

Detecting the rare and complex: ML for precision and efficiency at the LHC

COMETA Colloquium Thea Klæboe Årrestad (ETH Zürich)

Enfrainch

VBS WZjj

BSM H± Production

Non-VBS WZjj

Luminosity: HL-LHC - 90% of final LHC dataset! 111 idi Linu udiasel!

Non-VBS WZjj

Detectors: Better data BSM Hardaraduction

Non-VBS WZjj

Detectors: Better data BSM Hardaraduction

Analyses: Squeeze the most out of data!

Luminosity: HL-LHC - 90% of final LHC dataset! 111 idi Linu udiasel!

- Do distributions
Complex detectors

ML: Manage data rates predicted by the SM and Contract of the S
Predicted by the SM and Contract of the S

- V self-interactions and interactions with

MBM H± Production ML: Reconstruct complex patterns in

ML: Enhance S/√B

Non-VBS WZjj and model in tagged non-prompt, the prompt of \mathbb{R}^n ‣ Signals + tZq ,ZZ with unconstrained normalisations

Forward (quark) jets

• Quark/gluon separation

- Jet resolution
- Pileup mitigation

V

V

q

q

Vector-bosons

- Hadronic final states
- Jet substructure
- Longitudinal/transverse

Event • A lot of event information

cds.cern.ch/record/2714080

CERN 70 years!

港》 一款 La sixième session du Consul fut organisée à Paris du 29 juin au
1^{et} juillet 1953. C'est à cette occasion que la Convention établissant l'Organisation fut signée, sous rèserve de ratification, par douze Etats membres. for the Eingins of Street Ing is known to bereign For the Serees Patieted Bapabilie Pour la Educatione Pédévale Subject to catefrank 2. timber $37.1933.$ They reconnect cartified for still for each one For the Engine of the Sotherizade Four 1a Reynalde das Payer-Dise For the Engine of Seights. Four in Royman de Selgique When Sugar & replation Sous reserved religion From the Reykman-Shil die 14
Ermsdie-Grantages art die
17 Irrednische die Brevi For the Ruts-2 Stagles of Syste Scitets.
and Forthers Inclosed for the Hogins of Wilson Prior de Roymann de Decembris Bochfensi Clorence blast to adjection some reased to receivedom 2814.00 For the Franch Sepublic fing in Bipolityse Presistes for the Engine of Swins four la figurant de Ealth Wands Press Room say revent de ratification Tout Dalles Mer fre Touchen Suchten Fir the Engine of Granue Four in Hoycane da Grèce for the Employmenties of Settosylkod **Page 3x Employments Future** Remainied ratification Rudivies Salis some remove de selification. for linky positive experts and the interesting experience
Touche Jeune interesting experience
power where it radification For Pitcher for the Faincell People's Septible
of Topiciatie Q_{λ} antonio and but necessar to sucification The Stath Session of the CERN Council took place in Parts on 29 June-1 July 1953. It was here that the Convention establishing the Organization was signed, subject to ratification, by twelve States.

Sep 29th 1954

La sixième session du Conseil fut organisée à Paris du 29 juin au
1^{et} juillet 1953. C'est à cette occasion que la Convention établissant l'Organisation fut signée, sous rèserve de ratification, par douze Etats membres. For the Seraes Patern! Bapibilio Four in Highlings Philoson For the Einglish of Streng Ing is known to bereign culture on Subject to catapachine 7. Einenberg y_{μ} ($y + 3$. They recovered contains to still be cation For the Ecopius of the Sotherizada Four 1a Reynalds das Payerthia For the Engine of Seights. First in Roymann da Belgique When believed to respond in sous revove de sal funbo For the Rotted Stagles of Syart Schedu. From the Reykone-Shill de imfor the Singles of Wilson's Pour le fromme de Datement and the there Instead Grands chratagns at de-1-Treinals du hord Doctopensi Clonerin blast to religiostion some reams so racification 2814.00 For the Franch Sepublic four is bipoblique framptes. For the Engine of Avenue Tour le Enymous de Euble · Row abando True Sang reserve de ratification Jour Darles mes fre Toucher Supharm Subject to endification For the Sington of Greene Four in Hoycane da Ordon Page 3x Employmentos Sulawa Rudivies Remainied ratification Salis some ressure de religiation For Italy For Pinette For the Faiscal Douts's Septible. **Four In Myskinger FAIR-MITH** Gabriedo pourse Sarle Savie insurance of Toyle large Pepulates de Tougoslavia antonio annot long reacter to restigiation

The Sixth Session of the CERN Council took place in Paris on 29 June-1 July 1953. It was here that the Convention establishing the Organization was signed, subject to ratification, by twelve States.

Sep 29th 1954

La sixième session du Conseil fut organisée à Paris du 29 juin au 1e juillet 1953. C'est à cette occasion que la Convention établissant l'Organisation fut signée, sous rèserve de ratification, par douze Etats membres. Ing la depasse de Serviga For the Seraes Patern! Beposite Four in Educations Philosofie For the Einglos of Streng t'illemps Subject to catapantin 4. Uncuber 1413 / Beerlette cartains to set in case on For the Constructor O'Car better-inner Finar 1a Reynalds das Paya-Dis For the Engine of Seights. Four in Anysum on Selgique **Victorian** belged to related to university see fine For the Rotted Stagles of Steet Scitets. Fried 14 Roykam-Stat de im For the Hogins of Wilson's and the there Instead ireate diretages at de 17 Total Studies, St., Stores *Dolfof*anni Divanna blast to adviction some resent to recipient 2812.99 For the Provin Sepublic four is bipobilities from the For the Eligible of Section Tour le Enymous de Euble alamah Land Jour Walles an revert de ratification all pale mote sustain religion For the Singles of Greene Four in Hoycane da Ordon For the Englishmentian of Switzerland Page 34 SmcNelvering Sulawa June reserve so ratification. Kindoniel Satis some reasons de religiostica For Italy Four 11 Paulis For the Faiscal Douts's Septitis Four In Bepablique FACONSTER of Traile levie. Pepulates de Tougoslavia Javie wine some viewe de confection fent univer to subspiration

The Sixth Session of the CERN Council took place in Paris on 29 June-1 July 1953. It was here that the Convention establishing the Organization was signed, subject to ratification, by twelve States.

Sep 2nd 1955

A PROPOSAL FOR THE

DARTMOUTH SUMMER RESEARCH PROJECT

ON ARTIFICIAL INTELLIGENCE

J. McCarthy, Dartmouth College M. L. Minsky, Harvard University N. Rochester, I.B.M. Corporation

C. E. Shannon, Bell Telephone Laboratories

August 31, 1955

,

a perceptron "may eventually be able to learn, make decisions, and translate languages."

July 4th 2012

July 4th 2012

Sep 30th 2012

E Large Scale Visual Recognition Challenge 2012 (ILSVRC2012 ● も● 愛書/愛春● 脚まきもの音楽 |公園の全部会で関連後回の漢字の画家理念研究の本地のの画面対策図書図会会以理じ

Held in conjunction with **PASCAL Visua Back to Main page**

All results

- · Task 1 (classification)
- Task 2 (localization)
- · Task 3 (fine-grained classification
- Team information and abstracts

Task 1

■国際海湖→海波鎮海戦 ▲山ヶ湖・日本:・西方

2024

The Nobel Prize in Physics 2024

Popular information

 \checkmark

Ill. Niklas Elmehed © Nobel Prize Outreach John J. Hopfield

Prize share: 1/2

Ill. Niklas Elmehed © Nobel Prize Outreach Geoffrey Hinton Prize share: 1/2

The Nobel Prize in Physics 2024 was awarded jointly to John J. Hopfield and Geoffrey E. Hinton "for foundational discoveries and inventions that enable machine learning with artificial neural networks"

nobelprize.org/prizes/physics/2024

2024

The Nobel Prize in Physics 2024

Popular information

 \checkmark

Ill. Niklas Elmehed © Nobel Prize Outreach John J. Hopfield

Prize share: 1/2

Ill. Niklas Elmehed © Nobel Prize Outreach Geoffrey Hinton Prize share: 1/2

The Nobel Prize in Physics 2024 was awarded jointly to John J. Hopfield and Geoffrey E. Hinton "for foundational discoveries and inventions that enable machine learning with artificial neural networks"

nobelprize.org/prizes/physics/2024

arxiv:2404.19756

nonlinear,

fixed

linear,

learnable

.......

 σ_2 -

 \mathbf{w}_2 -

 σ_1 –

 \mathbf{W}_1

こへ ス オ

Model

Deep)

nonline learnable

 $\mathbf{\Phi}_{2}$

Ф.

T1037 / 6vr4 90.7 GDT (RNA polymerase domain) T1049 / 6y4f 93.3 GDT (adhesin tip)

Experimental result

Computational prediction

sequence-the structure prediction component of the 'protein folding problem'⁸-has been an important open research problem for more than 50 years⁹. Despite recent

T1037 / 6vr4 90.7 GDT (RNA polymerase domain) T1049 / 6y4f 93.3 GDT (adhesin tip)

Experimental result

Computational prediction

sequence—the structure prediction component of the 'protein folding problem'⁸—has been an important open research problem for more than 50 years⁹. Despite recent

I"ML for accelerated discovery"

· DIE & WELT

Union will Überschüsse

in Sozialkassen horten

Lodeserver in Kraskey and Rentsmen

 -32 conset

ELa Audiencia Nacional a

uerella contra los expestore

110

 2.5

"Perché l'Italia Cologio con Napolitano: huma ide

CERN Summer student 2012

m^H = **"ML for accelerated discovery"** \mathcal{F}_1 *VH* → *bb* **P** = 0.0026 CMS¹⁰⁰ *VH* → *bb* 2011–2012 - 4*σ*_m *P* = 0.081 **BDT** γ classifier ϵ DIE & WELT

VH + *bb***_{***VH***} +** *bb*

Jnion will Überschüsse

Sozialkassen horten

CERN Summer student 2012

data that are expected to be the most useful for a given measurement. This enables the incredibly rich initial data only a small number of features. For example, in the aforemention B_s decay, a human-designed tracking algorithm first reconstruct paths taken by the muon and the antimuon in a magnetized particle-physics detector, and from these paths the momenta of the particles are inferred. However, only the dimuon mass and the angle between them are used in the BDT. The rest of the kinematic information is discarded.

For many tasks, information can be lost when these human-

increase the power of the measurement of the measurement. The measurement of the measurement of the measurement. \sim The emergence of the set of the se Rule-based γ selector sensitivity without using machine learning, which varies from 15% to 125%.

hediate convolution layers to predict a boy

tonnes of liquid argon, detects neutrinos sent from the booster neu-

40 000 papers so far!

Date of paper

40 000 papers so far!

Date of paper 1985

An Evolutionary Procedure for Machine Learning

Max-Planck-Institut für Physik und Astrophysik - Werner-Heisenberg-Institut für Physik -8000 Munich 40, West Germany

Abstract:

We discuss an evolutionary procedure for machine learning and present in detail an application of this procedure to the control of a robot TURTLE, which, beginning from a state of total ignorance, is able to develop the ability to circumnavigate a variety of obstacles. The procedure discussed is related to the strategy signature table method used in computer game playing.

MPI-PAE/PTh 64/84 October 1984

Leonard D. Mlodinow*

and

Ion O. Stamatescu**

NEURAL NETWORKS AND CELLULAR AUTOMATA IN EXPERIMENTAL HIGH ENERGY PHYSICS

B. DENBY

Laboratoire de l'Accélérateur Linéaire, Orsay, France

Received 20 September 1987; in revised form 28 December 1987

Within the past few years, two novel computing techniques, cellular automata and neural networks, have shown considerable promise in the solution of problems of a very high degree of complexity, such as turbulent fluid flow, image processing, and pattern recognition. Many of the problems faced in experimental high energy physics are also of this nature. Track reconstruction in wire chambers and cluster finding in cellular calorimeters, for instance, involve pattern recognition and high combinatorial complexity since many combinations of hits or cells must be considered in order to arrive at the final tracks or clusters. Here we examine in what way connective network methods can be applied to some of the problems of experimental high energy physics. It is found that such problems as track and cluster finding adapt naturally to these approaches. When large scale hard-wired connective networks become available, it will be possible to realize solutions to such problems in a fraction of the time required by traditional methods. For certain types of problems, faster solutions are already possible using model networks implemented on vector or other massively parallel machines. It should also be possible, using existing technology, to build simplified networks that will allow detailed reconstructed event information to be used in fast trigger decisions.

NEURAL NETWORKS AND CELLULAR AUTOMATA IN EXPERIMENTAL HIGH ENERGY PHYSICS

B. DENBY

Laboratoire de l'Accélérateur Linéaire, Orsay, France

Received 20 September 1987; in revised form 28 December 1987

Within the past few years, two novel computing technique considerable promise in the solution of problems of a very high processing, and pattern recognition. Many of the problems faced i Track reconstruction in wire chambers and cluster finding in cell and high combinatorial complexity since many combinations of hi tracks or clusters. Here we examine in what way connective nety experimental high energy physics. It is found that such probler approaches. When large scale hard-wired connective networks become problems in a fraction of the time required by traditional methods. possible using model networks implemented on vector or other ma existing technology, to build simplified networks that will allow d trigger decisions.

Institut Langevin **ONDES ET IMAGES**

What's in the article?

- Introduces neural networks to the HEP community for the first time
	- Simple units sum their inputs & apply an activation function
	- Outputs connect to other inputs via weights, and
	- Perform a useful task by mapping from inputs to outputs
- Proposes a recurrent neural network algorithm for track finding (Denby-Peterson algorithm)
- Highlights the **parallel nature** of calculating with neural networks and its interest for experimental triggers
- Also discusses feed-forward neural networks for **template matching, and the possibility of using learning**

40 000 papers so far!

