# Physics Requirements on Vertex Detectors Performance

*Summarizing the work in the Feasibility Report and some recent studies*

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# Every aspect of the Physics program needs an excellent vertex

- HIGGS: Jet flavour identification (tagging) of b-, c-, g-, tau- etc… Measure of Higgs couplings
- Z: Jet flavour identification (inclusive tagging) but also exclusive tagging for HF EWK observables Rb, Rc, AFB
- W : Jet flavour identification (tagging/calibnration), CKM parameters Vcb
- FLAVOUR: precise reconstruction of PV/SV/TV for flavour physics
  - e.g. time dependent CPV measurement, rare decays $B \to K^{*}\tau\tau$, $\tau$ precise lifetime measurement
- BSM: long lived particle signatures

# Range of different performances

## From sensors to DAQ

- **Tracking**
  - Track seeding (depending on the tracking system)
  - Track momentum resolution
  - Low momentum track reconstruction
  - hit (in)efficiency

- **Vertexing**:
  - Primary interaction vertex
  - Secondary and tertiary (D-meson, tau-leptons, flavour tagging)
  - Vertex properties beyond resolution: Charge of displaced vertex, particle composition (interaction with PID)

- **Occupancy/Rate**
  - Beam induced background
  - Fake tracks mitigation
  - Triggerless readout
- **Timing information**

$\sqrt{s}$ dependence

# W,Z,H and top
## Identifying Jets flavour

- Many crucial physics measurements need to exploit hadronic decays of Z,W,H,top (i.e. jets):
  - At different center of mass energies from $\sqrt{s}$=90 to 365GeV
  - Because of larger BR, in addition to the leptonic final states. i.e. ZH recoil with hadronic Z decays, top properties)
  - Clean final state allows measurements “hard” at LHC, i.e. with charm or strange jets (H->cc, Vcs)
  - Jet flavour identification helps reduce combinatoric
- Need pure and efficient reconstruction and tagging of jet flavor/types (“inclusive” tagging): GNN algorithms such as ParticleNetIDEA
  - Final optimisation, based on the measurement uncertainties, needs to take into account all the steps including software & analysis

https://doi.org/10.1140/epjc/s10052-022-10609-1

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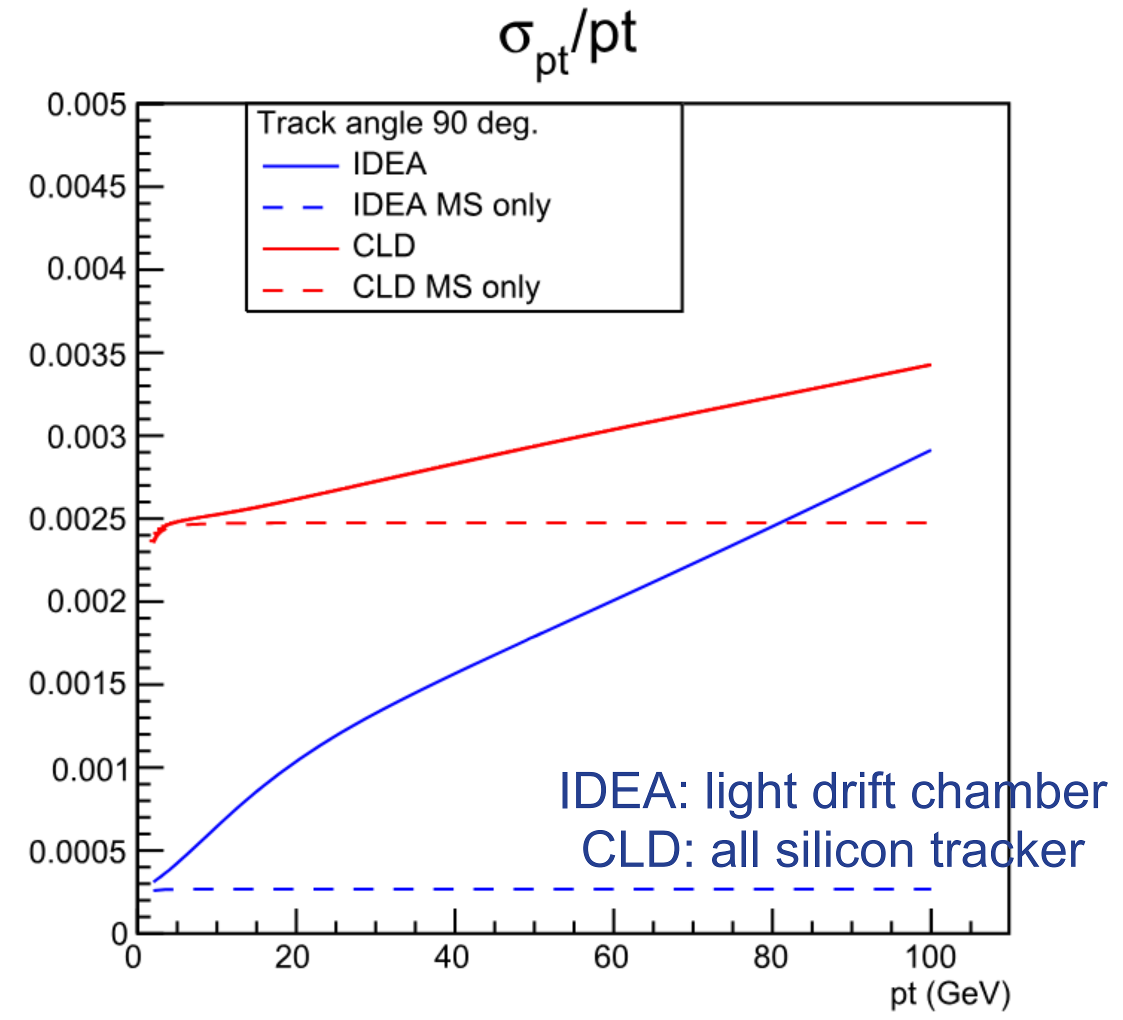
# Dissecting tagger performance

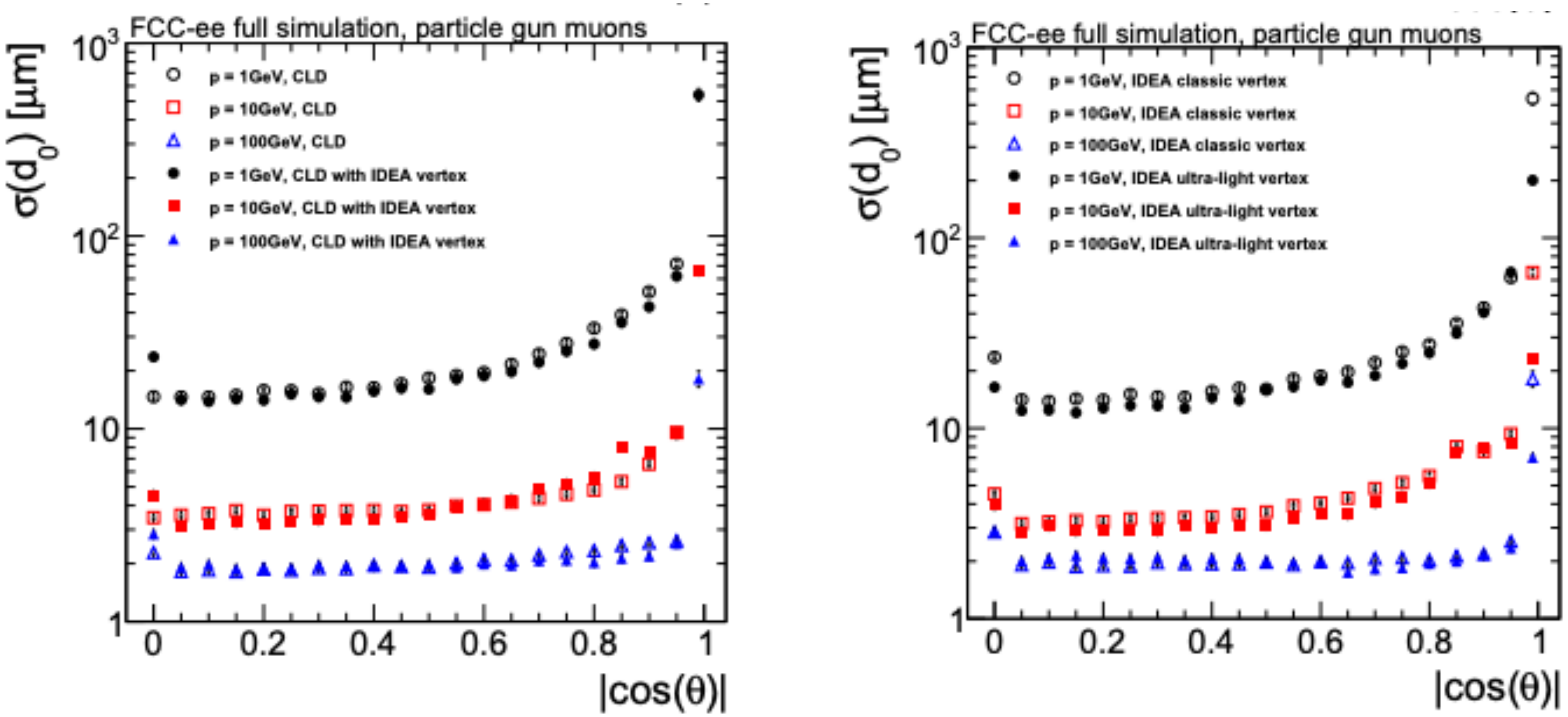
- Impact parameter resolution is a major driver for b/c tagging
  - Single point resolution
  - Radial distance of first tracking layer <-> beam pipe radius
  - Number of layers
  - Material budget $X/X_0$

DELPHES




- Studies now in FullSim to evaluate the dependency from point resolution
  - CLD, CAD and Ultra-light geom.

FULL-SIM

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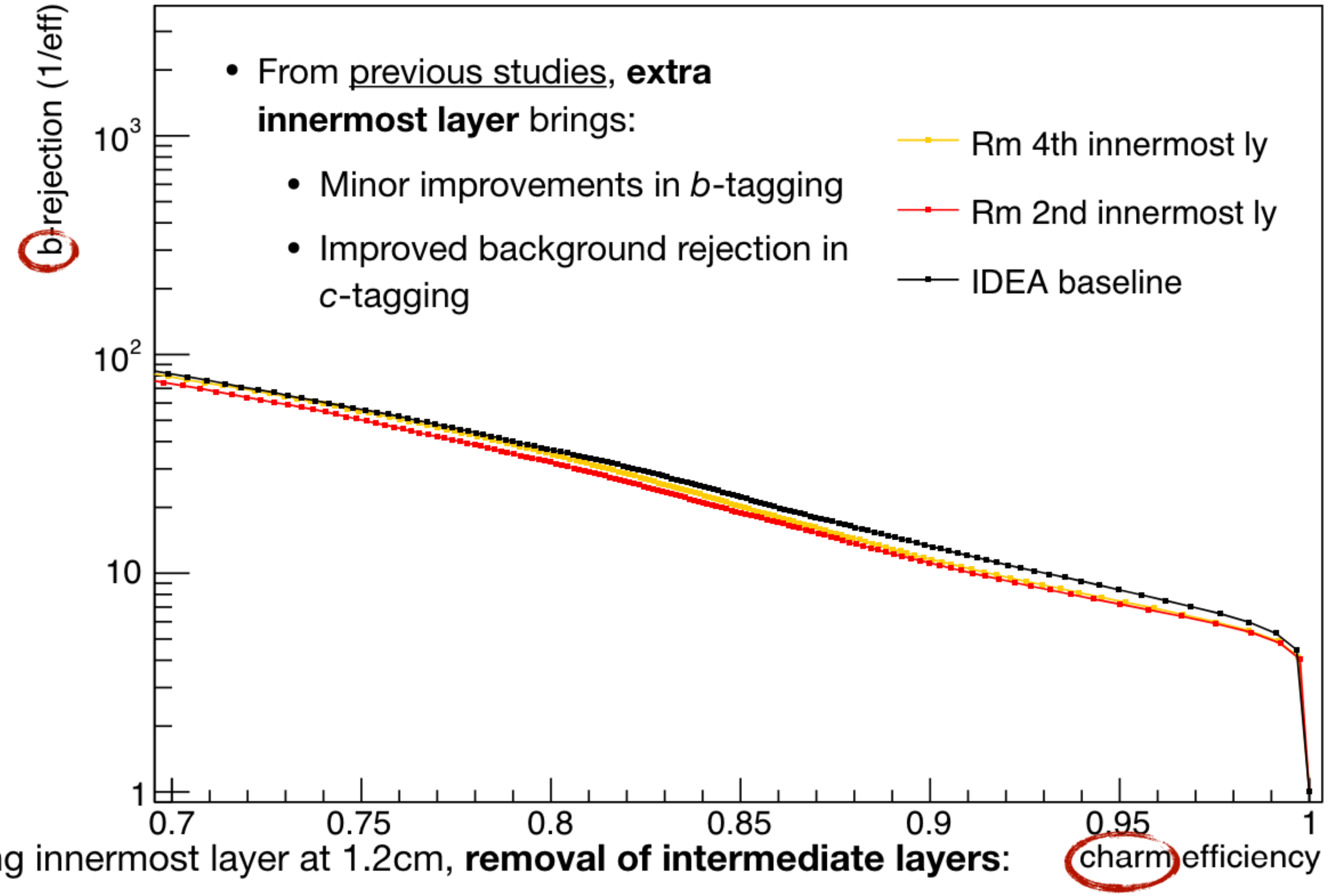
# Changing Number of Layers

