Physics Requirements on Vertex Detectors Performance

Thanking all the colleagues I stole material from: L. Gouskos, A. Ilg, E. Perez, L. Roaring, A. Ciarma, A. Sciandra, M. Selvaggi…etc etc…

Patrizia Azzi (INFN) - MAPS detectors technologies for the FCC-ee vertex detectors

Introduction

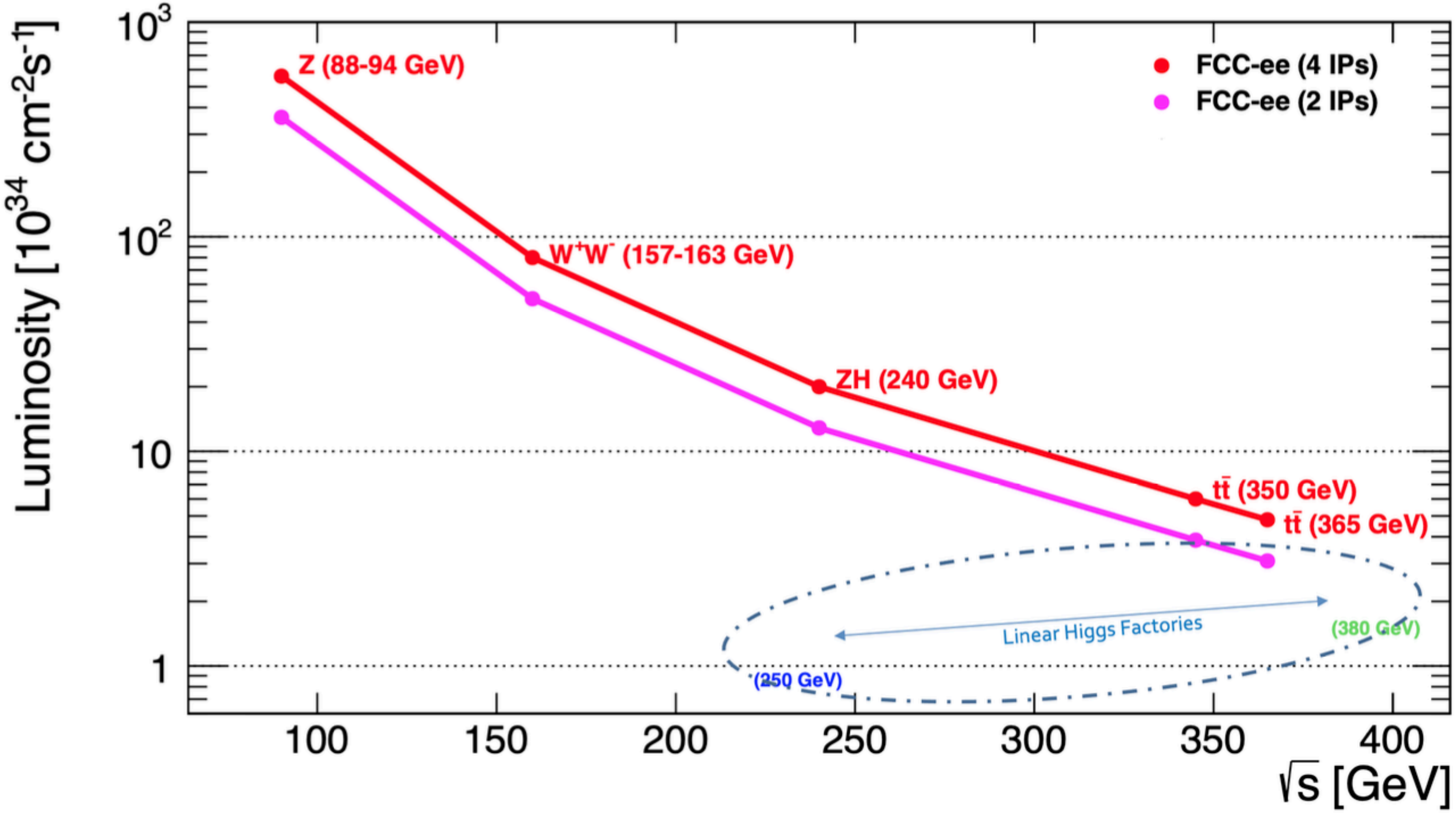
Revising physics requirements for EWK/Higgs/top factory

- **The detector requirements for a EWK/Higgs/top factor such as te FCC-ee need to be extensively revised. This has been the driving idea behind of the work of the past years.**

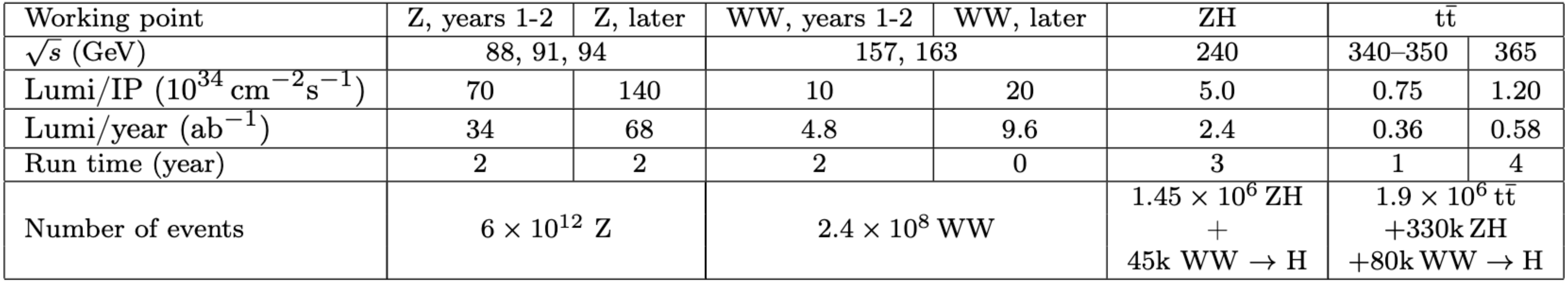
- **Several reasons:**
  - Different experimental environment —> See next talk by M. Boscolo
  - Exquisite precision on EWK measurement at the Z and WW
  - When statistical errors are minuscule the focus is on the control and reduction of systematic uncertainties (from acceptance, construction quality, stability…)
  - Huge statistics at the Z allows a unique ad extensive Flavor program with specific reconstruction needs
  - Huge statistics at the Z allows a unique discovery potential for very weakly coupled BSM particles that needs to be considered in the detector design
  - A whole program at $\sqrt{s}$=365GeV for top and Higgs that might have yet different detector needs

FCC-ee Energy range & luminosity

Producing in a clean environment all the heaviest SM particles



FCC-ee Energy range & luminosity

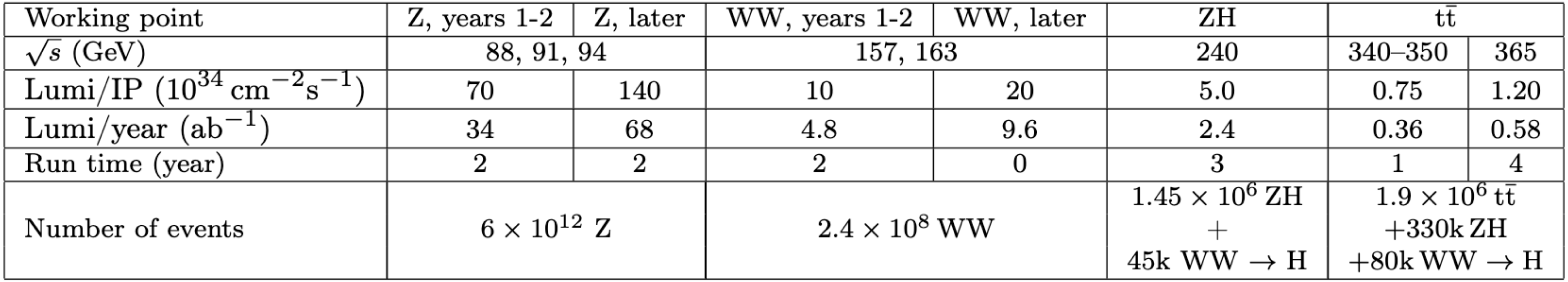


Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW → H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW → H	

“Tera-Z”

FCC-ee Energy range & luminosity

LEP Data statistics accumulated every 2 minutes!



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In each detector:
10^5 Z/sec, 10^4 W/hour,
1500 Higgs/day, 1500 top/day

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"Tera-Z"

Never produced before at a lepton collider!

Extracting detector requirements

- Choose representative measurements or searches, that are key to the e^+e^- physics program and that put constraints on the performance of one, or several, subdetectors

  - ➤ Reducing major experimental systematics uncertainties
  - ➤ Extending sensitivities/acceptance

- Ultimately, which processes set the tightest constraints on a given performance metrics will be known **only when analyses are completed** (interplay of reconstruction tools, backgrounds etc)

  - ➤ Different detector concepts could make different trade-offs
  - ➤ Multiple detector options allow to diversify the design

Physics that needs an excellent vertex detector

HIGGS: Jet flavour identification (tagging) of b-, c-, g-, tau- etc… Measure of Higgs couplings

Z: Jet flavour identification (tagging) for HF EWK observables Rb, Rc, AFB,

W : Jet flavour identification (tagging), CKM parameters V_{cb}

Pure WP for calibration

FLAVOUR: precise reconstruction of PV/SV/TV for flavour physics

e.g. time dependent CPV measurement, rare decays $B \to K^*\tau\tau$, τ 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: how low can we go?

- **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**

√s dependence

Generic requirements

Need to find a middle ground

- Complete coverage
- Smallest possible inner radius
- Exquisite spatial resolution
- Small occupancy for beam related backgrounds
- Smallest material budget
- Excellent alignement
- Effective cooling

…Needs and constraints can be different at different $\sqrt{s}$

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One word on the context

Vertex connection with the main tracker & simulatio tools

- **“Case studies” allow to evaluate the effect of different design choices via the final measurement uncertainties.**
  - Different for different √s
  - Need to consider also tracking

* F. Bedeschi

- **Availability of Delphes with fancy covariance matrix approach* allows to properly treat point resolution error and multiple scattering effects from material.**
  - But no account for fakes and pattern recognition errors (impacting also DAQ)
  - Vertex design choices can impact significantly also these aspects, but we need FullSimulation with complete background treatment and reconstruction: no simple solution, trade offs are necessary.
    - These would be related to: **granularity, redundancy, hermeticity.**

Work In Progress

Basics of vertex dectector

- **The tracks impact parameter is driven by the performance of the Vertex detector that is placed closest to the interaction point and provides and very precise position information.**
- **Precise Impact parameter is key for the primary and secondary (tertiary) vertex reconstruction, for identification of heavy quarks (b,c) and taus leptons, and for lifetime measurements.**

$$\sigma(d_0) = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

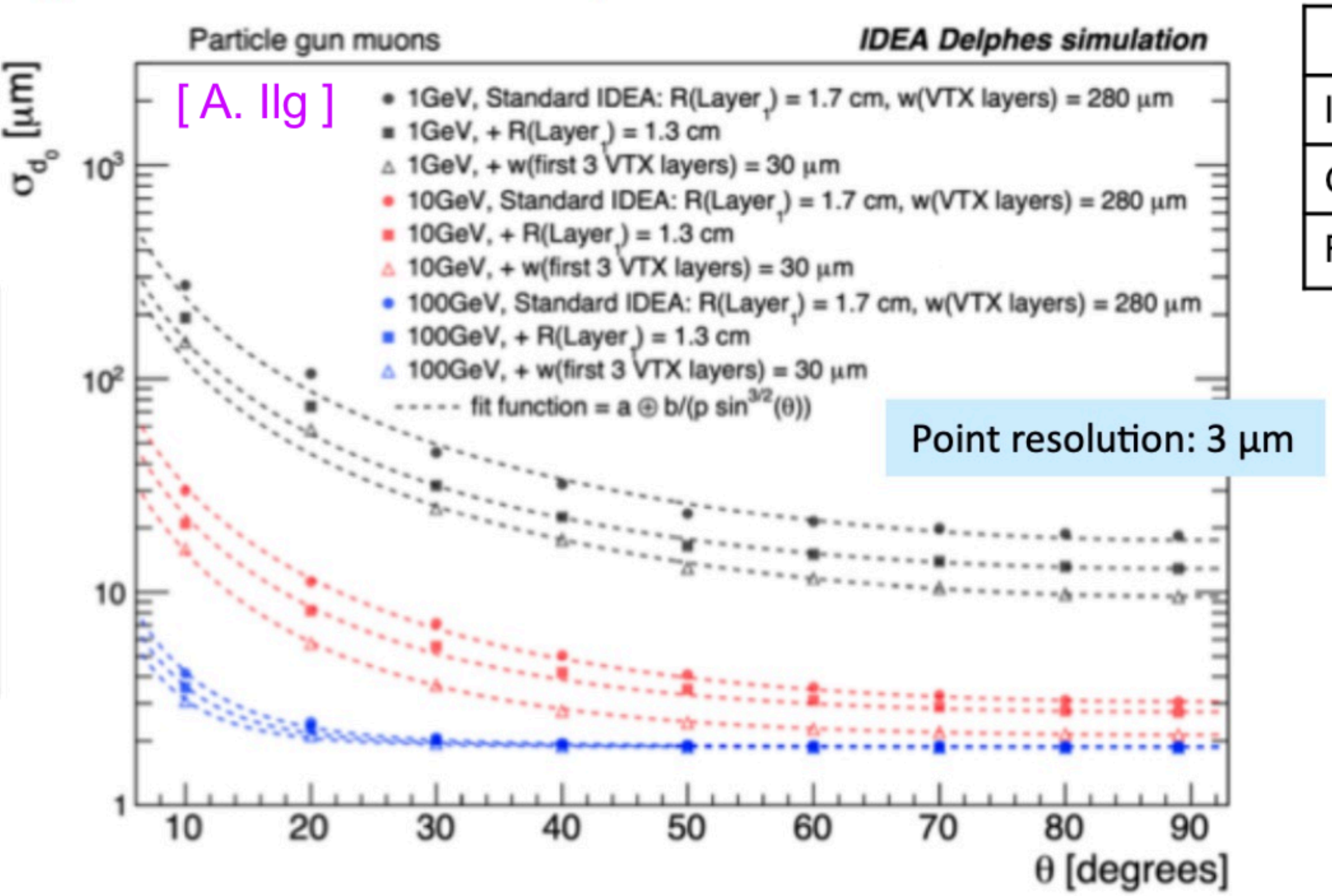
- The asymptotic term a is driven by the single hit resolution, while the multiple scattering contribution depends on the material budget.
- The samples generated in Delphes for the MidTerm report physics studies, considered a beam pipe of r=1cm, with the first layer at r=1.2cm and single hit resolution of 3um. Some alternative designs have been explored as well to extract specific requirements on the VXD.

Impact parameter resolution

Delphes studies

- Closer (■), lighter (△): Substantial improvement on impact parameter resolution in particular at low momenta

A. Ilg, L. Freitag, 6th FCC Physics Workshop



Point resolution: 3 μm

	r beam pipe	1st VTX layer
ILC	12 mm	14 mm
CLIC	29 mm	31 mm
FCC-ee / CEPC	10 mm	12 mm

Central beam-pipe:
0.67% / sin θ of X0

New studies are in progress with FullSimulation and more realistic digitization

W,Z,H and top

Identifying Jets

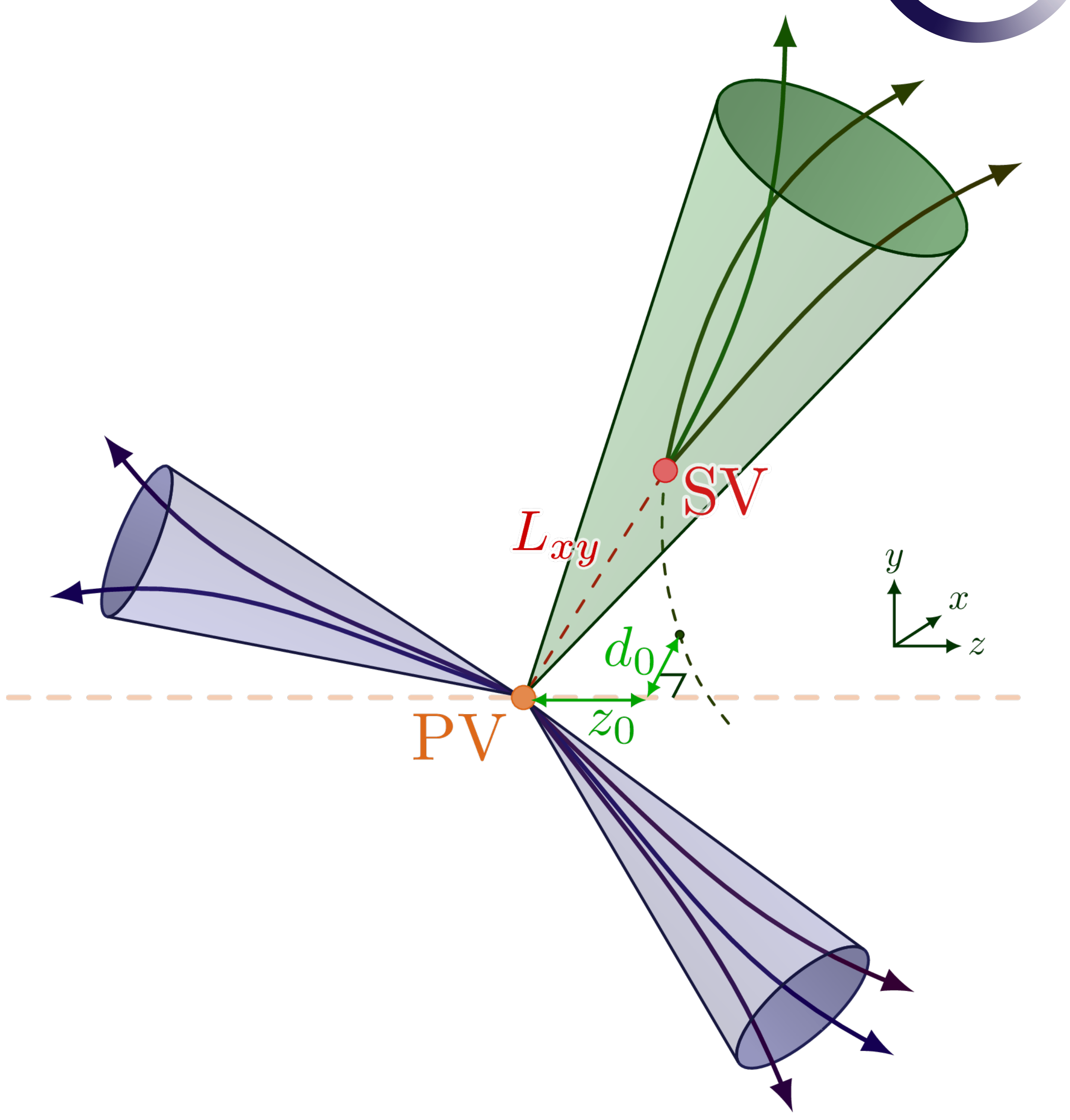
- **Many crucial physics measurements need to exploit hadronic decays of Z,W,H,top (i.e. jets):**
  - At different center of mass energies from √s=90 to 365GeV
  - Because of larger BR, in addition to the leptonic final states. i.e. ZH recoil with hadronic Z decays, top properties)
  - Clean final state 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*

Flavor tagging principles

From hadron to lepton colliders

- **Bottom and charm tagging:**
  - Large lifetime (~1/0.1ps) and decay length (~500μm)
  - Significantly displaced tracks and vertices:
    - Primar vertex reconstruction
    - Secondary and tertiary vertex reco
  - Large track multiplicity (~5 charged), larger than light quarks or glues
  - “Soft” non isolated charged lepton inside the jet in 20/10% of te time for b/c-hadrons decay

