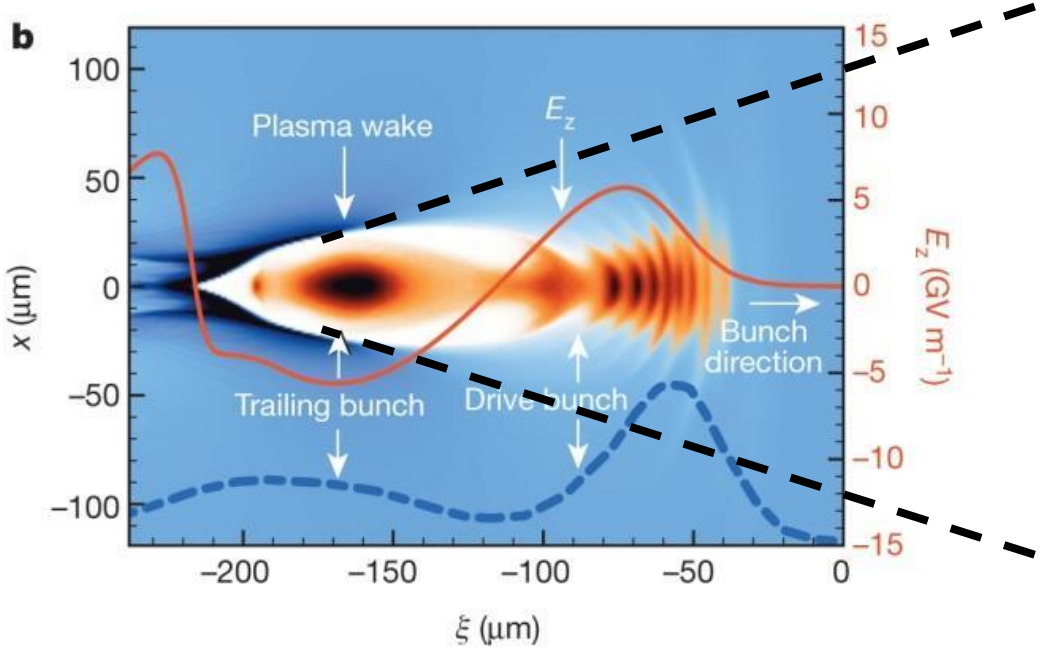
Massachusetts Institute of Technology

BERKELEY LAB



Litos, et al. Nature '14 (FACET @ SLAC)

GPT-5.2 Plus '26

Searches for electroweak states at future plasma wakefield colliders

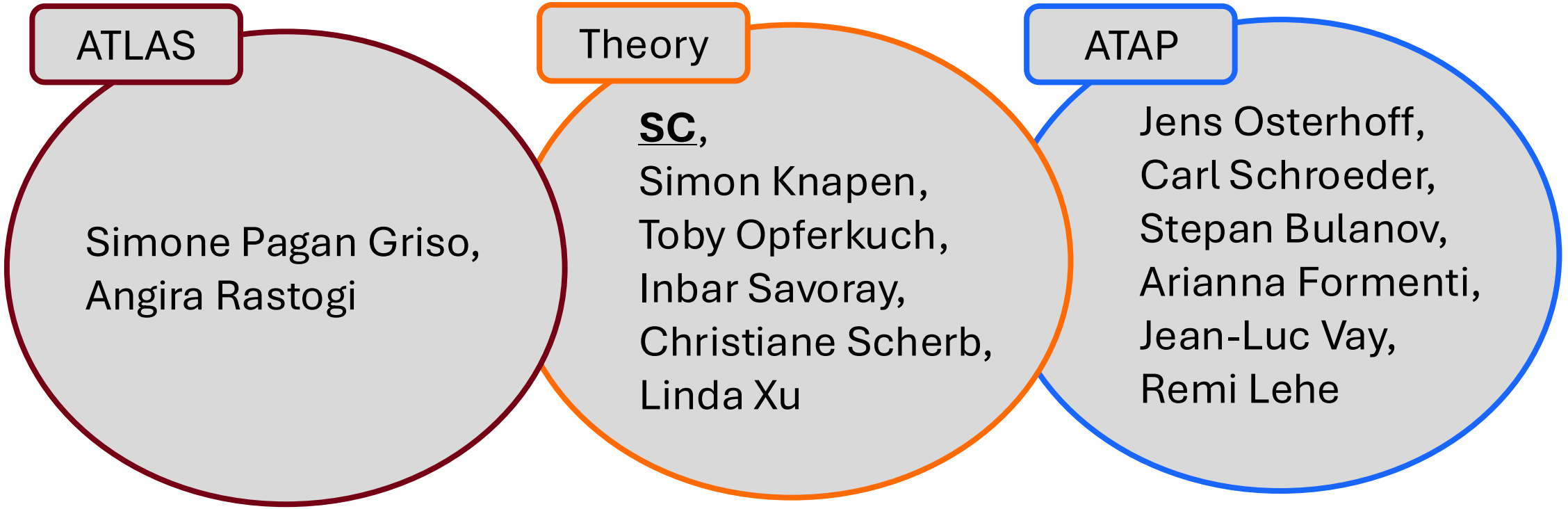
SC, S. Knapen, T. Opferkuch, I. Savoray, C. Scherb, W. L. Xu [arXiv: 2512.09995]
+ **SC** [Work in progress]

So Chigusa

3/3/2026 @ 2nd Hokkaido Workshop on Particle Physics at Crossroads

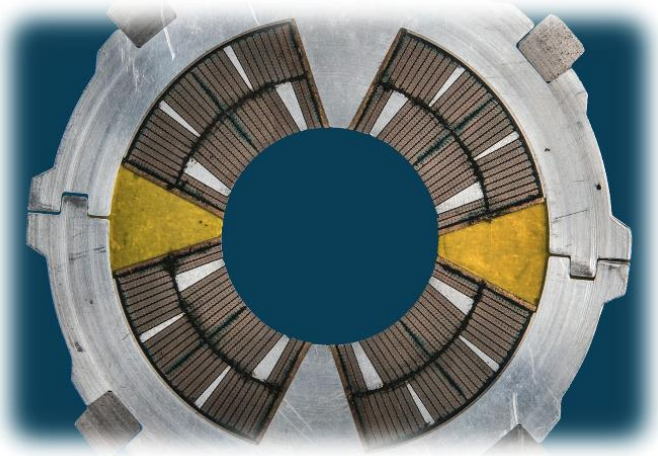
Berkeley community of wakefield colliders

ATAP = “Accelerator Technology & Applied Physics Division”



Options for 10 TeV-scale colliders

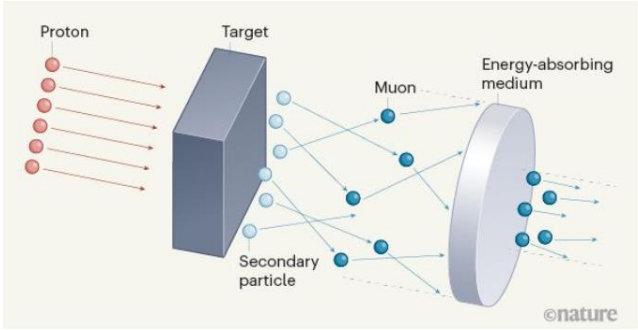
❖ 100 TeV pp



❖ Challenges

- 16 T dipole magnets
- 100 km tunnel
- radiation-hardness

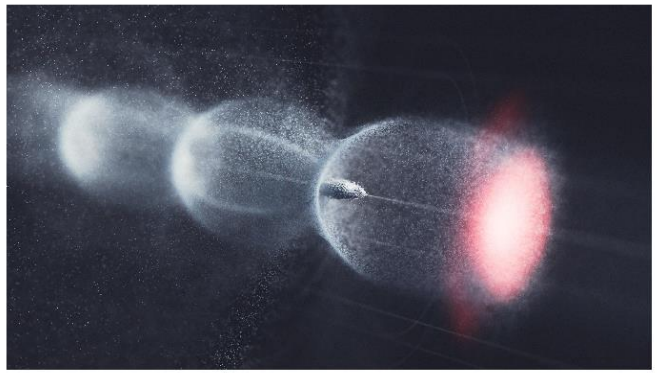
❖ Muon collider



❖ Challenges

- muon cooling
- neutrino radiation
- fast ramping magnets

❖ Plasma wakefield

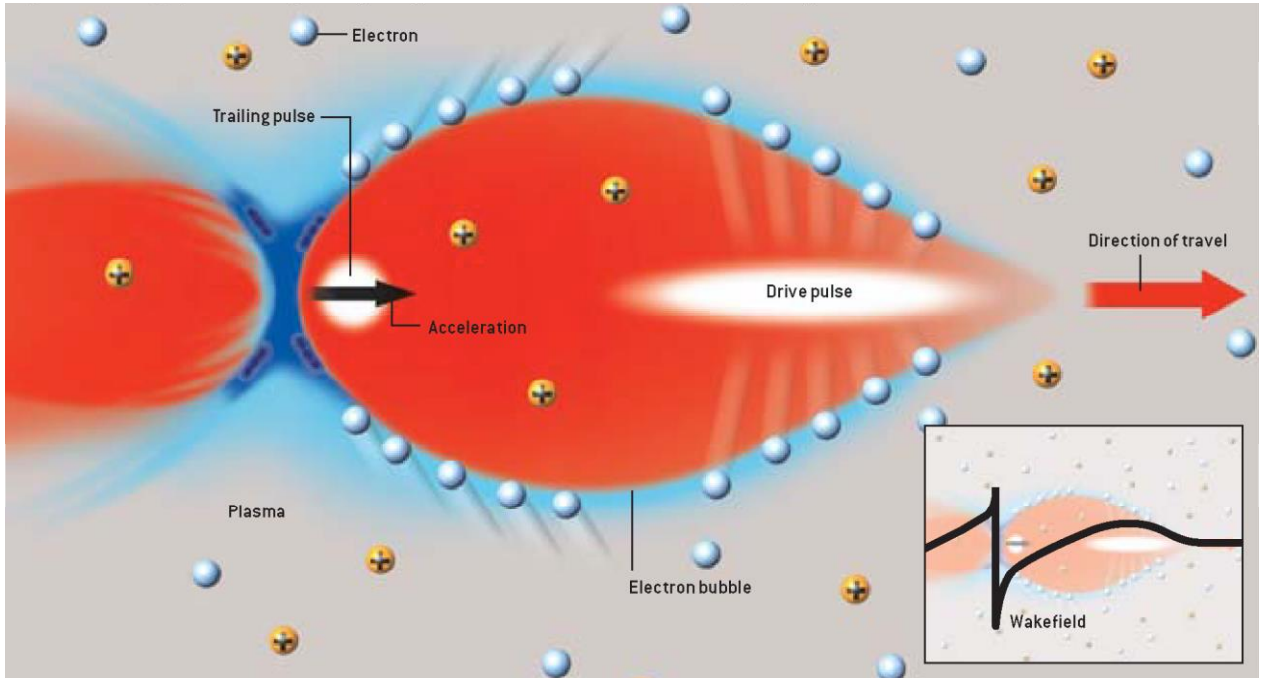


❖ Challenges

- beamstrahlung
- e^+ acceleration
- staging

Plasma wakefield

- Drive beam (laser, e^- beam, or etc.) blows out plasma e^-
- Strong EM field emerges: "wakefield"



Joshi, "Plasma accelerators". Scientific American '06

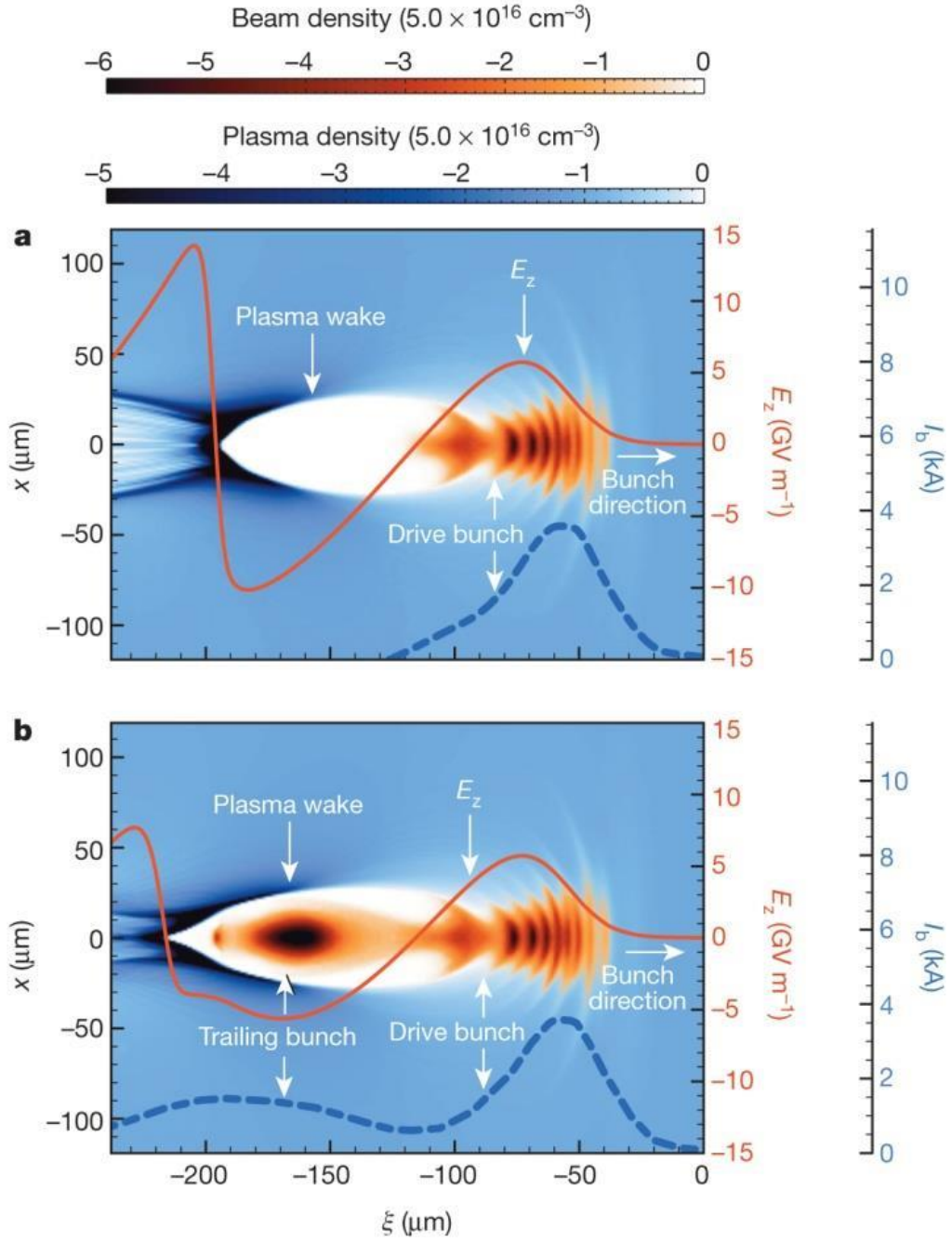
Plasma wakefield acceleration

- Pros
  - Strong acceleration gradients

    up to $\sim O(100)$ GV/m

    cf. RF limited $< O(100)$ MV/m

- Cons (or "challenges")
  - Small bunch size → beamstrahlung
  - e^+ acceleration & focusing
  - Multiple stages needed