## Charm tagging sensitive to the # of layers

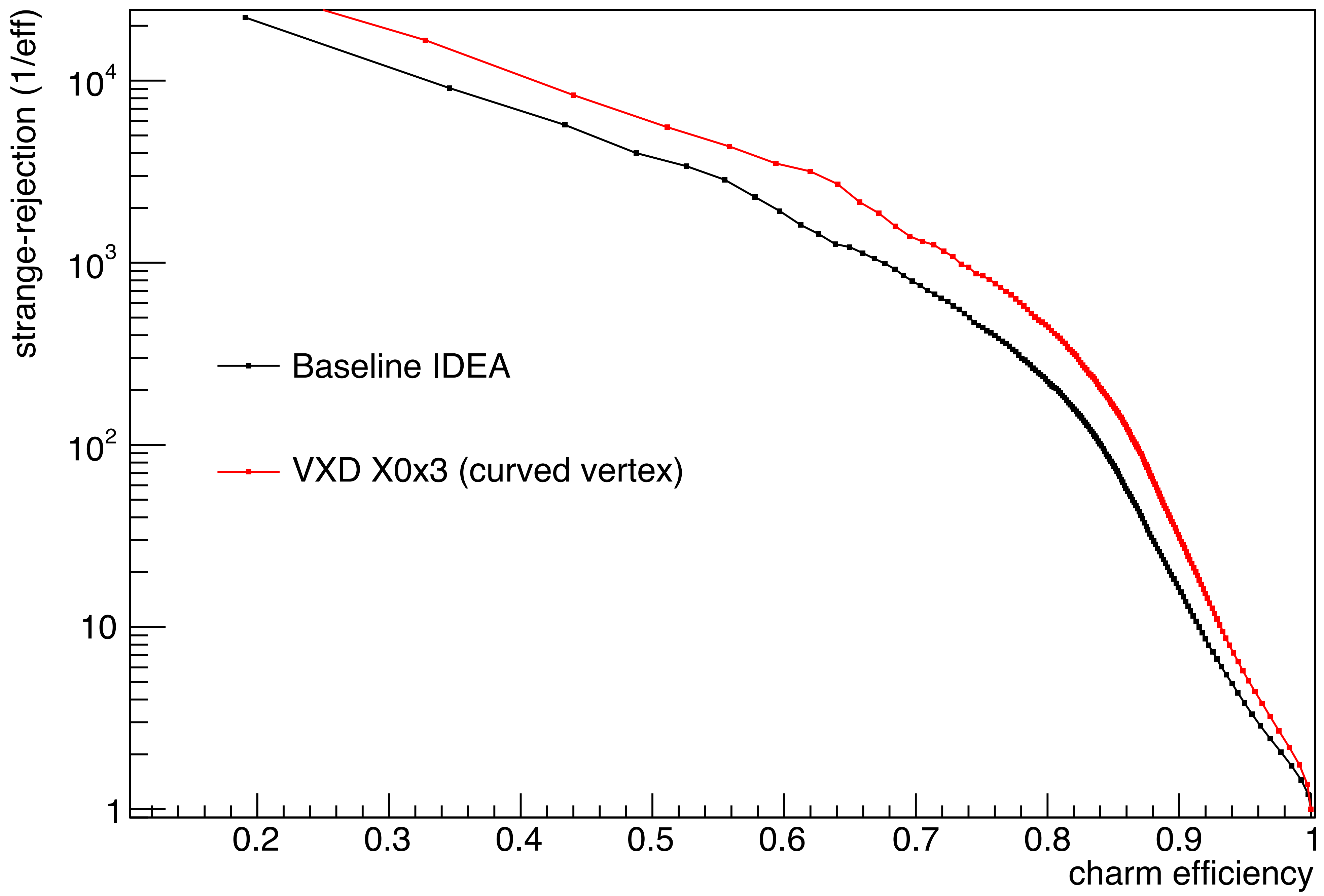
- New studies retraining the tagger with Delphes:
  - Innermost layer at 1.2cm
  - Remove intermediate layers 2nd(2cm) and 4th innermost(15cm)

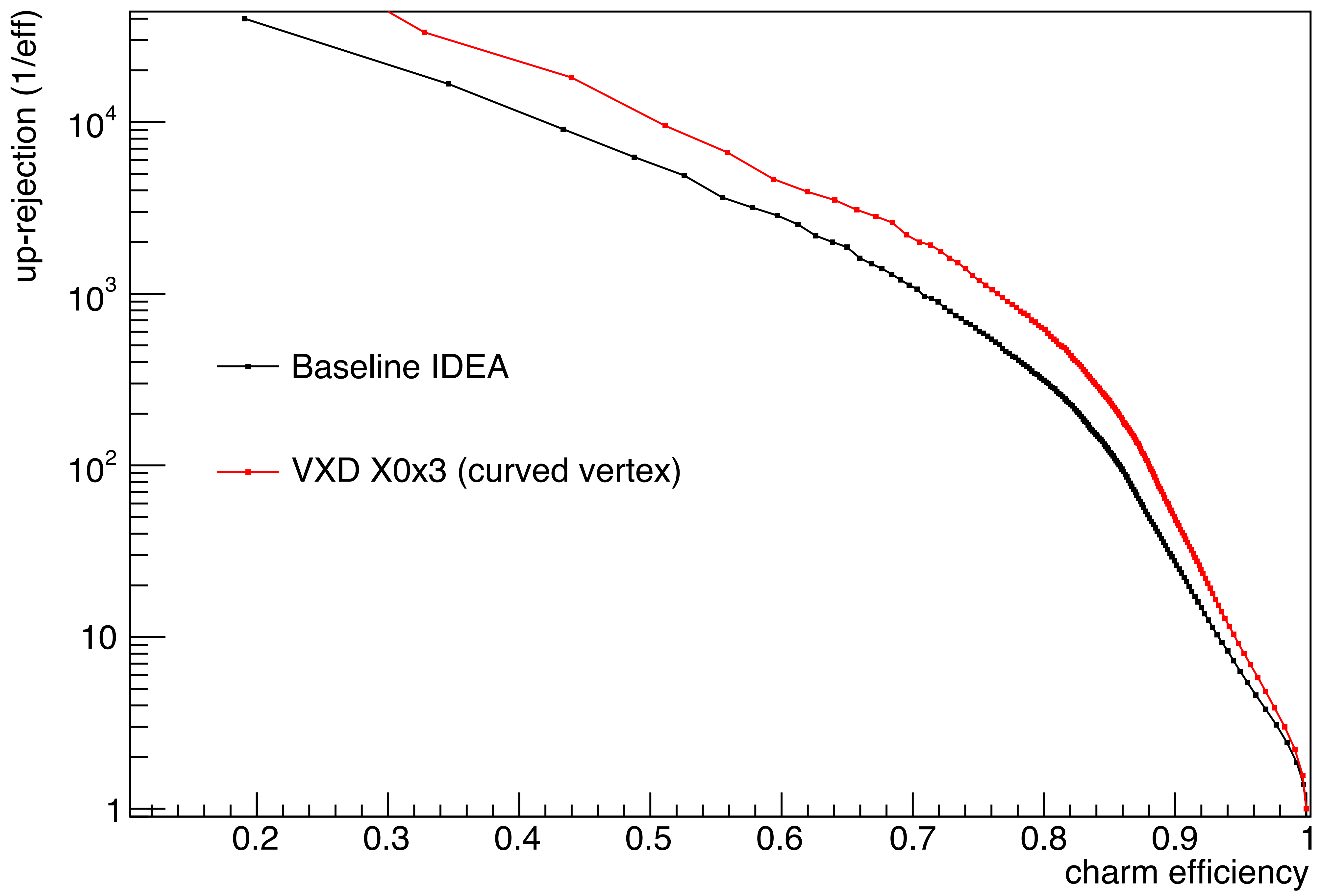



- From previous studies, **extra innermost layer** brings:
  - Minor improvements in *b*-tagging
  - Improved background rejection in *c*-tagging

- Assuming innermost layer at 1.2cm, **removal of intermediate layers**:

# Changing the Material Budget

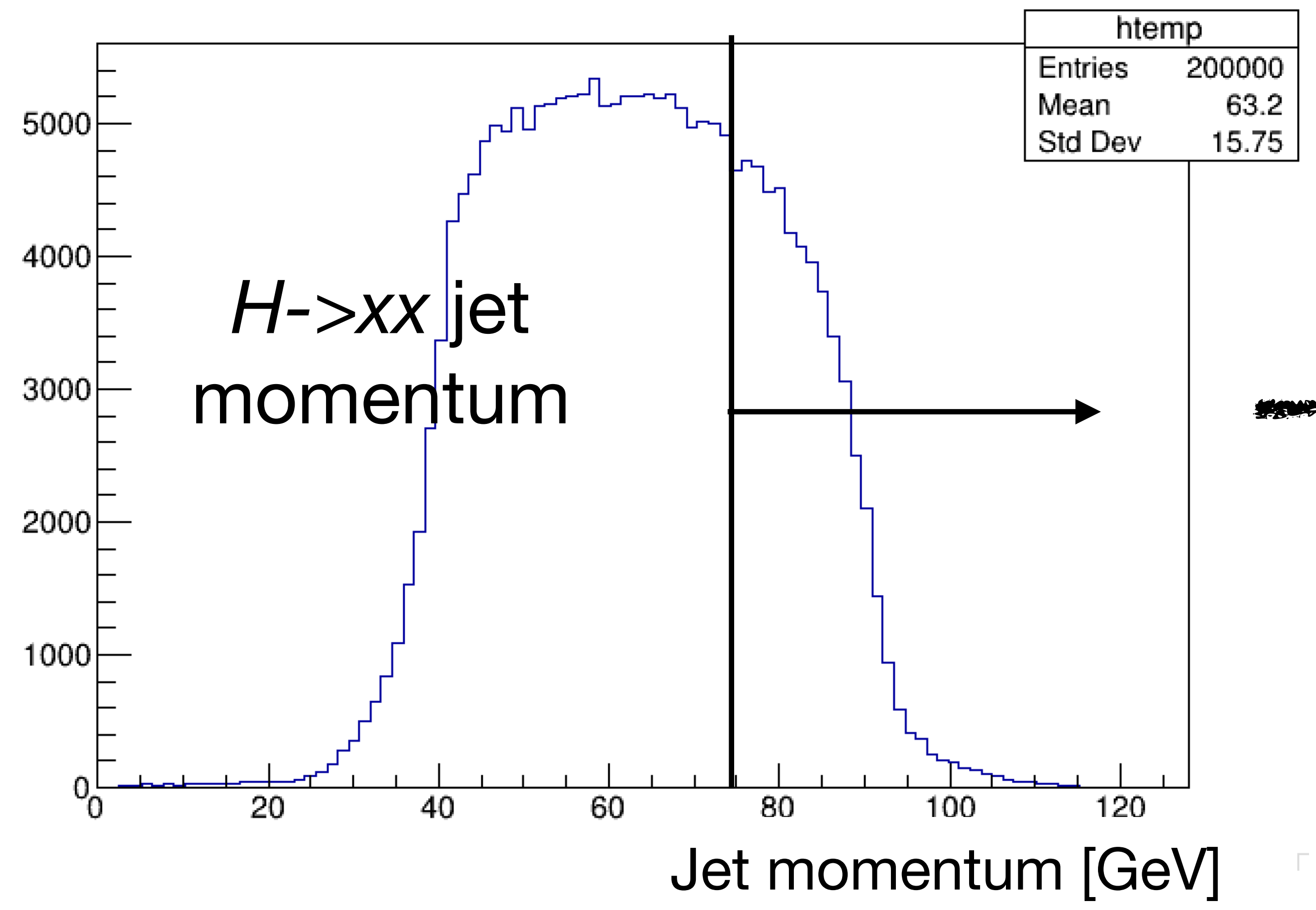


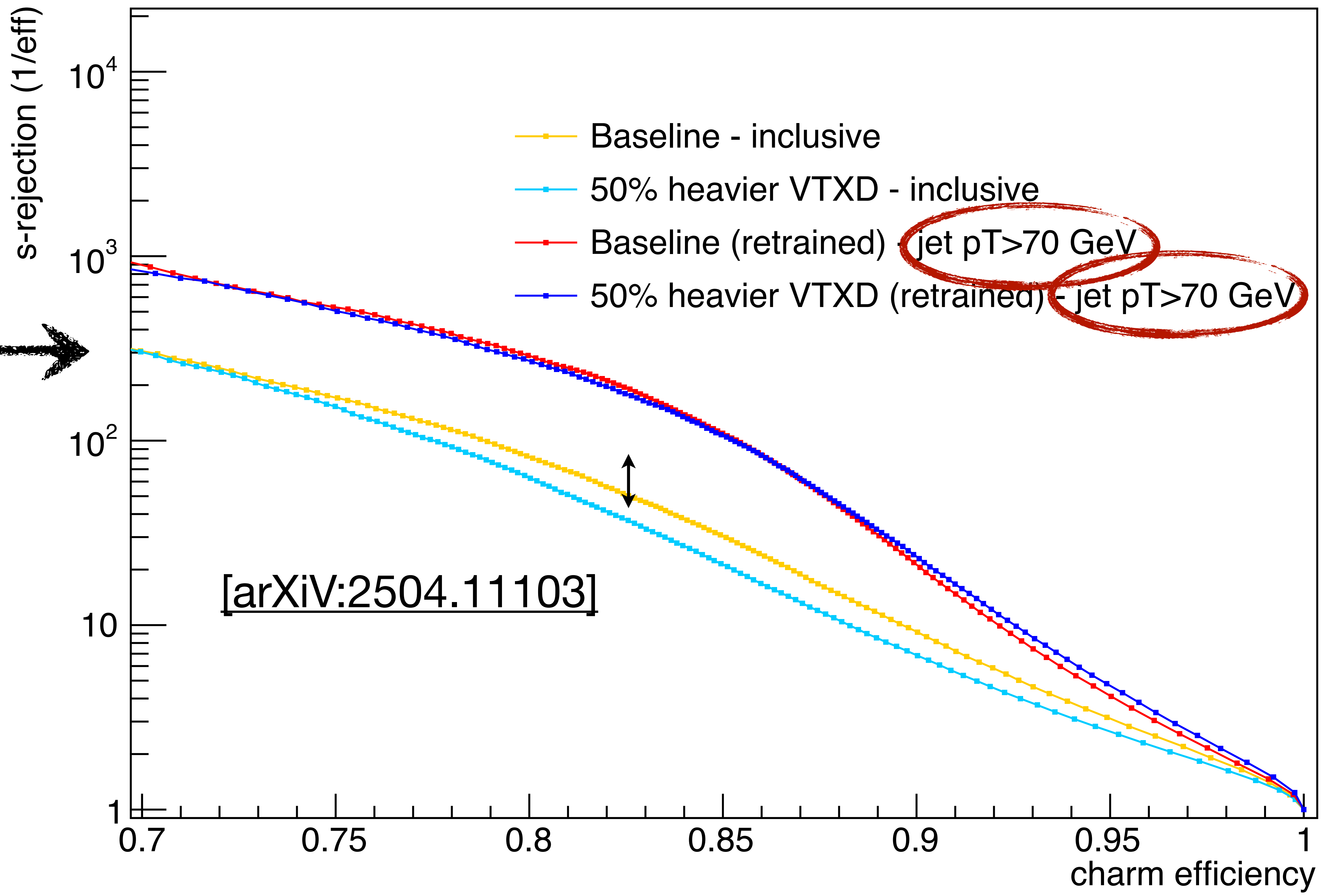




- Curved VXD detectors (Ultra-Light) may allow for a factor ~2-3 reduction in VXD material budget
  - Studied impact from +30% relative variation in radiation length for all VXD layers
- Non-negligible impact from reduced vertex material budget
  - **Can gain in flavor-tagging performance with less material!**
- For very large (>~5x, i.e. non-realistic) increase of beam-pipe material budget, impact of material in first VXD layer is not very significant