- **Note: higher performance on bottom/charm in helps classification of strange, light quarks, gluons, etc…**



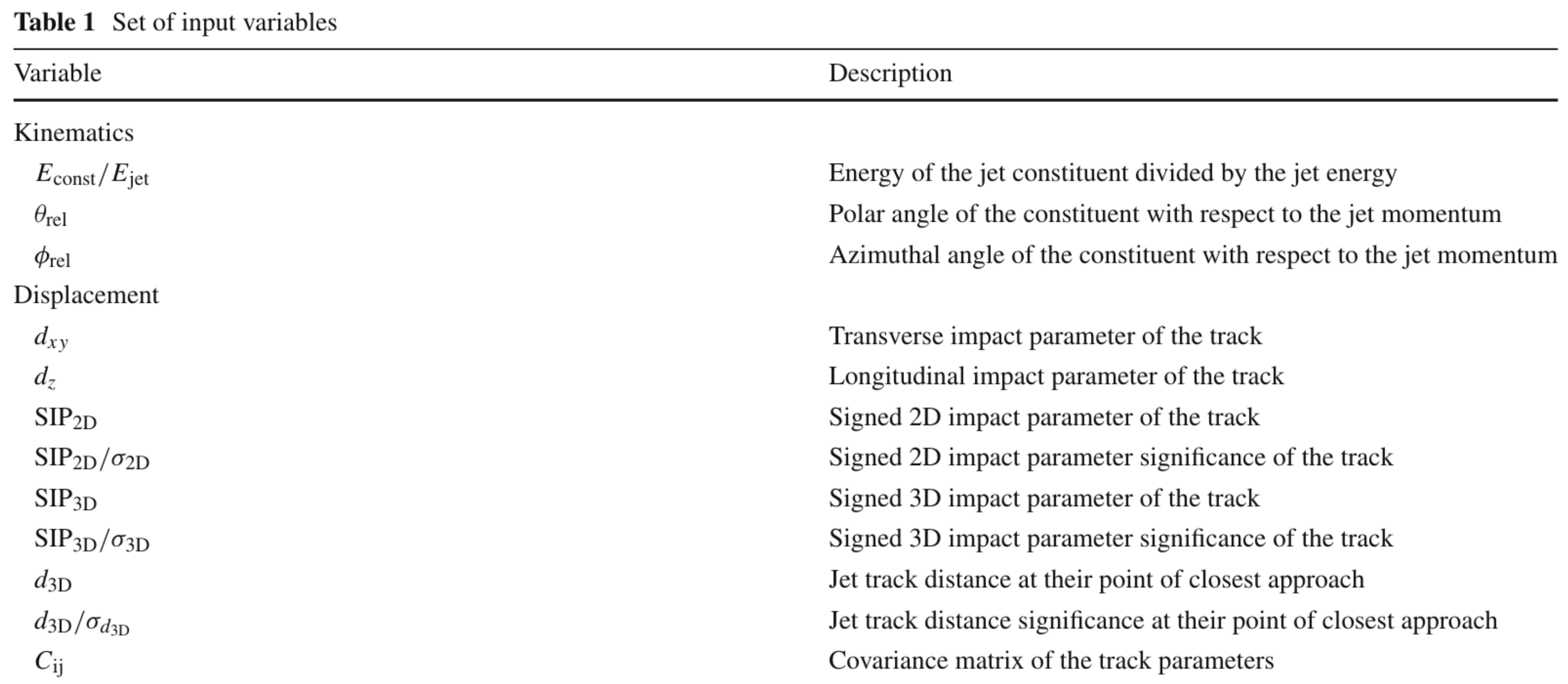


Table 1 Set of input variables

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

Uncertainties on the track IP and PV, SV and TV reconstruction are inputs to the algorithm

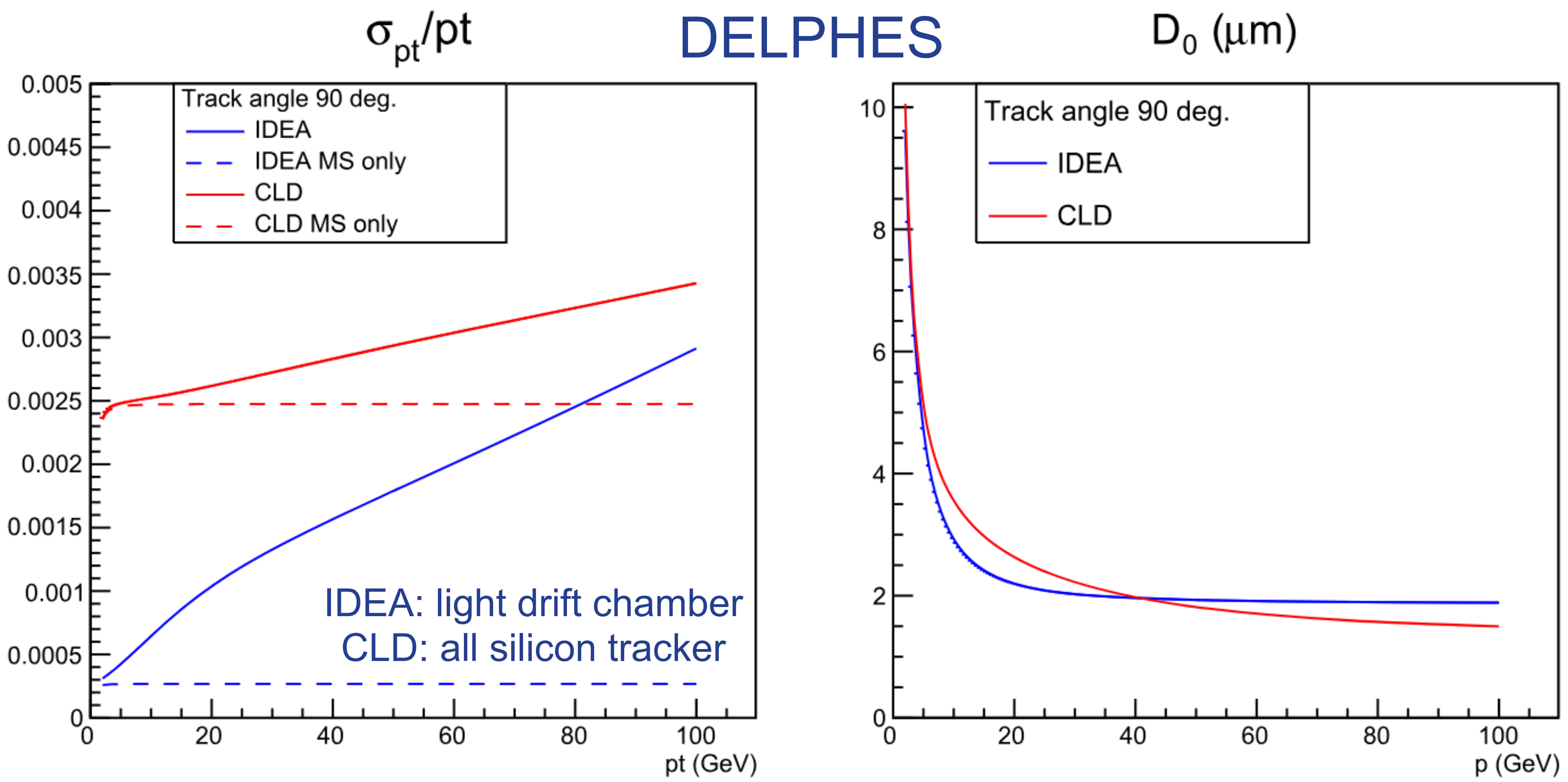
Dissecting tagger performance

Connecting detector characteristics to macroscopic quantities

- **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/X₀
- **Studies in Delphes with FastCovTracking (and now also in FullSim) to evaluate the dependency from point resolution**
  - Input: $3\mu m$ point resolution
  - Here CDR geometries

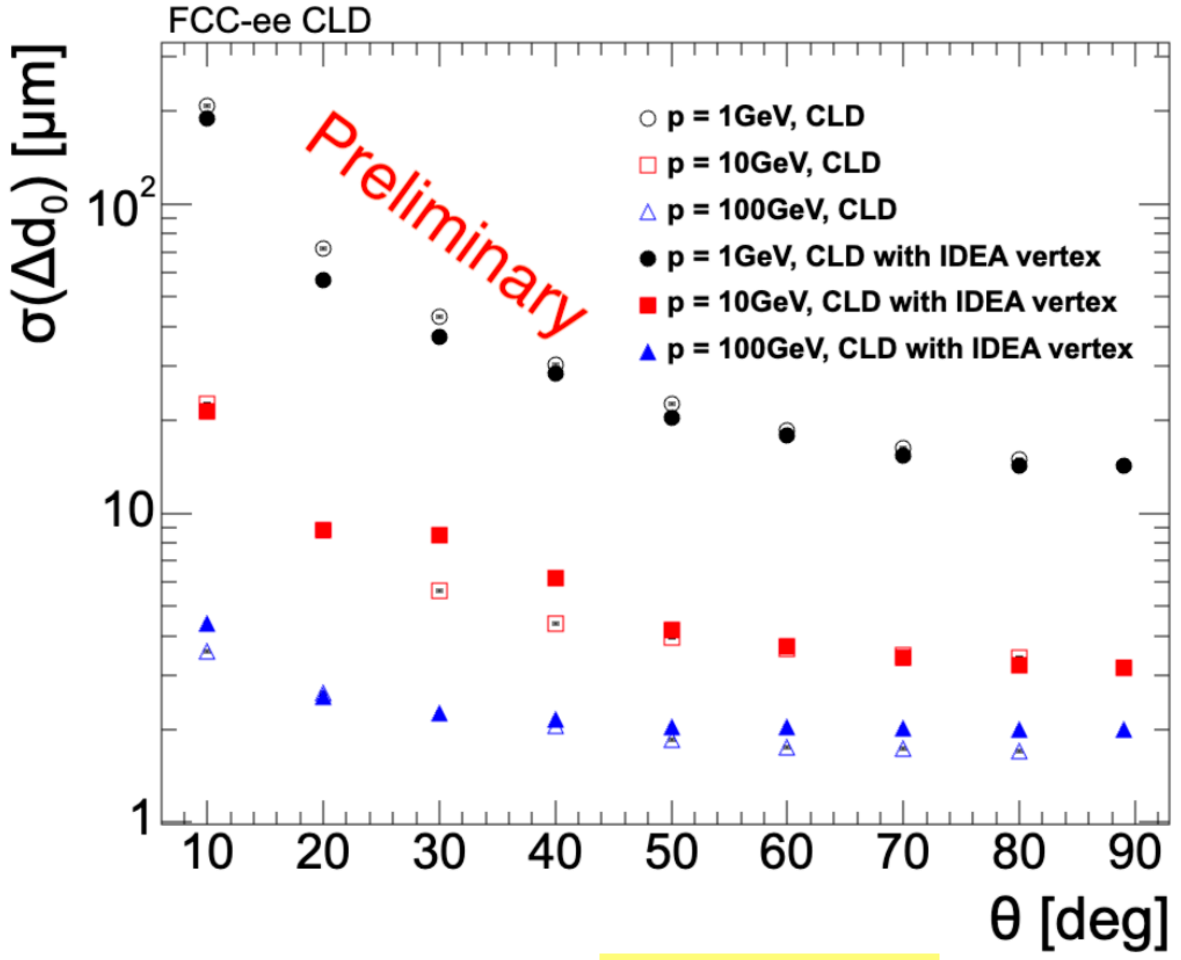
At the moment no detailed digitisation and clustering available in FullSim for the vertex detectors (WIP). Will need them for refined optimisation about the geometry and placement

DELPHES



IDEA: light drift chamber
CLD: all silicon tracker

FULL-SIM



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

Armin Ilg

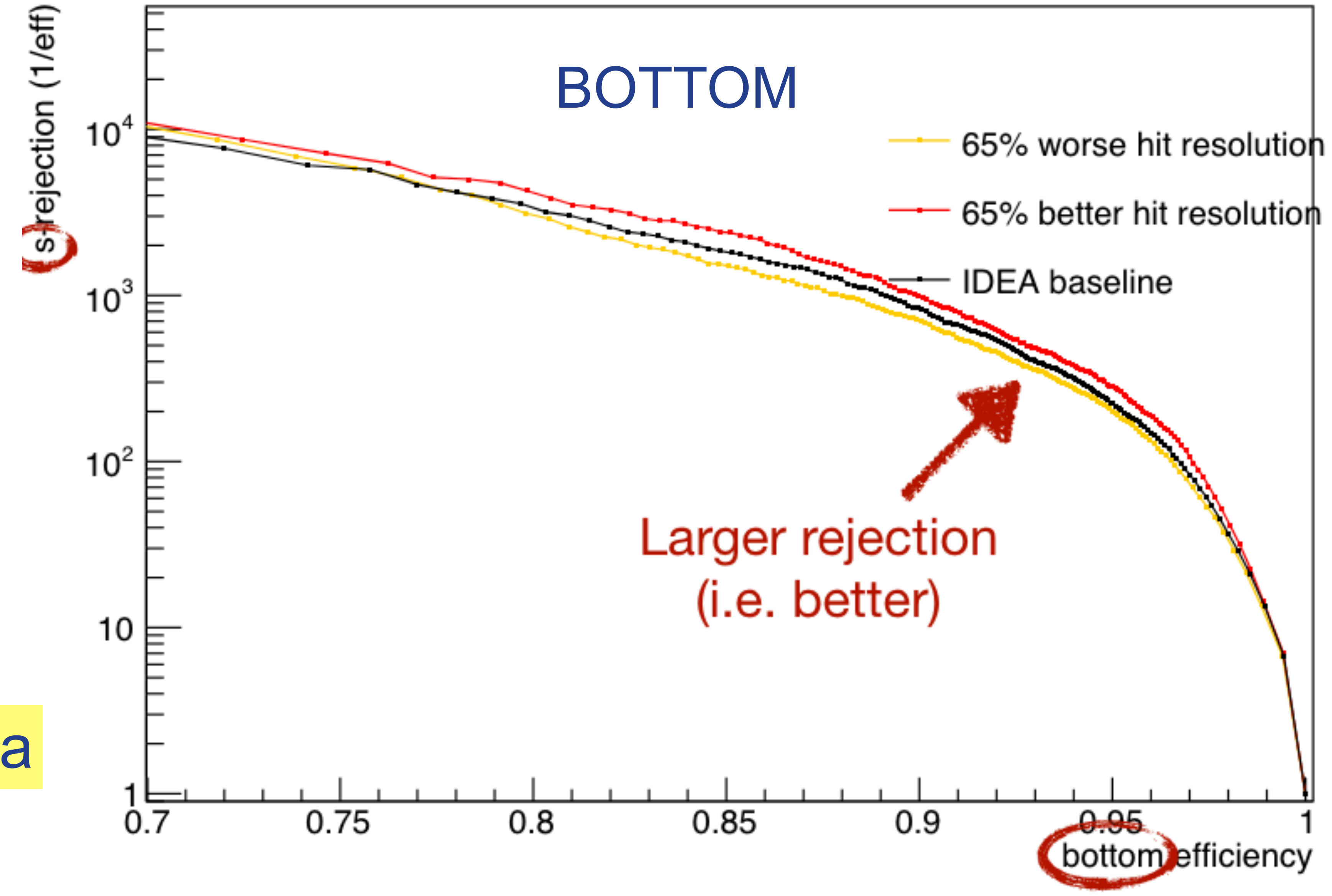
Dissecting tagger performance

Connecting detector characteristics to macroscopic quantities

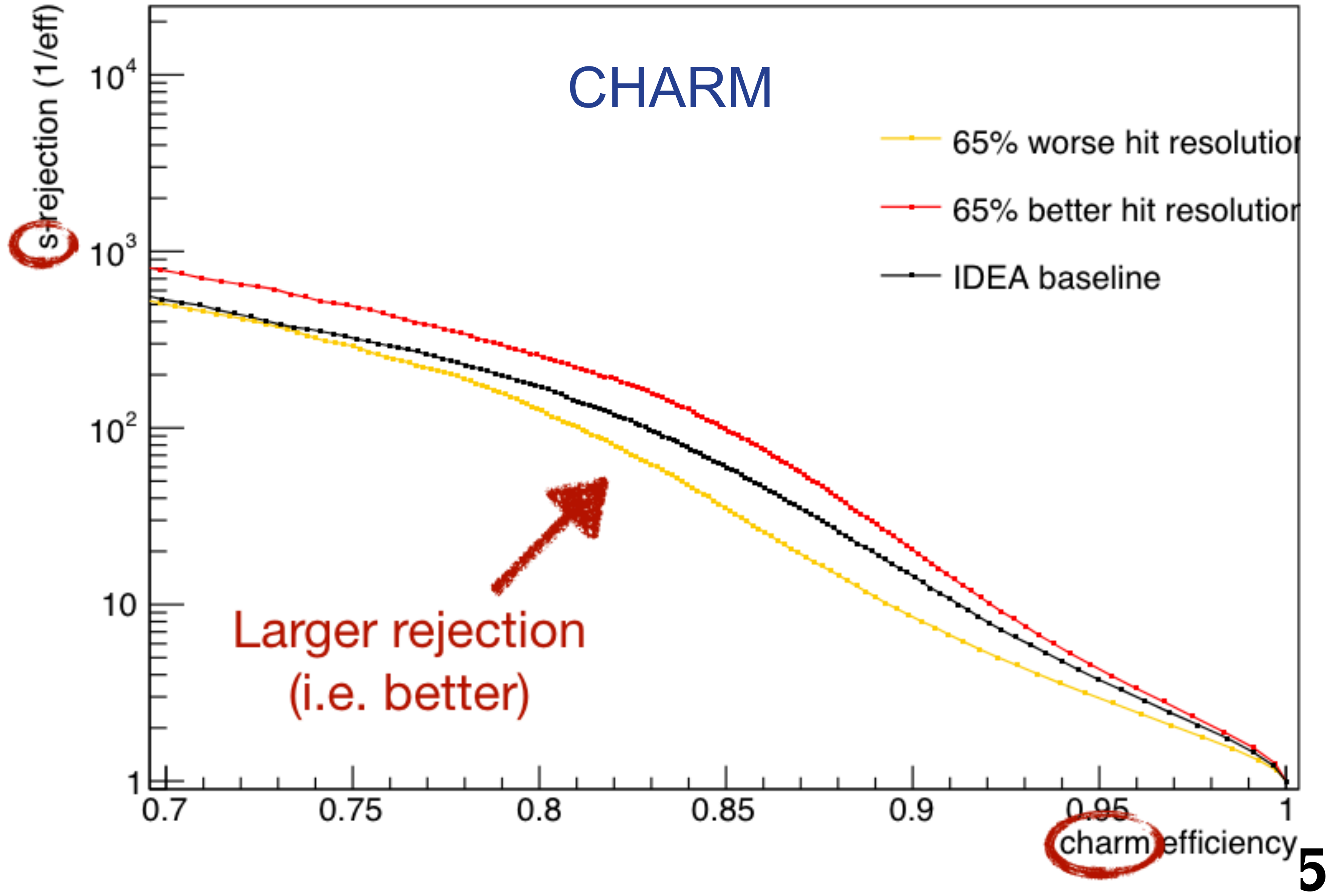
- Impact parameter resolution is a major driver for b/c tagging
  - Single point resolution
  - Radial distance of first tracking layer <-> beam pipe radius
  - Number of layers
  - Material budget X/X_0

- New studies in Delphes retraining the tagger:
  - Negligible effect on bottom, but visible on charm

Andrea Sciandra



Larger rejection (i.e. better)



