Evaluating strange-tagging performance for SiD fast- and full-simulation

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SLAC NATIONAL ACCELERATOR LABORATORY
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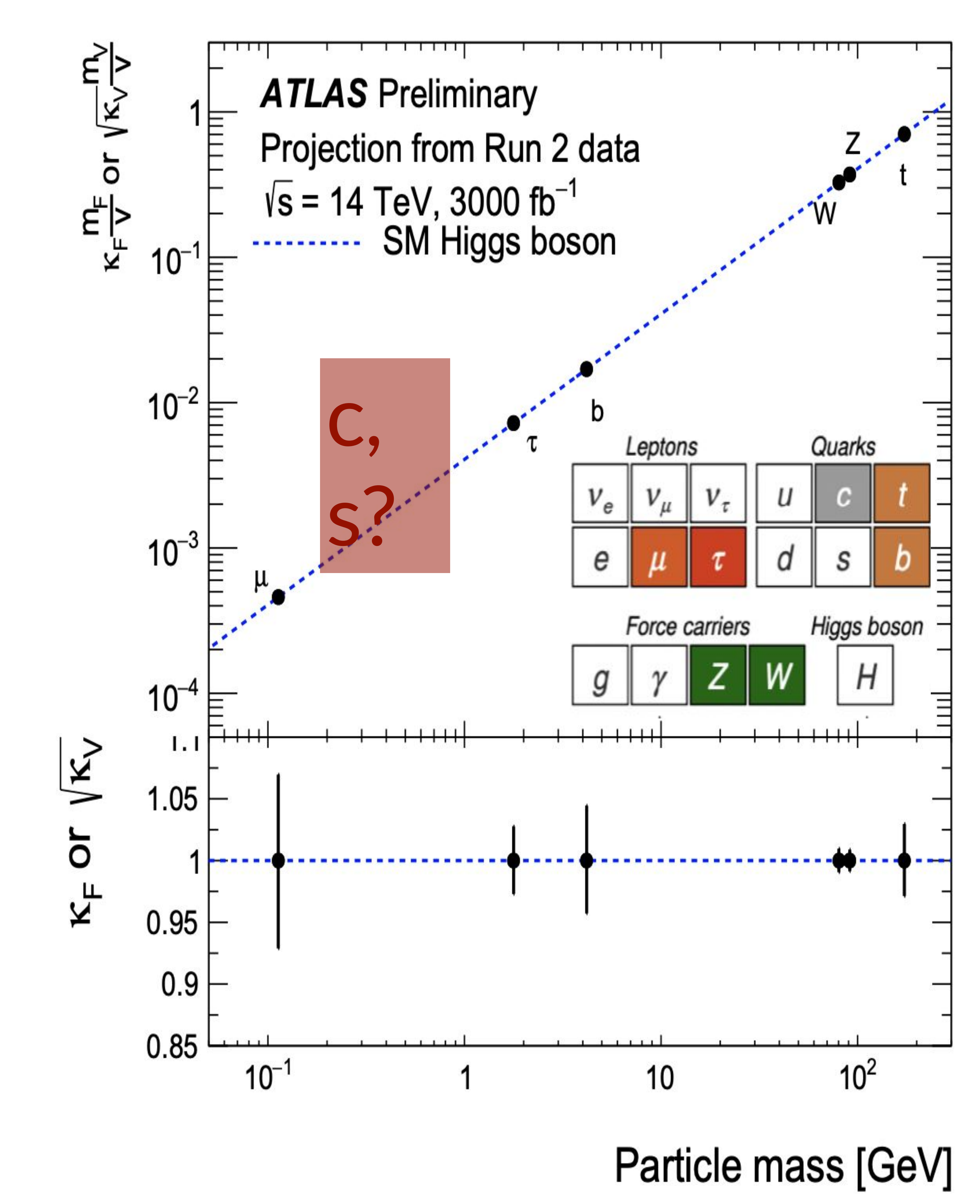
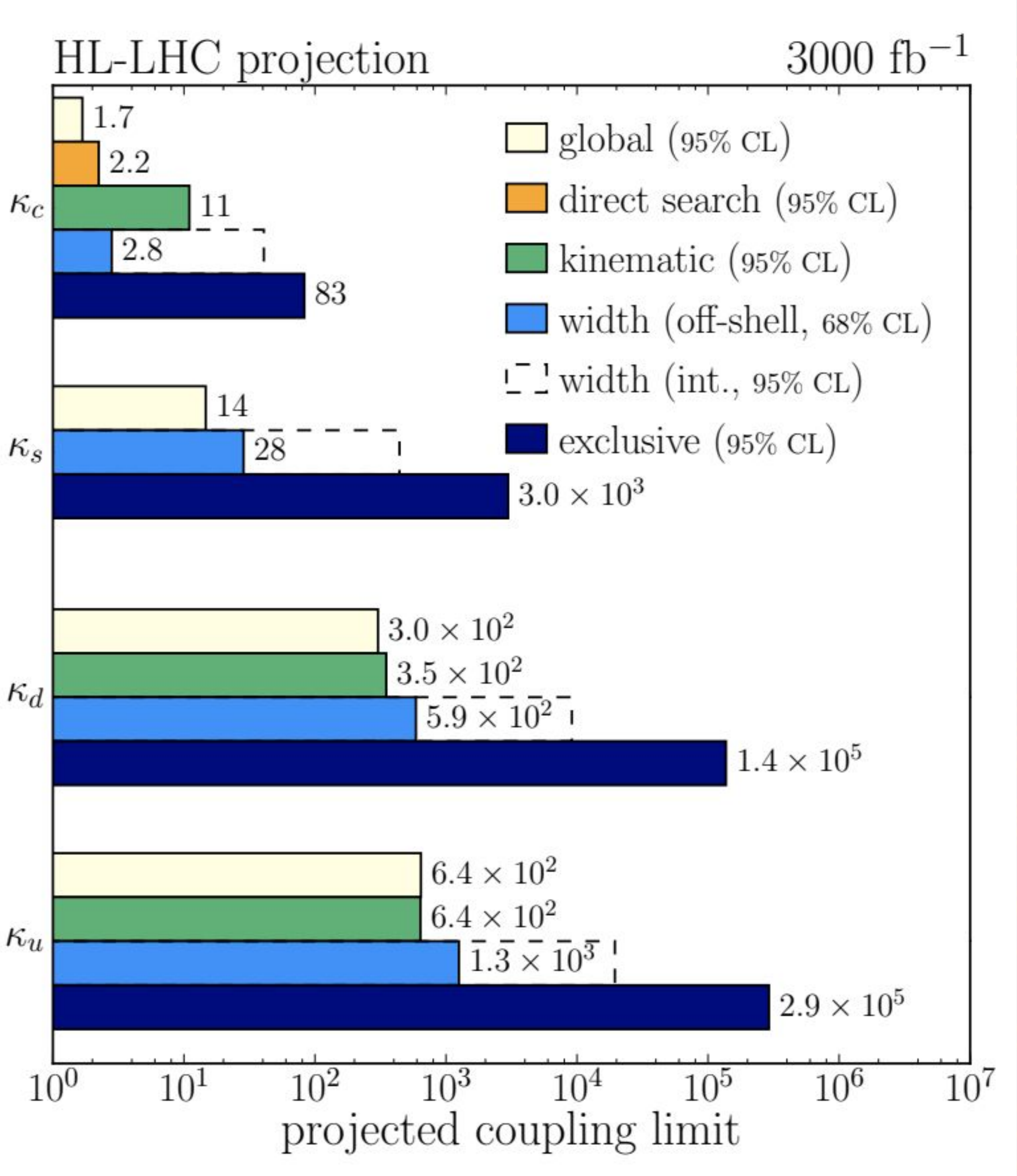
Stanford University
U.S. DEPARTMENT OF ENERGY

Higgs at HL-LHC

The High Luminosity era of LHC will dramatically expand the physics reach for Higgs physics:

- **2-5% precision for many of the Higgs couplings**
- **BUT much larger uncertainties on Zγ and charm and ~50% on the self-coupling**





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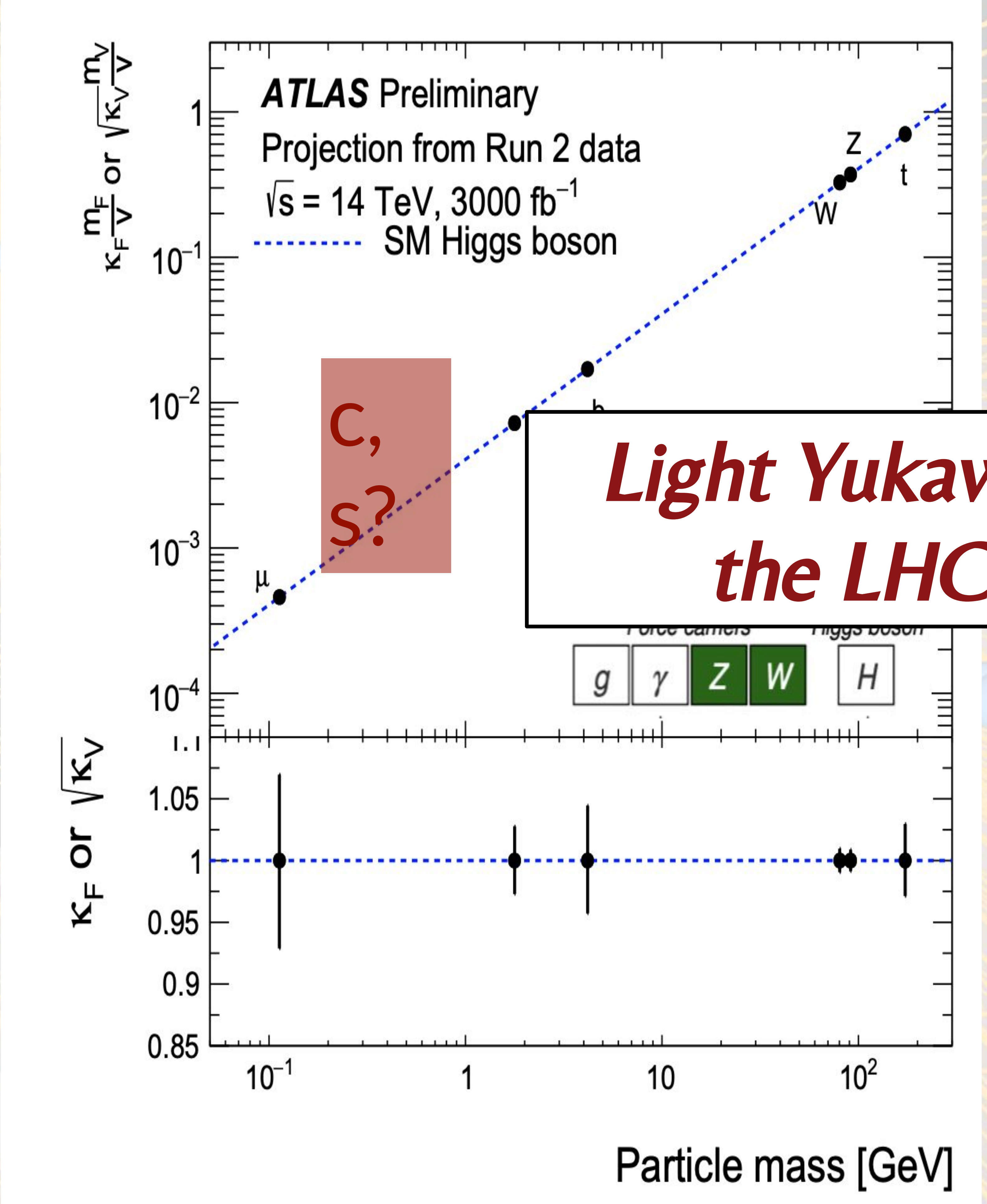
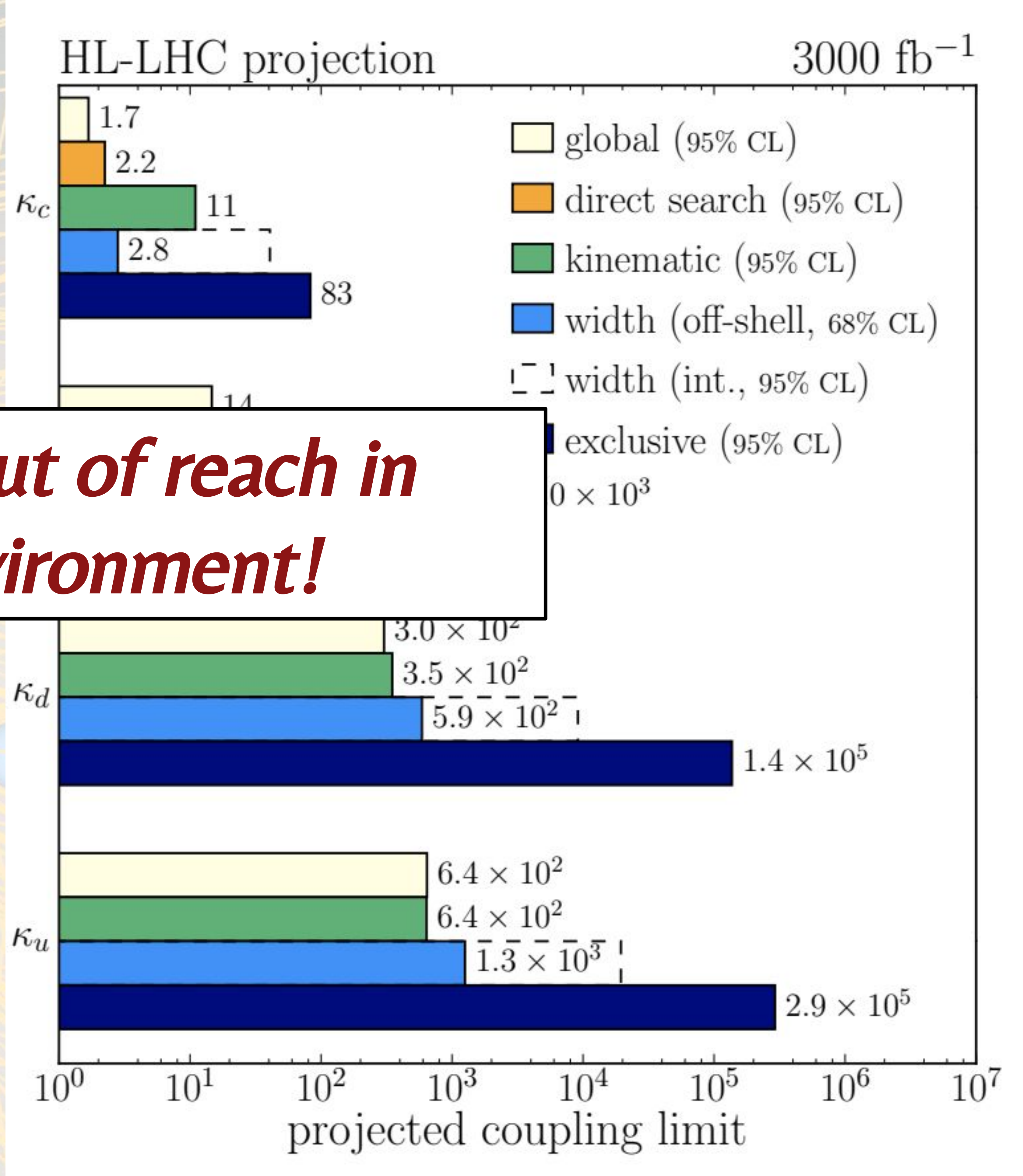
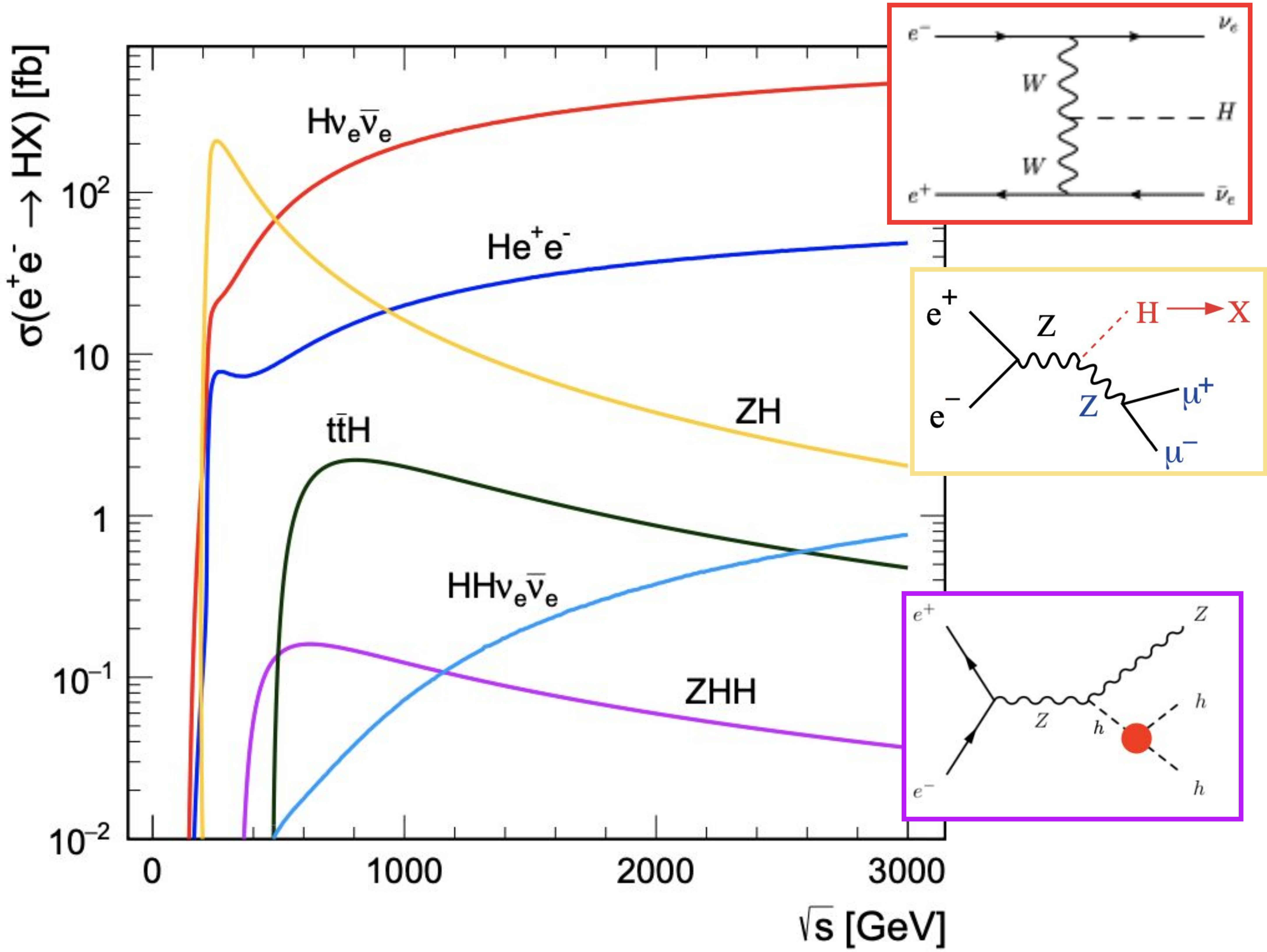


Light Yukawa out of reach in the LHC environment!



Higgs at e^+e^-

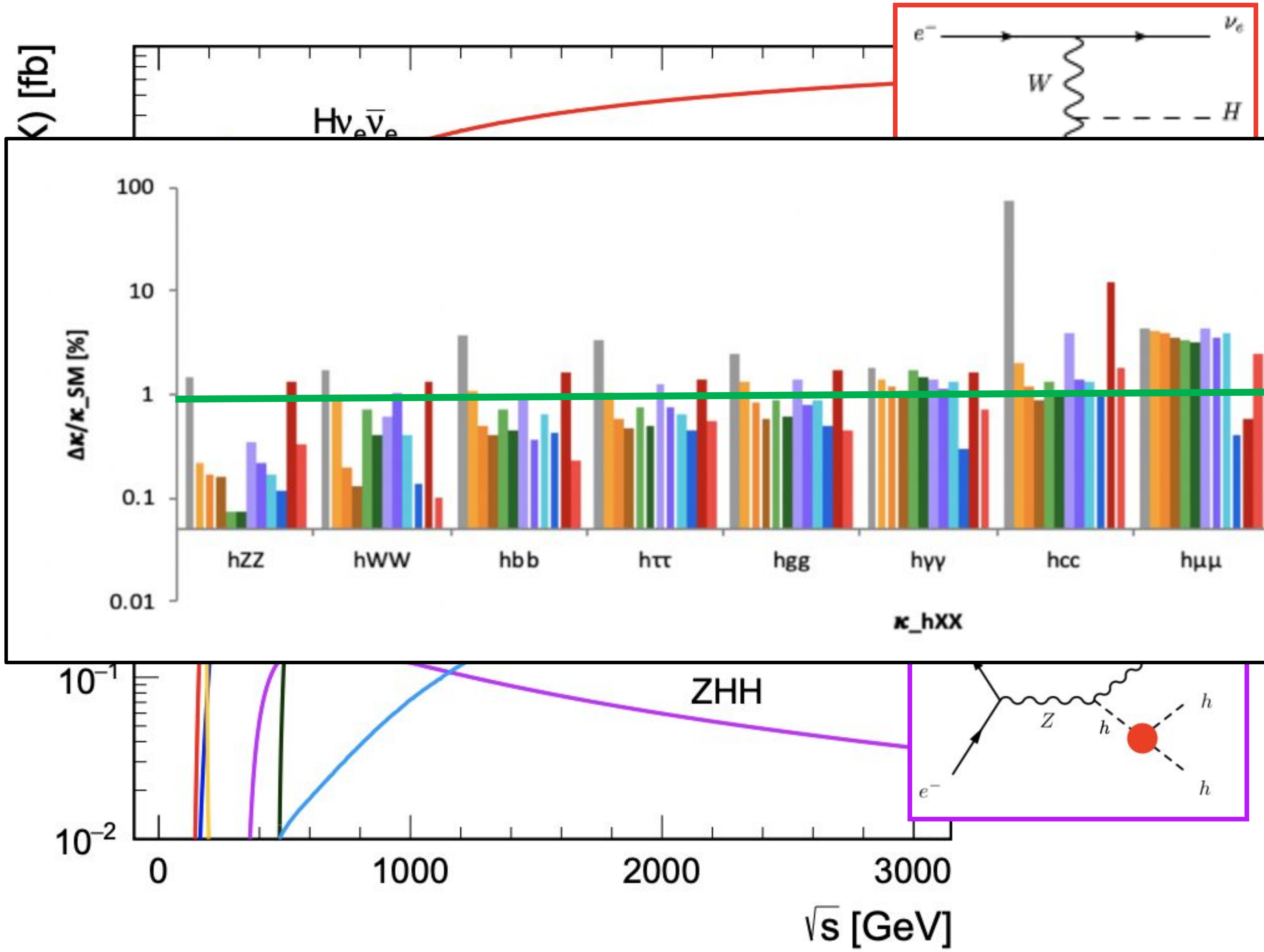
[The Energy Frontier 2021 Snowmass Report]

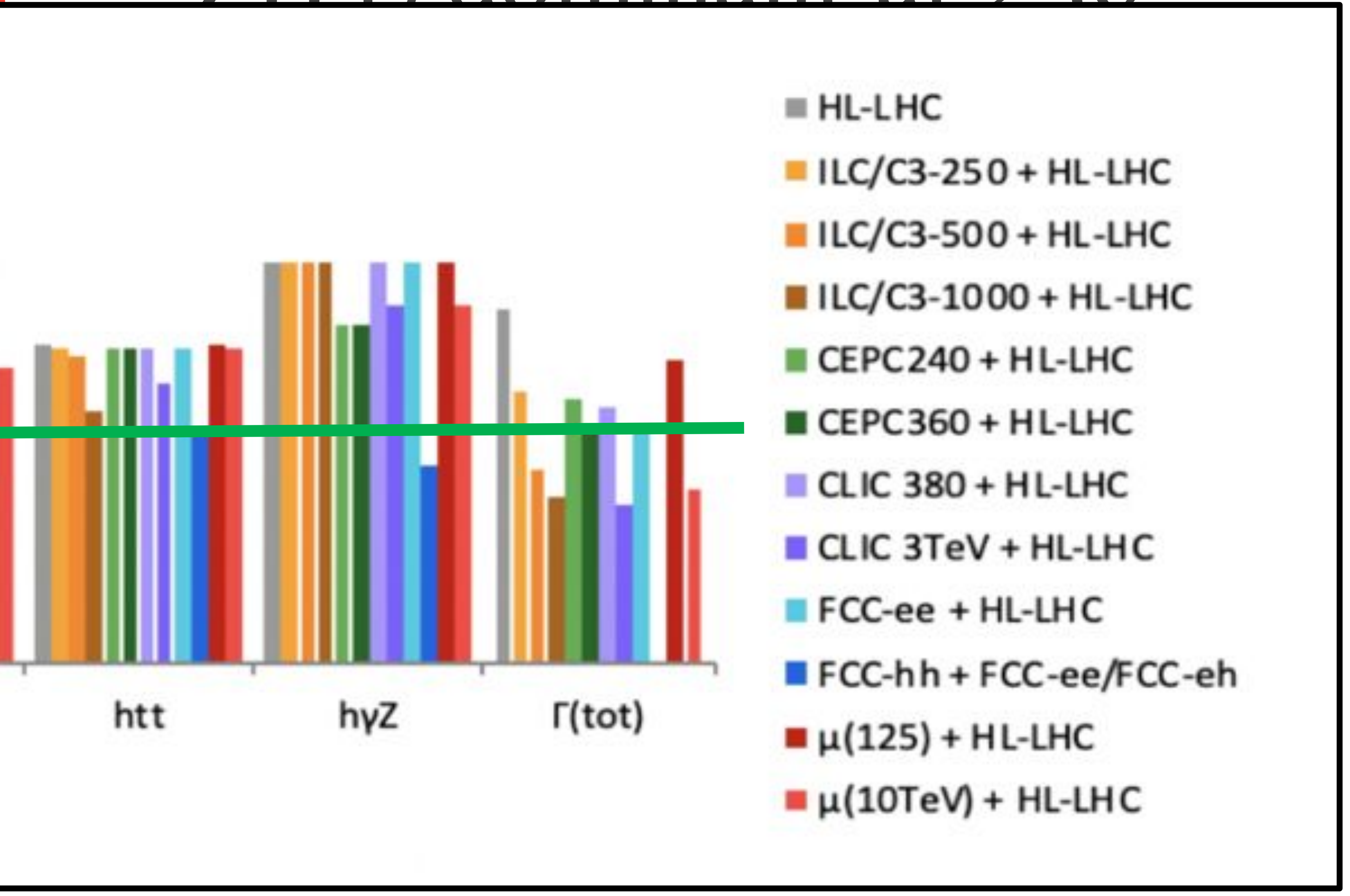


- ZH is dominant at 250 GeV
- Above 500 GeV:
  - Hνν dominates
  - ttH opens up
  - **HH accessible with ZHH**

Higgs at e^+e^-

The Energy Frontier 2021 Snowmass Report





- ZH is dominant at 250

Goal is to reach sub-percent precision for Higgs couplings – improve by 1 order of magnitude w.r.t HL-LHC

Beyond EFT, is there more?

