New Physics at Plasma Wakefield Colliders

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SISSA

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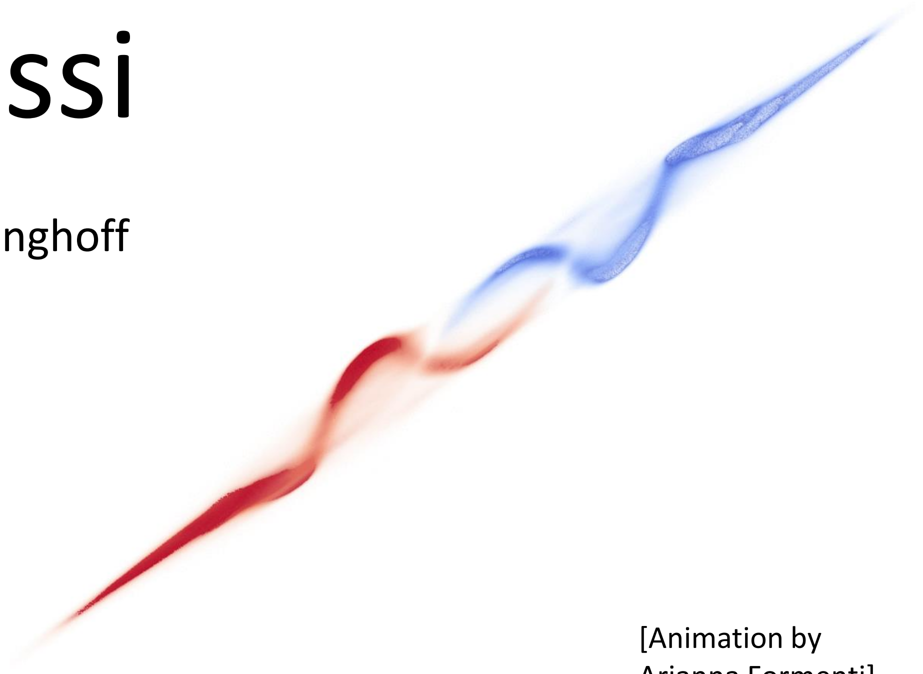

[Animation by Arianna Formenti]

The high energy frontier

3 paths to 10 TeV

100 TeV
proton collider

10 TeV
muon collider

10 TeV
wakefield

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100 TeV
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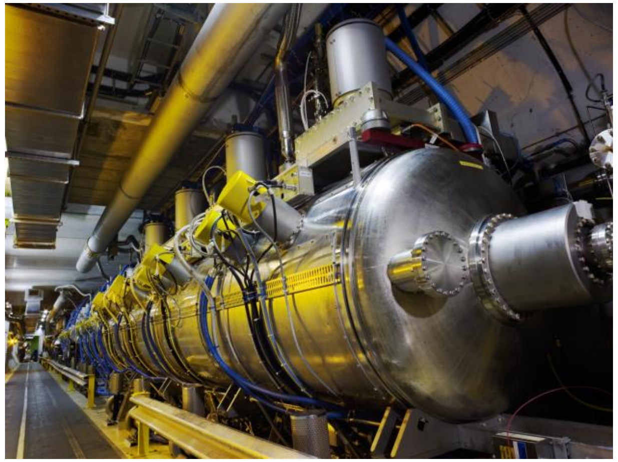
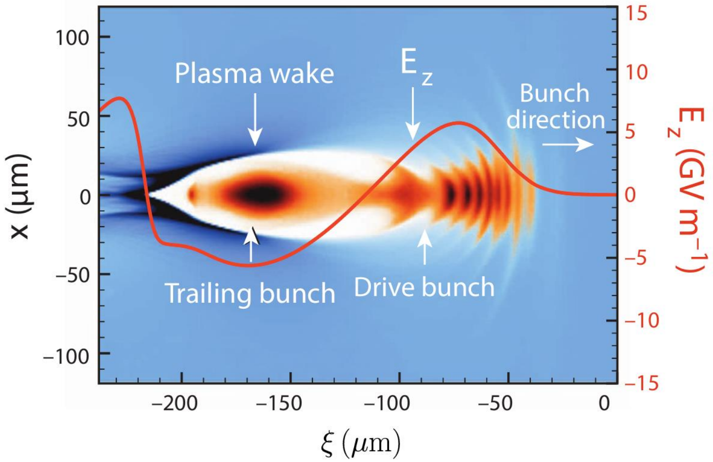
$E_{\max} \approx 200\ \mathrm{MV/m}$ →



RF cavities

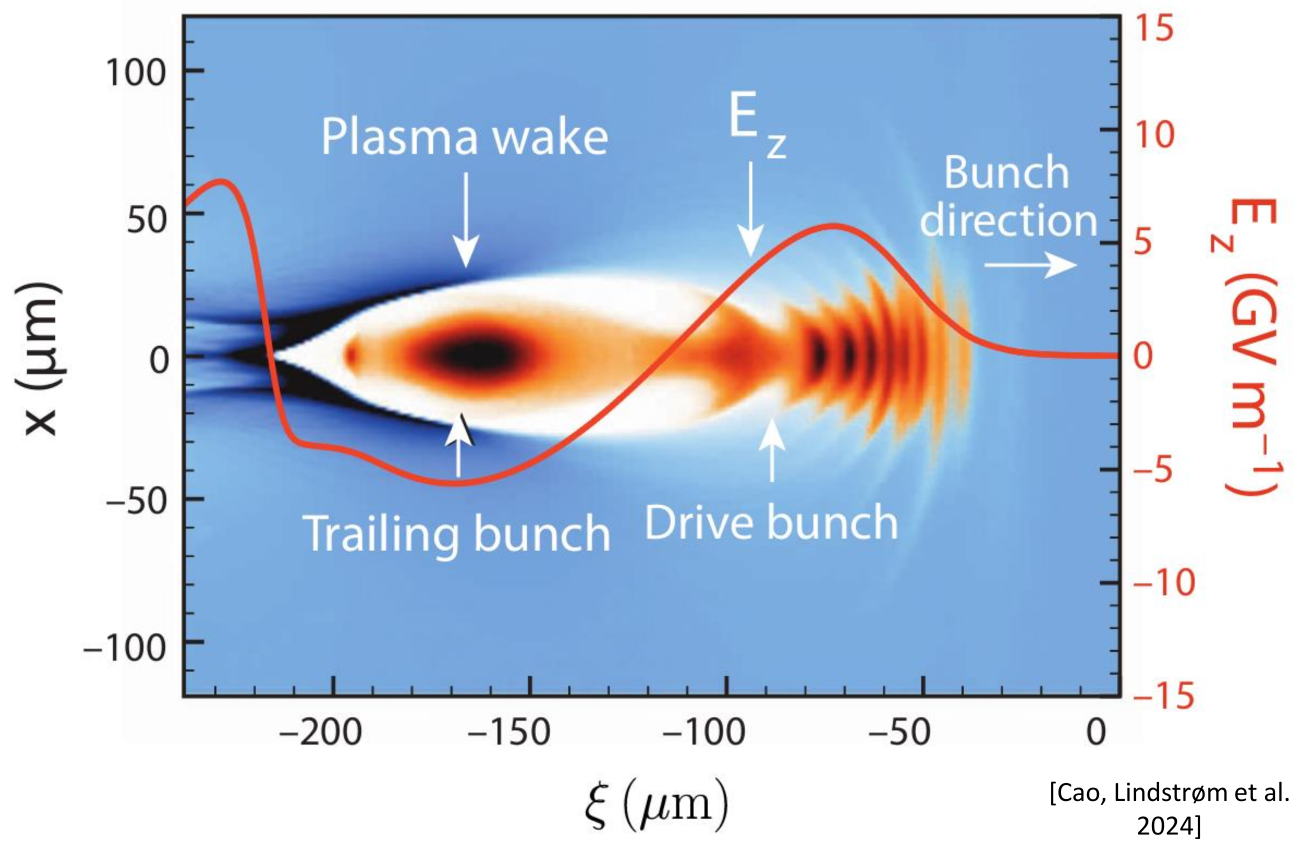


[Cao, Lindstrøm et al. 2024]

