FCC-*ee* ParticleNet Tagger

& IDEA Detector Tracker

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Thanks to Dolores, Jan & Michele
for helpful feedback!

Brookhaven National Laboratory

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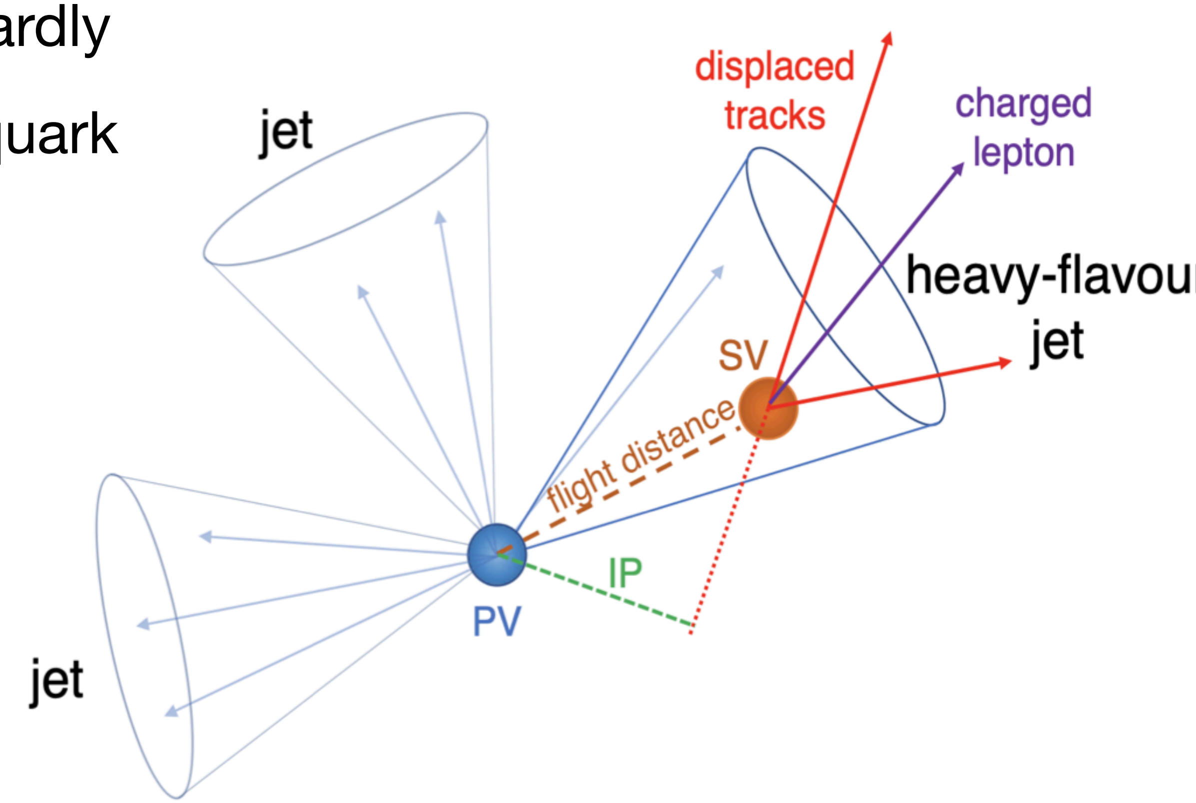
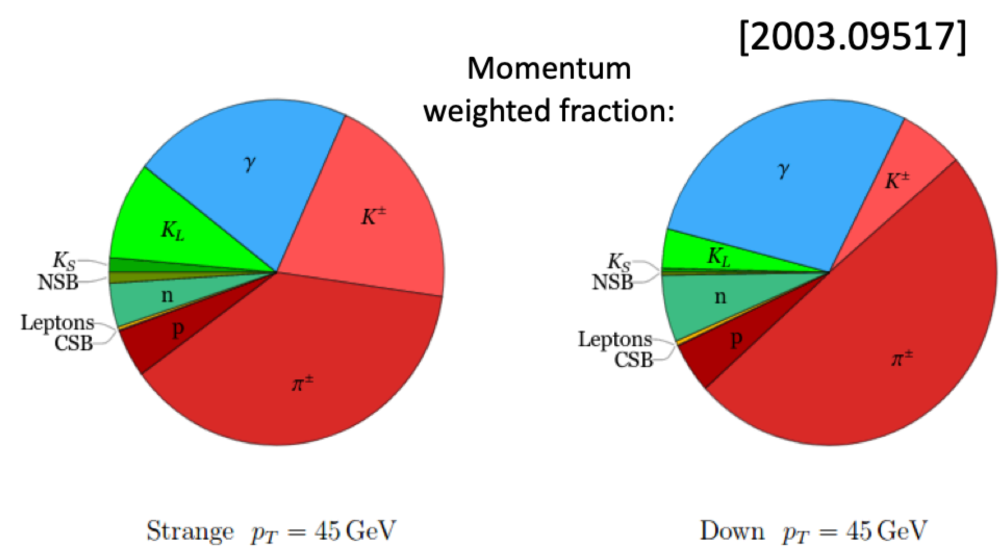
Introduction & Motivation

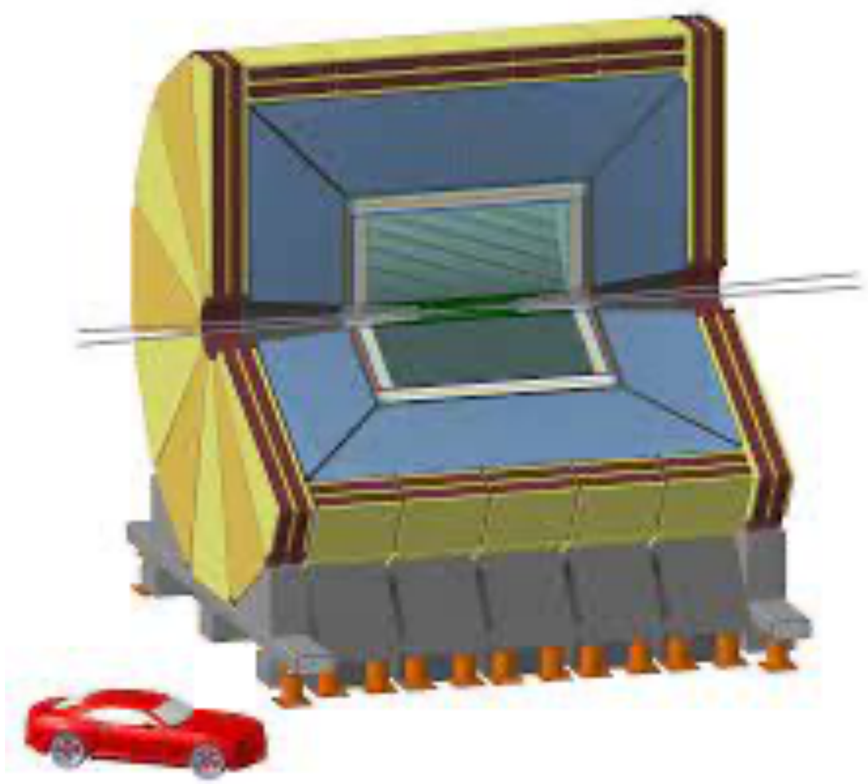
- Flavor tagging is key for e^+e^- program, in particular to access challenging Higgs-boson decay modes like *cc* & *ss* - hardly accessible at the LHC -, precise determination of top-quark properties, strong coupling, hadronization, etc…
- *Bottom* & *charm* tagging based on:
  - Large lifetime
  -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

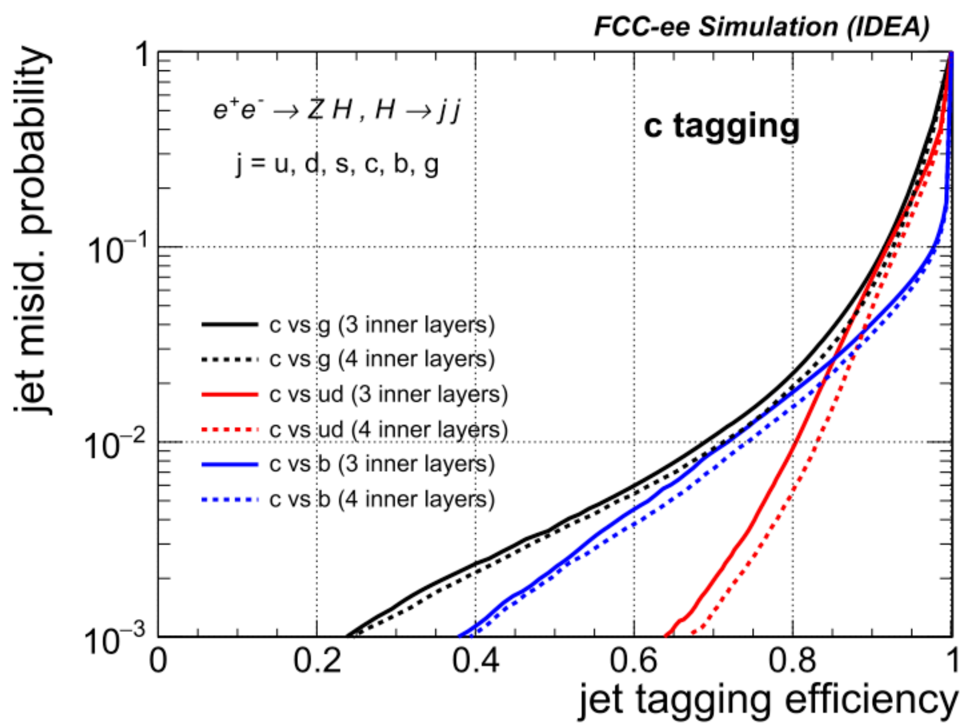




The IDEA Tracker as an Opportunity

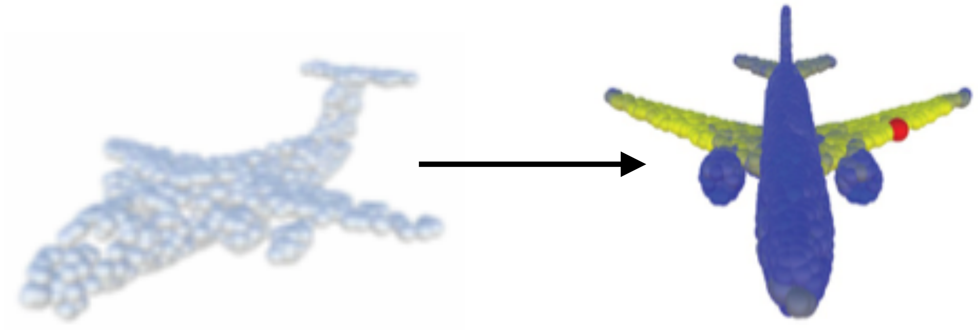
- Different possible detector scenarios, *tracker* particularly relevant to flavor-tagging
  - **Amount (e.g. n. of layers)** & **quality of material**
  - **Hit resolution**
  - PID capabilities: timing, energy loss (gas/silicon)
- Baseline IDEA detector as a well-established reference for detector-performance 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 *innermost* VTXD barrel layers: (1.2cm, 2cm, 3.15cm, 15cm)