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- **Impact parameter resolution is a major driver for b/c tagging**
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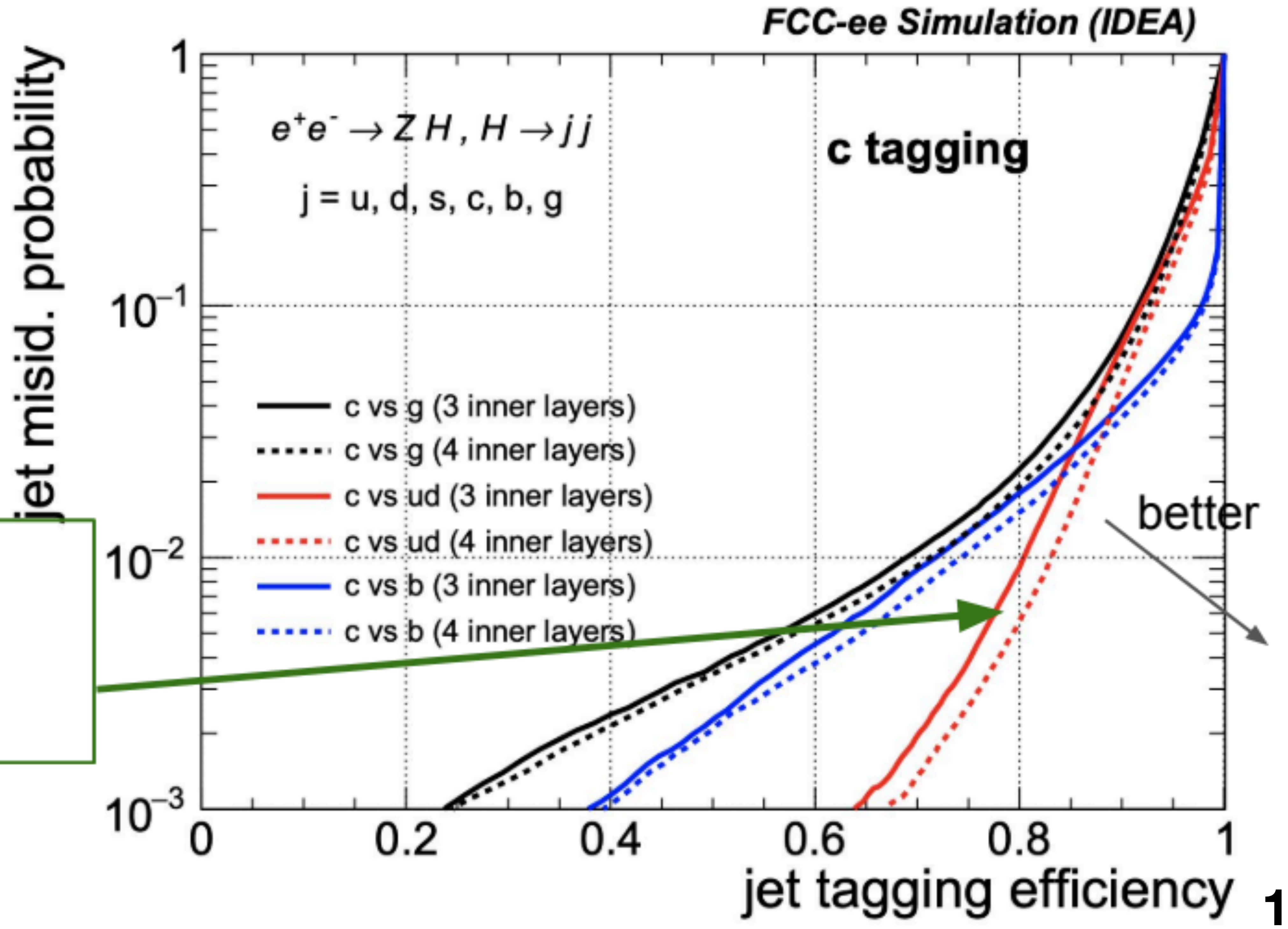
  - Number of layers
  - Material budget X/Xo

- The distance of the first vertex detector layer to the interaction point is the most important parameter for IP resolution and consequently b and c tagging performance.
  - In this study: 3layers, innermost at 1.5 cm
  - Addition 4th layer at 1cm (before change of beam pipe radius)

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

INITIAL STUDY



30-40% improvement in bkg rej using :
1st layer at 1 cm

Dissecting tagger performance

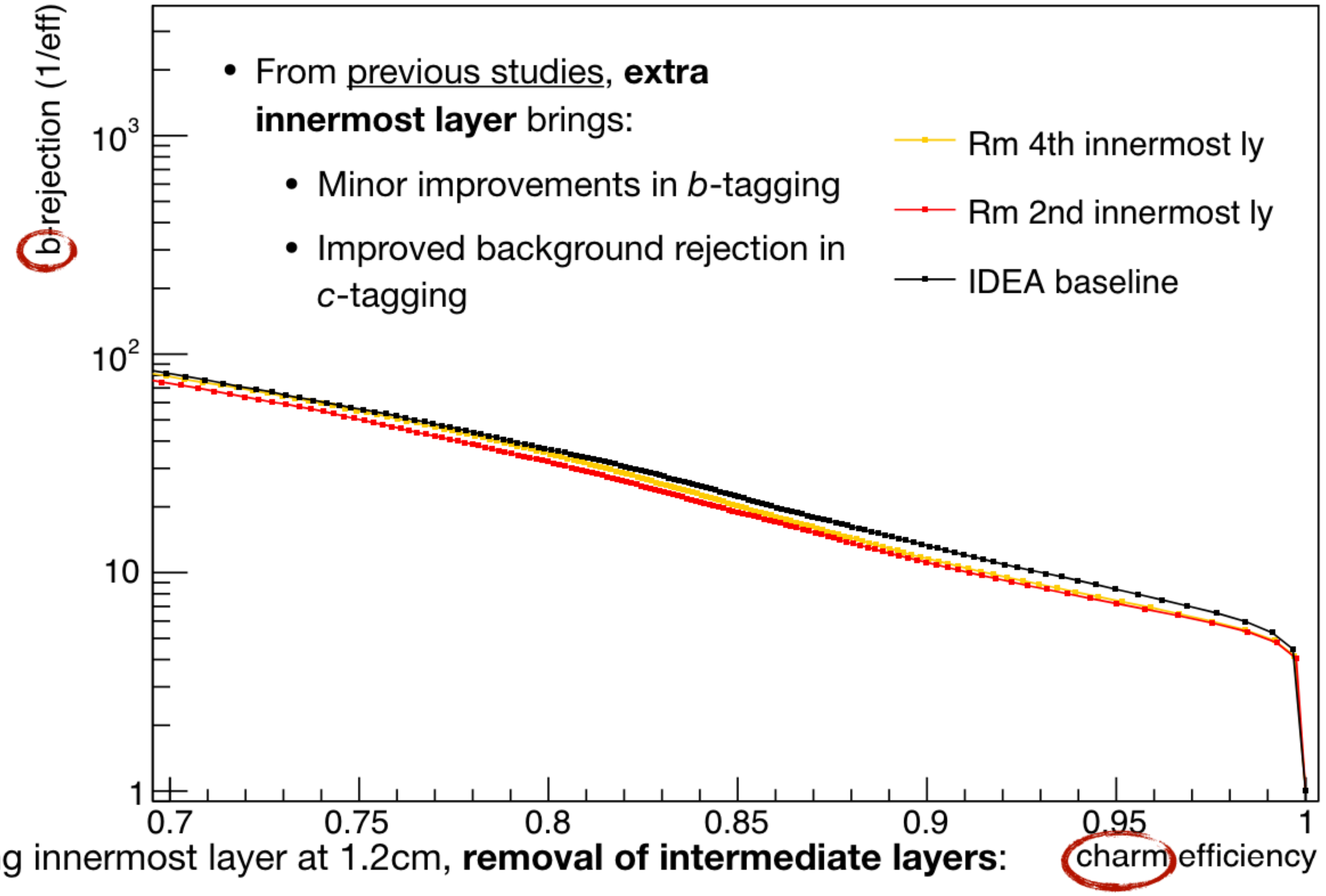
Connecting detector characteristics to macroscopic quantities

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

- 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/Xo

- New studies retraining Delphes:
  - Innermost layer at 1.2cm
  - Remove 2nd and 4th innermost
- As seen before: charm tagging sensitive to the number of pixel layers (while bottom not)

Andrea Sciandra



- 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:**

Dissecting tagger performance

Connecting detector characteristics to macroscopic quantities

- **Impact parameter resolution is a major driver for b/c tagging**
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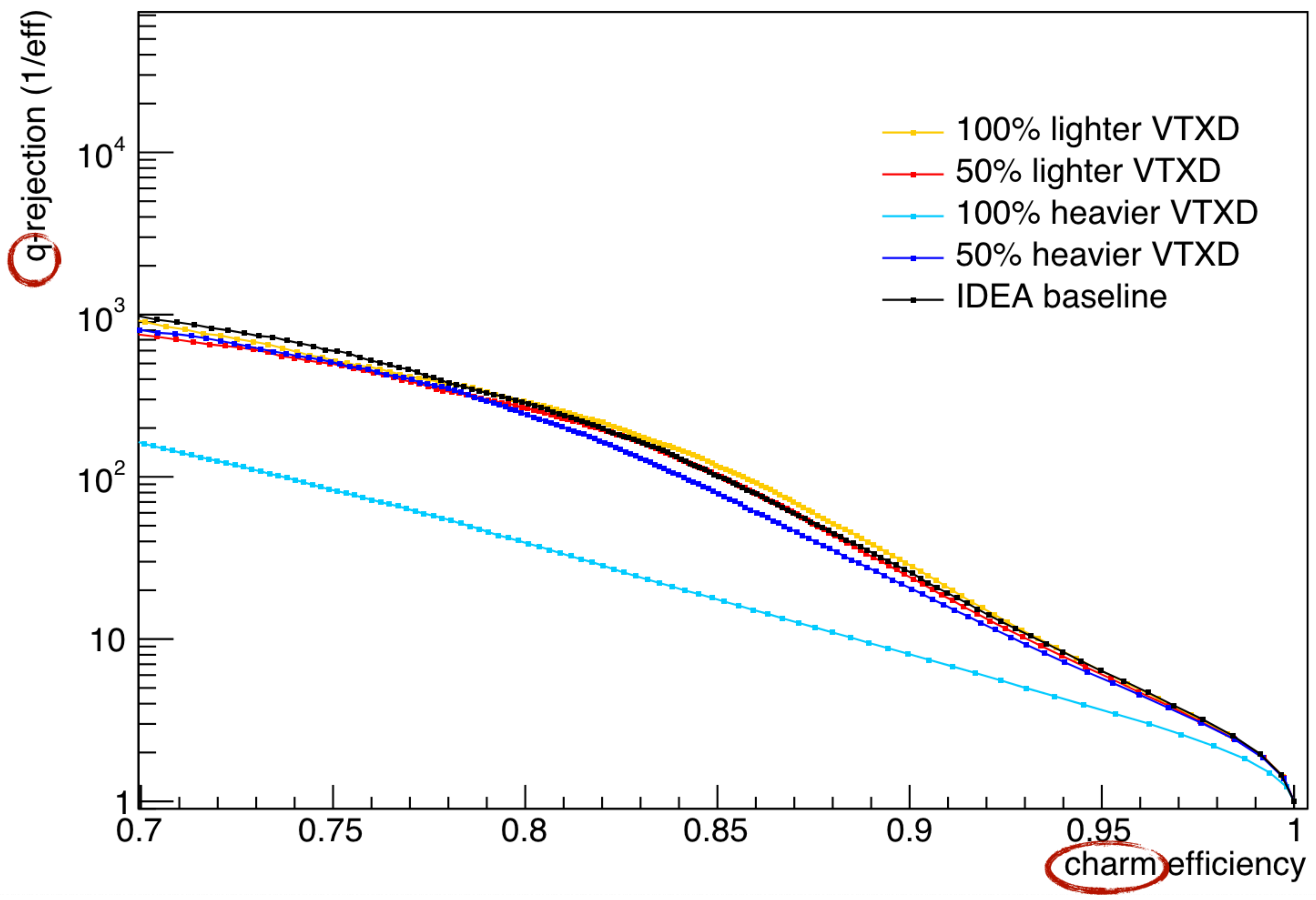
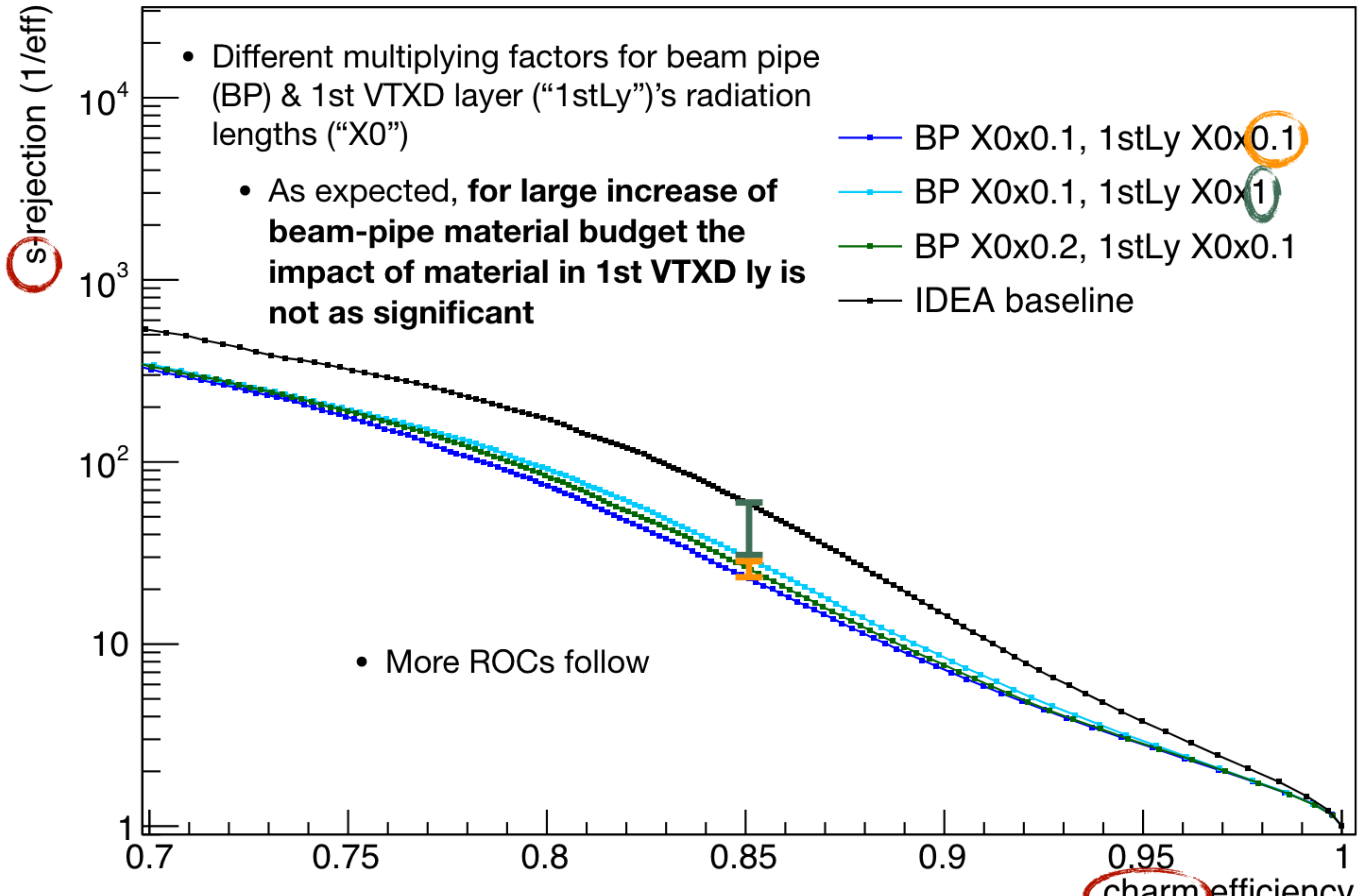
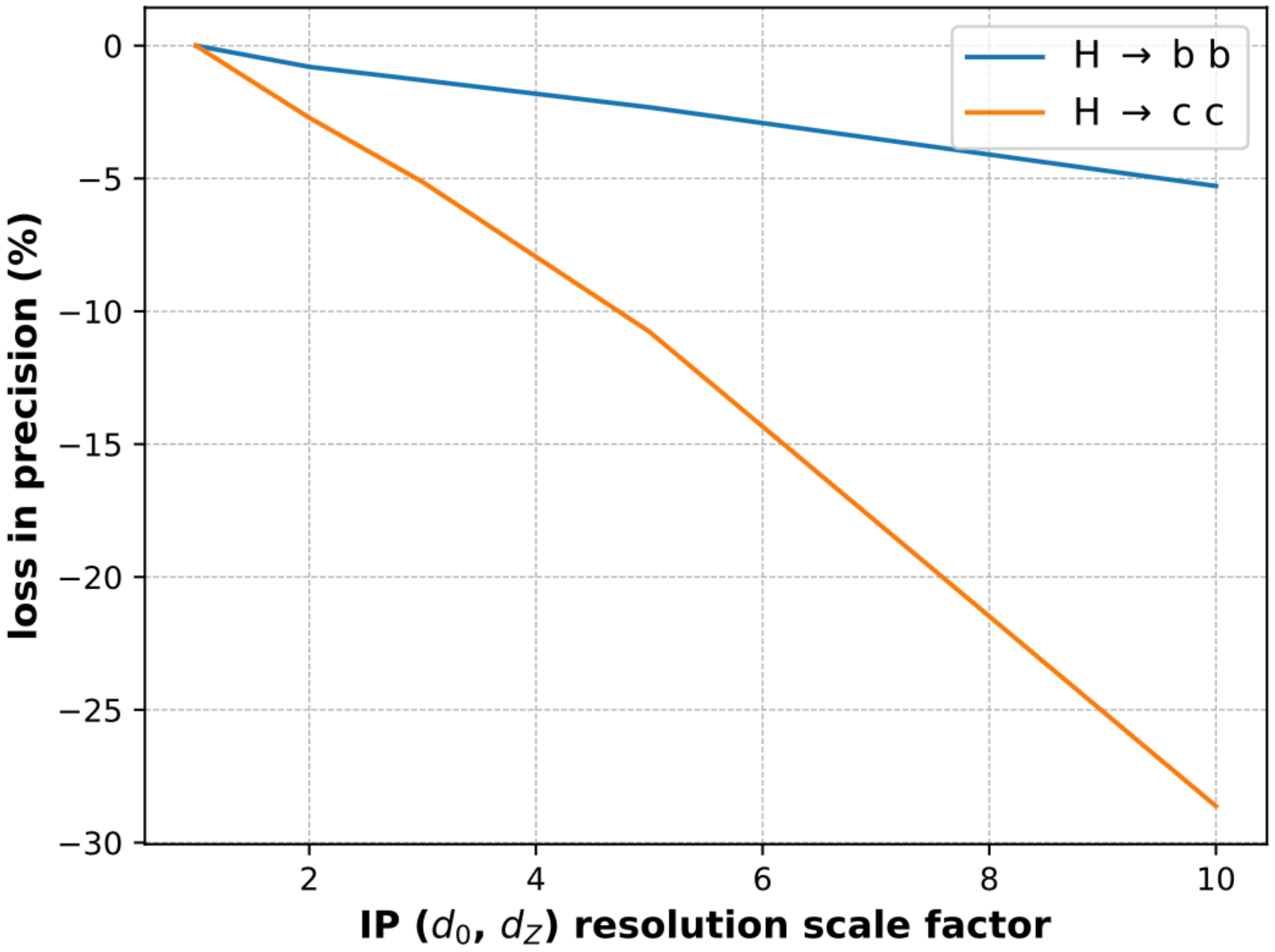




- Different multiplying factors for beam pipe (BP) & 1st VTXD layer ("1stLy")'s radiation lengths ("X0")
  - As expected, **for large increase of beam-pipe material budget the impact of material in 1st VTXD ly is not as significant**
  - More ROCs follow