Plasma wakefield acceleration

Plasma wakefield acceleration

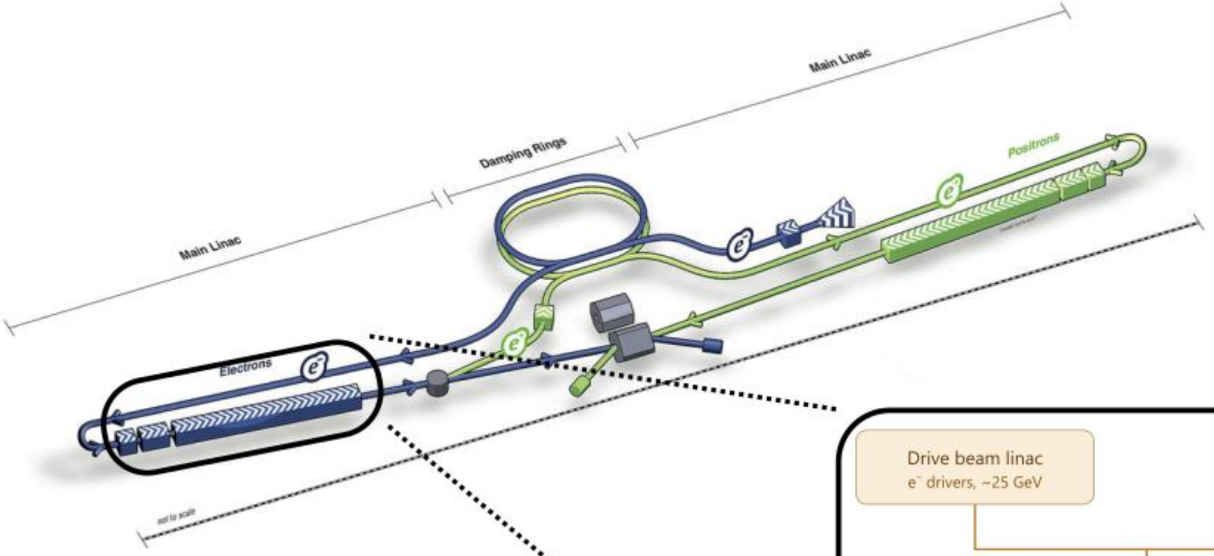
One acceleration stage

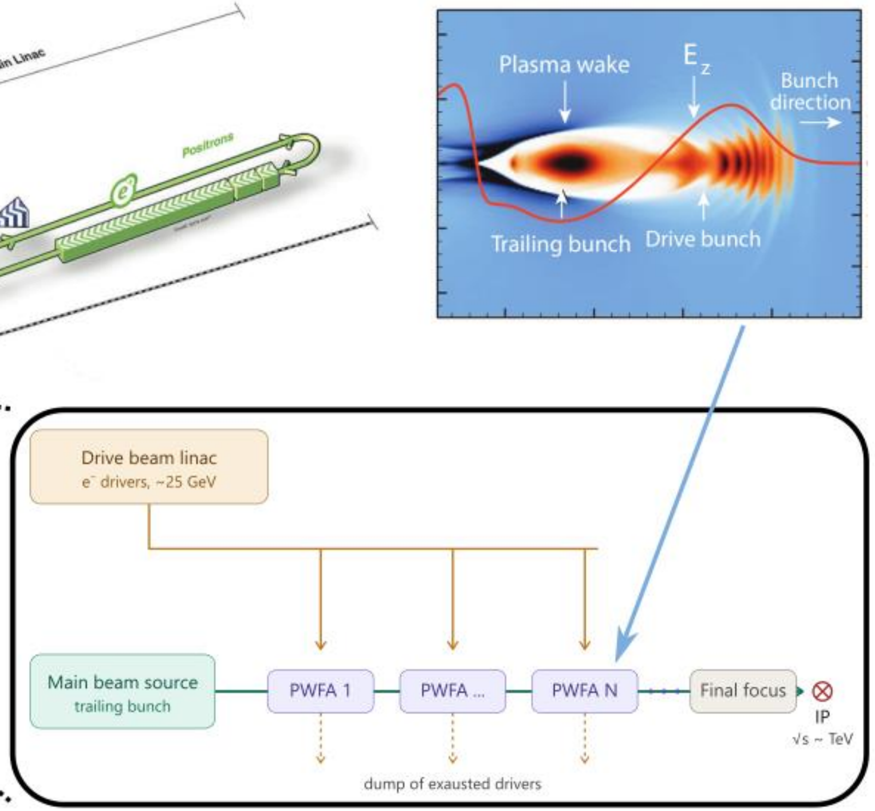


[Cao, Lindstrøm et al. 2024]

E_z up to 100 GV/m

Wakefield collider





[Based on the
design proposed for ILC,
figure by Rey Hori]

Extreme beamstrahlung

Plasma wavelength: $\lambda_p \sim 1/E_z$

Efficient acceleration demands the trailing bunch to fit in the plasma wake

$$\sigma_{x,y} \sim 1\text{ nm}$$

But we also need to collide enough particles to achieve luminosity: $N \sim 10^9$

$$L_{\text{geom}} = \frac{N^2 f T}{4\pi\sigma_x\sigma_y} \sim 10\text{ ab}^{-1}$$

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$$\mathcal{L}_{\text{geom}} = \frac{N^2 f T}{4\pi\sigma_x\sigma_y} \sim 10\ \text{ab}^{-1}$$

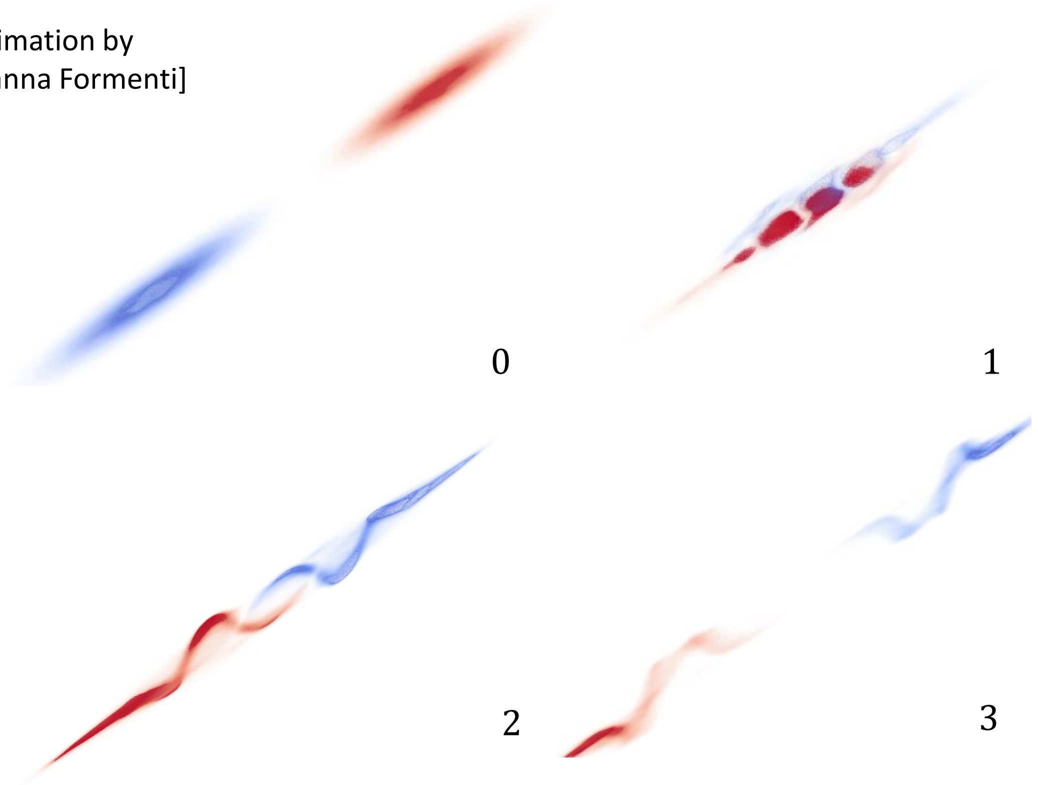
↓

Beamstrahlung parameter: $\Upsilon = \frac{5}{6}\frac{\alpha\gamma N}{m_e^2\sigma_z(\sigma_x+\sigma_y)} \sim 10^3$ ⟵ This is extreme!

LHC: $\Upsilon \sim 10^{-6}$

MuC10: $\Upsilon \sim 0.1$

[Animation by
Arianna Formenti]



The shape of the beam

$$L_{\text{geom}} = \frac{N^2 f T}{4\pi\sigma_x\sigma_y} \sim 10\ \text{ab}^{-1}$$

$$\Upsilon = \frac{5}{6}\frac{\alpha\gamma N}{m_e^2\sigma_z(\sigma_x + \sigma_y)}$$

Flat beams $\sigma_x \gg \sigma_y$

Less beamstrahlung, harder to build

Round beams $\sigma_x \sim \sigma_y$

More beamstrahlung, easier to build

Which particles to accelerate?

The response of plasma is asymmetric in charge

↓

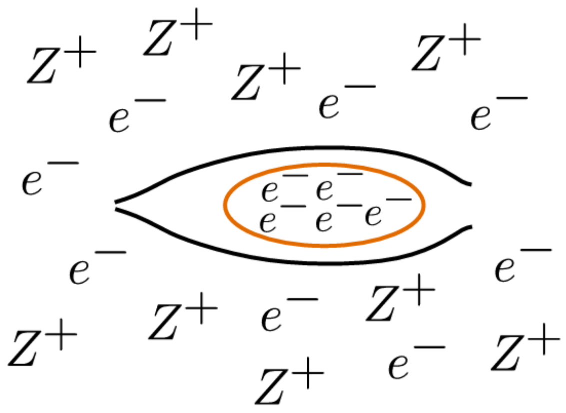
Positron acceleration problem

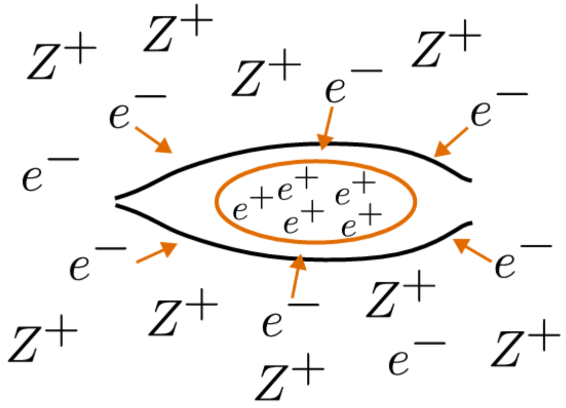
It's hard to achieve beam quality and luminosity when accelerating positrons

↓

e^-e^- or $\gamma\gamma$
more likely than e^+e^-

$\gamma\gamma$ is obtained by shining a laser on e^- beams

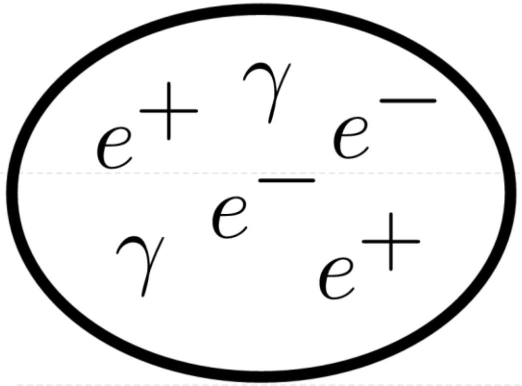




Leptons as composite particles

- At high energy, due to interactions, also leptons effectively behave as composite particles
- This is captured by LePDFs (a perturbative analog of PDFs, but for leptons)
- But the very intense interactions in the environment of a wakefield collider (beamstrahlung) require a separate treatment

