UNIVERSIDA

Partic
Pheno

Universidad de
May 2023

Giovanna

Particle Physicist (Phenor
https://sites.google.com/
https://github.com/gfcott

PhD in Physics, Universit
Associate Professor, Univ
Young Researcher at SAP
LHC Long-Lived Particles Working Group, Theory co-convener, CERN

```
};
FeynmanGauge = True;


(* ************************** *)
(* *****   Change  log   ***** *)
(* ************************** *)
(* v1.1: Public release of LO model file *)
(* v2.1: Added Goldstone couplings for Feynman Gauge and NLO implementation *)
(* v2.2: Corrected relative sign between Yukawa and gauge couplings. *)

(* ************************** *)
(* *****    Parameters   ***** *)
(* ************************** *)
M$Parameters = {
    (* External Parameters *)

    VeN1 == {
        ParameterType    -> External,
    BlockName        -> NUMIXING,
        OrderBlock       -> 1,
        Value            -> 1.0,
    ComplexParameter -> False,
    TeX              -> Subscript[V,eN1],
        Description      -> "Mixing between ve flavor/gauge state and N1 mass state"
    },

    VeN2 == {
```

@CMS, CERN

Particle Phenomenology I : An introduction to the LHC and beyond

- What is it?
- How it operates?
- Why it matters?

Particle Phenomenology II: Reinterpretation and Tools

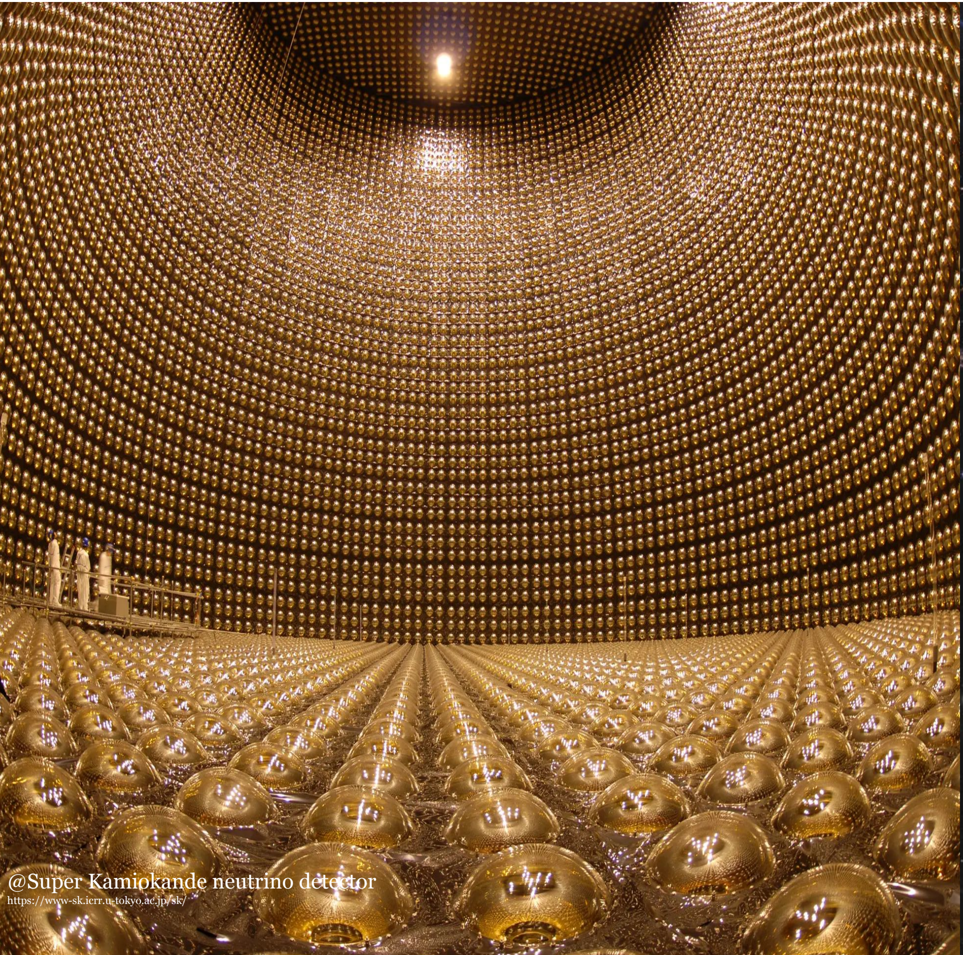
- What do particle phenomenologists do in practise?
- How we do it?
- Why should we keep doing it?

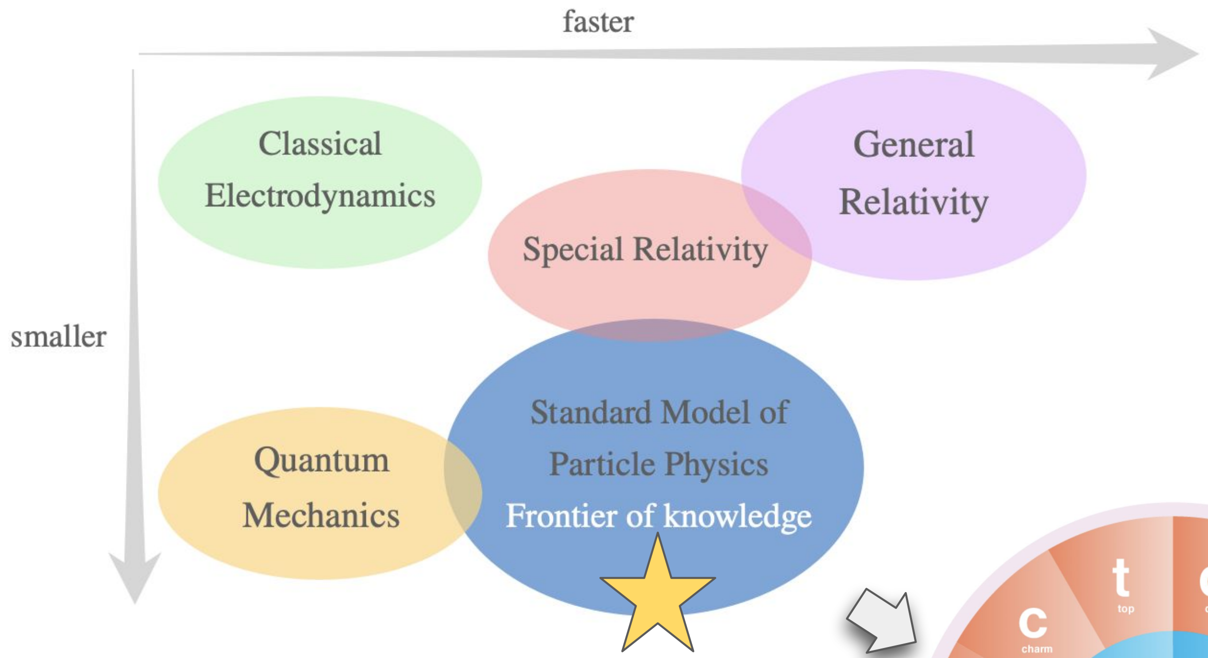
@symmetrymagazine

@ CERN postcard, visión artística del LHC y el Universo
https://visit.cern/node/614

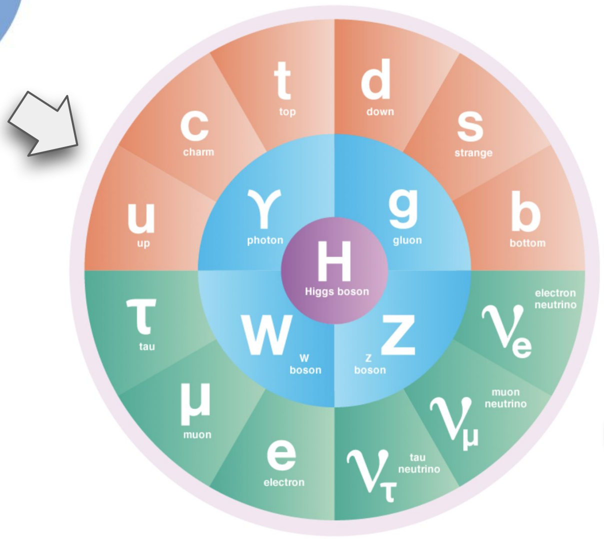
Nobel Prize 2015 to T. Kajita and A. McDonald

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

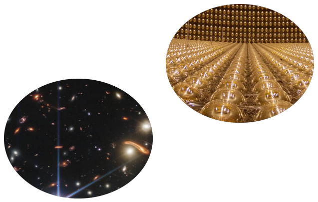




We are here



?

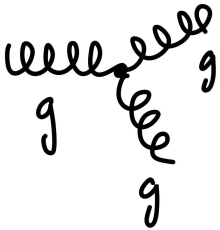


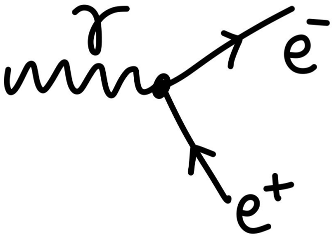
I am here with people doing *beyond* the Standard Model (BSM) particle phenomenology

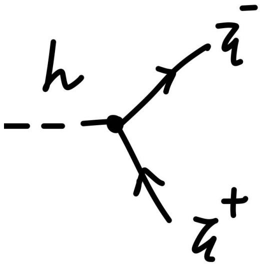
But, what we know first: Modelo Estándar de Física de Partículas

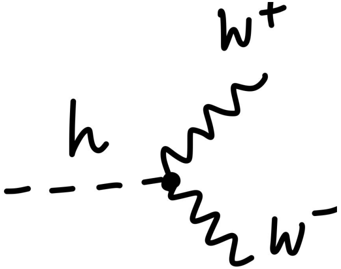
$SU(3)_C \times SU(2)_L \times U(1)_Y$

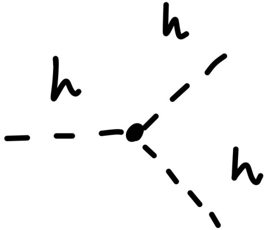
$$\mathcal{L} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Partículas de fuerza (BOSONES)}} + \underbrace{i\bar{\psi}\not{D}\psi}_{\text{Partículas de materia (FERMIONES)}} + \underbrace{\bar{\psi}\, y_{ij}\, \psi_j\, \phi}_{\text{Masa de Partículas}} + \underbrace{|D_\mu \phi|^2 - V(\phi)}_{\text{Campo de Higgs}} + h.c.$$











El Universo lo entendemos a distintas escalas. ¿Qué podemos *medir*?

Teorías

Relatividad General

Cuerpos masi
interactúan e
espacio-tiemp
mediante la f
gravedad
Podemos medir:
Espacio
Tiempo
Curvatura
Masa/Energía (
Luz
Ondas Gravitacionales

Modelo Estándar de Partículas Elementales

Podemos medir sus propiedades:
Masa/Energía
Carga eléctrica (y otros de sus números cuánticos)

frecuente)

Algunas Interrogantes Abiertas motivan Nuevas Teorías

s de neutrinos,
gía y Materia
Oscura Nuevas
Fuerzas?
Nuevas Partículas
Elementales?

puestas a prueba

en Experimentos

Phenomenology

Theory

Experiment

Particle Phenomenology: From Theory to Experiment

1) Motivation

Dark Matter
Baryogenesis
Neutrino Masses
Anomaly explanations

2) Theory Models

SUSY Multiple NP with SM gauge charges (RPV, split SUSY)
Higgs Portal NP predominantly coupled to the Higgs (Hidden Valley)
Gauge Portal New vector mediators can produce NP (Z', dark photon)
Dark Matter Non SUSY, hidden sector DM produced as final state at colliders (EWK Multiplets, FIMP, SIMPs)
RH Neutrinos RHnu masses in the GeV to TeV range (SM+N, Left-Right Symmetry)

3) Phenomenology

Search strategies
Identify signatures
Model reinterpretation

4) Experiment

Implement and reconstruct those signatures
Hunt them in the Data
Experimental results

Particle Phenomenology: From Theory to Experiment

1) Motivation
Dark Matter
Baryogenesis
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2) Theory Models
SUSY Multiple NP with SM gauge charges (RPV, split SUSY)
Higgs Portal NP predominantly coupled to the Higgs (Hidd
Gauge Portal New vector mediators can produce NP (Z', da
Dark Matter Non SUSY, hidden sector DM produced as fin… …IPs)
RH Neutrinos RHnu masses in the GeV to TeV range (SM

Focus is LHC in these lectures

3) Phenomenology
Search strategies
Identify signatures
Model reinterpretation

4) Experiment
Implement and reconstruct those signatures
Hunt them in the Data
Experimental results

CERN

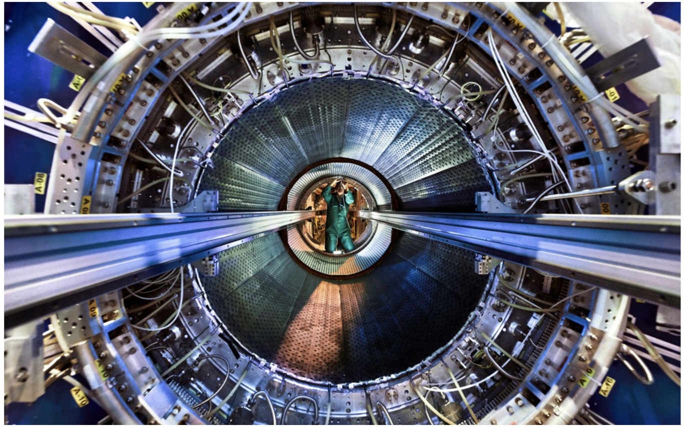
News › News › Topic: Accelerators

Voir en français

Large Hadron Collider restarts

Beams of protons are again circulating around the collider's 27-kilometre ring, marking the end of a multiple-year hiatus for upgrade work

22 APRIL, 2022



NEWS FEATURE | 25 May 2022

How the revamped Large Hadron Collider will hunt for new physics

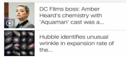
The particle-smashing machine has fired up again — sparking fresh hope it can find unusual results.

Elizabeth Gibney

World Africa Americas Asia Australia More Audio

Scientists restart Large Hadron Collider in quest for dark matter

By Sara Spary, CNN
Updated 1304 GMT (2104 HKT) April 22, 2022



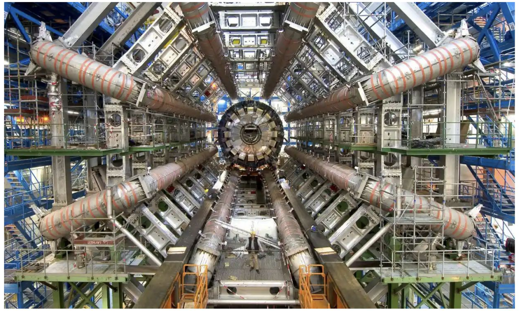
More From CNN

DC Films boss: Amber Heard's chemistry with 'Aquaman' cast was a...

Hubble identifies unusual wrinkle in expansion rate of the...

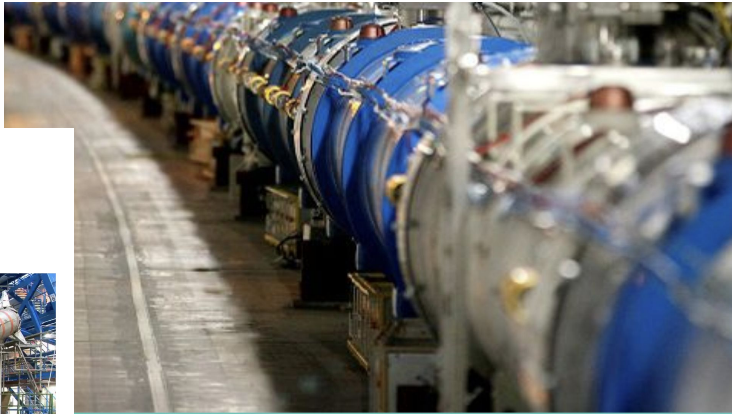
Large Hadron Collider to restart and hunt for a fifth force of nature

Latest run is expected to scrutinise findings from last year that may turn into another blockbuster discovery



The Large Hadron Collider has been given an upgrade ahead of its latest run, including the addition of powerful magnets designed to squeeze protons into finer, denser beams. Photograph: Cern/PA

The Large Hadron Collider (LHC) will restart on Friday after a three-year hiatus and is expected to resolve a scientific cliffhanger on whether a mysterious anomaly could point to the existence of a fifth fundamental force of nature.



Giovanna Cottin*
26 ABR 2022 01:57 PM
Tiempo de lectura: 3 minutos

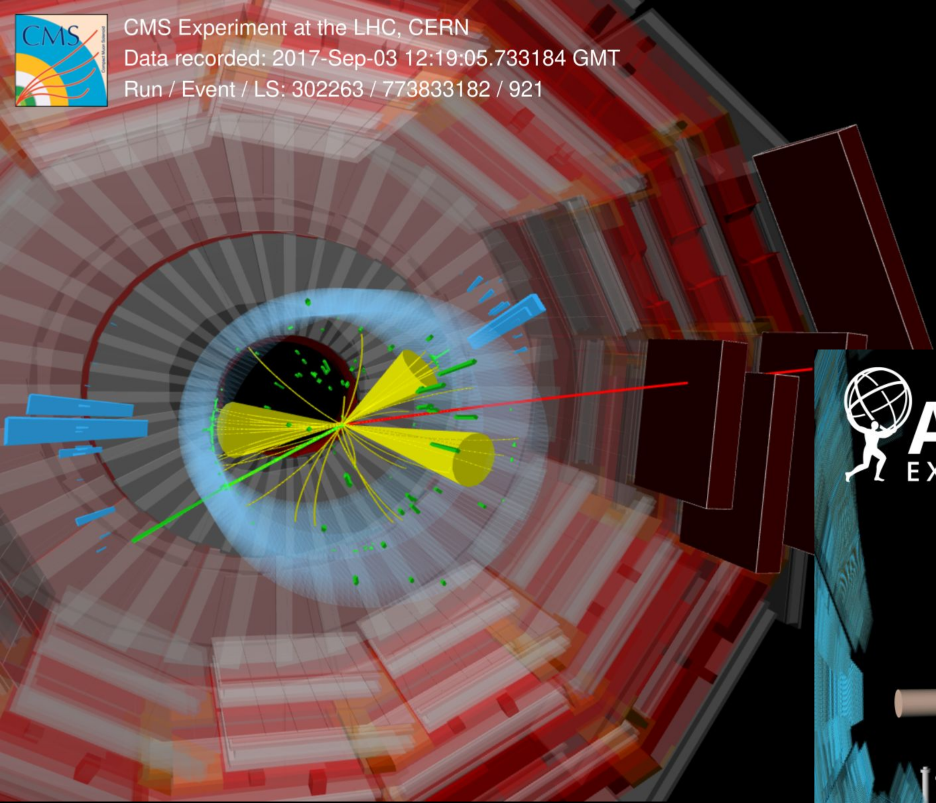
El esperado reinicio del Gran Colisionador de Hadrones

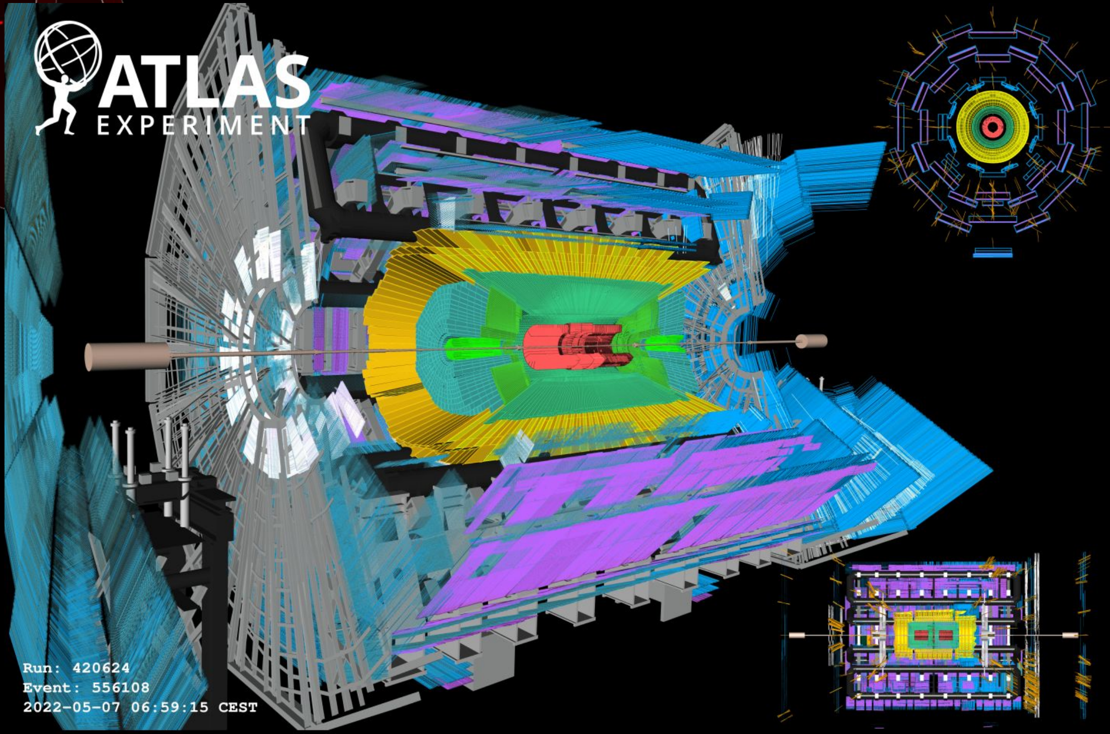
QUÉ PASA Opinión Física

CERN video on LHC restart : https://www.youtube.com/watch?v=J5WYR017Lls
CERN News : https://home.cern/news/news/accelerators/large-hadron-collider-restarts
Nature : https://www.nature.com/articles/d41586-022-01388-6
The Guardian UK: https://www.theguardian.com/science/2022/apr/21/large-hadron-collider-restart-fifth-force-nature
G. Cottin @QuePasa: https://www.latercera.com/que-pasa/noticia/el-esperado-reinicio-del-gran-colisionador-de-hadrones/


LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km
@CERN


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
27 km
@CERN
CERN
www.cern.ch
Accelerating Science



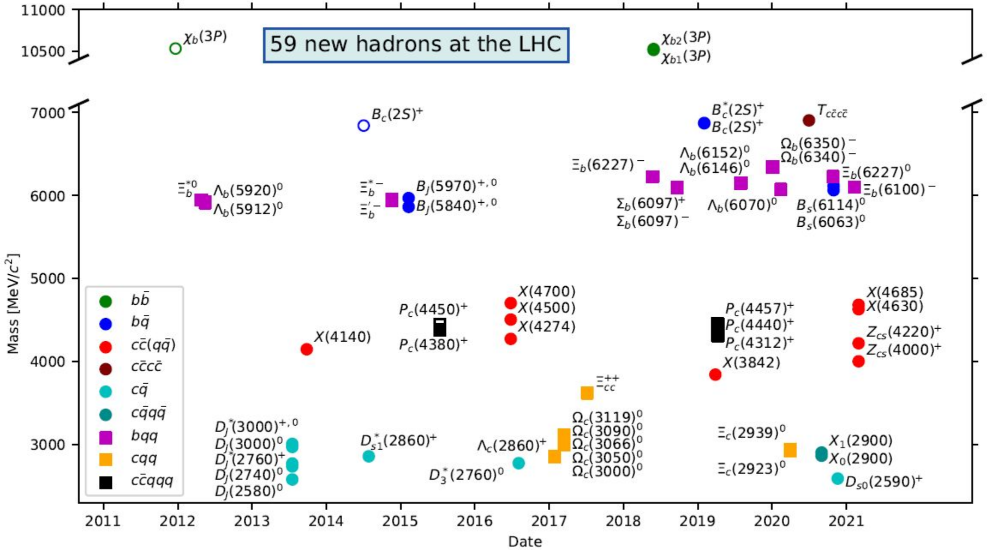


CERN Document Server: https://cds.cern.ch/
CMS-PHO-EVENTS-2022-002
ATLAS-PHOTO-2022-028

New particles can manifest at many HEP experiments, at the LHC and beyond

The LHC was built with the goal to find them !

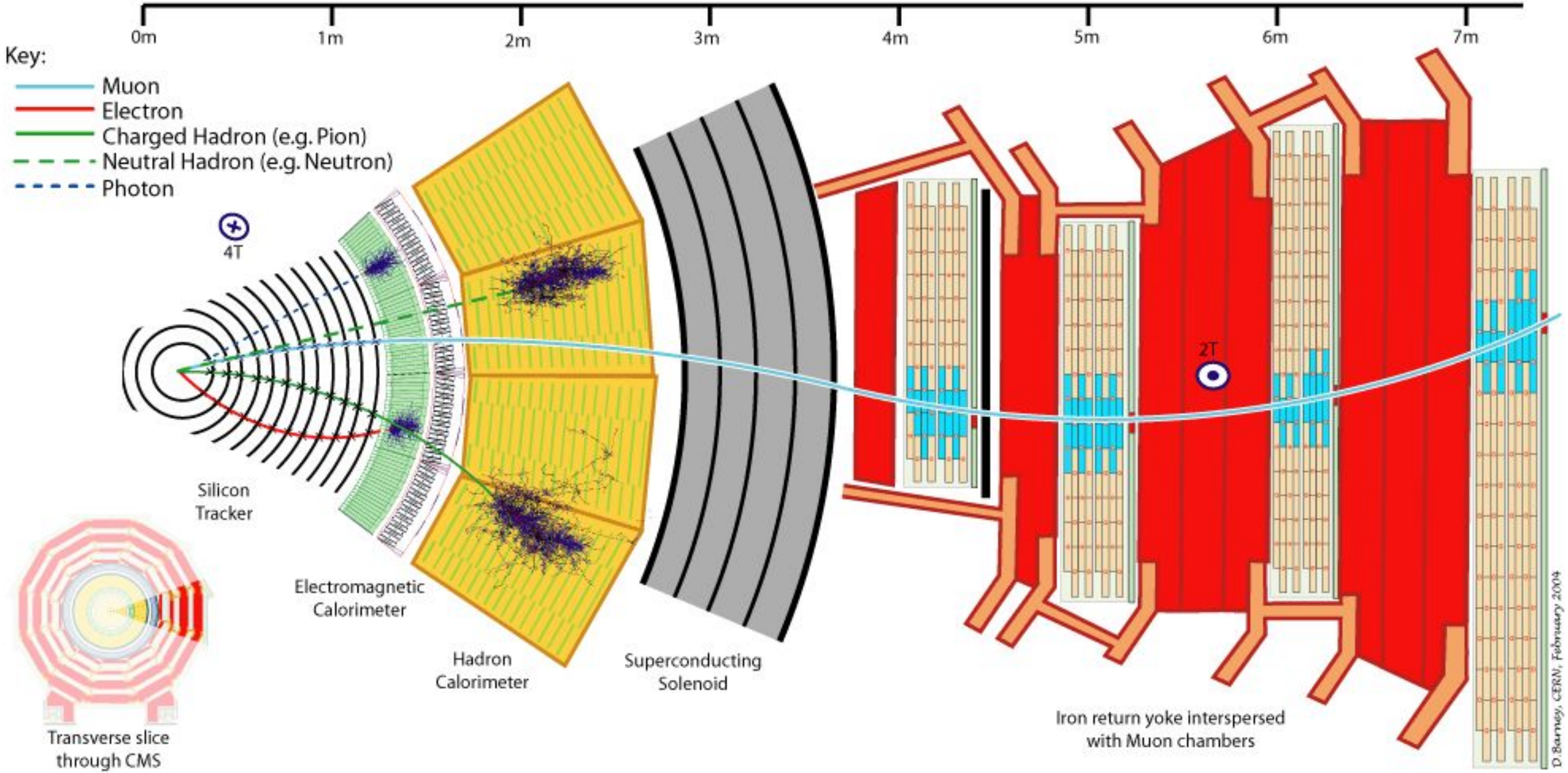
Nobel Prize 2013 to F. Englert and P. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*



@https://home.cern/news/news/physics/59-new-hadrons-and-counting

"A machine built for the pursuit of pure knowledge", quote from *Nobel Dreams* by Gary Taubes

How can we measure those manifestations at LHC experiments?

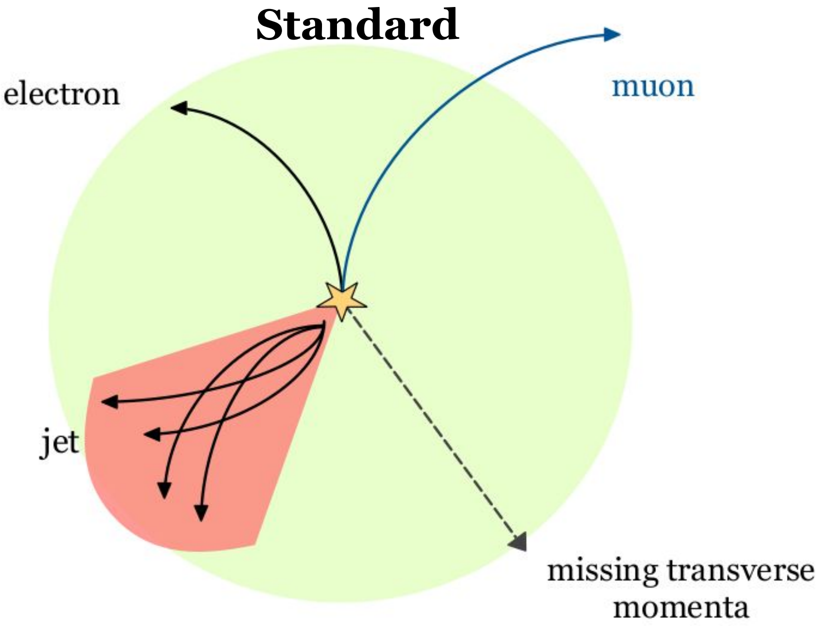


@CMS, CERN

We can construct different observables

Depending on *where* the particle decays and which quantum numbers it has, this will give rise to different signatures inside LHC detectors

A Long-Lived Particle is considered as such decaying from a few microns to several meters (depending on the detector)



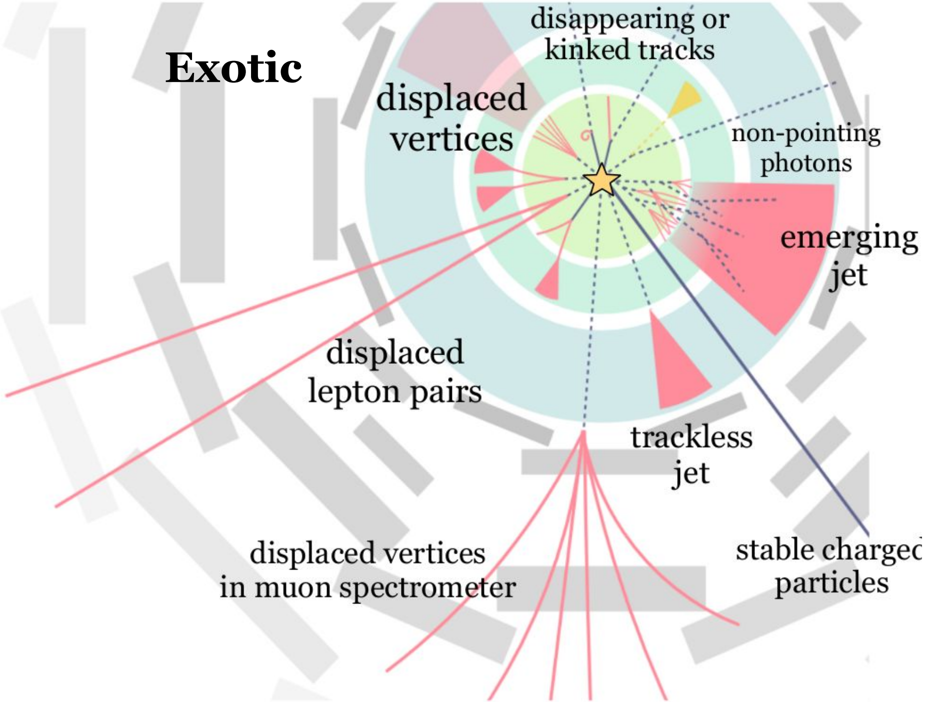


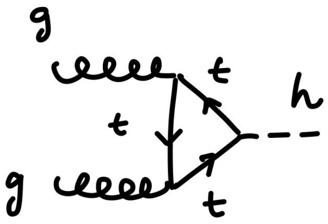
Image by G. Cottin

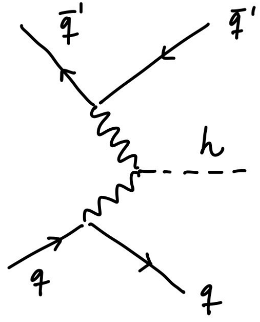
LLP Image adapted from Heather Russel.

