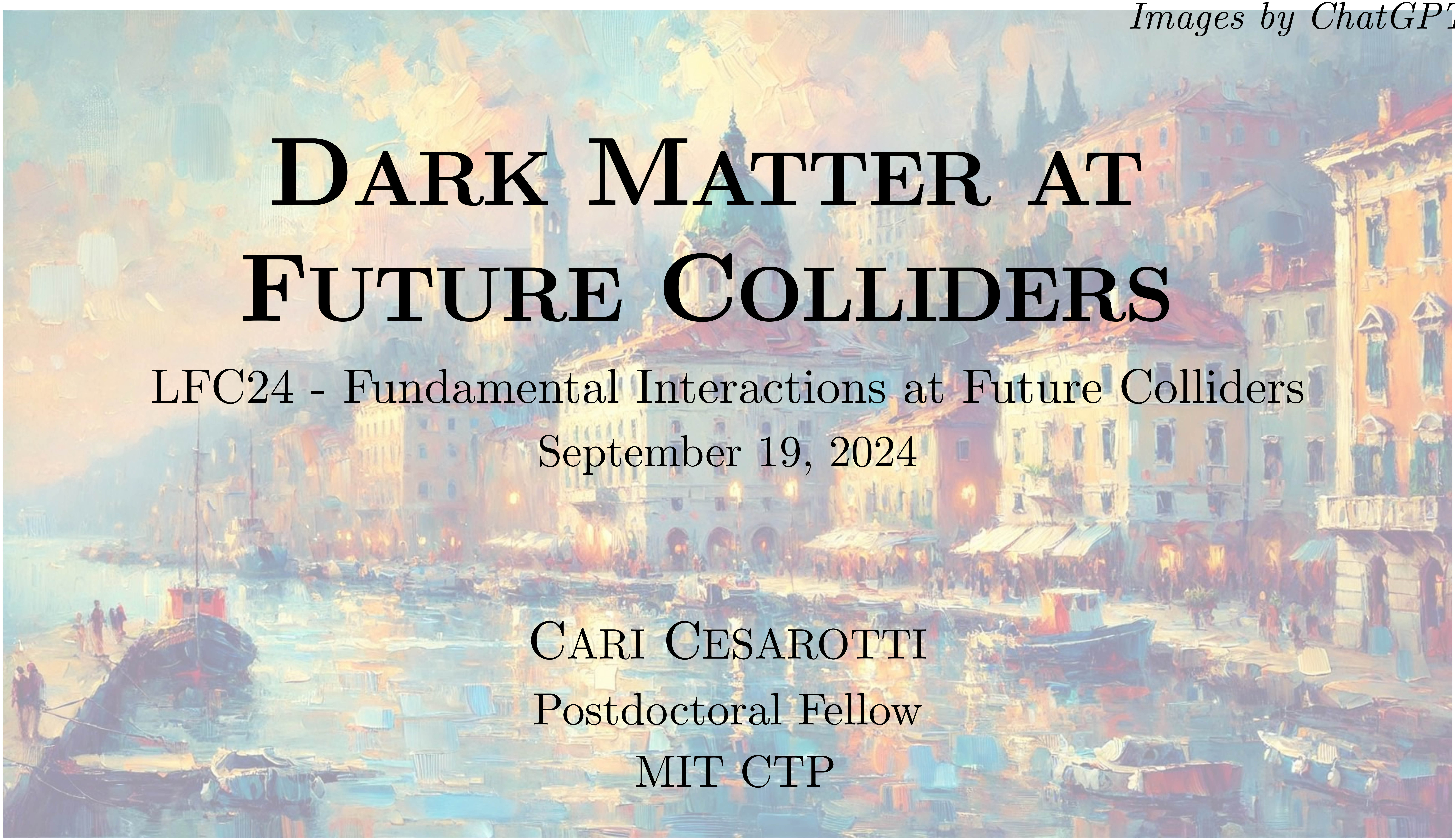


Images by ChatGPT

Dark Matter at Future Colliders

LFC24 - Fundamental Interactions at Future Colliders

September 19, 2024

Cari Cesarotti

Postdoctoral Fellow

MIT CTP

Open Questions of Particle Physics

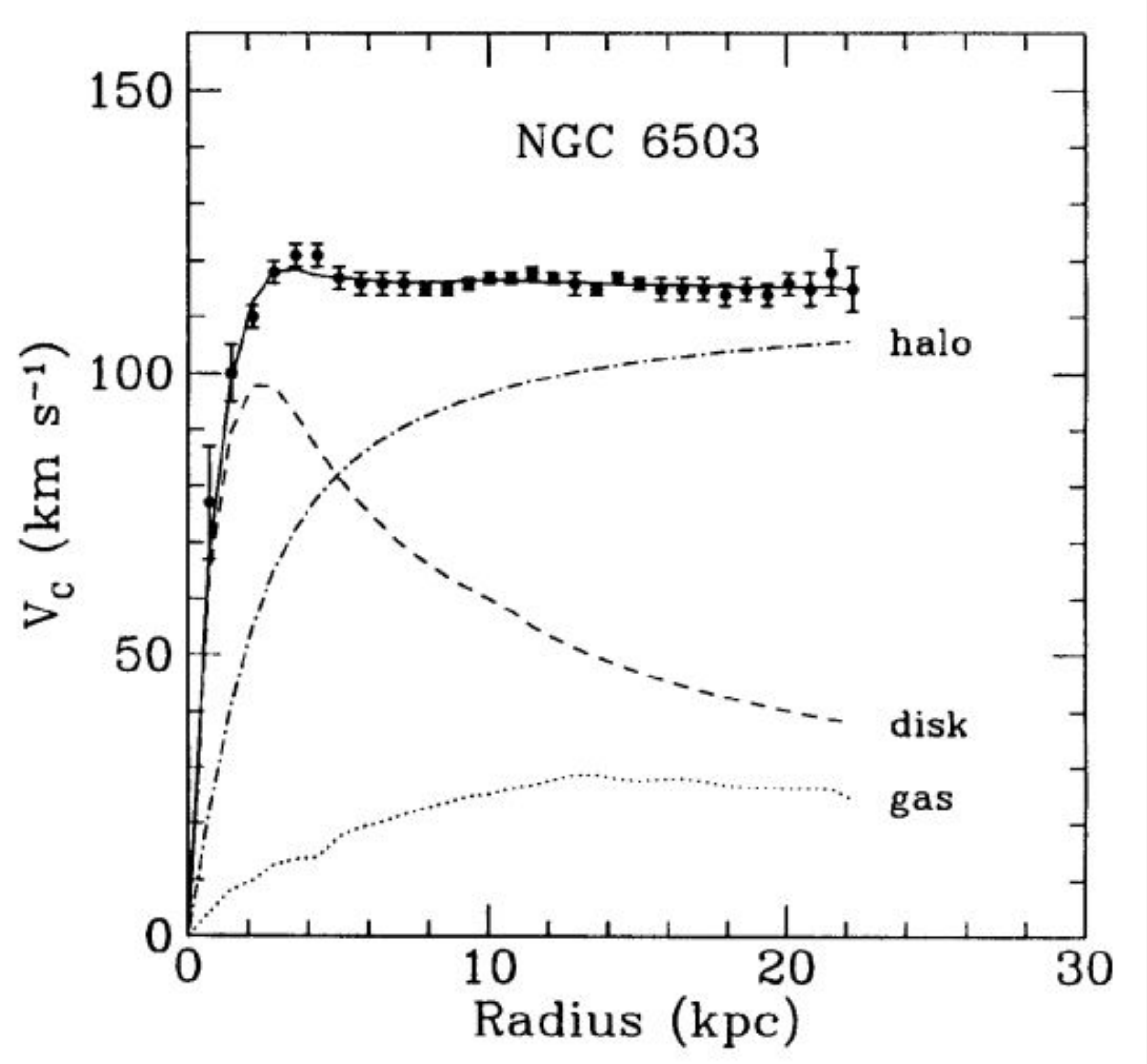
A persistent, fundamental question in physics:

What is dark matter?

Open Questions of Particle Physics

A persistent, fundamental question in physics:

What is dark matter?



What is its particle nature?

Does it have particle nature?

Open Questions of Particle Physics

Many scales over which DM *could* appear

Open Questions of Particle Physics

Many scales over which DM *could* appear

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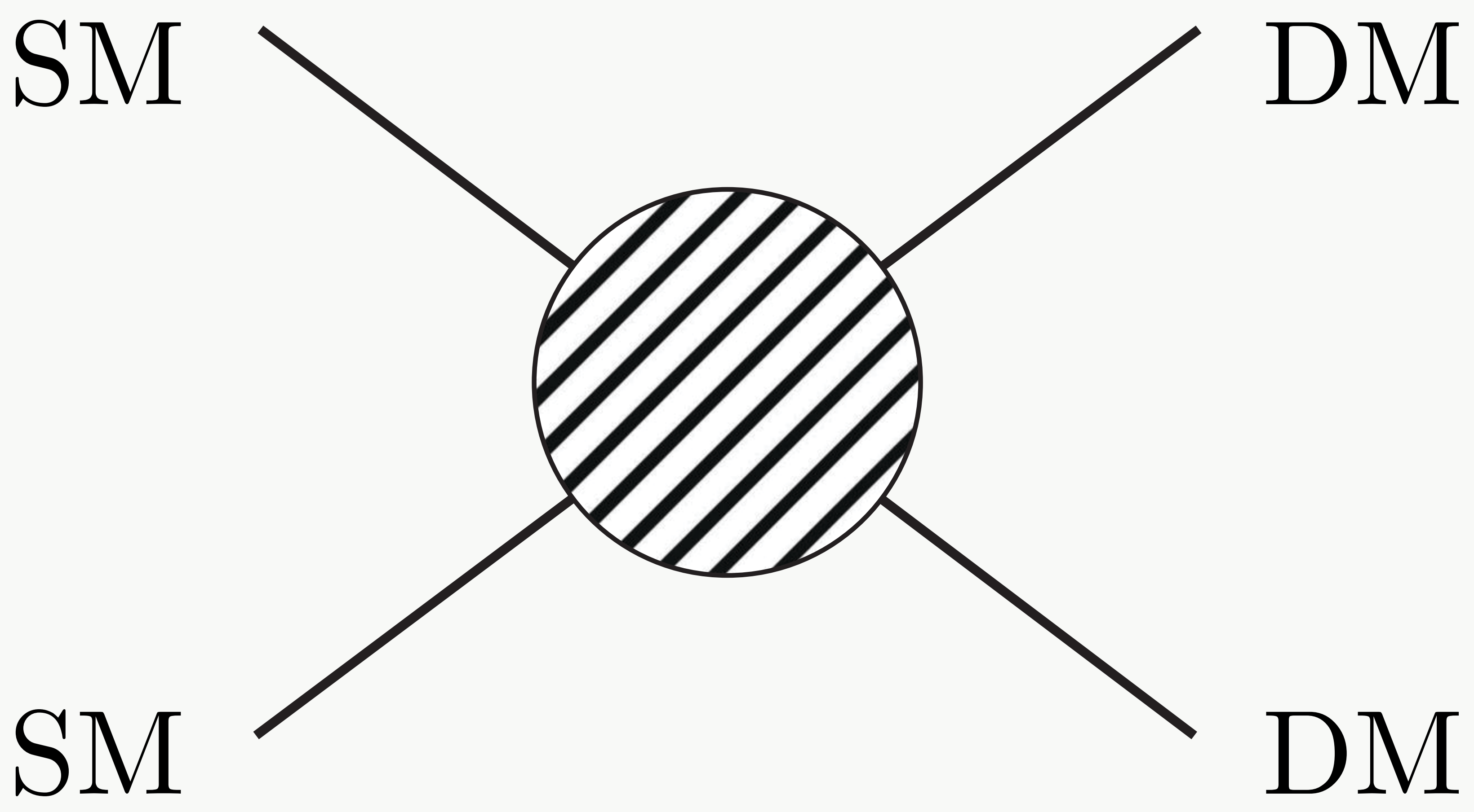
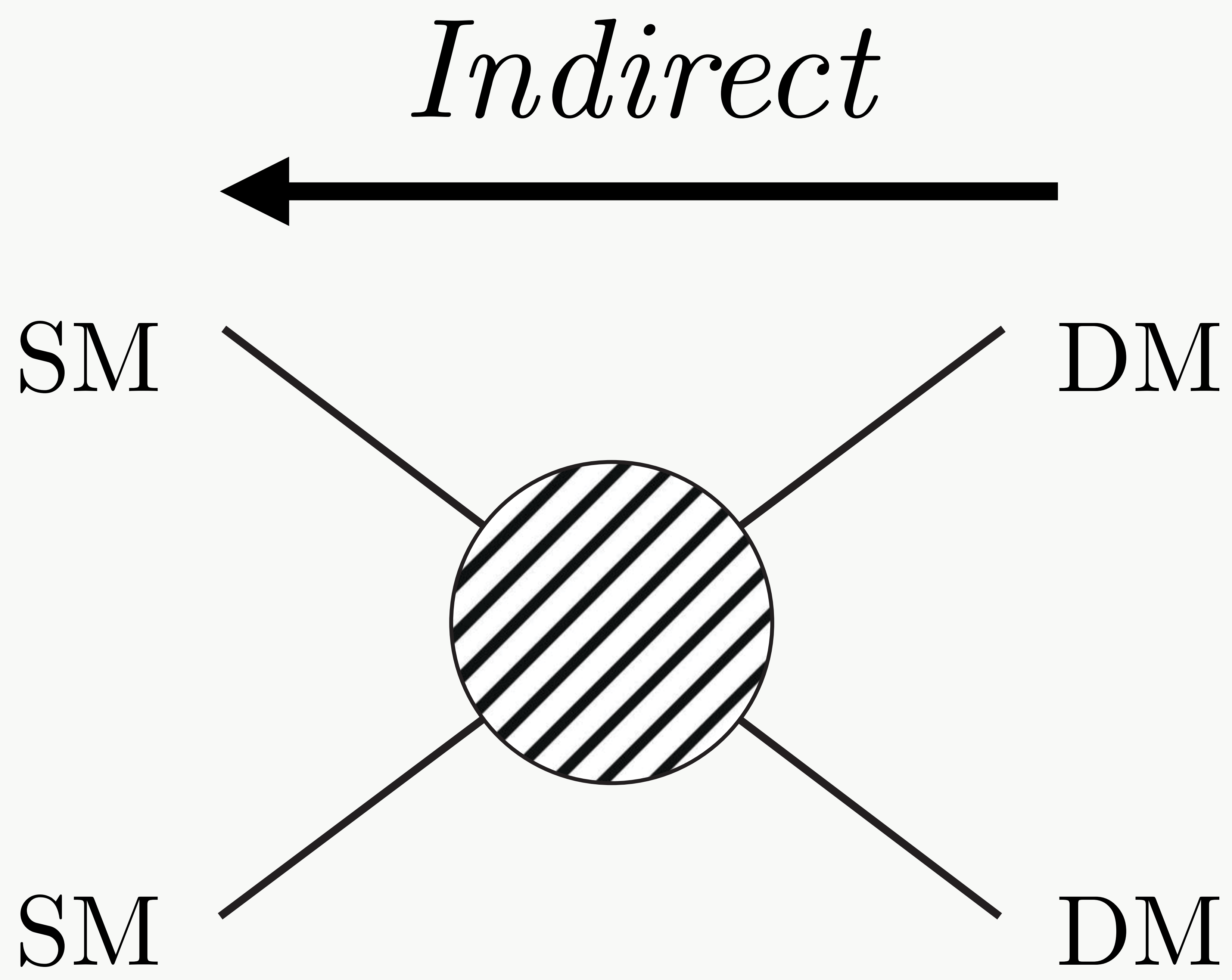
Dark Matter at Colliders

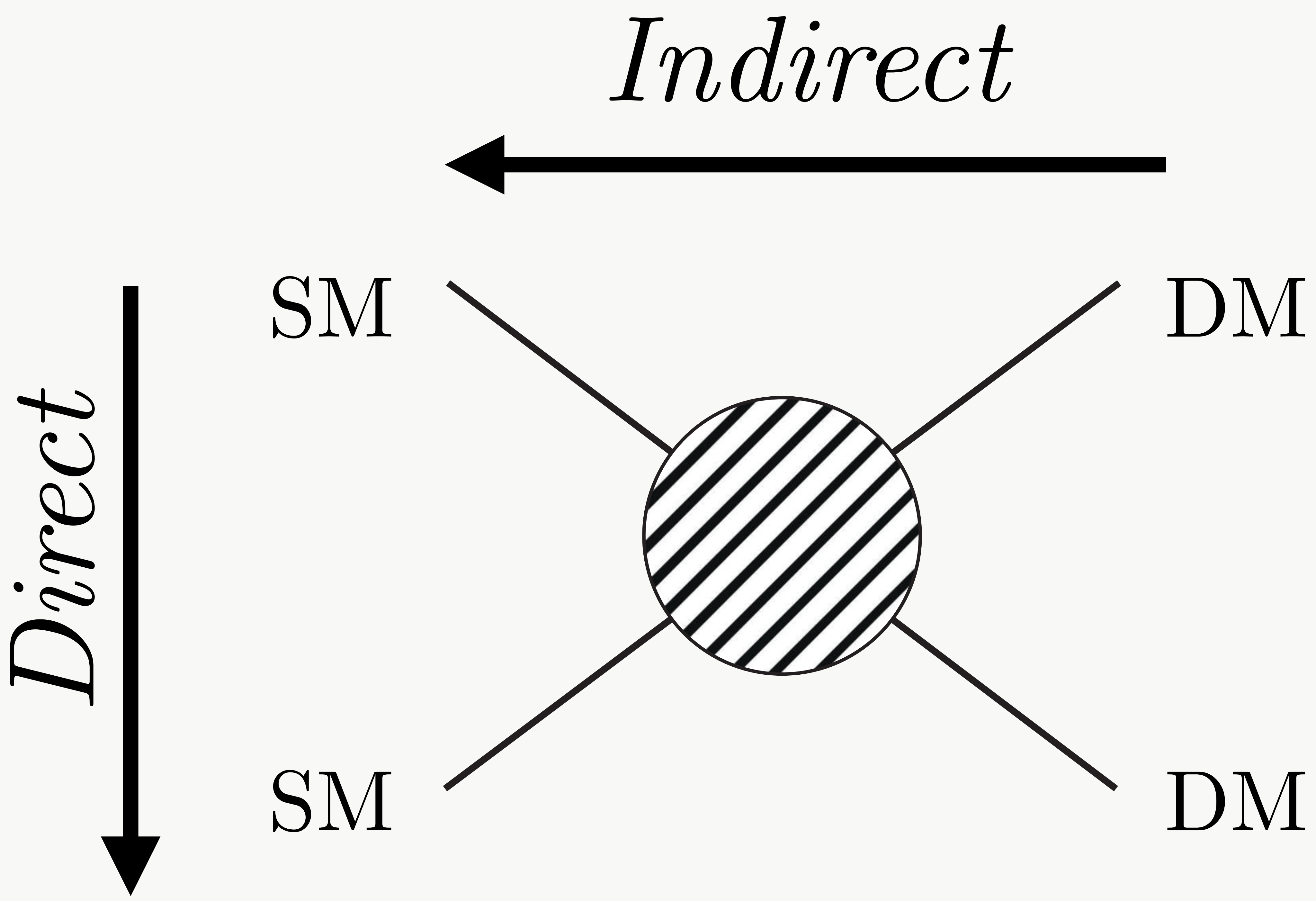


Dark Matter at Colliders



Indirect detection via cosmic rays subject to big uncertainties

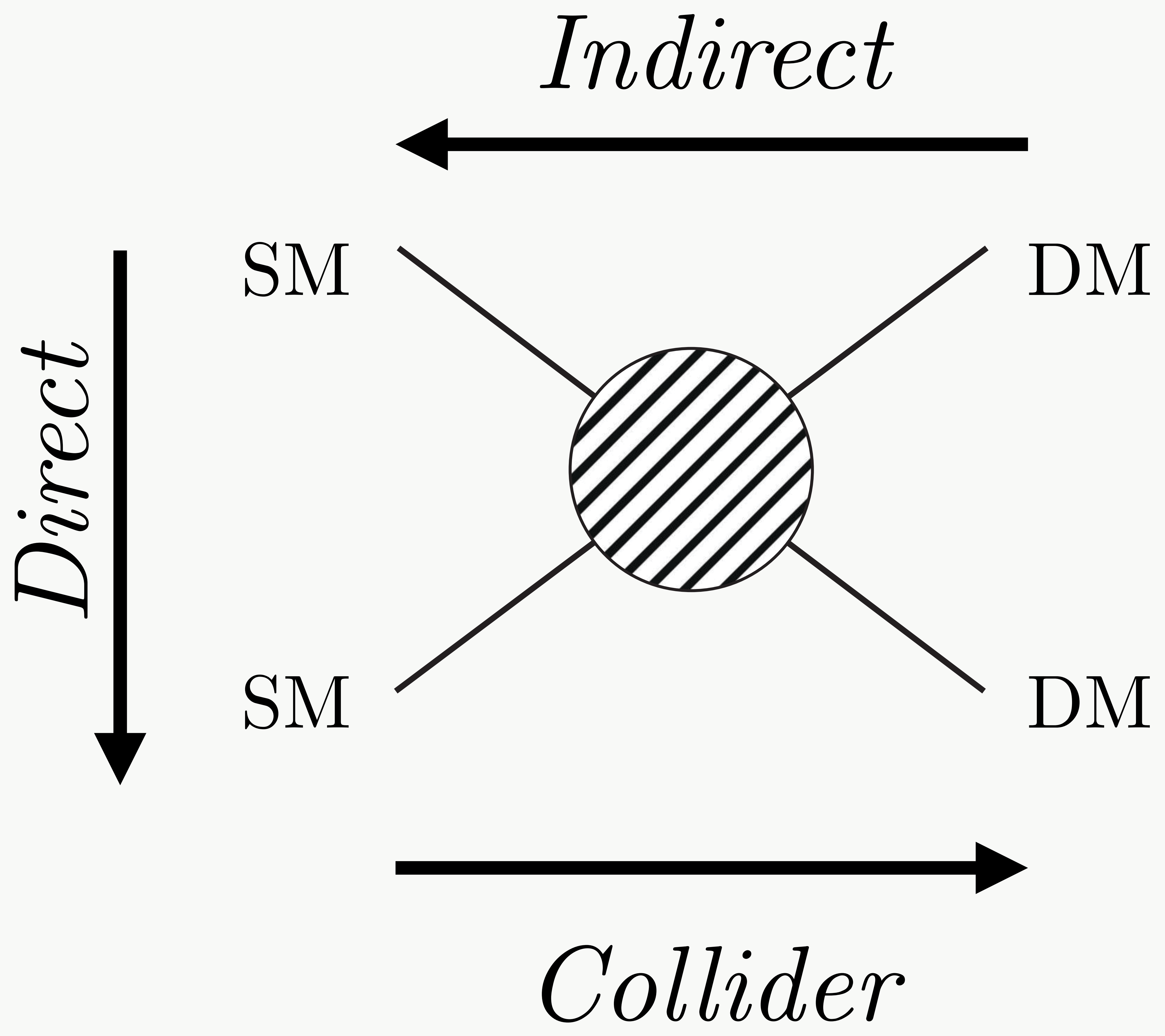
Dark Matter at Colliders



Indirect detection via cosmic rays subject to big uncertainties

Direct detection suffers because low pT transfer → high background

Dark Matter at Colliders



Indirect detection via cosmic rays subject to big uncertainties

Direct detection suffers because low pT transfer → high background

Colliders are *complementary* probes

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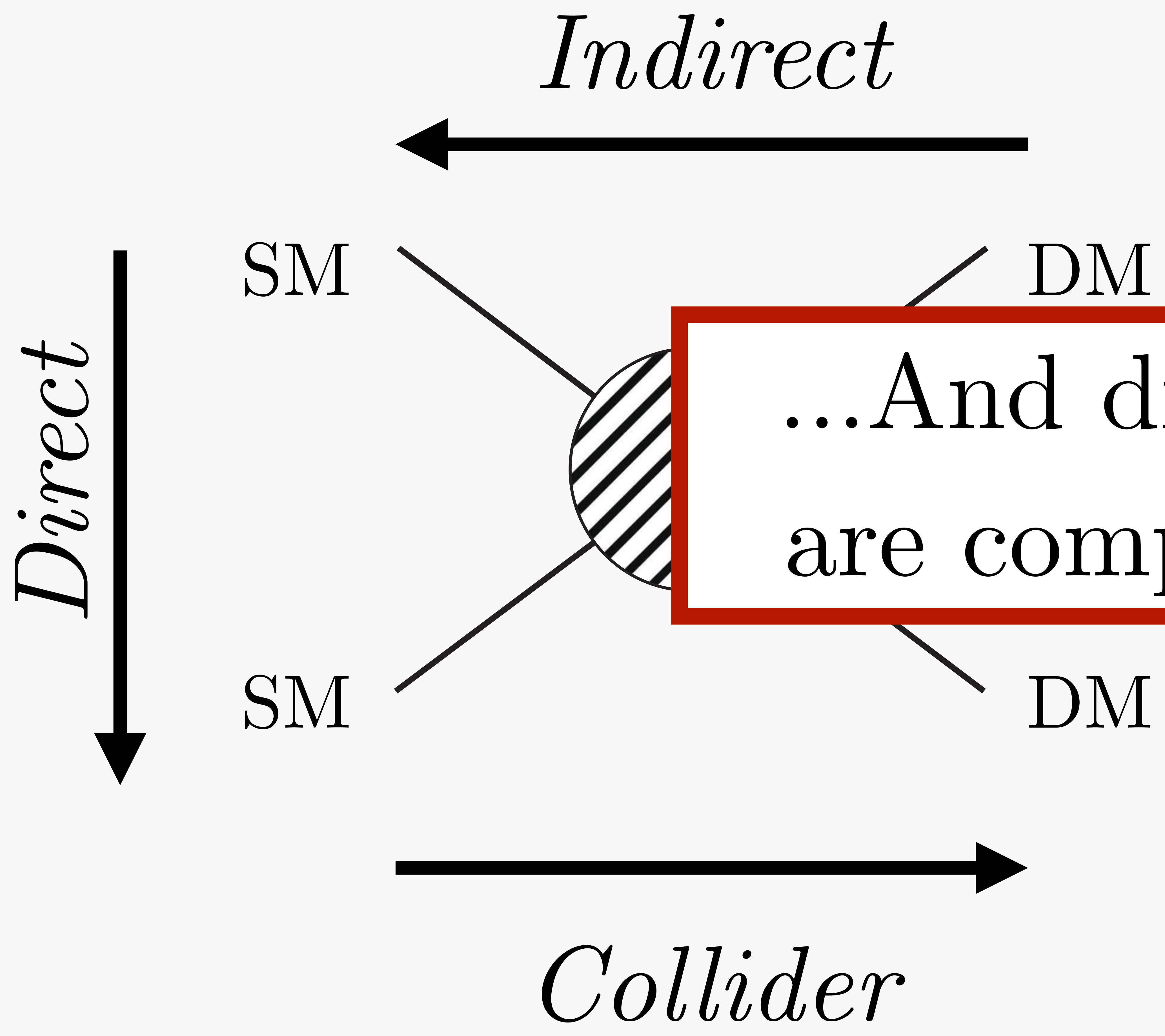
Dark Matter at Colliders



Indirect detection via cosmic rays subject to big uncertainties

…cause low pT

…ground

…And different future colliders are complements to each other

Colliders are *complementary* probes

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Dark Matter at Future Colliders

(Future *Circular* Colliders)

Energy Frontier

Energy ↑

FCC-hh (SPPC)

$E \sim \mathcal{O}(100 \text{ TeV})$

FCC-ee (CEPC)

$E \sim \mathcal{O}(100 - 350 \text{ GeV})$

Precision Frontier

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Dark Matter at Future Colliders

(Future *Circular* Colliders)

Energy Frontier

Energy

FCC-hh (SPPC)

$E \sim \mathcal{O}(100 \text{ TeV})$

MuC

$E \sim \mathcal{O}(3 - 10 \text{ TeV})$

FCC-ee (CEPC)

$E \sim \mathcal{O}(100 - 350 \text{ GeV})$

Precision Frontier

Dark Matter at Future Colliders

(Future *Circular* Colliders)

Energy Frontier

FCC-hh (SPPC)

$E \sim \mathcal{O}(100 \text{ TeV})$

- Clean Environment
- Indirect effect sensitivity
- Z-pole run for flavor couplings

Energy

FCC-ee (CEPC)

$E \sim \mathcal{O}(100 - 350 \text{ GeV})$

Precision Frontier

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Dark Matter at Future Colliders

(Future *Circular* Colliders)

Energy Frontier

Energy

FCC-hh (SPPC)

$E \sim \mathcal{O}(100\ \text{TeV})$

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- High energy to probe heavy states

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Precision Frontier

Dark Matter at Future Colliders

(Future *Circular* Colliders)

Energy Frontier

Energy

FCC-hh (SPPC)

$E \sim \mathcal{O}(100 \text{ TeV})$

MuC

$E \sim \mathcal{O}(3 - 10 \text{ TeV})$

- High energy to probe heavy states
- Primarily EW interactions

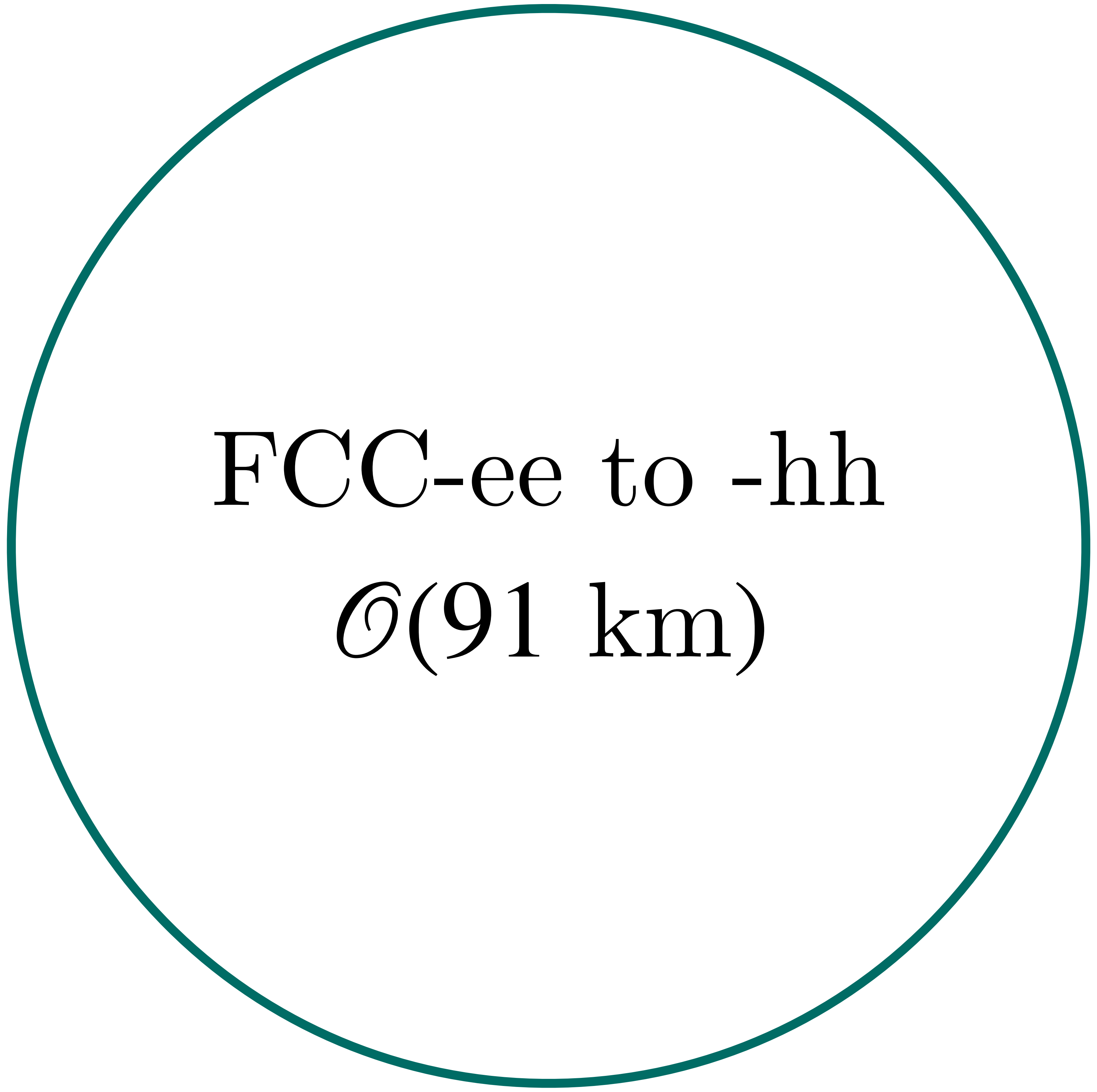
FCC-ee (CEPC)

$E \sim \mathcal{O}(100 - 350 \text{ GeV})$

Precision Frontier

Comparison of Colliders

FCC

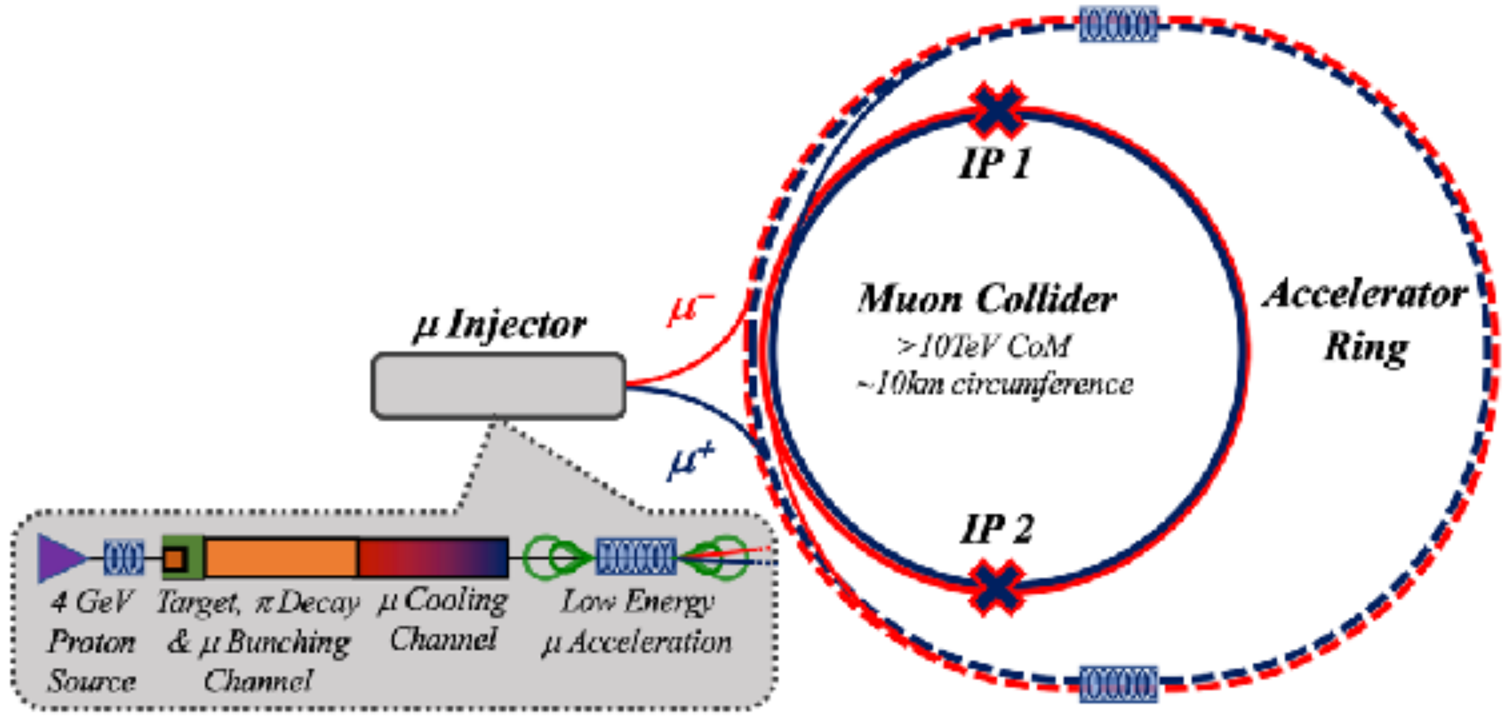


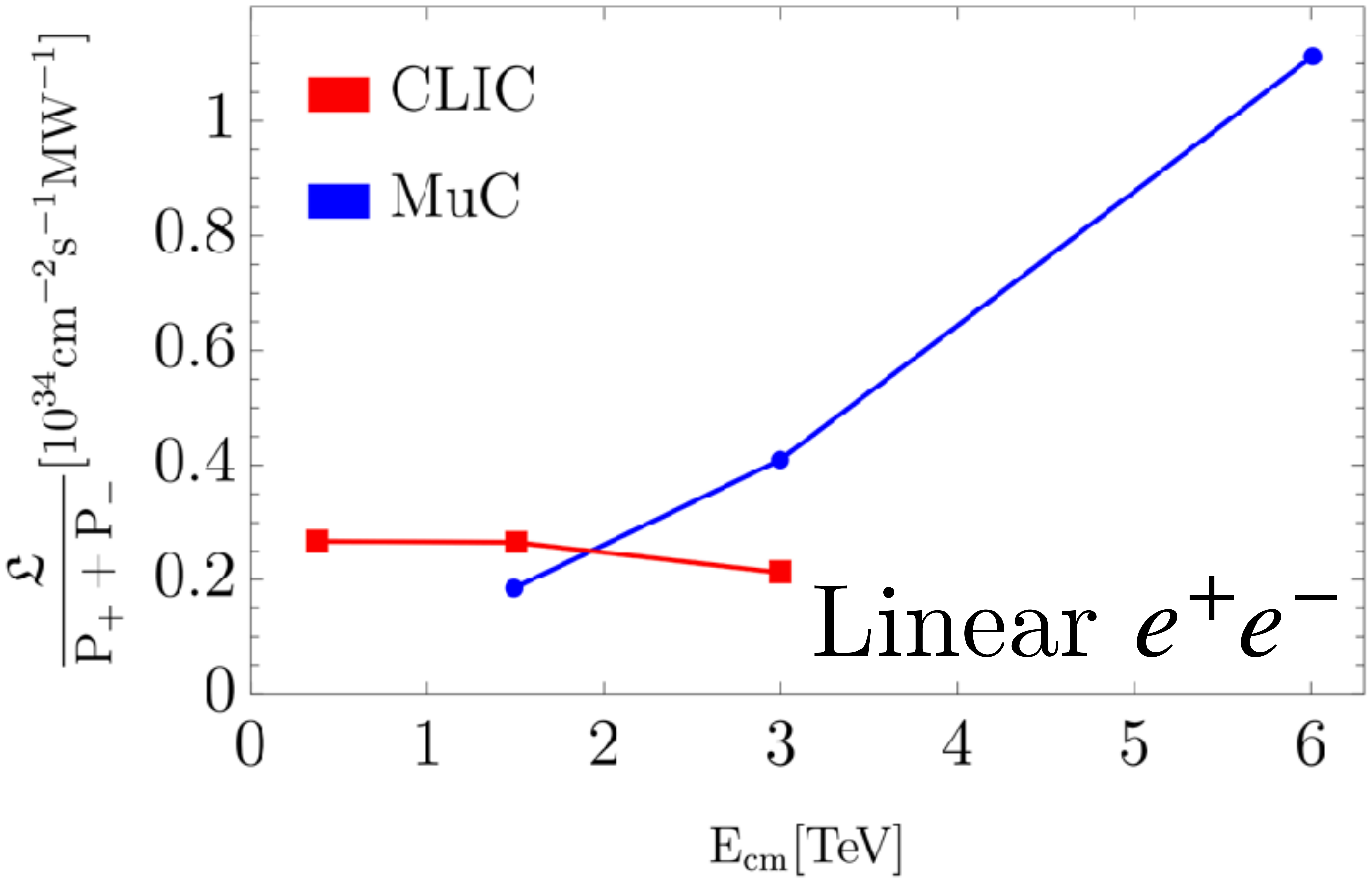
$\sqrt{s}\ \sim m_Z$ to 100 TeV

MuC*

$\mathcal{O}$(10 km)

$\sqrt{s} = 10$ TeV





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Models of Dark Matter

Which are most motivated for colliders?

WIMP Scenario

Higgs Portal

Thermal DM

Dark Sector

Cesarotti

Models of Dark Matter

Which are most motivated for colliders?

