Higgs couplings & detector requirements at the FCC-ee

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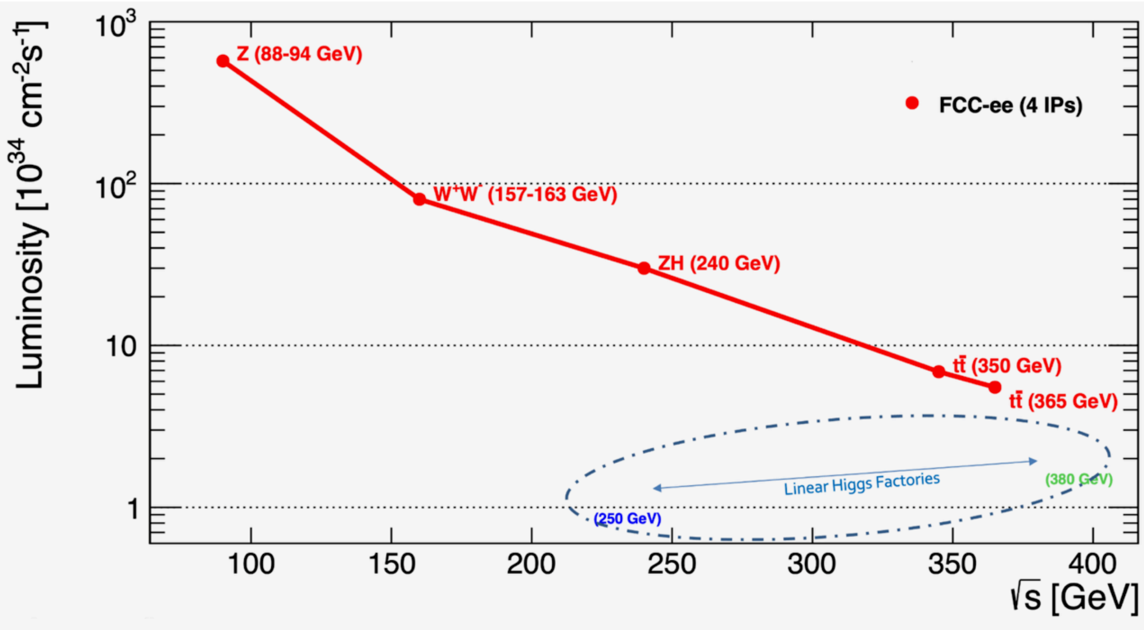
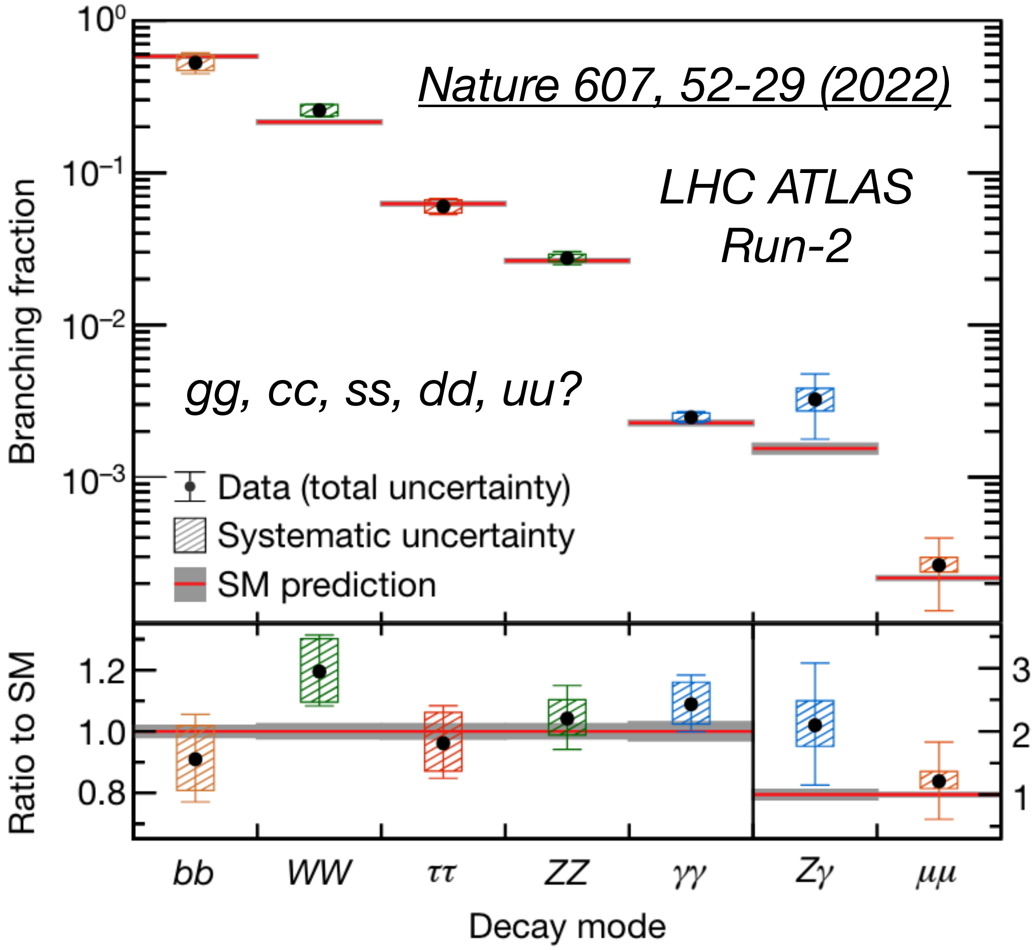
FUTURE
CIRCULAR
COLLIDER

The Future Circular Collider (FCC) e^+e^- Physics Goals

- FCC-*ee* : proposed 91 km circular collider @CERN after HL-LHC with 4 interaction points (IP) running for 15 yrs, start around 2045
- Amazing potential for precision Higgs measurements. Goals:
  - **O(10) improvements in Higgs couplings**, as compared to HL-LHC
  - Access currently **challenging decay modes** like *cc* **and "impossible" hadronic decay modes**: *gg* & *ss*
  - Access **absolute g_Z coupling**
  - Unique opportunity to **test** the **electron Yukawa** coupling at $\sqrt{s}$ = 125 GeV (if time allows)
  - **Higgs self-coupling** from the *ZH* cross sections at 240 and 365 GeV
- Not just Higgs… QCD & EWK physics, quark-flavor physics, searches for FCNC, top-quark properties (with $\sqrt{s}$ = 345 - 365 GeV), etc…
- Exquisite luminosity allows for ultimate precision, with 4 IPs:
  - 200k Z bosons / second (LEP dataset each minute)
  - 20k W bosons / hour
  - **4k Higgs bosons / day**
  - 6k tops / day





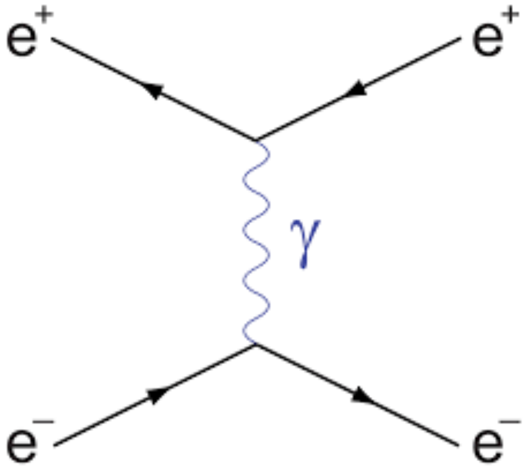
Nature 607, 52-29 (2022)

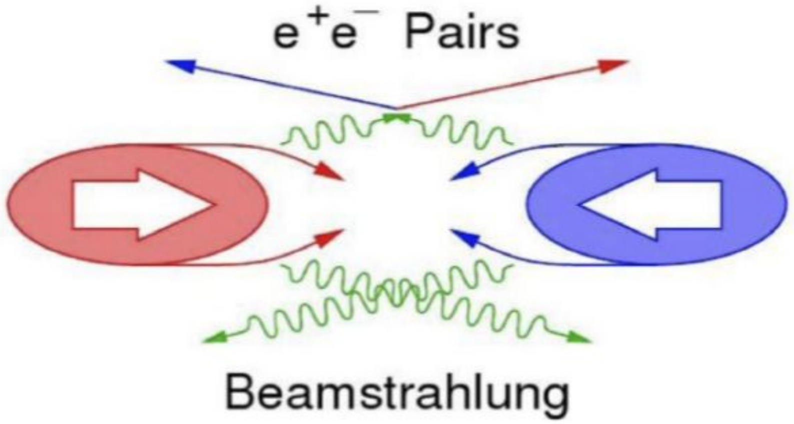
LHC ATLAS Run-2

gg, cc, ss, dd, uu?

Detector Requirements from non-Higgs Physics

- Need detectors able to withstand with a large dynamic range in energy and luminosity
- Most machine-induced reqs imposed by runs at *Z* pole and ttbar energies
  - Large collision rates (~33 MHz) and continuous beams
  - Large event rates (~100 kHz)
    - Fast detector response / triggerless design challenging (and rewarding)
    - High occupancy in inner layers/forward region (Bhabha scattering)
  - Beam backgrounds
- Complex Machine Detector Interface
  - Last focusing quadrupole ~2.2m from the IP
- Detector requirements from flavor, QCD/EWK and BSM physics program:
  - Good track momentum resolution (low material budget), IP/vertex resolution, PID capabilities, photon resolution, IP resolution for large displacement
- **How sensitive are Higgs couplings @FCC-ee to detector properties and layouts?**

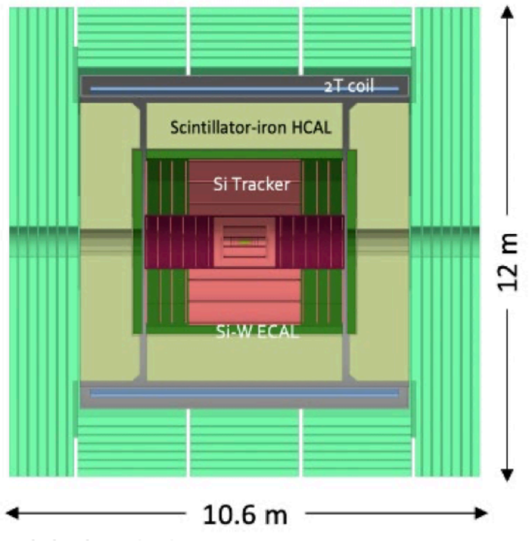




Detector **Benchmarks**

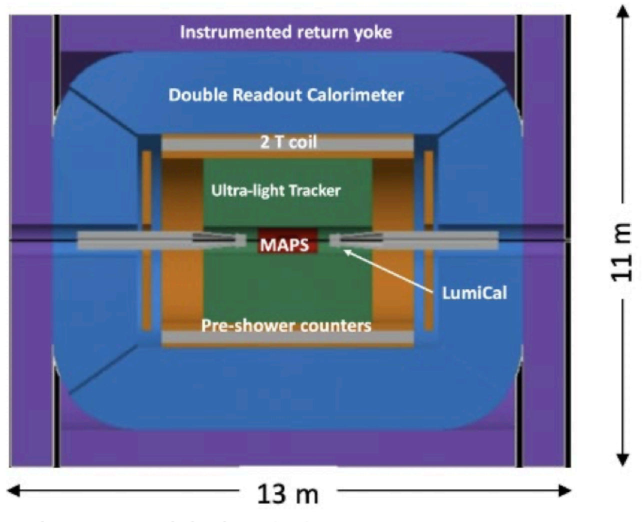
From FCC-ee CDR

CLD



- ILC-> CLIC detector -> CLD
- Full Silicon vertex / tracker
- CALICE-like calorimetry
- Large coil, muon system
- Checking whether a time projection chamber could operate in the FCC-ee environment

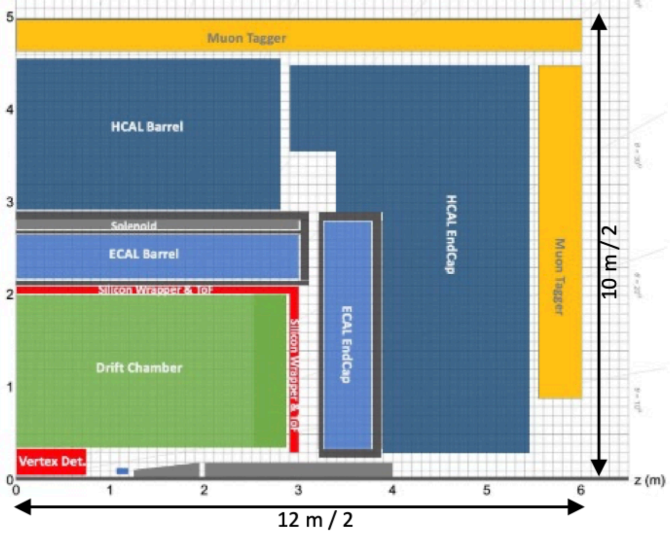
IDEA



- Silicon vertex detector
- Ultra light drift chamber with powerful particle identification
- Monolithic dual readout calorimeter
- Muon system

Baseline for studies shown in the following

ALLEGRO

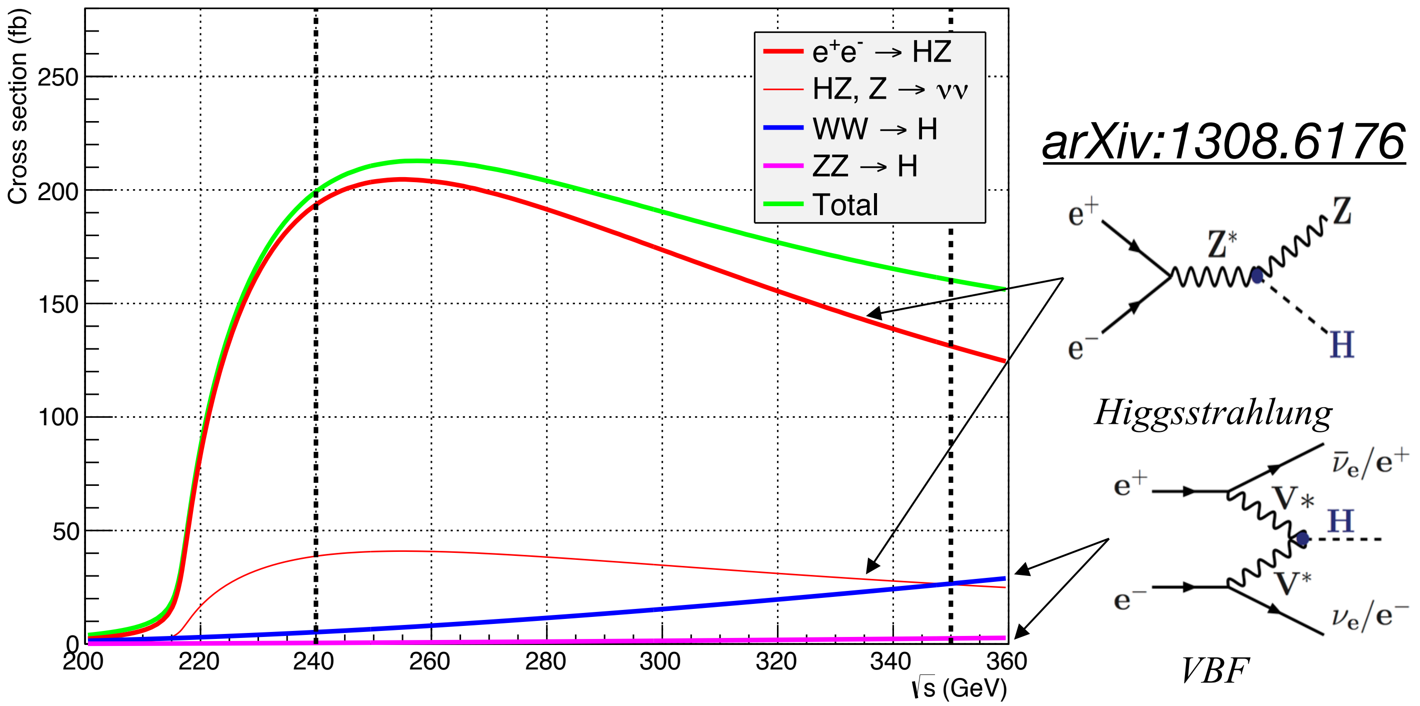


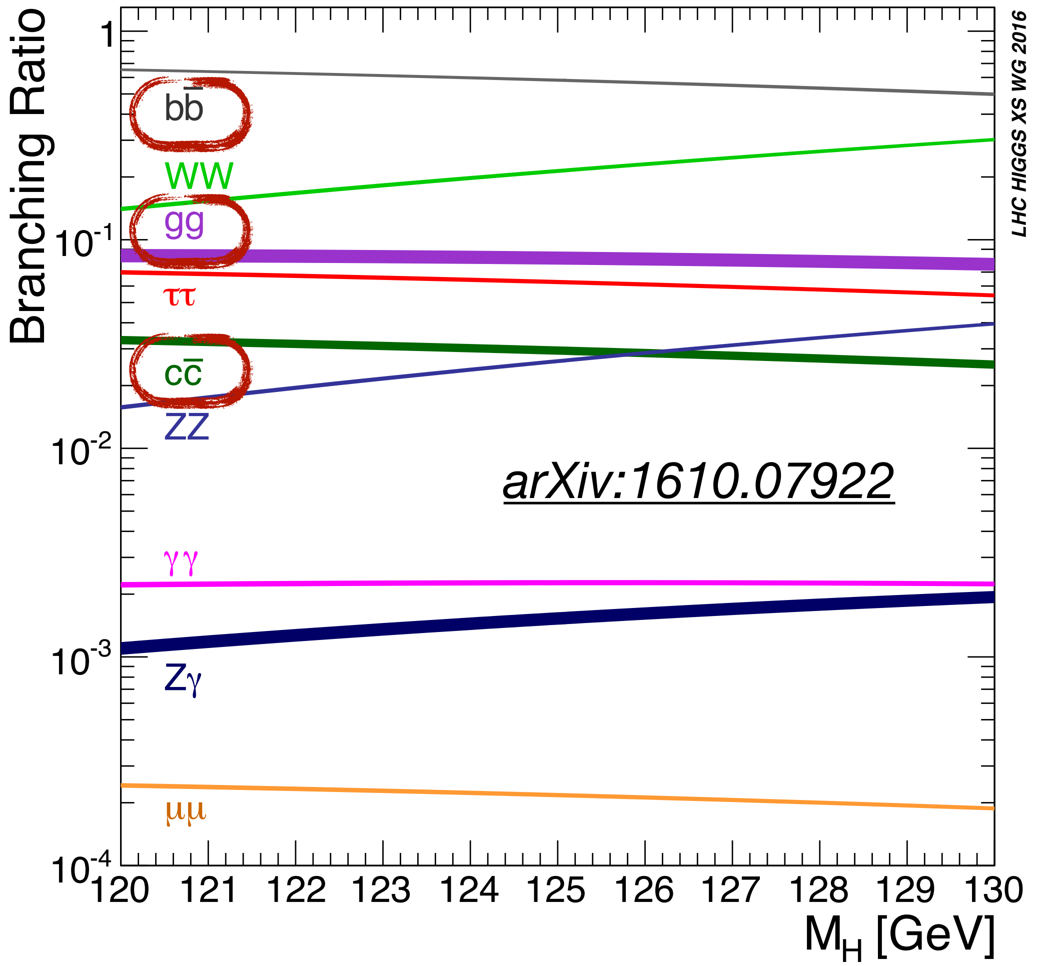
- Silicon vertex detector
- Ultra light drift chamber with powerful particle identification
- High granularity Noble Liquid ECAL
- CALICE- or TileCal-like HCAL
- Muon system

