Rare decays at Future Colliders

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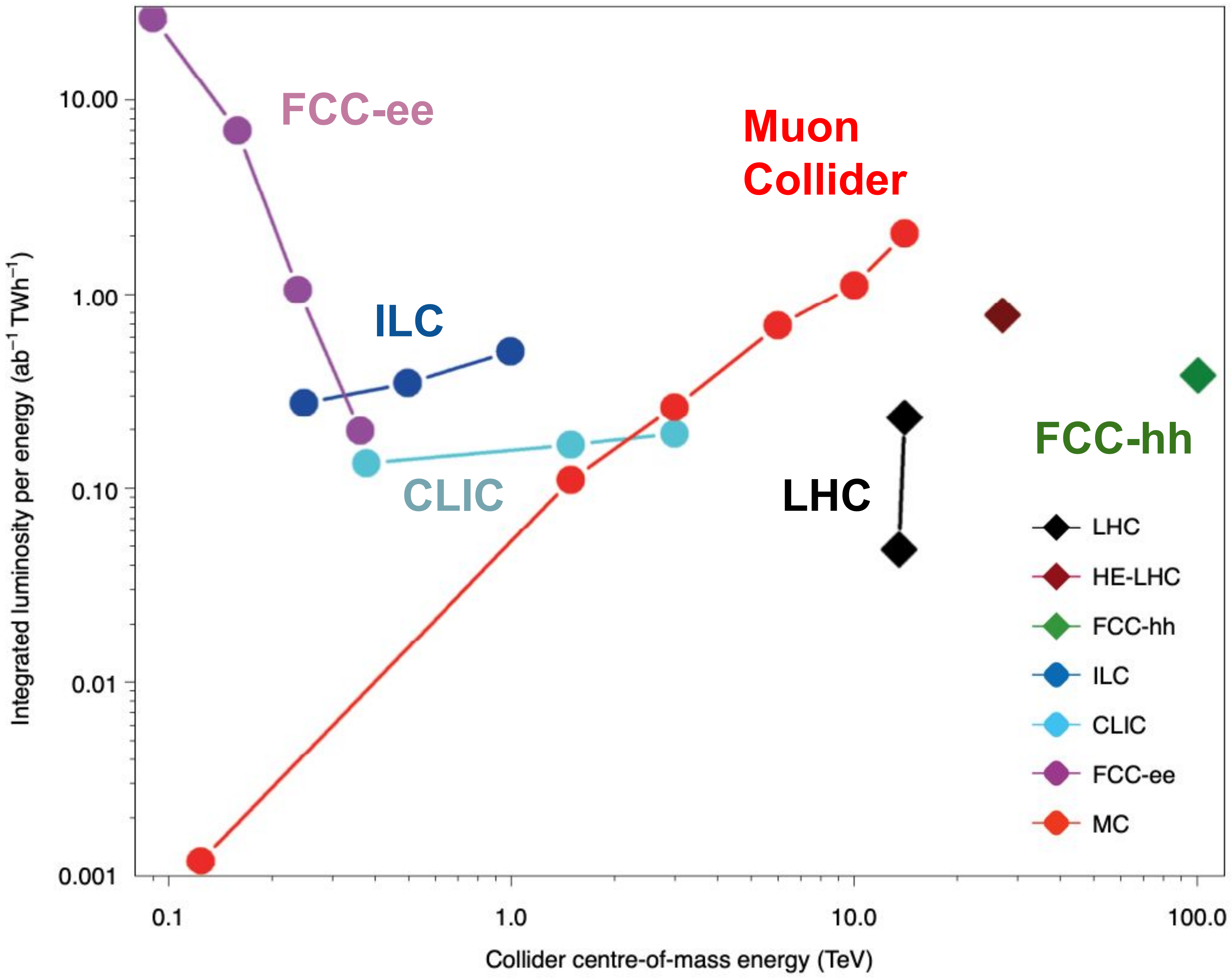
Future high intensity machines?

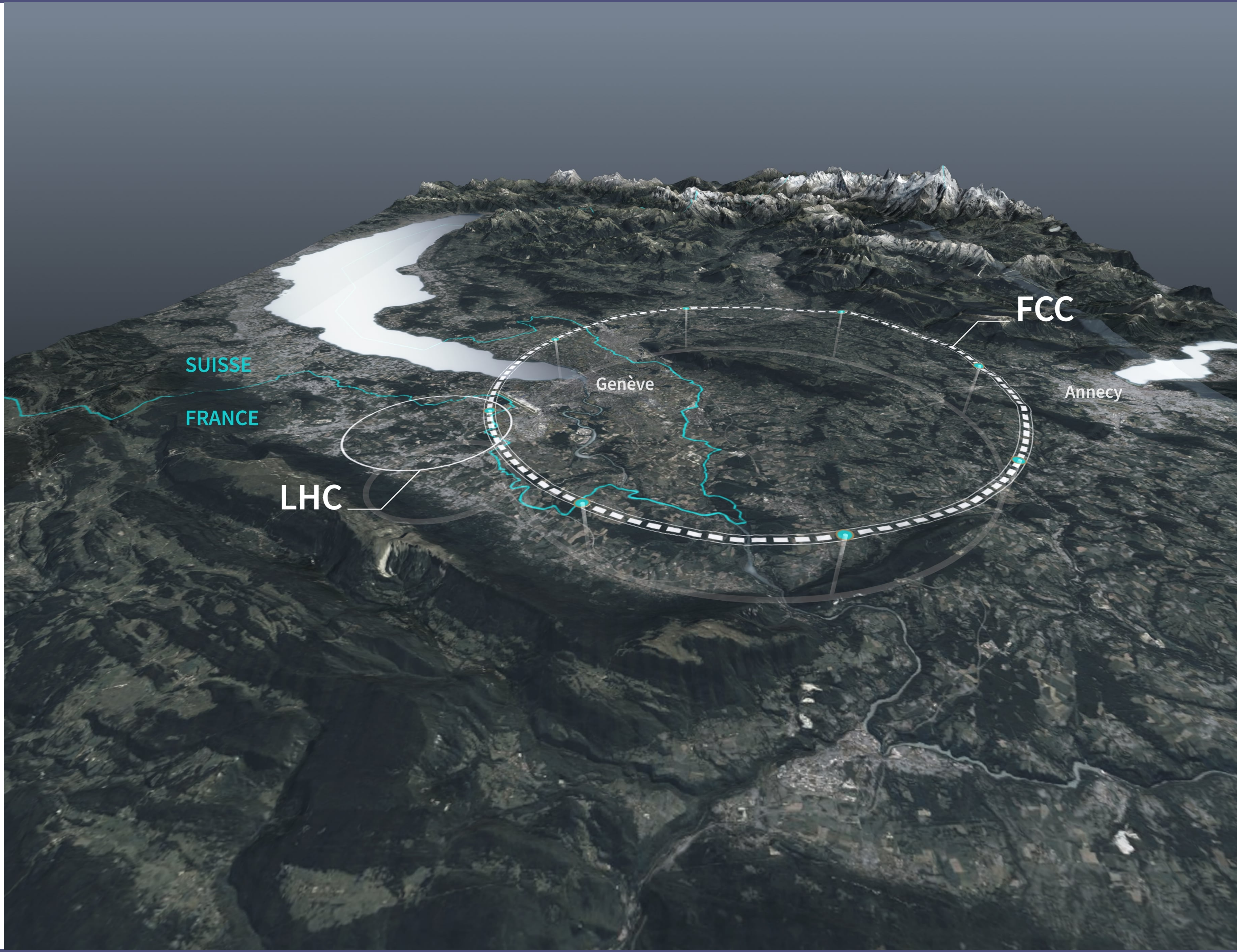
- **FCC-ee (CEPC)** is highly efficient at low COM
    - **High intensity** at the Z^0-pole
- **Muon colliders** increase efficiency with energy
    - **High intensity** at the **energy frontier**
- pp colliders (**FCC-hh**) simpler for **high intensity** and **energy frontier**, tricky for missing energy final states
- **Linear colliders** are excellent for cost-effective **energy frontier/Higgs factory** but not the best option for high intensity
- Physics potential has plenty "back of the envelope" values available



Integrated luminosity/energy as a function of COM energy
[Federico Meloni / arxiv:2007.15684]

The FCC-ee

- 91 km circumference
- 4 collision points
- 16 years operation
- 4-running periods; Z^0-pole, W^+W^-, Z^0H, $t\bar{t}$
- Most interest for rare decays is at the Z^0-pole
- Can upgrade to FCC-hh



The FCC-ee

- Z^0-pole run will deliver 6×10^{12} Z^0s in total
  - "LEP in a minute"
  - $\mathcal{O}(10^{12})$ beauty hadrons produced
    - About $10\times$ Belle II [arxiv:1808.10567]
    - LHCb UII expects $\mathcal{O}(10^{14})$ [LHCB-TDR-023]
- Fills a niche between LHCb and Belle II
- We must determine what kind of detectors we need

