The CLIC Physics Potential for long-lived and exotic signatures

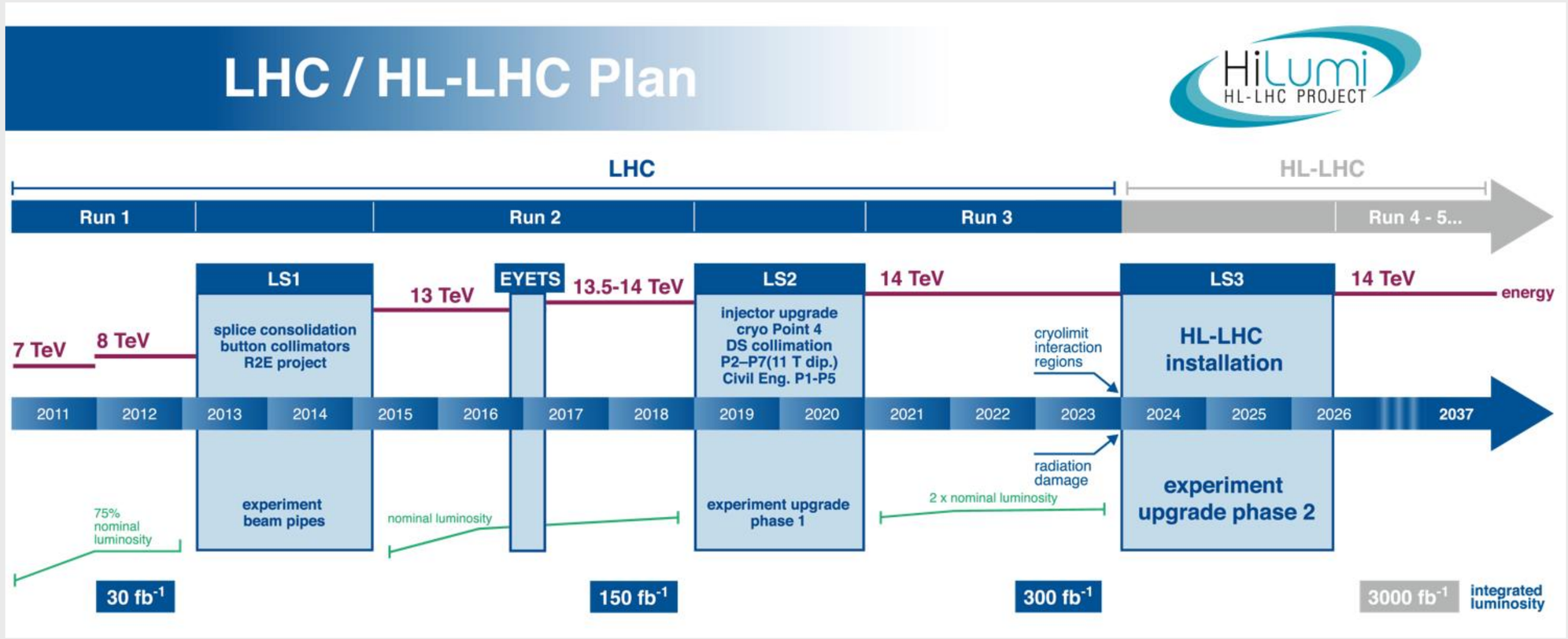
A summary of results from the Yellow Report "CLIC physics potential for new physics"

JAN. 23 2019 ROBERTO FRANCESCHINI (ROMA 3 UNIVERSITY)

CLIC Week 2019 - https://indico.cern.ch/event/753671/

Still looking for new physics

SUBTLE IS THE LORD



LHC: New Physics is either heavy or shows up in subtle ways

ICHEP14

ICHEP16

ICHEP18

*LHC: New Physics is either **even heavier** or shows up in **even subtler** ways*

No guarantee for discovery

- neither at the LHC
- nor at any future collider

A demonstrated capability to cope with a large and diverse set of experimental signatures is a key item in the wishlist of features fro any future collider project

Sensitivity to a broad spectrum of signatures is a key asset, that *will survive changes in the theory knowledge/prejudice*

Challenges for detectors

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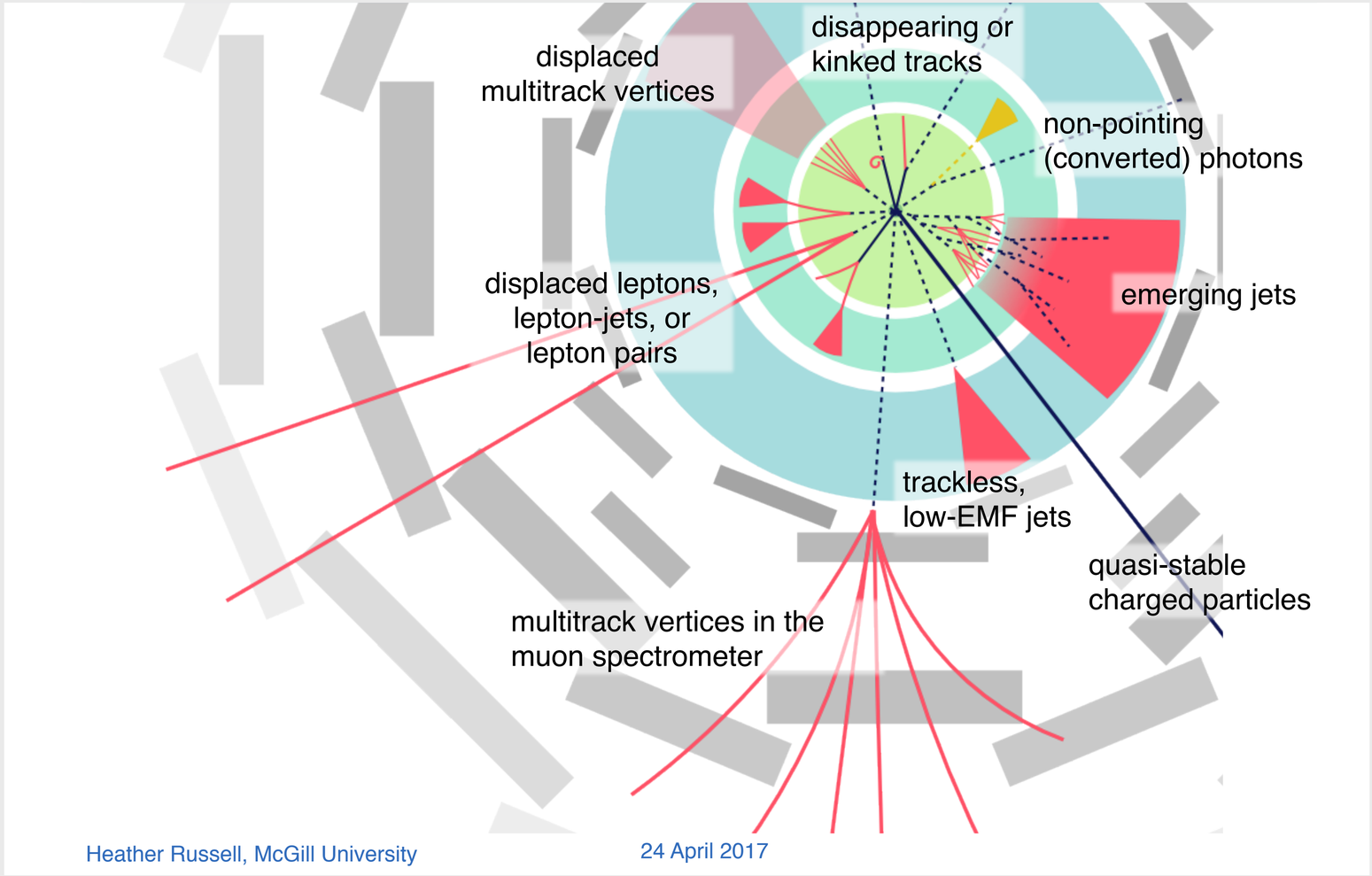


Current “general purpose” experiments were really designed for pretty standard signals, e.g. $H \rightarrow \gamma\gamma$ or jets+mET

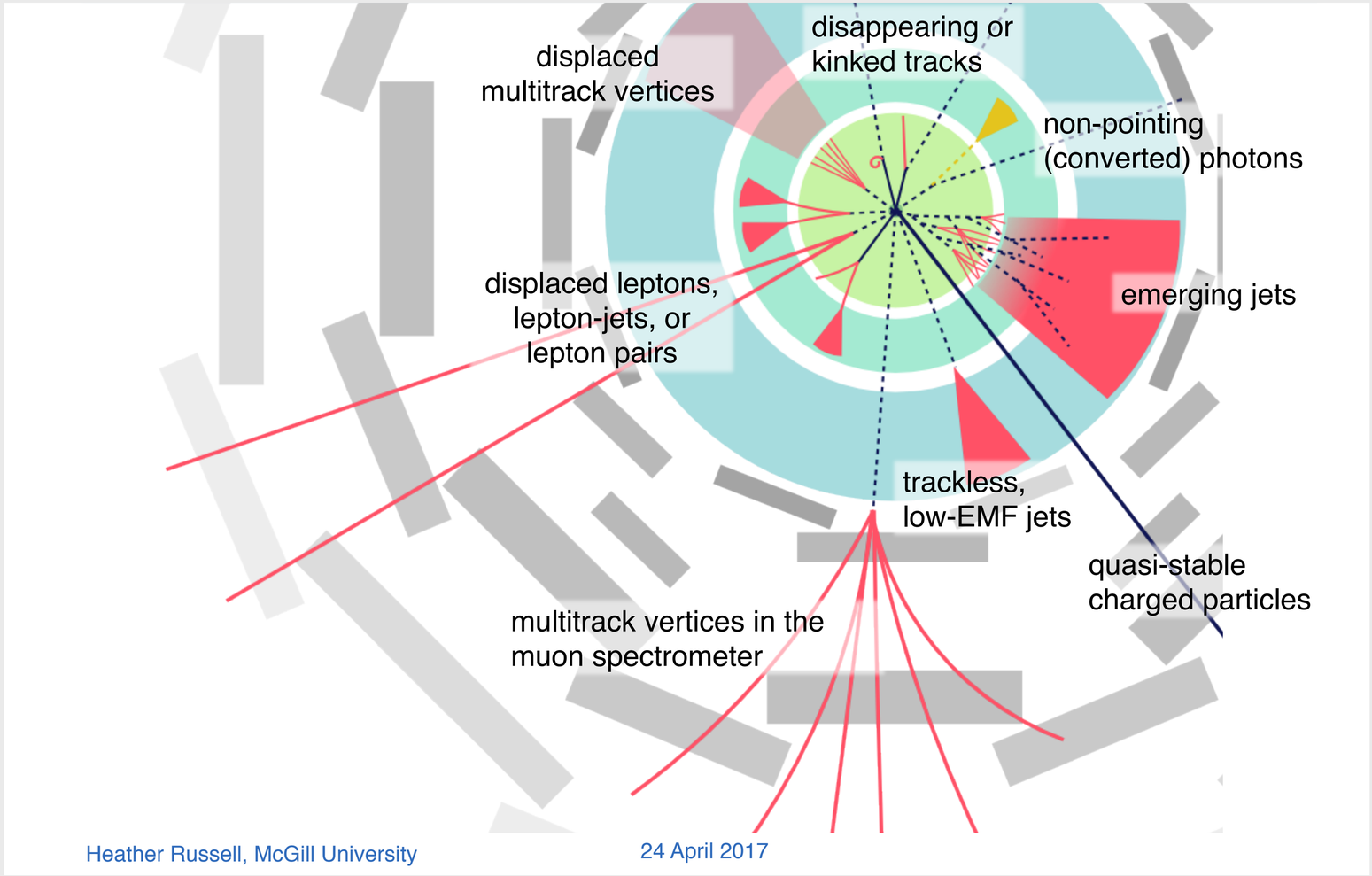
- Now is the time to think about what can be done in future detectors.
- CLIC (and ILC) can exploit full detector simulation

Please note these signals are not necessarily a way to “jump off the ship”. Most of them, if not all(!), can arise in the MSSM if one relaxes some (motivated?) UV assumptions.

Long Lived Particles Forum

NEXT MEETING AT CERN 27 TO 29 MAY 2019

latest meeting in Amsterdam



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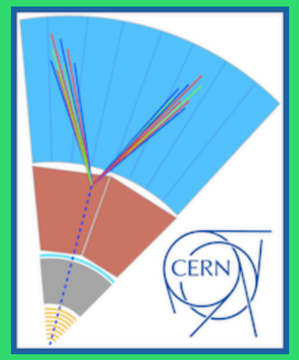
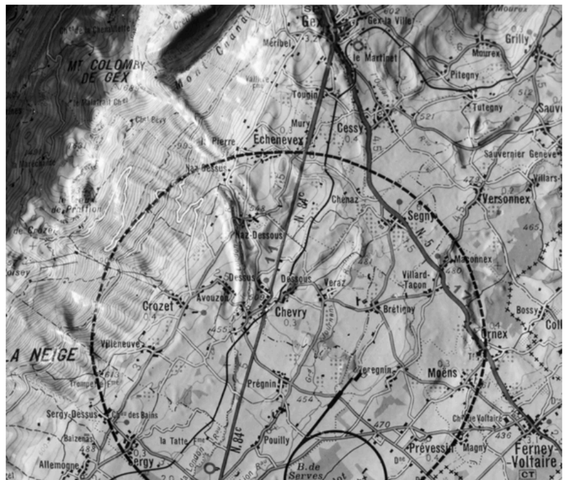


Searching for long-lived particles at the LHC: Fifth workshop of the LHC LLP Community

27-29 May 2019
CERN
Europe/Zurich timezone

Search...

Overview
Timetable
Participant List



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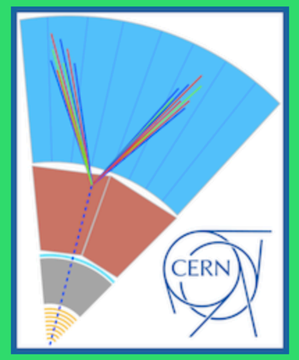

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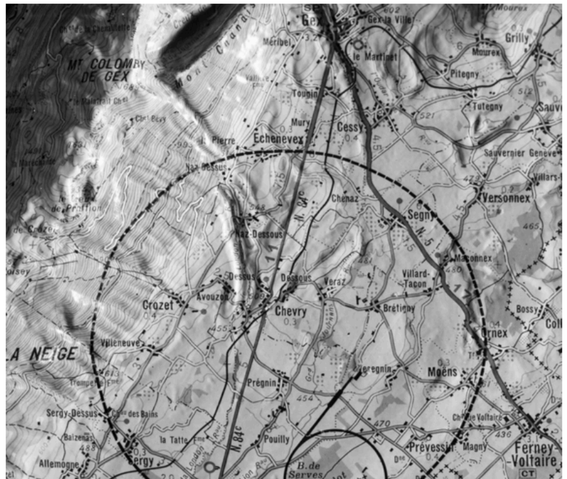

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Challenges for detectors

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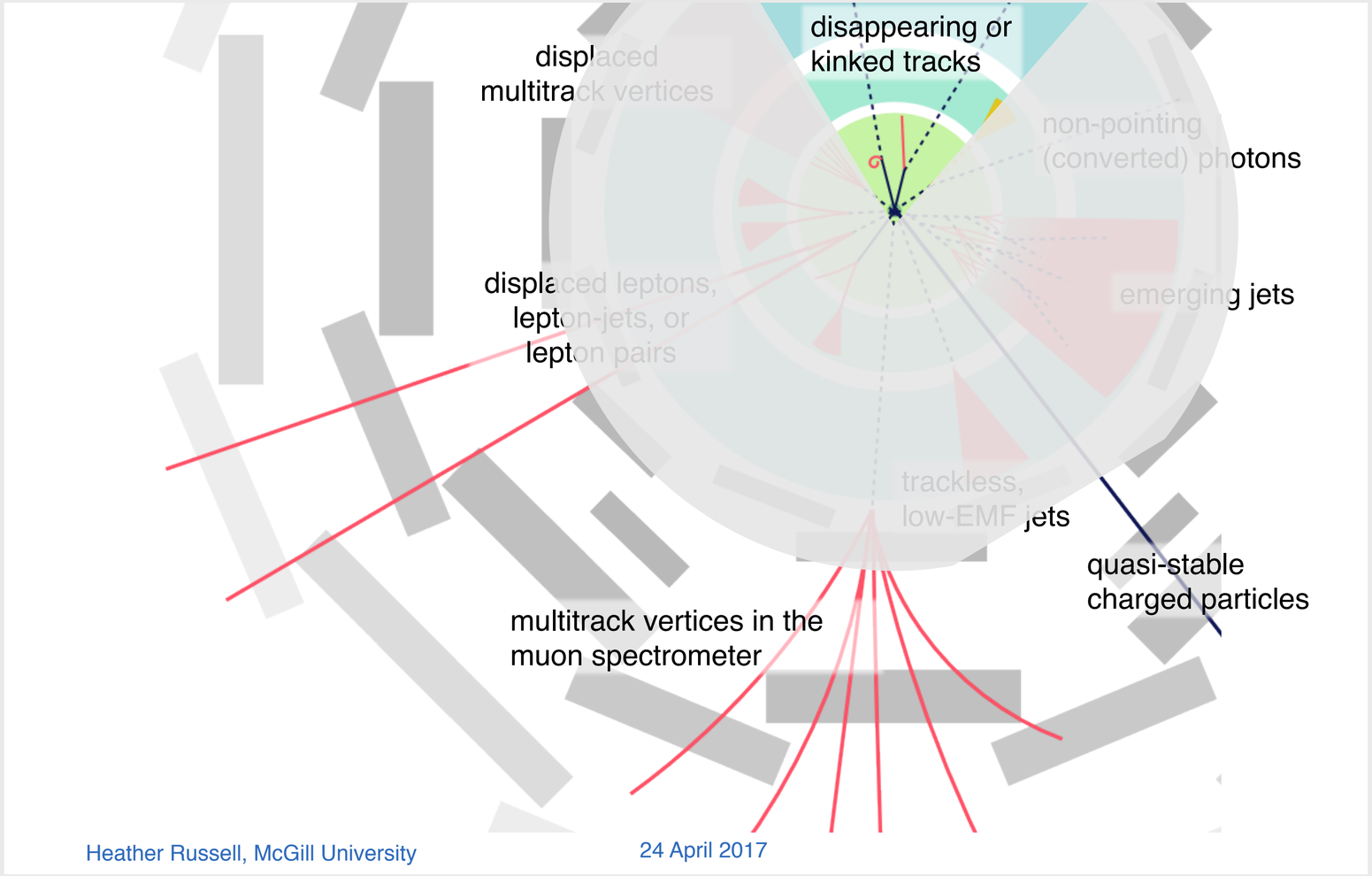

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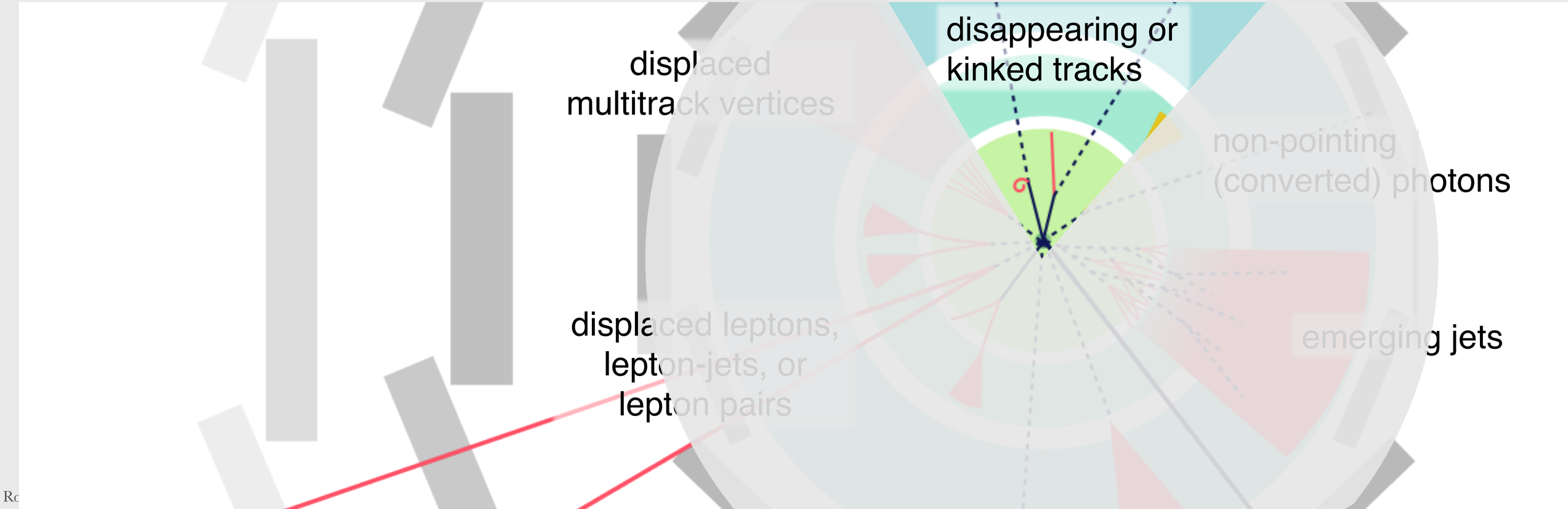

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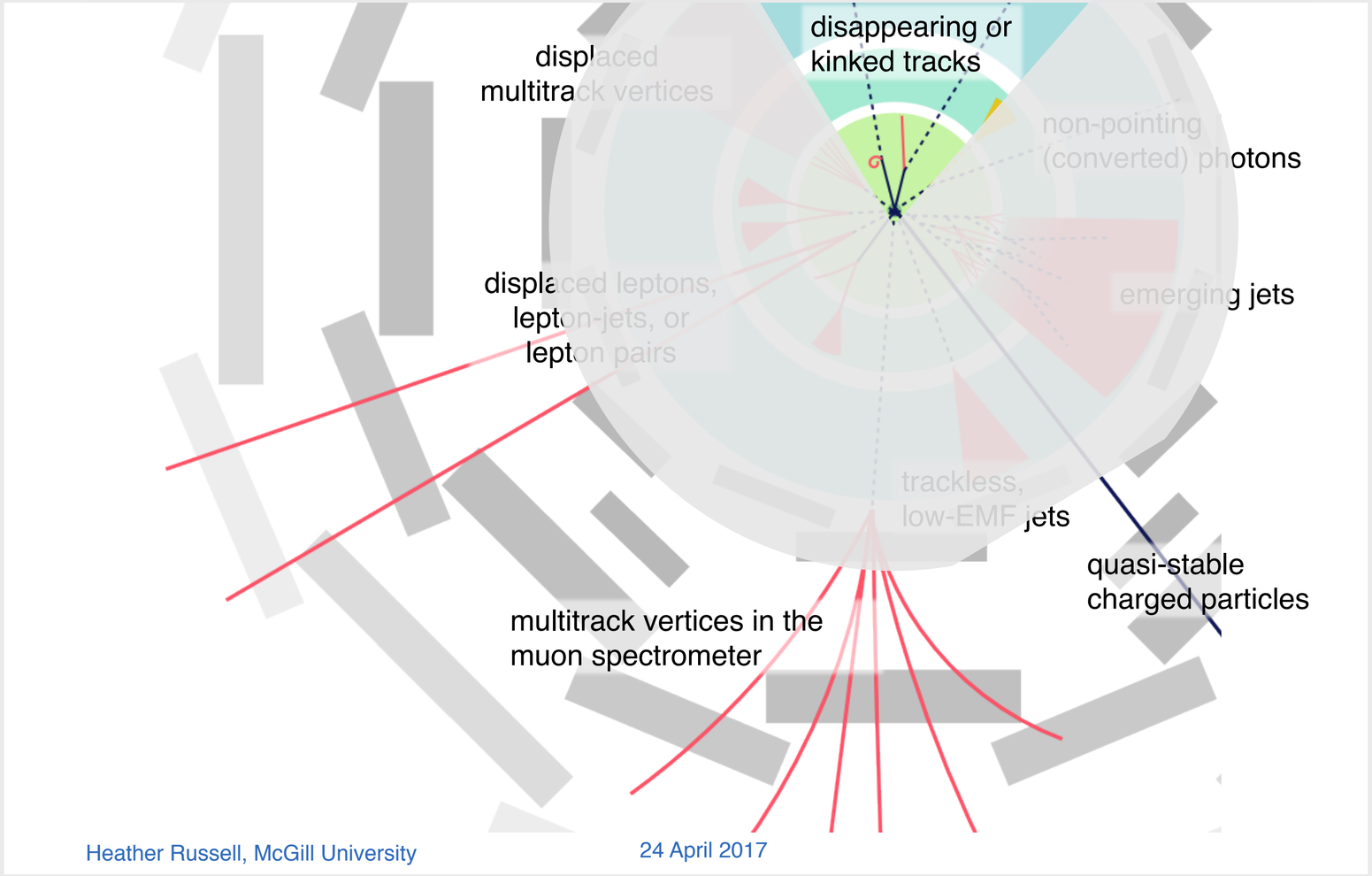