Should systematically access impact of detector developments in physics benchmarks

Higgs Production @FCC-ee

- Focus on Higgs couplings, properties (mass, width & CP discussed by M. Cepeda)
- At 240 GeV Higgs boson is produced in association with a *Z* boson
  - Tag *Z* and measure Higgs **couplings**!
- Use the analysis to study and optimise the tracker design and performance



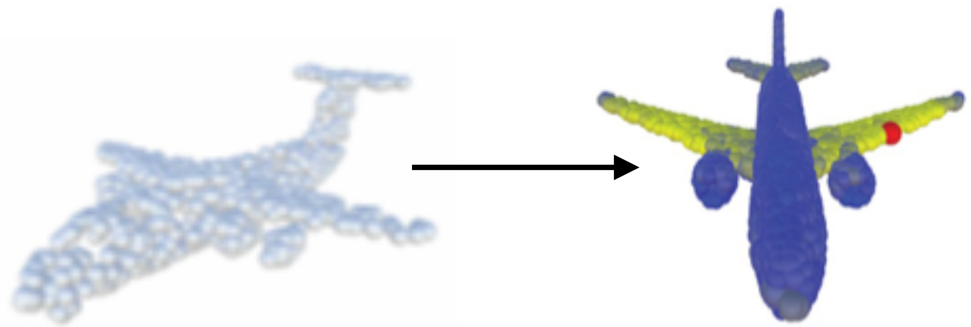


	Process	Cross-section [pb^{-1}]
Signal	ZH	0.2032195
	$Z(\nu\nu)H$	0.046191
	$e^+e^- \to Z(\nu\nu)H(b\bar{b})$	0.0269
	$e^+e^- \to Z(\nu\nu)H(c\bar{c})$	0.001335
	$e^+e^- \to Z(\nu\nu)H(gg)$	0.003782
	$e^+e^- \to Z(\nu\nu)H(s\bar{s})$	$1.109 \cdot 10^{-05}$
	$e^+e^- \to Z(\nu\nu)H(\tau\tau)$	0.002897
Background	$e^+e^- \to ZZ$	1.35899
	$e^+e^- \to W^+W^-$	16.4385
	$e^+e^- \to Z/\gamma^*(q\bar{q})$	52.6539
	$e^+e^- \to Z(\nu\nu)H(W^+W^-)$	0.00994
	$e^+e^- \to Z(\nu\nu)H(ZZ)$	0.00122
	$e^+e^- \to q\bar{q}H,\ q = u, d, s, c, b$	0.13635

Decay	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to s\bar{s}$	$H \to gg$	$H \to WW$	$H \to ZZ$	$H \to \tau\tau$
Branching fraction	58.2%	2.9%	0.024%	8.2%	9.7%	1.3%	2.6%

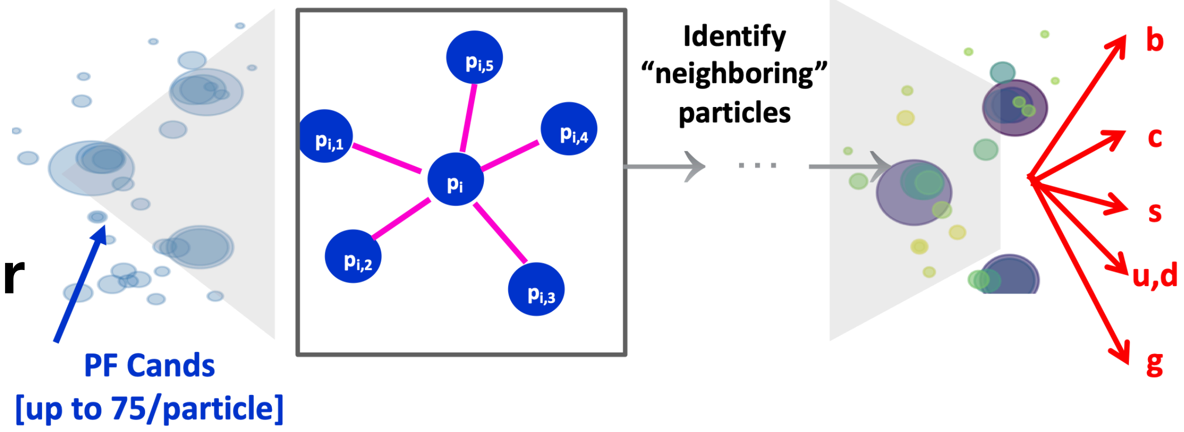
Jet Flavour Tagging - The ParticleNet Tagger

- 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
- 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
- Powerful identification of ***b, c, s, d, u, τ*** **&** ***g*** **jets**!
- **ParticleNet retrained & evaluated on different detector configurations for studies discussed in the following!**

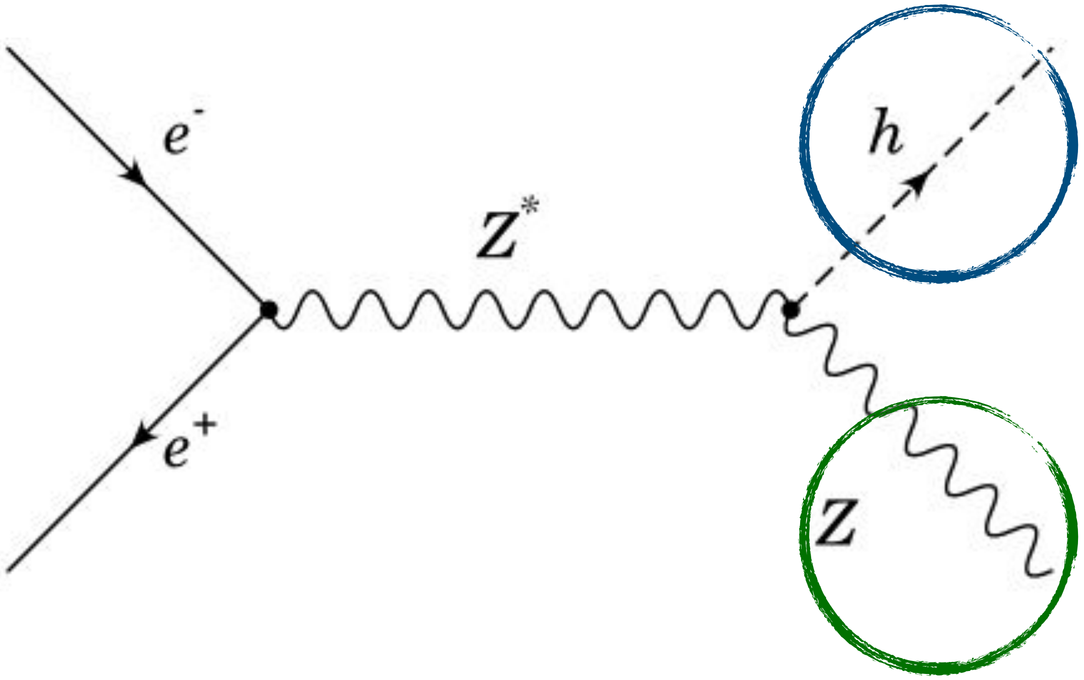


From arXiv:1801.07829

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



Z(->ll,vv,jj)H - General Strategy



- Higgs boson reconstruction:
    - Particular focus on hadronic decays, e.g. -> *bb/cc/gg/ss*(?)…

- *Z*-boson reconstruction:
    - Explore several decay modes
    - Usage of “recoil mass”

- Key features:
    - Optimal identification (“tagging”) of hadronic decays
        - Simultaneous extraction across different flavours
    - “In-situ” constrain of background uncertainties to better than O(1%)
- Three analysis channels: *Z(->ll, vv, qq)H* with similar strategy
    - Categorise events using jet-flavour tagger scores (bb, cc, ss, gg, …)
    - Signal extraction through simultaneous fit across categories of Higgs decay products’ invariant mass
    - **This analysis: natural framework to access impact of detector proposals to the full Higgs physics program**

Z(->ll,vv,jj)H - Expected Precision @240 GeV

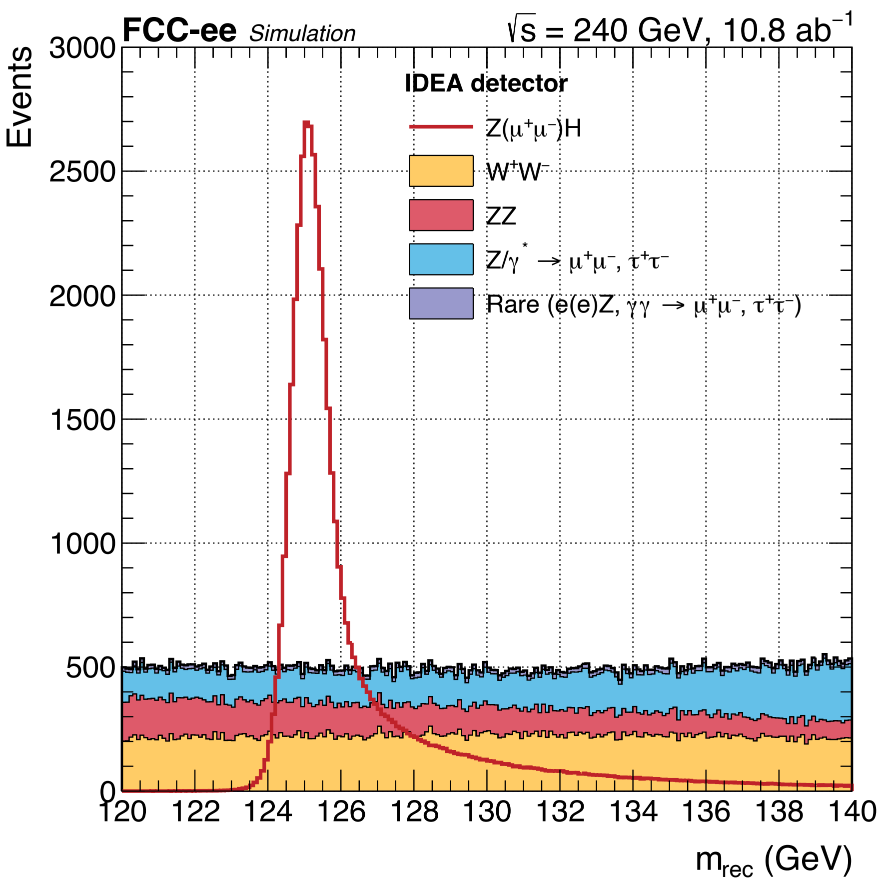
Analysis	$H\rightarrow b\bar{b}$	$H\rightarrow c\bar{c}$	$H\rightarrow gg$	$H\rightarrow s\bar{s}$	$H\rightarrow ZZ$	$H\rightarrow WW$	$H\rightarrow \tau\tau$
$Z\rightarrow l^+l^-$	0.68	4.02	2.18	234	13.7	1.78	4.1
$Z\rightarrow q\bar{q}$	0.32	3.52	3.07	409	52.1	8.74	110
$Z\rightarrow \nu\bar{\nu}$	0.33	2.27	0.94	137	19.8	1.89	22
comb	0.21	1.66	0.80	105	10.1	1.16	4.0

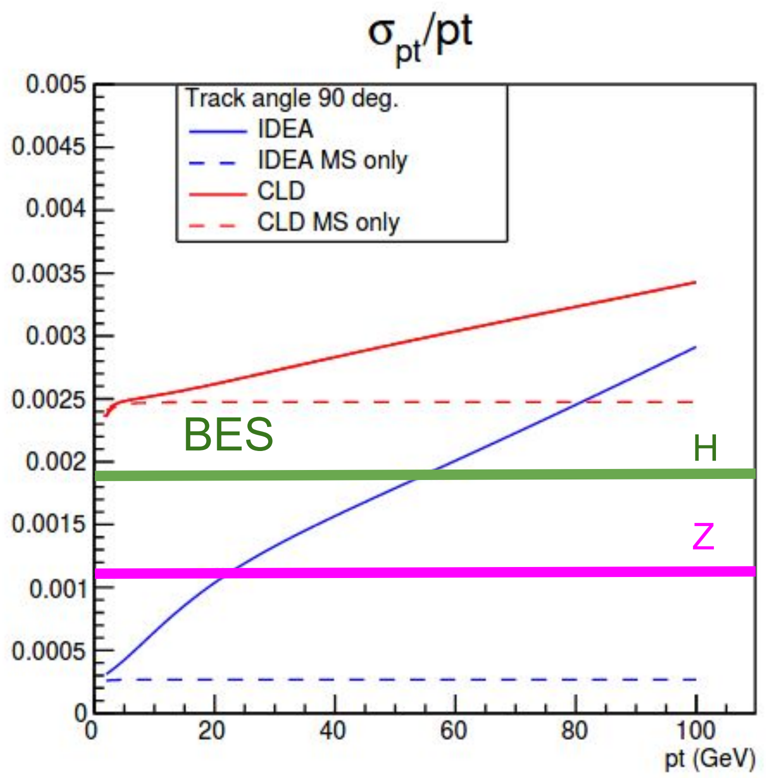
Relative uncertainty (in %) at 68% CL on signal strengths in the various Higgs decay channels

- Exploiting Delphes-based simulation of IDEA detector concept
- Signal & most background processes: free normalisations correlated across categories determined by the fit
- Meet physics goals:
  - **Improve precision by O(10) wrt HL-LHC**
  - Extend to couplings that are (probably) impossible at the HL-LHC (charm, strange above all)
    - **Opportunity to fully establish Higgs coupling to second generation charged fermions!**