Date of paper

 $-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu-g_sf^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu -\tfrac{1}{4}g^2_sf^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu+$ $-\frac{1}{2}ig_s^2(\bar{q}_i^{\sigma}\gamma^{\mu}q_j^{\sigma})g_{\mu}^a+\bar{G}^a\partial^2G^a+g_sf^{abc}\partial_{\mu}\bar{G}^aG^bg_{\mu}^c-\partial_{\nu}W_{\mu}^+\partial_{\nu}W_{\mu}^-\,$ $M^2W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_\omega}M^2Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H \frac{1}{2}m_h^2H^2-\partial_\mu\phi^+\partial_\mu\phi^- -M^2\phi^+\phi^- -\frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 -\frac{1}{2c_w^2}M\phi^0\phi^0 -\beta_h[\frac{2M^2}{g^2}+$ $\frac{2M}{q}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right] + \frac{2M^4}{q^2}\alpha_h - ig_c w[\partial_\nu Z^0_\mu(W_\mu^+W_\nu^ W^+_\nu \hat{W}^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu W_{\nu} \partial_{\nu} W_{\mu}^{+})] - ig s_w [\partial_{\nu} A_{\mu} (\tilde{W}_{\mu}^{+} W_{\nu}^{-} - W_{\nu}^{+} W_{\mu}^{-}) - A_{\nu} (W_{\mu}^{+} \partial_{\nu}^{'} W_{\mu}^{-} W_{\mu}^- \partial_{\nu} W_{\mu}^+) + A_{\mu} (W_{\nu}^+ \partial_{\nu} W_{\mu}^- - W_{\nu}^- \partial_{\nu} W_{\mu}^+) - \frac{1}{2} g^2 W_{\mu}^+ W_{\mu}^- W_{\nu}^+ W_{\nu}^- +$ $\frac{1}{2}g^2W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$ $g^2s_w^2(A_\mu W_\mu^+A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+W_\nu^-) + g^2s_wc_w[A_\mu Z_\nu^0(W_\mu^+W_\nu^- W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu - g \alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2]$ $gM W^+_{\mu} W^-_{\mu} H - \frac{1}{2} g \frac{M}{c^2} Z^0_{\mu} Z^0_{\mu} H - \frac{1}{2} i g [W^+_{\mu} (\phi^0 \partial_{\mu} \phi^- - \phi^- \partial_{\mu} \phi^0) W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ (\phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{g^2_w}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) +$ $i g s_w MA_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - i g \frac{1-2 c_{w}^2}{2 c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) +$ $ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] \frac{1}{4}g^2\frac{1}{c^2_{\omega}}Z^0_{\mu}Z^0_{\mu}[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-]-\frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_{\mu}\phi^0(W^+_{\mu}\phi^-+$ $W^-_\mu \phi^+) - \frac{1}{2} ig^2 \frac{s^2_\mu}{c_\mu} Z^0_\mu H(W^+_\mu \phi^- - W^-_\mu \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- +$ $W_{\mu}^{-} \phi^{+}$) + $\frac{1}{2} i g^{2} s_{w} A_{\mu} H (W_{\mu}^{+} \phi^{-} - W_{\mu}^{-} \phi^{+}) - g^{2} \frac{s_{w}}{c_{w}} (2c_{w}^{2} - 1) Z_{\mu}^{0} A_{\mu} \phi^{+} \phi^{-}$ $g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_i^\lambda (\gamma \partial + m_u^\lambda) u_i^\lambda \bar{d}_j^{\lambda}(\gamma\partial+m_d^{\lambda})d_j^{\lambda}+ig s_w A_{\mu}[-(\bar{e}^{\lambda}\gamma^{\mu}e^{\lambda})+\frac{2}{3}(\bar{u}_j^{\lambda}\gamma^{\mu}u_j^{\lambda})-\frac{1}{3}(\bar{d}_j^{\lambda}\gamma^{\mu}d_j^{\lambda})]+$ $\frac{ig}{4c_w}Z_{\mu}^{0}[(\bar{\nu}^{\lambda}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})+(\bar{e}^{\lambda}\gamma^{\mu}(4s_w^2-1-\gamma^5)e^{\lambda})+(\bar{u}_j^{\lambda}\gamma^{\mu}(\frac{4}{3}s_w^2-1-\gamma^5)\nu^{\lambda})]$ $(1-\gamma^5)u_j^{\lambda}) + (\bar{d}_j^{\lambda}\gamma^{\mu}(1-\frac{8}{3}s_w^2-\gamma^5)d_j^{\lambda})] + \frac{ig}{2\sqrt{2}}W^+_{\mu}[(\bar{\nu}^{\lambda}\gamma^{\mu}(1+\gamma^5))\gamma^{\lambda}) +$ $(\bar{u}_j^{\lambda}\gamma^{\mu}(1+\gamma^5)C_{\lambda\kappa}d_j^{\kappa})]+\frac{ig}{2\sqrt{2}}W_{\mu}^{-}[(\bar{e}^{\lambda}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})+(\bar{d}_j^{\kappa}C_{\lambda\kappa}^{\dagger}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})]$ $[\gamma^5 u_j^{\lambda}] + \frac{ig}{2\sqrt{2}} \frac{m_e^{\lambda}}{M} [-\phi^+ (\bar{\nu}^{\lambda} (1-\gamma^5)e^{\lambda}) + \phi^- (\bar{e}^{\lambda} (1+\gamma^5)\nu^{\lambda})] \tfrac{g}{2}\tfrac{m_\epsilon^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) +$ $m_u^{\lambda}(\bar{u}_j^{\lambda}C_{\lambda\kappa}(1+\gamma^5)d_j^{\kappa}]+\frac{ig}{2M\sqrt{2}}\phi^- [m_d^{\lambda}(\bar{d}_j^{\lambda}C_{\lambda\kappa}^{\dagger}(1+\gamma^5)u_j^{\kappa})-m_u^{\kappa}(\bar{d}_j^{\lambda}C_{\lambda\kappa}^{\dagger}(1-\gamma^5)u_j^{\kappa})]$ $\left[\gamma^5\right]u_j^\kappa\big]-\frac{q}{2}\frac{m_u^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda)-\frac{q}{2}\frac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda)+\frac{iq}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5 u_j^\lambda)-\phi^0(\bar{u}_j^\lambda\gamma^5)$ $\frac{ig}{\partial \mu} \frac{m_d}{M} \phi^0(\bar{d}_i^{\lambda} \gamma^5 d_i^{\lambda}) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 \frac{M^2}{c_m^2}X^0+\bar{Y}\partial^2Y+igc_wW^+_\mu(\partial_\mu\bar{X}^0X^--\partial_\mu\bar{X}^+X^0)+ig s_wW^+_\mu(\partial_\mu\bar{Y}X^- \partial_{\mu}\bar{X}^{+}Y)+ig c_{w}W_{\mu}^{-}(\partial_{\mu}\bar{X}^{-}X^{0}-\partial_{\mu}\bar{X}^{0}X^{+})+ig s_{w}W_{\mu}^{-}(\partial_{\mu}\bar{X}^{-}Y \partial_{\mu}\bar{Y}X^{+}\rangle+ig c_{w}Z_{\mu}^{0}(\partial_{\mu}\bar{X}^{+}X^{+}-\partial_{\mu}\bar{X}^{-}X^{-})+ig s_{w}A_{\mu}(\partial_{\mu}\bar{X}^{+}X^{+} \partial_{\mu}\bar{X}^{-}X^{-}$) – $\frac{1}{2}gM[\bar{X}^{+}X^{+}H+\bar{X}^{-}X^{-}H+\frac{1}{c^{2}}\bar{X}^{0}X^{0}H]+$ $\frac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] +$ $\bar{i}gMs_w[\bar{X}^0X^-\phi^+-\bar{X}^0X^+\phi^-]+\frac{1}{2}igM[\bar{X}^+X^+\phi^0-\bar{X}^-X^-\phi^0]$

 $\frac{2M}{q}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right] + \frac{2M^4}{q^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W_\mu^+W_\nu^ W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu W_{\nu} \partial_{\nu} W_{\mu}^{+}) \Big] - ig s_w [\partial_{\nu} A_{\mu} (\tilde{W}_{\mu}^{+} W_{\nu}^{-} - W_{\nu}^{+} W_{\mu}^{-}) - A_{\nu} (W_{\mu}^{+} \partial_{\nu}^{+} W_{\mu}^{-} W_{\mu}^- \partial_{\nu} W_{\mu}^+) + A_{\mu} (W_{\nu}^+ \partial_{\nu} W_{\mu}^- - W_{\nu}^- \partial_{\nu} W_{\mu}^+) - \frac{1}{2} g^2 W_{\mu}^+ W_{\mu}^- W_{\nu}^+ W_{\nu}^- +$ $\int \frac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \nonumber$ $g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g \alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2]$ $g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} i g [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ (\phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{g^2_w}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) +$ $ig s_w MA_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) -ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) +$ $ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W_\mu^{\mp} W_\mu^- [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] \frac{1}{4}g^2\frac{1}{c^2_{\omega}}Z^0_{\mu}Z^0_{\mu}[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-]-\frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_{\mu}\phi^0(W^+_{\mu}\phi^-+$ $W^{-}_{\mu}\phi^{+})-\frac{1}{2}ig^{2}\frac{s_{w}^{2}}{c_{w}}Z^{0}_{\mu}H(W^{+}_{\mu}\phi^{-}-W^{-}_{\mu}\phi^{+})+\frac{1}{2}g^{2}s_{w}A_{\mu}\phi^{0}(W^{+}_{\mu}\phi^{-}+$ $W_{\mu}^-\phi^+)+\tfrac{1}{2} i g^2 s_w A_\mu H(W_\mu^+\phi^- -W_\mu^-\phi^+)-g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z_\mu^0 A_\mu\phi^+\phi^-$ $g^1s_w^2A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda(\gamma\partial+m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial \nu^\lambda - \bar{u}_j^\lambda(\gamma\partial+m_u^\lambda)u_j^\lambda \bar{d}_j^{\lambda}(\gamma\partial+m_d^{\lambda})d_j^{\lambda}+ig s_w A_{\mu}[-(\bar{e}^{\bar{\lambda}}\gamma^{\mu}e^{\lambda})+\frac{2}{3}(\bar{u}_j^{\lambda}\gamma^{\mu}u_j^{\lambda})-\frac{1}{3}(\bar{d}_j^{\lambda}\gamma^{\mu}d_j^{\lambda})]+$ $\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda)+(\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda)+(\bar{u}_j^\lambda\gamma^\mu(\frac{4}{3}s_w^2-1-\gamma^5)\nu^\lambda)]$ $1-\gamma^5) u_j^{\lambda}) + (\bar{d}_j^{\lambda} \gamma^{\mu} (1-\tfrac{8}{3} s_w^2 - \gamma^5) d_j^{\lambda})] + \tfrac{ig}{2\sqrt{2}} W^+_{\mu} [(\bar{\nu}^{\lambda} \gamma^{\mu} (1+\gamma^5) \zeta^{\lambda}) +$ $\label{eq:3.16} \big(\bar{u}_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa\big)\big]+ \tfrac{ig}{2\sqrt{2}}W^-_\mu\big[\big(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda\big) +\big(\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger\gamma^\mu(1+\gamma^5)\nu^\lambda\big)\big]$ $\gamma^5) u_j^\lambda \big] + \tfrac{ig}{2\sqrt{2}} \tfrac{m_\ell^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1-\gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1+\gamma^5) \nu^\lambda)] \frac{g m_e^\lambda}{2 M} [H(\bar{e}^\lambda e^\lambda) + i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2 M \sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda \kappa} (1 - \gamma^5) d_j^\kappa) +$ $m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa] + \tfrac{ig}{2M\sqrt{2}}\phi^- [m_d^\lambda(\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger(1+\gamma^5)u_j^\kappa) - m_u^\kappa(\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger(1-\gamma^5)u_j^\kappa]$ $\gamma^5[u_j^\kappa]-\frac{q}{2}\frac{m_\alpha^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda)-\frac{q}{2}\frac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda)+\frac{ig}{2}\frac{m_\alpha^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5 u_j^\lambda)-\phi^0(\bar{u}_j^\lambda\gamma^5)$ $\frac{ig}{2}\frac{m_d^{\lambda}}{M}\phi^0(\bar{d}_j^{\lambda}\gamma^5d_j^{\lambda}) + \bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2-N^2)$ $\frac{M^2}{c_w^2}X^0+\bar{Y}\partial^2Y+igc_wW^+_\mu(\partial_\mu\bar{X}^0X^--\partial_\mu\bar{X}^+X^0)+ig s_wW^+_\mu(\partial_\mu\bar{Y}X^- \bar{\partial}_{\mu}\bar{X}^+Y$ + $ig c_w W_{\mu}^-(\partial_{\mu}\bar{X}^-X^0 - \partial_{\mu}\bar{X}^0X^+)$ + $ig s_w W_{\mu}^-(\partial_{\mu}\bar{X}^-Y \partial_{\mu}\bar{Y}X^{+}\big)+ig c_{w}Z_{\mu}^{0}(\partial_{\mu}\bar{X}^{+}X^{+}-\partial_{\mu}\bar{X}^{-}X^{-})+ig s_{w}A_{\mu}(\partial_{\mu}\bar{X}^{+}X^{+} \partial_{\mu}\bar{X}^{-}X^{-} - \frac{1}{2}gM[\bar{X}^{+}X^{+}H + \bar{X}^{-}X^{-}H + \frac{1}{c_{w}^{2}}\bar{X}^{0}X^{0}H] +$ $\begin{array}{c} \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+-\bar{X}^-X^0\phi^-] +\frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+-\bar{X}^0X^+\phi^-] +\\ igMs_w[\bar{X}^0X^-\phi^+-\bar{X}^0X^+\phi^-] +\frac{1}{2}igM[\bar{X}^+X^+\phi^0-\bar{X}^-X^-\phi^0] \end{array}$

 $-{1\over 2}\partial_\nu g^a_\mu\partial_\nu g^a_\mu-g_sf^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu-{1\over 4}g^2_sf^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu+$ $\begin{array}{l} \frac{1}{2} i g_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \end{array}$ $M^2W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H \frac{1}{2}m_h^2H^2-\partial_\mu\phi^+\partial_\mu\phi^- -M^2\phi^+\bar{\phi}^--\frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0-\frac{1}{2c_w^2}M\phi^0\phi^0-\beta_h[\frac{2M^2}{g^2}+$

GEN

pp collisions up to production of stable particles [Easy & Fast]

detector response simulation [Hard & Slow]