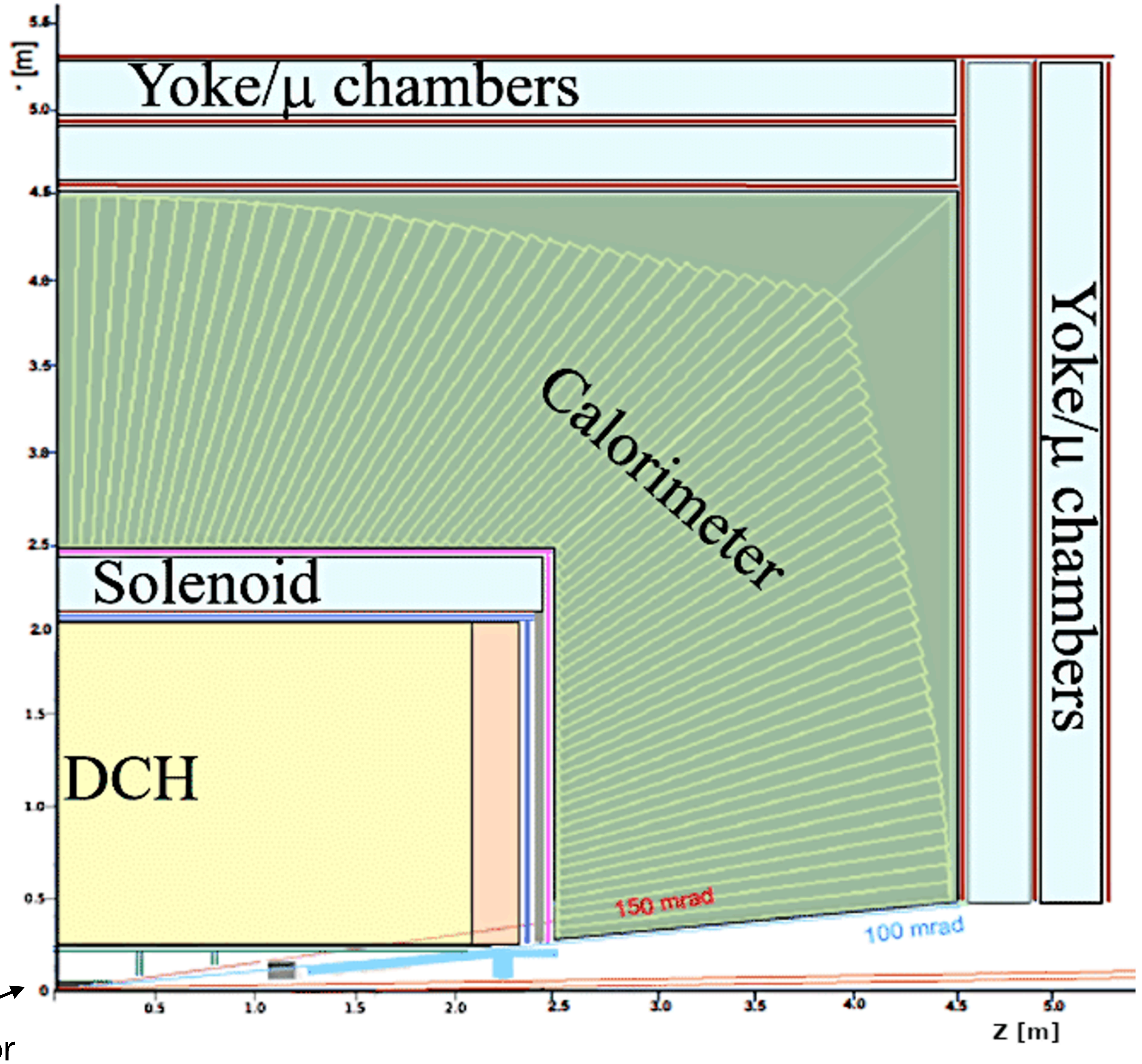
Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

Advantageous properties of Belle II ($\Upsilon(4S)$), LHC (pp) and FCC-ee (Z^0) [arxiv:2106.01259]

The IDEA detector

[Gabriella Gaudia: ICHEP 2022]

- One of the candidates for a future detector design
- Plenty development activity over the past few years
  - See talks at the FCC weeks and ECFA meetings
- Need to marry this work by detector experts with the physics requirements

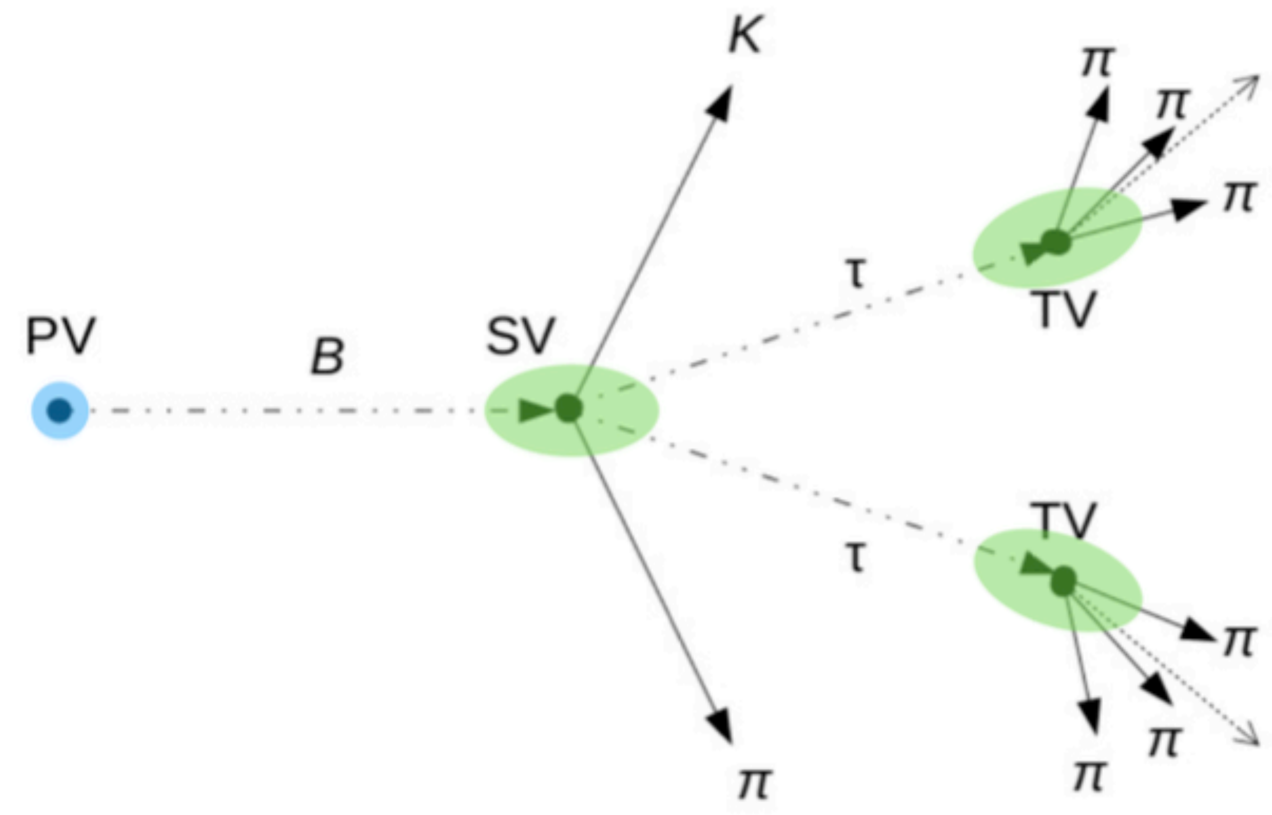


Quarter cross-section of the IDEA design

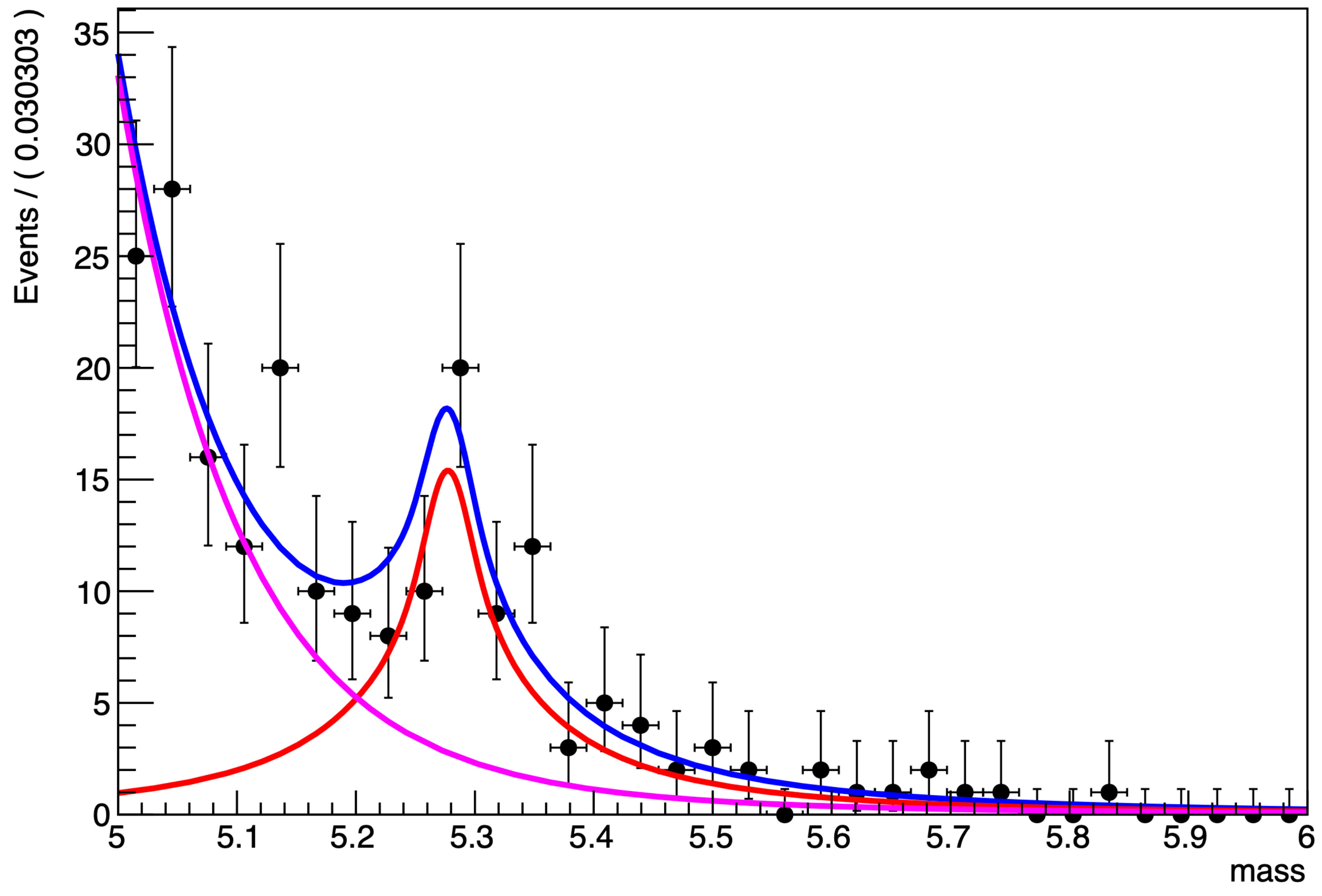
$B^0 \to K^{*0}\tau^+\tau^-$

[Tristan Miralles, Stephane Monteil]

