CERN 70th Anniversary, Bergen Norway Thea Klæboe Årrestad (ETH Zürich)

CERN 70: A Laboratory for AI Research

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 catapantin 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 Grande diretagne 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 reasons 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 reacher 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.

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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

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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

[CERN Seminar: W-mass measurement in CMS](http://High-precision%20measurement%20of%20the%20W%20boson%20mass%20at%20CMS)

[CERN Seminar: W-mass measurement in CMS](http://High-precision%20measurement%20of%20the%20W%20boson%20mass%20at%20CMS) [arxiv:2404.19756](https://arxiv.org/abs/2404.19756)

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

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"Al for accelerated discovery"

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

Experimental result

Computational prediction

"Al for accelerated discovery"

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

Experimental result

Computational prediction

I"ML for accelerated discovery"

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"Perché l'Italia Cologio con Napolitano: huma ide

CERN Summer student 2012

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

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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

CERN 70: A Laboratory for AI Research

?

Train (GPT-4):

- **• 2.1525 floating point operations**
- **• ~25,000 A100 GPUs**
- **• 90-100 days**
- **• \$63 million**
- **• Trained on 13 trillion tokens**

- **Train (GPT-4):
•** 2.15²⁵ floating point operations
• ~25,000 A100 GPUs
• 90-100 days
• \$63 million
• Trained on 13 trillion tokens
-
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I'm looking for a really good Svensken, Dansken and Nordmannen joke. Could you help me?

Certainly! Here's a classic "Svensken, Dansken, och Nordmannen" joke:

Svensken, Dansken, and Nordmannen were stranded on a desert island. They found a bottle, rubbed it, and out popped a genie.

The genie said, "I'll grant each of you one wish."

Svensken said, "I wish I was back in Stockholm, sitting at my favorite café with a cold beer."

Poof-he was gone.

Dansken said, "I wish I was back in Copenhagen, enjoying a hot dog and a Carlsberg."

Poof-he was gone.

Nordmannen looked around and said, "I'm feeling lonely. I wish Svensken and Dansken were back here with me!"

Inference (GPT-4): • Multiple clusters of 128 GPUs • Model carefully mapped onto hardware

- Loosing many of our best people to private companies (salaries, interesting problems)
- Where can we contribute? Where are we special?

• Cannot compete with industry

A personal take - we have to be humble

• Where can we contribute? Where are we special?

• High fidelity

 \circledS

Here is the subtly flawed image of Albert Einstein, where a minor detail, such as his hair being parted on the wrong side or a slight facial proportion, creates a small but noticeable inaccuracy.

• Where can we contribute? Where are we special?

• High fidelity

 \circledS

Here is the subtly flawed image of Albert Einstein, where a minor detail, such as his hair being parted on the wrong side or a slight facial proportion, creates a small but noticeable inaccuracy.

• Uncertainty treatment First SBI paper with Neural Likelihood Ratios 506.02169v2 [stat.AP] 18 Mar 2016 First Separate Separate

for statistica a simulator rameters θ c the likeliho likelihood-fr is available.

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Approximating Likelihood Ratios with Calibrated Discriminative Classifie

• Where can we contribute? Approxi Where are we special? • https://indico.cern.ch/event/465572/

2015 New Yorkshops of the Physics workshops and the Physics workshops are all the Physics workshops are all the Physics and The Physics are all the Physics and The Physics are all the Physics are all the Physics are all t

• https://doi.org/10.6084/m9.figshare.4291565.v1

• High fidelity • https://indico.cern.ch/event/465572/

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$Kyle$ Cra ^{Approximating} Likenhood Ratios 101 ateu Discrimina Approximating Likelihood Ratios with Calibrated Discriminative Classifiers

²Kyle Cranmer¹, Juan Pavez², and Gilles Louppe¹ $\rm ^2Federico$ Santa María University ¹New York University

cial problems with known exact likelihoods illustrate the potential of the proposed

inference that is complementary to Approximate Bayesian Computation, and which does not require a prior on the model parameters. Experimental results on artificompier $\begin{array}{c} \text{and} \text{ } \text{st} \ \text{and} \ \text{at} \ \text{in} \$

2016 NeurIPS Keynote

 $\mathcal{P}(\mathcal{P}(\mathcal{P}))=\mathcal{P}(\mathcal{P}(\mathcal{P}))$

• Where can we contribute? Where are we special?

- High fidelity
- Uncertainty treatment
- Extreme high throughput, lowlatency constraints

• Where can we contribute? Where are we special?

- High fidelity
- Uncertainty treatment
- Extreme high throughput, lowlatency constraints
- And extremely complex and exciting problems!

