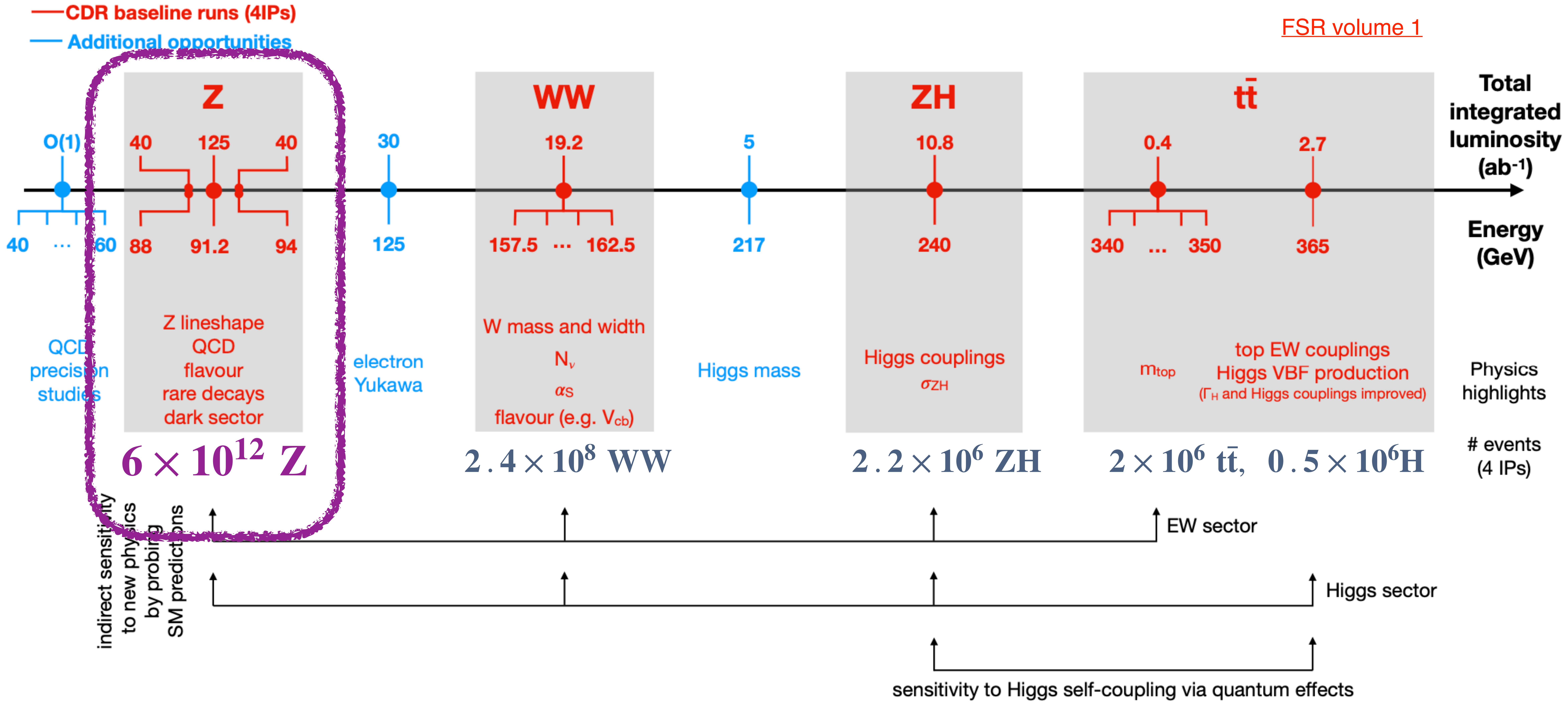
FCC-ee flavor physics perspective

CEPC workshop, Guangzhou
07.11.2025

Xunwu Zuo
on behalf of FCC flavor study group

FCC-ee physics runs

FSR volume 1



FCC-ee as flavor factory

Best option for next-generation flavor machine

Advantage over Belle II

- About 14x more B^0/B^+ than Belle II (50 ab^{-1})
- All species of b-hadrons are produced

Advantage over LHCb

- Clean collision environment, much better photon, electron reconstruction
- Precisely known initial energy —> missing energy information

particle count $(\times 10^9)$	B^0 $(\bar{B}^0)$	$B^\pm$	B_s $(\bar{B}_s)$	$B_c^\pm$	Λ_b $(\bar{\Lambda}_b)$	c $(\bar{c})$	$\tau^\pm$
Belle II	55	55	0.6	N.A.	N.A.	130	90
FCC-ee	770	770	170	7	150	1400	400

Outline

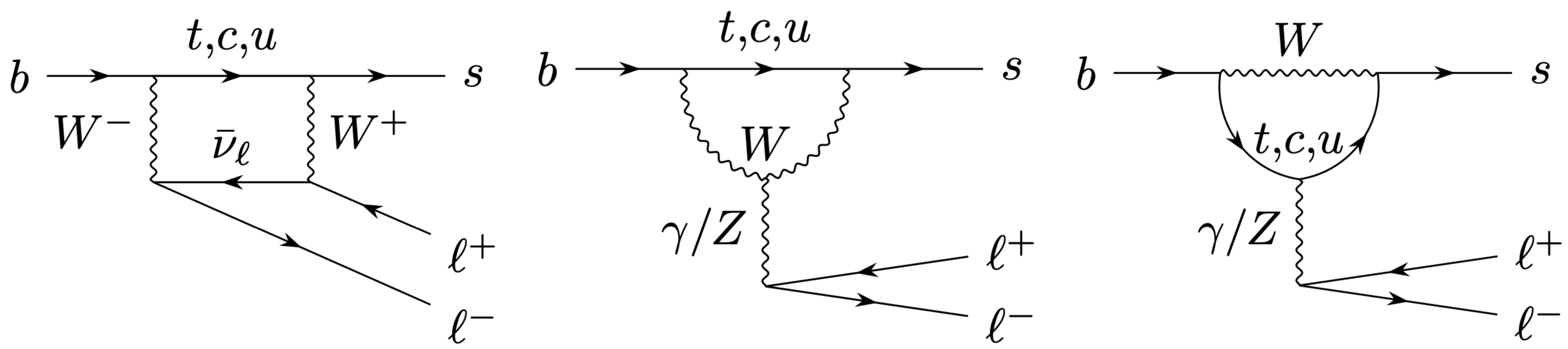
Selected flavor studies

- Unique probes for rare decays
- Novel CKM measurements
- Opportunities tau, charm, and more

Complete coverage of a vast flavor landscape. See more by Lorenzo Calibbi

Probes for rare decays

$b \to s\ell\ell$

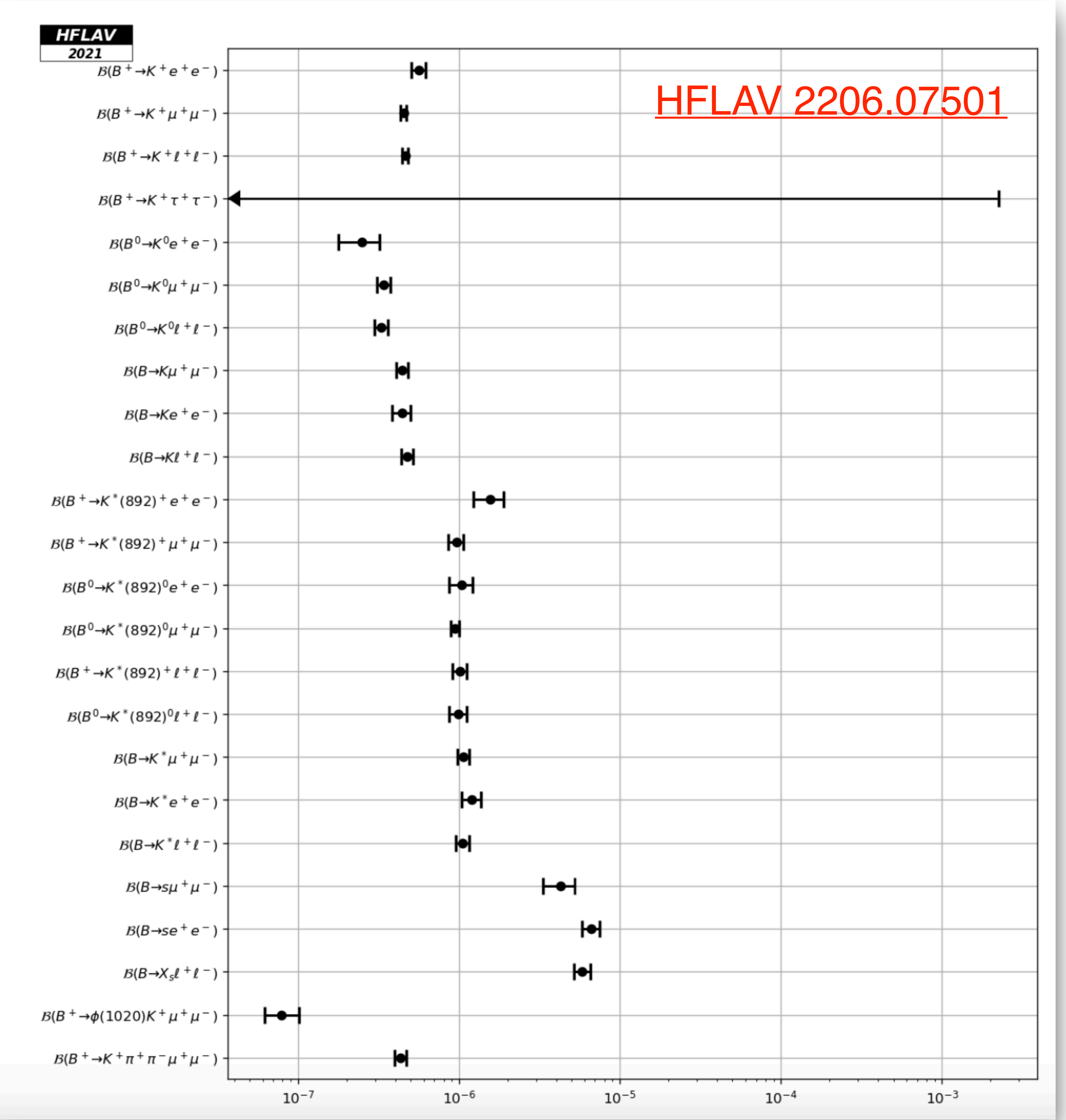


Case study - $B^0 \to K^{*0}\tau^+\tau^-$

- Expected $BR_{\text{SM}}(B \to K\tau\tau) \sim O(10^{-7})$
- Belle II (365 fb^{-1}): $< 1.8 \times 10^{-3}$ 2504.10042
- Belle II (50 ab^{-1}): $< 5.3 \times 10^{-4}$ 2207.06307

requires an excellent detector

- PID efficiency
- Energy resolution
- Vertex resolution
- Missing energy info

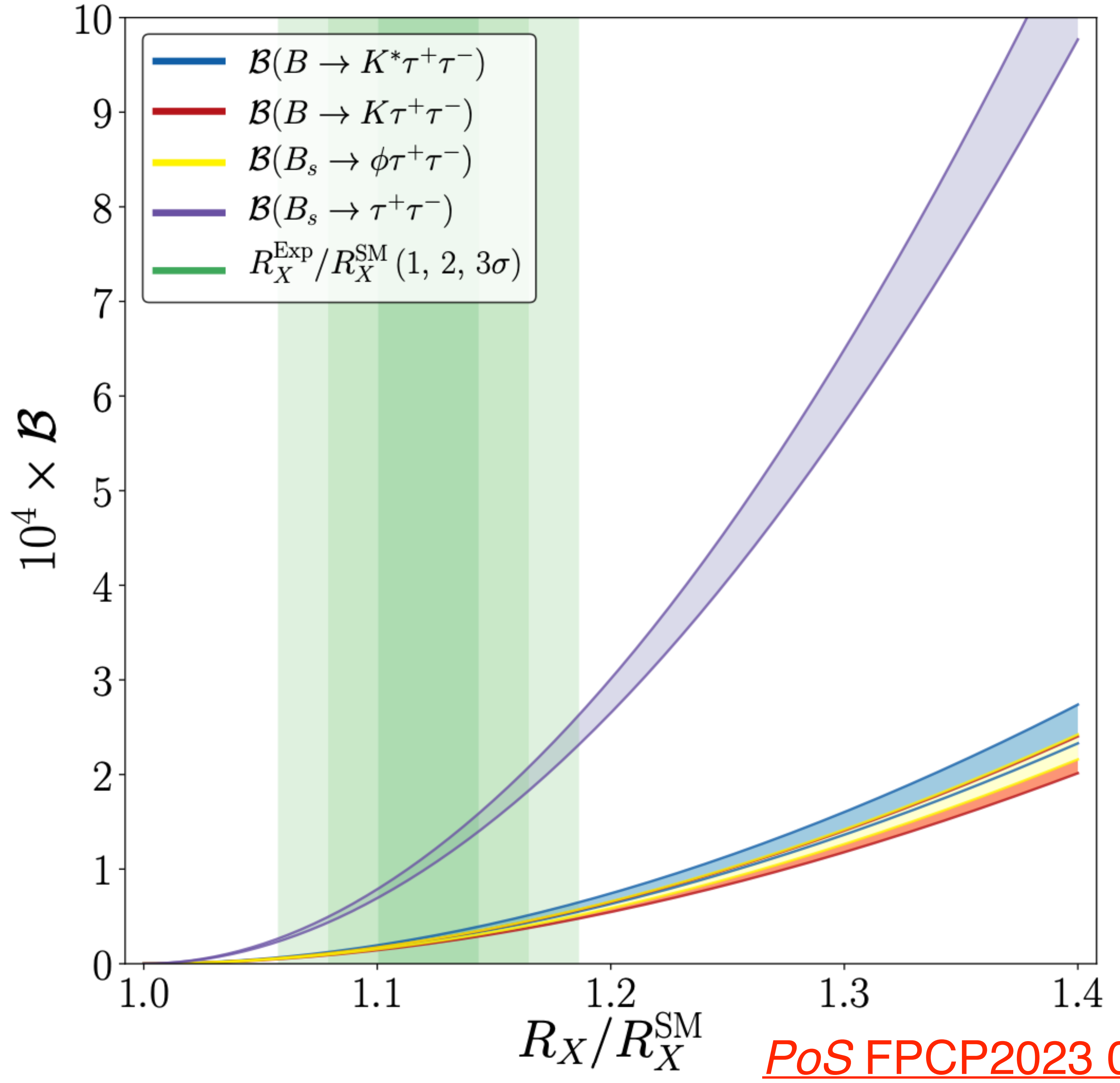


HFLAV 2206.07501

Case study - $B_s \to \tau^+\tau^-$

- Theory motivation: O(10^4) enhancement allowed for $B_s \to \tau^+\tau^-$
- Challenge at Belle II: limited amount of B_s
- Challenge at LHCb: difficult to reduce backgrounds
- Expect strong constraint at Tera-Z

$\delta \approx 5 \times 10^{-6}$, ~10X SM



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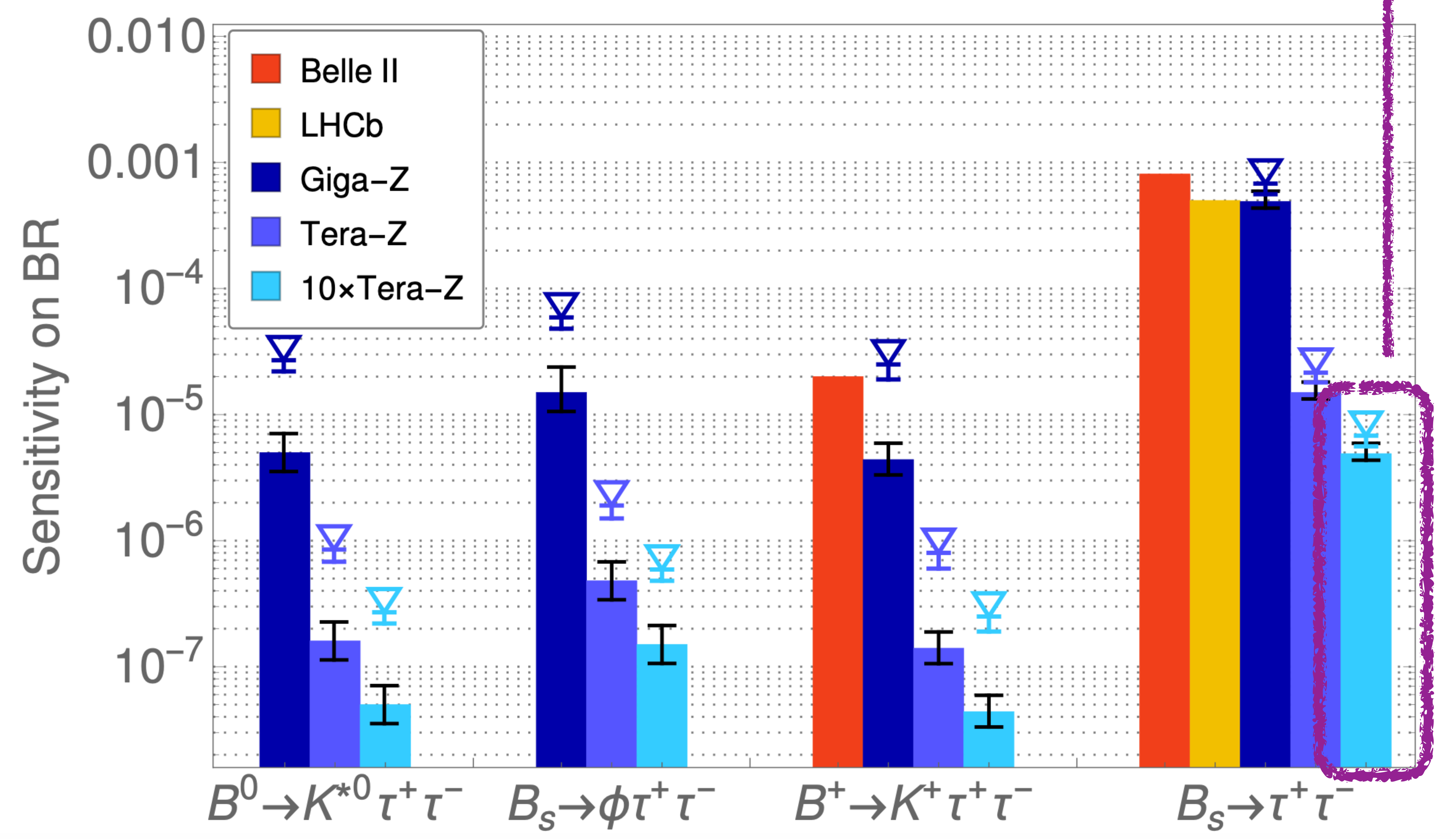

