Tao Fest

TAO at future lepton colliders

Yang Ma
Centre for Cosmology, Particle Physics and Phenomenology (CP3)
Université catholique de Louvain (UCLouvain)
May 14, 2026

https://yangphy.github.io/

Once upon a time…

Once upon a time…

One week before the Spring Festival, 2016

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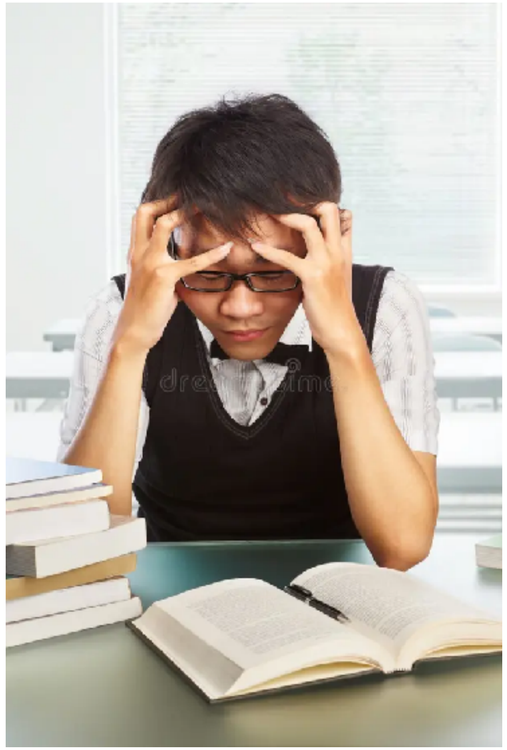
One week before the Spring Festival, 2016

万家灯火，一人愁

I was waiting for a PhD offer



KU COLLEGE OF LIBERAL ARTS & SCIENCES
The University of Kansas

January 29, 2016

Dear Yang

Congratulations! The Admissions Committee of the Physics and Astronomy Department has reviewed your application materials, and we are pleased to inform you, your application to the graduate program has been approved by the Department. Admission has been recommended to Graduate Studies, and you will receive official notification from them. Please take time to review the Graduate Studies General Policies and standards.

We would like to offer you a Graduate Teaching Assistantship (GTA) on behalf of the Department of Physics and Astronomy. This appointment will be for 20 hours a week, a 50% appointment. Tuition is waived for GTAs with appointments of 40% or more, but you must pay a portion of the required campus fees, which is approximately $280 per semester.

This offer of support is for the 2016-17 academic year. We anticipate this level of support for up to four Semesters total, not including Summer Sessions. The offer is subject to availability of funding, and it is contingent upon your continued eligibility to hold a GTA position. The amount of the stipend will be at least $9,100 per Semester. Eligibility requirements include but are not limited to being in good academic standing and making satisfactory progress toward a graduate degree, as determined by the Office of Graduate Studies as well as the department in which you are enrolled. For a list of policies specific to GTAs and Graduate Research Assistants (GRAs) please refer to the Graduate Studies guidelines. The continuation of support will also be based on adequate performance of duties assigned.

In addition to the GTA position, the Admissions Committee has selected you as a nominee for two very prestigious scholarship opportunities: the Dorothy Clark Lettice Scholarship and the John H. Nelson Scholarship. The nominations have already been submitted on your behalf, so there is no additional action required from you. As these are just nominations, we cannot guarantee you will be granted the awards, but please know that your nomination alone speaks to

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IL: Yes, that is my Ph.D. supervisor at Madison

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YM: So this is your “academic father?”

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IL: Yes, that is my Ph.D. supervisor at Madison

YM: So this is your “academic father?”

IL: Exactly!

YM: How is this guy?

IL: Good!!!!

Three days after the Spring Festival

Three days after the Spring Festival

University of Pittsburgh

Kenneth P. Dietrich School of Arts and Sciences
Department of Physics and Astronomy

100 Allen Hall
3941 O'Hara Street
Pittsburgh, PA 15260
412-624-9000
Fax: 412-624-9163
www.physicsandastronomy.pitt.edu

February 11, 2016

Mr. Yang Ma
Rm302, Apartment 5, Lanyuan
Huxi Campus, Chongqing University
Chongqing, 401331401331
CHINA

Dear Mr. Ma,

Congratulations! I am pleased to inform you that the Graduate Admissions Committee of the Department of Physics and Astronomy has recommended your admission to the Graduate Program at the University of Pittsburgh beginning with the fall 2016 term. Details of the financial support package are described in the attached letter from our Chairperson, Adam Leibovich.

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Sorry, Ian!

my academic brother

I am going to Pittsburgh

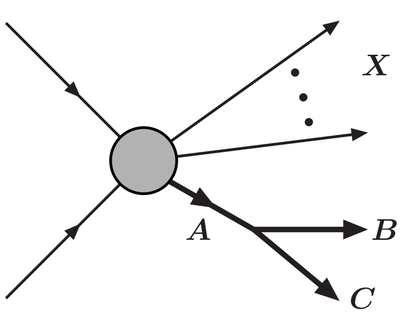
EW radiations at high energies

Electroweak Splitting Functions and High Energy Showering 1611.00788

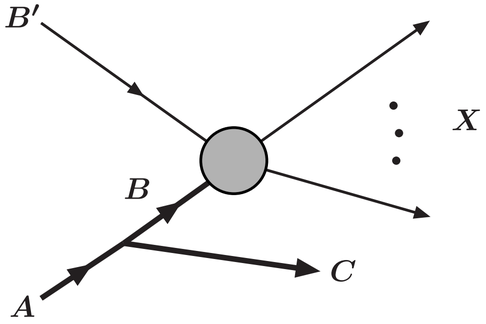
Junmou Chen, Tao Han and Brock Tweedie

Pittsburgh Particle physics, Astrophysics, and Cosmology Center, Department of Physics and Astronomy, University of Pittsburgh, 3941 O'Hara St., Pittsburgh, PA 15260, USA

E-mail: juc44@pitt.edu, than@pitt.edu, bat42@pitt.edu



$$d\sigma_{X,BC} \simeq d\sigma_{X,A} \times d\mathcal{P}_{A\to B+C}$$



$$d\sigma_{AB'\to CX} \simeq d\mathcal{P}_{A\to B+C} \times d\sigma_{BB'\to X}$$

When $Q > Q_{EW}$, EW splittings show up

Towards future muon colliders

PHYSICAL REVIEW D **103,** L031301 (2021)

Letter

2007.14300

High energy leptonic collisions and electroweak parton distribution functions

Tao Han,* Yang Ma,† and Keping Xie‡

PITT PACC, Department of Physics and Astronomy, University of Pittsburgh, 3941 O'Hara Street, Pittsburgh, Pennsylvania 15260, USA

$$\sigma(\ell^+\ell^- \to F + X) = \int_{\tau_0}^1 d\tau \sum_{ij} \frac{d\mathcal{L}_{ij}}{d\tau} \hat{\sigma}(ij \to F),$$

$$\frac{d\mathcal{L}_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_\tau^1 \frac{d\xi}{\xi} \left[f_i(\xi, Q^2) f_j\left(\frac{\tau}{\xi}, Q^2\right) + (i \leftrightarrow j) \right]$$

(Received 28 August 2020; revised 16 November 2020; accepted 26 January 2021; published 18 February 2021)

In high-energy leptonic collisions well above the electroweak scale, the collinear splitting mechanism of the electroweak gauge bosons becomes the dominant phenomena via the initial state radiation and the final state showering. We point out that at future high-energy lepton colliders, such as a multi-TeV muon collider, the electroweak parton distribution functions (EW PDFs) should be adopted as the proper description for partonic collisions of the initial states. The leptons and electroweak gauge bosons are the EW partons, that evolve according to the unbroken Standard Model (SM) gauge group and that effectively resum potentially large collinear logarithms. We present a formalism for the EW PDFs at the leading-log (LL) accuracy. We calculate semi-inclusive cross sections for some important SM processes at a future multi-TeV muon collider. We conclude that it is appropriate to adopt the EW PDF formalism for future high-energy lepton colliders.

Towards future muon colliders

2005.10289

Vector boson fusion at multi-TeV muon colliders

Antonio Costantini,[a] Federico De Lillo,[b] Fabio Maltoni,[b,c] Luca Mantani,[b,d] Olivier Mattelaer,[b] Richard Ruiz[b] and Xiaoran Zhao[b]

[a] *INFN, Sezione di Bologna, via Irnerio 46, I-40126 Bologna, Italy*

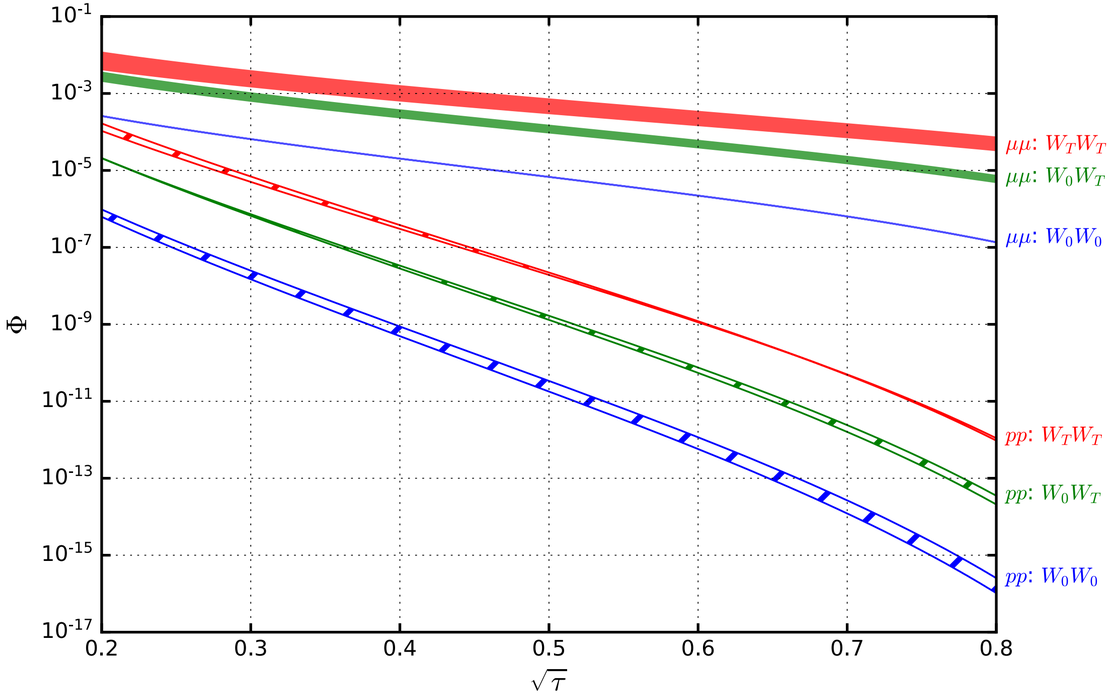
[b] *Centre for Cosmology, Particle Physics and Phenomenology* (CP3), *Université Catholique de Louvain, Chemin du Cyclotron, B-1348 Louvain la Neuve, Belgium*

[c] *Dipartimento di Fisica e Astronomia, Università di Bologna e INFN, Sezione di Bologna, via Irnerio 46, I-40126 Bologna, Italy*

[d] *Institut für Theoretische Physik, Universität Heidelberg, Germany*

E-mail: antonio.costantini@bo.infn.it, federico.delillo@uclouvain.be, fabio.maltoni@uclouvain.be, luca.mantani@uclouvain.be, olivier.mattelaer@uclouvain.be, richard.ruiz@uclouvain.be, xiaoran.zhao@uclouvain.be

“MuC is a VBF machine”



Towards future muon colliders

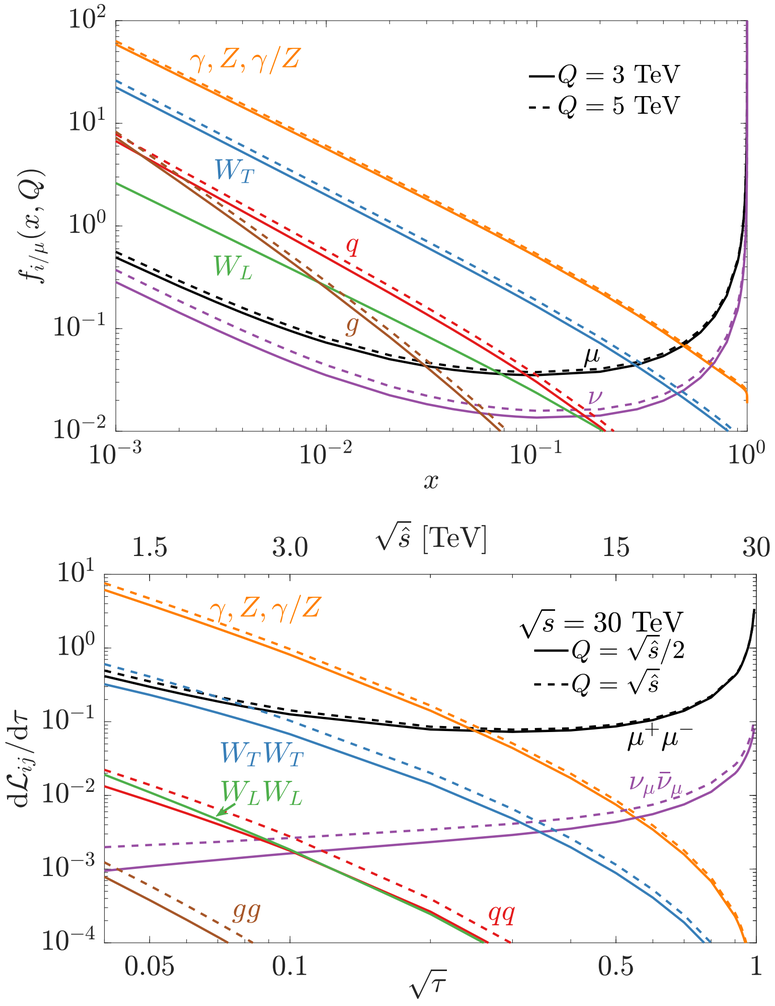
“This is my way to complete a project:
Once we decide on what to do, we rush it out without sleep!”

Towards future muon colliders

“This is my way to complete a project:
Once we decide on what to do, we rush it out without sleep!”

“Yang, you need to take some rest!”