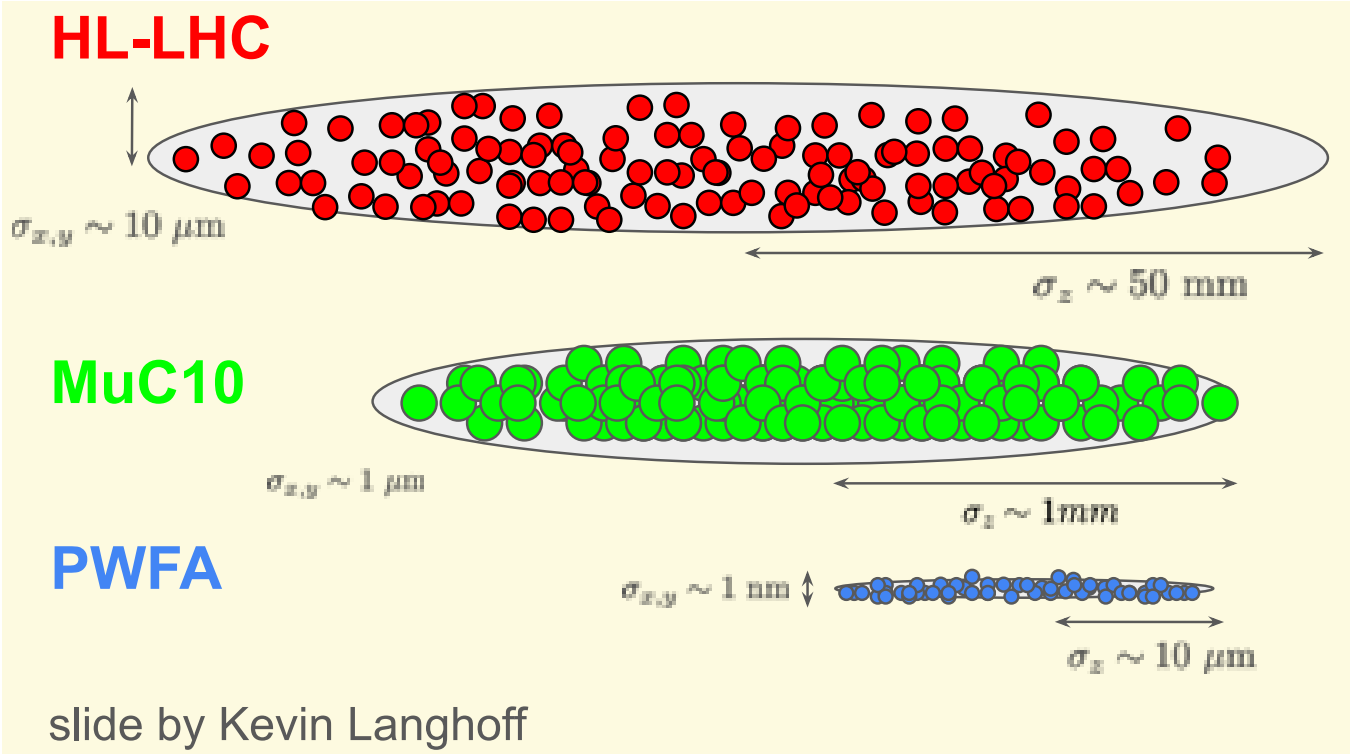


Litos, et al. Nature '14 (FACET @ SLAC)

Beam geometry

❖ Relatively compact beam

N	f [Hz]	$\frac{1}{\sigma_x\sigma_y}$ [cm^{-2}]	$\mathcal{L}$ [cm^{-2}s^{-1}]
2×10^{11}	40M	10^6	10^{35}
2×10^{12}	300k	10^8	10^{35}
10^9	50k	10^{14}	10^{35}



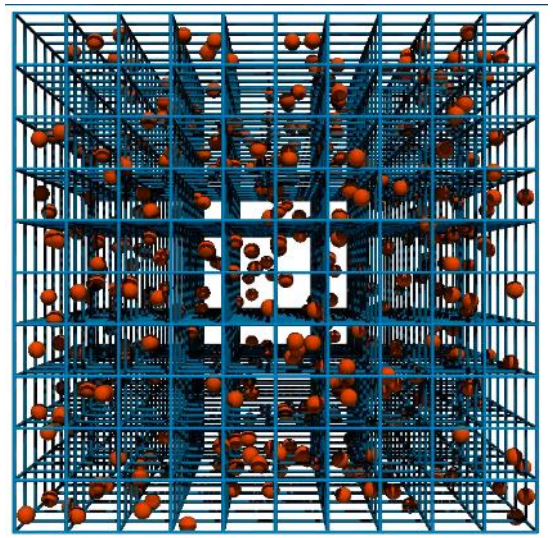
slide by Kevin Langhoff

❖ Geometric luminosity

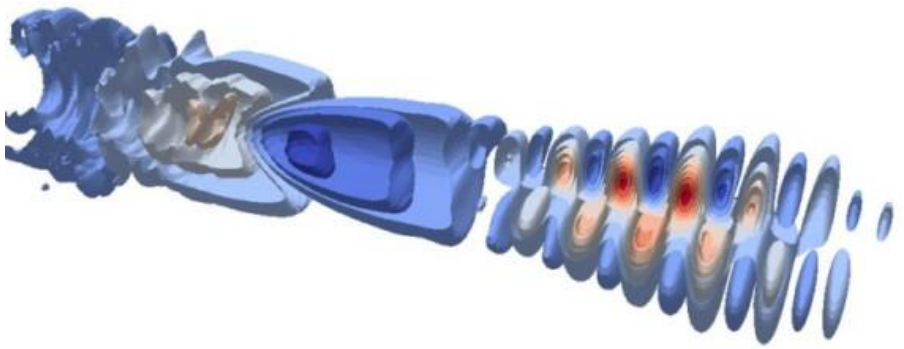
- $\mathcal{L} = \frac{fN^2}{4\pi\sigma_x\sigma_y}$

Beam-beam interaction and beamstrahlung

- Beam-induced EM field leads to
  - Disruption
  - Beamstrahlung
- Particle-in-cell (PIC) simulation

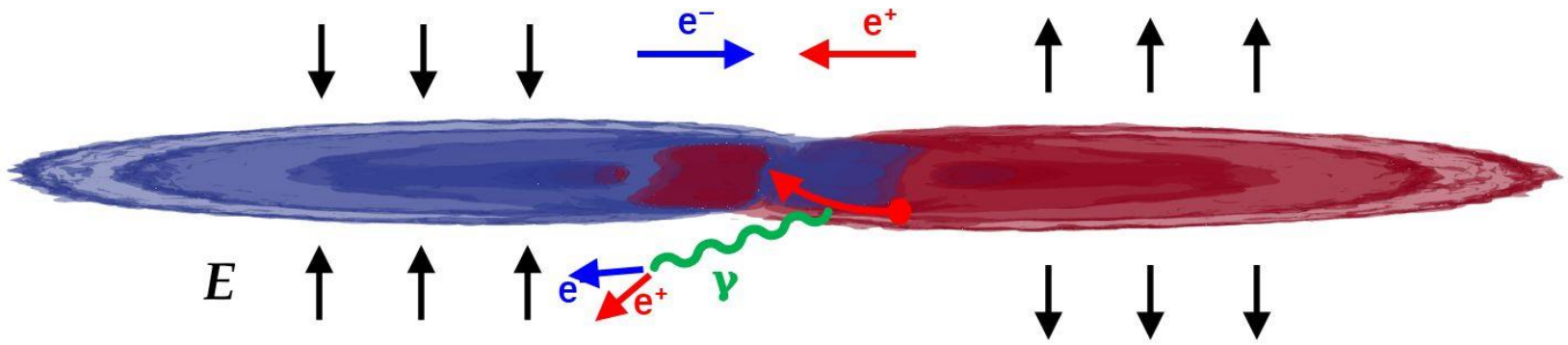


- WarpX: advance open-source PIC code



Figures and animation by Arianna Formenti & Remi Lehe

Beamstrahlung



- Field strength parameter
  - $\Upsilon \equiv \frac{e}{m_e^3}\sqrt{\left|\left(F_{\mu\nu}p_e^{\nu}\right)^2\right|}$ Yokaya & Chen '92
  - $\Upsilon_{\max} \simeq \frac{2\alpha N E_e}{m_e\sigma_z(\sigma_x+\sigma_y)} \sim \begin{cases} 10^{-6,-1}\ (\mathrm{HLLHC, MuC}) \\ 10^{5}\ (\mathrm{wakefield}) \end{cases}$; cf. $\mathcal{L} \propto \frac{1}{\sigma_x\sigma_y}$
- Strong beamstrahlung for wakefield collider
  - Flat beam ($\sigma_x \gg \sigma_y$) can reduce beamstrahlung while keeping luminosity

Collider options I: e^+e^- vs e^-e^- vs $\gamma\gamma$

❖ What to collide?

- e^+e^- ····
- $\gamma\gamma$ ····
- e^-e^- ····

Difficulty

Challenging

Relatively easy

Physics reach

···· seems good

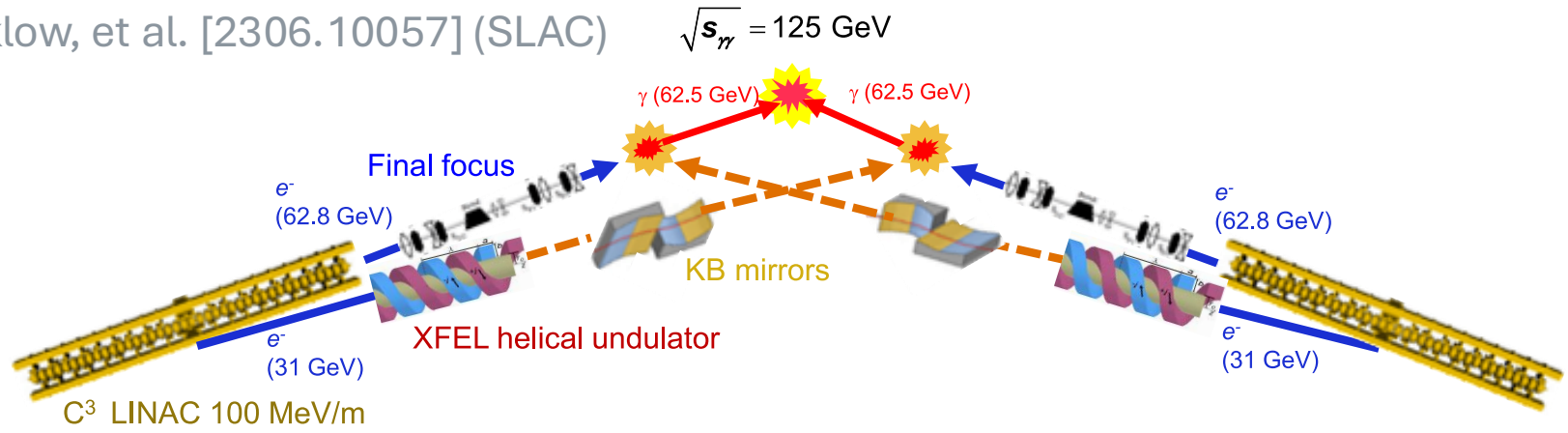
···· ?

···· maybe interesting

cf. μTRISTAN

❖ $\gamma\gamma$ option with inverse Compton scattering

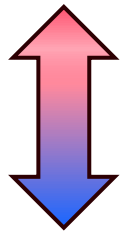
Barklow, et al. [2306.10057] (SLAC)

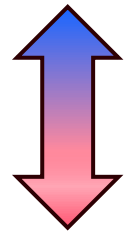


Collider options II: flat vs round beams

❖ Beam shape?

- Flat: $\sigma_x \gg \sigma_y$ .... Challenging .... Low
- Round: $\sigma_x \sim \sigma_y$ .... Normal .... High





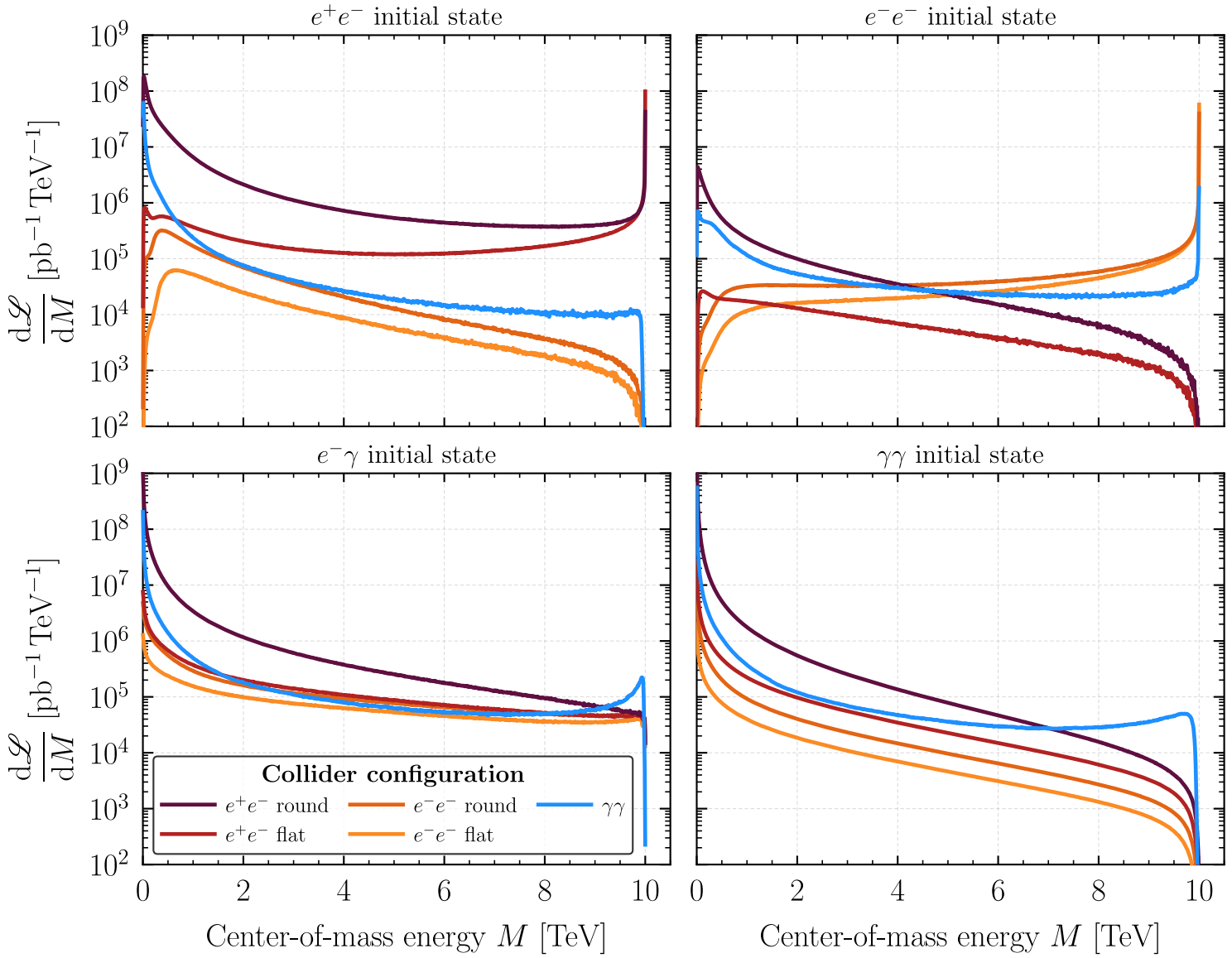
❖ Summary of collider options

- 5 options: e^+e^- flat/round vs. e^-e^- flat/round vs. $\gamma\gamma$
- Let's compare physics reach!

Luminosity profile

- Universal setup
  - $\sqrt{s} = 10\ \mathrm{TeV}$
  - $\mathcal{L}_{\mathrm{geom}} = 7.52\ \mathrm{ab}^{-1}\ \mathrm{yr}^{-1}$

- Sizable portion of collisions still have $M \simeq 10\ \mathrm{TeV}$!