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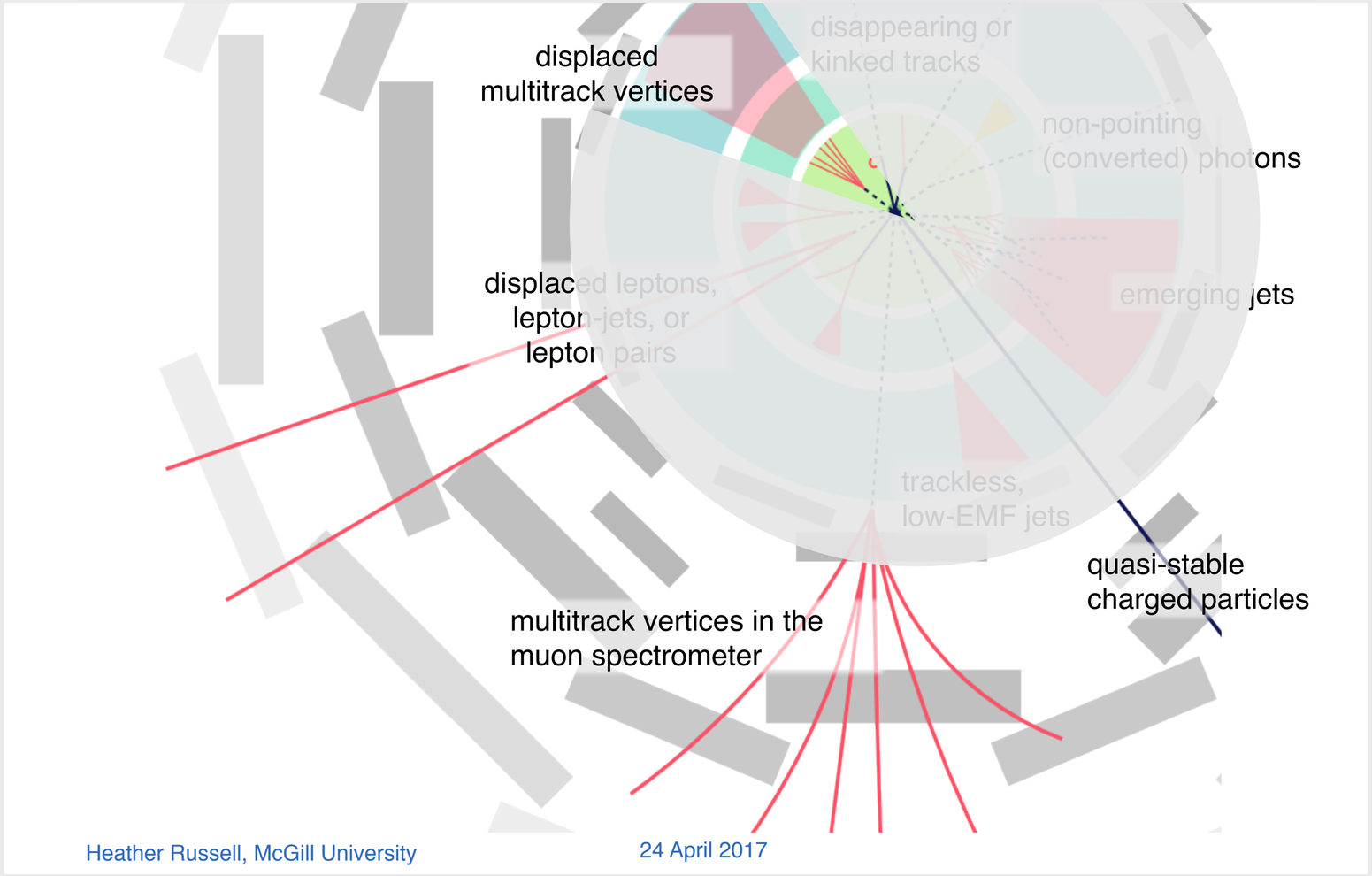

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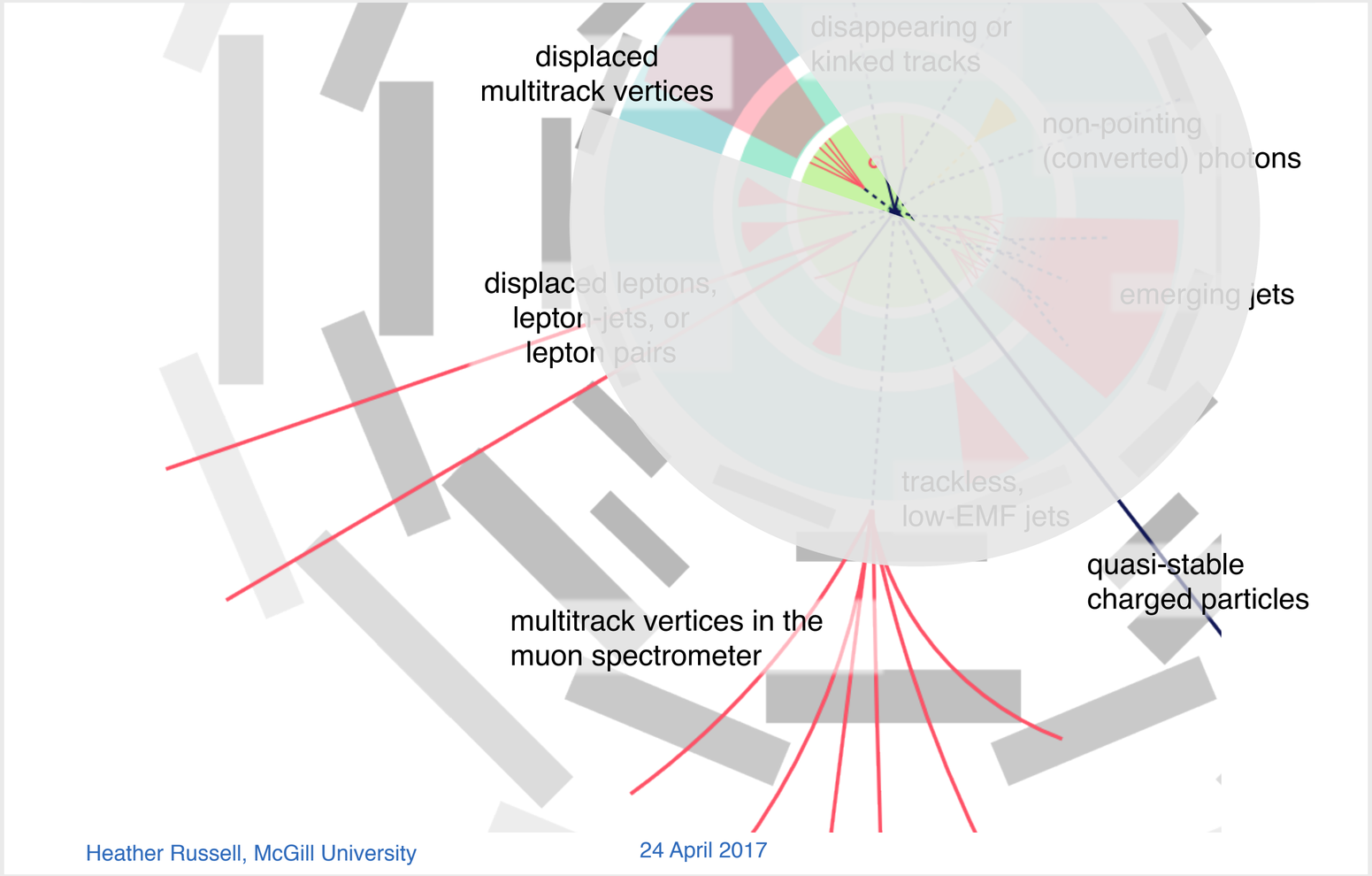

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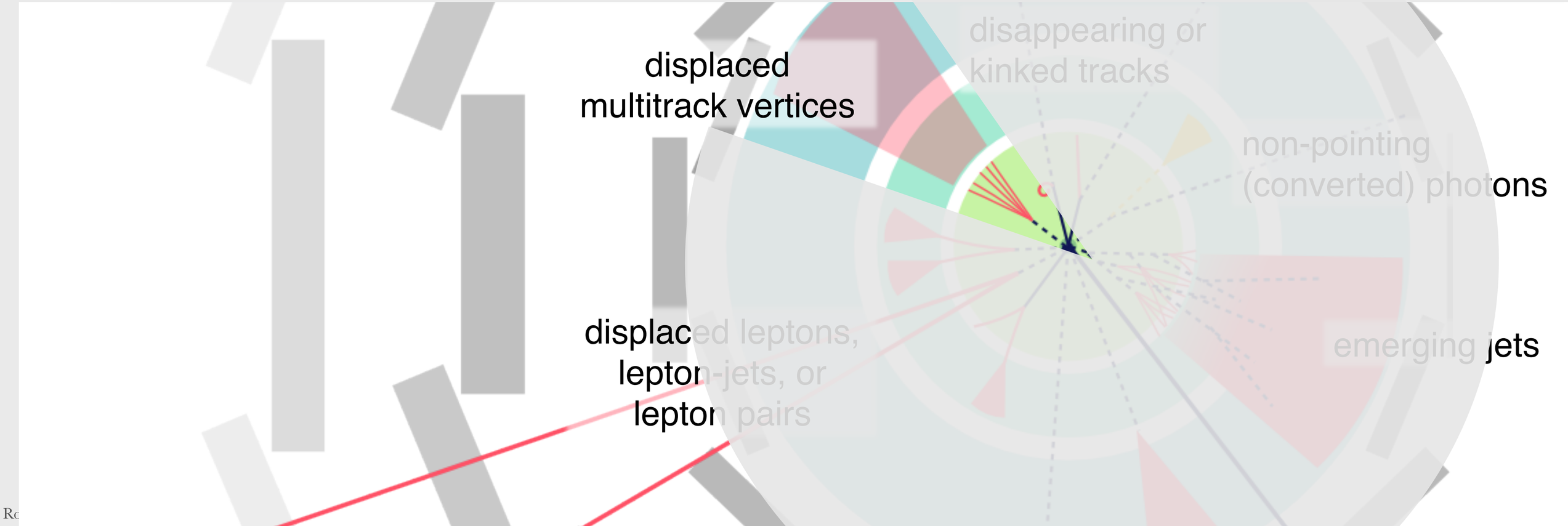

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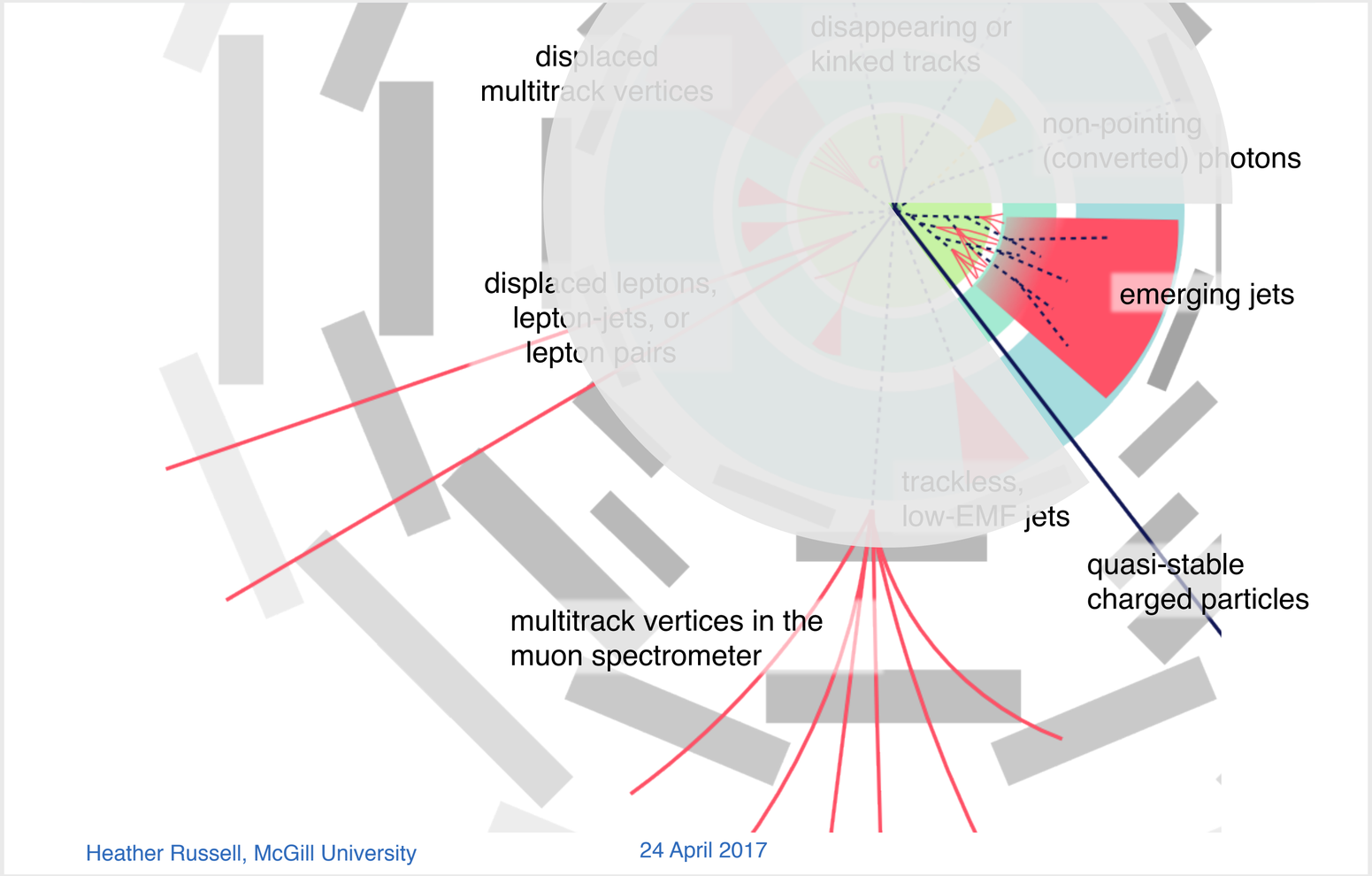
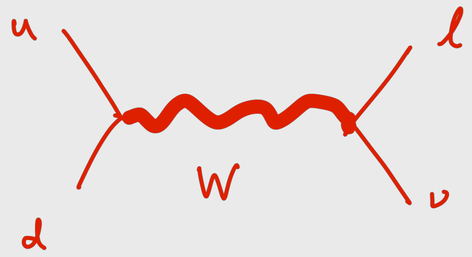


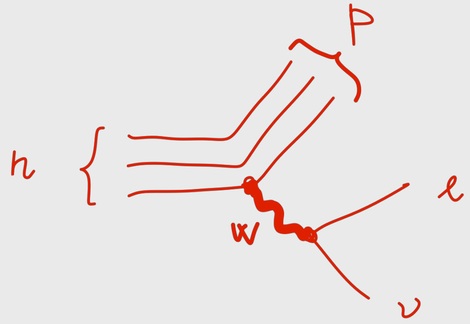
… plenty of other options. A white paper is coming from the Long Lived Forum to summarize.

Three generic reasons why this can happen



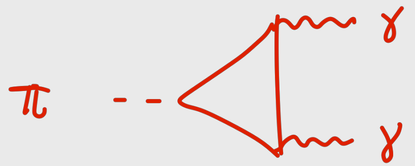
$\pi \to \ell\nu$

heavy mediator
from a hierarchical larger mass scale



$n \to pe\bar{\nu}$

small phase-space
from symmetry

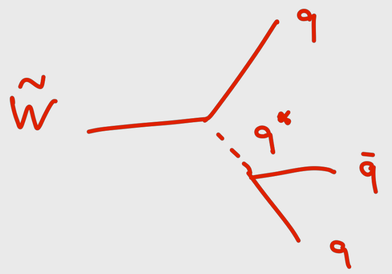


$\pi \to \gamma\gamma$

small coupling
from symmetry breaking

- it happens in QCD (!)
- the necessary ingredients are just the same as for the formulation of any model of particle physics (mass scales and their hierarchies, symmetries and their breaking, …)

Many generic BSM reasons why this can happen

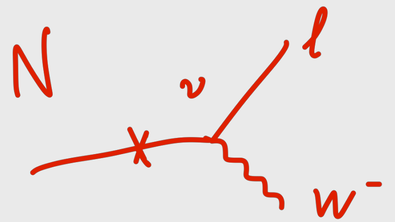


$\tilde{\lambda}_i^0 \to q\tilde{q}^* \to q\bar{q}q$

heavy mediator
from a hierarchical larger mass scale

$\tilde{h}^+ \to \tilde{h}^0 W^{+*}$

small phase-space
from symmetry



$N^0 \to \ell^+ W^-$

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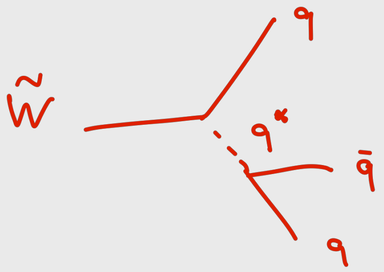
Many generic BSM reasons why this can happen

long life-time may be dictated by other physics requirements as well

late-time decay in the Early Universe to fulfill out-of-equilibrium condition for baryon number generation



$\tilde{\lambda}_i^0 \to q\tilde{q}^* \to q\bar{q}q$

heavy mediator
from a hierarchical larger mass scale

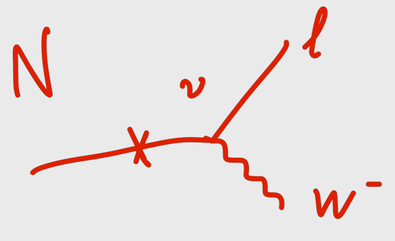
Dark Matter candidate

$\tilde{h}^+ \to \tilde{h}^0\, W^{+*}$

small phase-space
from symmetry

relic abundance $\Omega \sim M_{DM}/g$
so g≪1 for light particles

$\gamma_D \to \ell^+\ell^-$



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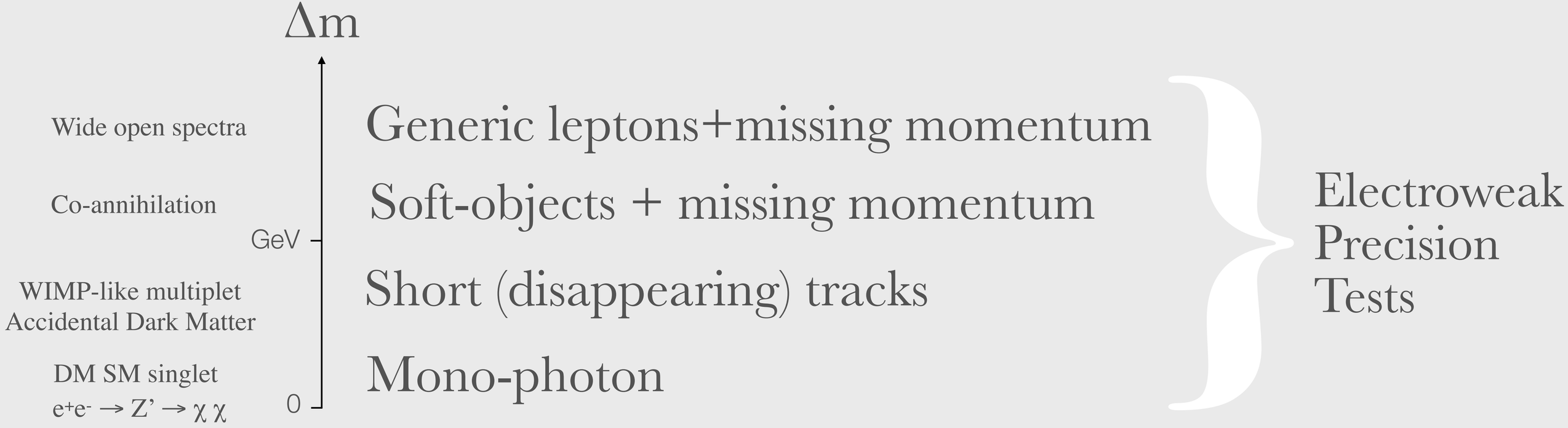
Direct searches

DarkMatter

Electroweak Dark Matter: LSP (+NLSP)



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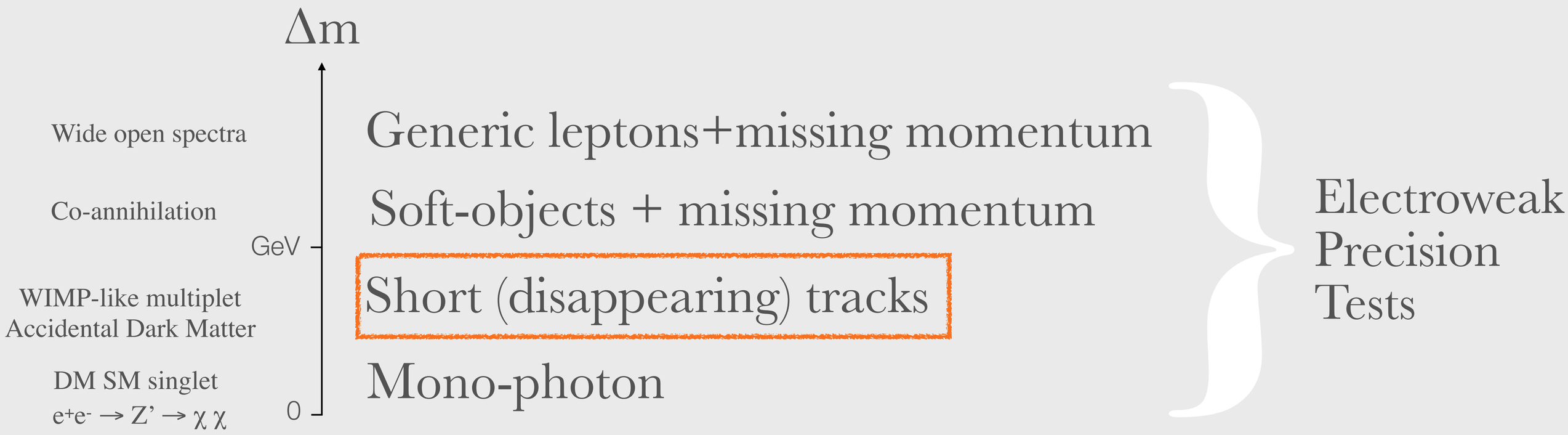
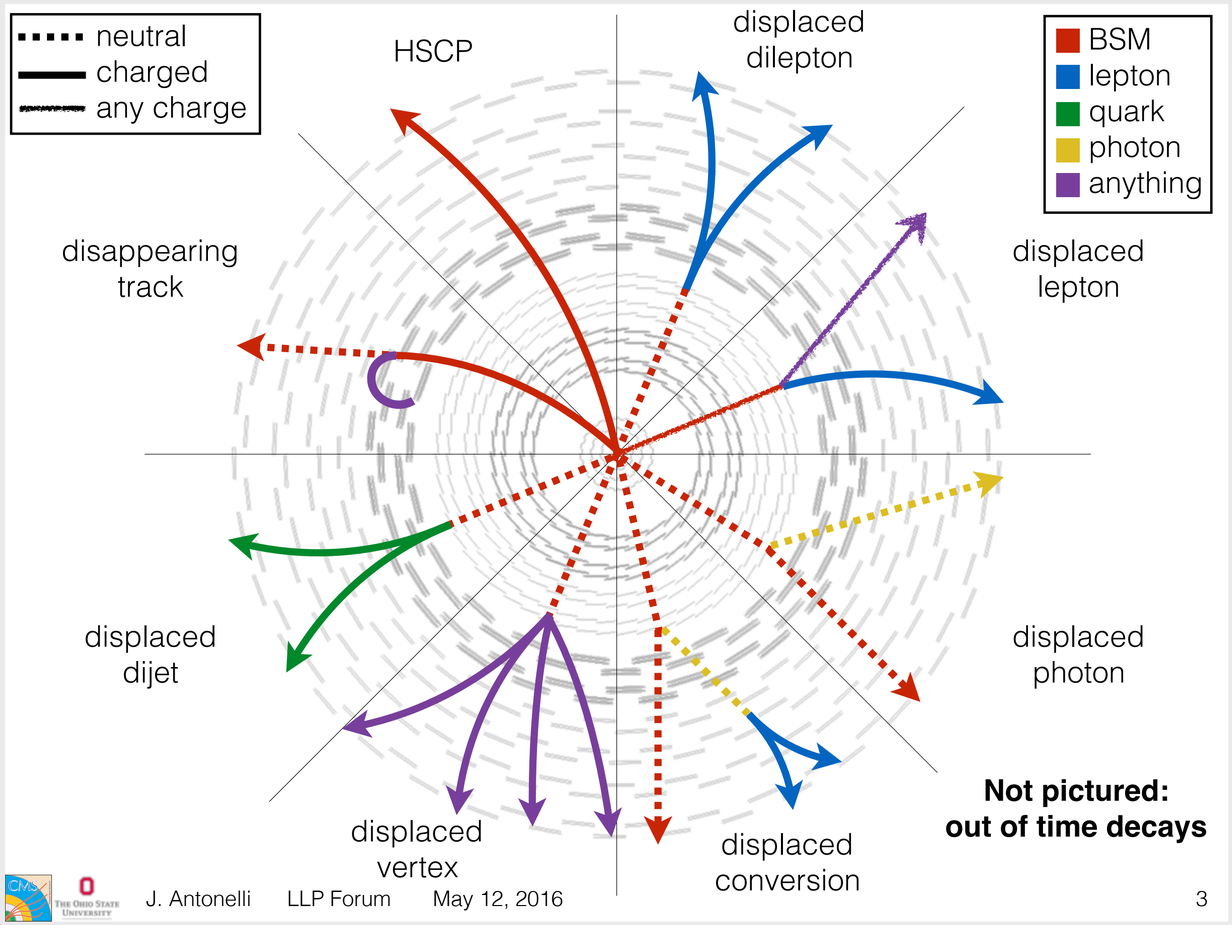
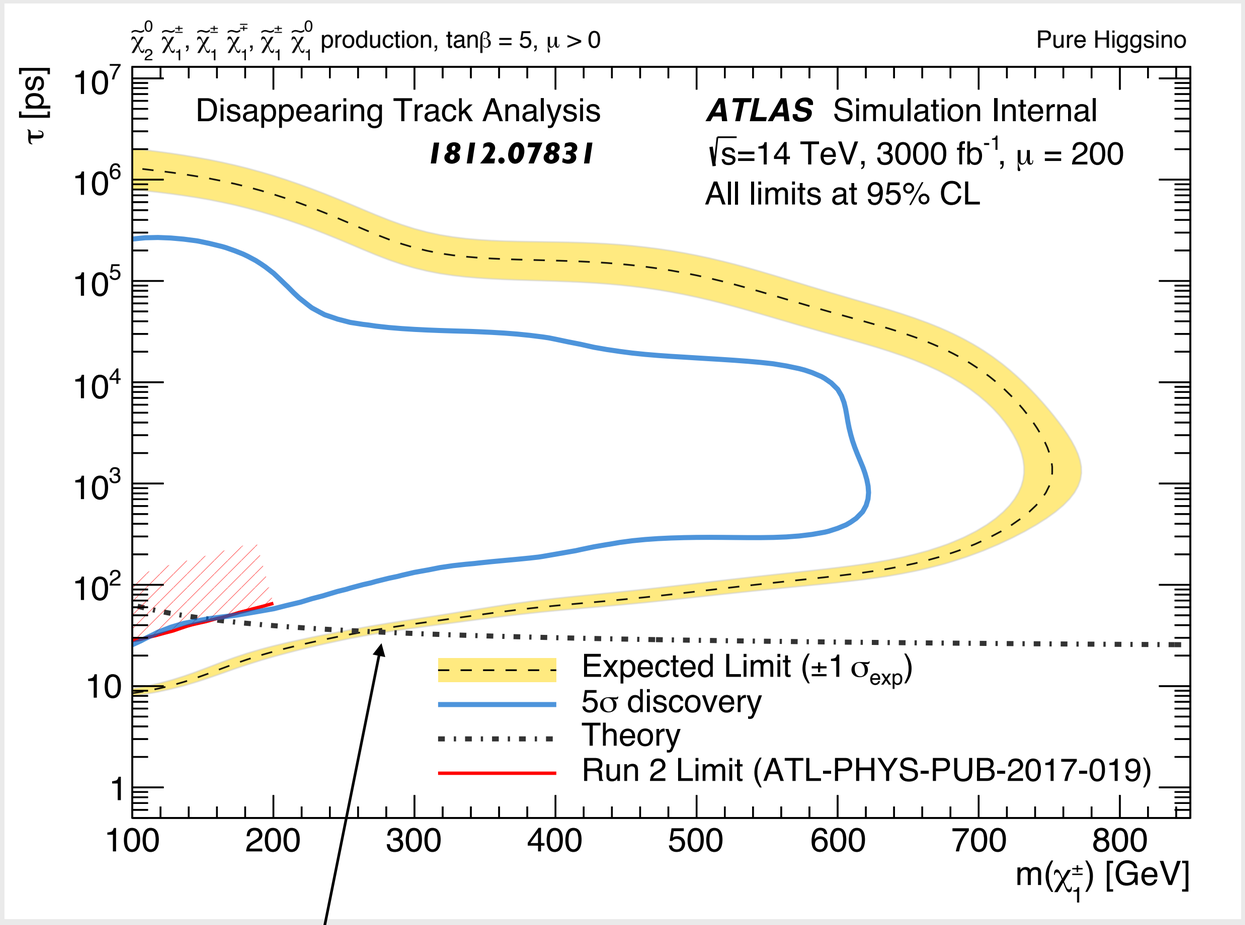