The partonic picture of multi-TeV muC



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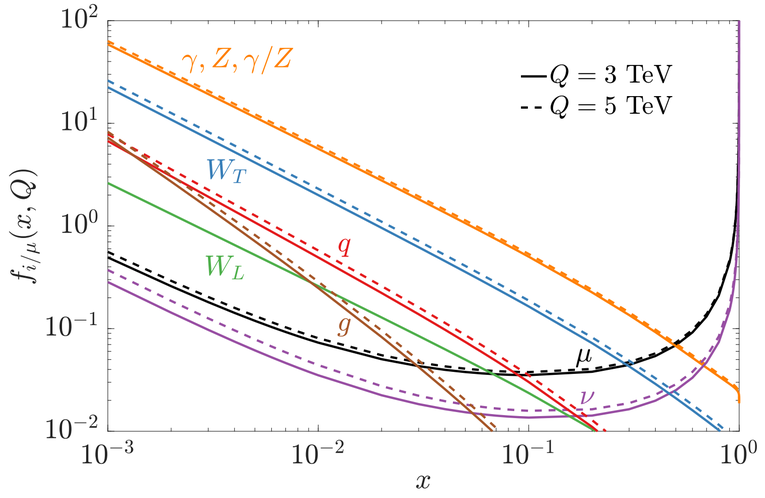

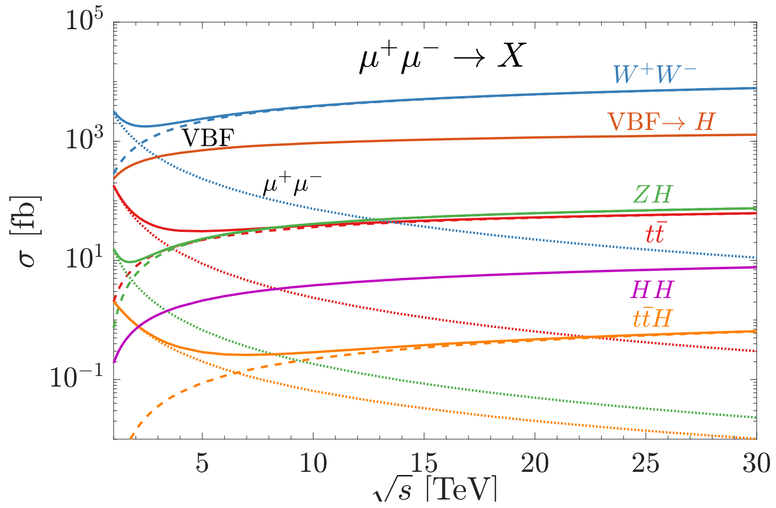

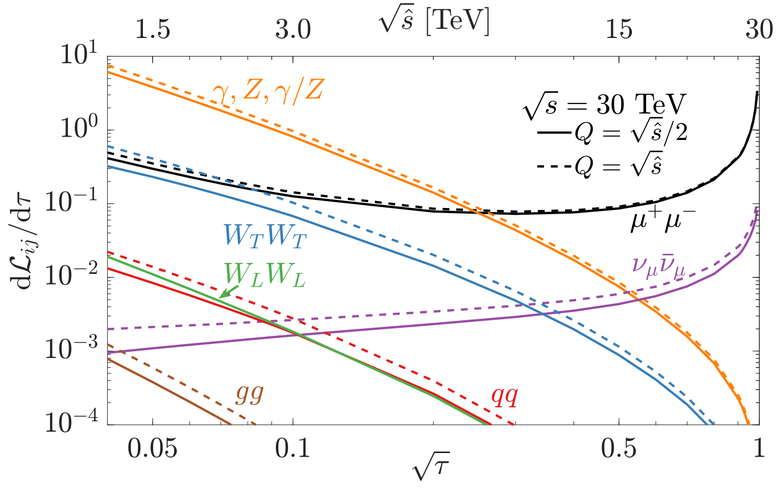

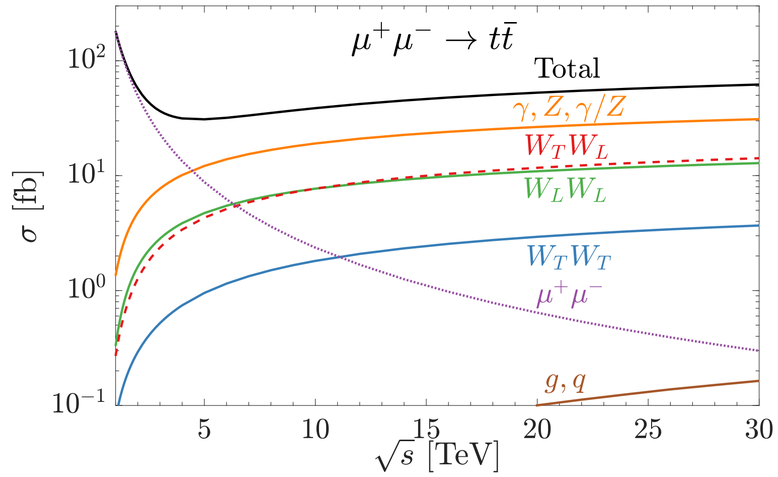

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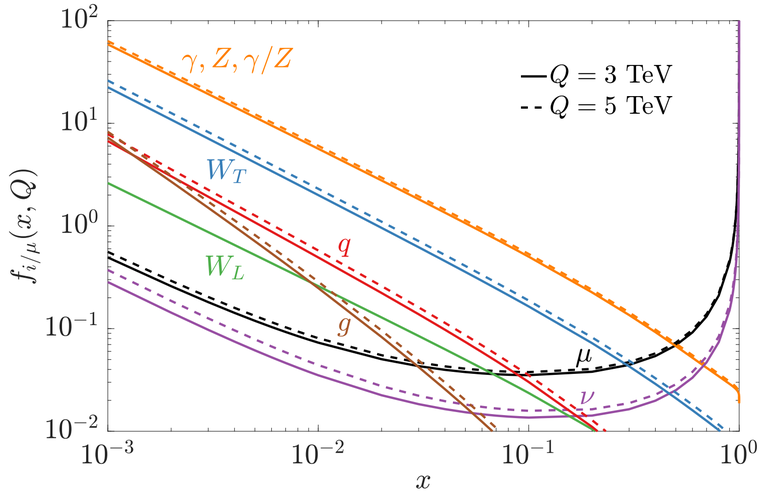
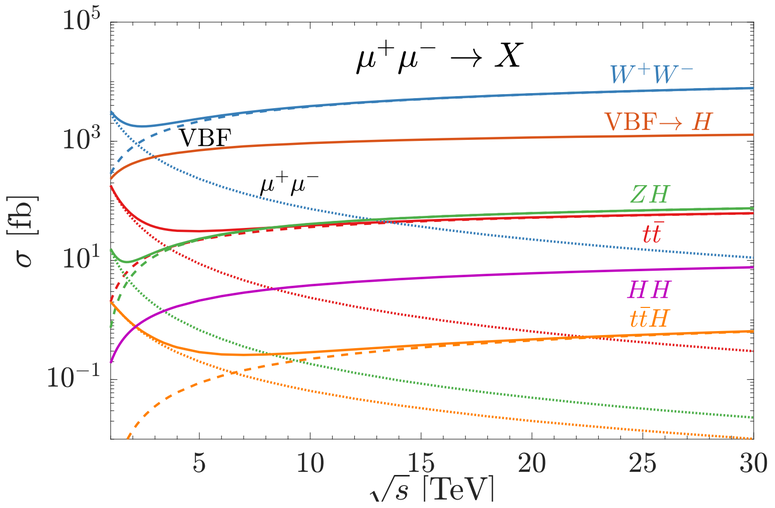
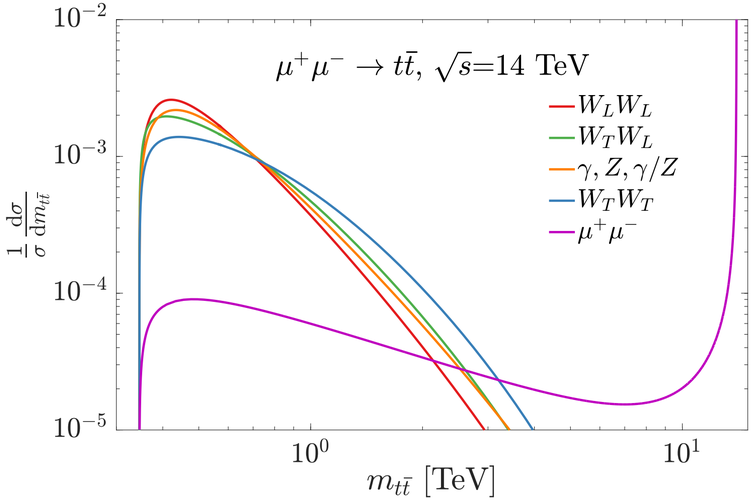
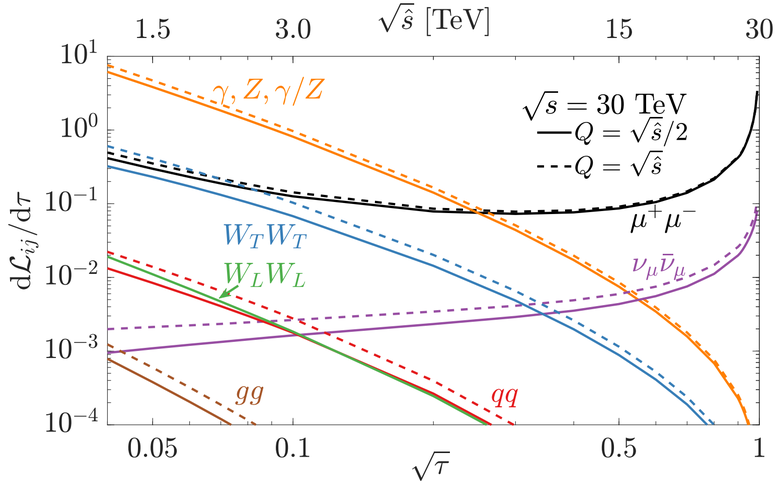
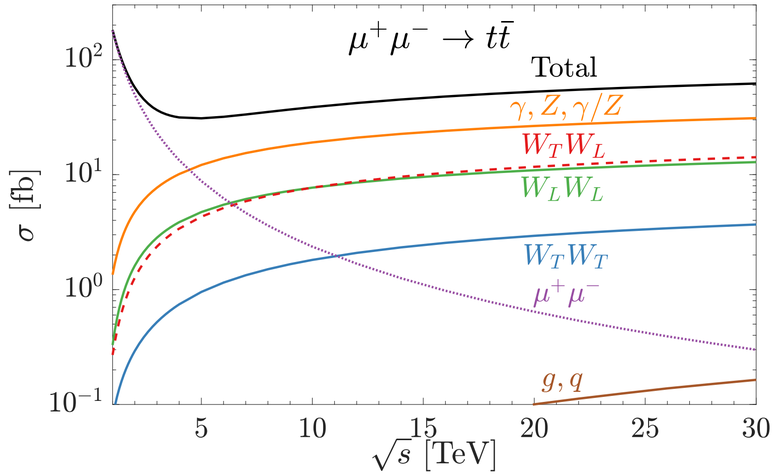
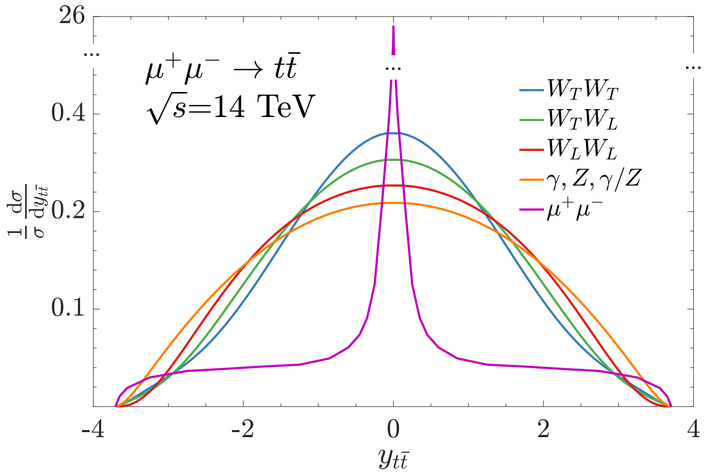












Colored partons in leptons

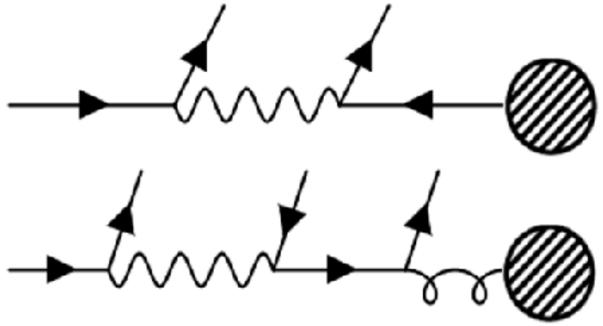
Quark and gluon contents of a lepton at high energies

2103.09844

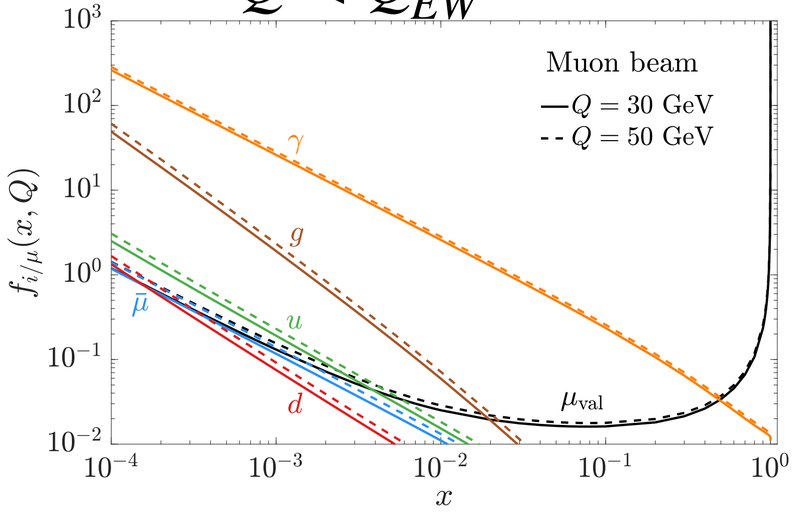
Tao Han, Yang Ma and Keping Xie

Pittsburgh Particle Physics, Astrophysics and Cosmology Center,
Department of Physics and Astronomy, University of Pittsburgh,
3941 O'Hara St, Pittsburgh, PA 15260, U.S.A.

