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

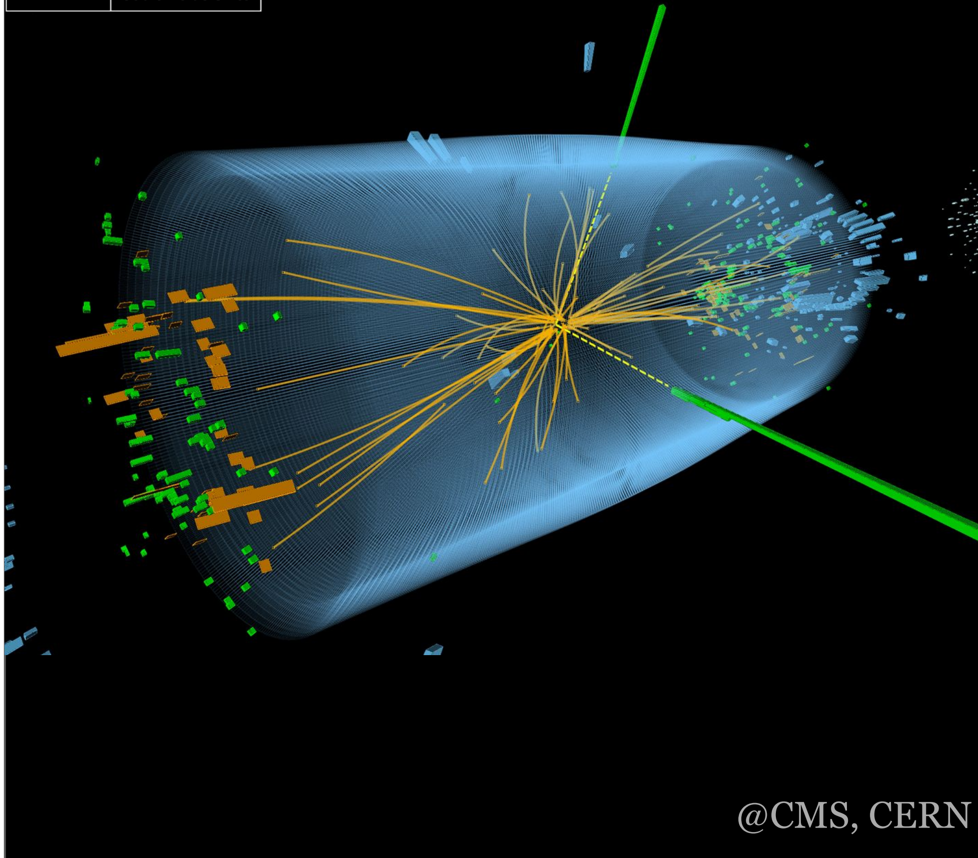
Particle Phenomenology

Universidad de Concepción, Chile
May 2023

Giovanna Cottin

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

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

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

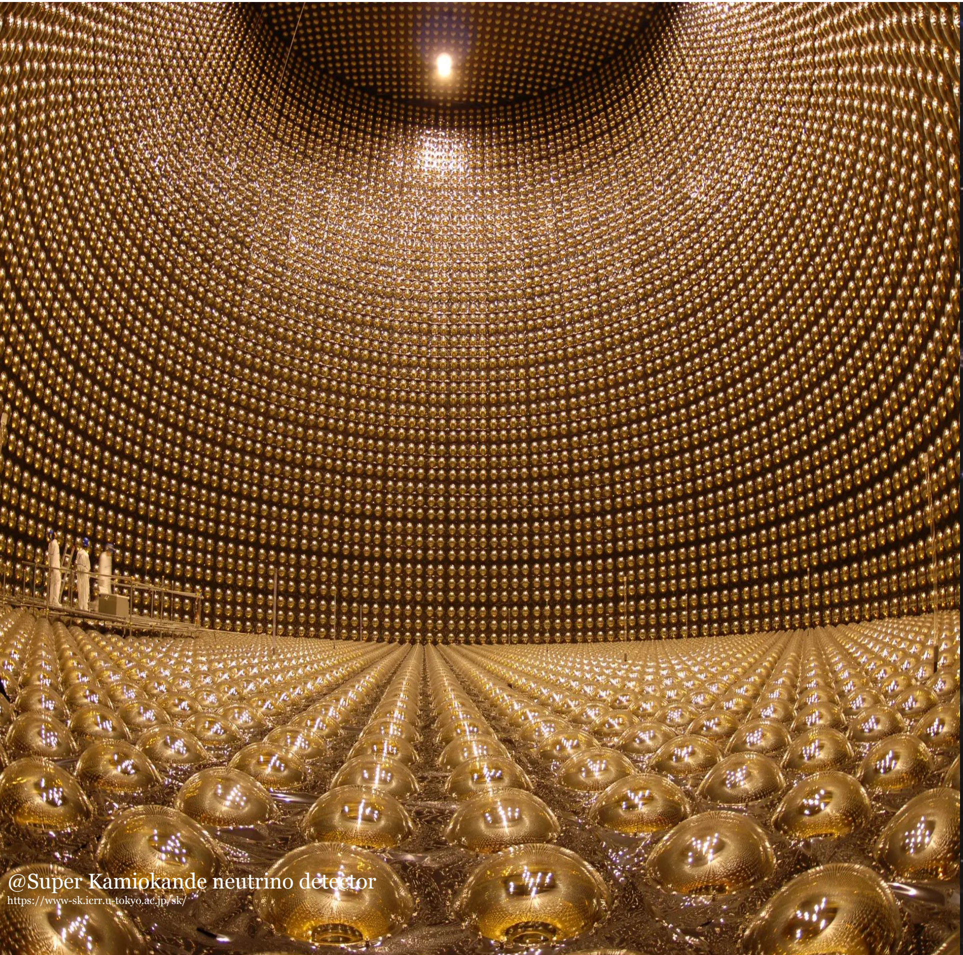
Particle Phenomenology II: Reinterpretation and Tools

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

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

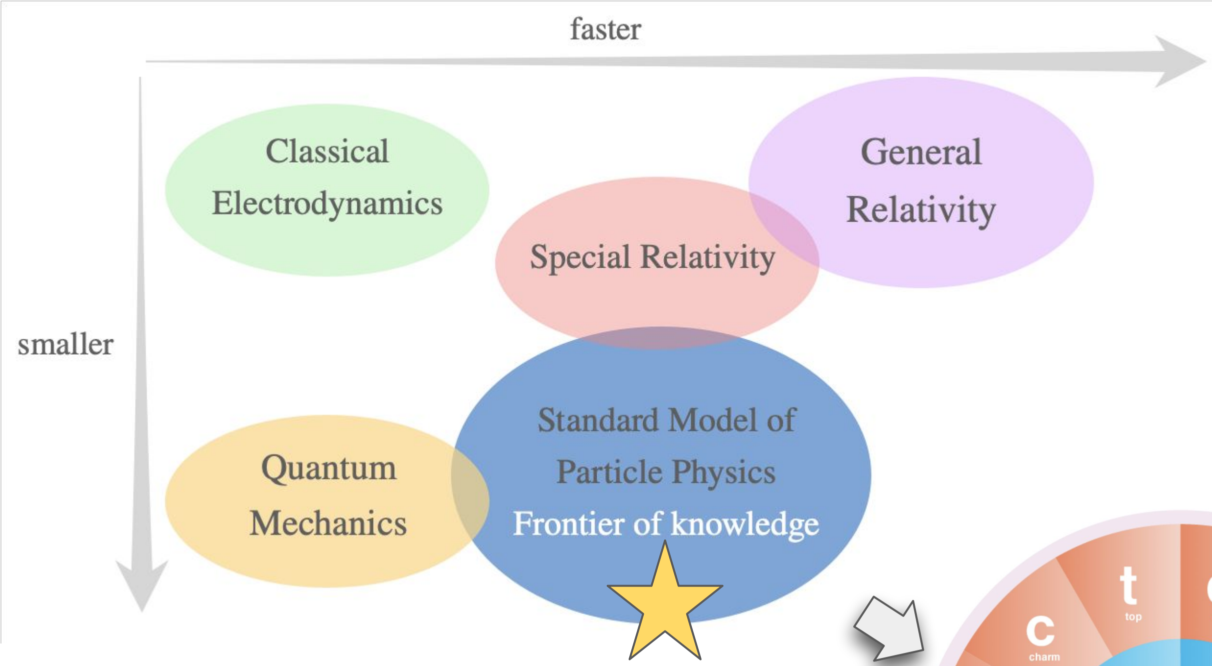
Nobel Prize 2015 to T. Kajita and A. McDonald

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

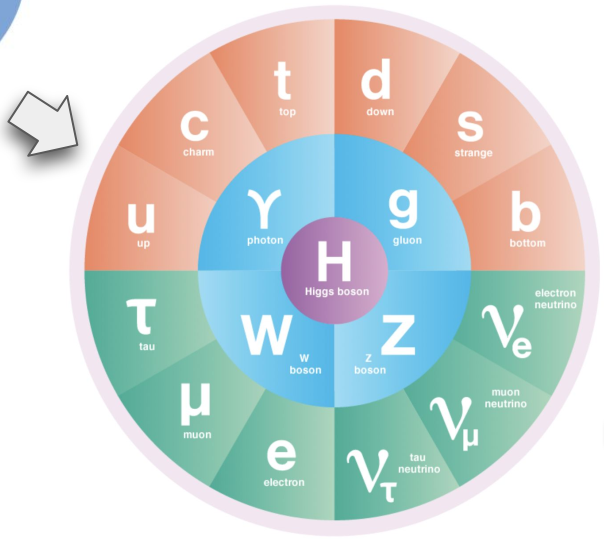


@Super Kamiokande neutrino detector
https://www-sk.icrr.u-tokyo.ac.jp/sk/

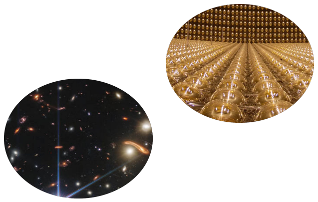
@JamesWebb Telescope, July 2022
https://www.nasa.gov/image-feature/goddard/2022/nasa-s-webb-delivers-deepest-infrared-image-of-universe-yet



We are here



?

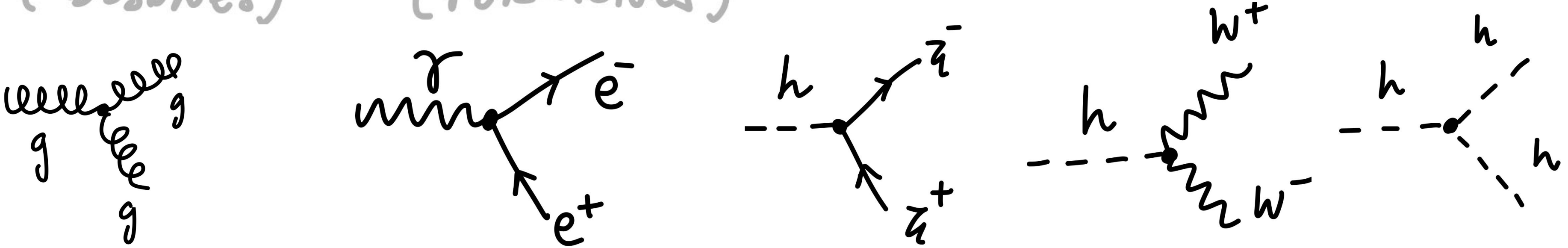


I am here with people doing *beyond* the Standard Model (BSM) particle phenomenology

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

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

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



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

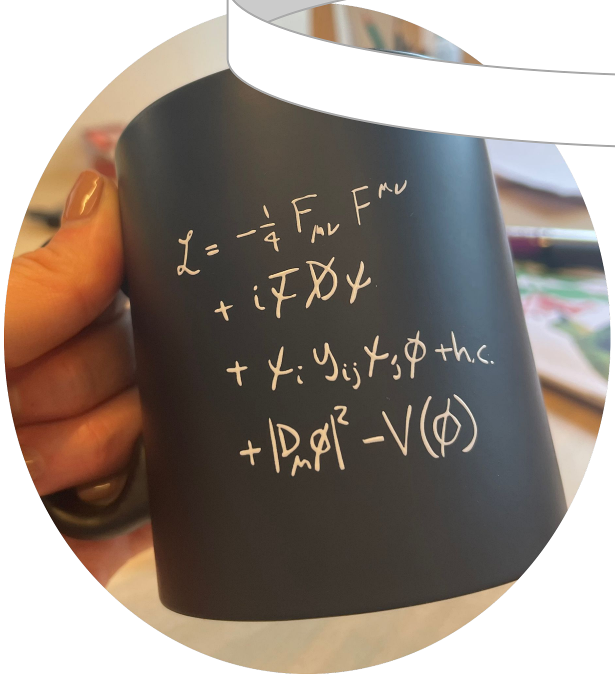
s de neutrinos,
gía y Materia
Oscura Nuevas
Fuerzas?
Nuevas Partículas
Elementales?

puestas a prueba

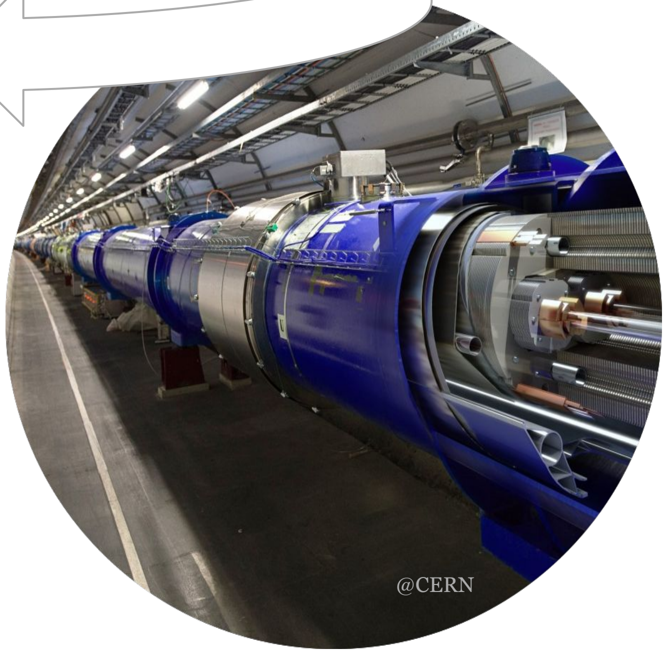
en Experimentos

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

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RH Neutrinos RHnu masses in the GeV to TeV range (SM

