New Physics models at the precision & intensity frontiers

Stefania Gori
UC Santa Cruz

Beyond the SM from Colliders to the Early Universe workshop
Carena-Wagner fest

Chicago,
May 30, 2023

What's this talk about

- Physics and memories with Carlos and Marcela since 2009
- Higgs physics and the connection to dark sectors (precision physics)
- Dark sector physics at high intensity experiments: DarkQuest

Meeting Carlos and Marcela in 2009

I first met Carlos at the SUSY conference in Boston, June 2009
(my first time in the US!).
My first impression: how many questions does he ask during talks??

Then I visited Chicago and met Marcela in November 2009

Then another SUSY conference,
Bonn, 2010

I moved to Chicago in September 2010: the start of my “US adventure”:

Professionally incredibly stimulating…
and a lot of fun! These guys know how to party!

Fun memories over the years: Aspen

2018

Partying

Eating/drinking

… and…

Fun memories over the years: Aspen

2021

2022

2018

Partying

Eating/drinking

… and…

Fun memories over the years: Aspen

2016

No Carlos here.

We are keeping up the tradition!

Partying

Eating/drinking

… and volleyball

Fun memories over the years: Aspen

2016

Carlos, you should visit us and play in Santa Cruz!

No Carlos here.

We are keeping up the tradition!

Papers with Carlos and Marcela

Search for Higgs Bosons in SUSY Cascade Decays and Neutralino Dark Matter,
SG, P. Schwaller, **C.E.M. Wagner**, Phys. Rev. D 83 (2011) 115022

W plus two Jets from a Quasi-Inert Higgs Doublet,
Q.H. Cao, **M. Carena**, SG, A. Menon, P. Schwaller, **C.E.M. Wagner**, L.T. Wang, JHEP 1108 (2011) 002

Signals of CP Violation Beyond the MSSM in Higgs and Flavor Physics
W. Altmannshofer, **M. Carena**, SG, A. de la Puente, Phys. Rev. D 84 (2011) 095027

A 125 GeV SM-like Higgs in the MSSM and the gamma-gamma Rate,
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LHC Discovery Potential for Non-Standard Higgs Bosons in the 3b Channel,
M. Carena, SG, A. Juste, A. Menon, **C.E.M. Wagner**, L.T. Wang, JHEP 1207 (2012) 091

Light Stau Phenomenology and the Higgs gamma-gamma Rate,
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Vacuum Stability and Higgs Diphoton Decays in the MSSM,
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Light Stops, Light Staus and the 125 GeV Higgs,
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Find the intruder

W+jets

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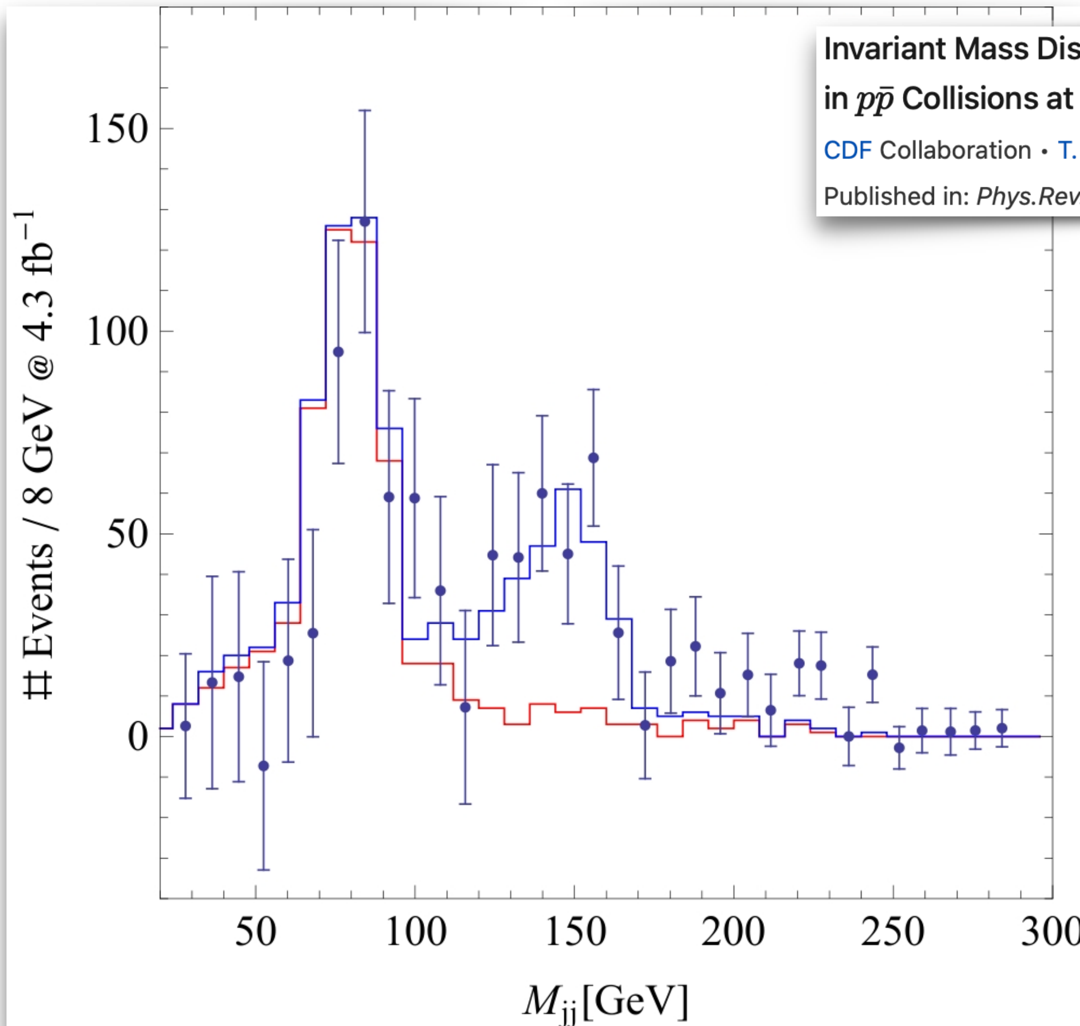

Invariant Mass Distribution of Jet Pairs Produced in Association with a W boson in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

CDF Collaboration • T. Aaltonen (Helsinki Inst. of Phys.) et al. (Apr, 2011)

Published in: *Phys.Rev.Lett.* 106 (2011) 171801 • e-Print: 1104.0699 [hep-ex]

3.2 σ excess at CDF

our solution:

$$p\bar{p} \to H^\pm \to W^\pm H^0/W^\pm A^0 \to \ell^\pm \nu jj$$

W+jets and the Panda Collaboration

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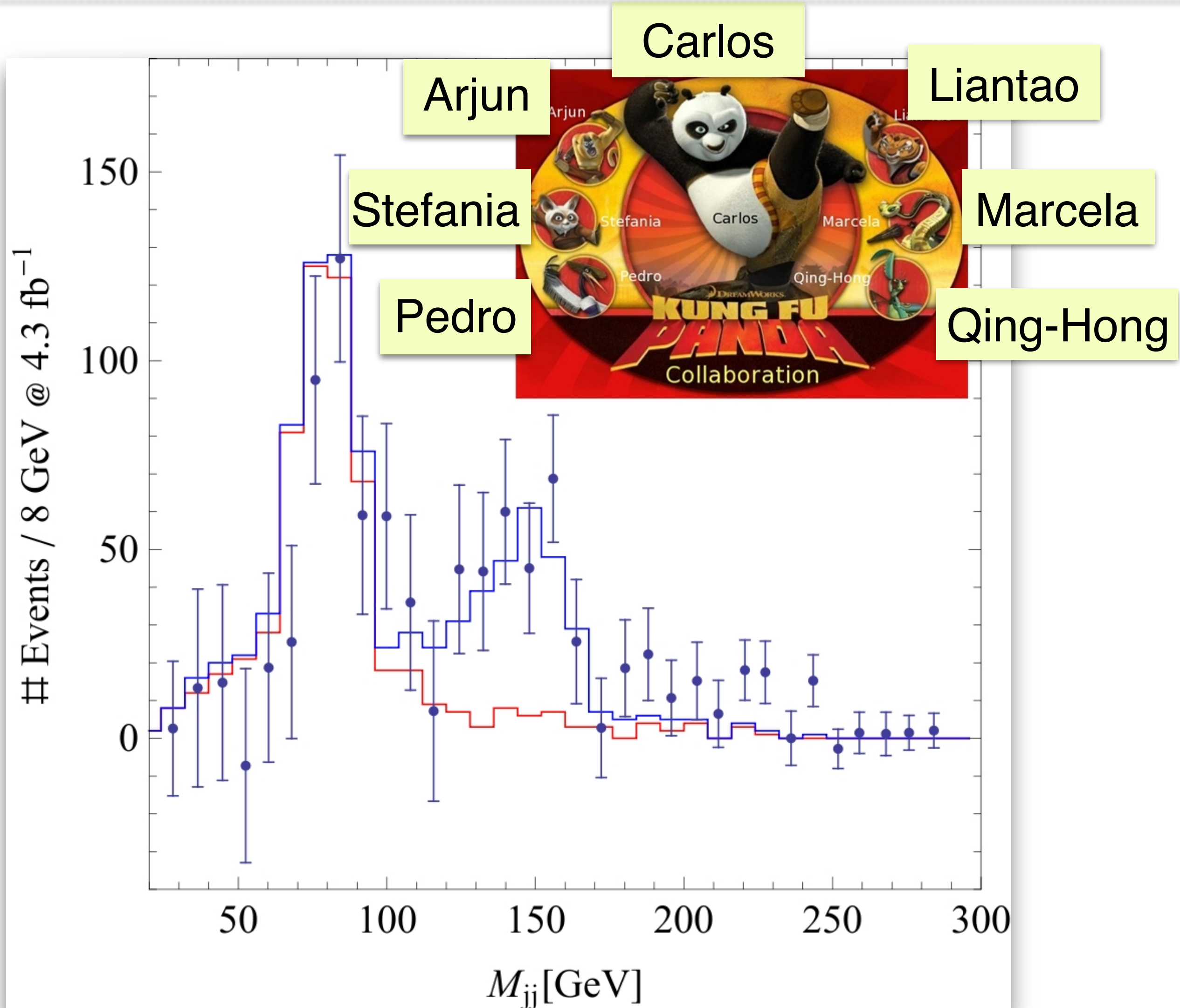

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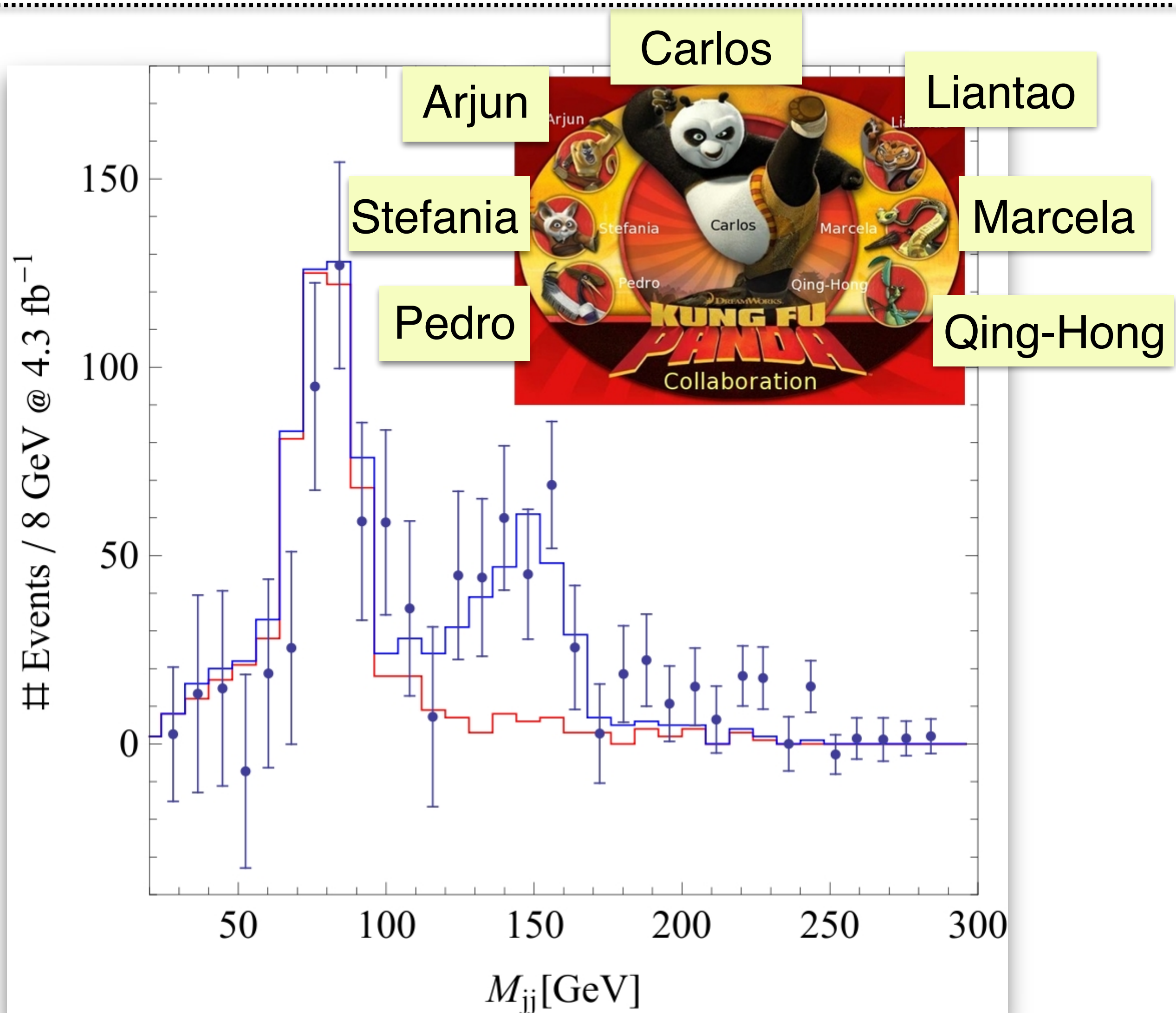


Higgs pheno before the Higgs discovery

Signals of CP Violation Beyond the MSSM in Higgs and Flavor Physics

Wolfgang Altmannshofer (Fermilab), Marcela Carena (Fermilab and Chicago U., EFI), Stefania Gori (Chicago U., EFI), Alejandro de la Puente (Fermilab and Notre Dame U.) (Jul, 2011)

Published in: *Phys.Rev.D* 84 (2011) 095027 • e-Print: 1107.3814 [hep-ph]

MSSM+additional 1/M suppressed effective operators that carry CP violation.

