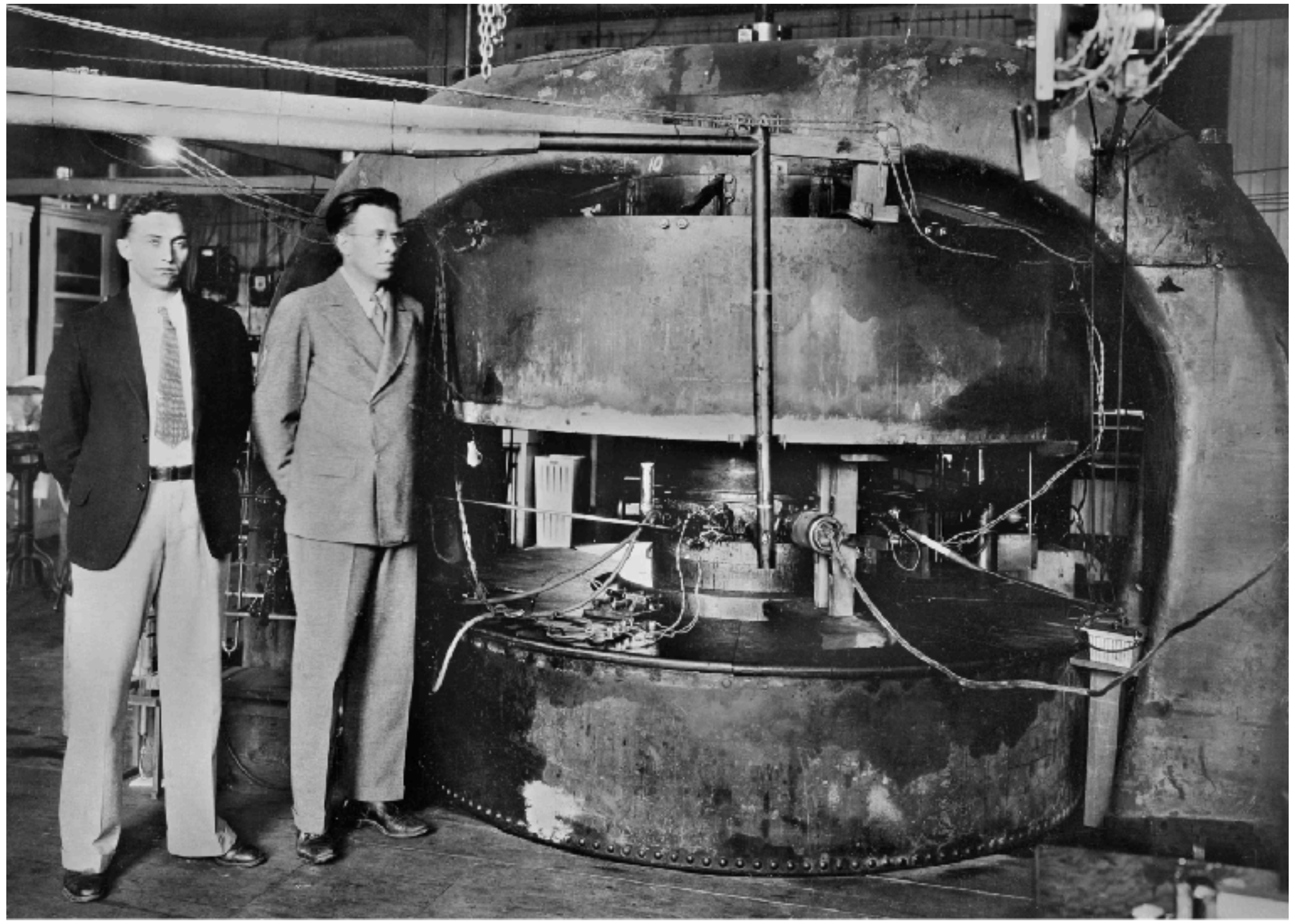
Higgs Physics and Resonance Searches at 10 TeV Wakefield Colliders

Kevin Langhoff

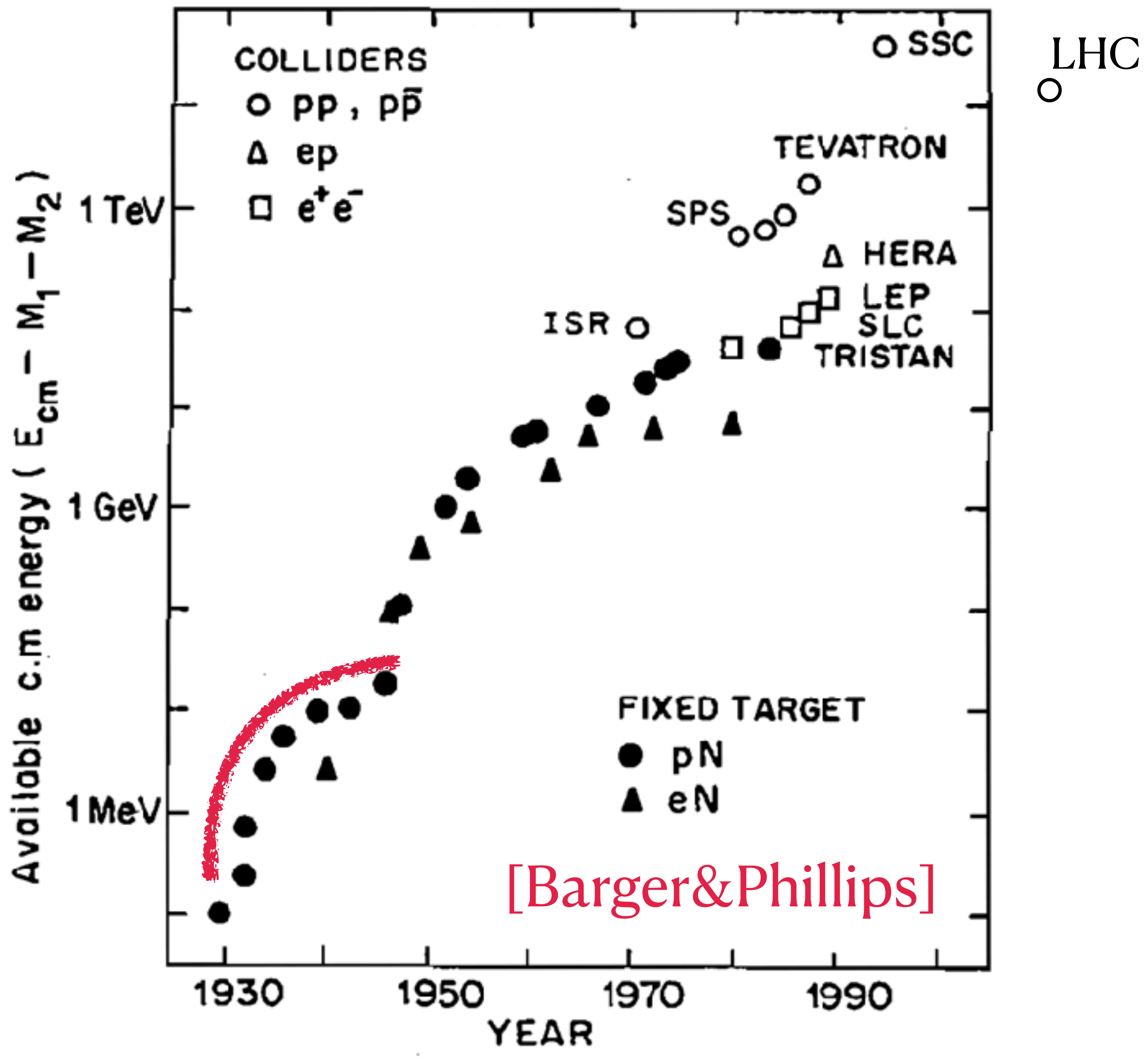
August 31, 2026

Obvious Statement

Discovery correlates with technological advancement.



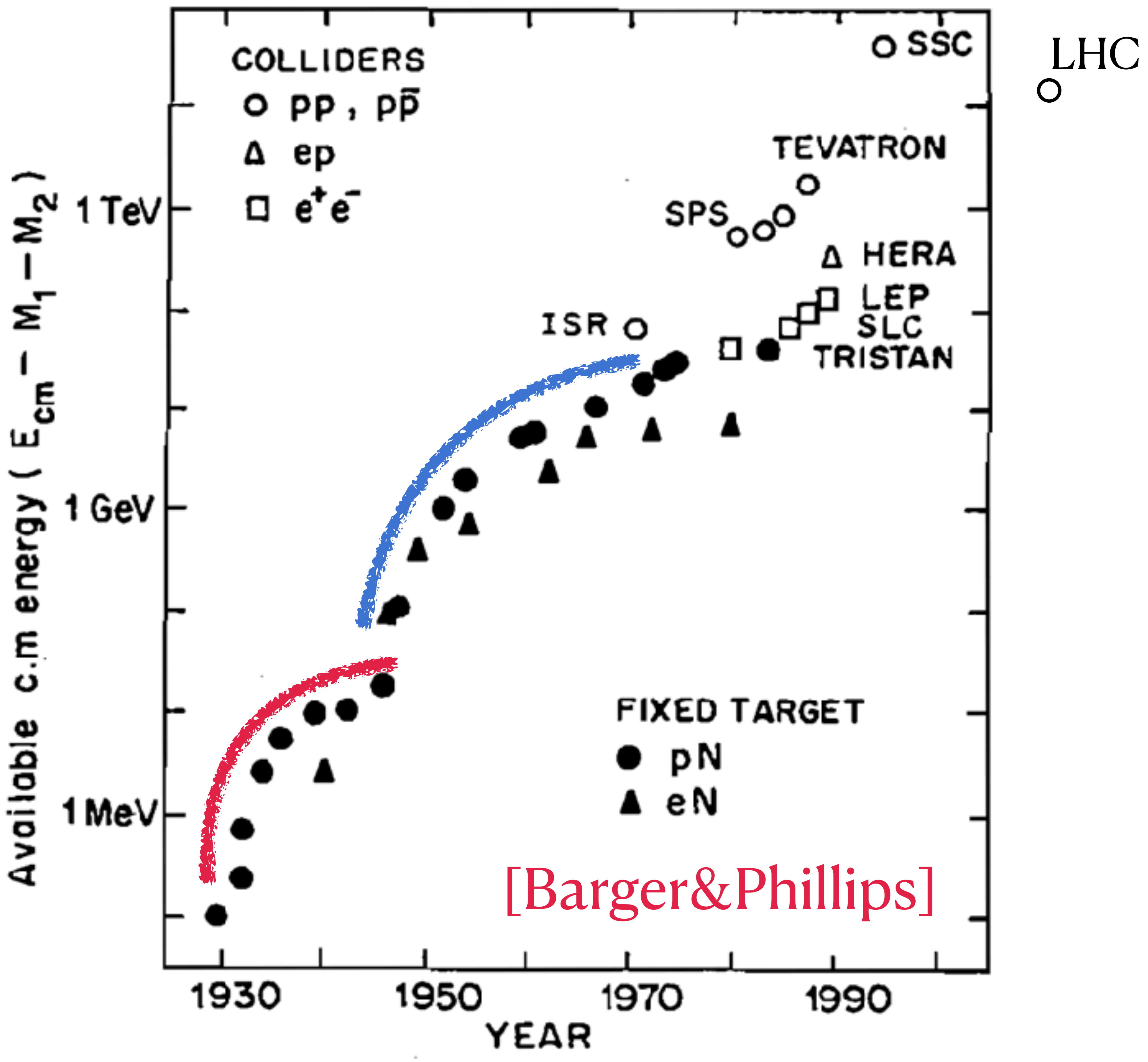
Cyclotron Era



Obvious Statement

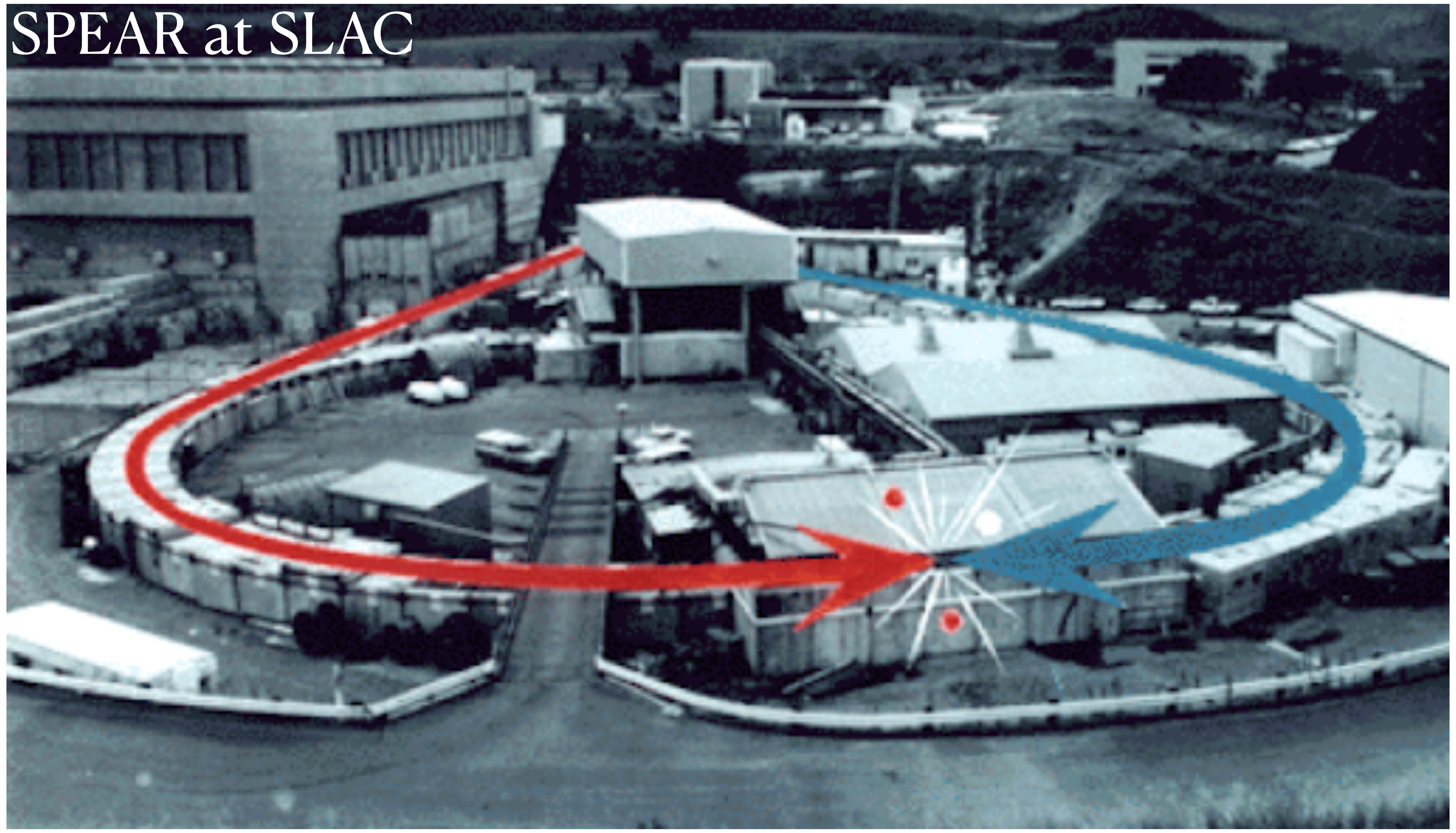
Discovery correlates with technological advancement.

Synchrotron Era

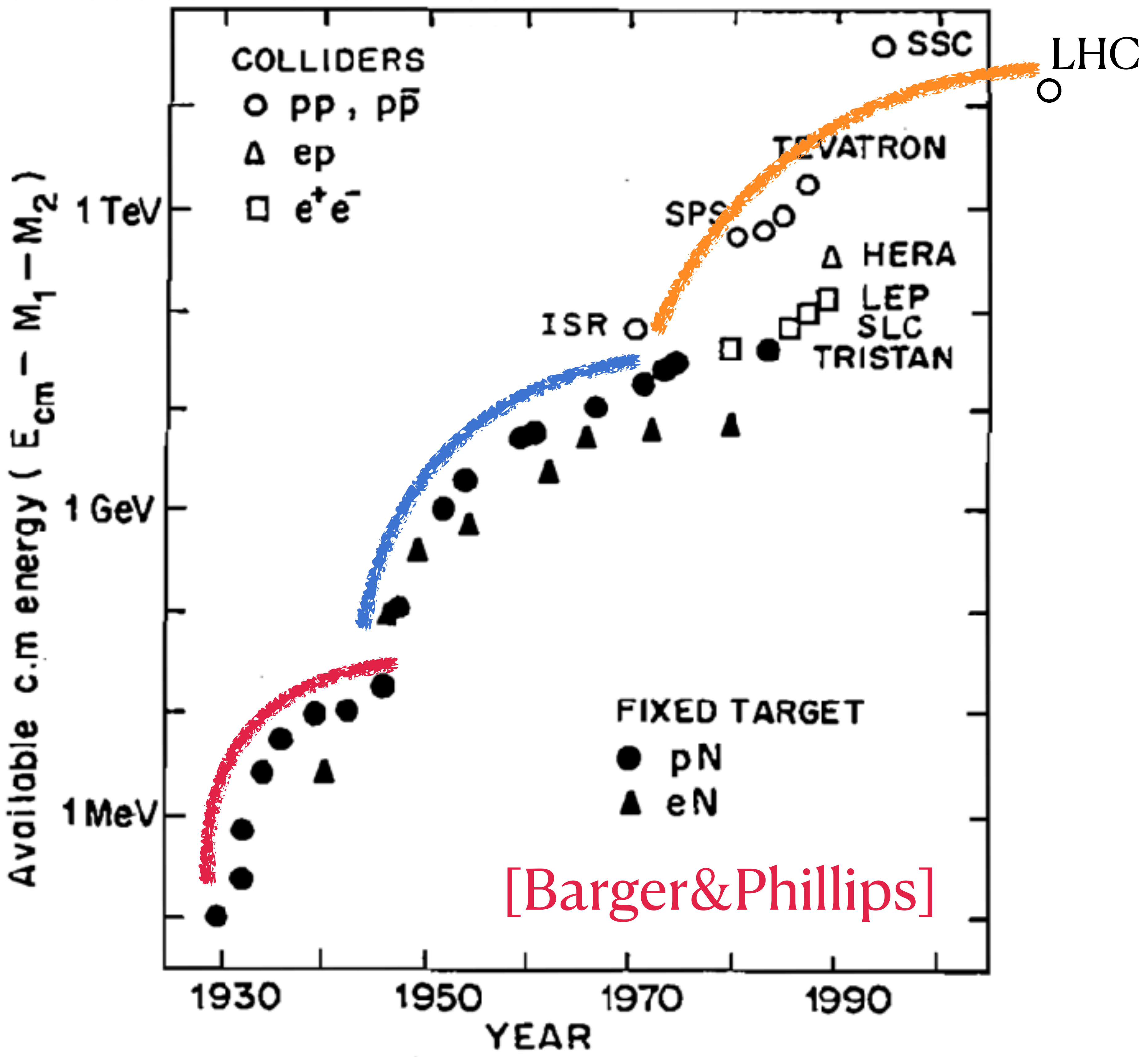


Obvious Statement

Discovery correlates with technological advancement.

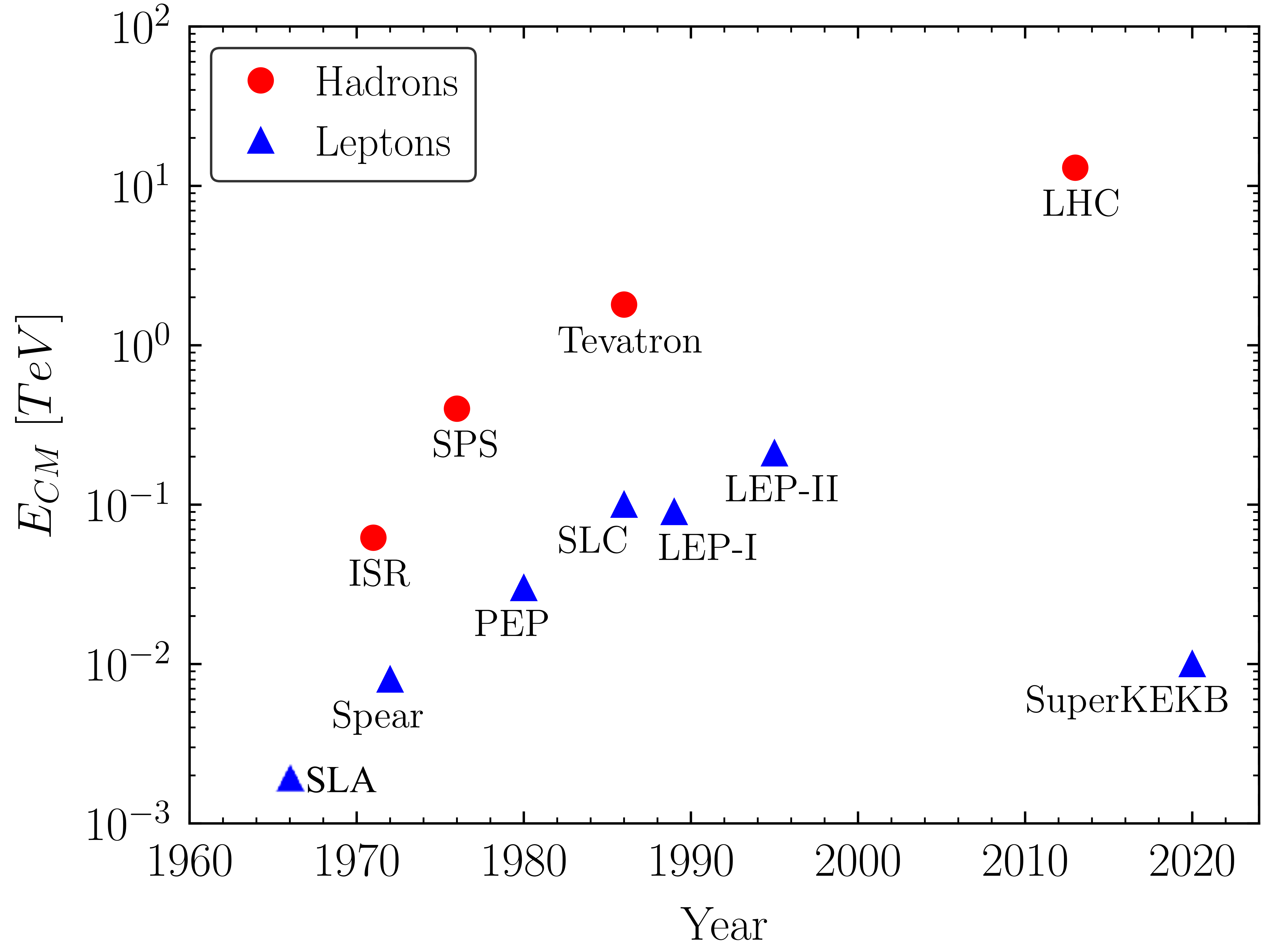


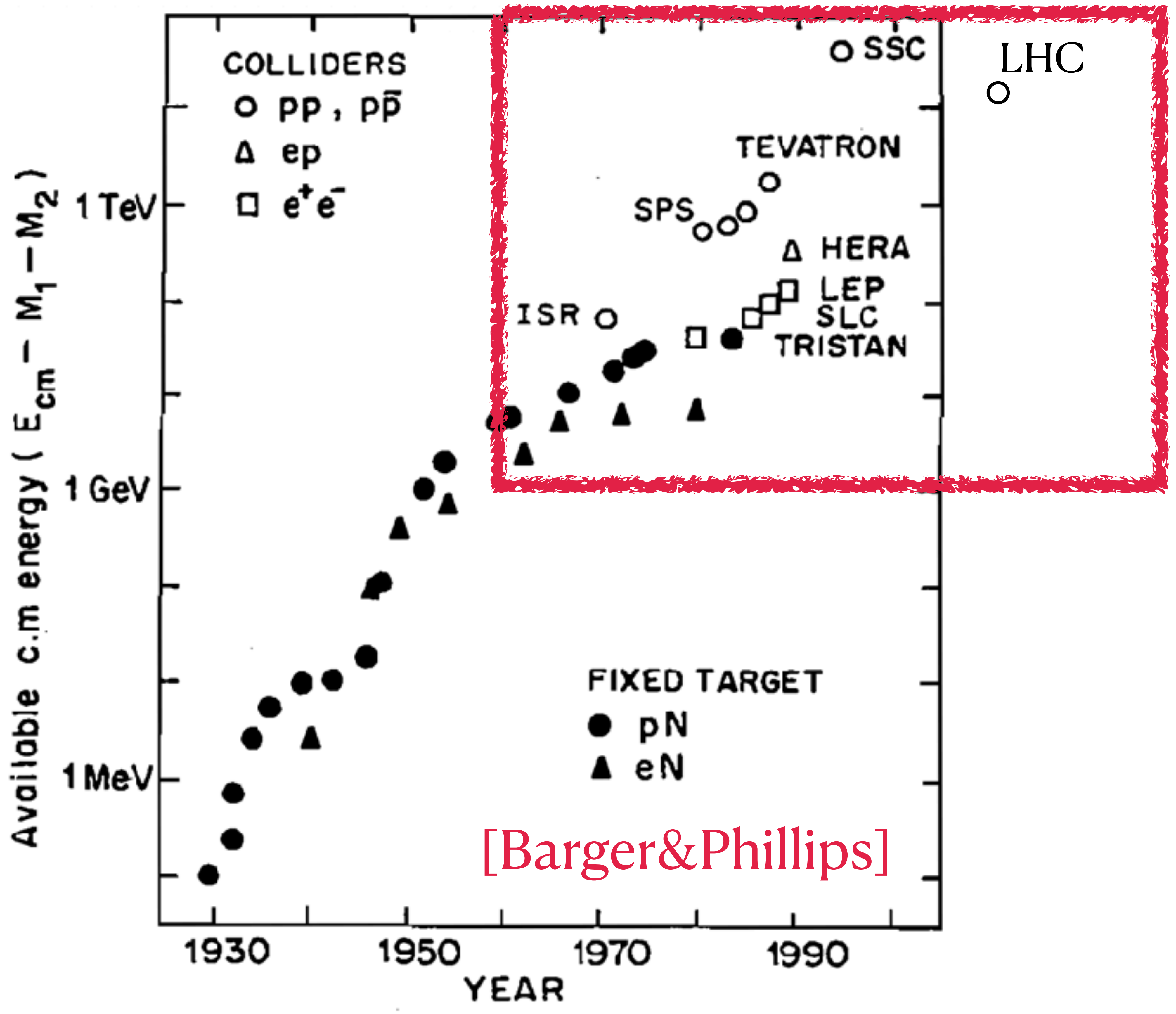
Collider Era



Obvious Statement

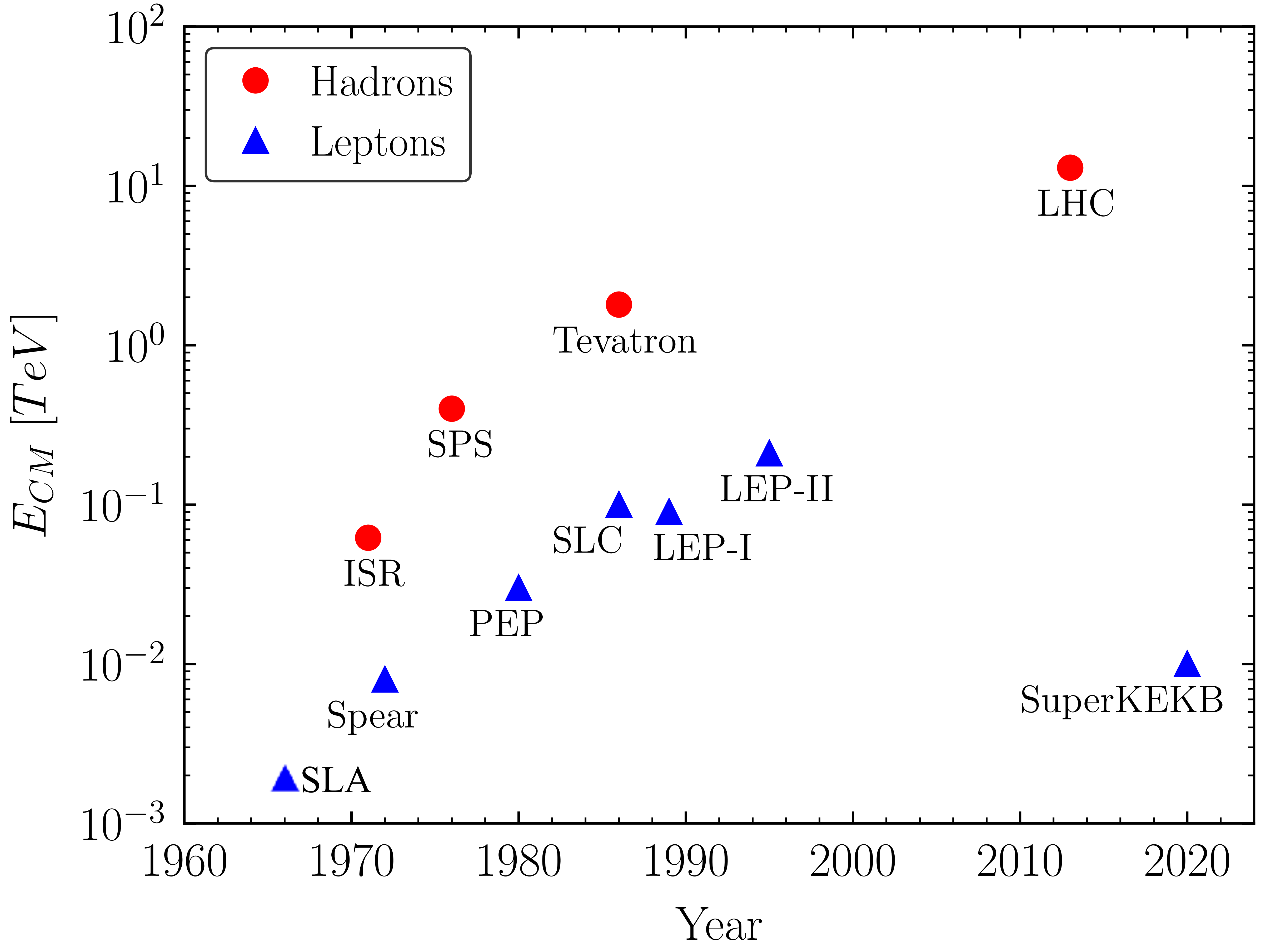
Discovery correlates with technological advancement.

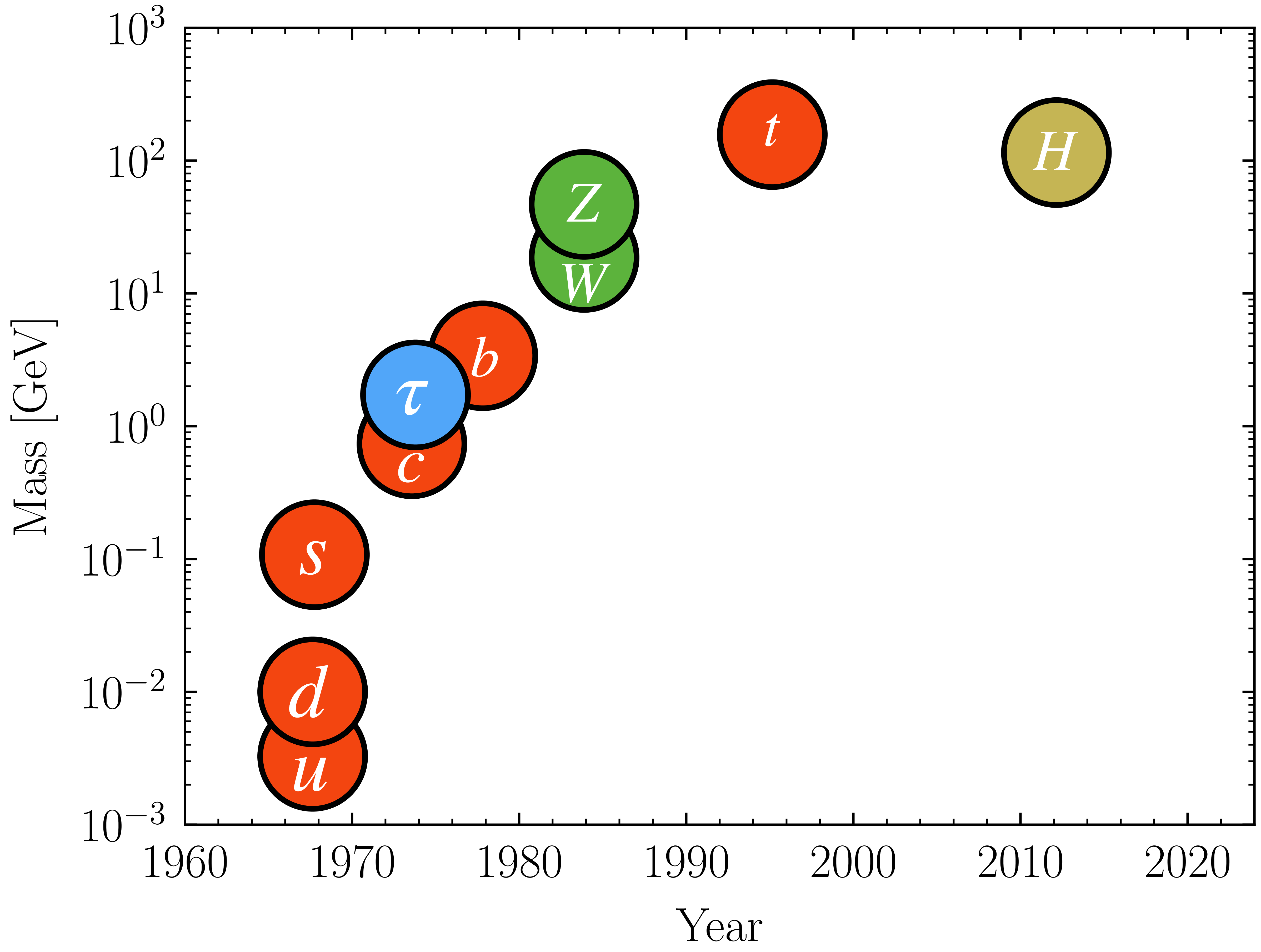




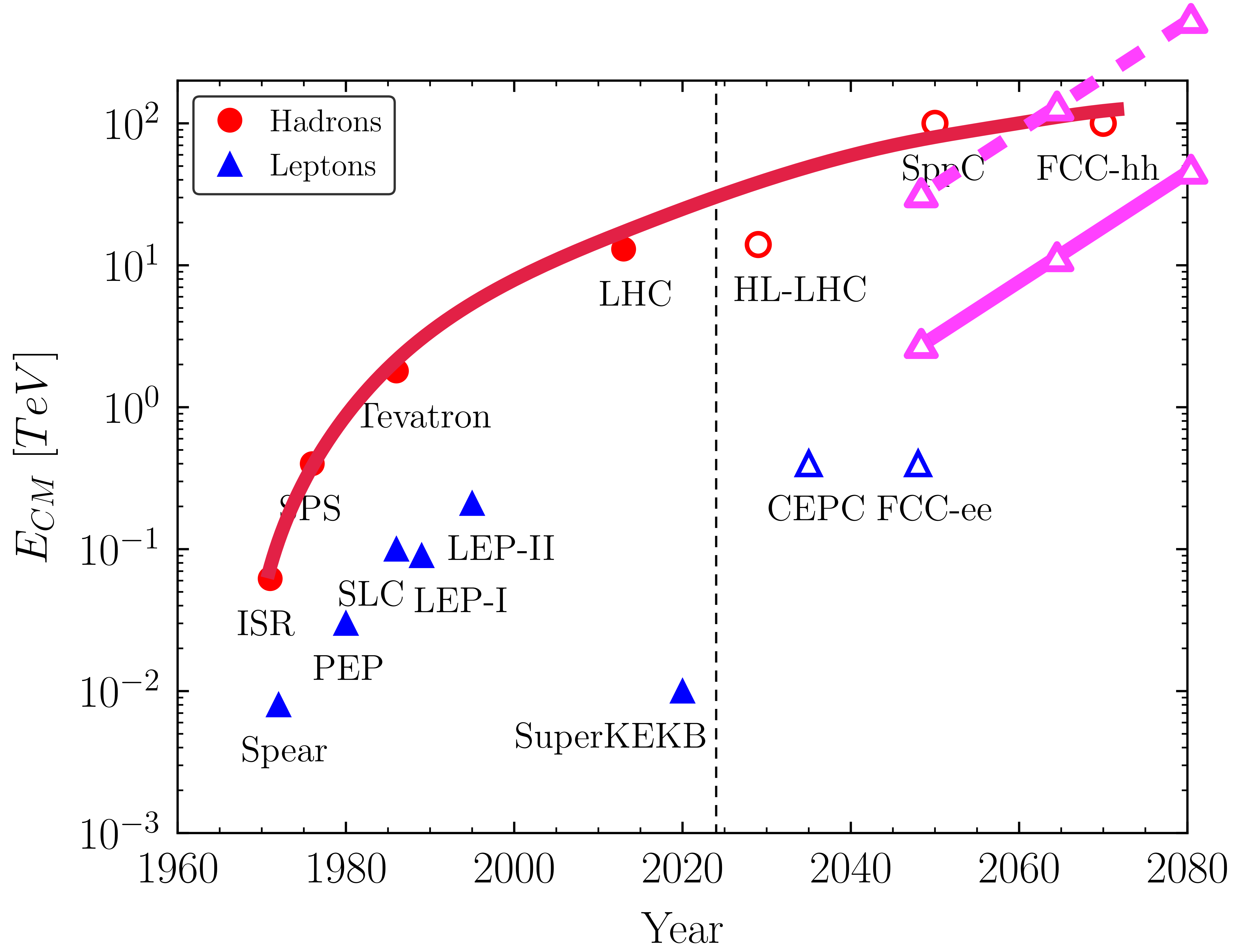
Obvious Statement

Discovery correlates with technological advancement.

