

Particle Phenomenology

Universidad de Concepción, Chile
May 2023

Giovanna Cottin

Particle Physicist (Phenomenologist)

<https://sites.google.com/view/giovannacottinburacchio/>

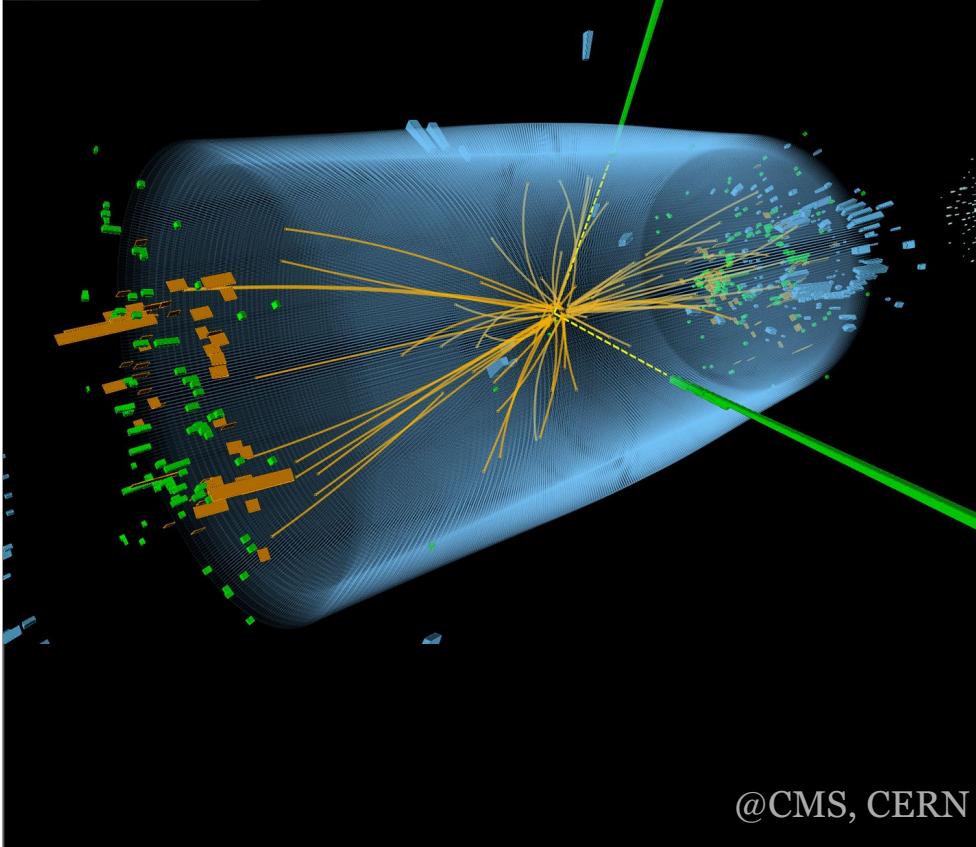
<https://github.com/gfcottin/CursoParticlePhenomenology>

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



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

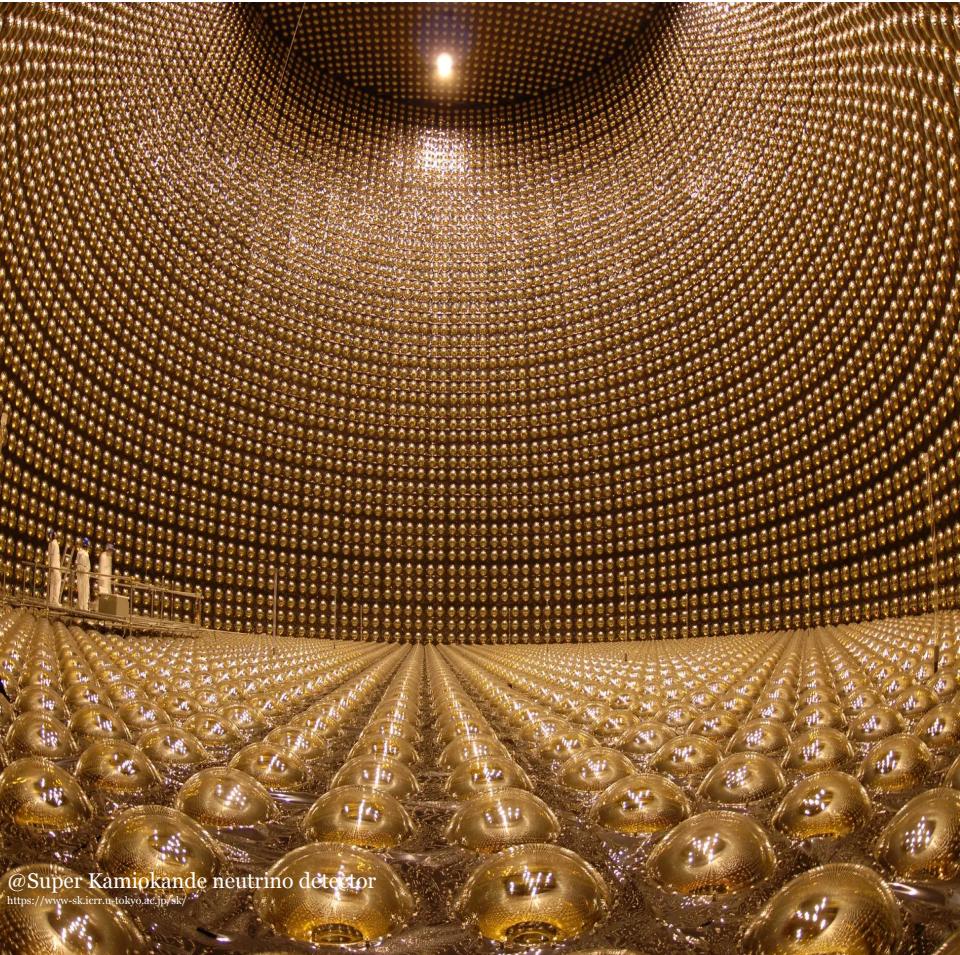
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"



What is it?

How it operates?

Why it matters?



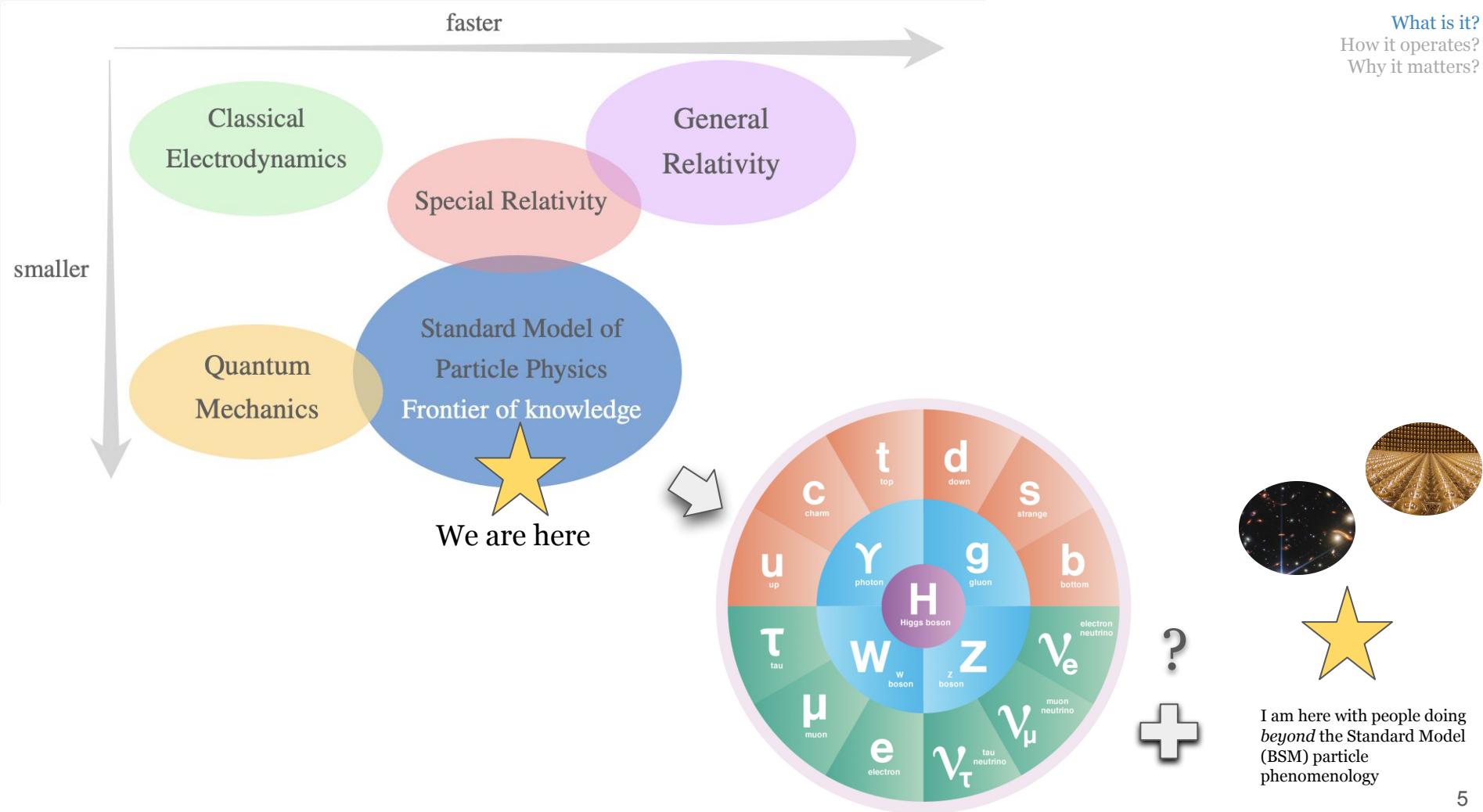
@Super Kamiokande neutrino detector

<https://www.scierr.t.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>

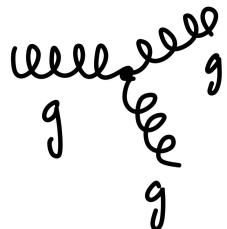


But, what we know first: Modelo Estándar de Física de Partículas

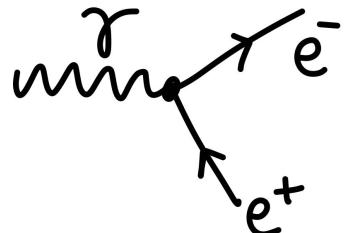
$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \gamma^\mu \psi + \bar{\psi} y_{ij} \psi_j \phi + |D_\mu \phi|^2 - V(\phi) + h.c.$$

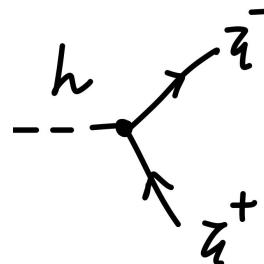
Partículos de fuerza
(BOSONES)



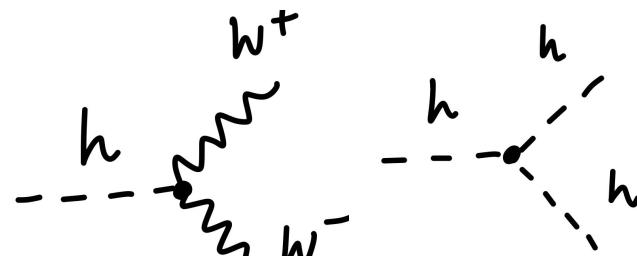
Partículos de materia
(FERMIONES)



Masa de Partículas



Campo de Higgs



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

Teorías

Relatividad General

Cuerpos masivos interactúan en el espacio-tiempo mediante la fuerza de gravedad

Podemos medir:

Espacio

Tiempo

Curvatura

Masa/Energía (de)

Luz

Ondas Gravitacionales

Modelo Estándar de Partículas Elementales

puestas a prueba

Podemos medir sus propiedades:

Masa/Energía

Carga eléctrica (y otros de sus números cuánticos)

en Experimentos

frecuente)

Algunas Interrogantes Abiertas motivan Nuevas Teorías

de neutrinos, Energía y Materia

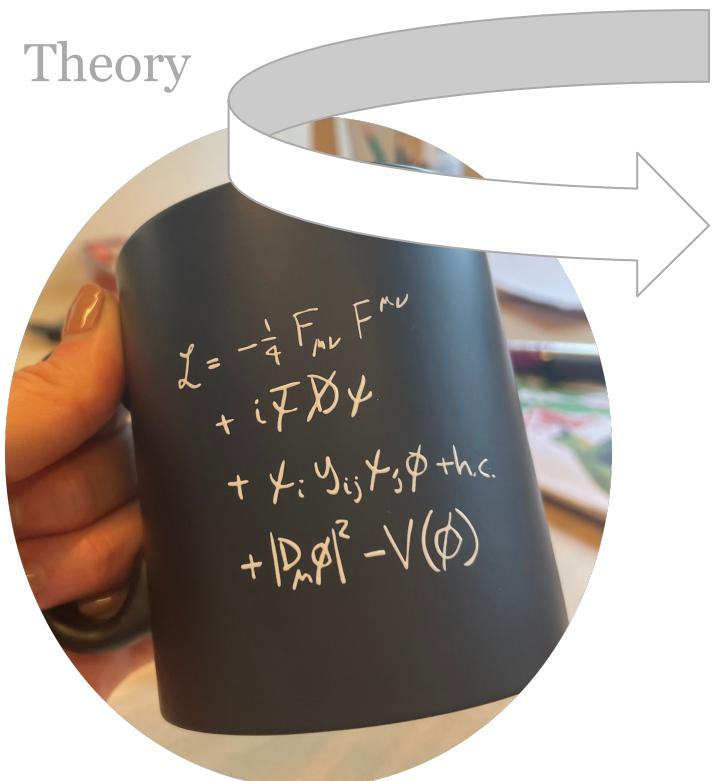
Oscara Nuevas

Fuerzas?

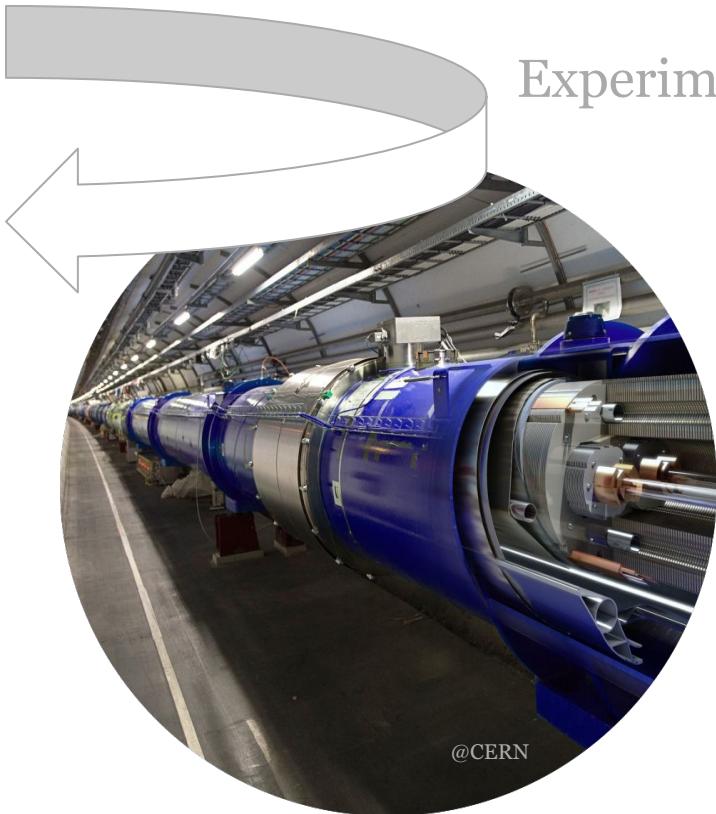
Nuevas Partículas Elementales?

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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Focus is LHC in these lectures



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LHC restarts

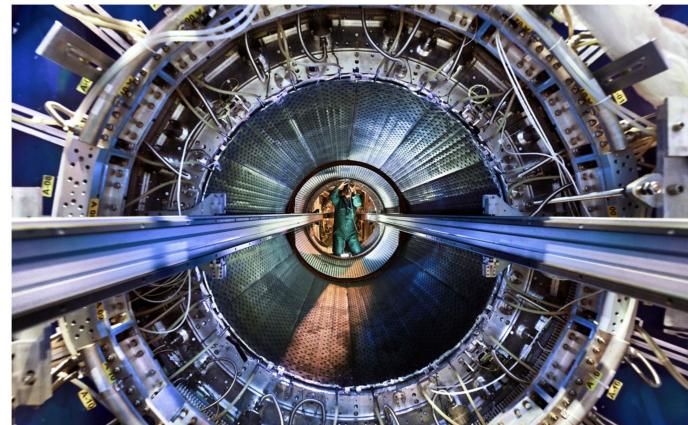
Friday, 22 April 2022

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



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-collisionador-de-hadrones/>

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

Scientists restart Large Hadron Collider in quest for dark matter

By Sean Sperry, CNN
© Updated 12:04 GMT (21:04 HKT) April 22, 2022



More From CNN

DC firms back Amber Heard's privacy request

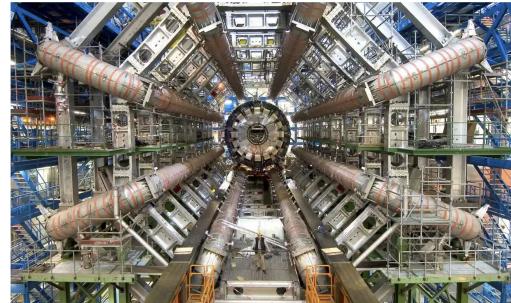
Hubble identifies unusual source in expansion rate of the universe

... plus

pli PremiumBeat by premiumbeat

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 Física

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



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



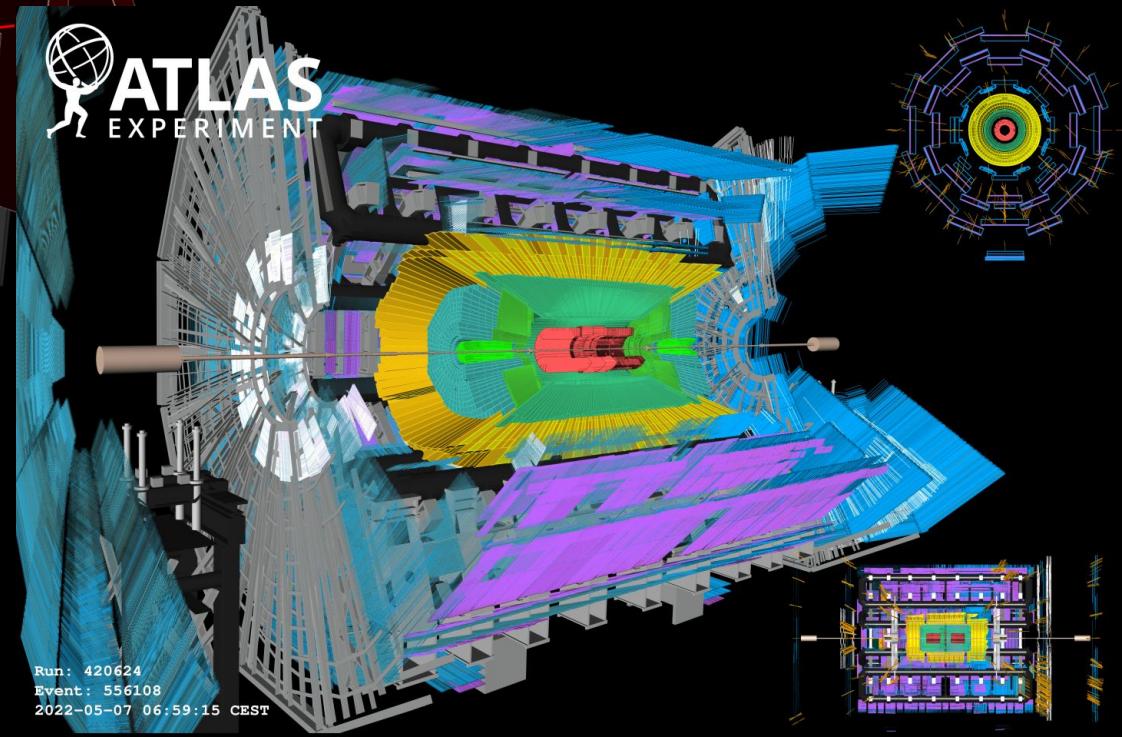
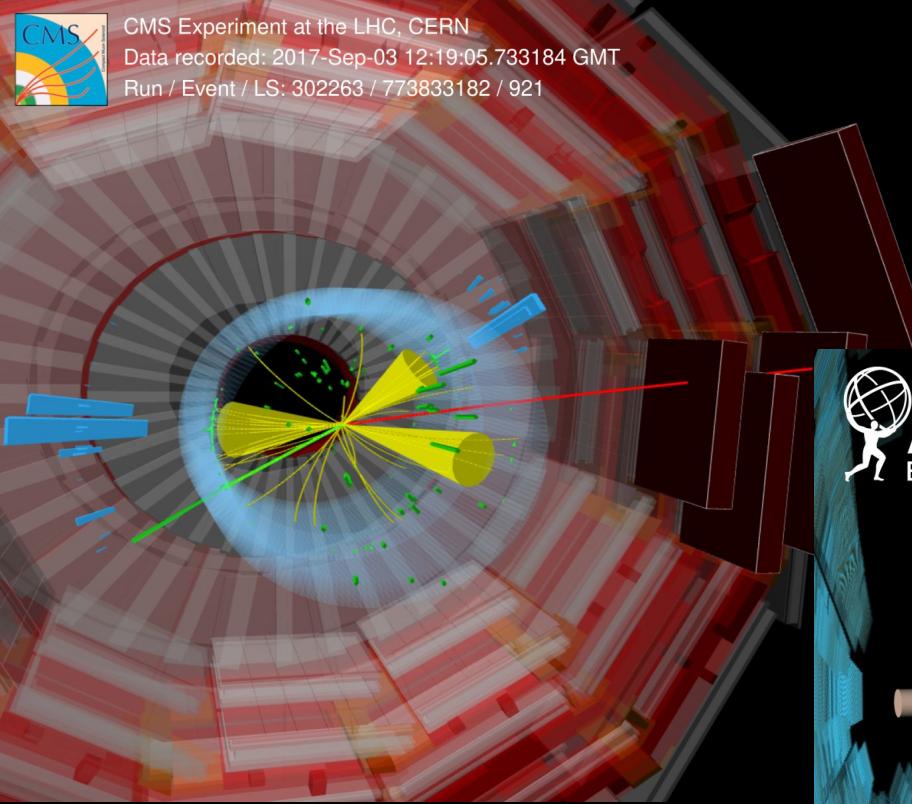
@CERN



CMS Experiment at the LHC, CERN

Data recorded: 2017-Sep-03 12:19:05.733184 GMT

Run / Event / LS: 302263 / 773833182 / 921

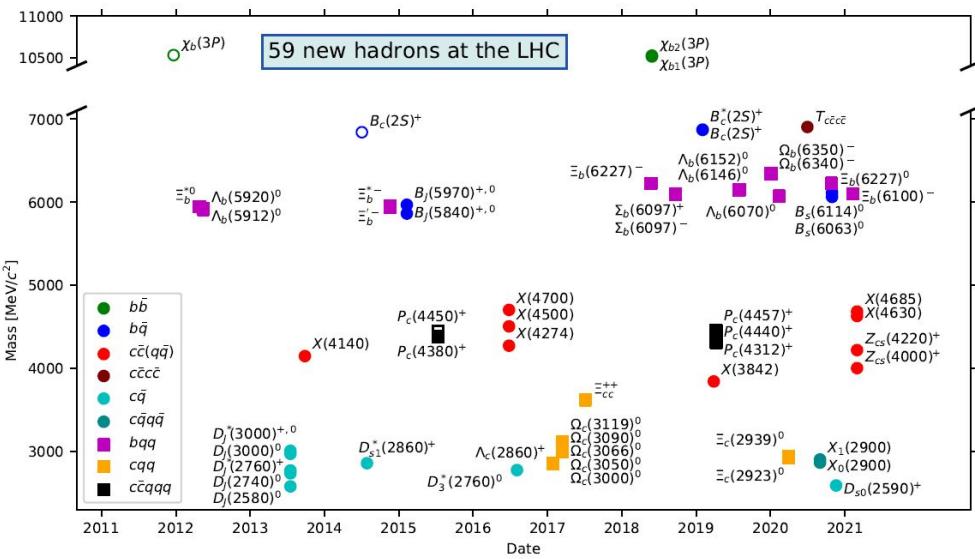


CERN Document Server: <https://cds.cern.ch/>
CMS-PHO-EVENTS-2022-002
ATLAS-PHOTO-2022-028

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

The LHC was built with the goal
to find them !