WIMP Scenario

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WIMP DARK MATTER

Relic Abundance

$$\Omega h^2 \sim 0.2 \times \left(\frac{m_{DM}}{\text{TeV}}\right)^2 \times \left(\frac{0.3}{g'}\right)^4$$

$$10\ \text{GeV} < m_\chi < 100\ \text{TeV}$$

TeV-scale DM naturally freezes out with weak-interaction couplings

EW phenomena at 100 GeV - TeV scale contains many open questions

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WIMP DARK MATTER

Relic Abunda

Motivated reason to search in collider reach

ally freezes out with
on couplings

$$\Omega h^2 \sim 0.2 \times \left(\frac{m_{DM}}{\text{TeV}}\right) \times \left(\frac{\quad}{g'}\right)$$

$10 \text{ GeV} < m_\chi < 100 \text{ TeV}$

EW phenomena at 100 GeV - TeV scale contains many open questions

Cesarotti

Wimp Dark Matter

(At high-energy colliders)

EW n-plet	Mass [TeV]
$2_{1/2}$	1.08
3_0	2.86
$4_{1/2}$	4.8
5_0	13.6
5_1	9.9
$6_{1/2}$	31.8
7_0	48.8
9_0	113

Electroweak Multiplets

Can arise in SUSY scenarios

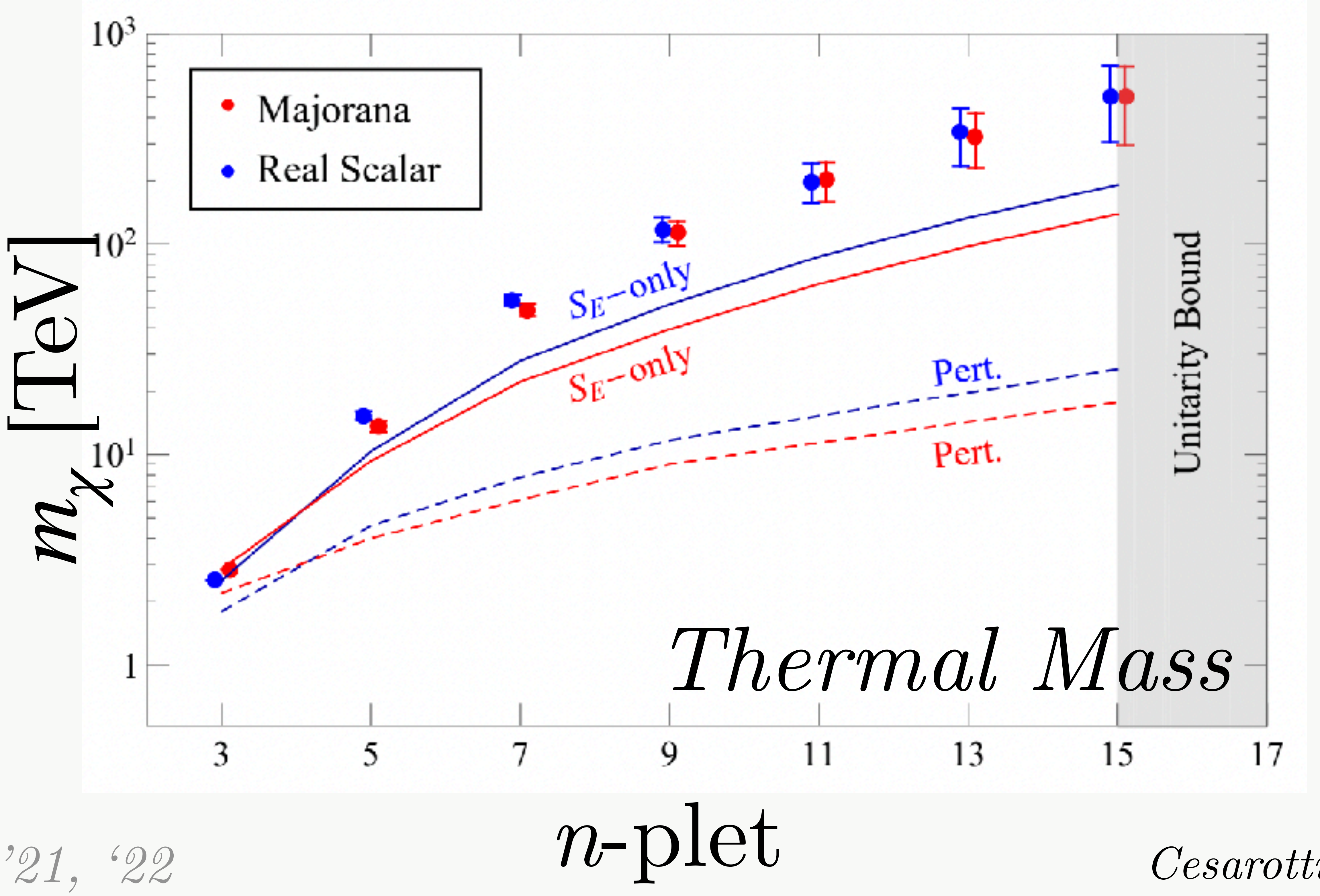
n-plet

$$\begin{pmatrix} \vdots \\ \chi^+ \\ \chi^0 \\ \chi^- \\ \vdots \end{pmatrix}$$

Predicted at $\sim$ TeV scale

$\Delta m \sim \mathcal{O}(100)$ GeV

DM candidate



Han, Liu, Wang, Wang ‘20

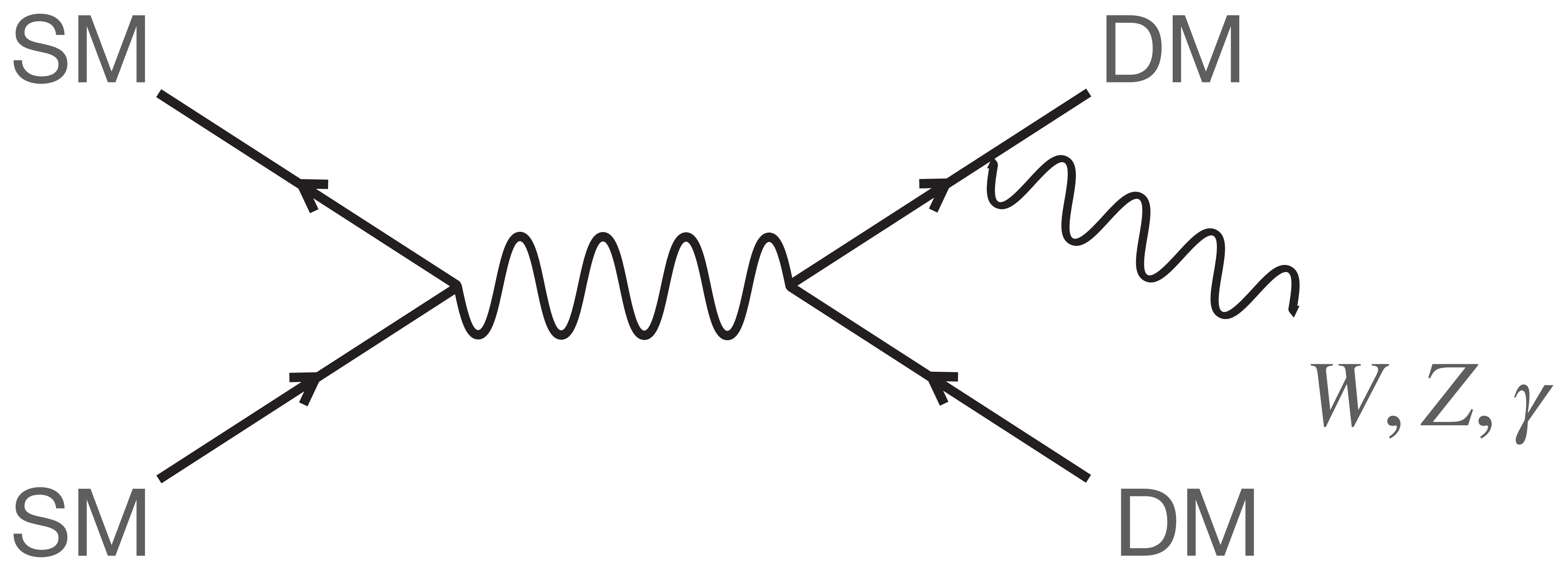
Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio ’21, ‘22

WIMP DARK MATTER

Consider detection strategies (at *high-energy* future colliders)

Mono-X

$ff \to \chi\bar{\chi} + X$



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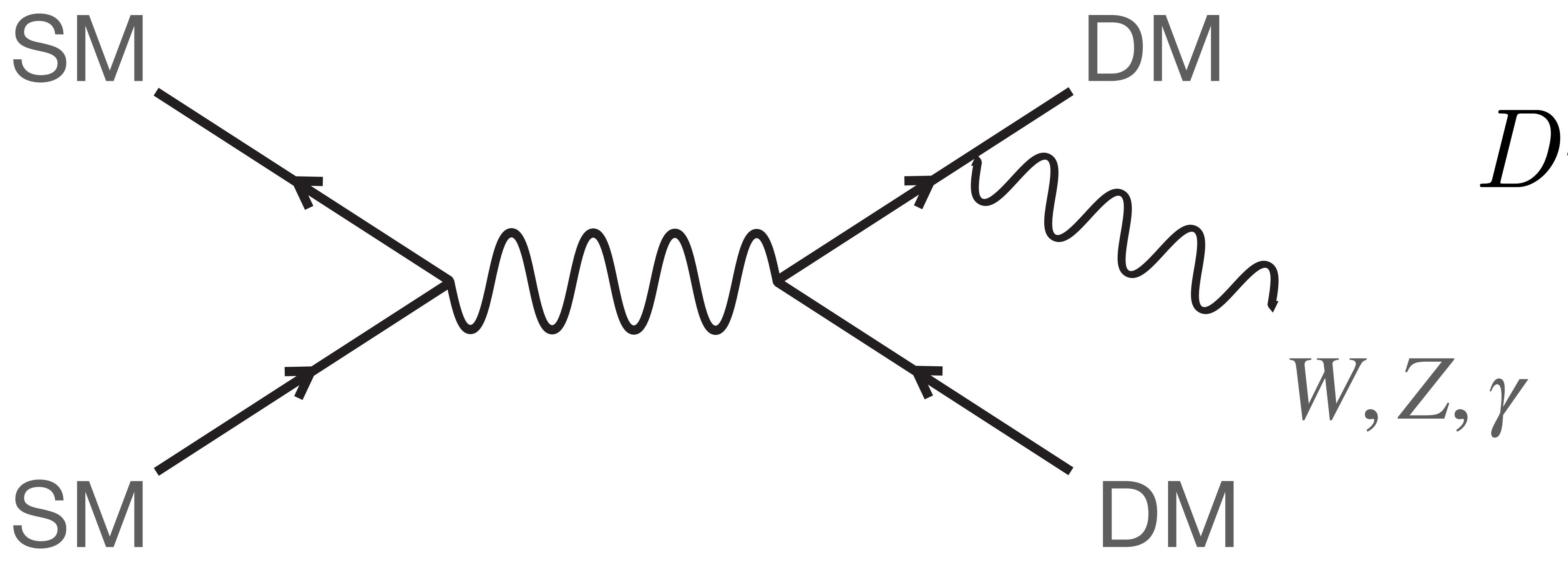
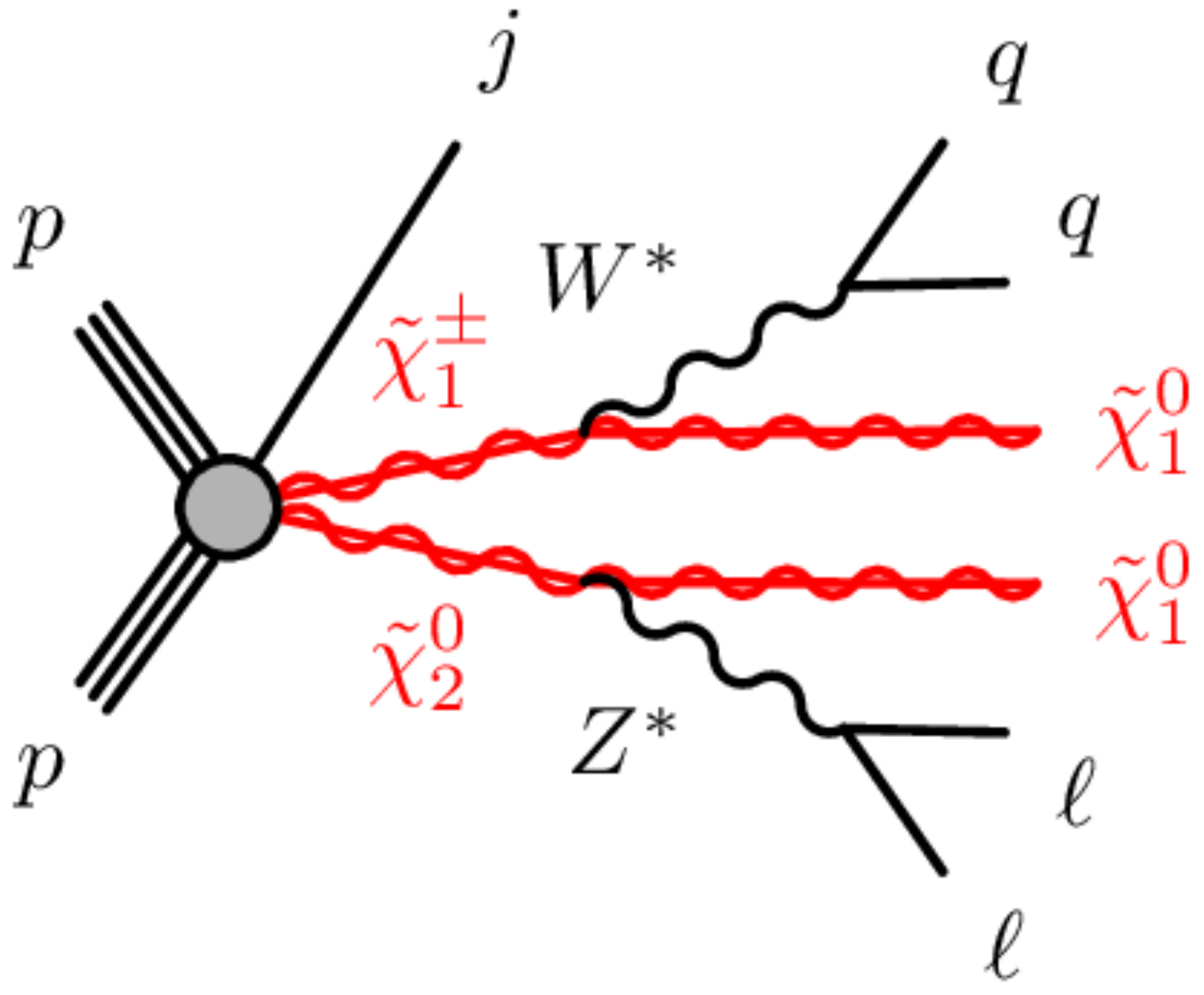


Kinematic cuts

Disappearing Track

$\chi^{\pm} \to \chi^0 \pi^{\pm}$



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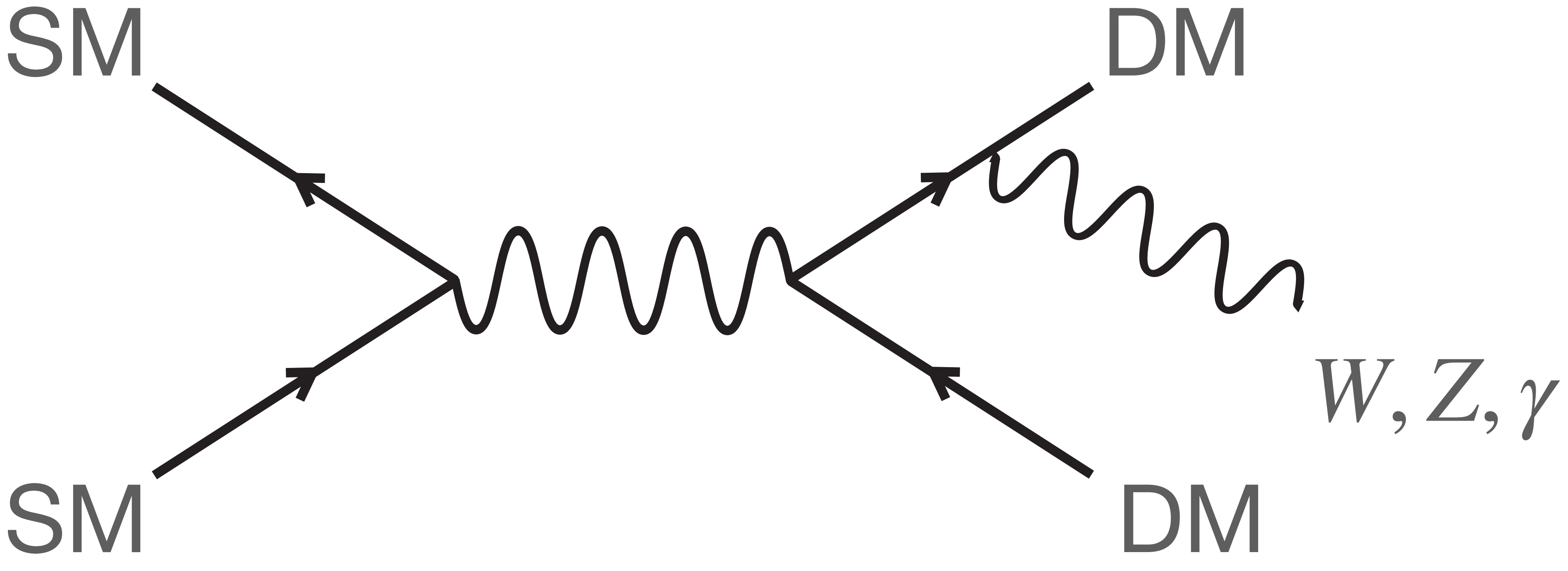

Identify DM with *kinematics* and *energetic X*

X: Vectors (W, Z, γ), jet, Higgs, etc.

Significance: $\dfrac{S}{\sqrt{S + B + \epsilon(B^2 + S^2)}}$

Backgrounds are large!

Cuts: $p_T^X \gtrsim 100$ GeV, $\not{E}_T \sim m_\chi$, MIM, etc.

Han, Liu, Wang, Wang '20
Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio '21, '22

FCC Study Vol 1, '18
M. Cirelli, F. Sala, M. Taoso, '14

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WIMP DARK MATTER

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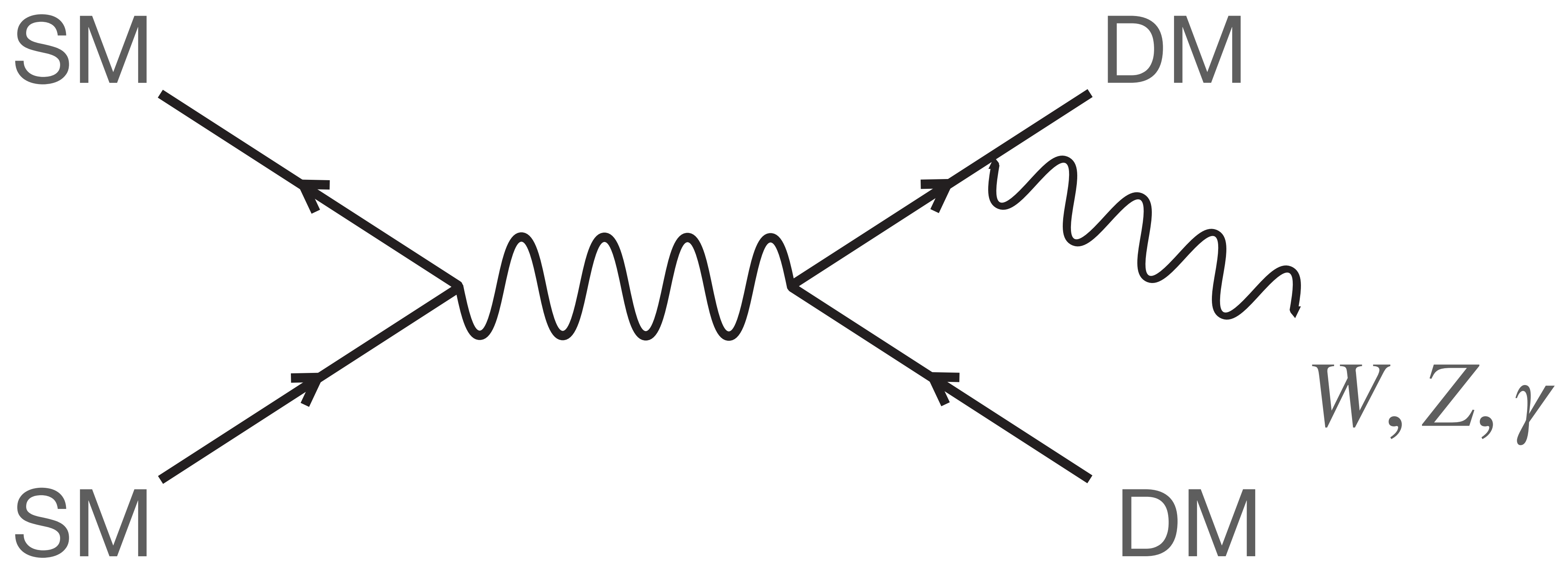

Need efficient detectors & ID

Backgrounds are SM processes with ν or missing particle reconstruction

(Ex: MuC)

mono-γ bkg: $\ell^+\ell^- \to \gamma\nu\bar{\nu}$,

mono-Z bkg: $\ell^+\ell^- \to Z\nu\bar{\nu}$,

mono-W bkg: $\ell^+\ell^- \to W^\mp\nu + \ell^\pm(\text{lost})$

FCC Study Vol 1, '18

M. Cirelli, F. Sala, M. Taoso, '14

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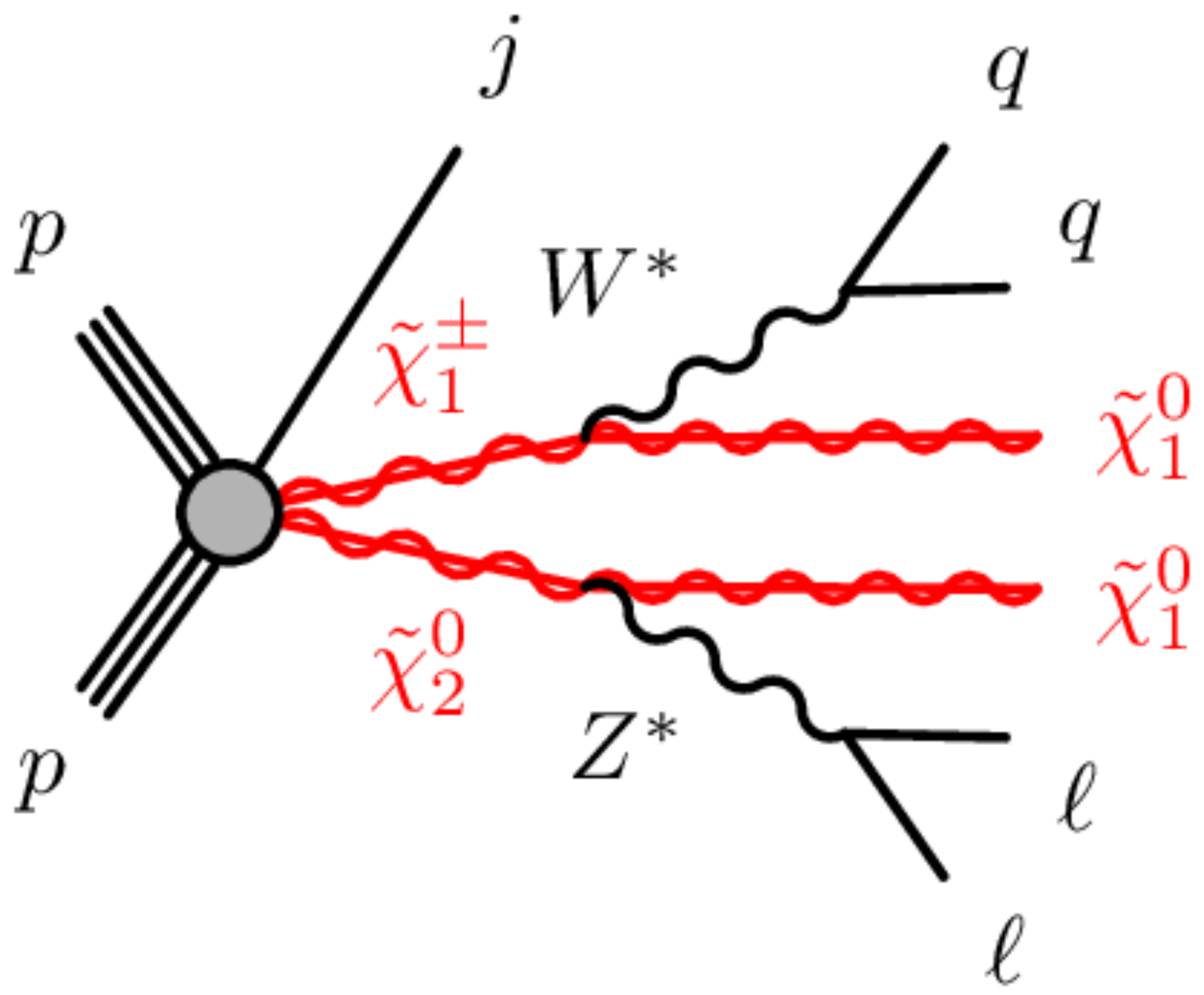
WIMP DARK MATTER

Additional background mitigation can be done with DT

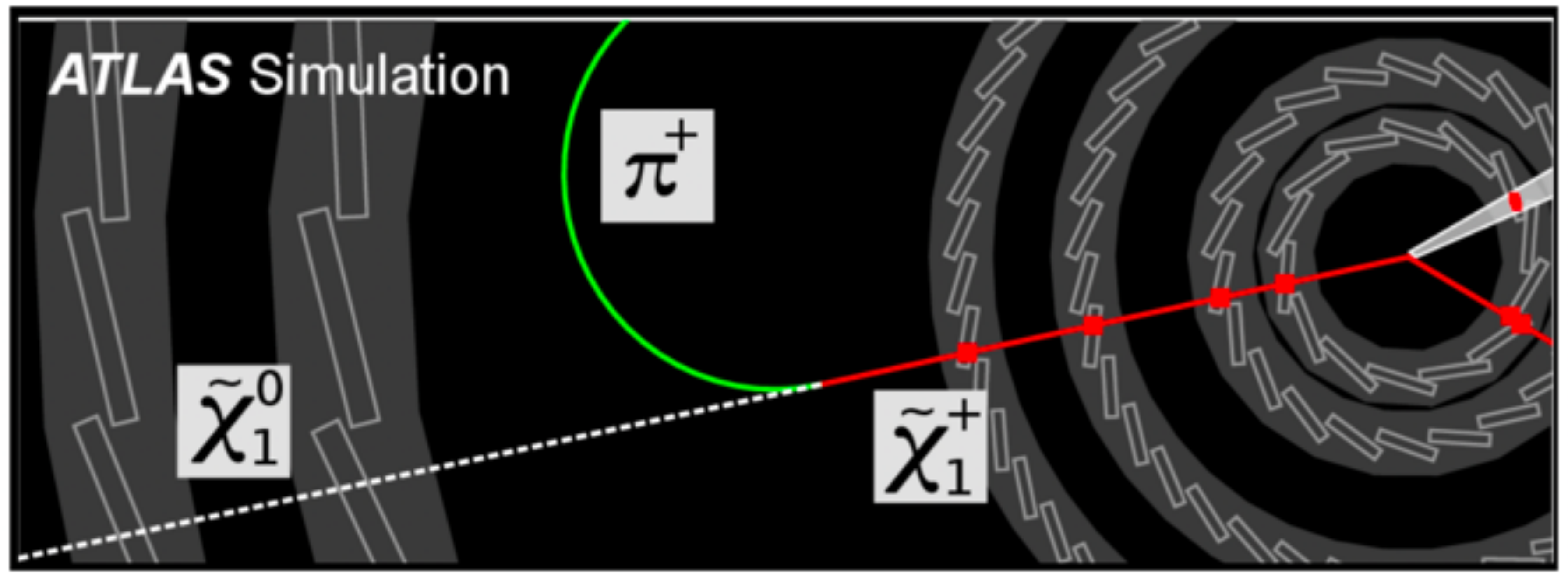
Disappearing Track

$ff \to \chi^+\chi^-$

$\chi^\pm \to \chi^0\pi^\pm$



Highly dependent on detector performance



$$c\tau_{\chi^\pm} \sim \frac{48}{(n^2-1)}\ \text{cm}$$

Difficult for inner tracker resolution &

FCC-hh: Pile-up effects

MuC: BIB mitigation

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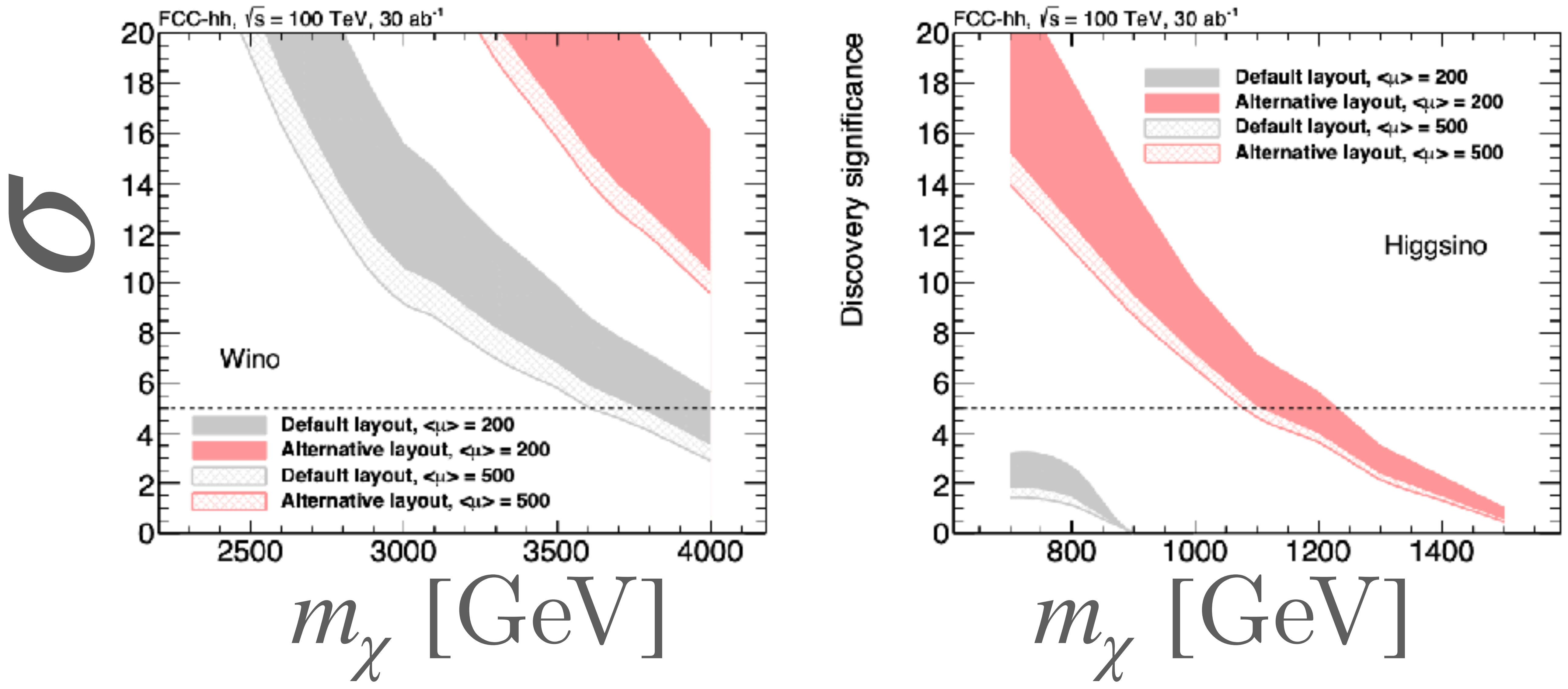
Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio '21, '22

Wimp Dark Matter

Disappearing Track

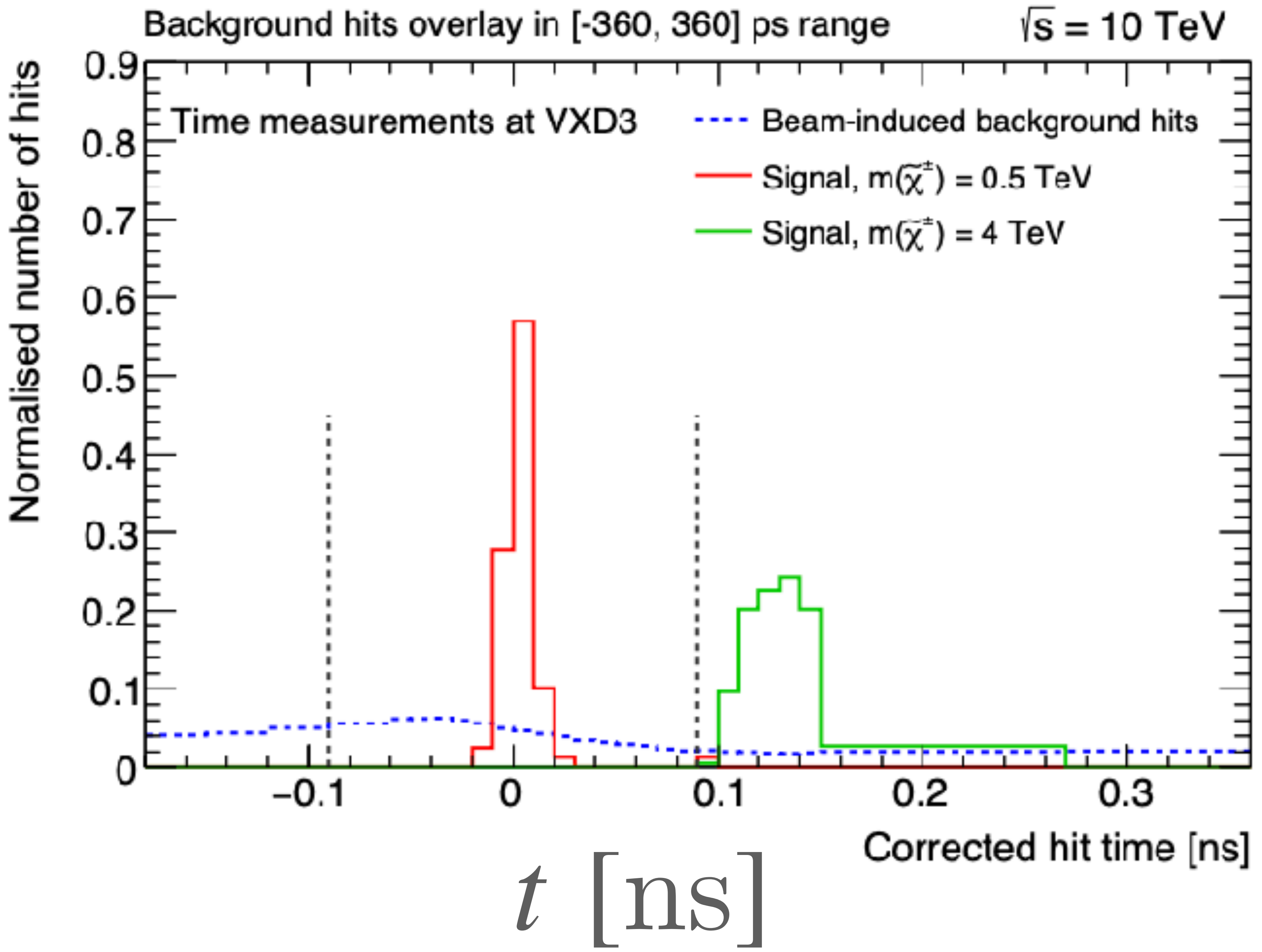
FCC-hh: Pile-up effects



Detector improvements

Timing resolution & closer tracker layers

MuC: BIB mitigation



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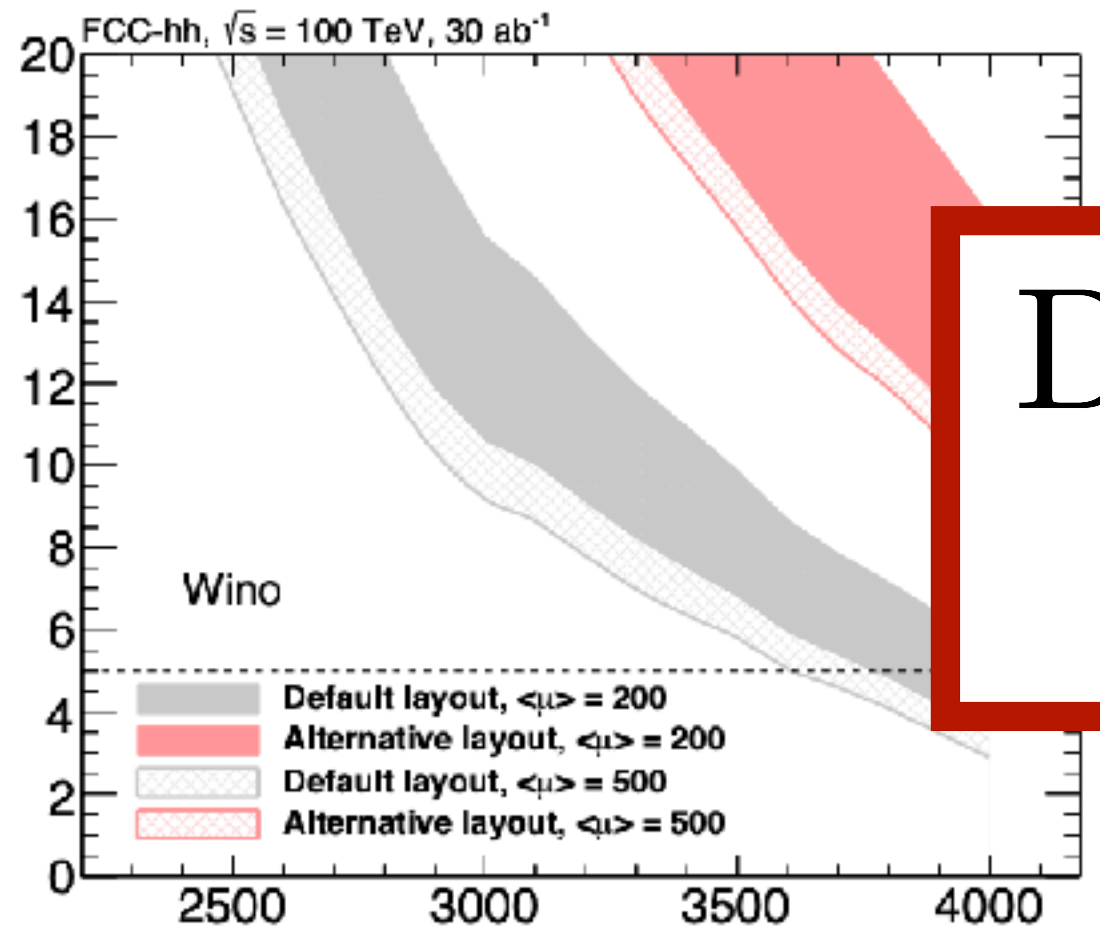
Wimp Dark Matter

Disappearing Track

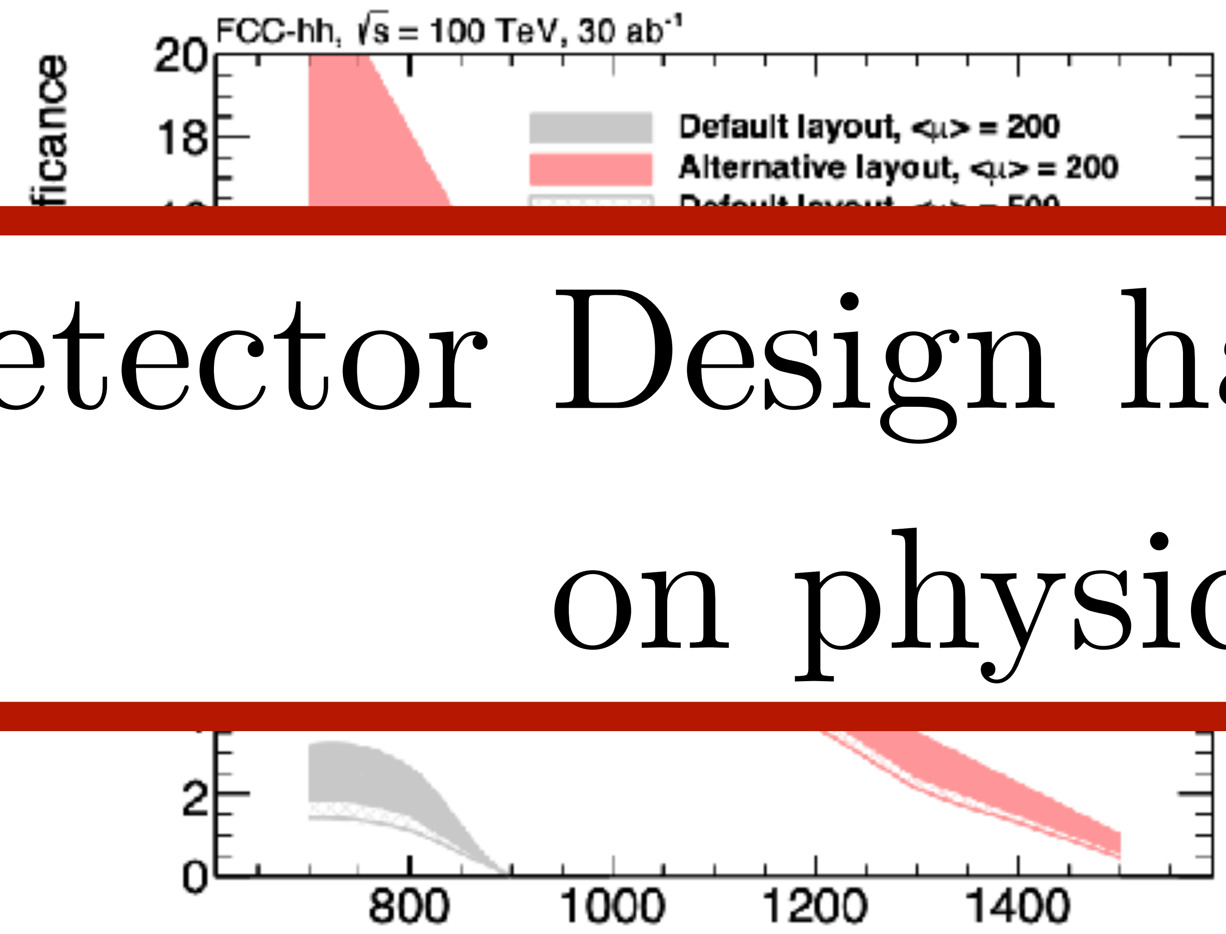
FCC-hh: Pile-up effects

MuC: BIB mitigation

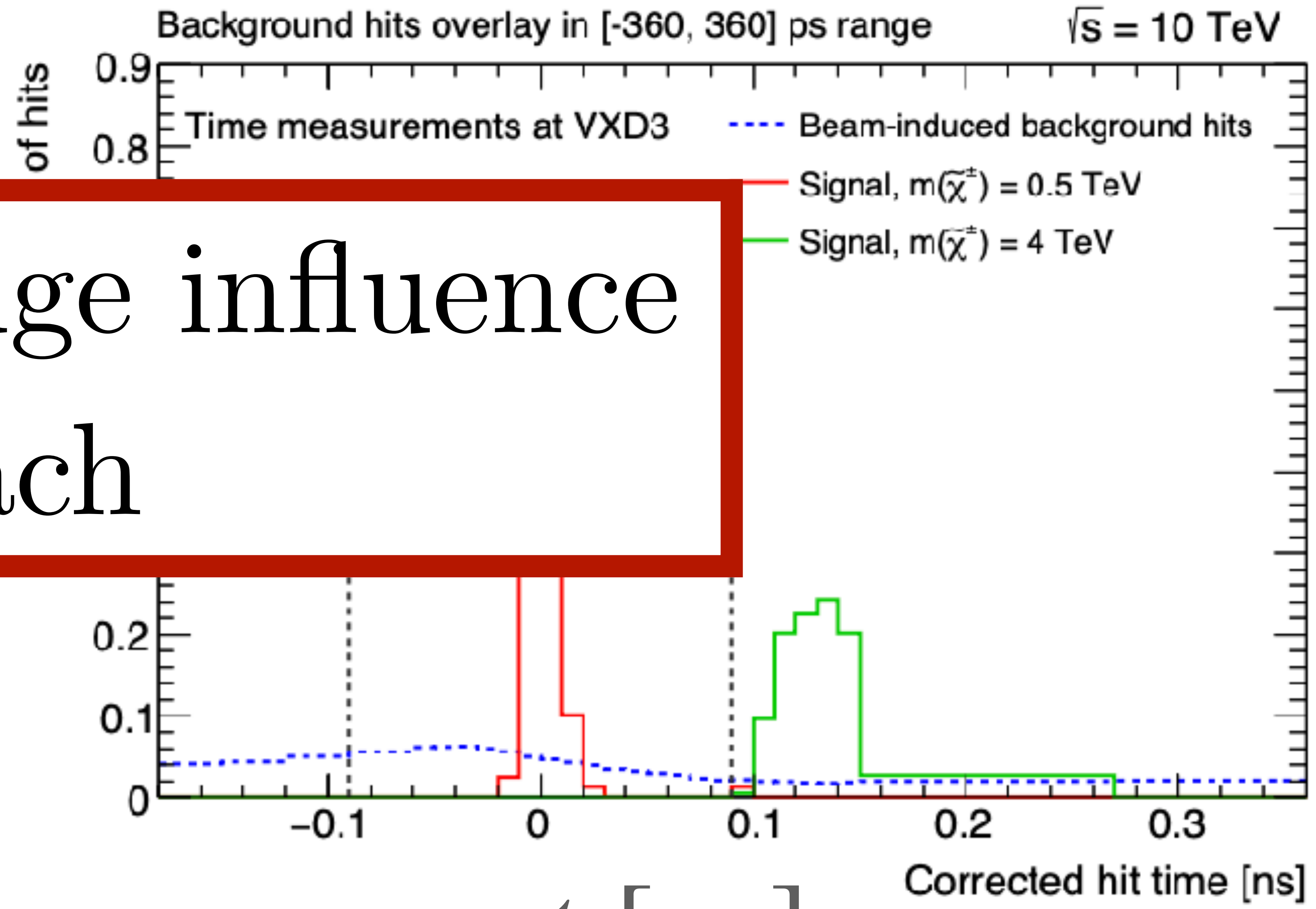
σ



m_χ [GeV]



m_χ [GeV]



t [ns]