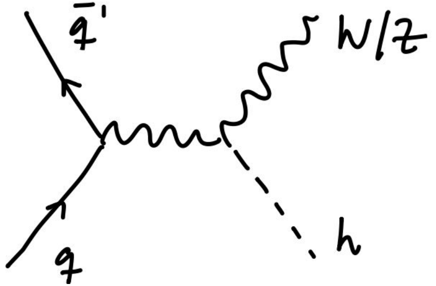
Long-lived Particle Community White Paper, J. Alimena, .. , **G. Cottin**, et al, J.Phys.G 47 (2020) 9, 090501

Un caso real: midiendo el Bosón de Higgs

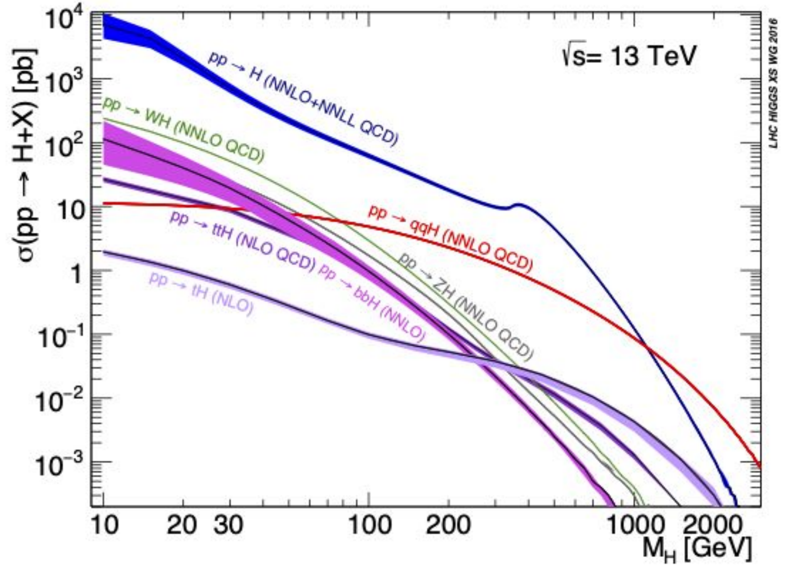
Production





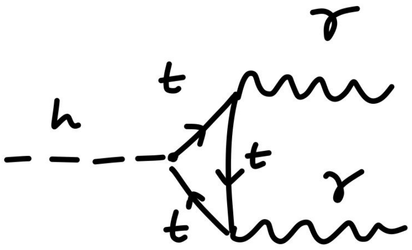


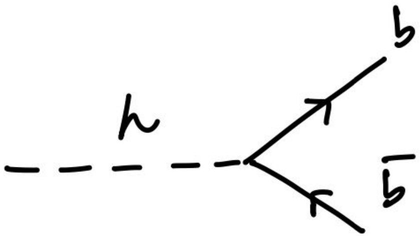
En el LHC se seleccionan los eventos con el Trigger (i.e Vector Boson Fusion, requiring at least two jets with pT > X GeV)



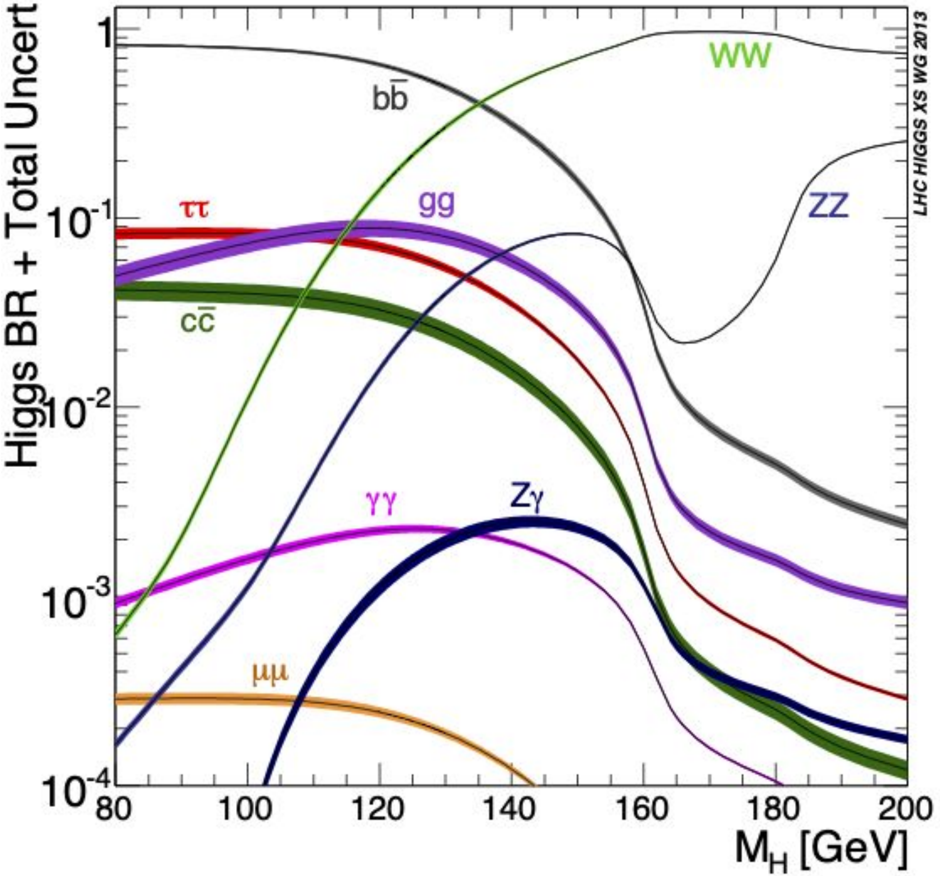
@LHC Higgs Working Group
https://twiki.cern.ch/twiki/bin/view/LHCPhysics

Decay



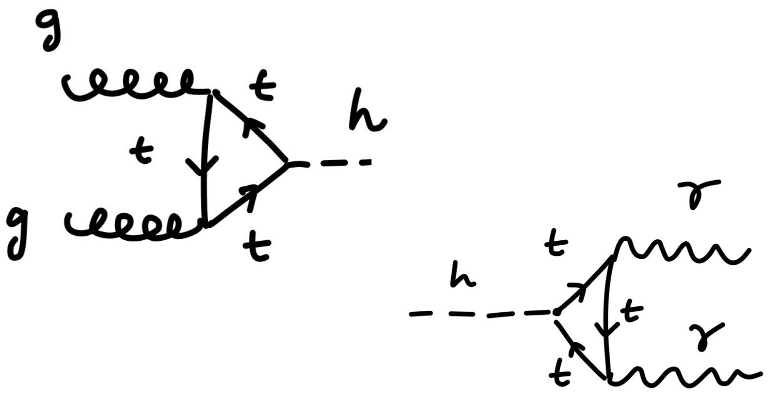


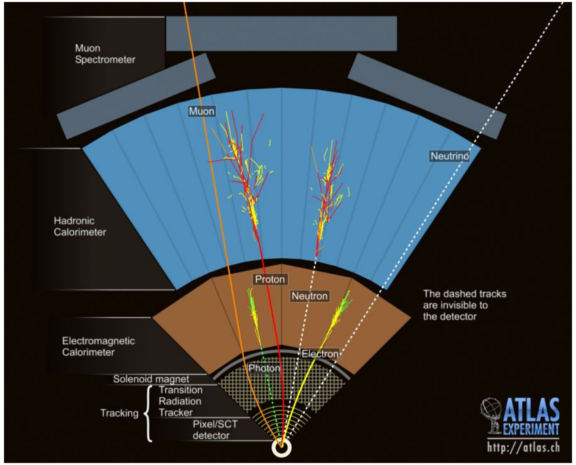
Luego de producir un Higgs detectamos sus decaimientos (i.e reconstruimos los fotones, leptones (del Z decay) o “jets”)

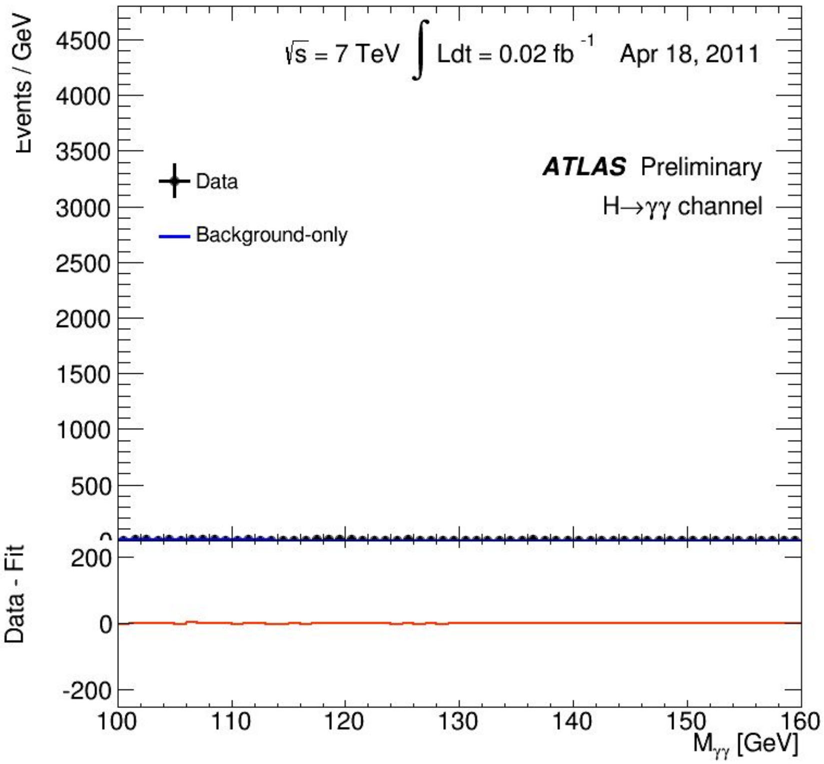


@LHC Higgs Working Group
https://twiki.cern.ch/twiki/bin/view/LHCPhysics

Juntando todo, se mide el Bosón de Higgs





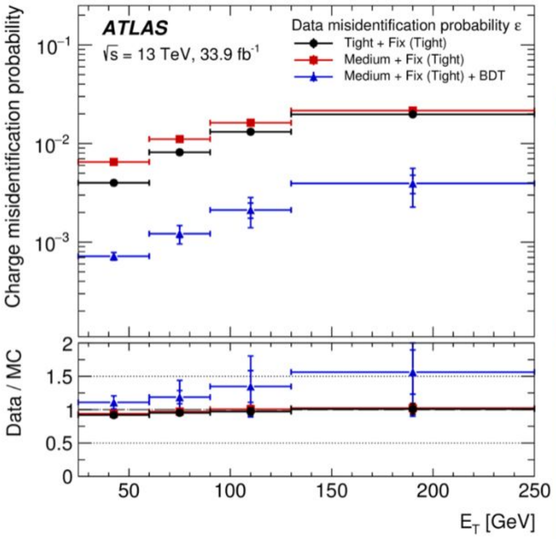


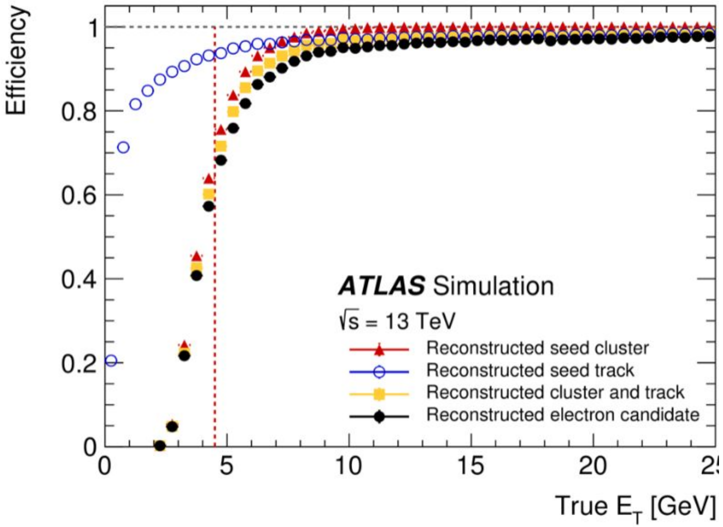
https://cds.cern.ch/record/2230893?ln=es

So, what is an electron? (i.e. or any other particle)

For Experimentalists:

EPJC 79, 639 (2019)





For Theorists/Phenomenologists:

$$i\bar{\Psi}\gamma^{\mu}D_{\mu}\Psi - m_{\psi}\bar{\Psi}\psi + \ldots$$

Necesitamos simular la respuesta experimental !


```
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      11 -1    0    0    0    0 +0.0000000000e+00 +0.0000000000e+00 +1.5000000000e+03 1.5000000000e+03 5.1099890000e-04 0.0000e+00 -1.0000e+00
     -11 -1    0    0    0    0 -0.0000000000e+00 -0.0000000000e+00 -1.5000000000e+03 1.5000000000e+03 5.1099890000e-04 0.0000e+00 1.0000e+00
    1012  1    1    2    0    0 -7.2980127368e+02 -5.9445443626e+02 -1.0790851259e+03 1.5000000000e+03 4.4675420000e+02 7.6553e-01 -1.0000e+00
    1012  1    1    2    0    0 +7.2980127368e+02 +5.9445443626e+02 +1.0790851259e+03 1.5000000000e+03 4.4675420000e+02 6.7074e-01 1.0000e+00
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<pdfrwt beam="2">  1      -11 0.10000000E+01 0.15000000E+04</pdfrwt>
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LES HOUCHES accord i.e. J. Butterworth et al https://arxiv.org/pdf/1003.1643.pdf

Theory meets Reality

Many theory models predicting new particles addressing

Neutrino Masses
Dark Matter
Baryogenesis
Anomaly explanations ...

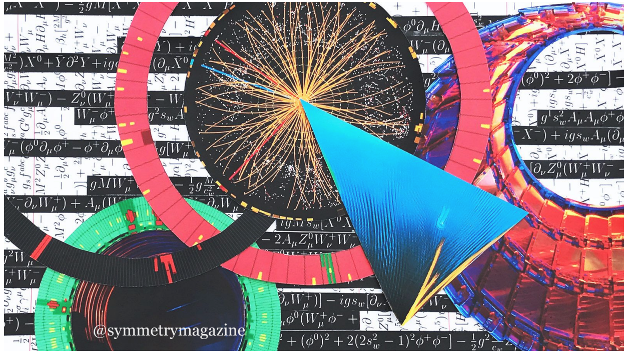
Not always being looked for @ High Ener
Physics experiments

- Not optimal analysis strategy within experiments nor standard definition of particle observables
- Lack of person power/time/resources
- No optimal experiment for your model or not even an existing detector able to catch your hypothetical particles

Particle Phenomenologists are needed !

to make testable theoretical predictions at experiments (we need to understand both the theory and - how to simulate - the experiment)

A phenomenologist path



Characterization of BSM Physics ⟺ Usage/Design ⟺ Evaluate Experimental Response

Characterization of BSM Physics

- Model building
- Identify production modes
- Identify decay patterns
- Hard Code your model (i.e. dedicated software as FeynRules/SARAH/SPHENO)

Usage/Design

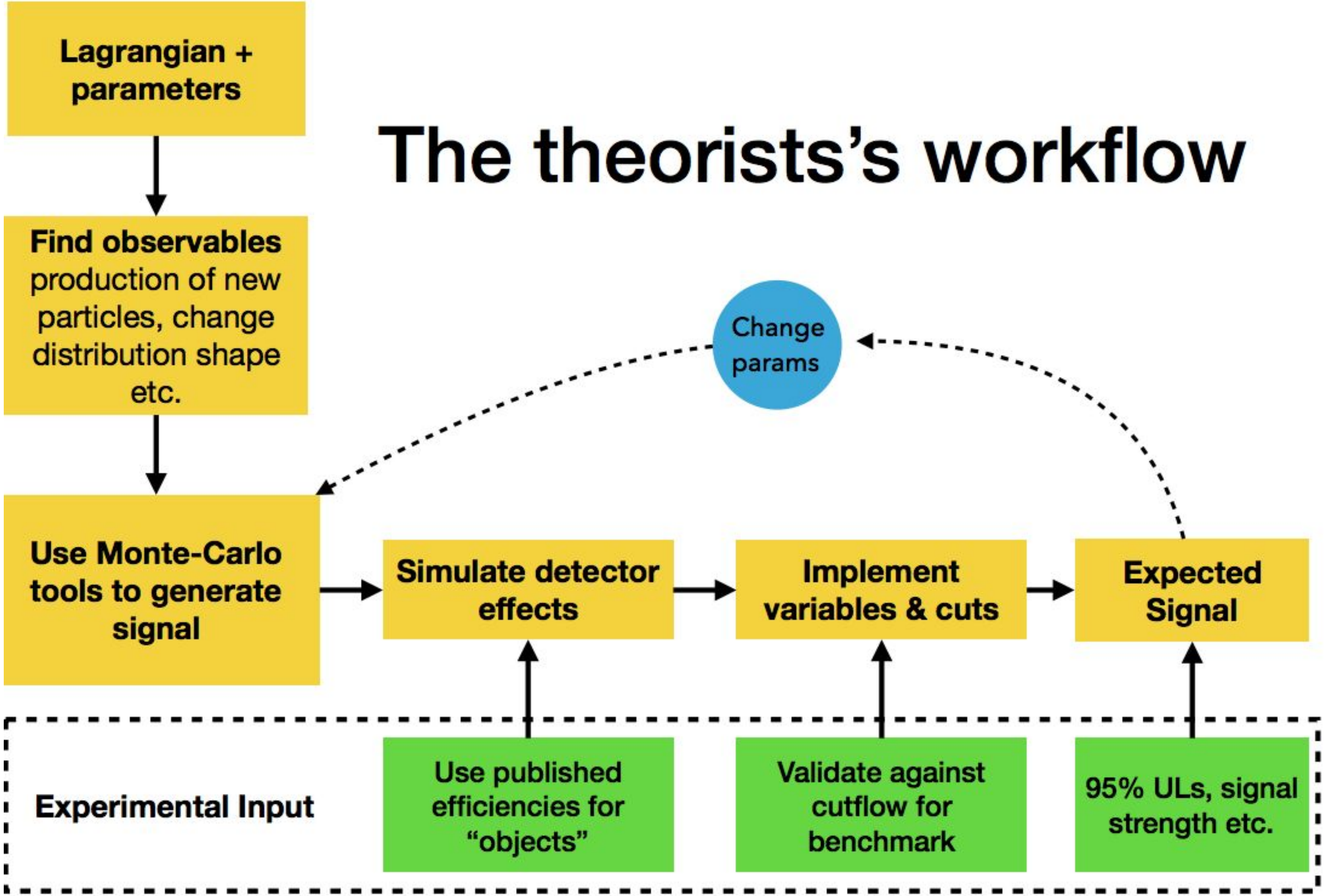
- Identify Software (i.e. Monte Carlo as Madgraph, Pythia, Herwig ...)
- Design/Implement Observables (i.e. invariant mass, displaced vertex, jets)
- Hard Code your strategy/analysis (i.e. can use standard software as MadAnalysis, Rivet or your own)

Evaluate Experimental Response

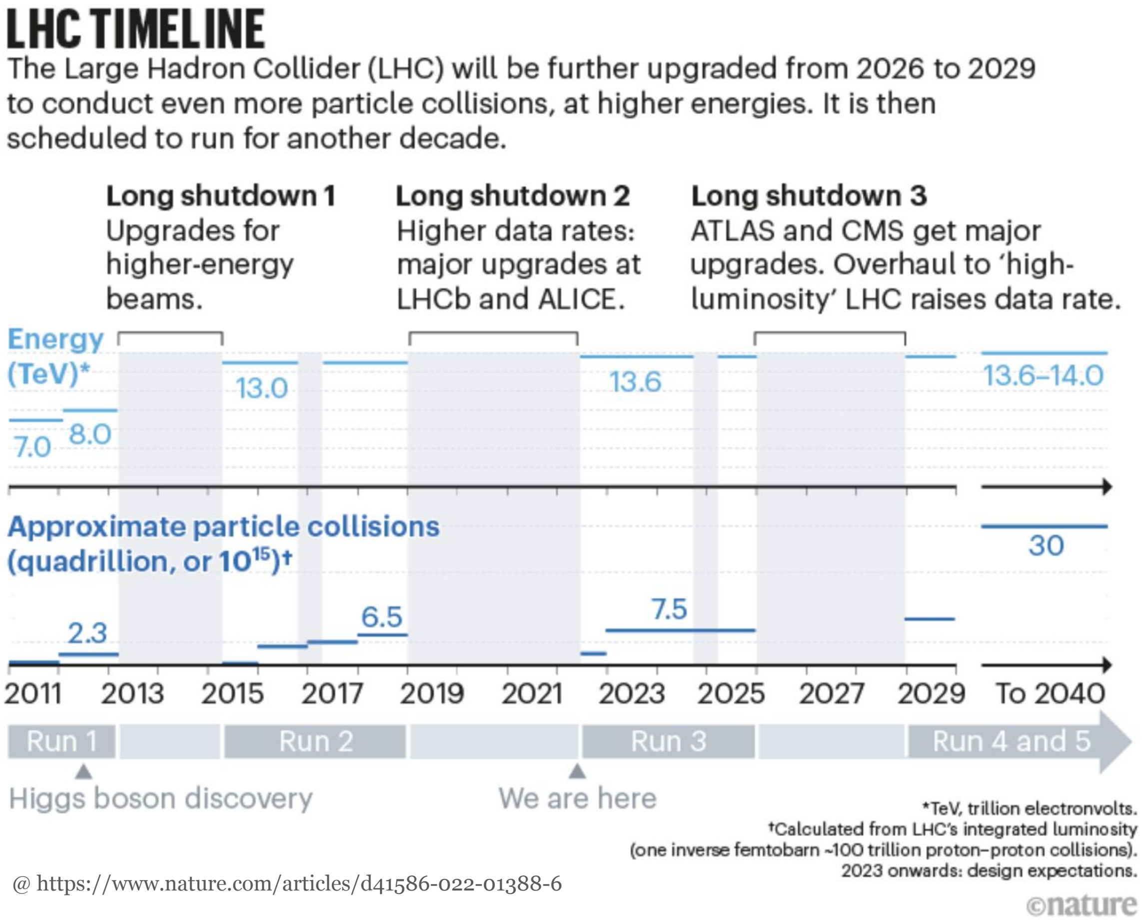
- Detector Simulation (i.e. software as DELPHEs or custom made to your analysis needs)
- Identify experimental information/efficiencies to characterize response to your objects and observables (i.e. Can use open data/HEPData)

In detail

Slide from Nishita Desai @ LLP Workshop, CERN

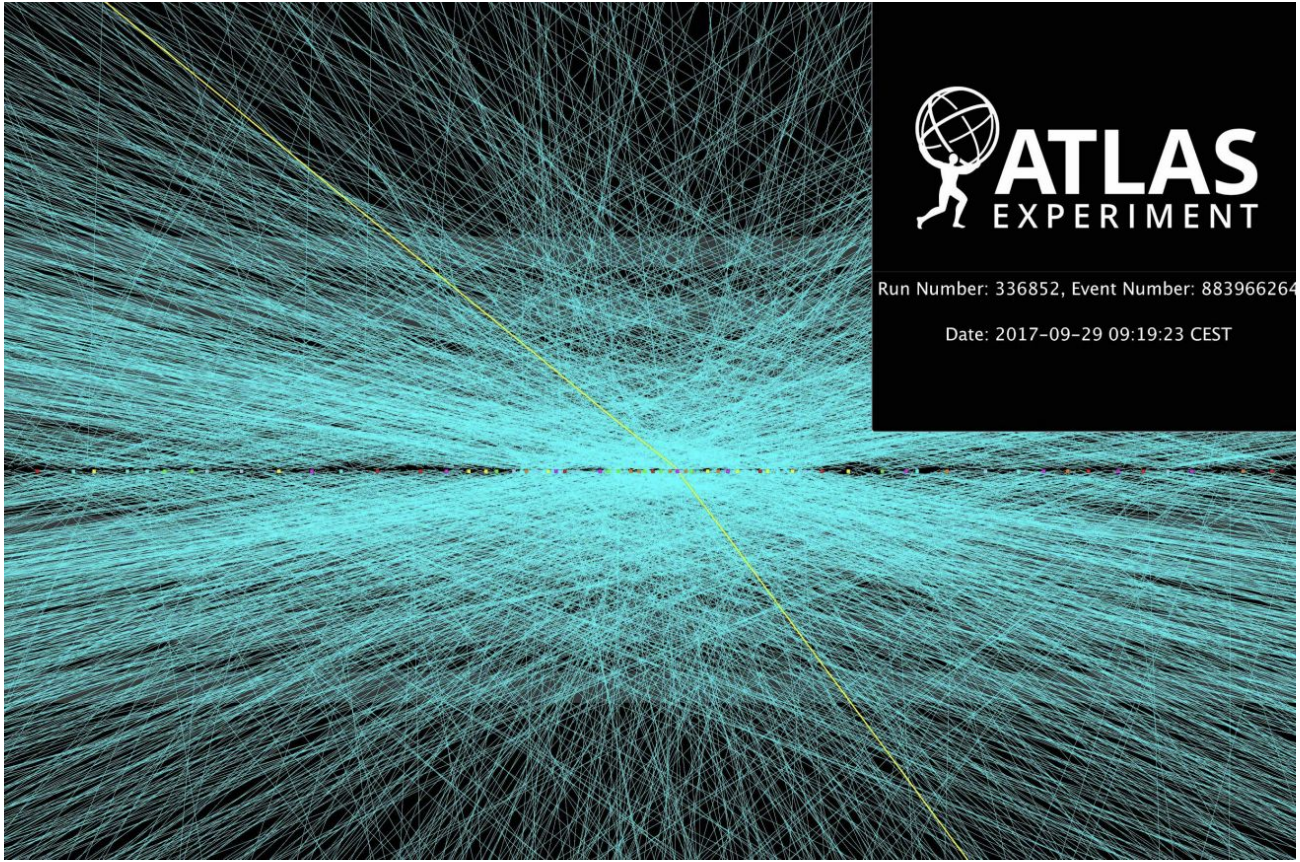


The LHC will run for the next ~20 years



@ https://www.nature.com/articles/d41586-022-01388-6

… looking like this …we don't want to miss the new physics we know must be around !



Next lecture

Concrete examples of the Workflow/Path destacando limitaciones actuales (i.e. opportunities !)

@symmetrymagazine

UNIVERSIDAD ADOLFO IBÁÑEZ

Fondecyt
Fondo Nacional de Desarrollo Científico y Tecnológico

Agencia Nacional de Investigación y Desarrollo
Ministerio de Ciencia, Tecnología, Conocimiento e Innovación
Gobierno de Chile

With support from Fondecyt 11220237

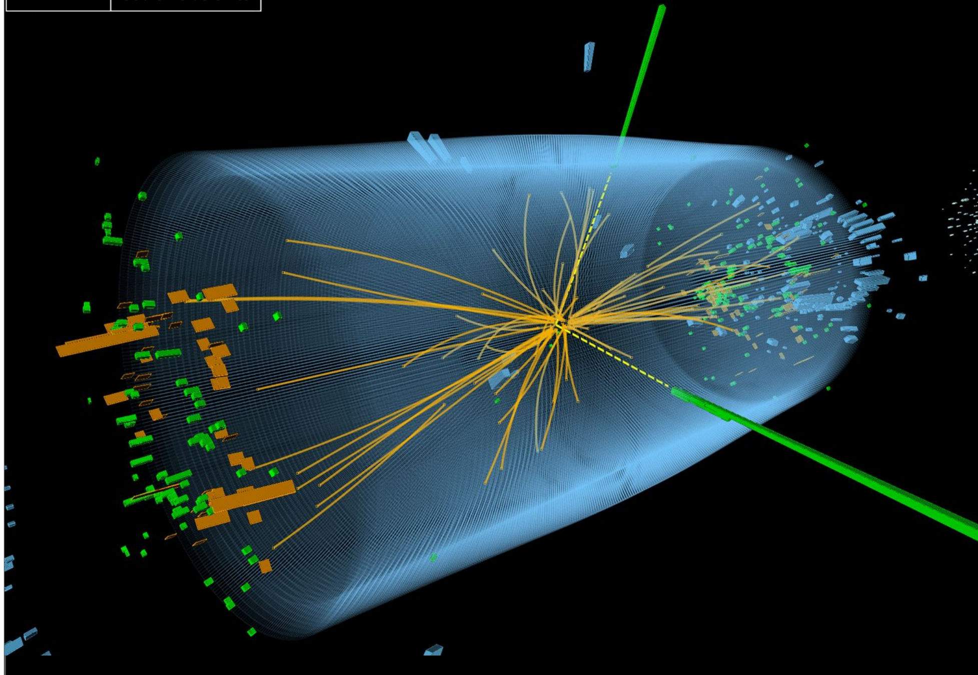
Particle Phenomenology

Universidad de Concepción, Chile
May 2023

Giovanna Cottin

Particle Physicist (Phenomenologist)
https://sites.google.com/view/giovannacottinburacchio/
https://github.com/gfcottin/CursoParticlePhenomenology

PhD in Physics, University of Cambridge, UK
Associate Professor, Universidad Adolfo Ibáñez, Santiago, Chile
Young Researcher at SAPHIR Millennium Institute, Chile
LHC Long-Lived Particles Working Group, Theory co-convener, CERN



@CMS, CERN

Particle Phenomenology I : An introduction to the LHC and beyond

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Particle Phenomenology II: Reinterpretation and Tools

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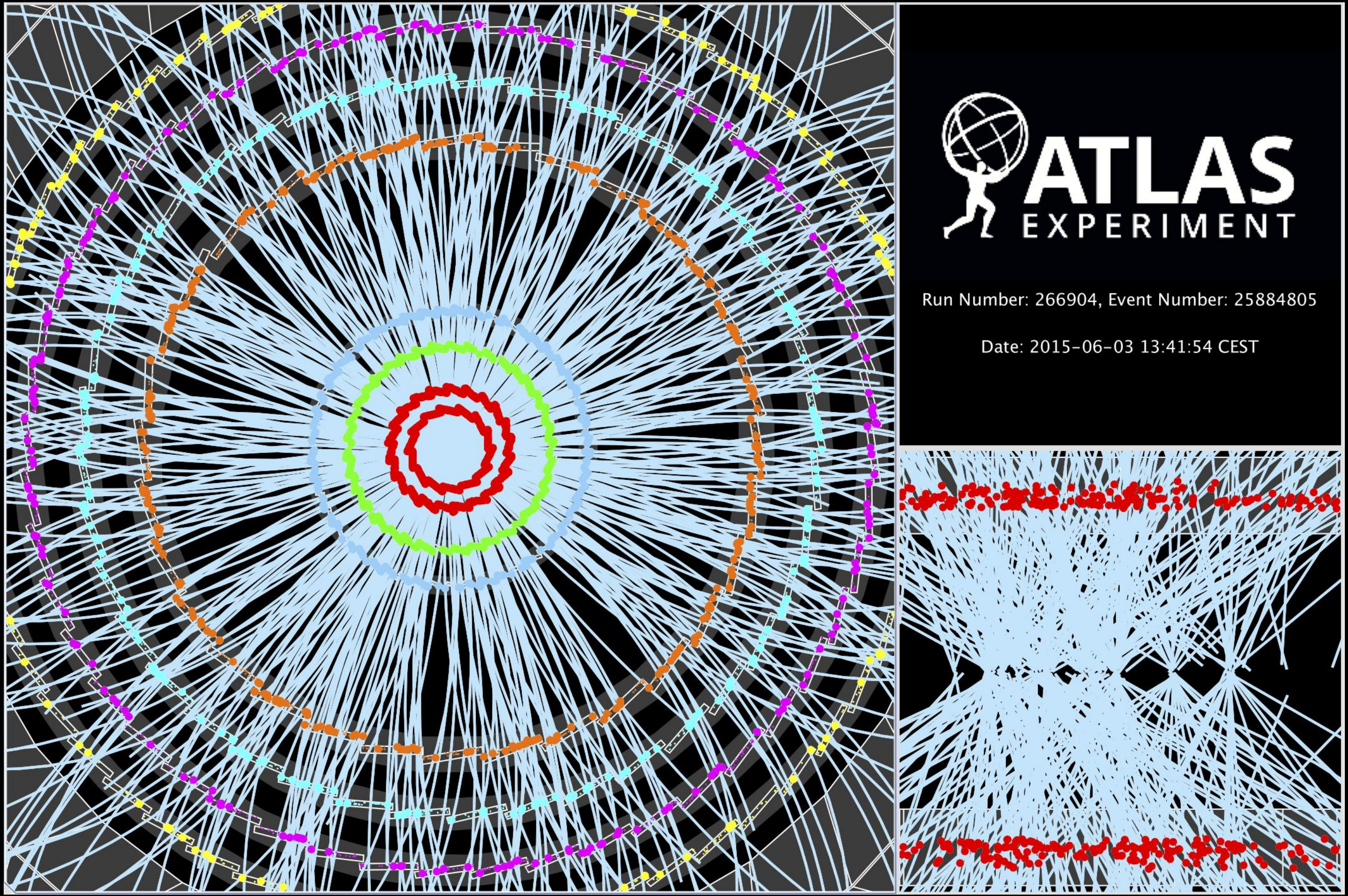
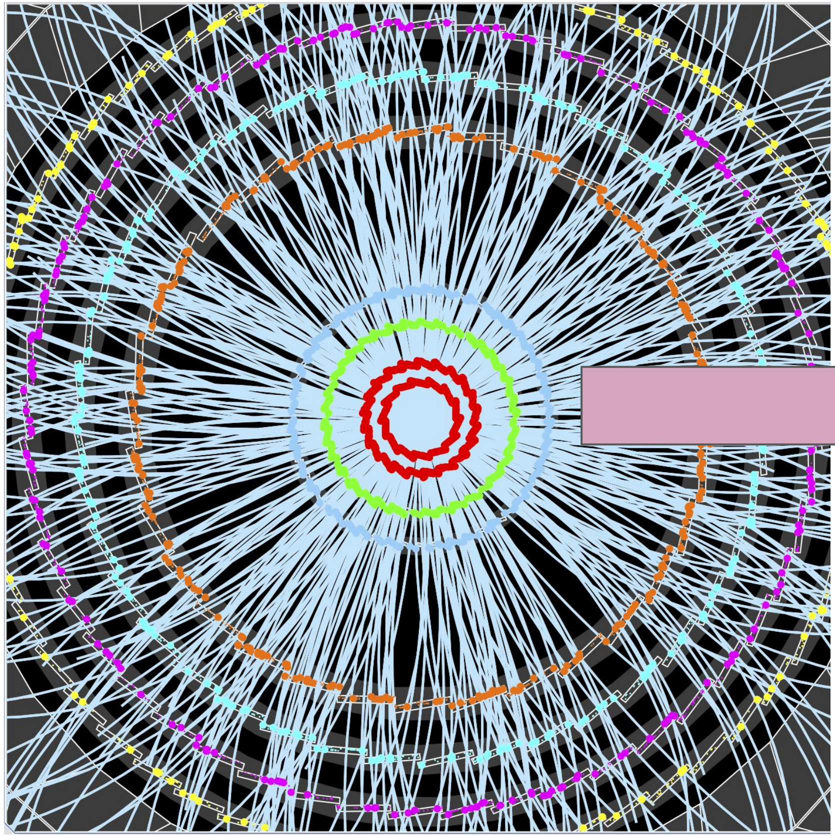
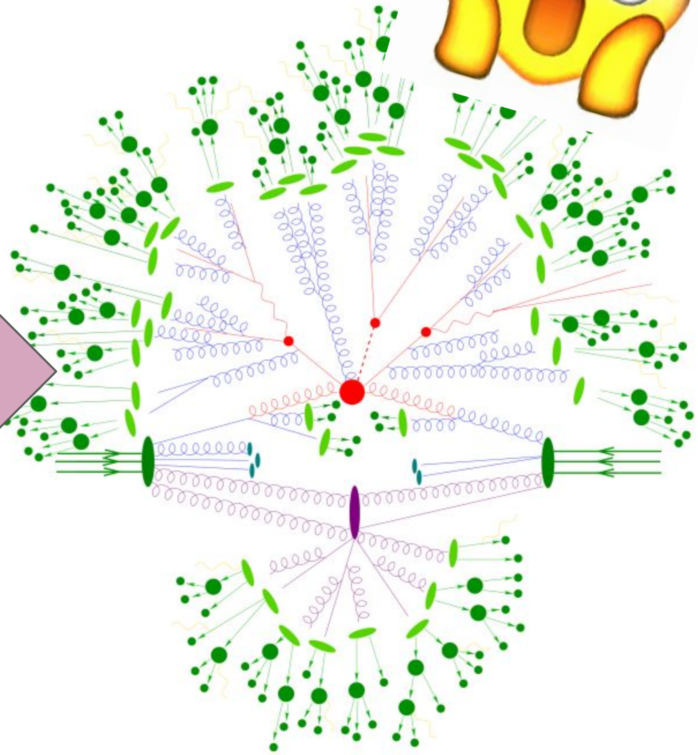
@symmetrymagazine


ATLAS
EXPERIMENT
Run Number: 266904, Event Number: 25884805
Date: 2015-06-03 13:41:54 CEST

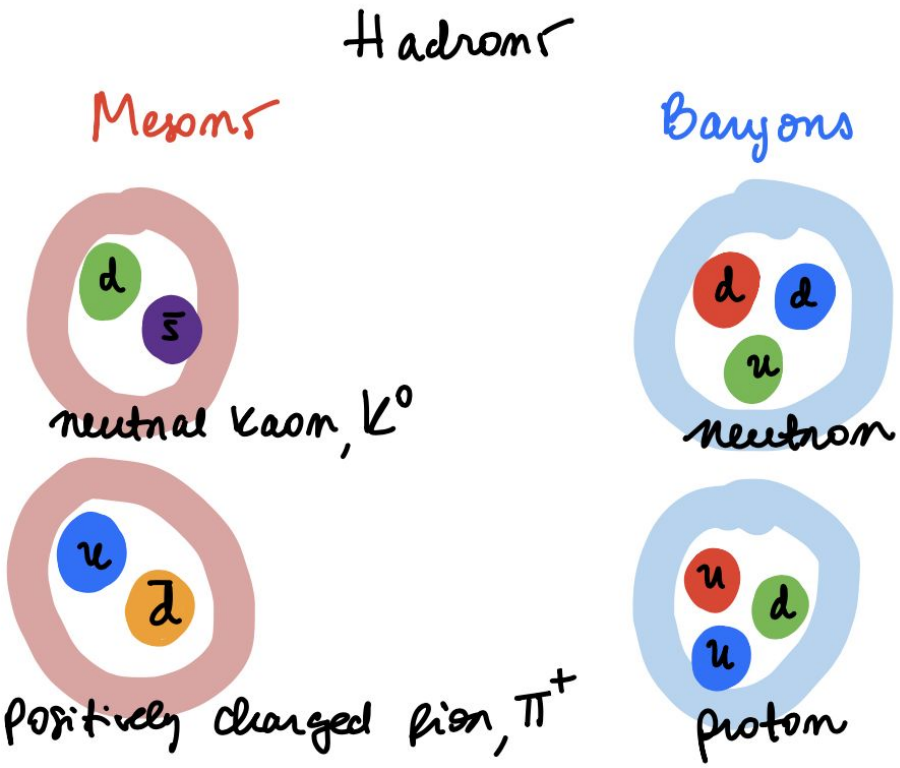
Phenomenologists need to simulate this !

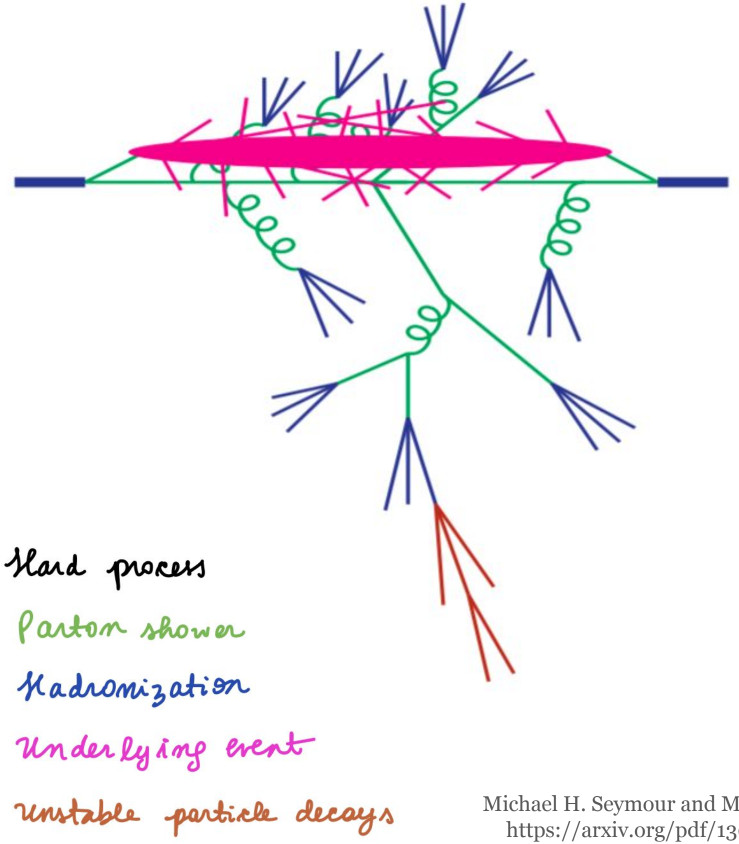


@ATLAS, CERN



Estos son a grandes rasgos los pasos que se están simulando !





Michael H. Seymour and Marilyn Marx
https://arxiv.org/pdf/1304.6677.pdf

Image by G. Cottin

En la práctica la máquina calcula

FeynRules

A Mathematica package to calculate Feynman rules

FeynRules is a Mathematica® package that allows the calculation of Feynman rules in momentum space for *any* QFT physics model.

