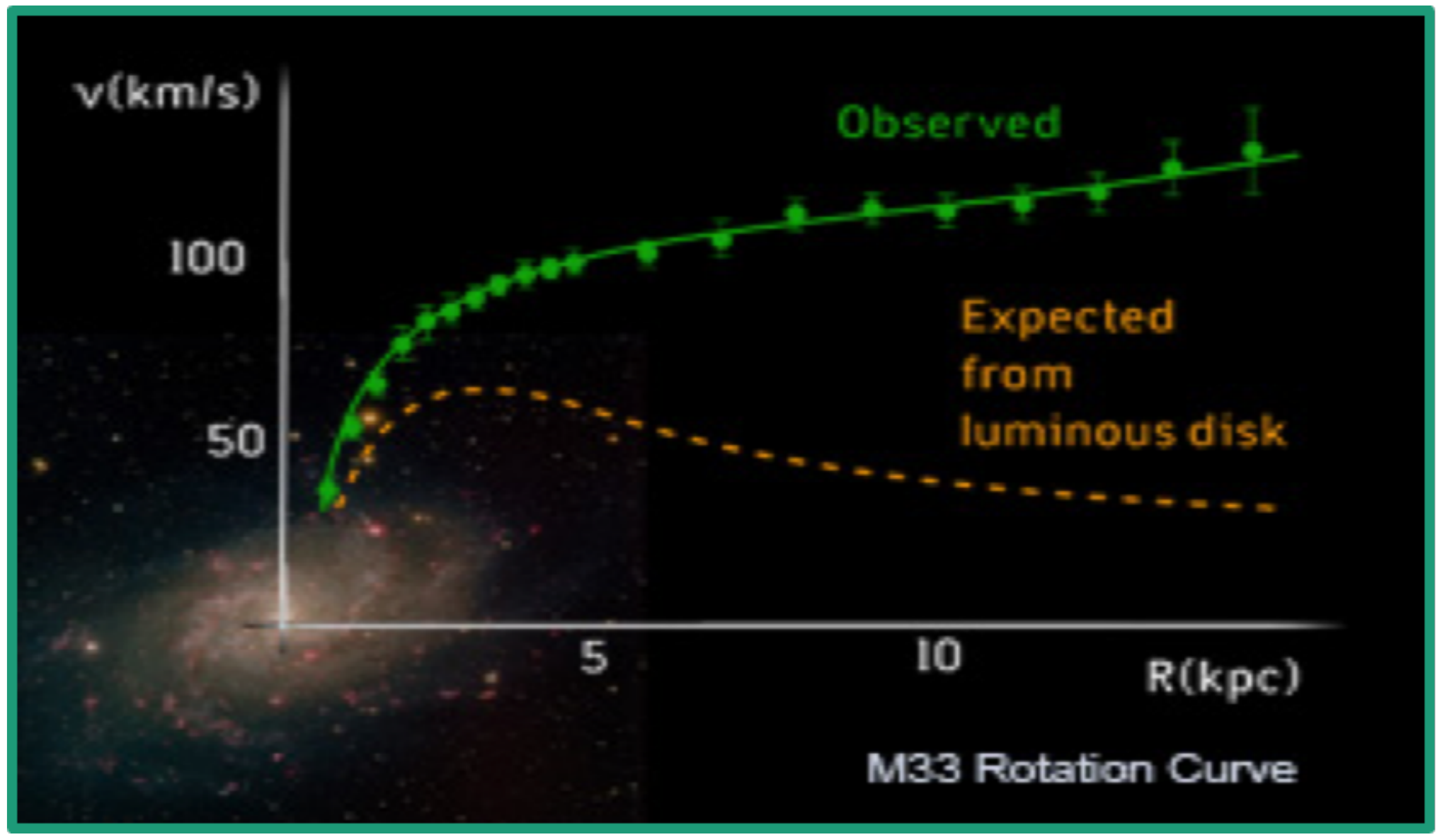
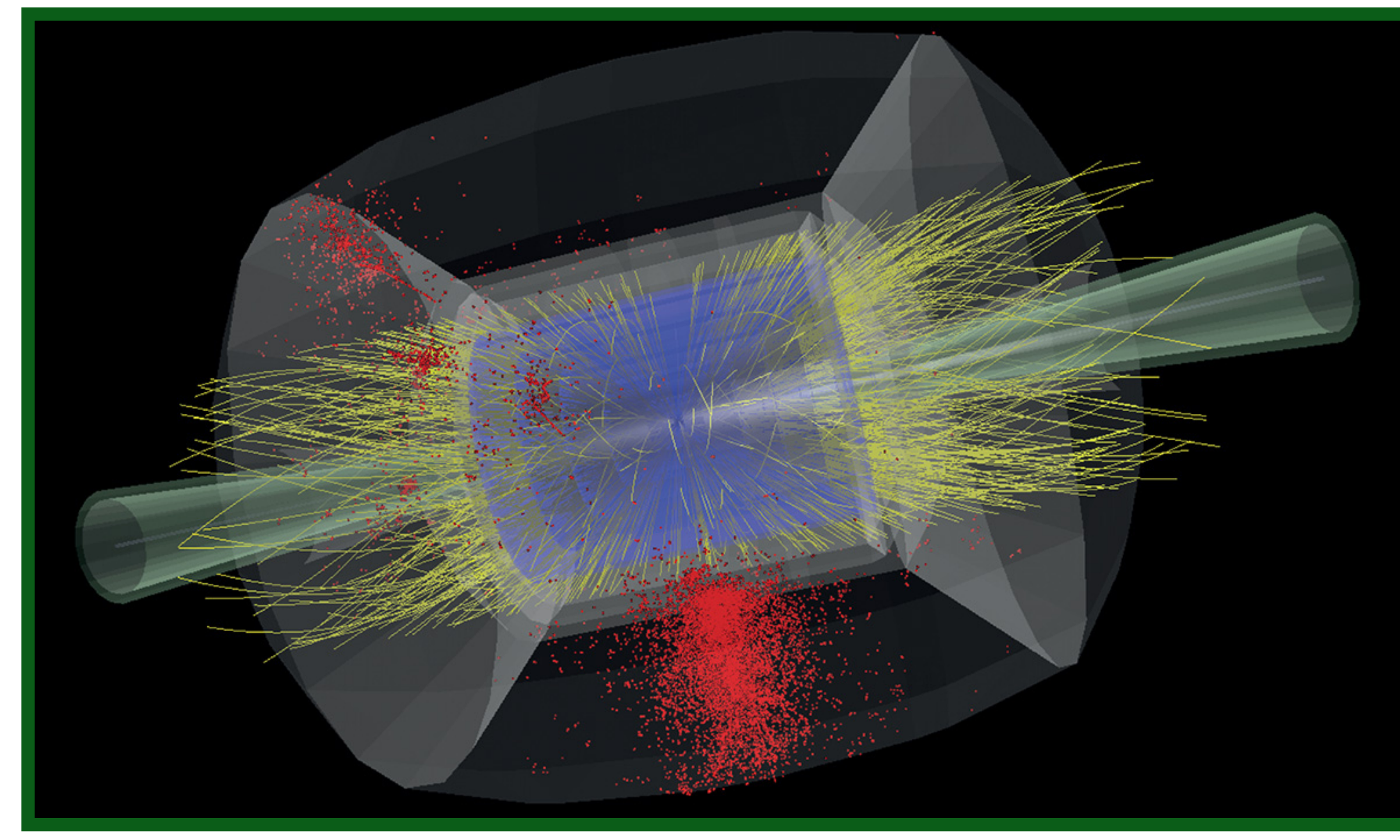
Particle Dark Matter at Future Muon Colliders





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APEC Seminar
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Based on 2006.01348, 2301.12524, 2309.11241

w/ Salah Nasri and Mohammed Belfkir

1. Introduction

Introduction

- The discovery of a Higgs boson at the Large Hadron Collider (LHC) validated the standard model (SM) as a low energy (~EW scale) description of nature.

- The SM is unable to address, however, several outstanding questions like neutrino mass, origin of baryon asymmetry in the universe or the dark matter problem among others.

- High-energy collider experiments are one of the best places to look for extensions of the SM and test its validity. This can be done in three ways:

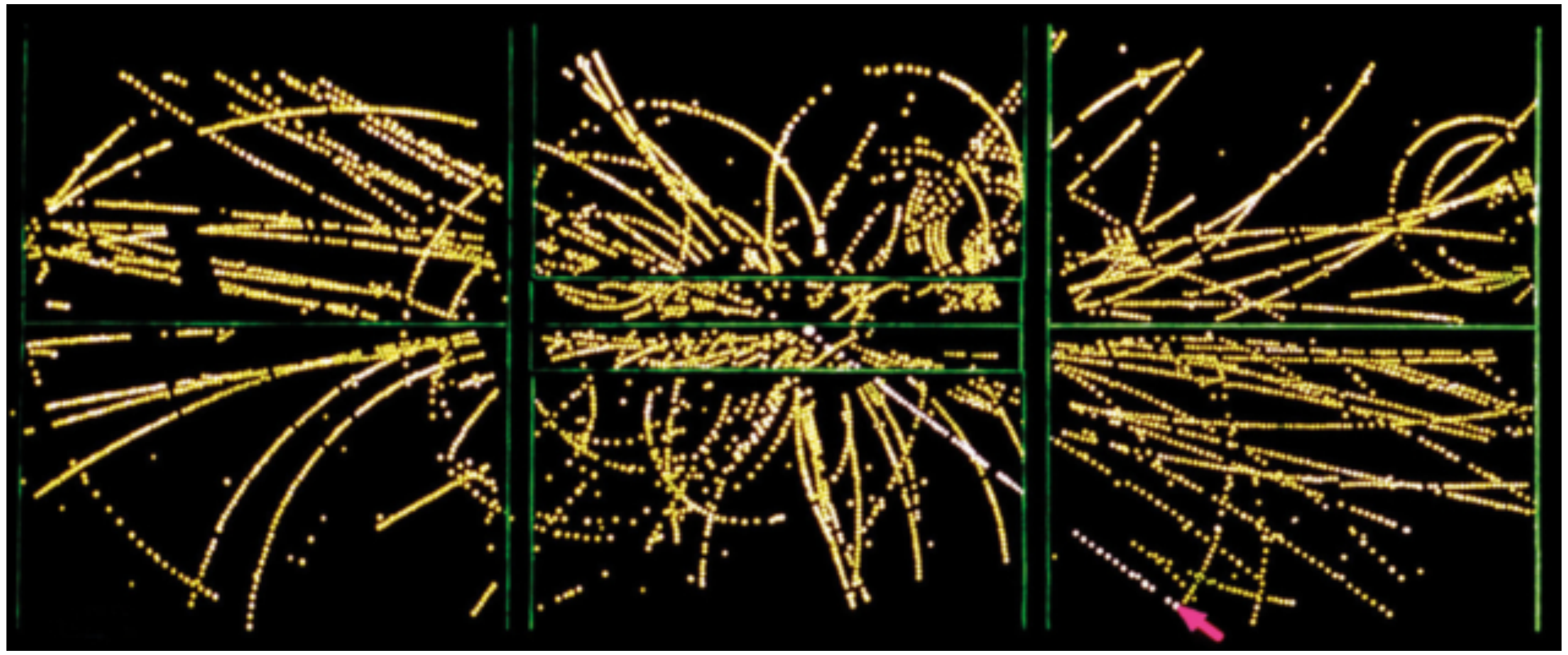
  - Direct searches of new particles
  - Tails of kinematic distributions
  - Precise measurements of SM Higgs boson couplings

- Historically the collider physics strategy consists of building high energy hadron colliders for discovery then construct lepton colliders for precision measurements (and/or new discovery) and so on…

The Super Proton-Antiproton Synchrotron

Operation: 1981-1990
Collision energy: 546-630 GeV
Integrated luminosity: up to 1.6×10^{37} cm^{-2}
Achievements: discovery of the W and Z-bosons.

Tunnel



Event display recorded in 1982 by UA1 collaboration

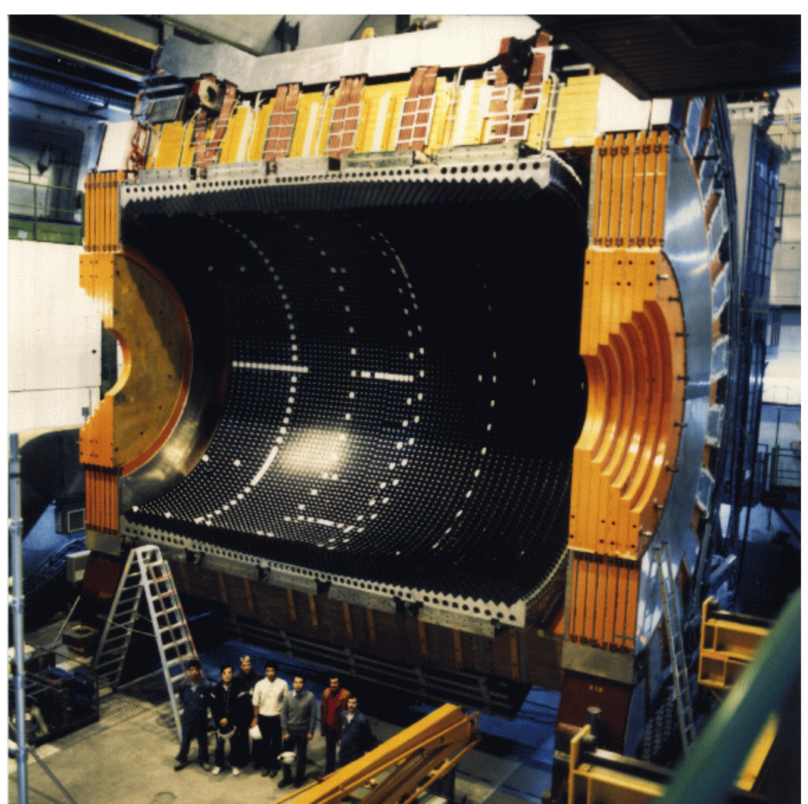
The Large Eectron-Positron (LEP) collider

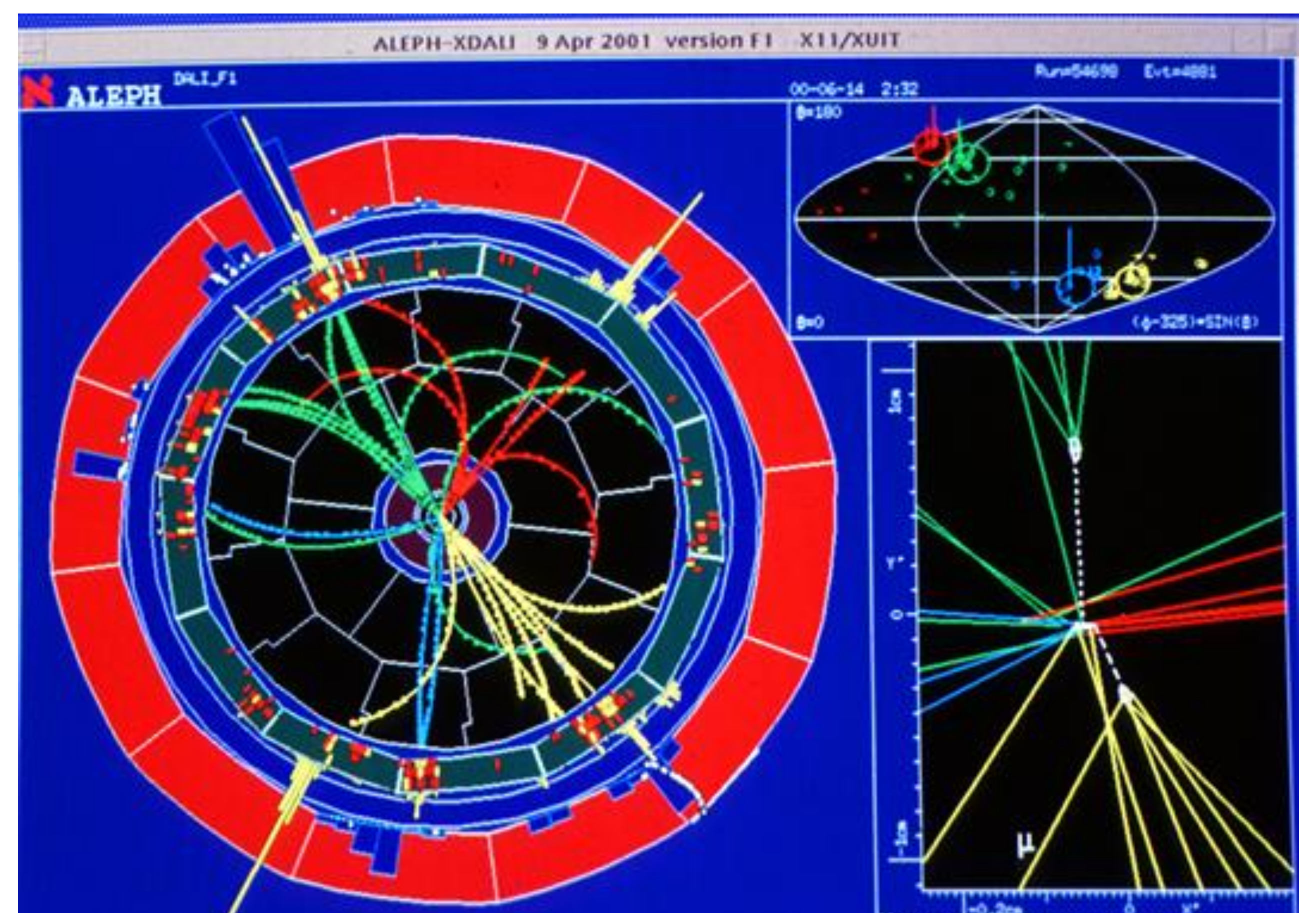
Operation: 1989-2000

Collision energy: 91.2-209 GeV

Integrated luminosity: up to $\approx 10^{32}\ \mathrm{cm}^{-2}$

Achievements: precision measurements; studies of QCD…

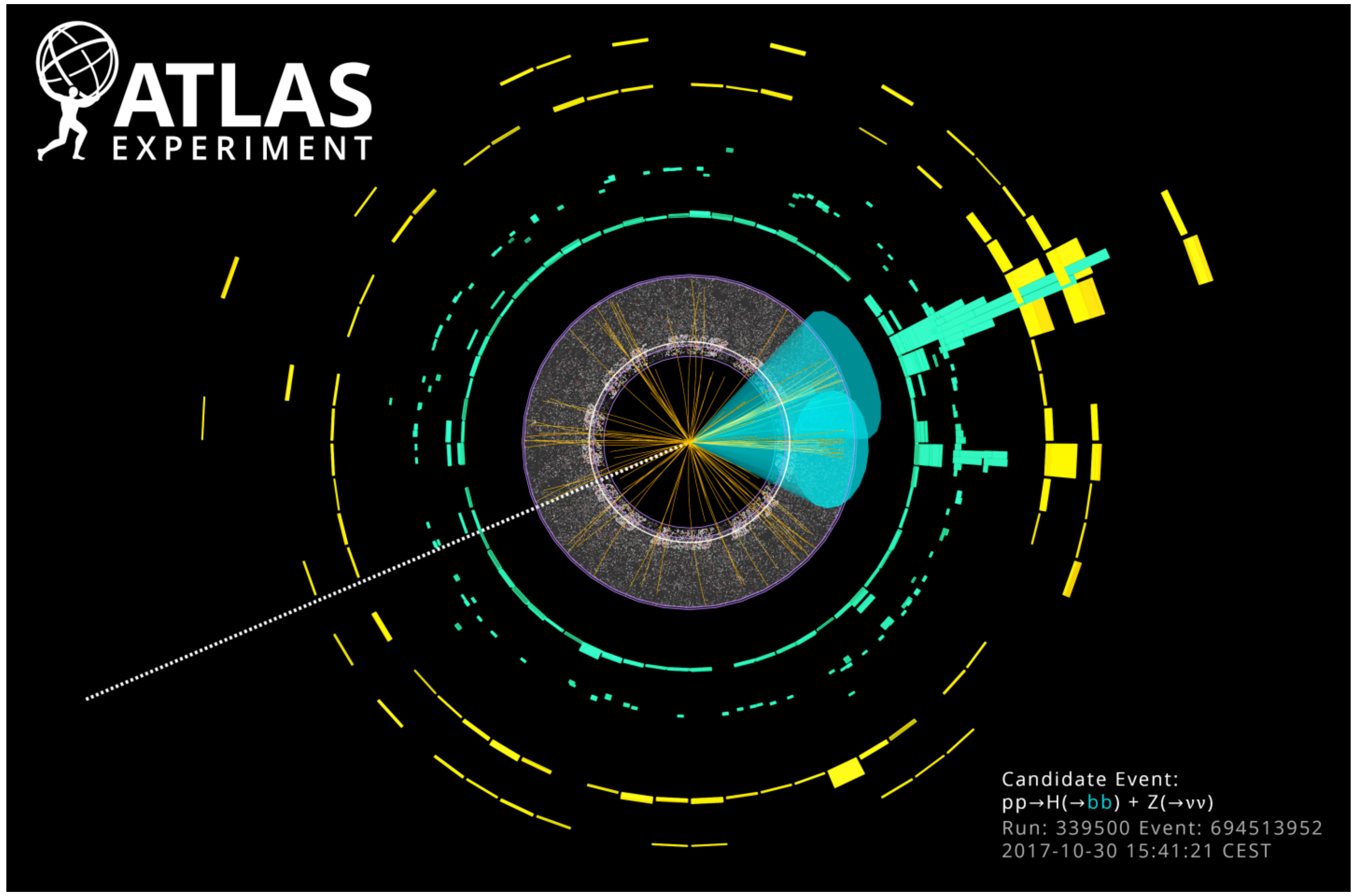




The Large Hadron Collider

Operation: 2010—present (until ~2030)
Collision energy: 7-13.6 TeV
Integrated luminosity: up to $10^{34}\ \mathrm{cm}^{-2}$ (so far)
Achievements:

- discovery of the SM Higgs boson
- Many precision measurements
- Strong bounds on various new physics candidates
- Discovery of various new hadrons (i.e. pentaquark).



Future Colliders (FCC-ee, ILC, FCC-hh…) ?

Operation: from 2045 (?)