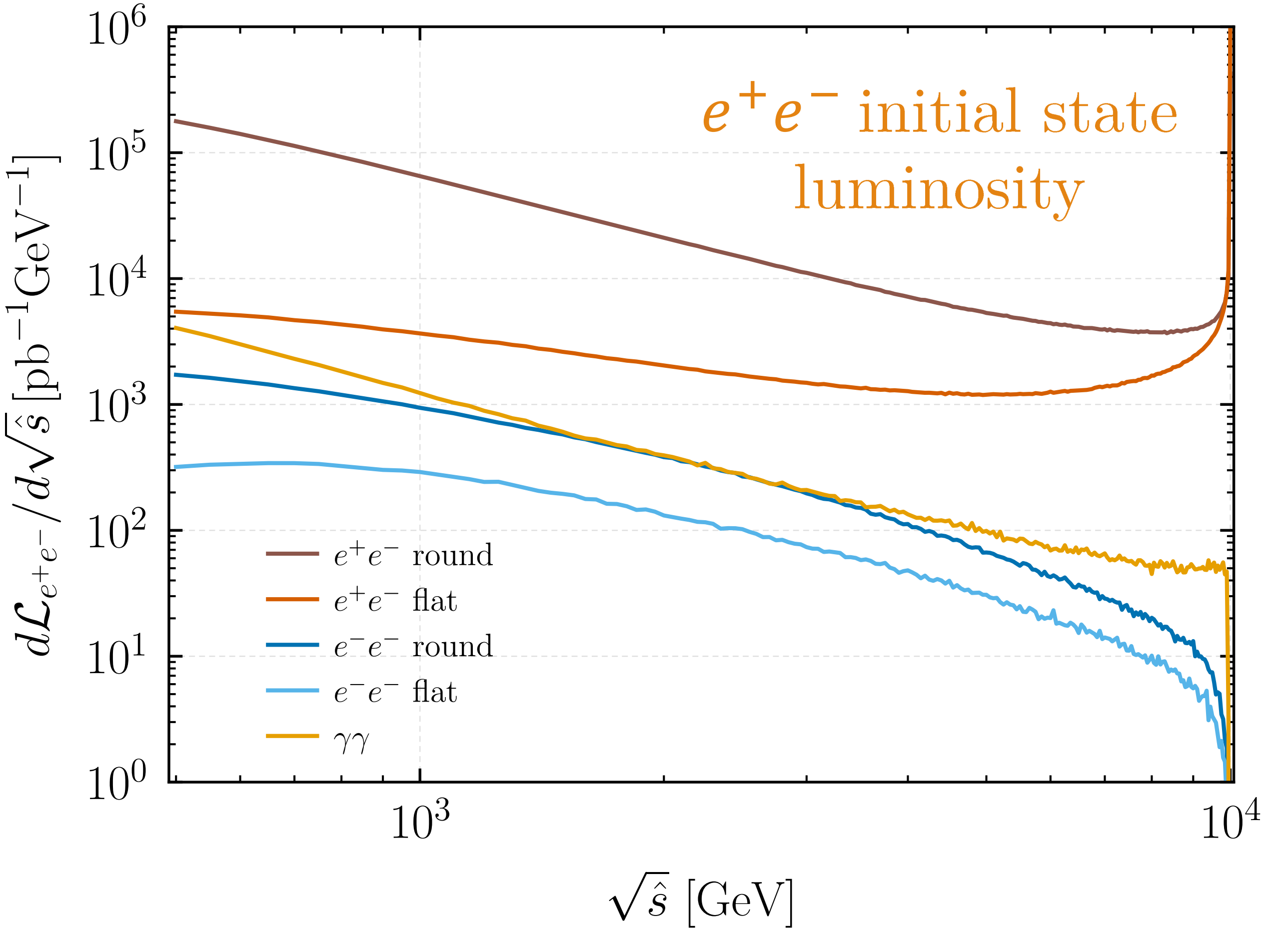
$e^- \sim$



The luminosity spectra

- Beamstrahlung is very efficient in redistributing luminosity between both: sub-nominal energies and different particles