Detector Design has huge influence on physics reach

Detector improvements

Timing resolution & closer tracker layers

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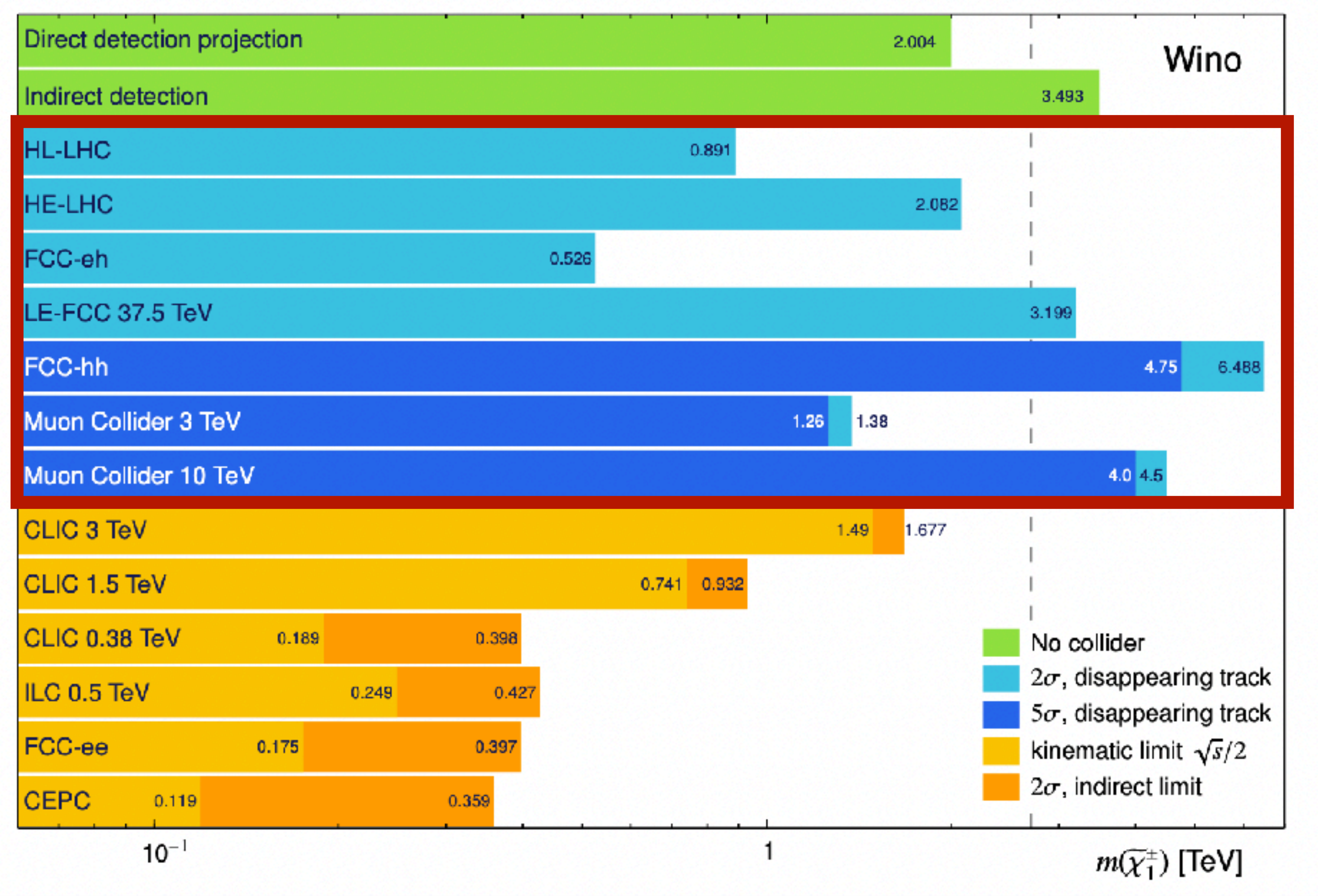
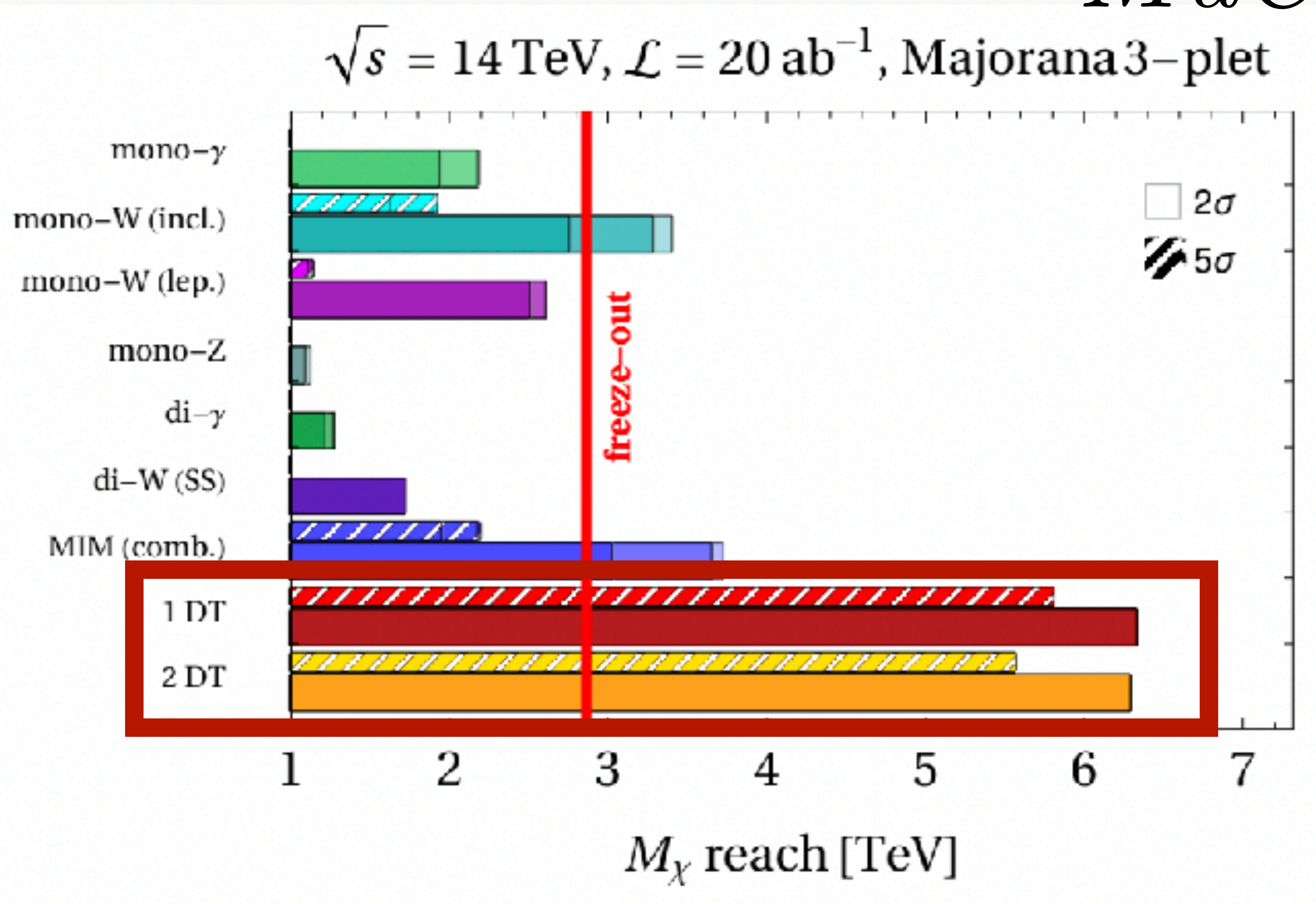
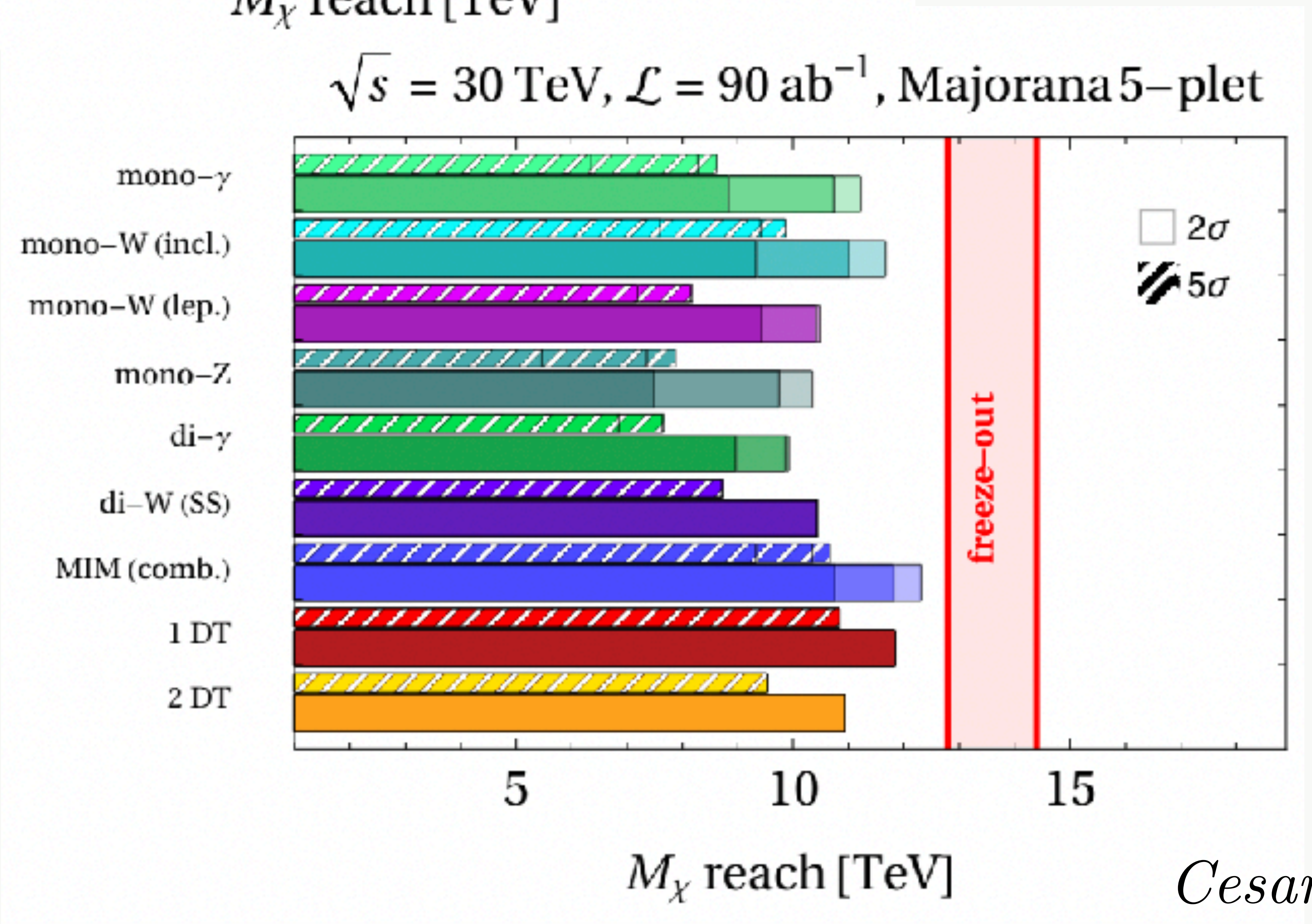
WIMP Dark Matter

Example: Wino



MuC Reach





Saito, Svada, Terashi, Asai '19

Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio '21, '22

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WIMP Dark Matter

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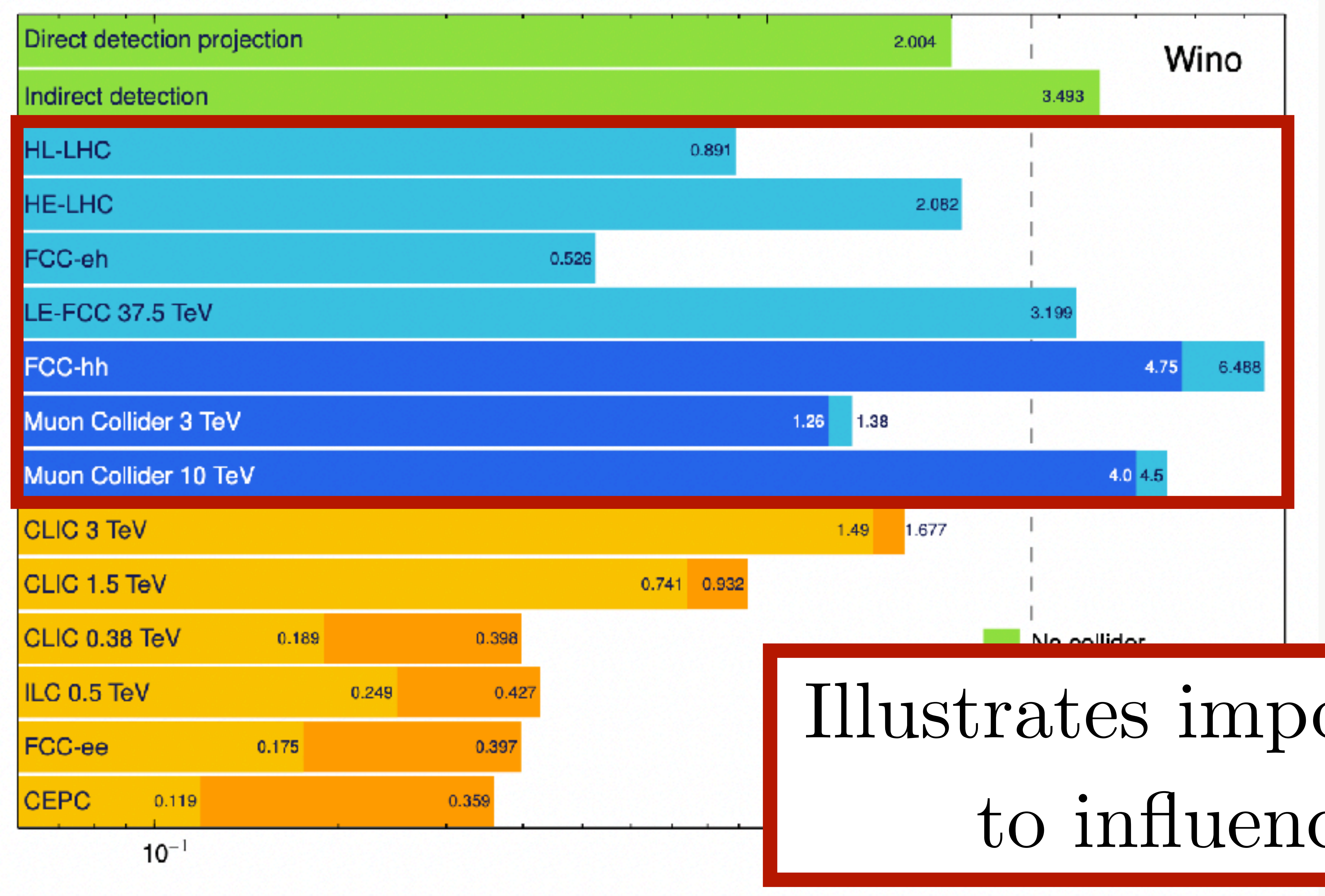

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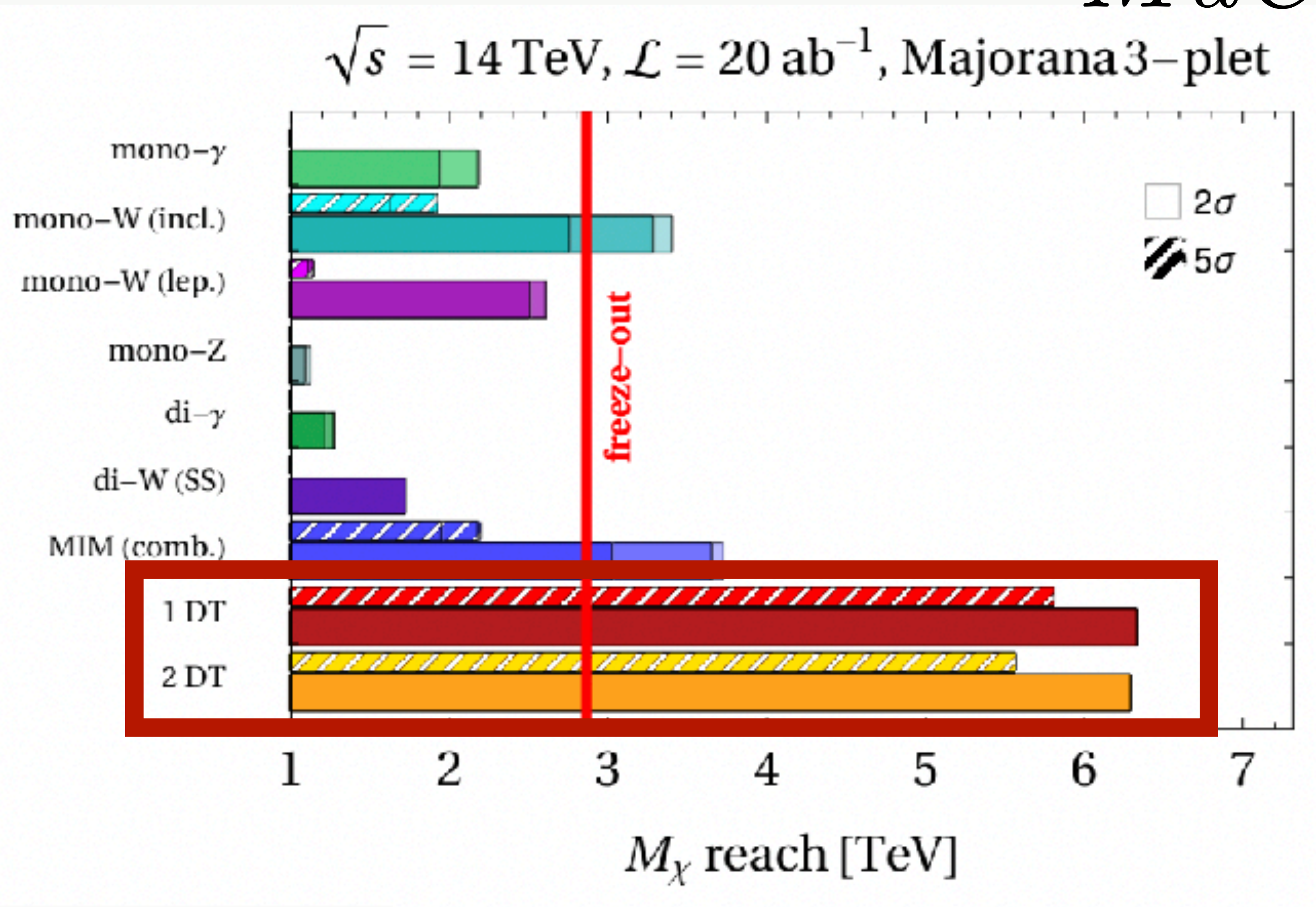

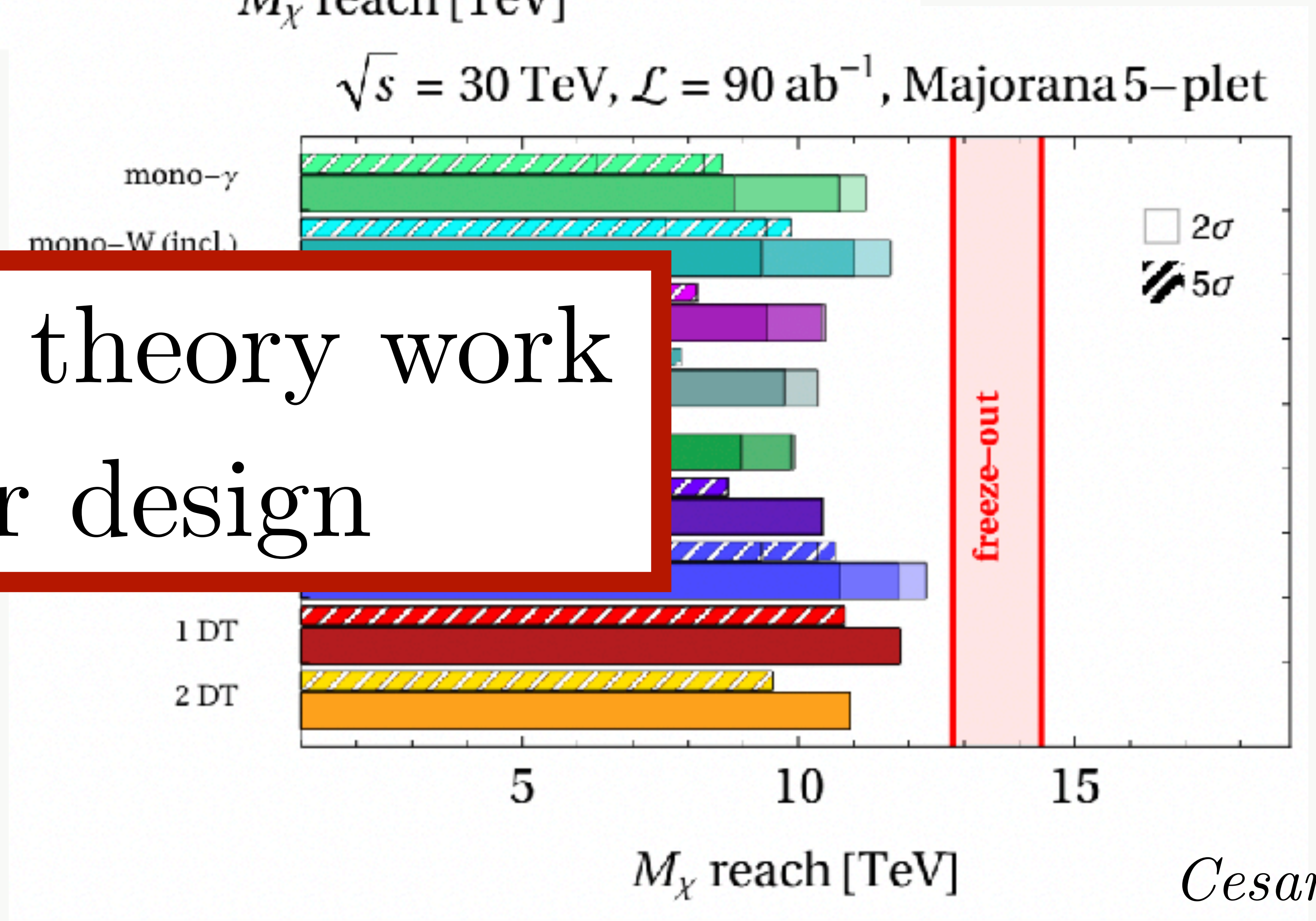

Illustrates importance of theory work to influence detector design

Saito, Svada, Terashi, Asai '19

Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio '21, '22

R. Capdevilla, F. Meloni, R. Simoniello, J. Zurita 23

Models of Dark Matter

Which are most motivated for colliders

WIMP Scenario

Higgs Portal

Thermal DM

Dark Sector

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Leptophilic Dark Matter

(At lepton colliders)

Consider other paradigms beyond the WIMP that could be both (thermal) dark matter and discoverable at colliders

For example, a model with a scalar portal that couples *leptophilically* (proportional to Yukawa couplings)

$$\mathcal{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l \bar{l} \qquad g_l = g_e \frac{m_l}{m_e}$$

D' Ambrosio, Giudice, Isidori, Strumia '02

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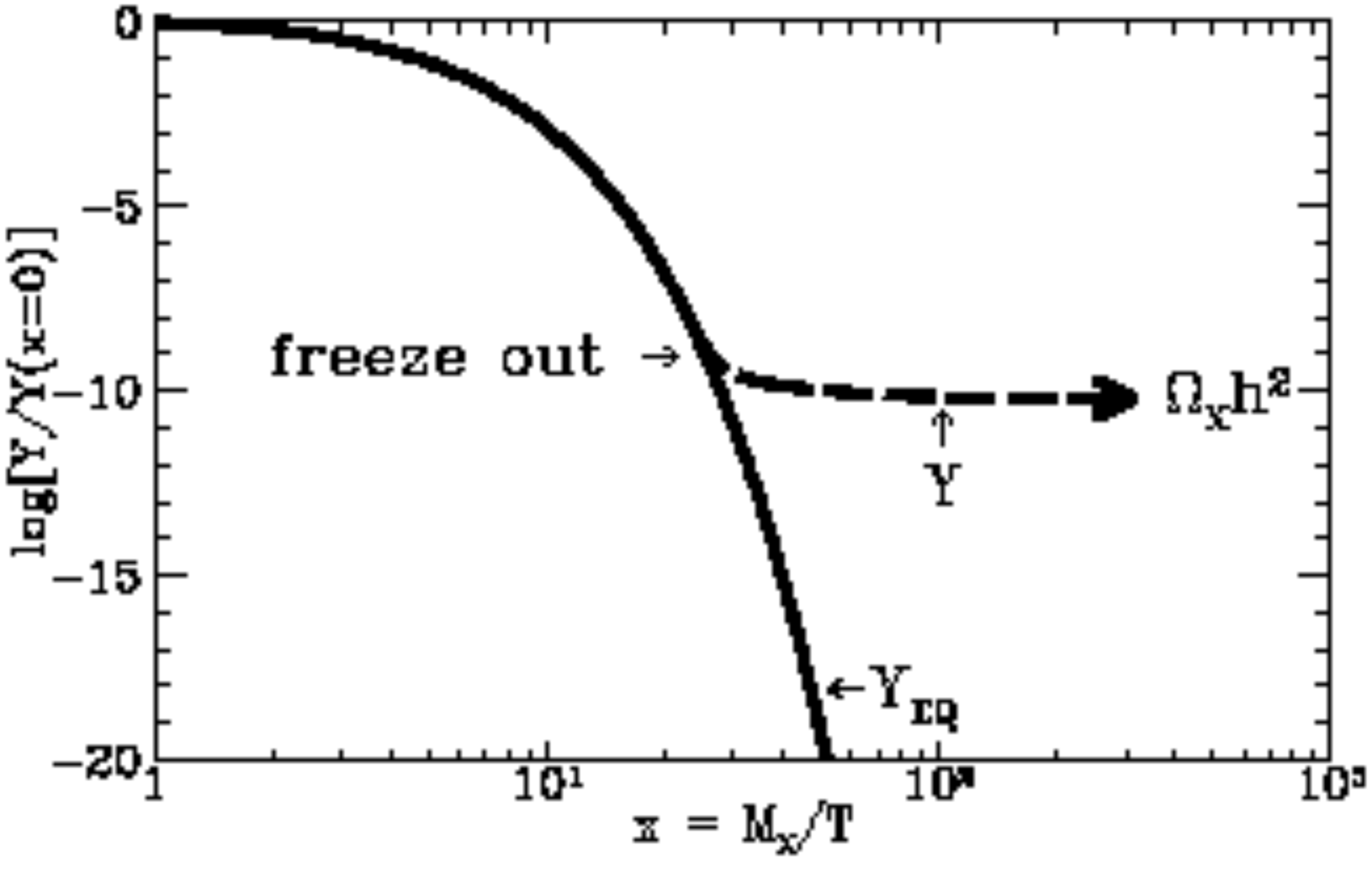
Ex: Leptophilic Dark Matter

$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l\bar{l}$$

χ is DM

φ is portal



Observed relic abundance $\mathbf{\Omega}_\chi$ sets relations between parameters

Ex: Leptophilic Dark Matter

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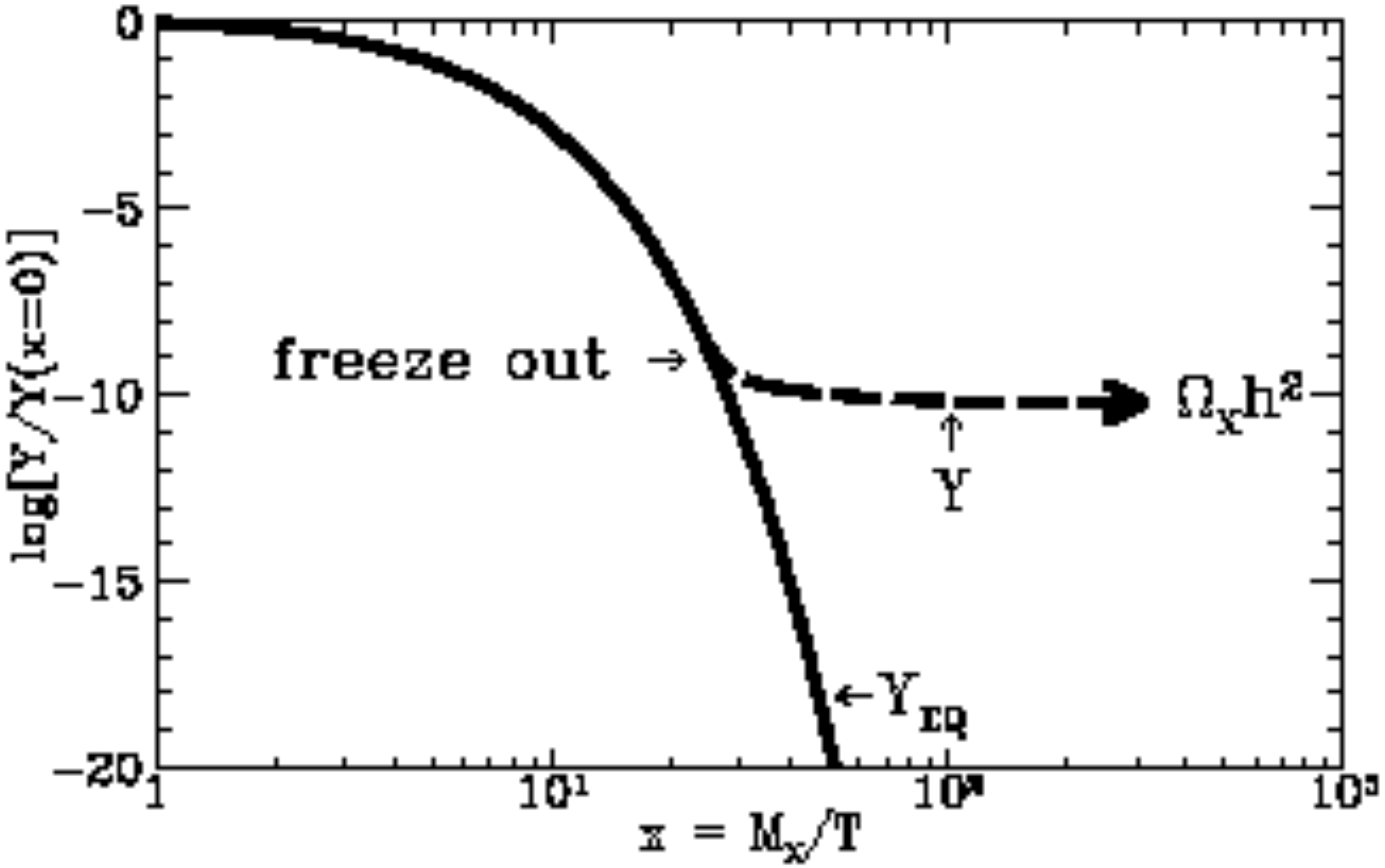

Observed relic abundance Ω_χ sets relations between parameters

Solve Boltzmann Equation

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle[n_\chi^2 - (n_\chi^{\rm eq})^2]$$

$$\sigma v_{\chi\chi\to\ell\ell} = \frac{g_\chi^2 g_\ell^2 m_\chi^2 v^2}{8\pi(m_\varphi^2 - 4m_\chi^2)^2} \propto g_\chi^2 g_\ell^2 \left(\frac{m_\chi}{m_\varphi}\right)^4 \frac{1}{m_\chi^2}$$

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$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l\bar{l}$$

χ is DM

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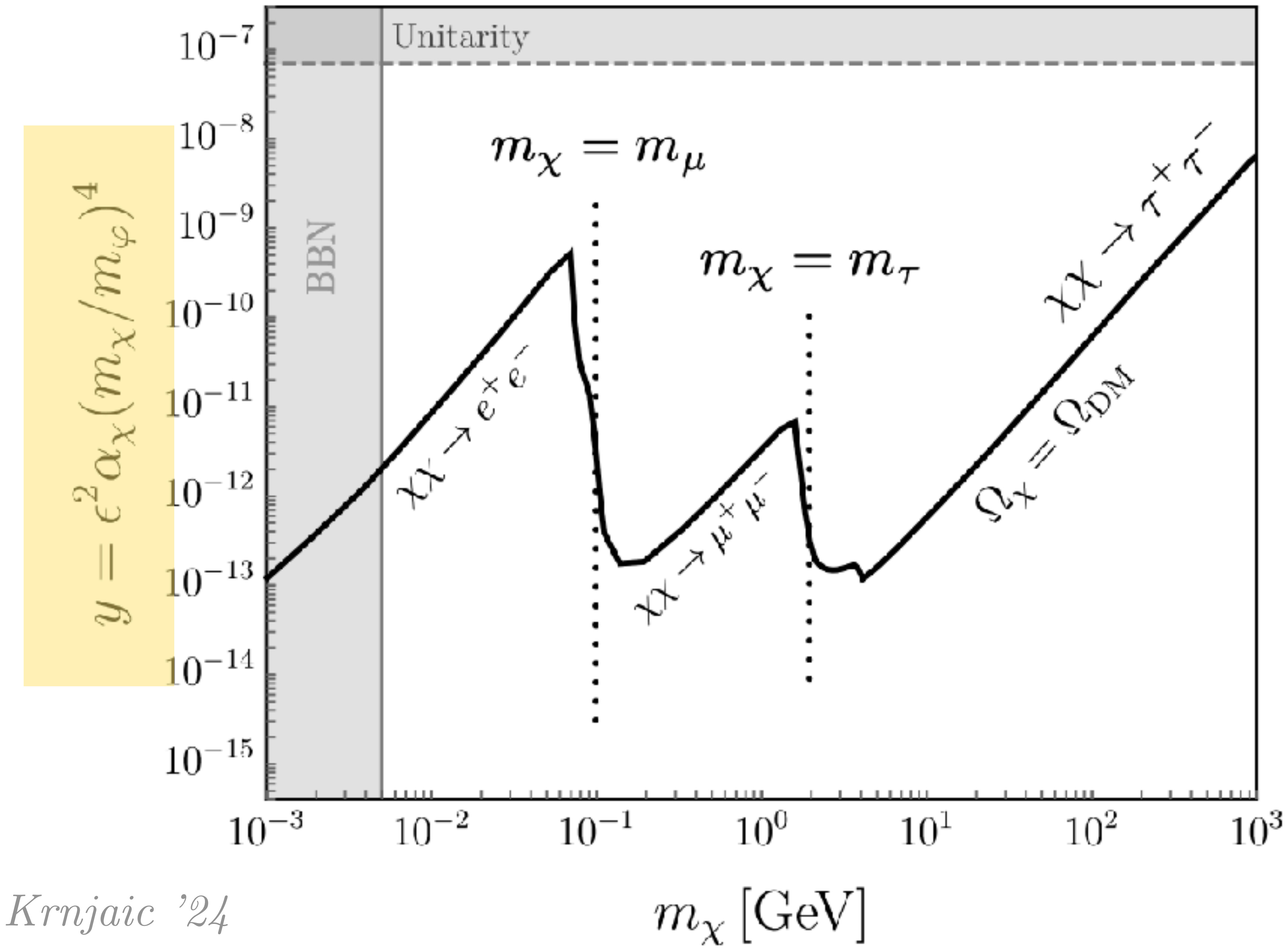
Thermal Target