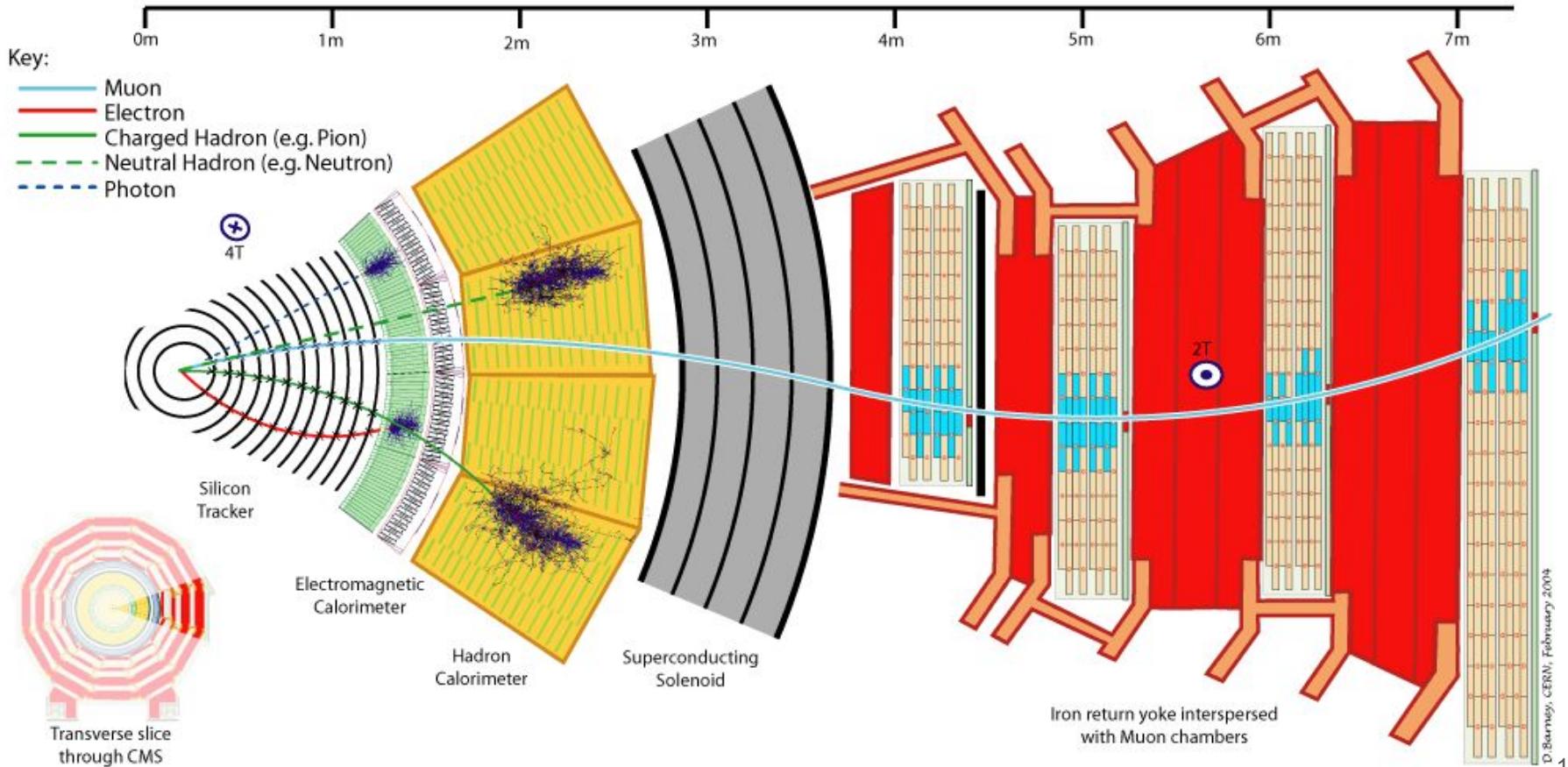
Nobel Prize 2013 to F. Englert and P. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments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



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)

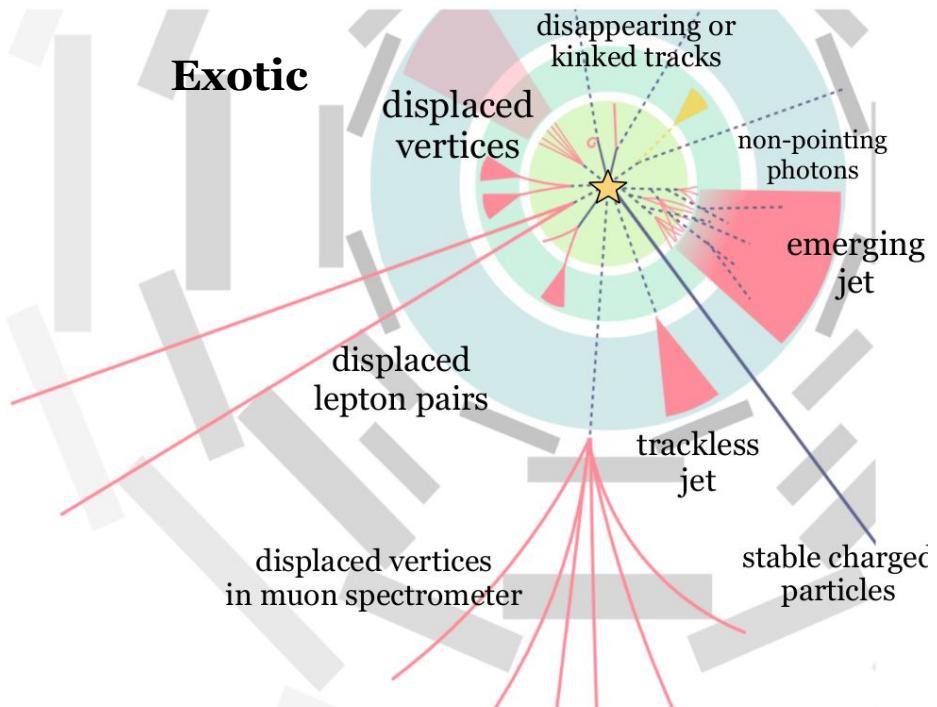
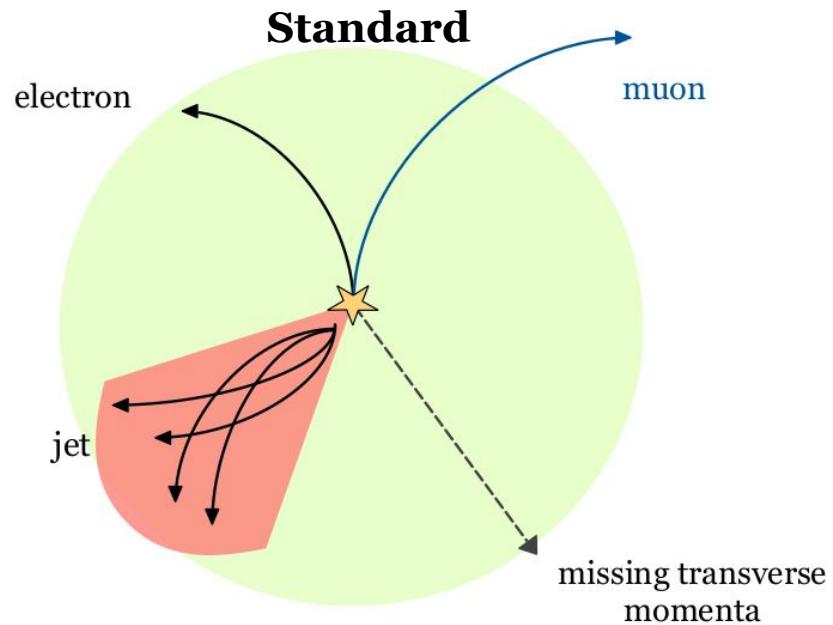


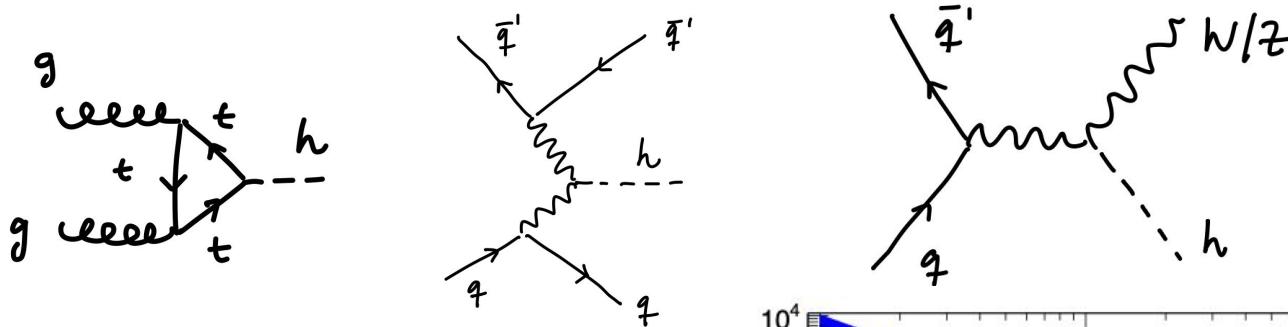
Image by G. Cottin

LLP Image adapted from Heather Russel.

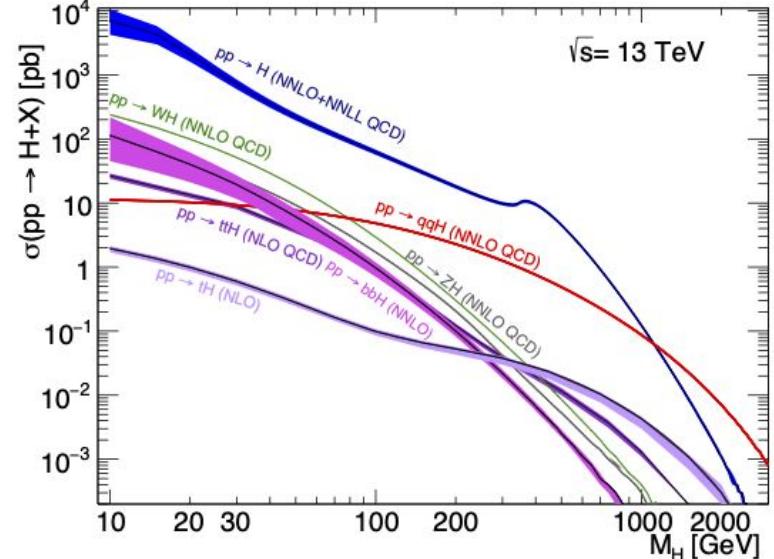
Long-lived Particle Community White Paper, J. Alimena, .. , G. Cottin, et al, *J.Phys.G* 47 (2020) 0, 090501

Un caso real: midiendo el Bosón de Higgs

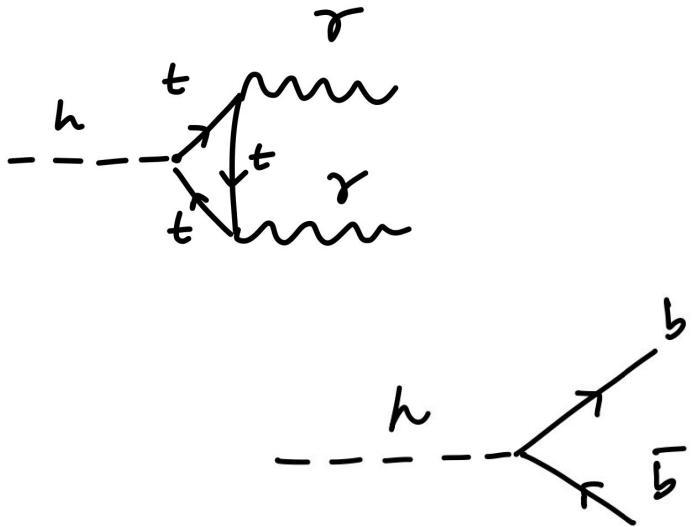
Production



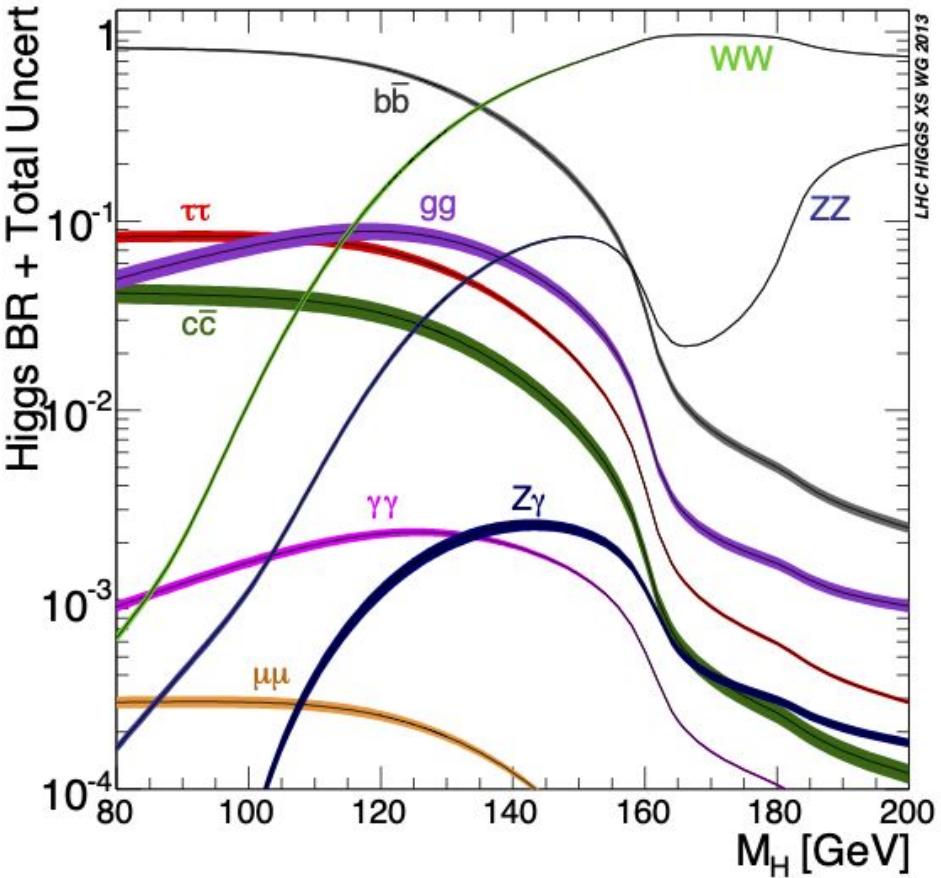
En el LHC se seleccionan los eventos con el Trigger (i.e Vector Boson Fusion, requiring at least two jets with $pT > X$ GeV)



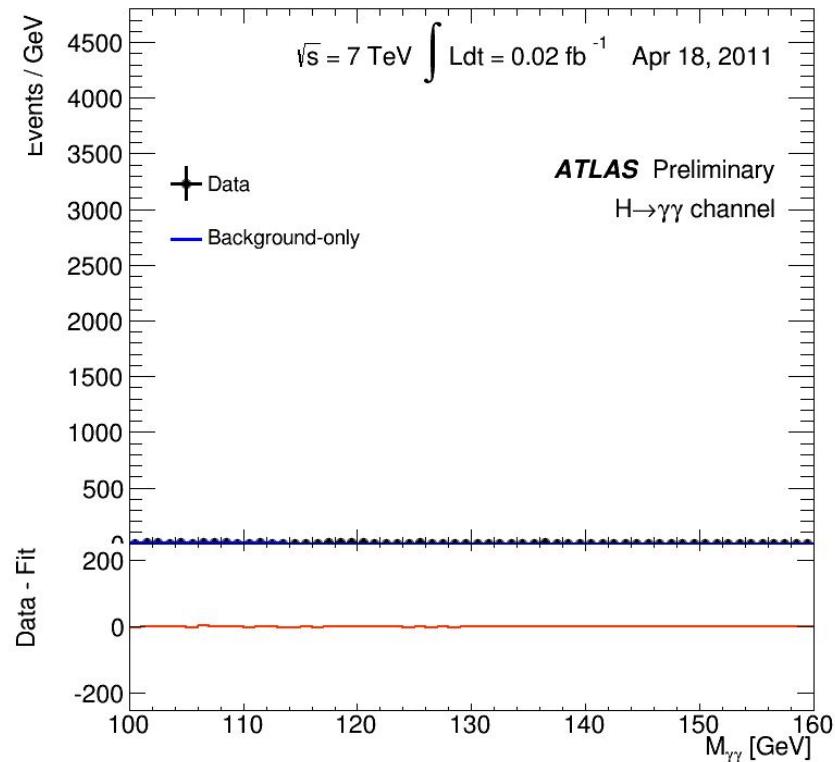
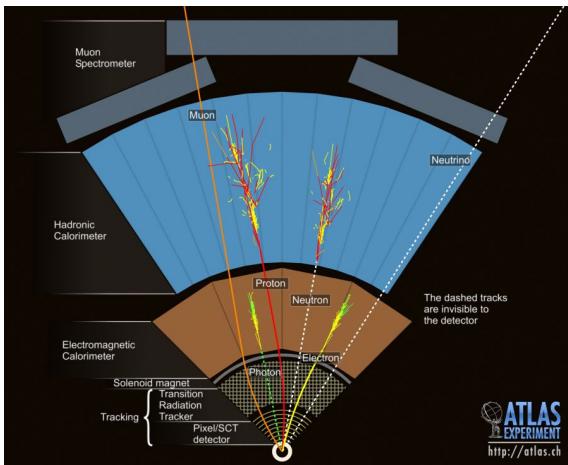
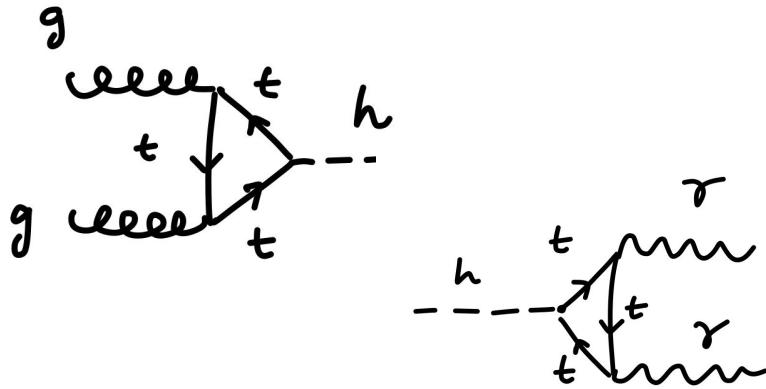
Decay



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



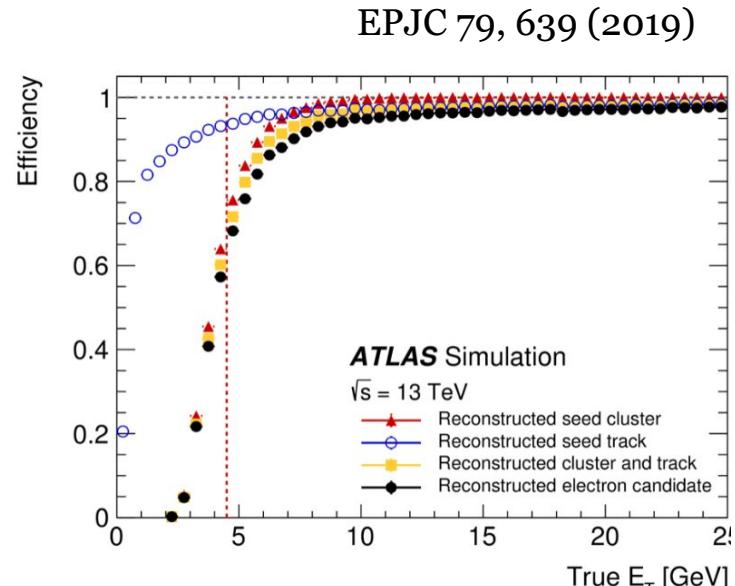
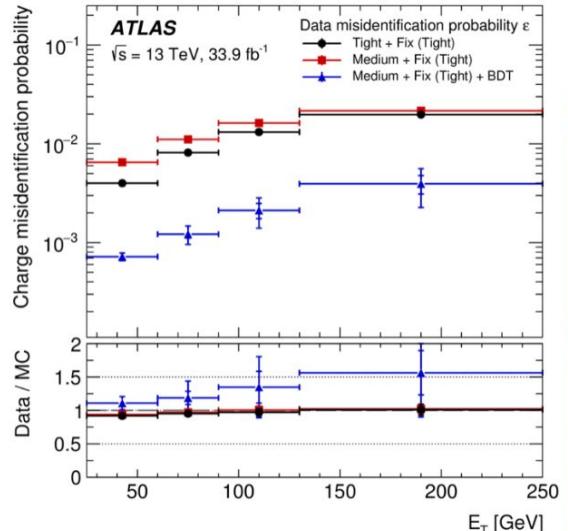
Juntando todo, se mide el Bosón de Higgs



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

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

For Experimentalists:



For Theorists/Phenomenologists:

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

Necesitamos simular la respuesta experimental !

```

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    -11 -1      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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Theory meets Reality

Many theory models predicting
new particles addressing

Neutrino Masses
Dark Matter
Baryogenesis
Anomaly explanations ...



Not always being looked for @ High Energy 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



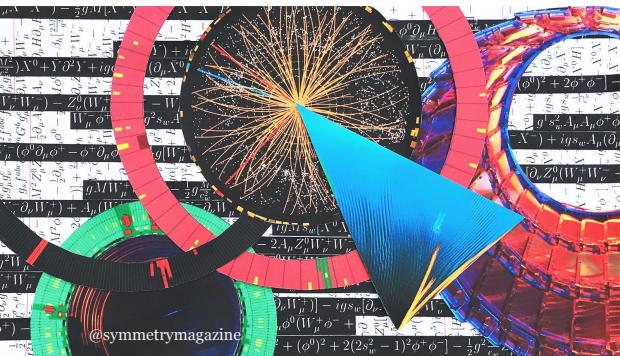
Philosopher's Path@ Kyoto

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)

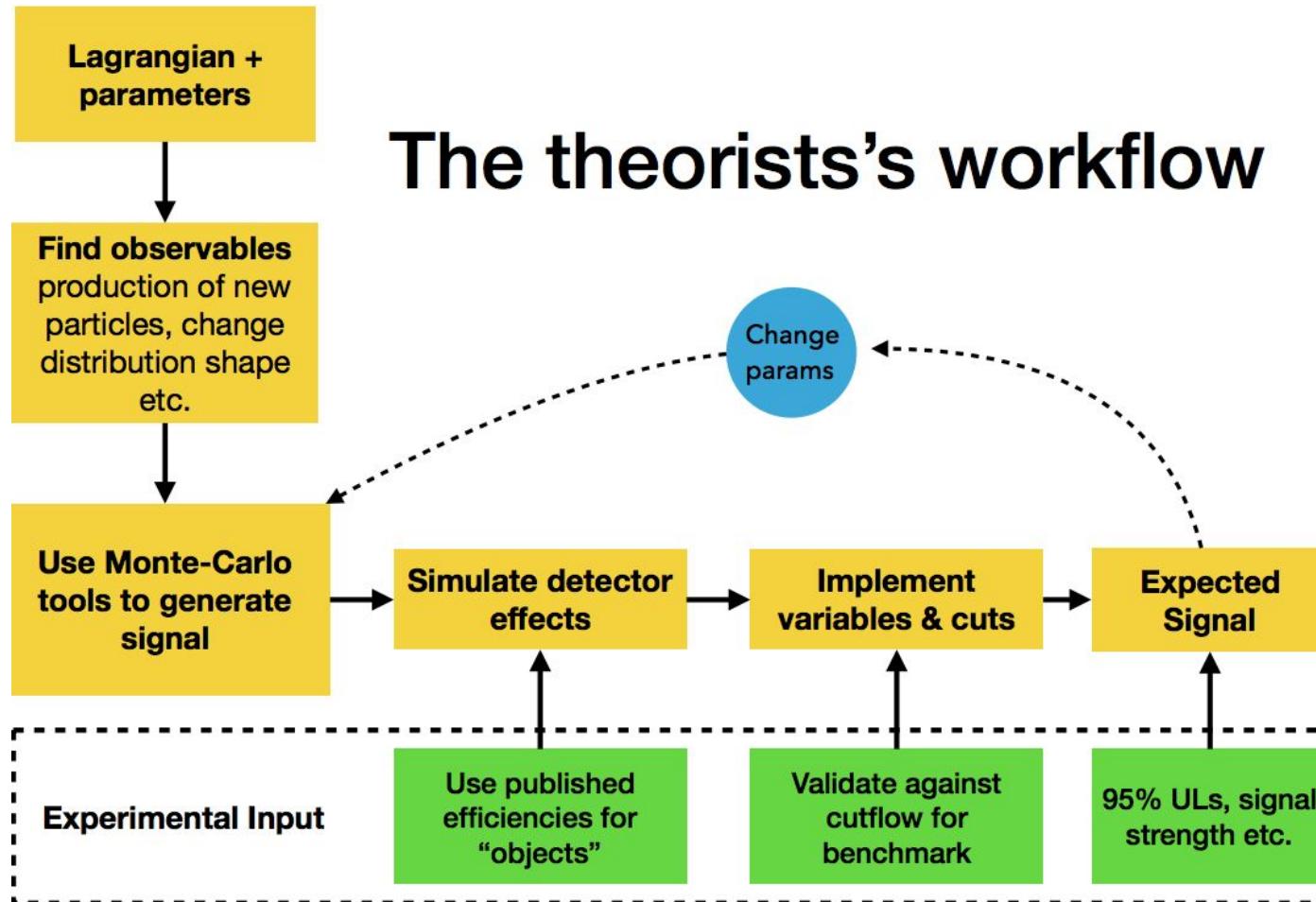


Evaluate Experimental Response

- 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

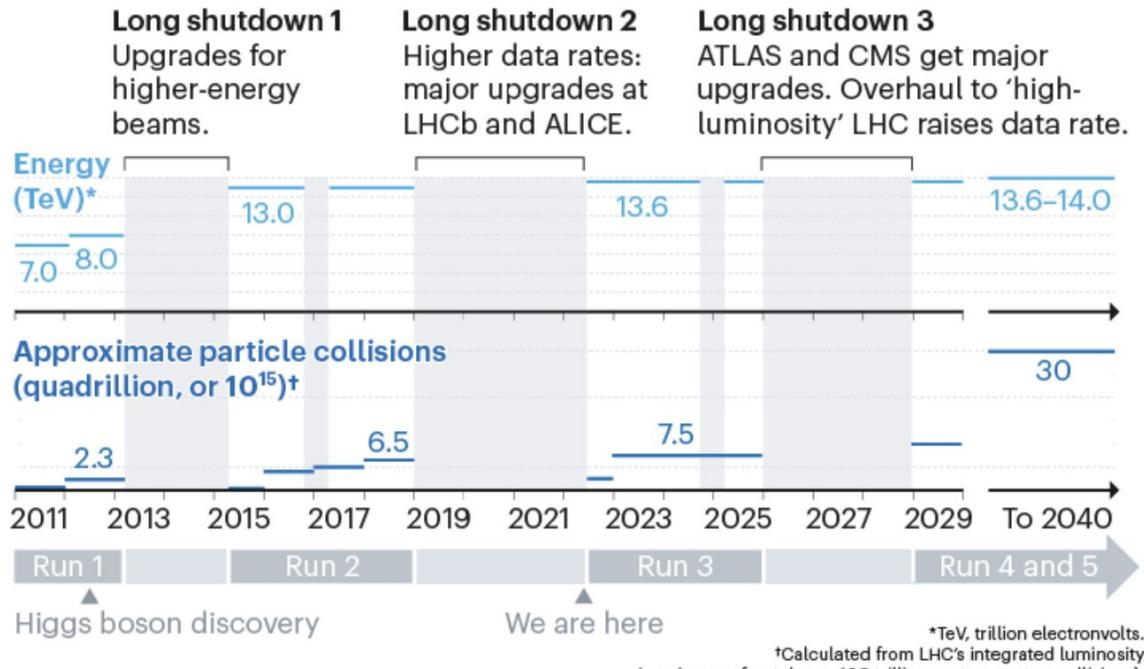
Slide from Nishita Desai @ LLP Workshop, CERN



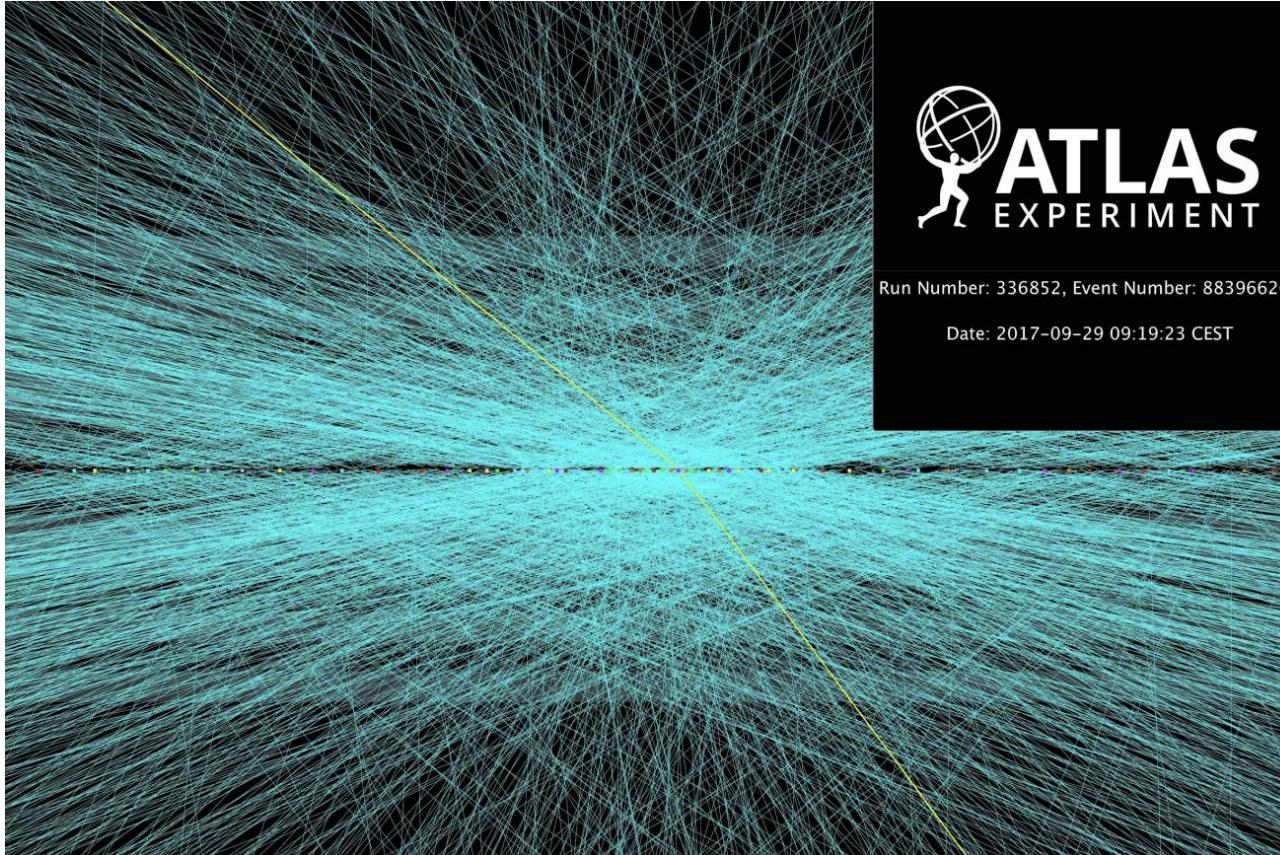
The LHC will run for the next ~20 years

LHC TIMELINE

The Large Hadron Collider (LHC) will be further upgraded from 2026 to 2029 to conduct even more particle collisions, at higher energies. It is then scheduled to run for another decade.



... 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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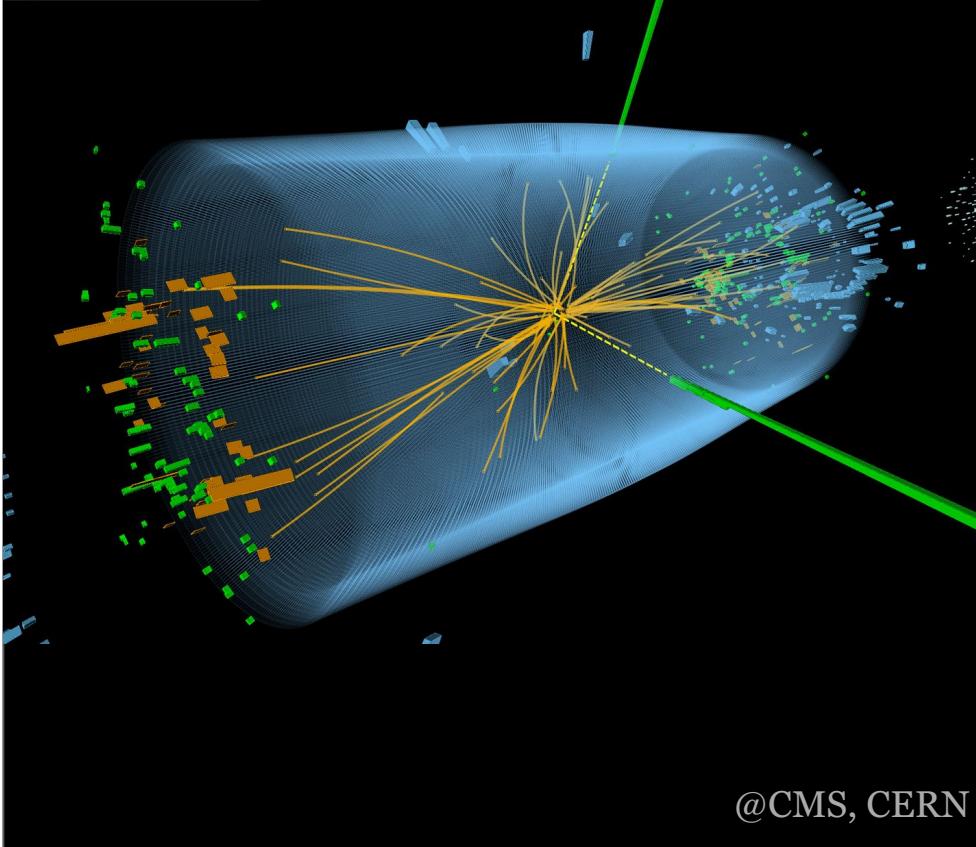
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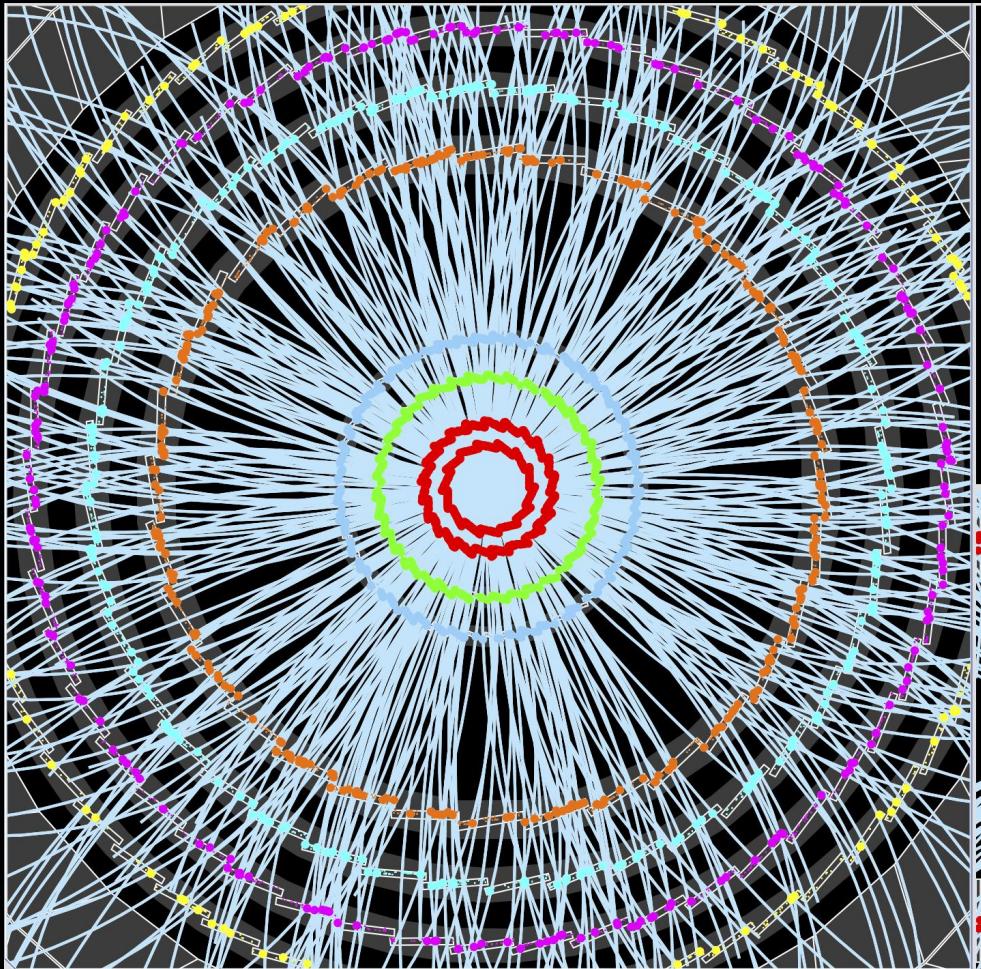


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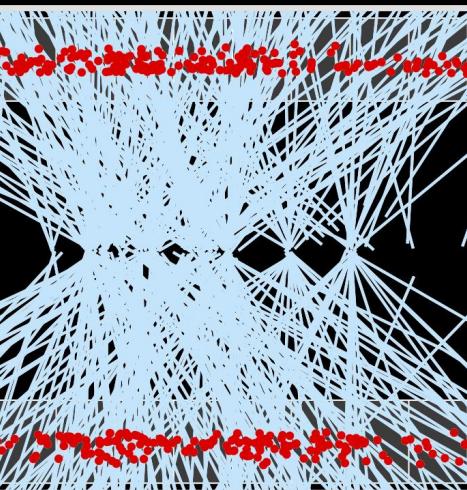
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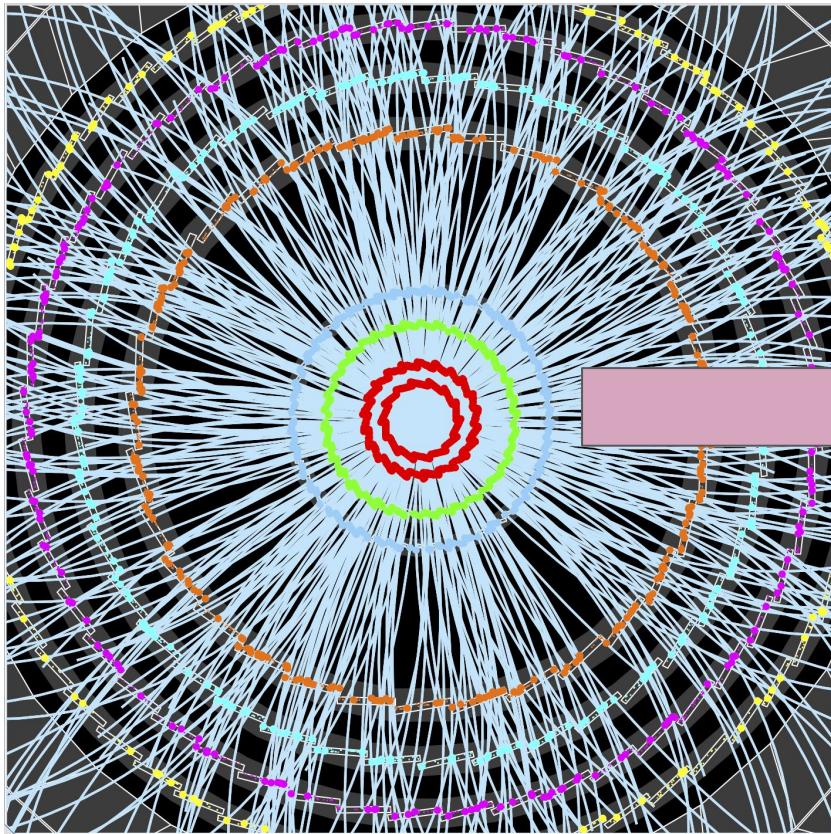
 **ATLAS**
EXPERIMENT

Run Number: 266904, Event Number: 25884805

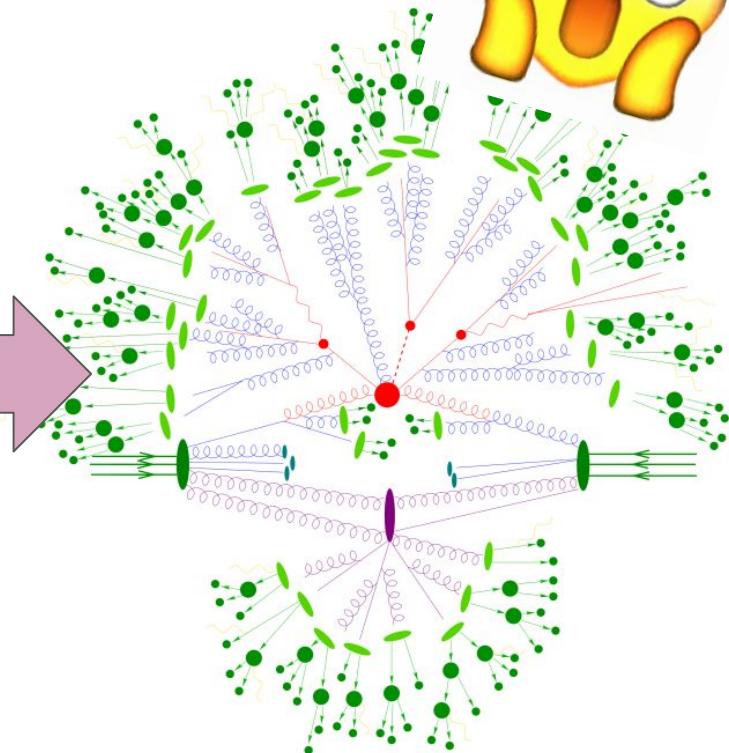
Date: 2015-06-03 13:41:54 CEST



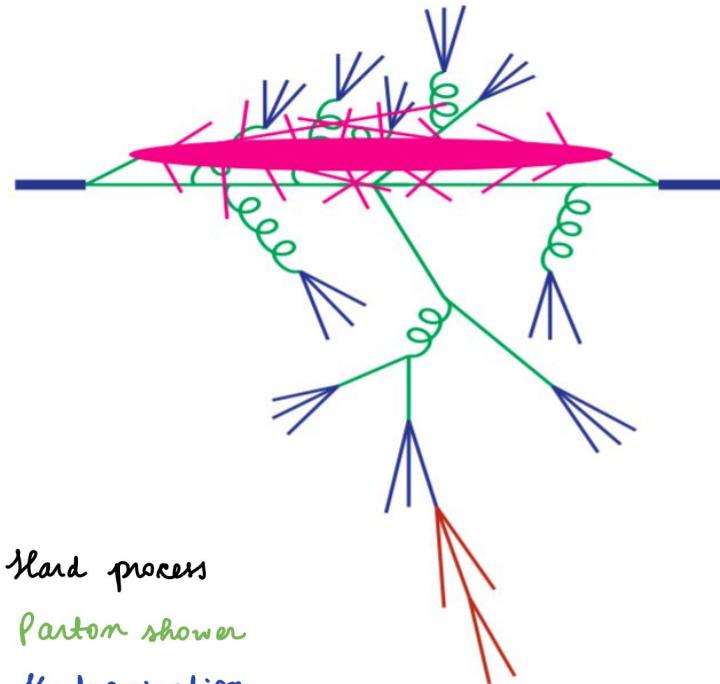
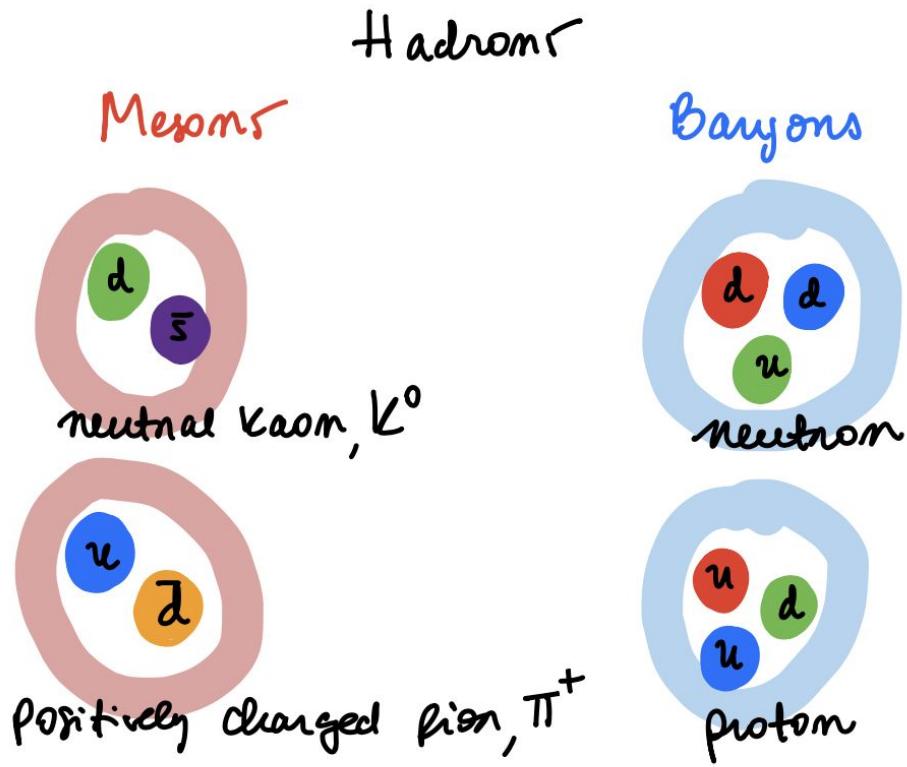
Phenomenologists need to simulate this !



@ATLAS, CERN



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



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 L0 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 == {
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    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>



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

Remember this?

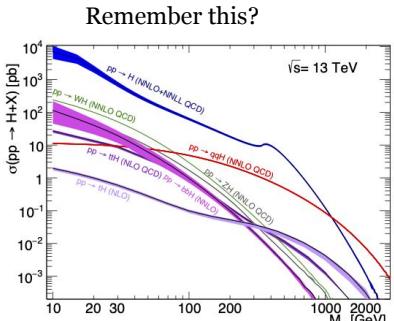
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  1012 1  1  2  0  0  -7.2980127356e+02 -5.945453626e+02 1.500000000e+03 4.467542000e+02
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PYTHIA 8.3

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

Remember this?

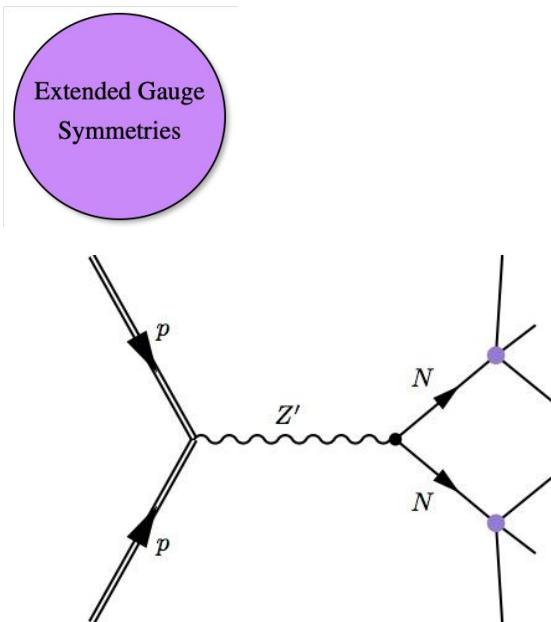


Remember this?

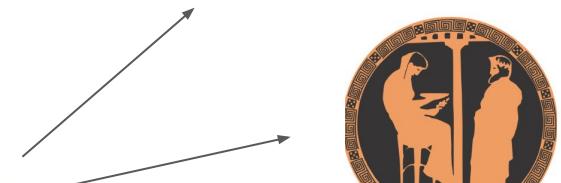
Generamos eventos con Monte Carlo, recordemos que en quantum mechar las amplitudes son realmente probabilidades!

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 lifetime)
- * A compact and efficient way to benchmark models, as oppose to the design of separate (potentially redundant) searches for each UV model



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

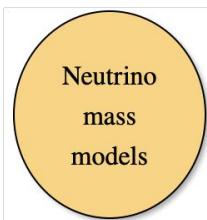


PYTHIA 8.3

Examples of the Workflow / Challenges

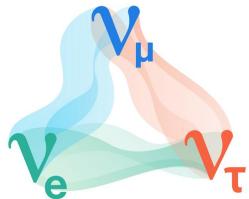
1) Characterize/Signal/Background generation

- 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](https://arxiv.org/abs/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



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

$$\mathcal{L}_{\nu_{\text{mass}}} = \frac{1}{2} (\bar{\nu}_L^c \bar{N}_R) M_\nu \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix} + h.c.$$

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

$$M_N \gg m_D$$

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

$$m_N \approx M_N$$

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

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

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

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

$$M \ll M_N \quad \text{Inverse seesaw} \rightarrow V_N^2 \sim m_\nu / \mu$$

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

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

$$pp \rightarrow W^\pm \rightarrow N l^\pm$$

$$N \rightarrow l^\pm q\bar{q}$$

$$N \rightarrow l'^\pm l^\mp \nu_\ell$$

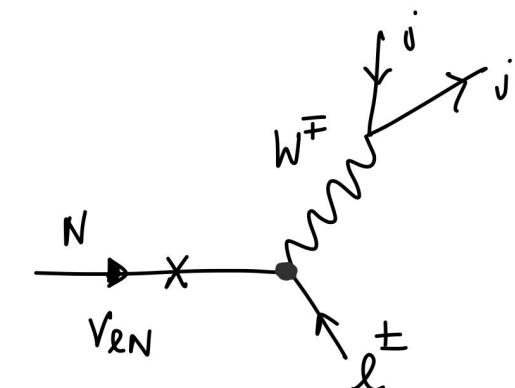
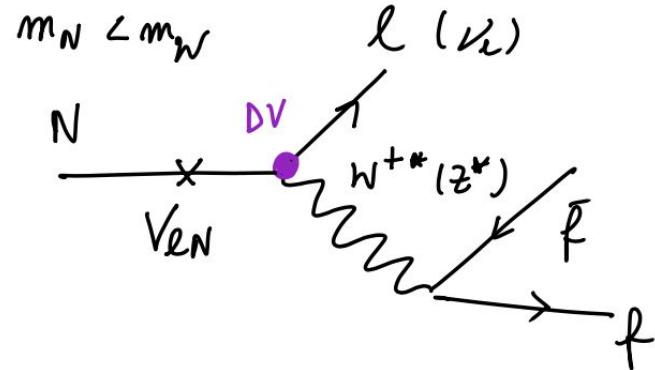
$$N \rightarrow \nu q\bar{q}$$

Identity signal



$$\Gamma \sim G_F^2 |V_{RN}|^2 m_N^5$$

Small mixings and \sim GeV scale HNL \Rightarrow LLP!



Identity signal topology and observables

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 account off-shell WR exchange in

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 N s that show a relative enhancement. Their production is still significant via W_R^* , as long as there is sufficient energy available from