E-mail: than@pitt.edu, mayangluon@pitt.edu, xiekeping@pitt.edu



$Q < Q_{EW}$



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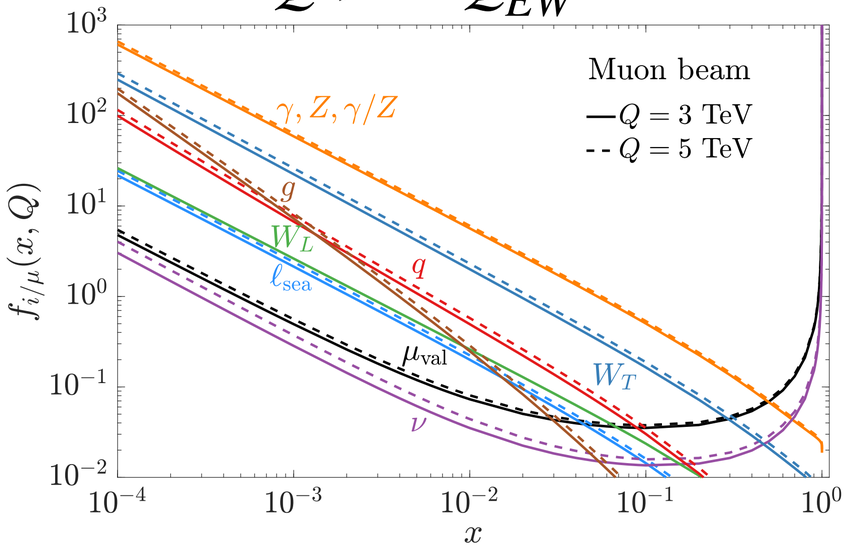
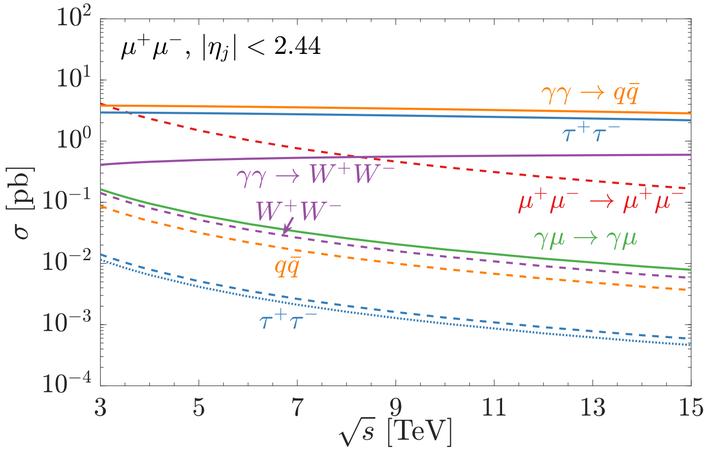
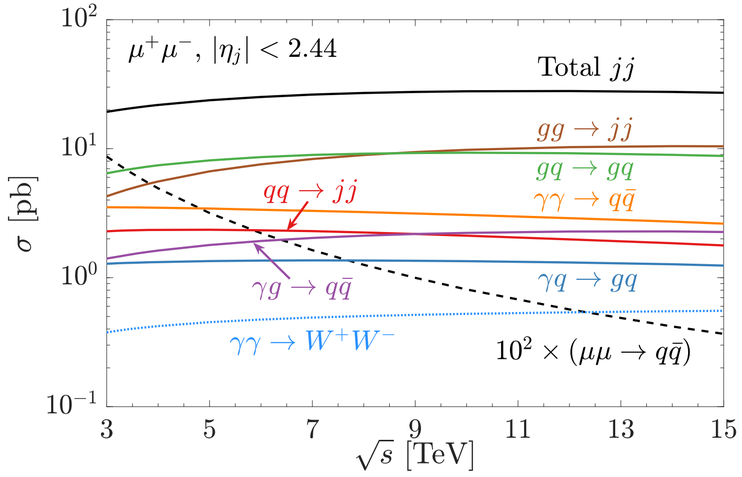


The SM exception at muC





$$p_T^j > \left(4 + \frac{\sqrt{s}}{3\ \text{TeV}}\right)\ \text{GeV},$$

$$m_{ij} > 20\,\text{GeV}, \quad |\eta_j| < 3.13\ (2.44)$$

$$\gamma\gamma \to q\bar{q}, \qquad \gamma g \to q\bar{q}, \qquad \gamma q \to gq,$$
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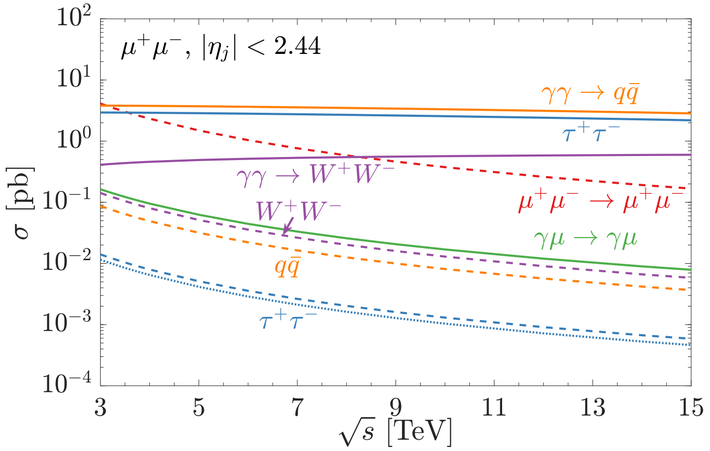

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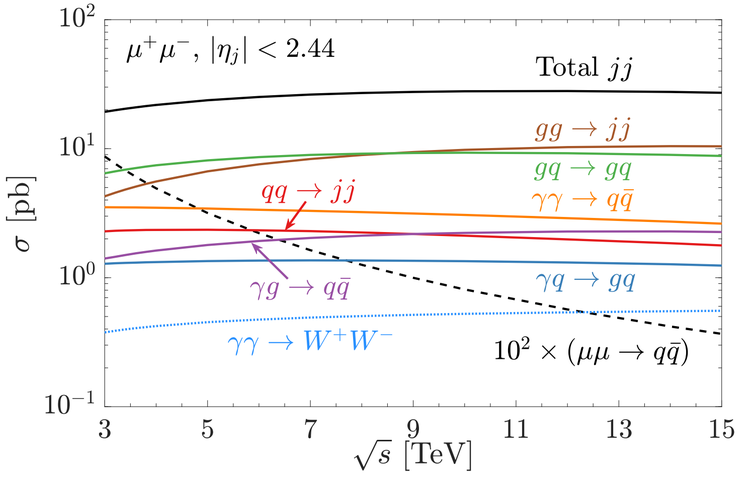

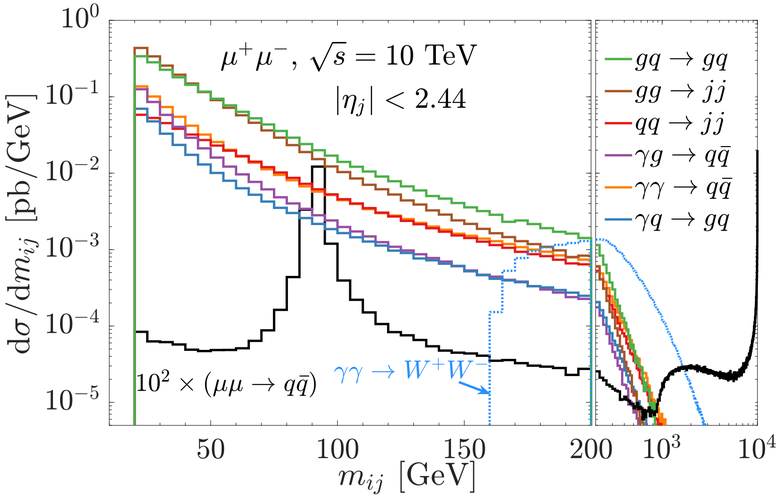

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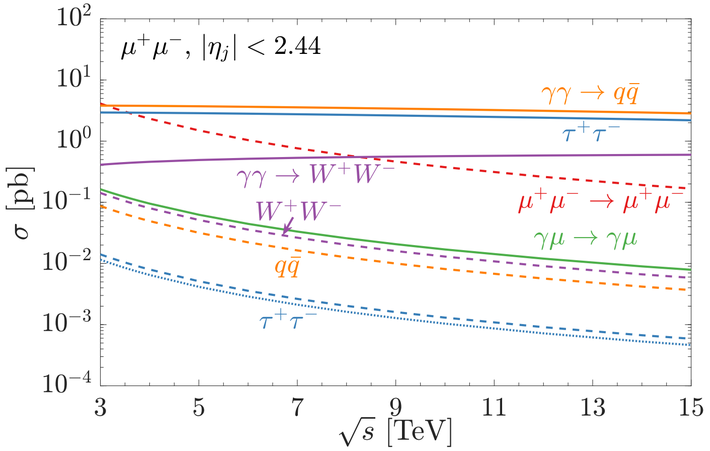

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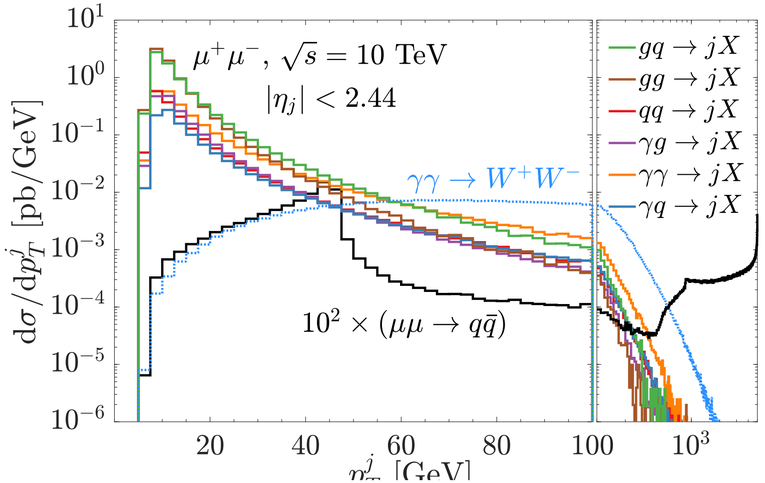

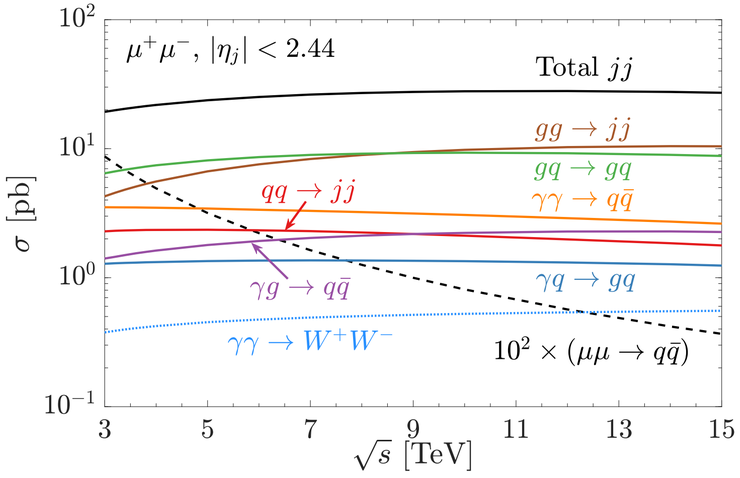

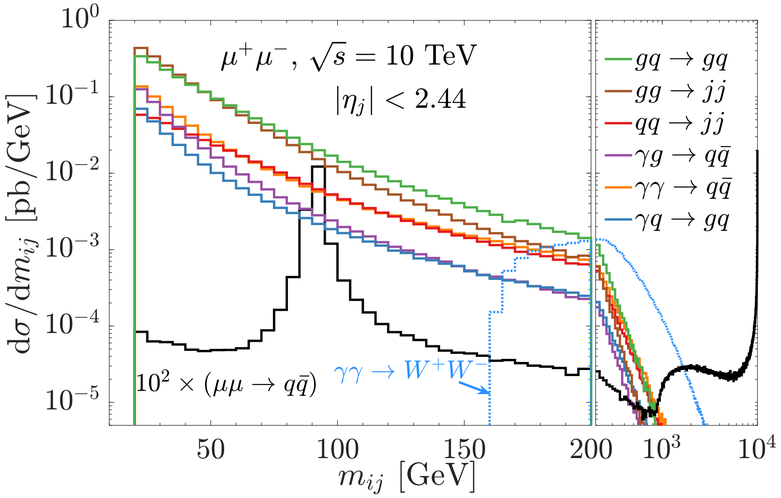

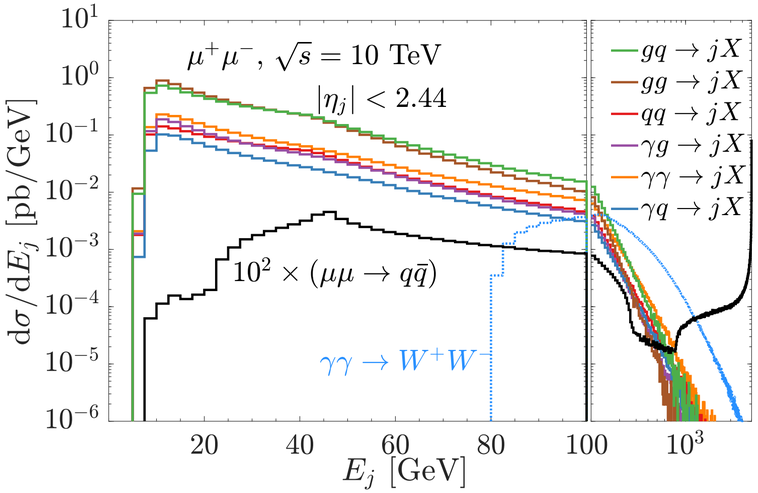

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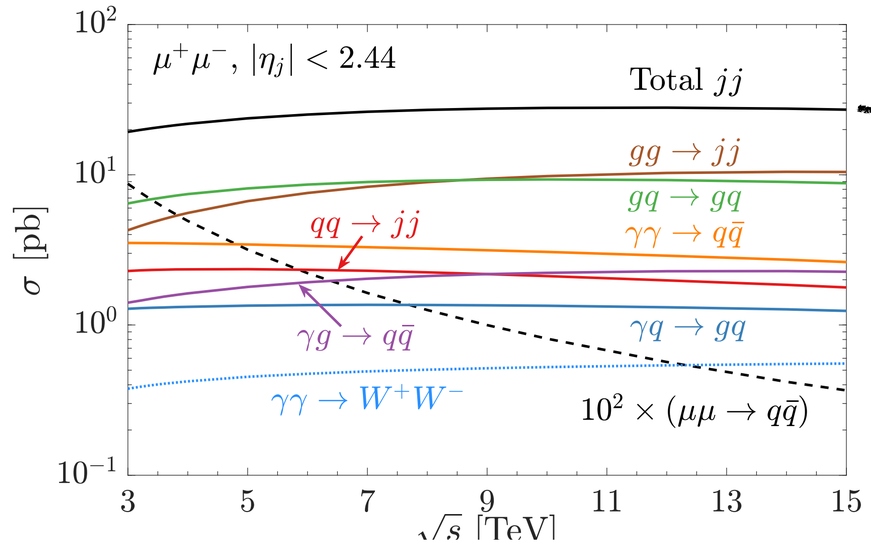

