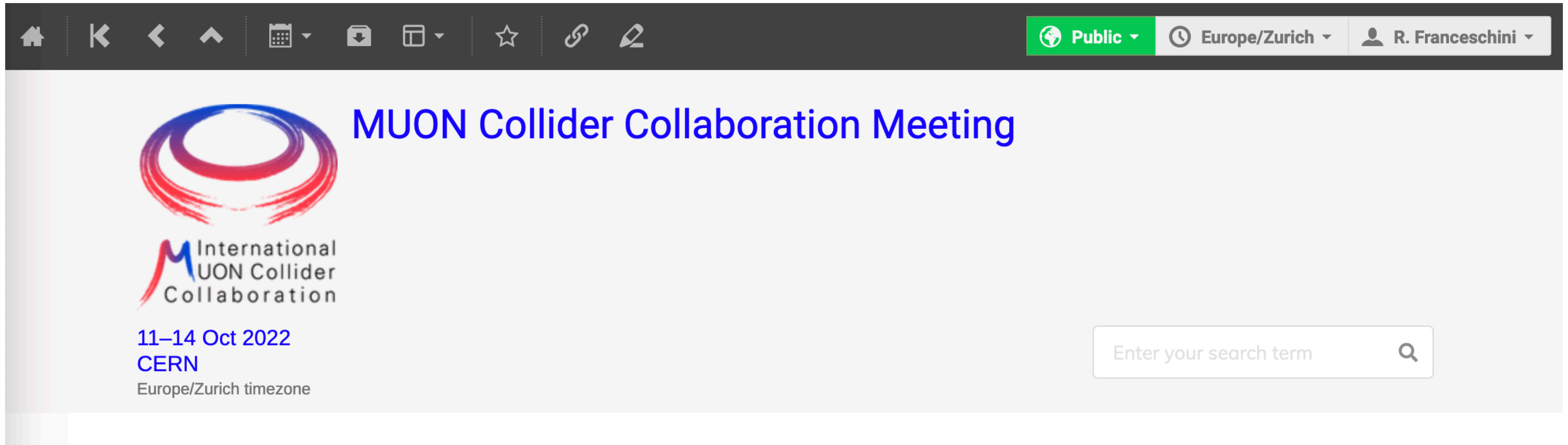
ANNUAL MEETING SUMMARY

“hep-ph” contributions



TALKS WITH GENERAL SCOPE

“One ring to rule them all, one ring to find them” … - J.R.R.Tolkien

Muon collider: physics

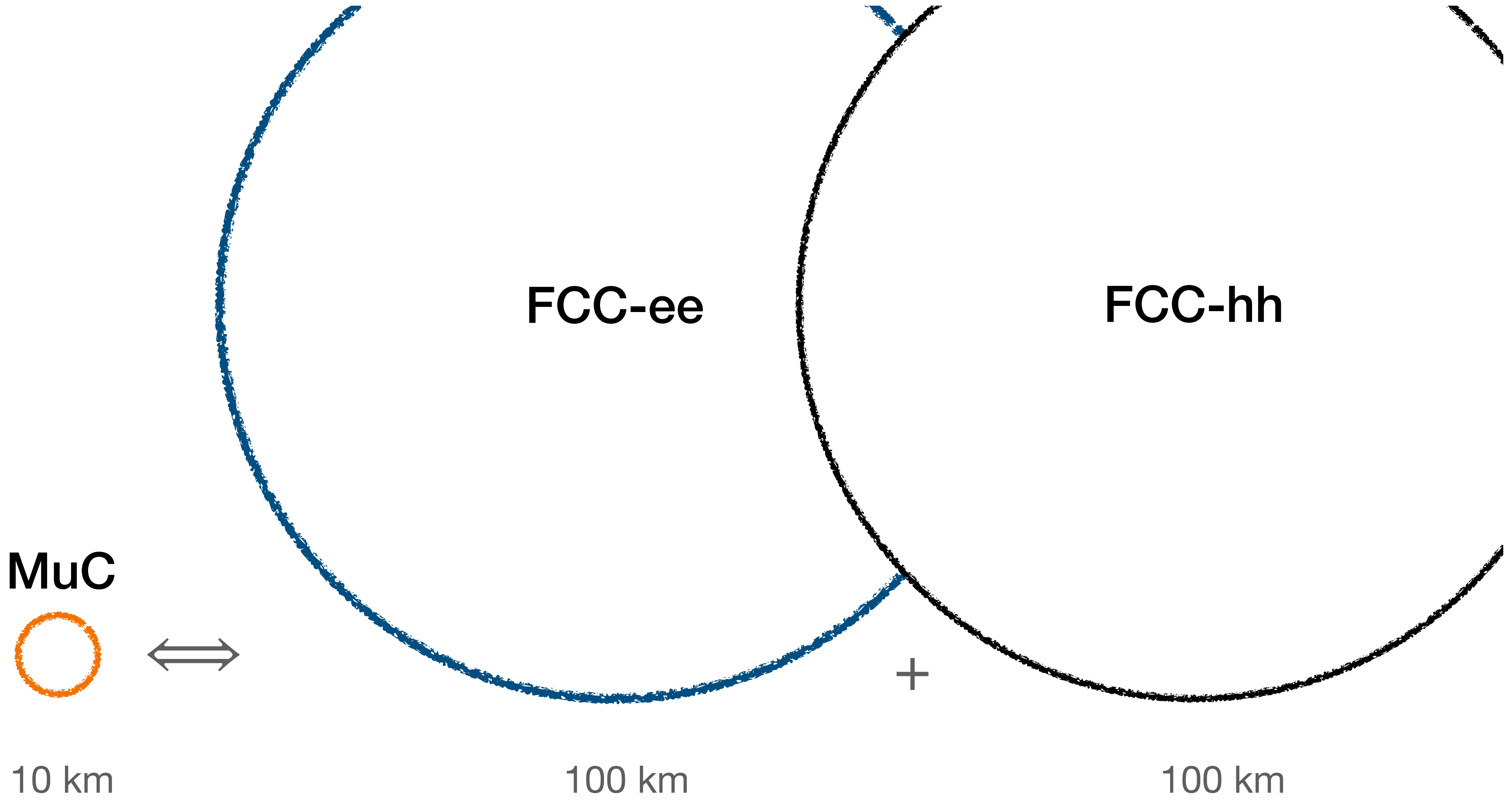
Fabio Maltoni
Université catholique de Louvain
Università di Bologna

Frank Simon’s
original art work.
Adapted

Muon collider physics

The essentials #3: compactness

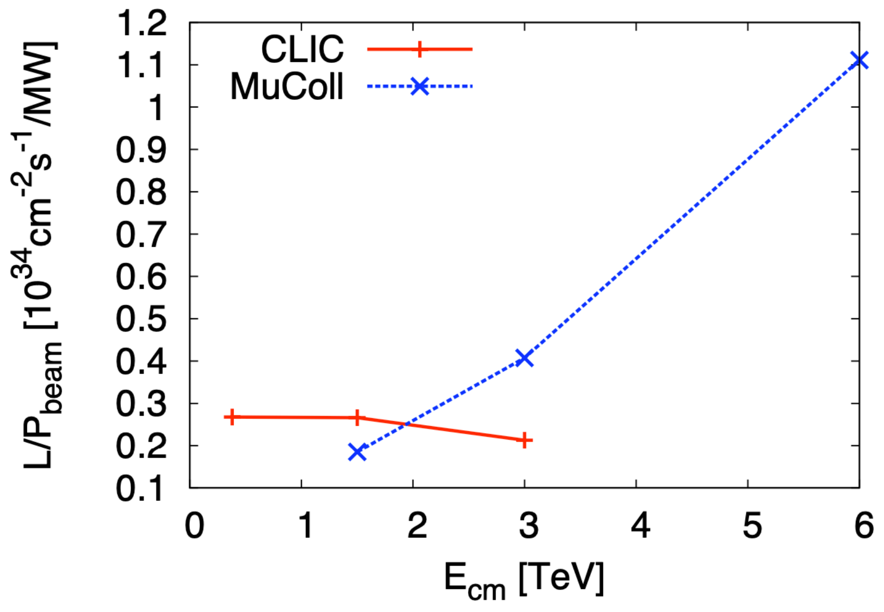
1] O(10) TeV Energy small hybrid collider:



x

t

2] Luminosity growing with energy:



⇒MuC is an STCC = Space-Time-Compact Collider

⇒ Goal of the tens:
10 TeV , 10 iab, 10 x smaller and O(10) x faster than the FCC

Muon collider physics
The essentials

- A O(10 TeV) muC is in the range of what could be technically achievable. R&D is necessary.

- It would radically change the way we do collider physics, opening the exploration of EW phenomena at higher scales through an hybrid direct/indirect approach in a clean environment.

- Given what we know now from the LHC + what will learn from HL-LHC what are the muC physics drivers?

Reports of the working groups: Physics *Andrea Wulzer*
30/7-018 - Kjell Johnsen Auditorium, CERN 08:50 - 09:05

Physics Summary

Andrea Wulzer

ICREA

IFAE
Institut de Física
d'Altes Energies

First Collaboration Meeting
(Oct. 11-14 2022)

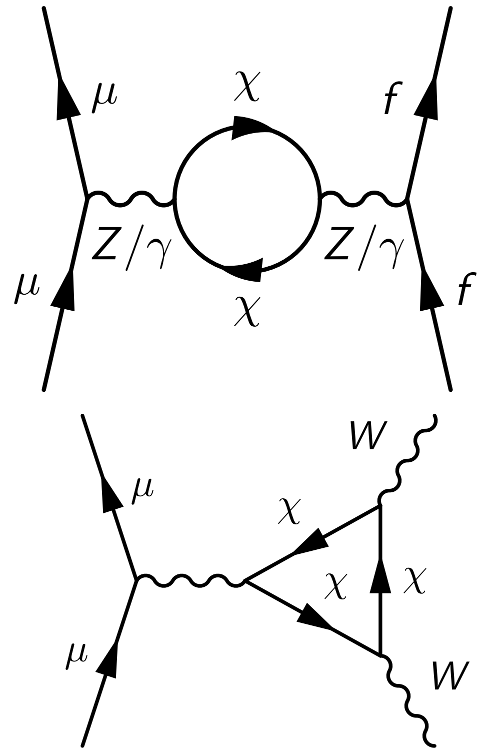
Reports of the working groups: Physics — Andrea Wulzer

30/7-018 - Kjell Johnsen Auditorium, CERN — 08:50 - 09:05

Dark Matter

[Xiaoran Zhao]

- mono-X,di-X and DT for low mass region $M_\chi < \frac{\sqrt{s}}{2}$
- Indirect probes are good at thresholds $M_\chi \sim \frac{\sqrt{s}}{2}$
- and can probe high mass $M_\chi > \frac{\sqrt{s}}{2}$
- Soft/collinear radiations shift NC to NC+CC
- Hard radiations affect the dynamics and sensitivities
- Statistic uncertainties in $\mathcal{O}(0.1 \sim 1\%)$ level: need further improvements on theoretical predictions(NLO+NLL or higher?)



	3 TeV			10 TeV			30 TeV		
	DL	$e^{\mathrm{DL}}-1$	SL($\frac{\pi}{2}$)	DL	$e^{\mathrm{DL}}-1$	SL($\frac{\pi}{2}$)	DL	$e^{\mathrm{DL}}-1$	SL($\frac{\pi}{2}$)
$\ell_L \to \ell'_L$	-0.46	-0.37	0.25	-0.82	-0.56	0.33	-1.23	-0.71	0.41
$\ell_L \to q_L$	-0.44	-0.36	0.25	-0.78	-0.54	0.34	-1.18	-0.69	0.42
$\ell_L \to e_R$	-0.32	-0.27	0.13	-0.56	-0.43	0.17	-0.85	-0.57	0.21
$\ell_L \to u_R$	-0.27	-0.24	0.11	-0.48	-0.38	0.15	-0.72	-0.51	0.18
$\ell_L \to d_R$	-0.24	-0.21	0.10	-0.43	-0.35	0.13	-0.64	-0.47	0.16
$\ell_R \to \ell'_L$	-0.32	-0.27	0.13	-0.56	-0.43	0.17	-0.85	-0.57	0.21
$\ell_R \to q_L$	-0.30	-0.26	0.12	-0.53	-0.41	0.16	-0.79	-0.55	0.21
$\ell_R \to \ell'_R$	-0.17	-0.16	0.07	-0.30	-0.26	0.09	-0.46	-0.37	0.12
$\ell_R \to u_R$	-0.12	-0.12	0.05	-0.22	-0.20	0.07	-0.33	-0.28	0.08
$\ell_R \to d_R$	-0.09	-0.09	0.04	-0.17	-0.16	0.05	-0.25	-0.22	0.06

Note: we are currently not able to make sufficiently accurate predictions for this study (and many others)

AN "INTERPOLATOR" MODEL

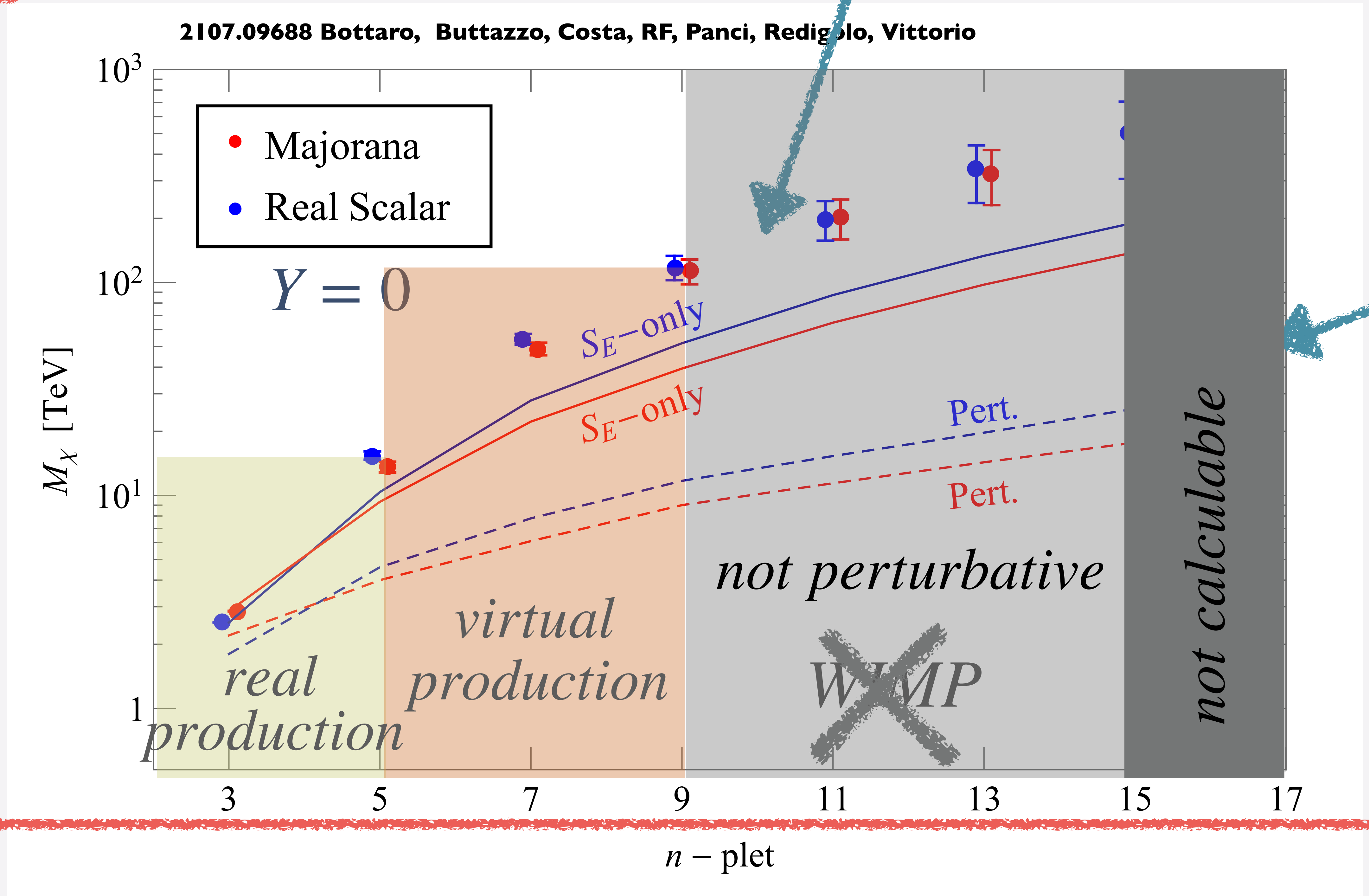
mass of the DM

$$\Omega_{nr} \sim \frac{1}{\sigma_{ann}} \sim \frac{M^2}{C_n \cdot g^2}$$

weak charge of the DM

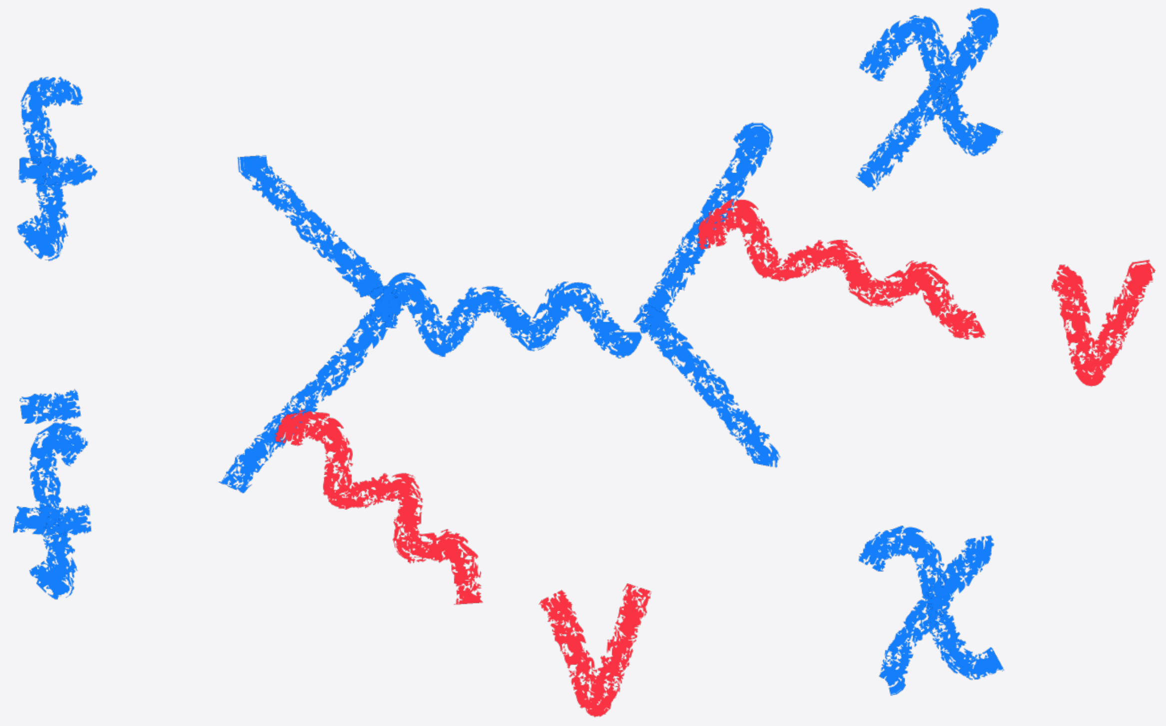
given n the mass is predicted

σ_{ann} < perturbative unitarity

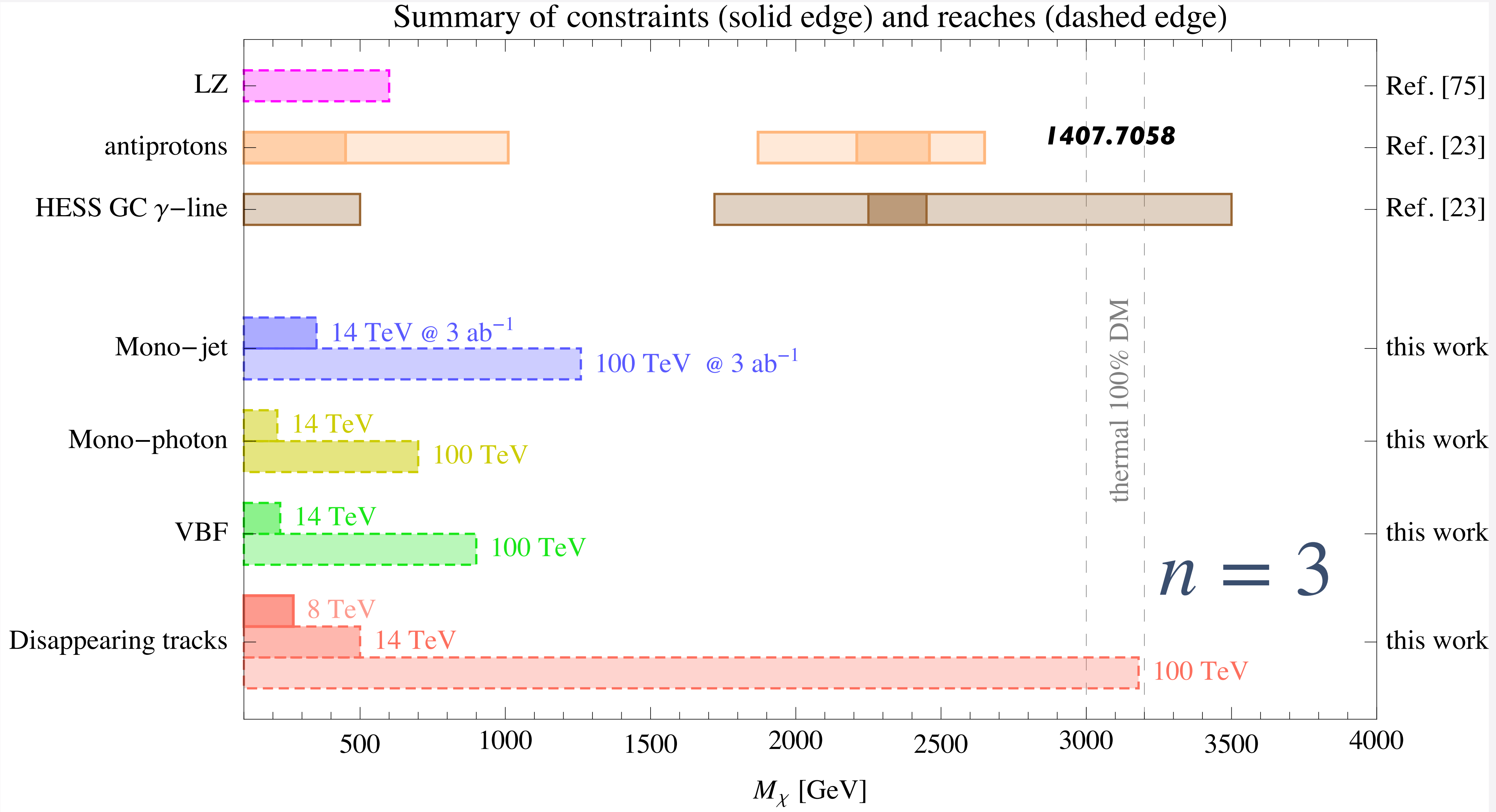


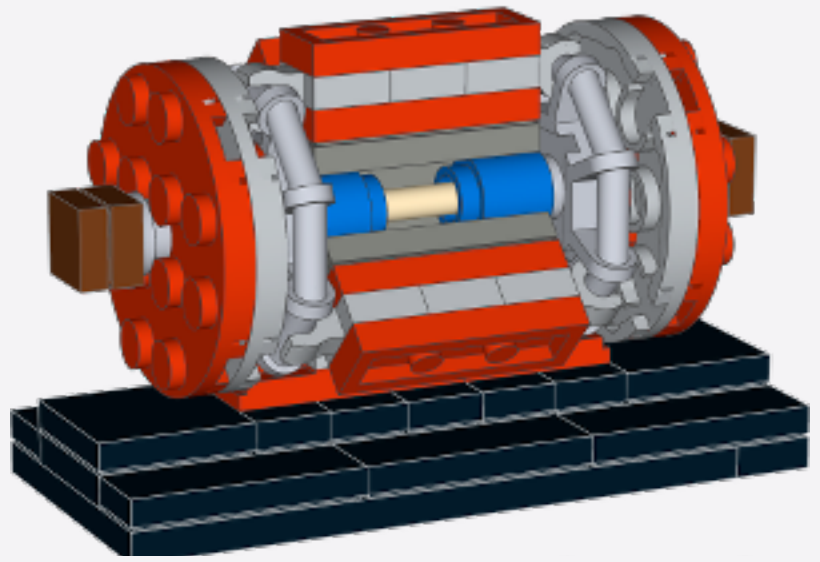
If Dark Matter feels SM weak interactions we can use the general n-plet WIMP to measure how well we are able to test this hypothesis and possibly discover or exclude one or several or the whole category of DM candidates.

DIRECT PRODUCTION



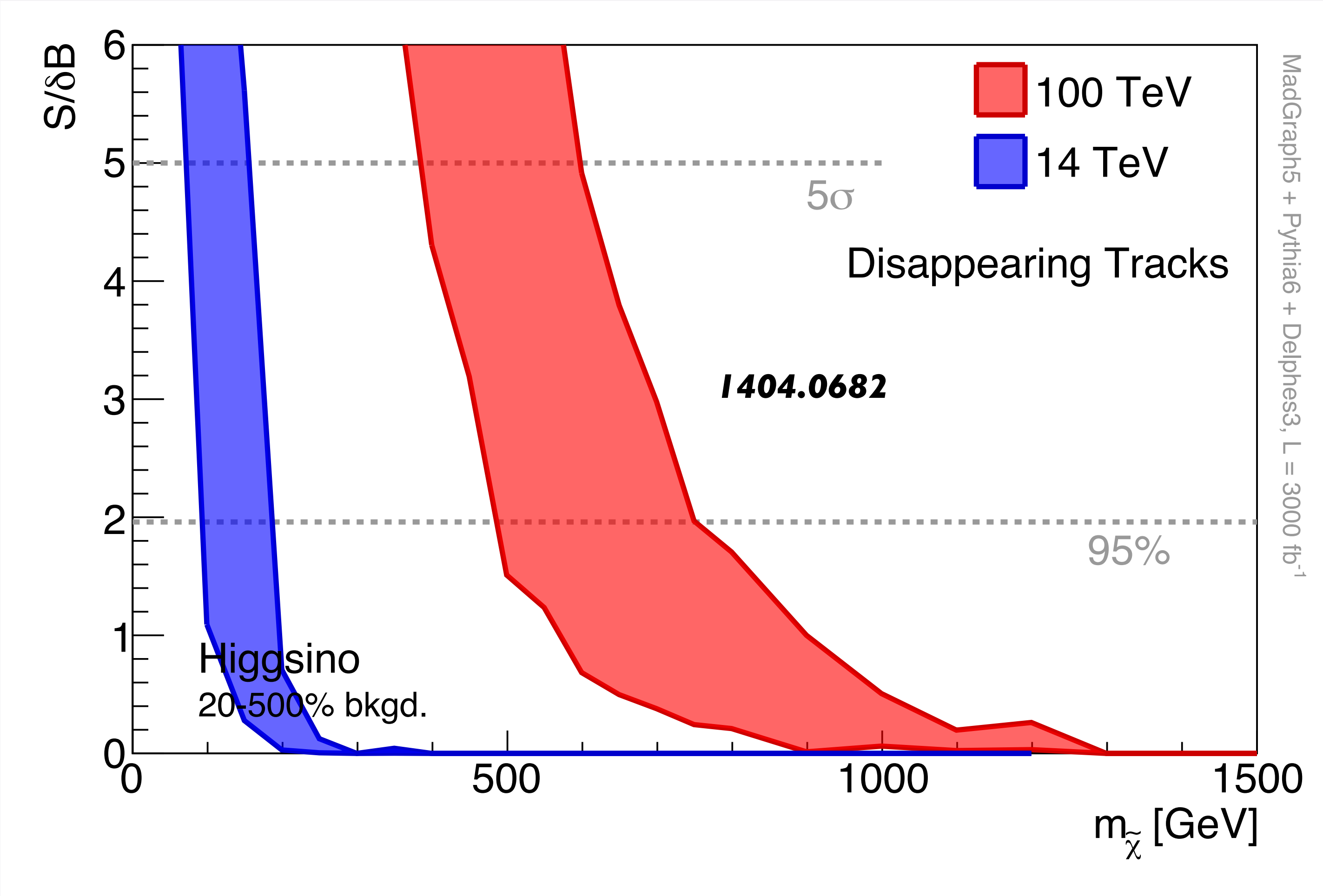
Production of Dark Matter weak multiplet states and observation of the decay products or associated productions





2040s

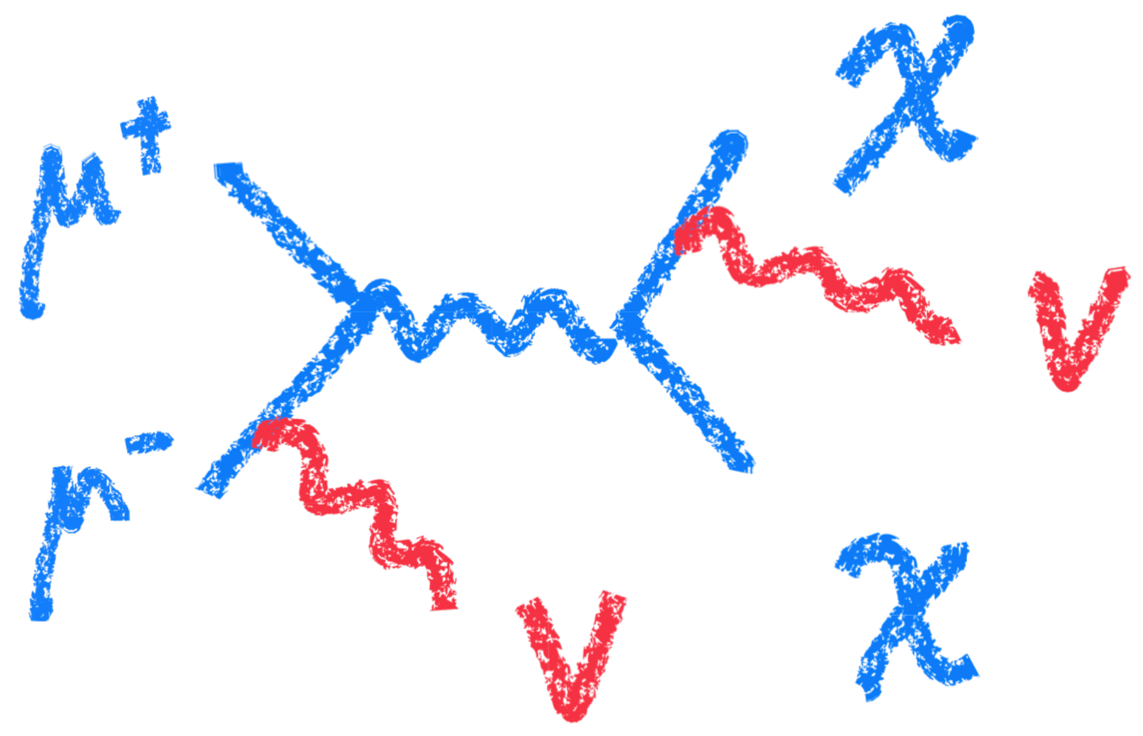
up to 10+ TeV



$$\mu^+\mu^- \to \chi\chi + X$$

MONO-X

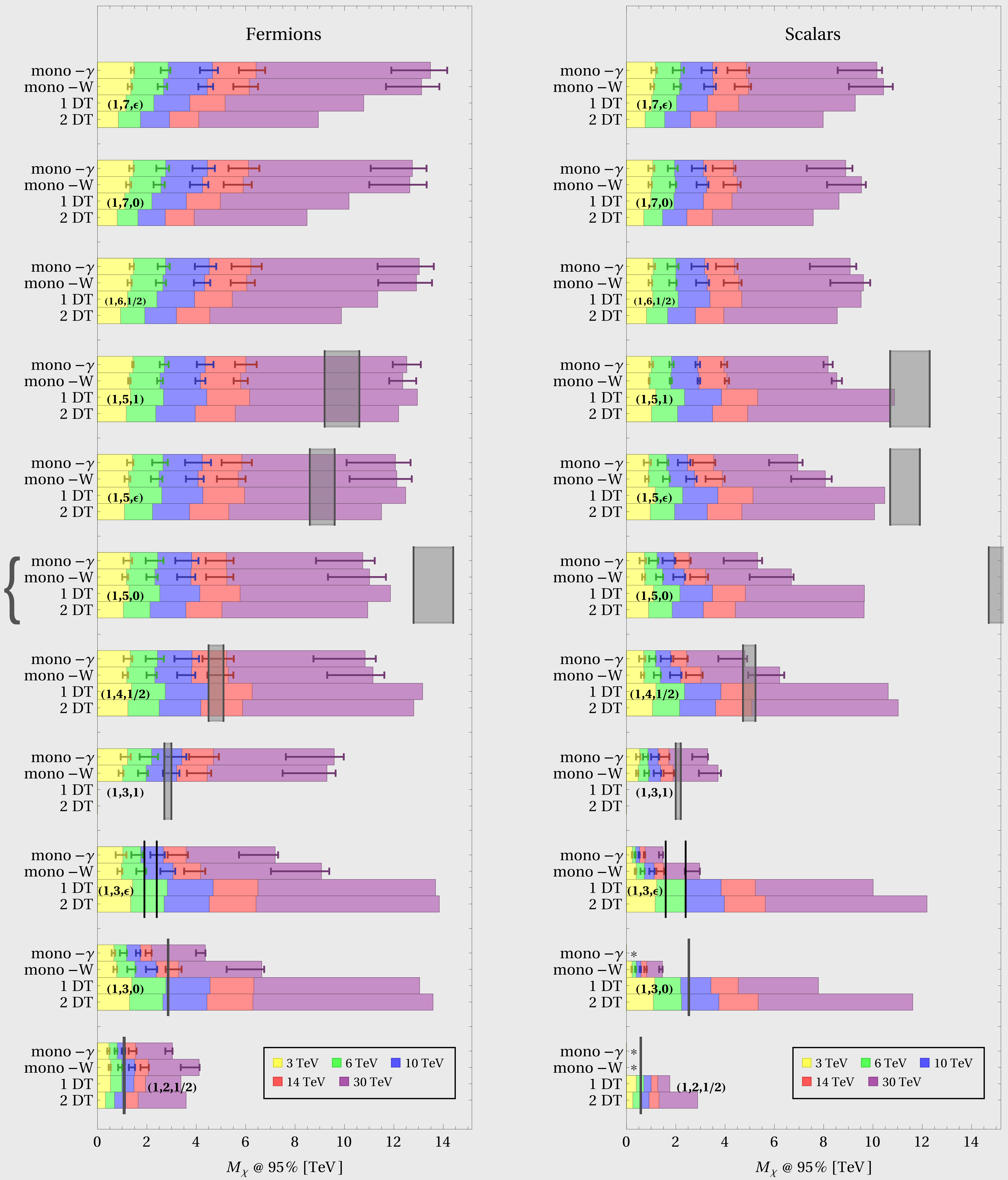
X $=\gamma, W, \ldots$



Large χ mass requires CoM energy!

Weak radiation yield the most constraining channel "mono-W"

mono-γ
mono-W
tracklets



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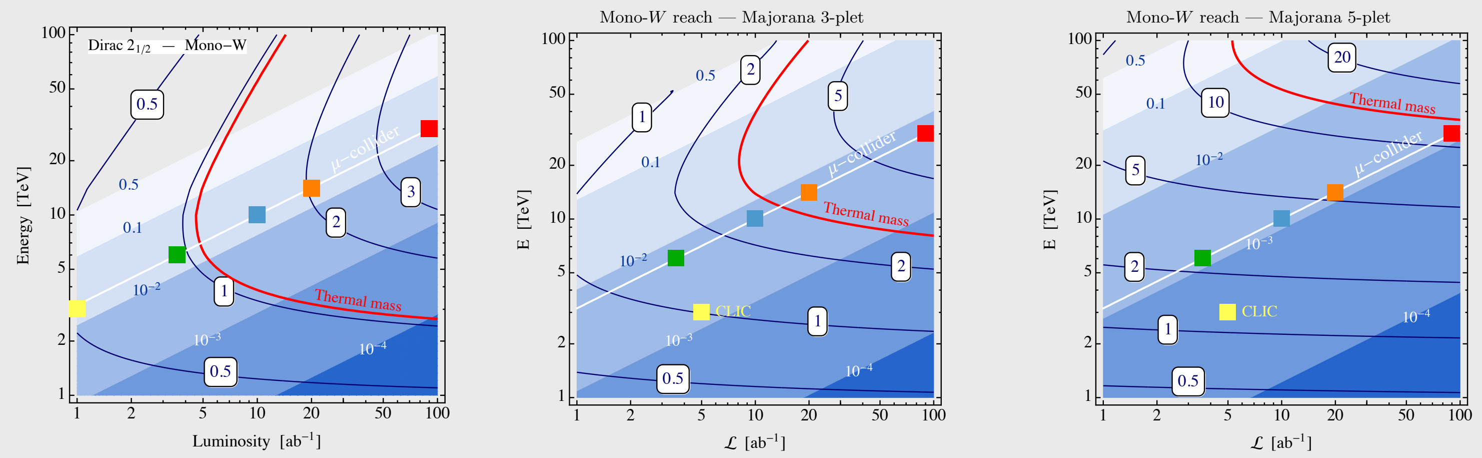
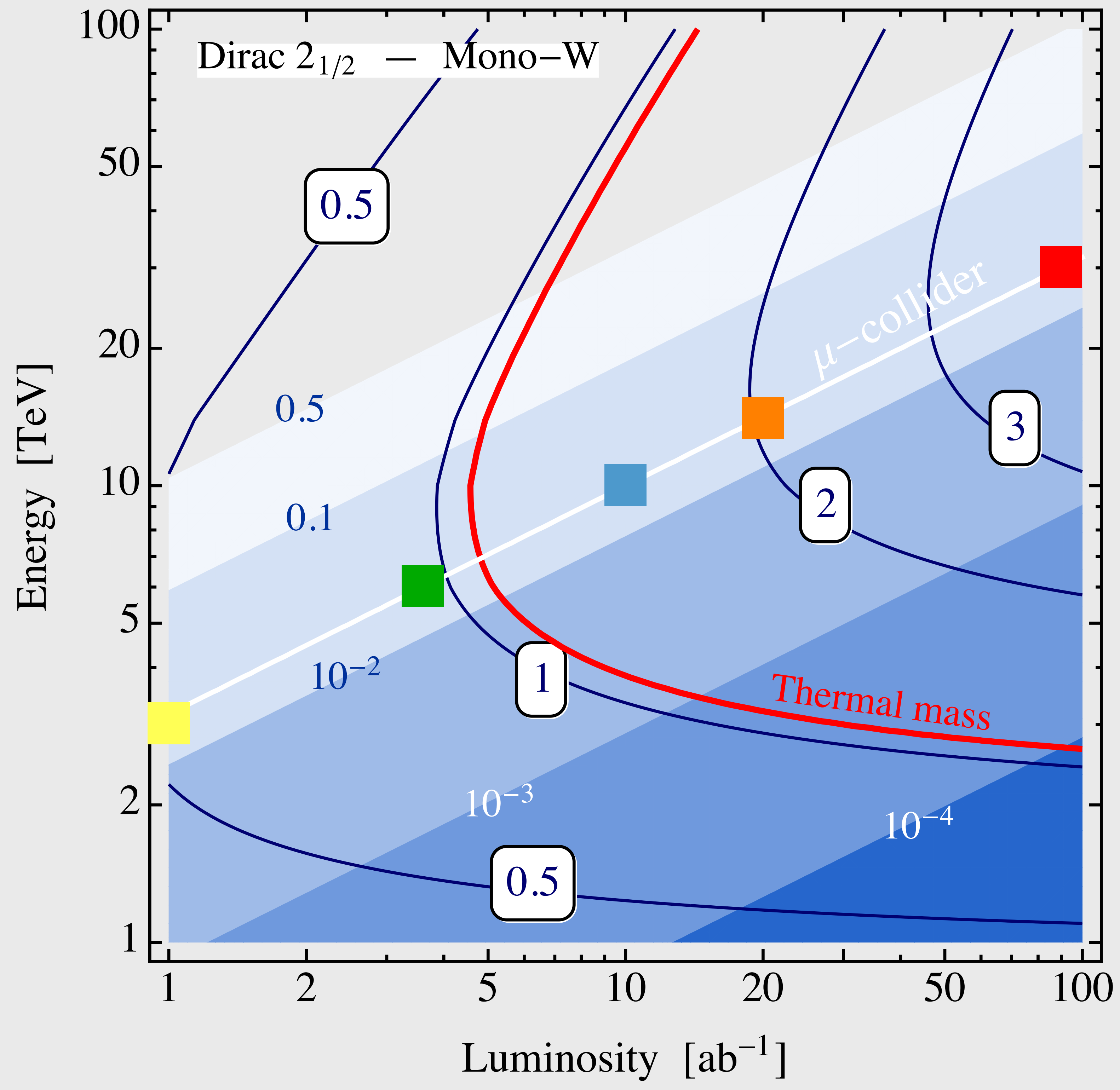
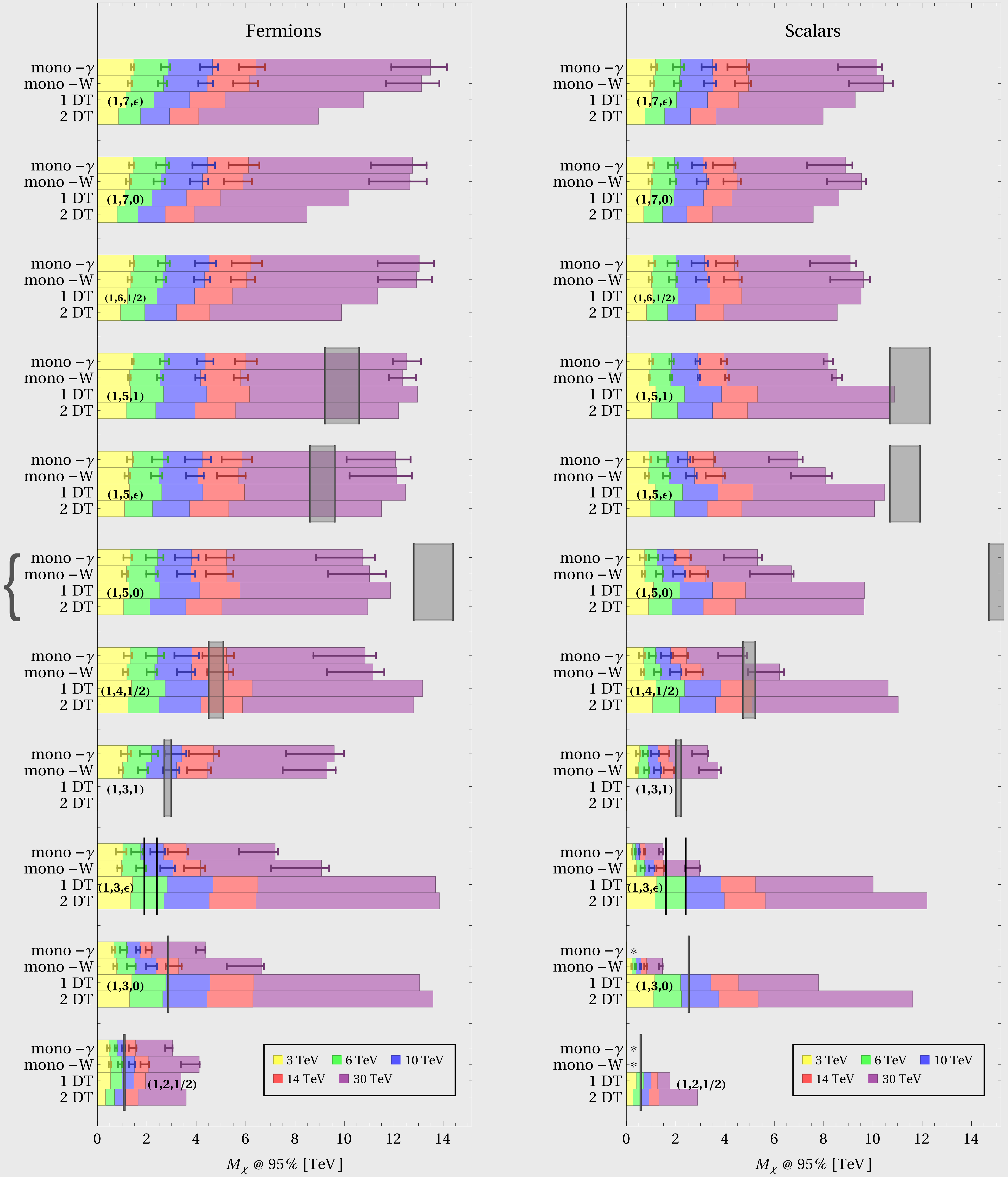