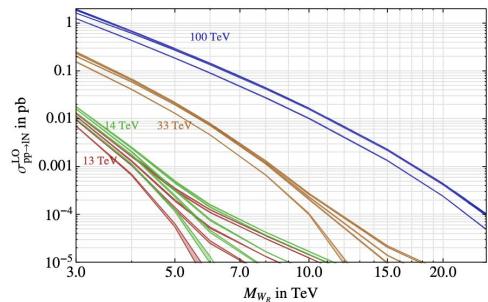
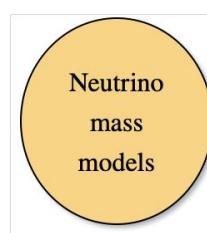
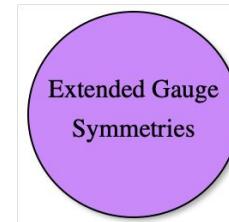
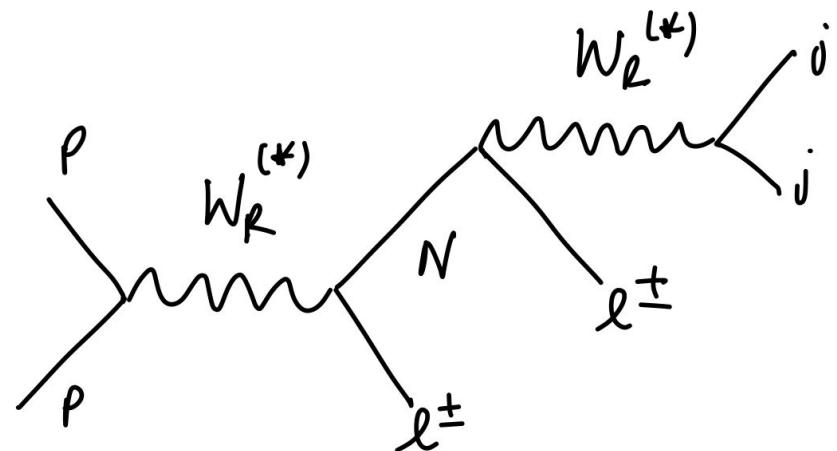


FIG. 3. Drell-Yan production cross section of $pp \rightarrow W_R^\pm \rightarrow \ell^\pm N$. For each indicated interaction energy, the curves from upper to lower are relative to $m_N = 50, 100, 500, 1000, M_{W_R}/2$, showing normal phase space suppression. In addition, notice the relative enhancement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



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

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



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

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



Giovanna Cottin

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

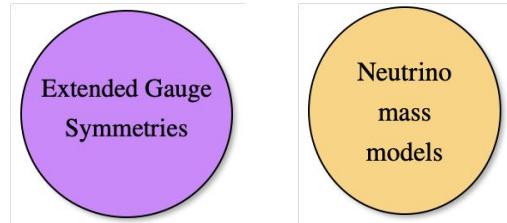


Goran Popara gpopara@irb.hr via phys.ntu.edu.tw

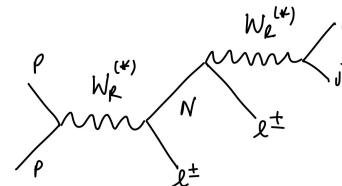
to Giovanna ▾

Dear Giovanna,

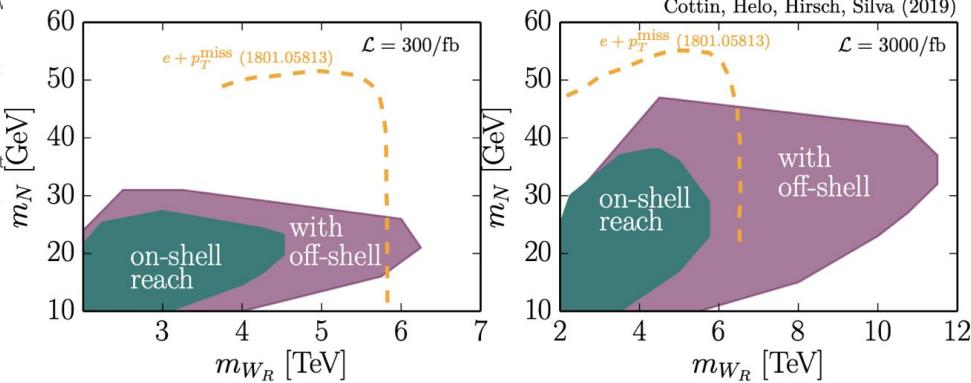
the way you can do this is to merge all of the ks_*.dat files into one single file and then run the generator on that file. Each line in those files represents an independent process, so you can freely add and remove them. We separated the files since it was easier to run them on the cluster that way.



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

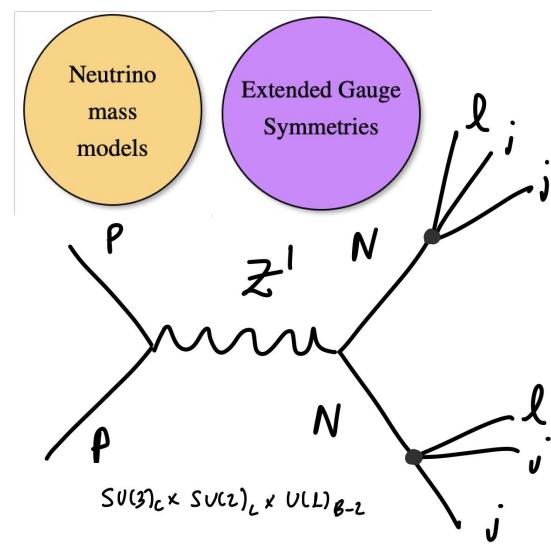


G. Cottin, J.C. Helo, M. Hirsch, D. Silva, PRD 99, 115013 (2019)



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 ...)

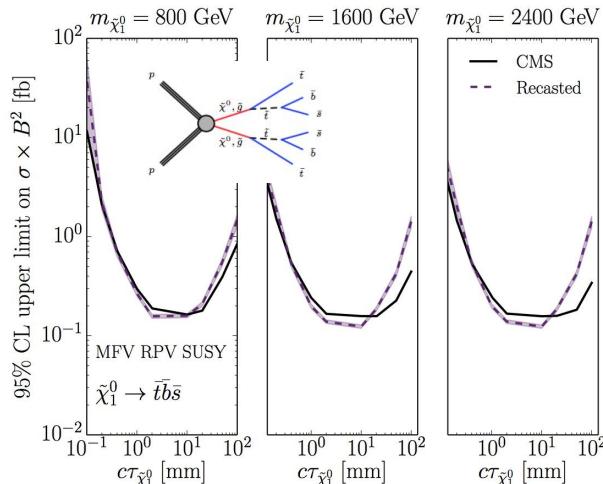


C.W. Chiang, G. Cottin, A. Das, S. Mandal JHEP 12 (2019) 070

(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

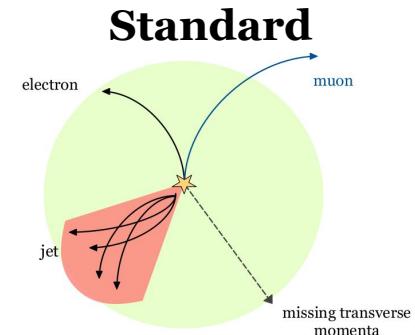
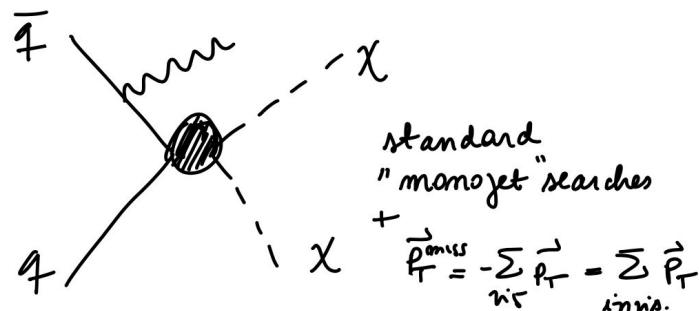
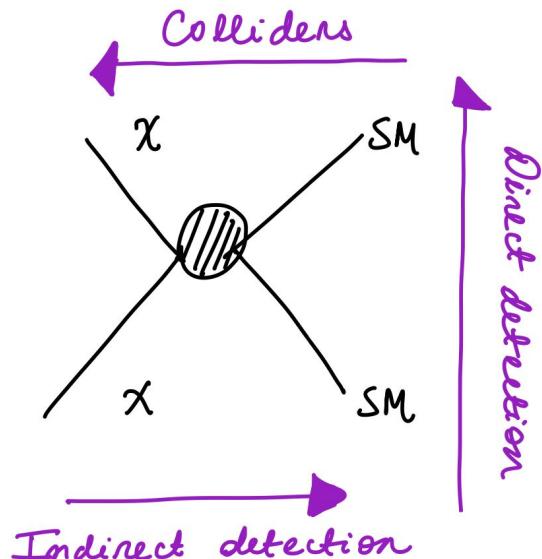


2) Usage/Design -> Propose your own search if standard cuts are not optimal for your signal

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

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

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

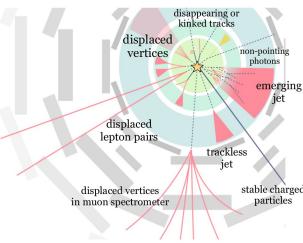
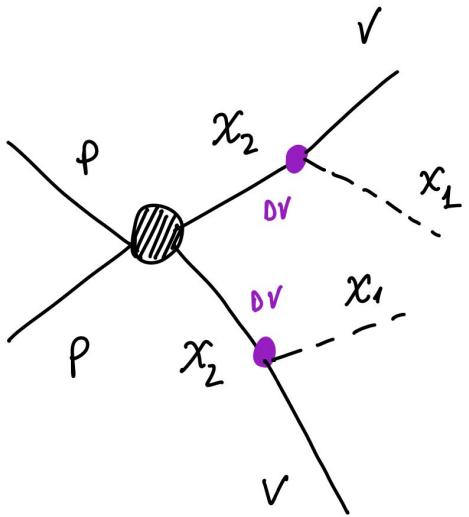


To see “nothing”, you have to understand everything !

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!

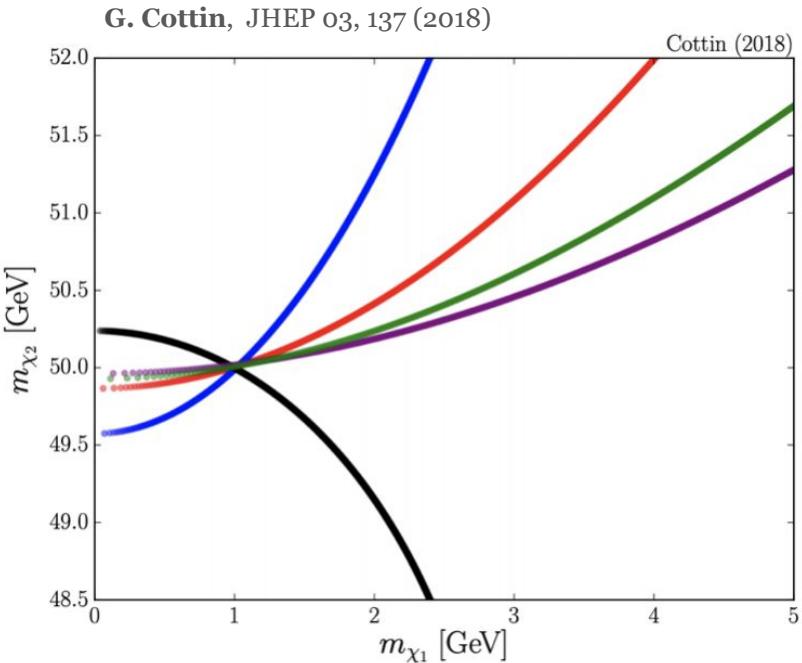


$$\Gamma \sim \lambda^2 \left(\frac{\Delta m}{\Lambda} \right)^n \Delta m$$

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

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

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

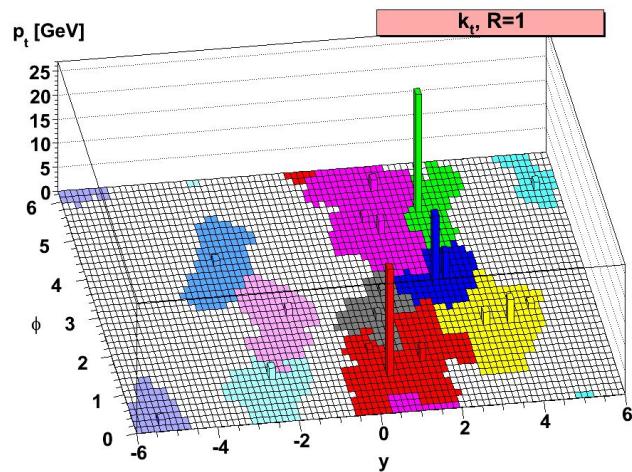
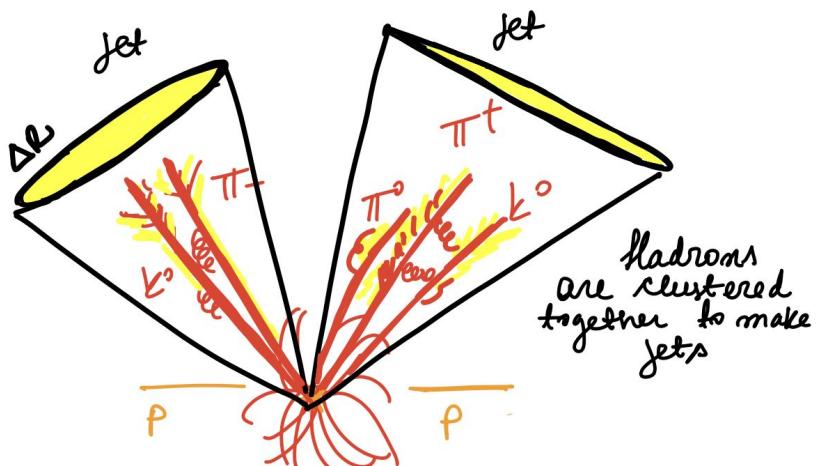
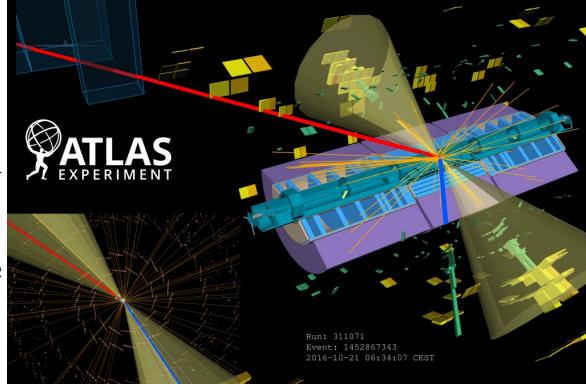


By proposing a **new mass variable** for the masses system, can solve on an event by event basis, and the system is fully constrain

The DM mass could be measured at colliders !

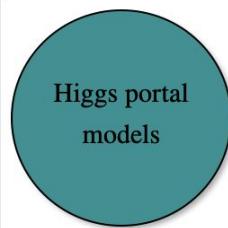
3) Evaluate Experimental Response -> Simulation !

- 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?



4) Implement your search and estimate reach

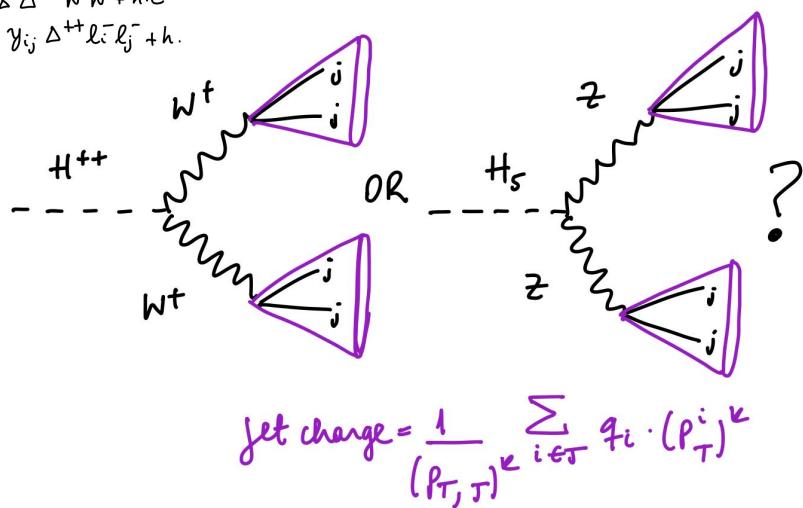
- Define significance (i.e. can I assume o bkg? Can I estimate all my backgrounds? Are there any background uncertainties? How they will escalate with luminosity if I am proposing a new search at a future collider for example?)
- Will I do a cut and count analysis? Or I can Machine Learn my search by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



SM + $SU(2)$ -triplets (Δ)

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

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

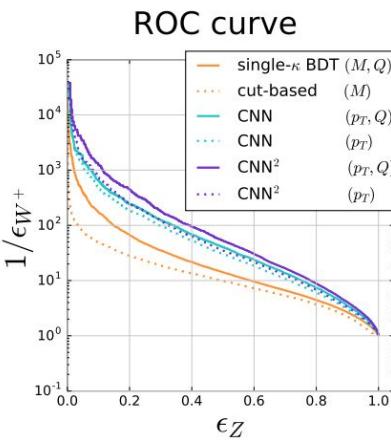


Field, Feynman, Nucl. Phys. B136 (1978) 1.

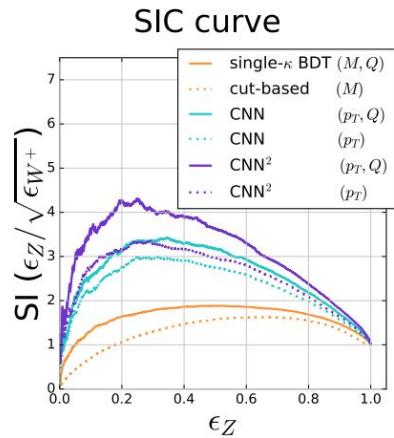
By reusing Feynman's jet charge with deep learning, could distinguish jets from doubly charged or neutral gauge bosons

$$N = \tau \cdot BR \cdot L \cdot \text{eff}$$

$$\text{Significance} = \frac{N}{\sqrt{B}} , \frac{N}{\sqrt{B+DB}}, \dots \text{mono sophisticated?}$$



ROC curve

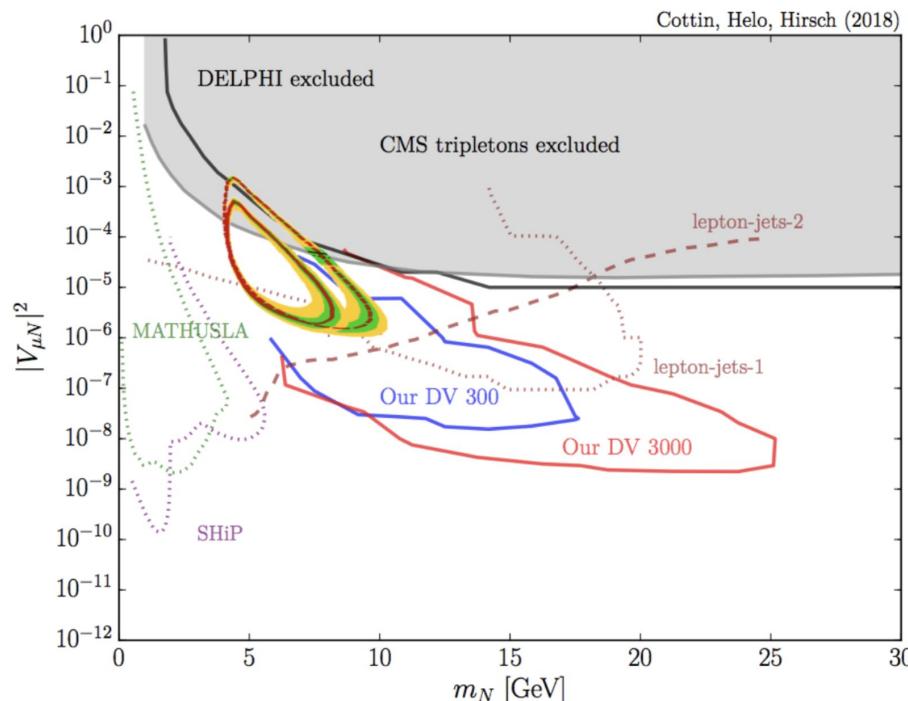
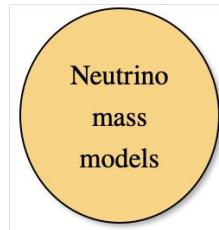


J. Chen, C.W. Chiang, G. Cottin, D. Shih [Phys.Rev.D 101 \(2020\) 5](#)

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)



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

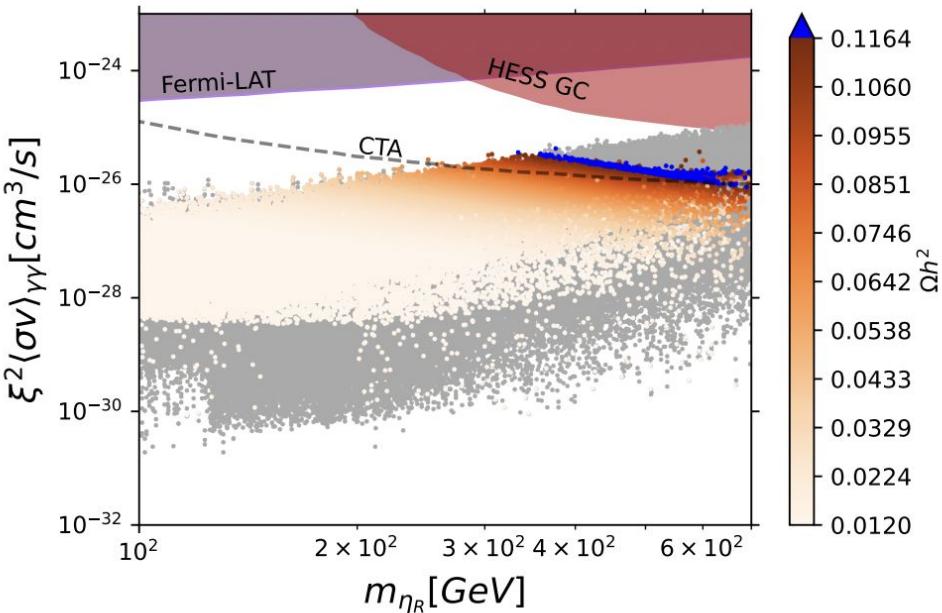
Strategy updated in R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, JHEP 01 (2022) 044



@symmetrymagazine

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

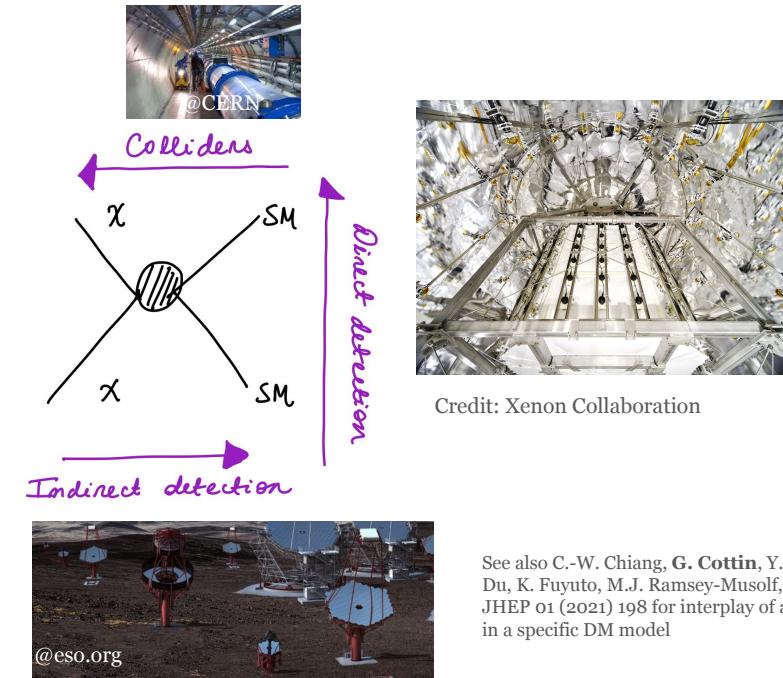
Hard code your model and use dedicated software as