Location: Japan, Europe, China…

Collision energy: 91.2 GeV—100 TeV

Integrated luminosity: up to $10^{37}\ \mathrm{cm}^{-2}$

Expected achievements: discovery of new physics? more Higgs, top, and Z-boson precision measurements. More studies of QCD…

Introduction

- Lepton colliders are suitable for precise measurements due to their clean environment.
- Hadron colliders on the other hand can reach higher energies and are the best places to make discoveries.

Can we have a collider which has the best of these two?

In principle a future muon collider can both run at a very high energy and possess a clean environment.

There is only one challenge: a muon is unstable and decays weakly into an electron and neutrinos.

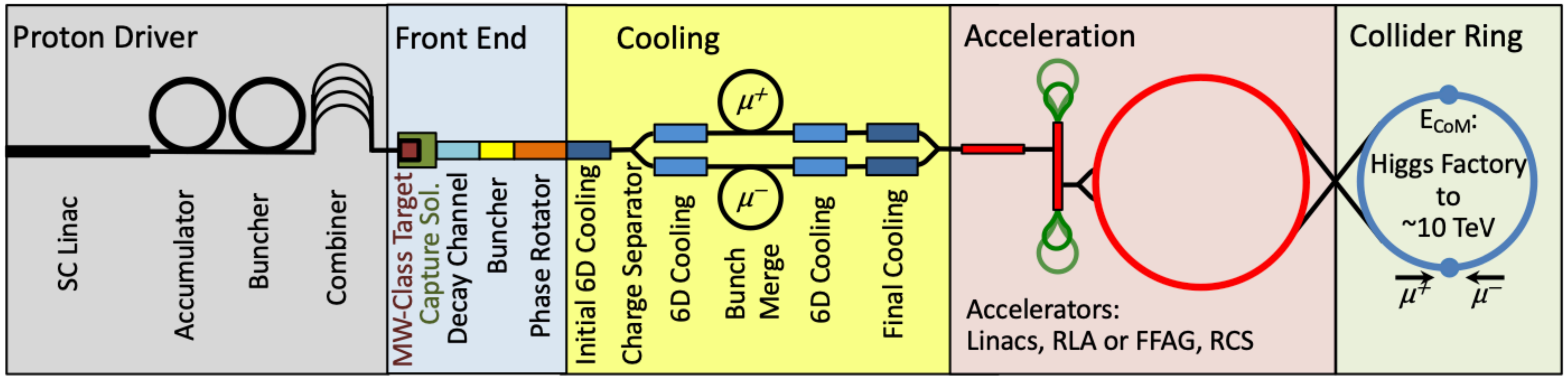
==> This problem may be solved by either the Muon Accelerator Program (R. B. Palmer; 2014) or LEMMA (M. Antonelli et al., 2015).

2. Muon colliders

Acceleration possibilities

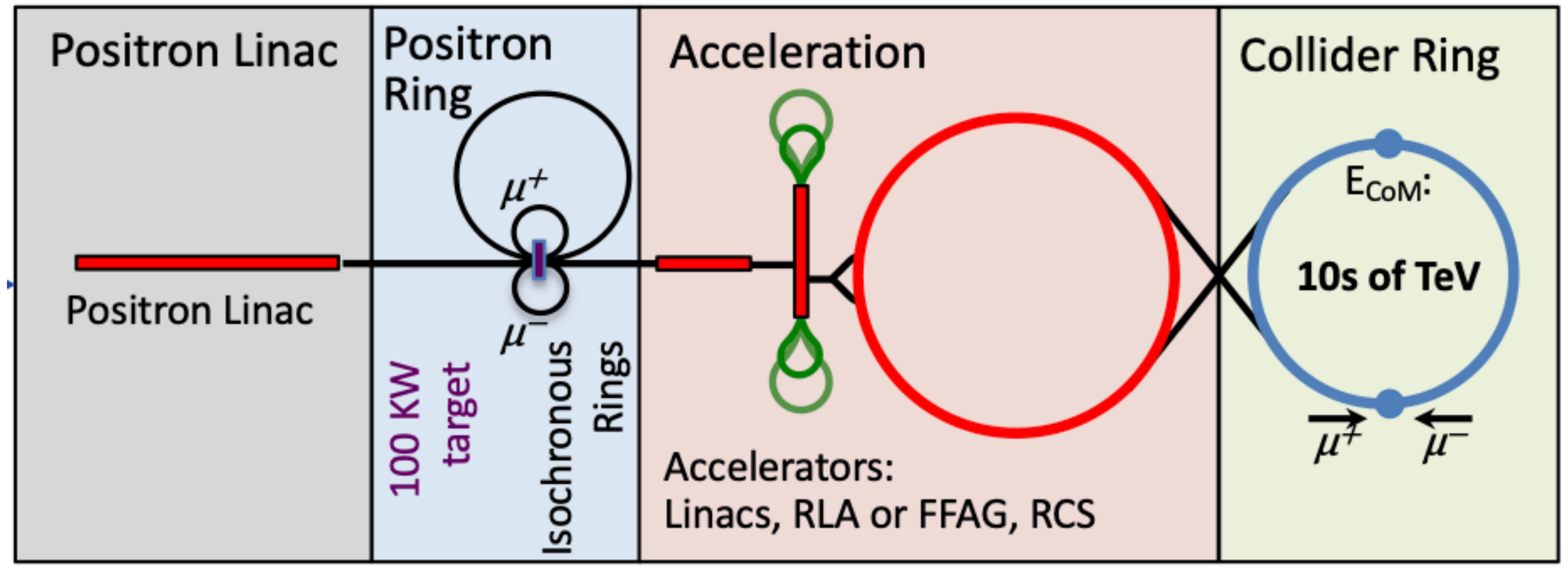
- **MUON ACCELERATOR PROJECT (MAP)**

$$p \to \pi^+ \to \mu^+$$



- **LOW EMITTANCE MUON ACCELERATOR (LEMMA)**

$$e^+ \; (45 \text{ GeV}) + e^-(0 \text{ GeV}) \to \mu^+\mu^-$$



From J. P. Delahauge et al., arXiv: 1901.06150

Muons vs Protons

What is the center-of-mass energy that is necessary to achieve the same beam-level cross section for protons?

Example: $2 \to 1$ **annihilation**

$$\sigma_p(2 \to 1) = \sum_{i,j} \int_{\tau_0}^{1} \mathrm{d}\tau \frac{\mathrm{d}\mathscr{L}_{ij}}{\mathrm{d}\tau} [\hat{\sigma}_{ij}]_p \delta\left(\tau - \frac{M^2}{s_p}\right)$$

$$\frac{\mathrm{d}\mathscr{L}_{ij}}{\mathrm{d}\tau} = \frac{1}{1+\delta_{ij}} \int_{\tau}^{1} \frac{\mathrm{d}x}{x} [f_{i/p}(x,\mu_F) f_{j/p}(x,\mu_F) + (i \leftrightarrow j)]$$

Let us have the following assumptions:

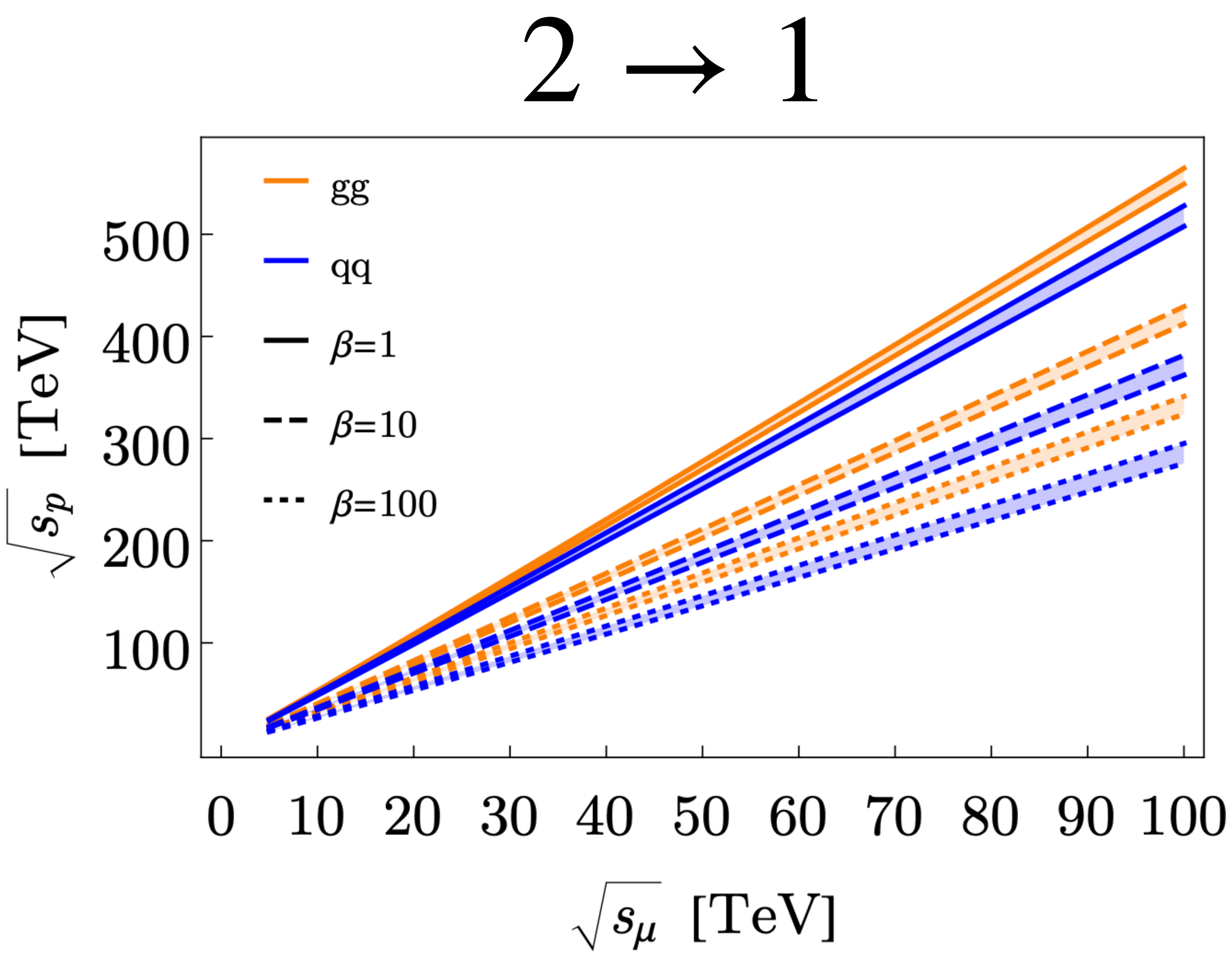
$$\mu_F = \sqrt{\hat{s}}/2; s_\mu = \hat{s} = M^2 \quad \text{and} \quad \sigma_\mu = [\hat{\sigma}]_\mu$$

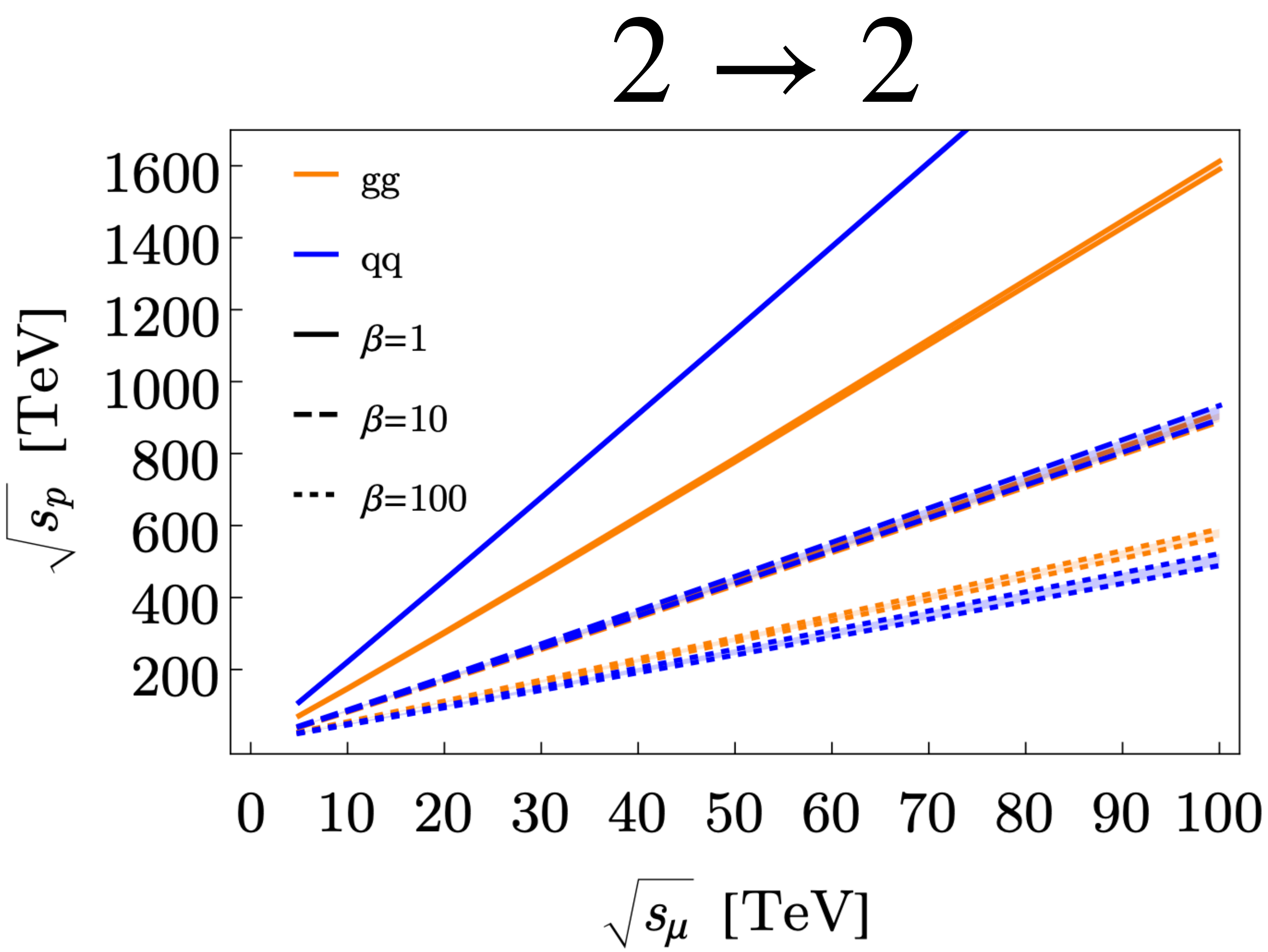
Therefore

$$\sigma_p = \sigma_\mu \qquad \Longrightarrow \frac{[\hat{\sigma}]_p}{[\hat{\sigma}]_\mu} \sigma_{ij} \frac{\mathrm{d}\mathscr{L}_{ij}}{\mathrm{d}\tau} \left(\frac{s_\mu}{s_p}, \frac{\sqrt{s_\mu}}{2}\right) = 1$$

We can solve this numerically for different values of the ratio $\beta \equiv [\hat{\sigma}]_p / [\hat{\sigma}]_\mu$

Muons vs Protons



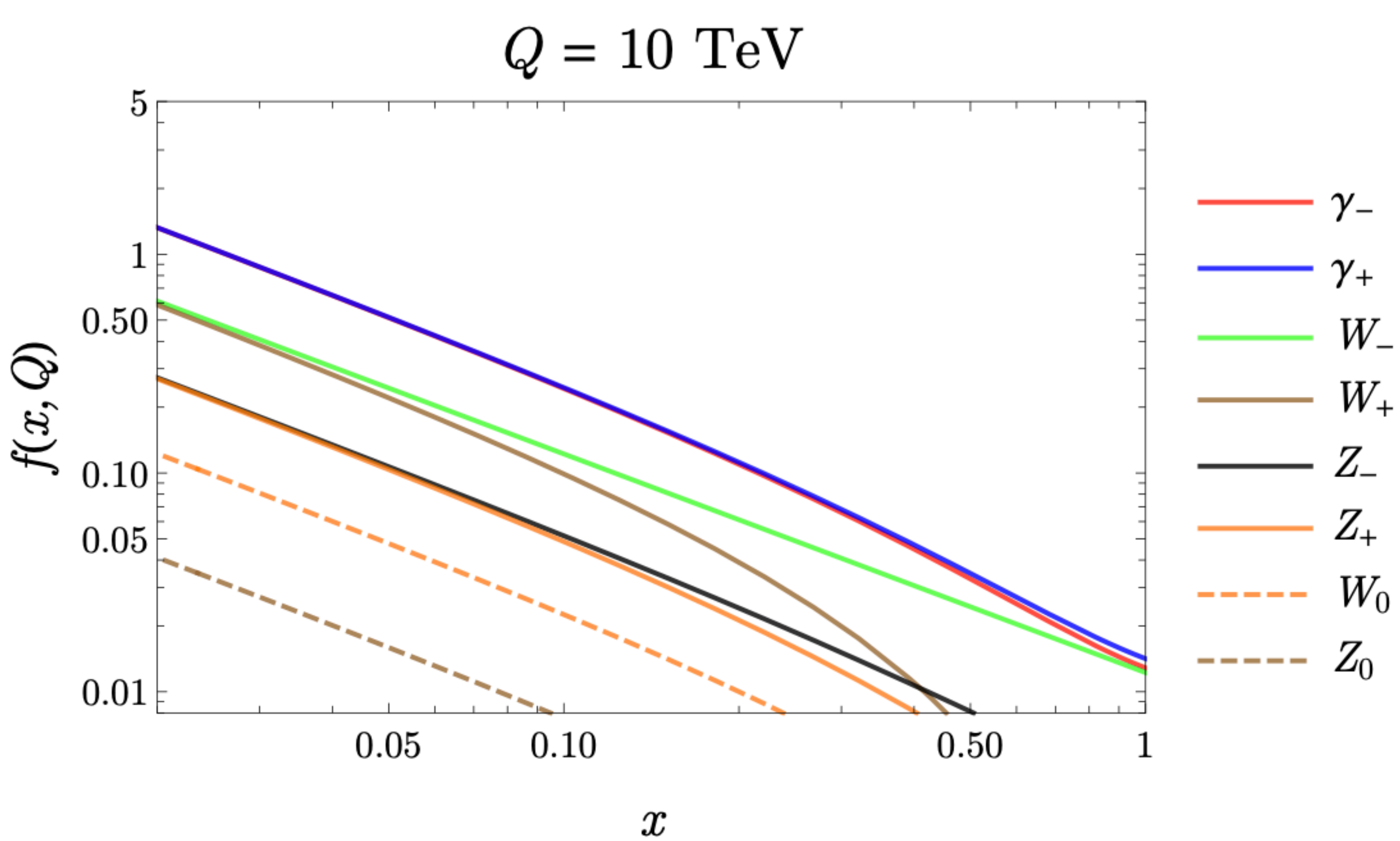


Taken from the Muon's Smasher Guide (arXiv: 2103.14043)

Vector-boson fusion

Well above the production threshold of a state X, the production cross section gets important contribution from vector-boson fusion (VBF) channels or equivalently the virtual gauge boson contents of a muon become very relevant

$$\sigma(\mu\mu \to F) = \sum_{i,j} \int_{\tau_0}^{1} \mathrm{d}x_1 \int_{\tau_0/x_1}^{1} \mathrm{d}x_2 f_{i/\mu^+}(x_1, \mu_F) f_{j/\mu^-}(x_2, \mu_F) \hat{\sigma}(ij \to F)$$



$Q \equiv \mu_F$ is factorisation scale

Vector-boson fusion

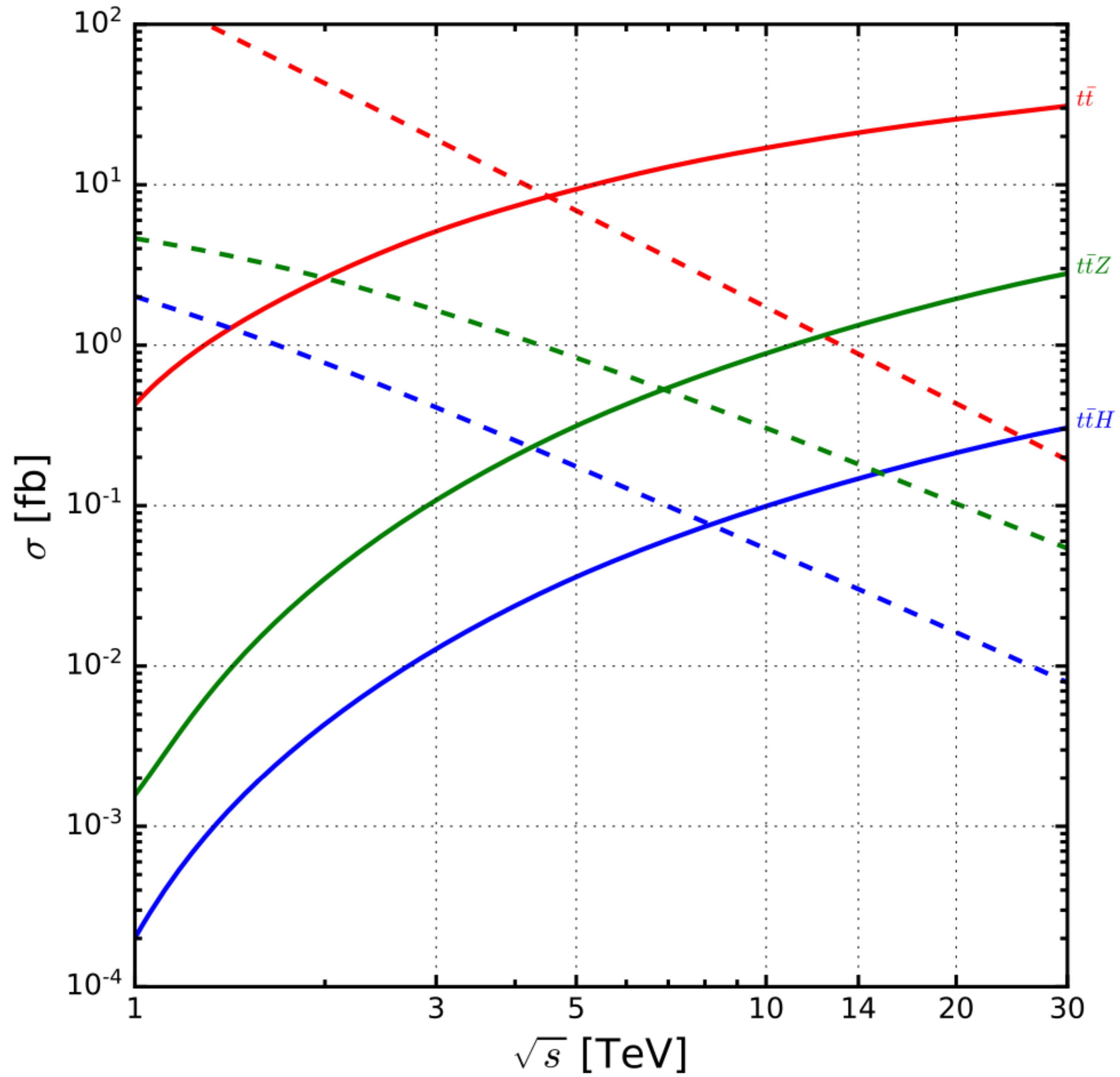
There is a crossover between VBF contribution and annihilation channel at around a few TeVs (Constantini et al., 2005.10289)

$$\frac{\sigma_{\rm VBF}}{\sigma_{\rm ann}} \propto \begin{cases} \alpha_W^2 \frac{s}{M_V^2} \log^3 \frac{s}{M_V^2} & \text{for SM} \\ \alpha_W^2 \frac{s}{M_X^2} \log^2 \frac{s}{M_V^2} \log \frac{s}{M_X^2} & \text{for BSM} \end{cases}$$