 $\frac{2M}{q}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right] + \frac{2M^4}{q^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W_\mu^+W_\nu^ W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu W_{\nu} \partial_{\nu} W_{\mu}^{+}) \Big] - ig s_w [\partial_{\nu} A_{\mu} (\tilde{W}_{\mu}^{+} W_{\nu}^{-} - W_{\nu}^{+} W_{\mu}^{-}) - A_{\nu} (W_{\mu}^{+} \partial_{\nu}^{+} W_{\mu}^{-} W^{-}_{\mu}\partial_{\nu}W^{+}_{\mu} + A_{\mu}(W^{+}_{\nu}\partial_{\nu}W^{-}_{\mu} - W^{-}_{\nu}\partial_{\nu}W^{+}_{\mu})] - \frac{1}{2}g^{2}W^{+}_{\mu}W^{-}_{\mu}W^{+}_{\nu}W^{-}_{\nu} +$ $-\frac{1}{2}g^2\overset{\sim}{W^+_\mu}W^-_\nu\overset{\sim}{W^+_\mu}W^-_\nu + g^2c_w^2(Z^{\tilde{0}}_\mu W^+_\mu Z^{\tilde{0}}_\nu\overset{\sim}{W^-_\nu} - Z^0_\mu Z^{\tilde{0}}_\mu W^+_\nu W^-_\nu) + \cdots$ $g^2 \tilde{s}_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] \tfrac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4 (\tilde{\phi}^+ \phi^-)^2 + 4 (\phi^0)^2 \phi^+ \phi^- + 4 H^2 \phi^+ \phi^- + 2 (\phi^0)^2 H^2]$ $gMW_{\mu}^{+}W_{\mu}^{-}H - \frac{1}{2}g\frac{M}{c_{\nu}^{2}}Z^{0}_{\mu}Z^{0}_{\mu}H - \frac{1}{2}ig[W_{\mu}^{+}(\phi^{0}\partial_{\mu}\phi^{-} - \phi^{-}\partial_{\mu}\phi^{0}) W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ (\phi^+\partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w}(Z^0_\mu (H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) +$ $ig s_w MA_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) -ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) +$ $ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W_\mu^{\mp} W_\mu^- [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] \frac{1}{4}g^2\frac{1}{c^2_{\omega}}Z^0_{\mu}Z^0_{\mu}[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-]-\frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_{\mu}\phi^0(W^+_{\mu}\phi^-+$ $W^{-}_{\mu}\phi^{+}\big) -\tfrac{1}{2}ig^{2}\tfrac{s_{w}^{2}}{c_{w}}Z^{0}_{\mu}H(W^{+}_{\mu}\phi^{-}-W^{-}_{\mu}\phi^{+}) +\tfrac{1}{2}g^{2}s_{w}A_{\mu}\phi^{0}(W^{+}_{\mu}\phi^{-}+$ $W_\mu^-\phi^+) + \frac{1}{2} i g^2 s_w A_\mu H(W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^-$ $g^1s_w^2A_\mu\overset{.}{A}_\mu\phi^+\phi^- -\bar{e}^\lambda(\gamma\partial+m_e^\lambda)e^\lambda-\bar{\nu}^\lambda\gamma\partial\nu^\lambda-\bar{u}_j^\lambda(\gamma\partial+m_u^\lambda)u_j^\lambda \bar{d}_j^{\lambda}(\gamma\partial+m_d^{\lambda})d_j^{\lambda}+ig s_w A_{\mu}[-(\bar{e}^{\bar{\lambda}}\gamma^{\mu}e^{\lambda})+\frac{2}{3}(\bar{u}_j^{\lambda}\gamma^{\mu}u_j^{\lambda})-\frac{1}{3}(\bar{d}_j^{\lambda}\gamma^{\mu}d_j^{\lambda})]+$ $\frac{i g}{4 c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4 s_w^2 - 1 - \gamma^5) \bar{e}^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3} s_w^2 1-\gamma^5)u_j^{\lambda} + (\bar{d}_j^{\lambda}\gamma^{\mu}(1-\frac{8}{3}s_w^2-\gamma^5)d_j^{\lambda})] + \frac{ig}{2\sqrt{2}}W^+_{\mu}[(\bar{\nu}^{\lambda}\gamma^{\mu}(1+\gamma^5))\lambda^{\lambda}) +$ $(\bar{u}_j^{\lambda}\gamma^{\mu}(1+\gamma^5)C_{\lambda\kappa}d_j^{\kappa})]+ \tfrac{ig}{2\sqrt{2}}W^-_{\mu}[(\bar{e}^{\lambda}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})+(\bar{d}_j^{\kappa}C_{\lambda\kappa}^{\dagger}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})]$ $\gamma^5) u_j^\lambda\big]\big] +\tfrac{ig}{2\sqrt{2}}\tfrac{m_\epsilon^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda)+\phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)]\, \tfrac{g}{2}\tfrac{m_a^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) +$ $m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa] + \tfrac{ig}{2M\sqrt{2}}\phi^- [m_d^\lambda(\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger(1+\gamma^5)u_j^\kappa) - m_u^\kappa(\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger(1-\gamma^5)u_j^\kappa]$ $\gamma^5[u_j^\kappa]-\frac{q}{2}\frac{m_\alpha^\lambda}{M}H(\bar u_j^\lambda u_j^\lambda)-\frac{q}{2}\frac{m_d^\lambda}{M}H(\bar d_j^\lambda d_j^\lambda)+\frac{ig}{2}\frac{m_\alpha^\lambda}{M}\phi^0(\bar u_j^\lambda\gamma^5 u_j^\lambda) \frac{ig}{2}\frac{m_d^{\lambda}}{M}\phi^0(\bar{d}_j^{\lambda}\gamma^5d_j^{\lambda}) + \bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2-N^2)$ $\frac{M^2}{c_m^2}X^0+\bar{Y}\partial^2Y+igc_wW^+_\mu(\partial_\mu\bar{X}^0X^--\partial_\mu\bar{X}^+X^0)+ig s_wW^+_\mu(\partial_\mu\bar{Y}X^- \partial_{\mu}\bar{X}^{+}Y)+ig c_{w}W_{\mu}^{-}(\partial_{\mu}\bar{X}^{-}X^{0}-\partial_{\mu}\bar{X}^{0}X^{+})+ig s_{w}W_{\mu}^{-}(\partial_{\mu}\bar{X}^{-}Y \partial_\mu \bar{Y}X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+X^+ - \partial_\mu \bar{X}^-X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+X^+ \partial_{\mu}\bar{X}^{-}X^{-}$) – $\frac{1}{2}gM[\bar{X}^{+}X^{+}H+\bar{X}^{-}X^{-}H+\frac{1}{c_{w}^{2}}\bar{X}^{0}X^{0}H]+$ $\tfrac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+-\bar X^-X^0\phi^-] +\tfrac{1}{2c_w}igM[\bar X^0X^-\phi^+-\bar X^0X^+\phi^-] +$ $\left[\tilde{X}^0 M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} \tilde{i} g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0] \right] \, .$

 $-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu-g_sf^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu -\tfrac{1}{4}g^2_sf^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu+$ $-\frac{1}{2} ig_s^2 \left(\bar{q}_i^{\sigma} \gamma^{\mu} q_j^{\sigma} \right) g_{\mu}^{\dot{a}} + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_{\mu} \bar{G}^a G^b g_{\mu}^c - \partial_{\nu} W_{\mu}^+ \partial_{\nu} W_{\mu}^- M^2\overline{W^+_\mu W^-_\mu} - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H \frac{1}{2}m_h^2H^2-\partial_\mu\phi^+\partial_\mu\phi^- -M^2\phi^+\bar{\phi}^--\frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0-\frac{1}{2c_w^2}M\phi^0\phi^0-\beta_h[\frac{2M^2}{g^2}+$

GEN

pp collisions up to production of stable particles [Easy & Fast]

DIGI+RECO

Energy deposits→digital signals -> reconstructed by the reconstruction software [Hard & Slow]

SIM

detector response simulation [Hard & Slow]

 $\frac{2M}{q}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right] + \frac{2M^4}{q^2}\alpha_h - igc_w[\partial_\nu Z_\mu^0(W_\mu^+W_\nu^- W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu W_{\nu} \partial_{\nu} W_{\mu}^{+}) \Big] - ig s_w [\partial_{\nu} A_{\mu} (\tilde{W}_{\mu}^{+} W_{\nu}^{-} - W_{\nu}^{+} W_{\mu}^{-}) - A_{\nu} (W_{\mu}^{+} \partial_{\nu}^{+} W_{\mu}^{-} W_{\mu}^-\partial_{\nu}W_{\mu}^+)+A_{\mu}(W_{\nu}^+\partial_{\nu}W_{\mu}^--W_{\nu}^-\partial_{\nu}W_{\mu}^+)]-\frac{\mathrm{i}}{2}g^2W_{\mu}^+W_{\mu}^-W_{\nu}^+W_{\nu}^-+$ $\frac{1}{2}g^2W_\mu^+W_\nu^-W_\mu^+W_\nu^- + g^2c_w^2(Z_\mu^0W_\mu^+Z_\nu^0W_\nu^- - Z_\mu^0Z_\mu^0W_\nu^+W_\nu^-) + \nonumber\ g^2s_w^2(A_\mu W_\mu^+A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+W_\nu^-) + g^2s_wc_w[A_\mu Z_\nu^0(W_\mu^+W_\nu^- W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu - g \alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] \frac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2]$ $g\dot{M}W^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_\nu}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)]^{\!\!\mathsf{w}} + \tfrac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ \phi^+\partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w}(Z^0_\mu (H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z^0_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) +$ $ig s_w MA_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) -ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) +$ $ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W_\mu^{\mp} W_\mu^- [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] \frac{1}{4}g^2\frac{1}{c^2}\,Z^0_\mu Z^0_\mu [H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-]-\frac{1}{2}g^2\frac{s_w^2}{c_w}\,Z^0_\mu\phi^0(W^+_\mu\phi^-+$ $W^{-}_{\mu}\phi^{+})-\frac{1}{2}ig^{2}\frac{s_{w}^{2}}{c_{w}}Z^{0}_{\mu}H(W^{+}_{\mu}\phi^{-}-W^{-}_{\mu}\phi^{+})+\frac{1}{2}g^{2}s_{w}A_{\mu}\phi^{0}(W^{+}_{\mu}\phi^{-}+$ $W_{\mu}^-\phi^+) + \frac{1}{2} i g^2 s_w A_{\mu} H(W_{\mu}^+\phi^- - W_{\mu}^-\phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_{\mu}^0 A_{\mu} \phi^+ \phi^-$ $g^1s_w^2A_\mu\overset{.}{A}_\mu\phi^+\phi^- -\bar{e}^\lambda(\gamma\partial+m_e^\lambda)e^\lambda-\bar{\nu}^\lambda\gamma\partial\nu^\lambda-\bar{u}_j^\lambda(\gamma\partial+m_u^\lambda)u_j^\lambda \bar{d}_j^{\lambda}(\gamma\partial+m_d^{\lambda})d_j^{\lambda}+ig s_w A_{\mu}[-(\bar{e}^{\bar{\lambda}}\gamma^{\mu}e^{\lambda})+\frac{2}{3}(\bar{u}_j^{\lambda}\gamma^{\mu}u_j^{\lambda})-\frac{1}{3}(\bar{d}_j^{\lambda}\gamma^{\mu}d_j^{\lambda})]+$ $\frac{ig}{4c_w}Z_{\mu}^{0}[(\bar{\nu}^{\lambda}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})+(\bar{e}^{\lambda}\gamma^{\mu}(4s_{w}^{2}-1-\gamma^5)e^{\lambda})+(\bar{u}_{j}^{\lambda}\gamma^{\mu}(\frac{4}{3}s_{w}^{2}-1))$ $1-\gamma^5)u_j^{\lambda} + (\bar{d}_j^{\lambda}\gamma^{\mu}(1-\frac{8}{3}s_w^2-\gamma^5)d_j^{\lambda})] + \frac{ig}{2\sqrt{2}}W^+_{\mu}[(\bar{\nu}^{\lambda}\gamma^{\mu}(1+\gamma^5))\lambda^{\lambda}) +$ $\label{eq:3.16} \left(\bar{u}_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa\right)]+\tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda)+(\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger\gamma^\mu(1+\gamma^5)\nu^\lambda)]$ $\gamma^5) u_j^\lambda]] + \frac{ig}{2\sqrt{2}} \frac{m_\alpha^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1-\gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1+\gamma^5) \nu^\lambda)] \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) +$ $m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa] + \tfrac{ig}{2M\sqrt{2}}\phi^- [m_d^\lambda(\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger(1+\gamma^5)u_j^\kappa) - m_u^\kappa(\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger(1-\gamma^5)u_j^\kappa]$ $\gamma^5[u_j^\kappa]-\frac{q}{2}\frac{m_\alpha^\lambda}{M}H(\bar u_j^\lambda u_j^\lambda)-\frac{q}{2}\frac{m_d^\lambda}{M}H(\bar d_j^\lambda d_j^\lambda)+\frac{ig}{2}\frac{m_\alpha^\lambda}{M}\phi^0(\bar u_j^\lambda\gamma^5 u_j^\lambda) \frac{ig}{\partial} \frac{m_d^{\lambda}}{M} \phi^0(\bar{d}_i^{\lambda} \gamma^5 d_i^{\lambda}) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 \frac{M^2}{c_m^2}X^0+\bar{Y}\partial^2Y+igc_wW^+_\mu(\partial_\mu\bar{X}^0X^--\partial_\mu\bar{X}^+X^0)+ig s_wW^+_\mu(\partial_\mu\bar{Y}X^- \overline{\partial}_{\mu}\overline{X}+Y)+ig_{\mathcal{C}_W}W_{\mu}^{\perp}(\partial_{\mu}\overline{X}-X^0-\partial_{\mu}\overline{X}^0X^+)+ig_{\mathcal{S}_W}W_{\mu}^{\perp}(\partial_{\mu}\overline{X}-Y-\overline{X}^0X^+Y^+))$ $\partial_{\mu}\bar{Y}X^{+}\big)+ig c_{w}Z_{\mu}^{0}(\partial_{\mu}\bar{X}^{+}X^{+}-\partial_{\mu}\bar{X}^{-}X^{-})+ig s_{w}A_{\mu}(\partial_{\mu}\bar{X}^{+}X^{+} \partial_{\mu}\bar{X}^{-}X^{-}$) – $\frac{1}{2}gM[\bar{X}^{+}X^{+}H+\bar{X}^{-}X^{-}H+\frac{1}{c^{2}}\bar{X}^{0}X^{0}H]+$ $\frac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] +$ $\left[\tilde{X}^0 M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0] \right] \, .$

 $-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu-g_sf^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu -\tfrac{1}{4}g^2_sf^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu+$ $\begin{array}{l} \frac{1}{2} i g_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \end{array}$ $M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_\nu}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H \frac{1}{2}m_h^2H^2-\partial_\mu\phi^+\partial_\mu\phi^- -M^2\phi^+\bar{\phi}^--\frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0-\frac{1}{2c^2_\nu}M\phi^0\phi^0-\beta_h[\frac{2M^2}{g^2}+$

GEN

pp collisions up to production of stable particles [Easy & Fast]

SIM

detector response simulation [Hard & Slow]

$10⁰$ Particle n $E_b(6227)$ $\Sigma_b(6)$ $\Sigma_h(6)$ $\chi_{c0}(4700)$ $\chi_{c0}(4500)$ $\chi_{c1}(4274)$ \bar{z}^{++}_{cc} $\Omega_c(3119)^0$ $\vert \Omega_c(3090) \rangle$ $\Omega_c(3066)^0$ $\Lambda_c(2860)^+$ $\Omega_c(3050)^6$ $\Omega_c(3000)^0$ $D_3^*(2760)^6$ 2018 2017

Date of arXiv

PRESSMEDDELANDE

Nobelpriset i fysik 2013

Kungl. Vetenskapsakademien har beslutat utdela Nobelpriset i fysik 2013 till

François Englert

Université Libre de Bruxelles, Bryssel, Belgien

Peter W. Higgs University of Edinburgh, Storbritannien

"för den teoretiska upptäckten av en mekanism som bidrar till förståelsen av massans ursprung hos subatomära partiklar, och som nyligen, genom upptäckten av den förutsagda fundamentala partikeln, bekräftats av ATLAS- och CMS-experimenten vid **CERN:s accelerator LHC"**

Äntligen här!