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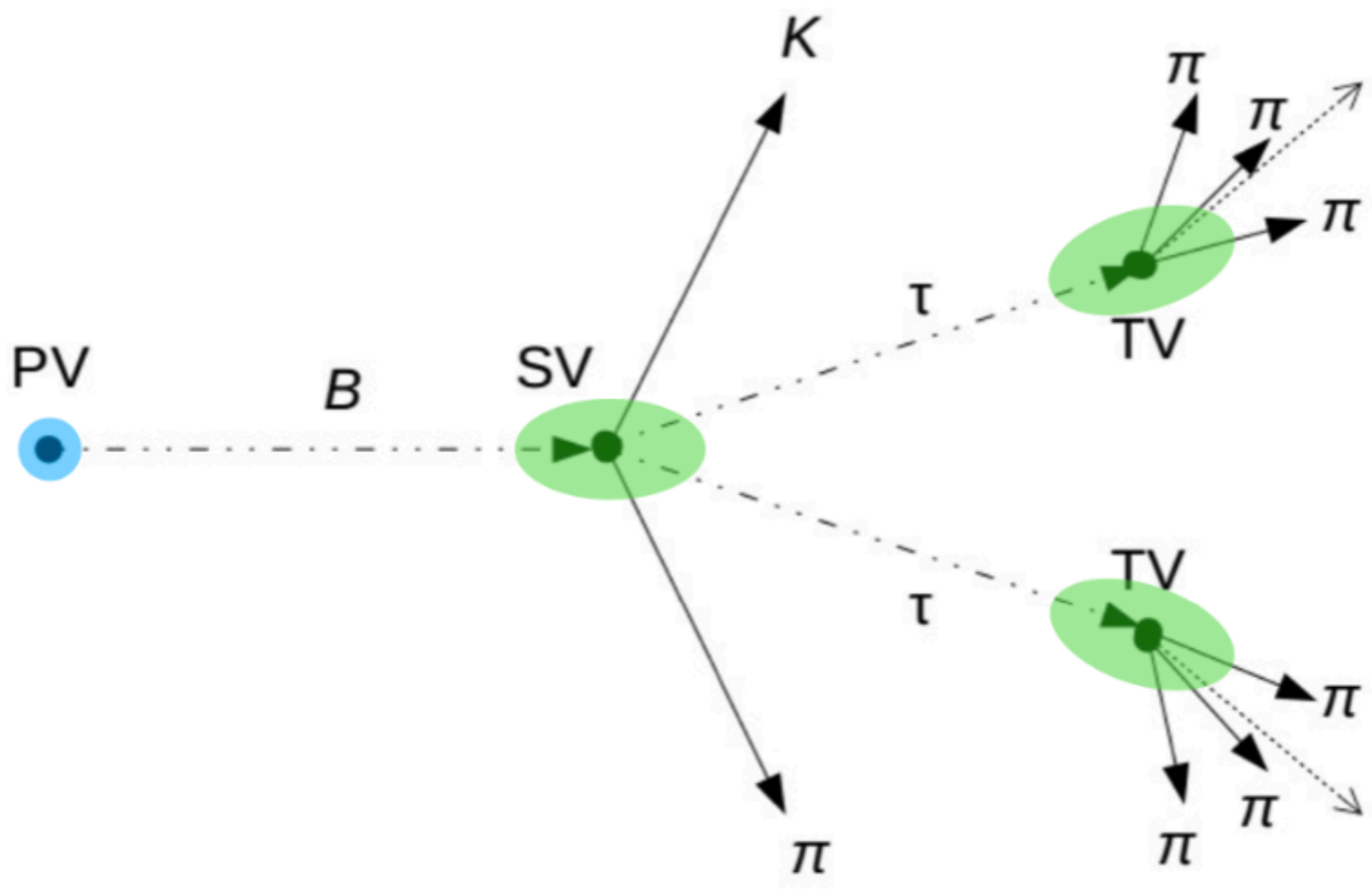
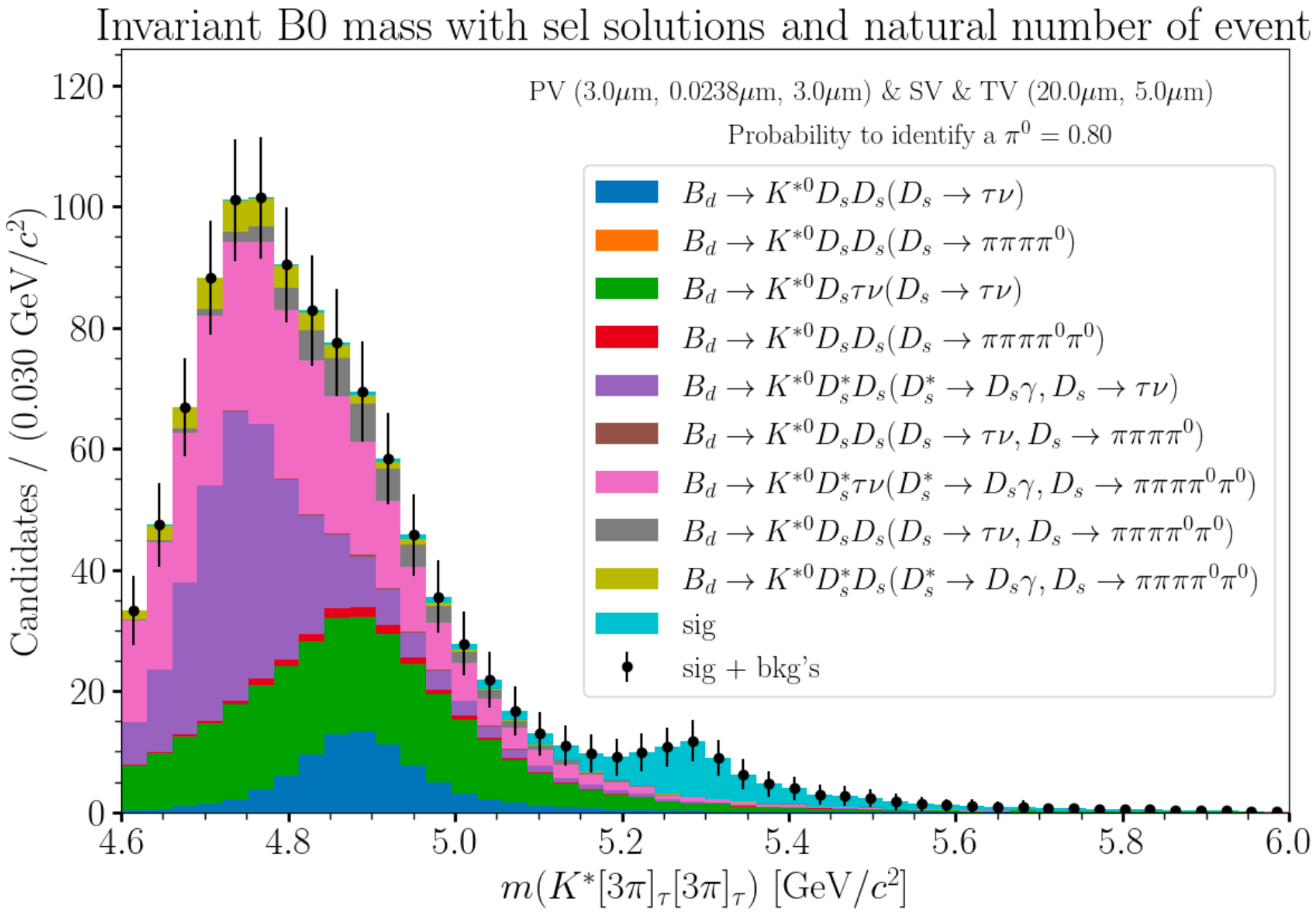
Case study - $B^0 \to K^{*0}\tau^+\tau^-$

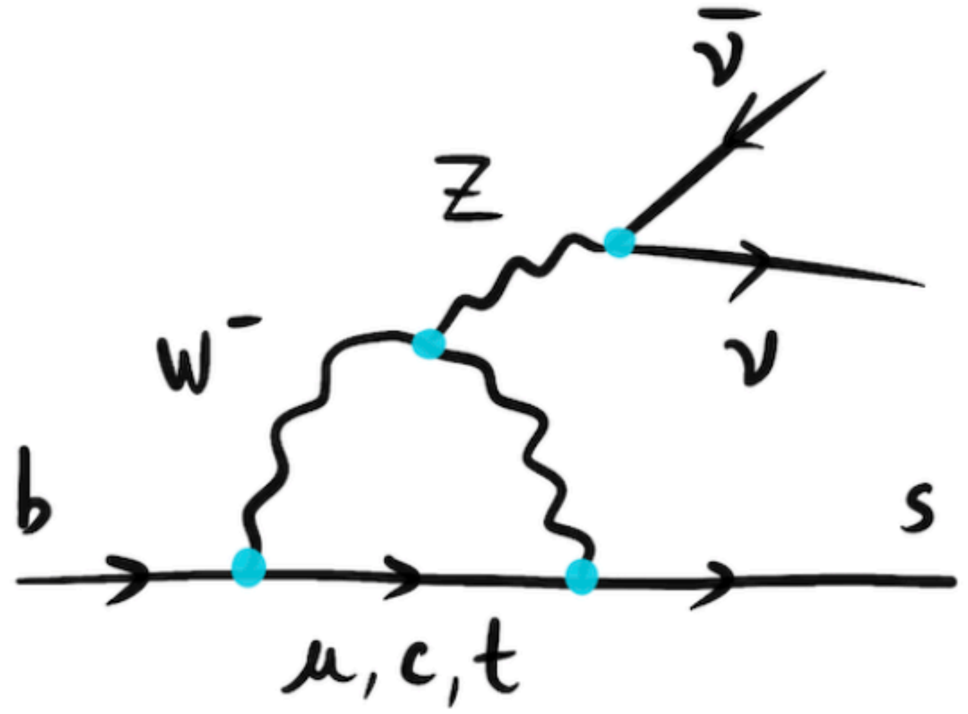


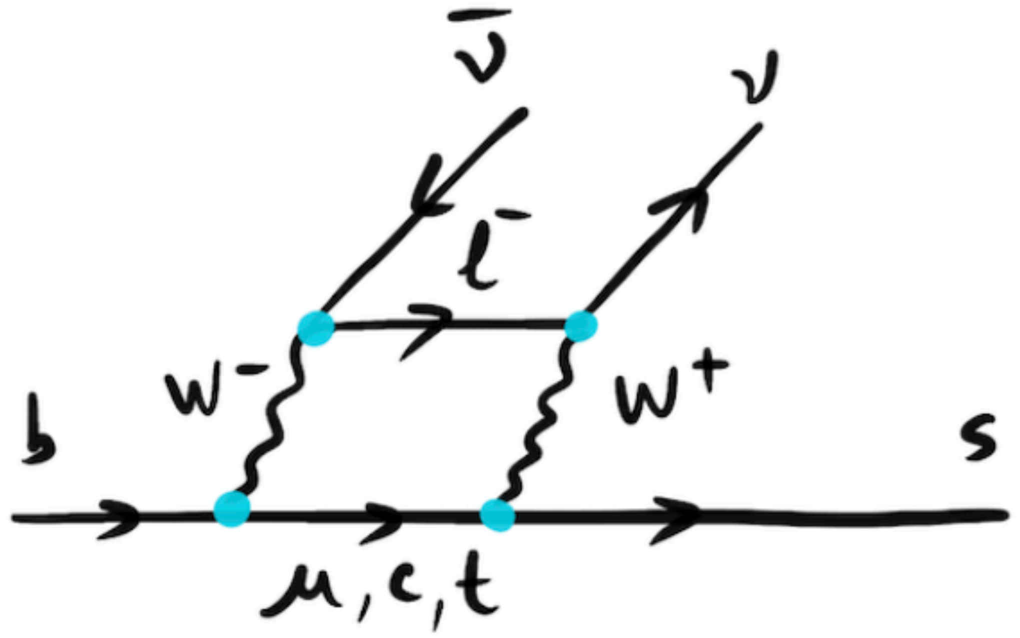
- Event kinematics fully reconstructable (with 4-fold ambiguity)
- Expect 3σ significance with nominal IDEA detector
  - Extensive detector study: strong dependence on vertex resolution and material budget

Tristan Miralles et al.



$b \to s\nu\nu$ transition





Decay mode	SM prediction $\times 10^6$	Experimental value $\times 10^6$	Source
$B^+ \to K^+\nu\bar{\nu}$	5.22 ± 0.32	13 ± 4	arXiv:2311.14647
$B^0 \to K^0_S\nu\bar{\nu}$	2.12 ± 0.15	< 13 (90% C.L.)	arXiv:1702.03224
$B^+ \to K^{*+}\nu\bar{\nu}$	11.27 ± 1.51	< 40 (90% C.L.)	arXiv:1303.3719
$B^0 \to K^{*0}\nu\bar{\nu}$	9.47 ± 0.32	< 18 (90% C.L.)	arXiv:1702.03224

talk by C. Santos

- **Belle II**: $B^+ \to K^+\nu\nu$ established
  - Expect 10% precision with 50 ab^{-1}
- **LHCb**: measurement not possible

- **Tera-Z**: high precision expected
  - Unique probes of $B_s \to \phi\nu\nu$, $\Lambda_b \to \Lambda\nu\nu$

Modes	$\mathscr{B}_{SM}$ $(\times 10^{-6})$	Signature
$B^0 \to K^{*0}\nu\bar{\nu}$	7.9	$K^{*0} \to K^\pm\pi^\mp$
$B^0_s \to \phi\nu\bar{\nu}$	9.7	$\phi \to K^+K^-$
$B^0 \to K^0_S\nu\bar{\nu}$	2.0	$K^0_S \to \pi^+\pi^-$
$\Lambda^0_b \to \Lambda\nu\bar{\nu}$	8.6	$\Lambda \to p\pi^-$

Prompt decays
- Requirements on Kaon/pion ID

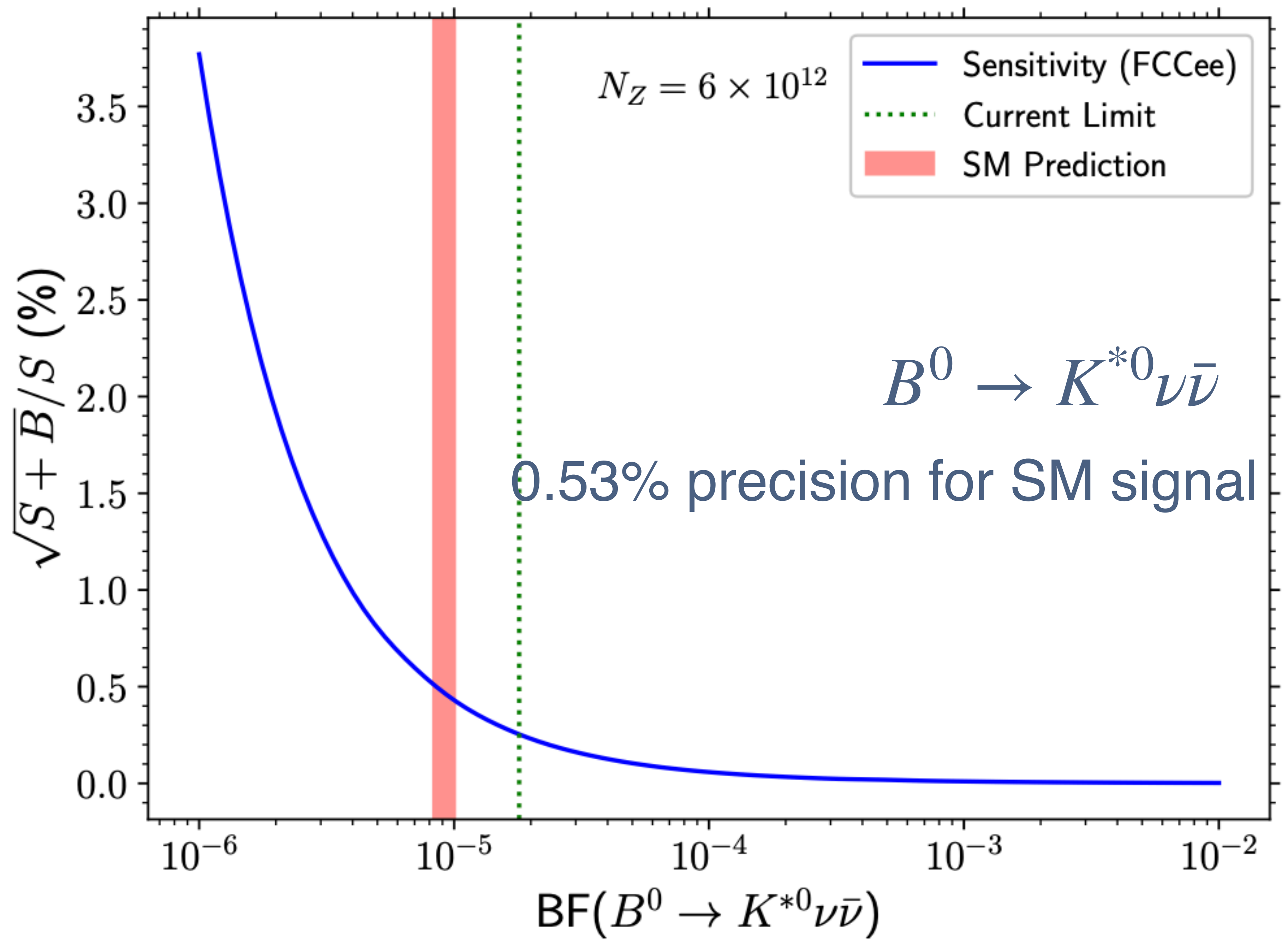
Long-lived
- Requirements on displaced vertexing and proton ID

arxiv:2309.11353

Case study - $b \to s\nu\nu$

Precision most dependent on PID, vertexing, and total stats

- With perfect PID, **O(1%) precision** for $B^0 \to K^{*0}\nu\bar{\nu}$ and $B_s^0 \to \phi\nu\bar{\nu}$
- With 80% K_S^0, Λ reco eff, expect better than **10% precision** for $B^0 \to K_S^0\nu\bar{\nu}, \Lambda_b^0 \to \Lambda\nu\bar{\nu}$