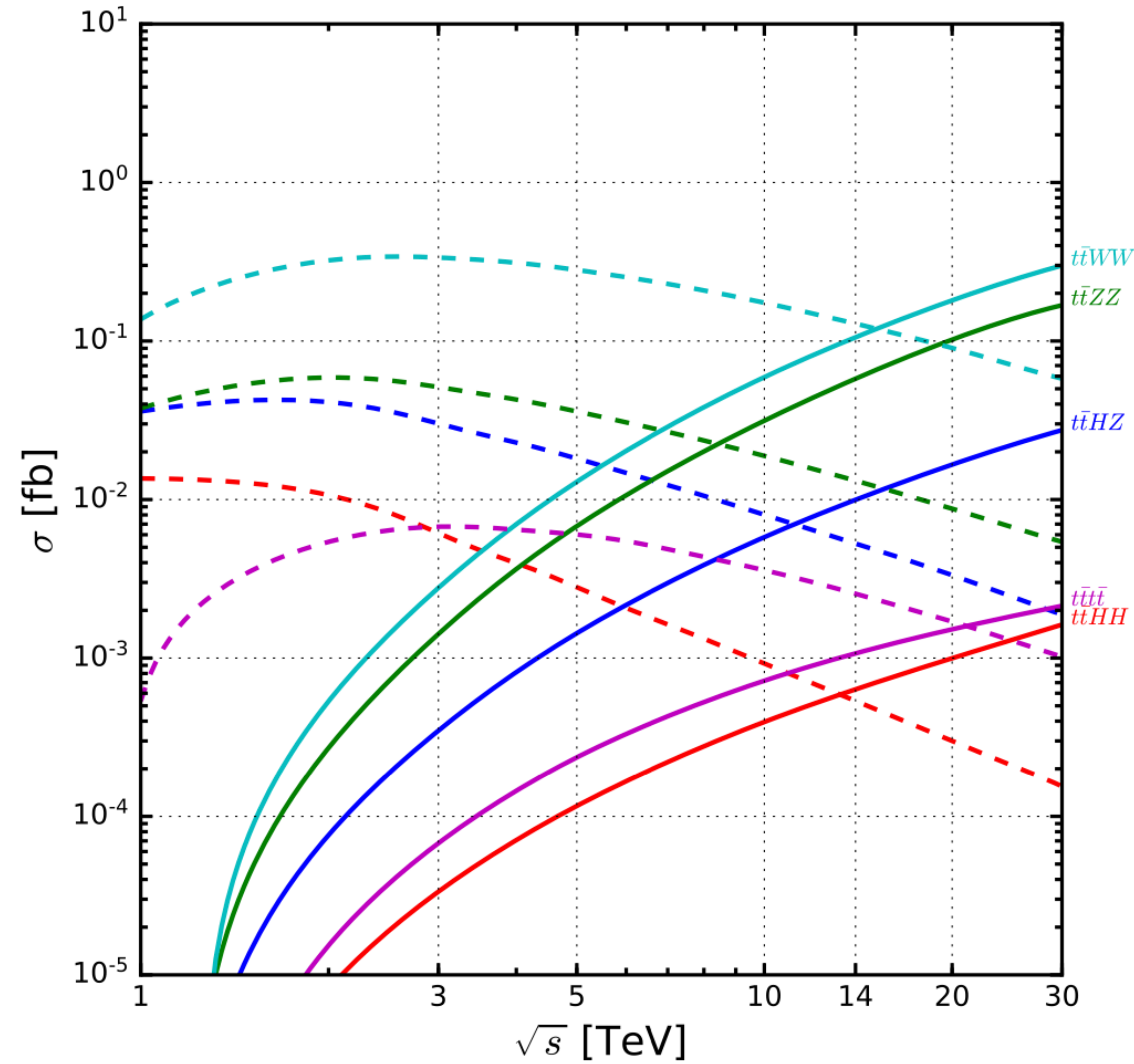
where we assume $M_X^2 \ll s$

The position of the crossover depends on the number of particles in the final state and their masses.

Vector-boson fusion (SM)



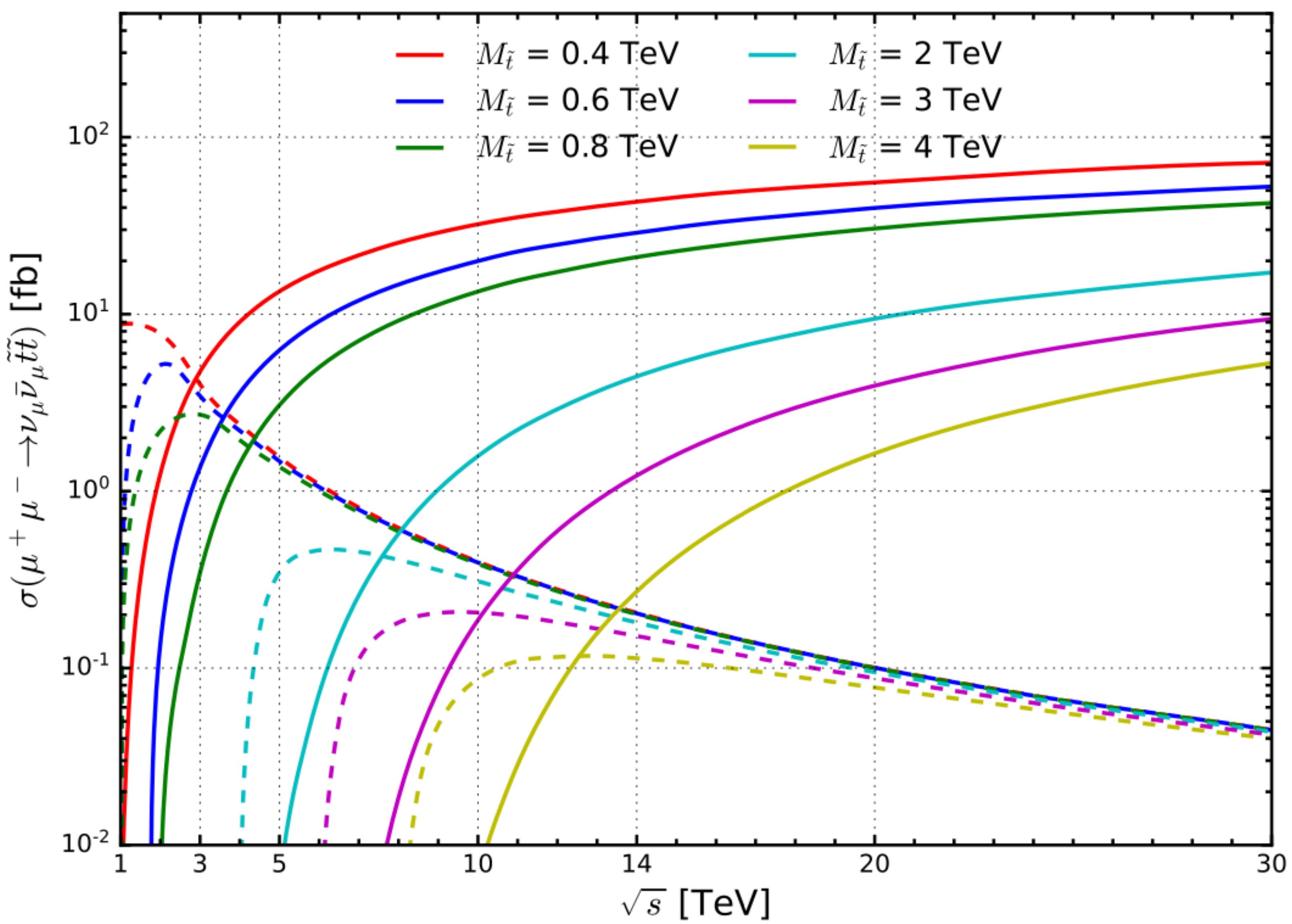
(a)



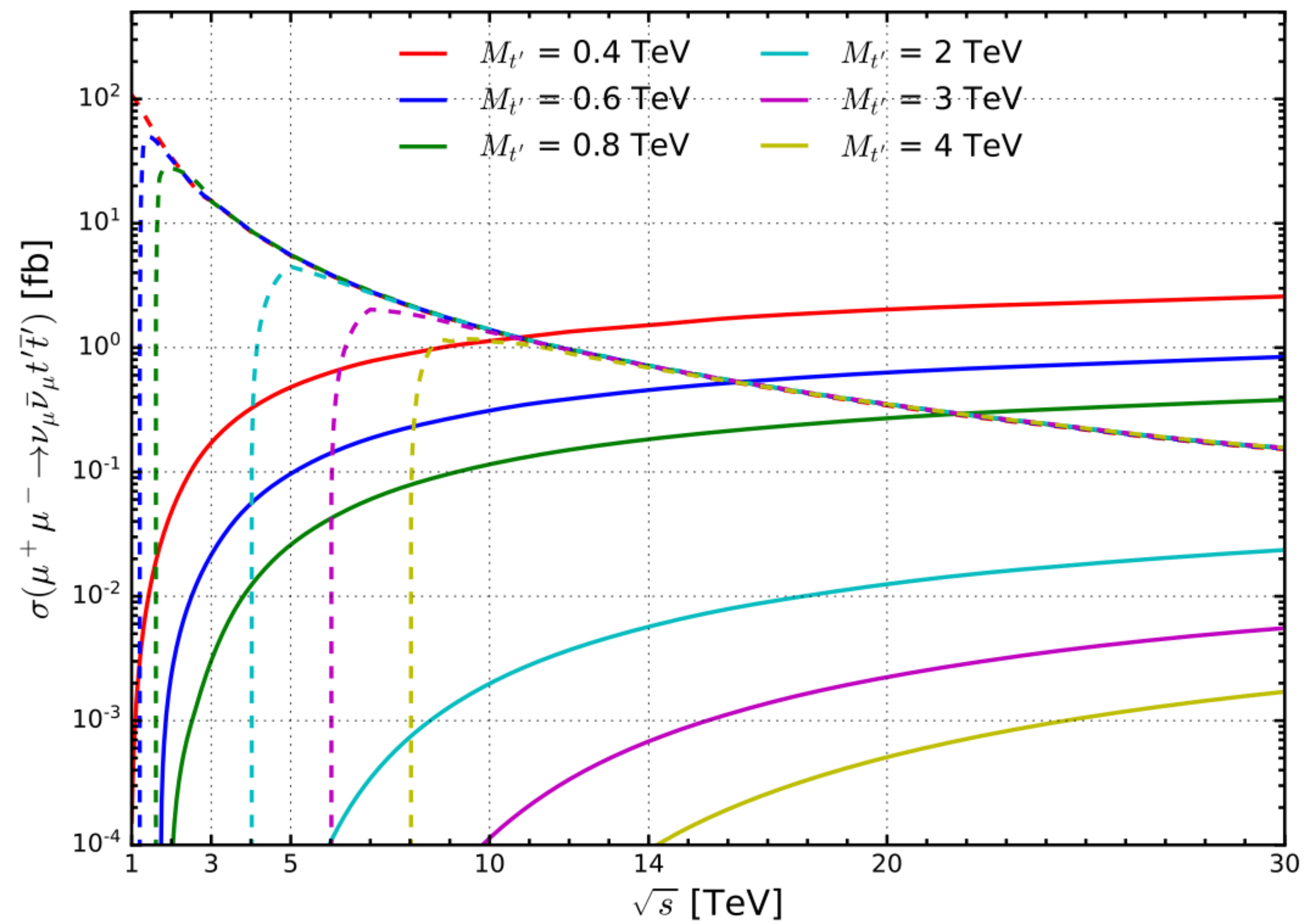
(b)

Vector-boson fusion (BSM)

$\mu^+\mu^- \to \tilde{t}\tilde{t}$

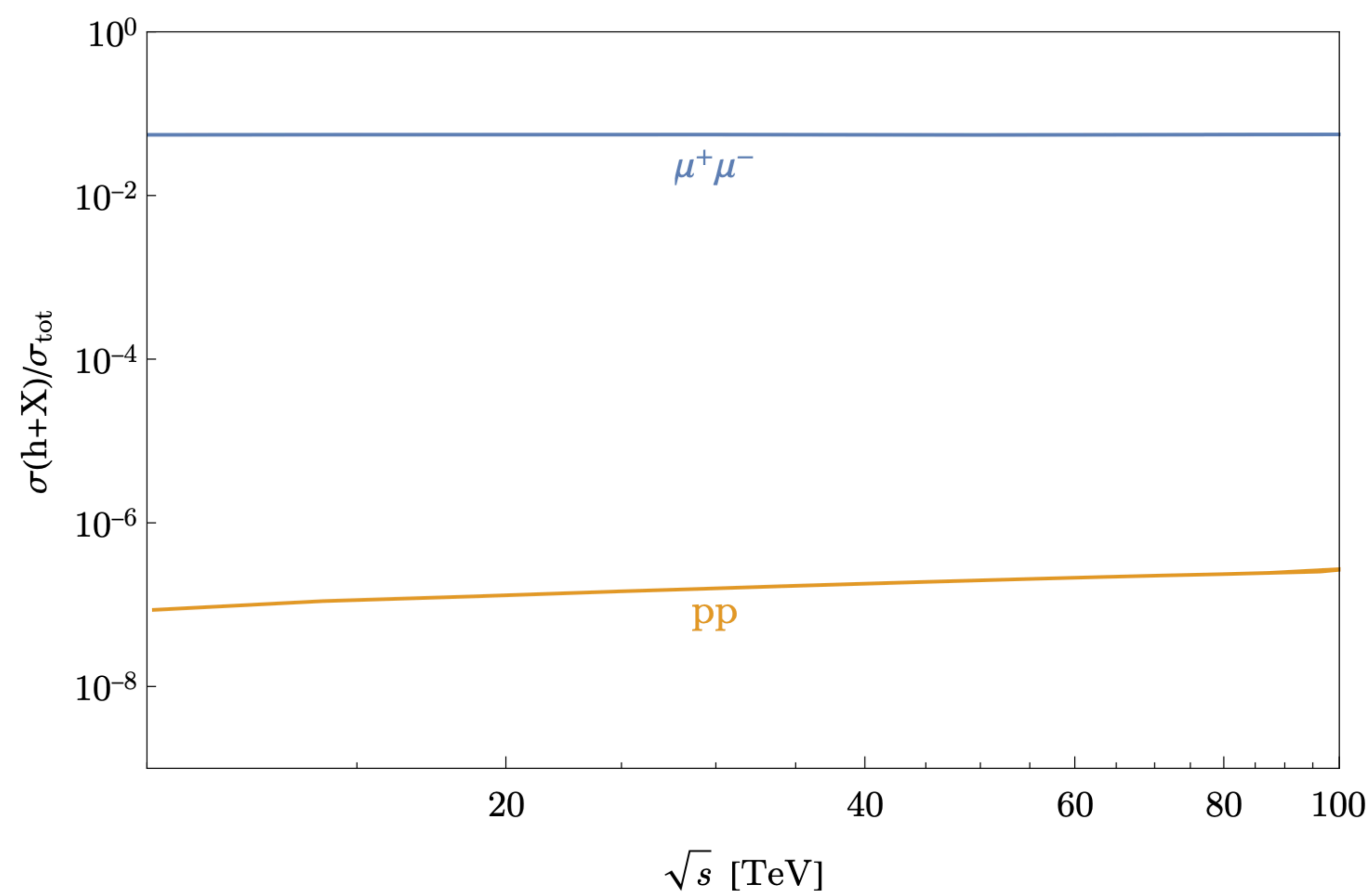


$\mu^+\mu^- \to T\bar{T}$



Signal vs backgrounds

One of the advantages of the muon colliders is that it has larger signal-to-background ratios than in proton colliders.



$$\sigma(\mu\mu \to h + X) = \sigma(\mu\mu \to h\nu\nu)$$

$$\sigma(\mu\mu)_{\mathrm{total}} = \sum_{i=h,\gamma,Z,W} \sigma(\mu\mu \to i + X)^{\mathrm{VBF}}$$

$$\sigma(pp \to h + X) = \sigma(gg \to h)^{\mathrm{N3LO}}$$

$$\sigma(pp)_{\mathrm{total}} = \sigma(pp \to b\bar{b})^{\mathrm{NNLO}}$$

Even the cross section for the SM Higgs Boson at the LHC is about 50 times larger than at muon colliders!!! (at 14 TeV).

Challenges

There are also disadvantages/difficulties that face this ambitious program.

- Require sophisticated schemes for the production and captures of muons.
- The muon decays in a few micro seconds $\Longrightarrow$ very hard to create high-quality muon beams.
- Beam-induced backgrounds (BIBs) degrade the jet energy resolution.
- Neutrinos produced in the decays of muons can cause environmental hazard?

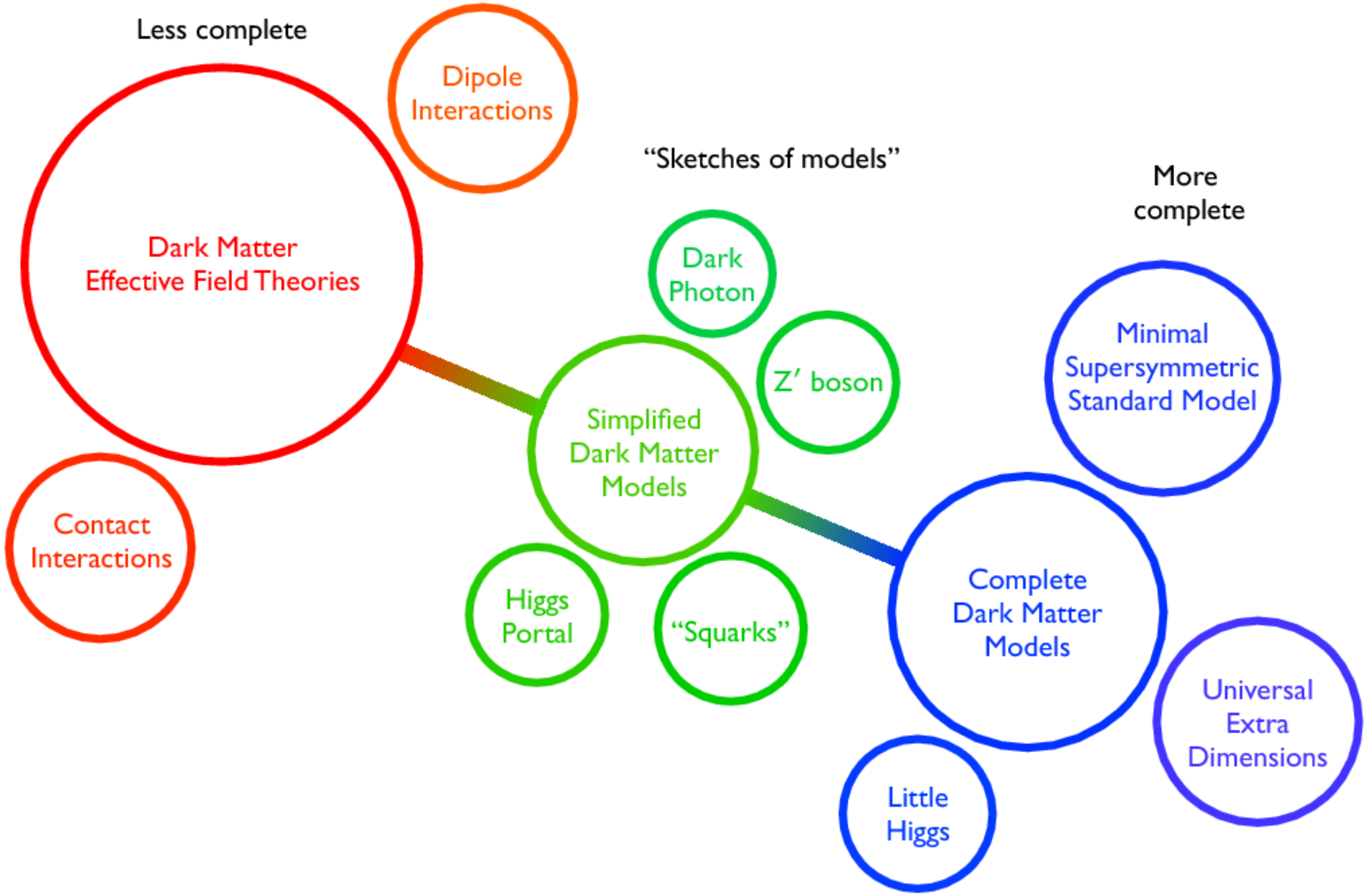
NEVER GIVE UP

Many studies!!