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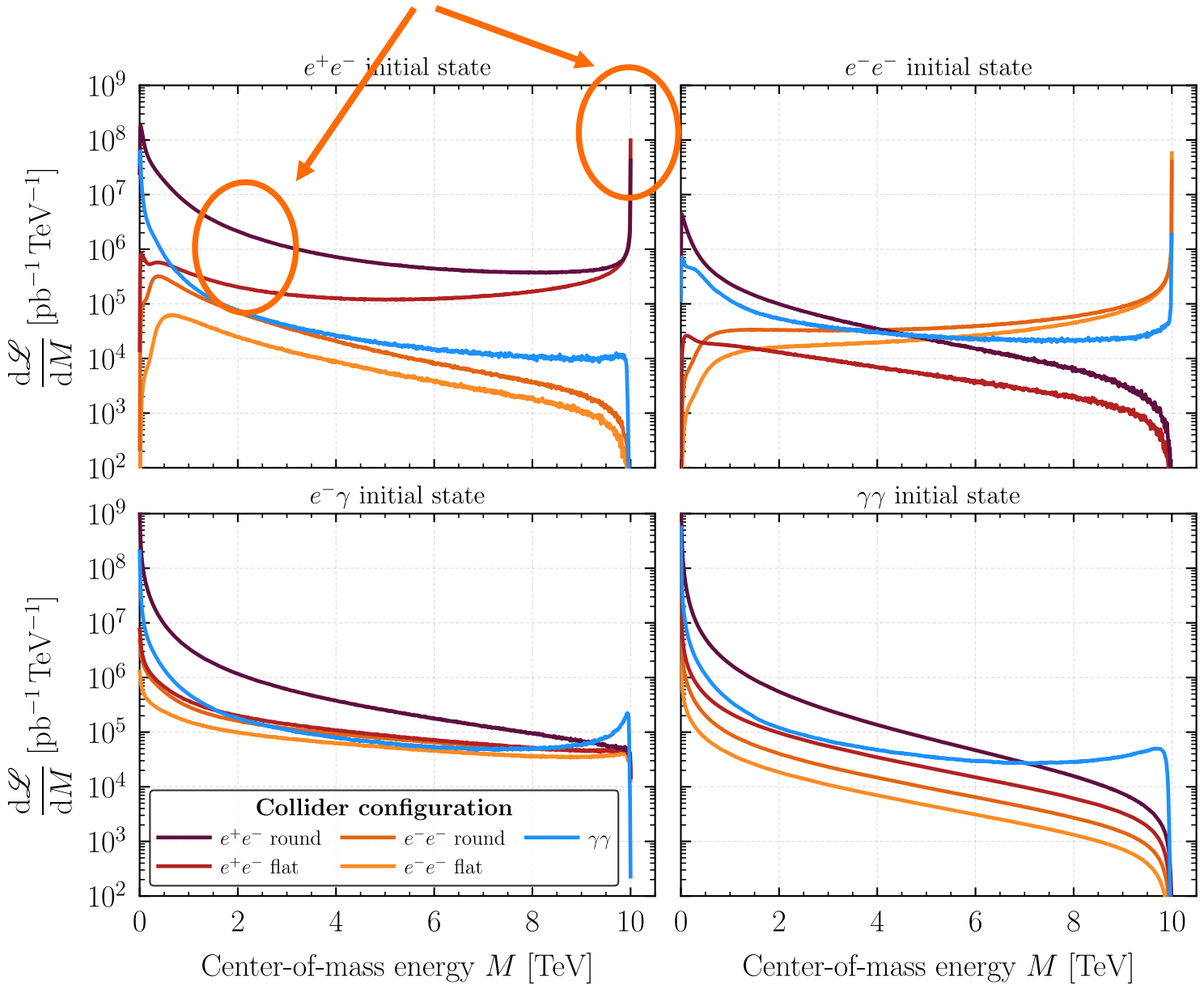

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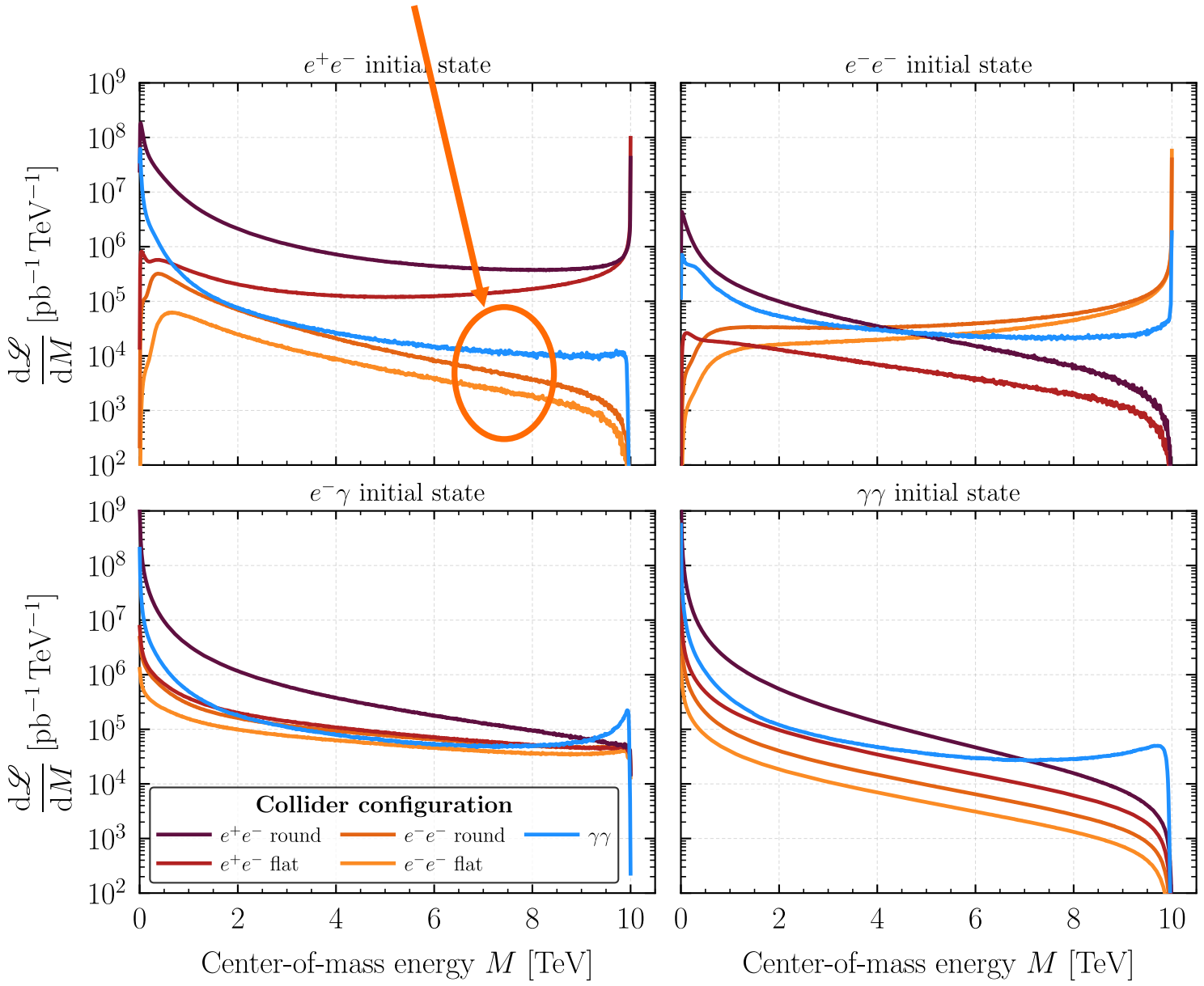
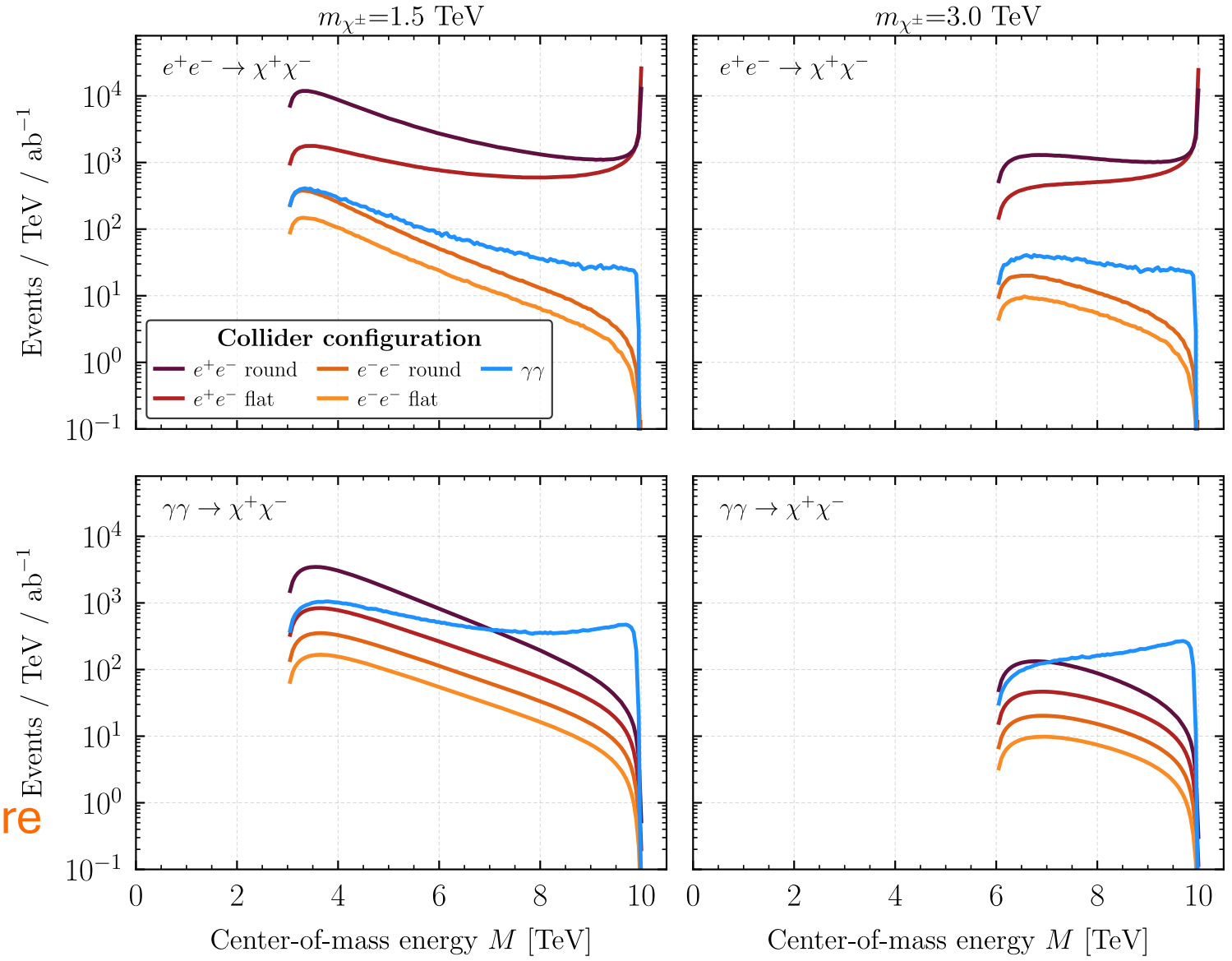


Chargino production rate

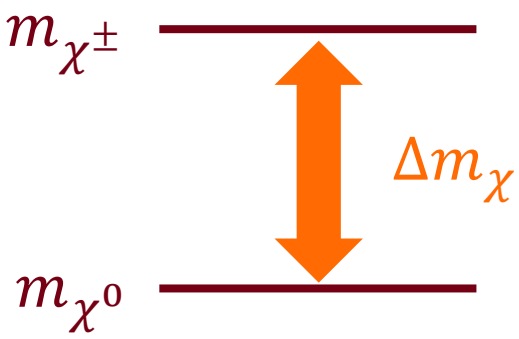
- Consider pair production
  - $e^+e^-/\gamma\gamma \to \chi^+\chi^-$
  - Large σ @ prod. threshold

- We found…
  - $e^+e^- > \gamma\gamma > e^-e^-$
  - Round ≳ Flat
  - Round beam is better for production despite the folklore

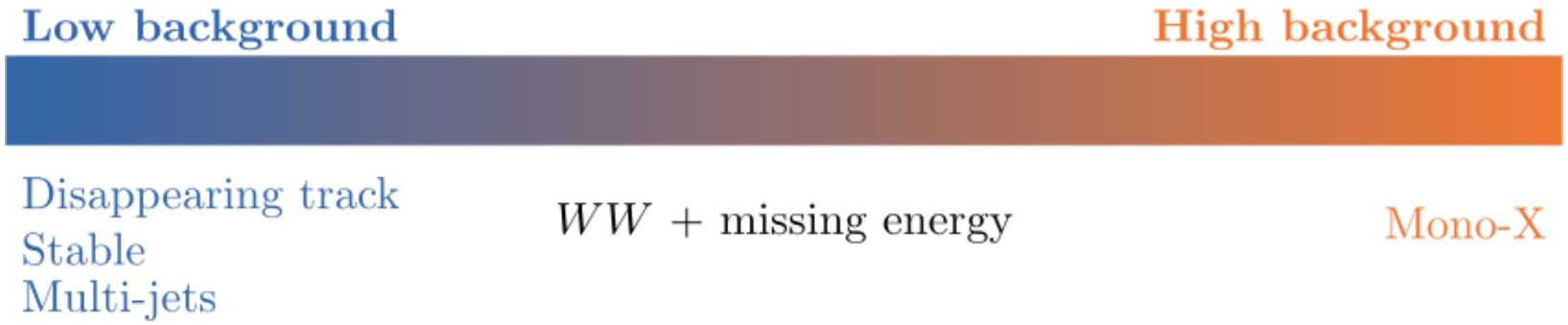


Models and search channels

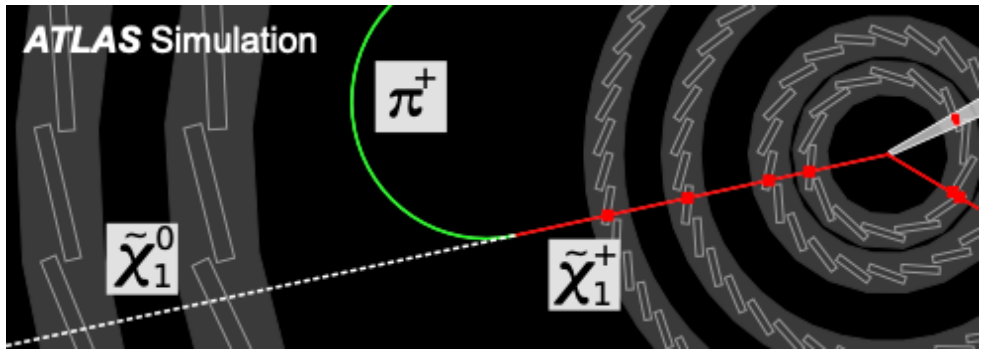
- Heavy $SU(2)_L$ multiplets with mass difference in charged/neutral components
  - Higgsino-like doublet
  - Wino-like triplet