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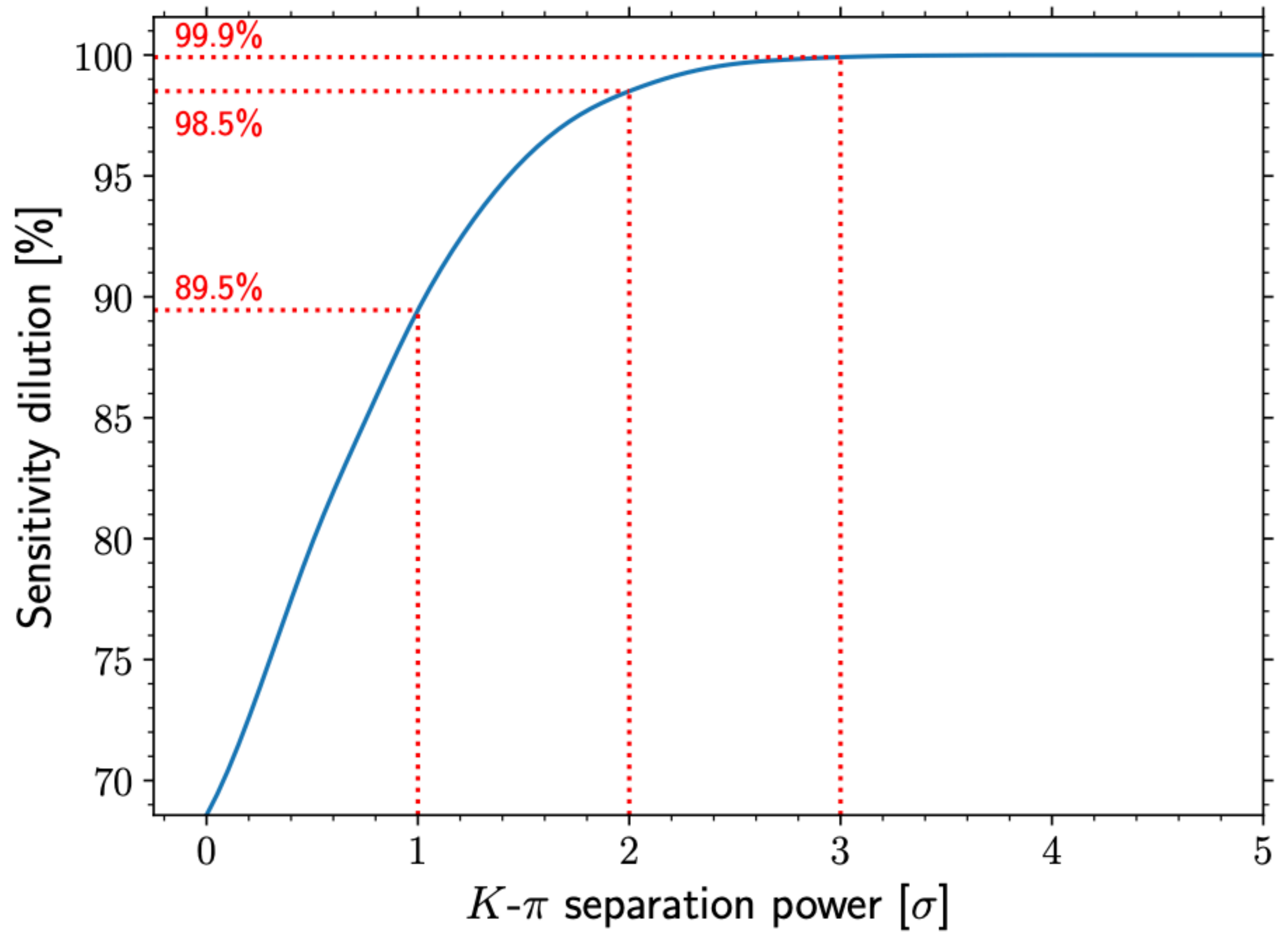
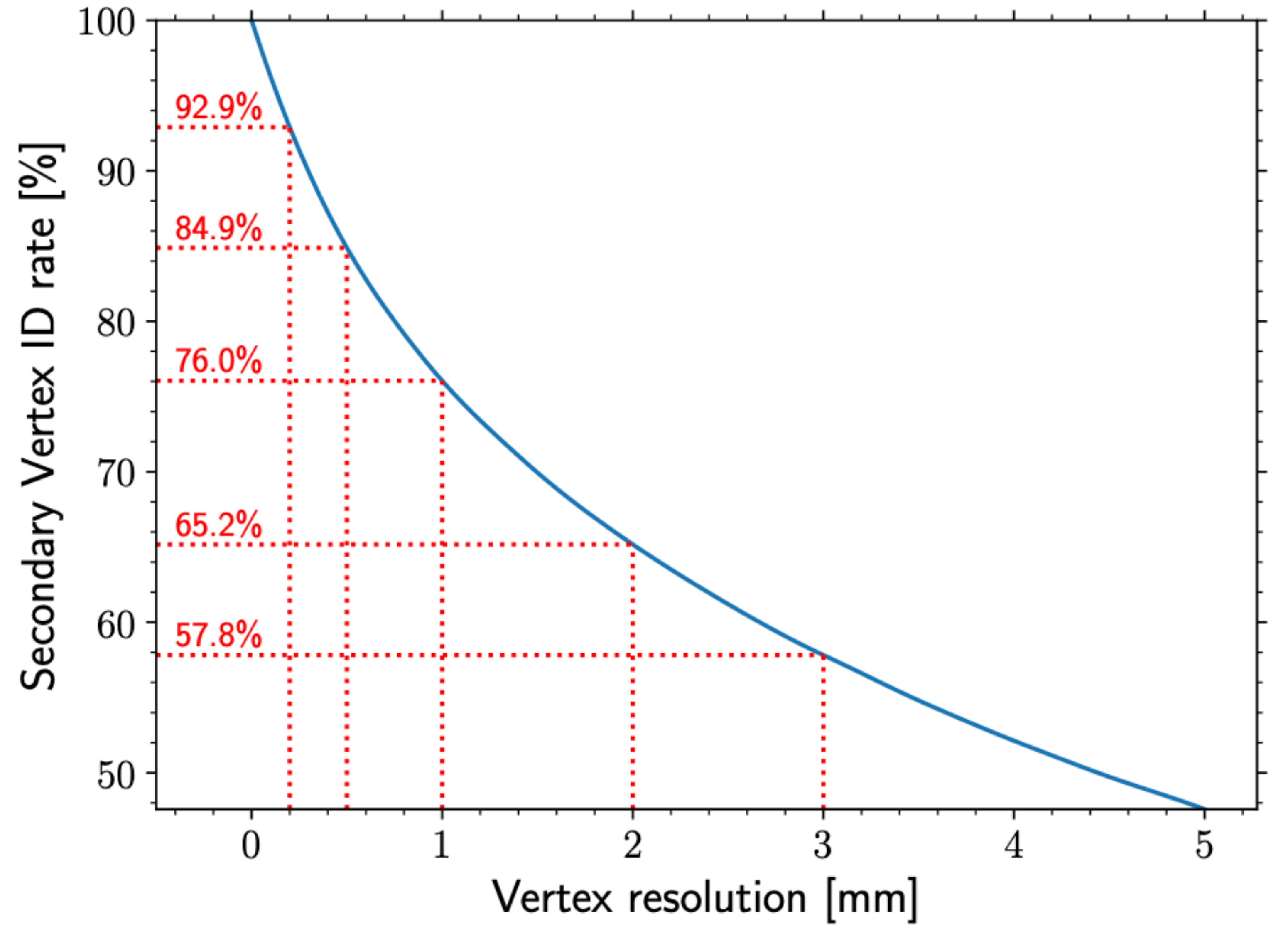
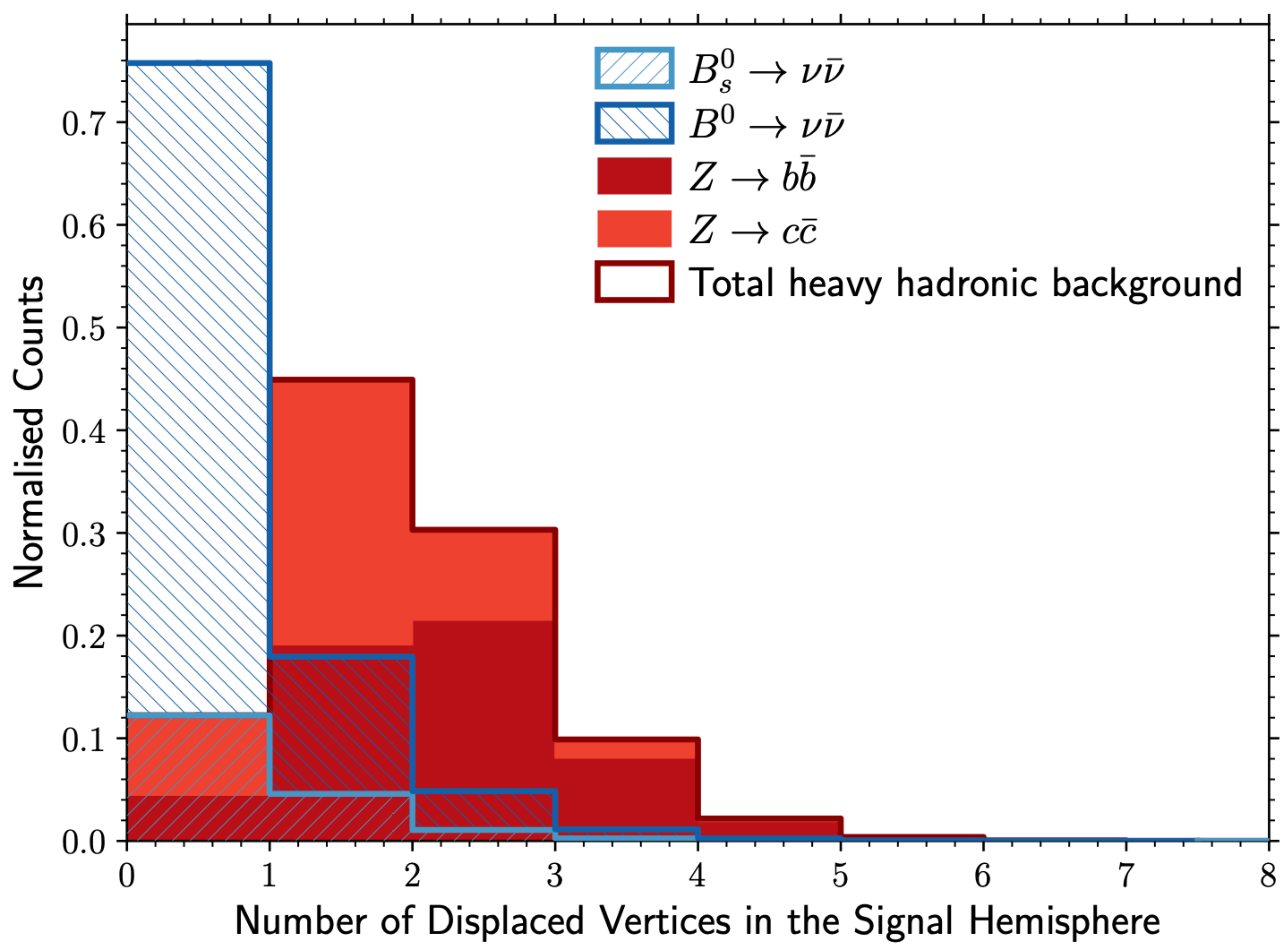
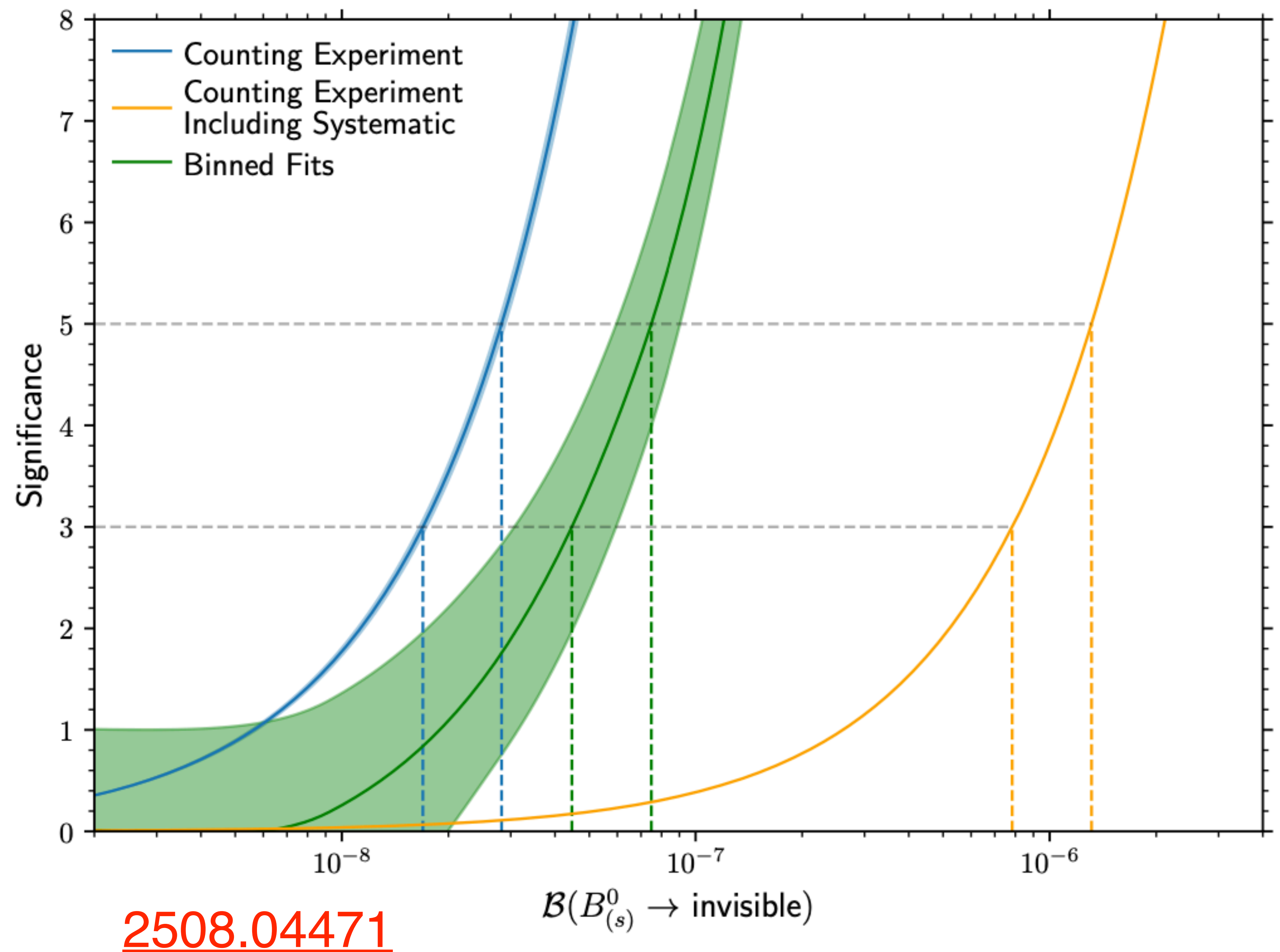




Case study - $B_{(s)} \to \nu\nu$

- Heavily suppressed in SM, null test
- $\mathscr{B}(B_{(s)} \to \nu\nu) \approx 10^{-25}$, $\mathscr{B}(B_{(s)} \to 4\nu) \approx 10^{-15}$, can be enhanced by $\mathscr{B}(B_{(s)} \to \gamma\nu\nu)$
- No visible decay product, rely on missing energy and absence of objects





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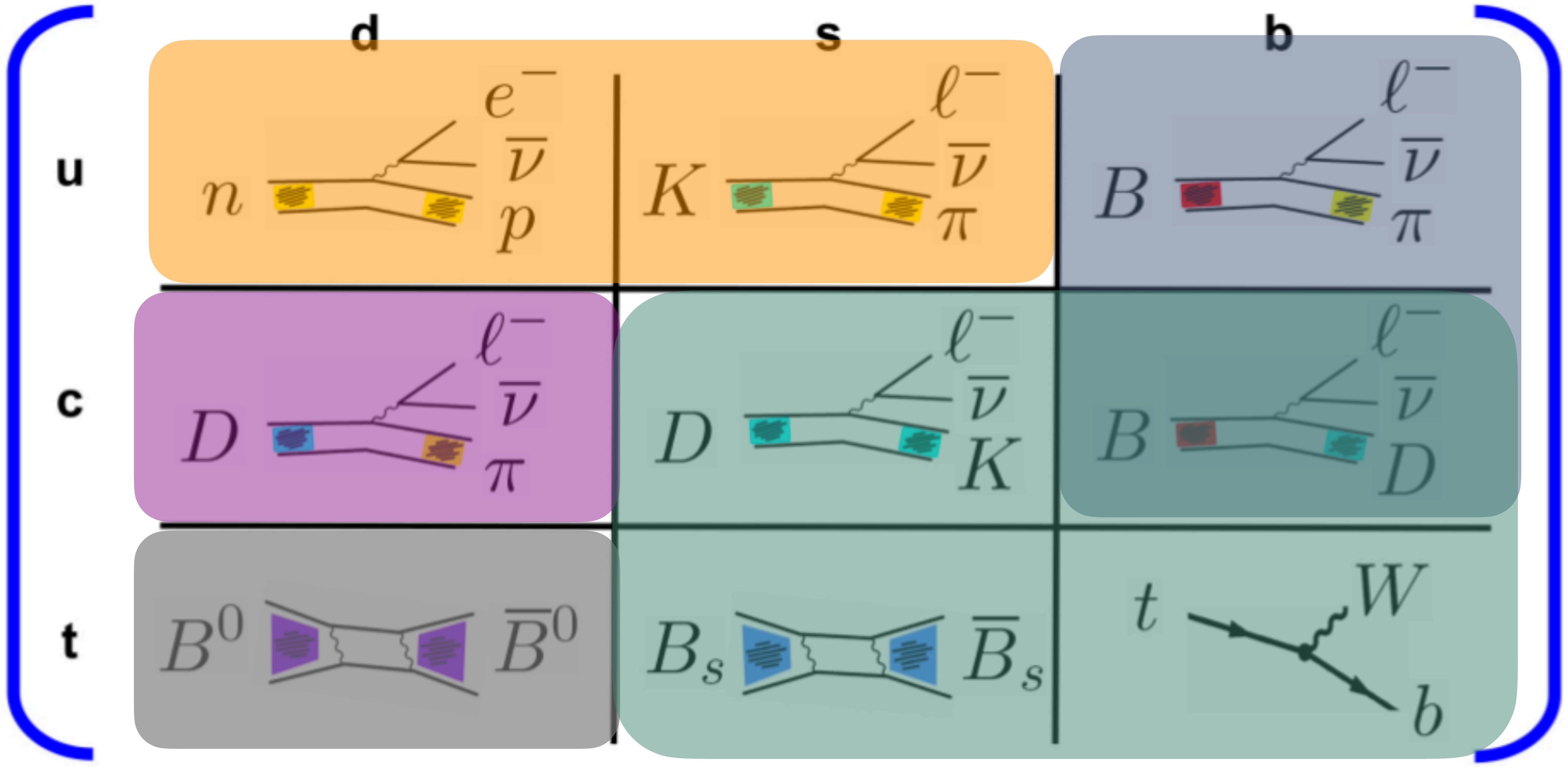
CKM measurements

CKM at FCC-ee

New methodology to explore at FCC-ee

Likely no advantage at FCC-ee

V =



From $B^+(B_c^+)$ leptonic decay

Possibility with W decay, precision to be studied

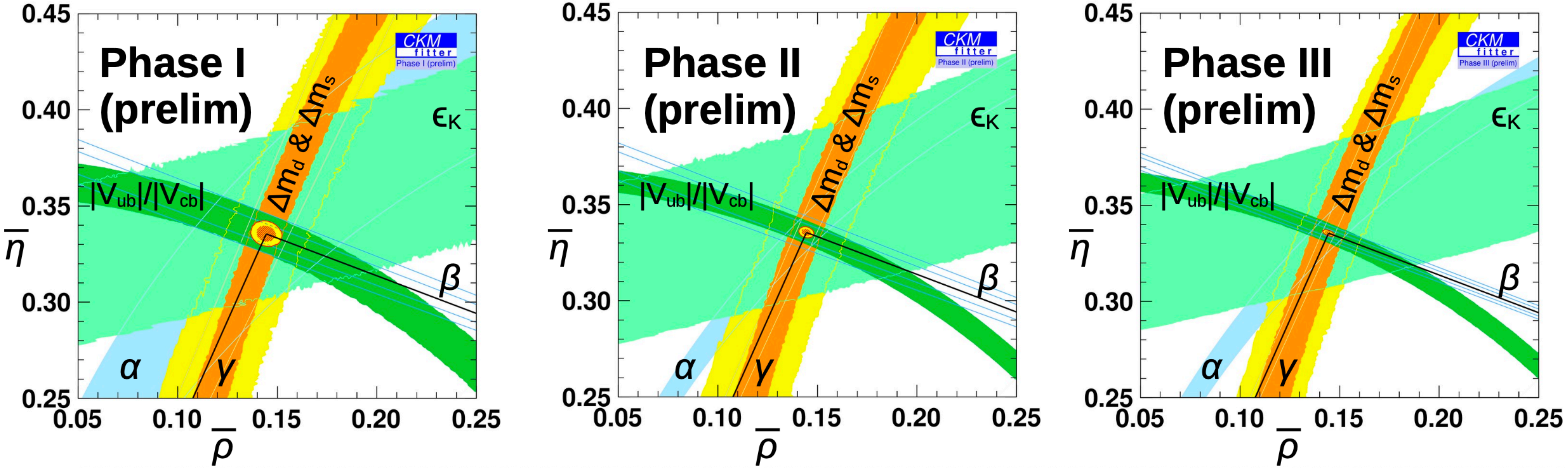
Direct W or top decay

Can FCC-ee do something?

UT: projections

Courtesy of Luiz Vale Silva

- **Phase I**, 2030's: Belle II @ 10 ab^{-1} & LHCb @ 50 fb^{-1}
- **Phase II**, 2040's: Belle II @ 50 ab^{-1} & LHCb @ 300 fb^{-1}
- **Phase III**, 2050's: Phase II & FCC-ee (6×10^{12} Z + 3×10^{8} WW)
- Central values adjusted to avoid tension among observables



$b \to q\ell\nu$

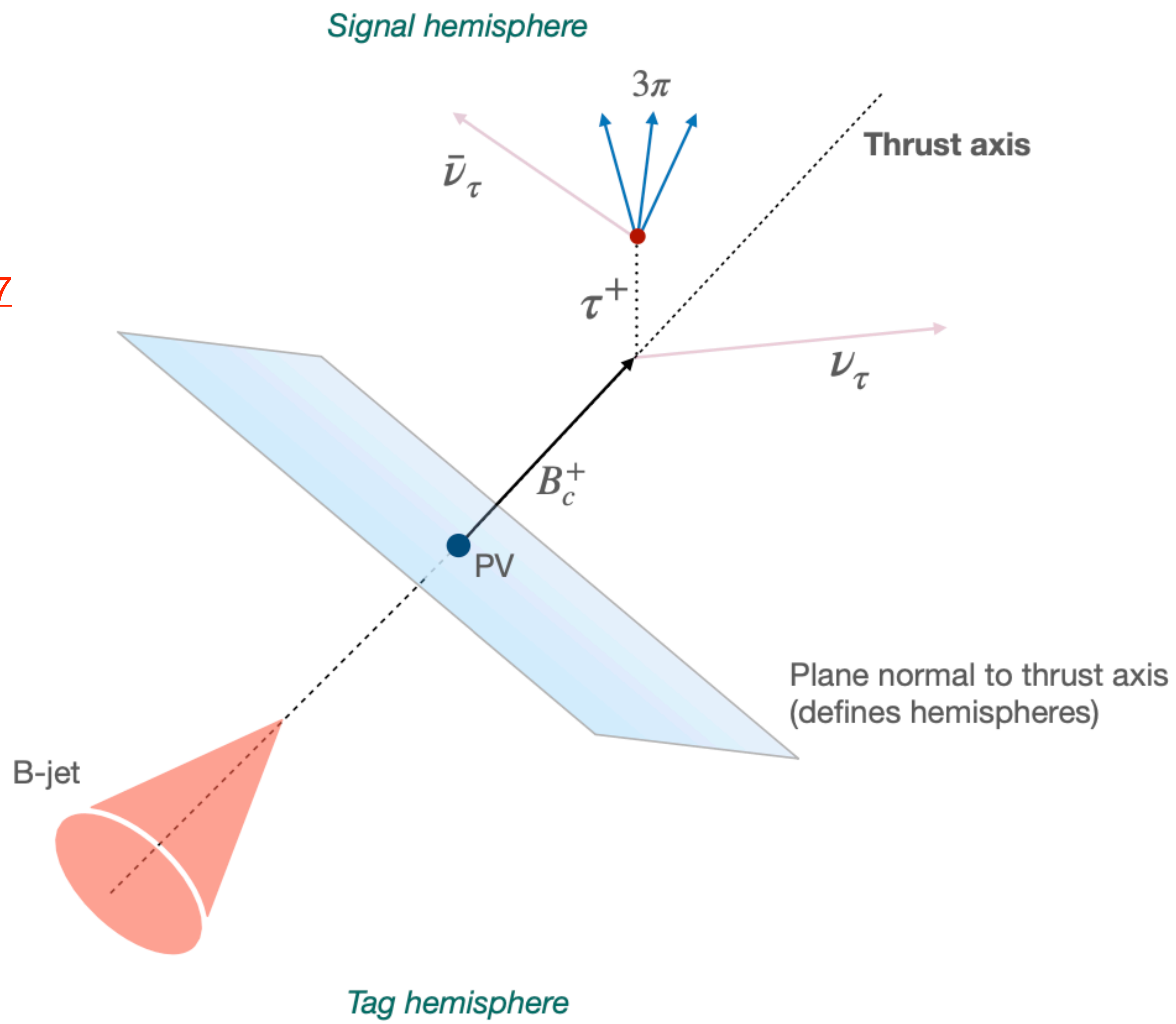
Case study - $B^+/B_c^+ \to \tau^+\nu_\tau$

- Difficult to identify at LHCb
- No B_c^+ at Belle II, $B^+ \to \tau^+\nu_\tau$ measurable to 5% 1808.10567

At Tera-Z factory

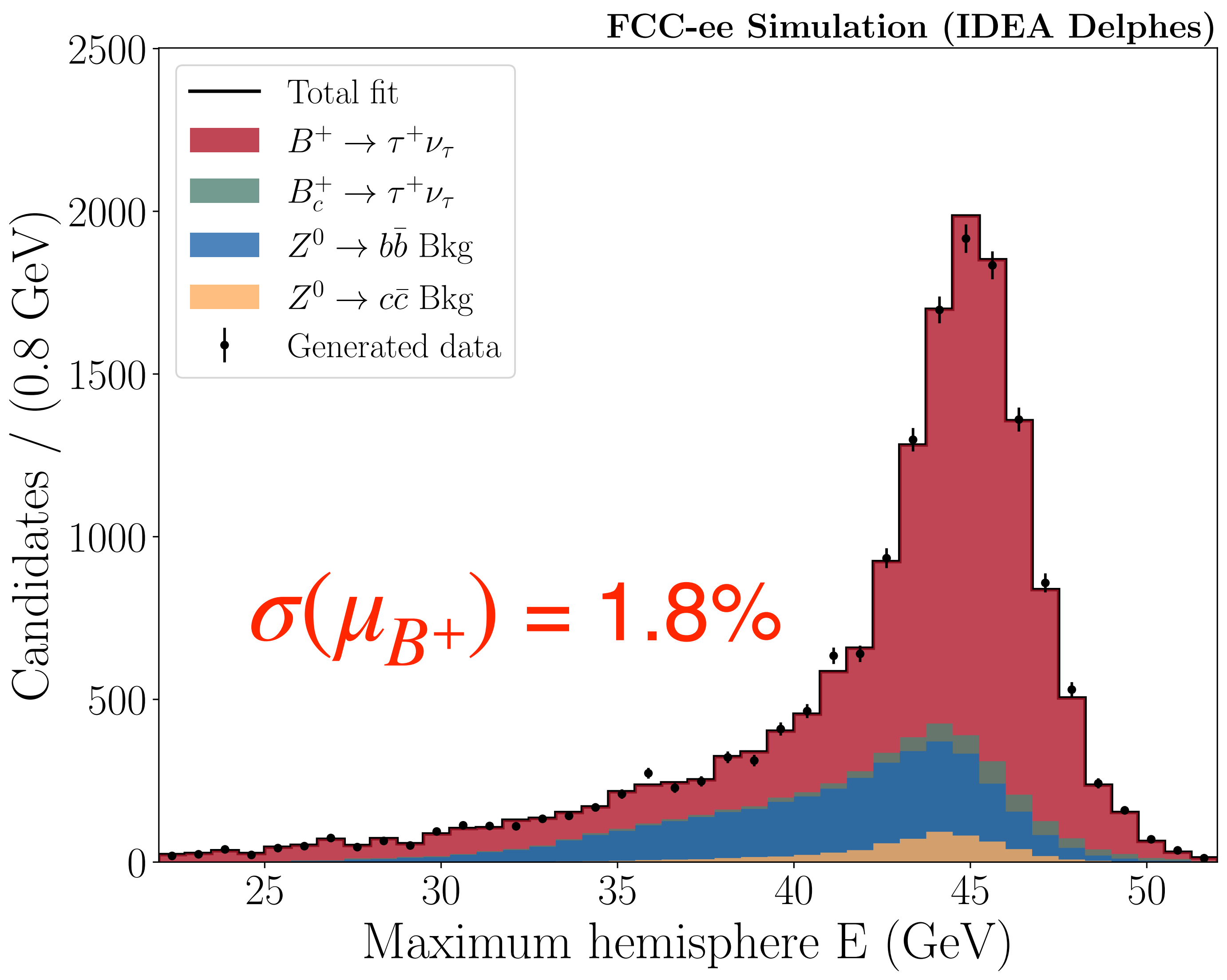
- 1~2% precision for $\tau \to 3\pi^\pm$ mode 2105.13330 2305.02998
- O(1%) precision for $\tau \to e/\mu$ mode 2007.08234
- Few kinematic handles, some backgrounds irreducible
- Ultimate precision relies on τ-ID in all modes