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$\epsilon \equiv g_e/e$

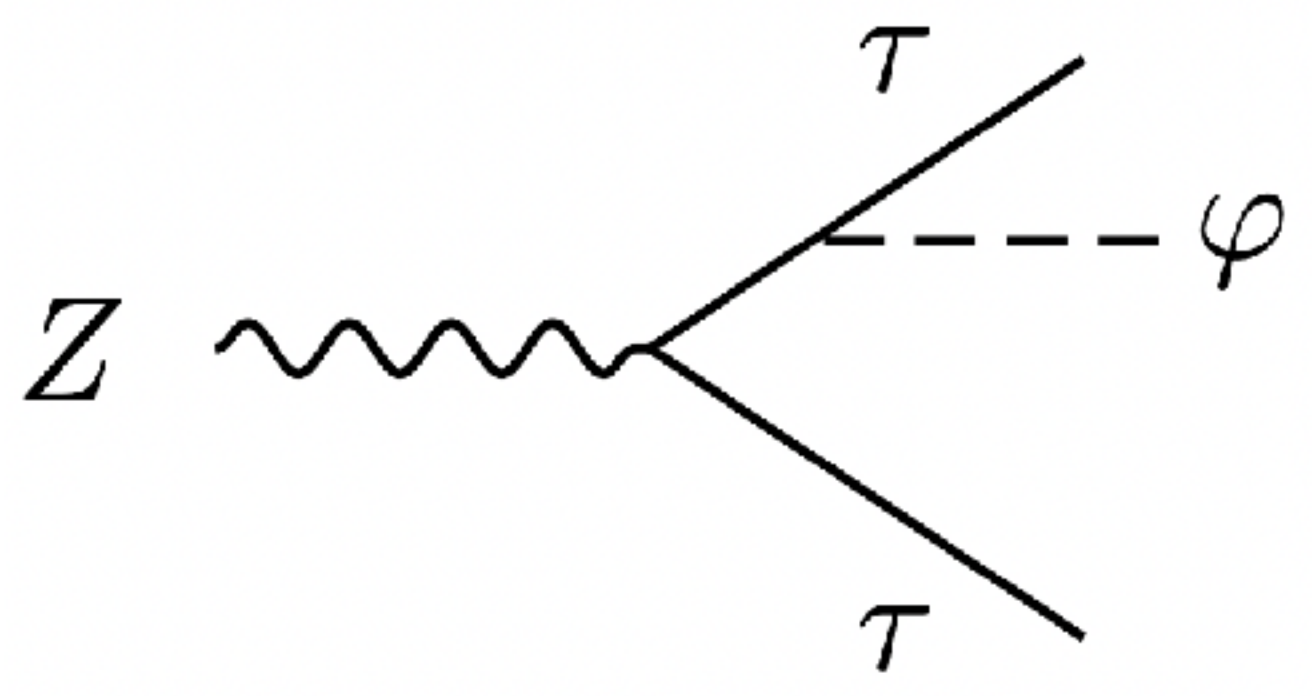
CC, Krnjaic '24

Leptophilic Dark Matter

For FCCee, sensitivity is going to *light, weakly coupled* states

Tera-Z Run

Strongest bound set by to $Z \to \tau\tau$



Allows access to 3rd gen particles

Improves bounds from LEP

$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l \bar{l}$$

Bound set by uncertainty in BR

CC, Krnjaic '24

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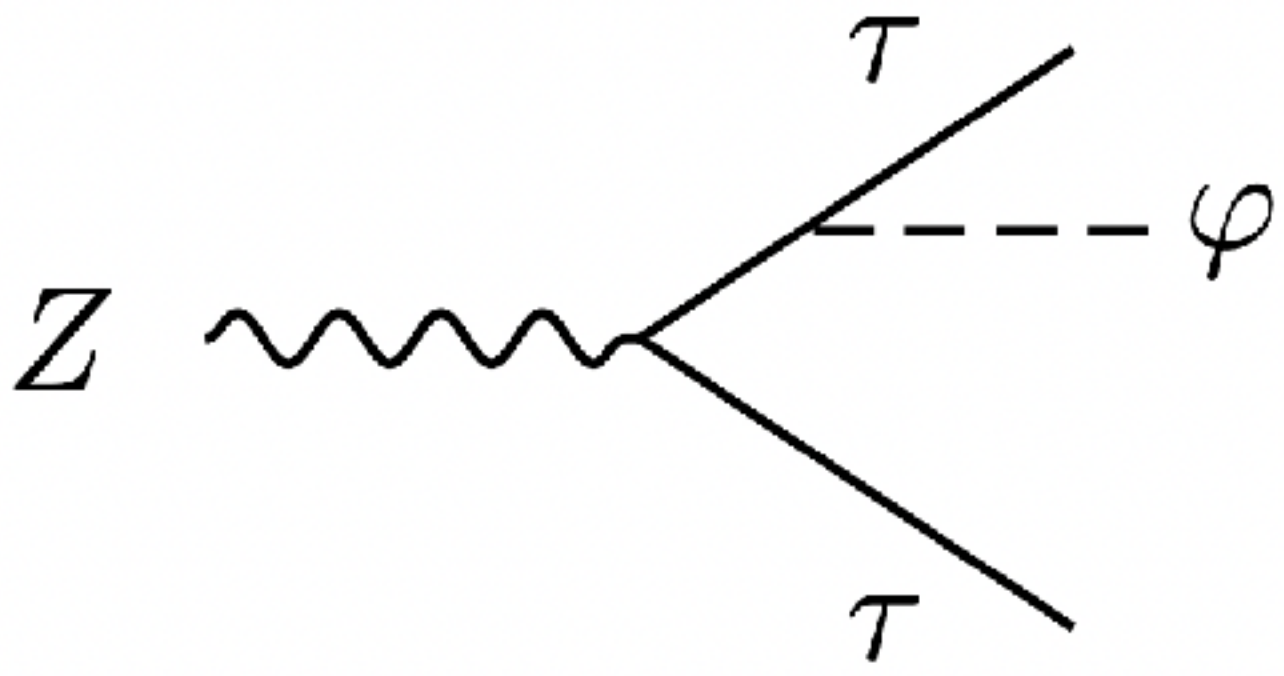

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Bound set by uncertainty in BR

Previous LEP: $(1.7 \times 10^7\ Z$'s$)$

$\Gamma(Z \to \tau\tau) = 84.08 \pm 0.22$ MeV

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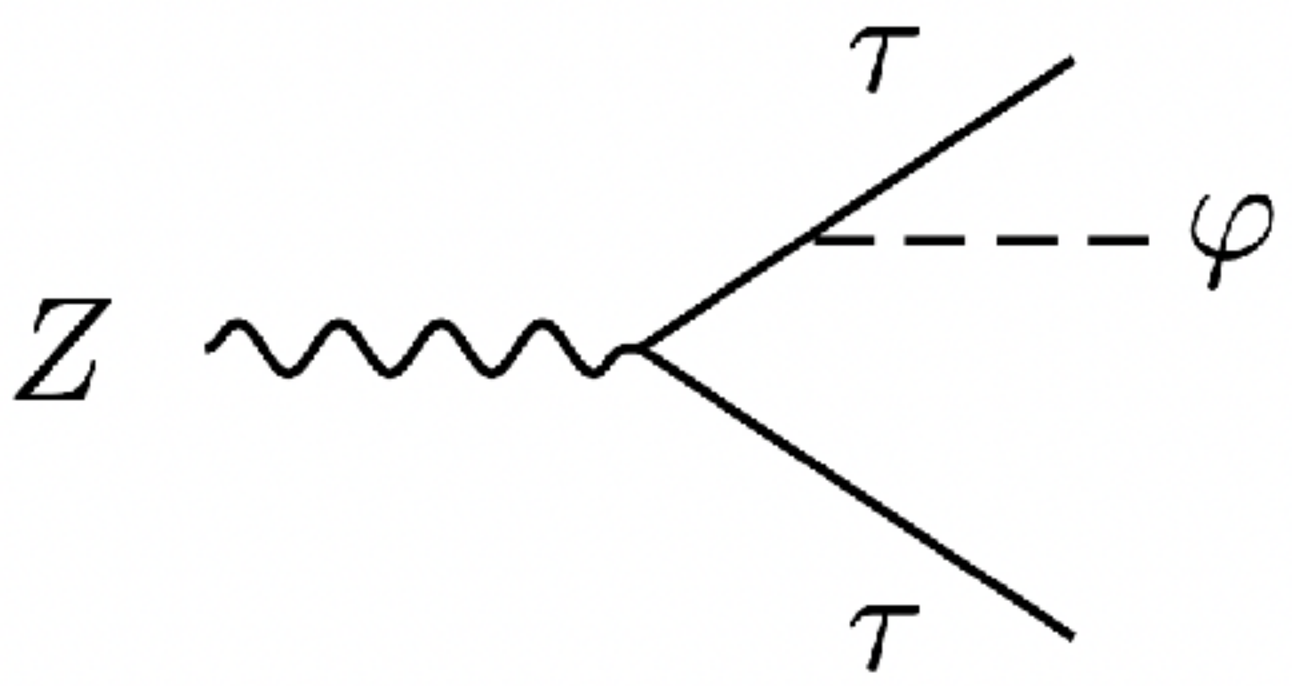

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Bound set by uncertainty in BR

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$\Gamma(Z \to \tau\tau) = 84.08 \pm 0.22$ MeV

FCCee Tera-Z: $(10^{12}\ Z\text{'s})$

$\Delta\Gamma \times \sqrt{N_{LEP}/N_{FCC}}$

Assume primary improvements come from statistics

***CC**, Krnjaic '24*

Cesarotti

Leptophilic Dark Matter

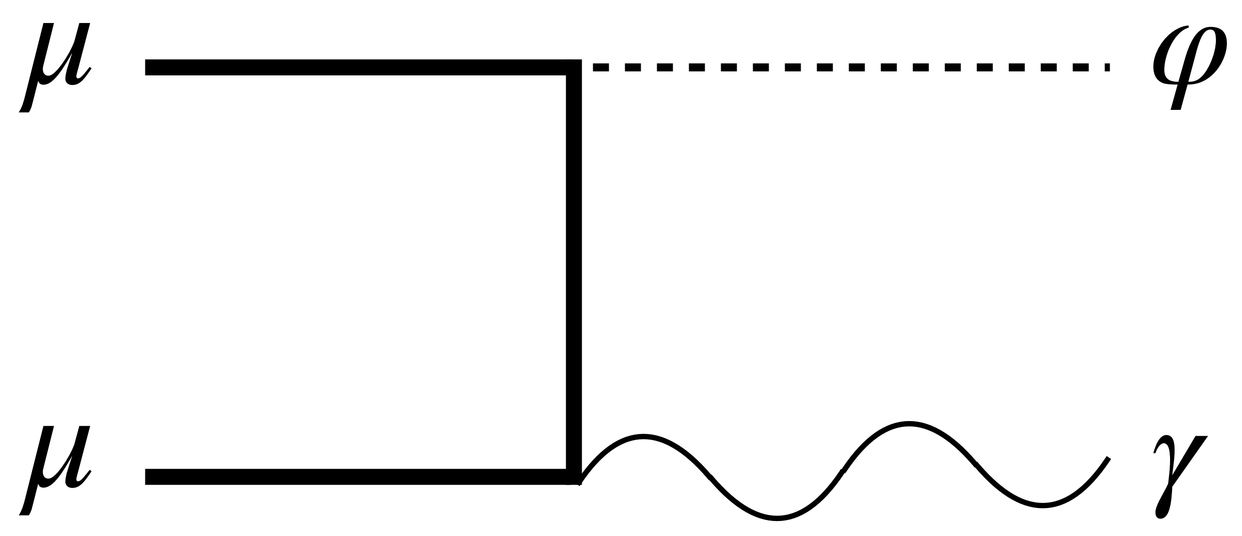
For MuC, sensitivity is going to be to *heavy* states

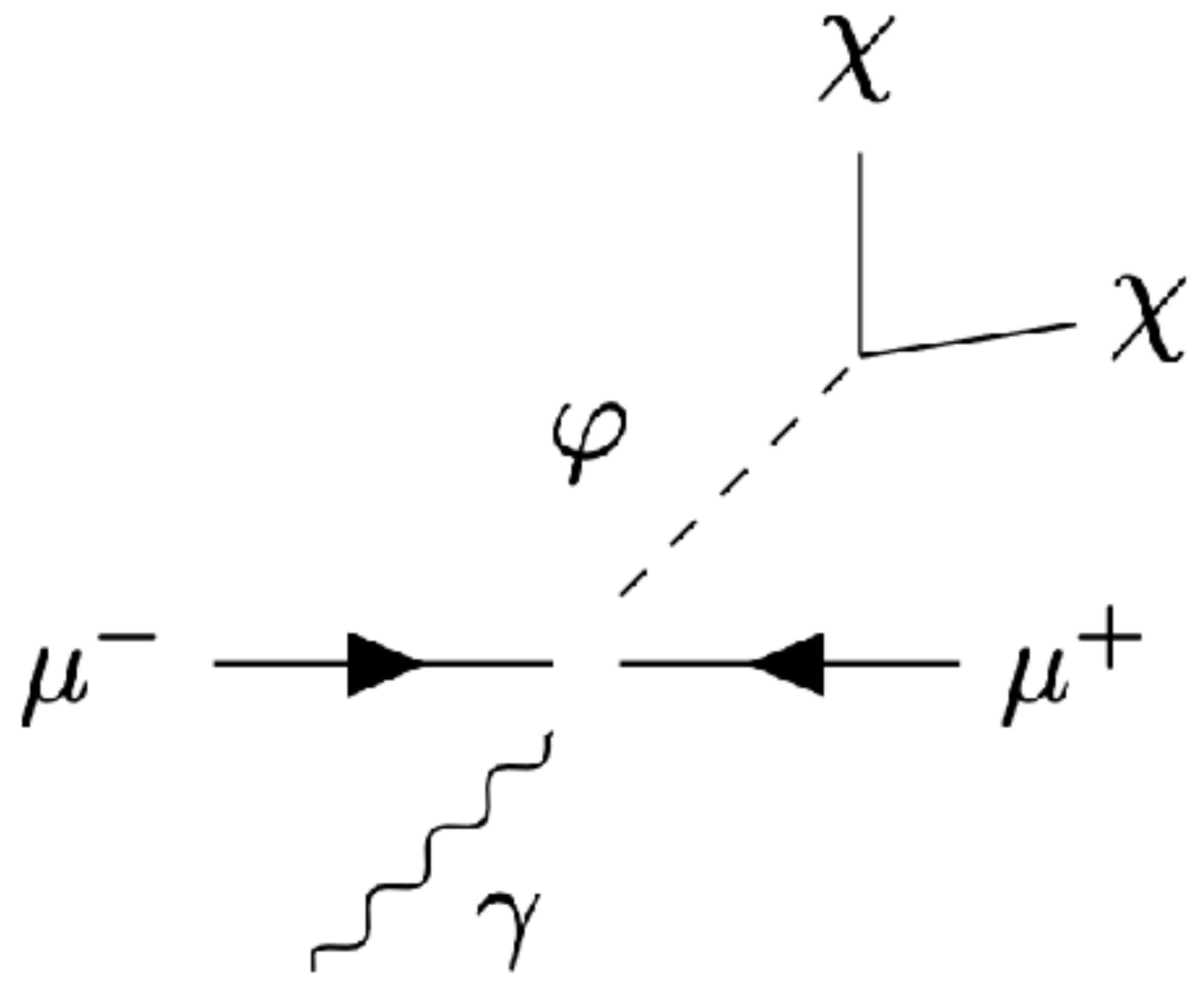
$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi\sum_{l=e,\mu,\tau} g_l l\bar{l}$$

Mono-X Search

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

$$E_\gamma \sim \sqrt{s}/2$$





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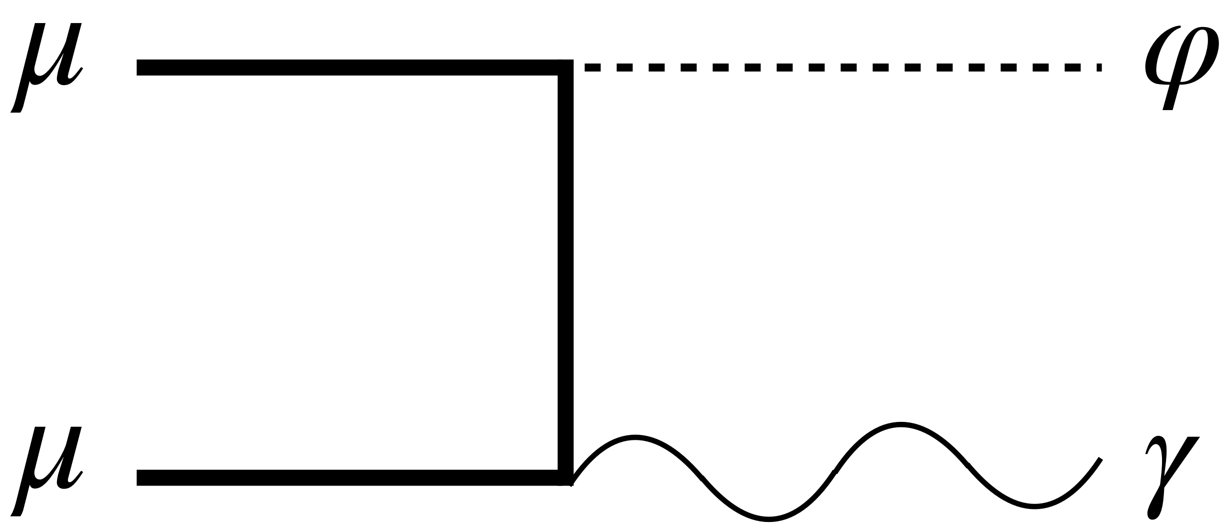
$$\mu^+\mu^- \to \varphi\gamma$$

$$E_\gamma \sim \sqrt{s}/2$$



$$\sqrt{s} = 3,\ 10\ \text{TeV}$$

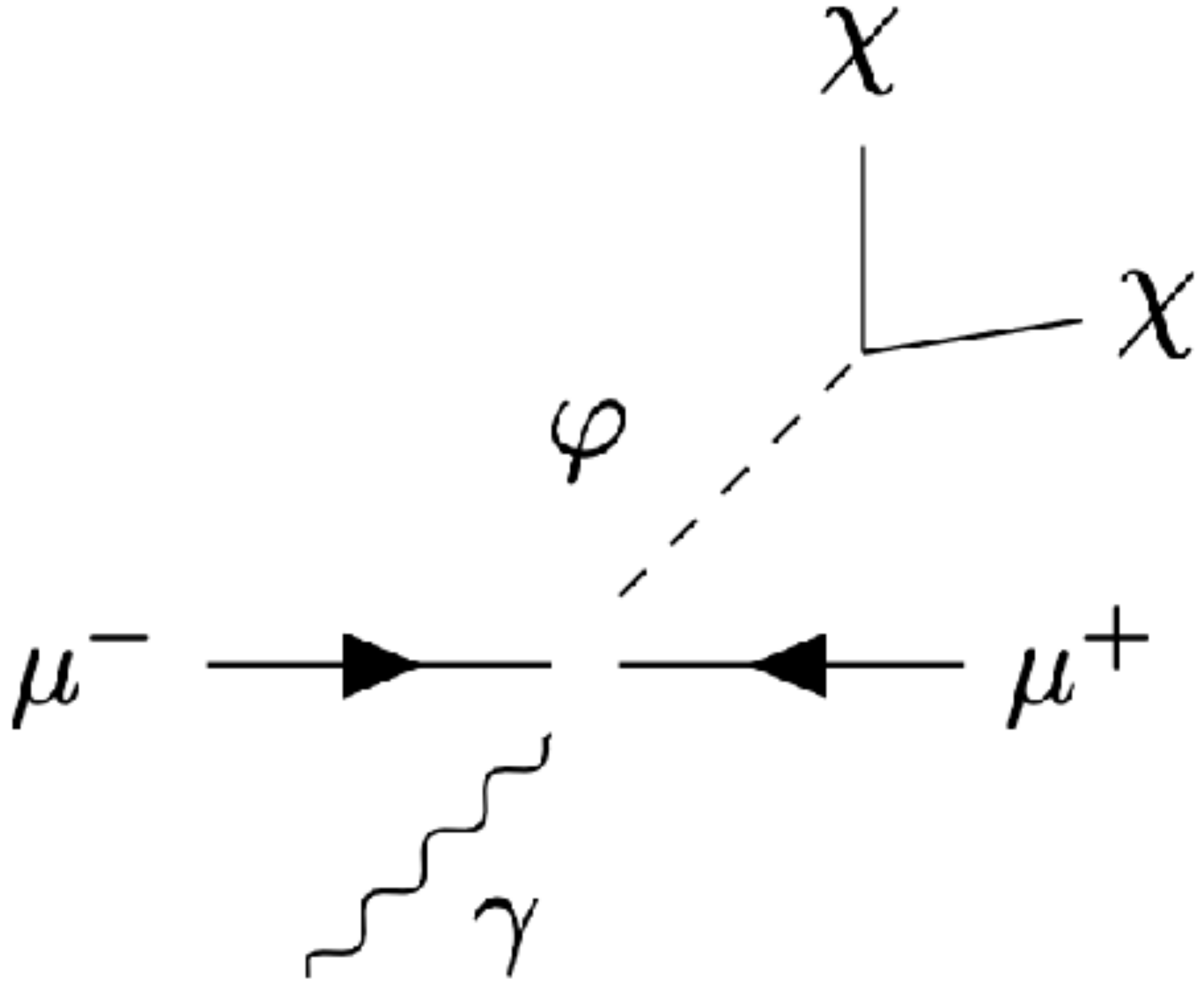
$$\sigma_E = 3\%$$

$$\mathscr{L} = 1,\ 10\ \text{ab}^{-1}$$

$$|\eta| < 2.5$$

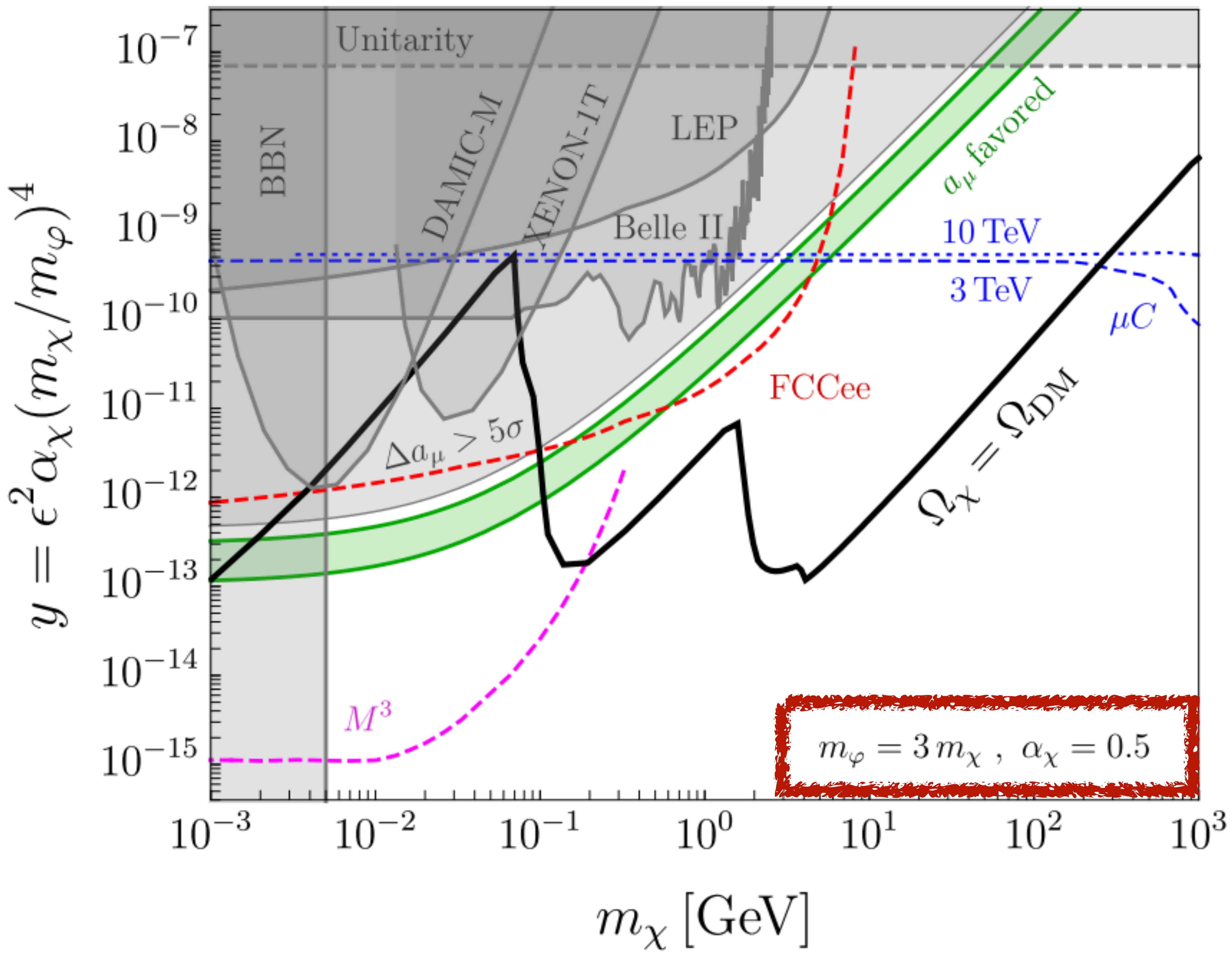
Primary Background:

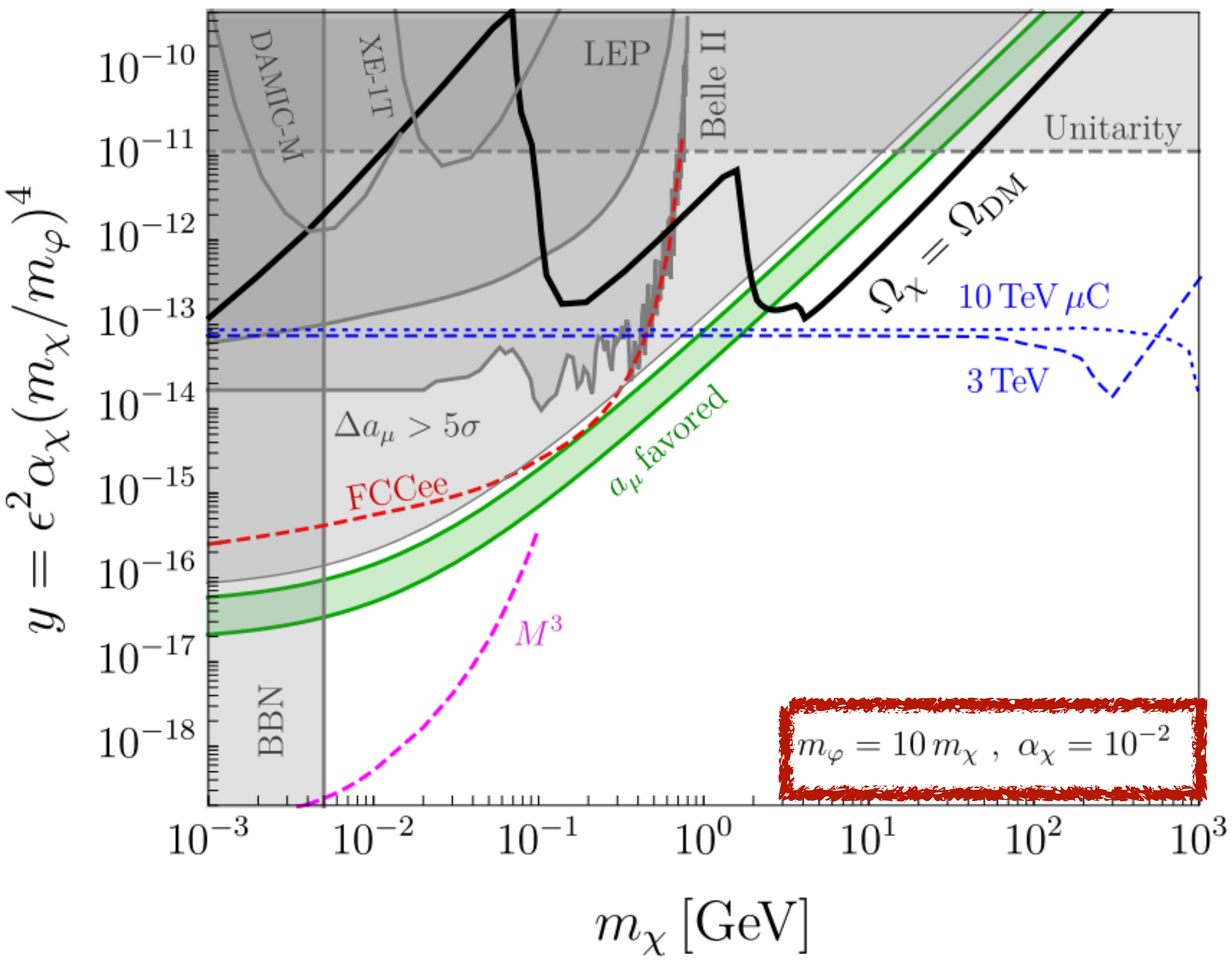
$$\mu^+\mu^- \to \nu\bar{\nu}\gamma$$



Leptophilic Dark Matter

FCCee & MuC probe *complementary* regions





CC, Krnjaic '24

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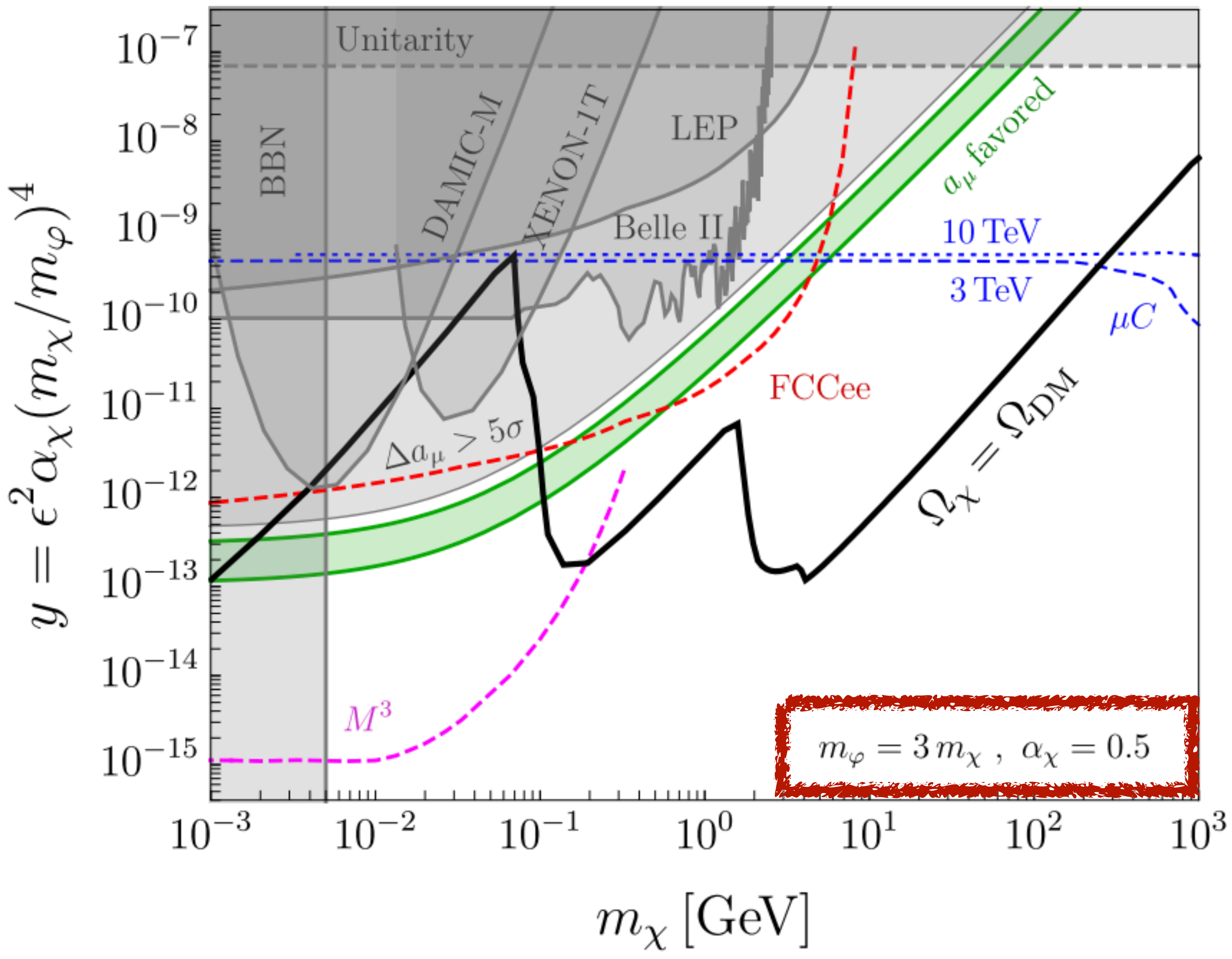
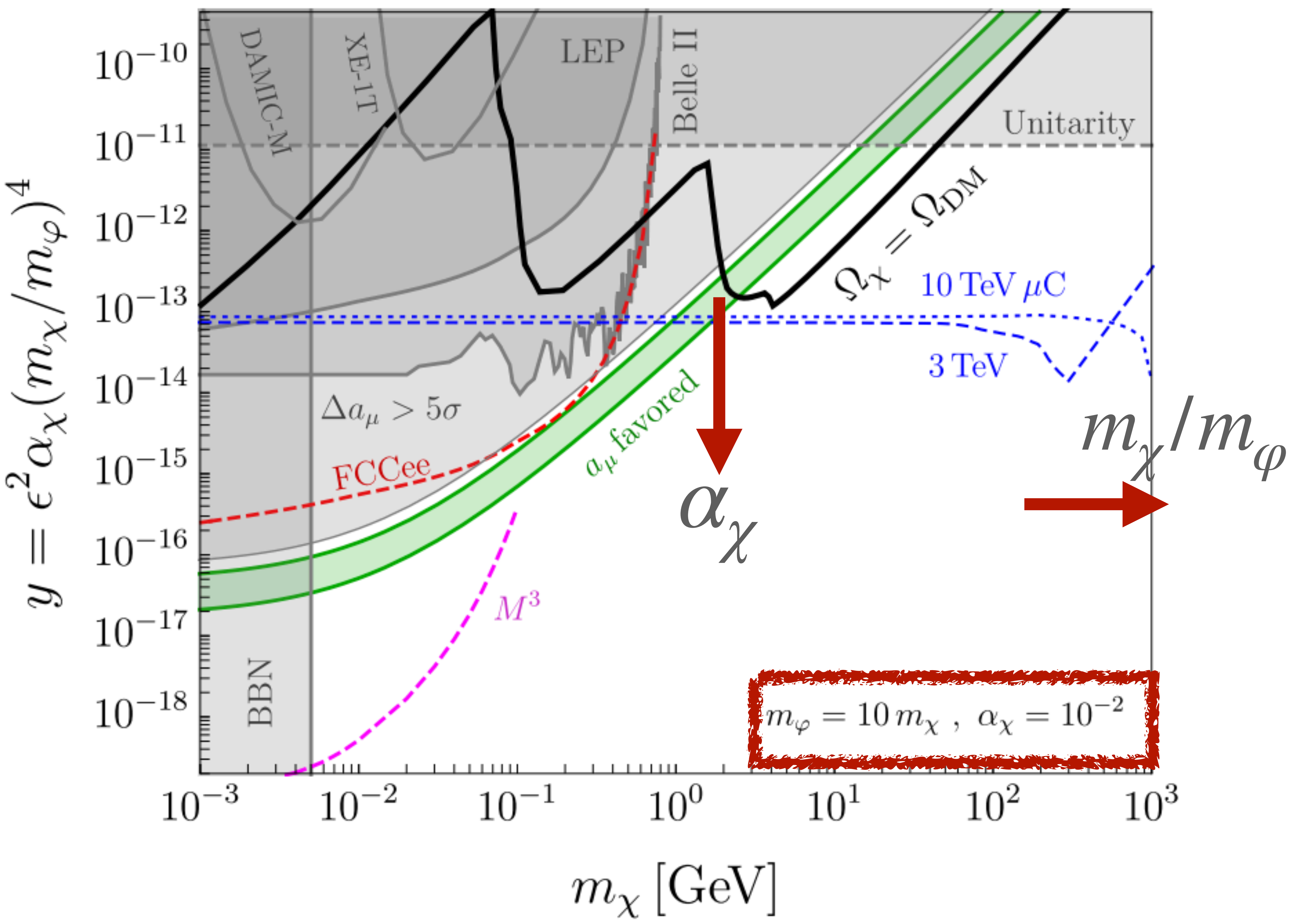




Models of Dark Matter

Which are most motivated for colliders

WIMP Scenario

Higgs Portal

Thermal DM

Dark Sector

Dark Sector Portals

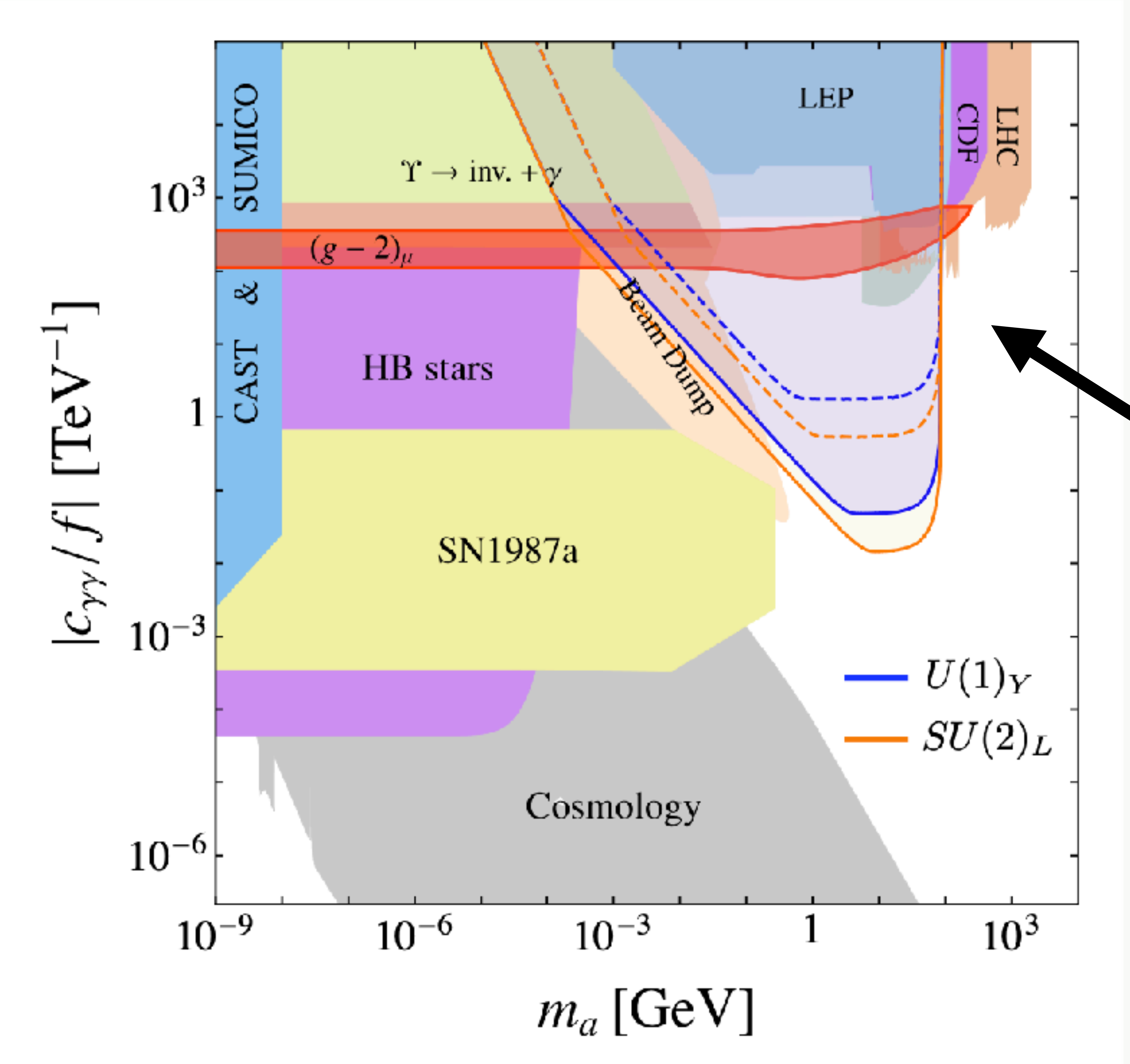
$\tau \ll 1$s from BBN constraints

Can be prompt, DV, or stable

Cesarotti

Dark Sector Portals

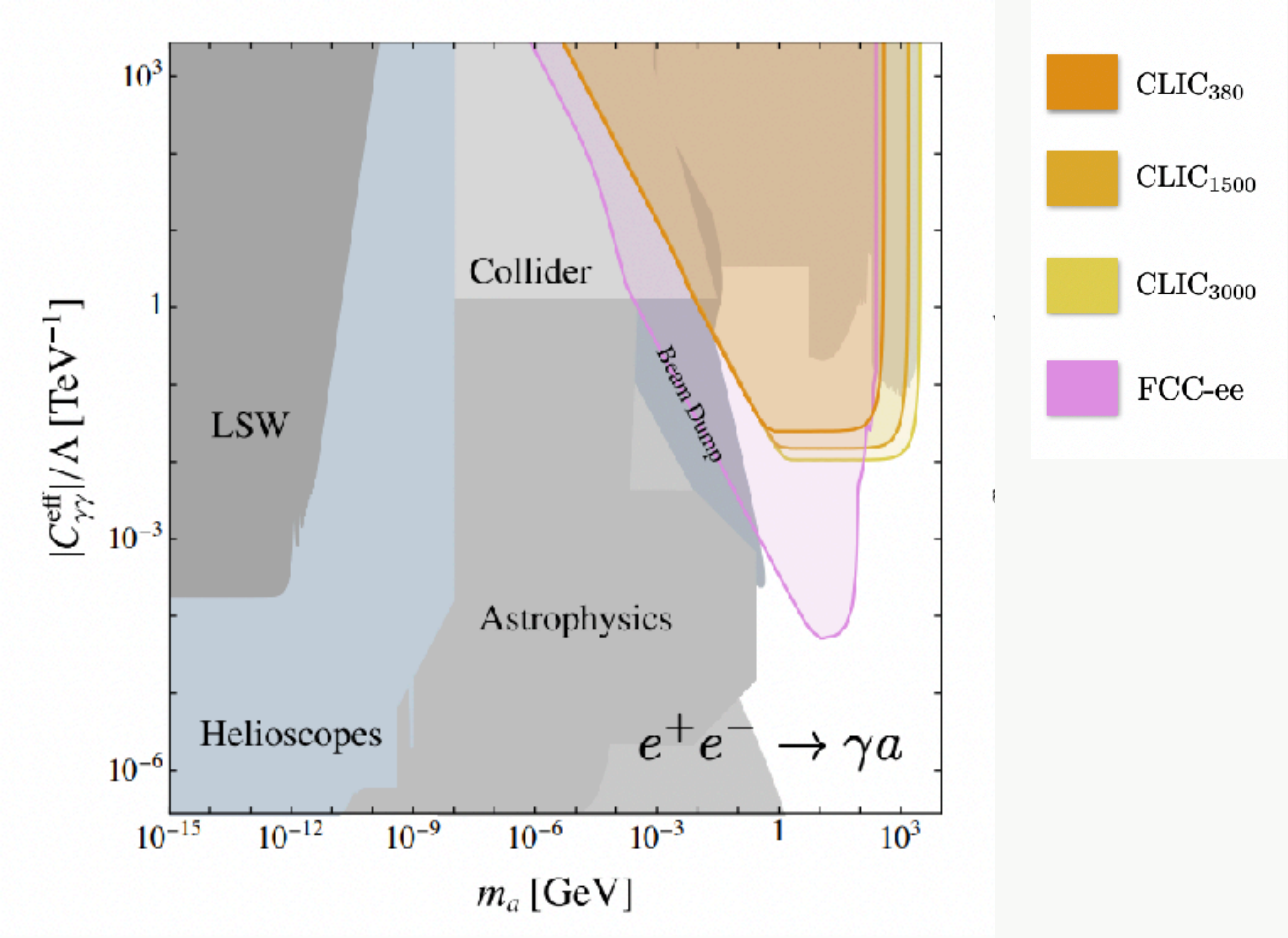
(These and many more)