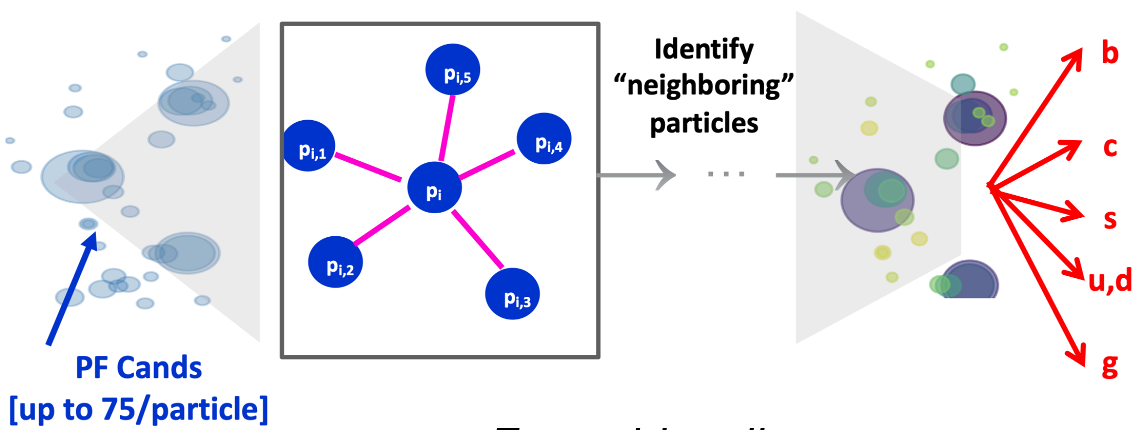


The ParticleNet Tagger

- 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



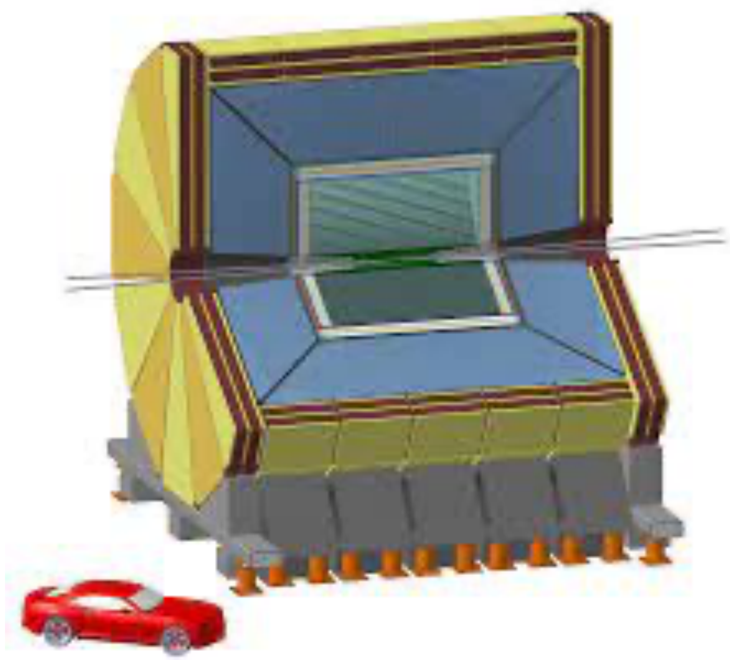
From this article



From this talk

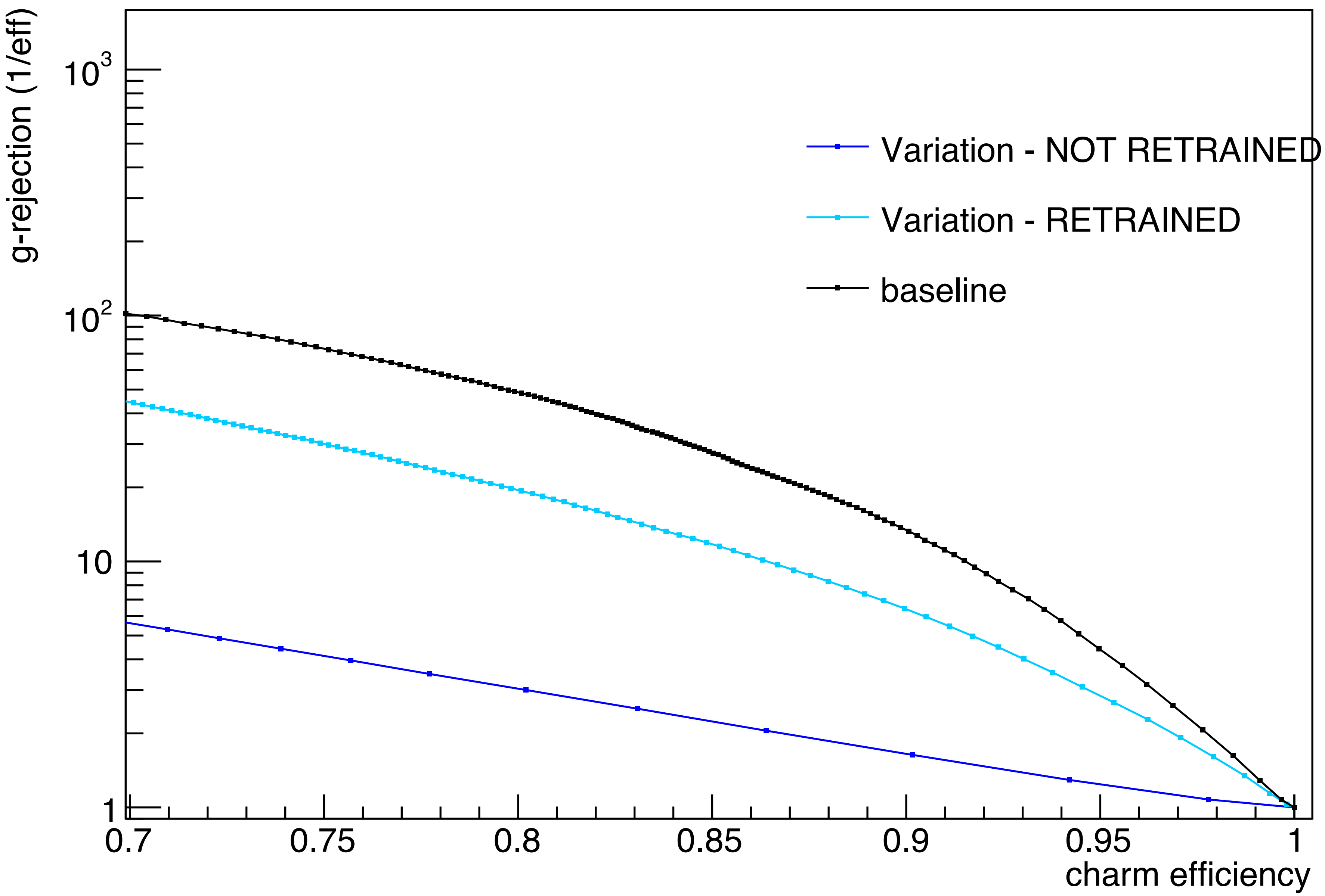
The IDEA for Tagger Studies & Setup

- 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.**



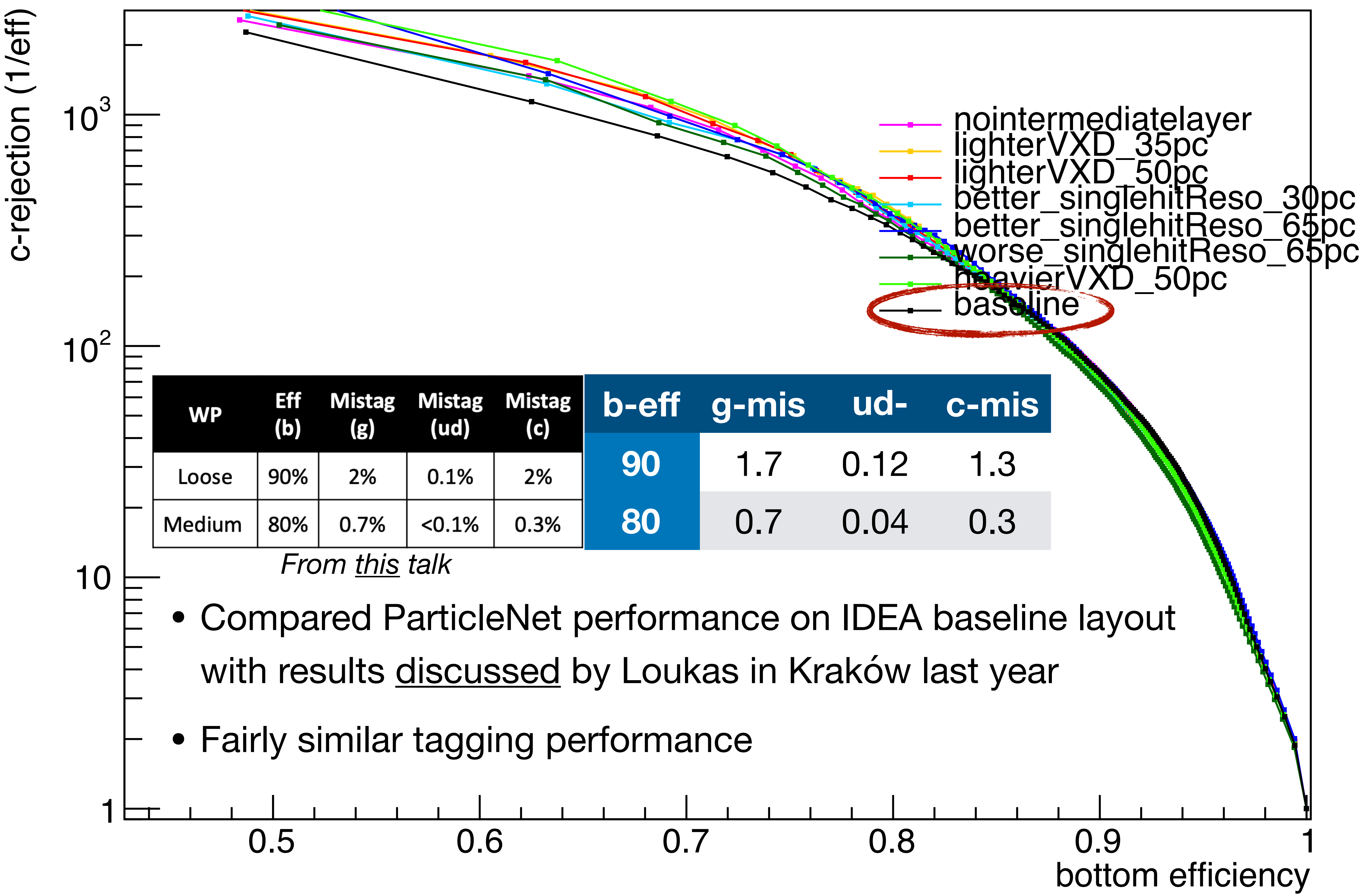
- Process key4hep files to get ntuples, *inputs to flavor-tagger* trainings
- Perform trainings (on GPUs) for different tracker scenarios & evaluate gain/drop in tagging performance
- These steps (simulate->process->retrain->evaluate) are repeated for each single detector-configuration variation
  -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

Why is Retraining Necessary?