Focus is LHC in these lectures

3) Phenomenology

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Identify signatures
Model reinterpretation

4) Experiment

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Hunt them in the Data
Experimental results

CERN

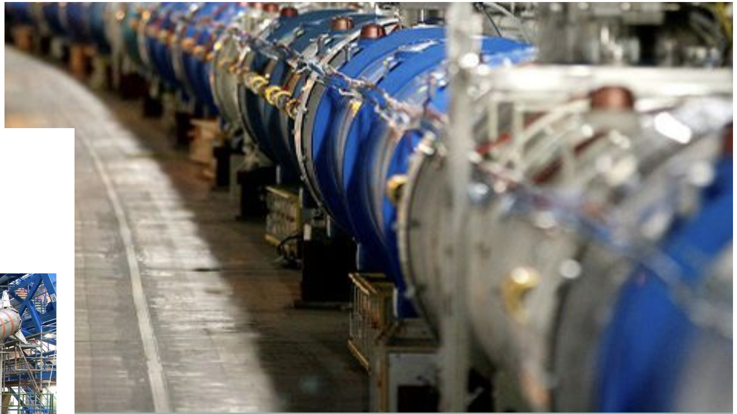
News › News › Topic: Accelerators

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

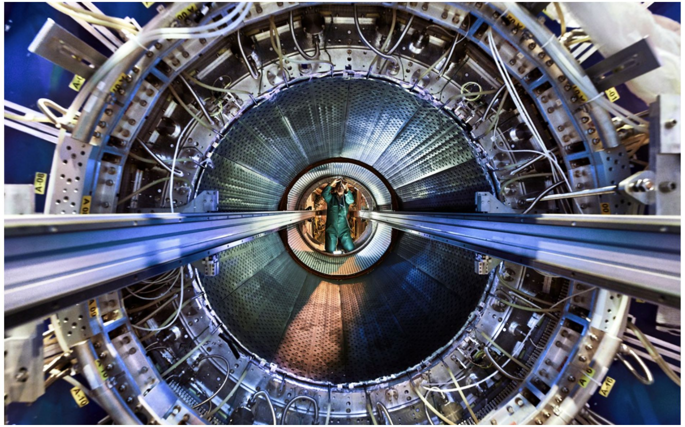


NEWS FEATURE | 25 May 2022

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



CNN World Africa Americas Asia Australia More Audio Log I

Scientists restart Large Hadron Collider in quest for dark matter

By Sara Spary, CNN

Updated 1304 GMT (2104 HKT) April 22, 2022

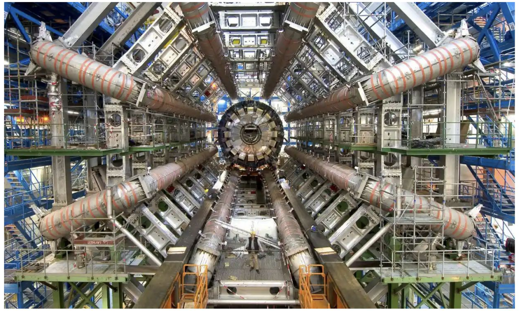
More From CNN

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

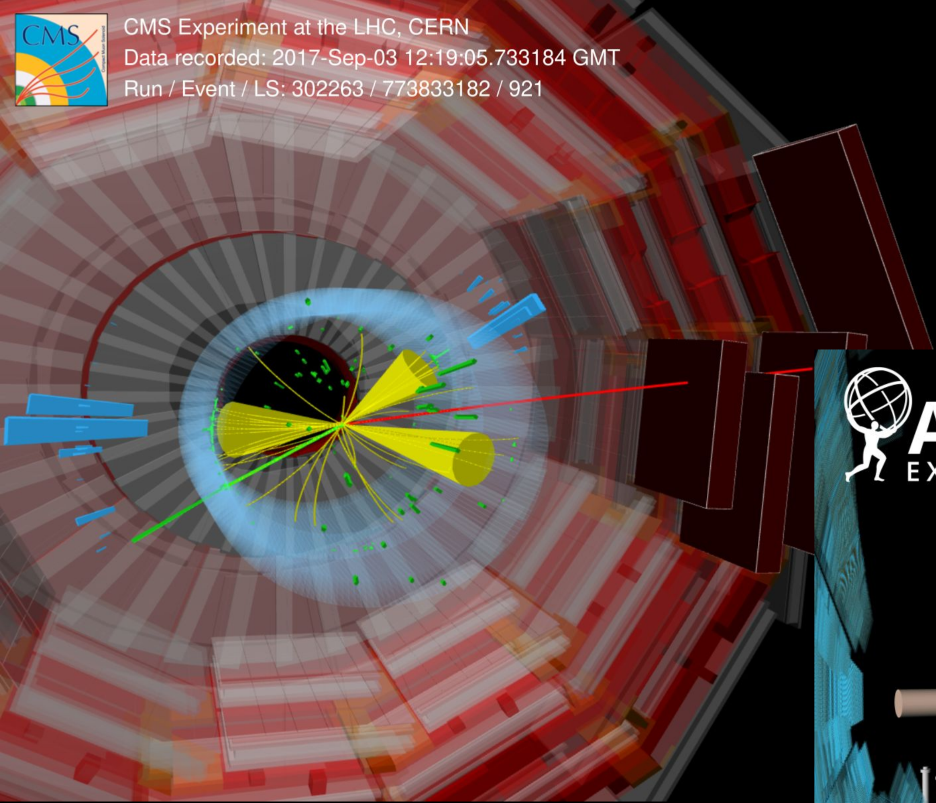
El esperado reinicio del Gran Colisionador de Hadrones

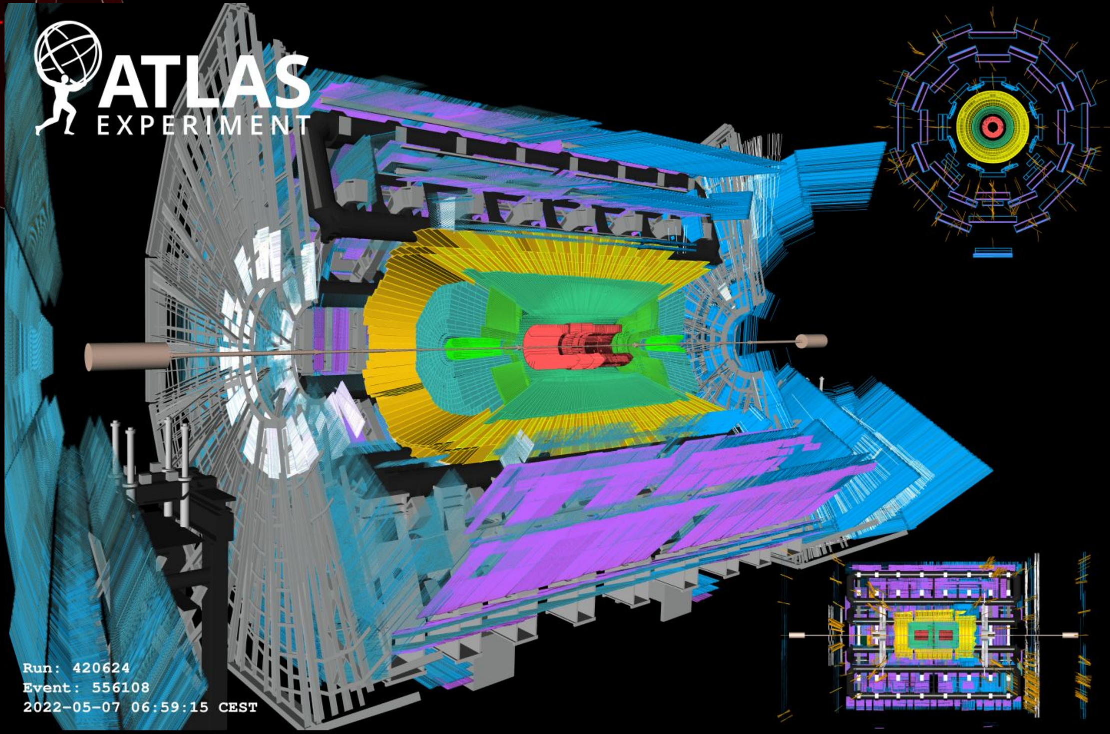
QUÉ PASA Opinión Física ...

CERN video on LHC restart : https://www.youtube.com/watch?v=J5WYRo17Lls
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
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km
@CERN


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



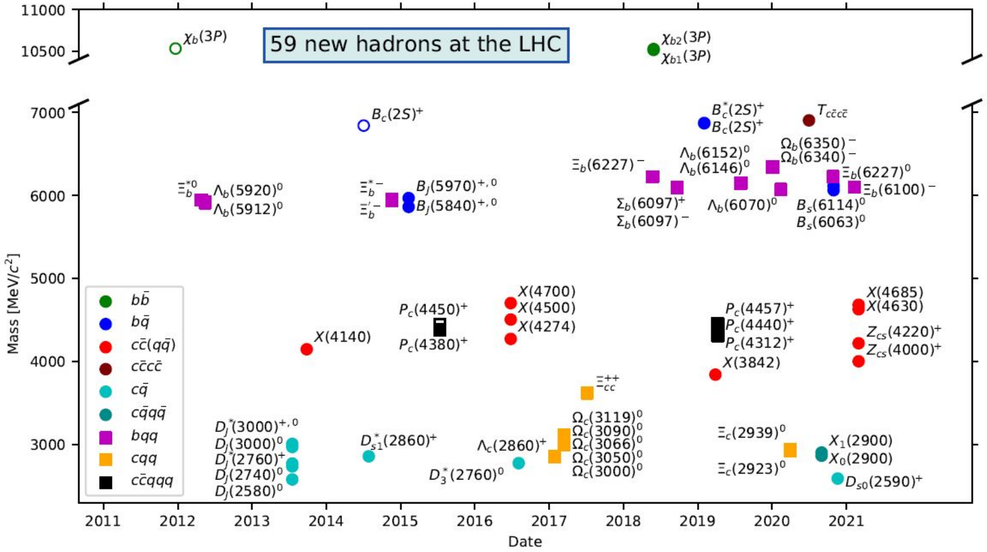


CERN Document Server: https://cds.cern.ch/
CMS-PHO-EVENTS-2022-002
ATLAS-PHOTO-2022-028

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

The LHC was built with the goal to find them !

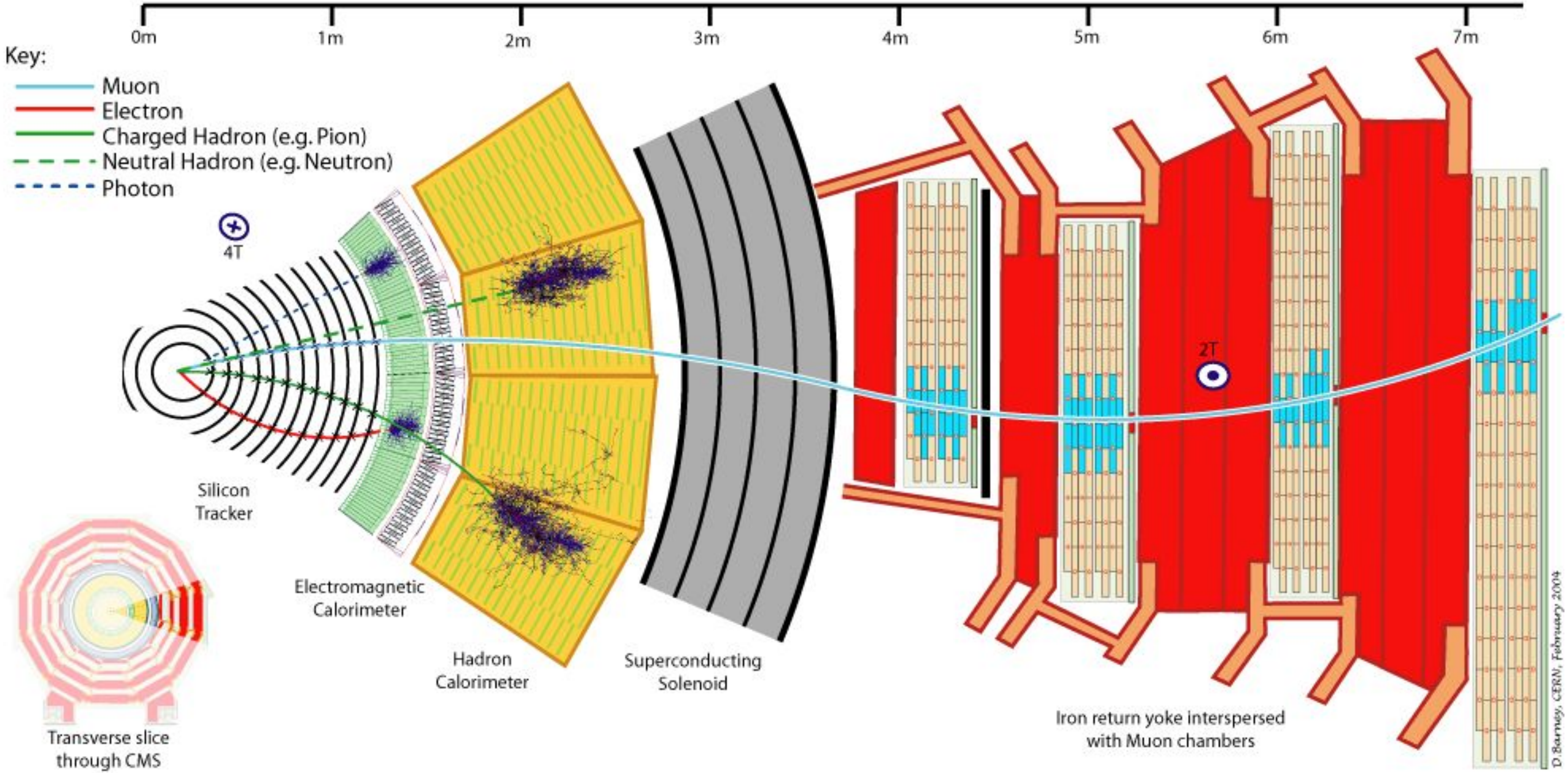
Nobel Prize 2013 to F. Englert and P. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments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