```
  URLs         -> {"https://feynrules.irmp.ucl.ac.be/wiki/HeavyN"}
};
FeynmanGauge = True;


(* ************************** *)
(* *****  Change  log   ***** *)
(* ************************** *)
(* v1.1: Public release of LO model file *)
(* v2.1: Added Goldstone couplings for Feynman Gauge and NLO implementation *)
(* v2.2: Corrected relative sign between Yukawa and gauge couplings. *)

(* ************************** *)
(* *****   Parameters   ***** *)
(* ************************** *)
M$Parameters = {
    (* External Parameters *)

    VeN1 == {
        ParameterType    -> External,
    BlockName        -> NUMIXING,
        OrderBlock       -> 1,
        Value            -> 1.0,
    ComplexParameter -> False,
    TeX              -> Subscript[V,eN1],
        Description      -> "Mixing between ve flavor/gauge state and N1 mass state"
    },

    VeN2 == {
```

http://feynrules.irmp.ucl.ac.be/wiki/HeavyN

MadGraph

https://cp3.irmp.ucl.ac.be/projects/madgraph/
https://arxiv.org/abs/1405.0301

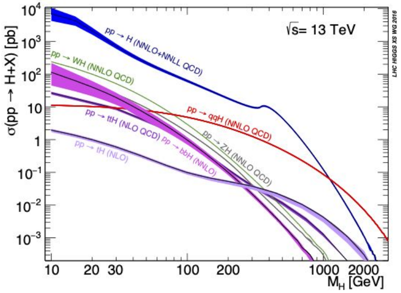
PYTHIA 8.3

https://pythia.org/
https://arxiv.org/abs/1410.3012

Remember this?