Track **Momentum Resolution**

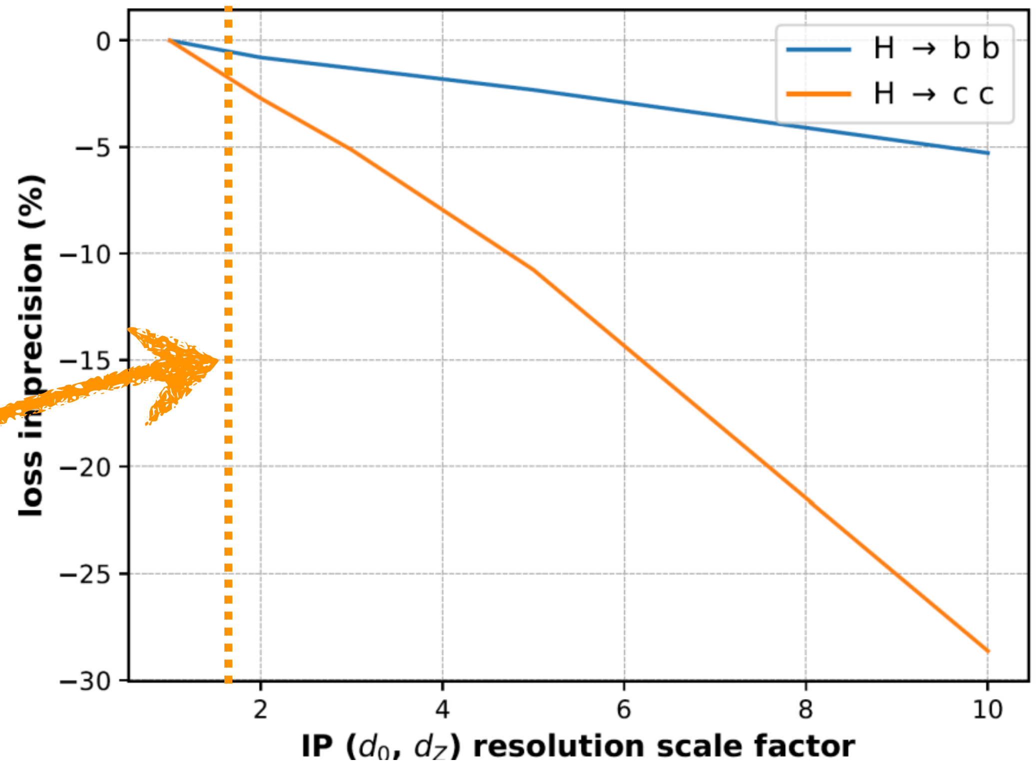
- ***ZH* production cross-section** can be extracted from the **recoil mass distribution**
- Sensitivity dominated by the Z(μμ) final state
    - Superior momentum resolution, driven by tracking
- Track momentum resolution limits sensitivity if larger than beam energy spread (BES = 0.182% at 240 GeV, i.e 222 MeV)
    - Multiple-scattering limit < BES
    - **Transparent tracker is key!**





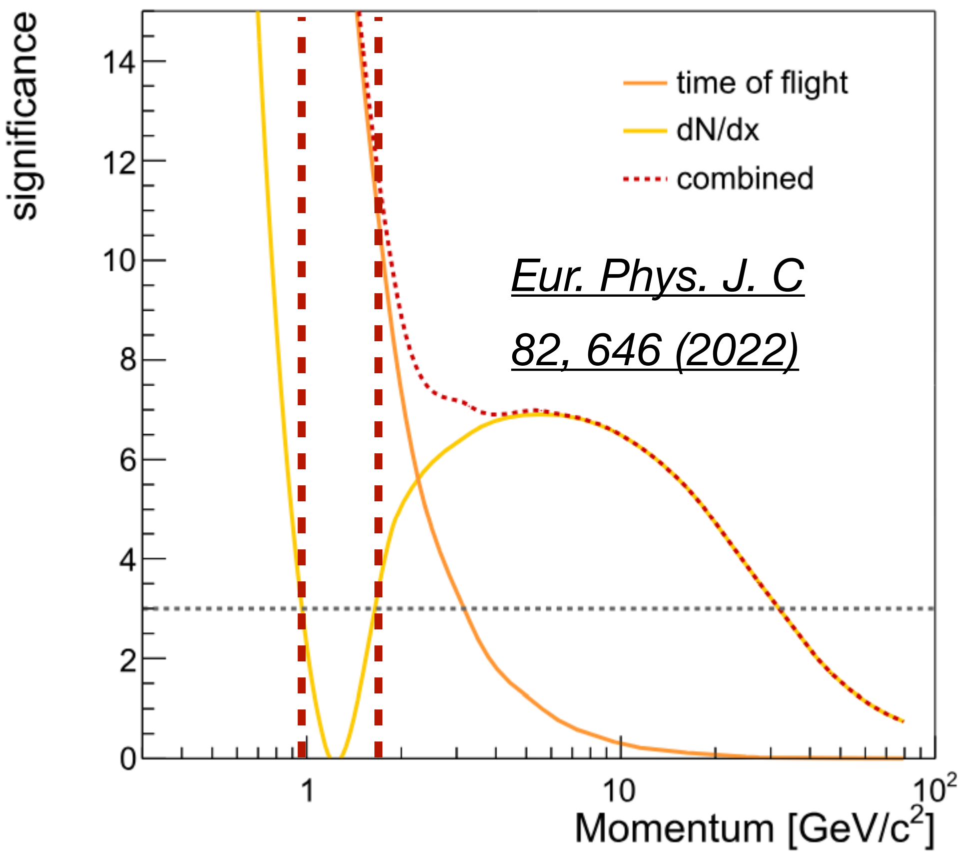
Impact Parameter Resolution & Vertexing

- 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 first tracking layer** (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
    - Evaluated Higgs couplings performance
- Small effects observed in H→bb (and H→cc)

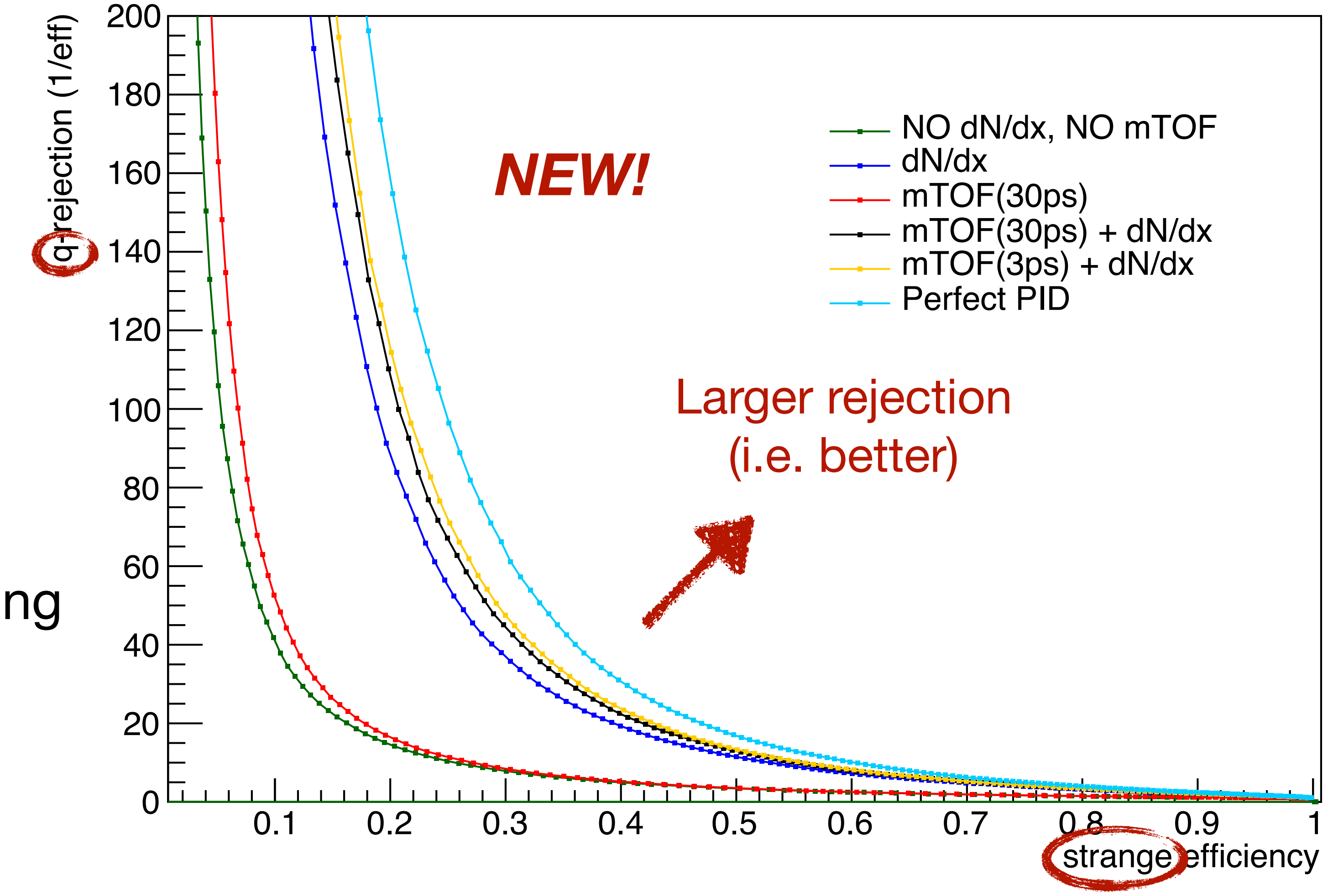
Charged Hadron Particle Identification



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

- Particle Identification (PID) is a crucial ingredient for strange-quark jet identification (H→ss)
- Need:
  - Cluster counting (*dN/dx*) measurement at high momentum - Cherenkov detectors (RICH)
  - Time of Flight (ToF) measurement at low momentum (~1 GeV)

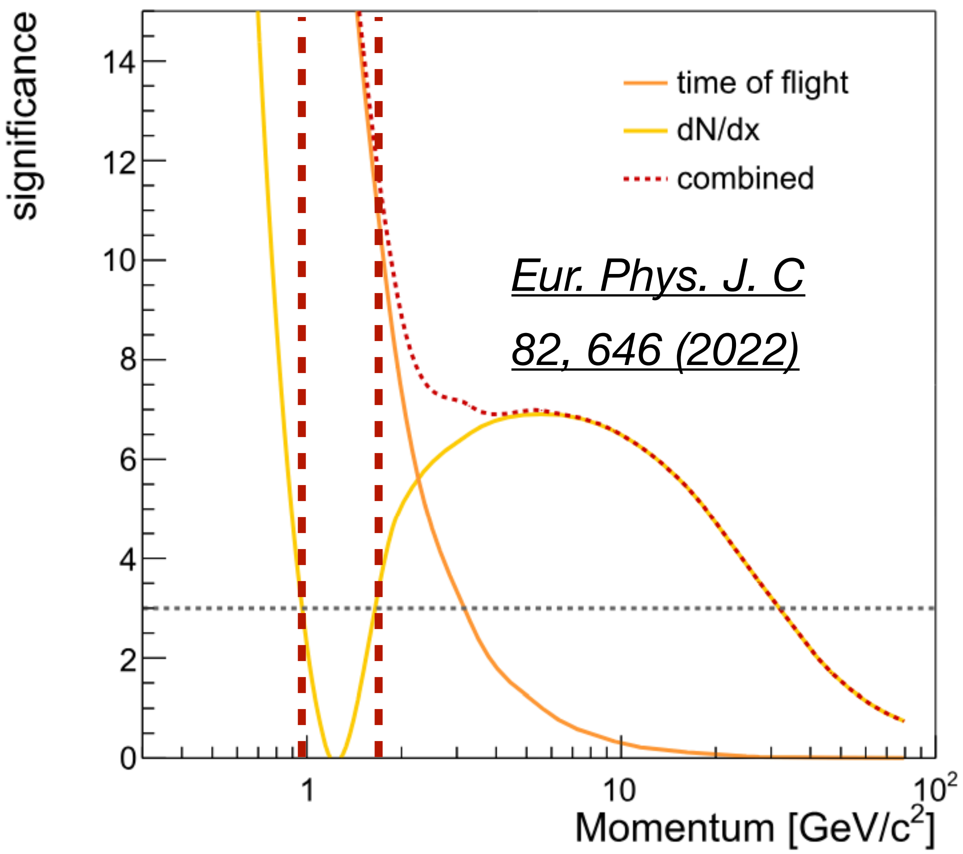
- Tagger retraining shows that:
  - IDEA detector concept PID performance close to "perfect" (i.e. truth) PID
  - Impact of ***dN/dx*** >> **ToF** on strange tagging



NEW!

Larger rejection (i.e. better)

Charged Hadron Particle Identification



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- Need:
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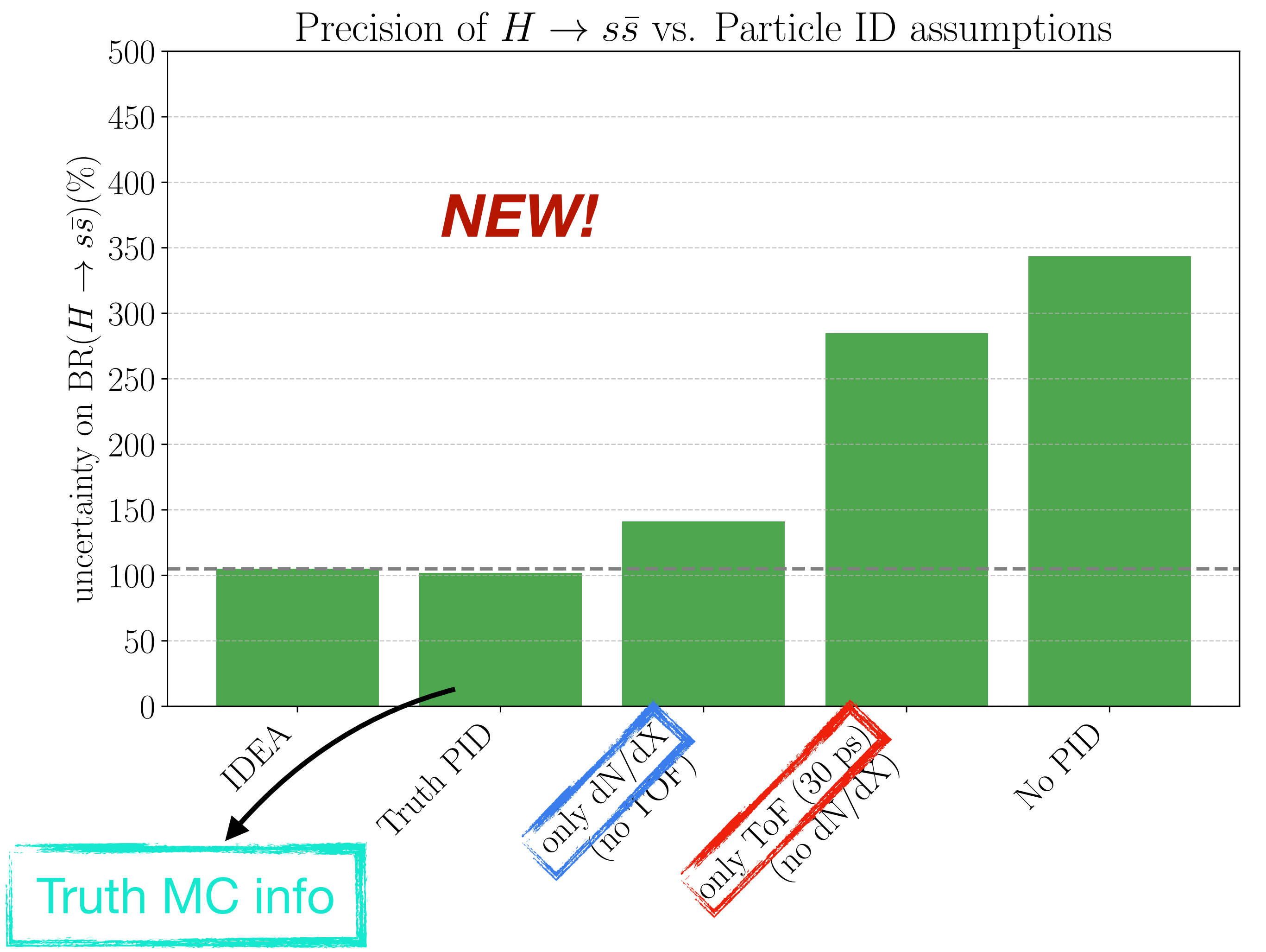
- From full propagation through the *ZH* analyses:
  - IDEA detector concept PID performance close to “perfect” PID
  - Impact of ***dN/dx*** >> **ToF**
    - Observe factor ~3 degradation in H→ss when **lacking *dN/dx* information**
  - **PID really crucial for H→ss determination**