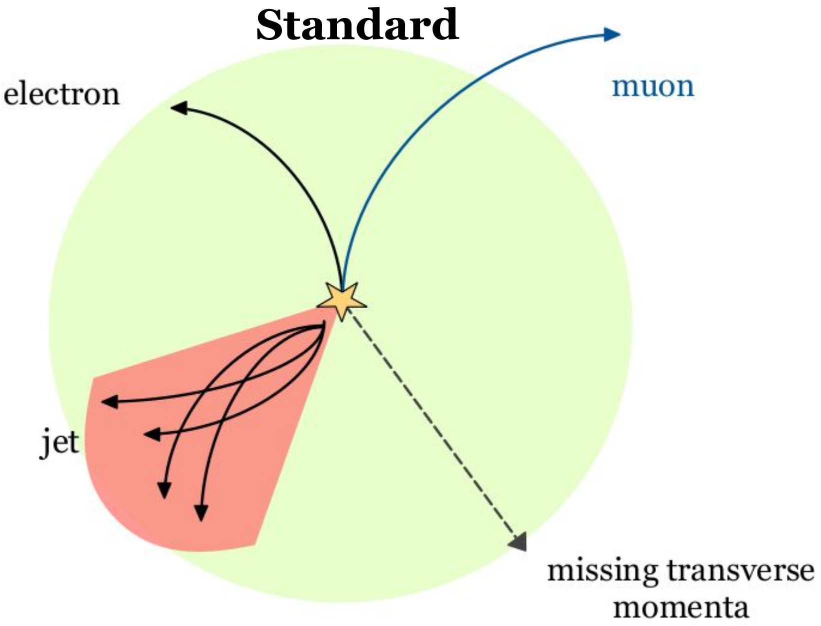


@CMS, CERN

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)



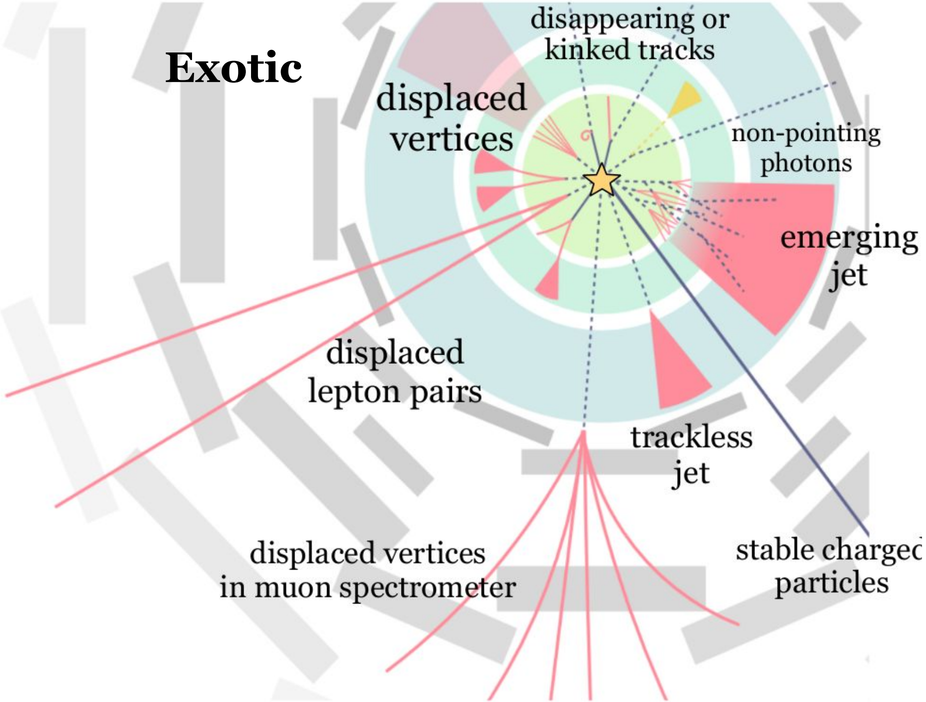


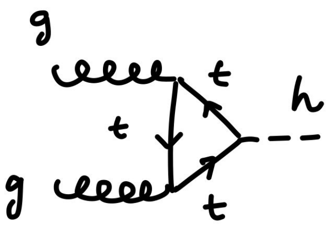
Image by G. Cottin

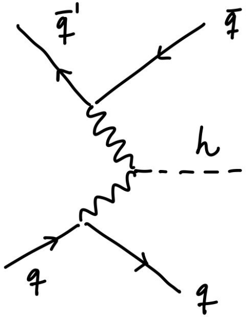
LLP Image adapted from Heather Russel.

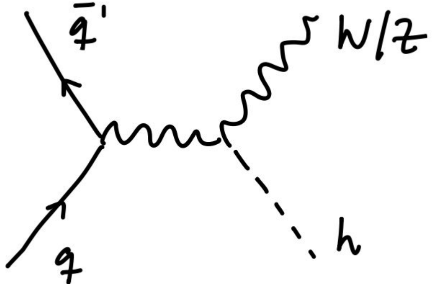
Long-lived Particle Community White Paper, J. Alimena, .. , **G. Cottin**, et al, J.Phys.G 47 (2020) 9, 090501

Un caso real: midiendo el Bosón de Higgs

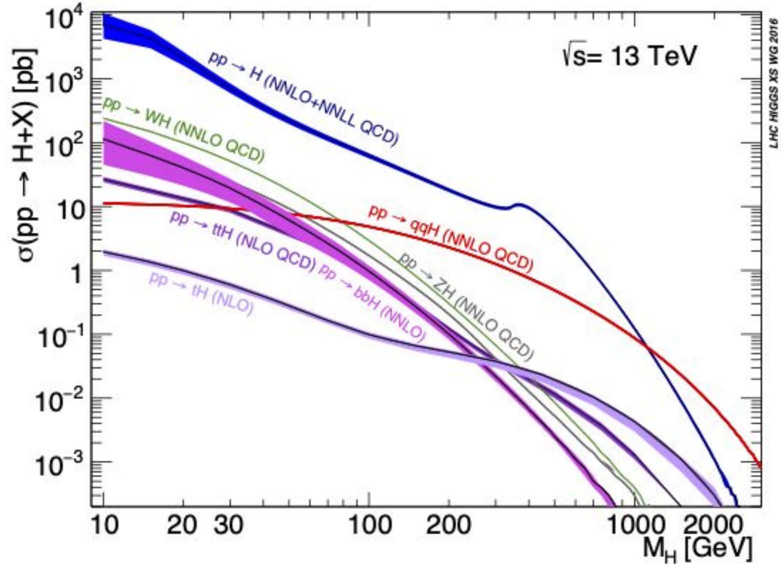
Production





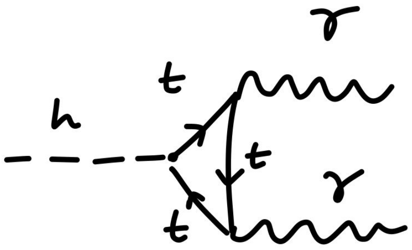


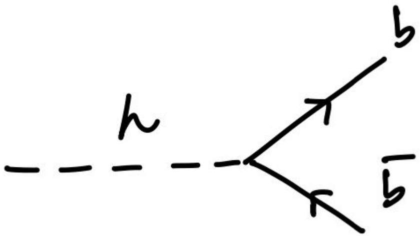
En el LHC se seleccionan los eventos con el Trigger (i.e Vector Boson Fusion, requiring at least two jets with pT > X GeV)

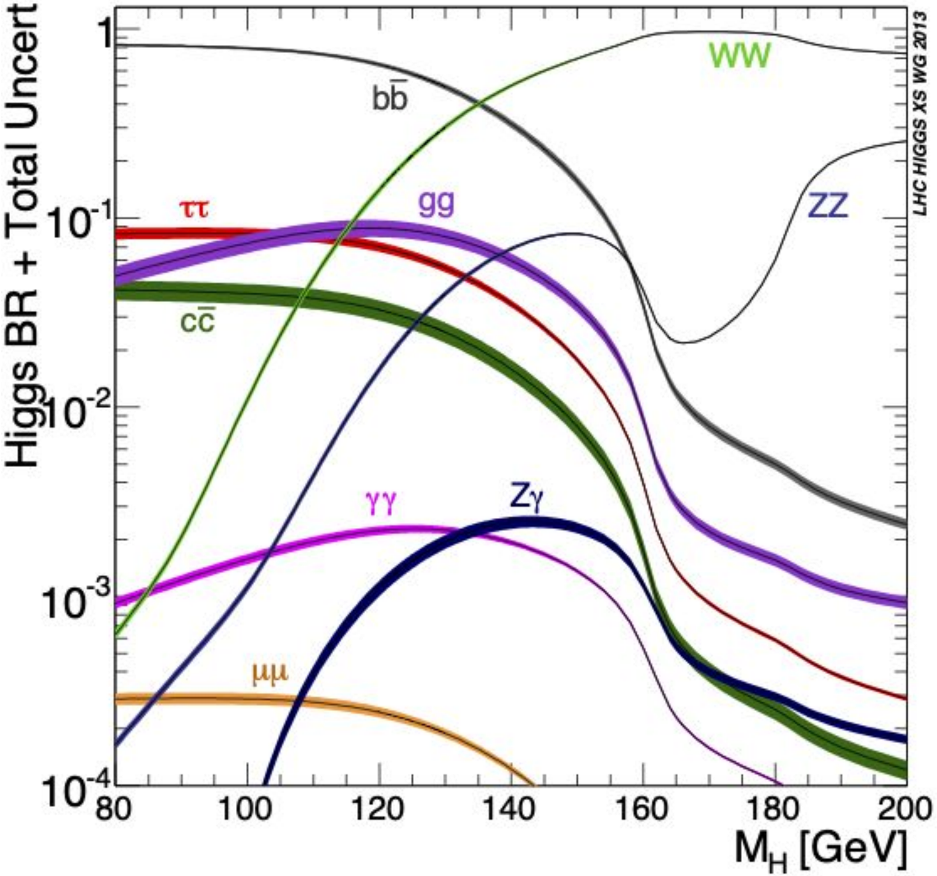


@LHC Higgs Working Group
https://twiki.cern.ch/twiki/bin/view/LHCPhysics

Decay



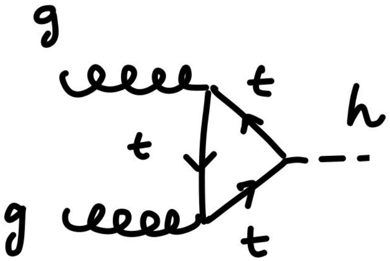


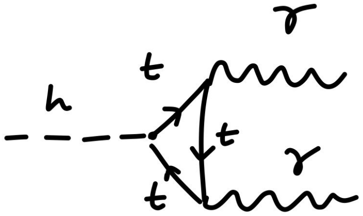


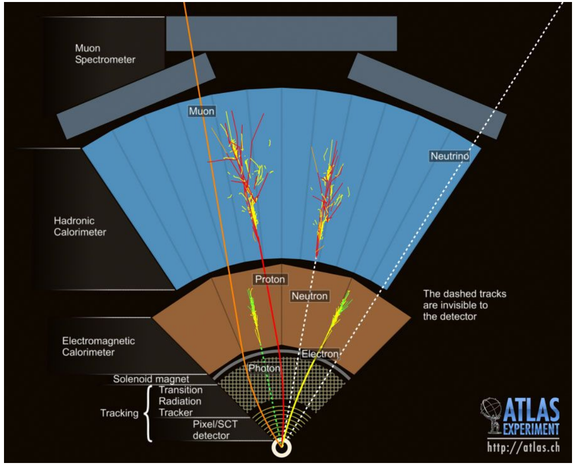
@LHC Higgs Working Group
https://twiki.cern.ch/twiki/bin/view/LHCPhysics

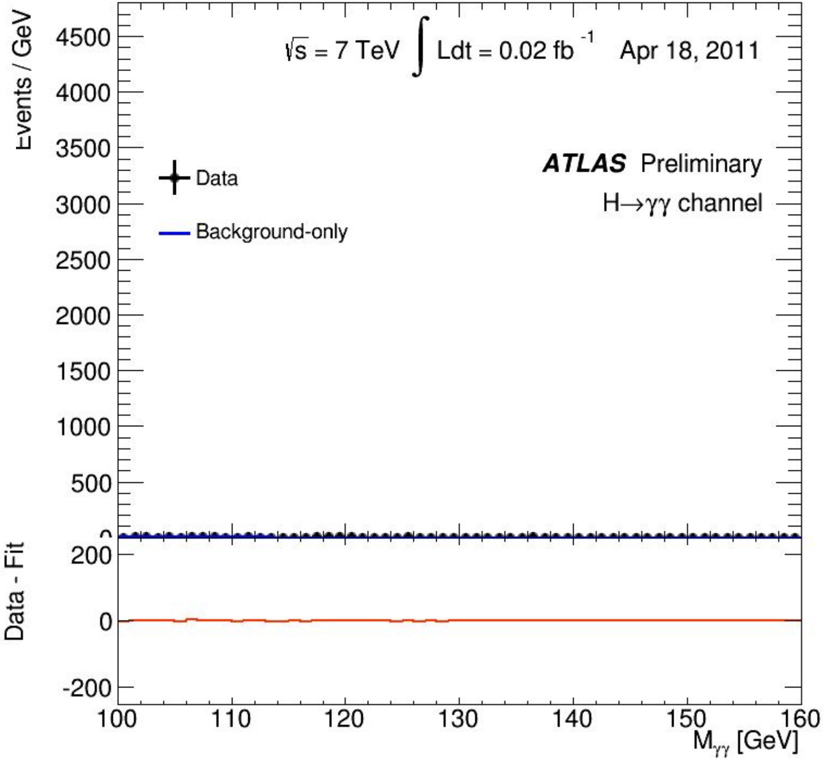
Luego de producir un Higgs detectamos sus decaimientos (i.e reconstruimos los fotones, leptones (del Z decay) o “jets”)