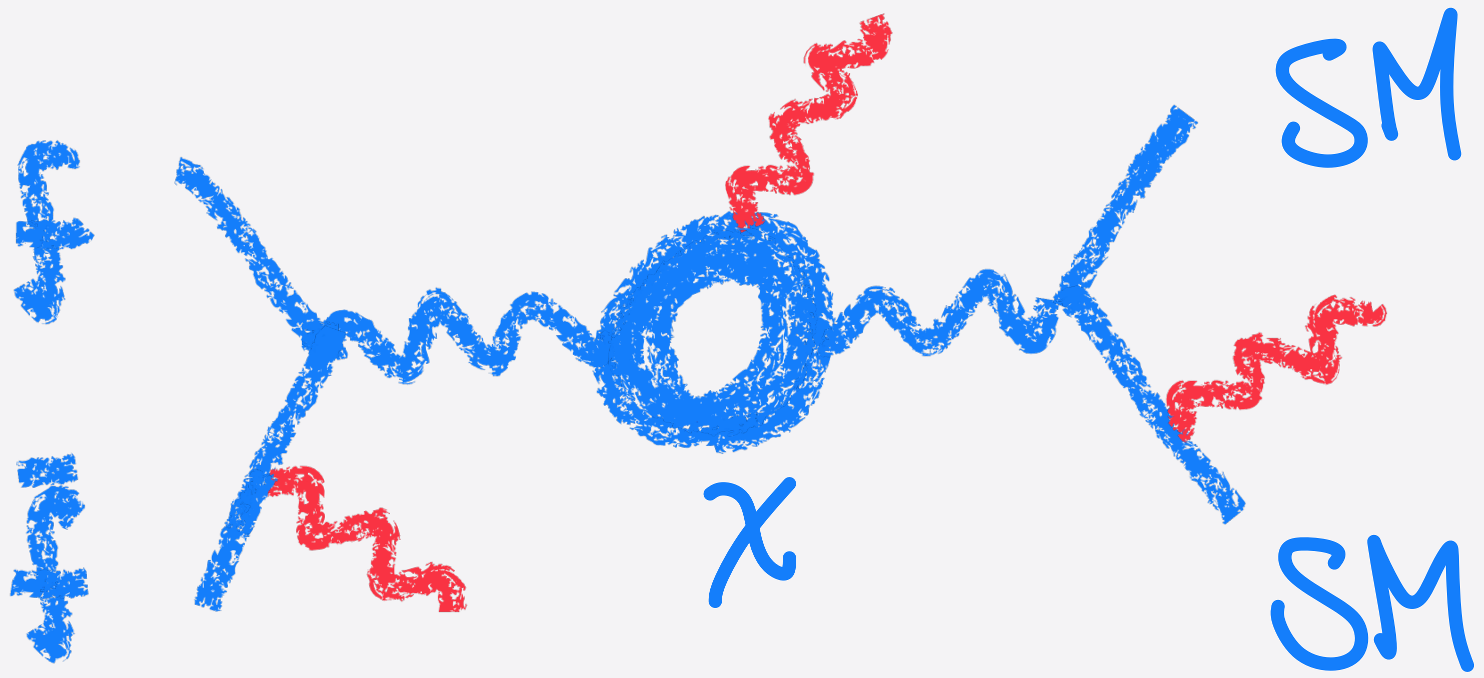


mono-γ
mono-W
tracklets

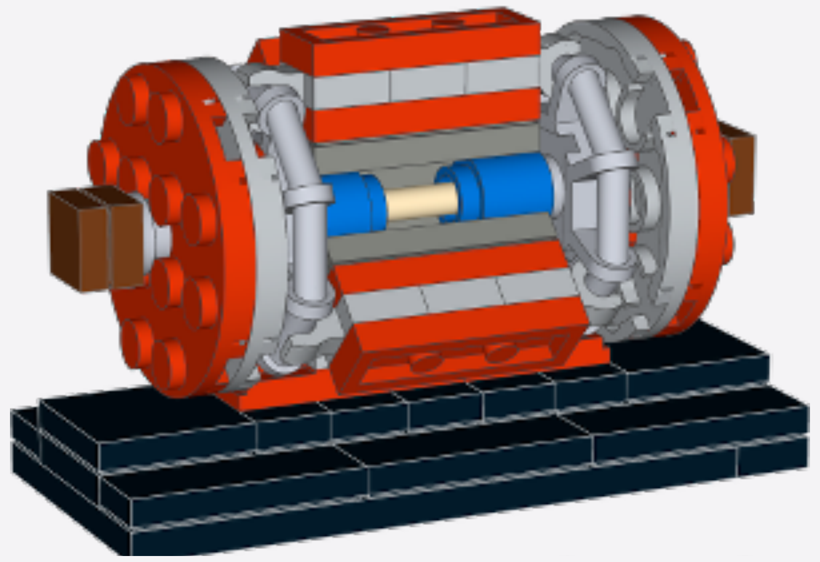


RF, Xiaoran Zhao in progress

VIRTUAL* PRODUCTION

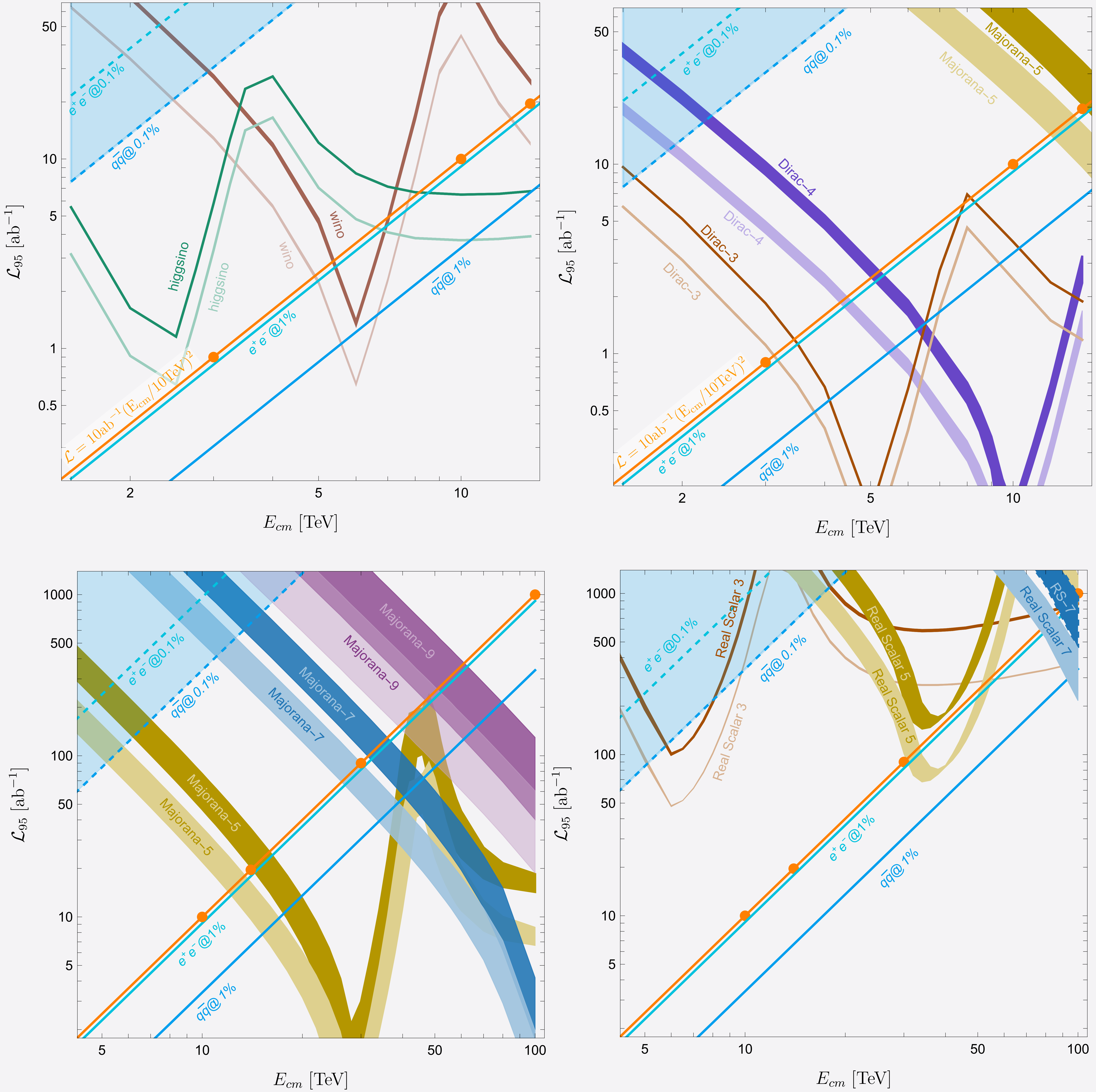


Virtual or propagating DM affects SM production rates



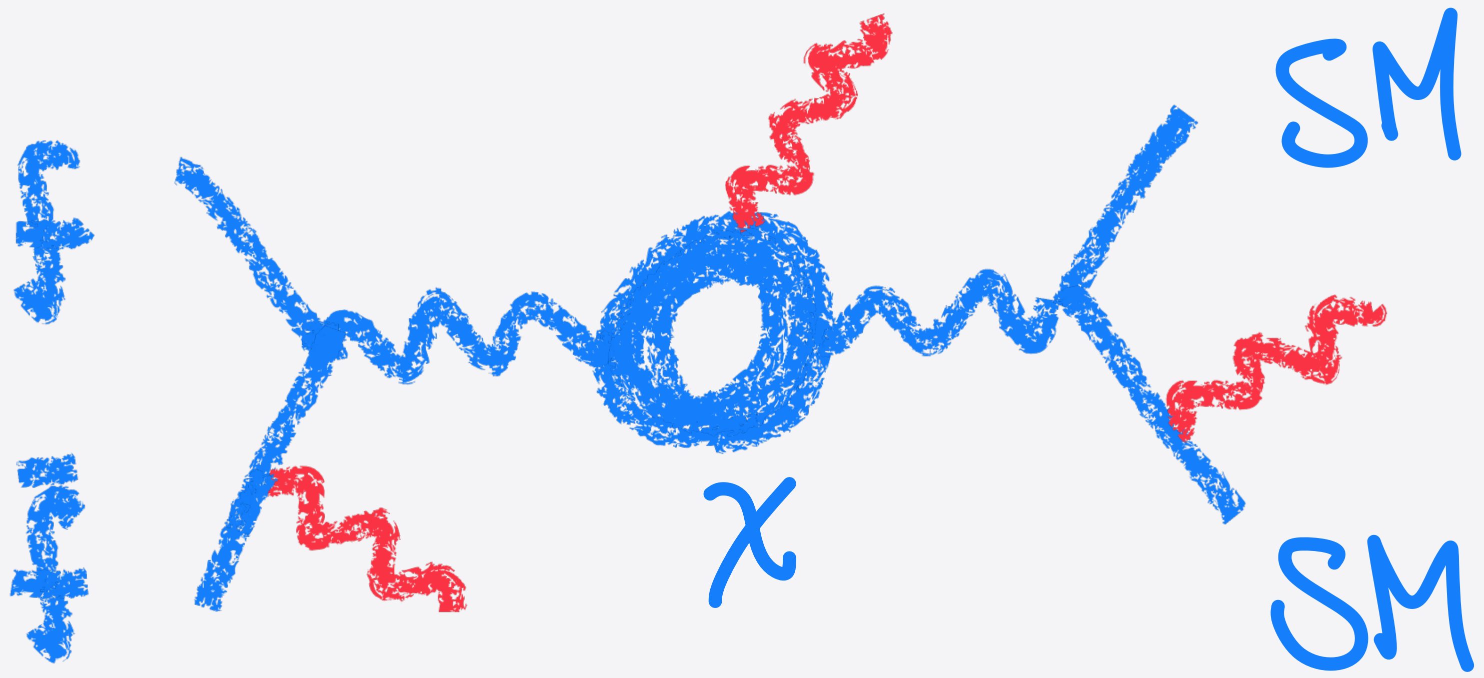
2040s

up to 10+ TeV



RF, Xiaoran Zhao in progress

VIRTUAL* PRODUCTION



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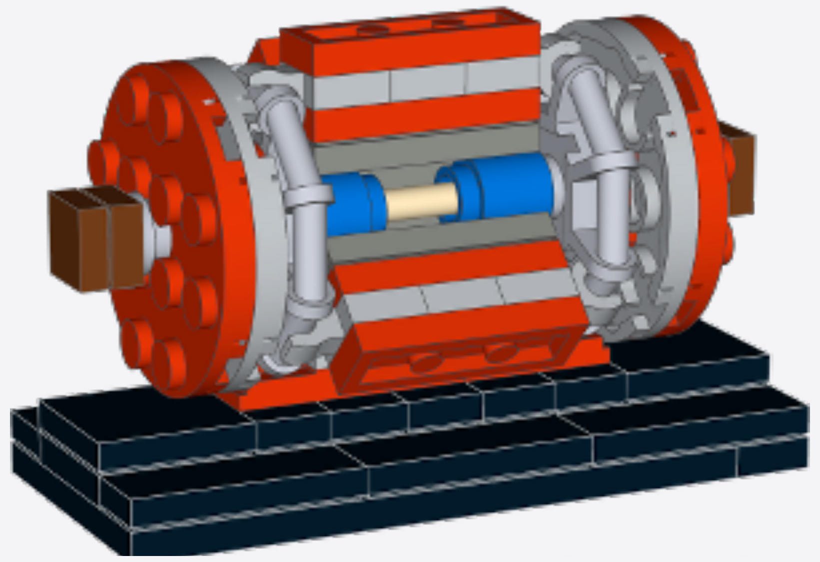
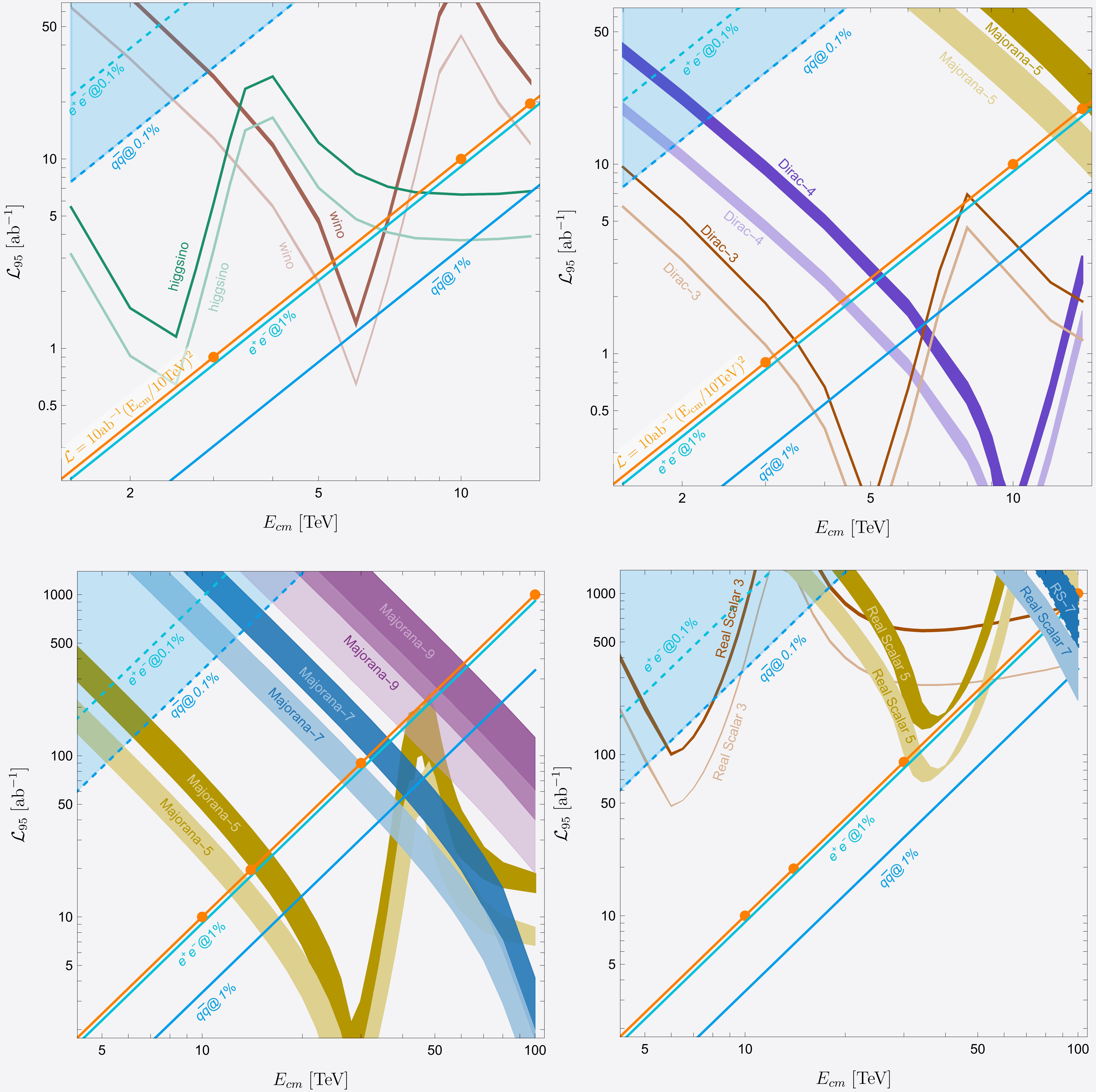


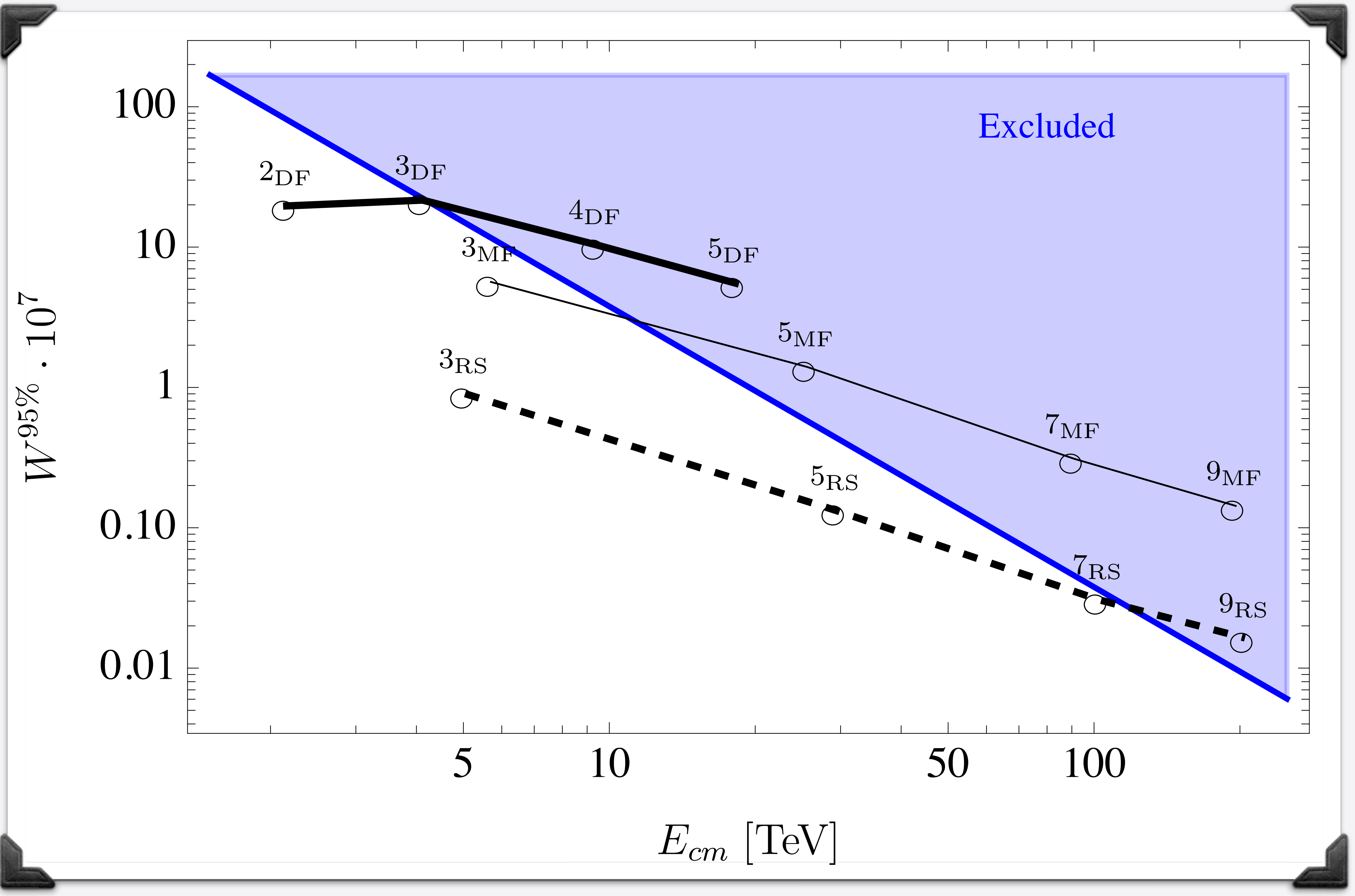
>2040s

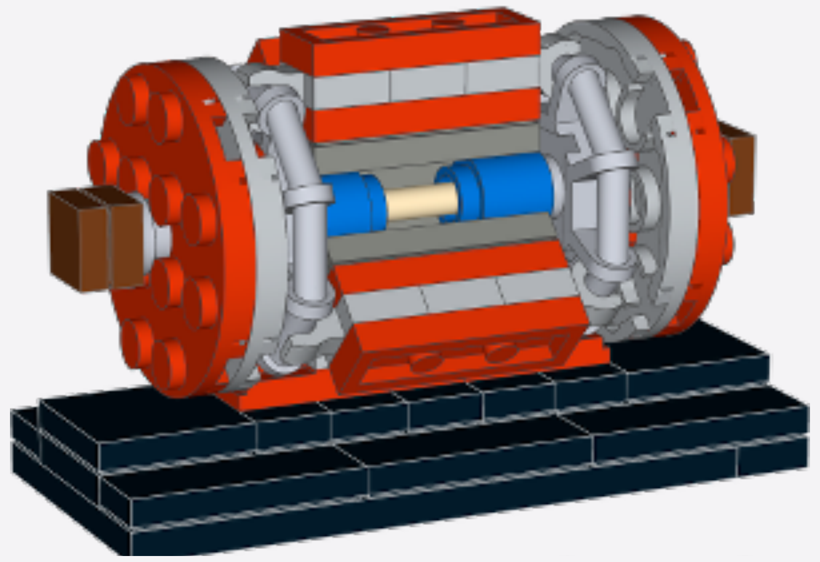
up to 100+ TeV



RF, Xiaoran Zhao in progress

VIRTUAL* PRODUCTION





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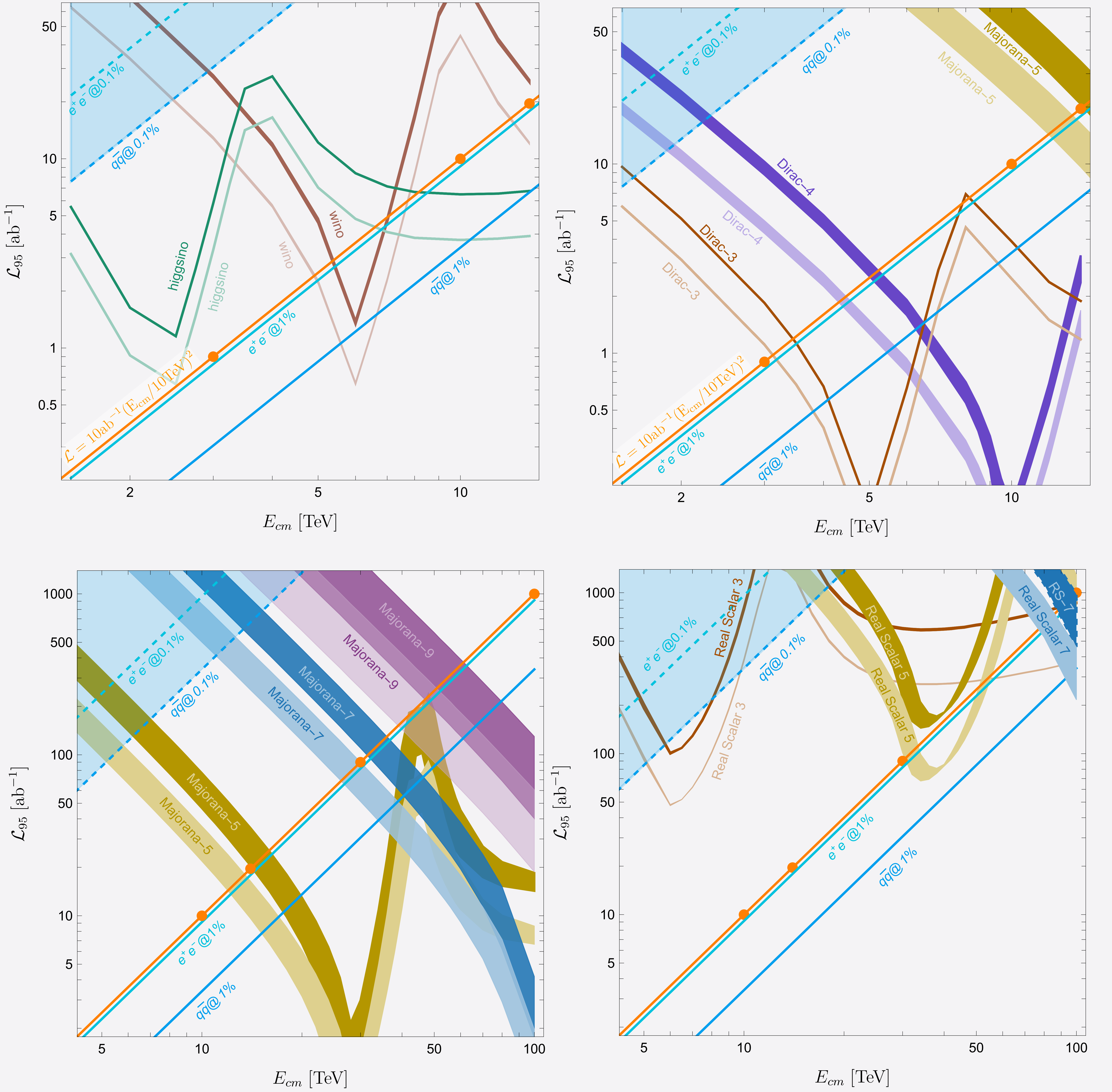

PRELIMINARY

DM spin	EW n-plet	M_χ (TeV)	$\Lambda_{\rm Landau}/M_\chi$	$(\sigma v)^{J=0}_{\rm tot}/(\sigma v)^{J=0}_{\rm max}$	ΔM_0 [MeV]	$\Lambda^{\rm max}_{\rm UV}(\Delta M_0^{\rm min})/M_\chi$	ΔM_- [MeV]
Complex scalar	2	0.58 ± 0.01	$> M_{\rm Pl}$	-	0.22 - 4.6×10^4	-	4.2 - 9600
	4	4.98 ± 0.05	$> M_{\rm Pl}$	0.004	0.22 - 10^4	-	3.2 - 2000
	6	34.9 ± 0.5	$\simeq 6 \times 10^{13}$	0.016	0.54 - 2300	-	280 - 660
	8	88 ± 2	2×10^4	0.12	0.89 - 1.2 $\times10^3$	-	324 - 507
	10	167 ± 4	20	0.45	1.27 - 800	-	340 - 450
Dirac fermion	2	1.08 ± 0.01	$> M_{\rm Pl}$	-	0.22 - 5000	2 $\times10^5$	4.8 - 7800
	4	4.8 ± 0.1	$\simeq M_{\rm Pl}$	0.013	0.21 - 2200	$\times10^5$	3.6 - 2600
	6	31.7 ± 0.5	2×10^4	0.057	0.51 - 510	$\times10^4$	185 - 780
	8	82 ± 2	14	0.37	0.86 - 800	3000	290 - 550

PRELIMINARY

DM spin	EW n-plet	M_χ (TeV)	$(\sigma v)^{J=0}_{\rm tot}/(\sigma v)^{J=0}_{\rm max}$	$\Lambda_{\rm Landau}/M_{\rm DM}$	$\Lambda_{\rm UV}/M_{\rm DM}$
Real scalar	3	2.53 ± 0.01	–	3×10^{37}	$4 \times 10^{24}*$
	5	15.4 ± 0.7	0.002	5×10^{36}	2×10^{24}
	7	54.2 ± 3.1	0.022	2×10^{19}	2×10^{24}
	9	117.8 ± 15.4	0.088	3×10^3	2×10^{24}
	11	199 ± 42	0.25	20	3×10^{24}
	13	338 ± 102	0.6	3.5	3×10^{24}
Majorana fermion	3	2.86 ± 0.01	–	3×10^{37}	$8 \times 10^{12}*$
	5	13.6 ± 0.8	0.003	3×10^{17}	5×10^{12}
	7	48.8 ± 3.3	0.019	1×10^4	4×10^7
	9	113 ± 15	0.07	30	3×10^7
	11	202 ± 43	0.2	6	3×10^7
	13	324.6 ± 94	0.5	2.6	3×10^7

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Monte Carlo Tools

[Mario Chiesa]

Conclusions

- only few MC event generators for high-energy μ-colls available, generally only at LO accuracy
- in principle it is possible to transpose all the technology developed for high-precision generators for hadron colliders to the leptonic environment
- in practice, some new challenges arise, mainly connected to the large $\sqrt{s}$ and the large final-state multiplicities, Sudakov corrections

EW and QCD physics at the muon collider

[Yang Ma]

Improving understanding of **partons in the proton**

MuC is **also** a Vector Bosons Collider

(but **also** a muon collider: this is its **dual** nature)

Compare the "EW LHC" with LHC

pp VS $\mu\mu$

$$\mathcal{L}_{W^+_{\lambda_1}W^-_{\lambda_2}} = \int_\tau^1 \frac{\mathrm{d}\xi}{\xi} f_{W_{\lambda_1}}(\xi,\mu_f) f_{W_{\lambda_1}}(\frac{\tau}{\xi},\mu_f)$$

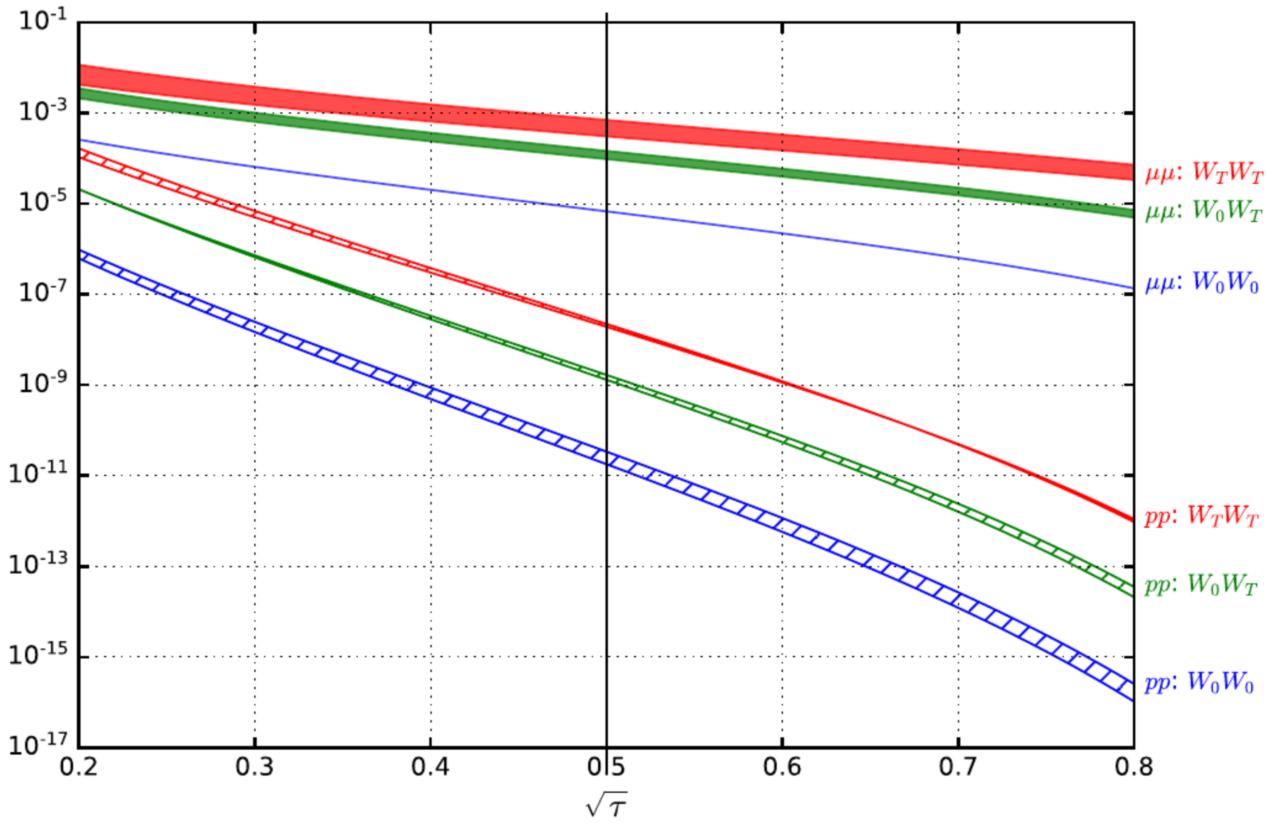
Consider the two colliders in the same ring

$$\sqrt{s}_{\mu\mu} = \sqrt{s}_{pp}$$

For $2 \to 1$ processes, take a benchmark

$$\sqrt{\tau} = \frac{M}{\sqrt{s}} = \frac{1}{2}$$

The ratio $\mu\mu/pp$ is larger than 10^4!



[2005.10289]

PARALLEL TALKS

The physics case of a very forward muons detector — *Maximilian Ruhdorfer*

40/S2-D01 - Salle Dirac, CERN — 09:00 - 09:30

The physics case of a very forward muon detector

Maximilian Ruhdorfer
Cornell University

International MUON Collider Collaboration

Muon Collider Collaboration Meeting
October 12, 2022

Work in progress
with R. Masarotti, E. Salvioni *and* A. Wulzer

The physics case of a very forward muons detector *Maximilian Ruhdorfer*

40/S2-D01 - Salle Dirac, CERN 09:00 - 09:30

This Talk

ϕ can be Dark Matter

ϕ can be part of the model that stabilizes the Higgs mass

ϕ can modify the Higgs potential

1. Physics case for very forward muon detector (idealized)

- Focus on scalar Higgs portal to invisible new physics

$$-\frac{\lambda}{2}\phi^2|H|^2$$

marginal portal

$$\frac{c_d}{2f^2}\partial_\mu\phi^2\partial^\mu|H|^2$$

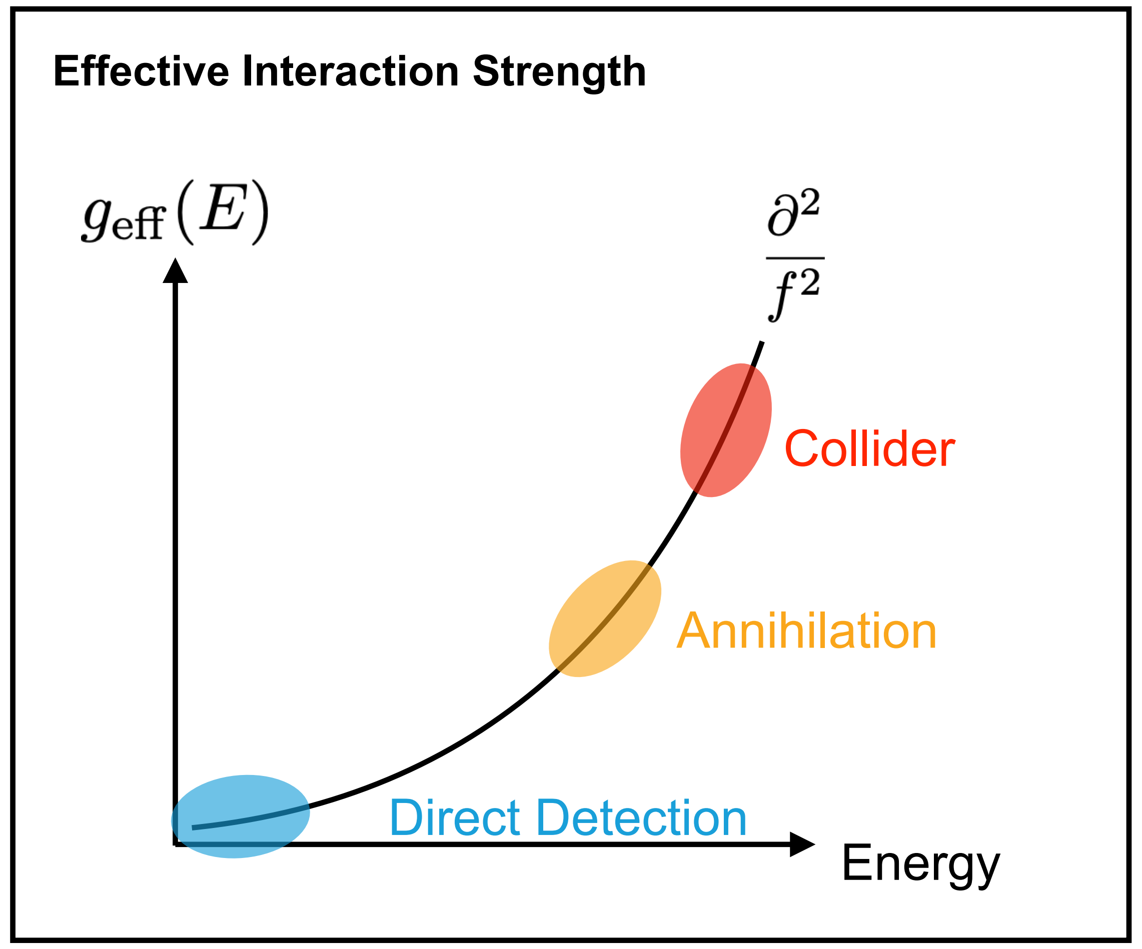
derivative portal

- Assume perfect resolution of MIM,…

2. Realistic case study: invisible Higgs decays

- Include accelerator and detector effects (beam energy spread,…)
- New BGs become important

ϕ can be Dark Matter



RUDHORFER

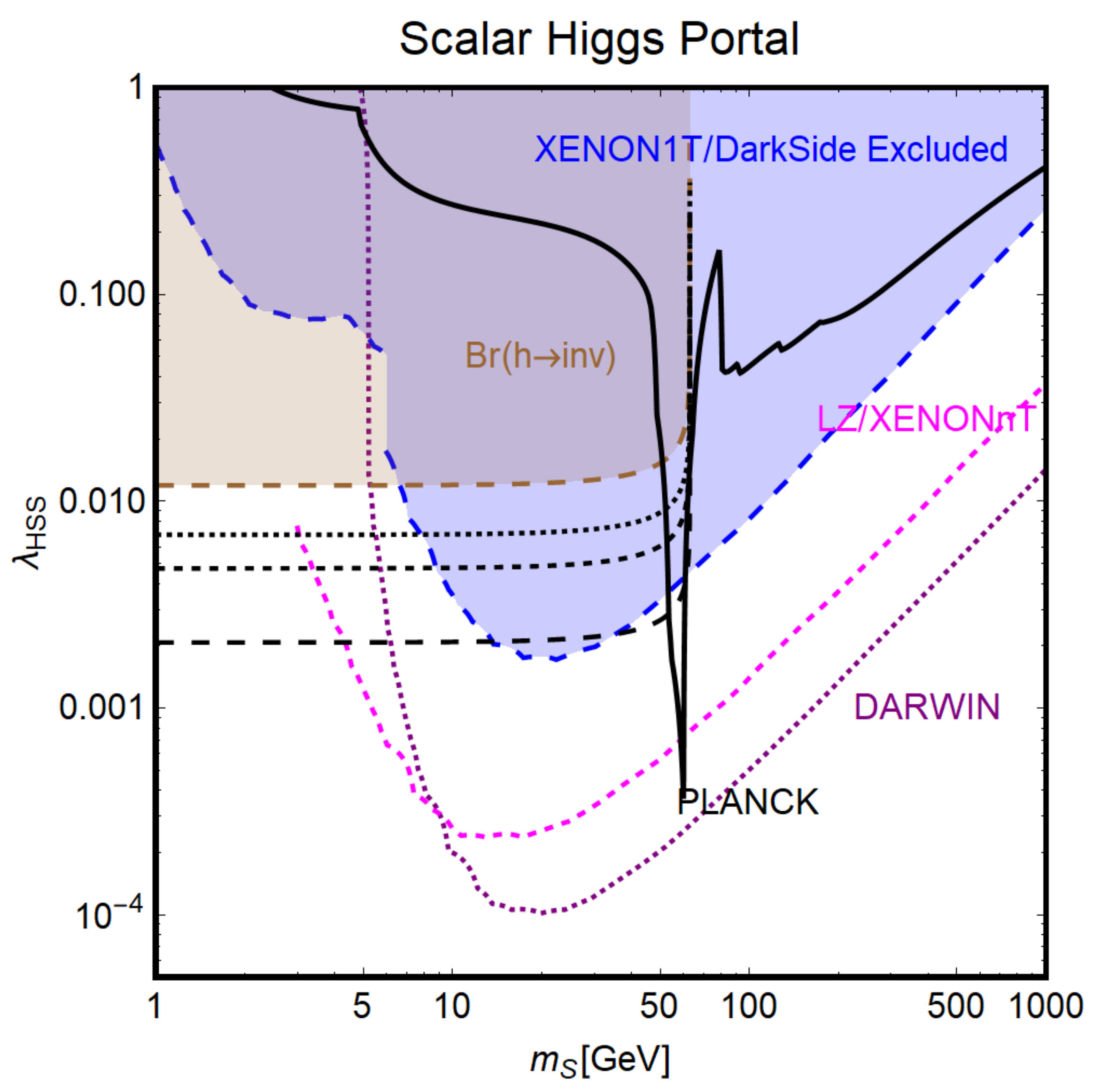
The physics case of a very forward muons detector *Maximilian Ruhdorfer*

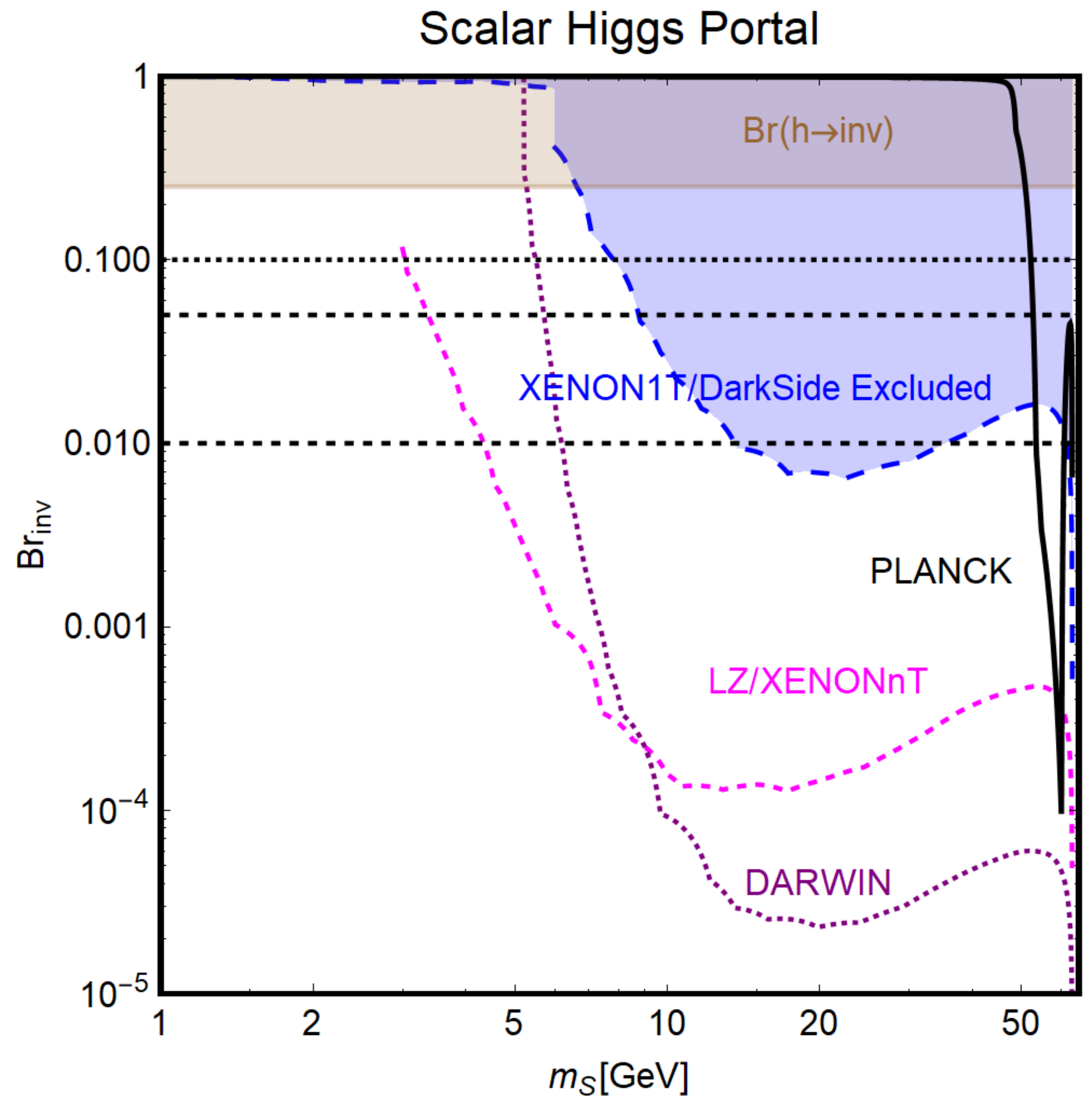
40/S2-D01 - Salle Dirac, CERN 09:00 - 09:30

ϕ can be Dark Matter

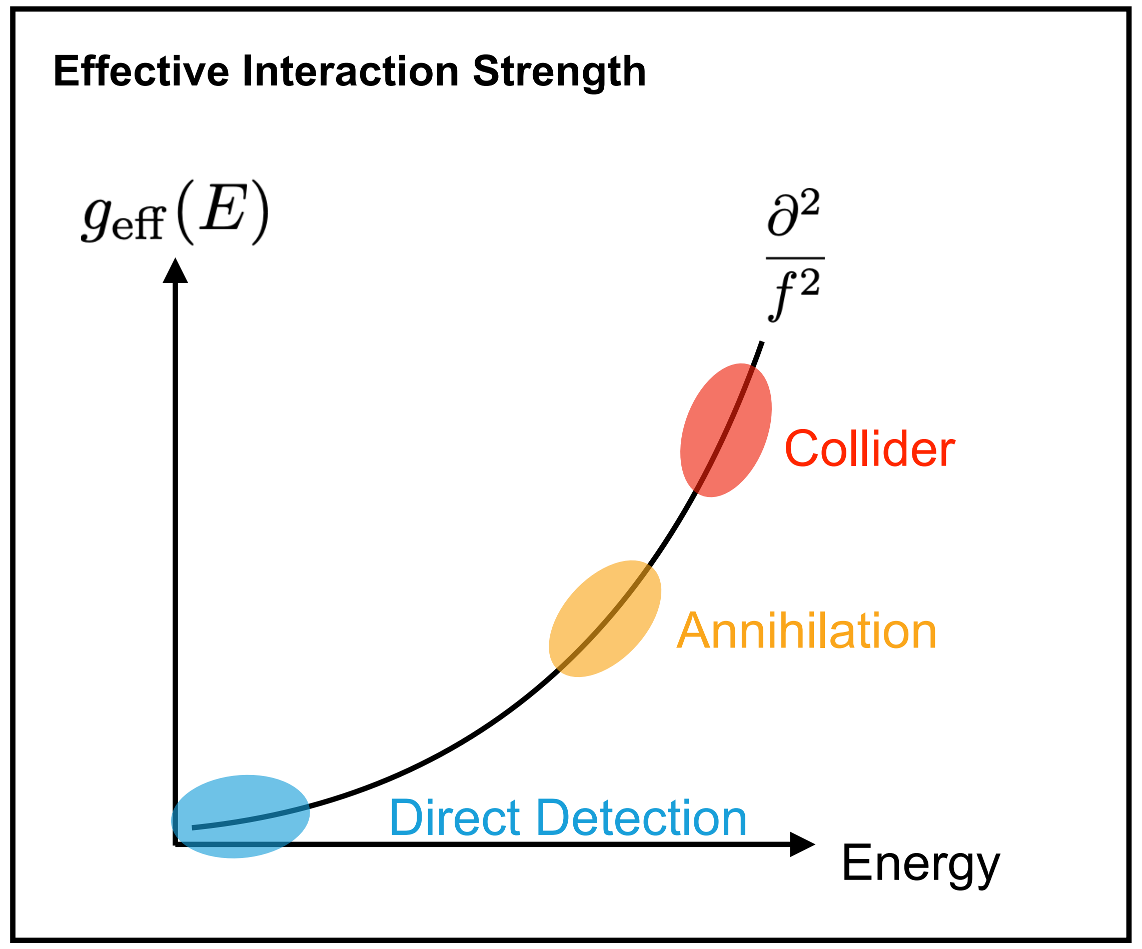
ϕ can be part of the model that stabilizes the Higgs mass

ϕ can modify the Higgs potential





ϕ can be Dark Matter



Goldstone bosons tend to not be stable, e.g. $\pi^0 \to \gamma\gamma$

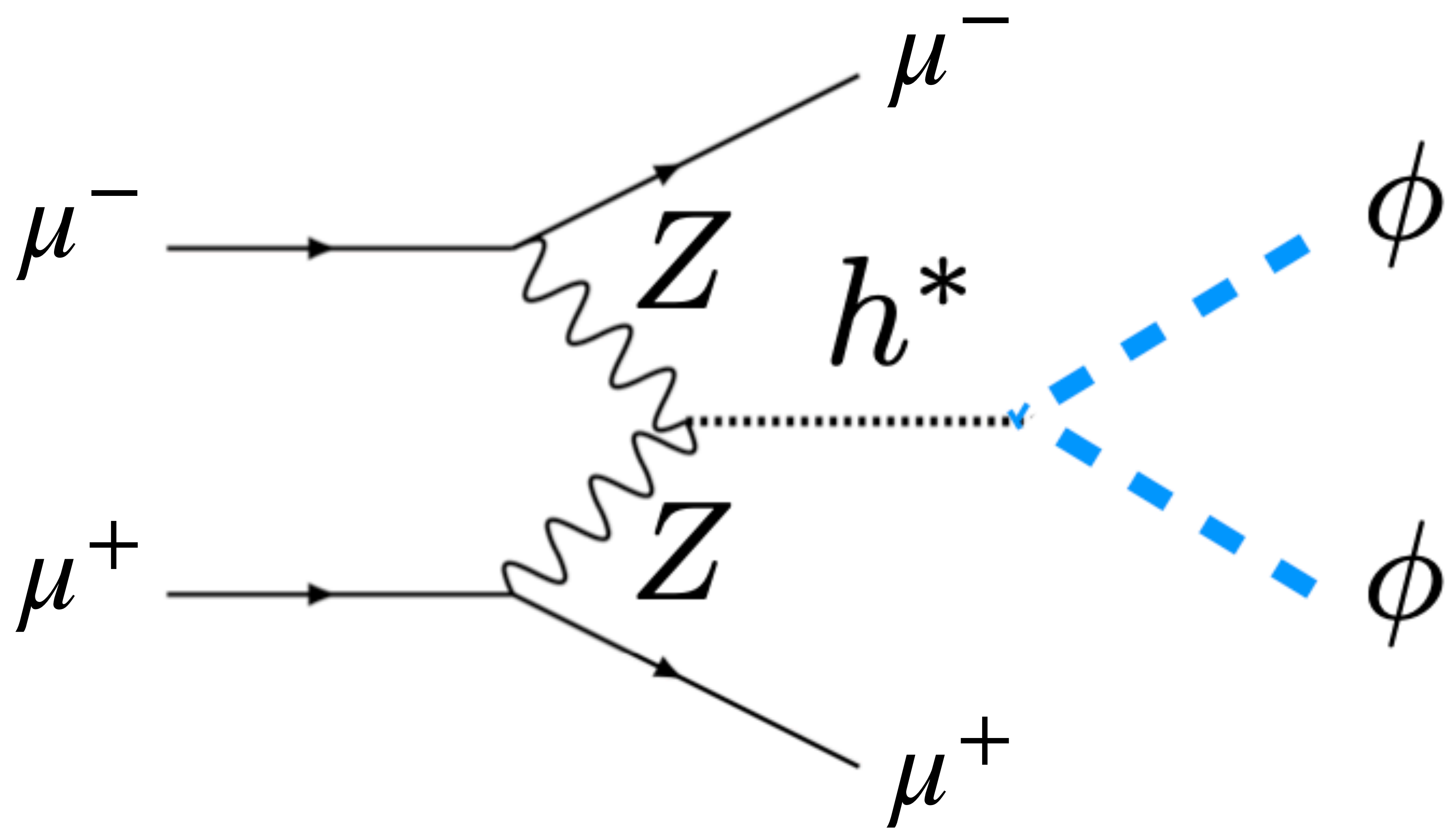
Stability of ϕ is unwarranted unless a symmetry is imposed

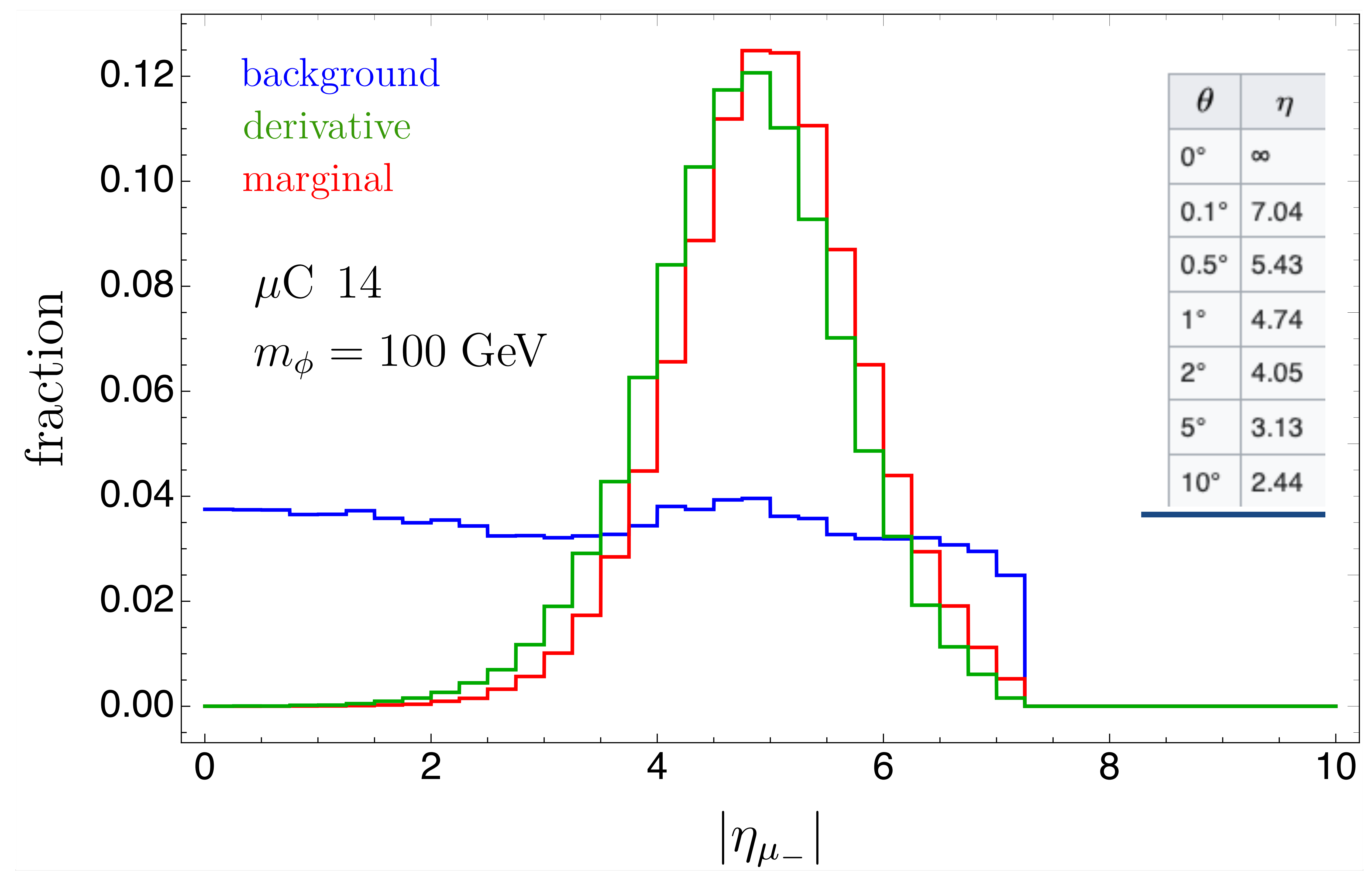
RUDHORFER

The physics case of a very forward muons detector *Maximilian Ruhdorfer*

40/S2-D01 - Salle Dirac, CERN 09:00 - 09:30

Main BG: $\mu^-\mu^+ \to \mu^-\mu^+\nu\bar{\nu}$





θ	η
0°	∞
0.1°	7.04
0.5°	5.43
1°	4.74
2°	4.05
5°	3.13
10°	2.44

Assume for now coverage of $|\eta_\mu| < 6$

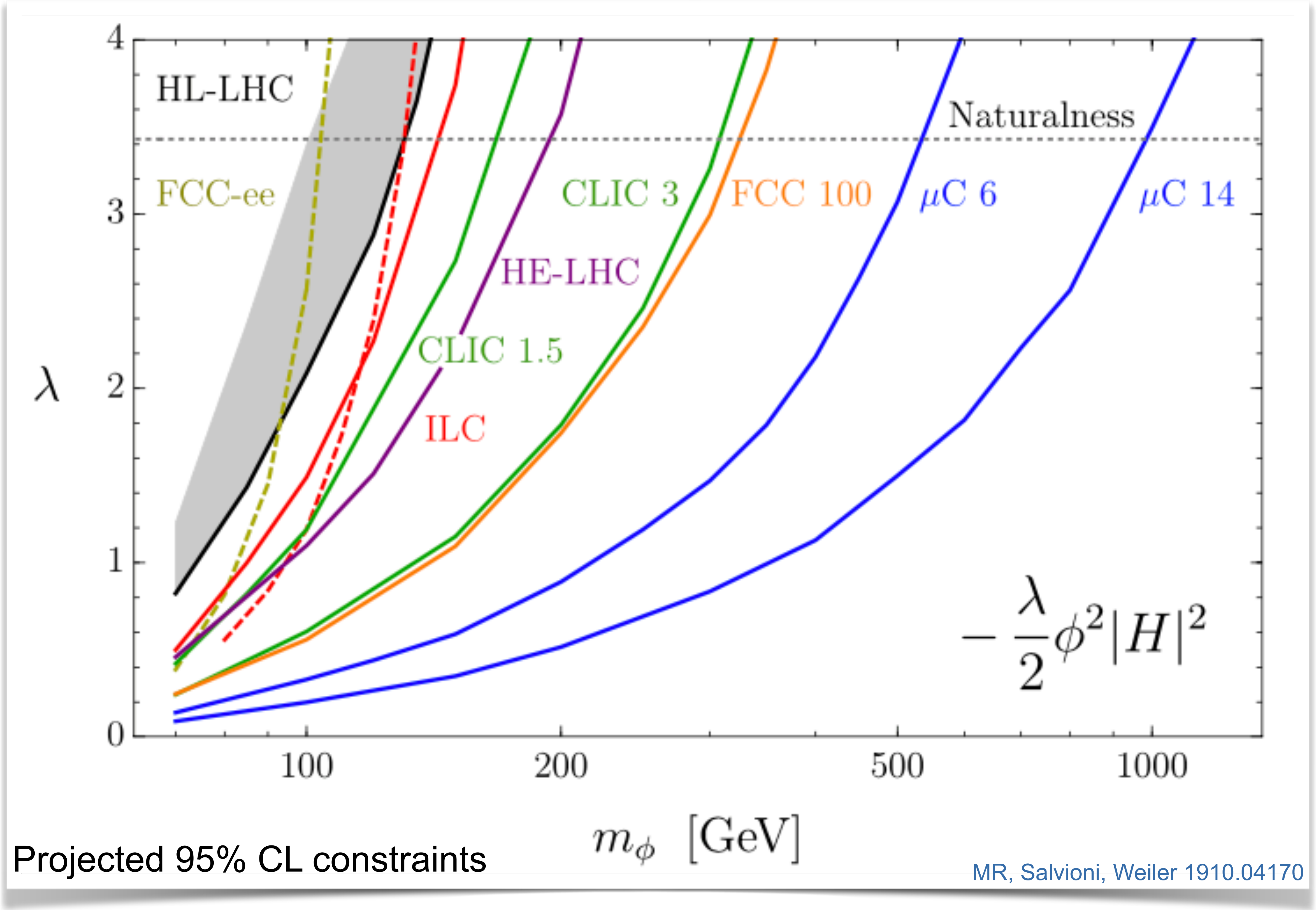
RUDHORFER

The physics case of a very forward muons detector — *Maximilian Ruhdorfer*

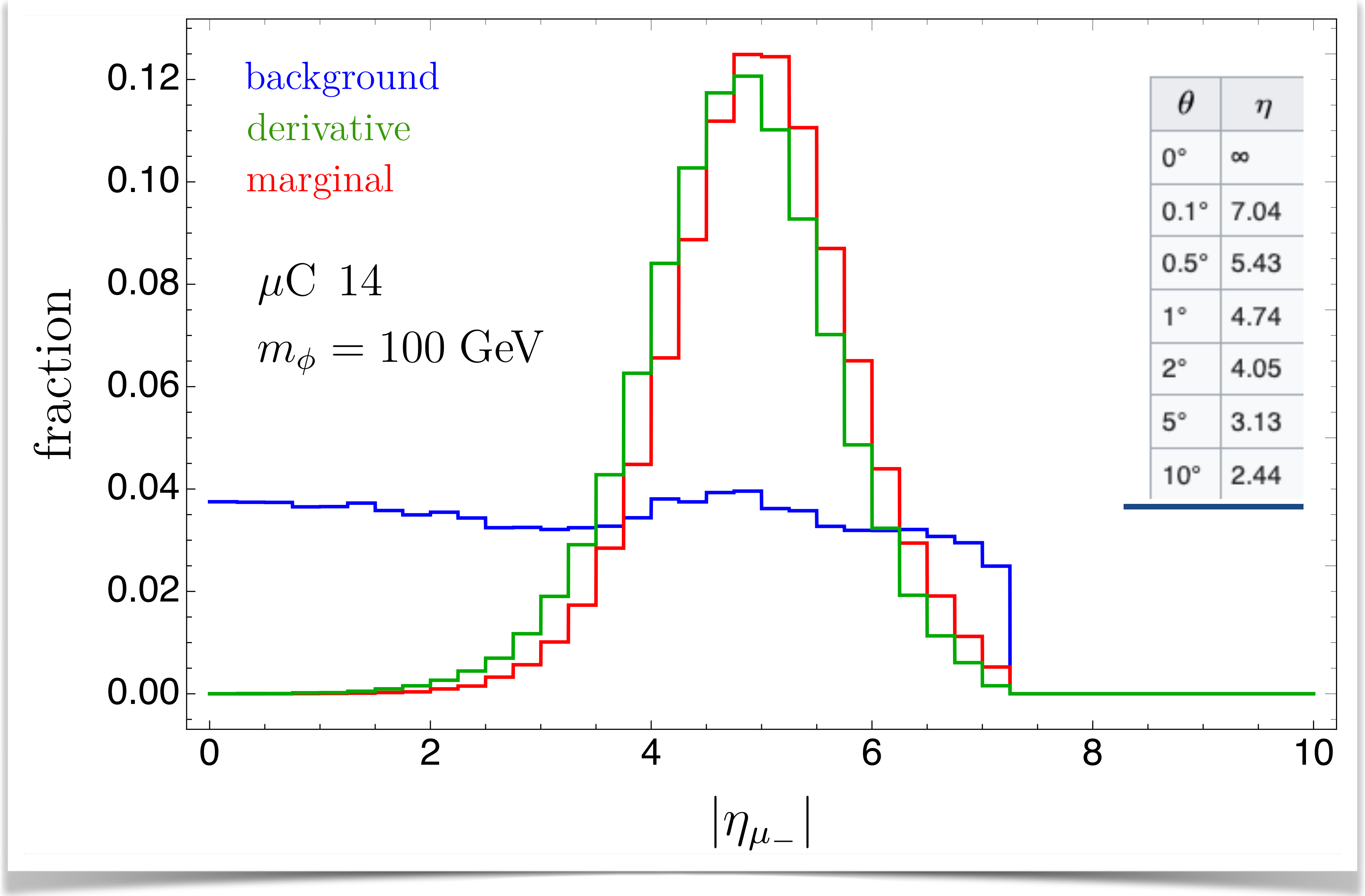
40/S2-D01 - Salle Dirac, CERN — 09:00 - 09:30

$$\lambda = \sqrt{4N_c\, y_t^2} \approx 3.4$$

	HL-LHC	CLIC 1.5	HE-LHC	CLIC 3	FCC 100	μC 6	μC 14
m_ϕ [GeV]	130	170	190	310	330	540	990



Main BG: $\mu^-\mu^+ \to \mu^-\mu^+\nu\bar{\nu}$



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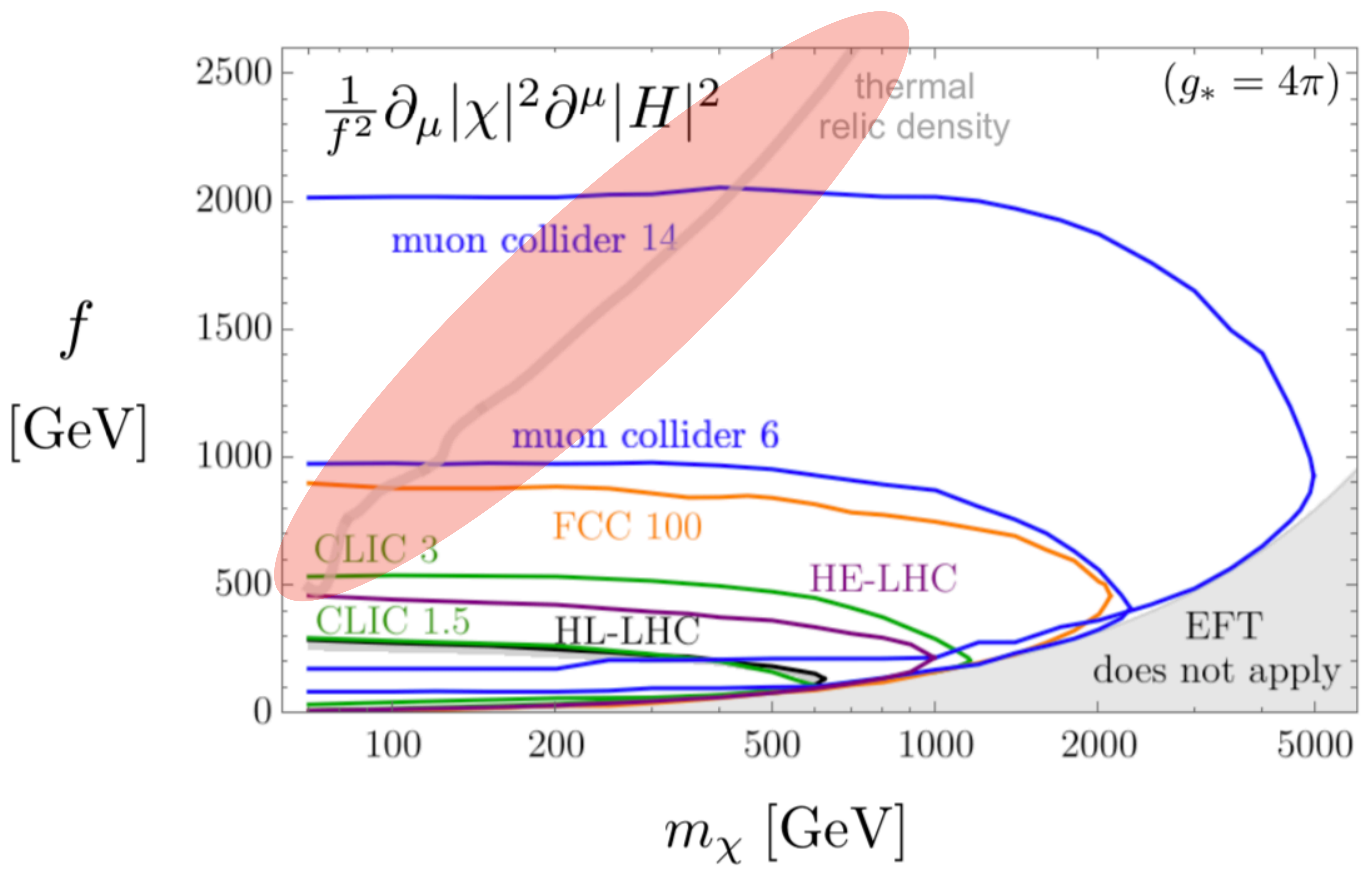
RUDHORFER