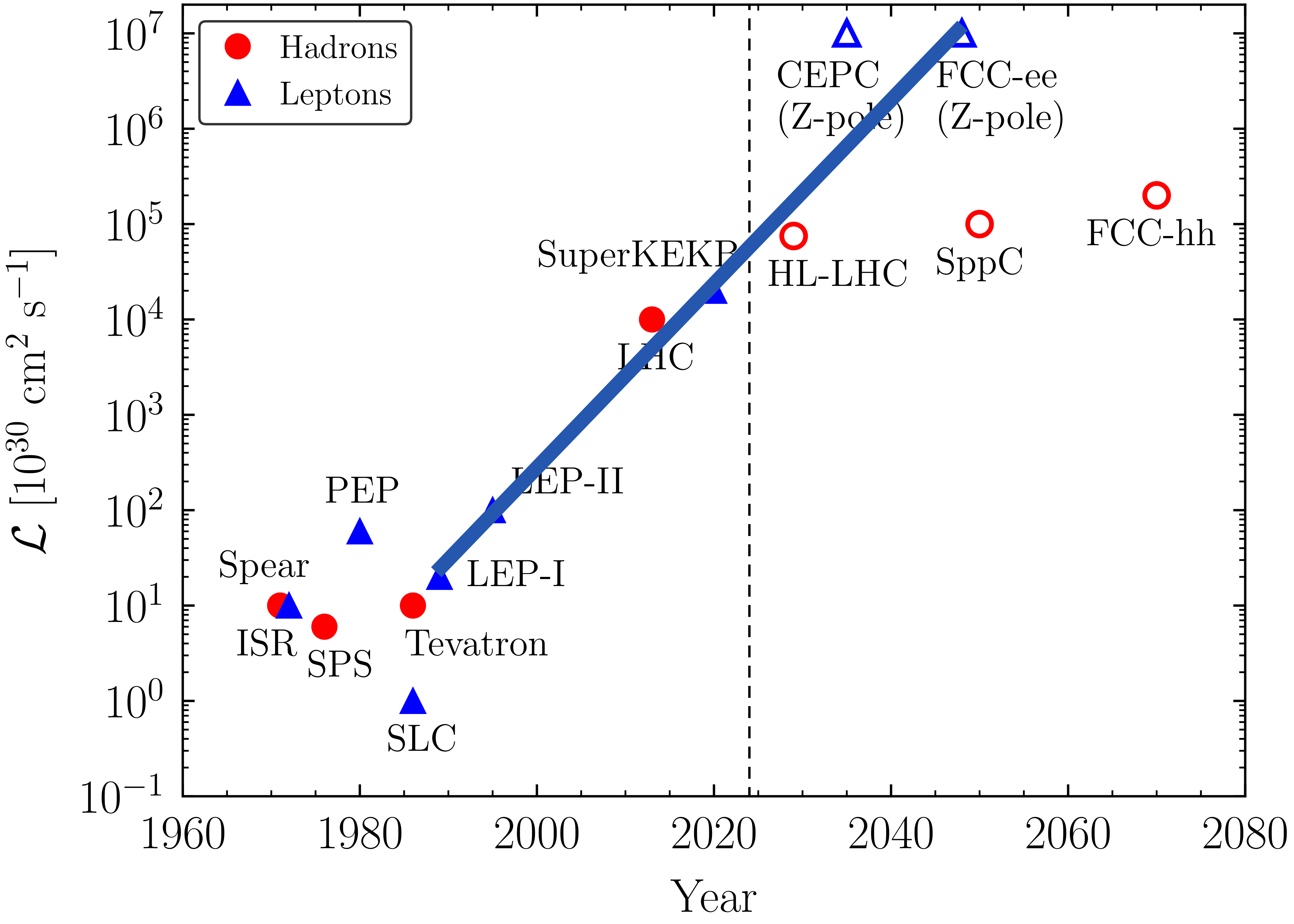




Possibilities for Progress

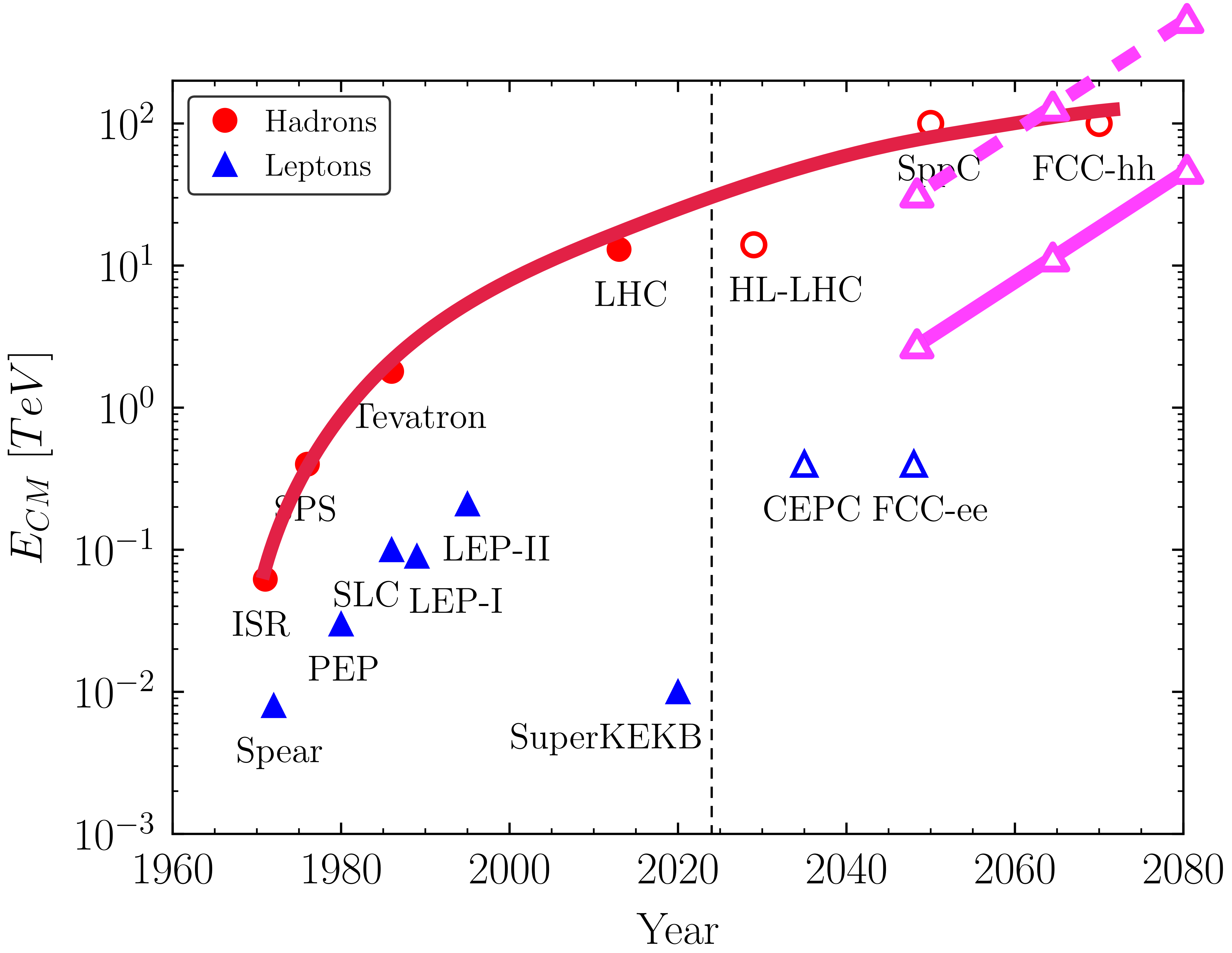


Is there a leptonic path to high energy?



Is luminosity a path to discovery?

Possibilities for Progress



Is there a leptonic path to high energy?

Personal Opinion:

Developing revolutionary accelerator technology to expand the energy frontier is the most valuable pursuit for modern particle physics.

Theory Inputs for Wakefield Colliders

Theory input offers a useful perspective to guide accelerator design to achieve key benchmark objectives.

Zeroth Order Question: How are key theory benchmarks affected by:

	1. Beamstrahlung?	***2. Beam Type (e^+e^-, e^-e^-, $\gamma\gamma$)?***
Heavy Electroweak States Chigusa, Knapen , Opferkuch, Savoray, Scherb, Xu [2512.09995]	✓	$e^+e^- > \gamma\gamma > e^-e^-$ **
Resonances Capressi, **KL**, Opferkuch [2603.18146]	✓✓	$e^+e^- > \gamma\gamma \sim e^-e^-$ **
Higgs Precision Fraser, Knapen, **KL**, Szafron [2603.18146]	✓*	$e^+e^- > \gamma\gamma \gtrsim e^-e^-$ **

**Assuming it can be independently measured. Otherwise analogous to PDF uncertainties.*

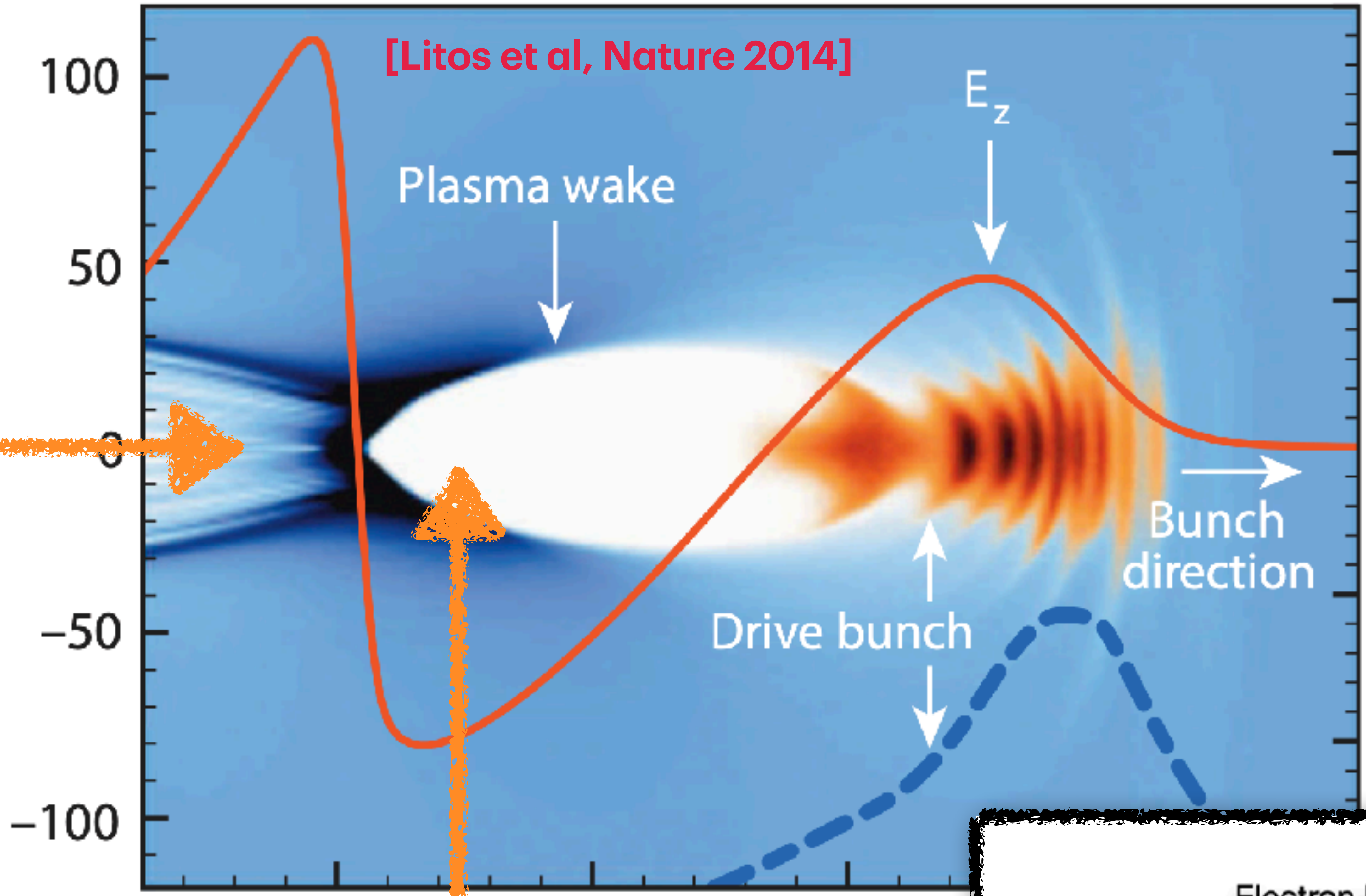
***Assuming equal geometric luminosity.*

Review of Aspects of Wakefield Colliders Relevant for ALL Analyses

1. Beam Types
2. Beamstrahlung

1. Beam Types

Beam Types

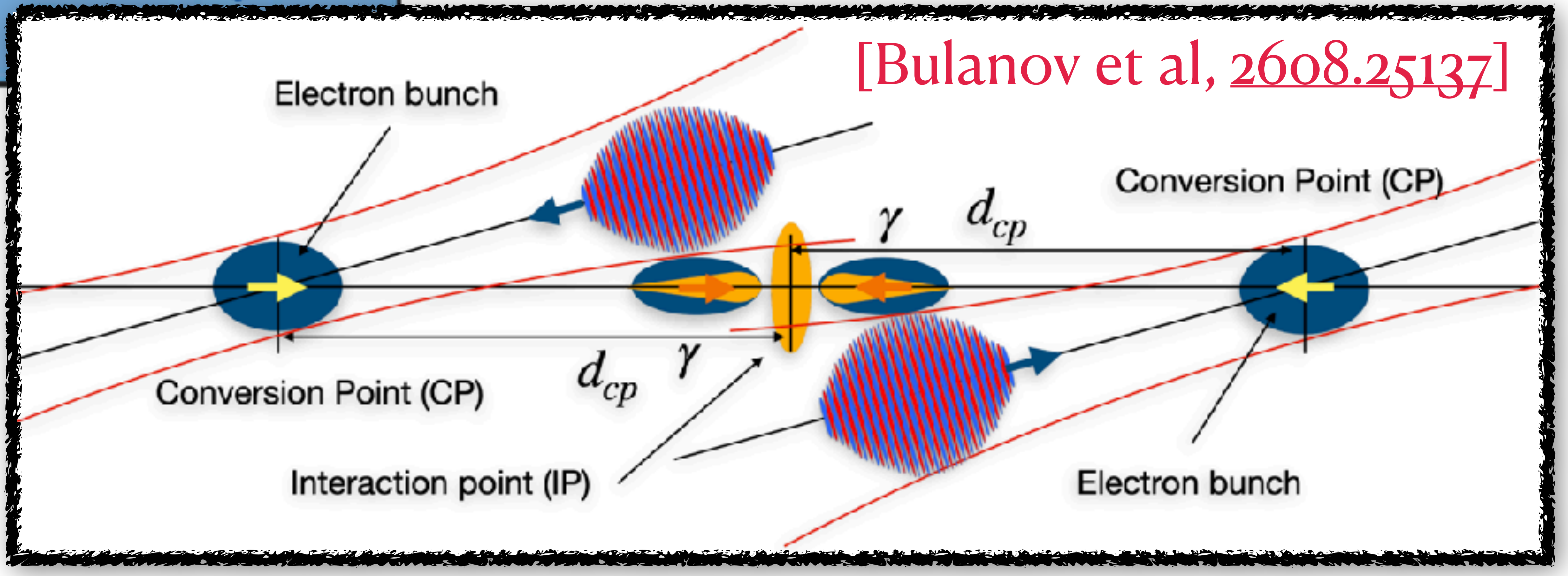


Positrons are more difficult

Great location for ***electrons***

Questions

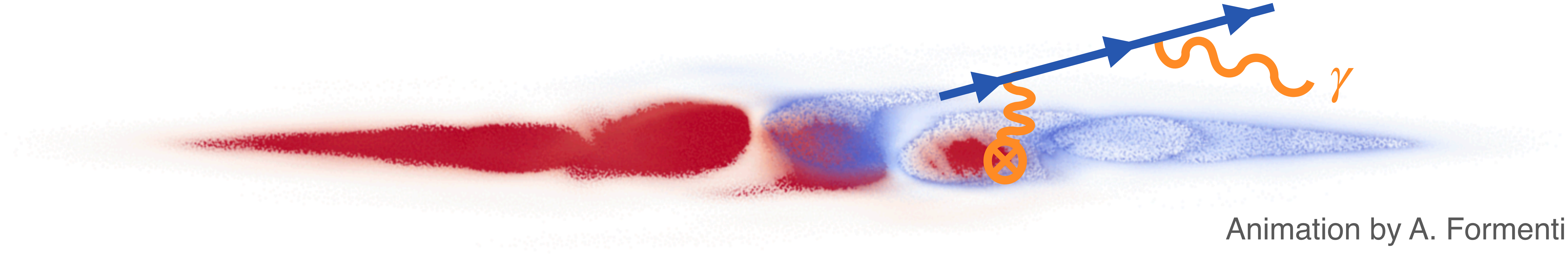
1. Can we just build a e^-e^- collider?
2. If e^+ can be accelerated, what luminosity is required to "beat" e^-e^-?
3. Is it worth converting $e^-e^- \to \gamma\gamma$?



2. Beamstrahlung

Animation by A. Formenti et al.

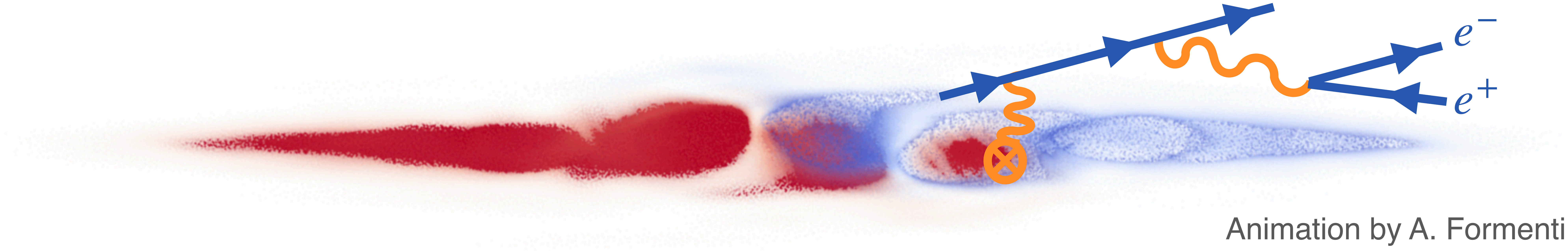
Beamstrahlung



Animation by A. Formenti et al.

Violent beam collisions produce radiation called *beamstrahlung*.

Beamstrahlung



Animation by A. Formenti et al.

Violent beam collisions produce radiation called *beamstrahlung*.

This also produces additional e^+e^- pairs.

These particles can also generate hard collisions.

Mesoscopic analogue of *Initial State Radiation (ISR)*.

Luminosity Spectra

Define the *Luminosity Spectra*:

$$\frac{d\mathscr{L}_{ij}}{d\sqrt{s}} = \left(\begin{array}{l} \text{Lumi of } ij \text{ collisions} \\ \text{at CoM energy } \sqrt{s} \end{array} \right)$$

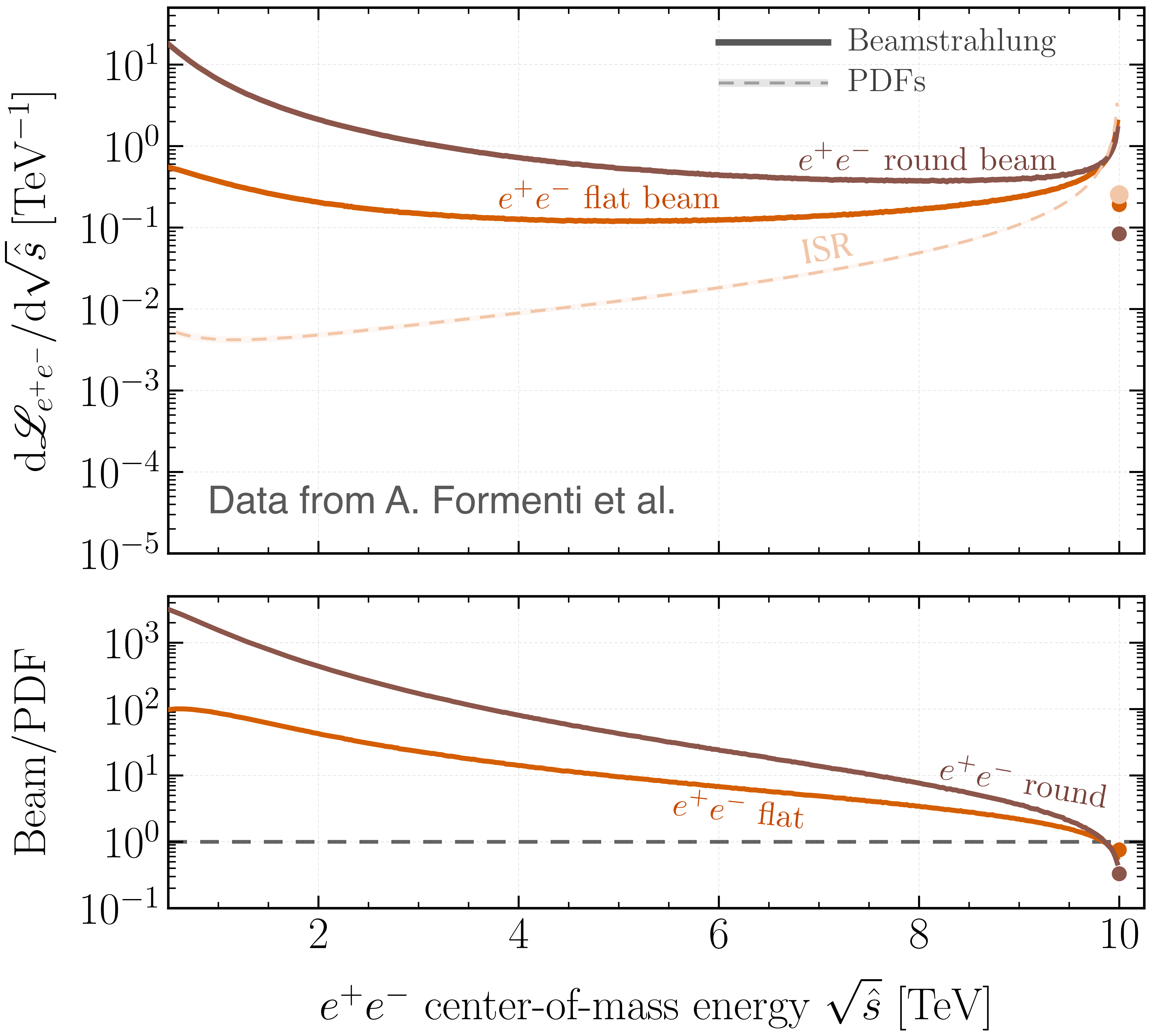
Beam Parameters [C. Schreoder et. al, JNIST 2023]

$N_e = 1.2 \times 10^9$

$\sigma_z = 8.5 \mu\text{m}$

$$(\sigma_x, \sigma_y) = \begin{cases} (1.5, 1.5)\,\text{nm}, & \text{round} \\ (6, 0.4)\,\text{nm}, & \text{flat} \end{cases}$$

$L_{\text{geo,inst}} = 7.5\,\text{ab}^{-1}/\text{year}$



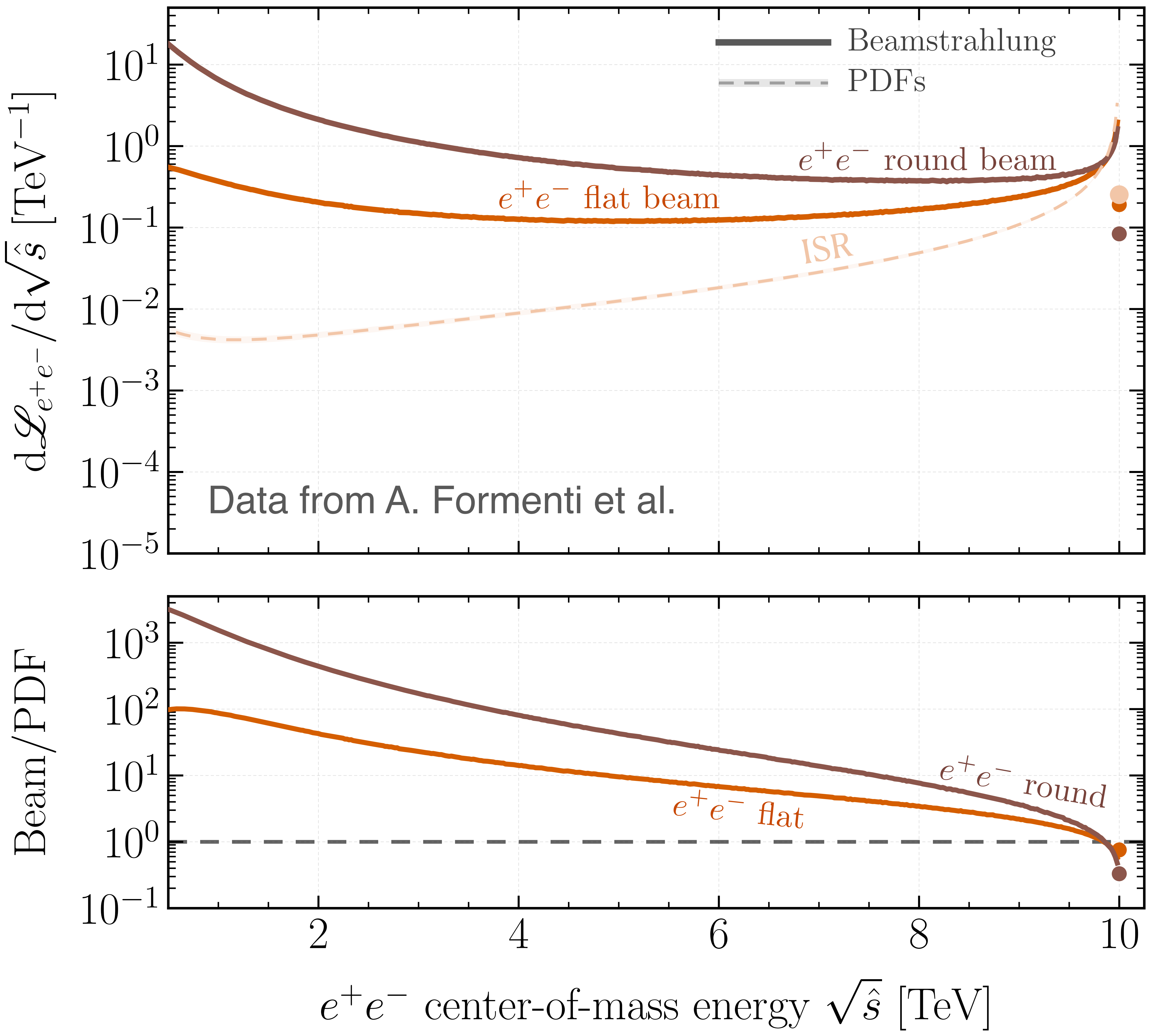
Luminosity Spectra

Define the *Luminosity Spectra*:

$$\frac{d\mathscr{L}_{ij}}{d\sqrt{s}} = \left(\begin{array}{c} \text{Lumi of } ij \text{ collisions} \\ \text{at CoM energy } \sqrt{s} \end{array} \right)$$

For example, consider e^+e^- collisions

- Lumi of e^+e^- collisions enhanced at low E.