Impact on measurement precision

Bottom and Charm Yukawa coupling



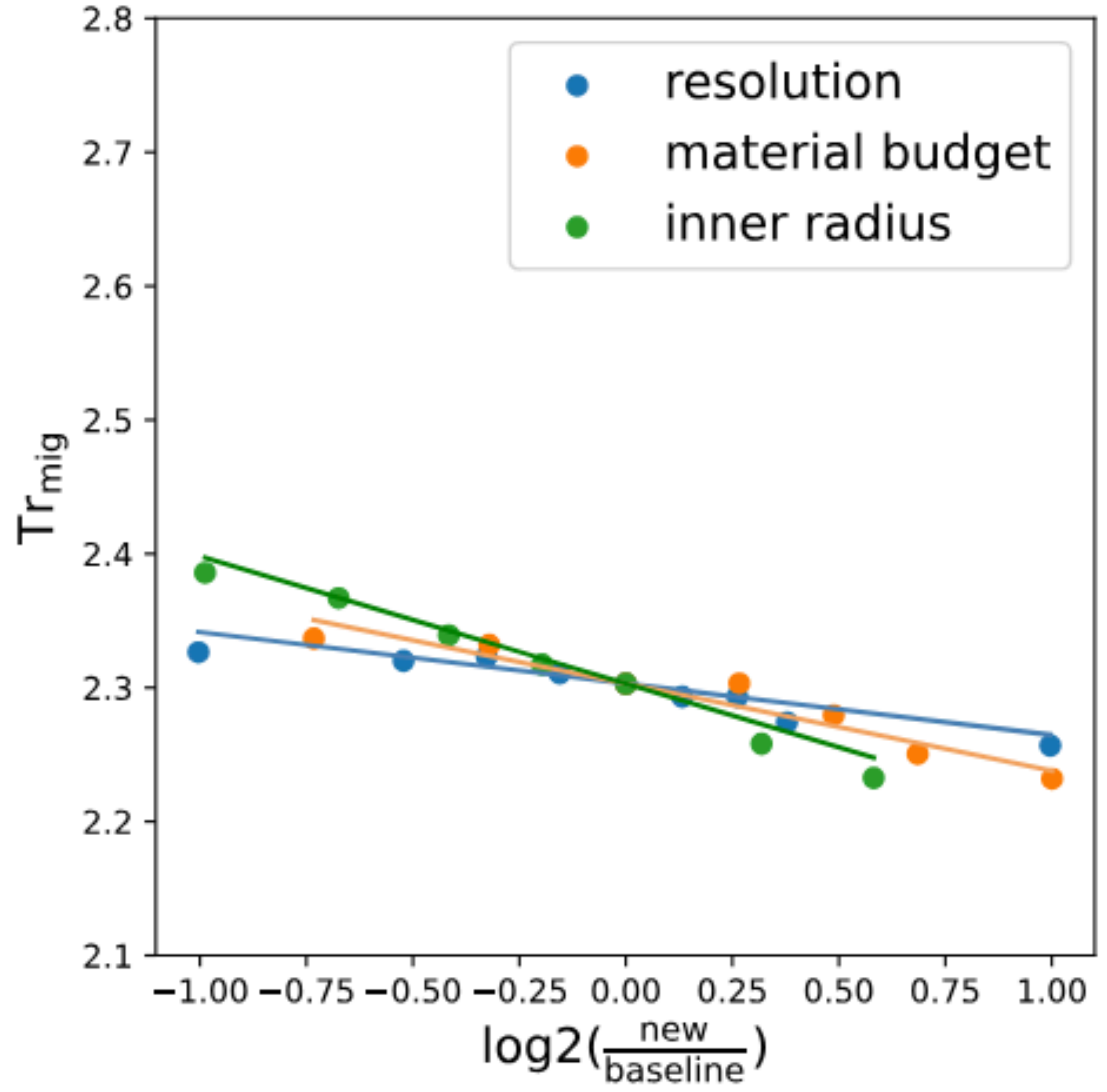
- **Charm Yukawa unique precise measurement at FCC-ee**
- **Dependence of the final precision on IP resolution**
  - Need the full analysis, combining several final states
  - Bigger effect on the charm Yukawa than on bottom:
    - Small S/B ratio
    - Short flight distance of the charm requires better resolution to be resolved

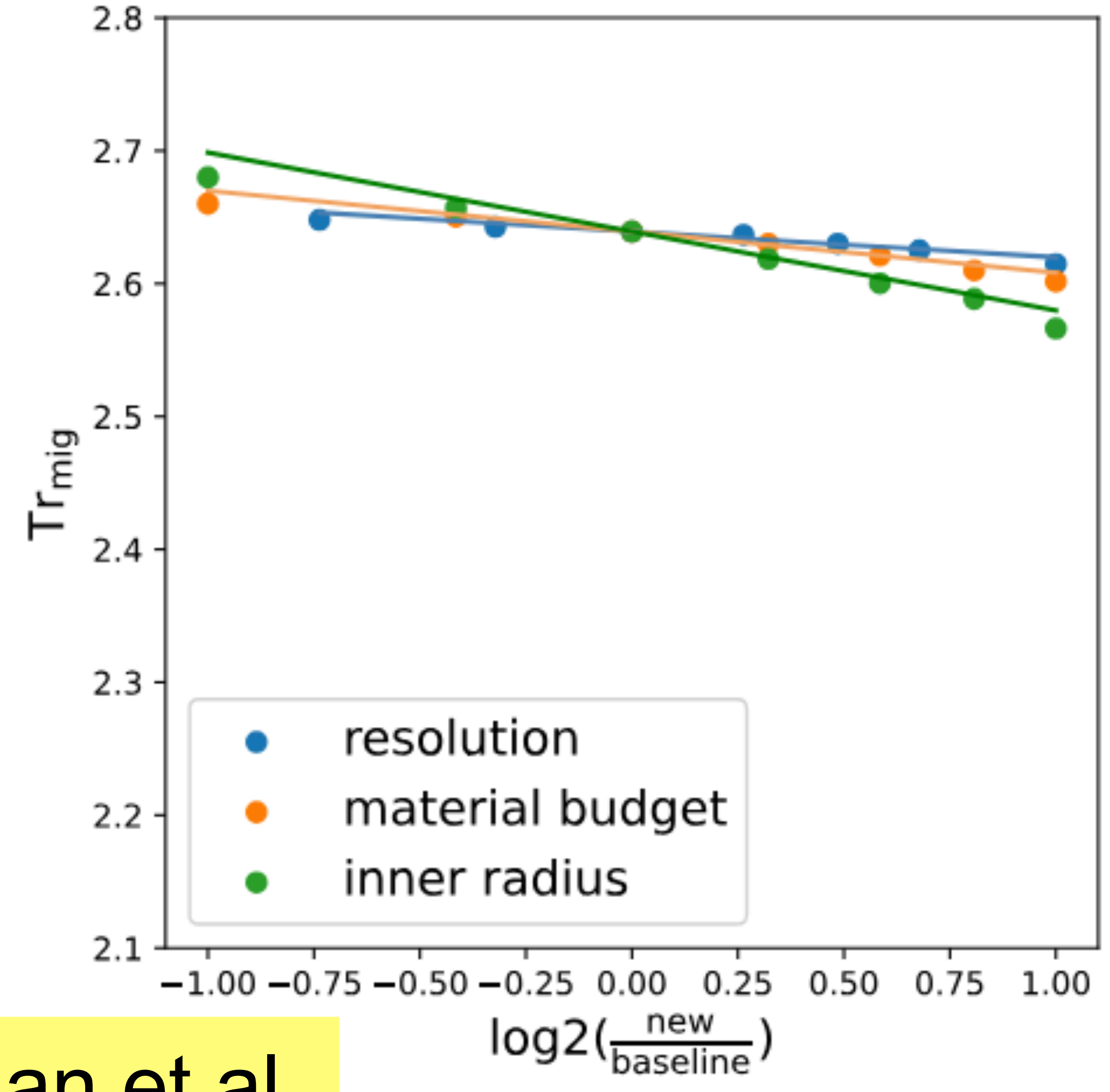
Factor 2 degradation(improvement) in the IP brings factor 3% degradation(improvement) on the measurement: $\delta\mu(Hcc) = 2.05\,\% \rightarrow 2.64\,\%$

Impact on measurement precision

https://arxiv.org/pdf/2309.13231

- **A CEPC study of the variation of precision on signal strength as a function of detector parameters, such as material budget, single hit resolution and radius of the 1st layer.**
  - Comparison of LCFI+ with ParticleNet: important not to neglect the impact of different software
  - ParticleNet has a lower dependence on the geometric parameters.
  - However, both methods have the same order of impact for three different geometric parameters.
  - Both identify the inner radius as the most sensitive to flavor tagging performance and spatial resolution as the least sensitive
- **Study considers effect on variation of accuracy of final measurements for various processes**



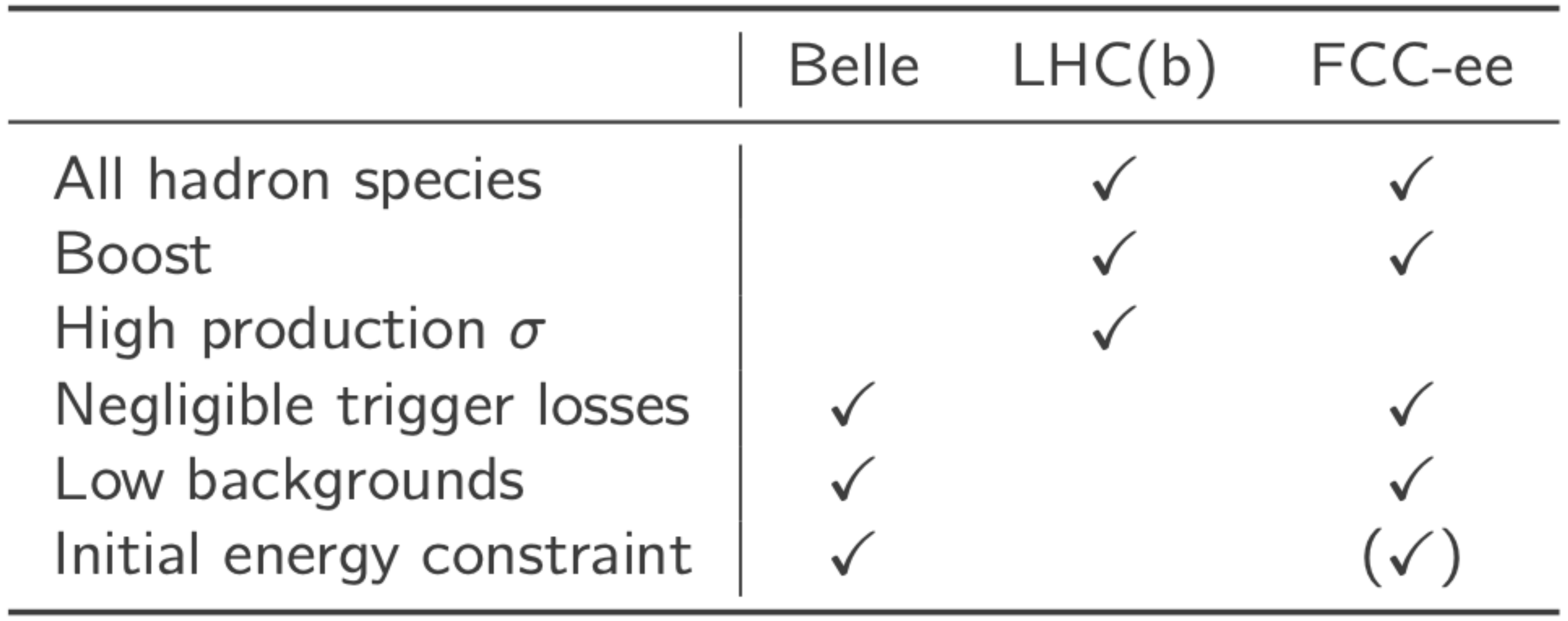


M. Ruan et al.

Requirements from flavour physics

Tera-Z unique flavour physics environment

- **Z pole run provide extensive opportunities not only for EWPO, but also for unique flavour physics measurements**
  - About 15 times more $B^{0,+}$ mesons compared to Belle II
  - b-quark boost $\langle\beta\gamma\rangle \approx 6$ for ultra-clean selection



	Belle	LHC(b)	FCC-ee
All hadron species		✓	✓
Boost		✓	✓
High production σ		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

- **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**

Secondary and tertiary vertices

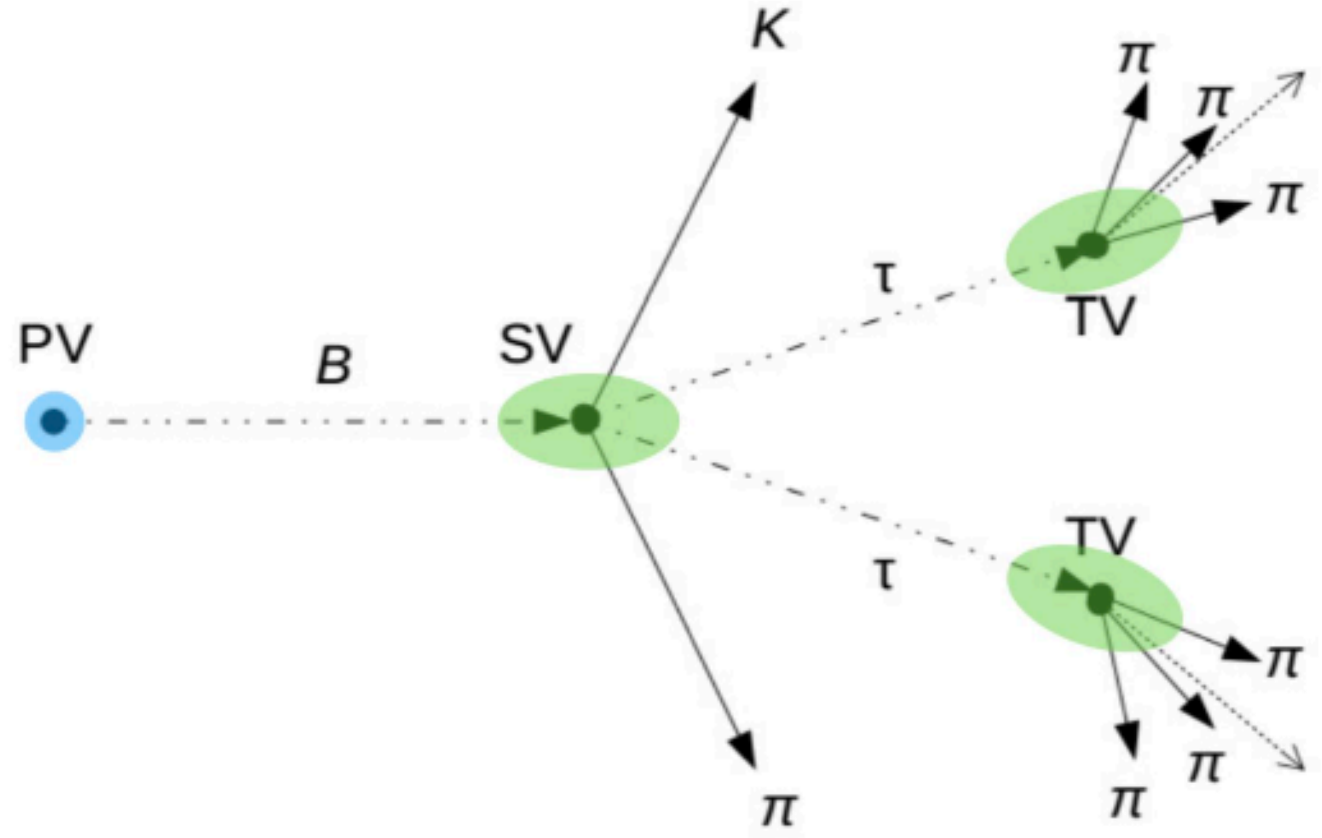
- **Primary vertex in Z->hadron events has typically $\sigma_{x,z} = 2 - 3\mu m$ and $\sigma_y \approx O(0.1)\mu m$ using a beam spot constraint**

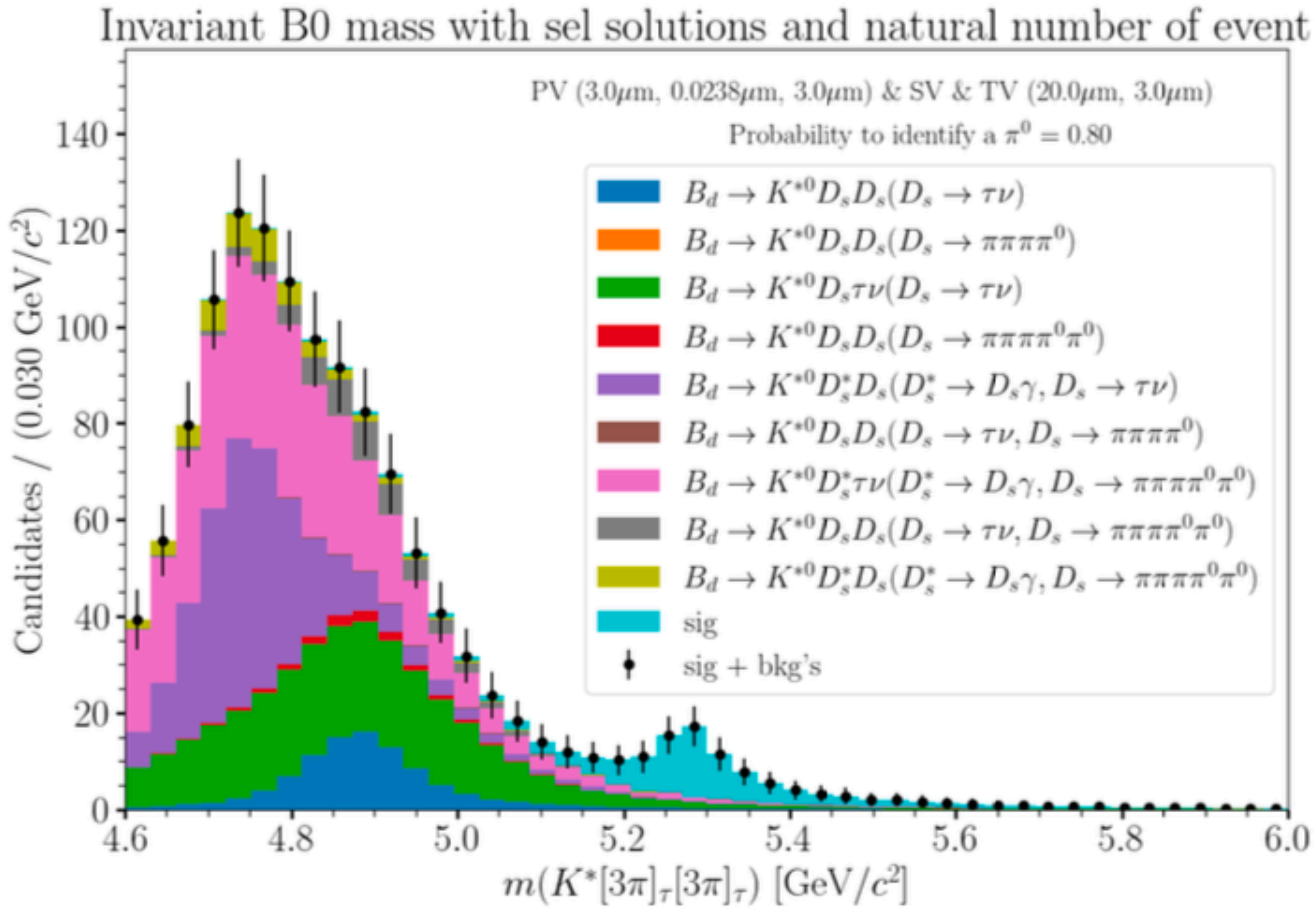
- **Secondary(Tertiary) vertices resolution in our studies with IDEA spans between 10 and 80microsns and depends on many factors:**
  - number of tracks in the vertex
  - track momenta
  - angular separation of the tracks