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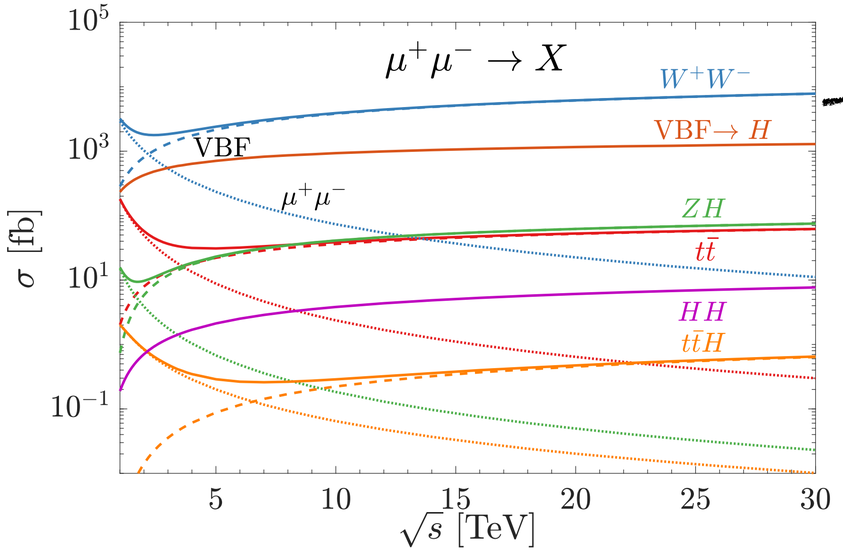
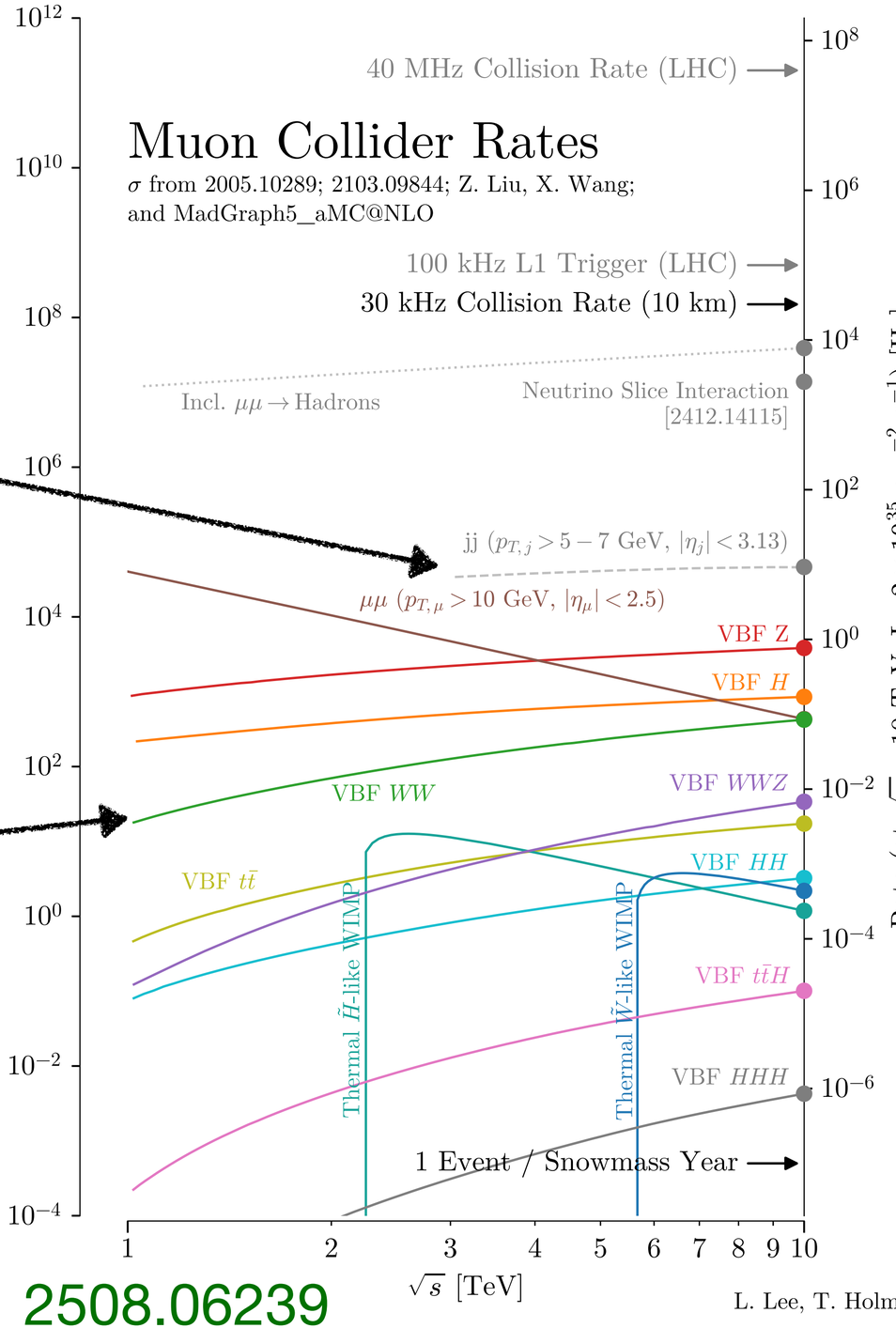




2508.06239

L. Lee, T. Holmes

The partonic picture at high-energy lepton colliders

"MuC is an EW version of LHC"

Yang Ma

Pittsburgh Partcile-physics, Astrophysics, and Cosmology Center,
Department of Physics and Astronomy,
University of Pittsburgh, PA 15260, USA

April 28, 2021

SLAC

In collaboration with **Tao Han** and **Keping Xie**

[T. Han, Y. Ma, K.Xie 2007.14300]

[T. Han, Y. Ma, K.Xie 2103.09844]

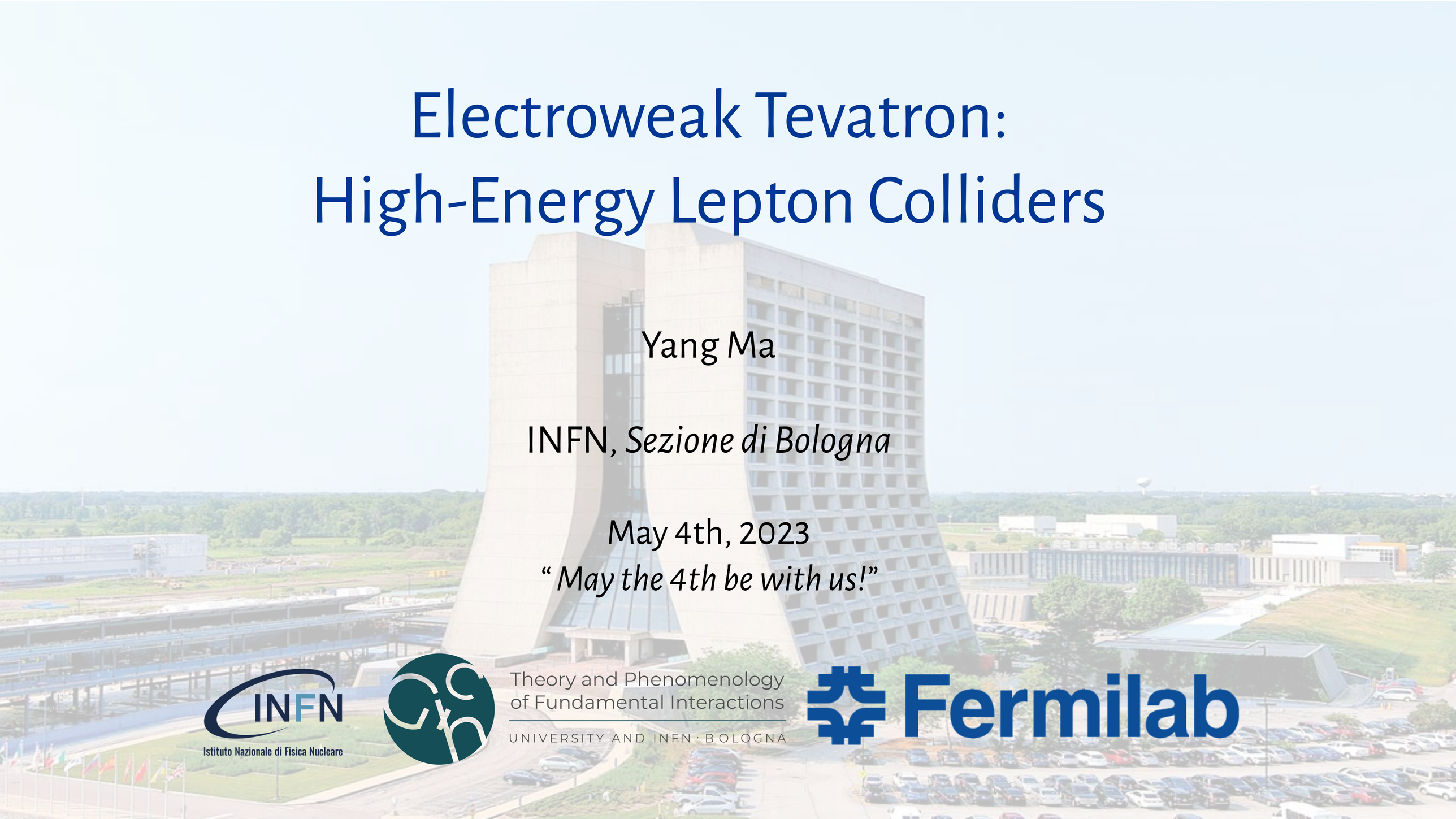
Electroweak Tevatron: High-Energy Lepton Colliders

Yang Ma

INFN, *Sezione di Bologna*

May 4th, 2023

“May the 4th be with us!”



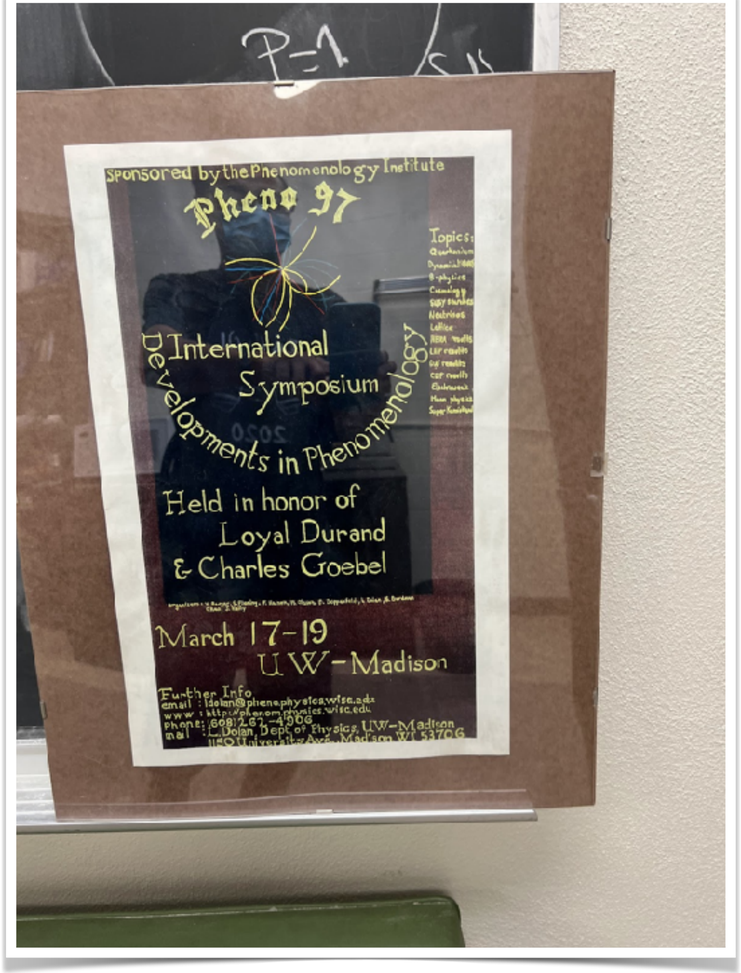
2022 at Pitt

“Do you drink beer?”

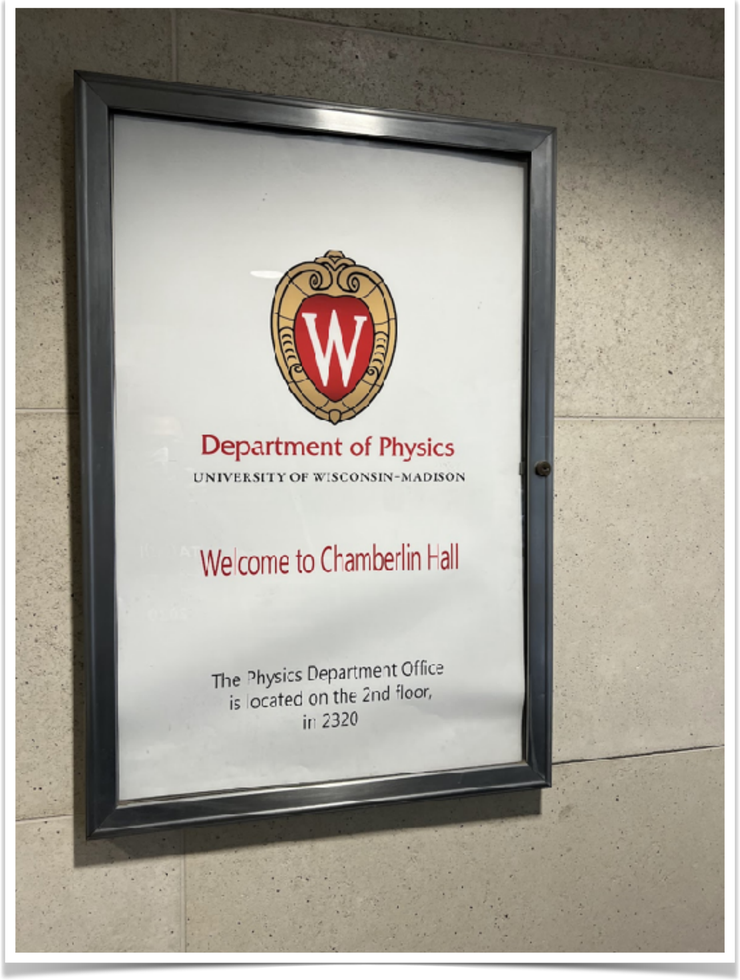
“I can learn!”