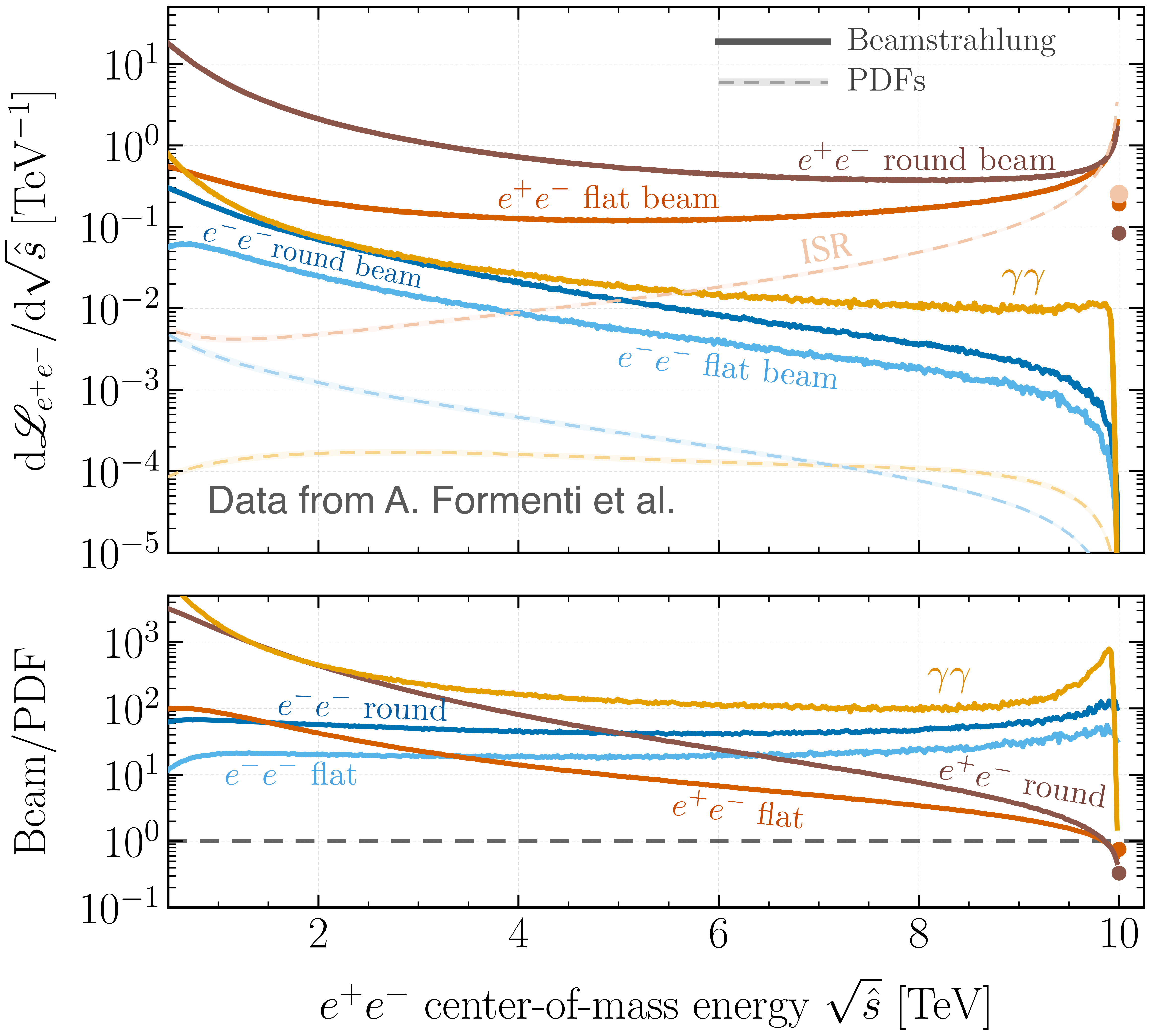
Luminosity Spectra

Define the *Luminosity Spectra*:

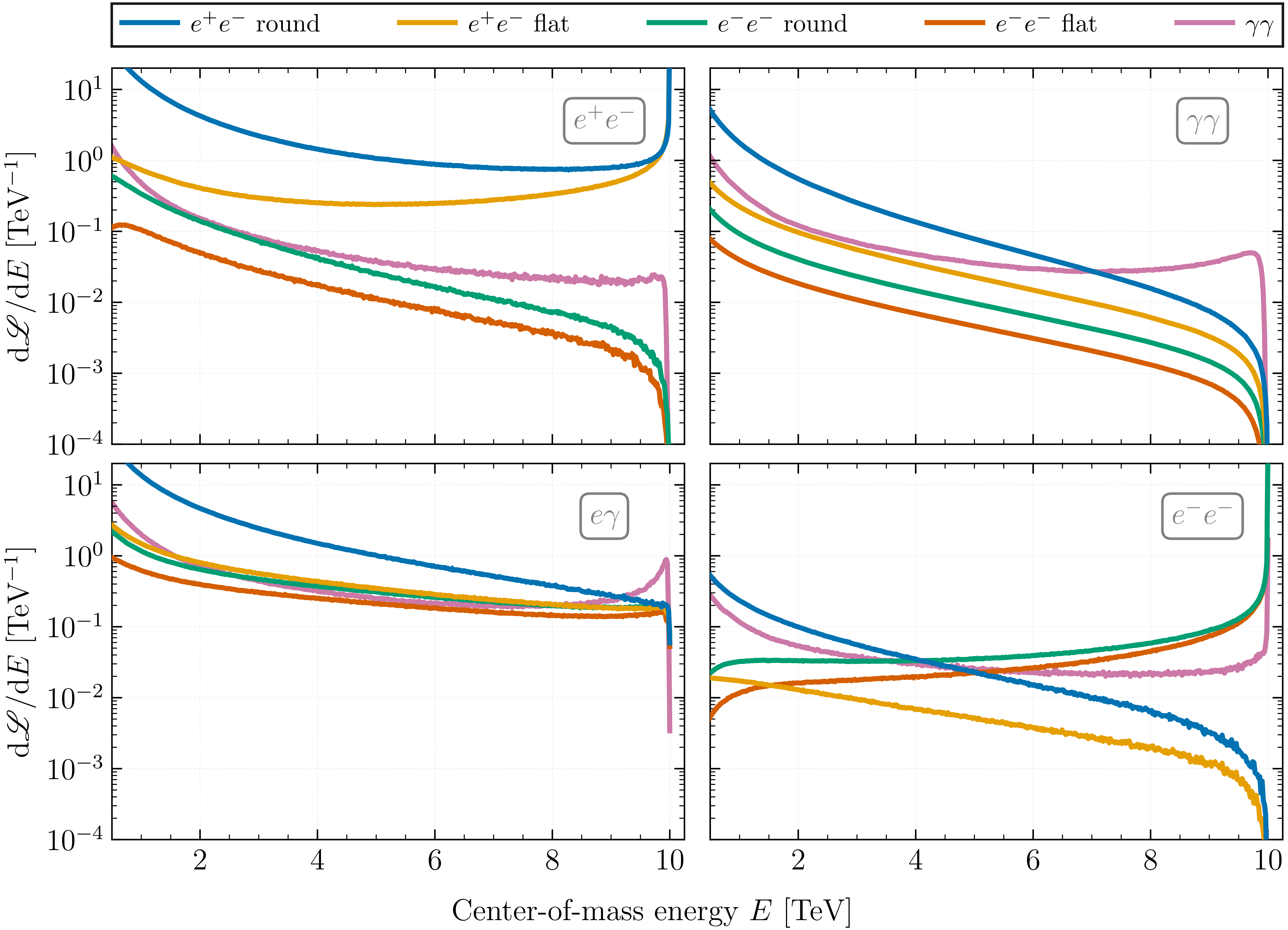
$$\frac{d\mathscr{L}_{ij}}{d\sqrt{s}} = \left(\begin{array}{c} \text{Lumi of } ij \text{ collisions} \\ \text{at CoM energy } \sqrt{s} \end{array} \right)$$

For example, consider e^+e^- collisions

- Lumi of e^+e^- collisions enhanced at low E.
- $e^-e^-/\gamma\gamma$ colliders also have e^+e^- collisions.



Many Types of Collisions

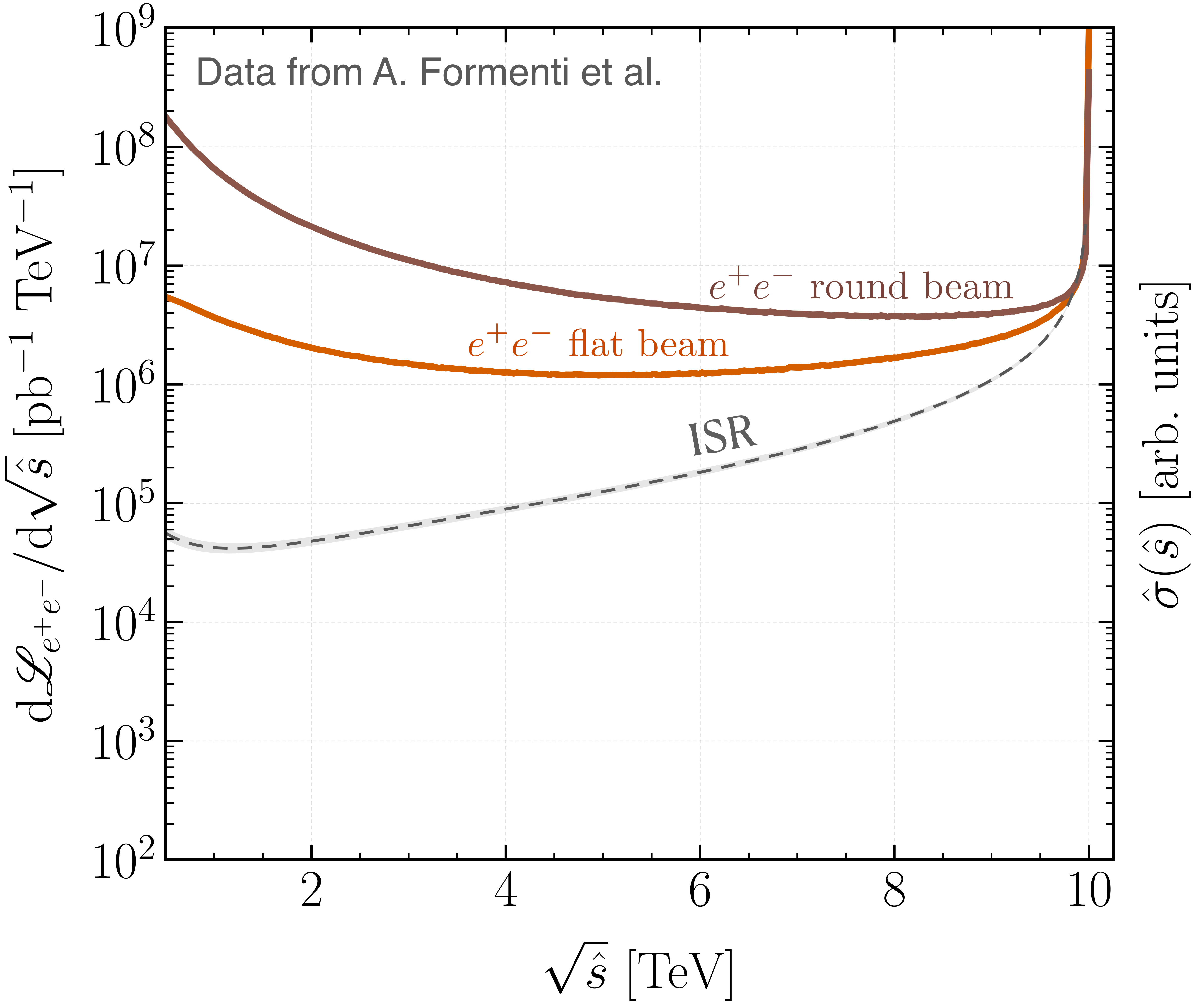


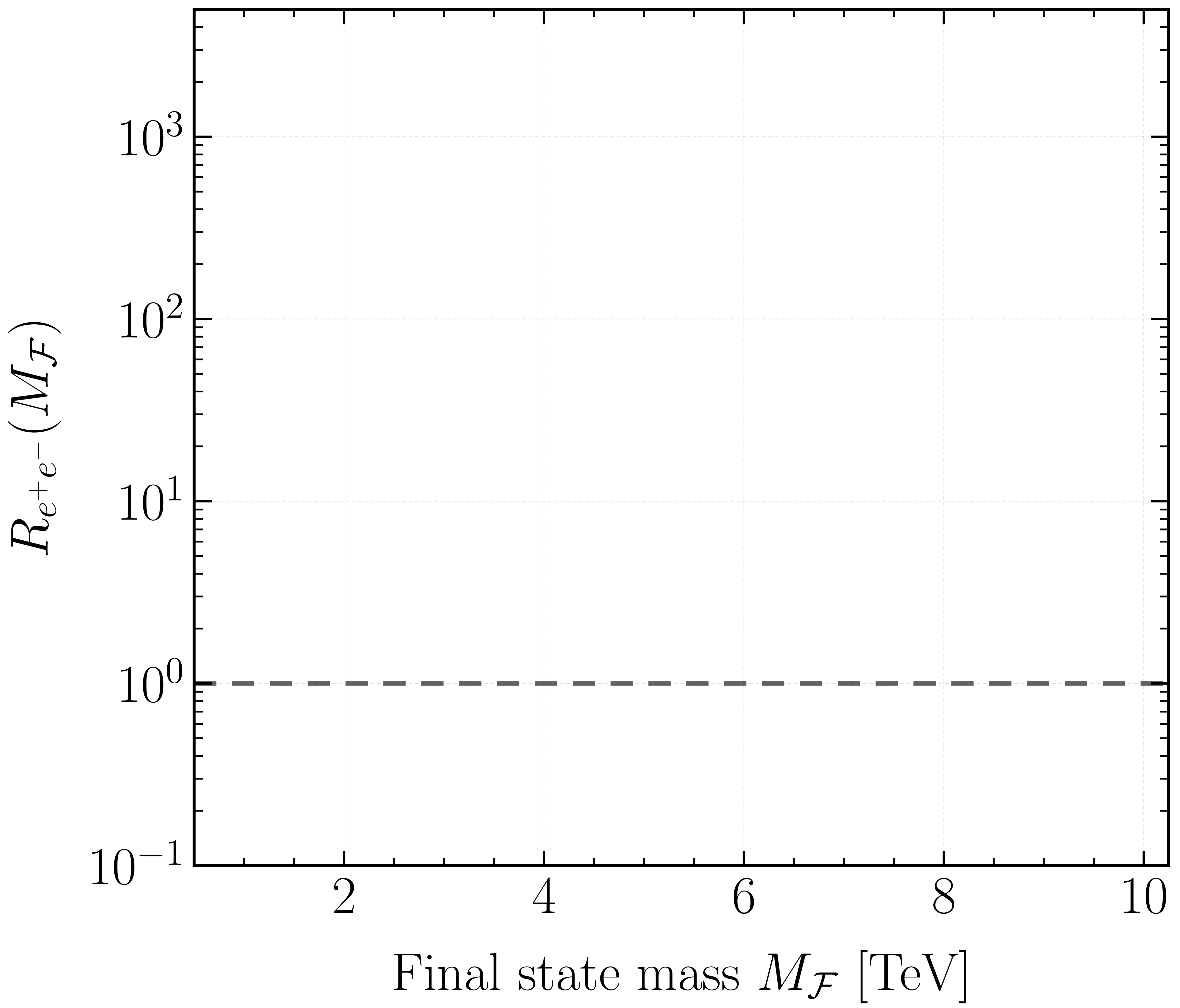
Beamstrahlung Enhancement

$$\boxed{R_{e^+e^-}(M_{\mathcal{F}}) = \frac{\int_{\tau_{\mathcal{F}}}^{1} d\tau\,(d\mathscr{L}_{e^+e^-}^{\text{beam}}/d\tau)\,\hat{\sigma}(\tau s)}{\int_{\tau_{\mathcal{F}}}^{1} d\tau\,(d\mathscr{L}_{e^+e^-}^{\text{ISR}}/d\tau)\,\hat{\sigma}(\tau s)}}$$

Beamstrahlung Enhancement

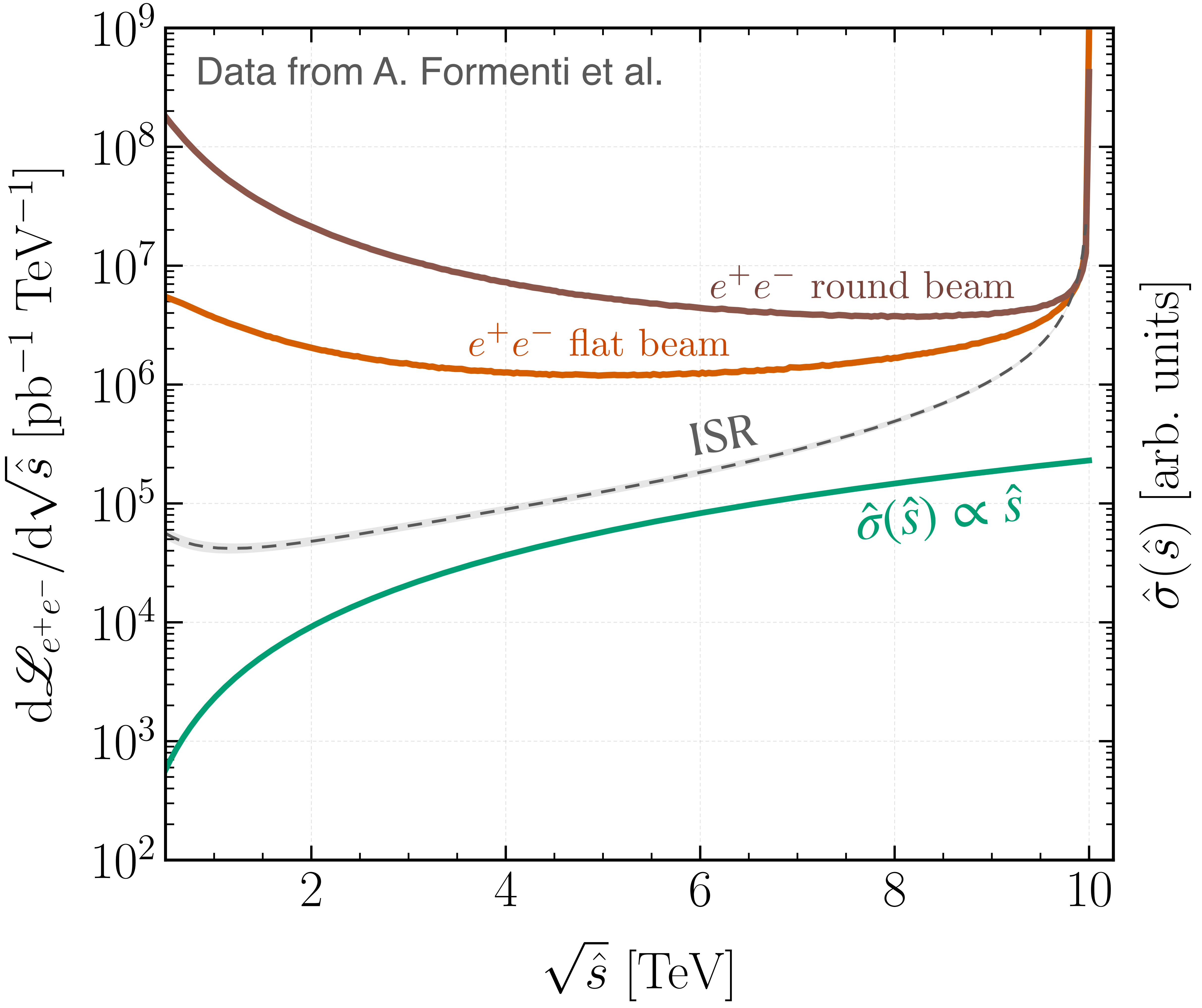
$$R_{e^+e^-}(M_{\mathscr{F}}) = \frac{\int_{\tau_{\mathscr{F}}}^{1} d\tau \, (d\mathscr{L}^{\text{beam}}_{e^+e^-}/d\tau) \, \hat{\sigma}(\tau s)}{\int_{\tau_{\mathscr{F}}}^{1} d\tau \, (d\mathscr{L}^{\text{ISR}}_{e^+e^-}/d\tau) \, \hat{\sigma}(\tau s)}$$

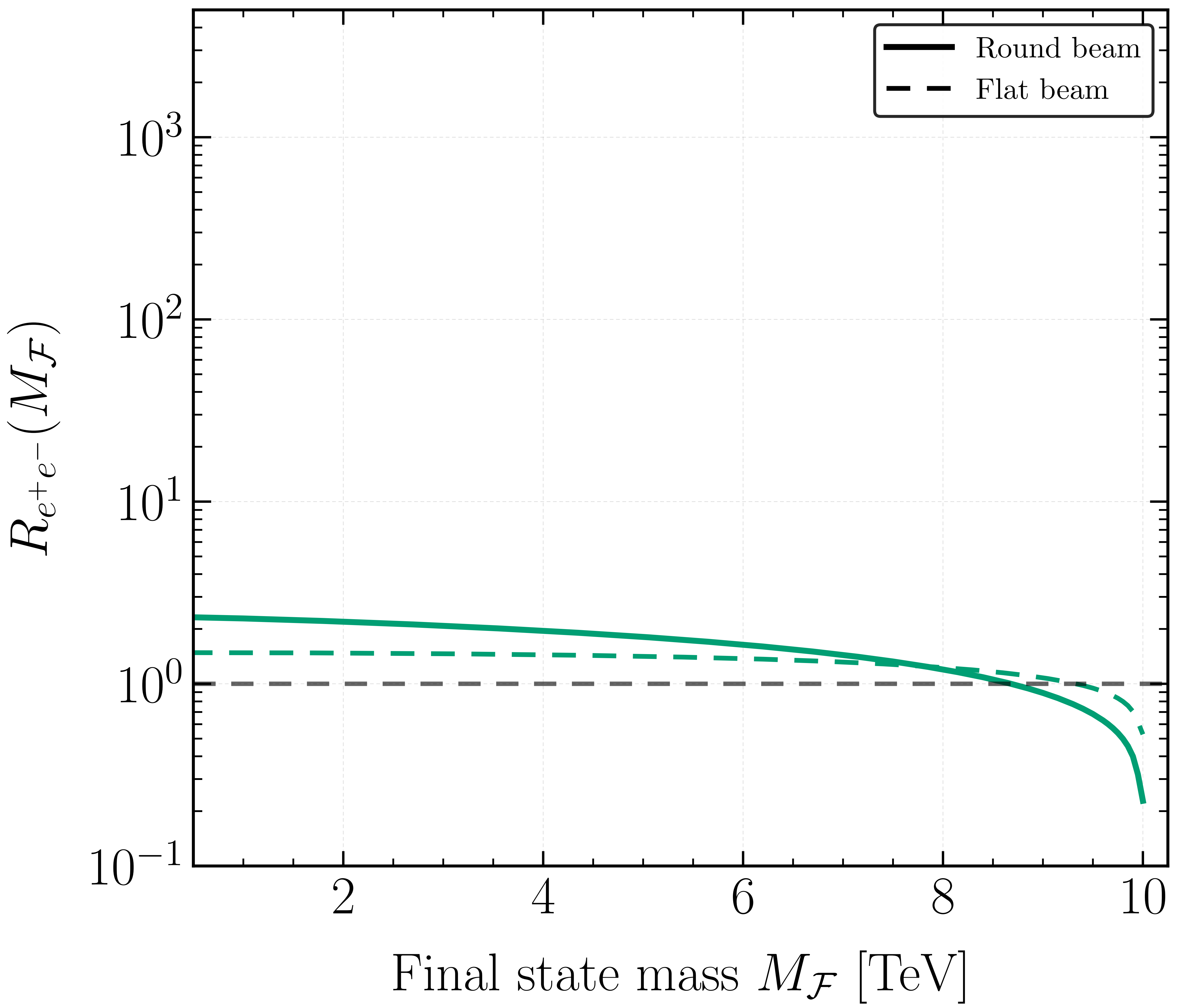




Beamstrahlung Enhancement

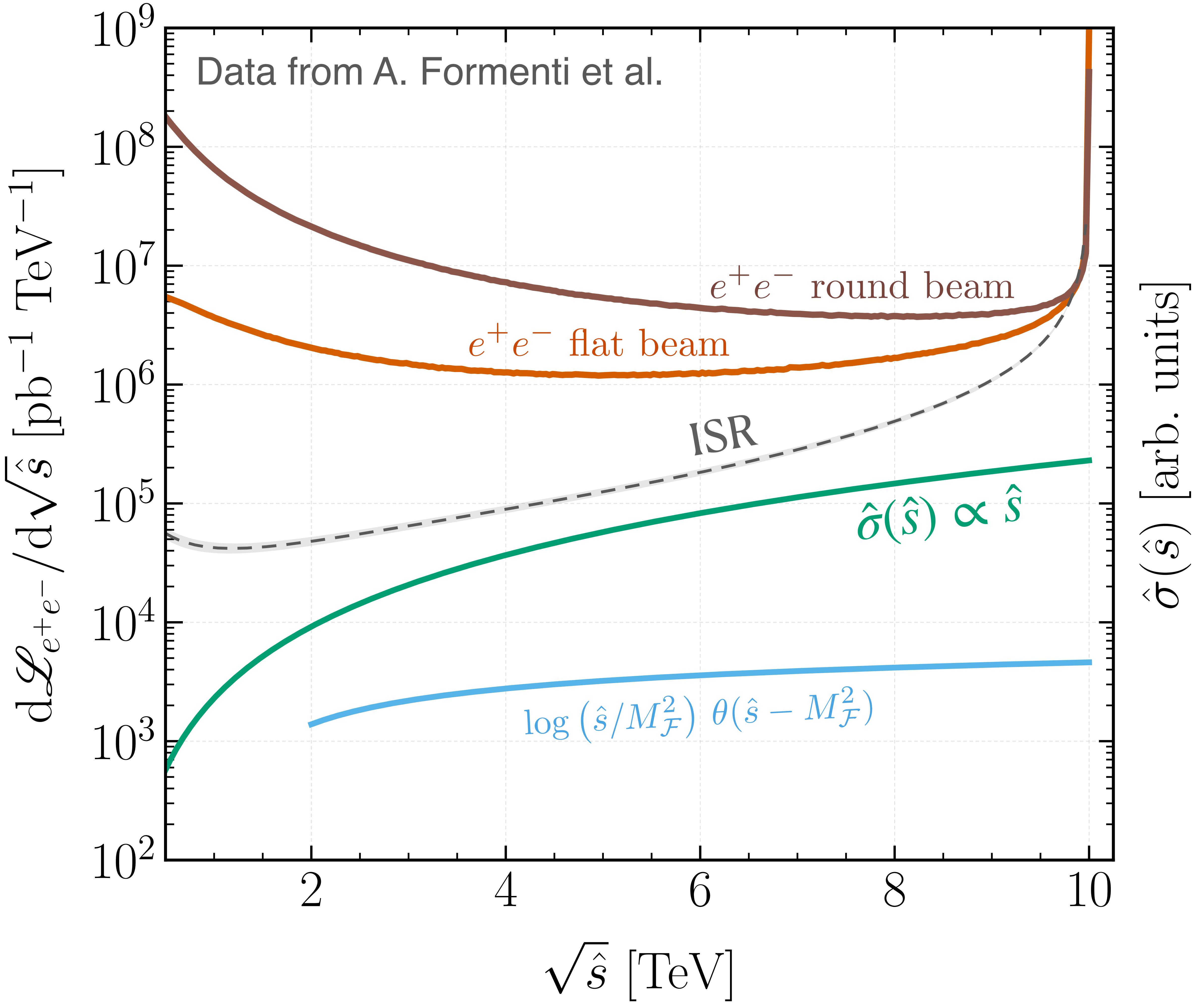
$$R_{e^+e^-}(M_{\mathcal{F}}) = \frac{\int_{\tau_{\mathcal{F}}}^{1} d\tau \, (d\mathcal{L}^{\text{beam}}_{e^+e^-}/d\tau) \, \hat{\sigma}(\tau s)}{\int_{\tau_{\mathcal{F}}}^{1} d\tau \, (d\mathcal{L}^{\text{ISR}}_{e^+e^-}/d\tau) \, \hat{\sigma}(\tau s)}$$

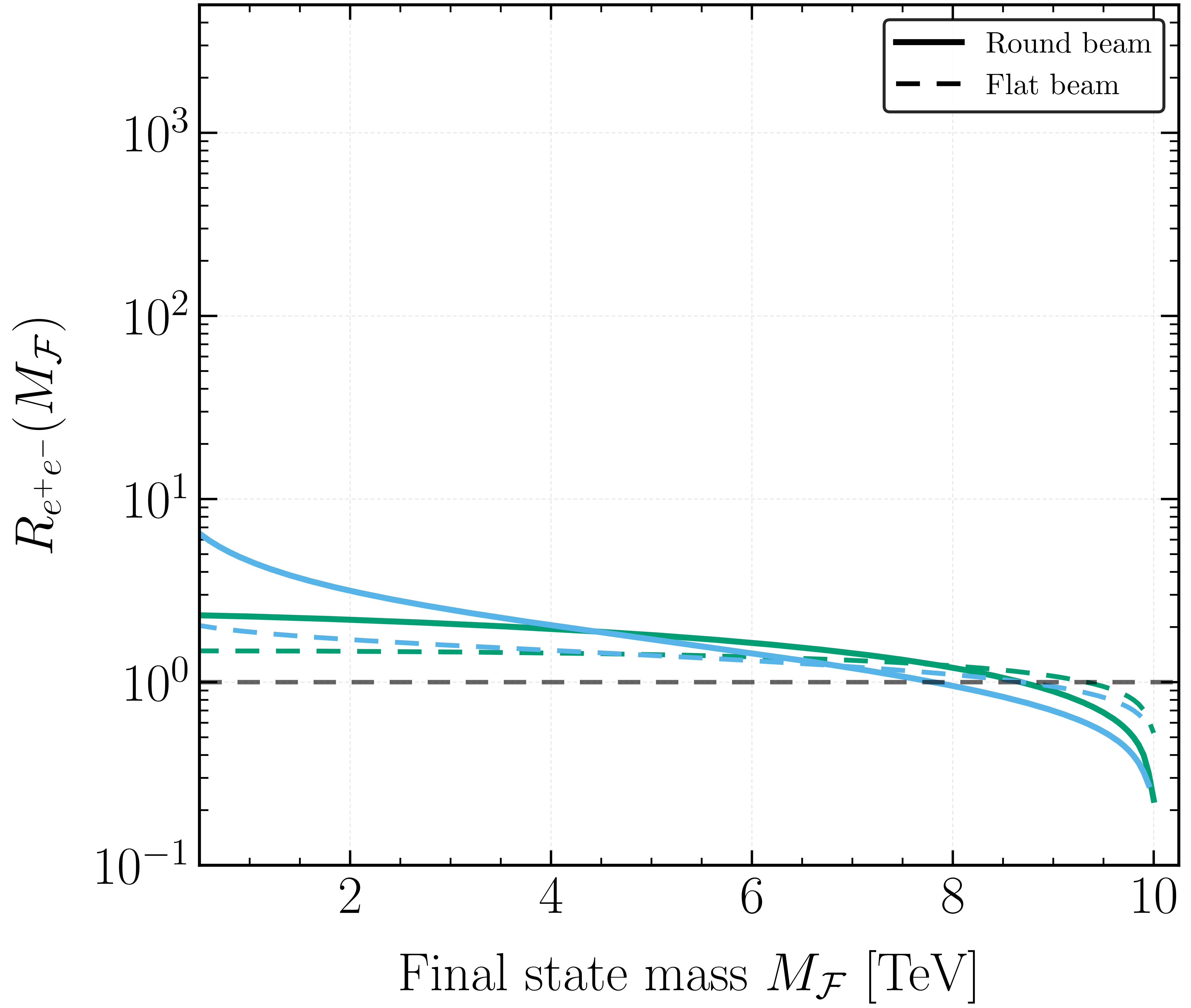




Beamstrahlung Enhancement

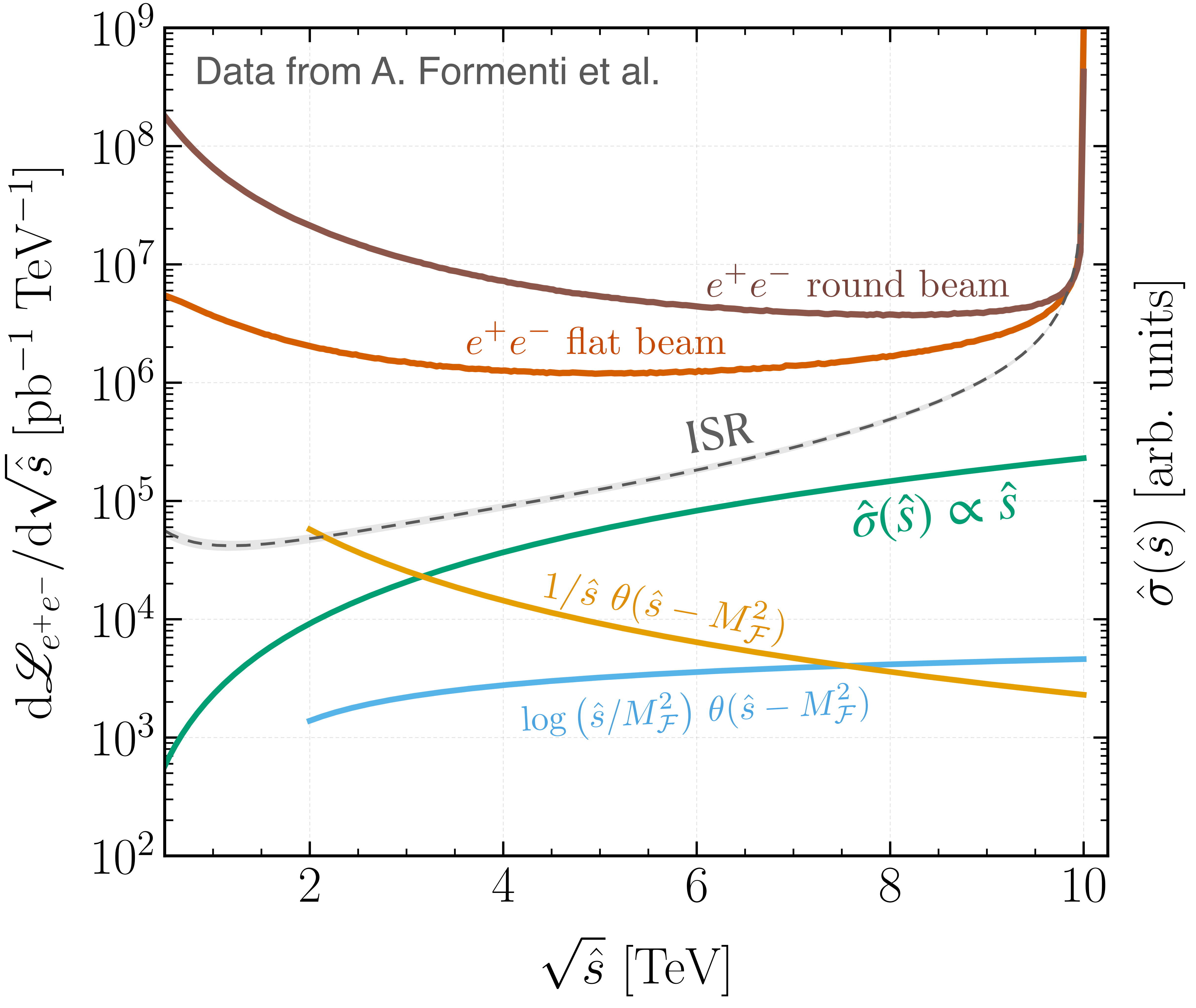
$$R_{e^+e^-}(M_{\mathscr{F}}) = \frac{\int_{\tau_{\mathscr{F}}}^{1} d\tau\, (d\mathscr{L}^{\text{beam}}_{e^+e^-}/d\tau)\, \hat{\sigma}(\tau s)}{\int_{\tau_{\mathscr{F}}}^{1} d\tau\, (d\mathscr{L}^{\text{ISR}}_{e^+e^-}/d\tau)\, \hat{\sigma}(\tau s)}$$