- Higgs boson: D. Butazzo et al. (1807.04743), M. Chiesa et al. (2005.10289), P. Bandyopadhyay et al. (2010.02597), D. Butazzo et al. (2012.11555), T. Han et al. (2108.05362), T. Han et al. (2102.08386), T. Han et al. (2008.12204), M. Forslund et al. (2308.02633), Z. Liu et al. (2308.06323).
- Muon g-2 and flavor: R. Capdevilla et al. (2006.16277, 2101.10334), D. Butazzo et al. (2012.02769), W. Yin et al. (2012.03928), G. Huang et al. (2103.01617), P. Asadi et al. (2104.05720), A. Azatov et al. (2205.13552).
- EWPT and Leptogenesis: W. Liu et al. (2101.10469), W. Liu et al. (2109.15087).
- Dark matter: T. Han et al. (2009.11287), R. Capdevilla et al. (2102.11292), A. Jueid et al. (2301.12524), M. Belfkir et al. (2309.11241).
- PDFs: T. Han et al. (2103.09844), T. Han et al. (2007.14300), F. Garosi et al. (2303.16964), S. Frixione et al. (2309.07516).
- Neutrino Physics: J. Liu et al. (2207.07382), A. Jueid et al. (2306.01255), S. Jana et al. (2308.07375).

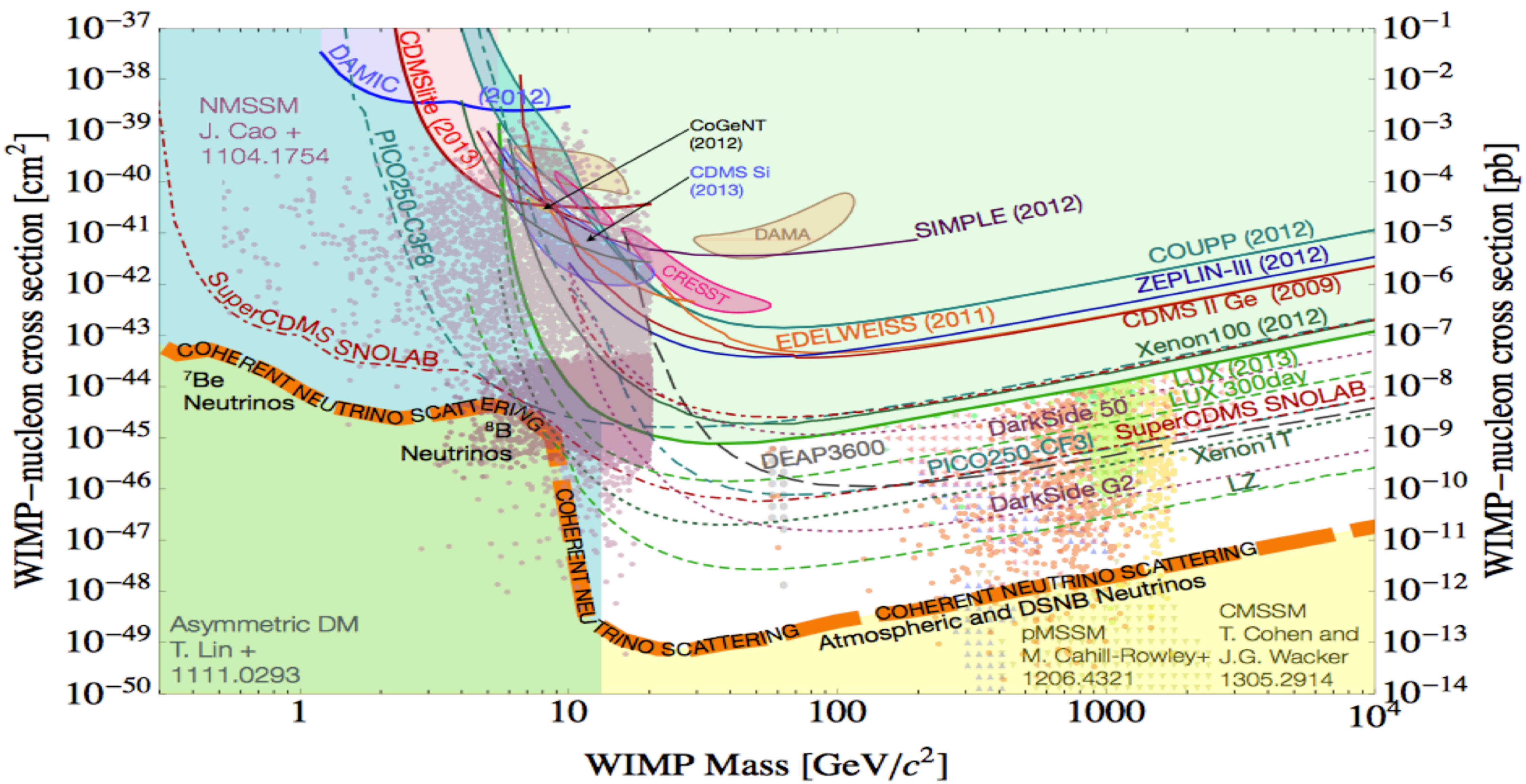
3. Minimal Lepton Portal DM

The dark matter landscape



Credit: T. Tait

Direct detection is more harsh for WIMP: Close to the neutrino floor



PROBLEM: **dark-matter direct searches are strongly correlated with collider searches.**

→ **Strong bounds imply expected weak signals at colliders.**

- **The strong bounds from direct-detection experiments tend to exclude the simplest dark-matter model; e.g. *the singlet model.***

What if the dark matter candidate is a singlet Majorana fermion?

- Usually, these simple dark-matter models lead to s-wave annihilation channels; Models with s-wave annihilations are almost excluded (Leane, Slatyer, Beacom and Ng; 2018).
- Collider searches at the Large Hadron Collider tend to exclude couplings of order $\mathcal{O}(1)$ and light masses (see e.g. the summary plots in ATL-PHYS-PUB-2020-021)
- An alternative solution is to consider (or reconsider) Majorana singlet fermions as dark-matter candidates:

    i. The elastic scattering of dark-matter off the nucleus is induced at the one-loop order $\longrightarrow$ The corresponding cross-section is always suppressed even for couplings of order $\mathcal{O}(1)$.

    ii. Hard to produce at hadron colliders for a wide class models $\longrightarrow$ Explain why it is not observed so far?

    iii. Annihilation cross section occurs through p-wave amplitudes; no signal, no problem.

    iv. Lepton colliders may play the role of discovery machines for these models.

A Minimal Lepton portal dark-matter model

We suggest a new minimal model where extend the Standard Model with two gauge-singlets; a charged scalar S and a right-handed singlet Majorana fermion N_R.

They transform under $SU(3)_c \times SU(2)_L \times U(1)_Y$ as

$$S: \ (\mathbf{1}, \mathbf{1})_{+2} \text{ and } N_R: \ (\mathbf{1}, \mathbf{1})_0$$

These extra states are odd under an extra Z_2 symmetry (called matter parity) while all the SM particles are even, i.e. $\{S, N_R\} \to \{-S, -N_R\}$ and $\{V^\mu, f, \Phi\} \to \{V^\mu, f, \Phi\}$

The most general interaction Lagrangian can be written as

$$\mathscr{L}_{\text{int}} \supset \sum_{\ell=e,\mu,\tau} Y_\ell \bar{\ell}^c_R S N_R + \lambda_2 |S^\dagger S|^2 + \lambda_3 |\Phi^\dagger \Phi| |S^\dagger S|$$

The scalar singlet (S) is electrically-charged and plays the role of a mediator between dark matter and the SM sectors:

$$\mathscr{L}_{\text{gauge}} \supset -i\left(eA^\mu - e\tan\theta_W Z^\mu\right) S^\dagger \overleftrightarrow{\partial}_\mu S$$

UV realizations

- If you would like neutrinos to be massive, add two extra right handed neutrinos (N_2, N_3) and an inert scalar isodoublet Φ_2.

  $\Longleftrightarrow$ decouple the two other right-neutrinos and make the other couplings small and you will get Leptogenesis as a bonus.

- We can embed this into e.g. a $SU(5)$ theory: the matter fields in the $\mathbf{10}_F$ and $\bar{\mathbf{5}}_F$ representations and the charged singlet belongs to the $\mathbf{10}_H$ representation, while N_R belongs to the singlet representation $\mathbf{1}_N$

$$\mathscr{L} = g_{\alpha\beta}\overline{\mathbf{10}}_{F_\alpha} \otimes \mathbf{10}_H \otimes \mathbf{1}_{N_\beta} \supset g_{\alpha\beta}\ell^T_{R\alpha}CN_\beta S^+$$

- You can also have it in a flipped-$SU(5) \otimes U(1)_X$ grand-unified theory: The lepton field is a singlet of $SU(5)$, and N_R is a member of the $\mathbf{10}_F$ representation

$$\mathscr{L} = \frac{h_{\alpha\beta}}{\Lambda}\overline{\mathbf{10}}_{F_\alpha} \otimes \bar{\mathbf{1}}_{F_\beta} \otimes \mathbf{10}_H \otimes \mathbf{1}_S \supset \frac{h_{\alpha\beta}\langle \mathbf{10}_H\rangle}{\Lambda} N^T C \ell_R S^-$$

What about the various constraints?

After electroweak symmetry breaking; one lefts with two extra states (N_R and $H^\pm$) and seven extra parameters (three are interconnected via lepton-flavor violation and one is irrelevant in phenomenological studies). The parameters are

- General case: $\{M_{H^\pm}, M_{N_R}, \lambda_2, \lambda_3, Y_{eN}, Y_{\mu N}, Y_{\tau N}\}$
- Relevant for DM: $\{M_{H^\pm}, M_{N_R}, \lambda_2, \lambda_3, Y_{\ell N}\}$

$$Y_{\ell N} = \sqrt{Y_{eN}^2 + Y_{\mu N}^2 + Y_{\tau N}^2}$$

Theoretical constraints

(i) Vacuum stability: the scalar potential should bounded from below (Branco et al.; 2012)

(ii) Perturbativity & Perturbative unitarity

(iii) False vacuum

Experimental constraints

(i) $H \to \gamma\gamma$

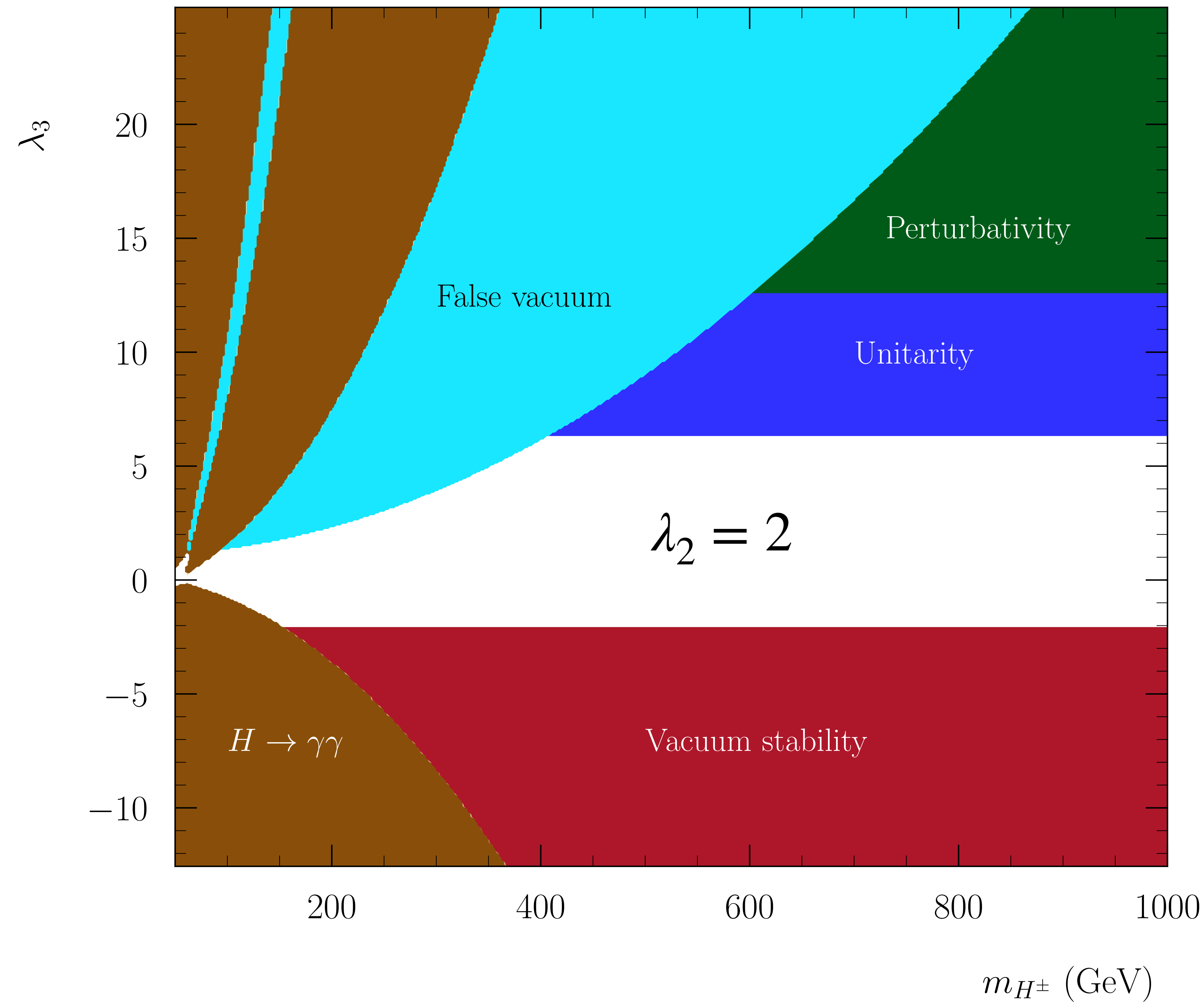
(ii) Higgs invisible decay ($H \to NN$): relevant for $m_H > 2m_N$

(iii) Charged lepton flavor violating decays; $\ell_\alpha \to \ell_\beta \gamma$ and $\ell_\alpha \to \ell_\beta \ell_\gamma \overline{\ell}_\gamma$

(iv) Searches of charginos at LEP-II.

Summary of theoretical and experimental constraints

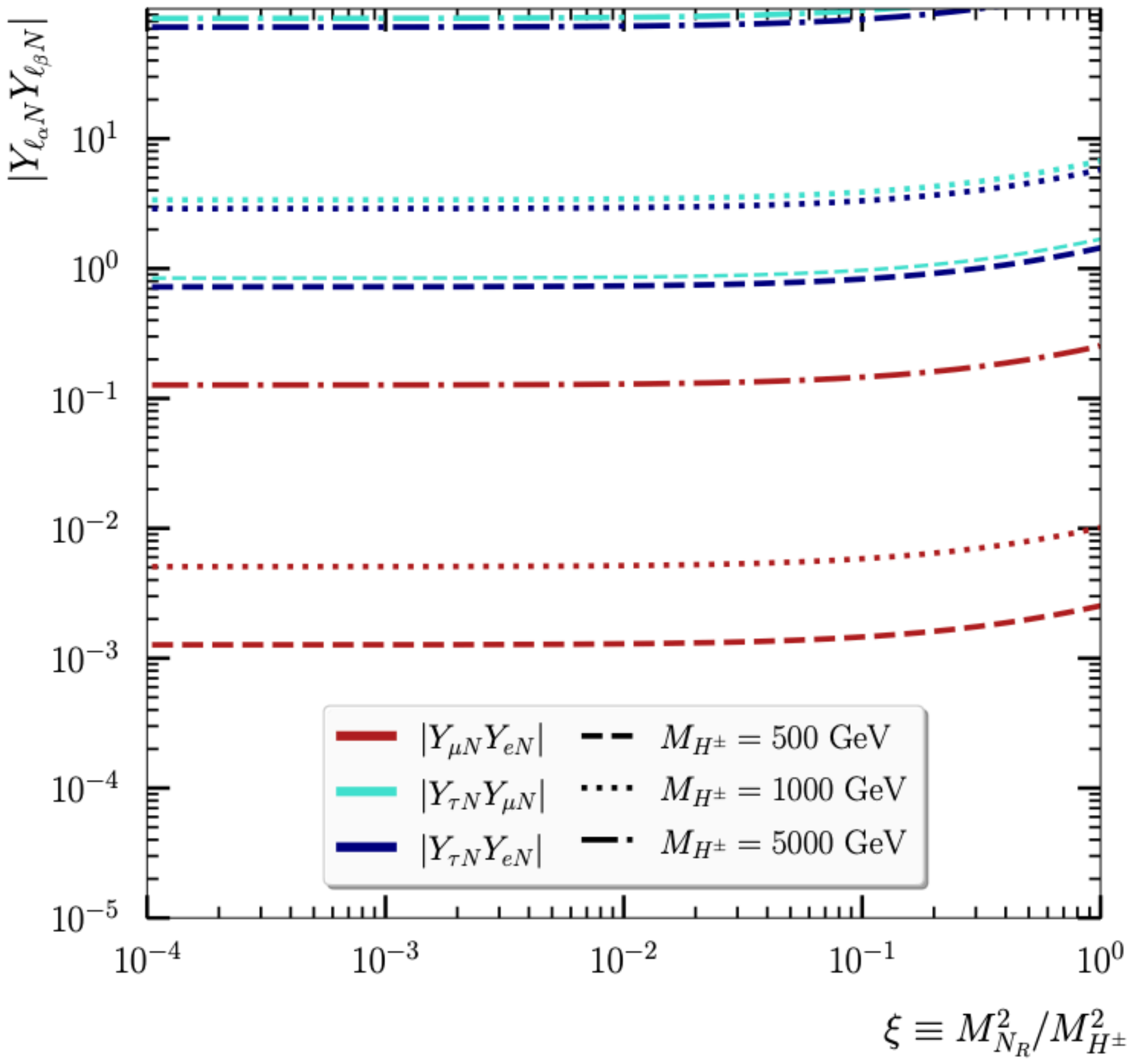
- Perturbativity and unitarity constraints exclude large values of λ_3.
- The bounds on the charged Higgs mass do not depend on λ_3 for $\lambda_3 \approx \mathcal{O}(1)$.
- If λ_3 is large, false vacuum constraints exclude light charged scalar masses; i.e. one has $m_{H^\pm} \geq 350$ GeV for $\lambda_3 = 5$.
- For $\lambda_3 > 0$, there is a region where the constraints from $H \to \gamma\gamma$ completely vanish.



Charged lepton flavor violation

Bounds on $\mathrm{BR}(\ell_\alpha \to \ell_\beta \gamma)$ **from MEG and BABAR**

$$\left\{ |Y_{eN}Y_{\mu N}|, |Y_{\mu N}Y_{\tau N}|, |Y_{\tau N}Y_{eN}| \right\} < \left\{ \left(\frac{2.85 \times 10^{-5}}{\mathrm{GeV}}\right)^2, \left(\frac{3.07 \times 10^{-4}}{\mathrm{GeV}}\right)^2, \left(\frac{2.87 \times 10^{-4}}{\mathrm{GeV}}\right)^2 \right\} \times \frac{M_{H^\pm}^2}{|F(\xi)|}$$



The constraints on $|Y_{iN}Y_{jN}|$ are very severe if $H^\pm$ is light and become weak for $m_{H^\pm} \simeq \mathcal{O}(10^3)$ GeV.

- $Y_{eN} \simeq \mathcal{O}(1) \gg Y_{\tau N} \geq Y_{\mu N}$: Interesting for e^+e^- colliders.
- $Y_{eN} \simeq Y_{\mu N} \simeq Y_{\tau N} \simeq \mathcal{O}(10^{-2})$: can be tested in hadronic collisions (very hard to achieve the correct relic density).
- $Y_{\mu N} \simeq \mathcal{O}(1) \gg \ (\geq) Y_{\tau N} \gg Y_{eN}$: Interesting for $\mu^+\mu^-$ colliders.