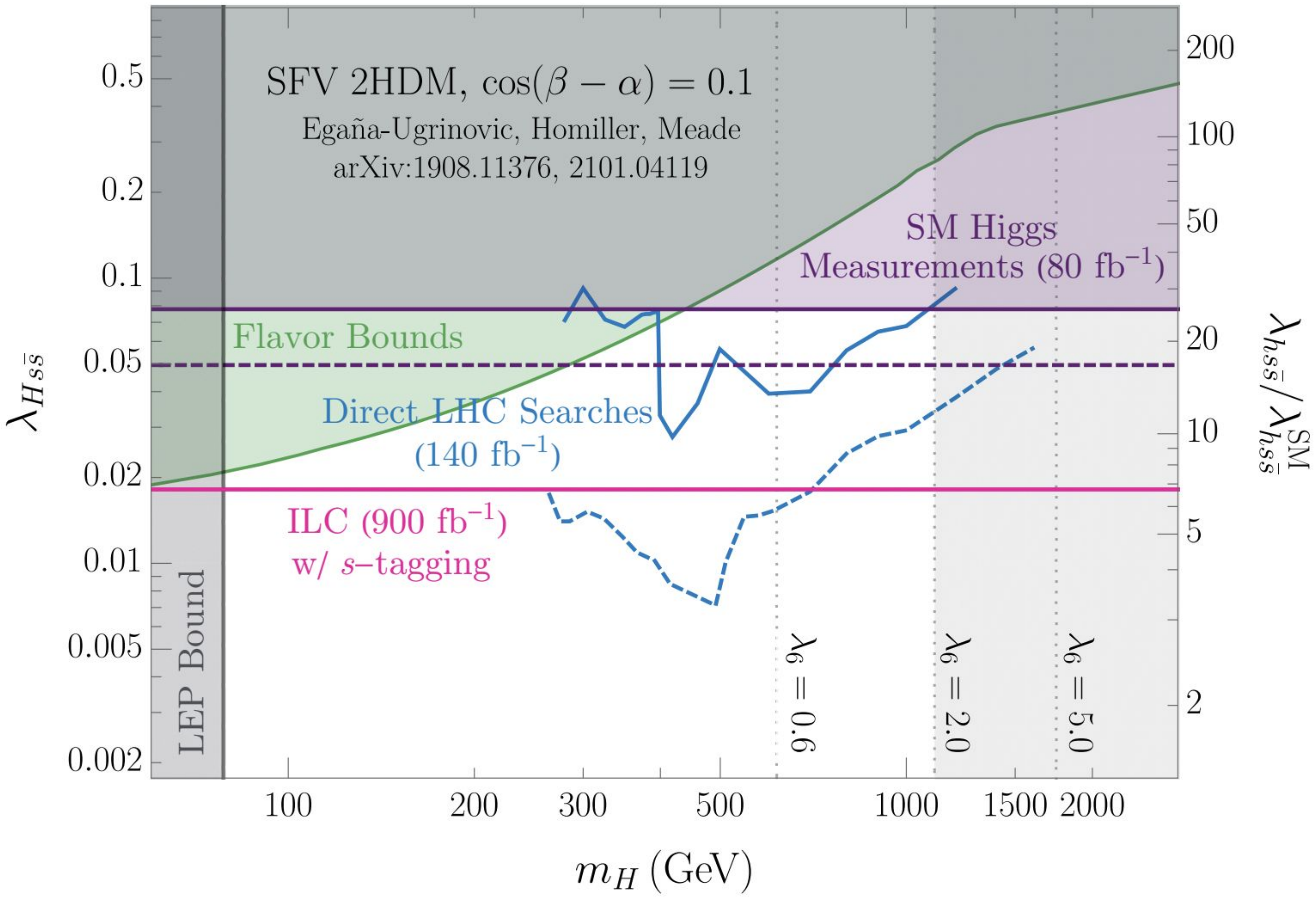
Higgs to strange coupling is an appealing signature for probing new Physics

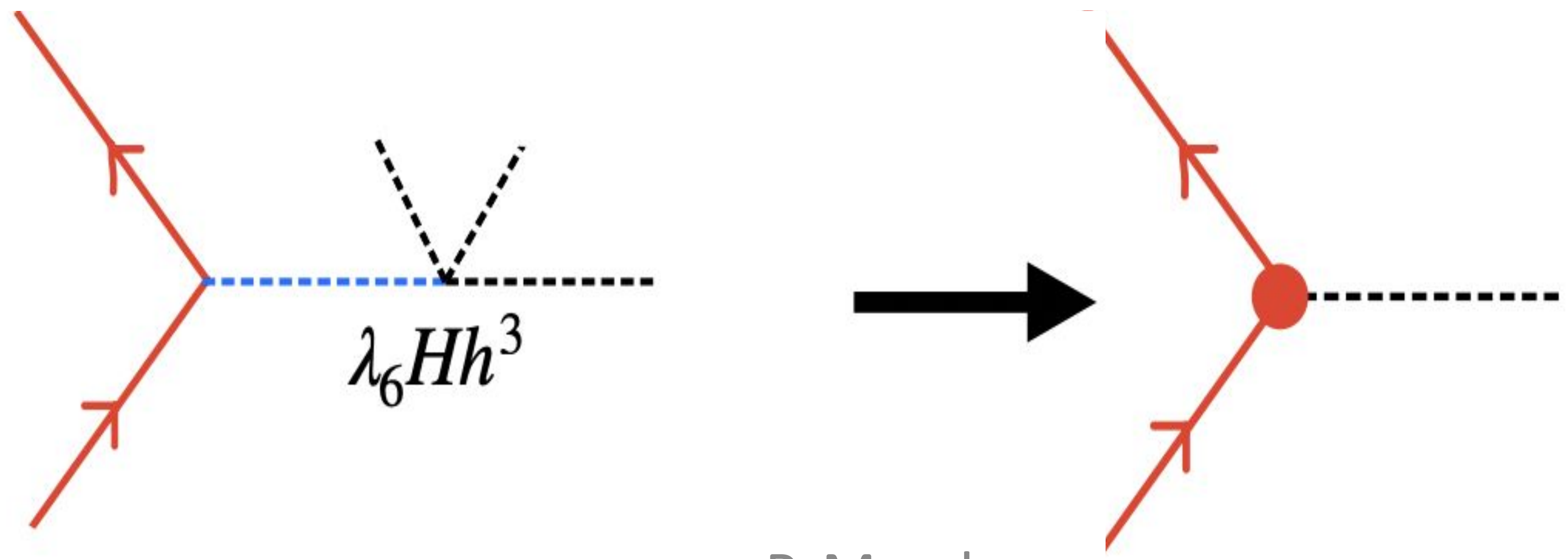
Is the Higgs the source for all flavor?

An option, **Spontaneous Flavor Violation (SFV)**

New physics can couple in a strongly flavor dependent way if it is aligned in the down-type quark or up-type quark sectors

- It allows for large couplings of additional Higgs to strange/light quarks
- No flavor-changing neutral currents



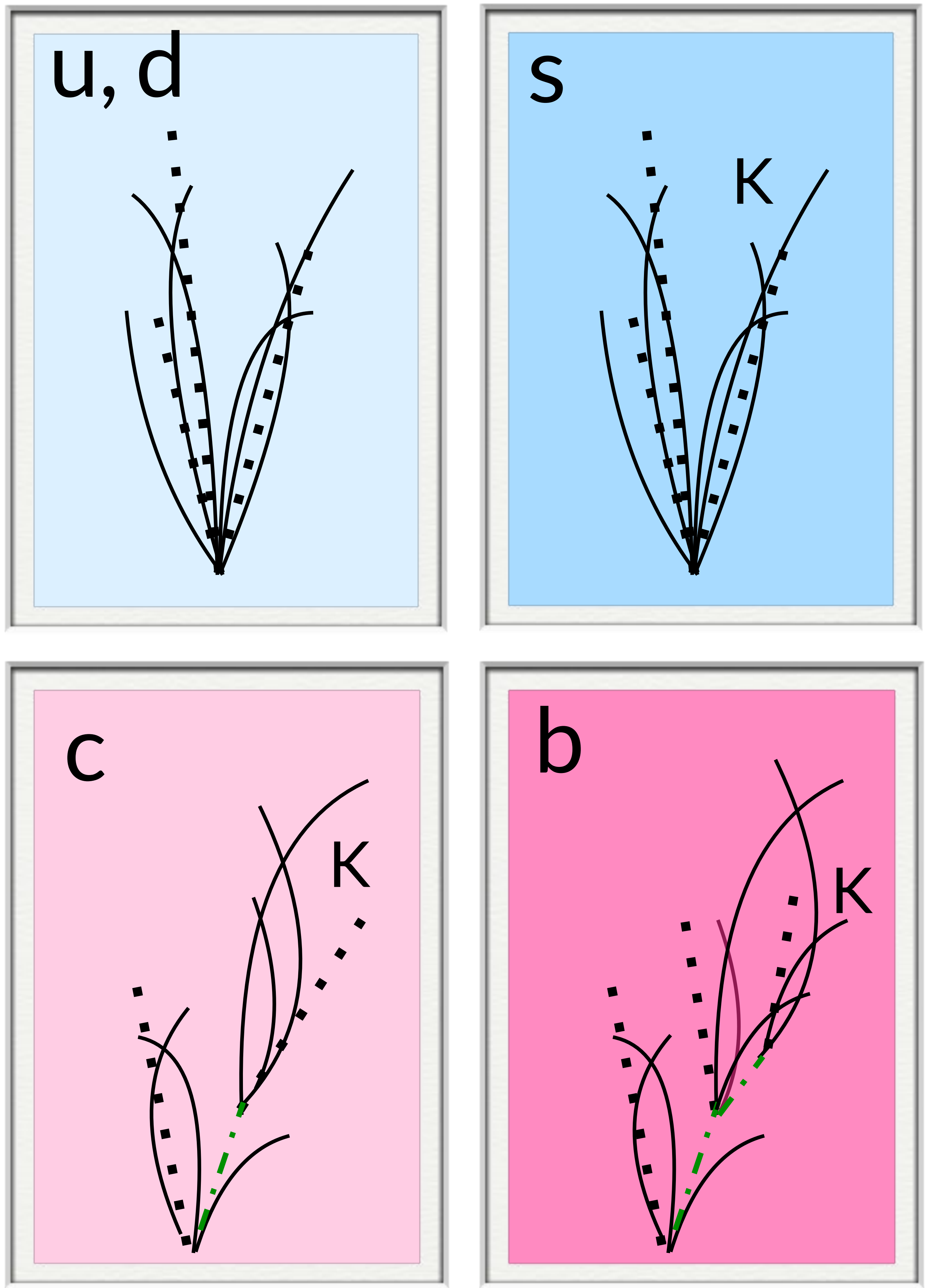


$$\sim \frac{1}{\Lambda^2}(sh\bar{s})h^2$$

P. Meade

s-tagging

strange tagging is a challenging but not impossible task for detectors at e^+e^- colliders



- b,c, and s jets contain at least one strange hadron
- Strange quarks mostly hadronize to prompt kaons which carry a large fraction of the jet momentum
- Strange hadron reconstruction:
  - $K^{\pm}$ PID
  - K^0_L PF (neutral)
  - $K^0_S \rightarrow \pi^+\pi^-$ (~70%) / $\pi^0\pi^0$ (~30%)
  - $\Lambda^0 \rightarrow p\pi^-$ (~65%)

Distinctive two-prong vertices topology

Jet flavour	Number of secondary vertices (excluding V^0s)	Number of strange hadrons (e.g., $K^{\pm}$, $K^0_{L/S}$, and Λ^0)
Bottom	2	≥1
Charm	1	≥1
Strange	0	≥1
Light	0	0

s-tagging

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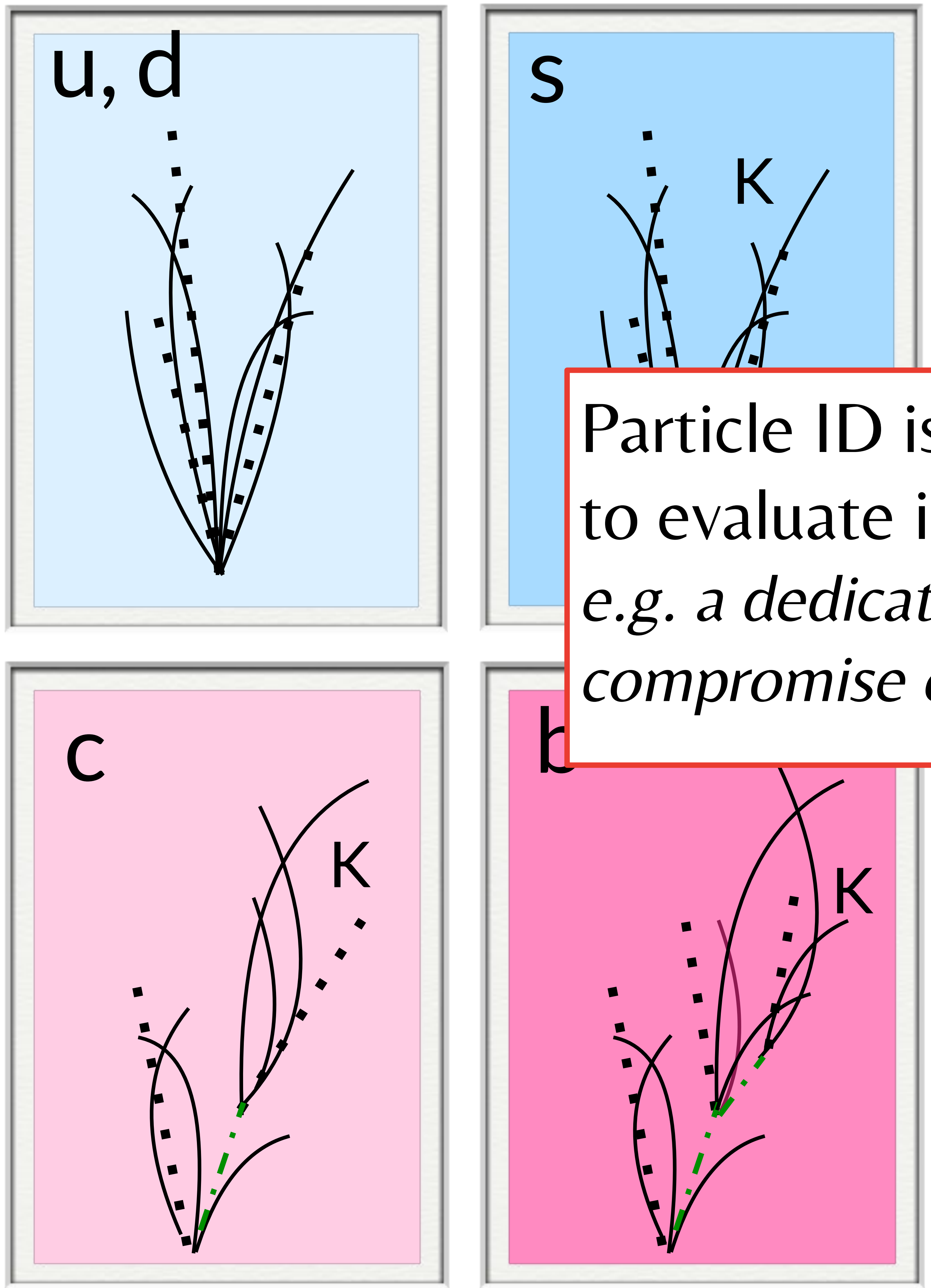

- b,c, and s jets contain at least one strange hadron
- Strange quarks mostly hadronize to prompt kaons which carry a large fraction of the jet momentum
- Strange hadron reconstruction:

Particle ID is crucial for strange-tagging, however we have to evaluate it in parallel to other Higgs benchmarks!
e.g. a dedicated PID device in front of the calorimeter could compromise other physics measurements

Distinctive two-prong vertices topology

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Strange	0	$\geq$1
Light	0	0

Towards a flexible framework for detector studies

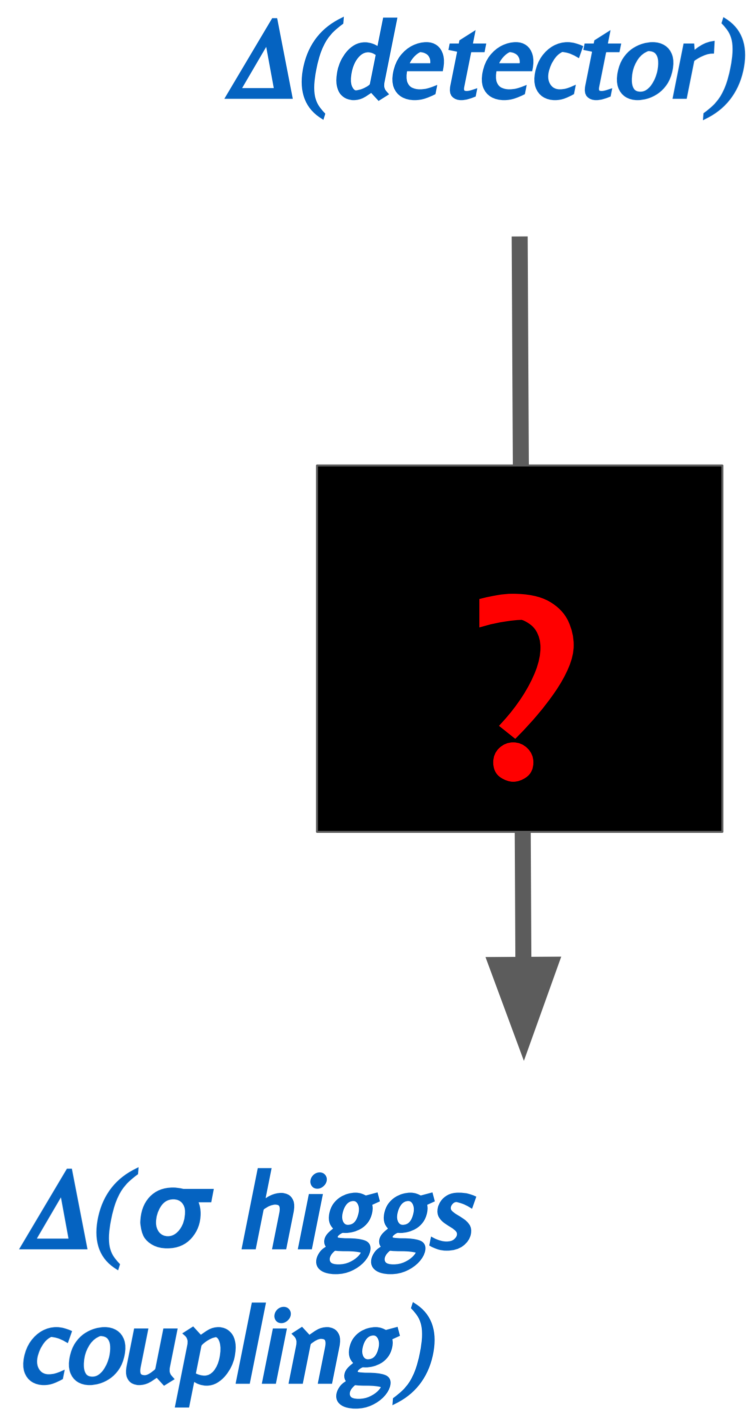
Determining the physics impact of detector choices is paramount for detector design

- The goal of this effort is to systematically study different detector/sub-detector options starting from the impact on jet identification and progressing eventually towards the impact on Higgs couplings.
  - Compare different detector concepts (SiD and IDEA) with FastSim
  - Compare FastSim against FullSim

End-product:

- A versatile framework, building on existing tools, critical for R&D exploration
- Answer ***how detector variations impact precision on Higgs couplings.***

This effort is complementary and synergistic with existing ones. It's important to approach this problem from different angles



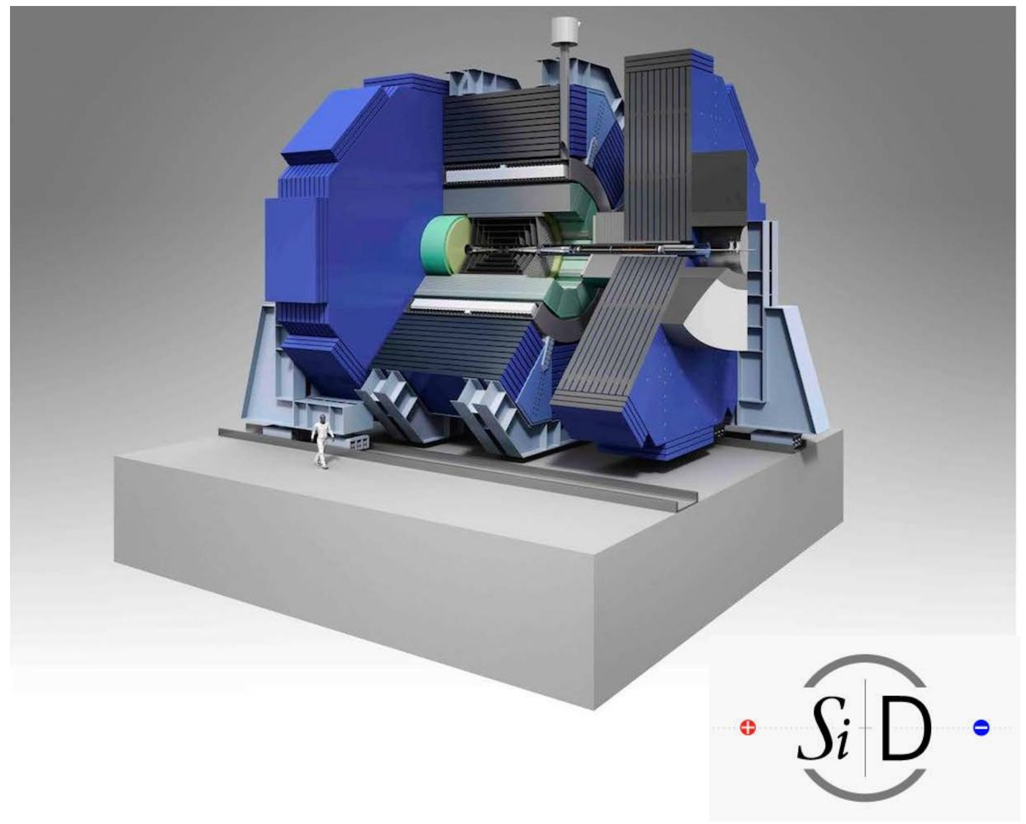
Detectors at future e^+e^- colliders

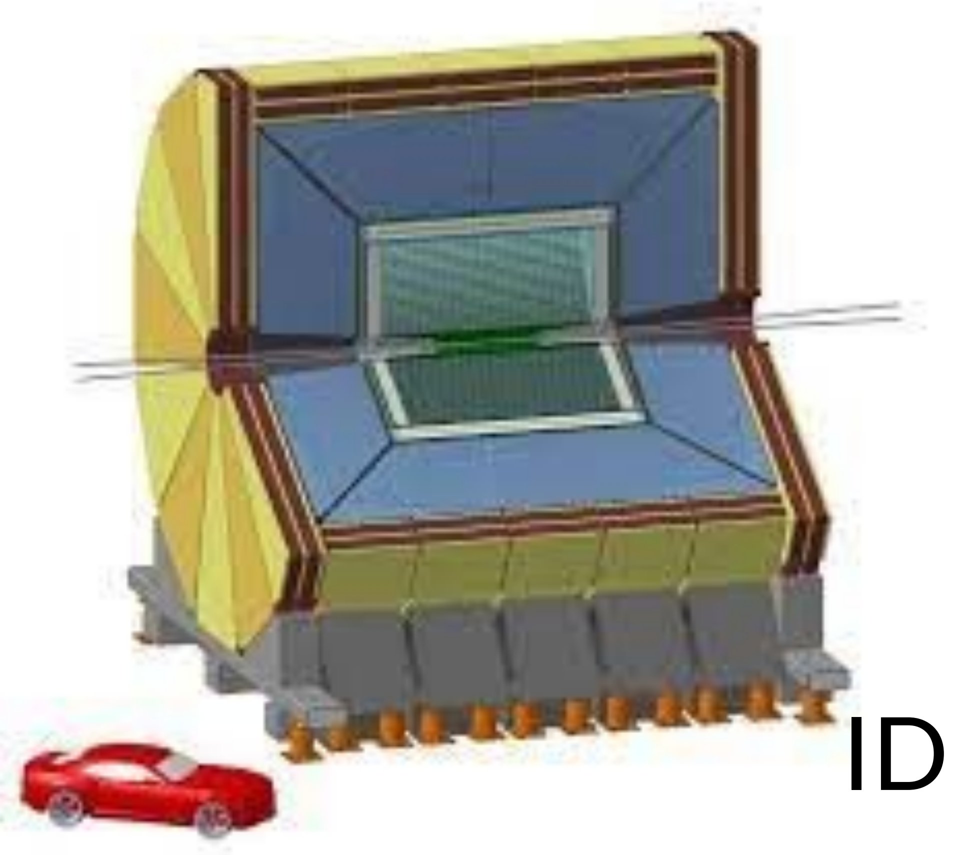
arXiv:2003.01116

Stringent detector requirements from ZH reconstruction

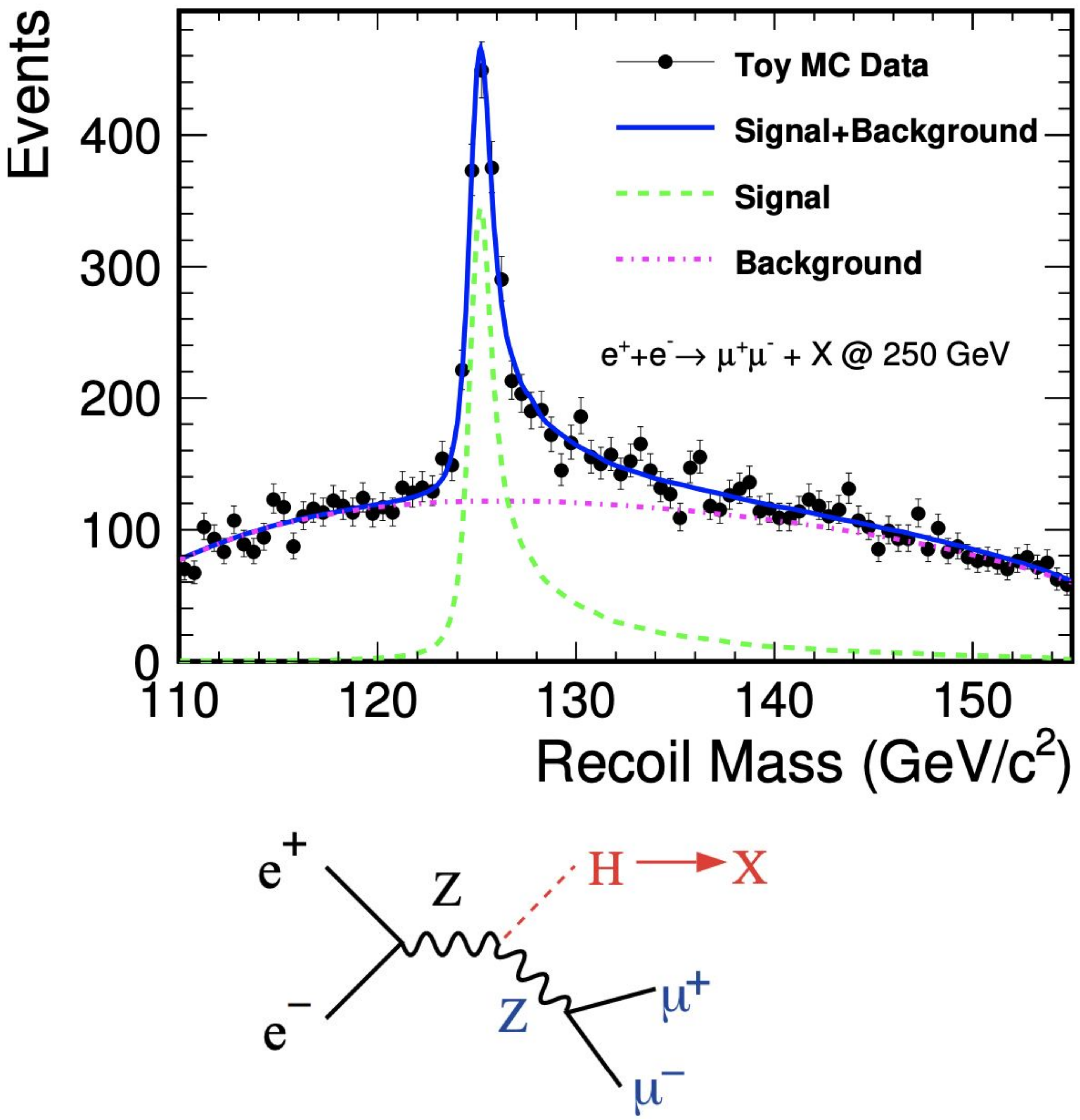
Detector designs at e^+e^- colliders are converging to very similar strategies

- Strong magnetic field 2-5 T
- (Ultra) low material budget tracker (<0.3% X0 per layer)
  - Close to the interaction region (10-25 mm)
- High granularity calorimetry
  - Particle Flow reconstruction → plays a big part in many designs





IDEA



Detectors at future e^+e^- colliders

Focus on SiD concept for ILC and IDEA concept for FCC-ee for this study.