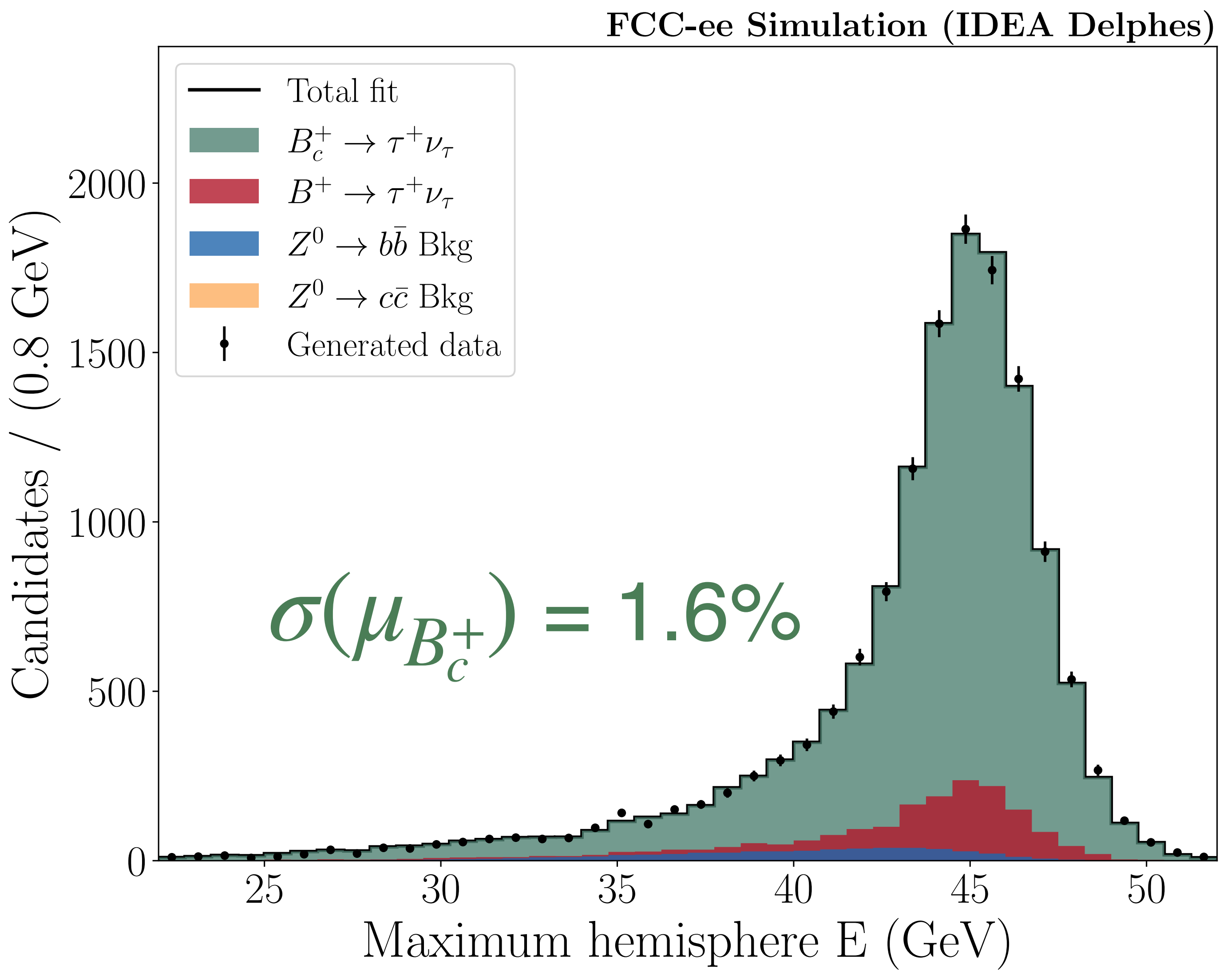
$$\mathscr{B}(B_q^+ \to \tau^+\nu_\tau)^{\mathrm{SM}} = \tau_{B_q^+}\frac{G_F^2\,|V_{qb}|^2 f_{B_q^+}^2\, m_{B_q^+}\, m_\tau^2}{8\pi}(1-\frac{m_\tau^2}{m_{B_q^+}^2})^2 \quad , \quad q = u, c$$



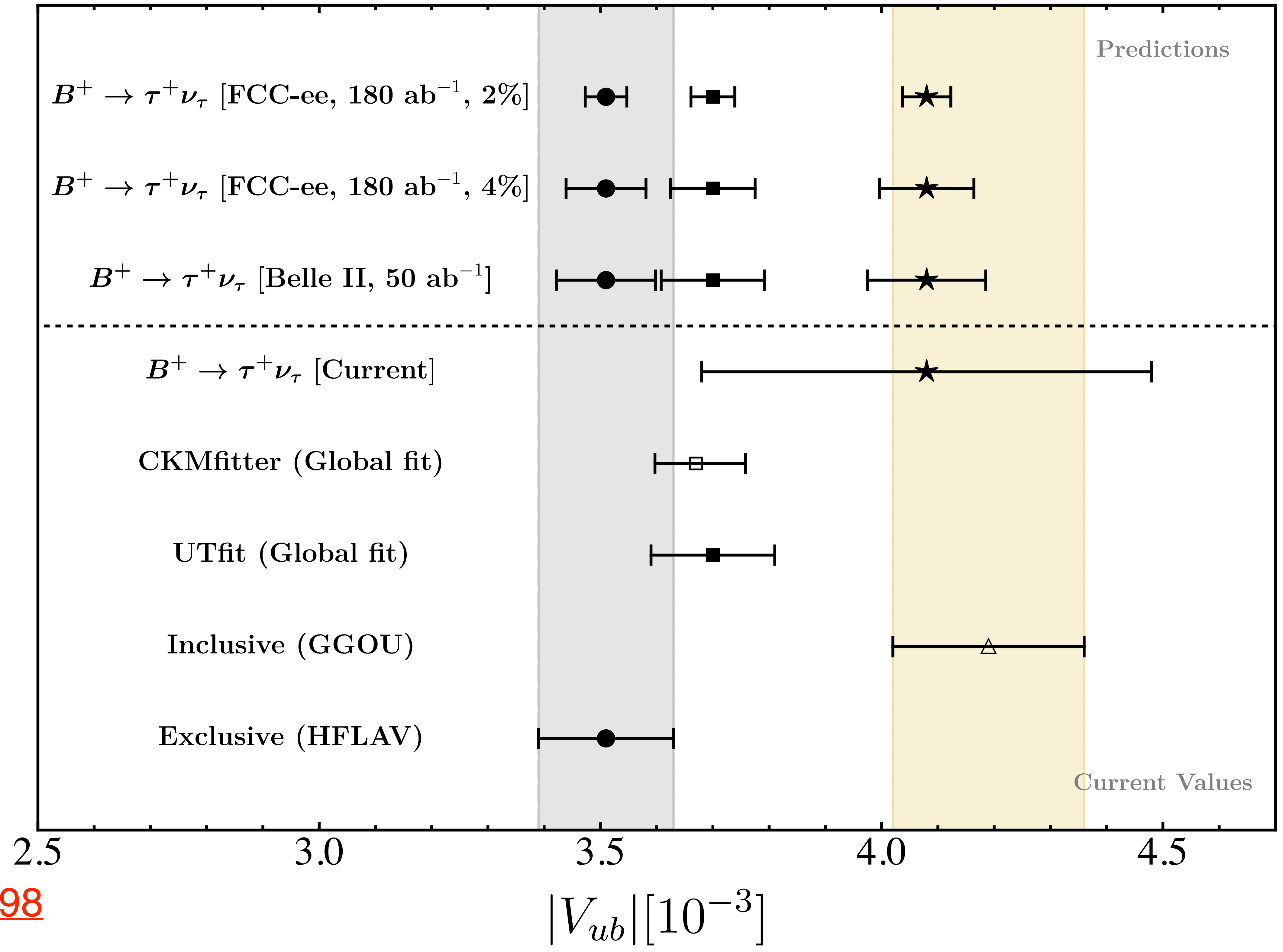
Case study - $B^+/B_c^+ \to \tau^+\nu_\tau$

- Good separation between B^+ and B_c^+
- First chance to observe (measure) $B_c^+ \to \tau^+\nu_\tau$
- Strong constraint to phase space related to $R(D), R(D^*)$ anomalies





- Determine $|V_{ub}|$ at 1% precision
- Similarly, determine with knowledge of $f_{B_c^+}$, or vice versa



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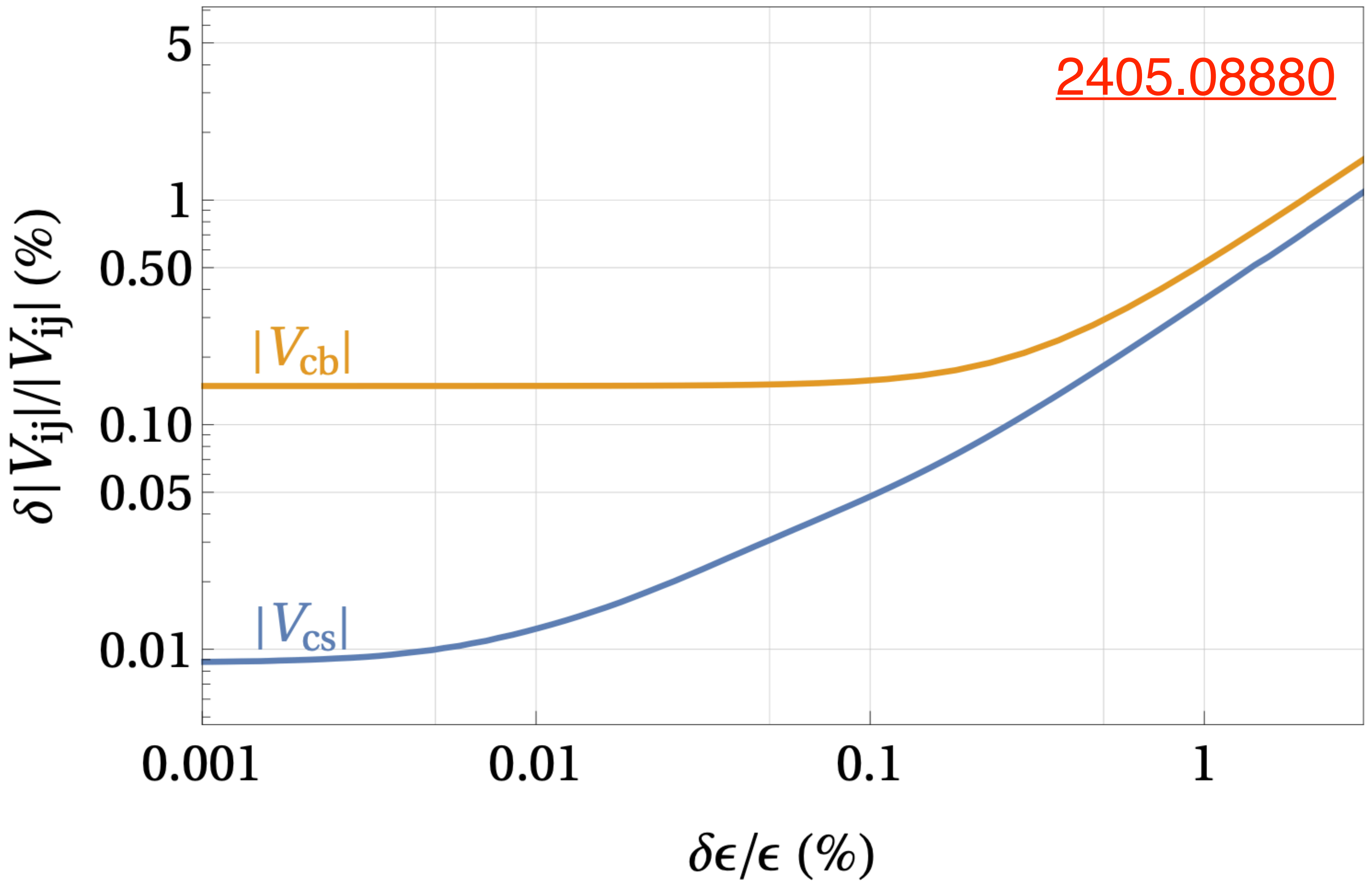
Direct CKM measurements — $|V_{cs}|, |V_{cb}|$

- At LEP, O(10%) precision on $|V_{cs}|$ DELPHI ALEPH OPAL
- At Tera-Z, O(0.01%) precision on $|V_{cs}|$, O(0.1%) on $|V_{cb}|$

$|V_{cs}|, |V_{cb}|$ with $WW \to 4q$ channel



$|V_{cb}|$ with $WW \to \ell\nu qq$ channel

Exp uncert most from mis-tag and bkg rate:

Scena 1. unc. from Herwig vs Pythia

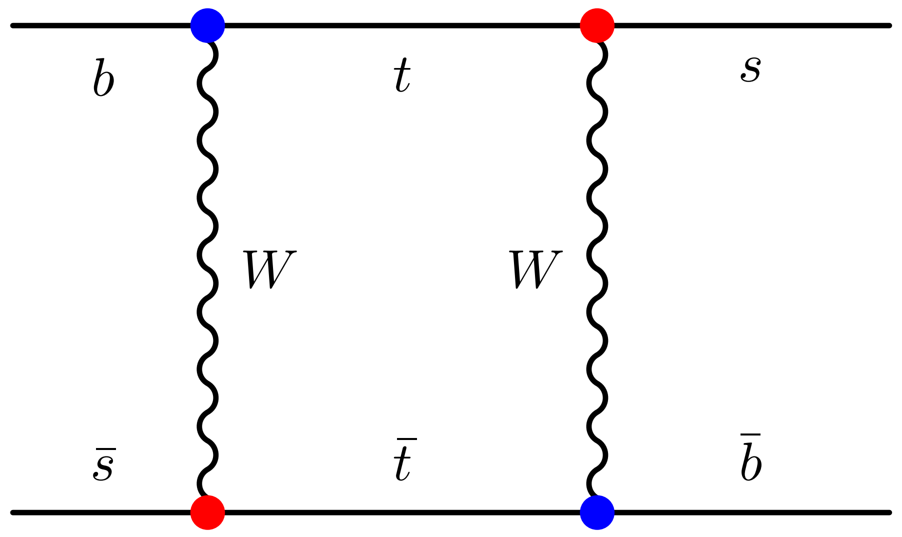
Scena 2. 8x better

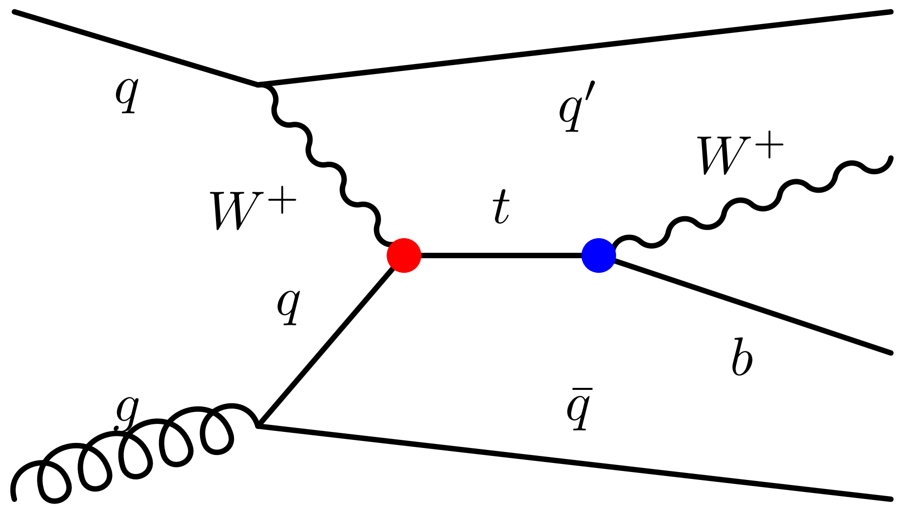
2406.01675

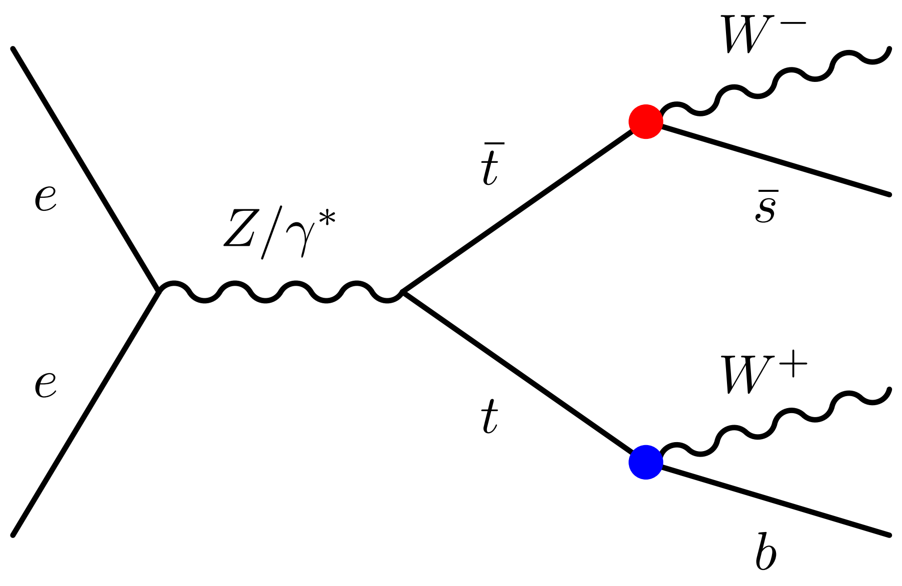
Uncertainty	Stat.	Syst., Secnario 1	Syst., Secnario 2
Unpolarized, Baseline (5 ab^{-1})	0.72%	1.5%	0.20%
Unpolarized, Extended (20 ab^{-1})	0.36%	1.5%	0.20%
WW Threshold (5×10^7 WW)	0.95%	1.5%	0.20%
Unpolarized, Baseline + WW	0.57%	1.1%	0.15%
Unpolarized, Extended + WW	0.33%	1.1%	0.18%
Polarized, Baseline (0.5 ab^{-1})	1.5%	1.5%	0.20%
Polarized, Extended (2 ab^{-1})	0.75%	1.5%	0.20%

More in talk by Zhaoling Zhang

Direct CKM measurements — $|V_{ts}|$







• $|V_{tb}|$ • $|V_{ts}|$

- Current (PDG): from $B_s^0 - \bar{B}_s^0$ mixing at LHCb
  - $|V_{ts}| = (41.5 \pm 0.9) \times 10^{-3}$ (**2.2%** precision)
  - Assume no NP in the loop, dominated by LQCD uncertainty

- Direct measurement at LHC: single top production
  - $|V_{ts}|^2 + |V_{td}|^2 = 0.06 \pm 0.06$, far from SM precision