Juntando todo, se mide el Bosón de Higgs







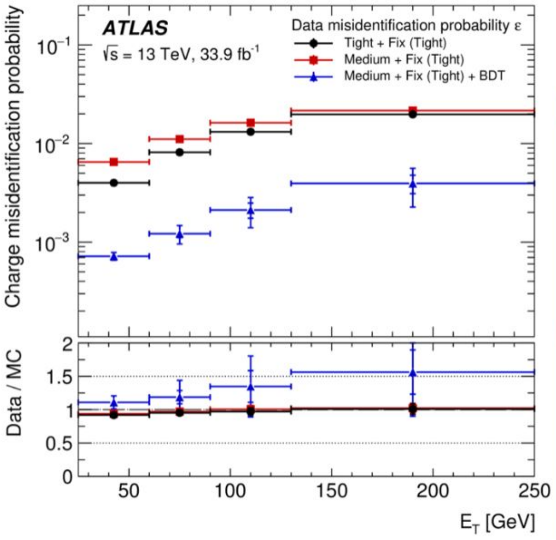


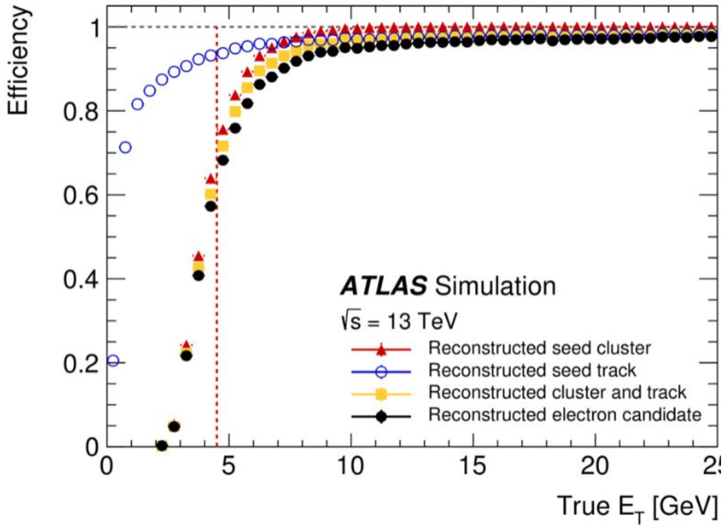
https://cds.cern.ch/record/2230893?ln=es