François Englert och Peter W. Higgs delar årets Nobelpris i fysik för teorin om hur partiklar får sin massa. Oberoende av varandra föreslog de teorin samtidigt år 1964 (Englert tillsammans med sin numera avlidne kollega Robert Brout). Först 2012 bekräftades deras idéer genom upptäckten av en så kallad Higgspartikel vid CERNlaboratoriet utanför Genève i Schweiz.

Den i år prisbelönta teorin är en central del i fysikens standardmodell som beskriver hur världen är uppbyggd. Allting, från blommor och människor till stjärnor och planeter, består enligt standardmodellen av några få byggstenar, materiepartiklar. Dessa partiklar styrs av krafter som förmedlas av kraftpartiklar som ser till att allt fungerar som det ska.

Hela standardmodellen vilar på att det också finns en särskilt sorts partikel, Higgspartikeln. Denna är en vibration av ett osynligt fält som fyller rymden. Till och med när universum verkar tömt på allt, finns fältet där. Utan det skulle vi inte finnas, för det är genom kontakten med fältet som partiklarna får sin massa. Den av Englert och Higgs föreslagna teorin beskriver hur detta går till.

Den 4 juli 2012 bekräftades teorin i och med upptäckten and a later of the theorem and a compact in

partikelkolliderare, LHC (Large Hadron Collider), är troligen den största och mest komplicerade maskin som någonsin byggts av människor. Ur miljarder partikelkrockar i LHC lyckades två grupper, ATLAS och CMS, med cirka 3 000 forskare var, vaska fram Higgspartikeln.

Även om det är ett storverk att finna Higgspartikeln, den sista pusselbiten som fattades i standardmodellen, så är standardmodellen inte den sista biten i pusslet om hela universum. Ett av skälen är att vissa partiklar, neutriner, beskrivs i standardmodellen som masslösa, medan ny forskning pekar mot att de faktiskt har massa. Ett annat skäl är att modellen bara omfattar den synliga materien, vilken endast är en femtedel av all materia som finns i världsalltet. Att hitta den mystiska mörka materien är ett av målen för den fortsatta jakten på okända partiklar vid CERN.

François Englert, belgisk medborgare. Född 1932 (80 år) i Etterbeek, Belgien. Fil.dr 1959 vid Université Libre de Bruxelles, Bryssel, Belgien. Professor emeritus vid Université Libre de Bruxelles, Bryssel, Belgien.

www.ulb.ac.be/sciences/physth/people_FEnglert.html

Peter W. Higgs, brittisk medborgare. Född 1929 (84 år) i Newcastle upon Tyne, Storbritannien. Fil.dr 1954 vid King's College, University of London, Storbritannien. Professor emeritus vid University of Edinburgh, Storbritannien.

www.ph.ed.ac.uk/higgs/

 $O(10)$ 10^{-18} m 10^{-15} m **GEN** pp collisions up to production of stable particles [Easy & Fast]

 $O(10^2)$

 10^{-6} m

Not in this talk

 $-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu -g_sf^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu -\frac{1}{4}g^2_sf^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu +\frac{1}{2}g^2_b g^b_\mu g^c_\nu$ $\bar{z}_1^1i g_s^2(\bar{q}_i^\sigma\gamma^\mu q_j^\sigma) g_u^a+\bar{G}^a\partial^2 G^a+g_s f^{abc}\partial_\mu\bar{G}^a G^b g_u^c-\partial_\nu W^+_u\partial_\nu W^-_u\,.$ $M^2 W^+_\mu W^-_\mu - \frac{1}{2} \partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_\mu} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H \frac{1}{2}m_h^2H^2-\partial_\mu\phi^+\partial_\mu\phi^--M^2\phi^+\phi^--\frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0-\frac{1}{2c^2_m}M\phi^0\phi^0-\beta_h[\frac{2M^2}{a^2}]$ $\frac{2M}{a}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right] + \frac{2M^4}{a^2}\alpha_h - igc_w[\partial_\nu Z_\mu^0(W_\mu^+W_\nu^ W^+_\nu \hat{W}^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - ig s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu)]$ $W_{\mu}^{-} \partial_{\nu} W_{\mu}^{+} + A_{\mu} (W_{\nu}^{+} \partial_{\nu} W_{\mu}^{-} - W_{\nu}^{-} \partial_{\nu} W_{\mu}^{+})] - \frac{1}{2} g^{2} W_{\mu}^{+} W_{\mu}^{-} W_{\nu}^{+} W_{\nu}^{-}$ $W_u^-W_u^+W_u^- + q^2c_w^2(Z_u^0W_u^+Z_u^0W_u^- - Z_u^0Z_u^0)$ ${}^2\tilde{s}^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu)]$ $W^+_v W^-_n) - 2A_u Z_u^0 W^+_v W^-_v - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-]$ $\frac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2]$ $gMW_u^+W_u^-H-\frac{1}{2}g\frac{M}{c^2}Z_u^0Z_u^0H-\frac{1}{2}ig[W_u^+(\phi^0\partial_\mu\phi^- -\phi^-\partial_\mu\phi^0) W^-_\mu(\phi^0\partial_\mu\phi^+-\phi^+\partial_\mu\phi^0)]+\tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^--\phi^-\partial_\mu H)-W^-_\mu(H\partial_\mu\phi^+$ $\phi^+ \partial_u H)] + \frac{1}{2} g_-^{\perp} (Z_u^0 (H \partial_u \phi^0 - \phi^0 \partial_u H) - ig_{\infty}^{\frac{2}{3}} M Z_u^0 (W_u^+ \phi^- - W_u^- \phi^+) +$ $ig s_w MA_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) +$ $ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] \frac{1}{4}g^2\frac{1}{c_{\mu}^2}Z_{\mu}^0Z_{\mu}^0[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z_{\mu}^0\phi^0(W_{\mu}^+\phi^- +$ $W_{\mu\nu}^{\dagger} \phi^+$ = $\frac{1}{2} i g^2 \frac{s_{\mu\nu}^2}{2} Z_{\mu}^0 H(W_{\mu}^{\dagger} \phi^- - W_{\mu}^- \phi^+) + \frac{1}{2} g^2 s_w A_{\mu} \phi^0 (W_{\mu}^{\dagger} \phi^- +$ $W^-_u\phi^+)+\frac{1}{2}ig^2s_wA_\mu H(W^+_u\phi^- - W^-_u\phi^+)-g^2\frac{s_w}{c_w}(2c_w^2-1)Z_u^0A_\mu\phi^+\phi^$ $g^1 s_w^2 A_u A_u \phi^+ \phi^- - \bar{e}^{\lambda} (\gamma \partial + m_e^{\lambda}) e^{\lambda} - \bar{\nu}^{\lambda} \gamma \partial \nu^{\bar{\lambda}} - \bar{u}_i^{\lambda} (\gamma \partial + m_u^{\lambda}) u_i^{\lambda}$ $d_3^{\lambda}(\gamma \partial + m_d^{\lambda})d_j^{\lambda} + ig s_w A_{\mu} [-(\bar{e}^{\lambda}\gamma^{\mu}e^{\lambda}) + \frac{2}{3}(\bar{u}_j^{\lambda}\gamma^{\mu}u_j^{\lambda}) - \frac{1}{3}(\bar{d}_j^{\lambda}\gamma^{\mu}d_j^{\lambda})] +$ $-\mathcal{Z}^0_\mu [(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2-\gamma^5))$ $1-\gamma^5)u_j^\lambda\big)+(\bar d_j^\lambda\gamma^\mu(1-\tfrac83s_w^2-\gamma^5)d_j^\lambda\big)\big]+\tfrac{ig}{2\sqrt{2}}W_\mu^+[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\bar\lambda^\lambda)\cdot$ $(\bar{u}_j^{\lambda}\gamma^{\mu}(1+\gamma^5)C_{\lambda\kappa}d_j^{\kappa})]+\frac{ig}{2\sqrt{2}}W_{\mu}^{-}[(\bar{e}^{\lambda}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})+(\bar{d}_j^{\kappa}C_{\lambda\kappa}^{\dagger}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})]$ $\big[\gamma^5(u_j^\lambda)\big] + \frac{ig}{2\sqrt{2}}\frac{m_0^\lambda}{M}\big[\varphi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)\big] -\frac{q}{2}\frac{m_d^{\lambda}}{M}[H(\bar{e}^{\lambda}e^{\lambda})+i\phi^0(\bar{e}^{\lambda}\gamma^5e^{\lambda})]+\frac{ig}{2M\sqrt{2}}\phi^+[-m_d^{\kappa}(\bar{u}_j^{\lambda}C_{\lambda\kappa}(1-\gamma^5)d_j^{\kappa})+$ $m_u^\lambda (\bar{u}_j^\lambda C_{\lambda \kappa}(1+\gamma^5) d_j^\kappa] + \frac{ig}{2M\sqrt{2}}\phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda \kappa}^\dagger (1+\gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda \kappa}^\dagger (1+\gamma^5) u_j^\kappa]$ $\gamma^5) u_j^\kappa\big] -\frac{g}{2}\frac{m_u^\lambda}{M} H(\bar u_j^\lambda u_j^\lambda) -\frac{g}{2}\frac{m_d^\lambda}{M} H(\bar d_j^\lambda d_j^\lambda) +\frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar u_j^\lambda\gamma^5 u_j^\lambda) -\big]$ $\frac{ig}{\alpha} \frac{m_d}{\omega} \phi^0(\bar{d}_i^{\lambda} \gamma^5 d_i^{\lambda}) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2$ $\frac{M^2}{c^2}X^0+\bar{Y}\partial^2Y+igc_wW^+_u(\partial_\mu\bar{X}^0X^--\partial_\mu\bar{X}^+X^0)+ig s_wW^+_u(\partial_\mu\bar{Y}X^-)$ $\int \mathcal{D}_{\mu}\bar{X}^+Y) +ig c_w W^-_u (\partial_{\mu}\bar{X}^-X^0 - \partial_{\mu}\bar{X}^0X^+) +ig s_w W^-_u (\partial_{\mu}\bar{X}^-Y)$ $\partial_\mu \bar{Y}X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+X^+ - \partial_\mu \bar{X}^-X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+X^+ + \bar{X}^-X^-)$ $\partial_{\mu}\bar{X}^{-}X^{-} - \frac{1}{2}gM[\bar{X}^{+}X^{+}H + \bar{X}^{-}X^{-}H + \frac{1}{c^{2}}\bar{X}^{0}X^{0}H] +$ $\frac{1-2c_w^2}{2c}igM[\bar{X}^+X^0\phi^+-\bar{X}^-X^0\phi^-] +\frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+-\bar{X}^0X^+\phi^-] +$ $\bar{\chi}^{*}gMs_{w}[\bar{X}^{0}X^{-}\phi^{+}-\bar{X}^{0}X^{+}\phi^{-}]+\frac{1}{2}igM[\bar{X}^{+}X^{+}\phi^{0}-\bar{X}^{-}X^{-}\phi^{0}]$

Generative signal dels for detector response

GEN

 $O(10)$

 10^{-18} m

Detector design, data acquisition and triggering

Data analysis

Detector reconstruction and tagging

 $M_S M_B^* + M_B M_S^*$

Dijet invariant mass

Monte Carlo simulation takes us over 20 orders of magnitude in length!

~40 quadrillion collisions recorded at LHC

[CMSOfflineComputingResults](https://twiki.cern.ch/twiki/bin/view/CMSPublic/CMSOfflineComputingResults)

[cmsexperiment.web.cern.ch](https://cmsexperiment.web.cern.ch/news/using-golden-decay-channel-understand-production-higgs-boson)

We had to collide billions of protons, only around 10 signal events were needed to claim discovery!

[cmsexperiment.web.cern.ch](https://cmsexperiment.web.cern.ch/news/using-golden-decay-channel-understand-production-higgs-boson)

We had to collide billions of protons, only around 10 signal events were needed to claim discovery!

We have a lot of high that we want to use to quality simulated data train AI algorithms!

But we have even more unlabelled data we'd like to use!

Supervised versus unsupervised

- V self-interactions and interactions with

VBS WZjj

BSM H± Production

Non-VBS WZjj and model in tagged non-prompt, the prompt of \mathbb{R}^n ‣ Signals + tZq ,ZZ with unconstrained normalisations

ML: Enhance S/√B

detector response simulation [Hard & Slow]

pp collisions up to production of stable particles [Easy & Fast]

Detector reconstruction and tagging

э,

 \mathbf{Q} , \mathbf{Q}

Data representation

Jet tagging - our MNIST!

Quark, gluon

 \mathbf{Q} , \mathbf{Q}

b-quark? W boson?