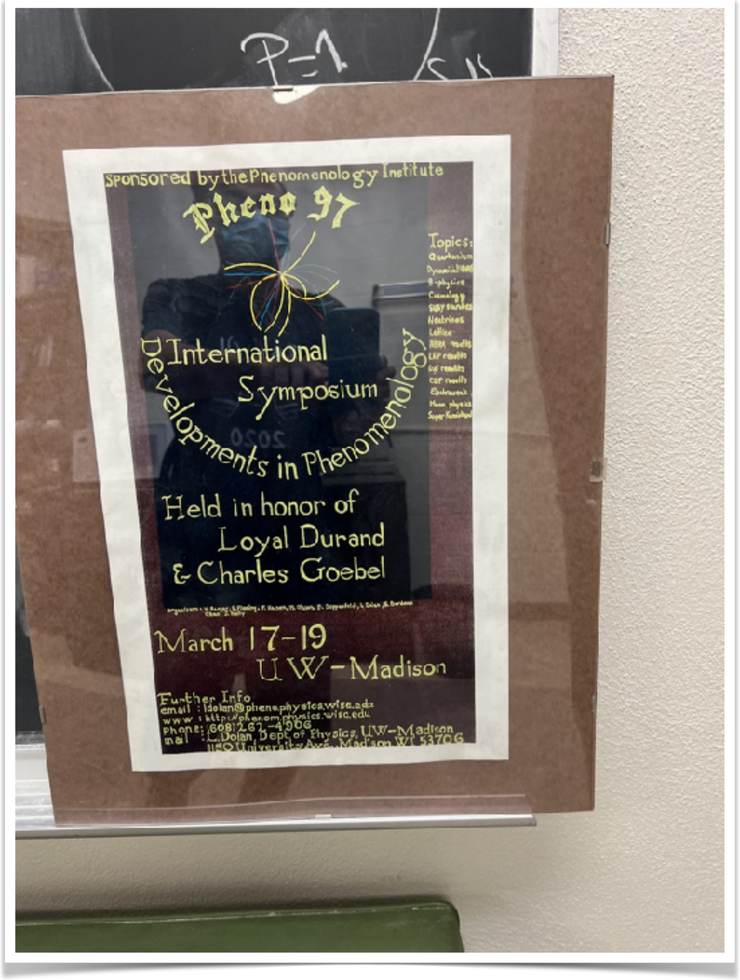
2022 at Madison

2022 at Madison



2022 at Madison



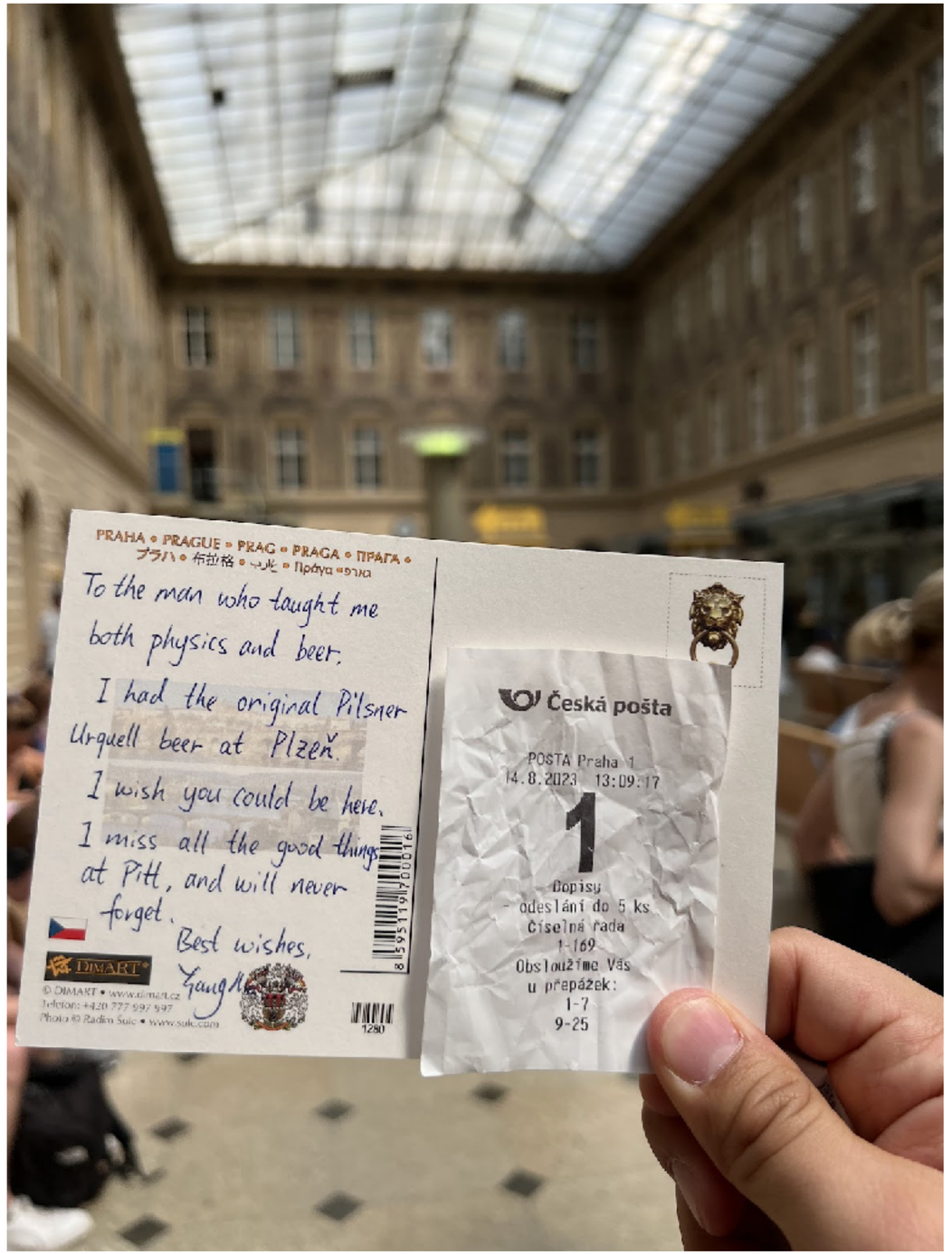


2023 summer

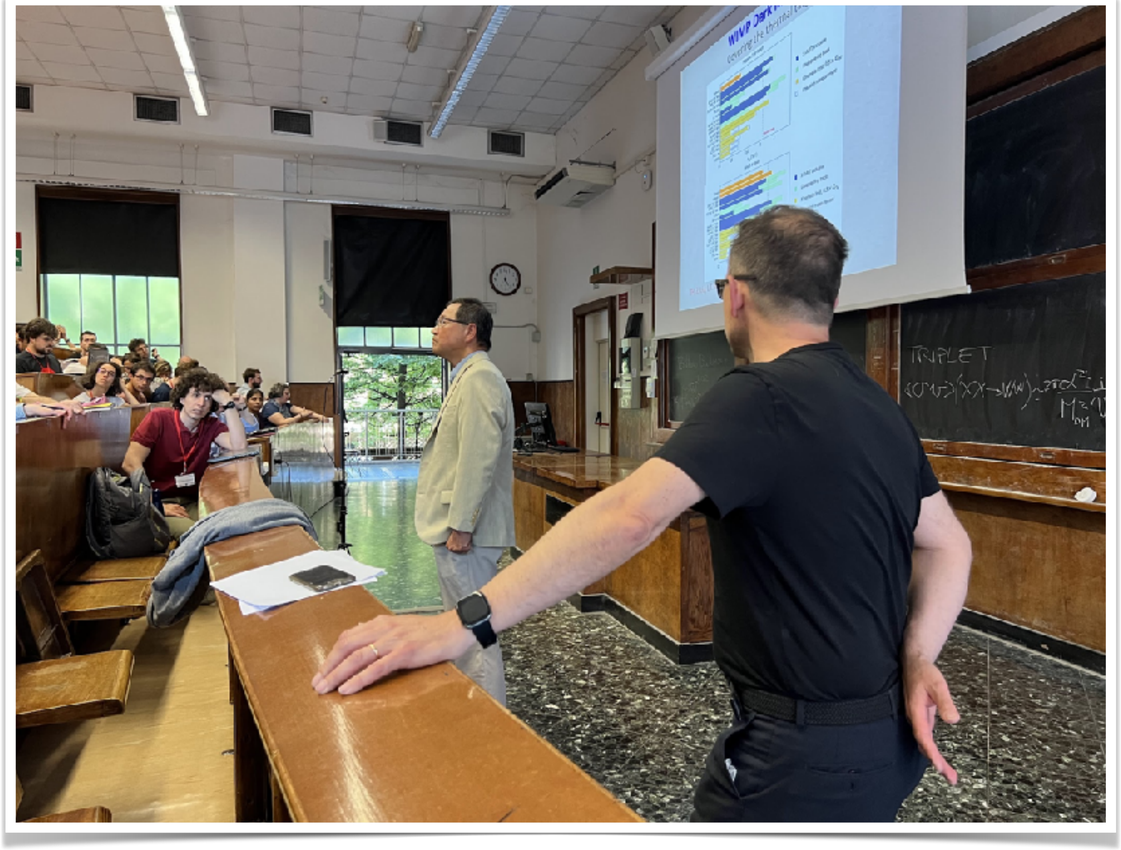
2023 summer


NÁVŠTĚVNICKÉ CENTRUM

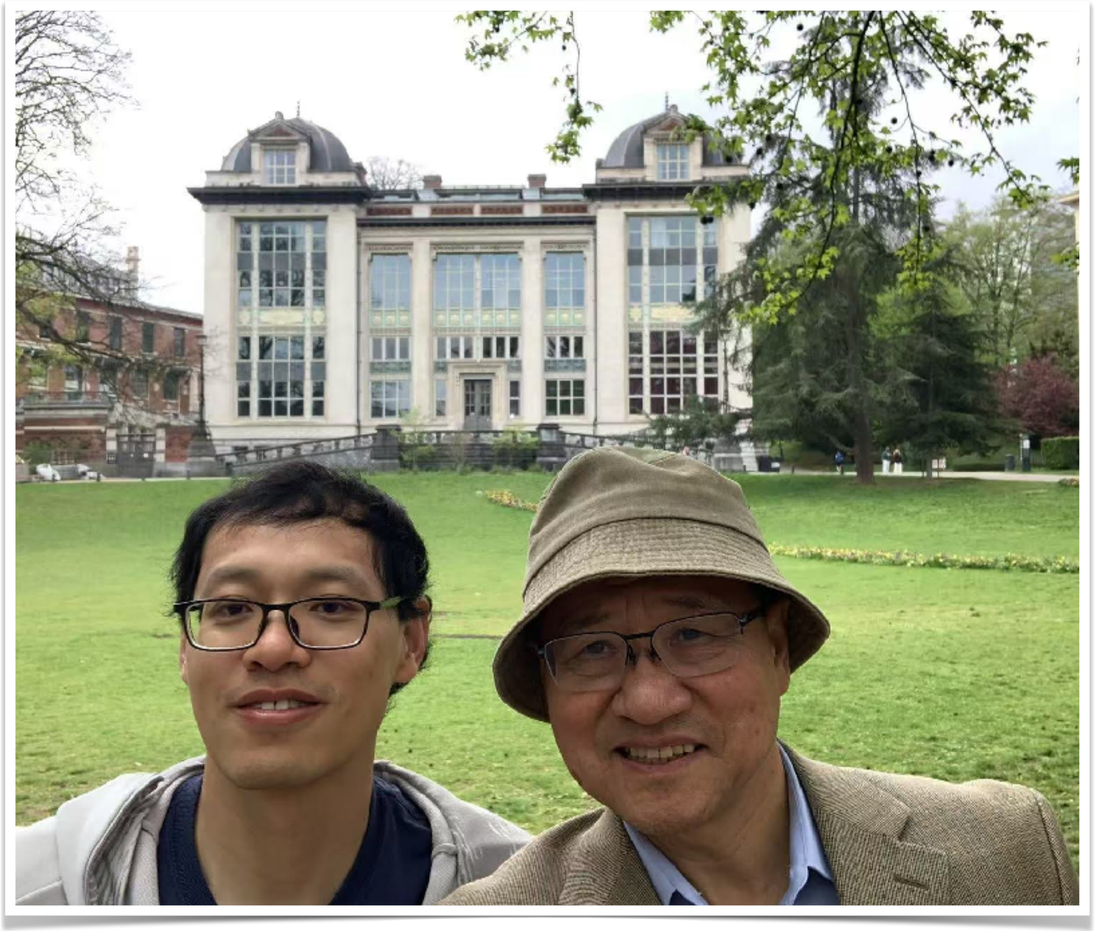

Pilsner Urquell


PRAHA • PRAGUE • PRAG • PRAGA • ΠΡΑΓΑ •
To the man who taught me both physics and beer.
I had the original Pilsner Urquell beer at Plzeň.
I wish you could be here.
I miss all the good things at Pitt, and will never forget.
Best wishes,
Yang
DIMART
Česká pošta
POSTA Praha 1
14.8.2023 13:09:17
1
Doplsu
- odeslání do 5 ks
Číselná řada
1-169
Obsloužíme Vás
u přepážek:
1-7
9-25