- $b \to s\tau^+\tau^-$ yet to be observed - $\mathcal{O}(10^{-7})$ BF
  - Not expected at Belle II, expect limit $\mathcal{O}(10^{-5})$ - $\mathcal{O}(10^{-4})$
  - Current limit from BABAR $\mathcal{O}(10^{-4})$ - $\mathcal{O}(10^{-3})$ [arxiv:1605.09637]
- Many NP models expect NP to couple primarily to the Higgs and the third generation Ben Stefanek: 2nd ECFA Workshop 2023
- Focus on the the 3-prong $\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}$ decay
- Use energy-momentum conservation to resolve ν kinematics
- BDT trained with candidate kinematics to reduce backgrounds
- Signal yield extracted with an unbinned ML fit to the candidate B mass



Schematic of the signal decay

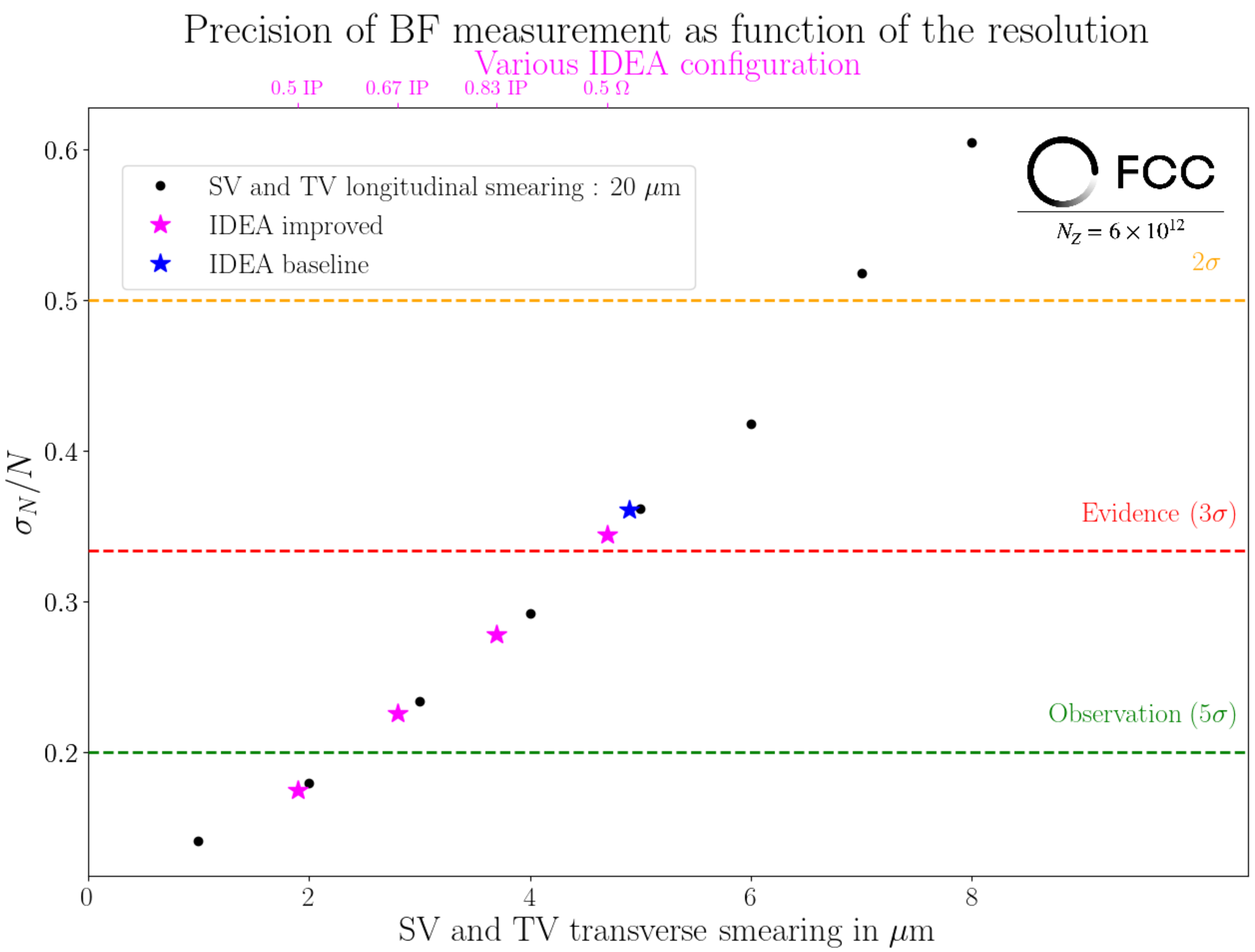


B^0 candidate invariant mass fit to rescaled signal and background MC

Vertex detector performance

[Tristan Miralles, Stephane Monteil]

- Emulate improved IP resolution
  - Significantly improves potential
- 30% improved single hit resolution $\implies > 3\sigma$
- Material budget found to be main limitation
- Very challenging



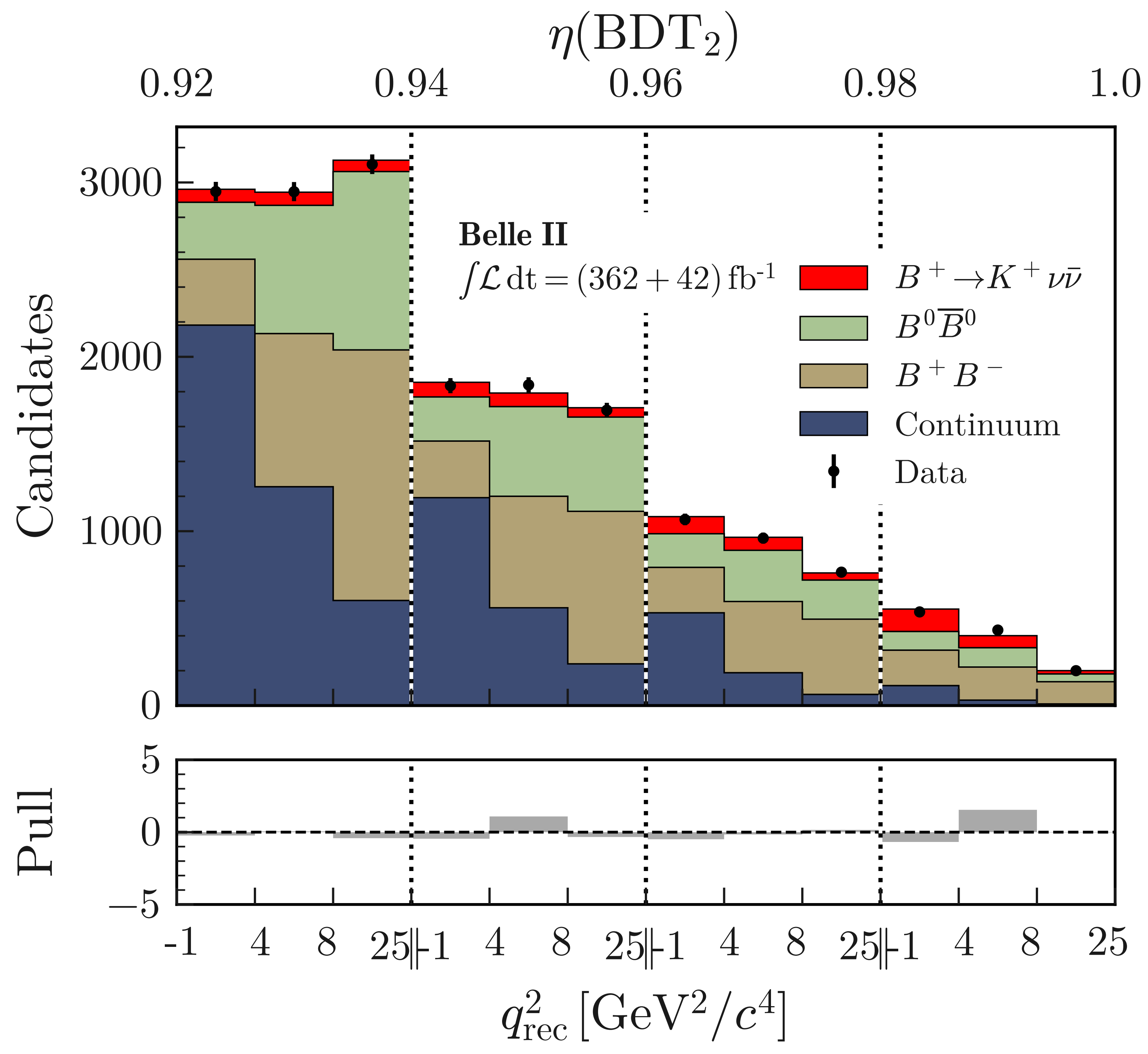
$B^0 \to K^{*0}\tau^+\tau^-$

[Tristan Miralles, Stephane Monteil]