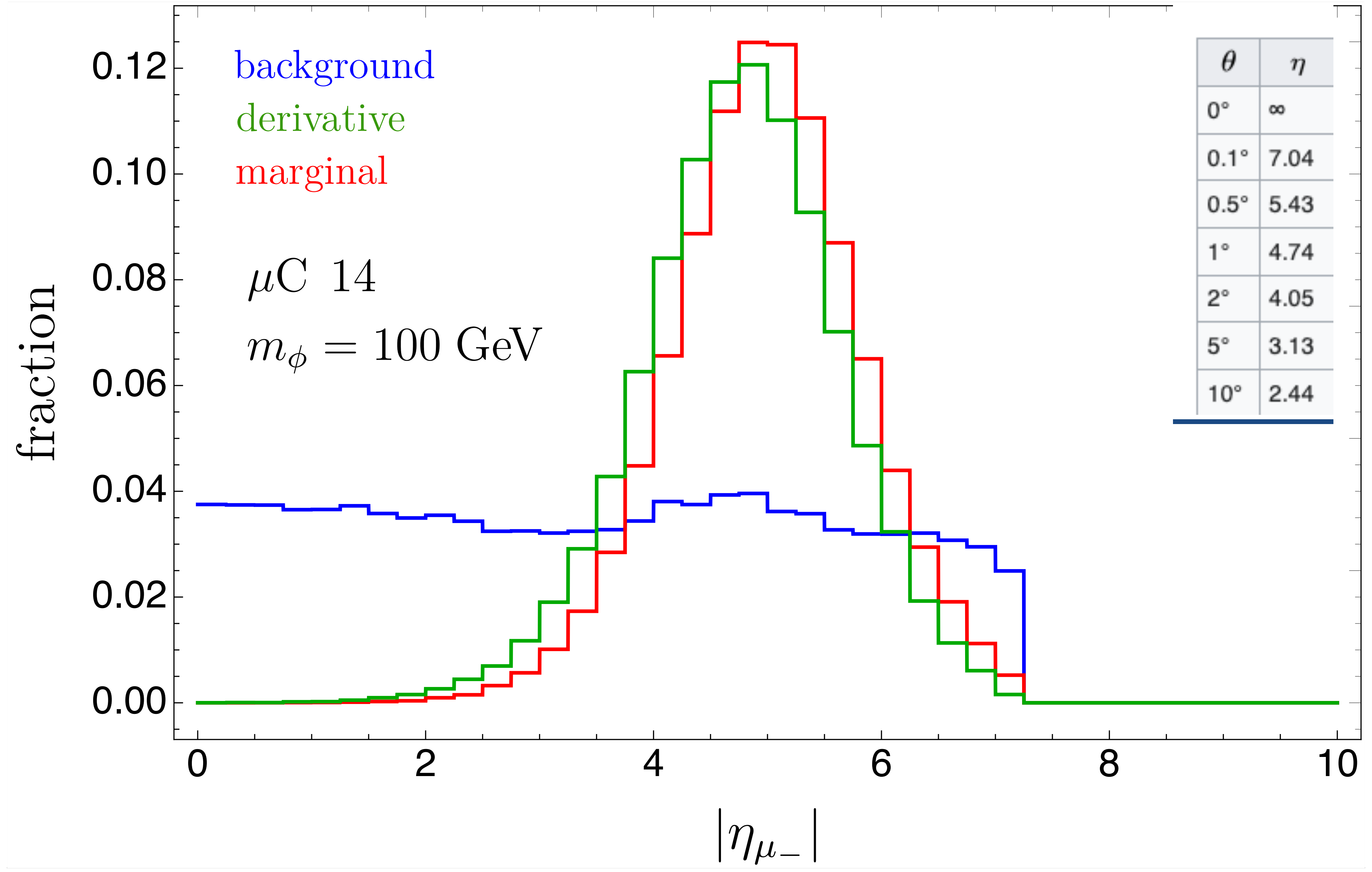
The physics case of a very forward muons detector	*Maximilian Ruhdorfer*
40/S2-D01 - Salle Dirac, CERN	09:00 - 09:30



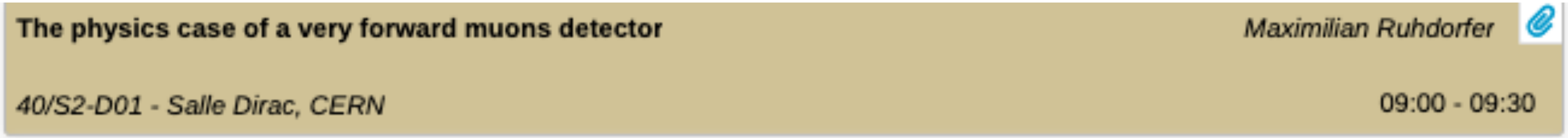
Projected 95% CL constraints

MR, Salvioni, Weiler 1910.04170

Main BG: $\mu^-\mu^+ \to \mu^-\mu^+\nu\bar{\nu}$

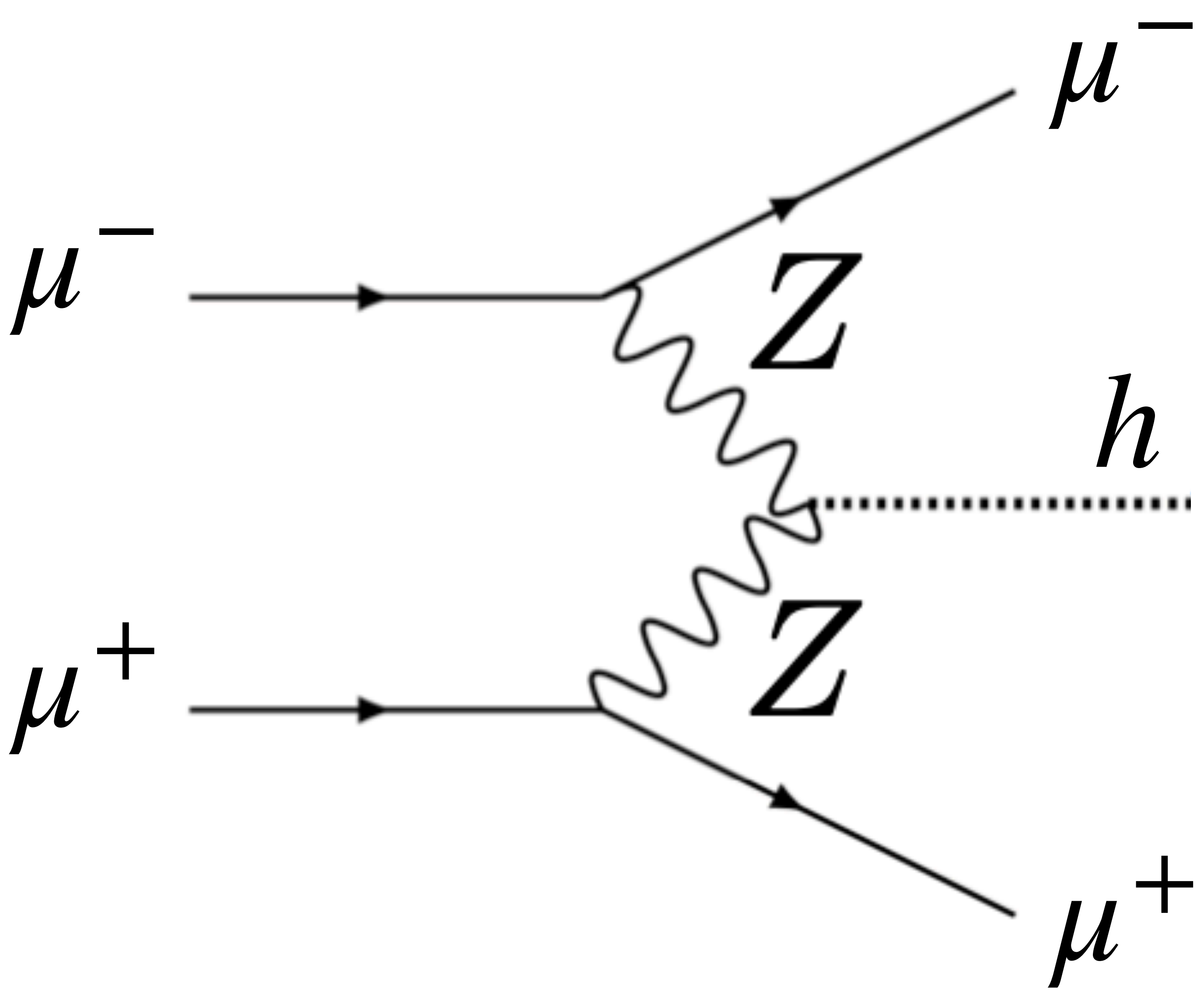


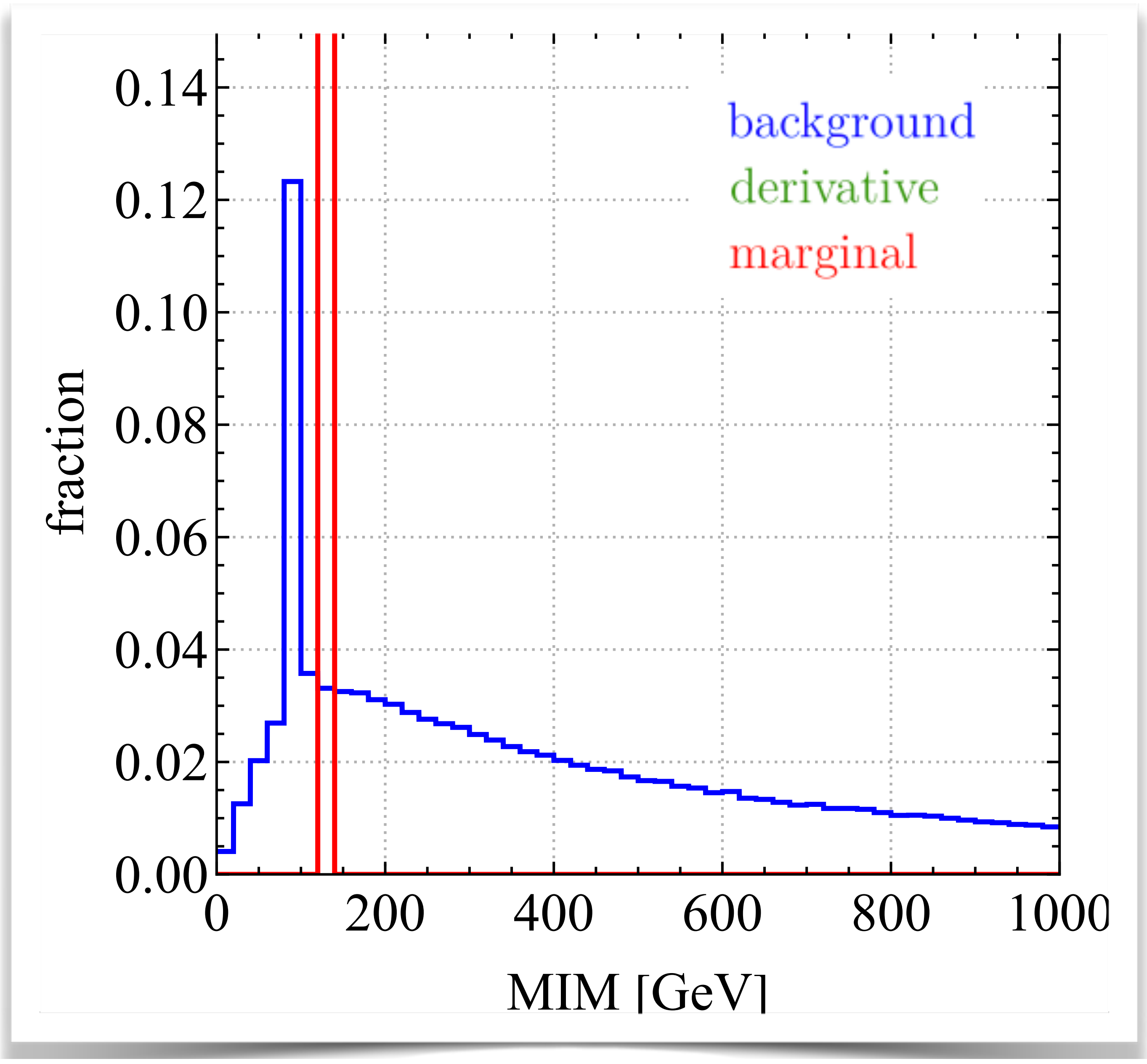
Assume for now coverage of $|\eta_\mu| < 6$



A realistic benchmark: invisible Higgs decays

- At FCC-hh: $\mathrm{BR}(h \to \mathrm{inv}) < 2.5 \cdot 10^{-4}$ FCC Collaboration '19





→ $\mathrm{MIM} \in [120, 130]$ GeV

- Cut on $\mathrm{MIM}, M_{\mu\mu}, \Delta\eta_{\mu\mu}, \not{E}_T, \min(E_{\mu^-}, E_{\mu^+})$

RUDHORFER

The physics case of a very forward muons detector *Maximilian Ruhdorfer*

40/S2-D01 - Salle Dirac, CERN 09:00 - 09:30

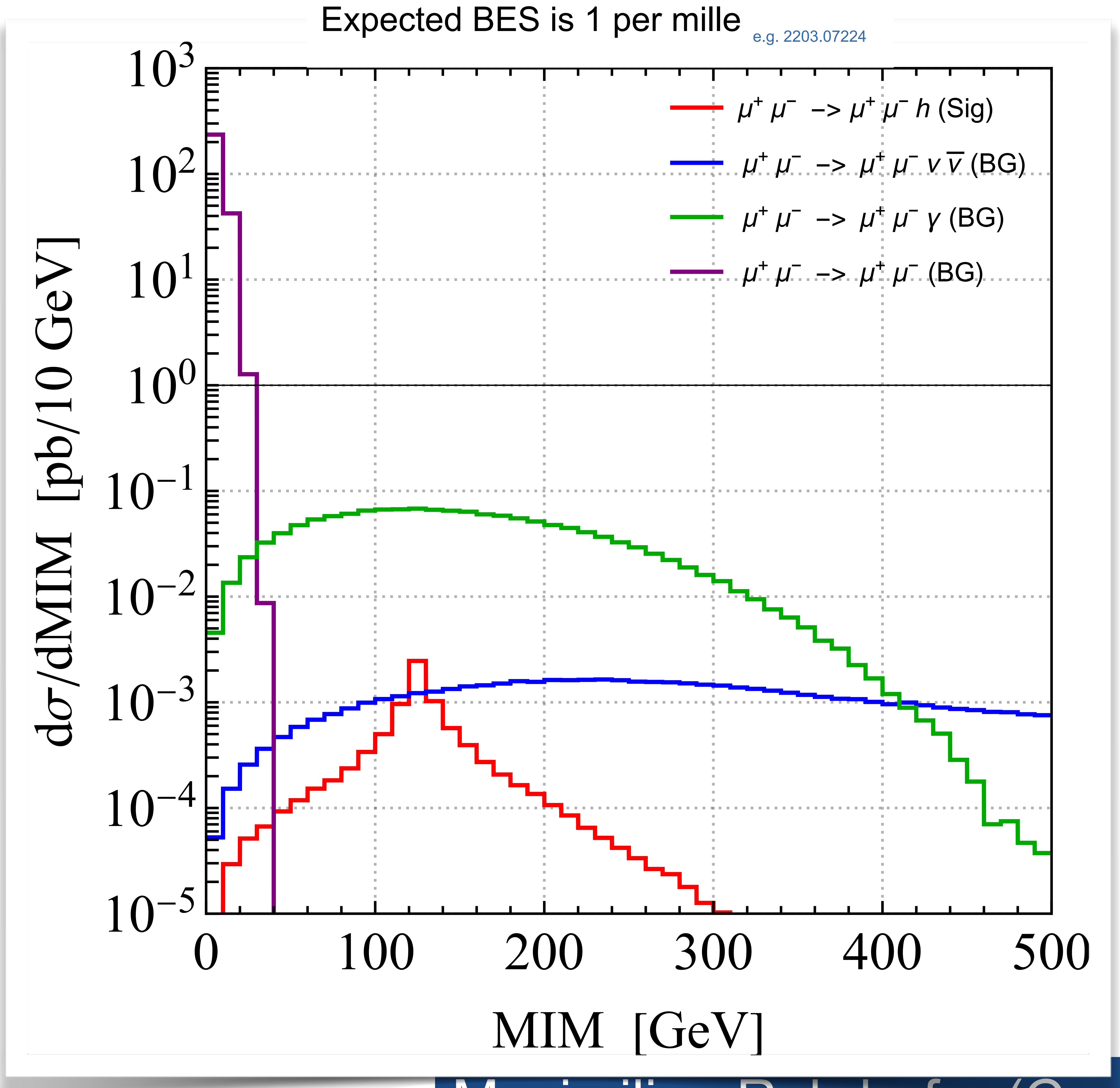
$$\not{p} = (\sqrt{s}, \vec{0}) - p_{\mu^+} - p_{\mu^-} + \ ?$$

1. Beam energy spread (BES)

2. Beam angular spread (BAS)

3. Uncertainty in energy measurement

4. Lost particles (especially photons)



RUDHORFER

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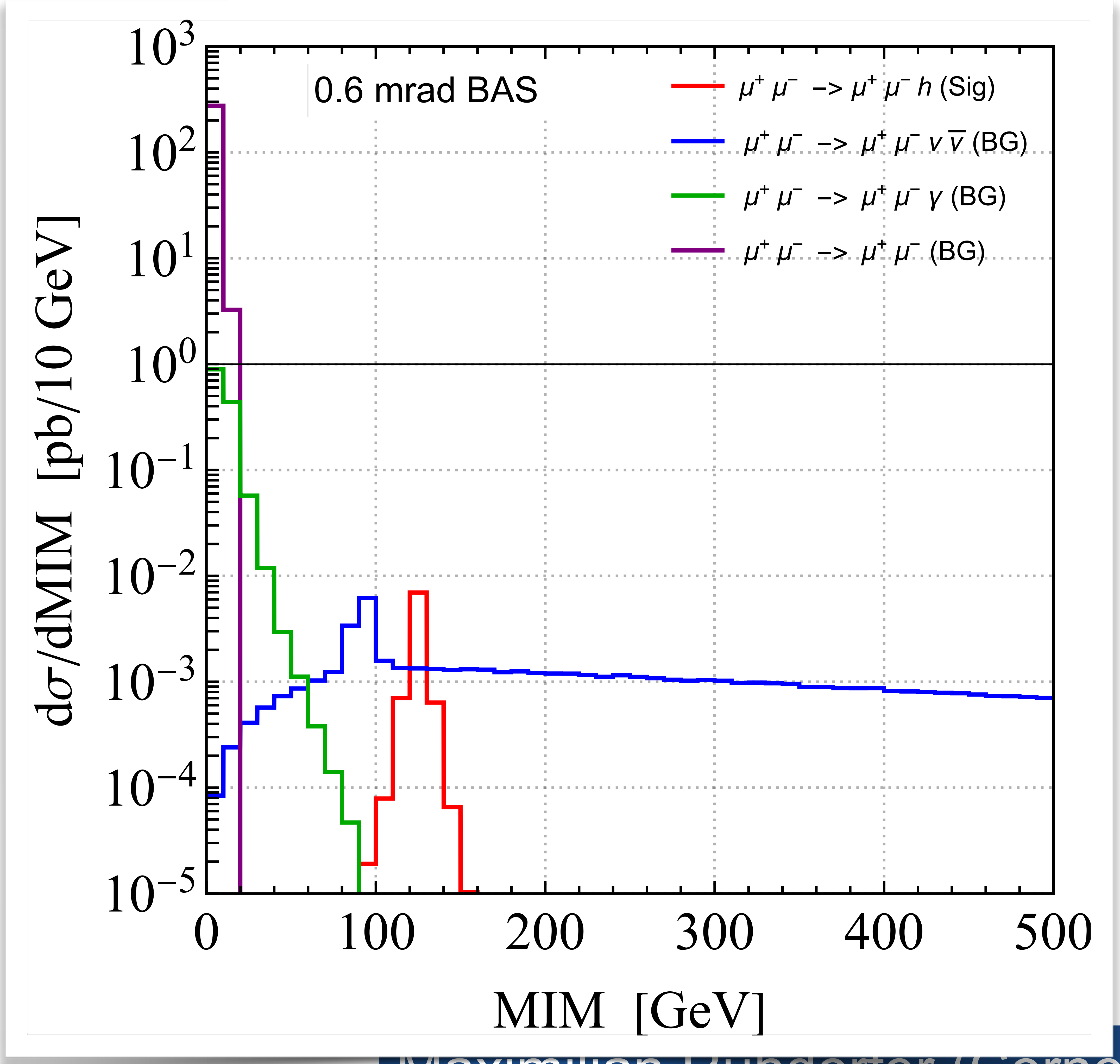
2. Beam angular spread (BAS)
3. Uncertainty in energy measurement
4. Lost particles (especially photons)



Maximilian Ruhdorfer (Corne

RUDHORFER

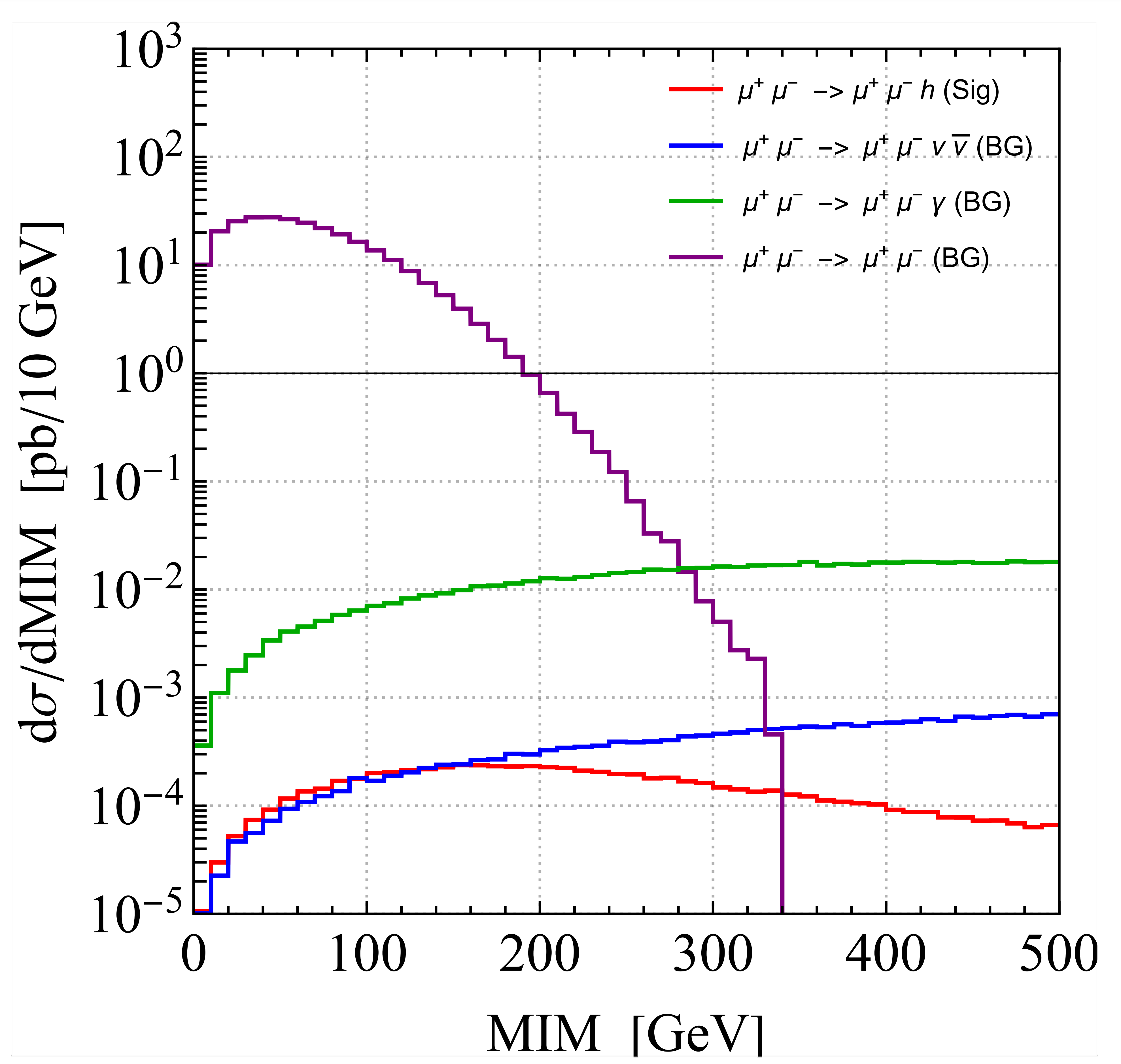
The physics case of a very forward muons detector — *Maximilian Ruhdorfer*

40/S2-D01 - Salle Dirac, CERN — 09:00 - 09:30

$$\not{p} = (\sqrt{s}, \vec{0}) - p_{\mu^+} - p_{\mu^-} + \;?$$

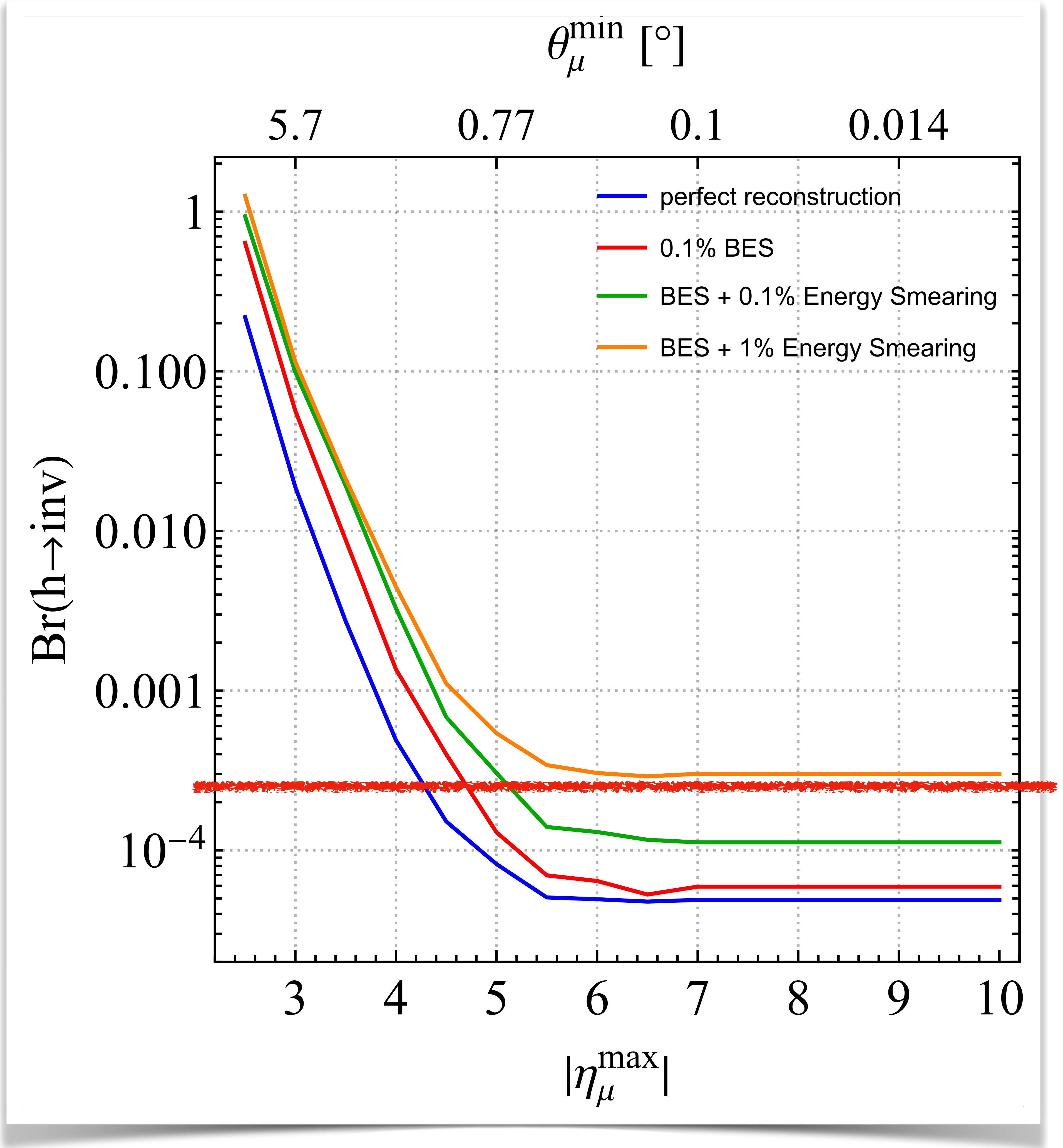
1. Beam energy spread (BES)
2. Beam angular spread (BAS)
3. Uncertainty in energy measurement
4. Lost particles (especially photons)

$\delta E_\mu / E_\mu$ 1% uncertainty



The physics case of a very forward muons detector	*Maximilian Ruhdorfer*
40/S2-D01 - Salle Dirac, CERN	09:00 - 09:30

- Sensitivity to BR($h \to$ inv) with all effects combined



1. Perfect 4-momentum reconstruction
2. 0.1% BES
3. 0.1% BES + 0.1% energy uncertainty
4. 0.1% BES + 1% energy uncertainty

FCC-hh projection: $2.5 \cdot 10^{-4}$

MA

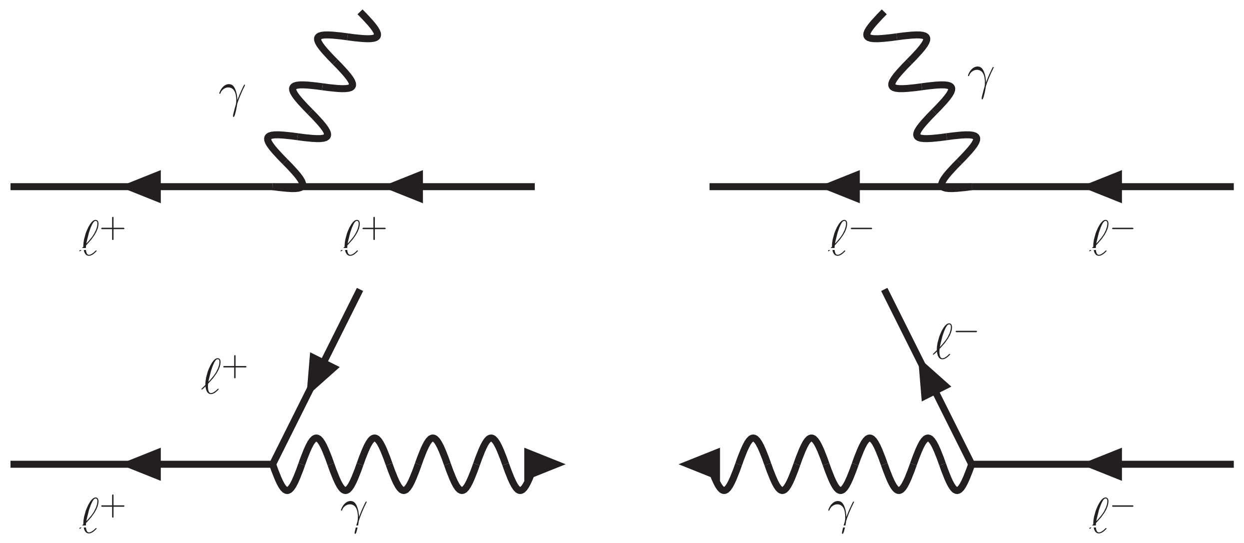
EW and QCD physics at the muon collider *Dr Yang Ma*

40/S2-D01 - Salle Dirac, CERN 09:30 - 10:00

People have been doing:

- $\ell^+\ell^-$ annihilation

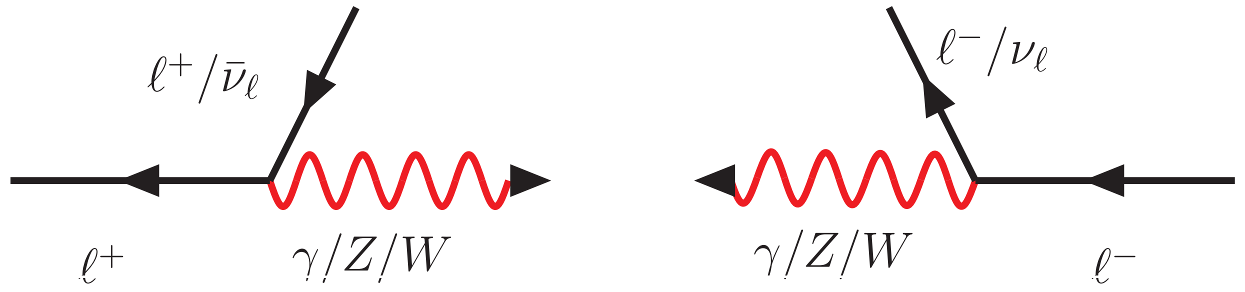
- EPA and ISR



- "Effective W Approx." (EWA)

  [G. Kane, W. Repko, and W. Rolnick, PLB 148 (1984) 367]

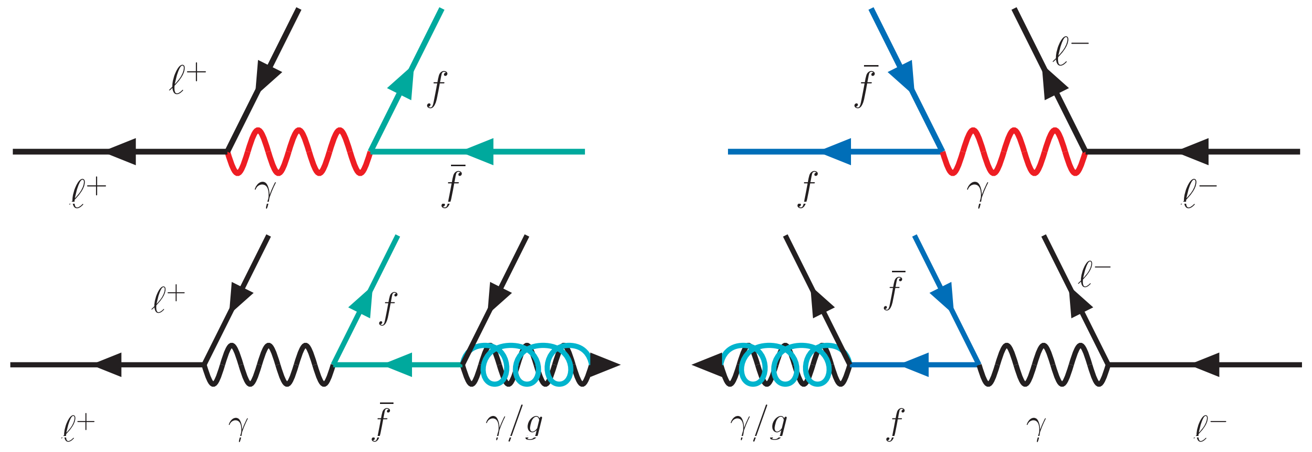
  [S. Dawson, NPB 249 (1985) 42]



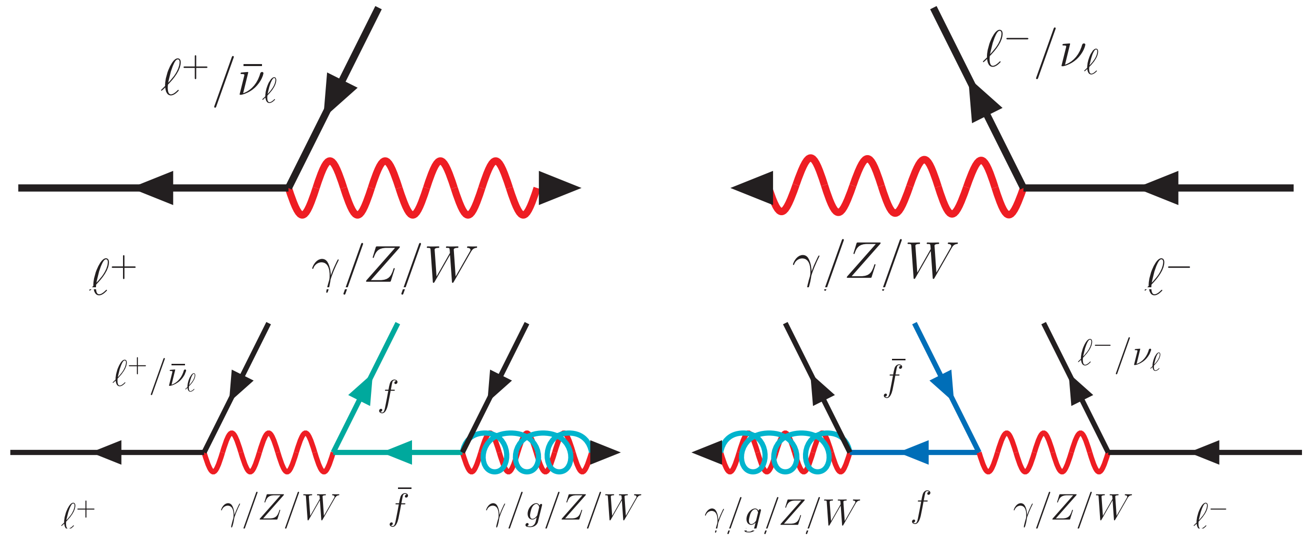
We will add:

[T. Han, Y. Ma, K.Xie 2007.14300, 2103.09844]

- Above $\mu_{\rm QCD}$: QED⊗QCD
  q/g emerge



- Above $\mu_{\rm EW} = M_Z$: EW⊗QCD
  EW partons / corrections to the above

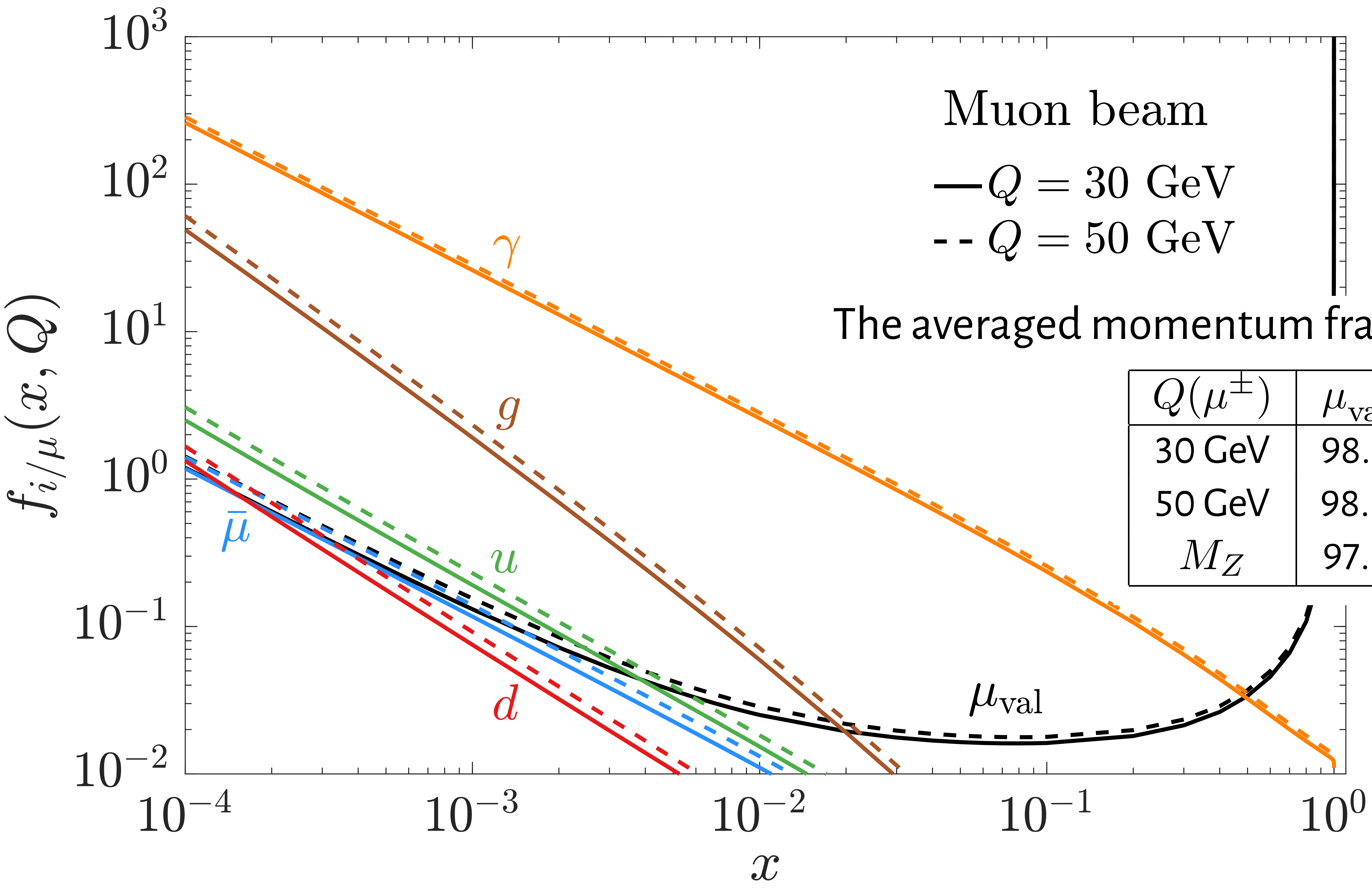


In the end, everything is parton, i.e. need the full SM PDFs.

EW and QCD physics at the muon collider — *Dr Yang Ma*

40/S2-D01 - Salle Dirac, CERN — 09:30 - 10:00

MA

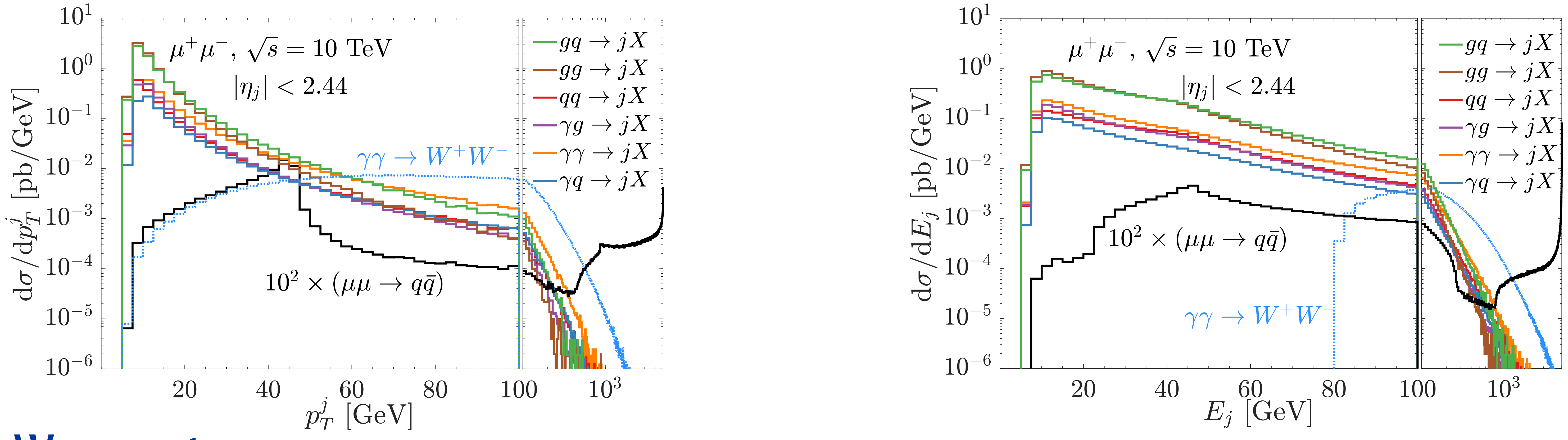


The averaged momentum fractions $\langle x_i \rangle = \int x f_i(x) \mathrm{d}x$ *in* %

$Q(\mu^{\pm})$	$\mu_{\rm val}$	γ	ℓsea	q	g
30 GeV	98.2	1.72	0.019	0.024	0.0043
50 GeV	98.0	1.87	0.023	0.029	0.0051
M_Z	97.9	2.06	0.028	0.035	0.0062

Inclusive jet distributions at a 10 TeV muon collider

Important guidelines for future analysis



We expect

- Jet production dominates over WW production until $p_T > 60$ GeV;
- WW production takes over around energy ~ 200 GeV.

The SM EW sector, as well as any possible BSM, can only be seen in the high p_T (E_j) range.

Copious q/g-jets within acceptance.

Concrete impact in analyses, i.e. h or resonance searches, yet to be evaluated.