2024 in Bologna

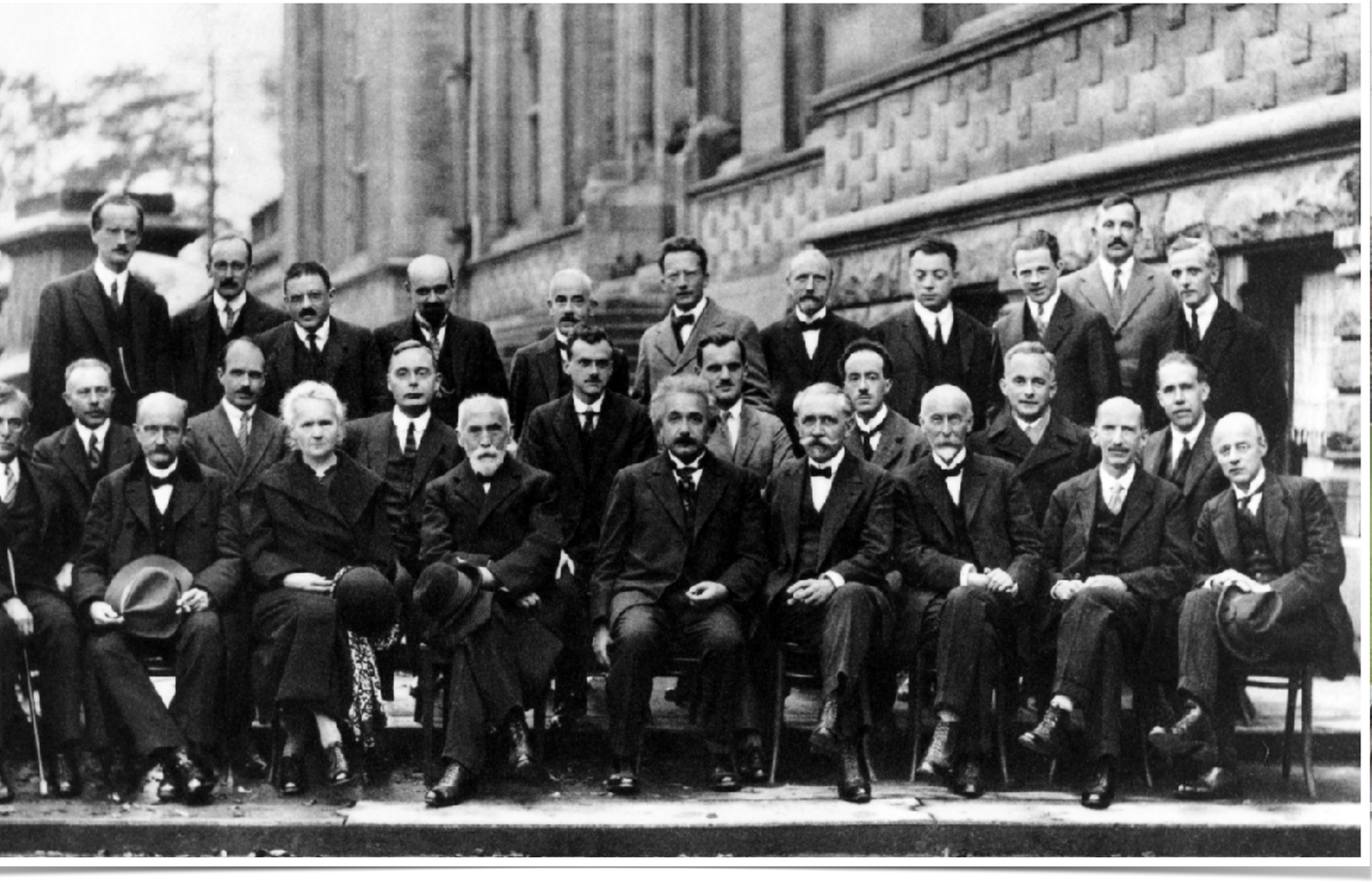


2025 in Brussels



2025 in Brussels

Solvay Conference 1927



“Solvay Meeting 2025”

2025 in Brussels

TAO at future lepton colliders

Sorry, I learned to use acronym….

TAO at future lepton colliders

Sorry, I learned to use acronym….

ELECTRA = ELECtroweak Radiation

TAO at future lepton colliders

Sorry, I learned to use acronym….

ELECTRA = ELECtroweak Radiation

TAO = Tau dipOle moments

2604.14281

2606.xxxxx

2606.yyyyy

Formulae TAO

$$\Gamma^\mu(q^2) = -ieQ_f\left[\gamma^\mu F_1(q^2) + \frac{\sigma^{\mu\nu}q_\nu}{2m_f}\left(iF_2(q^2) + F_3(q^2)\gamma^5\right)\right] \qquad a_f = F_2(0), \qquad d_f = \frac{eQ_f}{2m_f}F_3(0)$$

$$a_\ell^{\text{QED, 1-loop}} = \frac{\alpha}{2\pi} \simeq 0.00116$$

$$\Gamma_Z^\mu(q^2) = -ieQ_f\left[\frac{\gamma^\mu}{c_W s_W}(g_V^f + g_A^f\gamma^5) + \frac{\sigma^{\mu\nu}q_\nu}{2m_f}\left(iF_2^Z(q^2) + F_3^Z(q^2)\gamma^5\right)\right] \qquad a_f^Z = F_2^Z(m_Z^2), \qquad d_f^Z = \frac{eQ_f}{2m_f}F_3^Z(m_Z^2)$$

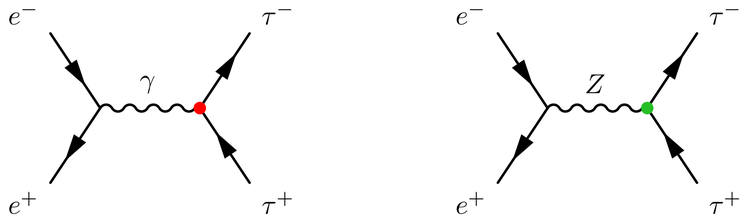
$$\mathscr{L} \supset \frac{\mathcal{C}_{\ell B}}{\Lambda^2}\,\bar{\ell}_L\sigma^{\mu\nu}e_R\varphi B_{\mu\nu} + \frac{\mathcal{C}_{\ell W}}{\Lambda^2}\,\bar{\ell}_L\sigma^{\mu\nu}e_R\,\tau_I\varphi\,W^I_{\mu\nu} + \text{h.c.}$$

$$\mathscr{L} \supset \frac{v+H}{\sqrt{2}\Lambda^2}\left(\mathcal{C}_{\ell\gamma}\,\bar{\ell}\sigma^{\mu\nu}P_R\,\ell F_{\mu\nu} + \mathcal{C}_{\ell Z}\,\bar{\ell}\sigma^{\mu\nu}P_R\,\ell Z_{\mu\nu}\right) + \text{h.c.}$$

$$\mathcal{C}_{\ell\gamma} \equiv c_W\mathcal{C}_{\ell B} - s_W\mathcal{C}_{\ell W},$$
$$\mathcal{C}_{\ell Z} \equiv -c_W\mathcal{C}_{\ell W} - s_W\mathcal{C}_{\ell B}$$

$$\Delta a_\tau = \frac{2\sqrt{2}m_\tau v}{e\Lambda^2}\text{Re}(\mathcal{C}_{\tau\gamma}), \quad d_\tau = \frac{\sqrt{2}v}{\Lambda^2}\text{Im}(\mathcal{C}_{\tau\gamma}),$$
$$\Delta a_\tau^Z = \frac{2\sqrt{2}m_\tau v}{e\Lambda^2}\text{Re}(\mathcal{C}_{\tau Z}), \quad d_\tau^Z = \frac{\sqrt{2}v}{\Lambda^2}\text{Im}(\mathcal{C}_{\tau Z}).$$

FCCee: look for the linear term

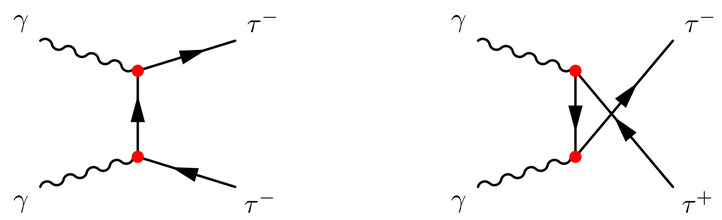


$$\sigma_{\ell^+\ell^-\to\tau^+\tau^-} = \sigma^{\rm SM}_{\ell\ell} + \sigma^{\rm Lin}_{\ell\ell} + \sigma^{\rm Quad}_{\ell\ell}$$

$$\sigma^{\rm SM}_{\ell\ell} = \frac{\beta}{12\pi}\left[\frac{e^4(1+2\tau)}{s} + \frac{2e^2 g_Z^2 g_V^2 s\Delta(1+2\tau)}{\Delta^2 s^2 + M_Z^2\Gamma_Z^2} + \frac{g_Z^4 s(g_V^2+g_A^2)\left(g_V^2(1+2\tau)+g_A^2(1-4\tau)\right)}{\Delta^2 s^2 + M_Z^2\Gamma_Z^2}\right],$$

$$\sigma^{\rm Lin}_{\ell\ell} = \frac{\beta m_\tau v}{\sqrt{2}\pi s\Lambda^2}\,{\rm Re}\left[e^3\mathcal{C}_{\tau\gamma} + \frac{e g_Z^2 g_V^2 \mathcal{C}_{\tau\gamma}\Delta s^2}{\Delta^2 s^2 + M_Z^2\Gamma_Z^2} - \frac{g_Z g_V \mathcal{C}_{\tau Z} s^2(e^2\Delta + g_Z^2(g_V^2+g_A^2))}{\Delta^2 s^2 + M_Z^2\Gamma_Z^2}\right],$$

$$\sigma^{\rm Quad}_{\ell\ell} = \frac{\beta v^2(1+8\tau)}{12\pi\Lambda^4}\left[e^2|\mathcal{C}_{\tau\gamma}|^2 + \frac{g_Z^2|\mathcal{C}_{\tau Z}|^2 s^2(g_V^2+g_A^2)}{\Delta^2 s^2 + M_Z^2\Gamma_Z^2} - \frac{2e g_Z g_V {\rm Re}(\mathcal{C}^*_{\tau\gamma}\mathcal{C}_{\tau Z})\Delta s^2}{\Delta^2 s^2 + M_Z^2\Gamma_Z^2}\right]$$
$$- \frac{\beta v^2\tau}{\pi\Lambda^4}\left[e^2\left({\rm Im}\,\mathcal{C}_{\tau\gamma}\right)^2 + \frac{g_Z^2\left({\rm Im}\,\mathcal{C}_{\tau Z}\right)^2 s^2(g_V^2+g_A^2)}{\Delta^2 s^2 + M_Z^2\Gamma_Z^2} - \frac{2e g_Z g_V {\rm Im}\,\mathcal{C}_{\tau\gamma}{\rm Im}\,\mathcal{C}_{\tau Z}\Delta s^2}{\Delta^2 s^2 + M_Z^2\Gamma_Z^2}\right]$$



$$\hat\sigma_{\gamma\gamma\to\tau^+\tau^-} = \hat\sigma^{\rm SM}_{\gamma\gamma} + \hat\sigma^{\rm Lin}_{\gamma\gamma} + \hat\sigma^{\rm Quad}_{\gamma\gamma} + \mathcal{O}\left(\frac{1}{\Lambda^6}\right)$$

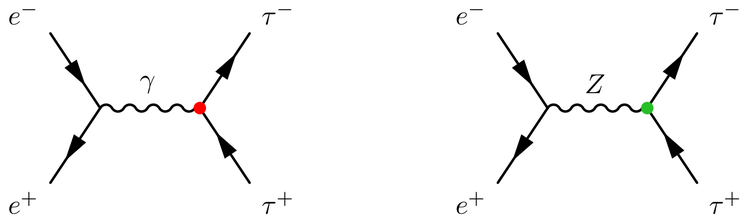
$$\hat\sigma^{\rm SM}_{\gamma\gamma} = \frac{e^4}{4\pi\hat s}\left[(1+4\hat\tau-8\hat\tau^2)\log\left(\frac{1+\hat\beta}{1-\hat\beta}\right) - \hat\beta(1+4\hat\tau)\right],$$

$$\hat\sigma^{\rm Lin}_{\gamma\gamma} = \frac{\sqrt{2}e^3 m_\tau v}{\pi\hat s}\frac{{\rm Re}\,\mathcal{C}_{\tau\gamma}}{\Lambda^2}\log\left(\frac{1+\hat\beta}{1-\hat\beta}\right),$$

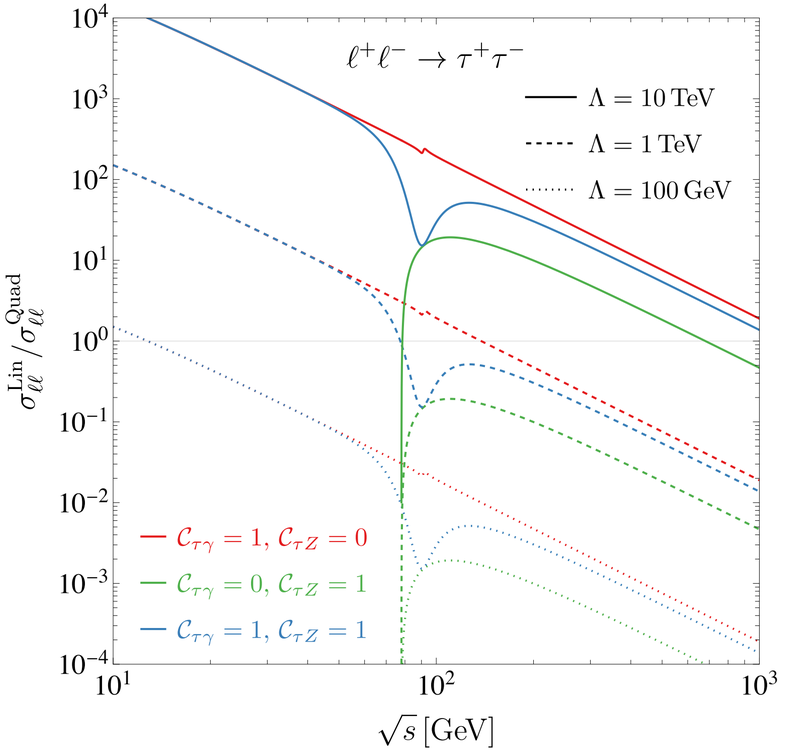
$$\hat\sigma^{\rm Quad}_{\gamma\gamma} = \frac{e^2v^2}{\pi}\frac{1}{\Lambda^4}\left[\left(\left({\rm Re}\,C_{\tau\gamma}\right)^2 - \left({\rm Im}\,C_{\tau\gamma}\right)^2\right)\hat\tau\log\left(\frac{1+\hat\beta}{1-\hat\beta}\right) + 2|\mathcal{C}_{\tau\gamma}|^2\hat\beta\right]$$

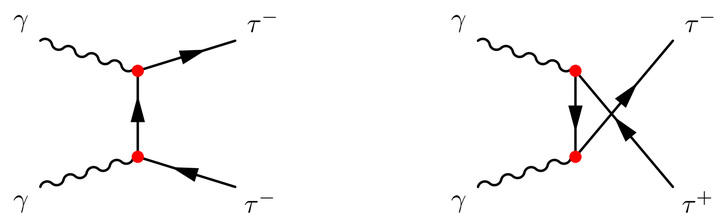
where $\hat\tau = m_\tau^2/\hat s$ and $\hat\beta = \sqrt{1-4\hat\tau}$