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

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

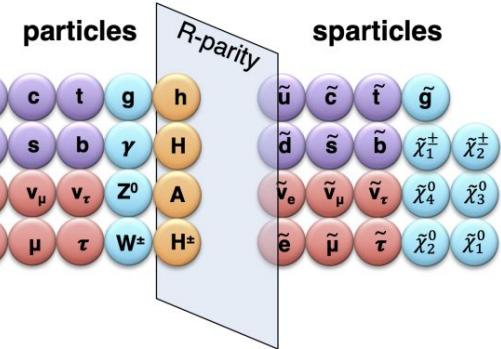
<https://lapth.cnrs.fr/micromegas/>



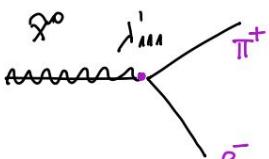
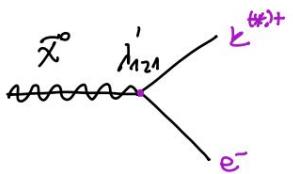
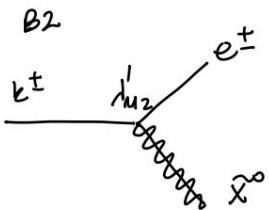
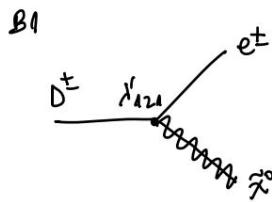


or even Super Kamiokande !

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



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

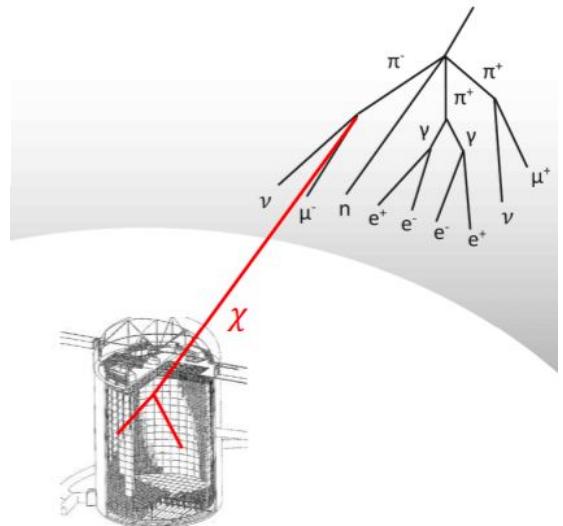


$$\Gamma \sim \lambda_{AAA}^{1/2} m_{\tilde{f}}^{-4} m_N^5$$

showing 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](https://arxiv.org/abs/1910.12839)

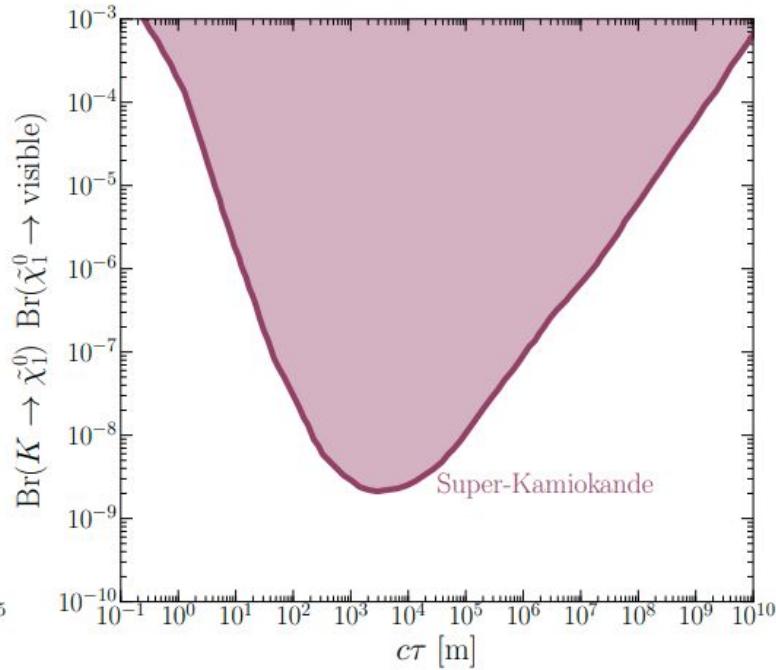
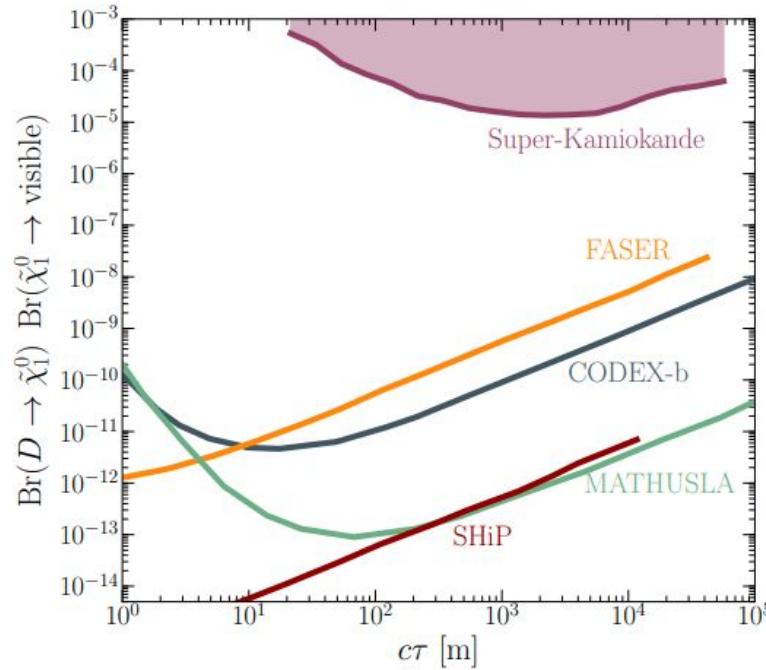




SUSY



Understand comparison with (future) collider experiments ! (kaon gap at colliders)



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 ...)

This is a screenshot of a GitHub repository page. At the top, there are buttons for 'May 13, 2016 (v1)', 'Presentation', and 'Open Access'. The repository title is 'Future Colliders' by 'Watts, Gordon;'. Below the title, it says 'A 10 minute contributed talk on future colliders given at the APSNW 2016 conference' and 'Uploaded on May 20, 2016'. The main content area has two sections: 'Adding your recasting code' and 'Repository Structure'. The 'Adding your recasting code' section contains a note about contributing code and contact information. The 'Repository Structure' section describes the folder organization and lists several items under 'Displaced Vertices'.

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

Adding your recasting code

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

Repository Structure

The repository folder structure is organized according to the 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

Summarizing, to do BSM phenomenology

Expertise still needed in

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 !

5) Present results/discovery potential for your model

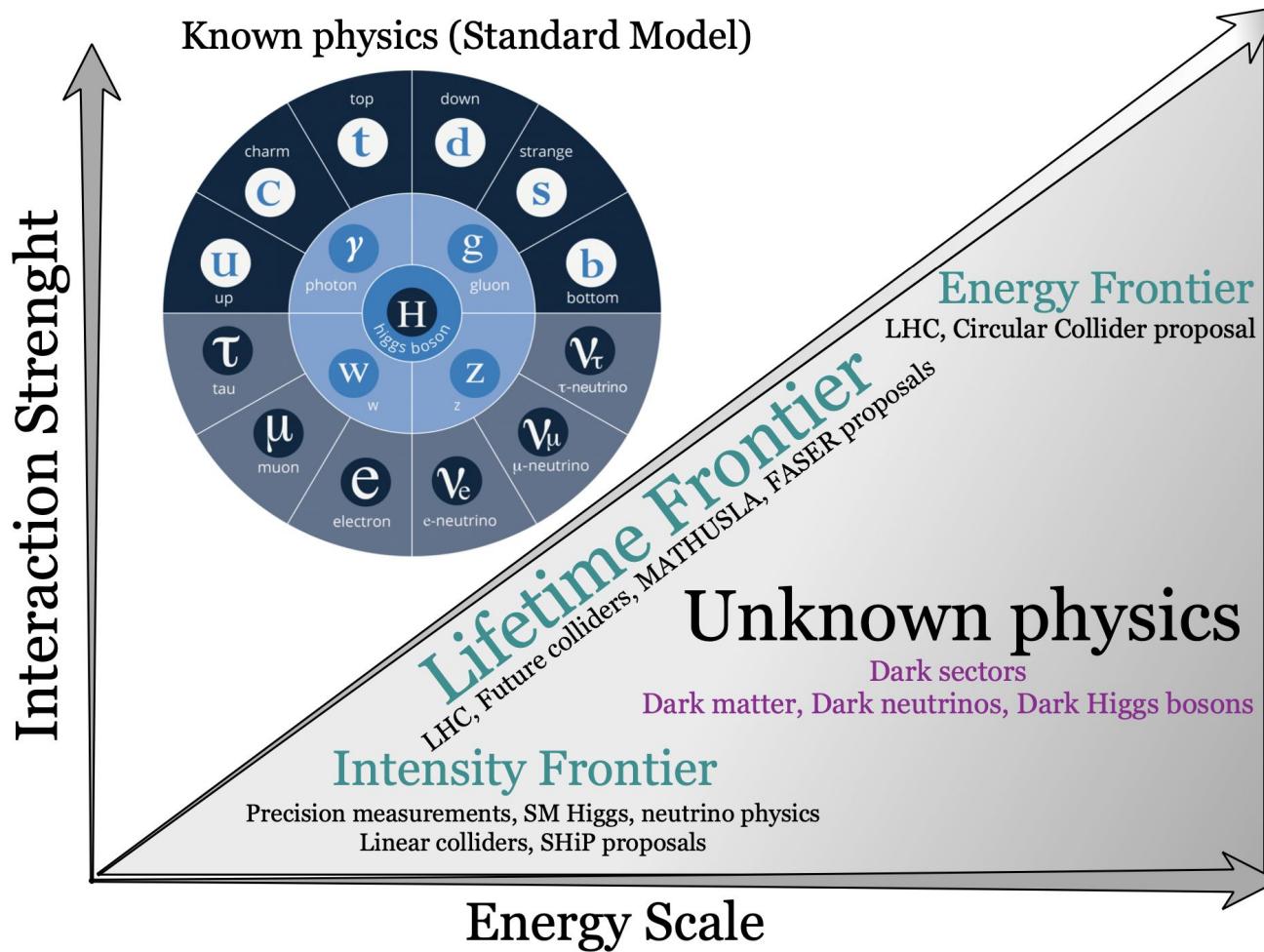
- **Understand other constraints to your model** (may need to do parallel reinterpretations)
- May apply dedicated limit software (i.e. CheckMate, global fitters ... understand their limitations, not all experimental searches are coded and maybe not all will apply to your model)
- **State power/complementarity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

Theories >> Experimental searches

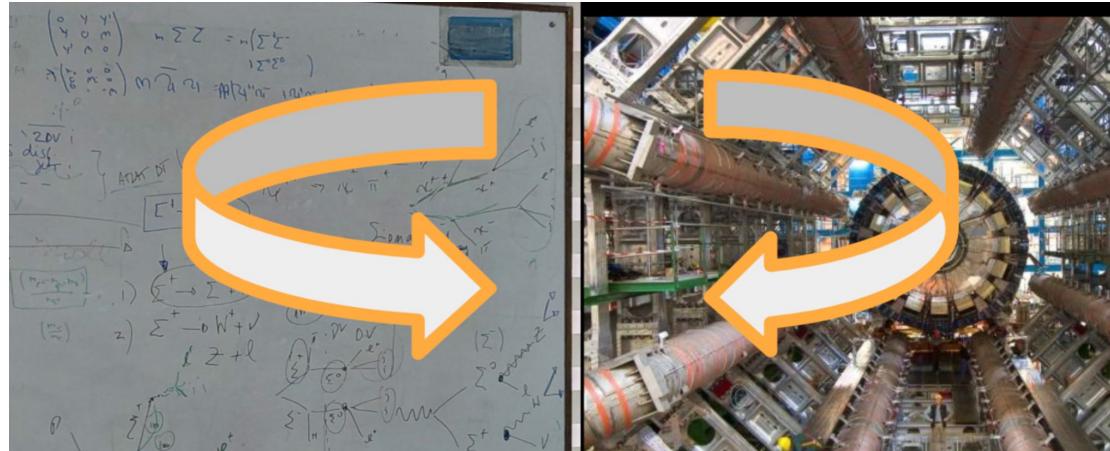
4) Estimate discovery potential/exclusion reach

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

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



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

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Field Theory in the E-W Standard Model - G. Burdman (USP)

Statistical & Machine Learning for HEP - TBC

Higgs & Beyond - J. Ellis (King's College London & CERN)

Collider experiments: the LHC & beyond - R. Forte (CERN)

Astro-Particle Physics - A. Jersón (Adolfo Ibáñez U)

Special Lecture on ATLAS New Small Wheels - S. Kuleshov (UNAB)

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J.C. Heijo (U. de Chile)

I. Schmidt (UTFSM)

A. Vega (UV)

A. Zerwelch (UTFSM)

Enquiries & Correspondence
Kate Ross
Email: Physics.School@cern.ch

Discussion Leaders

N. Bernini (New York University, Abu Dhabi)

G. Coriani (UdA)

J.G. Heijo (U. de Chile)

R. Hernandez-Pinto (Sinaloa U)

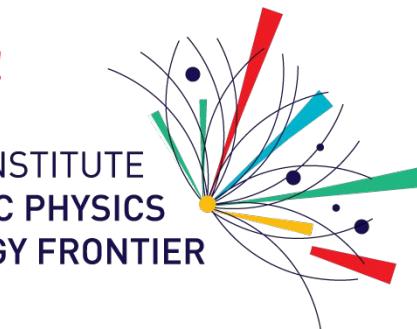
P. Magañaes (UCM)



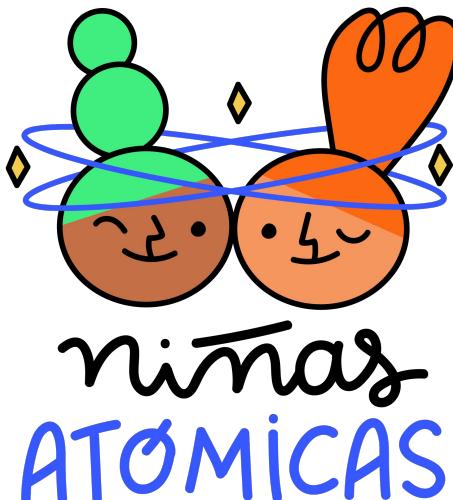
Growing opportunities for particle phenomenology in Chile
Many schools also abroad (CERN School, ICTP, GGI,
LUND, MAINZ)

If you are interested, let me know !

MILLENNIUM INSTITUTE
FOR SUBATOMIC PHYSICS
AT HIGH-ENERGY FRONTIER
SAPHIR



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<https://www.institutosaphir.cl/>

La Física de Partículas

Años antes del presente
nacen materia y energía
dáandonos 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

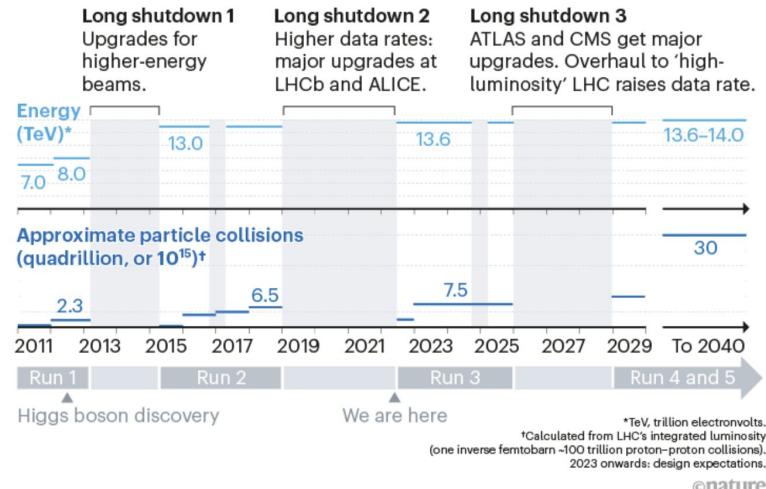
Backup

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

LHC TIMELINE

The Large Hadron Collider (LHC) will be further upgraded from 2026 to 2029 to conduct even more particle collisions, at higher energies. It is then scheduled to run for another decade.



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

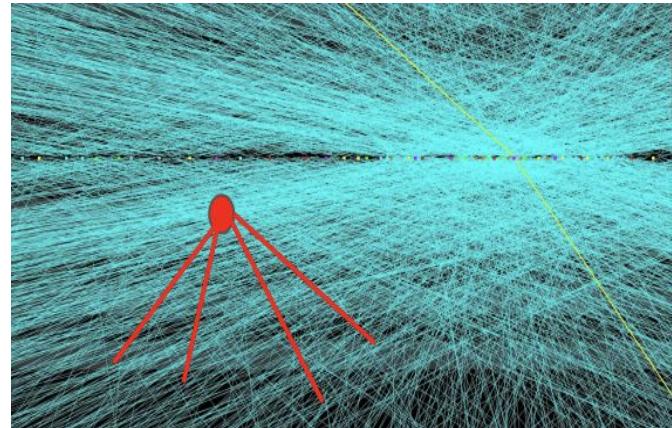
Limitations of this hunt

- 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!).

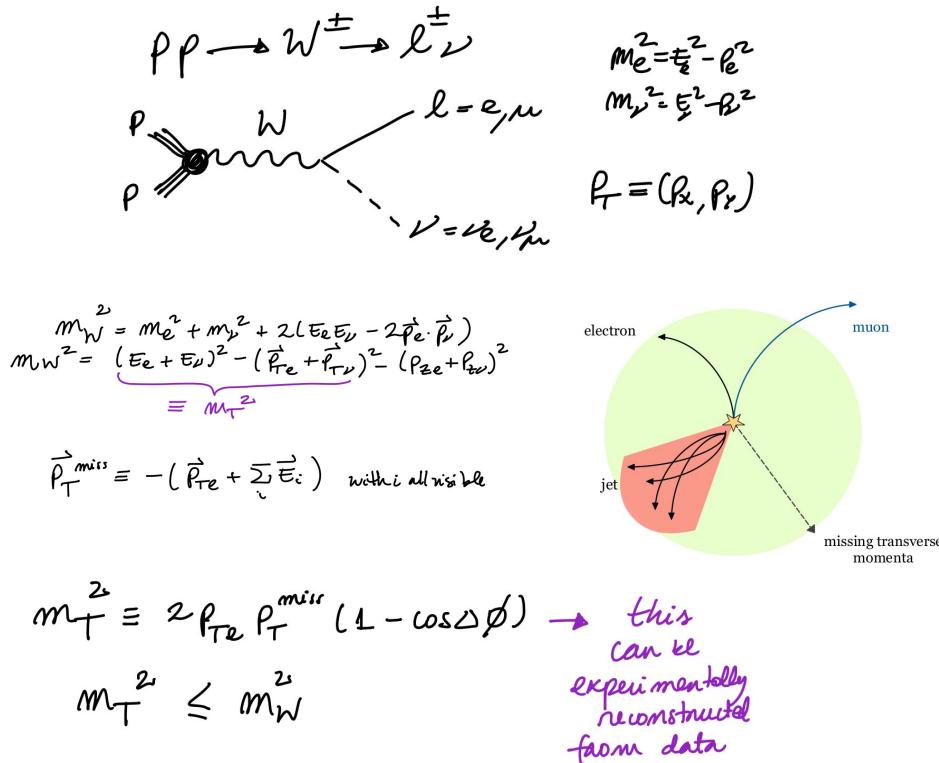


*Also been working on ALPs models, SUSY, and models with extended gauge symmetries

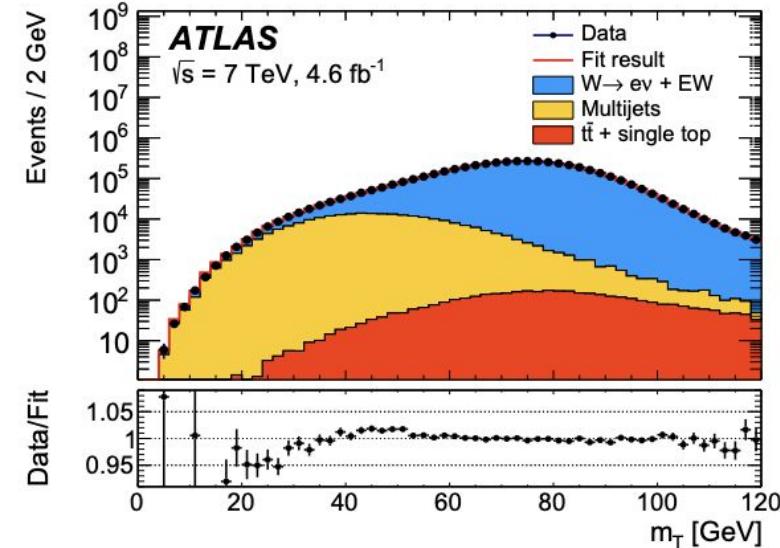