Short (disappearing) tracks

HIGGSINO DM | O(CM) DISAPPEARING TRACKS





HL-LHC up to 300 GeV

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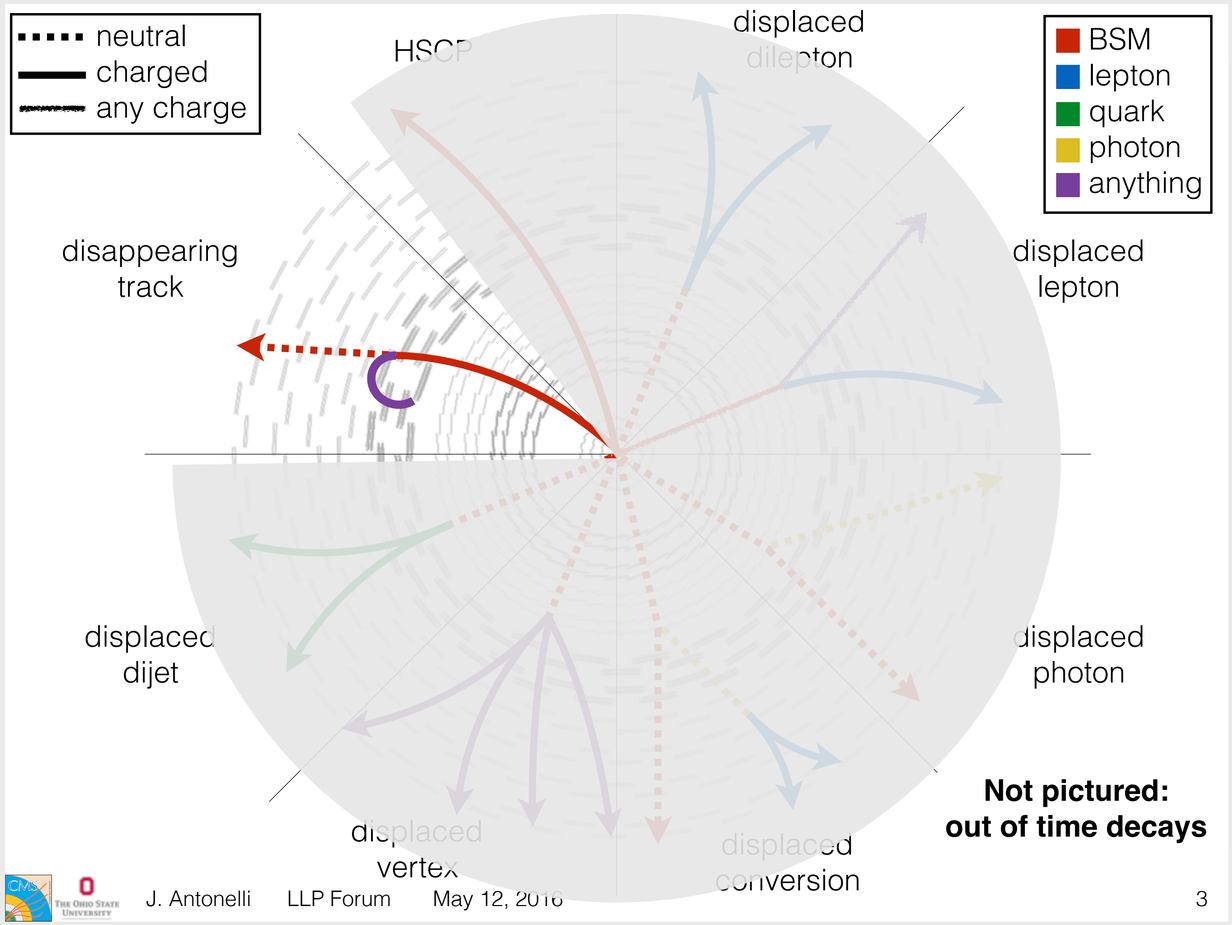

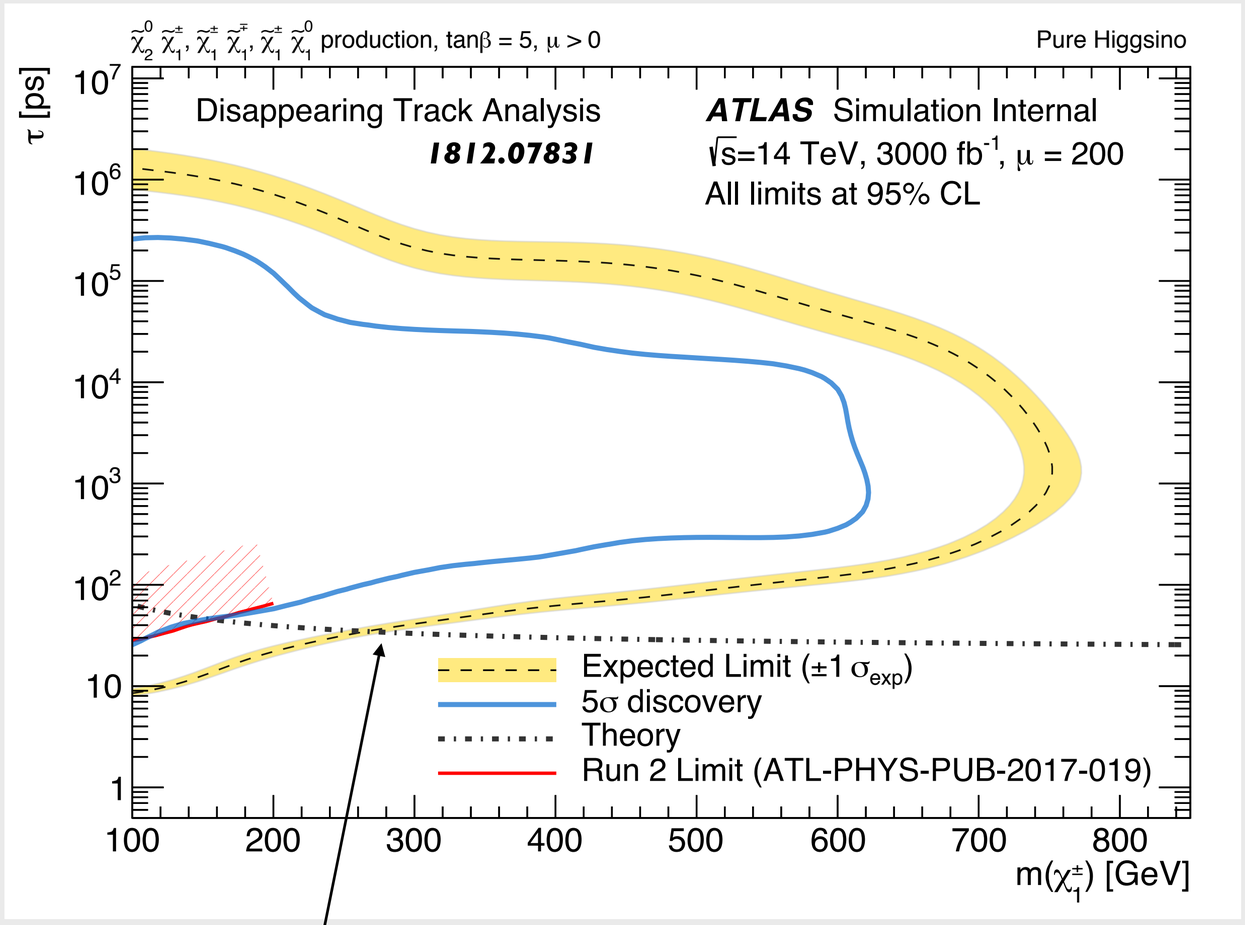

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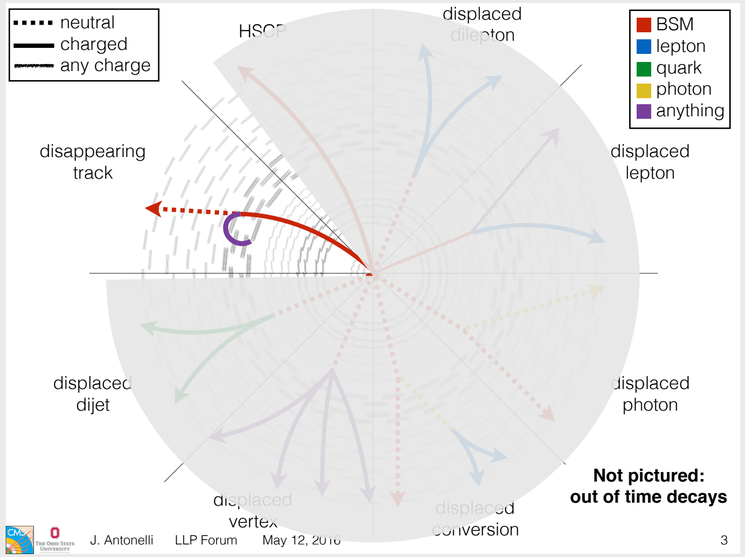
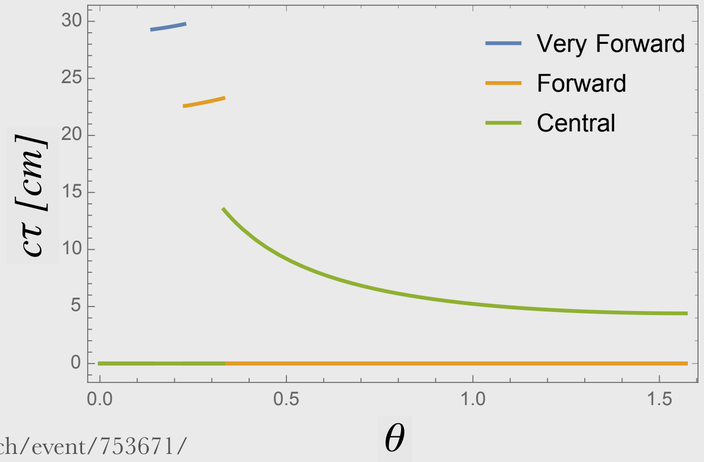


CLICdp-Note-2017-001

SIMPLIFIED RECONSTRUCTION

Assume track is seen when

- $c\tau > 4.4$ cm/sinθ ($19° < \theta < 90°$)
- $c\tau > 22$ cm/cosθ ($13° < \theta < 19°$)
- $c\tau > 29$ cm/cosθ ($0° < \theta < 13°$)



Clean experimental environment:

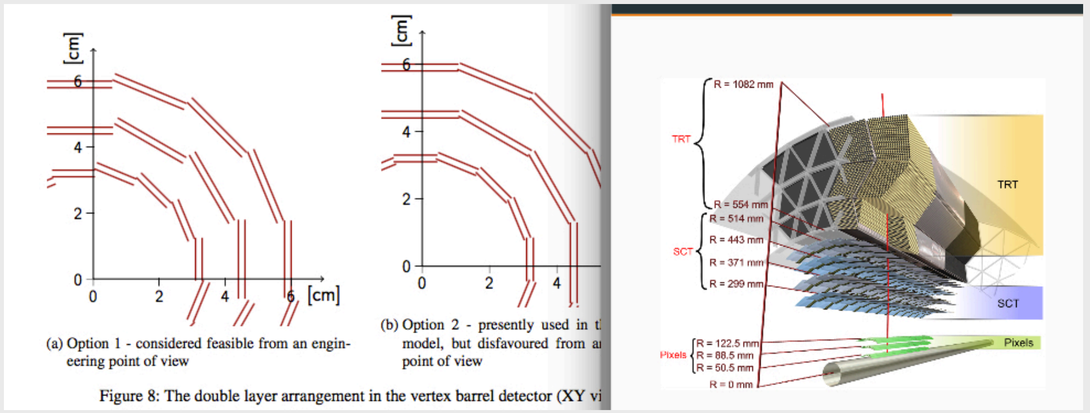
- No trigger
- No QCD background
- Tracker is closer to the beam

Challenges:

- boost cannot make h̃ tracks longer

CLIC Efficient at d≳ 4 cm

LHC Efficient at d≳ 10 cm



HL-LHC can put bounds on Higgsino up to ~300 GeV

Exponential rate gain when $c\tau < 10$ cm

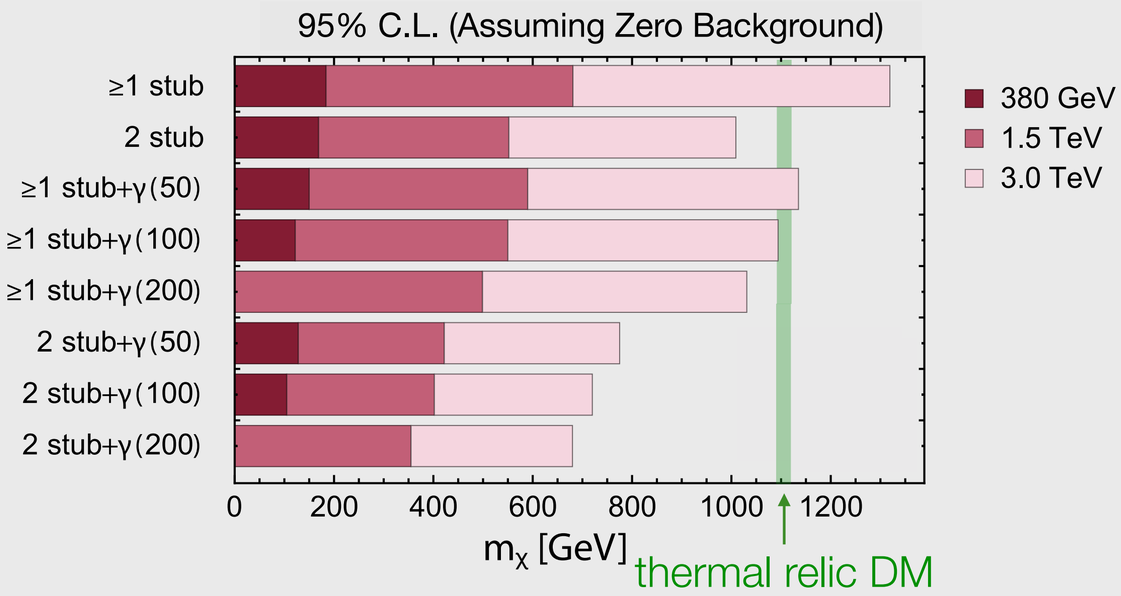
Short (disappearing) tracks

HIGGSINO DM

O(CM) DISAPPEARING TRACKS

ASSUME PURE HIGGSINO LIFETIME

$c\tau$ = 1.2 cm @ 200 GeV → 0.7 cm @ 1 TeV



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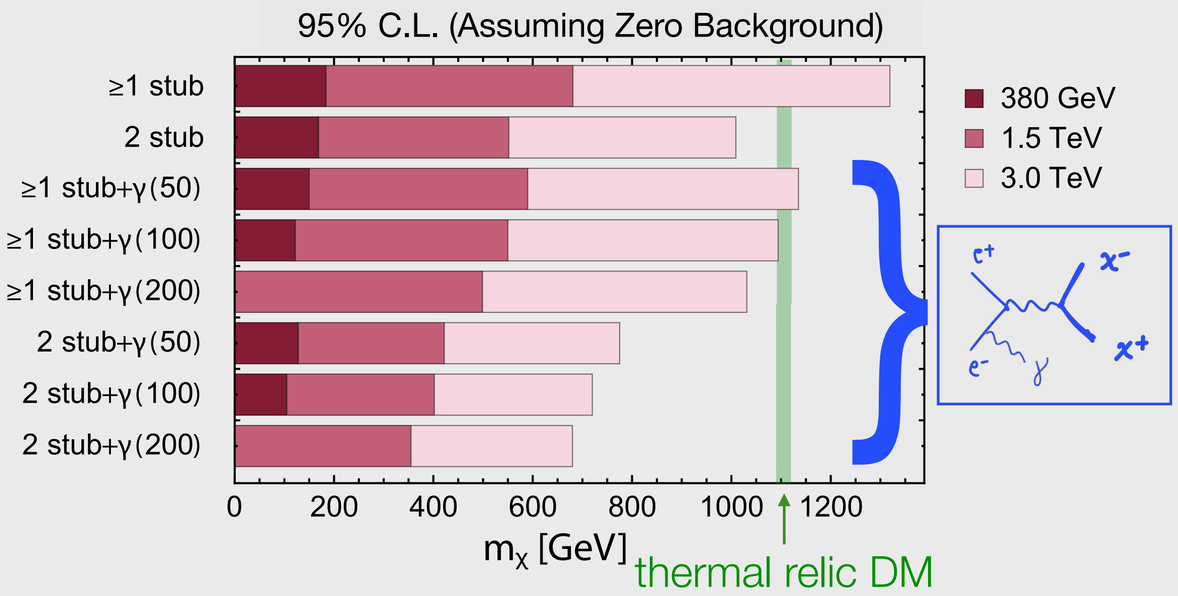

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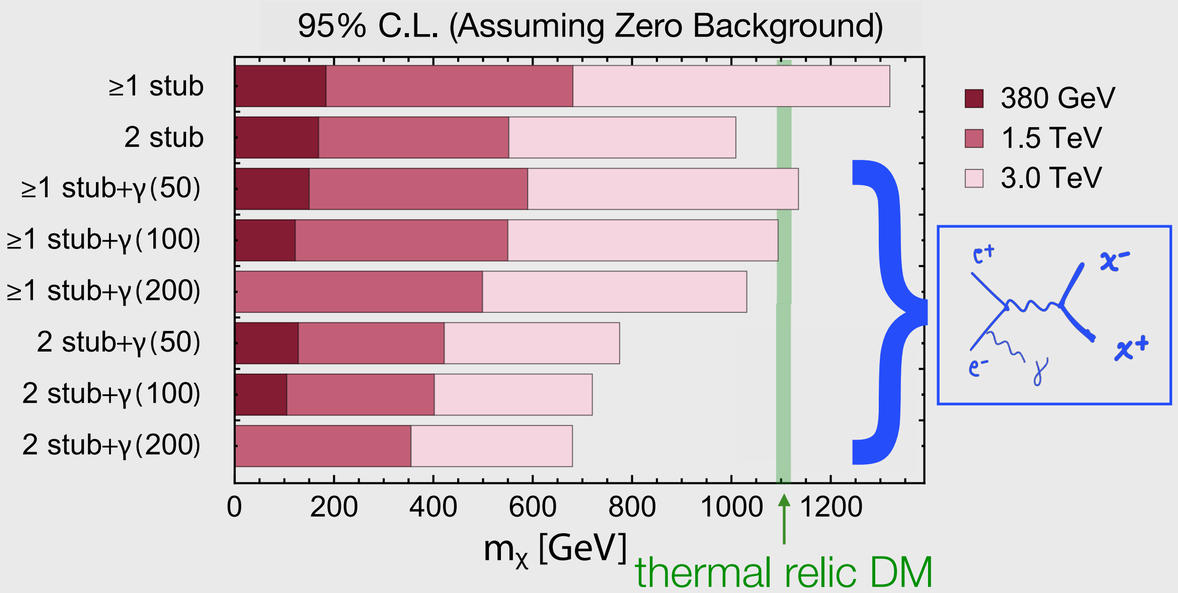

background evaluation needed

CLIC 3 TeV yields 10 events per ab^{-1} for 1.1 TeV Higgsino thermal DM candidate

Short (disappearing) tracks

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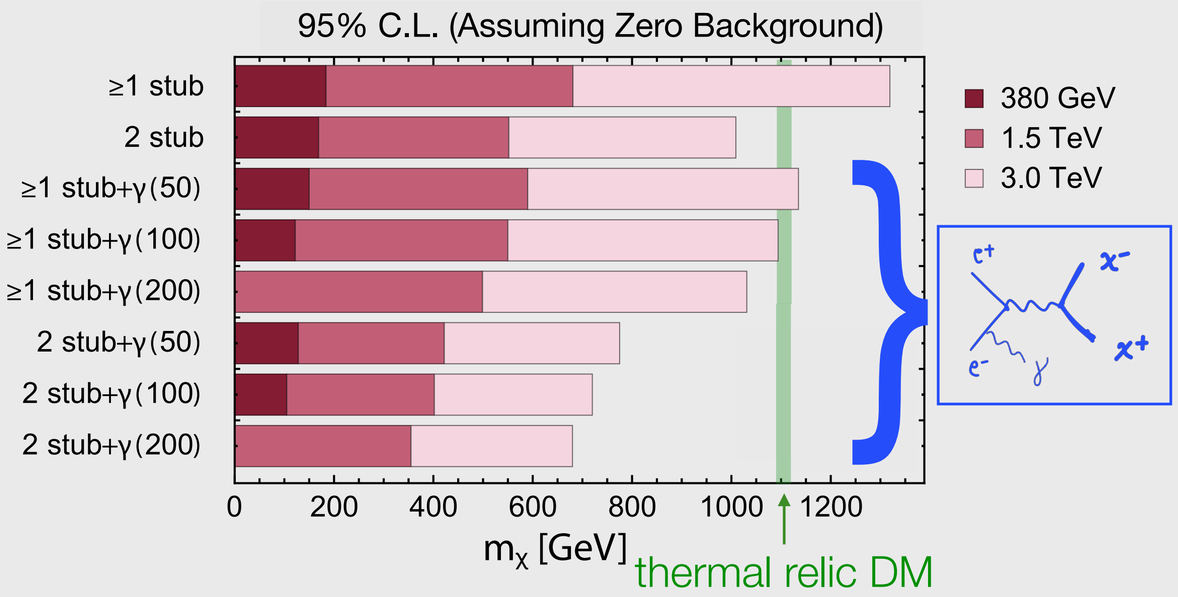