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 !


```
<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
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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 ...

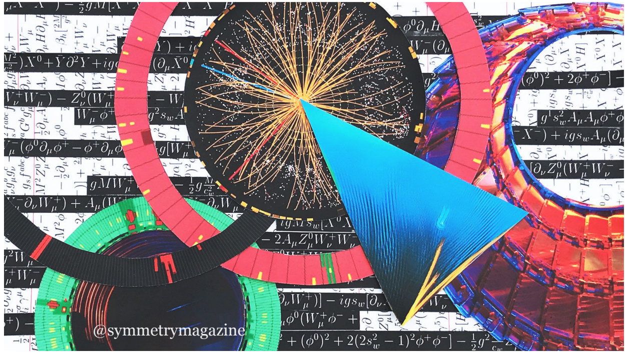
Not always being looked for @ High Ener
Physics experiments

- 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

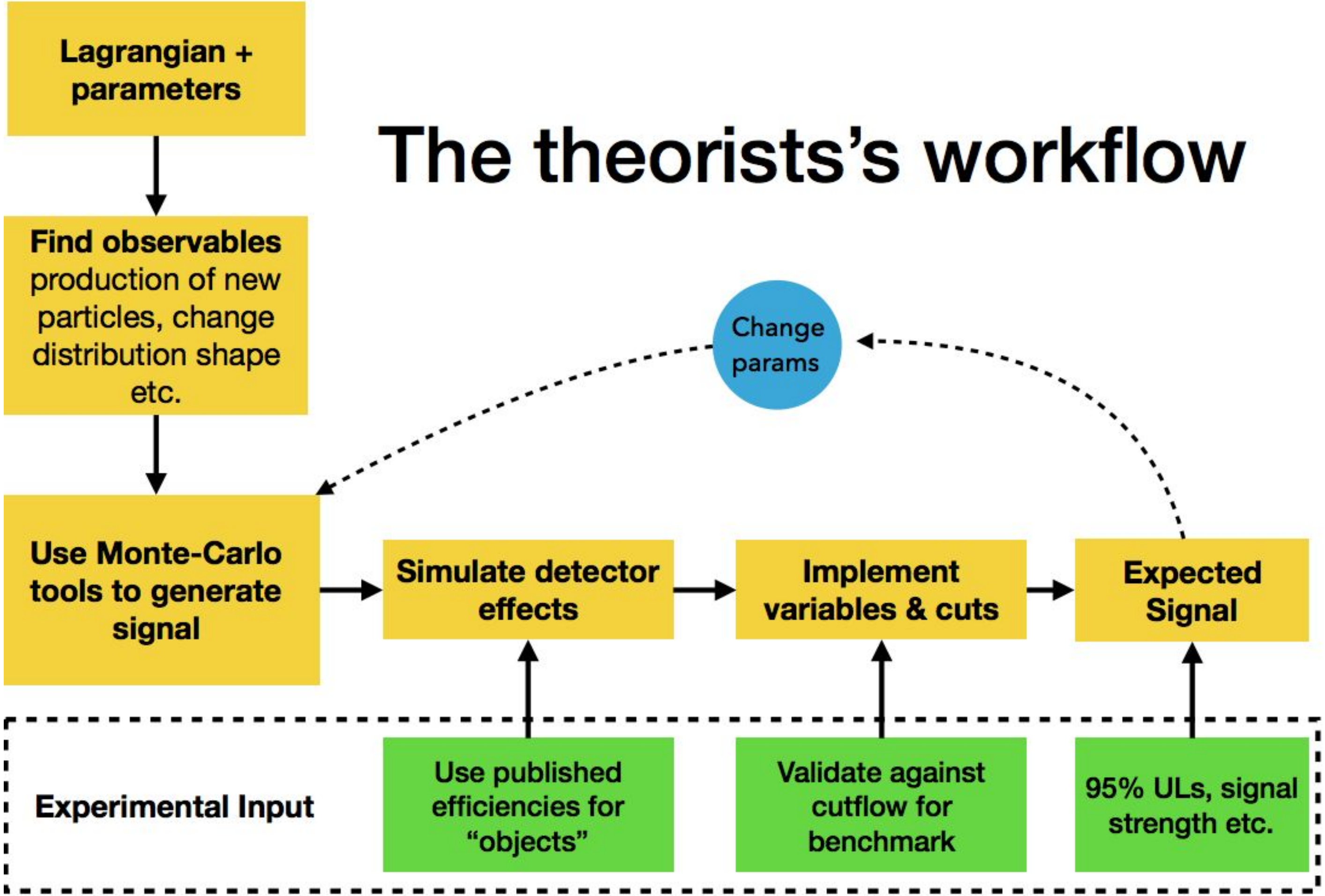
- Identify Software (i.e. Monte Carlo as Madgraph, Pythia, Herwig ...)
- Design/Implement Observables (i.e. invariant mass, displaced vertex, jets)
- Hard Code your strategy/analysis (i.e. can use standard software as MadAnalysis, Rivet or your own)

Evaluate Experimental Response

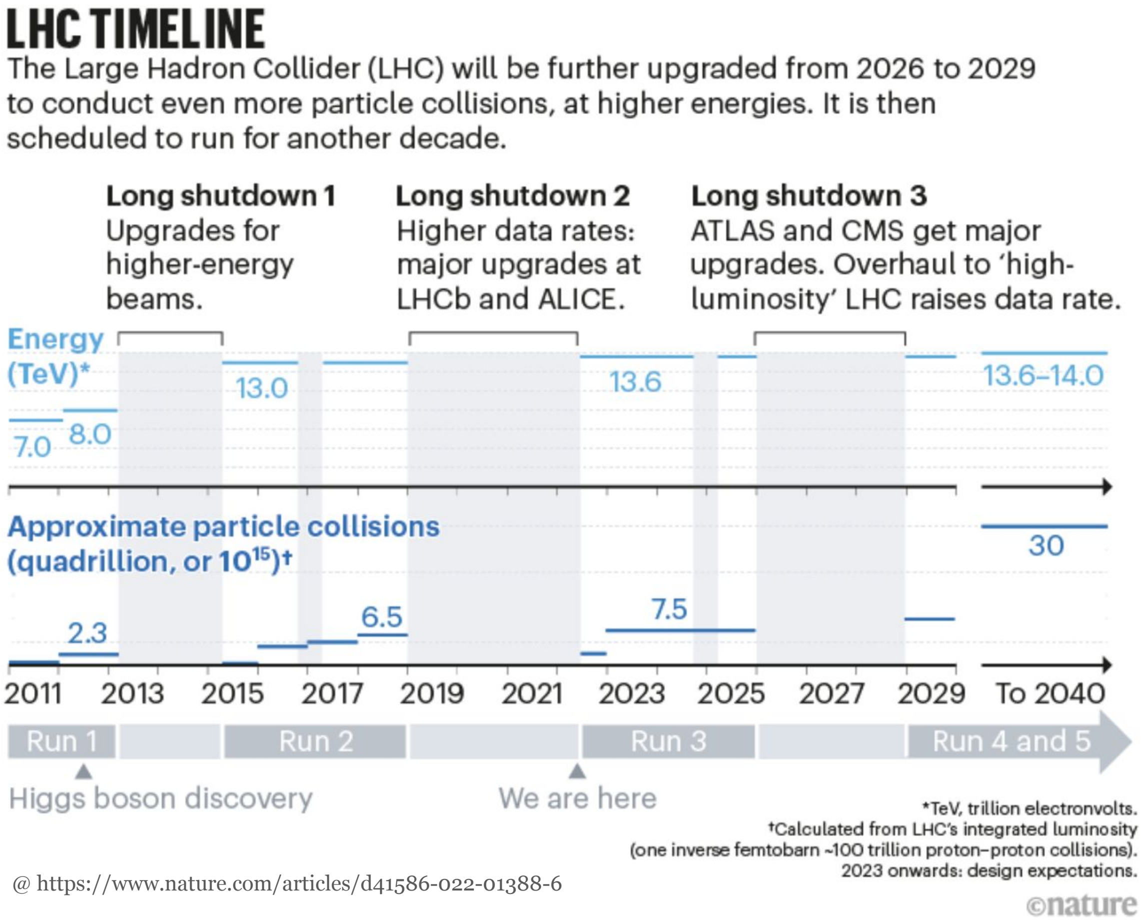
- Detector Simulation (i.e. software as DELPHEs or custom made to your analysis needs)
- Identify experimental information/efficiencies to characterize response to your objects and observables (i.e. Can use open data/HEPData)

In detail

Slide from Nishita Desai @ LLP Workshop, CERN

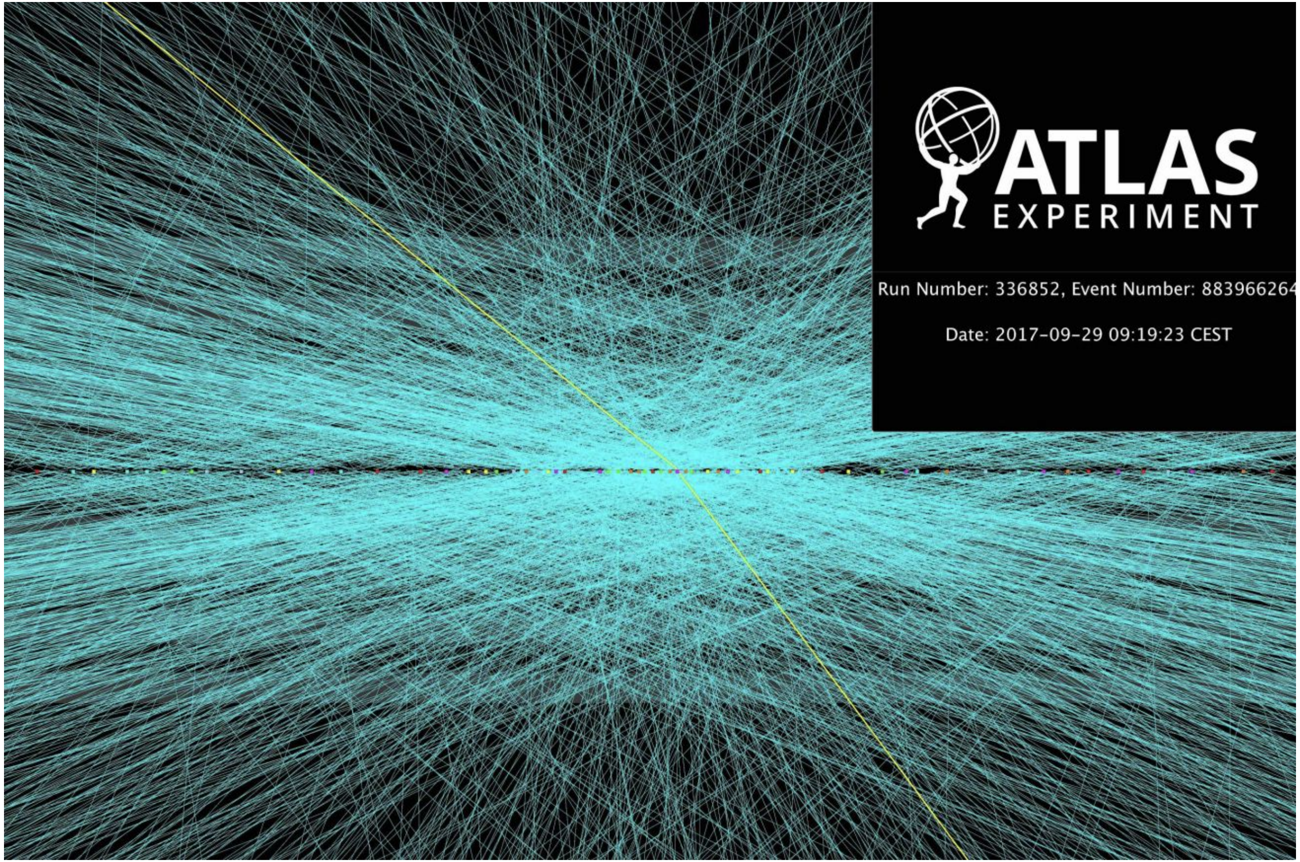


The LHC will run for the next ~20 years



@ 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 !)

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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/

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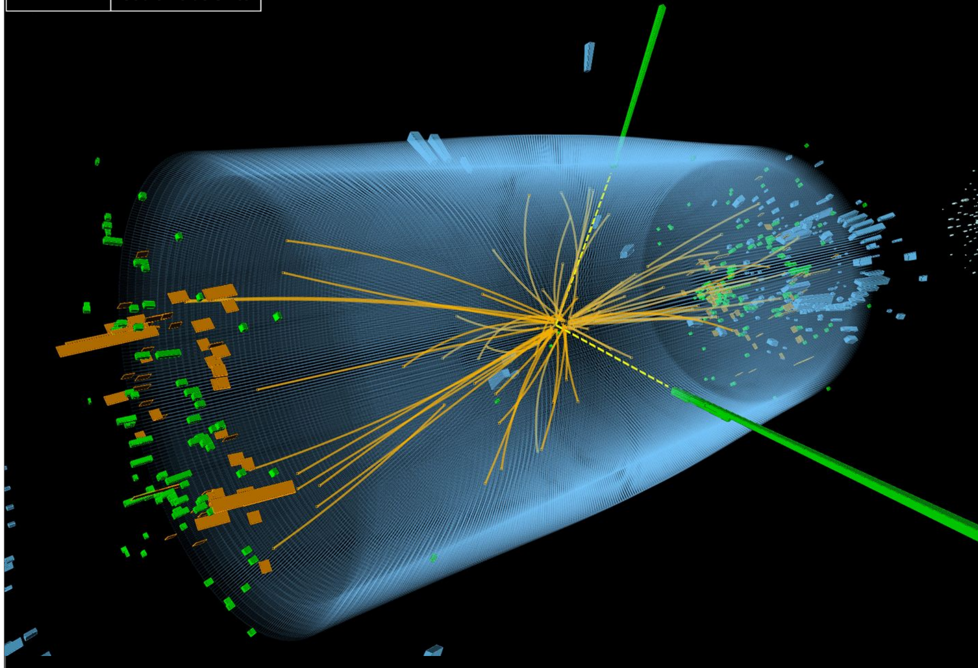
Associate Professor, Universidad Adolfo Ibáñez, Santiago, Chile
Young Researcher at SAPHIR Millennium Institute, Chile
LHC Long-Lived Particles Working Group, Theory co-convener, CERN



@CMS, CERN

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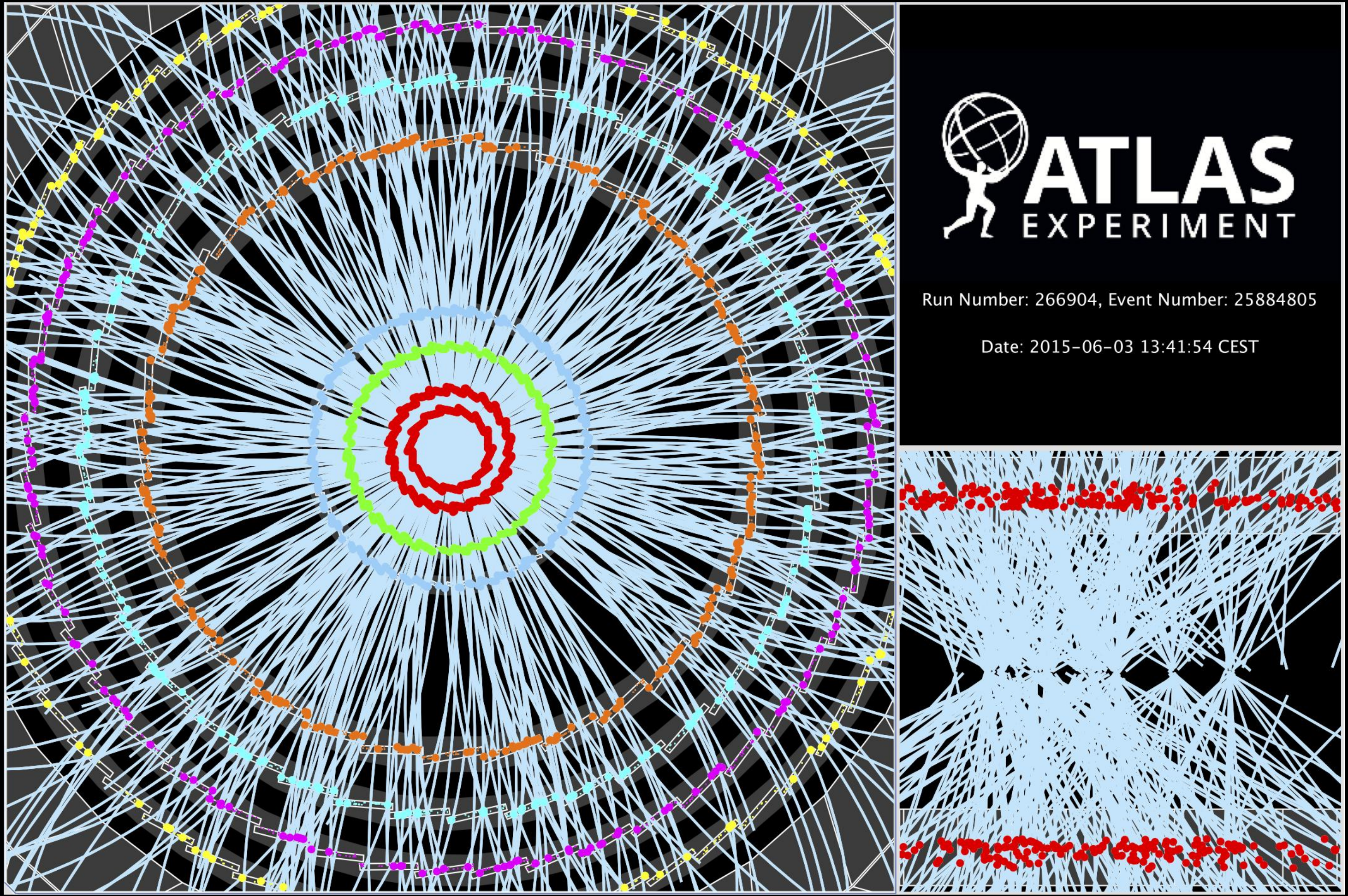
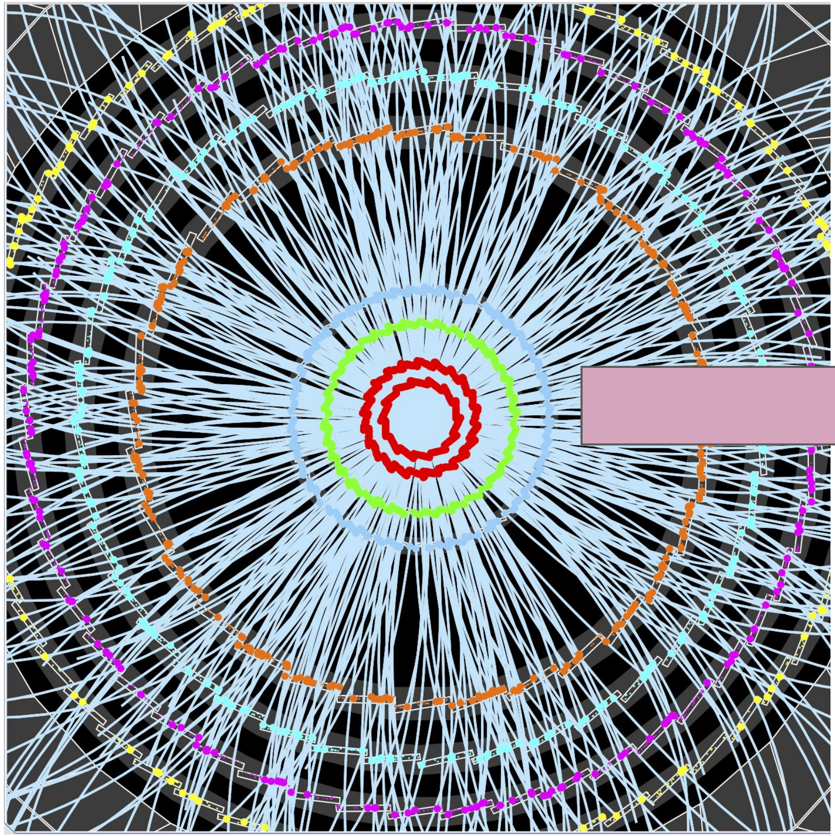
- Why should we keep doing it?

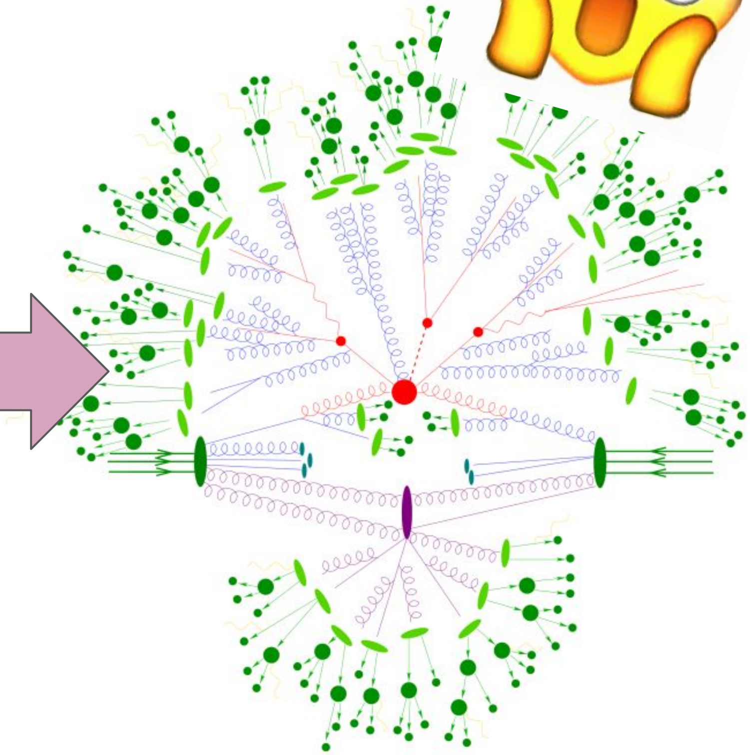
@symmetrymagazine


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

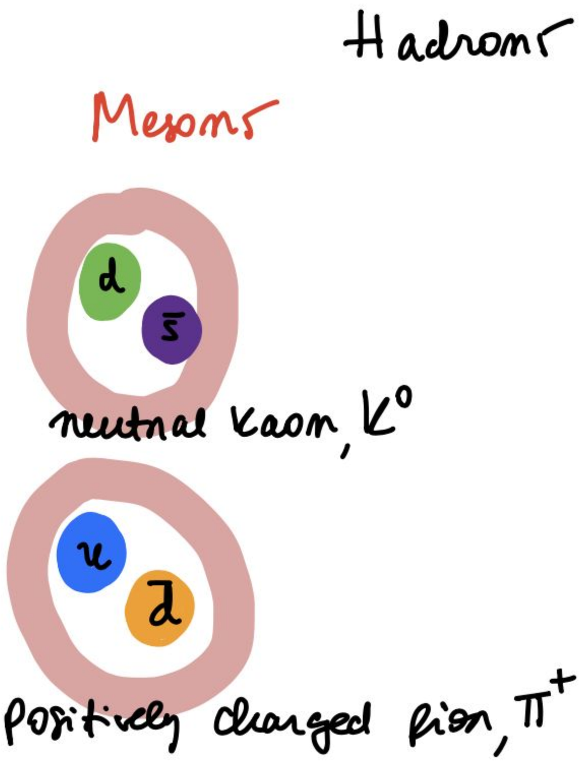
Phenomenologists need to simulate this !

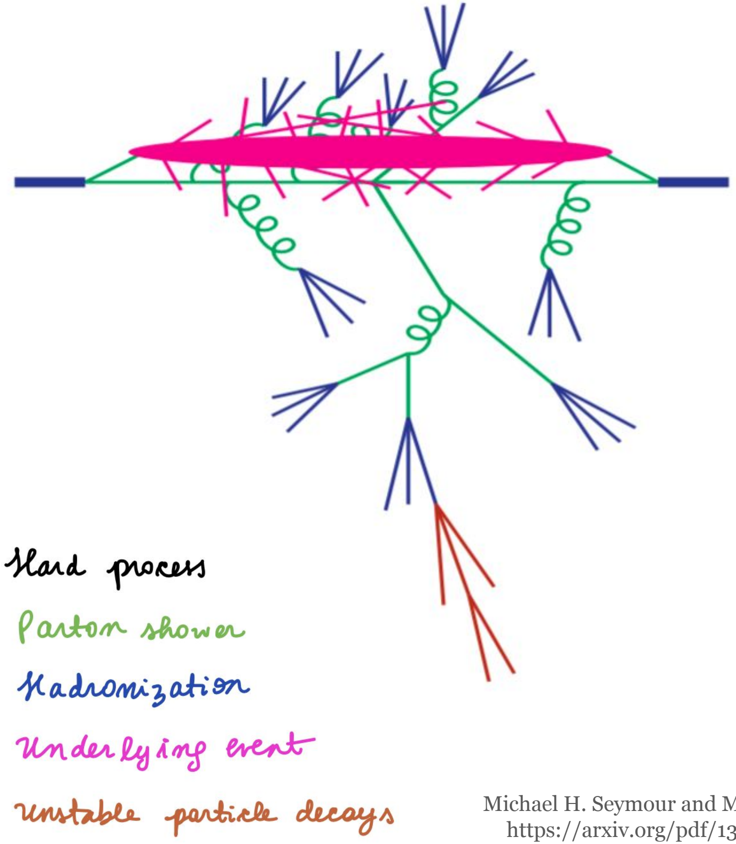


@ATLAS, CERN



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

MadGraph

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

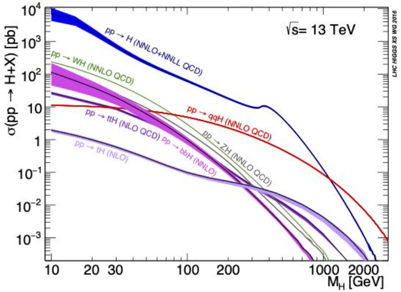
PYTHIA 8.3
https://pythia.org/
https://arxiv.org/abs/1410.3012

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

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?

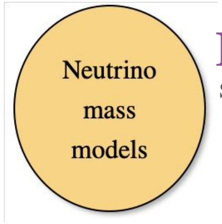


Generamos eventos con Monte Carlo, recordemos que en quantum mechanics las amplitudes son realmente probabilidades!