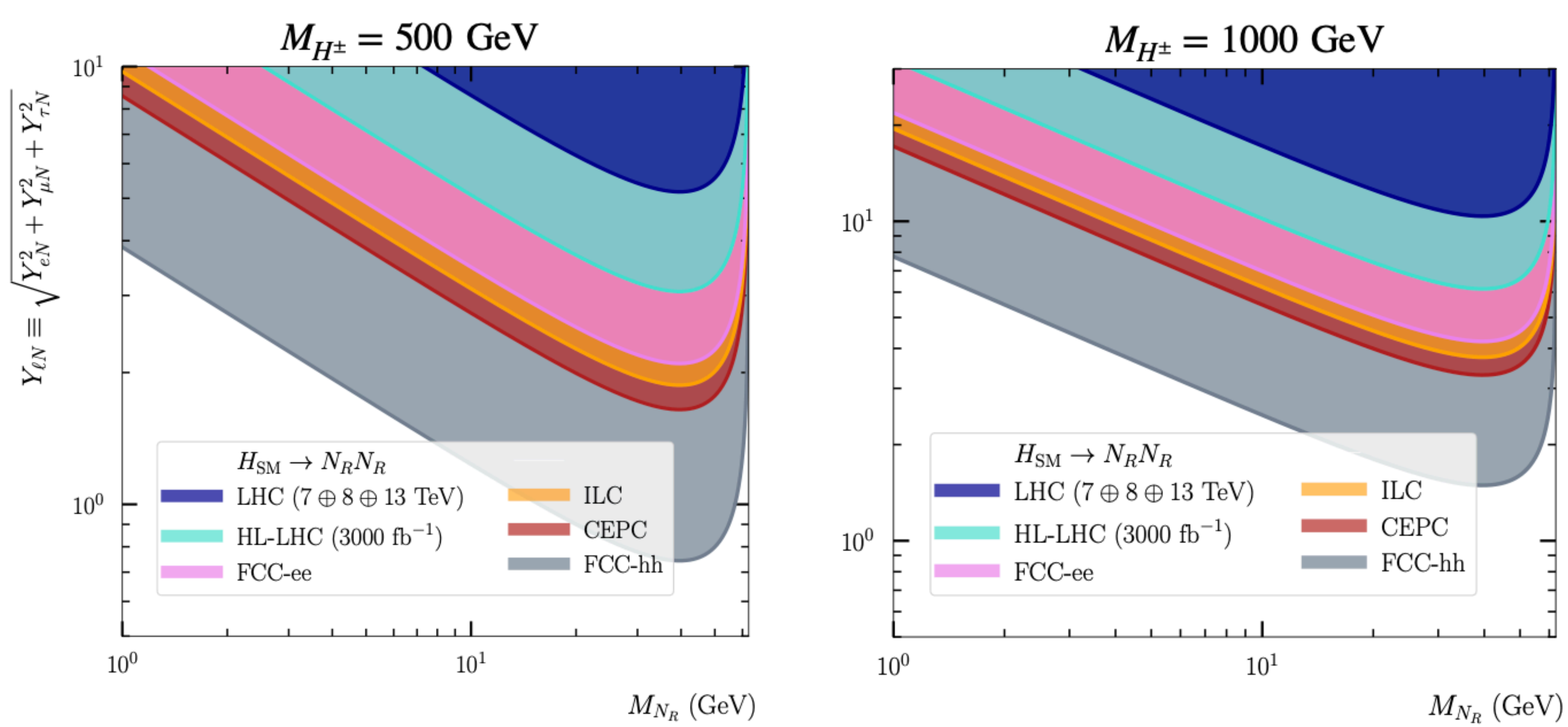
Higgs invisible decay

$$Y_{\ell N} < \left(\frac{2^{11} \pi^5 \Gamma_H^{\rm SM}}{\beta_N^3 m_H \lambda_3^2 v^2 m_N^2 |C_0 + C_2|^2 \mathscr{R}_{\rm exp}} \right)^{1/4}$$

$$\mathscr{R}_{\rm exp} = \frac{1}{B_{H \to \rm invisible}^{\rm up.bound}} - 1 \qquad C_{0,2} \equiv C_{0,2}(m_N^2, m_H^2, m_N^2, m_\ell^2, m_{H^\pm}^2, m_{H^\pm}^2)$$

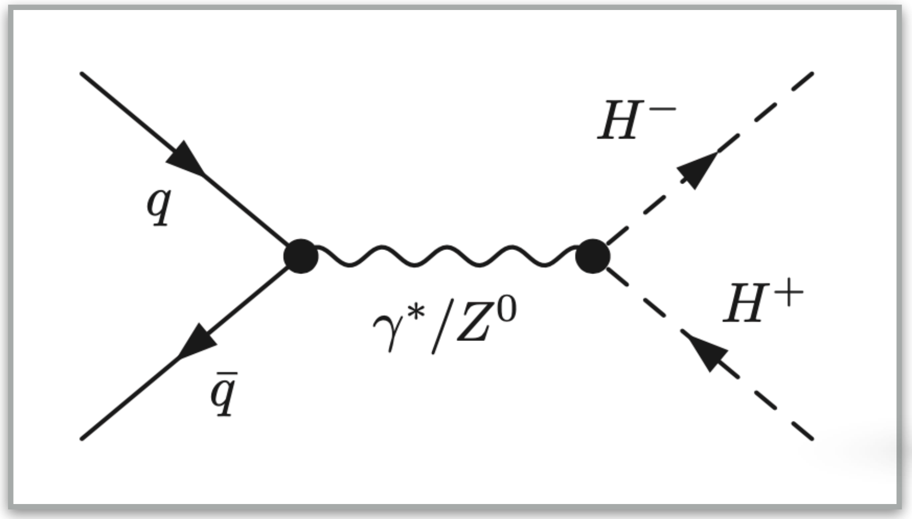
Passarino-Veltman functions

- The future constraints on $Y_{\ell N}$ are expected to be very important for light charged Higgs boson.
- Still some room for future studies to be focused on light dark-matter masses.
- Note that it's very hard to produce the correct relic density for $M_{N_R} < 10$ GeV if we assume the perturbativity of the couplings.



Status at the Large Hadron Collider

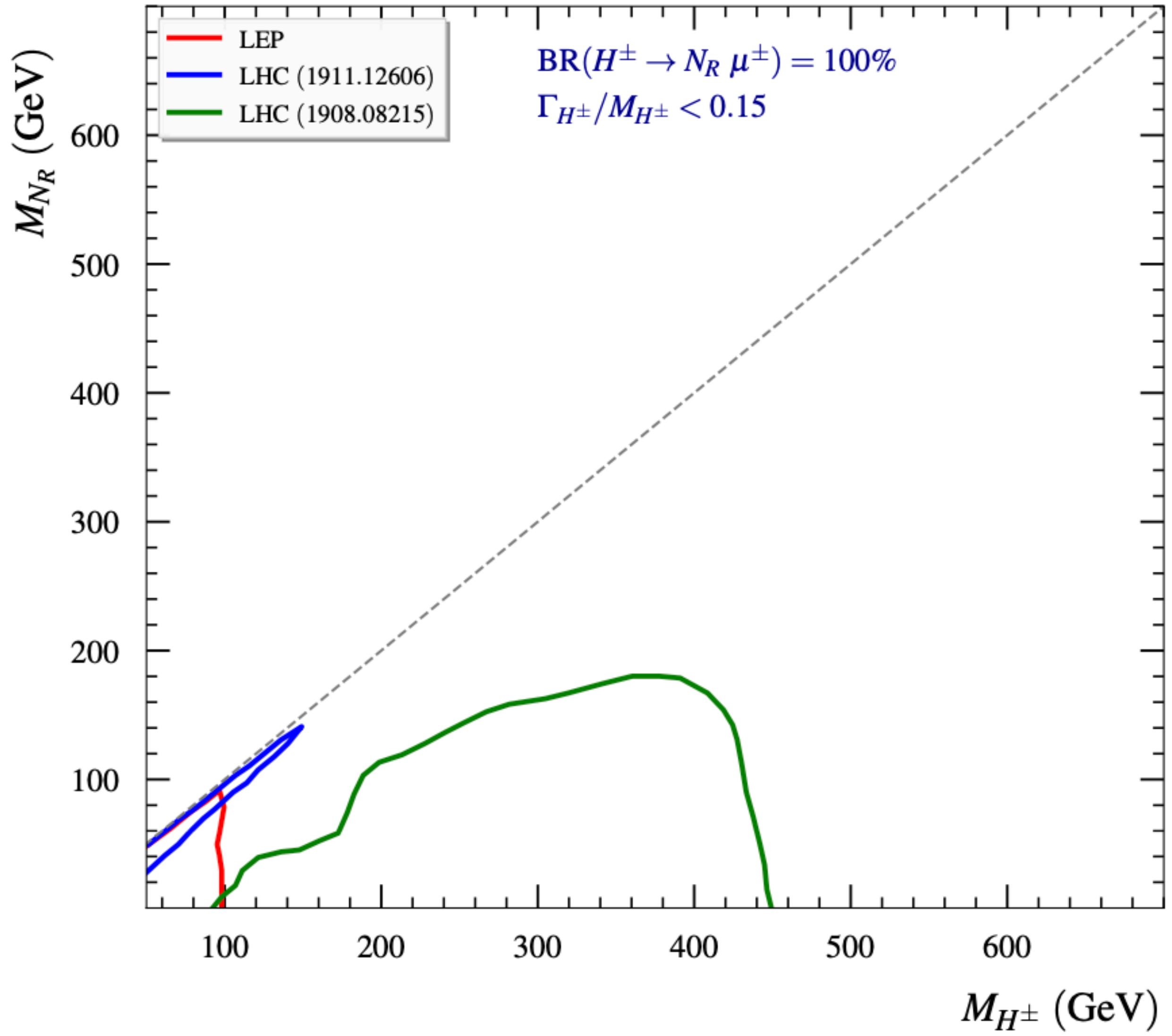
- The model can be constrained from re-interpretation of the results of sleptons/charginos (using MadAnalysis 5).
- In our model, we can pair produce the charged Higgs boson through $q\bar{q}$ annihilation and then decay them to charged leptons plus large MET.
- ATLAS has searched for sleptons/charginos defining eight signal regions — depend on the jet multiplicity $n_{\rm jet} = 0,1$ and the bins for the stranverse mass M_{T2} —.
- Masses of the charged Higgs boson up to 400 GeV can be excluded.
- No sensitivity at all for small mass splitting $(m_{H^\pm} - m_N)$.



$+$ ≤ 2 partons

+ Merging

Destructive interference between γ^* and Z^0



Dark matter relic abundance

The relic abundance of N_R gets contributions that can be categorized into sets (assuming freeze-out mechanism):

(i) Annihilation into SM particles: important for $Y_{\ell N} = \sqrt{Y_{eN}^2 + Y_{\mu N}^2 + Y_{\tau N}^2} \approx \mathcal{O}(1)$

$$N_R N_R \to \ell_\alpha^\pm \ell_\beta^\mp$$

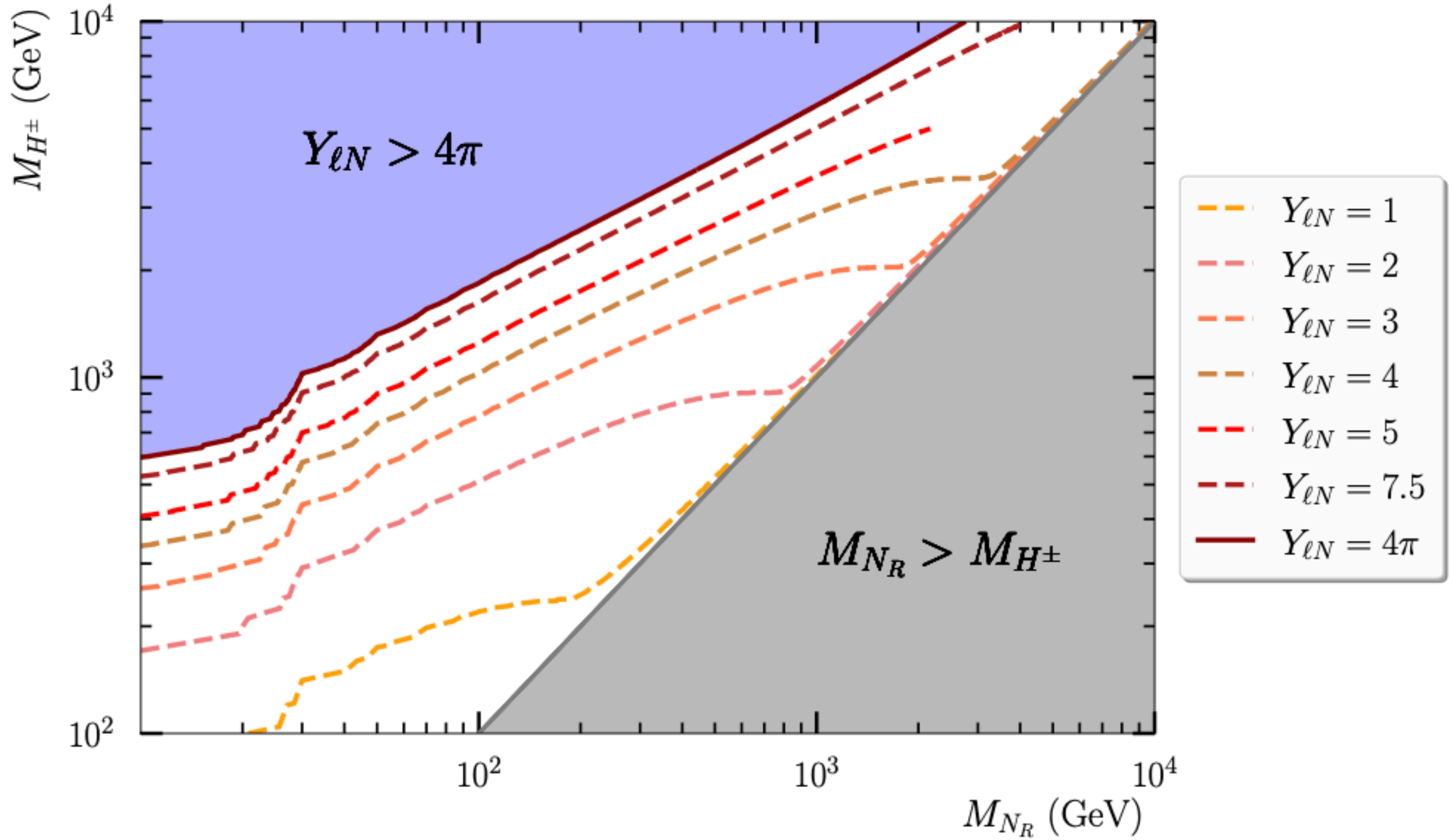
$$N_R N_R \to H^* \to \tau\tau, b\bar{b}, t\bar{t}, Z^0 Z^0, W^+W^-, HH$$

(ii) Co-annihilation channels: dominates for tiny mass-splitting ($\Delta < M_{N_R}/10$)

$$N_R H^\pm \to \ell^\pm H, W^\pm \nu_\ell, \ell^\pm Z, \ell^\pm \gamma$$

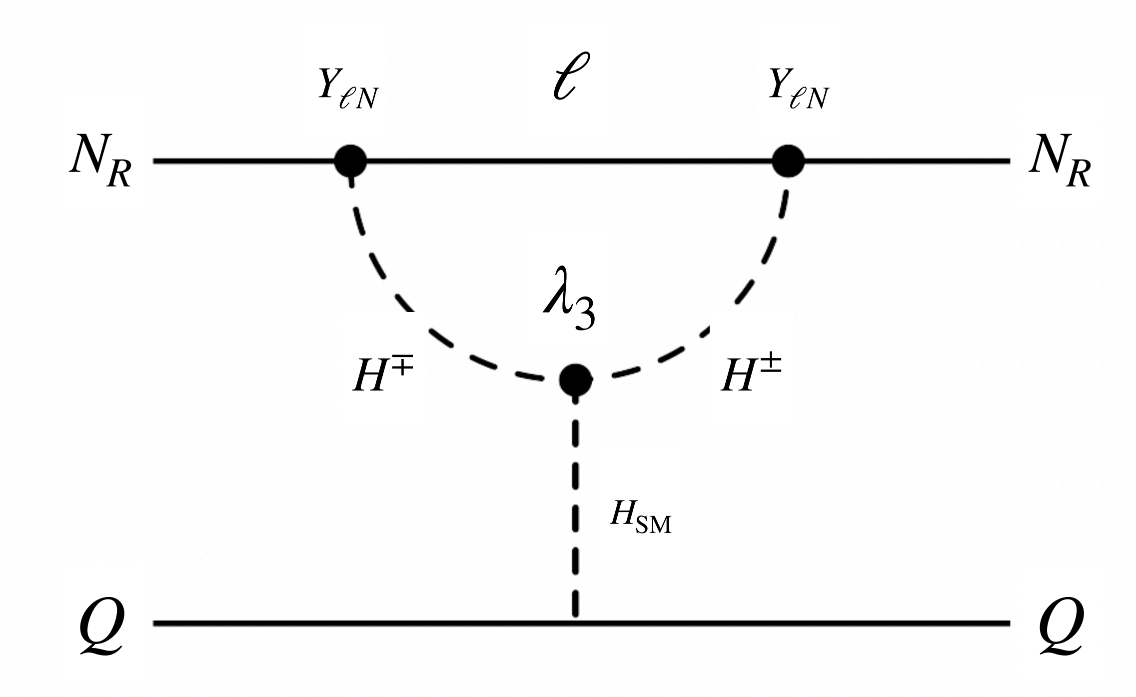
$$H^\pm H^\mp \to \ell^\pm \ell^\mp, q\bar{q}, HH, ZZ, W^\pm W^\mp, ZH, t\bar{t}$$

Dark matter relic abundance



Direct detection constraints

The spin-independent nucleus-N_R elastic cross section occurs at the one(two)-loop order



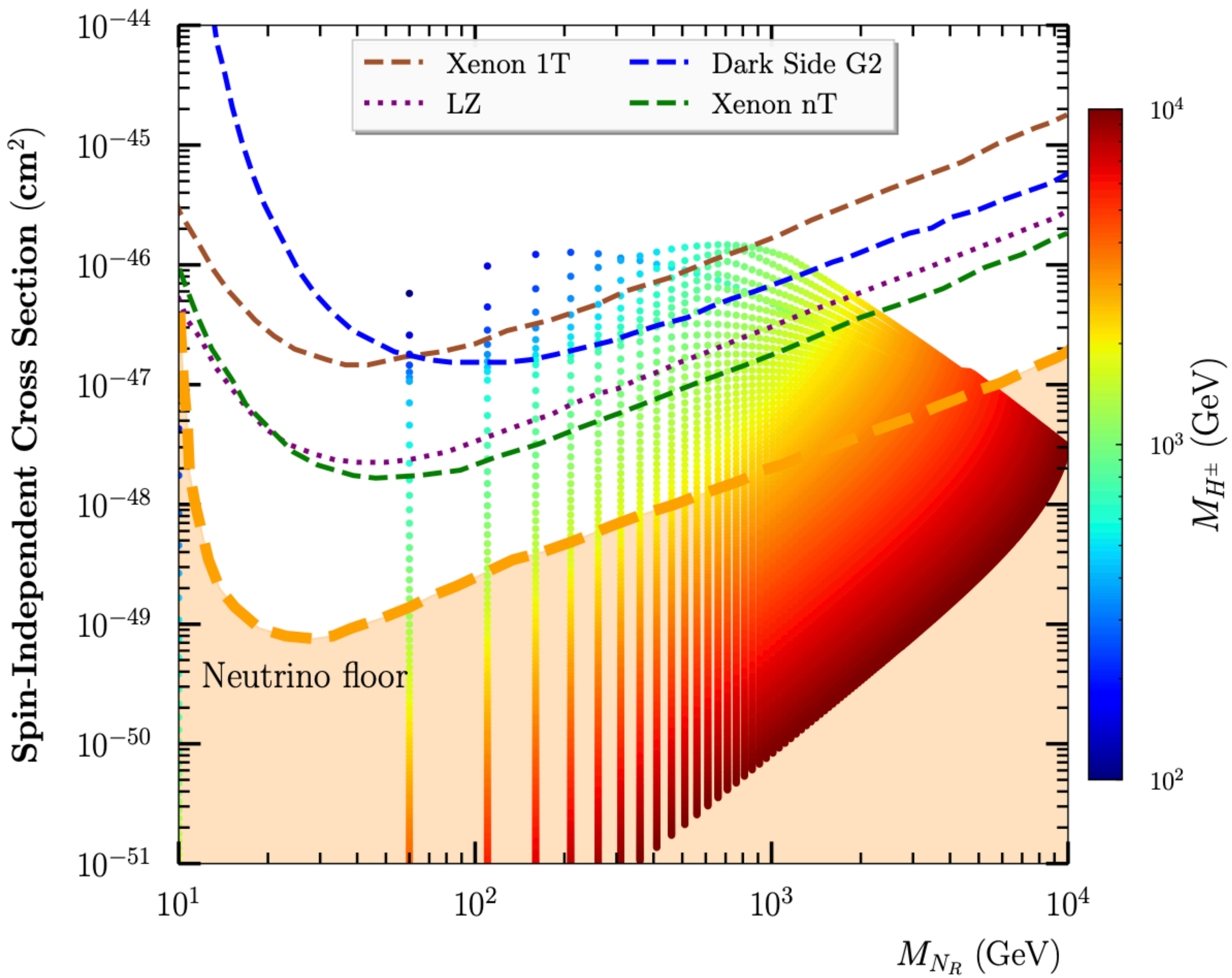
We get something like

$$\sigma_{\rm SI} \propto \left(\text{Nuclear matrix elements}\right)^2 \times \left| \frac{\tilde{y}(Q^2 \approx 0)}{M_{H^\pm}^2} \right|^2 \times \text{phase space}$$

Effective Higgs-N_R coupling

$$\tilde{y}(Q^2 \approx 0) = -\frac{\lambda_3 v |Y_{\ell N}^2|}{16\pi M_{H^\pm}} \varrho_N \times \left[1 - (1 - \varrho_N^{-2}) \log(1 - \varrho_N^2)\right] \quad (\varrho_N = M_{N_R}/M_{H^\pm})$$

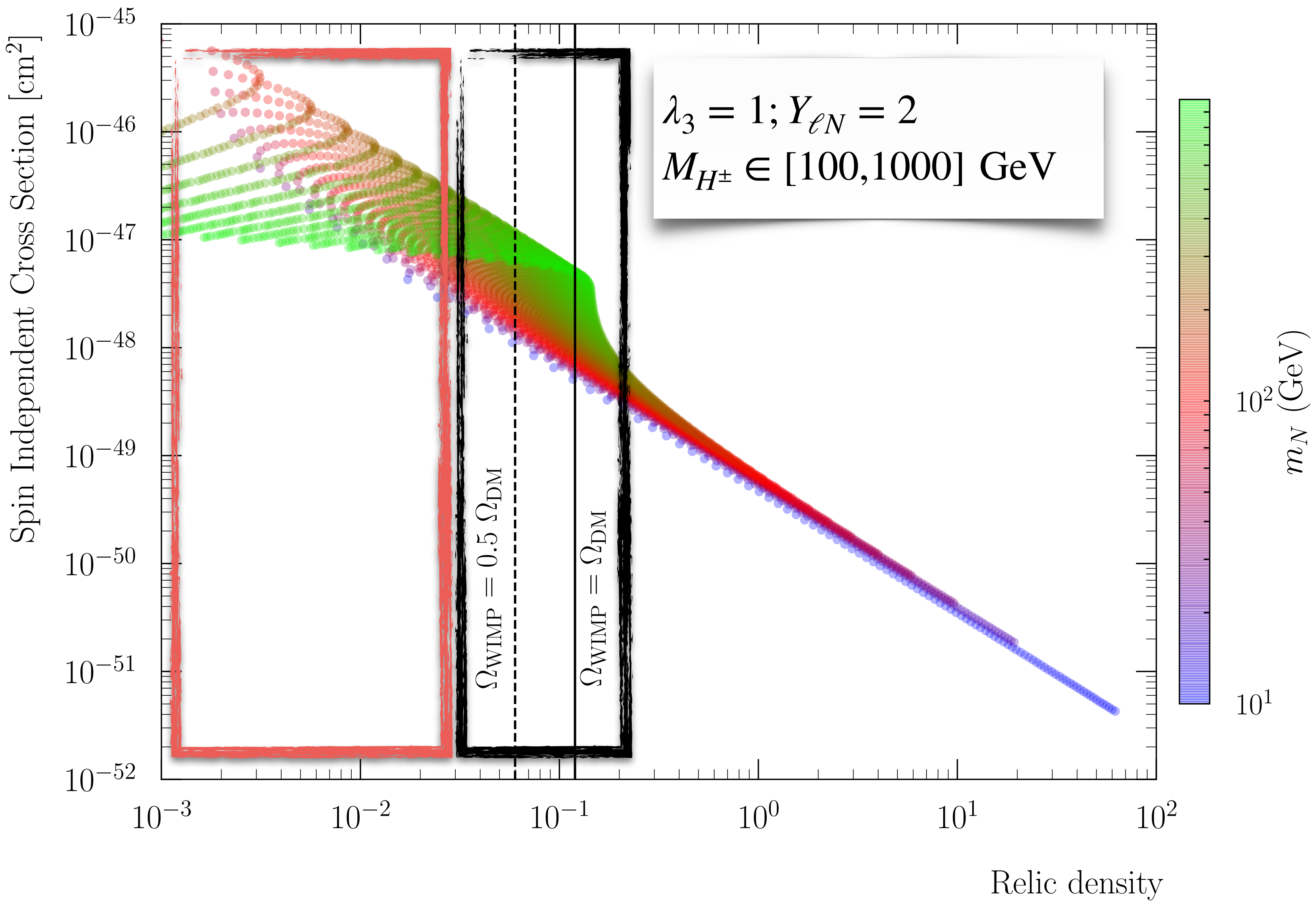
Direct detection constraints



Correlations: Ωh^2 vs $\sigma_{\rm SI}$

- Strong anti-correlation is observed between the spin-independent cross section ($\sigma_{\rm SI}$) and the relic abundance of N_R.