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

“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%

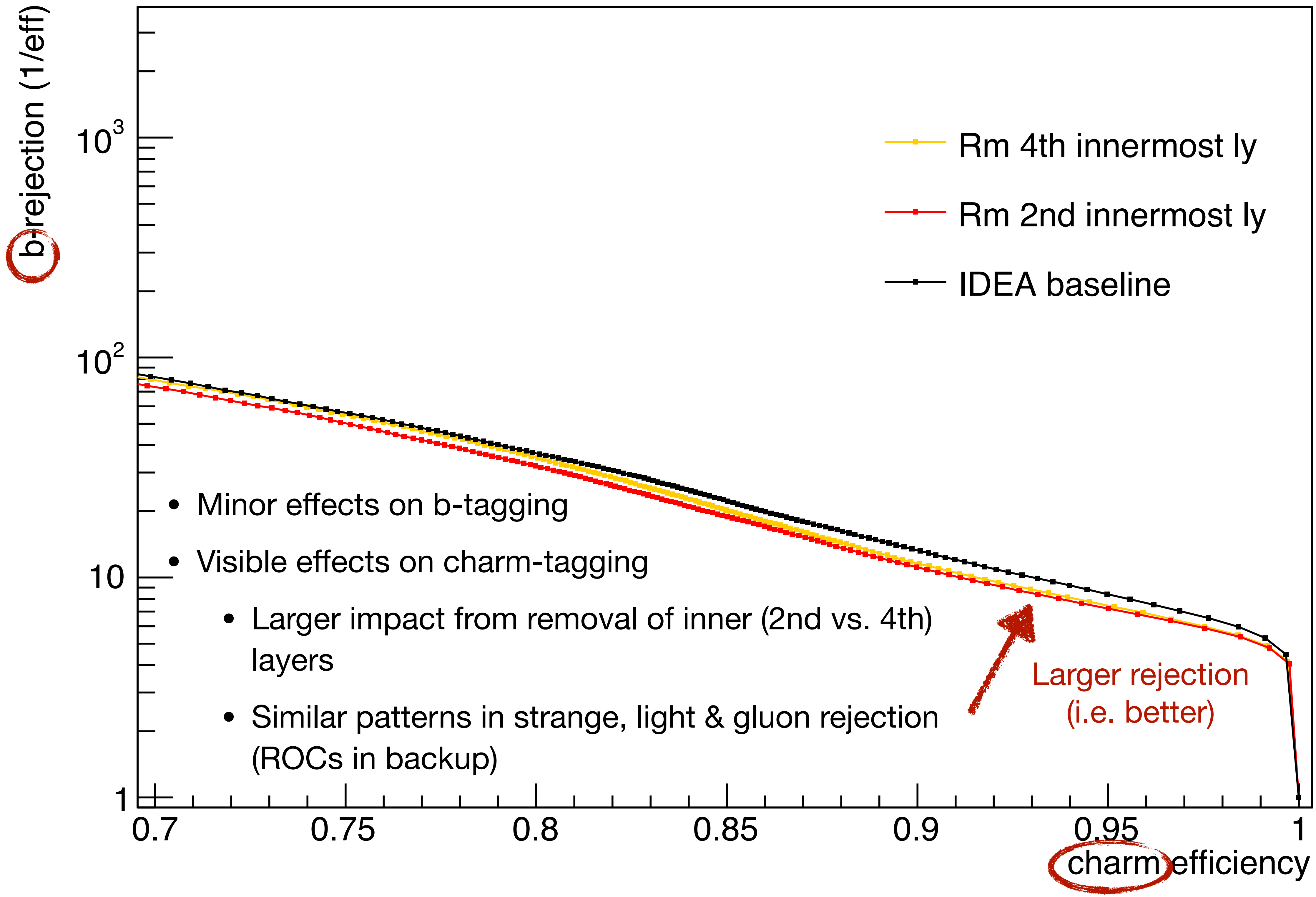
From this talk

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

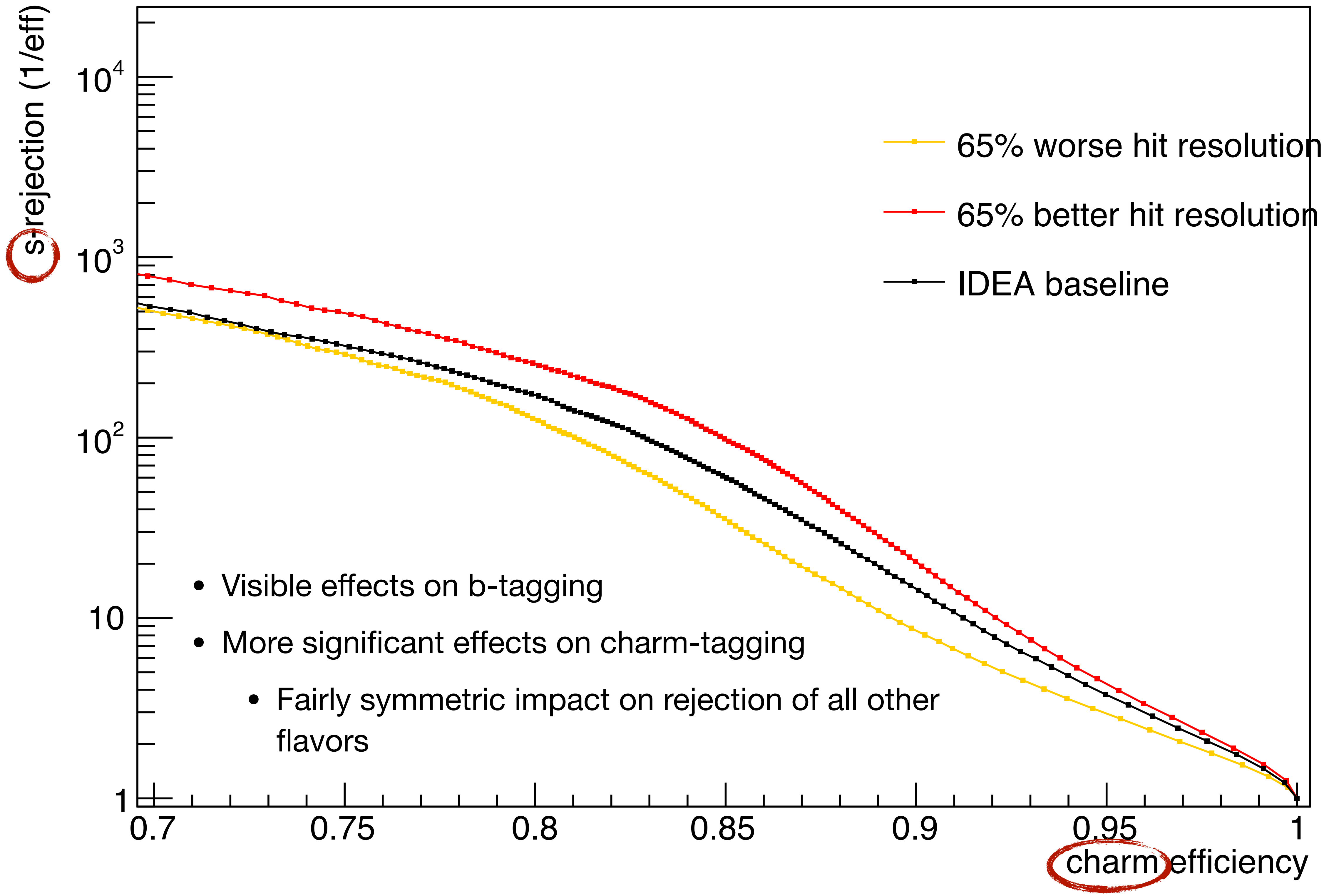
Number of Pixel Layers



- 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

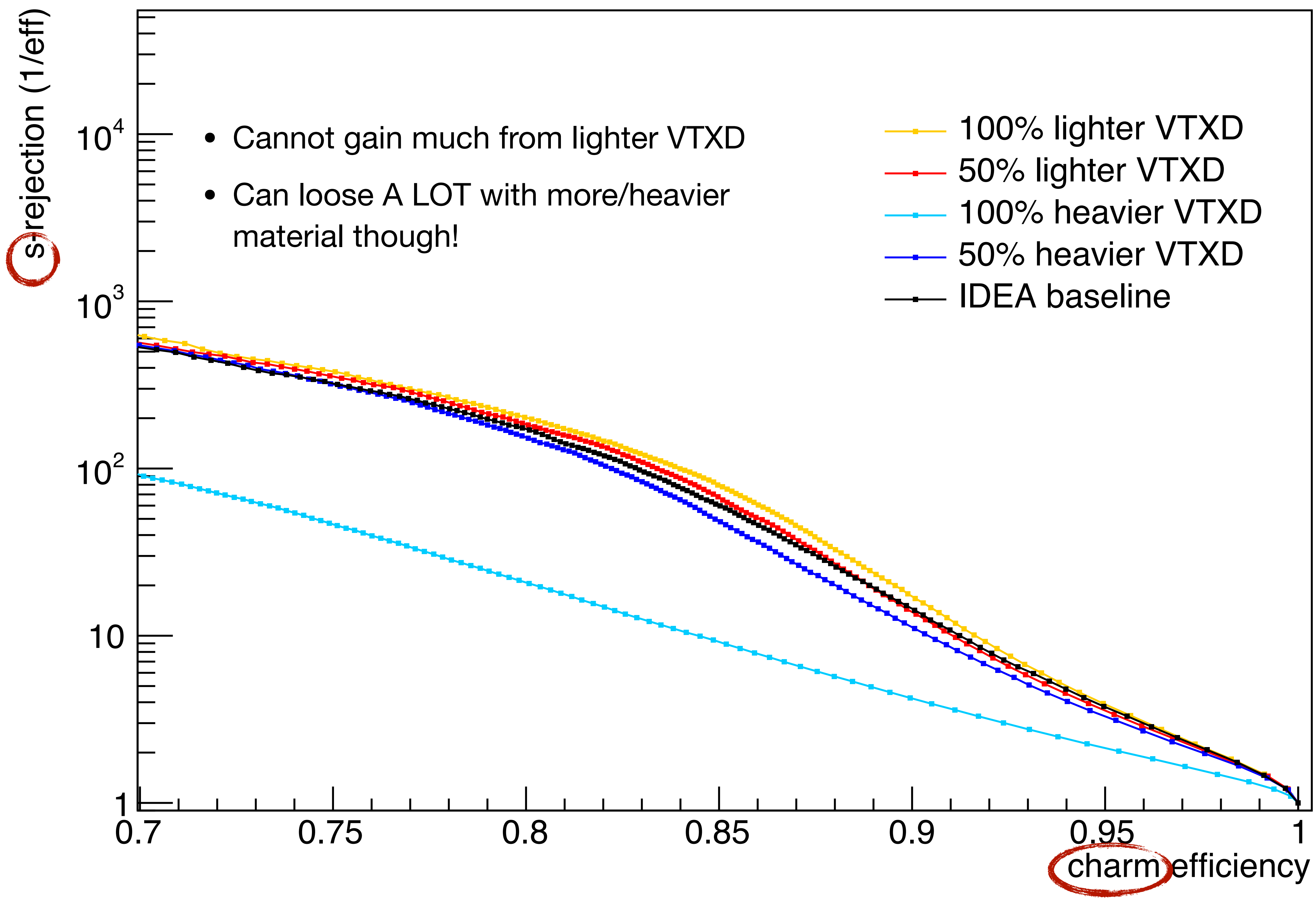
Pixel Hit Resolution



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

Pixel-Detector
Material Budget

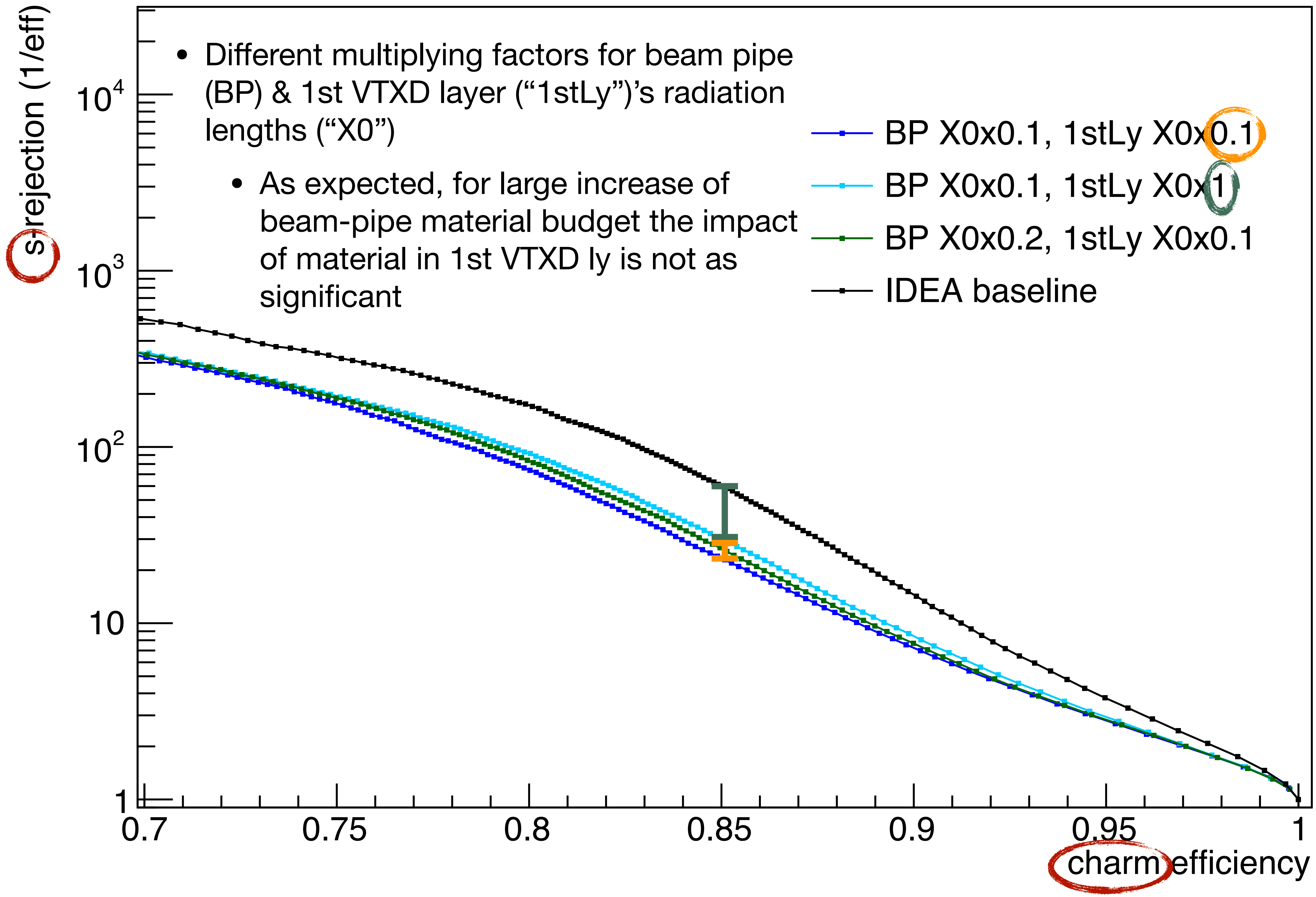
Pixel-Detector Material Budget



Pixel & Beam-Pipe Material Budget

Beam-pipe & Pixel-Detector Material Budget

- Interesting, because of plans/studies for copper cooling manifold, see Francesco's talk in Annecy & Manuela's MDI report today



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
- 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
- Possibility to include **vertex information**, see Franco’s talk at PP meeting last week
- **Propagating tagger-performance changes through Higgs coupling analyses**
  - More details in Iza’s talk
- Independently of flavor taggers: performing studies of ***H->invisible*** **sensitivity as a function of calorimetry properties** (*E* resolution, granularity, etc…) - analysis discussed in Diallo’s talk
- 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 late Summer** (feasibility-study constraints: PED draft by EOY)