# Pixel-Detector Material Budget at High(er) Momentum

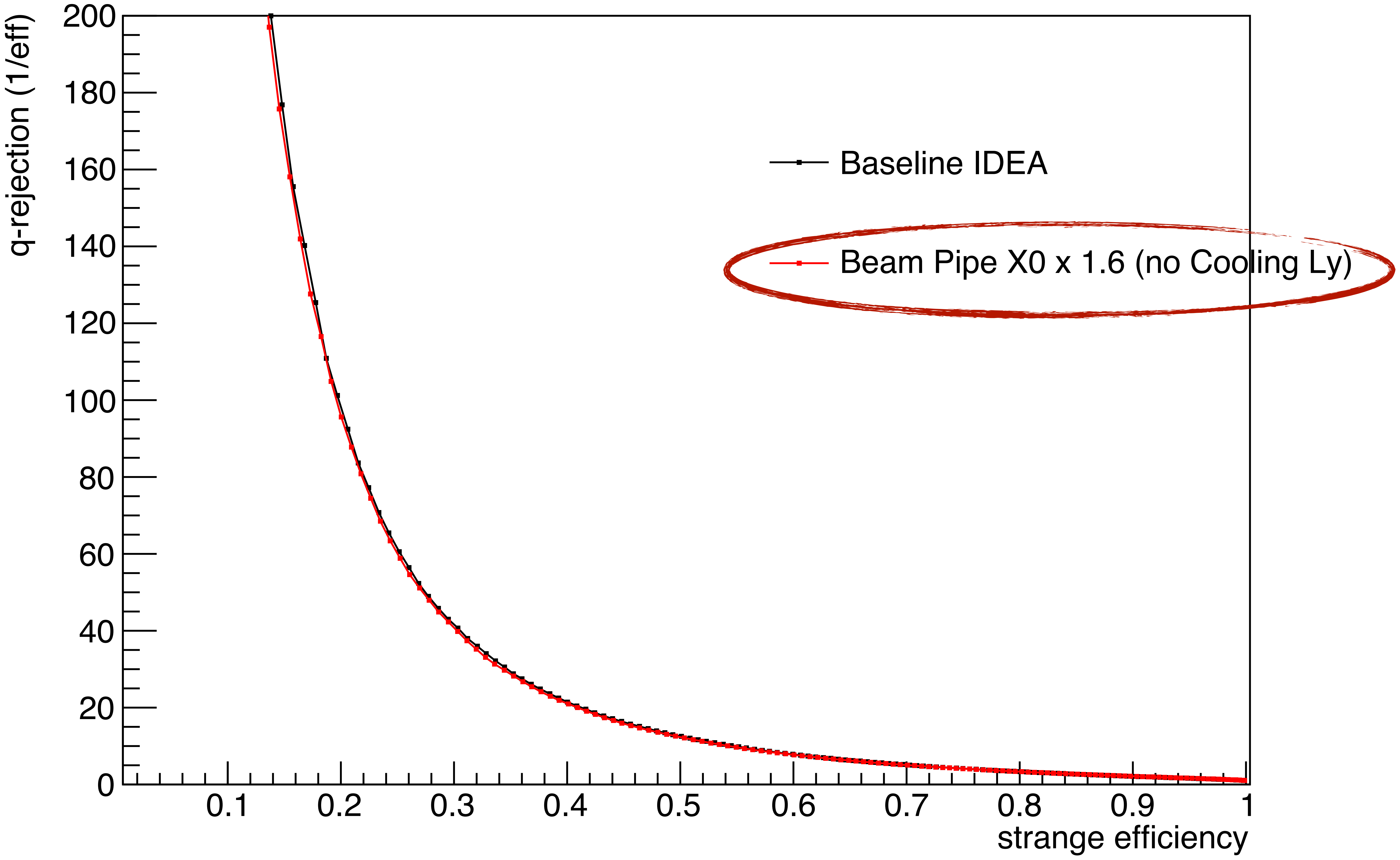
- As expected, **impact of multiple Coulomb interactions on performance becomes insignificant at high momentum**
  - Relevant for potential *differential measurements & higher center-of-mass points*
- Need retraining on kinematic sub-phase-space to observe ~perfect performance recovery



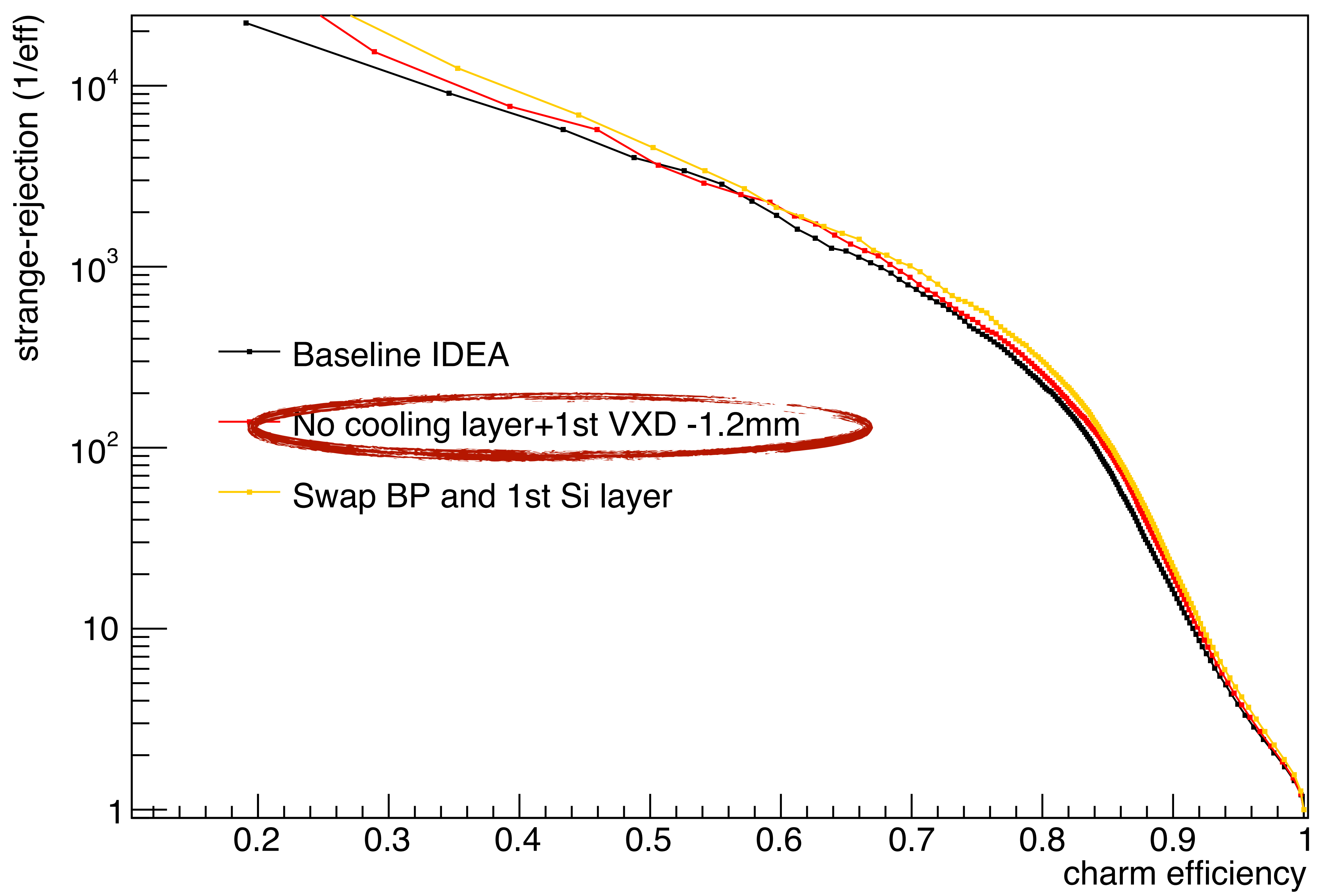



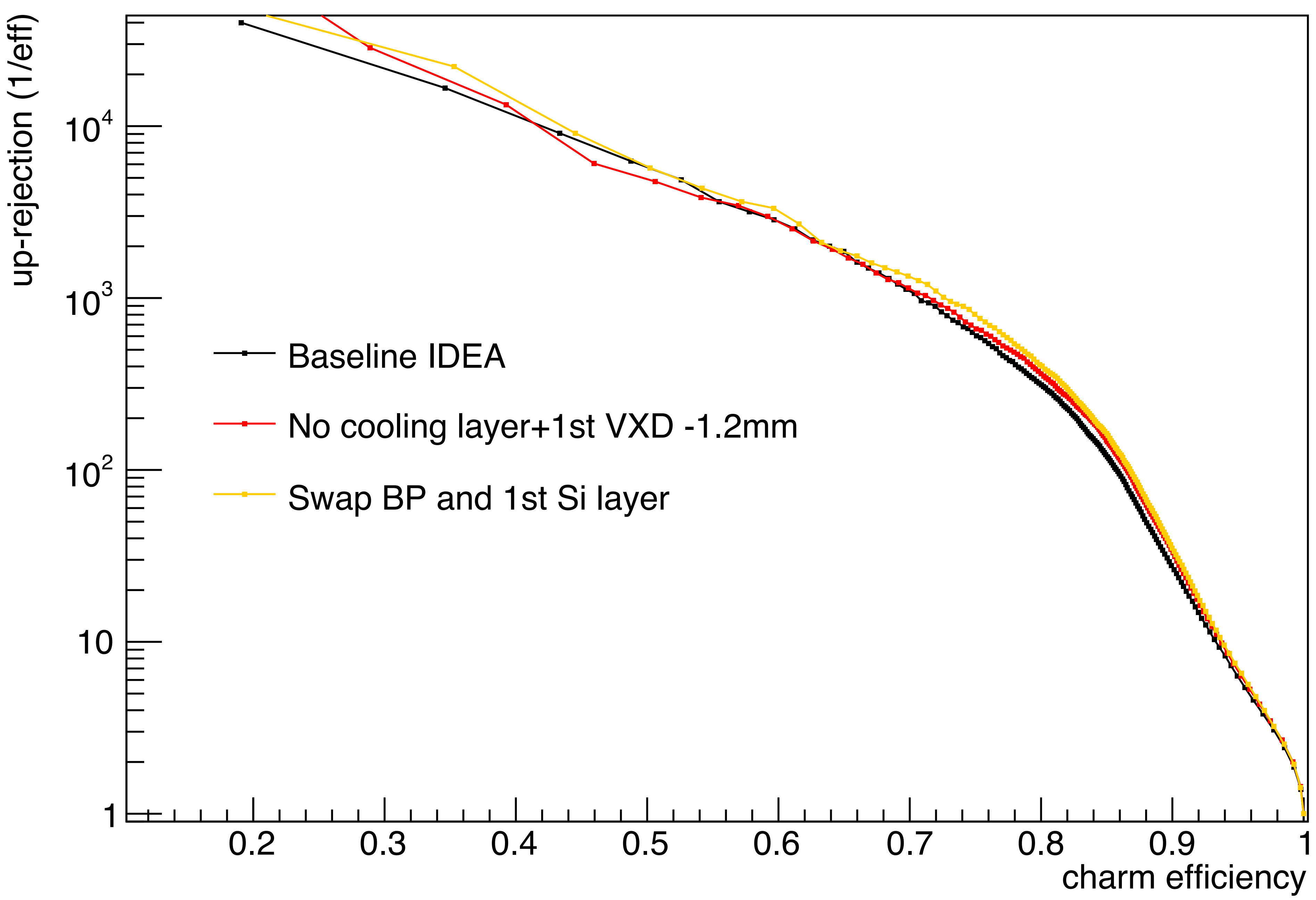
# Beam-Pipe Material Budget (Recent Studies)

- Performed more (realistic) material-budget studies, inspired by G. Nigrelli's studies
- Given default (0.68%X0), studied following relative changes:
  - -25% (0.51%X0)
  - -41% (0.40%X0)
  - +18% (0.8%X0)
  - **-63% (0.25%X0, no cooling layer)**
- **No significant impact (<~1-5%) directly coming from changes in beam-pipe material budget**
  - **N.B. picture may be quite different for e.g. soft B-physics**