ALP at FCC-ee

$e^+e^- \to Z$ Utilizing *Tera-Z* run

$Z \to a\gamma \qquad a \to \gamma\gamma$



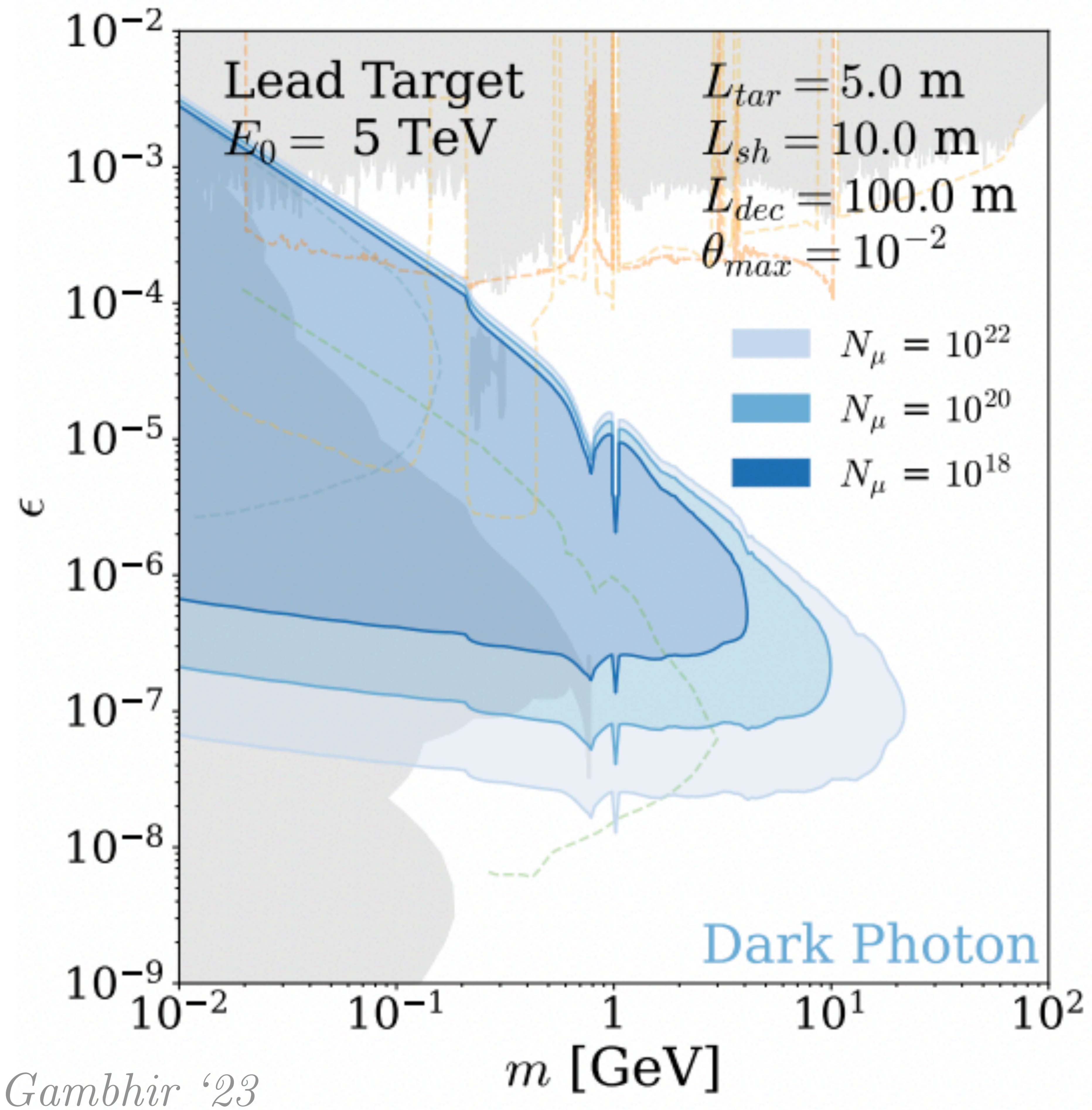
M. Bauer, M. Heiles, M. Neubert, A. Thamm '18

Cesarotti

Dark Sector Portals

(These and many more)

Dark Photon Z' at MuC beam dump



CC, R. Gambhir '23

Life time of Z'

$$l_{\rm NP} = \gamma\tau_0 \approx \frac{E_0}{m_{\rm NP}} \times \frac{1}{g^2 m_{\rm NP}}$$

$$\approx \left(\frac{E_0}{\rm TeV}\right) \times \left(\frac{g}{10^{-6}}\right)^{-2} \times \left(\frac{m_{\rm NP}}{10\ \rm MeV}\right)^{-2} \times 100\rm m$$

Use as an *auxiliary* experiment

Higher energy → larger γ → smaller ϵ

Conclusions

WIMPs are *motivated* models for *known unknowns* accessible at colliders — we can probe only with *high-energy machines*

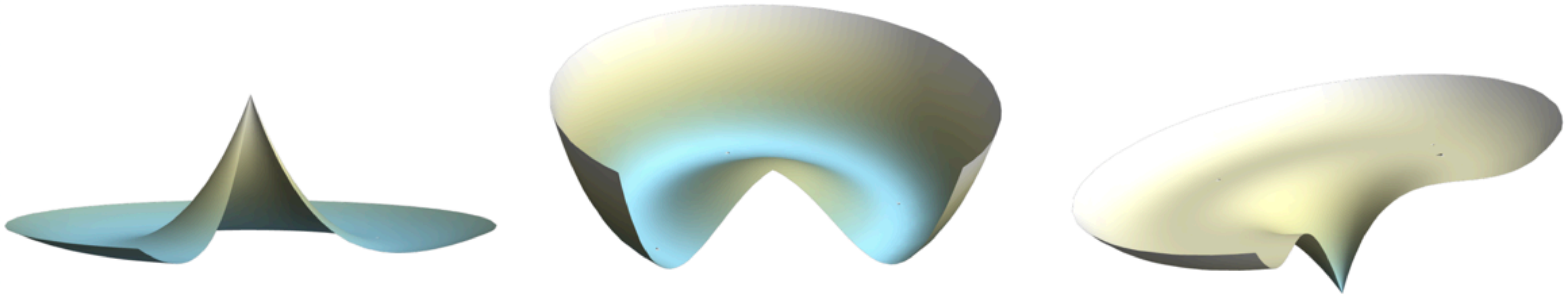
Detector design has influence on physics reach
Theory informs physics of interest

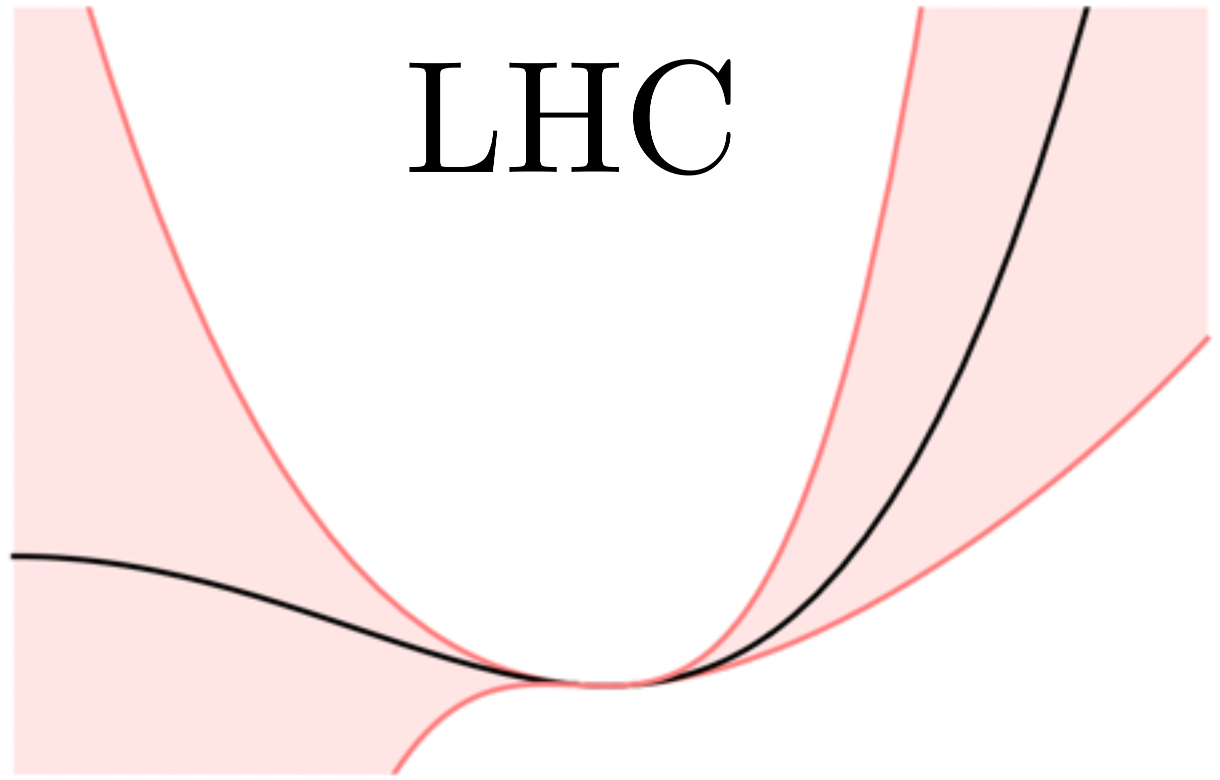
} Why theoretical studies should be done *now*