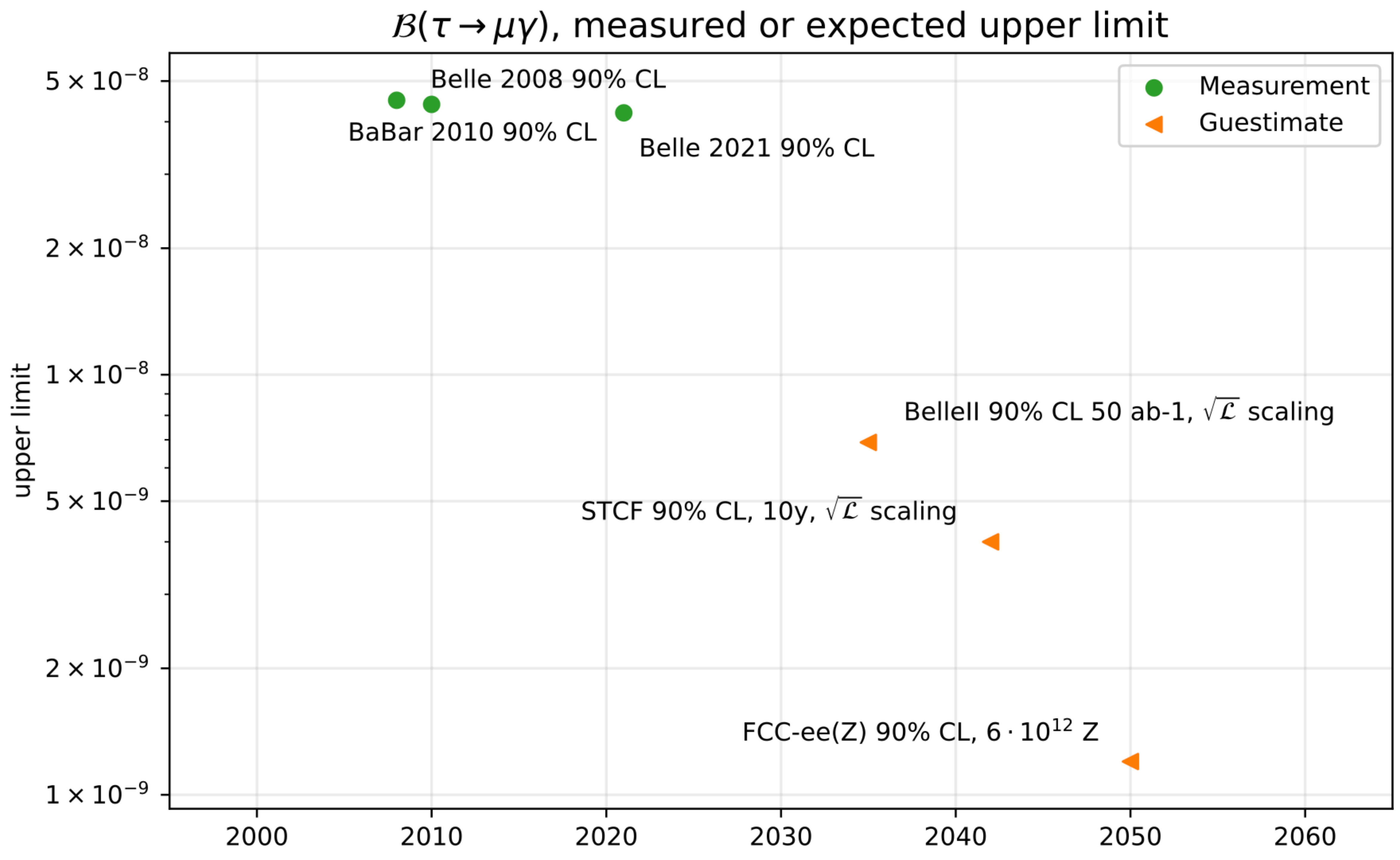
- Potential at e^+e^- colliders
  - Model-independent direct measurement
  - FCC-ee expects $2 \times 10^6 \times 2 \times |V_{ts}|^2$ ~ 6600 cases of $t \to Ws$
  - Expect precision on $|V_{ts}|$ at 3.1% or better FCC note: Vts
  - Similar measurement for $|V_{tb}|$, expect O(0.1%) precision

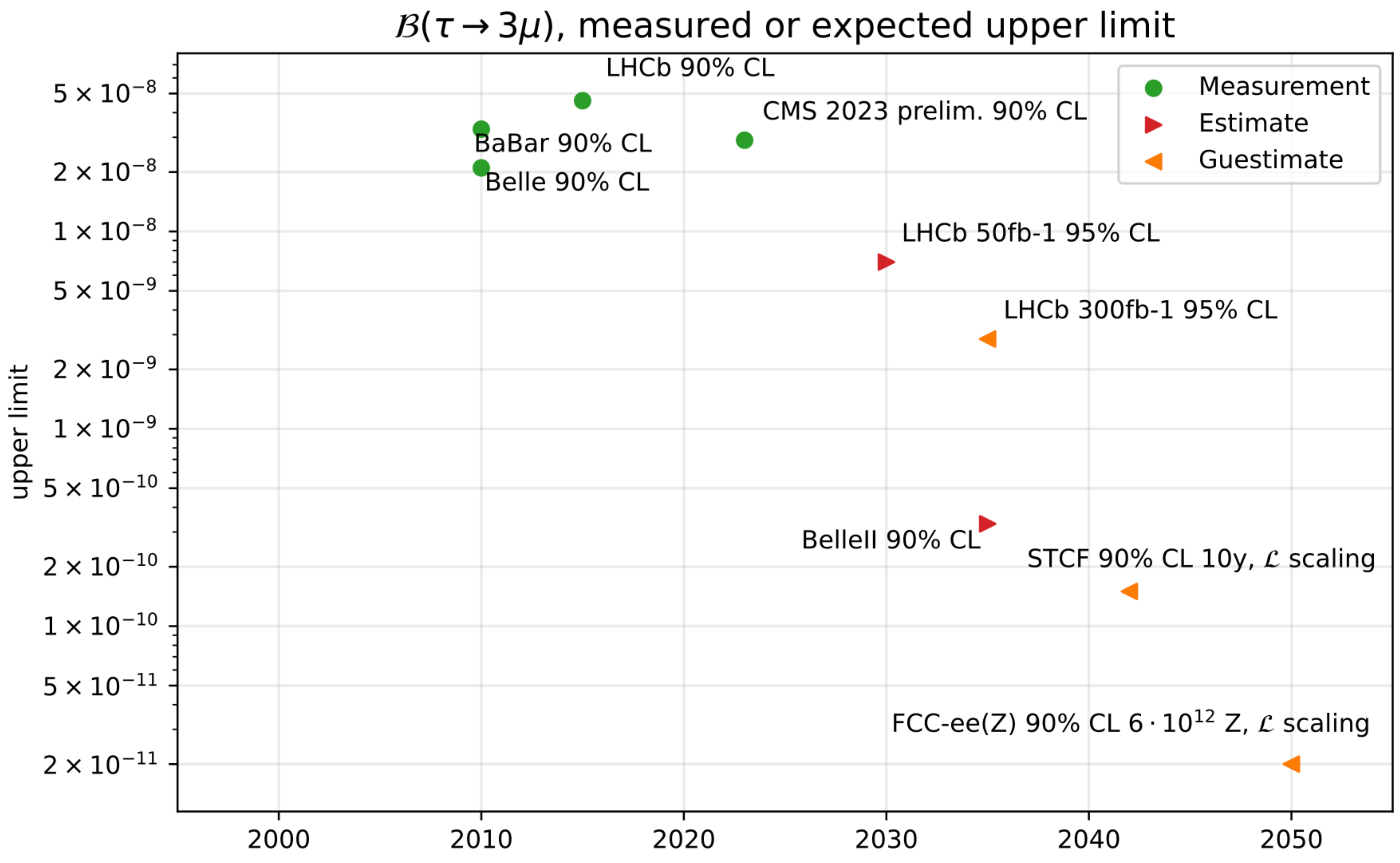
Tau, Charm

τ: CLFV

Discussion on tau LFU covered by Lorenzo Calibbi

- Lepton number is an accidental symmetry in SM, linked to small neutrino masses
- FCC-ee expect to probe $\tau \to \mu\gamma$ at O(10^{-9}) and $\tau \to 3\mu$ at O(10^{-11})

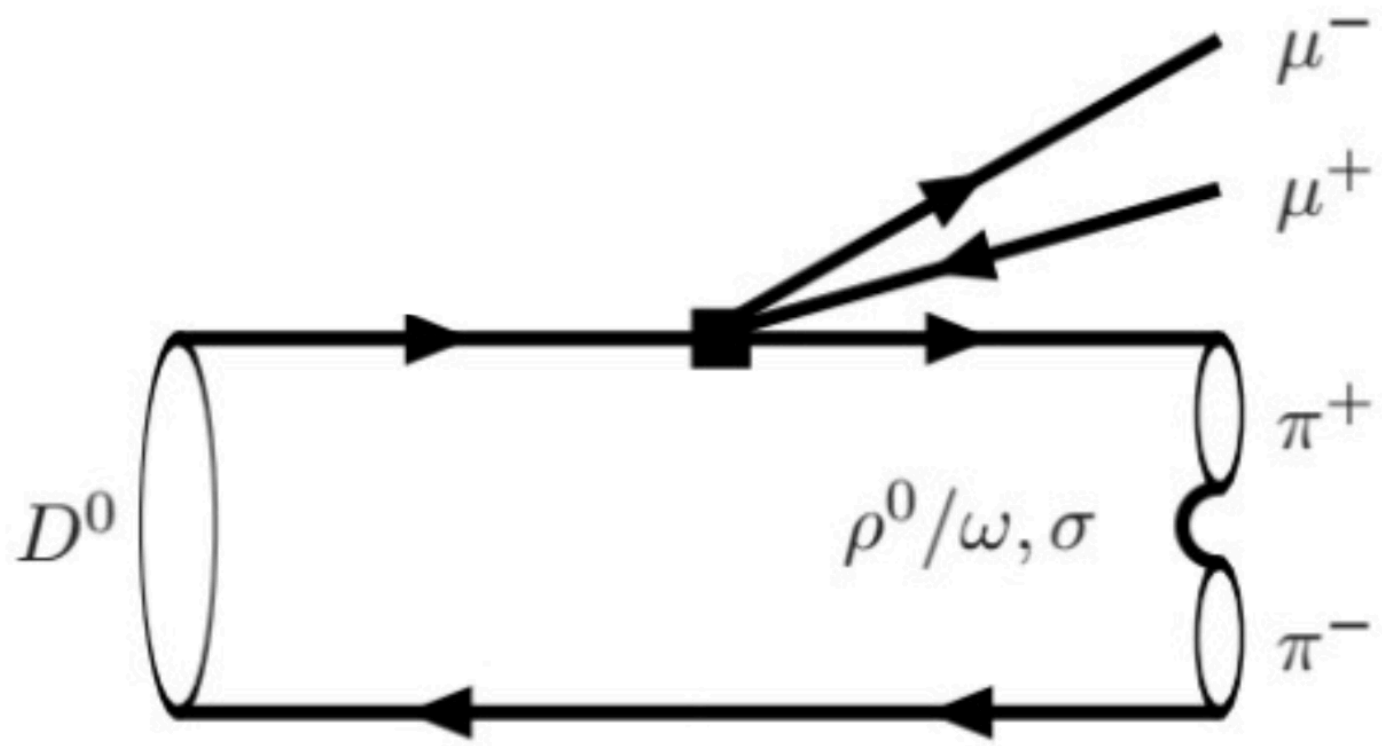




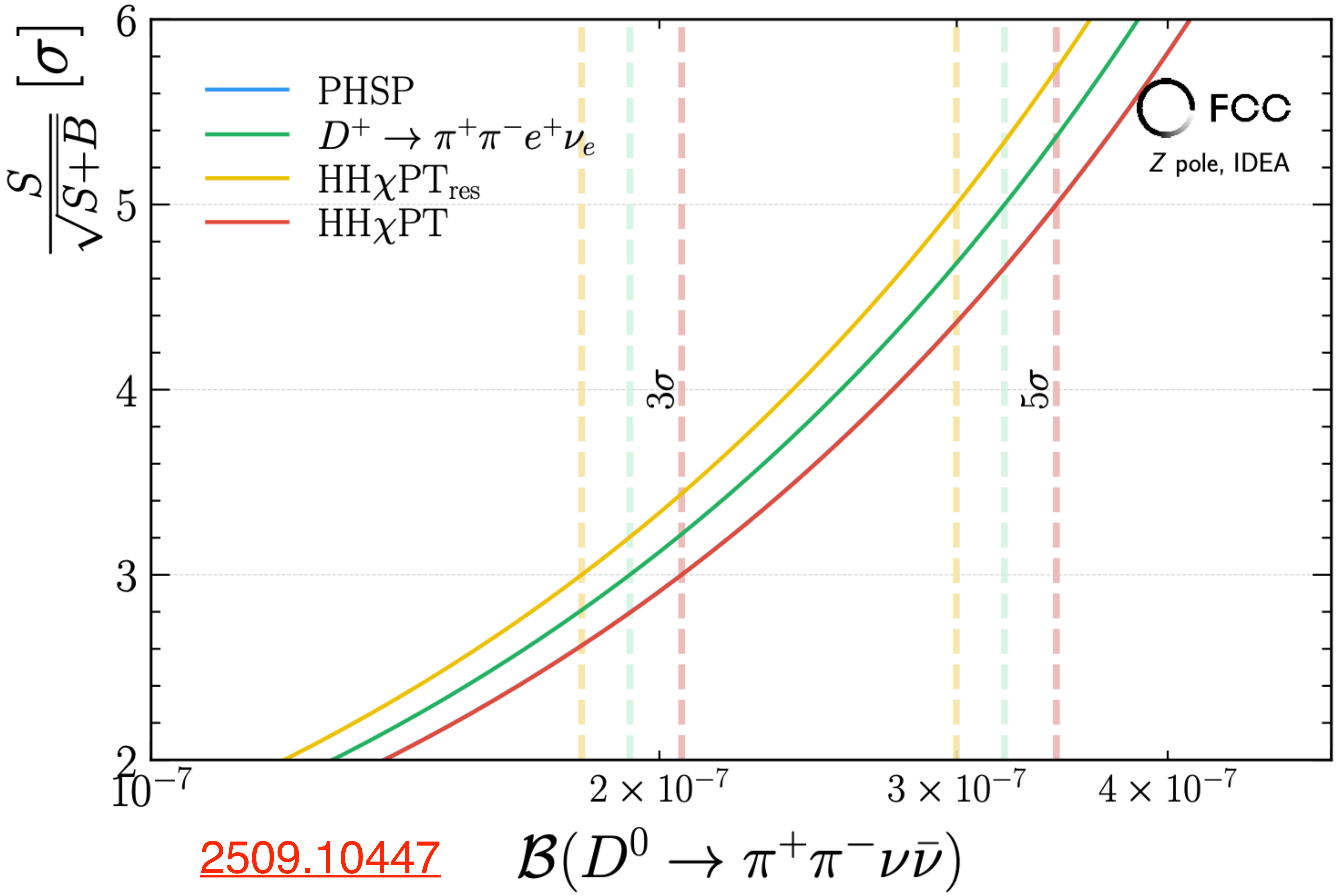
FCC note: tau physics

Charm: $c \to u\nu\nu$

- $c \to u\nu\nu$ highly suppressed in SM $\to$ clean null test
- $D^0 \to \pi^0\nu\nu$ <O(10^{-4}) from BESIII 2112.14236
- Expect >100x improvement at FCC-ee (by naive lumi scaling)



- Angular measurements of $D^0 \to K^+K^-\mu\mu$ and $D^0 \to \pi^+\pi^-\mu\mu$ at LHCb 1806.10793 2111.03327
- $D^0 \to \pi^+\pi^-\nu\nu$ can be probed at FCC-ee at O(10^{-7}) level



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Summary

FCC-ee is an excellent flavor factory

- Complete coverage of flavor program
- Highly complementary to Belle II and LHCb
- Many unique new probes
- High precision for whole flavor landscape

Flavor at FCC-ee/CEPC is a rich realm, much more to explore!

Ads: Flavours@FCC WS

- 4 workshops in 2025-2027
- First one at CERN, Nov. 19 - 21, 2025
- You are invited: https://indico.cern.ch/event/1588013/

Flavours at FCC Workshop

Nov 19 – 21, 2025
CERN
Europe/Zurich timezone

Enter your search term

- Overview
- Videoconference
- Scientific Program
- Timetable
- Registration

FCC Secretariat

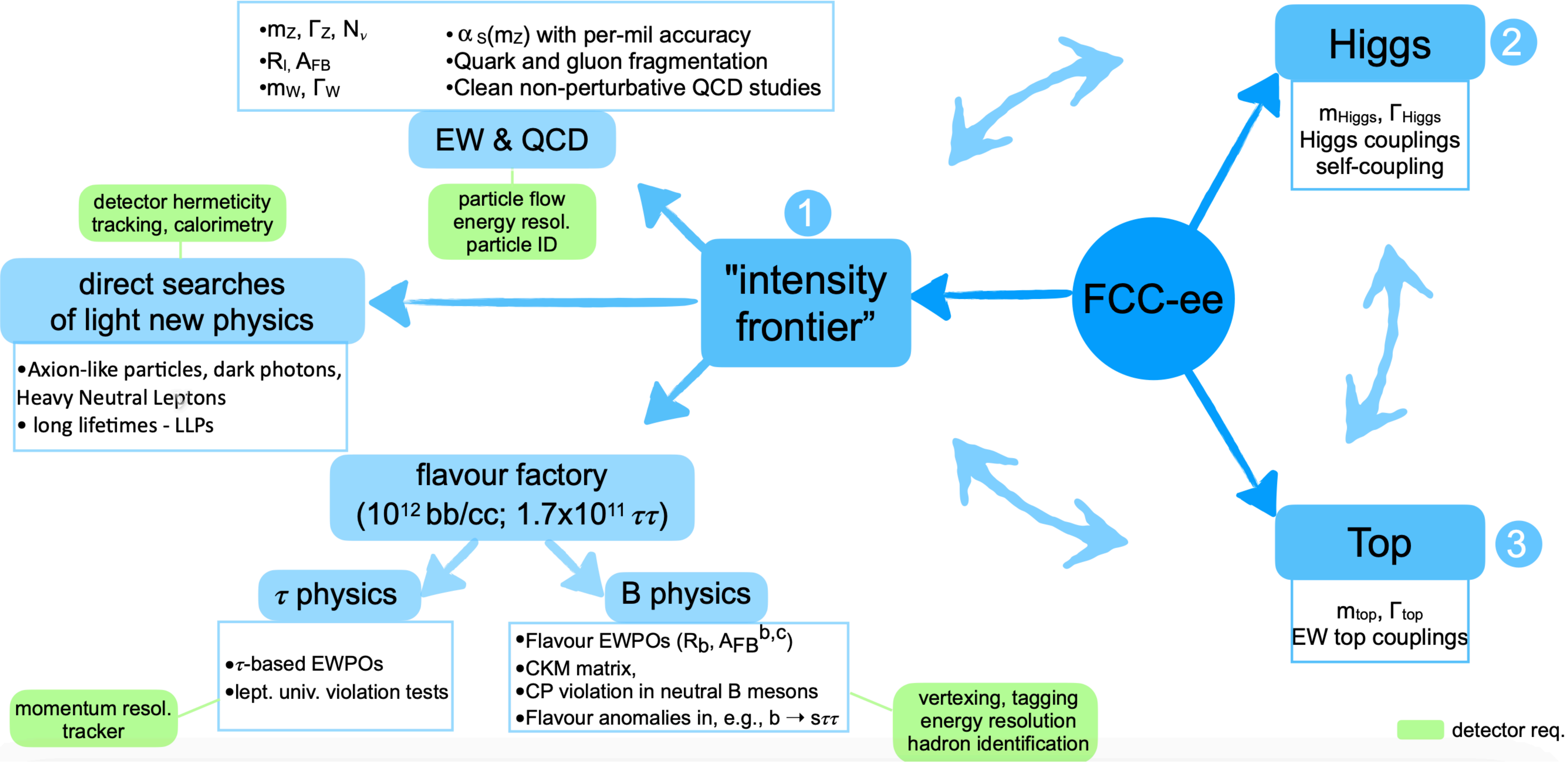
fcc.secretariat@cern.ch

Physics at the Flavoured Circular Collider: preparing for heavy quark and lepton studies in the post HL-LHC/Belle II era

Experimentalists and theorists from the world-wide particle physics community are invited to participate in an extended workshop, beginning autumn 2025 and scheduled to continue until summer 2027 to deepen our understanding of the potential of the FCC-ee for heavy-flavour physics in the quark and lepton sector. This will build on the studies performed for the Conceptual Design Report and Feasibility Study Report and seek to set the agenda, and prepare the tools, for physics in the post HL-LHC and Belle II era.