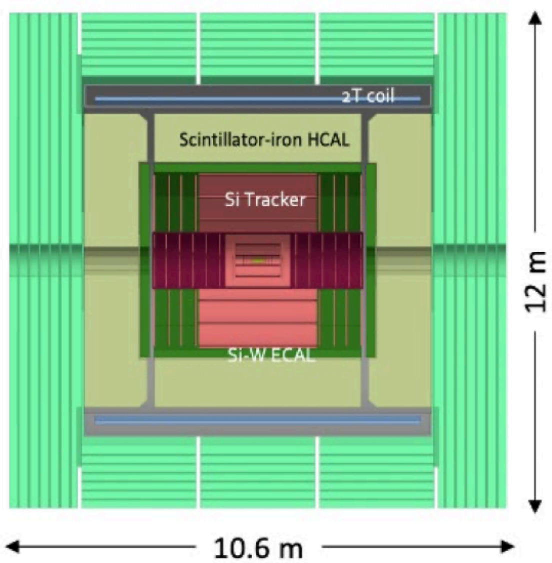
BACKUP

Current Detector Concepts

Current Detector Concepts

From this talk

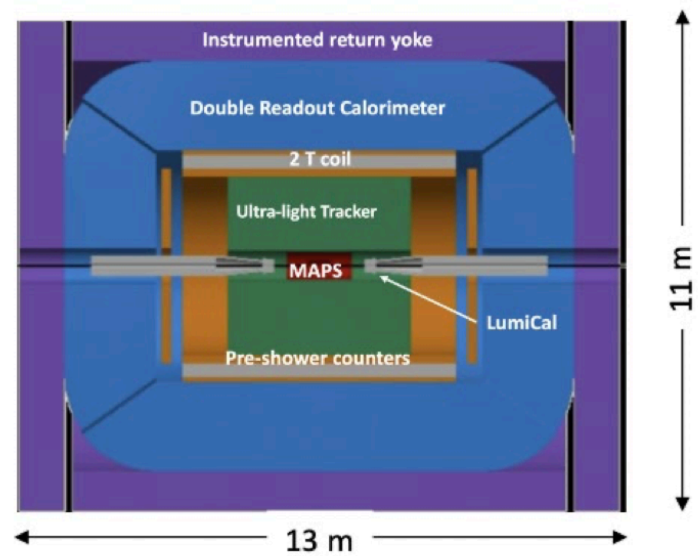
CLD



- 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)?
  - …

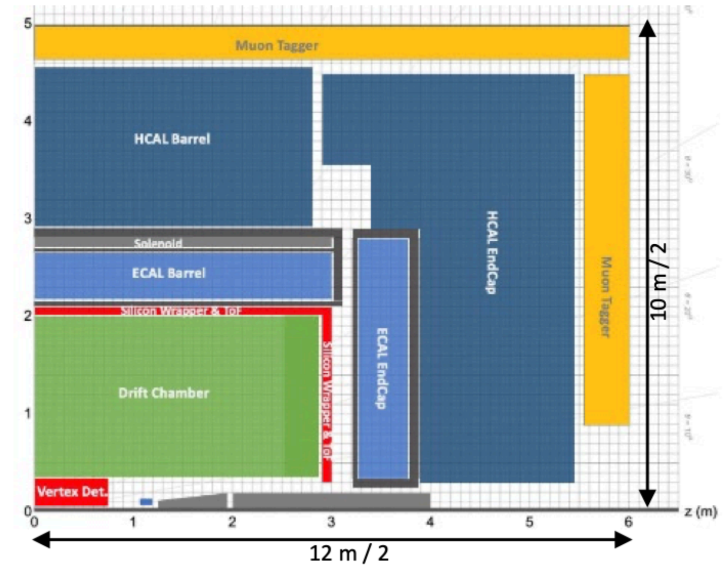
CDR

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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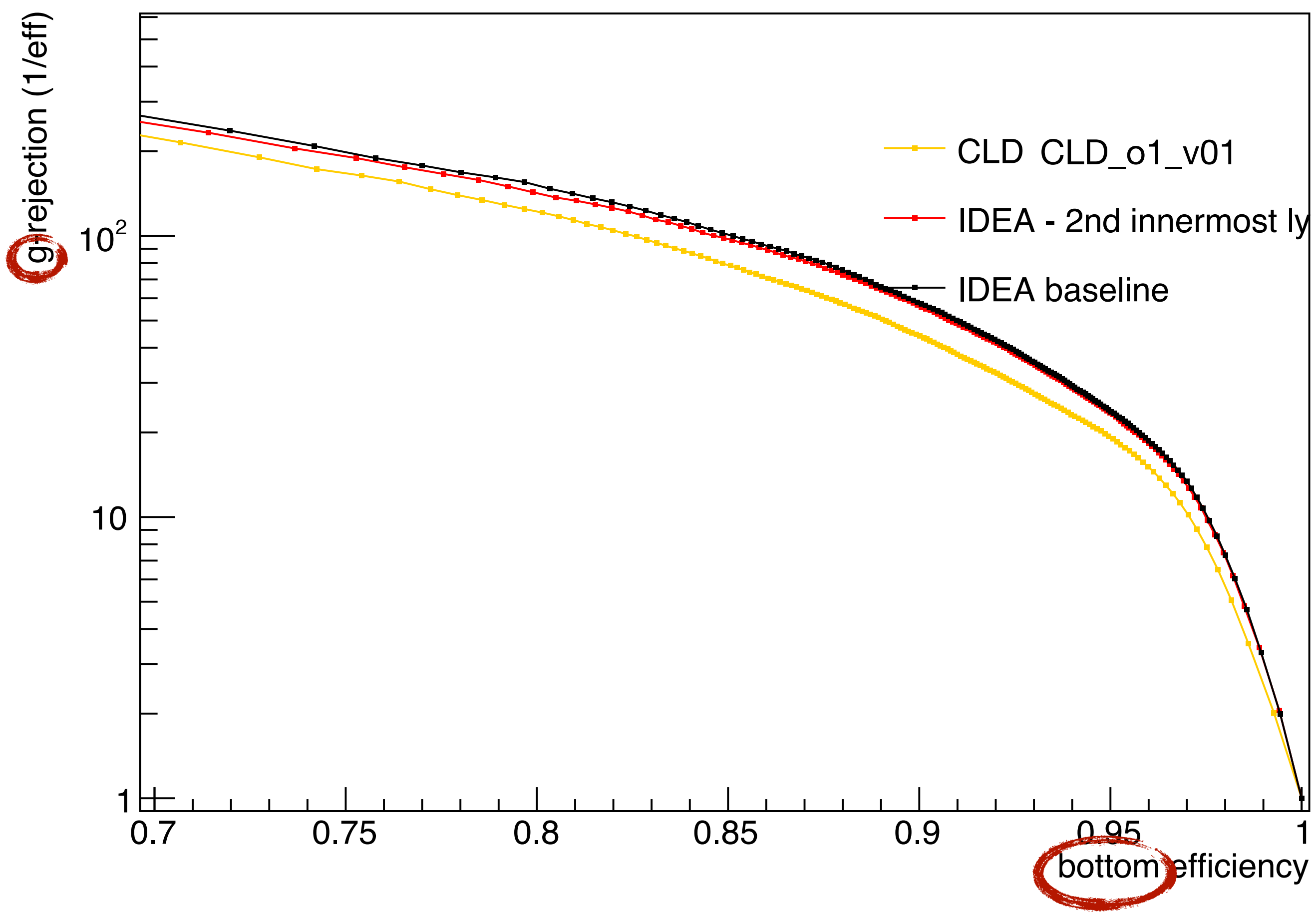
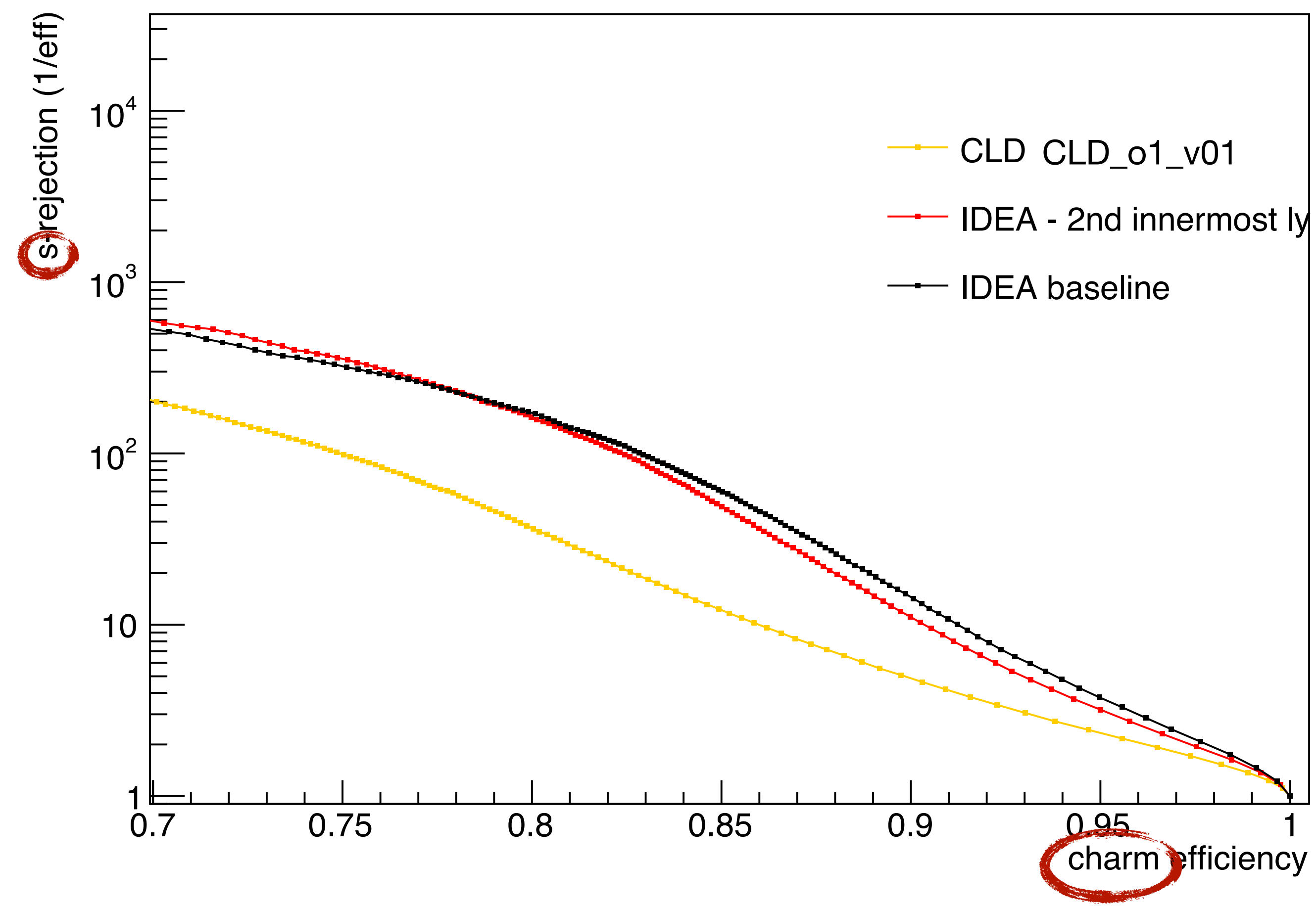
Bonus: CLD Fast Simulation

CLD vs. IDEA

- **CLD CLD_o1_v01**: BP at 1cm too, full Si vtx+tracker: **3(vs. 5) VTXD layers & innermost at 1.8(vs.1.2)cm**
  - **CLD Delphes card needs update!**
- **No powerful PID**
  - **Alike IDEA**'s ultra light drift chamber





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

Delphes cards

IDEA Delphes card - Details

N.B. It was observed at the PP meeting that these resolution values should be 7μm instead (ARCADIA inner 3 layers vs. AtlasPix3 outer 2 layers/disks)

```
# 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

N.B. It was observed at the PP meeting that the official CLD implementation in Delphes is outdated, as compared to CLD layout in full simulation (e.g. now the innermost layer is at 1.3cm, see Andre's talk)

```
# 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 }
```

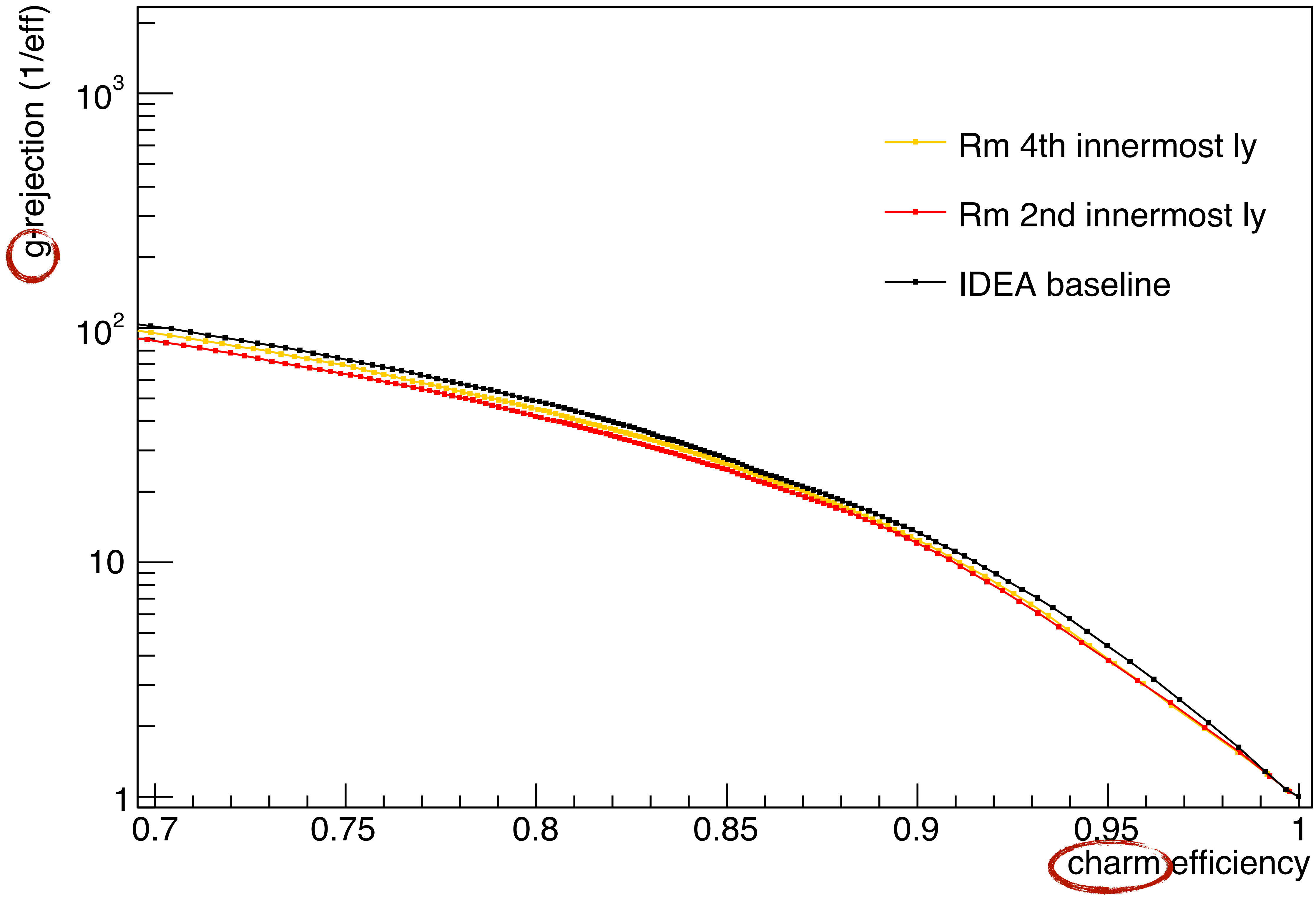
...