Different future colliders are complements to each other

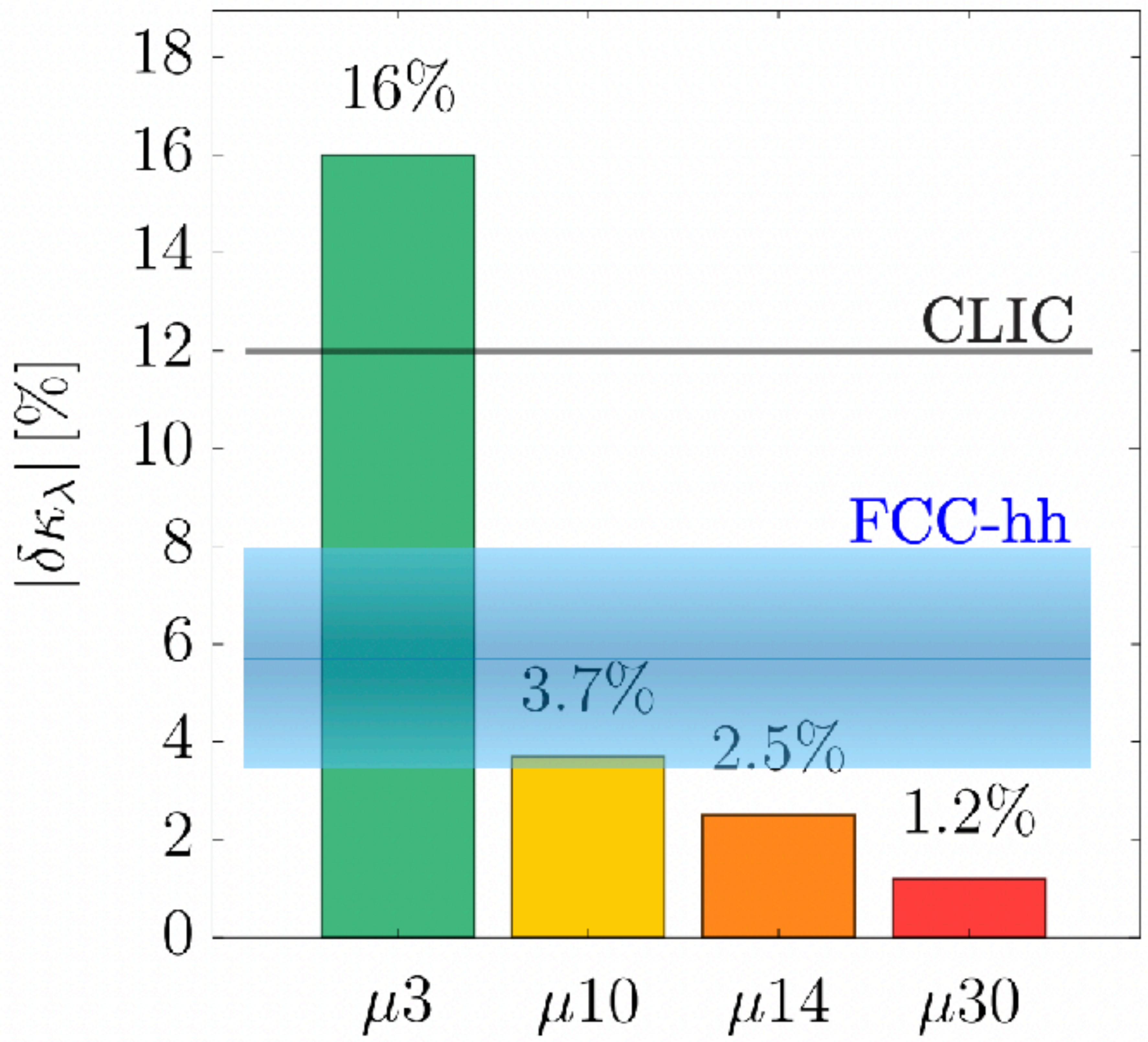
Backups

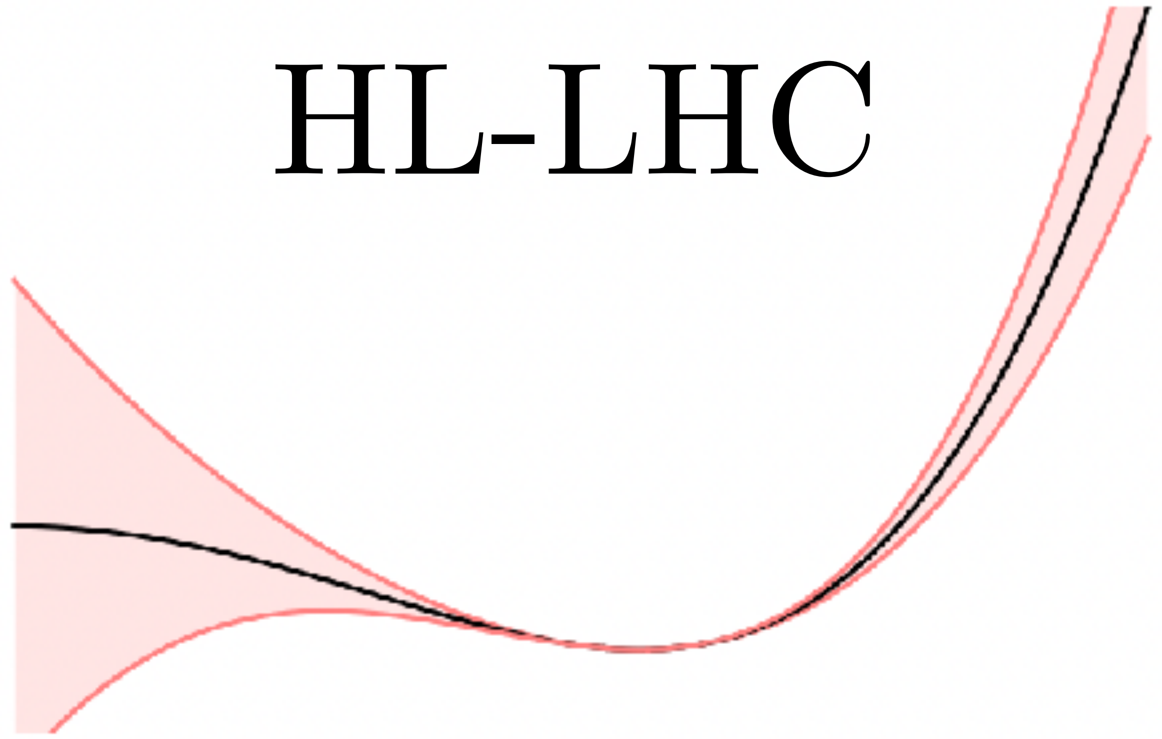
Higgs Potential

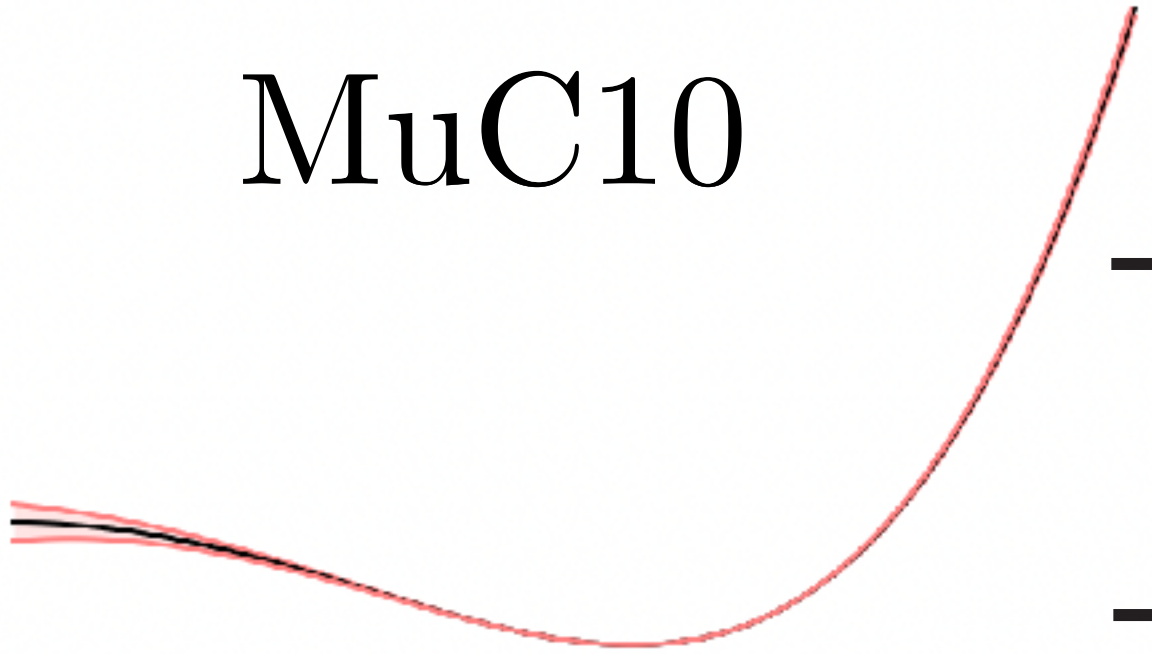


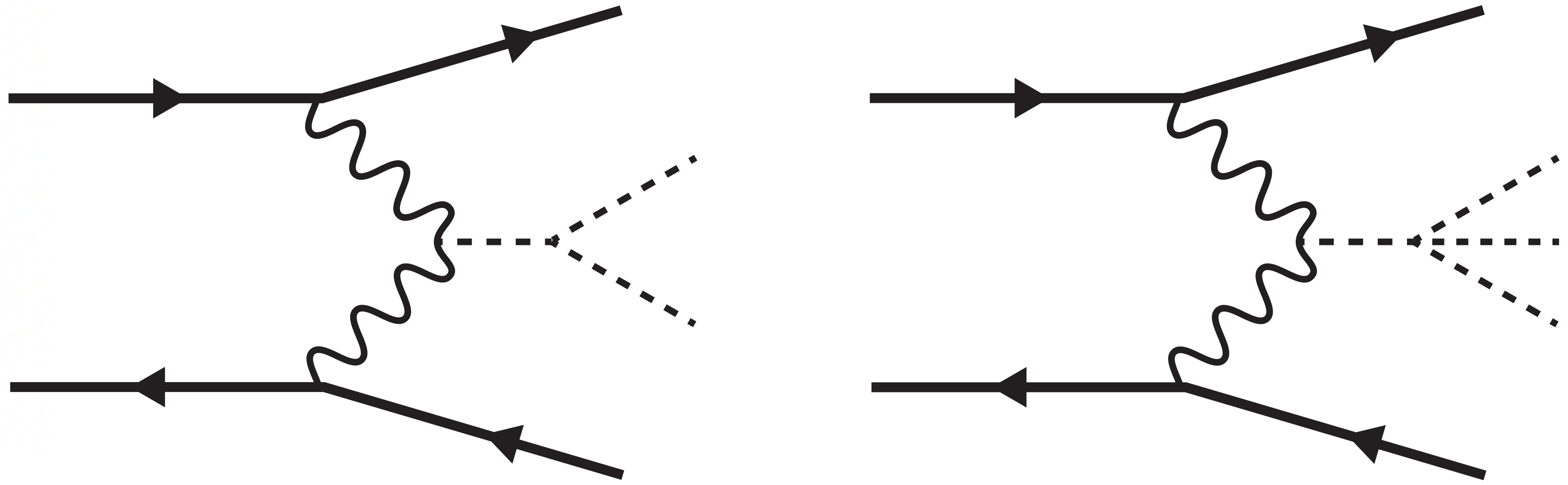


Towards a Muon Collider 23



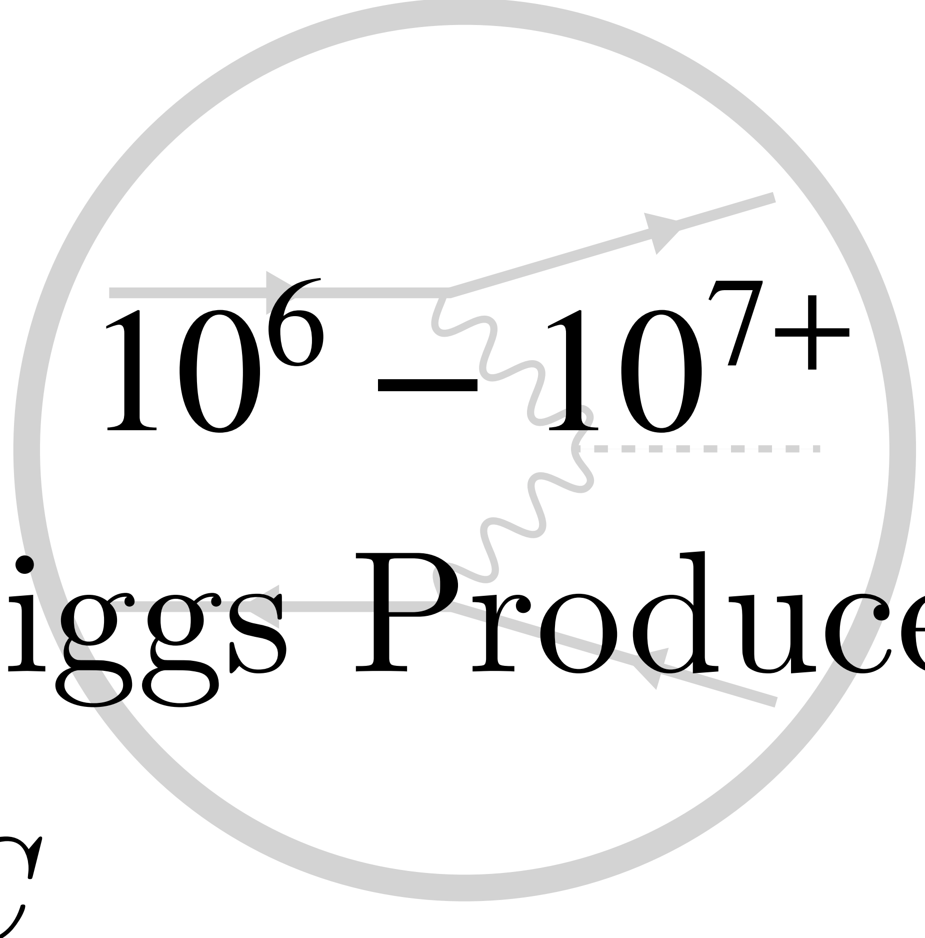






Cesarotti

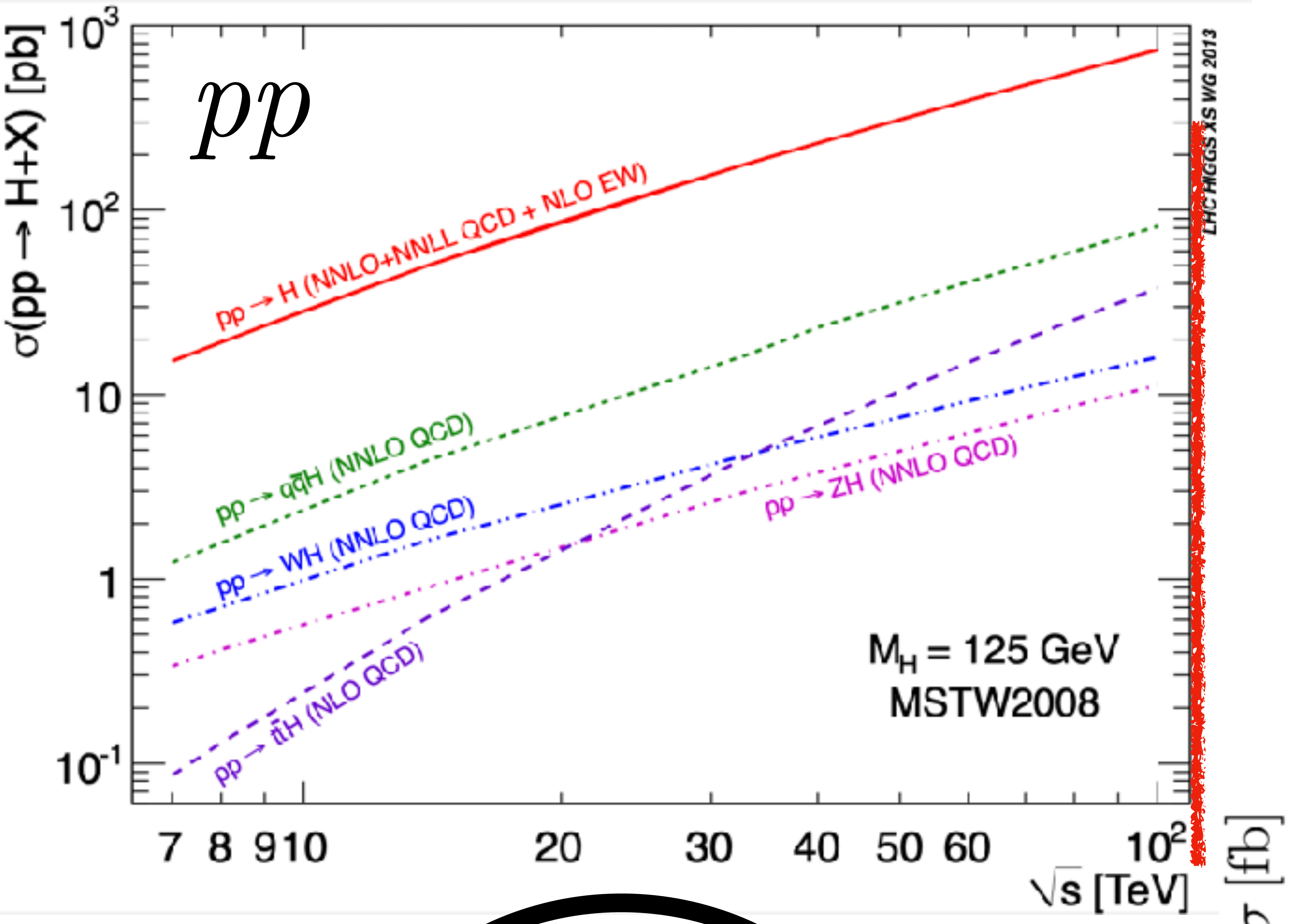
Higgs Production

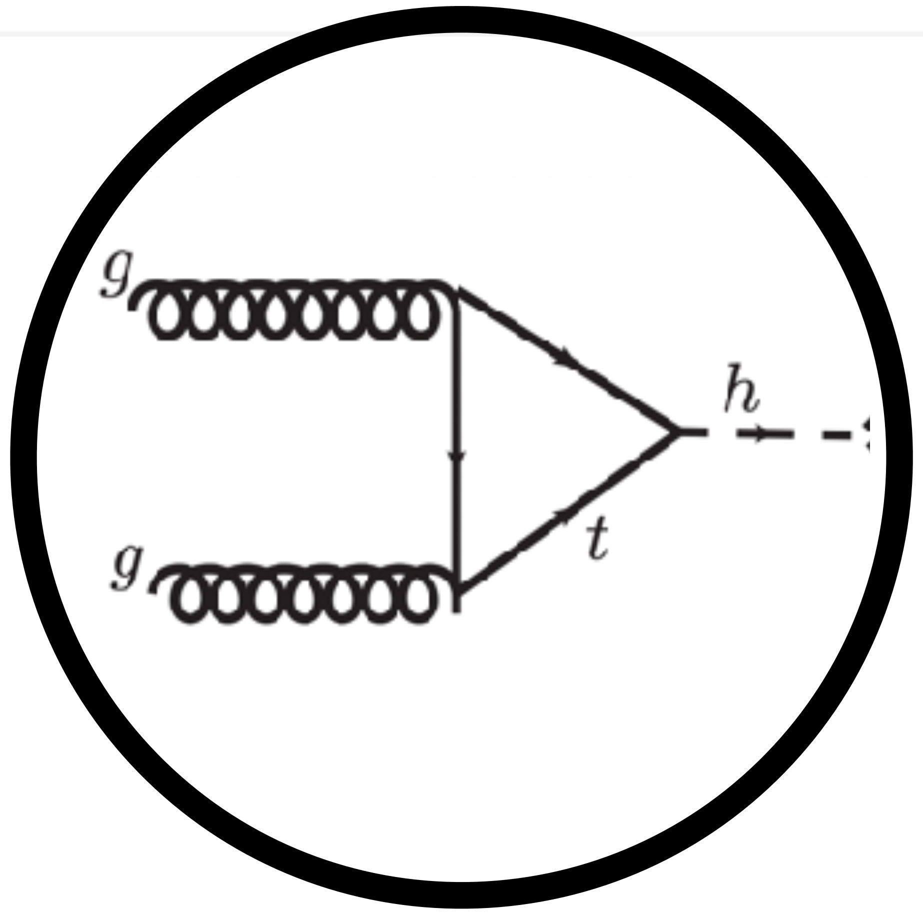


$10^6 - 10^{7+}$

Higgs Produced

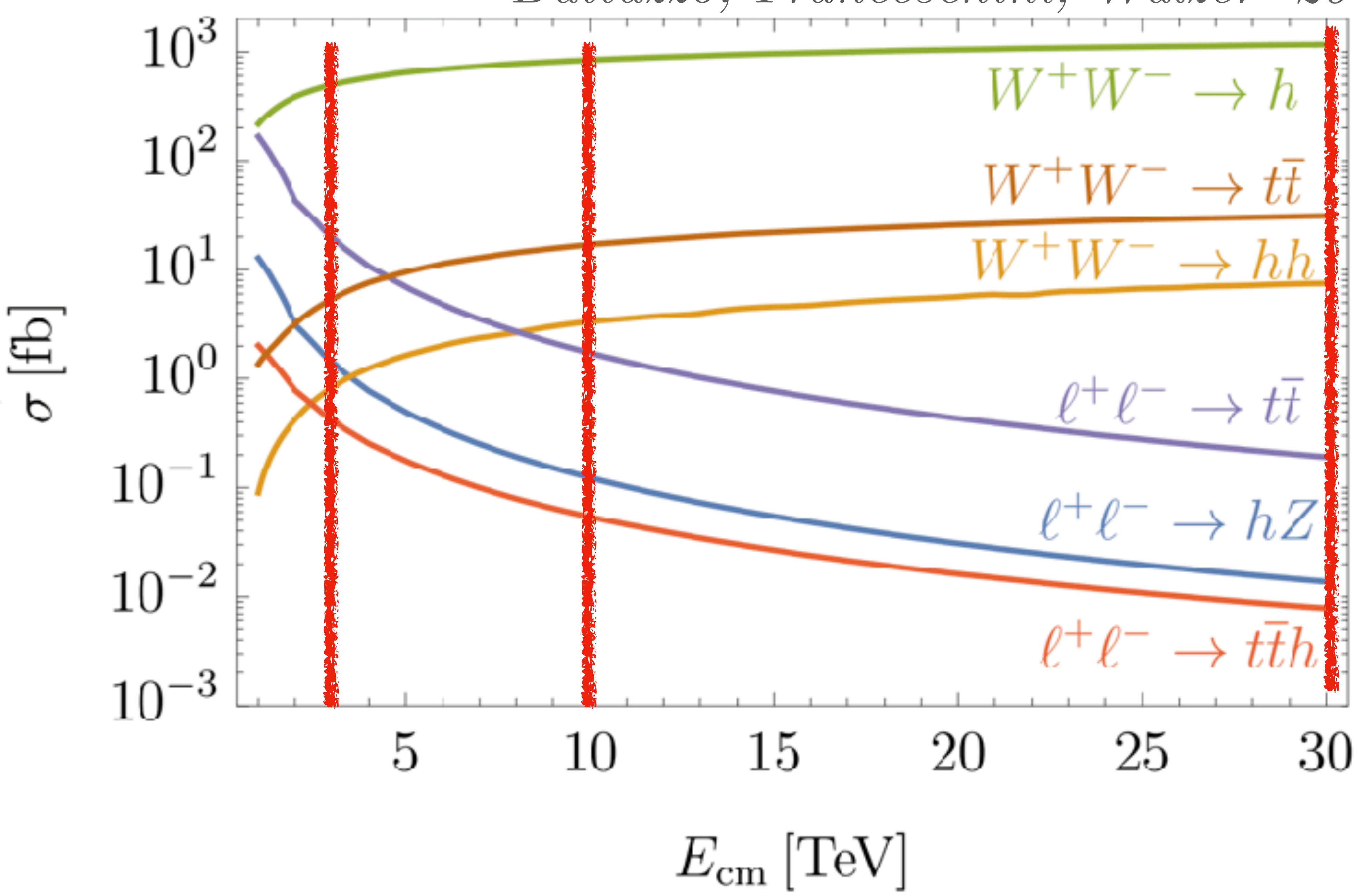
LHC HIGGS WG





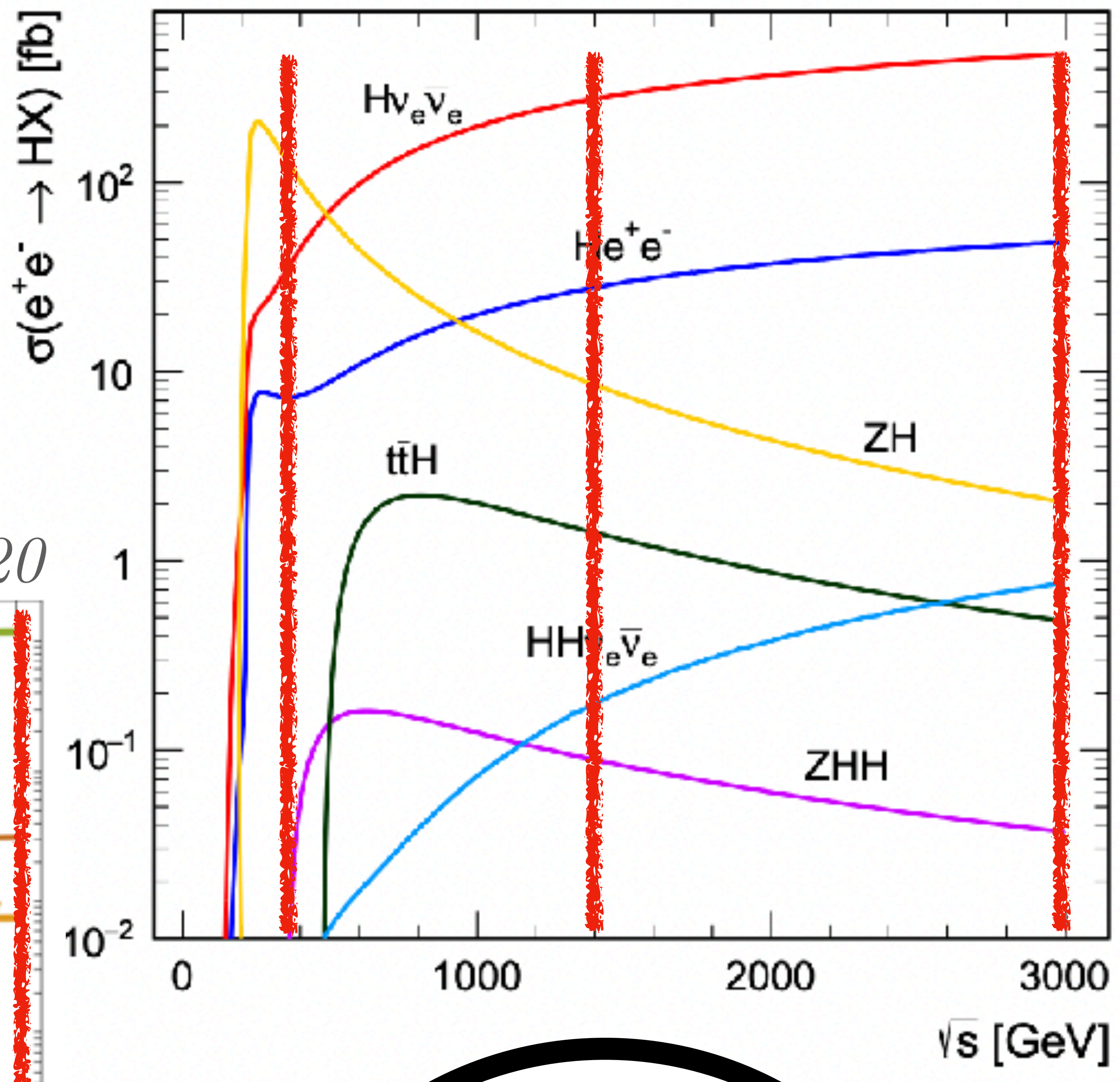
MuC

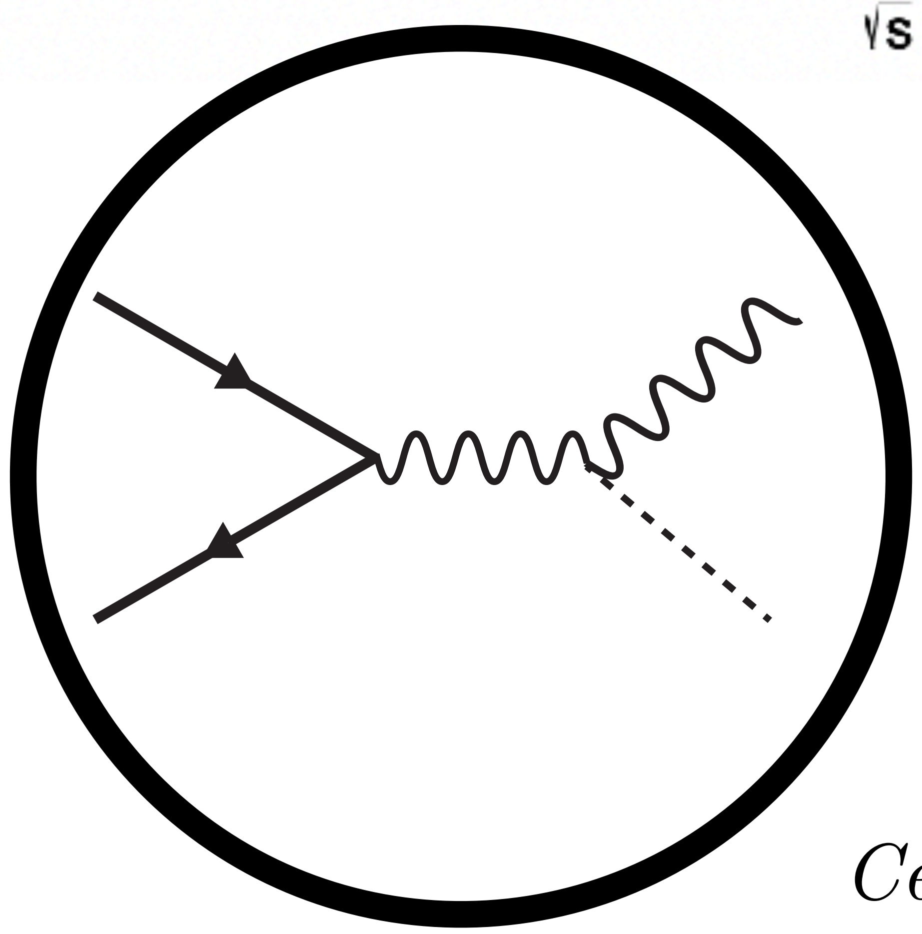
Buttazzo, Franceschini, Wulzer '20



CLiC Summary Report

e^+e^-

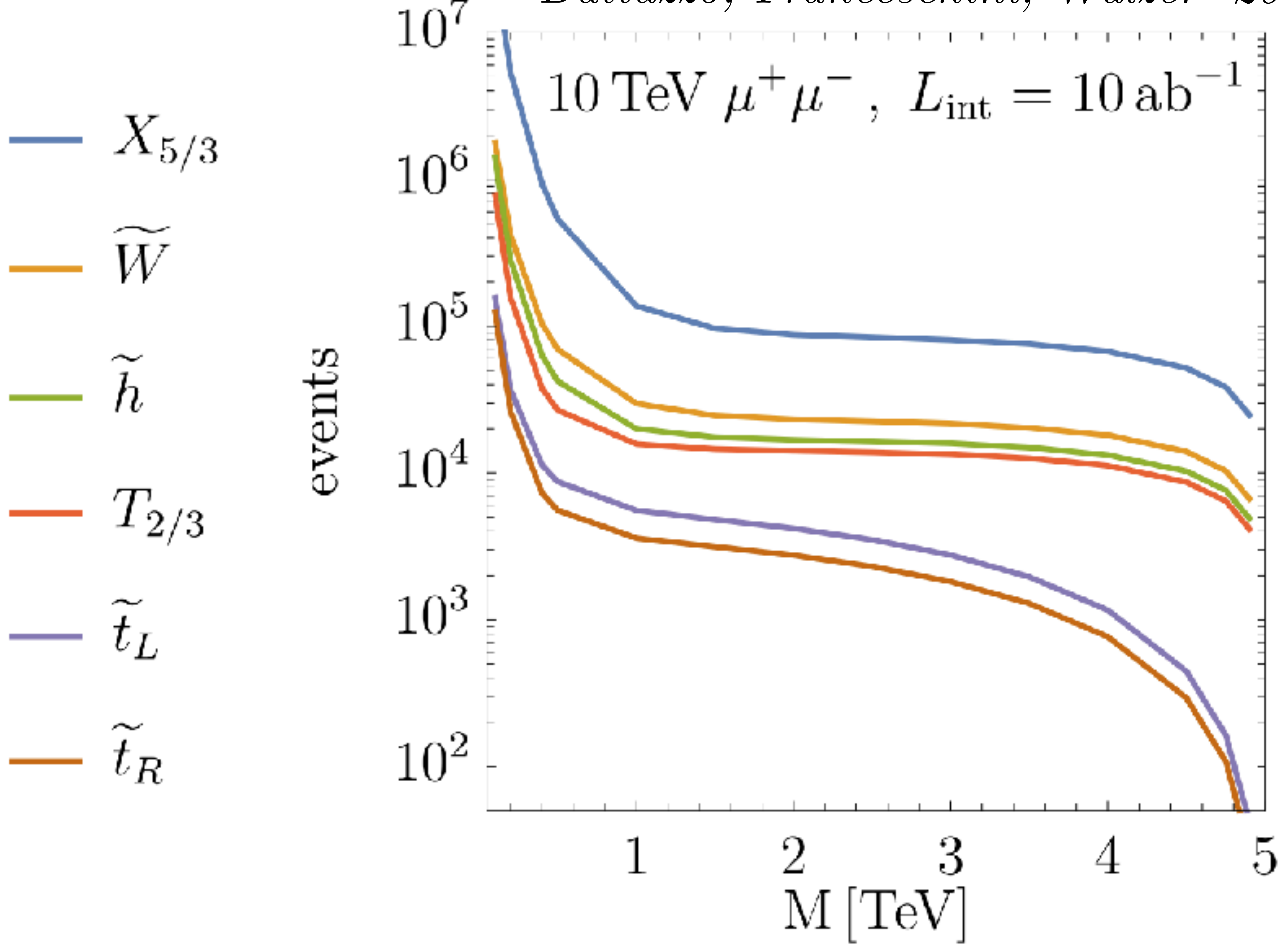




Cesarotti

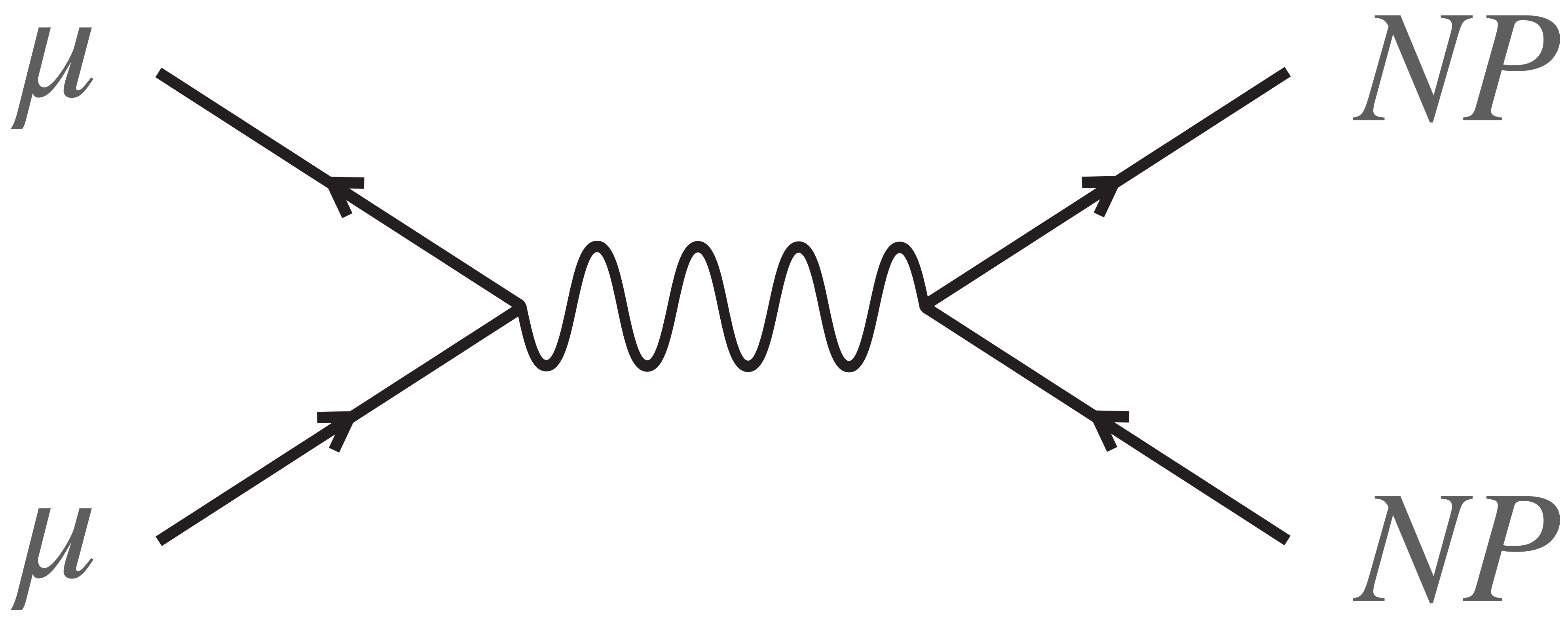
Ex: Generic Direct Production

Buttazzo, Franceschini, Wulzer '20



$$m_{NP} \sim \sqrt{s}/2$$

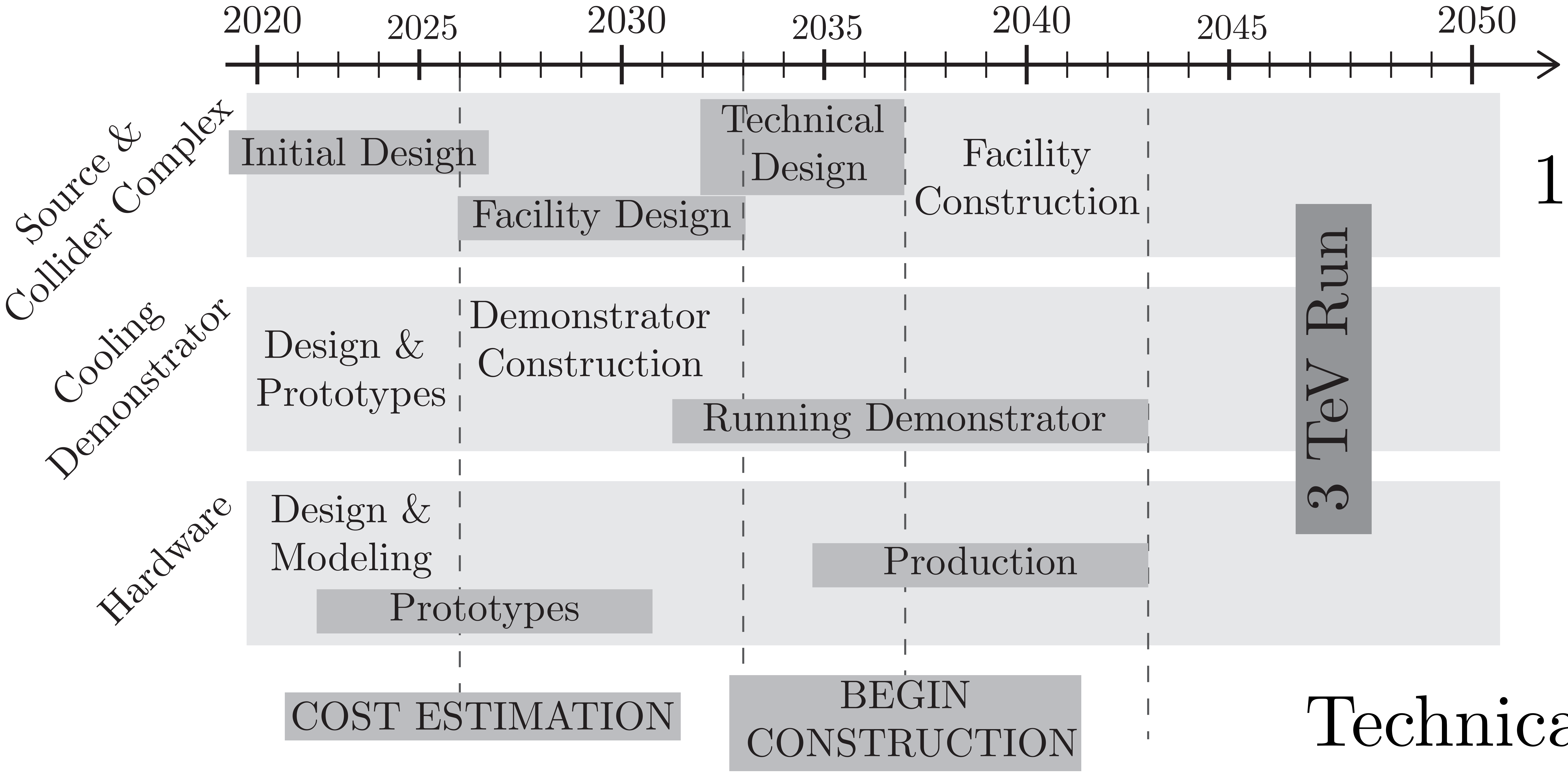
$$\mathscr{L} \sim \frac{N_\mu}{\text{bunch}} \times E^2$$



Sensitivity is maintained up to kinematic thresholds

Cesarotti

Muon Collider Timescales



2055:
10 TeV Run?

Technically Limited Timeline*

Comparison of Colliders

pp

Composite

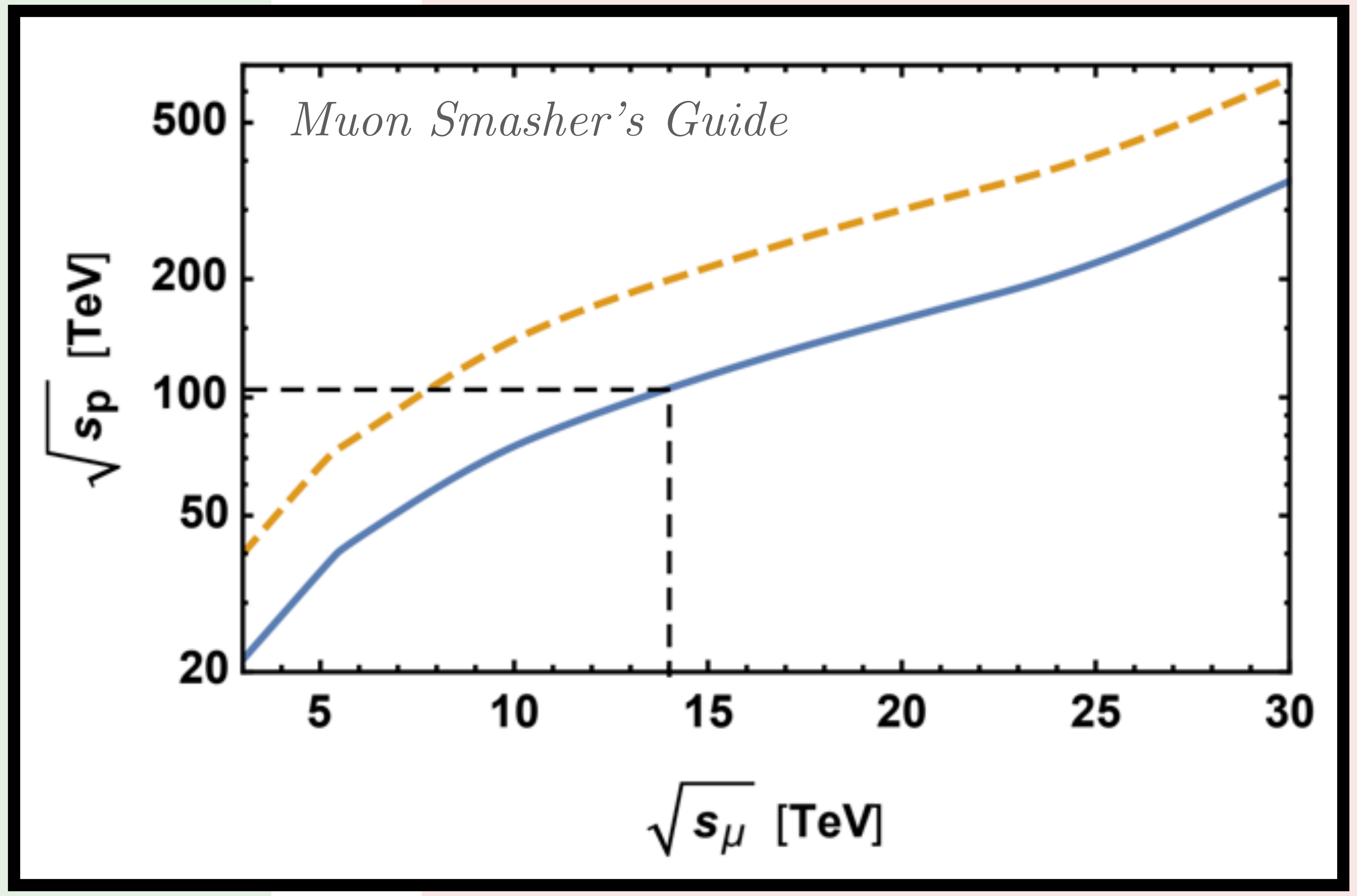
$\sqrt{\hat{s}} \ll \sqrt{s}$ *

$\mu^+\mu^-$

Fundamental

$\sqrt{\hat{s}} \sim \sqrt{s}$

e^+e^-



Cesarotti

Comparison of Colliders

pp

Composite

$\sqrt{\hat{s}} \ll \sqrt{s}$ *

$\mu^+\mu^-$

Fundamental

$\sqrt{\hat{s}} \sim \sqrt{s}$

$$P \propto \gamma^4 = \left(\frac{E}{m}\right)^4$$

$$P_\mu / P_e \sim 10^{-9}$$

$\mathcal{O}(1 - 100?)$ TeV

e^+e^-

$\mathcal{O}(100 - 300)$ GeV

Cesarotti

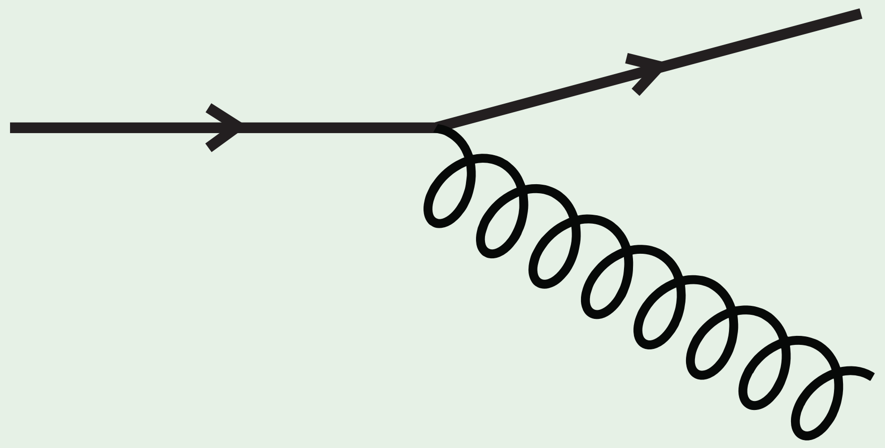
Comparison of Colliders

pp

Composite

$\sqrt{\hat{s}} \ll \sqrt{s}$ *

QCD



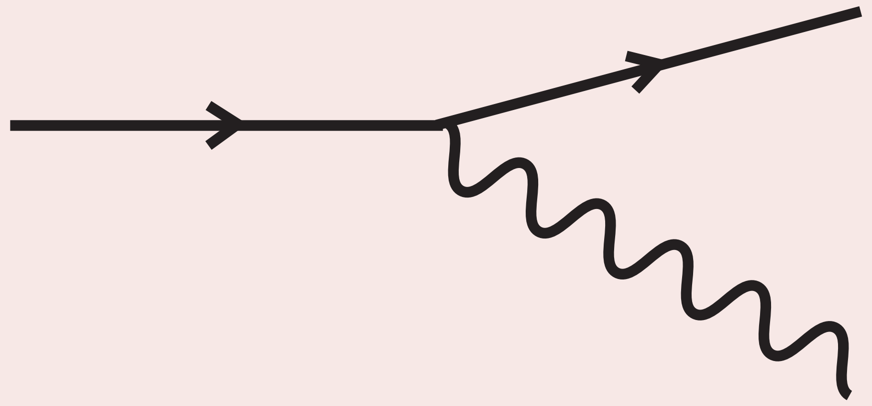
$\mu^+\mu^-$

Fundamental

$\sqrt{\hat{s}} \sim \sqrt{s}$

$\mathcal{O}(1-100?)$ TeV

Electroweak



e^+e^-

$\mathcal{O}(100-300)$ GeV

Cesarotti

Future Collider Timescales

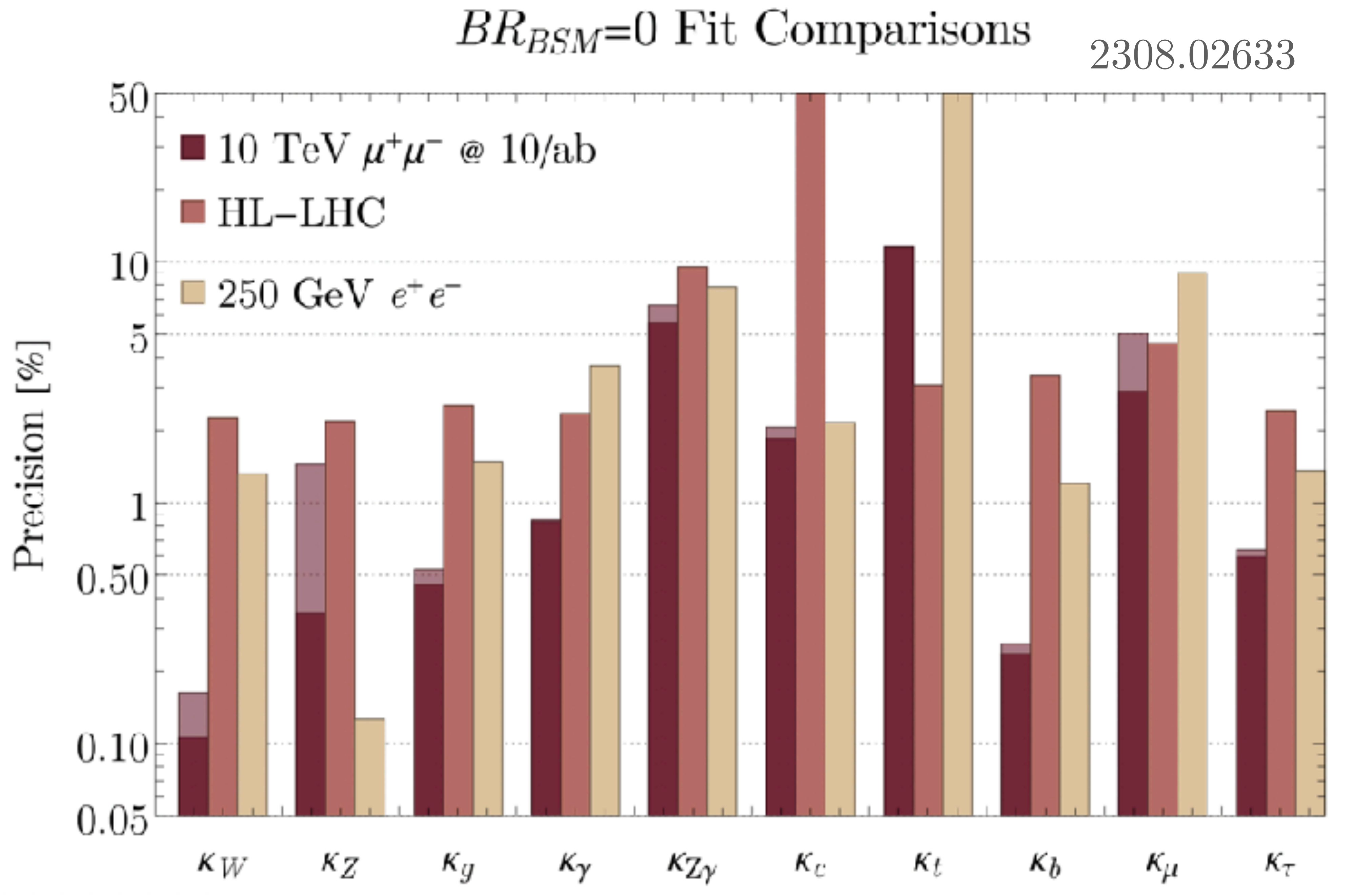
Higgs Couplings

Consider precision in κ framework

$10^6 - 10^{7+}$ Higgs Produced

1905.03764 2308.02633

κ-0 fit	HL-LHC	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ 10000
κ_W [%]	1.7	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.06
κ_Z [%]	1.5	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.23
κ_g [%]	2.3	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.15
κ_γ [%]	1.9	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	1.0
κ_c [%]	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	0.89
κ_t [%]	3.3	–	6.9	1.6	–	–	2.7	–	–	–	1.0	6.0
κ_b [%]	3.6	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.16
κ_μ [%]	4.6	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.0
κ_τ [%]	1.9	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.31



Scenario	BR_{inv}
kappa-0	fixed at 0

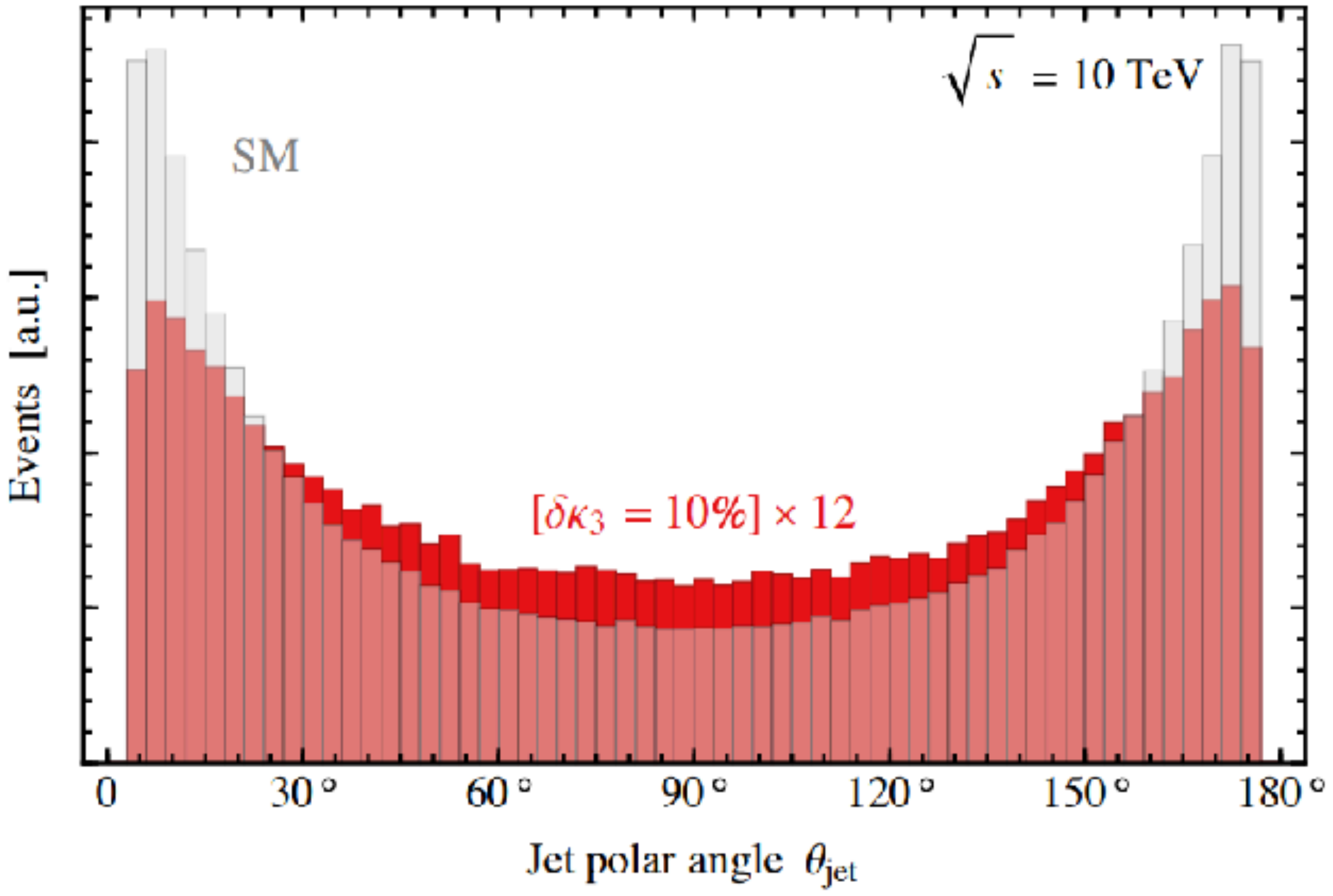
Meade & Forslund

Slide Credit: D Buttazzo

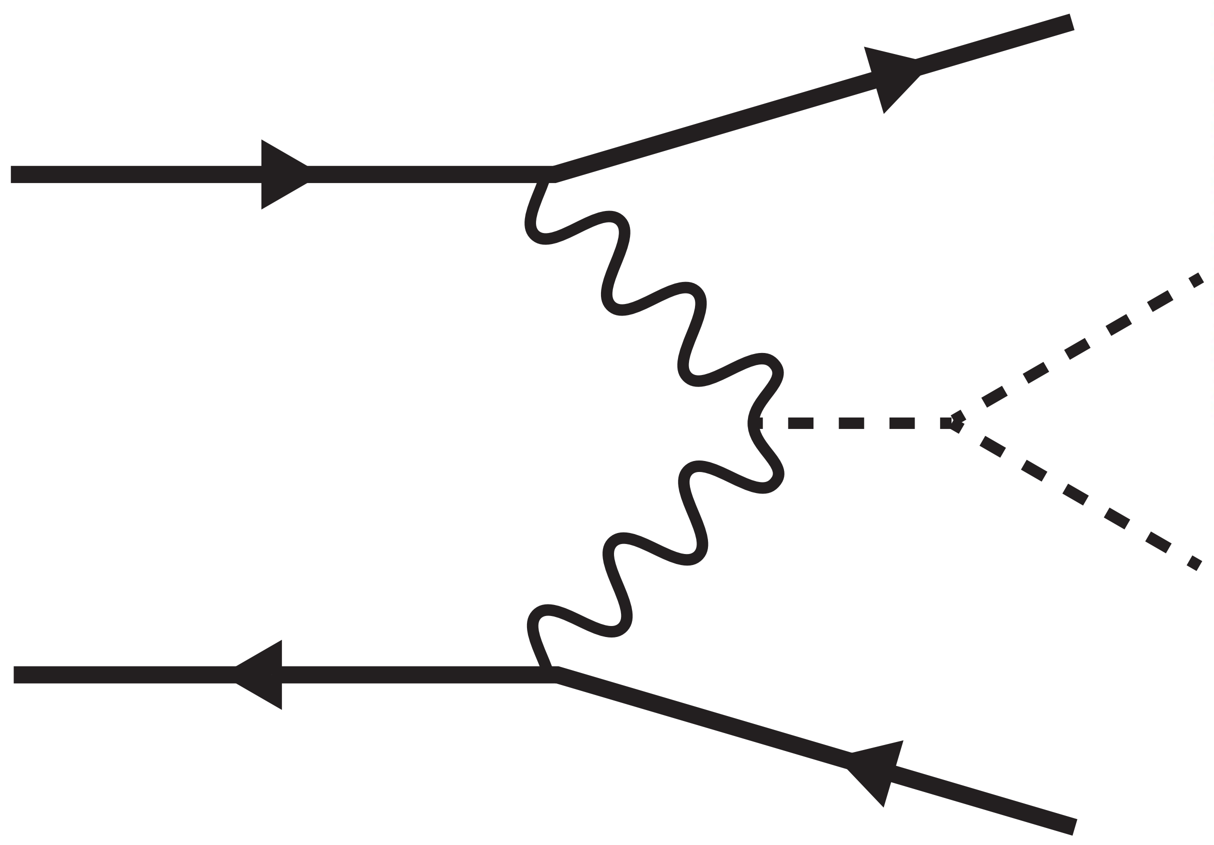
Higgs Potential

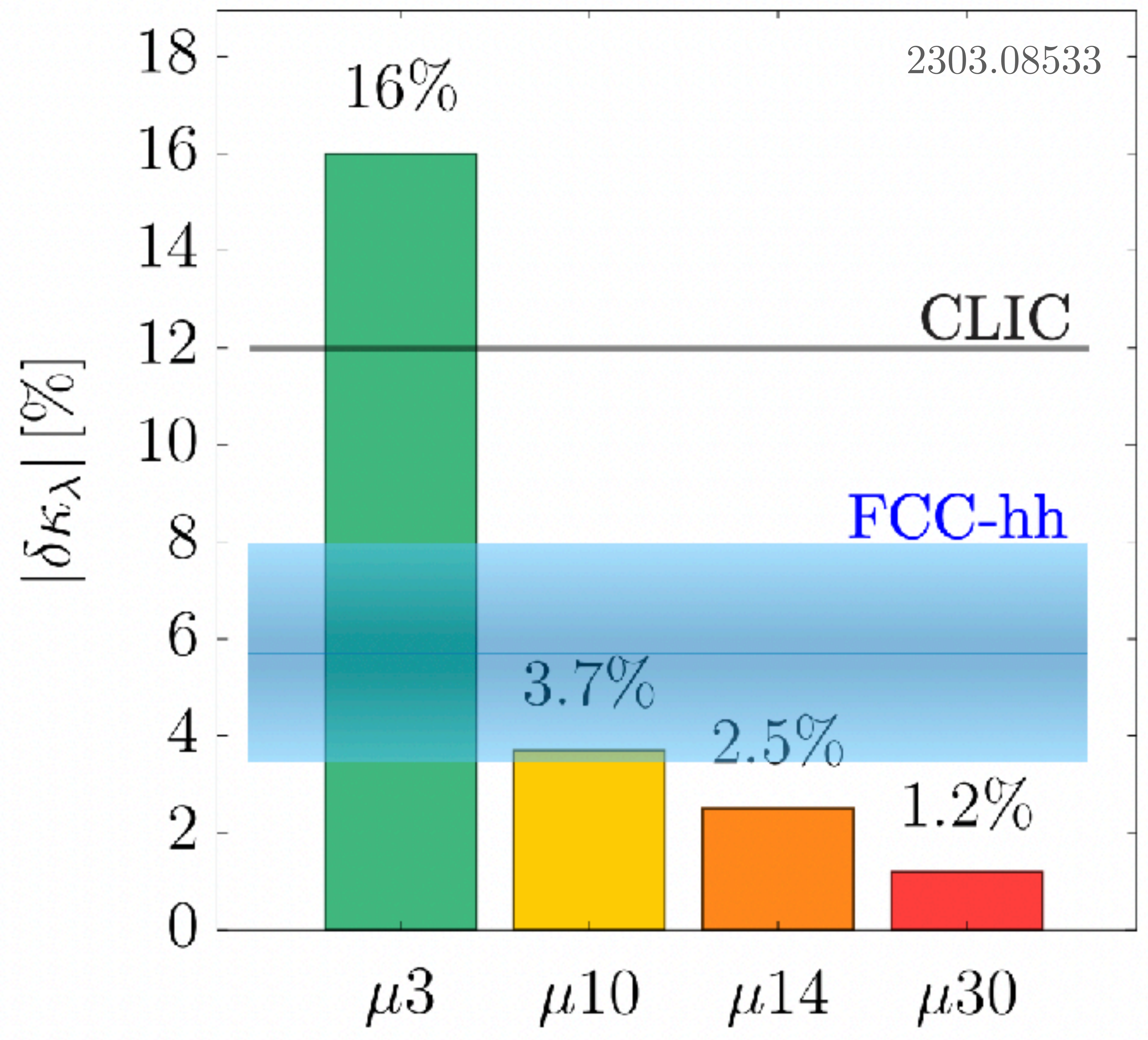
E [TeV]	$\mathscr{L}$ [ab^{-1}]	N_{rec}	$\delta\kappa_3$
3	5	170	~ 10%
10	10	620	~ 4%
14	20	1340	~ 2.5%
30	90	6'300	~ 1.2%

Central region to cut out BiB



$hh \to 4b$





Buttazzo, Franceschini, Wulzer 2012.11555,
Han et al. 2008.12204, Costantini et al. 2005.10289

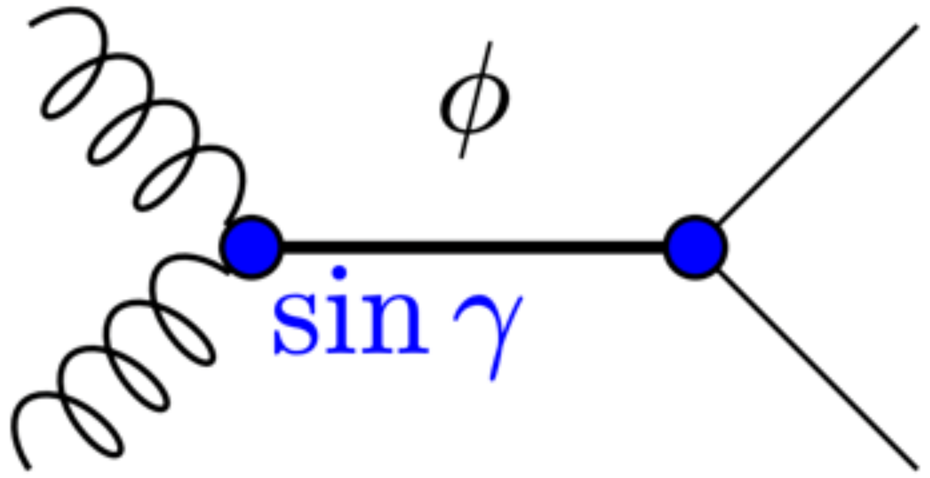
Ex: New Physics with Higgs Mixing

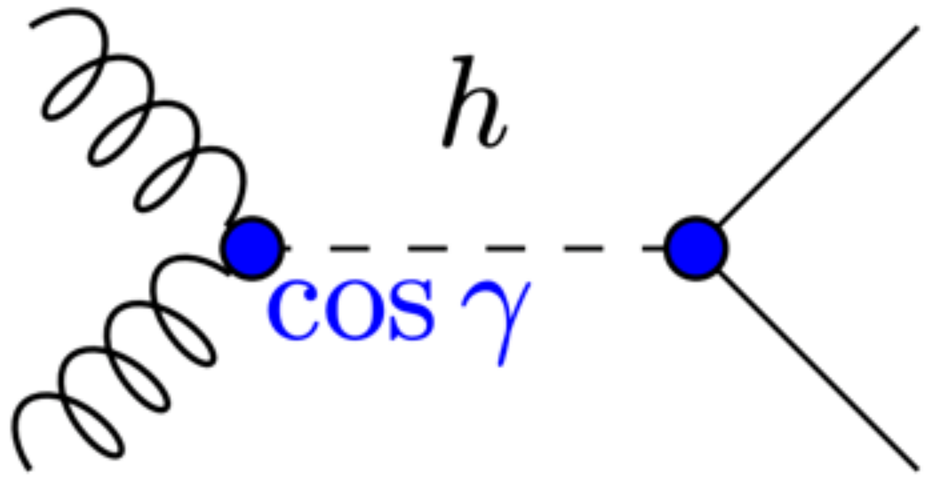
Benchmark model: New singlet S mixes with Higgs

$$h = h_0 \cos\gamma + S \sin\gamma$$

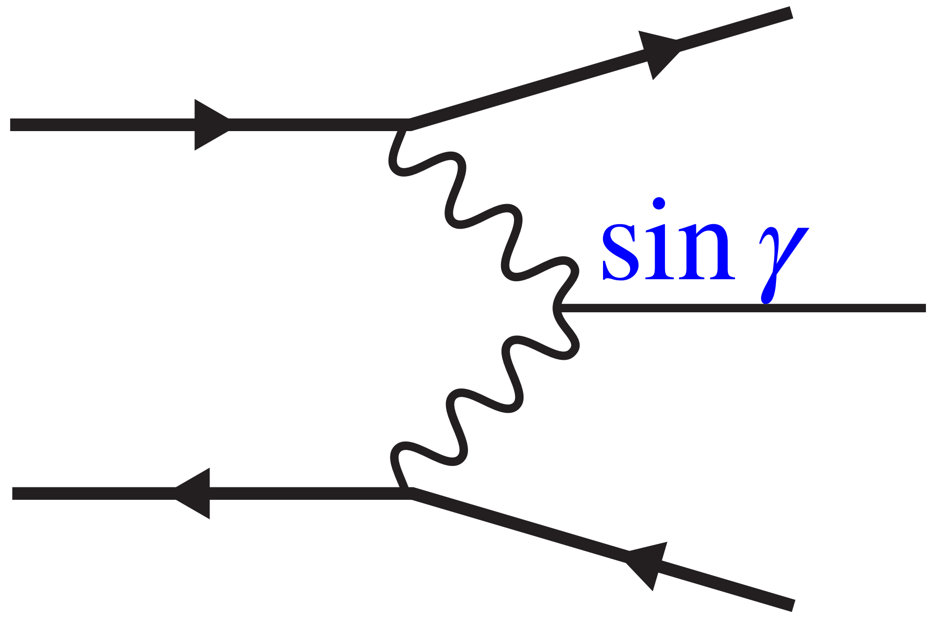
$$\phi = S \cos\gamma - h_0 \sin\gamma$$