- ***SiD:*** all silicon vtx and tracker, sampling ECAL and HCAL, 5T B-field
- ***IDEA:*** silicon vtx, DCH + Si wrapper, DRO calorimeter, 2 T B-field → PID with dN/dx, TOF, supreme JER

	ILD	SID	IDEA	CLD	ALLEGRO
Vertex Inner Radius (cm)	1.6	1.4	1.2	1.2	1.2
Tracker technology	TPC+Silicon	Silicon	Si+Drift Chamber	Si	Si+Drift Chamber
Outer Tracker Radius (m)	1.77	1.22	2	3.3	2
ECal thickness	24 X_0	26 X_0	Dual RO	22 X_0	22 X_0
HCal thickness	5.9 λ_0	4.5 λ_0	7 λ_0	6.5 λ_0	9.5 λ_0
HCal Outer Radius (m)	3.3	2.5	4.5	3.5	4.5
Solenoid field (T)	3.5	5	2	2	2
Solenoid length (m)	7.9	6.1	6	7.4	6
Solenoid Radius (m)	3.4	2.6	2.1	4	2.7

$\frac{\sigma(\mathbf{E})}{\mathbf{E}}$	SiD	IDEA
ECAL	$\frac{17\%}{\sqrt{E}} \oplus 1\%$	$\frac{3\%}{\sqrt{E}} \oplus \frac{0.2\%}{E} \oplus 0.5\%$
HCAL	$\frac{55.9\%}{\sqrt{E}} \oplus 9.4\%$	$\frac{30\%}{\sqrt{E}} \oplus \frac{5\%}{E} \oplus 1\%$

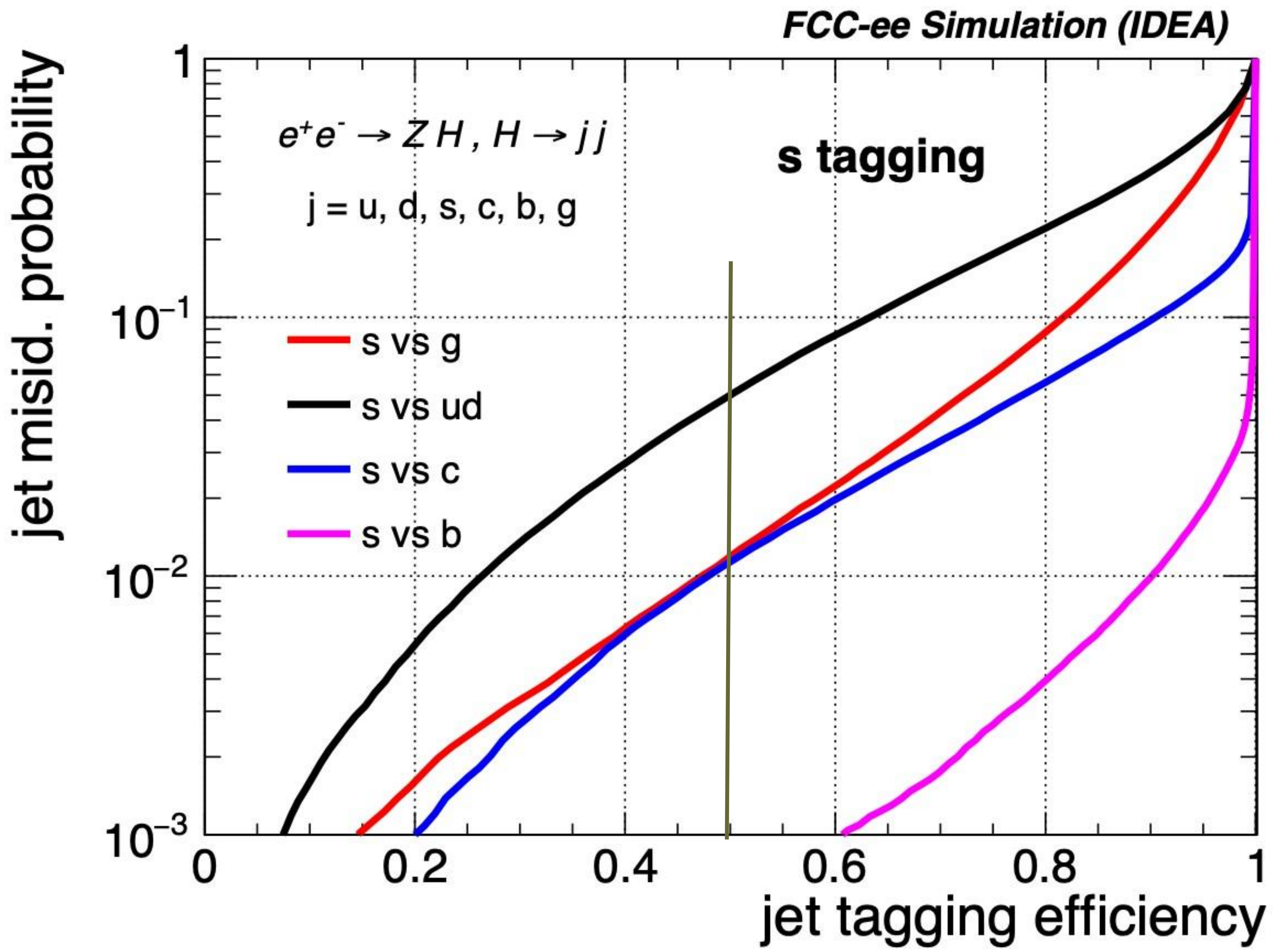
ILC TDR 2008.00338

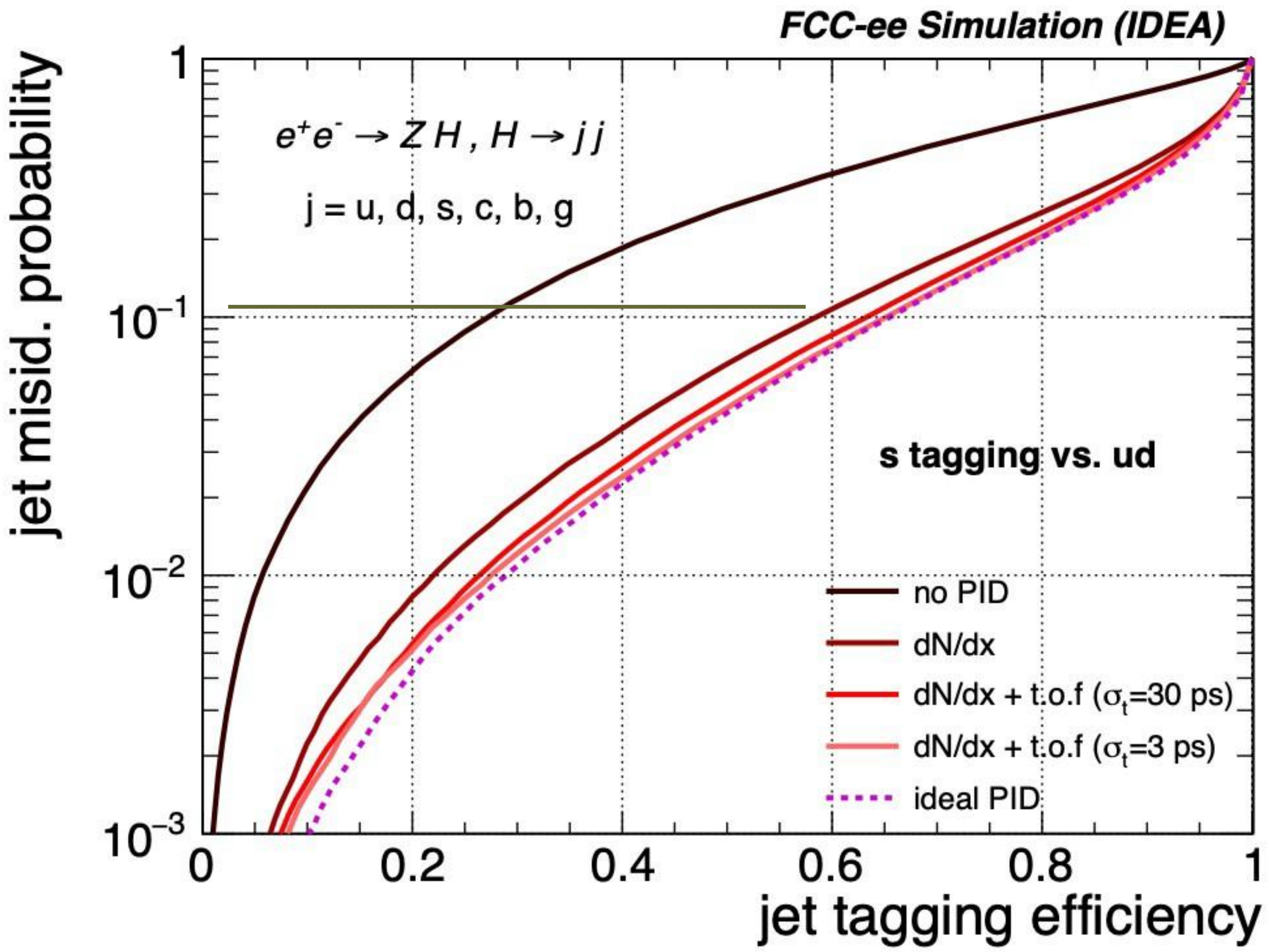
PRD 101 056019 (2020)
EPJ C 82 646 (2022)

Strange tagging performance

IDEA-like detector and Particle cloud graph neural network (fast sim)

- Both TOF and dN/dx (3σ < 30 GeV) included as inputs
- No PID to PID with dN/dx → at fixed mistag, efficiency doubles





WP	Eff (s)	Mistag (g)	Mistag (ud)	Mistag (c)	Mistag (b)
Loose	90%	20%	40%	10%	1%
Medium	80%	9%	20%	6%	0.4%

Analysis pipeline for jet flavor tagging studies

1. Sample generation:
- Whizard 3.1.4 + Pythia6
- Z(→νν)H(→uu/dd/cc/ss/bb/gg)
- 1.5M events (3M jets) per flavor

2. Fast simulation:
- Delphes with edm4hep output using k4SimDelphes

3. Preprocessing:
- Jet Clustering on PFCandidates and tree flattening using FCCAnalyses

4. ParticleNet training:
- Using the weaver framework
- Use 1.8M jets/per flavor with 80%/20% train-val split

5. Infererce
- Within FCCAnalyses
- Using 1.2M jets/flavor

DELPHES fast simulation

KEY4HEP

FCCAnalyses

weaver-core

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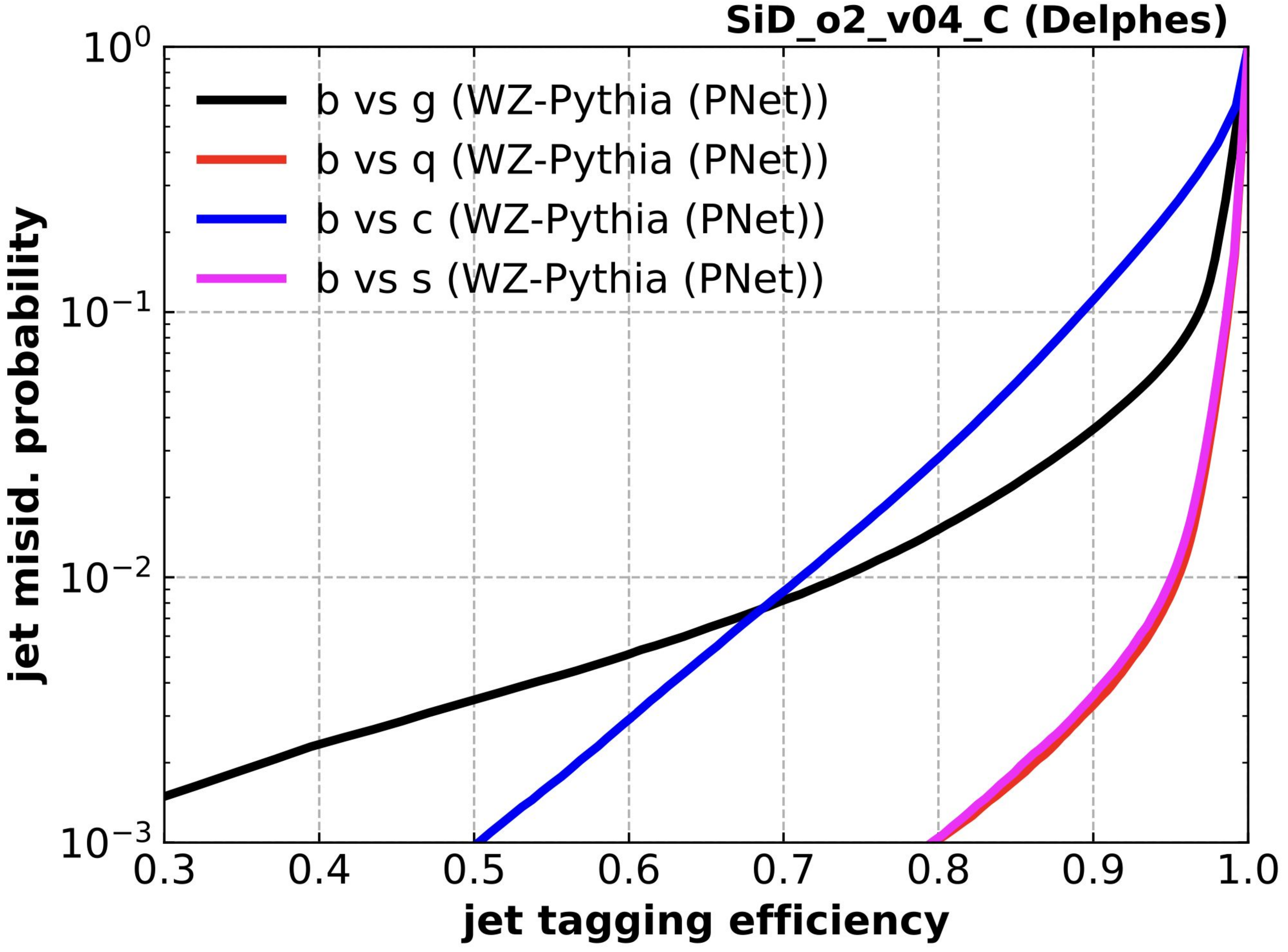

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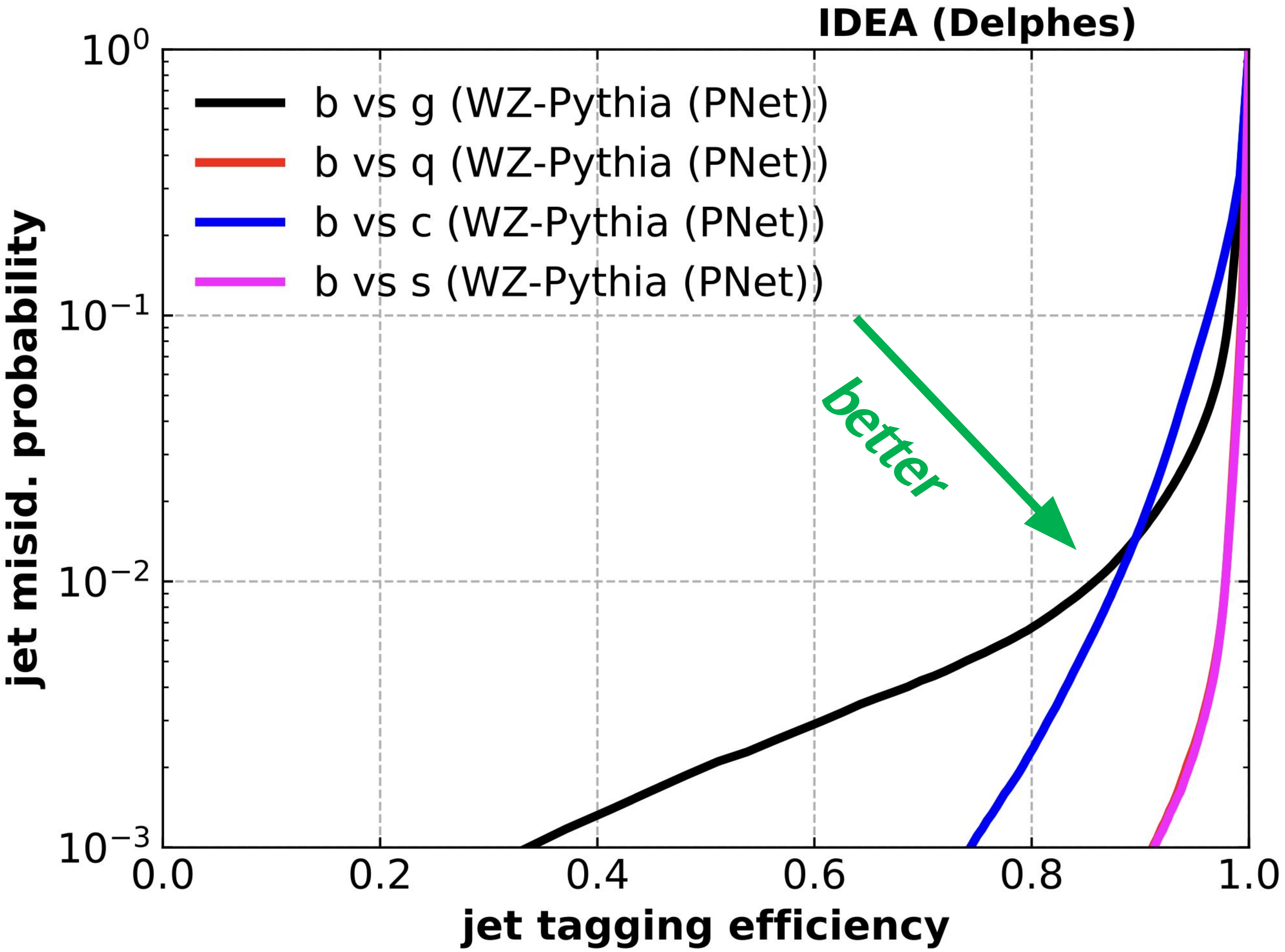
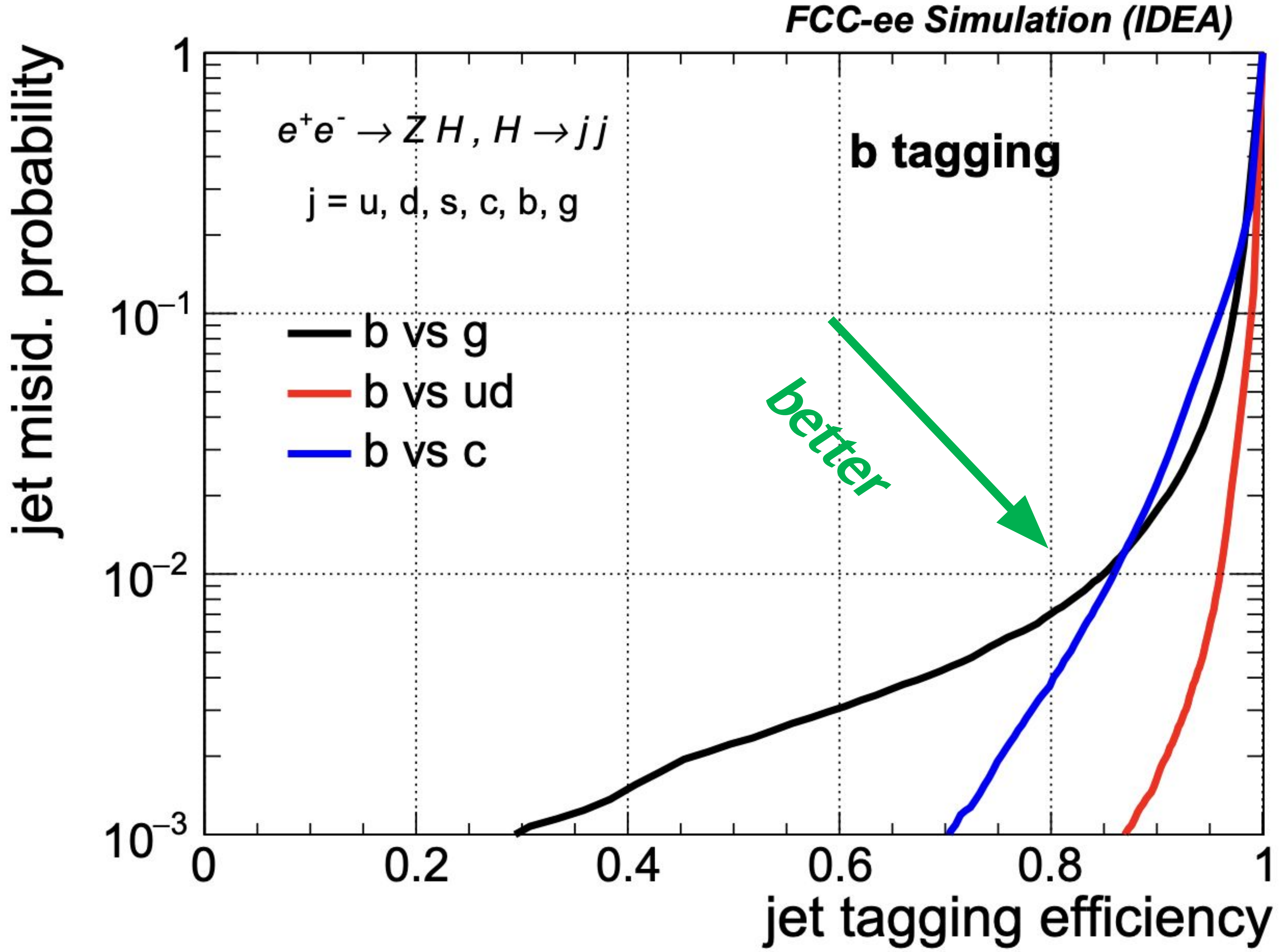
Benchmarking our results

[Eur. Phys. J. C **82**, 646 (2022)] : Jet Flavour Tagging for Future Colliders with Fast Simulation



Our results



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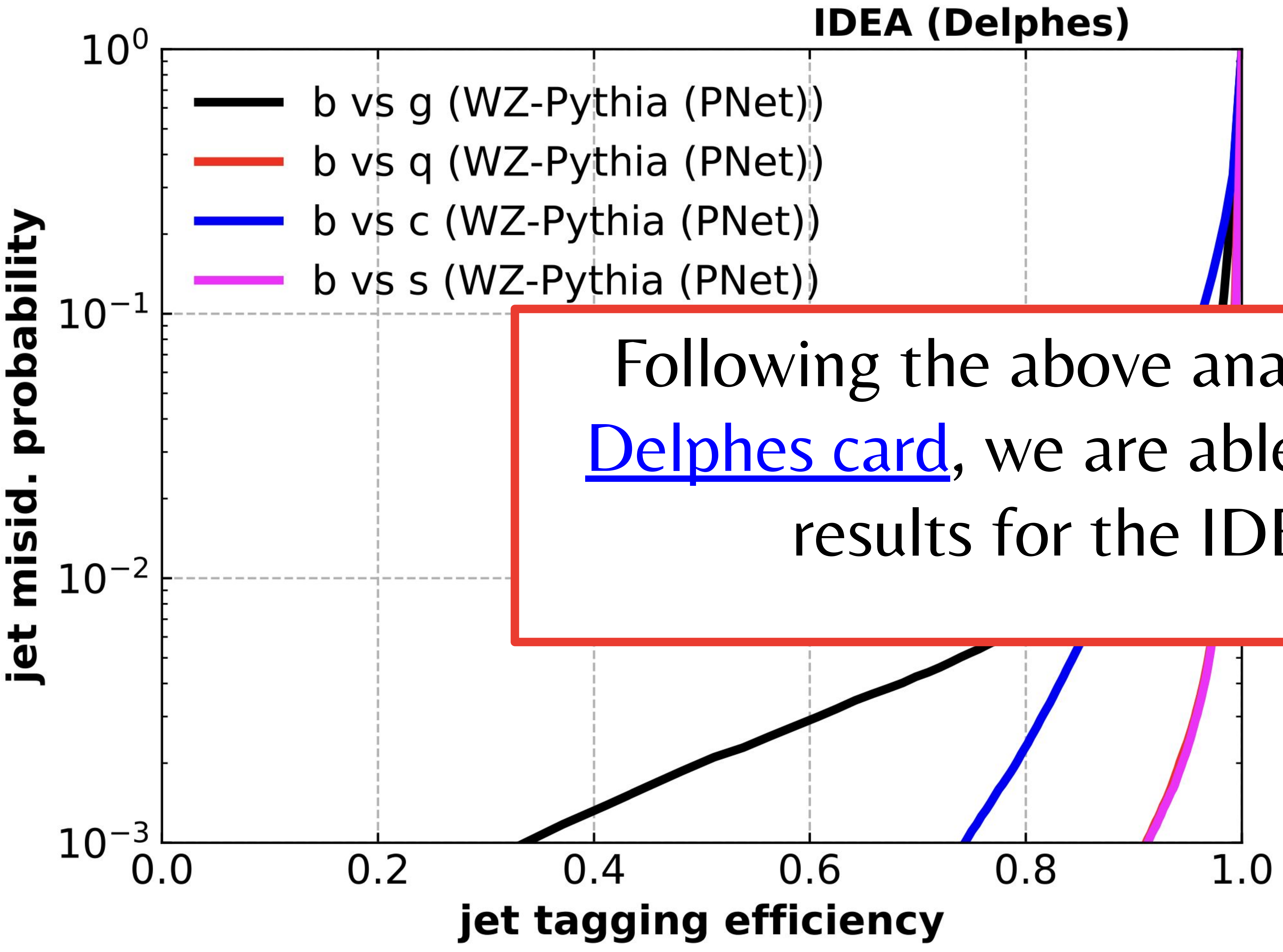

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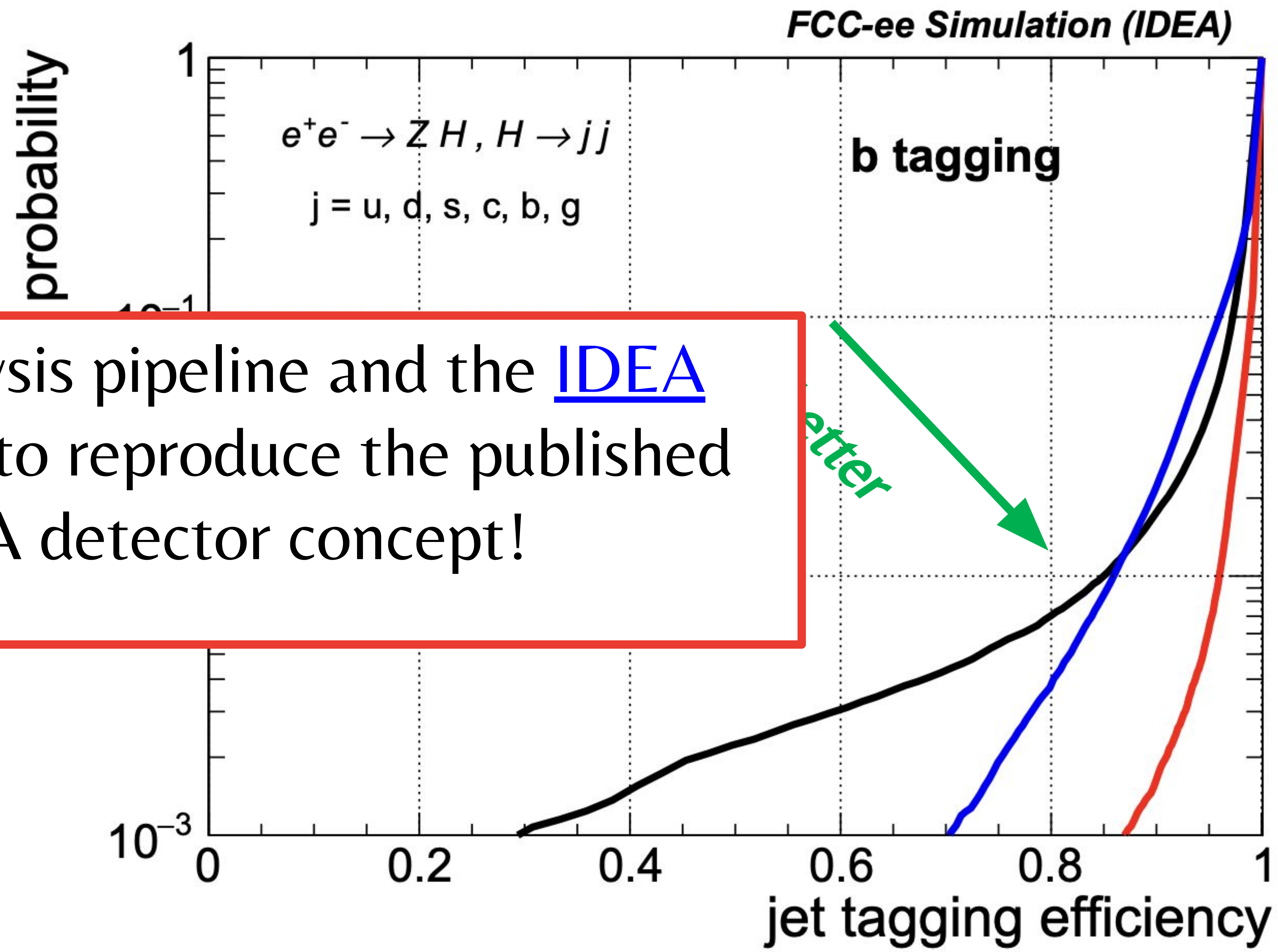


Eur. Phys. J. C **82**, 646 (2022)

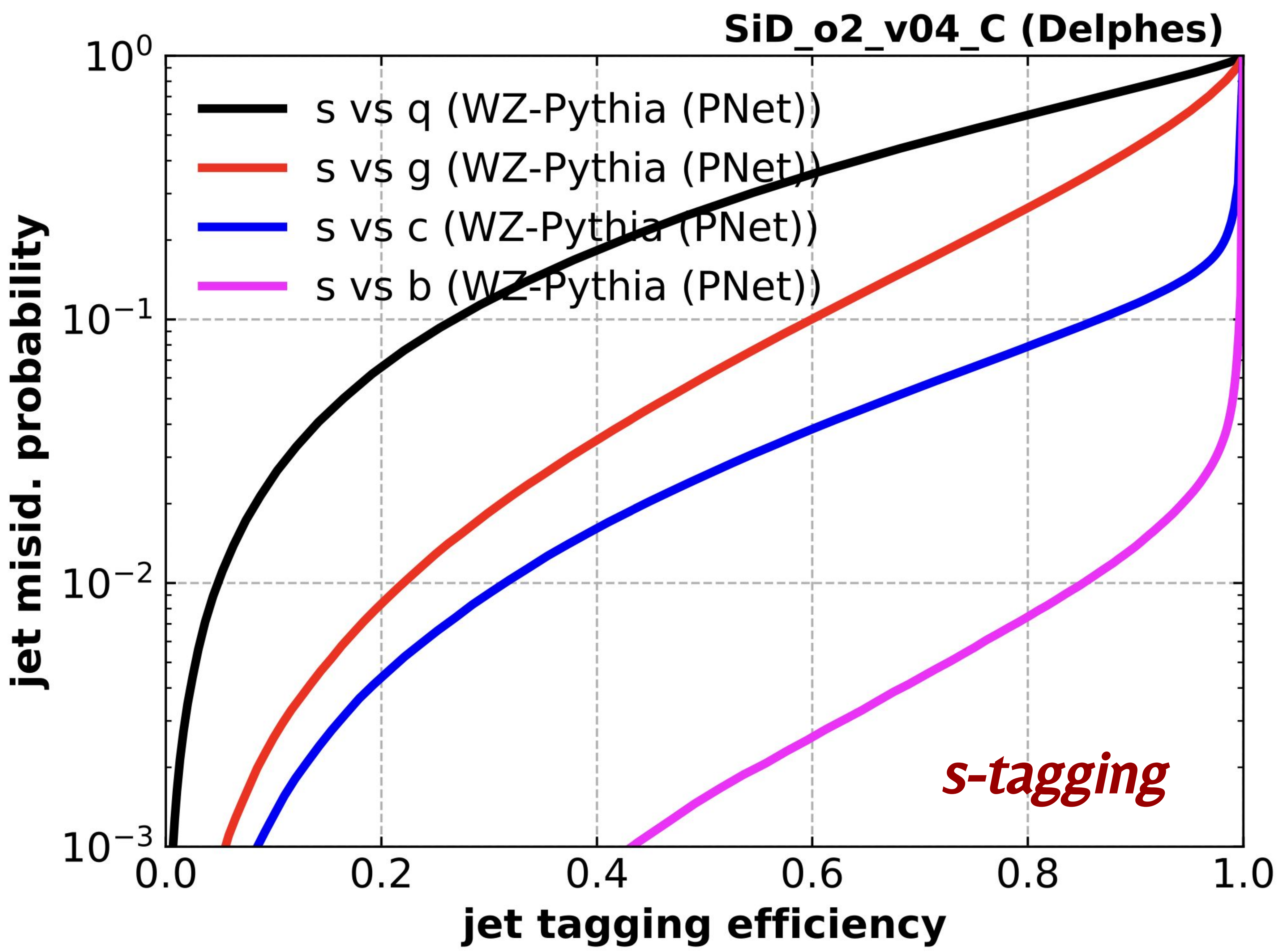
Following the above analysis pipeline and the IDEA Delphes card, we are able to reproduce the published results for the IDEA detector concept!

Jet flavor tagging for SiD using Particle Net

- Existing Delphes card for SiD, based on ILC TDR performance: https://dsid.hepforge.org/ (~9 years old).

- We wrote a new Delphes card to include newer developments in Delphes, such as the TrackCovariance, ClusterCounting modules, ***assuming same tracking performance as for IDEA.*** We call this the **SiD_o2_v04_C** scenario.

- We also consider a modified scenario for SiD, with the resolution of the ECAL and the HCAL matching that of the IDEA dual calorimeter → **SiD_o2_v04_D** scenario.