 $-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu-g_sf^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu -\tfrac{1}{4}g^2_sf^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu+$ $-\frac{1}{2} ig_s^2 (\bar{q}_i^{\sigma} \gamma^{\mu} \bar{q}_j^{\sigma}) g^{\dot{a}}_{\mu} + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_{\mu} \bar{G}^a G^b g^c_{\mu} - \partial_{\nu} W^+_{\mu} \partial_{\nu} W^-_{\mu} M^2\overline{W_\mu^+W_\mu^-}-\tfrac{1}{2}\partial_\nu Z_\mu^0\partial_\nu Z_\mu^0-\tfrac{1}{2c_w^2}M^2Z_\mu^0Z_\mu^0-\tfrac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu-\tfrac{1}{2}\partial_\mu H\partial_\mu H \label{eq:1D1V} \tfrac{1}{2}m_h^2H^2-\partial_\mu\phi^+\partial_\mu\phi^- -M^2\phi^+\bar{\phi}^--\tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0-\tfrac{1}{2c_w^2}M\phi^0\phi^0-\beta_h[\tfrac{2M^2}{g^2}+$ $\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right] + \frac{2M^4}{g^2}\alpha_h - ig_c^w[\partial_\nu Z_\mu^0(W_\mu^+W_\nu^ \begin{array}{c} W^+_\nu \tilde W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - ig s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\nu)] \end{array}$ $\begin{array}{c} W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\ \frac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \end{array}$ $g^2s_w^2(A_\mu W_\mu^+A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+W_\nu^-) + g^2s_wc_w[A_\mu Z_\nu^0(W_\mu^+W_\nu^- W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g \alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2]$ $gMW_\mu^+W_\mu^-H-\frac{1}{2}g\frac{M}{c_\nu^2}Z_\mu^0Z_\mu^0H-\frac{1}{2}ig[W_\mu^+(\phi^0\partial_\mu\phi^--\phi^-\partial_\mu\phi^0) W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g[W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z^0_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) +$ $ig s_w MA_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) +$ $ig s_w A_\mu (\phi^+ \partial_\mu \dot{\phi}^- - \phi^- \partial_\mu \dot{\phi}^+) - \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu [H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-]-\frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^-+$ $W_{\mu}^{-} \phi^{+}) - \frac{1}{2} ig^{2} \frac{s_{w}^{2}}{c_{w}} Z_{\mu}^{0} H (W_{\mu}^{+} \phi^{-} - W_{\mu}^{-} \phi^{+}) + \frac{1}{2} g^{2} s_{w} A_{\mu} \phi^{0} (W_{\mu}^{+} \phi^{-} +$ $\begin{array}{l} W^-_\mu \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \frac{s_w}{c_w} (2 c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\ g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}^\lambda_j (\gamma \partial + m_u^\lambda) u^\lambda_j \ - \end{array}$ $\begin{array}{l} \bar{d}_j^\lambda(\gamma\partial+m^\lambda_d)d^\lambda_j+ig s_w A_\mu[-(\bar{e}^{\lambda}\gamma^\mu e^\lambda)+\frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j)-\frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)]+\\ \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda)+(\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda)+(\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2-1-\gamma^5)e^\lambda])\end{array}$ $1-\gamma^5)u_j^\lambda)+(d_j^\lambda \gamma^\mu(1-\tfrac83 s_w^2-\gamma^5)d_j^\lambda)]+\tfrac{ig}{2\sqrt2}W_\mu^+[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\overset{\infty}{\bigstar})+$ $(\bar{u}_j^{\lambda}\gamma^{\mu}(1+\gamma^5)C_{\lambda\kappa}d_j^{\kappa})]+\frac{ig}{2\sqrt{2}}W_{\mu}^{-}[(\bar{e}^{\lambda}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})+(\bar{d}_j^{\kappa}C_{\lambda\kappa}^{\dagger}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda}].$ $[\gamma^5]u_j^{\lambda}]]+\frac{ig}{2\sqrt{2}}\frac{m_e^{\lambda}}{M}[-\phi^+(\bar{\nu}^{\lambda}(1-\gamma^5)e^{\lambda})+\phi^-(\bar{e}^{\lambda}(1+\gamma^5)\nu^{\lambda})]-1$ $\frac{q}{2}\frac{m_e^{\lambda}}{M}[H(\bar{e}^{\lambda}e^{\lambda})+i\phi^0(\bar{e}^{\lambda}\gamma^5e^{\lambda})]+\frac{ig}{2M\sqrt{2}}\phi^+[-m_d^{\kappa}(\bar{u}_j^{\lambda}C_{\lambda\kappa}(1-\gamma^5)d_j^{\kappa})+$ $m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa] + \tfrac{ig}{2M\sqrt{2}}\phi^- [m_d^\lambda(\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger(1+\gamma^5)u_j^\kappa) - m_u^\kappa(\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger(1-\gamma^5)u_j^\kappa]$ $\left[\gamma^5\right)u_j^\kappa\big]-\frac{q}{2}\frac{m_u^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda)-\frac{q}{2}\frac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda)+\frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5 u_j^\lambda)-\frac{q}{2}\phi^0(\bar{u}_j^\lambda u_j^\lambda).$ $\begin{array}{l} \frac{i g}{2}\frac{m_d^{\lambda}}{\lambda}\phi^0(\bar{d}_j^{\lambda}\gamma^5d_j^{\lambda}) + \bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2-M^2)X^-\\ \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + i g c_w W^+_ \mu(\partial_\mu \bar{X}^0X^--\partial_\mu \bar{X}^+X^0) + i g s_w W^+_ \mu(\partial_\mu \bar{Y}X^-- \end{array}$ $\overset{\circ}{\partial}_{\mu}\bar{X}^{+}Y)+ig c_{w}W^{-}_{\mu}(\partial_{\mu}\bar{X}^{-}X^{0}-\partial_{\mu}\bar{X}^{0}X^{+})+ig s_{w}W^{-}_{\mu}(\partial_{\mu}\bar{X}^{-}Y-\partial_{\mu}\bar{X}^{X+})+ig c_{w}Z^{\alpha}_{\mu}(\partial_{\mu}\bar{X}^{+}X^{+}-\partial_{\mu}\bar{X}^{-}X^{-})+ig s_{w}A_{\mu}(\partial_{\mu}\bar{X}^{+}X^{+} \partial_{\mu}\bar{X}^{-}X^{-} - \frac{1}{2}gM[\bar{X}^{+}X^{+}H + \bar{X}^{-}X^{-}H + \frac{1}{c_{w}^{2}}\bar{X}^{0}X^{0}H] +$ $\begin{array}{c} \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+-\bar{X}^-X^0\phi^-] +\frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+-\bar{X}^0X^+\phi^-] +\\ igMs_w[\bar{X}^0X^-\phi^+-\bar{X}^0X^+\phi^-] +\frac{1}{2}igM[\bar{X}^+X^+\phi^0-\bar{X}^-X^-\phi^0] \end{array}$