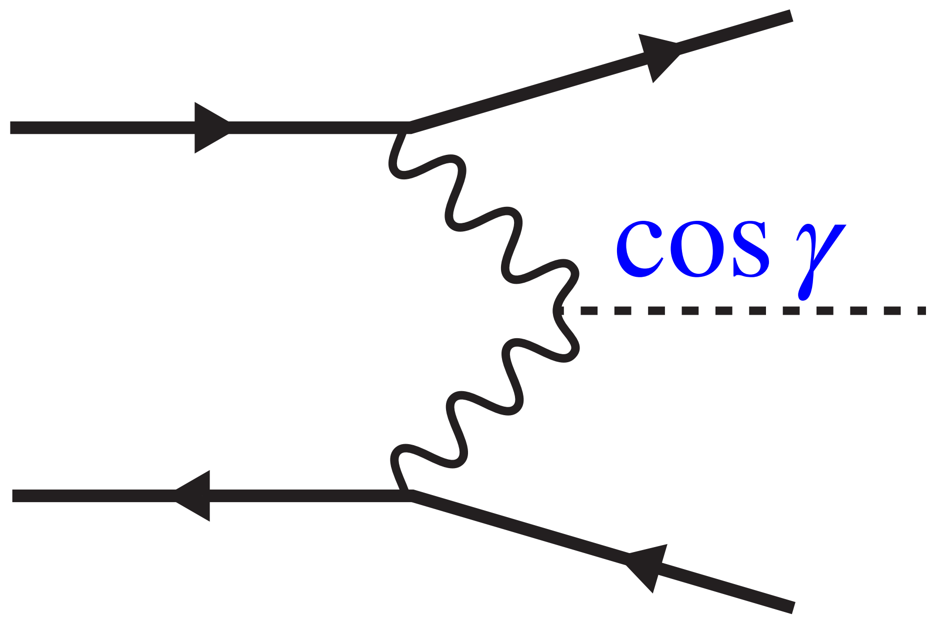
pp Collider Production





l^+l^- Collider Production





Buttazzo, Redigolo, Sala, Tesi 1807.04743

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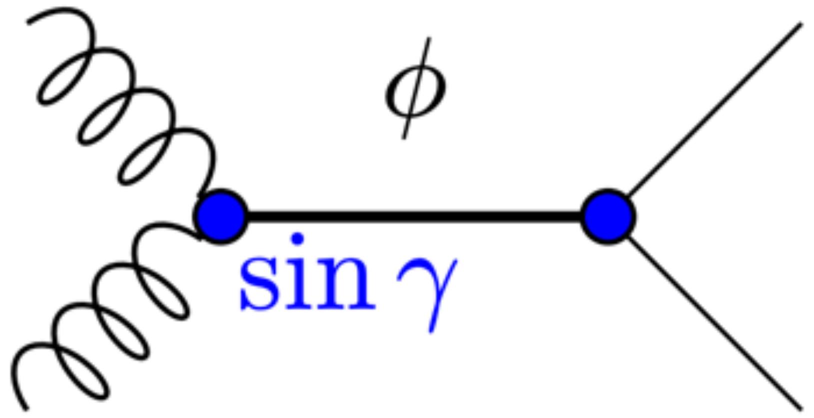
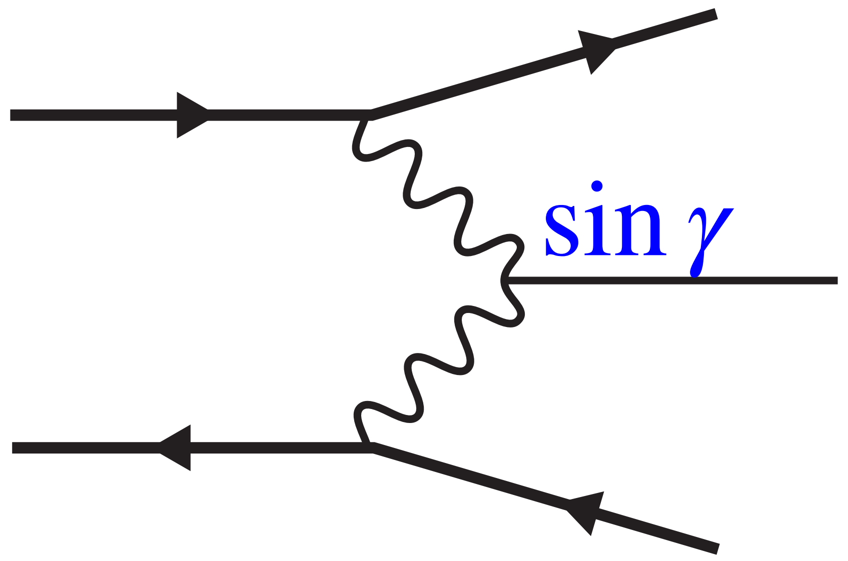
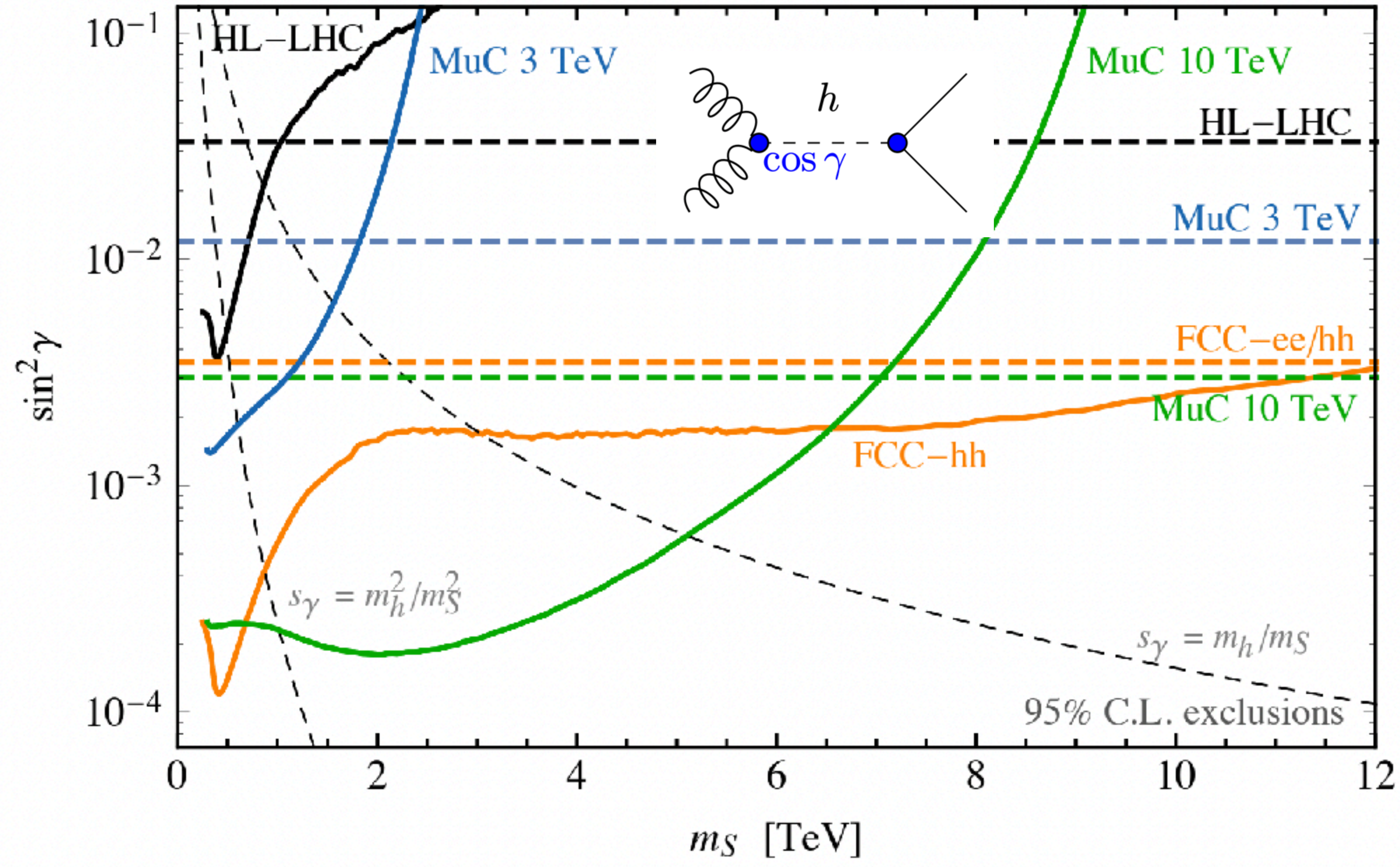
$$\phi \to hh, ZZ, WW$$







Buttazzo, Redigolo, Sala, Tesi 1807.04743

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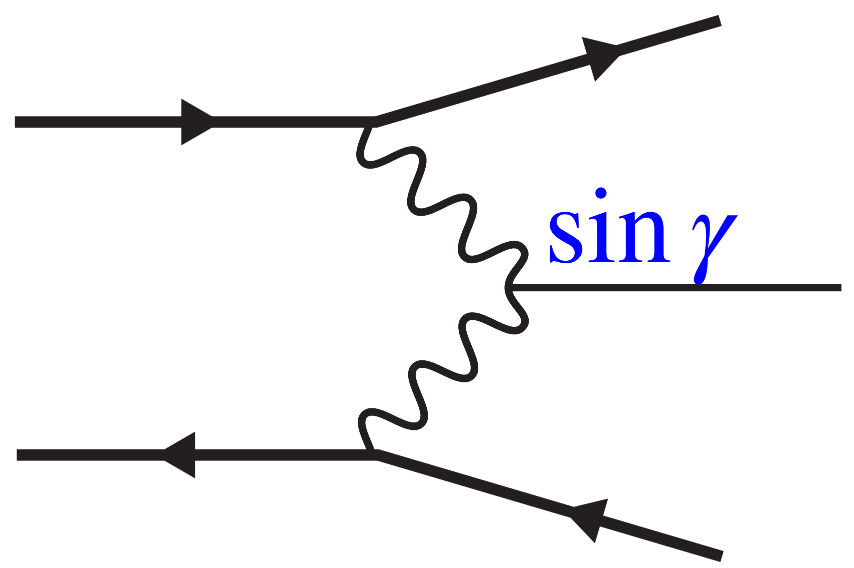
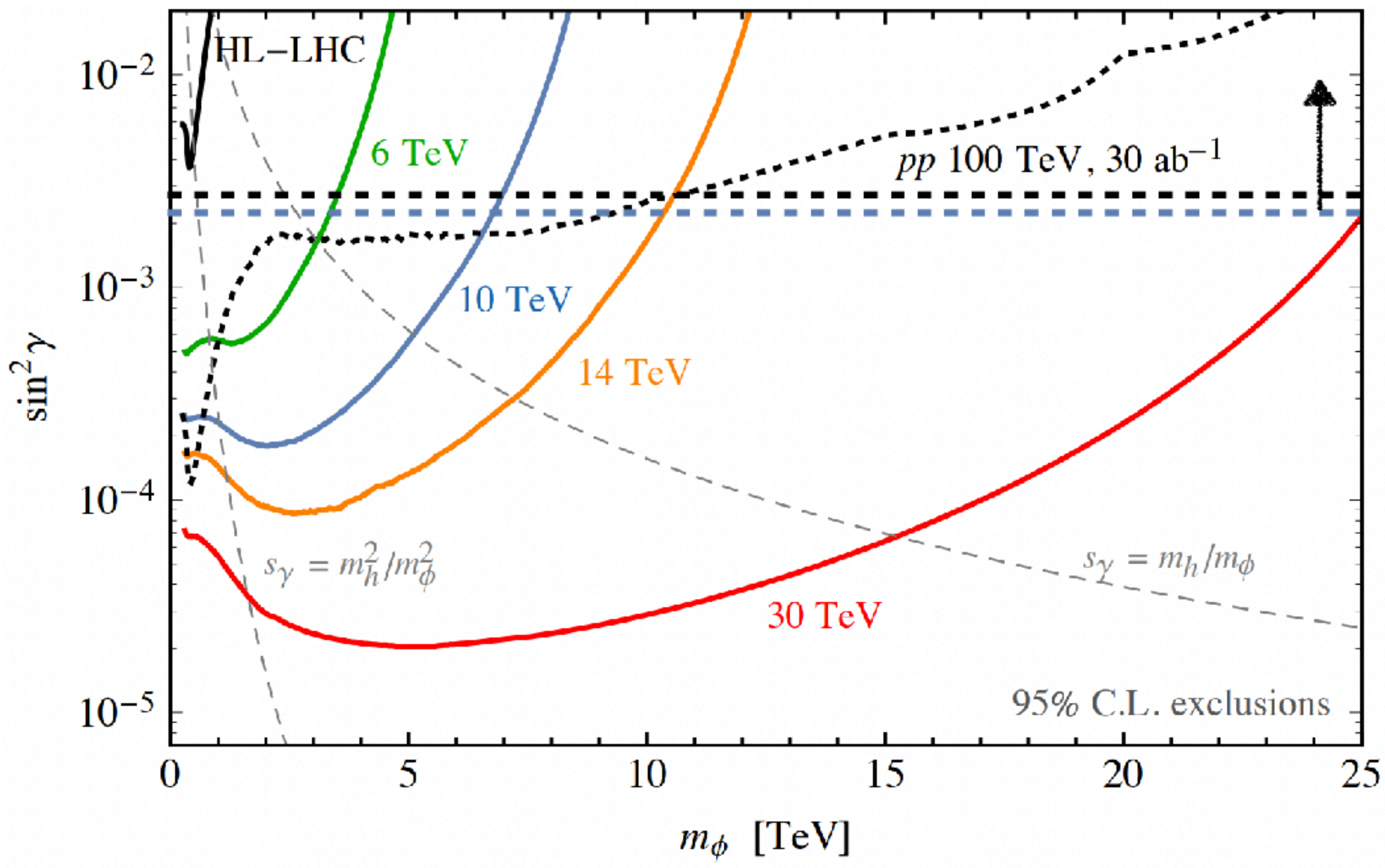




Buttazzo, Redigolo, Sala, Tesi 1807.04743

Ex: Leptophilic Dark Matter

E

Type III 2HDM

$H_1 \sim (1,2)_{1/2}$
$H_2 \sim (1,2)_{-1/2}$

$$\mathscr{L} \supset \lambda_u H_1 Q \bar{u} + \lambda_d Q H_1^\dagger Q \bar{d} + \lambda_\ell H_2 L \bar{e}$$

$$V(H_1, H_2, S) = S\left(\mu_{11} H_1^\dagger H_1 + \mu_{12} H_1^\dagger H_2 + \mu_{12}^* H_2^\dagger H_1 + \mu_{22} H_2^\dagger H_2\right) \quad +S \sim (1,1)_0$$

Each get vev v_1, v_2

Diagonalize into SM Higgs h and heavy Higgs H

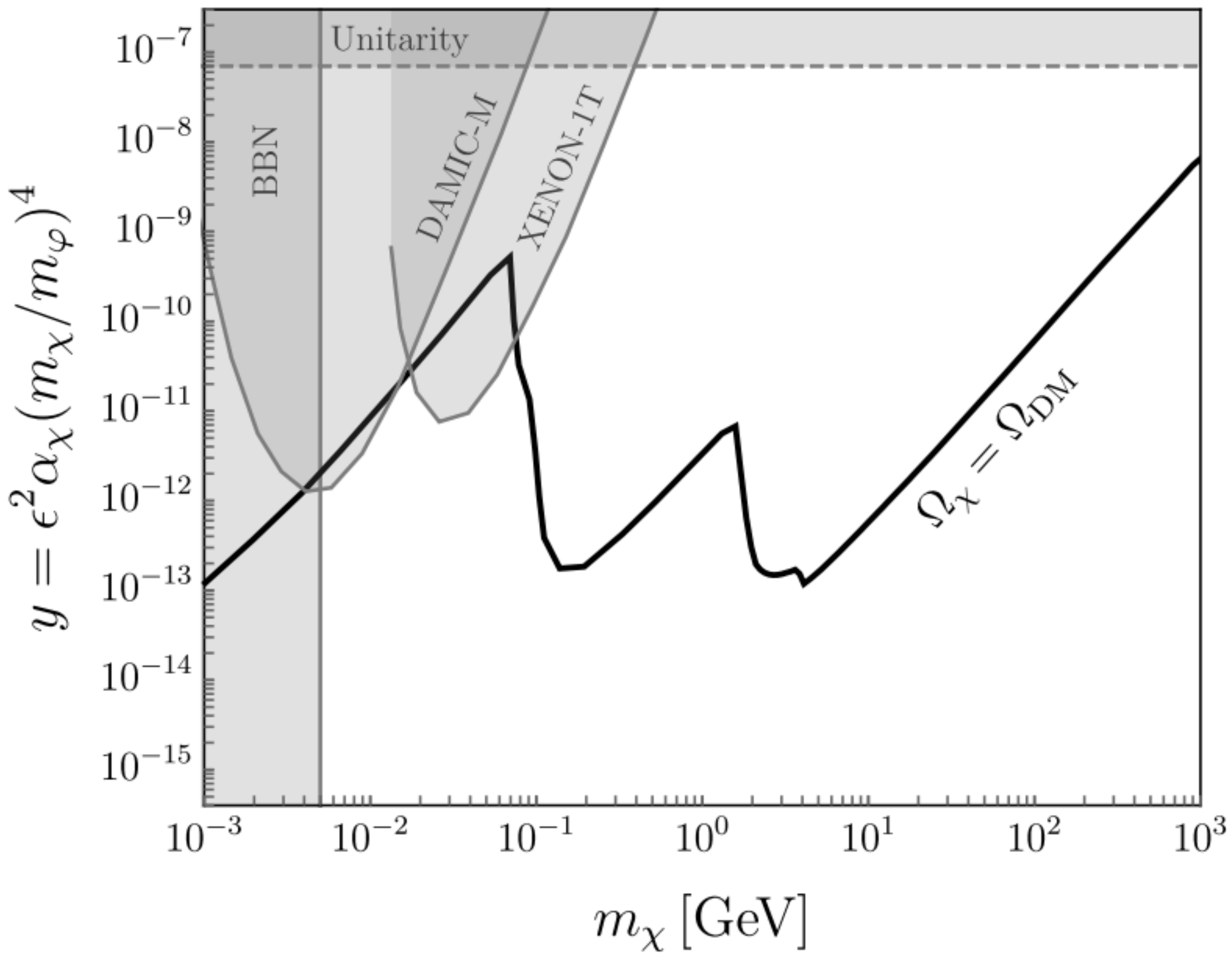
Work in regime of parameters, esp $\tan\beta \equiv \frac{v_2}{v_1} \gg 1$

$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l \bar{l}$$

$$g_l = g_e \frac{m_l}{m_e}$$

CC, Krnjaic '24 (to come)

Other bounds



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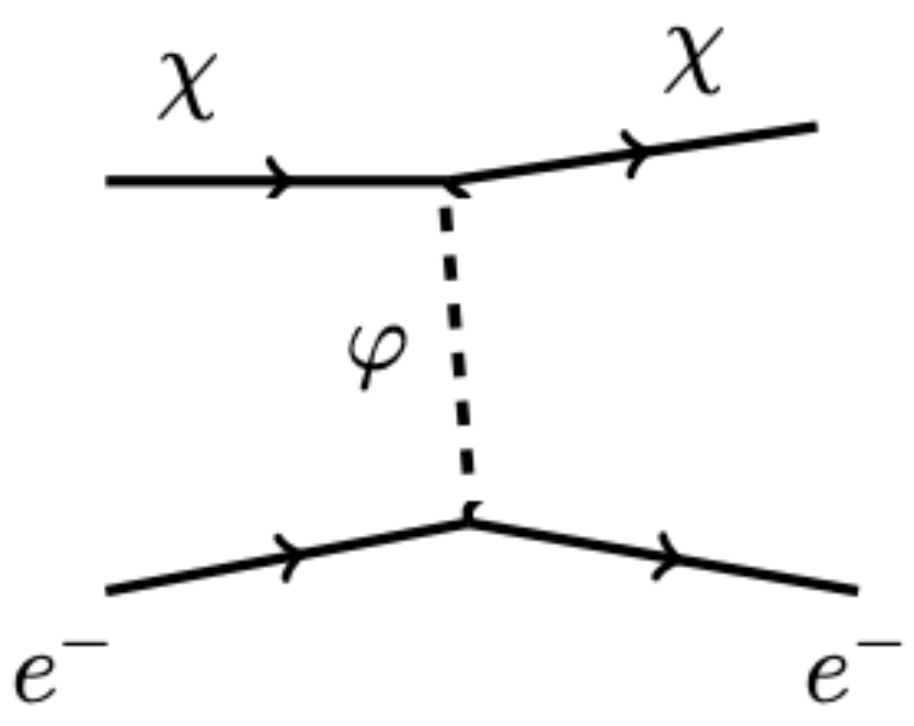


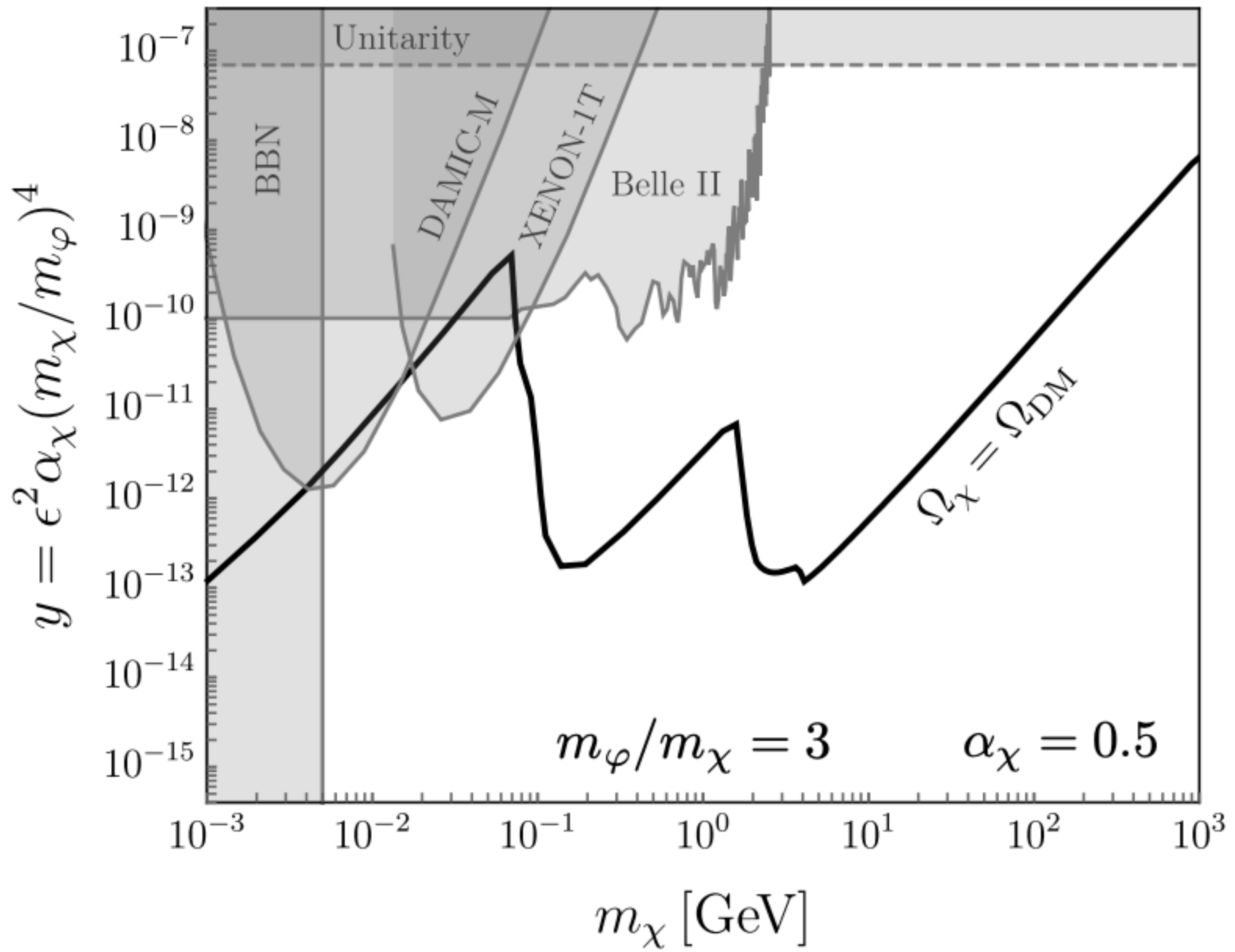
Direct Detection

DAMIC-M 2302.02372

XENON-IT 2112.12116

CC, Krnjaic '24 (to come)

Other bounds



$$\mathcal{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l\bar{l}$$

B Factories

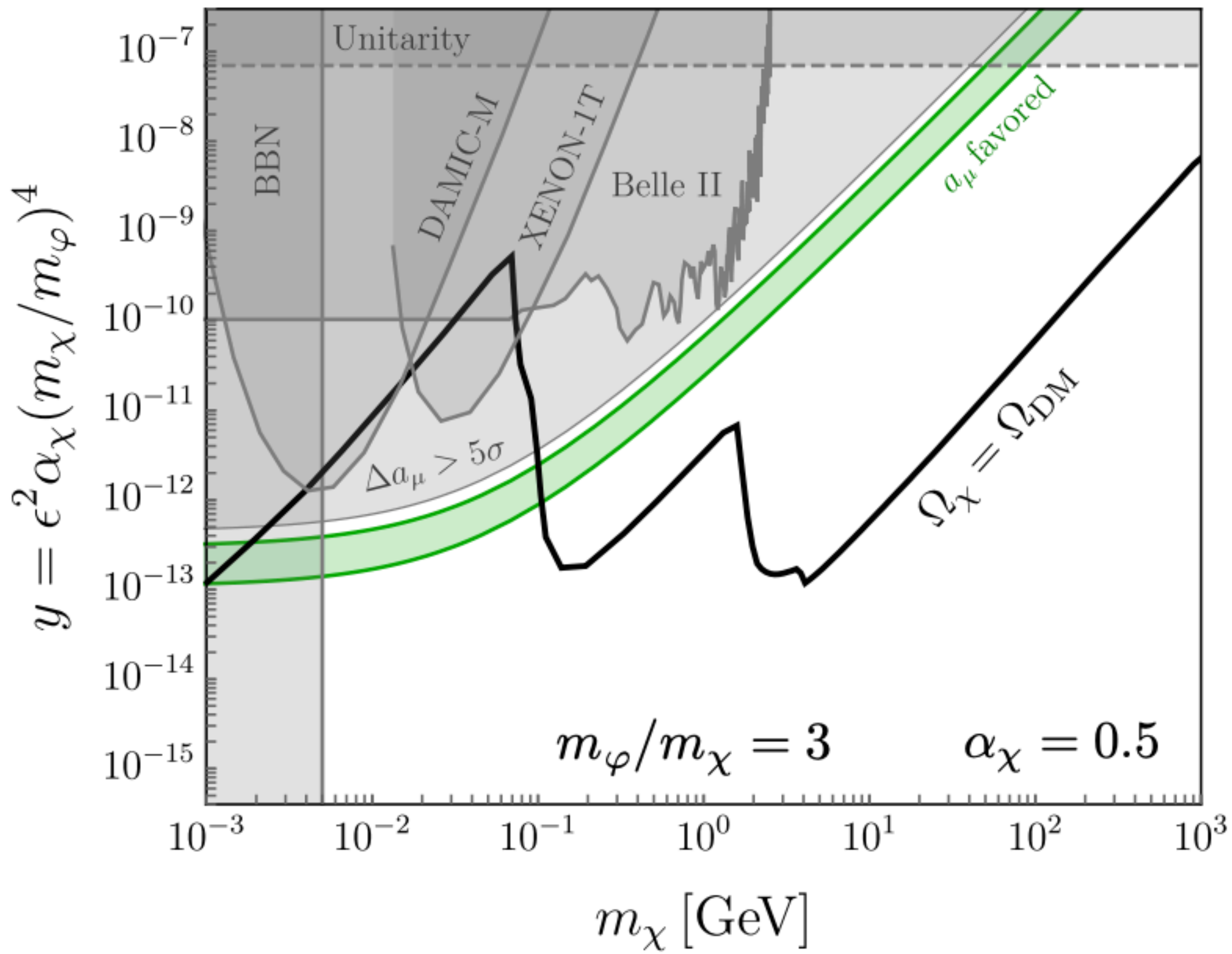
$$e^+e^- \to \mu^+\mu^-\varphi$$

(Dimuon + missing energy)

Belle II Collaboration 2212.03066

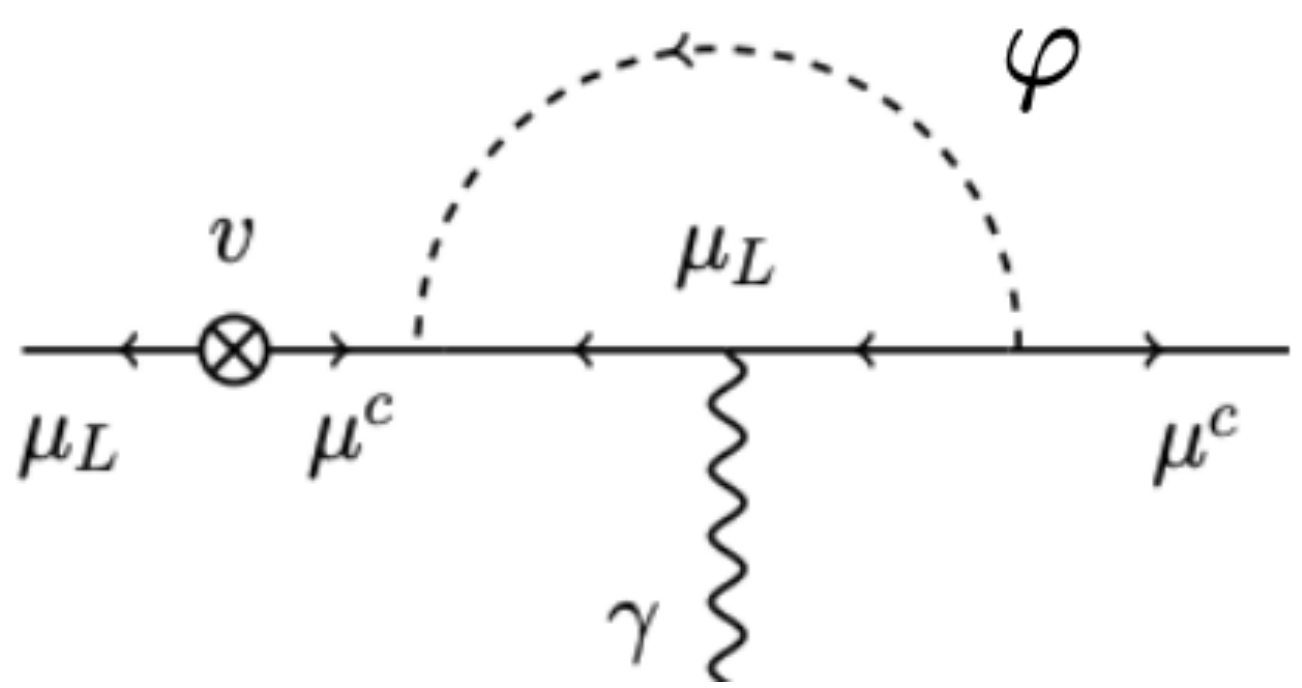
CC, Krnjaic '24 (to come)

Other bounds



$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l \bar{l}$$

Muon g-2



Muon *g-2* 2311.08282

CC, Krnjaic '24 (to come)

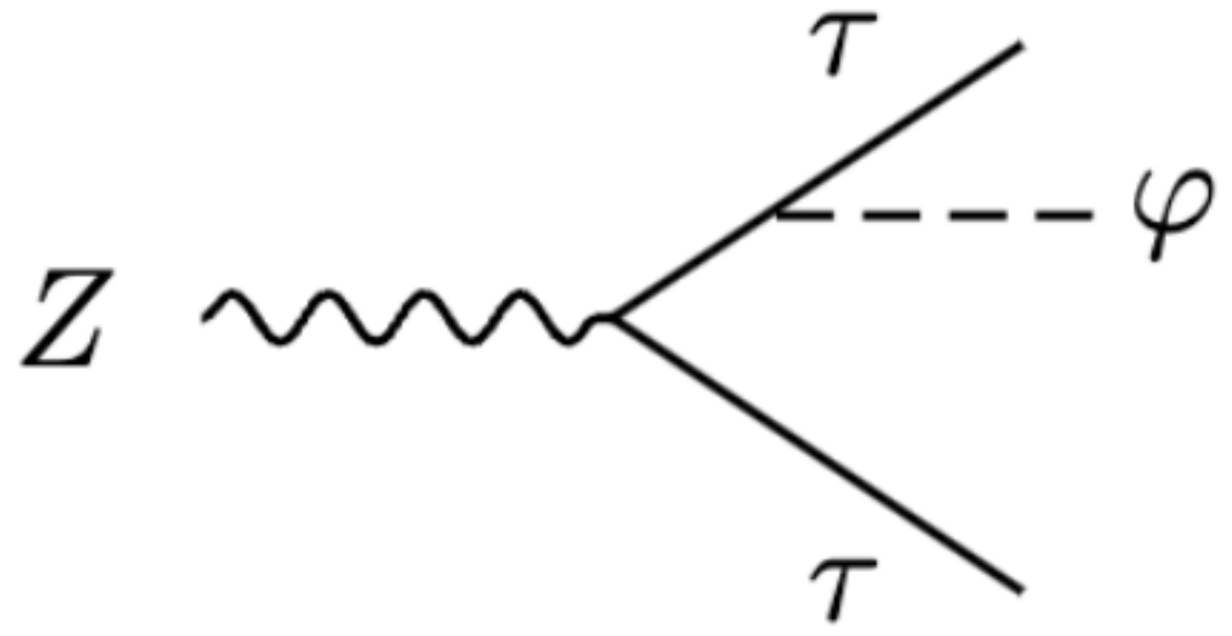
BOUNDS FROM FCCEE

Tera-Z run at FCCee can also set significant bounds from rare Z decays

$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l\bar{l}$$

Strongest bound set by couplings to $Z \to \tau\tau$

Bound set by uncertainty in BR



CC, Krnjaic '24 (to come)

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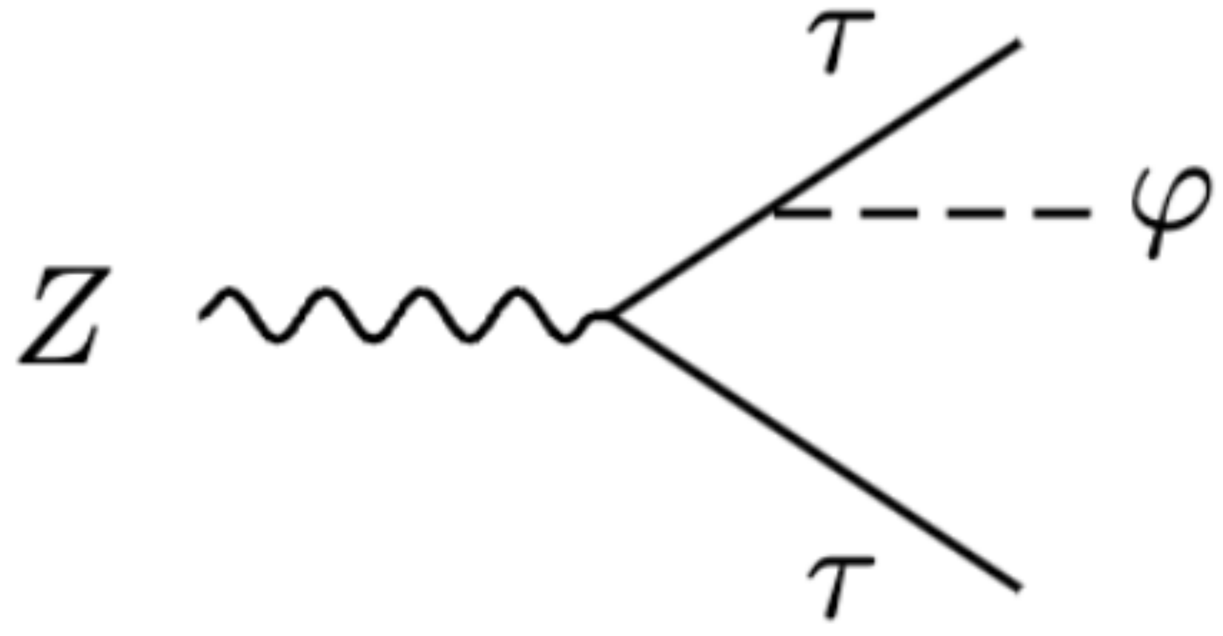
Bound set by uncertainty in BR



Previous LEP: $(1.7 \times 10^7 \; Z\text{'s})$

$\Gamma(Z \to \tau\tau) = 84.08 \pm 0.22$ MeV

FCCee Tera-Z: $(10^{12} \; Z\text{'s})$

Assume primary improvements come from statistics

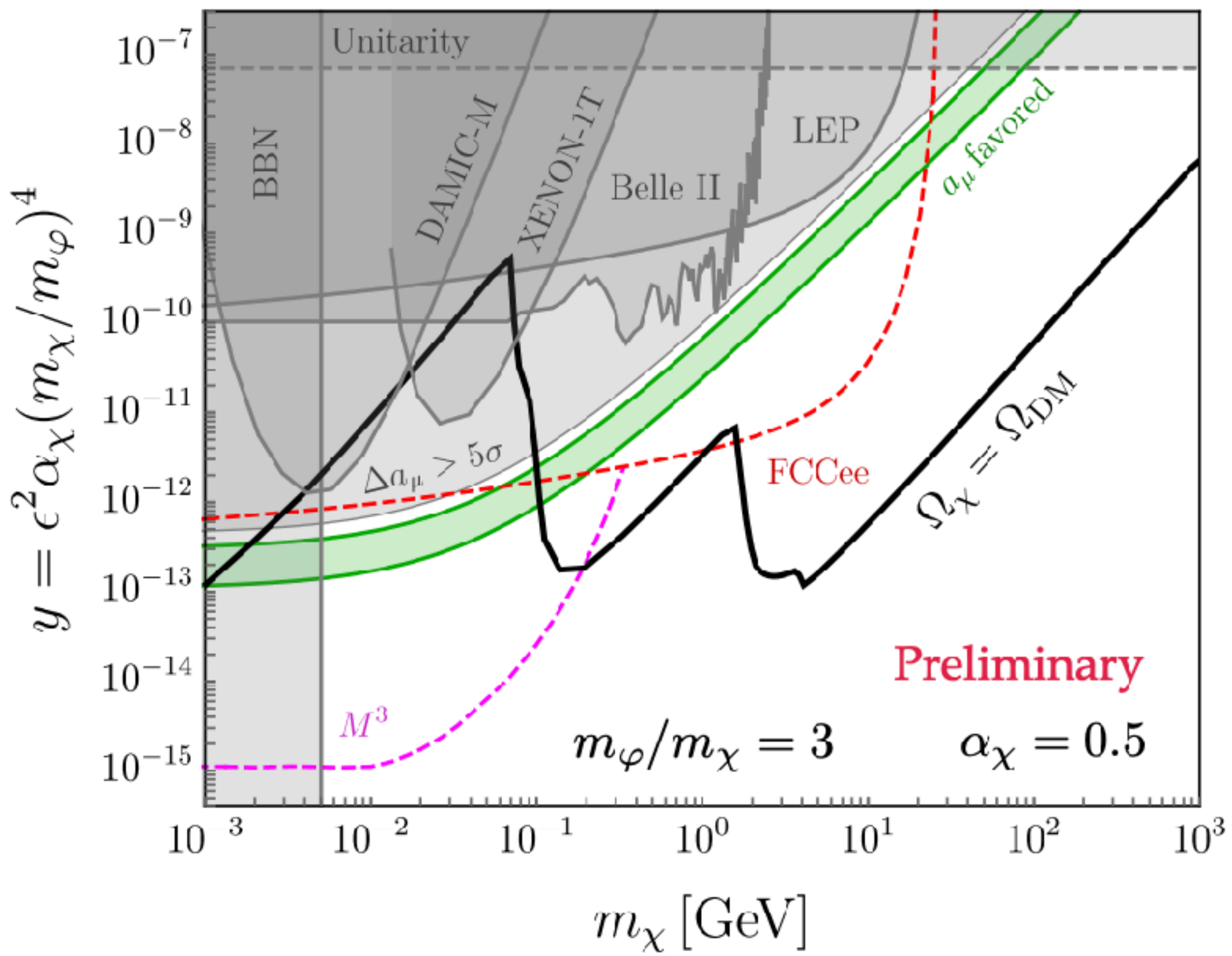
$\Delta\Gamma \times \sqrt{N_{LEP}/N_{FCC}}$

CC, Krnjaic '24 (to come)

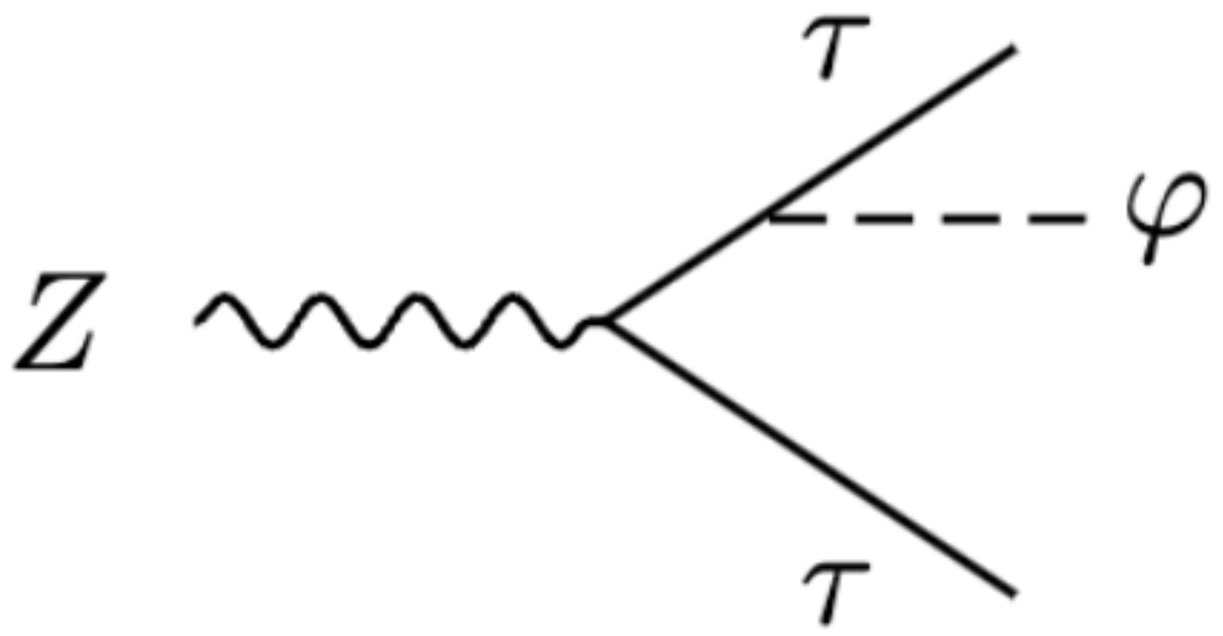
Bounds from FCCee

Tera-Z run at FCCee can also set significant bounds from rare Z decays

$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l\bar{l}$$



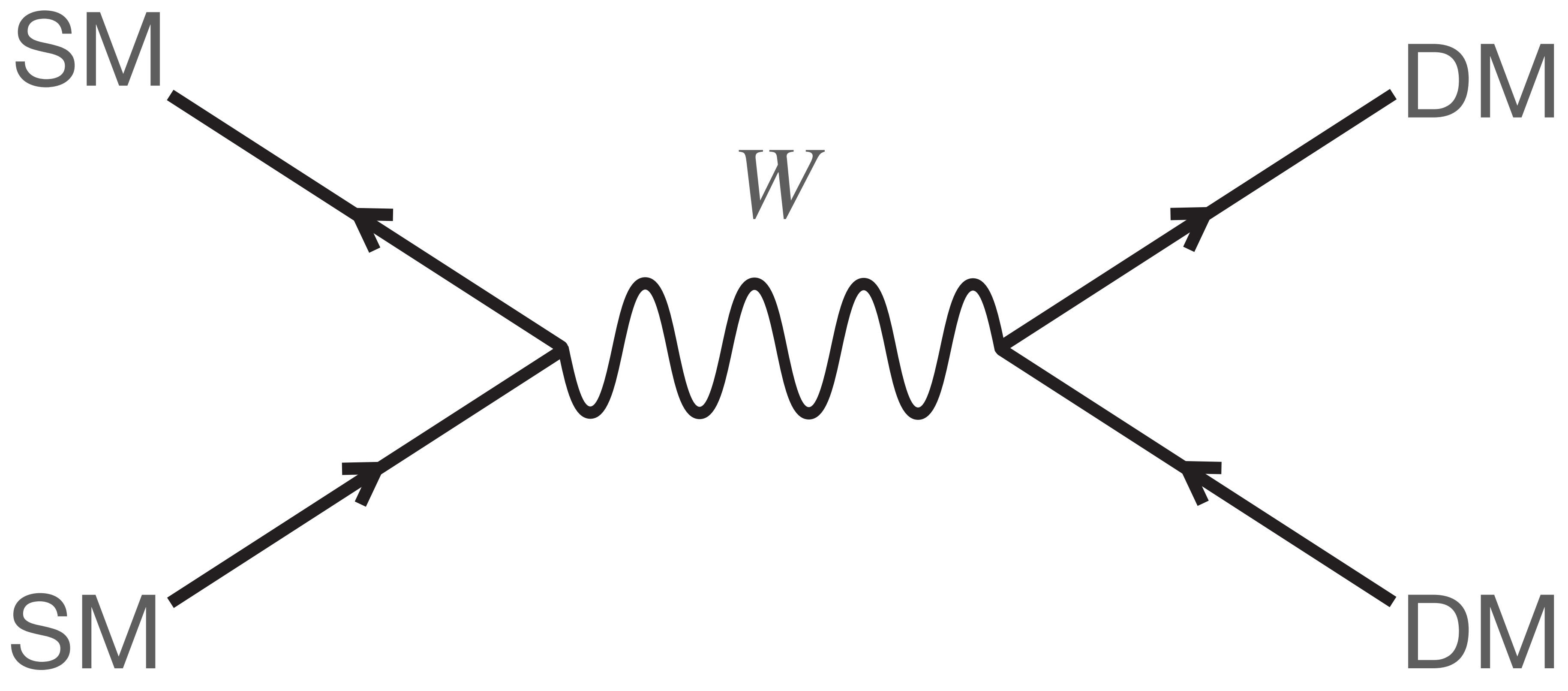
2σ in $\Delta\Gamma(Z \to \tau\tau)$

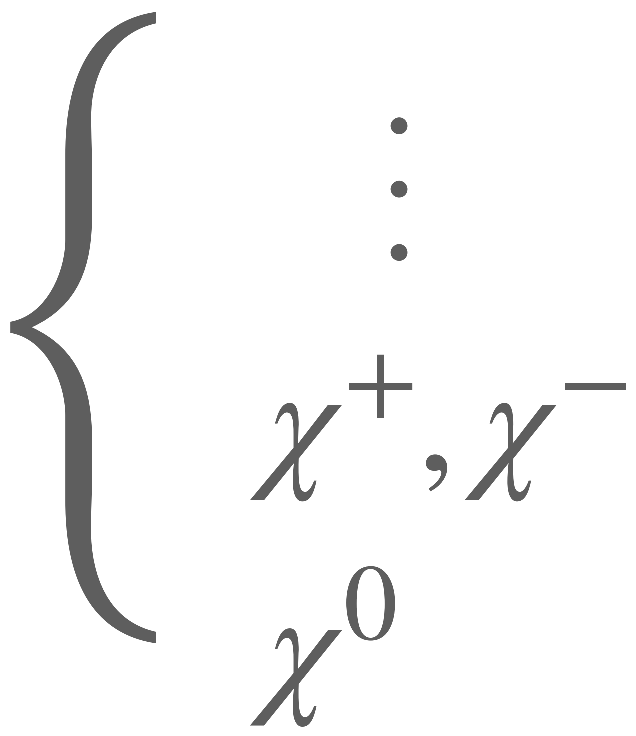


CC, Krnjaic '24 (to come)