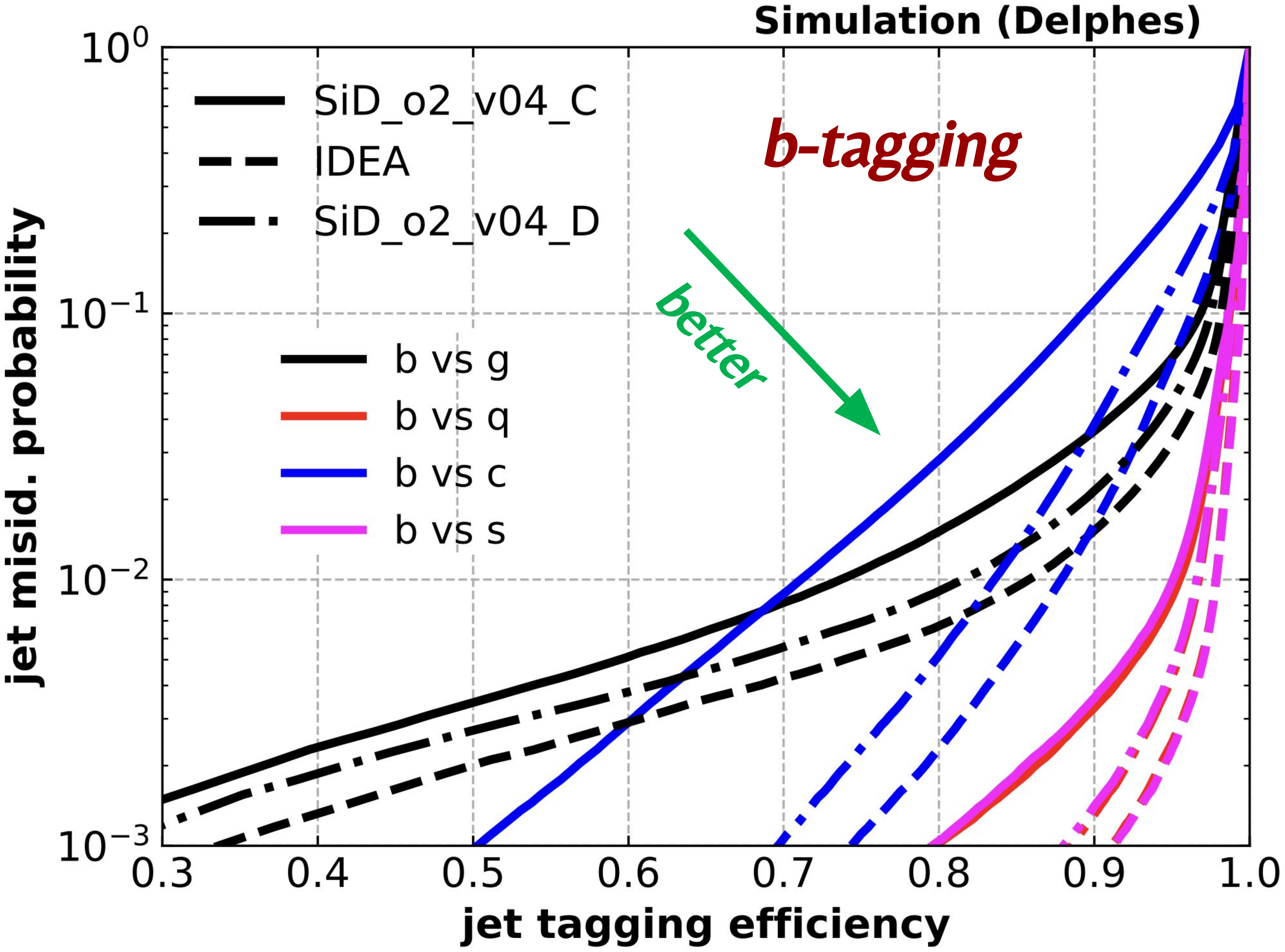
WP	Eff (s)	Mistag (g)	Mistag (q)	Mistag (c)	Mistag (b)
Loose	90%	45%	75%	12%	1.3%
Medium	80%	27%	55%	8%	0.7%

Comparison of different detector configurations

Two configurations for SiD detector concept vs IDEA

- Improvement in b-tagging driven by calorimeter resolution → better reconstruction of PF Objects
- Some gain also from PID, especially for b vs c.

For b-tagging, vertexing/tracking performance drives the discrimination power, with added gains coming from the ability to accurately reconstruct neutrals in the calorimeters



Comparison of different detector configurations

Two configurations for SiD detector concept vs IDEA

- ***Significant gains in strange vs udg and b discrimination from PID.***
- Improved calorimeter resolution only brings marginal gain

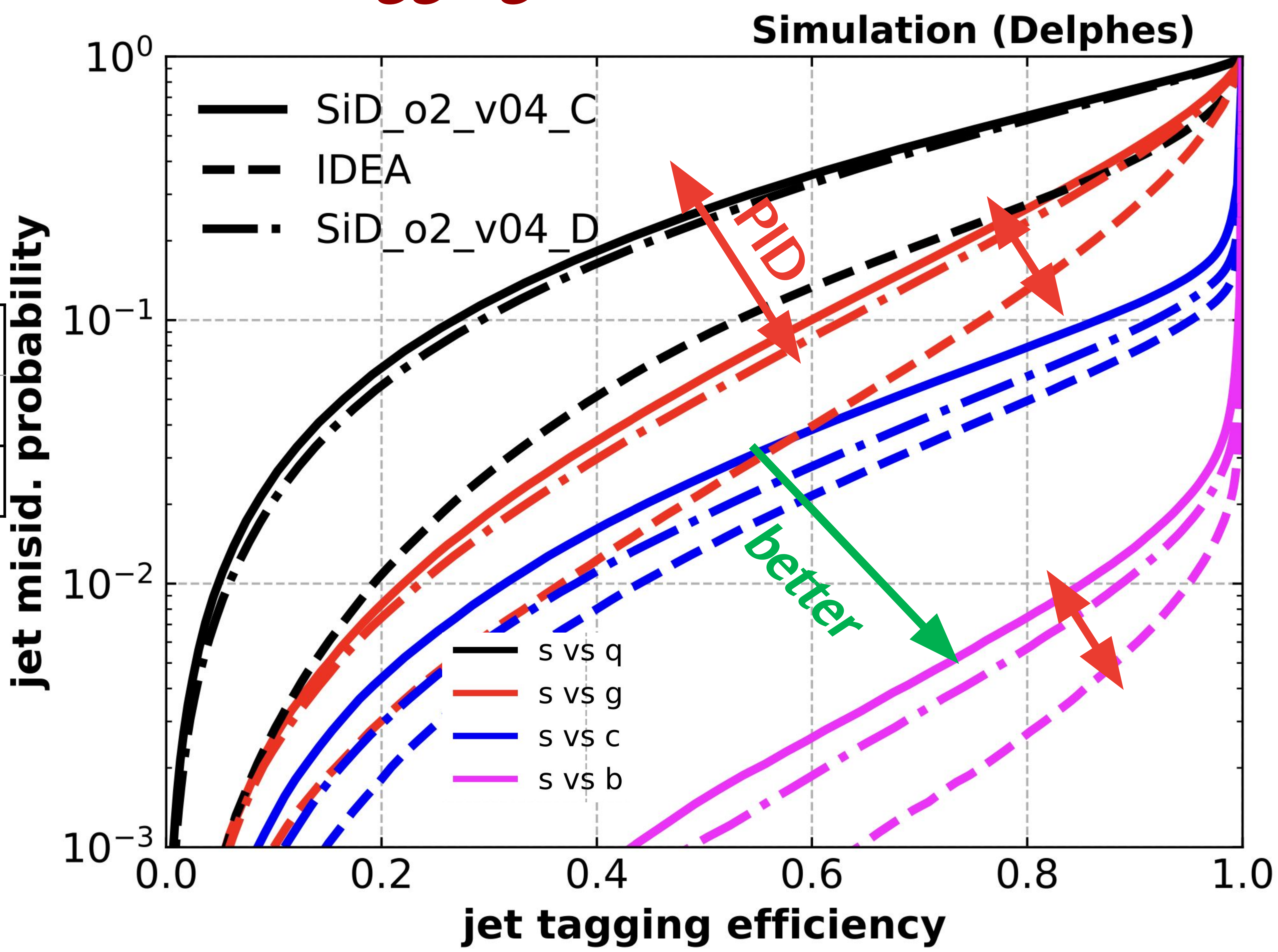
SiD_o2_v04_C (_D)

WP	Eff (s)	Mistag (g)	Mistag (q)	Mistag (c)	Mistag (b)
Loose	90%	45 (42)%	75 (75)%	12 (9)%	1.3 (1.1)%
Medium	80%	27 (24)%	55 (55)%	8 (6)%	0.7 (0.6)%

IDEA

WP	Eff (s)	Mistag (g)	Mistag (q)	Mistag (c)	Mistag (b)
Loose	90%	27%	41%	7.5%	0.6%
Medium	80%	13%	27%	5%	0.3%

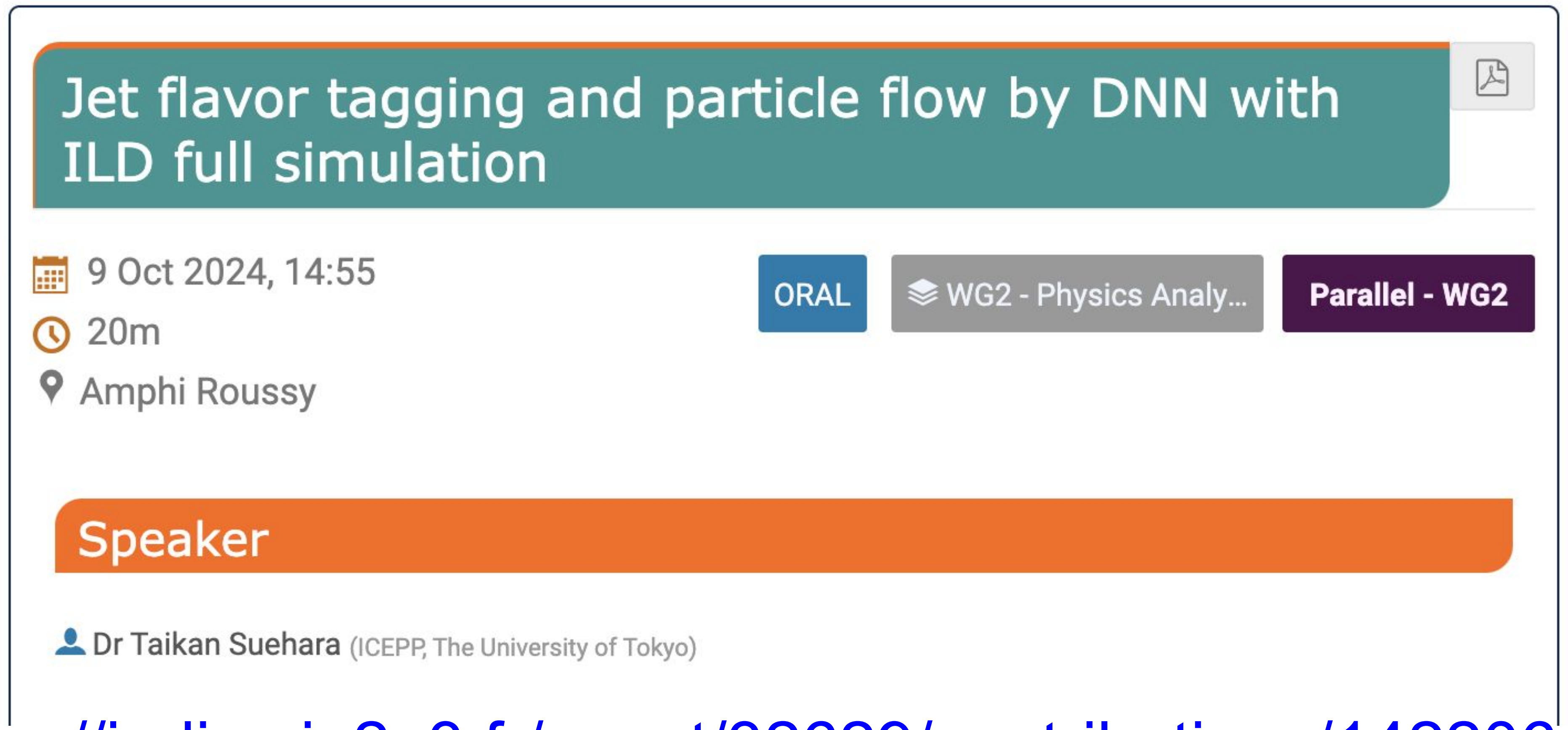
s-tagging



Comparison of different detector configurations

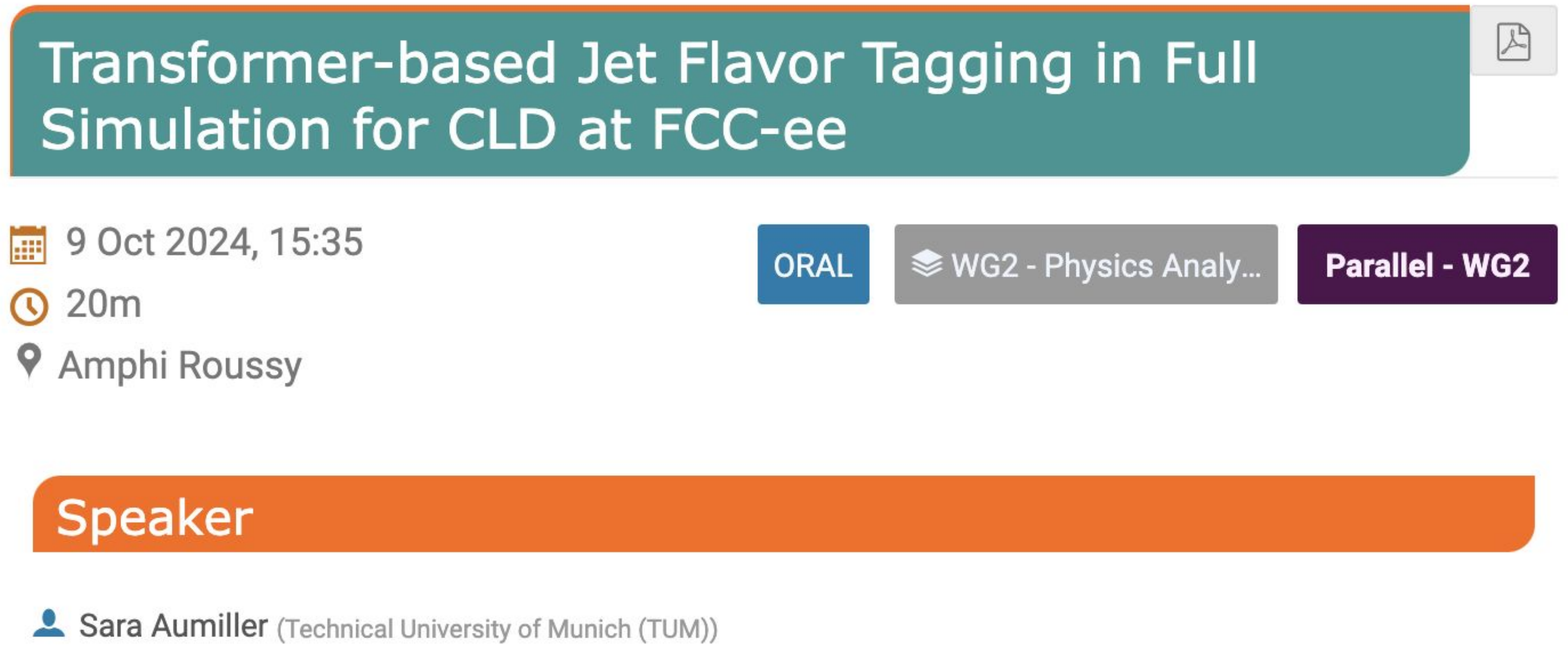
Impact on jet-flavor tagging

- We have built a framework to evaluate and compare jet flavor tagging performance of different detector concepts ***on an equal footing.***
- Further work is needed for the SiD concept to evaluate:
  - how tagging performance includes when adding dedicated PID detector (e.g. RICH)
  - how that would affect the assumed performance of other detector components



https://indico.in2p3.fr/event/32629/contributions/142206/

- ***Important caveat*** in these studies: relying on fast-simulation!
- We need to benchmark our results against realistic, full-simulation → in the process of implementing PNet in SiD full simulation.
- ***Very important work presented in this workshop in that direction for other detector concepts***
- *However*, we should be careful to make apples-to-apples comparison (make sure Delphes description – key4geo versions match, same input features for the training, same NN architecture!)



https://indico.in2p3.fr/event/32629/contributions/142548/

Conclusions and next steps

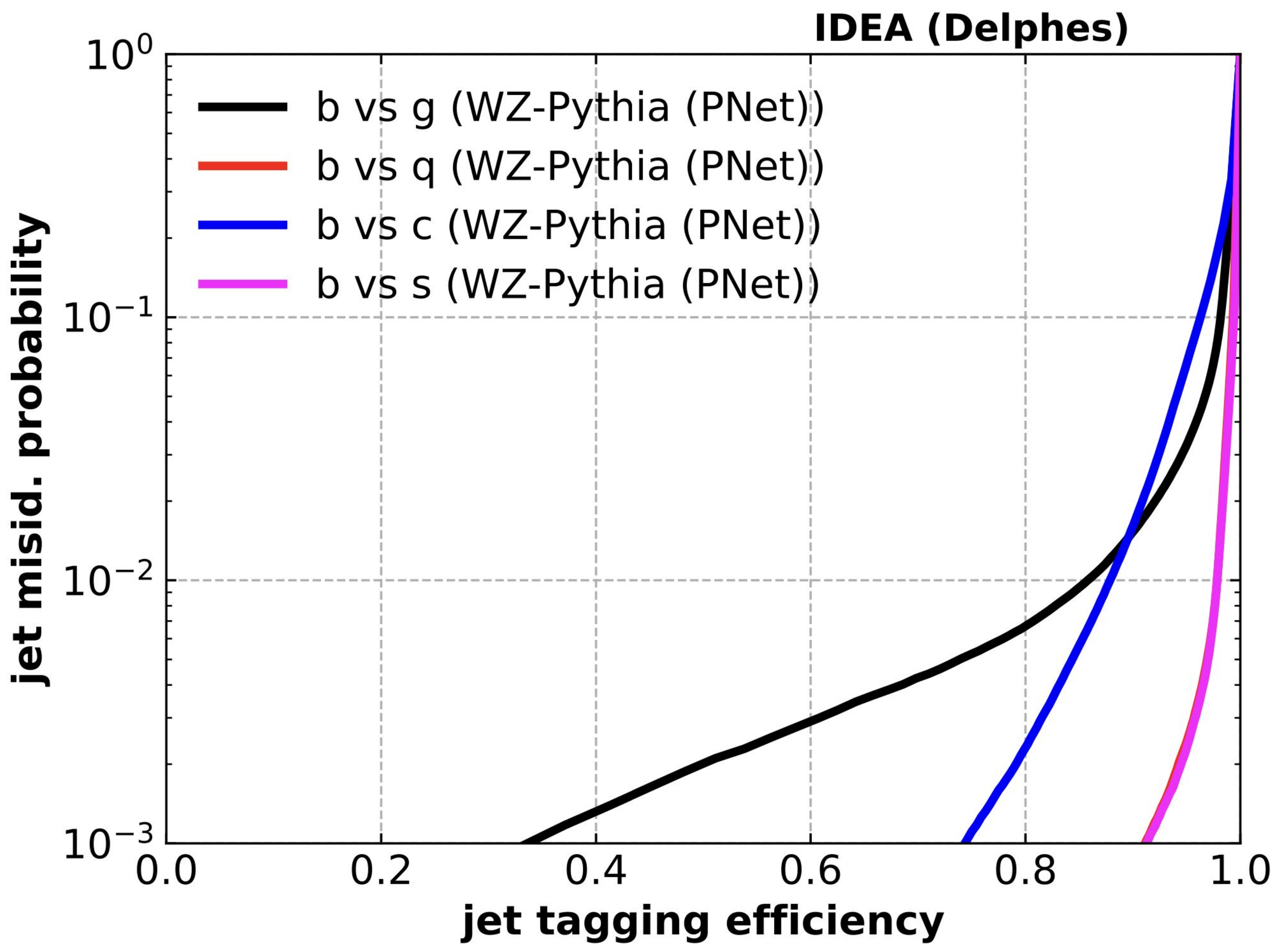
- We have provided a first evaluation of the jet flavour tagging performance for two configurations of the SiD concept using Particle Net and introducing new Delphes card for SiD.
- We used IDEA to benchmark and validate our results.
- As expected, *s-tagging significantly benefits from PID capabilities.*

- Moving forward, we are planning to:
  - study how Delphes results compare apples-to-apples with full simulation.
  - evaluate various subdetector performance and contribution to tagging
  - evaluate the complementarity in momentum reach of charged hadron ID from dN/dx, dE/dx, ToF

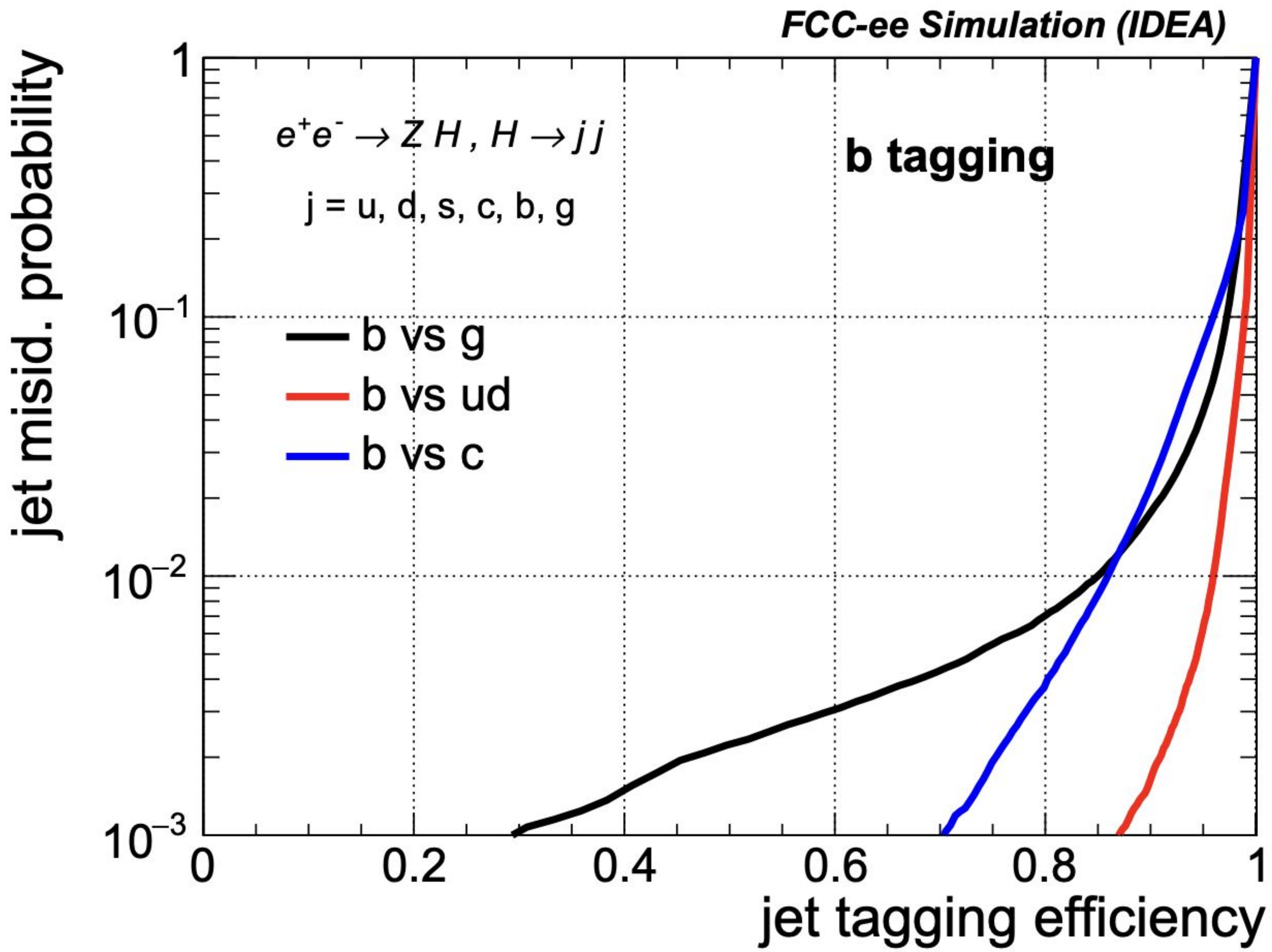
Backup

Benchmarking PNet Performance for IDEA detector concept

b-tagging



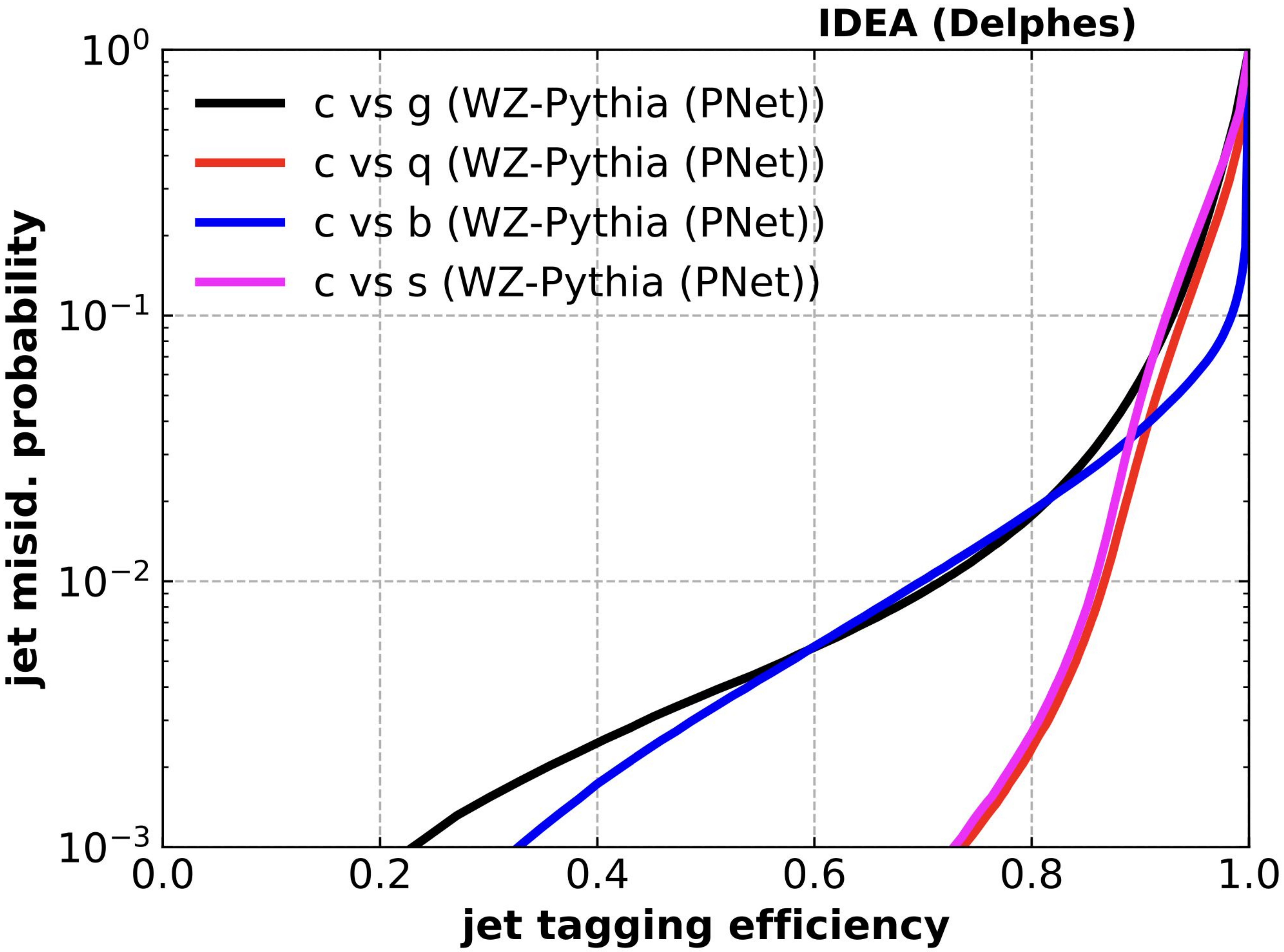
Our results



[*Eur. Phys. J. C* **82**, 646 (2022)]