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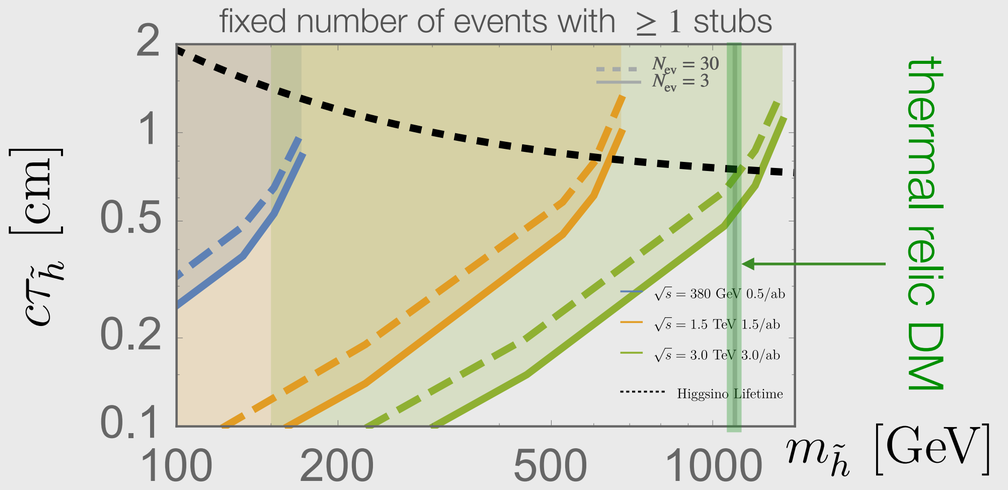
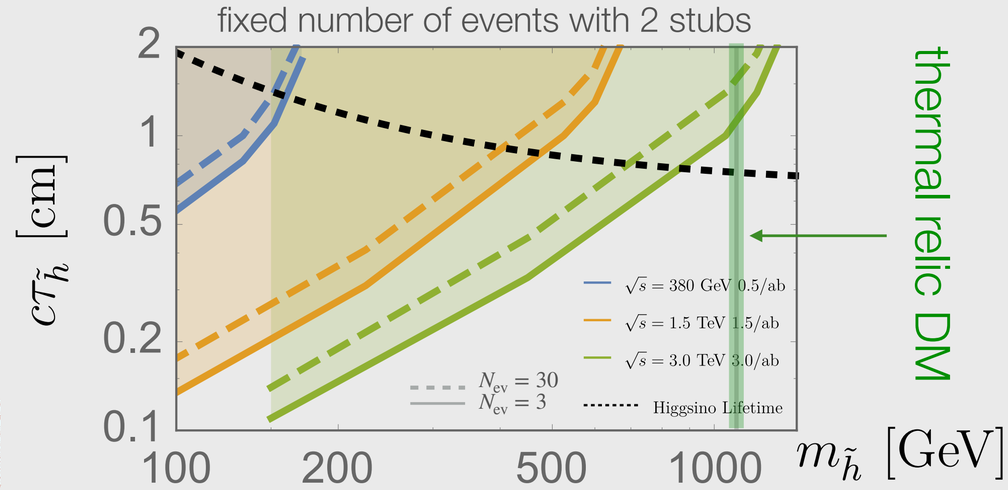
LIFETIME AS PARAMETER (NON-PURE HIGGSINO)





Hidden Sector

via simplified models

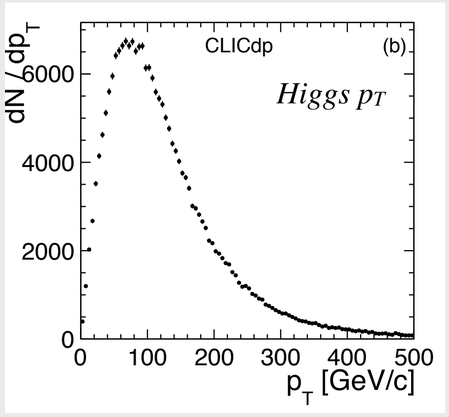
Hidden Valley Displaced Vertex

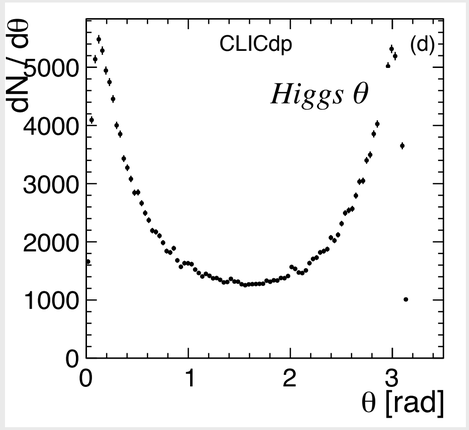
CLICDP-NOTE-2018-001

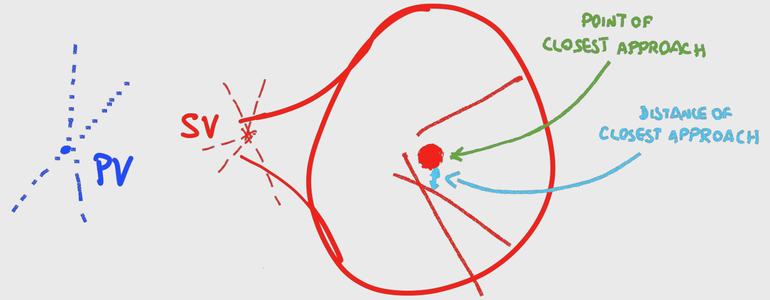
$e^+e^- \to h\,\nu\nu$ $\quad h \to \pi_V\,\pi_V$ $\quad \overset{c\beta\gamma\tau_0}{\cdots\cdots\cdots\cdots} \quad \pi_V \to bb$

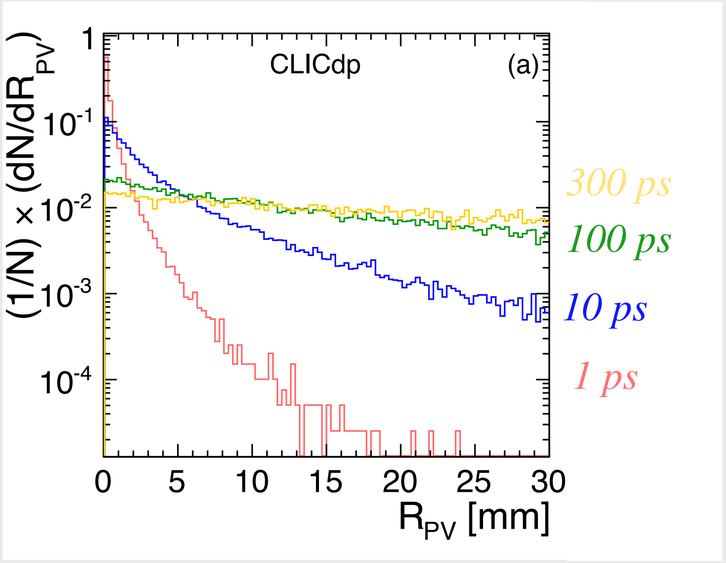
Point Of Closest Approach +
Distance Of Closest Approach

Process	π_v^0 lifetime [ps]	π_v^0 mass [GeV/c^2]	cross section [pb]
$h^0 \to \pi_v^0\pi_v^0$	*1,10,100,300*	*25,35,50*	$0.42 \cdot BR$
$e^+e^- \to q\bar{q}$	-	-	2.95
$e^+e^- \to q\bar{q}\nu\bar{\nu}$	-	-	0.55
$e^+e^- \to q\bar{q}q\bar{q}$	-	-	1.32
$e^+e^- \to q\bar{q}q\bar{q}\nu\bar{\nu}$	-	-	0.07









Hidden Valley Displaced Vertex

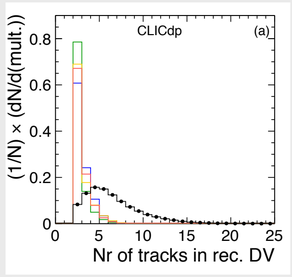
CLICDP-NOTE-2018-001

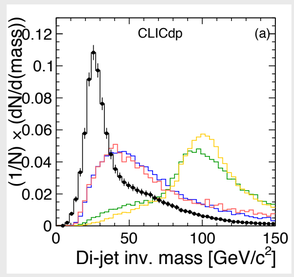
$e^+e^- \to h\,\nu\nu$ $\quad h \to \pi_V\,\pi_V$ $\quad \overset{c\beta\gamma\tau_0}{\cdots\cdots\cdots\cdots} \quad \pi_V \to bb$

N=4 exclusive k_T jets

qq *qqvv* *qqqq* *qqqqvv*

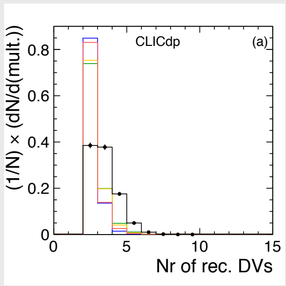
# of tracks

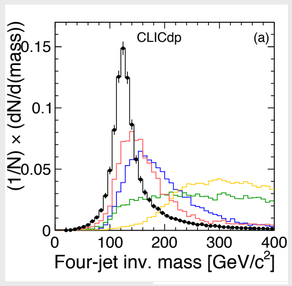




Mass of jj

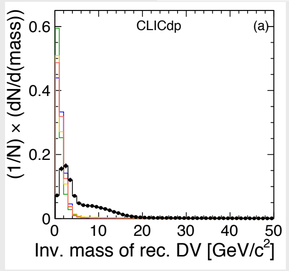
# of DV

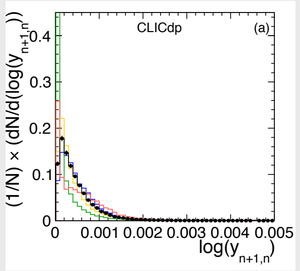




Mass of 4j

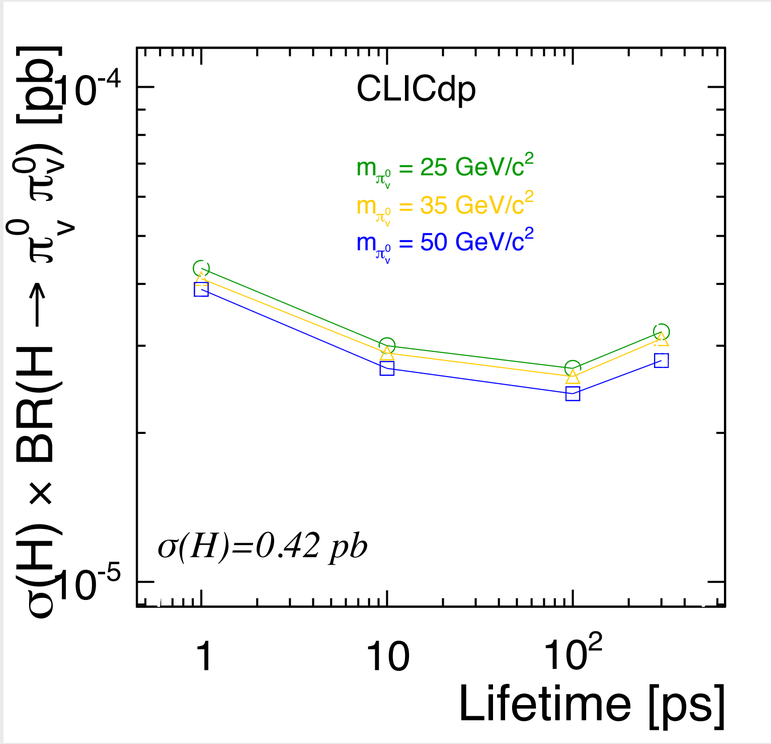
Mass of DV





Jets y_{34} and y_{23}

Boosted Decision Tree: $\varepsilon_S \gtrsim 0.1$

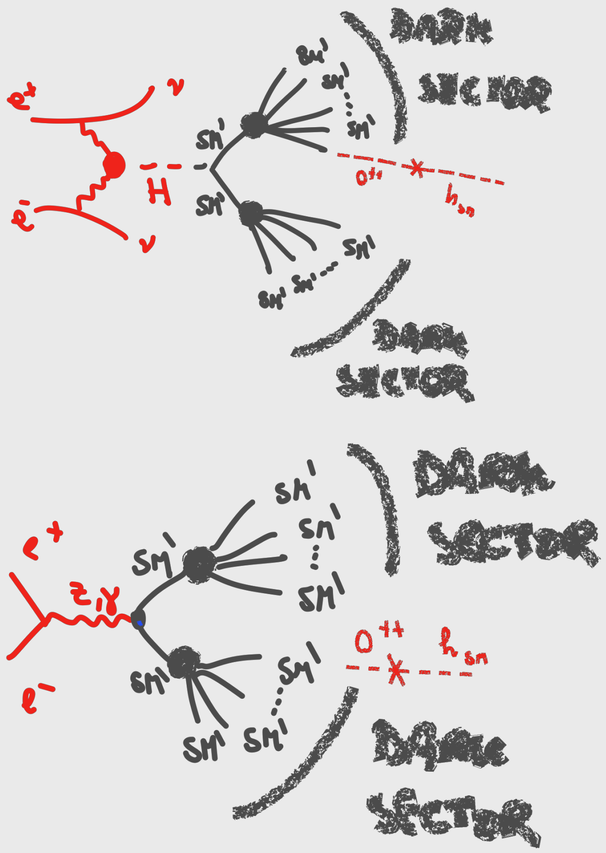


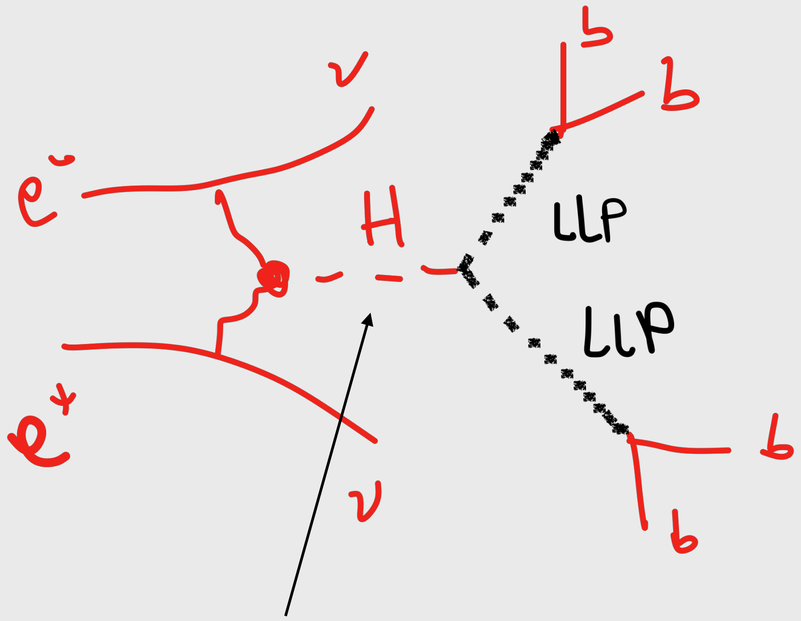
re-use of simplified models

Heavy Higgs Displaced Decay

BASED ON CLICDP-NOTE-2018-001 | $e^+e^- \to H\,\nu\nu$ | $H \to LLP\ LLP$ | $c\beta\gamma\tau_0$ | $LLP \to bb$

"Neutral Naturalness" scenarios: Folded SUSY, fraternal Twin Higgs, …



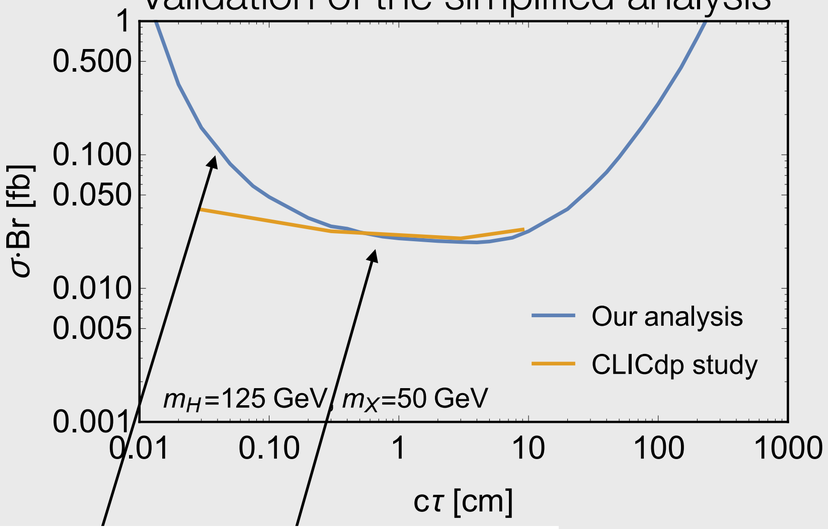


m_H=125, 200, 400, 600, 800, 1000 GeV

CLIC 3 TeV simplified analysis:

- Interaction point Significance > 16
- "Loose" 90% b-tag efficiency
- ΔR_{bb} >0.5 for isolation
- 0.5 efficiency for N_{track}>5

Validation of the simplified analysis

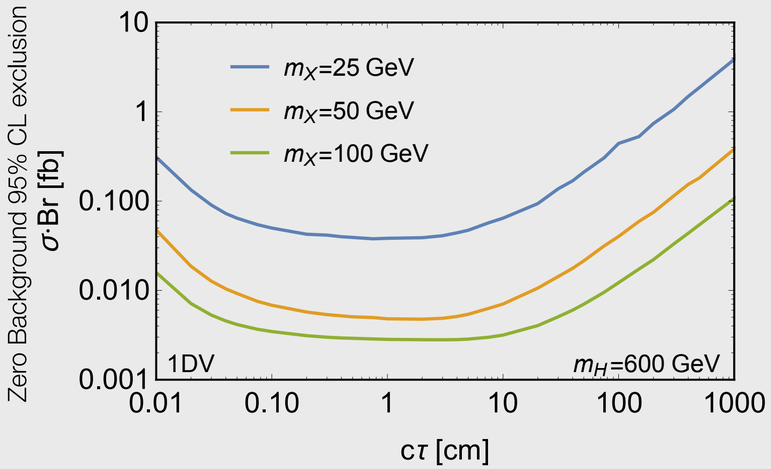


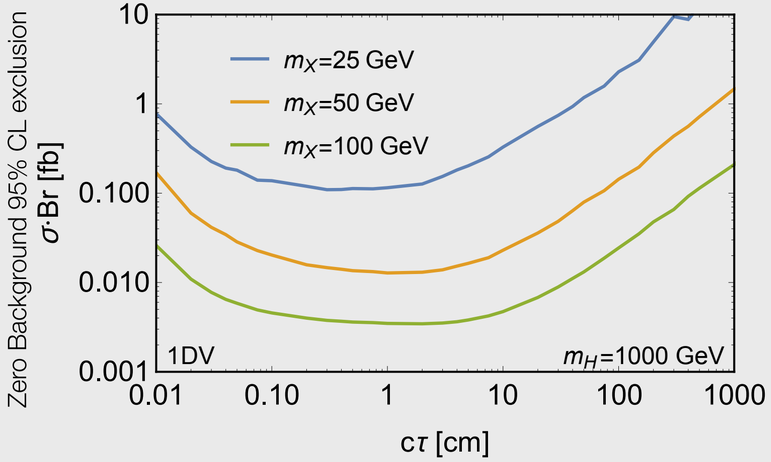
In general conservative good agreement

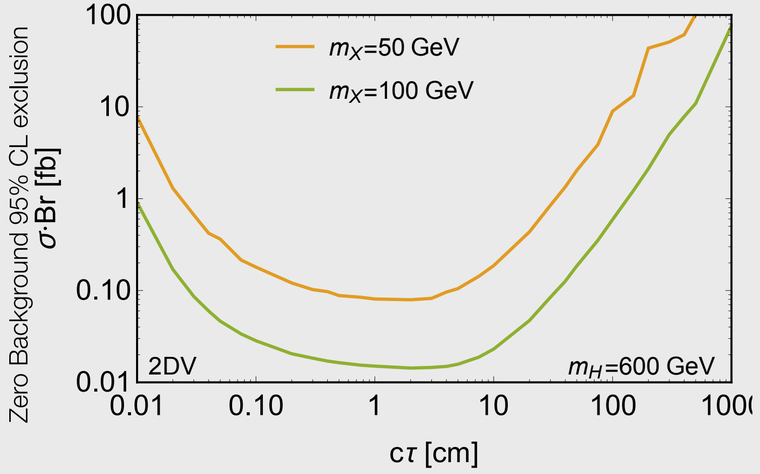
Heavy Higgs Displaced Decay

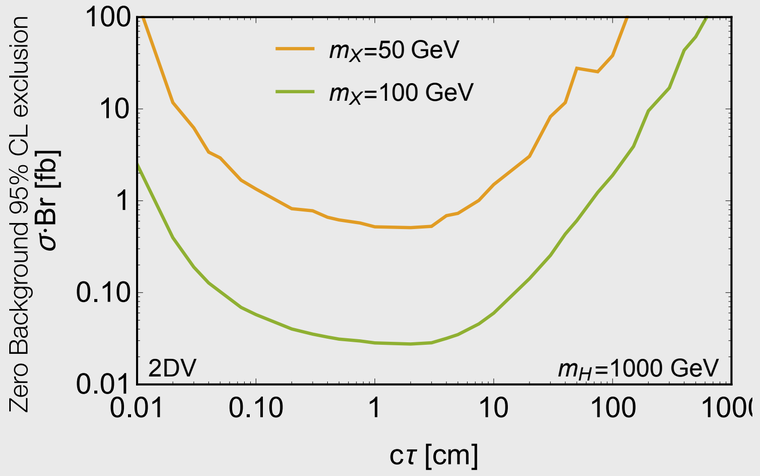
BASED ON CLICDP-NOTE-2018-001

$e^+e^- \to H\,\nu\nu$ $\quad H \to LLP\ LLP$ $\quad \overset{c\beta\gamma\tau_0}{\cdots\cdots\cdots\cdots} \quad LLP \to bb$





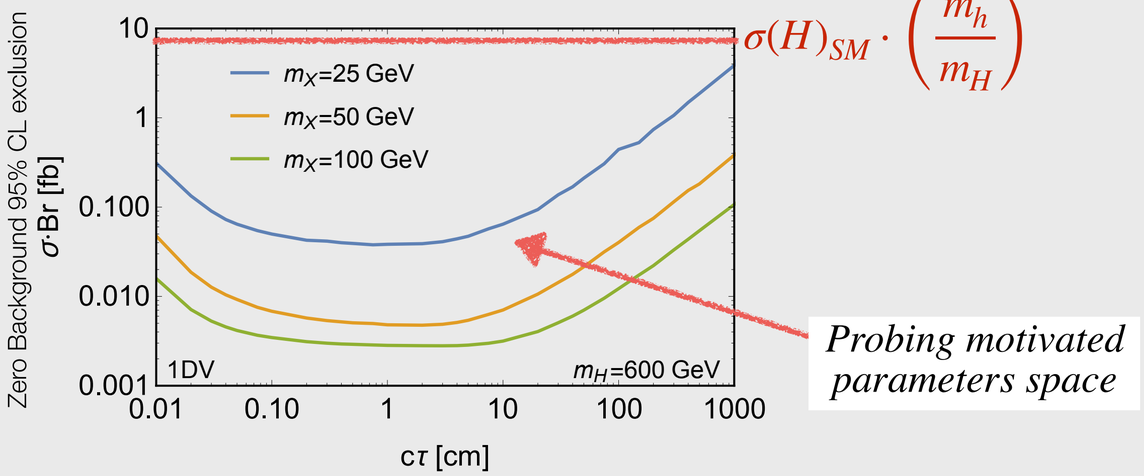




Heavy Higgs Displaced Decay

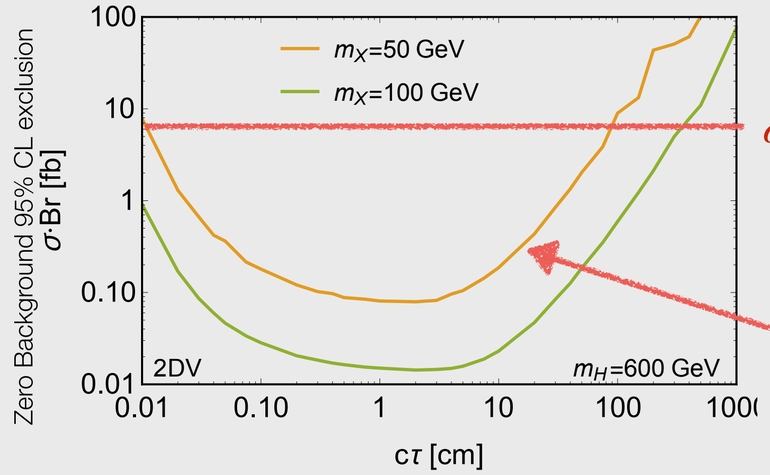
BASED ON CLICDP-NOTE-2018-001

$e^+e^- \rightarrow H\,\nu\nu$ $\quad H \rightarrow LLP\ LLP$ $\quad \overset{c\beta\gamma\tau_0}{\cdots\cdots\cdots\cdots} \quad LLP \rightarrow b\bar{b}$