Fig. 1.: An example jet image of a Lorentz boosted top quark jet after *[arXiv:1511.05190](https://arxiv.org/abs/1511.05190)*

Fig. 1.: An example jet image of a Lorentz boosted top quark jet after *[arXiv:1511.05190](https://arxiv.org/abs/1511.05190)*

preprocessing has been applied [10]. $N = N \cdot N$ ages have notable di↵erences with respect to typical natural images in CV. **But… inhomogeneous geometry, high sparsity**

But... permutation-invariance

 $\mathcal{L}_{\mathcal{A}}$

 \blacksquare

 \mathbb{R}^n

While designed to take advantage of advances in computer vision, jet im-

recurrent neural network (RNN), e.g., GRU/LSTM; 1D CNN, GRU/LSTM; 1D CNNs; e.g., GRU/LSTM; 1D CNNs; e.g., GRU/
In the connection of the connection of

Point Cloud: Set of N-dimensional vectors **(e.g set of particles and their 4-momentum)**

• [ParticleNet](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.101.056019) (GNN on point cloud) [LundNet](https://arxiv.org/abs/2012.08526f) (GNN,Lund plane) [ABCNet](https://arxiv.org/abs/2001.05311) (GNN, attention) [Point Cloud Transformers](https://arxiv.org/abs/2102.05073) (transformer, attention) [ParticleNeXt](https://indico.cern.ch/event/980214/contributions/4413544/) (GNN, attention, Lund) [ParT](https://arxiv.org/abs/2202.03772) (transformer, attention)

SOTA: Graph Neural Networks acting on point cloud data

Transformers and (self-)attention

• Allows particles to interact with each other ("self") and find out which other particles they should pay more attention to ("attention")

Adding (Self-)Attention

Weighted sum over all input vectors:

Weight (how related inputs are):

• Allows particles to interact with each other ("self") and find out which other particles they should pay more attention to ("attention")

Map to [0,1]:

$$
w_{ij} = \frac{\exp w'_{ij}}{\sum_{j} \exp w'_{ij}}
$$

$$
\boldsymbol{\mathcal{W}}'_{ij} = \boldsymbol{\mathcal{X}}_i{}^{\mathsf{T}} \boldsymbol{\mathcal{X}}_j
$$

Adding (Self-)Attention

Transformers and (self-)attention

xi xj

Weighted sum over all input vectors:

 $y_i = \sum_i w_{ij} x_j$

Weight (how related inputs are):

Map to [0,1]:

$$
w_{ij} = \frac{\exp w'_{ij}}{\sum_{j} \exp w'_{ij}}
$$

$$
\boldsymbol{w}_{ij}^{\prime} = \boldsymbol{x}_i^{\mathsf{T}} \boldsymbol{x}_j
$$

Adding (Self-)Attention

• Allows particles to interact with each other ("self") and find out which other particles they should pay more attention to ("attention")

Attention weights: weighted importance between each pair of particles

- Determine relationship between all particles of point cloud
- Several attention layers \rightarrow different important features (multi-head attention)

Transformers and (self-)attention

ABCNet:

Pixel intensity = particle importance w.r.t most energetic particle in jet, from attention weights **Learned through attention!** C^- −0.4 + **ide** −0.2 → 0.2 →

VBS WZjj **District** -200 x (cm) z (cm) 300

complex detectors

MBM H± Production ML: Reconstruct complex patterns in

Non-VBS WZjj

pp collisions up to production of stable particles [Easy & Fast]

Detector reconstruction and tagging

detector response simulation [Hard & Slow]

CMS Experiment at the LHC, CERN

Data recorded: 2010-Nov-14 18:37:44 420271 GMT(19:37:44 CEST) Run / Event: 151076 / 405388

Hom billions of sensors to particles?

[arxiv:2309.06782](https://arxiv.org/abs/2309.06782)

Classical Particle Flow Graph Neural Network

5

CMS Simulation Preliminary $t\bar{t}$ + PU, \sqrt{s} = 14 TeV Machine-Learned Particle Flow reconstruction

GNN-based model inference time scales approximately linearly with increasing input size

Charged hadrons Neutral hadrons Photons **HFHAD**

[arxiv:2309.06782](https://arxiv.org/abs/2309.06782)

CMS Simulation Preliminary $t\overline{t}$ + PU, \sqrt{s} = 14 TeV Particle Flow reconstruction

PF baseline scales non-linearily with increasing input size

Classical Particle Flow Graph Neural Network

machine-learned particle flow (bottom). The trajectories correspond to the particle flow candidates

PF baseline scales non-linearily

Classical Particle Flow Graph Neural Network

5

GNN-based model inference time with increasing input size scales approximately linearly with increasing input size

Muons

[arxiv:2309.06782](https://arxiv.org/abs/2309.06782)

pp collisions up to production of stable particles [Easy & Fast]

detector response simulation [Hard & Slow]

Train on simulation, test on data **Train on simulation, test on data**

If data and simulation differ, this is **sub-optimal**! **If data and simulation differ, this is sub-optimal!**

Bias in particle physics

Searches at LHC always start by

• assuming **Standard Model** and some **signal hypothesis**

This is fine when we know what "signal" is (like Higgs)

- **Tailor search** to a given theory
- Powerful, but **limited to model of choice**

Some variable of interest

Bias in particle physics

Searches at LHC always start by

• assuming **Standard Model** and some **signal hypothesis**

This is fine when we know what "signal" is (like Higgs)

- **Tailor search** to a given theory
- Powerful, but **limited to model of choice**
- How do we know we are looking for the right thing in the enormous New Physics model landscape?

Anomaly detection for New Physics searches

1

_ σ
⑦

Standard Model (simulated events)

LEARN THIS FROM DATA

LOOK FOR ANYTING THAT DOESNT LOOK LIKE THIS

Types of anomaly detection

Find (non-resonant) out-of-distribution datapoints Find (resonant) overdensities in distributions d (non-resonant) out-of-distribution datapoints **Find (resonant)** ov

2007.01850, 2007.15830, 2010.07940, 2102.08390, 2104.09051, 2105.07988, 2105.10427, 2105.09274, 2106.1016.10209386, 21100.1091010
1110901141117, UVETUENSILIES III UISLIINULIUIIS

Outlier detection Detecting overdensities [1807.10261, 1808.08979, 1808.08992, 1811.10276, 1903.02032, 1912.10625, 2004.09360, 2006.05432,

Outlier detection

Compressed representation of x. Latent space $\mathbf{\mathfrak{R}}^k$, k < m \times n prevents memorisation of input, must learn

Outlier detection

 $\mathscr{L}(\mathbf{x}, \hat{\mathbf{x}})$ is Mean Squared Error $(\mathbf{x}, \hat{\mathbf{x}})$, "high error events" proxy for "degree of abnormality"

$\mathscr L(\mathbf x, \hat{\mathbf x})$ is Mean Squared l $\mathscr L(\mathbf x, \hat{\mathbf x})$ is Mean Squared

Outlier detection in analysis 2 E.g CASE

Finding overdensities • CURTAINS: Train an invertible [Raine et al: 2203.09470]

Senriched sample in data bunda Benriched sample in data Semi-Visible Jets

parameter varies.

parameter varies.

Finding overdensities - CWoLa bumphunt Mass of the Mediator: *mZ*⁰ Production Rate: Mass of the Dark Hadrons: Searching for Dark Matter with Semi-Visible Jets at CMS Semi-Visible Jets Mass of the Mediator: *mZ*⁰ Production Rate: Mass of the Dark Hadrons: Mass of the Mediator: *mZ*⁰ Production Rate: Mass of the Dark Hadrons: Searching for Dark Matter with Semi-Visible Jets at C Semi-Visible Jets Searching for Dark Matter with The Test at CMS \blacksquare Mass of the Mediator: *mZ*⁰ Production Rate: Searching for Dark Matter with Search at Semi-Visible Jets. Mass of the Mediator: *mZ*⁰ Production Rate: Mass of the Dark Hadrons: Mass of the Mediator: *mZ*⁰ Production Rate: Mass of the Dark Hadrons: Mass of the Mediator: *mZ*⁰ Production Rate: Mass of the Dark Hadrons: Mass of the Mediator: *mZ*⁰ Production Rate: Mass of the Dark Hadrons: Searching for Dark Matter with Semi-Visible Jets at CMS Semi-Visible Jets Searching for Dark Matter with Semi-Visible Jets and Dark Matter with Semi-Visible Jets at Company and Dark Ma Semi-Visible Jets Searching for Dark Matter with Semi-Visible Jets at CMS Semi-Visible Jets SVJ Parameters Searching for Dark Matter with Semi-Visible Jets at CMS Semi-Visible Jets

degenerate. S enriched sample in data Semi-Visible Jets

parameter varies.

/Pictures/URlogo.png

Semi-Visible Jets

/Pictures/URlogo.png

SVJ Parameters

Production Rate: *Z*⁰ ⇥ *Br*(*Z*⁰ !

Semi-Visible Jets

Production Rate: *Z*⁰ ⇥ *Br*(*Z*⁰ !

degenerate.

Production Rate: *Z*⁰ ⇥ *Br*(*Z*⁰ !

degenerate.

Semi-Visible Jets

Semi-Visible Jets SVJ Parameters

> *Z* 0

Production Rate:

degenerate.

Semi-Visible Jets

m Z 0

The phenomenology can be characterized by 5 free parameters:

Production Rate:

Mass of the Dark Hadrons:

The phenomenology can be characterized by 5 free parameters:

Mass of the Mediator:

Production Rate: *Z*0⇥ *Br*(*Z*⁰ ! Mass of the Dark Hadrons:

The phenomenology can be characterized by 5 free parameters:

Mass of the Mediator:

Production Rate: *Z*0⇥ *Br*(*Z*⁰ ! Mass of the Dark Hadrons:

Dark Hadrons are mass

SVJ Parameters

The phenomenology can be characterized by 5 free parameters:

Mass of the Mediator:

Production Rate: *Z*⁰ ⇥ *Br*(*Z*⁰ ! Mass of the Dark Hadrons:

Dark Hadrons are mass

Searching for Dark Matter with Semi-Visible Jets at CMS

 $-$

SVJ Parameters

The phenomenology can be characterized by 5 free parameters:

Searching for Dark Matter with Semi-Visible Jets at CMS

Semi-Visible Jets SVJ Parameters

The phenomenology can be characterized by 5 free parameters:

Semi-Visible Jets SVJ Parameters

The phenomenology can be characterized by 5 free parameters:

Searching for Dark Matter with Semi-Visible Jets at CMS

The phenomenology can be characterized by 5 free parameters:

*Z*⁰ ⇥ *Br*(*Z*⁰ !

Mass of the Dark Hadrons:

The phenomenology can be characterized by 5 free parameters:

The phenomenology can be characterized by 5 free parameters:

Production Rate: *Z*⁰ ⇥ *Br*(*Z*⁰ ! Mass of the Dark Hadrons:

Dark Hadrons are mass

The phenomenology can be characterized by 5 free parameters:

Production Rate: *Z*⁰ ⇥ *Br*(*Z*⁰ ! Mass of the Dark Hadrons:

Dark Hadrons are mass

The phenomenology can be characterized by 5 free parameters:

Semi-Visible Jets SVJ Parameters

The phenomenology can be characterized by 5 free parameters:

The phenomenology can be characterized by 5 free parameters:

Production Rate:

mdark

Semi-Visible Jets SVJ Parameters

The phenomenology can be characterized by 5 free parameters:

is shown for each search method applied to a variety of signal models. For a resonance mass *maa* **search edge (right), we show for each signal model (columns), we show for each signal model (columns), and search signals** searched for!

VBS WZjj

BSM H± Production

Non-VBS WZjj

Generative of **a godels** for Simulation

 $O(10)$

 10^{-18} m

 $\begin{array}{c}\nonumber -\frac{1}{2}\partial_{\nu}g^{a}_{\mu}\partial_{\nu}g^{a}_{\mu}-g_{s}f^{abc}\partial_{\mu}g^{a}_{\nu}g^{b}_{\mu}g^{c}_{\nu}-\frac{1}{4}g^{2}_{s}f^{abc}f^{ade}g^{b}_{\mu}g^{c}_{\nu}g^{d}_{\mu}g^{e}_{\nu}+\nonumber\\ \frac{1}{2}ig^{2}_{s}(\bar{q}^{a}_{i}\gamma^{\mu}q^{a}_{j})g^{a}_{\mu}+\bar{G}^{a}\partial^{2}G^{a}+g_{s}f^{abc}\partial_{\mu}\bar{G}^{a}G^{b}g^{c}_{\mu}-\partial_{$

 $\frac{1}{2}m_h^2H^2-\partial_\mu\phi^+\partial_\mu\phi^- -M^2\phi^+\bar{\phi}^--\frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0-\frac{1}{2c_{\rm c}^2}M\phi^0\phi^0-\beta_h[\frac{2M^2}{a^2}+$

 $\begin{array}{l} \frac{1}{2} m_h^2 H^2 - \sigma_\mu \phi^* \sigma_\mu \phi^- - M^2 \phi^* \phi^- - \frac{1}{2} \sigma_\mu \phi^* \sigma_\mu \phi^0 - \frac{1}{2 c_w^2} M \phi^* \phi^0 - \beta_h [\frac{1}{g^2} + \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2 \phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - ig c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W$

 $gM W^+_\mu W^-_\mu H - \frac{1}{2} g \frac{M}{c^2} Z^0_\mu Z^0_\mu H - \frac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)]^+ + \frac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \phi^- \partial_\mu H)]^+$

 $(\phi^+\partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w}(Z^0_\mu (H\partial_\mu \phi^0 - \phi^0\partial_\mu H) - ig \frac{s_w^2}{c_w} M Z^0_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) +$

 $ig s_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) -ig \textstyle{\frac{1-2c_w^2}{2c_w}} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) +ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \textstyle{\frac{1}{4}} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] -$

 $\begin{array}{c} \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_{\mu}Z^0_{\mu}[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-]-\frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_{\mu}\phi^0(W^+_{\mu}\phi^-+ \end{array}$

 $\label{eq:W-phi+} \begin{array}{c} V^-_w \phi^+) - \frac{1}{2} i g^2 \frac{s^2_w}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \frac{s_w}{c_w} (2 c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \frac{1}{2} s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial$