Benchmarking PNet Performance for IDEA detector concept

c-tagging



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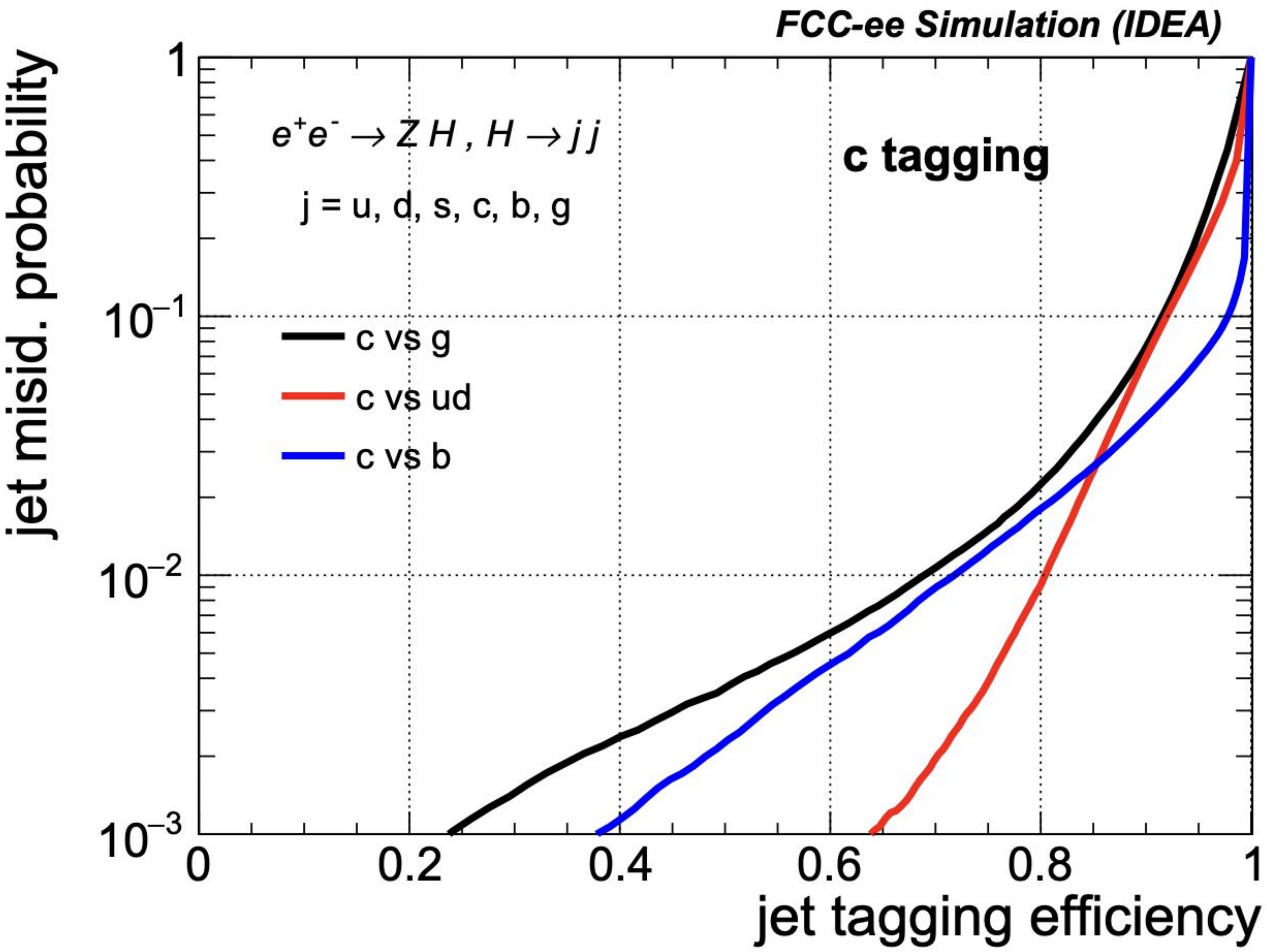

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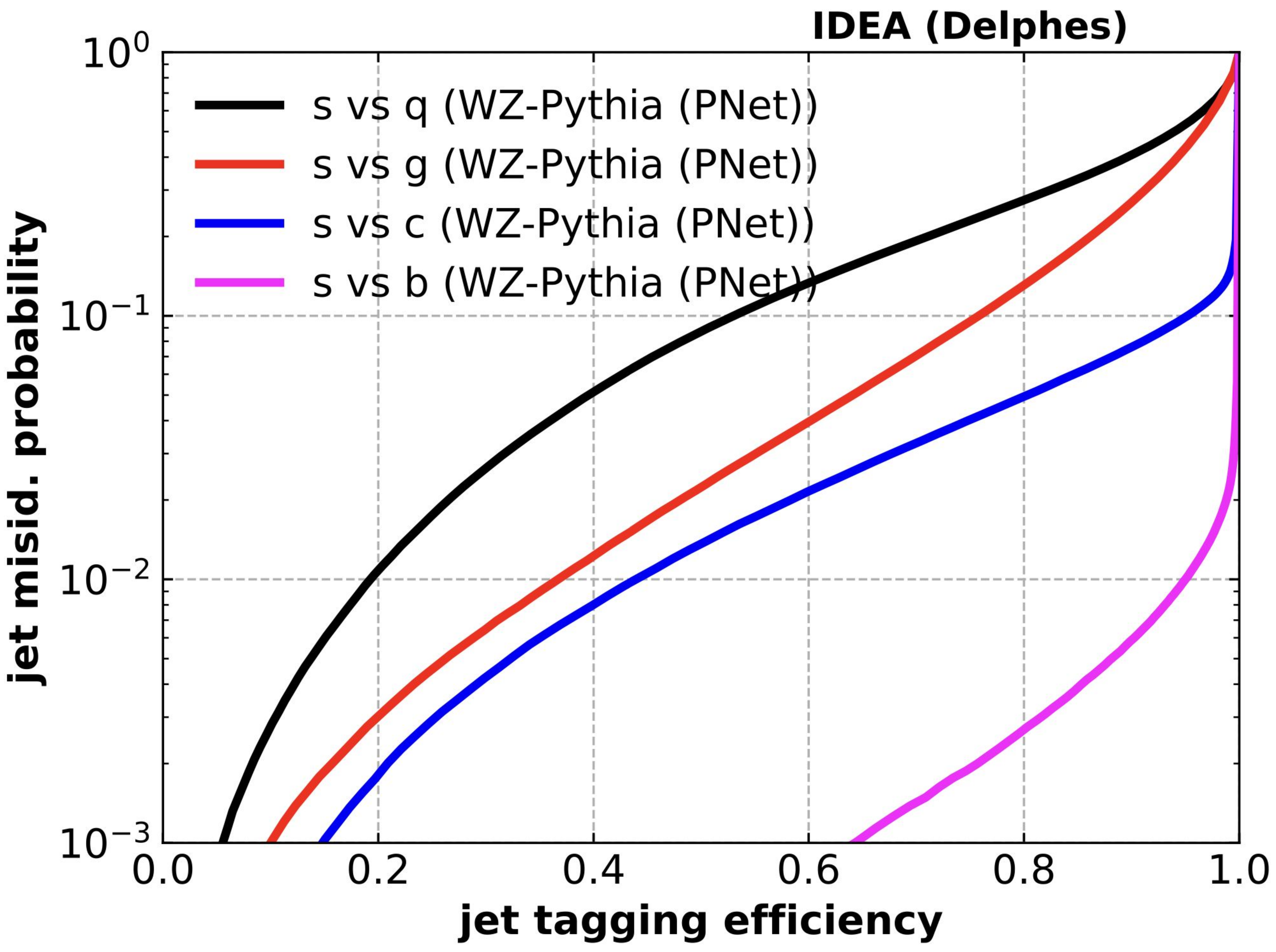
Benchmarking PNet Performance for IDEA detector concept

s-tagging



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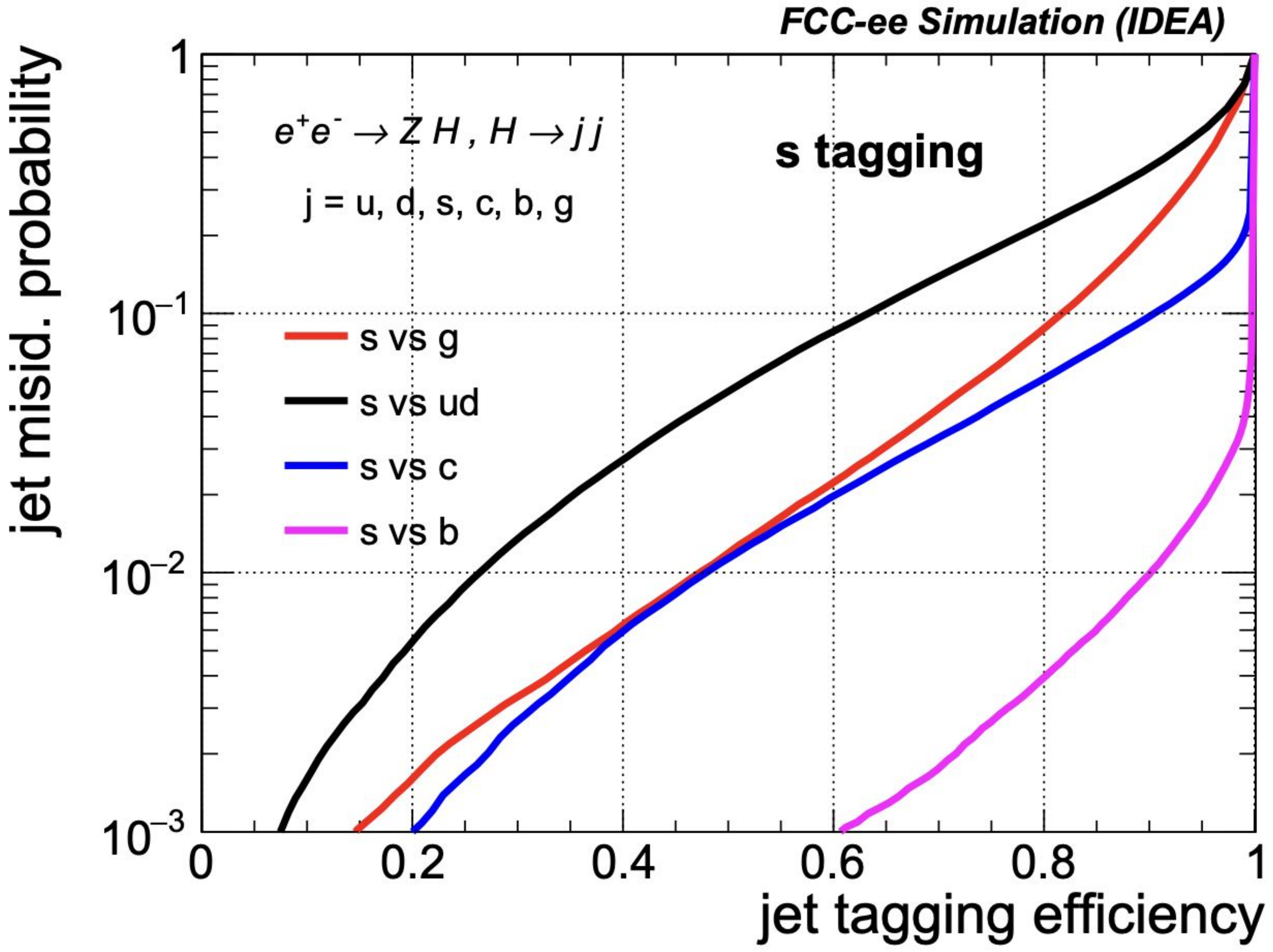

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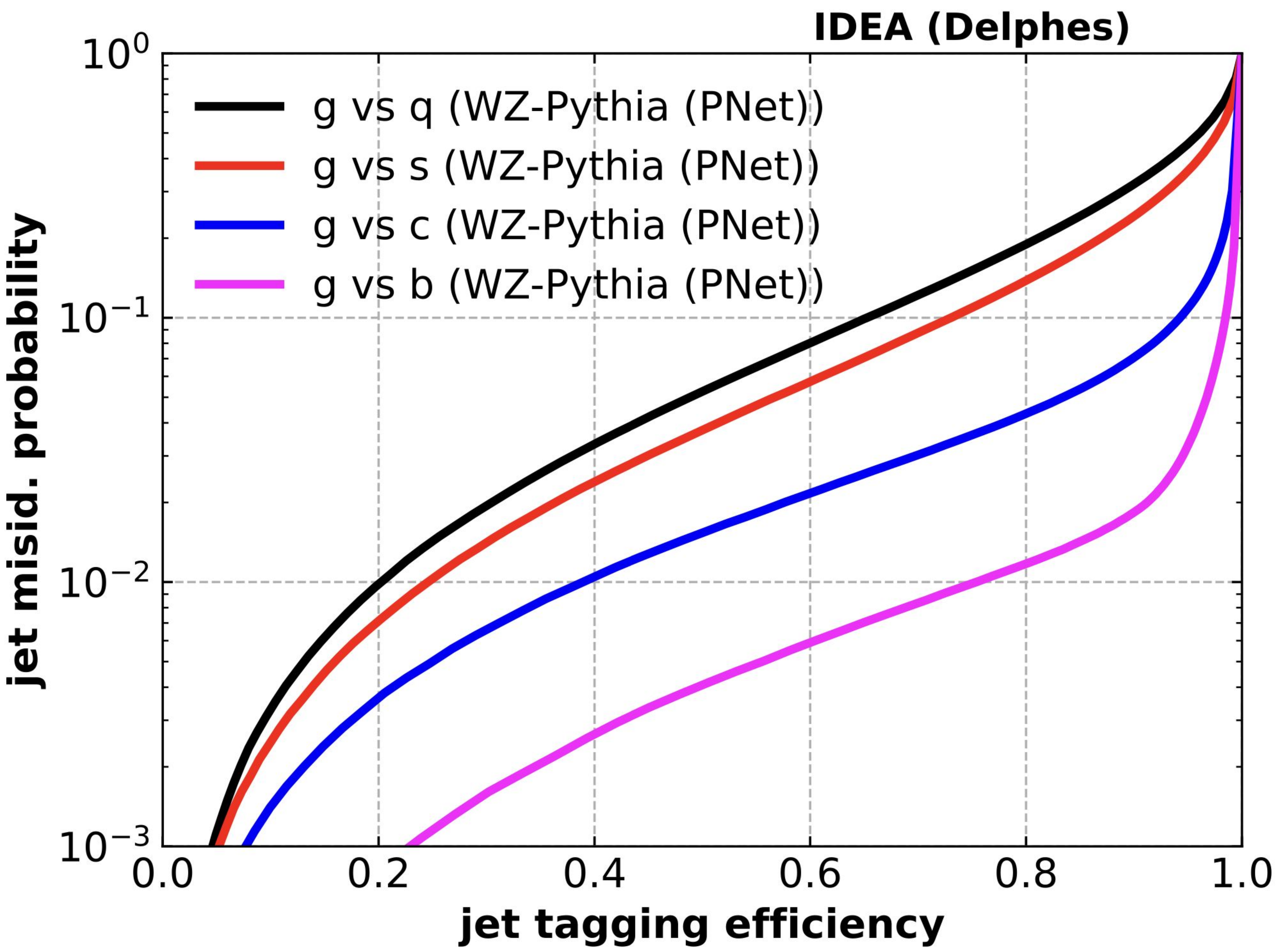
Benchmarking PNet Performance for IDEA detector concept

g-tagging



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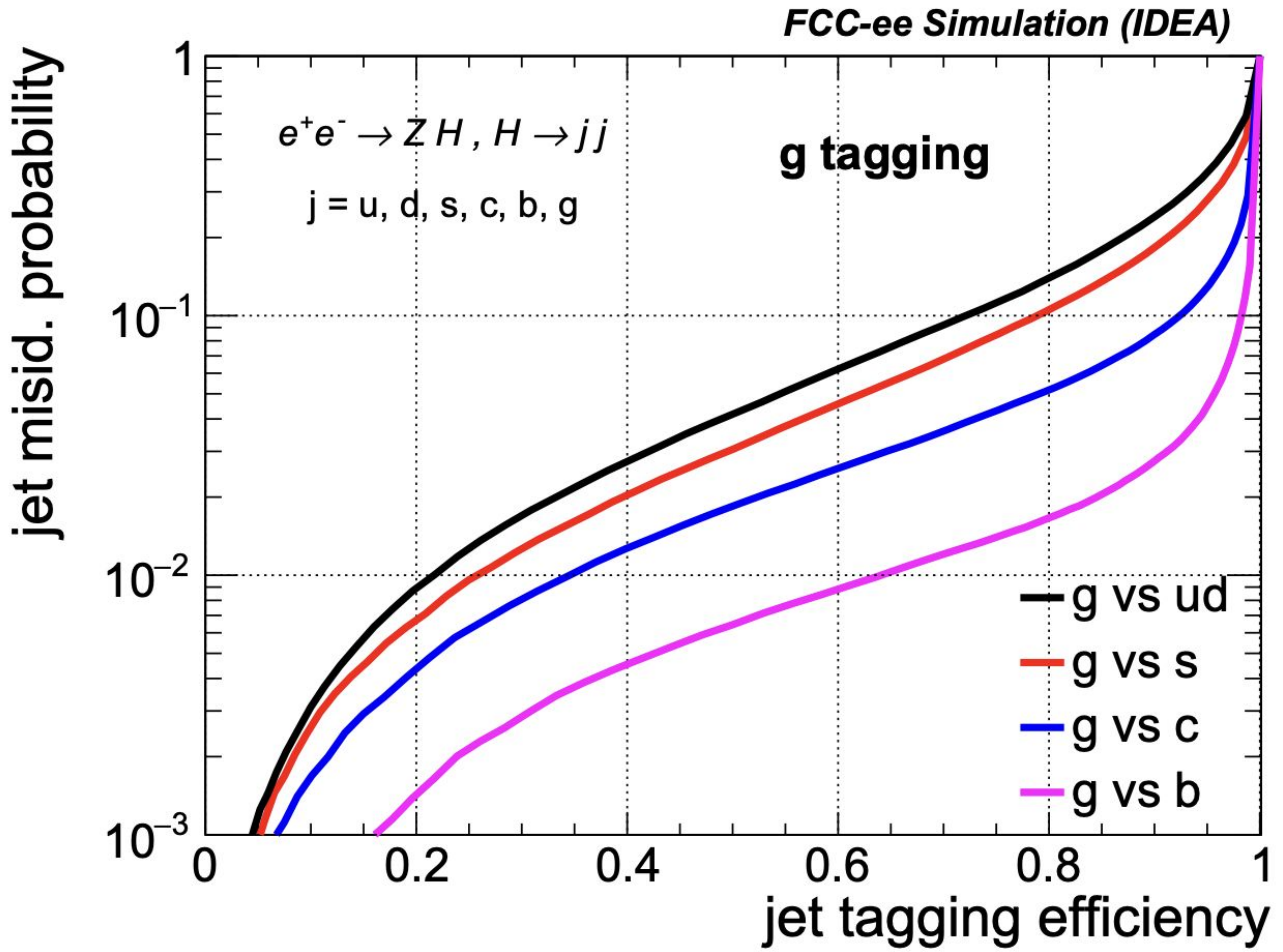

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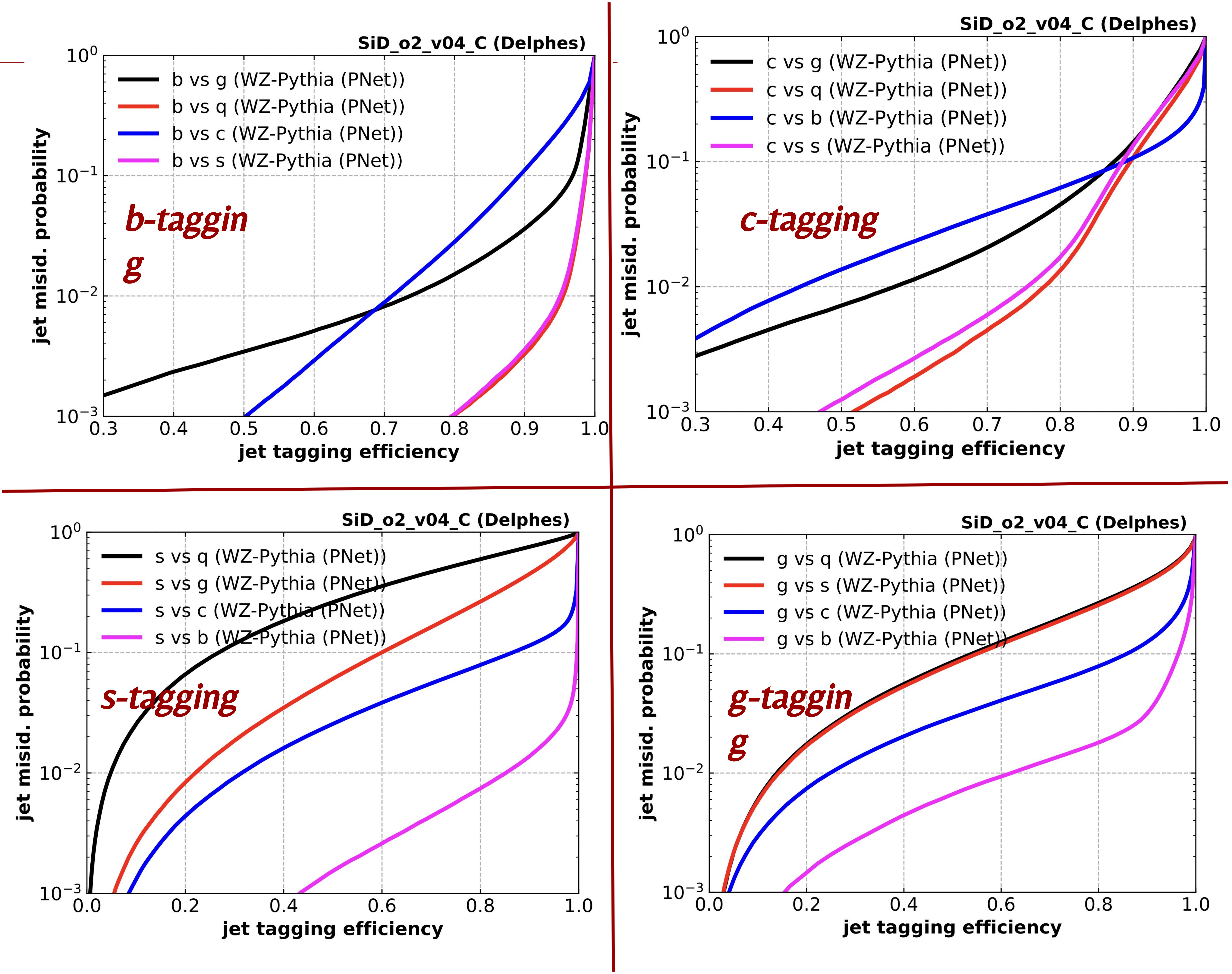
ROC Curves

SiD_o2_v04_C

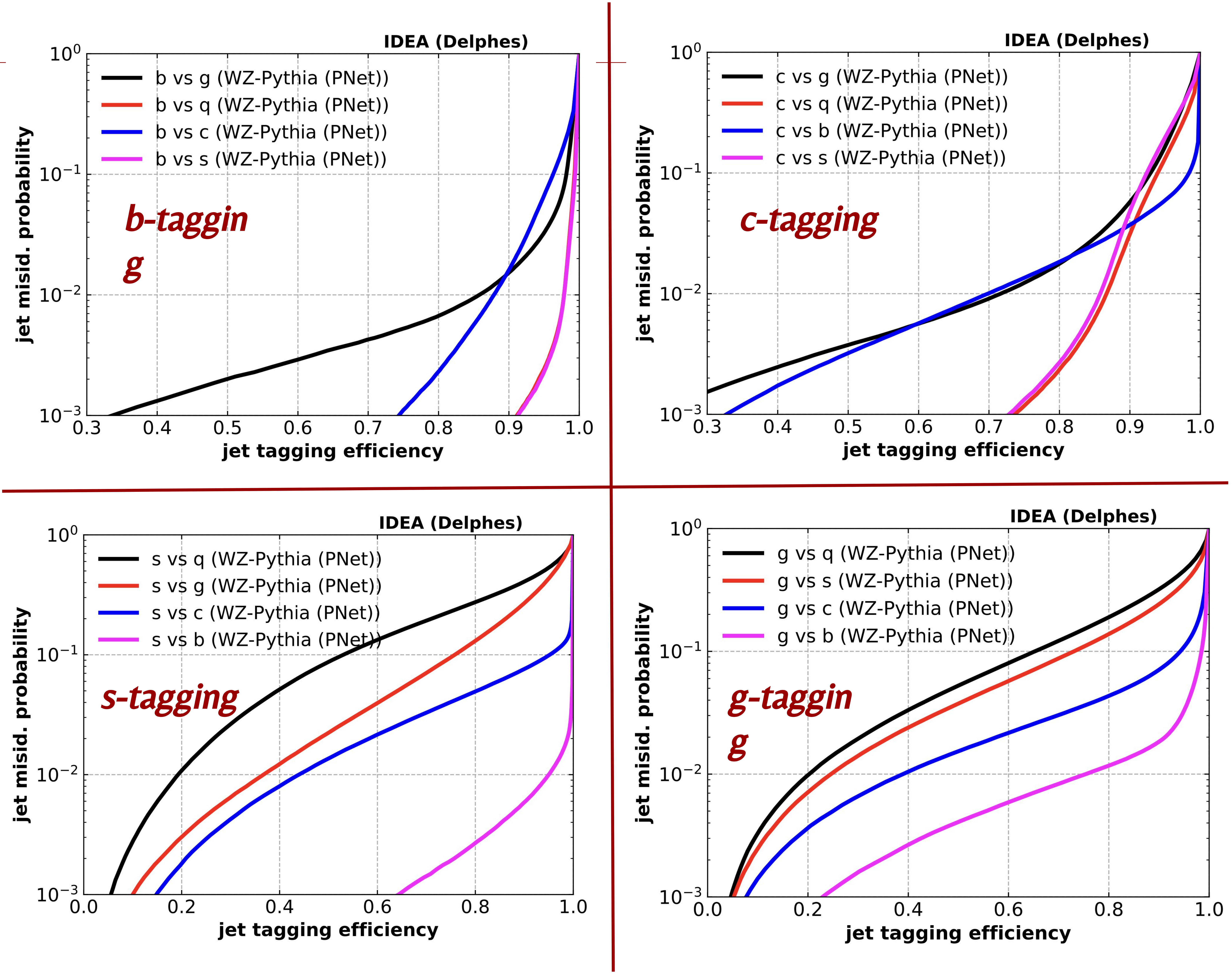
- Assume same tracking performance as for IDEA
- Inferior calorimeter performance compared to IDEA



ROC Curves

IDEA

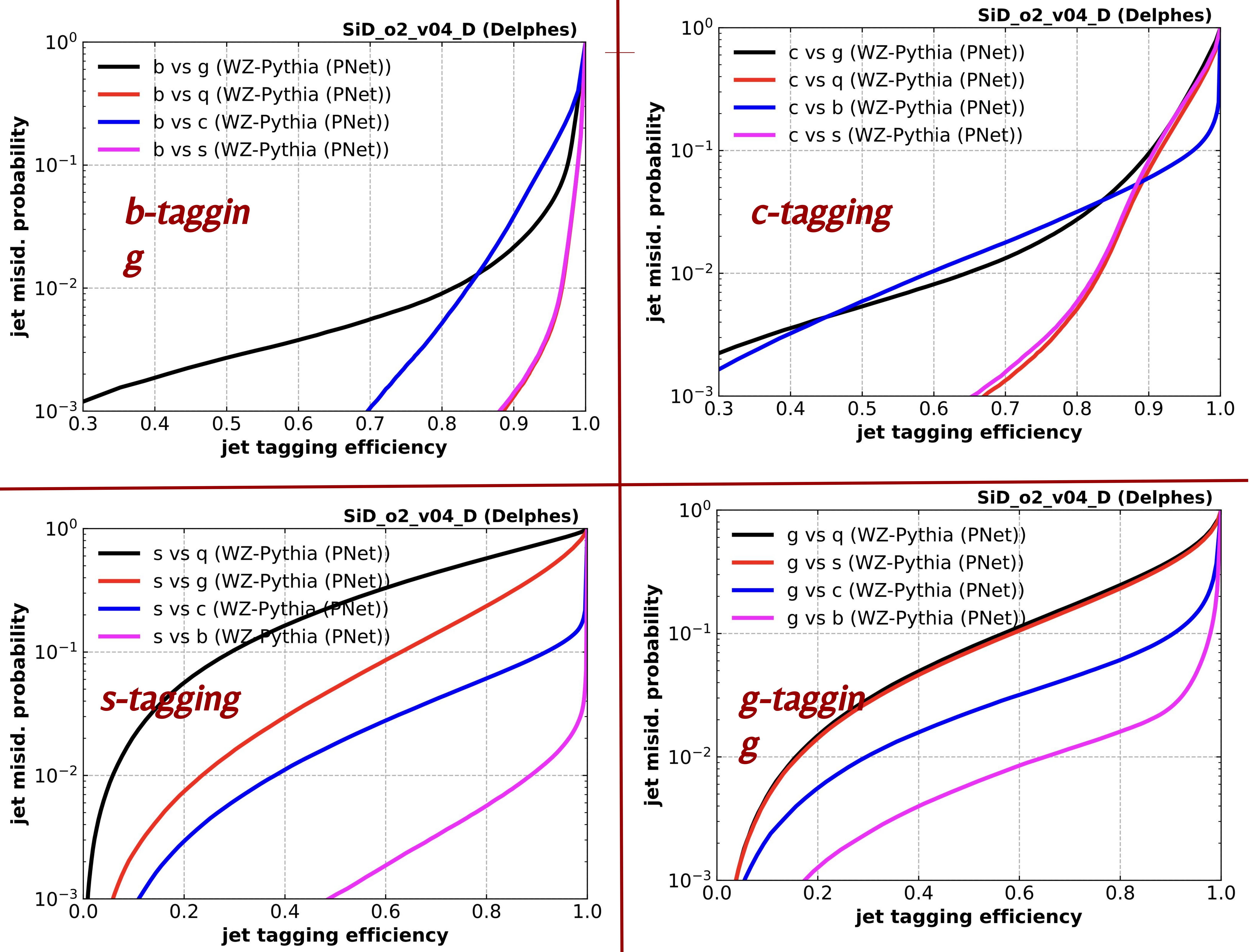
- Using official [IDEA Delphes card](https://github.com/delphes/delphes).