Ex: WIMP Dark Matter

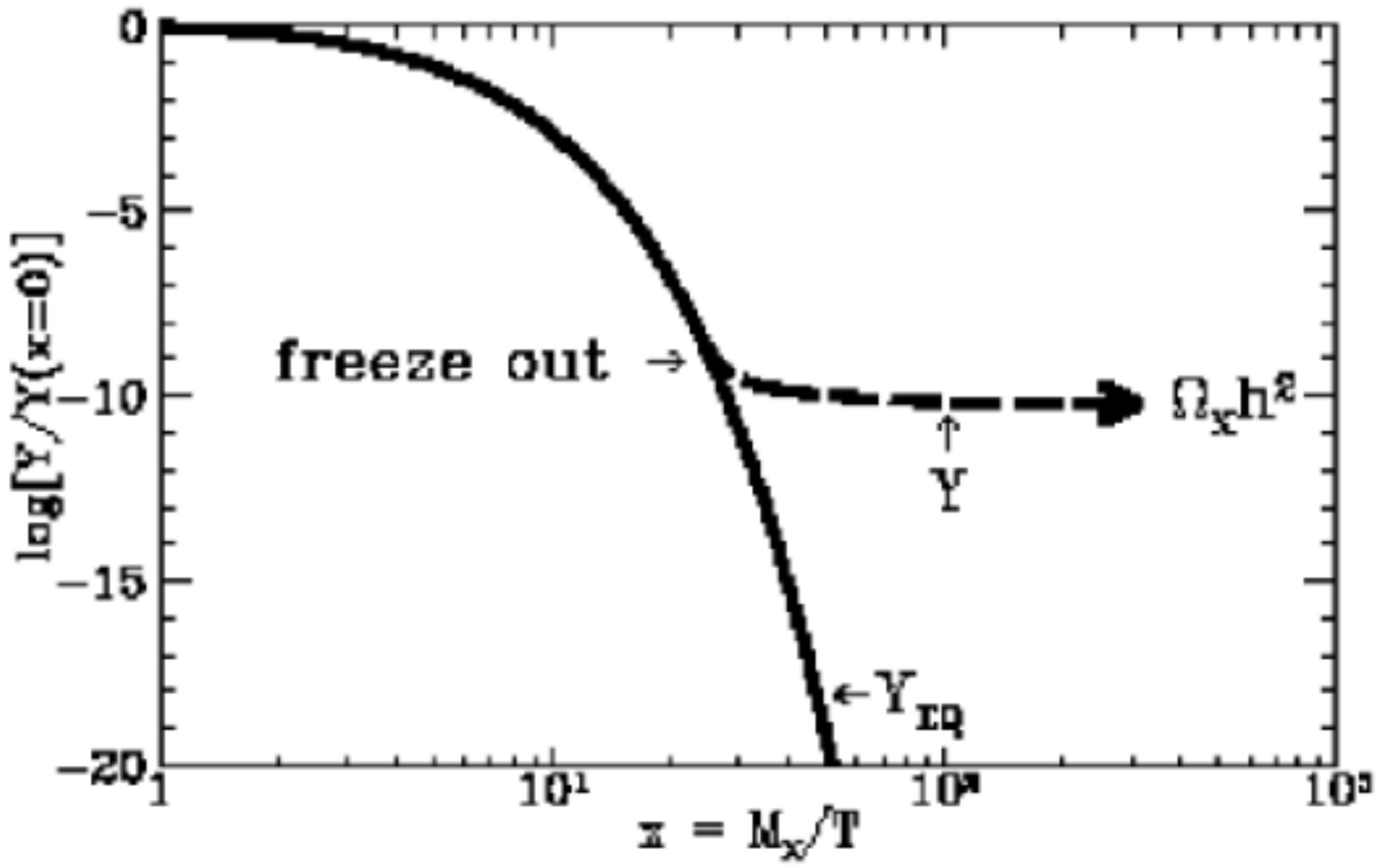
For dark matter models coupling to EW bosons, MuC is an ideal place for searches





Mass fixed by freeze-out abundance

EW n-plet	Mass [TeV]
$2_{1/2}$	1.08
3_0	2.86
$4_{1/2}$	4.8
5_0	13.6
5_1	9.9
$6_{1/2}$	31.8
7_0	48.8
9_0	113



Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio 2107.09688, 2205.04486

Ex: General Indirect Production

EFT Approach for Energy ↔ Precision

$$\mathscr{L} \supset \frac{g^2}{\Lambda^2}\mathcal{O}^6 + \ldots$$

Say you can measure something to 1% precision

$$g \sim 1$$

$$\frac{\Delta\mathcal{O}}{\mathcal{O}} = 0.01 \approx \frac{E^2}{\Lambda^2}$$

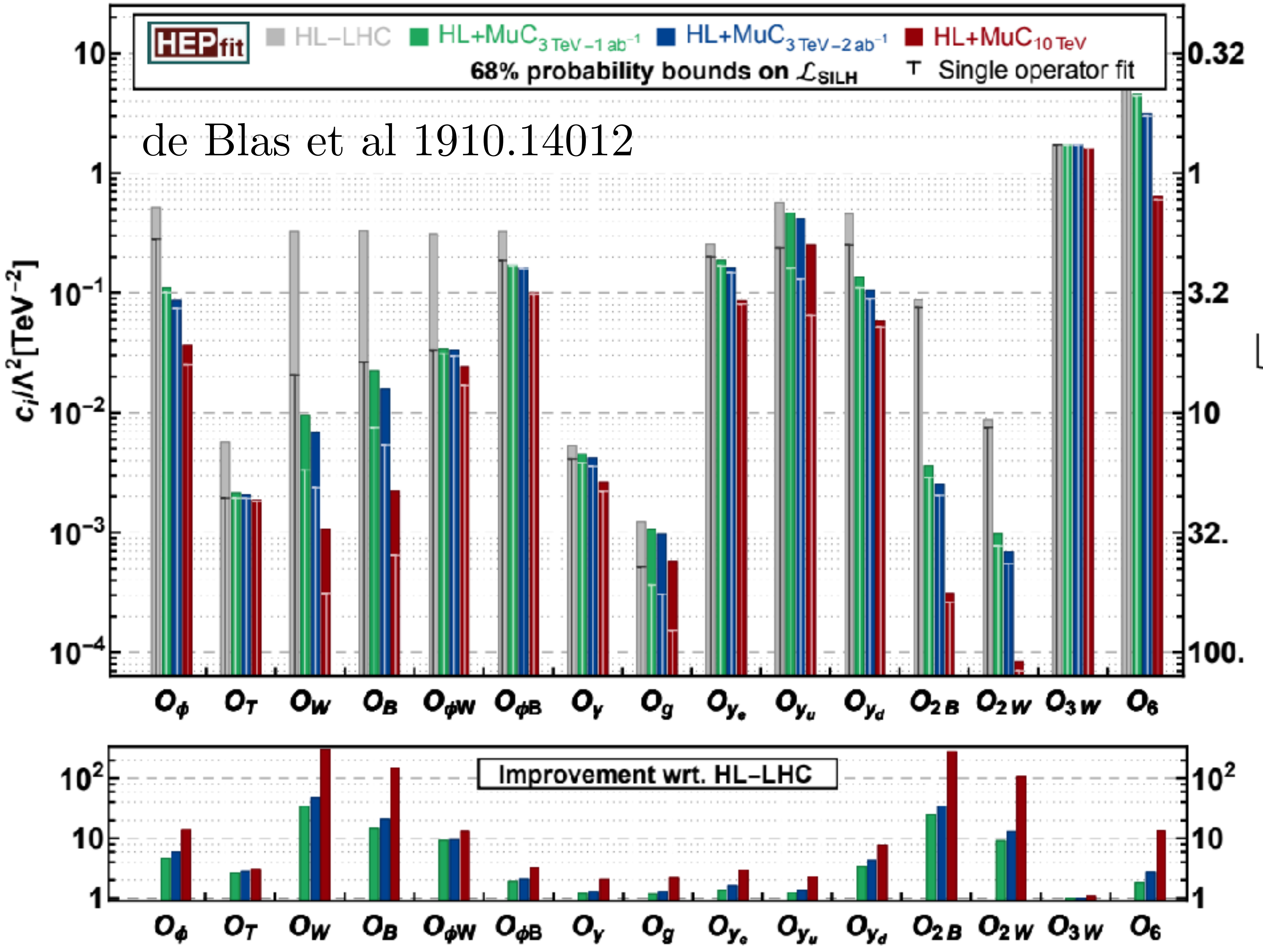
$E \sim 10$ TeV

$\Lambda \sim 100$ TeV

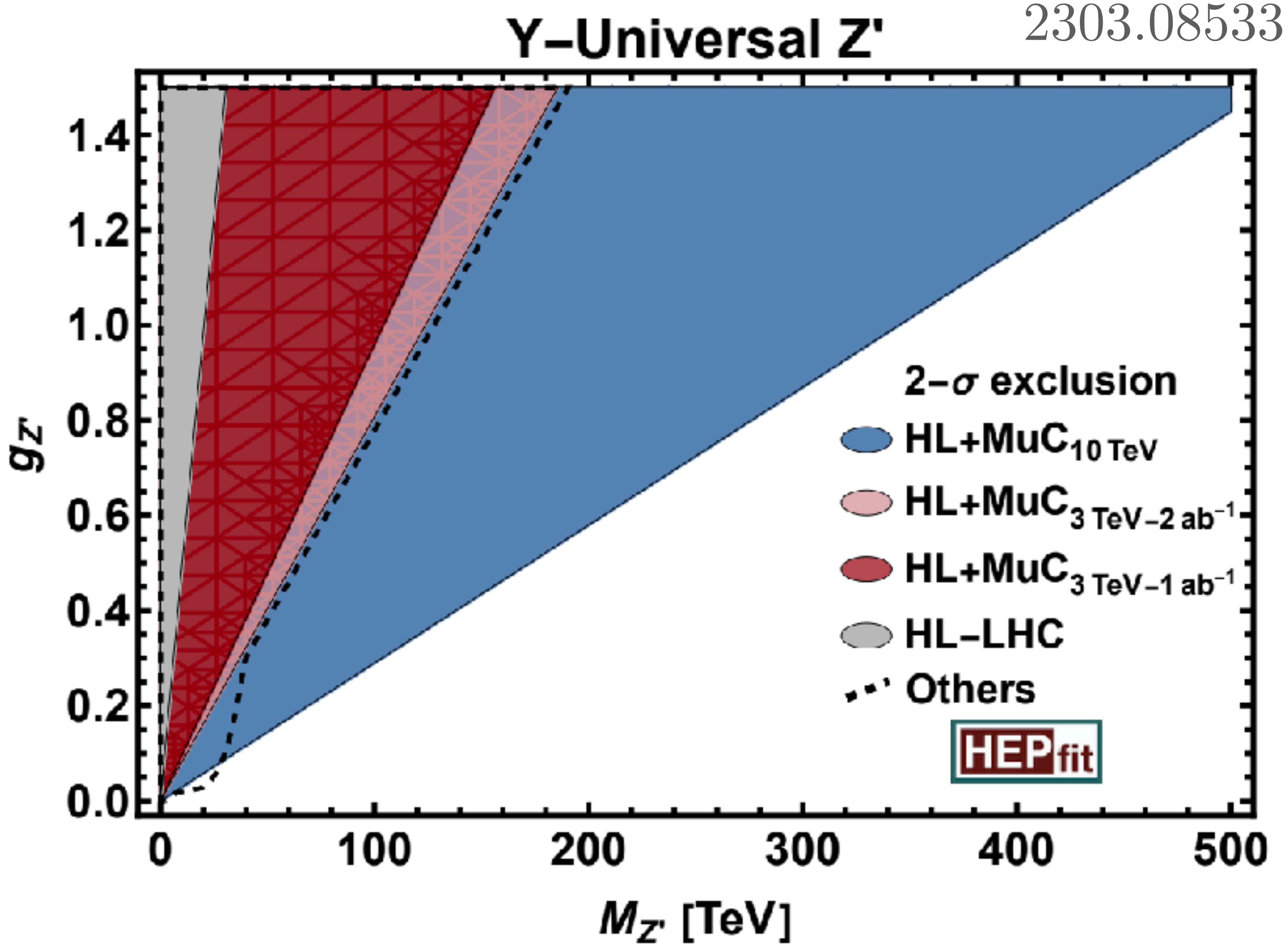
Can still be probing new physics at much higher scales!

Physics Reach of MuC

EFT Approach for Energy ↔ Precision



2303.08533



Muon-philic Forces

$$\mathscr{L}_{UV} \supset y_\psi H^\dagger L_2 \psi^c + \kappa \psi \mu^c + (M_\psi + y' S)\psi\bar{\psi} + hc$$

New vector-like fermion

$+\psi \sim (1,1)_1$

E

$$\mathscr{L}_{eff} \supset \frac{y}{v} S H^\dagger L \mu_R^c + hc$$

$$\mathscr{L}_{int} \supset y S \mu \bar{\mu}$$

CC, Kahn, Krnjaic, Rocha, Spitz '23

Muon-philic Forces

$$\mathscr{L}_{UV} \supset y_\psi H^\dagger L_2 \psi^c + \kappa \psi \mu^c + (M_\psi + y' S)\psi \bar{\psi} + hc$$

E

$E \ll M_\psi$

New vector-like fermion

$+\psi \sim (1,1)_1$

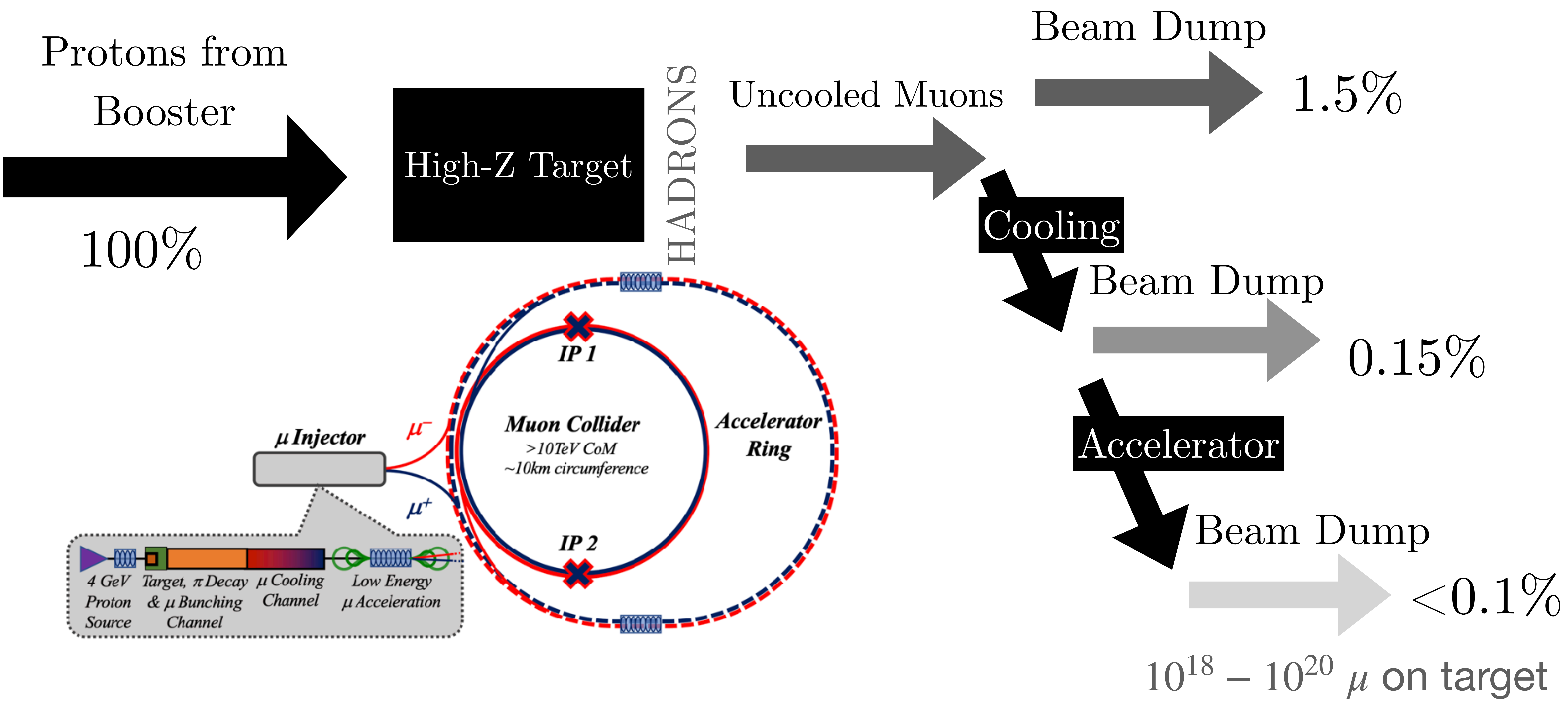
$$\mathscr{L}_{eff} \supset \frac{y' y_\psi \kappa}{M_\psi^2} S H^\dagger L \mu_R^c + hc$$

(SSB)

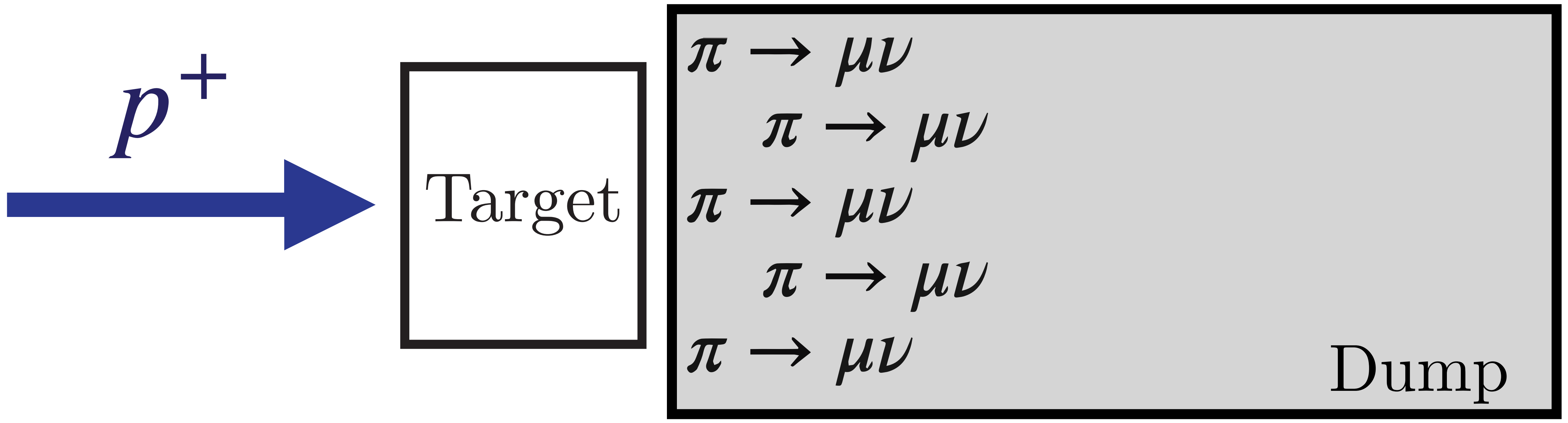
$$\mathscr{L}_{int} \supset y S \mu \bar{\mu}$$

CC, Kahn, Krnjaic, Rocha, Spitz '23

Demonstrators & Beam Dumps

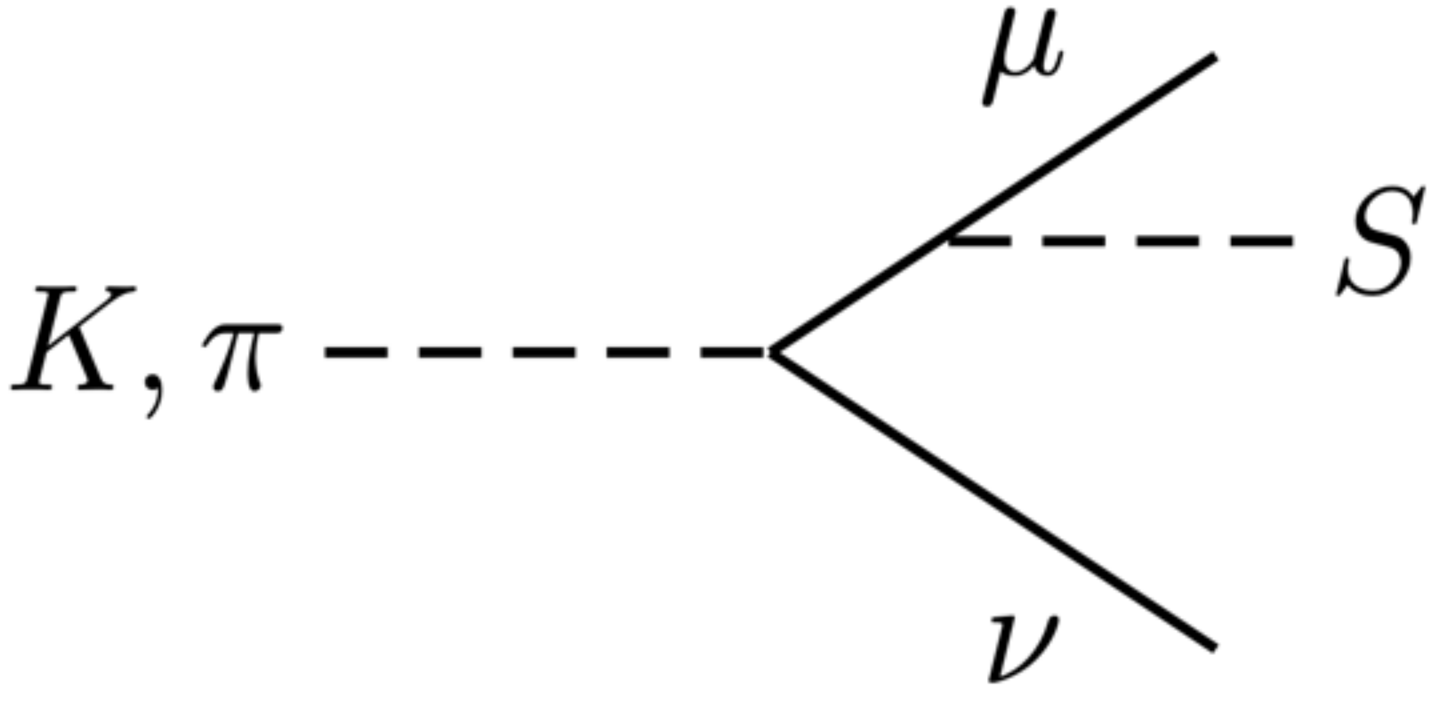


Signatures with Proton Beam-on-target

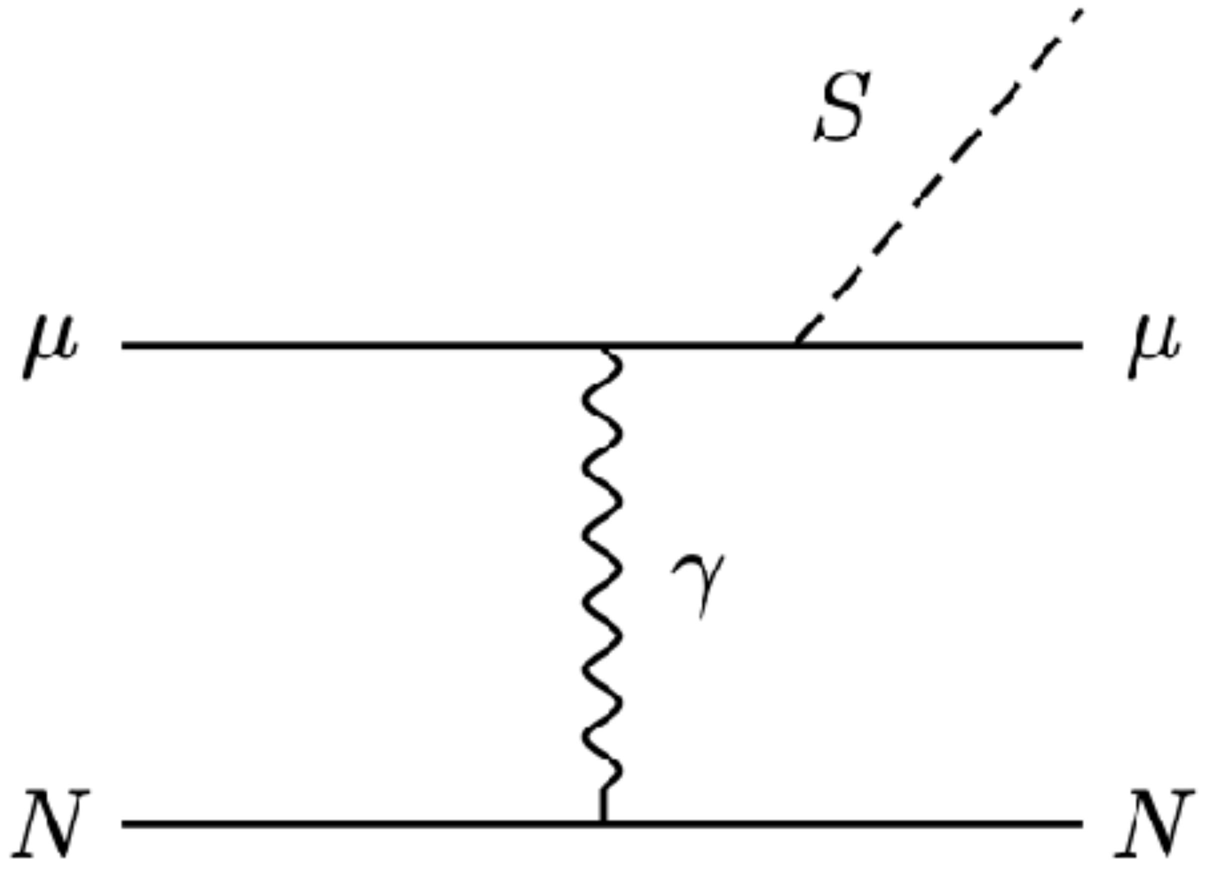


$$\mathscr{L}_{int} \supset yS\mu\bar{\mu}$$

Rare decays of mesons



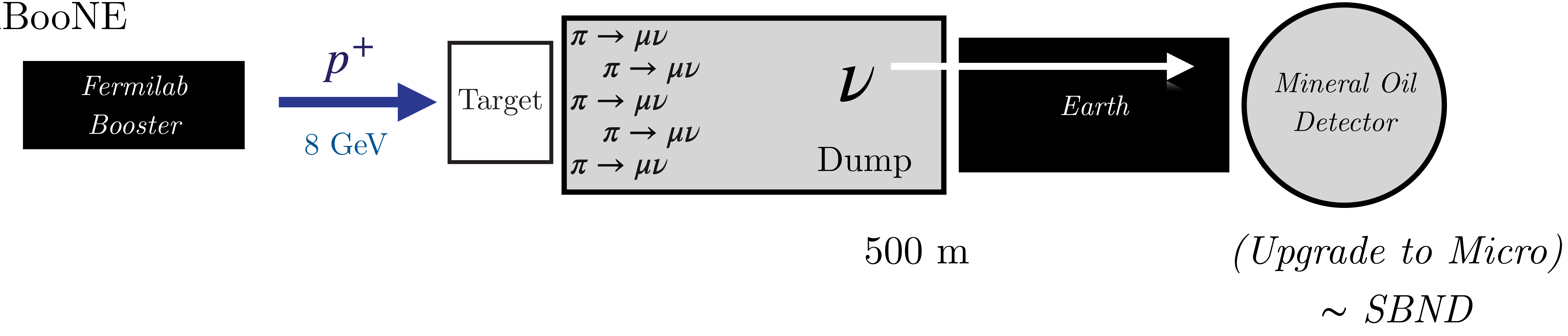
Scattering of muons in material



CC, Kahn, Krnjaic, Rocha, Spitz '23

Mini/MicroBooNE

MiniBooNE



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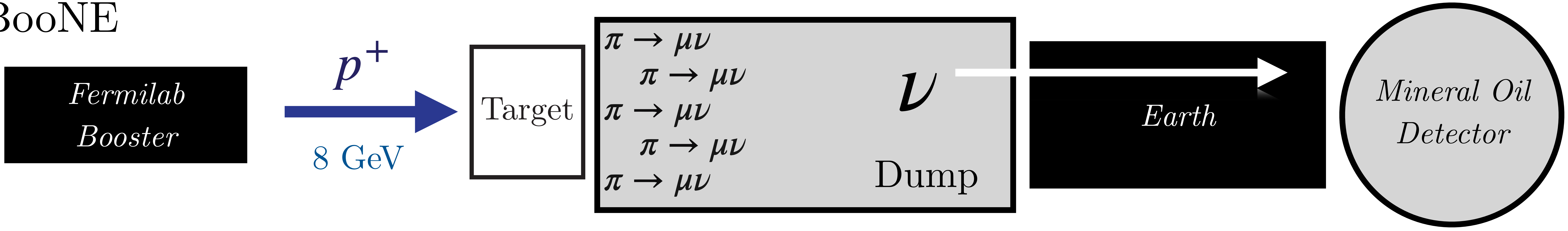
MINI/MICROBOONE

MiniBooNE

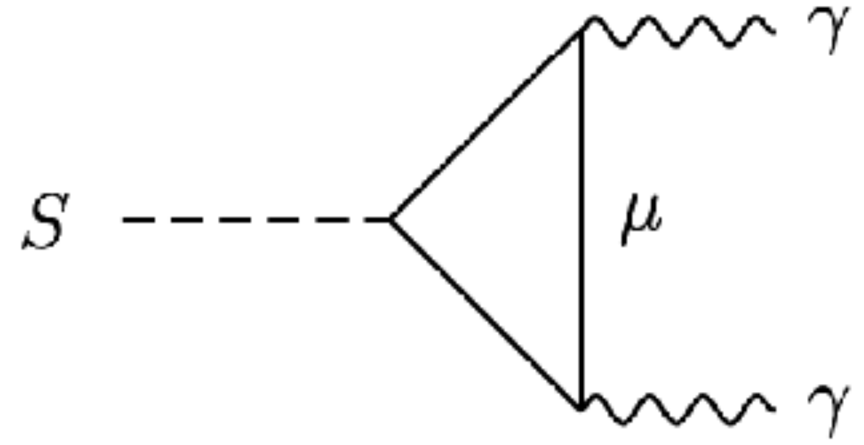


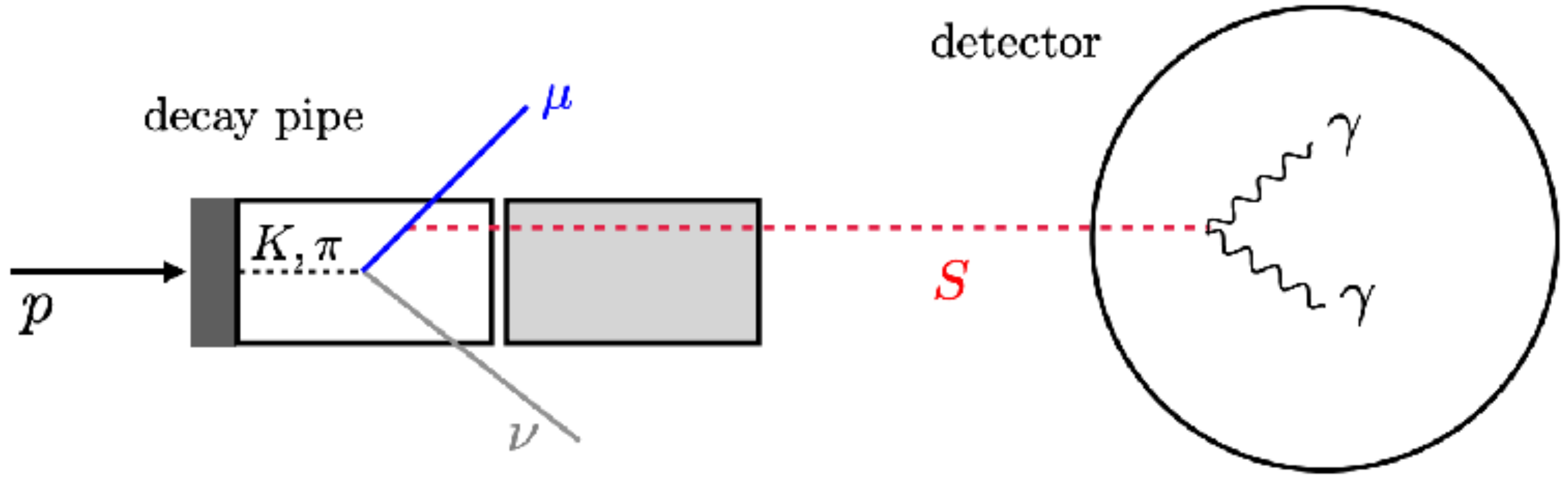
500 m

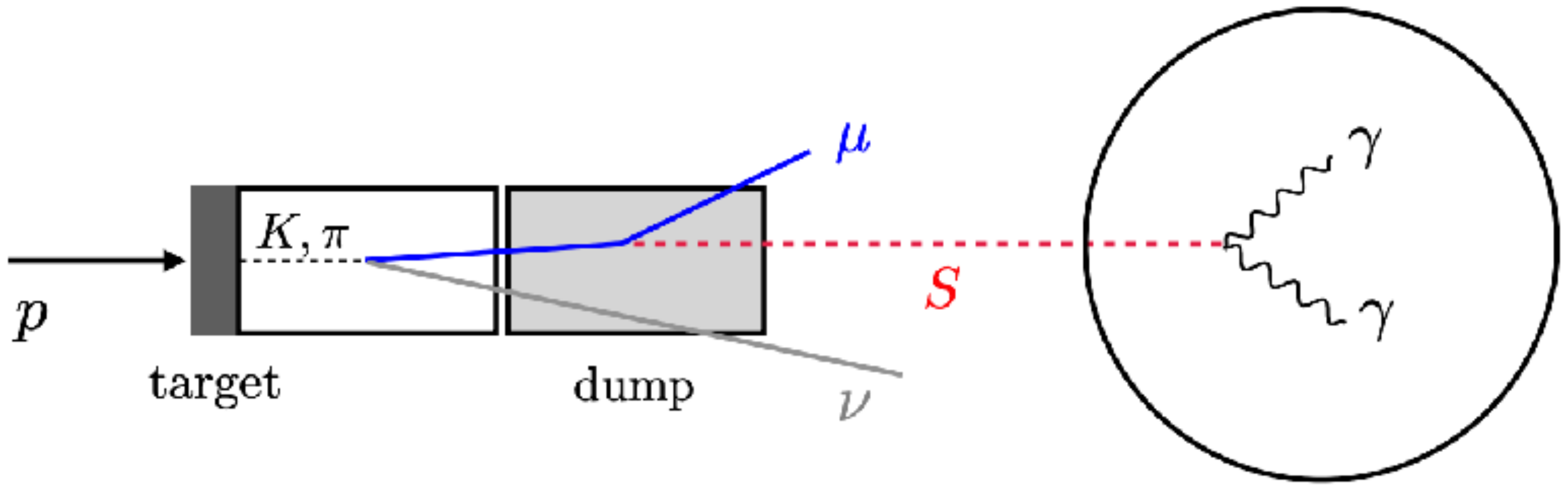
(Upgrade to Micro)

~ SBND

RECAST



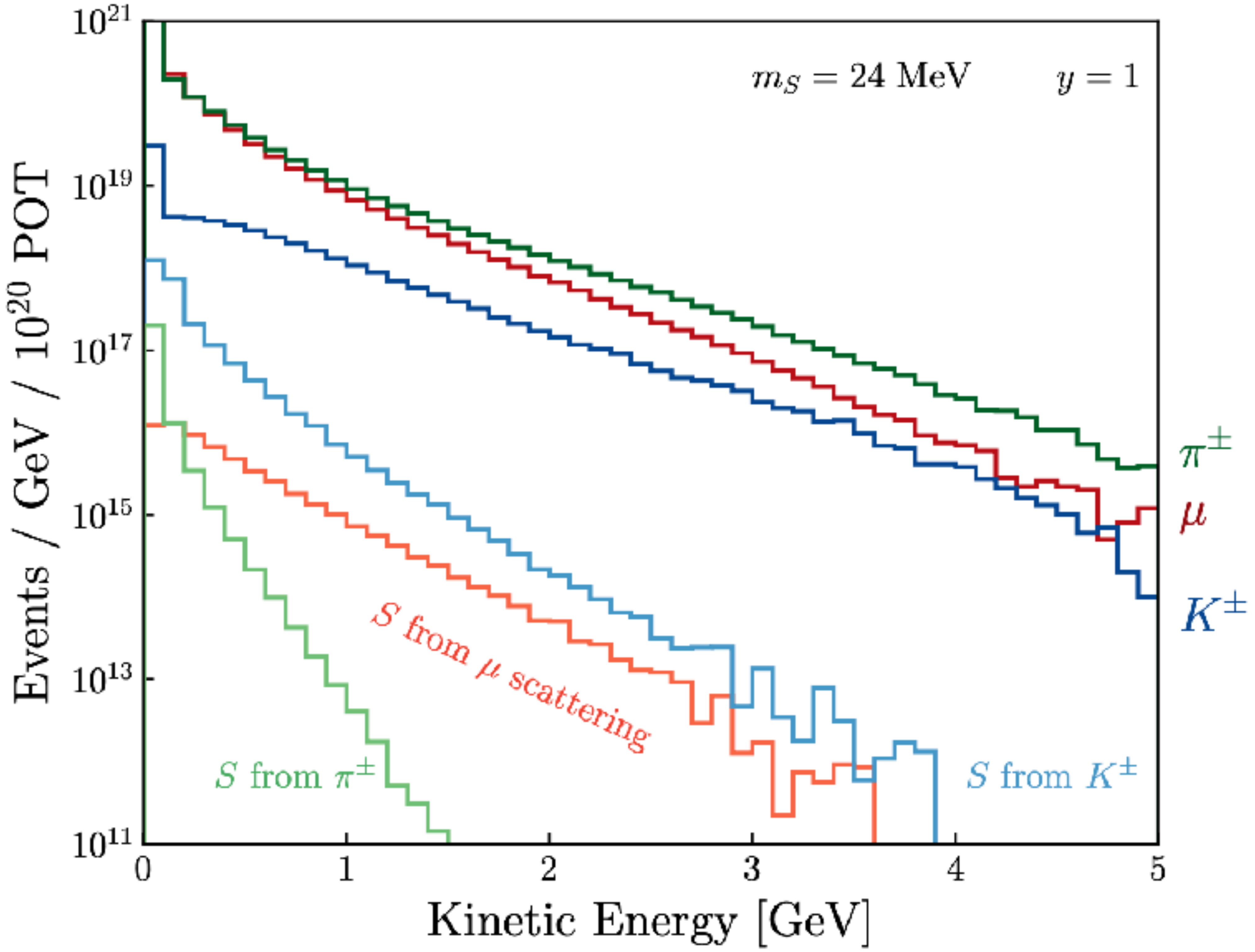




Chen, Pospelov, Zhong '17

CC, Kahn, Krnjaic, Rocha, Spitz '23

S production and Background



Immediate recast is possible because the BooNEs measured neutrino induced NC π^0 production, with $m_{\gamma\gamma}$ reported

$$\nu_\mu N \to \nu_\mu N \pi^0 (\pi^0 \to \gamma\gamma)$$

We have our data set and our background!

CC, Kahn, Krnjaic, Rocha, Spitz '23