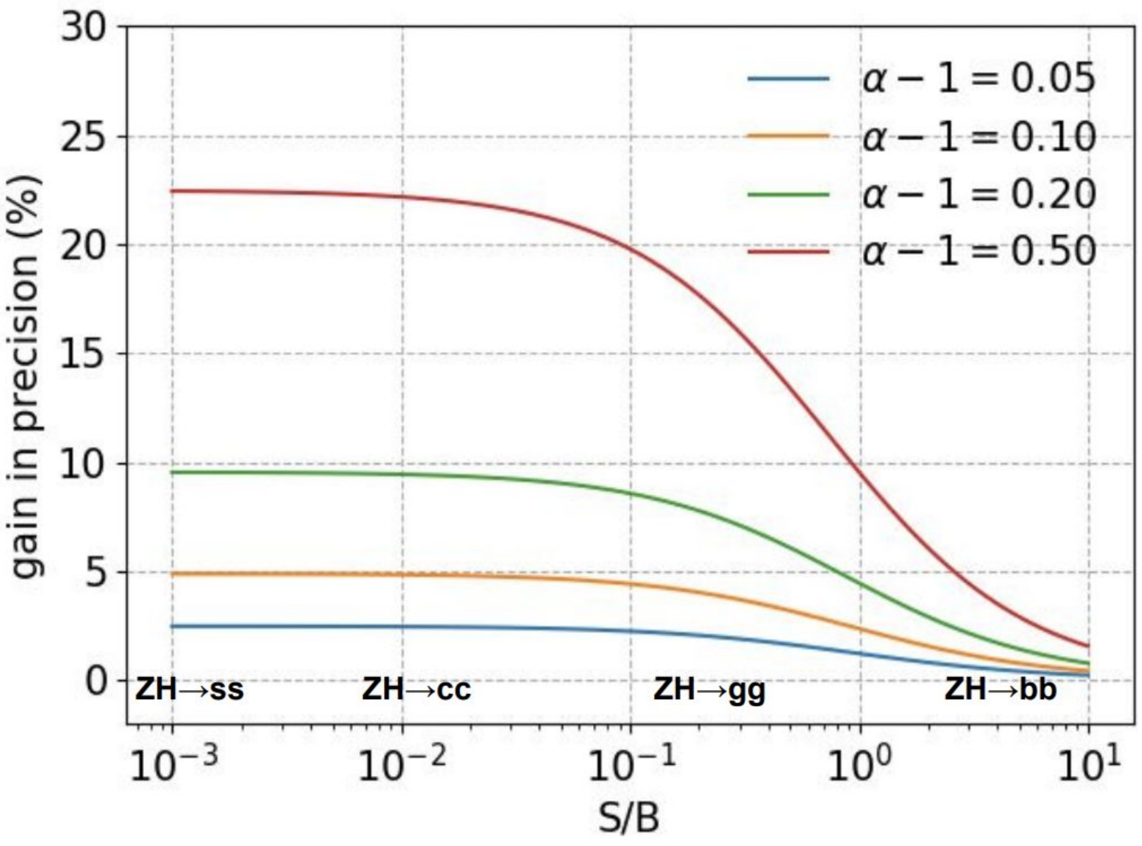


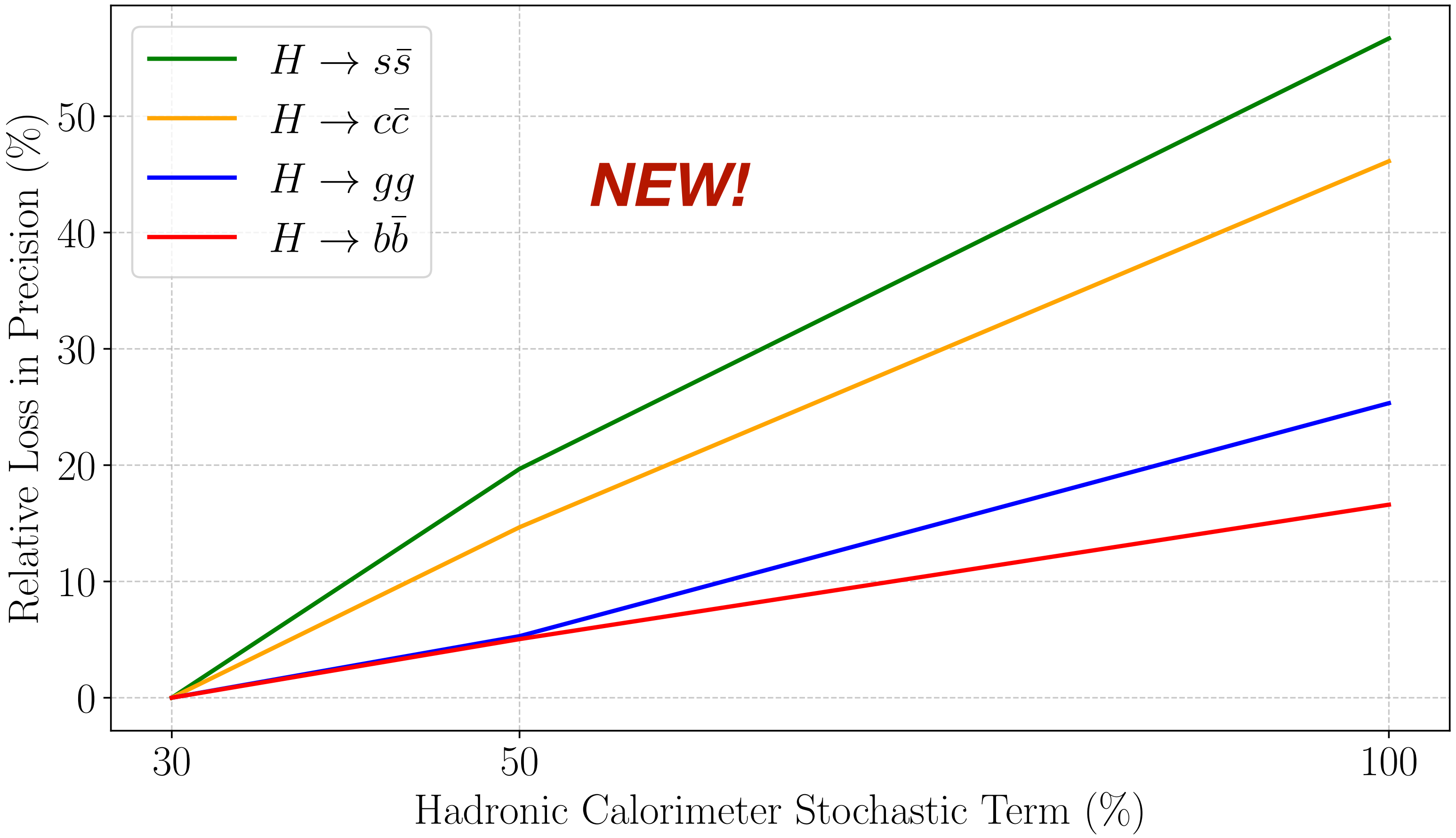
NEW!

Truth MC info

Hadronic Calorimeter & Jet Resolution

- With a perfect particle-flow algorithm, jet energy resolution is dominated by neutral (HCal) resolution
- Largest gain from JER expected for S/B << 1
    - If relative improvement α, expect √α increase in precision
- From full propagation of changes in hadronic calorimeter energy resolution, observe degradation scaling as expected





NEW!

Dual readout 30%/√E

ATLAS 50%/√E

CMS 100%/√E

Conclusion

- Exciting Higgs (but not only!) physics program possible at the FCC-*ee*
  - Expected to improve **Higgs couplings** measurement by a **factor ~10**, compared to HL-LHC
  - Fully establish coupling to **second generation charged fermions**
- Studied **impact of vertex, PID & calorimeter detectors** on Higgs couplings, by means of full propagation through the *ZH* analyses
  - Inputs to final Feasibility Study Report, due in early 2025
- Realistic variations in the **vertex detector** layout, material budget & hit resolution expected to have **minor impact**
- **Powerful PID system**, especially equipped with *dN(E)/dx* measurement is **crucial for determination of Higgs-to-strange** decay
- Sizable contribution of **hadronic calorimeter & jet resolution**
- **Current detector concepts do meet needs for the Higgs couplings program**
- Future: access Higgs couplings (and more!) detector requirements with full simulation

BACKUP

FCC-ee Machine

FCC-ee: the Physics Case

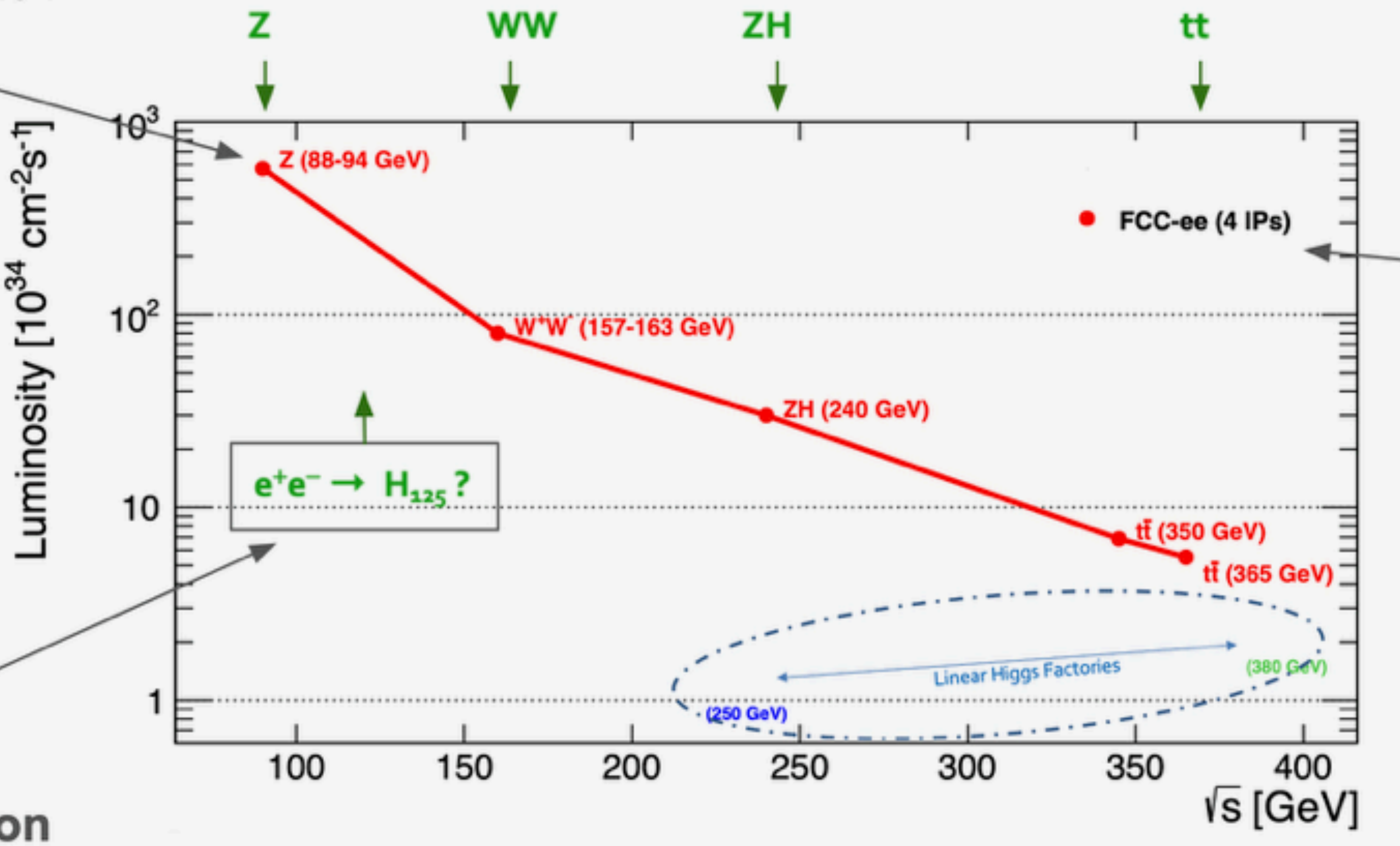
Courtesy of P. Janot

Optimal energy range for SM particles

Physics programme from 88 GeV to 365 GeV to challenge our knowledge of existing physics with unprecedented BSM sensitivity

LEP1 statistics in a few minutes

Detector calibration and alignment
Efficiency increased by factor 10^5!



Serve 4 interaction points

Gain in ab^{-1}, MW/ab^{-1} and CO_2-eq/ab^{-1}
Redundancy for precision measurements
Satisfy the many detector requirements
Increase discovery potential
Exploit all skills of the community

Highest luminosities

Best physics outcome (Z, W, H, top)
in the smallest amount of time
Increase discovery potential

First step towards 100 TeV pp collisions

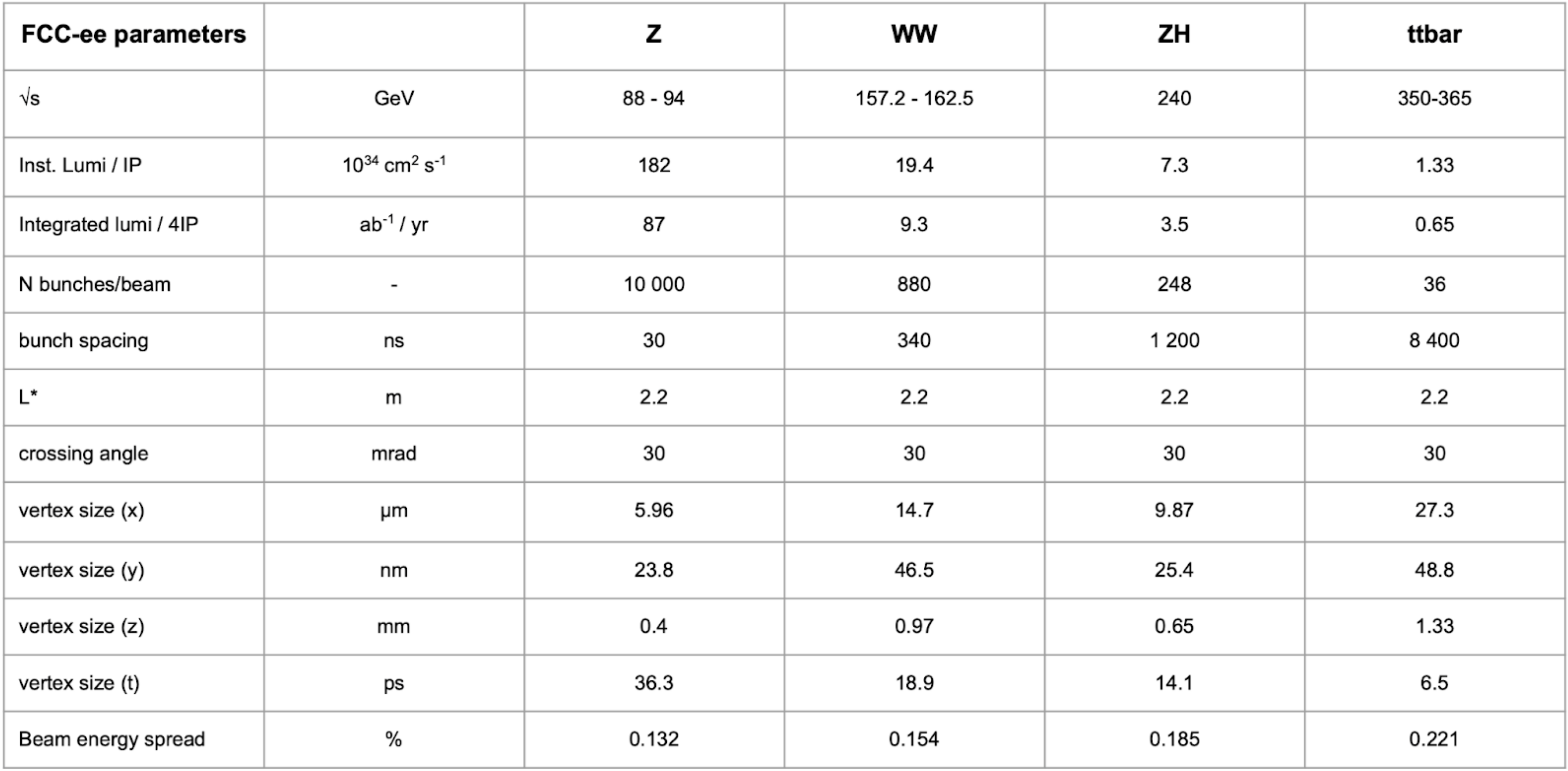
√s monochromatisation

Unique opportunity for electron Yukawa

Exquisite √s calibration (also √s spread, boost, …)

Both with resonant depolarisation (Z, H, W) and with dimuon events
Essential for precision measurements