A possible solution to the positron acceleration problem



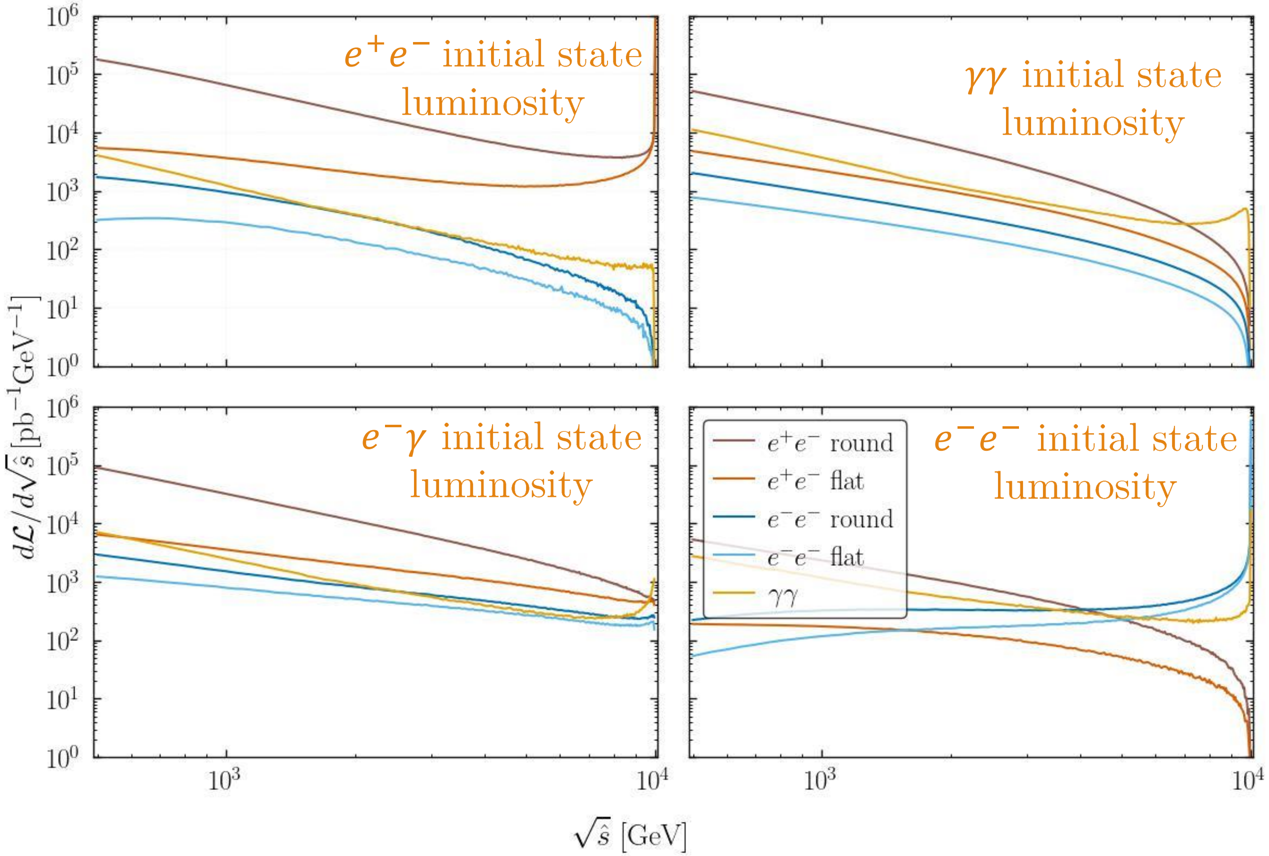
The luminosity spectra

- We must consider all the initial states all at once

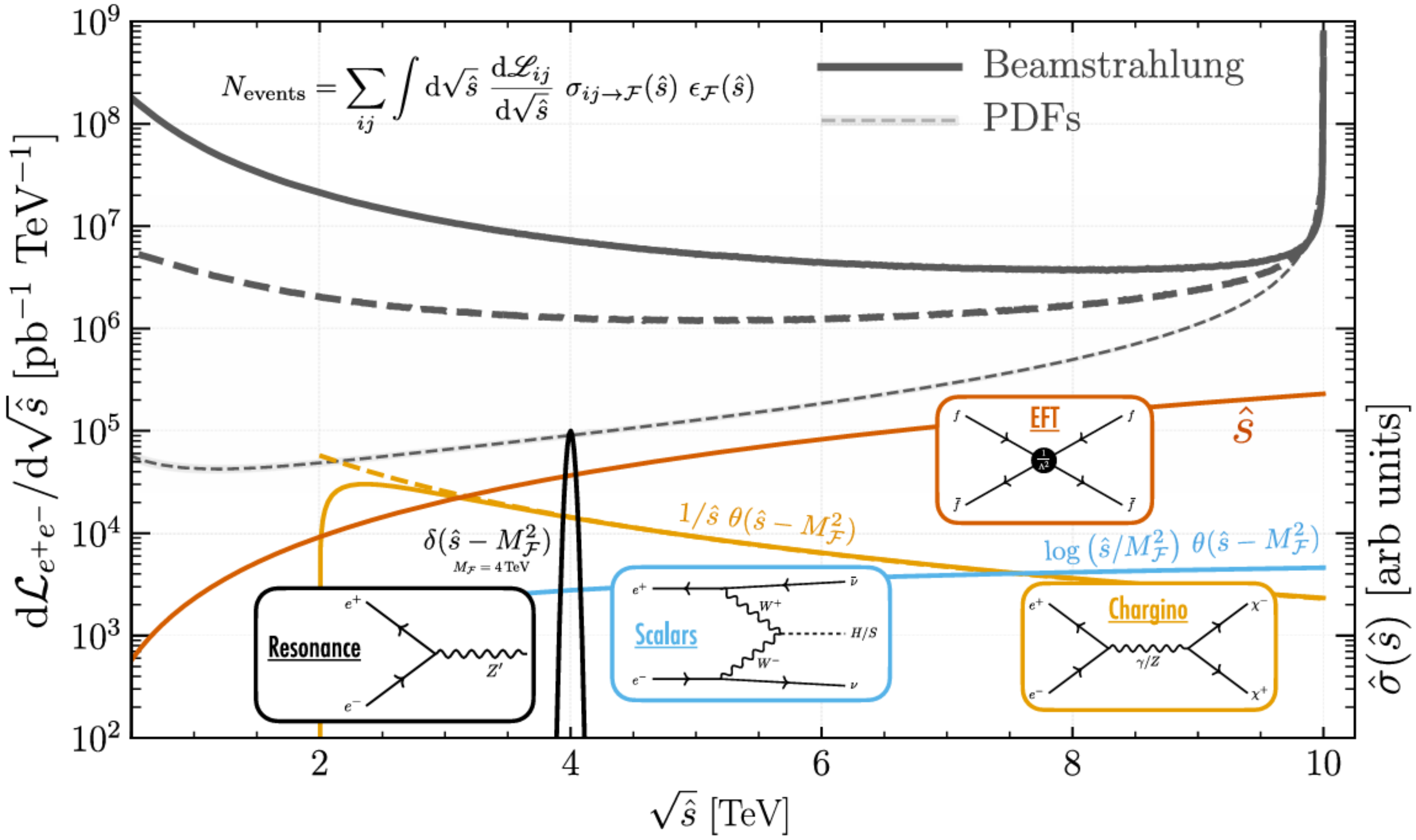
e^+e^- e^-e^- $\gamma\gamma$ $e^\pm\gamma$

- Also, the rapidity distribution of luminosity is very different from other lepton colliders

Ask me later

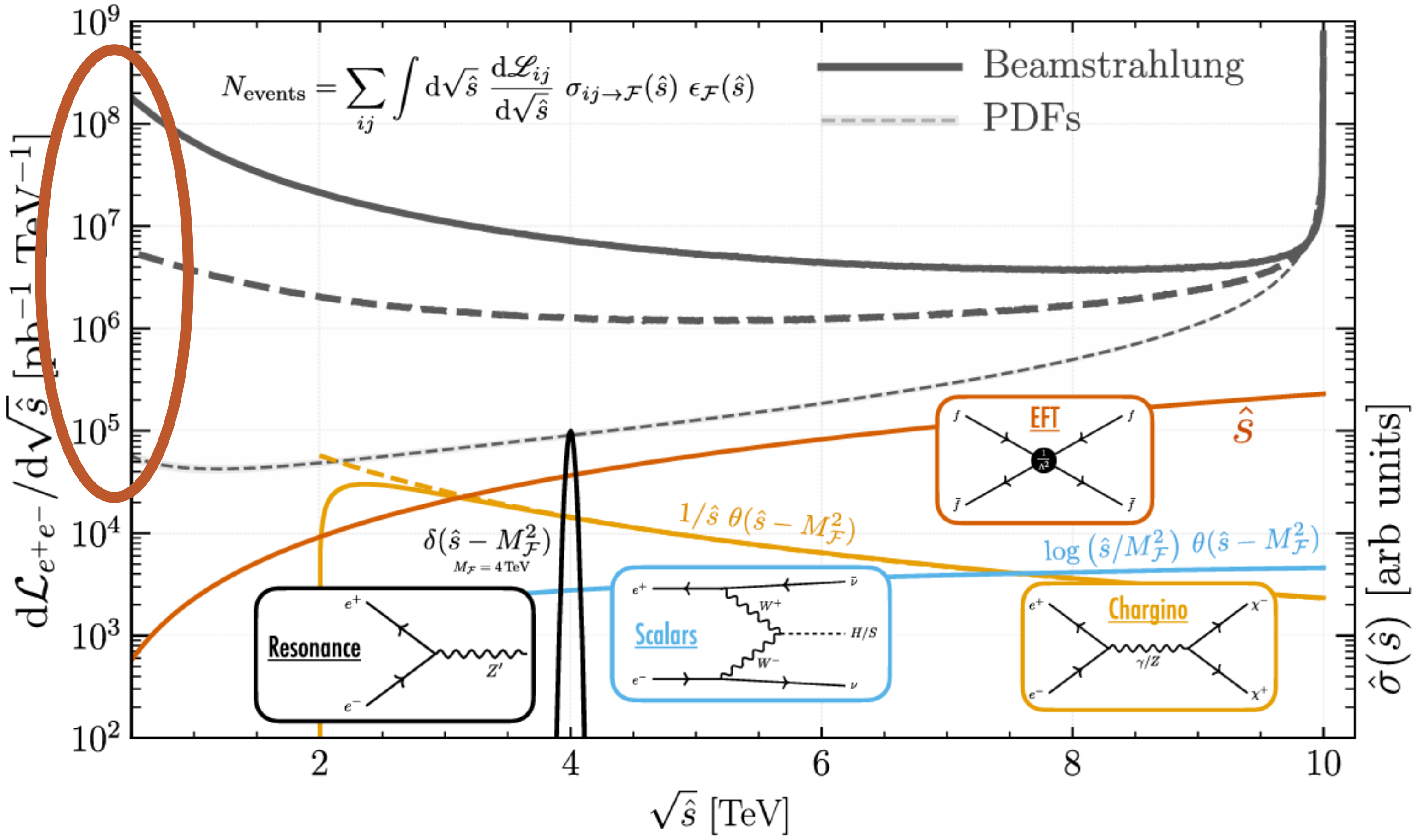


Beamstrahlung enhancement

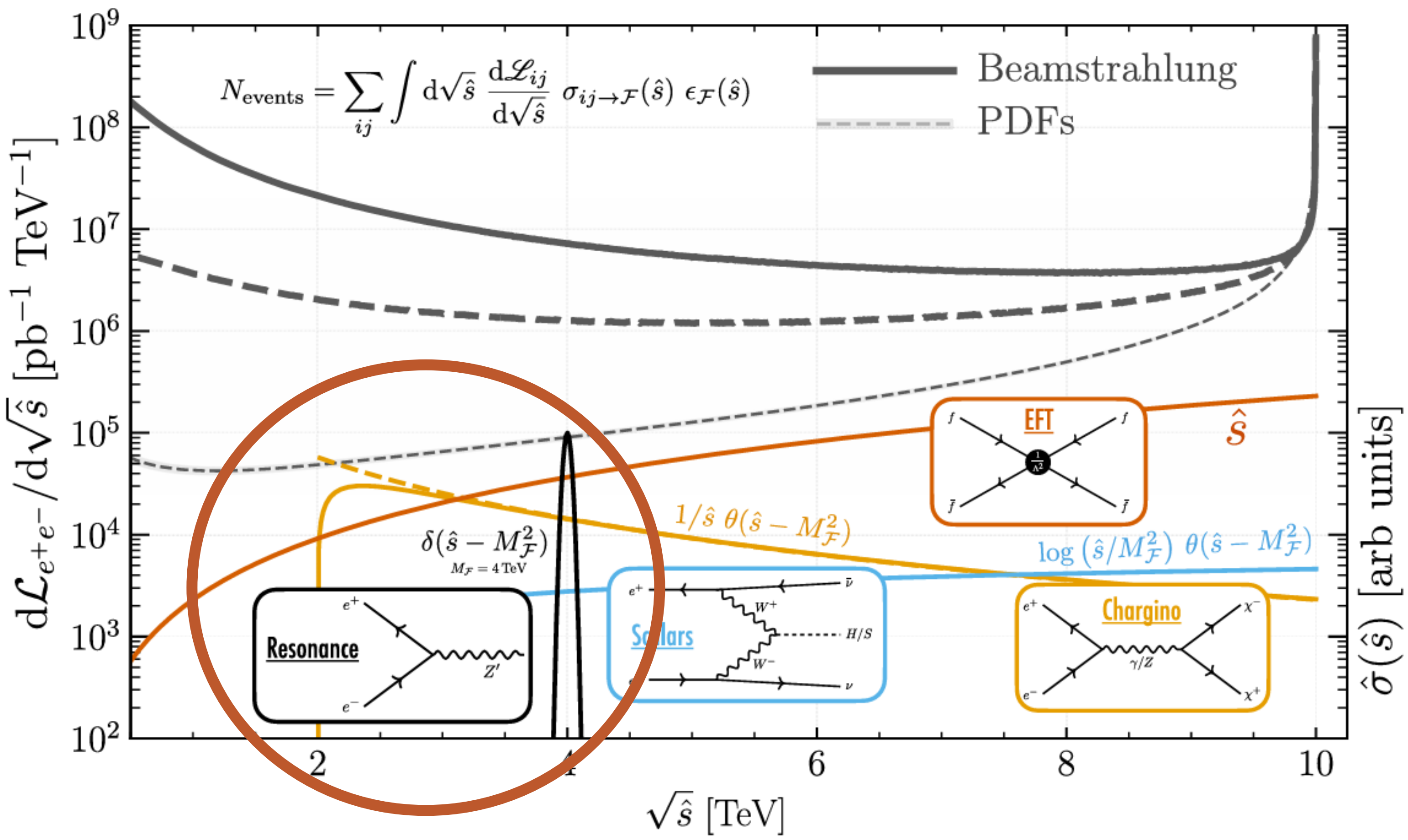


Beamstrahlung enhancement

Several orders of magnitude enhancement at low energies



Beamstrahlung enhancement



S-channel resonances benefit from the largest possible beamstrahlung enhancement

Our example model

Kinetically mixed Z'