ROC Curves

SiD_o2_v04_D

- Assume same tracking performance as for IDEA
- Also match calorimeter performance to the one of IDEA



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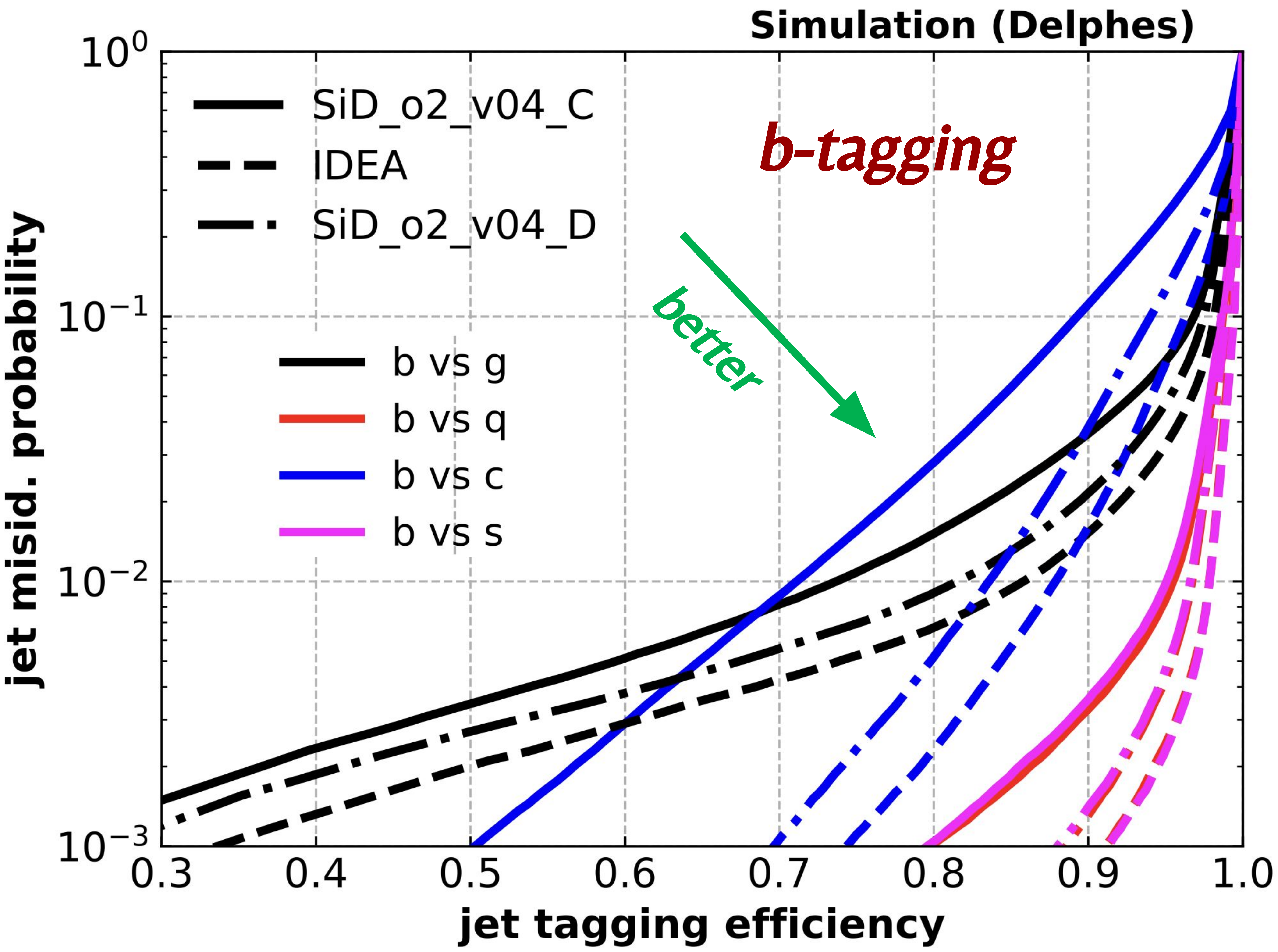

Comparison of different detector configurations

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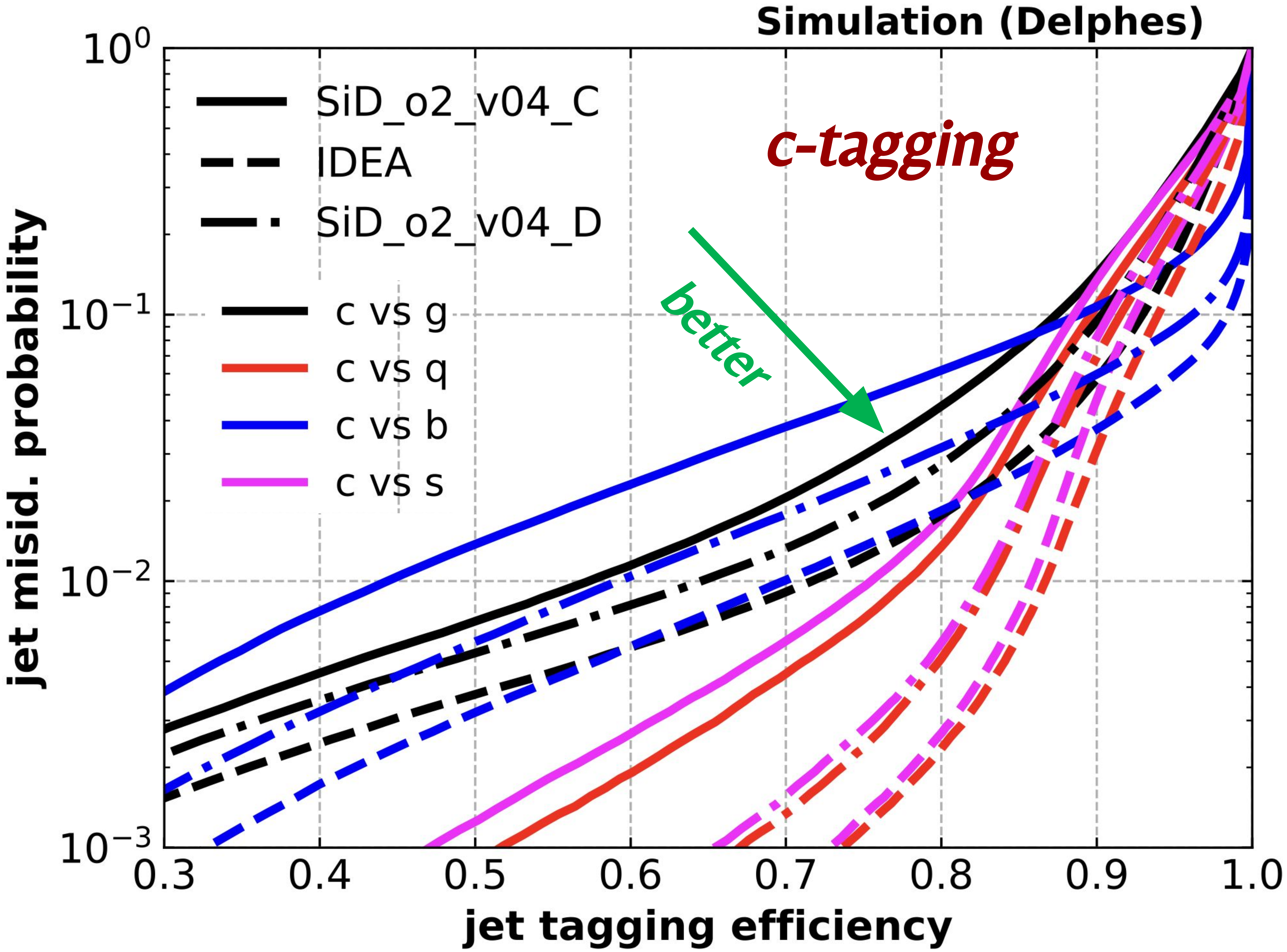

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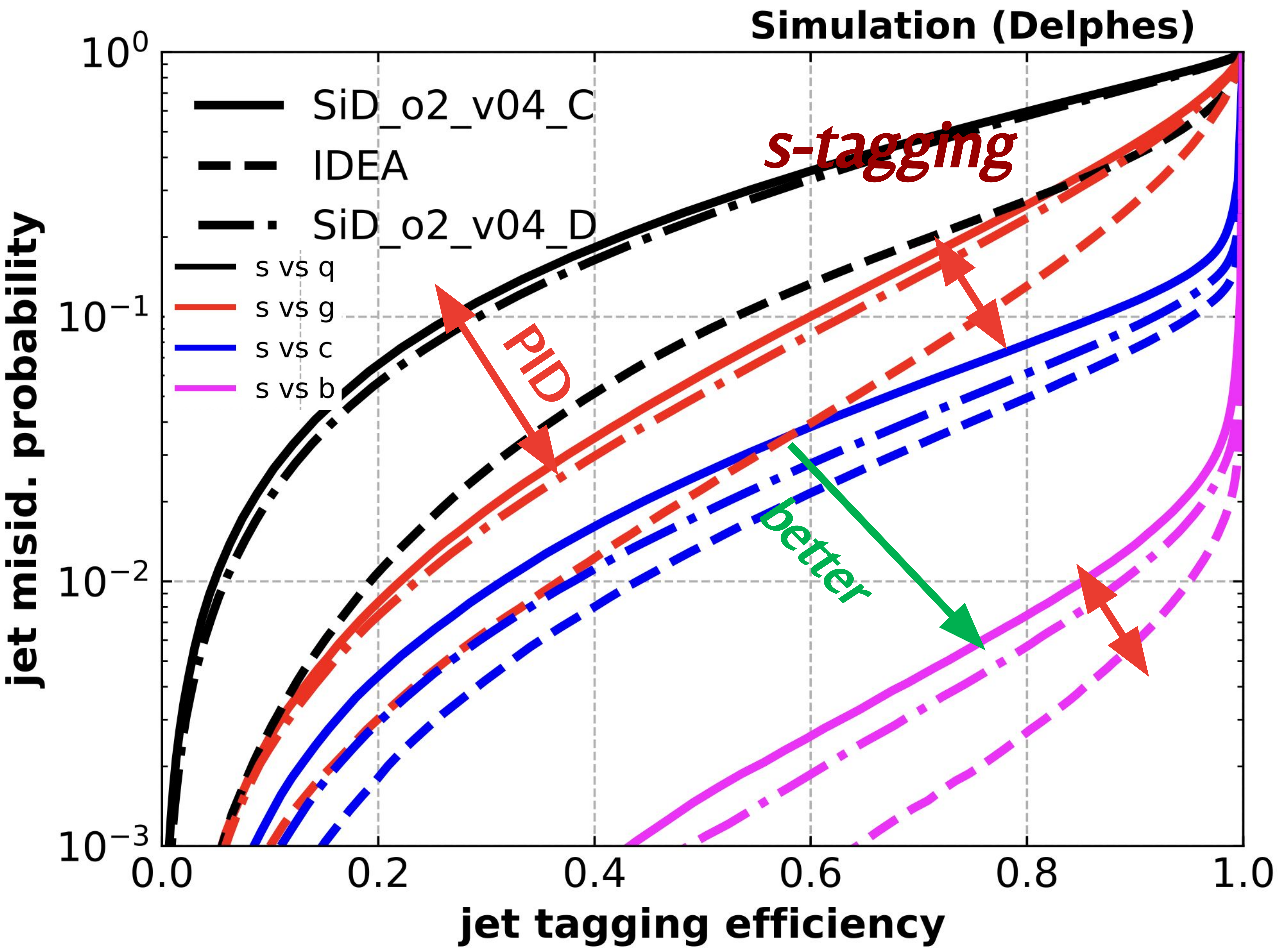
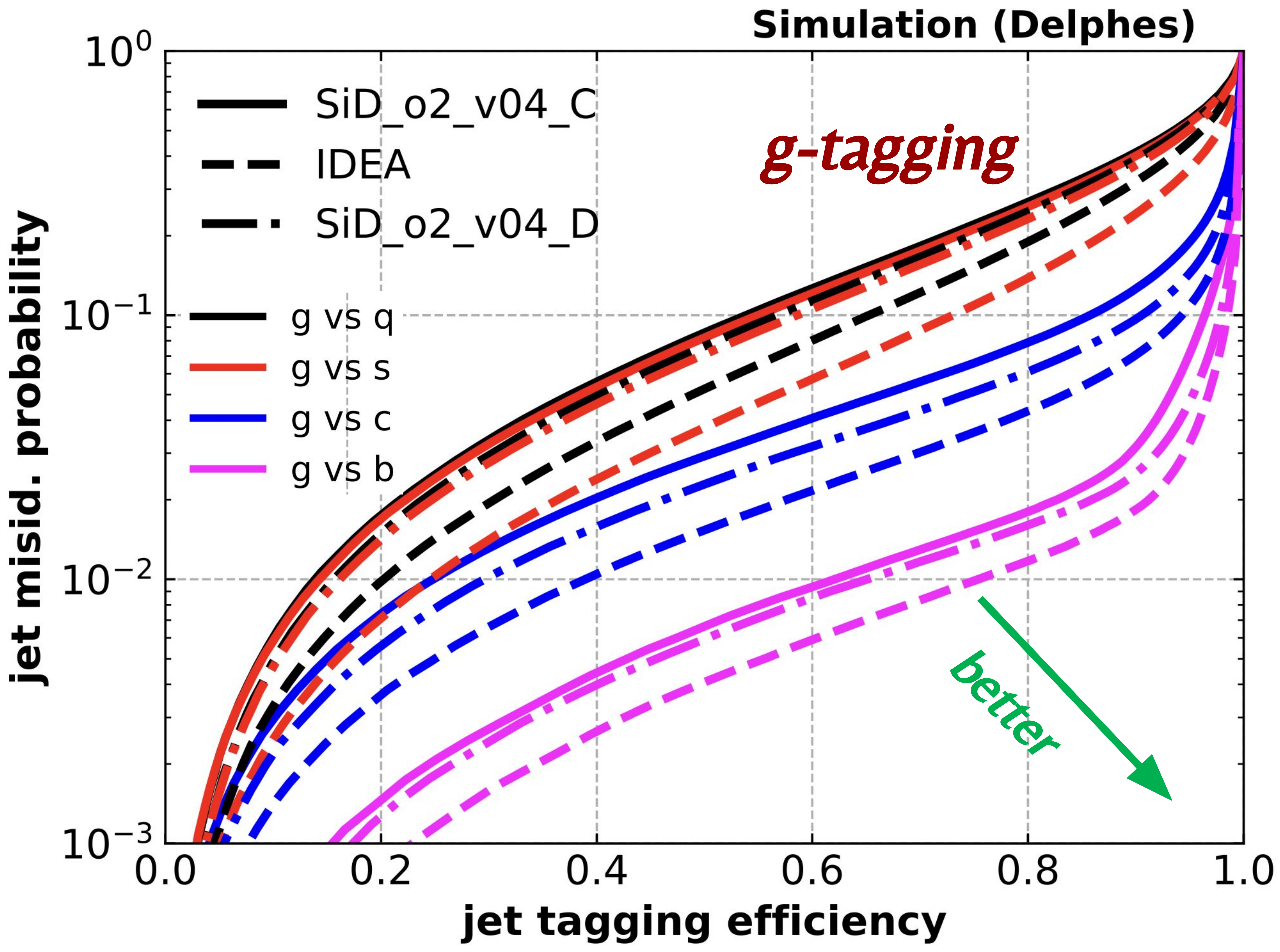
- Improved calorimeter resolution only brings marginal gain



Comparison of different detector configurations

Two configurations for SiD detector concept vs IDEA

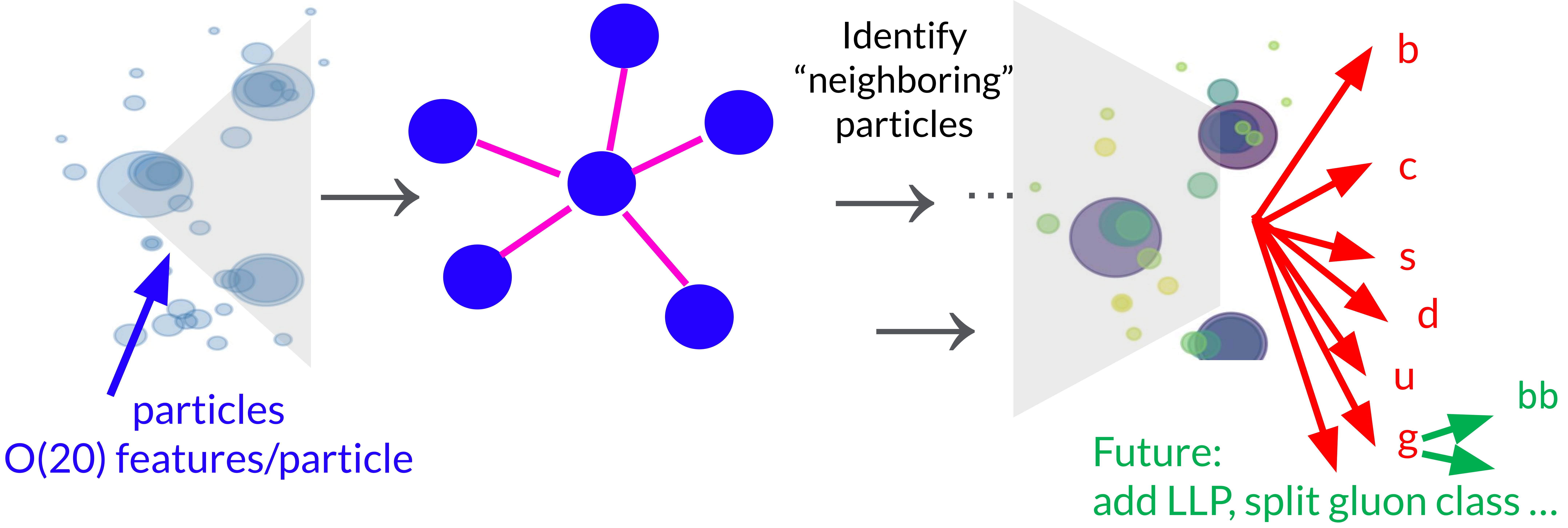
- Improvement in gluon-tagging driven almost exclusively by PID capabilities
- Small effect of improved calorimeter resolution



Particle cloud represented as a graph

PRD 101 056019 (2020)
EPJ C 82 646 (2022)

Jet representation: Particle cloud i.e. unordered set of particles
Network architecture: Graph Neural Networks
Particles: vertices of graph; interactions b/w particles: edges of graph
Hierarchical learning approach: local → global structures



L. Gouskos

Particle Net input features

- Use relative kinematics of PFOs with respect to the jet
- Use track displacement related information: impact parameters and significance, track parameters and their covariance matrix
- Use ID-related variables, including charge, TOF mass and cluster-counting

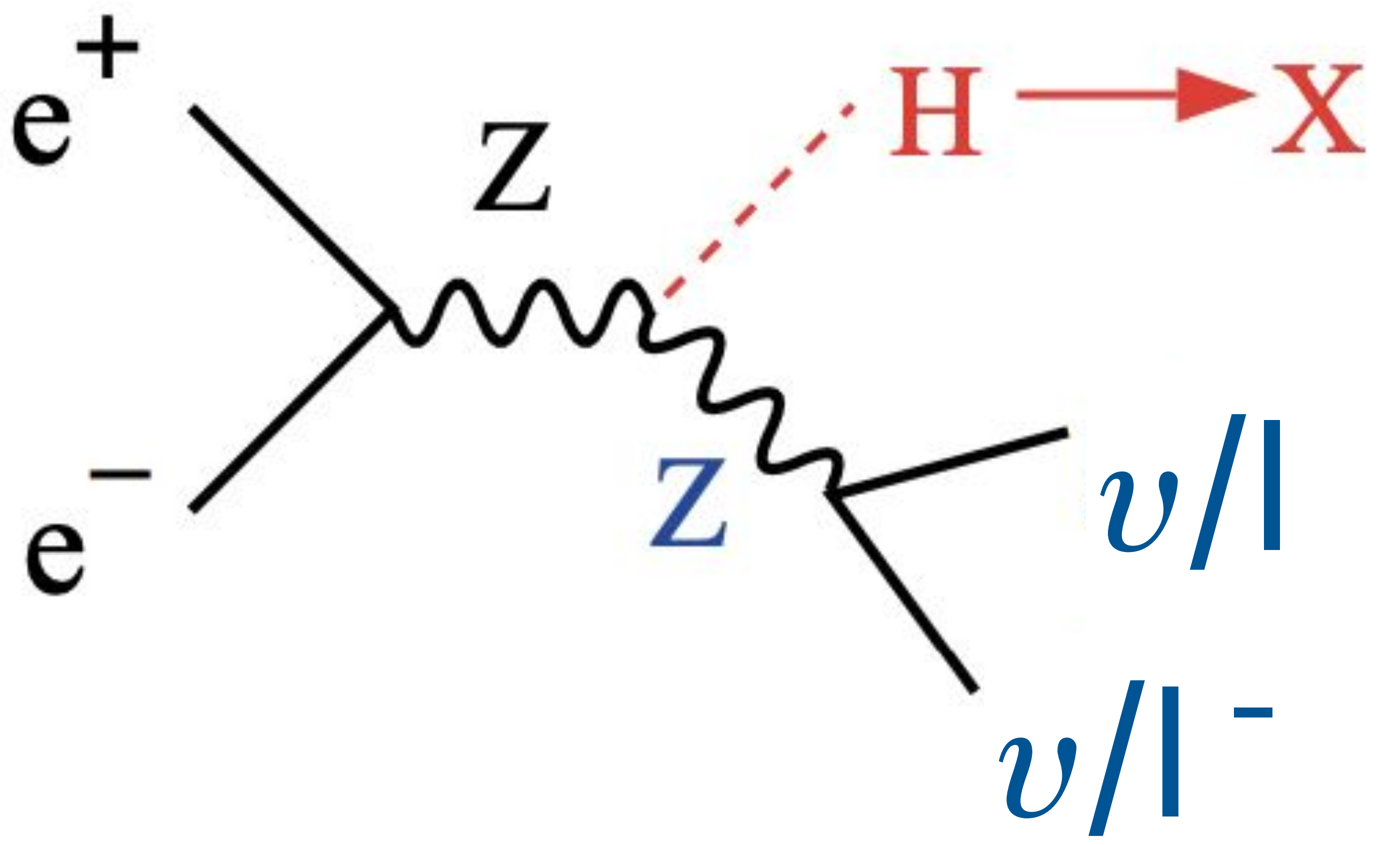
Variable	Description
	Kinematics
$\log E_{const}/E_{jet}$	log of the relative energy of the jet constituent with respect to the jet energy
θ_{rel}	polar angle of the constituent with respect to the jet momentum
ϕ_{rel}	azimuthal angle of the constituent with respect to the jet momentum
	Displacement
d_0	transverse impact parameter of the track
z_0	longitudinal impact parameter of the track
SIP_{2D}	signed 2D impact parameter of the track
SIP_{2D}/σ_{2D}	signed 2D impact parameter significance of the track
SIP_{3D}	signed 3D impact parameter of the track
SIP_{3D}/σ_{3D}	signed 3D impact parameter significance of the track
d_{3D}	distance between p.c.a. of constituents tracks and jet axis
C_{ij}	covariance matrix of the track parameters
	Identification
q	electric charge of the particle
$m_{t.o.f}$	mass calculated from time-of-flight
dN/dx	number of primary ionisation clusters along track
$isMu$	if the particle is identified as a muon
$isEl$	if the particle is identified as an electron
$isGamma$	if the particle is identified as a photon
$isChargedHad$	if the particle is identified as a charged hadron
$isNeutralHad$	if the particle is identified as a neutral hadron

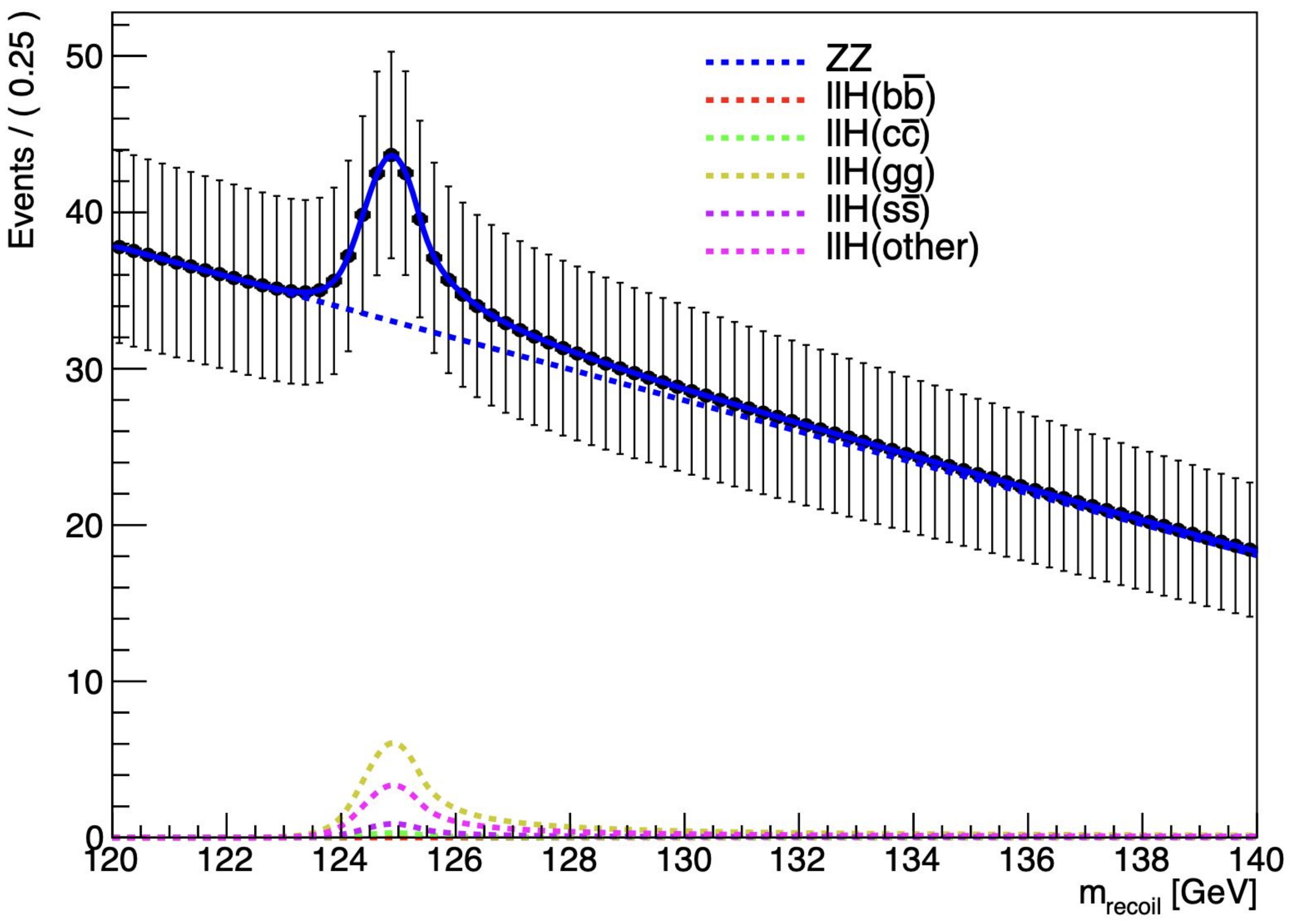
https://cds.cern.ch/record/2825441/files/CERN_Report.pdf