 $\frac{d}{d_{{j}}^{\lambda}(\gamma\partial+m_{d}^{\lambda})d_{{j}}^{\lambda}+ig s_{w}A_{\mu}[-(\bar{e}^{\lambda}\gamma^{\mu}e^{\lambda})+\frac{2}{3}(\bar{u}_{j}^{\lambda}\gamma^{\mu}u_{j}^{\lambda})-\frac{1}{3}(\bar{d}_{j}^{\lambda}\gamma^{\mu}d_{j}^{\lambda})]+\\\frac{ig}{4c_{w}}Z_{\mu}^{0}[(\bar{\nu}^{\lambda}\gamma^{\mu}(1+\gamma^{5})\nu^{\lambda})+(\bar{e}^{\lambda}\gamma^{\mu}(4s_{w}^{2}-1-\gamma^{5})e^{\lambda})+(\bar{u}_{j}^{\lambda}\gamma^$

 $\begin{array}{c} 1-\gamma^5)u_{j}^{\lambda})+(\bar{d}_{j}^{\lambda}\gamma^{\mu}(1-\frac{8}{3}s_{w}^{2}-\gamma^5)d_{j}^{\lambda})]+\frac{ig}{2\sqrt{2}}W^+_{\mu}[(\bar{\nu}^{\lambda}\gamma^{\mu}(1+\gamma^5)\bar{\lambda}^{\lambda})+\\ (\bar{u}_{j}^{\lambda}\gamma^{\mu}(1+\gamma^5)C_{\lambda\kappa}d_{j}^{\kappa})]+\frac{ig}{2\sqrt{2}}W^-_{\mu}[(\bar{e}^{\lambda}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})+(\bar{d}_{j}^{\kappa}C_{\lambda\kappa}^{\dagger$

 $\gamma^5|u_j^\lambda]\big] +\tfrac{ig}{2\sqrt{2}}\tfrac{m_\alpha^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda)+\phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)]\,-$

 $-\frac{q}{2}\frac{m_{e}^{\lambda}}{M}[H(\bar{e}^{\lambda}e^{\lambda})+i\phi^0(\bar{e}^{\lambda}\gamma^5 e^{\lambda})]+\frac{ig}{2M\sqrt{2}}\phi^+[-m_{d}^{\kappa}(\bar{u}_{j}^{\lambda}C_{\lambda\kappa}(1-\gamma^5)d_{j}^{\kappa})+$

 $m_{u}^{\lambda}(\bar{u}_{j}^{\lambda}C_{\lambda\kappa}(1+\gamma^{5})d_{j}^{\kappa}]+\frac{ig}{2M\sqrt{2}}\phi^{-}[m_{d}^{\lambda}(\bar{d}_{j}^{\lambda}C_{\lambda\kappa}^{\dagger}(1+\gamma^{5})u_{j}^{\kappa})-m_{u}^{\kappa}(\bar{d}_{j}^{\lambda}C_{\lambda\kappa}^{\dagger}(1-\gamma^{5})u_{j}^{\kappa}].$ $\left[\gamma^5\right)u_j^\kappa\right]-\frac{q}{2}\frac{m_\alpha^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda)-\frac{q}{2}\frac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda)+\frac{ig}{2}\frac{m_\alpha^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5 u_j^\lambda)-\phi^0(\bar{u}_j^\lambda\gamma^5 u_j^\lambda).$

 $\frac{i g}{2} \frac{m_d^{\lambda}}{M} \phi^0(\bar{d}_j^{\lambda} \gamma^5 d_j^{\lambda}) + \bar{X}^+(\partial^2 - M^2) X^+ + \bar{X}^-(\partial^2 - M^2) X^- + \bar{X}^0(\partial^2 -$

 $\frac{M^2}{c^2}\Big)X^0+\bar{Y}\partial^2Y+igc_wW^+_\mu(\partial_\mu\bar{X}^0X^--\partial_\mu\bar{X}^+X^0)+igs_wW^+_\mu(\partial_\mu\bar{Y}X^-$

 $\partial_\mu \bar{X}^+Y) + igc_w W_\mu^-(\partial_\mu \bar{X}^-X^0 - \partial_\mu \bar{X}^0X^+) + igs_w W_\mu^-(\partial_\mu \bar{X}^-Y - \partial_\mu \bar{Y}X^+) + igc_w Z_\mu^0(\partial_\mu \bar{X}^+X^+ - \partial_\mu \bar{X}^-X^-) + igs_w A_\mu(\partial_\mu \bar{X}^+X^+ - \partial_\mu \bar{X}^-X^-) - \frac{1}{2}g M [\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2} \bar{X}^0X^0H] +$

 $\begin{array}{l}\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+-\bar{X}^-X^0\phi^-] +\frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+-\bar{X}^0X^+\phi^-] +\\ igMs_w[\bar{X}^0X^-\phi^+-\bar{X}^0X^+\phi^-] +\frac{1}{2}igM[\bar{X}^+X^+\phi^0-\bar{X}^-X^-\phi^0] \end{array}$

60% of CPU used for simulation!

 $O(10)$ $O(10^3)$

Particle reconstruction from

Energy deposits→digital Energy deposits→digital signals→reconstructed by signals→reconstructed by the reconstruction software the reconstruction software $\mathbb{R}^{N_{\mathrm{max}}}\times \mathbb{R}^{N_{\mathrm{max}}}\times \mathbb{R}^{N_{\mathrm{$ [Hard & Slow]

detector response

simulation [Hard & Slow]

Trajectory simulation

81%

DIGI+RECO

Particle reconstruction from

Calorimeter simulation

theoretical control of the control of

Surrogate model

(GAN, VAE, Normalizing Flow, ...) Pution of GEANT4 events→digital and deposits→digital and deposits→

FAST and ACCURATE? simulation (Slow) and the simulation $\frac{1}{2}$

theoretical control of the control of

SLOW but ACCURATE

Calorimeter simulation

Particle reconstruction from

the simulation of th

the simulated or real (data) in the simulated or real (data) in the simulated or real (data) in the simulated

dels" for GEANT4 etc

 81%

 \sim 01%

Diffusion models

Learn systematic decay of information due to noise, then reverse process and recover the information back from the noise.

FastCaloGAN Being used in ATLAS! 100 networks (slices in η) O(500) voxels

ATL-SOFT-PUB-2020-006; ATLAS 2109.02551

VBS WZjj

BSM H± Production

Non-VBS WZjj

Detector design, data acquisition and triggering

 $-\tfrac{1}{2}\partial_\nu g^a_\mu\partial_\nu g^a_\mu-g_sf^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu-\tfrac{1}{4}g^2_sf^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu+\tfrac{1}{2}ig^2_s\big(\bar{q}^{\sigma}_i\gamma^\mu q^\sigma_j\big)g^a_\mu+\bar{G}^a\partial^2G^a+g_sf^{abc}\partial_\mu\bar{G}^aG^b g^c_\mu-\partial_\nu W^+_ \mu\partial_\nu W^-_\mu M^{2}\bar{W}_{\mu}^{+}W_{\mu}^{-}-\frac{1}{2}\partial_{\nu}Z^{0}_{\mu}\partial_{\nu}Z^{0}_{\mu}-\frac{1}{2c^{2}}M^{2}Z^{0}_{\mu}Z^{0}_{\mu}-\frac{1}{2}\partial_{\mu}\tilde{A}_{\nu}\partial_{\mu}A_{\nu}-\frac{1}{2}\partial_{\mu}H\partial_{\mu}H \frac{1}{2}m_h^2H^2-\partial_\mu\phi^+\partial_\mu\phi^- -M^2\phi^+\bar{\phi}^--\frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0-\frac{1}{2c_\nu^2}M\phi^0\phi^0-\beta_h[\frac{2M^2}{a^2}+$ $\begin{array}{l} \frac{2M}{2}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M}{g^2}\alpha_h - i g c_w [\partial_\nu Z^0_\mu(W_\mu^+W_\nu^- - W_\nu^+W_\mu^-) - Z^0_\nu(W_\mu^+W_\mu^- - W_\mu^- \partial_\nu W_\mu^+ + Z^0_\mu(W_\nu^+W_\nu^- - W_\nu^- W_\mu^+ W_\mu^-) - i g s_w [\partial_\nu A_\mu(W_\mu^+W_\nu^- - W_\mu^- \partial_\nu W_\mu^+ + Z^0_\mu(W_\nu^+ \partial_\nu W_\mu^- - W_\mu^- W_\nu^+ W_\mu$ $W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] \frac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] \label{eq:2.1} \begin{array}{c} g M W^+_\mu W^-_\mu H - \frac{1}{2} g \frac{M}{c^2} Z^0_\mu Z^0_\mu H - \frac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\ W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ \, . \end{array}$ $[\phi^+\partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w}(Z^0_\mu (H\partial_\mu \phi^0 - \phi^0\partial_\mu H) - ig \frac{s_w^2}{c_w} M Z^0_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) +$ $ig s_w MA_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) +$ $ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] \frac{1}{4}g^2\frac{1}{c^2}\frac{Z^0_\mu}{Z^0_\mu}[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-]-\frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^-+$ $W^-_\mu\phi^+)-\frac{1}{2}ig^2\frac{s^2_\mu}{c_\mu}Z^0_\mu H(W^+_\mu\phi^--W^-_\mu\phi^+)+\frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^-+$ $\begin{array}{l} W^-_\mu \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \frac{s_w}{c_w} (2 c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{c}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}^\lambda_\beta (\gamma \partial + m_u^\lambda) u^\lambda_\beta - \end{array}$ $\frac{1}{2}\left(\bar{d}_j^\lambda(\gamma\partial+m_d^\lambda)d_j^\lambda+ig s_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda)+\frac{2}{3}(\bar{u}_j^\lambda\gamma^\mu u_j^\lambda)-\frac{1}{3}(\bar{d}_j^\lambda\gamma^\mu d_j^\lambda)\right]+0$ $\frac{ig}{ic_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda)+(\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda)+(\bar u^{\lambda}_j\gamma^\mu(\frac{4}{3}s_w^2-\gamma^5)\nu^\lambda)]$ $1-\gamma^5)u_j^{\lambda}\big) +(\bar{d}_j^{\lambda}\gamma^{\mu}(1-\frac{8}{3}s_w^2-\gamma^5)d_j^{\lambda})\big] +\frac{ig}{2\sqrt{2}}W^+_{\mu}\big[(\bar{\nu}^{\lambda}\gamma^{\mu}(1+\gamma^5)\hat{\lambda}^{\lambda}) +$ $(\bar{u}_j^{\lambda}\gamma^{\mu}(1+\gamma^5)C_{\lambda\kappa}d_j^{\kappa})]+\tfrac{ig}{2\sqrt{2}}W^-_{\mu}[(\bar{e}^{\lambda}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})+(\bar{d}_j^{\kappa}C_{\lambda\kappa}^{\dagger}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})]$ $\left[\gamma^5(u_i^{\lambda})\right] + \frac{ig}{2\sqrt{2}}\frac{m_c^{\lambda}}{M}\left[-\phi^+(\bar{\nu}^{\lambda}(1-\gamma^5)e^{\lambda}) + \phi^-(\bar{e}^{\lambda}(1+\gamma^5)\nu^{\lambda})\right] -\frac{q}{2}\frac{m_{e}^{\lambda}}{M}[H(\bar{e}^{\lambda}e^{\lambda})+i\phi^{0}(\bar{e}^{\lambda}\gamma^{5}e^{\lambda})]+\frac{ig}{2M\sqrt{2}}\phi^{+}[-m_{d}^{\kappa}(\bar{u}_{j}^{\lambda}C_{\lambda\kappa}(1-\gamma^{5})d_{j}^{\kappa})+$ $m_u^{\lambda}(\bar{u}_j^{\lambda}C_{\lambda\kappa}(1+\gamma^5)d_j^{\kappa}]+\tfrac{ig}{2M\sqrt{2}}\phi^- [m_d^{\lambda}(\bar{d}_j^{\lambda}C_{\lambda\kappa}^{\dagger}(1+\gamma^5)u_j^{\kappa})-m_u^{\kappa}(\bar{d}_j^{\lambda}C_{\lambda\kappa}^{\dagger}(1-\gamma^5)u_j^{\kappa})]$ $\gamma^5) u_j^\kappa\big] - \frac{q}{2} \frac{m_u^\lambda}{M} H(\bar{u}_j^\lambda u_j^\lambda) - \frac{q}{2} \frac{m_d^\lambda}{M} H(\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0(\bar{u}_j^\lambda \gamma^5 u_j^\lambda) \frac{ig}{2} \frac{m_d^2}{M} \phi^0 (\bar{d}_i^{\lambda} \gamma^5 d_i^{\lambda}) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 \frac{\bar{M}^2}{c^2}X^0+\bar{Y}\partial^2Y+igc_wW^+_\mu(\partial_\mu\bar{X}^0X^--\partial_\mu\bar{X}^+X^0)+ig s_wW^+_\mu(\partial_\mu\bar{Y}X^-+g)\,.$ $\begin{array}{l} \partial_\mu \bar{X}^+ Y) + i g c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{X}^0 X^+) + i g c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H]$ $\tfrac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+-\bar X^-X^0\phi^-] +\tfrac{1}{2c_w}igM[\bar X^0X^-\phi^+-\bar X^0X^+\phi^-] +$ $\int_{-i}^{w} g M s_{w} [\bar{X}^{0} X^{-} \phi^{+} - \bar{X}^{0} X^{+} \phi^{-}] + \frac{1}{2} \int_{0}^{w} g M [\bar{X}^{+} X^{+} \phi^{0} - \bar{X}^{-} X^{-} \phi^{0}]$

-60

GEN

 10^{-15} m

 $O(10$

 10^{-6} m

 $O(10)$

 10^{-18} m

pp collisions up to production of stable particles [Easy & Fast]

detector response simulation [Hard & Slow]

CMS Experiment at the LHC CERN

Data recorded: 2010-Nov-14 18:37:44 420271 GMT(19:37:44 CEST) Run / Event: 151076 / 405388

Edibition collisions /s **Exportate** / collision **ESTEPS of data / S.**

97

• Dodge

On-detector ML

Geneva Lake

Geneva **LHCb** \mathbf{A} **Data temporarily stored** *<u><i><u>District Department</u>*</u> **in detector electronics for 12(4) µs**

L1 trigger: ~1000 AMD FPGAs 8 March 2024 Fast ML at the Edge - Sioni Summers 8 March 2024 Fast ML at the Edge - Sioni Summers \sim

Decide which event to keep within ~12 µs latency

> **Discard >99% of collisions!**

those shown below - AMD/Xilinx Ultrascale+ FPGAs

those shown below - AMD/Xilinx Ultrascale+ FPGAs

CMS Level 1 Trigger

those shown below - AMD/Xilinx Ultrascale+ FPGAs

CMS Level 1 Trigger

CMS Level 1 Trigger

those shown below - AMD/Xilinx Ultrascale+ FPGAs

• Final output is one bit: keep or discard event • Final output is one bit: keep or discard event • Final output is one bit: keep or discard event **5% internet traffic to L1 (63 Tb/s HL-LHC)**

A

those shown below - AMD/Xilinx Ultrascale+ FPGAs

 \sim Final output is one bit: \sim

 \sim Final output is one bit: \sim

 \sim System organised in layers with \sim

 \sim System organised in layers with \sim

 \sim System in layers with \sim 1-2 μ per step μ

• Dodge

• Dodge

On-detector ML

LHCb

Geneva Lake

Optical links for CMS DATA 99.72% of events rejected! 110 kHz

CMS Car

REAR READ

• Dodge

• Dodge

On-detector ML

LHCb

Geneva Lake

Optical links for CMS DATA 99.72% of events rejected! 110 kHz

CMS Car

Anty Mr.

