e-06 1
1 VTXHIGH -0.3263 0.3263 0.315 0.00047 0.0937 2 0 1.5708 7e-06 7e-06 1
```

...

```
  2 VTXDSK 0.105 0.29 -0.93 0.00028 0.0937 2 0 1.5708 7e-06 7e-06 1
  2 VTXDSK 0.075 0.29 -0.62 0.00028 0.0937 2 0 1.5708 7e-06 7e-06 1
  2 VTXDSK 0.0365 0.2515 -0.2575 0.00028 0.0937 2 0 1.5708 7e-06 7e-06 1
  2 VTXDSK 0.0365 0.2515 0.2575 0.00028 0.0937 2 0 1.5708 7e-06 7e-06 1
  2 VTXDSK 0.075 0.29 0.62 0.00028 0.0937 2 0 1.5708 7e-06 7e-06 1
  2 VTXDSK 0.105 0.29 0.93 0.00028 0.0937 2 0 1.5708 7e-06 7e-06 1
```

CLD Delphes card - Details

```
# barrel  name        zmin    zmax    r          w (m)       X0         n_meas   th_up (rad) th_down (rad)    reso_up (m)    reso_down (m)   flag

1 PIPE -100 100 0.01 0.00235 0.35276 0 0 0 0 0 0
1 VTX -0.125 0.125 0.0175 4.5e-005 0.0937 2 0 1.5708 3e-006 3e-006 1 }  1st layer
1 VTX -0.125 0.125 0.0185 4.5e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
1 VTX -0.125 0.125 0.037 4.5e-005 0.0937 2 0 1.5708 3e-006 3e-006 1 }  2nd layer
1 VTX -0.125 0.125 0.038 4.5e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
1 VTX -0.125 0.125 0.057 4.5e-005 0.0937 2 0 1.5708 3e-006 3e-006 1 }  3rd layer
1 VTX -0.125 0.125 0.058 4.5e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
```

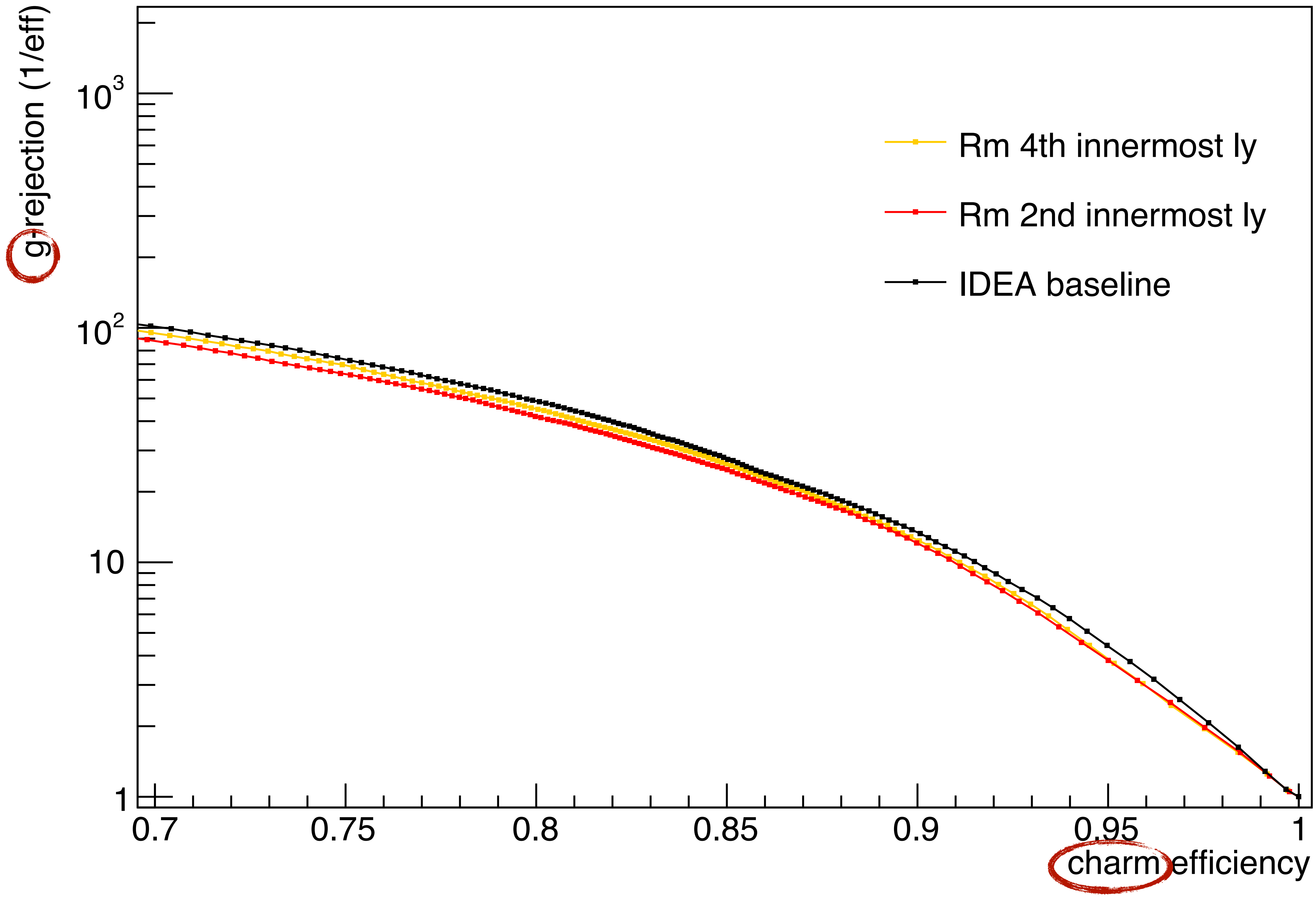
...