- Regions where the predicted $\sigma_{\rm SI}$ is enhanced are hard to exclude as they correspond to $\xi \equiv \Omega_N h^2/\Omega_{\rm Planck} h^2 \ll 1$



4. Lepton Portal DM at muon colliders

Phenomenology at muon colliders: BPs

For the case of muon colliders, we need to choose the following scenario

$$Y_{\mu N} \geq \ (\approx) Y_{\tau N} \gg Y_{eN}$$

Benchmark scenario	BP1	BP2	BP3	BP4
Parameters				
M_{N_R} (GeV)	50	200	598	1000
$M_{H^\pm}$ (GeV)	500	500	600	1500
Y_{Ne}	10^{-4}	5×10^{-4}	10^{-3}	5×10^{-3}
$Y_{N\mu}$	2.8	1.6	1	2
$Y_{N\tau}$	5×10^{-2}	5×10^{-1}	5×10^{-1}	2
λ_3	4	5	5	6

DM production at muon colliders

Optimistic scenario: Luminosity increases linearly with the center-of-mass energy

$$\sqrt{s_{\mu\mu}} \;=\; 3{,}10, \text{ and } 30 \text{ TeV}$$

$$\Longrightarrow \quad \textbf{Decent statistics for signal events!}$$

$$\int \mathscr{L}\mathrm{d}t \;=\; 1{,}10, \text{ and } 90 \text{ ab}^{-1}$$

DM production at muon colliders

(i) DM production plus X ($N_R N_R + X$)

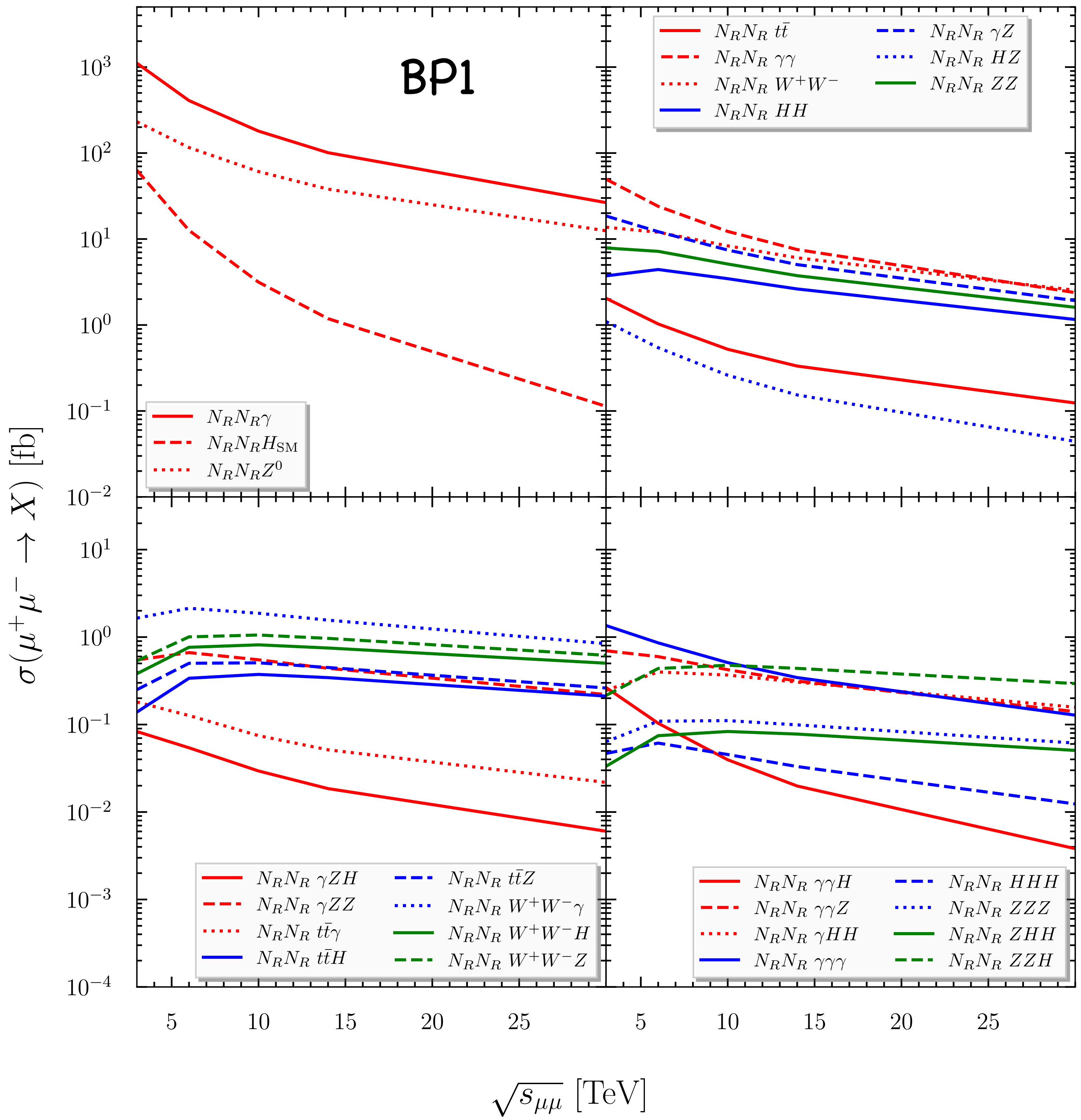
- $N_R N_R + \gamma \Longrightarrow$ High-energetic photon plus MET.
- $N_R N_R + Z \Longrightarrow$ 2 leptons or two jets plus MET.
- $N_R N_R + H_{\rm SM} \Longrightarrow b\bar{b} + \mathrm{MET}; gg + \mathrm{MET}; \cdots$.

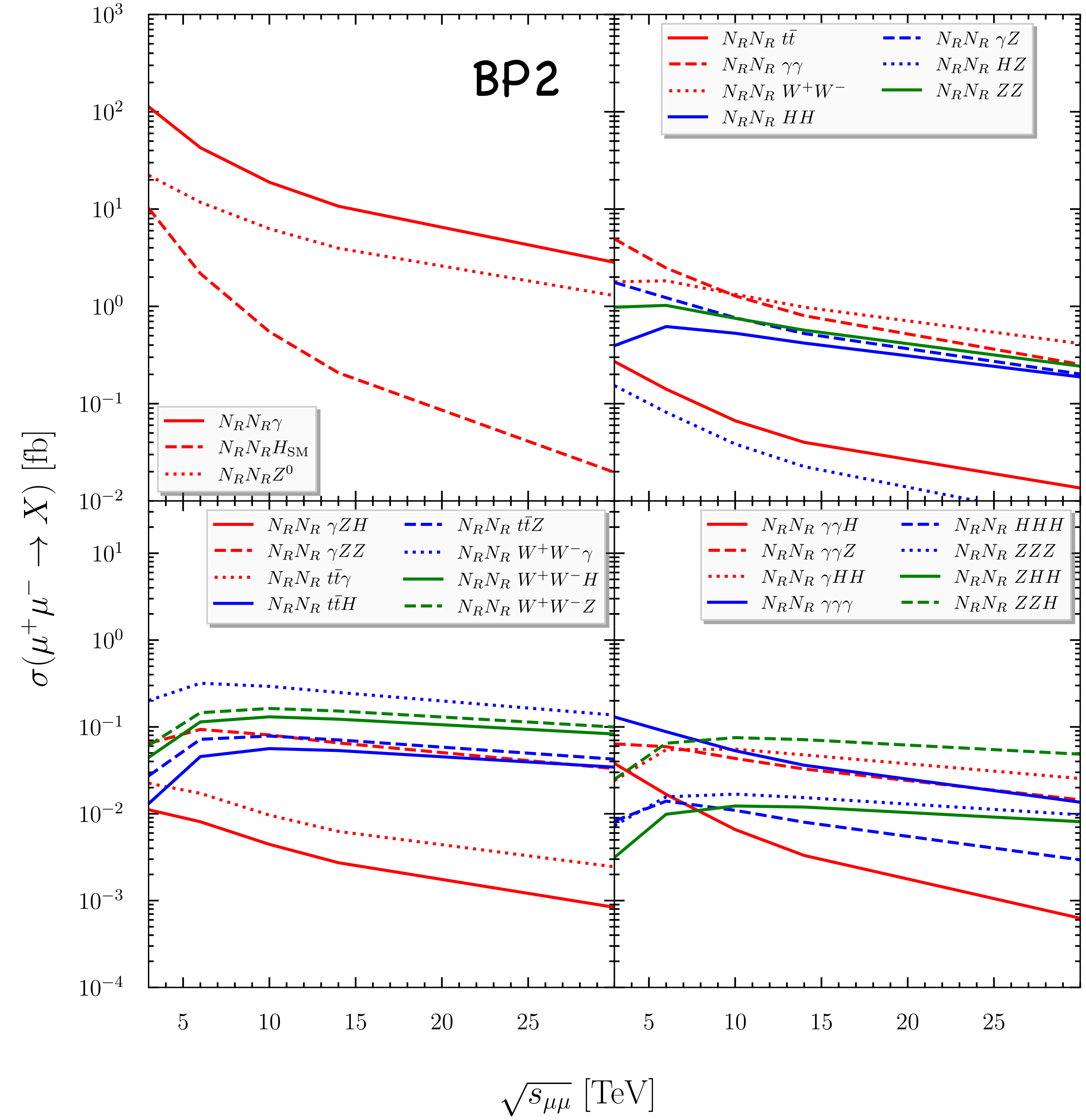
(ii) DM production plus XY ($N_R N_R + XY$)

- $N_R N_R + \gamma\gamma \Longrightarrow$ 2 photons plus MET.
- $N_R N_R + \gamma Z \Longrightarrow$ one photon + 2 leptons or two jets plus MET.
- $N_R N_R + ZZ/HZ/W^+W^-/HH/t\bar{t} \Longrightarrow$ variety of final-state particles depending on the decay products of the heavy resonances.

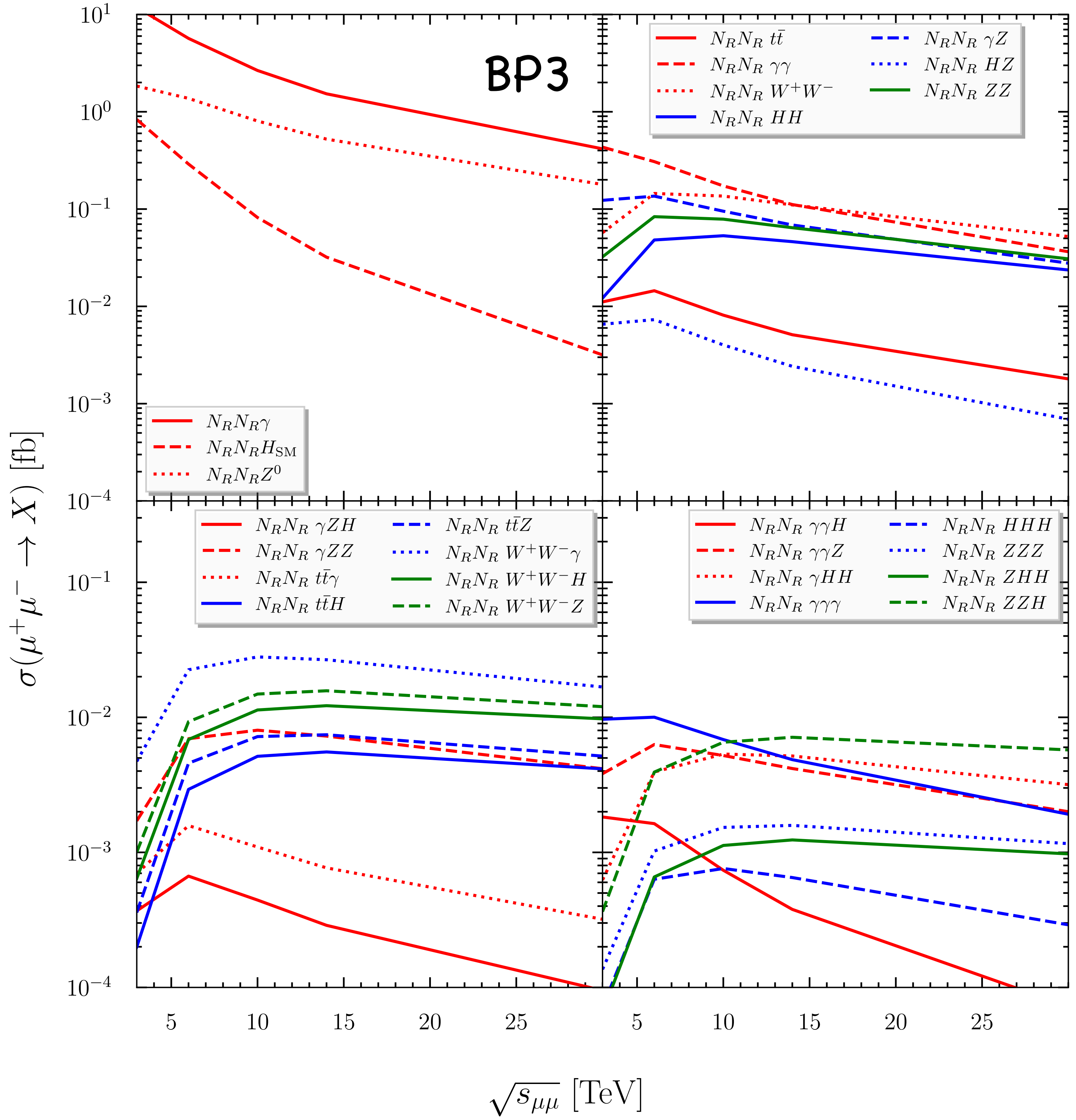
(iii) DM production plus three SM particles ($N_R N_R + XYZ$)

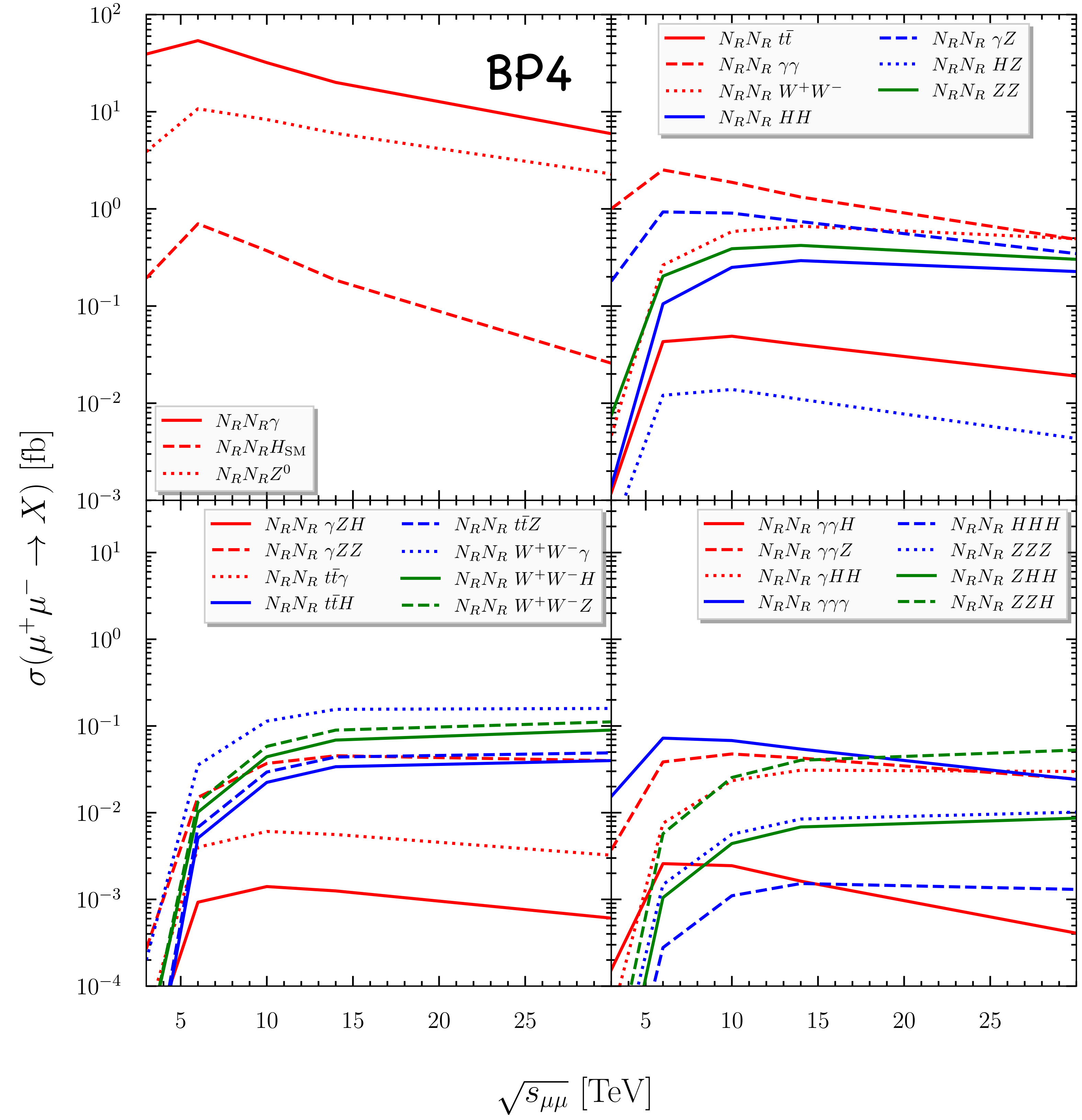
DM production at muon colliders: results





DM production at muon colliders: results





DM production at muon colliders: signal vs backgrounds

		$\sigma \times$ BR (fb) (number of events)		
		3 TeV	10 TeV	30 TeV
$N_R N_R + \gamma$	BP1	$1.11 \times 10^3 (1.11 \times 10^6)$	$1.80 \times 10^2 (1.80 \times 10^6)$	$2.38 \times 10^1 (2.65 \times 10^6)$
	BP2	$1.13 \times 10^2 (1.13 \times 10^5)$	$1.88 \times 10^1 (1.88 \times 10^5)$	$2.83 \times 10^0 (2.55 \times 10^5)$
	BP3	$1.18 \times 10^1 (1.18 \times 10^3)$	$2.65 \times 10^0 (2.65 \times 10^4)$	$0.41 \times 10^0 (3.69 \times 10^4)$
	BP4	$3.92 \times 10^1 (3.95 \times 10^4)$	$3.20 \times 10^1 (3.20 \times 10^5)$	$5.94 \times 10^0 (5.35 \times 10^5)$
	bkgs	$3.02 \times 10^3 (3.02 \times 10^6)$	$3.29 \times 10^3 (3.29 \times 10^7)$	$3.36 \times 10^3 (3.02 \times 10^8)$
$N_R N_R + Z(\to \ell\ell)$	BP1	$1.68 \times 10^1 (1.68 \times 10^4)$	$4.44 \times 10^0 (4.44 \times 10^4)$	$0.91 \times 10^0 (8.19 \times 10^4)$
	BP2	$1.62 \times 10^0 (1.62 \times 10^3)$	$0.46 \times 10^0 (4.58 \times 10^3)$	$9.39 \times 10^{-2} (8.45 \times 10^3)$
	BP3	$0.13 \times 10^0 (0.13 \times 10^3)$	$0.58 \times 10^{-1} (0.58 \times 10^3)$	$1.30 \times 10^{-2} (1.17 \times 10^3)$
	BP4	$0.28 \times 10^0 (0.28 \times 10^3)$	$0.61 \times 10^0 (0.61 \times 10^4)$	$0.17 \times 10^0 (1.53 \times 10^4)$
	bkgs	$2.75 \times 10^1 (2.75 \times 10^4)$	$2.57 \times 10^1 (2.57 \times 10^5)$	$4.69 \times 10^1 (4.22 \times 10^6)$
$N_R N_R + Z(\to q\bar{q})$	BP1	$1.59 \times 10^2 (1.59 \times 10^5)$	$4.20 \times 10^1 (4.20 \times 10^5)$	$8.61 \times 10^0 (7.75 \times 10^5)$
	BP2	$1.53 \times 10^1 (1.53 \times 10^4)$	$4.33 \times 10^0 (4.33 \times 10^4)$	$0.89 \times 10^0 (8.00 \times 10^4)$
	BP3	$1.26 \times 10^0 (1.26 \times 10^3)$	$0.55 \times 10^0 (5.54 \times 10^3)$	$0.12 \times 10^0 (1.11 \times 10^4)$
	BP4	$2.67 \times 10^0 (2.67 \times 10^3)$	$5.73 \times 10^0 (5.73 \times 10^4)$	$1.57 \times 10^0 (1.41 \times 10^5)$
	bkgs	$4.76 \times 10^2 (4.76 \times 10^5)$	$6.71 \times 10^2 (6.71 \times 10^6)$	$1.01 \times 10^3 (0.91 \times 10^8)$
$N_R N_R + H_{\rm SM}(\to b\bar{b})$	BP1	$2.05 \times 10^1 (2.05 \times 10^4)$	$1.02 \times 10^0 (1.02 \times 10^4)$	$3.67 \times 10^{-2} (3.30 \times 10^3)$
	BP2	$5.83 \times 10^0 (5.83 \times 10^3)$	$0.31 \times 10^0 (0.31 \times 10^4)$	$1.12 \times 10^{-2} (1.01 \times 10^3)$
	BP3	$0.47 \times 10^0 (0.47 \times 10^3)$	$0.47 \times 10^{-1} (0.47 \times 10^3)$	$1.81 \times 10^{-3} (1.63 \times 10^2)$
	BP4	$0.11 \times 10^0 (0.11 \times 10^3)$	$0.21 \times 10^0 (0.21 \times 10^4)$	$1.47 \times 10^{-2} (1.32 \times 10^3)$
	bkgs	$4.76 \times 10^2 (4.76 \times 10^5)$	$6.71 \times 10^2 (6.71 \times 10^6)$	$1.01 \times 10^3 (0.91 \times 10^8)$