```
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
```

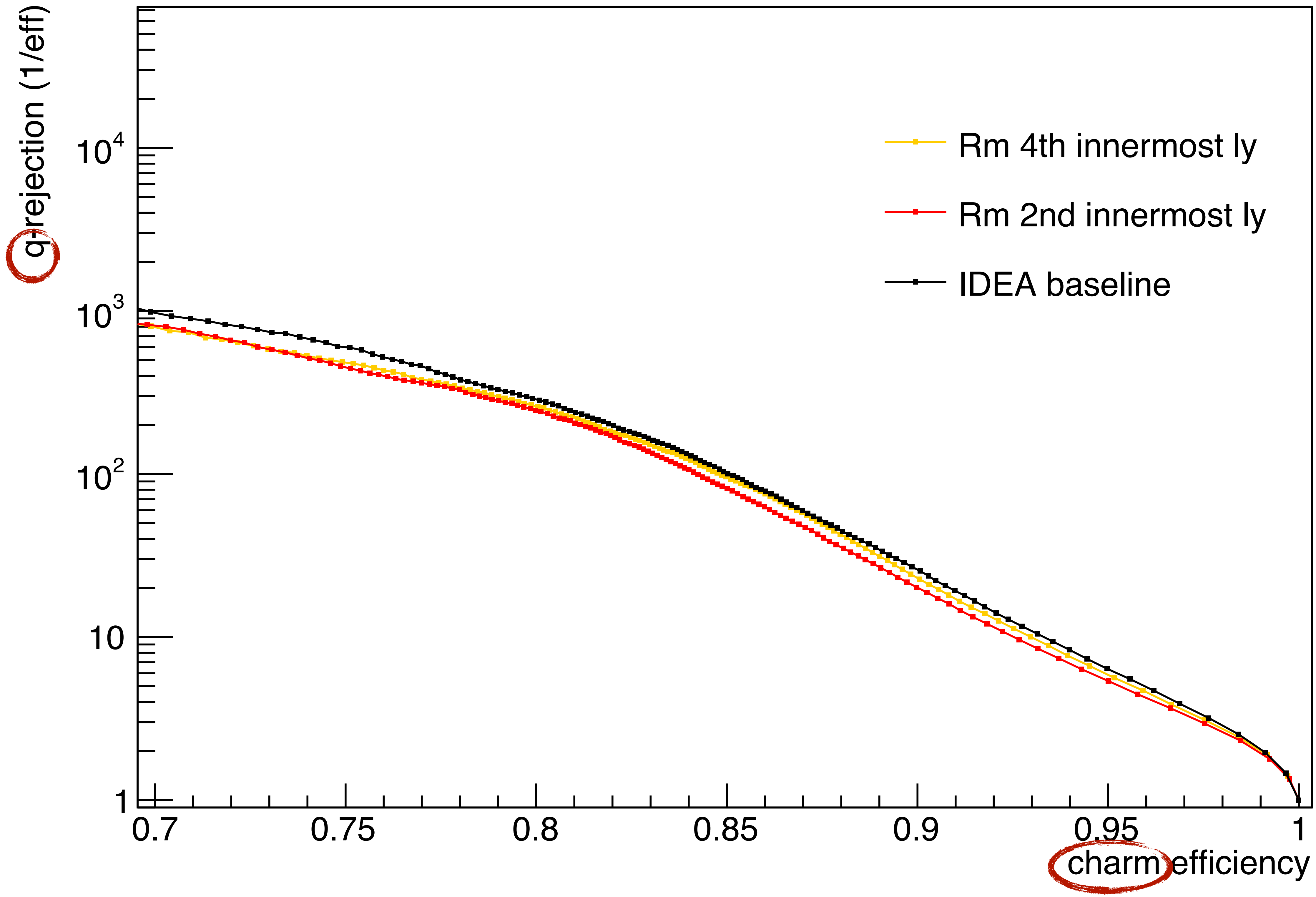
More… ROCs

Number of Pixel Layers

Number of Pixel Layers

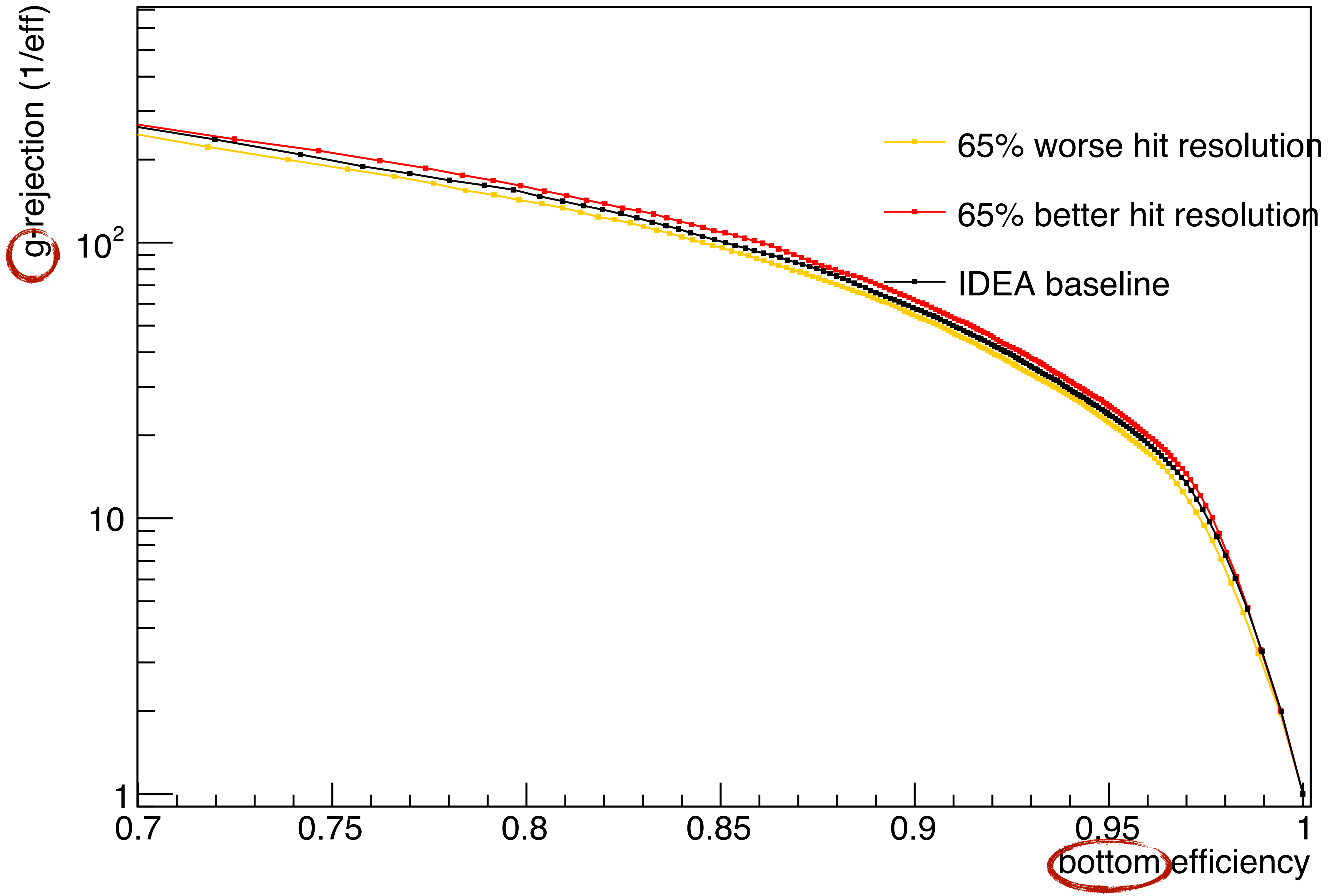


Number of Pixel Layers

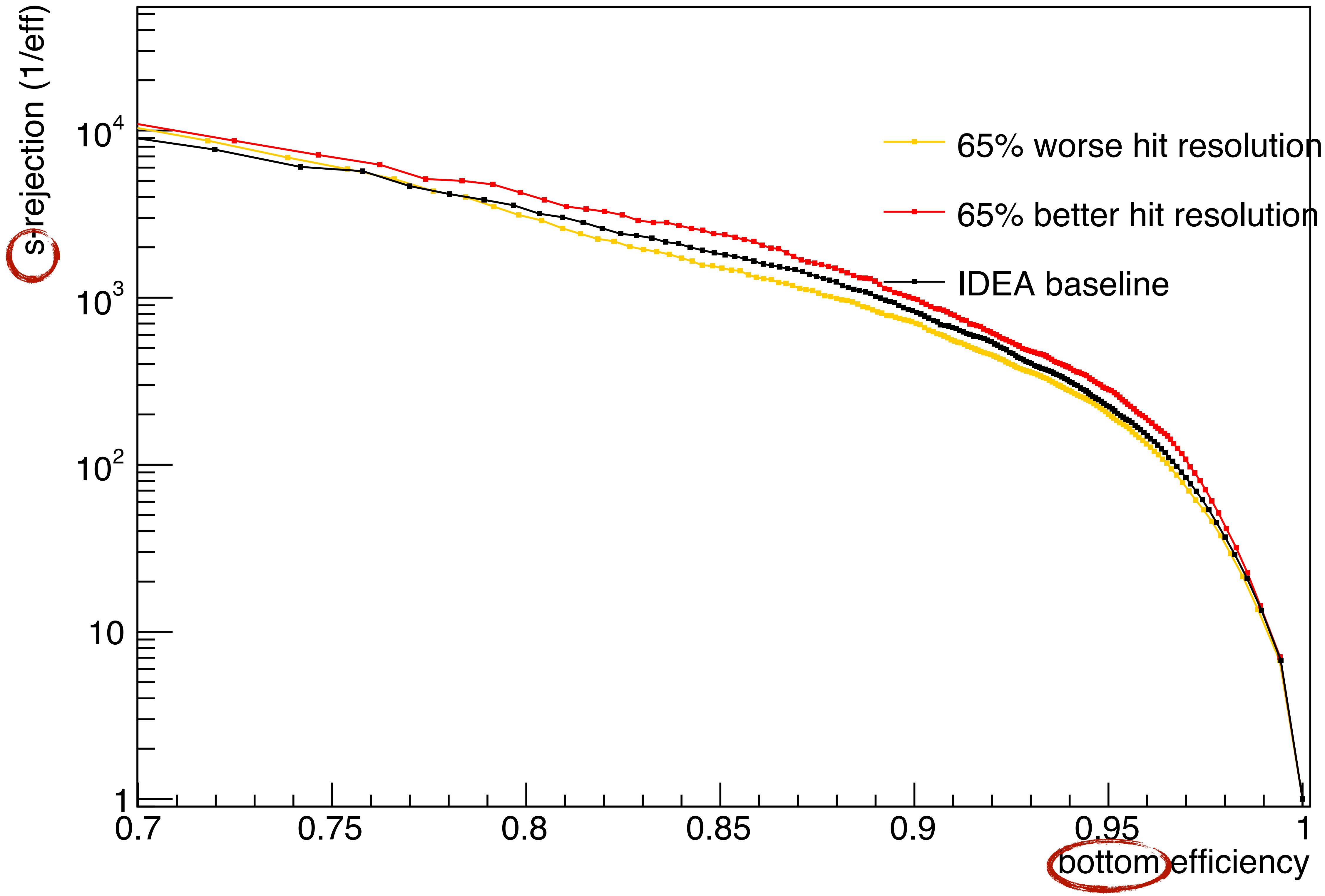


Pixel
Hit Resolution

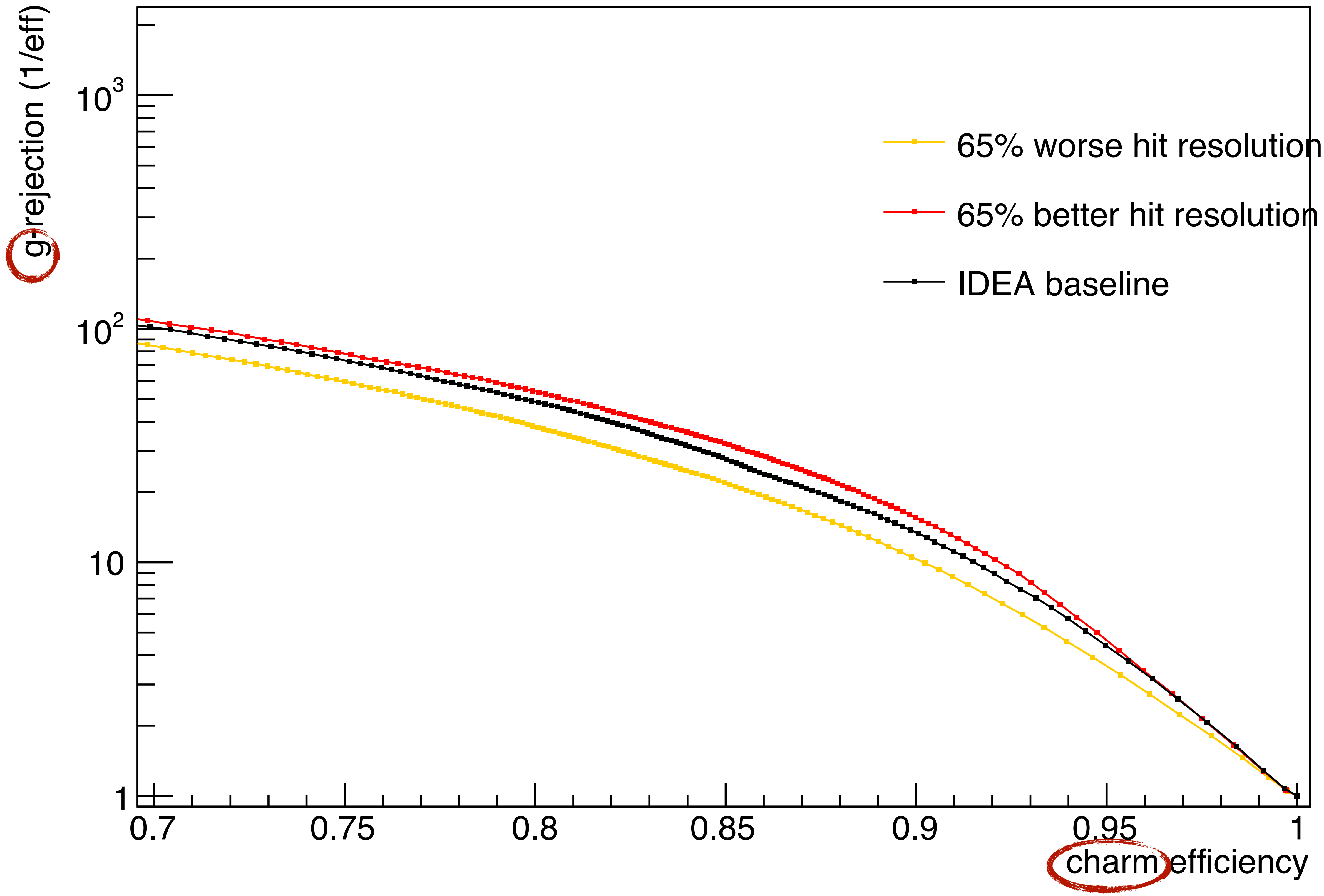
Pixel Hit Resolution



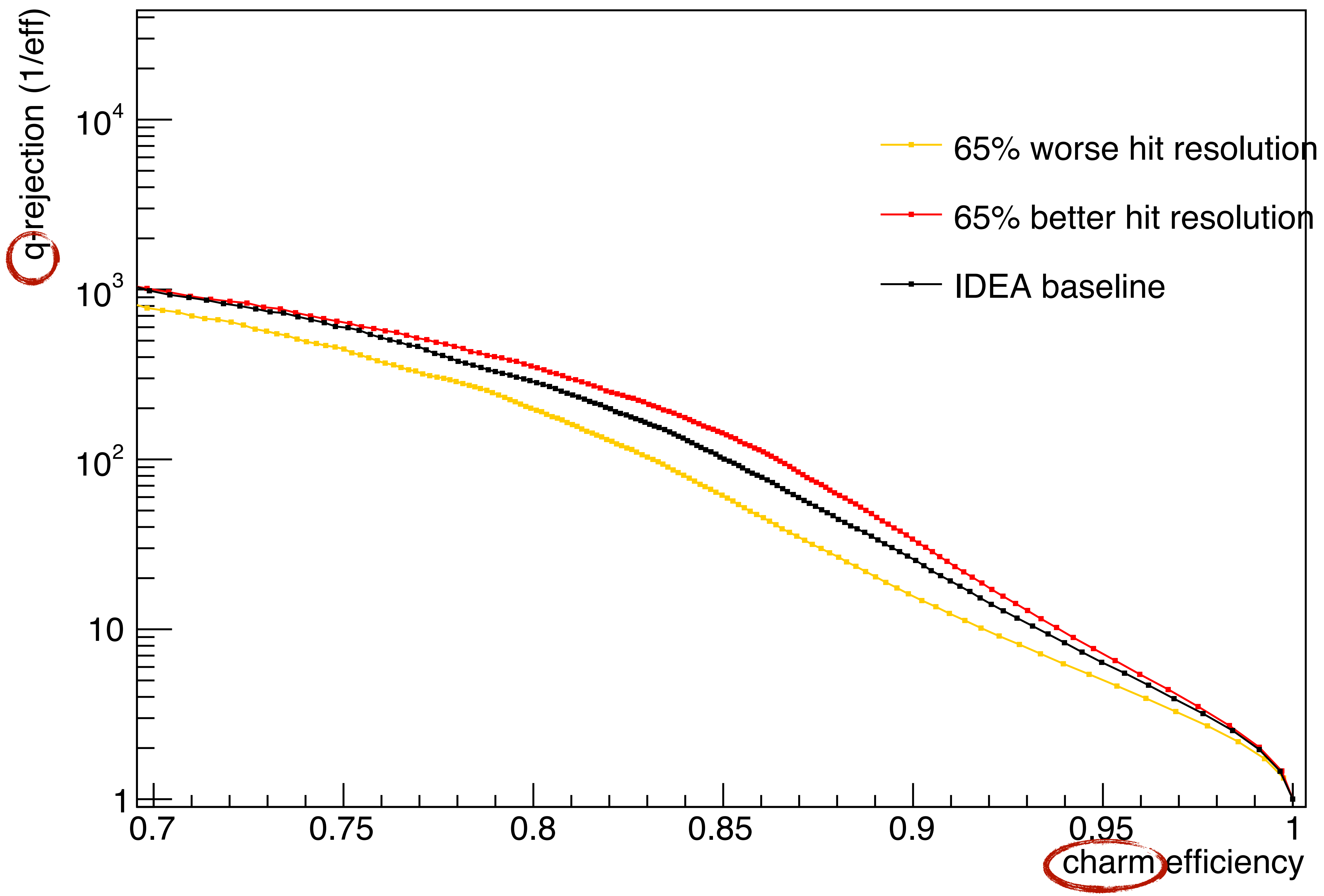
Pixel Hit Resolution



Pixel Hit Resolution