Analysis strategy to target H → ss

Exploit Z boson reconstruction in the ZH associated mode

- At 250 GeV the total Zh cross section can be extracted independently of the Higgs boson's detailed properties by counting events with an identified Z boson
- Looking at 0 or 2 leptons Z decay modes





$$M_{rec} = \sqrt{(\sqrt{s} - E_Z)^2 - \vec{p}_Z^{\,2}}$$

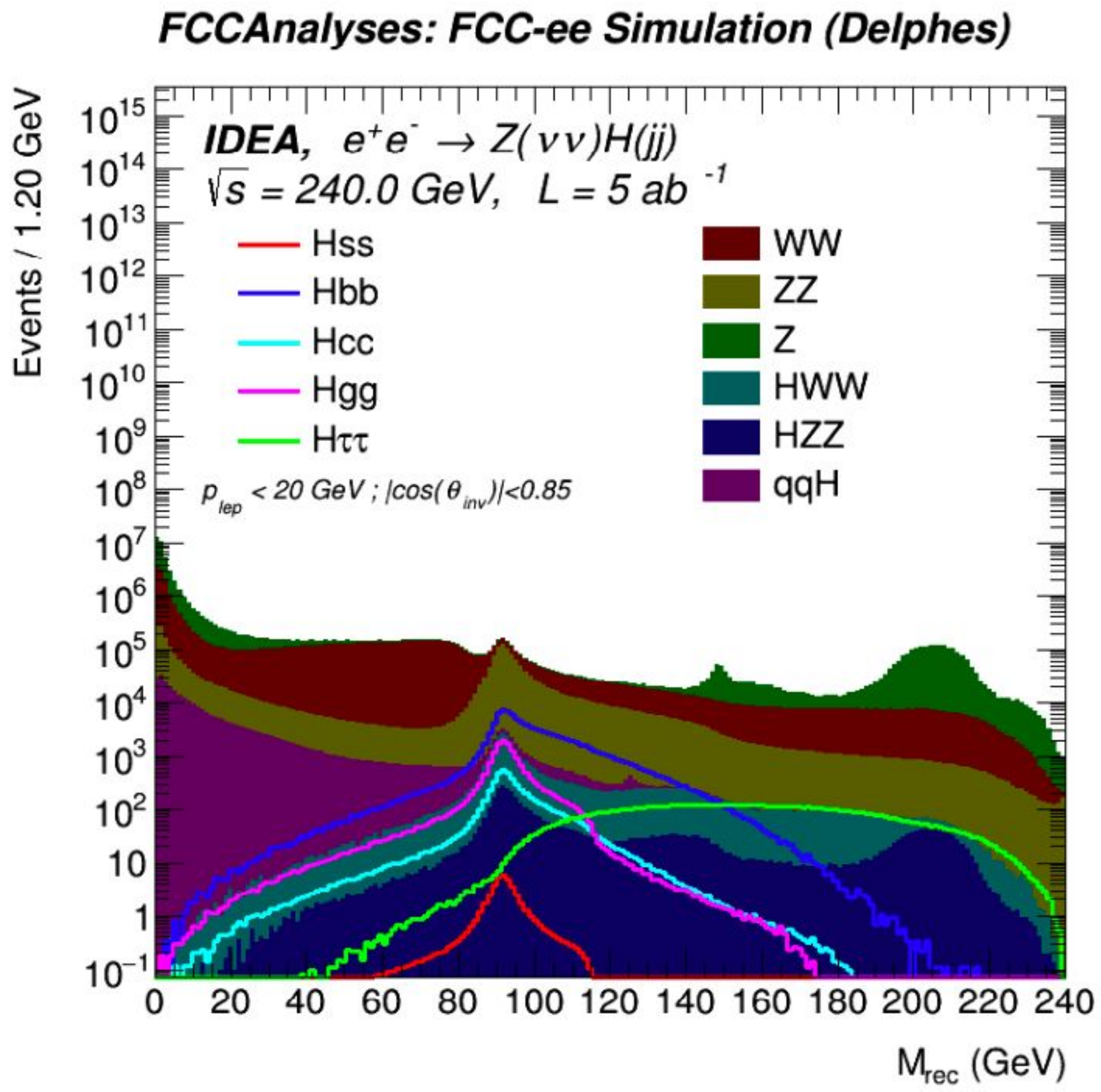
arXiv:2203.0753

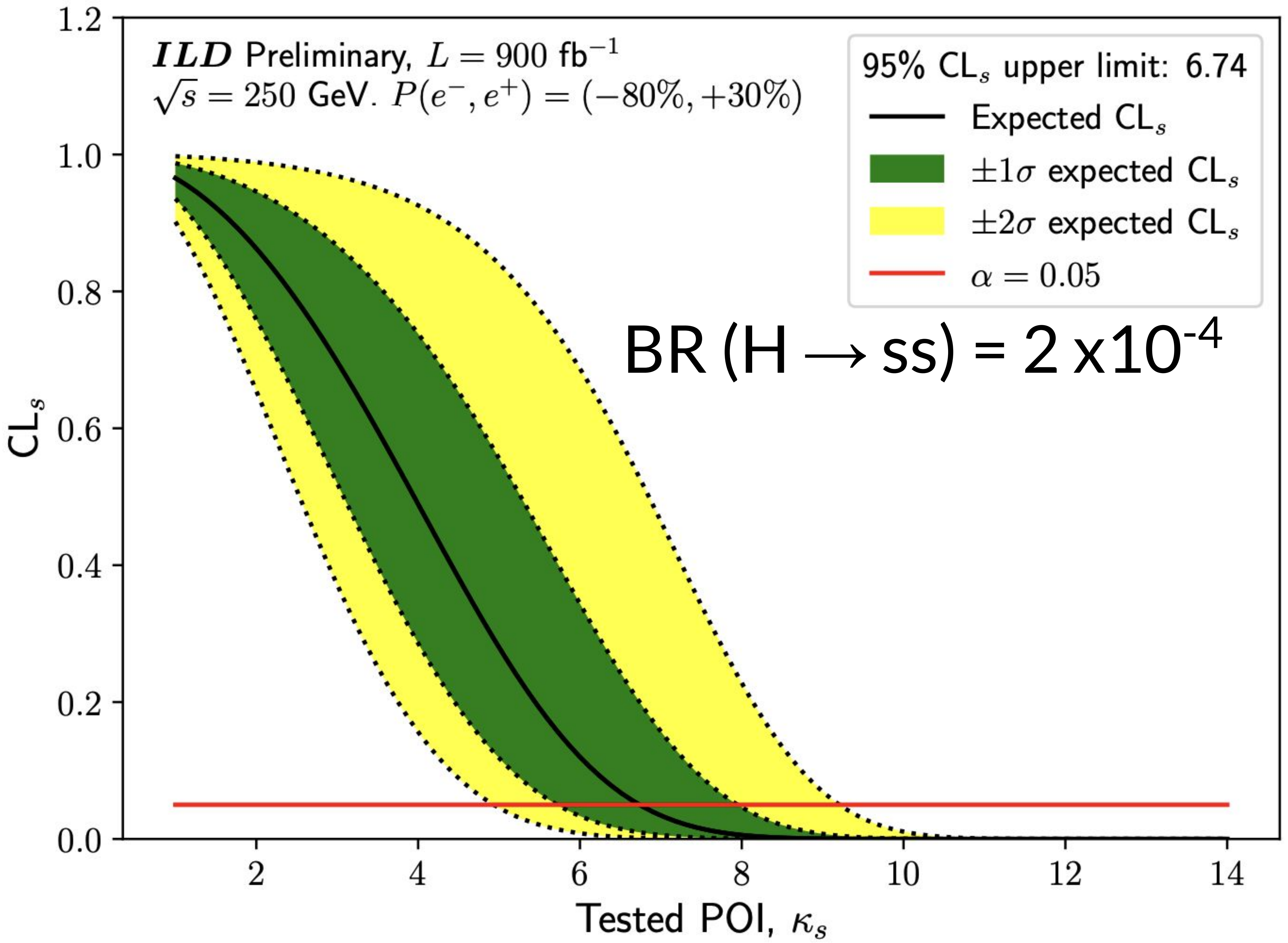
L. Gouskos @FCC week

Constraints on s-coupling

Compatible results for both FCC and ILC like analyses

- ILD combined limit of κ_s < 6.74 at 95% CL with 900/fb at 250 GeV (i.e. half dataset)
  - No PID worsen the results by 8%
- FCC for Z(νν) only sets a limit of κ_s < 1.3 at 95% CL with 5/ab at 250 GeV and 2 IPs

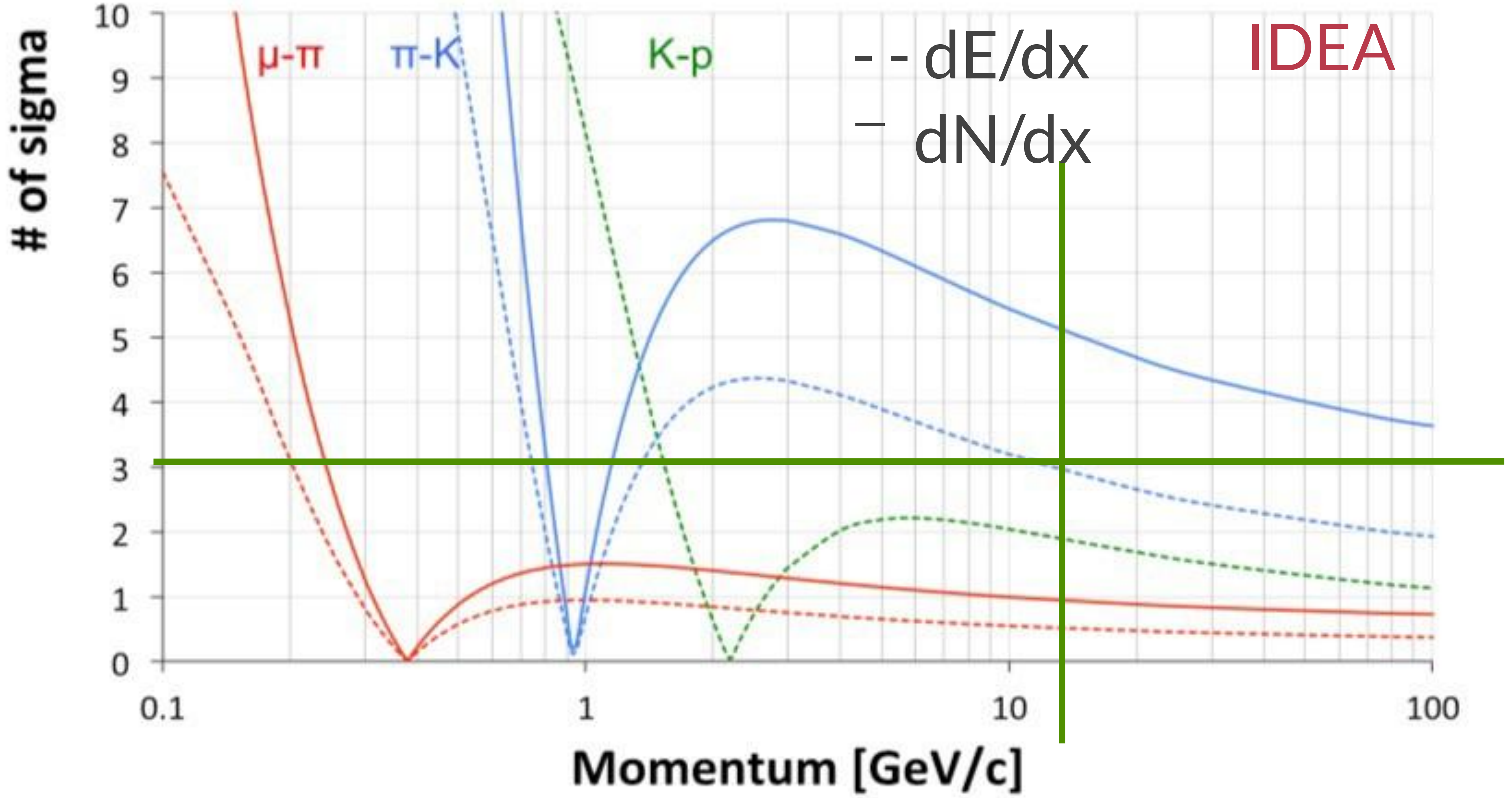


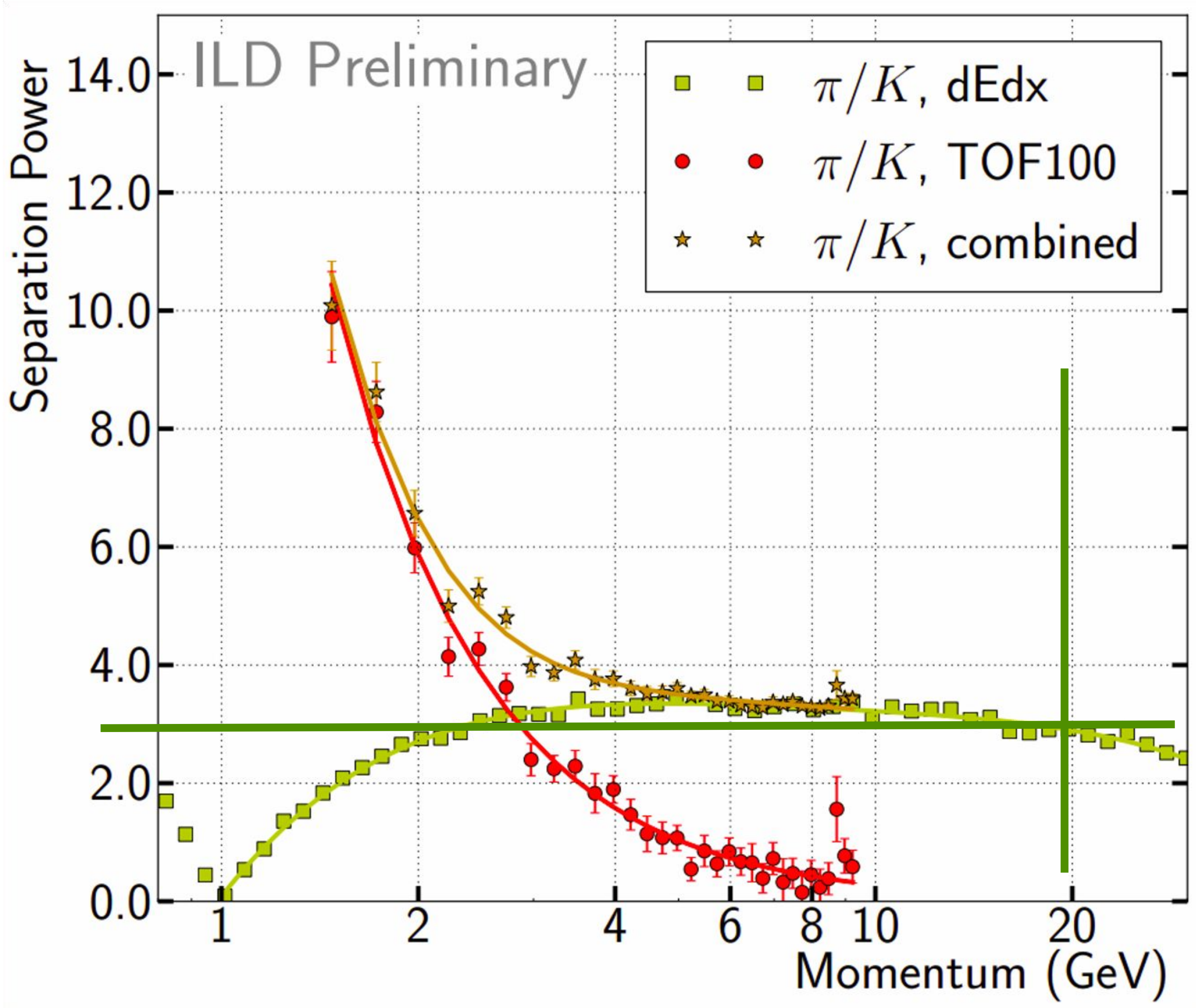


Particle ID for s-tagging

Combining different strategies for optimal PID performance across a wide p_T range

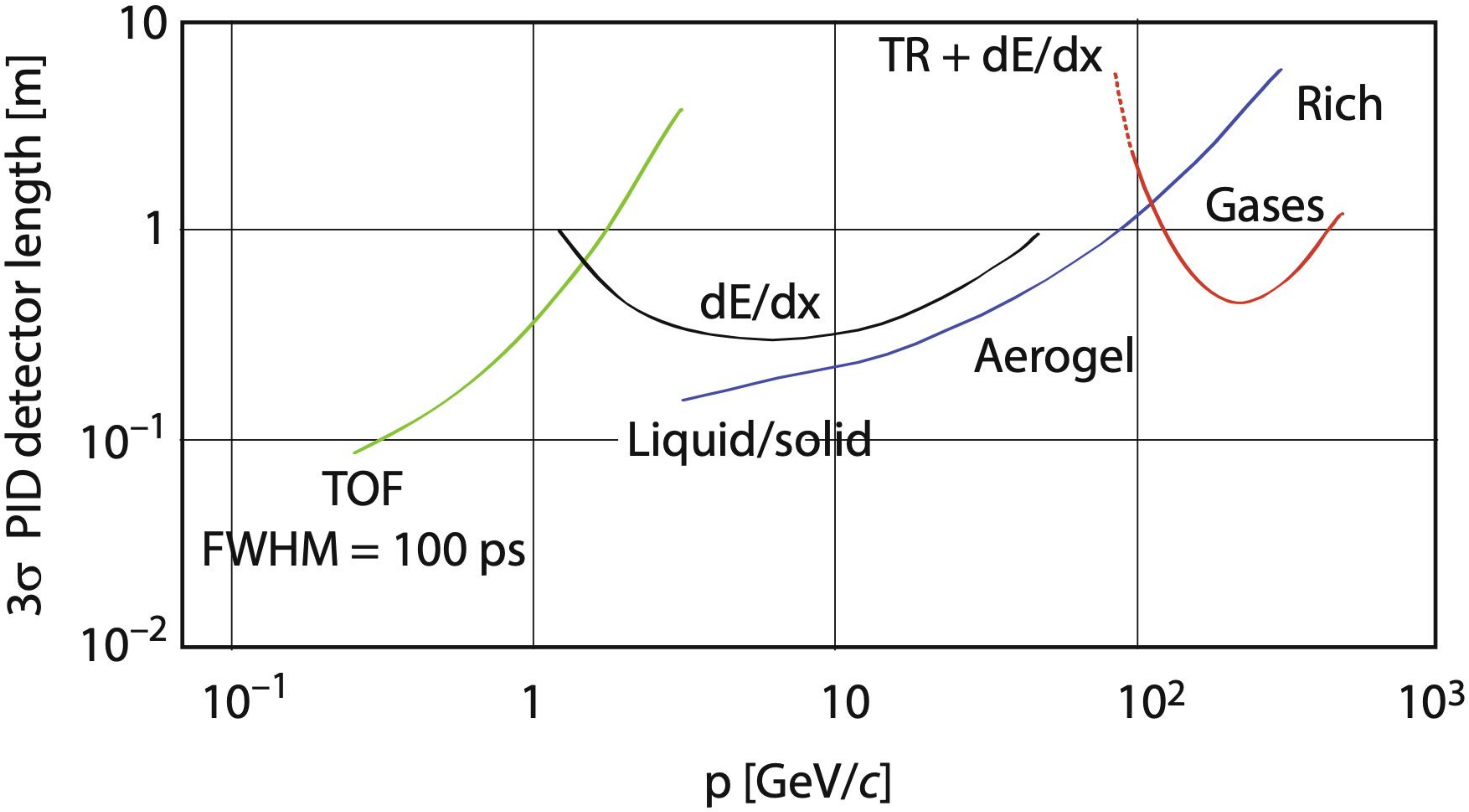
- dE/dx from silicon (< 5 GeV) and large gaseous tracking detectors (< 30 GeV)
- < 5 GeV, time-of-flight (i.e. 100 ps from ECAL)





Particle ID for s-tagging

Combining different strategies for optimal PID performance across a wide p_T range



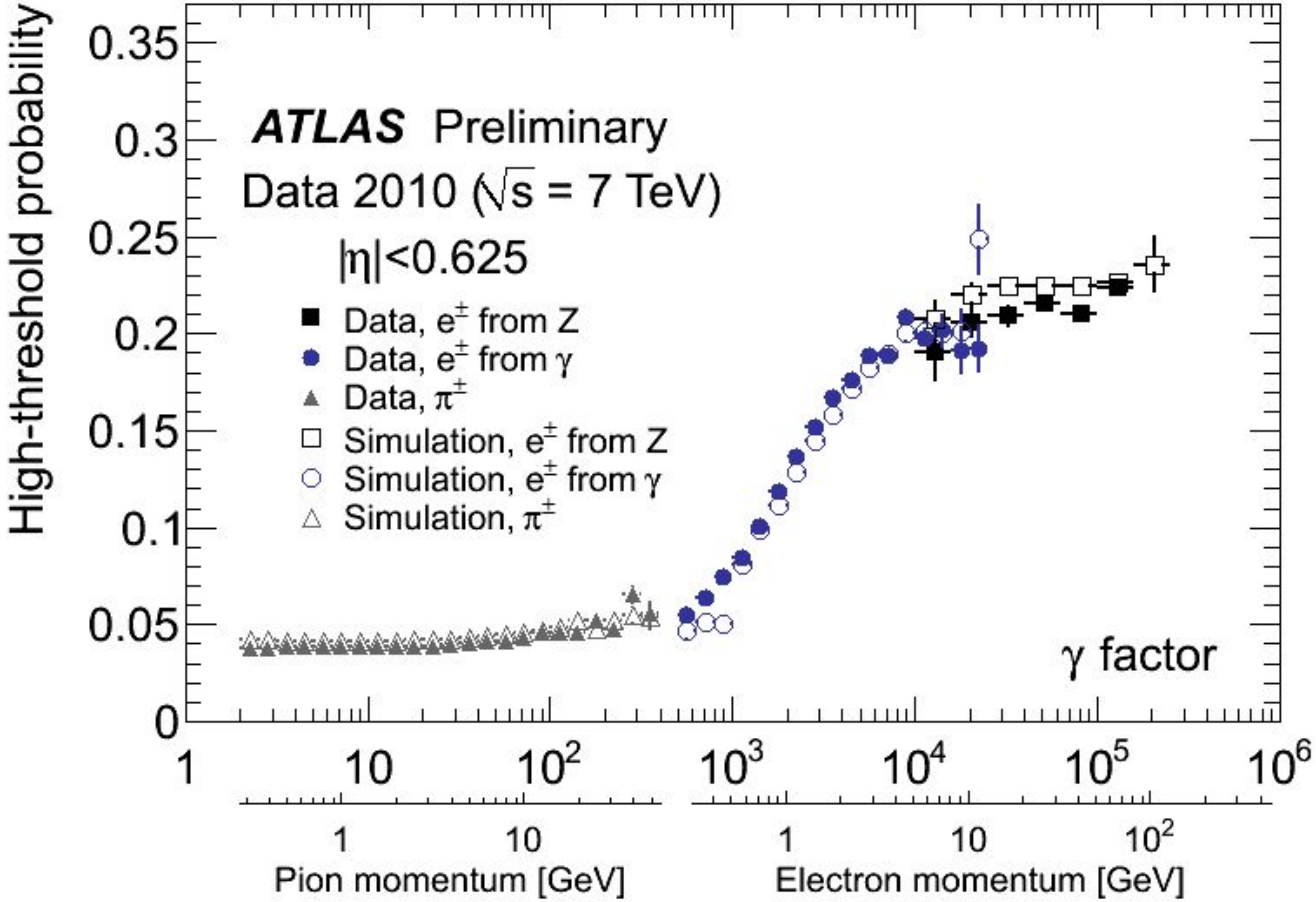
e/π separation with TR+dE/dx

e/π separation via detection of transition radiation photons

Transition radiation is emitted when a highly relativistic charged particle with a Lorentz factor $\gamma > 10^3$ traverses boundaries between materials of different dielectric constants.

To achieve the best e/π separation, TR and dE/dx-based measurements are combined in a single likelihood function for a particle type.

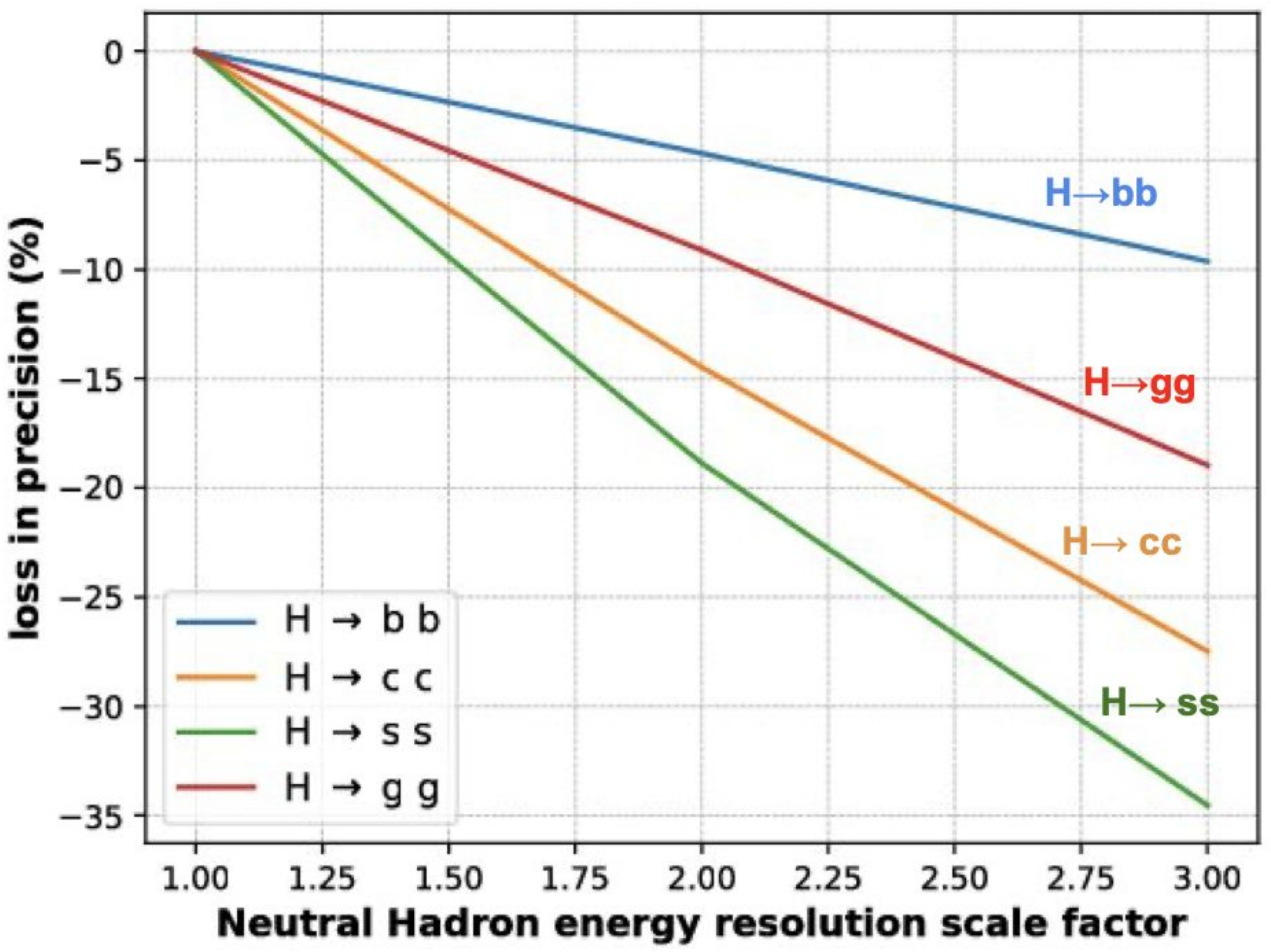
The HT fraction is defined as the fraction of hits on track that exceed the high threshold (6-7 KeV)



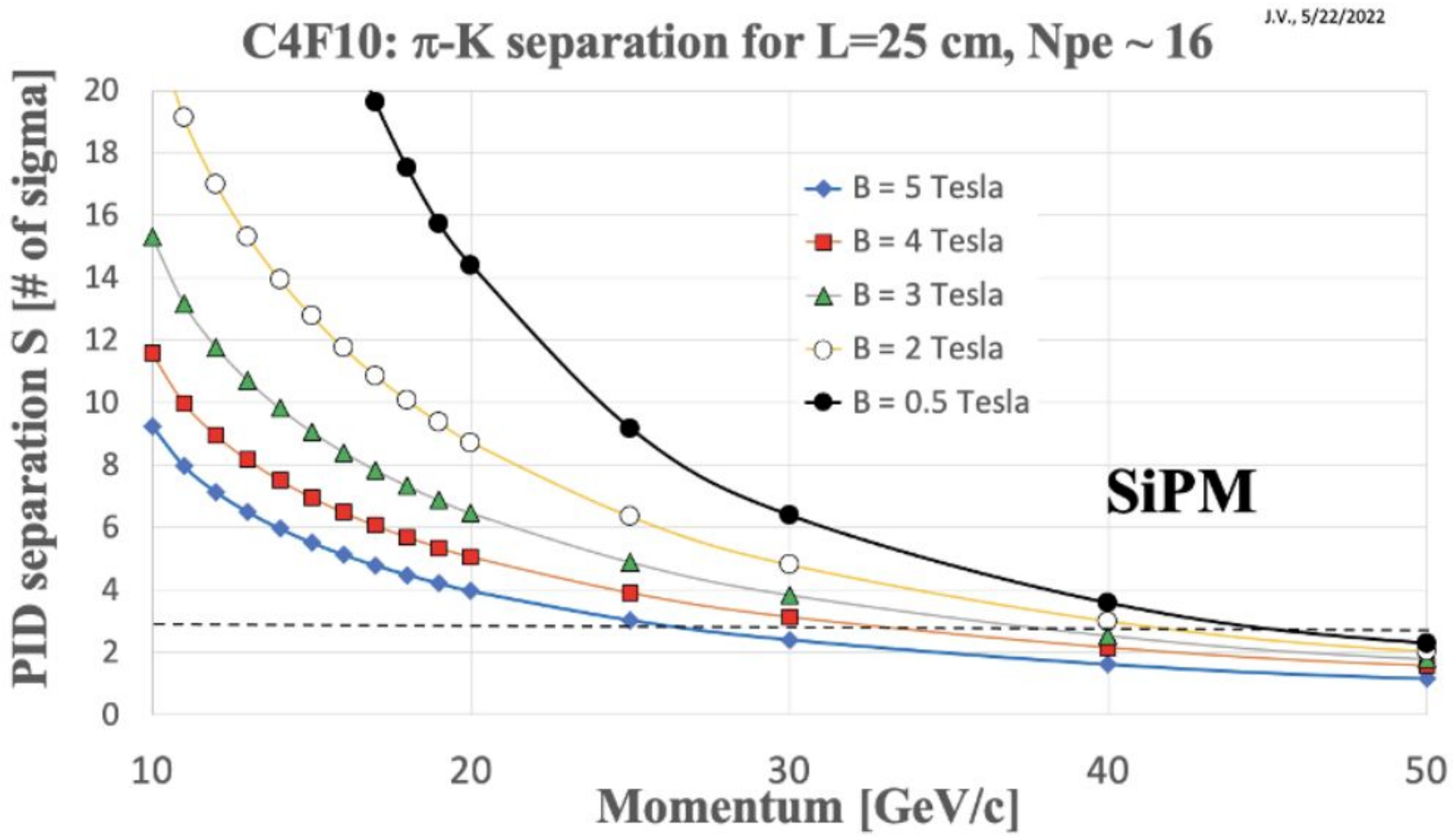
Lesson learned and moving forward

Use H → ss to inform detector design, while monitoring other benchmarks' performance

- Neutral Hadron energy resolution
- dE/dx and dN/dx: powerful PID essential for H-strange coupling
- Timing resolution to be further investigated but less critical for s-tagging
- RICH for improved reconstruction of $K^{+/-}$ at high momentum (< 30 GeV)



Compact RICH



Detector benchmarks at e+e- colliders

The goal of measuring Higgs properties with sub-% precision translates into ambitious detector requirements

Initial state	Physics goal	Detector	Requirement
e^+e^-	hZZ sub-%	Tracker	σ_{p_T}/p_T=0.2% for $p_T < 100$ GeV
			$\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}/$ GeV for $p_T > 100$ GeV
		Calorimeter	4% particle flow jet resolution
			EM cells 0.5×0.5 cm^2, HAD cells 1×1 cm^2
			EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$
			shower timing resolution 10 ps
	$hb\bar{b}/hc\bar{c}$	Tracker	$\sigma_{r\phi} = 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1} \mu m$
			5μm single hit resolution

Arxiv:2209.14111 Arxiv:2211.11084 DOE Basic Research Needs Study on Instrumentation

- Requirements driven by Higgs-specific benchmarks
- Technological advances can open new opportunities and additional physics benchmarks (i.e. H→ss) can add more stringent requirements

Detector parameters

SiD

Barrel	Technology	Inner radius	Outer radius	z extent
Vertex detector	Silicon pixels	1.4	6.0	+/- 6.25
Tracker	Silicon strips	21.7	122.1	+/- 152.2
ECAL	Silicon pixels-W	126.5	140.9	+/- 176.5
HCAL	RPC-steel	141.7	249.3	+/- 301.8
Solenoid	5 Tesla SC	259.1	339.2	+/- 298.3
Flux return	Scintillator-steel	340.2	604.2	+/- 303.3
Endcap	**Technology**	**Inner z**	**Outer z**	**Outer radius**
Vertex detector	Silicon pixels	7.3	83.4	16.6
Tracker	Silicon strips	77.0	164.3	125.5
ECAL	Silicon pixel-W	165.7	180.0	125.0
HCAL	RPC-steel	180.5	302.8	140.2
Flux return	Scintillator/steel	303.3	567.3	604.2
LumiCal	Silicon-W	155.7	170.0	20.0
BeamCal	Semiconductor-W	277.5	300.7	13.5

https://pages.uoregon.edu/silicondetector/sid-dimensions.html

IDEA

TABLE I. – *The main parameters of the IDEA concept detector.*

Parameters	
vertex technology	silicon
vertex inner/outer radius (cm)	1.7/34
tracker technology	drift chamber and silicon wrapper
tracker half length (m)	2.0
tracker outer radius (m)	2.0
solenoid field (T)	2.0
solenoid bore radius/half length (m)	2.1/3.0
preshower absorber	lead
preshower R_{min}/R_{max} (m)	2.4/2.5
DR calorimeter absorber	copper
DR calorimeter R_{min}/R_{max} (m)	2.5/4.5
overall height/length (m)	11/13