- Different search strategies depending on Δm_χ

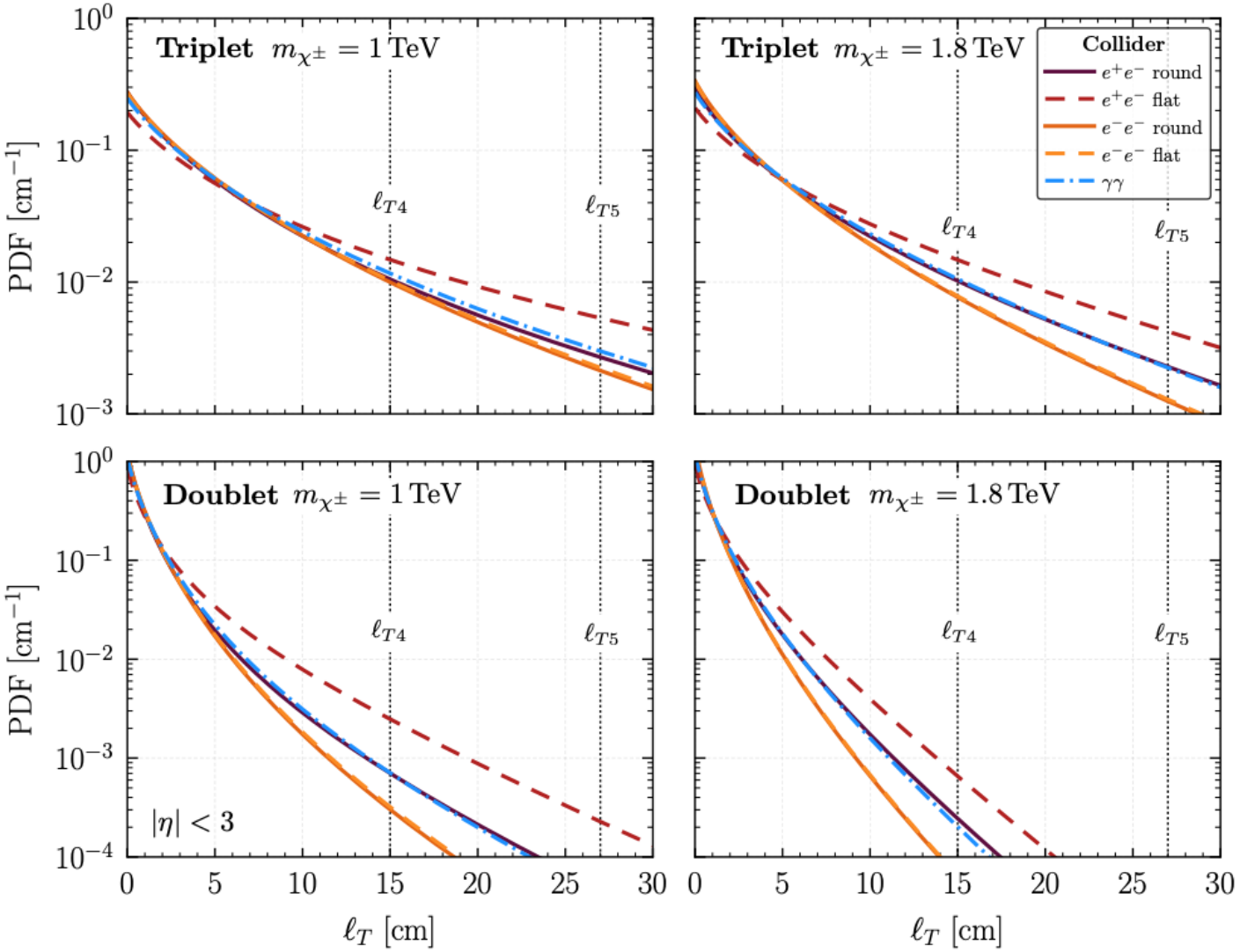


Example: disappearing track



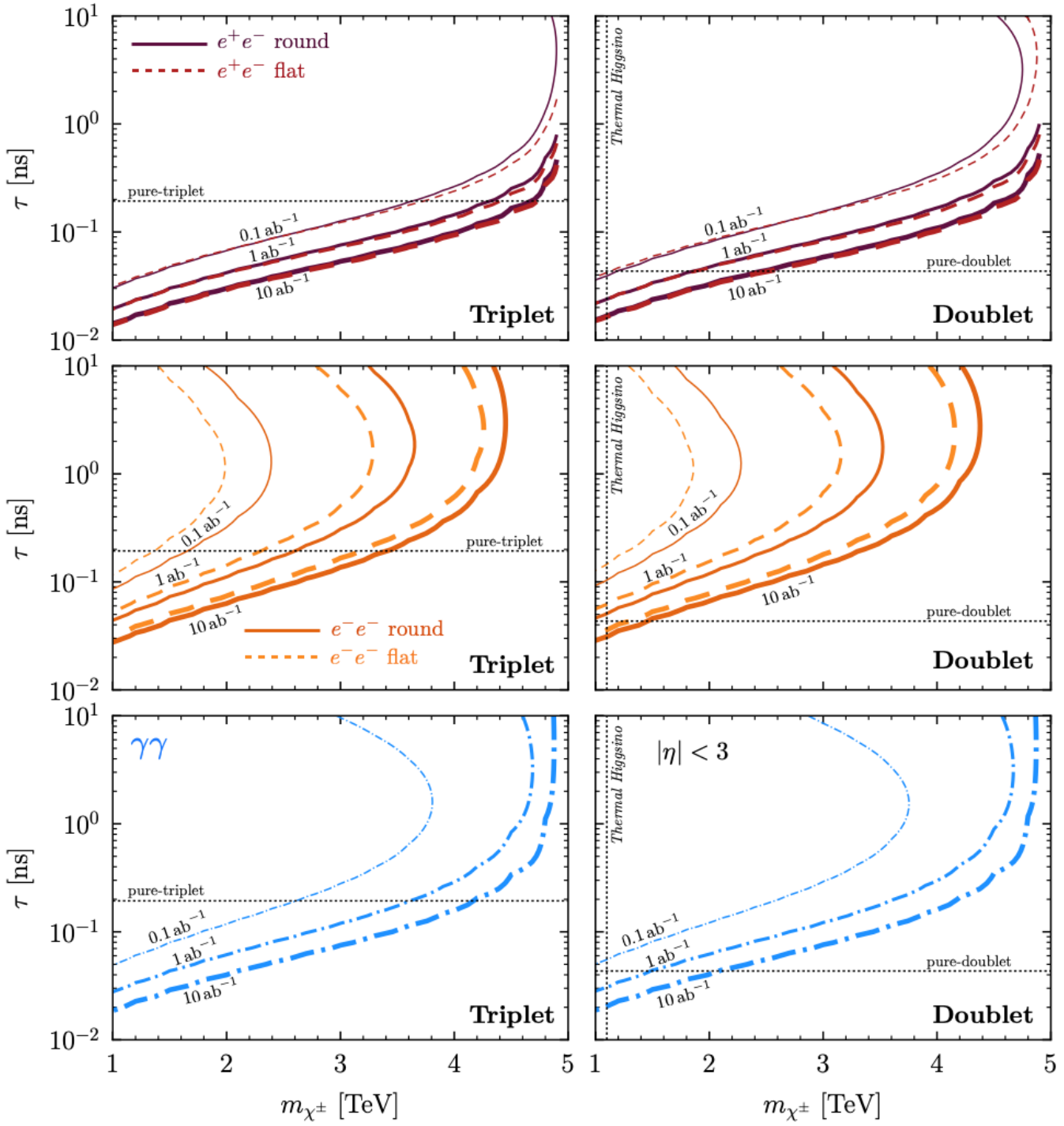
ATLAS [1712.02118]

- Search for long-lived particles decay in the tracker region
- Require transverse flight length
  - $\ell_{T4} < \ell_T < \ell_{T5}$



Disappearing track reach

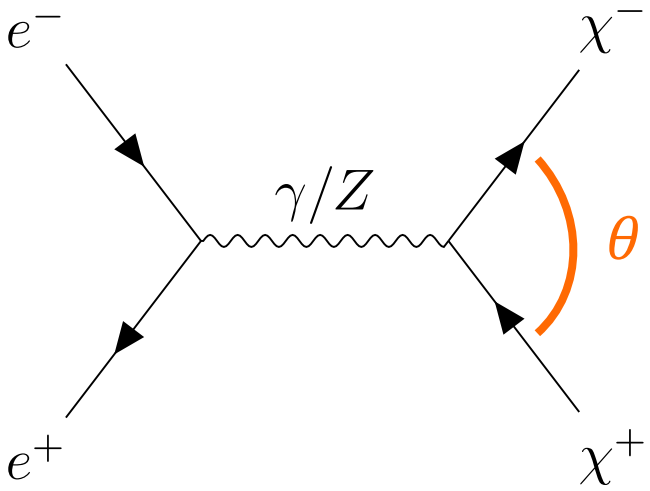
- 10 events contour
- Sensitivity comparison
  - $e^+e^- > \gamma\gamma > e^-e^-$
  - Round > Flat up to a few TeV
  - Flat $\gtrsim$ Round for $\sim$ 5 TeV