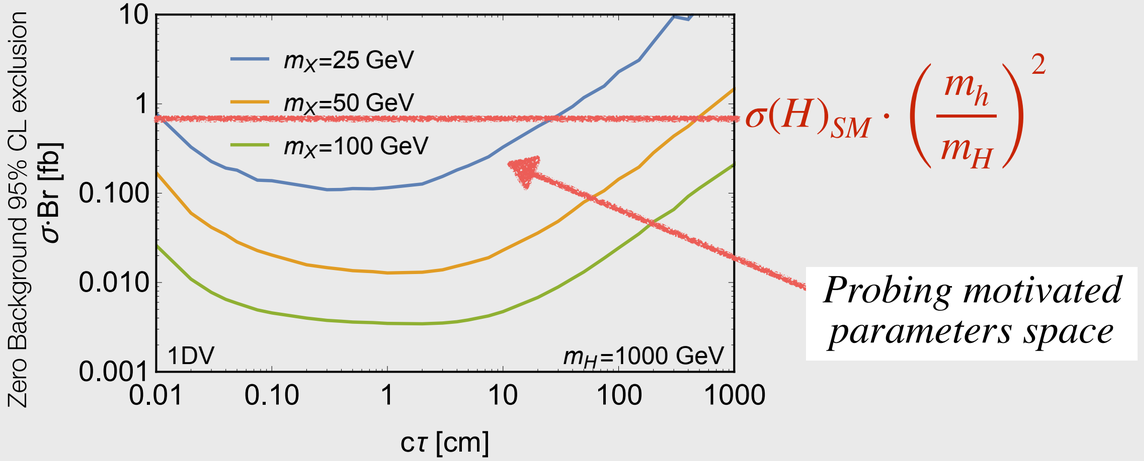
$$\sigma(H)_{SM} \cdot \left(\frac{m_h}{m_H}\right)^2$$

Probing motivated parameters space



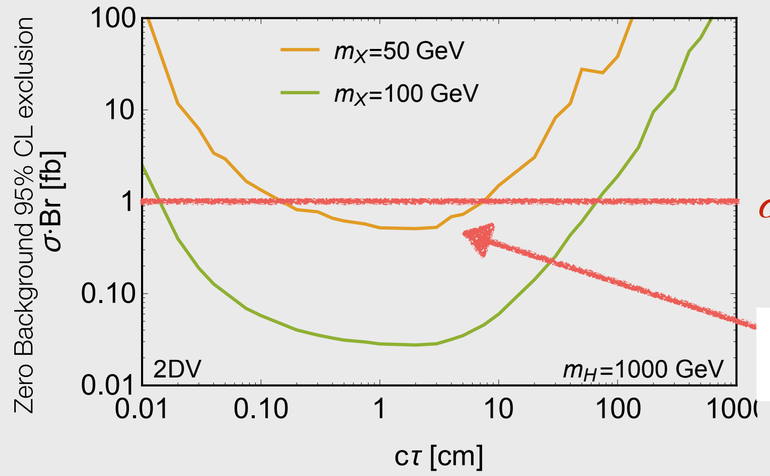
$$\sigma(H)_{SM} \cdot \left(\frac{m_h}{m_H}\right)^2$$

Probing motivated parameters space



$$\sigma(H)_{SM} \cdot \left(\frac{m_h}{m_H}\right)^2$$

Probing motivated parameters space



$$\sigma(H)_{SM} \cdot \left(\frac{m_h}{m_H}\right)^2$$

Probing motivated parameters space

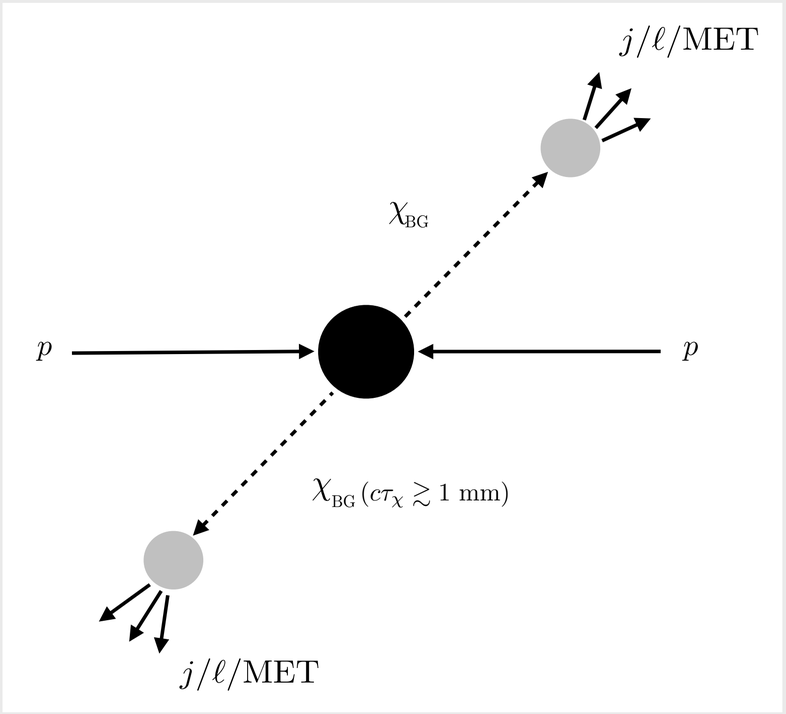
Baryogenesis

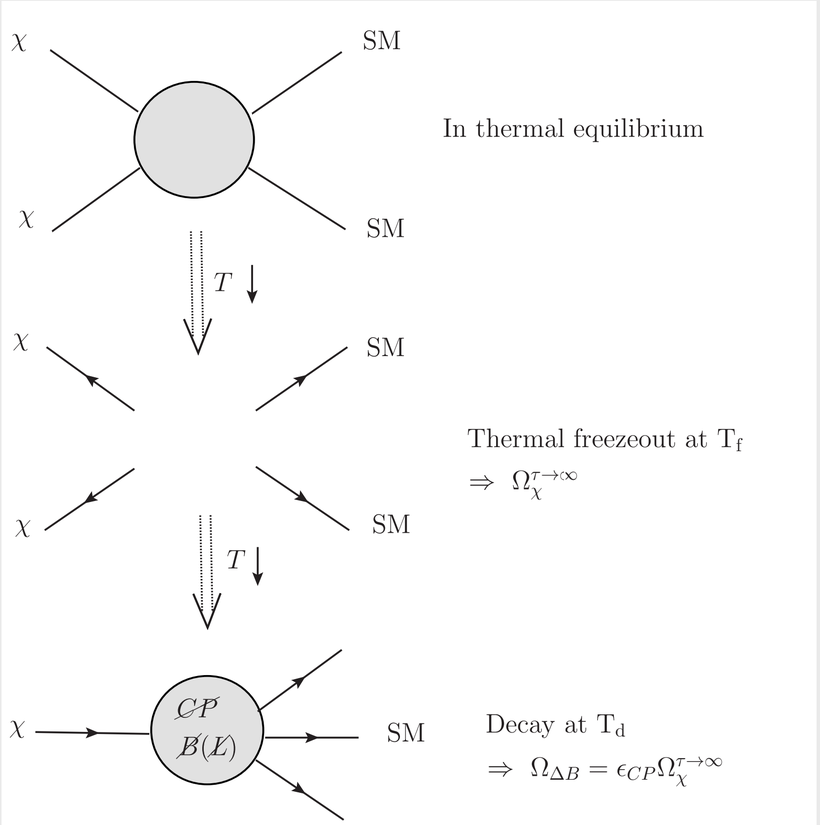
WIMP Baryogenesis

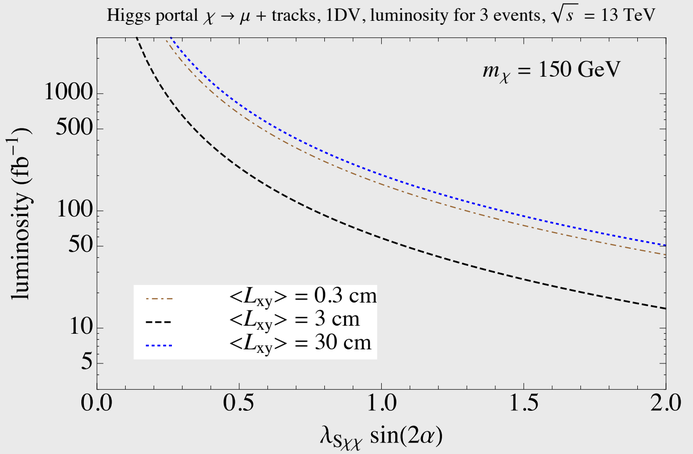
SMALL COUPLINGS | N_B FROM OUT-OF-EQUILIBRIUM DECAY OF WOULD-BE WIMP

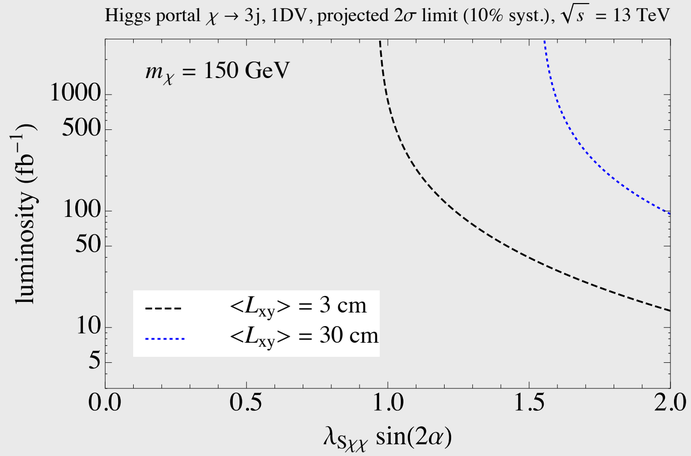
Would-be WIMP can be SM-singlet or SM-charged

$$\mathcal{L}^{\text{singlet}}_{\text{prod}} \supset \frac{c_H}{\Lambda_H}\chi^2|H|^2 + \frac{c_q}{\Lambda_q^2}(\bar{\chi}\Gamma\chi)(\bar{q}\Gamma' q) + \frac{c_g}{\Lambda_g^3}\chi^2(G_{\mu\nu})^2 + \dots,$$



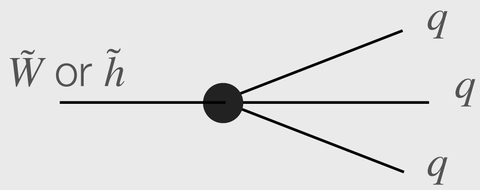






Possible $e^+e^- \to \nu\nu$ + 2 DV signal

WIMP Baryogenesis

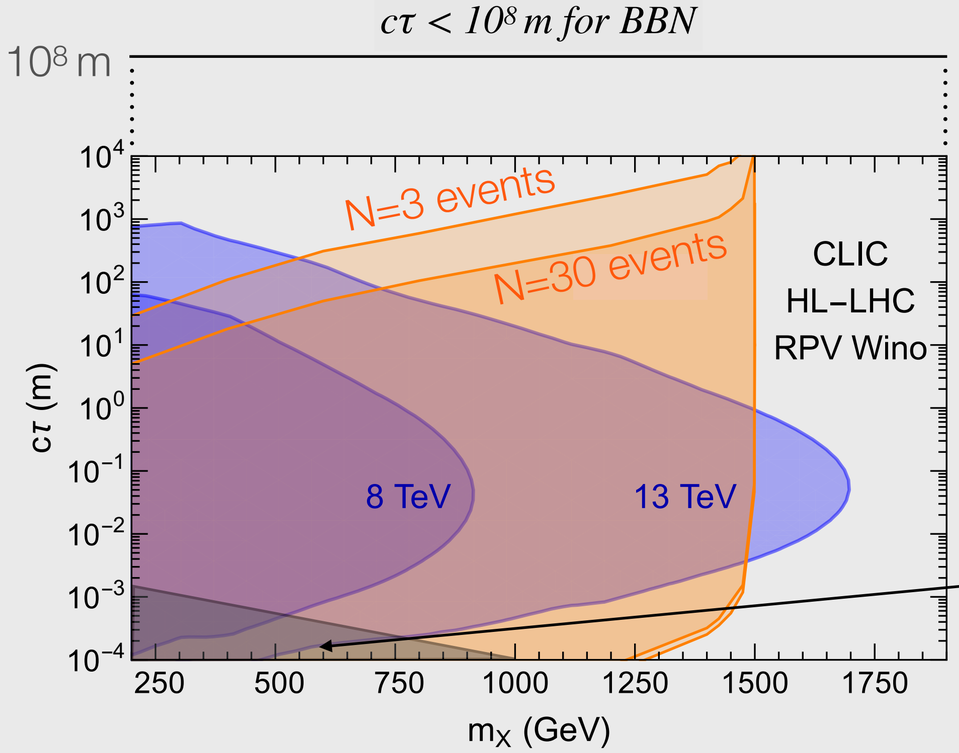


BASED ON CLICDP-NOTE-2018-001

DISPLACED DECAYS TO HADRONS

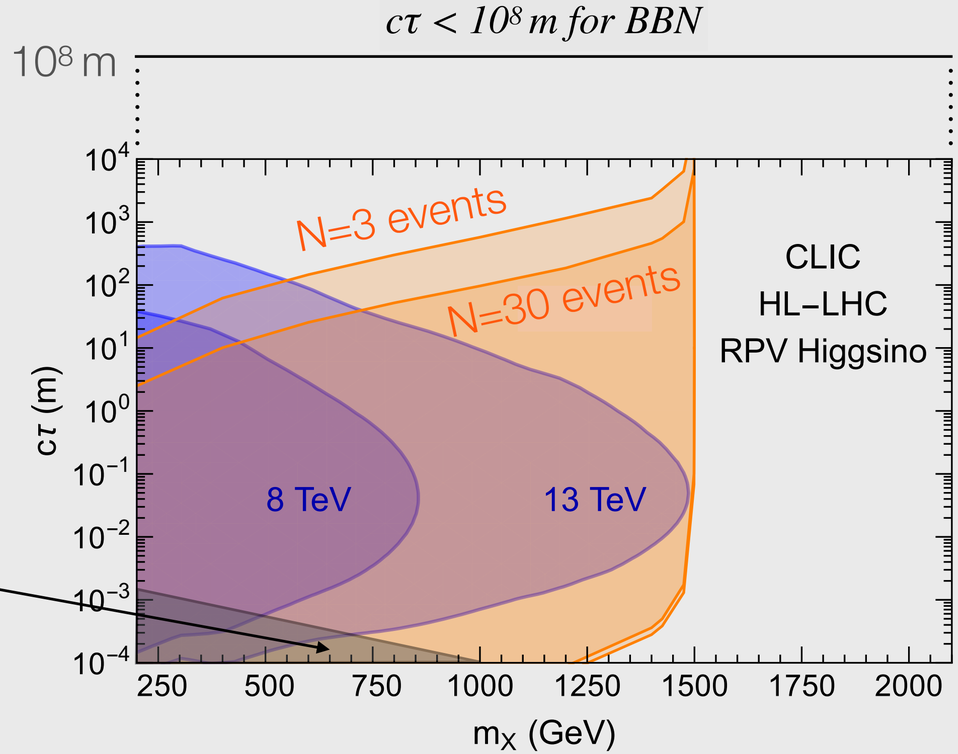
$$e^+e^- \to \chi\chi\,\nu\nu \to \nu\nu + 2\,(\mathrm{DV} \to \mathrm{jjj})_\chi$$

assume 100% efficient vertex finder in $3\cdot10^{-3}$ m < cτ < 0.1 m (CLICdp-Note-2018-001)



Cosmology requires

- before nucleo-synthesis
  $c\tau_\chi < 10^8 m$
- out-of-equilibrium
  $\tau_\chi > 1/H(T \sim m_\chi)$



- Standard “targets” such as vanilla SUSY, compositeness of Higgs and other states, sub-TeV WIMPs are all being probed and are under a fair amount of pressure
- Motivations for new physics to be out there are stronger than ever

- New physics can be accessible at future colliders, but no “no-loose theorem” as for LHC

  - ★ next generation of new physics exploration has to be necessarily “broad-band”

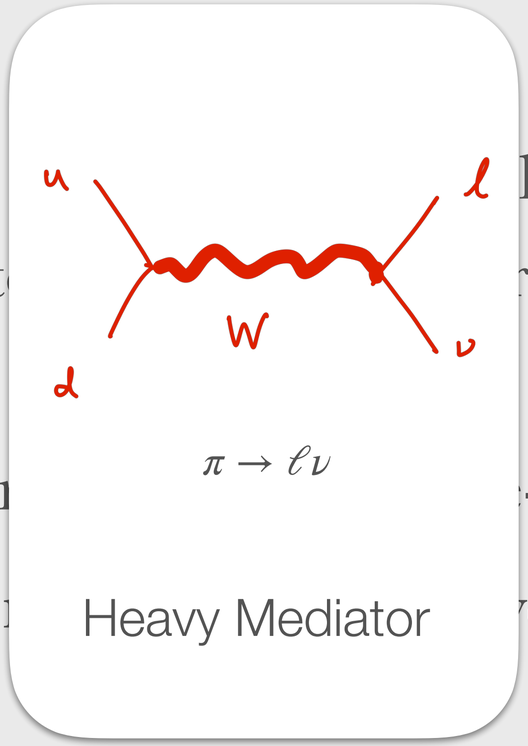
  - ★ macro/meso-scopic life-times are possible and motivated from several standpoints

CONCLUSIONS | PRECISION AND MASS REACH

- New physics can be accessible at future colliders, but no “no-loose theorem” as for LHC

★ next physics exploration has t road-band”

★ maci -times are possible and veral standpoints



- New physics can be accessible at future colliders, but no “no-loose theorem” as for LHC

★ next p
has t ro

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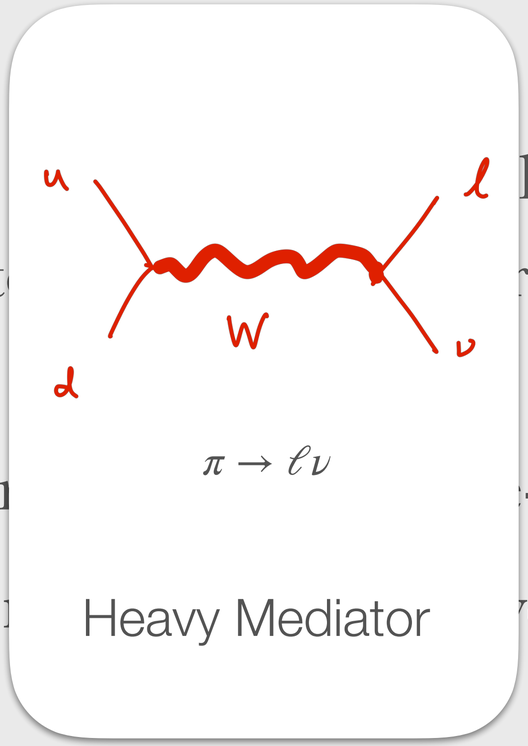

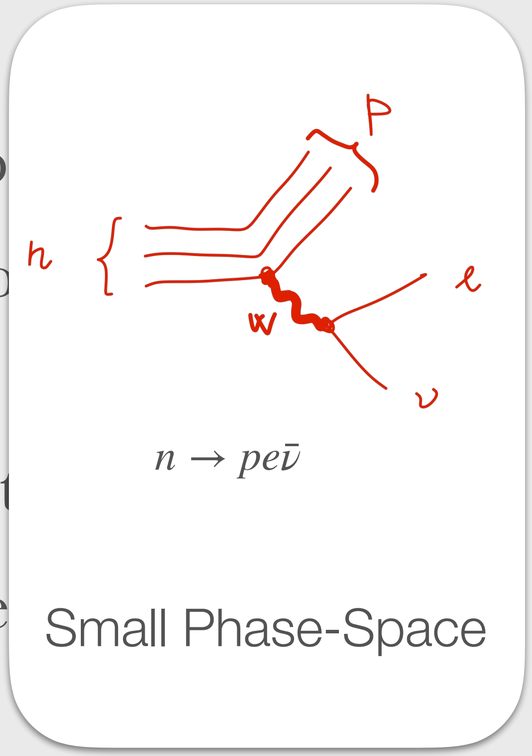

- New physics can be accessible at future colliders, but no “no-loose theorem” as for LHC

★ next p
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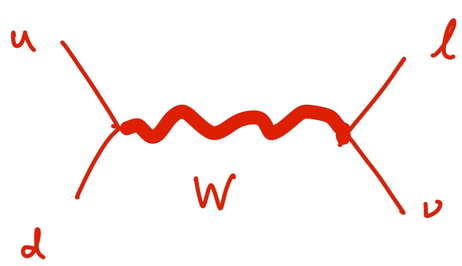
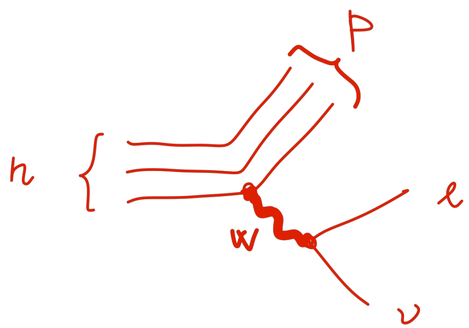


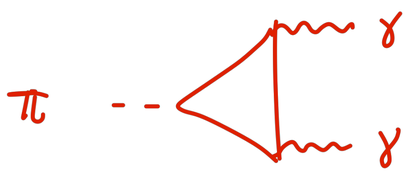
$\pi \to \ell\nu$

Heavy Mediator



$n \to pe\bar{\nu}$

Small Phase-Space



$\pi \to \gamma\gamma$

Small Coupling

CONCLUSIONS | WORK DONE

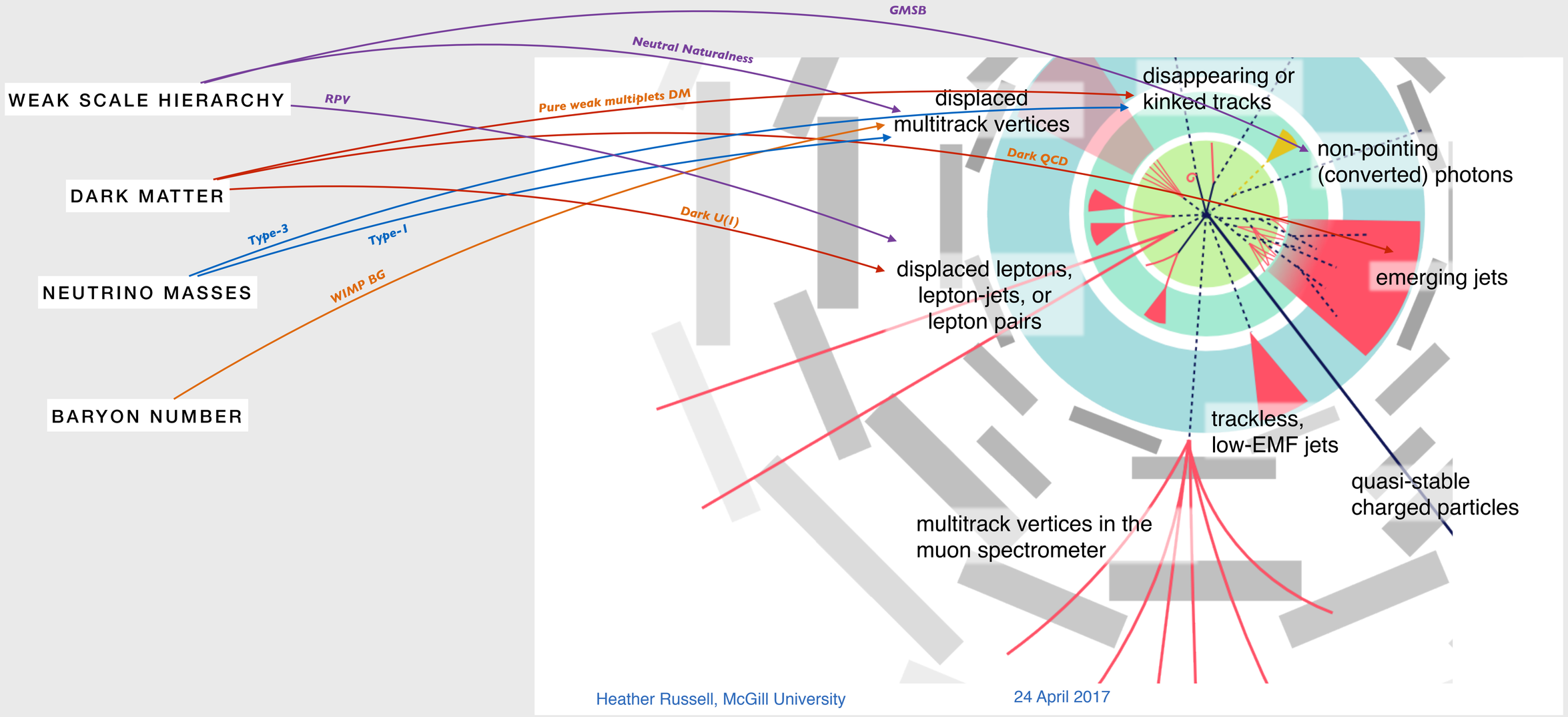
- long-lived decays of a 125 GeV Higgs (CLICdp)
- long-lived decays of a Heavy Higgs (pheno-level Yellow Report)
- long-lived decays of a “baryo-genitor” (pheno-level Yellow Report)
- short-tracks from a Higgsino DM candidate (pheno-level Yellow Report)