```
<event>
 4      1 +9.8868000e-15 1.50000000e+03 7.29735300e-03 8.34916000e-02
       11 -1    0    0    0    0 +0.0000000000e+00 +0.0000000000e+00 +1.5000000000e+03 1.5000000000e+03 5.1099890000e-04 0.0000e+00 -1.0000e+00
      -11 -1    0    0    0    0 -0.0000000000e+00 -0.0000000000e+00 -1.5000000000e+03 1.5000000000e+03 5.1099890000e-04 0.0000e+00 1.0000e+00
     1012  1    1    2    0    0 -7.2980127368e+02 -5.9445443626e+02 -1.0790851259e+03 1.5000000000e+03 4.4675420000e+02 7.6553e-01 -1.0000e+00
     1012  1    1    2    0    0 +7.2980127368e+02 +5.9445443626e+02 +1.0790851259e+03 1.5000000000e+03 4.4675420000e+02 6.7074e-01 1.0000e+00
<mgrwt>
<rscale>  0 0.15000000E+04</rscale>
<asrwt>0</asrwt>
<pdfrwt beam="1">  1       11 0.10000000E+01 0.15000000E+04</pdfrwt>
<pdfrwt beam="2">  1      -11 0.10000000E+01 0.15000000E+04</pdfrwt>
<totfact> 0.10000000E+01</totfact>
</mgrwt>
</event>
```


Remember this?



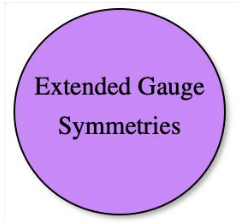
MadGraph y Phythia son códigos que computan cross-sections y genera eventos (i.e archivos con información de momentum) para procesos en colisionadores

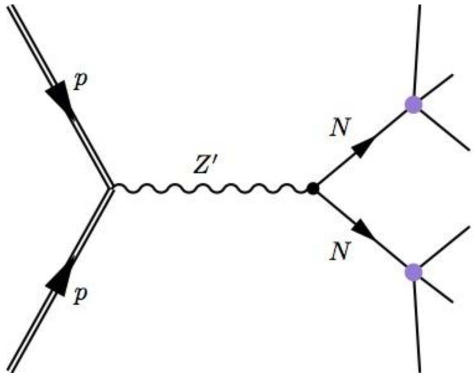
Generamos eventos con Monte Carlo, recordemos que en quantum mechar las amplitudes son realmente probabilidades!

A note on Simplified Models, which are an effective-Lagrangian description with :

* A limited number of new particles considered
* A specific production and decay channels (i.e 100% BR)
* A few free parameters (mainly masses, couplings or lfetime)
* A compact and efficient way to benchmark models, as oppose to the design of separate (potentially redundant) searches for each UV model

MadGraph





$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}V_{\mu\nu}^2 - \frac{1}{2}M_V^2 V_\mu^2 + iN^\dagger\bar{\sigma}^\mu\partial_\mu N$$
$$-\frac{M_N}{2}(N^2 + \text{h.c.}) + g' V_\mu \left(\sum_{\rm SM} Q_{B-L}\psi^\dagger\bar{\sigma}^\mu\psi + N^\dagger\bar{\sigma}^\mu N\right)$$
$$+\theta_{\mu N}\frac{g_W}{\sqrt{2}}\left(\mu_L^\dagger\bar{\sigma}^\mu W_\mu^- N + \text{h.c.}\right) + \ldots,$$

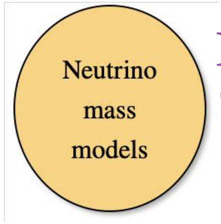
PYTHIA 8.3

B. Battel, M. Pospelov and B. Shuve, JHEP 1608 (2016)

Examples of the Workflow / Challenges

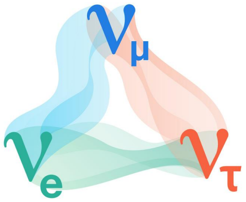
1) Characterize/Signal/Background generation

- Model building. Understand phenomenological region of interest (i.e mass ranges/couplings) to define signal
- Code your Model (i.e. build UFO or calculate your spectrum with SARAH/SPHENO)
- Use Monte Carlo to generate events (i.e. MadGraph, Pythia)
- Decay your particles (i.e. Pythia, MadSpin, correct usage of software cards)



Provide an answer for neutrino mass generation mechanism

See review in A. Atre, T. Han, S. Pascoli, B. Zhang, JHEP 05 (2009) 030, arXiv:0901.3589



Known

- Neutrino oscillations therefore neutrinos in the SM have mass

Unknown

- Neutrino mass mechanism involving HNL (i.e seesaw mechanism, inverse seesaw, ...)
- Specific BSM Model of neutrino mass generation (i.e new interactions of HNL beyond Yukawa ones?)
- HNL nature (Dirac or Majorana)
- HNL mass scale

See P. F. de Salas et al., JHEP 02 (2021) 071, arXiv:2006.11237

Seesaw Mechanism(s)

- Predicts HNLs
- HNLs mix with SM neutrinos
- Can be realised in many BSM models


@symmetrymagazine

Seesaw
P. Minkowski, Phys. Lett. 67B (1977)
R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44 (1980)
J. Schechter and J. W. F. Valle, Phys. Rev. D22, 2227 (1980)

Inverse seesaw
R. Mohapatra and J. Valle, Phys. Rev. D34 (1986) 1642

Minimal Type I Seesaw

Is not the only possibility ...

i.e Inverse Seesaw

$$\mathcal{L}_{\nu mass} = \frac{1}{2}(\overline{\nu_L^c}\ \overline{N_R})\mathcal{M}_\nu \begin{pmatrix}\nu_L \\ N_R^c\end{pmatrix} + h.c$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$M_N \gg m_D$

$$m_\nu \approx -m_D \cdot M_N^{-1} \cdot m_D^T$$

$$m_N \approx M_N$$

$$V_{\ell N} = m_D \cdot M_N^{-1} \Rightarrow V_{\ell N}^2 \sim m_\nu / M_N$$

$$V_{\ell N} = m_D \cdot M_N^{-1} \Rightarrow V_{\ell N}^2 \sim m_\nu / M_N$$

$$(\nu_L, N_R^c, S_L)$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D^T & \epsilon^T \\ m_D & M & M_N \\ \epsilon & M_N^T & \mu \end{pmatrix}$$

$\mu \ll M_N$ Inverse seesaw $\longrightarrow V_N^2 \sim m_\nu/\mu$

Pheno approach: consider a Simplified Model with one HNL, mass and mixing as independent parameters

Signal/Background generation and identification of relevant observables to discriminate between the two !

$pp \to W^{\pm} \longrightarrow N\ell^{\pm}$

$N \to \ell^{\pm} q \bar{q}$

$N \to \ell'^{\pm} \ell^{\mp} \nu_{\ell}$

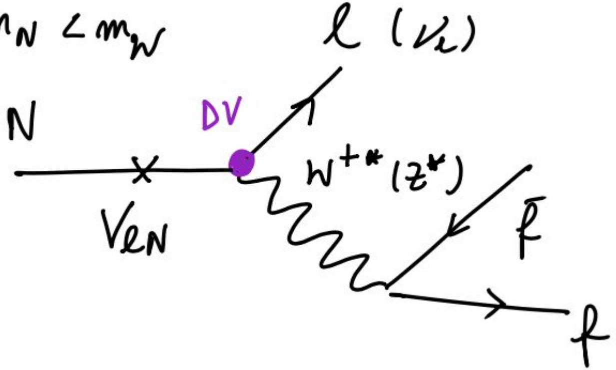
$N \to \nu q \bar{q}$

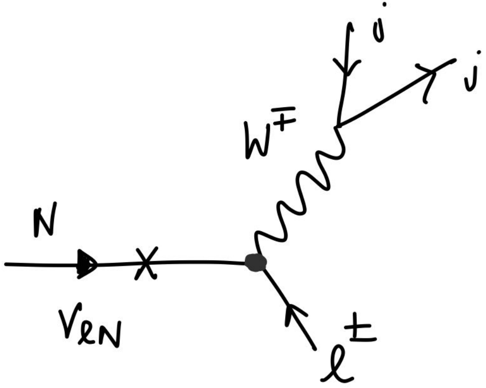
$\underbrace{\hphantom{N \to \ell'^{\pm} \ell^{\mp} \nu_{\ell}}}_{\text{Identity Signal}}$

$\Gamma \sim G_F^2 \, \underbrace{|V_{\ell N}|^2 m_N^5}_{}$

Small mixings and ~ GeV scale HNL $\Longrightarrow$ LLP!

$m_N < m_W$

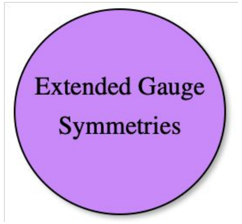


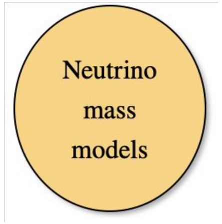


Identify signal topology and observables

@symmetrymagazine

2) Usage/Design -> Identify your tools/software or develop your own





- May need to develop your own Monte Carlo ...

Monte Carlo for Left-Right symmetric model that takes into accou
off-shell WR exchange in

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Model makes weak interactions parity symmetric and gives mass to neutrinos through symmetry breaking!

M. Nemevšek, F. Nesti, G. Popara, PRD 97, 11508 (2018)

While heavier m_N are suppressed by phase space, for larger M_{W_R} the off shell process favors lighter Ns that show a relative enhancement. Their production is still significant via W_R^*, as long as there is sufficient energy available from

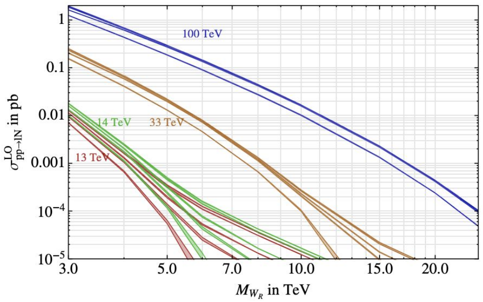
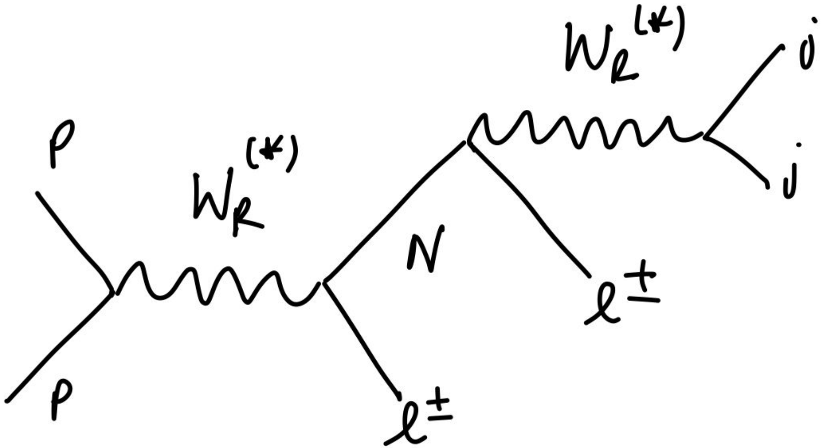
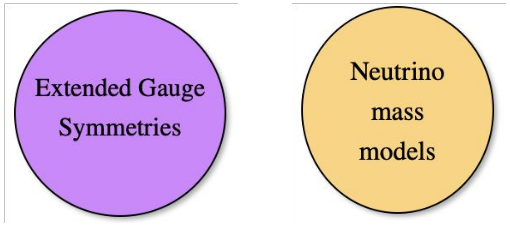


FIG. 3. Drell-Yan production cross section of $pp \to W_R^\pm \to \ell^\pm N$. For each indicated interaction energy, the curves from upper to lower are relative to $m_N = 50, 100, 500, 1000, M_{W_R}/2$, showing normal phase space suppression. In addition, notice the relative enhancement of the lighter m_N curves for heavier W_R, where the ℓN is produced via off shell intermediate W_R. The bands represent the uncertainty due to different PDF sets.



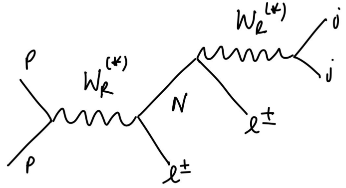
The production becomes dominated by the off shell contribution for right-W masses $\gtrsim$ 5 TeV

2) Usage/Design -> Identify your tools/software or develop your own



- Or perhaps may need to LEARN to use a non-standard Monte Carlo to constrain your Model with your proposed search

$$\Gamma_N \sim \frac{m_N^5}{m_{W_R}^4}$$



still can not run KS generator   Inbox ×   displacedNeutrinos ×

Giovanna Cottin
Dear Goran, I have been trying to run the KS code you sent me last week, but I still have problems, so I w

5

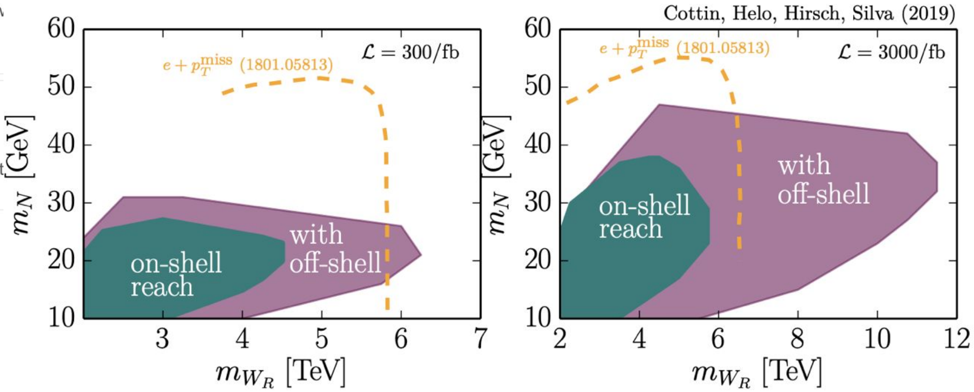
Giovanna Cottin
Hi again Goran, In order to run several processes, how should I run many cards (for example "ks_e_e.dat

Goran Popara gpopara@irb.hr via phys.ntu.edu.tw
to Giovanna

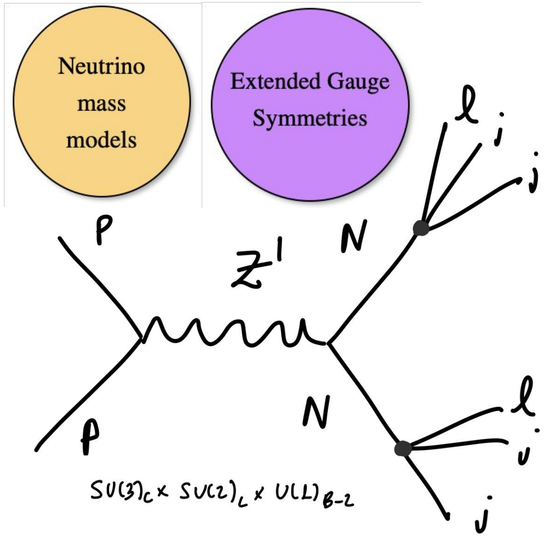
Dear Giovanna,

the way you can do this is to merge all of the ks_*.dat files into one single file and then run the generator on that file. Each line in those files represents an independent process, so you can freely add and remove them. We separated the files since it was easier to run them on the cluster that way.

G. Cottin, J.C. Helo, M. Hirsch, D. Silva, PRD 99, 115013 (2019)



2) Usage/Design -> Reinterpret an existing search to your model



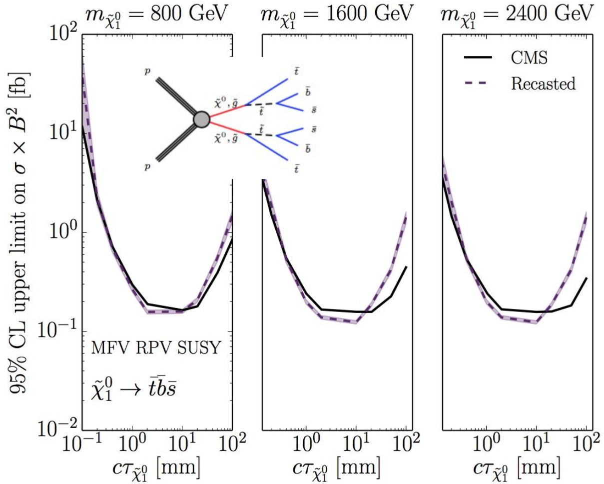
- Trigger? Are there any for my signal? (i.e. lepton pT> 120 GeV Is this lepton isolated? Displaced?)
- Define analysis cuts to maximize your significance (which you will need to define) and remove backgrounds (if you can simulate them)
- **Can recast ongoing search** (after coding and validate it against experimental cutflows/limits) and/or learn usage of standard tools and software (i.e. MadAnalysis, ROOT, Rivet ...)

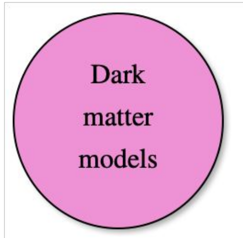
C.W. Chiang, **G. Cottin**, A. Das, S. Mandal JHEP 12 (2019) 070

(i.e. CMS prescription in 1808.03078 used for **Validation**)

10 Extending the search to other signal models

This search for displaced vertices applies to other types of long-lived particles decaying to multiple jets. Here we present a generator-level selection that can be used to reinterpret the results of our analysis. For signal models in which there are two long-lived particles, this generator-level selection approximately replicates the reconstruction-level efficiency. The selection is based on the number and momenta of generated jets in the event, the displacements of the long-lived particles, and the momenta of their daughter particles. The generated jets are those clustered from all final-state particles except neutrinos, using the anti-k_T algorithm with a distance parameter of 0.4, but are rejected if the fraction of energy from electrons is greater than 0.9 or if the fraction of energy from muons is greater than 0.8. The daughter particles are



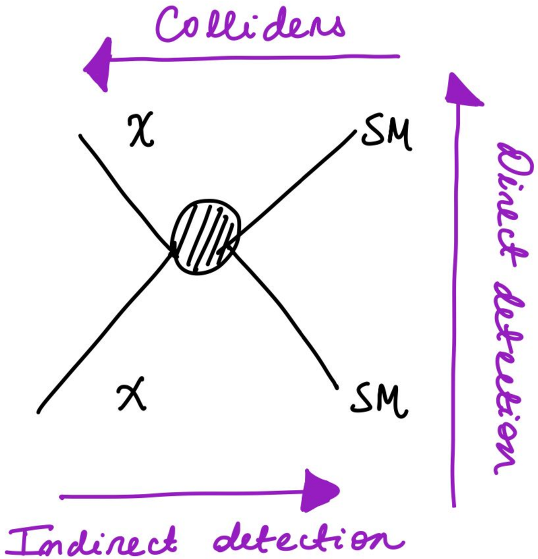


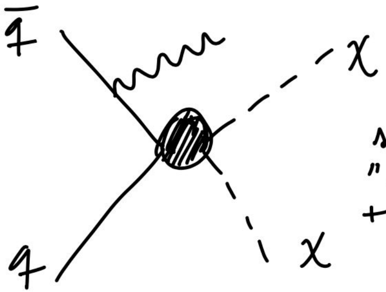
2) Usage/Design ->Propose your own search if standard cuts are not optimal for your signal

See O. Buchmueller et al., Simplified Models for Displaced Dark Matter Signatures, JHEP 09(2017) 076

It is costum to construct simplified models for collider searches within EFT (to study the models systematically)

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda^{d-4}} \sum_i c_i^{(d)} O_i^{(d)}$$



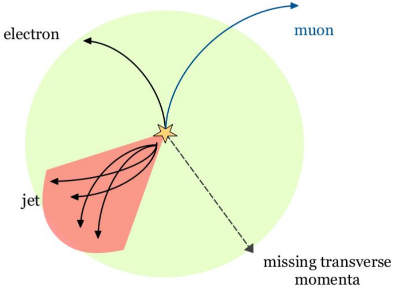


standard "monojet" searches

+

$$\vec{p}_T^{\,miss} = -\sum_{vis} \vec{p}_T = \sum_{invis.} \vec{p}_T$$

Standard

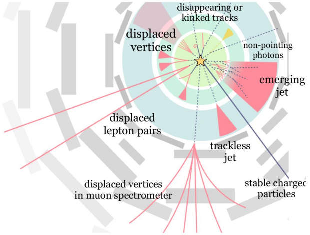


To see "nothing", you have to understand everything !

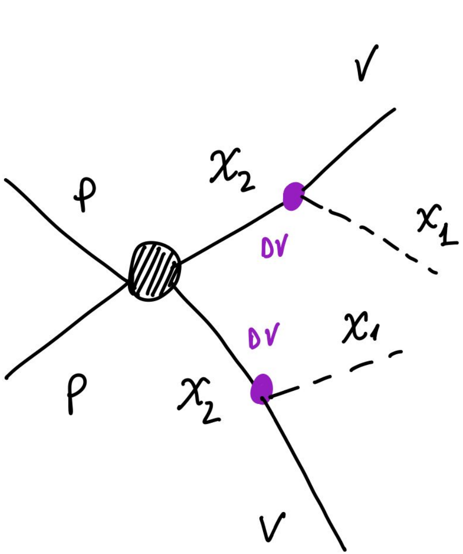
Dark matter models

2) Usage/Design ->Propose your own search if standard cuts are not optimal for your signal. Can even define new observables or physics objects!

Exotic



Or ! you can understand one key thing!



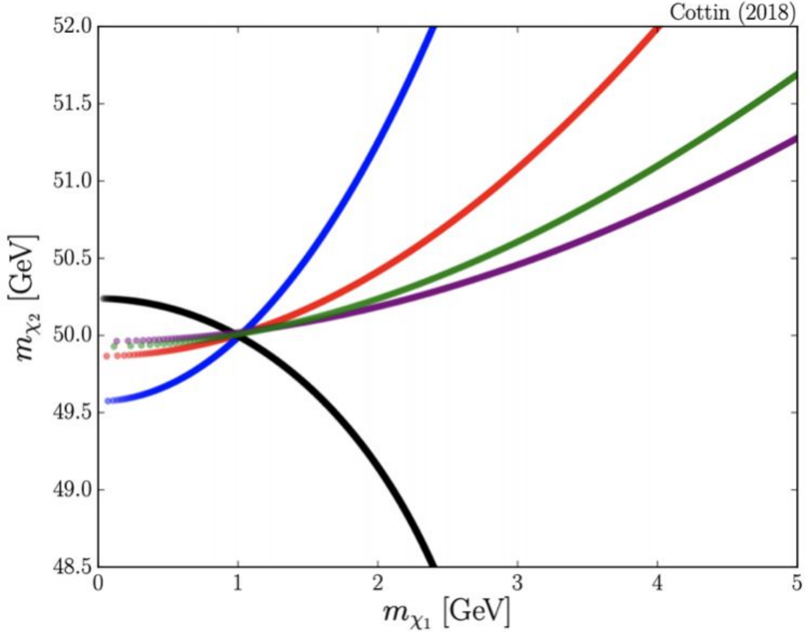
$$\Gamma \sim \lambda^2 \left(\frac{\Delta m}{\Lambda}\right)^n \Delta m$$

$$c\tau = \Gamma^{-1}$$

$$p_{\chi_2} = |p_{\chi_2}|\underbrace{\hat{n}}$$

assuming known displaced vertex position can get knowledge on the direction of momentum

G. Cottin, JHEP 03, 137 (2018)

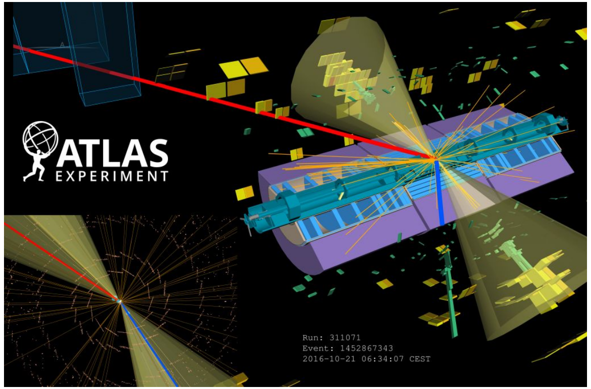


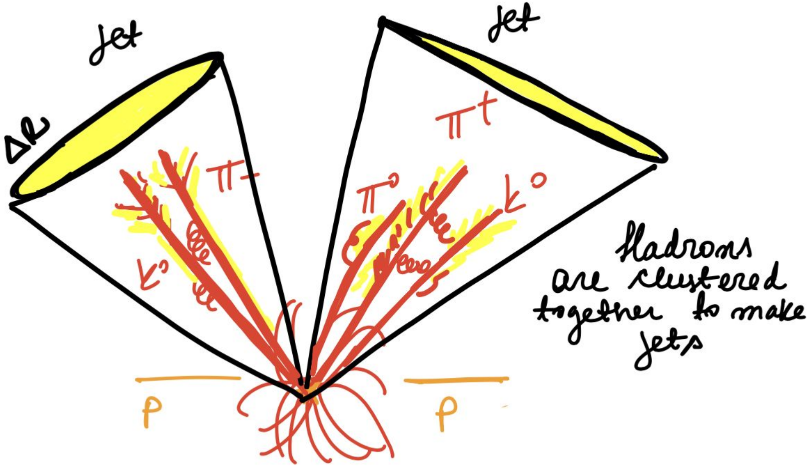
By proposing a new mass variable for the masses system, can solve on an event by event basis, and the system is fully constrain

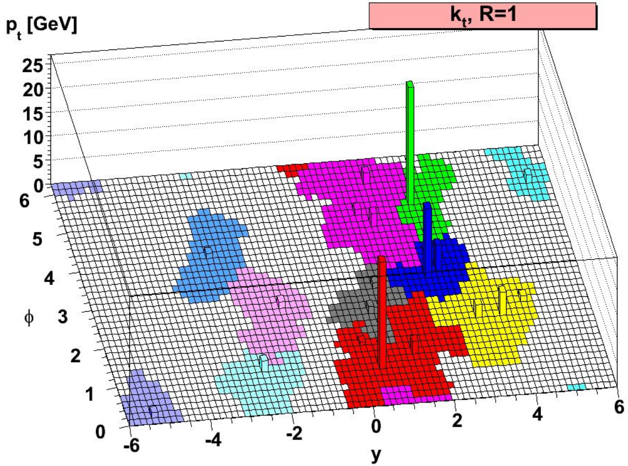
The DM mass could be measured at colliders !

3) Evaluate Experimental Response -> Simulation !

- Need to think of object reconstruction. (i.e. What is an electron or a jet?
- Know software as Fastjet, clustering algorithms as antiKt to quantify detector response. Can use standard tools as DELPHEs or develop your own)
- Understand limitations of standard fast detector simulation (i.e. LLPs, trackless-jets, etc)
- Understand object efficiencies. Are they known? Can I assume 100% efficiency for a future experiment? (i.e Can use HepData for ongoing experiments)
- Can hunt directly with CERN open data?







M. Cacciari et al, arXiv:0802.1189

4) Implement your search and estimate reach

Higgs portal models

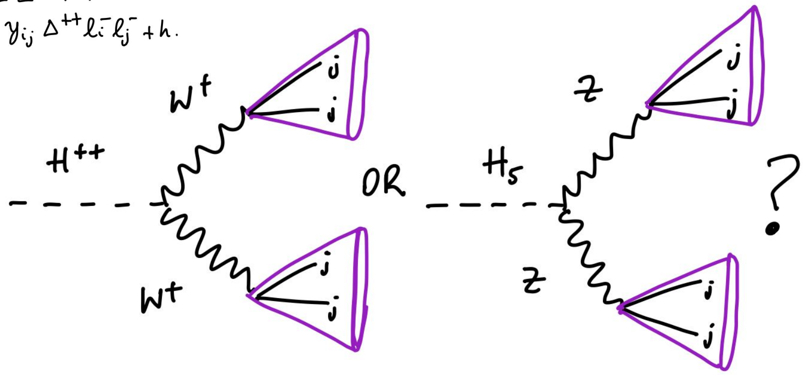
- Define significance (i.e. can I assume 0 bkg? Can I estimate all my backgrounds? Are there any background uncertainties? How they will escalate with luminosity if I am proposing a new search at a future collider for example?)