Inclusive jet distributions at a 10 TeV muon collider

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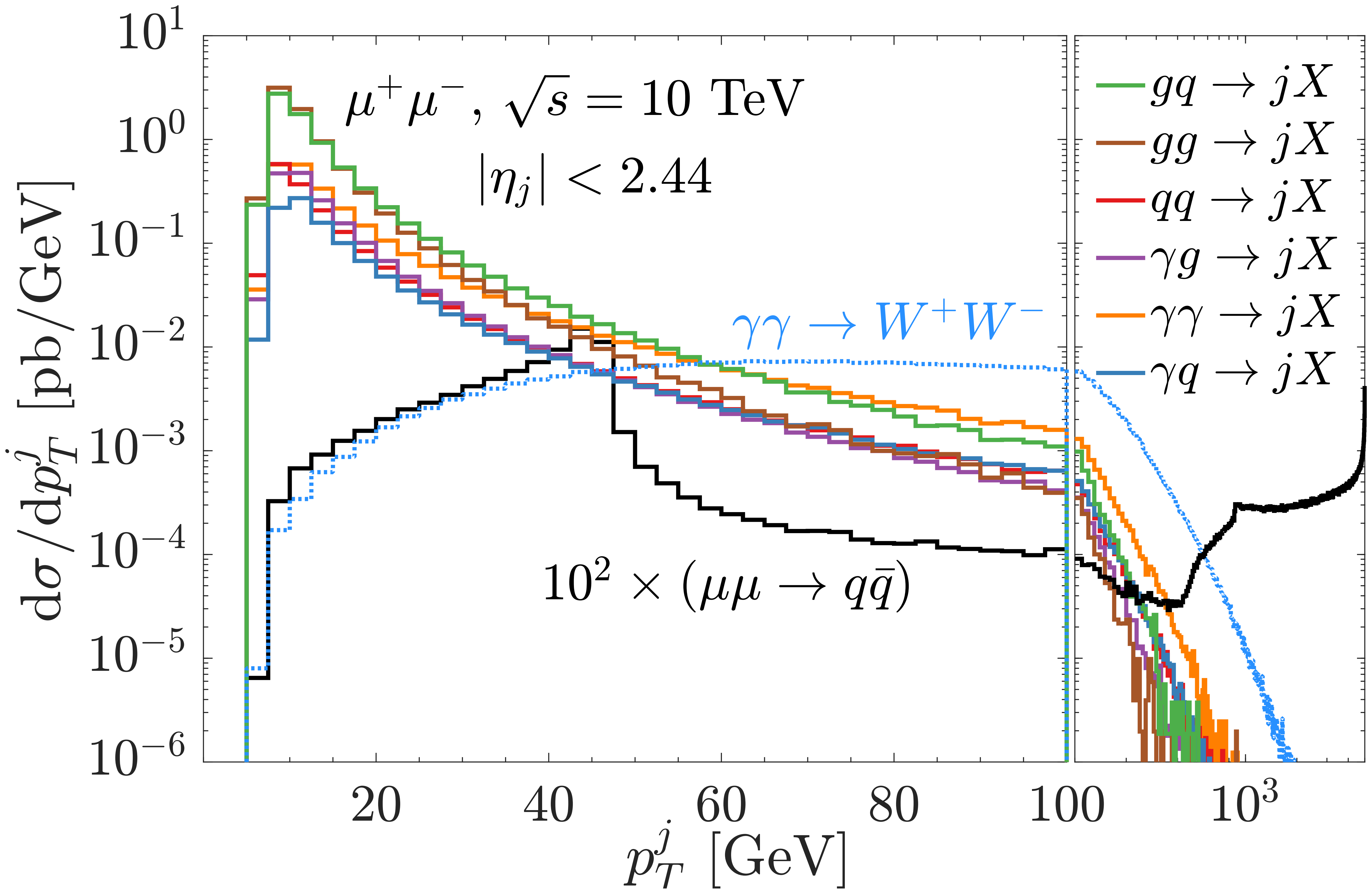

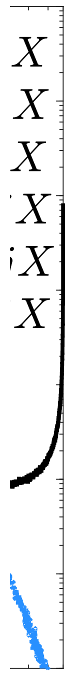

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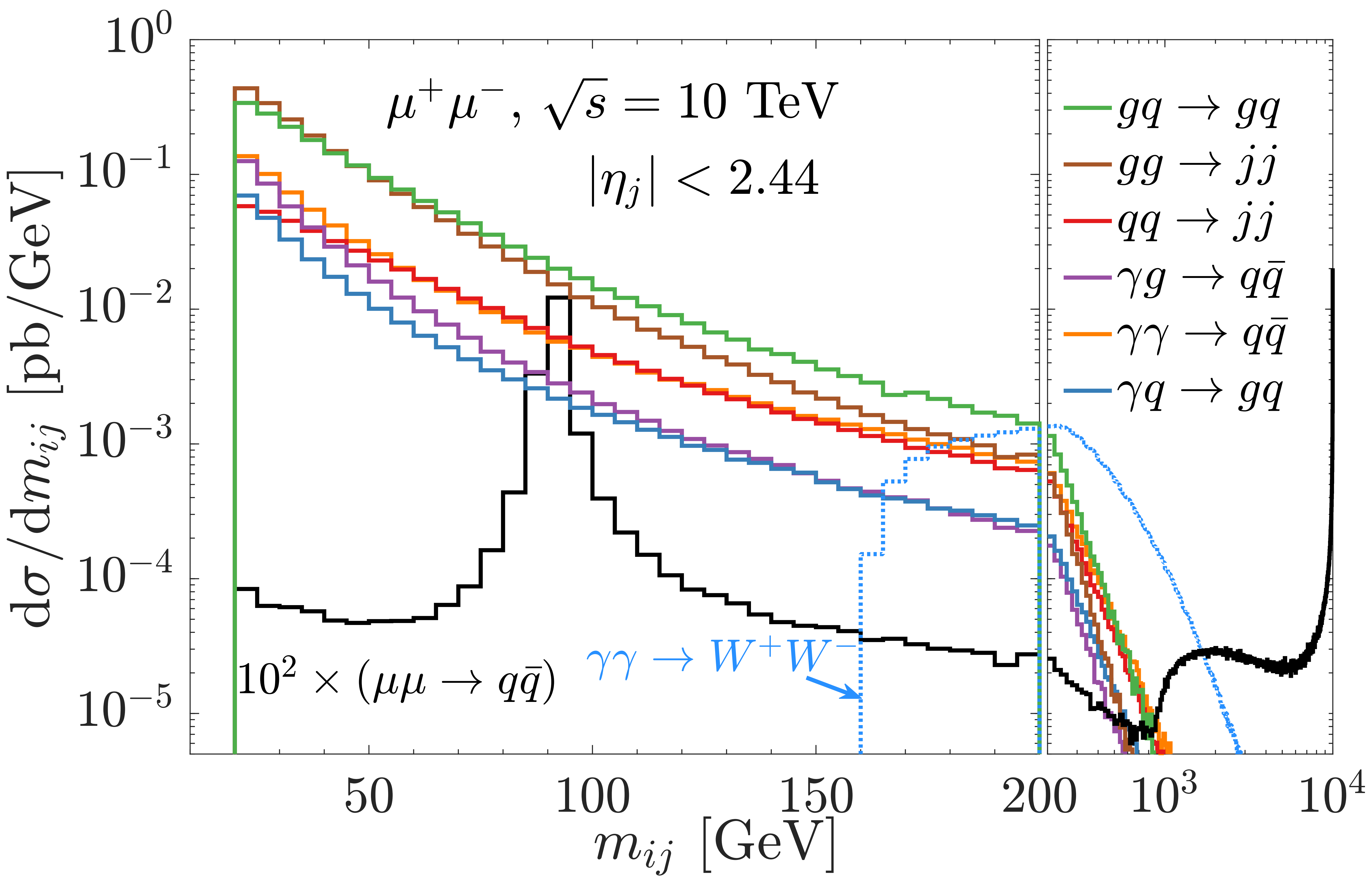

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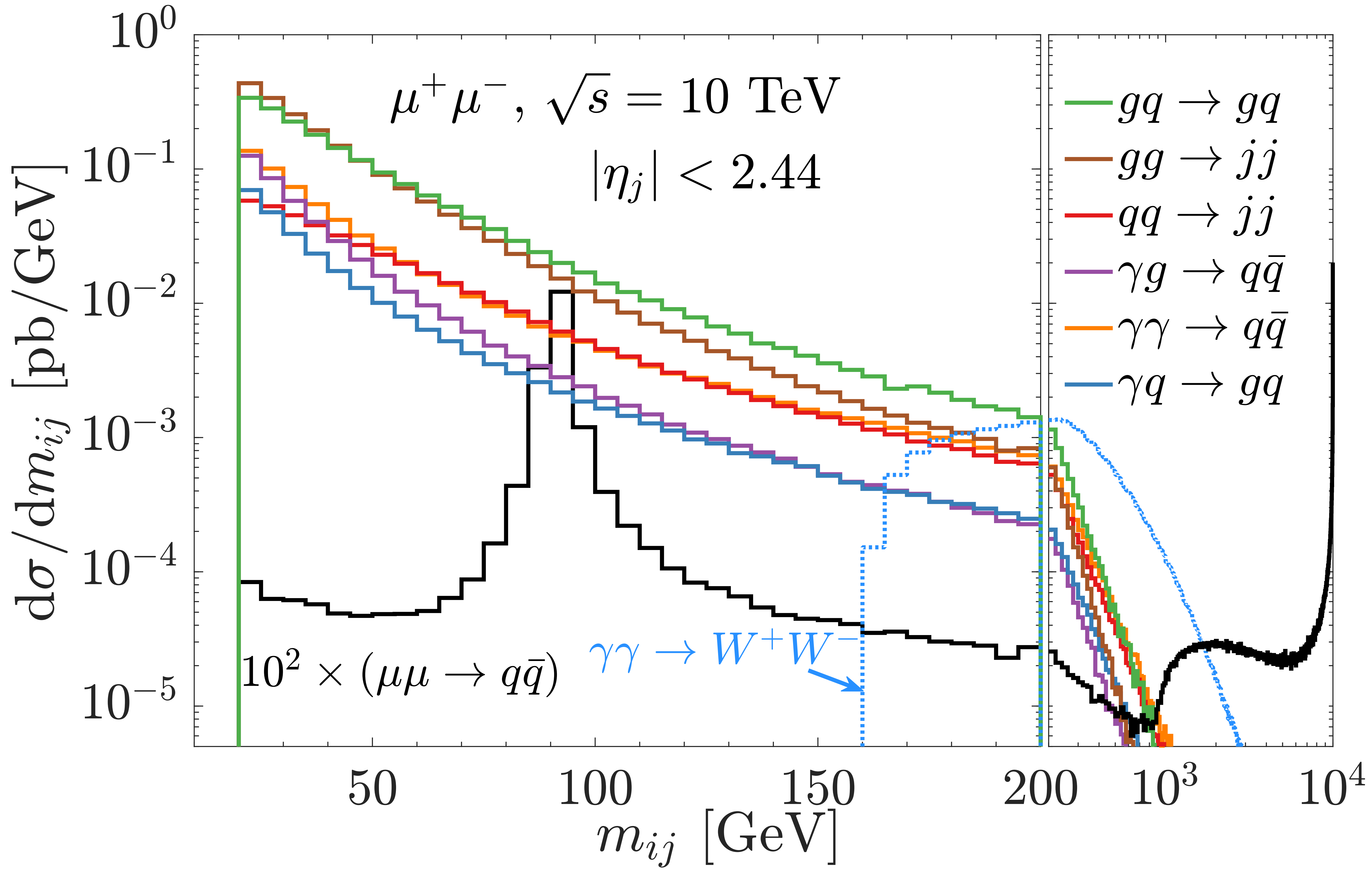

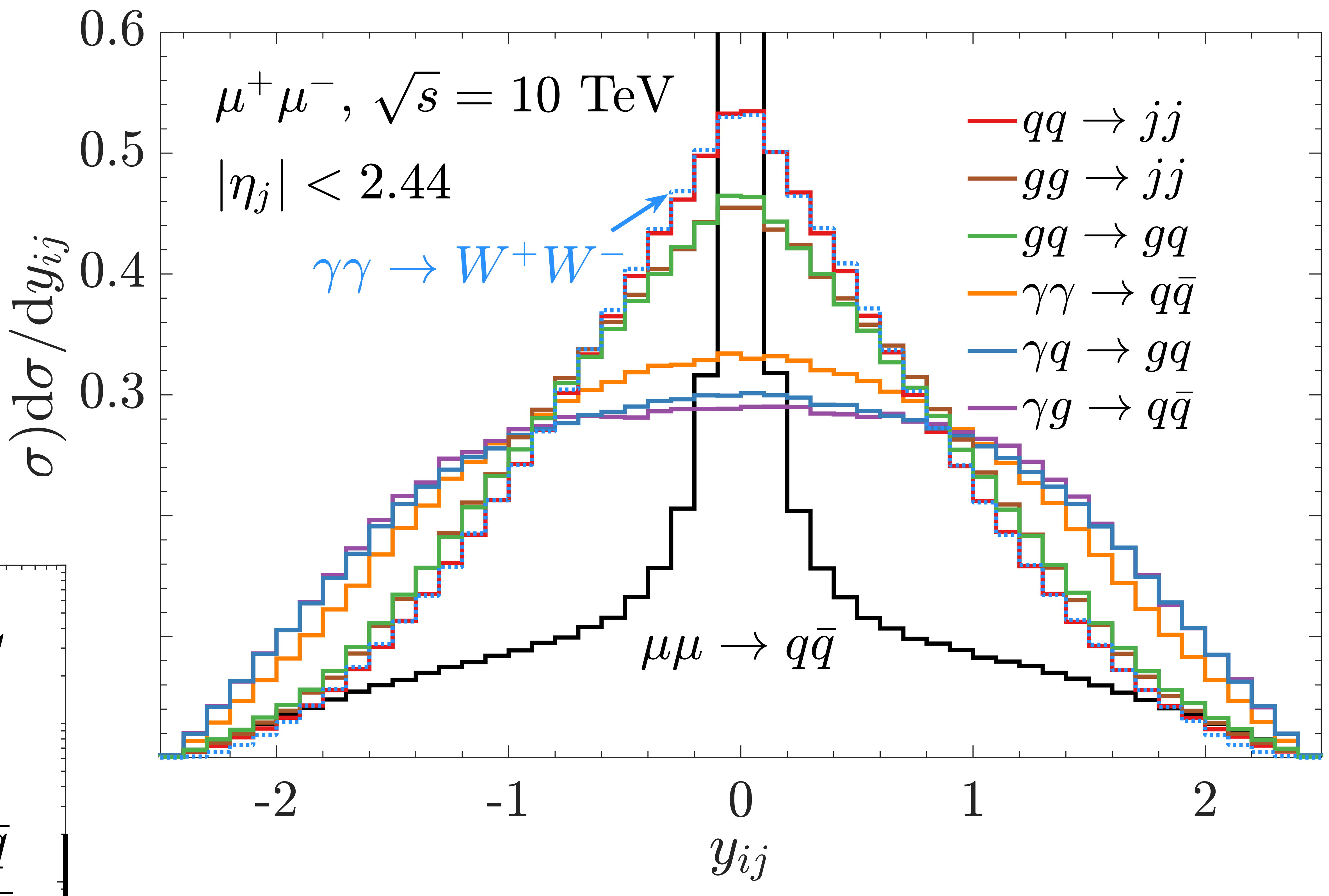

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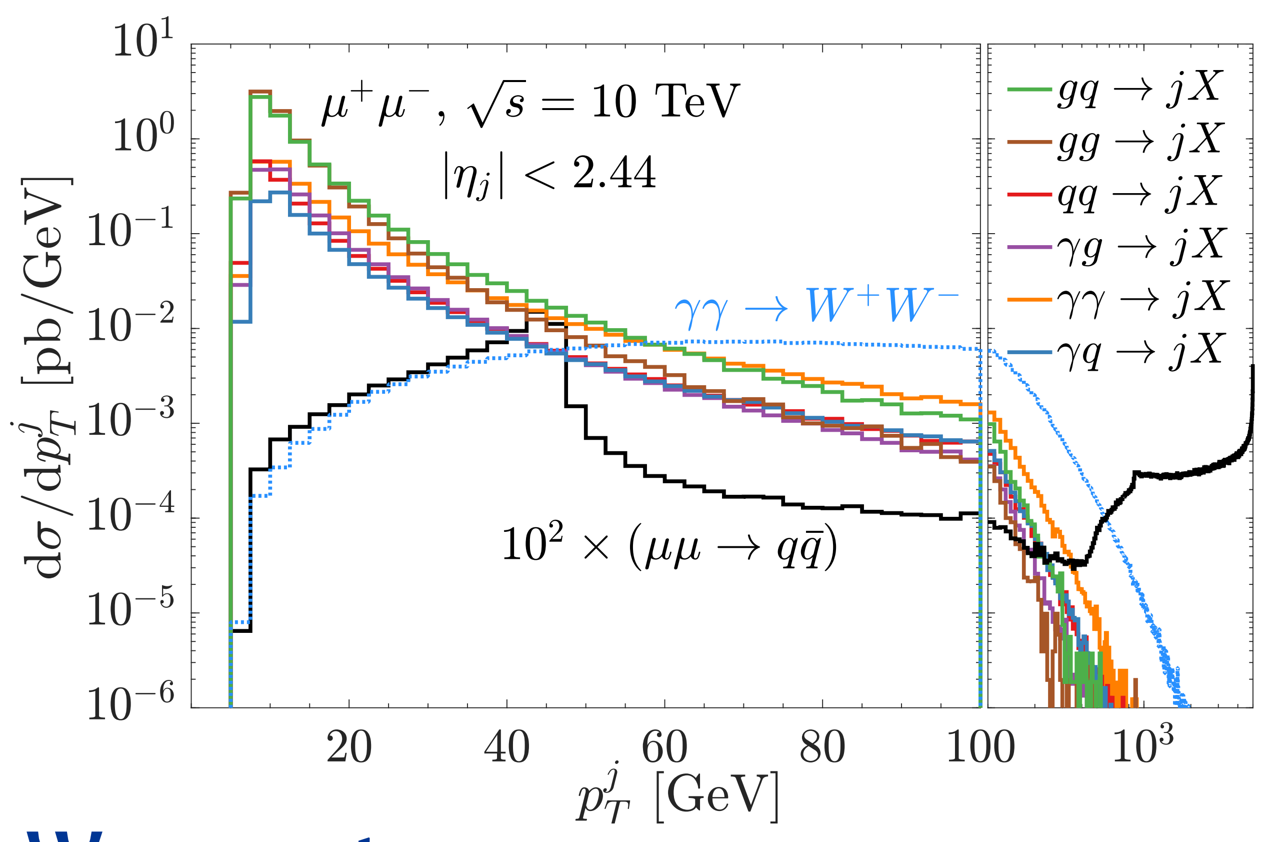

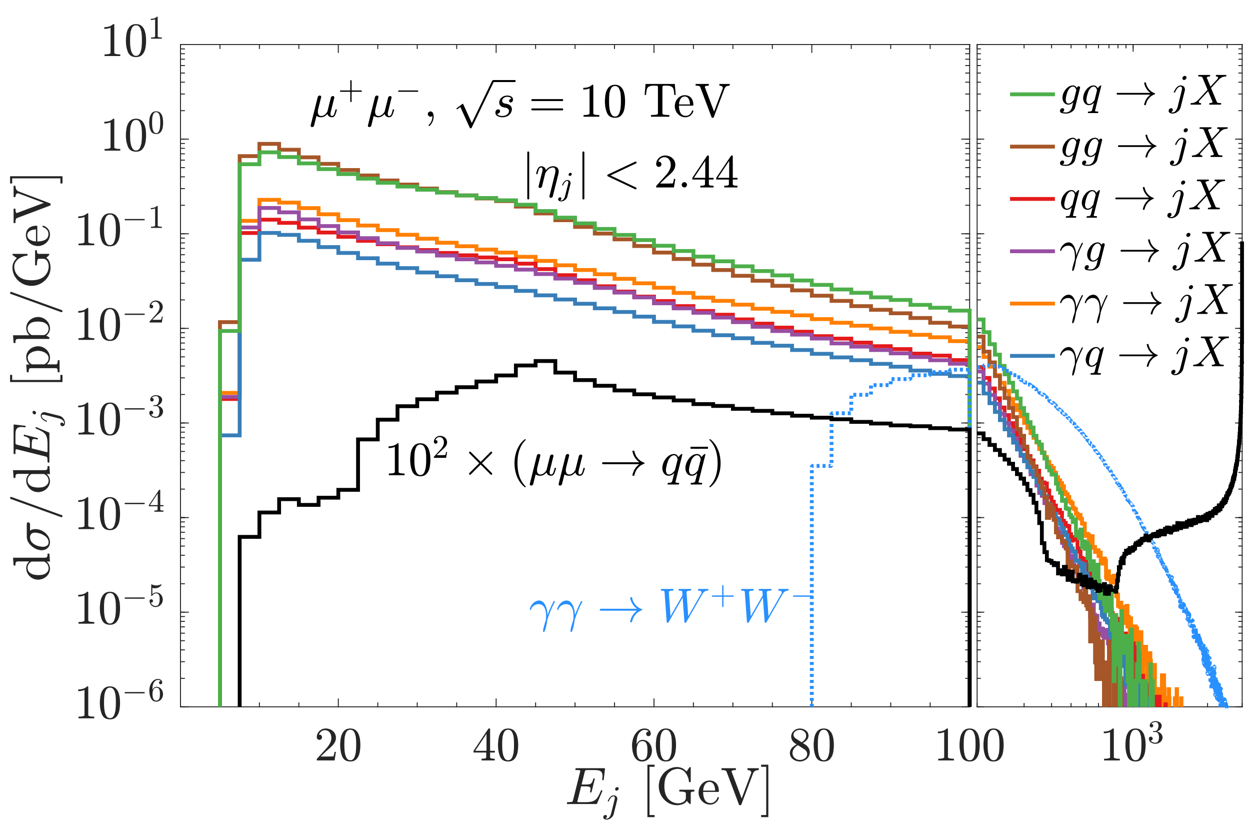

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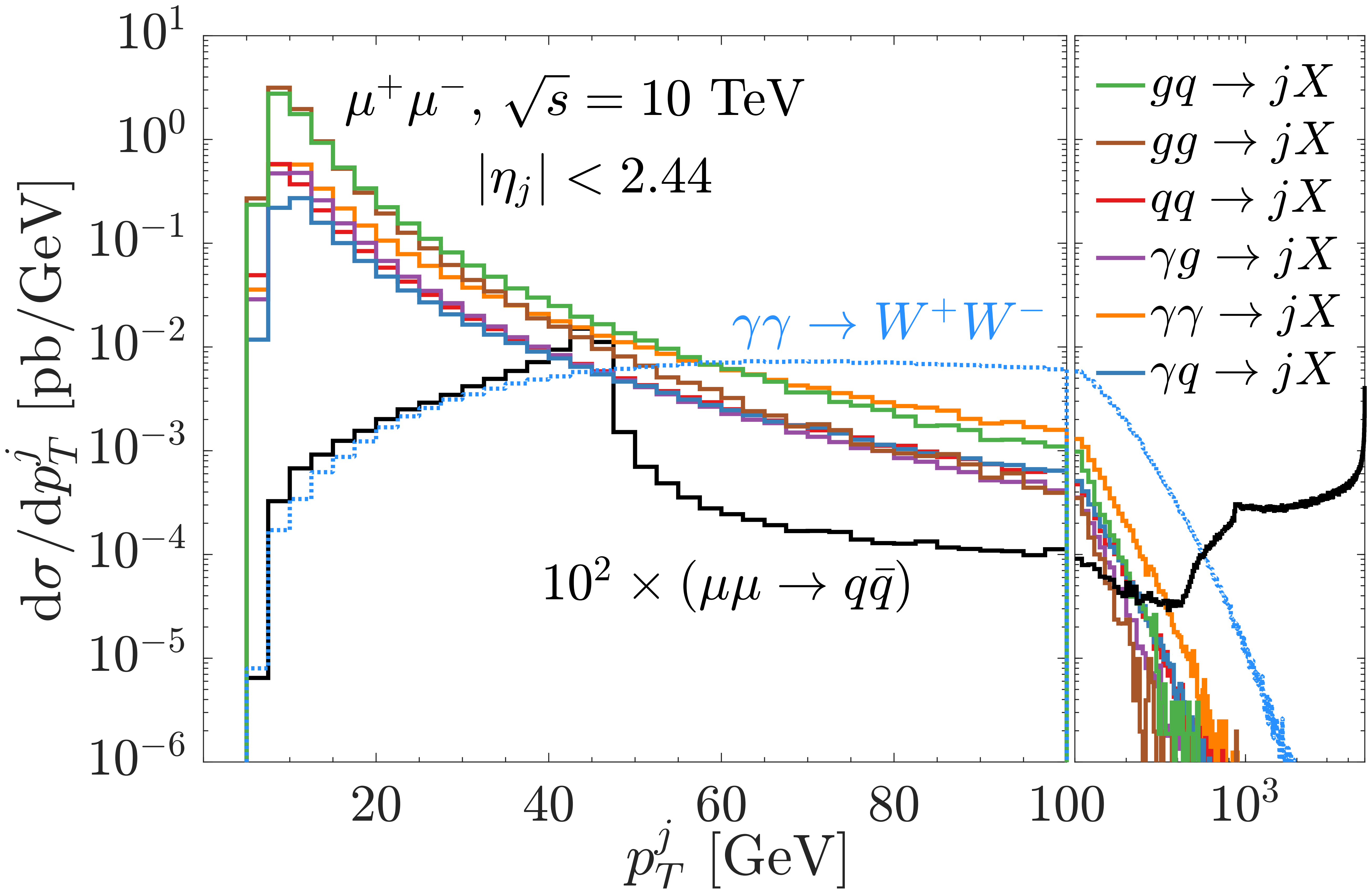

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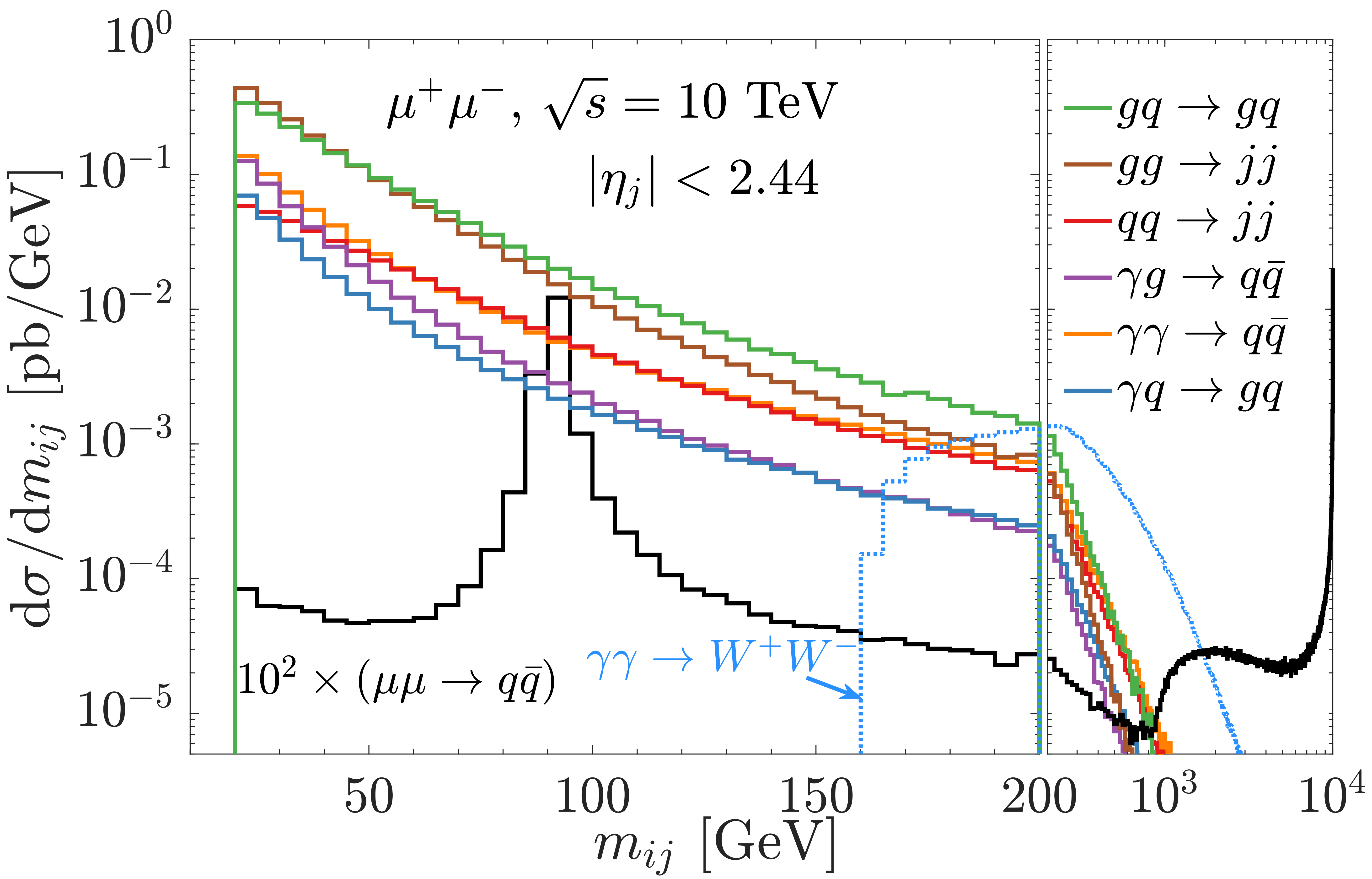

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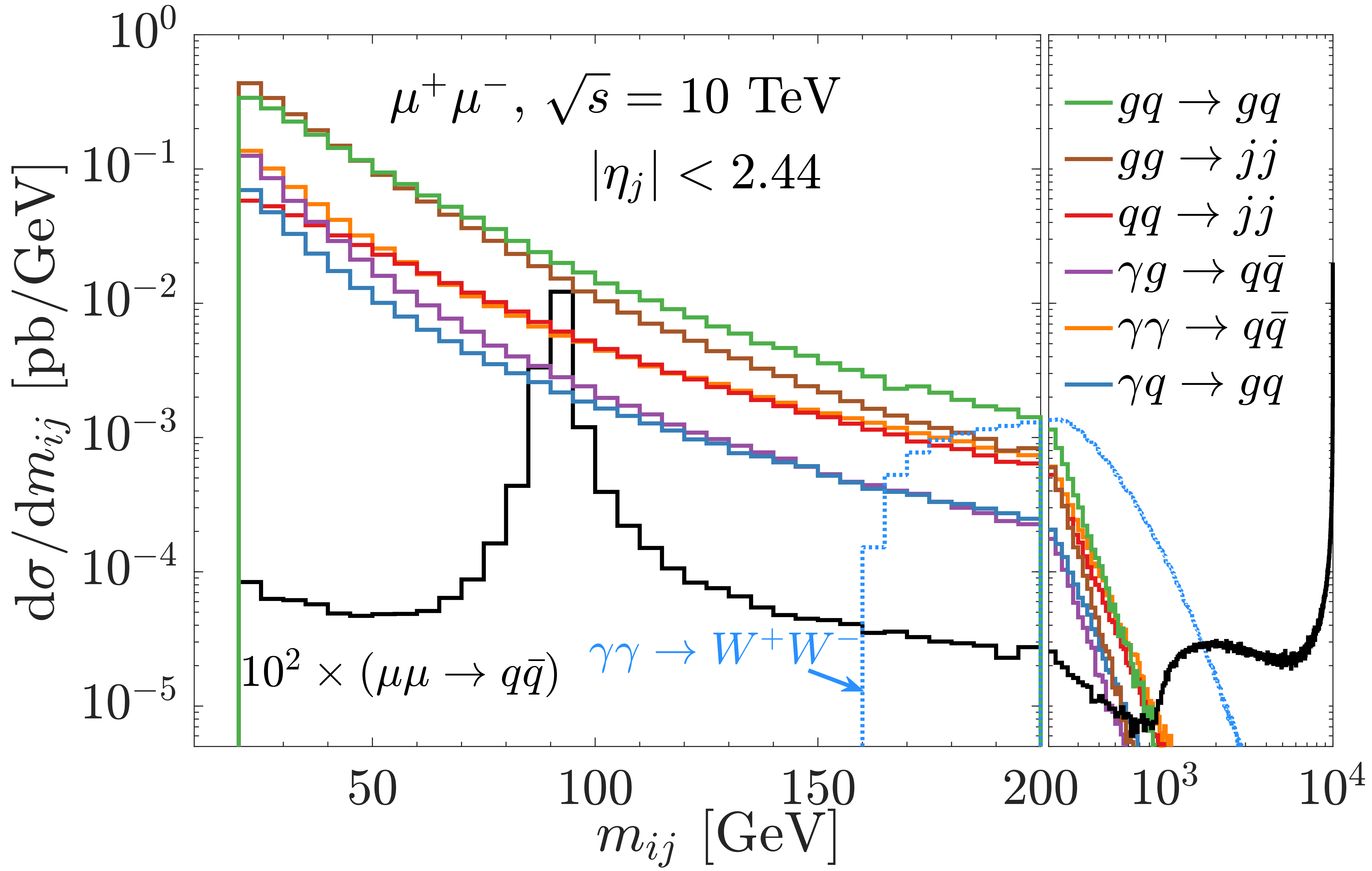
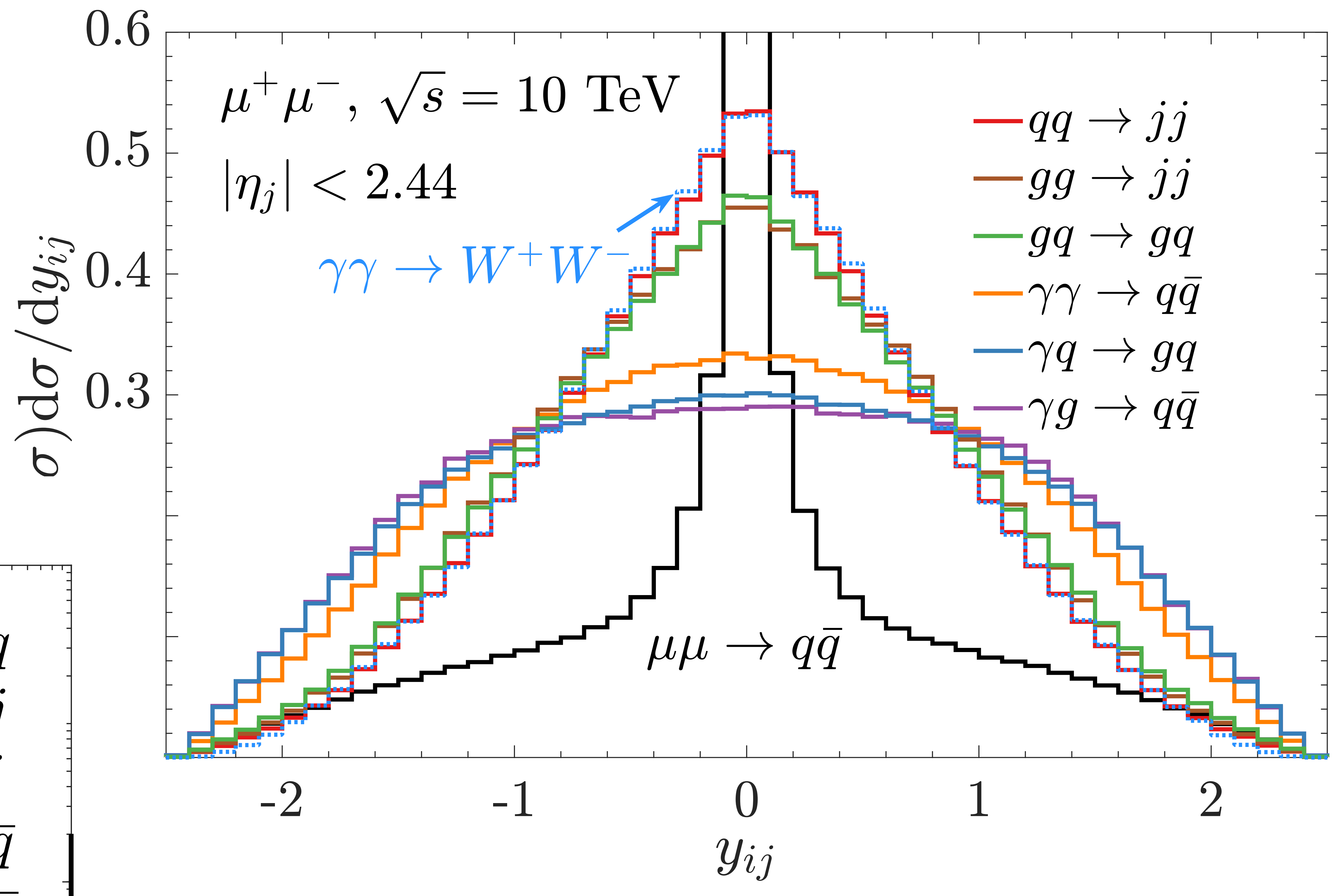
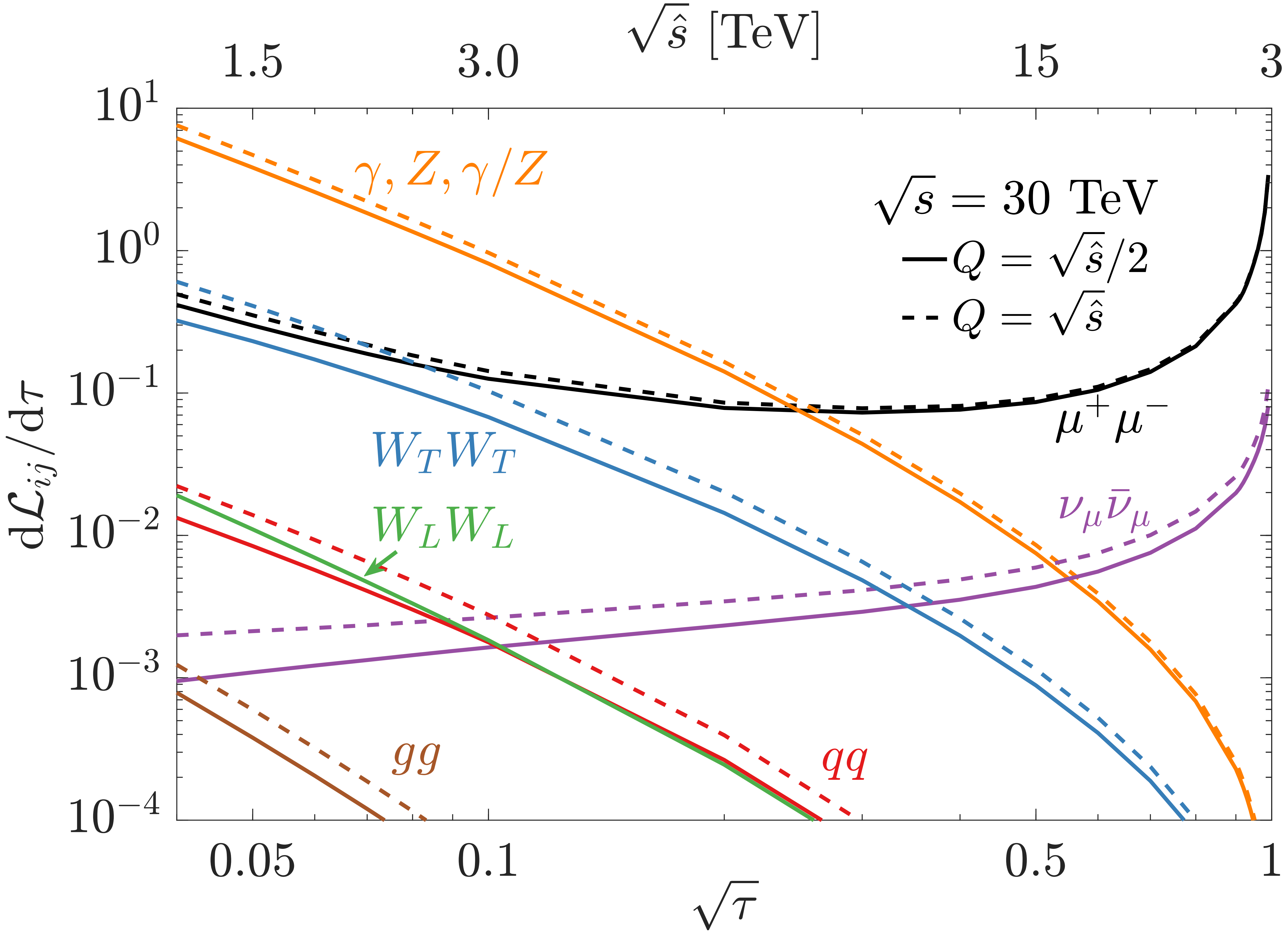




ge.

The EW parton luminosities of a 30 TeV muon collider



All SM particles are potentially "partons" inside the muon.

The rates are of course crucial, e.g. finding a lepton inside a quark is as likely as finding a quark inside a lepton

LFUV at muon collider *Admir Greljo*

6/R-012 - conference room, CERN 15:35 - 16:00

LFUV at MuC

Admir Greljo

UNIVERSITÄT BERN → University of Basel

FNSNF Swiss National Science Foundation
Eccellenza, Project-186866

13.10.2022, Muon Collider Collaboration Annual Meeting, CERN

Motivation

- The LHCb anomalies in $b \to s\mu^+\mu^-$ decays remind us that — New Physics might take an exotic form — an option we should embrace given the present status of the field.
- Several *anomalous* observables: BRs, angular distributions, LFUV ratios.
  see LHCb Implications next week
- Coherent explanation by a short-distance $bs\mu\mu$ contact interaction — $\mathcal{O}(10^{-5})G_F$ — the violation of perturbative unitarity $\lesssim 100\,\text{TeV}$
- New mass threshold in the vicinity of colliders?
- Today: Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552

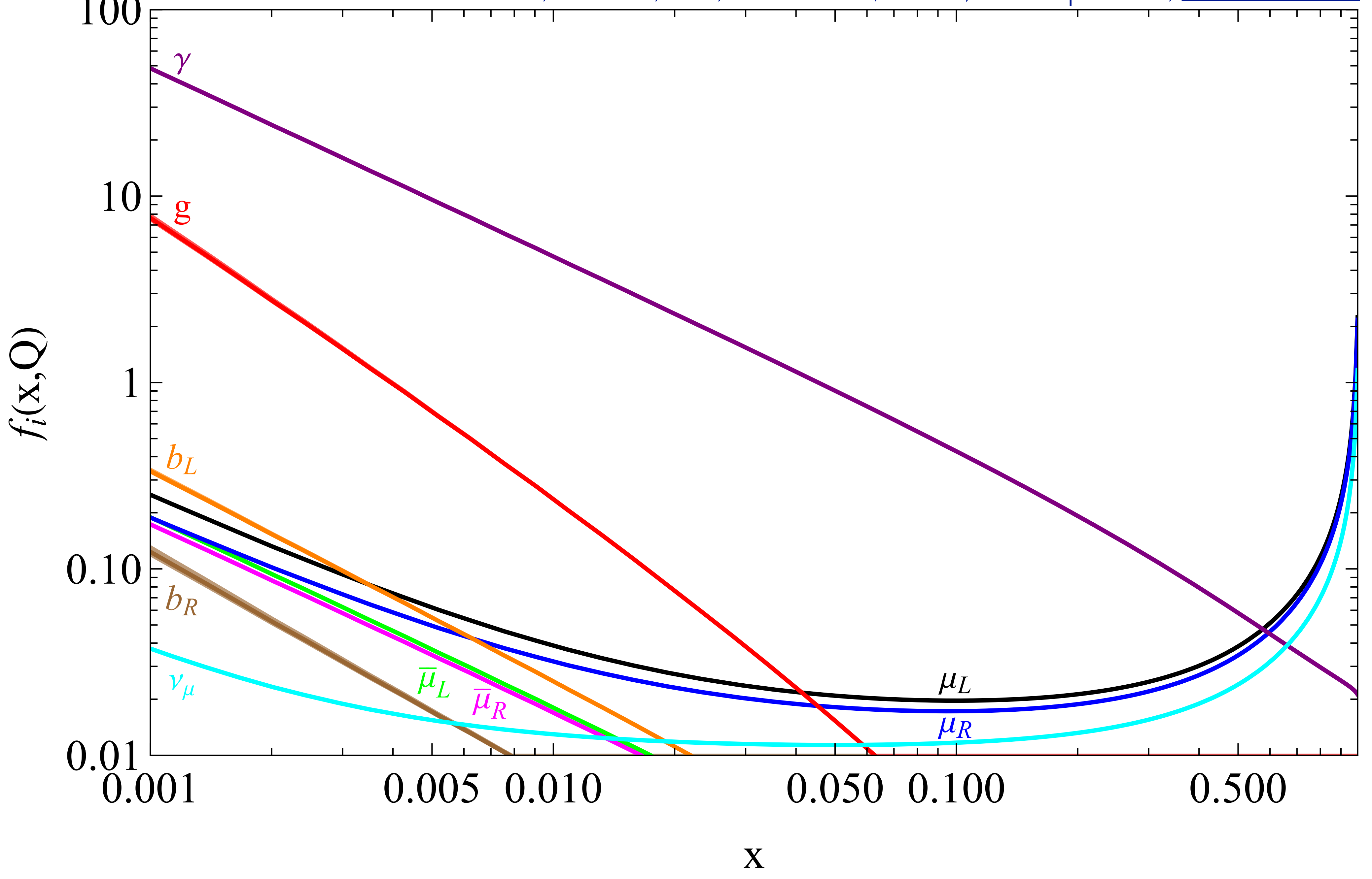
Complementary high-p_T searches at future colliders:
FCC-hh versus **MuC**

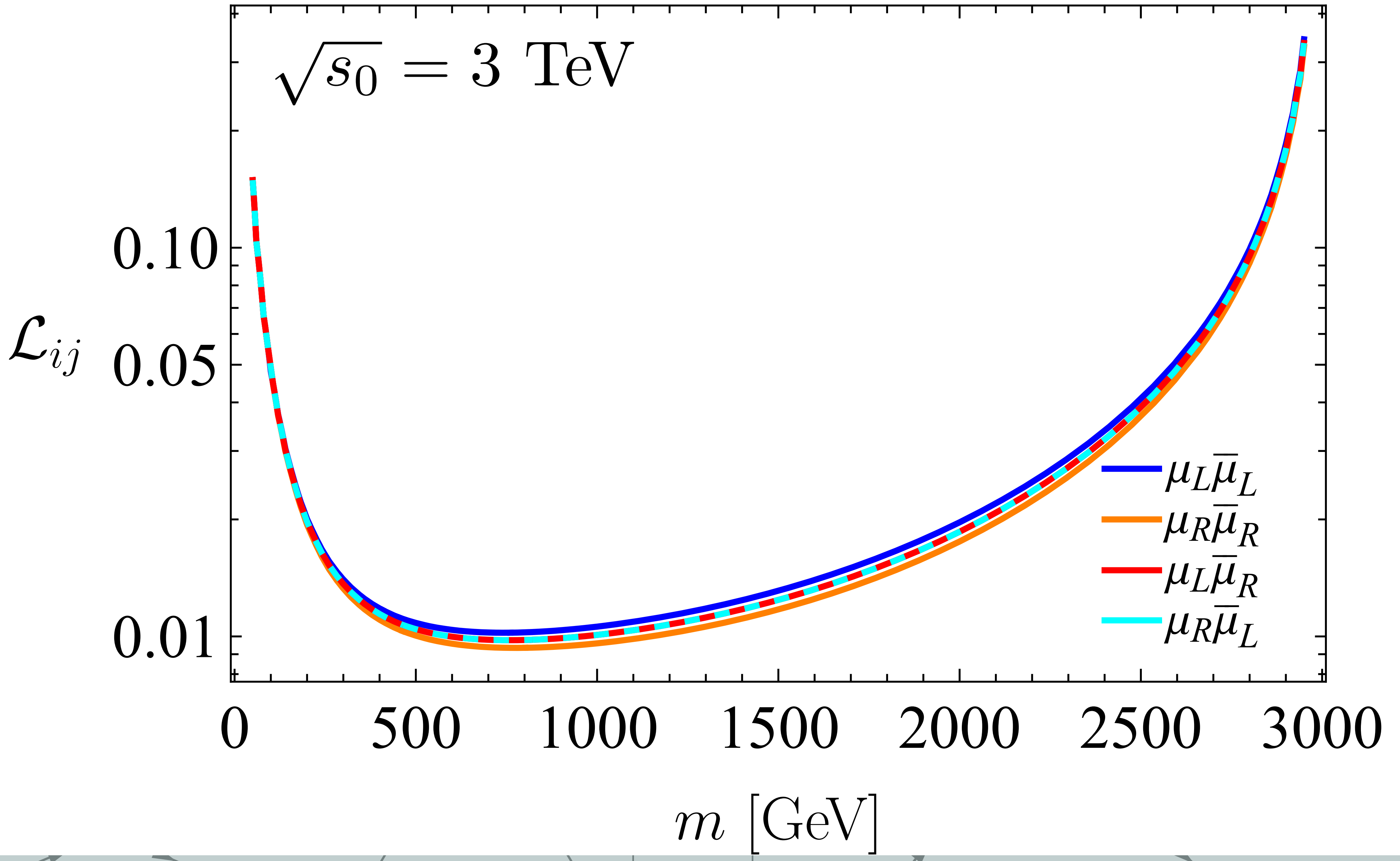
GRELJO

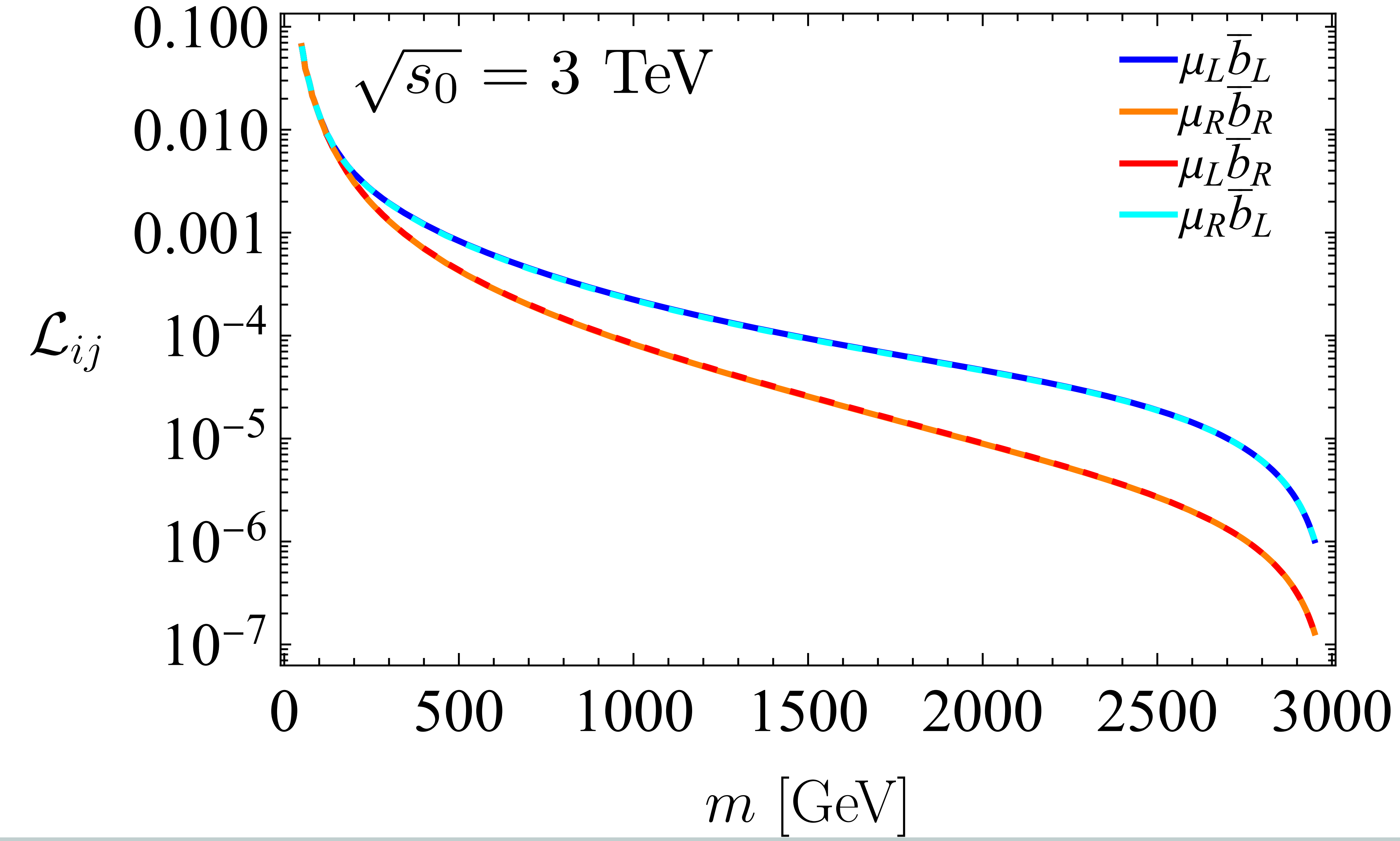
LFUV at muon collider

6/R-012 - conference room, CERN

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552







GRELJO

LFUV at muon collider — Admir Greljo
6/R-012 - conference room, CERN — 15:35 - 16:00