- Current FCC-ee and IDEA would not allow for discovery of this mode
  - Trying to play with detector performance - can get beyond 3 and even 5σ
- Clearly some work to do!
  - Better vertexing?
    - Easier said than done
  - Higher luminosity/longer run period?
    - Difficult/competition with other runs
  - **Consider other τ decays?**
    - **Leptonics harder to handle but would produce $\mathcal{O}(10)$ times the data**

$b \to s\nu\bar{\nu}$ motivation

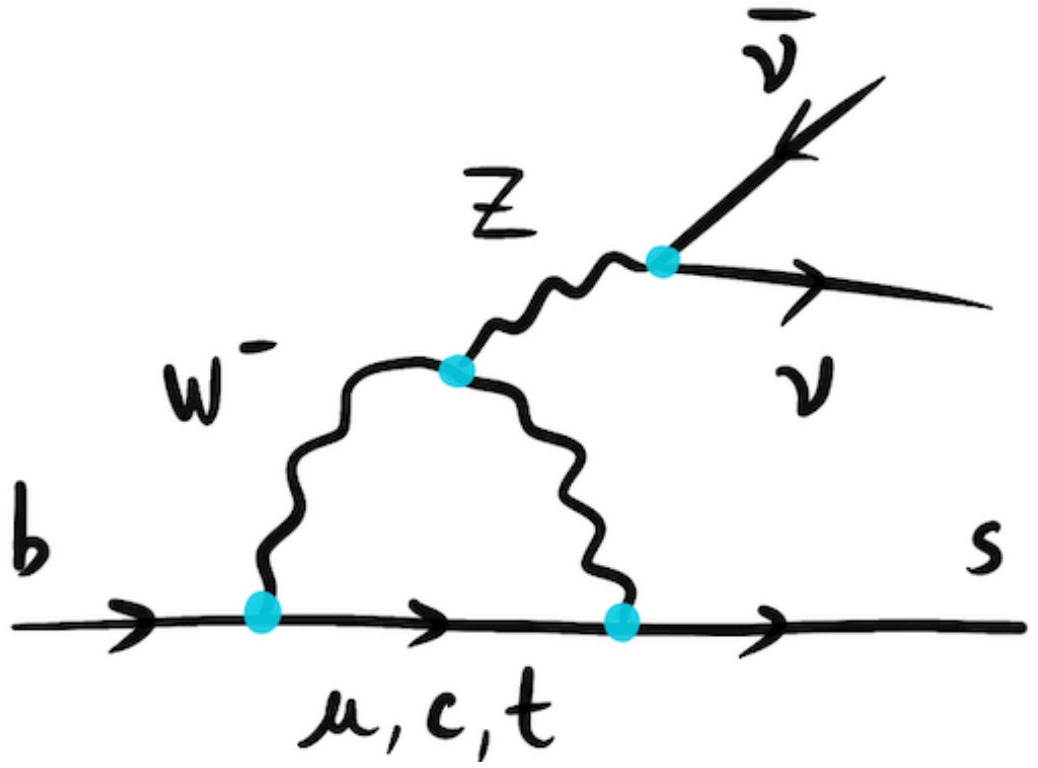
- Impossible at LHCb
- Yet to be observed, besides evidence for $B^+ \to K^+\nu\bar{\nu}$
  - 2.7σ tension with SM [arxiv:2311.14647]
- Theoretically cleaner than the corresponding $b \to sl^+l^-$
  - No long-distance charm loops!
  - Very nice for spotting BSM effects
  - Again 3rd generation leptons
- Plenty of theory interest, e.g $R_Y^{l/\nu} = \dfrac{\mathcal{B}(B \to Yl^+l^-)}{\mathcal{B}(B \to Y\nu\bar{\nu})}$ [arxiv:2309.11353]
- Novel probes of CPV from new physics [arxiv:2208.10880]

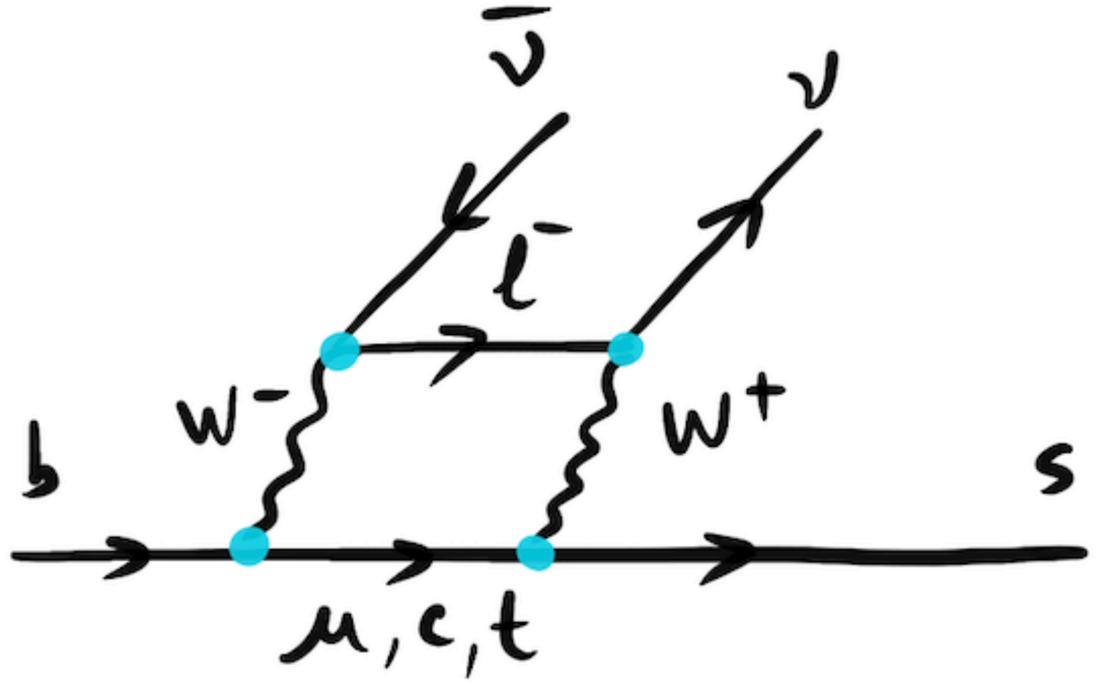


Plot of the maximum likelihood fit for $B^+ \to K^+\nu\bar{\nu}$ from inclusive tagging

Decay	B-factories	FCC-ee
$B^+ \to K^+\nu\bar{\nu}$	✔	✔
$B^+ \to K^{*+}\nu\bar{\nu}$	✔	✔
$B^0 \to K^0_S\nu\bar{\nu}$	✔	✔
$B^0 \to K^{*0}\nu\bar{\nu}$	✔	✔
$B^0_s \to \phi\nu\bar{\nu}$	✗	✔
$\Lambda^0_b \to \Lambda^{(*)0}\nu\bar{\nu}$	✗	✔

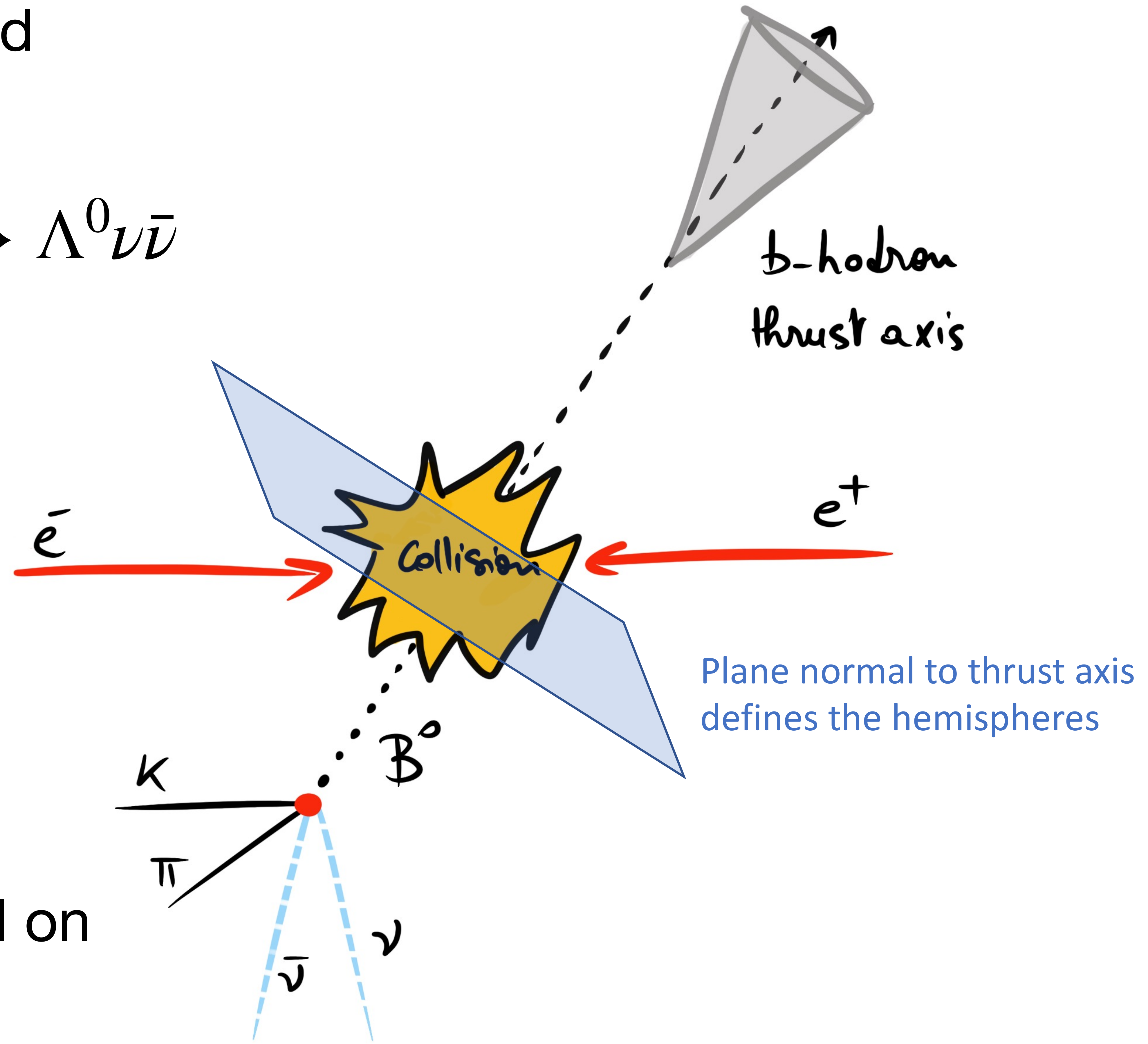
B decays accessible by B-factories and FCC-ee