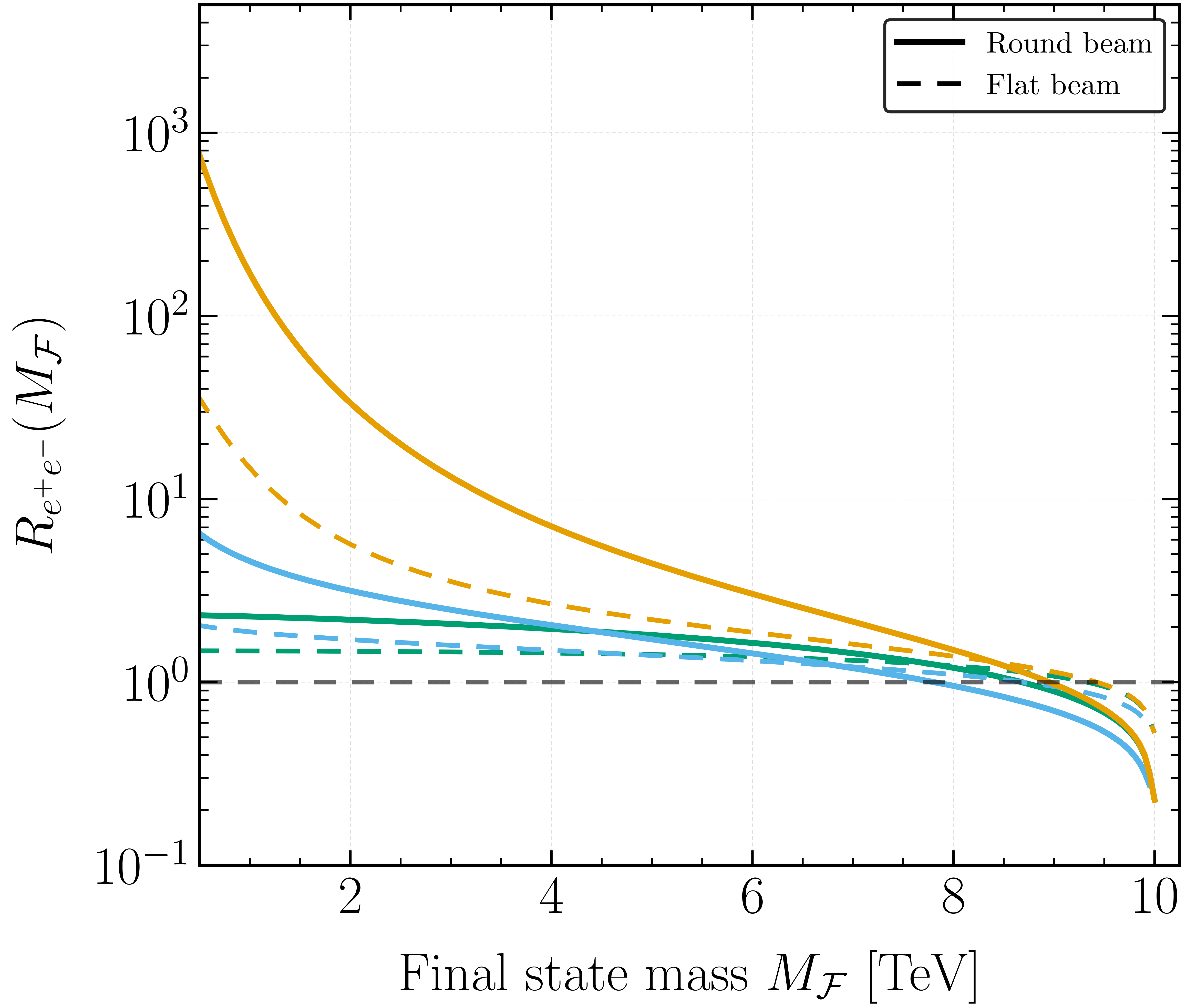




Beamstrahlung Enhancement

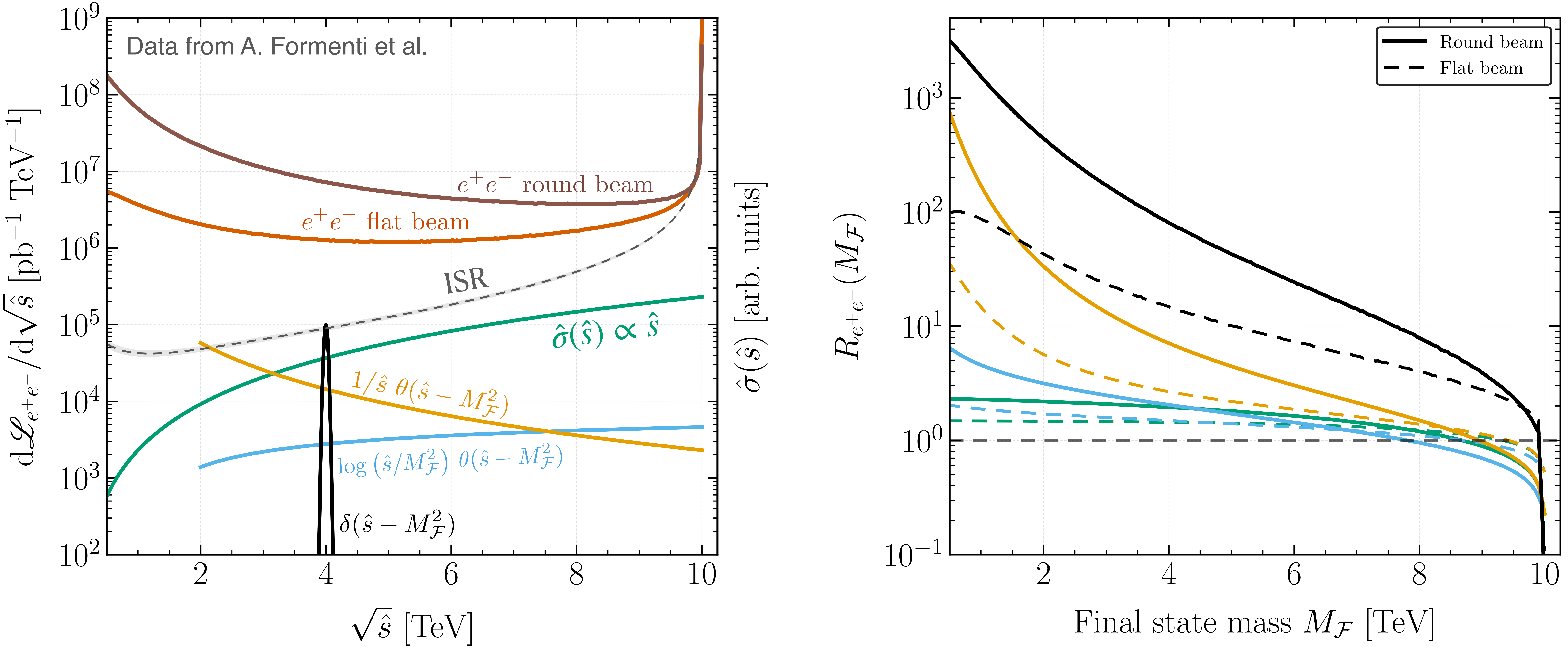
$$R_{e^+e^-}(M_{\mathcal{F}}) = \frac{\int_{\tau_{\mathcal{F}}}^{1} d\tau \, (d\mathscr{L}^{\text{beam}}_{e^+e^-}/d\tau) \, \hat{\sigma}(\tau s)}{\int_{\tau_{\mathcal{F}}}^{1} d\tau \, (d\mathscr{L}^{\text{ISR}}_{e^+e^-}/d\tau) \, \hat{\sigma}(\tau s)}$$





Beamstrahlung Enhancement

$$R_{e^+e^-}(M_{\mathscr{F}}) = \frac{\int_{\tau_{\mathscr{F}}}^{1} d\tau \, (d\mathscr{L}^{\text{beam}}_{e^+e^-}/d\tau)\, \hat{\sigma}(\tau s)}{\int_{\tau_{\mathscr{F}}}^{1} d\tau \, (d\mathscr{L}^{\text{ISR}}_{e^+e^-}/d\tau)\, \hat{\sigma}(\tau s)}$$

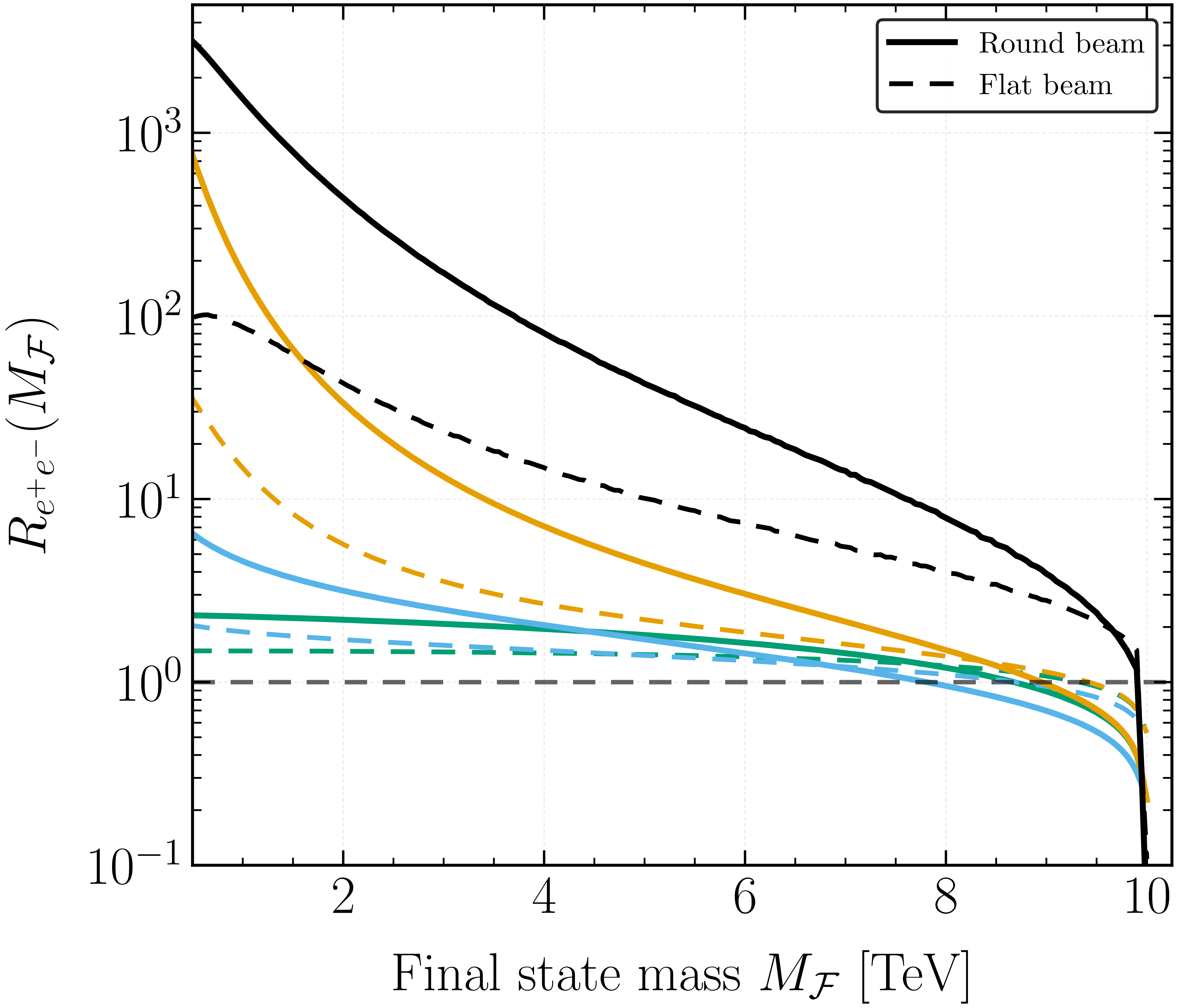


Beamstrahlung Enhancement

$$R_{e^+e^-}(M_{\mathscr{F}}) = \frac{\int_{\tau_{\mathscr{F}}}^{1} d\tau \, (d\mathscr{L}^{\text{beam}}_{e^+e^-}/d\tau) \, \hat{\sigma}(\tau s)}{\int_{\tau_{\mathscr{F}}}^{1} d\tau \, (d\mathscr{L}^{\text{ISR}}_{e^+e^-}/d\tau) \, \hat{\sigma}(\tau s)}$$

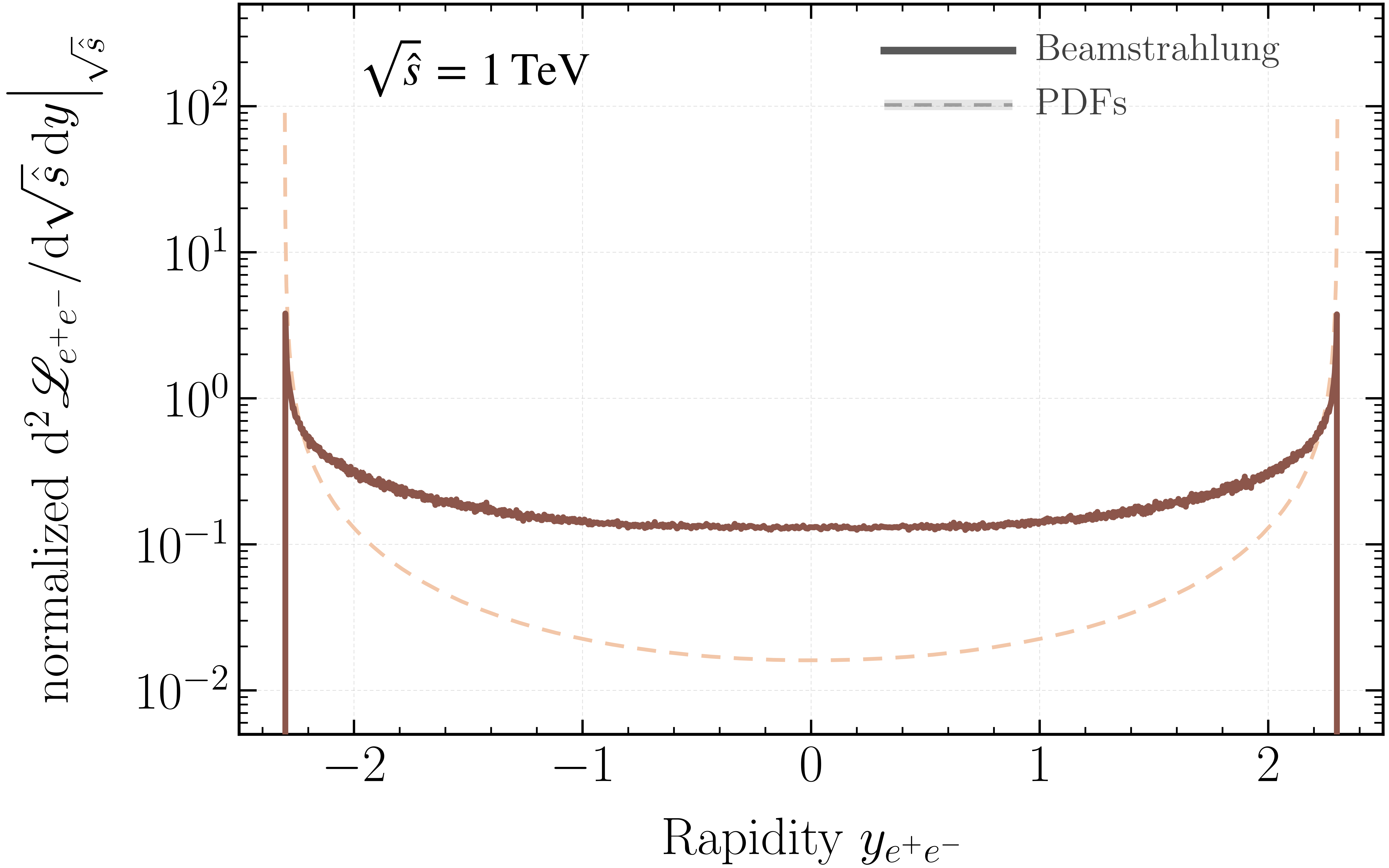
Not the full story!

Sometimes large changes to efficiencies.



Wakefield Collider Rapidity

Beamstrahlung creates more central (less forward peaked) collisions.



Two Case Studies

Precision Measurments of Electroweak Higgs Couplings
[2607.19463]
With Simon Knapen, Katie Fraser, and Robert Szafron

Searches for Heavy Resonances
[2603.18146]
With Toby Opferkuch and Massimo Capressi

Two Case Studies

Precision Measurments of Electroweak Higgs Couplings [2607.19463]

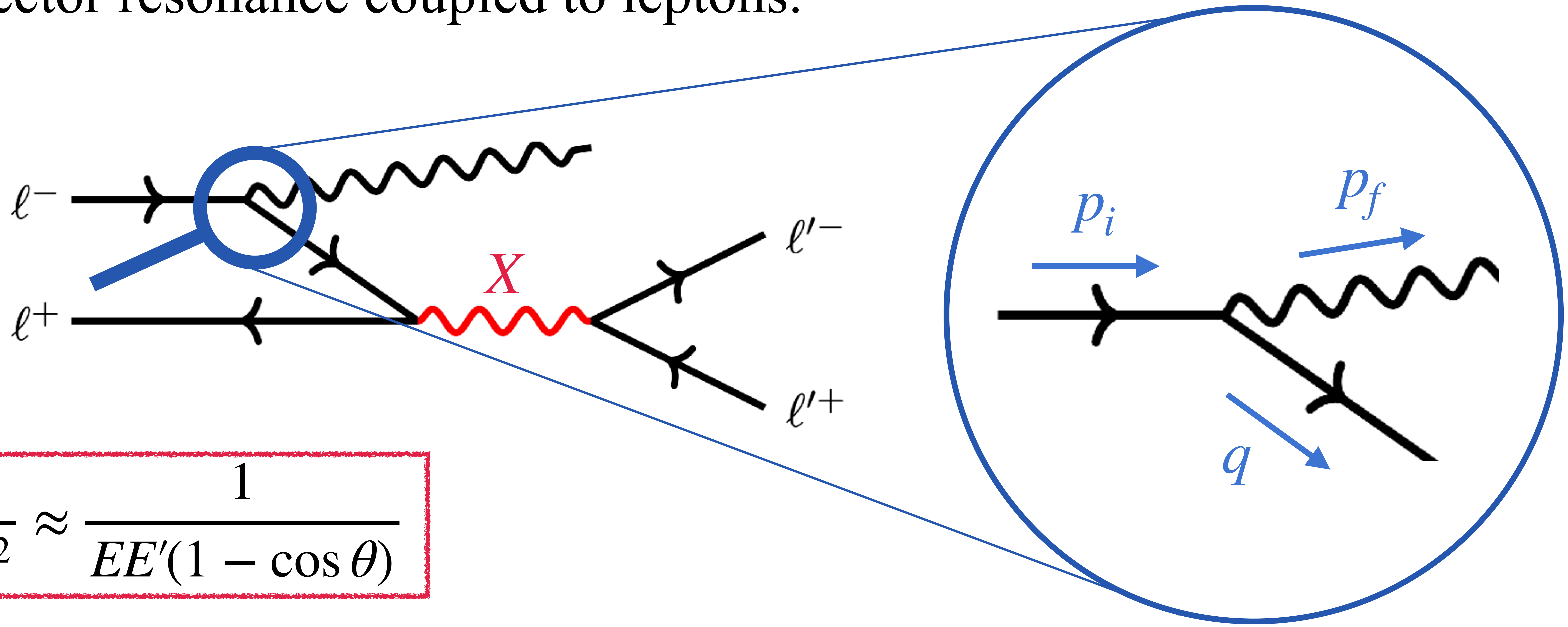
With Simon Knapen, Katie Fraser, and Robert Szafron

Searches for Heavy Resonances [2603.18146]

With Toby Opferkuch and Massimo Capressi

How do you typically look for Resonances

Consider a vector resonance coupled to leptons.



$$\mathcal{M} \propto \frac{1}{q^2} \approx \frac{1}{EE'(1 - \cos\theta)}$$

As $\theta \to 0$ the virtual lepton is nearly on shell and can be treated as a parton.

How do you typically look for Resonances

The cross section in terms of parton luminosity is

$$\sigma_X(s) = \int \frac{d\hat{s}}{s} \mathscr{L}_{ij}(\hat{s})\, \hat{\sigma}_{ij\to X}(\hat{s})$$

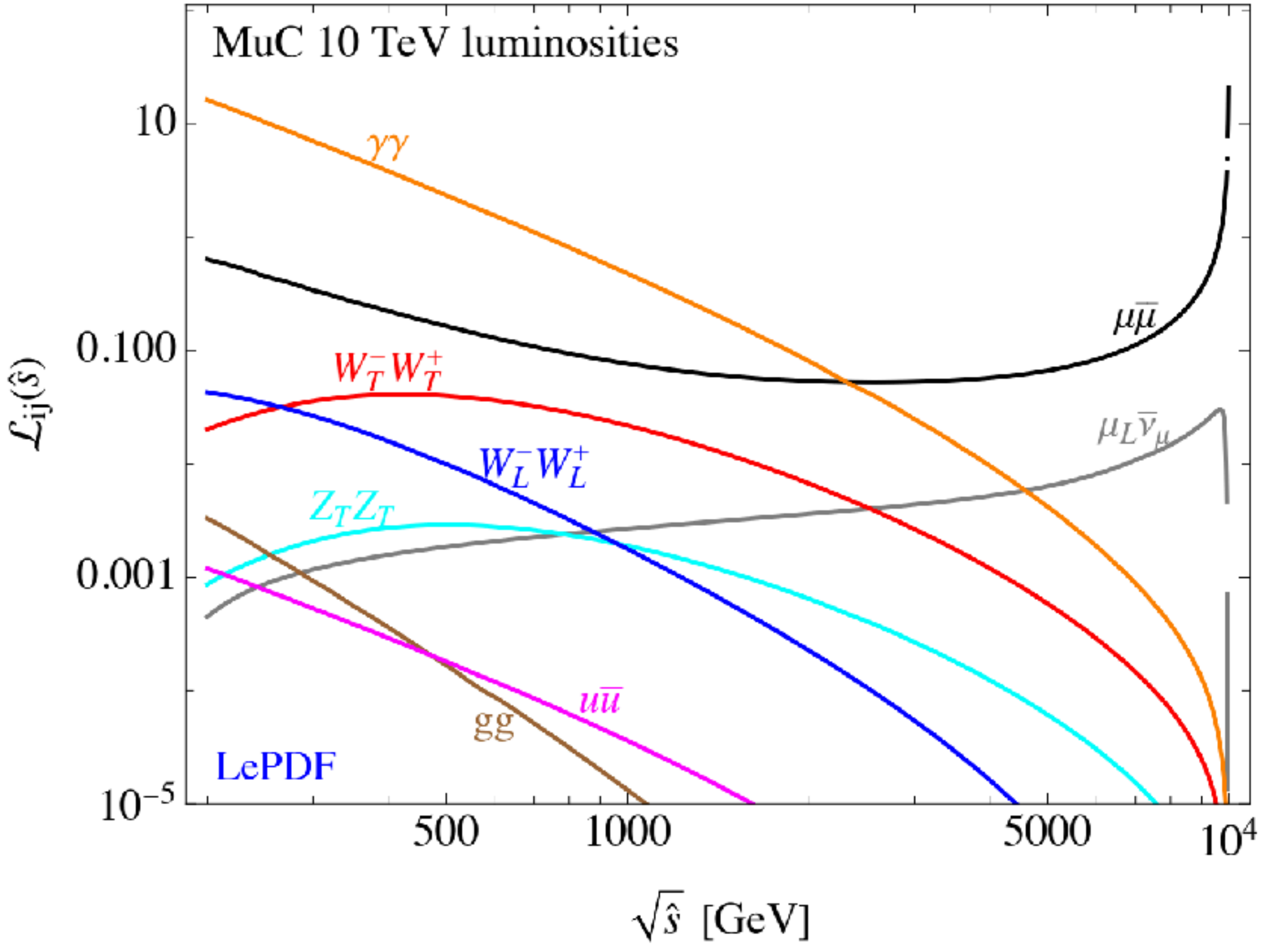
The Narrow Width Approximation (NWA) gives

$$\hat{\sigma}_{ab\to X}(\hat{s}) \approx \frac{12\pi^2 \Gamma_{X\to ij}}{M_X} \delta\left(\hat{s} - m_X^2\right)$$

Doing the integral gives

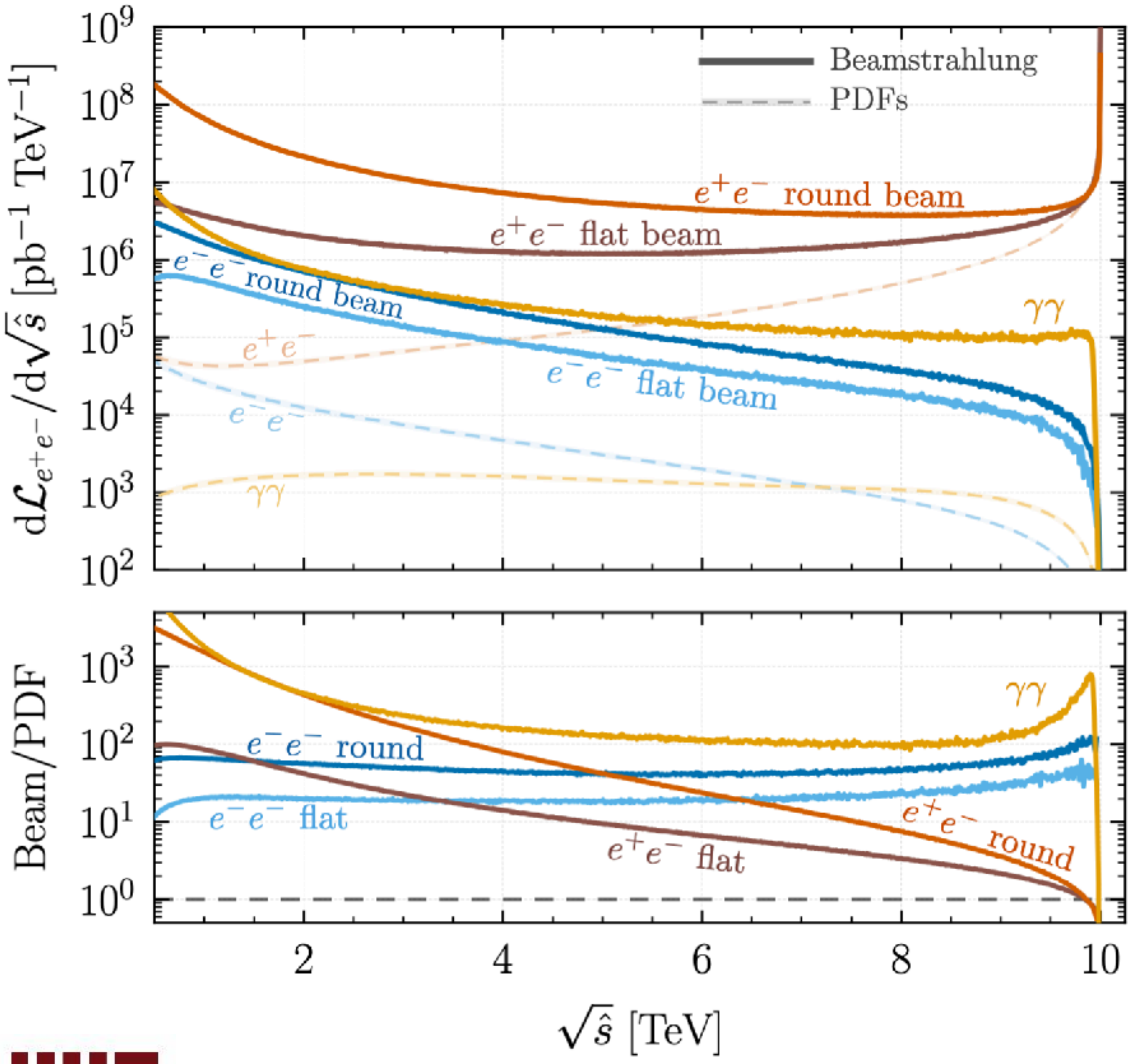
$$\sigma_X(s) \approx \frac{12\pi^2 \Gamma_{X\to ab}}{M_X} \boxed{\mathscr{L}_{ij}(M_X^2)}$$

Garosi, Marzocca, Trifinopoulos [2303.16964]



Parton luminosity functions scan **all energies** for resonances.

Beamstrahlung vs Parton Luminosity



Simple procedure for calculating rate at WF collider

$$\sigma_X(s) \approx \frac{12\pi^2\Gamma_{X\to ab}}{M_X} \boxed{\mathscr{L}_{ij}(M_X^2)}$$

Parton Lumi → Beamstrahlung Lumi.

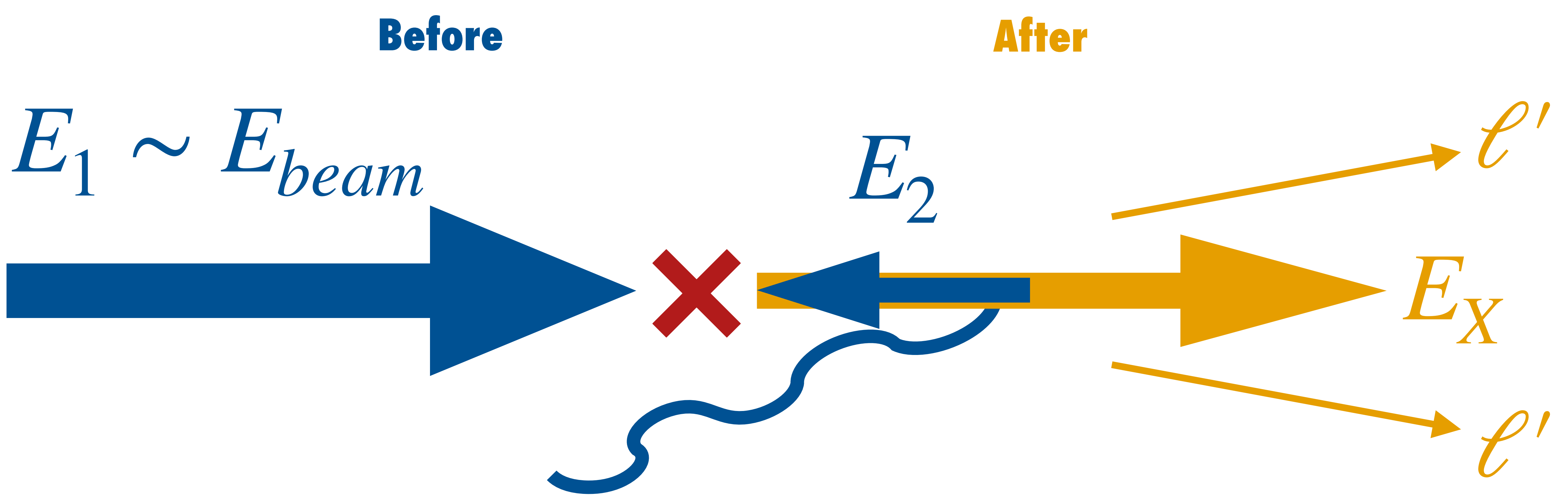
Beamstrahlung **much** larger then PDFs.

Resonance Rapidity Distributions

Story w/o Beamstrahlung:

Light resonances get large boosts.

$$y(M_X) \approx \frac{1}{2}\log\left(\frac{s}{M_X^2}\right)$$



Or perhaps more clearly, the leptons from the resonance have angles

$$\theta_\ell \sim \frac{M_X}{\sqrt{s}} \implies \text{Signal escapes detector for } M_X \lesssim 0.1\sqrt{s} \text{ for } \theta_{\text{det,min}} \approx 10°$$

Resonance Rapidity Distributions

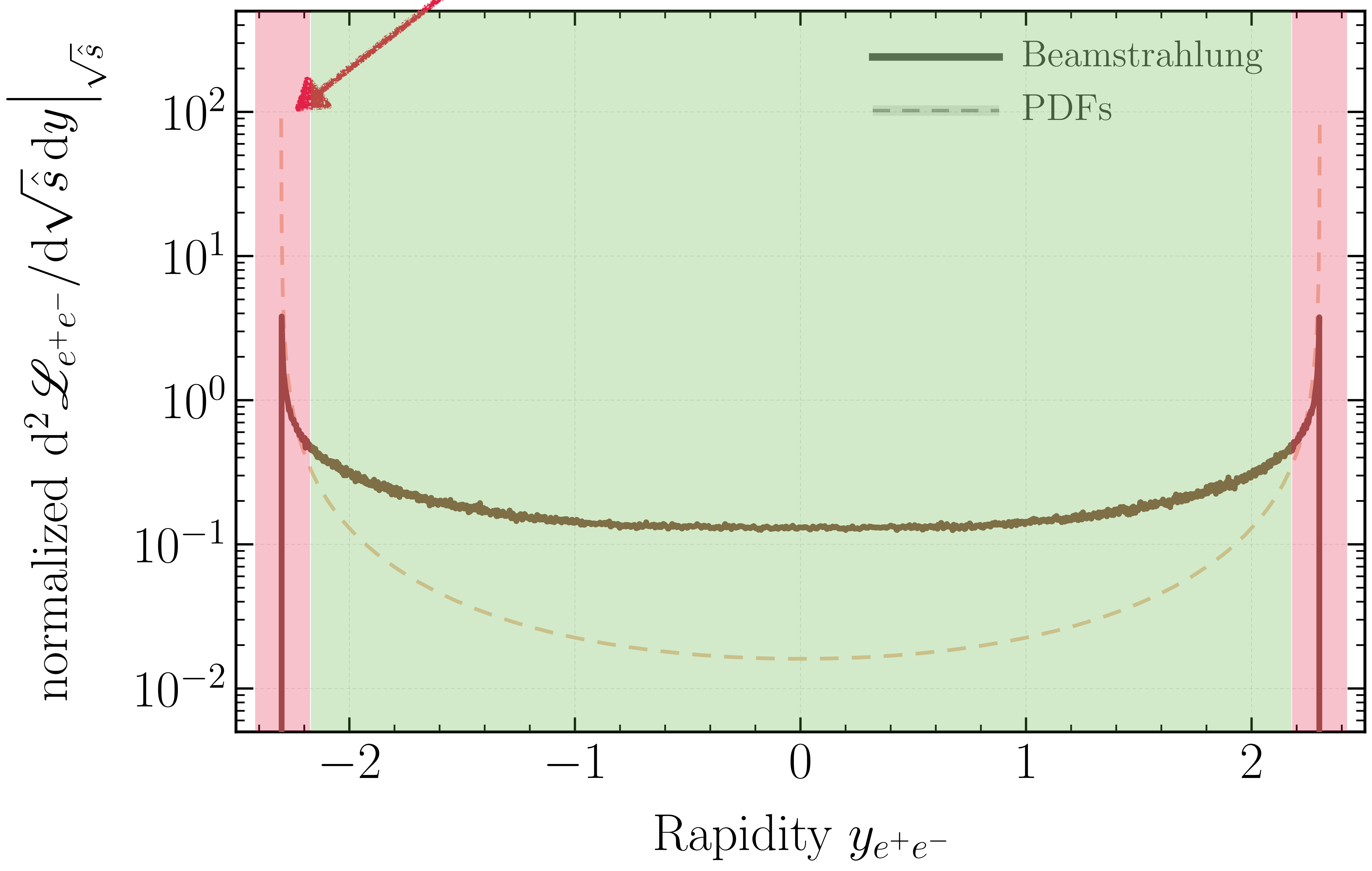
- When $y(M_X) < \eta_{\text{det}}$ we can cut on y to reduce background by $\mathcal{O}(10)$.

  $\Longrightarrow$ beamstrahlung hurts a bit.

- When $y(M_X) > \eta_{\text{det}}$ many events our lost outside the detector.