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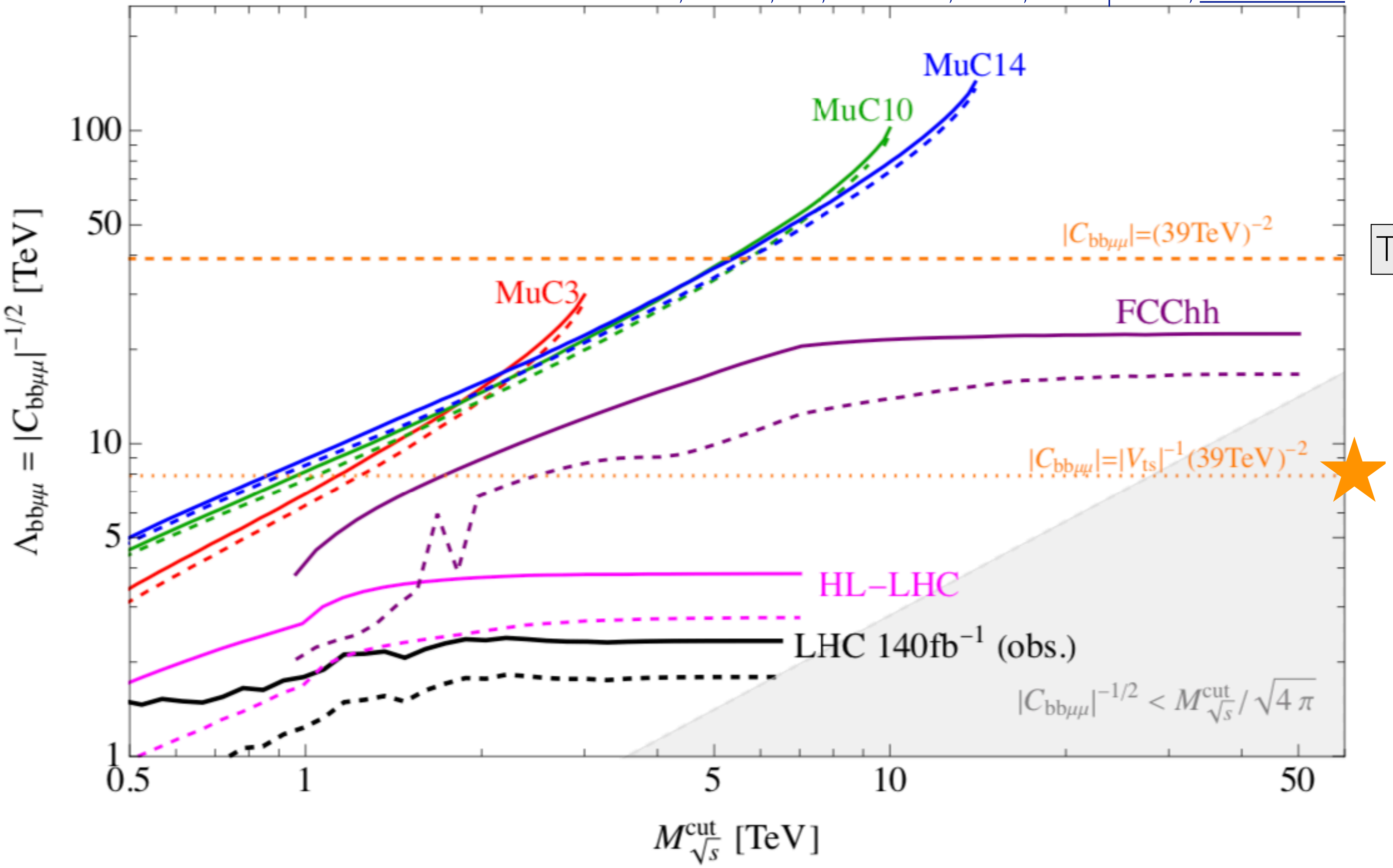

The pessimistic case

The realistic case

GRELJO

LFUV at muon collider *Admir Greljo*

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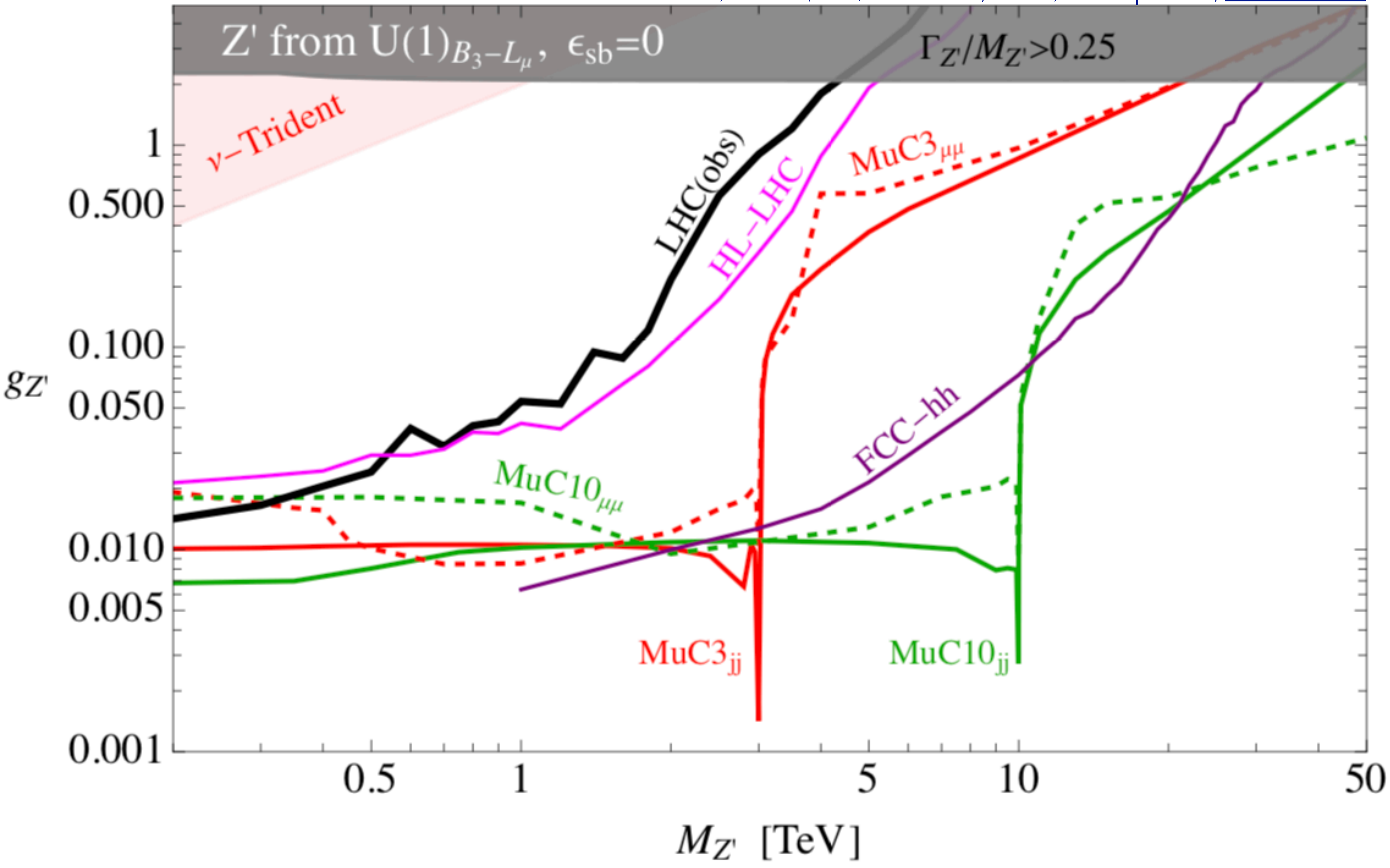
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552



$$\mu\mu \to \mu\mu$$

$$\mu\mu \to q_3\bar{q}_3$$

GRELJO

LFUV at muon collider	Admir Greljo
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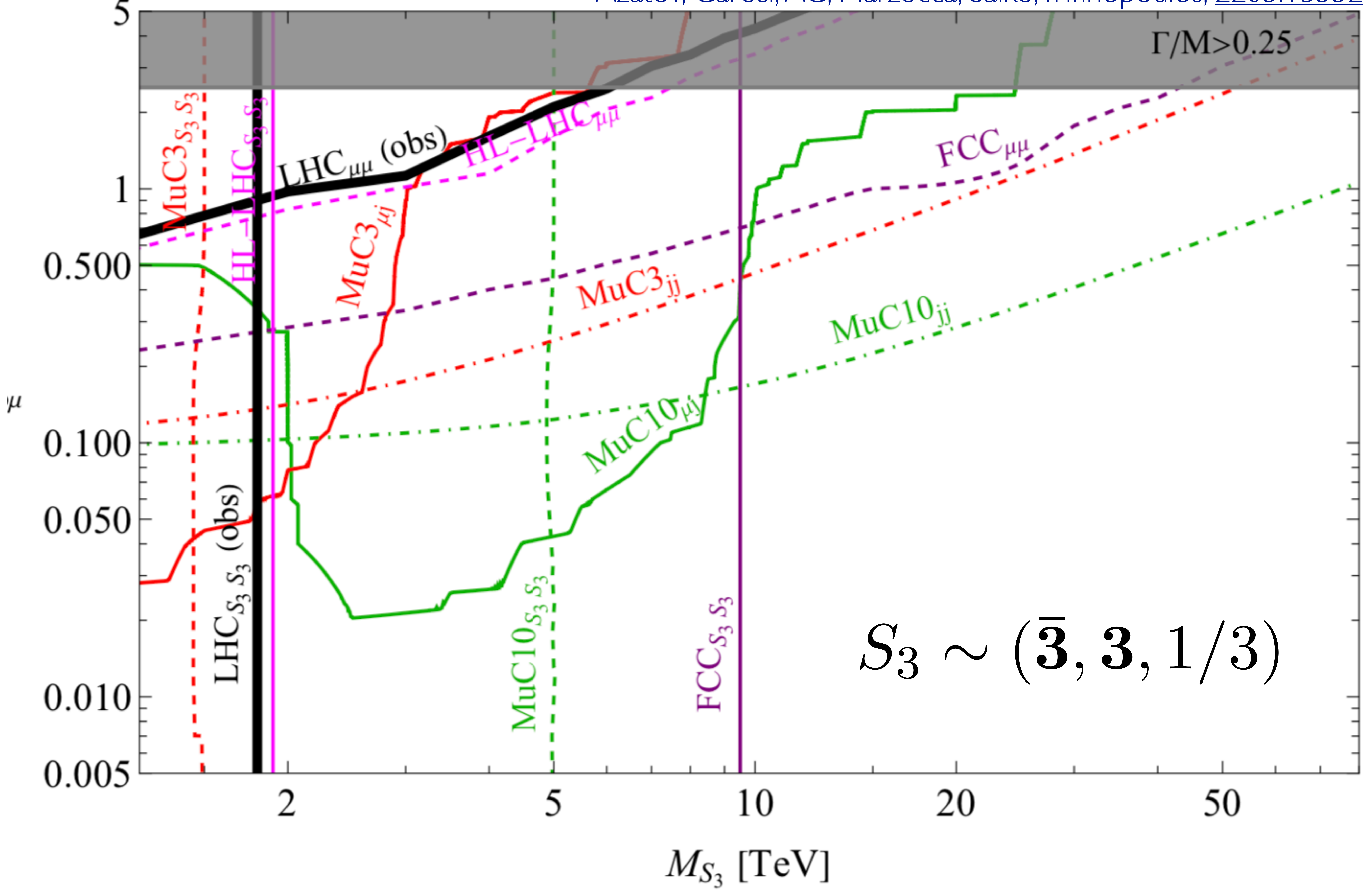

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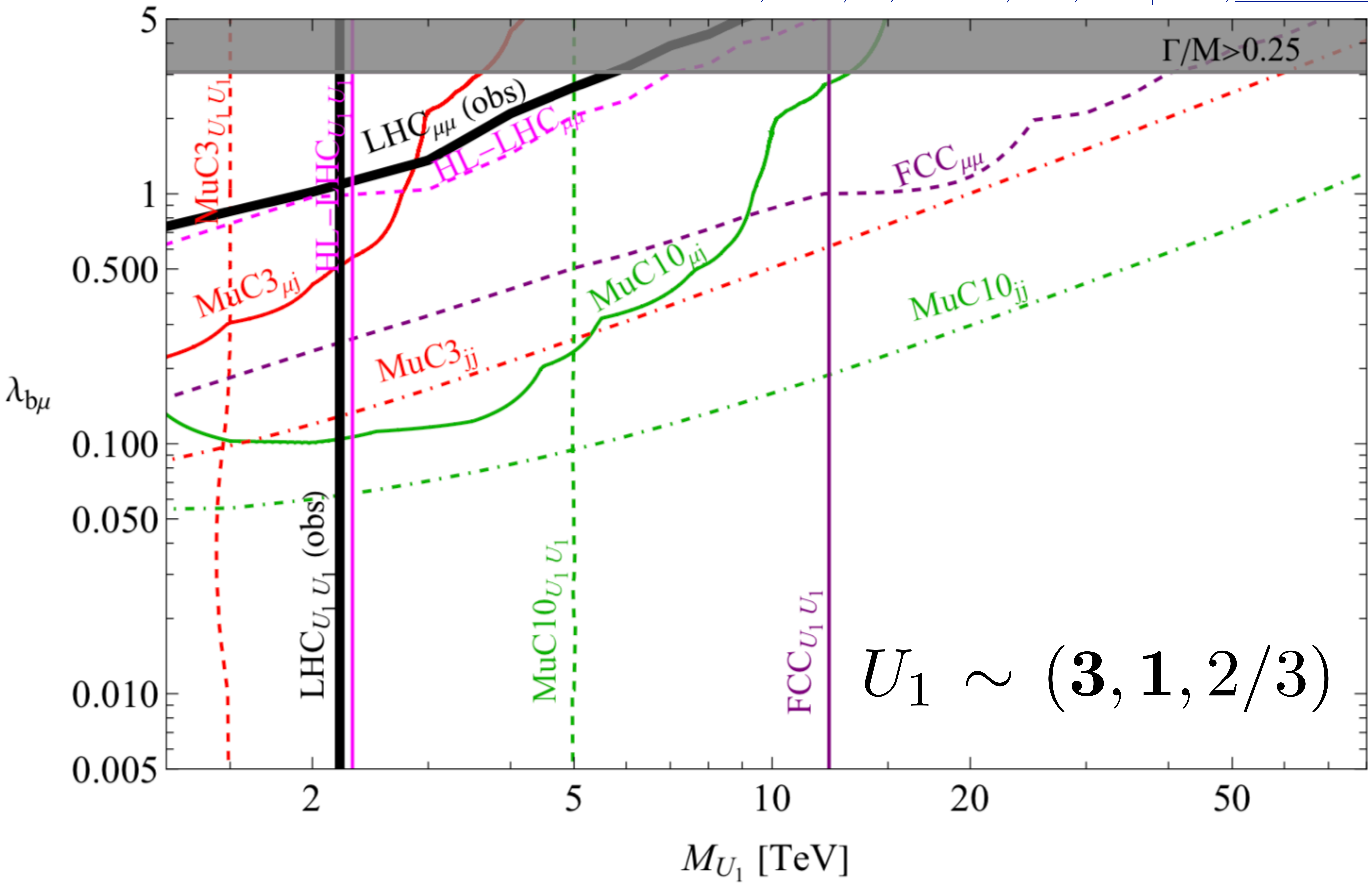


Dark Matter at muon colliders *Xiaoran Zhao*

40/S2-D01 - Salle Dirac, CERN 10:00 - 10:30

Dark matter at the muon colliders

Xiaoran Zhao[1]

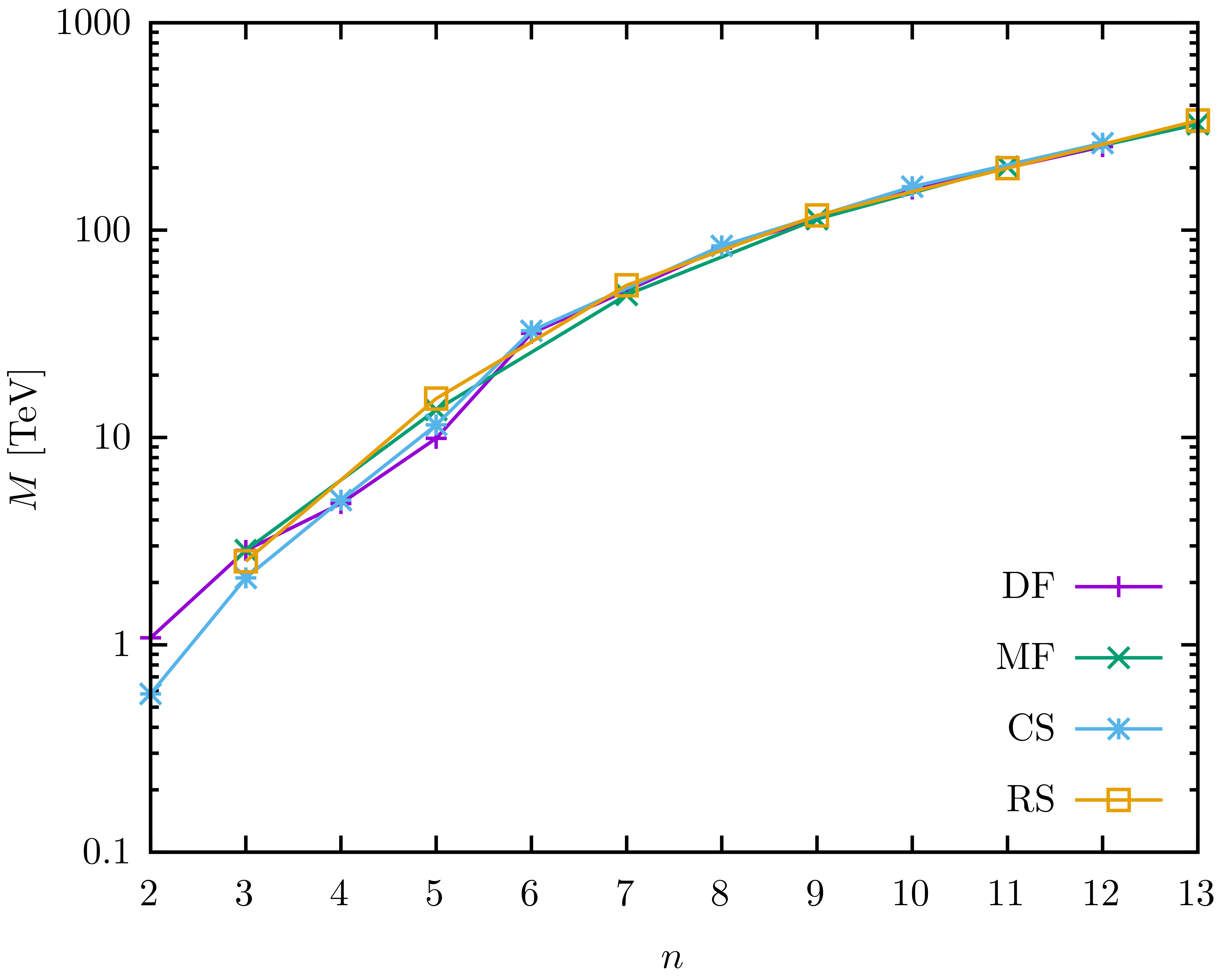
In collaboration with R. Franceschini

Based on arXiv:22xx.xxxxx

[1]Dipartimento di Matematica e Fisica, Università di Roma Tre and INFN, sezione di Roma Tre, I-00146 Rome, Italy

October 12, 2022

ZHAO



Bottaro et.al.2107.09688&2205.04486

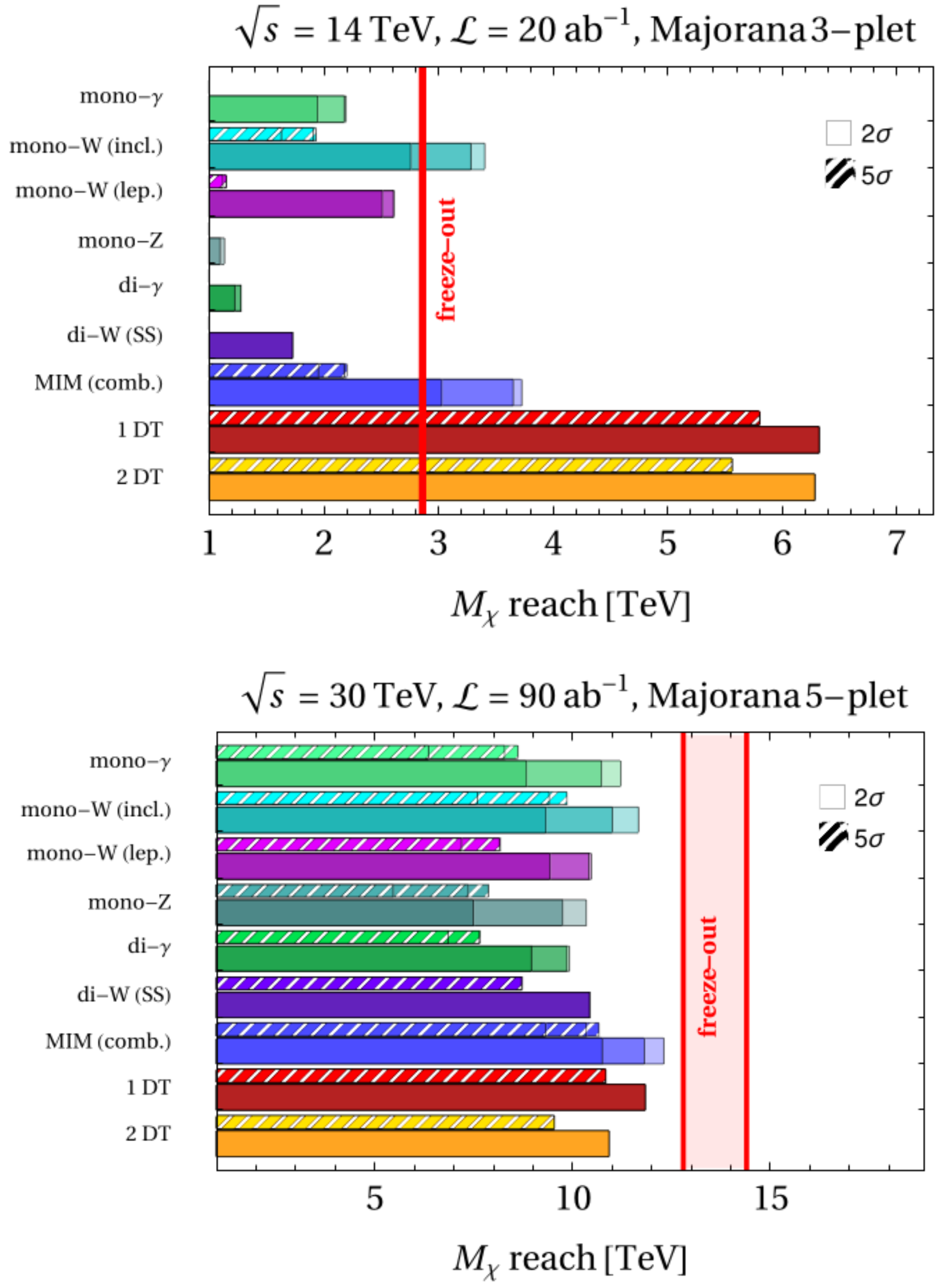
WIMP Dark Matter can be as heavy as 100 TeV

ZHAO

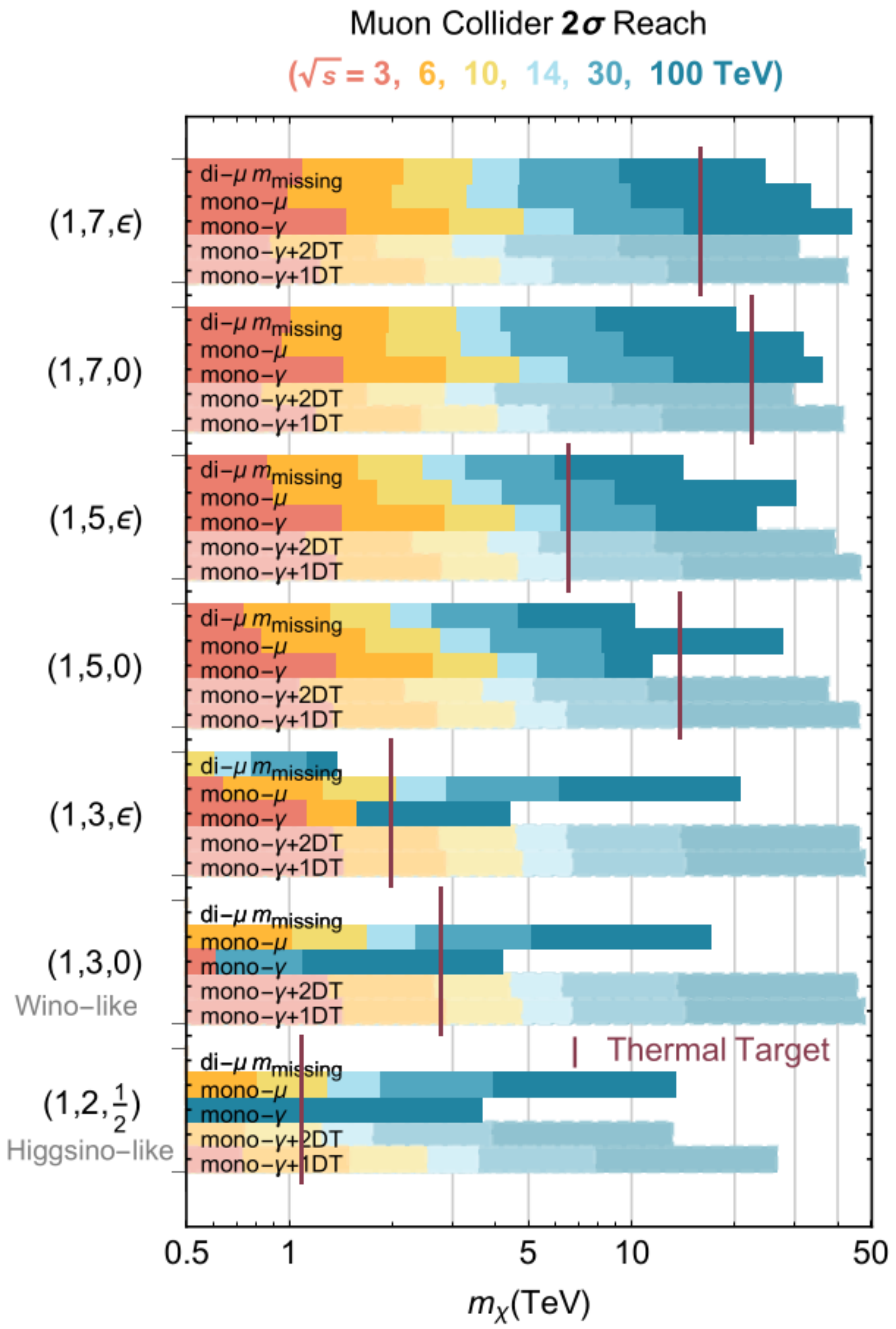
Dark Matter at muon colliders *Xiaoran Zhao*

40/S2-D01 - Salle Dirac, CERN 10:00 - 10:30

direct production at muon colliders



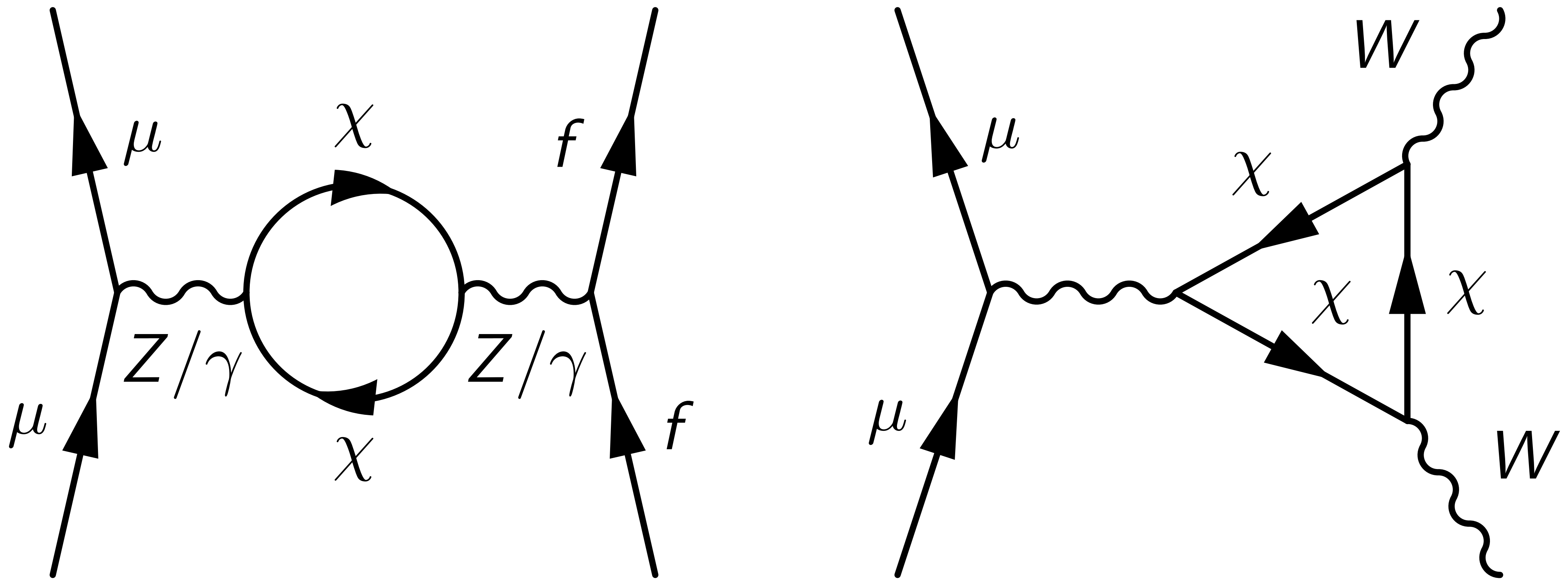
Bottaro et.al.2107.09688



Han,Liu,Wang,Wang,2009.11287

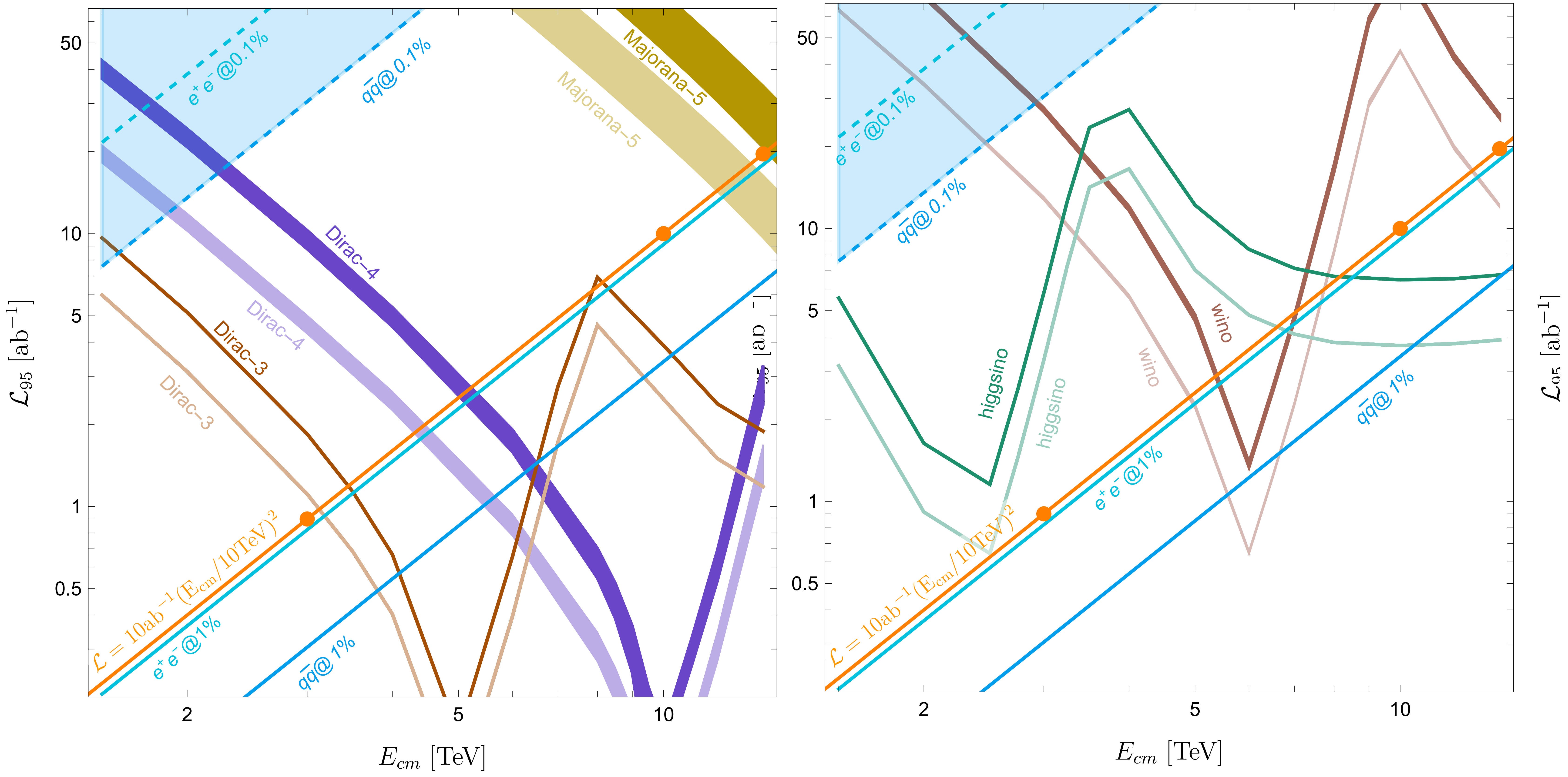
Indirect probes

- Direct production is limited by $M < \frac{\sqrt{s}}{2}$.
- Indirect probes through loop corrections: no such limit!



ZHAO

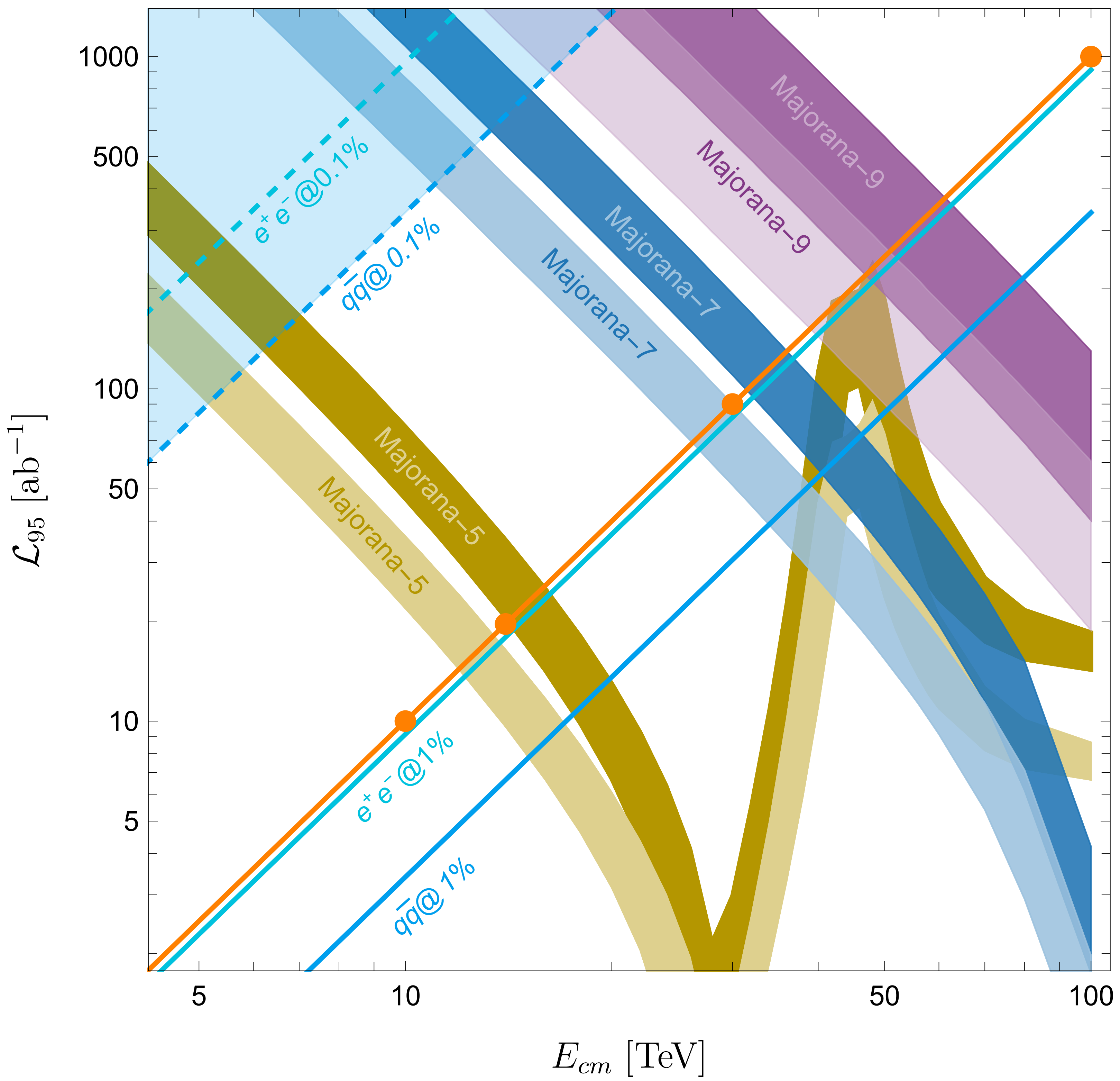
Dark Matter at muon colliders	*Xiaoran Zhao*
40/S2-D01 - Salle Dirac, CERN	10:00 - 10:30

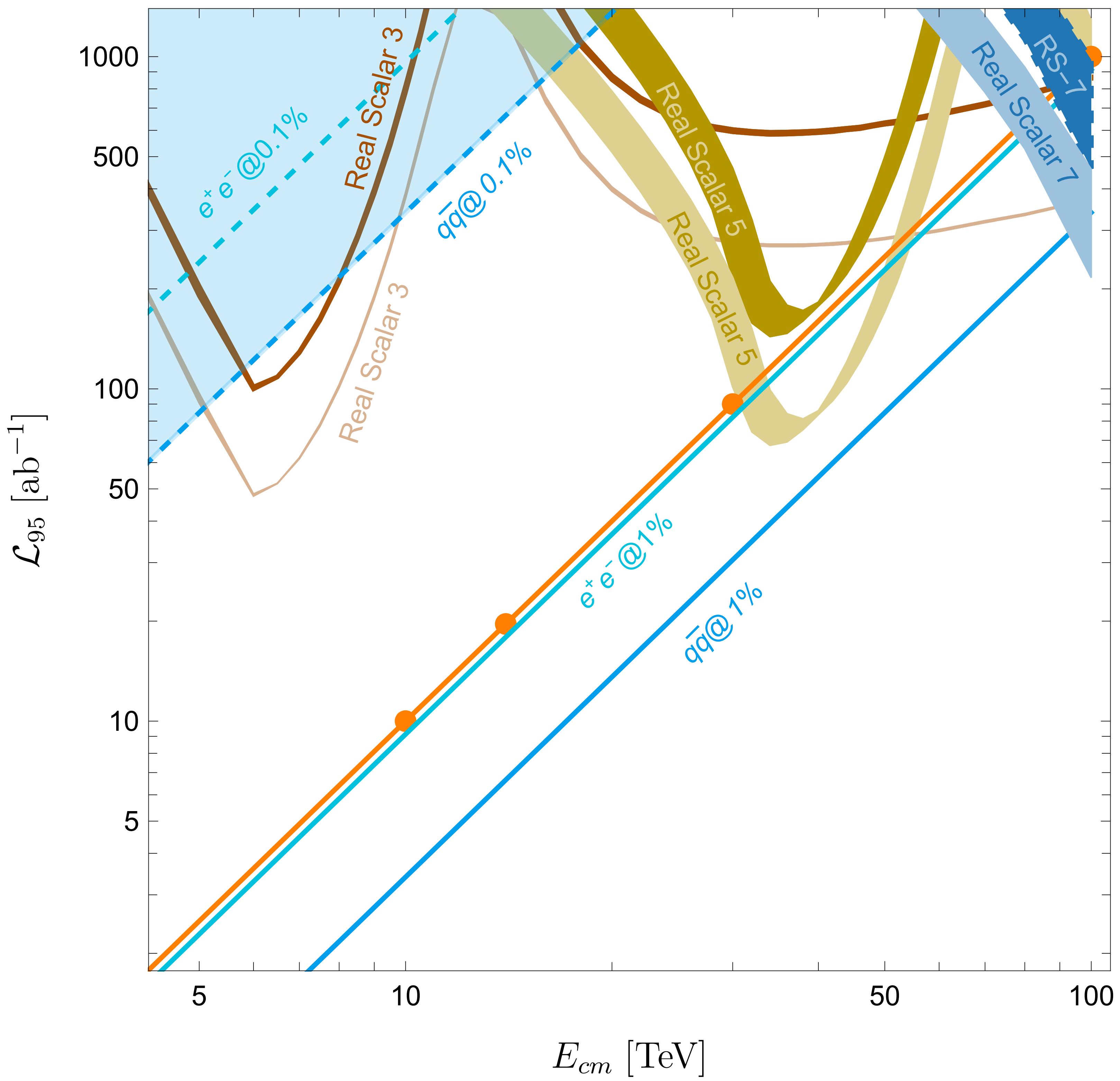


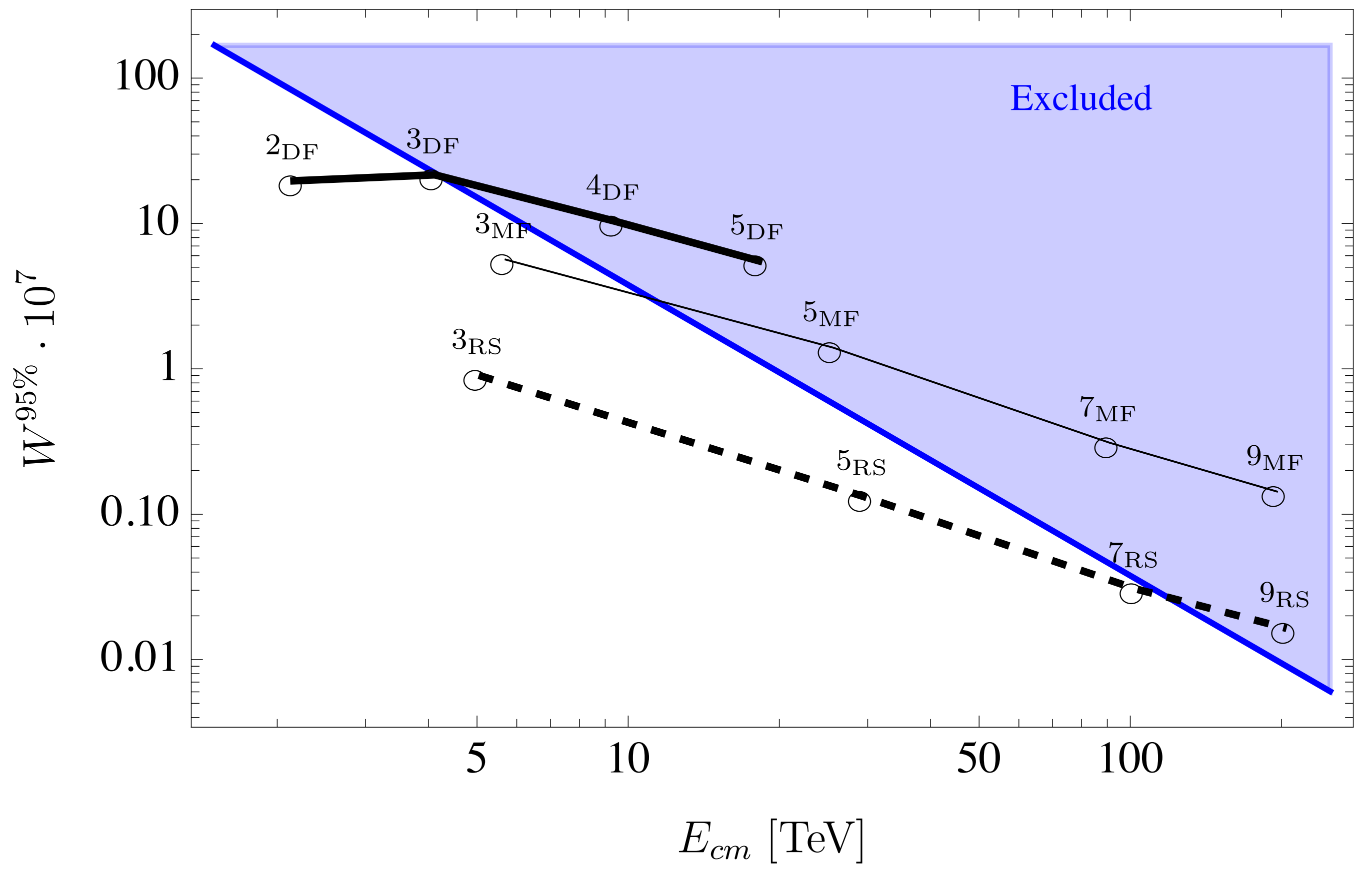
All fermionic dark matter candidates with $n \leq 5$ ($M \lesssim 15$ TeV) can be excluded for some center-of-mass energy at or below 14 TeV

ZHAO

Dark Matter at muon colliders	Xiaoran Zhao
40/S2-D01 - Salle Dirac, CERN	10:00 - 10:30







All dark matter candidates up to the maximal WIMP mass $M \simeq 100$ TeV can be excluded for some center-of-mass energy

Physics opportunities with a muon "beam dump" — Cari Cesarotti

6/R-012 - conference room, CERN — 10:00 - 10:30

Searching for New Physics at High-Energy Future Muon Colliders

Cari Cesarotti, MIT CTP Fellow

IMCC CERN Meeting

Oct 13, 2022

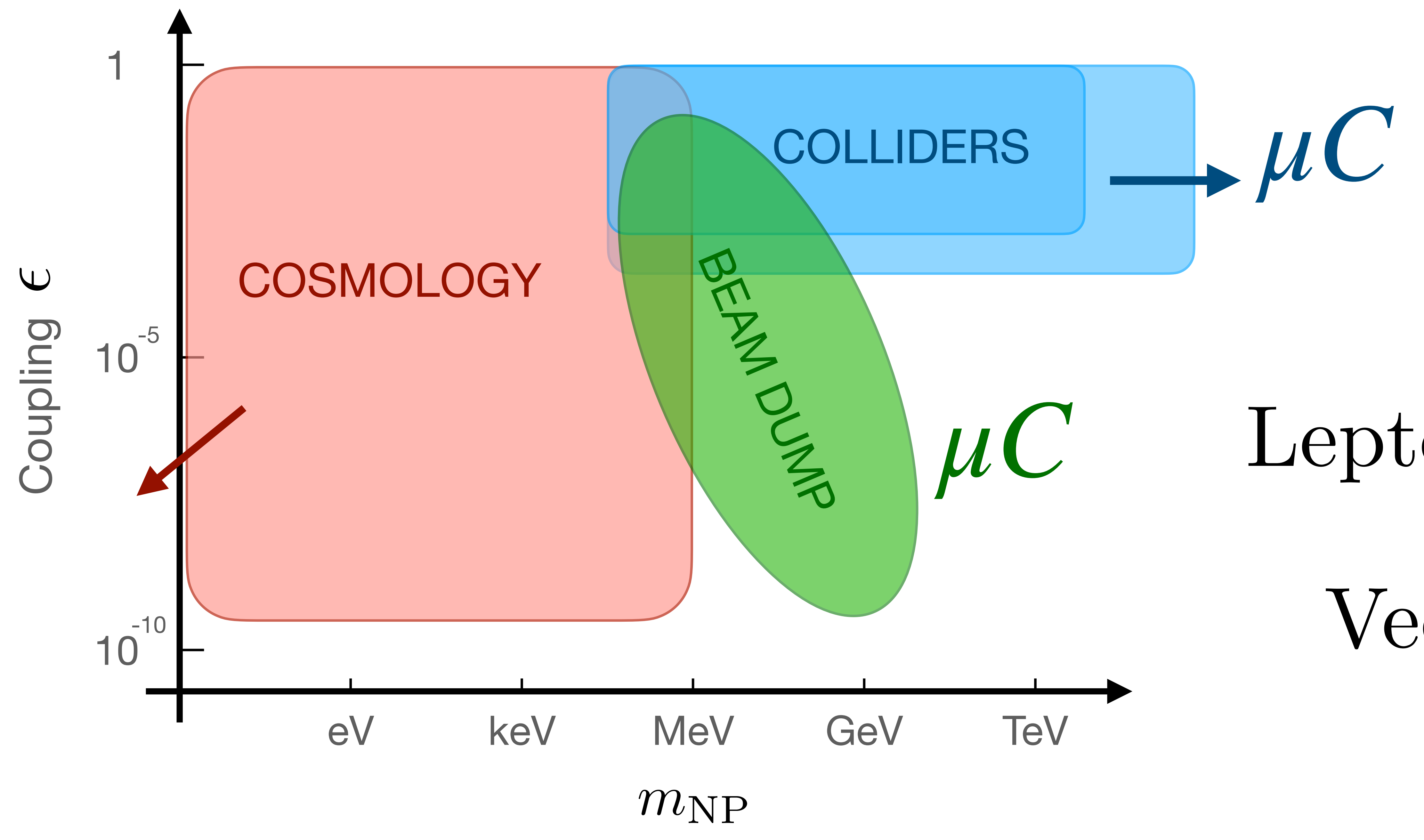
(2104.05720) w/ P. Asadi, R. Capdevilla, S. Homiller

(2202.12302) w/ S. Homiller, R. Mishra, M. Reece

Physics opportunities with a muon "beam dump" *Cari Cesarotti*

6/R-012 - conference room, CERN 10:00 - 10:30

Future multi-TeV μC provides a complementary physics program



Leptoquarks @ Collider

Vector Bosons @ BD

2104.05720 CC, P. Asadi, R Capdevilla, S. Homiller

2202.12302 CC, S. Homiller, R. Mishra, M. Reece

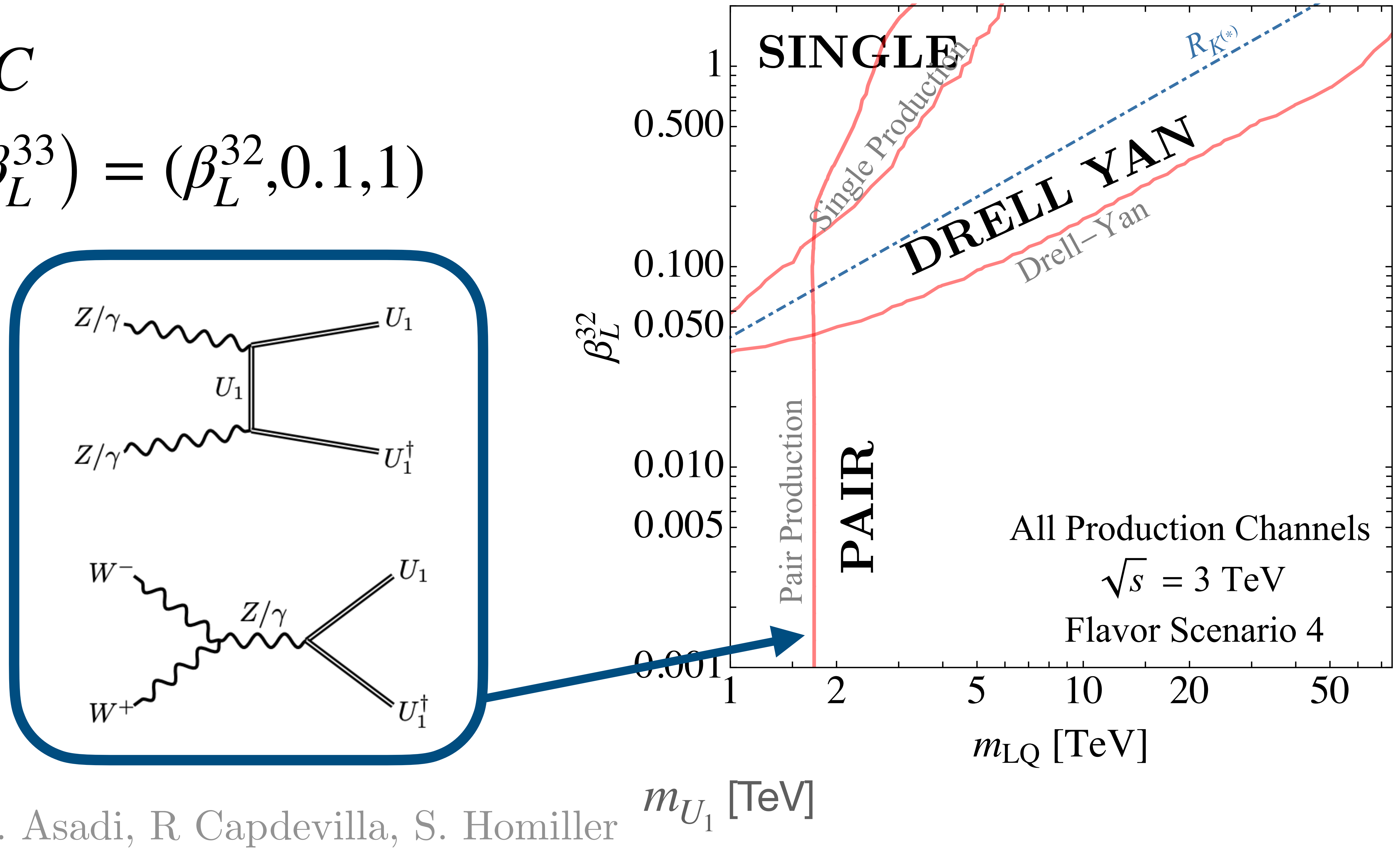
Leptoquarks

5σ confidence limits

3 TeV μC

$$\left(\beta_L^{22},\beta_L^{23},\beta_L^{33}\right) = (\beta_L^{32}, 0.1, 1)$$

Similar results to Greljo

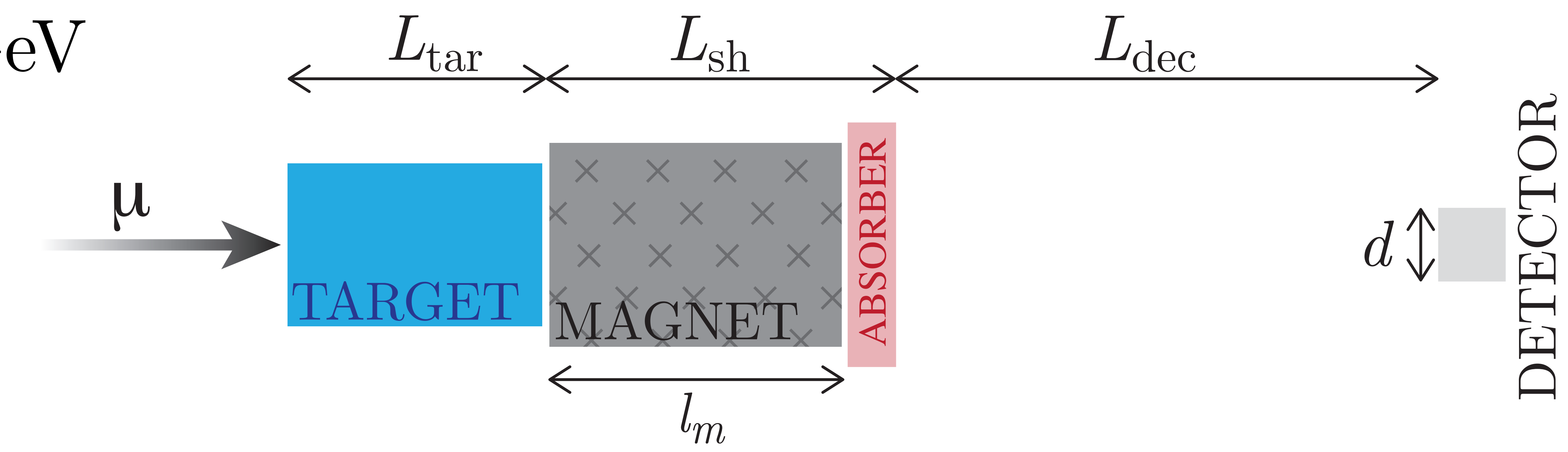


2104.05720 CC, P. Asadi, R Capdevilla, S. Homiller

A beam dump experiment at the μC allows us to push into both the energy and the intensity frontier