```
2 VTXDSK 0.045 0.102 -0.301 4.4e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
2 VTXDSK 0.045 0.102 -0.299 4.4e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
2 VTXDSK 0.0345 0.102 -0.231 4.4e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
2 VTXDSK 0.0345 0.102 -0.229 4.4e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
2 VTXDSK 0.024 0.102 -0.161 4.4e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
2 VTXDSK 0.024 0.102 -0.159 4.4e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
2 VTXDSK 0.024 0.102 0.159 4.4e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
2 VTXDSK 0.024 0.102 0.161 4.4e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
2 VTXDSK 0.0345 0.102 0.229 4.4e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
2 VTXDSK 0.0345 0.102 0.231 4.4e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
2 VTXDSK 0.045 0.102 0.299 4.4e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
2 VTXDSK 0.045 0.102 0.301 4.4e-005 0.0937 2 0 1.5708 3e-006 3e-006 1
```

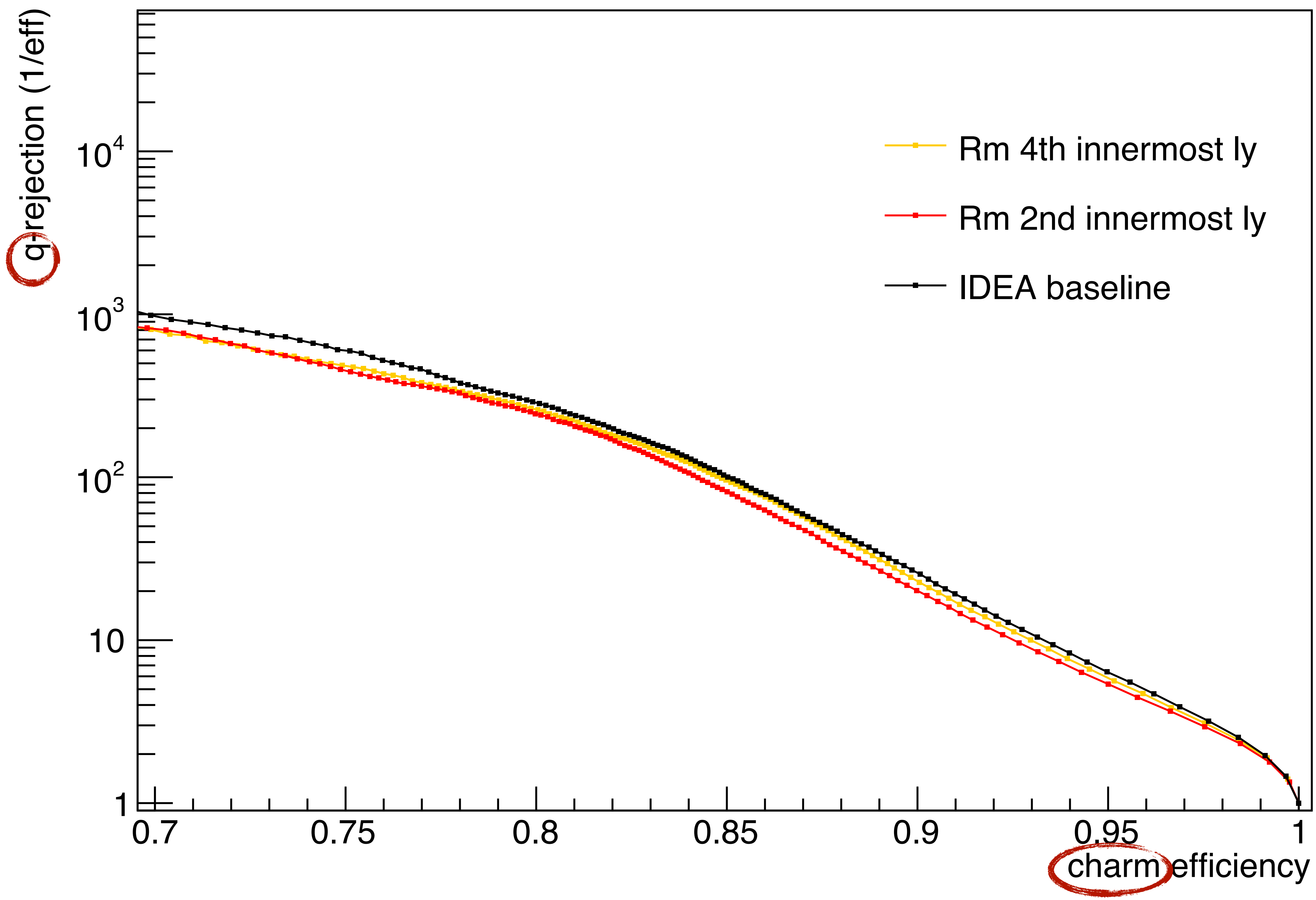
More ROCs

Number of Pixel Layers

Number of Pixel Layers

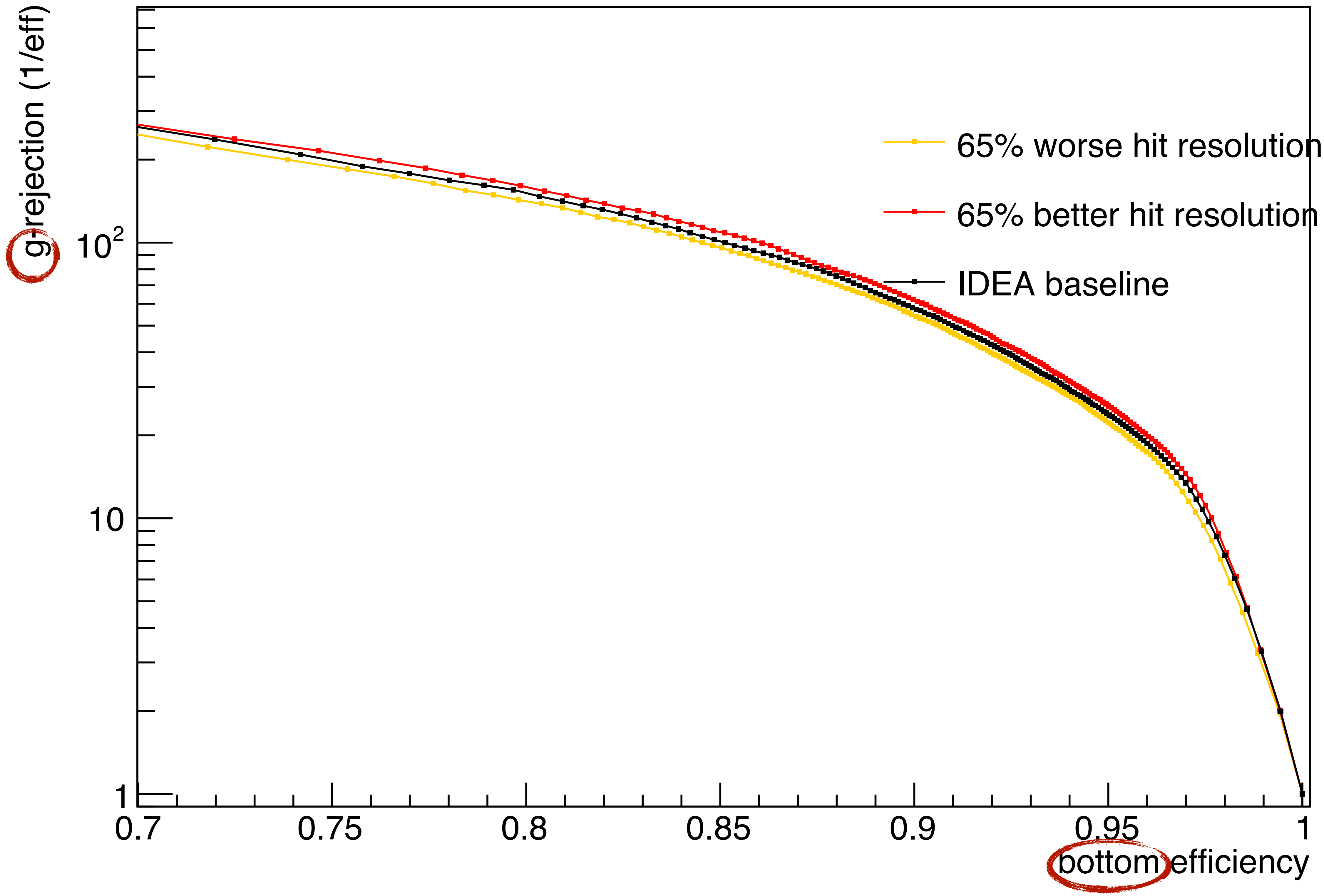


Number of Pixel Layers

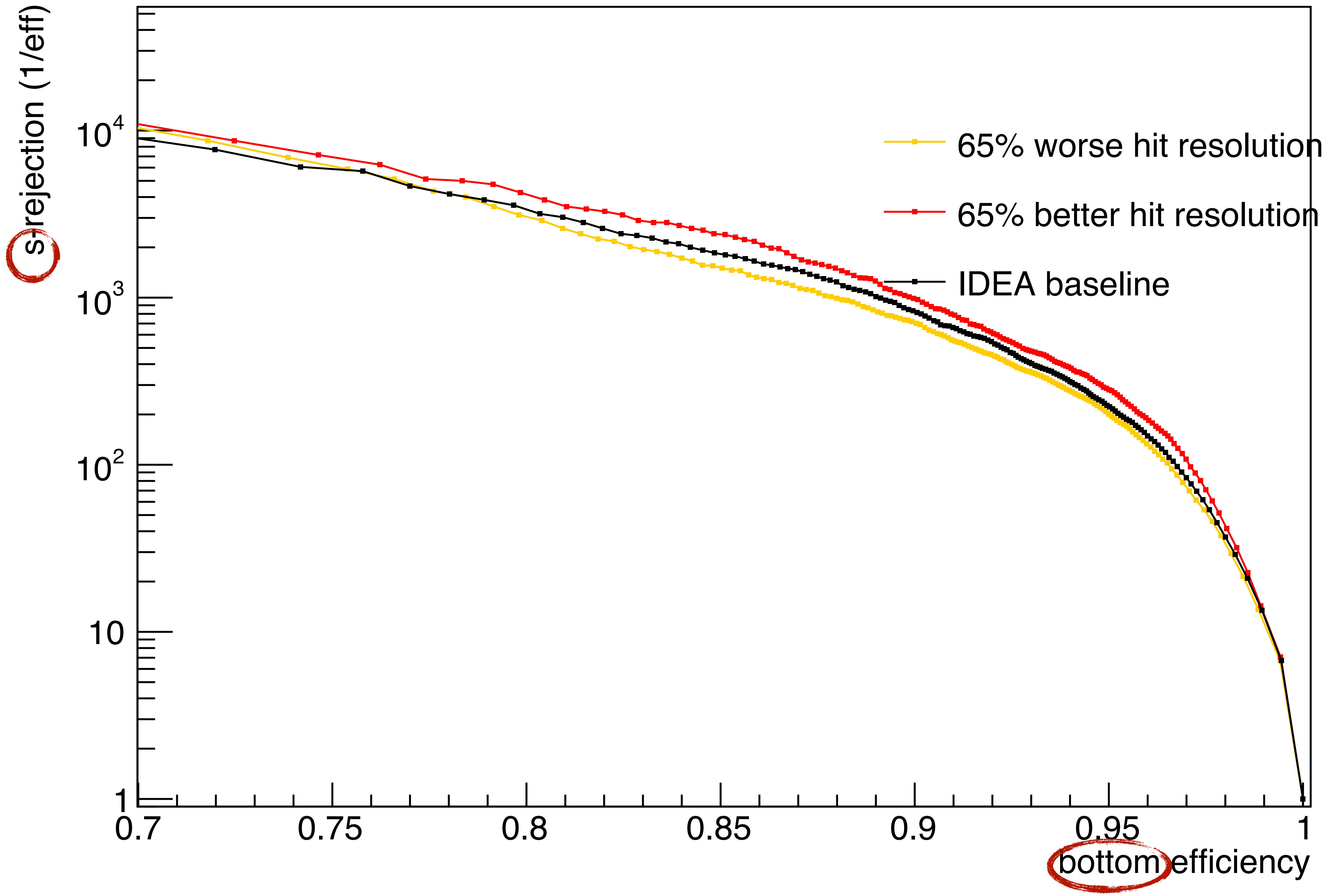


Pixel
Hit Resolution

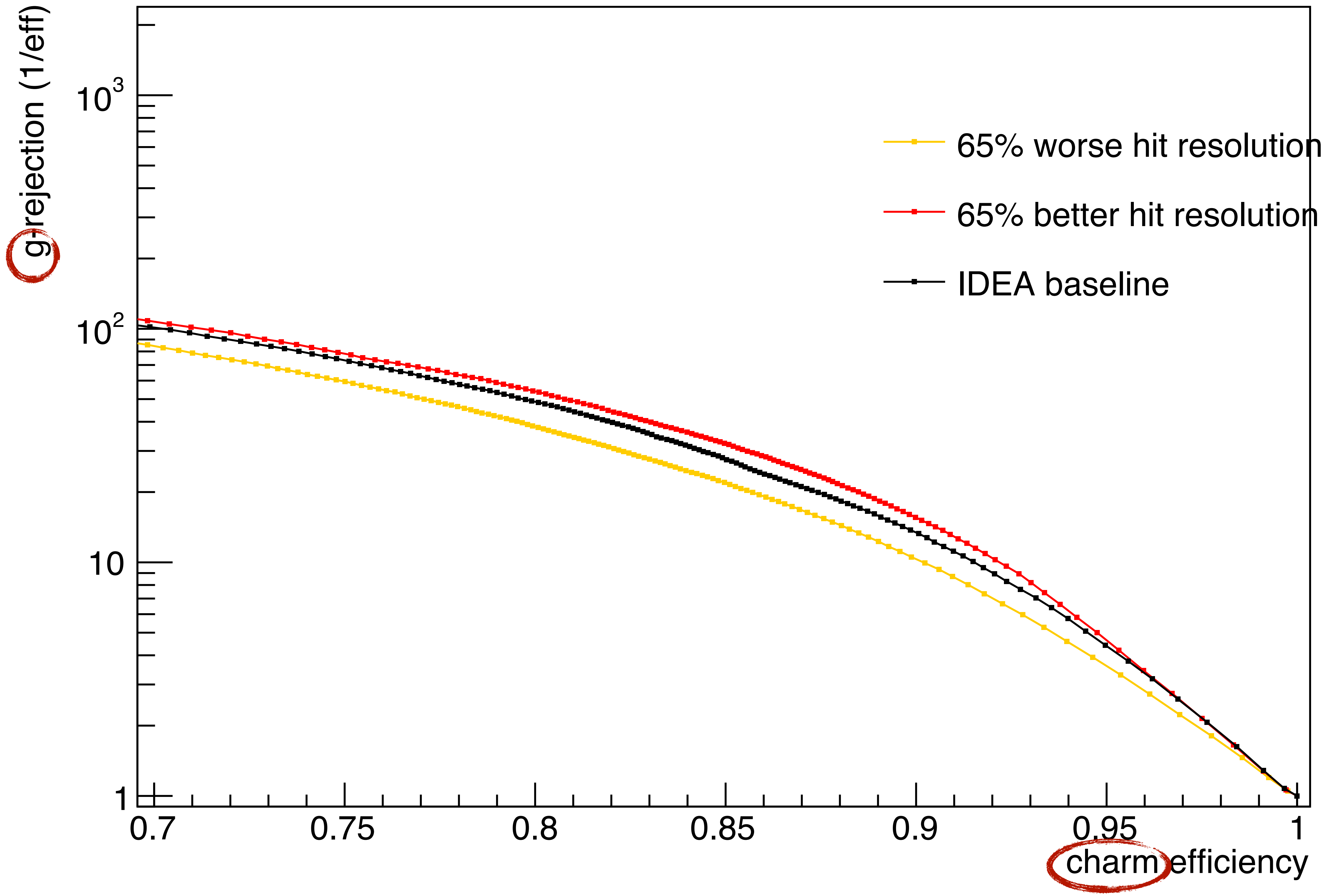
Pixel Hit Resolution



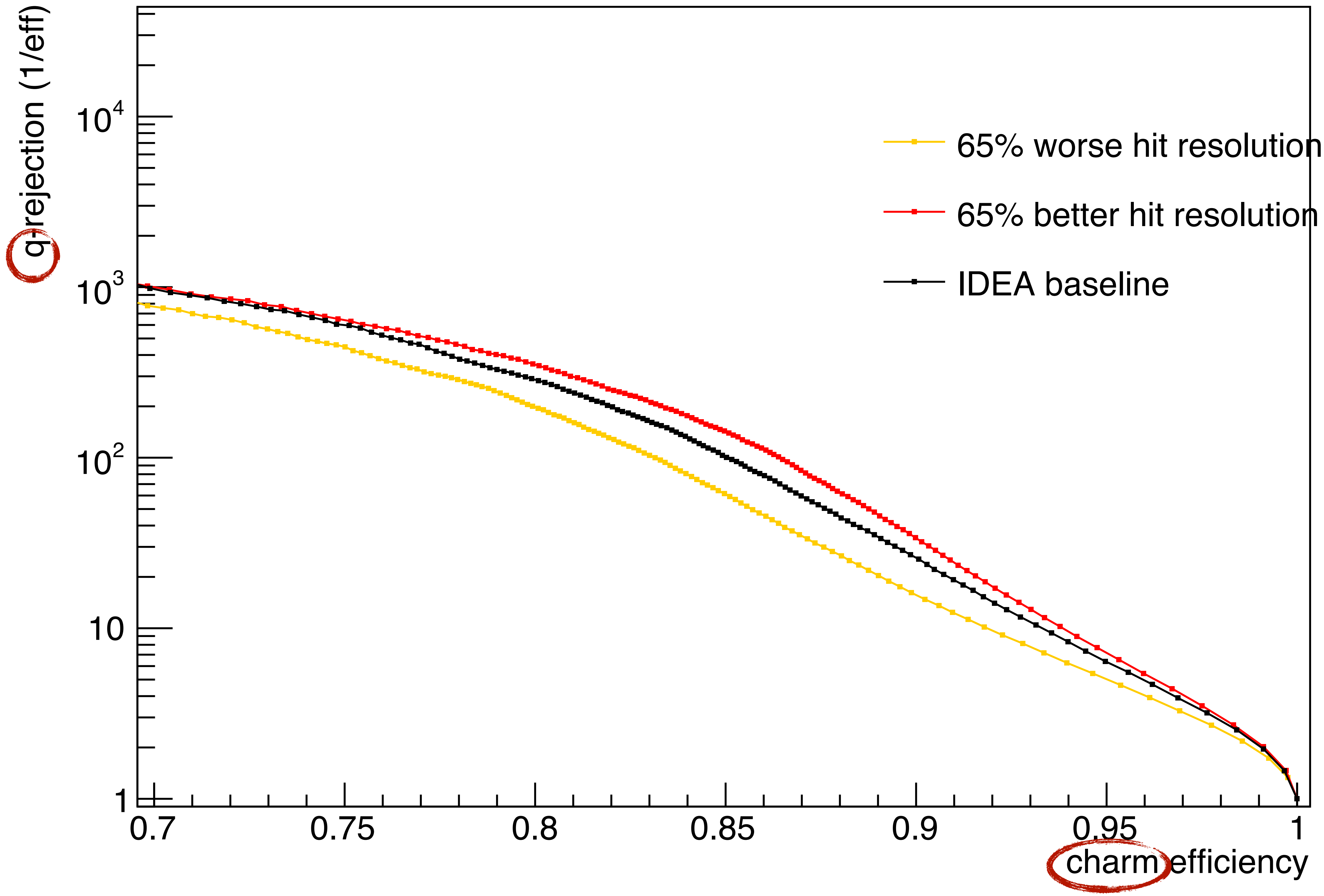
Pixel Hit Resolution