Higgs and flavor phenomenology for Tevatron and LHC.

Search for Higgs Bosons in SUSY Cascade Decays and Neutralino Dark Matter

Stefania Gori (Chicago U.), Pedro Schwaller (Illinois U., Chicago and Argonne), Carlos E.M. Wagner (Chicago U. and Argonne and Chicago U., EFI) (Mar, 2011)

Published in: *Phys.Rev.D* 83 (2011) 115022 • e-Print: 1103.4138 [hep-ph]

"Due to the large QCD background, searches for such a Higgs, decaying into a pair of bottom quarks, is very challenging at the LHC".

Study of boosted Higgs production from neutralino and chargino decay and compatibility with DM scenario.

Dreaming of the Higgs

A 125 GeV SM-like Higgs in the MSSM and the gamma-gamma Rate,
M. Carena, SG, N.R. Shah, **C.E.M. Wagner**, JHEP 1203 (2012) 014 arXiv: 1112.3336

This paper was after the first LHC hints for a Higgs at ~(124 - 126) GeV with possibly an enhanced gamma gamma rate:

4.9 fb^{-1} at 7 TeV

ATLAS-CONF-2011-163

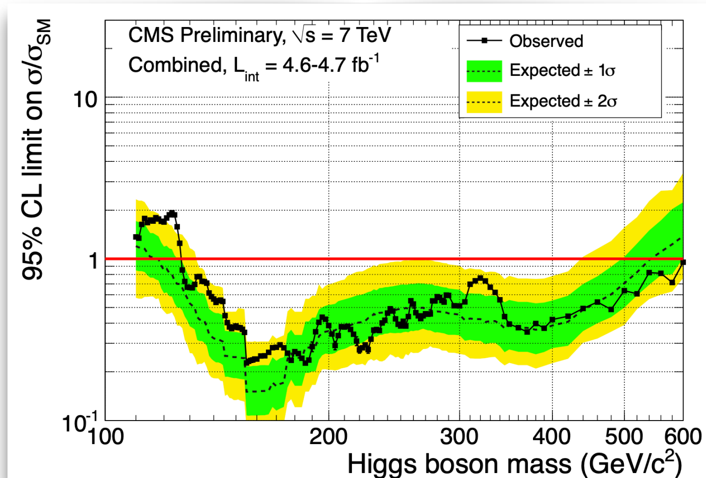
global significance of 2.3σ
local significance of 3.6σ

$H\to\gamma\gamma$
$H\to ZZ\to 4l$
$H\to WW^*\to l\nu\ l\nu$

CMS-PAS-HIG-11-032

global significance of 1.9σ
local significance of 2.6σ

$H\to\gamma\gamma$
$H\to ZZ\to 4l$
$H\to WW^*\to l\nu\ l\nu$
$H\to bb$
$H\to\tau\tau$



(The enhancement of the di-photon rate persisted after the Higgs discovery)

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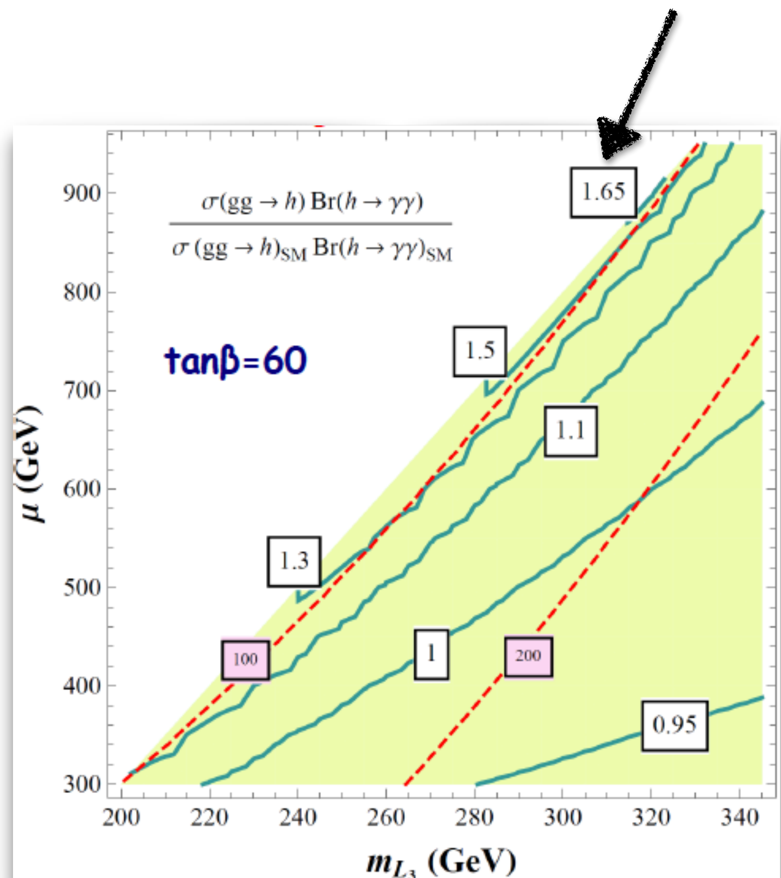
1. In the MSSM, stops have to lift the mass of the Higgs by ~ 35 GeV.

1.1 stops in the several hundred GeV mass range with somewhat large mixing, or 1.2 a large hierarchy between the two stop masses in the case that one of the two stops is light.

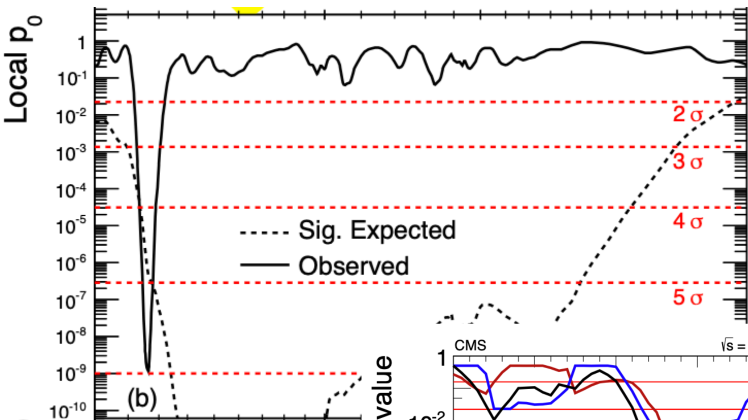
2. Light and heavily mixed staus can enhance the di-photon rate

$$\mathcal{M}^2_{\tilde\tau} \simeq \begin{pmatrix} m^2_{L_3} + m^2_\tau + D^\tau_L & m_\tau(A_\tau - \mu\tan\beta) \\ m_\tau(A_\tau - \mu\tan\beta) & m^2_{E_3} + m^2_\tau + D^\tau_R \end{pmatrix}$$

$$\Delta A_{\gamma\gamma} \propto -\frac{(\mu\tan\beta)^2 m^2_\tau}{m^2_{L3} m^2_{e3} - m^2_\tau(\mu\tan\beta)^2}$$

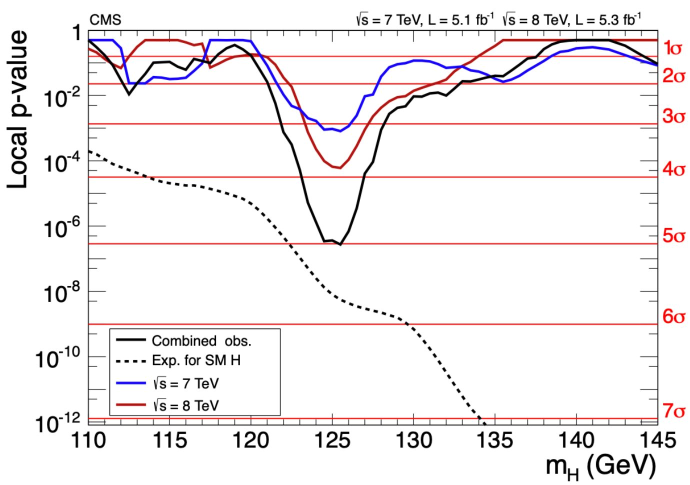


Discovery!



1207.7214

1207.7235



July 4, 2012
starting at 2am local time in Chicago

Discovery party

Discovery party

The reaction to the Higgs discovery

The year of the Higgs discovery was the most exciting year

Light Stau Phenomenology and the Higgs gamma-gamma Rate,
M. Carena, SG, N.R. Shah, **C.E.M. Wagner**, L.T. Wang, JHEP 1207 (2012) 175

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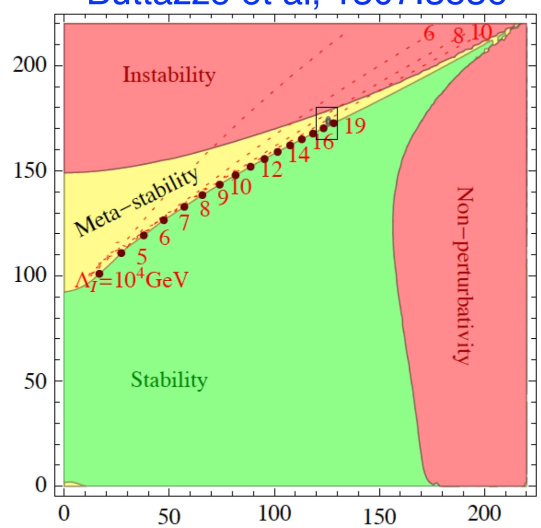
The SM has a metastable minimum

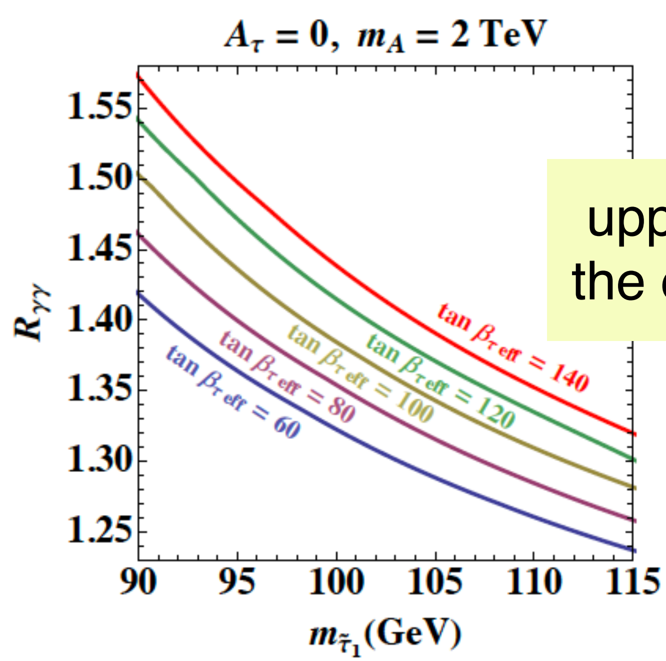
Buttazzo et al, 1307.3536



Light staus can destabilize the EW minimum. Appearance of **charged breaking minima**

$$V \supset -2 y_\tau \mu \tilde{L} \tilde{\tau} \phi_u + \tilde{L}^2 \tilde{\tau}^2 \left(y_\tau^2 - \frac{g_1^2}{2} \right)$$

$$y_\tau \mu \sim \sqrt{2} \frac{m_\tau}{v} \mu \tan\beta$$



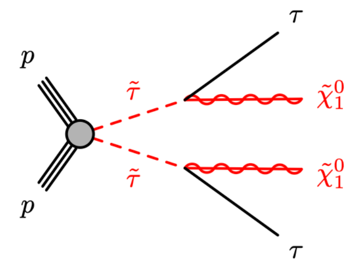
upper bound on the di-photon rate

Staus in 2023: still pretty hidden

Quoted proposed scenario: $m_{L3} = m_{e3}$ = 280 GeV, tan β = 60, μ = 650 GeV and M_1 = 35 GeV, giving a light stau ~ 95 GeV, a very light LSP, $m_{\chi 1}$ ~ 35 GeV and a light sneutrino, ~ 270 GeV.