- Will I do a cut and count analysis? Or I can Machine Learn my search by creating a new tagging algorithm when feeding my observables to a NN?

SM + SU(2)-triplets (Δ)

$V(\phi, \Delta)$

$v_\Delta \Delta^{++} W^- W^- + h.c$

$y_{ij} \Delta^{++} l_i^- l_j^- + h.$



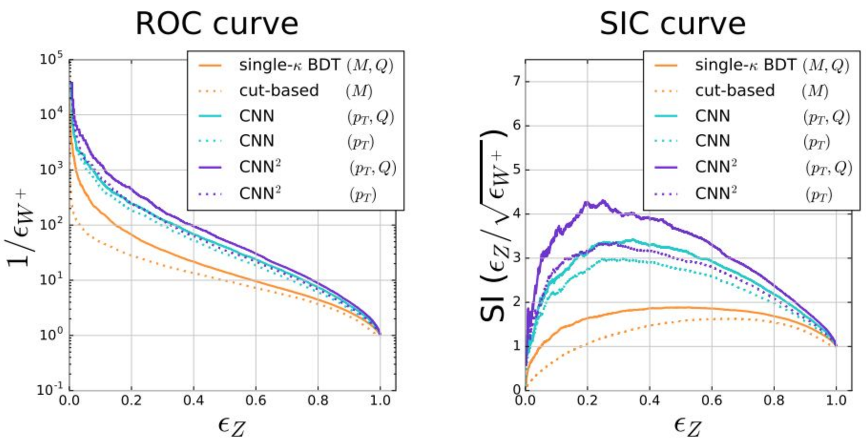
$$\text{jet charge} = \frac{1}{(p_{T,J})^\kappa} \sum_{i \in J} q_i \cdot (p_T^i)^\kappa$$

Field, Feynman, Nucl. Phys. B136 (1978) 1.

By reusing Feynman's jet charge with deep learning, could distinguish jets from doubly charged or neutral gauge bosons

$$N = \sigma \cdot BR \cdot \mathcal{L} \cdot \text{eff}$$

$$\text{Significance} = \frac{N}{\sqrt{B}}, \frac{N}{\sqrt{B+\Delta B}}, \ldots \text{more sophisticated?}$$

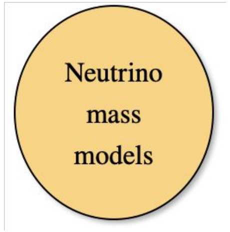


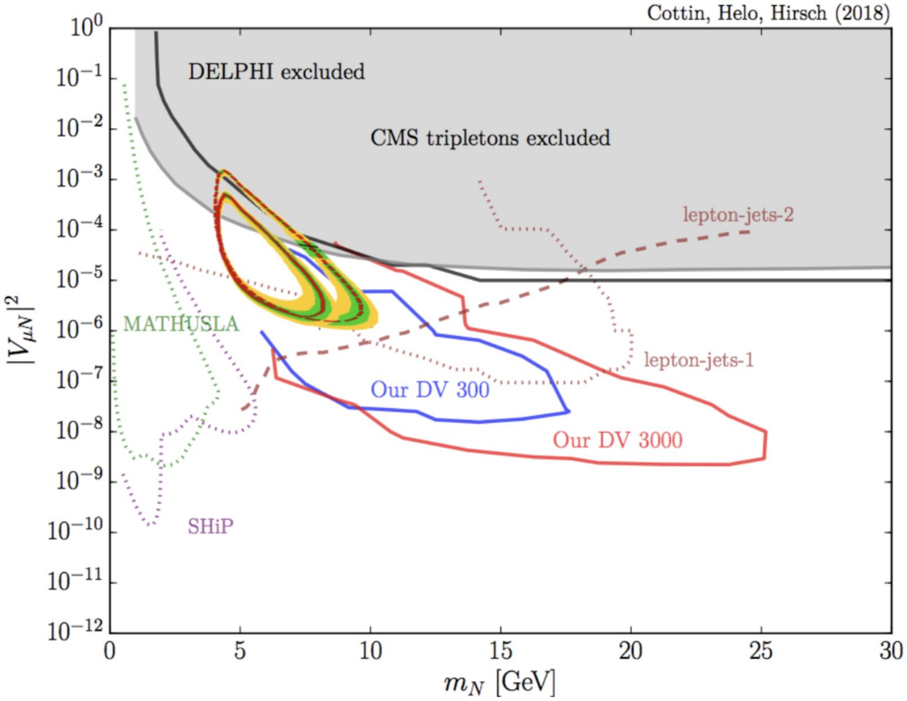
J. Chen, C.W. Chiang, **G. Cottin**, D. Shih Phys.Rev.D 101 (2020) 5

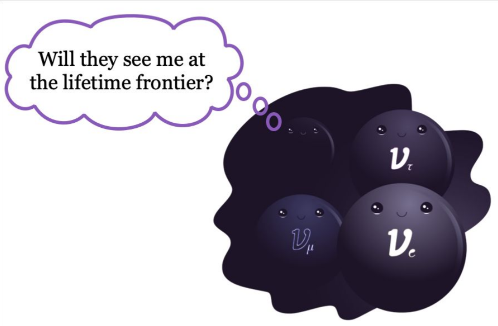
New Higgs bosons could be discovered with this new tagging method !

5) Evaluate and present your model discovery prospects/exclusion

- Provide limits in model parameters of interest
- Are there other constraints to my model? Maybe from other experiments?
- Contrast your model with data (i.e. Can use tools as CheckMate, SModels, HepFit, or maybe do your own global fit)







@symmetrymagazine

G. Cottin, J.C. Helo and M. Hirsch, Phys. Rev. D97 (2018)

Strategy updated in R. Beltrán, **G. Cottin**, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, JHEP 01 (2022) 044

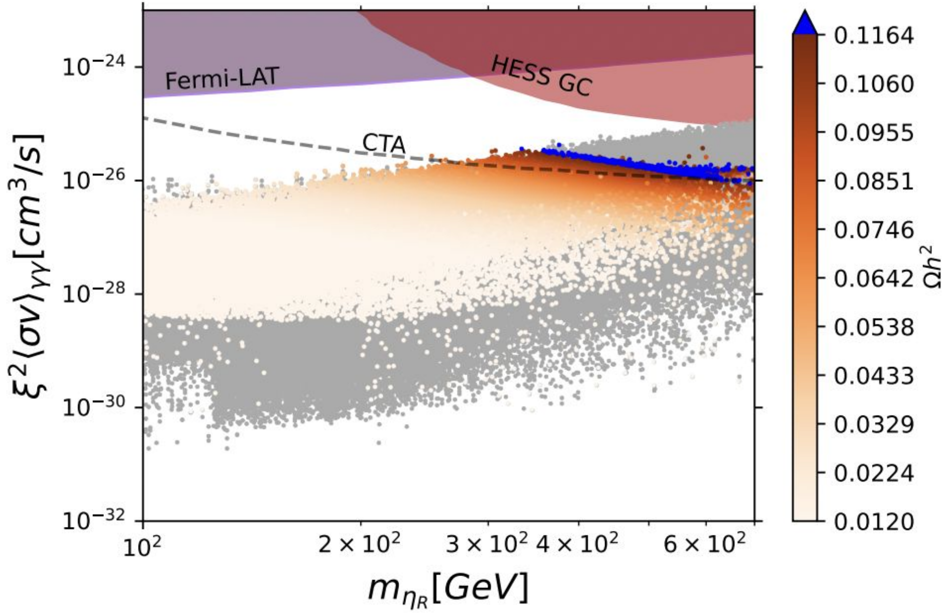
Dark matter models

And you can implement the pipeline at other HEP experiments even beyond colliders like direct detection or indirect detection (CTA)

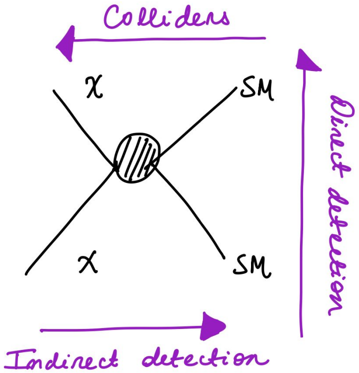
Hard code your model and use dedicated software as

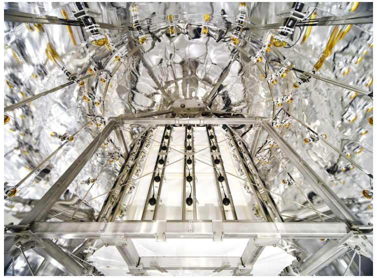
MicrOMEGAs: a code for the calculation of Dark Matter Properties including the **relic density**, direct and **indirect rates** in a general supersymmetric model and other models of New Physics

https://lapth.cnrs.fr/micromegas/

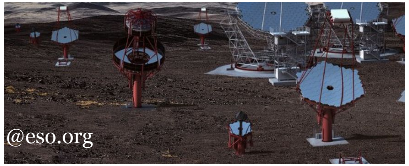


Revisiting the scotogenic model with scalar dark matter
I. M. Ávila, **G. Cottin**, Marco A. Díaz, J.Phys.G 49 (2022) 6, 065001





Credit: Xenon Collaboration

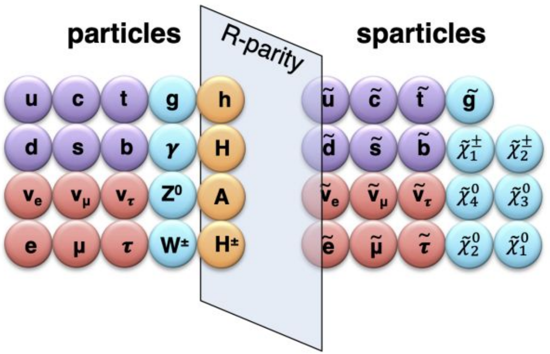


See also C.-W. Chiang, **G. Cottin**, Y. Du, K. Fuyuto, M.J. Ramsey-Musolf, JHEP 01 (2021) 198 for interplay of all in a specific DM model

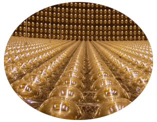
SUSY

or even Super Kamiokande !

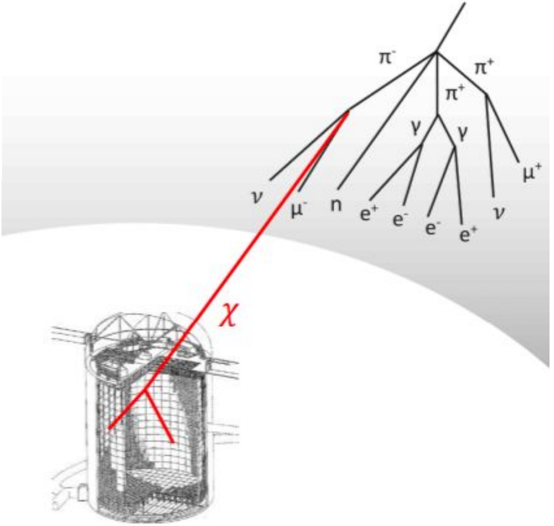
SUSY
S. Martin, A SUSY Primer, arXiv:9709356
SUSY RPV
R. Barbier et al, Phys.Rept. 420 (2005)
H. K. Dreiner, G. G. Ross, Nucl. Phys. B365 (1991)

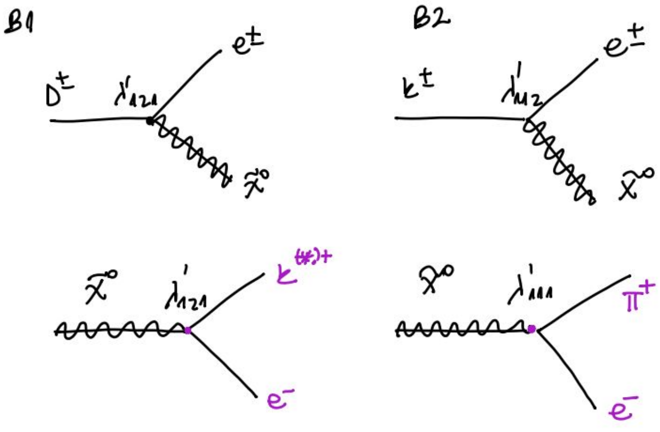


@https://cds.cern.ch/record/2809389/files/ATL-PHYS-PROC-2022-030.pdf



$$W_{RPV} = \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k$$



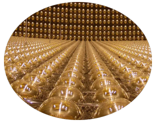


showering final states

$$\Gamma \sim \lambda'^2_{111} \, m_{\tilde{f}}^{-4} \, m_N^5$$

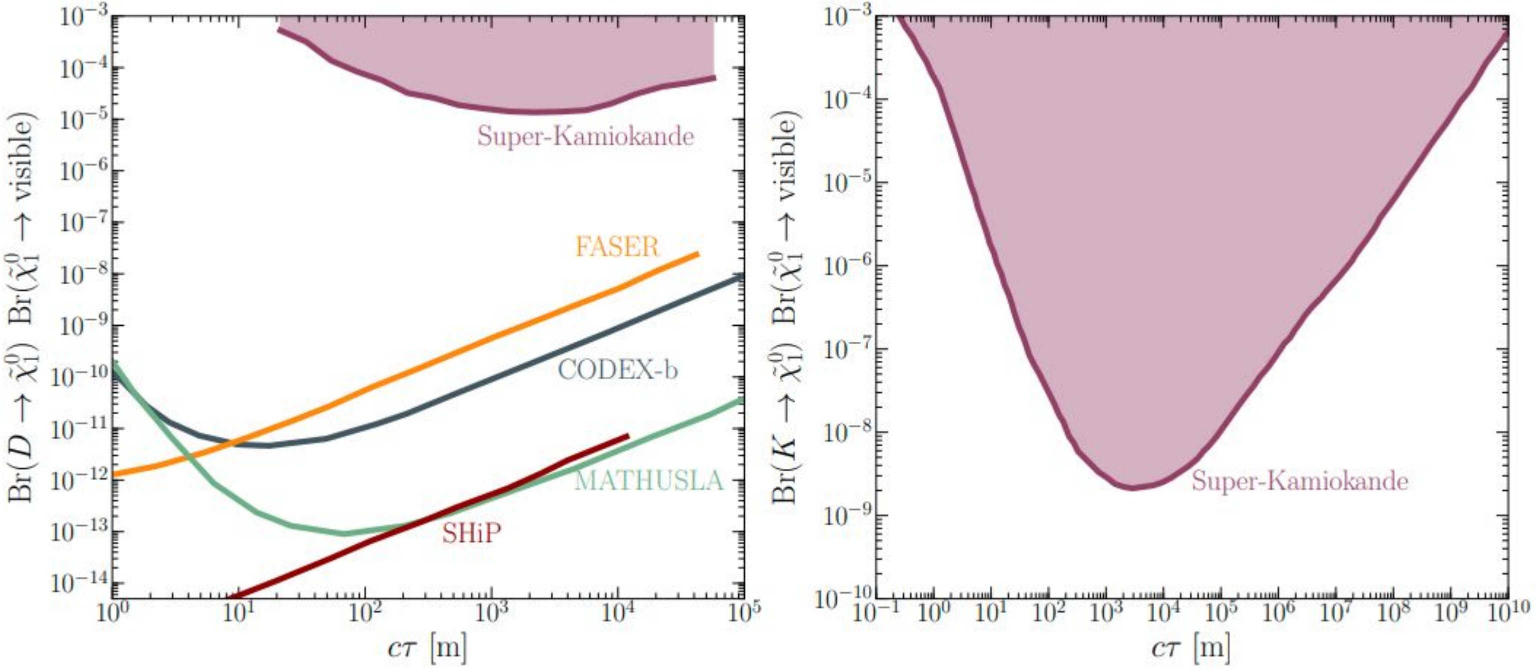
Seminal work in
Searches for Atmospheric Long-Lived Particles, C. Argüelles, P. Coloma, P. Hernández, V. Muñoz, JHEP 02 (2020) 190, arXiv: 1910.12839

SUSY



Understand comparison with (future) collider experiments !

(kaon gap at colliders)



Searching for light long-lived neutralinos at Super-Kamiokande, P. Candia, **G. Cottin**, A. Méndez, V. Muñoz, Phys.Rev.D 104 (2021) 5, 055024

Summarizing, to do BSM phenomenology

Expertise still needed in

Theories >> Experimental searches

1) Signal/Background generation

- **Model building**. Define your pheno space to study
- **Model coding and learning software** (i.e. FeynRules to build UFO or calculate your spectrum with SARAH/SPHENO)
- **Use Monte Carlo to generate events** for your model (i.e. MadGraph, Pythia, Herwig, MadSpin ...)
- **Develop new tools/software/techniques**
- **Understand how to use your available hardware** to do all above and what follows (i.e. /clusters/CPU/GPU time/server/maintenance/batch system)

2) Reinterpretation/Design

- **Coding/know how on HEP tools and software**
- **Creativity in designing searches and observables**
- **Understand experiment capabilities**
- Going public to help HEP Community is now being standardized (i.e github, zenodo ...)

Adding your recasting code

This is an open repository and if you have developed a cod
include it here. Please contact llp-recasting@googlegroups
information for including your code.

Repository Structure

The repository folder structure is organized according to th
and authors:

- Displaced Vertices
  - 13 TeV ATLAS Displaced Vertex plus MET by ALessa
  - 13 TeV ATLAS Displaced Vertex plus MET by GCottin
  - 8 TeV ATLAS Displaced Vertex plus jets by GCottin

May 13, 2016 (v1) | Presentation | Open Access

Future Colliders

Watts, Gordon;

A 10 minute contributed talk on future colliders given at the APSNW 2016 conference

Uploaded on May 20, 2016

January 24, 2020 (0.1) | Dataset | Open Access

Benchmark Data for AI Safety for High Energy Physics

Chase Shimmin; Benjamin Nachman;

Summarizing, to do BSM phenomenology

Expertise still needed in

Theories >> Experimental searches

3) Simulate Experimental Response

- Know detector capabilities
- **Know your physics objects and how to reconstruct them in software**
- **Know efficiencies or estimate behaviour**
- Understand assumptions made
- Team building with experimentalists !

4) Estimate discovery potential/exclusion reach

- **Understand statistical treatment**
- Strategy to maximize significance (i.e ML, learn tools as Keras, Tensorflow)
- Validation is key if recasting ongoing search

5) Present results/discovery potential for your model

- **Understand other constraints to your model** (may need to do parallel reinterpretations)
- May apply dedicated limit software (i.e. CheckMate, global fitters … understand their limitations, not all experimental searches are coded and maybe not all will apply to your model)
- **State power/complementarity with other efforts/experiments**

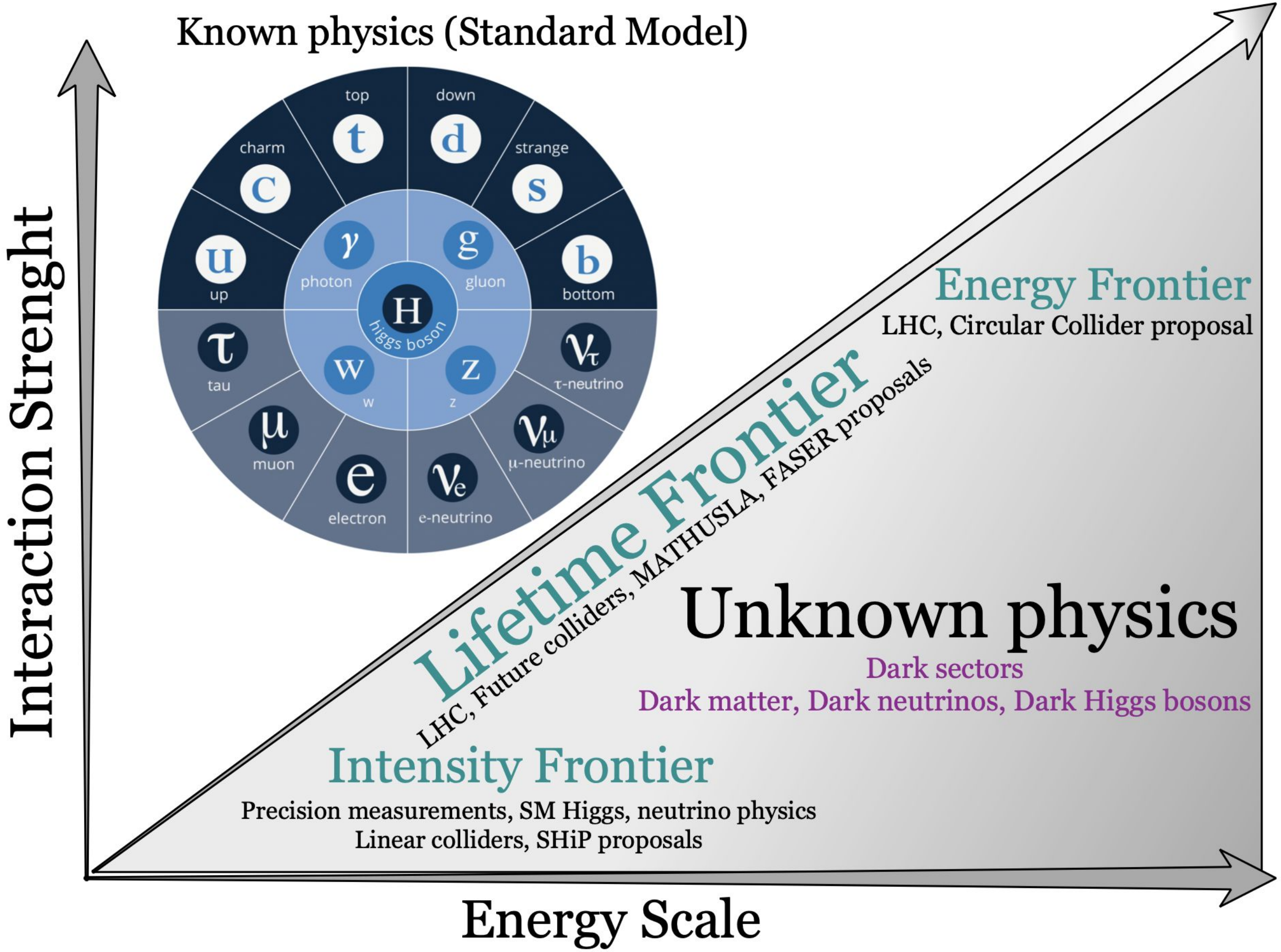
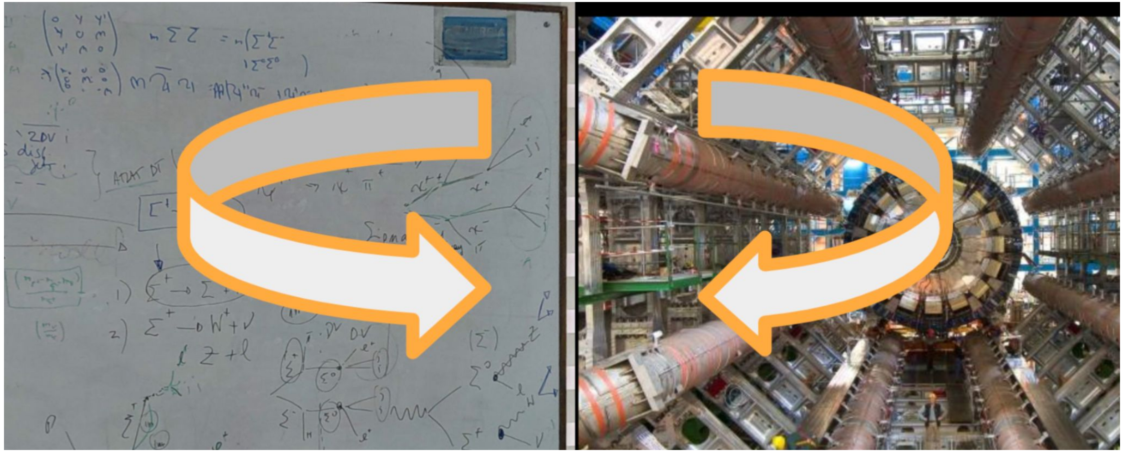


Image by G. Cottin. SM image @CERN

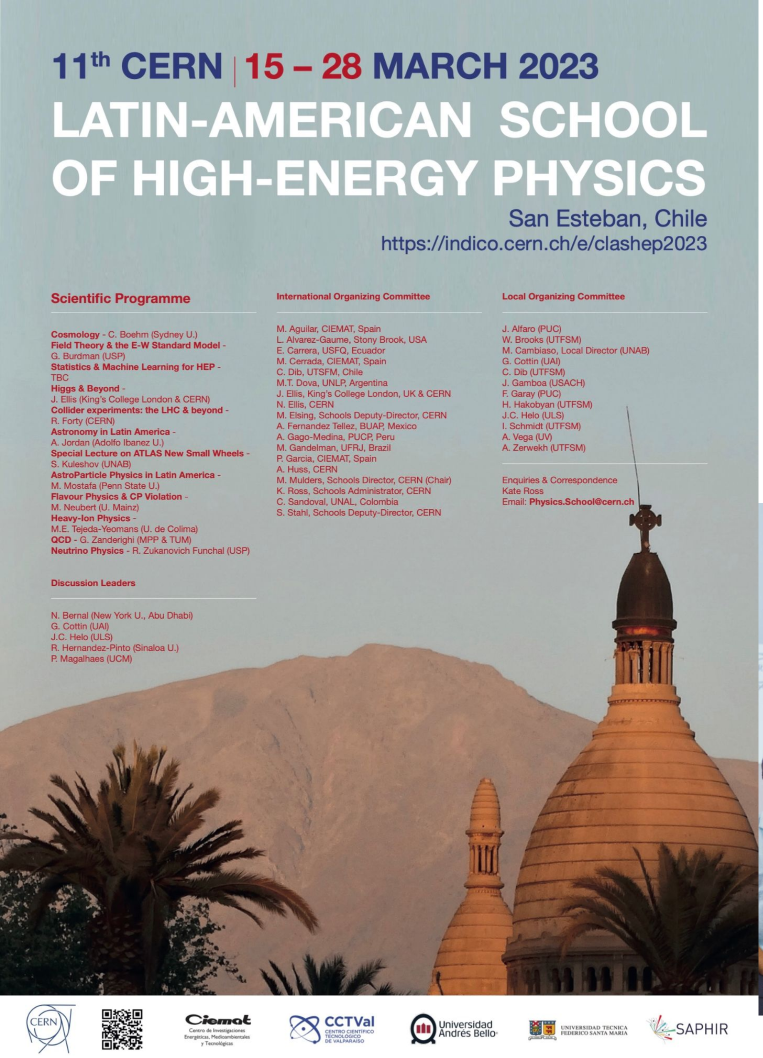
To aid in the goal of discovering BSM physics,
theory and experimental synergy is needed



BSM Phenomenology is the Bridge

Organization - Collaboration - Know How - Transferable Skills - Training - Global View of our Field

Growing opportunities for particle phenomenology in Chile
Many schools also abroad (CERN School, ICTP, GGI, LUND, MAINZ)
If you are interested, let me know !



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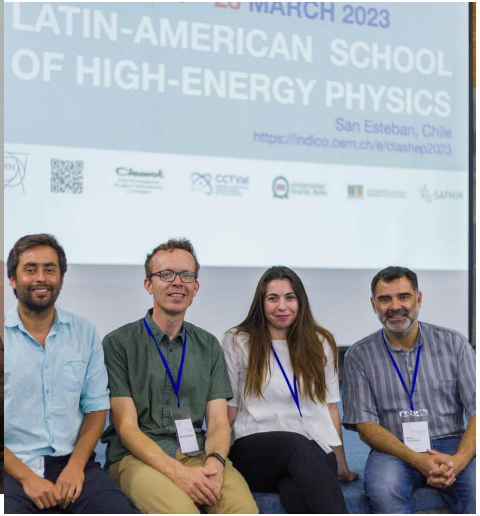


niñas
ATØMICAS

La Física de Partículas

Años antes del presente
nacen materia y energía
dándonos cosmología
y todo cuan aparente
del Universo existente.
“Son fermiones y bosones”,
la teoría propone,
los básicos elementos
forjadores de cimientos
que la ley física impone.

Hay partículas dispersas
partes de un humilde estudio
dibujante del preludio
del origen de las fuerzas,
de las cuatro tan diversas:
débil, fuerte y gravedad,
también la electricidad,
que moldean nuestro entorno.
Así se esboza el contorno
de nuestra realidad.

La búsqueda de verdad
nos ofrece interrogantes
angustiantes y abundantes.
Surge la oportunidad
de encontrar la identidad
en la materia y el origen
las partículas eligen.
Dejenlas colisionar !
y así podrán revelar
los misterios que las rigen.

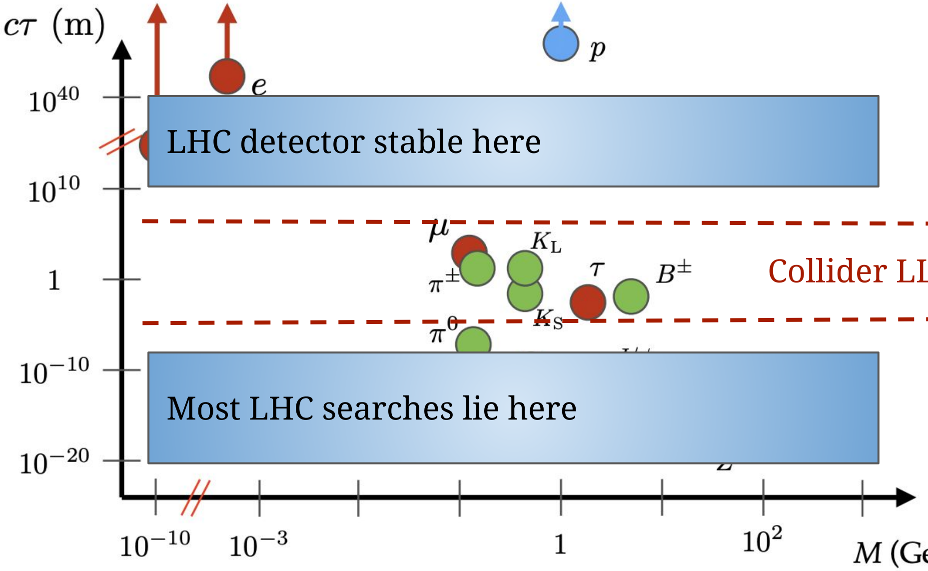
Giovanna Cottin

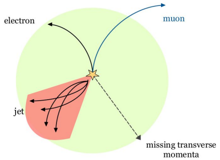
@ San Pedro de Atacama, Chile

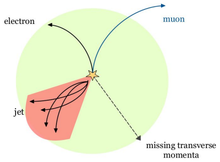
Backup

Future LHC Collider Phenomenology

Are we looking deep in all regions of parameter space?







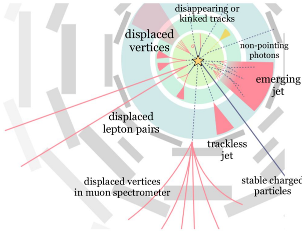


Image by B.Shuve.

Long-lived Particle Community White Paper, J. Alimena, … , **G.Cottin** et al, arXiv:1903.04497

11/198 ATLAS LLP searches with full 13 TeV data

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Winter201713TeV

The Lifetime Frontier was born

Science
$15
24 MAY 2019
sciencemag.org
AAAS

IN DEPTH

In a simulated event, the track of a decay particle called a muon (red), displaced slightly from the center of particle collisions, could be a sign of new physics.

PARTICLE PHYSICS

A hunt for long-lived particles ramps up

The Large Hadron Collider could be making new particles that are hiding in plain sight

By Adrian Cho

Are new particles materializing right under physicists' noses and going unnoticed? The world's great atom smasher, the Large Hadron Collider (LHC), could be making long-lived particles that slip through its detectors, some researchers say. Next week, they will gather at the LHC's home, CERN, the European particle physics laboratory near Geneva, Switzerland, to discuss how to capture them. They argue the LHC's next run should emphasize such searches, and some are calling for new detectors that could sniff out the fugitive particles.

It's a push born of anxiety. In 2012, experimenters at the $5 billion LHC discovered the Higgs boson, the last particle predicted by the standard model of particles and forces, and the key to explaining how fundamental particles get their masses. But the LHC has yet to blast out anything beyond the standard model. "We haven't found any new physics with the assumptions we started with, so maybe we need to change the assumptions," says Juliette Alimena, a physicist at Ohio State University (OSU) in Columbus who works with the Compact Muon Solenoid (CMS), one of the two main particle detectors fed by the LHC.

For decades, physicists have relied on a simple strategy to look for new particles: Smash together protons or electrons at ever-higher energies to produce heavy new particles and watch them decay instantly into lighter, familiar particles within the huge, barrel-shaped detectors. That's how CMS and its rival detector, A Toroidal LHC Apparatus (ATLAS), spotted the Higgs, which in a trillionth of a nanosecond can decay into, among other things, a pair of photons or two "jets" of lighter particles.

Long-lived particles, however, would zip through part or all of the detector before decaying. That idea is more than a shot in the dark, says Giovanna Cottin, a theorist at National Taiwan University in Taipei. "Almost all the frameworks for beyond-the-standard-model physics predict the existence of long-lived particles," she says. For example, a scheme called supersymmetry posits that every standard model particle has a heavier superpartner, some of which could be long-lived. Long-lived particles also emerge in "dark sector" theories that envision undetectable particles that interact with ordinary matter only through "porthole" particles, such as a dark photon that every so often would replace an ordinary photon in a particle interaction.

CMS and ATLAS, however, were designed to detect particles that decay instantaneously.

Like an onion, each detector contains lay of subsystems—trackers that trace charg particles, calorimeters that measure parti energies, and chambers that detect penetr ing and particularly handy particles call muons—all arrayed around a central po where the accelerator's proton beams c lide. Particles that fly even a few millimet before decaying would leave unusual sig tures: kinked or offset tracks, or jets t emerge gradually instead of all at once.