  $\Longrightarrow$ beamstrahlung helps a lot.

$$y(M_X) \approx \frac{1}{2} \log\left(\frac{s}{M_X^2}\right)$$



Inclusive Search: $e^+e^- \to (Z' \to \mu^+\mu^-) + \text{anything}$

Cuts:

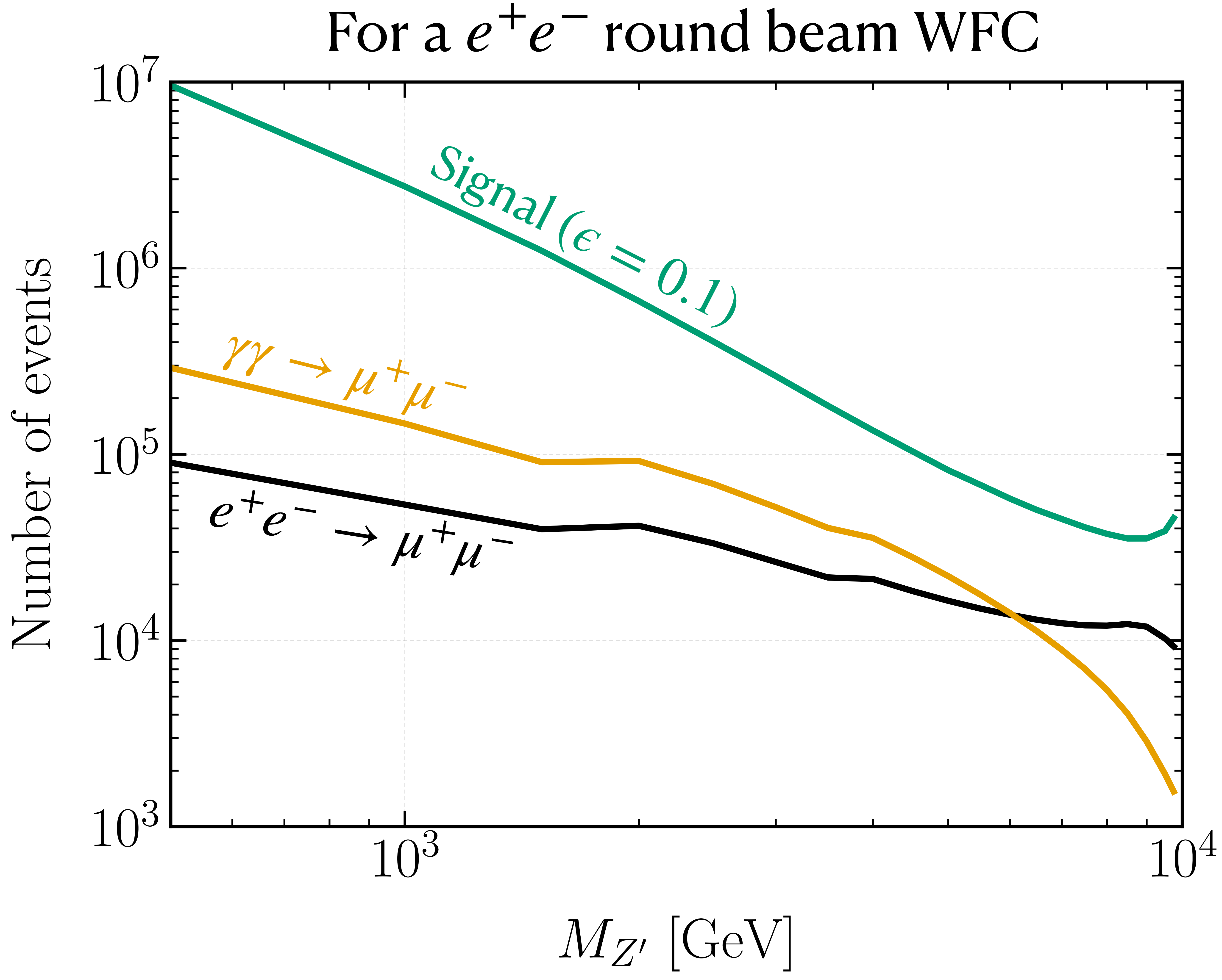
1. $|m_{\mu\mu} - M_{Z'}| \leq \Delta M_{Z'}$
2. ~~$\left| |y_{\mu\mu}| - \frac{1}{2}\log(s/M_{Z'}^2) \right| \leq \delta$~~

Detector Modeling:

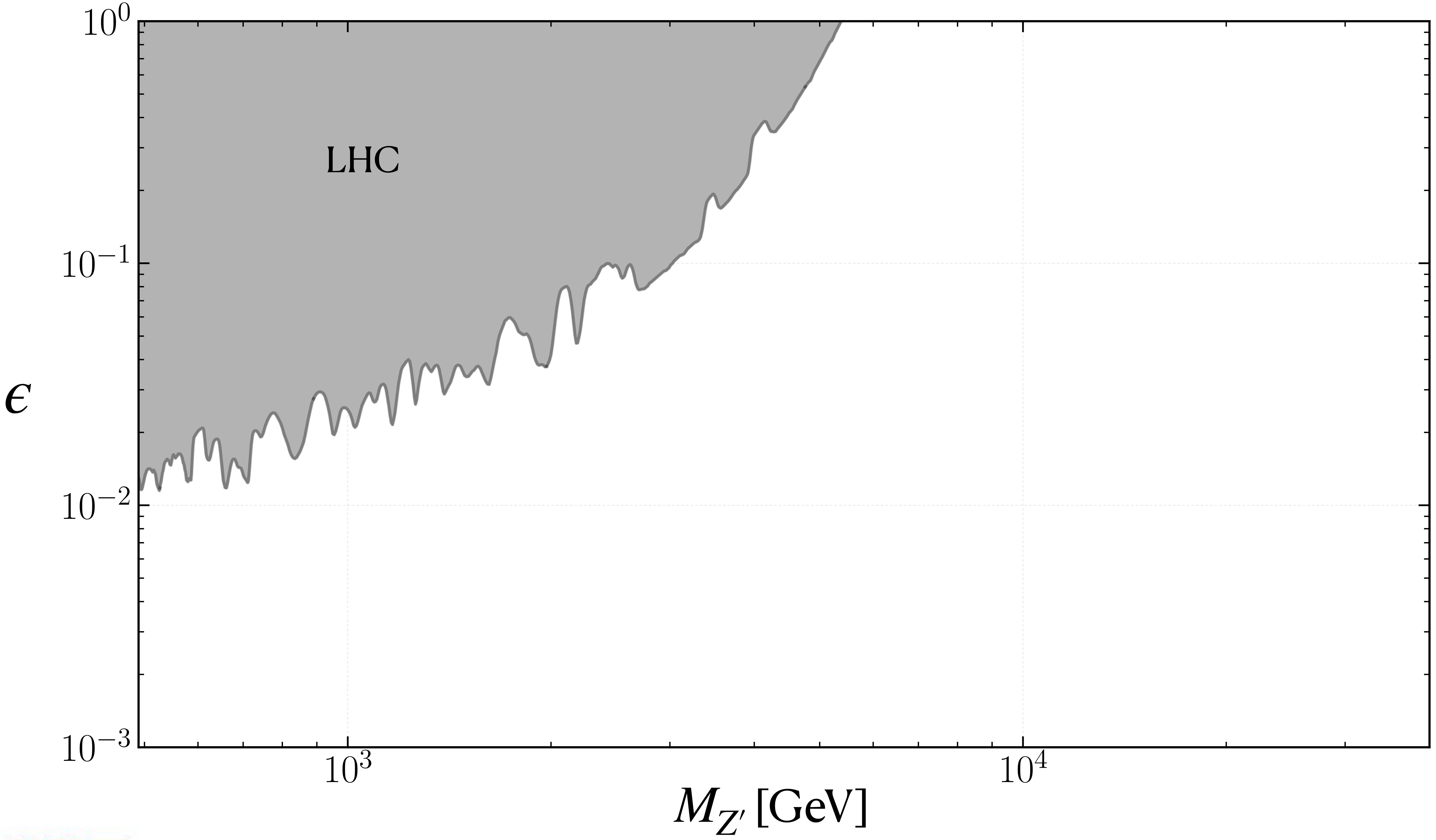
1. $\Delta \sim M_{Z'}\sigma(1/p_{T,\mu}) \approx 0.02 \times (M_{Z'}/\text{TeV})$
2. $|\eta_{\mu^\pm}| < 2.5$

SM Backgrounds:

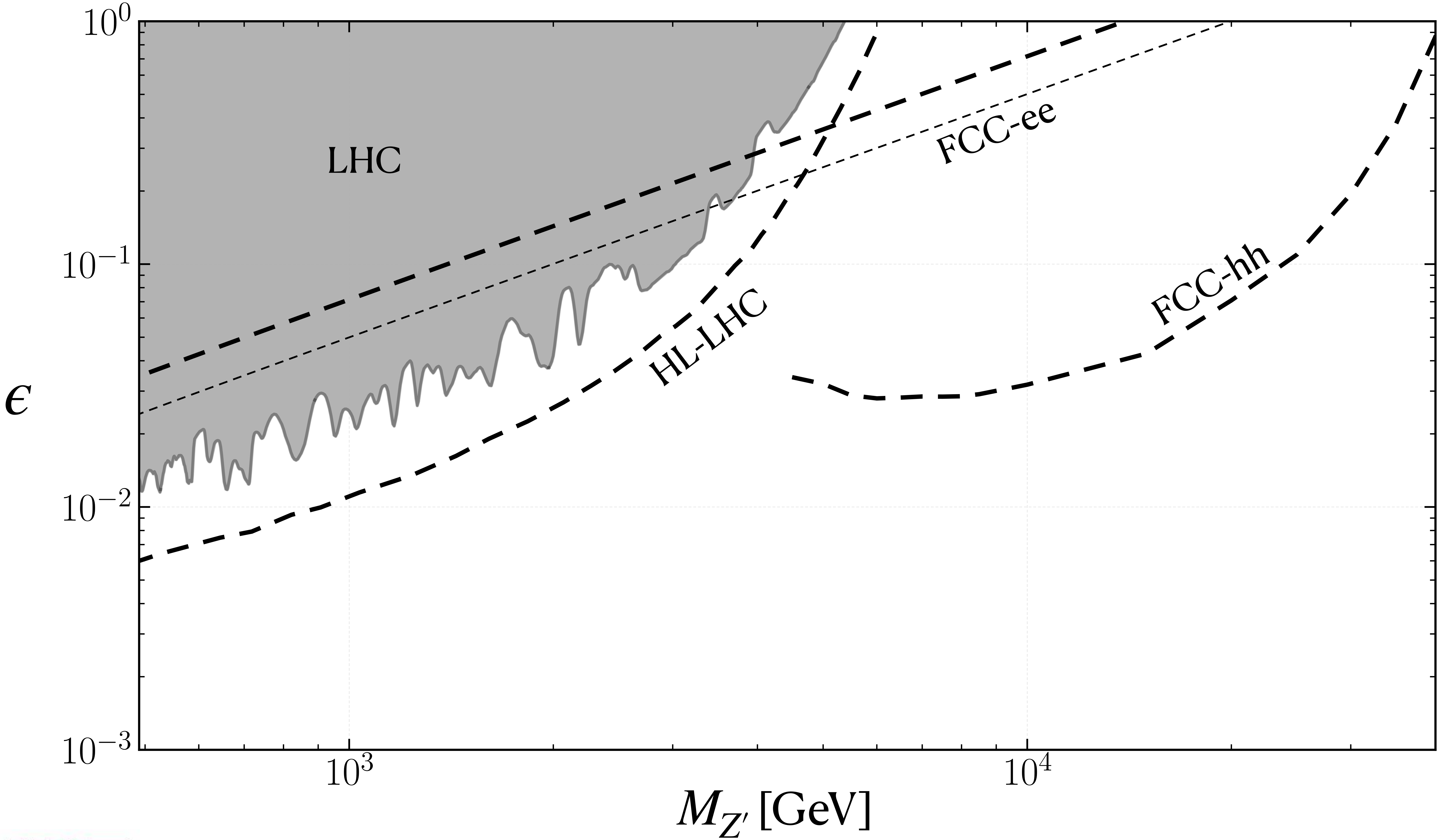
1. $e^+e^- \to (\gamma^*/Z^* \to \mu^+\mu^-)$
2. $\gamma\gamma \to \mu^+\mu^-$



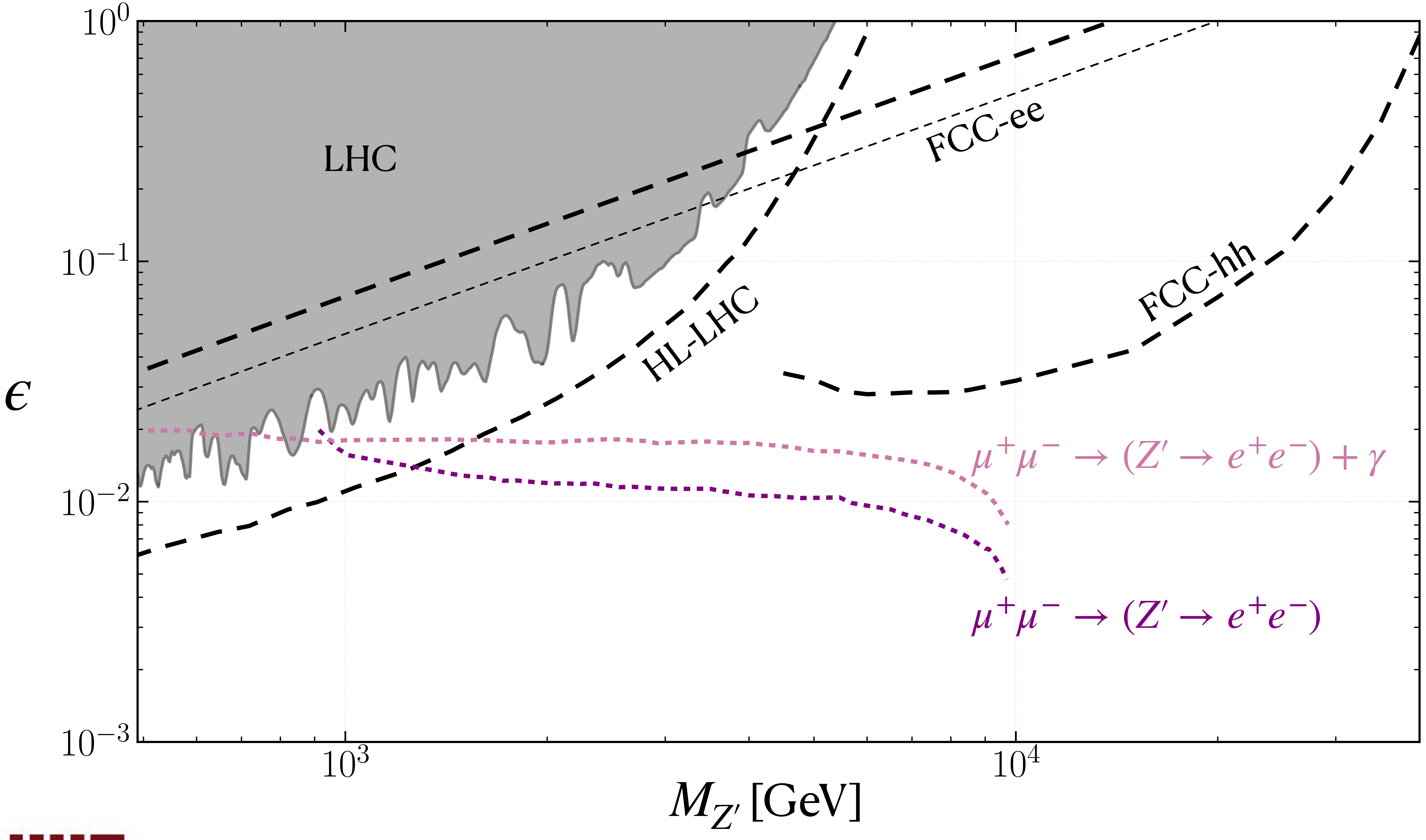
Example: Dark Photon Limits



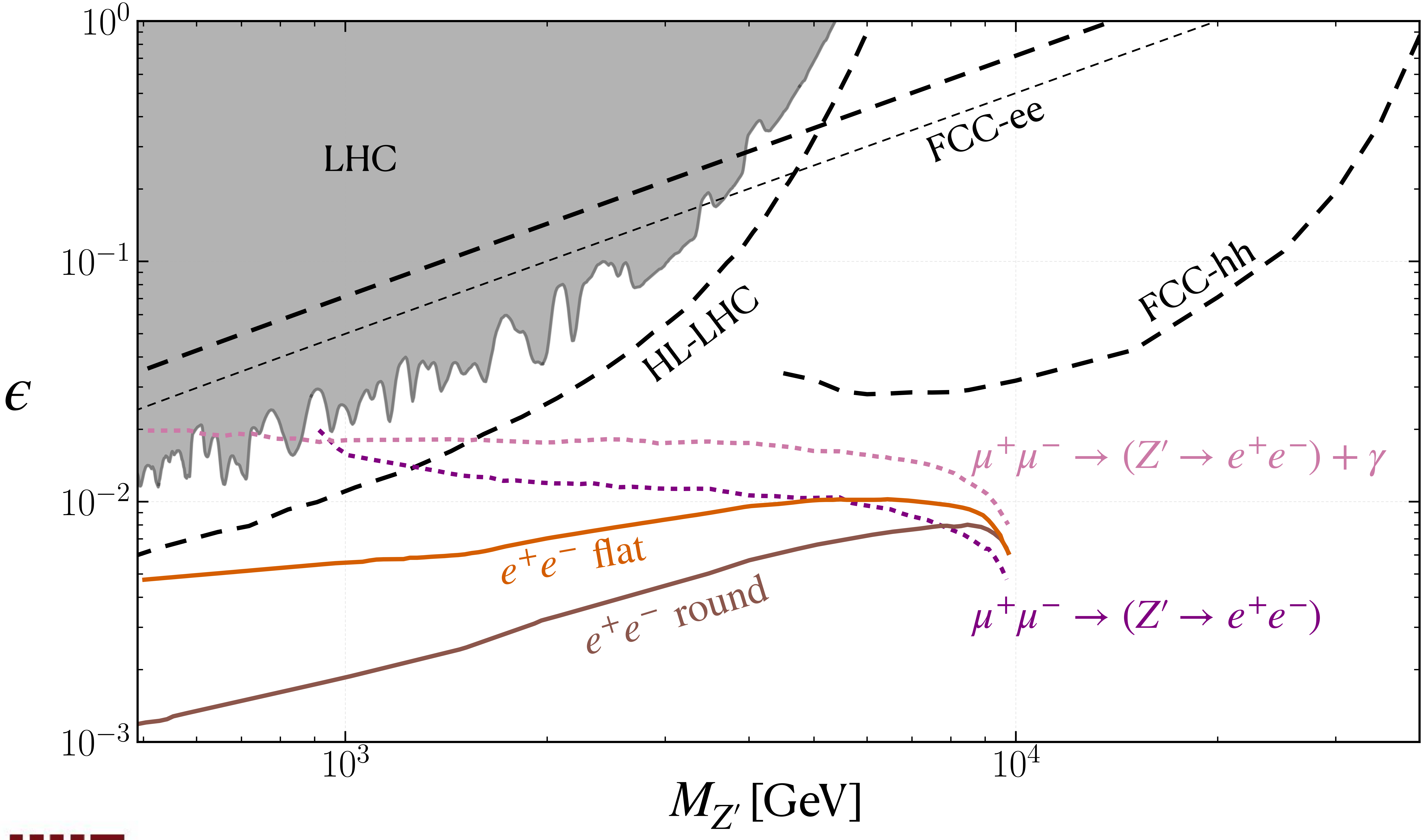
Example: Dark Photon Limits



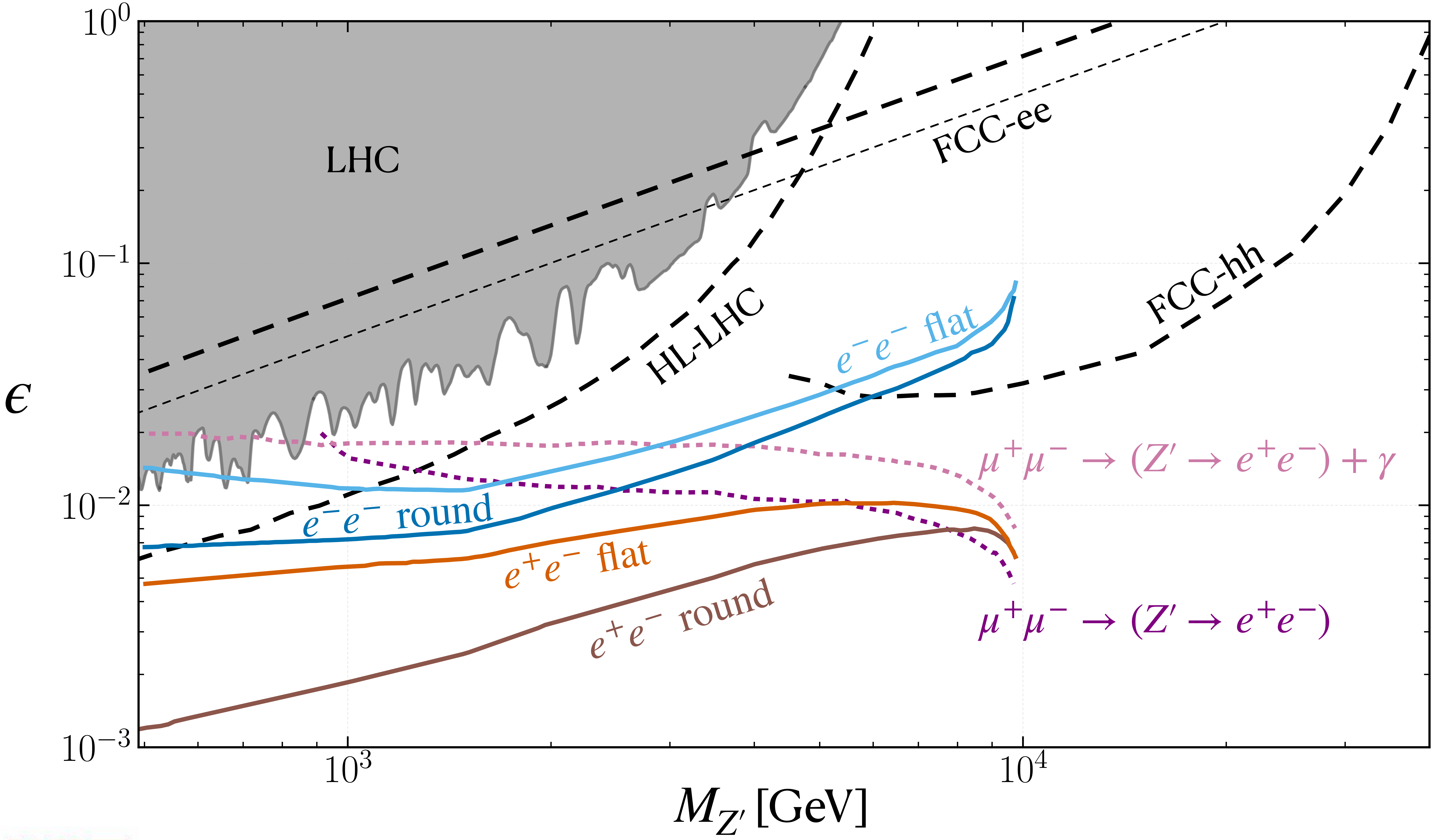
Example: Dark Photon Limits



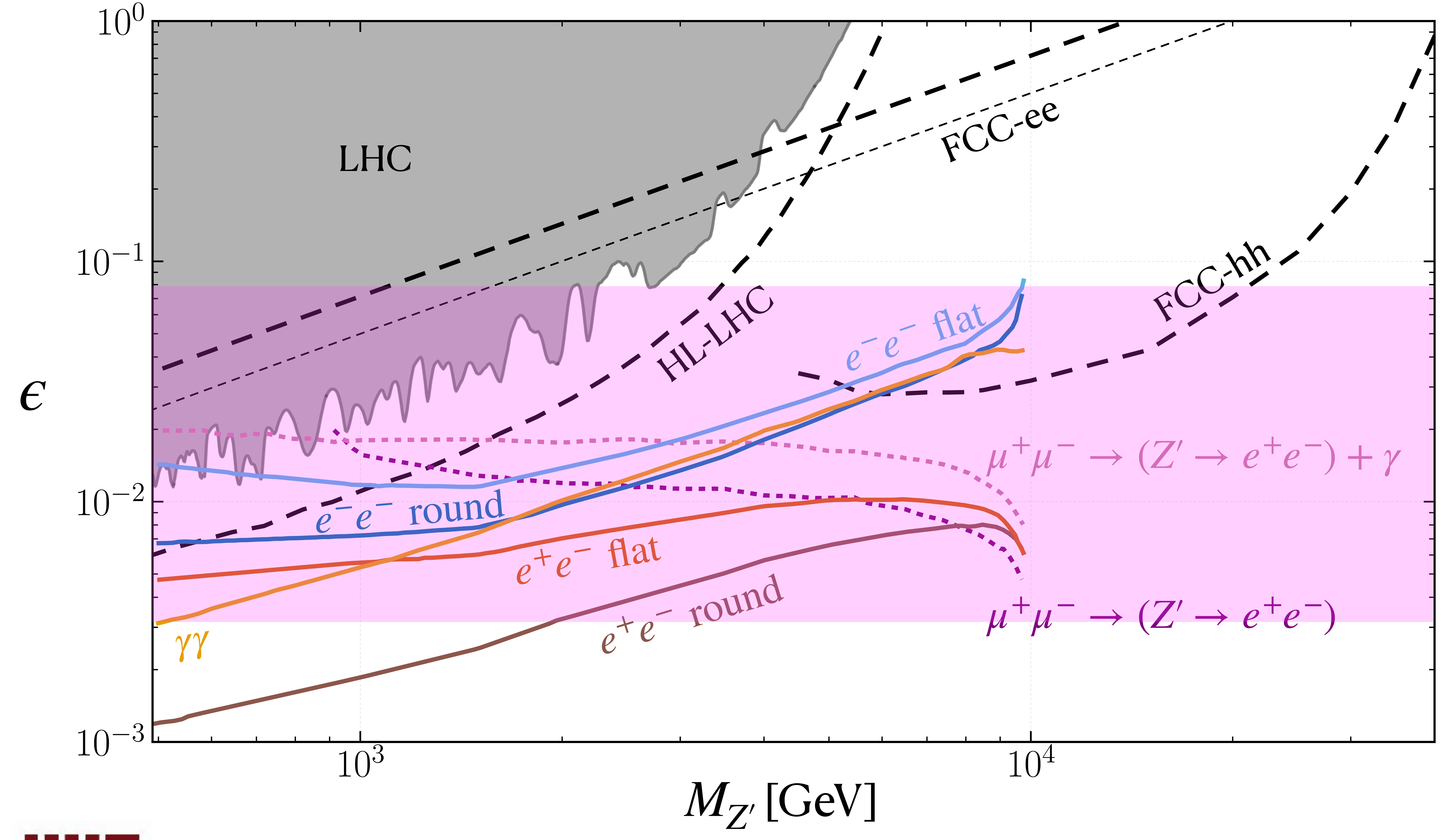
Example: Dark Photon Limits



Example: Dark Photon Limits



Example: Dark Photon Limits

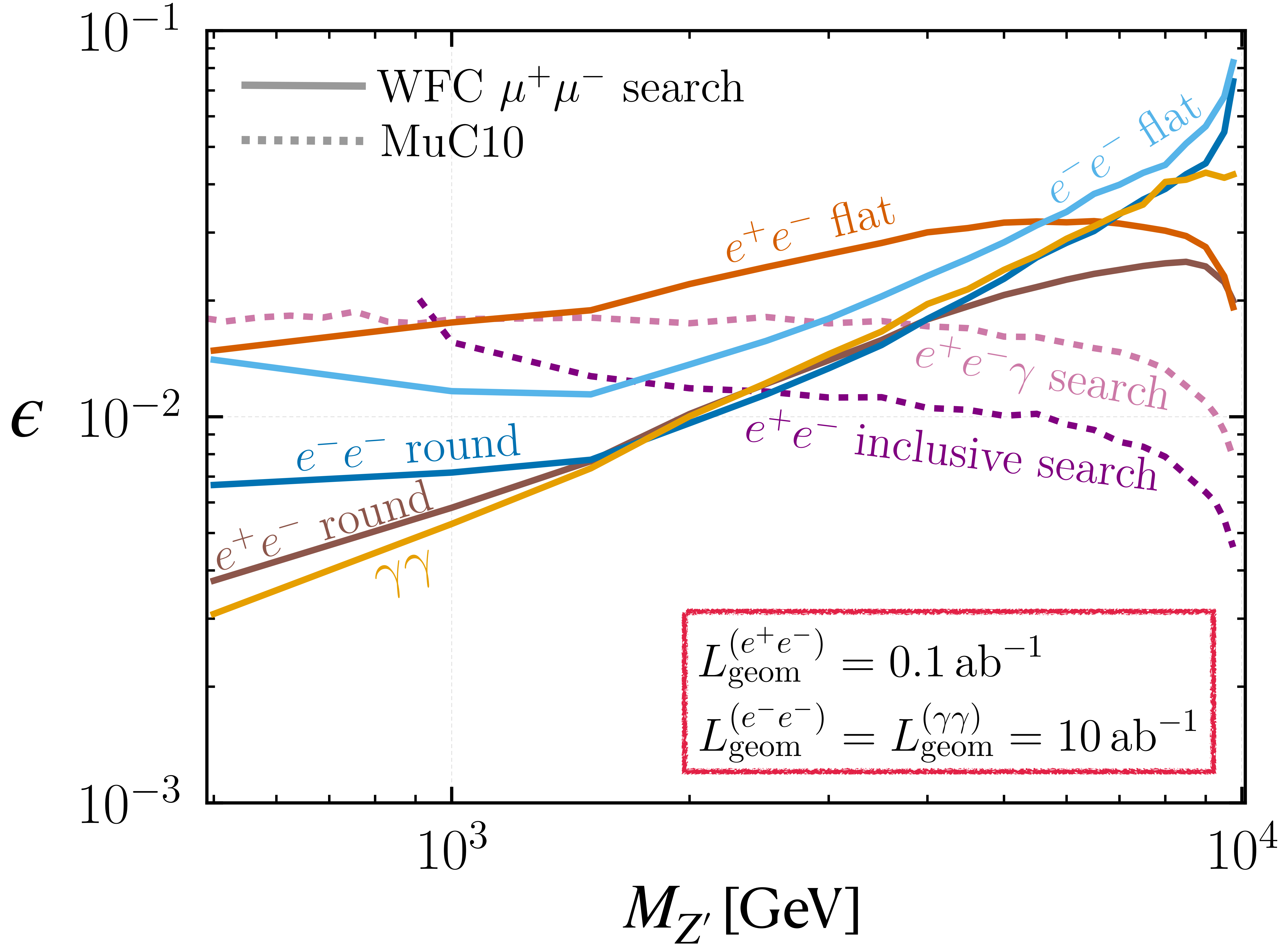


For 1-loop induced ϵ

$$\epsilon \approx \frac{ee_D}{16\pi^2} \in [.003,.08]$$

for $e_D \in [0.5, 4\pi]$

Example: Dark Photon Limits



Positrons ***worth factor of 100*** in $L_{\rm geom}$ for resonance searches (if coupled to leptons).