- **Need to determine the processes that would bring strongest constraints to estimate the ultimate requirements.**
  - these are unique measurements not possible in other types of machines

T. Miralles

Requirements from $B \to K^{*}\tau\tau$

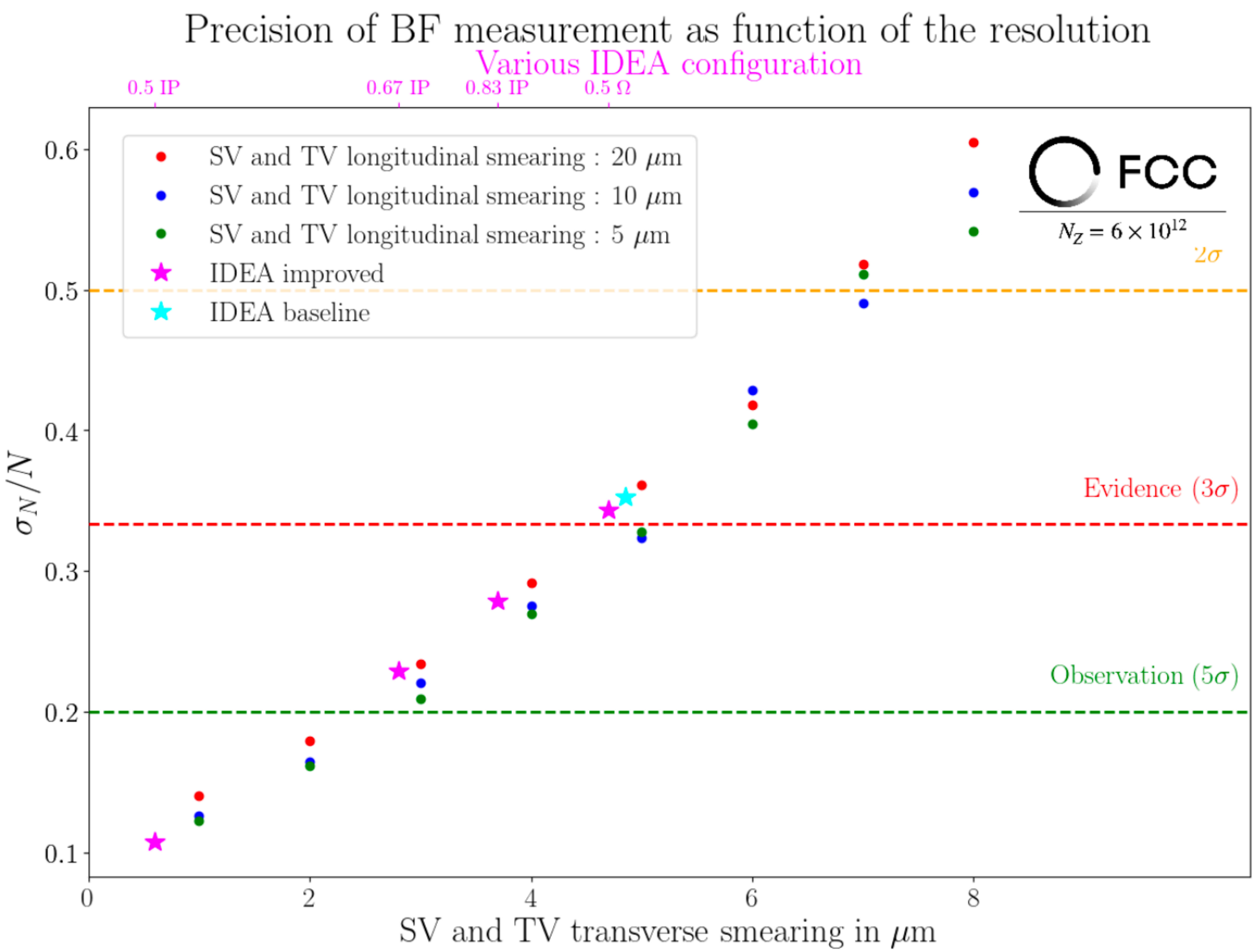




- **$B \to K^{*}\tau\tau$ is an important LFU test in $b \to s$ transitions**
  - BR$_{SM}$~O(10^{-7}) very small
  - Focus on the 3-prong τ decays ($3\pi + \nu$)
- **Very complex analysis with a very rich signature:**
  - 8 visible particles (1K, 7π)
  - 1 secondary vertex and tertiary vertices
  - Many backgrounds & combinatorics: need BDT for selection

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

Exploring different configurations



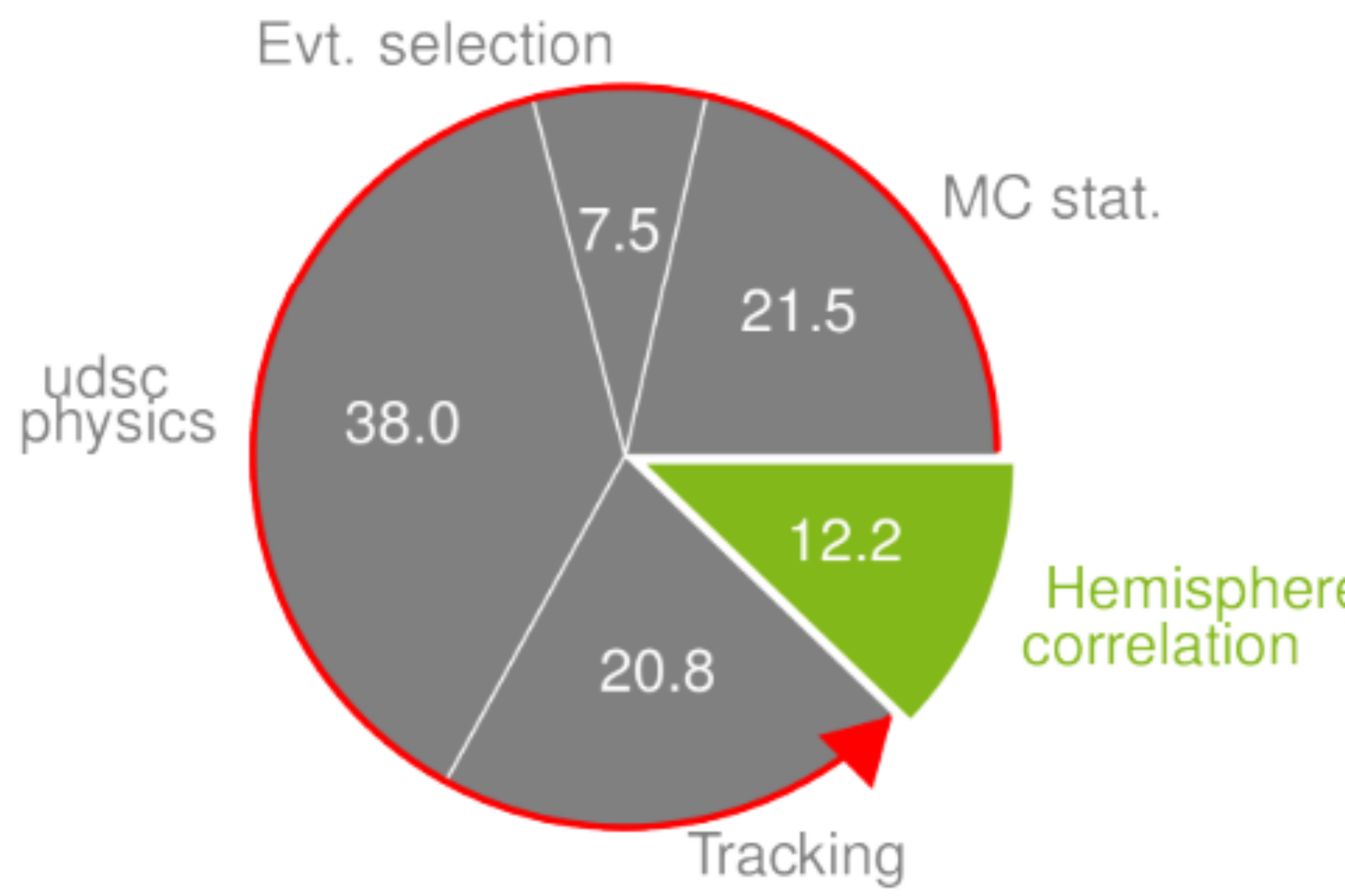
- **Neutrino reconstruction is the crucial part.**
  - It depends critically on the precise SV/TV precision
  - Need a transverse precision on the SV/TV better than 5um
- **Exploring different configurations:**
  - Improvement of Track momentum resolution not as crucial as improvement in the track IP

EWPO Meets Flavour

New synergies

L. Roherig

- **Several flavour measurements depend crucially on the correct B-hadron reconstruction of one of the sides.**
  - This could be crucial also for EWPO related to flavor (Rb, Rc, asymmetries etc...) since the large Tera-Z statistics allows to use exclusive decays to squeeze systematic uncertainties.
  - Explored exclusive b-hadron reconstruction in order to have an ultra-pure (≥99.8%) tagger for Rb measurement.
- **Ultimate requirements still not defined, but very interesting studies getting there**

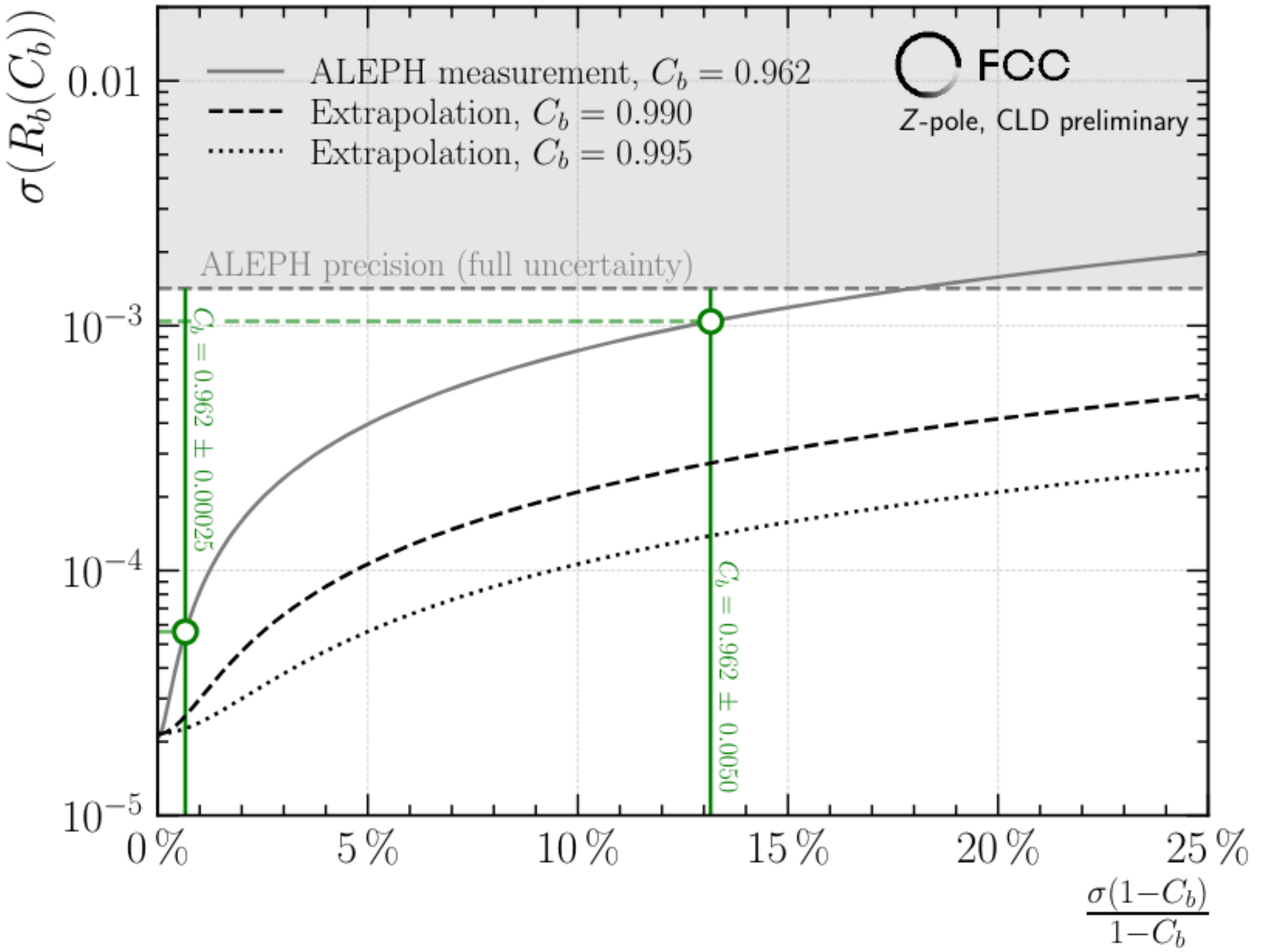


Observable	R_b	A^b_{FB}
b-hadrons	$B^+, B^0_d, B^0_s, \Lambda^0_b$	B^+, Λ_b
Knowledge of. . .	Flavour	Flavour, $\vec{p}$ & Q
	Remove *udsc*-physics contribution	
Advantages		Overcome mixing dilutions and hemisphere confusion
Remaining $\sigma_{\mathrm{syst.}}$	Hemisphere correlation C_b	QCD corrections

Reducing systematics on Rb

L. Roherig

Correlation between $\sigma(R_b)$ and C_b



- Two handles: Uncertainty on C_b and difference to $C_b = 1$

- **Main source of systematics:**
  - Hemisphere correlation ΔCb driven by PV determination
  - Various options explored to reduce the dependence: improvement in the PV precision determination or different track selection to overcome the PV bias.
  - Studies with CLD FullSim package
    - *note only smearing of vertex hits, no digitization*

L. Roherig

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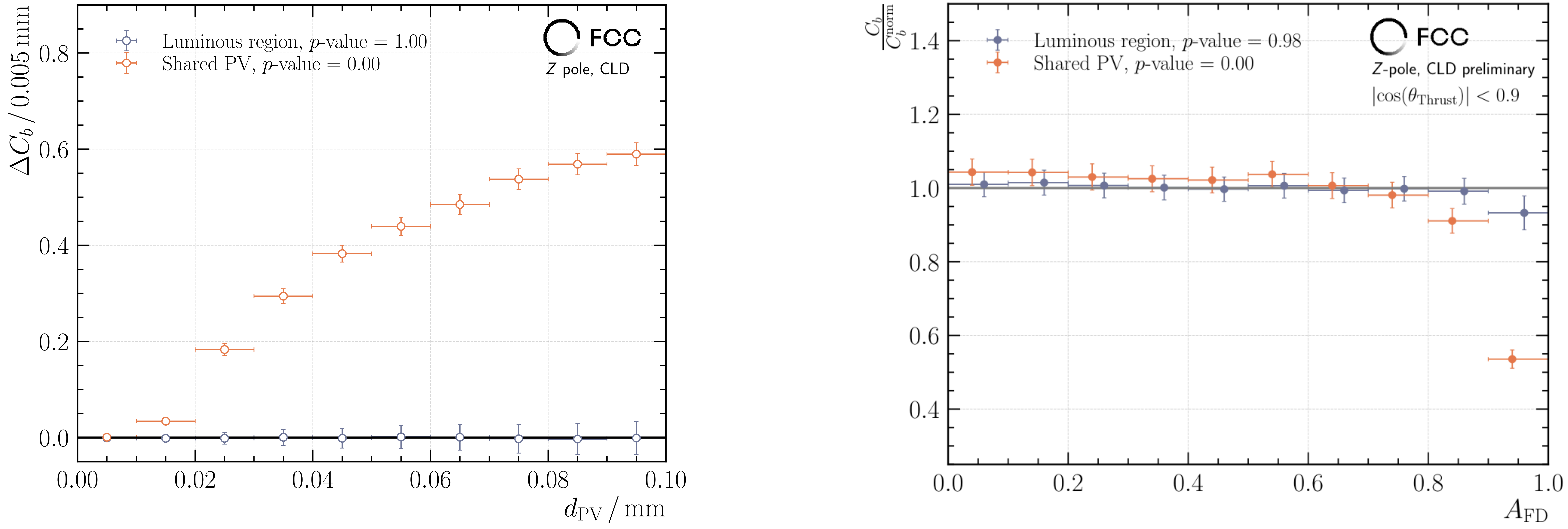
Reduce the PV bias on Cb



- **With the cut on the luminous region for the PV:**
  - the dependence of Cb on the PV resolution is removed
  - the dependence on the flight asymmetry is also removed

- **Still to explore dependence on IP resolution for assignement of tracks to PV important not only for the exclusive tagger, but also for the inclusive ones.**

Lifetime measurement and alignement

Just few words

M. Dam, A. Lusiani

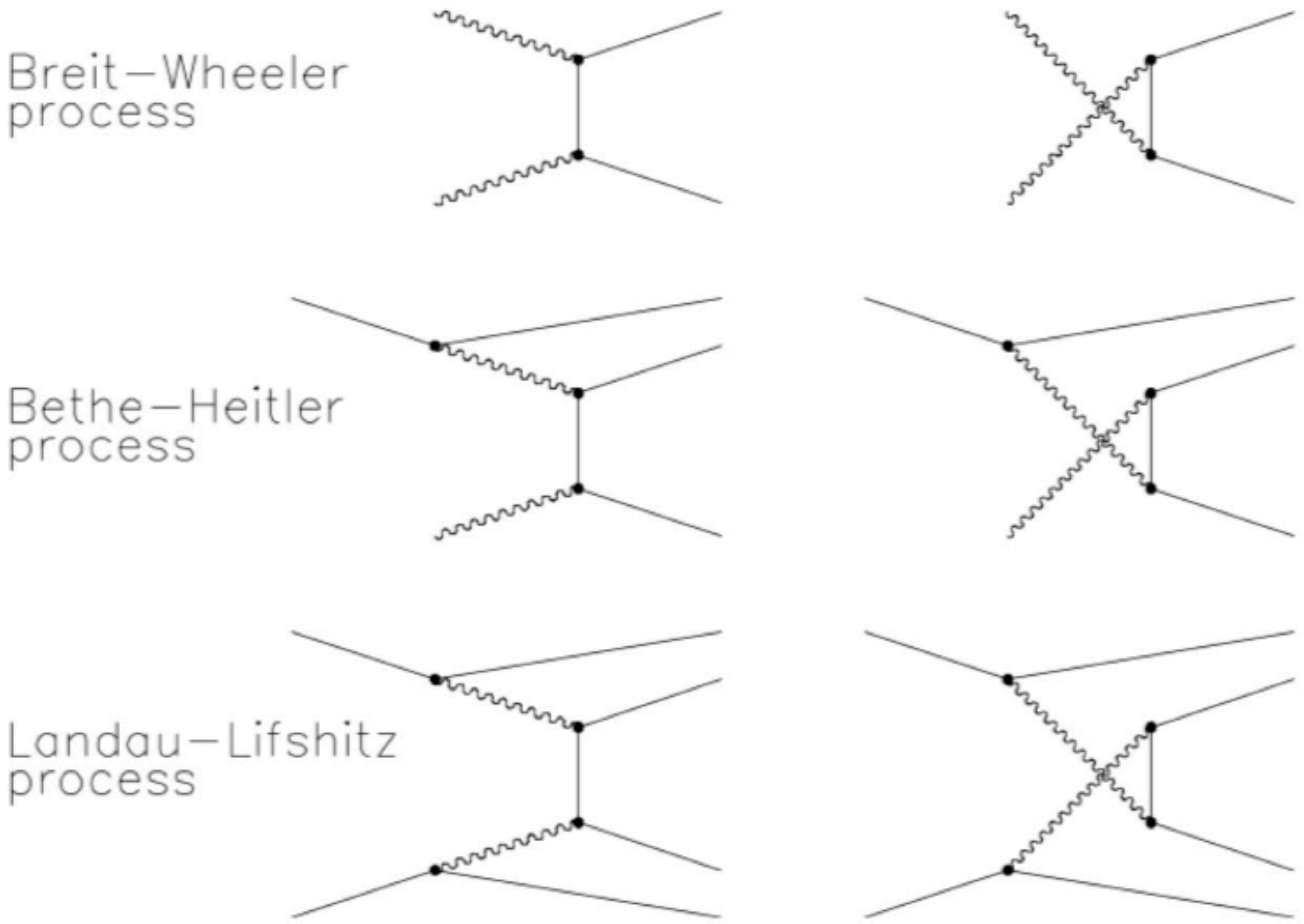
- **Precise measurements of the mass, the lifetime and the leptonic branching fraction of the tau lepton offer a crucial test of lepton flavour universality (LFU)**
  - e.g. potential to measure tau lifetime to sub-10-5
  - Would correspond to flight-distance measurement to a few tens of nanometers
  - 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.