Blabla

• Dodge

 \overline{a}

 \bullet

• Dodge

Optical links for CMS

ONANY High Level Trigger: 25'600 CPUs / 400 GPUs Latency: 3-400 ms

WAREE

<u>niversity</u>

Reject further 99%!

.HCb

103

ATLAS

DATA 99.9975% of events rejected! 1000 events/second ~5 GB/s

103

TIER 0: ∞

,,,,,,,,,,,

ATLAS DATA

99.9975% of events rejected! 1000 events/second ~5 GB/s

TIER 0: ∞

mmmm

ATLAS

DATA 99.9975% of events rejected! 1000 events/second ~5 GB/s

• Dodge

Geneva

On-detector ML

LEARN FORE TOOL AND PICK MACKED

To make sure we select "the right" 0.0025%, algorithms must be • Fast (get more data through) • Accurate (select the right data)

New Physics is produced less than 1 in a trillion (if at all)

Need more data!

"Probability" of producing "anything"

New Physics?

High Luminosity LHC

\overline{r} $\text{ructure} \rightarrow \text{pile-up of} \sim 60 \text{ events/x-ing}$ reconstructed vertices \mathbf{r} ts/x-ing)

ATLAS and CMS had to cope with monster pile-up

200 vertices and the HL-LHC with the HL-LHC with \sim verage 140) (average 140) (average 140)

The HL-LHC will compute a compute \sim

The HL-LHC will come online around 2026.

More collisions and more complex data.

Level-1 trigger: Detector: Latency O(1) µs

ATLAS

Geneva

 $\begin{array}{c}\n\mathbf{X} \text{MUW}^\circ \\
\mathbf{VIRTEX}^\omega \mathbf{S} \\
\mathbf{X} \text{GSUX30}^\omega \\
\text{FFSYSEQ10005} \\
\mathbf{FSSQ100005} \\
\mathbf{FSSQ1000005} \\
\mathbf{FSSQ20000000000000000$

ALICE

40 MHz ~Pb/s

LHCb

Fast inference on specialised hardware

ASIC inference FPGA inference

GPU inference

Ge

HLT trigger: Latency O(100) ms

• High-Level Trigger (HLT)

<µ**> 32 3000 P** \overline{z} **• L1 trigger 0)** • Particularly challenging for **0) 1222** 1222 1222 1222 1232 −1 **/1.0 104 0)** −1 **/1.0 2500** −1 **/1.0** • Hardware-based, implemented in austom-built electronics **2500** bascu, in ipici ici icu ii
Chica atau infauna atiau i **(**p **103** \blacksquare **(**p **2000** b**y***arity, no tracking information* **(**p **2000** بير
ر **ys R102 sLt mLn R** $\mathcal{L}_{\mathcal{D}}$ in the set of the tracking central to the tracking central to the tracking central to the tracking central to the tracking contract of the tracking contract of the tracking contract of the tracking contract **1500 mLn 1500 mLn u** $\sigma_{in}^{pp} = 69.2 mb$ **Journey to HL-LHC** $\frac{1}{2}$ $\frac{1}{2}$ **/u** $v_{\text{in}} = 09.2 \text{ m}$ **101 /du1000** LHU MISSION **de/1000 edddreRr100 dcR500 recR***• Tracking information & full detector granularity* **5e500 c510-1** run: **100** $0 \t 2^0$ **40 60 80 0 020** \mathbf{m}_1 **b** \mathbf{v}_2 is the step \mathbf{v}_3 **Mean number of interactions per crossing Mean number of interactions per crossing** 7×10^{33} , PU = 30, E = 7 TeV , 50 nsec bunch spacing $HL-\text{L}$ **TLAS, CWS operating: 40 MHz** Detector⁸MHz **Detectors** 40 MHz **40 MHz** Detectors • Trigger system reduces 40 MHz $\frac{1}{2}$ is a set of $\frac{1}{2}$ or $\frac{1}{2}$ is a set of $\frac{1}{2}$ Front end Front end pipelines**L** Lvl-1 c cept ≤ 100 kHz, Lvl-1 pipelines | | (collision rate to data rate to d
The collision rate to data rate **L1 output: 75 kHz 750 kHz**: 100 kHz *L1 output:* 100 kHz $37 \leq 2.5 (AT).$ **Readout Readout L1 trigger decision** $\left(\frac{Lv}{2}\right)$ b uffers $|$ b uffers $\vert \vert$ $\begin{array}{|c|c|c|c|c|}\n\hline\n\text{in} & \text{if } 2 \leq (4) \text{ we for } & \text{Friagase} \n\end{array}$ **~3 kHz Switching** Switching **in ~2.5 (4) µs for Trigger** $Accept \leq 1$ kHz network network a **ATLAS (CMS)** ept/reject **Example for PU/Feject** Processor Processo<mark>r</mark> K LAS & CMS will be: HLT Lvl-3 P_{frame} farms | | farms **12.5 µs 200 Hz** 7.5 **9 kHz** $~\sim$ 1 kHz

 $ncy \leq 2.5$ (AT) , 4 μsec (CM)

-
- $E \times 4034$

Nanosecond MI in — extreme pileup $\Lambda \cap L$:III: Λ is a formation and 200 overlapping *pp* collisions *ATLAS & CMS:* **Trigger System** • Current trigger systems **C0S Average 3ileuS, SS, 2018, C0S Average 3ileuS, SS, 2018, 105** \sim 40 billion inferences/s during HL-LHC Nanosecond ML inference on FPGAs!

Challenges Challenges Challenges Challenges Challenges Challenges Challenges Challenges Challenges Challenges

Simulated event display with average pileup of 140

3000

0

s = **13 TeV**

s = **13 TeV**

s = **13 TeV**

Tensor / STERAS / PyTorch / ONNX

pip install hls4ml pip install conifer

<https://github.com/fastmachinelearning/hls4ml> https://fastmachinelearning.org/hls4ml/

jet *AS High Granularity calorimeter*
• 6.5 million readout channels, 50 layers 200 PU **VBF H (γγ)** CMS High Granularty calorimeter

Idea: HGCAL will be 3D imaging capabilities 12 inch and 2D imaging capabilities 12 inch and 3D imaging capabilitie

- 750 kHz DAQ data
- High radiation
- Cooled to -30 → low power (Max 500 mW total)
- 1.5 µs latency

Variational Autoencoder

[ECON-T, D. Noonan](https://indico.cern.ch/event/1156222/contributions/5062791/attachments/2521161/4335130/DNoonan_ECON_Autoencoder_FastMLWorkshop_Oct_3_2022.pdf)

[ECON-T, D. Noonan](https://indico.cern.ch/event/1156222/contributions/5062791/attachments/2521161/4335130/DNoonan_ECON_Autoencoder_FastMLWorkshop_Oct_3_2022.pdf)

[AEs for compression also at LHCb](https://sse-ml-lhcb.gitlab.io/)!

ECON-T, D. Noonan *ECON-T, D. Noonan*

ECON-T, D. Noonan *ECON-T, D. Noonan*

ECON-T, D. Noonan *ECON-T, D. Noonan*

Anomaly Detection triggers

Trigger threshold Energy (GeV)

Level-1 rejects >99% of events! Is there a smarter way to select?

Anomaly Detection triggers

Trigger threshold Energy (GeV)

AD threshold

- - LOST DATA - - SELECTED DATA - - POSSIBLE NP SIGNAL

Everything here is normal

Everything here is abnormal

Outlier detection

Compressed representation of x. Latent space \mathfrak{R}^k , k < m \times n prevents memorisation of input, must learn

Outlier detection

 $\mathscr{L}(\mathbf{x}, \hat{\mathbf{x}})$ is Mean Squared Error $(\mathbf{x}, \hat{\mathbf{x}})$, "high error events" proxy for "degree of abnormality"

$\mathscr L(\mathbf x, \hat{\mathbf x})$ is Mean Squared E $\mathscr L(\mathbf x, \hat{\mathbf x})$ is Mean Squared

Outlier detection

SciPost Physics

 \mathbb{R}^k

Figure 2: Distribution of reconstruction error computed with a CNN autoencoder on test samples of $\begin{bmatrix} \text{S} & \text{SimpW} & \text{ISE} & \text{ISE} \\ \text{ISE} & \text{ISE} & \text{ISE} & \text{ISE} \end{bmatrix}$ napping is not easily invertible we do not use it for the autoencoder. Instead, 4-vectors by another component containing the invariant mass, Ve allow for $M = 10$ trainable linear combinations. These combined 4-vectors car _{tii}on on the hadronically decaying massive particles. In the original LOLA appro the momenta k_j onto observable Lorentz scalars and related observables [13].

in order to define a QCD-jet

๏ *Based on image and physics-*

in terms of its 20 highest-*p*^T constituents. The second simply passes each original constituent $\text{component containing } \text{the } \text{input}$ containing th the invariant most is, alternative in the letternative in the letternative in $k_{2,1}$ and down as it sees fits up and down as it se $\int d^2y$ (400 GeV) $\int d^2k^3y^1$ k^3y^2 $\int d^2y^3y^1$ $\int d^2y$ S_{total} of Fig. 1 $_{\text{wa}}$ $_{\text{ula}}$ $_{\text{wa}}$ $_{\text{A}}$ and the property of $_{\text{total}}$ of $_{\text{total}}$ ot maksE(xnc) = $\lim_{t \to \infty} \frac{1}{2}$ and $\lim_{t \to \infty} \frac{1}{2}$ For jets with fewer of rie
:
t
t *p*1 *^x p*² *x* 110 *w*1*,*⁴ *w*1*,*⁵ *jet.* <u>J</u> p igation for algorithens avecuated reducing formbinations of the sour*z* נונו
Ch:
מצט lining in the soft regime w also improves the \bar{y} ¹ $\begin{bmatrix} 2 \\ S \\ S \end{bmatrix}$ $\sqrt{k_3}$; $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ *we boost all 4 mo* ${\rm median~g}$ ${\rm G}$ ${\rm F}$ ${\rm C}$ ${\rm C}$ ${\rm F}$ ${\rm C}$ ${\rm C}$ ${\rm C}$ ${\rm C}$ ${\rm C}$ ${\rm C}$ ${\rm F}$ ${\rm C}$ ${\$ $\frac{1}{\sqrt{1}}$ with $\frac{1}{\sqrt{1}}$ is $\frac{1}{\sqrt{1}}$ (Section 5.1) $\frac{1}{\sqrt{1}}$ is is σ_{ij}^{\bullet} with σ_{ij}^{\bullet} and showled allow the network to learn which the network to learn which is learn which to learn which is not to learn which is constituents are part of the hard scatter and which are not. The α to the next layer, the next layer, the next layer, the Lorentz Layer.
The Lorentz Layer, the Lorentz Layer. in terms of its 20 highest-*p*^T constituents. The second simply passes each original constituent alternative it weight it weight it weight it weight it is done in the $k_{2,1}$ in $k_{2,2}$ it sees fit, in order in order in $k_{2,1}$ in $k_{2,2}$ in $k_{2,3}$ in $k_{2,4}$ in $k_{2,5}$ in $k_{2,5}$ in $k_{2,5}$ in $k_{2,5}$ in δ (400 GeV) $\lambda_1^k s_1^1$ $k_{3,2}$ \cdots $\delta_0^k s_n^1 N$ not maksE(xn) nu
in
אז *p*₁ *jet.* in:
ioi
it: is also improves the $\boldsymbol{\eta}$ $\begin{align} \mathbf{u}_1 \\ \mathbf{f}_2 \\ \mathbf{f}_3 \\ \mathbf{g}_1 \end{align}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ *m*² *p*¹ *p*₁*p*_{**n**} $\frac{1}{4}$ **p**₁*f***₂ p**₁*f***₂** *p*_{*f***₁^{***f***}_{***f***₁^{***f***}_{***f***}^{***f***}_{***f***^{***f***}_{***f***}^{***f***}***f***_{***f***}^{***f***}***f***_{***f***}^{***f***}***f***_{***f***}^{***f***}***f***_{***f***}***f***_{***f***}^{***f***}***<i>f***_{***f***}^{***f***}***f***_{***f***}^{***f***}***f***_{***f***}^{***}}}*} $\frac{1}{\sqrt{1}}$ contribution of $\frac{1}{\sqrt{1}}$ and $\frac{1}{\sqrt{1}}$ is similar to $\frac{1}{\sqrt{1}}$ is $\frac{1}{\sqrt{1}}$ $\kappa_{\mu i}^{\dagger} C_{i i}$ with $C^{\dagger} = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$ constituents are part of the hard scatter and which are not. The α to the next layer, the next layer, the lorentz Layer. The Lorentz Layer, the Lorentz Layer. The Lorentz Layer. $\sum_{i=1}^{\infty}$ all information from the jet-level kinematics we boost all 4-momental $\frac{1}{2}$ ̂ mapping is not easily invertible we do not use it for the automobility is for the automobility of $K \cap \Omega$ nother component contain \tilde{k})
kj
#0 me $\sqrt{2}$ $\frac{1}{2}$
 $\frac{1}{2}$
 $\frac{1}{2}$ \vec{k} $k_{0,j}$ ^{\sim} $\left(\widetilde{k} \right. \mathrm{e} ,j \mathrm{V} \right] = \mathrm{L} \mathrm{d} \mathrm{Q} _{\mathrm{e}}$ $\begin{bmatrix} \mathbf{\tilde{w}} & \mathbf{\tilde{w}} \\ \mathbf{\tilde{w}} & \mathbf{ab} \end{bmatrix} \mathbf{e}^{\mathbf{b}}$ $\sqrt{1}$ diffé $\frac{1}{\sqrt{2}}$ ed
B
BBB
BBBBBBBBBB $\begin{array}{cc} k_{2,1} & k_{2,2} \ k_{3,1} & k_{3,2} \end{array}$ $\left\{\begin{array}{c} \tilde{k}_{0,j} & k_{3,N} \ \tilde{z} & \tilde{z} \end{array}\right\}$ \tilde{k} *k*1*,j* ˜ *k*2*,j* て
Ki *k*3*,j* $\sum_{i=1}^{n}$ en
Eb
ide $\mathbf{E} = \mathbf{E} = \mathbf{E} \mathbf{E}$ \mathcal{R} ver immediately after the LOLA contains or make $\frac{1}{2}$. $\frac{255}{2}$ $\text{er after LOLA and the last layer, the autoencoder' network is}$ $f_{\mu,i} \longrightarrow^a k_{\mu,j} = k_{\mu,i} \hat{C}_{ij}$ with $\hat{C} = \begin{bmatrix} \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \end{bmatrix}$ $(k_{\mu,i}) =$ $\overline{}$ $\prod_{i=1}^{n}$ $k_{0,1}$ $k_{0,2}$ \cdots $k_{0,N}$ *k*1*,*¹ *k*1*,*² *··· k*1*,N* $k_{2,1}$ *k*₂, \sum_{i} *i k*₂, \sum_{i} 1 the **test** panel of Fig. 1 we use $N = 40$ constituents, after checking the 1 20 does not maks $\mathbf{B}(\mathbf{x};\mathbf{x})$ with fewer of raturally the entries remaining in the soft regime with zeros. $\overline{}$ a $\Longrightarrow k_{\mu,j} = k_{\mu,i} \hat{i} C_{ij}$ with $\hat{i} C^{\dagger} =$ $\begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix}$. *···* ⁰ *^C*1*,N*+1 *··· ^C*1*,M* . r, the autoenc $\mathbf{C}^{\mathbf{r}}$, the autoencoder network is $\mathbf{C}^{\mathbf{r}}_{2,N+1}$ ⁰
.
. $\frac{N+1}{N}$ $C_{N,N+1}$ ̂