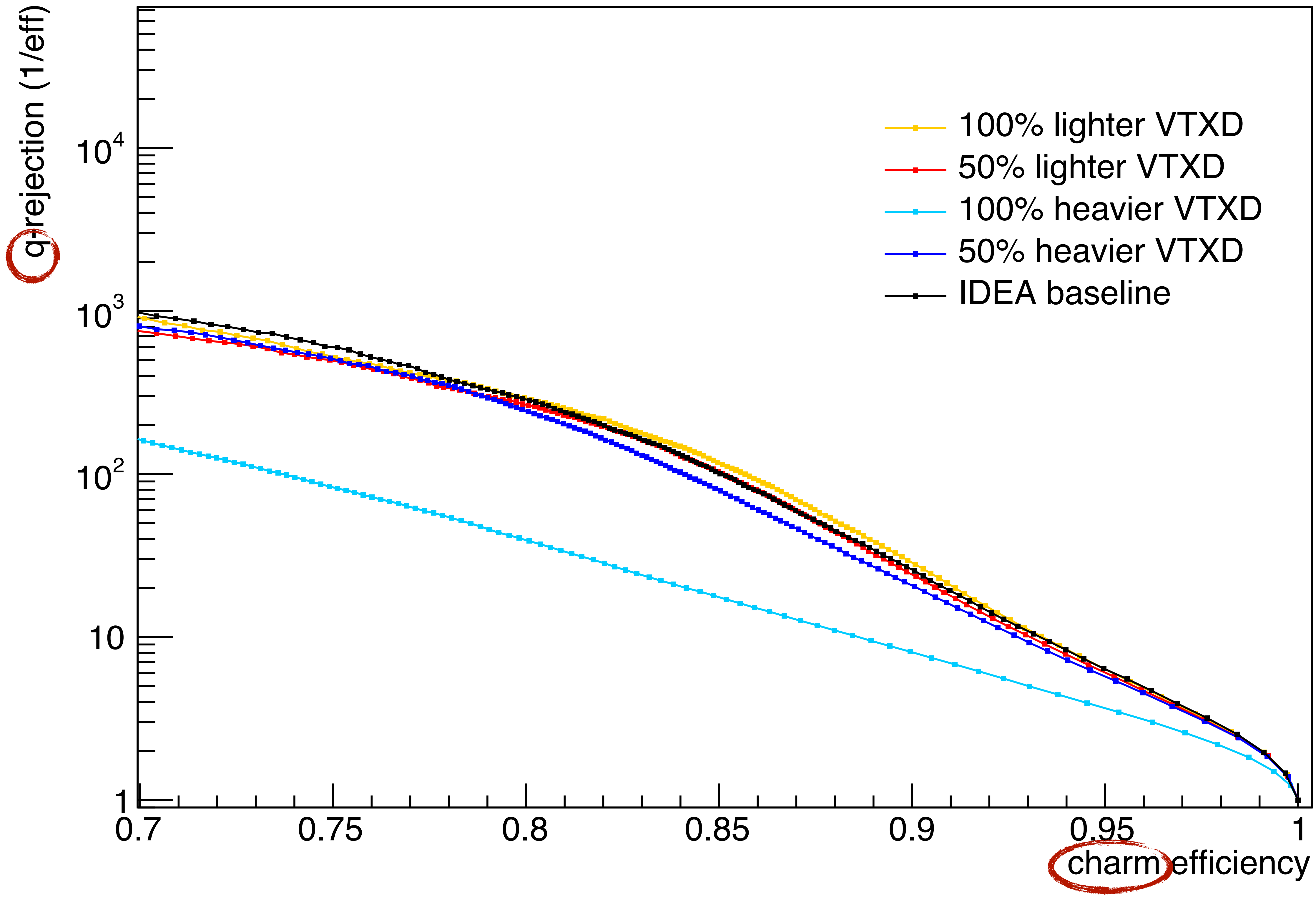


Pixel Hit Resolution

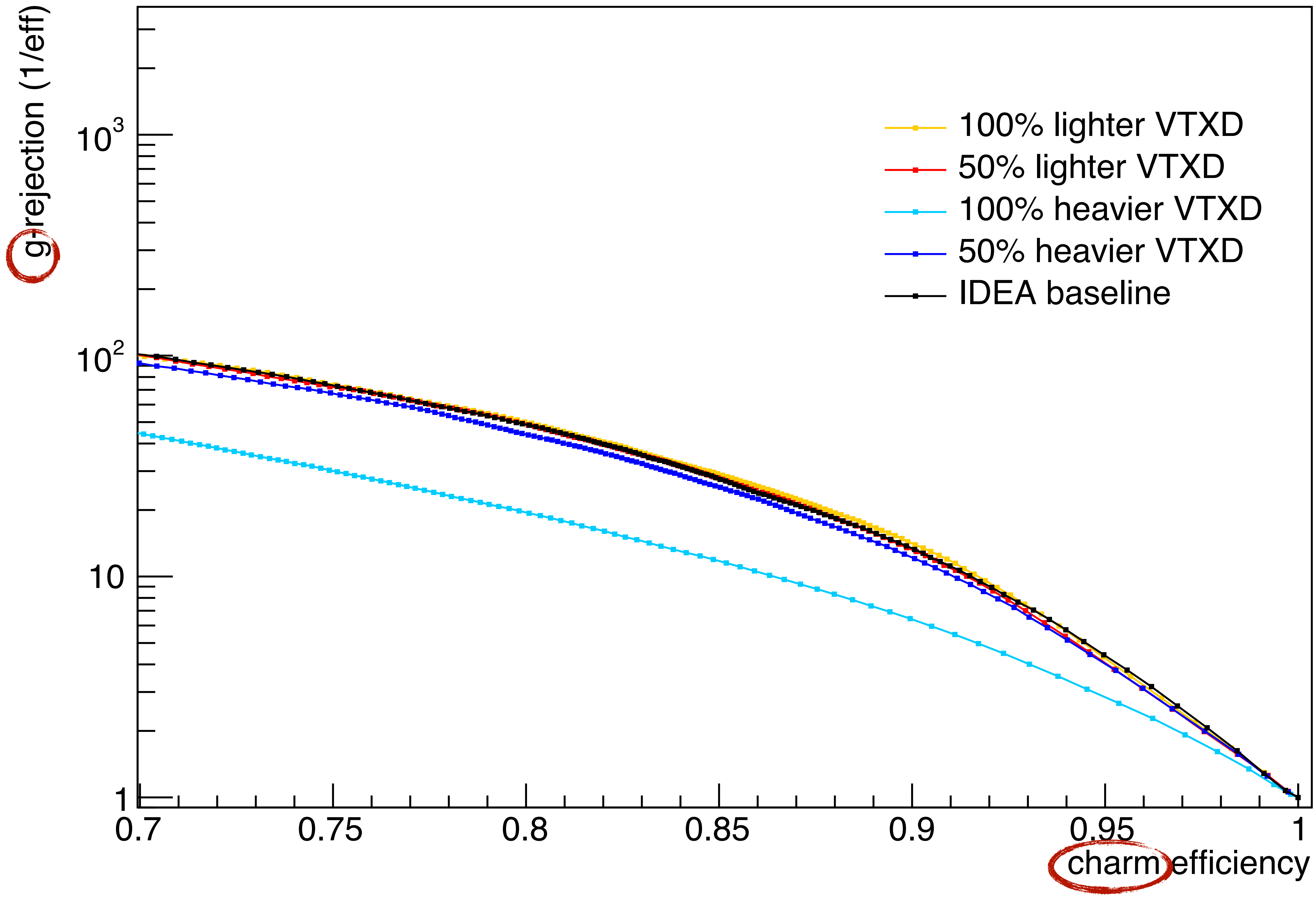


Pixel-Detector
Material Budget

Pixel-Detector Material Budget

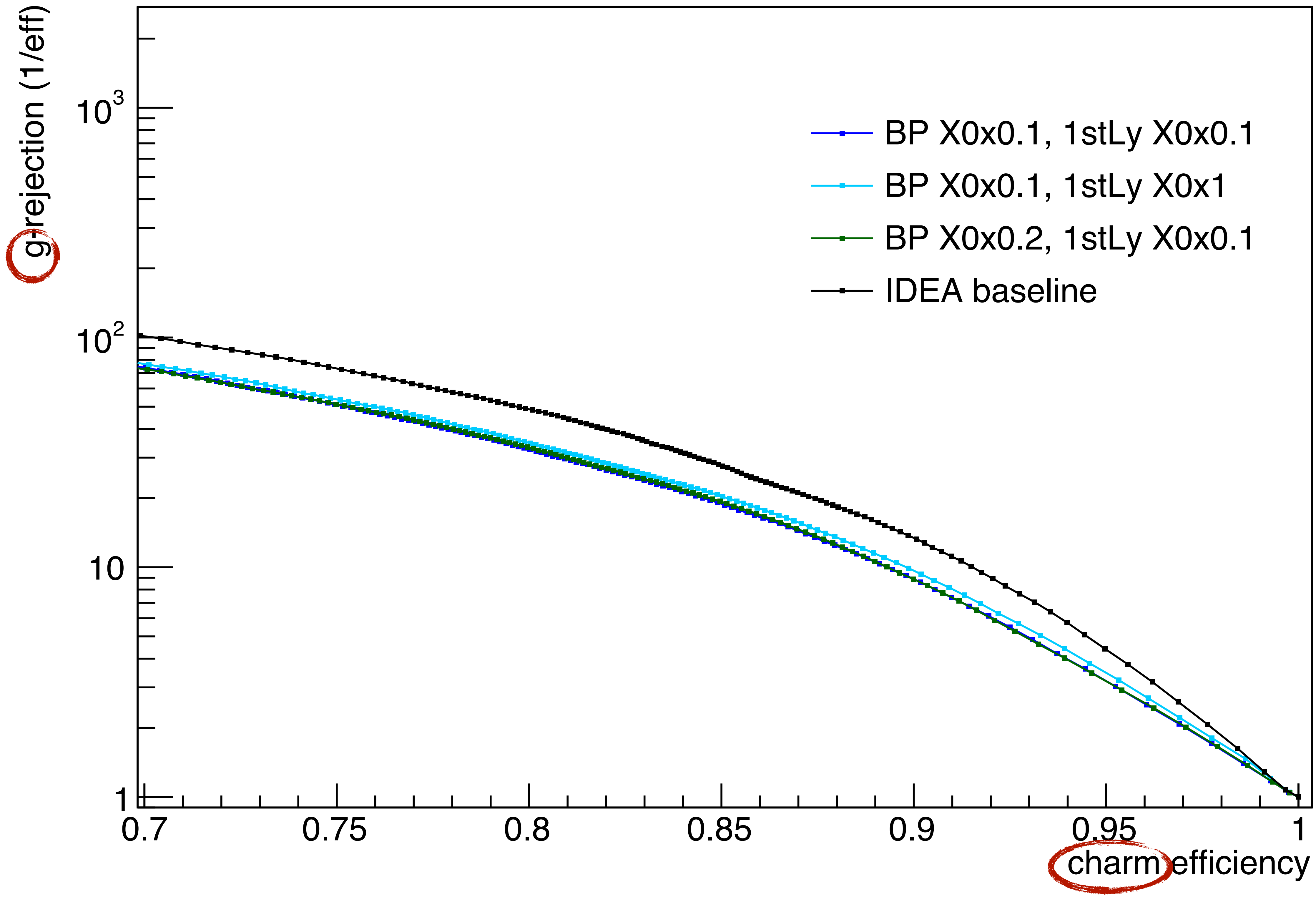


Pixel-Detector Material Budget

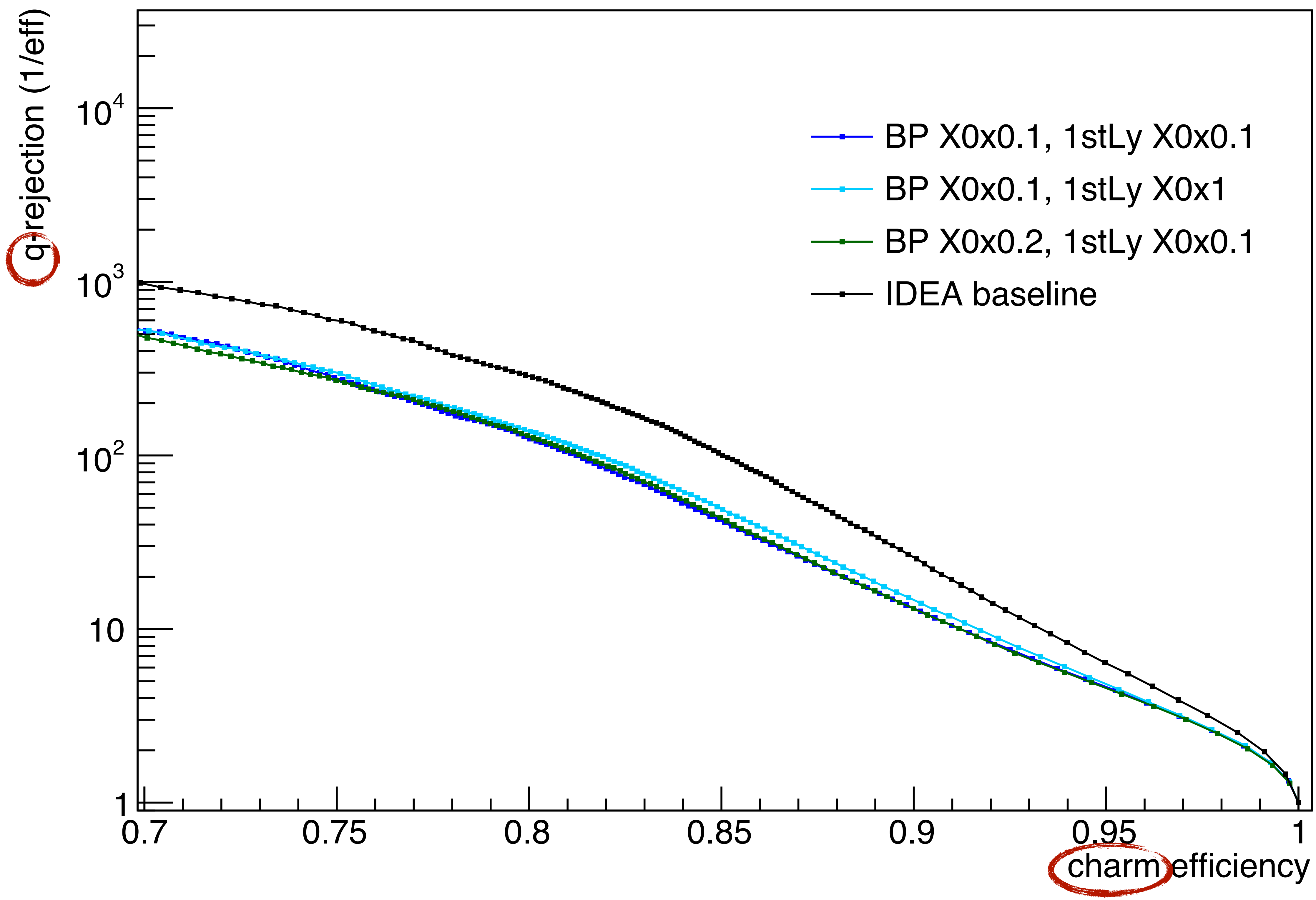


Pixel & Beam-Pipe Material Budget

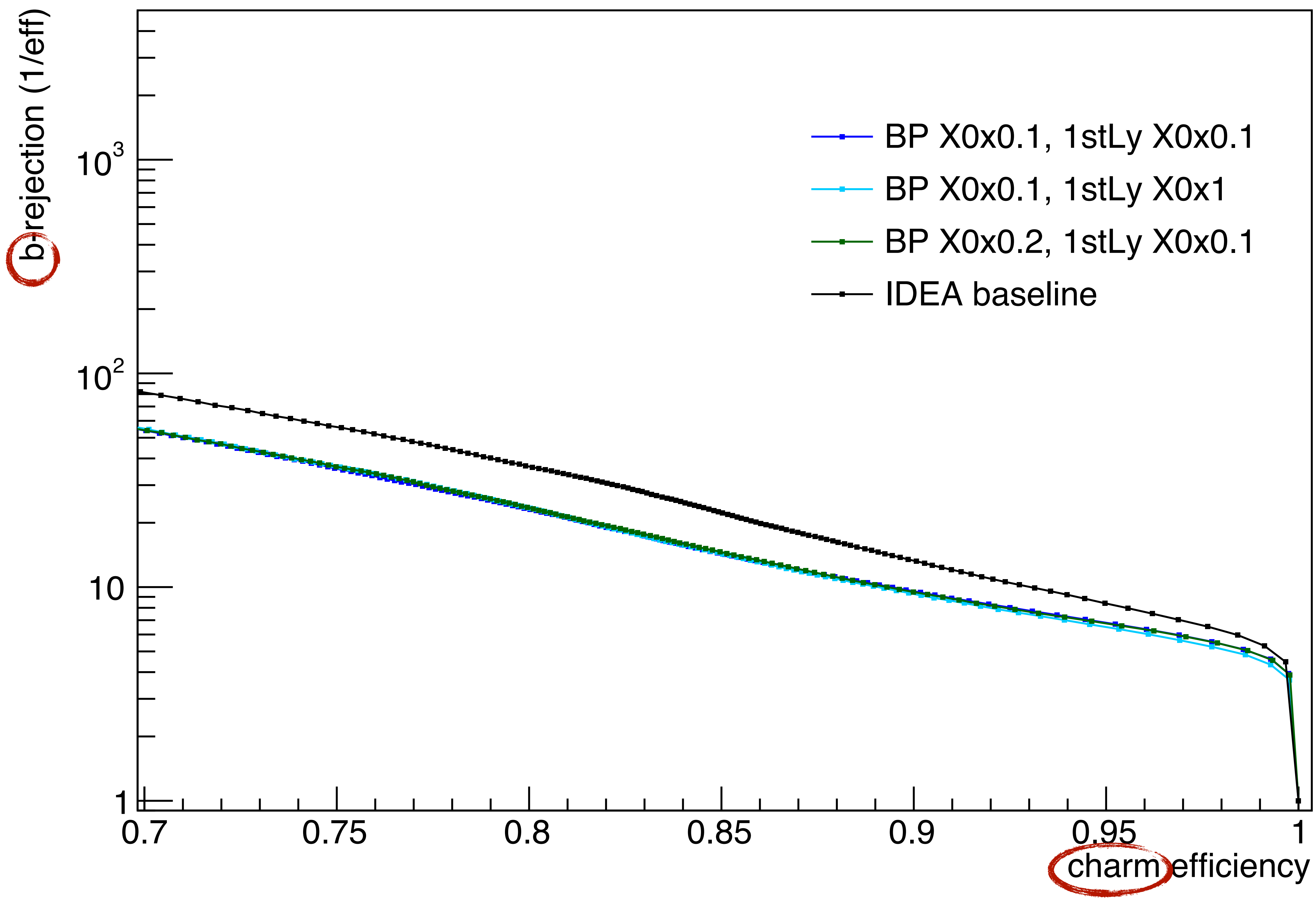
Pixel & Beam-Pipe Material Budget



Pixel & Beam-Pipe Material Budget

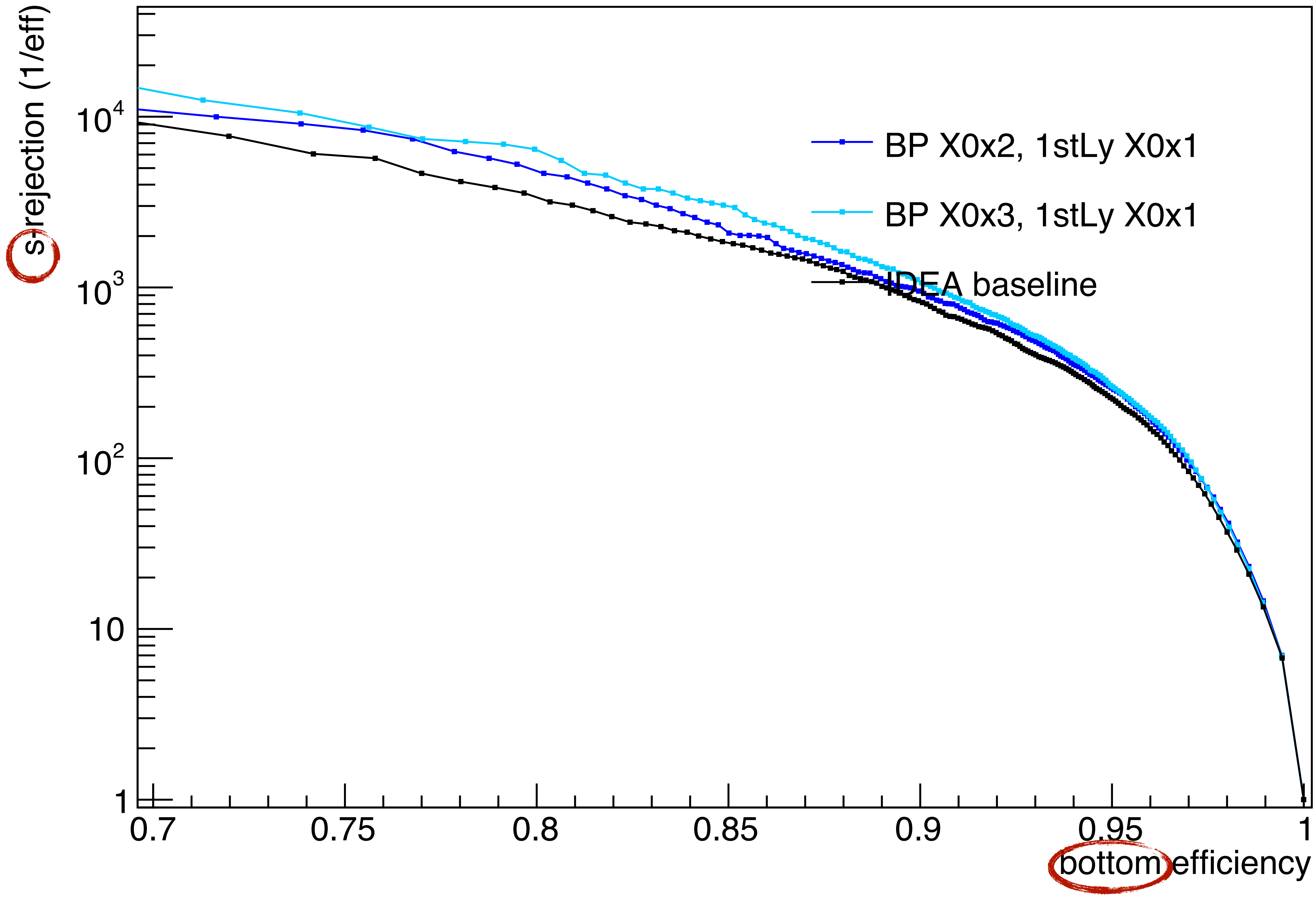