CONCLUSIONS | ACTION ITEMS

- short-tracks from a Higgsino DM candidate (CLICdp inputs, especially on background)
- long-lived decays of a Heavy Higgs (CLICdp validation of recast)
- long-lived decays of a “baryo-genitor” (CLICdp input and effort for the 3j DV)
- long-lived decays of a Heavy Neutrino (open chapter)
- long-lived decays of a dark photons and dark Z’ (open chapter)

CONCLUSIONS

MORE SIGNATURES ON THE TABLE*



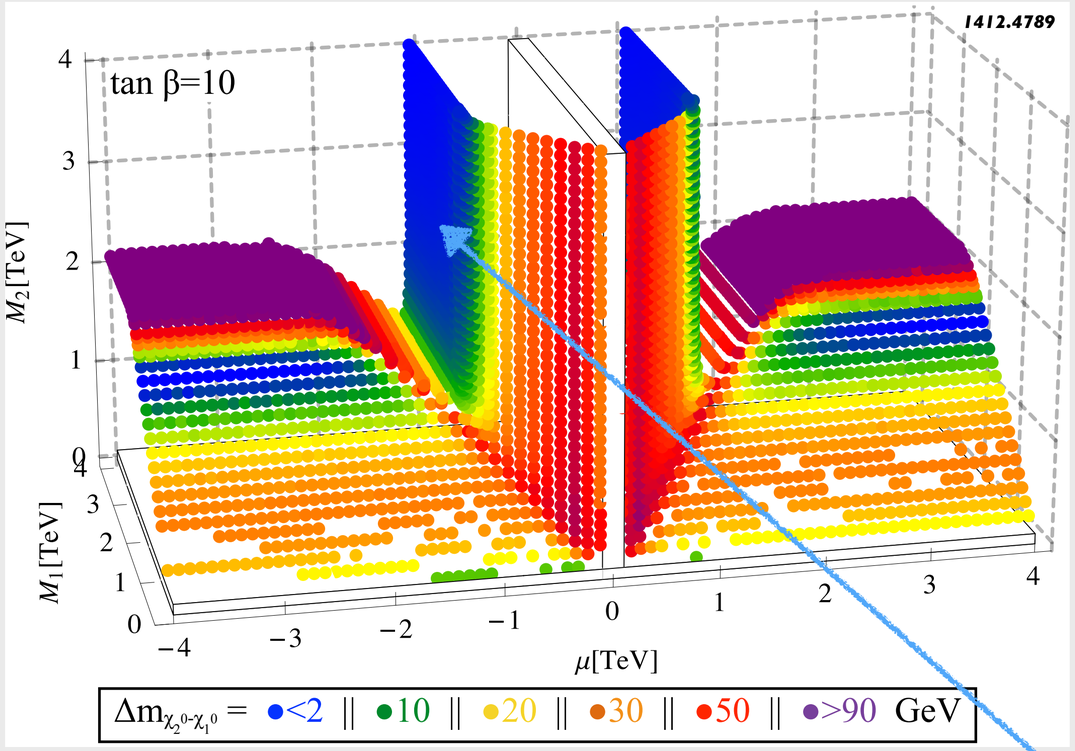
Thank you!

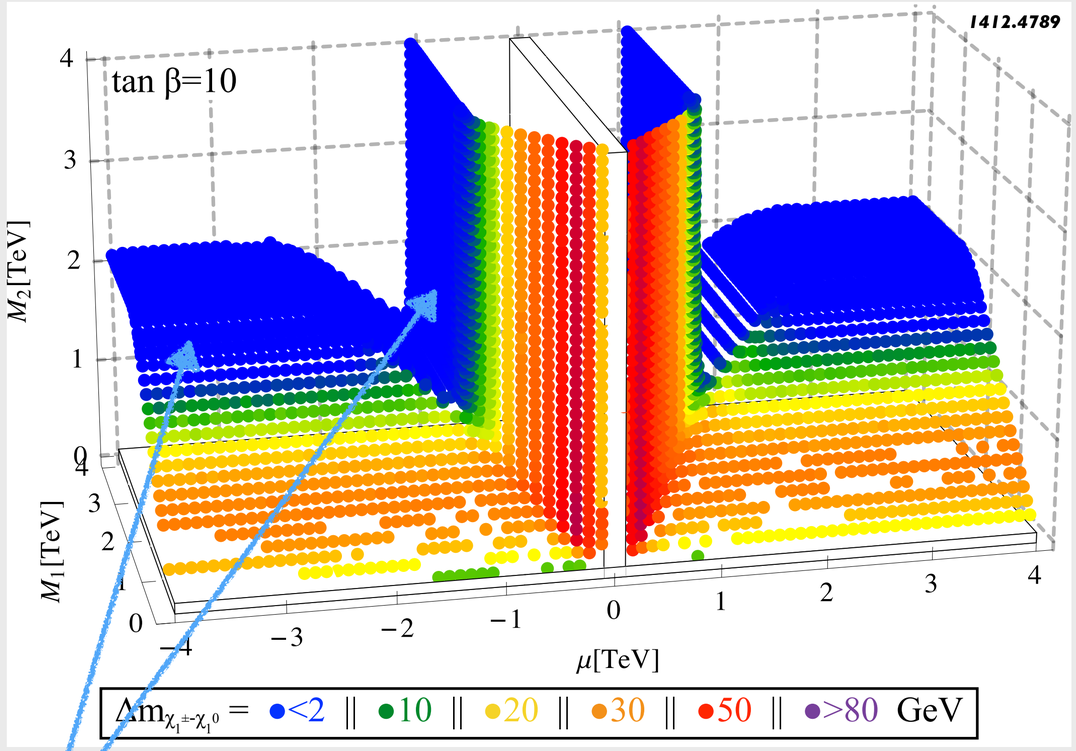
Contributors: *S. Alipour-Fard* [1], *W. Altmannshofer* [2], *A. Azatov* [3,4], *D. Azevedo* [5,6], *J. Baglio* [7], *M. Bauer* [8], *F. Bishara* [9,10], *J.-J. Blaising* [11], *S. Brass* [12], *D. Buttazzo* [13], *Z. Chacko* [14,15], *N. Craig* [1], *Y. Cui* [16], *D. Dercks* [9,17], *L. Di Luzio* [8,13,18], *S. Di Vita* [19], *G. Durieux* [9,20], *J. Fan* [21], *P. Ferreira* [5,22], *C. Frugiuele* [23], *E. Fuchs* [23], *I. García* [24,25], *M. Ghezzi* [7,26], *A. Greljo* [25], *R. Gröber* [8,27], *C. Grojean* [9,27], *J. Gu* [28], *R. Hunter* [29], *A. Joglekar* [16], *J. Kalinowski* [30], *W. Kilian* [12], *C. Kilic* [31], *W. Kotlarski* [32], *M. Kucharczyk* [33], *E. Leogrande* [25], *L. Linssen* [25], *D. Liu* [34], *Z. Liu* [14,15], *D. M. Lombardo* [35], *I. Low* [34,36], *O. Matsedonskyi* [23], *D. Marzocca* [4], *K. Mimasu* [37], *A. Mitov* [38], *M. Mitra* [39], *G. Moortgat-Pick* [9,17], *M. Mühlleitner* [40], *S. Najjari* [41], *M. Nardecchia* [4,25], *M. Neubert* [28,42], *J. M. No* [43], *G. Panico* [9,44,45,46], *L. Panizzi* [47,48], *A. Paul* [9,27], *M. Perelló* [24], *G. Perez* [23], *A. D. Plascencia* [8], *G. M. Pruna* [49], *D. Redigolo* [23,50,51], *M. Reece* [52], *J. Reuter* [9], *M. Riembau* [36], *T. Robens* [53,54], *A. Robson* [25,55], *K. Rolbiecki* [31], *A. Sailer* [25], *K. Sakurai* [31], *F. Sala* [9], *R. Santos* [5,22], *M. Schlaffer* [23], *S. Y. Shim* [56], *B. Shuve* [16,57], *R. Simoniello* [25,58], *D. Sokołowska* [30,59], *R. Ström* [25], *T. M. P. Tait* [60], *A. Tesi* [46], *A. Thamm* [25], *N. van der Kolk* [61], *T. Vantalon* [9], *C. B. Verhaaren* [62], *M. Vos* [24], *N. Watson* [63], *C. Weiland* [8,64], *A. Winter* [63], *J. Wittbrodt* [9], *T. Wojton* [33], *B. Xu* [38], *Z. Yin* [36], *A. F. Żarnecki* [30], *C. Zhang* [65]

WIMP: EW-ino as Dark Matter

MSSM

WITH R-PARITY



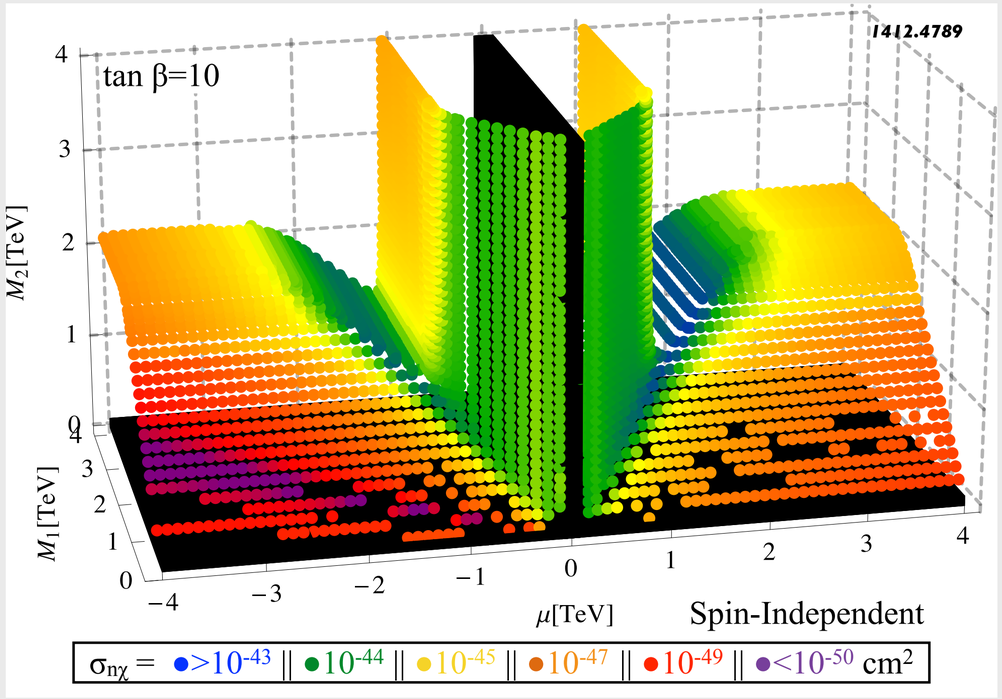


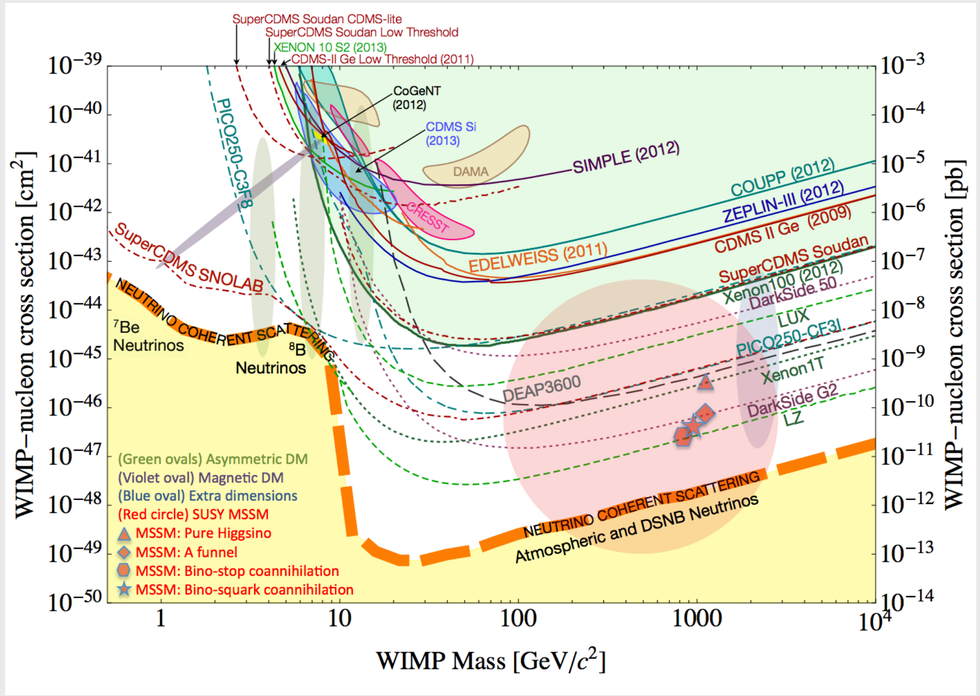
large parts of parameters space have almost degenerate multiplets

Direct Searches

WIMP

UNDER PRESSURE



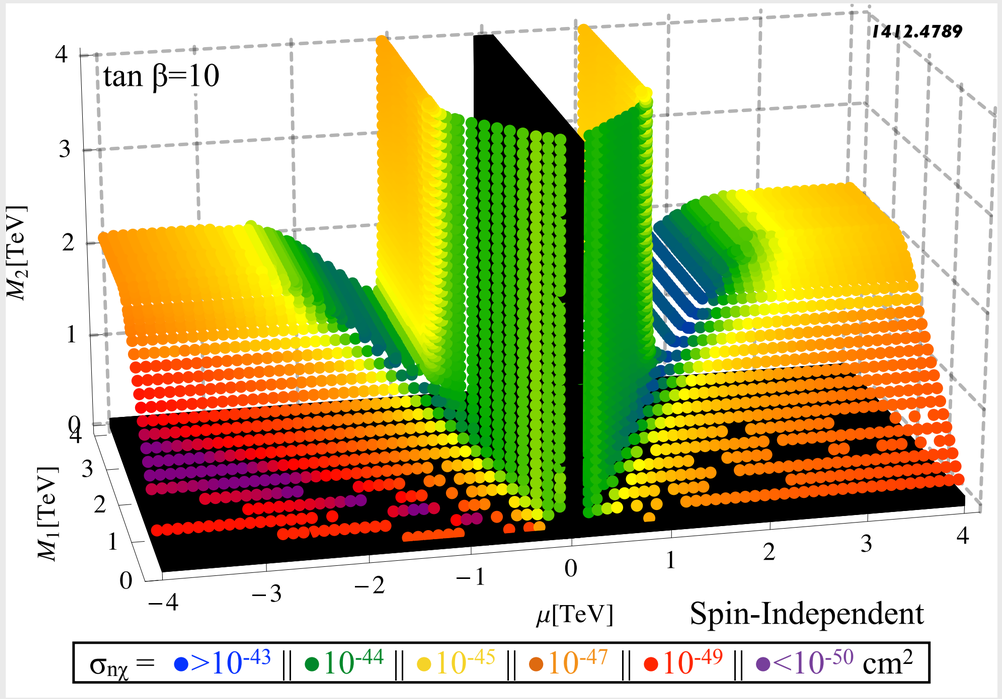


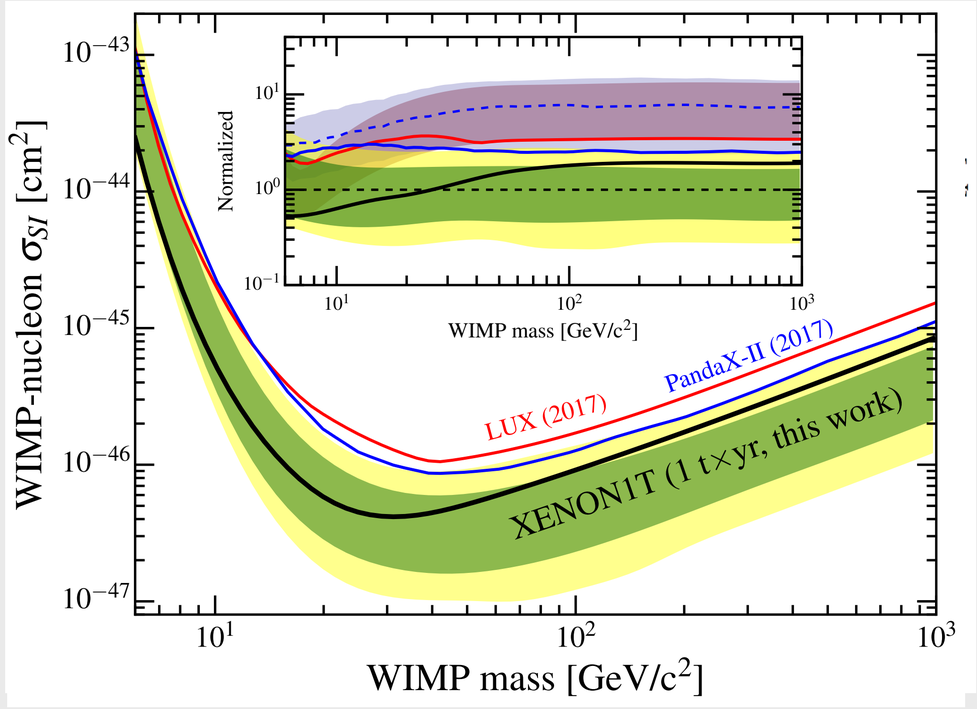
WIMP is under a fair amount of pressure, still an interesting candidate to test the capabilities of a future collider

Direct Searches

WIMP

UNDER PRESSURE





WIMP is under a fair amount of pressure, still an interesting candidate to test the capabilities of a future collider

Short (disappearing) tracks

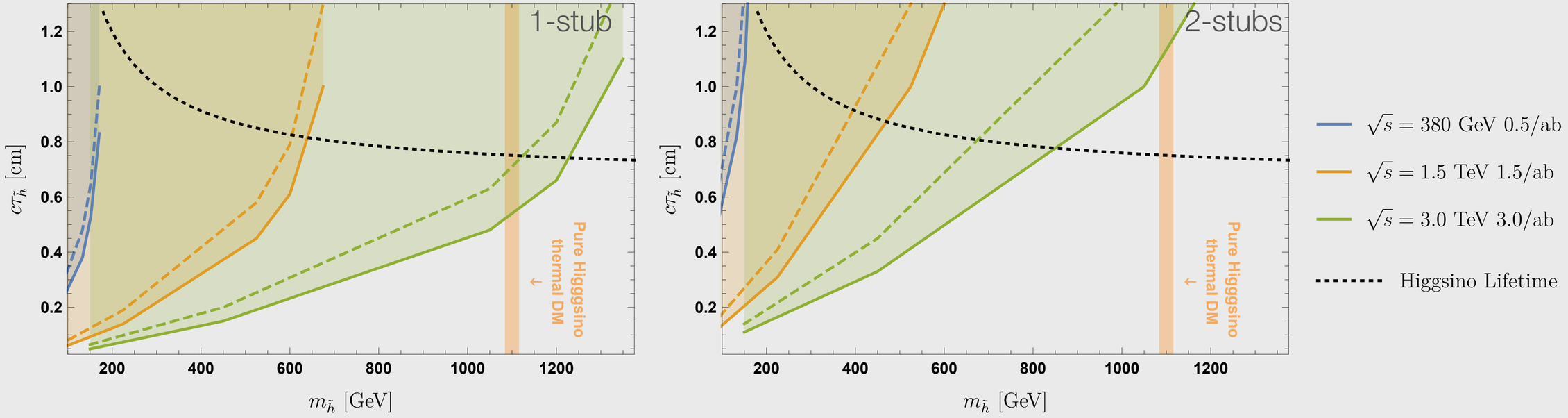
HIGGSINO DM

O(CM) DISAPPEARING TRACKS

Charged-Neutral mass splitting
can be different if Higgsino Mixed with other states (e.g. Wino)

TAKE LIFETIME AS FREE PARAMETER

ISOLINES FOR NUMBER OF EVENTS ASSUMED FOR DISCOVERY



Neutrino mass mechanisms

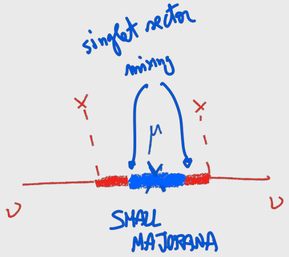
LEPTON NUMBER BREAKING

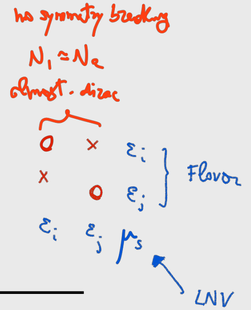
L – violation

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

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

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



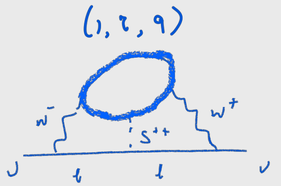


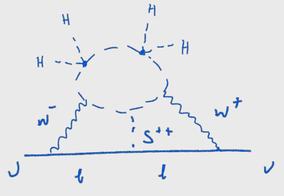
L – not accidental

new physics before 2012

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

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





L – gauged, SSB

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

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

Neutrinos, See-saw

Mediator of Neutrino mass mechanism

DOUBLY CHARGED

Generically $S^{++} \to \ell^+ \ell^+$ *(or* W^+W^+*)*

$$v_T = \frac{\kappa v^2}{\sqrt{2} M_T^2} \begin{cases} v_T < 100 \text{ KeV} & H^{++} \to \ell^+\ell^+ \\ v_T > 100 \text{ KeV} & H^{++} \to W^+W^+ \end{cases}$$

$$m_\nu \simeq \sqrt{2} v_T Y_\Delta$$

$$V(\Phi, \Delta) = -\left(\kappa \Phi^\top i\sigma^2 \Delta^\dagger \Phi + h.c.\right)$$

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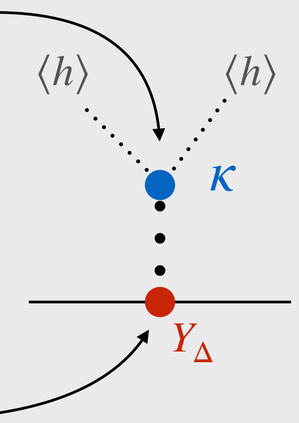