Latest FCC-ee Parameters

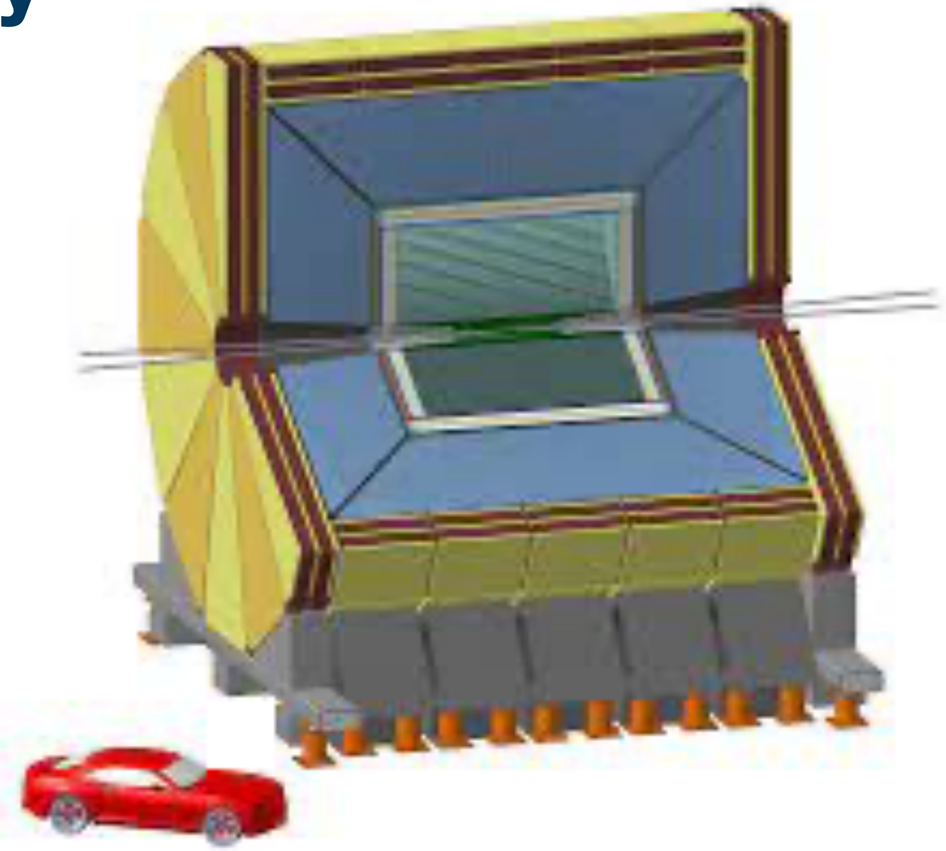


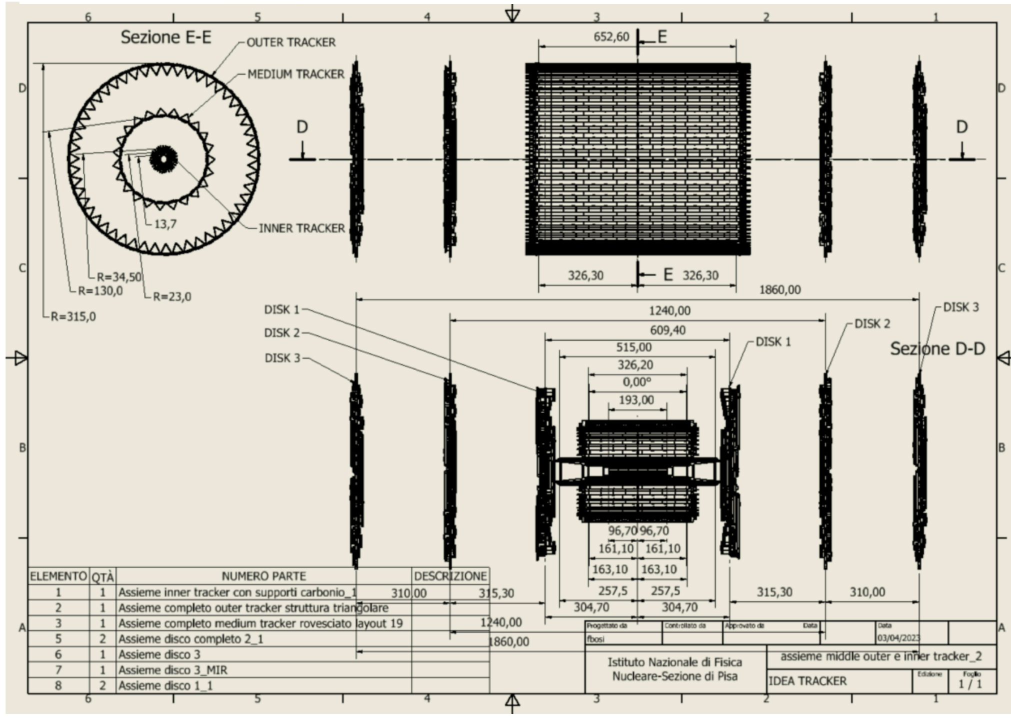
FCC-ee parameters		**Z**	**WW**	**ZH**	**ttbar**
√s	GeV	88 - 94	157.2 - 162.5	240	350-365
Inst. Lumi / IP	10^{34} cm^{2} s^{-1}	182	19.4	7.3	1.33
Integrated lumi / 4IP	ab^{-1} / yr	87	9.3	3.5	0.65
N bunches/beam	-	10 000	880	248	36
bunch spacing	ns	30	340	1 200	8 400
L*	m	2.2	2.2	2.2	2.2
crossing angle	mrad	30	30	30	30
vertex size (x)	µm	5.96	14.7	9.87	27.3
vertex size (y)	nm	23.8	46.5	25.4	48.8
vertex size (z)	mm	0.4	0.97	0.65	1.33
vertex size (t)	ps	36.3	18.9	14.1	6.5
Beam energy spread	%	0.132	0.154	0.185	0.221

IDEA Tracker

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



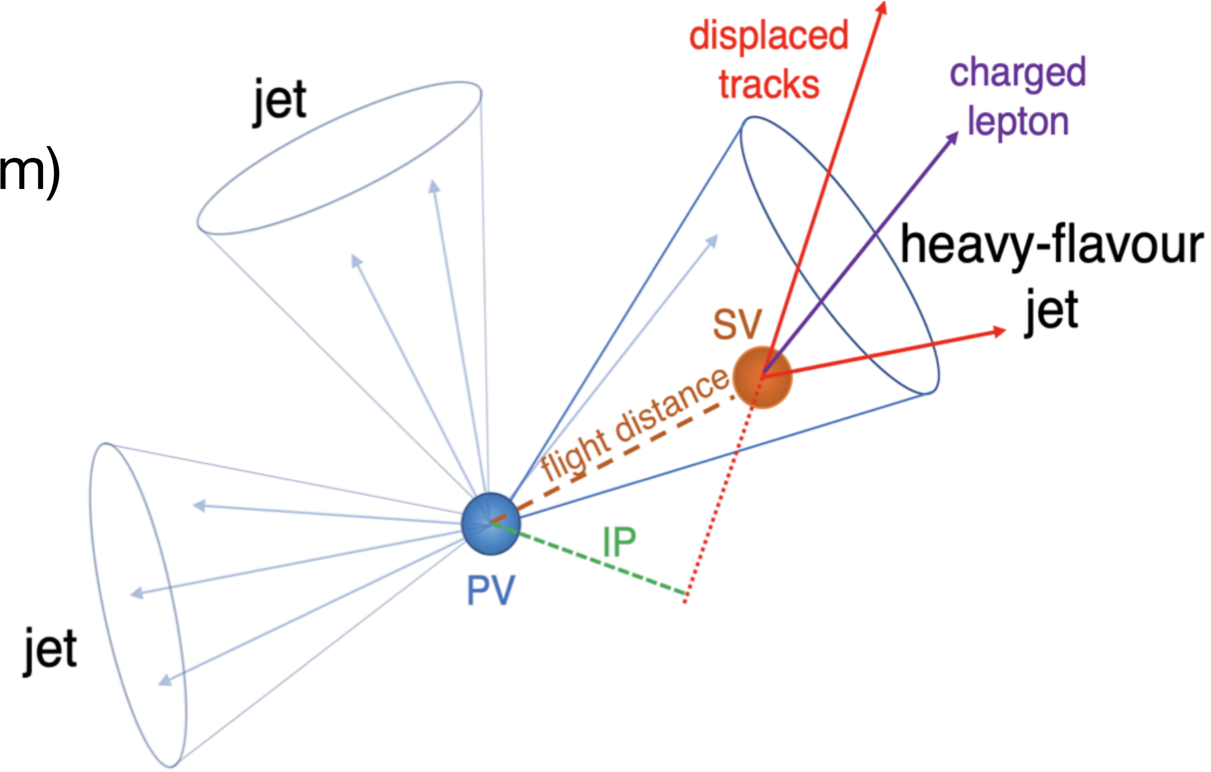


Latest IDEA tracker layout from F. Palla's talk

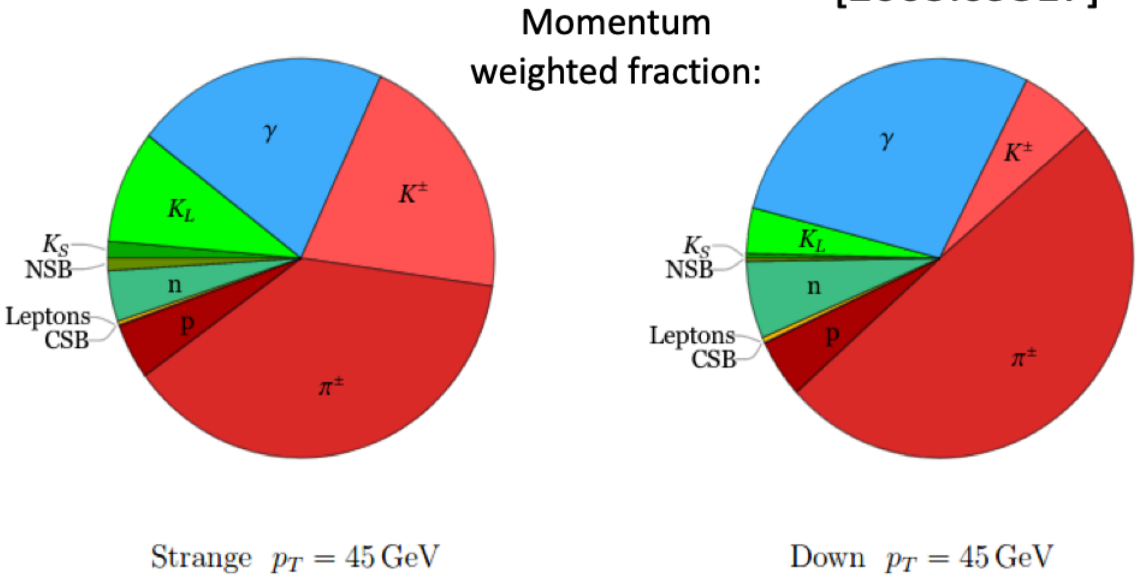
Flavour Tagging

Flavour-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]

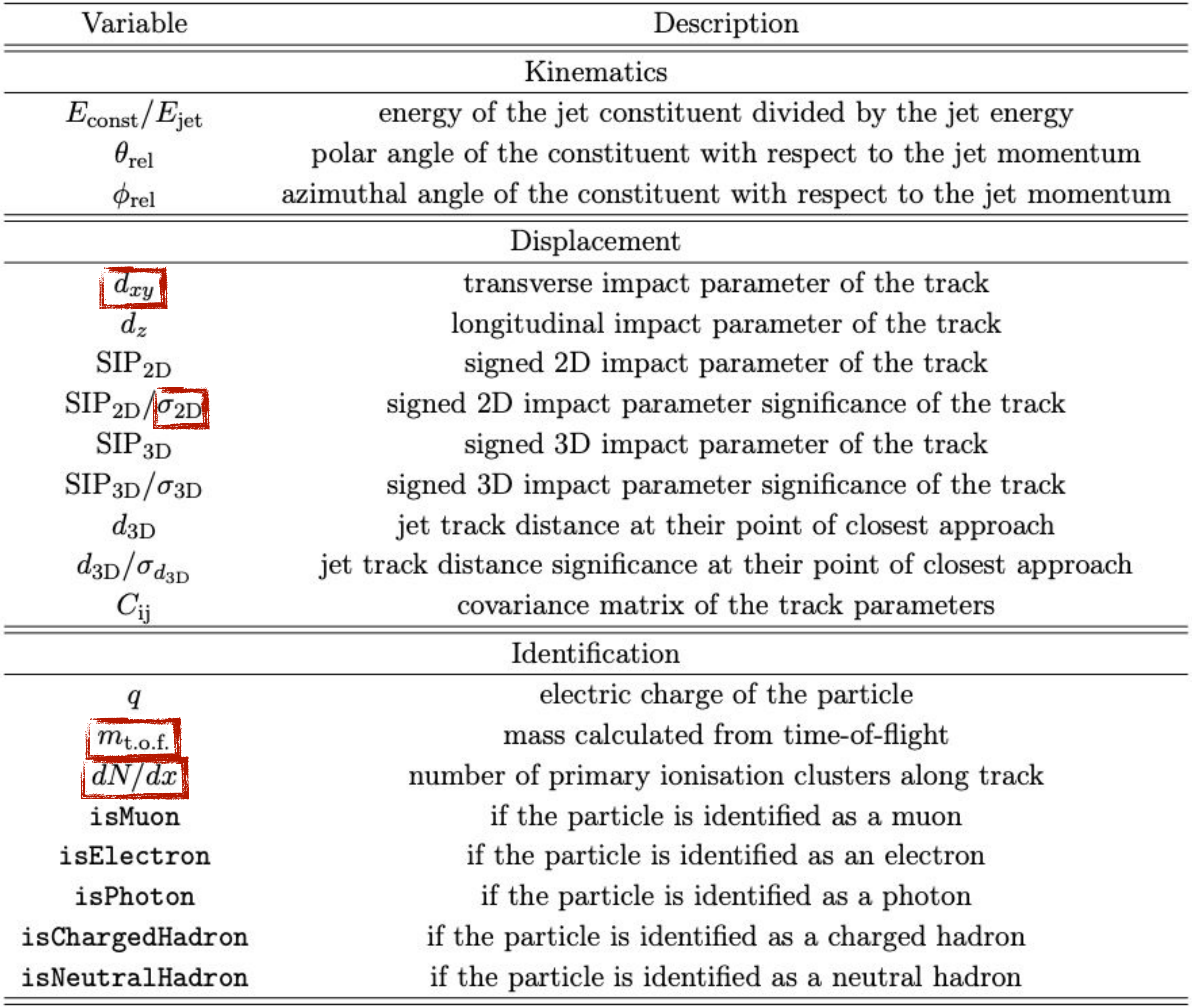


Momentum weighted fraction:

Strange $p_T = 45\,\text{GeV}$

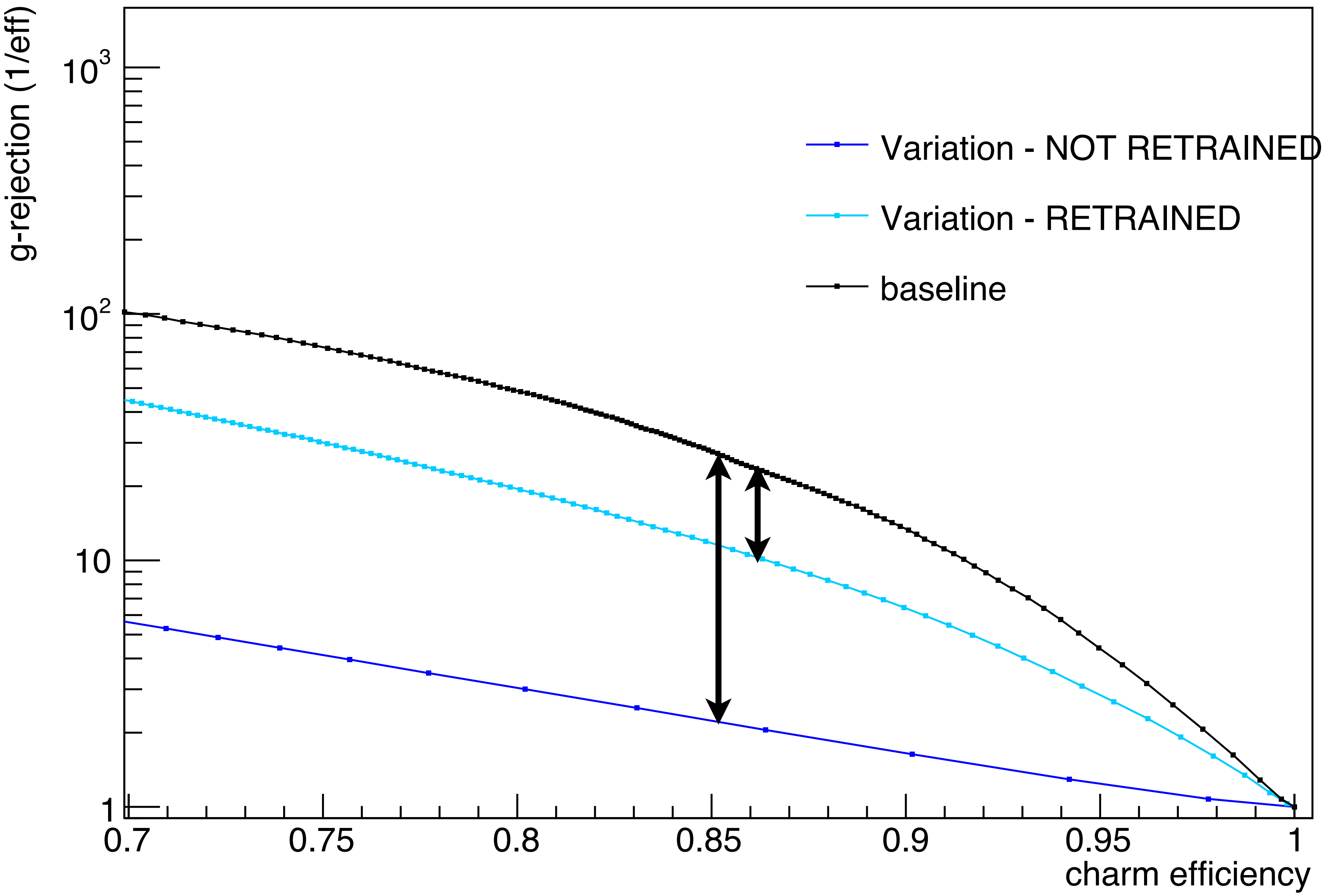
Down $p_T = 45\,\text{GeV}$

ParticleNet - Full List of Input Variables



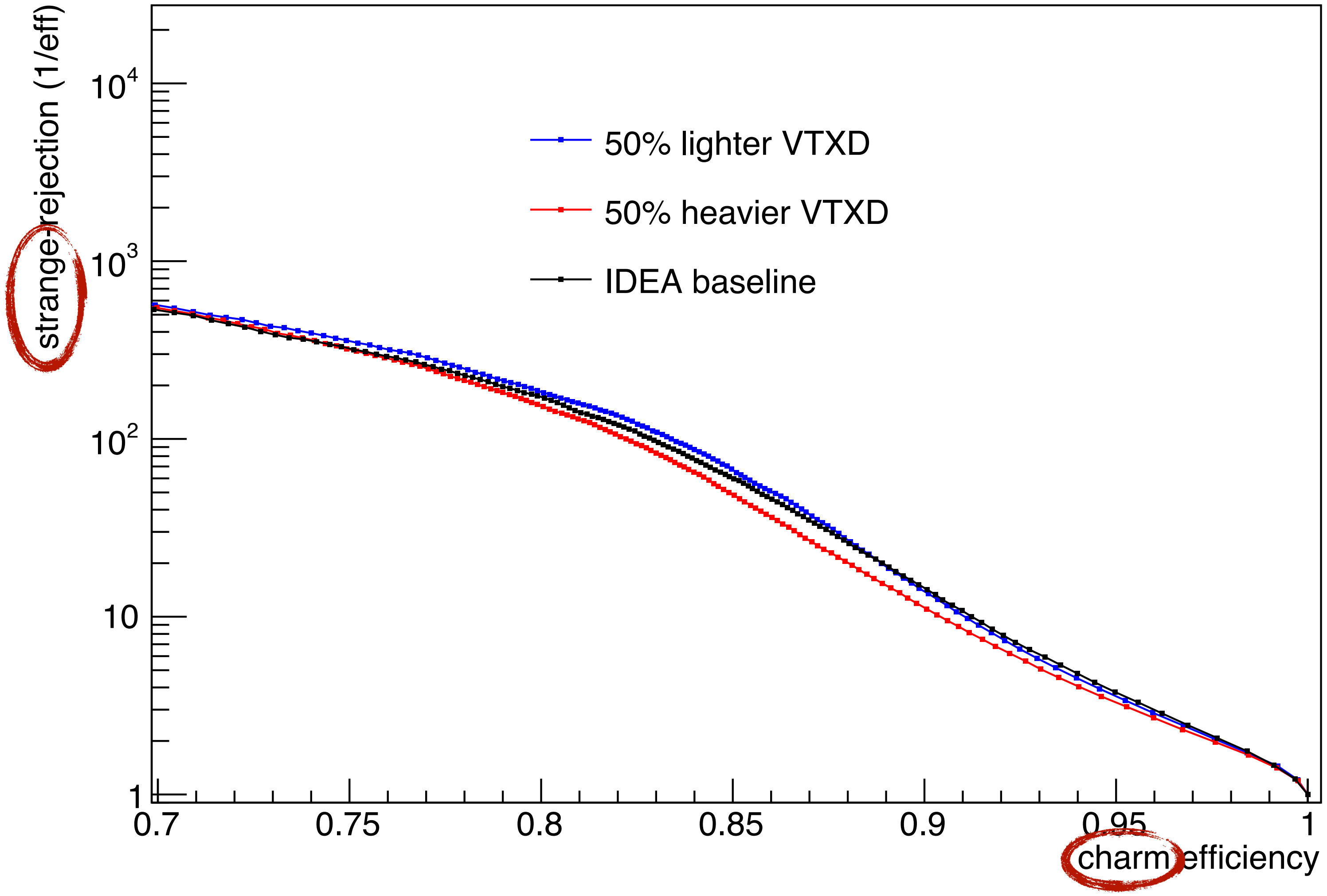
Variable	Description
	Kinematics
$E_{\mathrm{const}}/E_{\mathrm{jet}}$	energy of the jet constituent divided by the jet energy
θ_{rel}	polar angle of the constituent with respect to the jet momentum
ϕ_{rel}	azimuthal angle of the constituent with respect to the jet momentum
	Displacement
$\boxed{d_{xy}}$	transverse impact parameter of the track
d_z	longitudinal impact parameter of the track
$\mathrm{SIP}_{\mathrm{2D}}$	signed 2D impact parameter of the track
$\mathrm{SIP}_{\mathrm{2D}}/\boxed{\sigma_{\mathrm{2D}}}$	signed 2D impact parameter significance of the track
$\mathrm{SIP}_{\mathrm{3D}}$	signed 3D impact parameter of the track
$\mathrm{SIP}_{\mathrm{3D}}/\sigma_{\mathrm{3D}}$	signed 3D impact parameter significance of the track
d_{3D}	jet track distance at their point of closest approach
$d_{\mathrm{3D}}/\sigma_{d_{\mathrm{3D}}}$	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
$\boxed{m_{\mathrm{t.o.f.}}}$	mass calculated from time-of-flight
$\boxed{dN/dx}$	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?



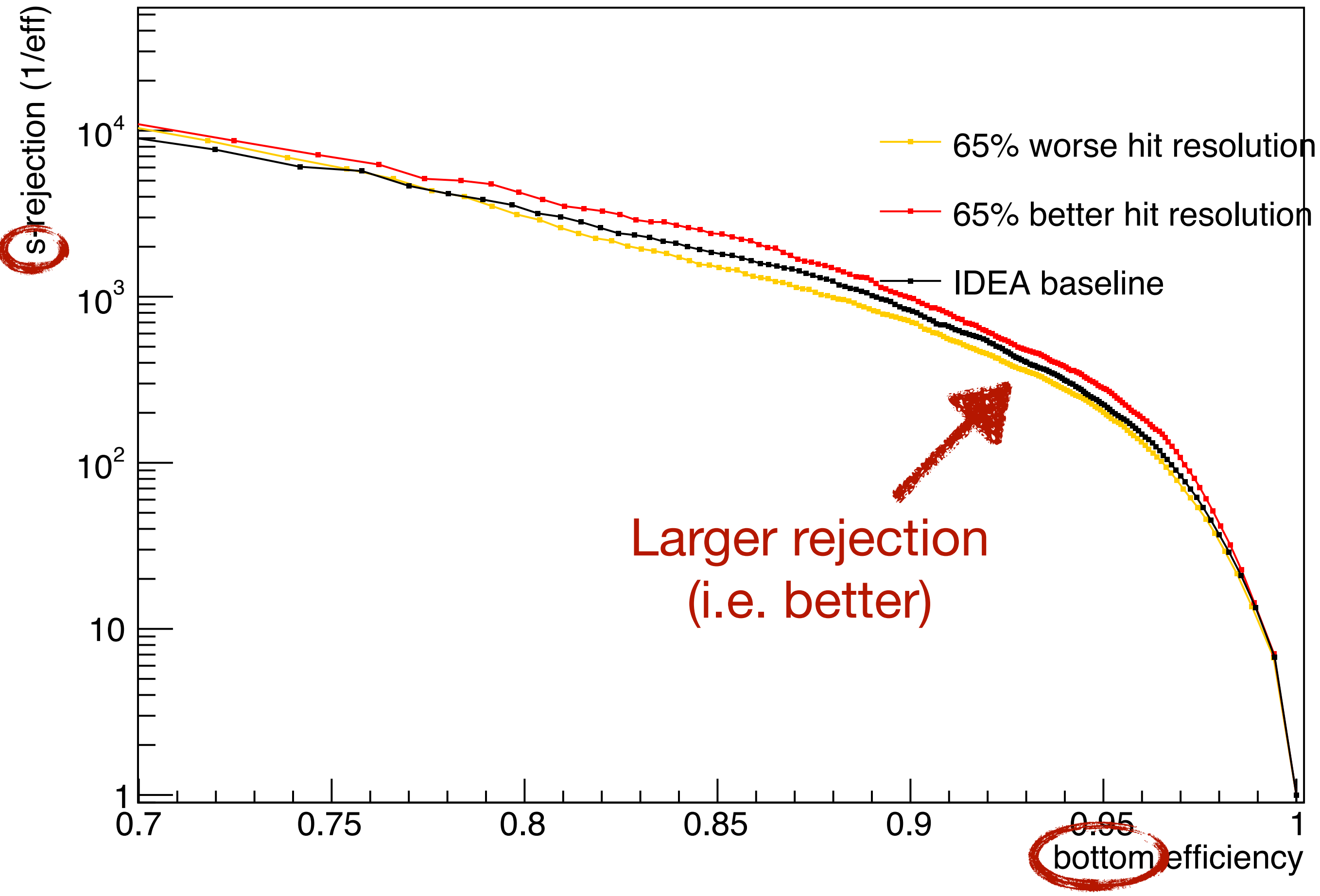
- Obviously, given a detector configuration, ParticleNet would be trained against it
- Re-training allows recovering of (a significant) part of drop in performance
    - **Need re-training for fair & meaningful performance assessment of each point in the detector-configuration space**

Pixel-Detector Material Budget

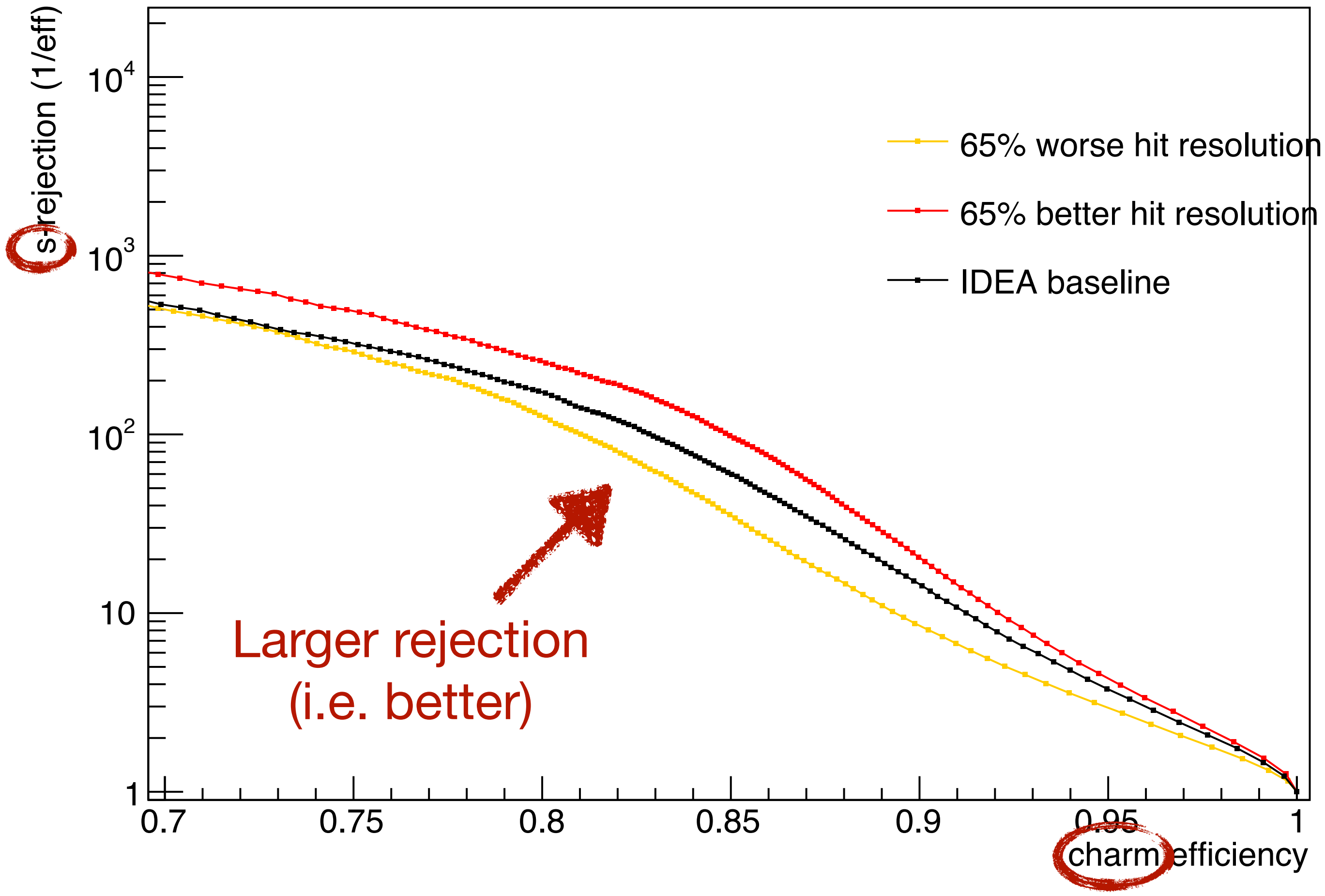


- May add many extra vertex layers, but eventually material (and real!) budget come into play
- Studied impact from ±50% relative variations in the radiation length for all of the vertex layers
- Asymmetric impact observed for *c*-tagging - minor on *b*-tagging:
  - Do not gain much from lighter vertex 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



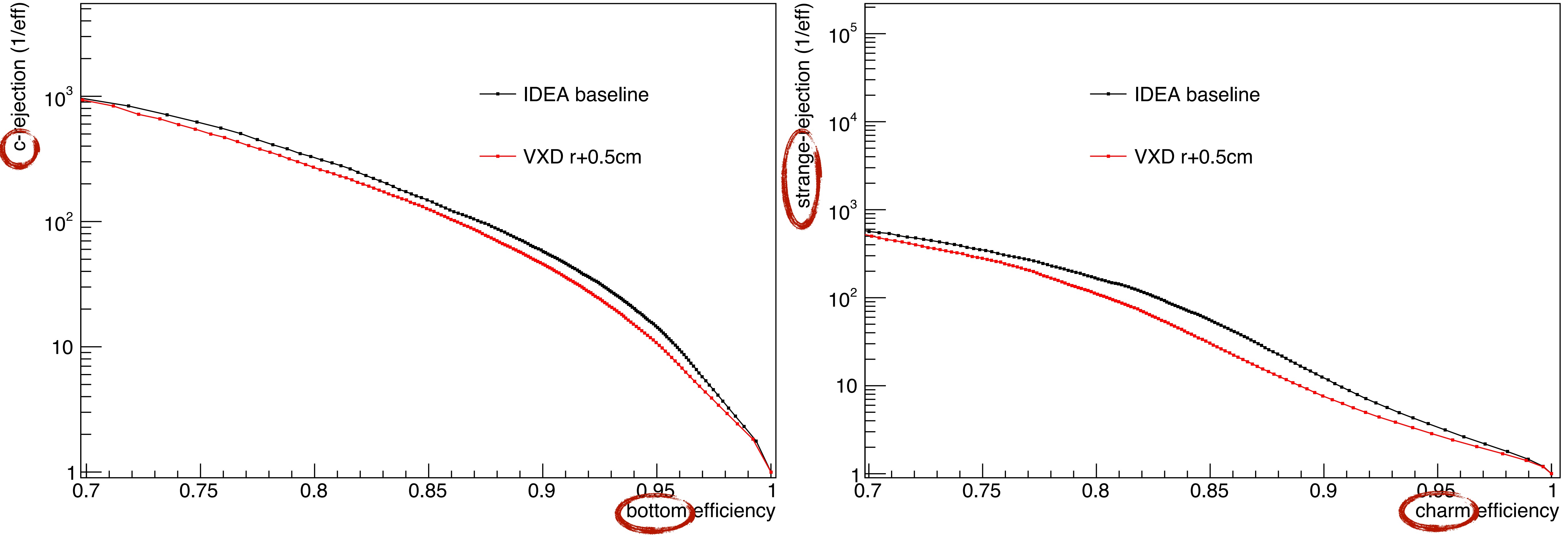
Larger rejection (i.e. better)



Larger rejection (i.e. better)

- 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

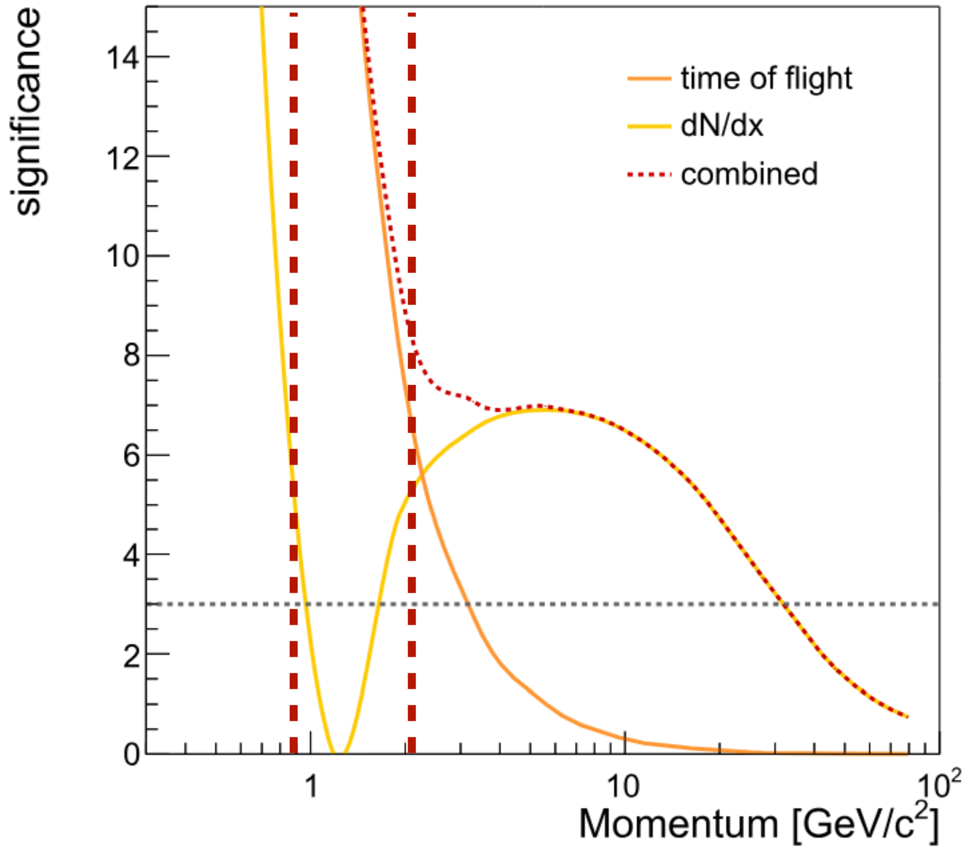


- Studied impact of **shifting VTXD barrel layers 0.5cm away from beam pipe**
- **Significant impact on bottom and charm tagging**, coming from worsening in impact-parameter resolution