Analysis setup

- Simulated datasets of the signal mode and inclusive background samples
  - Signal modes: $B^0 \to K^{*0}\nu\bar{\nu}$, $B_s^0 \to \phi\nu\bar{\nu}$, $B^0 \to K_S^0\nu\bar{\nu}$, $\Lambda_b^0 \to \Lambda^0\nu\bar{\nu}$
  - $b\bar{b}$, $c\bar{c}$ and $q\bar{q}$ with $q \in \{u, d, s\}$
- Decay topology split into high- and low-energy hemispheres
  - Defined by thrust axis $T = \sum_p \frac{|p \cdot \hat{n}|}{|p|}$
- Build s particle candidates from their expected final state based on vertex/track properties

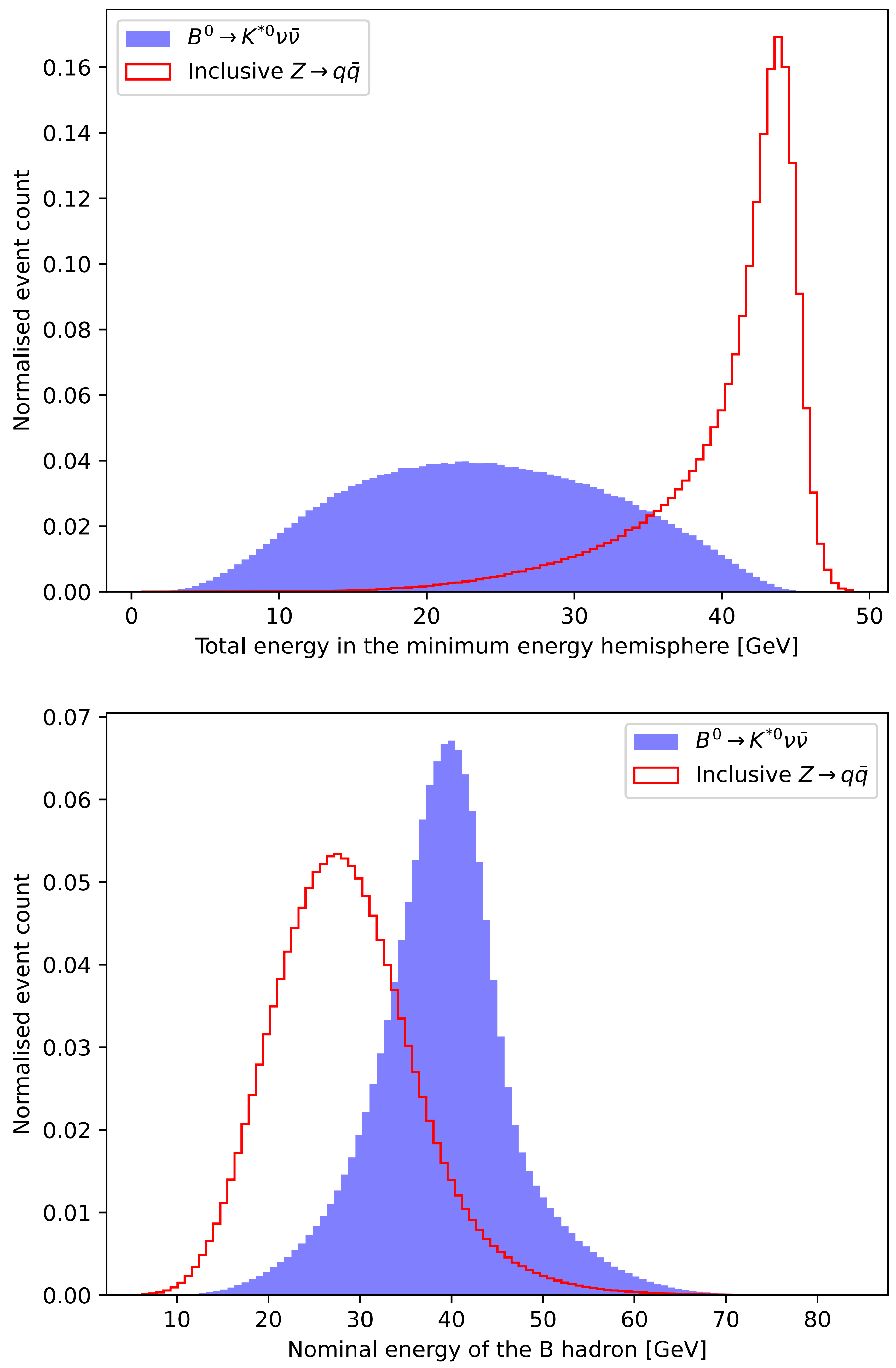


Sketch of a $B^0 \to K^*\nu\bar{\nu}$ event

Analysis setup

[arxiv:2309.11353]

- "Simple" analysis
- 2-stage BDT selection: Hemisphere properties followed by candidate properties
- Use bi-cubic splines to build efficiency maps of BDT cuts
  - $S(\epsilon^s_{\text{BDTs}}) = 2N_Z\,\mathscr{B}(Z\to b\bar{b})\,f_B\,\mathscr{B}(B\to Y\nu\bar{\nu})\,\mathscr{B}(Y\to f)\,\epsilon^s_{\text{pre}}\epsilon^s_{\text{BDT}}$
  - $B(\epsilon^x_{\text{BDTs}}) = \sum_{x\in\{b\bar{b},c\bar{c},q\bar{q}\}} 2N_Z\,\mathscr{B}(Z\to x)\,\epsilon^x_{\text{pre}}\,\epsilon^x_{\text{BDTs}}$
  - Optimise $S/\sqrt{S+B}$ as a function of ϵ^s_{BDTs}, ϵ^x_{BDTs} in the efficiency maps