Backup

Physics program



Detector concepts

CLD (CLIC-like detector)

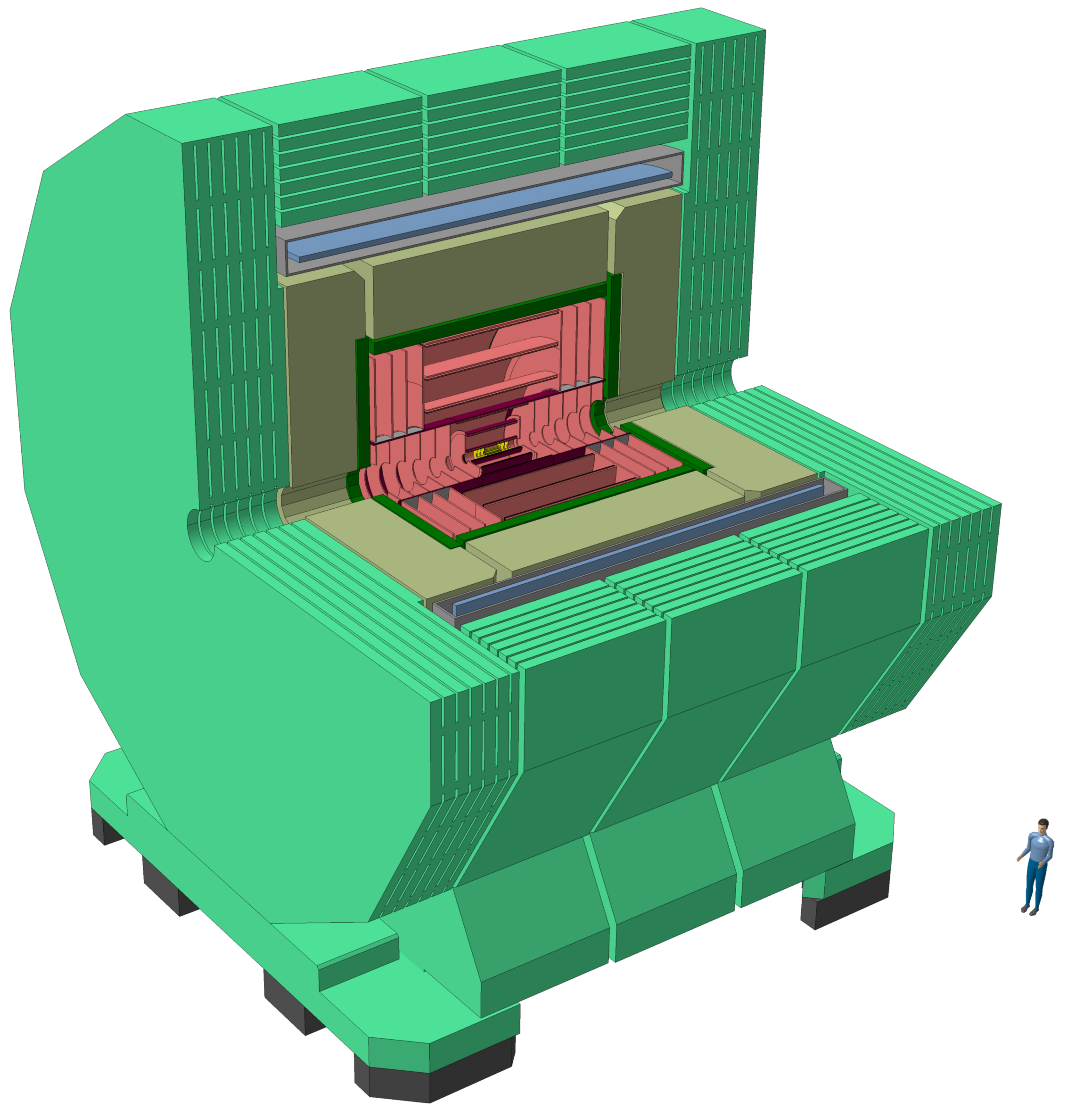
- Full silicon vertex detector and tracker
- High granularity silicon-tungsten ECAL + scintillator-steel HCAL
- Solenoid outside of calorimeter

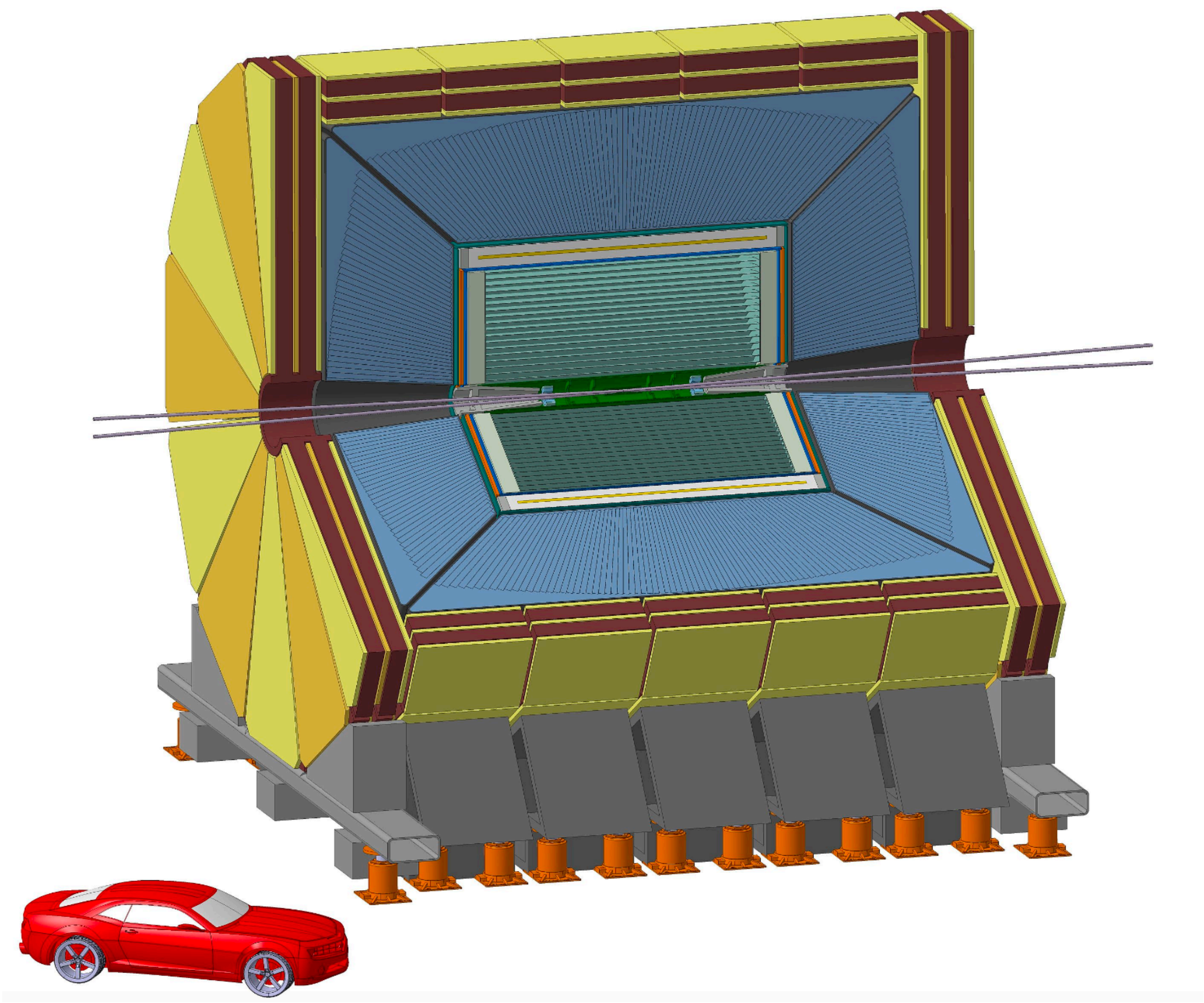
IDEA (Innovative detector for an electron-positron accelerator)

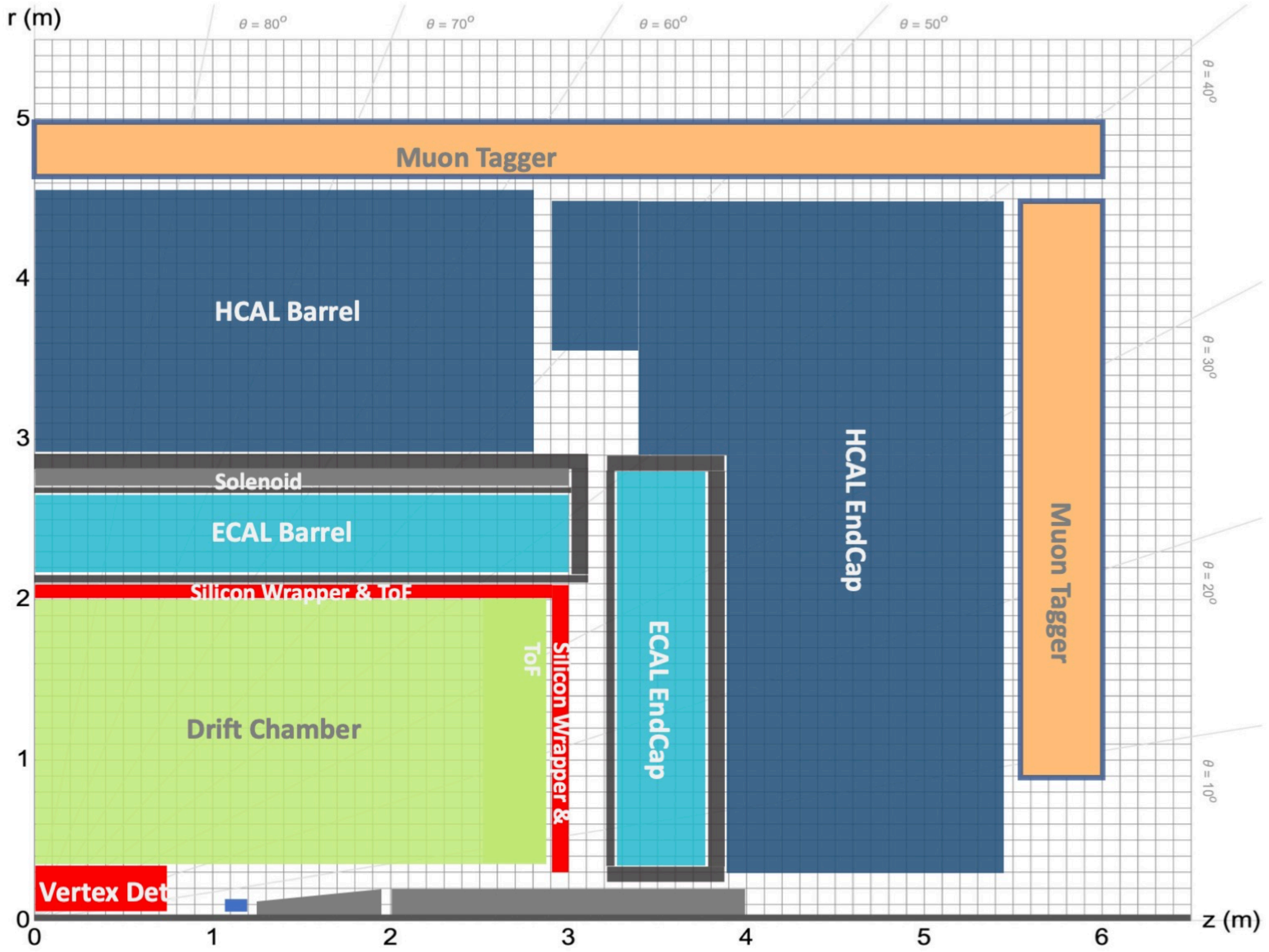
- Silicon vertex detector
- Low mass drift chamber
- Thin solenoid inside of duel-readout calorimeter (Cherenkov and scintillator)

ALLEGRO (A Lepton-Lepton collider Experiment with Granular Read-Out)

- Silicon vertex detector + silicon or gaseous tracker
- Noble liquid + Pb/W ECAL
- Solenoid between ECAL and HCAL







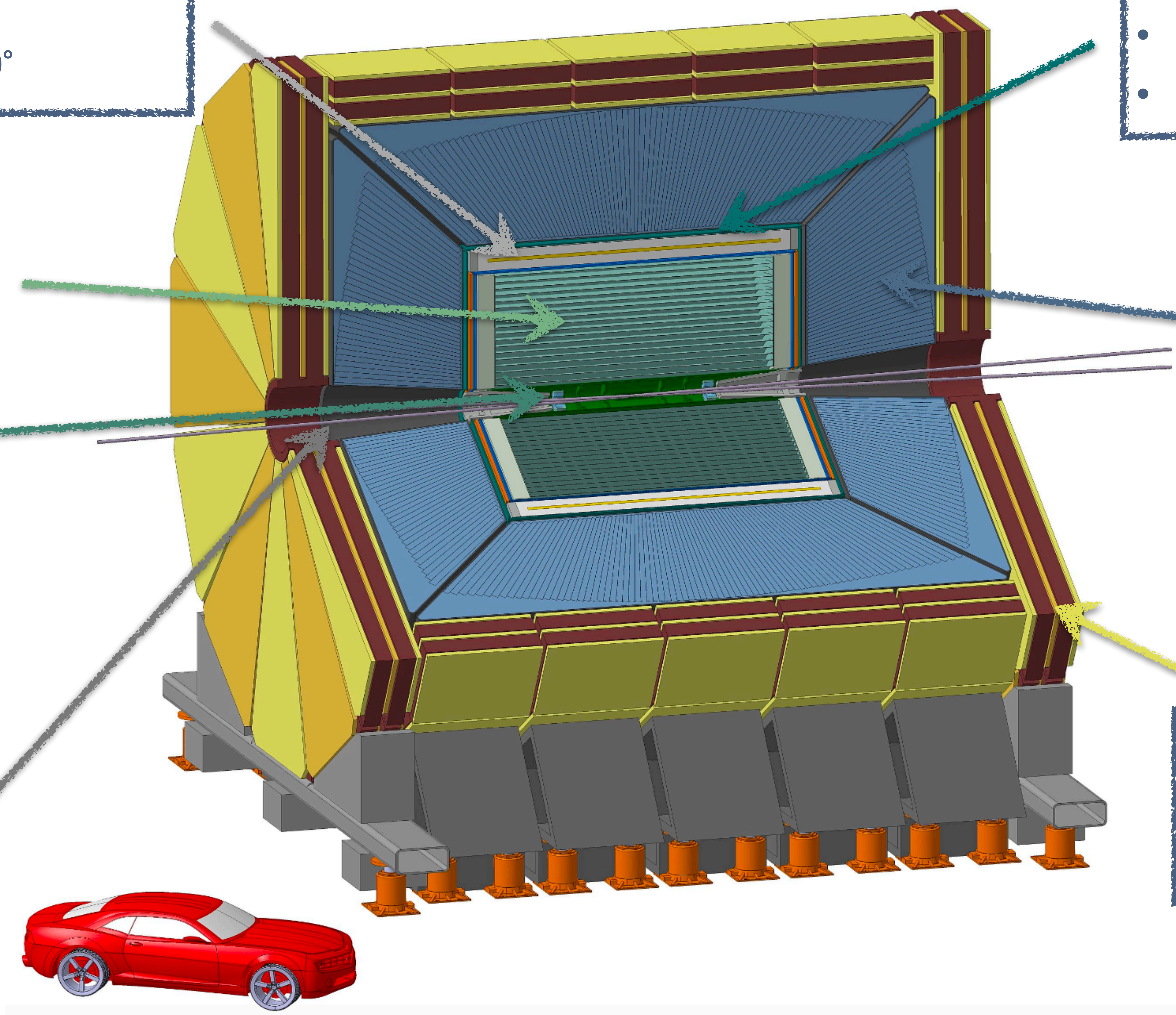
IDEA detector

Superconducting solenoid
- 2 T, R = 2.0 - 2.4 m
- $0.74\ X_0,\ 0.16\ \lambda\ @90^{\circ}$

Wire drift chamber
- 112 layers, R = 35 - 200 cm
- $0.016\ X_0 @ 90^{\circ}$

Silicon vertex detector
- 5 layers, R = 1.7 - 34 cm
- Pixel $20 \times 20\ \mu m^2$

Beam pipe
- R ~ 1.5 cm

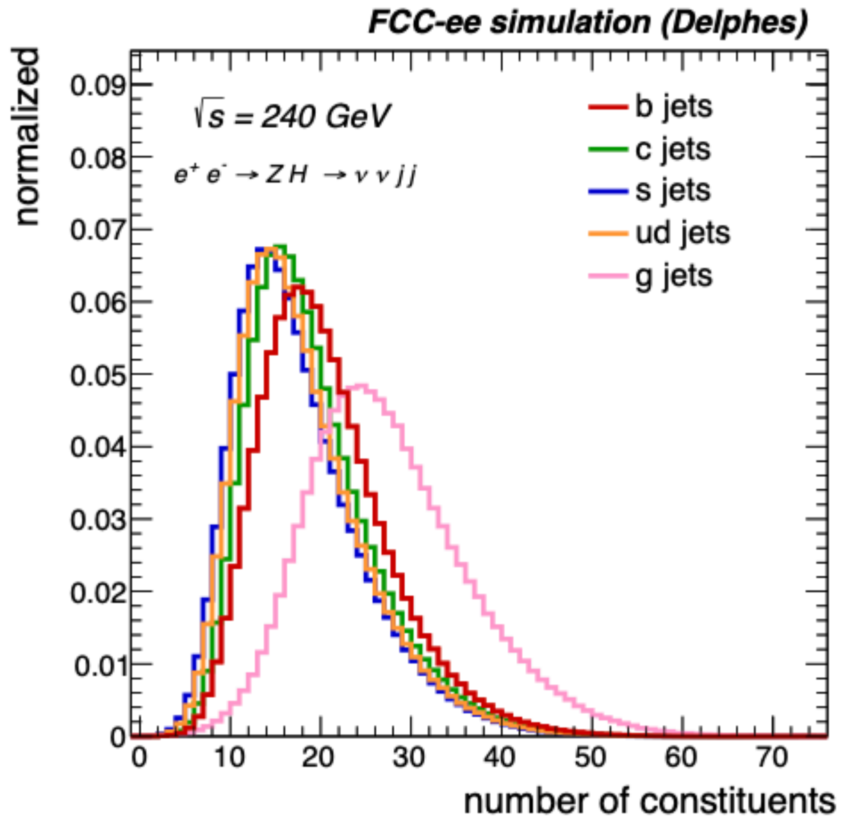


Preshower
- 2 layers, gas detector
- Spatial reso < 100 μm

Dual-readout calorimeter
- 2 m capillaries
- Alternate Cherenkov and scintillation fibers
- $\sigma_{EM} \approx \frac{10\,\%}{\sqrt{E}}$, $\sigma_{had} \approx \frac{30\,\%}{\sqrt{E}}$

Muon chambers
- 3 layers, gas detector
- Spatial reso < 400 μm

FCC jet flavor tagging



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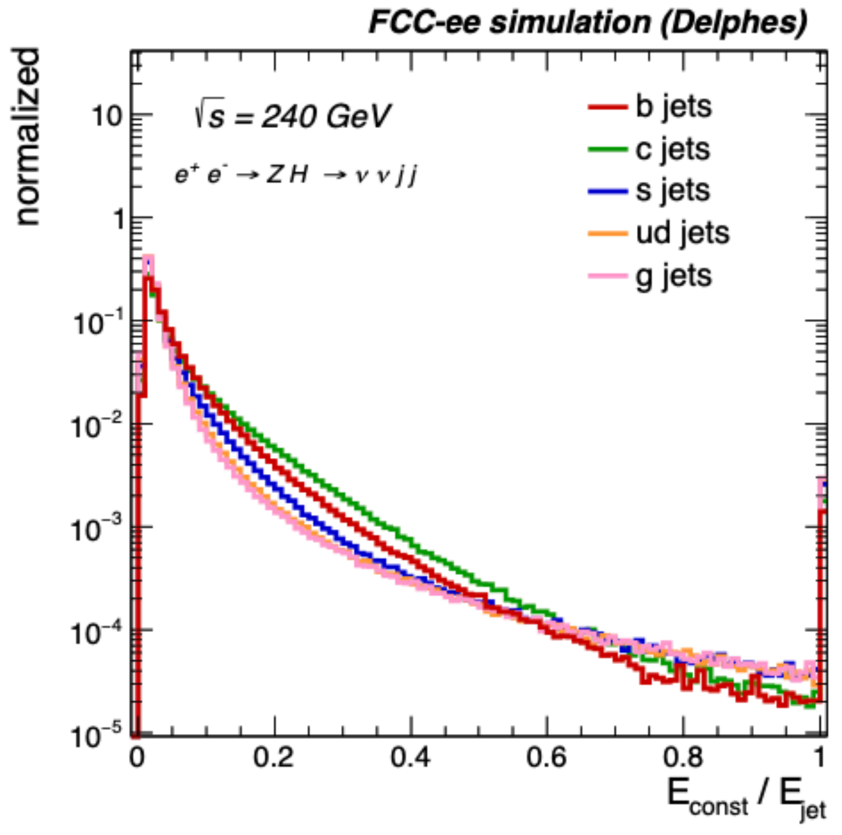

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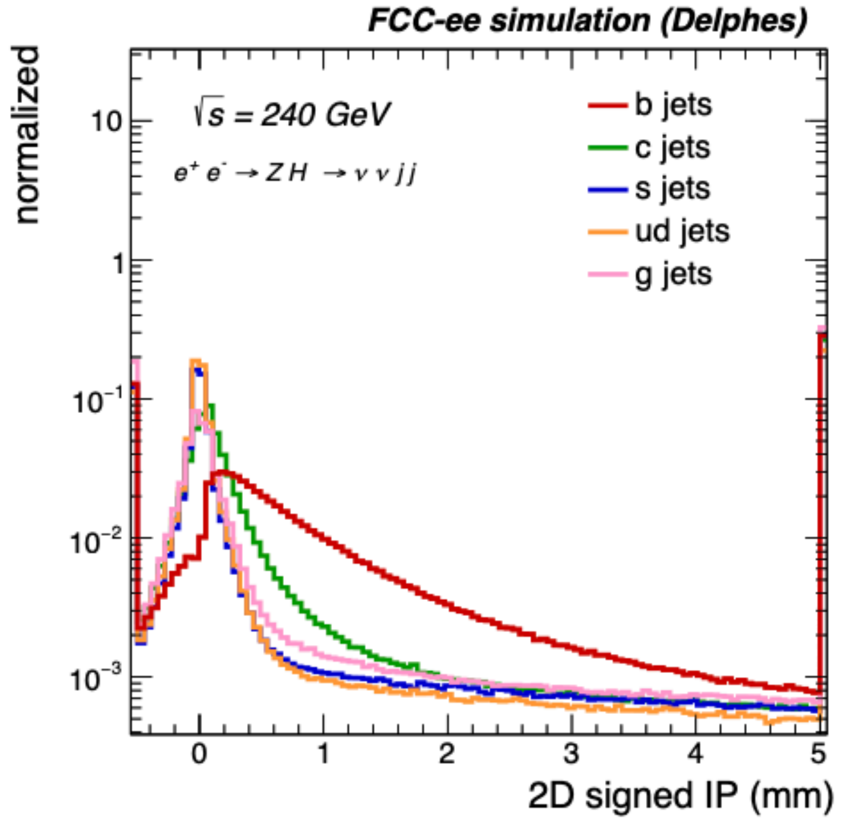