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 performed



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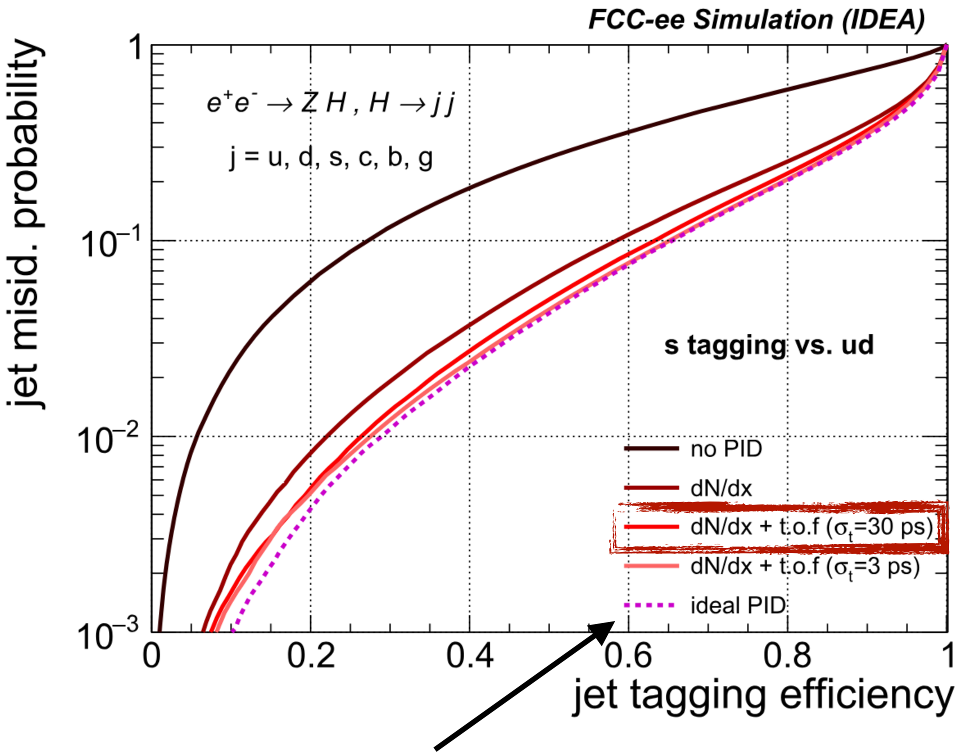
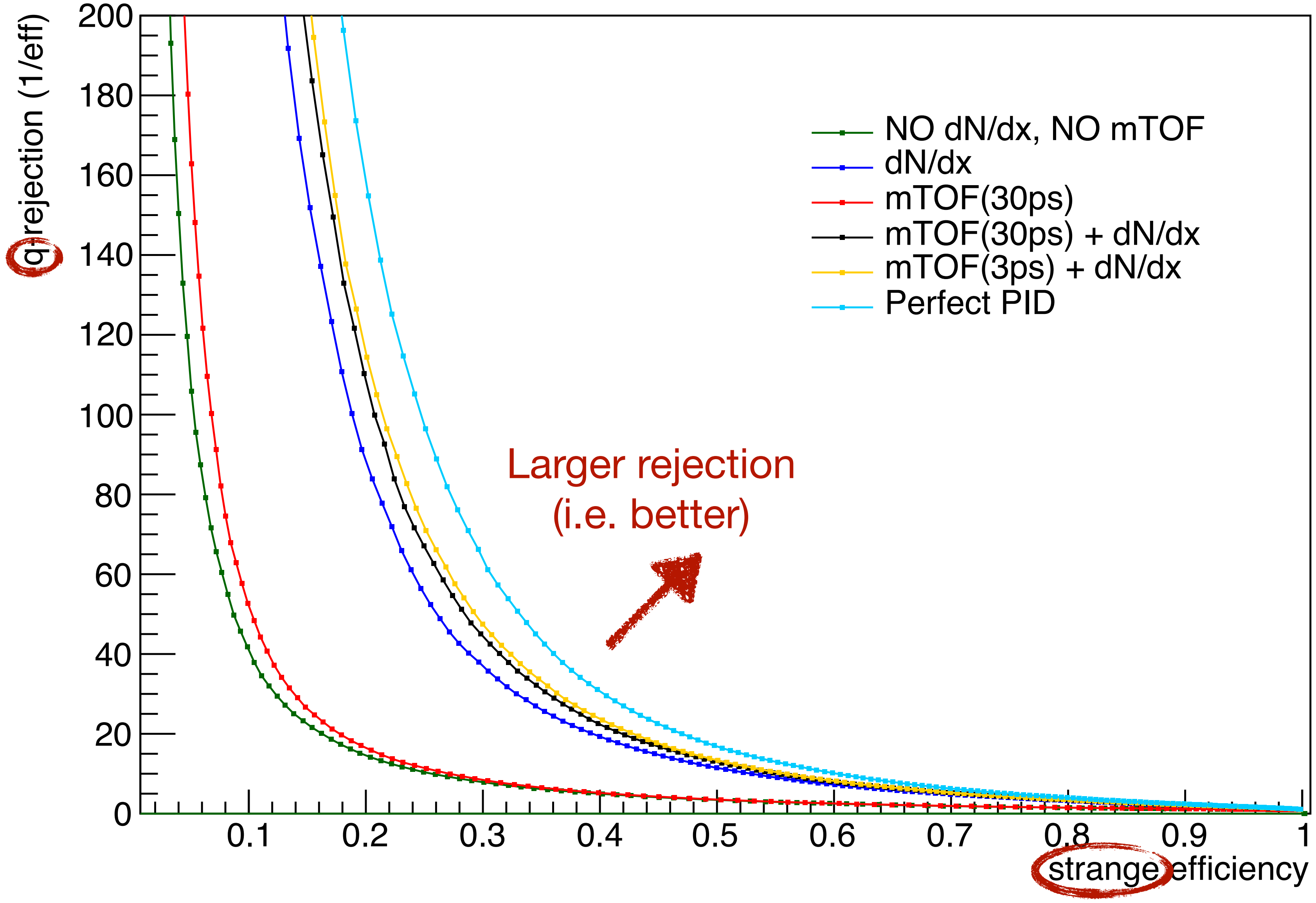


“Ideal” PID from *MC truth record*

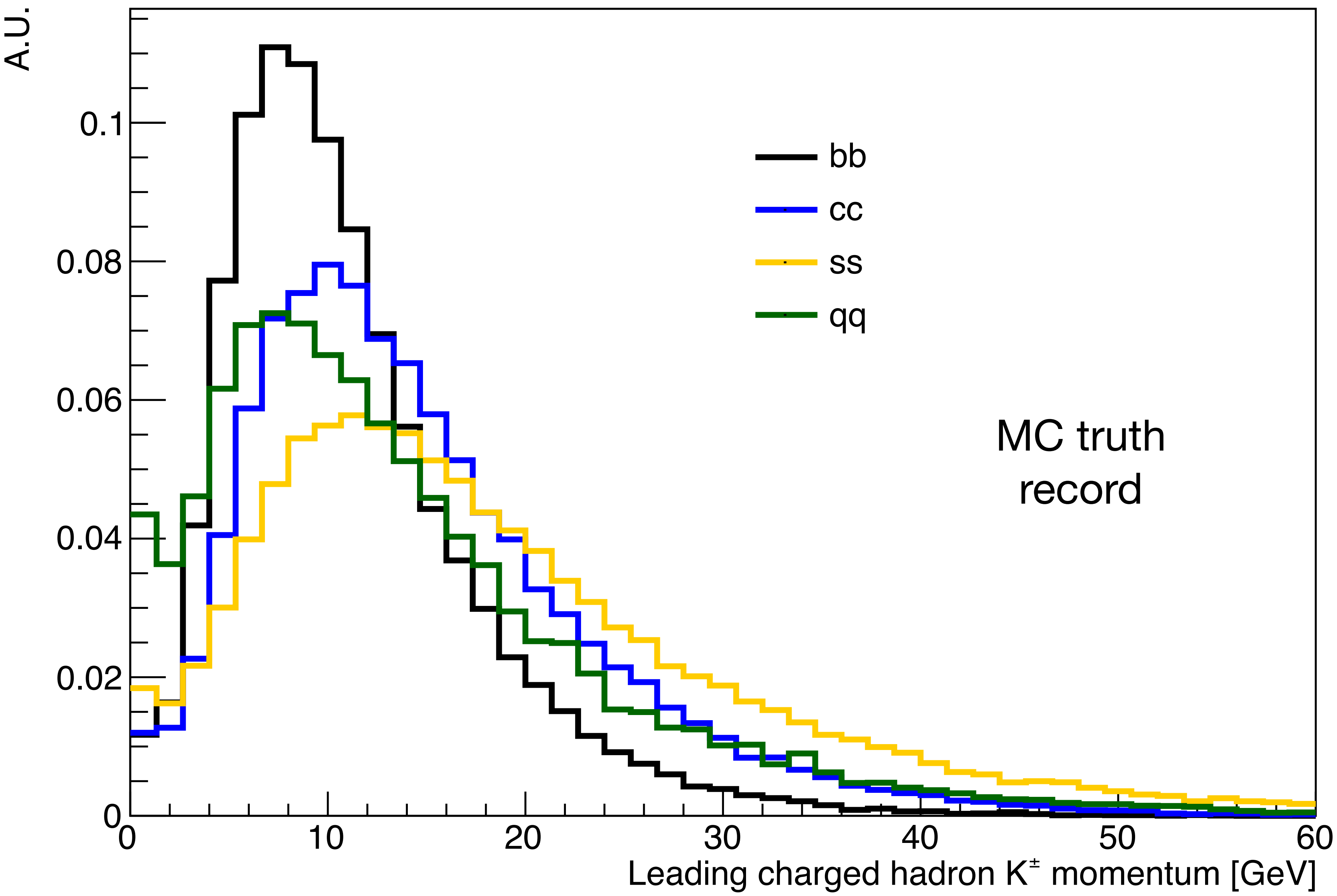
Strange Tagging & Light Rejection



Larger rejection
(i.e. better)

- **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)

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

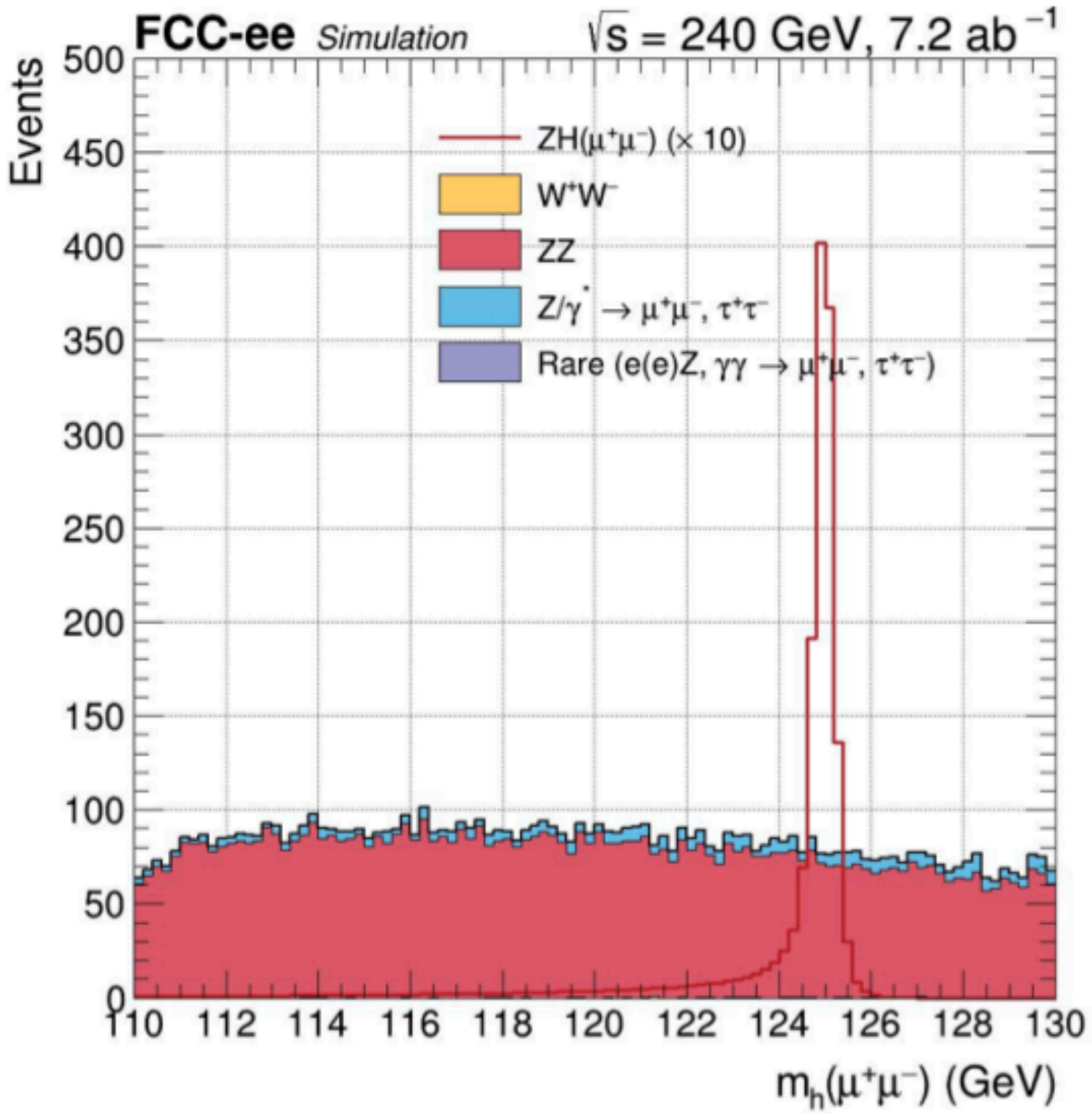


- Momentum of charged Kaons, when leading charged hadron in jet
- **Significantly higher jet momentum fraction in strange jets**

Higgs Couplings

Higgs-Boson Rare Decays: *μμ, γγ, Zγ*

- @ FCC-ee, √s=240 GeV, H→μμ and γγ in ZH events
  - Select events with 2 high-momentum muons or photons, m_{inv}~m_H, recoil mass~m_Z (~300 H→μμ, 4000 H→γγ after selection in 10/ab)
  - Classify events into 4 categories (Z→ee, μμ, νν, qq) based on number and flavor of leptons, and missing momentum
  - Simultaneous fit to m_{inv} distributions in 4 categories. Largest sensitivity from Z(qq) (μμ) or Z(νν) (γγ)