Pixel Hit Resolution

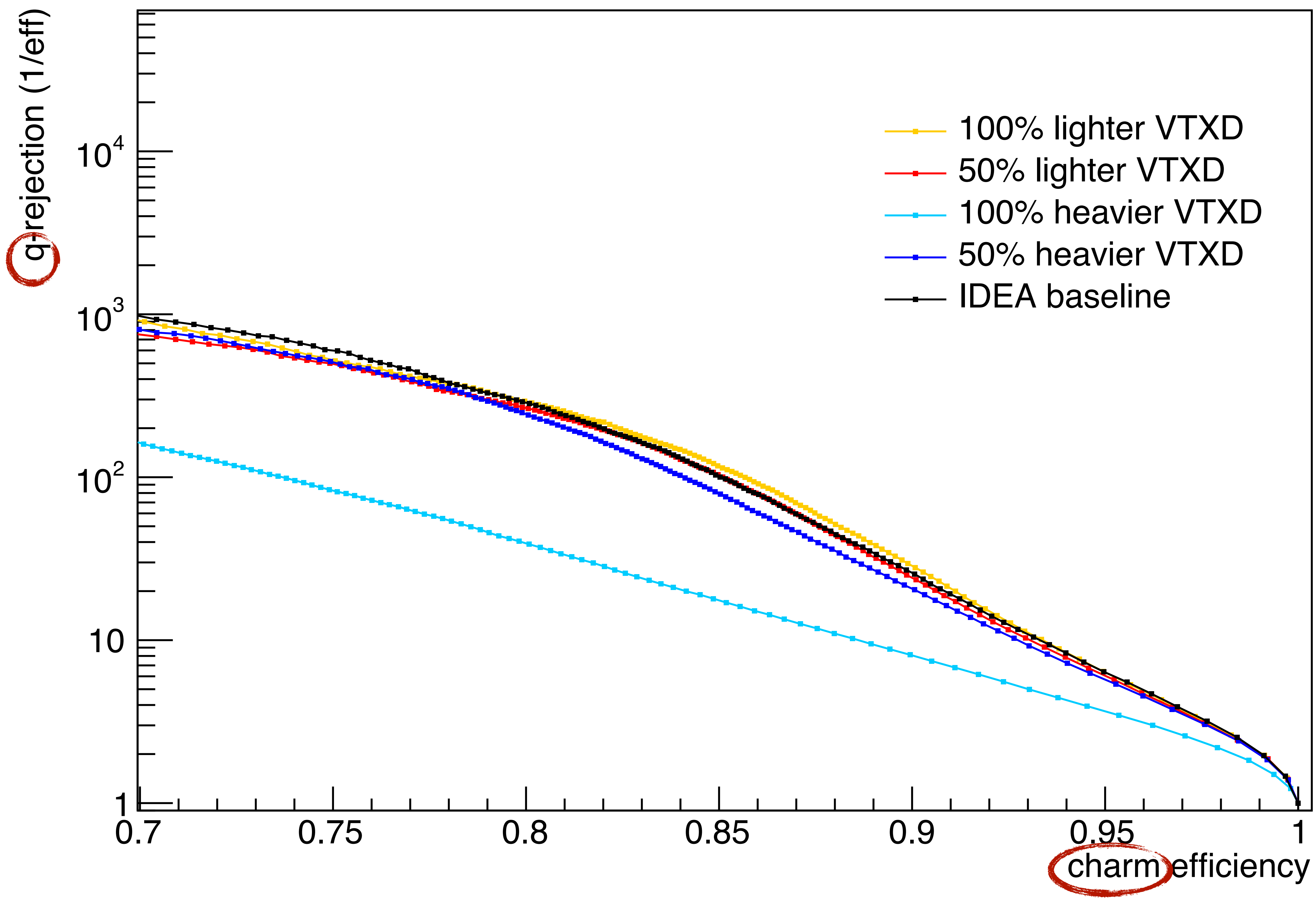


Pixel Hit Resolution

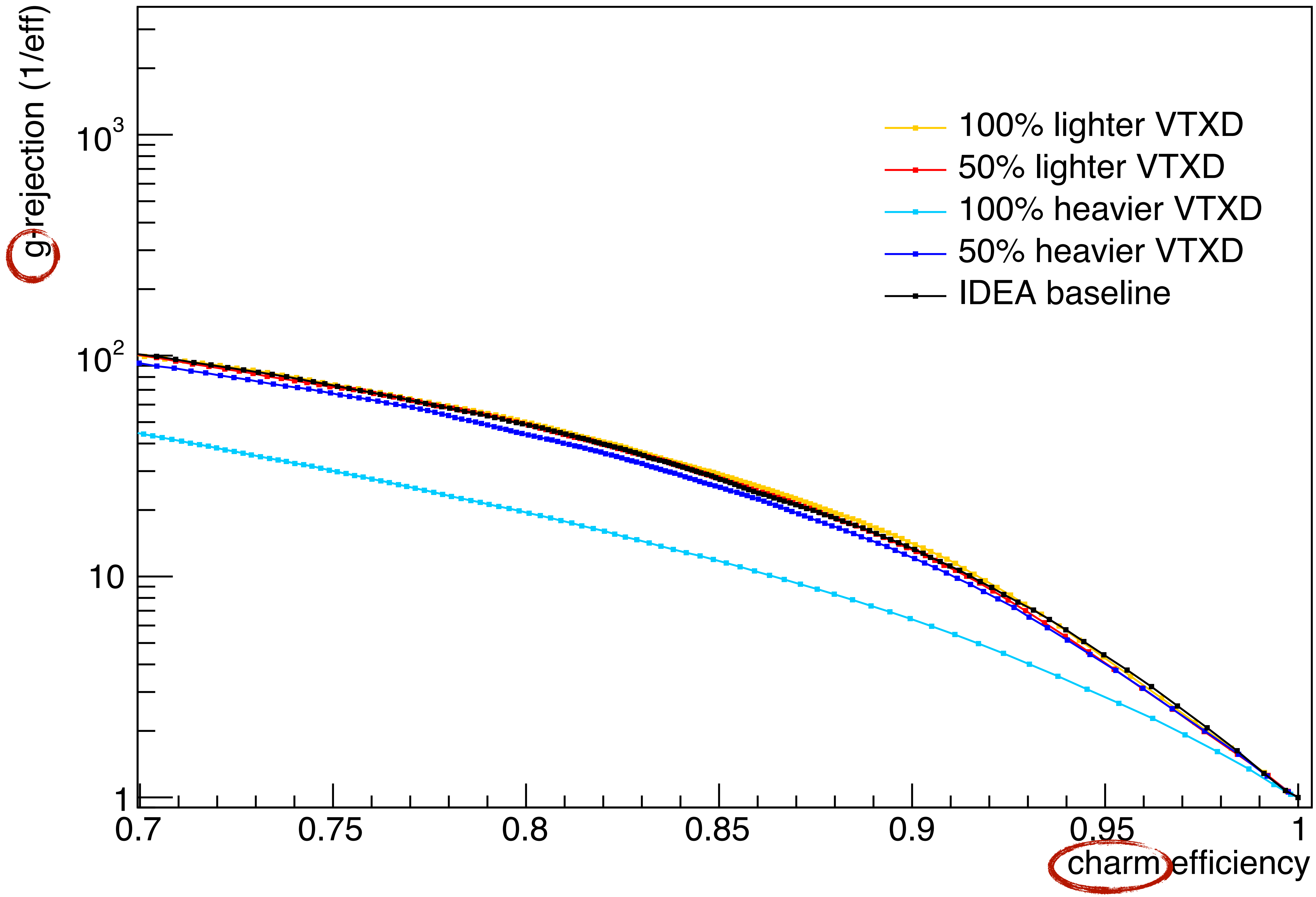


Pixel-Detector
Material Budget

Pixel-Detector Material Budget

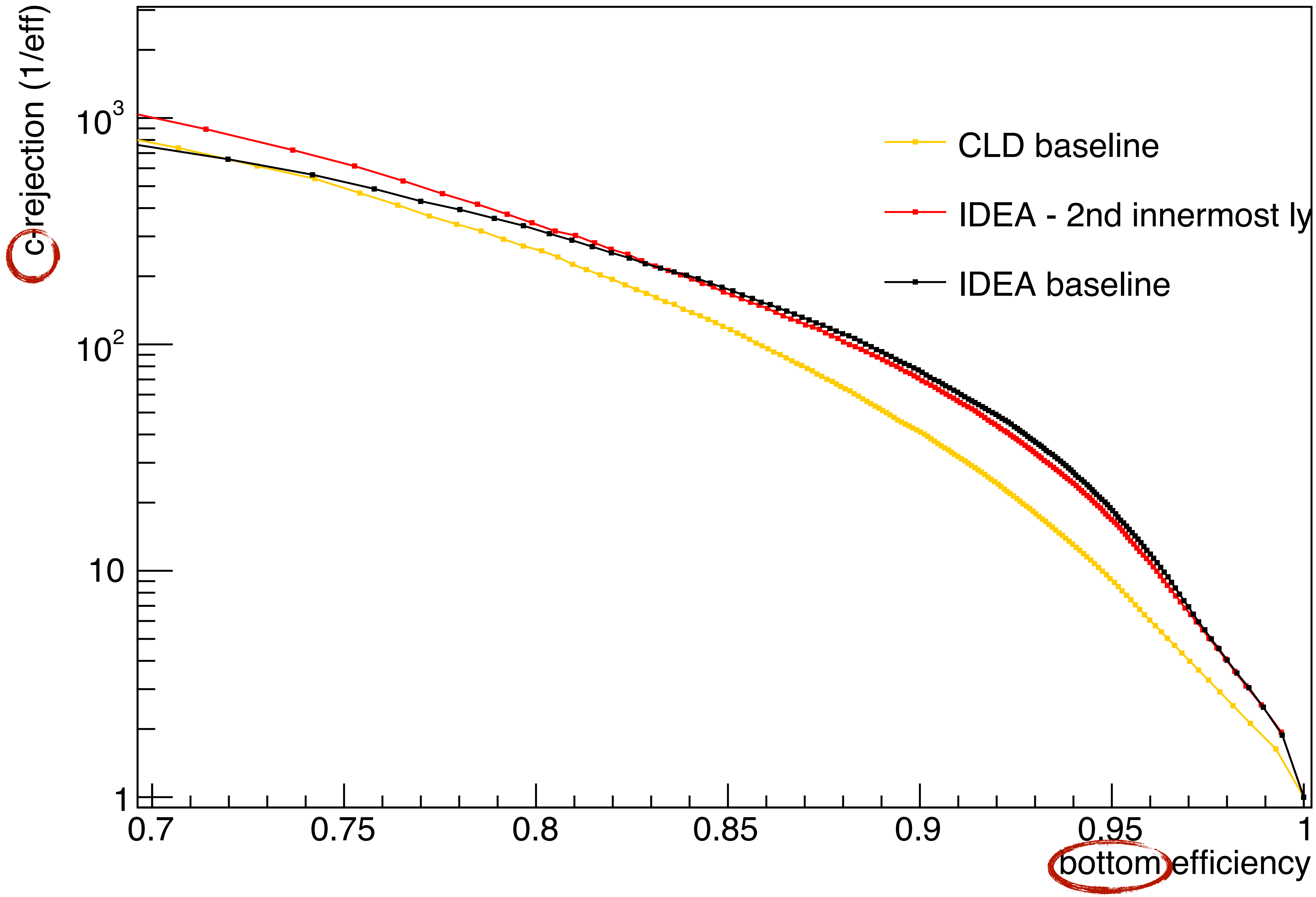


Pixel-Detector Material Budget



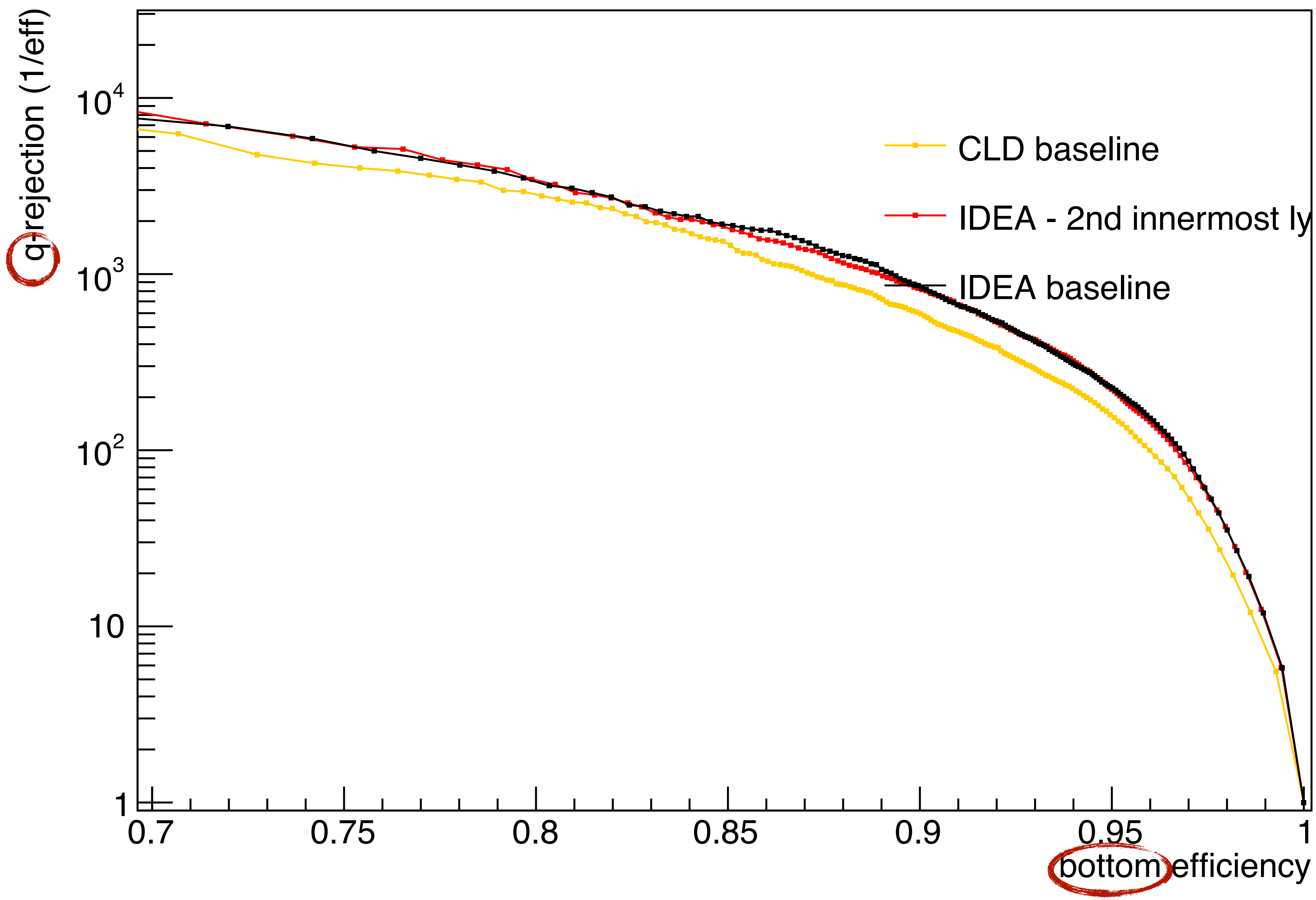
Bonus: CLD Fast Simulation