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)

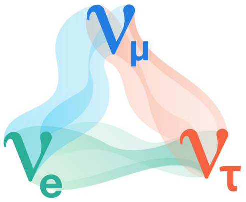


Provide an answer for neutrino mass generation mechanism

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



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 Mechanism(s)

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

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

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

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

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

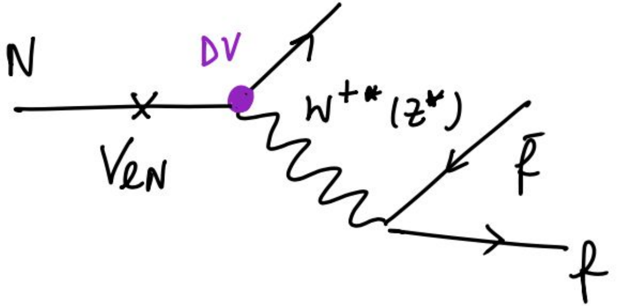
$N \to \ell'^{\pm} \ell^{\mp} \nu_{\ell}$

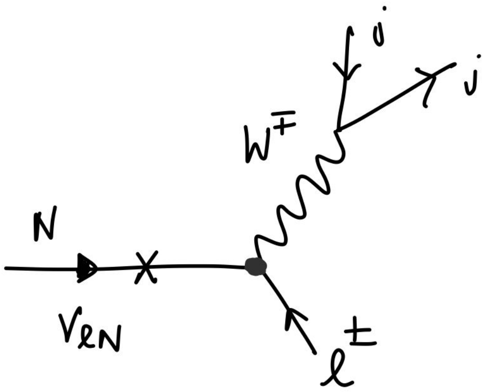
$N \to \nu q \bar{q}$

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

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

$m_N < m_W$

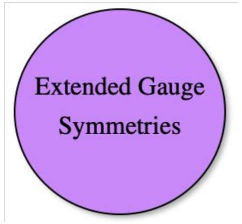


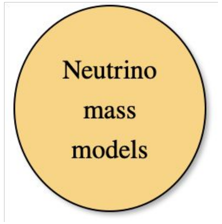


Identify signal topology and observables

@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

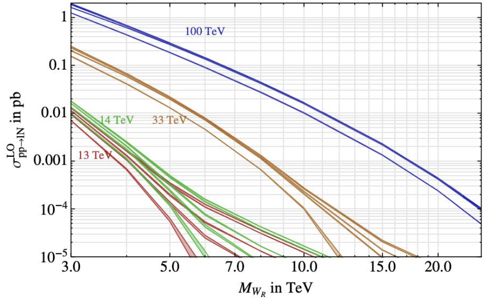
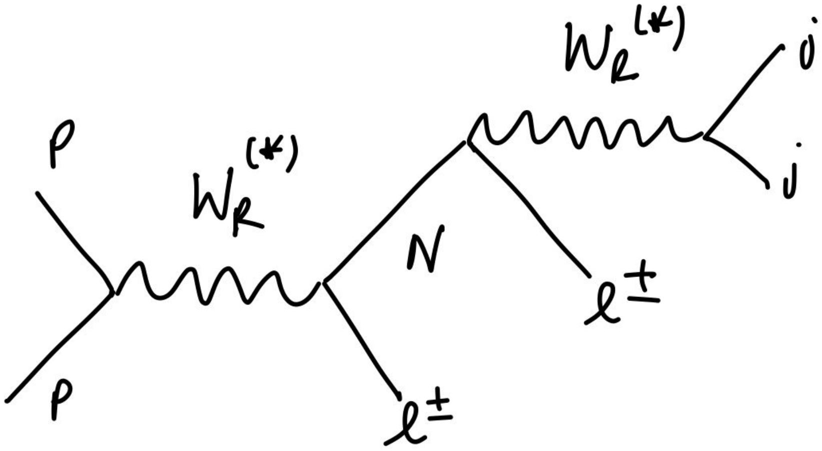
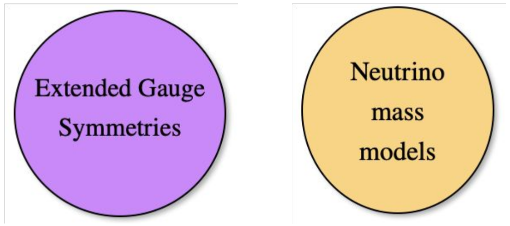


FIG. 3. Drell-Yan production cross section of $pp \to W_R^\pm \to \ell^\pm N$. For each indicated interaction energy, the curves from upper to lower are relative to $m_N = 50, 100, 500, 1000, M_{W_R}/2$, showing normal phase space suppression. In addition, notice the relative enhancement of the lighter 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.



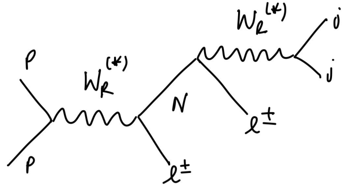
The production becomes dominated by the off shell contribution for right-W masses $\gtrsim$ 5 TeV

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

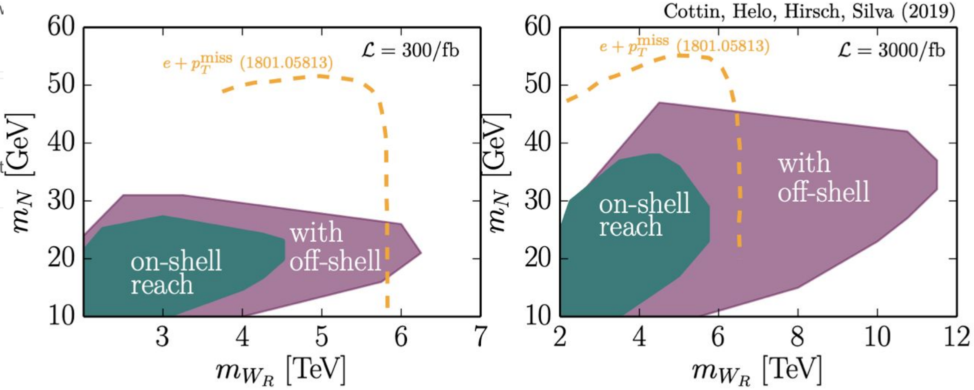
Giovanna Cottin
Hi again Goran, In order to run several processes, how should I run many cards (for example "ks_e_e.dat

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

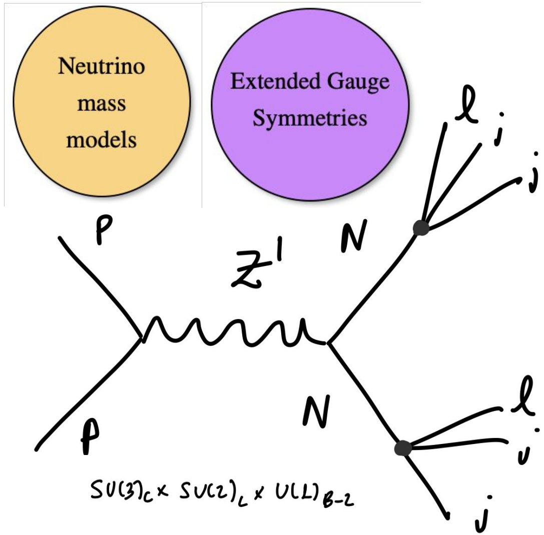
Dear Giovanna,

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



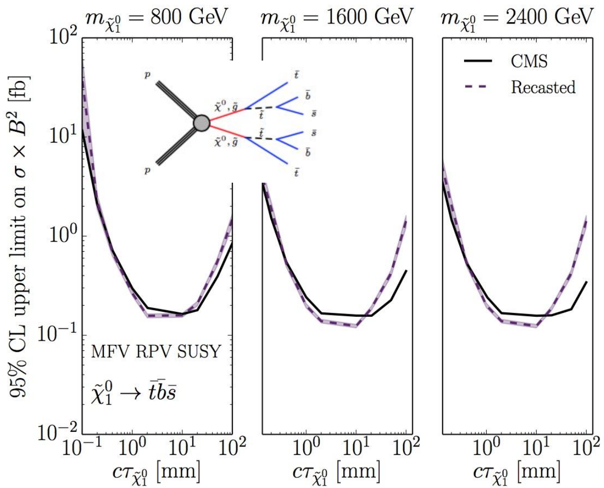
- Trigger? Are there any for my signal? (i.e. lepton pT> 120 GeV Is this lepton isolated? Displaced?)
- Define analysis cuts to maximize your significance (which you will need to define) and remove backgrounds (if you can simulate them)
- **Can recast ongoing search** (after coding and validate it against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