Occupancy

Beam background

A. Ciarma

- **Dominated by incoerent pair production from these processes evaluated with GuineaPig at different √s**
  - physics contribution is negligible
  - Compared with different vertex designs present in simulation



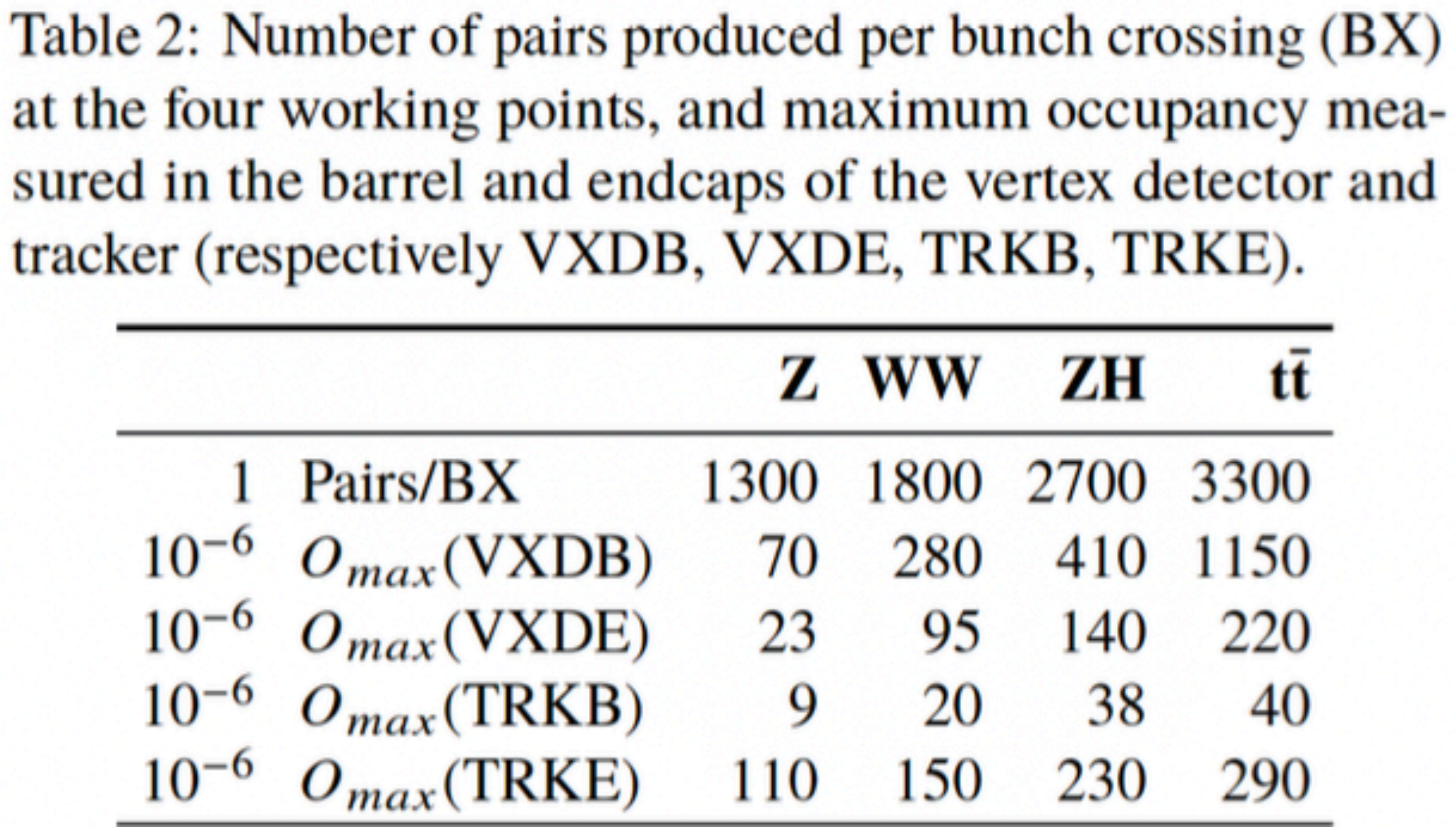
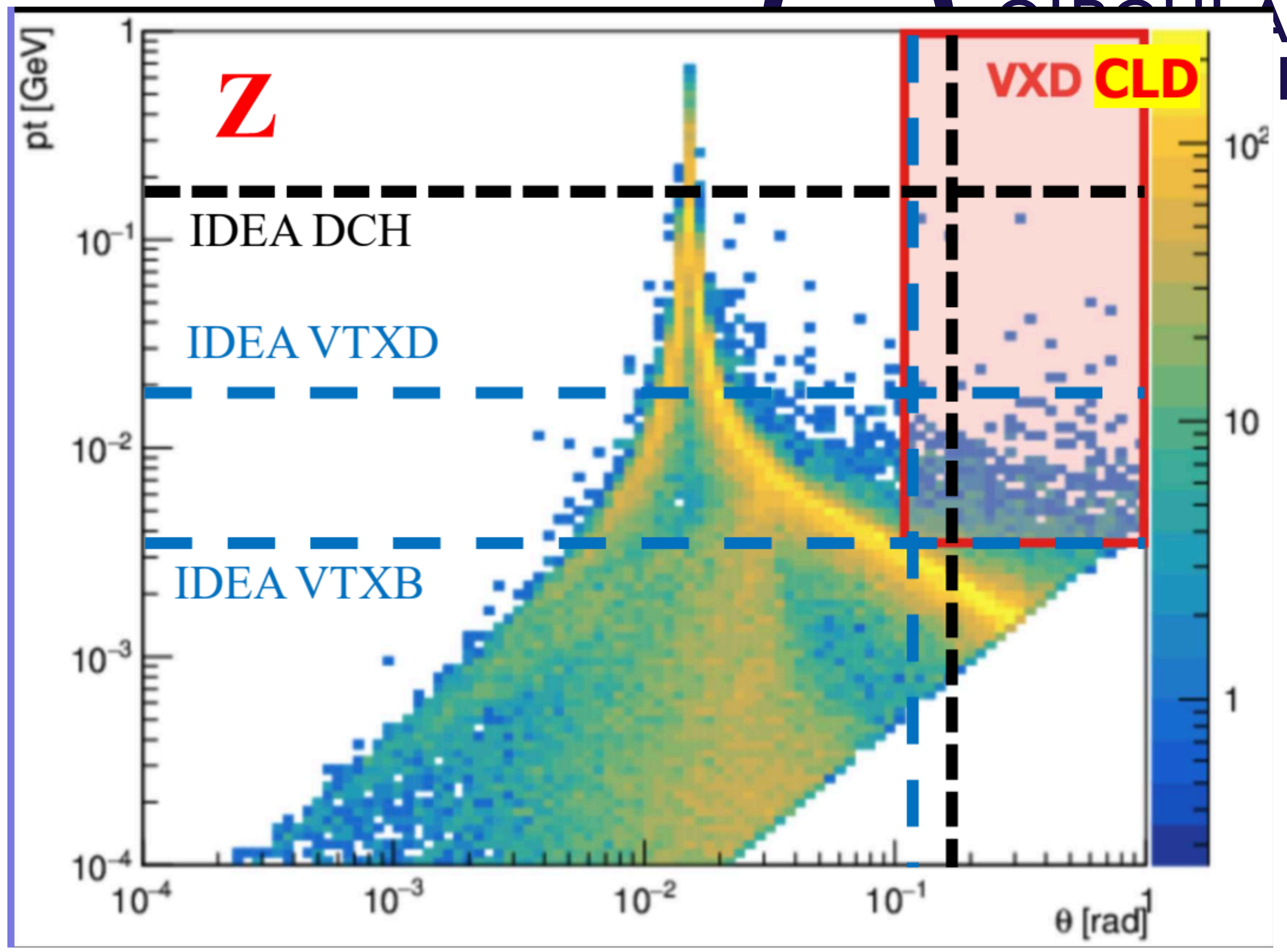
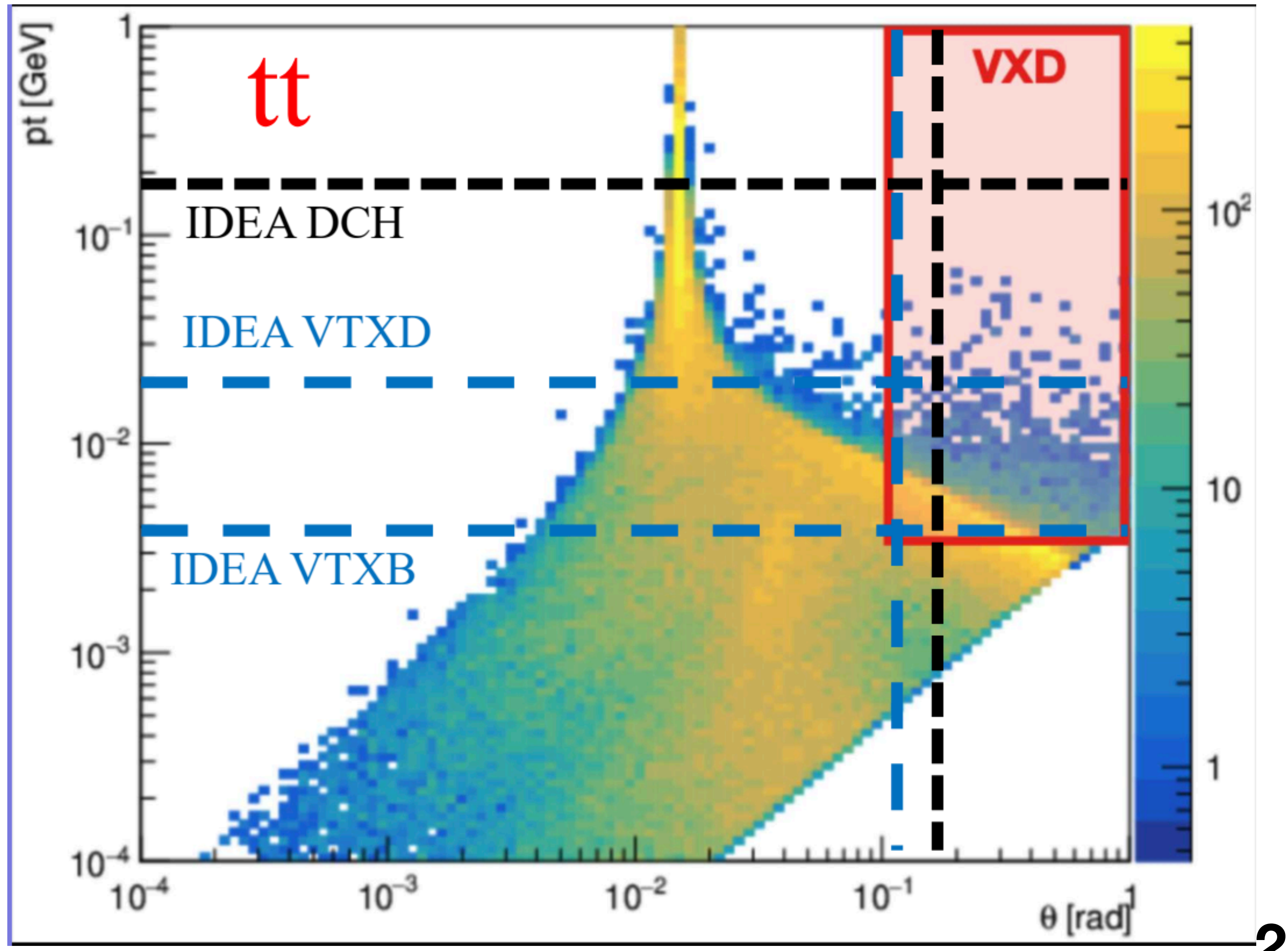


Table 2: Number of pairs produced per bunch crossing (BX) at the four working points, and maximum occupancy measured in the barrel and endcaps of the vertex detector and tracker (respectively VXDB, VXDE, TRKB, TRKE).

		Z	WW	ZH	$t\bar{t}$
1	Pairs/BX	1300	1800	2700	3300
10^{-6}	O_{max}(VXDB)	70	280	410	1150
10^{-6}	O_{max}(VXDE)	23	95	140	220
10^{-6}	O_{max}(TRKB)	9	20	38	40
10^{-6}	O_{max}(TRKE)	110	150	230	290





A.Ilg

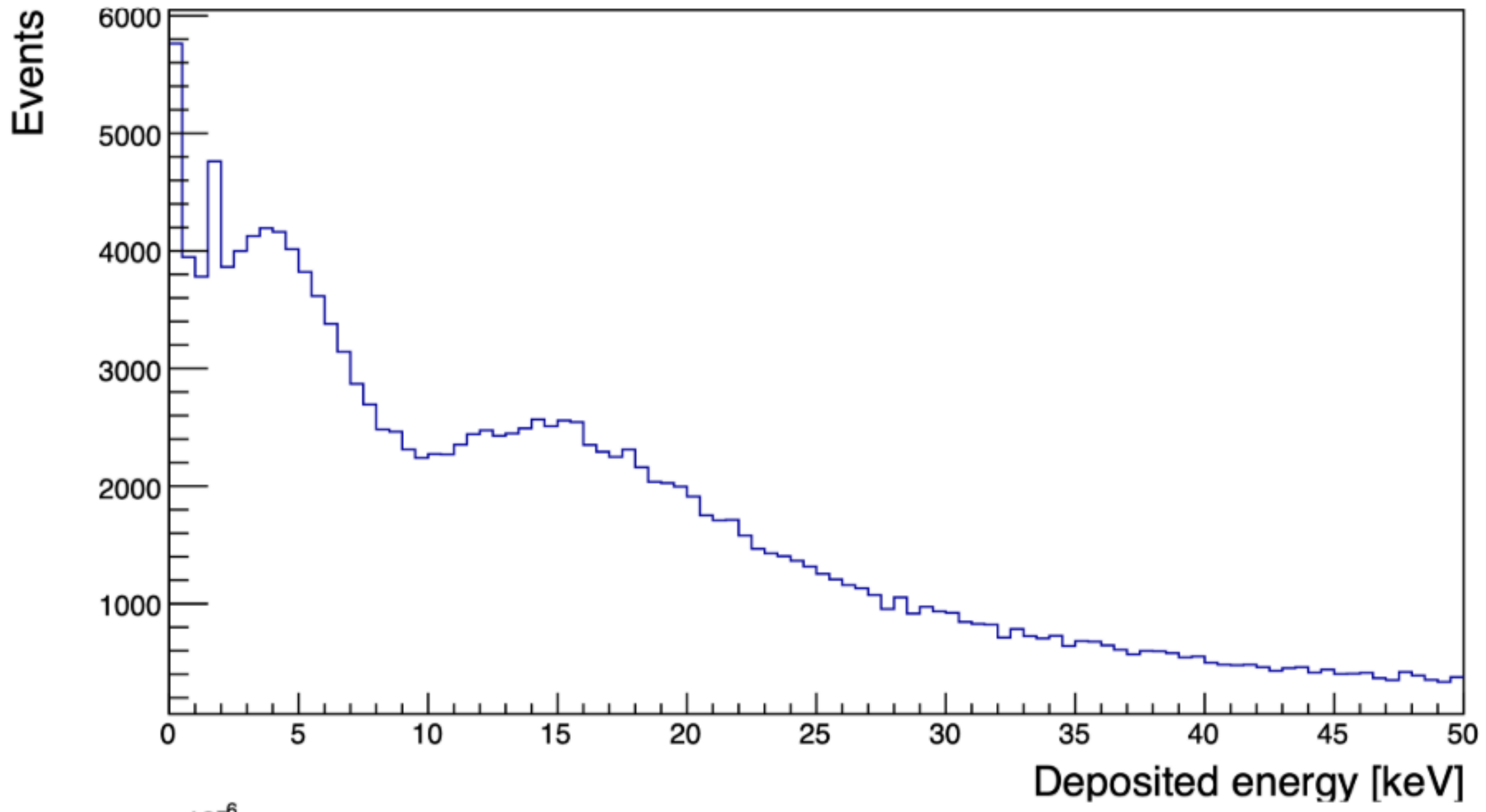
Occupancy in Vertex

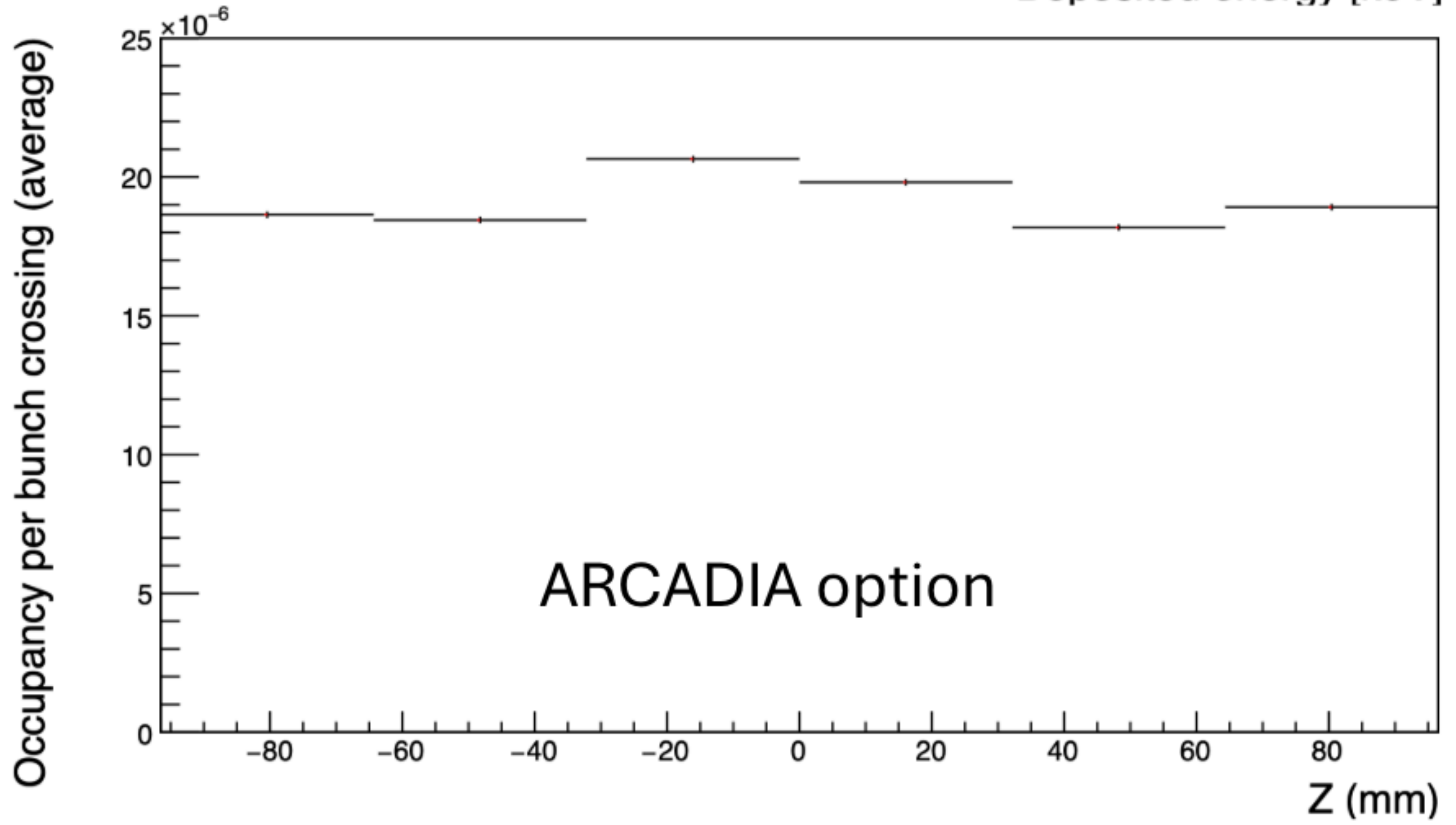
First comparisons

- Cluster size of 5, safety factor of 3, 25 µm pitch pixels
- Cut at 1.8 keV of deposited energy (500 e$^-$)