FCCee: look for the linear term

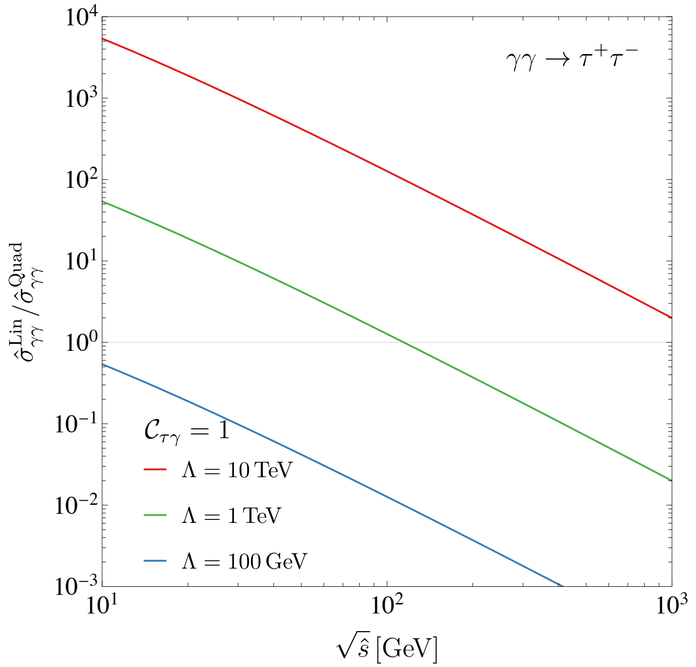


$$\sigma_{\ell^+\ell^-\to\tau^+\tau^-} = \sigma^{\rm SM}_{\ell\ell} + \sigma^{\rm Lin}_{\ell\ell} + \sigma^{\rm Quad}_{\ell\ell}$$



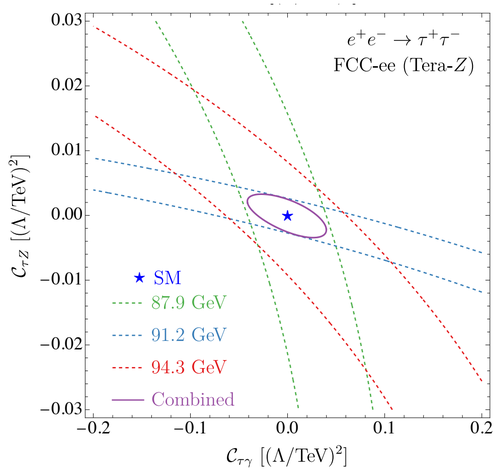


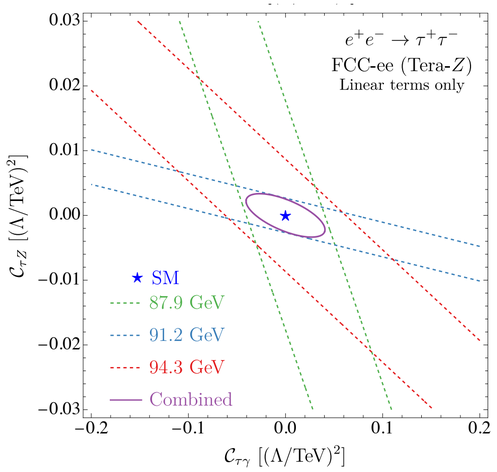
$$\hat{\sigma}_{\gamma\gamma\to\tau^+\tau^-} = \hat{\sigma}^{\rm SM}_{\gamma\gamma} + \hat{\sigma}^{\rm Lin}_{\gamma\gamma} + \hat{\sigma}^{\rm Quad}_{\gamma\gamma} + \mathcal{O}\left(\frac{1}{\Lambda^6}\right)$$