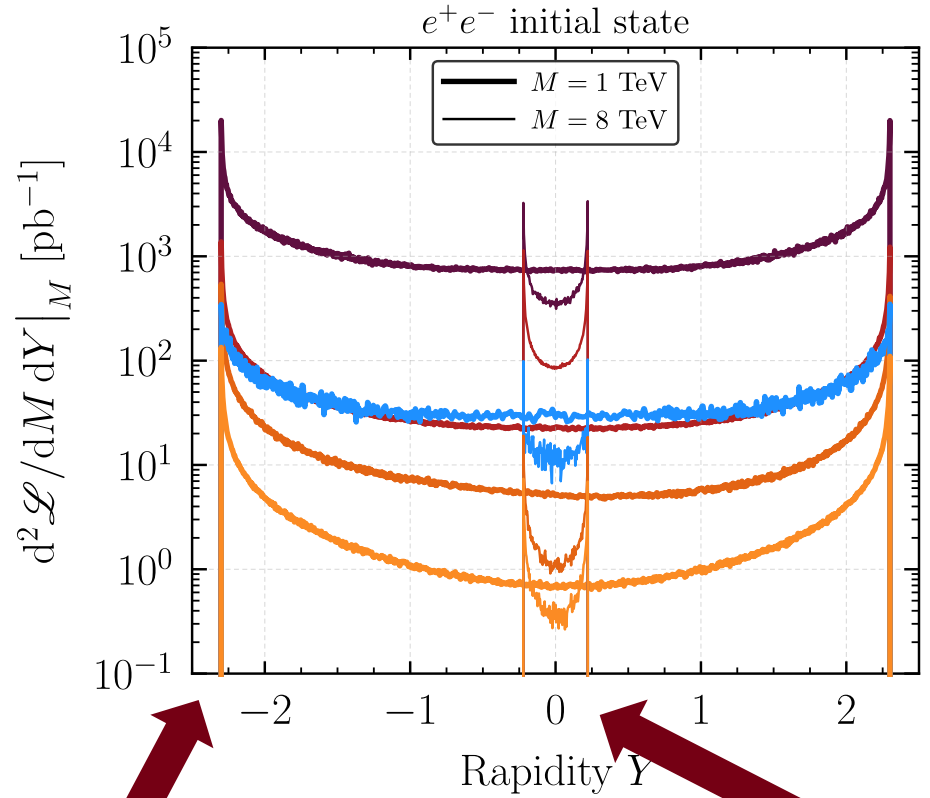


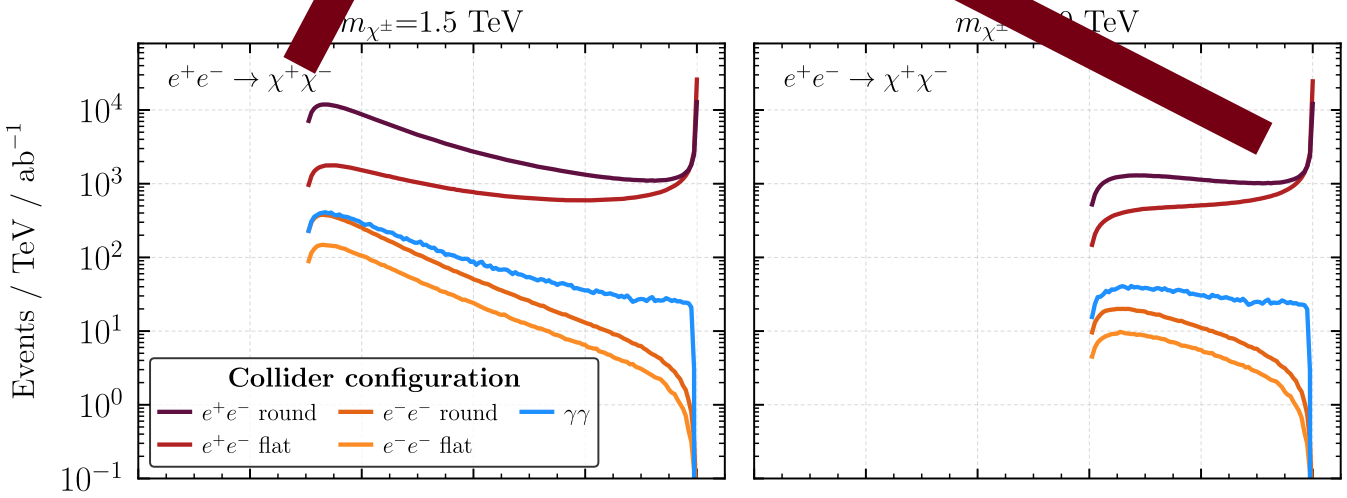
Towards full use of profile

❖ Example

- mass extraction from opening angle of 2 (disappearing) tracks



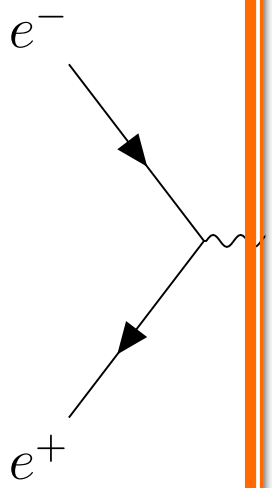


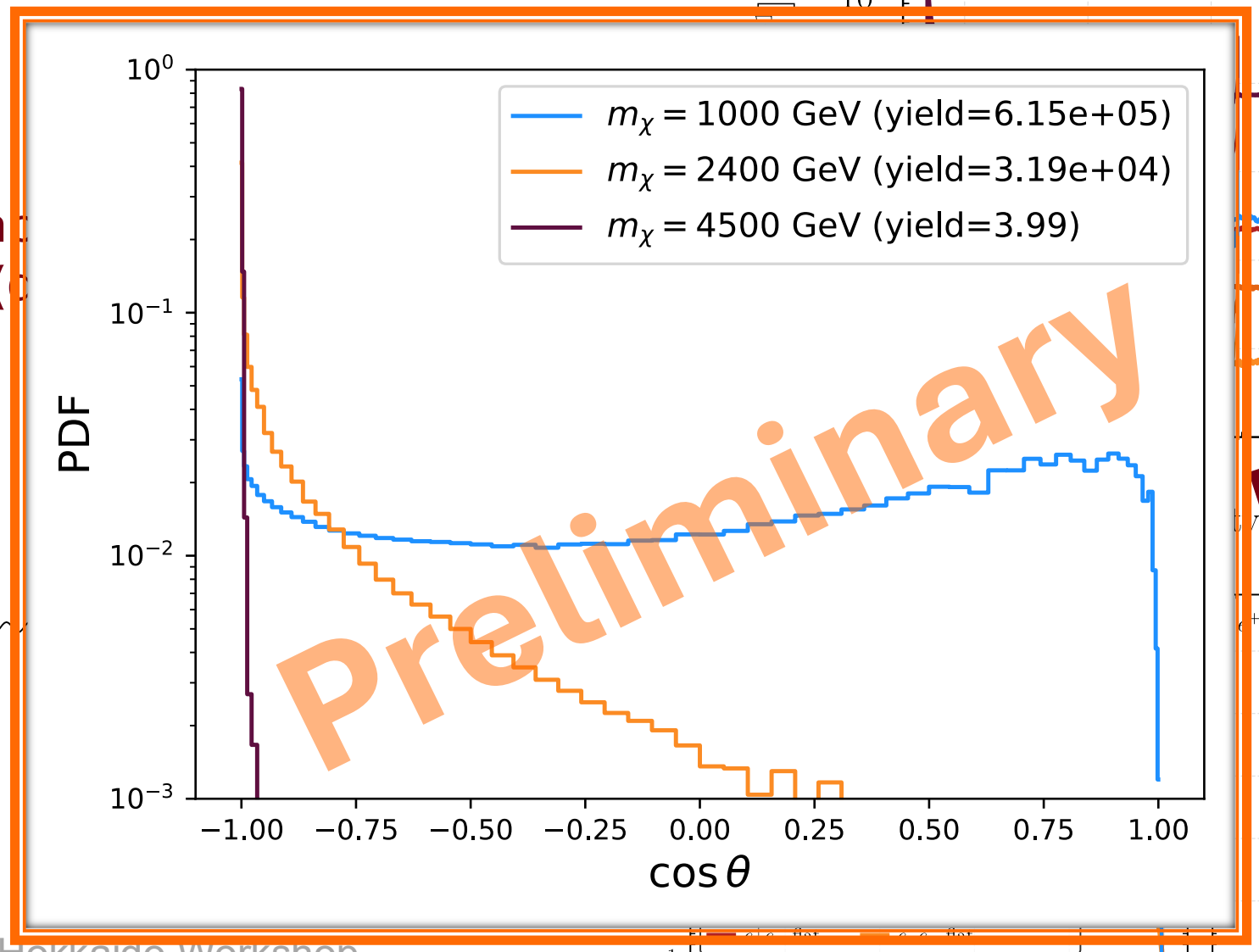


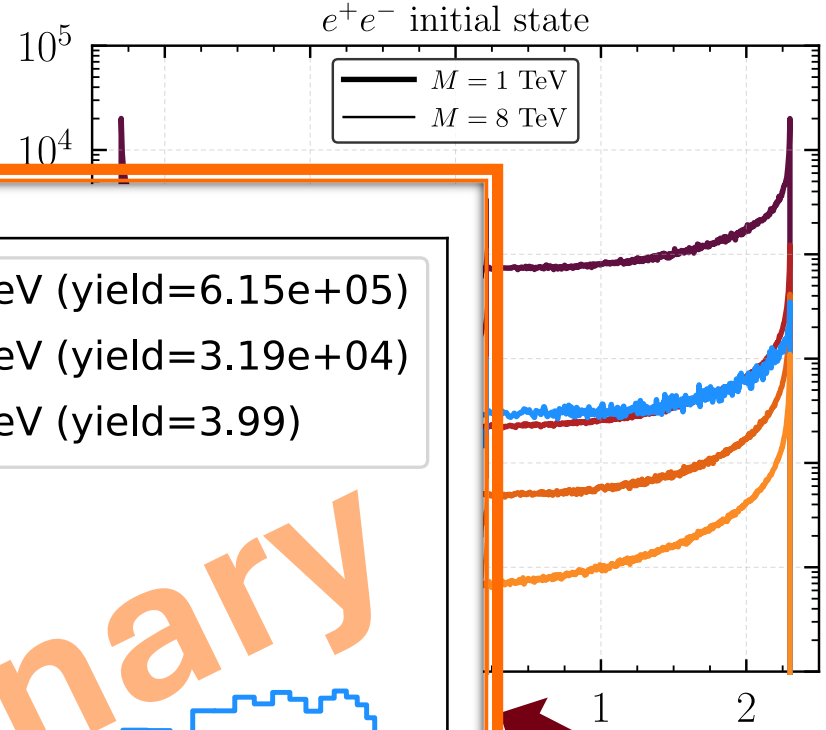
Towards full use of profile

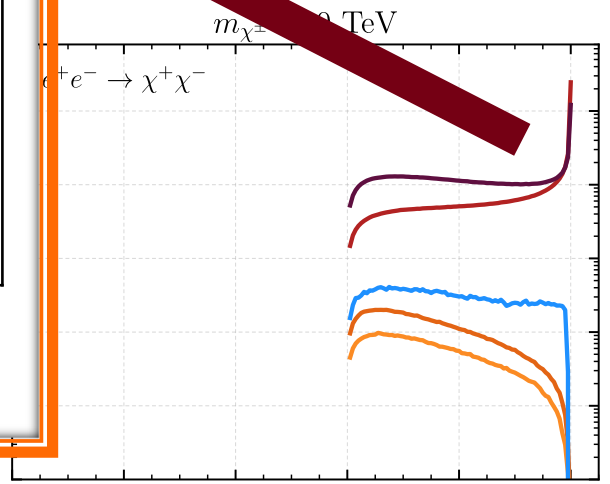
❖ Example

- mass extra
  angle of 2 (









Conclusion

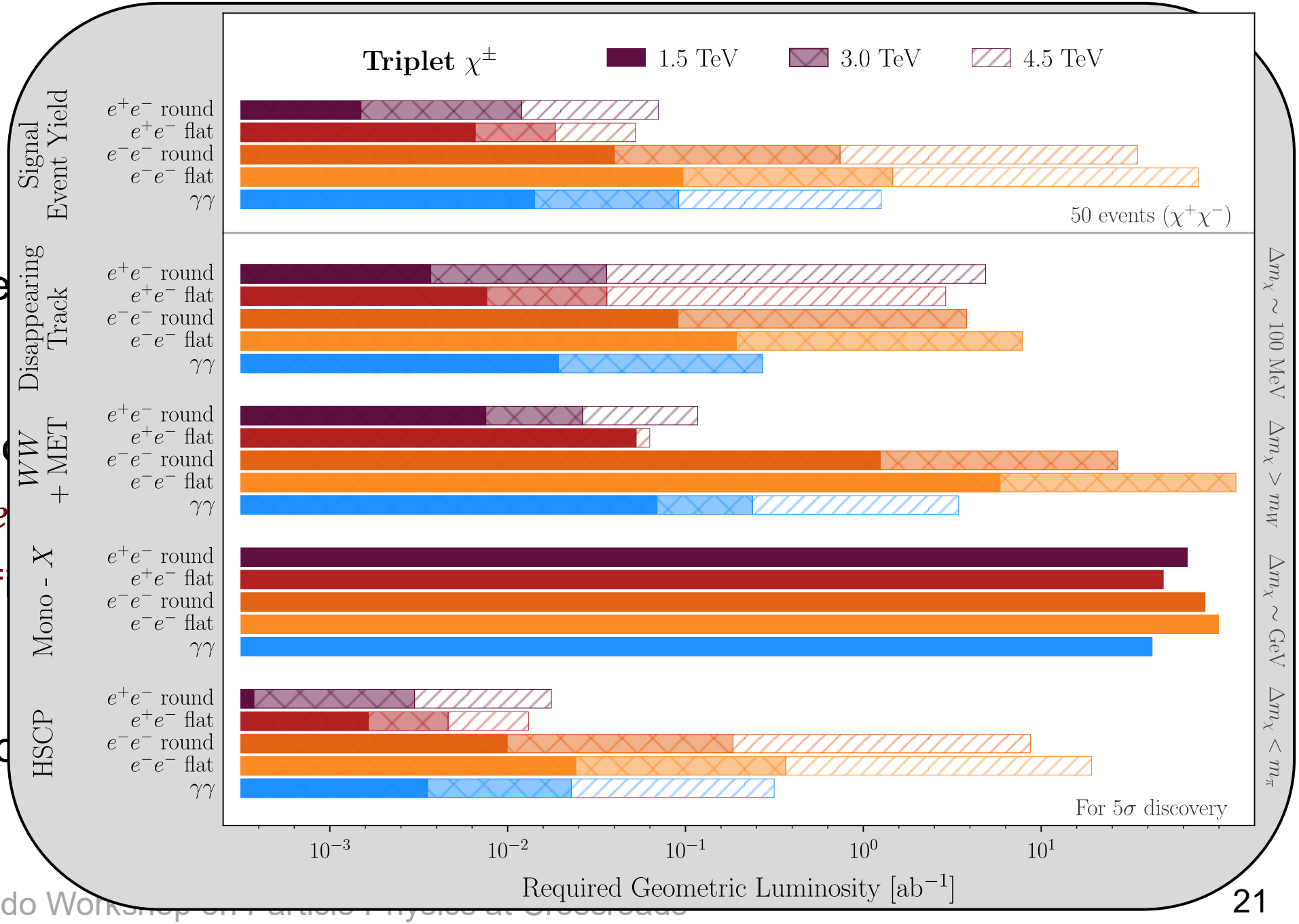
- Wakefield acceleration: interesting venue with unique challenges

- Comparison of collider options
  - $e^+e^- > \gamma\gamma > e^-e^-$
  - No clear benefits from flat beams

- Sizable fraction of beam remain to be @ $\sqrt{s}/2 \sim 5$ TeV

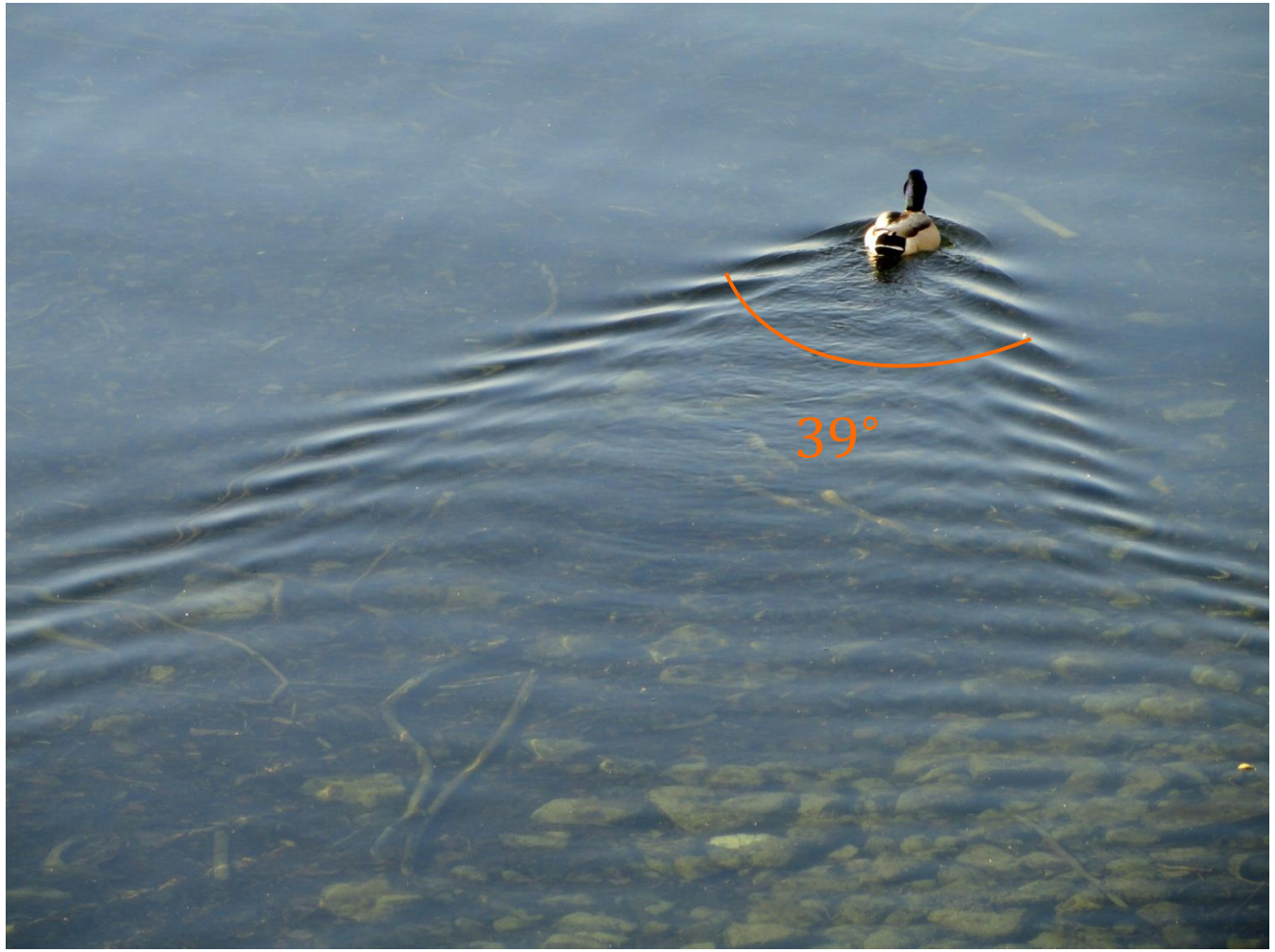
Conclusion

- ❖ Wakefield accele
- ❖ Comparison of c
  - $e^+e^- > \gamma\gamma > e$
  - No clear benef
- ❖ Sizable fraction c



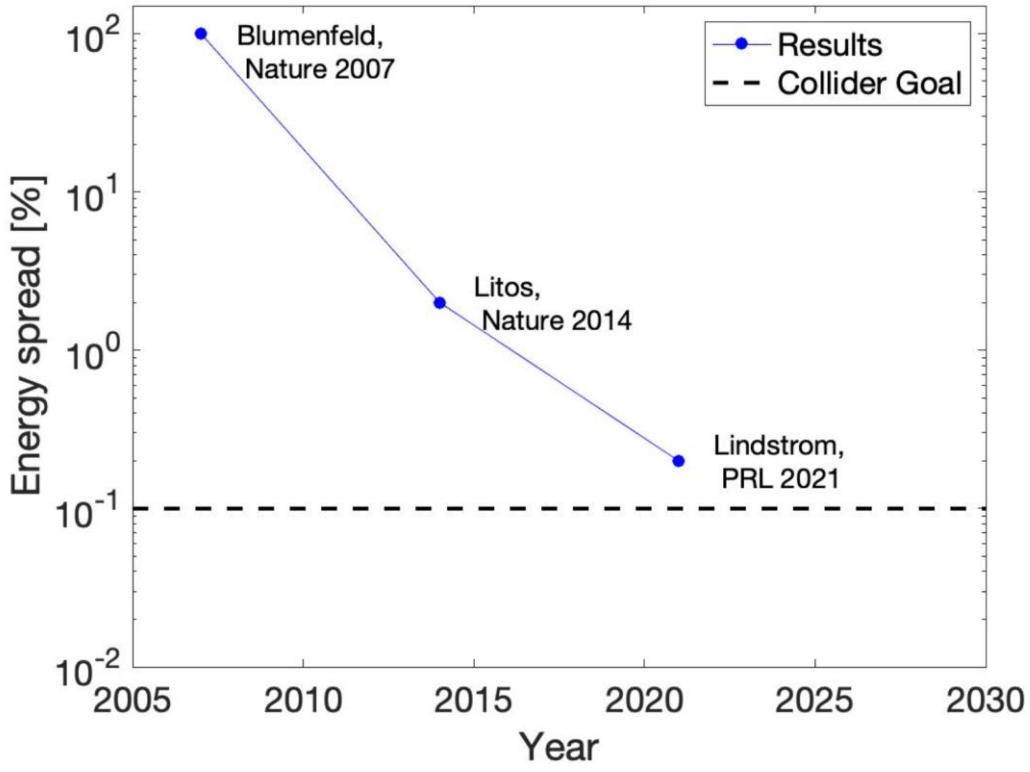
Backup slides

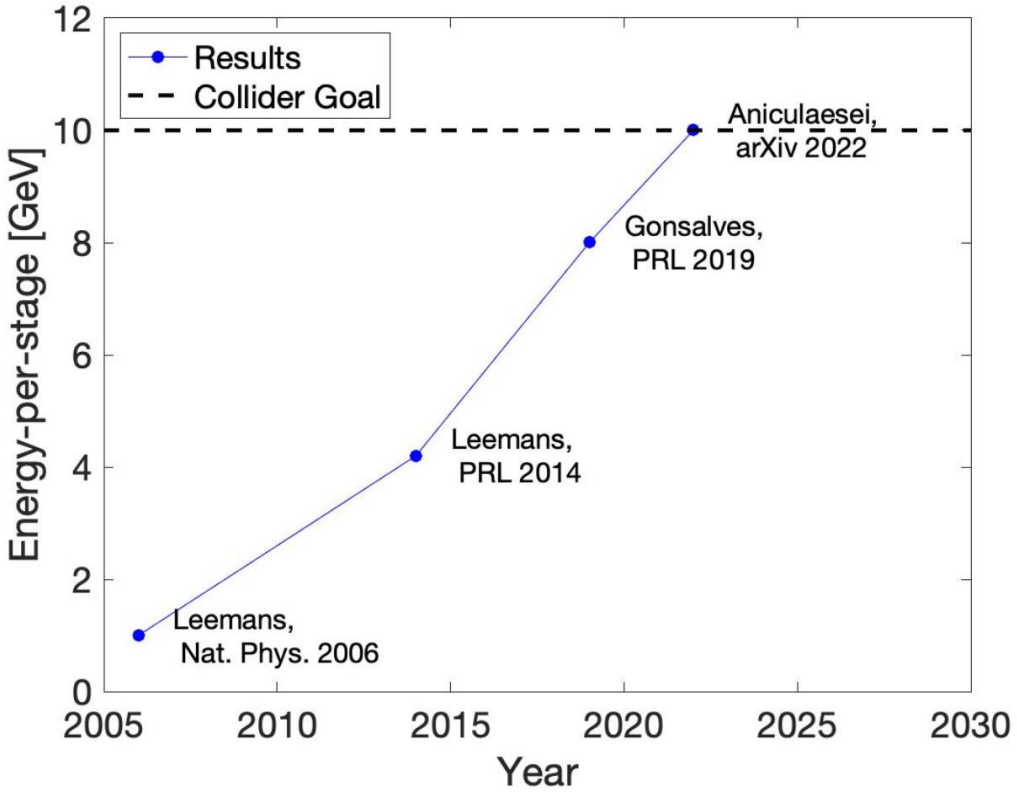
Duck wake (航跡波・曳き波)



Progress in e^- acceleration

❖ Tremendous efforts and technological improvements!