$$\mathcal{L} \supset \frac{\varepsilon e}{\cos^2 \theta_W} Z'_\mu J_Y^\mu$$

$\mu^+\mu^-$ final state in the wakefield collider search

Easy to recast to any other narrow resonance coupled to leptons

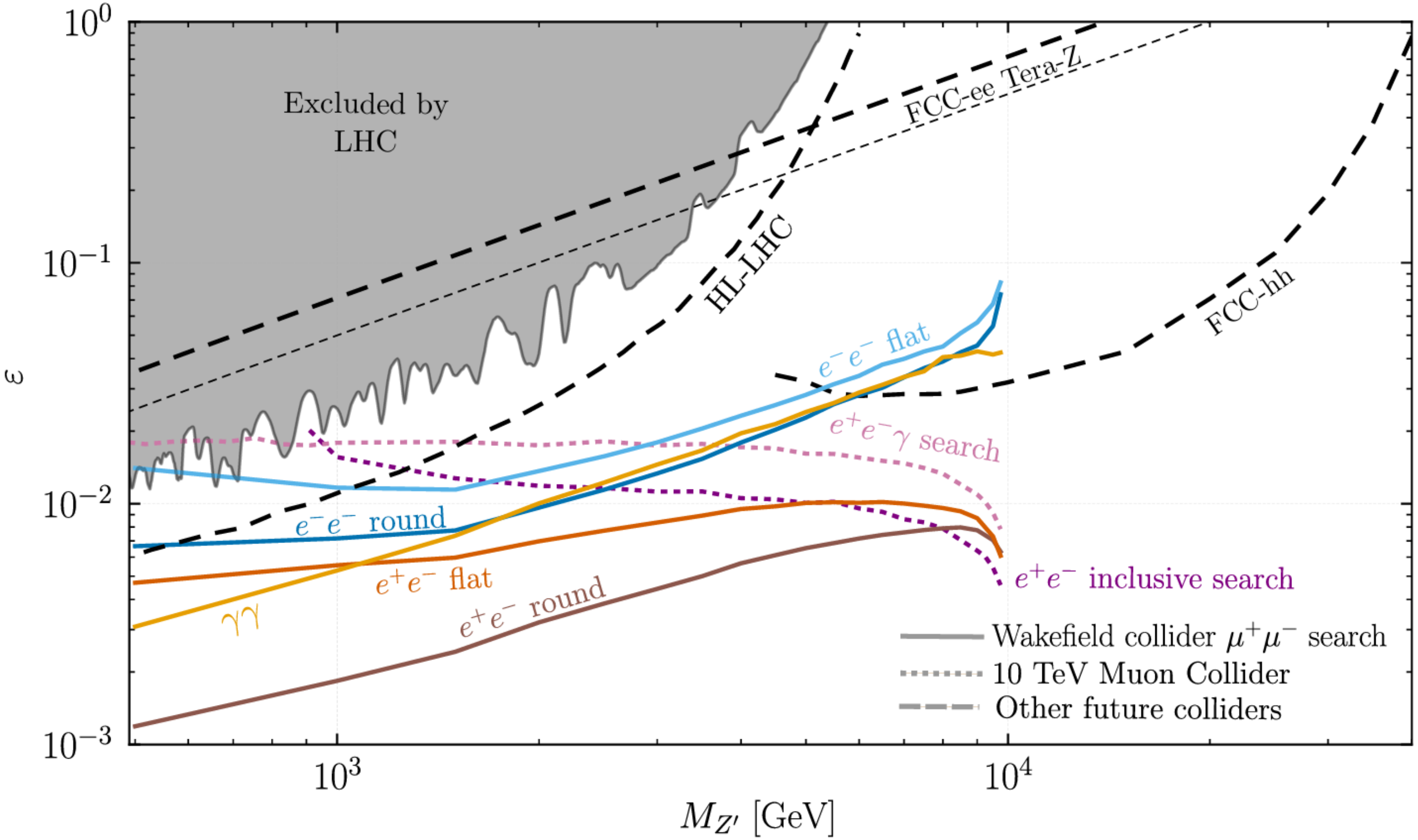
Most relevant processes

Signal: $e^+e^- \to Z' \to \mu^+\mu^-$

Background: $e^+e^- \to Z/\gamma \to \mu^+\mu^-$

$\gamma\gamma \to \mu^+\mu^-$

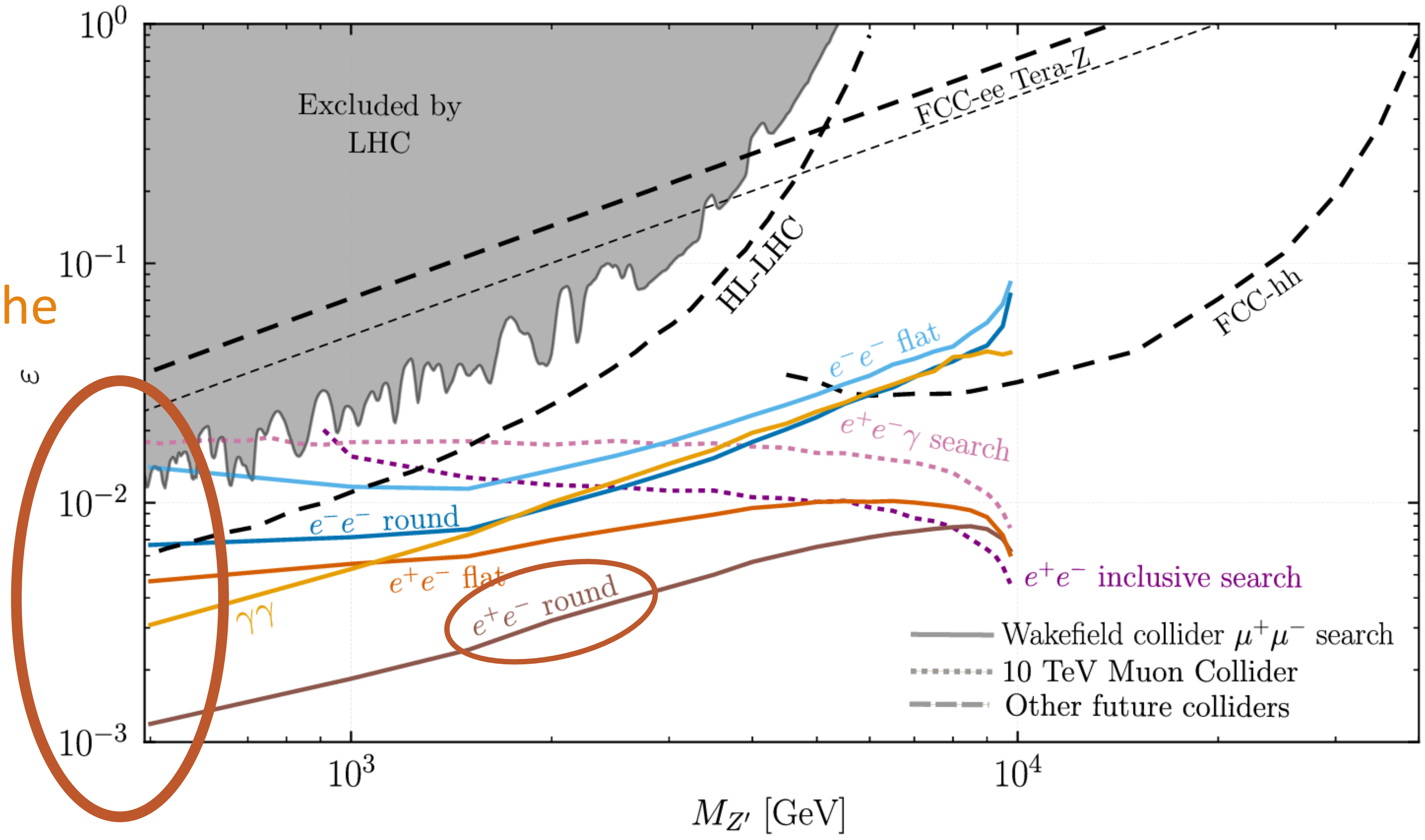
Results



Excluded by LHC
HL-LHC
FCC-ee Tera-Z
FCC-hh
e^-e^- flat
e^-e^- round
$e^+e^-\gamma$ search
e^+e^- inclusive search
e^+e^- flat
e^+e^- round
$\gamma\gamma$
Wakefield collider $\mu^+\mu^-$ search
10 TeV Muon Collider
Other future colliders
ε
$M_{Z'}$ [GeV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^3
10^4