Standard data analysis often assun such oddities are mistakes and junk, no Tova Holmes, an ATLAS member from University of Chicago in Illinois who searching for the displaced tracks of dec from long-lived supersymmetric partic "It's a bit of a challenge because the v we've designed things, and the softw people have written, basically rejects th things," she says. So Holmes and colleag had to rewrite some of that software.

More important is ensuring that the tectors record the odd events in the f place. The LHC smashes bunches of p tons together 400 million times a seco To avoid data overload, trigger systems CMS and ATLAS sift interesting collisi from dull ones and immediately disc data about 1999 of every 2000 collisi The culling can inadvertently toss long-lived particles. Alimena and colleag

@https://www.science.org/content/article/atom-smasher-could-be-making-new-particles-are-hiding-plain-sight

https://lpcc.web.cern.ch/lhc-llp-wg

CERN Accelerating science | Sign in

LPCC
LHC Physics Centre at CERN

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LHC LLP WG: Long-lived Particles at the LHC

To subscribe to the general WG mailing list, used to distribute announcements about WG meetings and available documents, go to http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-llpwg

Mandate:

The LHC Long-lived Particles Working Group (LHC LLP WG) brings together experimentalists and theorists to discuss the physics of new long-lived particles at the LHC. It also covers physics with unconventional experimental signatures. The WG builds on the experience of the LLP LHC Community and, preserving its main scientific objectives, it serves as a formal bridge with the relevant physics groups of the LHC experiments, to streamline the official endorsement of the WG's recommendations to the experiments. The WG will hold open meetings, typically at CERN, complementing the Workshops organized by the LLP LHC Community. The formation of dedicated subgroups, and possible closed meetings (restricted

Dark Matter WG
- WG documents
- WG Meetings

Electroweak WG
- WG Documents
- WG meetings

Forward Physics WG
- WG documents
- WG meetings

Conveners:

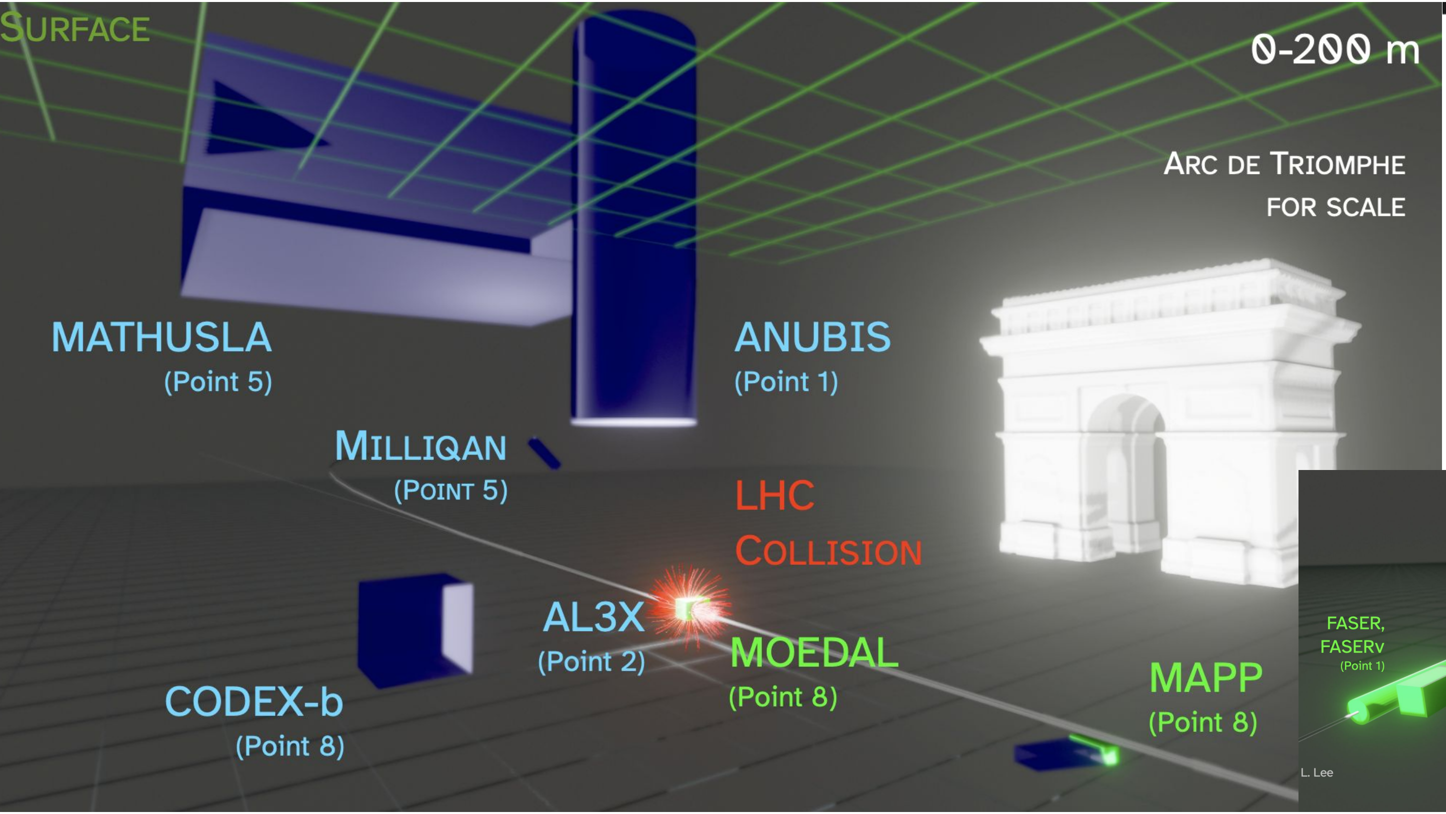
- ATLAS: Simone Pagan Griso and Emma Torro Pastor
- CMS: Alberto Escalante del Valle and Larry Lee
- FASER: Dave Casper
- LHCb: Federico Leo Redi and Carlos Vázquez Sierra
- MoEDAL: James Pinfold
- SND@LHC: Cristovao Vilela
- Theory: Giovanna Cottin, Nishita Desai and José Zurita
- Reach all through lhc-llpwg-admin@cern.ch

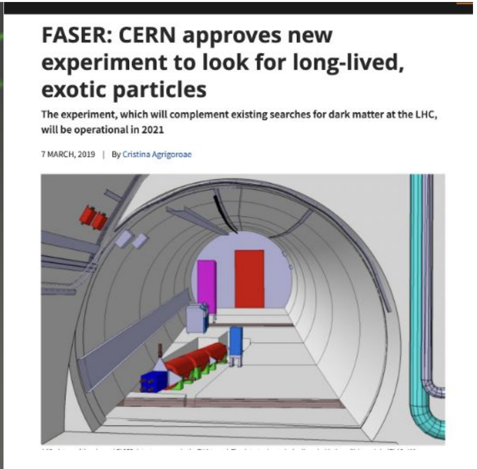
Models predicting Long-lived particles

Future Collider phenomenology

We don’t want to miss the new physics !

Slide from L. Lee @ LHCPC2021 @https://indico.cern.ch/event/905399/contributions/4282550/attachments/2261167/3837992/060921_LLee_NeutralFIPs.pdf

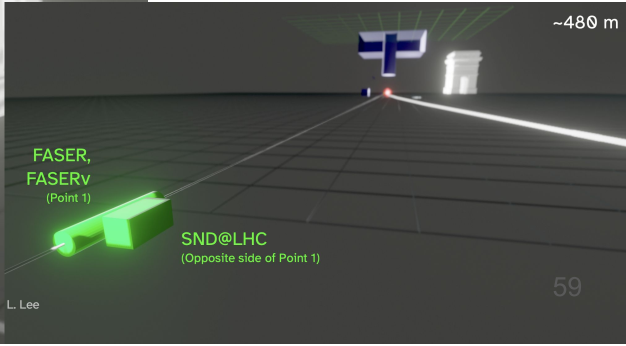




FASER: CERN approves new experiment to look for long-lived, exotic particles

The experiment, which will complement existing searches for dark matter at the LHC, will be operational in 2021

7 MARCH, 2019 | By Cristina Agrigoroae

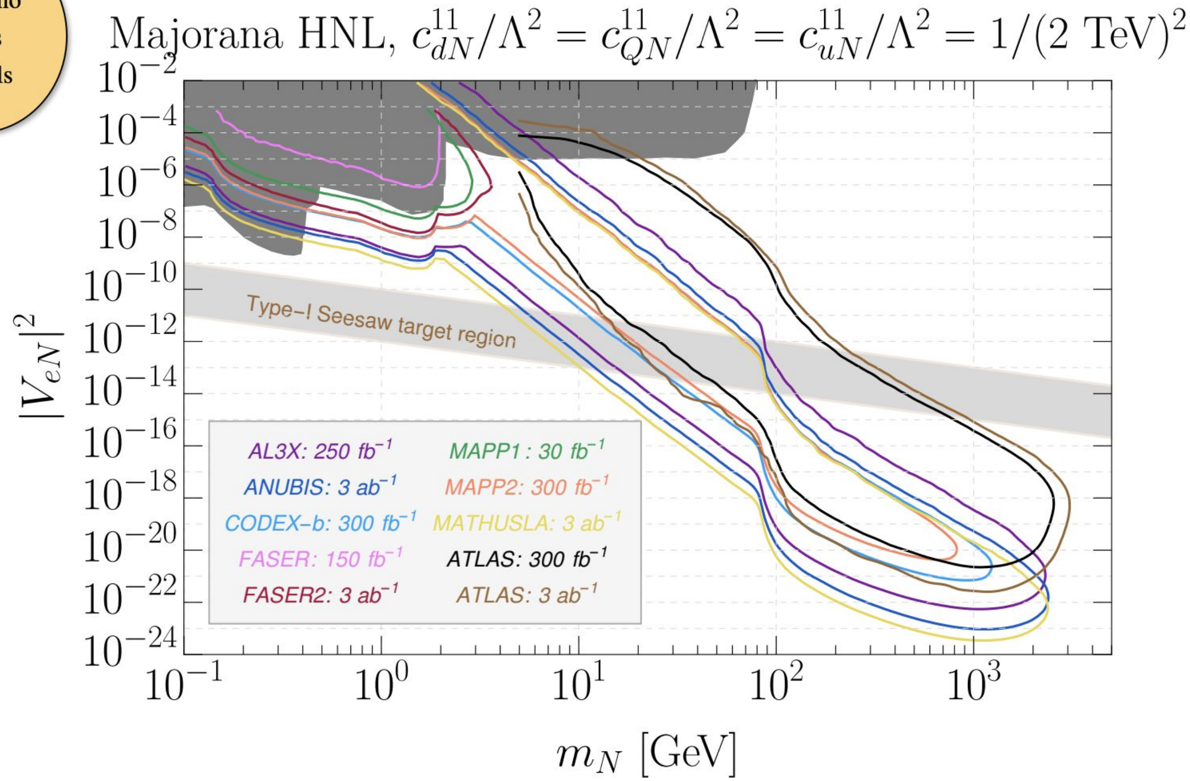


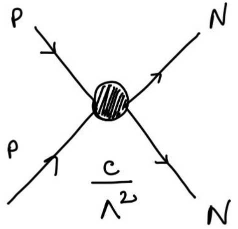
Effective Field Theory with heavy neutrinos

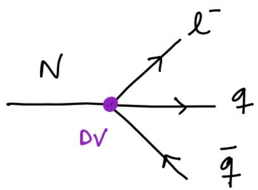
d=6 four-fermion operators with *pairs* of N

G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, JHEP 09 (2021) 039

$$\mathcal{L}_{N_R\,\mathrm{SMEFT}} = \mathcal{L}_{SM+N_R} + \sum_{d\geq 5} \frac{1}{\Lambda^{d-4}} \sum_i c_i^{(d)} \mathcal{O}_i^{(d)}$$



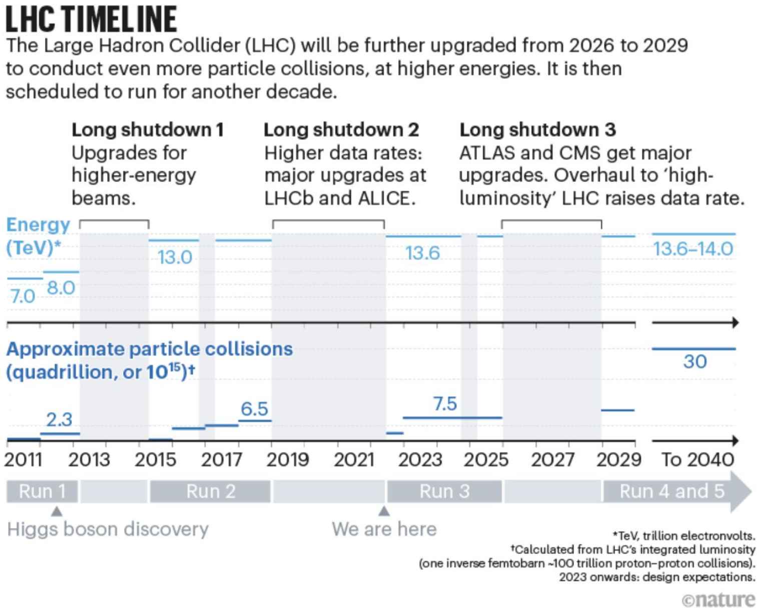




Complementary sensitivities can be achieved with new experiments!

Limitations of this hunt

- New particles are too heavy to be produced
- Lack of precision/technology to detect them
- Lack of data to make discoveries
- Backgrounds from known particles are often huge



Nik Spencer/*Nature*; Source: CERN

Experimental upgrades to beat them

- Increase in *pp* energies (to 13.6 trillion electron volts (TeV))
- Updated electronics and hardware, even entire new detectors
- More compact proton bunches, increasing the probability of collisions
- New triggers to select which events to save/new algorithms
- to process/analyze and reconstruct data

Limitations of this hunt

- New particles are too heavy to be produced
- Lack of precision/technology to detect them
- Lack of data to make discoveries
- Backgrounds from known particles are often huge

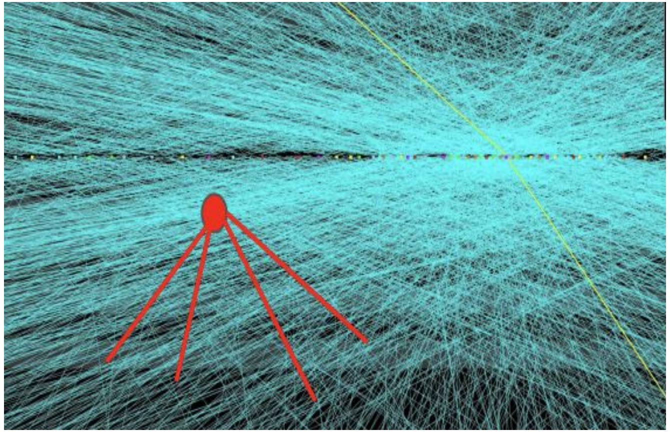
I proposed theory/phenomenology ideas to surpass them in this talk

- Utilize LHC detectors creatively to explore well-motivated models (with accessible masses) related to dark matter, neutrino masses, higgs portal, and more*

- Establish the physics case for novel detectors at current and future colliders*
  Exploit HEP experiment even beyond colliders to restrict BSM physics

- Repurpose current data to new models and propose innovative deep learning techniques that exploit new physics model phenomenology

- Theory predictions for long-lived particles benefit from minimal backgrounds, making it possible to make discoveries even with small signals (as they would look exotic like this !).



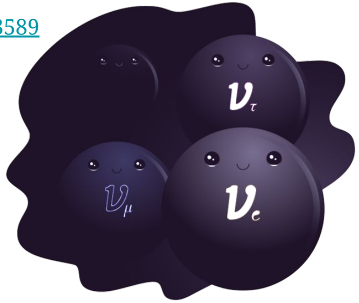
*Also been working on ALPs models, SUSY, and models with extended gauge symmetries
*Also worked on future 100 TeV Colliders, future electron-positron and electron-proton colliders

Heavy Neutral Leptons
Right-handed singlet fermions or sterile neutrinos can be LLP

HNL LLP Motivation

An answer for neutrino mass generation mechanism

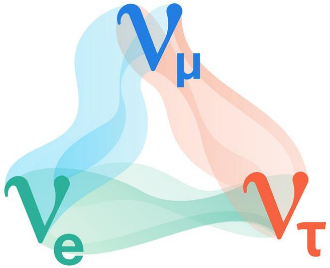
See review in A. Atre, T. Han, S. Pascoli, B. Zhang, JHEP 05 (2009) 030, arXiv:0901.3589



@symmetrymagazine

Known

- Neutrino oscillations therefore neutrinos in the SM have mass



See P. F. de Salas et al., JHEP 02 (2021) 071, arXiv:2006.11237

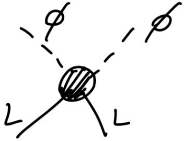
Unknown

- Neutrino mass mechanism involving HNL (i.e seesaw mechanism, inverse seesaw, …)
- Specific BSM Model of neutrino mass generation (i.e new interactions of HNL beyond Yukawa ones?)
- HNL nature (Dirac or Majorana)
- HNL mass scale

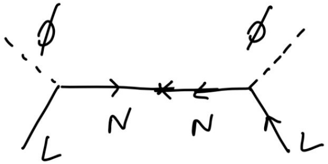
Seesaw
P. Minkowski, Phys. Lett. 67B (1977)
R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44 (1980)
J. Schechter and J. W. F. Valle, Phys. Rev. D22, 2227 (1980)
Inverse seesaw
R. Mohapatra and J. Valle, Phys. Rev. D34 (1986) 1642

Neutrino mass models

$$\mathcal{L}_5 = \frac{c}{\Lambda}\,\phi \bar{L}^c L \phi$$



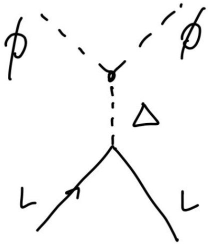
Opening up Weinberg's Operator



$$m_\nu \simeq \frac{(yv)^2}{\Lambda}$$

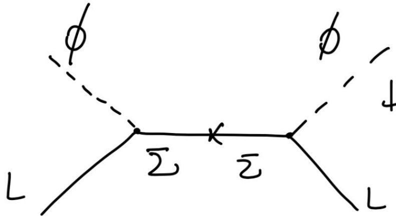
$N: (1,1,0)$

type I see-saw



type II see-saw

$\Delta: (1,3,1)$



type III see-saw

$\Sigma: (1,3,0)$

Seesaw Mechanism(s)

- Predicts HNLs
- HNLs mix with SM neutrinos
- Can be realised in many BSM models

@symmetrymagazine

Seesaw
P. Minkowski, Phys. Lett. 67B (1977)
R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44 (1980)
J. Schechter and J. W. F. Valle, Phys. Rev. D22, 2227 (1980)

Inverse seesaw
R. Mohapatra and J. Valle, Phys. Rev. D34 (1986) 1642

Minimal Type I Seesaw

Is not the only possibility ...

i.e Inverse Seesaw

$$\mathcal{L}_{\nu\,mass} = \frac{1}{2}\left(\overline{\nu_L^c}\ \overline{N_R}\right)\mathcal{M}_\nu\begin{pmatrix}\nu_L\\ N_R^c\end{pmatrix} + h.c$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$M_N \gg m_D$

$$m_\nu \approx -m_D \cdot M_N^{-1} \cdot m_D^T$$

$$m_N \approx M_N$$

$$V_{\ell N} = m_D \cdot M_N^{-1} \Rightarrow V_{\ell N}^2 \sim m_\nu / M_N$$

$$V_{\ell N} = m_D \cdot M_N^{-1} \Rightarrow V_{\ell N}^2 \sim m_\nu / M_N$$

$$(\nu_L, N_R^c, S_L)$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D^T & \epsilon^T \\ m_D & M & M_N \\ \epsilon & M_N^T & \mu \end{pmatrix}$$

$\mu \ll M_N$ Inverse seesaw $\longrightarrow V_N^2 \sim m_\nu/\mu$

Pheno approach: consider HNL mass and mixing as independent parameters

an example: minimal type I seesaw

See reviews for HNL phenomenology
M. Drewes, Int.J.Mod.Phys.E 22 (2013) 1330019, arXiv:1303.6912
F. Deppisch, P. S. Bhupal Dev, Apostolos Pilaftsis, New J.Phys. 17 (2015) 7, 075019, arXiv:1502.06541
Y. Cai, T. Han, Tong Li, R. Ruiz, Front.in Phys. 6 (2018) 40, arXiv: :1711.02180
The Present and Future Status of Heavy Neutral Leptons, Snowmass, arXiv: 2203.08039

- Predicts HNLs
- HNLs mix with SM neutrinos
- Can be realised in many BSM models

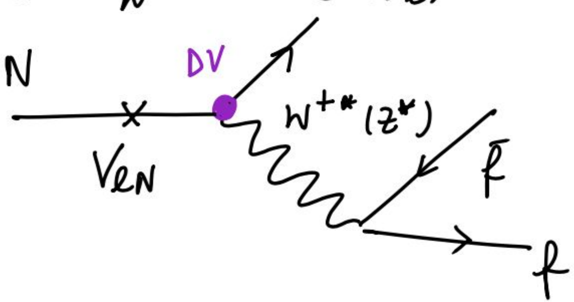
$$\mathcal{L}_{SM+N_R} = \mathcal{L}_{SM} + \bar{N}_R i \partial\!\!\!/ N_R - \left[\frac{1}{2}\bar{N}_R^c M_N N_R + \bar{L}\tilde{H} Y_N N_R + h.c.\right]$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

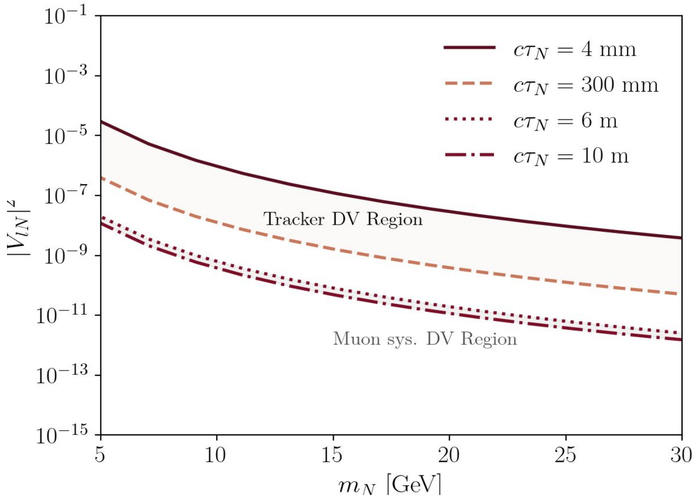
$$V_{\ell N} = m_D M_N^{-1} \Rightarrow V_{\ell N}^2 \sim m_\nu / M_N$$

$$\Gamma \sim G_F^2 \underbrace{|V_{\ell N}|^2 m_N^5}_{\text{Small mixings and} \sim \text{GeV scale HNL}} \Rightarrow \text{LLP!}$$

$m_N < m_W$



Adapted from G. Cottin, J.C. Helo and M. Hirsch, PRD 98 (2018)

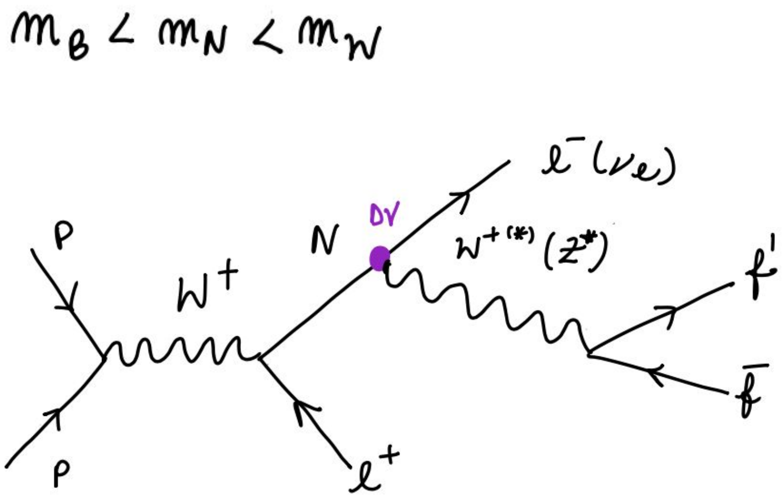


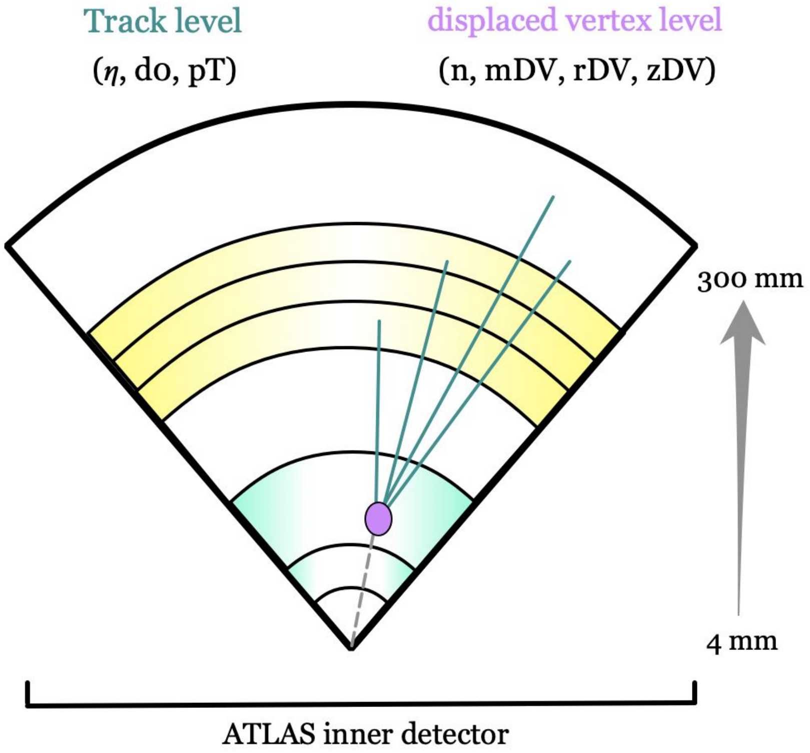
Pheno approach: consider HNL mass and mixing as independent parameters -> minimal HNL model

Catching HNLs with inner tracker displaced vertices

“HNL optimized” multitrack DV search strategy

First proposed in G. Cottin, J.C. Helo and M. Hirsch, PRD 98 (2018)
Builds up on ATLAS SUSY searches in 1710.04901, 1504.05162
Updated in R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, 2110.15096





For other proposals and mass regions at different lifetime frontier experiments see *The Present and Future Status of Heavy Neutral Leptons*, Snowmass, arXiv: 2203.08039

Image by G. Cottin

From M. Drewes and J. Hajer
https://arxiv.org/pdf/1903.06100.pdf

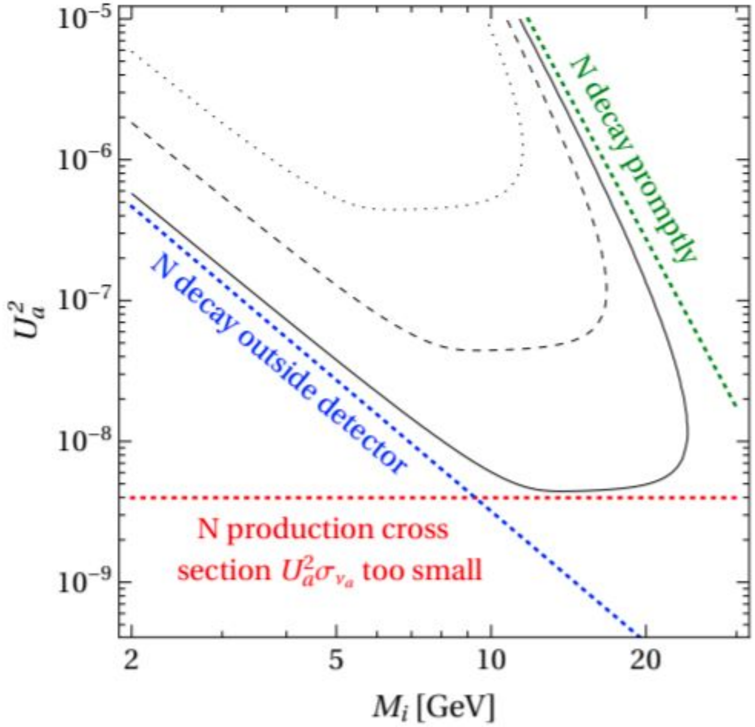


Figure 4: A simplified sensitivity estimate based on the analytic approximation (2) using $l_0 = 5\,\mathrm{mm}$ and $l_1 = 3\,\mathrm{m}$ illustrates the three main obstacles in improving the sensitivity (colored dotted lines). The three black sensitivity curves correspond to nine expected events for integrated luminosities of 3, 30, $300\,\mathrm{fb}^{-1}$, and we have assumed that all efficiencies are $100\,\%$.

Light neutralinos beyond LHC?
Super Kamiokande could catch them !

Seminal work in
Searches for Atmospheric Long-Lived Particles, C. Argüelles, P. Coloma, P. Hernández, V. Muñoz, JHEP 02 (2020) 190, arXiv: 1910.12839

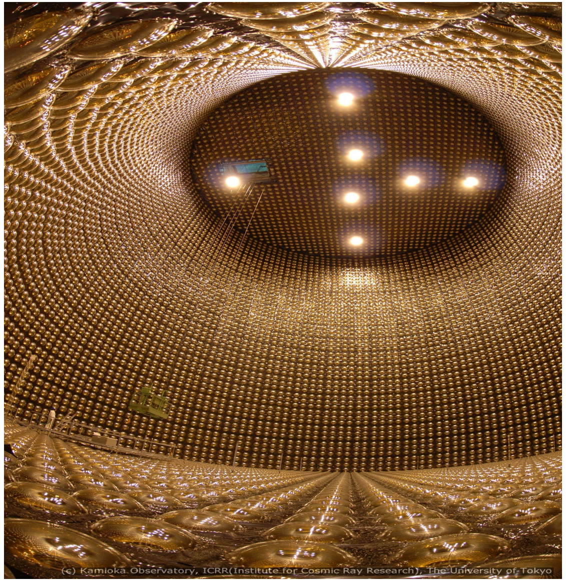


Image Source @ SK
http://www-sk.icrr.u-tokyo.ac.jp/sk/gallery/index-e.html

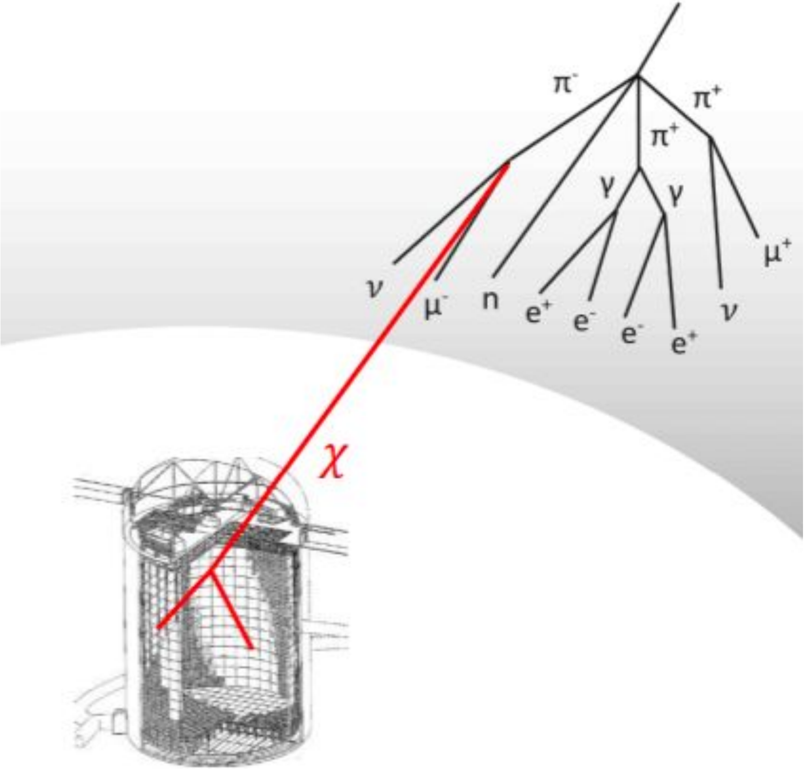


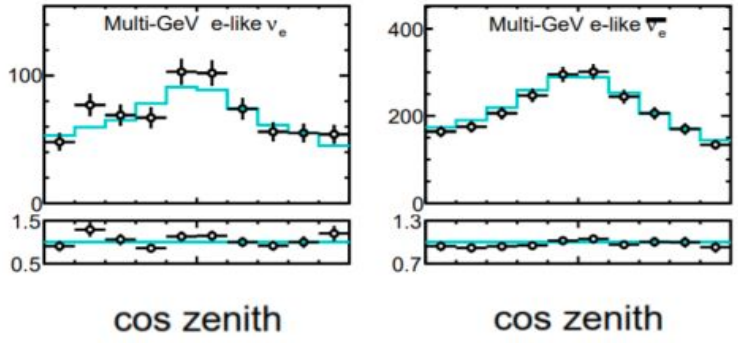
Image by P. Candia
Tenth Long-lived Particle Community Workshop, 2021

Slide from P. Candia, Tenth Long-lived Particle Community Workshop, 2021

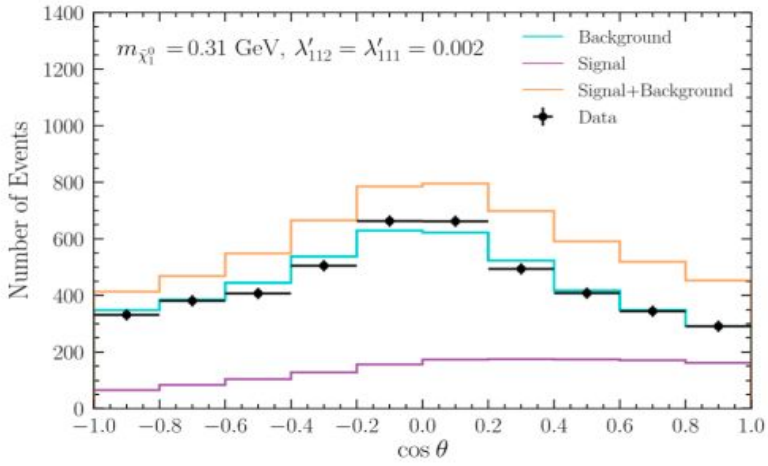
Probing BSM signals with SK data

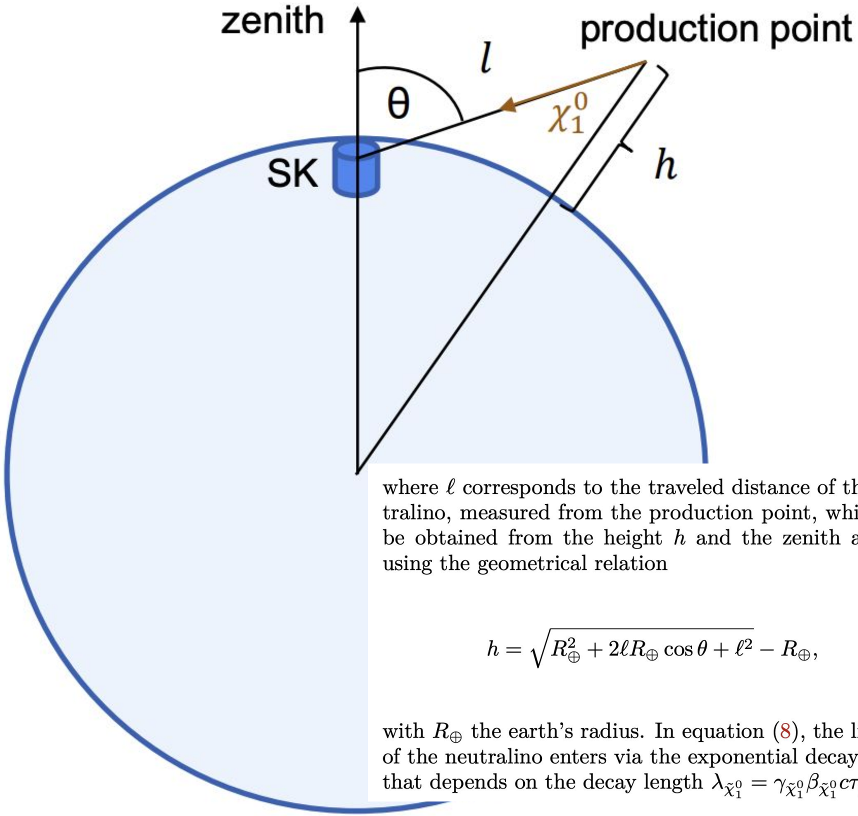
Super-K runs I-IV (5326 days)

Data obtained from [1710.09126]



We calculate an e-like signal, add it to the SM background, and compare to the SK data to probe BSM theories





where ℓ corresponds to the traveled distance of the neutralino, measured from the production point, which can be obtained from the height h and the zenith angle θ using the geometrical relation

$$h = \sqrt{R_\oplus^2 + 2\ell R_\oplus \cos\theta + \ell^2} - R_\oplus, \tag{9}$$

with $R_\oplus$ the earth's radius. In equation (8), the lifetime of the neutralino enters via the exponential decay factor that depends on the decay length $\lambda_{\tilde{\chi}_1^0} = \gamma_{\tilde{\chi}_1^0}\beta_{\tilde{\chi}_1^0}c\tau_{\tilde{\chi}_1^0}$.

The following coordinates are relevant for the production of the neutralino:

- l: Distance between the production point and the detector
- θ: zenith angle of the trajectory of the neutralino