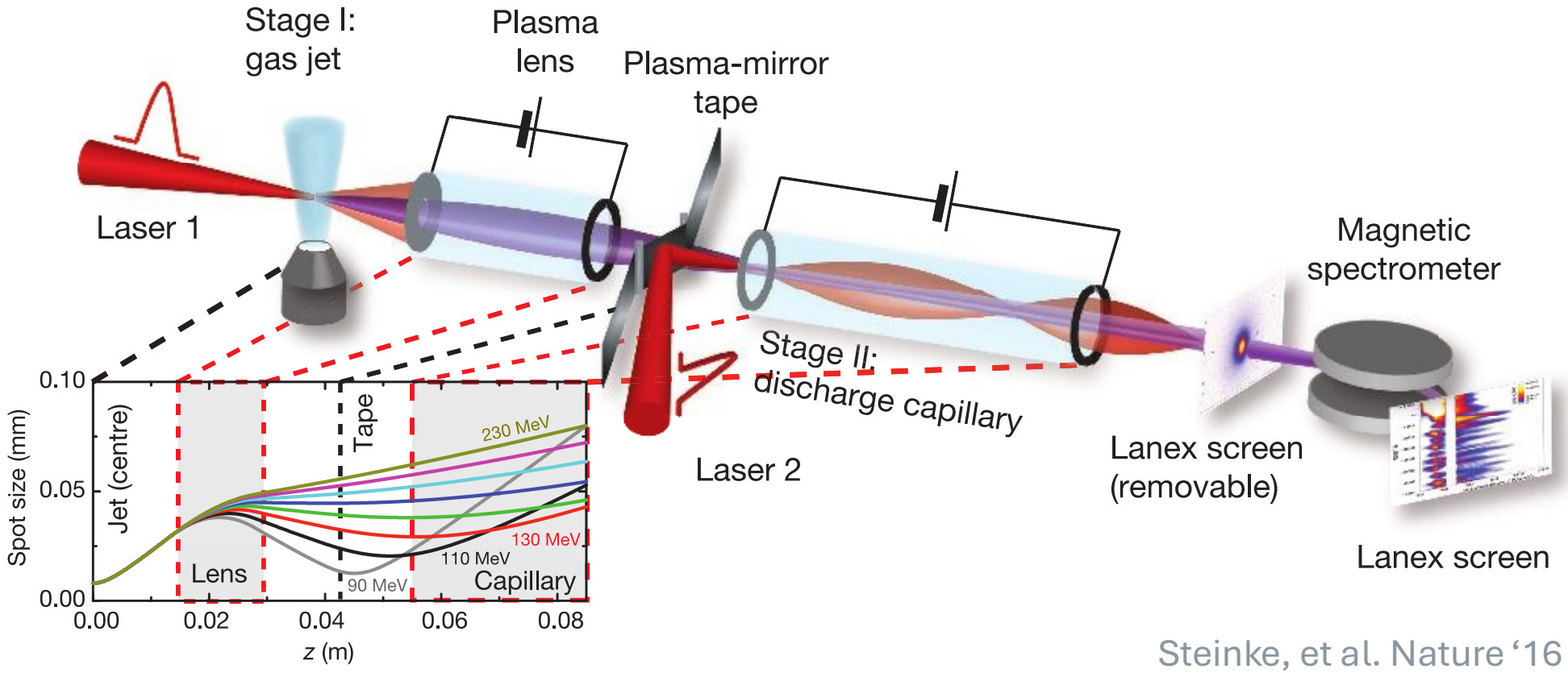


Figures by Spencer Gessner

❖ Also at our place… ATAP group @ LBNL

Staging demonstrated

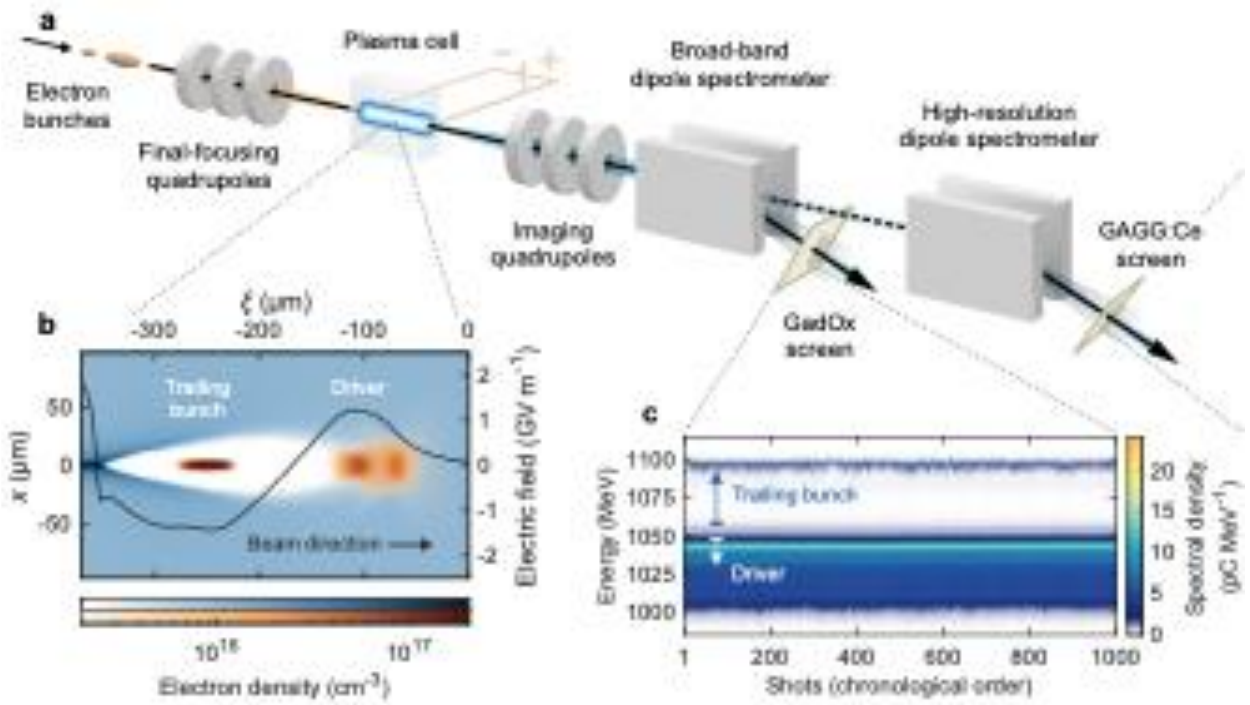
❖ BELLA LWFA facility at LBNL



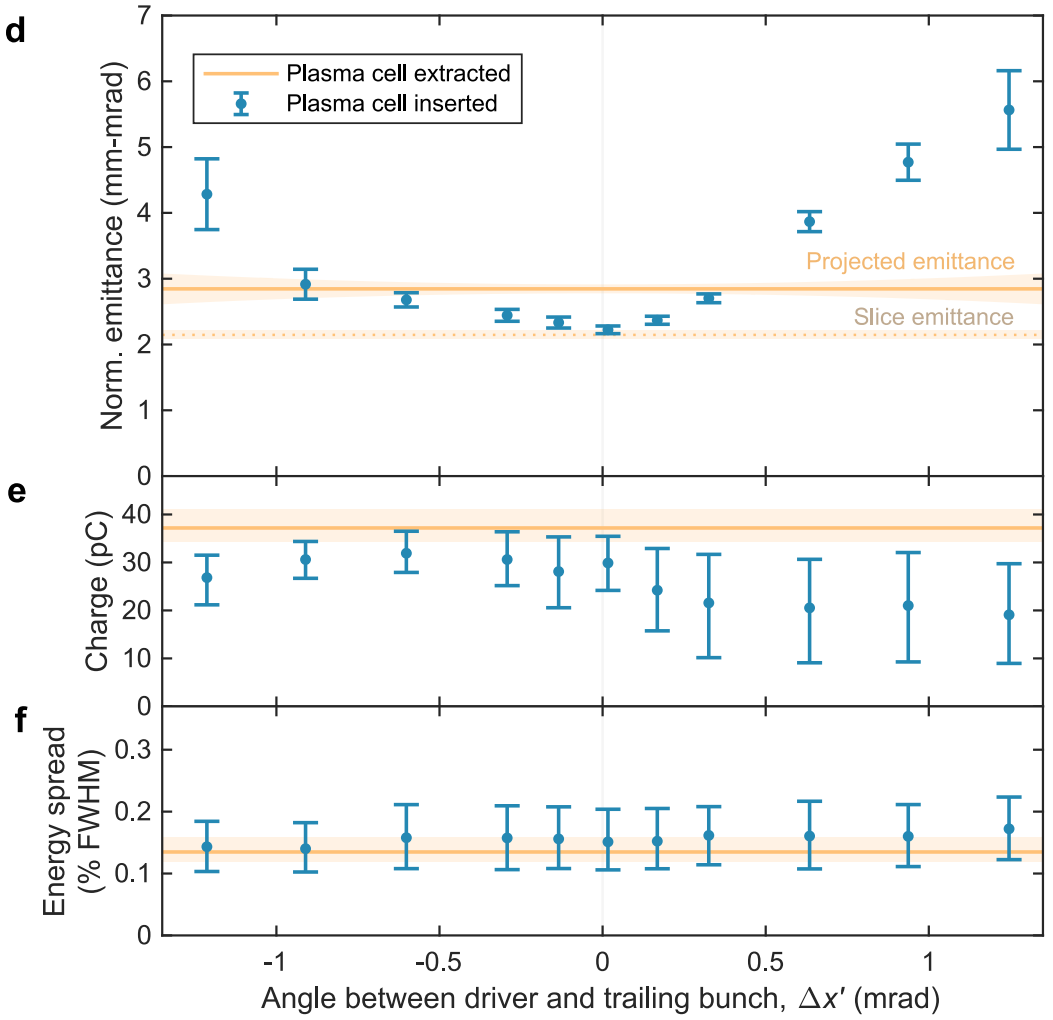
Steinke, et al. Nature '16

High-quality beam state-of-the-art

❖ FLASHForward PWFA facility



- Emittance, energy spread, charge preserved



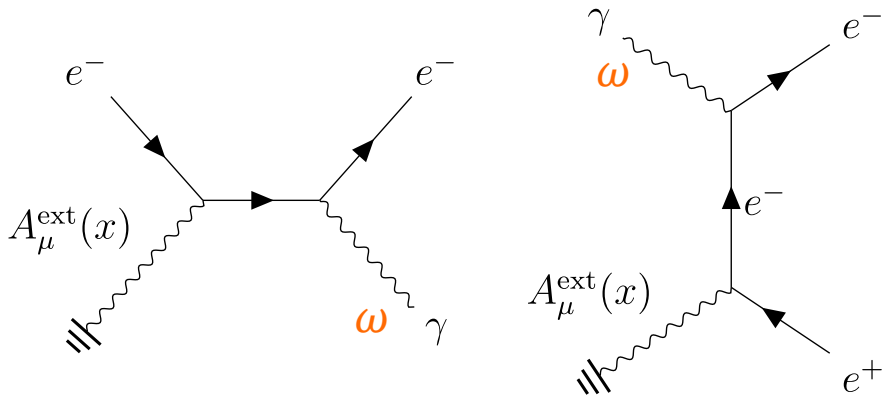
Lindstrøm, et al. Nat. Comm. '23

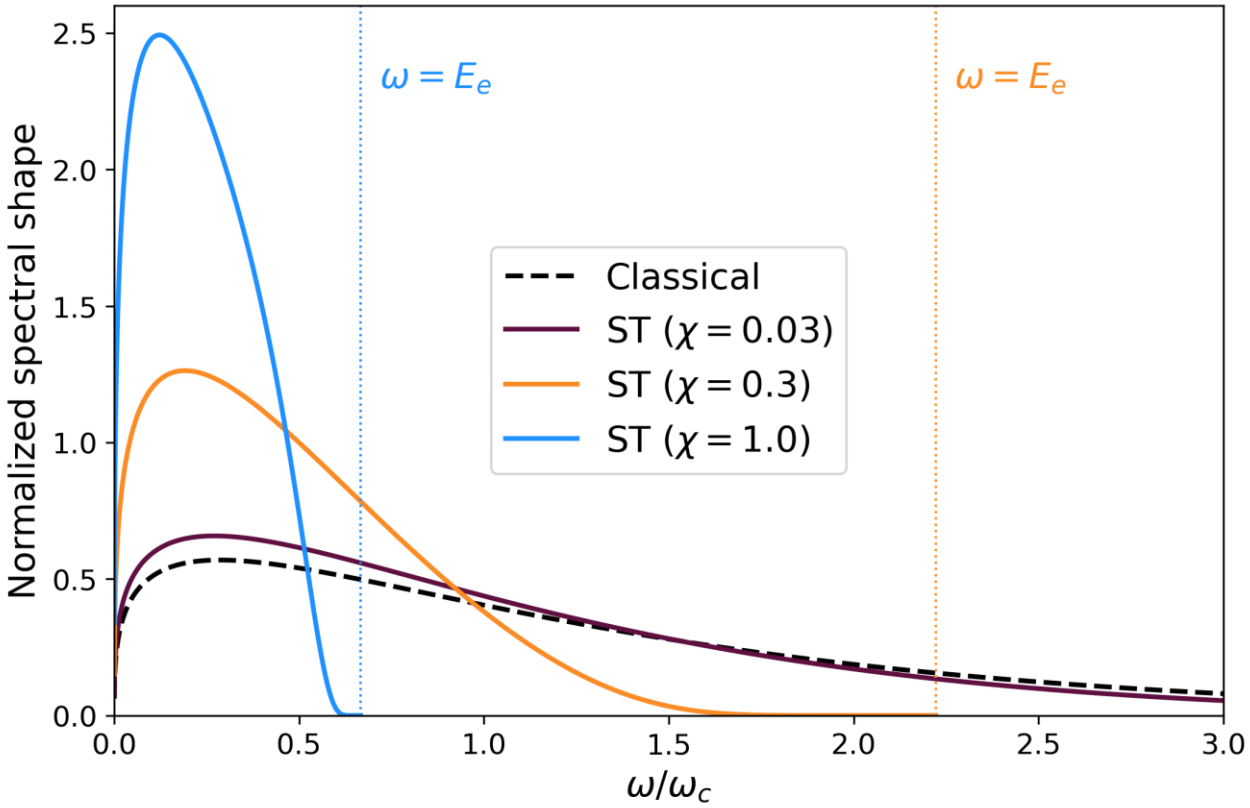
Quantum region of beamstrahlung

❖ Parameter of EM field strength

- $\Upsilon \equiv \frac{e}{m_e^3}\sqrt{\left|\left(F_{\mu\nu}p_e^{\nu}\right)^2\right|} = \frac{2\omega_c}{3E_e}$
- $\Upsilon \ll 1$: classical synchrotron
- $\Upsilon \gtrsim 1$: quantum