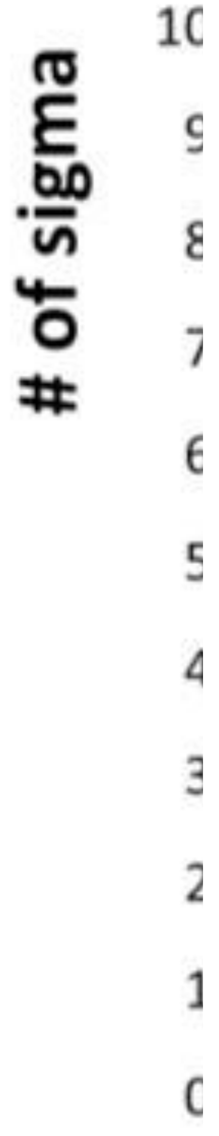
https://inspirehep.net/literature/1829133

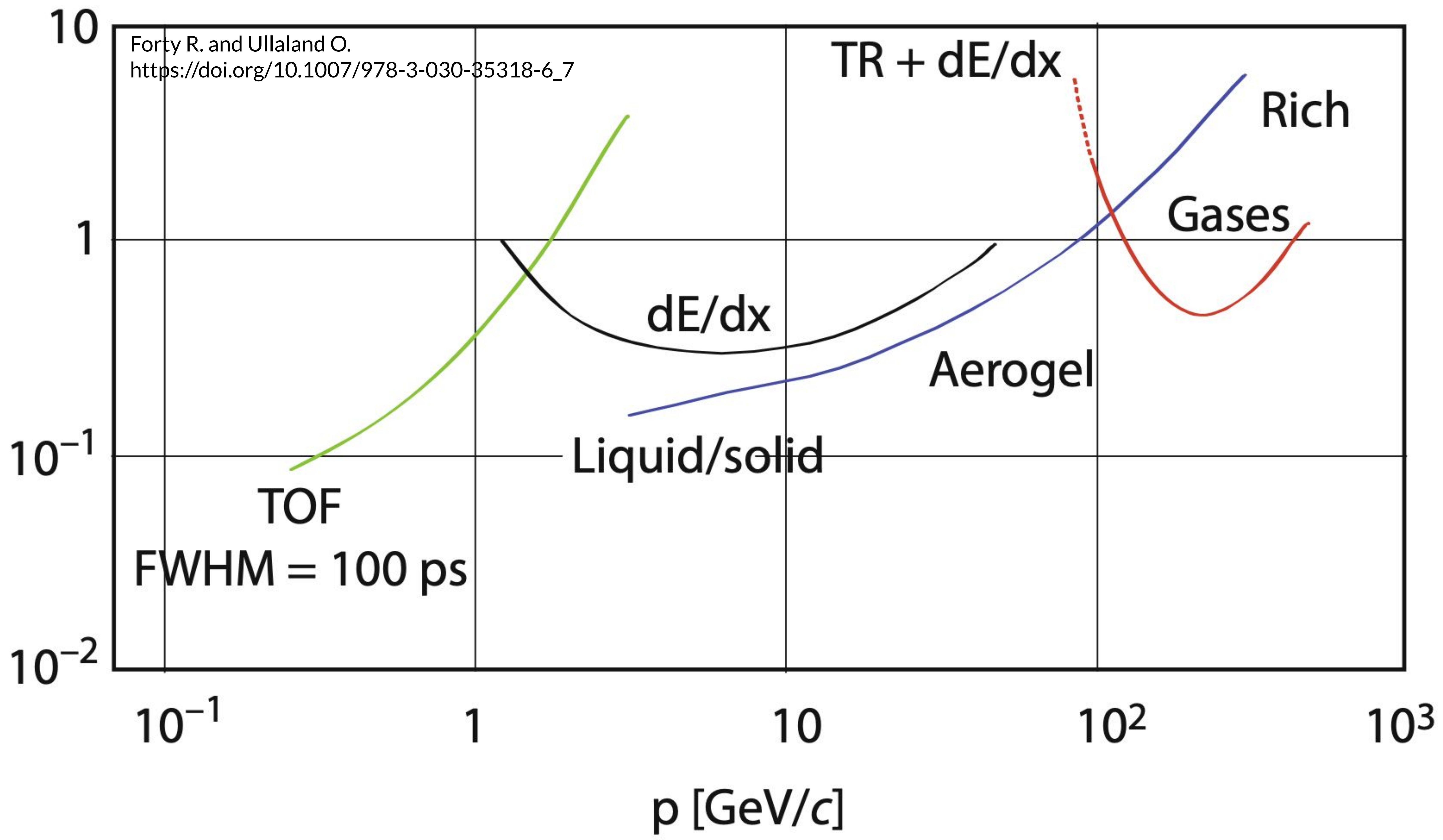
1912.04601
e2019-900045-4

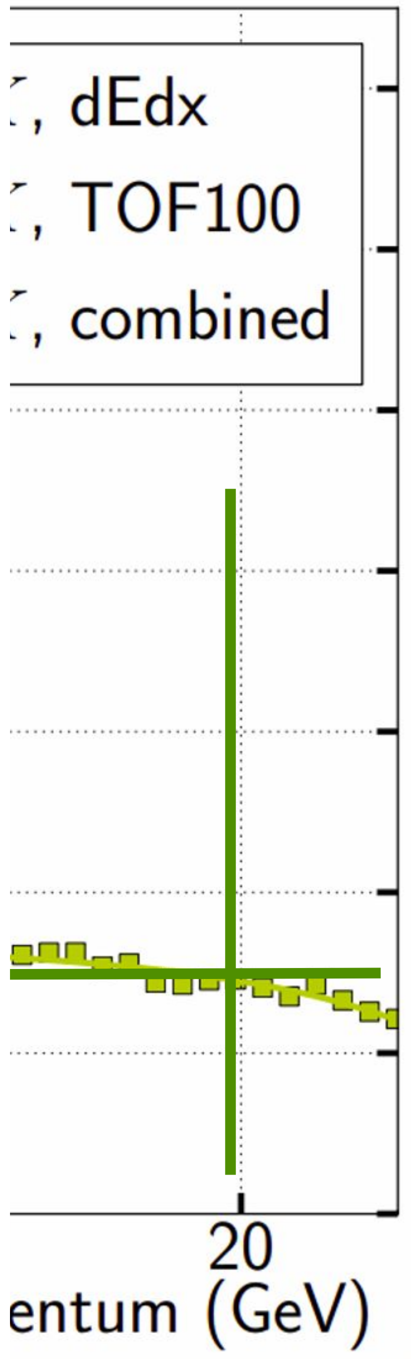
Particle ID for s-tagging

Combining different strategies for optimal PID performance across a wide p_T range

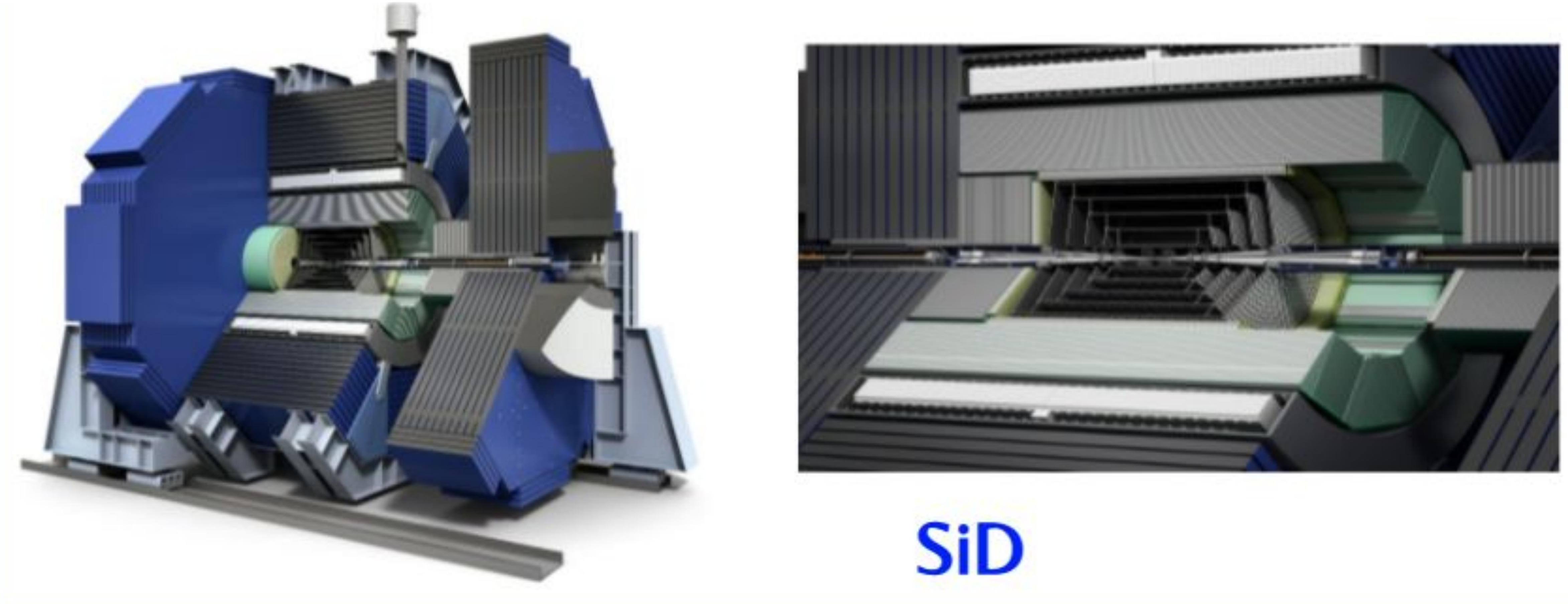
- dE
- <

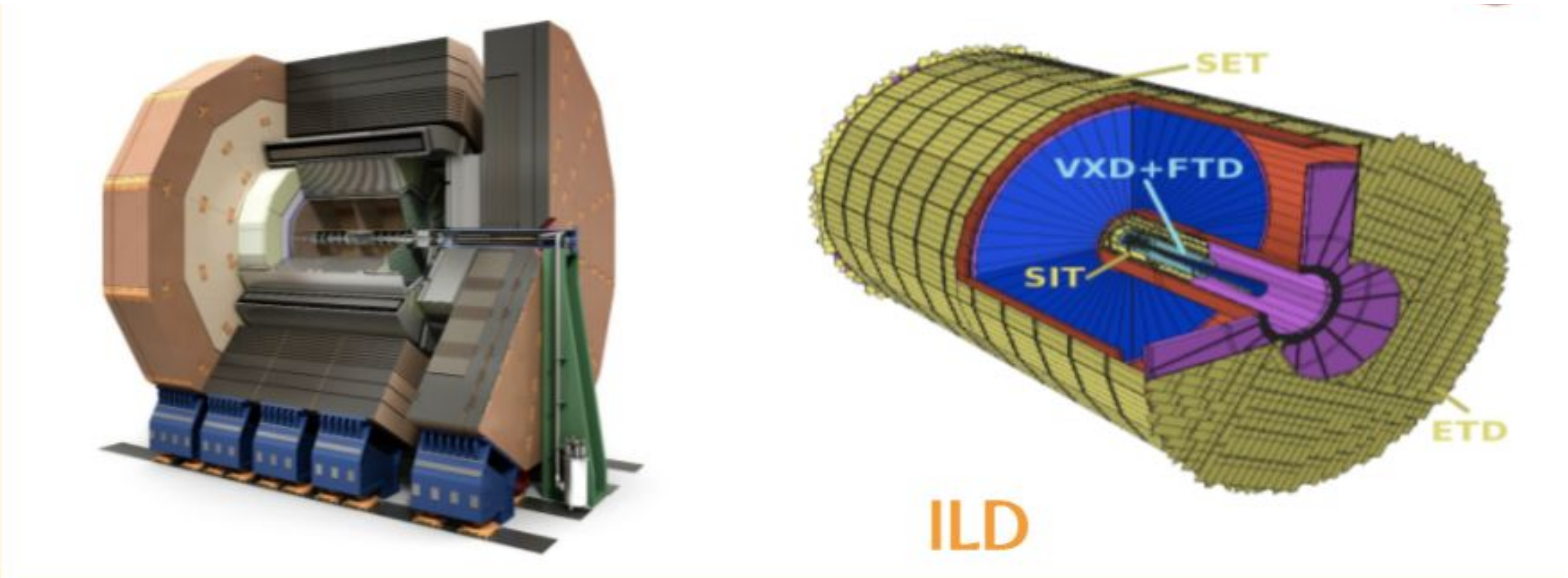






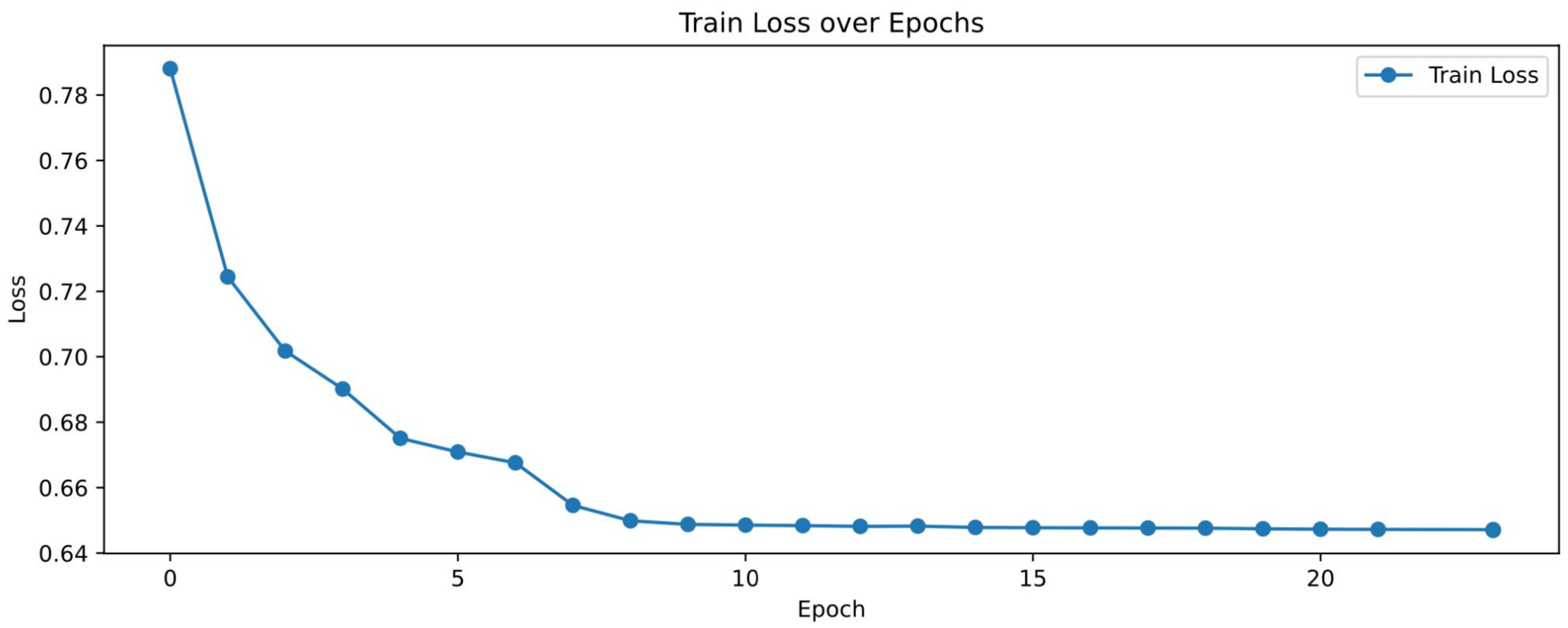
Detectors design at lepton colliders

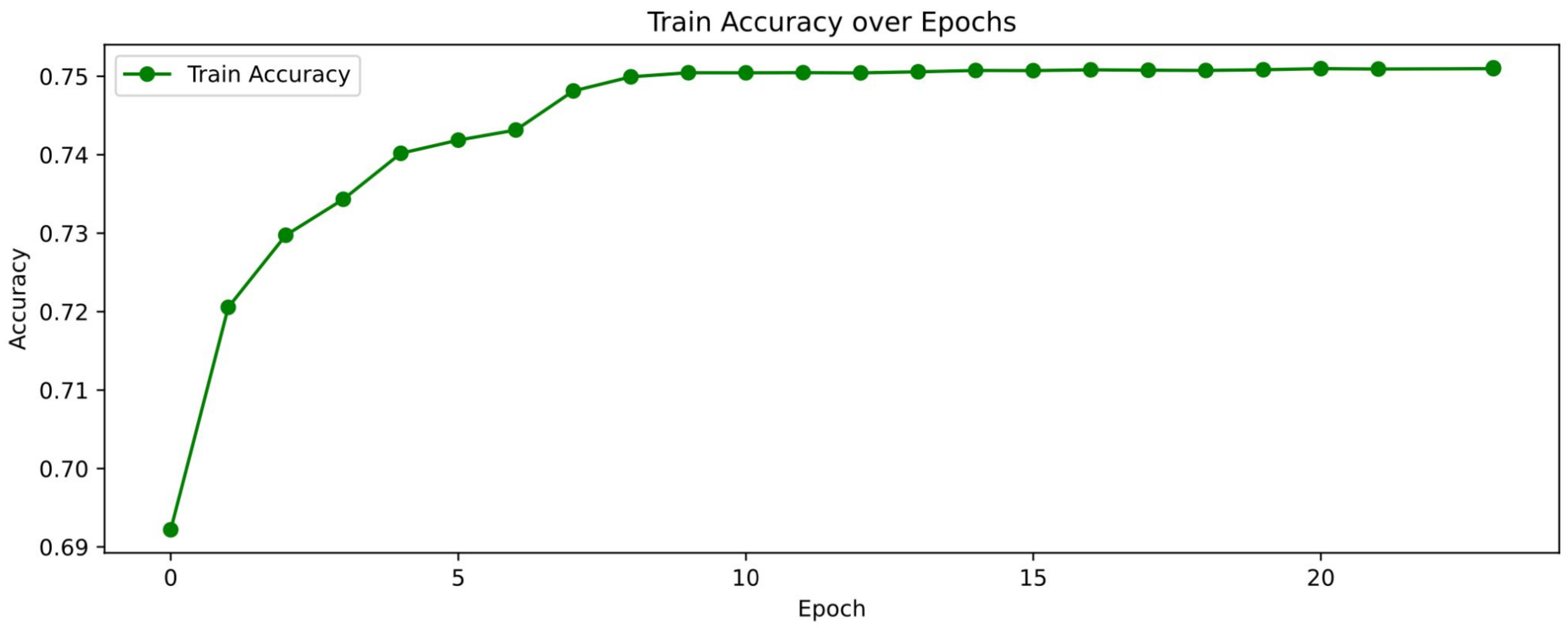


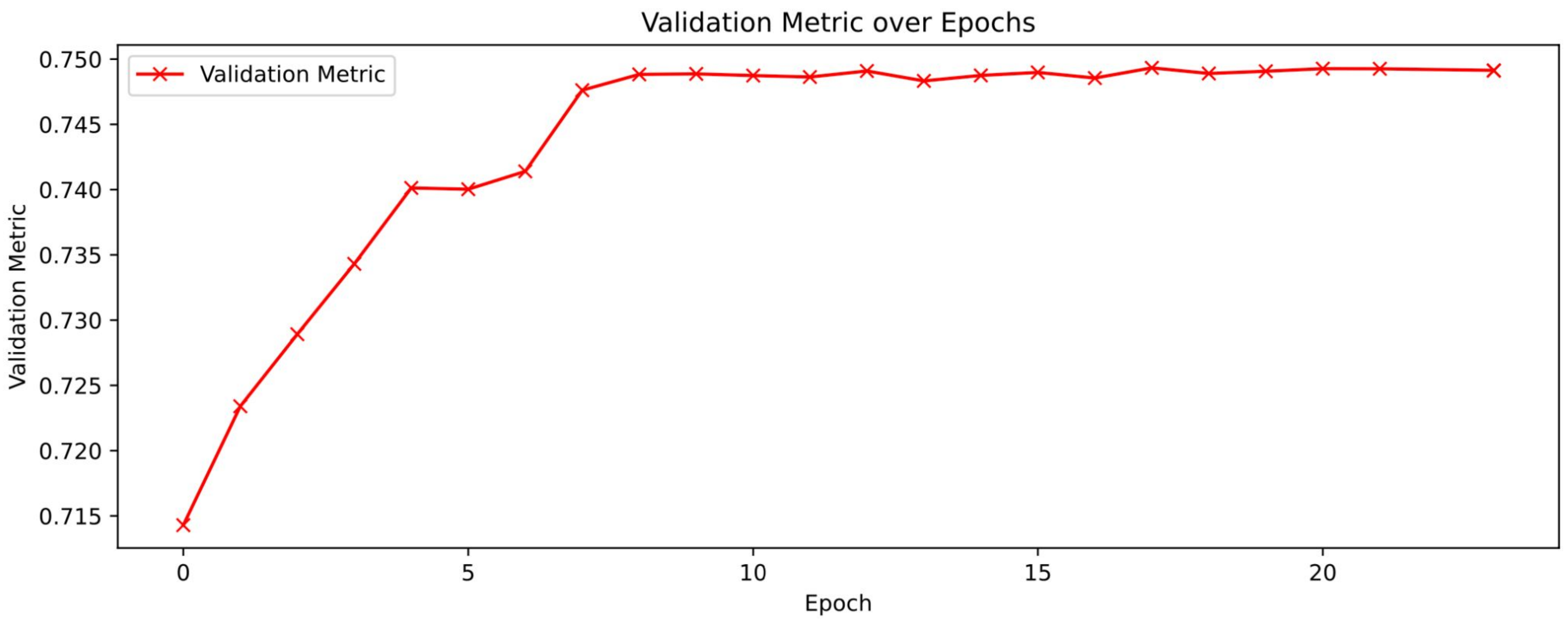


- Detector designs at e+e- colliders are converging to very similar strategies
  - Particle Flow reconstruction → plays a big part in many designs
- SiD like detector - Compact all silicon detector
- ILD like detector - Larger detector with Silicon+TPC tracker
  - Larger detector. Simulation and design work active in Europe / Japan
- IDEA detector - Using dual readout calorimeter, under study at CEPC/FCC-ee

Training


Train Loss over Epochs
Train Loss
Loss
0.78
0.76
0.74
0.72
0.70
0.68
0.66
0.64
0
5
10
15
20
Epoch

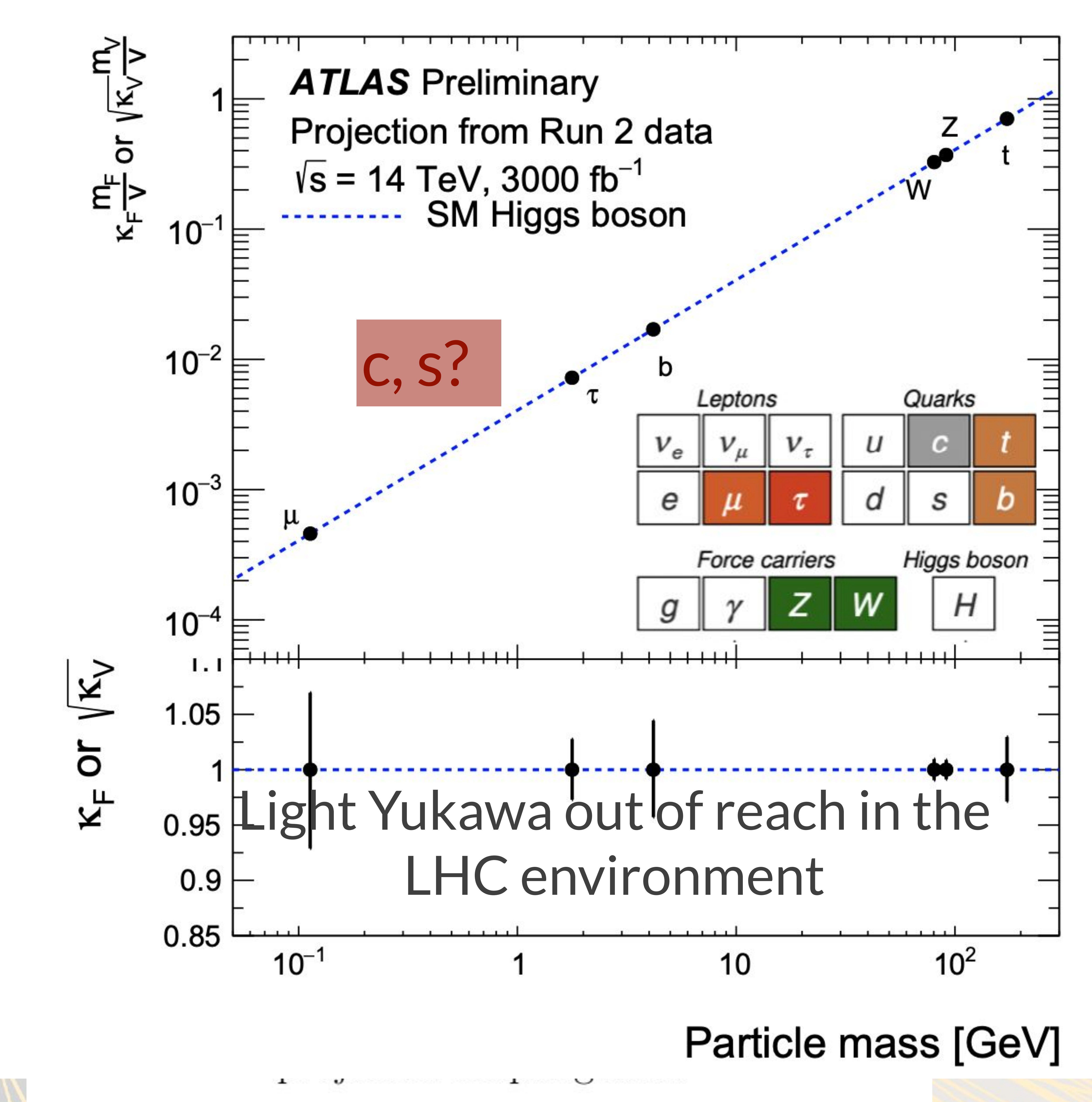

Train Accuracy over Epochs
Train Accuracy
Accuracy
0.75
0.74
0.73
0.72
0.71
0.70
0.69
0
5
10
15
20
Epoch


Validation Metric over Epochs
Validation Metric
Validation Metric
0.750
0.745
0.740
0.735
0.730
0.725
0.720
0.715
0
5
10
15
20
Epoch

Higgs at HL-LHC

The High Luminosity era of LHC will dramati

- **2-5% precision for many of the Higgs co**
- **BUT much larger uncertainties on Zγ a**

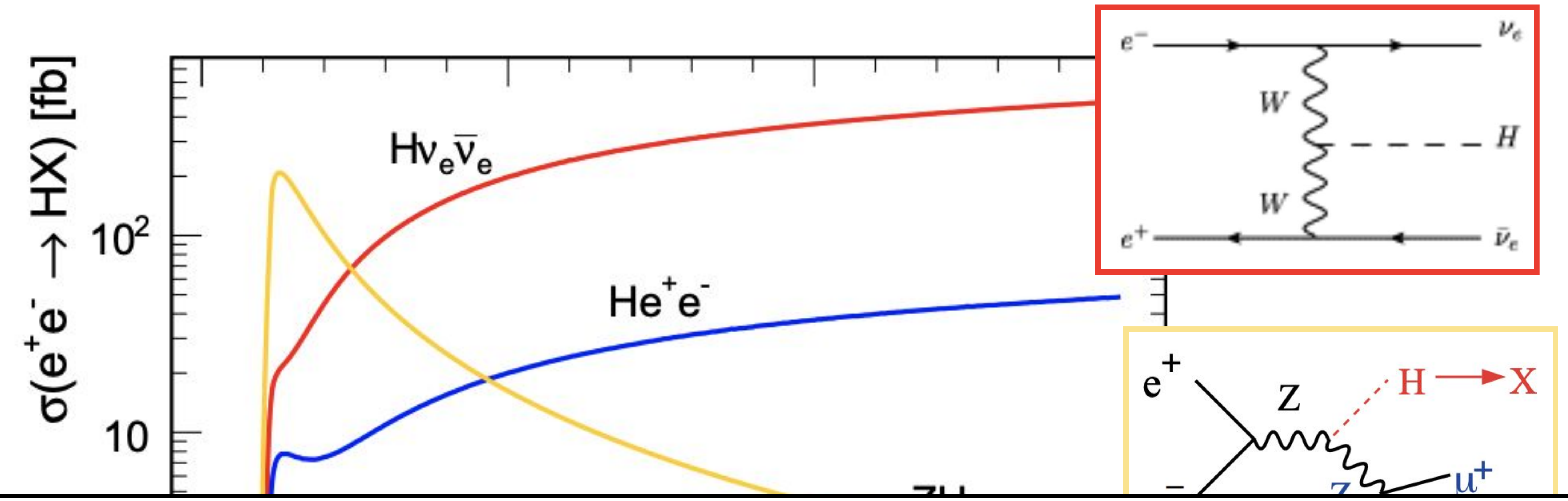


b/c/strange tagging

- The use of **precise timing information** would become very relevant for flavor tagging and providing an additional handle for separation between light quarks.
  - intermediate momentum $K^{\pm}$ ID from fast timing can become a significant contributor for b and c decays (s tag $K^{\pm}$ could be too high momentum for timing)
  - Detector design have a role too in capturing the high momenta V0 s that can decay deep into the tracker
    - Investigate optimal configurations for 4D tracking at future e+e- machines

Higgs at e^+e^-

The Energy Frontier 2021 Snowmass Report



- ZH is dominant at 250 GeV
- Above 500 GeV
  - Hvv dominates
  - ttH opens up
  - **HH accessible with ZHH**