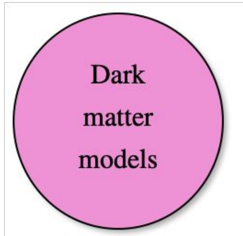
C.W. Chiang, **G. Cottin**, A. Das, S. Mandal JHEP 12 (2019) 070

(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



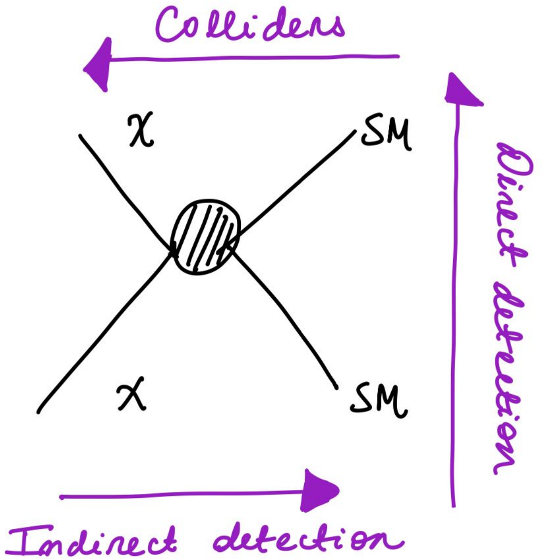


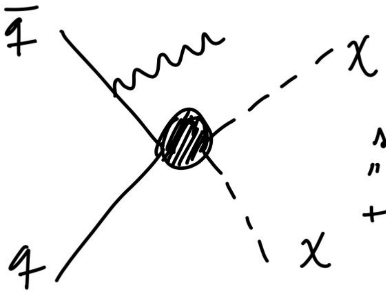
2) Usage/Design ->Propose your own search if standard cuts are not optimal for your signal

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)

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

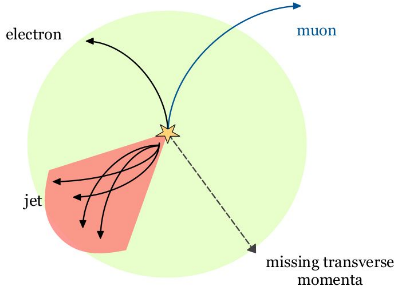




standard "monojet" searches

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

Standard

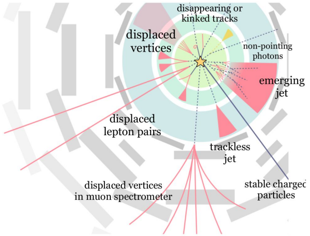


To see “nothing”, you have to understand everything !

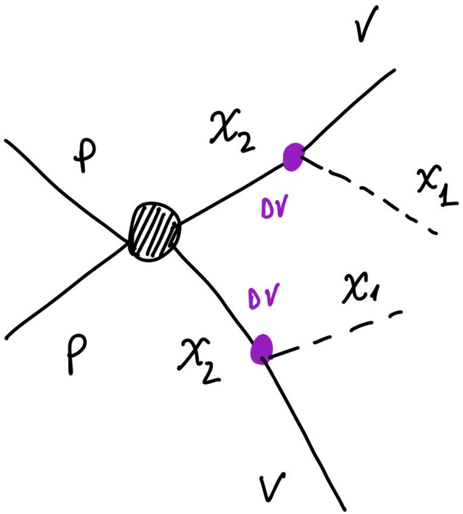
Dark matter models

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!



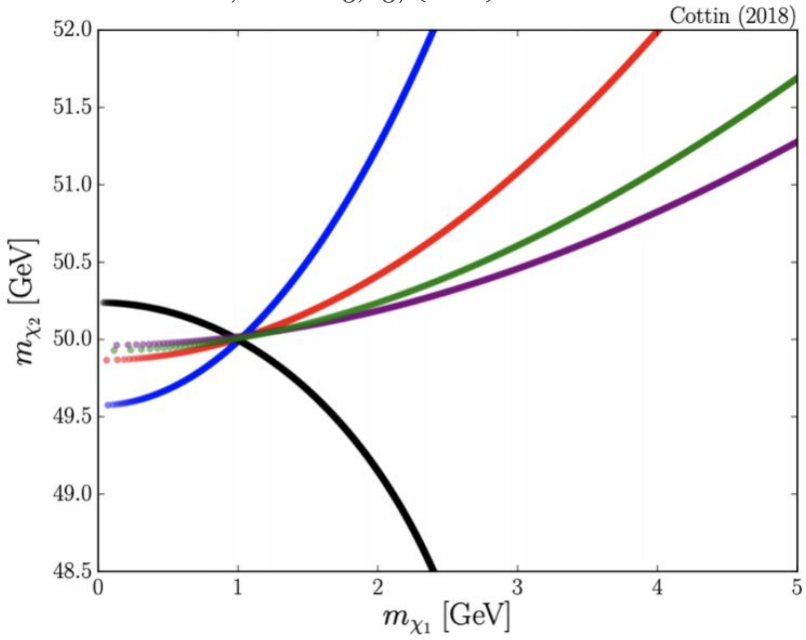
$$\Gamma \sim \lambda^2 \left(\frac{\Delta m}{\Lambda}\right)^n \Delta m$$

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

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

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

G. Cottin, JHEP 03, 137 (2018)

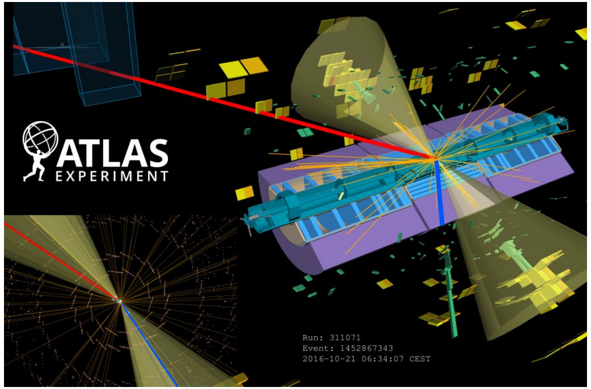


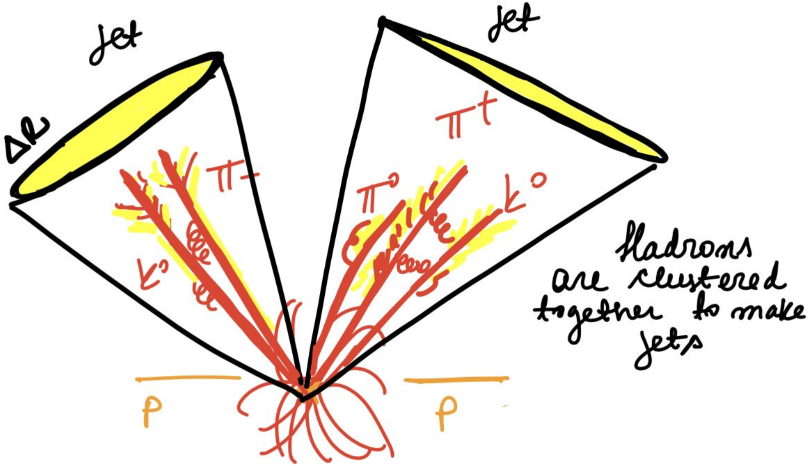
By proposing a new mass variable for the masses system, can solve on an event by event basis, and the system is fully constrain

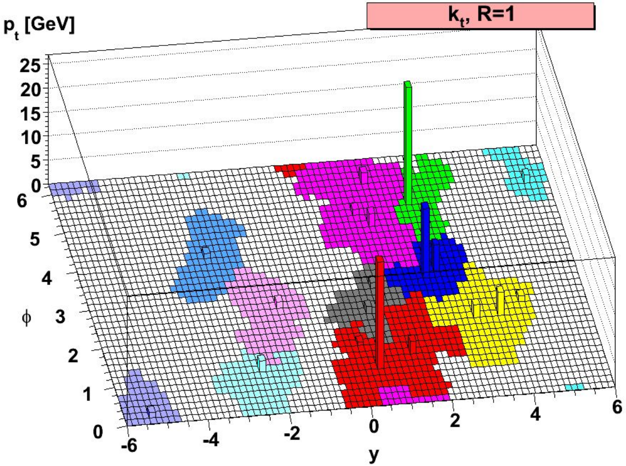
The DM mass could be measured at colliders !

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

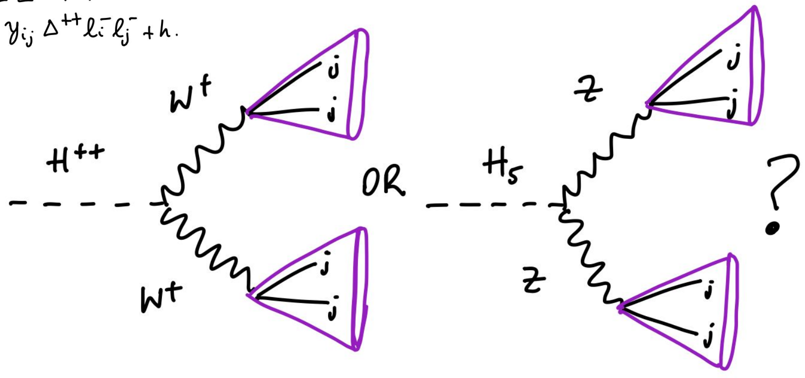
- Define significance (i.e. can I assume 0 bkg? Can I estimate all my backgrounds? Are there any background uncertainties? How they will escalate with luminosity if I am proposing a new search at a future collider for example?)
- Will I do a cut and count analysis? Or I can Machine Learn my search by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

SM + SU(2)-triplets (Δ)

$V(\phi, \Delta)$

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

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



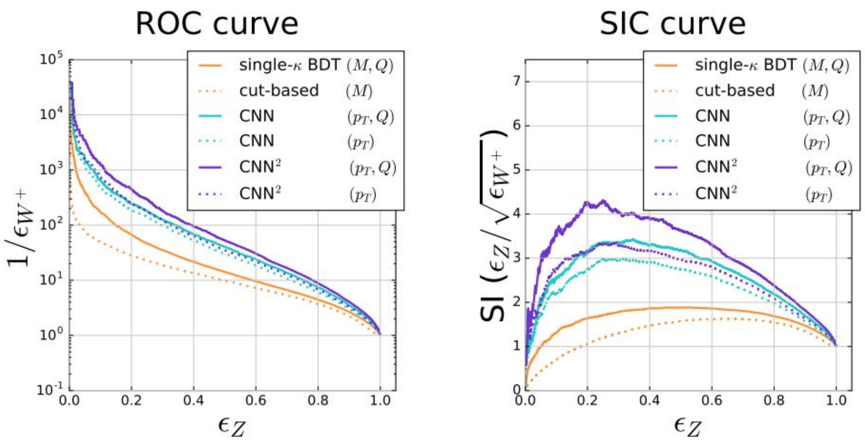
$$\text{jet charge} = \frac{1}{(p_{T,J})^\kappa} \sum_{i \in J} q_i \cdot (p_T^i)^\kappa$$

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

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

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

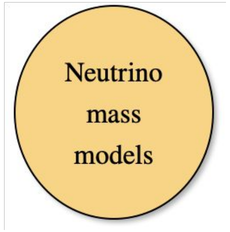


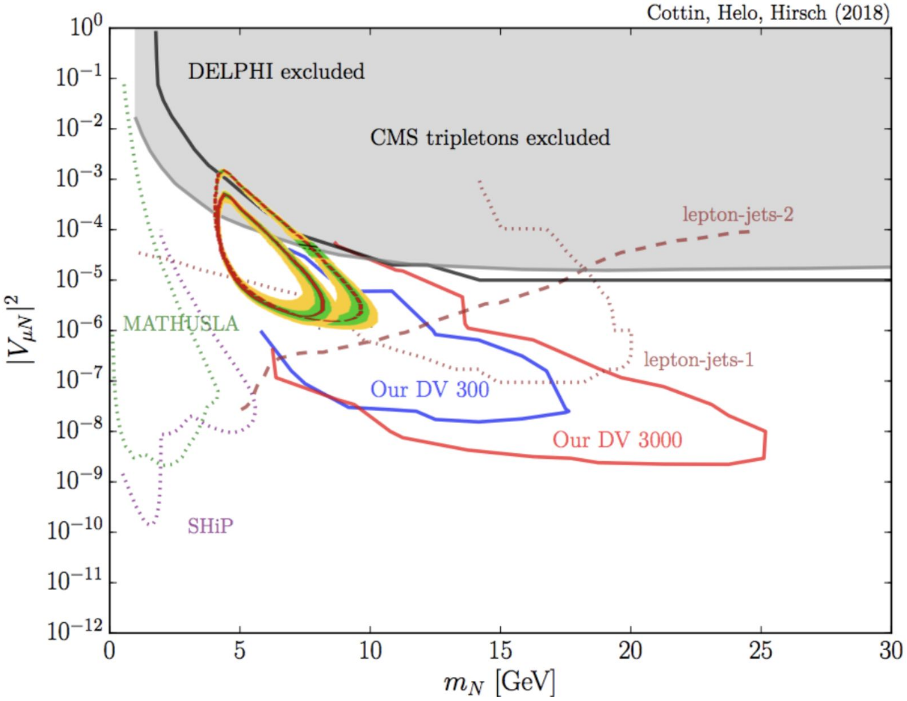