Sokolov-Ternov spectrum formula





❖ More compact beam, stronger field

- $\Upsilon_{\rm max} \simeq \frac{2\alpha N E_e}{m_e\sigma_z(\sigma_x+\sigma_y)} \sim \begin{cases} 10^{-6,-1}\ (\text{HLLHC, MuC}) \\ 10^{5}\ (\text{wakefield}) \end{cases}$

cf: $\chi \equiv (\omega/E_e)\Upsilon$ in strong QED

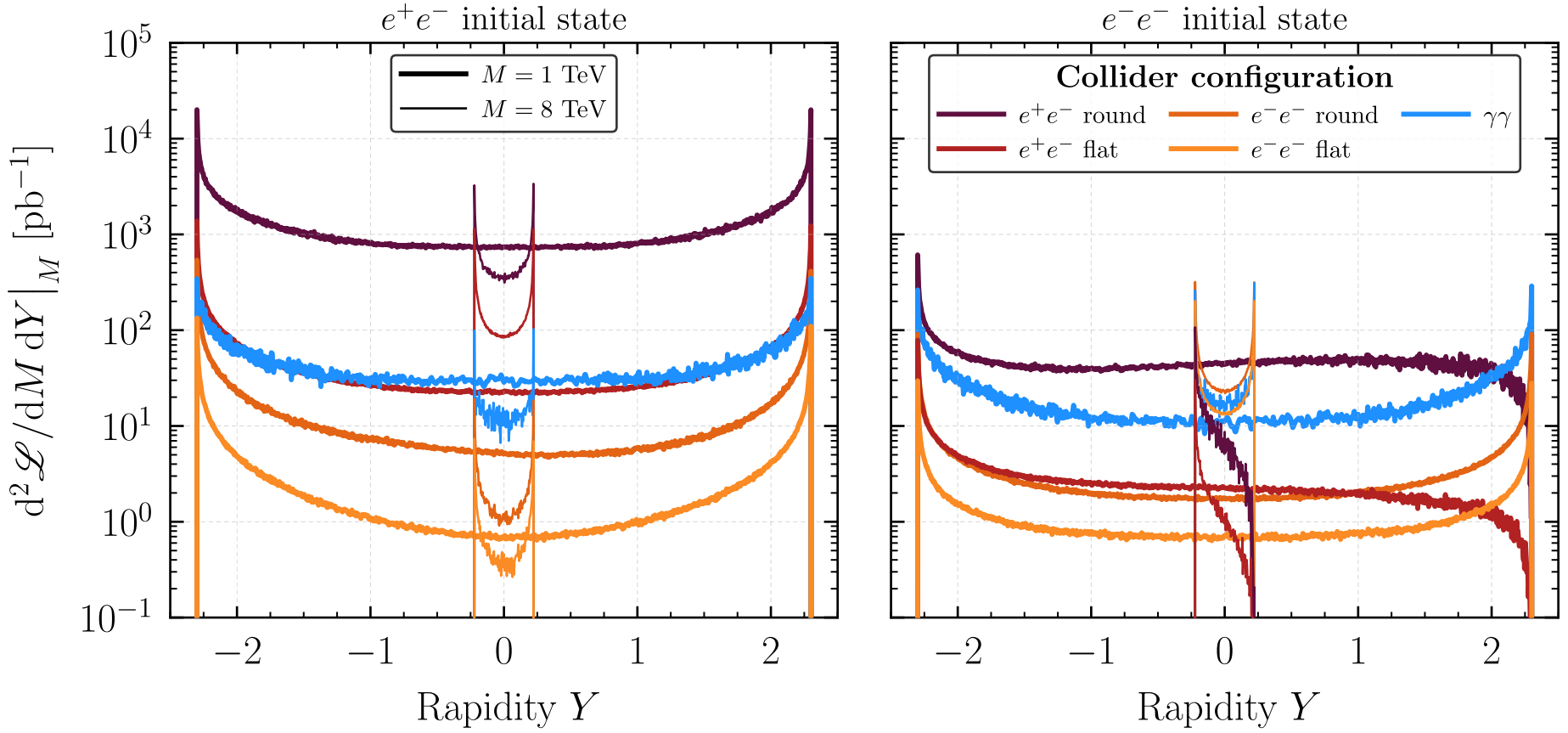
Yokaya & Chen '92

Q. Is 10 TeV wakefield collider really 10 TeV? A. Yes!

Collider configuration	Bunch size [nm] σ_x	σ_y	Integrated luminosity [pb^{-1}] $\mathscr{L}_{\rm int}^{0.95}$	$\mathscr{L}_{\rm int}^{0.20}$	$f_{0.20}$	$\mathscr{L}_{\rm int}^{0.01}$	$f_{0.01}$
e^+e^- round	1.55	1.55	1.5×10^7	1.2×10^6	8.0%	3.6×10^5	2.4%
e^+e^- flat	6	0.4	2.5×10^6	1.2×10^6	46.9%	6.5×10^5	25.9%
e^-e^- round	1.55	1.55	7.4×10^5	4.6×10^5	62.3%	2.6×10^5	35.4%
e^-e^- flat	6	0.4	6.8×10^5	5.2×10^5	75.5%	3.5×10^5	50.8%
$\gamma\gamma$ collider	[round e^-e^- initial beams with laser back-scattering]						
e^-e^-	1.55	1.55	4.0×10^5	6.8×10^4	16.8%	2.0×10^4	5.0%
$\gamma\gamma$			8.7×10^5	7.1×10^4	8.1%	5.0×10^2	0.06%

Longitudinal boost

❖ Collision between primary and secondary particles leads to large boost



Other new physics scenarios?

- Let's check production rates!
- Pair production cross section is large around prod threshold
- Then…
  - $e^+e^- > \gamma\gamma > e^-e^-$
  - Round ≳ Flat
  - Round beam is better for production despite the folklore

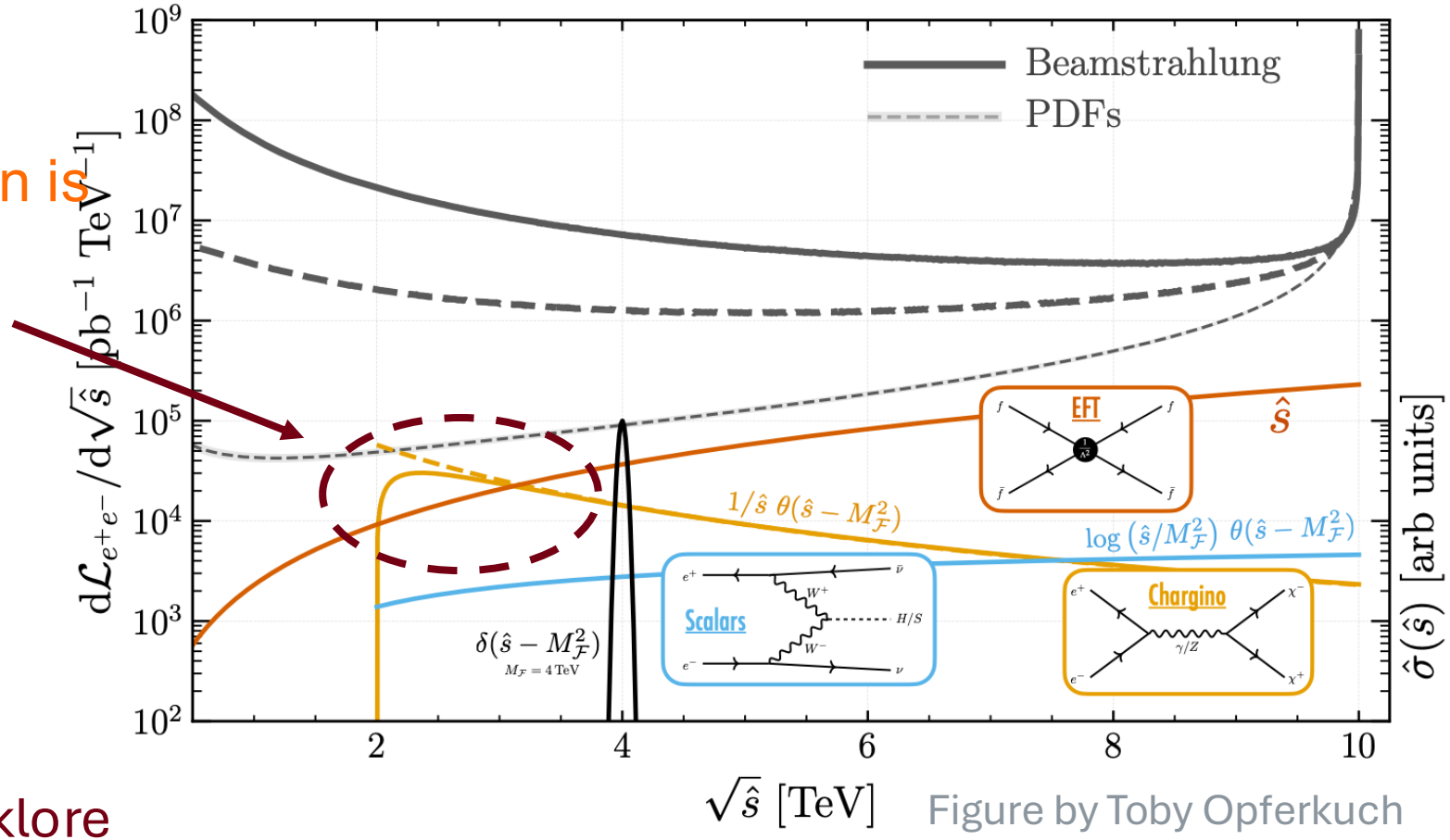
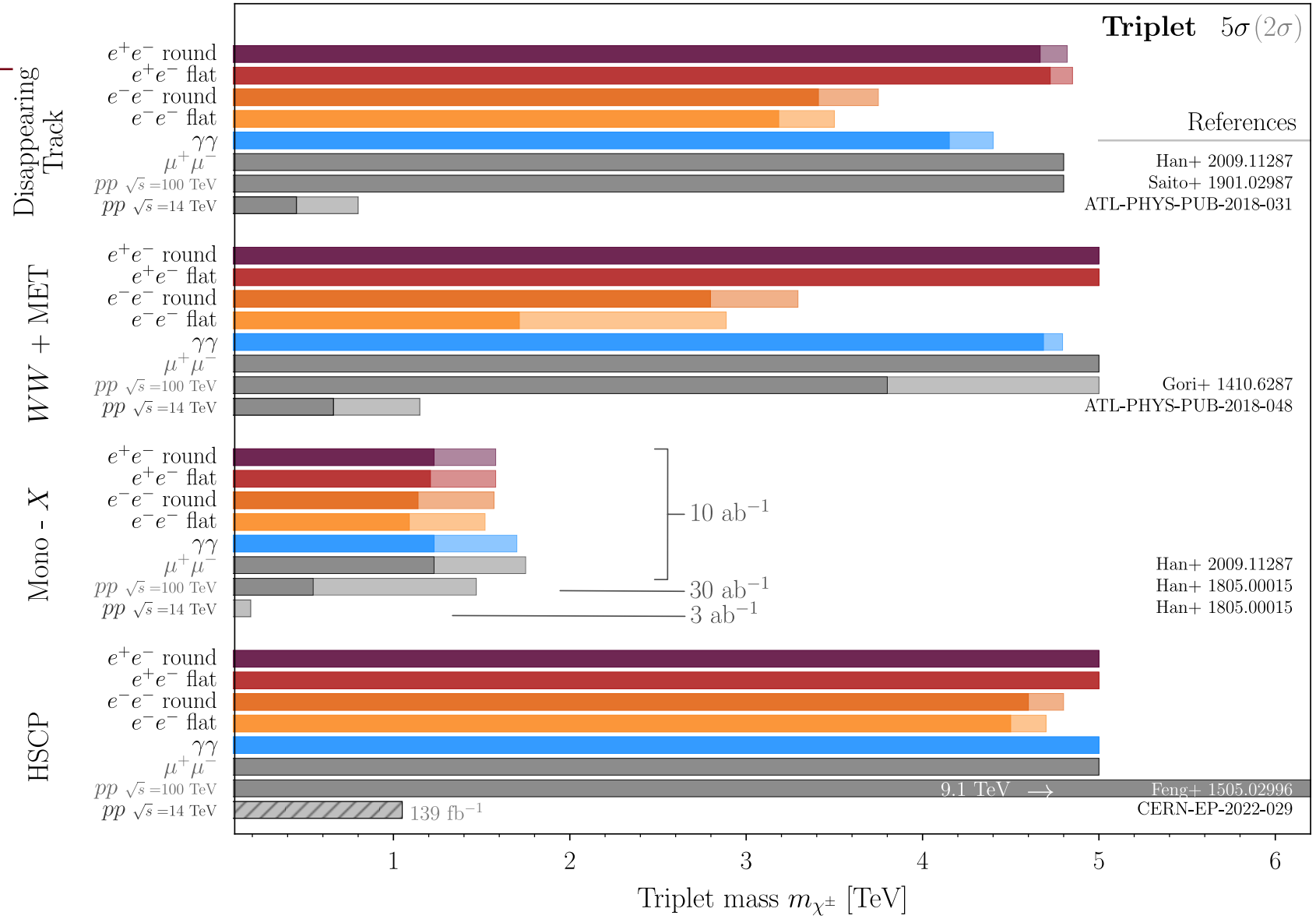
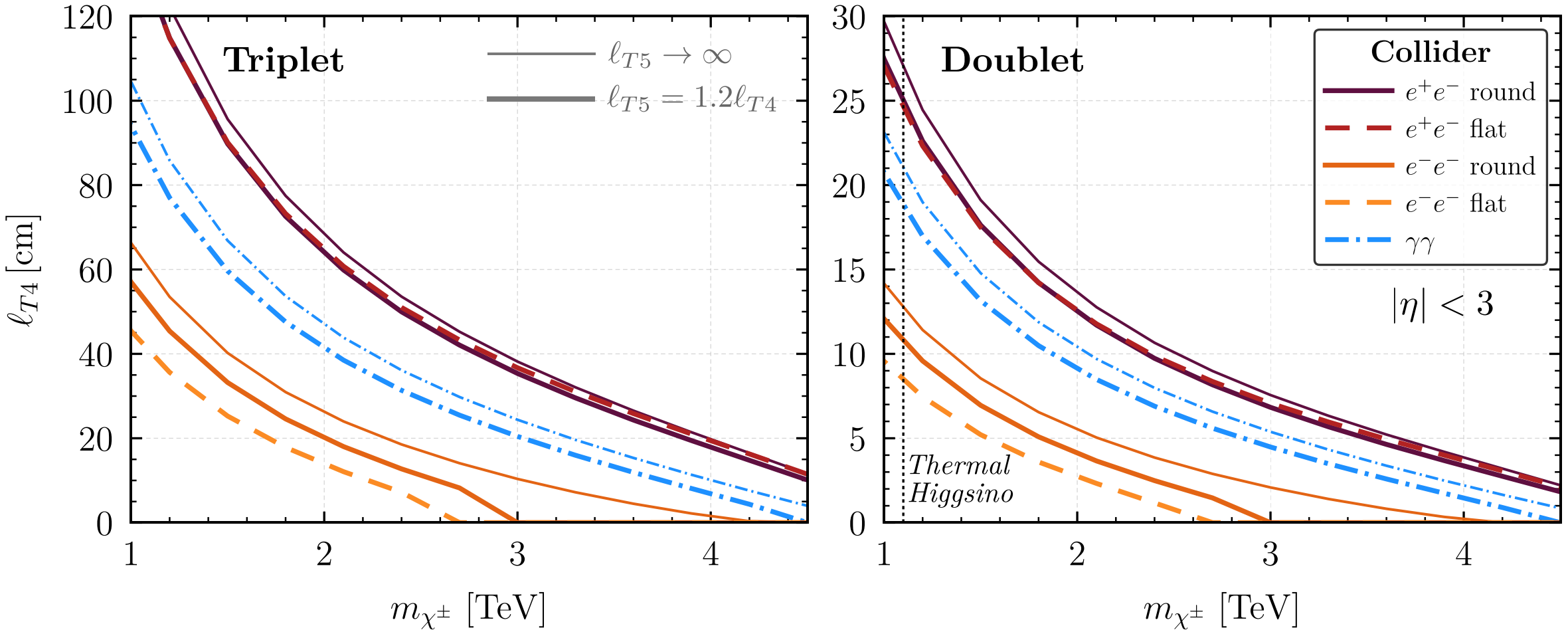