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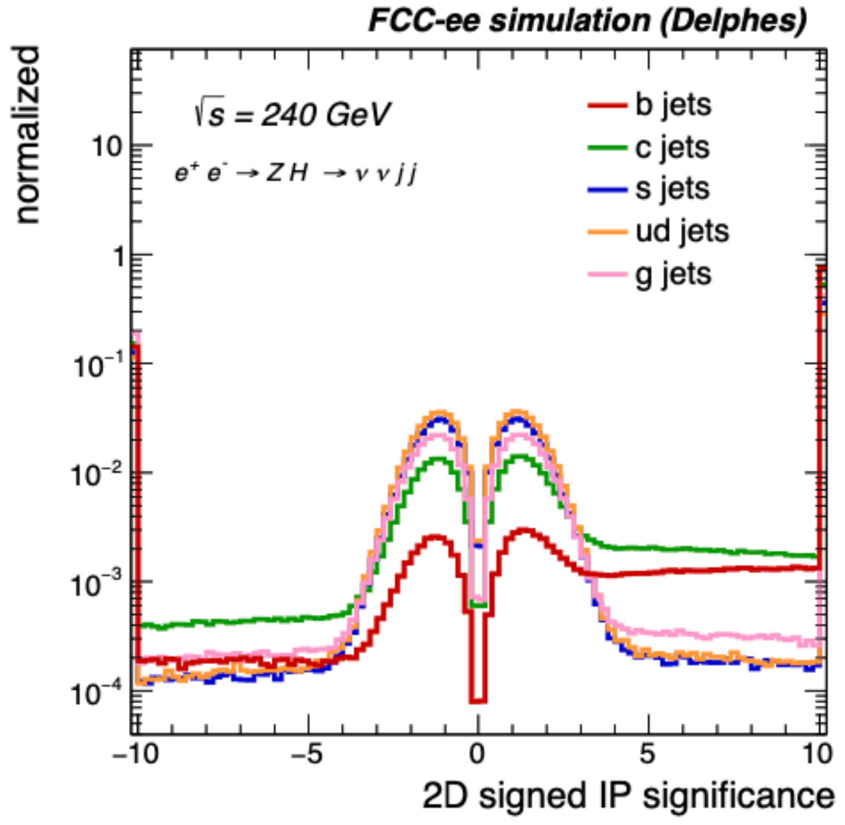

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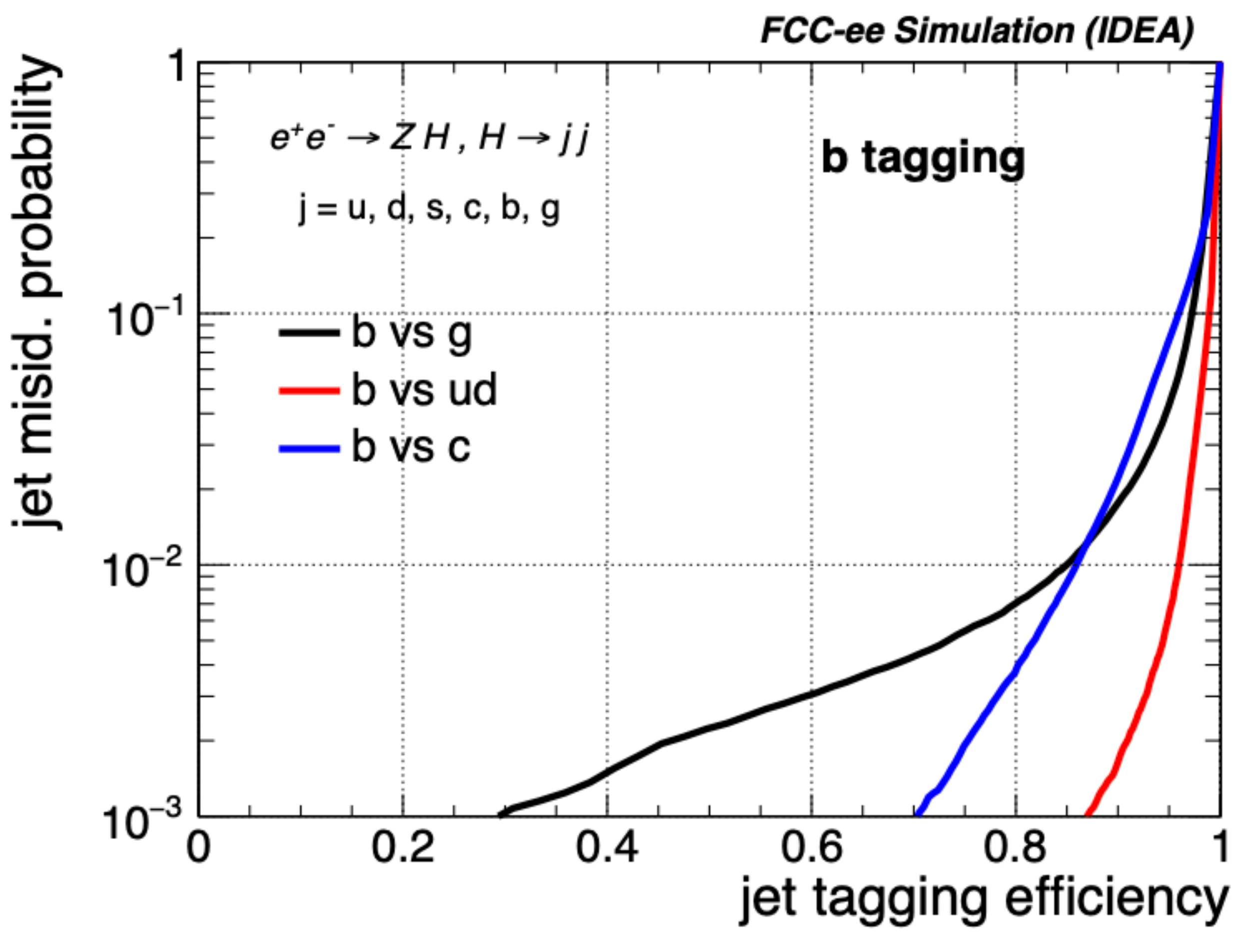

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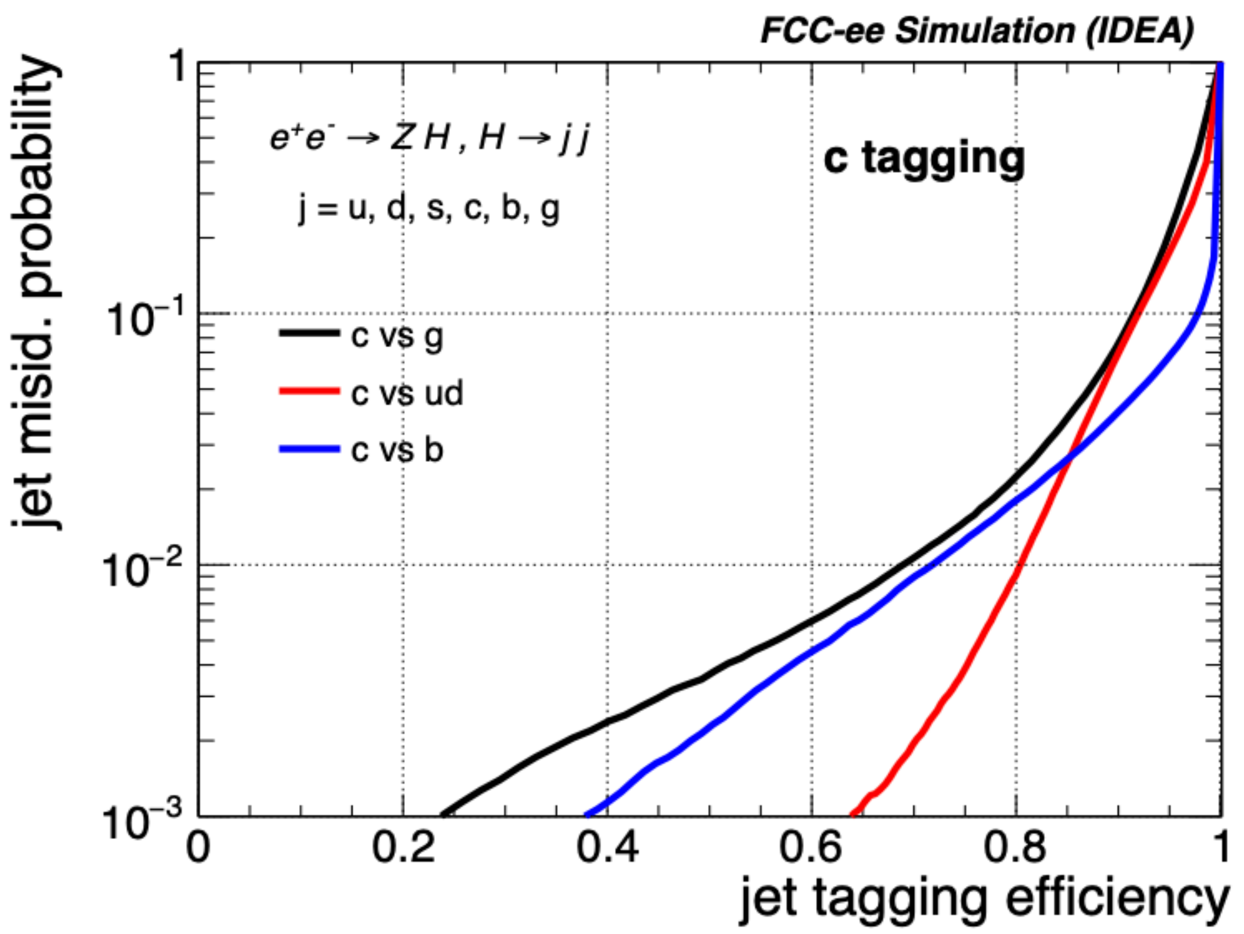

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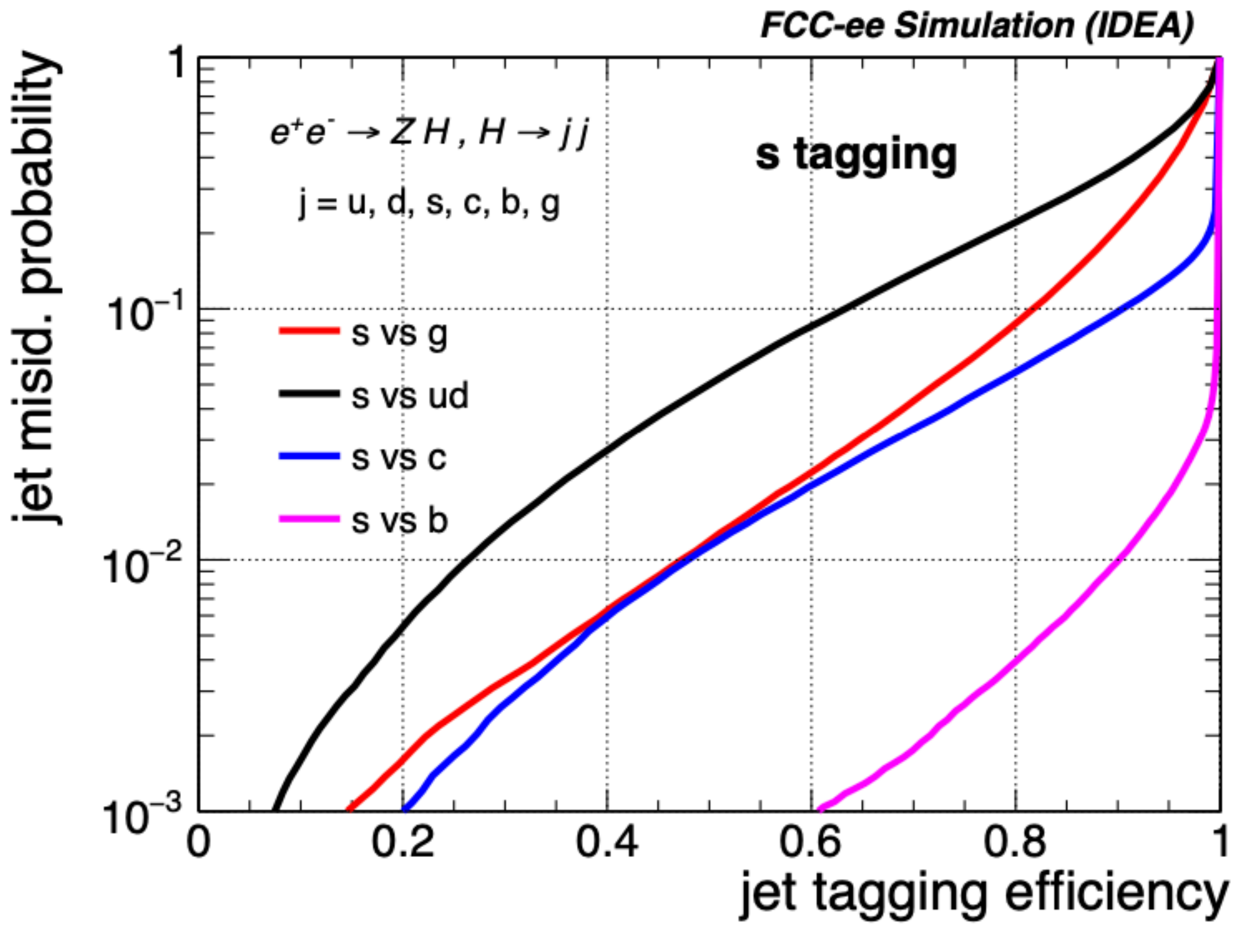

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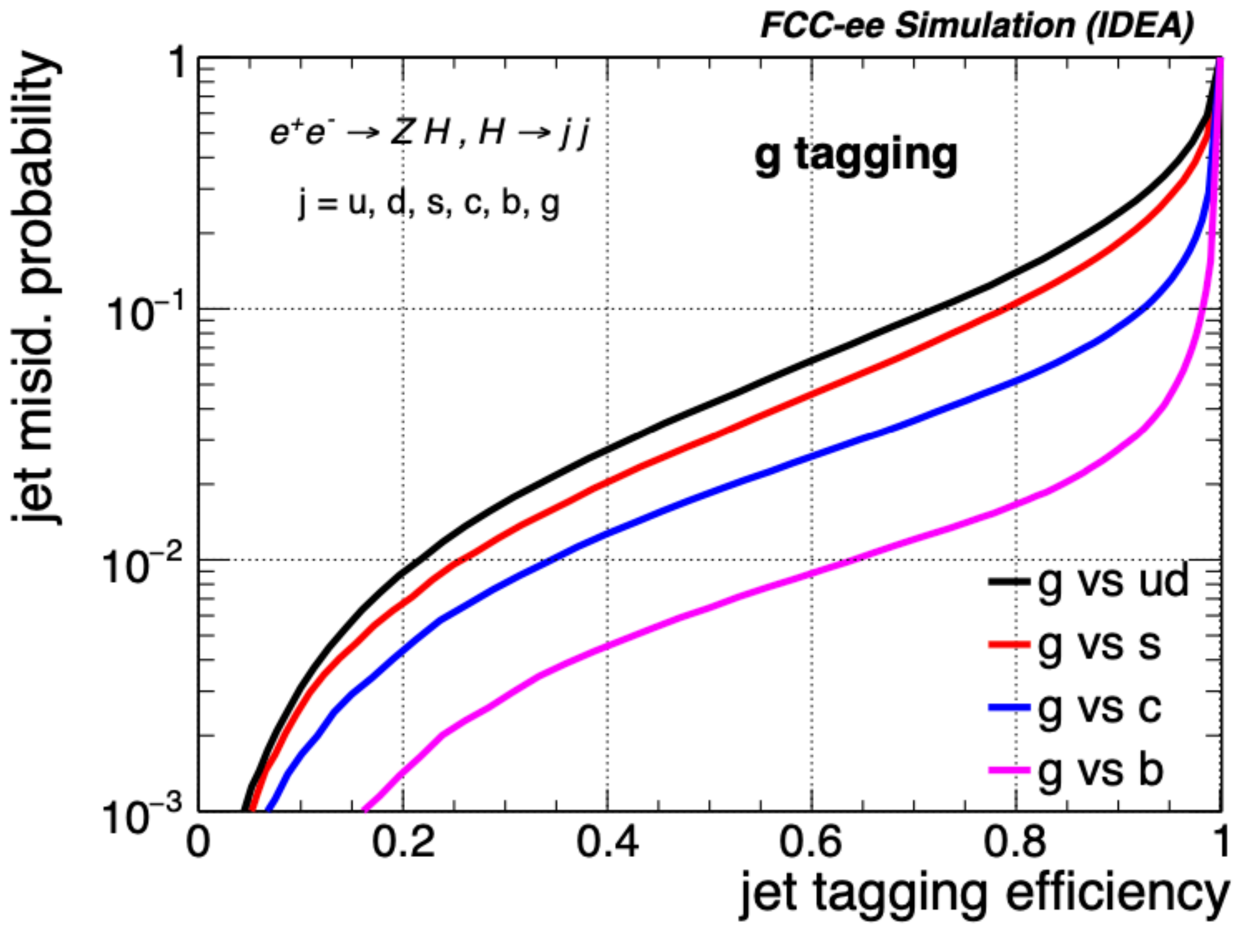
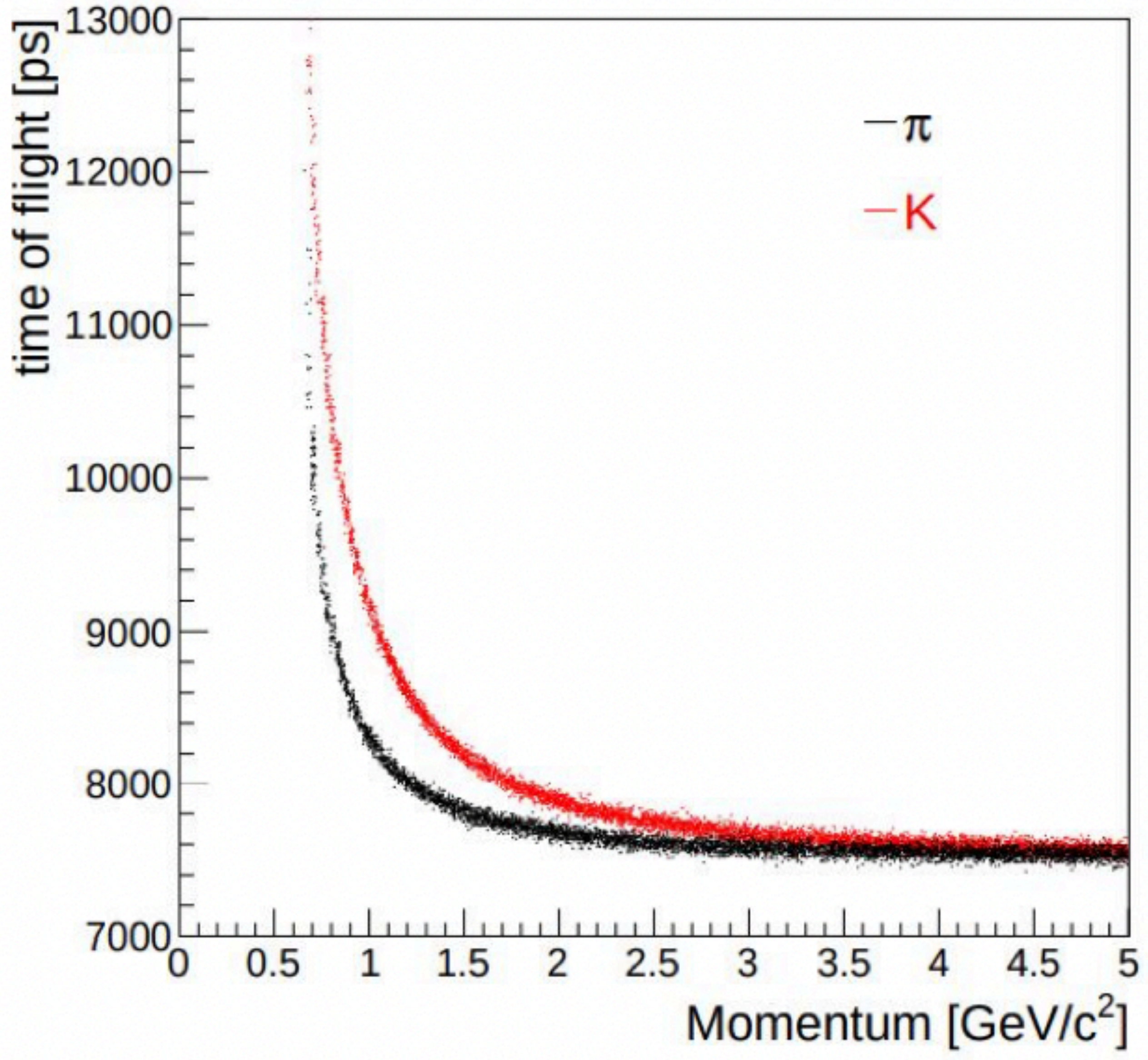


(d)