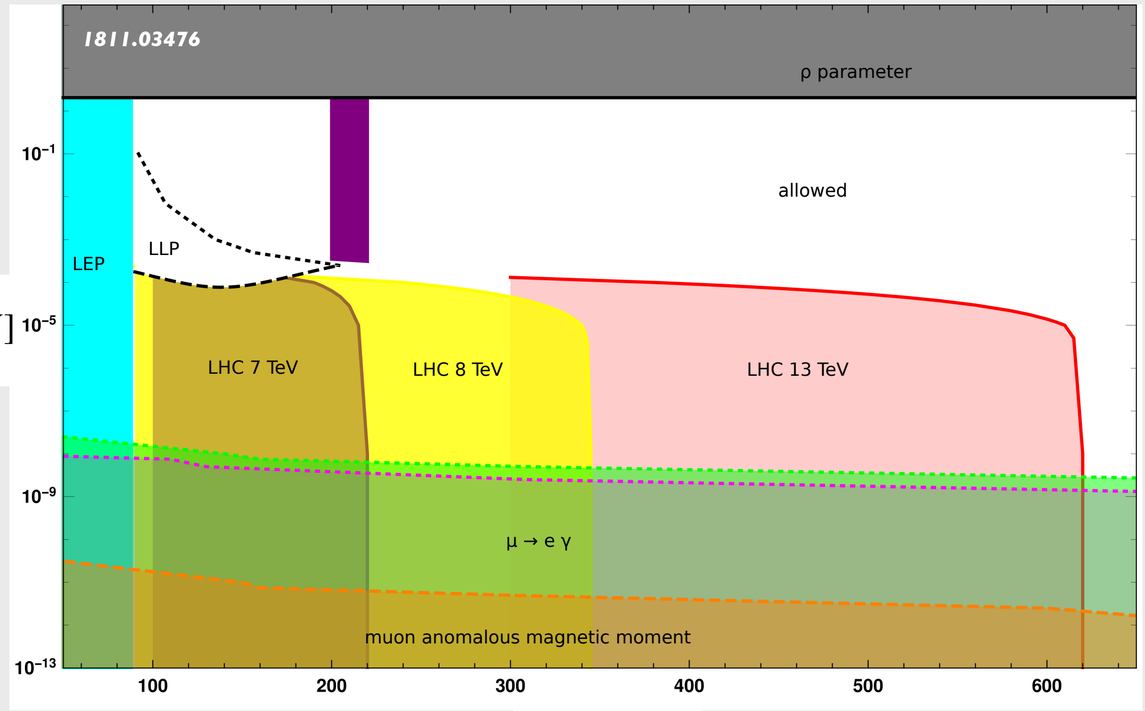

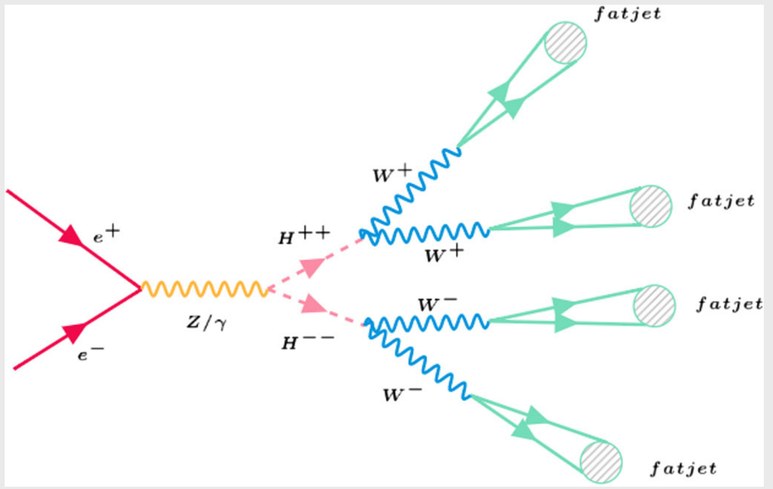

1.5 TeV

Exclude Type-2 seesaw below 1.5 TeV **for any Triplet VEV**

Mediator of Neutrino mass mechanism

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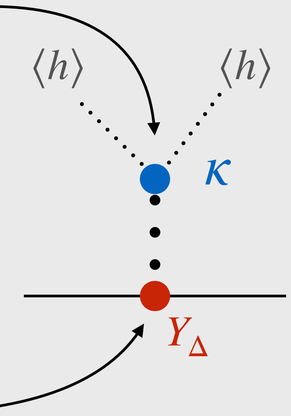

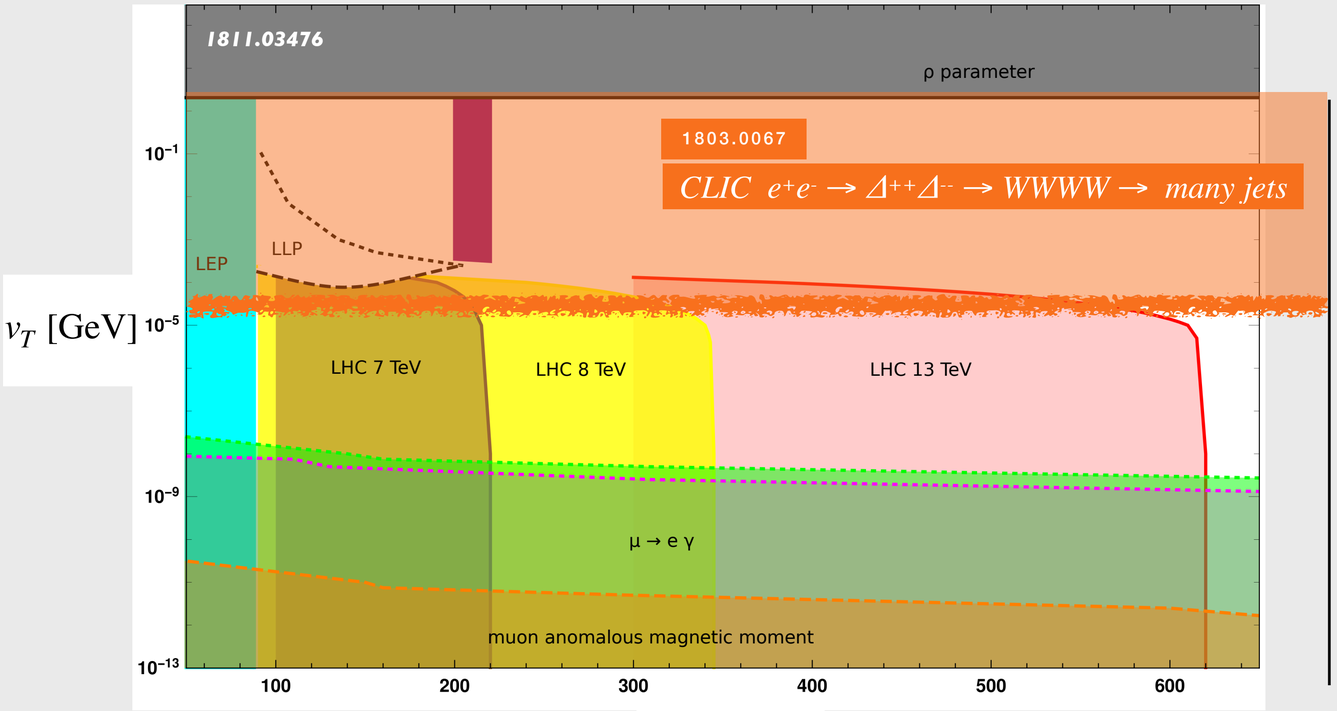

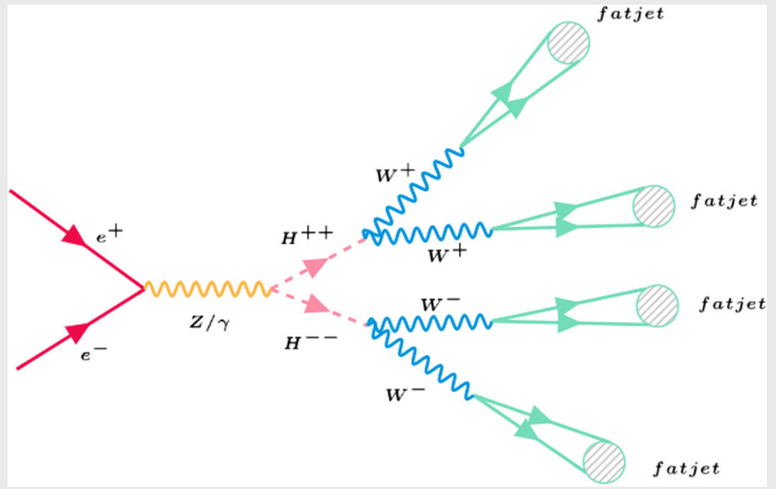

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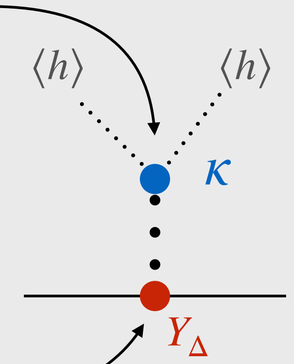

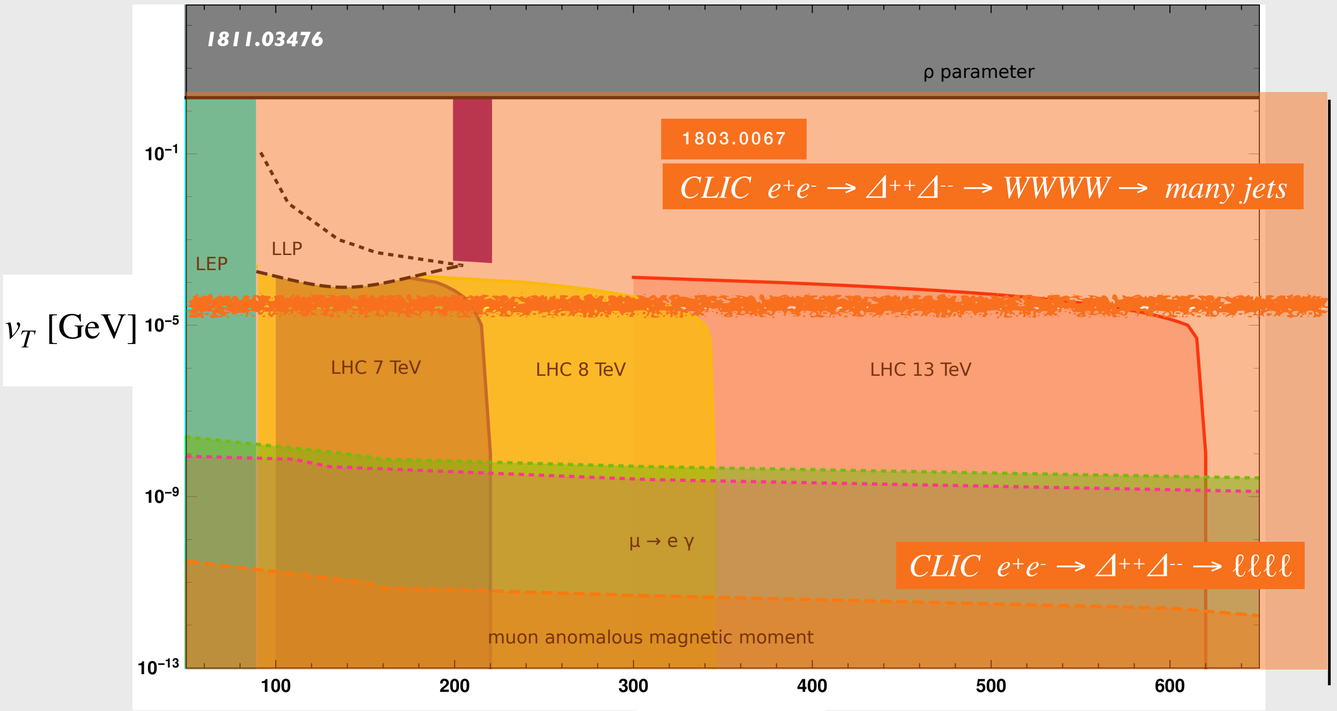

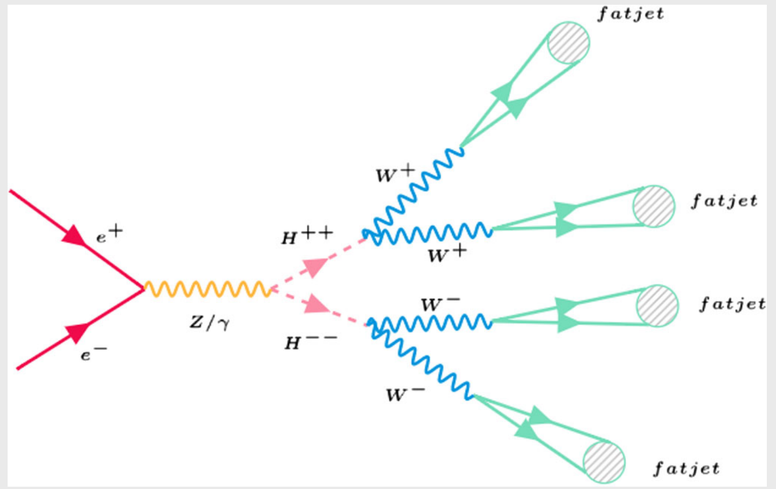

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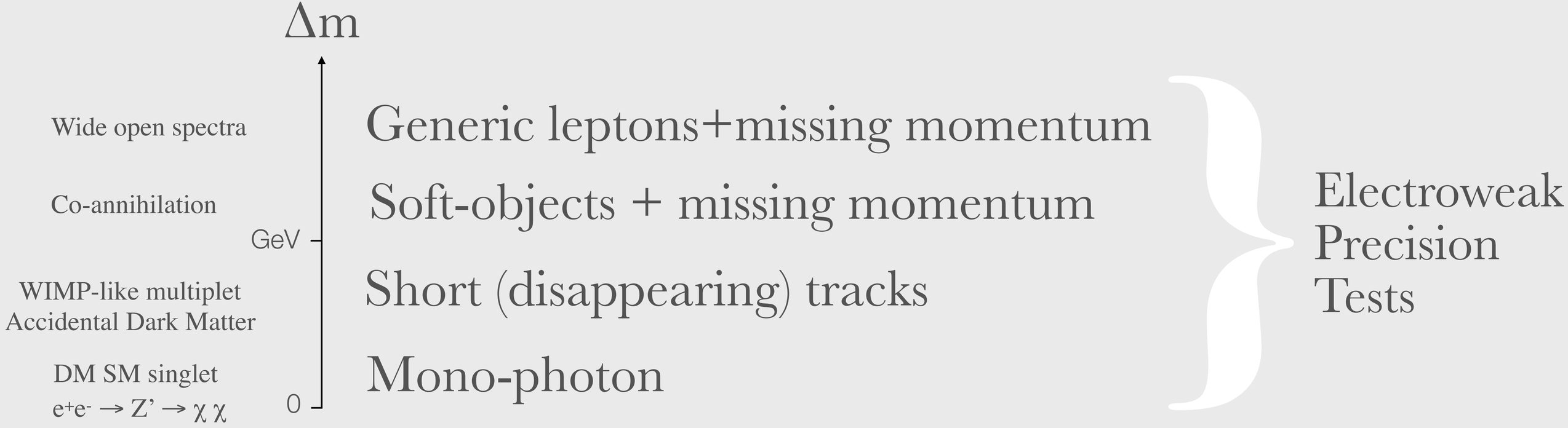
Electroweak Dark Matter: LSP (+NLSP)



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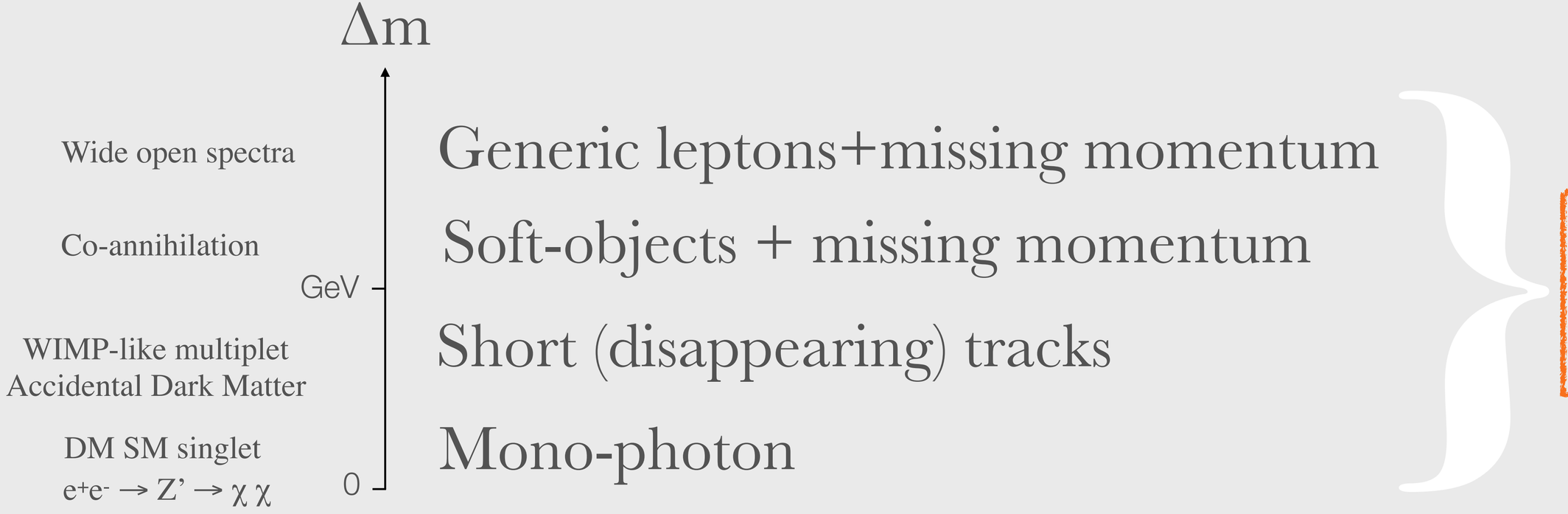
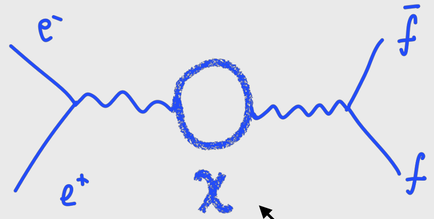


$e^+e^- \to f\bar{f}$

PRECISION

ANGULAR DISTRIBUTION



χ is heavy/light new physics

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{g^2 C^{\rm eff}_{WW}}{8} W^a_{\mu\nu} \Pi(-D^2/m^2_\chi) W^{a\mu\nu} + \frac{g'^2 C^{\rm eff}_{BB}}{8} B_{\mu\nu} \Pi(-\partial^2/m^2_\chi) B^{\mu\nu}$$

1504.03402

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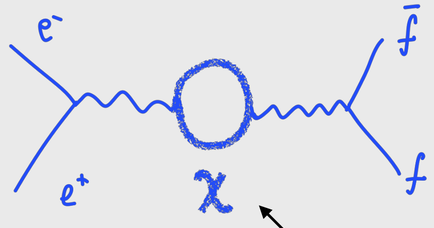
PRECISION

ANGULAR DISTRIBUTION



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1504.03402

HEAVY NEW PHYSICS (EFT LIMIT)

$$\Pi\left(\frac{s}{m^2}\right) \sim \frac{1}{480\pi^2} \cdot \frac{s}{m^2}$$

$$C_{WW}^{\rm eff} = \kappa(n^3 - n)/6,\ C_{BB}^{\rm eff} = \kappa 2 n Y^2$$

$$\kappa = \frac{1}{2}, 1, 4, 8 \text{ for RS,CS,MF,DF}$$

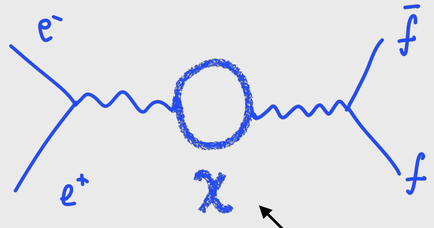
$$W = \frac{g^2 C_{WW}^{\rm eff}}{960\pi^2} \frac{m_W^2}{m_\chi^2} \quad Y = \frac{g'^2 C_{BB}^{\rm eff}}{960\pi^2} \frac{m_W^2}{m_\chi^2}$$

EFFECTS GROW WITH ENERGY

$e^+e^- \to f\bar{f}$

PRECISION

ANGULAR DISTRIBUTION



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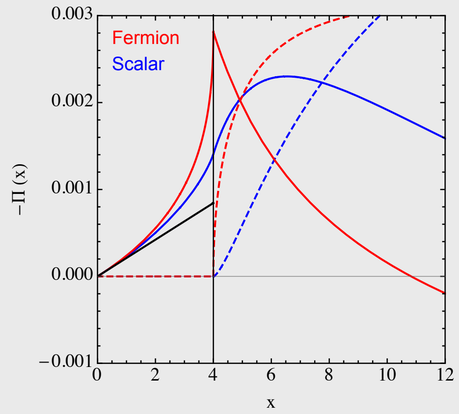
1504.03402

LIGHT NEW PHYSICS

$$\Pi(x) = \begin{cases} -\dfrac{8(x-3)+3x\left(\frac{x-4}{x}\right)^{3/2}\log\left(\frac{1}{2}\left(\left(\sqrt{\frac{x-4}{x}}-1\right)x+2\right)\right)}{144\pi^2 x} & \text{(scalars)} \\ -\dfrac{12+5x+3\sqrt{\frac{x-4}{x}}(x+2)\log\left(\frac{1}{2}\left(\left(\sqrt{\frac{x-4}{x}}-1\right)x+2\right)\right)}{288\pi^2 x} & \text{(fermions)} \end{cases}$$



PRECISION PHYSICS

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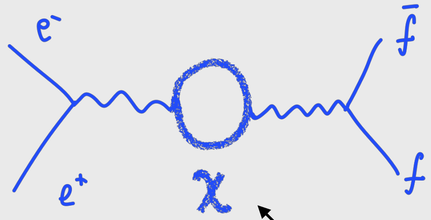

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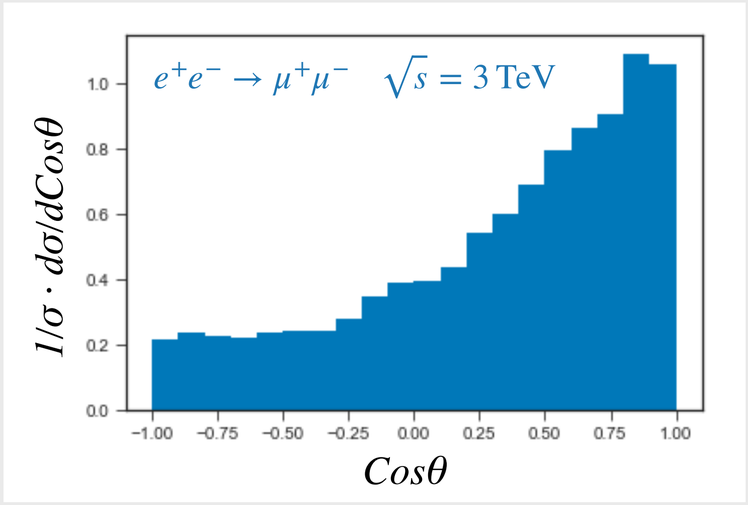
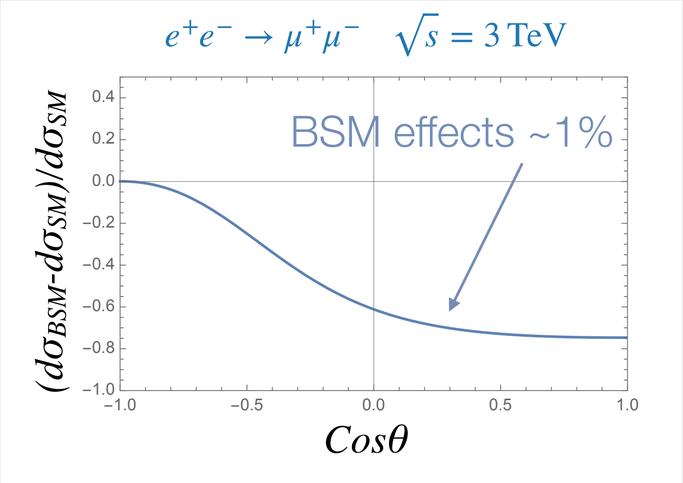


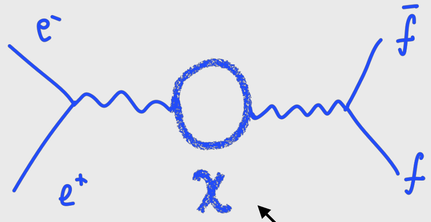


beams polarization is beneficial to increase NP effects

$e^+e^- \to f\bar{f}$

PRECISION

ANGULAR DISTRIBUTION



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$|cos\theta| < 0.95$ for all final states

χ^2 over 10 bins

$$\chi^2 = \sum_{i=1}^{10} \frac{\left(N_i^{\rm SM+BSM} - N_i^{\rm SM}\right)^2}{N_i^{\rm SM} + \left(\epsilon_i N_i^{\rm SM}\right)^2}$$

Systematic Unc.