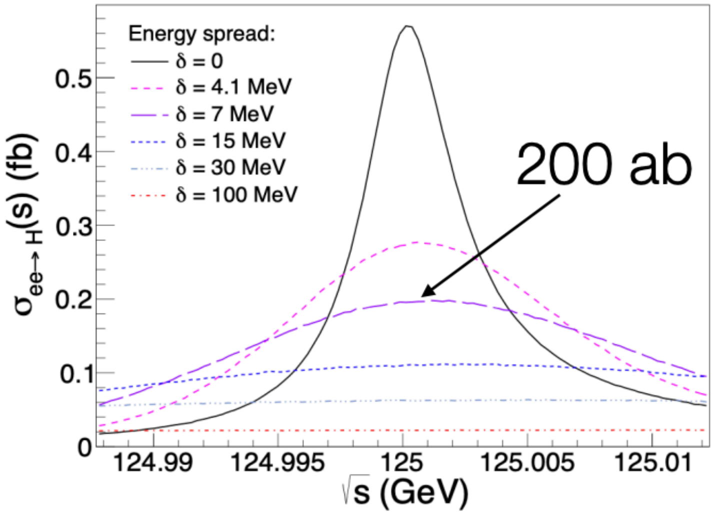


FCC-ee 10.8/ab @240 GeV: δBR/σBR(μμ)=16%, δBR/σBR(γγ)=3.1%

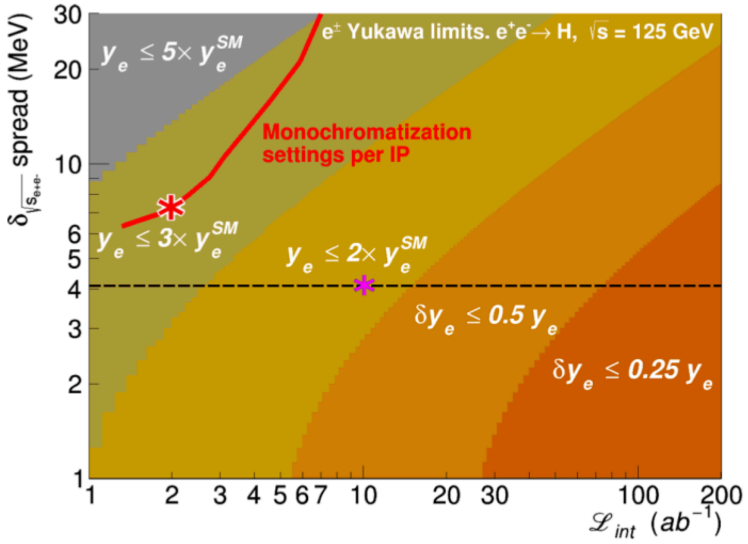
From G. Marchiori's talk @ICHEP2024

Electron Yukawa Coupling

- Dedicated run at $\sqrt{s}$=125 GeV could allow probing electron Yukawa coupling in s-channel (only way to access couplings to 1st gen)
  - Requires knowledge of Higgs mass to < 5 MeV, large luminosity, excellent beam chromatisation (energy spread ~ Γ_H)
  - Many Higgs decays considered, preselection followed by cut&count analysis on binary BDT classifier (signal vs background)



Target Higgs decay	Final state definition	Signal presel. efficiency
$H \to b\bar{b}$	2 (excl.) jets, 1 b-tagged jet, no $\tau_{\rm had}$	80%
$H \to gg$	2 (excl.) gluon-tagged jets, 0 isolated $\ell^\pm$	50%
$H \to \tau_{\rm had}\tau_{\rm had}$	Exactly 2 $\tau_{\rm had}$, 0 isolated $\ell^\pm$	65%
$H \to c\bar{c}$	2 (excl.) jets, 1 c-tagged jet, no $\tau_{\rm had}$	70%
$H \to WW^* \to \ell\nu 2j$	1 isolated $\ell^\pm$, $E_{\rm miss} > 2$ GeV, 2 (excl.) jets	~100%
$H \to WW^* \to 2\ell 2\nu$	2 isolated opp.-charge $\ell^\pm$, $E_{\rm miss} > 2$ GeV, 0 non-isol. $\ell^\pm$, 0 charged hadrons	~100%
$H \to WW^* \to 4j$	4 (excl.) jets, ≥ 1 c-tag jets, 0 b-,g-tag jets; jets with $m_{j1j2} \approx m_W$ not both c-tagged, 0 $\tau_{\rm had}$, 0 isolated $\ell^\pm$	70%
$H \to ZZ^* \to 2j2\nu$	2 (excl.) jets, $E_{\rm miss} > 30$ GeV, 0 isolated $\ell^\pm$, 0 $\tau_{\rm had}$	~100%
$H \to ZZ^* \to 2\ell 2j$	2 isolated opposite-charge $\ell^\pm$, 2 (excl.) jets, 0 $\tau_{\rm had}$	~100%
$H \to ZZ^* \to 2\ell 2\nu$	2 isolated opp.-charge $\ell^\pm$, $E_{\rm miss} > 2$ GeV, 0 non-isol. $\ell^\pm$, 0 charged hadrons	~100%
$H \to \gamma\gamma$	2 (excl.) isolated photons	~100%



arXiv:2107.02686

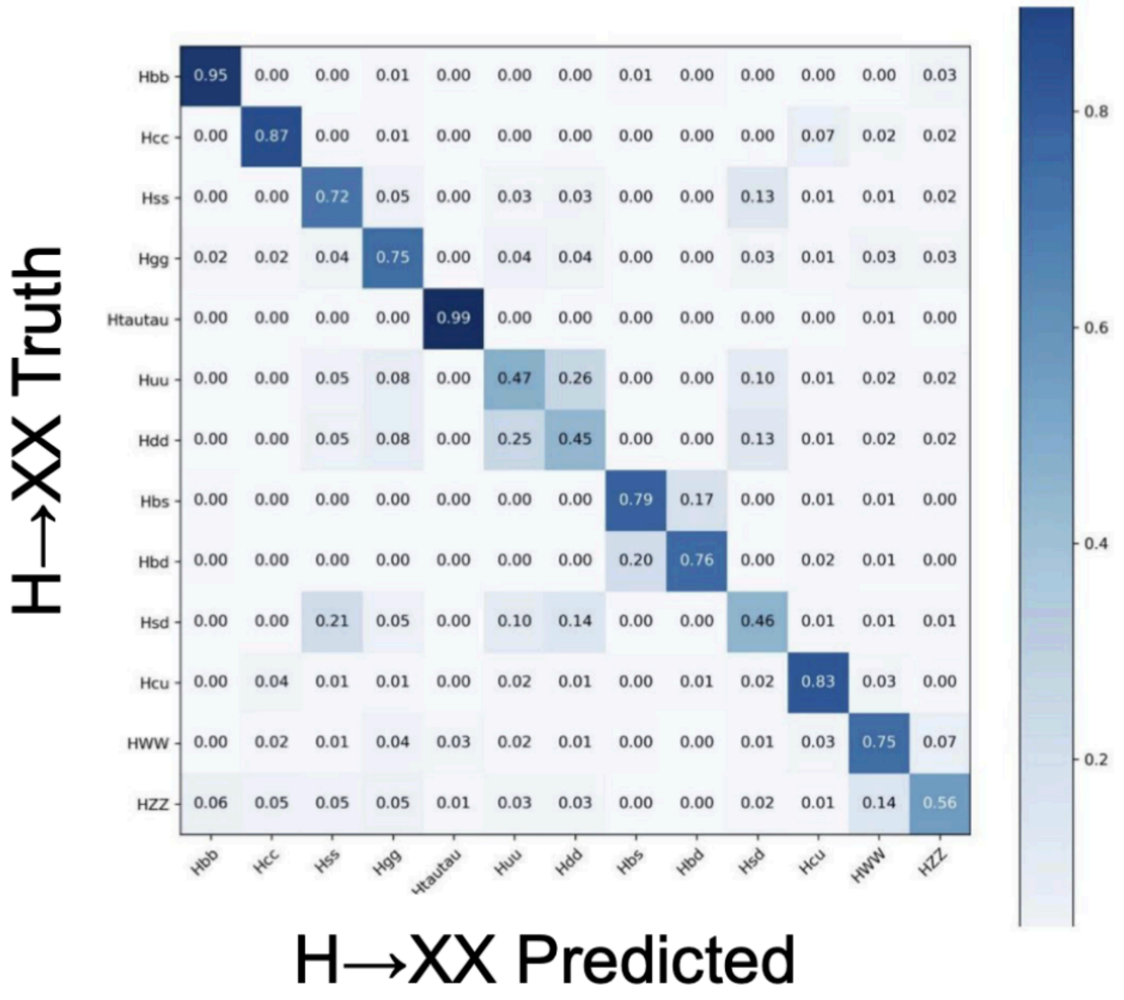
8/ab/yr (4 IP) with δ=7 MeV: 1600 ee→H/yr ⇒ y_e<1.6 y_e^{SM} in 2 yrs

To reach sensitivity to SM need optics w/ excellent monochromatisation AND L_{inst}

From G. Marchiori's talk @ICHEP2024

Higgs decays to quarks @ FCC-ee: 1st gen (*uu, dd*) & FCNC

- Extension of previous analysis using MVA with additional output classes (uu/dd/…) and floating freely in the final fit the normalisations of six additional Higgs decays



	Hbb	Hcc	Hss	Hgg	Htautau	Huu	Hdd	Hbs	Hbd	Hsd	Hcu	HWW	HZZ
Hbb	0.95	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.03
Hcc	0.00	0.87	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.02	0.02
Hss	0.00	0.00	0.72	0.05	0.00	0.03	0.03	0.00	0.00	0.13	0.01	0.01	0.02
Hgg	0.02	0.02	0.04	0.75	0.00	0.04	0.04	0.00	0.00	0.03	0.01	0.03	0.03
Htautau	0.00	0.00	0.00	0.00	0.99	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Huu	0.00	0.00	0.05	0.08	0.00	0.47	0.26	0.00	0.00	0.10	0.01	0.02	0.02
Hdd	0.00	0.00	0.05	0.08	0.00	0.25	0.45	0.00	0.00	0.13	0.01	0.02	0.02
Hbs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.79	0.17	0.00	0.01	0.01	0.00
Hbd	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.76	0.00	0.02	0.01	0.00
Hsd	0.00	0.00	0.21	0.05	0.00	0.10	0.14	0.00	0.00	0.46	0.01	0.01	0.01
Hcu	0.00	0.04	0.01	0.01	0.00	0.02	0.01	0.00	0.01	0.02	0.83	0.03	0.00
HWW	0.00	0.02	0.01	0.04	0.03	0.02	0.01	0.00	0.00	0.01	0.03	0.75	0.07
HZZ	0.06	0.05	0.05	0.05	0.01	0.03	0.03	0.00	0.00	0.02	0.01	0.14	0.56

10.8/ab at 240 GeV, vvjj only

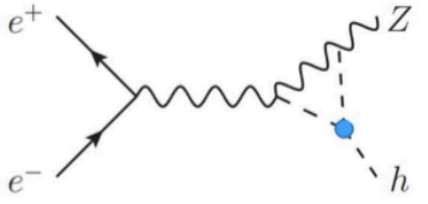
Final state	Upper limit on σBR @95% CL	BR(SM)
H→dd	1.4E-03	6E-07
H→uu	1.5E-03	1.4E-07
H→bs	3.7E-04	~1e-7
H→bd	2.7E-04	~1e-9
H→sd	7.7E-04	~1e-11
H→cu	2.5E-04	~1e-20

95% CL UL on σBR at 10^{-4} — 10^{-3} level with only vvjj final state at 240 GeV

From G. Marchiori's talk
@ICHEP2024

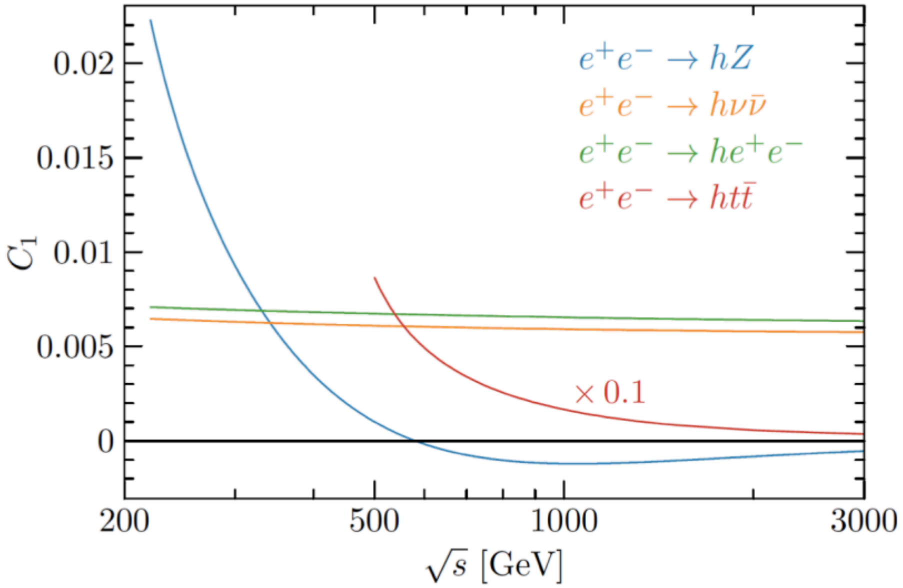
Higgs-Boson Self-Coupling

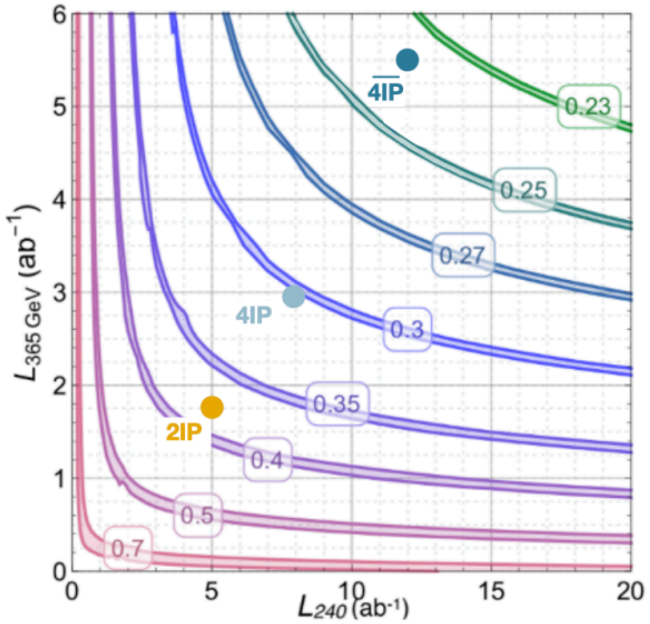
- FCC-ee: constrain $\kappa_\lambda=\lambda/\lambda_{SM}$ from single Higgs rate measurements, since κ_λ induces EW corrections to LO predictions



$$\sigma_{\mathrm{i,NLO}} = Z_H \sigma_{\mathrm{i,LO}}(1+\kappa_\lambda C_{1,i}) \qquad Z_H = \frac{1}{1-\kappa_\lambda^2 \delta Z_H} \qquad \delta Z_H \approx -0.00154$$

- C_1 depends on $\sqrt{s}$ ⇒ use measurements at 240 and 365 GeV to lift degeneracy between two solutions
- Expect $\delta\kappa_\lambda$ = 28% with 240 + 365 GeV runs





FCC-ee @240+365 GeV:
δκλ=28%

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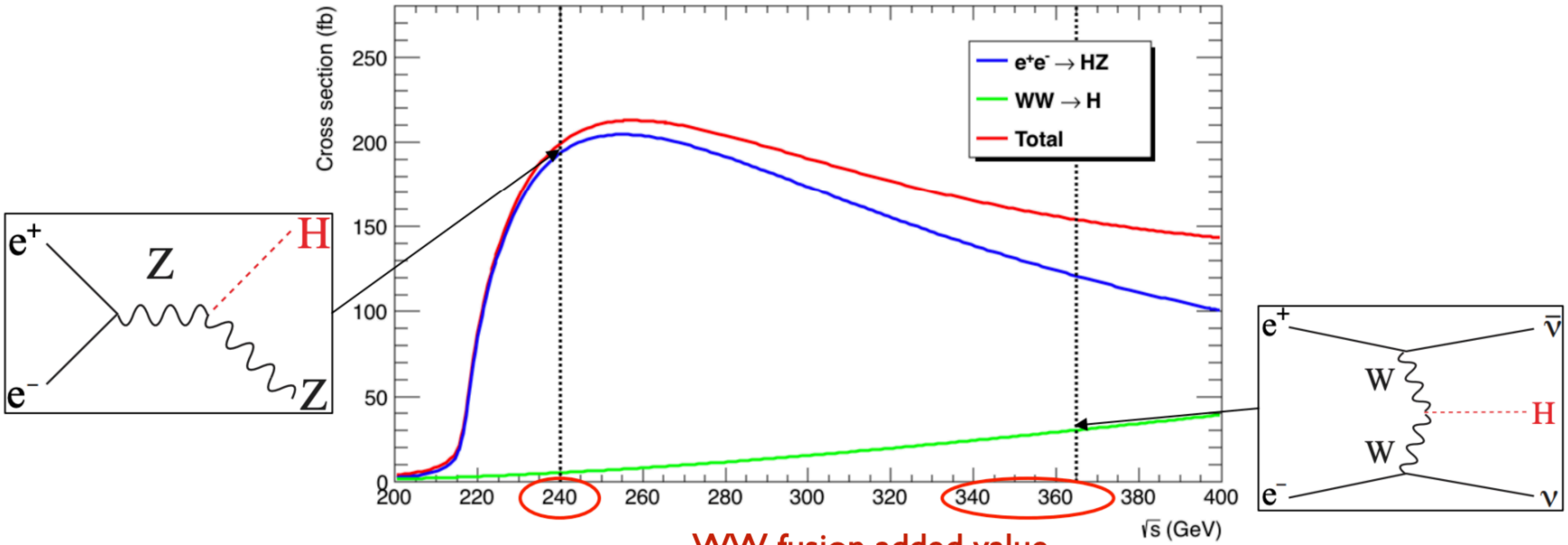
What can 365 GeV bring?



WW fusion added value

- vvH → vvbb ~ $g_W^2\, g_b^2 / \Gamma_H$
  - vvbb / (ZH(bb) ZH(WW)) ~ $g_Z^4 / \Gamma_H = R$
    - Γ_H precision at 1%
- Then do vvH → vvWW ~ g_W^4 / Γ_H
  - R / vvWW ~ g_W^4 / g_Z^4
    - g_W precision to few permil

Running at the top does not simply add statistics
it exploits complementary production mode to improve constraints