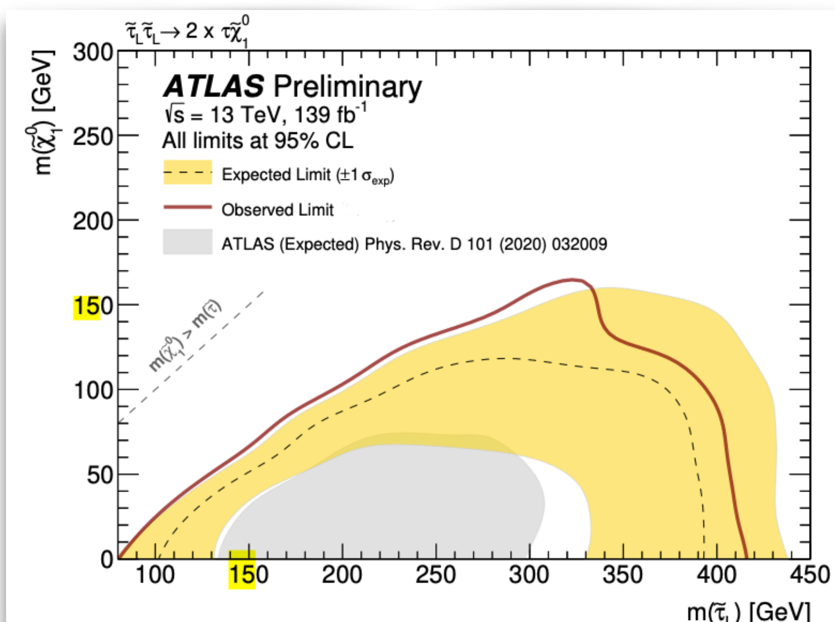
1205.5842

	Signature	8 TeV LHC (fb)	14 TeV LHC (fb)
$pp \to \tilde{\tau}_1 \tilde{\tau}_1$	$2\tau, \not{E}_T$	55.3	124.6
$pp \to \tilde{\tau}_1 \tilde{\tau}_2$	$2\tau, Z, \not{E}_T$	1.0	3.2
$pp \to \tilde{\tau}_2 \tilde{\tau}_2$	$2\tau, 2Z, \not{E}_T$	0.15	0.6
$pp \to \tilde{\tau}_1 \tilde{\nu}_\tau$	$2\tau, W, \not{E}_T$	14.3	38.8
$pp \to \tilde{\tau}_2 \tilde{\nu}_\tau$	$2\tau, W, Z, \not{E}_T$	0.9	3.1
$pp \to \tilde{\nu}_\tau \tilde{\nu}_\tau$	$2\tau, 2W, \not{E}_T$	1.6	5.3



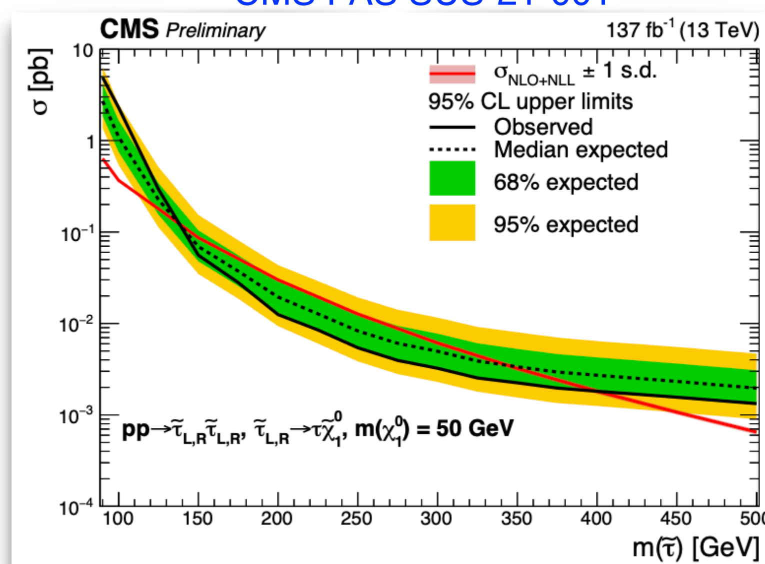
$$pp \to \tilde{\tau}_1 \tilde{\nu}_\tau \to \tilde{\tau}_1 (W \tilde{\tau}_1) \to \tau \chi_1 W \tau \chi_1$$

Our signature has not been looked for yet by ATLAS and CMS



ATLAS-CONF-2023-029

CMS PAS SUS-21-001



Future Higgs discoveries and the Higgs portal

Happy 10th Birthday
Higgs

"The Higgs is SM-like" but…

We need to understand if the Higgs

- interacts with the 2nd generation ← Future Higgs discovery (for Run III)
- interacts with itself
- is CP violating
- interacts with DM/a dark sector
- interacts with new Higgs bosons
- …

Future Higgs discoveries and the Higgs portal

Happy 10th Birthday Higgs

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- …

} $|H|^2$ is the lowest dimensional gauge and Lorentz invariant combination of SM fields that we can write down

⬇

The Higgs easily couples to any new physics

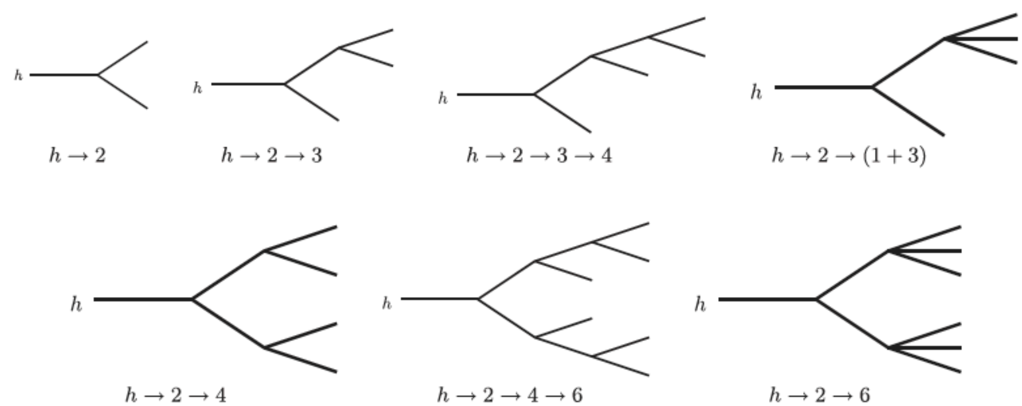
One of the only 3 possible renormalizable operators that connect the SM to gauge singlet particles (aka **dark sector** particles): $|H|^2 \, |S|^2$

Higgs portal

Higgs exotic decays

Aspen (summer 2012) was also the place where several colleagues (many from the Chicago area) and my self started the effort studying Higgs exotic decays

Exotic Decays of the 125 GeV Higgs Boson
1312.4992,
D. Curtin, R. Essig, SG, P. Jaiswal, A. Katz, T. Liu, Z. Liu, D. McKeen, J.Shelton, M. Strassler, Z. Surujon, B. Tweedie, Y-M. Zhong



Some inspiration from models like “Dark higgs”, Draper, Wagner, Wang, Zhang, 1009.3963 (NMSSM with an approximate PQ symmetry)

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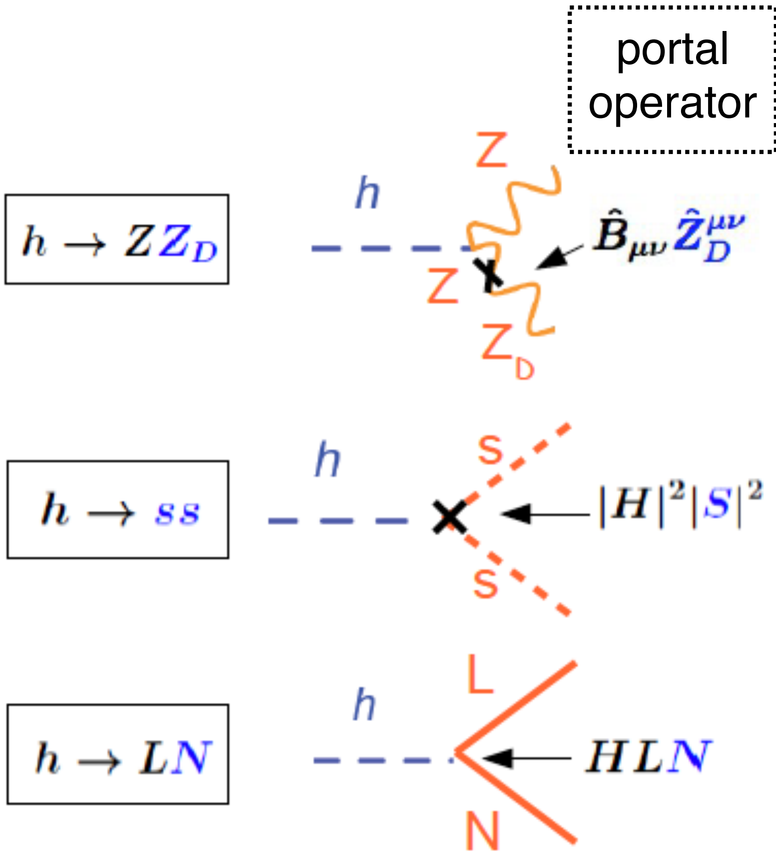

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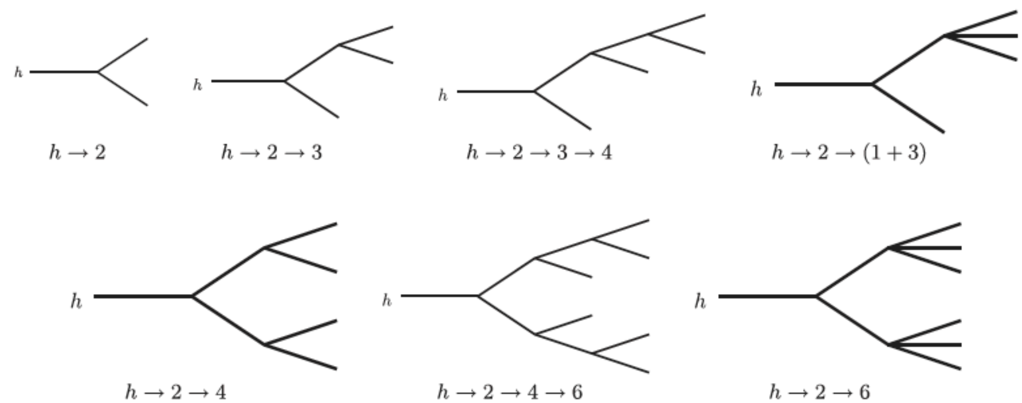

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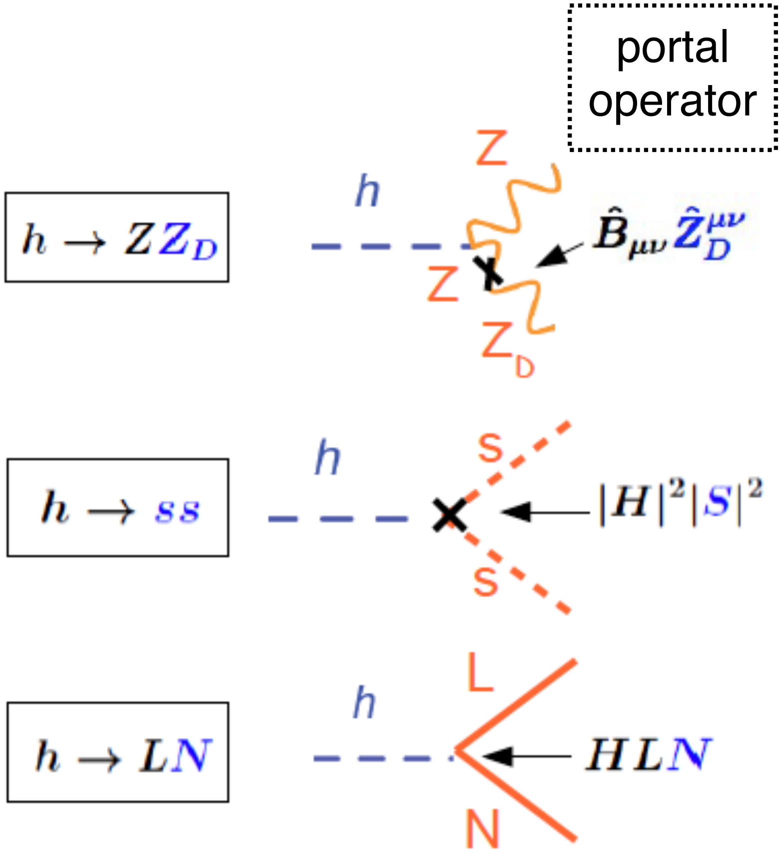

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The LHC can be thought as a high-intensity machine

- Now 7 million Higgs
- HL-LHC 170 million Higgs

This is particularly relevant for rare processes like Higgs exotic decays

Higgs exotic decays: one of the best ways to probe light new particles at the LHC

Lower bound on the interaction strength

If we ask for a thermal freeze-out scenario: $\epsilon Z^{\mu\nu} A'_{\mu\nu}$ $\kappa |H|^2 |S|^2$ $y H L N$

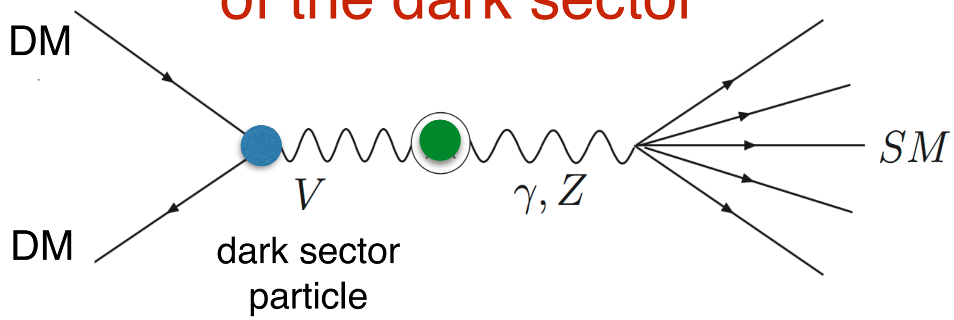
cannot be too small

Lower bound on the interaction strength

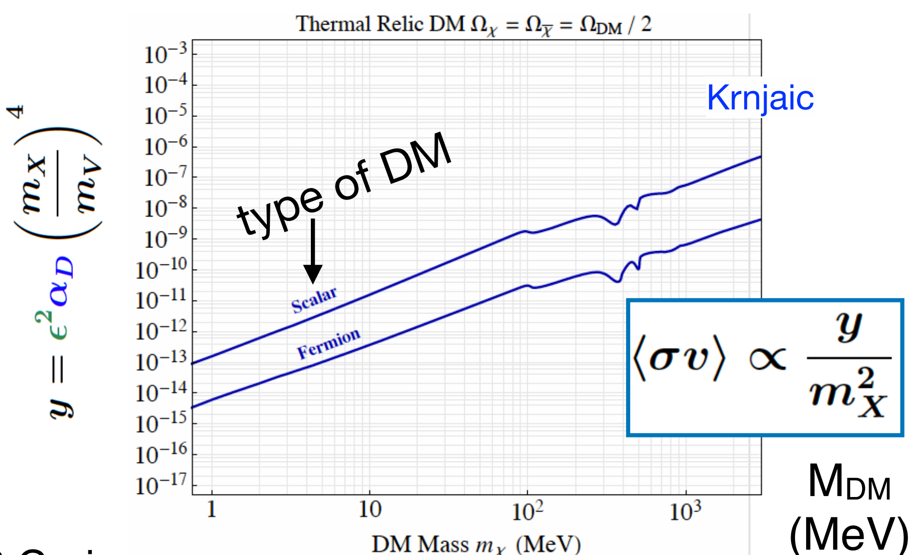
If we ask for a thermal freeze-out scenario: $\epsilon Z^{\mu\nu} A'_{\mu\nu}$ $\kappa |H|^2 |S|^2$ $y H L N$

cannot be too small

1. **DM is the lightest state** of the dark sector



Relic abundance regulated by ●, ●

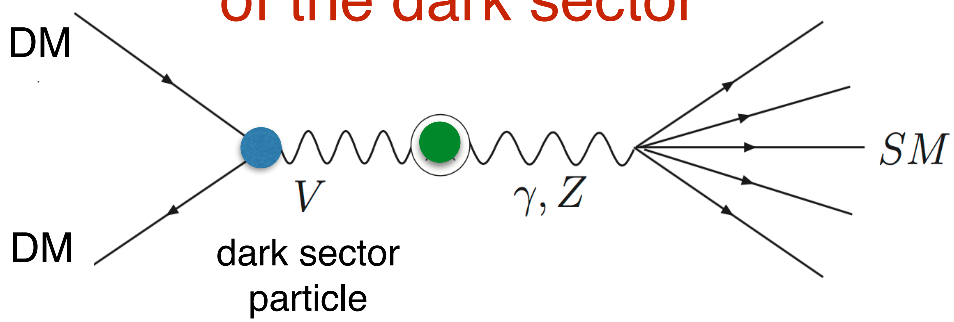


$$\langle \sigma v \rangle \propto \frac{y}{m_X^2}$$

Lower bound on the interaction strength

If we ask for a thermal freeze-out scenario: $\epsilon Z^{\mu\nu} A'_{\mu\nu}$ $\kappa|H|^2|S|^2$ $yHLN$