*Also worked on future 100 TeV Colliders, future electron-positron and electron-proton colliders

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](https://arxiv.org/abs/1701.07240)



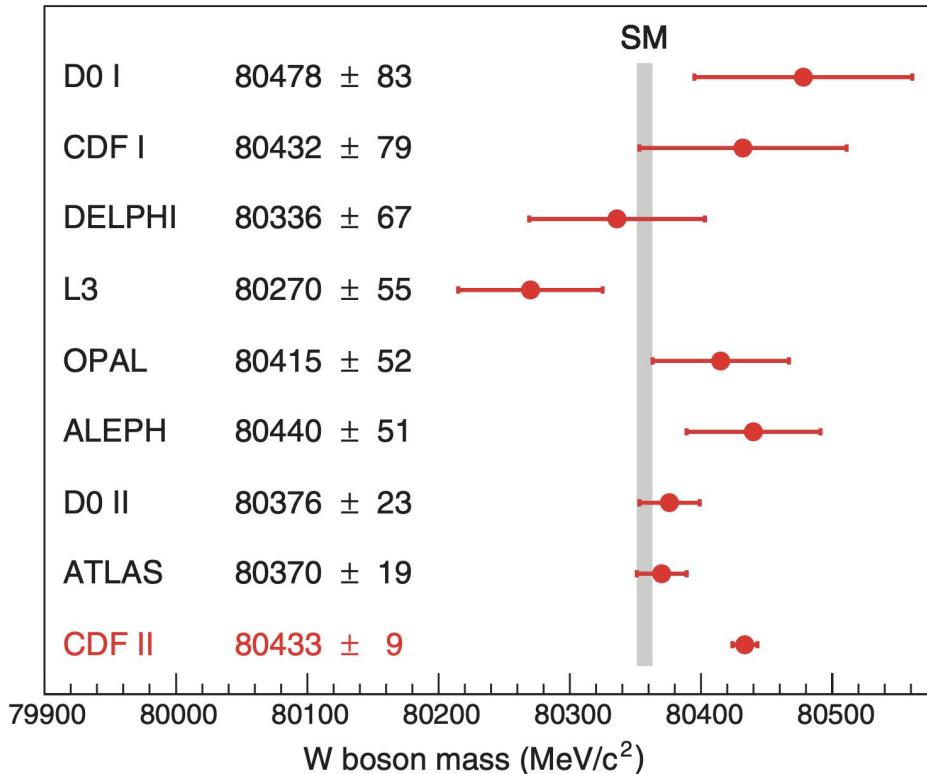
Mass extraction from templates that fit the kinematics, i.e.



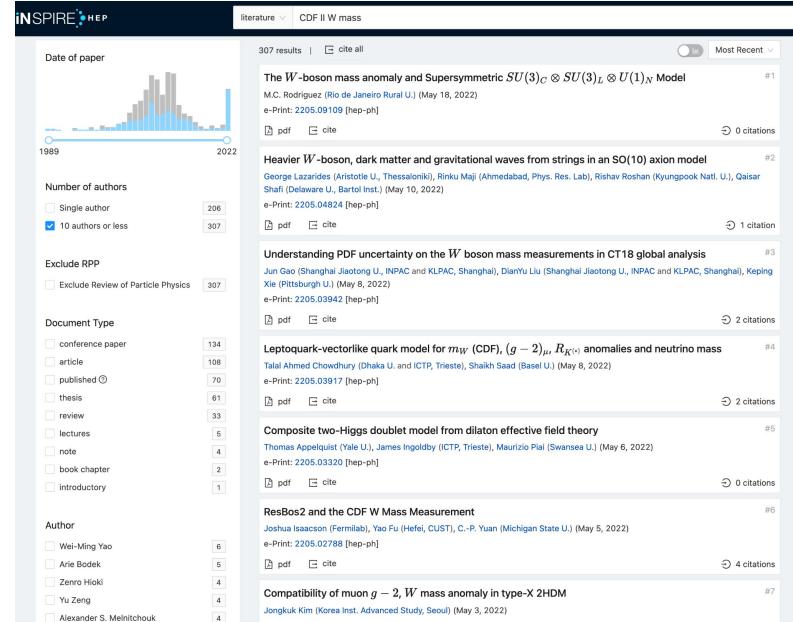
Run 3 of the LHC of top importance to elucidate this world tension

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!



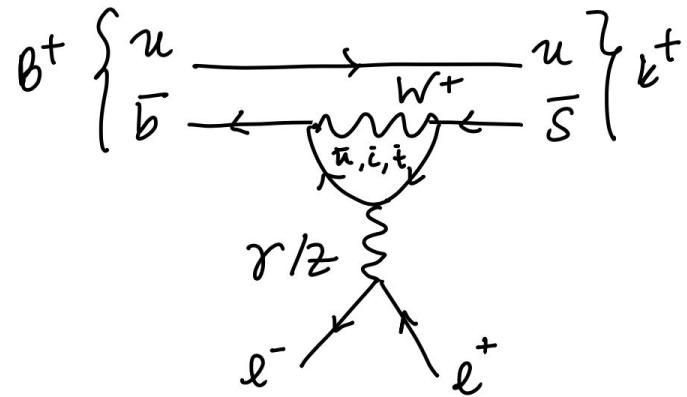
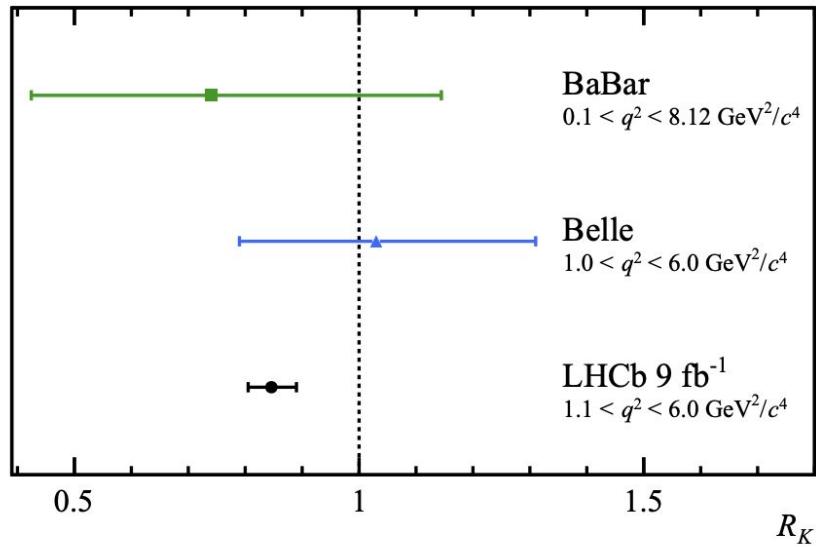
Can read more about the tension in: <https://www.symmetrymagazine.org/article/whats-up-with-the-w-boson-mass>
 Sane words about the statistical confusion of the measurements in: <http://resonaances.blogspot.com/>

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

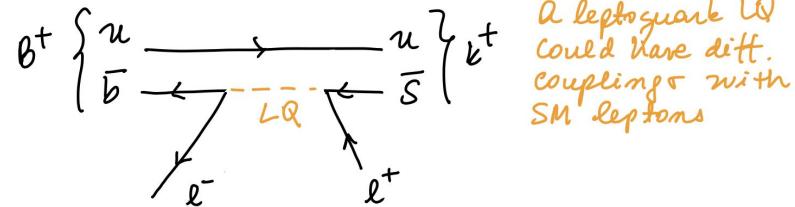
Latest R_K measurement in 2022 by the LHCb collaboration reports a **3.1sigma** deviation w.r.t the SM

Test of lepton universality in beauty-quark decays, LHCb collaboration, Nature Phys. 18 (2022) 3, 277-282, [arXiv:2103.11769](https://arxiv.org/abs/2103.11769)

$$R_K = \frac{B_n(B^+ \rightarrow K^+ \mu^+ \bar{\mu})}{B_n(B^+ \rightarrow J/\psi (\rightarrow \mu^+ \bar{\mu}) K^+)} / \frac{B_n(B^+ \rightarrow K^+ e^+ e^-)}{B_n(B^+ \rightarrow J/\psi (\rightarrow e^+ e^-) K^+)}$$



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



Future LHC Collider Phenomenology

Are we looking deep in all regions of parameter space?

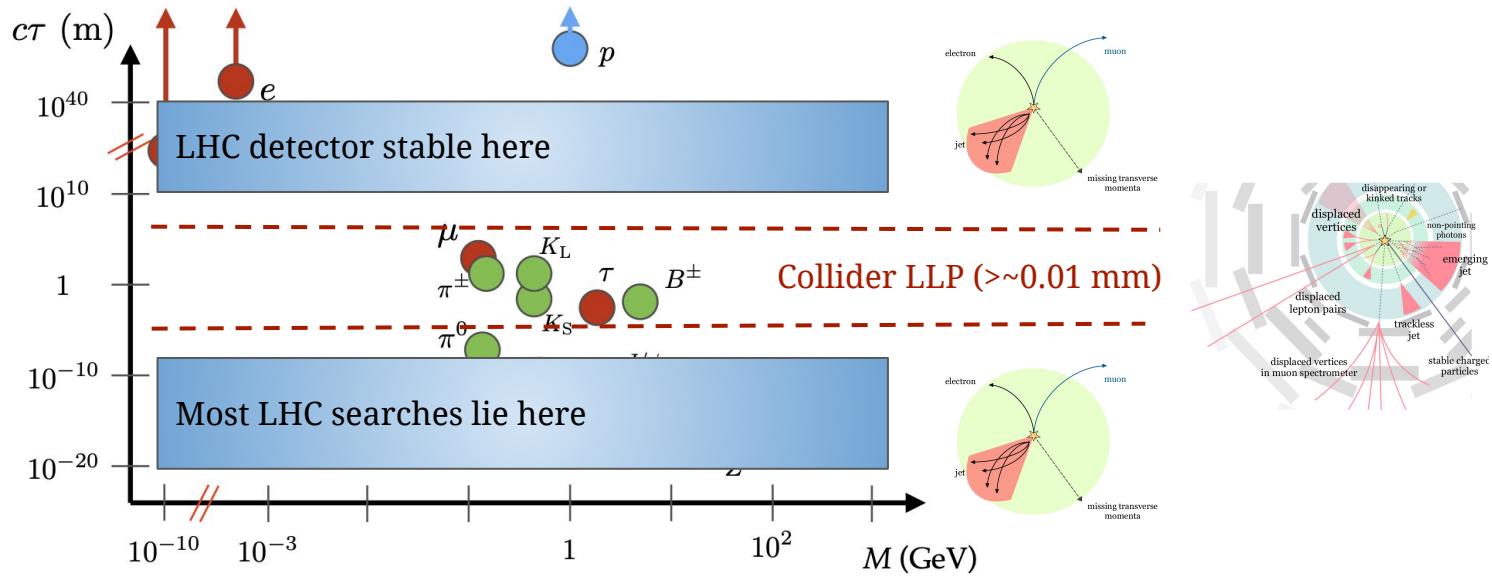


Image by B.Shuve.

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>

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

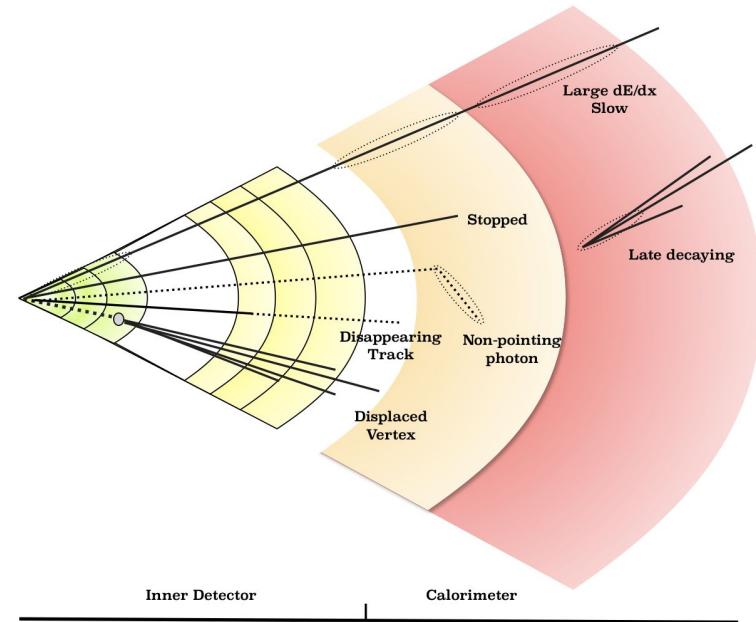
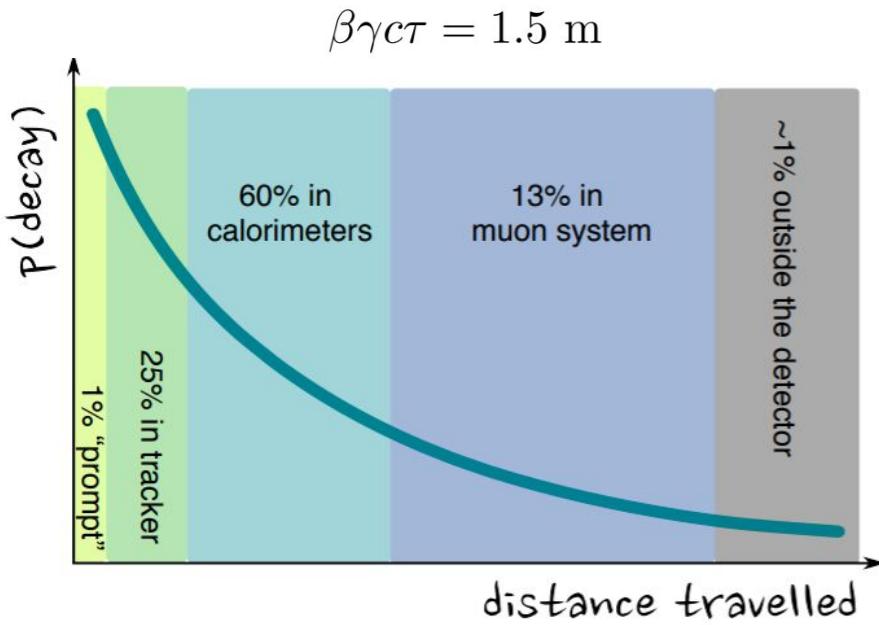
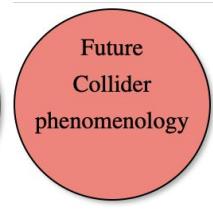
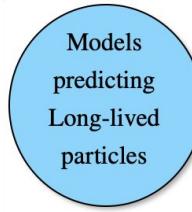
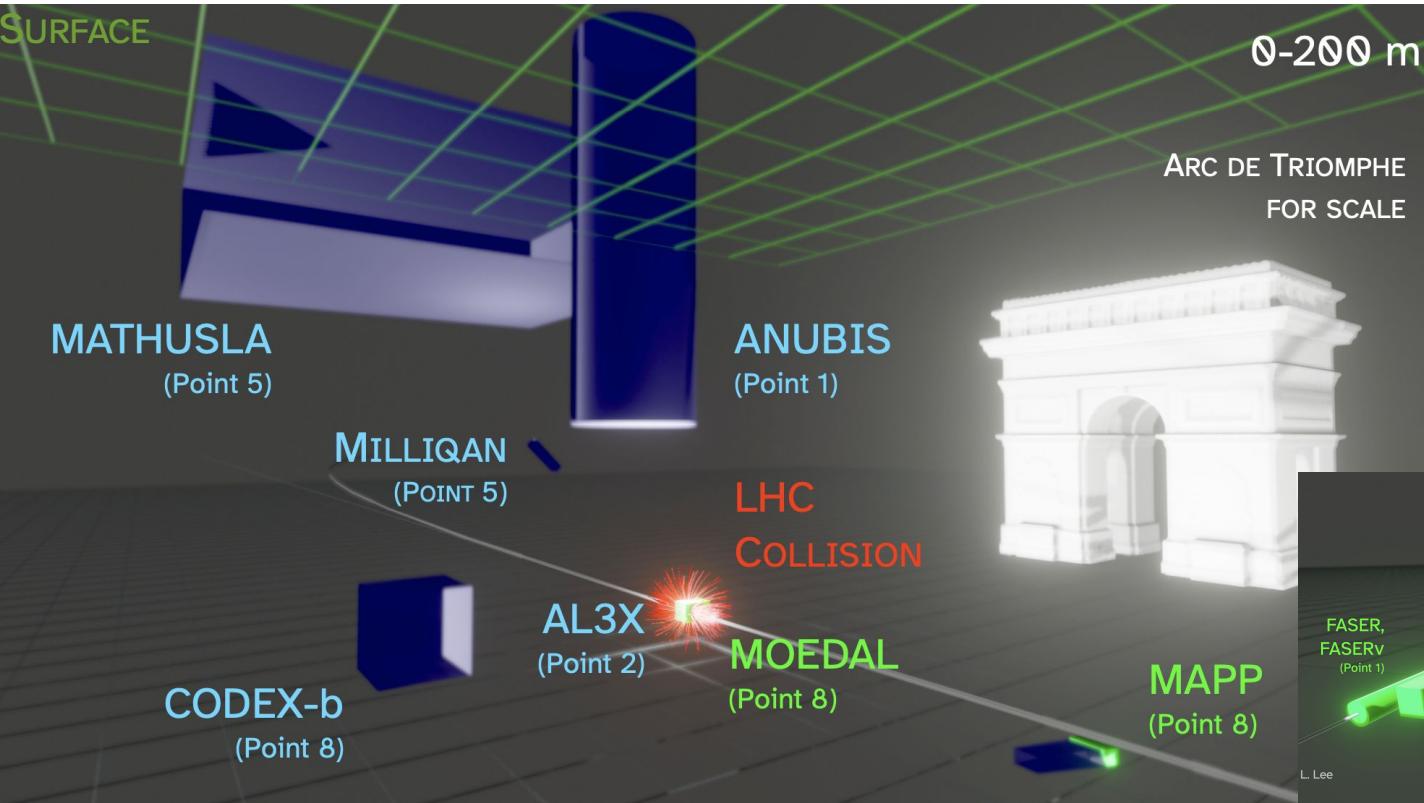


Image by Heather Russel (based on ATLAS geometry)
Long-lived Particle Community Workshop, 2017

Image by G. Cottin



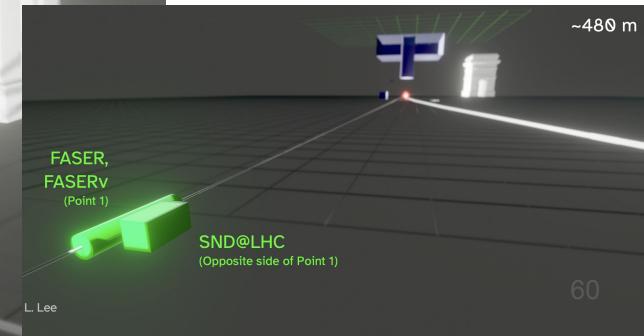
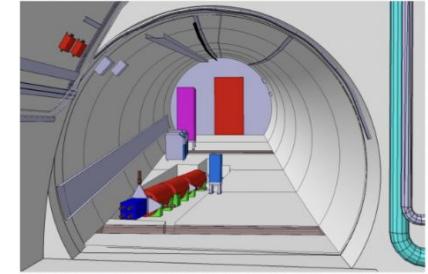
We don't want to miss the new physics !



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 Agriacore



L. Lee

The Lifetime Frontier was born



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

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 snuff 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, the 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 layers of subsystems—trackers that trace charged particles, calorimeters that measure particle energies, and chambers that detect penetrating and particularly handy particles called muons—all arrayed around a central point where the accelerator's proton beams collide. Particles that fly even a few millimetres before decaying would leave unusual signatures: kinked or offset tracks, or jets that emerge gradually instead of all at once.

Standard data analysis often assumes such oddities are mistakes and junk, notes Tova Holmes, an ATLAS member from the University of Chicago in Illinois who is searching for the displaced tracks of decays from long-lived supersymmetric particles. "It's a bit of a challenge because the way we've designed things, and the software people have written, basically rejects those things," she says. So Holmes and colleagues had to rewrite some of that software.

More important is ensuring that the detectors record the odd events in the first place. The LHC smashes bunches of protons together 40 million times a second. To avoid data overload, trigger systems in CMS and ATLAS sift interesting collisions from dull ones and immediately discard data about 1999 of every 2000 collisions. The culling can inadvertently toss out long-lived particles. Alimena and colleagues

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

CERN Accelerating science

LHC
LHC Physics Centre at CERN

ABOUT LHC WGS LHC PUBLICATIONS EVENTS NEWSLETTER

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:

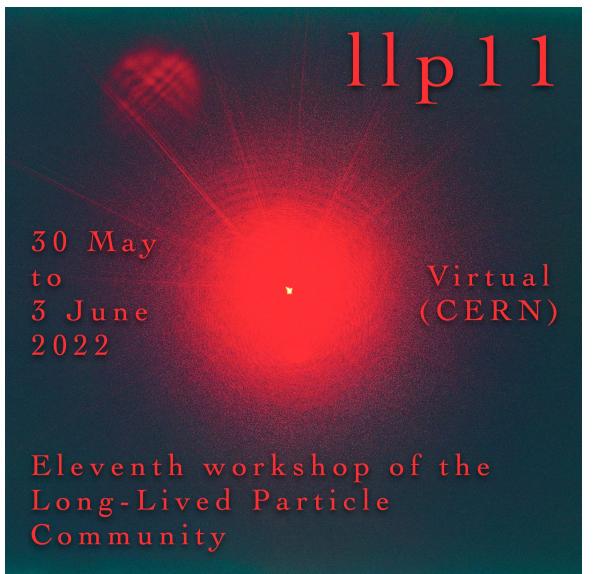
- ATLAS: Simone Pagan Griso and Emma Torro Pastor
- CMS: Alberto Escalante del Valle and Larry Lee
- FASER: Dave Casper
- LHCb: Federico Leo Redi and Carlos Vázquez Sierra
- MoEDAL: James Pinfold
- SND@LHC: Cristovao Vilela
- Theory: Giovanna Cottin, Nishita Desai and José Zurita
- Reach all through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

- EF09 - BSM: More general explorations
- Group topics
- Message
- Contacts
- Submitted LOI

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>

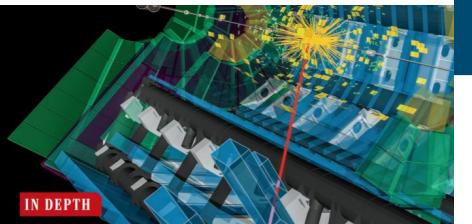


Activities within LLP Community and WG (whitepaper, regular workshops, recasting repo)

You can subscribe to LLP-WG egroup !

LLP Community White Paper [arXiv:1903.04497](https://arxiv.org/abs/1903.04497)