Figure by Toby Opferkuch

Comparison with other colliders

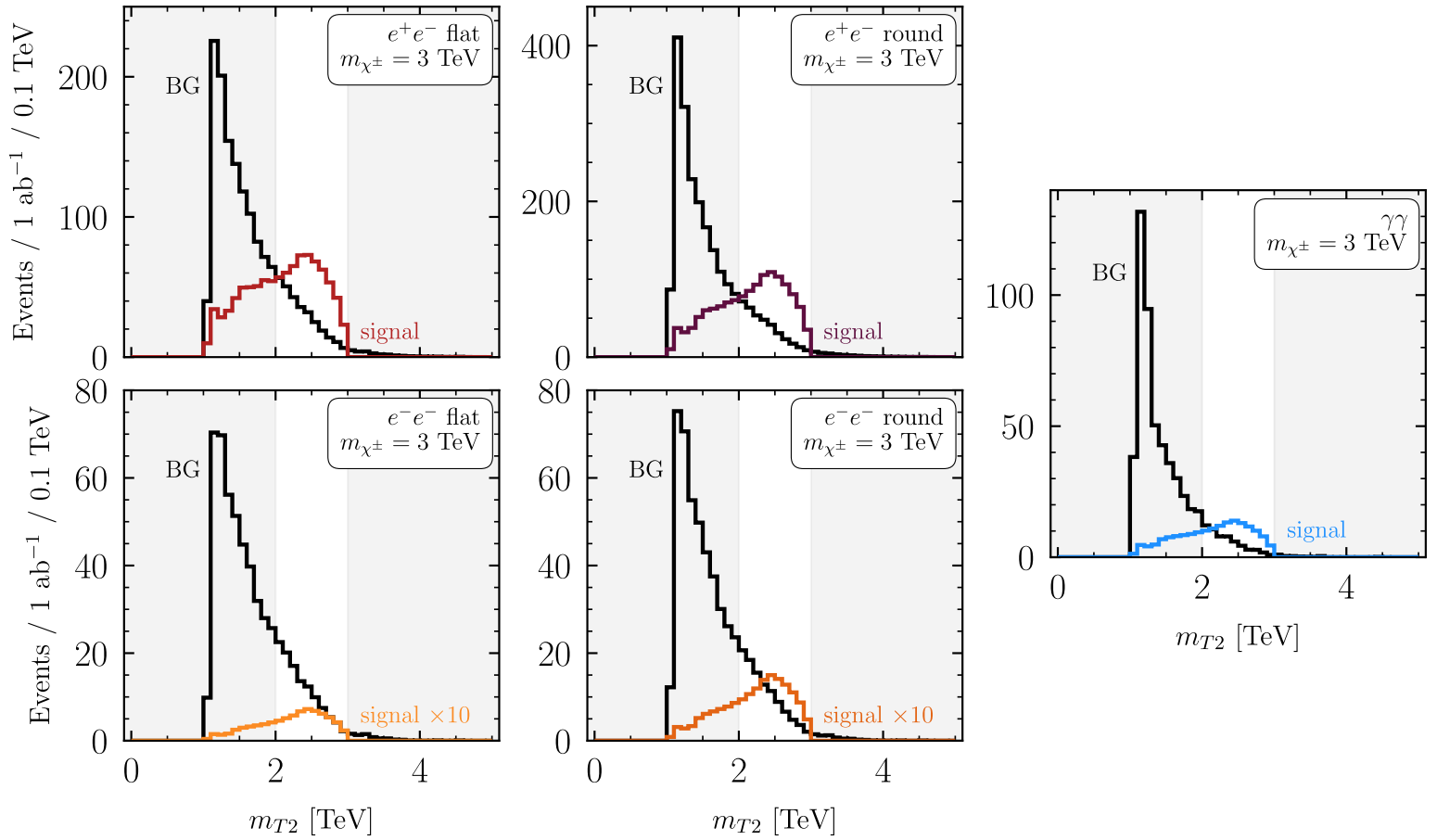


DT search implications to tracker design



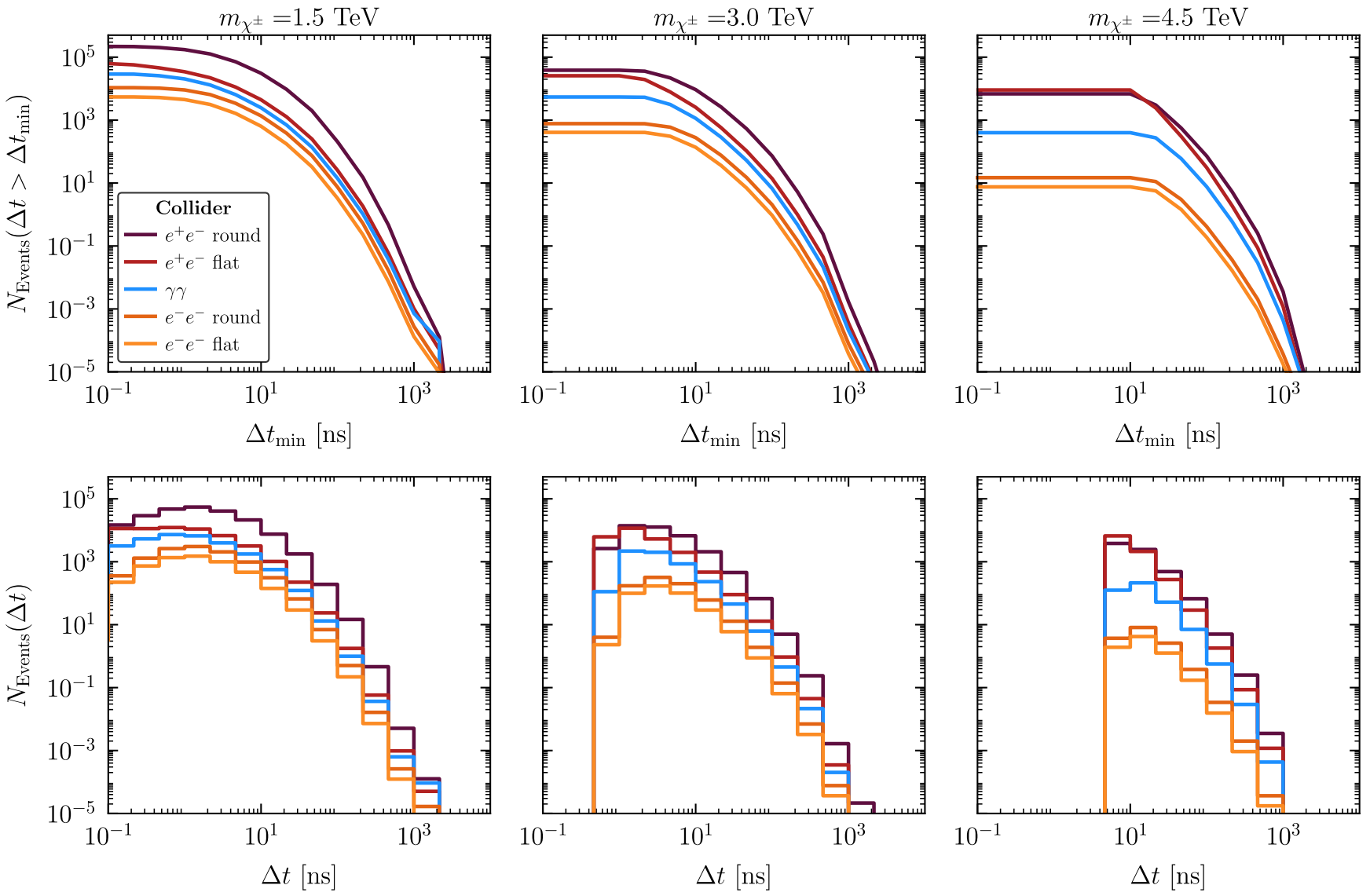
WW + MET search

❖ MET, H_T, M_{miss} & m_{T2} cuts works well to significantly reduce backgrounds



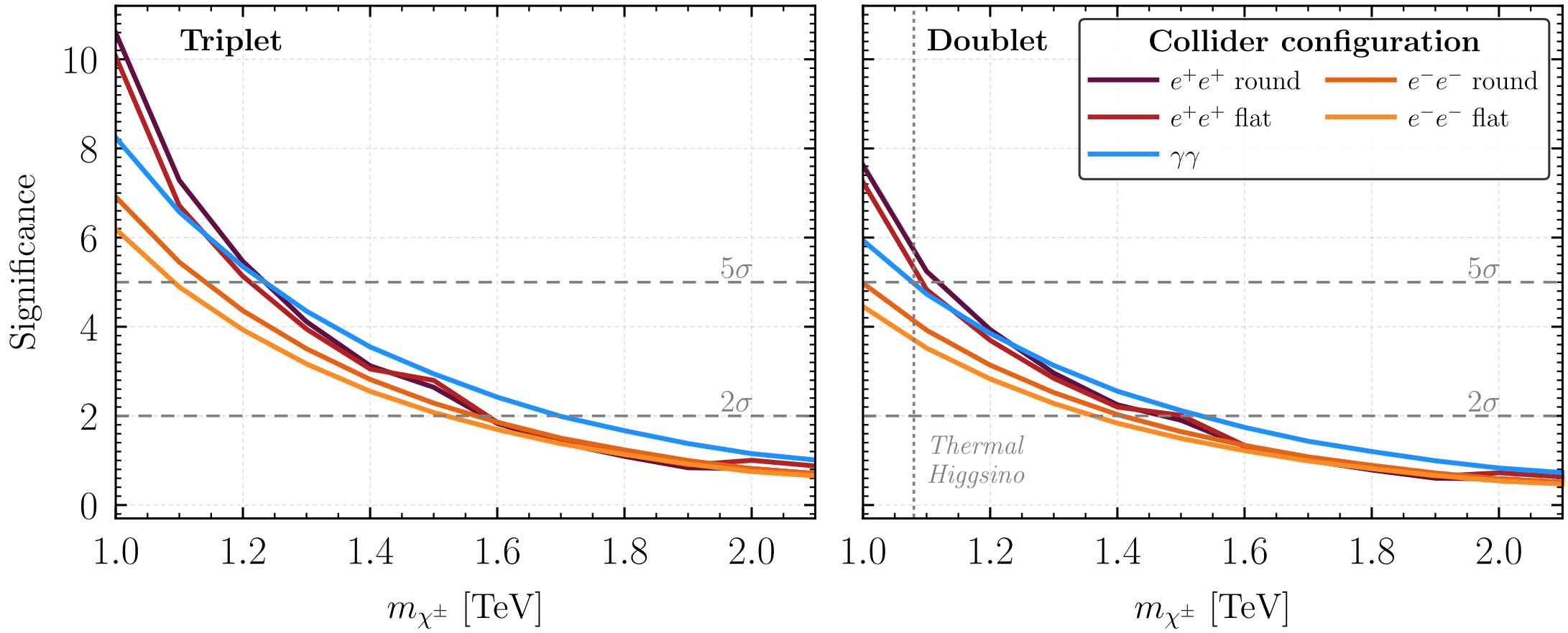
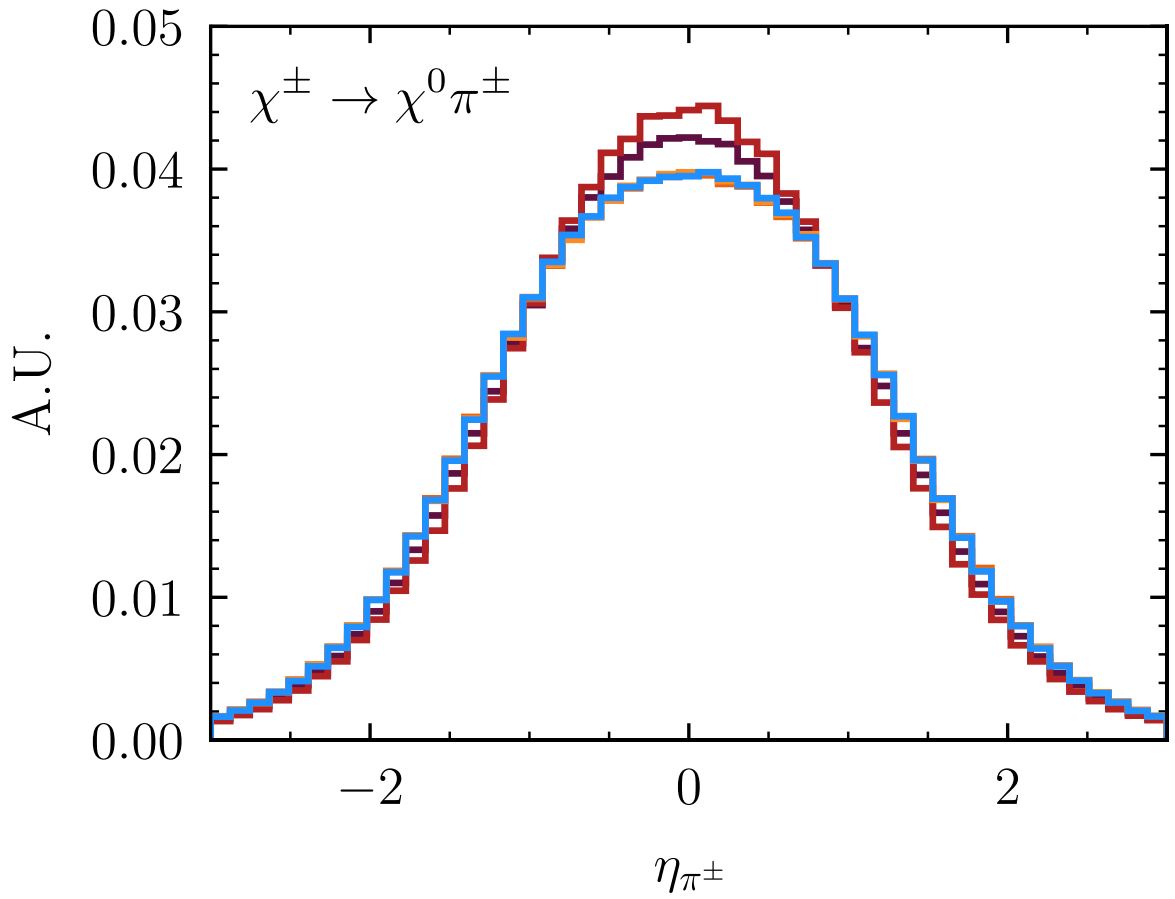
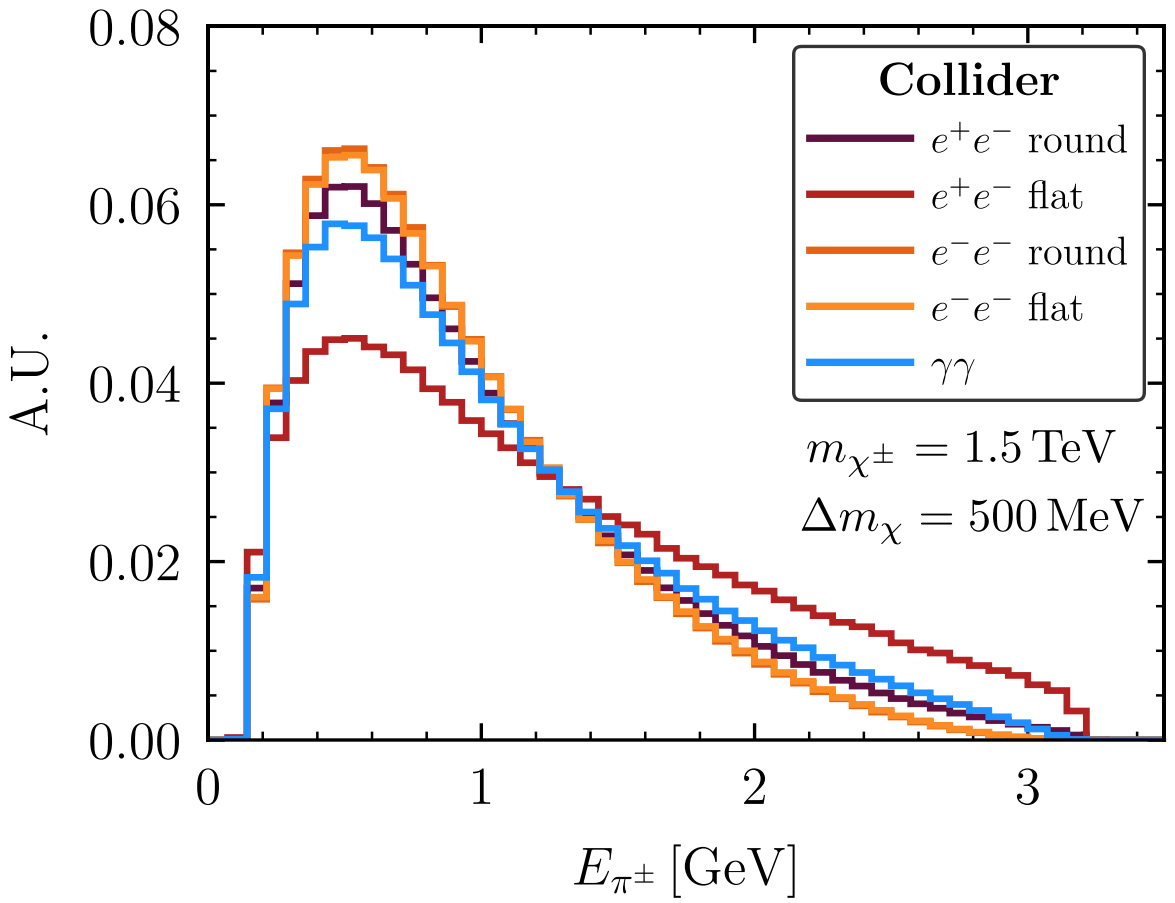
Massive stable charged particle search

- Timing resolution
  - $\Delta t \sim O(1)$ ns
  - $O(1)$ efficiency



Mono-$e^{\pm}$ search

❖ Binned analysis with $p_{T,\mathrm{miss}}$ and M_{miss} (still huge background)



Soft pion search