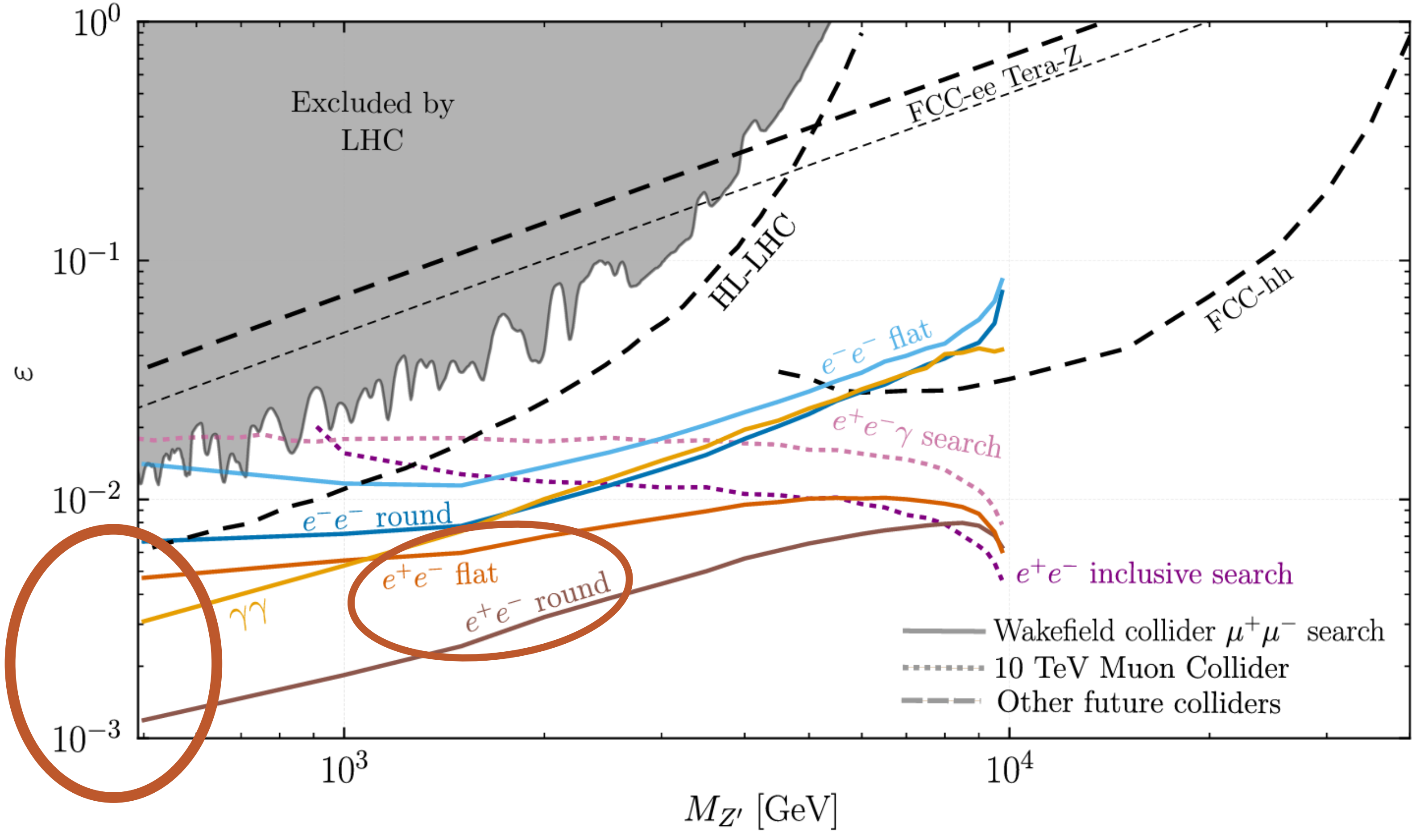
Results

e^+e^- round sets the strongest bound on ε



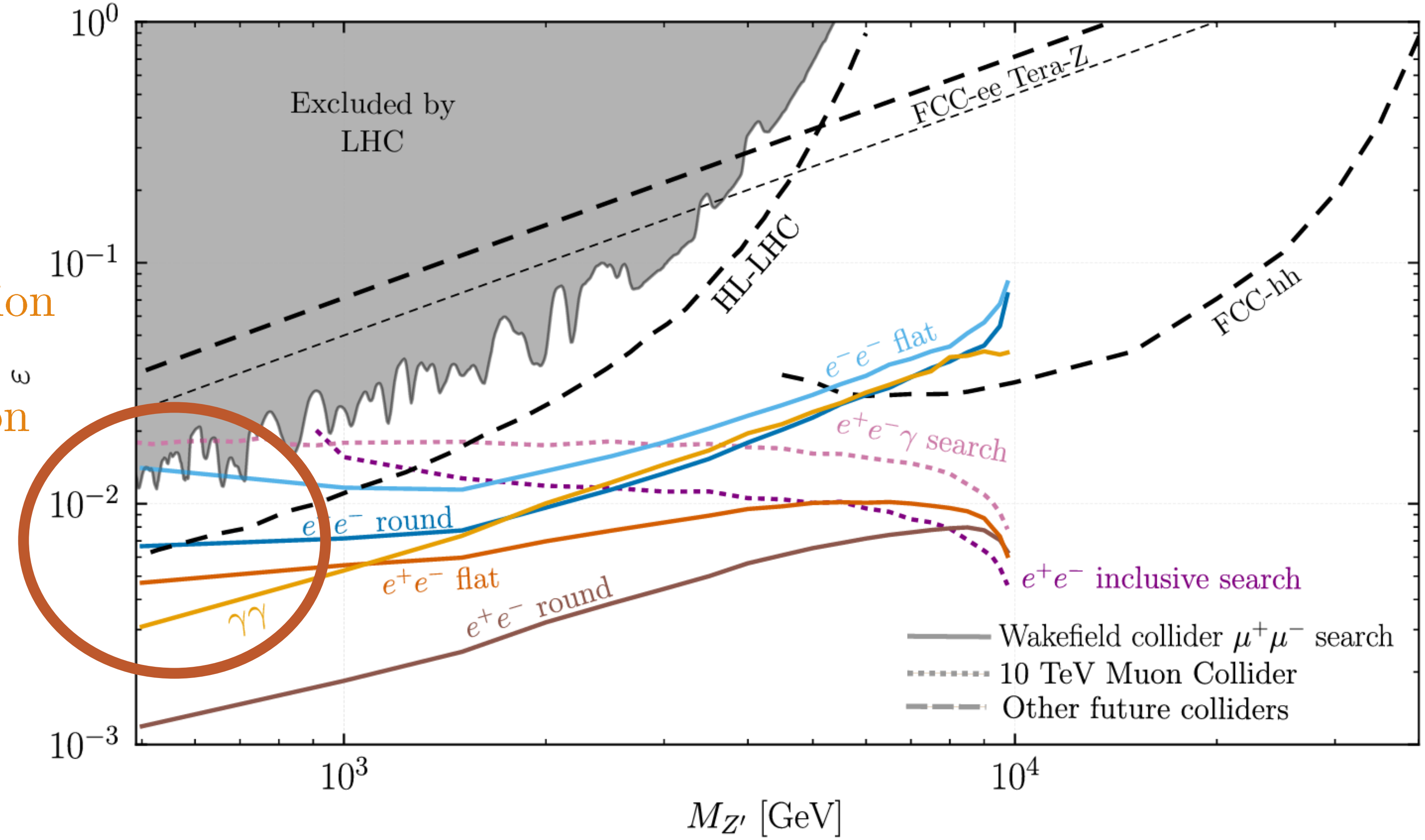
Results

Round beams outperform flat beams



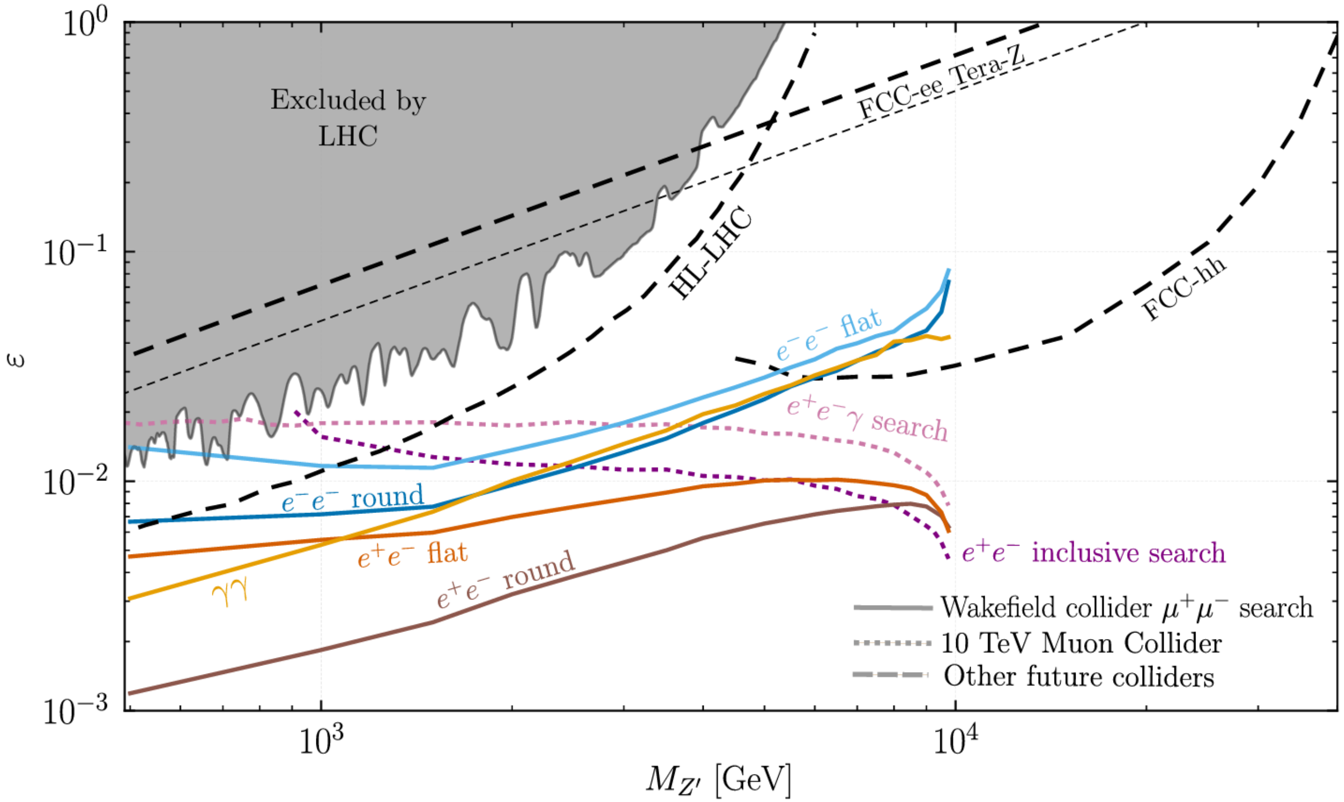
Results

If positron acceleration is not feasible
$\gamma\gamma$ is the best option



Conclusions

- e^+e^- round sets the strongest bound on ε
- Round beams outperform flat beams
- If positron acceleration is not feasible, $\gamma\gamma$ is the best option