- h: height at which the neutralino is produced

Column depth: $X = \int \rho(h, l)\, dl$

Slide from P. Candia, Tenth Long-lived Particle Community Workshop, 2021

Cascade equations and event rate

Cascade equation

$$\underbrace{\frac{d\Phi_{\chi_1^0}}{dE_{\chi_1^0}d\Omega dX}}_{\text{Differential neutralino production rate}} = \sum_M \int dE_M \frac{1}{\rho\lambda_M} \boxed{\frac{d\Phi_M}{dE_{\chi_1^0}d\Omega}} \frac{dn}{dE_{\chi_1^0}}$$

from MCEq
https://github.com/afedynitch/MCEq

ρ : atmospheric density at depth X

λ_M : decay length of the meson

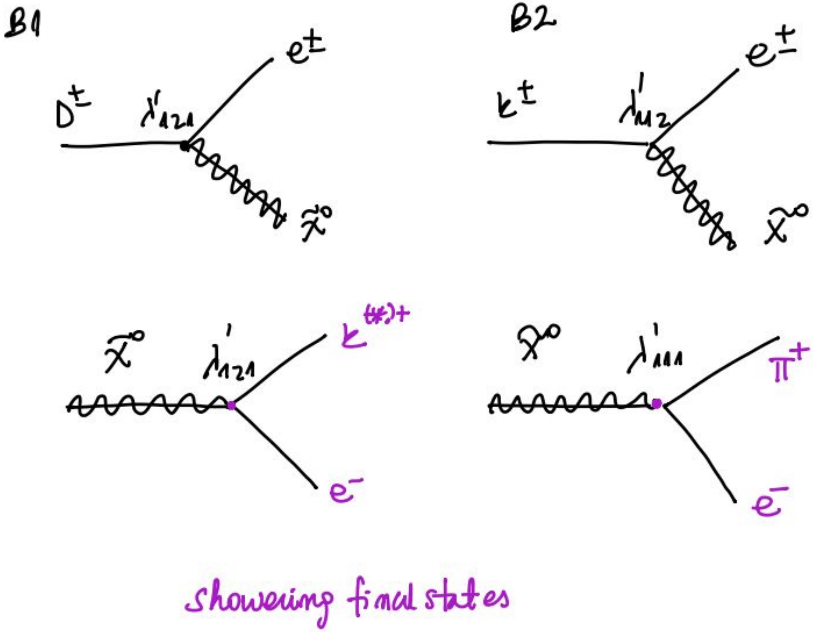
$\frac{d\Phi_M}{dE_{\chi_1^0}d\Omega}$: production rate of the parent meson

$\frac{dn}{dE_{\chi_1^0}}$: distribution of neutralinos produced in meson decays

Differential event rate

$$\frac{dN}{dE_{\chi_1^0}d\Omega} = \int dS_\perp \int dX \frac{d\Phi_{\chi_1^0}}{dE_{\chi_1^0}d\Omega dX} \overbrace{\underbrace{e^{-l/\lambda_{\chi_1^0}}\left(1 - e^{-\Delta l_{det}/\lambda_{\chi_1^0}}\right)}_{\text{Depends on neutralino lifetime } \lambda_{\chi_1^0}}}^{\text{Probability of decay in the detector volume}}$$

The differential event rate can be multiplied by the **exposure time** and integrated to get the **expected number of events**



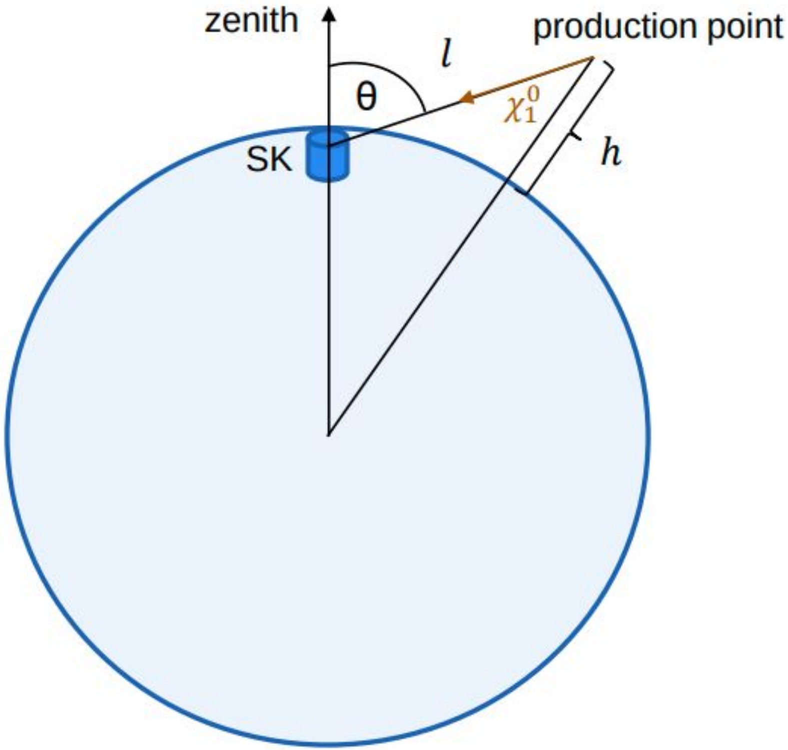
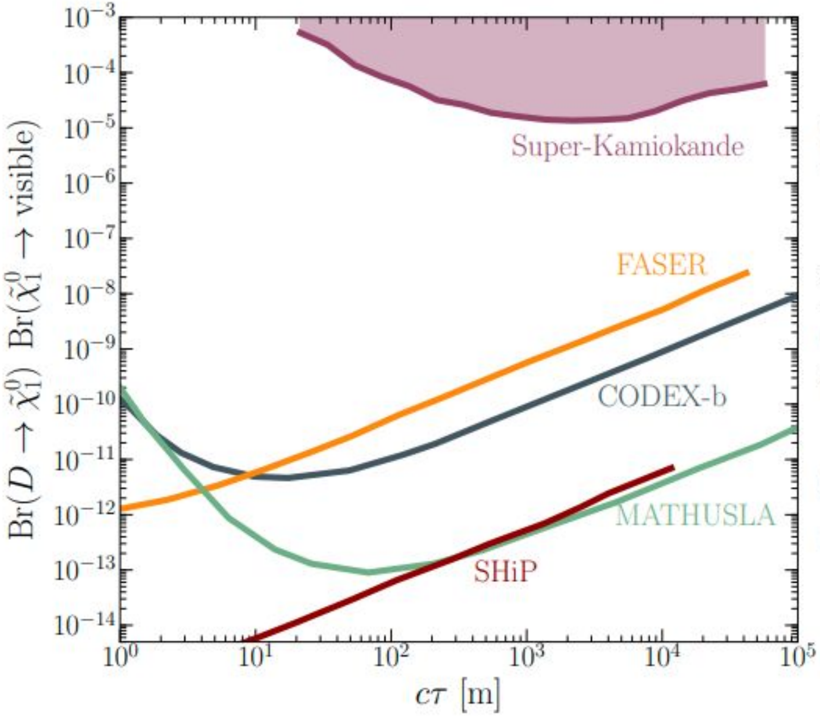


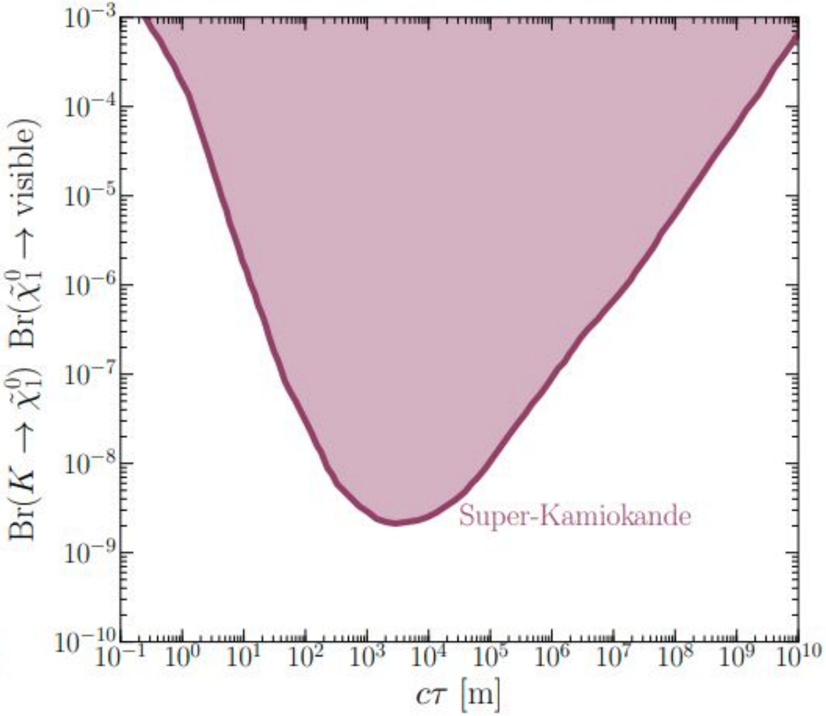
Image by P. Candia
Tenth Long-lived Particle Community Workshop, 2021

Meson production via cascade equation. Event rate is calculated considering the geometrical acceptance and neutralino probability of decay in the detector volume. We calculate the number of expected events for an *“e-like”* signal at SK (1710.09126)

Sensitivity reach with Super Kamiokande

P. Candia, G. Cottin, A. Méndez, V. Muñoz, Phys.Rev.D 104 (2021) 5, 055024, arXiv:2107.02804





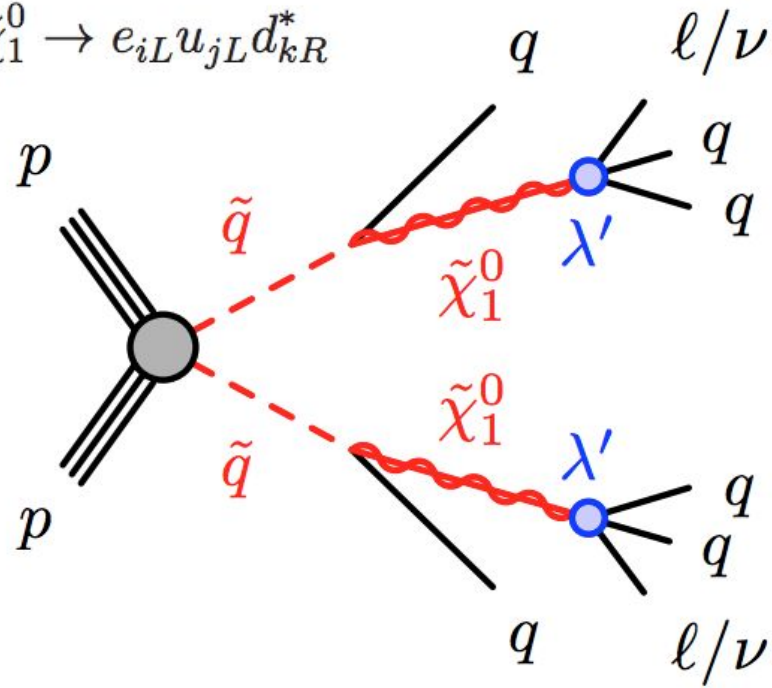
Lifetime frontier experiment projections
For SHiP, ATLAS: J. de Vries, H. Dreiner, D Schmeier, PRD 94 (2016) 035006 arXiv:1511.07436
For CODEX-b, FASER, MATHUSLA: D. Dercks, J. de Vries, D. Dreiner, Z.S. Wang, PRD 99 (2019) 055039, arXiv:1810.03617

RPV:
R. Barbier et al, Phys.Rept. 420 (2005)
H. K. Dreiner, G. G. Ross, Nucl. Phys. B365 (1991)

SUSY

$$\hat{W}_{\mathrm{RpV}} = \varepsilon_{ab}[\epsilon_i \hat{L}_i^a \hat{H}_u^b + \lambda_{ijk}\hat{L}_i^a \hat{L}_j^b \hat{E}_k + \lambda'_{ijk}\hat{L}_i^a \hat{Q}_j^b \hat{D}_k] + \lambda''_{ijk}\hat{U}_i \hat{D}_j \hat{D}_k$$

$$\tilde{\chi}_1^0 \to e_{iL} u_{jL} d_{kR}^*$$



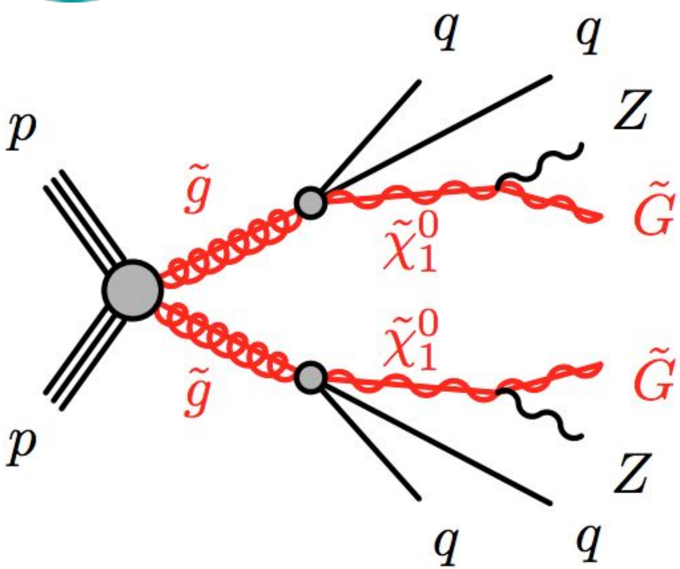
Small couplings give rise to macroscopic neutralino lifetime

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

SUSY particles in MSSM
I. Melzer-Pellmann, P. Pralavorio, Eur.Phys.J.C 74 (2014) 2801

GGM:
G. F. Giudice and R. Rattazzi, Phys. Rept. 322 (1999)

SUSY

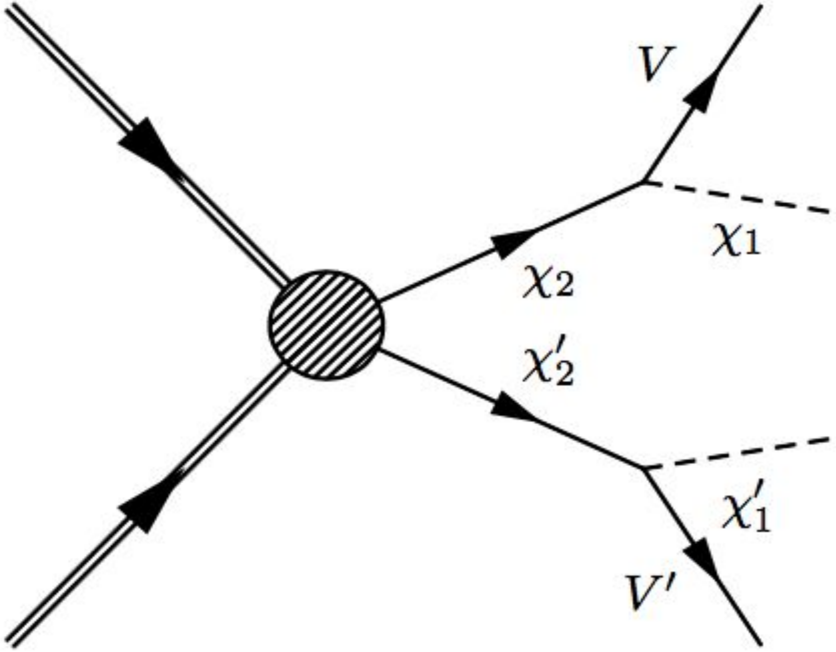


$$c\tau \simeq 130 \left(\frac{100\ \mathrm{GeV}}{m_{\tilde{\chi}_1^0}} \right)^5 \left(\frac{\sqrt{F}}{100\ \mathrm{TeV}} \right)^4 \times 10^{-3}\ \mathrm{mm}$$

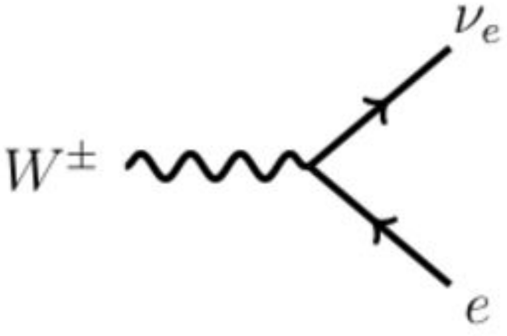
Decays to gravitino suppressed by SUSY-breaking scale

Some displaced GGM studies in:
B.C. Allanach, M. Badziak, G. Cottin, N. Desai, C. Hugonie, R. Ziegler, Eur.Phys.J. C76 (2016)
A. Delgado, G. F. Giudice, P. Slavic, Phys. Lett. B653 (2007)

Construction of a kinematic mass variable that takes into account the displaced vertex information, starting with the following hypothesis



Historic example of a kinematic mass variable, the transverse mass



$$m_W^2 = m_e^2 + m_\nu^2 + 2(E_e E_\nu - 2\vec{p}_e \cdot \vec{p}_\nu)$$

$$m_e^2 = E_e^2 - p_e^2$$
$$m_\nu^2 = E_\nu^2 - p_\nu^2$$
$$p_T \equiv (p_x, p_y)$$

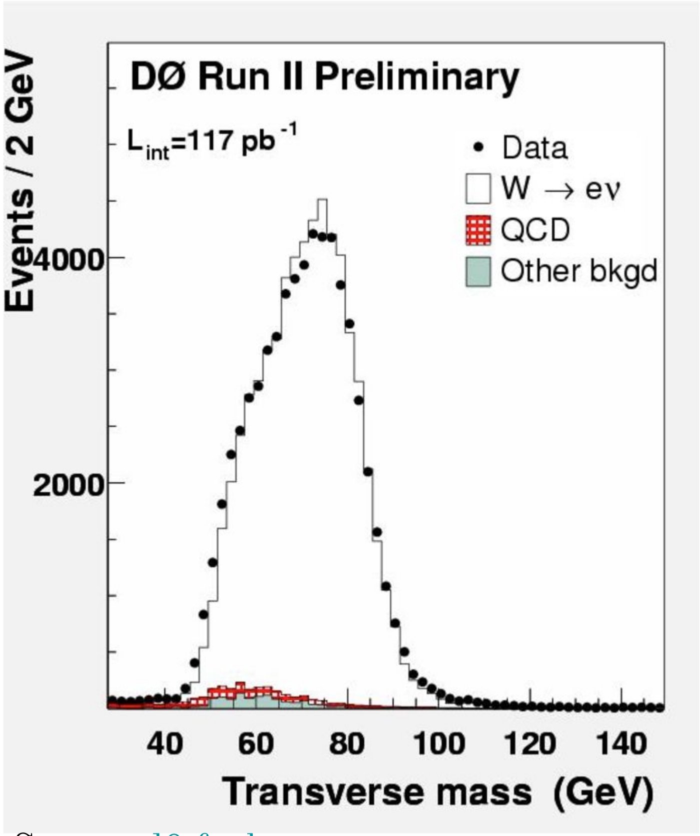
$$m_W^2 = (E_e + E_\nu)^2 - (\vec{p}_{Te} + \vec{p}_{T\nu})^2 - (p_{ze} + p_{z\nu})^2$$

$$m_T^2 \equiv (E_e + E_\nu)^2 - (\vec{p}_{Te} + \vec{p}_{T\nu})^2$$

$$m_T^2 \equiv m_e^2 + m_\nu^2 + 2(E_e E_\nu - \vec{p}_{Te} \cdot \vec{p_{T\nu}})$$

Can not directly compute W mass from the lepton and neutrino. But can know a lower limit as

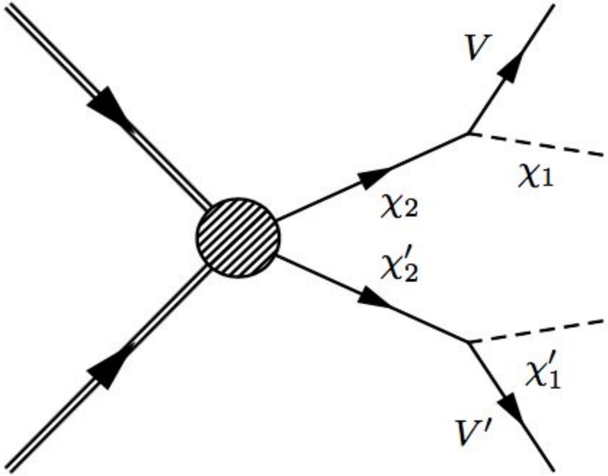
$$m_T^2 \leq m_W^2$$



Source: d0.fnal.gov

Cuts on this variable also had a big role in LHC Higgs searches

Our displaced case



$$m_{\chi_1}^2 = p_{\chi_1}^2 = p_{\chi_1'}^2$$
$$m_{\chi_2}^2 = (p_V + p_{\chi_1})^2 = (p_{V'} + p_{\chi_1'})^2$$

Including information on the displaced vertex positions **r**, we get extra knowledge on the direction of the momentum of the parent

$$p_{\chi_1}^x + p_{\chi_1'}^x = p_x^{\text{miss}}$$
$$p_{\chi_1}^y + p_{\chi_1'}^y = p_y^{\text{miss}}$$

$$\boldsymbol{p}_{\chi_2} = |\boldsymbol{p}_{\chi_2}|\frac{\boldsymbol{r}}{r} = |\boldsymbol{p}_{\chi_2}|\hat{\boldsymbol{r}}$$

$$m_{\chi_2}^2 = m_{\chi_1}^2 + m_V^2 + 2E_V\sqrt{m_{\chi_1}^2 + |\boldsymbol{p}_{\boldsymbol{\chi}_1}|^2} - 2\boldsymbol{p}_{\boldsymbol{V}} \cdot \boldsymbol{p}_{\boldsymbol{\chi}_1}$$
$$m_{\chi_2}^2 = m_{\chi_1}^2 + m_{V'}^2 + 2E_{V'}\sqrt{m_{\chi_1}^2 + |\boldsymbol{p}_{\boldsymbol{\chi}_1'}|^2} - 2\boldsymbol{p}_{\boldsymbol{V}'} \cdot \boldsymbol{p}_{\boldsymbol{\chi}_1'}$$

Unknowns

Define projections of three momenta of daughter and visible along the directions of the parent to help solve the system

$$(\boldsymbol{p}_{\boldsymbol{\chi}_1})_{\|\chi_2} = (\boldsymbol{p}_{\boldsymbol{\chi}_1} \cdot \hat{\boldsymbol{r}})\hat{\boldsymbol{r}}$$
$$(\boldsymbol{p}_{\boldsymbol{V}})_{\|\chi_2} = (\boldsymbol{p}_{\boldsymbol{V}} \cdot \hat{\boldsymbol{r}})\hat{\boldsymbol{r}}$$
$$(\boldsymbol{p}_{\boldsymbol{\chi}_1})_{\perp\chi_2} = \boldsymbol{p}_{\boldsymbol{\chi}_1} - (\boldsymbol{p}_{\boldsymbol{\chi}_1} \cdot \hat{\boldsymbol{r}})\hat{\boldsymbol{r}}$$
$$(\boldsymbol{p}_{\boldsymbol{V}})_{\perp\chi_2} = \boldsymbol{p}_{\boldsymbol{V}} - (\boldsymbol{p}_{\boldsymbol{V}} \cdot \hat{\boldsymbol{r}})\hat{\boldsymbol{r}}.$$

$$(\boldsymbol{p}_{\boldsymbol{\chi}_1})_{\perp\chi_2} = -(\boldsymbol{p}_{\boldsymbol{V}})_{\perp\chi_2}$$

$$\boldsymbol{p}_{\chi_1} = (A + B)\hat{\boldsymbol{r}} - \boldsymbol{p}_{\boldsymbol{V}}$$

$$\boldsymbol{p}_{\chi_1'} = (C + D)\hat{\boldsymbol{r}}' - \boldsymbol{p}_{\boldsymbol{V}'}$$

$$A \equiv (\boldsymbol{p}_{\chi_1} \cdot \hat{\boldsymbol{r}})$$

$$B \equiv (\boldsymbol{p}_{\boldsymbol{V}} \cdot \hat{\boldsymbol{r}})$$

$$C \equiv (\boldsymbol{p}_{\chi_1'} \cdot \hat{\boldsymbol{r}}')$$

$$D \equiv (\boldsymbol{p}_{\boldsymbol{V}'} \cdot \hat{\boldsymbol{r}}')$$

Assuming missing transverse momenta comes only from daughters

$$\boldsymbol{p}_T^{\text{miss}} = [(A + B)\hat{\boldsymbol{r}} - \boldsymbol{p}_{\boldsymbol{V}} + (C + D)\hat{\boldsymbol{r}'} - \boldsymbol{p}_{\boldsymbol{V}'}]_\perp$$

We can solve for A and C

$$A = A(p_X^{miss}, p_Y^{miss}, \hat{\boldsymbol{r}}, \hat{\boldsymbol{r}}', \boldsymbol{p}_{\boldsymbol{V}}, \boldsymbol{p}_{\boldsymbol{V}'})$$

$$C = C(p_X^{miss}, p_Y^{miss}, \hat{\boldsymbol{r}}, \hat{\boldsymbol{r}}', \boldsymbol{p}_{\boldsymbol{V}}, \boldsymbol{p}_{\boldsymbol{V}'})$$

We can rewrite the system as

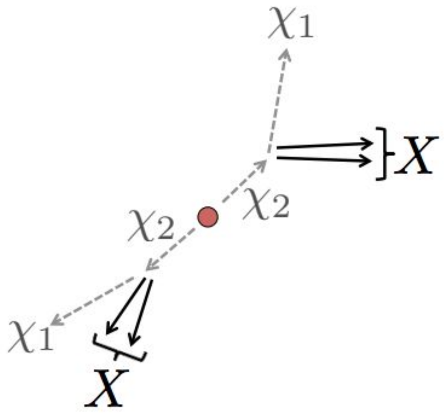
$$m_{\chi_2}^2 = m_{\chi_1}^2 + \alpha\sqrt{m_{\chi_1}^2 + \beta} + \gamma$$
$$m_{\chi_2}^2 = m_{\chi_1}^2 + \delta\sqrt{m_{\chi_1}^2 + \epsilon} + \zeta$$

$$\alpha \equiv 2E_V$$
$$\delta \equiv 2E_{V'}$$
$$\beta \equiv A^2 - B^2 + |\boldsymbol{p}_V|^2$$
$$\epsilon \equiv C^2 - D^2 + |\boldsymbol{p}_{V'}|^2$$
$$\gamma \equiv m_V^2 - 2(A+B)B + 2|\boldsymbol{p}_V|^2$$
$$\zeta \equiv m_{V'}^2 - 2(C+D)D + 2|\boldsymbol{p}_{V'}|^2$$

So we can solve event-by-event, the system is fully constrained.

In principle we have 8 solutions for the pair (m_{χ_1}, m_{χ_2})
But we are interested in the two requiring positive masses. We will see zero, one or sometimes two solutions per event.

Displaced Dark Matter Simplified Model



We use for our study the simplified displaced dark matter model in
JHEP 1709 (2017) 076 (Buchmueller, De Roeck, Hahn, McCullough, Schwaller, Sung,Yu)

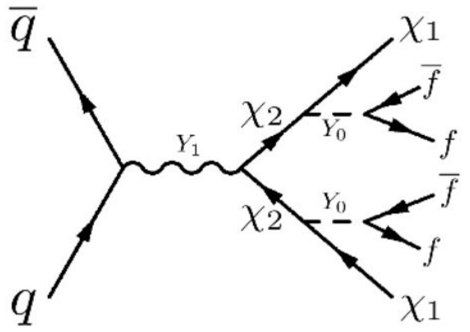


Figure 3. A representative diagram from the `DisplacedDM` model that produces displaced verticies plus $\not{E}_T$. The subscripts on Y indicate the spin of the mediator.

Simulation $q\bar{q} \to Y_1 \to \chi_2\bar{\chi}_2 \to \chi_1 Y_0 \chi_1 Y_0 \to \chi_1 f\bar{f}\chi_1 f\bar{f}.$

$c\tau \sim 20$ mm $\quad \Gamma_{\chi_2} = 1 \times 10^{-14}$

$m_{Y_1} = 1$ TeV $\quad m_{Y_0} = 40$ GeV

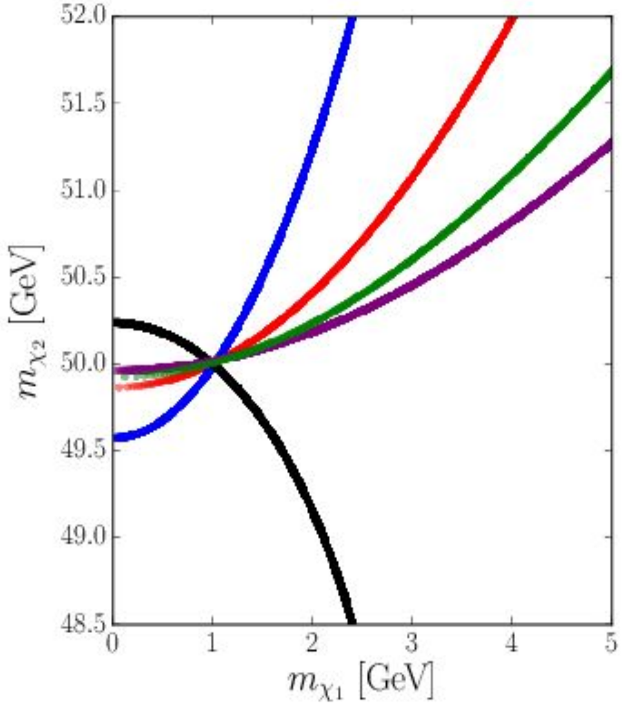
We first study events at truth level

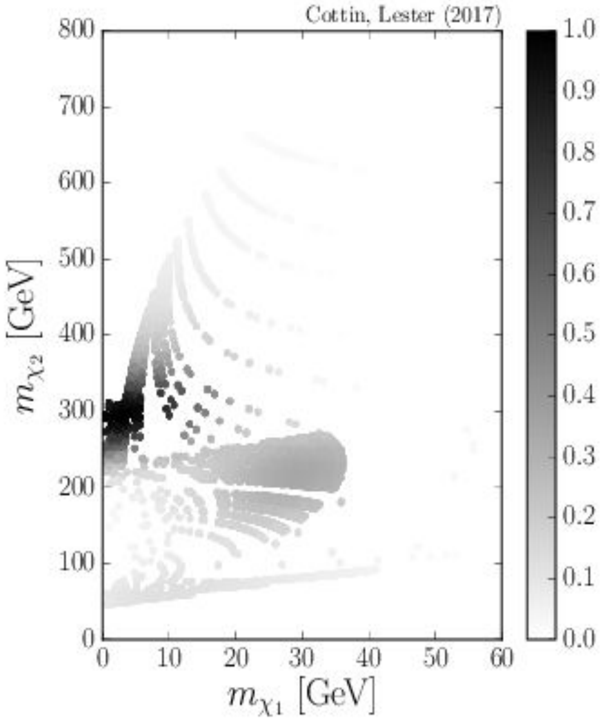
Event input

$$(\boldsymbol{r}, \boldsymbol{r'}, \boldsymbol{p_V}, \boldsymbol{p_{V'}}, p_x^{\text{miss}}, p_y^{\text{miss}})$$

$$\boldsymbol{r} \longrightarrow \boldsymbol{r} + \theta \boldsymbol{p_V}$$

$$\theta = [-0.1, 0.1]$$





$$\boldsymbol{r} \longrightarrow \boldsymbol{r} + \theta_1 \boldsymbol{p_V}$$

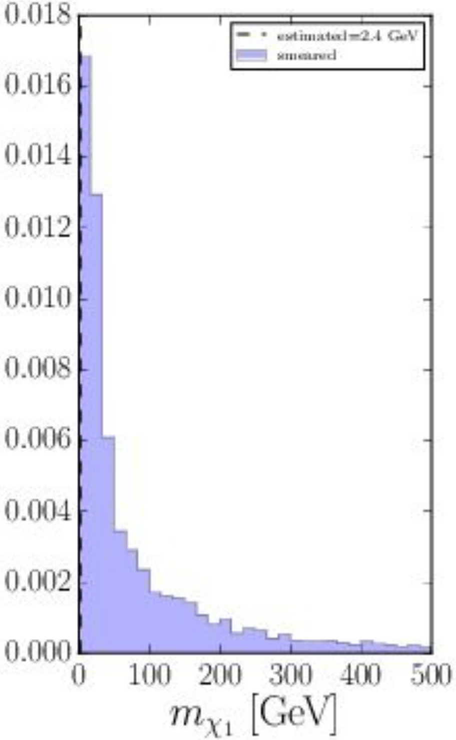
$$\boldsymbol{r'} \longrightarrow \boldsymbol{r'} + \theta_2 \boldsymbol{p_{V'}}$$

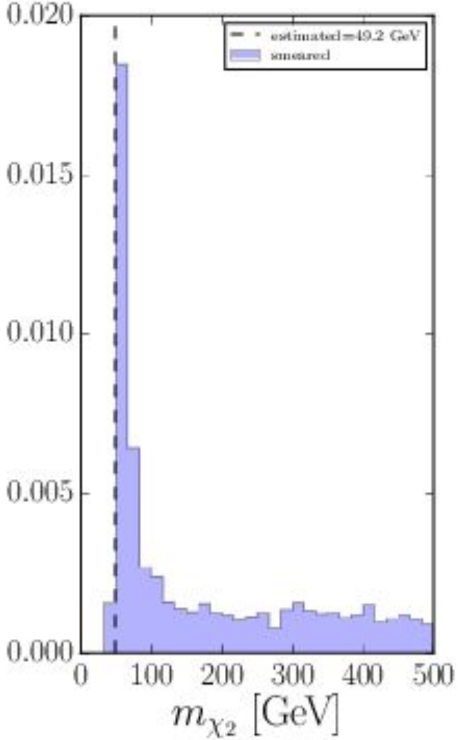
θ_1 and θ_2 are sampled from two different Normal distributions

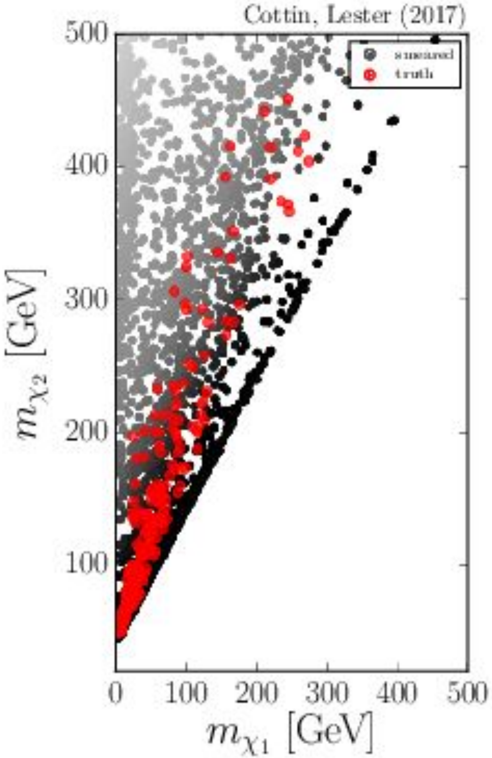
We do a detector simulation and generate the smeared quantities to solve the system again

Smeared quantities $(\boldsymbol{r}, \boldsymbol{r'}, \boldsymbol{p_V}, \boldsymbol{p_{V'}}, p_x^{\text{miss}}, p_y^{\text{miss}})$

Mass Estimation based on the 1st percentile : i.e (2.4, 49.2) for truth masses (1,50)







Our goal is to be able to extract both masses from the data.

Constructing a confidence region based on our mass estimates

Jets as Images : Deep Learning

Visual representation of a jet by displaying its energy in a grid of calorimeter towers. This image can be feed into a Neural Network (L.Oliviera et al, arXiv:1511.05190)

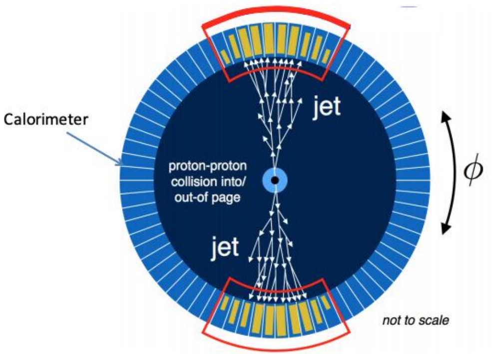
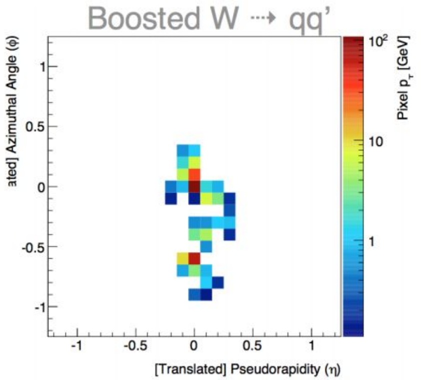
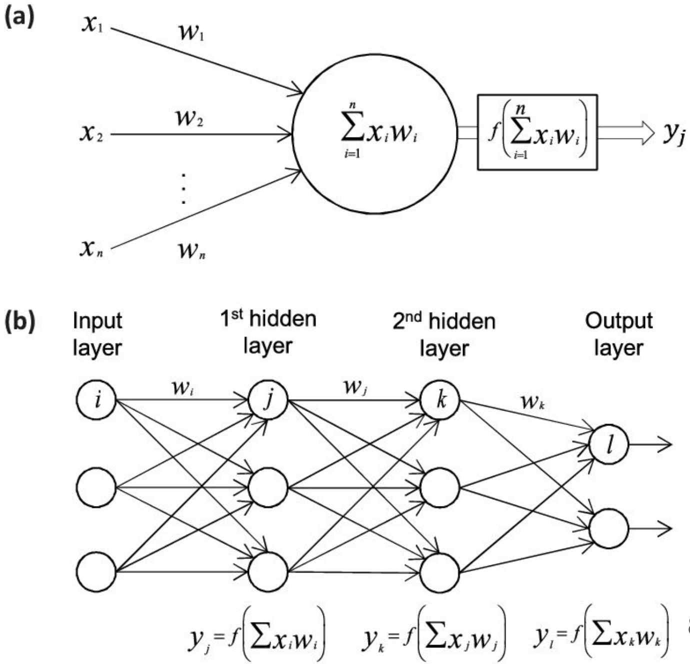


Figure credit: B. Nachman



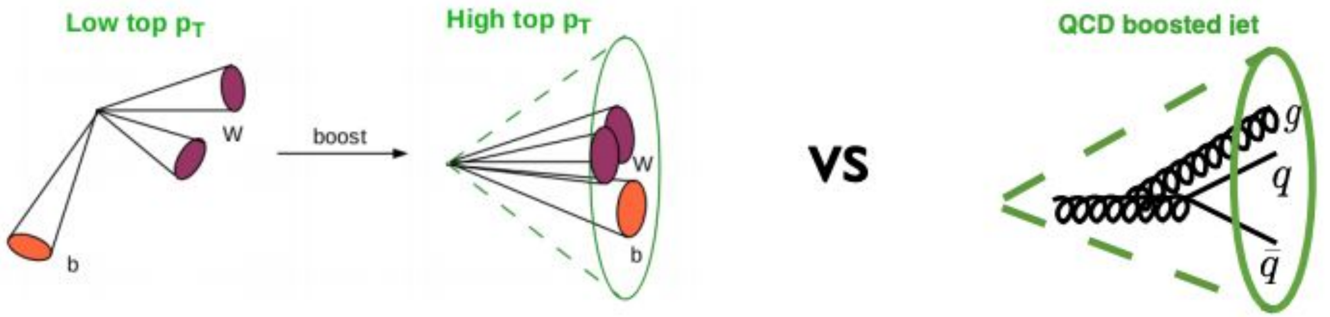


D. Shih @ PPP13 workshop

Existing Jet Classifiers with Deep Learning

Top tagging

Pearkes, Fedorko, Lister, Gay 2017
Egan, Fedorko, Lister, Pearkes, Gay 2017
Kasieczka, Plehn, Russell, Schell 2017
Butter, Kasieczka, Plehn, Russell 2018
Macaluso, Shih 2018
Butter et al 2019



D. Shih @ PPP13 workshop

Quark/gluon jet discrimination

Komiske, Metodiev, Schwartz 2017
Butter, Kasieczka, Plehn, Russell 2018
Macaluso, Shih 2018
Fraser, Schwartz 2018

Boosted weak boson/QCD-jets

ATL-PHYS-PUB-2017-004
ATLAS-CONF-2013-086
arXiv:1509.04939
CMS-PAS-JME-18-002

Our taggers : Boosted weak gauge bosons with jetCharge and Deep Learning J. Chen, C.-W. Chiang, **G. Cottin**, D. Shih Phys.Rev.D 101 (2020) 5

Many new physics particles, such as Z', W', or heavy Higgs bosons often decay to weak bosons, which are generally highly boosted and, when decaying hadronically, can form one collimated jet

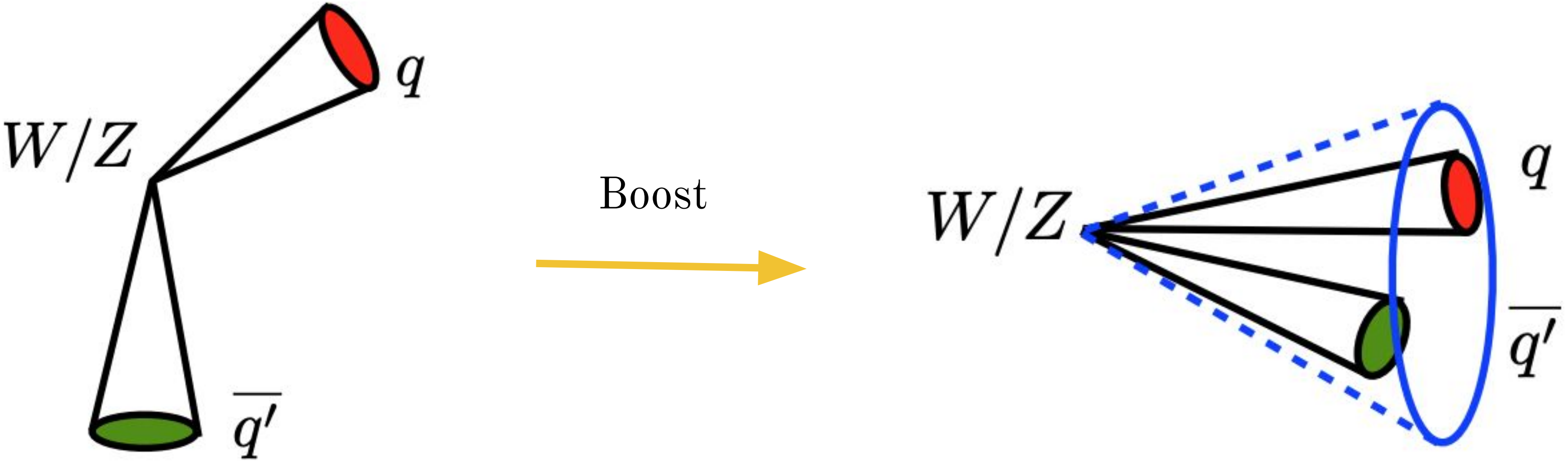


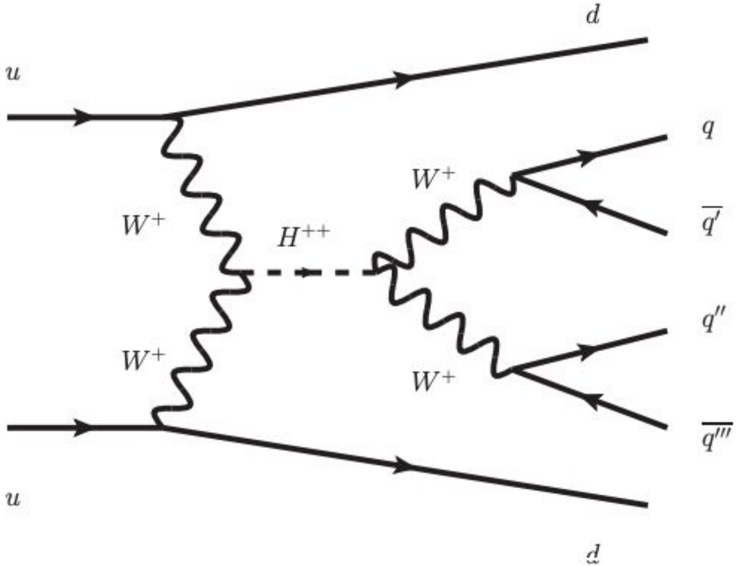
Image credit C.-W. Chiang

Our physics process

Motivated by a doubly charged Higgs decaying to W pairs

$$g v_\Delta \Delta^{++} W^- W^- + \text{h.c.}$$

$$y_{ij} \Delta^{++} \ell_i^- \ell_j^- + \text{h.c.}$$



Nucl. Phys. B 262, 463 (1985)

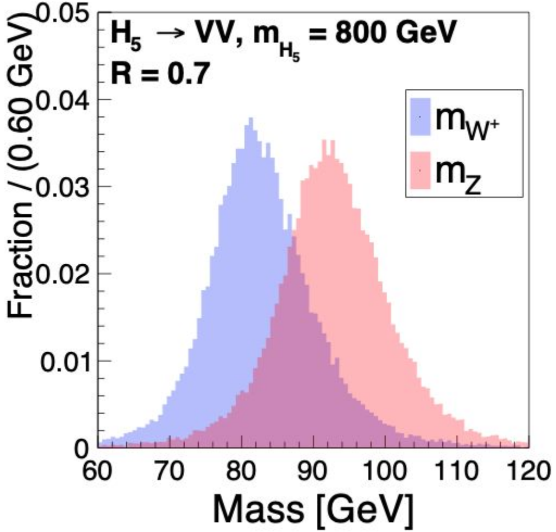
$$H_5^{\pm\pm} \rightarrow W^\pm W^\pm \rightarrow jjjj$$

$$H_5 \rightarrow ZZ \rightarrow jjjj$$

High-level Inputs

Jet invariant Mass

$$\mathcal{M}_J^2 = \left(\sum_{i\in J} E_i\right)^2 - \left(\sum_{i\in J} \mathbf{p}_i\right)^2$$

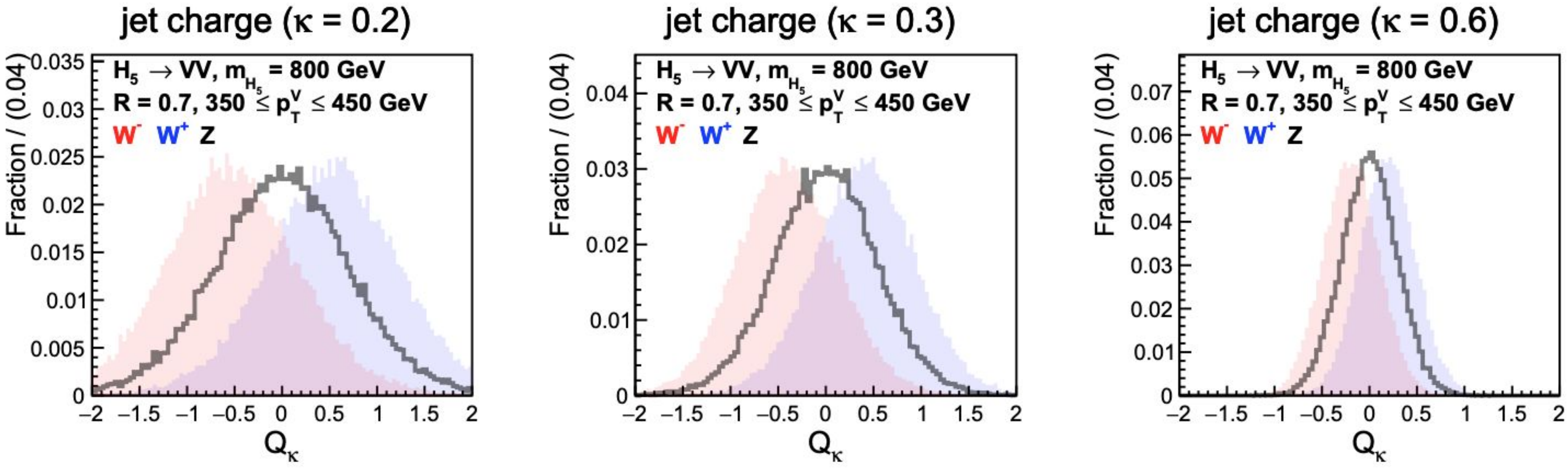


High-level Inputs

Jet Charge

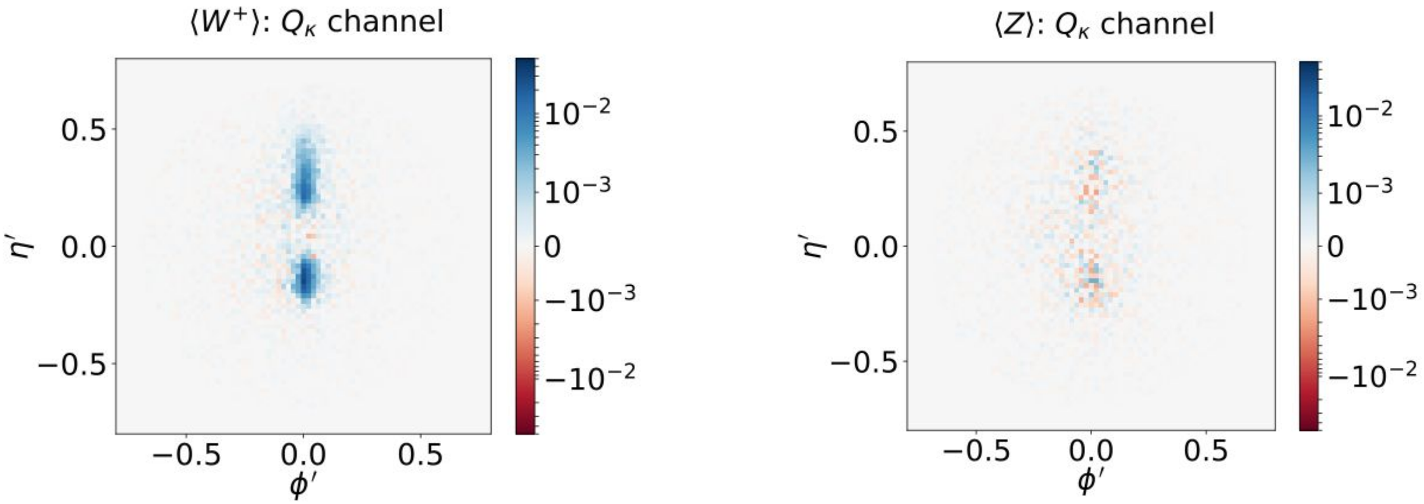
[Field, Feynman 1978, Nucl. Phys. B136 (1978) 1.]

$$\mathcal{Q}_\kappa = \frac{1}{p_{T,J}^\kappa}\sum_{i\in J} q_i \times (p_T^i)^\kappa$$