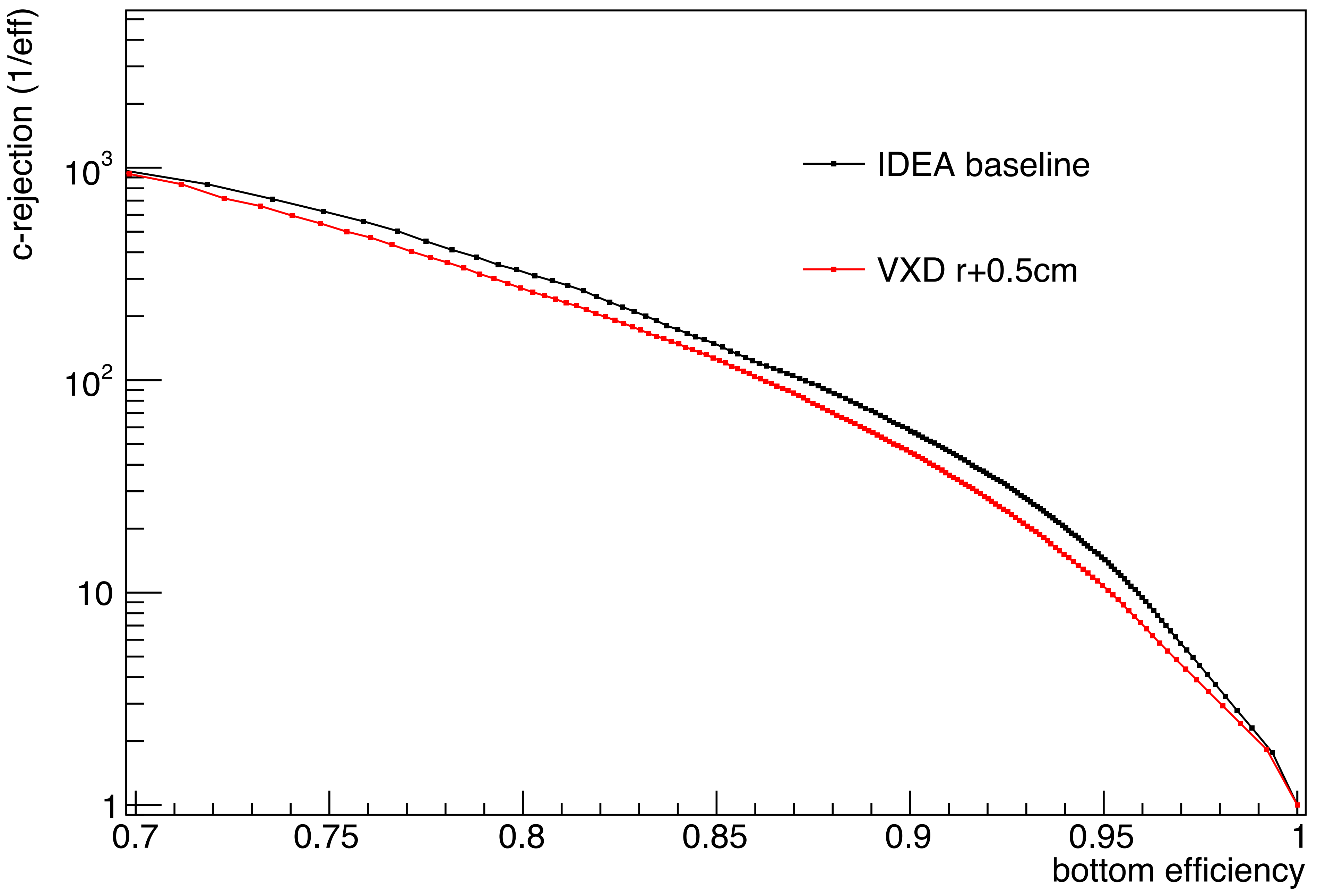
# Beam-Pipe **Material Budget** (Recent Studies II)

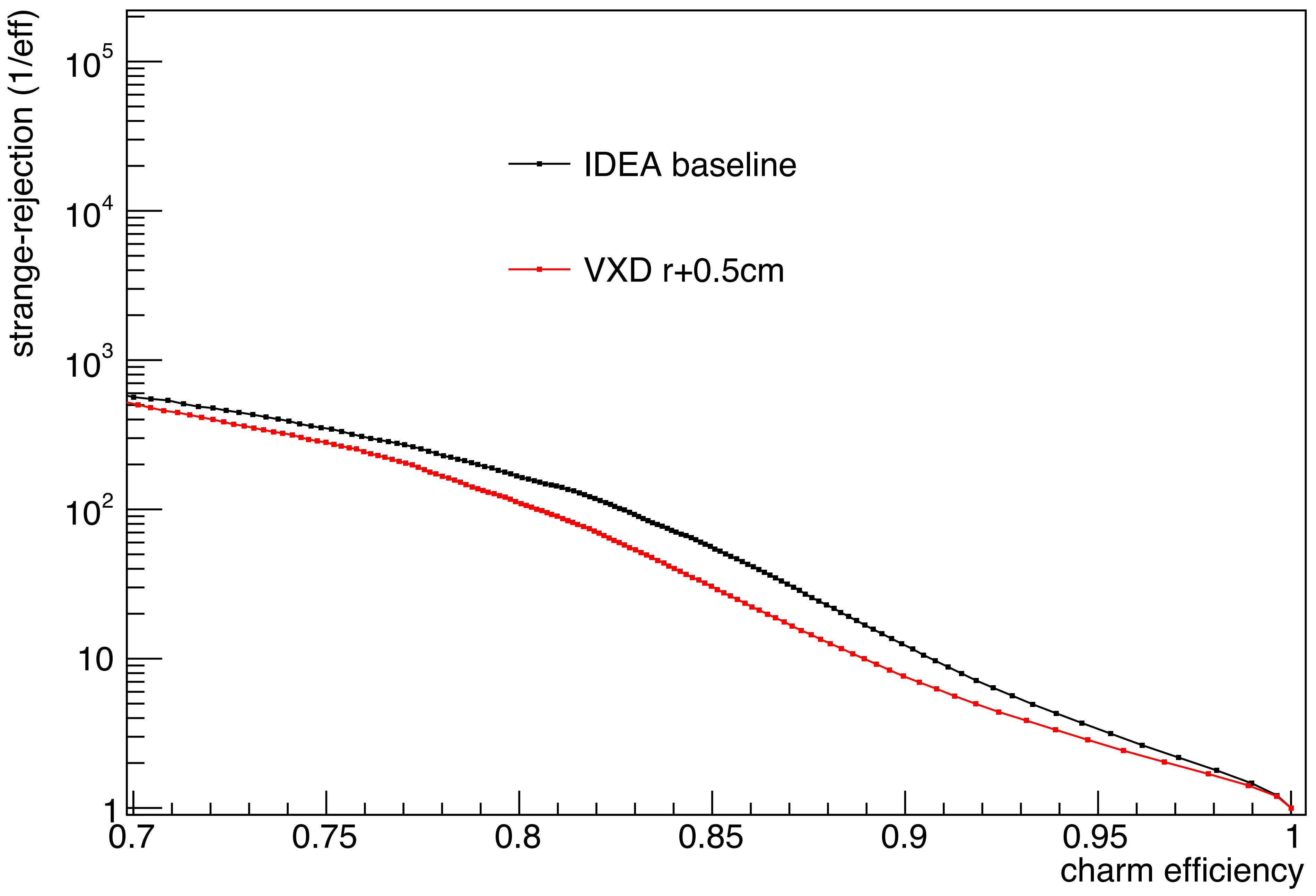



- Explored combinations of reduced Beam Pipe Material Budget with VXD closer to PV
  - First VXD layer 1.2mm closer to PV
    - No BP cooling layer, possible in case beam-pipe cooling layer not needed
  - Swap BP and first VXD layer, "extreme" case
- **Visible impact from first VXD layer closer to PV --> Proximity!**

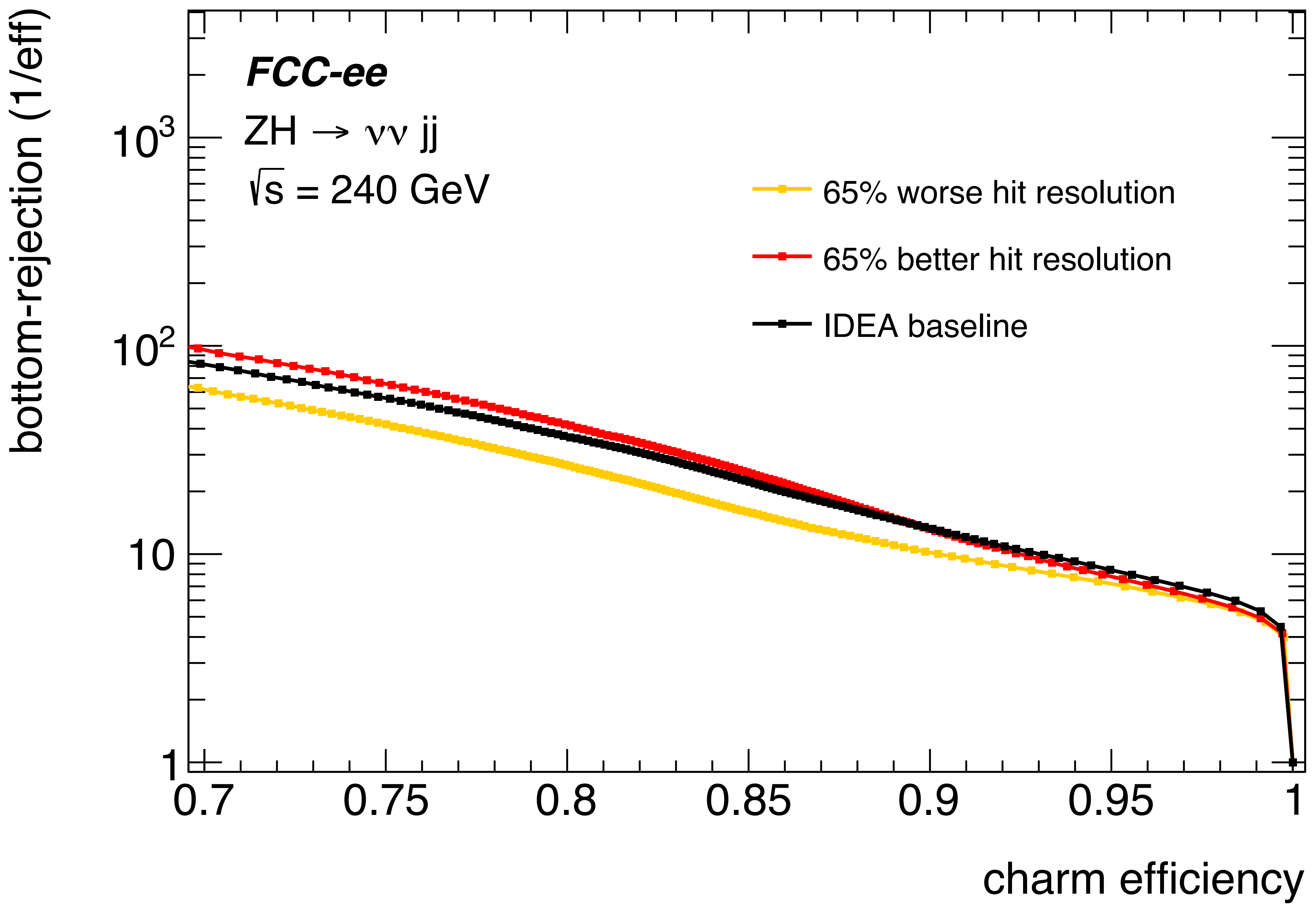
# Pixel-Detector Proximity to Interaction Point

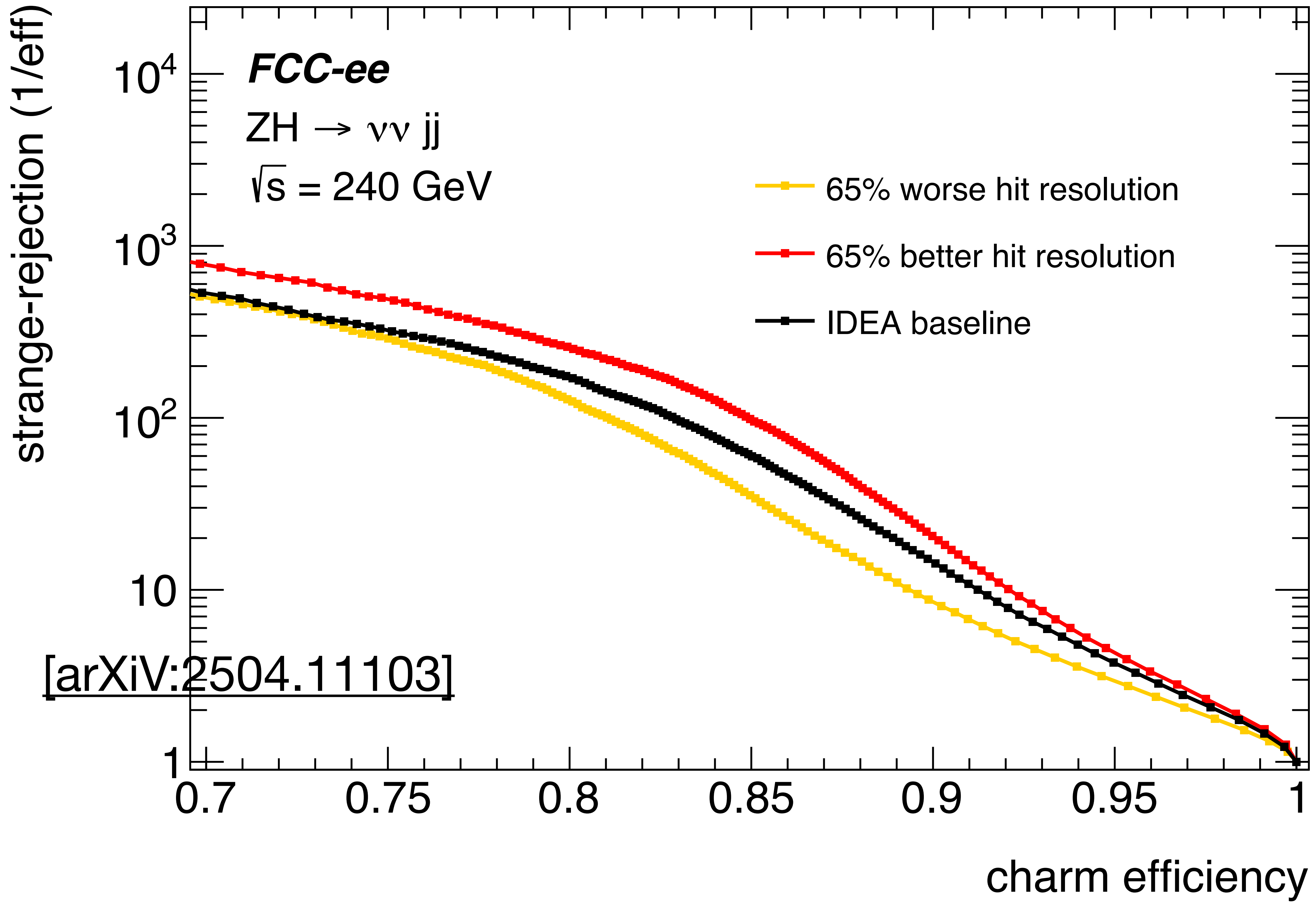



- Studied impact of **shifting all VTXD barrel layers 0.5cm away** from beam pipe
- **Significant impact on bottom and charm tagging**, coming from worsening in impact-parameter resolution