1. **DM is the lightest state of the dark sector**



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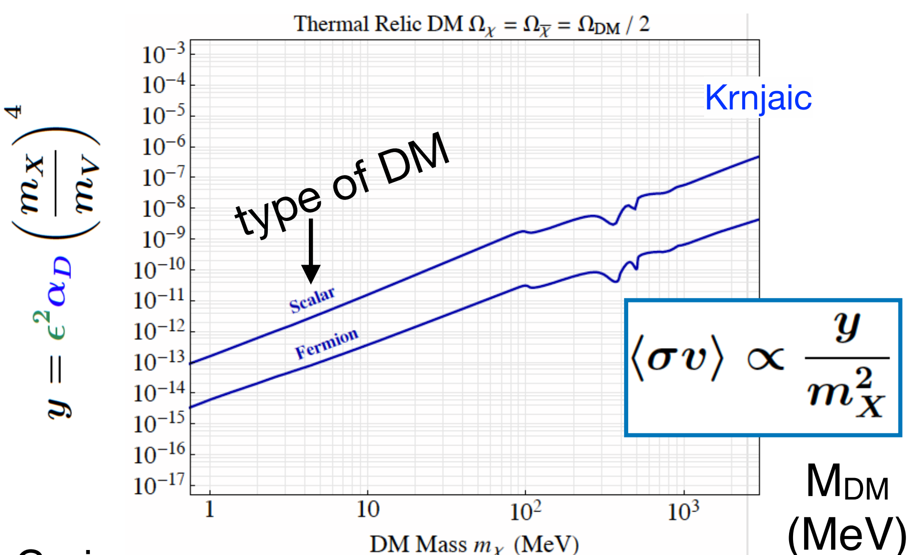
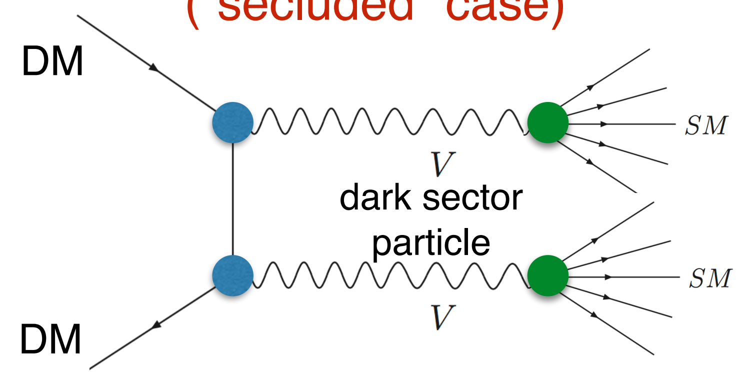
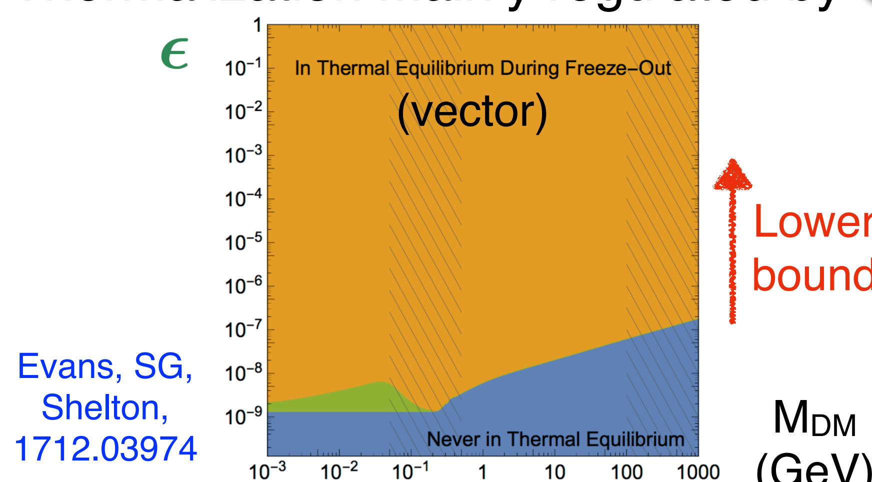


2. **One (or more) particles** of the dark sector **are lighter than DM** ("secluded" case)



Thermalization mainly regulated by ●

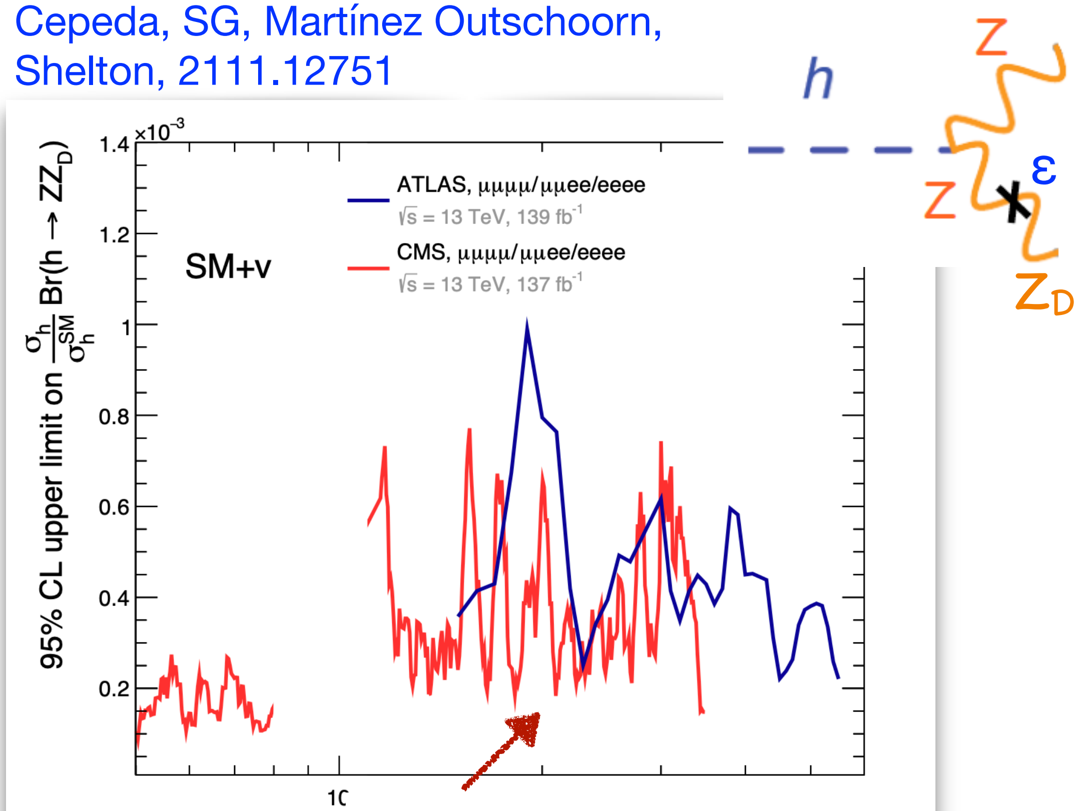


Dark photons and scalars from Higgs exotic decays

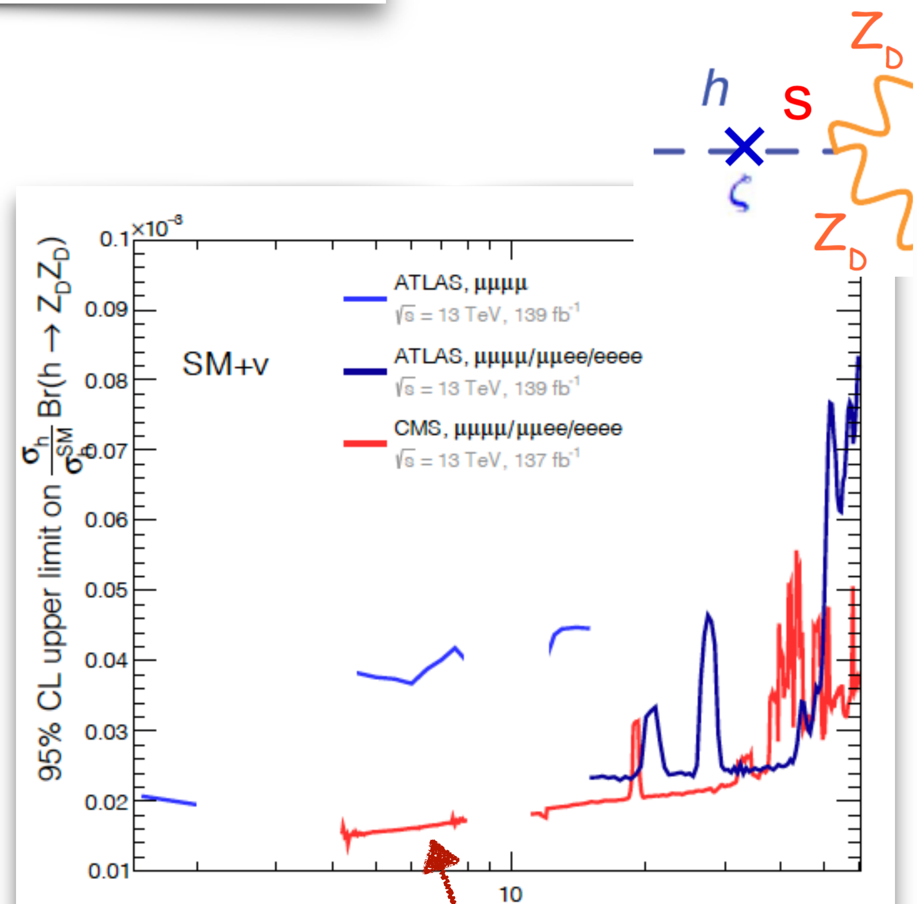
$$\mathcal{L} \supset \frac{\epsilon}{2\cos\theta}\hat{V}_{\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{8}\langle S\rangle^2 g_D^2(\hat{V}_\mu)^2 + \zeta|S|^2|H|^2$$

Curtin, Essig,SG, Shelton, 1412.0018

Cepeda, SG, Martínez Outschoorn, Shelton, 2111.12751



$\epsilon \lesssim 0.04$



$$\zeta' = \zeta\frac{m_h^2}{m_h^2 - m_S^2} \lesssim 10^{-4}$$

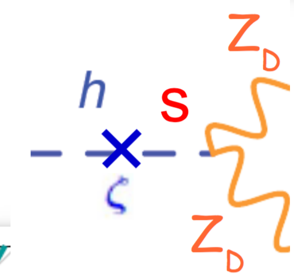
Prompt decays of the dark photon.

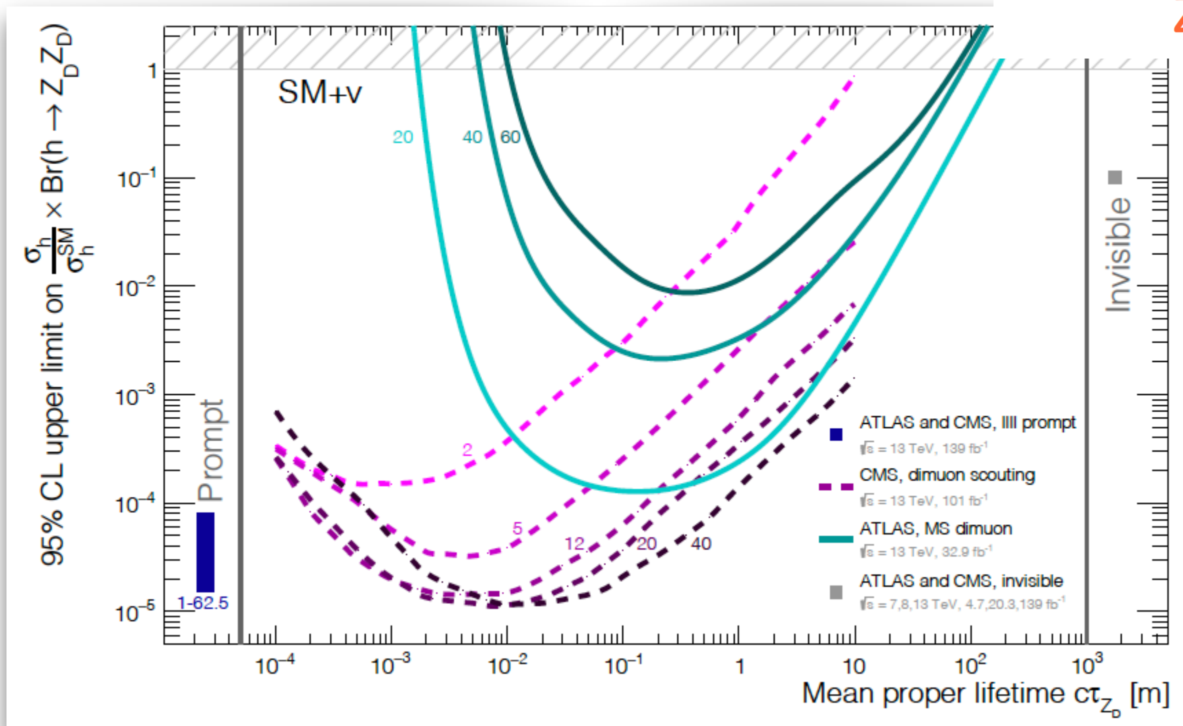
Dark photons and scalars from Higgs exotic decays

$$\mathcal{L} \supset \frac{\epsilon}{2\cos\theta}\hat{V}_{\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{8}\langle S\rangle^2 g_D^2(\hat{V}_\mu)^2 + \zeta|S|^2|H|^2$$

Curtin, Essig, SG, Shelton, 1412.0018

Cepeda, SG, Martínez Outschoorn, Shelton, 2111.12751





* Branching ratio depends on

$$\zeta' = \zeta\frac{m_h^2}{m_h^2 - m_S^2}$$

* Life time depends on ε. At low mass, calculation done with the R(s) ratio:

$$\Gamma_{Z_D} = R_{Z_D}\Gamma(Z_D \to \mu^+\mu^-) + \sum_{f=e,\mu,\tau,\nu_i}\Gamma(Z_D \to f\bar{f})$$

$$R_{Z_D}(m_{Z_D}) = R(s) \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Displaced decays of the dark photon.