	ARCADIA	ALICE ITS3
Occupancy	$\sim 20\times10^{-6}$	$\sim 30\times10^{-6}$
Hit rate	$170\ MHz/cm^2$	$250\ MHz/cm^2$

- Seems lower occupancy than previous study.
- Hit rate goes from 170 MHz/cm2 to O(250 MHz/cm2) with the ultra-light option (larger area per module)





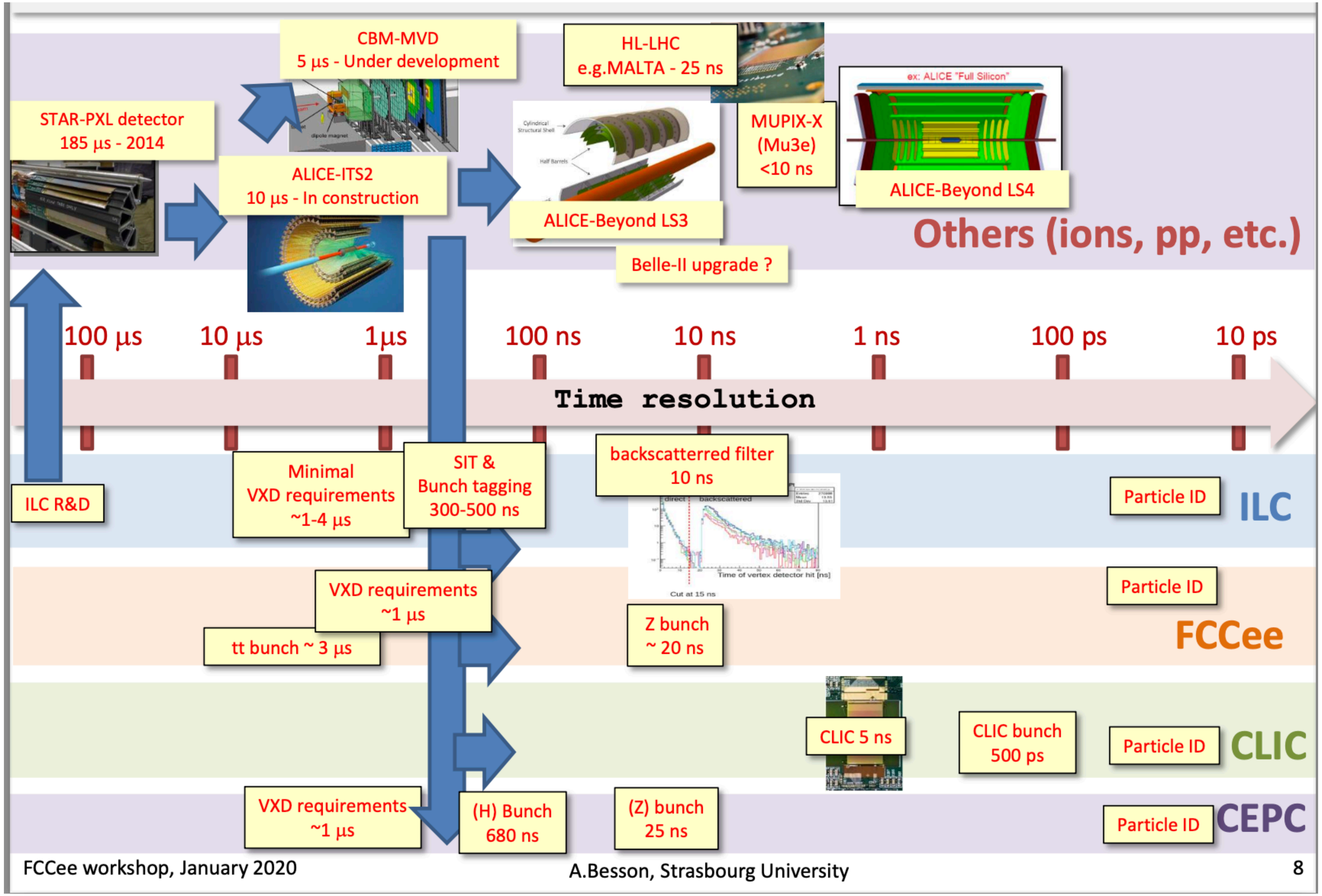
Occupancy and background

so many questions...

- Need to study the impact of backgrounds on physics and occupancy and DAQ: need digitization and track reconstruction! **Work in progress.**

- Many questions to answer (also as a function of $\sqrt{s}$):
  - What is the impact of the background hits, fakes?
  - Can we reduce background with cuts on clusters?
  - What is the impact of an increased threshold on physics?
  - What is the impact on the data rate?
  - Investigate triggerless acquisition. Or, what can we allow (impact on physics)

Summary of possible Timing uses



STAR-PXL detector
185 µs - 2014

CBM-MVD
5 µs - Under development

ALICE-ITS2
10 µs - In construction

HL-LHC
e.g.MALTA - 25 ns

MUPIX-X
(Mu3e)
<10 ns

ALICE-Beyond LS3

ALICE-Beyond LS4

Belle-II upgrade ?

Others (ions, pp, etc.)

100 µs | 10 µs | 1µs | 100 ns | 10 ns | 1 ns | 100 ps | 10 ps

`Time resolution`

ILC

ILC R&D

Minimal
VXD requirements
~1-4 µs

SIT &
Bunch tagging
300-500 ns

backscatterred filter
10 ns

Particle ID

FCCee

VXD requirements
~1 µs

tt bunch ~ 3 µs

Z bunch
~ 20 ns

Particle ID

CLIC

CLIC 5 ns

CLIC bunch
500 ps

Particle ID

CEPC

VXD requirements
~1 µs

(H) Bunch
680 ns

(Z) bunch
25 ns

Particle ID

FCCee workshop, January 2020

A.Besson, Strasbourg University

8

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

Timing in the Vertex detector

- **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 achieving precise timing measurements in the innermost layer of the VXD, without compromising heavily the material budget?**

Vertexing - Preliminary conclusions

- **Crucial aspects:**
  - single point resolution
  - contribution of multiple scattering dependent on the material budget of the vertex and beam-pipe
  - The radial distance of the first layer of the vertex detector

- **Examples show that in particular for Flavor Physics, the physics outcome of FCC-ee would gain of having better vertex detector performances than the one provided by the baseline detectors considered so far.**
  - Engineering studies indicate that the material of the vertex detector layers, compared to that of the baseline IDEA detector, can realistically be achieved.
  - It should be noted that these requirements, tighter than the ones presented for a linear collider detector, will have to be reached despite the additional constraints set by the FCC-ee environment on the readout electronics of the detector

Next steps for Vertex design optimization

- **New design of the tracker detector (with mechanical structure) implemented in FullSimulation will allow:**
  - develop realistic digitization model
  - Check performance due to different material distribution. Optimize design.
  - Test realistic effects of beam induced background on the outer tracker (in particular Drift Chamber)
  - *The plug&play capability of key4hep should facilitate the inclusion of vertex design in different proposals for detectors*

- **Develop new track (and event) reconstruction strategies**

- **Allow to re-evaluate physics performance and connect with overall final uncertainties on a measurement with specific hardware characteristics ad choices**

Summary table of vertex detector requirements

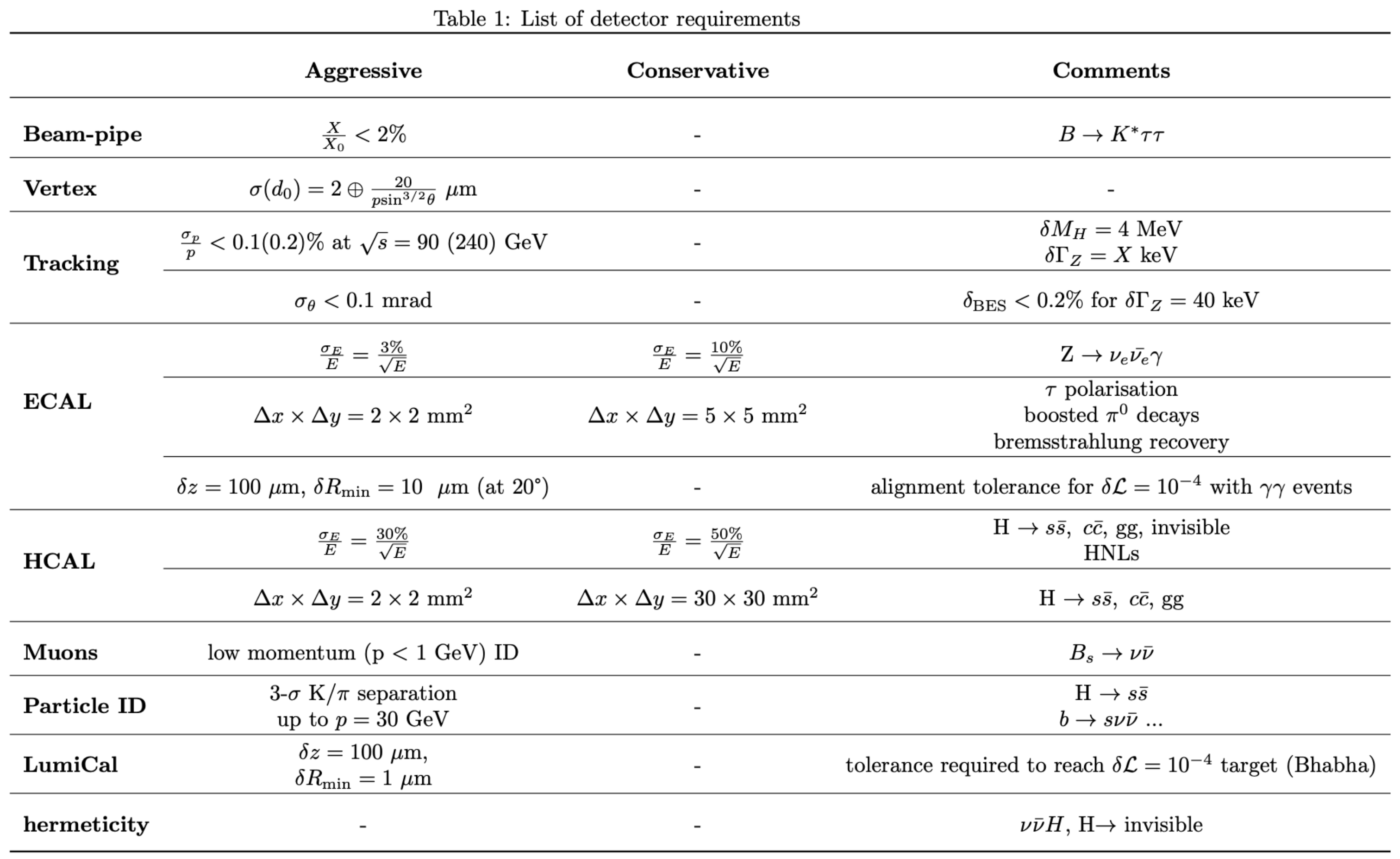


Table 1: List of detector requirements

		Aggressive	Conservative	Comments
Beam-pipe		$\frac{X}{X_0} < 2\%$	-	$B \rightarrow K^* \tau\tau$
Vertex		$\sigma(d_0) = 2 \oplus \frac{20}{p\sin^{3/2}\theta}\ \mu\text{m}$	-	-
Tracking		$\frac{\sigma_p}{p} < 0.1(0.2)\%$ at $\sqrt{s} = 90\ (240)$ GeV	-	$\delta M_H = 4$ MeV $\delta\Gamma_Z = X$ keV
		$\sigma_\theta < 0.1$ mrad	-	$\delta_{\text{BES}} < 0.2\%$ for $\delta\Gamma_Z = 40$ keV
ECAL		$\frac{\sigma_E}{E} = \frac{3\%}{\sqrt{E}}$	$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}}$	Z $\rightarrow \nu_e\bar{\nu}_e\gamma$
		$\Delta x \times \Delta y = 2 \times 2\ \text{mm}^2$	$\Delta x \times \Delta y = 5 \times 5\ \text{mm}^2$	τ polarisation boosted π^0 decays bremsstrahlung recovery
		$\delta z = 100\ \mu\text{m}$, $\delta R_{\text{min}} = 10\ \ \mu\text{m}$ (at 20°)	-	alignment tolerance for $\delta\mathcal{L} = 10^{-4}$ with $\gamma\gamma$ events
HCAL		$\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}}$	$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}}$	H $\rightarrow s\bar{s},\ c\bar{c}$, gg, invisible HNLs
		$\Delta x \times \Delta y = 2 \times 2\ \text{mm}^2$	$\Delta x \times \Delta y = 30 \times 30\ \text{mm}^2$	H $\rightarrow s\bar{s},\ c\bar{c}$, gg
Muons		low momentum (p < 1 GeV) ID	-	$B_s \rightarrow \nu\bar{\nu}$
Particle ID		3-σ K/π separation up to $p = 30$ GeV	-	H $\rightarrow s\bar{s}$ $b \rightarrow s\nu\bar{\nu}$ ...
LumiCal		$\delta z = 100\ \mu\text{m}$, $\delta R_{\text{min}} = 1\ \mu\text{m}$	-	tolerance required to reach $\delta\mathcal{L} = 10^{-4}$ target (Bhabha)
hermeticity		-	-	$\nu\bar{\nu}H$, H→ invisible

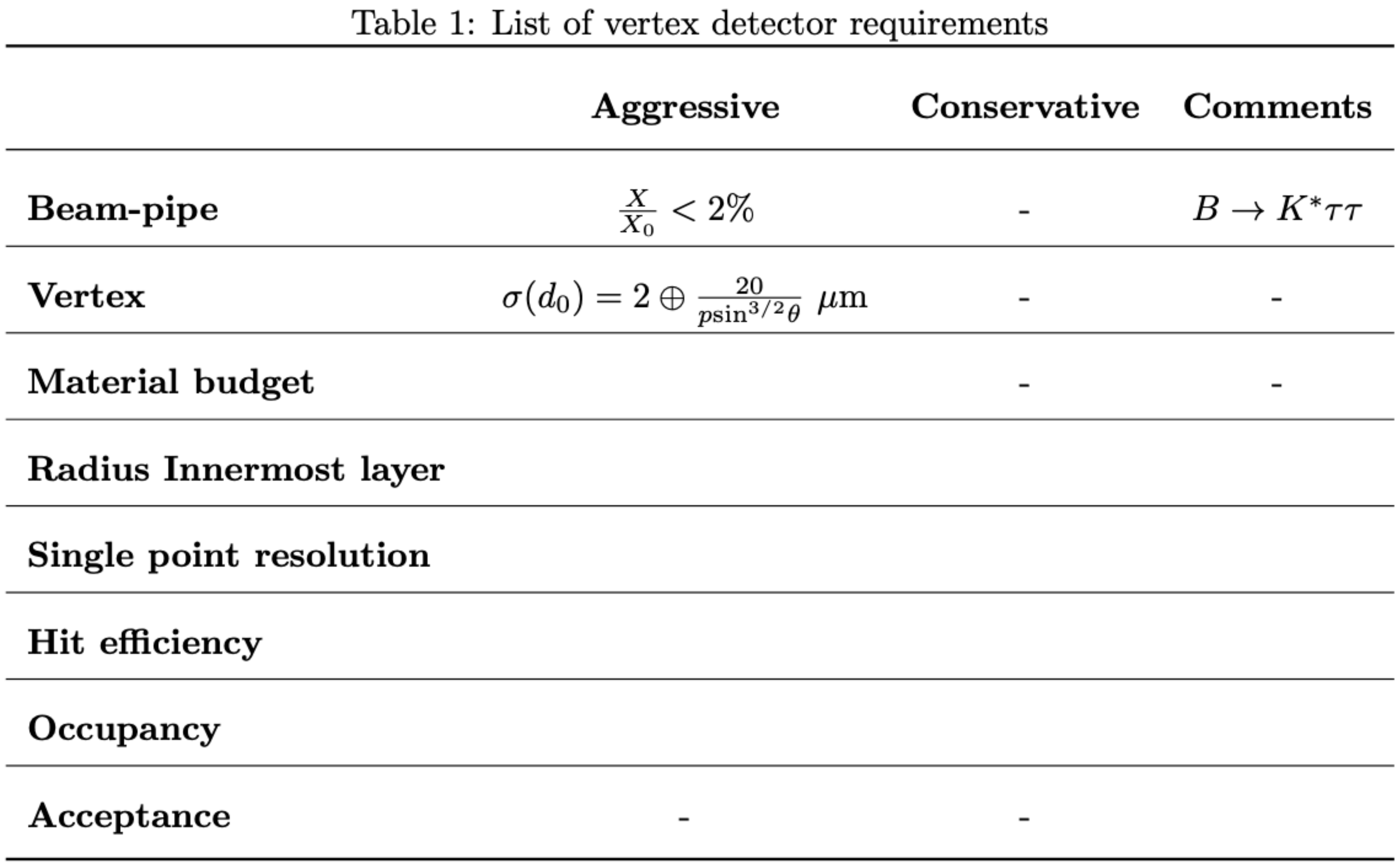


Table 1: List of vertex detector requirements

	Aggressive	Conservative	Comments
Beam-pipe	$\frac{X}{X_0} < 2\%$	-	$B \rightarrow K^* \tau\tau$
Vertex	$\sigma(d_0) = 2 \oplus \frac{20}{p\sin^{3/2}\theta}\ \mu\text{m}$	-	-
Material budget		-	-
Radius Innermost layer			
Single point resolution			
Hit efficiency			
Occupancy			
Acceptance	-	-	

- Maybe we can have some numbers filled by the end of this meeting!