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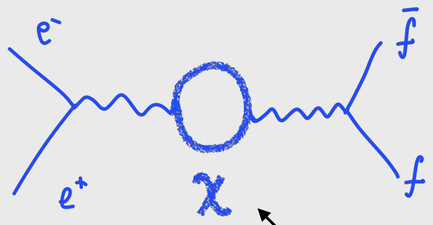
PRECISION | ANGULAR DISTRIBUTION



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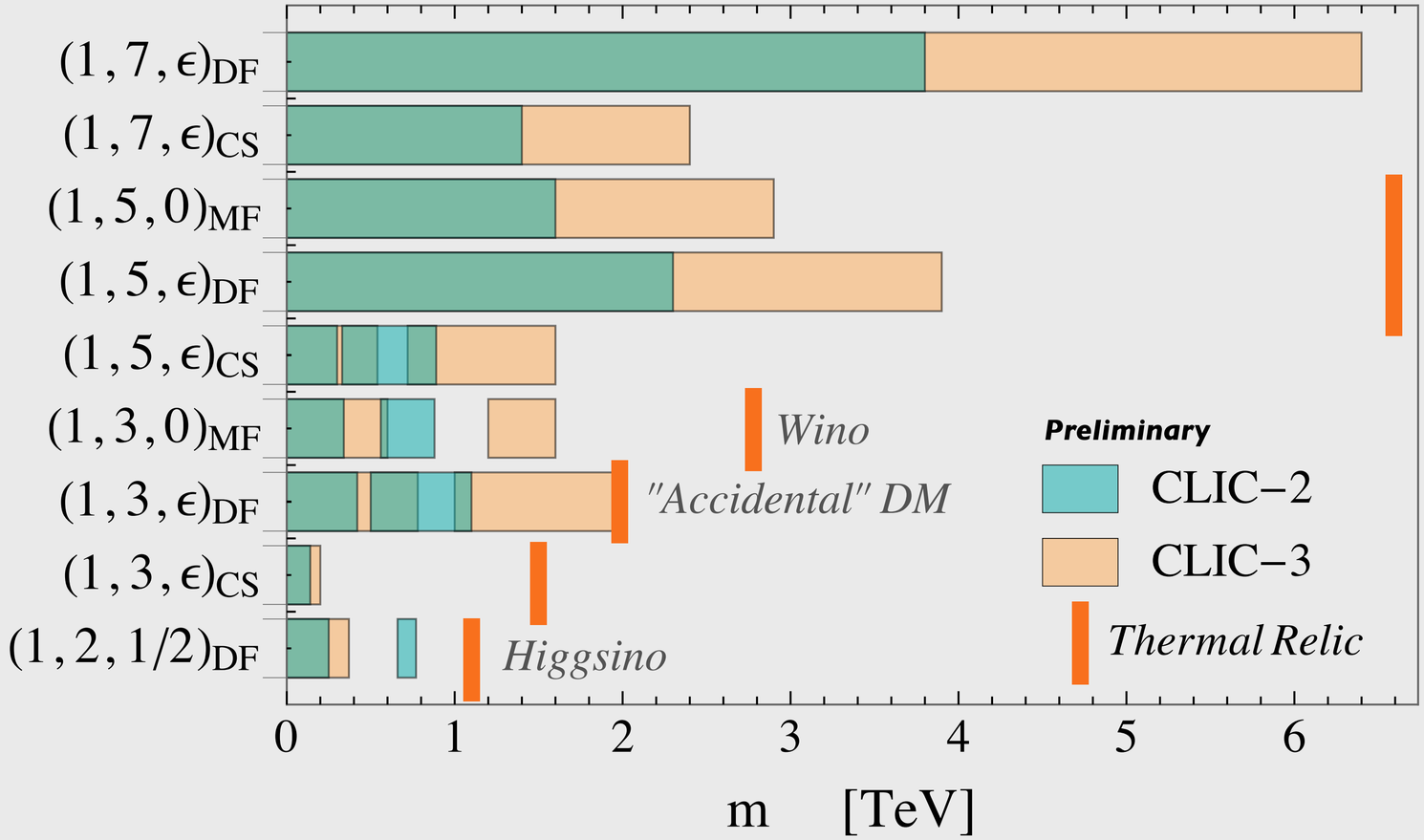

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PRECISION | ANGULAR DISTRIBUTION

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$(1,3,\epsilon)_{\mathrm{CS}}$	1.55	-
$(1,3,\epsilon)_{\mathrm{DF}}$	2.0	2.1 ✸
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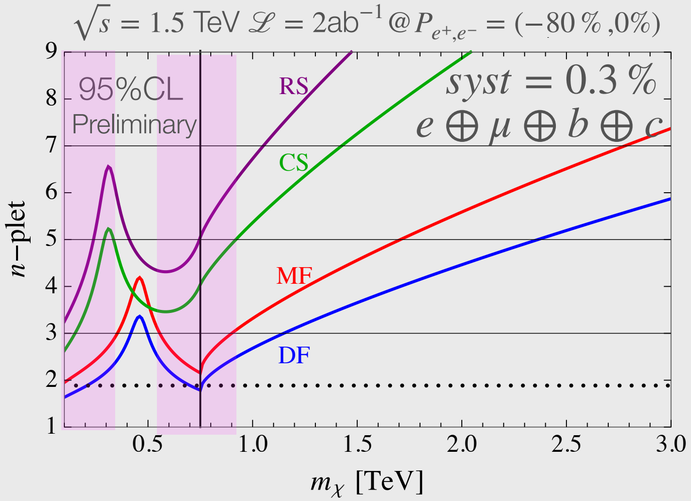

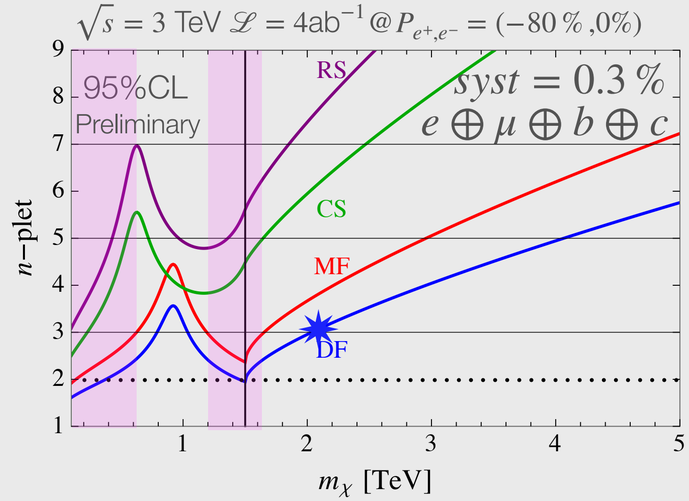

Higgsino of split-SUSY (heavy sfermions)

Wino of split-SUSY (heavy sfermions)

Accidental Dark Matter 3-plet Dirac Fermion

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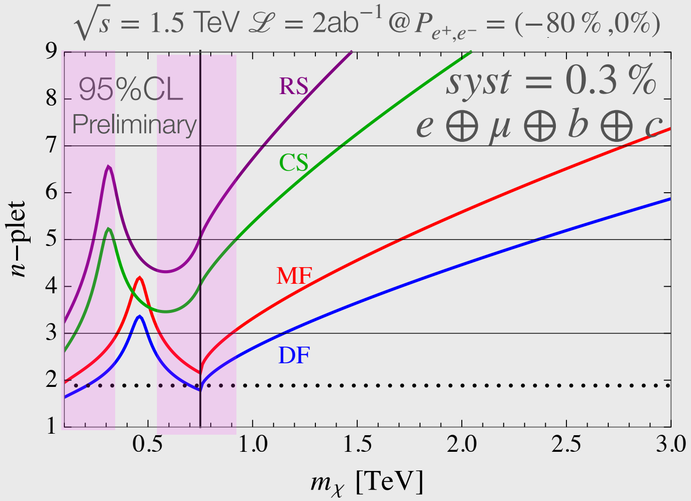

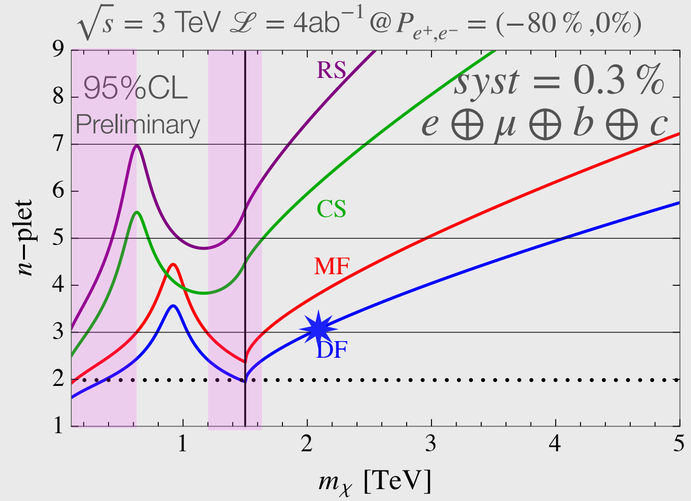

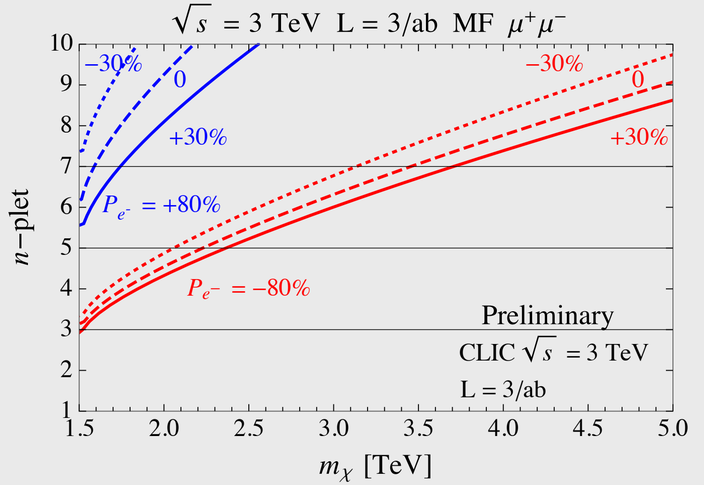

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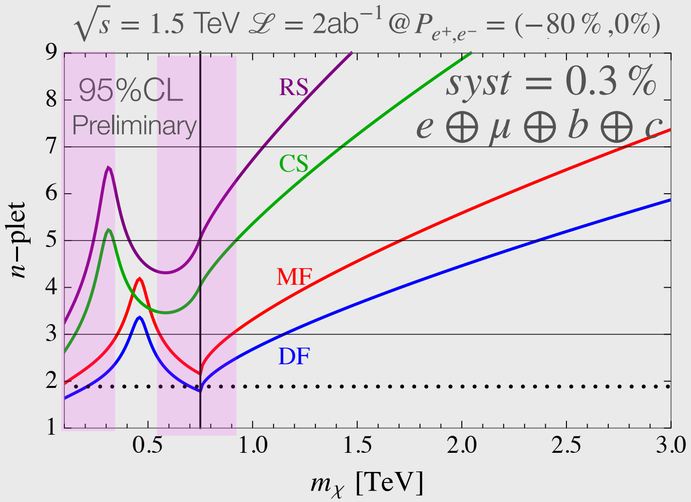

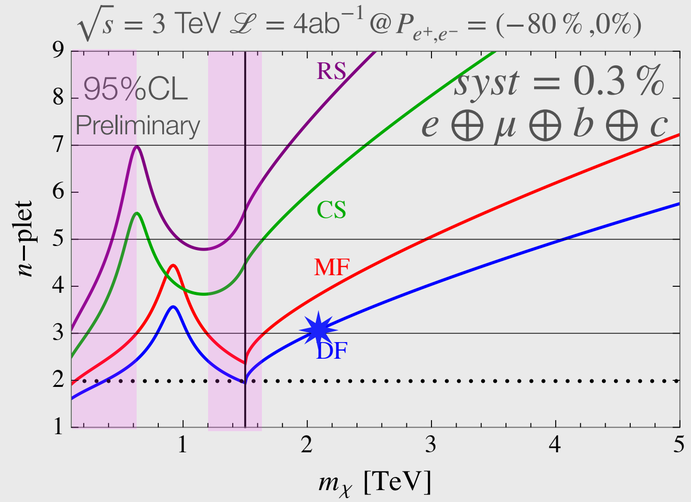

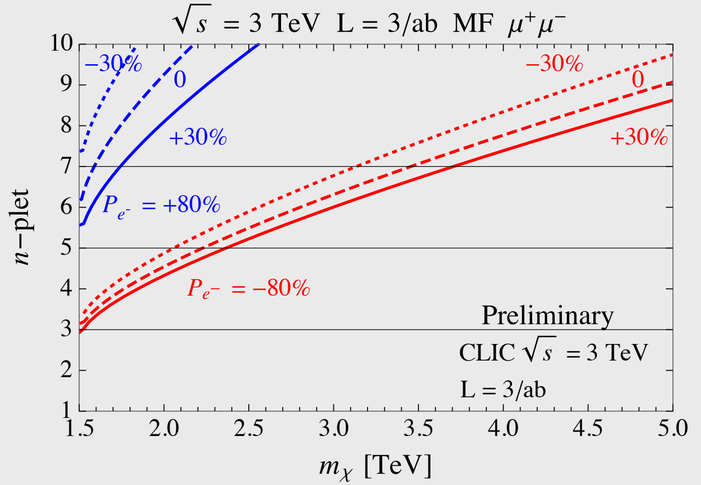

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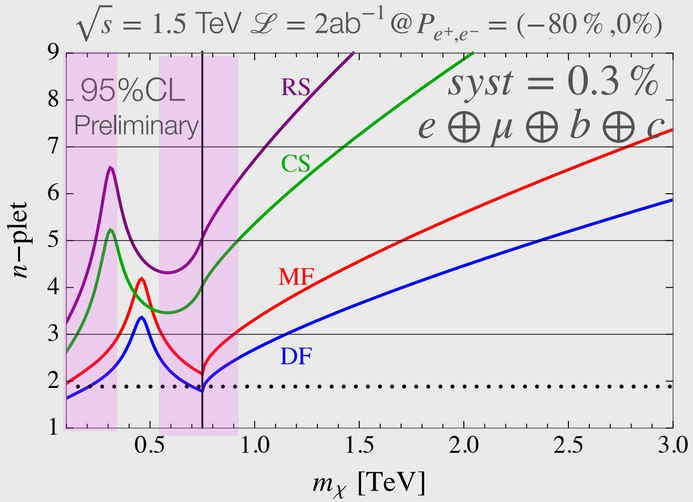

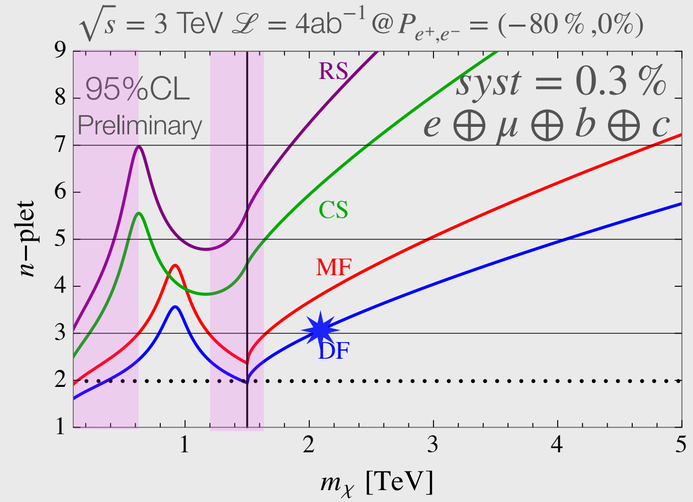

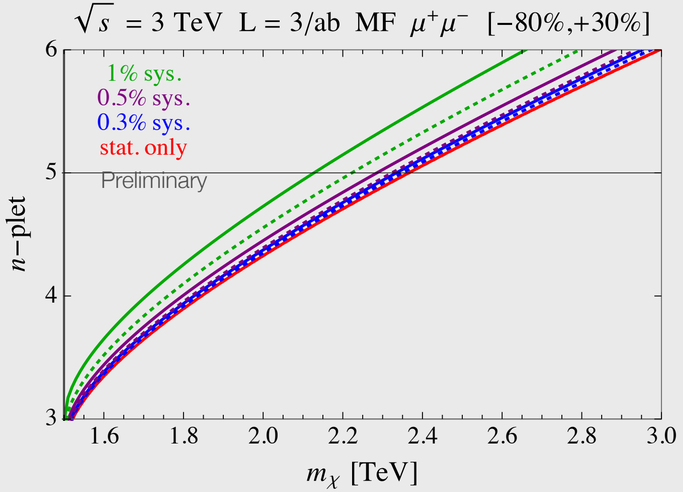

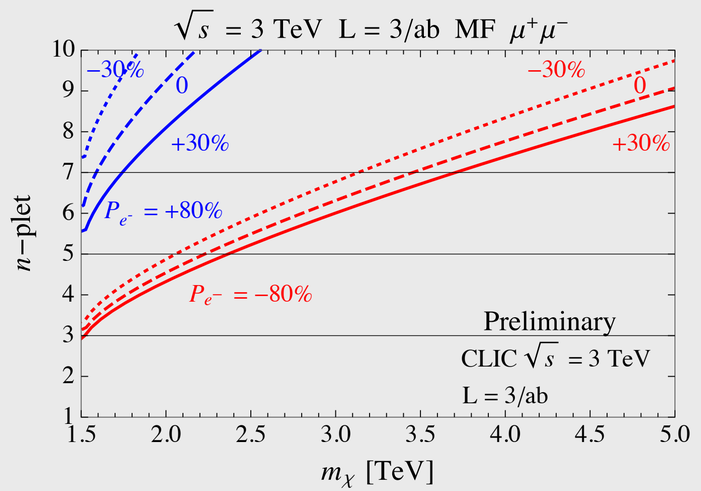

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PRECISION

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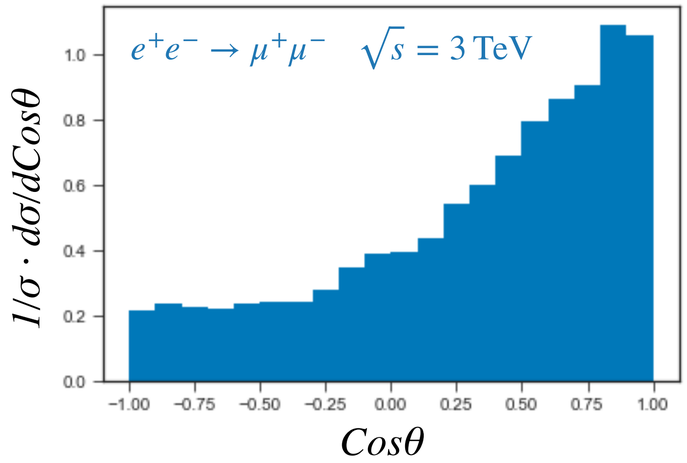
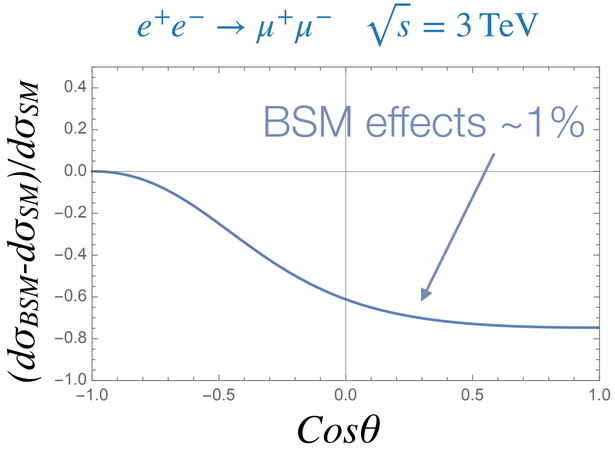
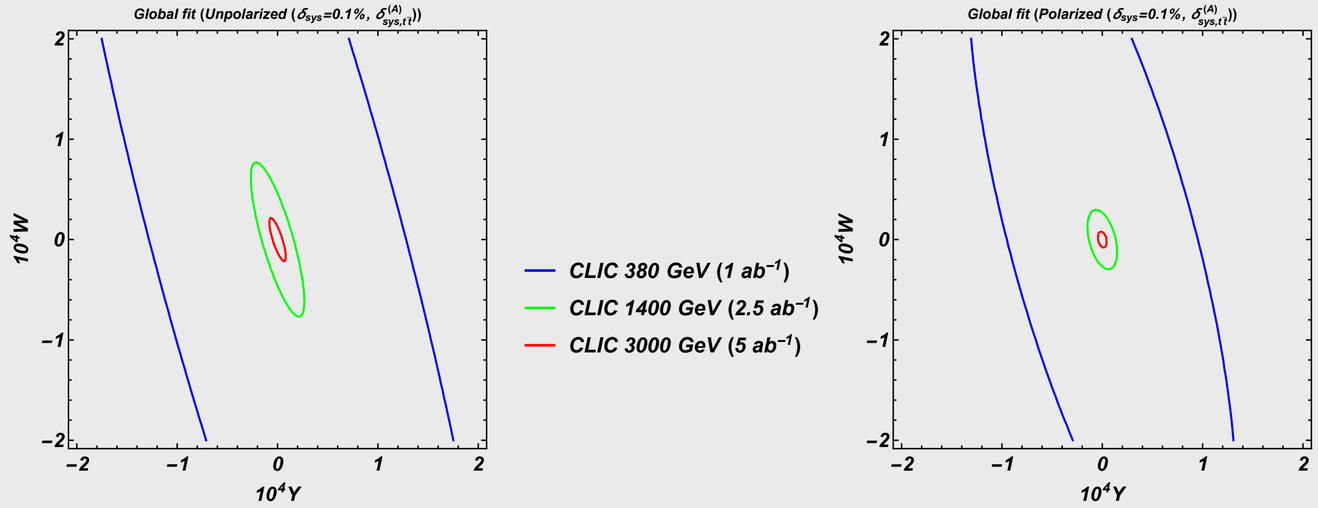
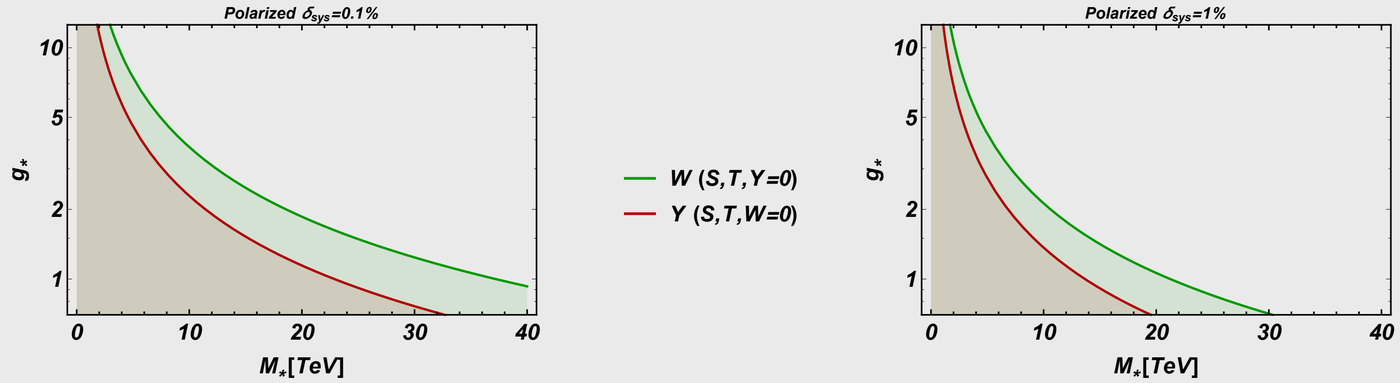






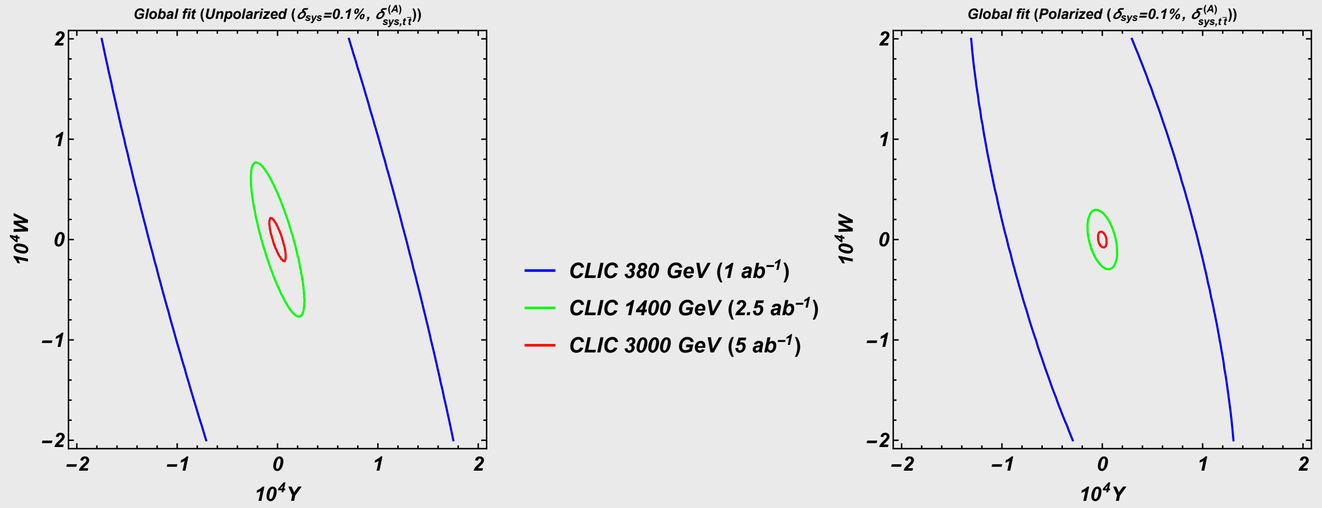
$$W = 2\frac{g^2}{g_\star^2}\frac{M_W^2}{M_\star^2}, \qquad Y = 2\frac{g'^2}{g_\star^2}\frac{M_W^2}{M_\star^2}.$$



$e^+e^- \to f\bar{f}$

PRECISION

ANGULAR DISTRIBUTION



$|cos\theta| < 0.95$ for all final states

χ^2 over 10 bins

$$\chi^2 = \sum_{i=1}^{10} \frac{\left(N_i^{\rm SM+BSM} - N_i^{\rm SM}\right)^2}{N_i^{\rm SM} + \left(\epsilon_i N_i^{\rm SM}\right)^2}$$

Systematic Unc.

$$W = 2\frac{g^2}{g_\star^2}\frac{M_W^2}{M_\star^2}, \quad Y = 2\frac{g'^2}{g_\star^2}\frac{M_W^2}{M_\star^2}.$$