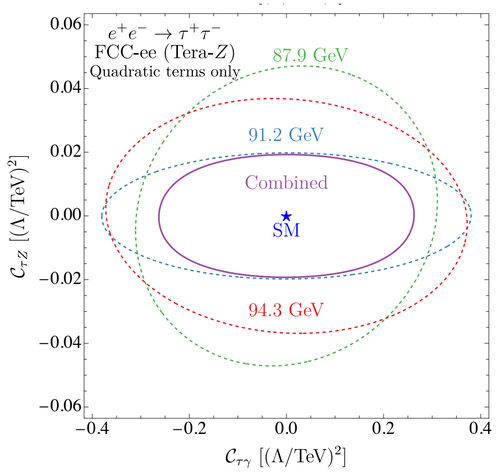


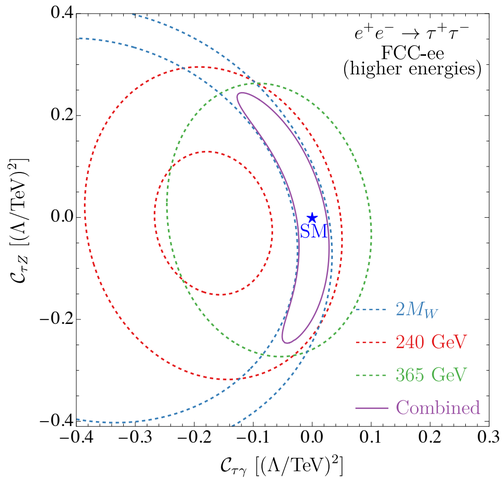
FCCee: preliminary results

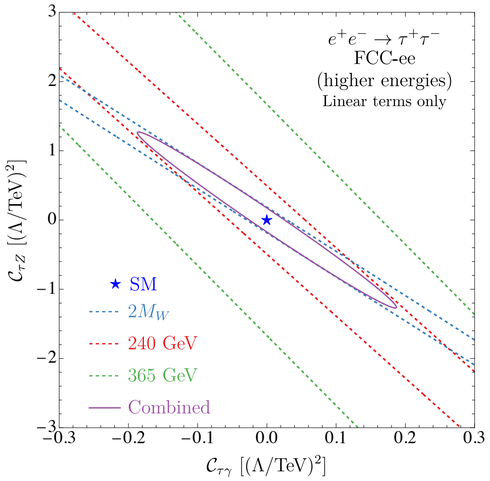
$e^+e^- \to \tau^+\tau^-$

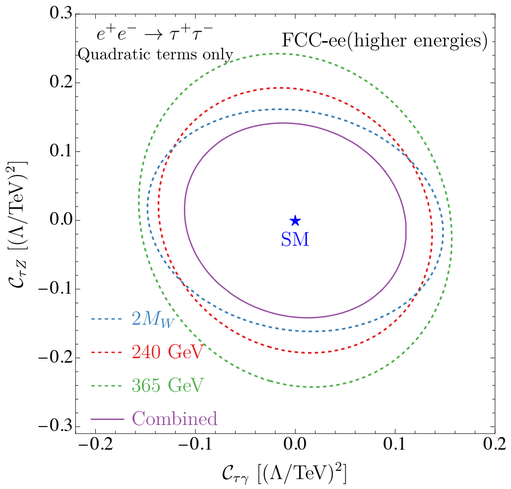




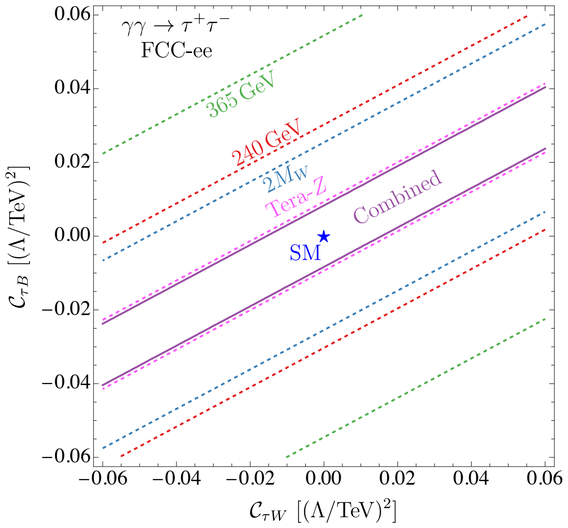


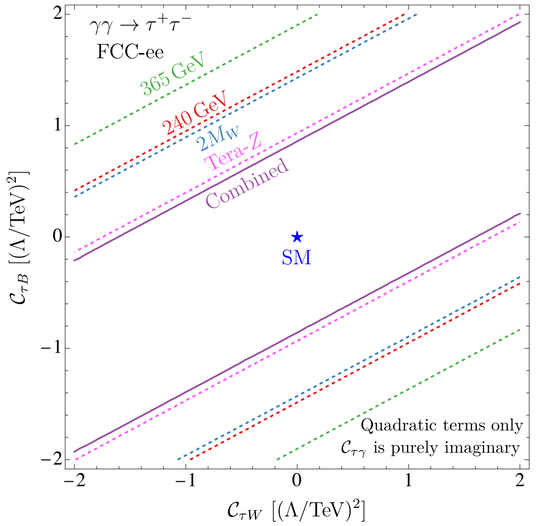




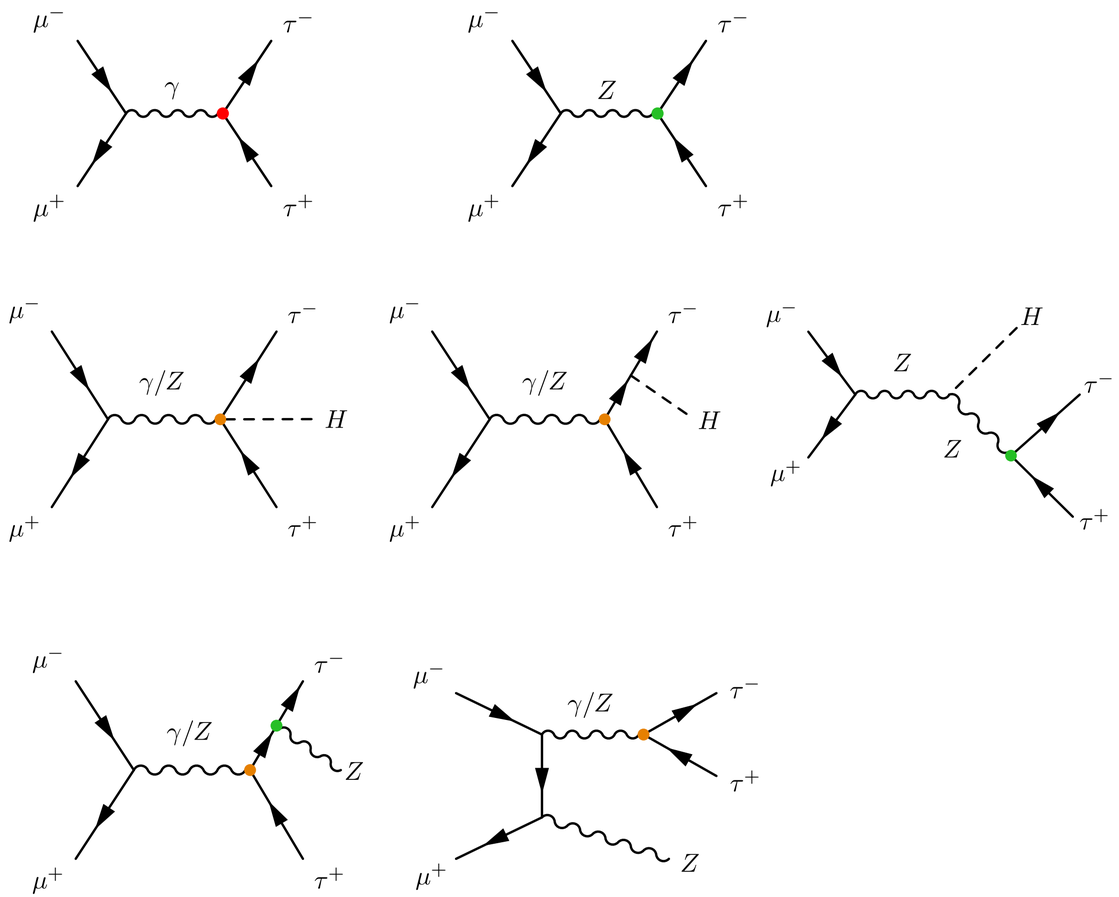


$\gamma\gamma \to \tau^+\tau^-$

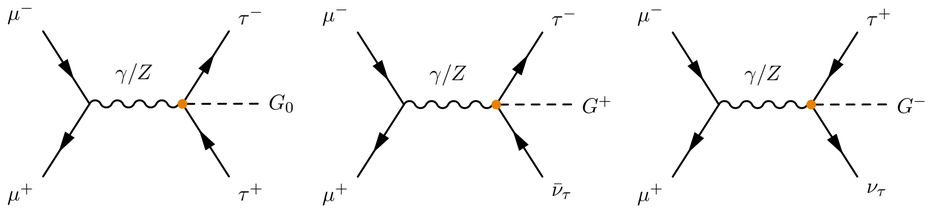




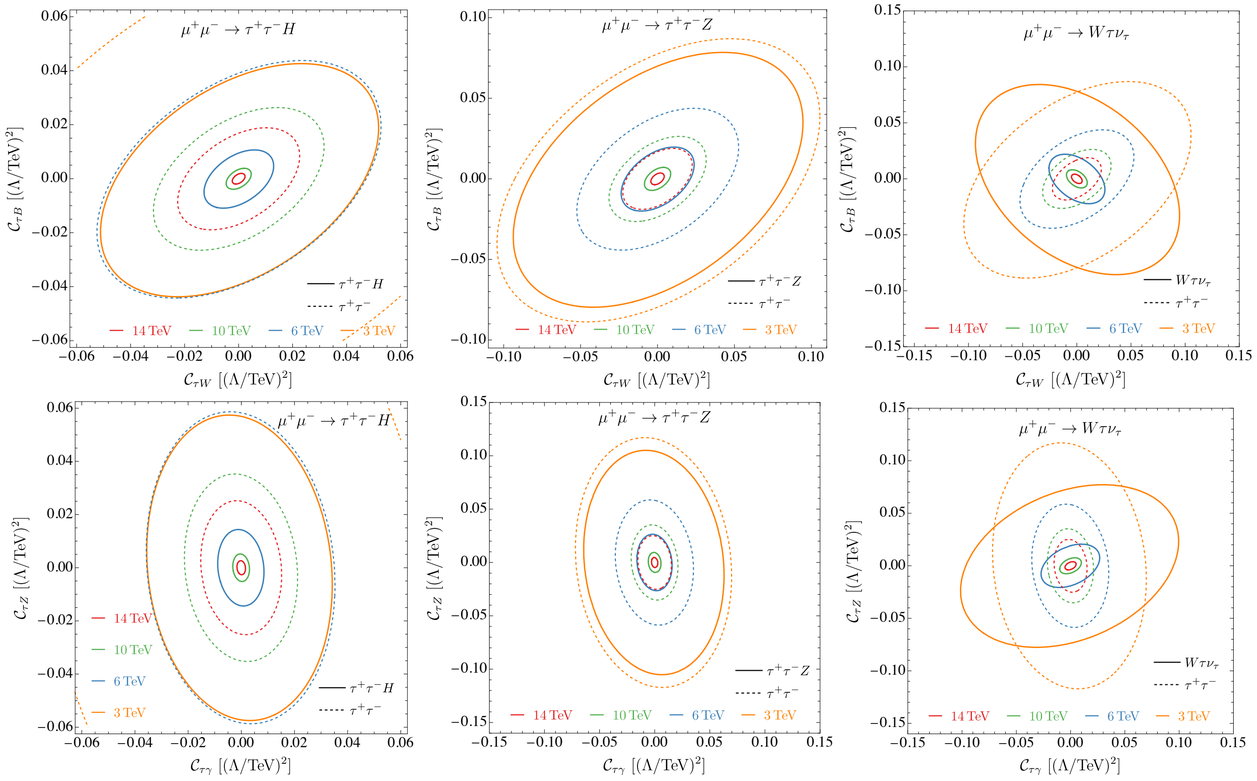
MuC: Chase energy enhancement

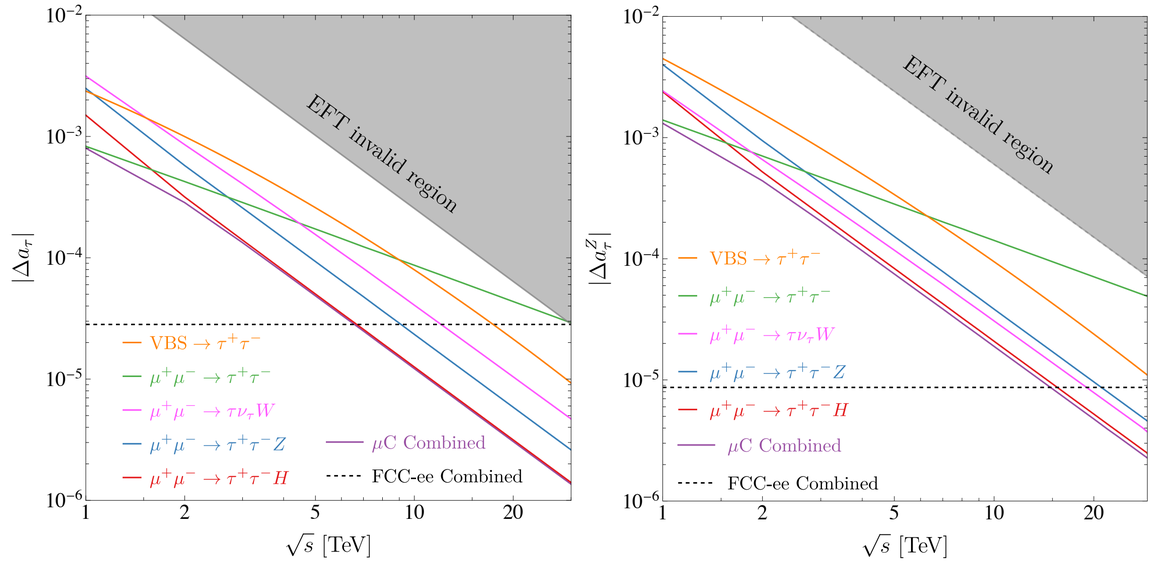


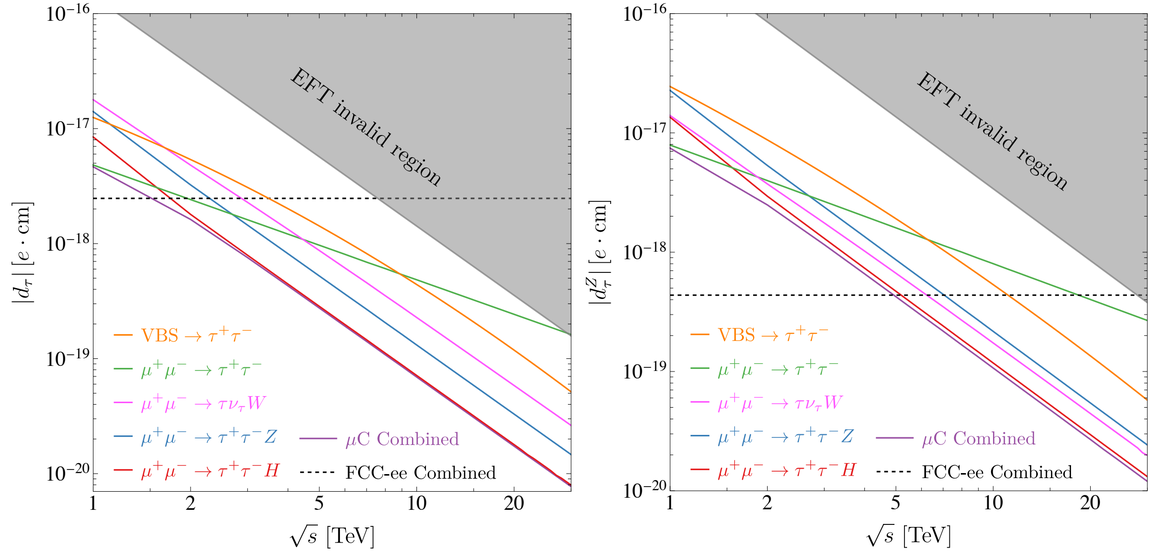
Process	$\sigma_{\mu\mu}^{\mathrm{SM}}$	$\sigma_{\mu\mu}^{\mathrm{Lin}}$	$\sigma_{\mu\mu}^{\mathrm{Quad}}$
$\mu^+\mu^- \to \tau^+\tau^-$	$\frac{1}{s}$	$\frac{1}{s}\frac{m_\tau v}{\Lambda^2}$	$\frac{1}{s}\frac{sv^2}{\Lambda^4}$
$\mu^+\mu^- \to \tau^+\tau^- H$	$\frac{m_\tau^2}{v^2}\frac{1}{s}$	$\frac{m_\tau}{v}\frac{1}{s}\frac{s}{\Lambda^2}$	$\frac{1}{s}\frac{s^2}{\Lambda^4}$
$\mu^+\mu^- \to \tau^+\tau^- V$	$\frac{1}{s}$	$\frac{m_\tau}{v}\frac{1}{s}\frac{s}{\Lambda^2}$	$\frac{1}{s}\frac{s^2}{\Lambda^4}$



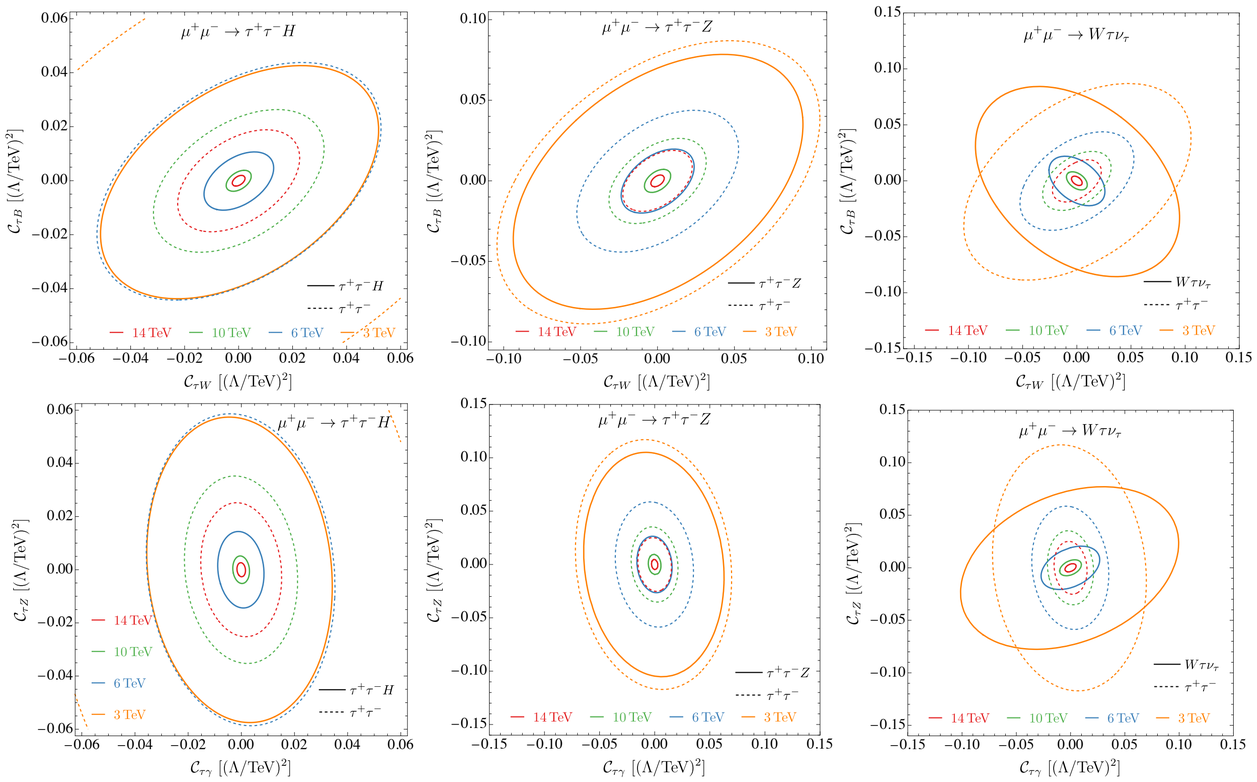
MuC: preliminary results



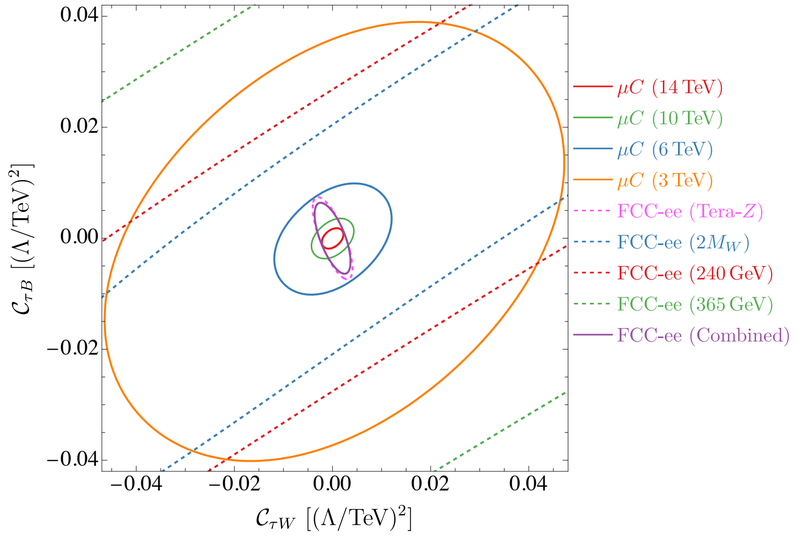


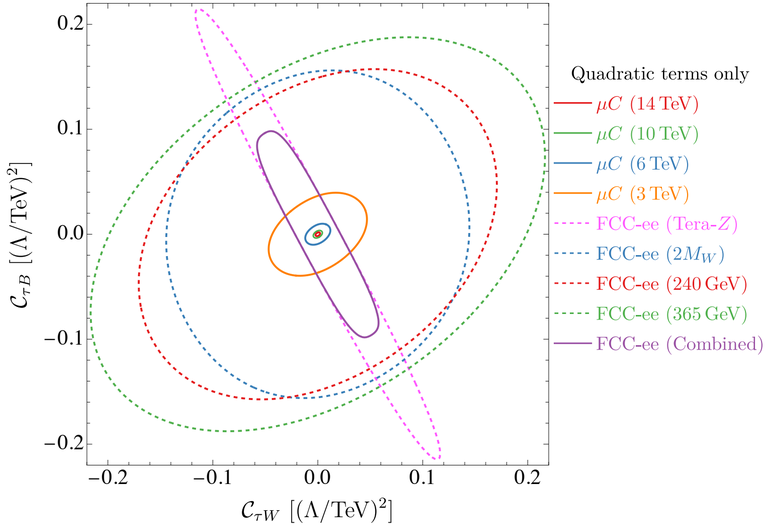


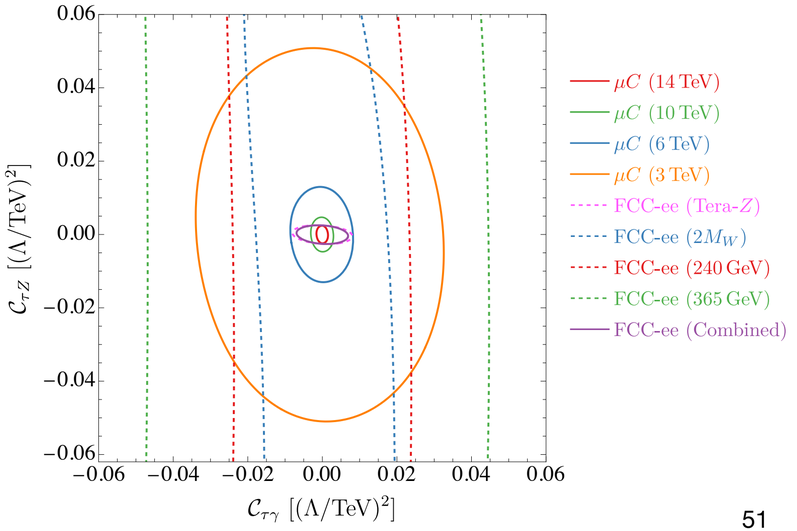
MuC: preliminary results

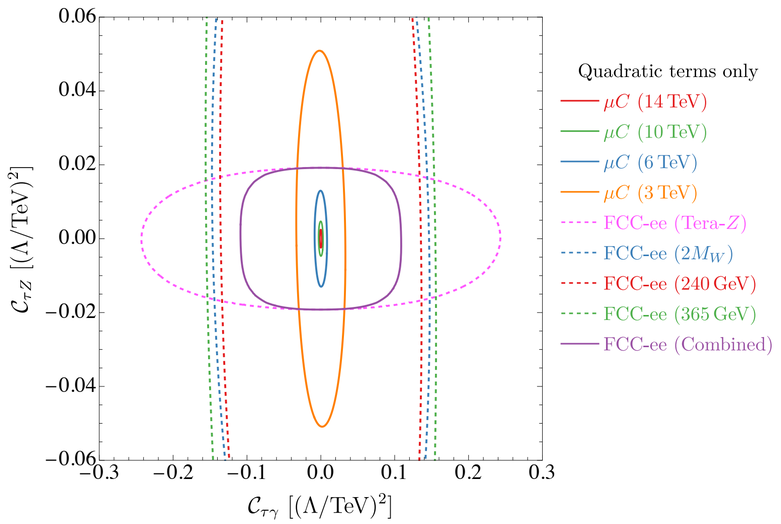


Global picture of TAO at future lepton colliders









A final announcement

A final announcement