# Bottom/Charm Tagging & Single-Point Resolution



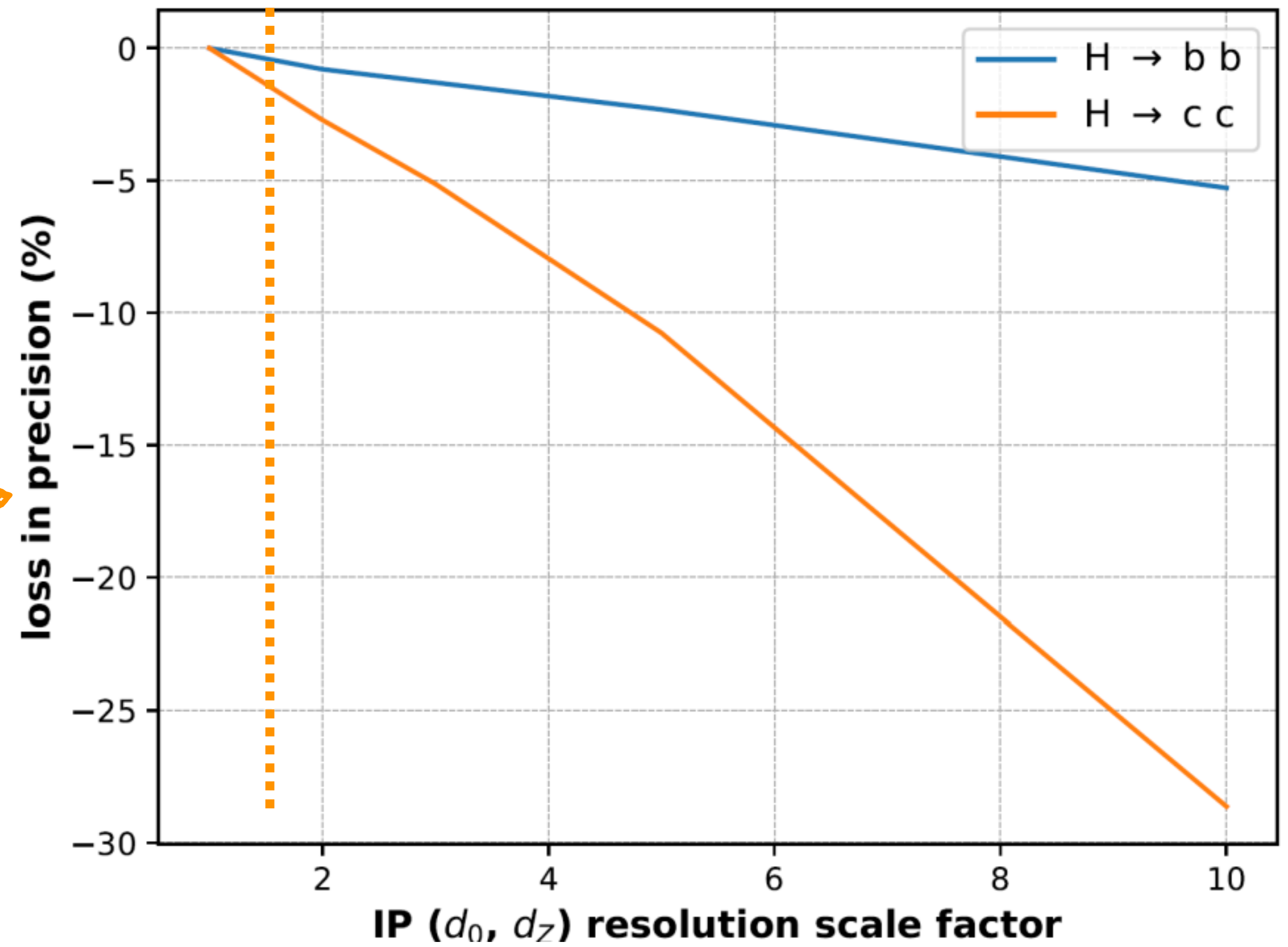



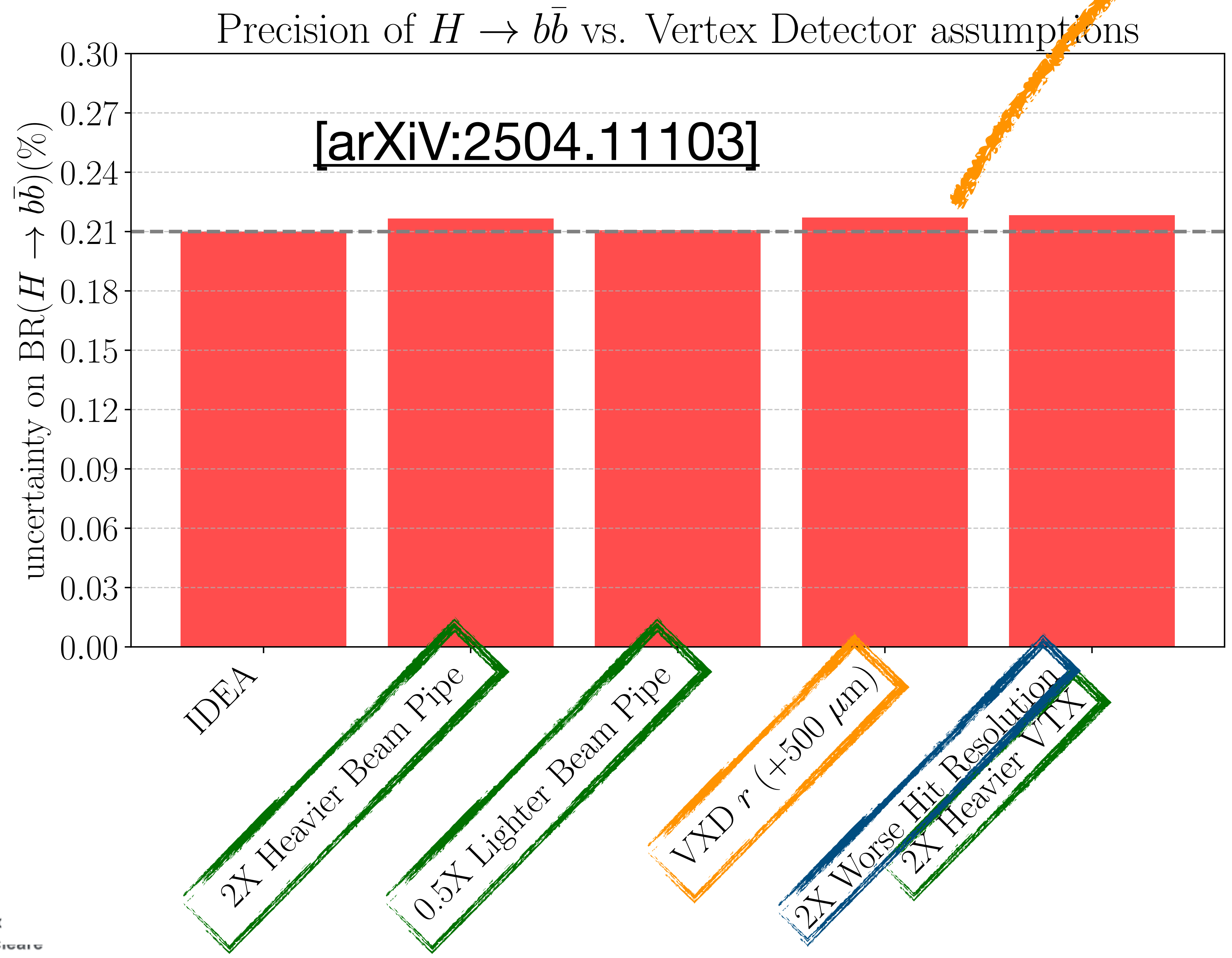

[arXiV:2504.11103]

- Visible effects on *b*- & *c*-tagging
- More significant effects on *c*-tagging
  - Fairly symmetric impact on rejection of all flavors
  - **Crucial role of single-point resolution** (*nominal: 3μm with 25x25μm² inner barrel pitch*) in rejection of major backgrounds for charm

# Impact on measurement precision

- The IP resolution is the major driver of charm and bottom jet identification
  - B (D) mesons travel a finite decay length of 500 (150) µm
- Worse impact on H→cc vs H→bb due to smaller displacement and smaller S/B




- Precise IP determination driven by:
  - **Single point resolution**
  - **Radial distance of VXD layers** (high *p*)
  - **Material budget** (low *p*) - eventually limited by beam-pipe material
- Studied these effects through full propagation:
  - Simulated each detector response through Delphes
  - Re-trained jet-flavour tagger
- **Marginal effects observed in Higgs couplings**

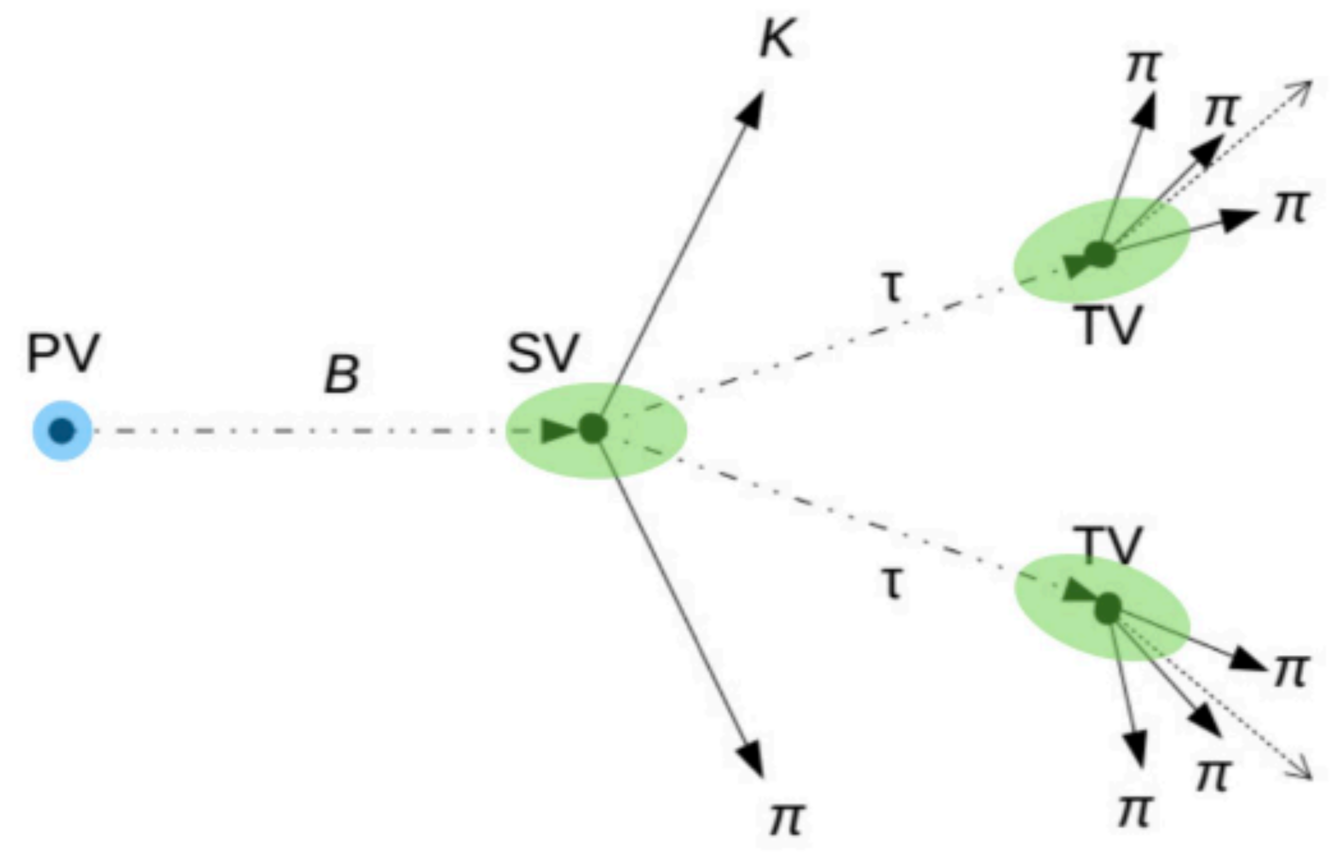
# Flavor: Requirements from $B \to K^*\tau\tau$