Two Case Studies

Precision Measurments of Electroweak Higgs Couplings

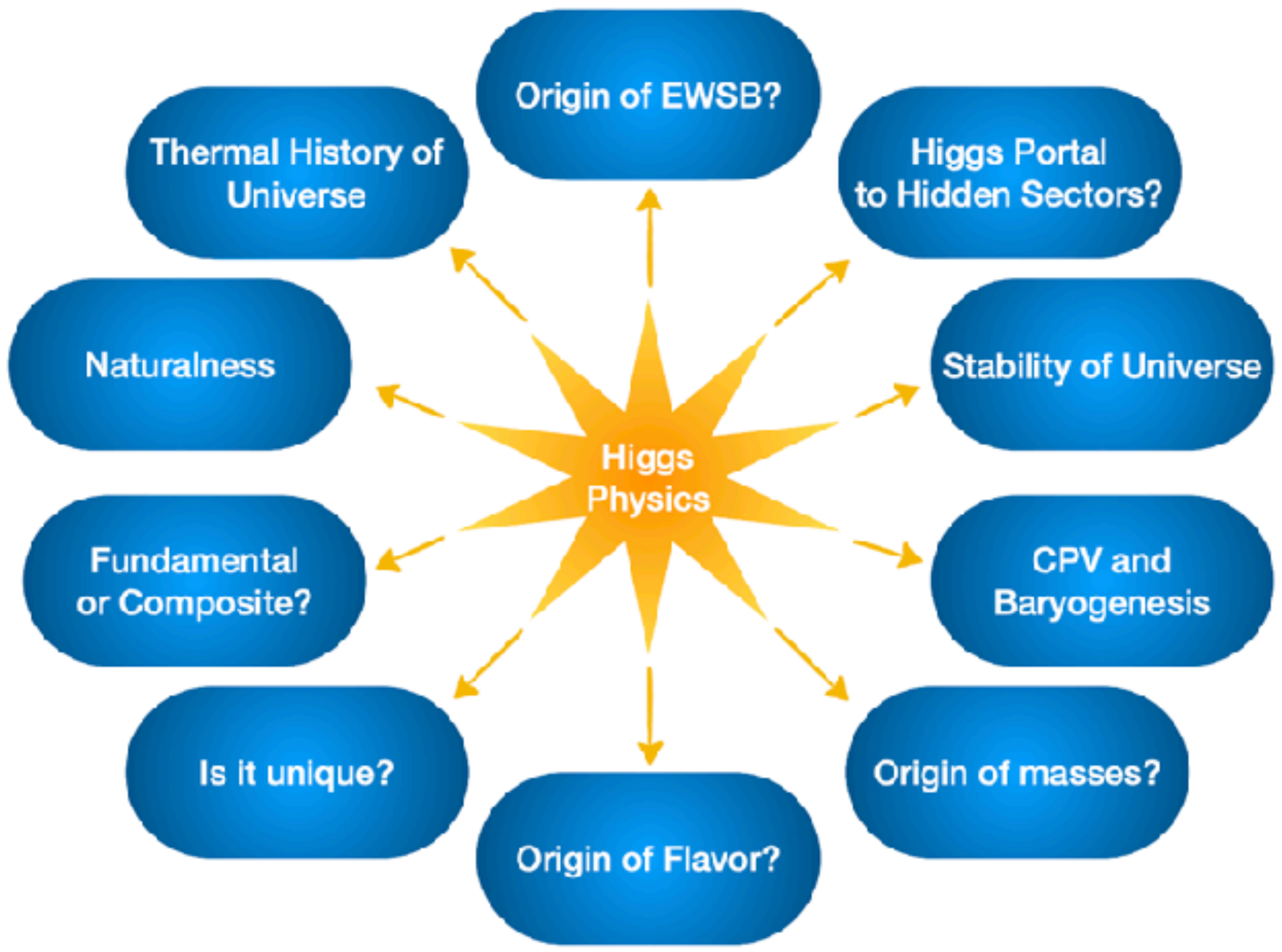
With Simon Knapen, Katie Fraser, and Robert Szafron

Searches for Heavy Resonances [2603.18146]

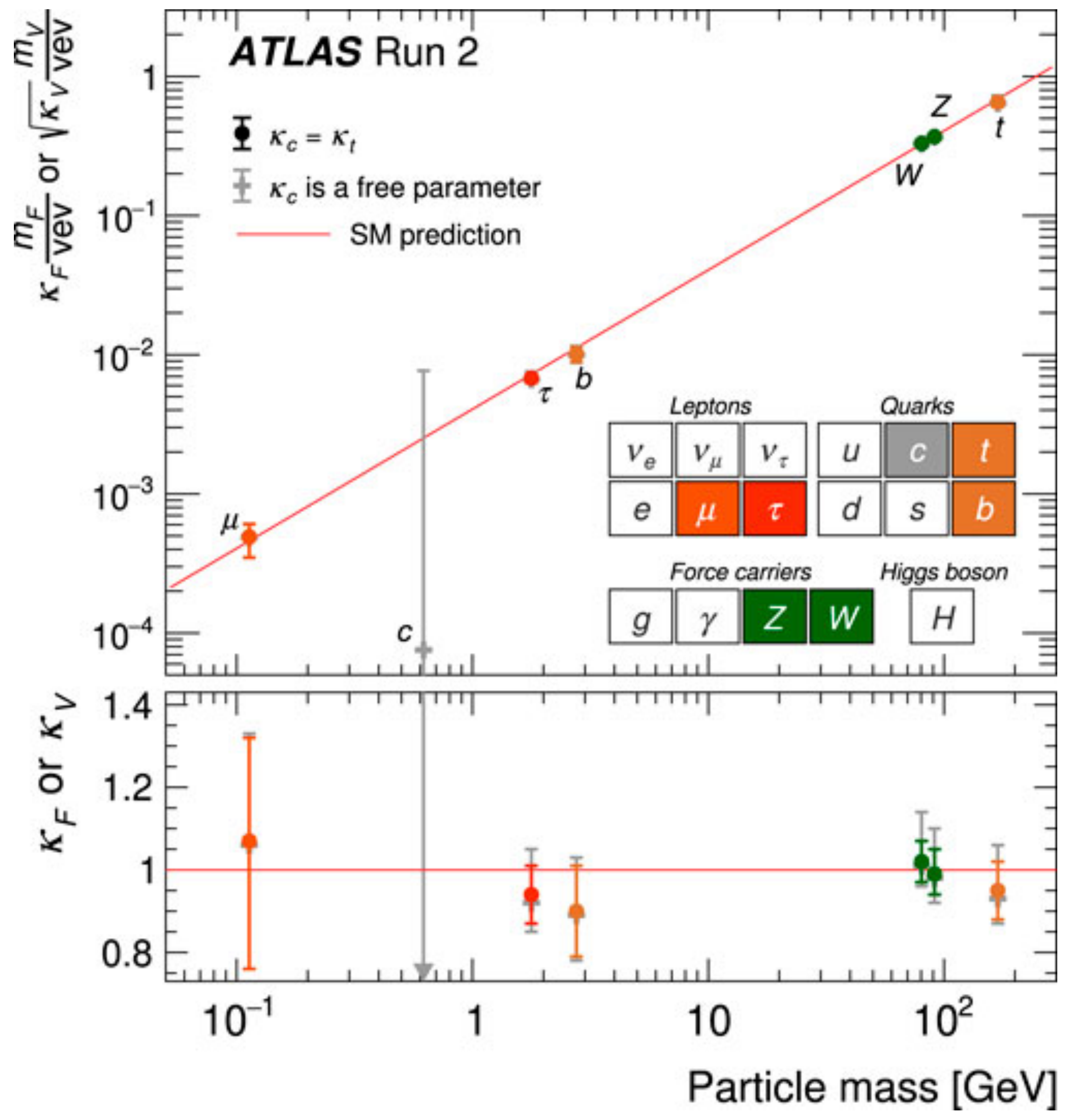
With Toby Opferkuch and Massimo Capressi

Higgs Couplings

The Higgs boson must be understood as well as possible.



[Snowmass Topical Report]

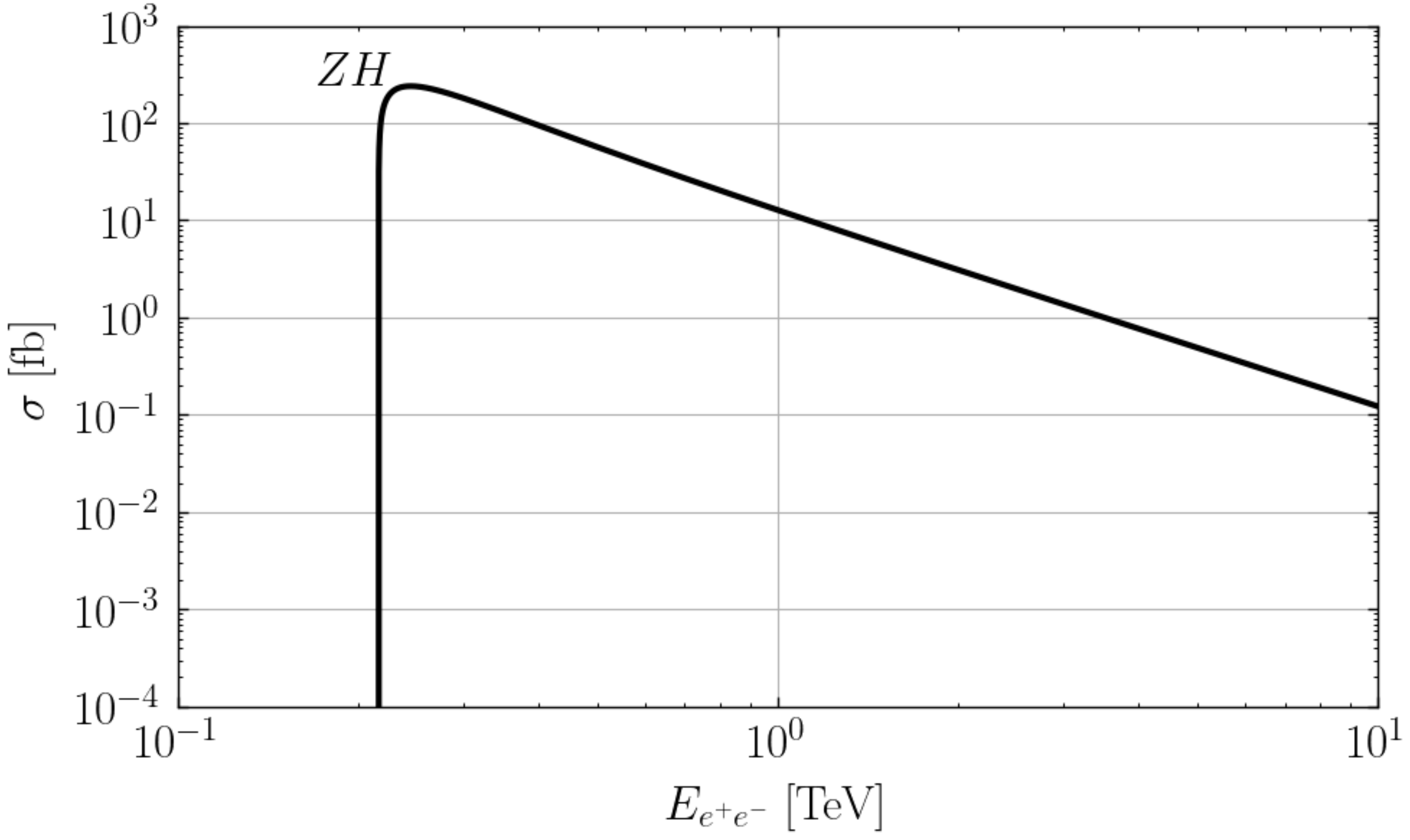


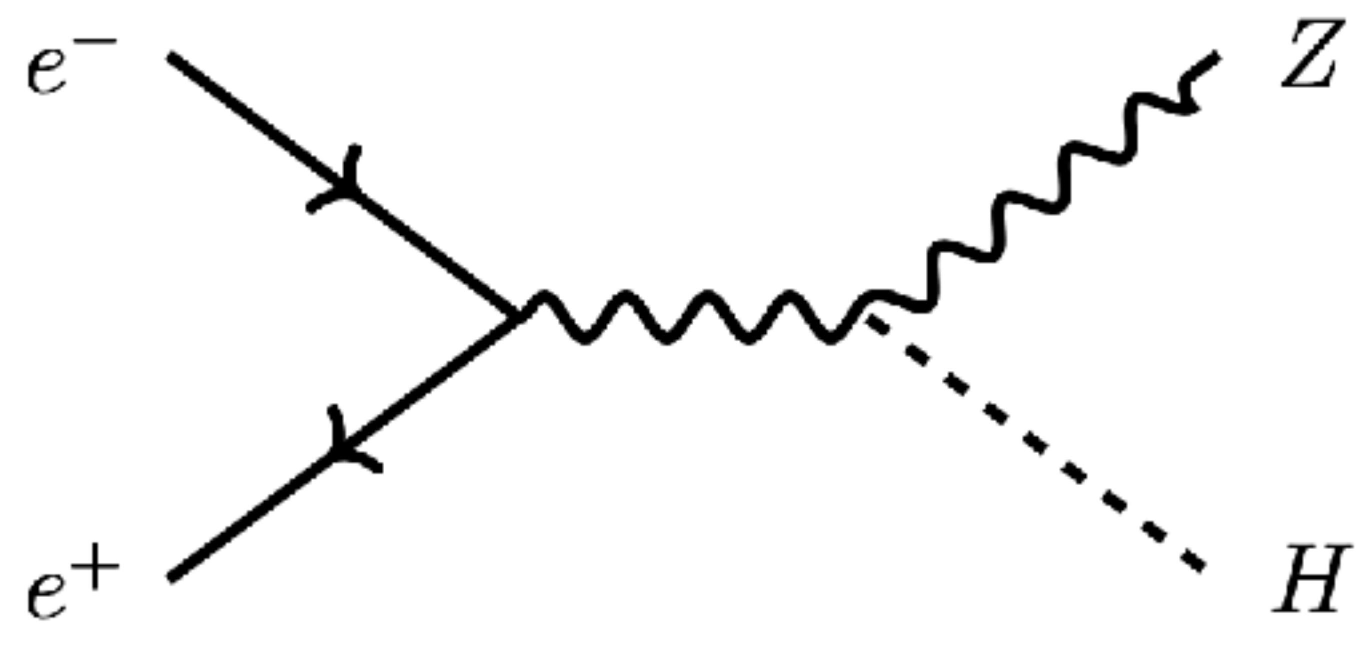
$$\mathcal{L} \supset \frac{2h}{v}\left[\kappa_W M_W^2 W^+W^- + \frac{\kappa_Z}{2} M_Z^2 Z^2 + \frac{\kappa_3}{4} M_H^2 h^2\right] + \frac{h^2}{v^2}\left[\kappa_{W_2} M_W^2 W^+W^- + \frac{\kappa_{Z_2}}{2} M_Z^2 Z^2 + \frac{\kappa_4}{8} M_H^2 h^2\right]$$

High Energy $\Longrightarrow$ High Statistics

Higgs Production Cross Sections

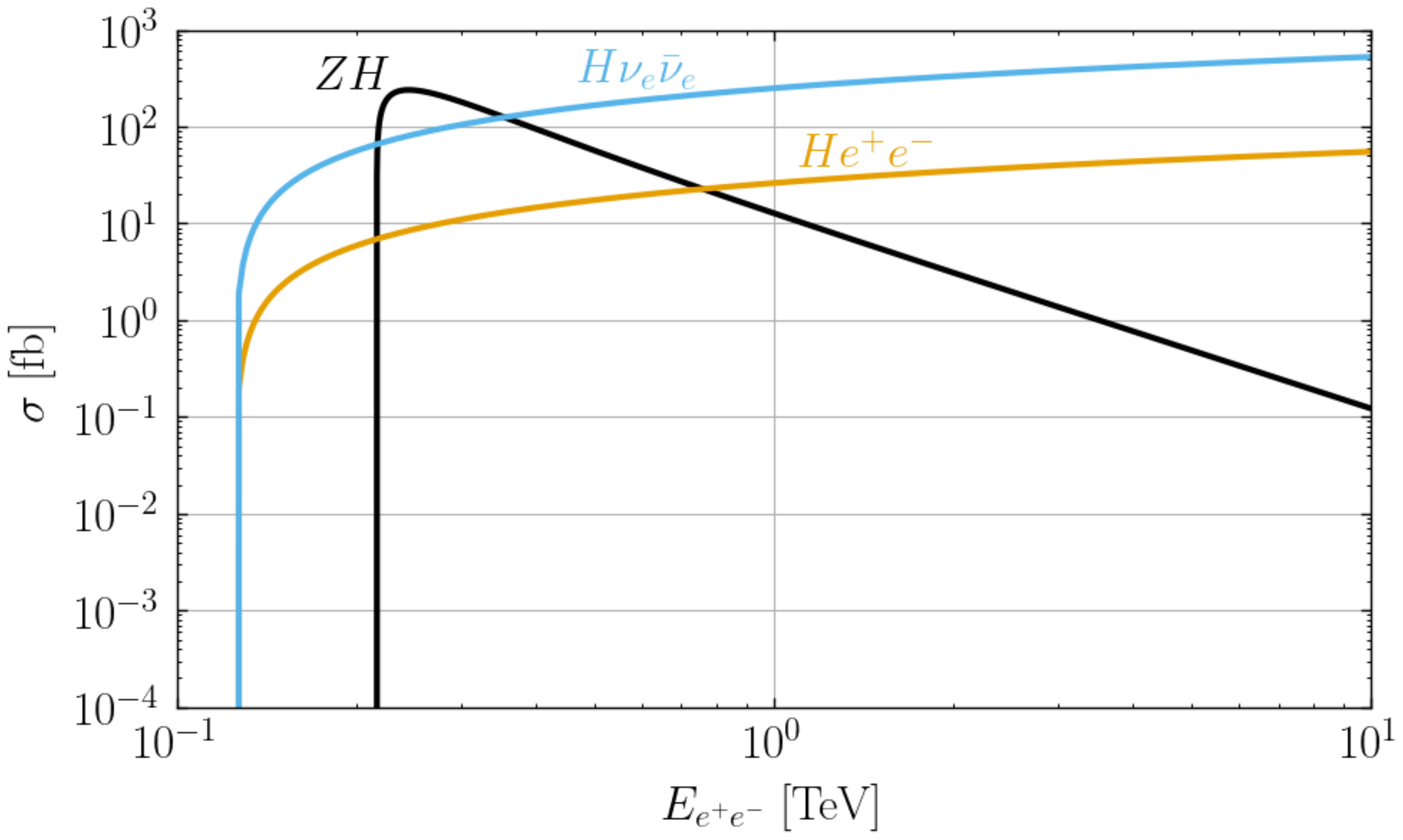
First consider single Higgs production

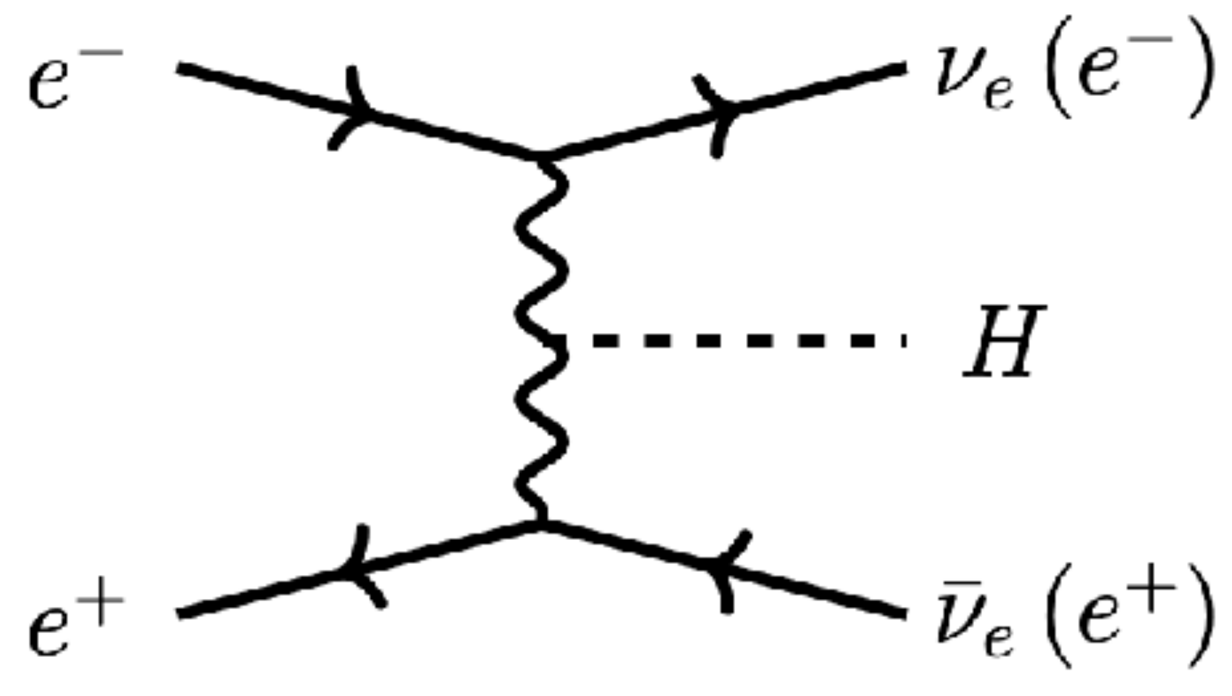


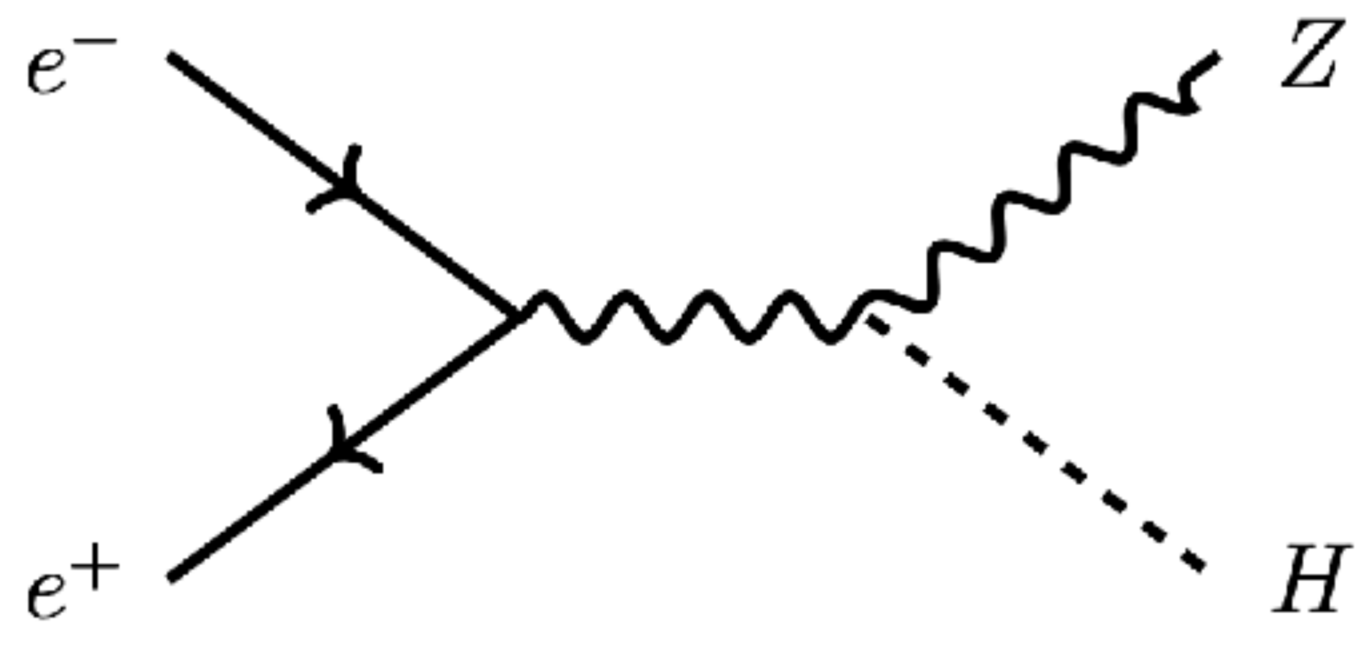


Higgs Production Cross Sections

First consider single Higgs production

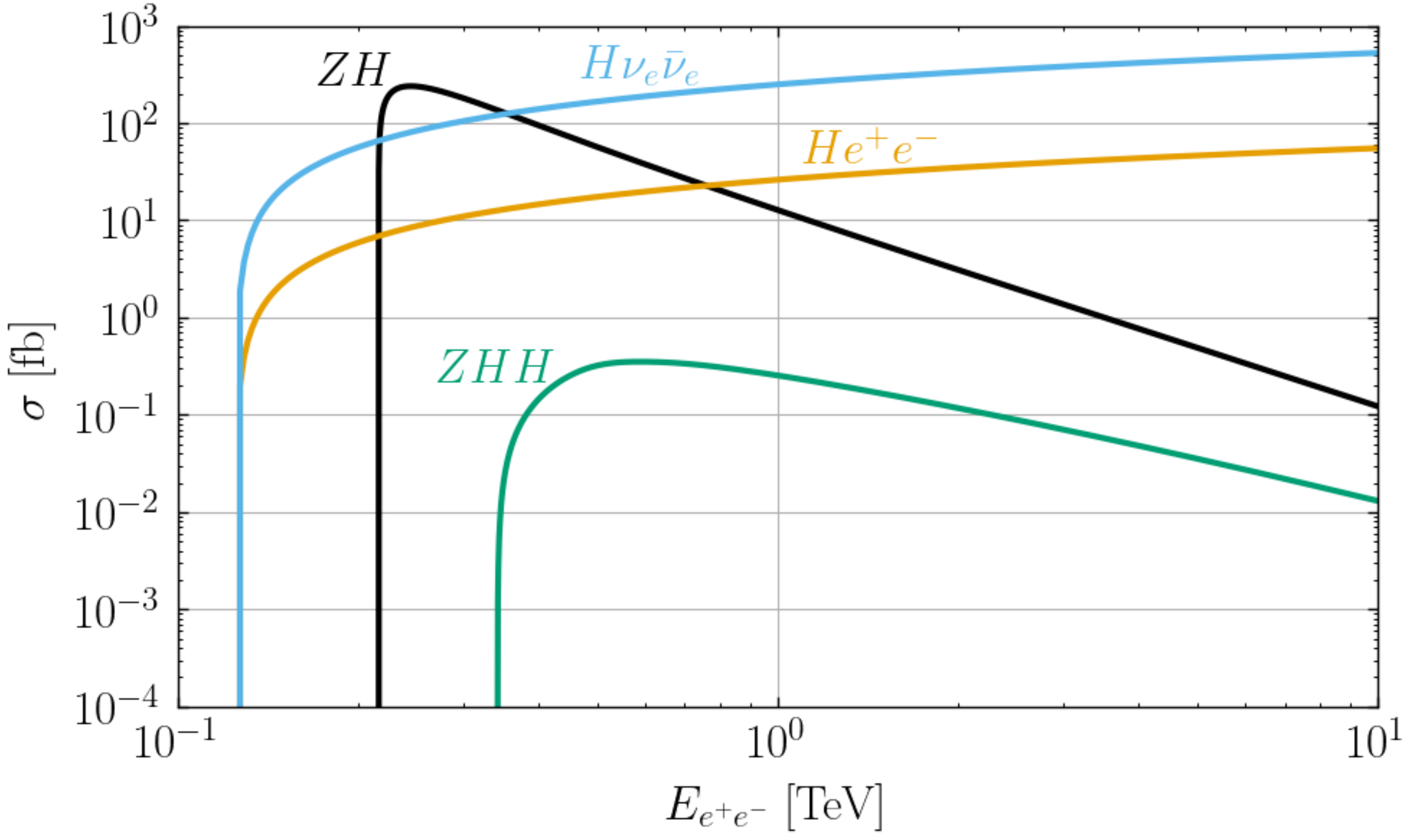


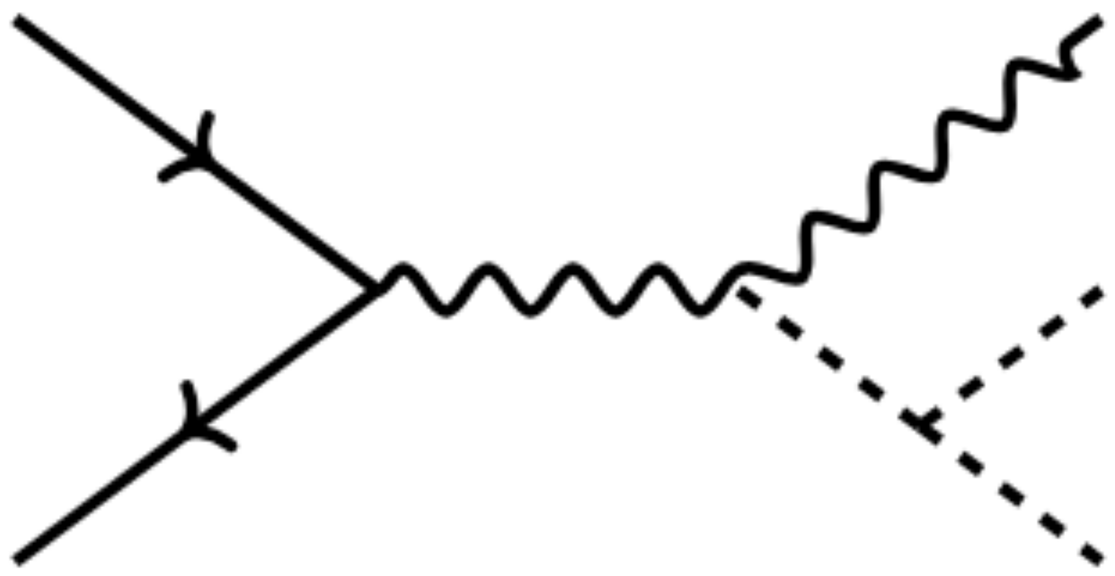




Higgs Production Cross Sections

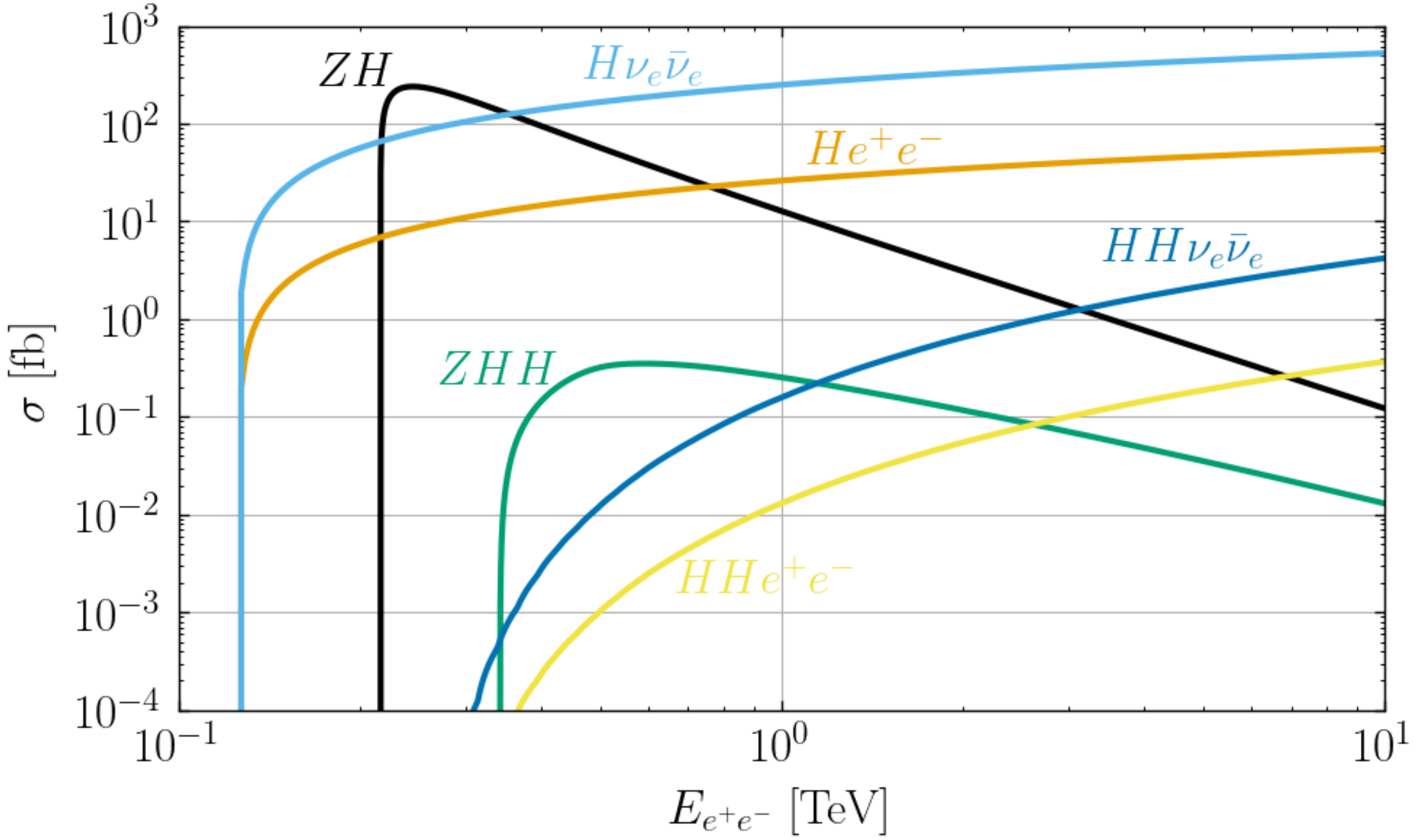
Now consider Di-Higgs production

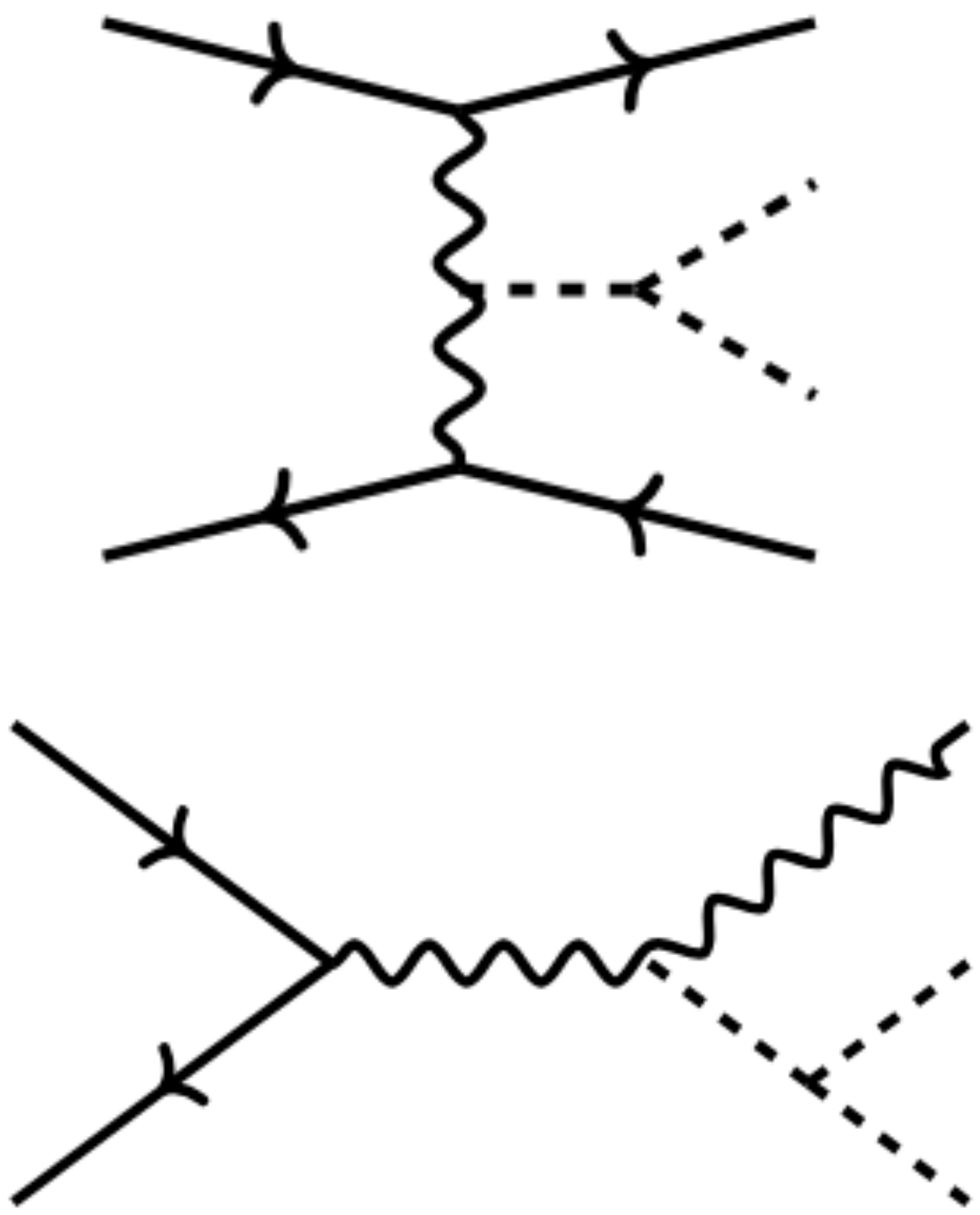




Higgs Production Cross Sections

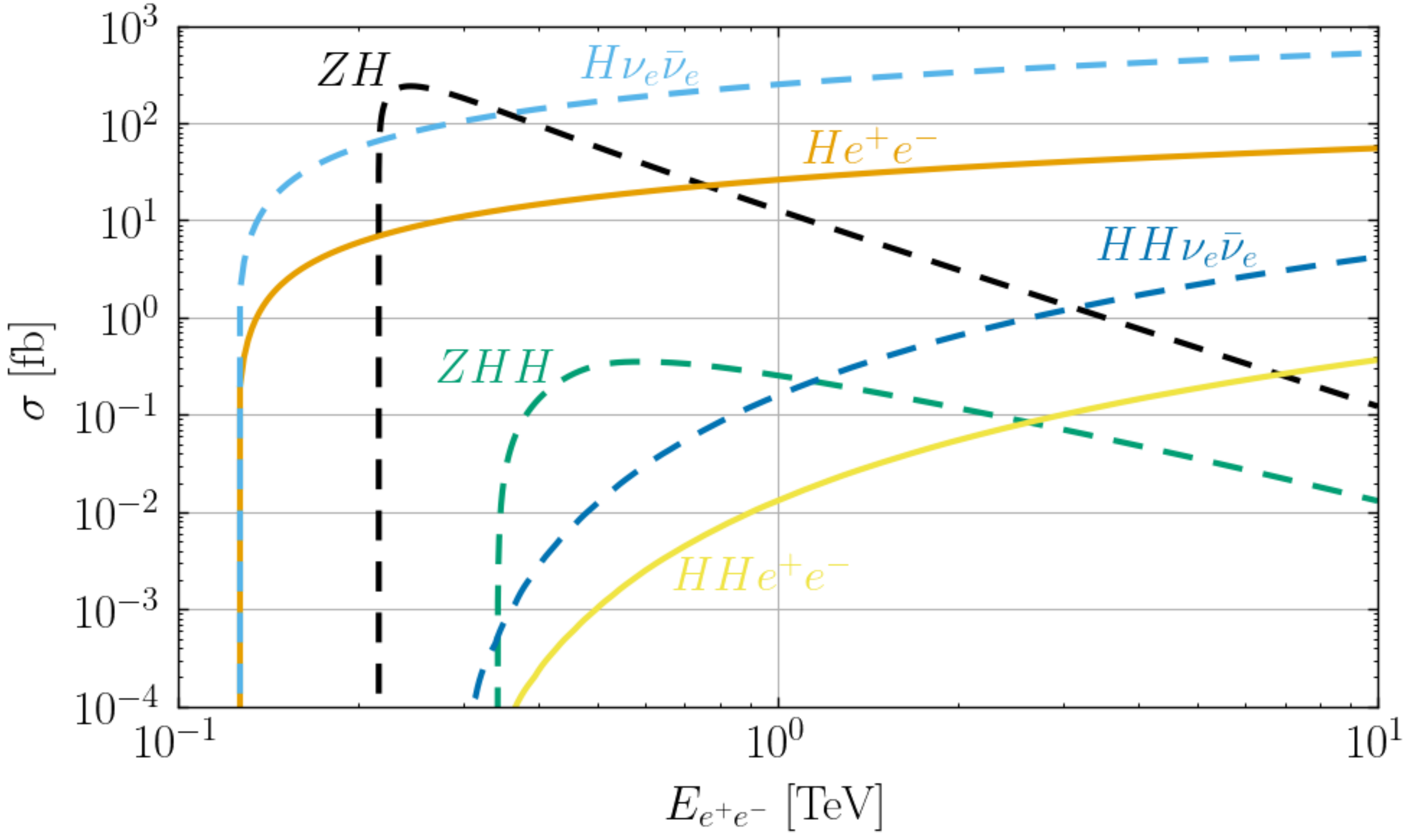
Now consider Di-Higgs production





Higgs Production Cross Sections

We lose the dashed line channels for e^-e^-.