LLP repo <https://github.com/llprecasting/recastingCodes>



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

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A hunt for long-lived particles ran

The Large Hadron Collider could be making new particles that are

By Adrian Cho

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menters at the Higgs boson. "It's 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, the Compact LHC Apparatus (ALICE), spotted the Higgs, which, in a trillionth of a nanosecond, decayed into, among other things, a pair of photons or two 'jets' of lighter particles.

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Standard data analysis

such oddities are mistakes

Tova Holmes, an ATLAS member at the University of Chicago in Illinois, is searching for the displaced tracks of

Adding your recasting code

This is an open repository and if you have developed a code for recasting a LLP analysis, we include it here. Please contact llp-recasting@googlegroups.com and we will provide you with information for including your code.

Repository Structure

The repository folder structure is organized according to the type of LLP signature and the authors:

- Displaced Vertices
 - 13 TeV ATLAS Displaced Vertex plus MET by Alessa
 - 13 TeV ATLAS Displaced Vertex plus MET by GConnor
 - 8 TeV ATLAS Displaced Vertex plus jets by GConnor
- Heavy Stable Charged Particles
 - 8 TeV CMS HSCP
 - 13 TeV ATLAS HSCP
- Disappearing Tracks
- Displaced Jets

Snowmass2021

WELCOME PAGE
ANNOUNCEMENTS
SNOWMASS CALENDAR
ETHICS GUIDELINES
- Organization

EF09 - BSM: More general explorations

Conveners

Tulika Bose, Zhen Liu, Simone Pagan Griso (more contact info)

CONFERENCE PROGRAMME

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Physics ▾ Technology ▾ Community ▾ In focus Magazine

SEARCHES FOR NEW PHYSICS | MEETING REPORT

Long-lived particles gather interest

21 July 2021



Dark Matter WG

- › WG documents
- › WG Meetings

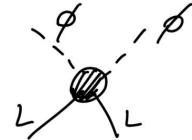
Electroweak WG

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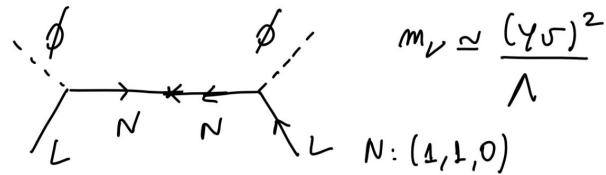
Forward Physics WG

- › WG documents
- › WG meetings

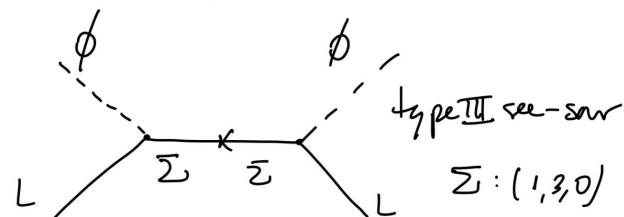
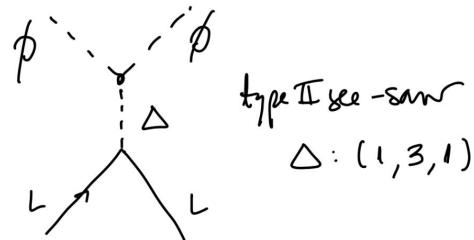
$$\mathcal{L}_T = \frac{c}{\Lambda} \phi \bar{\ell} \ell \phi$$



Opening up Weinberg's Operator



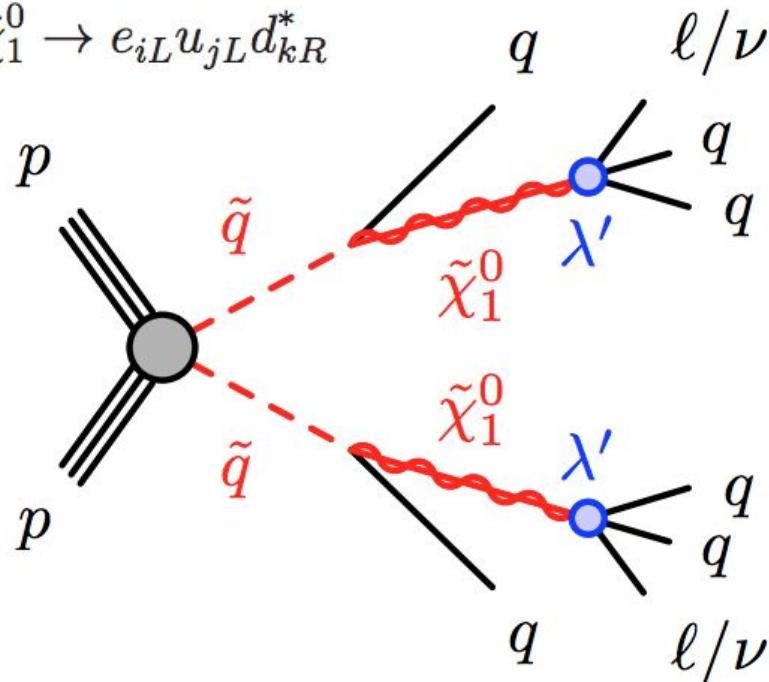
type I see-saw



SUSY

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

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

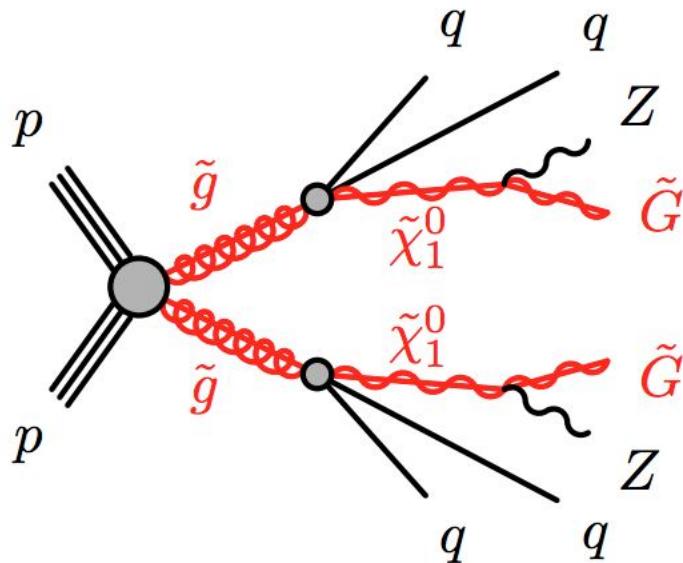


Small couplings
give rise to
macroscopic
neutralino lifetime

| 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 | $\tilde{W}^\pm \tilde{H}_u^\pm \tilde{H}_d^-$ | $\tilde{C}_1^\pm \tilde{C}_2^\pm$ |
| 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

SUSY



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

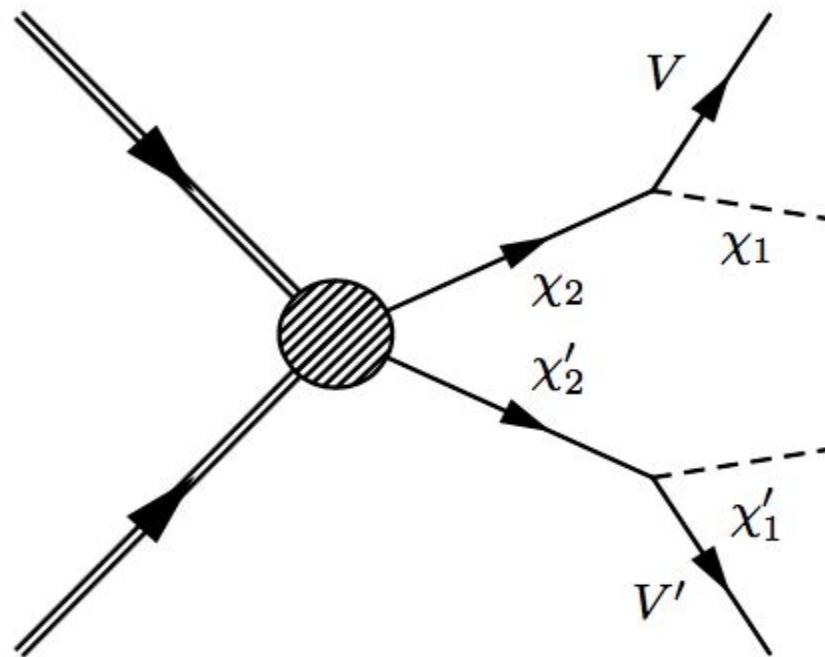
Decays to gravitino suppressed by
SUSY-breaking scale

Some displaced GGM studies in:

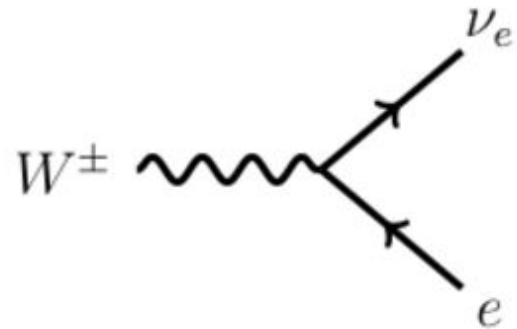
B.C. Allanach, M. Badziak, G. Cottin, N. Desai, C. Hugonie, R. Ziegler, [Eur.Phys.J. C76 \(2016\)](#)

A. Delgado, G. F. Giudice, P. Slavicek, [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



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

$$\begin{aligned}m_e^2 &= E_e^2 - p_e^2 \\m_\nu^2 &= E_\nu^2 - p_\nu^2 \\p_T &\equiv (p_x, p_y)\end{aligned}$$

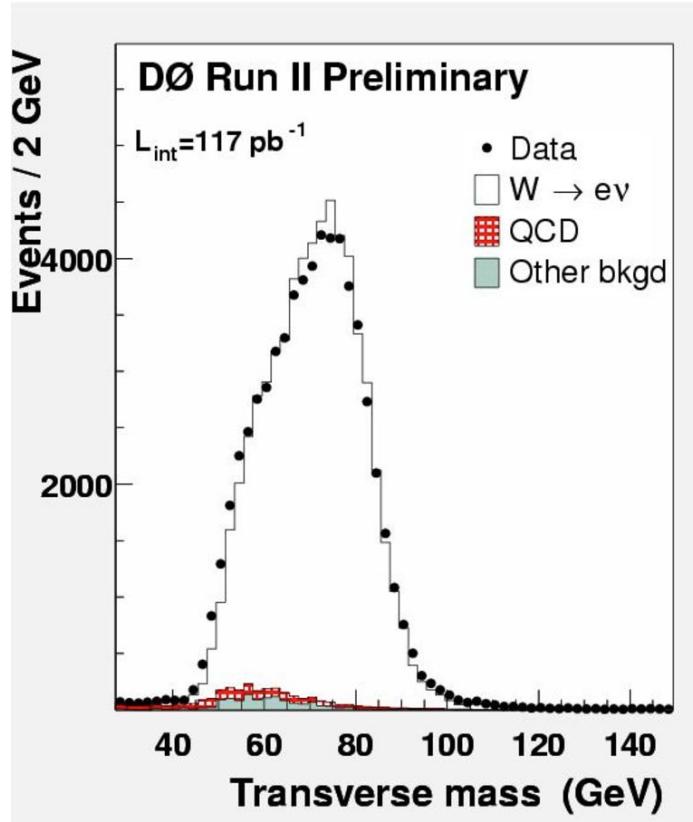
$$m_W^2 = (E_e + E_\nu)^2 - (\vec{p}_{Te} + \vec{p}_{T\nu})^2 - (p_{ze} + p_{z\nu})^2$$

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

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

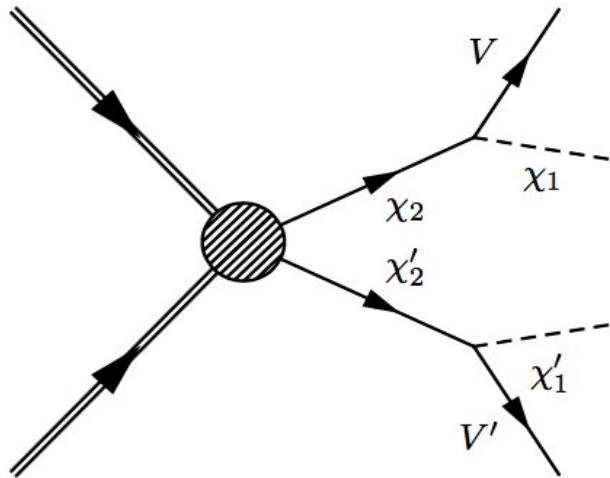
Can not directly compute W mass from the lepton and neutrino. But can know a lower limit as

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



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 \mathbf{r} , we get extra knowledge on the direction of the momentum of the parent

$$p_{\chi_1}^x + p_{\chi'_1}^x = p_x^{\text{miss}}$$

$$p_{\chi_1}^y + p_{\chi'_1}^y = p_y^{\text{miss}}$$

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

$$m_{\chi_2}^2 = m_{\chi_1}^2 + m_V^2 + 2E_V \sqrt{m_{\chi_1}^2 + |\mathbf{p}_{\chi_1}|^2 - 2\mathbf{p}_V \cdot \mathbf{p}_{\chi_1}}$$

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

Unknowns

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

$$(\mathbf{p}_{\chi_1})_{\parallel \chi_2} = (\mathbf{p}_{\chi_1} \cdot \hat{\mathbf{r}}) \hat{\mathbf{r}}$$

$$(\mathbf{p}_V)_{\parallel \chi_2} = (\mathbf{p}_V \cdot \hat{\mathbf{r}}) \hat{\mathbf{r}}$$