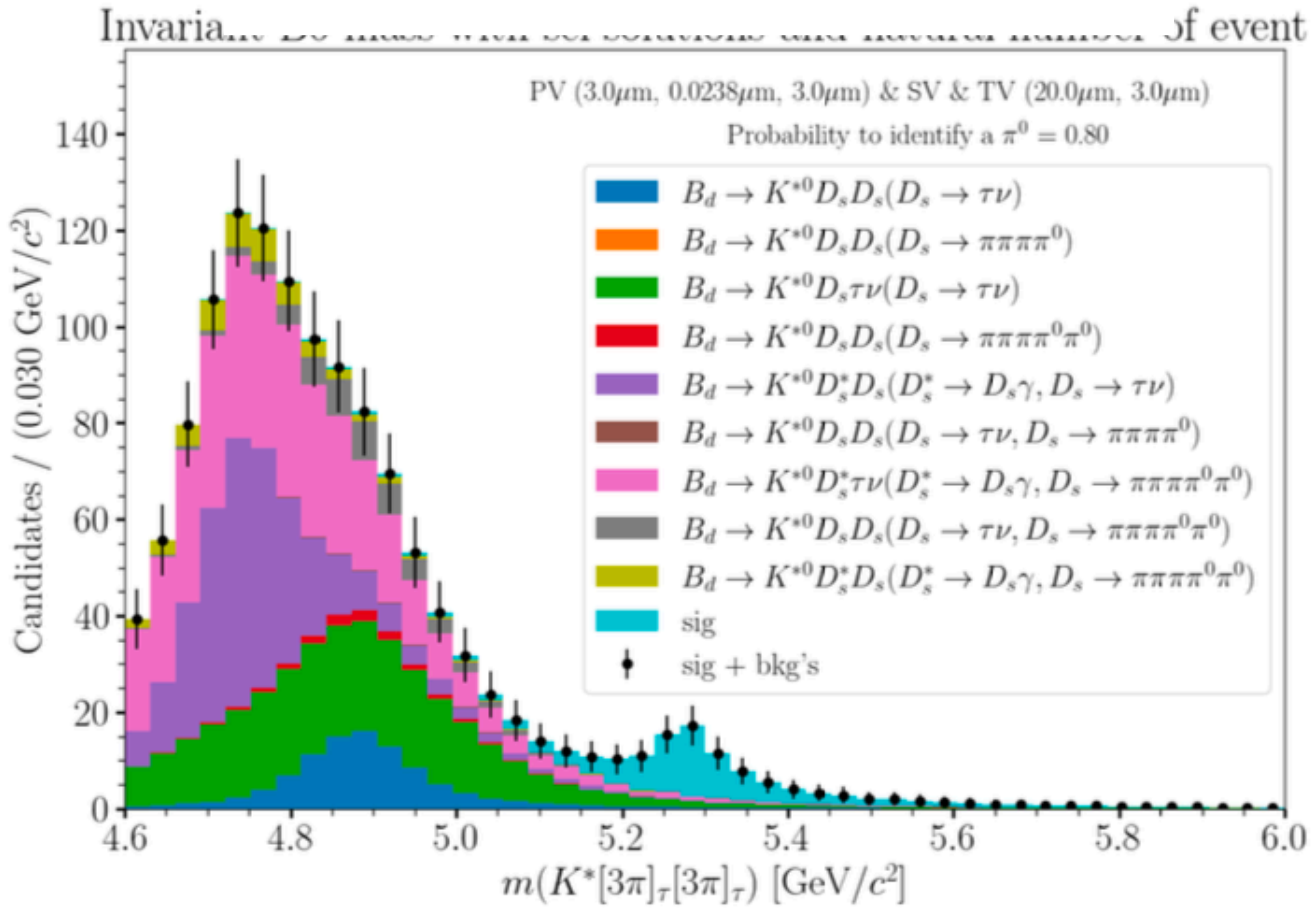
T. Miralles

- Requirements from flavour physics concern several aspects of the detector: vertexing, tracking, particleID, calorimetry

- Most relevant for vertex detectors are: Modes with neutrinos in the final state and taus $B \to K^*\tau\tau$ is an important LFU test in $b \to s$ transitions
  - $BR_{SM} \sim O(10^{-7})$ very small
  - Focus on the 3-prong $\tau$ decays $(3\pi + \nu)$

- Very complex analysis with a very rich signature:
  - 8 visible particles (1K, 7π)
  - 1 secondary vertex and tertiary vertices
  - Many backgrounds & combinatorics: need BDT for selection



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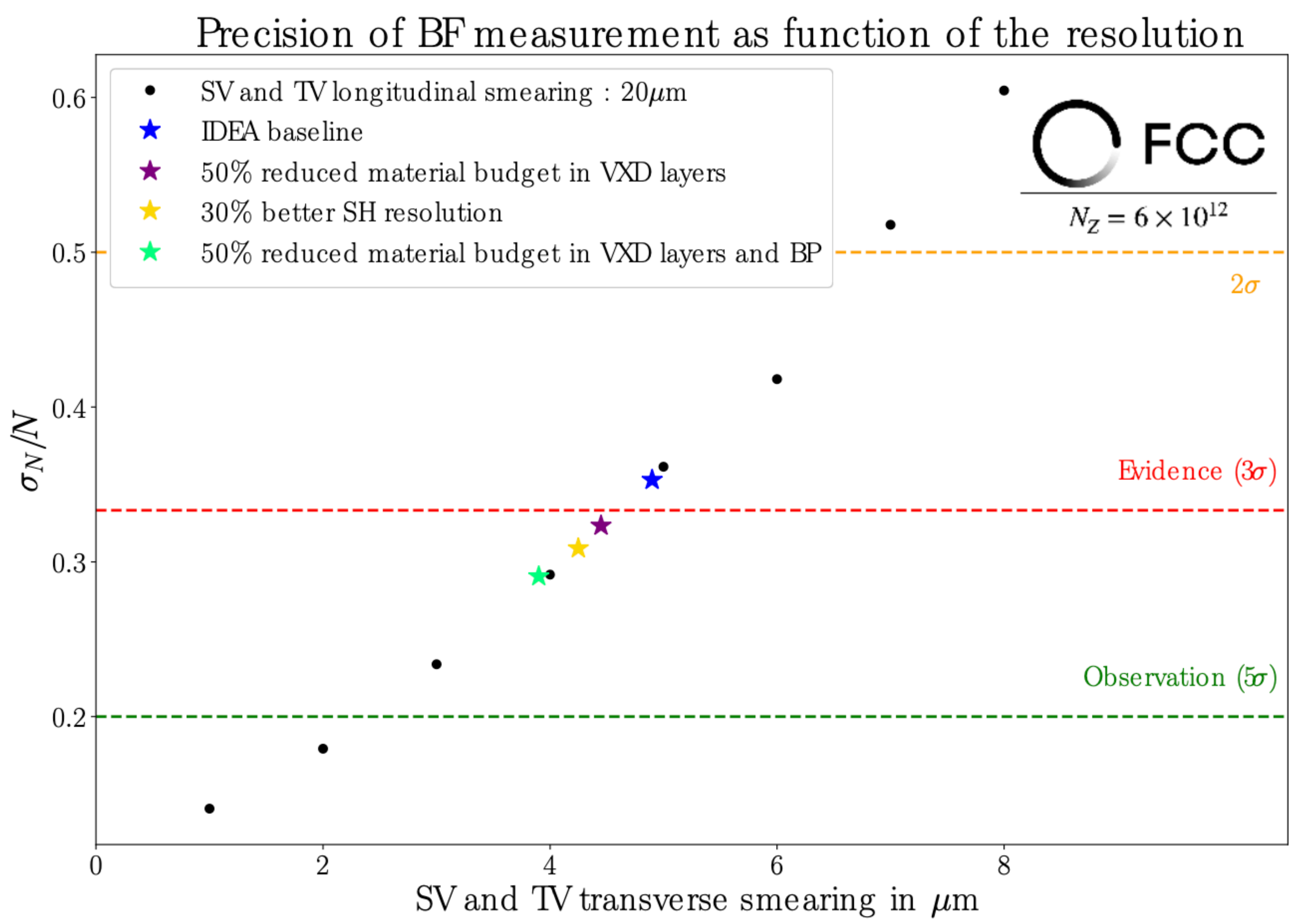
# Requirements from $B \rightarrow K^{*}\tau\tau$ (2)

## Exploring different configurations




- Neutrino reconstruction is the crucial part.
  - It depends critically on the precise SV/TV precision
  - Need a transverse precision on the SV/TV better than 5um
- 30% improvement in single-hit resolution and 50% less VXD material budget bring sensitivity >3σ
  - in nominal IDEA Delphes sim. BP material is twice the VXD

L. Roherig, S. Monteil, M. Selvaggi

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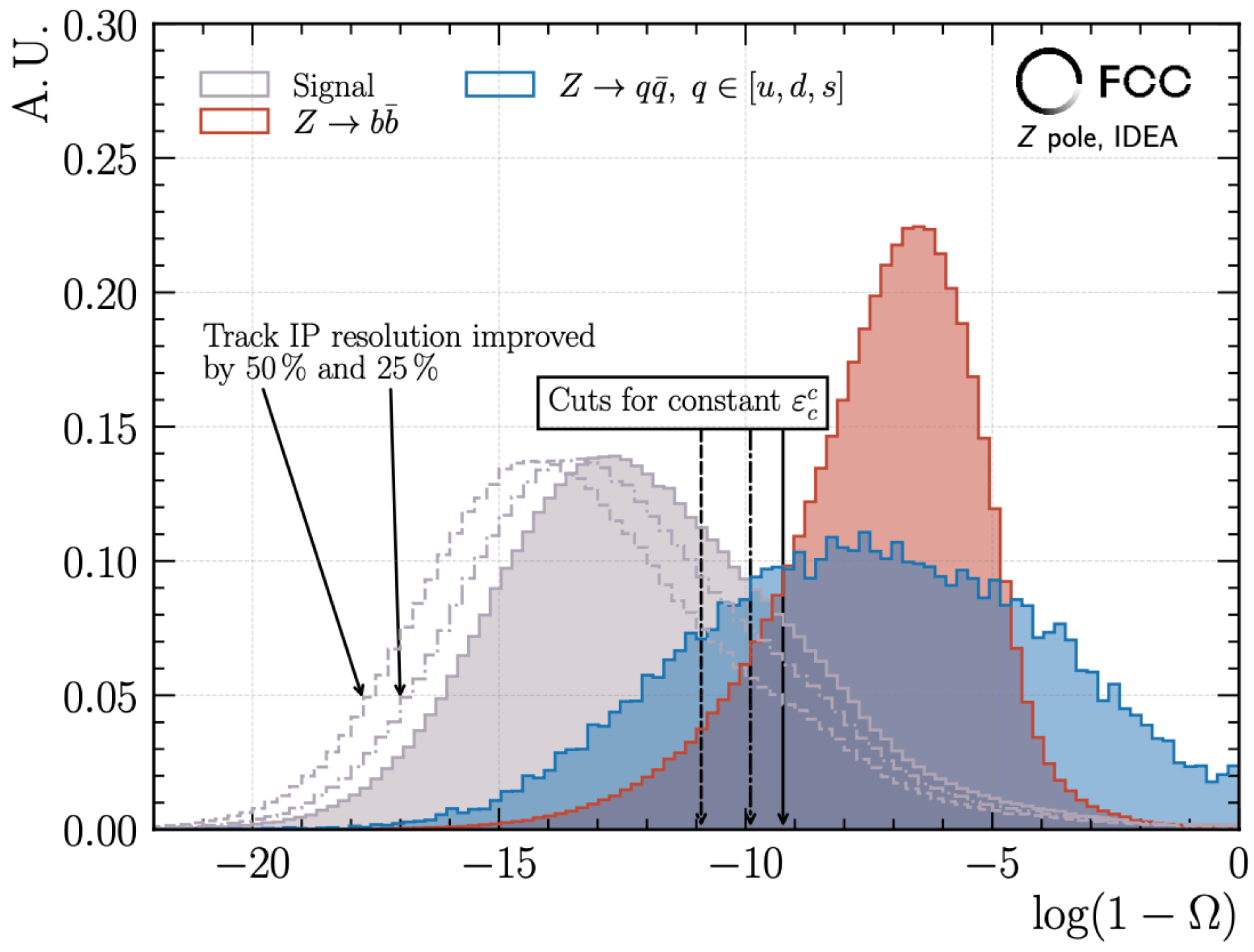
# Requirements from Rb,Rc

## Developing an Exclusive tagger

- In Rb: It allows hemispheres containing a b-hadron to be tagged with a purity larger than 99.8%  using selected decay modes of charged B meson
  - Cut on  b-hadron tracks displacement minimises the impact of the uncertainty on the correlation. The hemisphere correlation at only 10% brings down the corresponding  systematic uncertainty on Rbto the level of the statistical uncertainty (0.015%).
  - 20x improvement in Rb determination

- In Rc, using D0 → K+π− decays. Can reduce contamination from  Z → bb events by cutting on ‘pointing angle (from vertex reco).