Dark sectors at high intensity experiments

The **several portals** will lead to the **production of dark particles** at high intensity & high energy experiments

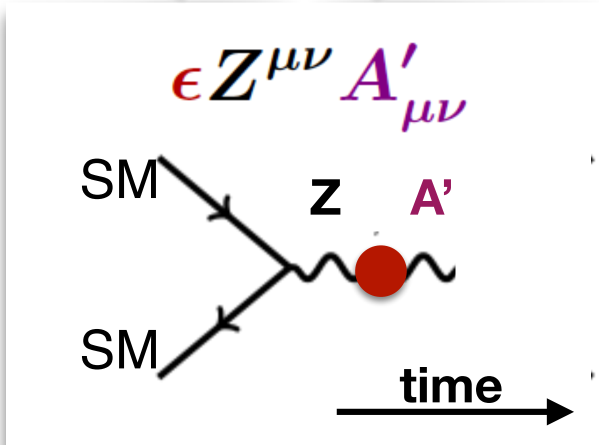
$\epsilon Z^{\mu\nu} A'_{\mu\nu}$ $\kappa |H|^2 |S|^2$

$y H L N$

(Typically) high energy

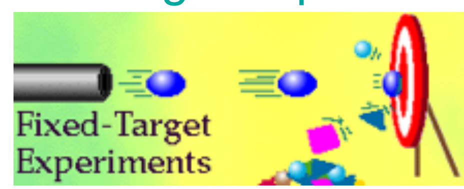
Colliding beam experiments

- B-factories (Belle-II) e^+e^- collider
- The LHC (pp collider)



(Typically) high intensity

Fixed target experiments

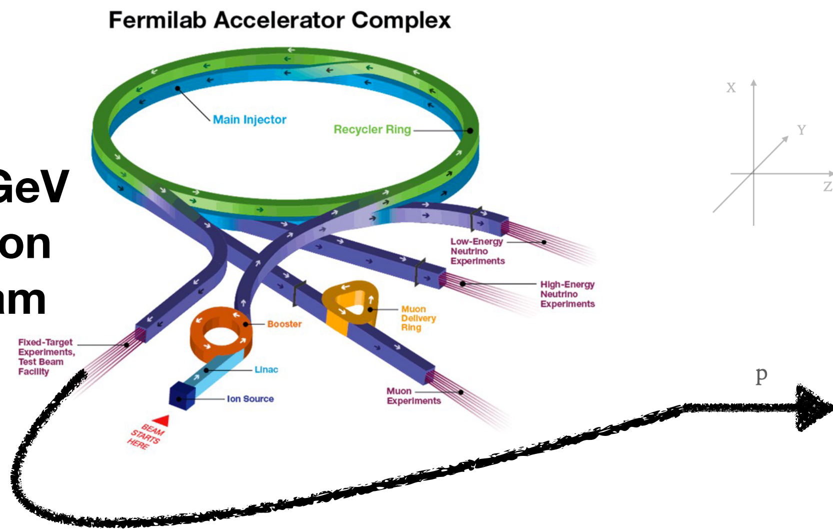


- Kaon exp. (NA62, KOTO)
- proton beam dump exp.
- electron beam dump exp.
- electron fixed target exp.
- neutrino exp.
- light meson (e.g. pion) exp.

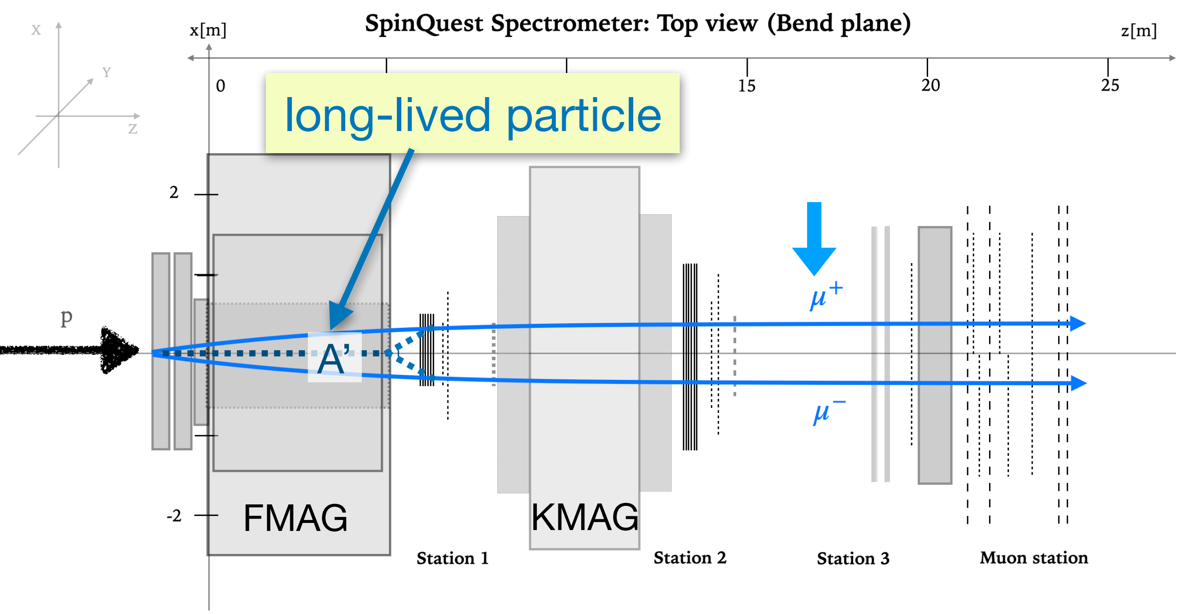
Proposing new experiments and searches to achieve a broad program of probes of the dark sector. Simplified model strategy vs. complete models

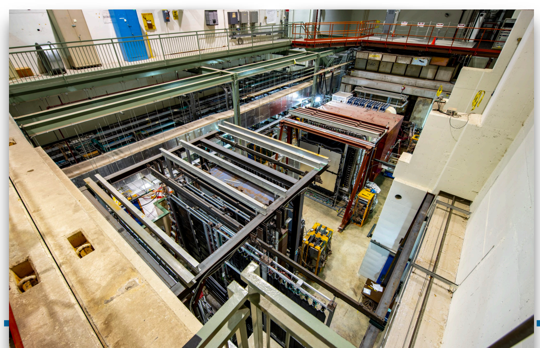
SpinQuest and DarkQuest

120 GeV proton beam



compact geometry





SeaQuest → SpinQuest

1706.09990

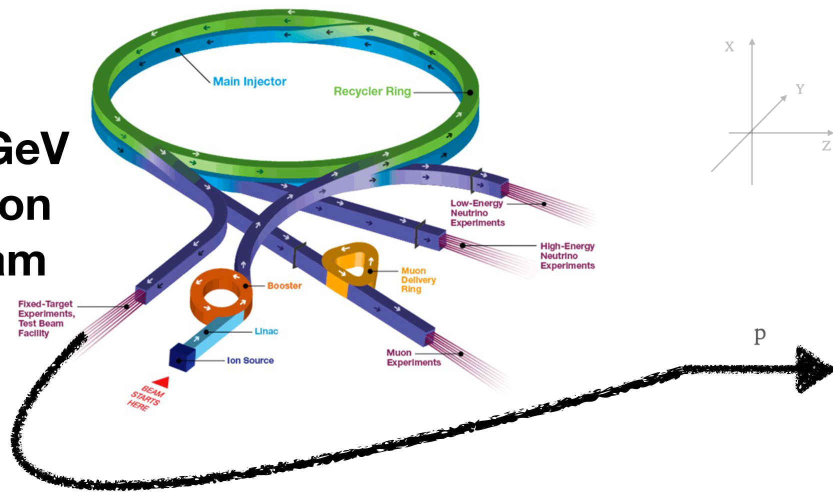
polarized target
+ displaced trigger

Nuclear physics: Measuring the Drell-Yan muon process for studies of the proton structure

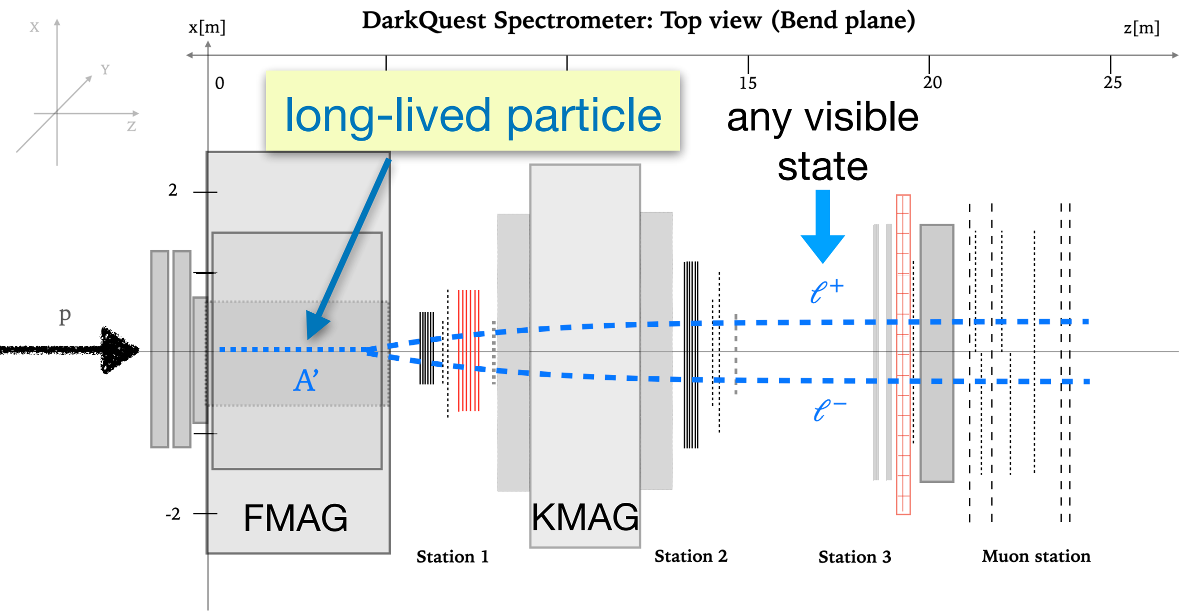
Particle Physics: Visible dark sector searches (muons)

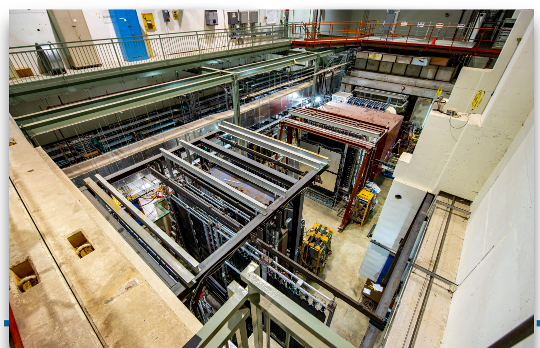
SpinQuest and DarkQuest

120 GeV proton beam



compact geometry





SeaQuest → SpinQuest → DarkQuest

1706.09990

polarized target
+ displaced trigger

proposed upgrade
(calorimeter +
more tracking layers +
hodoscope for triggering)

Nuclear physics: Measuring the Drell-Yan muon process for studies of the proton structure

Particle Physics: Visible dark sector searches (any visible)

Initial proposal:
Gardner, Holt, Tadepalli, 1509.00050
Berlin, SG, Schuster, Toro, 1804.00661

Snowmass white paper: 2203.08322

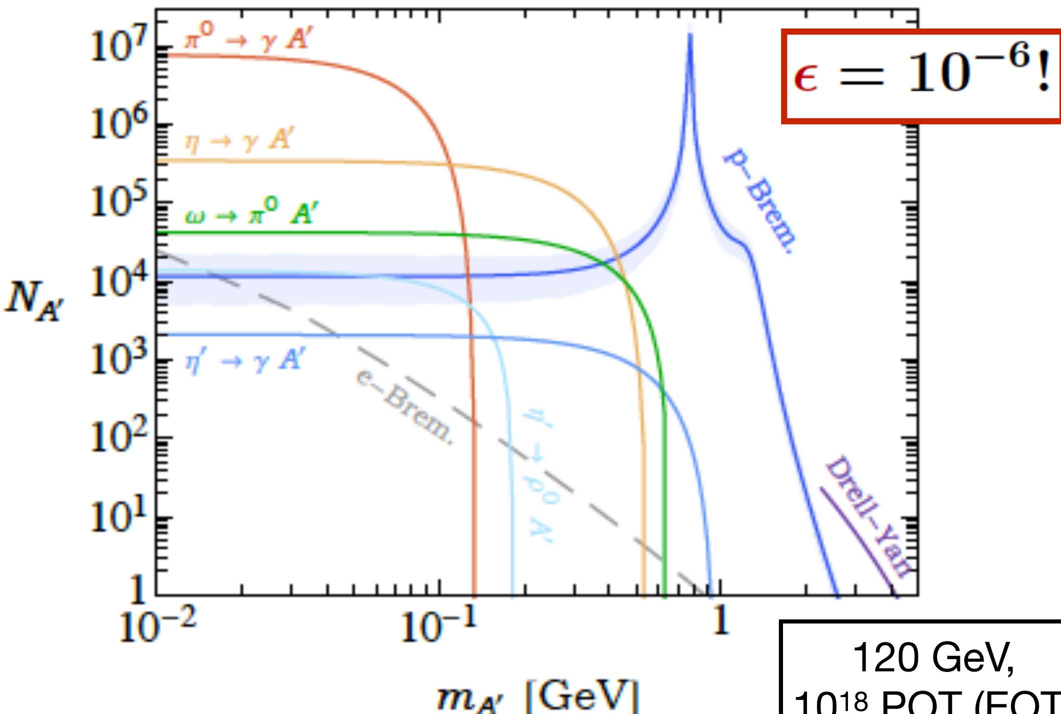
Why a high energy compact proton beam dump?