Pixel & Beam-Pipe Material Budget



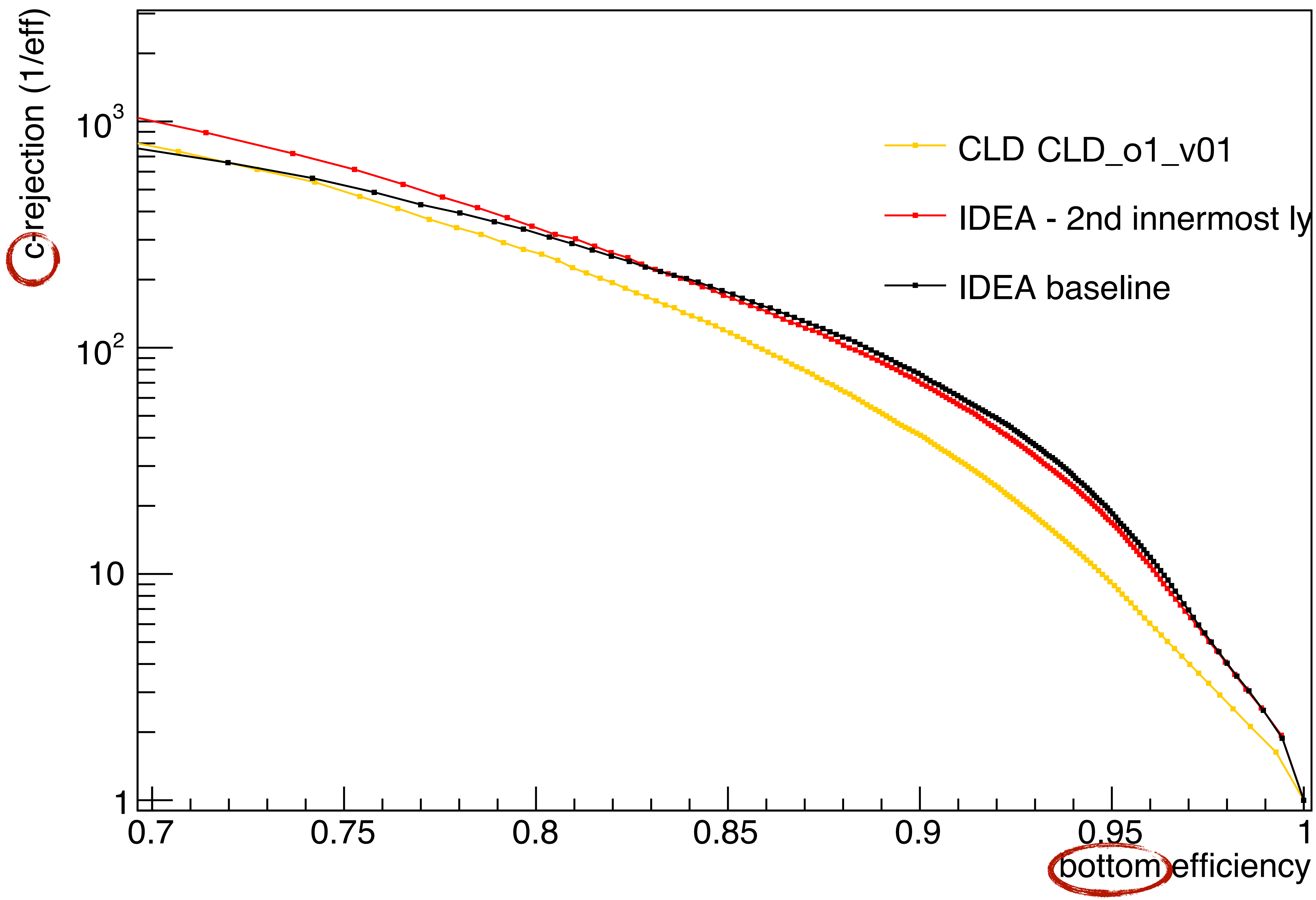
Pixel & Beam-Pipe Material Budget

- **Lighter beam pipe**
  - Factor 2/3 larger radiation length -> small perf gain, mostly compatible perf



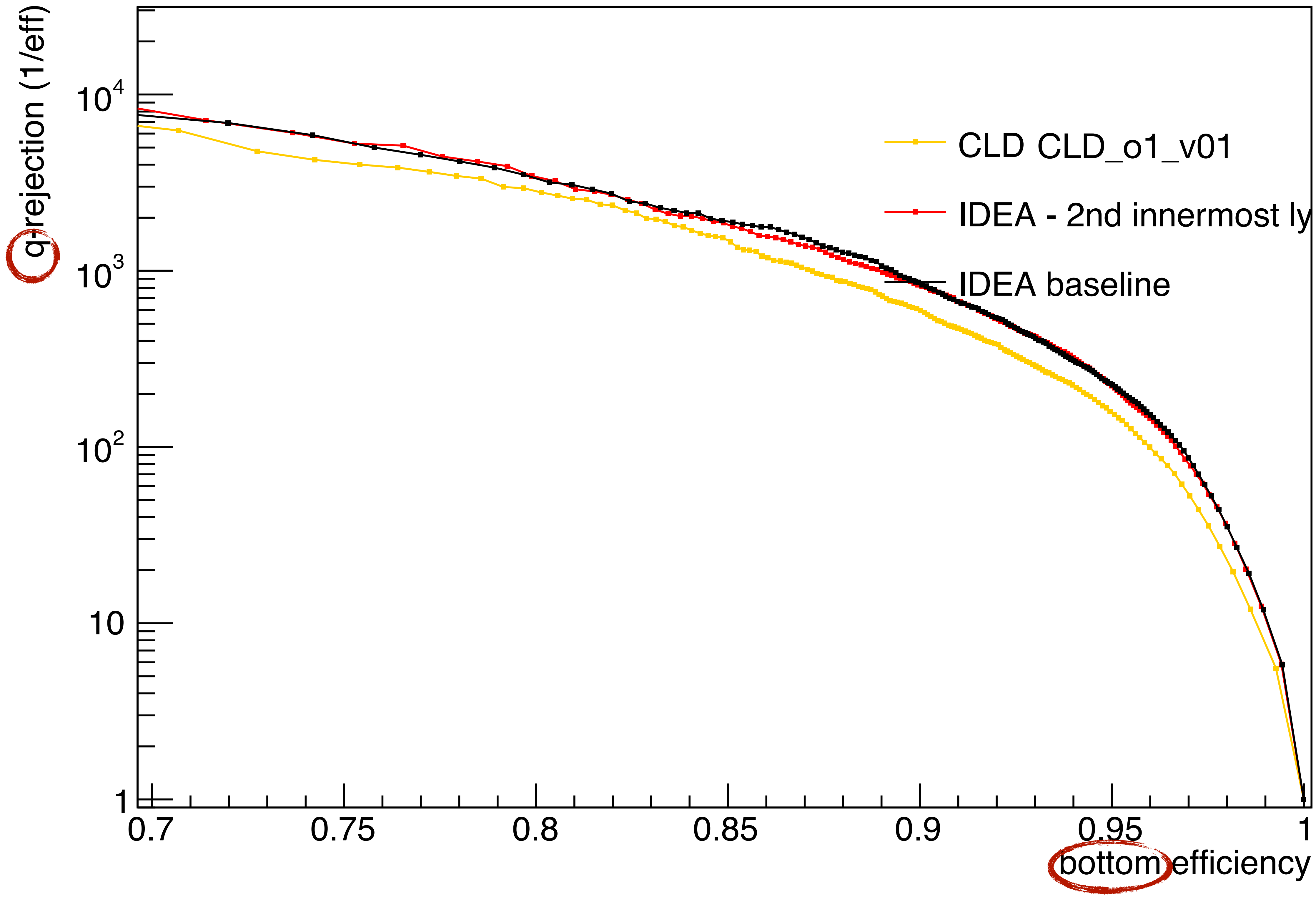
Bonus: CLD Fast Simulation

CLD vs. IDEA

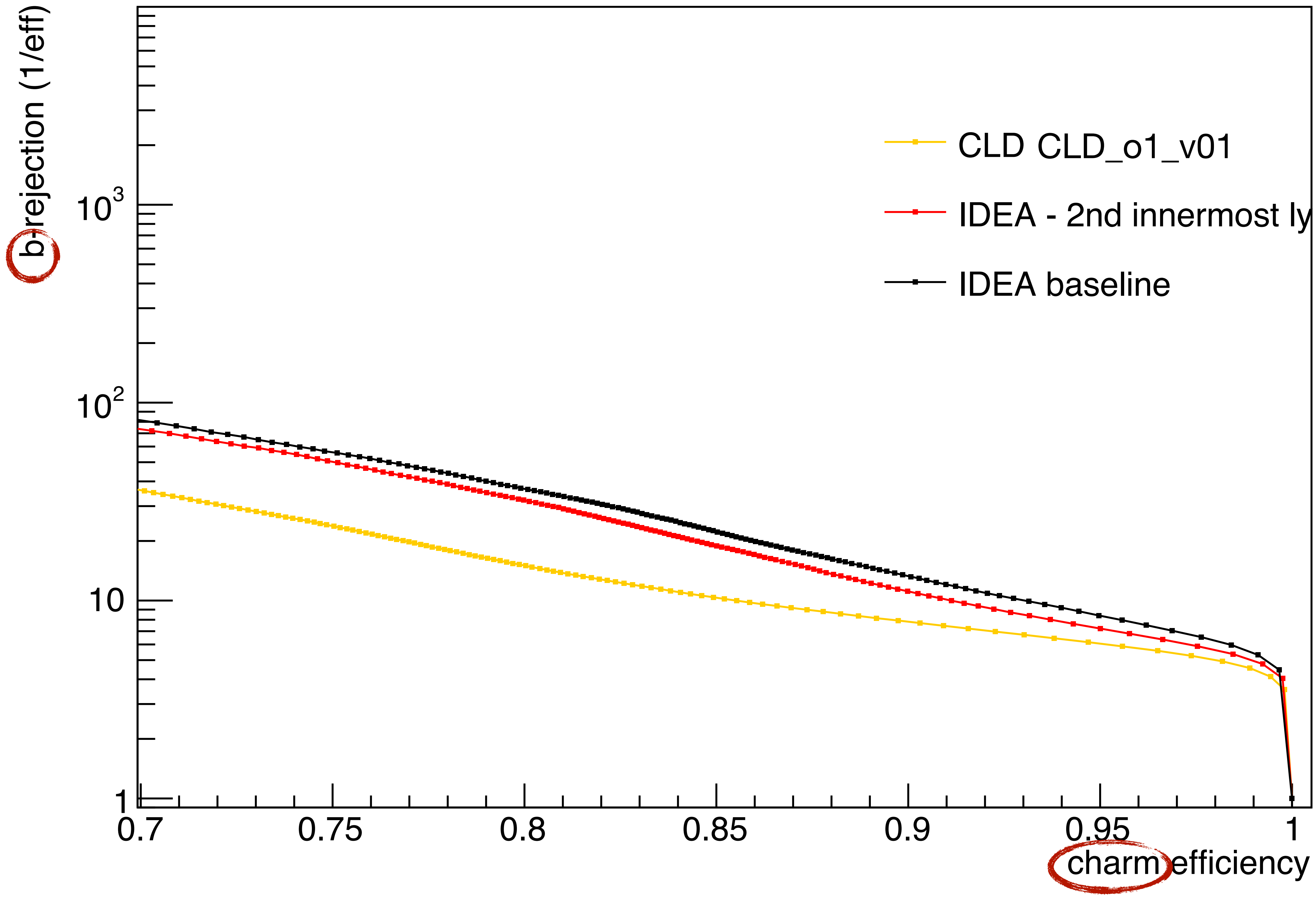


c-rejection (1/eff)
10^3
10^2
10
1
0.7
0.75
0.8
0.85
0.9
0.95
1
bottom efficiency
CLD CLD_o1_v01
IDEA - 2nd innermost ly