Can probe NP scenarios with:

- Very weak couplings
- Couplings to 2nd gen. leptons
- Masses $\lesssim$ 100 GeV



2202.12302 CC, S. Homiller, R. Mishra, M. Reece

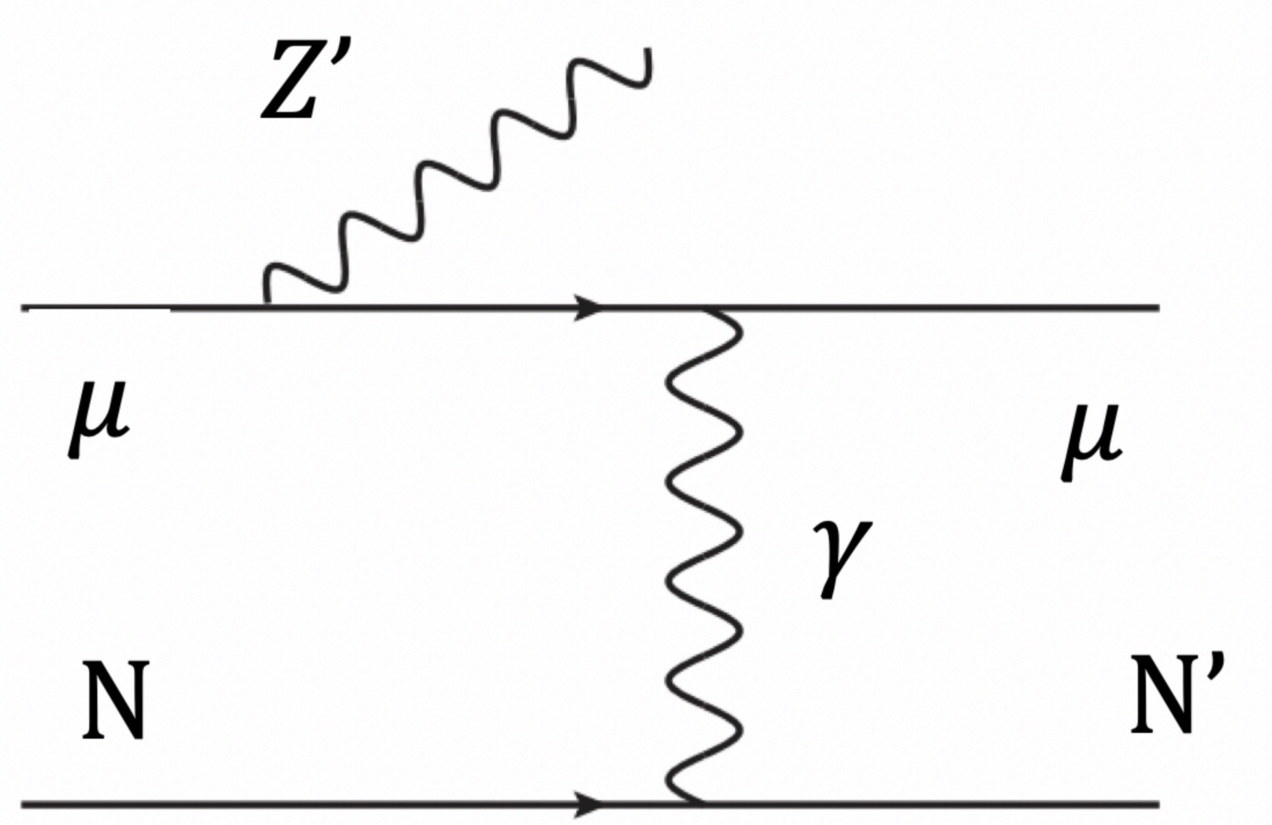
New physics Z' Scenarios

Dark Photon

$$\mathscr{L}_V \supset -i\epsilon e Z'_\mu \sum_{l\in e,\mu,\tau} \bar{l}\gamma^\mu l$$

$L_\mu - L_\tau$

$$\mathscr{L}_V \supset \mp i g Z'_\mu \sum_{l\in \mu,\tau} \left(\bar{l}\gamma^\mu l + \bar{\nu}_l \sigma^\mu \nu_l\right)$$



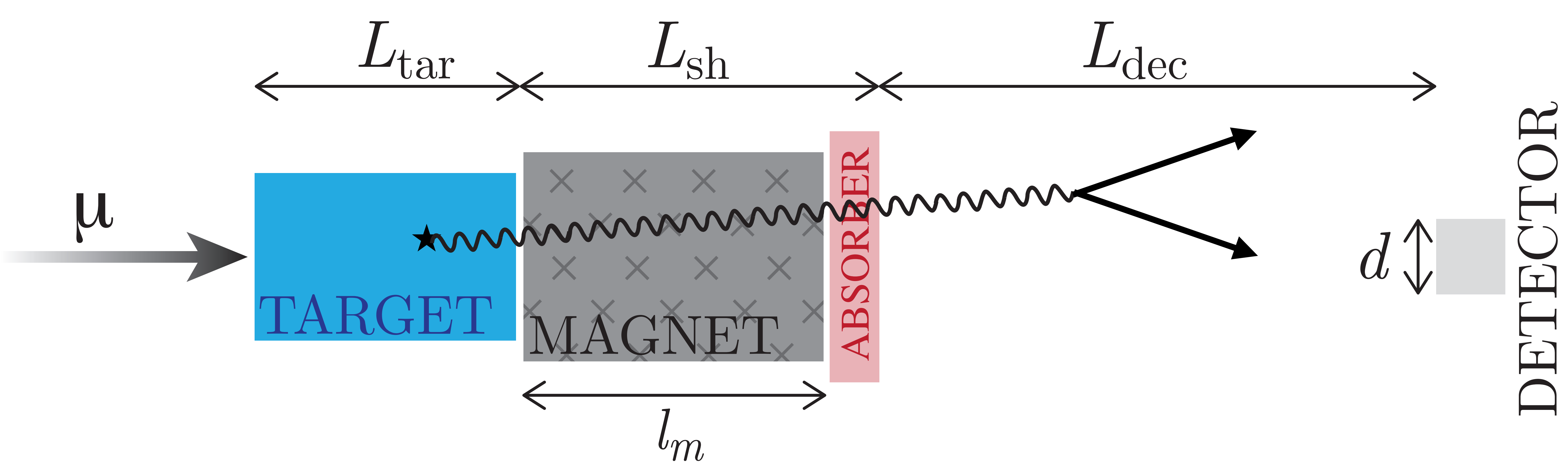
2202.12302 CC, S. Homiller, R. Mishra, M. Reece

CESAROTTI

Physics opportunities with a muon "beam dump" *Cari Cesarotti*

6/R-012 - conference room, CERN 10:00 - 10:30

Beam Dump Setup

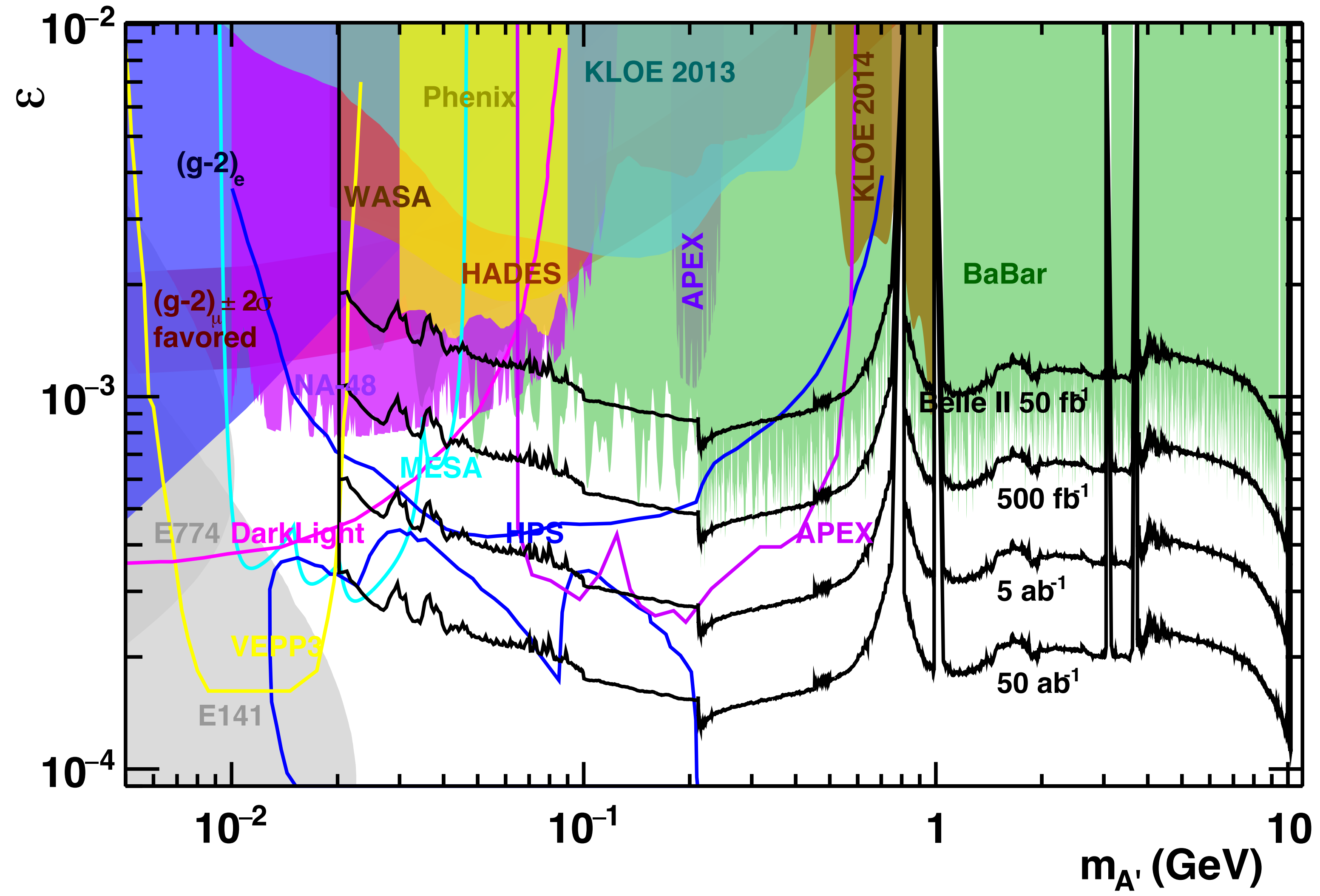


2202.12302 CC, S. Homiller, R. Mishra, M. Reece

"dark photon" search here means:

"shine through wall" experiment, also known as

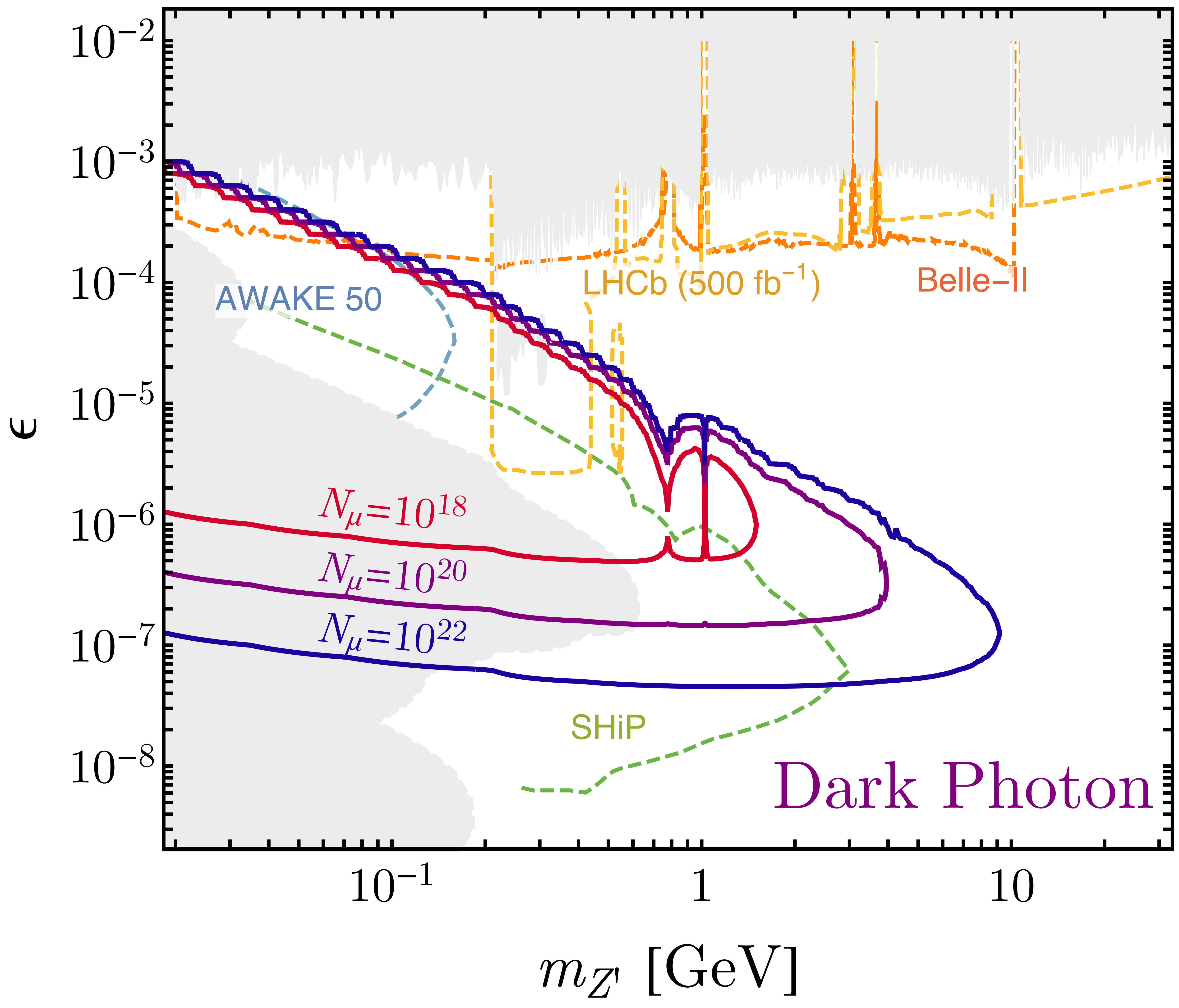
*"thick target" beam dump **visible** search*



CESAROTTI

Physics opportunities with a muon "beam dump" — *Cari Cesarotti*

6/R-012 - conference room, CERN — 10:00 - 10:30



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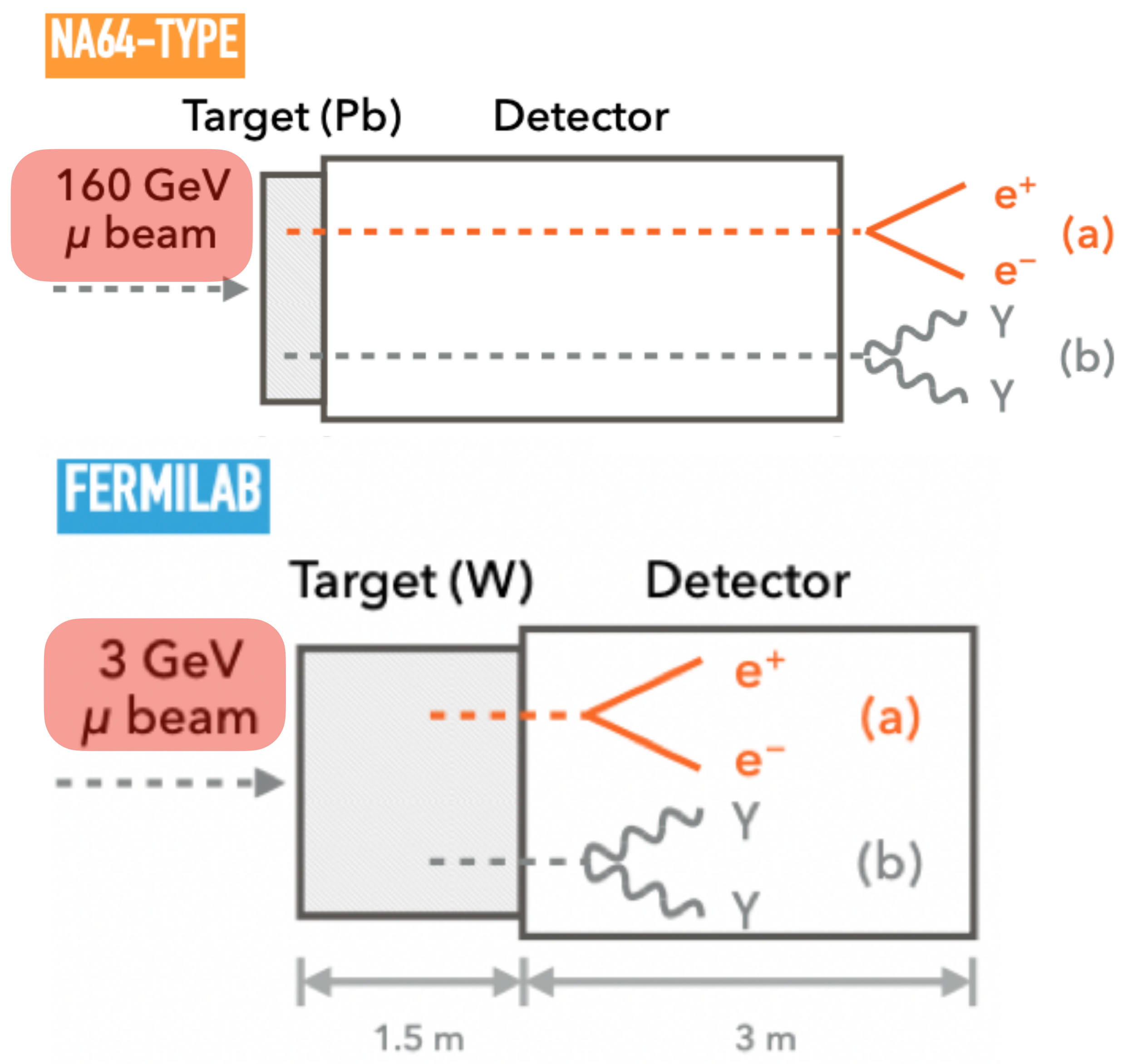


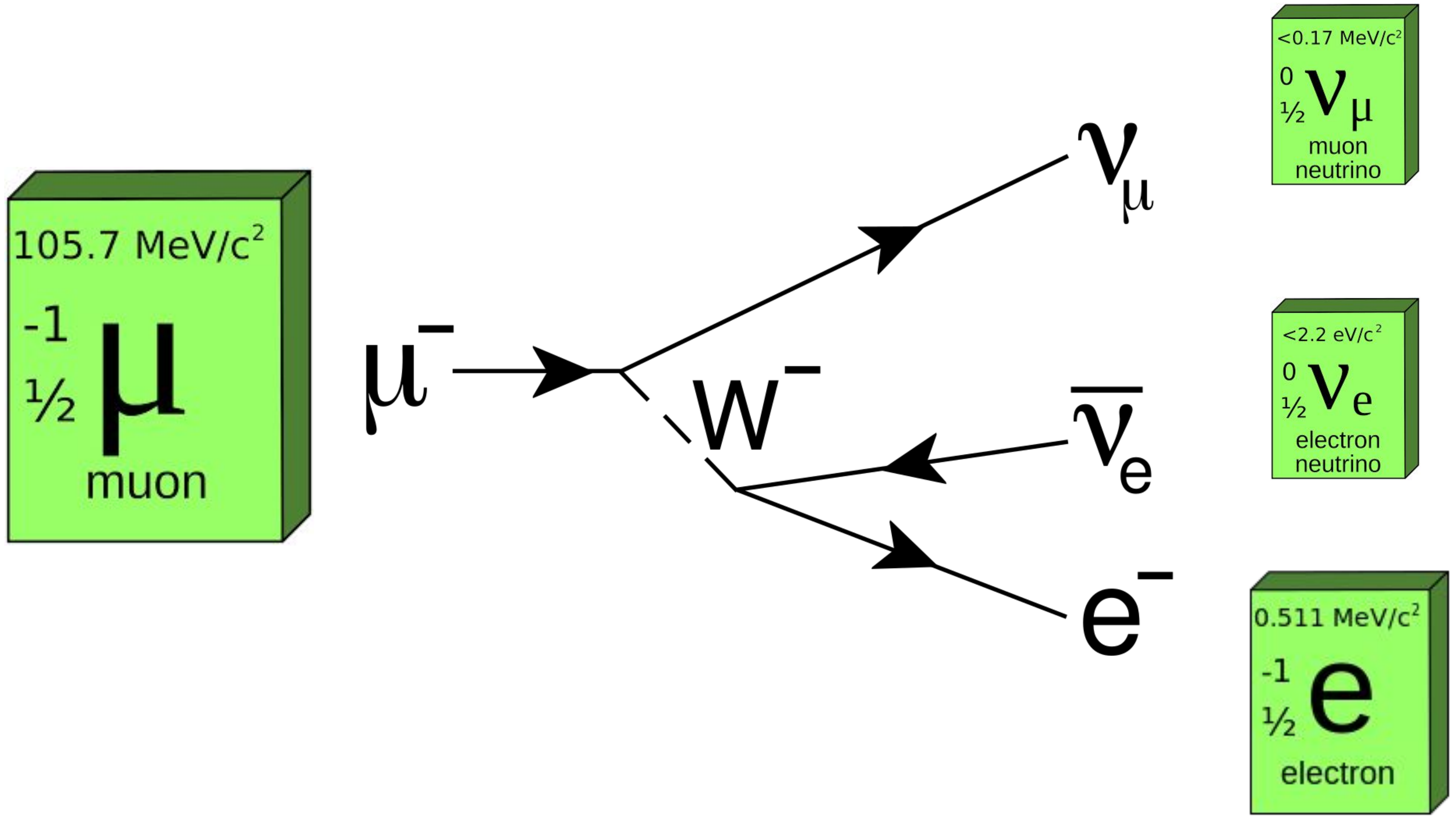
LI

Possible intermediate steps towards a Muon collider	*Qiang Li*
40/S2-D01 - Salle Dirac, CERN	08:30 - 09:00

Possible intermediate steps towards a Muon collider

from neutrino neutrino/lepton, electron muon to muon muon collisions?

"Exotica" Particle ➵ 😊 *"Exotica" Collider*



Qiang Li, Peking University 2022/10/12

arXiv:2205.15350, arXiv:2204.11871, arXiv:2201.07808, arXiv:2109.01265, arXiv:2107.13581, arXiv:2010.15144

LI

Possible intermediate steps towards a Muon collider — *Qiang Li*

40/S2-D01 - Salle Dirac, CERN — 08:30 - 09:00

Muon Collider: intermediate steps?

link

Matt Strassler | June 10, 2022 at 6:22 PM | Reply

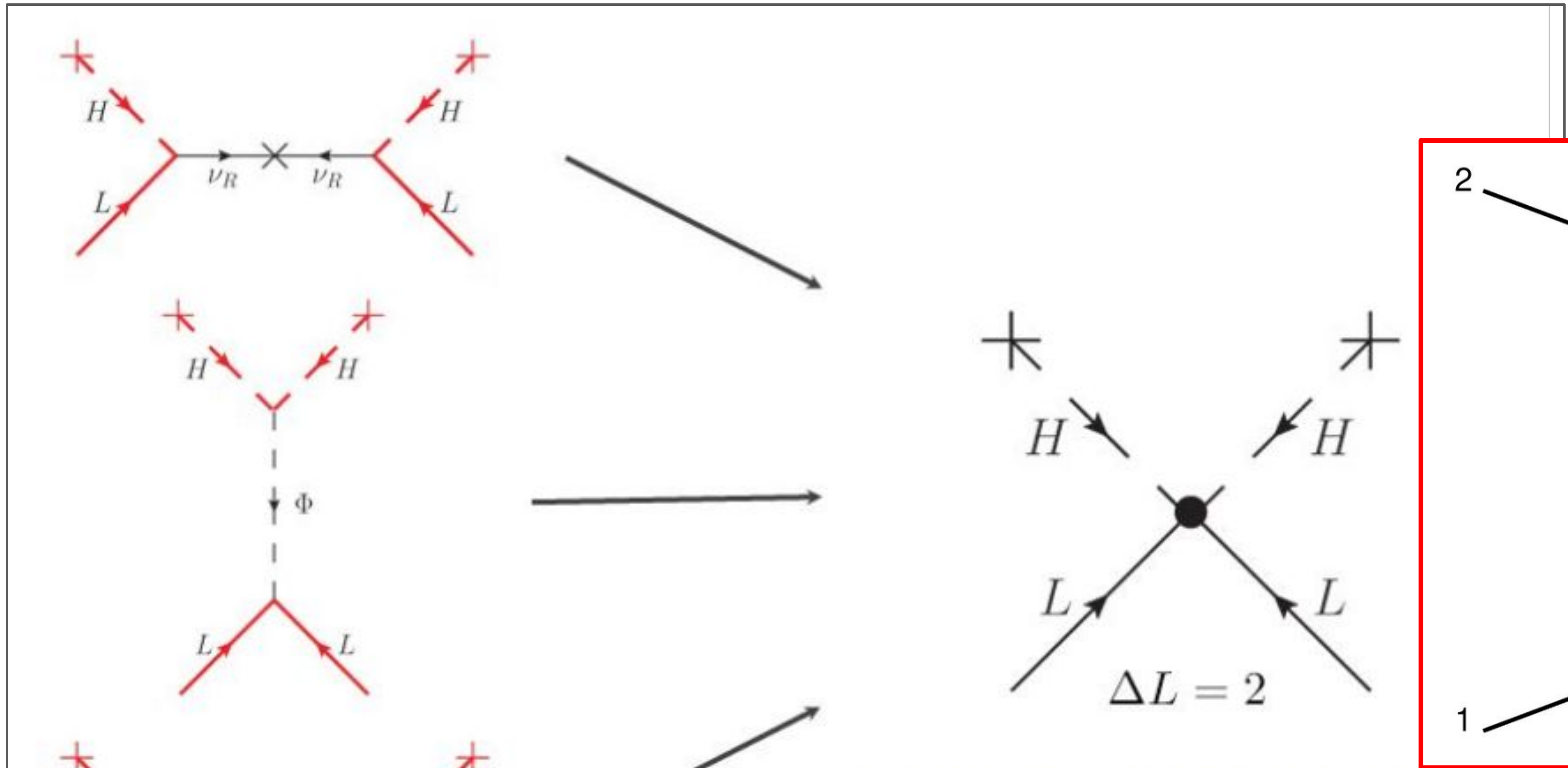
Andrew, these are very serious concerns too. But one cannot move before one has funding, and one cannot get funding without a clear argument as to why funding should be provided. At higher energy, the only clear arguments, right now, are for a Higgs/top factory. That will be an electron positron machine of some type, unless the ambitious muon collider project can demonstrate enough likelihood of success and enough intermediate physics goals (e.g. neutrino beams) that it can be justified as well. (Meanwhile other colliders at lower energy but very high luminosity might be pursued.)

19. Alain Blondel: alain.blondel@cern.ch question general but triggered by Steve Ritz. Establish the list of questions that are of great importance and should be answered across frontiers/experiments/facilities. Here is **a** question that I think if of key importance and is addressed in many 'frontiers' without being sufficiently asked as a unique question for which the various groups would gain to reflect in common:
– **given that neutrinos have masses, the question of existence and masses of right handed neutrinos (or their alternatives) should have a common discussion, formalism, expectations, visible consequences and what other problems they might solve, while understanding the possibilities, from the minimal one to those more complicated.** This is certainly the most likely new physics there is, and it seems to naturally result from the present discoveries. It was evident from the presentations today that this question appears in the neutrino frontier, rare processes, cosmic and energy frontier as well as instrumentation, and in Hitoshi's presentation, and yet there is not a uniform language or momentum to look for it in all possible ways – so it remains somewhat confidential.

Seattle Snowmass Summer Meeting 2022

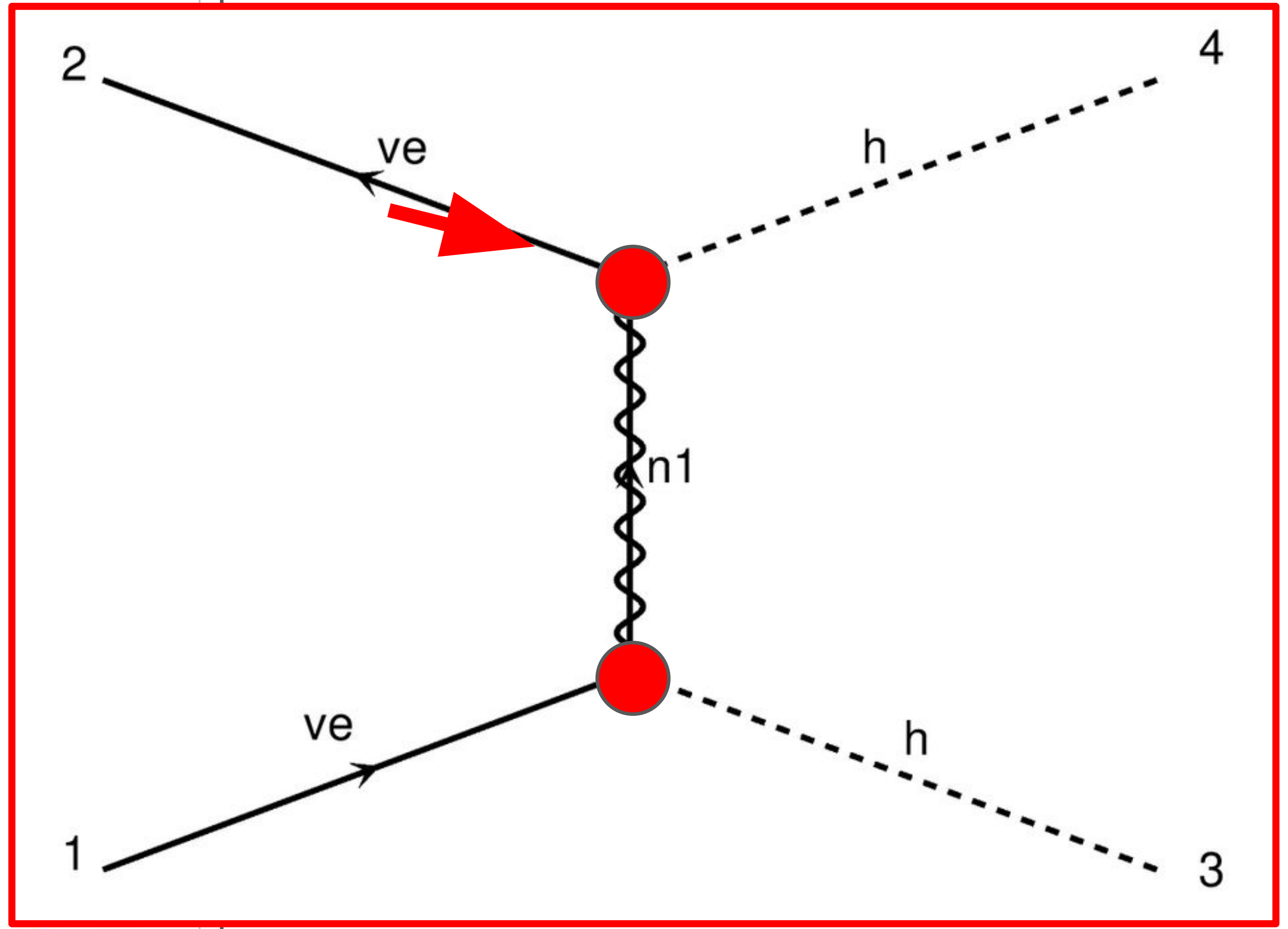
- **"...enough intermediate physics goals (e.g. neutrino beams)"**
- **neutrino mass …"This is certainly the most likely new physics there is…"**

Neutrino **Portal** to BSM



Dimension-5 Weinberg effective operator (1/M)LLHH (shorthand).

$$\left(\overline{(\ell_L)^c} H\right)_1 (\ell_L H)_1$$



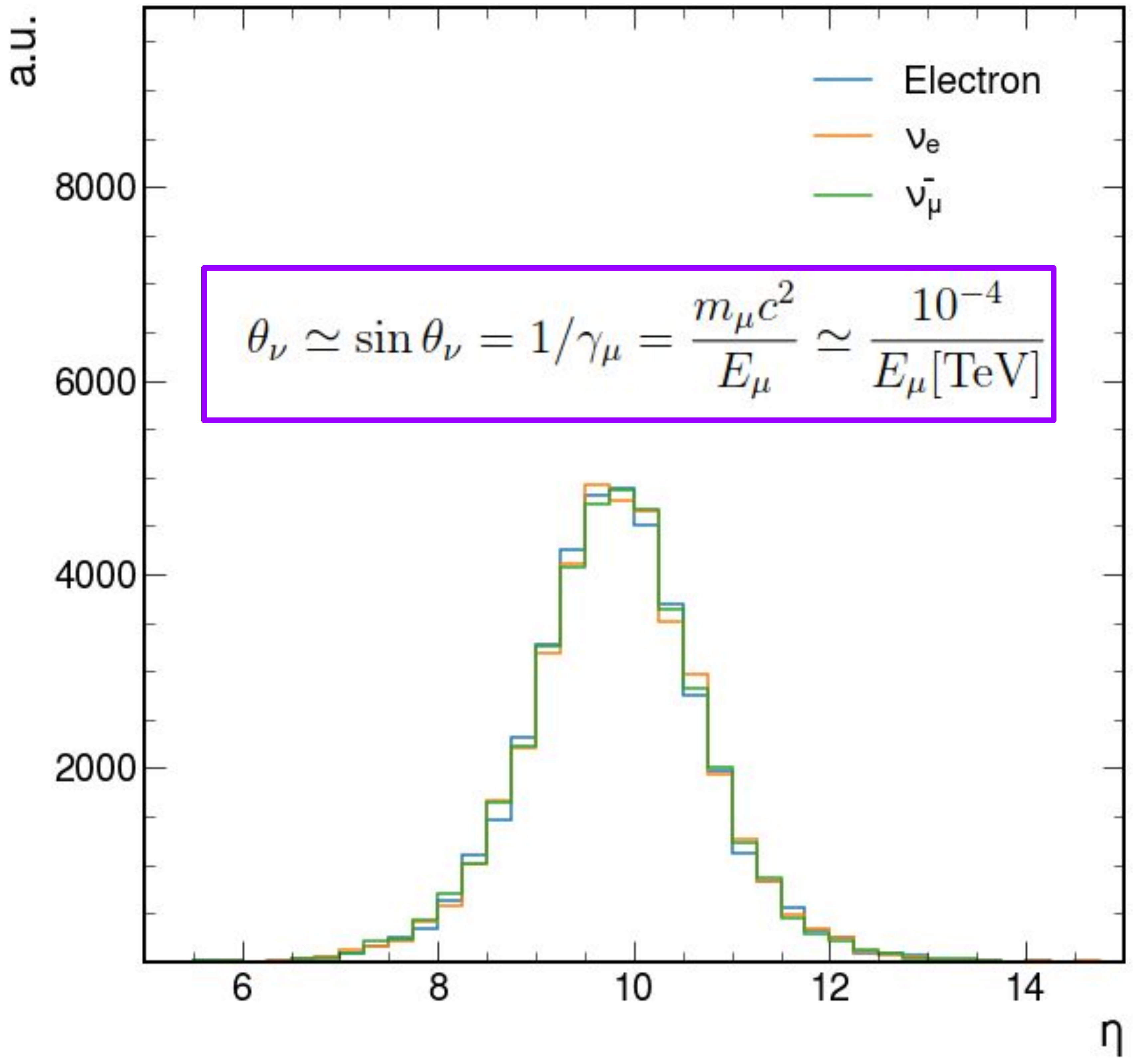
coupling ∝ heavy neutrino mass

LI

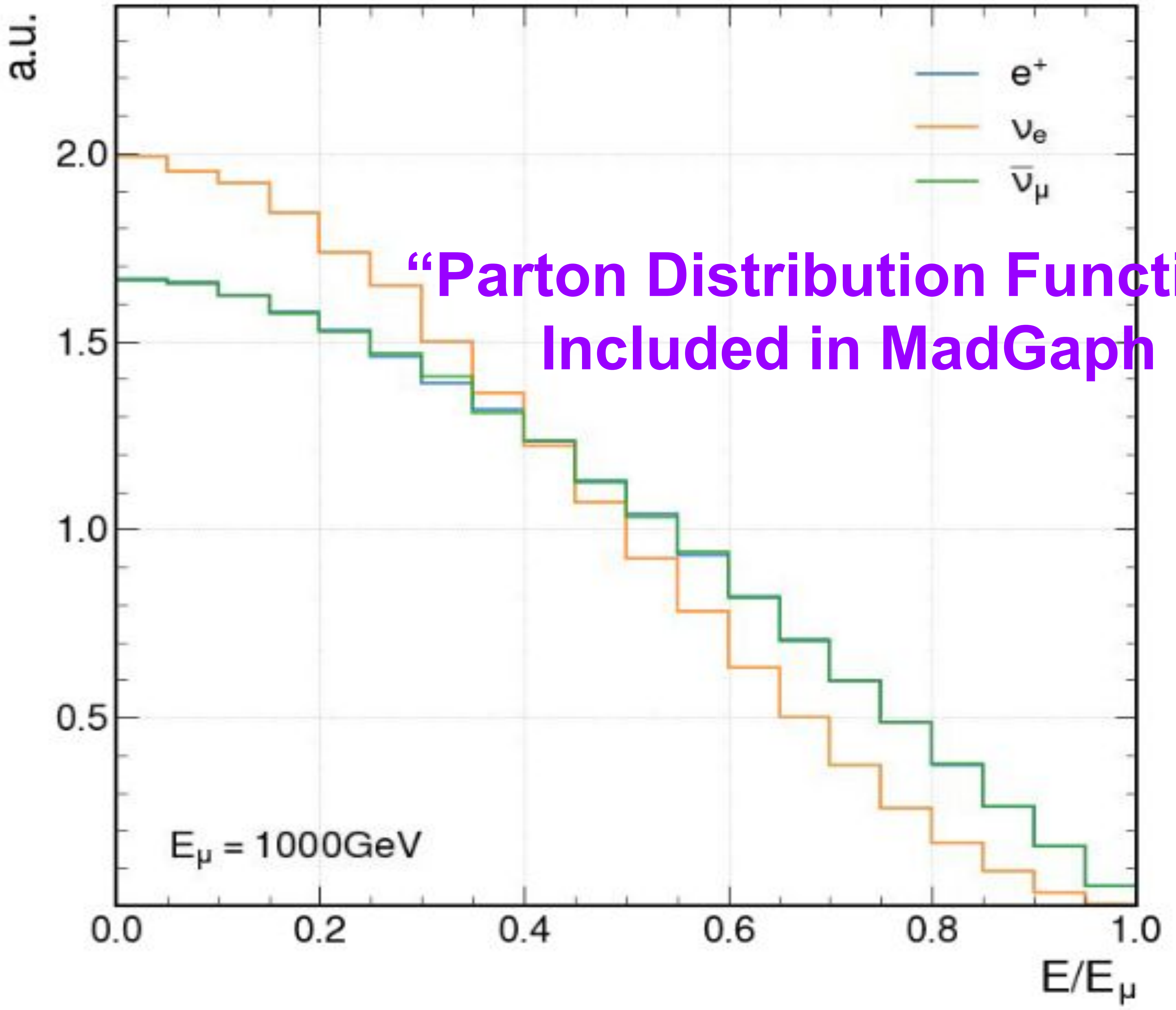
Possible intermediate steps towards a Muon collider — *Qiang Li*

40/S2-D01 - Salle Dirac, CERN — 08:30 - 09:00

Neutrino Beam from 1TeV Muon beam



$$\theta_\nu \simeq \sin\theta_\nu = 1/\gamma_\mu = \frac{m_\mu c^2}{E_\mu} \simeq \frac{10^{-4}}{E_\mu[\text{TeV}]}$$



"Parton Distribution Function"
Included in MadGaph

Highly collimated in angle, yet widely distributed in Energy

LI

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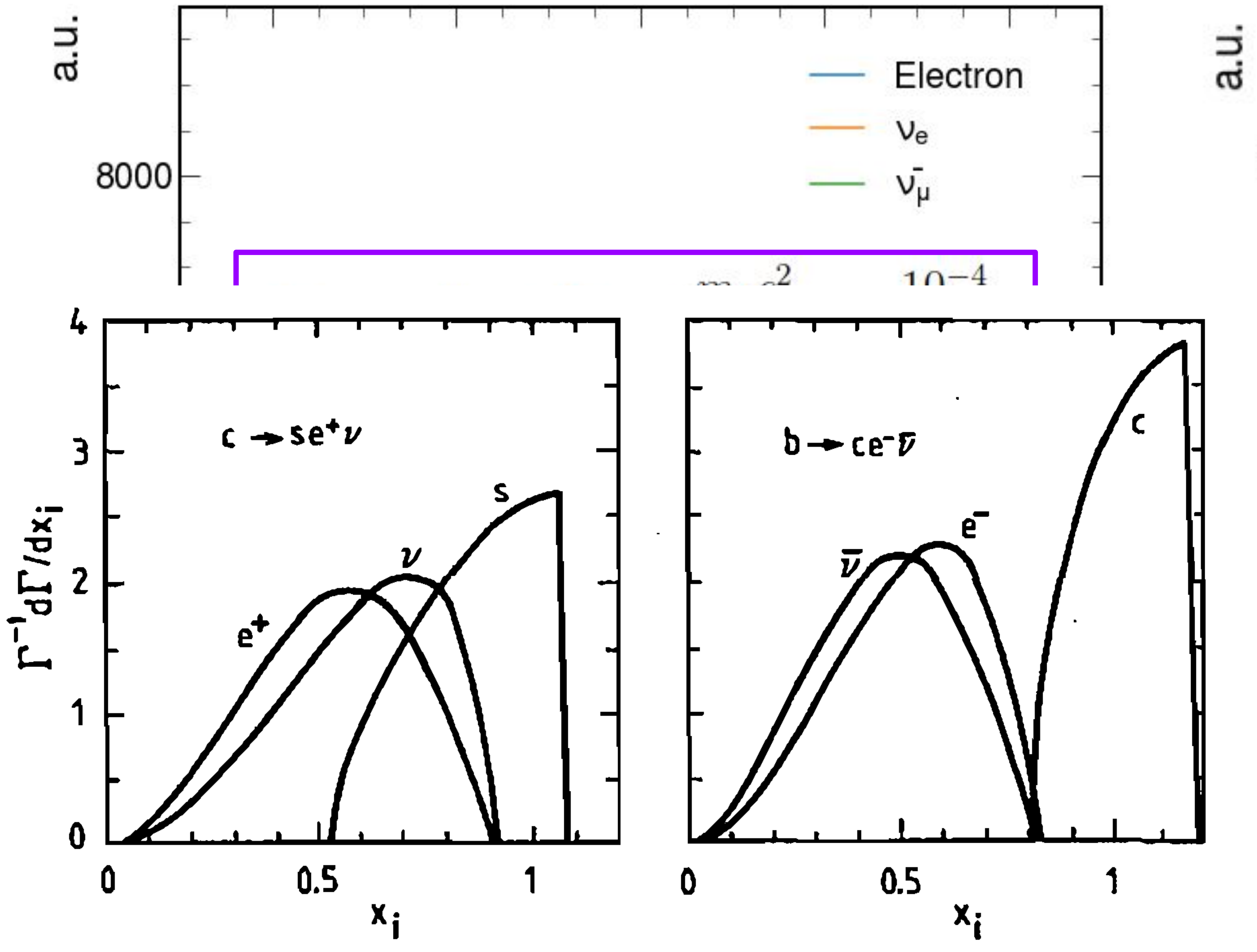
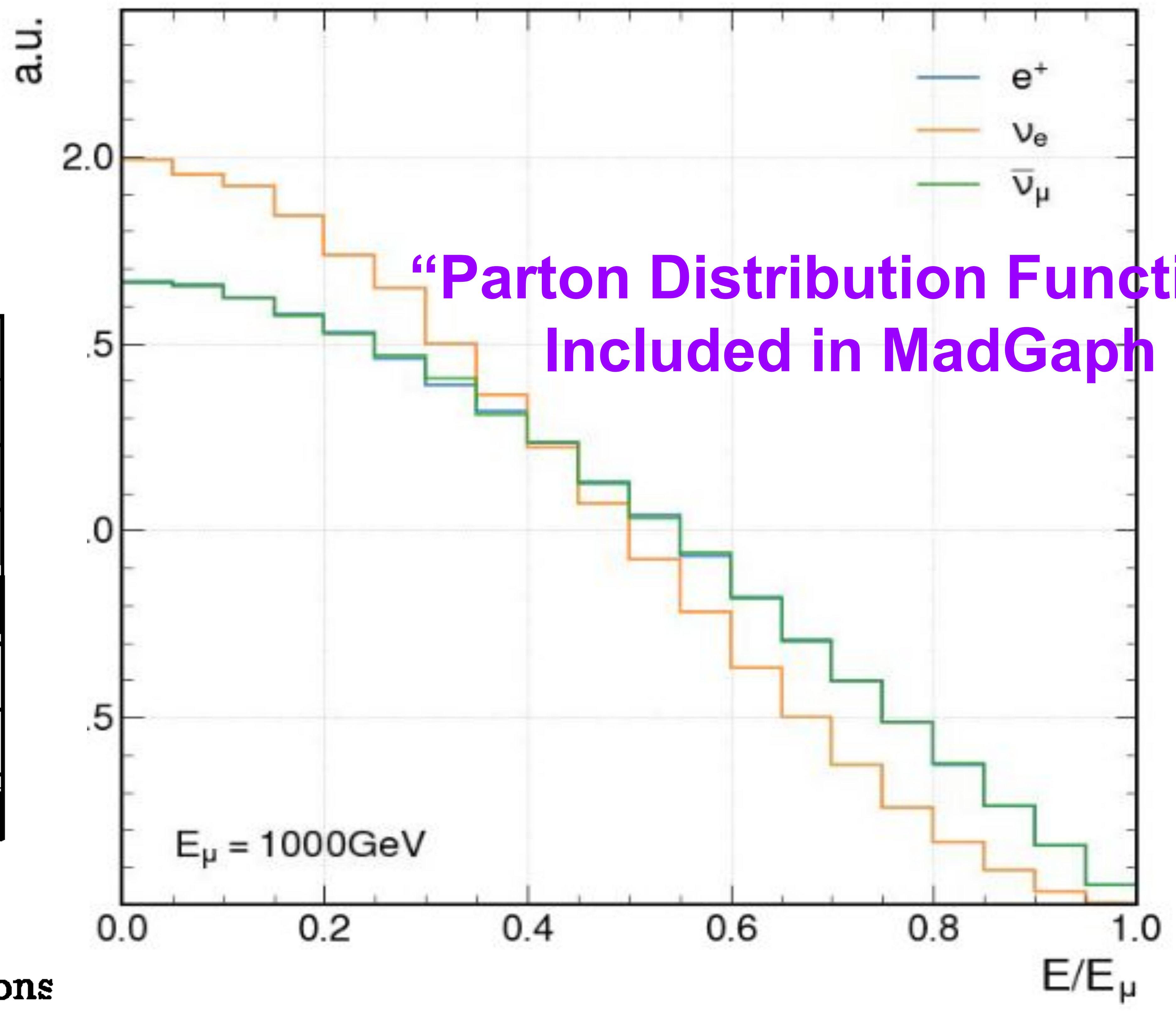


Fig. 3.10. Fractional energy spectra $x_i = 2E_i/m_Q$ of decay leptons and quarks from $Q = c, b$ semileptonic decay.