AD threshold

….in 50 nanoseconds! Currently recording 300 collisions per second in CMS!

First ML triggers in ATLAS and in CMS in 2024

[CMS DP2023_079](https://cds.cern.ch/record/2876546/files/DP2023_079.pdf) [L1CaloTriggerPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/L1CaloTriggerPublicResults#ATLAS_Level_1_calorimeter_eFEX_t)
Foundation models

Foundation models

Heterogeneous detector Multi-modal input!

 $x = (x_1, x_2)$ *f*(*x*; *w**) *y*

Too many models, too little learning?

Discrimination

New

Metric Learning

Instead of features like "says meow", can we make new and better features?

NN Something New

Neural embedding

Learning the space

-
-
-
-
-
-
-
-
-

•By looking at data, we can learn a lot

- Go over input piece by piece
- Analyze every aspect
- Compare every feature
- •Find distinctive style of the input
	- can be done e.g by looking for a deviation

Learning the space

Contrastive learning (self-supervised)

Cat A

Dog A

Cat A

Dog A

Augmented Cat A

Augmented Dog A

Cat A

Dog A

Augmented Cat A

Augmented Dog A

Augmented Cat A

Augmented Dog A

• Minimizing and maximizing distances learns a space

Contrastive learning (self-supervised)

Augmented Cat A

Cat A

Cat B $\dot{\mathcal{L}}$

No class labels used in training! How do we augment detector data?

Physically motivated augmentations?

No class labels used in training! How do we augment detector data?

Physically motivated augmentations?

 $x = (x_1, x_2, \ldots)$

Training 2: Fine tune for specific task (fast, small dataset, simulation)

Embedded Space can use any NN to embed

[arxiv:403.07066](https://arxiv.org/abs/2403.07066)

QM foundation models

 \rightarrow embedding quantum mechanics into AI algorithm

[arxiv:403.07066](https://arxiv.org/abs/2403.07066)

quark

H

From Phil Harris **[arxiv:403.07066](https://arxiv.org/abs/2403.07066)**

Theorists N-D Space

Capture Physics

NN

Capture Physics

(Graph) NN N-D Space

We can replace the QCD theorist with a NN (And it works better)

[arxiv:403.07066](https://arxiv.org/abs/2403.07066) From Phil Harris

Detector design, data acquisition and triggering

 $-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu -g_sf^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu -\frac{1}{4}g^2_sf^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu +\frac{1}{2}g^2_b g^b_\mu g^c_\nu$ $\bar{z}_1^1i g_s^2(\bar{q}_i^\sigma\gamma^\mu q_j^\sigma) g_u^a+\bar{G}^a\partial^2 G^a+g_s f^{abc}\partial_\mu\bar{G}^a G^b g_u^c-\partial_\nu W^+_u\partial_\nu W^-_u\,.$ $M^2 W^+_\mu W^-_\mu - \frac{1}{2} \partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_\mu} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H \frac{1}{2}m_h^2H^2-\partial_\mu\phi^+\partial_\mu\phi^--M^2\phi^+\phi^--\frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0-\frac{1}{2c^2_m}M\phi^0\phi^0-\beta_h[\frac{2M^2}{a^2}]$ $\frac{2M}{q}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{q^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W_\mu^+W_\nu^-)]$ $W_{\nu}^{+}W_{\mu}^{-})-Z_{\nu}^{0}(W_{\mu}^{+}\partial_{\nu}W_{\mu}^{-}-W_{\mu}^{-}\overset{3}{\partial}_{\nu}W_{\mu}^{+})+Z_{\mu}^{0}(W_{\nu}^{+}\partial_{\nu}W_{\mu}^{-}-W_{\nu}^{-}\partial_{\nu}W_{\mu}^{+})]=ig s_{w}[\overset{3}{\partial}_{\nu}A_{\mu}(W_{\mu}^{+}W_{\nu}^{-}-W_{\nu}^{+}W_{\mu}^{-})-A_{\nu}(W_{\mu}^{+}\partial_{\nu}W_{\mu}^{-})$ $W_{\mu}^{-} \partial_{\nu} W_{\mu}^{+} + A_{\mu} (W_{\nu}^{+} \partial_{\nu} W_{\mu}^{-} - W_{\nu}^{-} \partial_{\nu} W_{\mu}^{+})] - \frac{1}{2} g^{2} W_{\mu}^{+} W_{\mu}^{-} W_{\nu}^{+} W_{\nu}^{-}$ $W^-_\nu W^+_v W^-_\nu + q^2 c^2_\omega (Z^0_\nu W^+_v Z^0_\nu W^-_\nu - Z^0_\nu Z^0_\nu W^+_v W^-_\nu)$ - ${}^2\hat{s}_w^2(A^{'}_\mu W^+_\mu A^{'}_\nu W^-_\nu - A^{'}_\mu A^{'}_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A^{'}_\mu Z^0_\nu (W^+_\mu W^-_\nu)]$ $W^+_v W^-_n) - 2A_u Z_u^0 W^+_v W^-_v - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-]$ $\frac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2].$ $gMW_u^+W_u^-H-\frac{1}{2}g\frac{M}{c^2}Z_u^0Z_u^0H-\frac{1}{2}ig[W_u^+(\phi^0\partial_\mu\phi^--\phi^-\partial_\mu\phi^0) W_{\mu}^-(\phi^0\partial_{\mu}\phi^+ - \phi^+\partial_{\mu}\phi^0)] + \frac{1}{2}g[W_{\mu}^+(H\partial_{\mu}\phi^- - \phi^-\partial_{\mu}H) - W_{\mu}^-(H\partial_{\mu}\phi^+)$ $\phi^+ \partial_u H)] + \frac{1}{2} g_-^{\perp} (Z_u^0 (H \partial_u \phi^0 - \phi^0 \partial_u H) - ig_{\infty}^{\frac{2}{3}} M Z_u^0 (W_u^+ \phi^- - W_u^- \phi^+) +$ $ig s_w MA_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) +$ $ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] \frac{1}{4}g^2\frac{1}{c_{\mu}^2}Z_{\mu}^0Z_{\mu}^0[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z_{\mu}^0\phi^0(W_{\mu}^+\phi^- +$ $W_{\mu}^{-}\phi^{+}\big) - \frac{1}{2}ig^{2}\frac{s_{\mu}^{2}}{2\pi}Z_{\mu}^{0}H(W_{\mu}^{+}\phi^{-} - W_{\mu}^{-}\phi^{+}) + \frac{1}{2}g^{2}s_{w}A_{\mu}\phi^{0}(W_{\mu}^{+}\phi^{-} +$ $W_{\mu}^{-}\phi^{+}\big)+\frac{1}{2}ig^{2}s_{w}A_{\mu}H(W_{\mu}^{+}\phi^{-}-W_{\mu}^{-}\phi^{+})-g^{2}\frac{s_{w}}{s_{w}}(2c_{w}^{2}-1)Z_{\mu}^{0}A_{\mu}\phi^{+}\phi^{-}$ $g^1 s_w^2 A_u A_u \phi^+ \phi^- - \bar{e}^{\lambda} (\gamma \partial + m_e^{\lambda}) e^{\lambda} - \bar{\nu}^{\lambda} \gamma \partial \nu^{\bar{\lambda}} - \bar{u}_i^{\lambda} (\gamma \partial + m_u^{\lambda}) u_i^{\lambda}$ $d_3^{\lambda}(\gamma \partial + m_d^{\lambda})d_j^{\lambda} + ig s_w A_{\mu} [-(\bar{e}^{\lambda}\gamma^{\mu}e^{\lambda}) + \frac{2}{3}(\bar{u}_j^{\lambda}\gamma^{\mu}u_j^{\lambda}) - \frac{1}{3}(\bar{d}_j^{\lambda}\gamma^{\mu}d_j^{\lambda})] +$ $-\mathcal{Z}^0_\mu [(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2-\gamma^5))$ $1-\gamma^5)u_j^\lambda\big)+(\bar d_j^\lambda\gamma^\mu(1-\tfrac83s_w^2-\gamma^5)d_j^\lambda\big)\big]+\tfrac{ig}{2\sqrt{2}}W_\mu^+[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\bar\lambda^\lambda)\cdot$ $(\bar{u}_j^{\lambda}\gamma^{\mu}(1+\gamma^5)C_{\lambda\kappa}d_j^{\kappa})]+\frac{ig}{2\sqrt{2}}W_{\mu}^{-}[(\bar{e}^{\lambda}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})+(\bar{d}_j^{\kappa}C_{\lambda\kappa}^{\dagger}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda}].$ $\big[\gamma^5(u_j^\lambda)\big] + \frac{ig}{2\sqrt{2}}\frac{m_0^\lambda}{M}\big[\varphi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)\big] -\frac{q}{2}\frac{m_d^{\lambda}}{M}[H(\bar{e}^{\lambda}e^{\lambda})+i\phi^0(\bar{e}^{\lambda}\gamma^5e^{\lambda})]+\frac{ig}{2M\sqrt{2}}\phi^+[-m_d^{\kappa}(\bar{u}_j^{\lambda}C_{\lambda\kappa}(1-\gamma^5)d_j^{\kappa})+$ $m_u^\lambda (\bar{u}_j^\lambda C_{\lambda \kappa}(1+\gamma^5) d_j^\kappa] + \frac{ig}{2M\sqrt{2}}\phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda \kappa}^\dagger (1+\gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda \kappa}^\dagger (1+\gamma^5) u_j^\kappa]$ $\gamma^5) u_j^\kappa\big] -\frac{g}{2}\frac{m_u^\lambda}{M} H(\bar u_j^\lambda u_j^\lambda) -\frac{g}{2}\frac{m_d^\lambda}{M} H(\bar d_j^\lambda d_j^\lambda) +\frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar u_j^\lambda\gamma^5 u_j^\lambda) -\big]$ $\frac{i g}{2} \frac{m_d^2}{M} \phi^0(\bar{d}_i^{\lambda} \gamma^5 d_i^{\lambda}) + \bar{X}^+(\partial^2 - M^2) X^+ + \bar{X}^-(\partial^2 - M^2) X^- + \bar{X}^0(\partial^2$ $\frac{M^2}{c^2}X^0+\bar{Y}\partial^2Y+igc_wW^+_u(\partial_\mu\bar{X}^0X^--\partial_\mu\bar{X}^+X^0)+ig s_wW^+_u(\partial_\mu\bar{Y}X^-)$ $\int \mathcal{D}_{\mu}\bar{X}^+Y) +ig c_w W^-_u (\partial_{\mu}\bar{X}^-X^0 - \partial_{\mu}\bar{X}^0X^+) +ig s_w W^-_u (\partial_{\mu}\bar{X}^-Y)$ $\partial_{\mu}\bar{Y}X^{+}\big)+ig c_{w}Z_{\mu}^{0}(\partial_{\mu}\bar{X}^{+}X^{+}-\partial_{\mu}\bar{X}^{-}X^{-})+ig s_{w}A_{\mu}^{~}(\partial_{\mu}\bar{X}^{+}X^{+}).$ $\partial_{\mu}\bar{X}^{-}X^{-}$) – $\frac{1}{2}gM[\bar{X}^{+}X^{+}H+\bar{X}^{-}X^{-}H+\frac{1}{c^{2}}\bar{X}^{0}X^{0}H]+$ $\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+-\bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+-\bar{X}^0X^+\phi^-] +$ $\bar{\chi}^{*}gMs_{w}[\bar{X}^{0}X^{-}\phi^{+}-\bar{X}^{0}X^{+}\phi^{-}]+\frac{1}{2}igM[\bar{X}^{+}X^{+}\phi^{0}-\bar{X}^{-}X^{-}\phi^{0}]$

Generative signal dels for detector response

 10^{-18} m

 $O(10)$

GEN