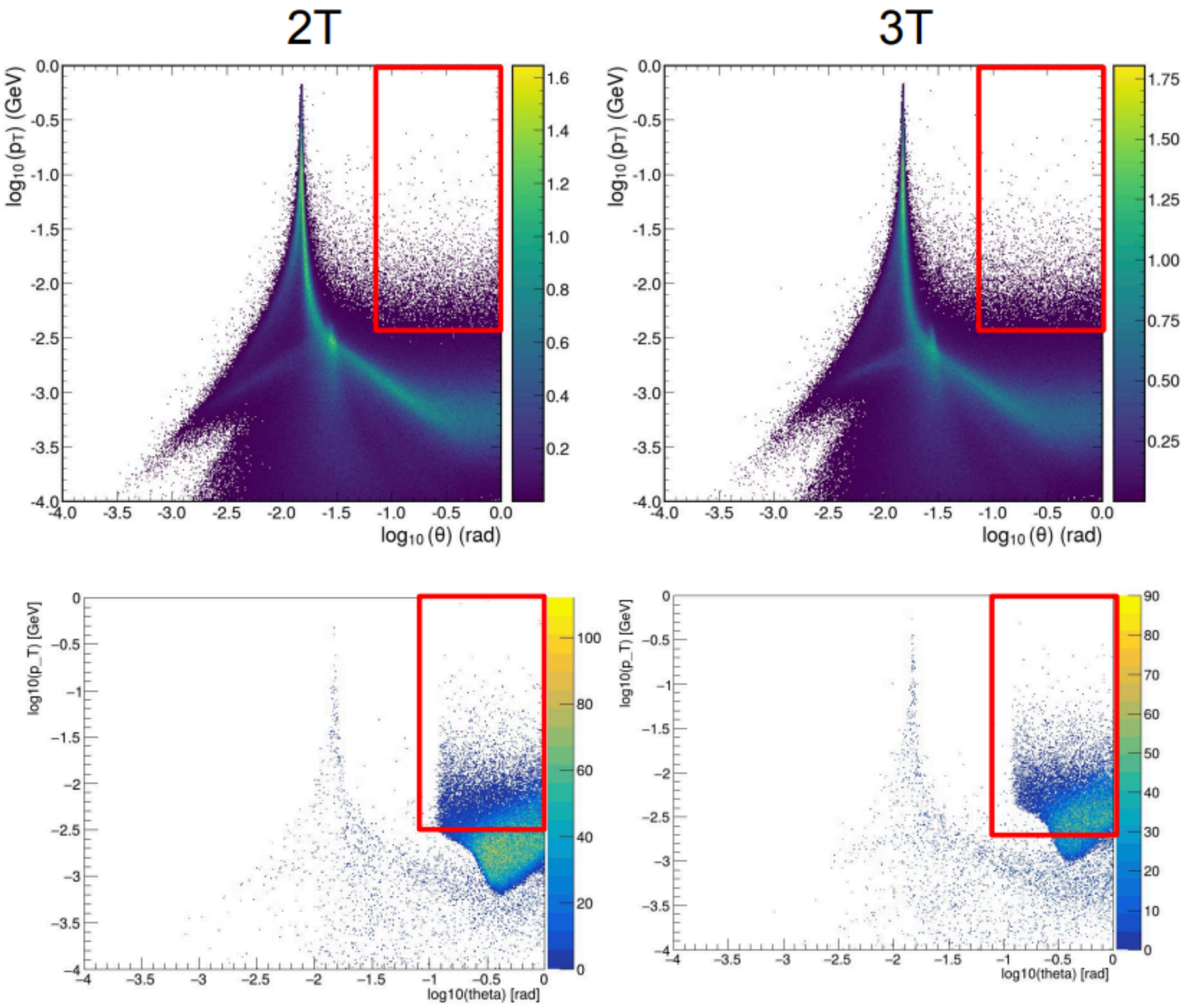
Jan Eysermans, Katie Kudela, Mariarosaria D'Alfonso, A. Ciarma, et al.



# Occupancy

## Beam background

- Dominated by incoerent pair production from these processes evaluated with GuineaPig in different conditions:
  - GP updated to correctly count the IPCs with hits in the first layer.
  - The top layer shows all IPCs, and the bottom layer only shows IPCs with corresponding gen-level hits on the first layer of the vertex detector
- physics contribution seems negligible, lots of low pt tracks
  - more work in progress now that tracking is available



# Conclusion & Plans

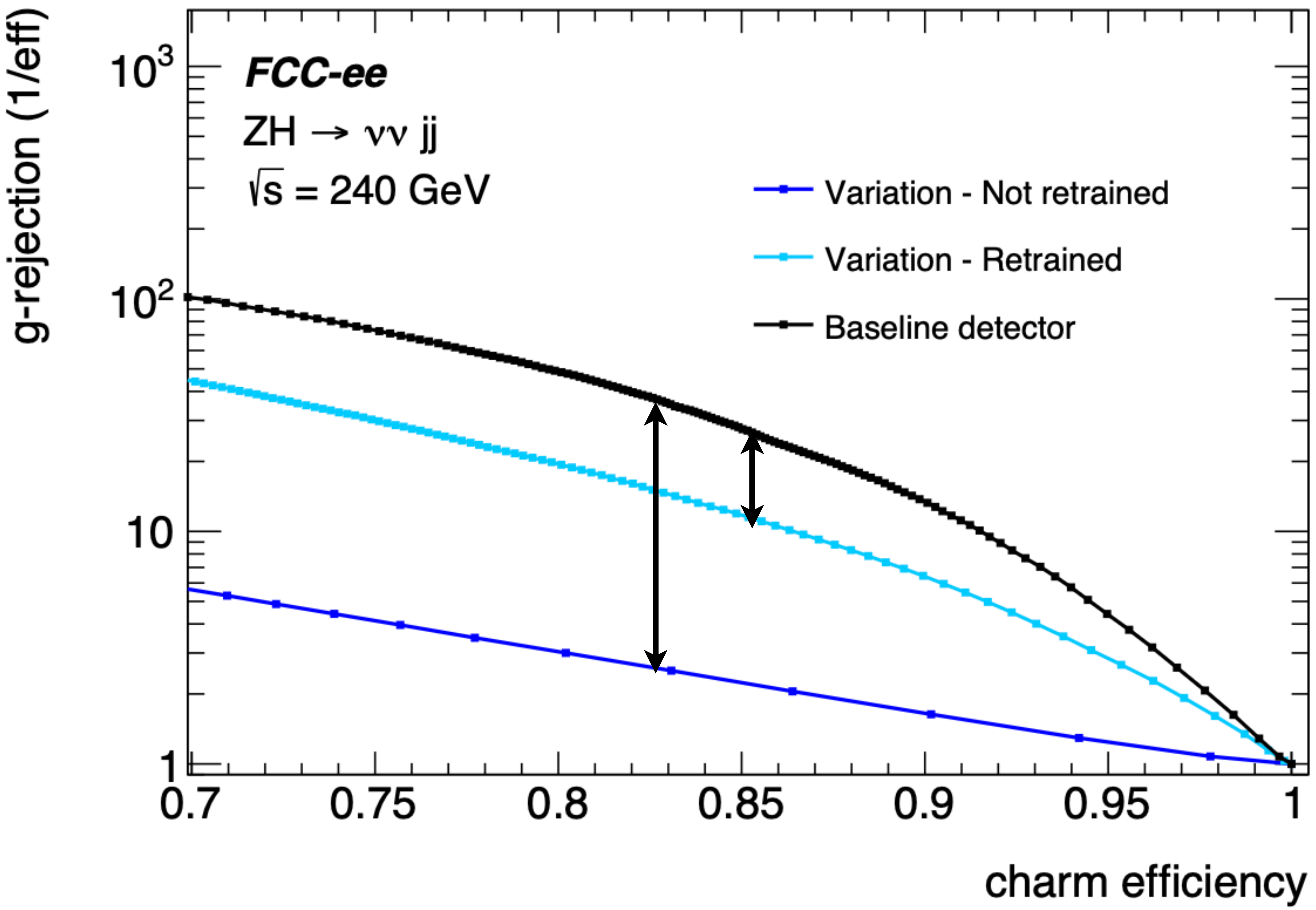
- Some flavor-physics searches, e.g. B → K*ττ, do require strong constraints on vertex reconstruction
  - BP & VXD material budget, single-hit resolution, SV/TV resolution smearing, …
- Studied impact of vertex-detector properties on Higgs physics with full propagation through ParticleNet & ZH analyses
  - Proximity to interaction point, number of pixel layers, single-hit resolution, material budget, etc…
  - Realistic variations in the vertex detector layout, material budget & hit resolution expected to have minor impact on Higgs couplings
- Exclusive tagger: Still to explore dependence on IP resolution for assignement of tracks to PV (important  also for the inclusive ones)
- Full Simulation and PFlow Reconstruction plus Background overlap will allow a clearer definition of the requirements for physics measurements, for the various vertex designs and concepts.
  - Current vertex detector concepts for IDEA seems to meet needs of our physics program

# BACKUP

# ParticleNet - Full List of Input Variables

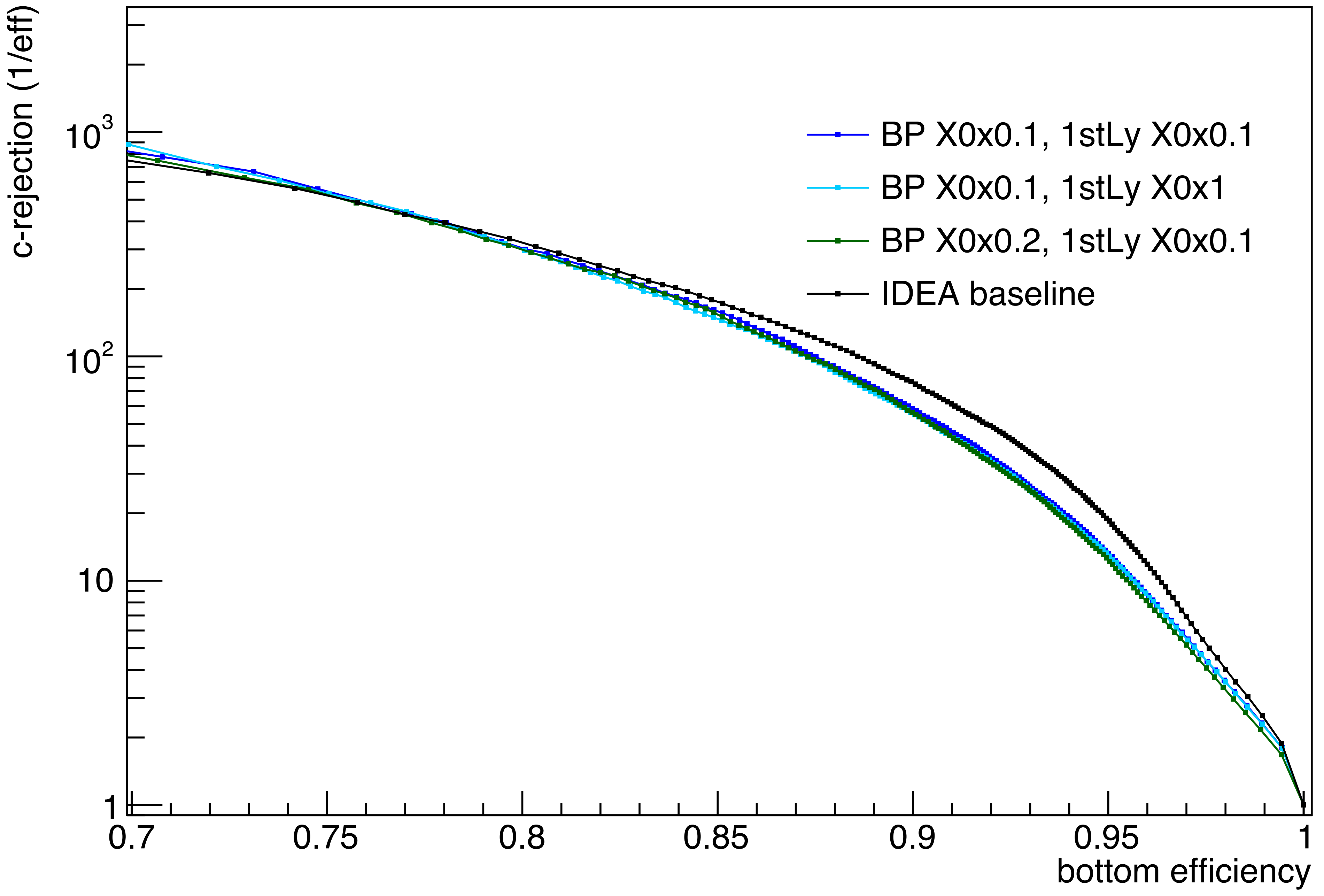
| Variable | Description |
|---|---|
| **Kinematics** | |
| $E_{\text{const}}/E_{\text{jet}}$ | energy of the jet constituent divided by the jet energy |
| $\theta_{\text{rel}}$ | polar angle of the constituent with respect to the jet momentum |
| $\phi_{\text{rel}}$ | azimuthal angle of the constituent with respect to the jet momentum |
| **Displacement** | |
| $d_{xy}$ | transverse impact parameter of the track |
| $d_z$ | longitudinal impact parameter of the track |
| $\text{SIP}_{\text{2D}}$ | signed 2D impact parameter of the track |
| $\text{SIP}_{\text{2D}}/\sigma_{\text{2D}}$ | signed 2D impact parameter significance of the track |
| $\text{SIP}_{\text{3D}}$ | signed 3D impact parameter of the track |
| $\text{SIP}_{\text{3D}}/\sigma_{\text{3D}}$ | signed 3D impact parameter significance of the track |
| $d_{\text{3D}}$ | 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 |
| $C_{\text{ij}}$ | 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 |

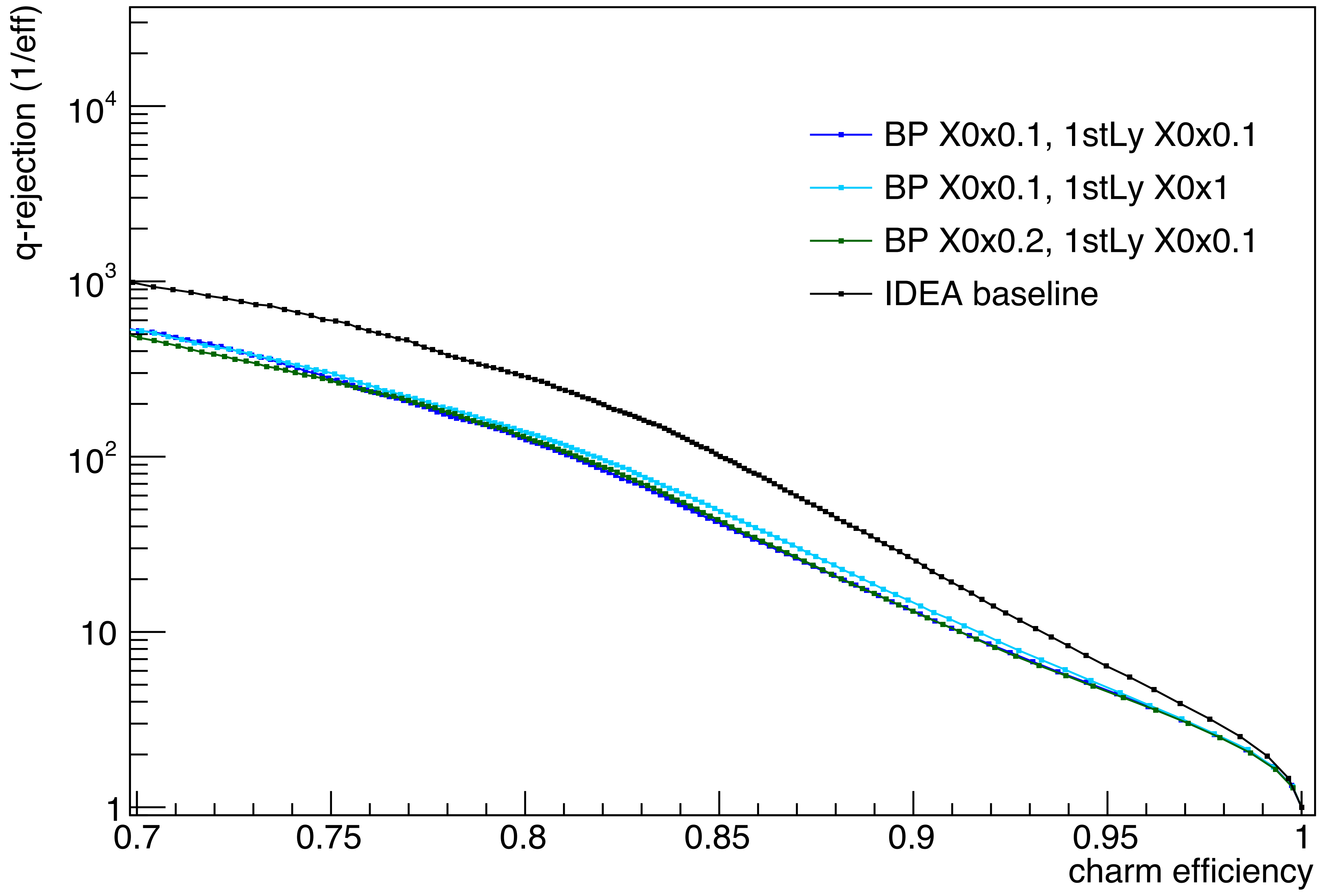
# ParticleNet - Why is Retraining Necessary?