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widely distributed in Energy

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om 1TeV Muon beam

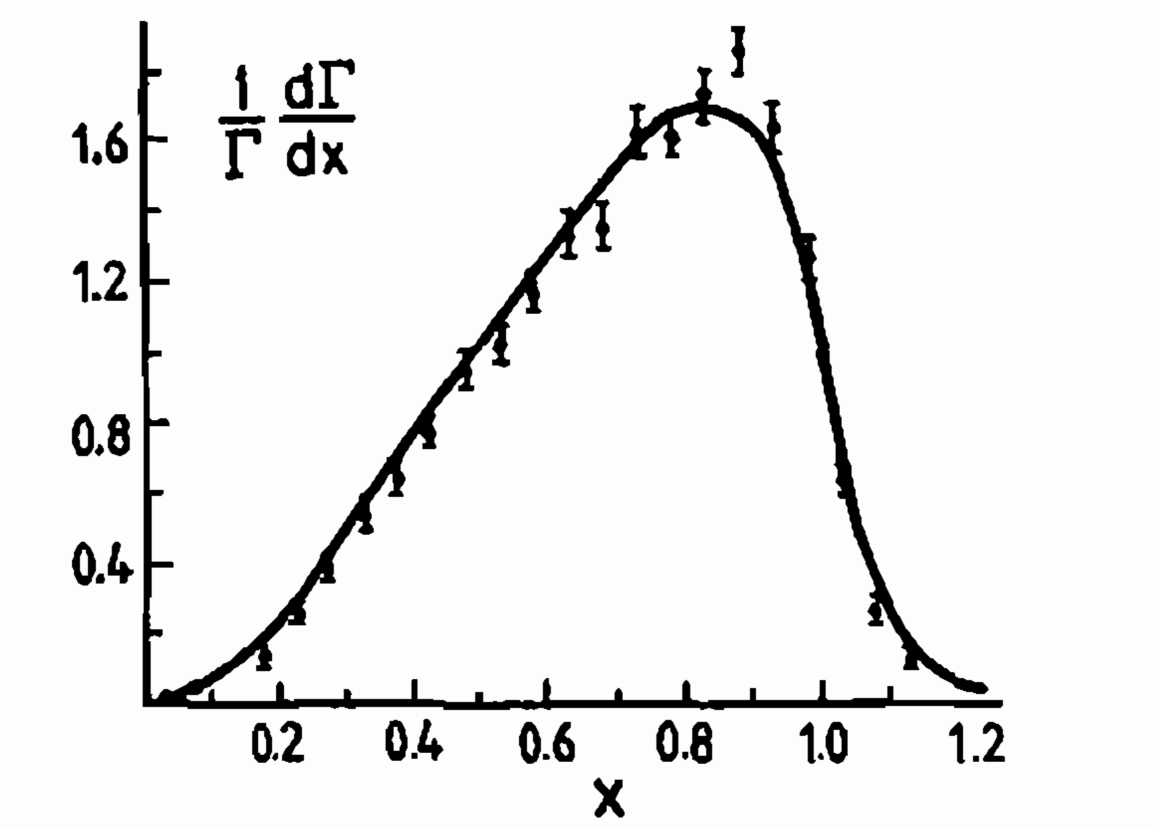
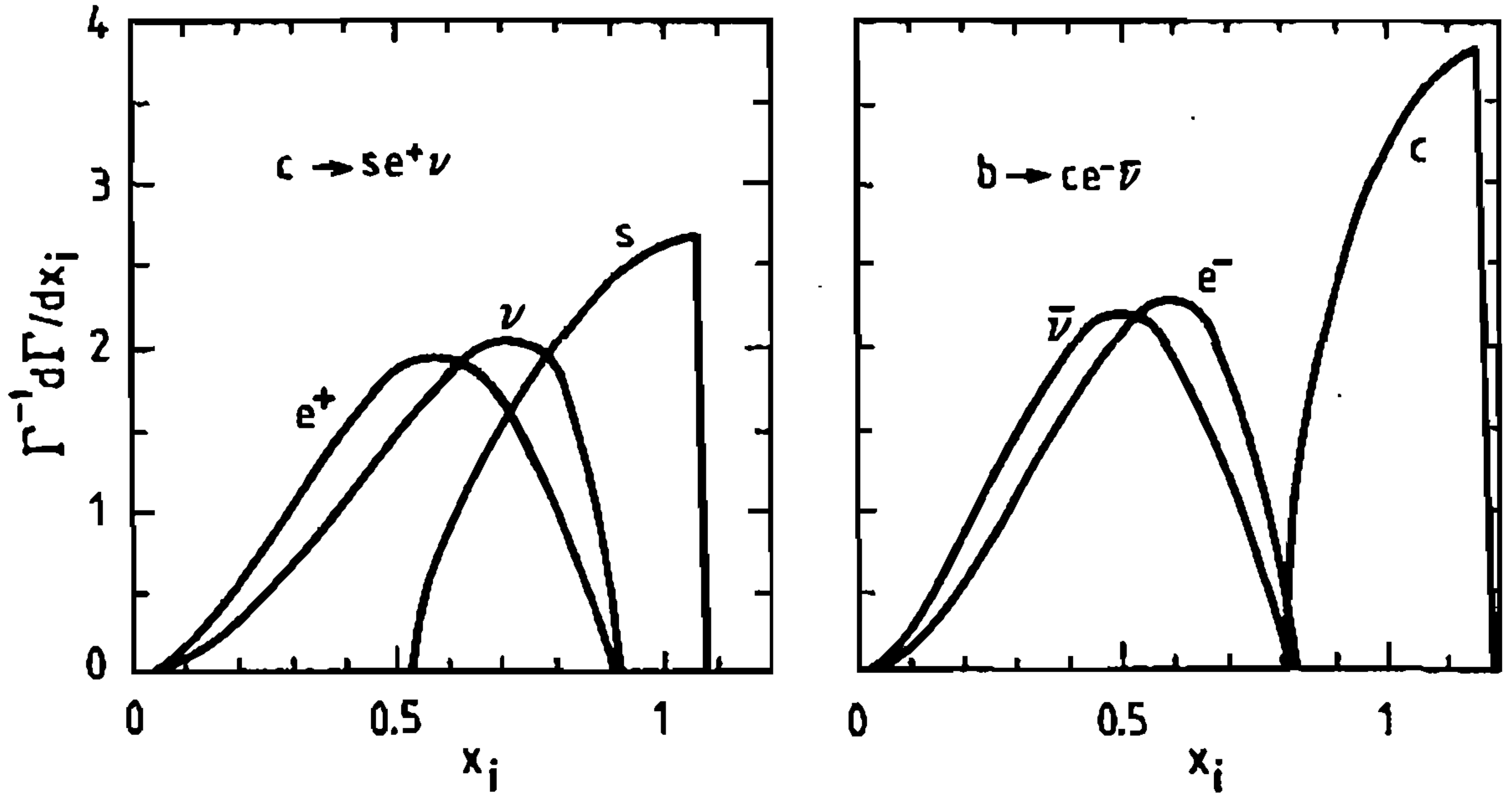


Fig. 3.2. Positron decay spectrum from muon decay; data from Phys. Rev. **119**, 1400 (1960). The theoretical curve includes radiative corrections and experimental resolution; the latter explains the tail above $x = 1$.



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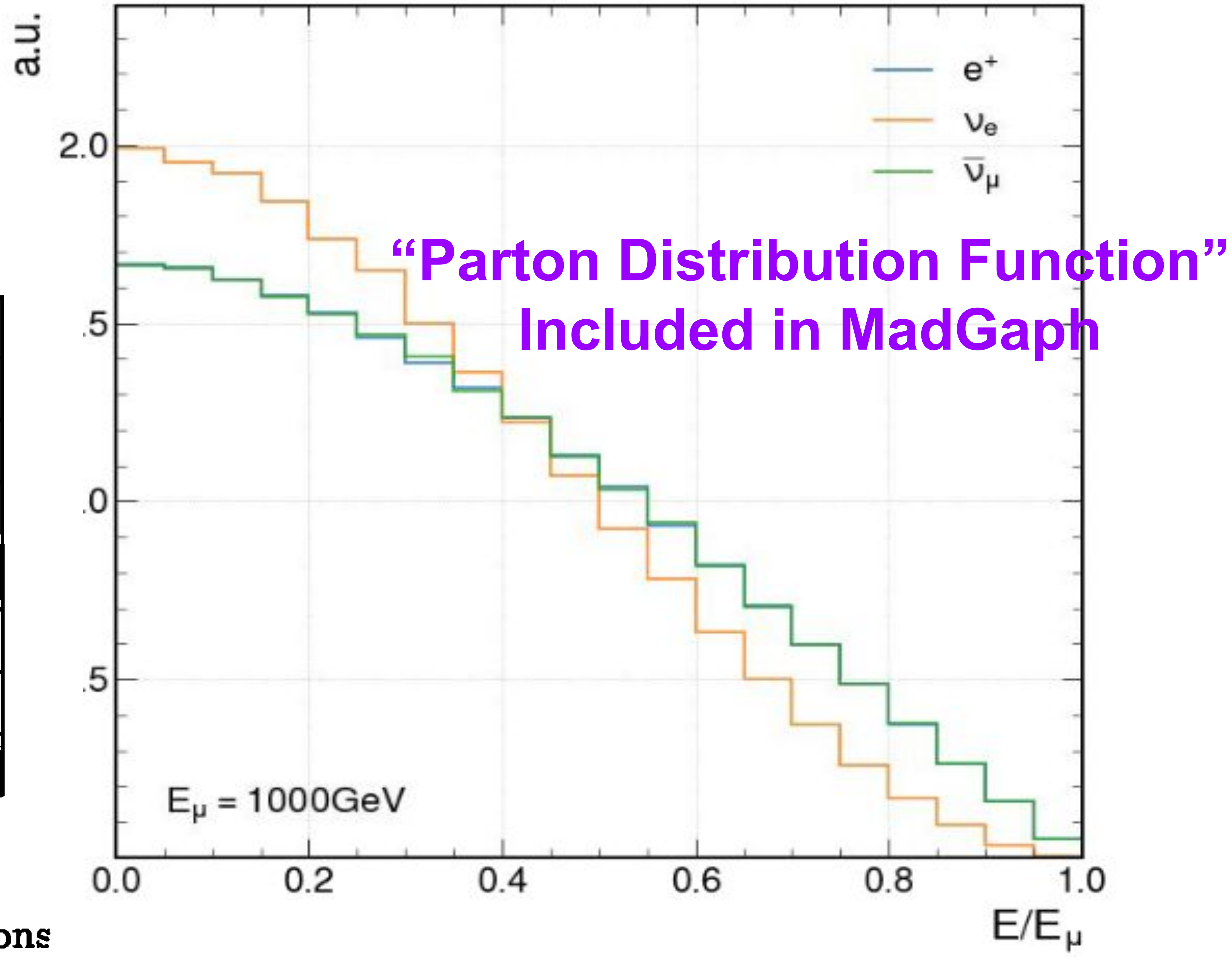

widely distributed in Energy

LI

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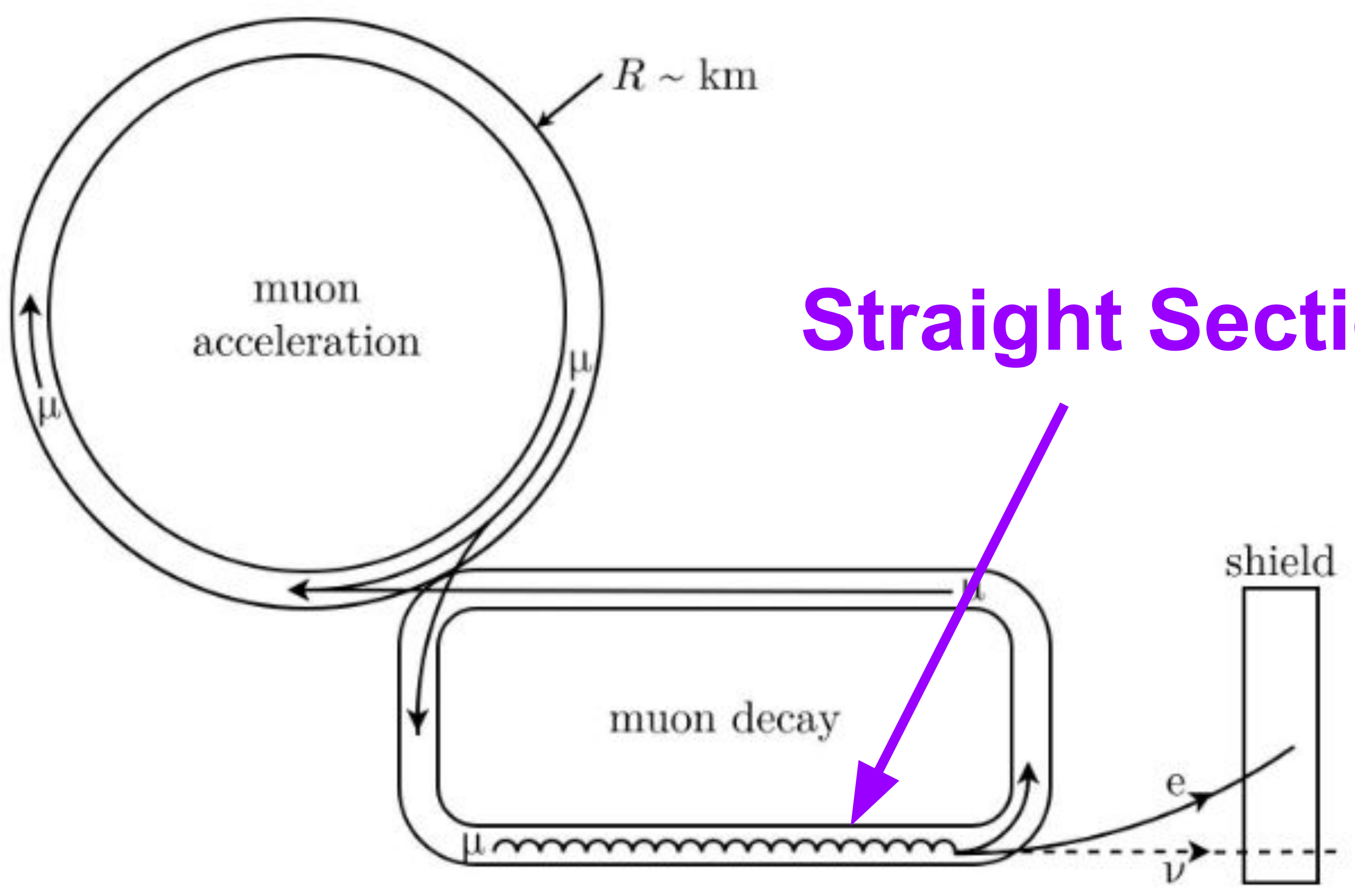
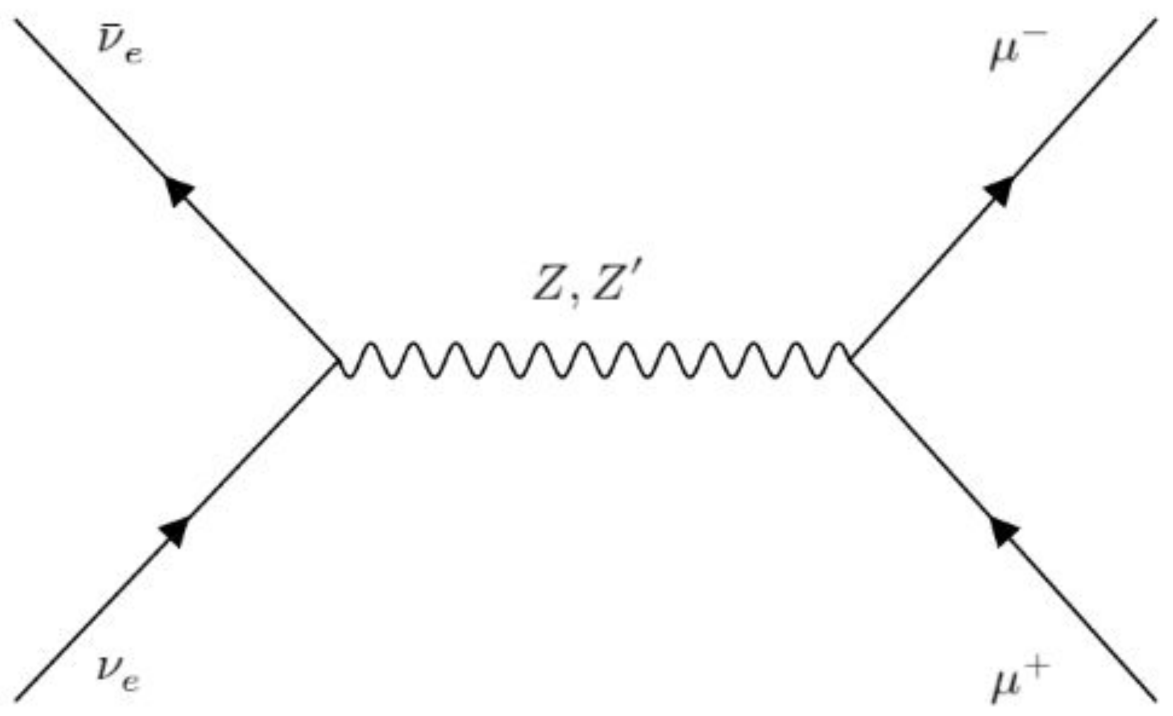
Neutrino Collider?



Straight Section

A small modulation of the muon decay angle through vertical bending, symbolized by the squiggly line, may be used to focus the neutrino beam.

Question: ?/fb in 1-10 years



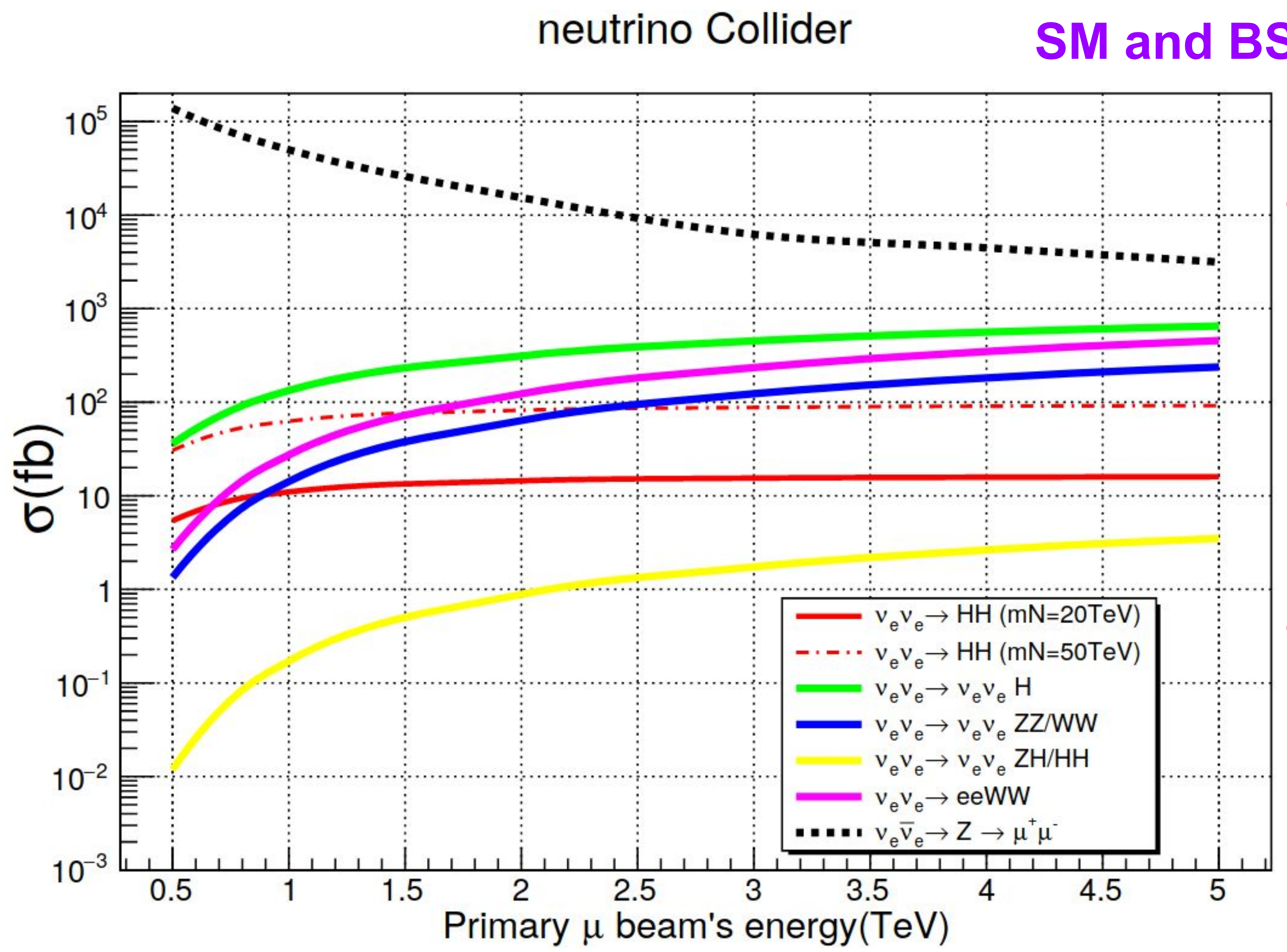
Neutrino (anti-)neutrino collisions

$$\nu_e\bar{\nu}_e \to Z \to \mu^+\mu^- .$$

$$\begin{aligned}
\nu_e\nu_e &\to HH \\
\nu_e\nu_e &\to ZZ\,, ZH \\
\nu_e\nu_e &\to \nu_e\nu_e H, \\
\nu_e\nu_e &\to \nu_e\nu_e ZZ\,, \nu_e\nu_e WW, \\
\nu_e\nu_e &\to \nu_e\nu_e ZH\,, \nu_e\nu_e HH, \\
\nu_e\nu_e &\to e^-e^-W^+W^+,
\end{aligned}$$

$$\begin{aligned}
\nu_e\nu_e &\to HH \\
\nu_e\nu_e &\to ZZ\,, ZH \\
\nu_e\nu_e &\to \nu_e\nu_e H, \\
\nu_e\nu_e &\to \nu_e\nu_e ZZ\,, \nu_e\nu_e WW, \\
\nu_e\nu_e &\to \nu_e\nu_e ZH\,, \nu_e\nu_e HH, \\
\nu_e\nu_e &\to e^-e^-W^+W^+,
\end{aligned}$$
14

Neutrino Collision Processes



SM and BSM (Heavy Majorana)

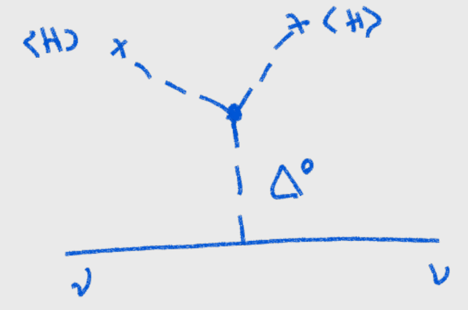
- **vvbar->Z:**
  large cross section
  >100pb
  can be observed in short time!
  ~days to weeks
- **May loosen requirement on beam quality!**

Neutrino mass mechanisms

LEPTON NUMBER BREAKING

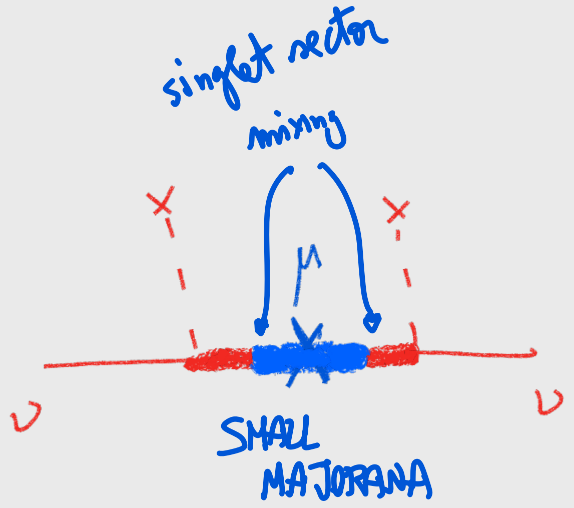
L – violation

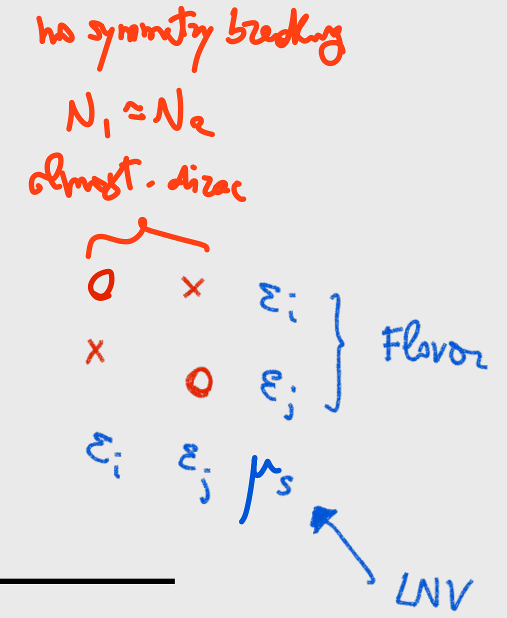
(1,1,0) (at least 2)



(1,3,1) (1 is enough)

(1,1,0) (at least 2+1)



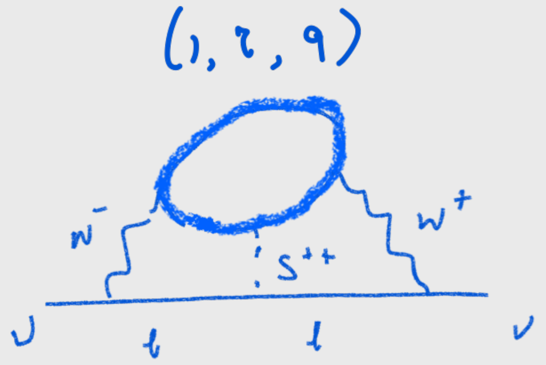


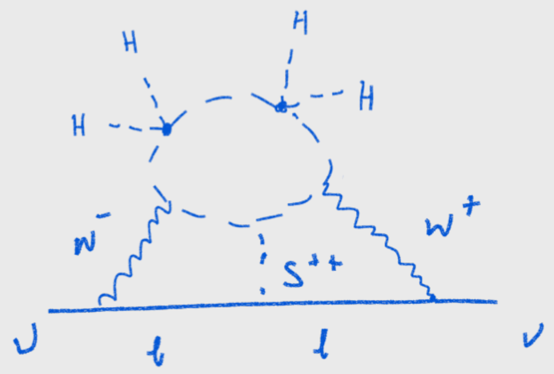
L – not accidental

new physics before 2012

$d = 5 \quad (1,2,1/2) \qquad \dfrac{(LH)^2}{\Lambda}$ UV

$d = 7 \quad (1,1,2) \qquad \dfrac{\left(DH\sigma_2 H\right)^2 S^{--}}{\Lambda^3}$ UV





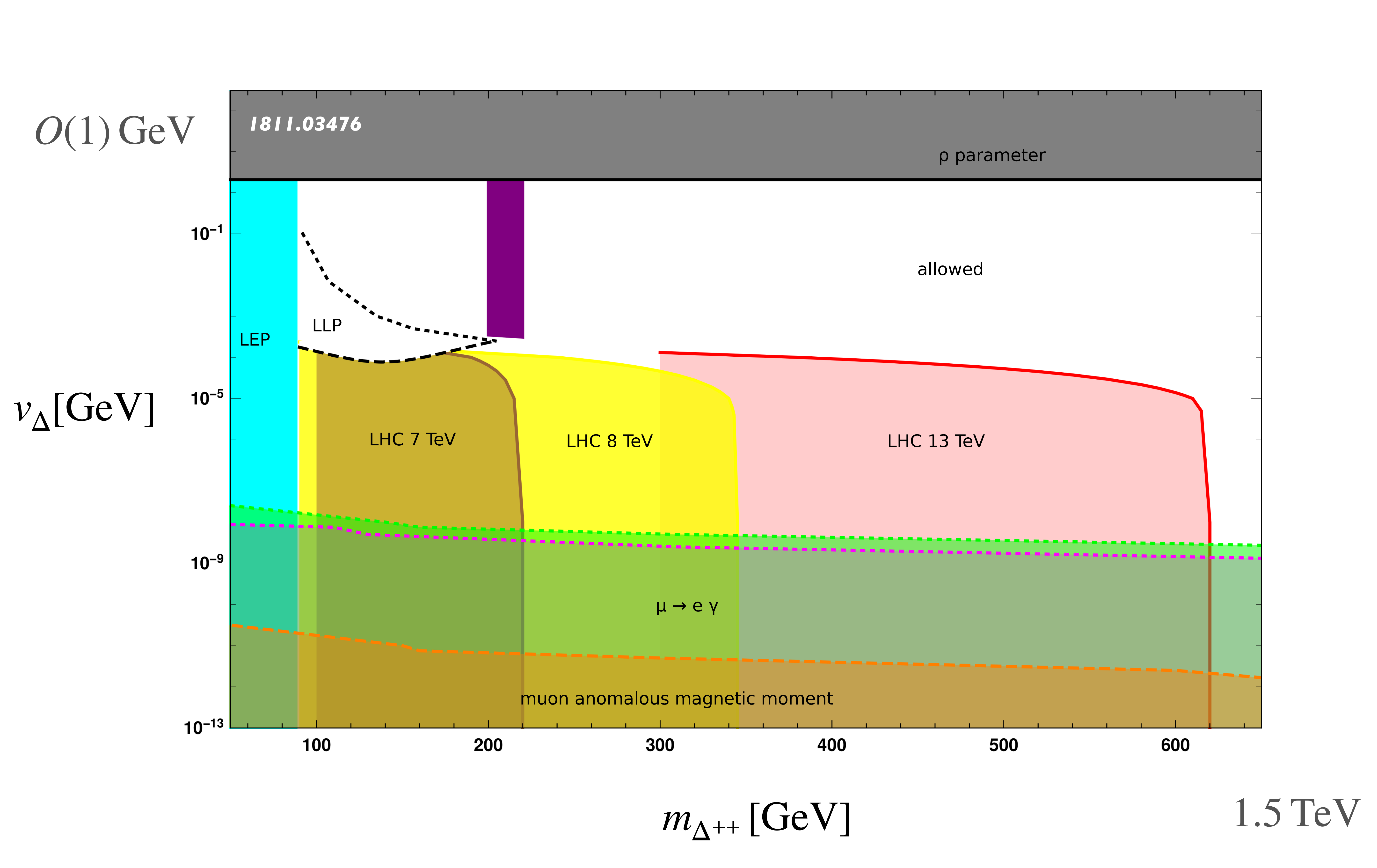
L – gauged, SSB

$SU(3) \otimes SU(2)_L \otimes SU(2)_L \otimes U(1)_{B-L}$

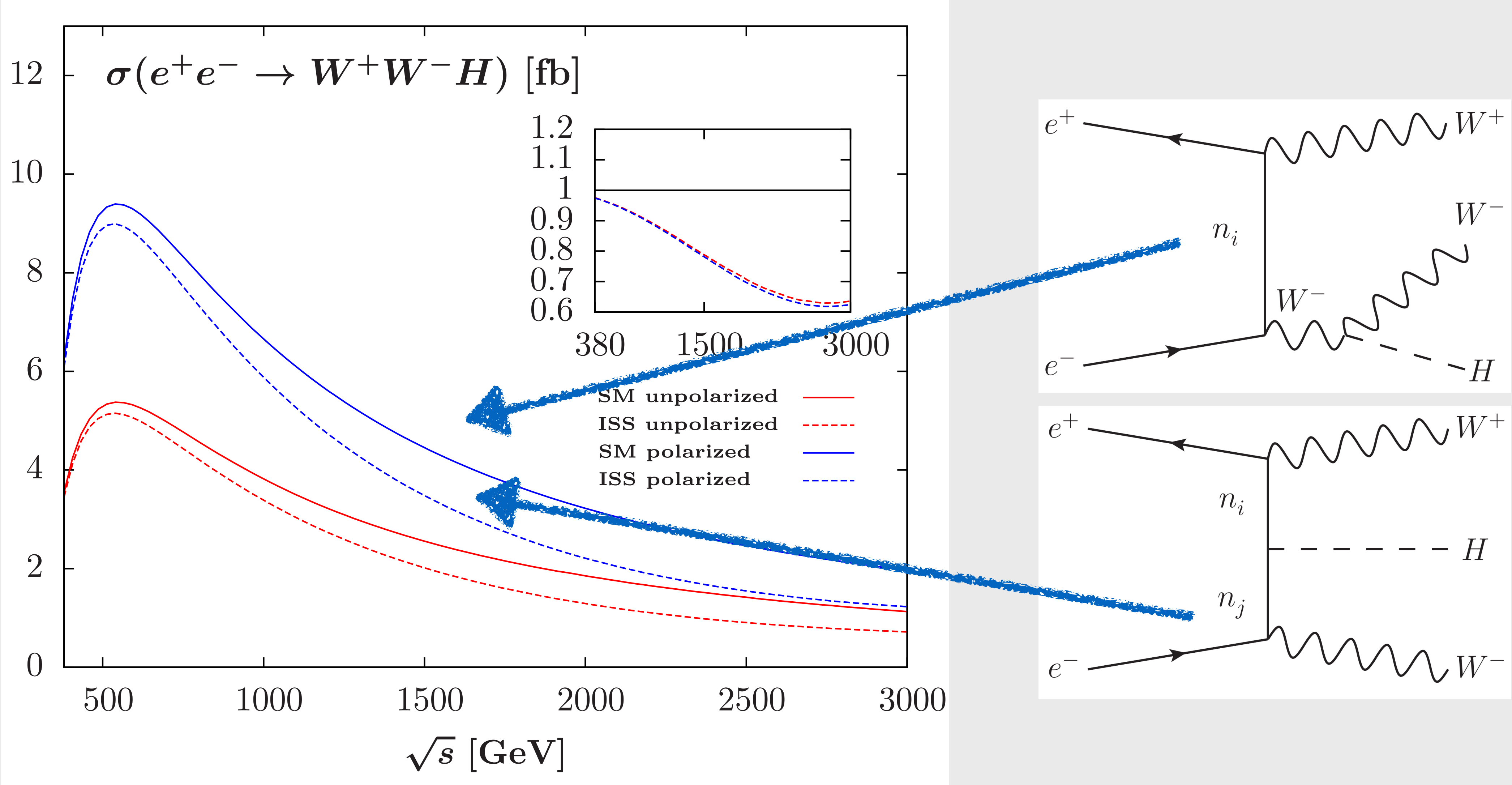
(1,2,1,1), (1,1,2,1), (1,2,2,1), (1,1,1,2),

Plenty of neutrino mass models in reach

Type-2 See-Saw **1803.00677 - Agrawal, Mitra, Niyogi, Shil, Spannowsky**

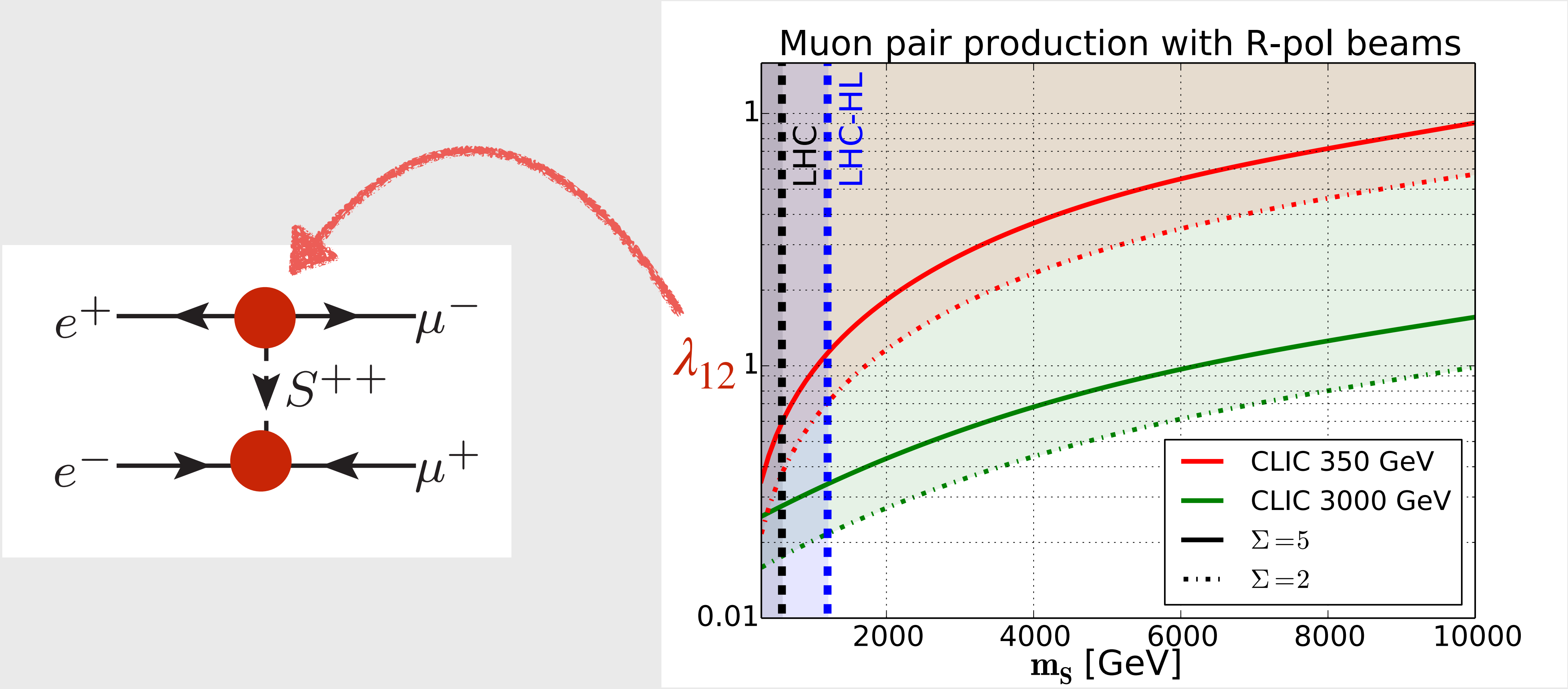


Inverse See-Saw **1712.07621 - Baglio, Pascoli, Weiland**



Exclude ISS RH Neutrino up to 10 TeV for Yukawa ~1

1807.10224 - Crivellin, Ghezzi, Panizzi, Pruna, Signer



Exclude S++ up to 10 TeV for triplet Yukawa ~0.1

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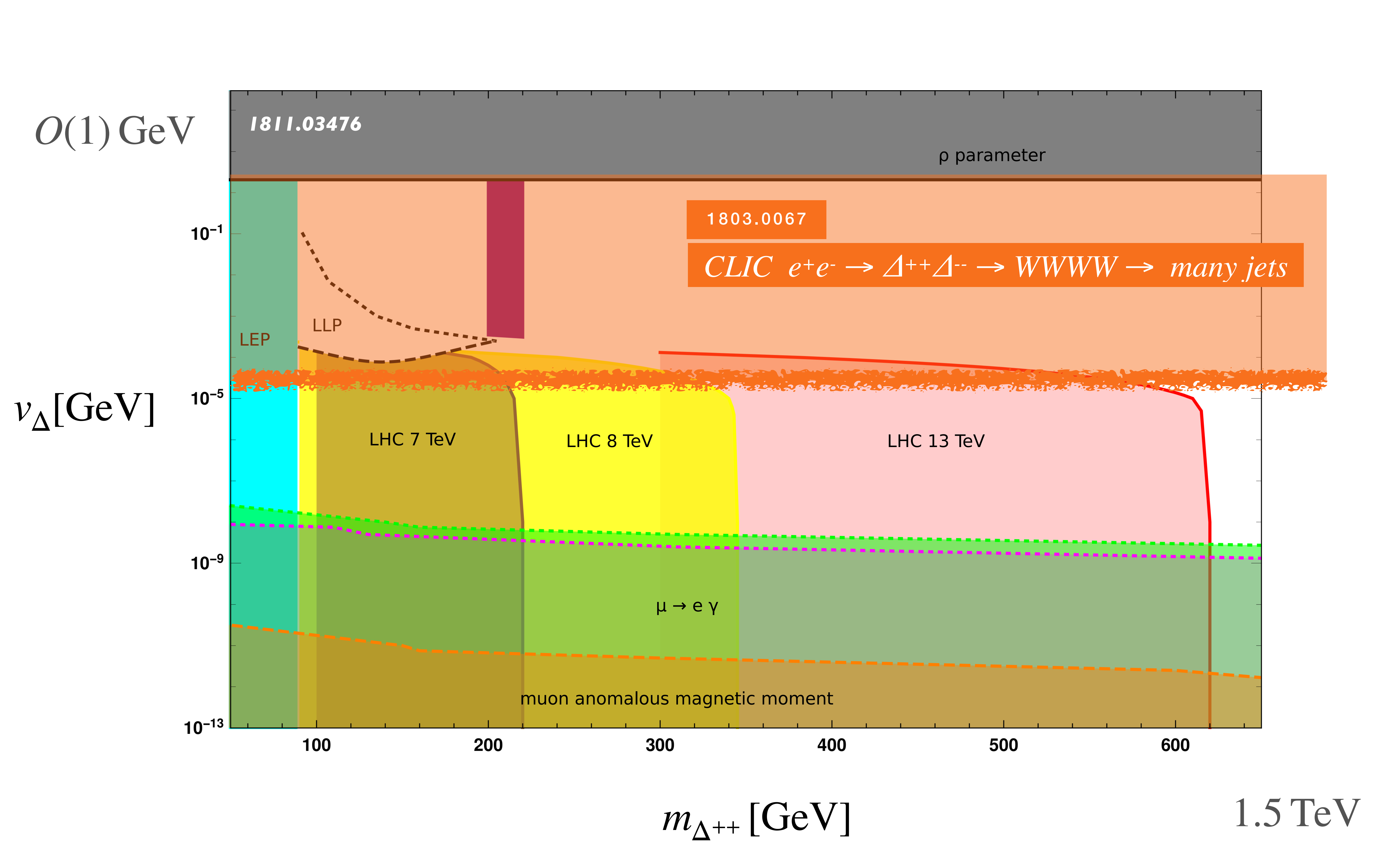

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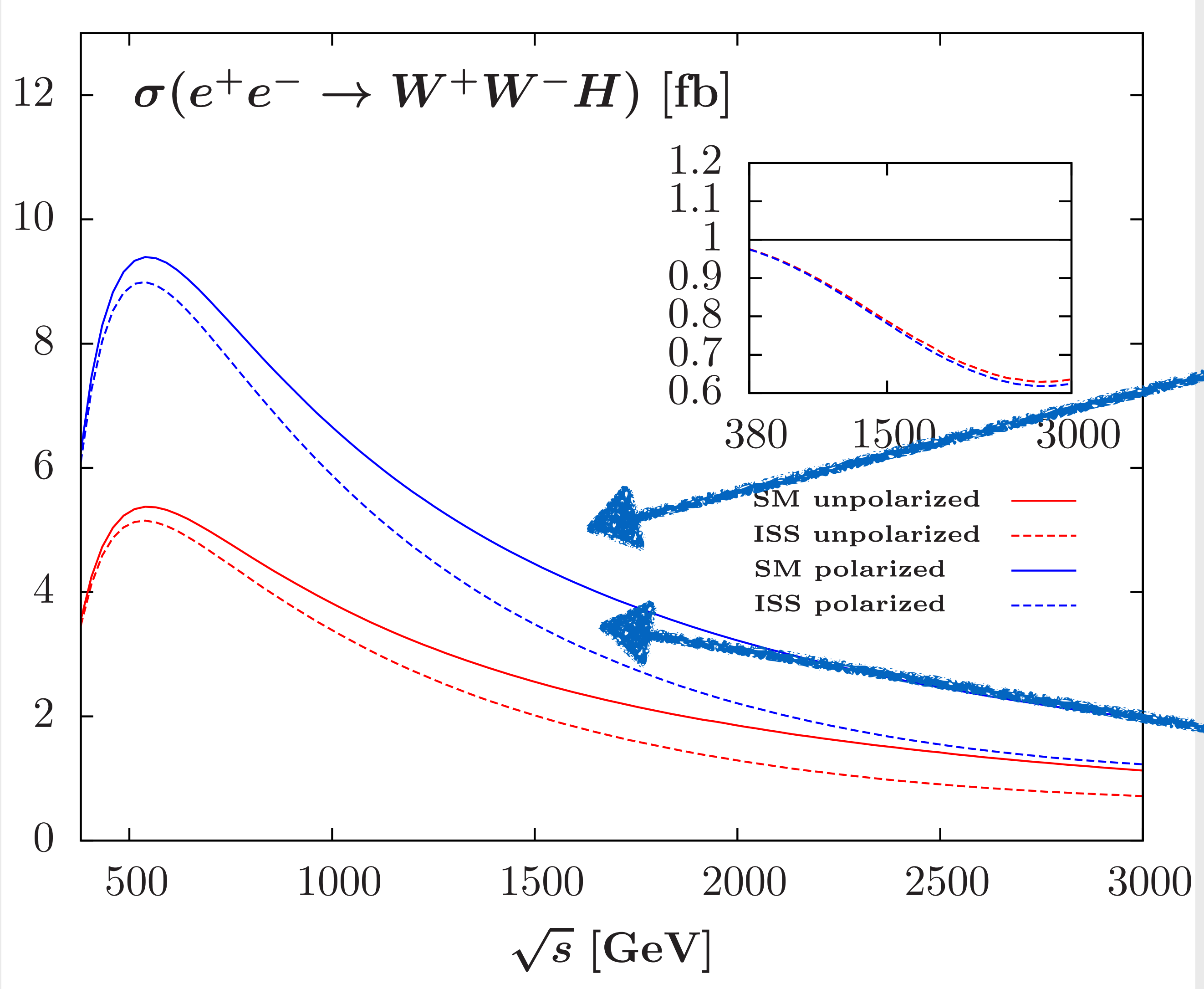

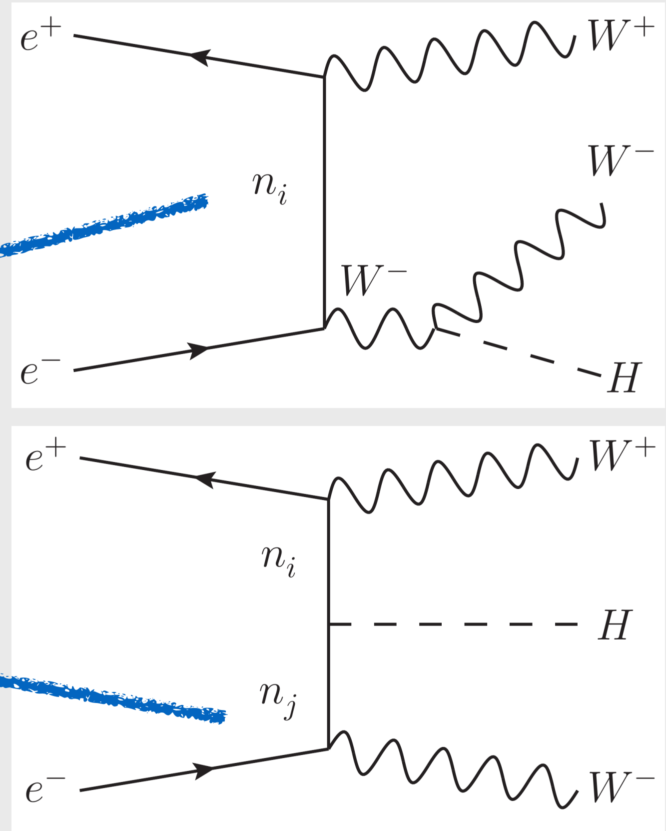

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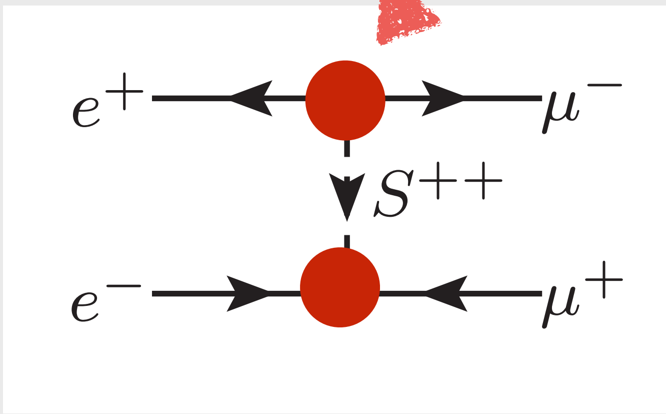

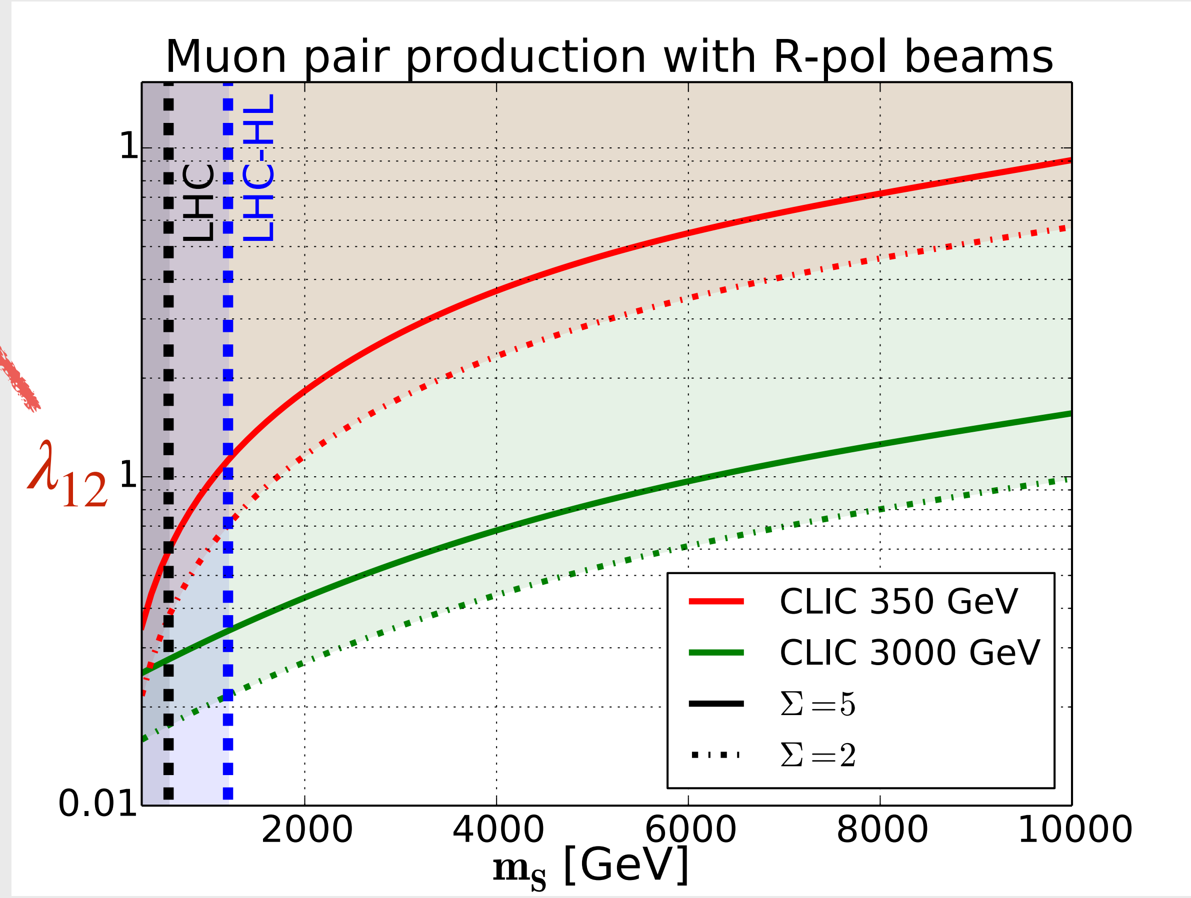

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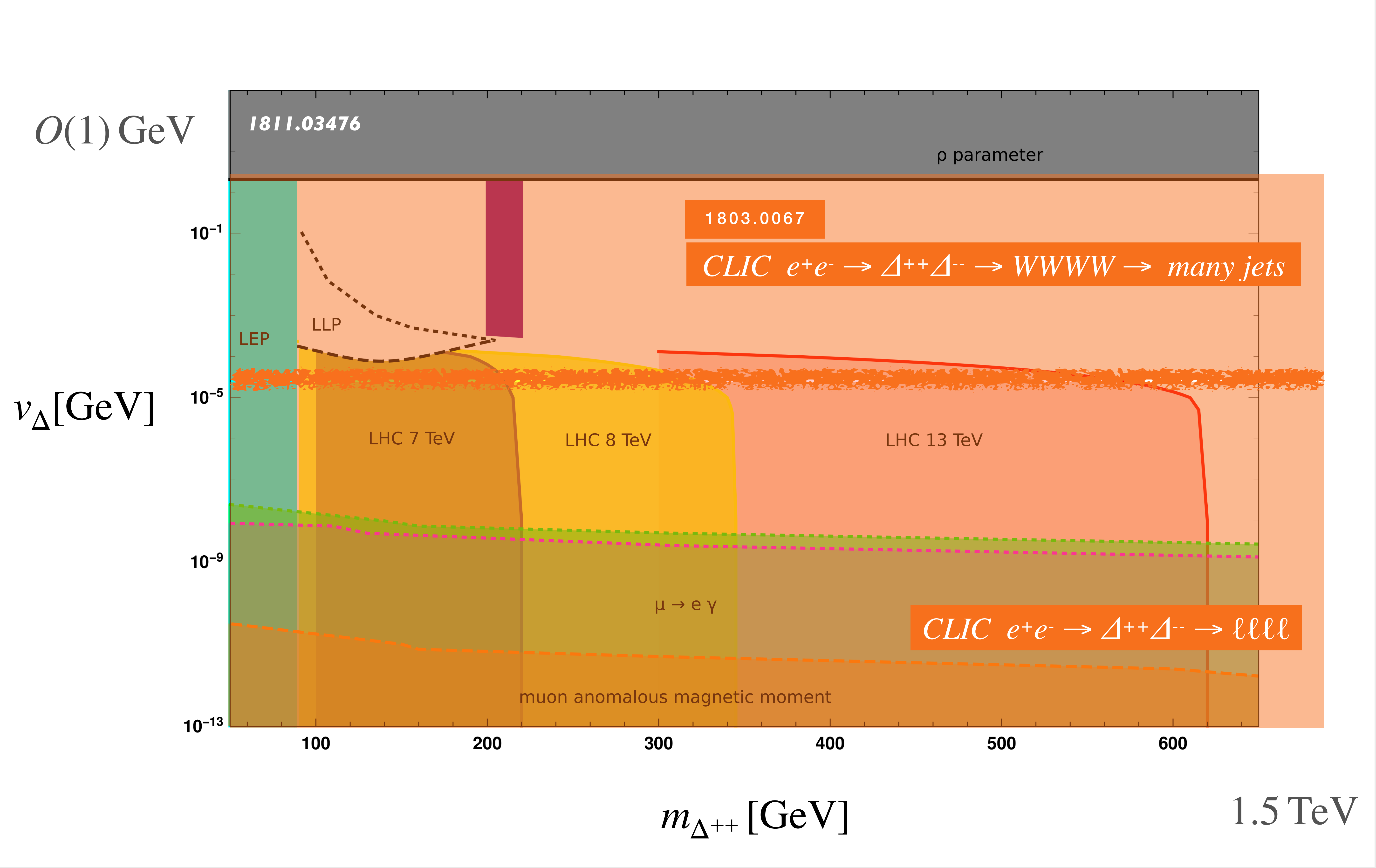