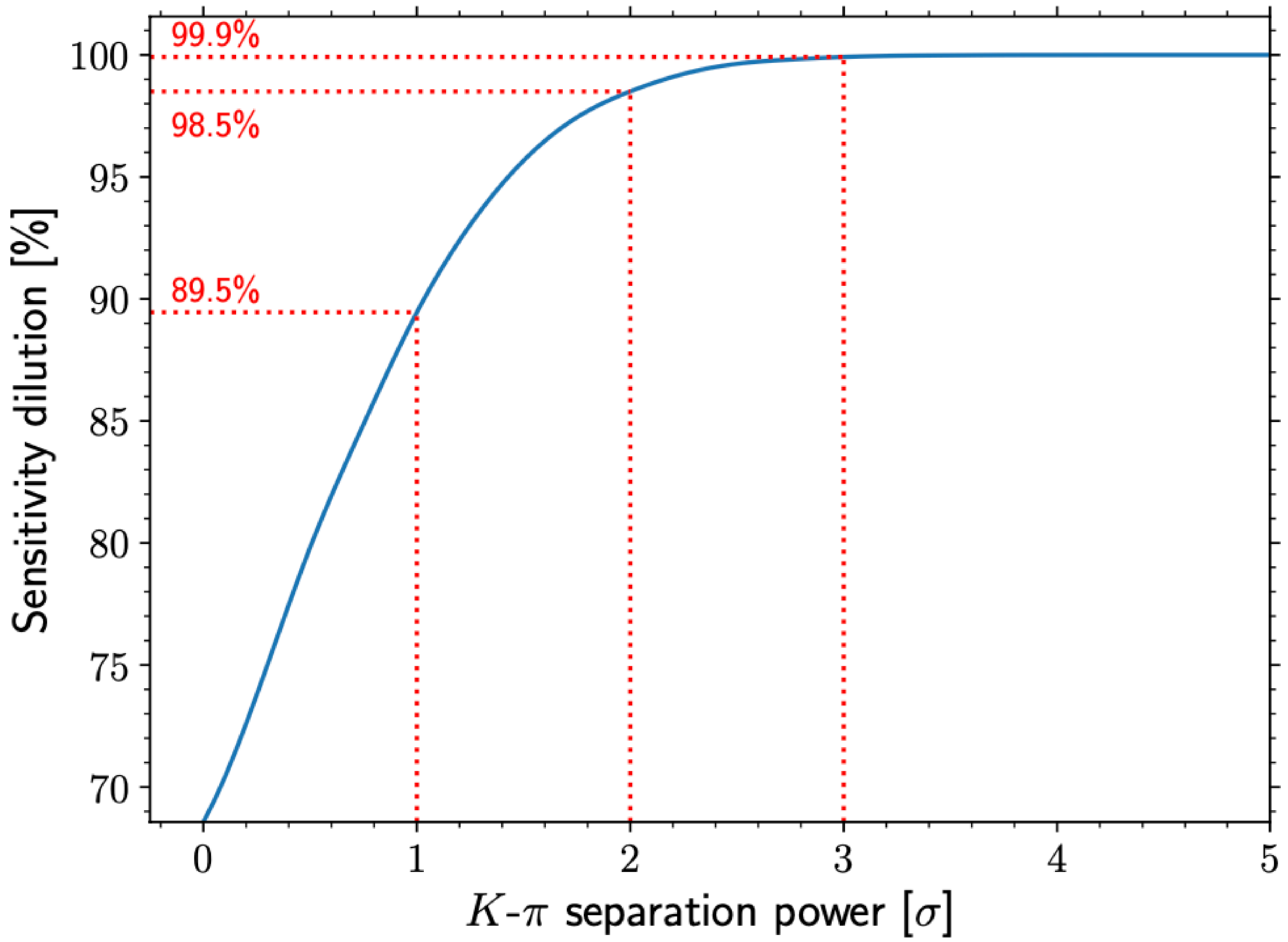
BACKUP

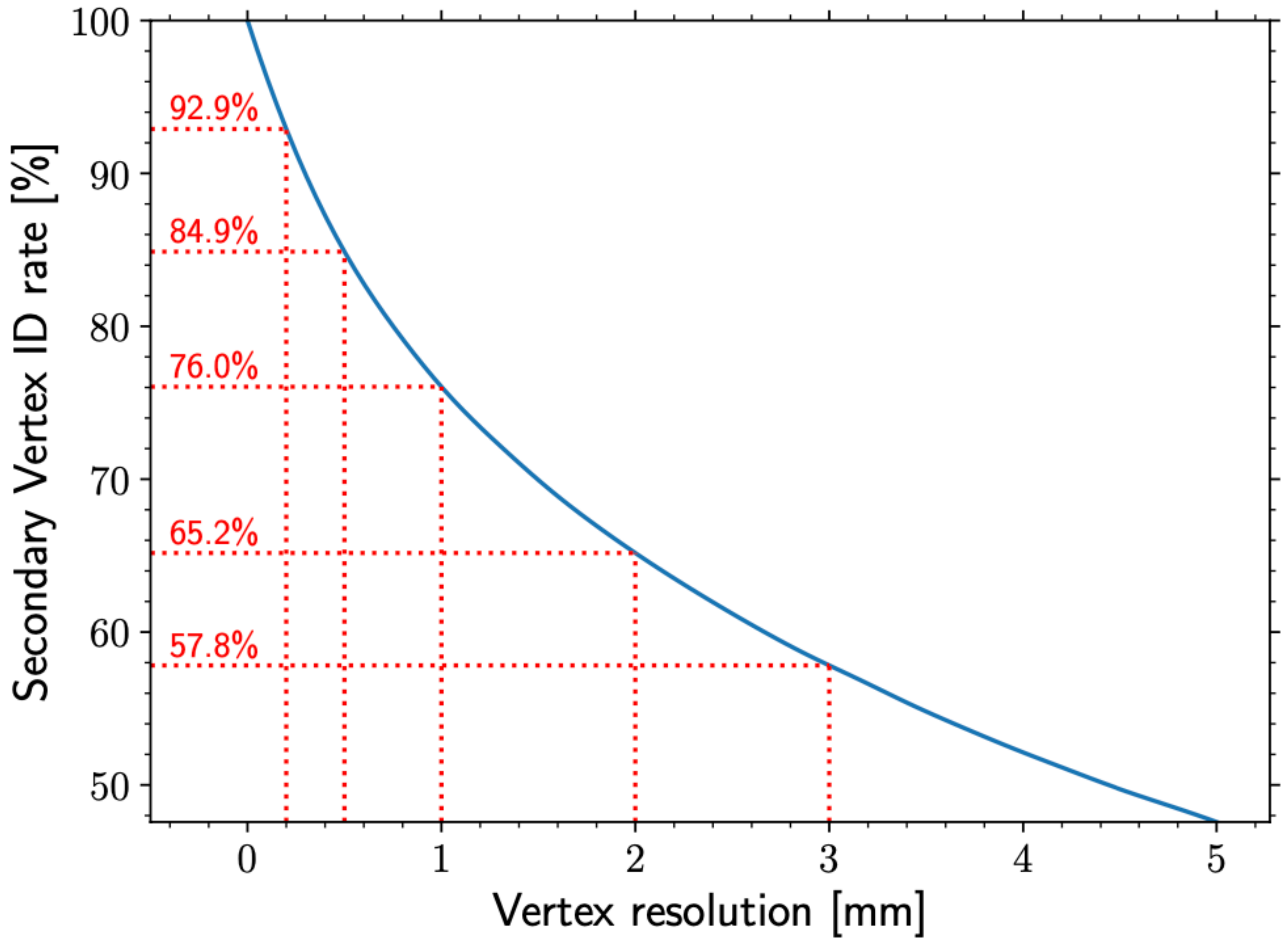
Vertex requirements: $b \to s\nu\bar{\nu}$

- Effective-operator coupling to 3rd generation **poorer constrained**, e. g. in ν_τ

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

- Particle-ID (2σ K/π separation) + SV resolution $\left(\mathcal{O}(10^{-1}\,\mathrm{mm})\right)$ not limiting! **. . . but**





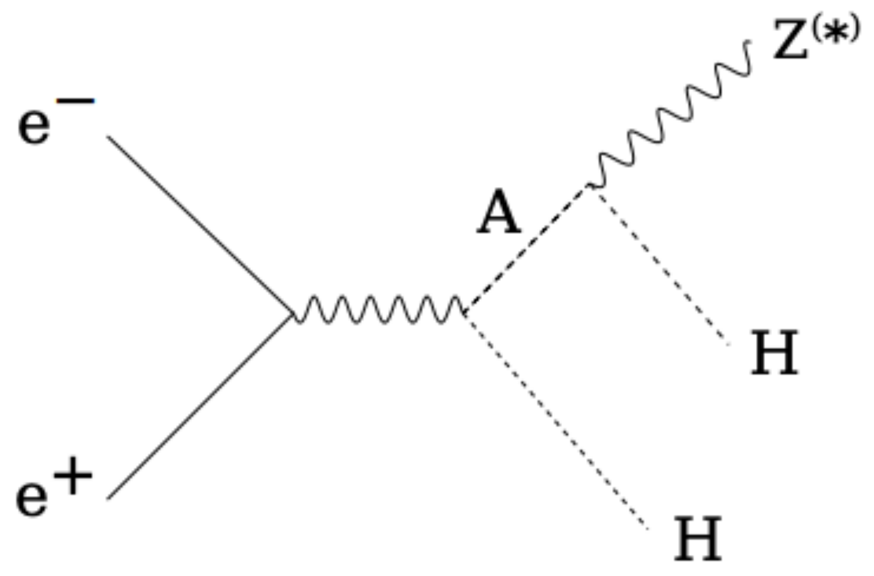
→ Systematic uncertainties significant **if no improvement** on b-fragmentation functions

© Y. Amhis et. al [2309.11353]

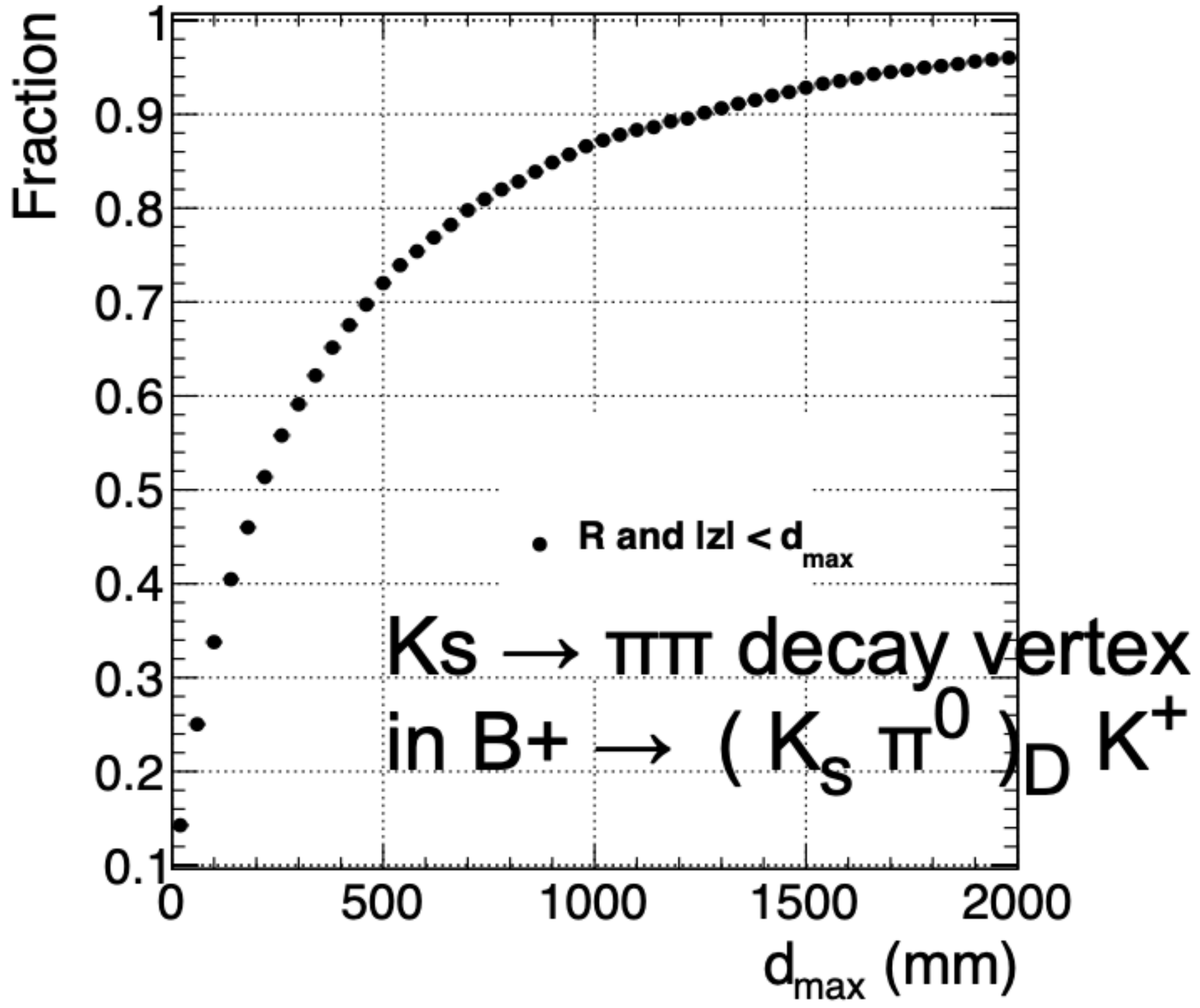
Requirements from very displaced vertices

- **Benchmarks concerning far detached vertices up to ~1m (or more!):**
  - K_s or Lambdas (relevant for B-physics but also for strange-tagging)
  - BSM processes with long lived particles (LLP), e.g. HNL, exotic Higgs decays etc.

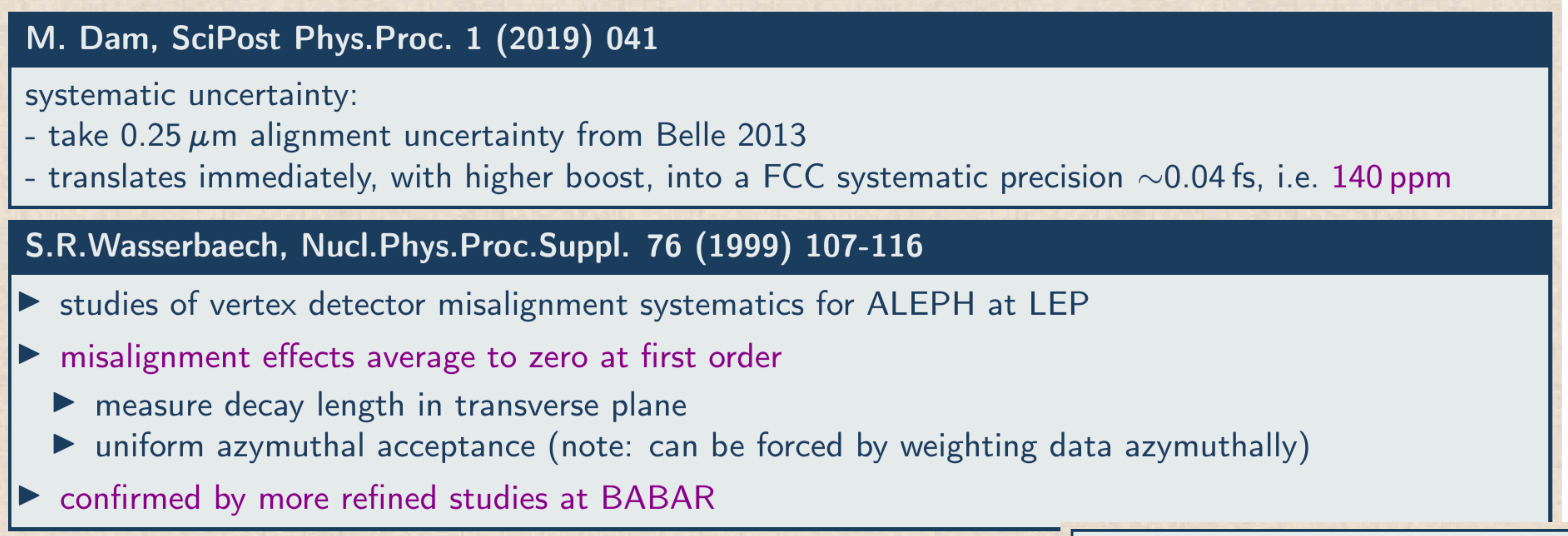
- **Needs: a large tracking volume, “continuous” tracking (that is many points/layers)**
  - Maybe timing for slow moving particles (Work in progress)



30% of the K_S decay at > 50 cm from the IP



More on requirements from tau lifetime

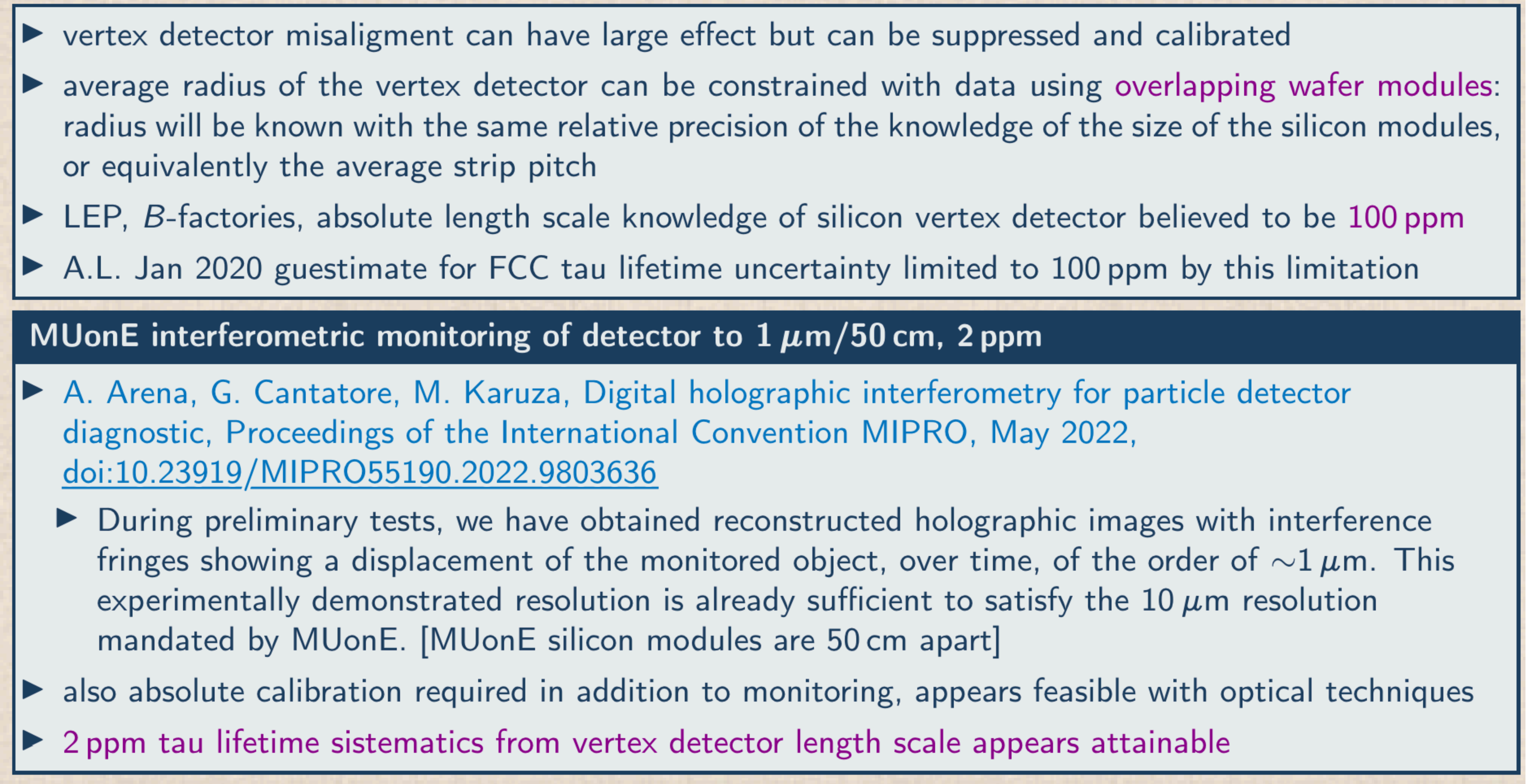


M. Dam, SciPost Phys.Proc. 1 (2019) 041

systematic uncertainty:
- take 0.25 μm 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 μm/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 μm. This experimentally demonstrated resolution is already sufficient to satisfy the 10 μm 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