1. Large production rates of dark particles

$$\mathcal{L} \supset \frac{\epsilon}{2\cos\theta}\hat{V}_{\mu\nu}\hat{B}^{\mu\nu}$$

In the case of a dark photon:

Berlin, SG, Schuster, Toro, 1804.00661



120 GeV,
10^{18} POT (EOT)

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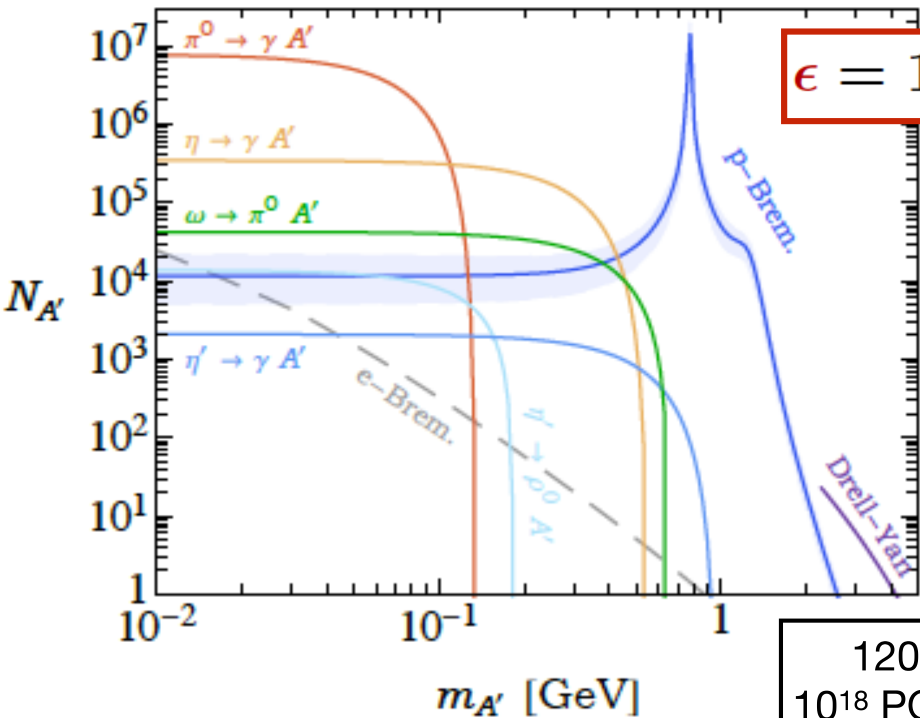


$\epsilon = 10^{-6}$!

120 GeV,
10^{18} POT (EOT)

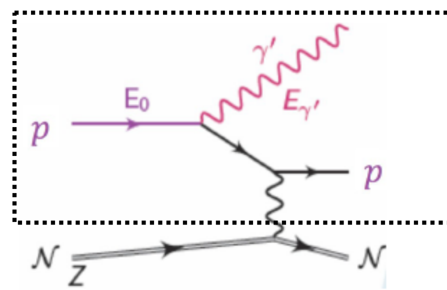
1. A lot of light mesons:
~10^{19} pions
past pion factories: ~10^{11} pi

2. Larger Bremsstrahlung production than at electron fixed target experiments:

proton: $\sigma \sim \alpha_{\rm em}\, \epsilon^2 \times \sigma_{pp}$

electron: $\sigma \sim \dfrac{\alpha_{\rm em}^3\, \epsilon^2}{m_{A'}^2}\, Z^2$

Blümlein et al, 1311.3870.
deNiverville et al, 1609.01770



Uncertainties in the calculation of the Bremsstrahlung
Generalized Williams-Weizsäcker approximation

$$E_p, E_{A'}, E_p - E_{A'} \gg m_p, m_{A'}, |p_T^{A'}|$$

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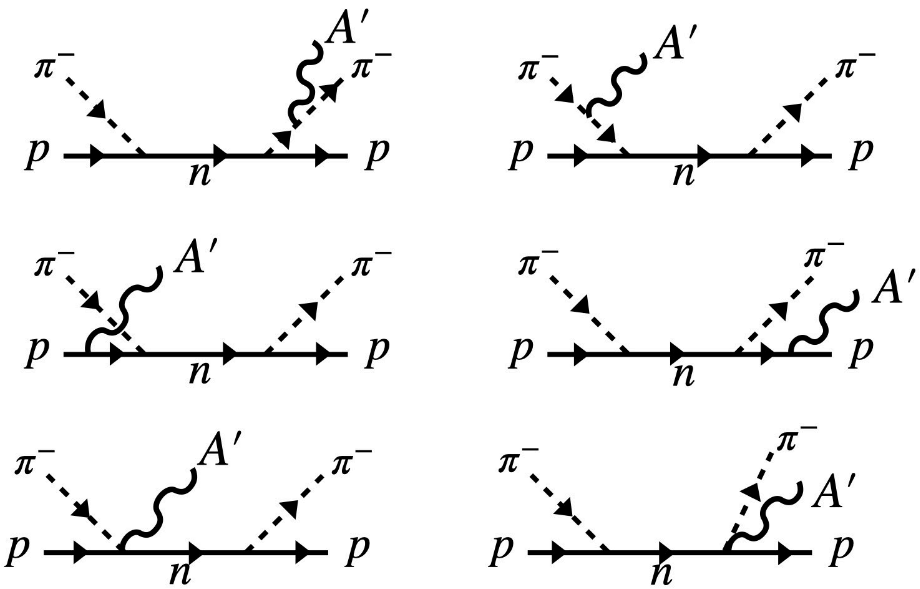
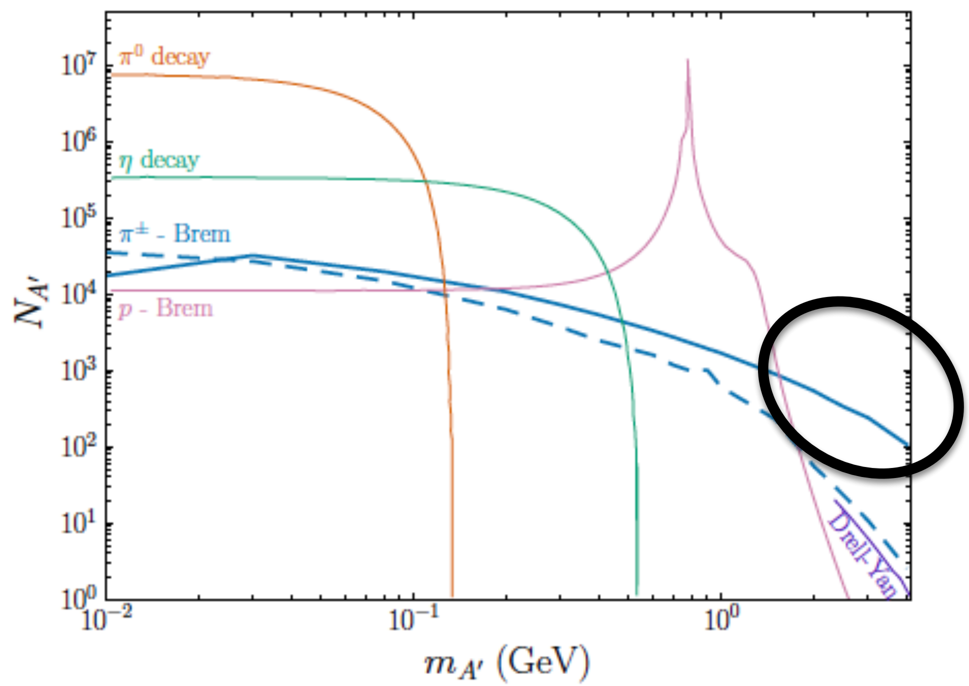
In the case of a dark photon:

Pion Bremsstrahlung



Secondary pion beam



Curtin, Kahn, Nguyen, appearing soon

Why a high energy compact proton beam dump?

1. Large production rates of dark particles

Large production of heavier mesons as well

Batell, Evans, SG, Rai, 2008.08108

	K mesons*		D mesons		B mesons		Leptons
$K^\pm$	$\sim 1.8 \times 10^{15}$	$D^\pm$	$\sim 6.8 \times 10^{14}$	$B^\pm$	$\sim 5.3 \times 10^7$	$\tau^\pm$	$\sim 4.7 \times 10^{10}$
K_L^0	$\sim 2.2 \times 10^{14}$	$D_s^\pm$	$\sim 2.0 \times 10^{13}$	$B_d, \bar{B}_d$	$\sim 5.3 \times 10^7$	$\tau_{D_s}^\pm$	$\sim 1.1 \times 10^{12}$
K_S^0	$\sim 1.2 \times 10^{17}$	$D^0, \bar{D}^0$	$\sim 1.3 \times 10^{14}$				

number that decay before
one nuclear interaction length

Comparison with meson factories:
NA62, KOTO ~ 10^{13} Kaons
Belle II (ultimate) 10^{10} B mesons

Why a high energy compact proton beam dump?

1. Large production rates of dark particles

$\mathcal{L} \supset \zeta |S|^2 |H|^2$

In the case of a dark scalar:

Large production of heavier mesons as well

Batell, Evans, SG, Rai, 2008.08108

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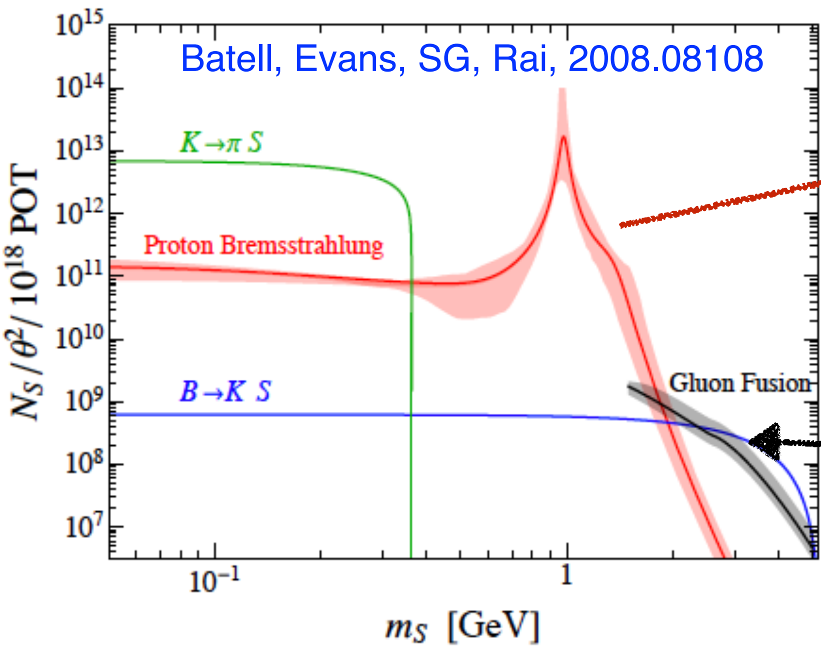

Williams-Weizsäcker approximation:

$$\frac{d\sigma_{\rm brem}}{dz\, dp_T^2} \approx \sigma_{pp}(s')\, P_{p\to pS}(z, p_T^2).$$

$$P_{p\to pS}(z, p_T^2) \approx |F_S(m_S^2)|^2 \frac{g_{SNN}^2\, \theta^2}{8\pi^2} \frac{z\,[m_p^2\,(2-z)^2 + p_T^2]}{[m_p^2\, z^2 + m_S^2\,(1-z) + p_T^2]^2}$$

leading order calculation.
O(1) corrections expected

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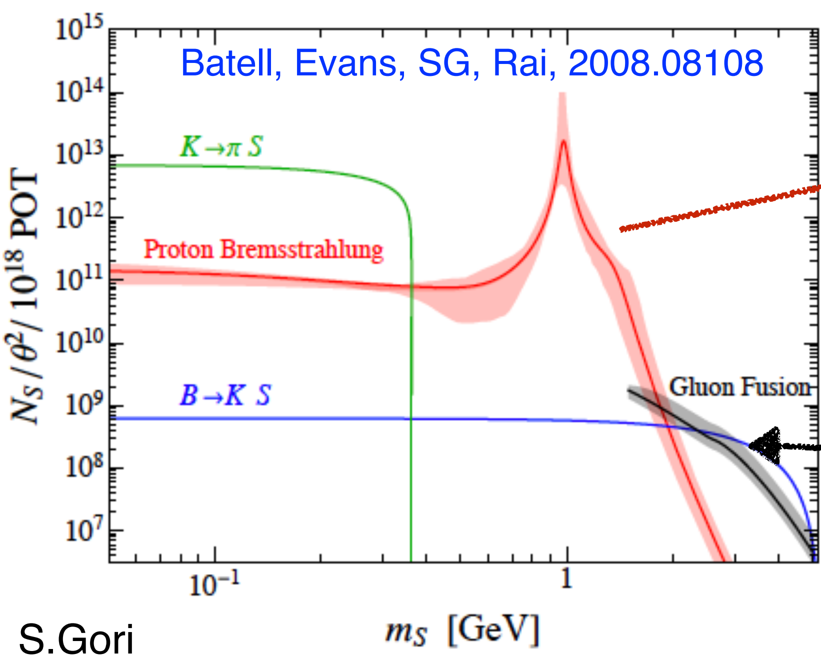
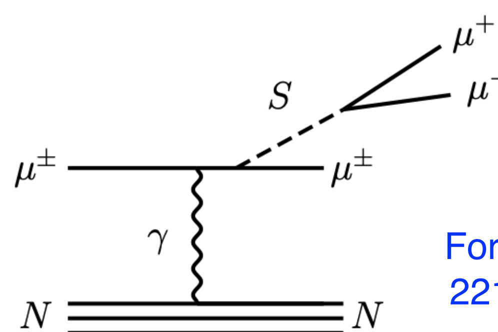


Comparison with meson factories:

Note: **very intense secondary muon beam**
Reach on muon-coupled dark sectors

example:



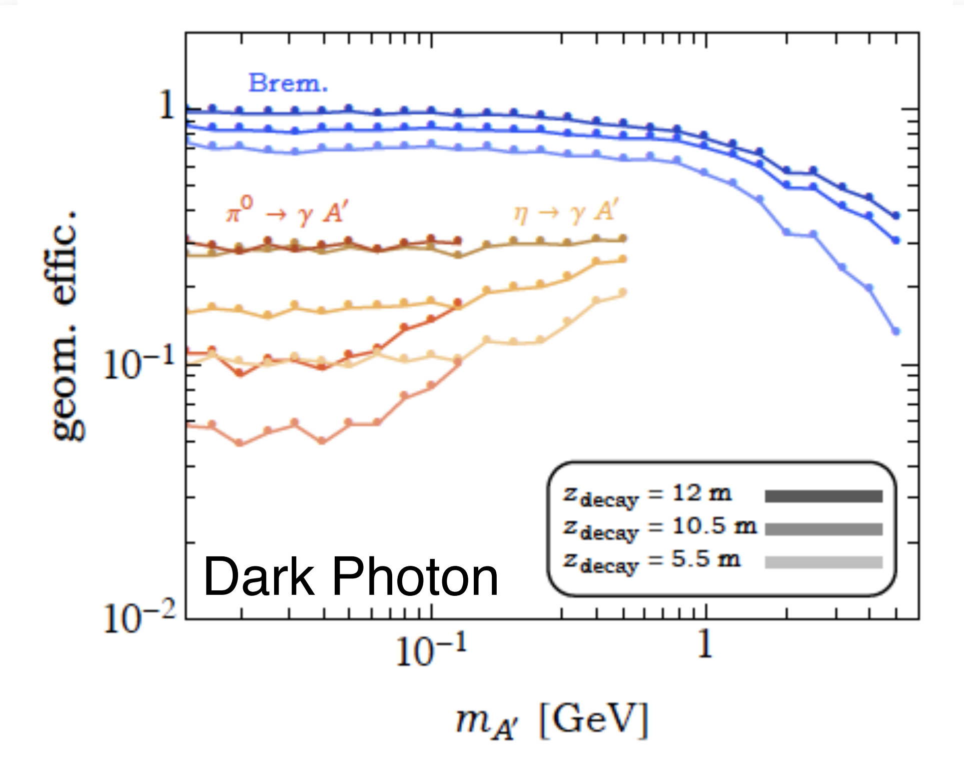
Forbes et al, 2212.00033

leading order calculation.
O(1) corrections expected

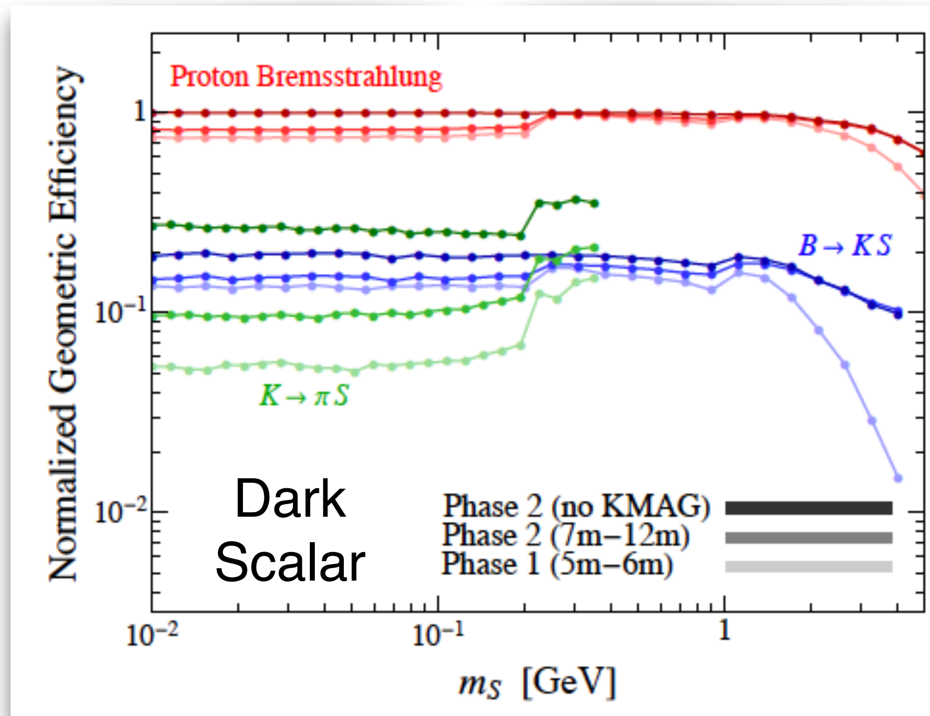
Why a high energy compact proton beam dump?