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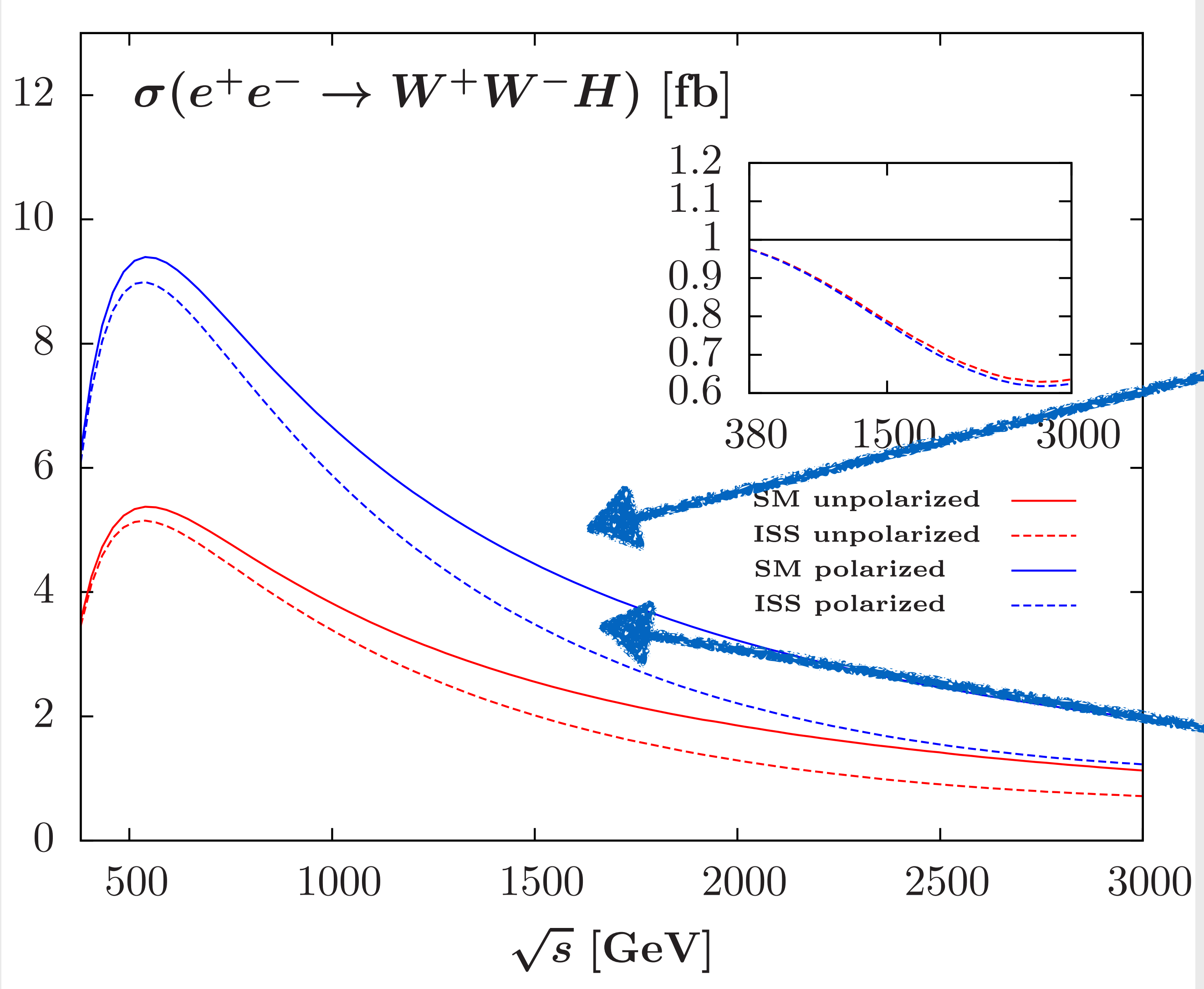

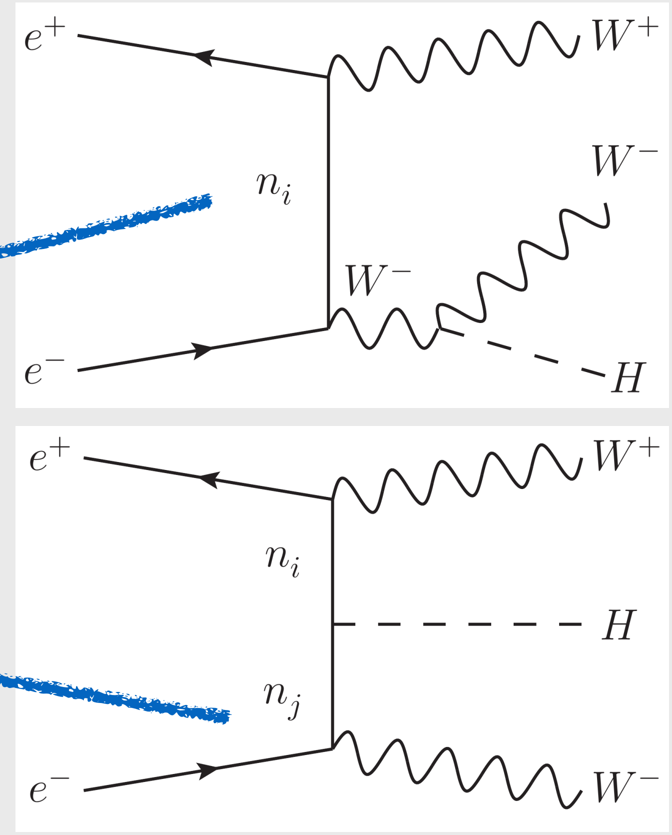

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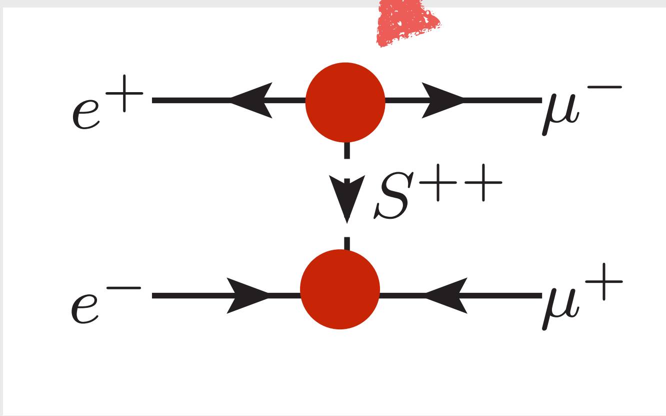

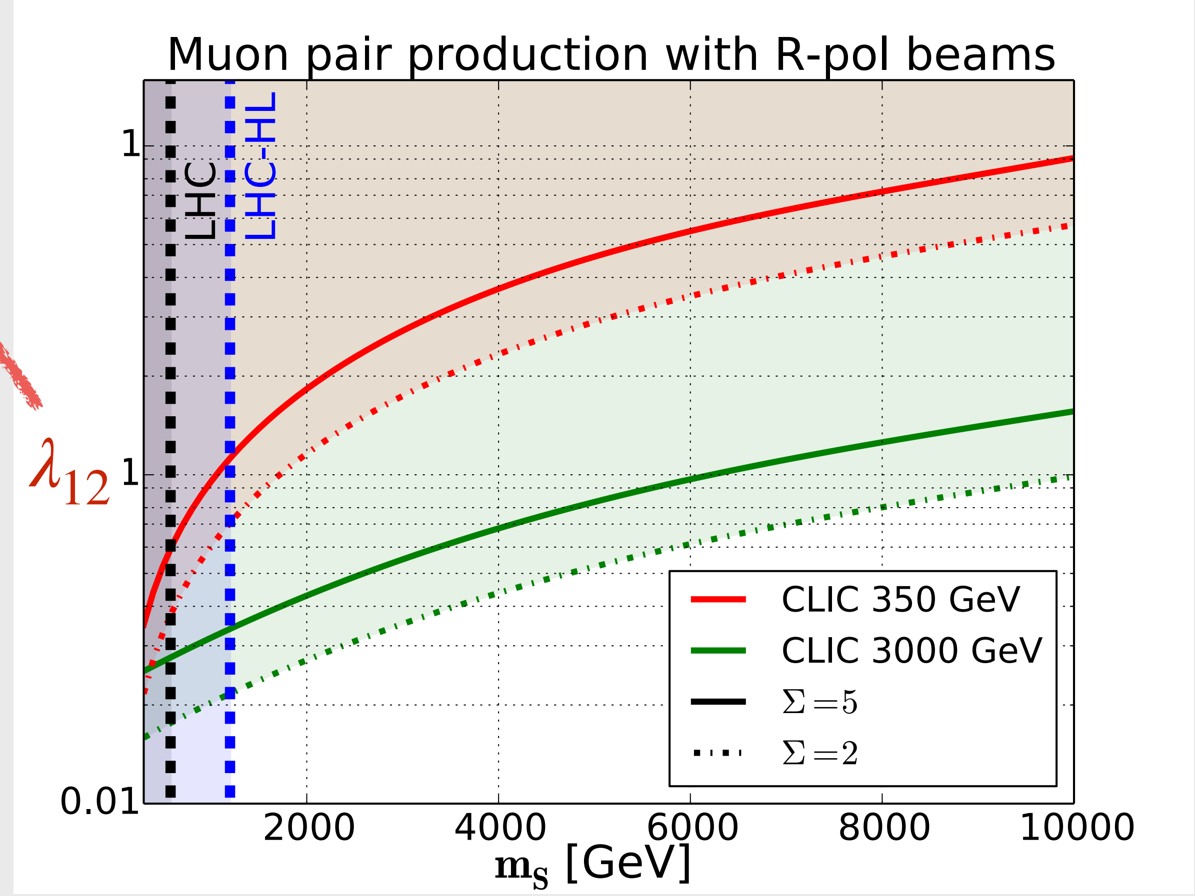

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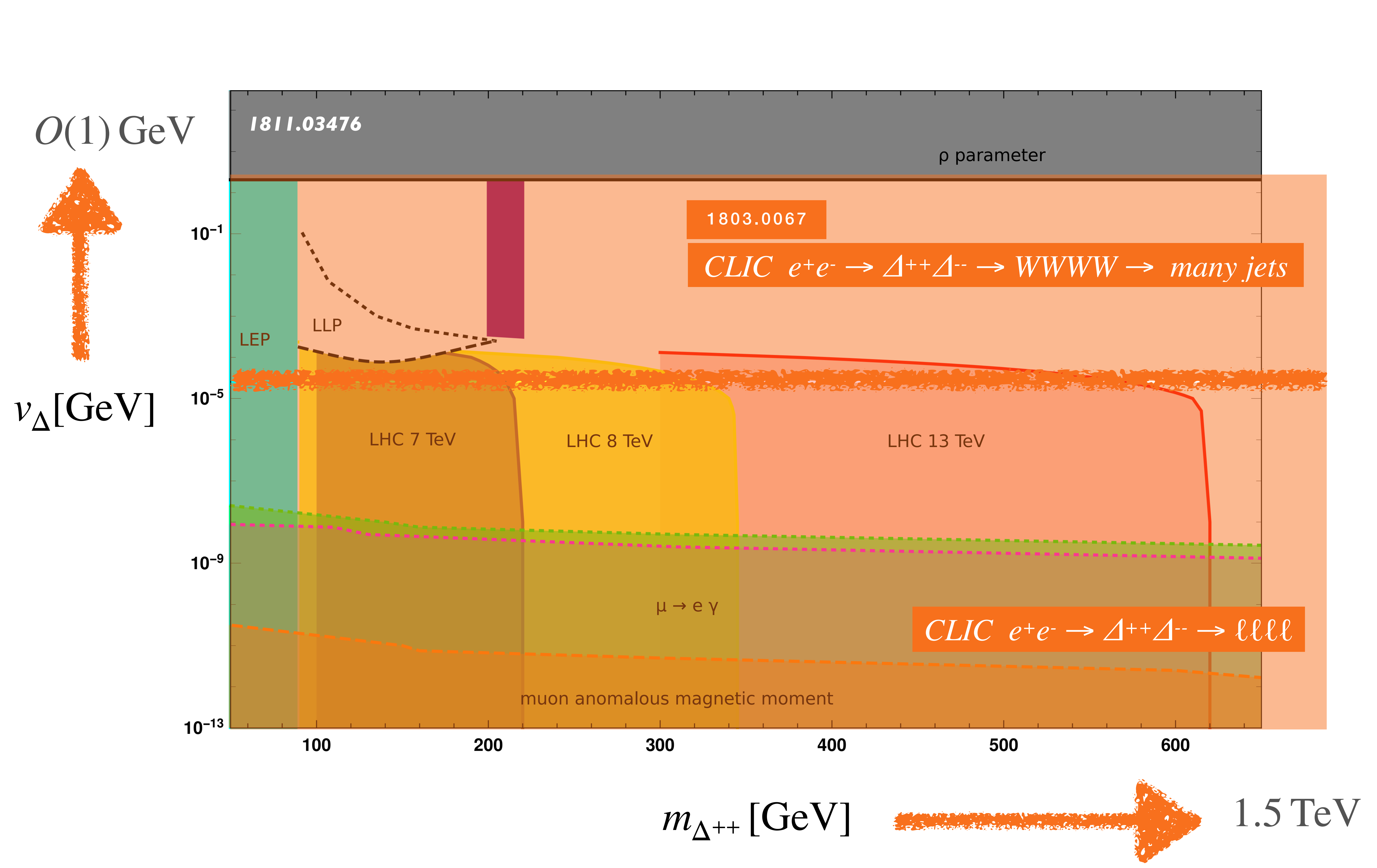

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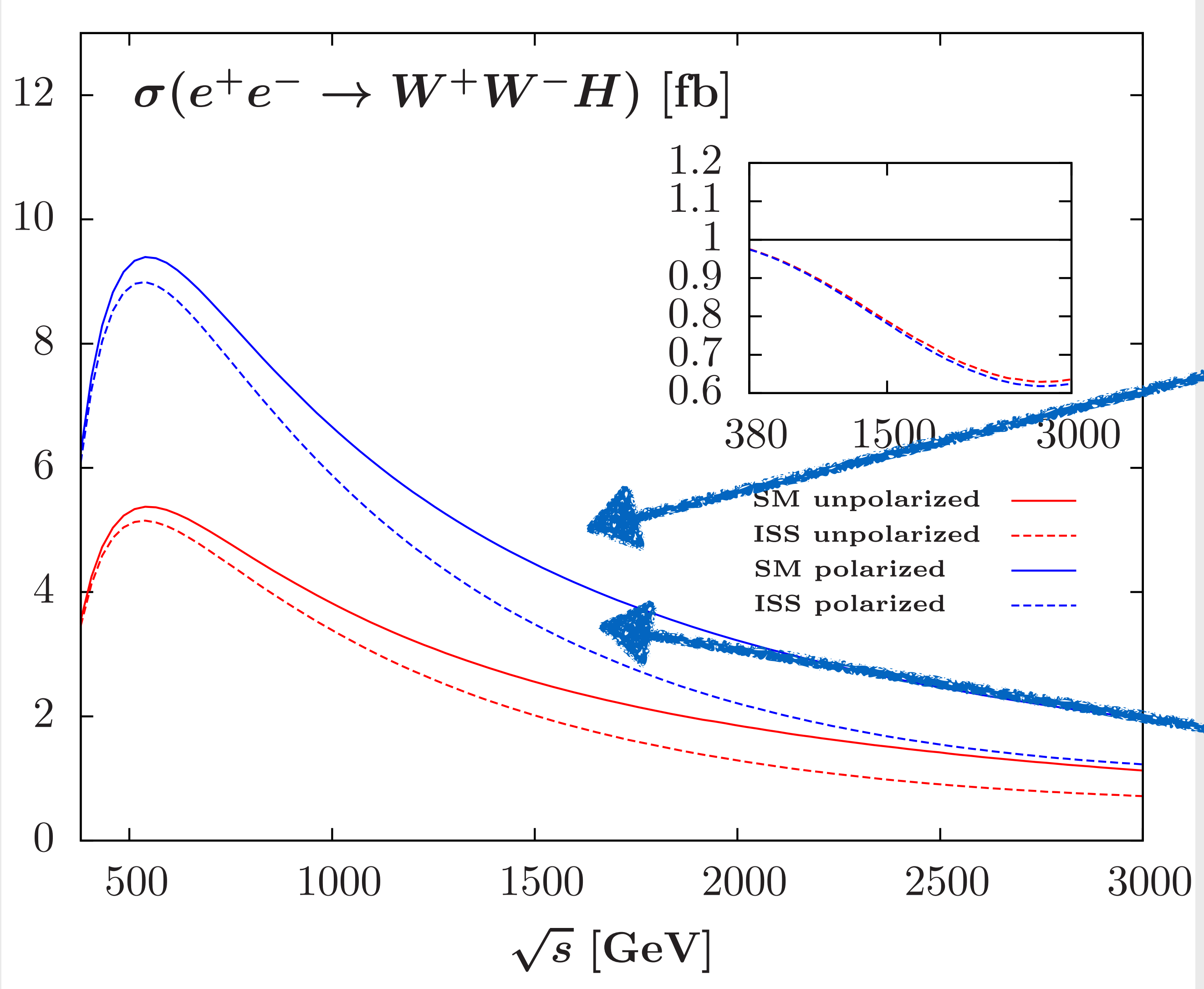

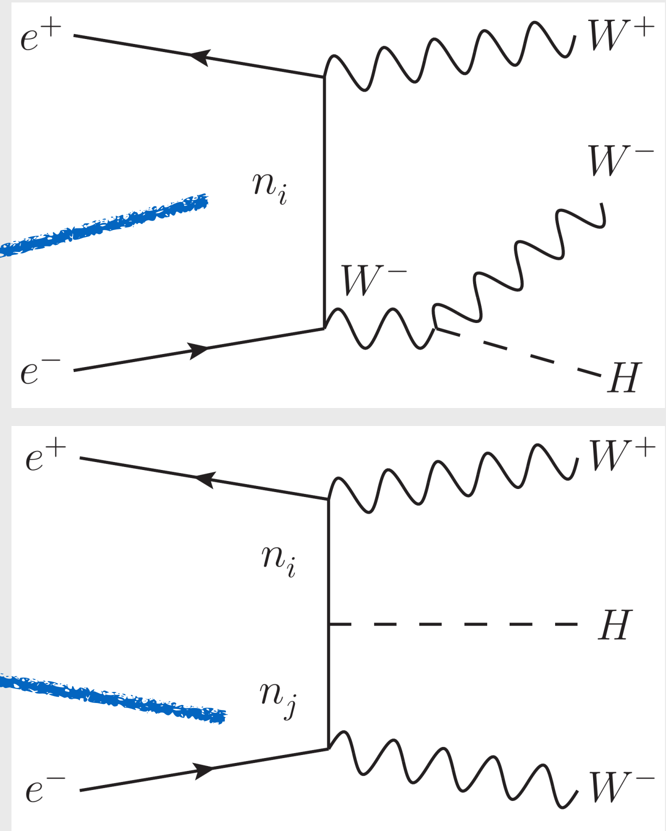

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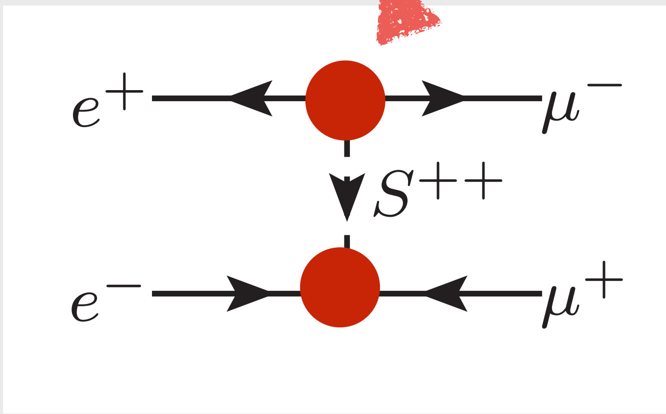
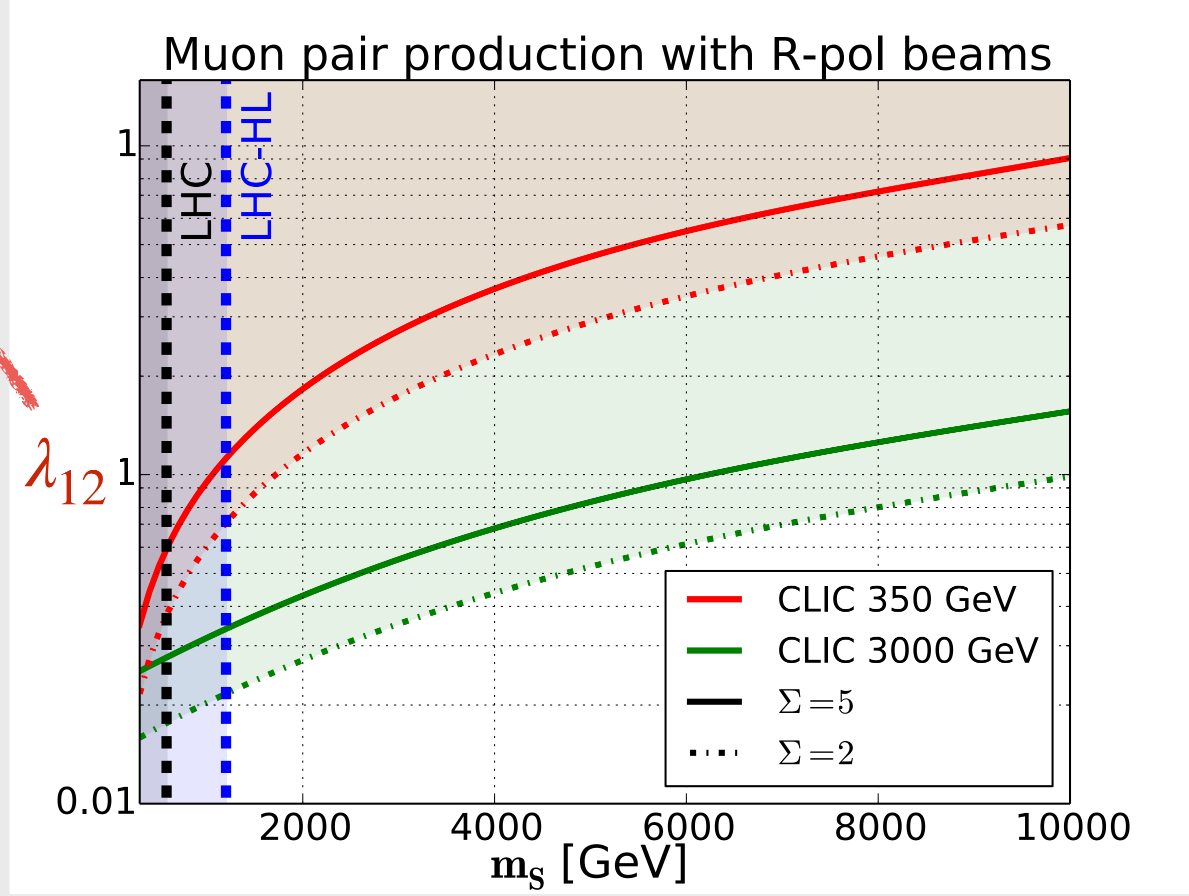




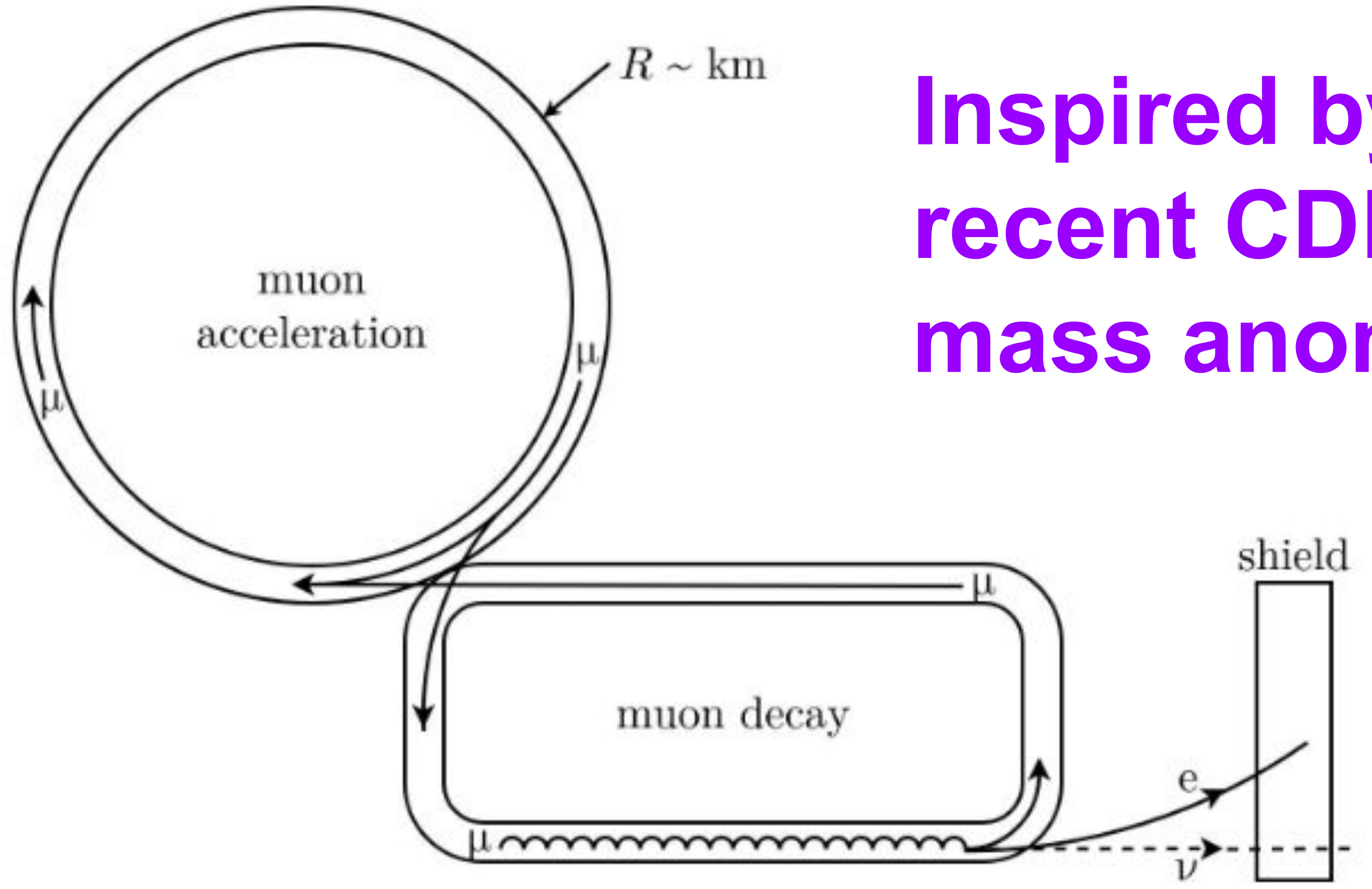
Exclude S++ up to 10 TeV for triplet Yukawa ~0.1

LI

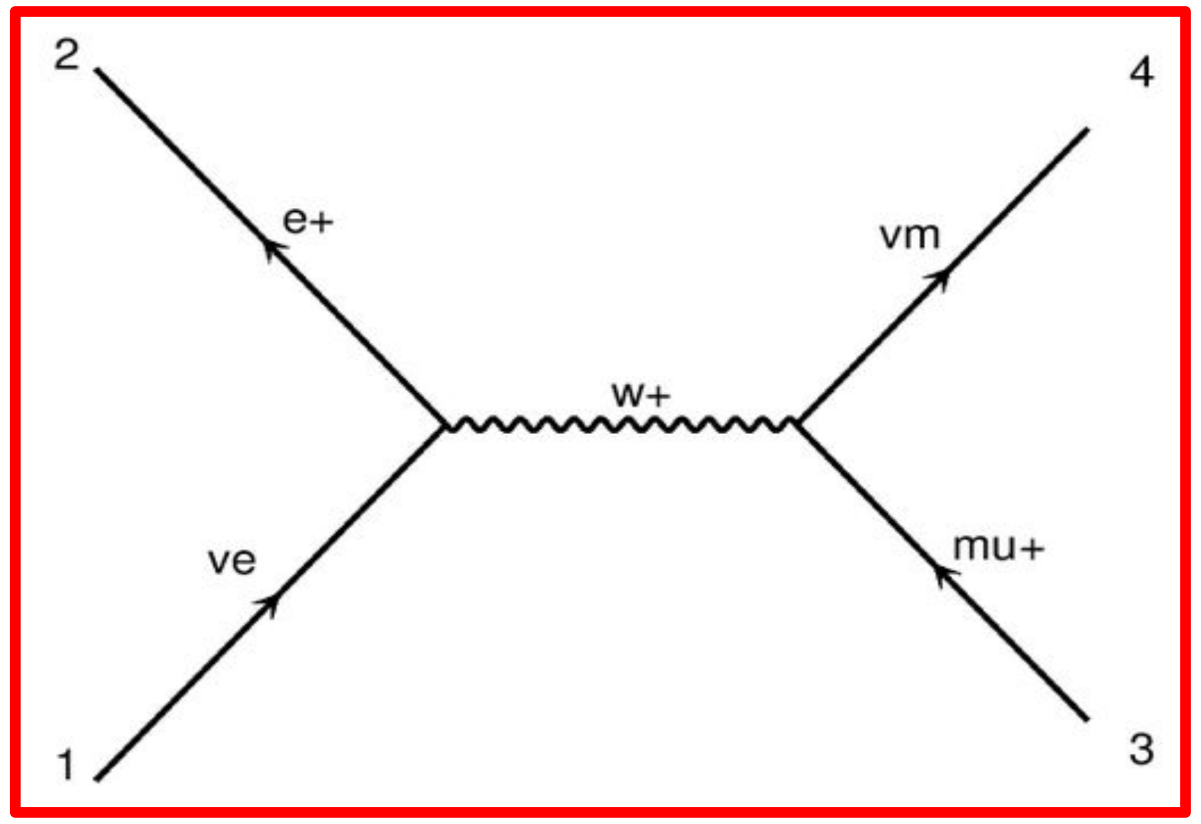
Possible intermediate steps towards a Muon collider *Qiang Li*

40/S2-D01 - Salle Dirac, CERN 08:30 - 09:00

Neutrino lepton Collider



Inspired by recent CDF W mass anomaly



The instantaneous luminosity of a neutrino lepton collider would be limited by two main factors: 1) the intensity of the neutrino beam compared with the incoming muon beam is suppressed by roughly $L_l/L_c \sim 0.1$, i.e., the fraction of the collider ring circumference occupied by the production straight section [22], 2) the neutrino beam spread, which may still be kept at 10 to 100 microns at the interaction point, by applying a small modulation on muon decay angle through vertical bending to achieve more focused neutrino beam [24].

Similar design, but with only one sided neutrino beam, 0.1-1/fb in 10 years?

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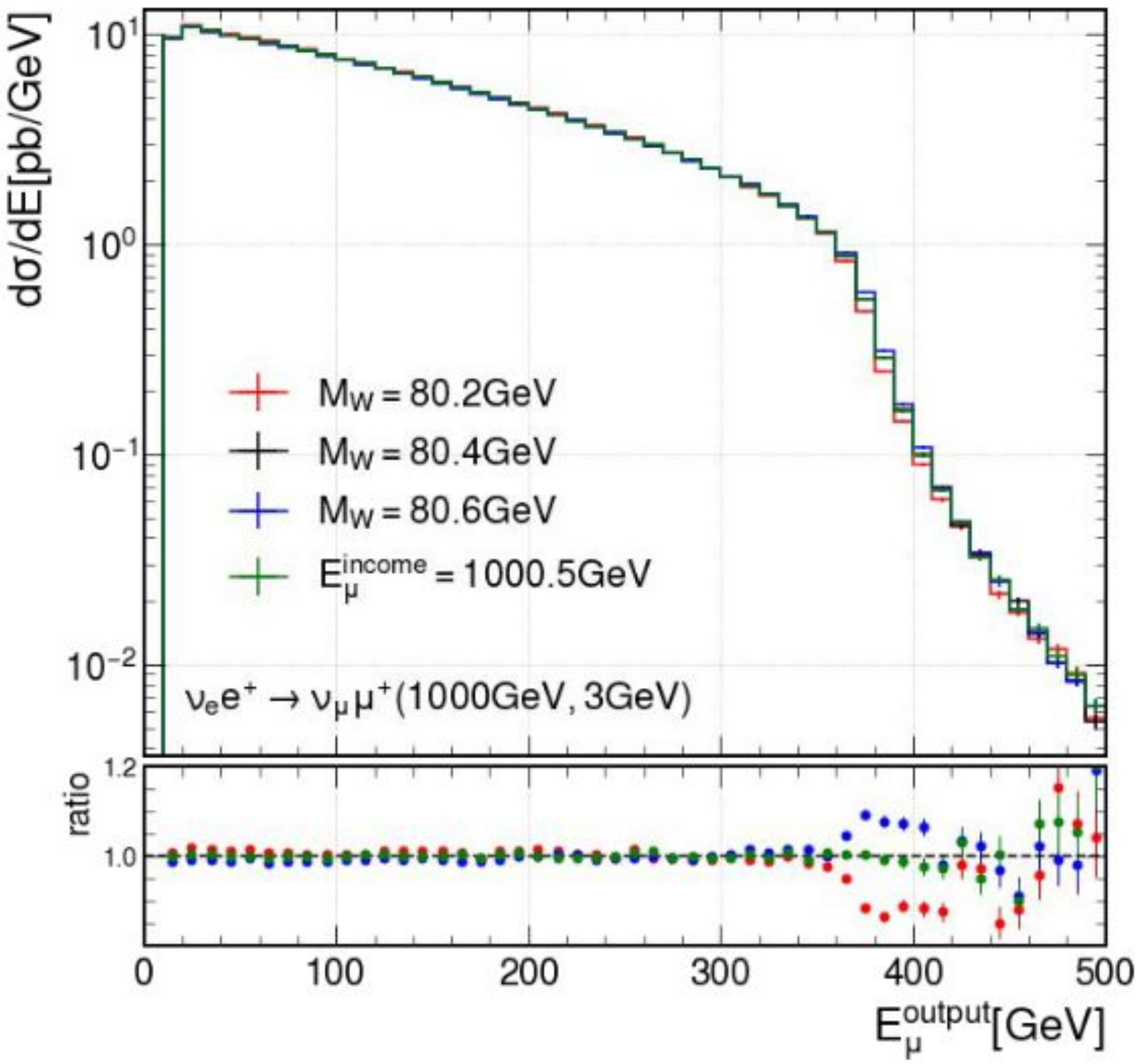
40/S2-D01 - Salle Dirac, CERN — 08:30 - 09:00

Single W production



Larger MW →

Higher incoming neutrino Energy →

Larger outgoing Muon Energy (More boosted)

fiducial rate measurement

$\delta\sigma/\sigma = 70 \cdot 10^{-4}$ yields

$\delta m_W / m_W = 1.2 \cdot 10^{-4}$

If pT(outgoing muon) > 40 GeV

the cross sections with **MW = 80.4 (80.41) are 166.2 (167.6) pb.**

Based on a simple counting experiment, **a 10 MeV accuracy on MW** can be achieved with an integrated luminosity of **only 0.1 fb−1.**

evidently the fiducial region of phase-space has a sensitivity to m_W

LI

Possible intermediate steps towards a Muon collider *Qiang Li*

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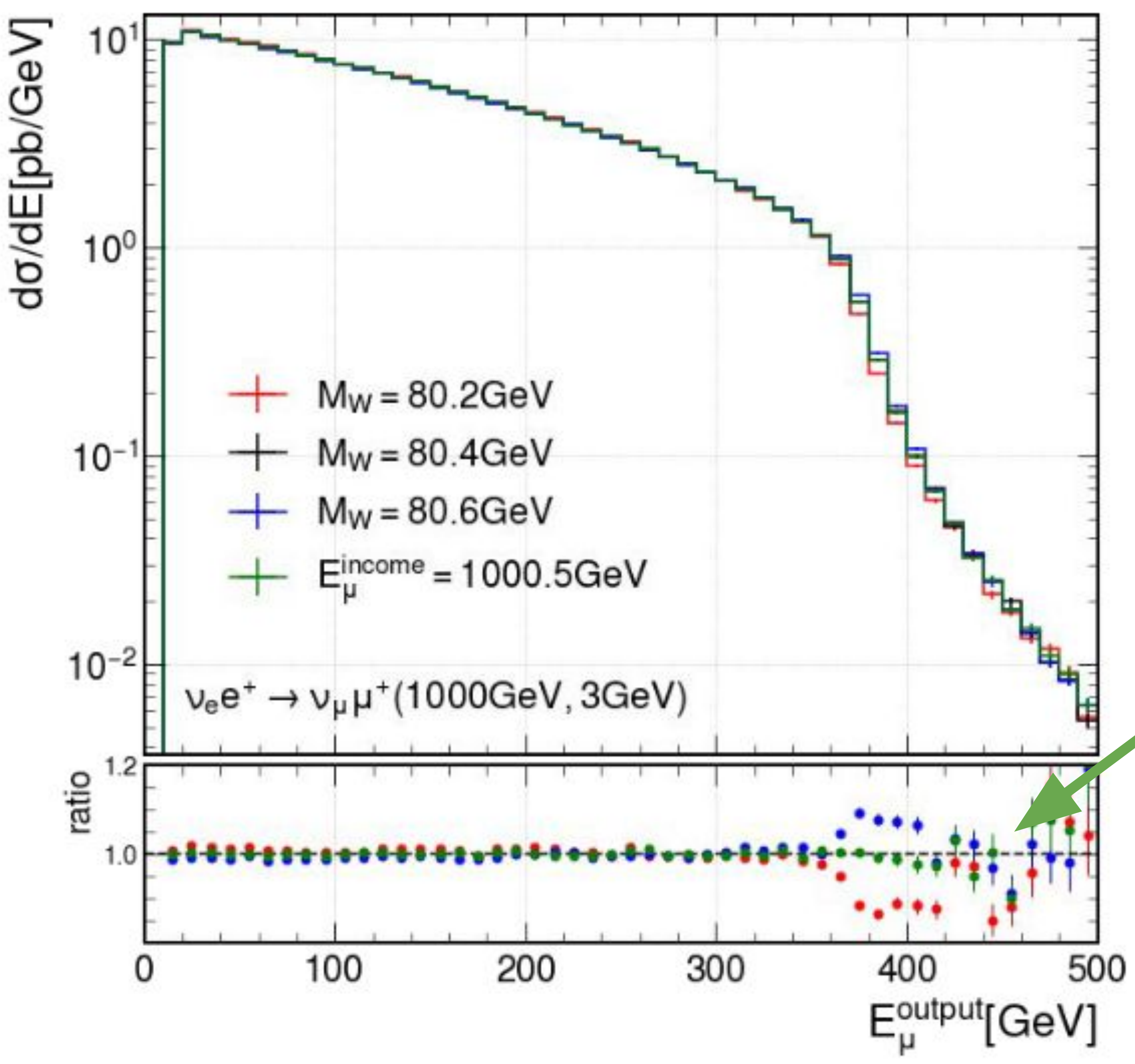
Robustness on W mass precision



We varied the incoming muon and electron beam energy by 0.5 GeV and 10 MeV, respectively, which are quite conservative following previous refs.

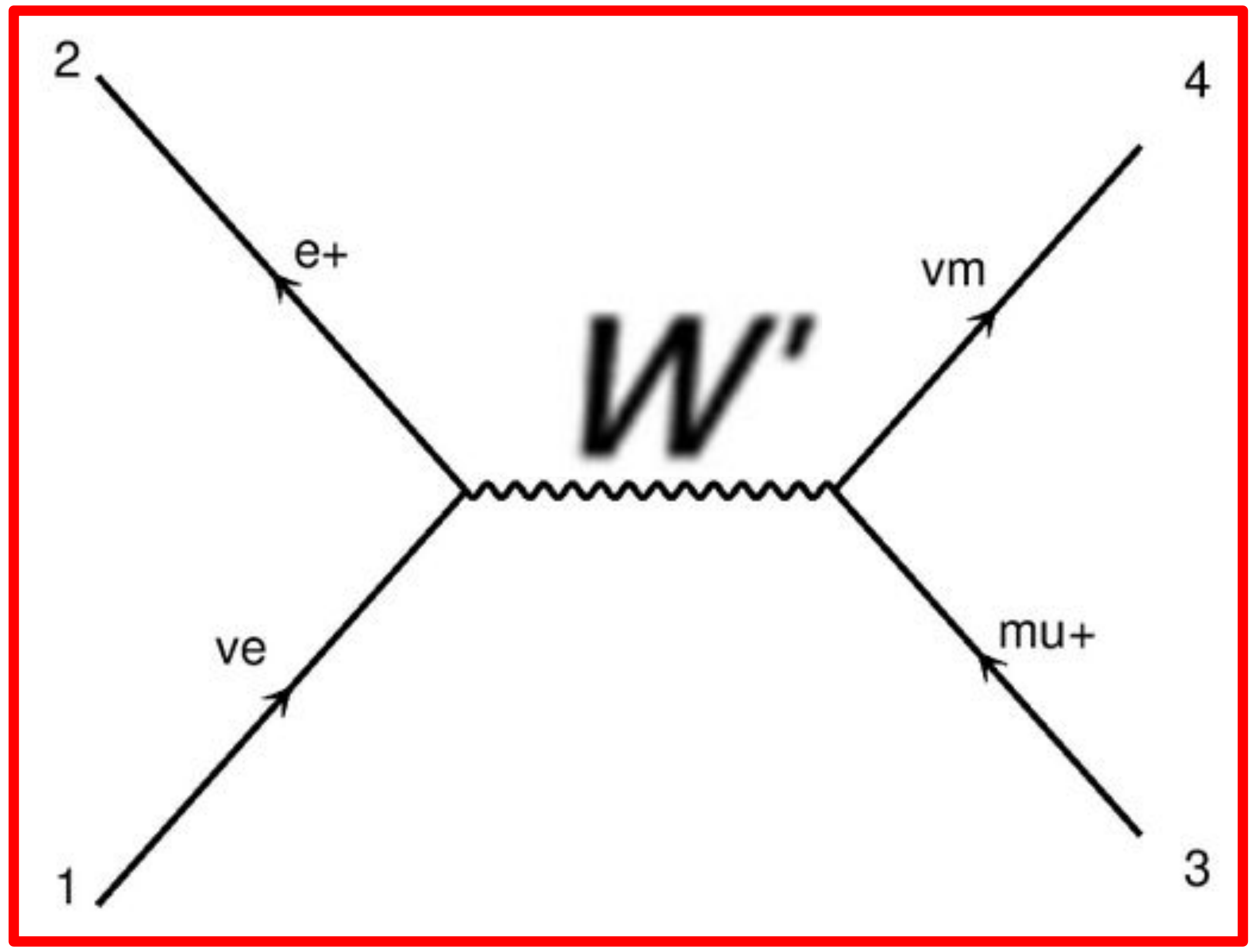
We found that the **cross sections changed by about 0.6 pb for both variations.**

This uncertainty could be **mitigated by using the shape of the outgoing muon energy**, by scanning different incoming beam energies, or by calibrating the incoming muon beam energy with the electron decay products.

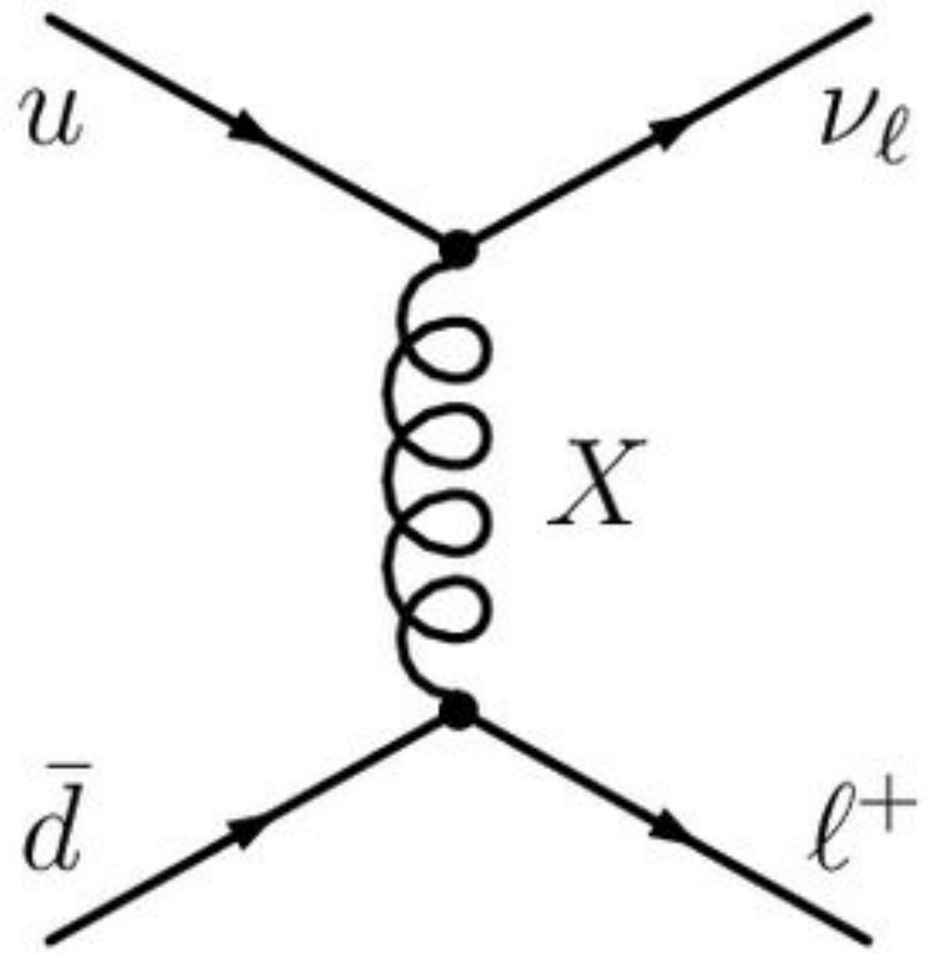
LI

More Physics from neutrino-lepton collisions

$$e^+e^- \to Z^{0(*)},\ \nu_e e^- \to \nu_e e^-,\ \tilde{\nu}_\mu e^- \to \tilde{\nu}_\mu e^-,$$
$$\nu_e e^+ \to W^{+(*)},\ \tilde{\nu}_\mu e^+ \to \tilde{\nu}_\mu e^+,\ \tilde{\nu}_\mu e^+ \to \tilde{\nu}_e \mu^+,$$
$$\tilde{\nu}_\mu \mu^- \to W^{-(*)},\ \nu_e \mu^- \to \nu_e \mu^-,\ \nu_e \mu^- \to e^- \nu_\mu.$$



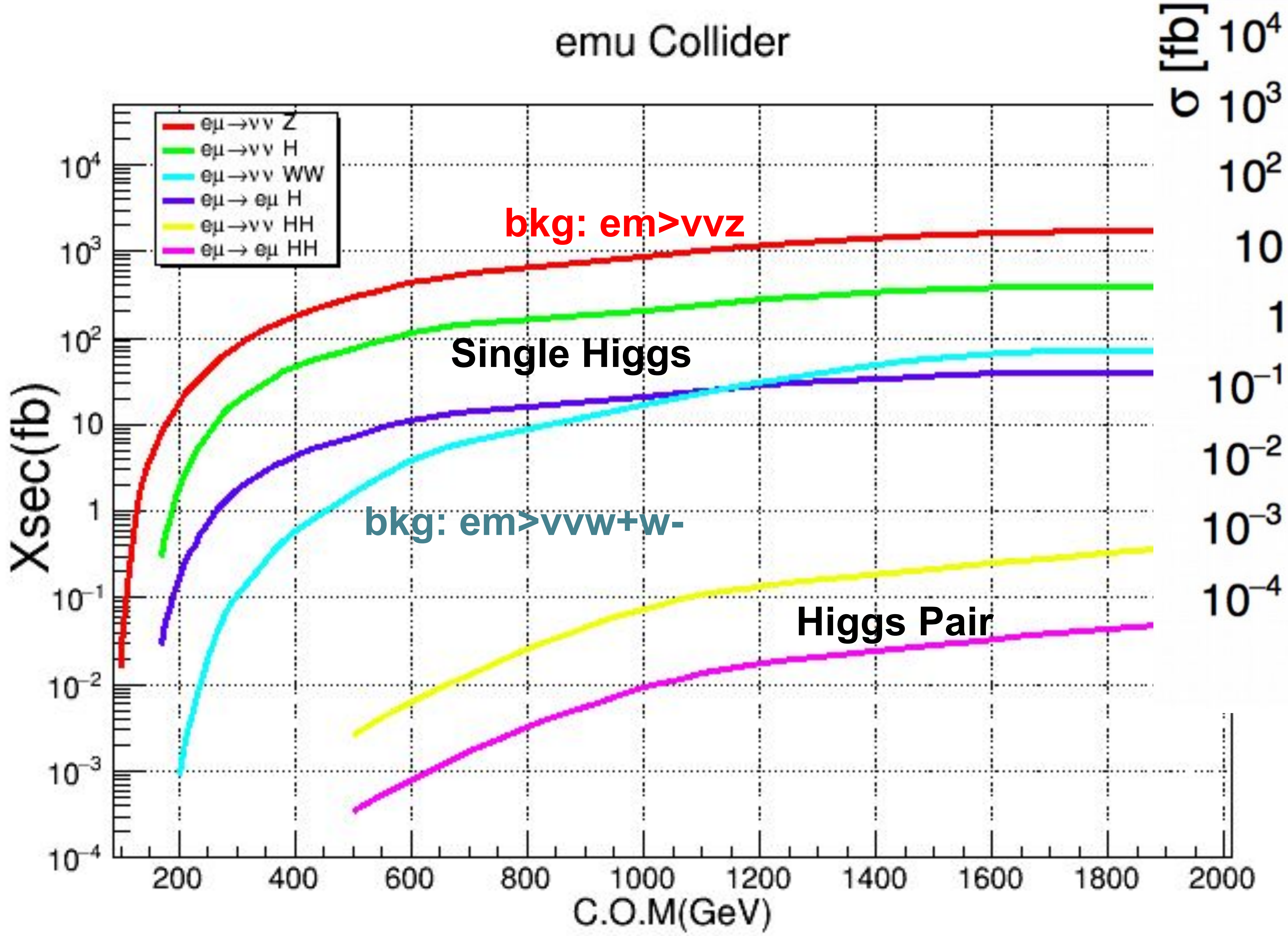
Anomalous Zvv couplings

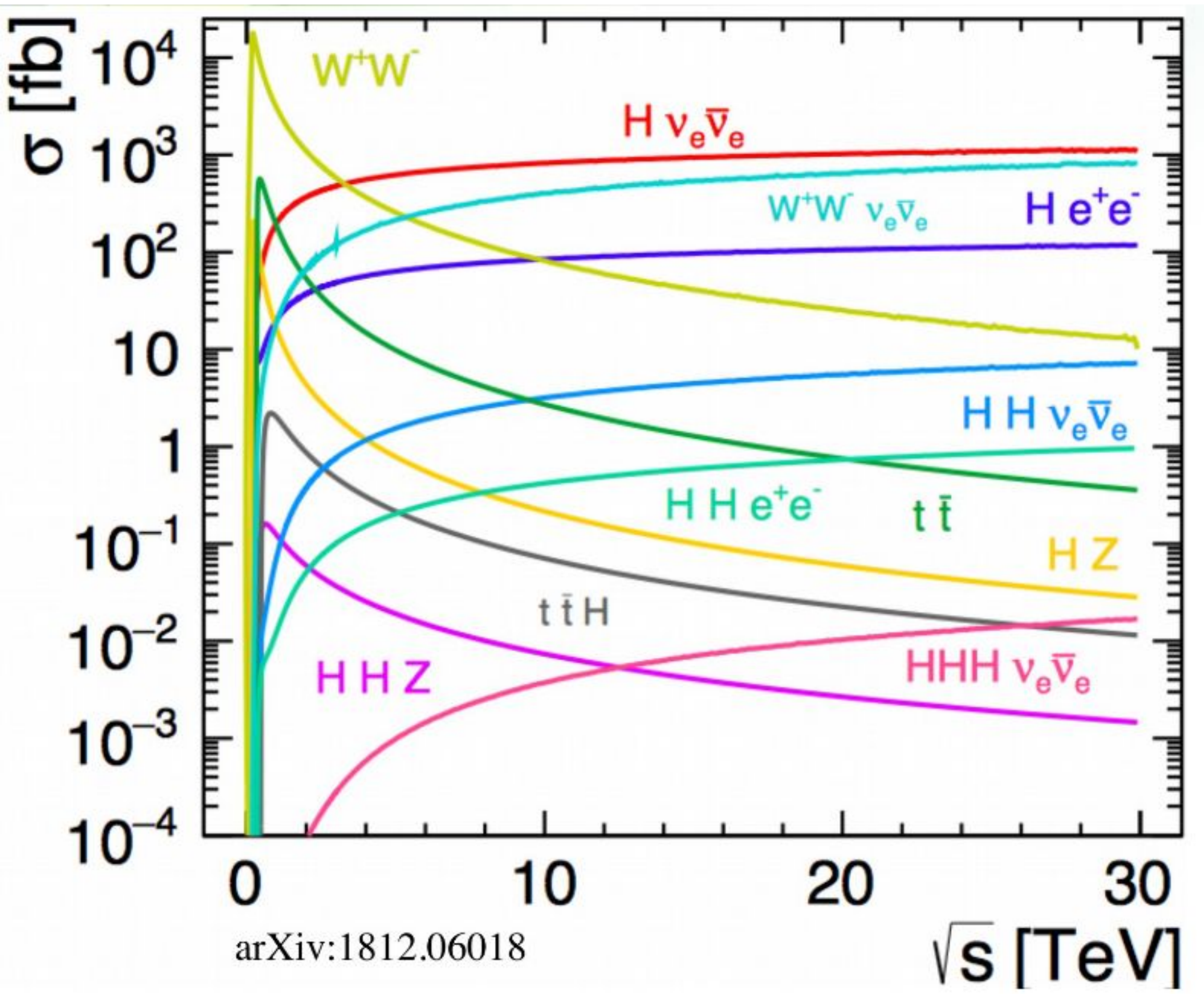


⇚ **leptoquark**

Possible intermediate steps towards a Muon collider	*Qiang Li*
40/S2-D01 - Salle Dirac, CERN	08:30 - 09:00

emu collider processes





mu-mu collider

A vector boson scattering/fusion machine