IDEA baseline

CLD vs. IDEA

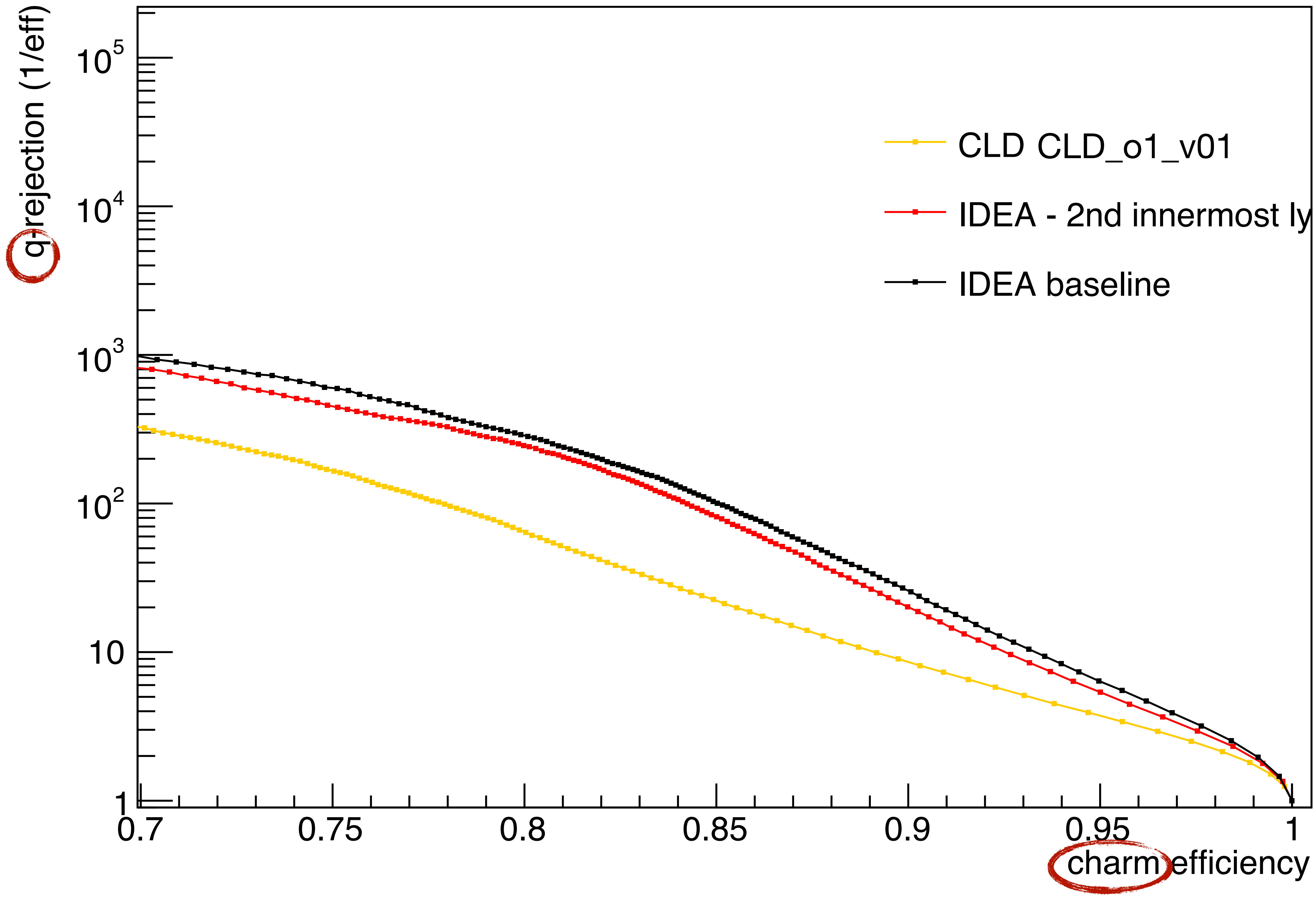

q-rejection (1/eff)
10^4
10^3
10^2
10
1
0.7
0.75
0.8
0.85
0.9
0.95
1
bottom efficiency
CLD CLD_o1_v01
IDEA - 2nd innermost ly
IDEA baseline

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 CLD_o1_v01
IDEA - 2nd innermost ly
IDEA baseline

CLD vs. IDEA



q-rejection (1/eff)
10^5
10^4
10^3
10^2
10
1
0.7
0.75
0.8
0.85
0.9
0.95
1
charm efficiency
CLD CLD_o1_v01
IDEA - 2nd innermost ly
IDEA baseline