- 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**

# Extreme Variations in BP Material Budget



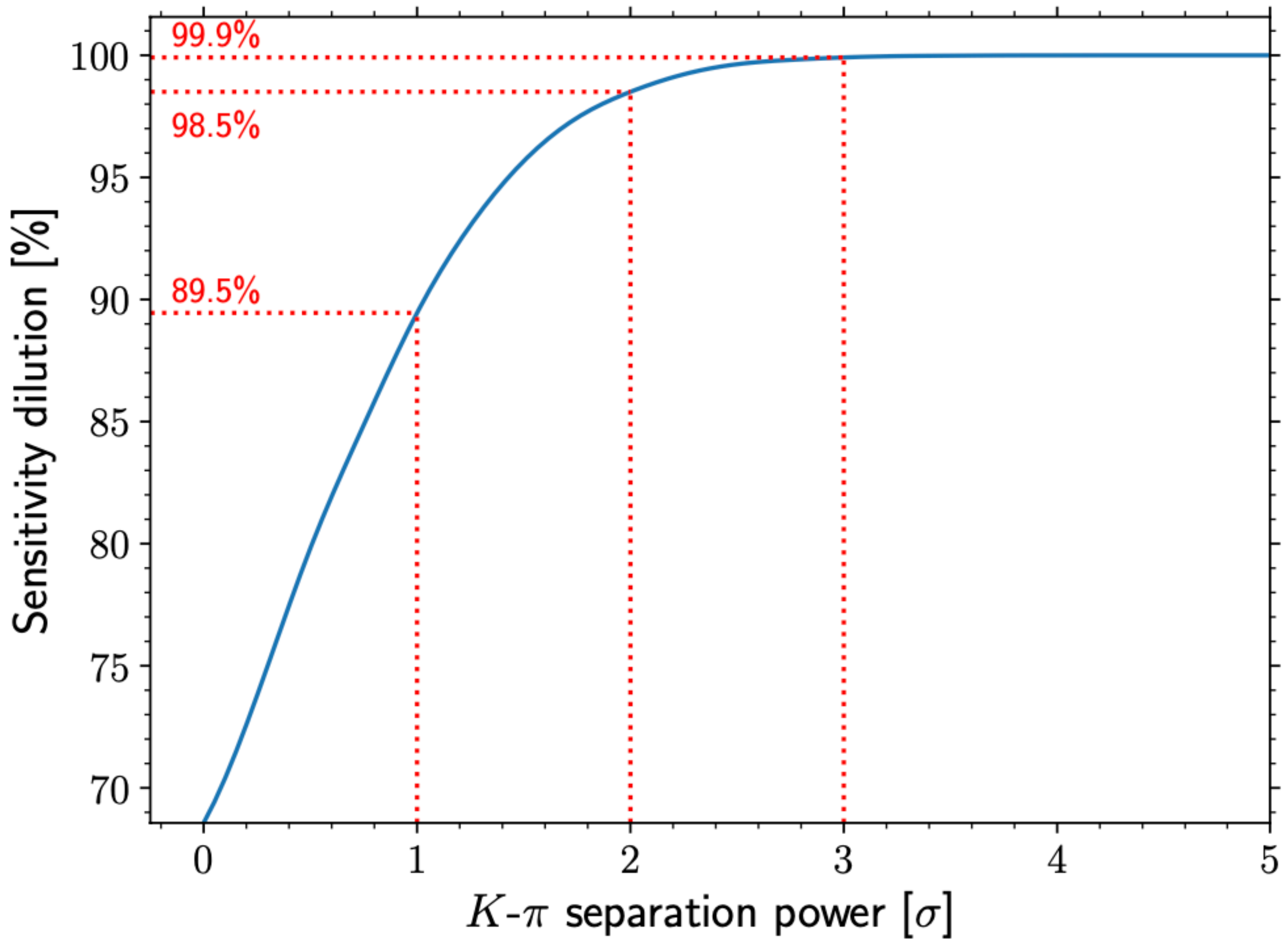



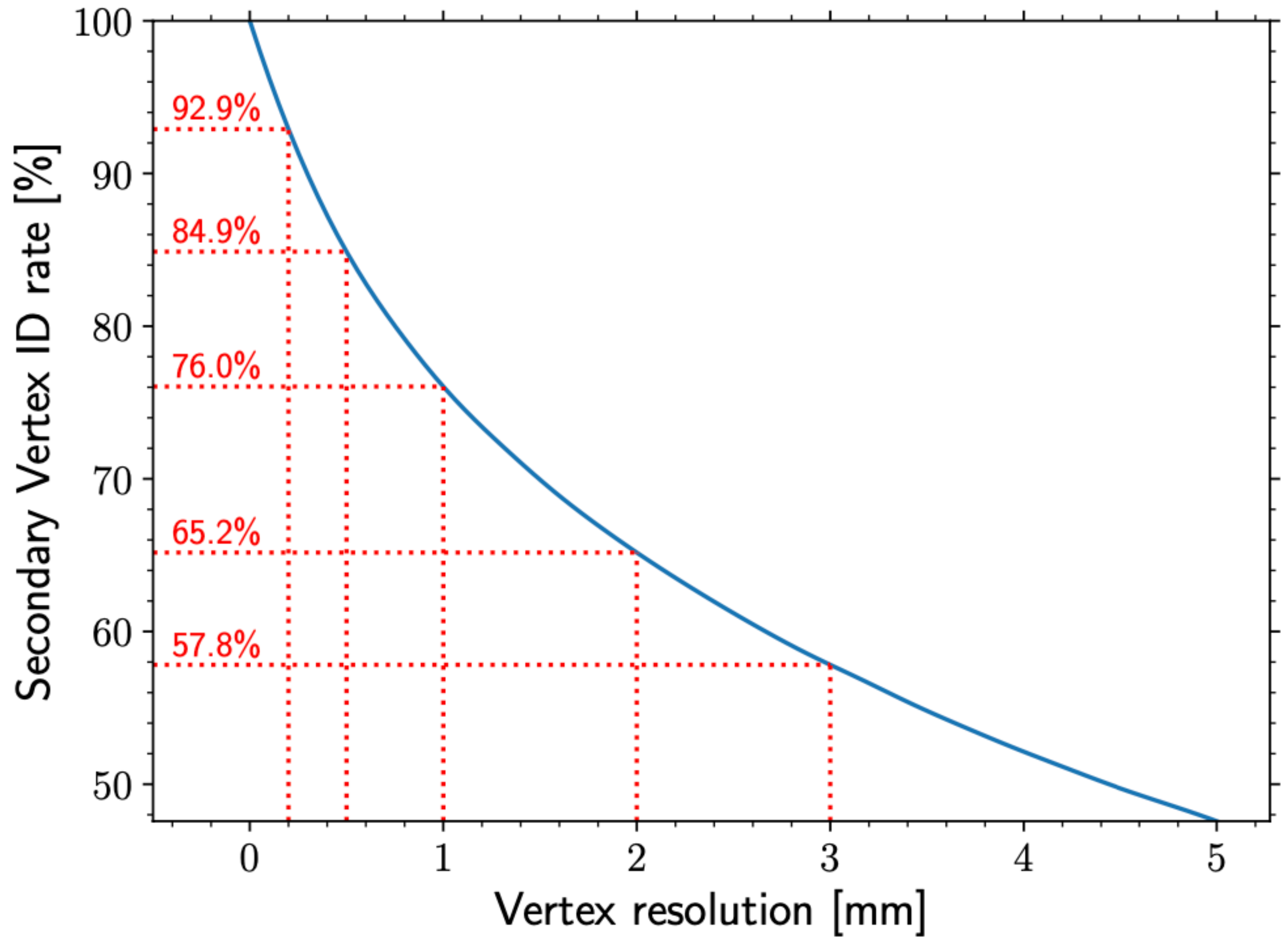
# Vertex requirements: $b \to s\nu\bar{\nu}$

- Effective-operator coupling to 3rd generation **poorer constrained**, e. g. in $\nu_\tau$

→ $\boxed{B^0 \to K^*\nu\bar{\nu}}$ experimentally cleaner than $B^0 \to K^*\tau^+\tau^-$ (+ theoretically immune to $c$-quark loops)

- Particle-ID ($2\sigma$ $K/\pi$ separation) + SV resolution ($\mathcal{O}(10^{-1}$ mm)) not limiting! **. . . but**




→ Systematic uncertainties significant **if no improvement** on $b$-fragmentation functions



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# Lifetime measurement and alignement

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## Just few words

M. Dam, A. Lusiani

- Precise measurements of the mass, the lifetime and the leptonic branching fraction of the tau lepton offer a crucial test of lepton flavour universality (LFU)
  - e.g. potential to measure tau lifetime to sub-10-5
  - Would correspond to flight-distance measurement to a few tens of nanometers
  - Relevant systematics from detector:
    - alignement: optimization of detector design with overlapping layers to be considered.
    - overall detector lenght: could be measured to 5ppm with techniques proposed by Muone. At LEP was 100ppm.

# More on requirements from tau lifetime

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**M. Dam, SciPost Phys.Proc. 1 (2019) 041**

systematic uncertainty:
- take 0.25 $\mu$m alignment uncertainty from Belle 2013
- translates immediately, with higher boost, into a FCC systematic precision $\sim$0.04 fs, i.e. 140 ppm

**S.R.Wasserbaech, Nucl.Phys.Proc.Suppl. 76 (1999) 107-116**

- studies of vertex detector misalignment systematics for ALEPH at LEP
- misalignment effects average to zero at first order
  - measure decay length in transverse plane
  - uniform azymuthal acceptance (note: can be forced by weighting data azymuthally)
- confirmed by more refined studies at BABAR

- vertex detector misaligment can have large effect but can be suppressed and calibrated
- average radius of the vertex detector can be constrained with data using overlapping wafer modules: radius will be known with the same relative precision of the knowledge of the size of the silicon modules, or equivalently the average strip pitch
- LEP, $B$-factories, absolute length scale knowledge of silicon vertex detector believed to be 100 ppm
- A.L. Jan 2020 guestimate for FCC tau lifetime uncertainty limited to 100 ppm by this limitation

**MUonE interferometric monitoring of detector to 1 $\mu$m/50 cm, 2 ppm**

- A. Arena, G. Cantatore, M. Karuza, Digital holographic interferometry for particle detector diagnostic, Proceedings of the International Convention MIPRO, May 2022, doi:10.23919/MIPRO55190.2022.9803636
  - During preliminary tests, we have obtained reconstructed holographic images with interference fringes showing a displacement of the monitored object, over time, of the order of $\sim$1 $\mu$m. This experimentally demonstrated resolution is already sufficient to satisfy the 10 $\mu$m resolution mandated by MUonE. [MUonE silicon modules are 50 cm apart]
- also absolute calibration required in addition to monitoring, appears feasible with optical techniques
- 2 ppm tau lifetime sistematics from vertex detector length scale appears attainable

E. Perez

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# General considerations on timing

- Few motivations for precise timing measurement have been explored, likely this will be expanded significantly next year with the FullSimulation:
- TOF measurements:
  - For PID: e.g. at 2m from the IP, in dedicated layer or in SiW Ecal. To compensate the dN/dx ~around 1GeV
  - Determination of mass and lifetime of new massive particles
- Time measurements in the calorimeters
  - Handles to exploit the shower development in space and time
    - Possible benefit remains to be studied in detail
  - DR calo: precision timing -> longitudinal segmentation
- Time measurements very close to the IP allows a determination of the "event t0":
  - Robust reference for the TOF measurements (it is always a Dt!)
  - Width of t0 distribution -> independent determination of the BES
  - (maybe) Exploit correlation between t0 and longitudinal position (within the bunch) of the interacting electrons
  - ...and maybe 4D tracking?
- Possible to achieve precise timing measurements in the innermost layer of the VXD, without compromising heavily the material budget?

# Explicit Inclusion of Secondary Vertex

Studies conducted on CLD full simulation [FCC note]

- Retrained PN tagger with added vertex position information and invariant mass of the vertices
- Invariant mass distribution features peak at K0 mass, vertex multiplicity material interactions from innermost vertex layers
- **Tagger performance does not benefit from explicit inclusion of secondary-vertex information**