$$(\mathbf{p}_{\chi_1})_{\perp \chi_2} = \mathbf{p}_{\chi_1} - (\mathbf{p}_{\chi_1} \cdot \hat{\mathbf{r}}) \hat{\mathbf{r}}$$

$$(\mathbf{p}_{\chi_1})_{\perp \chi_2} = -(\mathbf{p}_V)_{\perp \chi_2}$$

$$(\mathbf{p}_V)_{\perp \chi_2} = \mathbf{p}_V - (\mathbf{p}_V \cdot \hat{\mathbf{r}}) \hat{\mathbf{r}}.$$

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

$$\mathbf{p}_{\chi'_1} = (C + D)\hat{\mathbf{r}}' - \mathbf{p}_{V'}$$

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

$$B \equiv (\mathbf{p}_V \cdot \hat{\mathbf{r}})$$

$$C \equiv (\mathbf{p}_{\chi'_1} \cdot \hat{\mathbf{r}}')$$

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

Assuming missing transverse momenta comes only from daughters

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

We can solve for A and C

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

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

We can rewrite the system as

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

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

$$\alpha \equiv 2E_V$$

$$\delta \equiv 2E_{V'}$$

$$\beta \equiv A^2 - B^2 + |\mathbf{p}_V|^2$$

$$\epsilon \equiv C^2 - D^2 + |\mathbf{p}_{V'}|^2$$

$$\gamma \equiv m_V^2 - 2(A + B)B + 2|\mathbf{p}_V|^2$$

$$\zeta \equiv m_{V'}^2 - 2(C + D)D + 2|\mathbf{p}_{V'}|^2$$

**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)

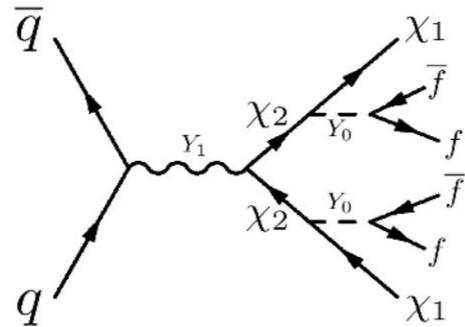
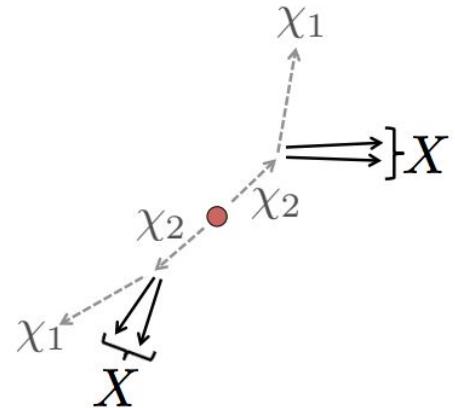


Figure 3. A representative diagram from the DisplacedDM model that produces displaced vertices plus \cancel{E}_T . The subscripts on Y indicate the spin of the mediator.

Simulation

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

$$\begin{aligned}c\tau &\sim 20 \text{ mm} & \Gamma_{\chi_2} &= 1 \times 10^{-14} \\m_{Y_1} &= 1 \text{ TeV} & m_{Y_0} &= 40 \text{ GeV}\end{aligned}$$

We first study events at truth level

Event input

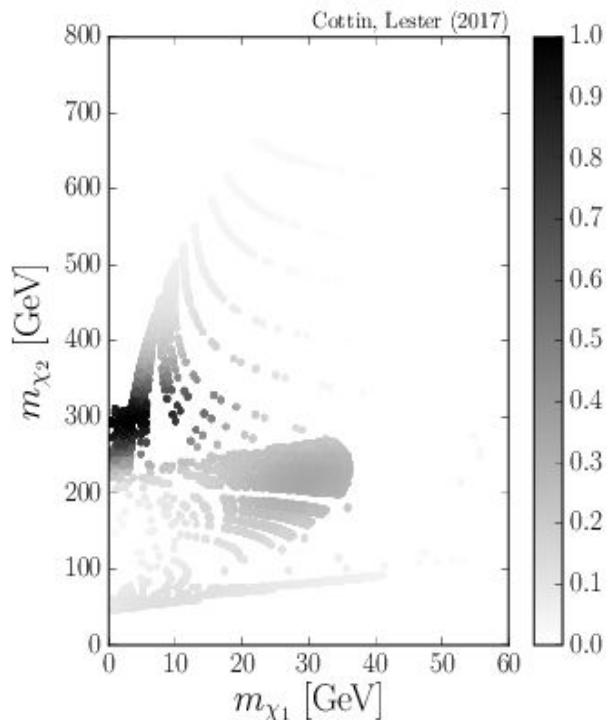
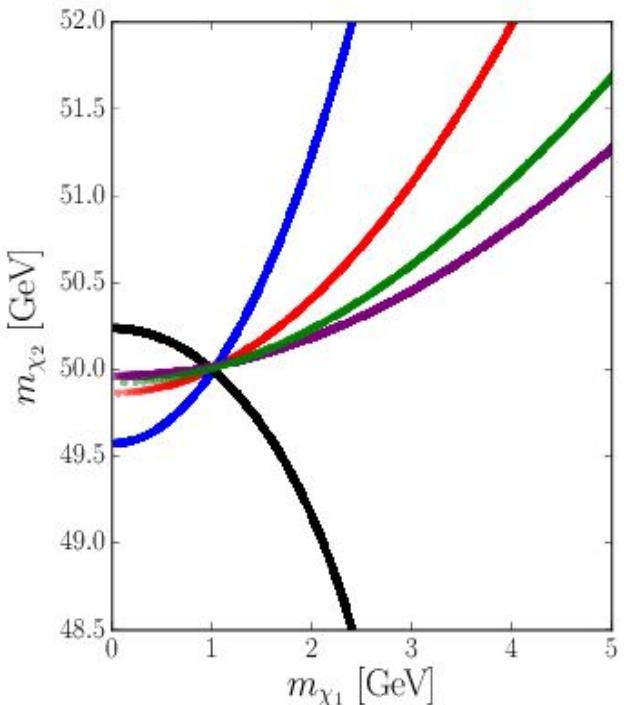
$$(r, r', p_V, p_{V'}, p_x^{\text{miss}}, p_y^{\text{miss}})$$

$$r \rightarrow r + \theta p_V$$

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

$$r \rightarrow r + \theta_1 p_V$$

$$r' \rightarrow r' + \theta_2 p_{V'}$$

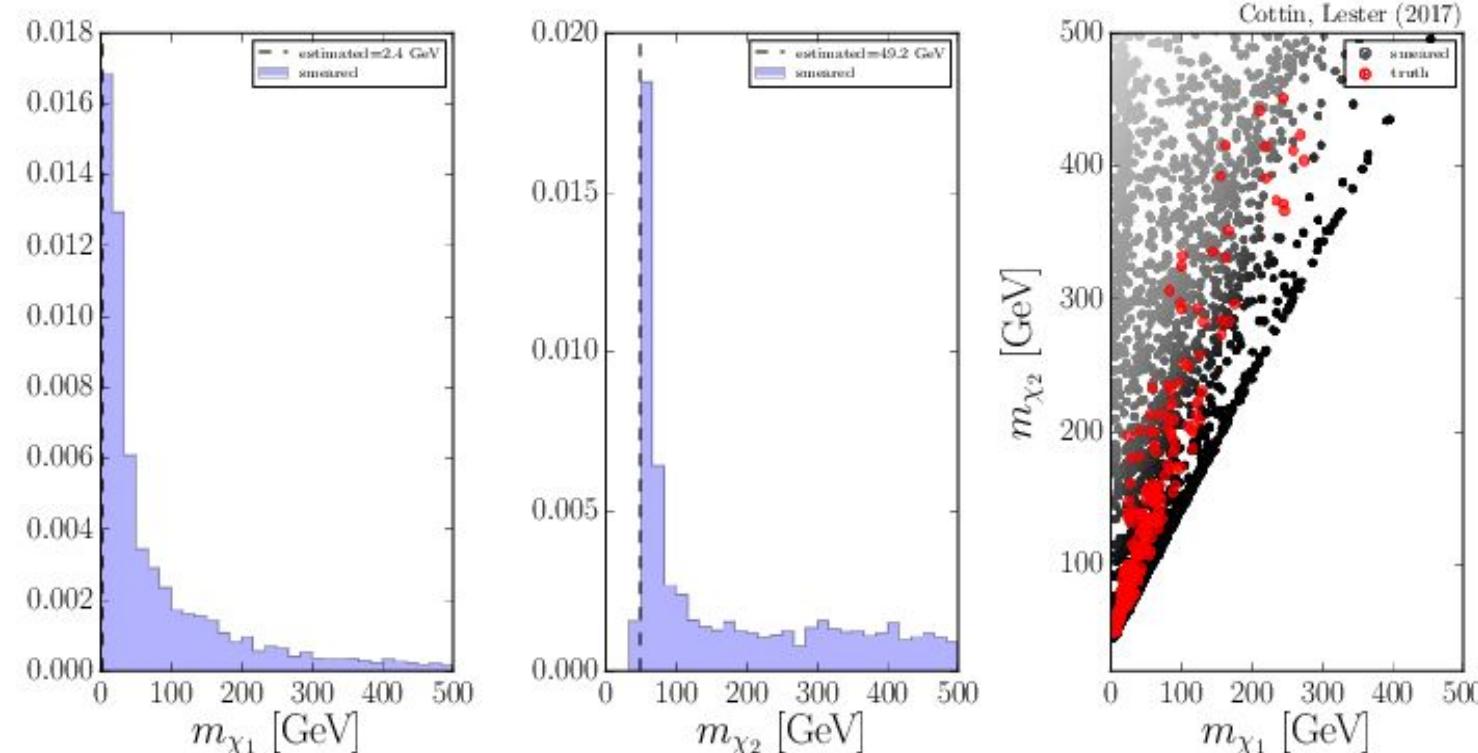


θ_1 and θ_2 are sampled from two different Normal distributions

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

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

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](https://arxiv.org/abs/1511.05190))

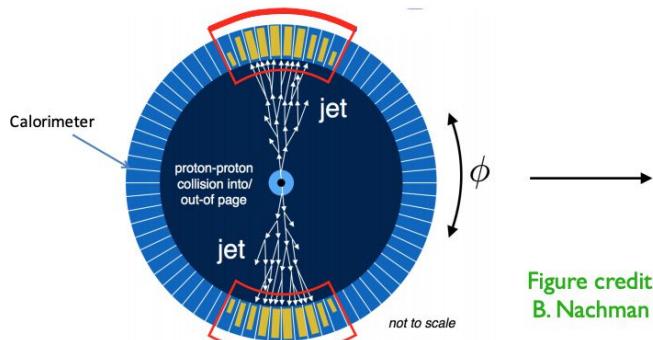
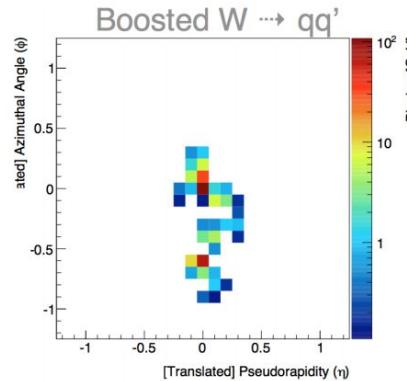
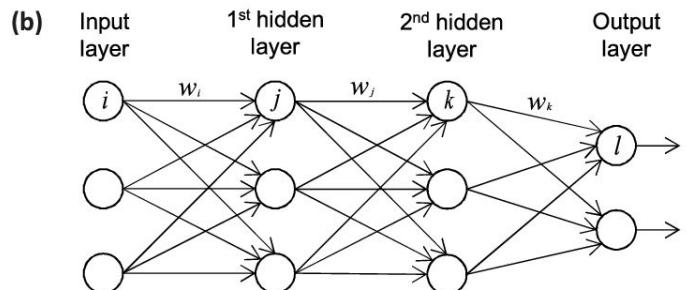
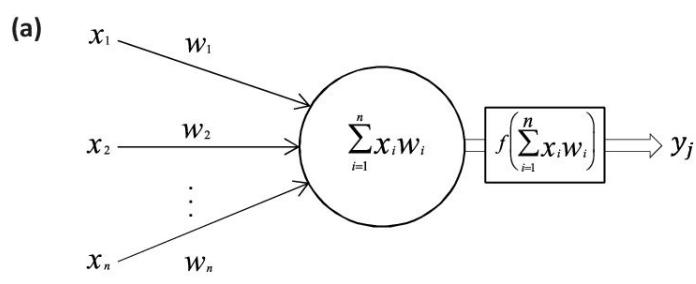


Figure credit:
B. Nachman



D. Shih @ PPP13 workshop

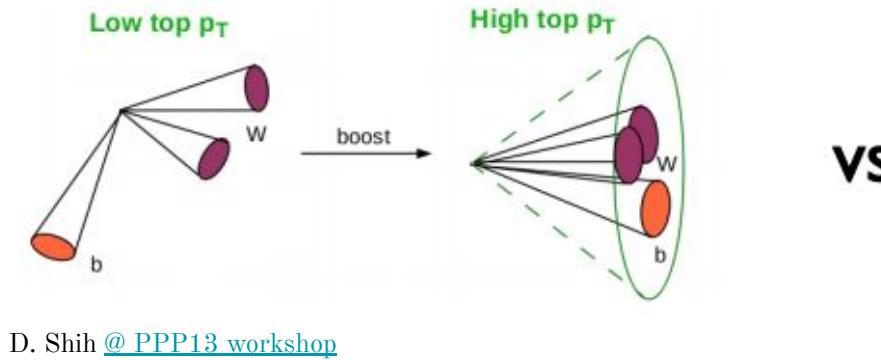


$$y_j = f\left(\sum x_i w_i\right) \quad y_k = f\left(\sum x_j w_j\right) \quad y_l = f\left(\sum x_k w_k\right) \quad 88$$

Existing Jet Classifiers with Deep Learning

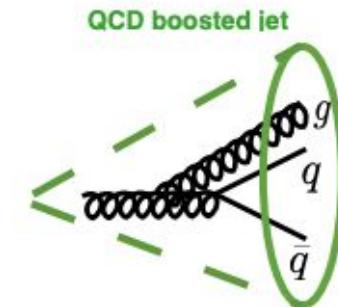
Top tagging

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](#)

VS



Quark/gluon jet discrimination

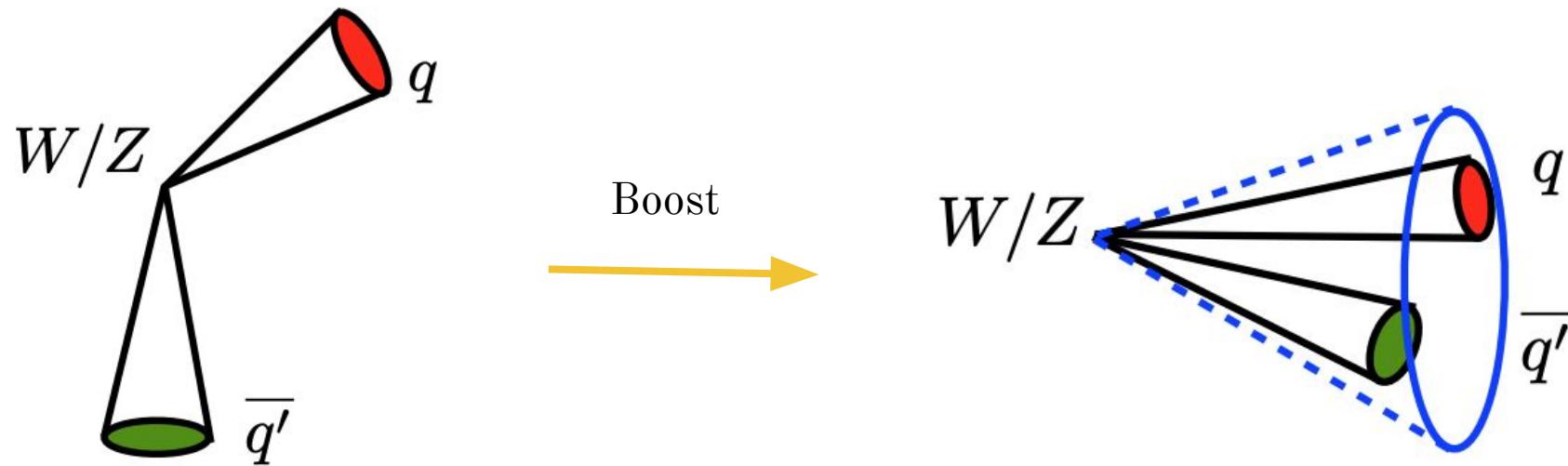
Komiske, Metodiev, Schwartz 2017
Butter, Kasieczka, Plehn, Russell 2018
Macaluso, Shih 2018
Fraser, Schwartz 2018

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

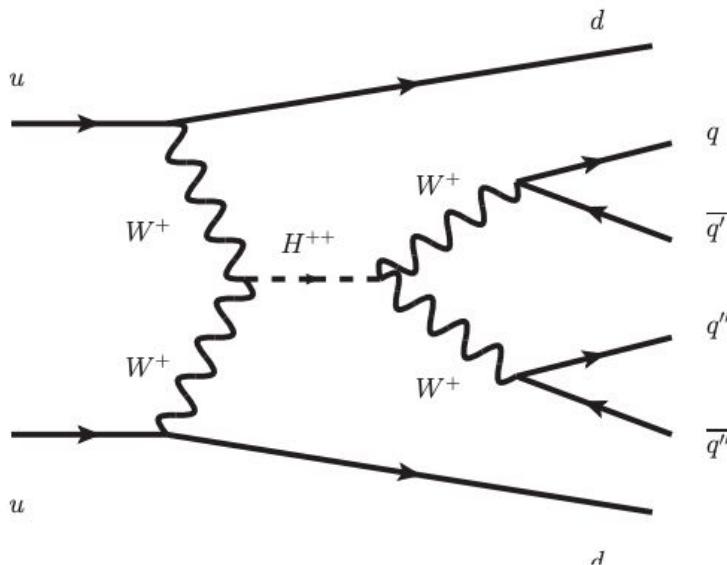
Many new physics particles, such as Z' , W' , or heavy Higgs bosons often decay to weak bosons, which are generally highly boosted and, when decaying hadronically, can form one collimated jet



Our physics process

Motivated by a doubly charged Higgs decaying to W pairs

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



[Nucl. Phys. B 262, 463 \(1985\)](#)

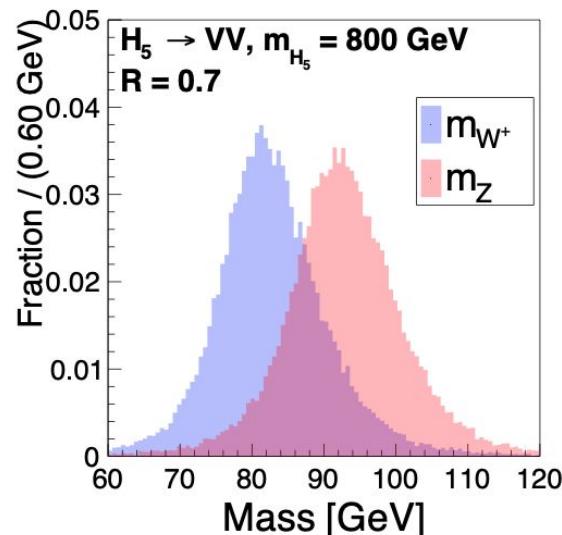
$H_5^{\pm\pm} \rightarrow W^\pm W^\pm \rightarrow jjjj$

$H_5 \rightarrow ZZ \rightarrow jjjj$

High-level Inputs

Jet invariant Mass

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

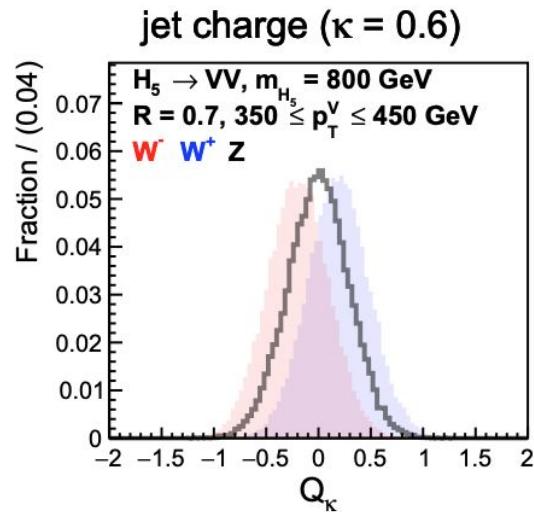
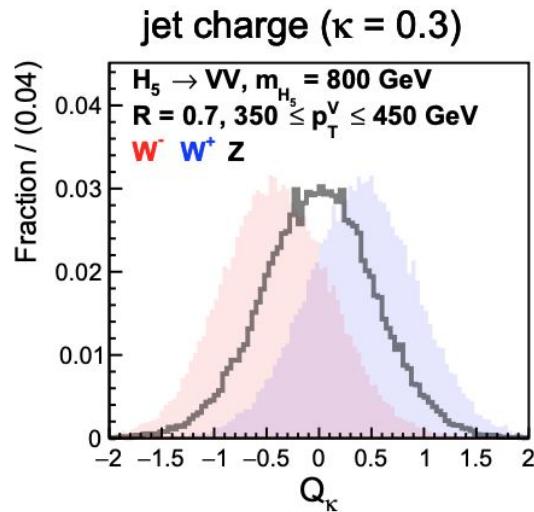
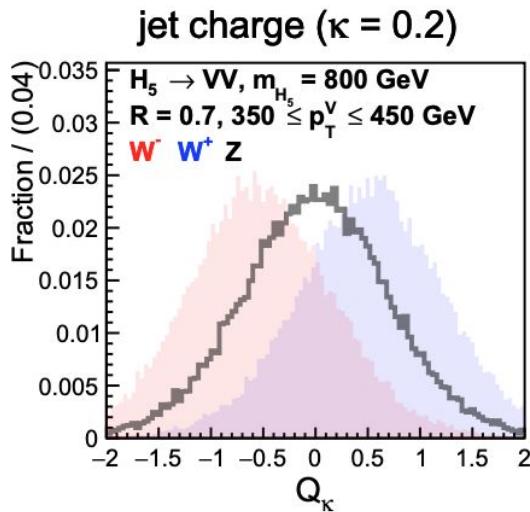


High-level Inputs

Jet Charge

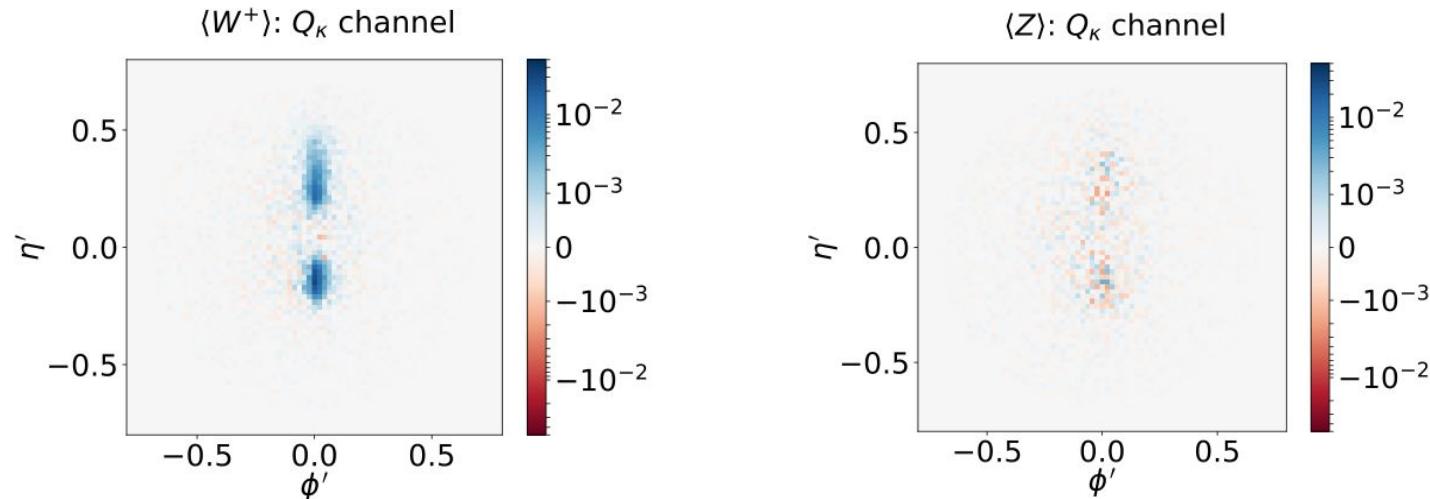
Field, Feynman 1978,
Nucl. Phys. B136
(1978) 1.

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



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

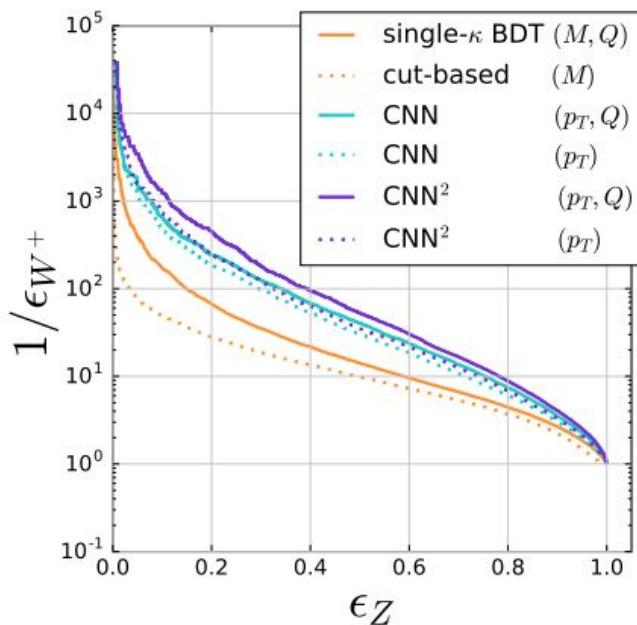
| | CNN | CNN^2 |
|---------------|---|--|
| Image | (75×75) pixels within $(\eta \leq 0.8, \phi \leq 0.8)$ | |
| Channels | p_T, Q_κ | p_T |
| Architecture | BN-32C6-MP2-128C4- MP2-256C6-MP2-512N- 512N | BN-32C3-32C3-MP2- 64C3-MP2-64C3-MP2- 64C3-64C3-128C5-256C5- 256N-256N |
| Settings | Relu Activation, 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

ROC curve



SIC curve