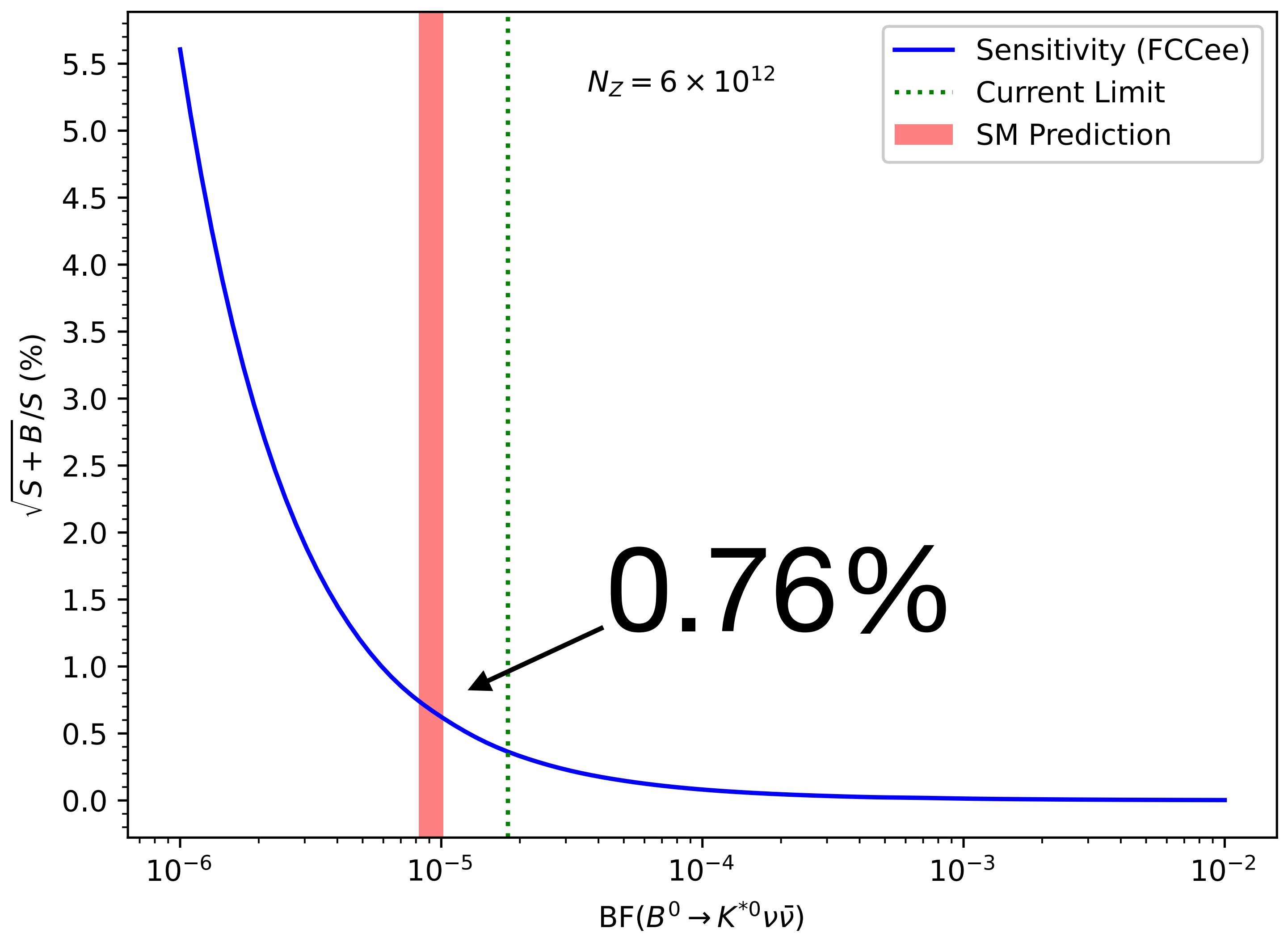


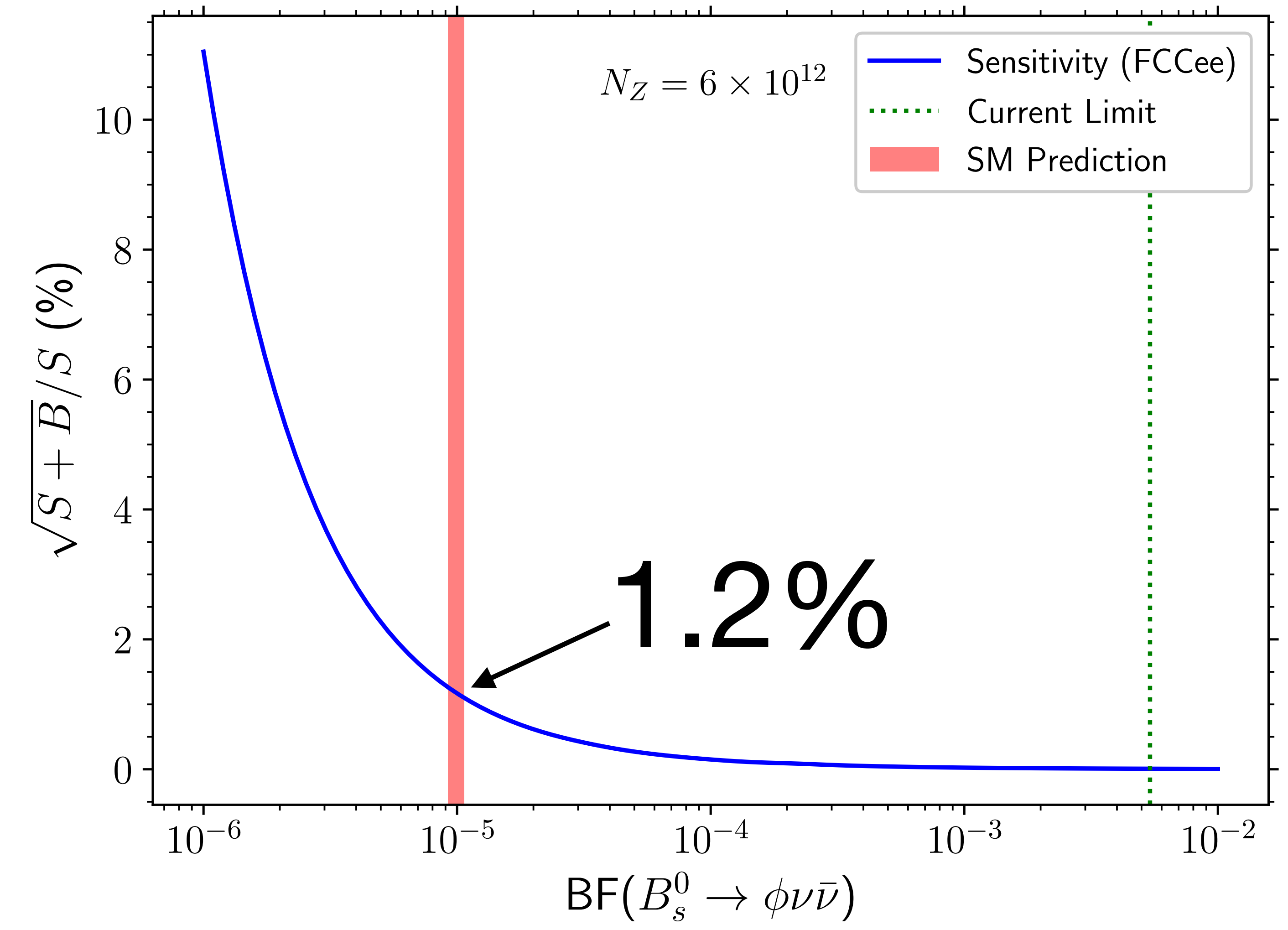
Most significant Stage 1 (top) and Stage 2 (bottom) features

$b \to s\nu\bar{\nu}$ BF sensitivity

[arxiv:2309.11353]

- Belle II expects $\mathcal{O}(10\%)$ uncertainty on $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$ with 50 ab^{-1}
  - Exciting potential with $B^+ \to K^+\nu\bar{\nu}$
- FCC-ee assuming perfect vertex seeding and PID:
  - $\mathcal{O}(1\%)$ uncertainty for $B^0 \to K^{*0}\nu\bar{\nu}$ & $B_s^0 \to \phi\nu\bar{\nu}$
  - $\mathcal{O}(3\%)$ uncertainty for $B^0 \to K_S^0\nu\bar{\nu}$
  - $\mathcal{O}(10\%)$ uncertainty for $\Lambda_b^0 \to \Lambda^0\nu\bar{\nu}$
- CEPC study for $B_s^0 \to \phi\nu\bar{\nu}$ [arxiv:2201.07374]



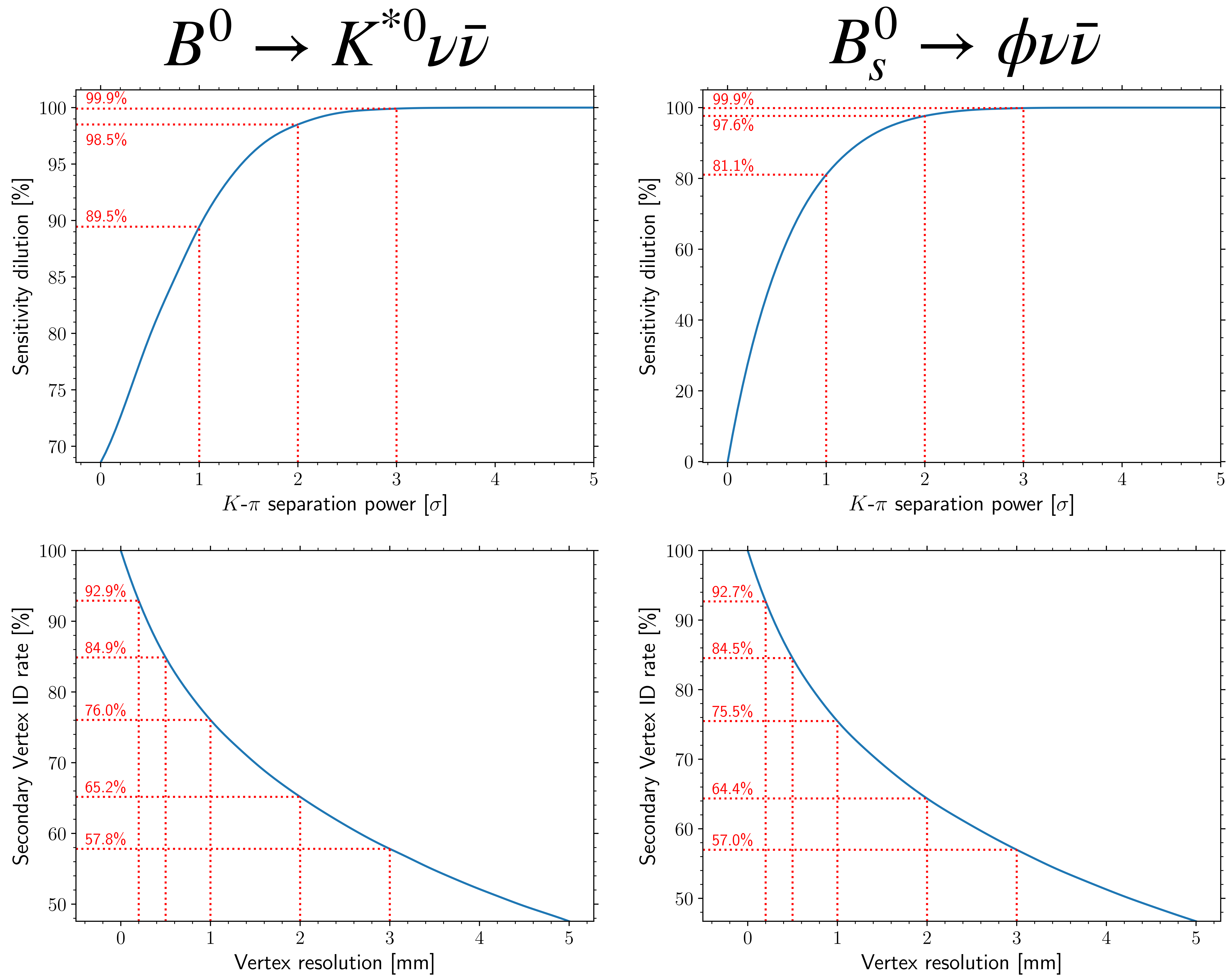


Sensitivity estimate as a function of BF for $B^0 \to K^{*0}\nu\bar{\nu}$ (top) & $B_s^0 \to \phi\nu\bar{\nu}$ (bottom)