Kaon vs Pion ID

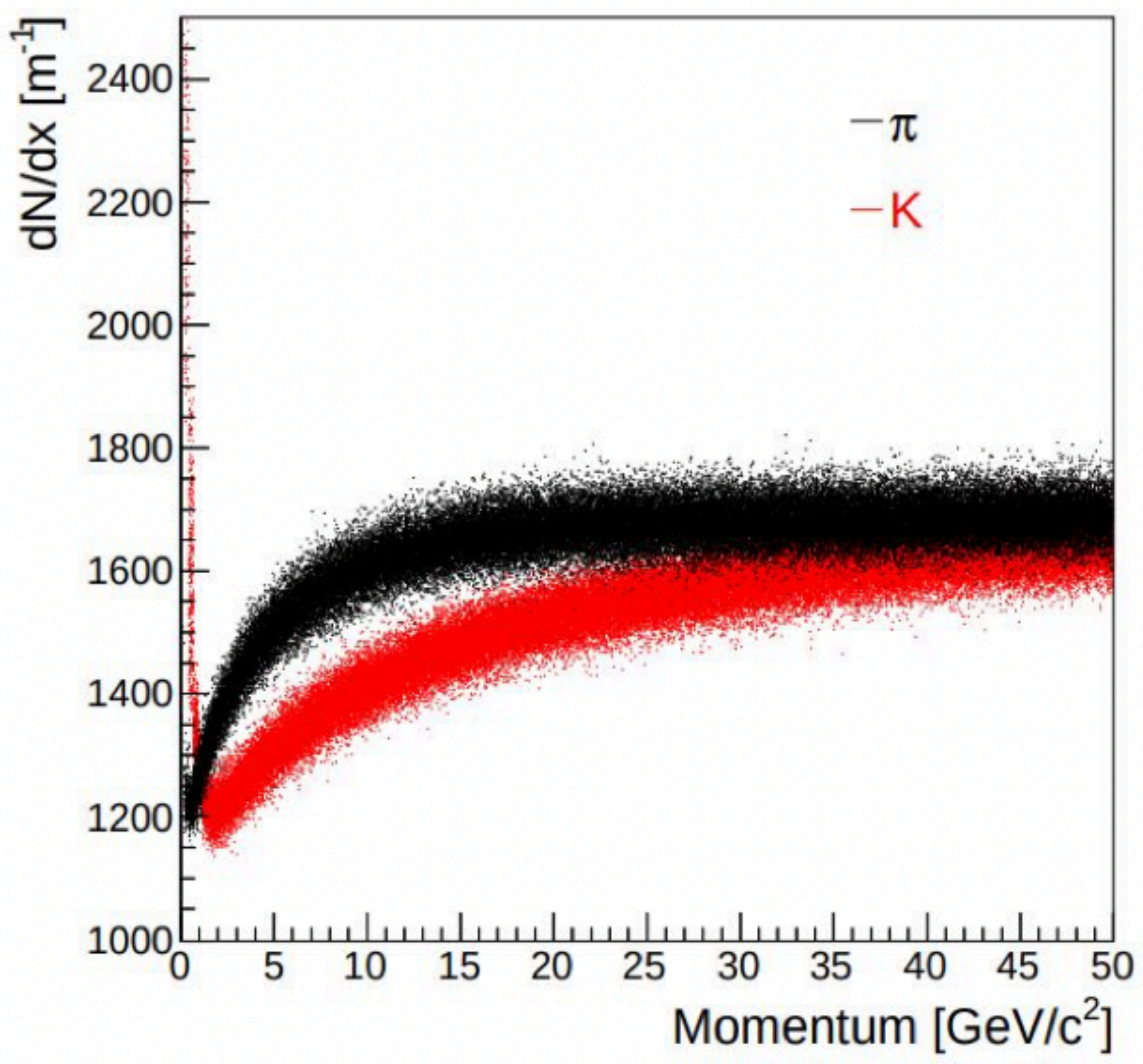
Time of Flight

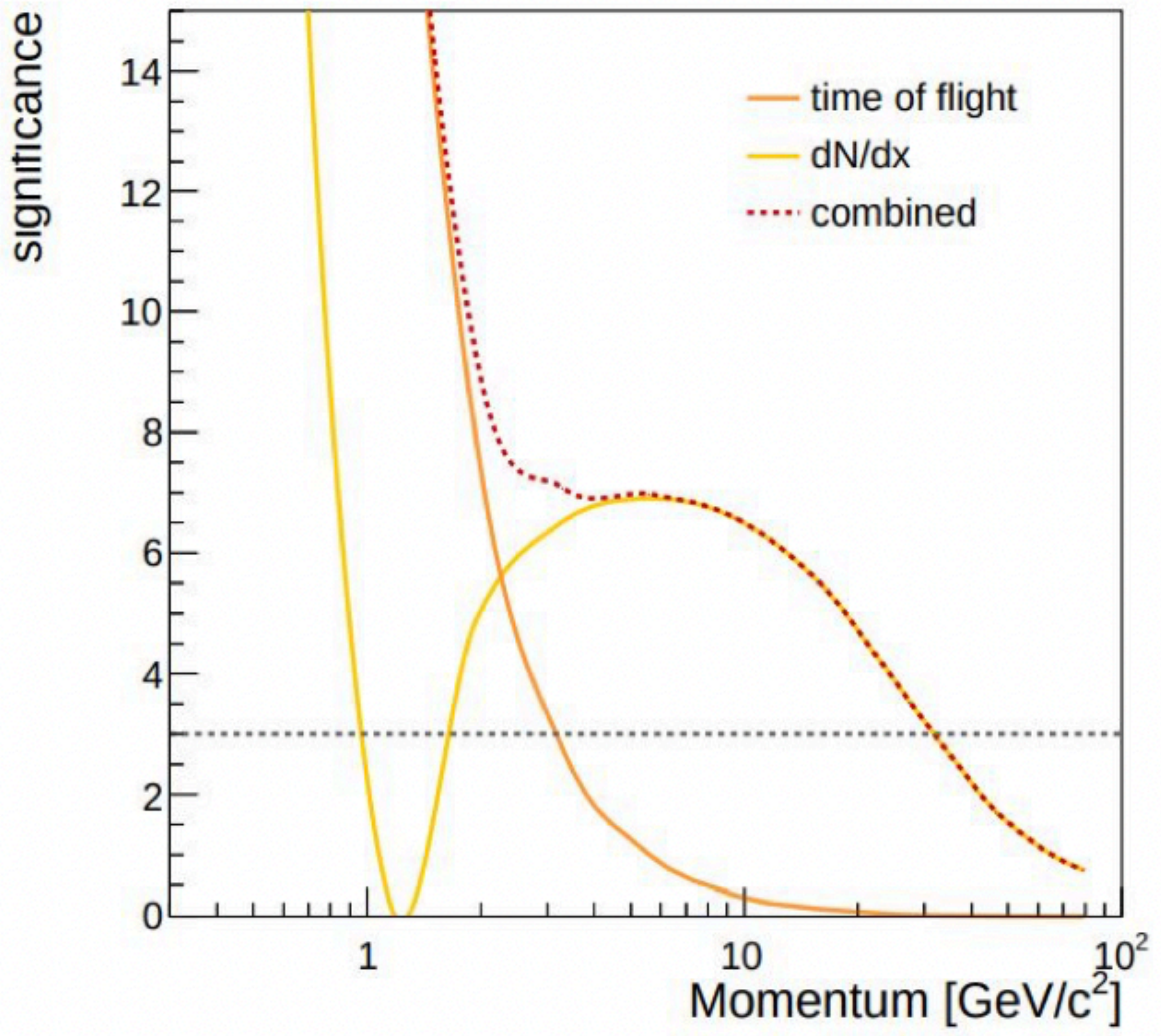
- Good K/π separation at low momenta



Cluster Counting

- Count number of primary ionization clusters along track path





3-sigma separation for tracks with **p < 30GeV**

Assume perfect ID in the kinematic region ($p < 30$ GeV) of study.

π^0 identification

- Need exquisite EM calorimetry for pi0 identification
  - $3\,\%/\sqrt{E}$ expected

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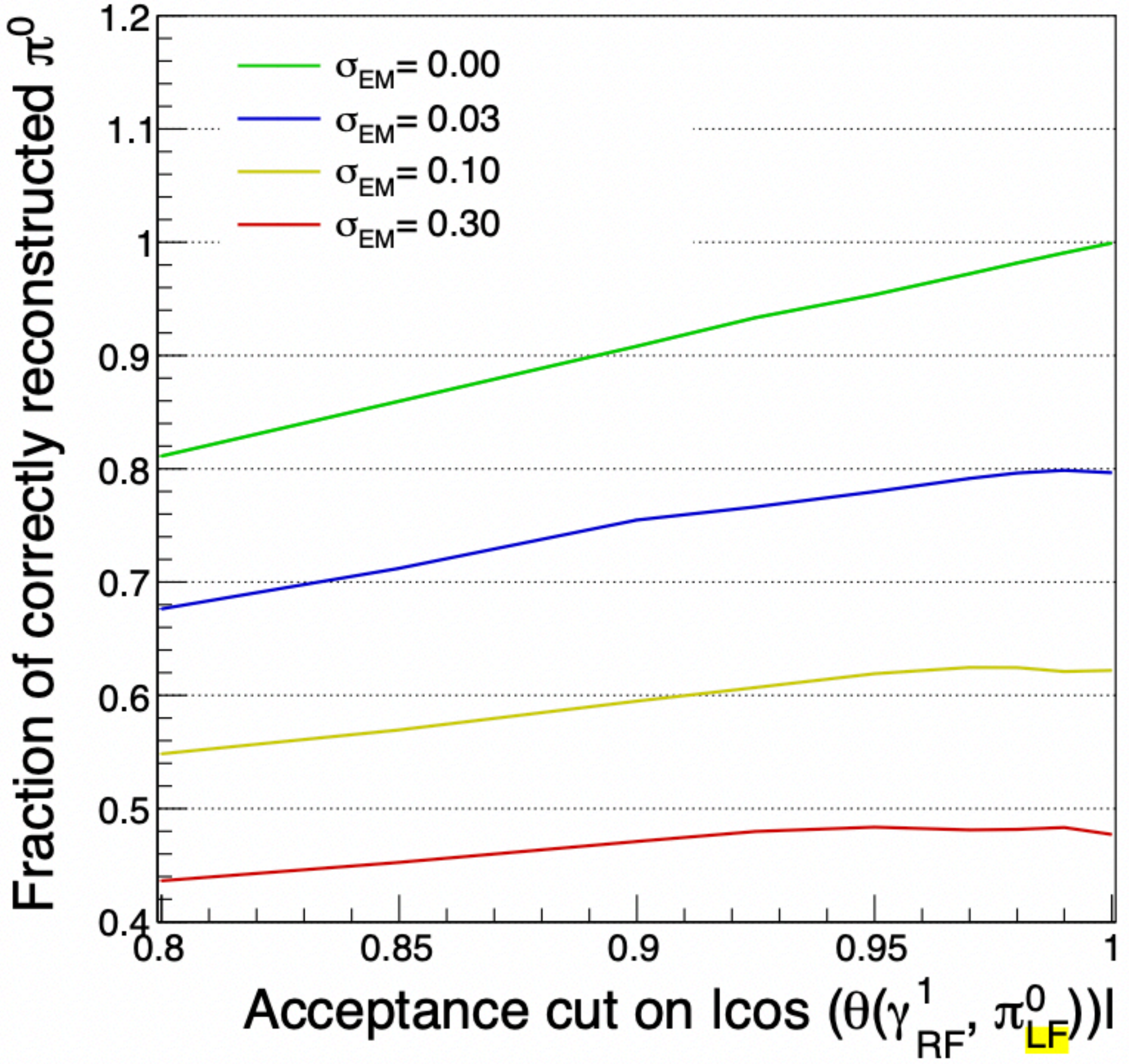

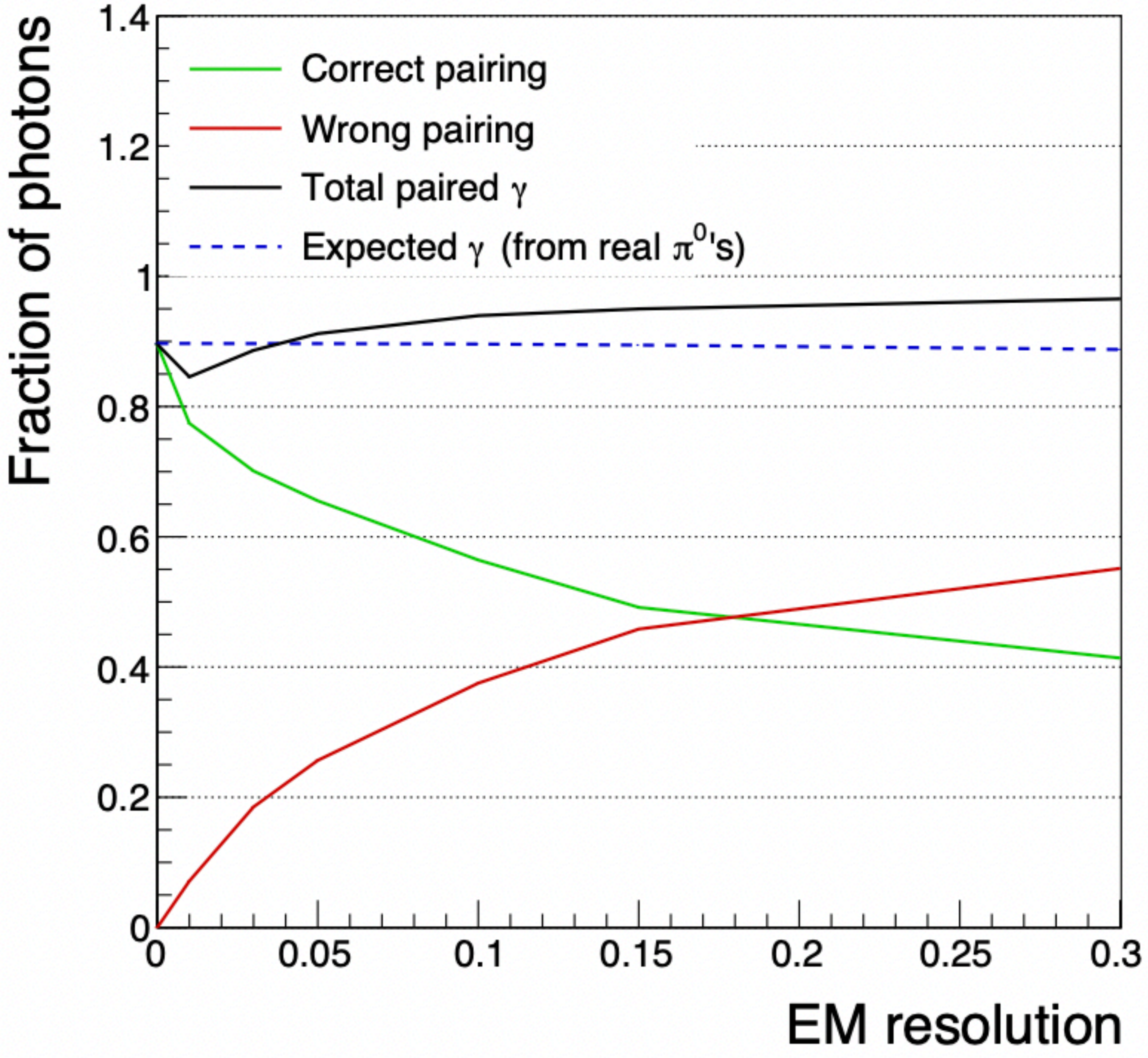

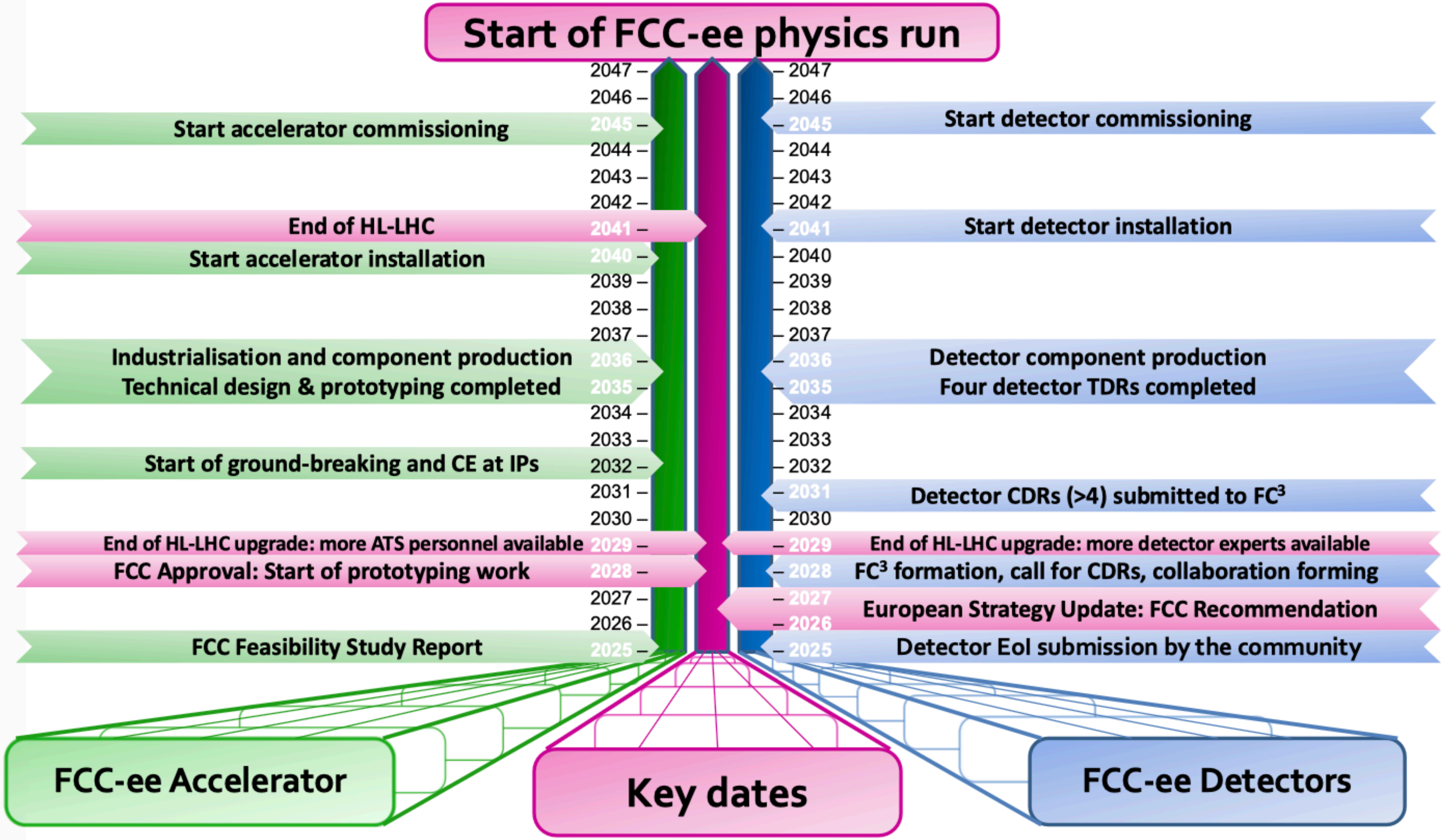
Start of FCC-ee physics run
2047
2046
2045
Start accelerator commissioning
Start detector commissioning
2044
2043
2042
2041
End of HL-LHC
Start detector installation
2040
Start accelerator installation
2039
2038
2037
2036
Industrialisation and component production
Detector component production
2035
Technical design & prototyping completed
Four detector TDRs completed
2034
2033
2032
Start of ground-breaking and CE at IPs
2031
Detector CDRs (>4) submitted to FC³
2030
2029
End of HL-LHC upgrade: more ATS personnel available
End of HL-LHC upgrade: more detector experts available
2028
FCC Approval: Start of prototyping work
FC³ formation, call for CDRs, collaboration forming
2027
2026
European Strategy Update: FCC Recommendation
2025
FCC Feasibility Study Report
Detector EoI submission by the community
FCC-ee Accelerator
Key dates
FCC-ee Detectors

Updated project cost for FCC-ee up to and including operation at ZH and 4 experiments
t-tbar upgrade requires additional 1.3 BCHF

Domain	**Cost [MCHF]**
Civil engineering	6160
Technical infrastructures	2840
Injectors and transfer lines	590
Booster and collider	4140
CERN contribution to four experiments	290
FCC-ee total	**14 020**
+ Four experiments (non-CERN part)	1300
FCC-ee total, including four experiments	**15 320**

Funding of FCC (and any other major future collider project) will come from two main sources:

- ❑ CERN Budget (i.e. revenues from Member and Associate Member States): would cover more than 50% of FCC investment cost
- ❑ External contributions:
  - additional voluntary contributions (in-cash or in-kind) from Member and Associate Member States
  - contributions from non-Member States
  - exploring possible contributions from the European Union in the next Multiannual Financial Framework (MFF 2028-2034)
  - exploring possible contributions of private donors (→ in Dec 2024, Council approved "*Policy for fundraising from private donors for scientific activities at CERN*")

Several funding models developed, based on different assumptions (e.g. constant or slightly increased CERN Budget)
→ final report will be submitted to Council and its subordinate bodies in August

Gianotti at FCC week 2025

FCC-ee

FCC-ee cost estimate (FSR 2025)

Capital cost (2024 CHF) for construction of the FCC-ee is summarised below. This cost includes construction of the entire new infrastructure and all equipment for operation at the Z, WW and ZH working points.

Domain	Cost [MCHF]
Civil engineering	6,160
Technical infrastructures	2,840
Injectors and transfer lines	590
Booster and collider	4,140
CERN contribution to four experiments	290
FCC-ee total	**14,020**
+ four experiments (non-CERN part)	1,300
FCC-ee total incl. four experiments	**15,320**

Note: Upgrade of SRF (800 MHz) & cryogenics for ttbar operation corresponds to additional cost of 1,260 MCHF

LCF / CLIC

Unit: MCHF	LCF 250 (LP)	Δ LCF 550 (FP)	CLIC 380	Δ CLIC 1500
Collider	3864	4204	2471	4684
Main Beam inj./transfer	1181	86	1046	23
Drivebeam inj./transfer	-	-	1060	302
Civil Engineering	2338	0	1403	703
Technical Infrastructure	1109	1174	1361	1404
Sum	**8492**	**5464**	**7341**	**7116**

LEP3

Cost Element	2 new Xpts	2 Exist Xpts
Accelerator	2705	2705
Injectors and Transfer Lines	295	295
Technical Infrastructures	435	435
Experiments	130	60
Civil Engineering	165	165
LHC Removal/LEP3 Installation	140	140
Total CERN (MCHF)	**3870**	**3800**
Experiments non-CERN part	900	270

FCC-hh (after FCC-ee)

Cost summary table in 2024 MCHF for the construction of FCC-hh.

Domain	FCC-hh Cost [MCHF]
FCC-ee dismantling	200
Collider*	13400
Injectors and transfer linear	1000
Civil Engineering	520
Technical infrastructures	3960
Experiments	N/A
Total	**19080**

*target price of 2.0 MCHF per 14.3 m long magnet with 1.0 MCHF of conductor, 0.5 MCHF for assembly, and 0.5 MCHF for components

Muon Collider

LHeC (cost estimate 2018, 60 GeV e-)

Budget Item	Cost
SRF System	805MCHF
SRF R&D and Proto Typing	31MCHF
Injector	40MCHF
Magnet and Vacuum System	215MCHF
SC IR magnets	105MCHF
Dump System and Source	5MCHF
Cryogenic Infrastructure	100MCHF
General Infrastructure and installation	69MCHF
Civil Engineering	386MCHF
Total	1756MCHF

→ ~2 BCHF (2025)