2. High geometric acceptance

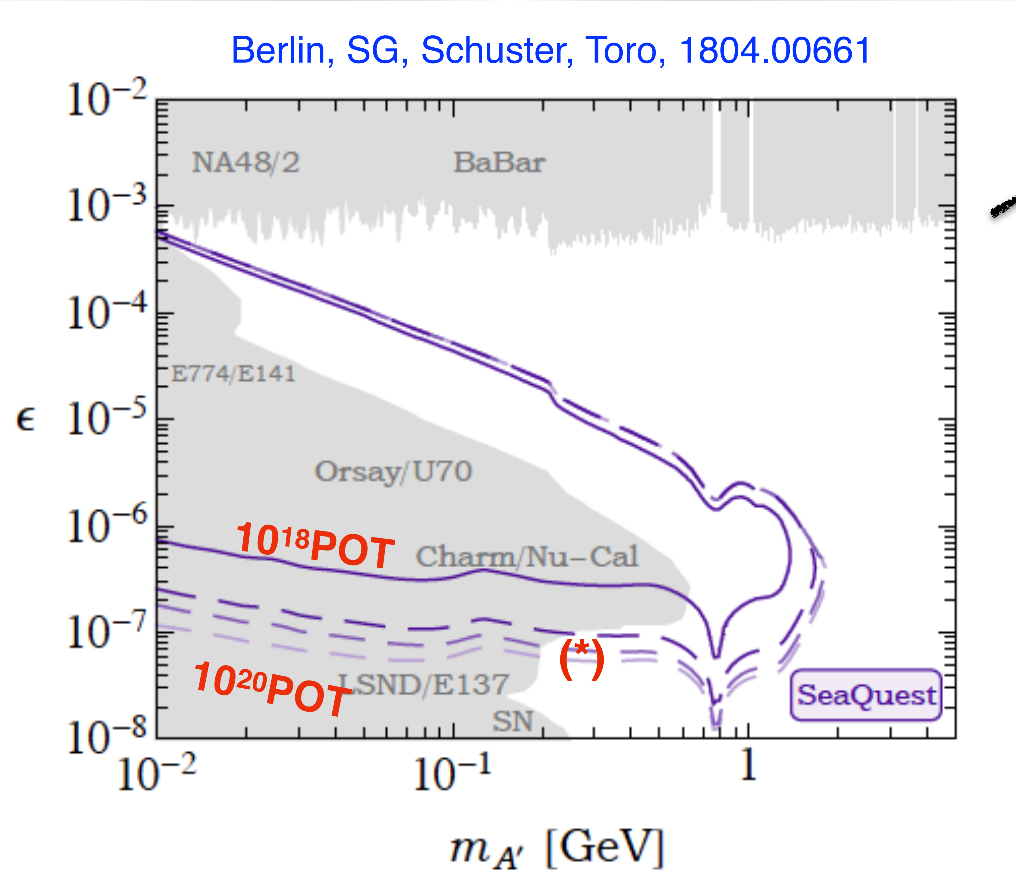
Berlin, SG, Schuster, Toro, 1804.00661



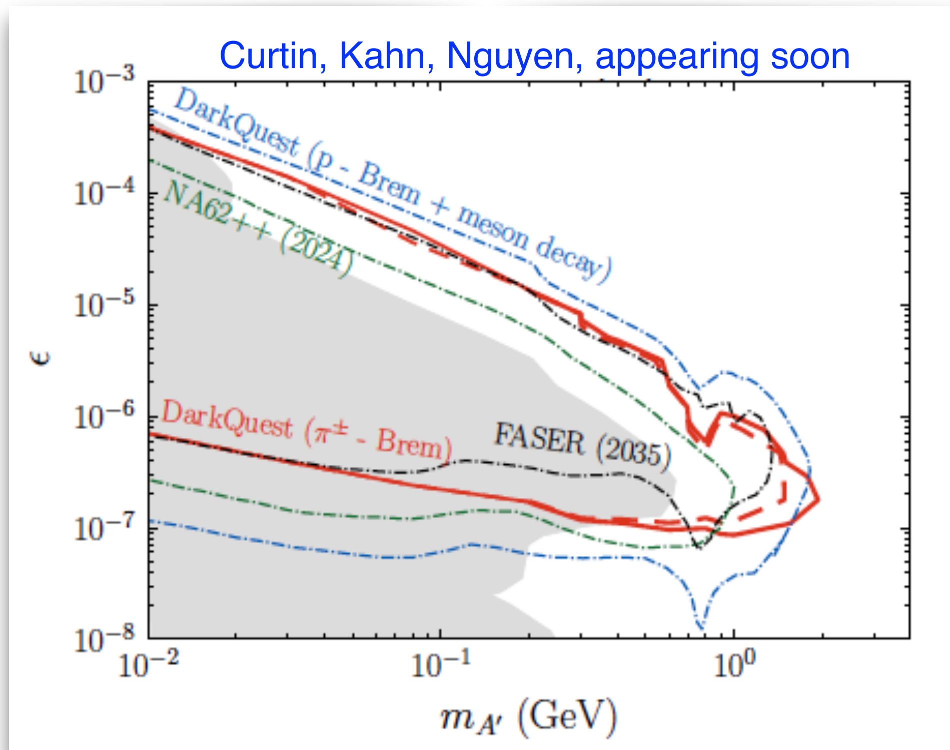
Batell, Evans, SG, Rai, 2008.08108



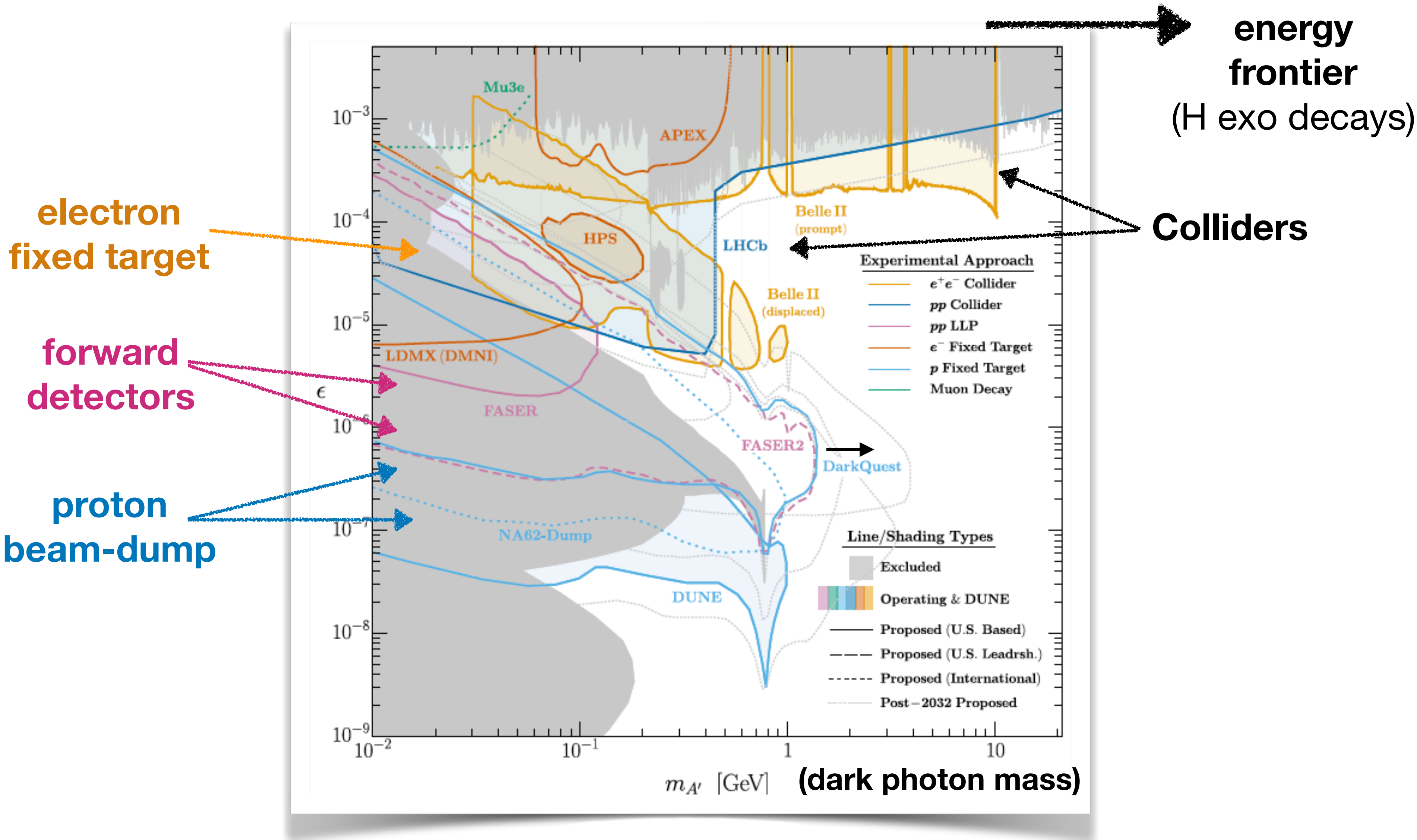
The reach on a minimal dark photon



(*) decay regions: (5-6)m, (5-9)m, (5-12)m



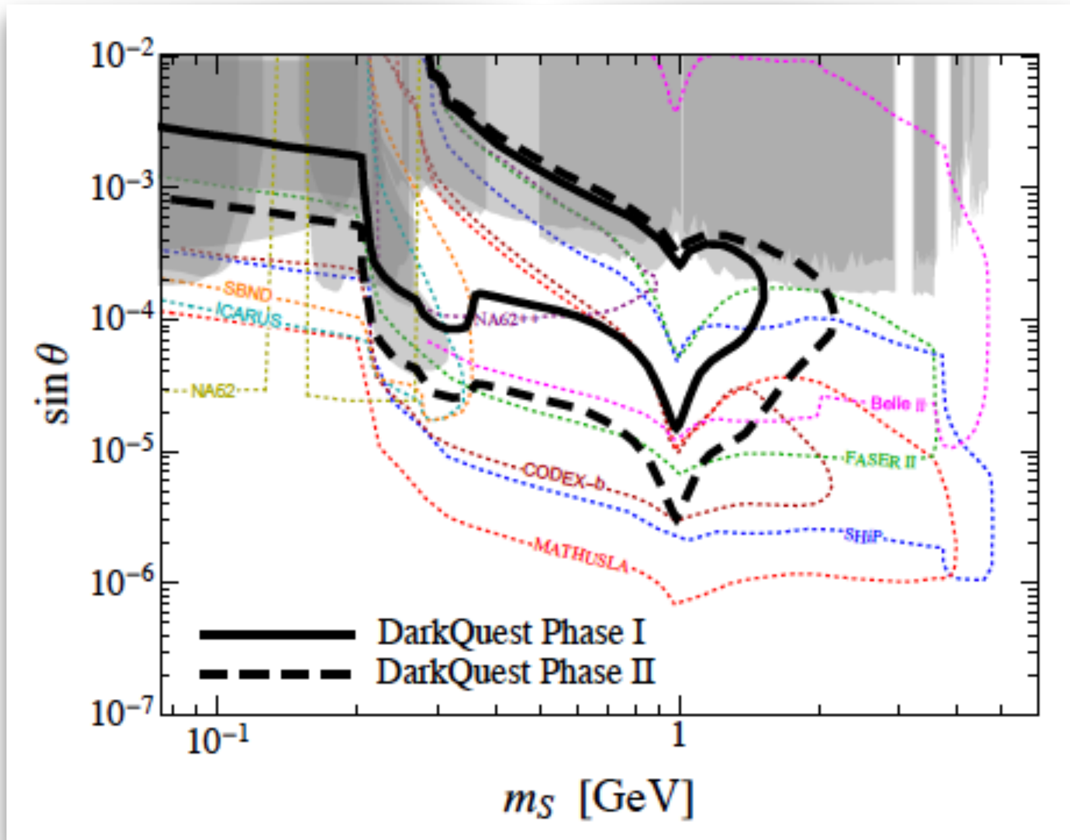
Putting it in a broader context



Batell, Blinov, Hearty, McGehee, 2207.06905,
Snowmass white paper

The reach on a minimal dark scalar

Batell, Evans, SG, Rai, 2008.08108



Large uncertainties in the calculations of branching ratios and life time of the scalar

Winkler, 1809.01876

- chiral perturbation theory
- perturbative spectator
- dispersion analyses

mass

Many searches can be performed

The main strength of the experiment is on dark photon and axion-mediated models + models with new muon-coupled particles.

Signature	Model
e^+e^-	dark photon dark Higgs leptophilic scalar*
$e^+e^-e^+e^-$	Higgsed dark photon
$e^\pm\pi^\mp, e^\pm K^\mp, \cdots$	sterile neutrino
$e^+e^- +$MET	inelastic dark matter strongly interacting dark matter hidden valleys
$\pi^+\pi^-, K^+K^-, \cdots$	dark Higgs*
$\gamma\gamma$	axion-like particle*

Several studies have been performed, including less minimal models for freeze-out Dark Matter.

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The main strength of the experiment is on dark photon and axion-mediated models + models with new muon-coupled particles.

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e^+e^-	dark photon dark Higgs leptophilic scalar*
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$e^+e^- + \text{MET}$	inelastic dark matter strongly interacting dark matter hidden valleys
$\pi^+\pi^-, K^+K^-, \cdots$	dark Higgs*
$\gamma\gamma$	axion-like particle*

Several studies have been performed, including less minimal models for freeze-out Dark Matter.

- Two examples:
  Inelastic DM models (IDM): χ_1 χ_2 co-annihilation,

$$A' \to \chi_1\chi_2, \ \chi_2 \to \chi_1 e^+e^-$$

long-lived since small mass splitting are needed for the co-annihilation to be efficient

$$\Gamma(\chi_2 \to \chi_1 e^+e^-) \simeq \frac{4\epsilon^2\,\alpha_{\rm em}\,\alpha_D\,\Delta^5 m_1^5}{15\pi m_{A'}^4}$$

- Strongly interacting DM models (SIMP): $3\pi_D \to 2\pi_D$ (QCD-like models)

$$A' \to \pi_D V_D, \ V_D \to \pi_D e^+e^-$$

$$A' \to \pi_D V_D, \ V_D \to e^+e^-$$

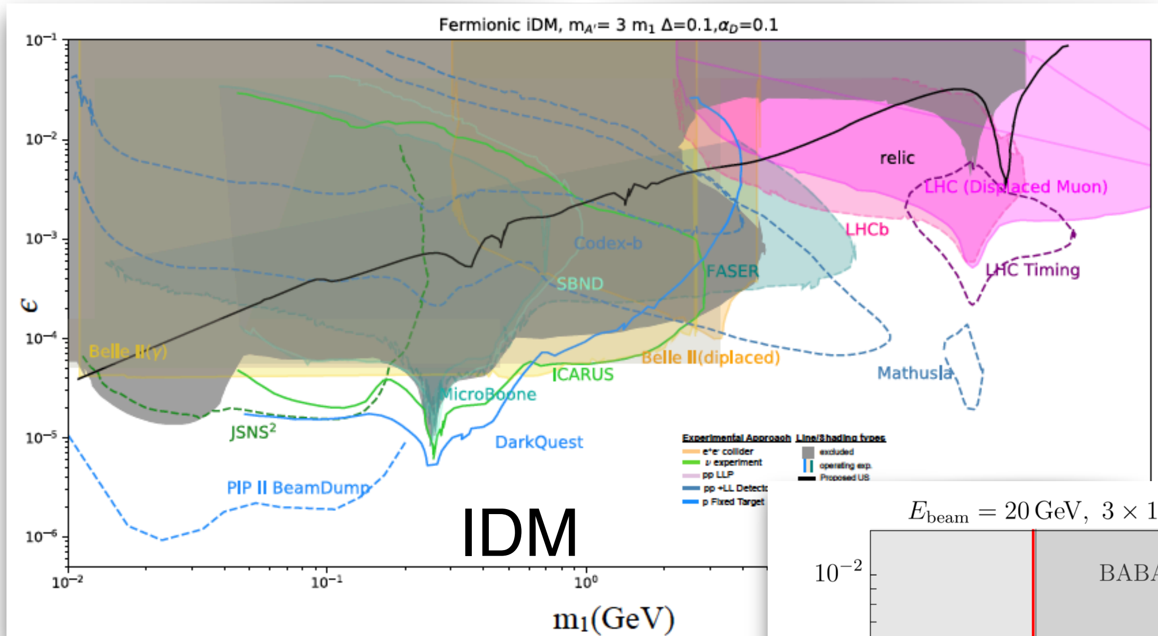
Berlin, Blinov, SG, Schuster, Toro, 1801.05805

long-lived

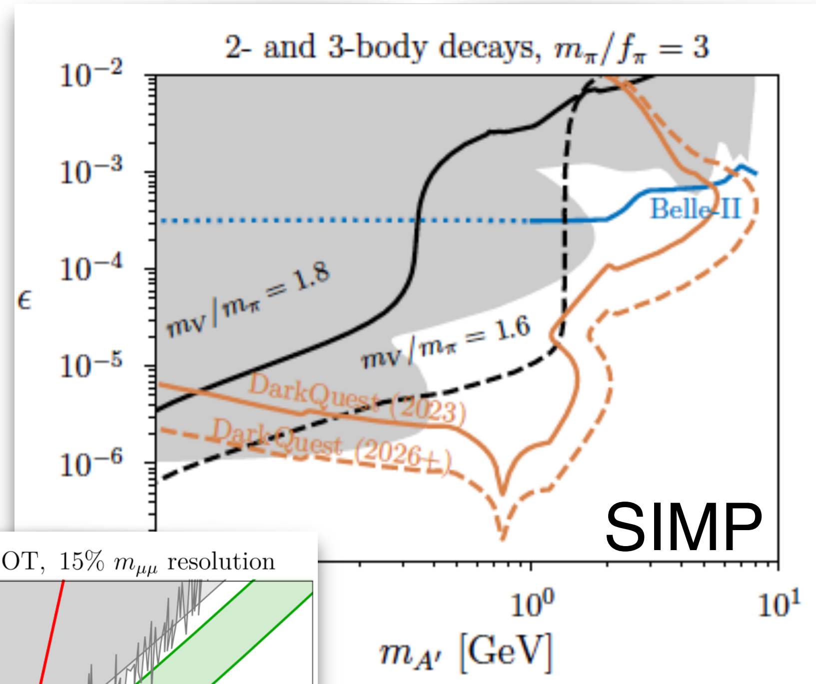
Width is $\varepsilon^2\,\alpha_{em}$ suppressed

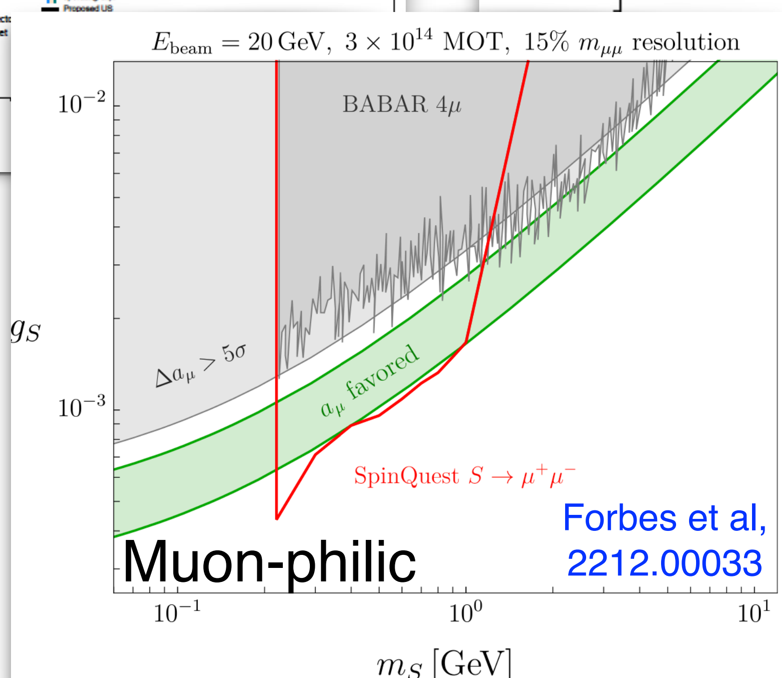
The reach on DM /anomaly motivated models

Harris, Schuster, Zupan, 2207.08990



Apyan et al, 2203.08322





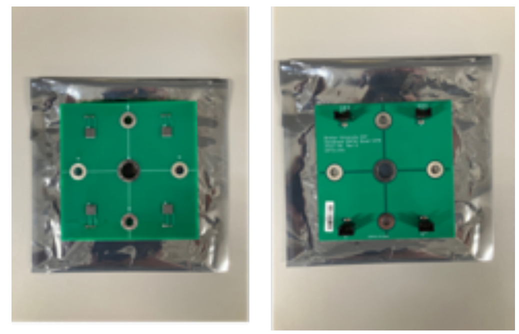
List of experimental studies

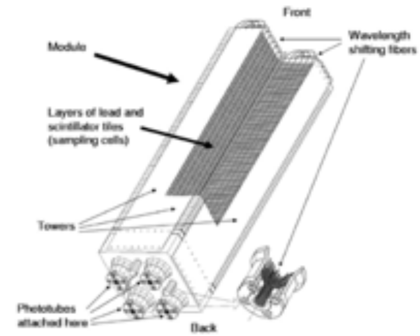
In the past two years a lot of progress has been made:

- ✱ Detector:
  - EMCal integration into the SpinQuest spectrometer
  - Extra Tracking layer integration into the SpinQuest spectrometer

- ✱ GEANT4 - based simulations:
  - EMCal simulations
  - Triggering
  - Tracking & vertexing
  - ParticleID: tracking + calorimeter information

Custom 4-ch SiPM Board



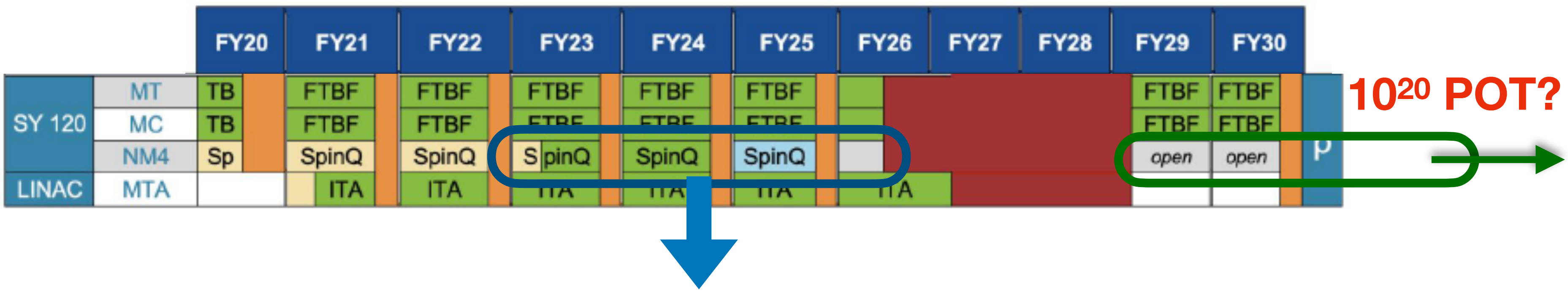


EMCal Test Stand at BU

Strong connections with the SpinQuest collaboration

Thank you, Carlos and Marcela!

SpinQuest/DarkQuest status and timeline



SpinQuest

DarkQuest

FY23 | FY24 | FY25 | FY26

- Simulation studies
- Trigger tests
- Electronic designs

Data taking for Spin physics & dark sector physics (muon channel)

Approved

- Adding tracking layers
- EMCal installation

Explore dark sector physics (all visible channels)

Proposed

~10^{18} POT