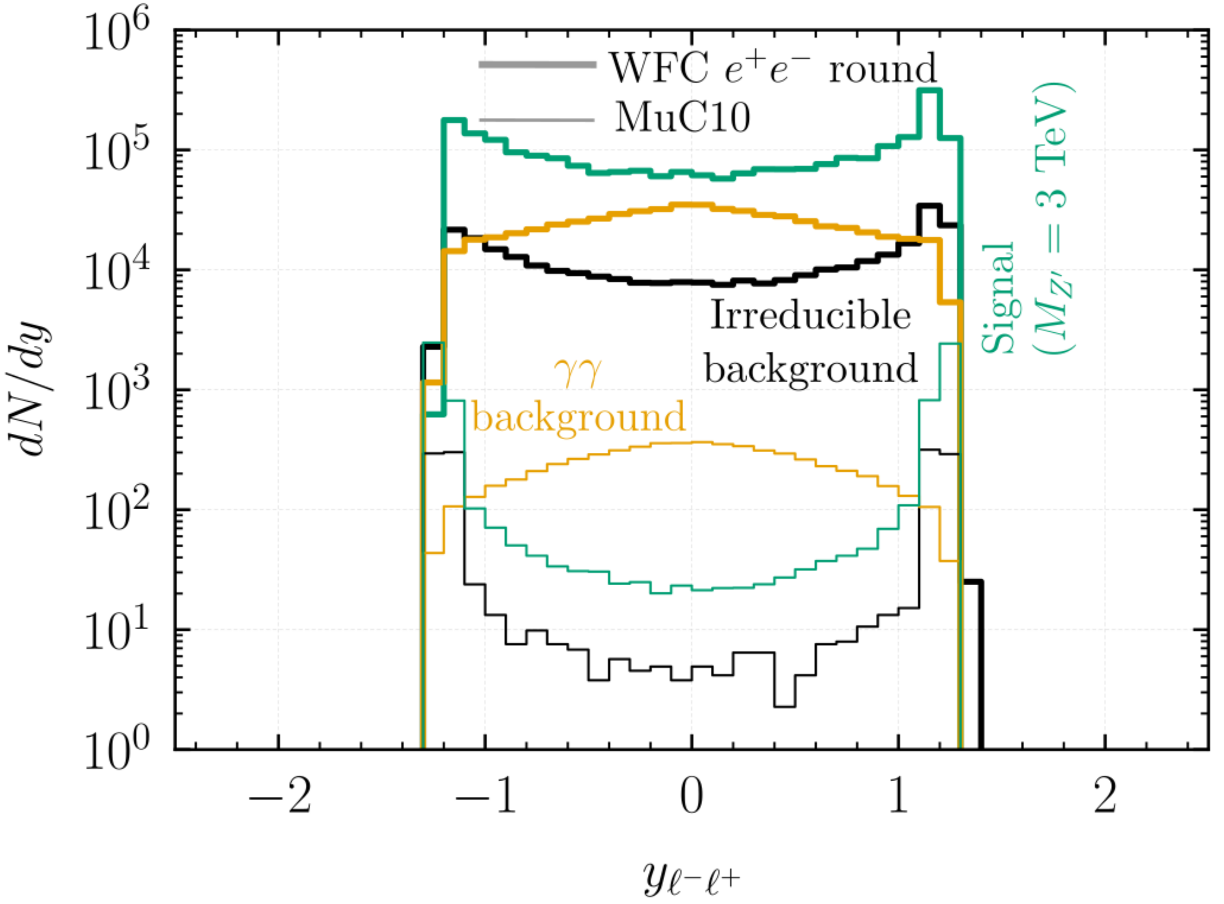


Thanks for the attention!

Backup

The rapidity distribution

Peak at:
$x_1 = 1$
$x_2 = m^2/s$



$$y_{\ell^-\ell^+} = \frac{1}{2}\log\frac{x_1}{x_2}$$

$$\hat{s} = x_1 x_2 s$$

Existing WFC facilities

Main ongoing experiments:

- **FACET II, SLAC** (USA): ongoing since 2020, built on the experience of FACET (2011-2016) it's the reference for PWFA using e^- drivers. It actually has 10 GeV e^- beams and it's the only one with an accepted upgrade for e^+ acceleration.
- **BELLA, LBNL** (USA): it's operating since 2013 and it's the reference for LWFA, they also have 10 GeV e^- beams.
- **AWAKE, CERN** (Switzerland): has operated from 2016 to 2025, it's the only experiment with drivers made of protons. Using protons at 400 GeV they have been able to achieve 2 GeV e^- beams; now it's undergoing a major update.

Other relevant ones:

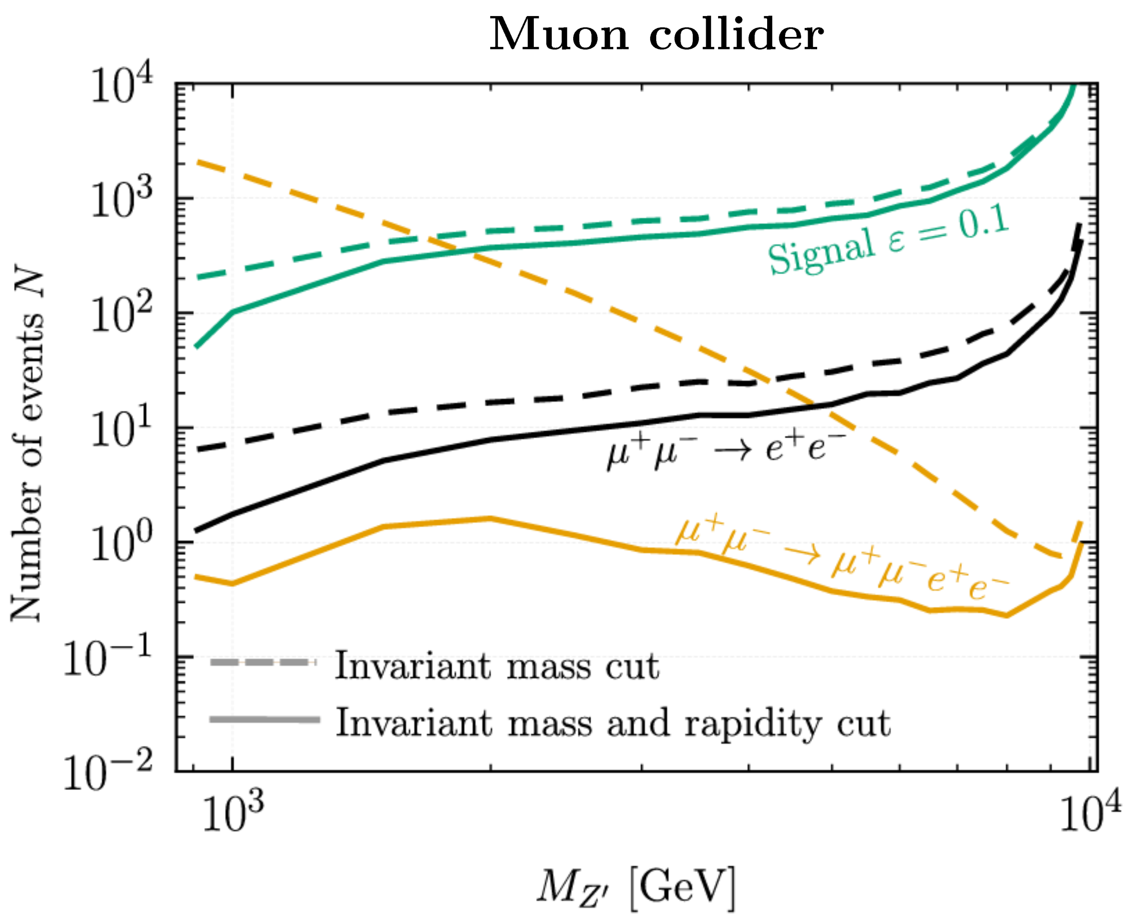
- FLASHForward & PETRA IV, DESY (Germany)
- EuPRAXIA project with 2 facilities: SPARC-LAB (Italy) & ELI (Czechia)