CNN Taggers using High-level Inputs based on Jet Images

Implemented with Keras. Taggers made from lower-level inputs, jet charge and pT per pixel



Average of jet images in the jet charge channel with fixed kappa = 0.15

Our CNNs

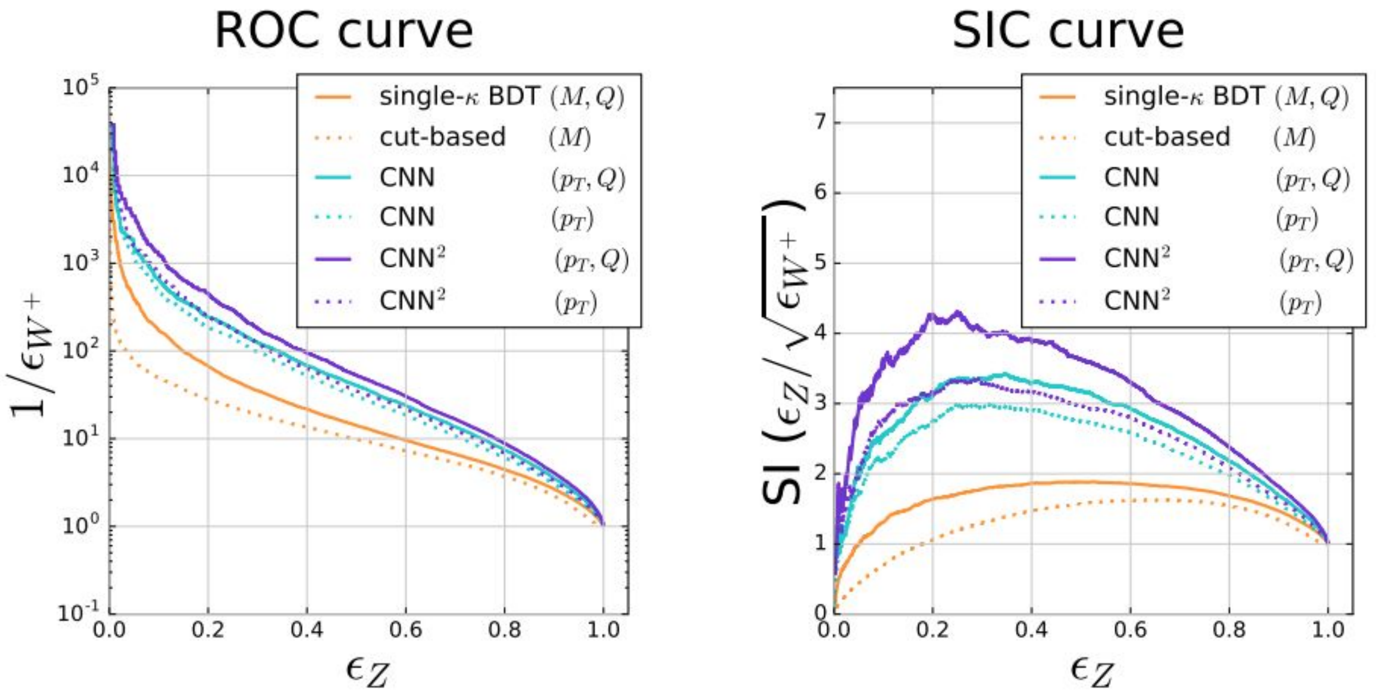
	CNN	CNN^2	
Image	(75×75) pixels within $(\lvert\eta\rvert \leq 0.8,\ \lvert\phi\rvert \leq 0.8)$		
Channels	$p_T,\ \mathcal{Q}_\kappa$	p_T	$\mathcal{Q}_\kappa$
Architecture	BN-32C6-MP2-128C4-MP2-256C6-MP2-512N-512N	BN-32C3-32C3-MP2-64C3-MP2-64C3-MP2-64C3-64C3-128C5-256C5-256N-256N	BN-32C3-32C3-MP2-64C4-64C4-MP2-256C6-MP2-256N
Settings	`Relu` Activation, `Padding=same`, *Dropout* $= 0.5$, l2 `Regularizer` $= 0.01$		
Preprocessing	*Centralization, Rotation, Flipping*		
Training	Adam Optimizer, `Minibatchsize`$=512$, *Cross entropy* loss		

A deeper Q tends to overfit in a W+/W- classification

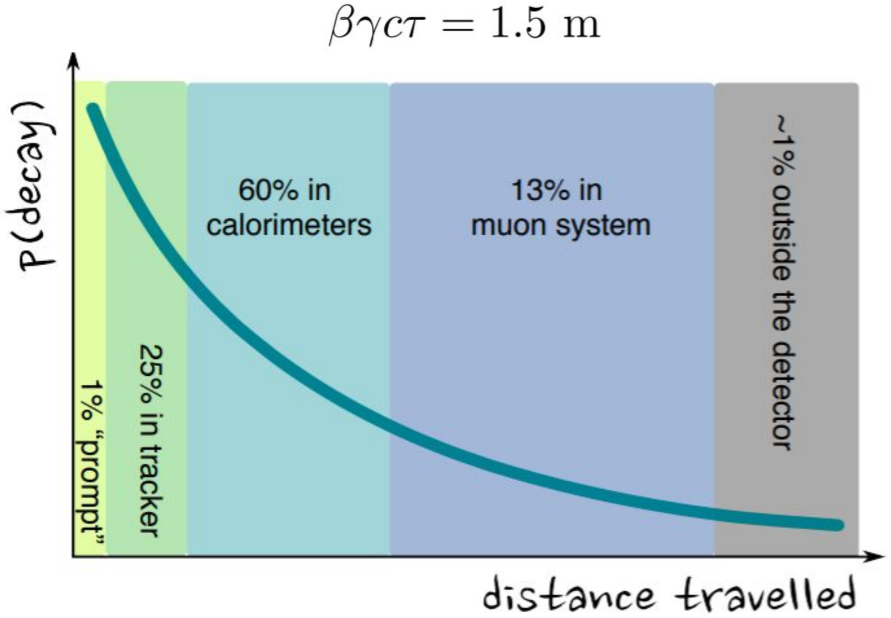
A deeper pT helps in Z/W+ classification

Example: Z/W+ Classification

~30% gain in background rejection rate by incorporating jet charge with our CNN taggers



LHC-LLP searches can target different lifetimes using different parts of the detectors. Detection usually requires special triggers and reconstruction



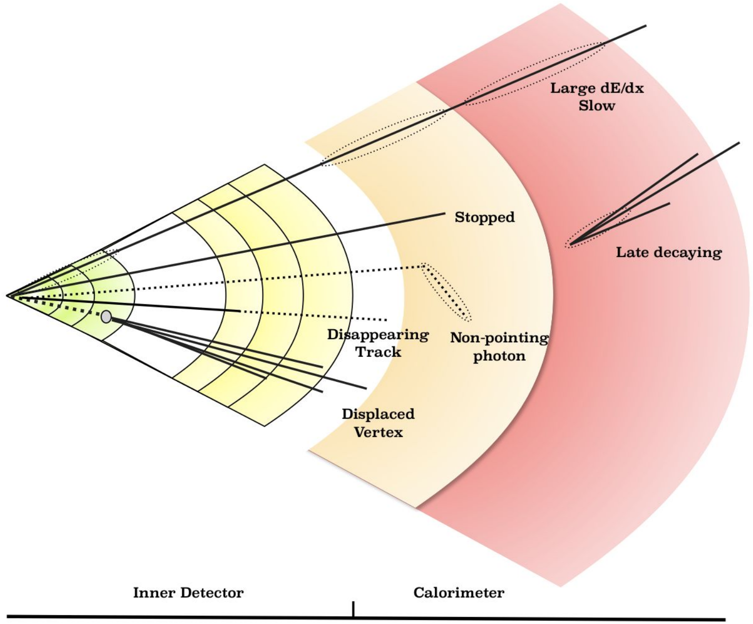
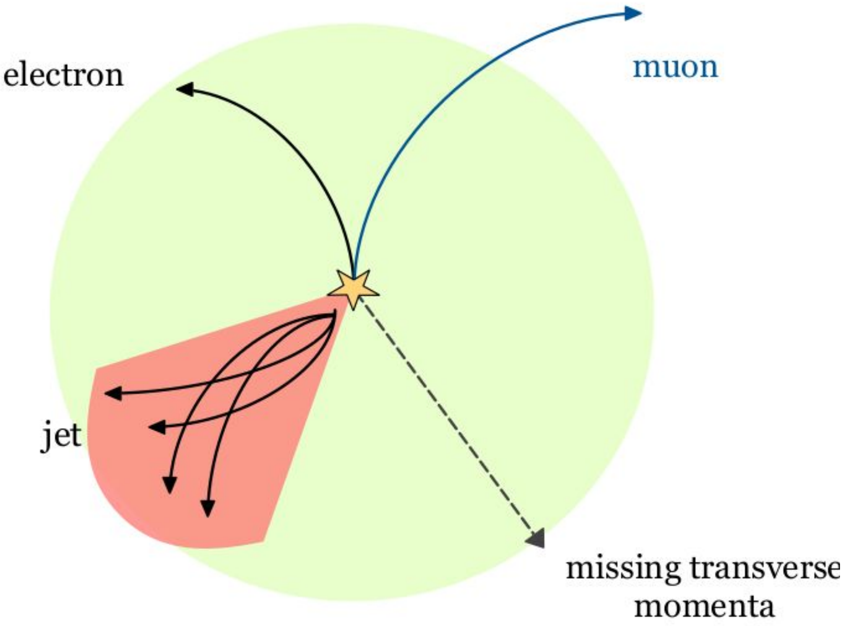


Image by Heather Russel (based on ATLAS geometry)
Long-lived Particle Community Workshop, 2017

Image by G. Cottin

Depending on where the LLP decays and which quantum numbers it has, this will give rise to different exotic signatures



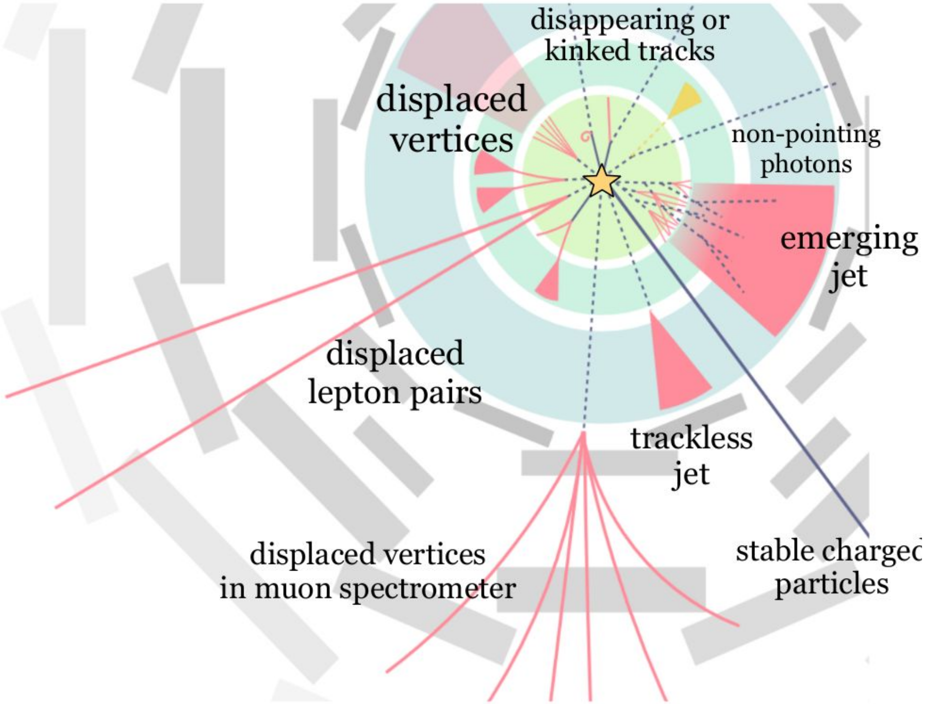


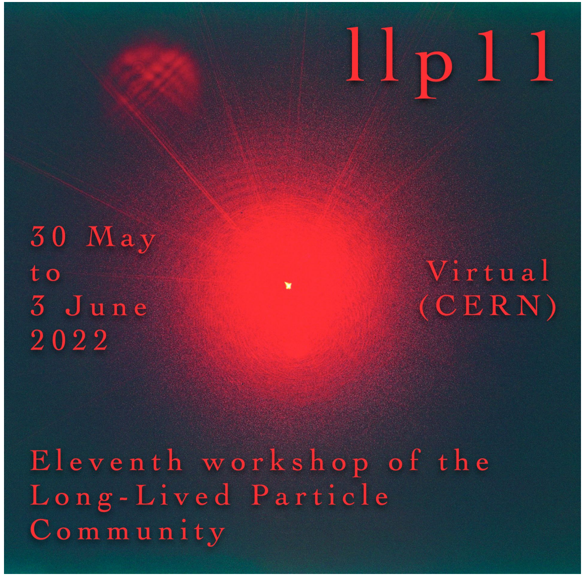
Image by G. Cottin

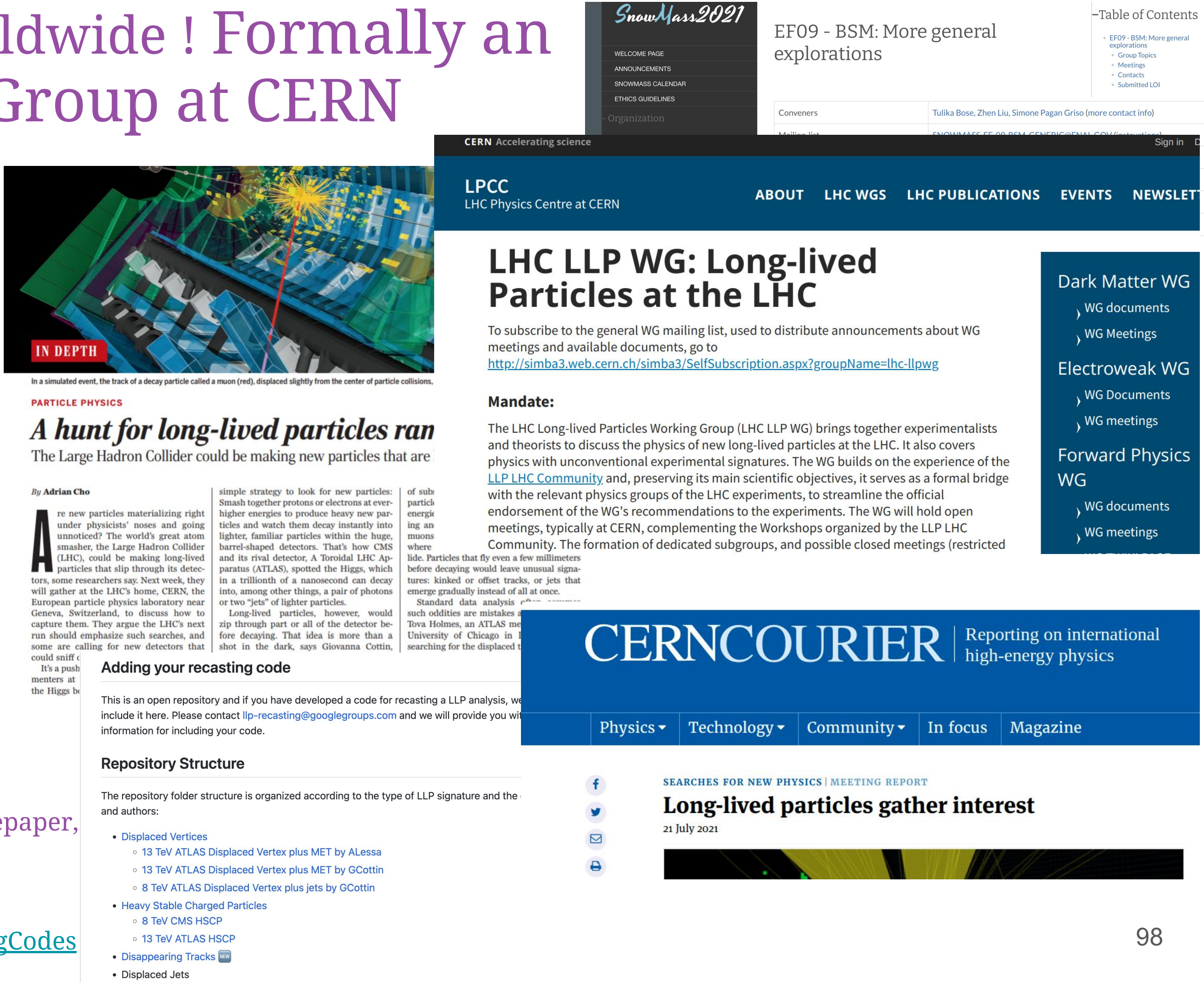
LLP Image adapted from Heather Russel.

Long-lived Particle Community White Paper, J. Alimena, .. , G. Cottin, et al, arXiv:1903.04497

Many LLP efforts worldwide ! Formally an LHC LLP Working Group at CERN

LLP Community https://cern.ch/longlivedparticles
LLP WG https://lpcc.web.cern.ch/lhc-llp-wg





Activities within LLP Community and WG (whitepaper, regular workshops, recasting repo)
You can subscribe to LLP-WG egroup !
LLP Community White Paper arXiv:1903.04497
LLP repo https://github.com/llprecasting/recastingCodes

Formally an LHC LLP Working Group at CERN

CERN Accelerating science

Sign in

LPCC
LHC Physics Centre at CERN

ABOUT LHC WGS LHC PUBLICATIONS EVENTS NEWSLETT

LHC LLP WG: Long-lived Particles at the LHC

To subscribe to the general WG mailing list, used to distribute announcements about WG meetings and available documents, go to http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-llpwg

Mandate:

The LHC Long-lived Particles Working Group (LHC LLP WG) brings together experimentalists and theorists to discuss the physics of new long-lived particles at the LHC. It also covers physics with unconventional experimental signatures. The WG builds on the experience of the LLP LHC Community and, preserving its main scientific objectives, it serves as a formal bridge with the relevant physics groups of the LHC experiments, to streamline the official endorsement of the WG's recommendations to the experiments. The WG will hold open meetings, typically at CERN, complementing the Workshops organized by the LLP LHC Community. The formation of dedicated subgroups, and possible closed meetings (restricted

Dark Matter WG
- WG documents
- WG Meetings

Electroweak WG
- WG Documents
- WG meetings

Forward Physics WG
- WG docum
- WG meetir

https://lpcc.web.cern.ch/lhc-llp-wg

You can get in touch and/or subscribe to the mailing list for news !

Main goals are:

- Facilitate communication between theorist and experimentalists
- Provide recommendation for benchmark models to be used in LLP interpretation
- Provide recommendation for presentation of experimental results in a useful way for reinterpretation
- Discuss new search directions based on new input from theory or experiment

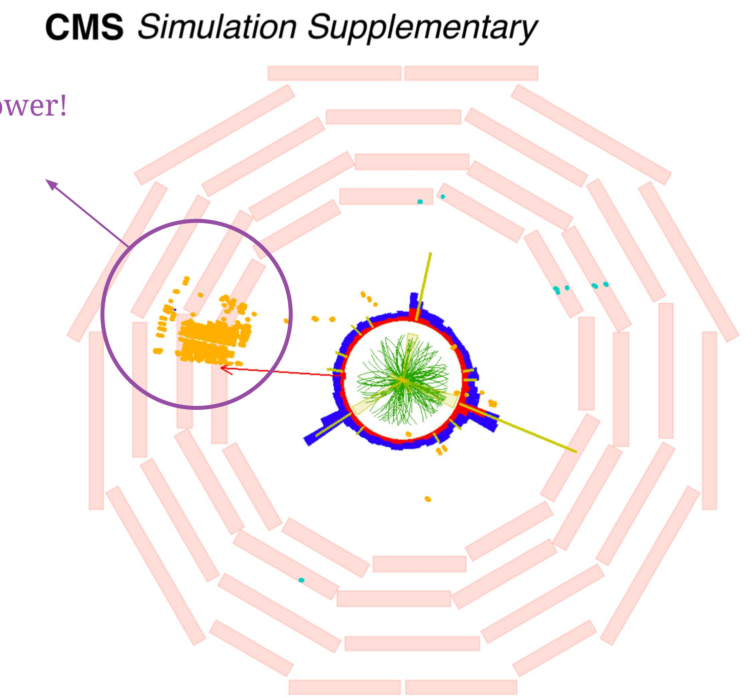
Conveners:

- ATLAS: Simone Pagan Griso and Emma Torro Pastor
- CMS: Alberto Escalante del Valle and Larry Lee
- FASER: Dave Casper
- LHCb: Federico Leo Redi and Carlos Vázquez Sierra
- MoEDAL: James Pinfold
- SND@LHC: Cristovao Vilela
- Theory: Giovanna Cottin, Nishita Desai and José Zurita
- Reach all through lhc-llpwg-admin@cern.ch

Tau-mixing not covered yet at LHC, what can we do?

2) New signature of a displaced shower in the CMS muon system

displaced shower!

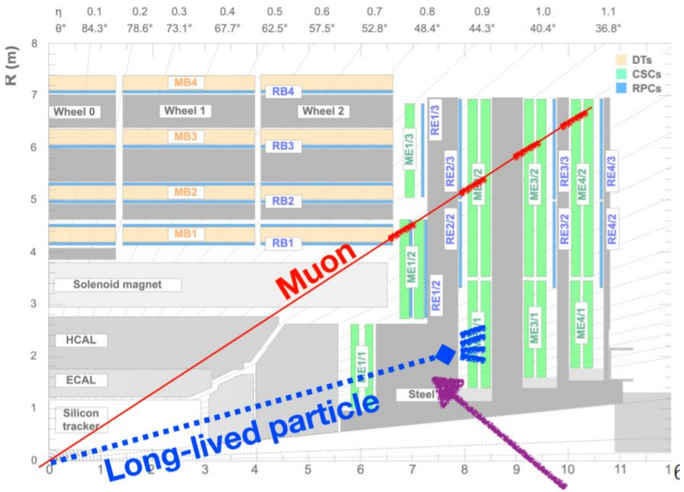


http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-20-015/

- We reinterpret* a search for a SM Higgs boson decaying to long-lived scalars (which can subsequently decay to taus), *Phy. Rev. Lett. 127 (2021)*, arXiv:2107.04838

- Search is sensitive to LLPs decaying to hadrons, *taus*, electrons, or photons. Large CMS steel shielding useful to suppress backgs.

- The CMS unique signature relies on large cluster of Cathode Strip Chamber (CSC) hits in the muon system (Nhits)

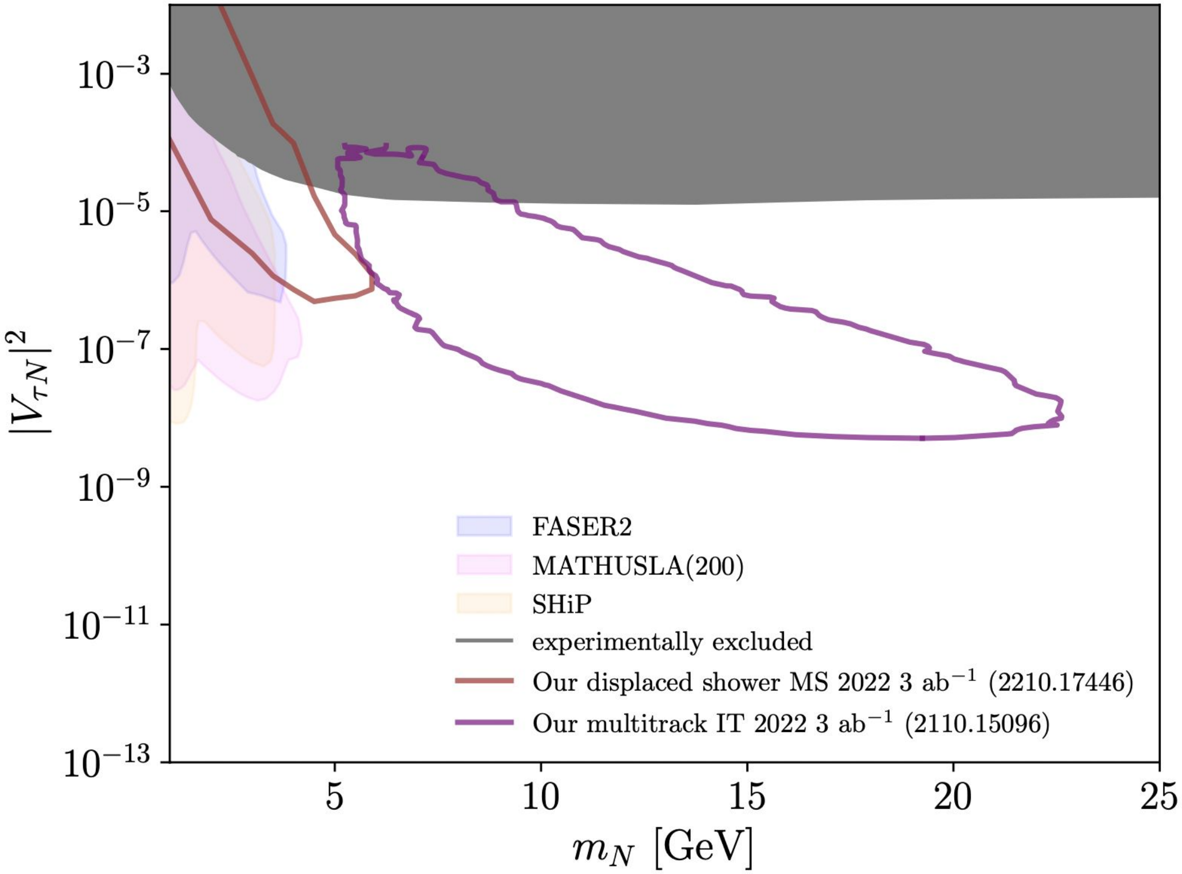


@ 7th LLP Workshop, see talk by Sven Dildick

* Reinterpretation relies on the implementation of a new Delphes module made specifically for muon system showers from LLP decays (https://github.com/delphes/delphes/pull/103)

Tau-mixing not covered yet at LHC, what can we do?

Propose new searches with current LHC detector subsystems !



FASER projection from F. Kling, S. Trojanowski (1801.08947)
MATHUSLA projection from J.C. Helo, M. Hirsch, Z.S. Wang (1803.02212)
SHiP projection from (1504.04956)

Not all the parameter space of all BSM models predicting HNLs is covered at the LHC, what can we do? Go to NRSMEFT to systematically study them !

$$\mathcal{L}_{N_R\,SMEFT} = \mathcal{L}_{SM+N_R} + \sum_{d\geq 5} \frac{1}{\Lambda^{d-4}} \sum_i c_i^{(d)} \mathcal{O}_i^{(d)}$$

d=6 four-fermion operators with *a single* HNL

R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, 2110.15096 (JHEP 01 (2022) 044)

Name	Structure (+ h.c.)	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{duNe}$	$(\overline{d_R}\gamma^\mu u_R)(\overline{N_R}\gamma_\mu e_R)$	54	162
$\mathcal{O}_{LNQd}$	$(\overline{L}N_R)\,\epsilon\,(\overline{Q}d_R)$	54	162
$\mathcal{O}_{LdQN}$	$(\overline{L}d_R)\,\epsilon\,(\overline{Q}N_R)$	54	162
$\mathcal{O}_{LNLe}$	$(\overline{L}N_R)\,\epsilon\,(\overline{L}e_R)$	54	162
$\mathcal{O}_{QuNL}$	$(\overline{Q}u_R)(\overline{N_R}L)$	54	162

First developed in
F. del Aguila, S. Bar-Shalom, A. Soni, J. Wudka, 0806.0876 (Phys.Lett.B670, 2008)
A. Aparici, K. Kim, A. Santamaria, J. Wudka, 0904.3244 (Phys.Rev.D80, 2009)
Basis for d<=9 in
H.-L. Li, Z. Ren, M.-L. Xiao, J.-H. Yu, Y.-H. Zheng, 2105.09329

d=6 four-fermion operators with *pairs* of HNL

G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, 2105.13851, (JHEP 09 (2021) 039)

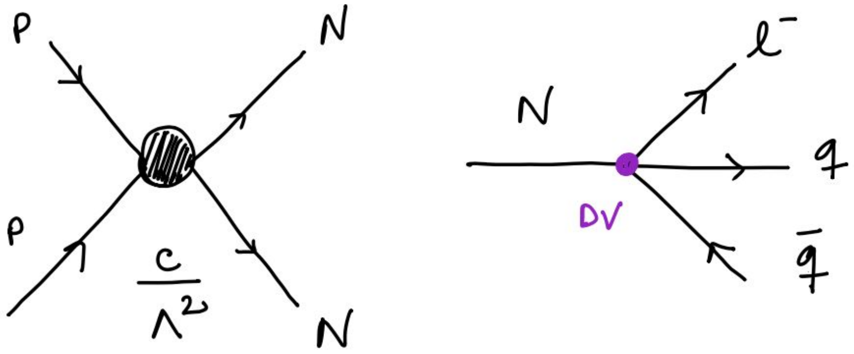
Name	Structure	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma^\mu d_R)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{uN}$	$(\overline{u_R}\gamma^\mu u_R)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{QN}$	$(\overline{Q}\gamma^\mu Q)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{eN}$	$(\overline{e_R}\gamma^\mu e_R)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{NN}$	$(\overline{N_R}\gamma_\mu N_R)(\overline{N_R}\gamma_\mu N_R)$	1	36
$\mathcal{O}_{LN}$	$(\overline{L}\gamma^\mu L)(\overline{N_R}\gamma_\mu N_R)$	9	81

Additional HNLs in EFT with LLPs at the LHC studies
d=5 in A. Caputo, P. Hernandez, J. Lopez-Pavon, J. Salvado, JHEP 06 (2017)
Jordy de Vries, H. K. Dreiner, J. Y. Günther, Z. S. Wang, G. Zhou, JHEP 03 (2021)
R.Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, JHEP 01 (2023)

N_RSMEFT sensitivity with displaced vertices

For *d=6* four-fermion operators with *pairs* of HNL G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, [2105.13851](), (JHEP 09 (2021) 039)

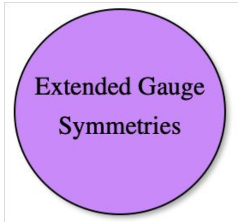
- Production dominated by the operator
- HNLs decay only via their mixing with the active neutrinos
- DV strategy proposed for ATLAS inner tracker
- Probability of displaced decay in fiducial volume in far detectors (extending model space coverage)

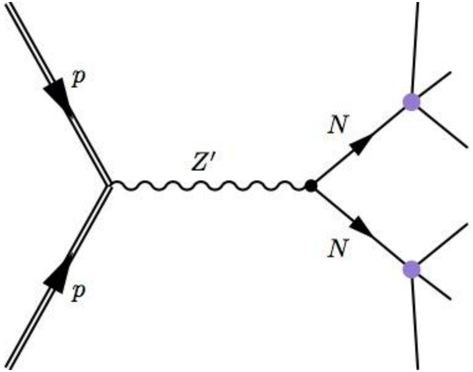


d=6, diff. mass regime in R.Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, JHEP 01 (2023)

Simplified Models are an effective-Lagrangian description with :

* A limited number of new particles considered
* A specific production and decay channels (i.e 100% BR)
* A few free parameters (mainly masses and lifetime)
* A compact and efficient way to benchmark models, as oppose to the design of separate (potentially redundant) searches for each UV model





$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}V_{\mu\nu}^2 - \frac{1}{2}M_V^2 V_\mu^2 + iN^\dagger\bar{\sigma}^\mu\partial_\mu N - \frac{M_N}{2}(N^2 + \text{h.c.}) + g'V_\mu\left(\sum_{\rm SM} Q_{B-L}\psi^\dagger\bar{\sigma}^\mu\psi + N^\dagger\bar{\sigma}^\mu N\right) + \theta_{\mu N}\frac{g_W}{\sqrt{2}}\left(\mu_L^\dagger\bar{\sigma}^\mu W_\mu^- N + \text{h.c.}\right) + \ldots,$$

B. Battel, M. Pospelov and B. Shuve, JHEP 1608 (2016)

Many LLP experiments needed to target complementary regions in model parameter space. We can help make the physics case for them to be a reality !

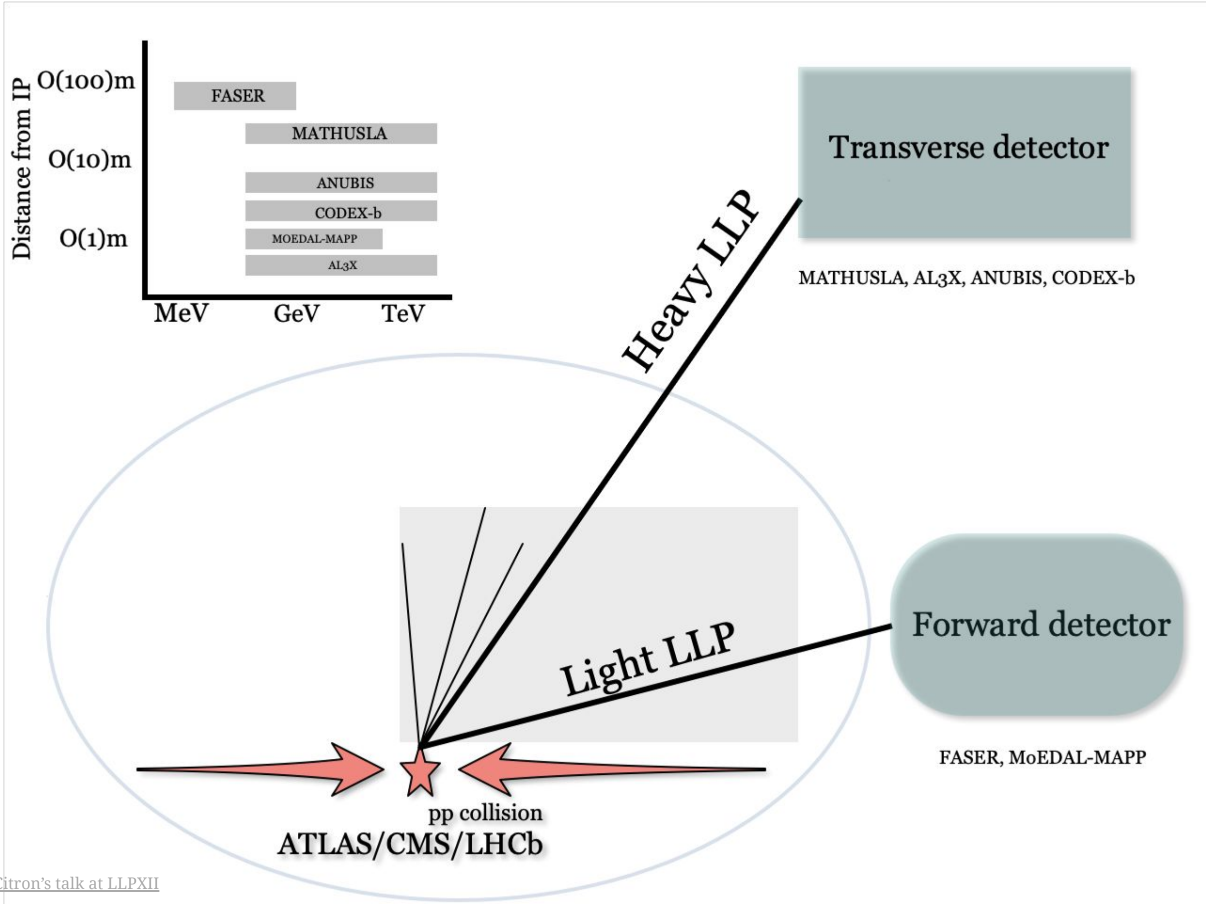


Image by G. Cottin inspired by M.Citron's talk at LLPXII

Examples of two LHC measurements: anomalies in the data could already be pointing to new physics?

W boson mass, measured in 2018 by the ATLAS collaboration, *Eur.Phys.J.C 78 (2018) 2*, arXiv:1701.07240

$pp \to W^\pm \to \ell^\pm \nu$

$m_e^2 = E_e^2 - p_e^2$

$m_\nu^2 = E_\nu^2 - p_\nu^2$

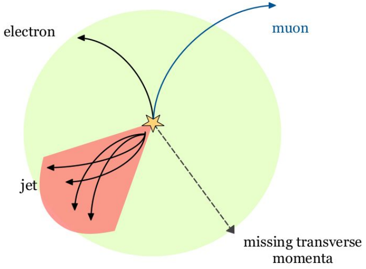
$p_T = (p_x, p_y)$

Mass extraction from templates that fit the kinematics, i.e.

$$m_W^2 = m_e^2 + m_\nu^2 + 2(E_e E_\nu - 2\vec{p}_e \cdot \vec{p}_\nu)$$

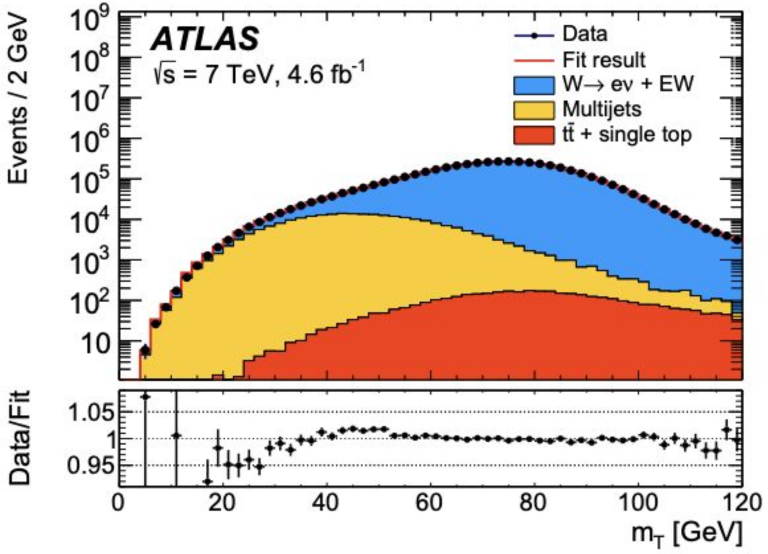
$$m_W^2 = \underbrace{(E_e + E_\nu)^2 - (\vec{p}_{Te} + \vec{p}_{T\nu})^2}_{\equiv\, m_T^2} - (p_{ze} + p_{z\nu})^2$$

$$\vec{p}_T^{\,miss} \equiv -(\vec{p}_{Te} + \sum_i \vec{E}_i)$$ with i all visible



$$m_T^2 \equiv 2 p_{Te}\, p_T^{miss} (1 - \cos\Delta\phi)$$ → this can be experimentally reconstructed from data

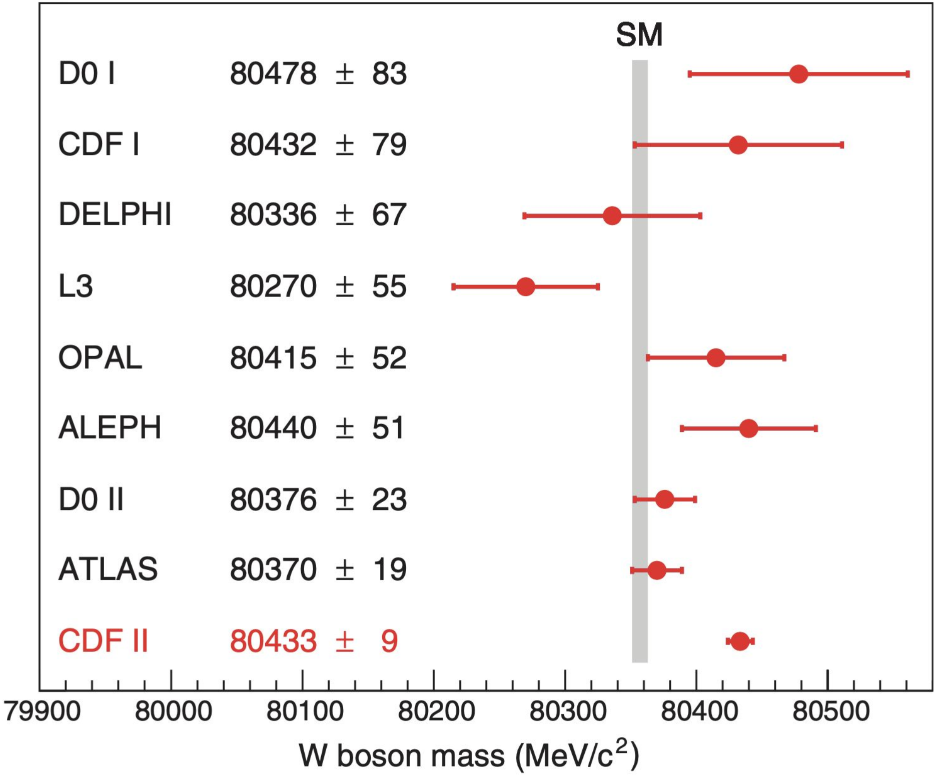
$$m_T^2 \leq m_W^2$$



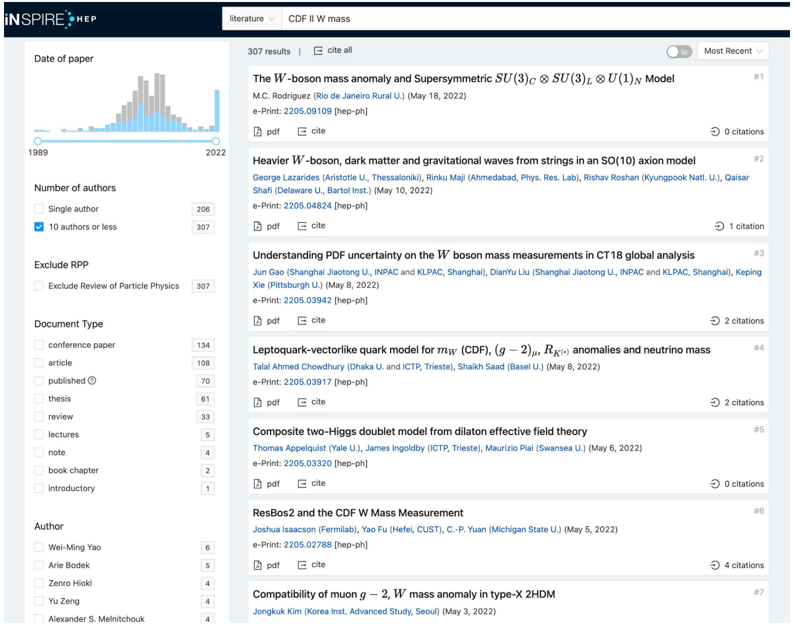
Run 3 of the LHC of top importance to elucidate this world tension

CDF result reports a difference with a significance of 7sigma w.r.t the SM prediction

High-precision measurement of the W boson mass with the CDF II detector, CDF Collaboration, [Science 376, 170–176 (2022)]()



"Ambulance chasing" with over 300 theory interpretations!



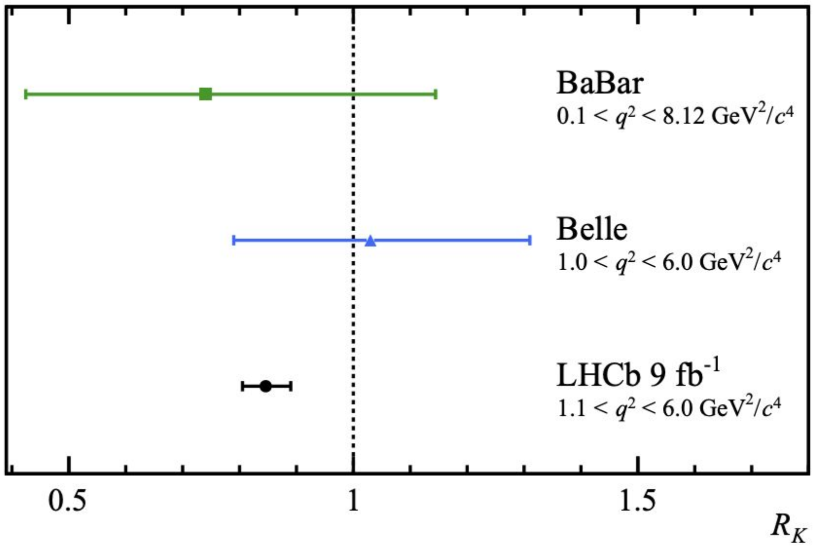
Can read more about the tension in: [https://www.symmetrymagazine.org/article/whats-up-with-the-w-boson-mass]()
Sane words about the statistical confusion of the measurements in: http://resonaances.blogspot.com/

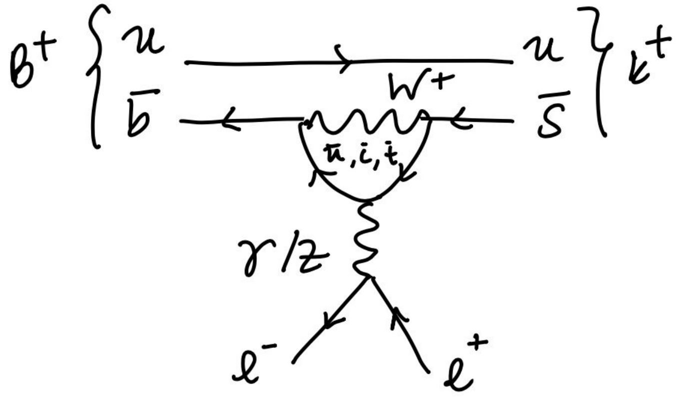
Run 3 of the LHC important to elucidate longstanding B anomalies -> GONEE! AS OF DEC.2022

Latest Rk measurement in 2022 by the LHCb collaboration reports a 3.1sigma deviation w.r.t the SM

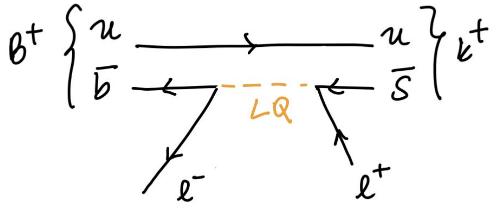
Test of lepton universality in beauty-quark decays, LHCb collaboration, Nature Phys. 18 (2022) 3, 277-282, arXiv:2103.11769

$$R_K = \frac{Br(B^+ \to K^+ \mu^+ \mu^-)}{Br(B^+ \to J/\psi(\to \mu^+ \mu^-) K^+)} \Bigg/ \frac{Br(B^+ \to K^+ e^+ e^-)}{Br(B^+ \to J/\psi(\to e^+ e^-) K^+)}$$





Popular theoretical models to explain this include LQ and *Z', just browse Inspire :)*



a leptoquark LQ could have diff. couplings with SM leptons