J. Chen, C.W. Chiang, **G. Cottin**, D. Shih Phys.Rev.D 101 (2020) 5

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

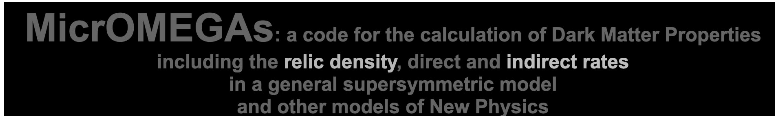
G. Cottin, J.C. Helo and M. Hirsch, Phys. Rev. D97 (2018)

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

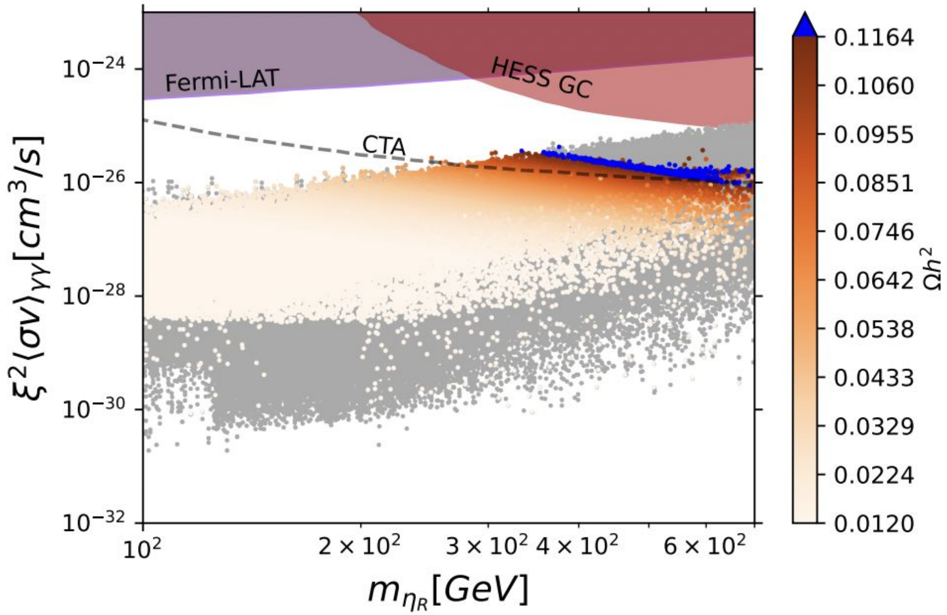
Dark matter models

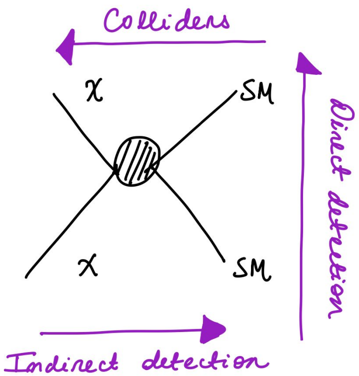
And you can implement the pipeline at other HEP experiments even beyond colliders like direct detection or indirect detection (CTA)

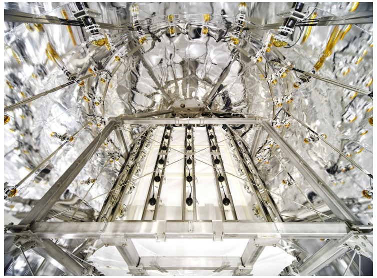
Hard code your model and use dedicated software as



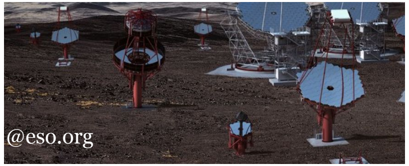
https://lapth.cnrs.fr/micromegas/







Credit: Xenon Collaboration



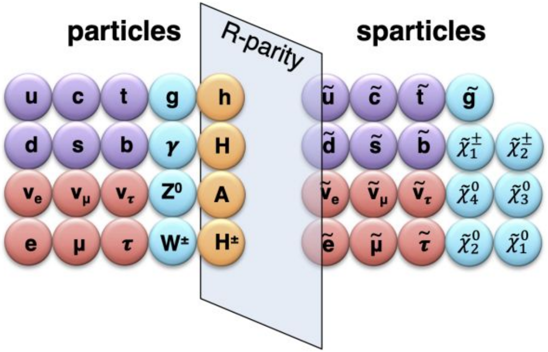
Revisiting the scotogenic model with scalar dark matter
I. M. Ávila, **G. Cottin**, Marco A. Díaz, J.Phys.G 49 (2022) 6, 065001

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

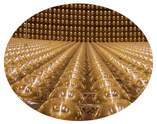
SUSY

or even Super Kamiokande !

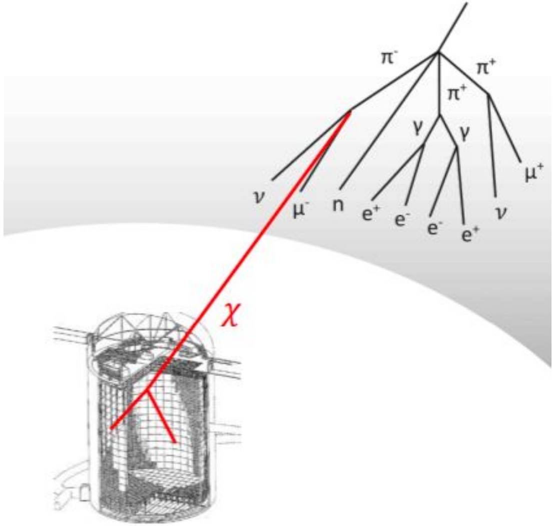
SUSY
S. Martin, A SUSY Primer, arXiv:9709356
SUSY RPV
R. Barbier et al, Phys.Rept. 420 (2005)
H. K. Dreiner, G. G. Ross, Nucl. Phys. B365 (1991)

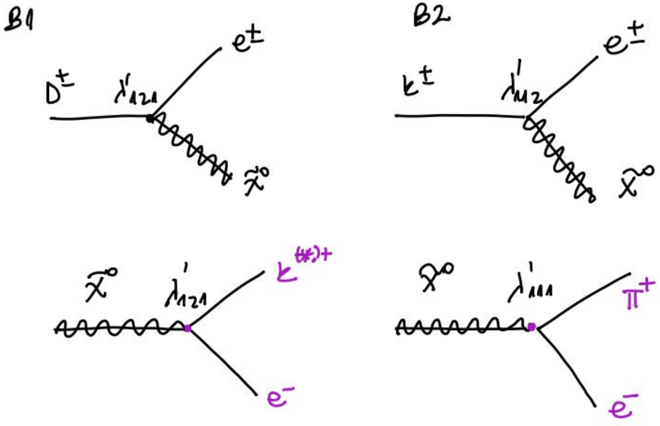


@https://cds.cern.ch/record/2809389/files/ATL-PHYS-PROC-2022-030.pdf



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

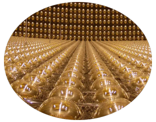




$$\Gamma \sim \lambda'^{2}_{111} \, m_{\tilde{f}}^{-4} \, m_N^{5}$$

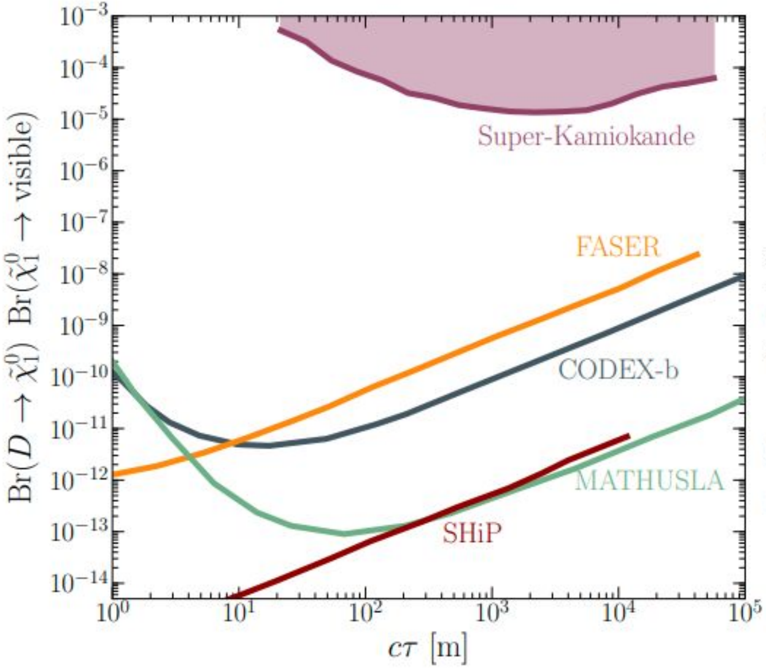
showering final states

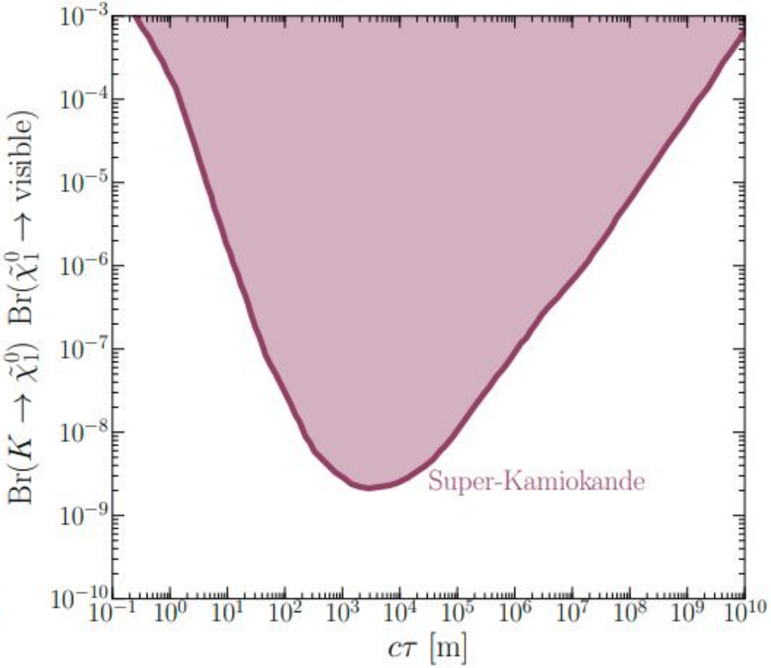
Seminal work in
Searches for Atmospheric Long-Lived Particles, C. Argüelles, P. Coloma, P. Hernández, V. Muñoz, JHEP 02 (2020) 190, arXiv: 1910.12839



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

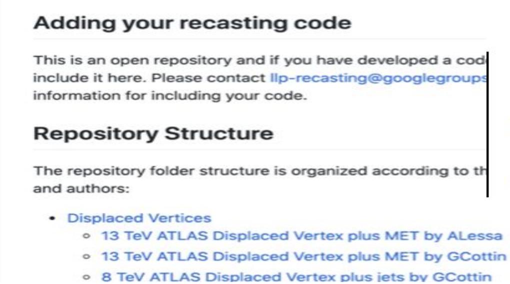
Theories >> Experimental searches

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 ...)

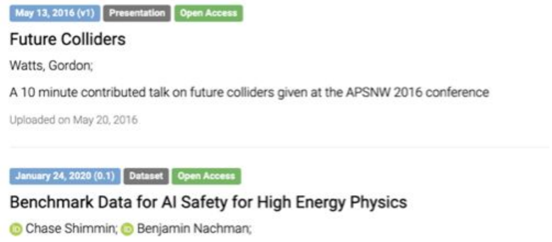

Adding your recasting code

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**

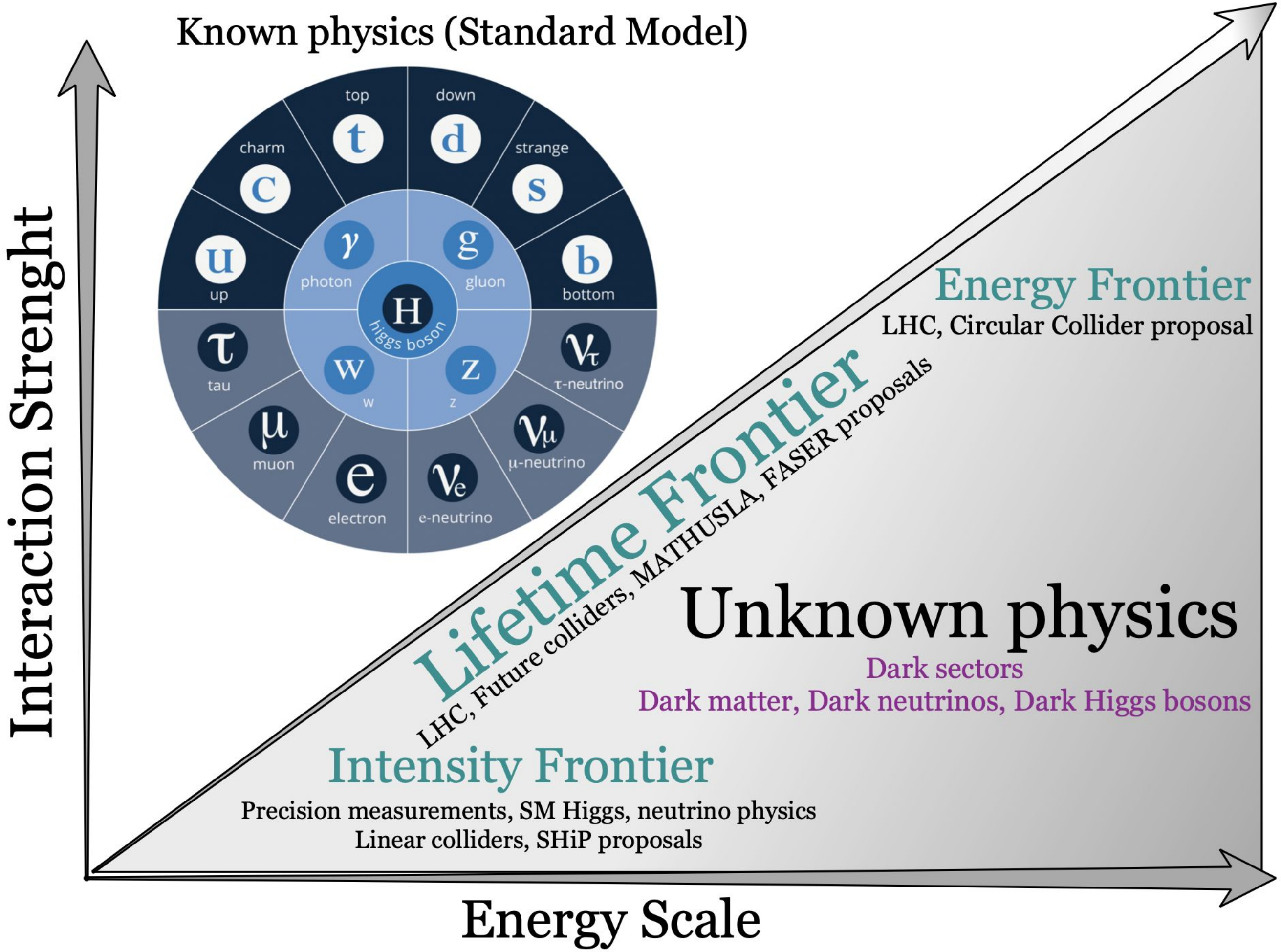
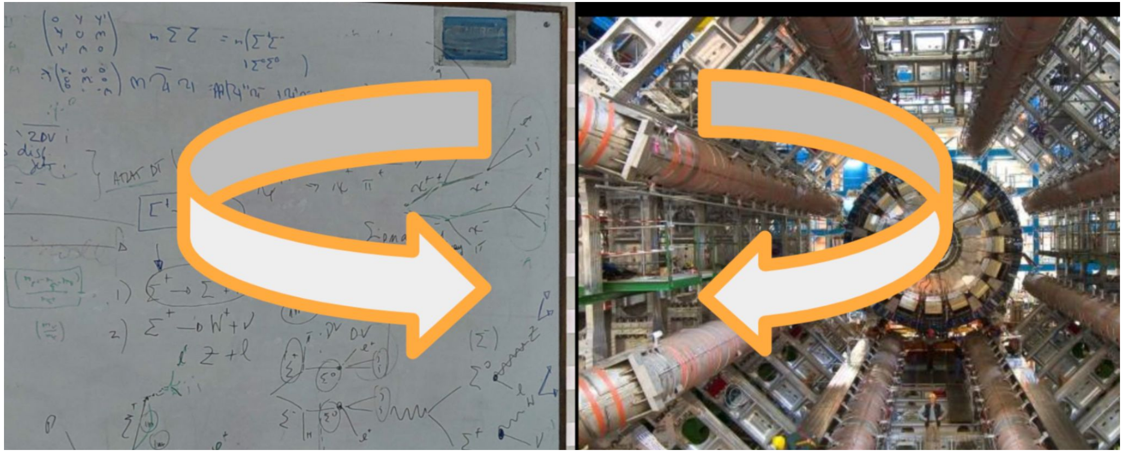


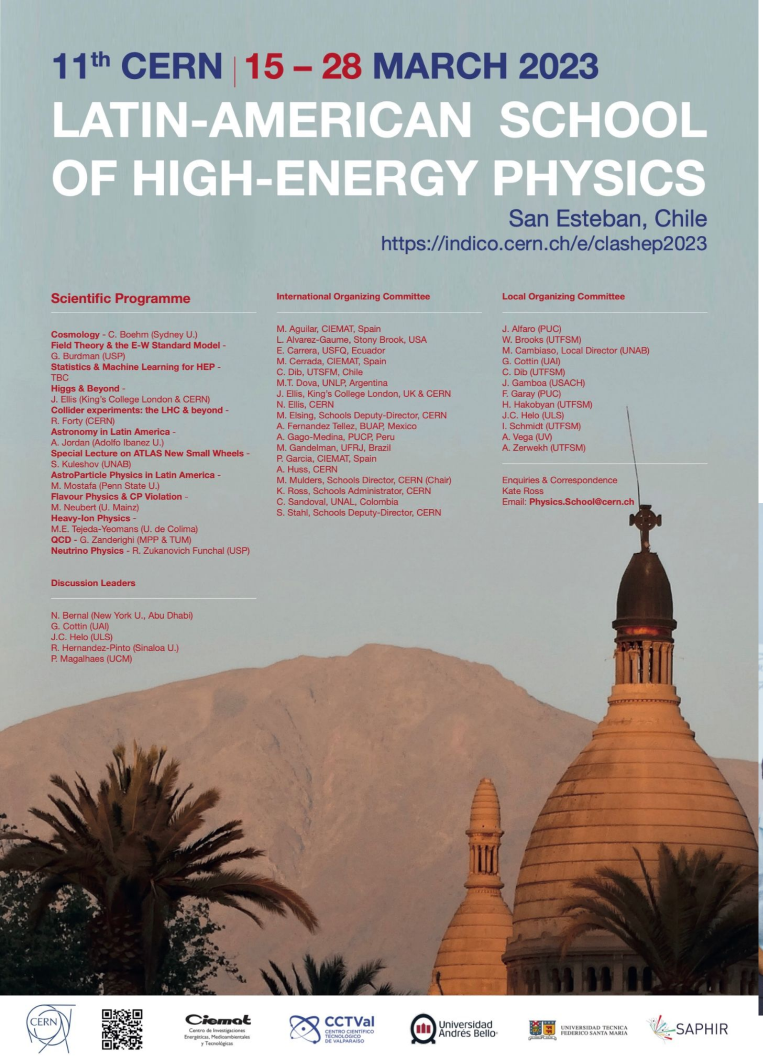
Image by G. Cottin. SM image @CERN

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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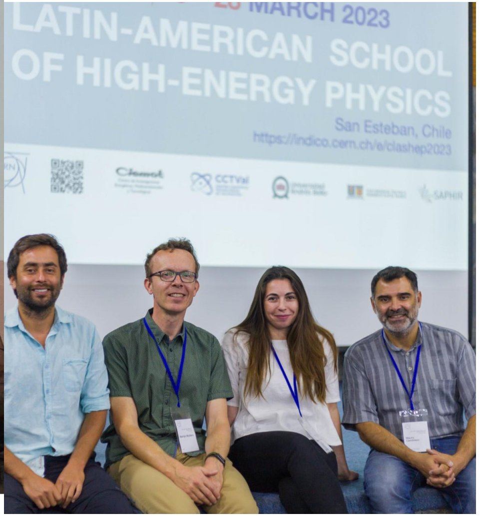

@saphir_millennium_institute

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