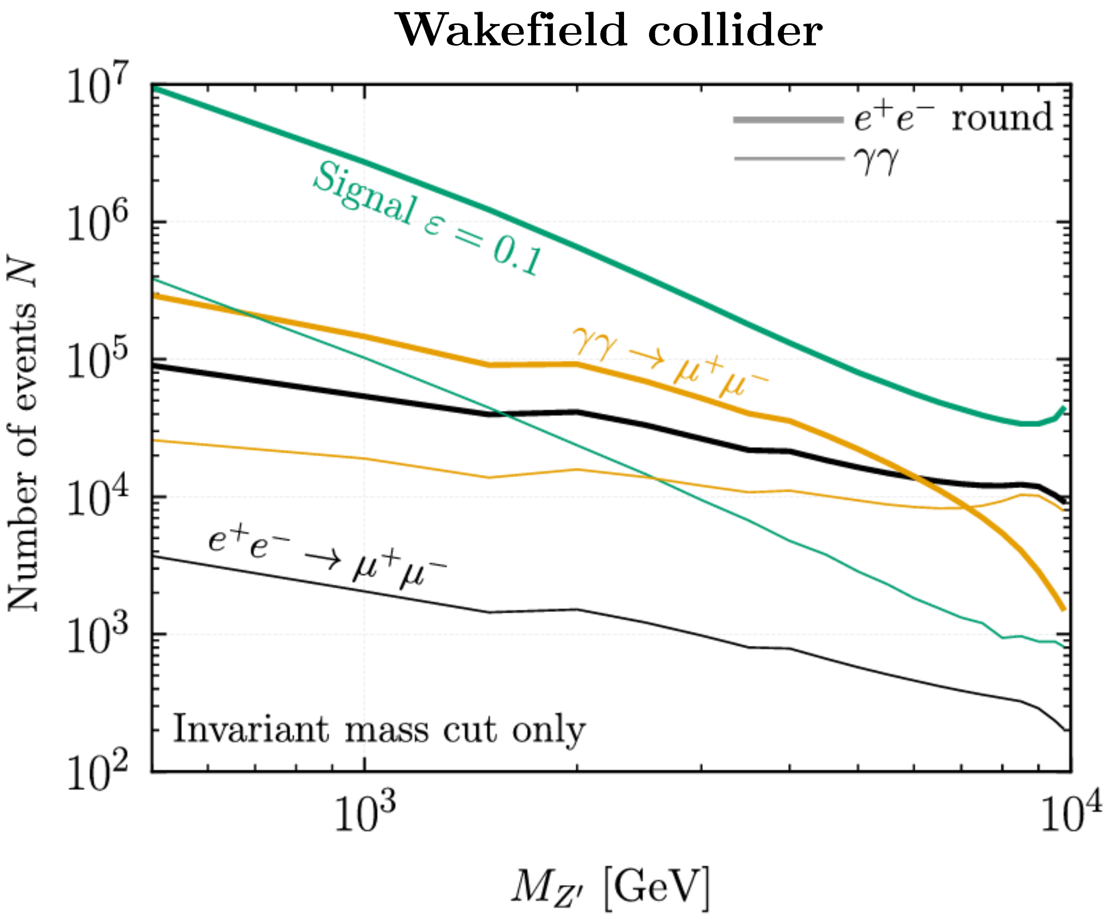
Detector resolution and cuts

TABLE I. Summary of acceptance cuts, selection cuts, and detector resolutions used in the analysis.

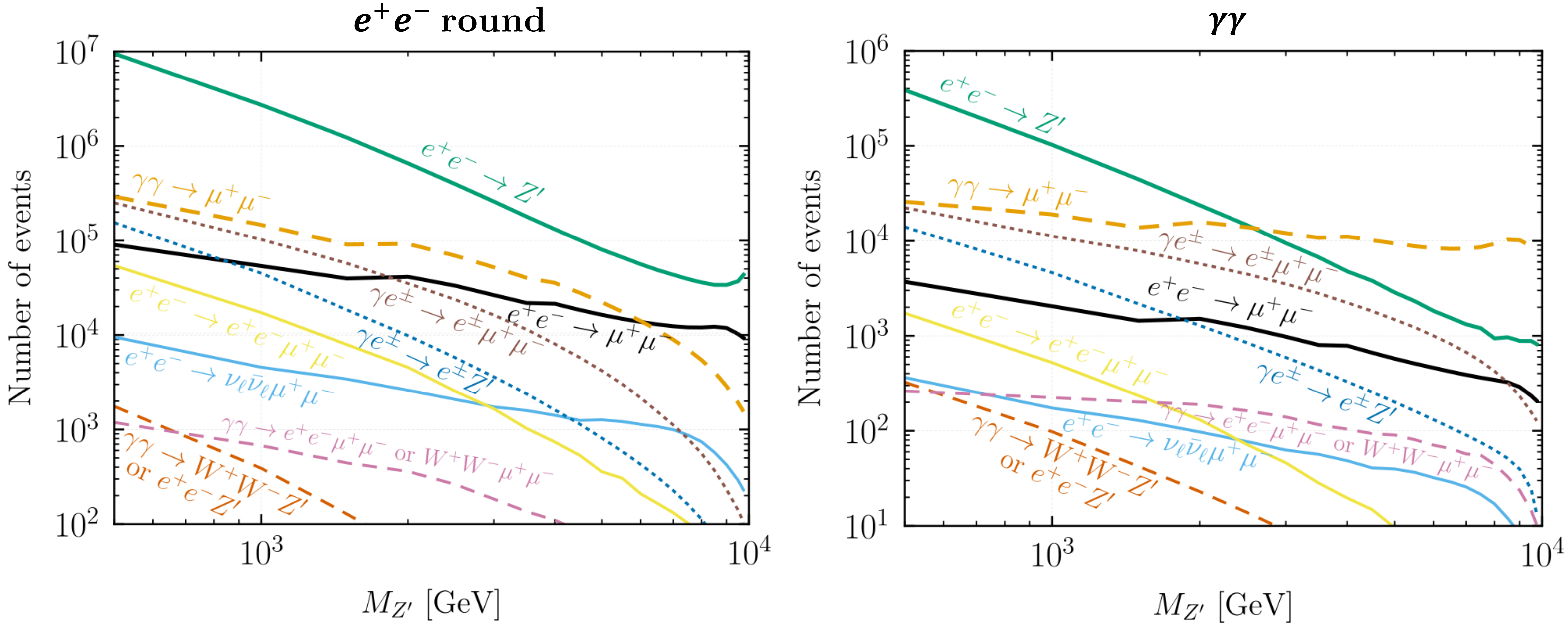
	MuC inclusive $\mu^+\mu^- \to e^+e^- + X$	**MuC exclusive** $\mu^+\mu^- \to e^+e^-\gamma$	**WFC** $e^\pm e^-/\gamma\gamma \to \mu^+\mu^- + X$
Acceptance Cuts			
$p_T^{\min}$	$25\,\text{GeV}$	$e^\pm: 25\,\text{GeV},\ \gamma: 25\,\text{GeV}$	$25\,\text{GeV}$
$\eta^{\max}$	2.5	2.5	2.5
$\Delta R^{\min}$	0.1	0.1	0.1
Resolution	$\sigma(E_e)/E_e = 1\%$	$\sigma(E_e)/E_e = 1\%$	$\sigma(1/p_{T\mu}) = 2\,\%/\text{TeV}$
Di-lepton resolution			
$\sigma_{m_{\ell\ell}}/m_{\ell\ell}$	0.7%	0.7%	$1\% \times m_{\mu\mu}/\text{TeV}$
σ_y	0.5%	0.5%	–
Selection Cuts			
Δ (invariant mass)	0.01	0.01	$0.015\, m_{\mu\mu}/\text{TeV}$
δ (rapidity)	0.01	–	–

Event rates comparison

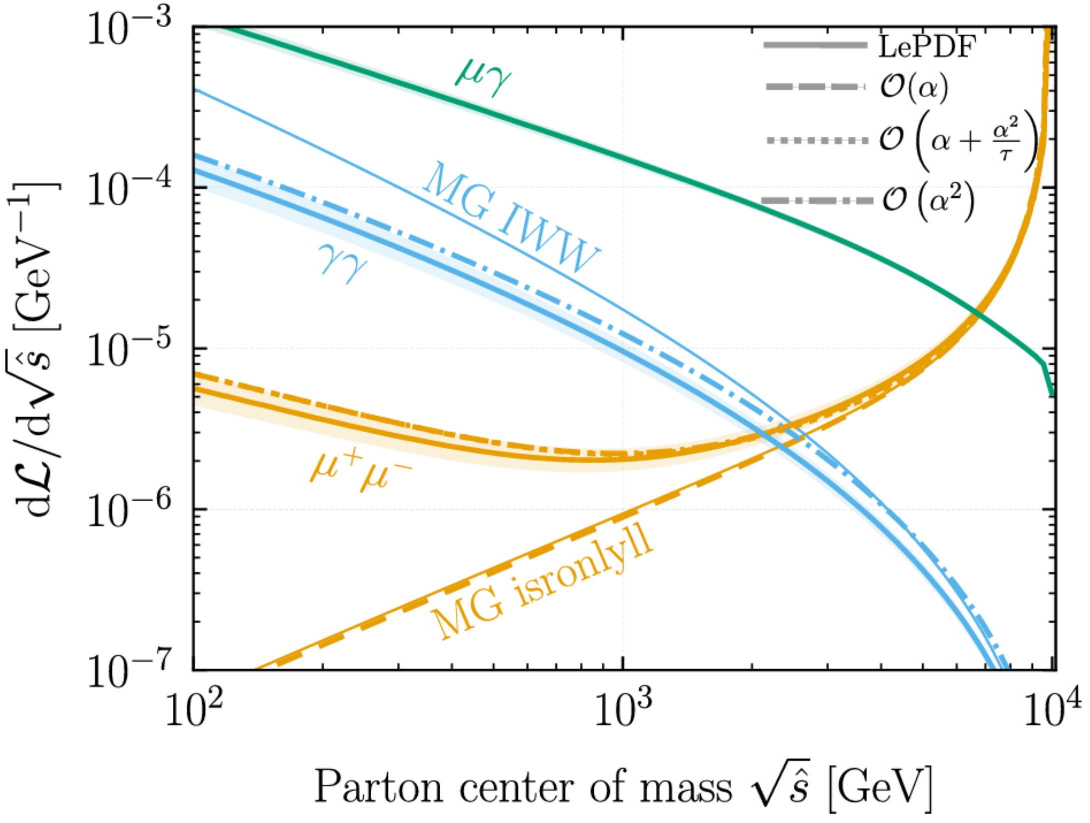




All the events of the WFC search



A closer look to LePDFs



(a) Muon beams