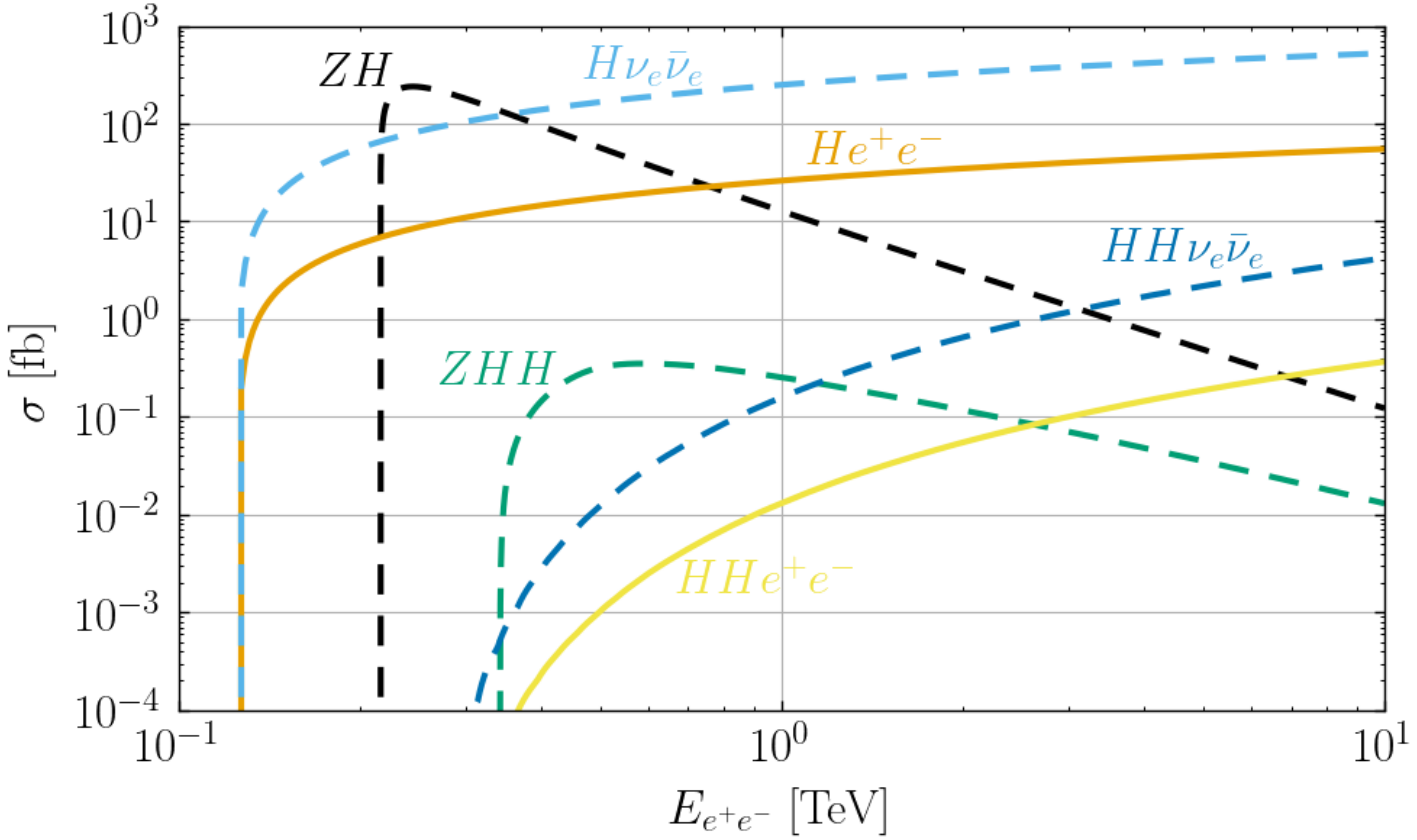


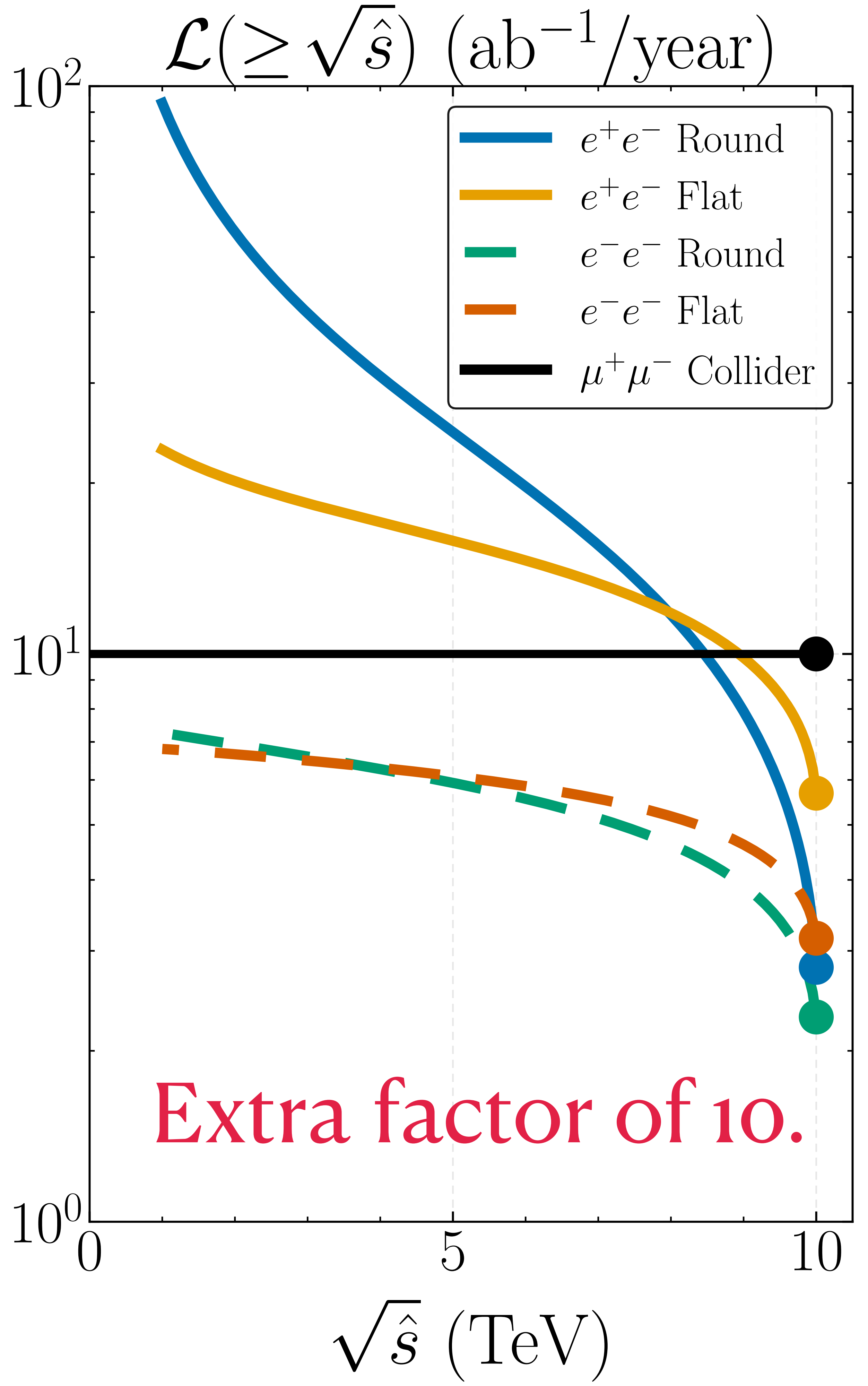
Naively implies factor of 10 worse.

Also, must account for luminosity.

Higgs Production Cross Sections

We lose the dashed line channels for e^-e^-.





Single Higgs Analysis
$(H \to b\bar{b})$

Single Higgs Analysis

Cuts (Incomplete list):

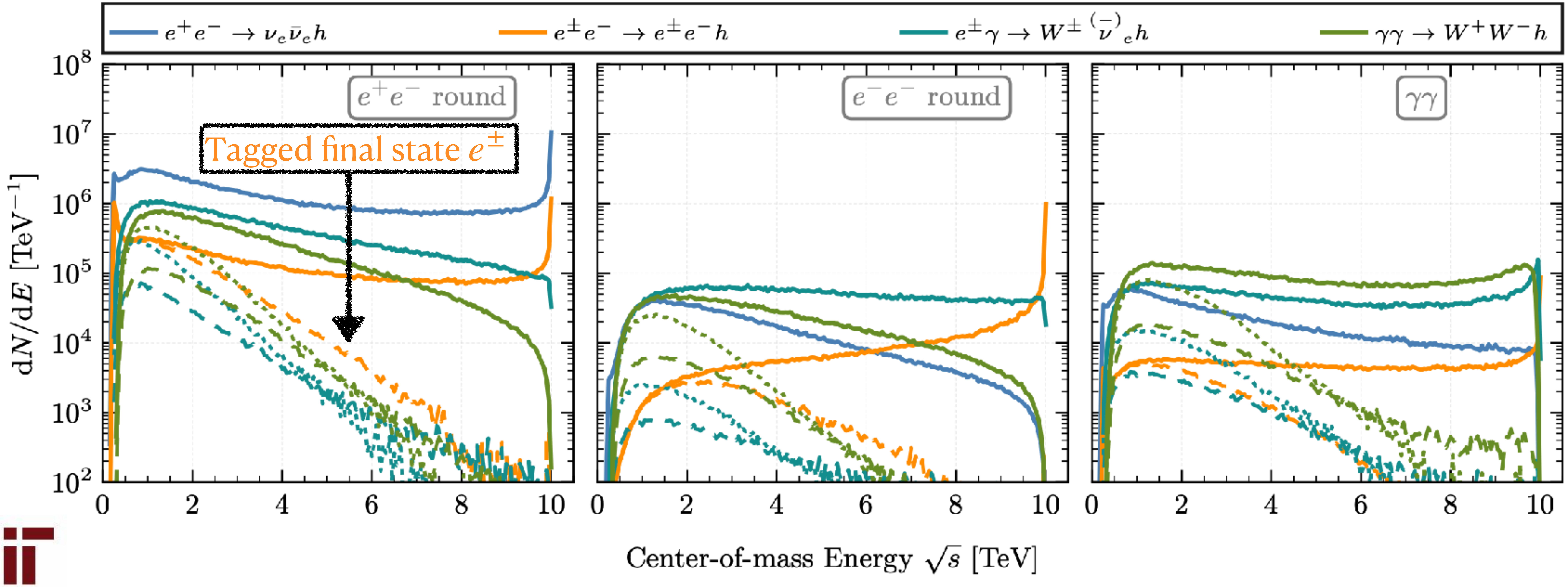
1. $|m_{b\bar{b}} - m_h| \leq 15$ GeV
2. $p_{T,b\bar{b}} > 30$ GeV

Detector Modeling:

1. $\sigma(E_b)/E_b = 0.1$
2. $|\eta_{b,\bar{b}}| < 2.5$

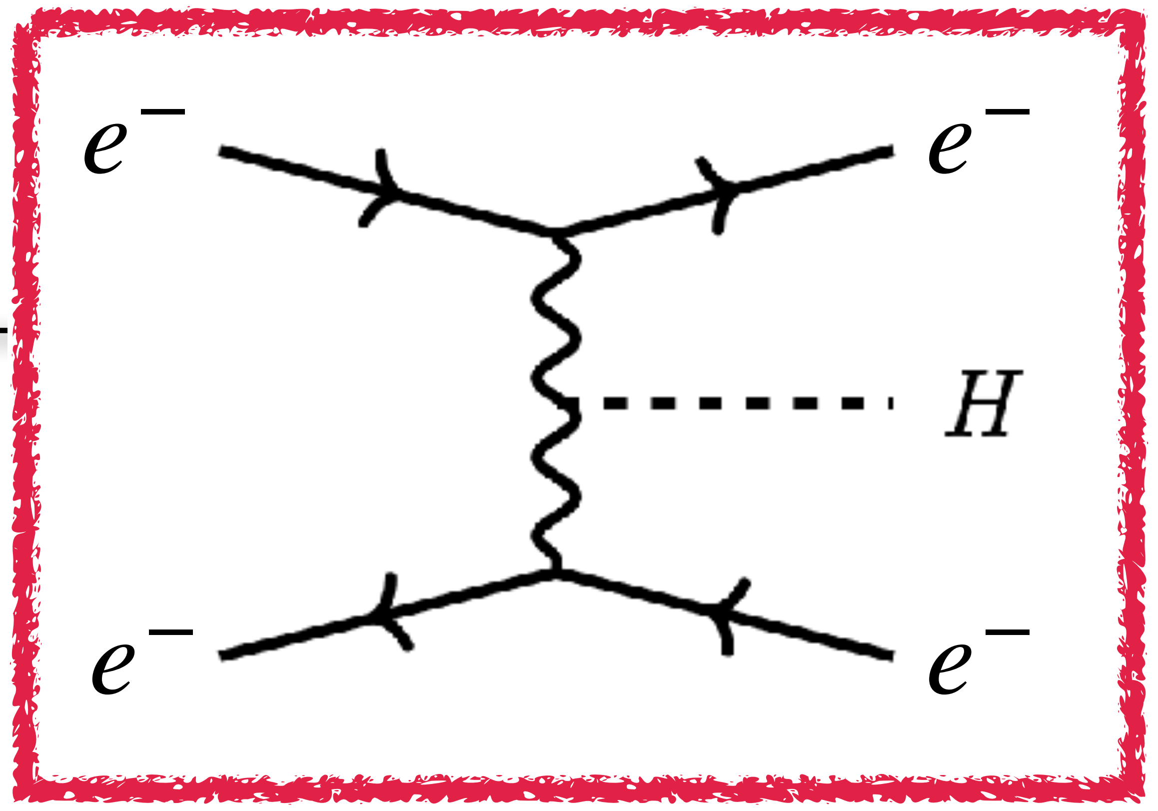
Backgrounds:

1. $Z^* \to b\bar{b}$
2. $\gamma\gamma \to b\bar{b}$

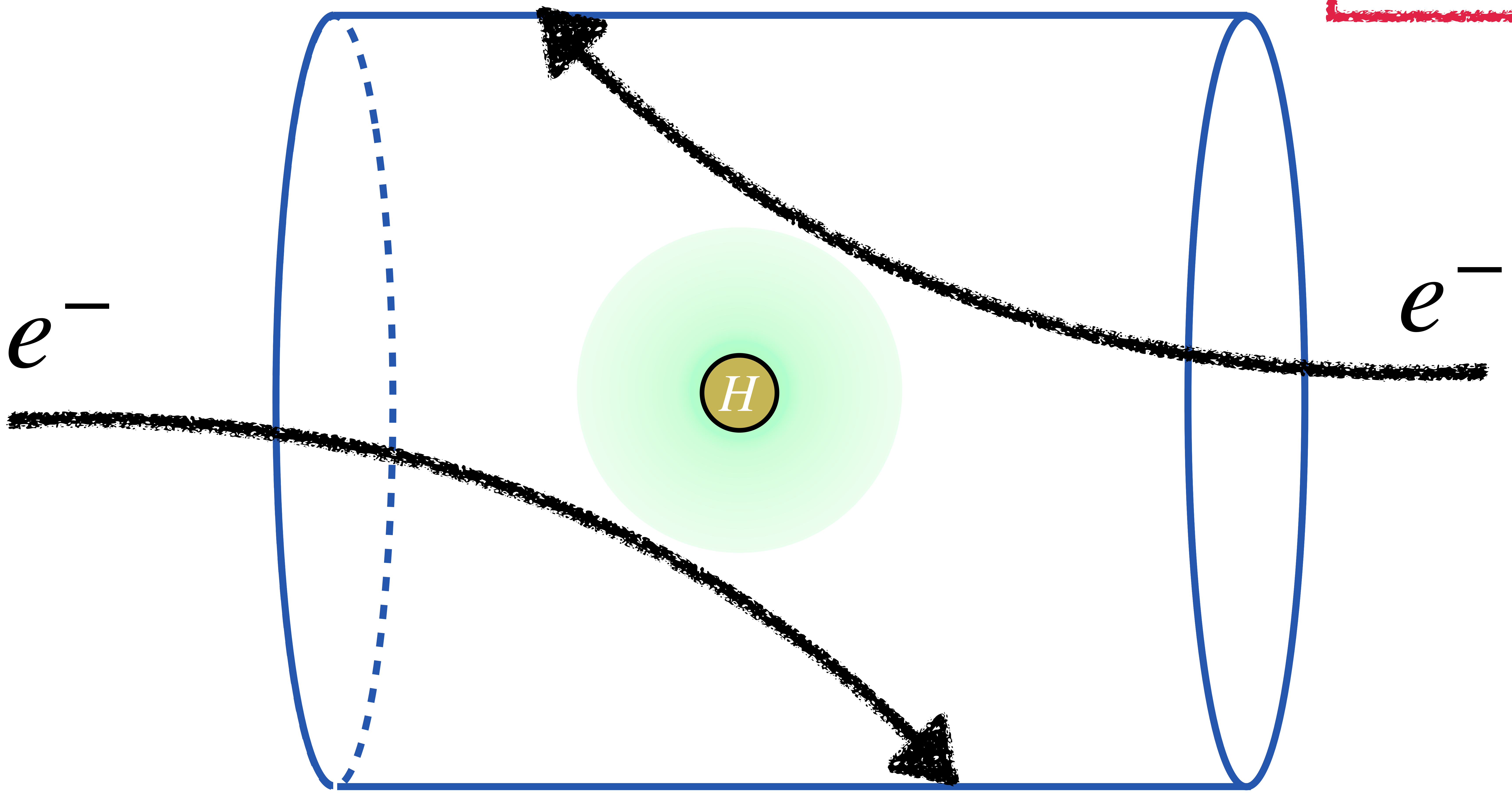


Tagging Forward Particles

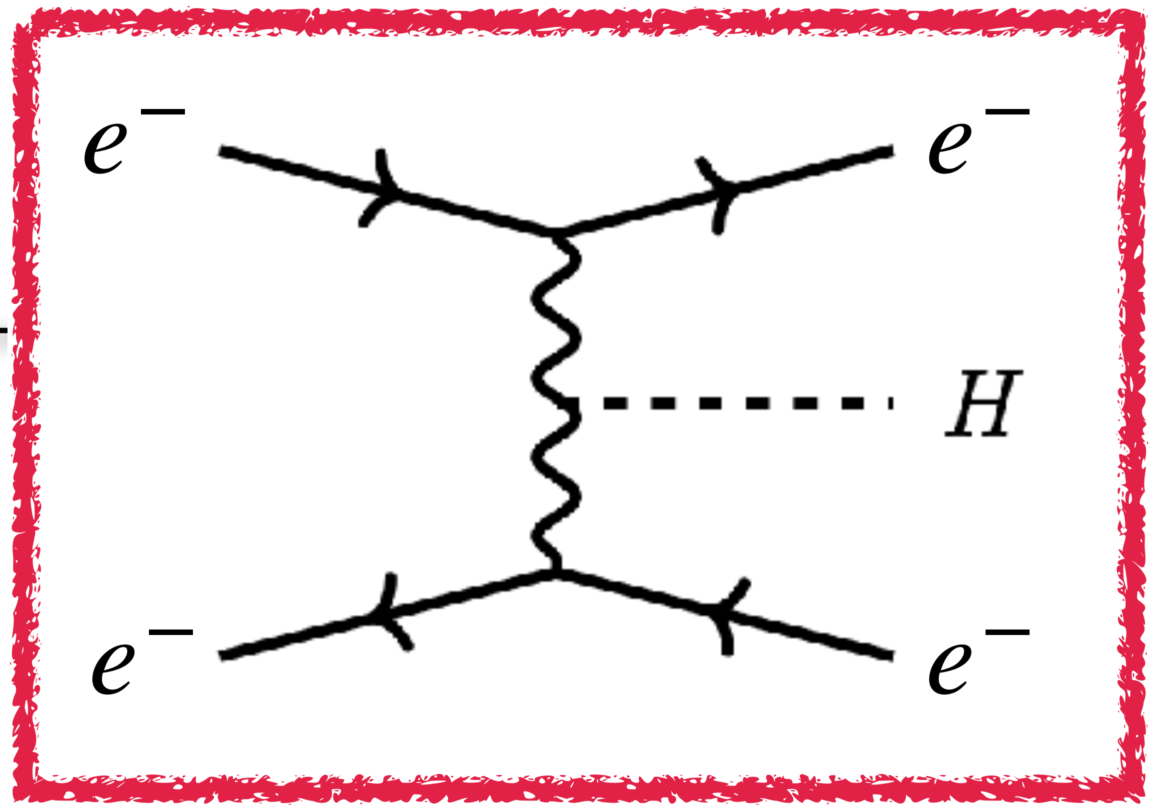
Tagging Forward Particles



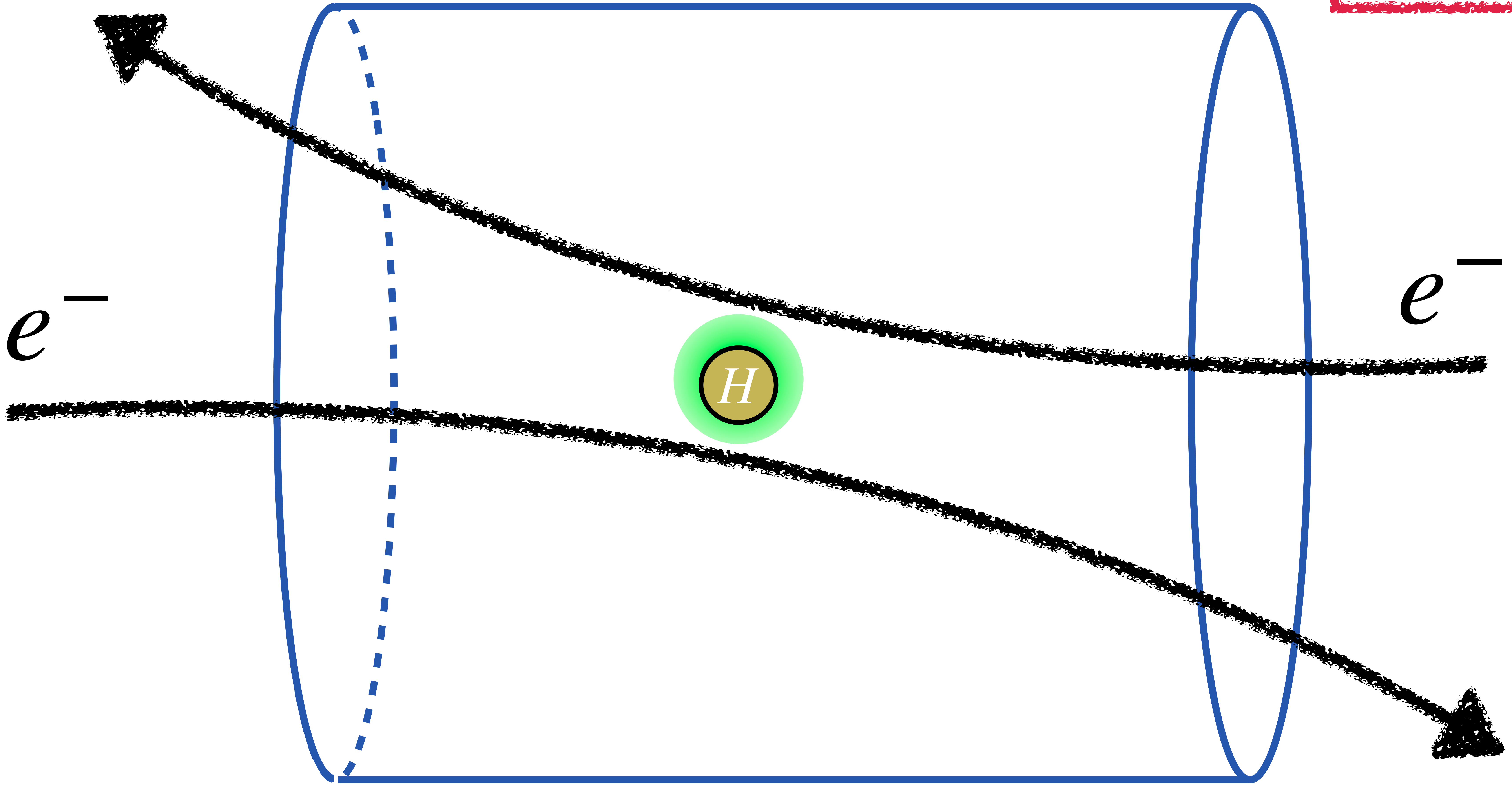
Low Energy



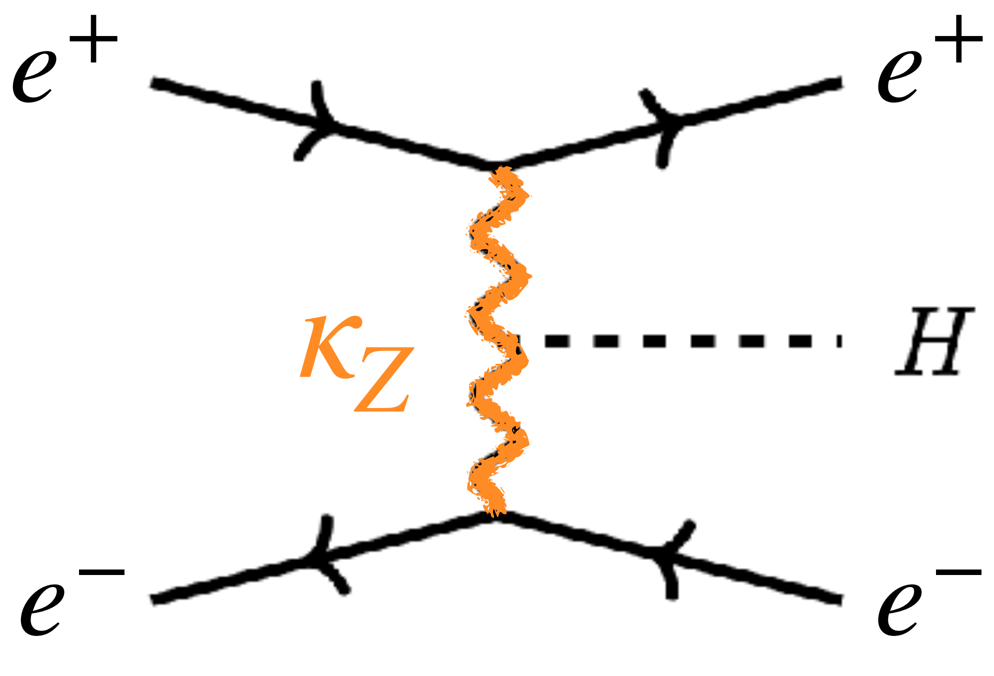
Tagging Forward Particles



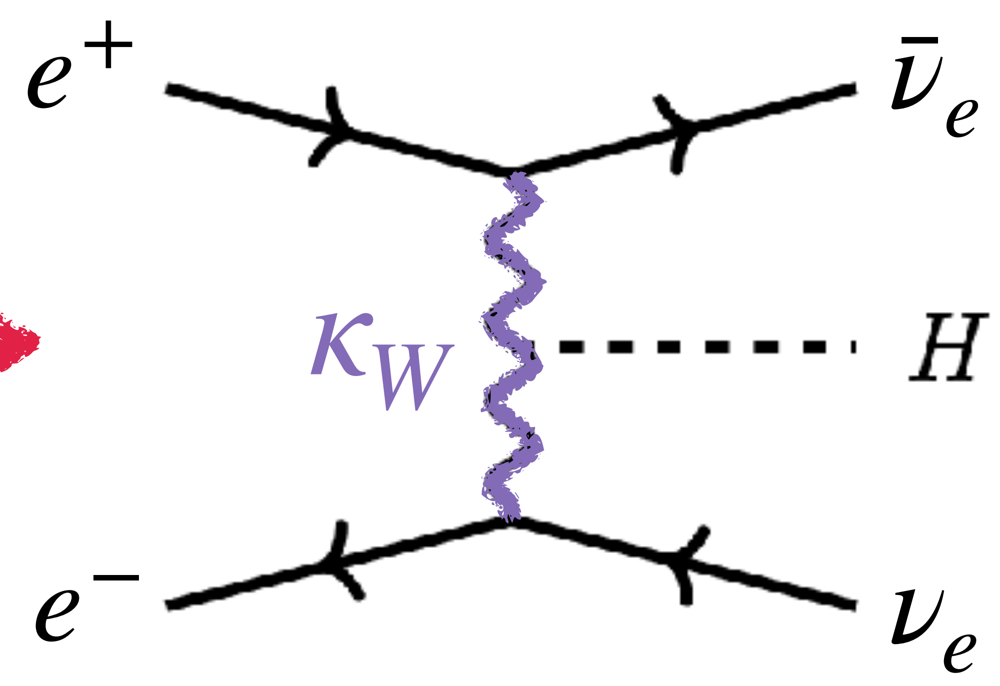
High Energy

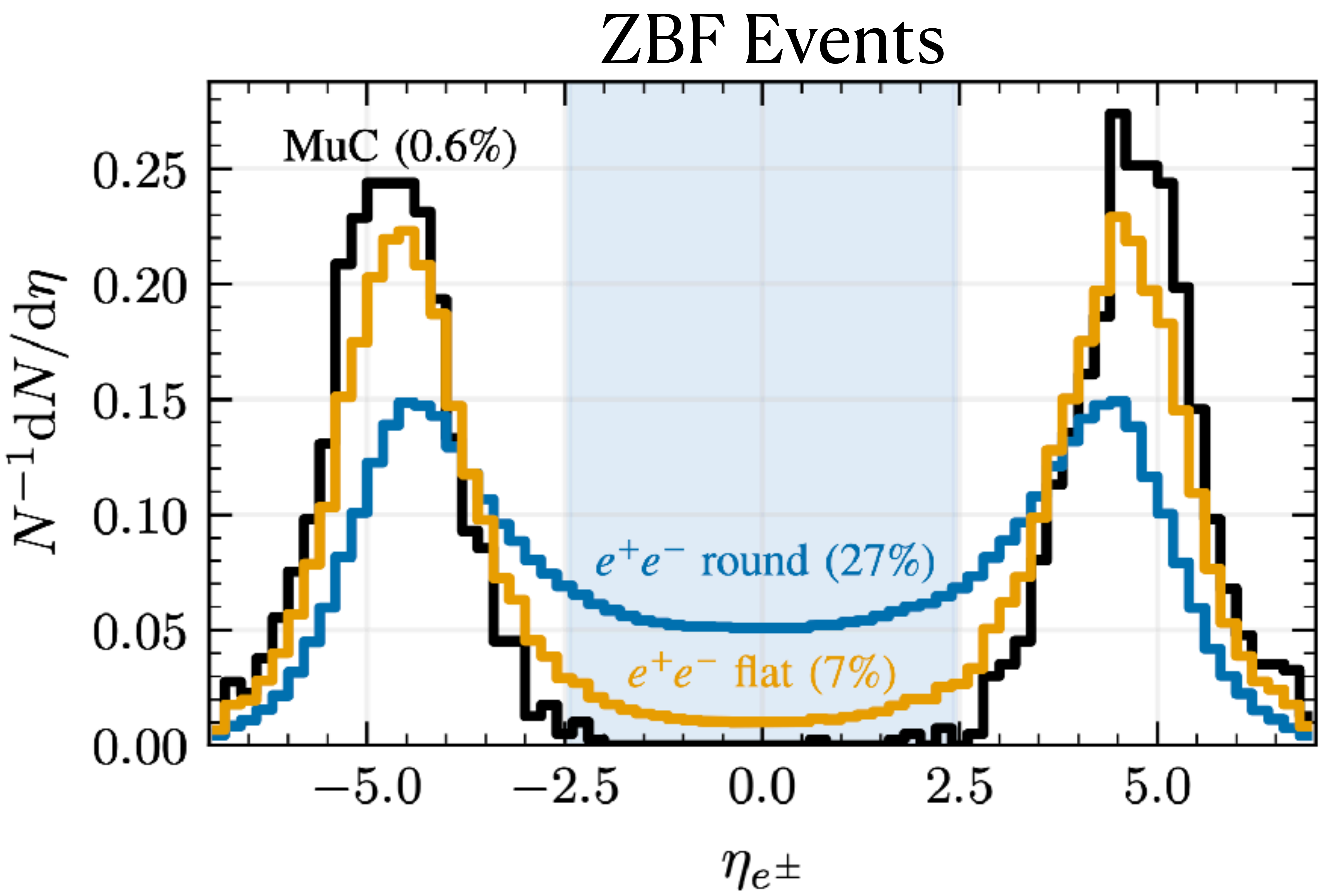


Tagging Forward Particles



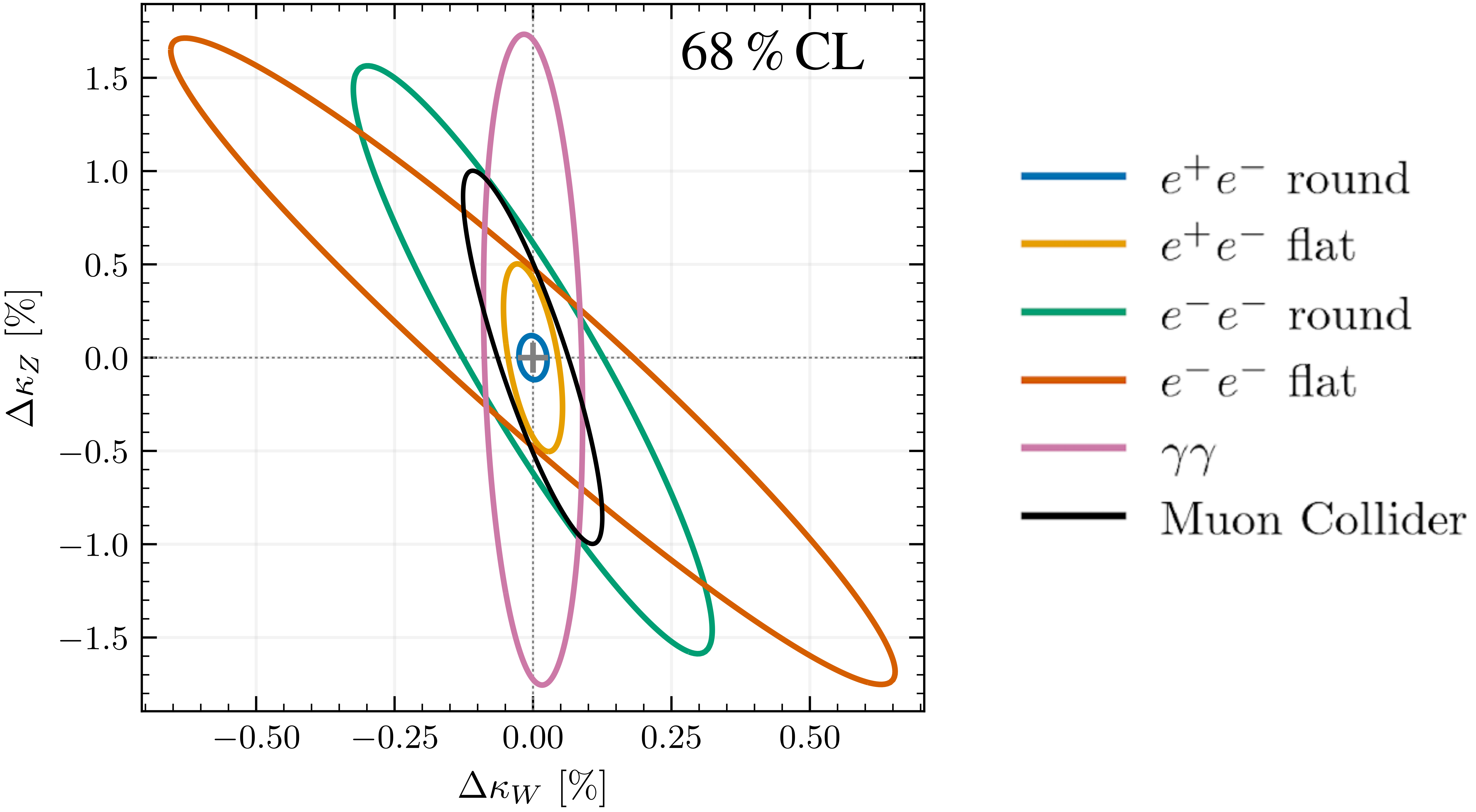
How to distinguish?





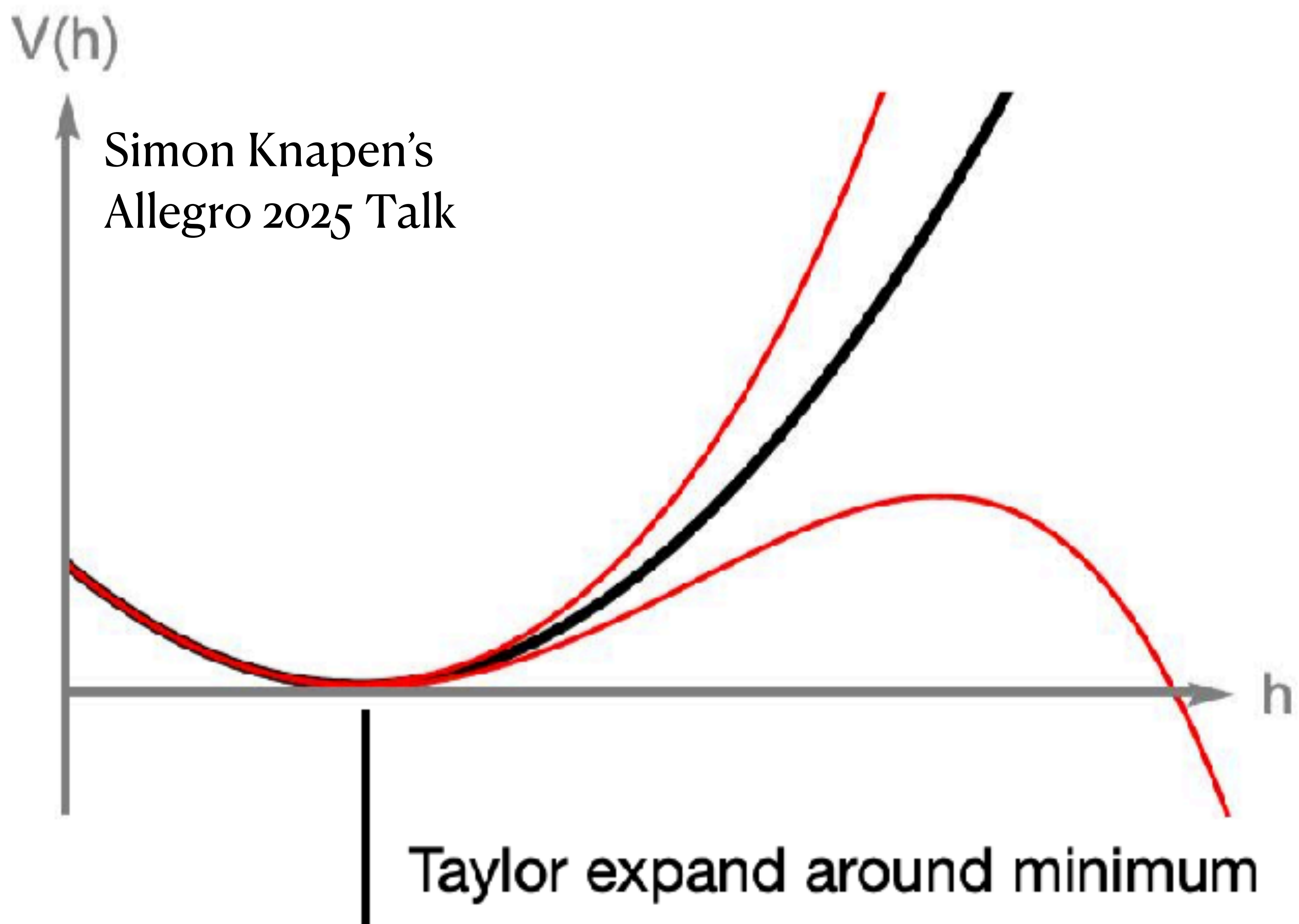
Sensitivity to κ_W and κ_Z

$$-\Delta \ln \mathcal{L}(\vec{\kappa}) = \sum_a \left[n_a^{\rm pred} - n_a^{\rm obs} + n_a^{\rm obs} \ln \frac{n_a^{\rm obs}}{n_a^{\rm pred}} \right] \quad \text{with} \quad n_a(\vec{\kappa}) = \frac{{\rm BR}_{b\bar{b}}(\vec{\kappa})}{{\rm BR}_{b\bar{b}}^{\rm SM}} \left(\kappa_W^2\, n_{a,{\rm WBF}}^{\rm SM} + \kappa_Z^2\, n_{a,{\rm ZBF}}^{\rm SM} \right) + n_{a,{\rm bkg}}$$



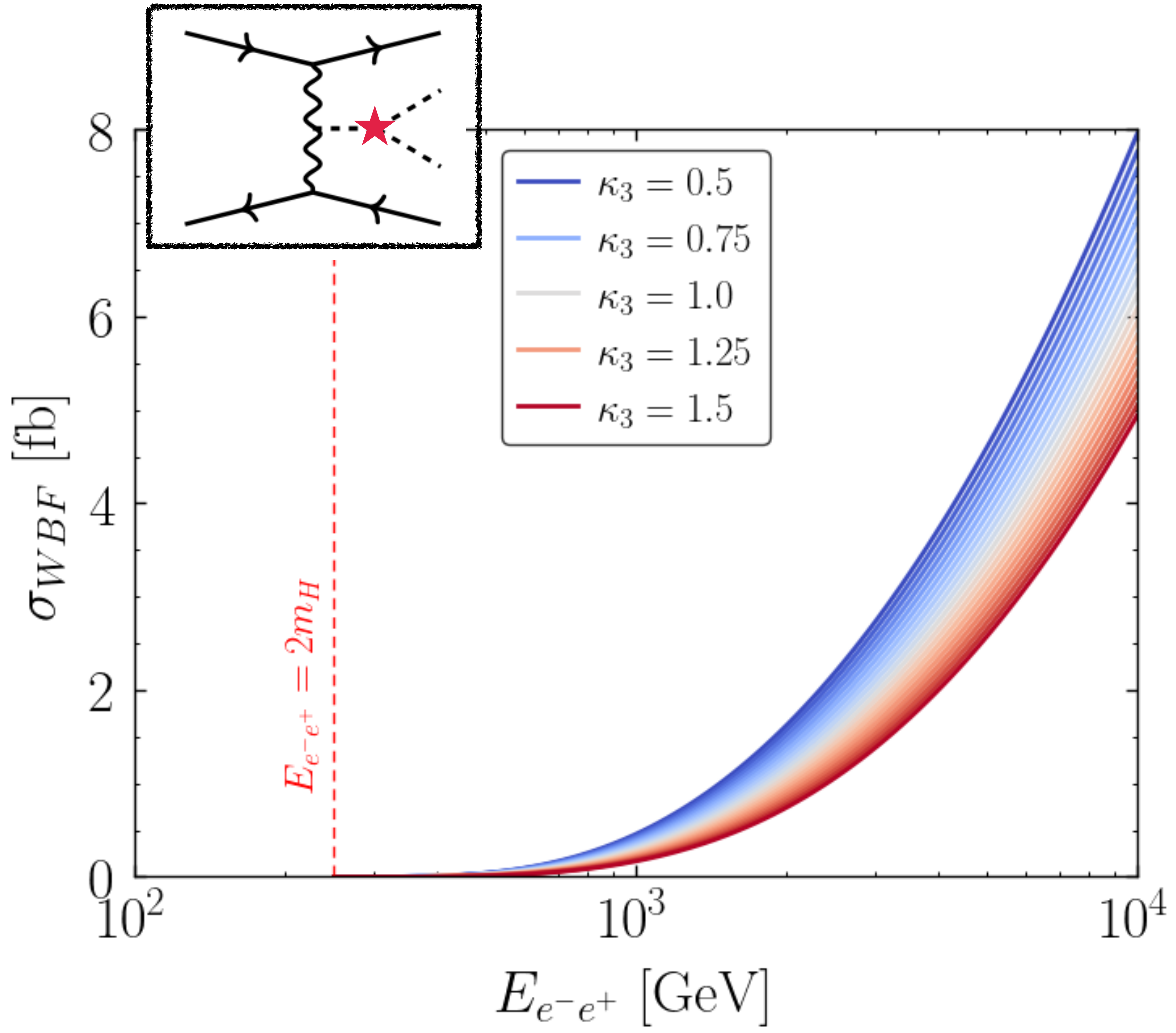
Double Higgs Analysis
($HH \rightarrow b\bar{b}b\bar{b}$)

Higgs Self Interaction is Directly Accessible



$$V(h) = v + c_2 h^2 + c_3 h^3 + c_4^4 h^4$$

G_F (measured) — mass (measured) — predicted



Double Higgs Analysis

Cuts (Incomplete list):

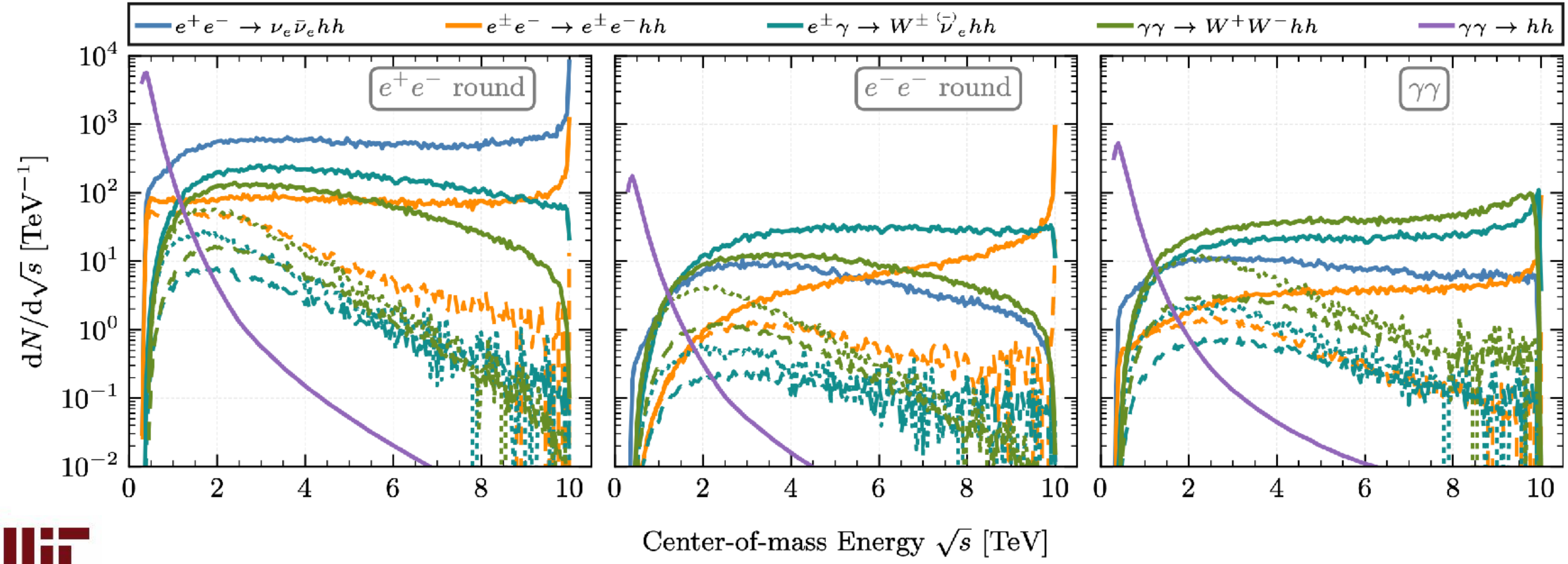
1. $|m_{b\bar{b}} - m_h| \leq 15$ GeV
2. ~~$p_{T,b\bar{b}} > 30$ GeV~~

Detector Modeling:

1. $\sigma(E_b)/E_b = 0.1$
2. $|\eta_{b,\bar{b}}| < 2.5$

Backgrounds:

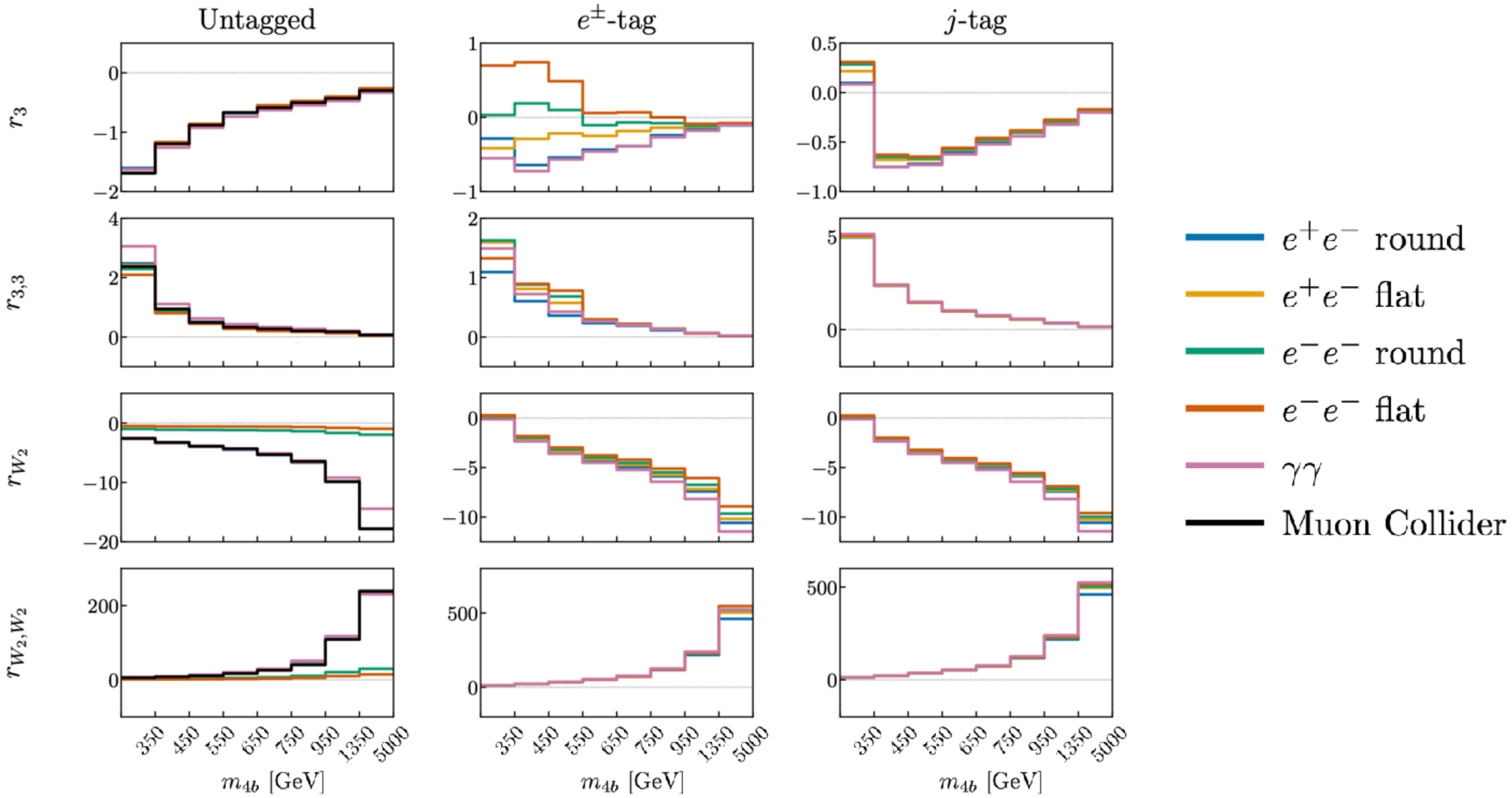
1. $Z^*Z^* \to b\bar{b}b\bar{b}$
2. ~~$\gamma\gamma \to b\bar{b}b\bar{b}$~~



Double Higgs Analysis (r Coefficients)

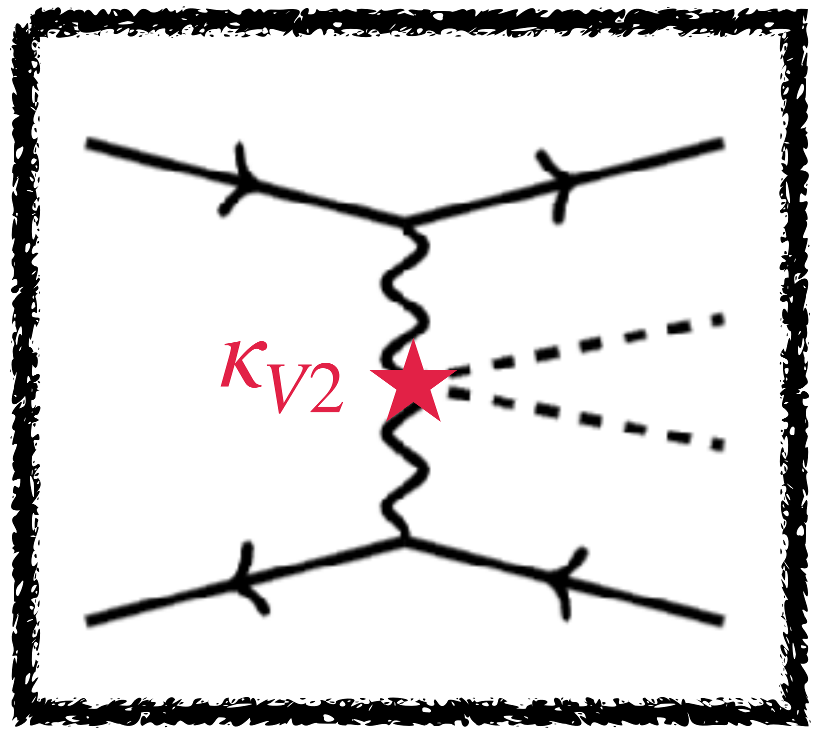
$$N_{ij}^{V}(\Delta\kappa_{V2}, \Delta\kappa_3) = N_{ij}^{V,\mathrm{SM}}\left[1 + r_{V2}^{ij}\Delta\kappa_{V2} + r_3^{ij}\Delta\kappa_3 + r_{V2,3}^{ij}\Delta\kappa_{V2}\,\Delta\kappa_3 + r_{V2,V2}^{ij}(\Delta\kappa_{V2})^2 + r_{3,3}^{ij}(\Delta\kappa_3)^2\right]$$

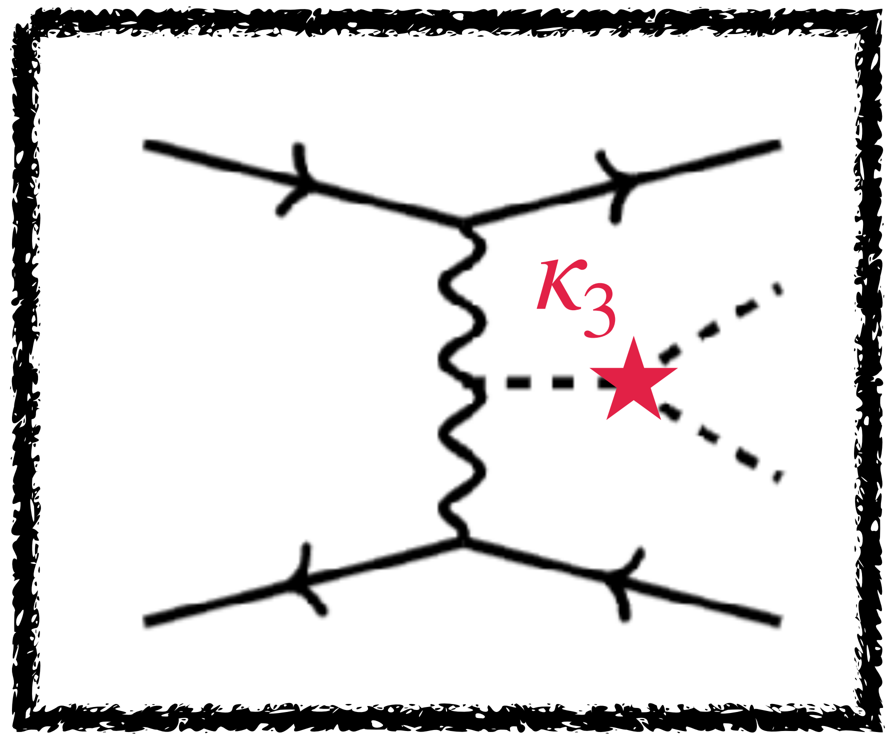
[Incomplete list]

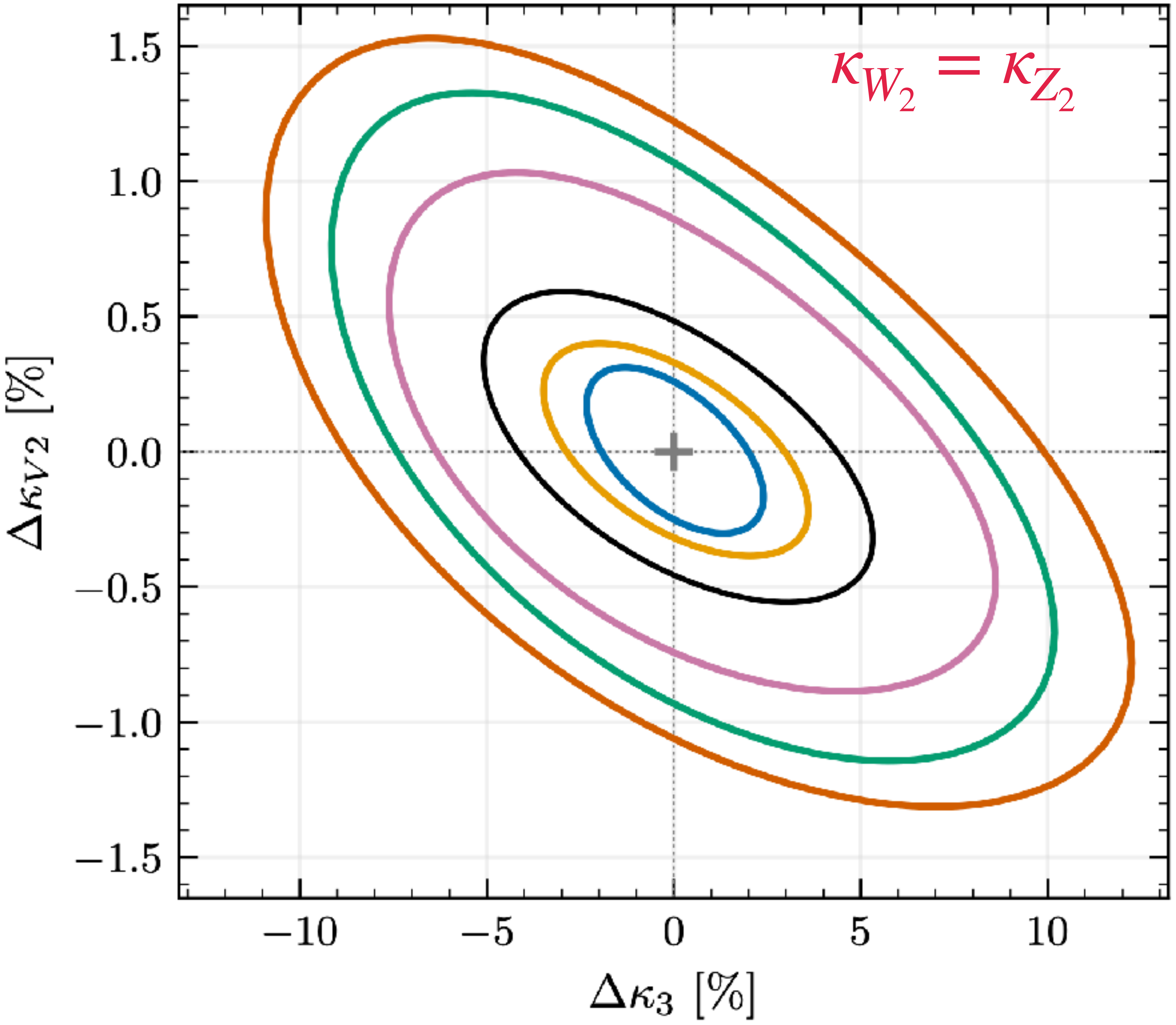


Higgs Self Interaction is Directly Accessible

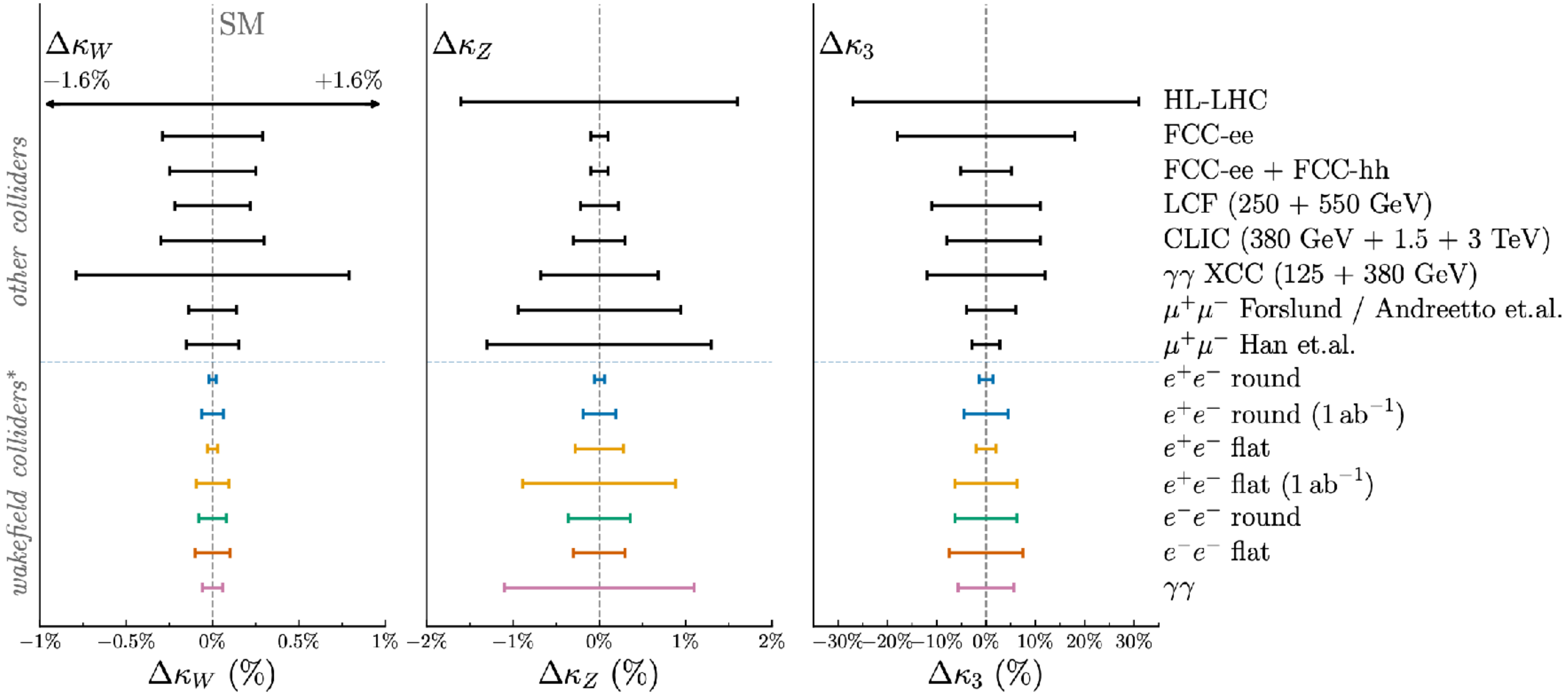
$$\mathcal{L} \supset \frac{2h}{v}\left[\kappa_W M_W^2 W^+W^- + \frac{\kappa_Z}{2} M_Z^2 Z^2 + \frac{\kappa_3}{4} M_H^2 h^2\right] + \frac{h^2}{v^2}\left[\kappa_{W_2} M_W^2 W^+W^- + \frac{\kappa_{Z_2}}{2} M_Z^2 Z^2 + \frac{\kappa_4}{8} M_H^2 h^2\right]$$







Sensitivity to κ_W, κ_Z, and κ_3



Conclusion

- Wakefield colliders are an interesting option to 10 TeV with unique qualities.
- Theory can inform very important R&D efforts.
  1. What is the luminosity cost of accelerating positrons?
  2. What is the luminosity cost of beam geometries (round or flat)?
  3. If only e^-e^- is possible, how much what is the luminosity cost of going to $\gamma\gamma$?

Lessons

- Beamstrahlung can be greatly beneficial!
- Positrons are valuable; worth $\mathcal{O}(10 - 100)$ in $\mathcal{L}_{\text{geom}}$ for several benchmarks.
- $\gamma\gamma$ occasionally outperforms e^-e^- colliders.
- Beamstrahlung modified event kinematics can play a huge role.

Thanks