$b \to s\nu\bar{\nu}$ detector requirements

[arxiv:2309.11353]

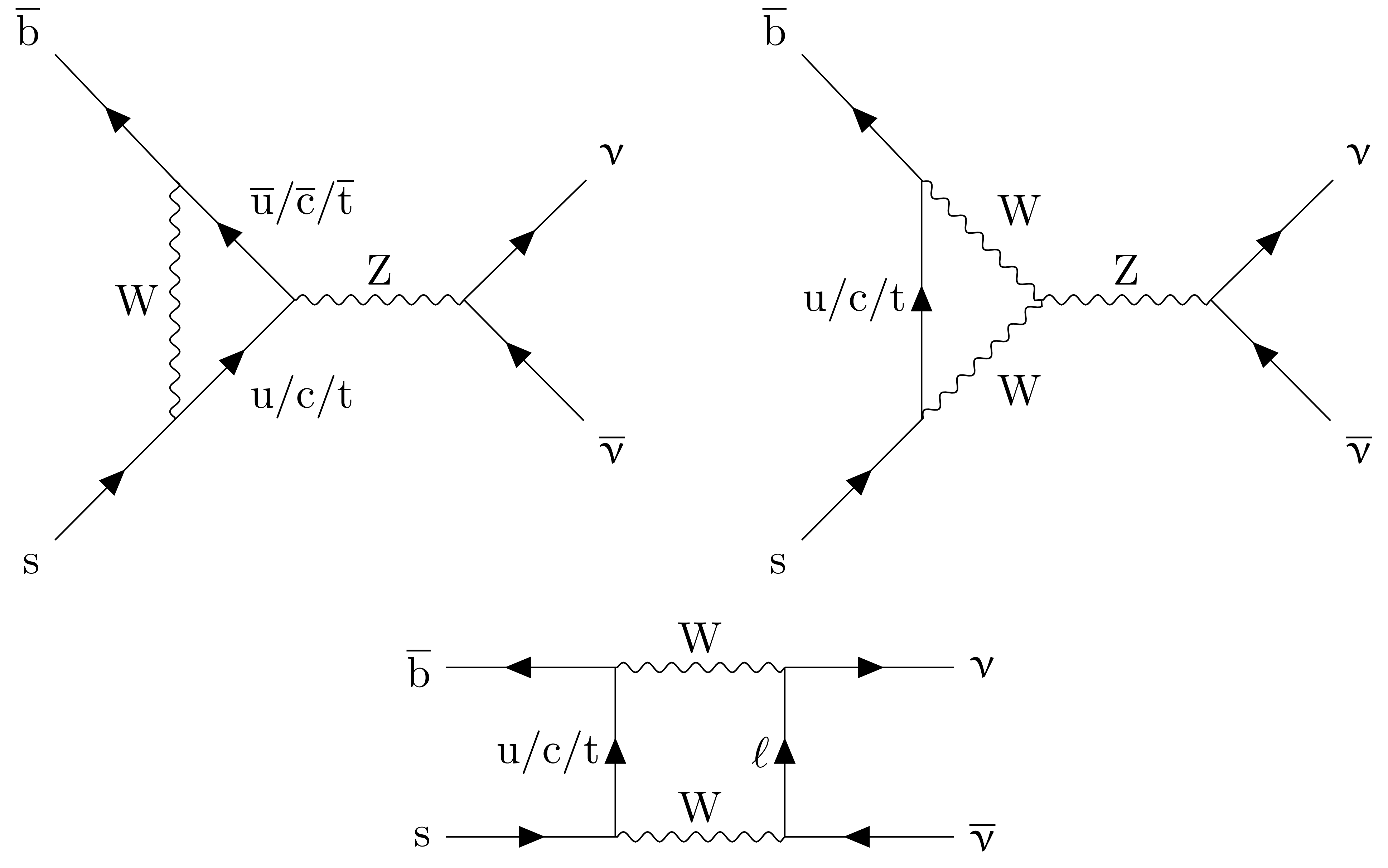
- Robust against $\pi - K$ mis-ID with at least $\sim 2\sigma$ separation
- Require ≤ 0.2mm vertex resolution
  - Well above the expected resolution $\mathcal{O}(10\mu\text{m})$
- More detailed studies in the future to evaluate the full detector requirements



$B^0_{(s)} \to \nu\bar{\nu}(\nu\bar{\nu})(\gamma)$

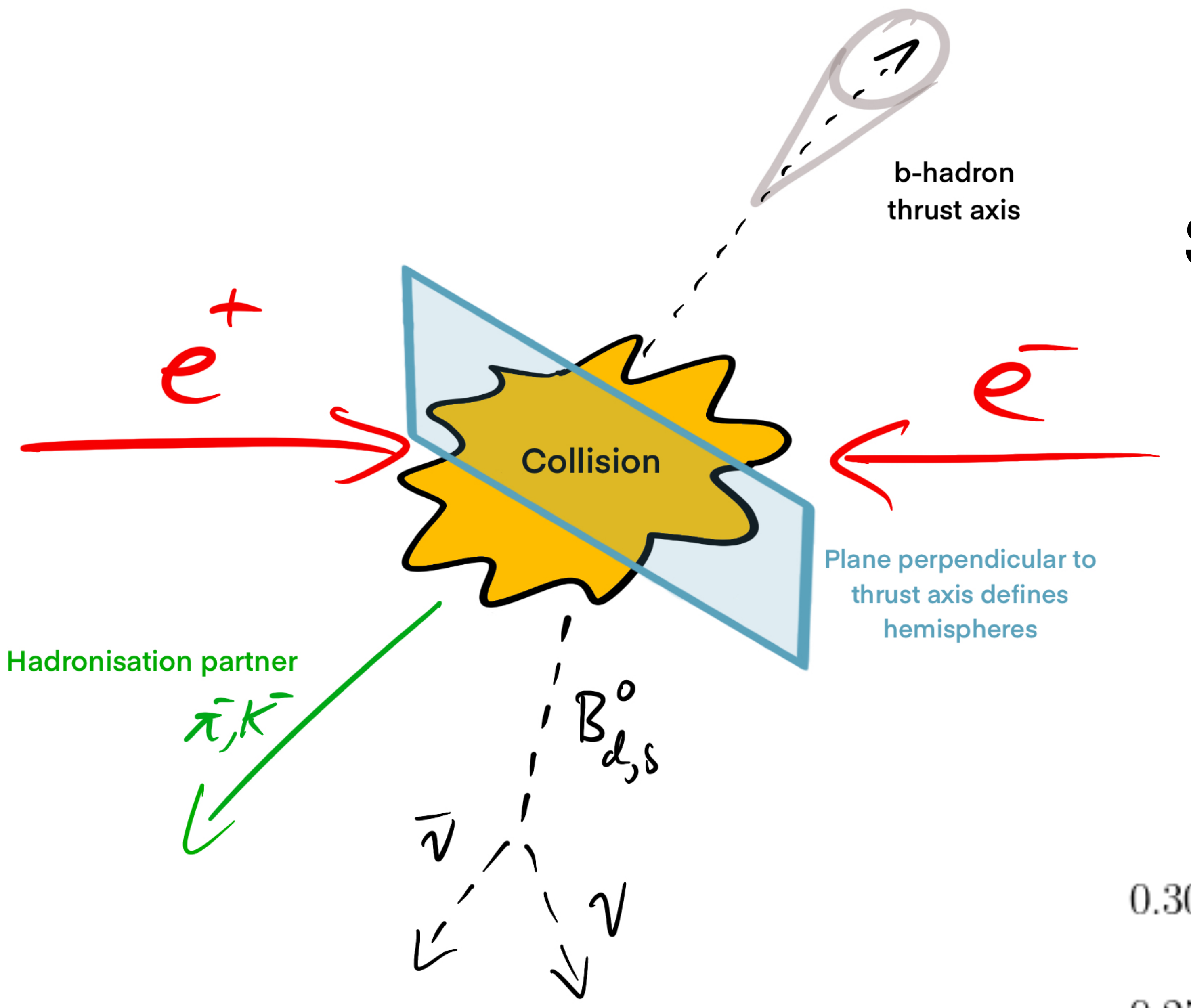
[PÁ Cartelle, M Kenzie, R Mangrulkar, ARW, E Wood]

- All are yet to be observed
  - Assuming $m_\nu = 0$
    helicity suppression $\Longrightarrow \mathscr{B}(B^0_{(s)} \to \nu\bar{\nu}) = 0$
  - With $m_\nu > 0$ suppressed $\propto (m_\nu/m_B)^2$ - $\mathscr{O}(10^{-25})$
  - $\mathscr{B}(B^0_{(s)} \to \nu\bar{\nu}\nu\bar{\nu})$ - $\mathscr{O}(10^{-15})$ [arxiv:1809.04606]
  - $\mathscr{B}(B^0_{(s)} \to \nu\bar{\nu}\nu\bar{\nu}\gamma)$ - $\mathscr{O}(10^{-9})$ [arxiv:9604378]
- Belle II expect sensitivity down to 10^{-6} for B^0 and 10^{-5} for B^0_s
- γ mode potentially in reach of a Tera-Z facility with SM conditions
- Otherwise observation $\Longrightarrow$ **unambiguous new physics**