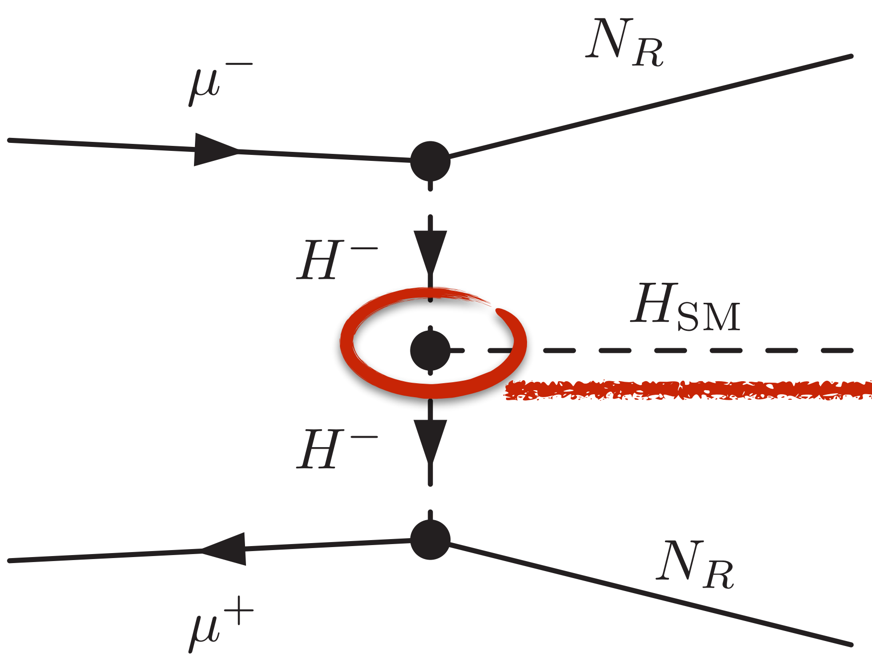
DM production at muon colliders: signal vs backgrounds

		$\sigma \times$ BR (fb) (number of events)		
		3 TeV	10 TeV	30 TeV
$N_R N_R + \gamma\gamma$	BP1	$4.97 \times 10^1 (4.97 \times 10^4)$	$1.23 \times 10^1 (1.23 \times 10^5)$	$2.38 \times 10^0 (2.38 \times 10^5)$
	BP2	$4.93 \times 10^1 (4.93 \times 10^3)$	$1.28 \times 10^0 (1.28 \times 10^4)$	$0.25 \times 10^0 (2.53 \times 10^4)$
	BP3	$0.43 \times 10^0 (0.43 \times 10^3)$	$0.17 \times 10^0 (1.73 \times 10^3)$	$0.36 \times 10^{-1} (3.64 \times 10^3)$
	BP4	$1.00 \times 10^0 (1.00 \times 10^3)$	$1.87 \times 10^0 (1.87 \times 10^4)$	$0.48 \times 10^0 (4.85 \times 10^4)$
	bkgs	$8.73 \times 10^1 (8.73 \times 10^4)$	$1.04 \times 10^2 (1.04 \times 10^6)$	$1.12 \times 10^2 (1.12 \times 10^7)$
$N_R N_R + \gamma Z(\to \ell\ell)$	BP1	$1.24 \times 10^0 (1.24 \times 10^3)$	$0.49 \times 10^0 (4.98 \times 10^3)$	$1.29 \times 10^{-1} (1.29 \times 10^4)$
	BP2	$1.76 \times 10^0 (1.76 \times 10^3)$	$0.76 \times 10^0 (7.64 \times 10^3)$	$0.20 \times 10^0 (2.02 \times 10^4)$
	BP3	$0.12 \times 10^0 (1.23 \times 10^2)$	$9.50 \times 10^{-2} (9.50 \times 10^2)$	$2.80 \times 10^{-2} (2.80 \times 10^3)$
	BP4	$0.18 \times 10^0 (1.79 \times 10^2)$	$9.05 \times 10^{-1} (9.05 \times 10^3)$	$3.46 \times 10^{-1} (3.46 \times 10^4)$
	bkgs	$1.57 \times 10^0 (1.57 \times 10^3)$	$1.59 \times 10^0 (1.59 \times 10^4)$	$2.97 \times 10^0 (2.67 \times 10^5)$
$N_R N_R + Z(\to \ell\ell)Z(\to \ell\ell)$	BP1	$3.53 \times 10^{-2} (3.53 \times 10^1)$	$2.29 \times 10^{-2} (2.29 \times 10^2)$	$7.21 \times 10^{-3} (7.21 \times 10^2)$
	BP2	$0.98 \times 10^0 (9.80 \times 10^2)$	$0.75 \times 10^0 (7.54 \times 10^3)$	$0.24 \times 10^0 (2.42 \times 10^4)$
	BP3	$3.23 \times 10^{-2} (3.23 \times 10^1)$	$7.87 \times 10^{-2} (7.87 \times 10^2)$	$3.08 \times 10^{-2} (3.08 \times 10^3)$
	BP4	$7.50 \times 10^{-3} (7.50 \times 10^0)$	$0.39 \times 10^0 (3.89 \times 10^3)$	$0.30 \times 10^0 (3.02 \times 10^4)$
	bkgs	$1.08 \times 10^{-1} (1.08 \times 10^2)$	$1.39 \times 10^{-1} (1.39 \times 10^3)$	$3.74 \times 10^{-1} (3.36 \times 10^4)$
$N_R N_R + V(\to q\bar{q})V(\to q\bar{q})$	BP1	$1.05 \times 10^1 (1.05 \times 10^4)$	$6.57 \times 10^0 (6.57 \times 10^4)$	$2.02 \times 10^0 (2.02 \times 10^5)$
	BP2	$2.76 \times 10^0 (2.76 \times 10^3)$	$2.08 \times 10^0 (2.08 \times 10^4)$	$0.65 \times 10^0 (6.57 \times 10^4)$
	BP3	$8.90 \times 10^{-2} (8.90 \times 10^1)$	$2.15 \times 10^{-1} (2.15 \times 10^3)$	$8.30 \times 10^{-2} (8.30 \times 10^3)$
	BP4	$1.30 \times 10^{-2} (1.30 \times 10^1)$	$9.74 \times 10^{-1} (9.74 \times 10^3)$	$7.96 \times 10^{-1} (7.96 \times 10^4)$
	bkgs	$6.63 \times 10^1 (6.63 \times 10^4)$	$1.71 \times 10^2 (1.71 \times 10^6)$	$3.34 \times 10^2 (3.01 \times 10^7)$
$N_R N_R + H_{\mathrm{SM}}(\to b\bar{b})H_{\mathrm{SM}}(\to b\bar{b})$	BP1	$1.21 \times 10^0 (1.21 \times 10^3)$	$1.12 \times 10^0 (1.12 \times 10^4)$	$3.77 \times 10^{-1} (3.77 \times 10^4)$
	BP2	$3.95 \times 10^{-1} (3.95 \times 10^2)$	$5.29 \times 10^{-1} (5.29 \times 10^3)$	$1.88 \times 10^{-1} (1.88 \times 10^4)$
	BP3	$1.22 \times 10^{-2} (1.22 \times 10^1)$	$5.32 \times 10^{-2} (5.32 \times 10^2)$	$2.36 \times 10^{-2} (2.36 \times 10^3)$
	BP4	$1.40 \times 10^{-3} (1.40 \times 10^0)$	$2.49 \times 10^{-1} (2.49 \times 10^3)$	$2.27 \times 10^{-1} (2.27 \times 10^4)$
	bkgs	$6.63 \times 10^1 (6.63 \times 10^4)$	$1.71 \times 10^2 (1.71 \times 10^6)$	$3.34 \times 10^2 (3.01 \times 10^7)$

5. Mono-Higgs advanced with ML

Why mono-Higgs is important?

Mono-Higgs production refers to the production of one or more DM particle in association with a SM Higgs boson.



$$\propto Y_{\ell N}^4 \lambda_3^2$$

Can be used to probe the Interaction of the mediator with the Higgs boson (a feature not available in other processes)

Problem: small rates and S/B!!

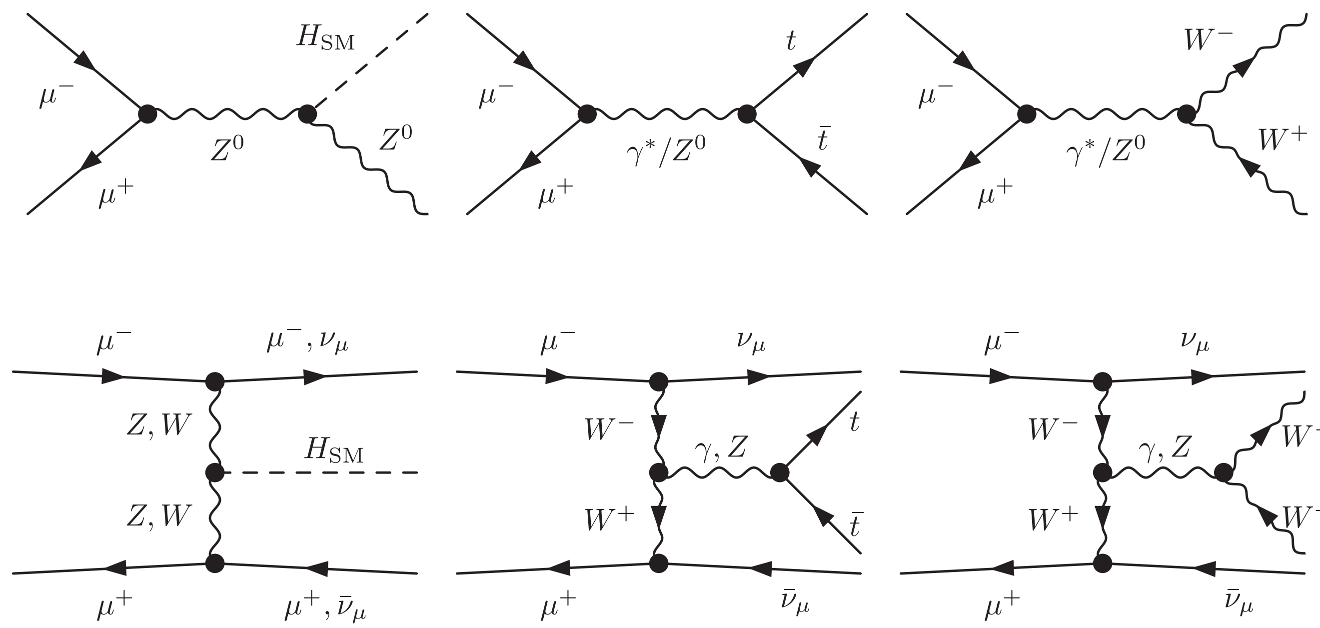
		3 TeV	10 TeV	30 TeV
$N_R N_R + H_{\rm SM}(\to b\bar{b})$	BP1	$2.05 \times 10^1 (2.05 \times 10^4)$	$1.02 \times 10^0 (1.02 \times 10^4)$	$3.67 \times 10^{-2} (3.30 \times 10^3)$
	BP2	$5.83 \times 10^0 (5.83 \times 10^3)$	$0.31 \times 10^0 (0.31 \times 10^4)$	$1.12 \times 10^{-2} (1.01 \times 10^3)$
	BP3	$0.47 \times 10^0 (0.47 \times 10^3)$	$0.47 \times 10^{-1} (0.47 \times 10^3)$	$1.81 \times 10^{-3} (1.63 \times 10^2)$
	BP4	$0.11 \times 10^0 (0.11 \times 10^3)$	$0.21 \times 10^0 (0.21 \times 10^4)$	$1.47 \times 10^{-2} (1.32 \times 10^3)$
	bkgs	$4.76 \times 10^2 (4.76 \times 10^5)$	$6.71 \times 10^2 (6.71 \times 10^6)$	$1.01 \times 10^3 (0.91 \times 10^8)$

Signal and Backgrounds

We consider $\mu^+\mu^- \to H_{\rm SM}\ (\to b\bar{b}) + N_R N_R$ which leads to signatures consisting of jets plus MET

- **Backgrounds**

Center-of-mass energy	3 TeV	10 TeV	30 TeV
	Cross section (fb)		
$\mu\mu \to H_{\rm SM}Z$	1.37×10^{0}	0.12×10^{0}	1.37×10^{-2}
$\mu\mu \to WW$	4.67×10^{2}	5.89×10^{1}	8.26×10^{0}
$\mu\mu \to ZZ$	2.61×10^{1}	3.28×10^{0}	4.60×10^{-1}
$\mu\mu \to t\bar{t}$	1.91×10^{1}	1.72×10^{0}	1.92×10^{-1}
$VV \to HZ$	9.87×10^{0}	3.53×10^{1}	7.59×10^{1}
$VV \to H_{\rm SM}$	4.98×10^{2}	8.45×10^{2}	1.17×10^{3}
$VV \to WZ$	3.98×10^{1}	3.19×10^{1}	1.26×10^{1}
$VV \to WW$	1.51×10^{2}	4.30×10^{2}	8.58×10^{2}
$VV \to ZZ$	5.66×10^{1}	2.03×10^{2}	4.30×10^{2}
$VV \to t\bar{t}$	5.22×10^{0}	1.71×10^{1}	3.14×10^{1}
$VV \to t\bar{t}W$	5.67×10^{-2}	1.05×10^{-1}	6.97×10^{-2}
$VV \to t\bar{t}Z$	1.10×10^{-1}	9.01×10^{-1}	2.77×10^{0}



Cut-based analysis strategy

The Higgs boson being produced with DM can be either resolved or boosted (depending on the amount of the missing energy).

- Resolved: Two well-separated jets can be identified and used to reconstruct the Higgs boson candidates.
- Boosted: The Higgs boson is identified as a single large-R jet.

At first step we follow closely three analysis strategies carried out by the ATLAS and the CMS collaboration: one for resolved regime and two for the boosted regime.

Resolved regime:

- Lepton and photon veto.
- $E_T^{\text{miss}} > 100$ GeV
- $\Delta\phi_{\text{min}} > 20^\circ$
- $p_T^{b\bar{b}} > 300$ GeV
- Other quality cuts.

Boosted regime

- Lepton and photon veto.
- $E_T^{\text{miss}} > 300$ GeV
- $N_{\text{J}} > 0$
- $m_{\text{J}} \in]70,180[$ GeV

Resolved regime: Results

Cut-flow table

	$VV + X$		$t\bar{t} + X$		$H + X$		BP1	
	Events	ε	Events	ε	Events	ε	Events	ε
Initial	7.4×10^5	–	24 367.3	–	5.1×10^5	–	20 500.0	–
$E_T^{\text{miss}} > 100$ GeV	$2.5 \times 10^5 \pm 90.6$	0.332	17 285.9 ± 8.3	0.709	$1.6 \times 10^5 \pm 73.7$	0.315	15 153.9 ± 9.2	0.739
Lepton veto	$1.6 \times 10^5 \pm 67.0$	0.670	13 647.4 ± 8.0	0.790	$1.5 \times 10^5 \pm 72.5$	0.961	15 108.2 ± 9.3	0.997
τ veto	$1.5 \times 10^5 \pm 60.1$	0.898	12 061.3 ± 7.6	0.884	$1.5 \times 10^5 \pm 72.1$	0.966	14 880.0 ± 9.3	0.985
Photon veto	$1.4 \times 10^5 \pm 56.2$	0.937	10 998.0 ± 7.2	0.912	$1.5 \times 10^5 \pm 72.0$	0.990	14 622.4 ± 9.4	0.983
≥2 small-R jets	$1.0 \times 10^5 \pm 41.6$	0.727	8967.4 ± 6.1	0.815	82 718.7 ± 46.7	0.561	10 729.8 ± 8.9	0.734
≥2 b-jets	1904.6 ± 0.6	0.019	1920.4 ± 1.6	0.214	19 203.6 ± 12.8	0.232	929.2 ± 1.1	0.087
$\Delta\phi > 0.35$	1732.2 ± 0.6	0.909	1190.6 ± 0.9	0.620	19 155.7 ± 13.1	0.998	769.3 ± 0.9	0.828
$N_b = 2$	1617.7 ± 0.5	0.934	1133.2 ± 0.9	0.952	19 064.6 ± 13.4	0.995	764.8 ± 0.9	0.994
$E_T^{\text{miss}} \in\ ]300, 1000]$ GeV	402.3 ± 0.1	0.249	432.4 ± 0.4	0.382	2195.4 ± 1.3	0.115	549.6 ± 0.6	0.719
$p_T^{b\bar{b}} > 300$ GeV	230.7 ± 0.1	0.574	319.5 ± 0.3	0.739	1942.0 ± 1.3	0.885	446.3 ± 0.5	0.812
$\Delta\phi(\vec{p}_{\text{miss}}, \vec{p}_{\text{H}}) > 2\pi/3$	224.2 ± 0.1	0.972	306.4 ± 0.3	0.959	1941.7 ± 1.3	1.000	317.7 ± 0.4	0.712
$m_{T,b}^{\text{min}} > 170$ GeV	208.5 ± 0.1	0.930	129.5 ± 0.1	0.422	1928.3 ± 1.4	0.993	314.0 ± 0.4	0.988
$m_{T,b}^{\text{max}} > 200$ GeV	208.0 ± 0.1	0.998	129.4 ± 0.1	1.000	1927.6 ± 1.4	1.000	313.6 ± 0.4	0.999
$N_{\text{jets}} < 3$	183.3 ± 0.1	0.882	81.7 ± 0.1	0.632	1921.4 ± 1.4	0.997	312.5 ± 0.4	0.996
$m_{b\bar{b}} \in\ ]80, 160[$ GeV	7.5 ± 0.0	0.041	3.6 ± 0.0	0.045	1520.7 ± 1.2	0.791	216.2 ± 0.3	0.692

Significance

Benchmark point	BP1	BP2	BP3	BP4
$\mathcal{S}$	5.40	1.61	0.14	2.62×10^{-2}

Boosted regime: Results

Cut-flow table

	$VV + X$		$t\bar{t} + X$		$H + X$		BP1	
	Events	ε	Events	ε	Events	ε	Events	ε
Initial	7.4×10^5	–	24 367.3	–	5.1×10^5	–	20 500.0	–
Lepton veto	$4.8 \times 10^5 \pm 157.6$	0.652	18 123.7 $\pm$ 7.9	0.744	$4.7 \times 10^5 \pm 91.4$	0.923	20 371.8 $\pm$ 1.9	0.994
τ veto	$4.6 \times 10^5 \pm 156.5$	0.956	16 321.9 $\pm$ 8.0	0.901	$4.5 \times 10^5 \pm 109.2$	0.955	20 029.1 $\pm$ 3.6	0.983
$E_T^{\text{miss}} > 300$ GeV	39 334.6 $\pm$ 18.6	0.085	7076.6 $\pm$ 6.1	0.434	12 253.7 $\pm$ 3.1	0.027	12 014.1 $\pm$ 9.2	0.600
N_{CA15} jets > 0	39 166.6 $\pm$ 18.6	0.996	7075.5 $\pm$ 6.1	1.000	12 182.3 $\pm$ 3.0	0.994	12 014.1 $\pm$ 9.2	1.000
N_{SD} jets > 0	37 419.0 $\pm$ 17.9	0.955	7060.5 $\pm$ 6.0	0.998	11 083.4 $\pm$ 2.7	0.910	11 118.7 $\pm$ 9.0	0.925
$M_{\text{SD}} \in\ ]70,\ 180[$ GeV	31 615.2 $\pm$ 15.3	0.845	4233.1 $\pm$ 3.9	0.600	9625.0 $\pm$ 2.3	0.868	6978.8 $\pm$ 6.8	0.628

Significance

Benchmark point		BP1	BP2	BP3	BP4
$\mathcal{S}$	AK10 jets	38.18	10.91	0.84	0.17
	CA15 jets	31.93	9.02	0.74	0.15
p	AK10 jets	0.15	4.91×10^{-2}	3.95×10^{-3}	8.23×10^{-4}
	CA15 jets	0.13	4.08×10^{-2}	3.46×10^{-3}	7.06×10^{-4}

Improvements with Boosted-Decision Trees

After a basic event selection, we train the BDT for the mixing of the samples from the four benchmark points using the following variables:

- Resolved regime:

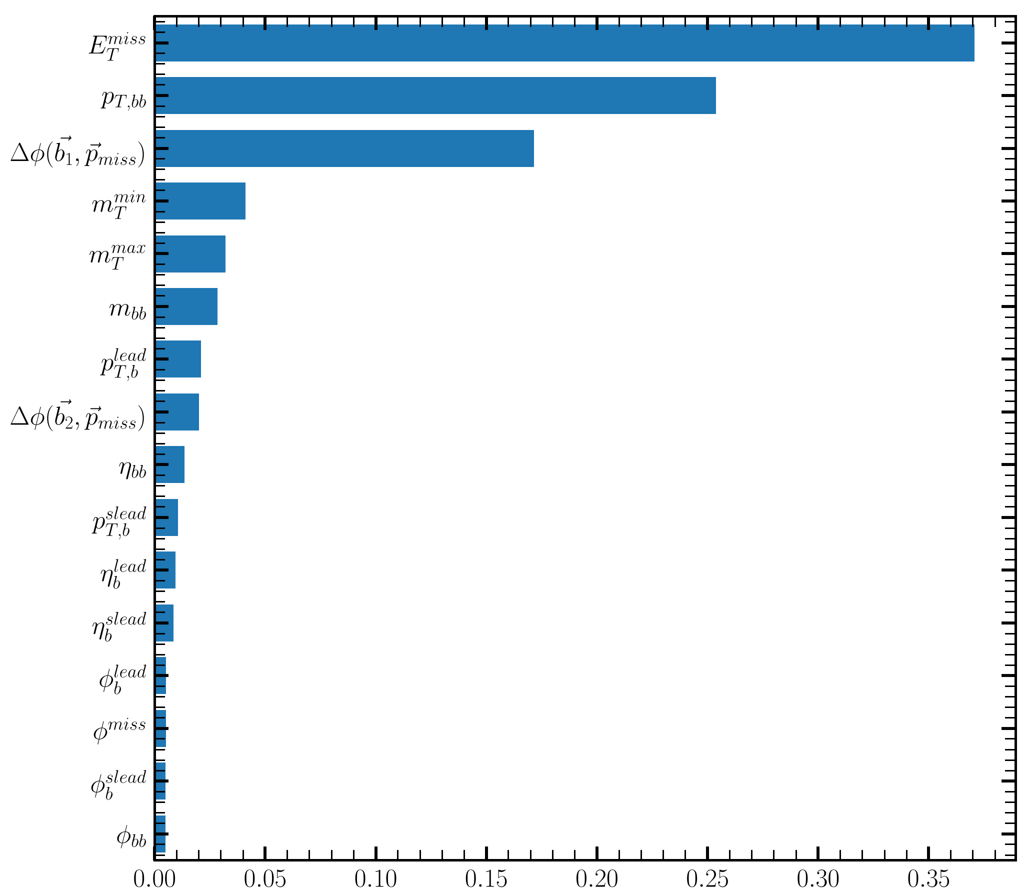
$$\{E_T^{\rm miss}, \phi_{\rm miss}, p_{T,b}^i, \phi_b^i, \eta_b^i, E_b^i, p_T^{bb}, \phi_{bb}, \eta_{bb}, E_{bb}, m_{bb}, \Delta\phi(\vec{b}_1, \vec{p}_{\rm miss}), \Delta\phi(\vec{b}_2, \vec{p}_{\rm miss}), m_T^{\rm min}, m_T^{\rm max}\}$$

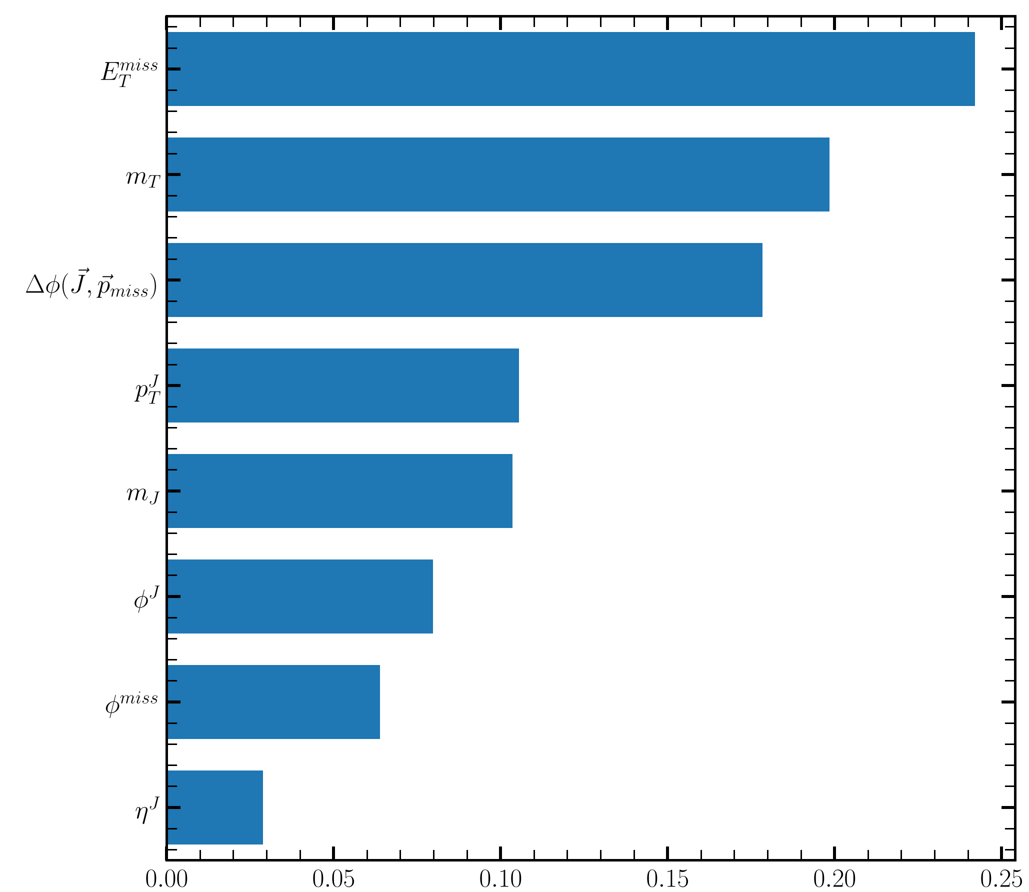
- Boosted regime with AK10 jets:

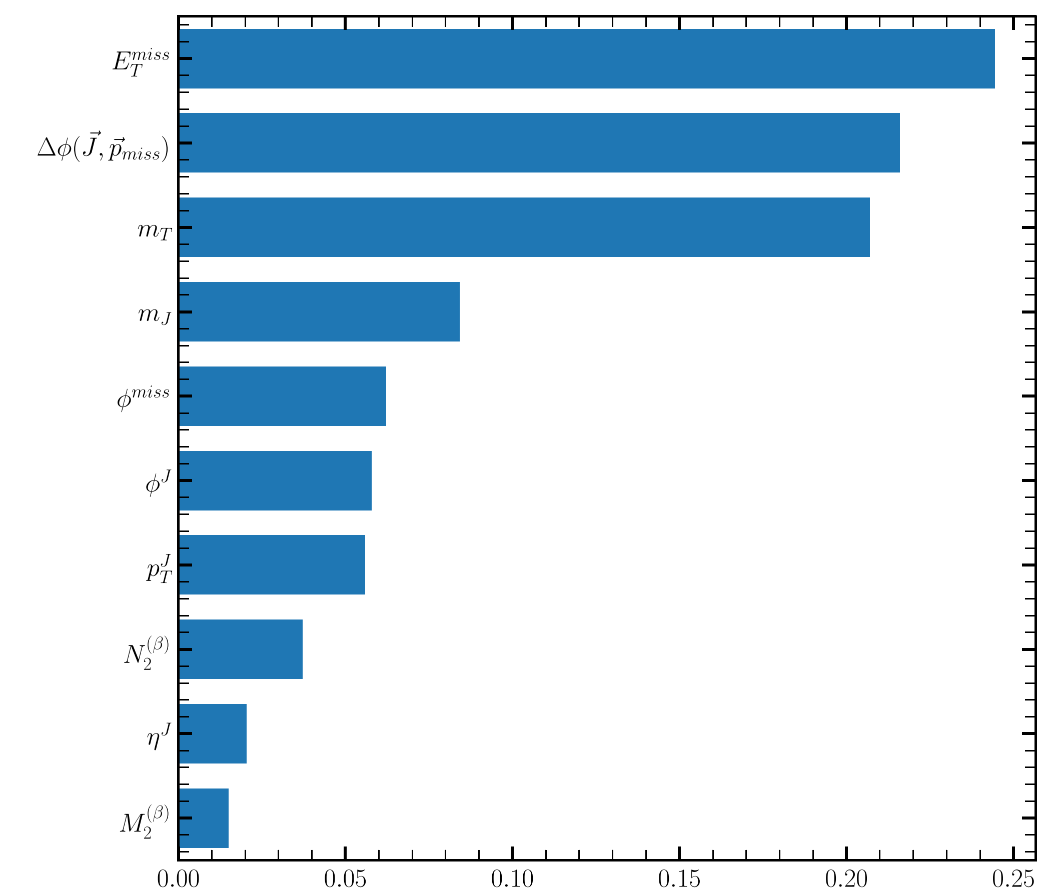
$$\{E_T^{\rm miss}, \phi_{\rm miss}, p_T^{\rm J}, \eta_{\rm J}, \phi_{\rm J}, E_{\rm J}, m_{\rm J}, \Delta\phi(\vec{\rm J}, \vec{p}_{\rm miss}), m_T\left({\rm J}, E_T^{\rm miss}\right)\}$$

- Boosted regime with CA15 jets:

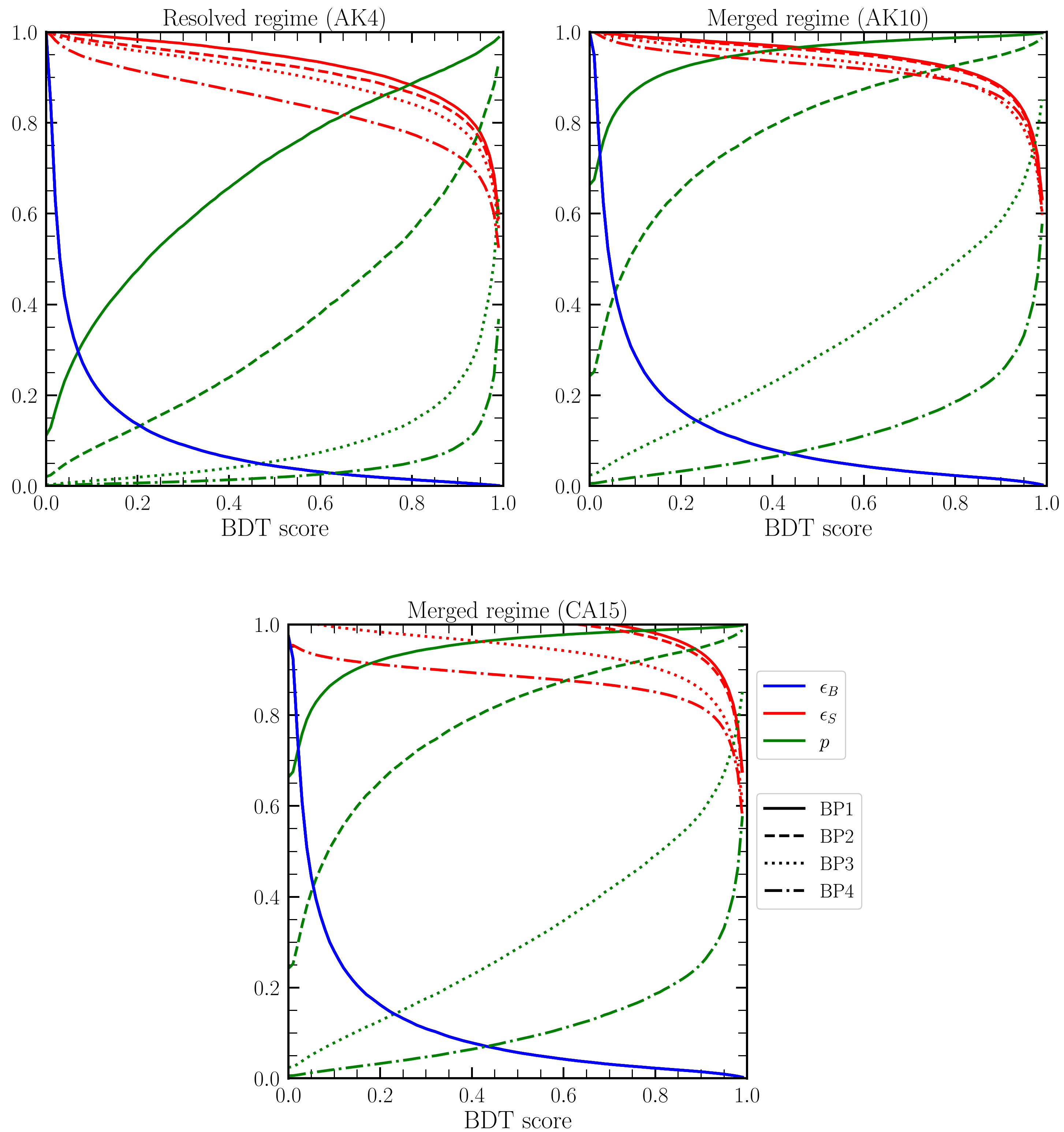
$$\left\{E_T^{\rm miss}, \phi_{\rm miss}, p_T^{\rm J}, \eta_{\rm J}, \phi_{\rm J}, E_{\rm J}, m_{\rm J}, \Delta\phi(\vec{\rm J}, \vec{p}_{\rm miss}), m_T\left({\rm J}, E_T^{\rm miss}\right), M_2^{(\beta)}, N_2^{(\beta)}\right\}$$







Improvements with BDTs



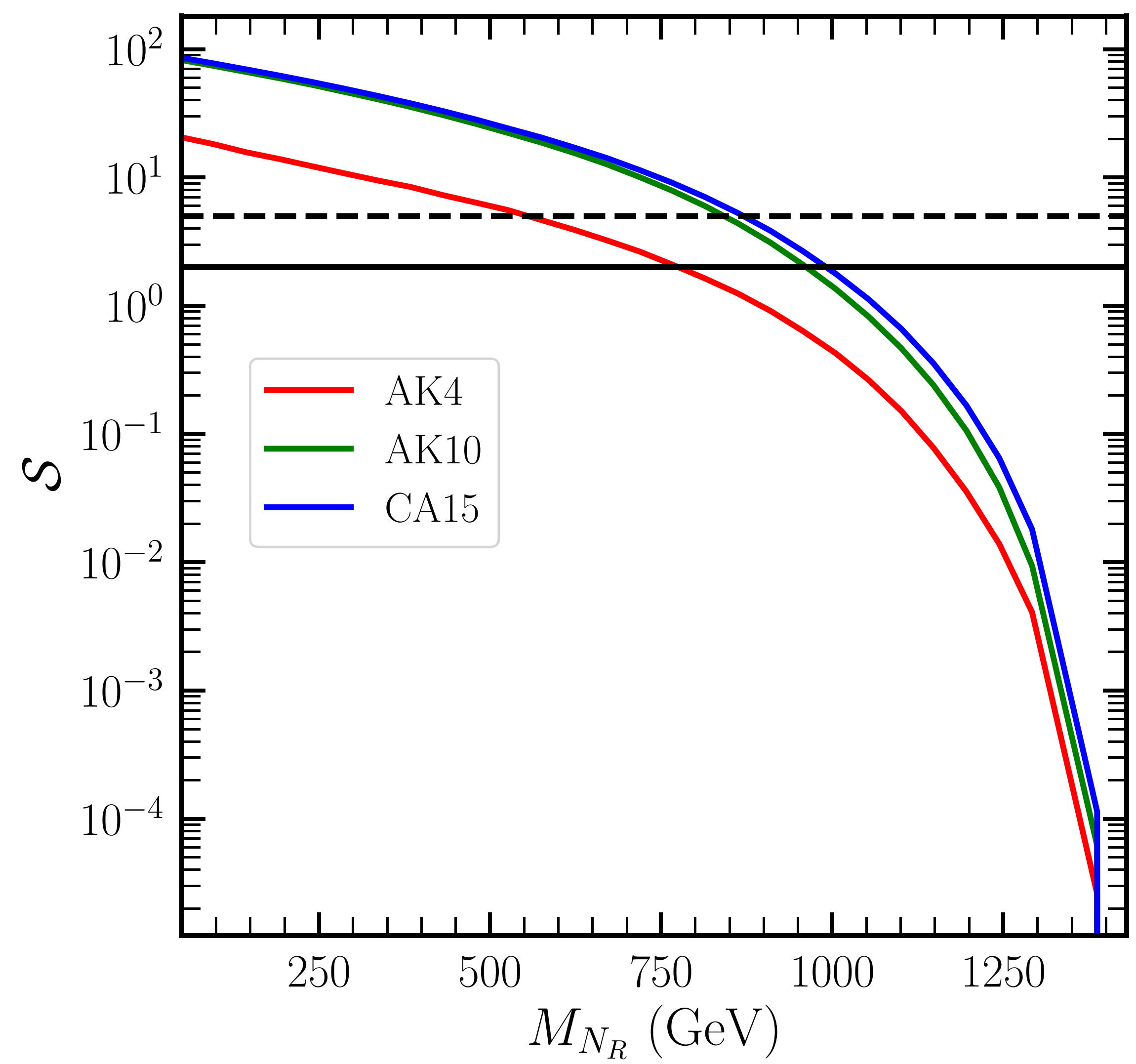
Impressive results for the signal purity!!

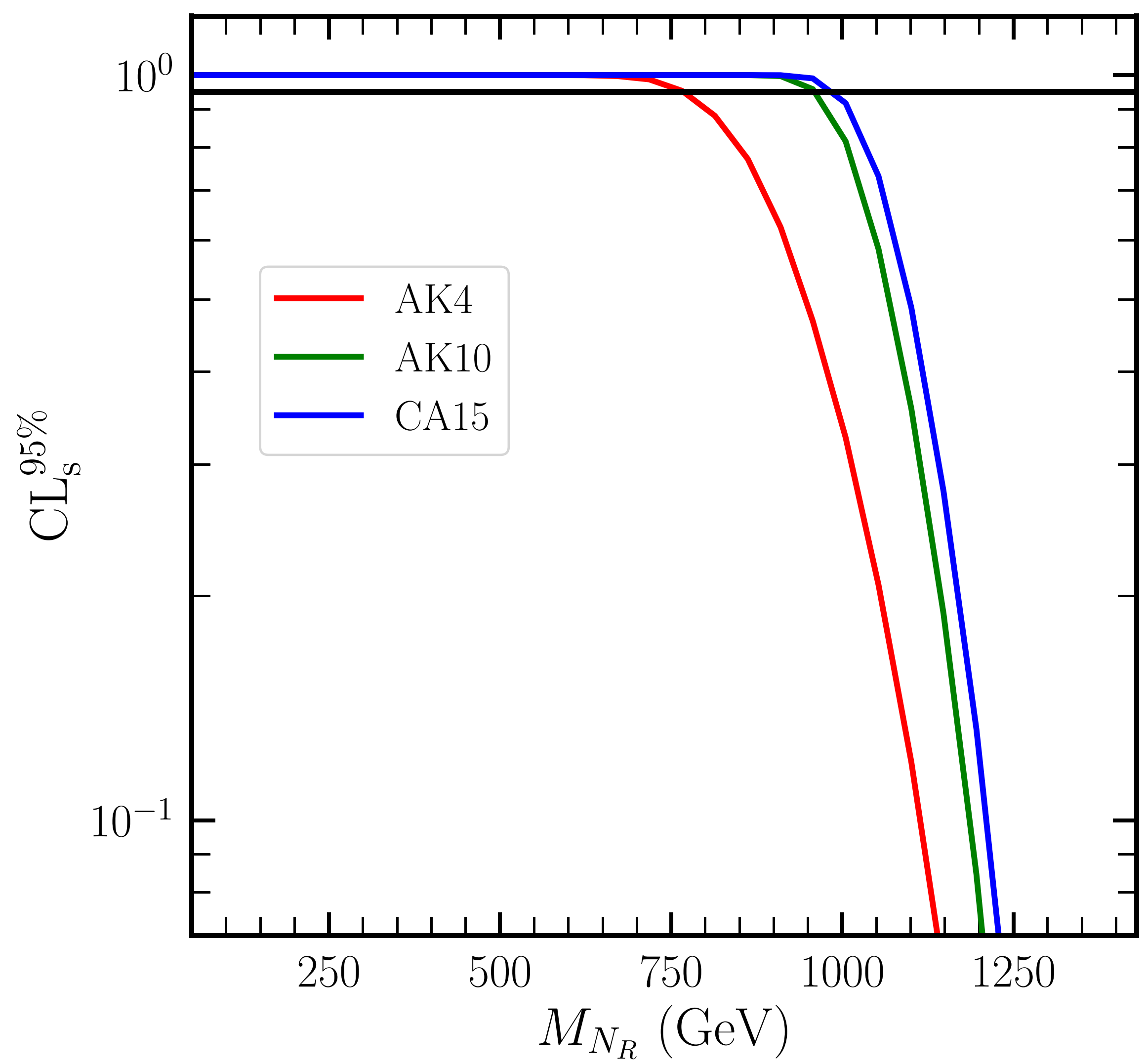
Improvements with BDTs

Benchmark point		BP1	BP2	BP3	BP4
Resolved (AK4)	$\mathcal{S}_{100\ \text{fb}^{-1}}$	33.85	9.59	1.77	0.63
	$\mathcal{S}_{1000\ \text{fb}^{-1}}$	75.69	21.45	3.97	1.42
Merged (AK10)	$\mathcal{S}_{100\ \text{fb}^{-1}}$	143.44	45.41	6.86	1.99
	$\mathcal{S}_{1000\ \text{fb}^{-1}}$	320.76	101.55	15.34	4.45
Merged (CA15)	$\mathcal{S}_{100\ \text{fb}^{-1}}$	149.20	47.83	7.66	2.60
	$\mathcal{S}_{1000\ \text{fb}^{-1}}$	333.62	106.95	17.13	5.81

Impressive enhancement of the signal significance!

Improvements with BDTs





DM masses up to 1 TeV can be excluded for 3 TeV muon collider!

Conclusions and Outlook

- We have studied the potential of future muon colliders in testing dark matter candidate interacting primarily with muons.
- We have analysed all the possible theoretical and experimental constraints.
- The model can be tested in a variety of production modes (totaling up to 54 channels).
- We then studied the sensitivity for a subleading channel, i.e. mono-Higgs.
- We also found that even basic ML algorithms can dramatically enhance the sensitivity at future muon colliders.
- More work is needed to study further channels, dark-matter characterization, … etc.