CLD vs. IDEA



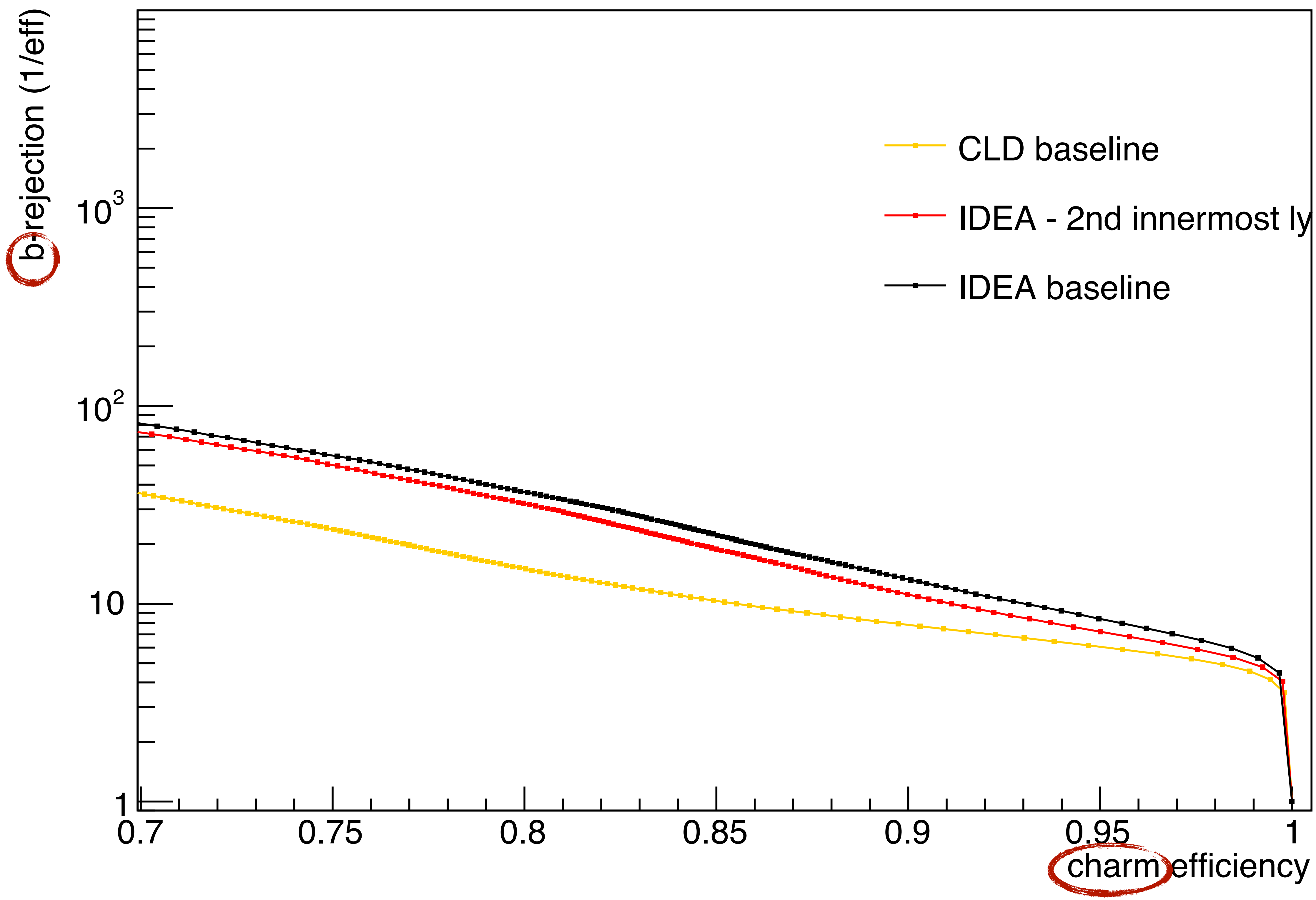
c-rejection (1/eff)
10^3
10^2
10
1
0.7
0.75
0.8
0.85
0.9
0.95
1
bottom efficiency
CLD baseline
IDEA - 2nd innermost ly
IDEA baseline

CLD vs. IDEA



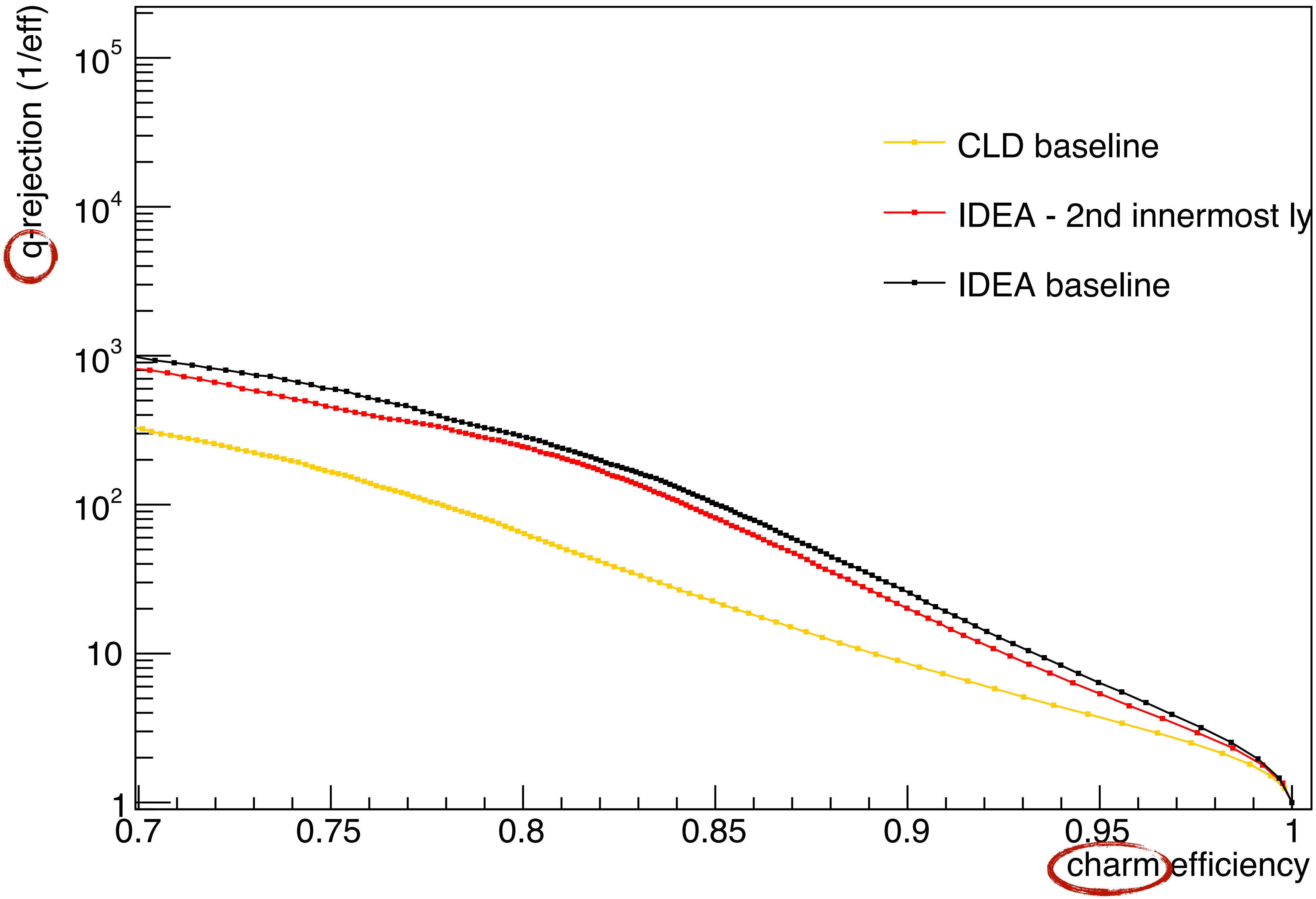
q-rejection (1/eff)
10^4
10^3
10^2
10
1
0.7
0.75
0.8
0.85
0.9
0.95
1
bottom efficiency
CLD baseline
IDEA - 2nd innermost ly
IDEA baseline

CLD vs. IDEA



b-rejection (1/eff)
10^3
10^2
10
1
0.7
0.75
0.8
0.85
0.9
0.95
1
charm efficiency
CLD baseline
IDEA - 2nd innermost ly
IDEA baseline

CLD vs. IDEA



q-rejection (1/eff)
10^5
10^4
10^3
10^2
10
1
CLD baseline
IDEA - 2nd innermost ly
IDEA baseline
0.7
0.75
0.8
0.85
0.9
0.95
1
charm efficiency