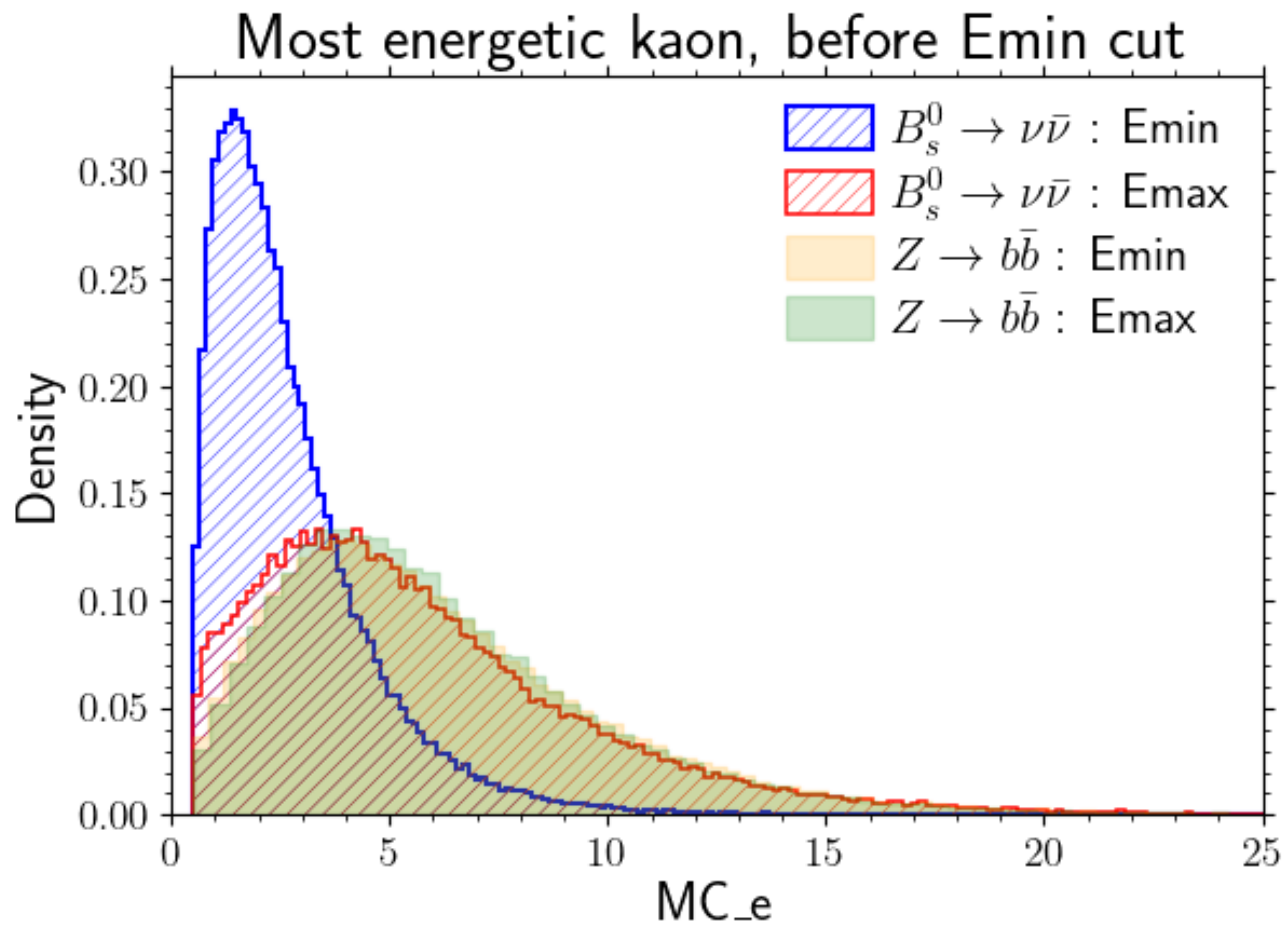


Simplest Feynman diagrams for $B^0_s \to \nu\bar{\nu}$

- Study is WIP - just B^0_s for now
- Analysis setup like $b \to s\nu\bar{\nu}$
- No s candidate to build
  - Signal hemisphere $\implies$ hardest h from hadronisation: low p, from PV
  - Other $\implies$ hardest h from a decay: high p, displaced vertex

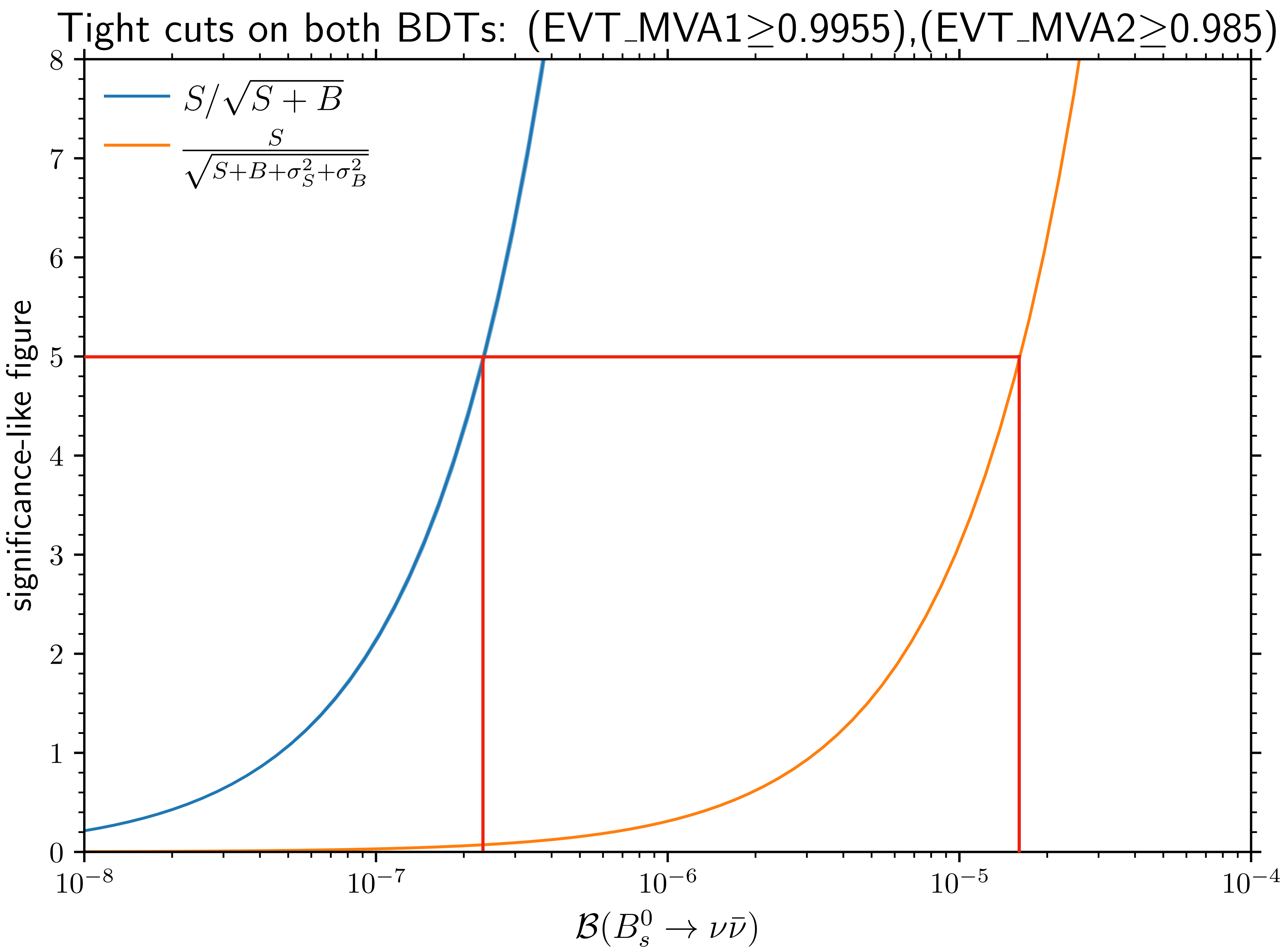


Sketch of a $B^0_{(s)} \to \nu\bar{\nu}$ event



Signal and background separation from hadronisation partner kinematics

- Clearly needs more work to squeeze down below 10^{-5}
- Highly dependent on efficiency of background rejection
  - Considering exclusive MC samples



Dependence of significance on BF: with perfect background expectation (blue) and including the error on the S, B expectations (orange)

Not an exhaustive list

- Ratio of $B^0_{(s)} \to \mu^+\mu^-$, powerful test of minimal flavour violation
- $b \to s\mu^+\mu^-$ beyond the HL-LHC high-p_T searches (FCC-hh/μ) [arxiv:2205.13552]
- $b \to s\gamma, b \to se^+e^-$
- Other flavour rare decays
- $H/t\bar{t}$ runs
  - Flavour violation - $H \to bs, cu$ & $H \to \tau\mu, \tau e$ (similar for Z^0) [arxiv:1209.1397, arxiv:1202.5704]
  - $t \to Hc, Hu$
- Muon colliders
  - $\mu^+\mu^- \to b\bar{s} + s\bar{b}$ complementary probes to $b \to s\mu^+\mu^-$

Summary

- FCC-ee can fill the niche between LHCb and Belle II
  - Rely on building from previous knowledge - e.g. SuperKEKB luminosity struggles
- Never before observed processes will be possible
  - $B_s^0 \to \phi\nu\bar{\nu}$, $\Lambda_b^0 \to \Lambda^0\nu\bar{\nu}$
  - $b \to s\tau^+\tau^-$
  - Potential for differential measurements, novel CPV searches etc…
- Existing limits and branching fractions will be improved upon
- Future work
  - Consider $B^+ \to K^+\nu\bar{\nu}$ and $B_c^+ \to D^+\nu\bar{\nu}$
  - Detailed detector requirement studies
- Muon colliders can provide complementary high intensity experiments

Thanks for listening

- Inspiration from
  - Matt Kenzie - ECFA-UK
  - Yasmine Amhis - QCD@LHC 2024
  - Jure Zupan - Inaugural US Muon Collider Meeting