 $O(10^3)$ $O(10)$ 10^{-18} m 10^{-15} m 10^{-6} m **GEN** pp collisions up to production of stable particles [Easy & Fast]

SIM

detector response
simulation [Hard & Slow]

 $-\tfrac{1}{2}\partial_\nu g^a_\mu\partial_\nu g^a_\mu-g_sf^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu-\tfrac{1}{4}g^2_sf^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu+\tfrac{1}{2}ig^2_s\big(\bar{q}^{\sigma}_i\gamma^\mu q^{\sigma}_j\big)g^a_\mu+\bar{G}^a\partial^2G^a+g_sf^{abc}\partial_\mu\bar{G}^aG^bg^c_\mu-\partial_\nu W^+_ \partial_\nu W^-_\mu \begin{array}{l} M^2W^+_\mu W^-_\mu-\frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu-\frac{1}{2c_w^2}M^2Z^0_\mu Z^0_\mu-\frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu-\frac{1}{2}\partial_\mu H\partial_\mu H-\frac{1}{2}\partial_\mu H^2\partial_\mu Z^0_\mu-\frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu-\frac{1}{2}\partial_\mu H\partial_\mu H-\frac{1}{2c_w^2}M\phi^0\phi^0-\frac{1}{2c_w^2}M\phi^0\phi^0-\beta_h[\frac{2M^2}{g^2}+\\ \end$ $\begin{array}{l} \frac{1}{2} m_h H^2 - \partial_\mu \phi \cdot \partial_\mu \phi^- - m^2 \phi \cdot \phi^- - \frac{1}{2} \partial_\mu \phi \cdot \partial_\mu \phi^0 - \frac{1}{2 c_w^2} m \phi \cdot \phi^- - \partial_h [\frac{1}{g^2} + \frac{1}{g^2} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2 \phi^+ \phi^-)] + \frac{2 M^4}{g^2} \alpha_h - ig c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - W_\nu^+ W_\nu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu$ $W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g \alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2]$ $gMW_\mu^+W_\mu^-H-\frac{1}{2}g\frac{M}{c_-^2}Z_\mu^0Z_\mu^0H-\frac{1}{2}ig[W_\mu^+(\phi^0\partial_\mu\phi^--\phi^-\partial_\mu\phi^0) W^-_\mu\big(\phi^0\partial_\mu\phi^+ -\phi^+\partial_\mu\phi^0\big)\big] +\tfrac12 g \big[W_\mu^+\big(H\partial_\mu\phi^--\phi^-\partial_\mu H\big)-W_\mu^-\big(H\partial_\mu\phi^+-\phi^-\big) \big]$ $\phi^+\partial_\mu H)]+\tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0-\phi^0\partial_\mu H)-ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^--W^-_\mu\phi^+)+$ $ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1 - 2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) +$ $ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W_\mu^{\mp} W_\mu^- [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] \frac{1}{4}g^2\frac{1}{c^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-]-\frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^-+$ $\begin{array}{c} \ ^{43}C_{ee}^{e\quad \ \ \mu} \ \ \mu \end{array} \begin{array}{c} \ ^{43}C_{ee}^{e\quad \ \ \mu} \ \ \mu \end{array} \begin{array}{c} \ ^{43}C_{ee}^{e\quad \ \ \mu} \end{array} \begin{array}{c} \ ^{42}C_{ee}^{e\quad \ \ \mu} \end{array} \begin{array}{c} \ ^{45}C_{ee}^{e\quad \ \ \mu} \end{array} \begin{array}{c} \ ^{45}C_{ee}^{e\quad \ \ \mu} \end{array} \begin{array}{c} \ ^{45}C$ $\begin{array}{l} \frac{d}{d\hat{g}}(\gamma\partial+m\hat{g})d\hat{g}+ig s_w A_{\mu}[-(\bar{e}^{\lambda}\gamma^{\mu}e^{\lambda})+\frac{2}{3}(\bar{u}\hat{g}\gamma^{\mu}u\hat{g})-\frac{1}{3}(\bar{d}\hat{g}\gamma^{\mu}d\hat{g})] +\\ \frac{ig}{d\omega}\bar{Z}_{\mu}^{0}[(\bar{\nu}^{\lambda}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})+(\bar{e}^{\lambda}\gamma^{\mu}(4s_w^2-1-\gamma^5)e^{\lambda})+(\bar{u}\hat{g}\gamma^{\mu}(\frac{4}{3}s_w^2 (\bar{u}_j^{\lambda}\gamma^{\mu}(1+\gamma^5)C_{\lambda\kappa}d_j^{\kappa})]+\frac{ig}{2\sqrt{2}}W_{\mu}^{-}[(\bar{e}^{\lambda}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})+(\bar{d}_j^{\kappa}C_{\lambda\kappa}^{\dagger}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda}].$ $[\gamma^5]u_j^{\lambda}]\big]+\frac{ig}{2\sqrt{2}}\frac{m_{\alpha}^{\lambda}}{M}[-\phi^+(\bar{\nu}^{\lambda}(1-\gamma^5)e^{\lambda})+\phi^-(\bar{e}^{\lambda}(1+\gamma^5)\nu^{\lambda})] \tfrac{q}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) +$ $m_u^{\lambda}(\bar{u}_j^{\lambda}C_{\lambda\kappa}(1+\gamma^5)d_j^{\kappa})+\frac{ig}{2M\sqrt{2}}\phi^{-}[m_d^{\lambda}(\bar{d}_j^{\lambda}C_{\lambda\kappa}^{\dagger}(1+\gamma^5)u_j^{\kappa})-m_u^{\kappa}(\bar{d}_j^{\lambda}C_{\lambda\kappa}^{\dagger}(1-\gamma^5)u_j^{\kappa}].$ $(\gamma^5)u_j^\kappa]-\frac{q}{2}\frac{m_\alpha^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda)-\frac{q}{2}\frac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda)+\frac{ig}{2}\frac{m_\alpha^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5 u_j^\lambda)-\phi^0(\bar{u}_j^\lambda u_j^\lambda)$ $\begin{array}{l} \frac{i g}{2}\frac{m_d^{\lambda}}{M}\phi^0(\bar{d}_j^{\lambda}\gamma^5 {d}_j^{\lambda}) + \bar{X}^+(\partial^2-M^2) X^+ + \bar{X}^-(\partial^2-M^2) X^- + \bar{X}^0(\partial^2-M^2) X^- \end{array}$ $\frac{\tilde{M}^2}{c^2}\tilde{X}^0+\tilde{Y}\partial^2\tilde{Y}+igc_wW^+_\mu(\partial_\mu\bar{X}^0X^--\partial_\mu\bar{X}^+X^0)+ig s_wW^+_\mu(\partial_\mu\bar{Y}X^- \partial_\mu \bar{X}^+ Y) + ig c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{X}^X)^+) + ig c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^0 X^-)$ $\partial_{\mu}\bar{X}^{-}X^{-}$) – $\frac{1}{2}gM[\bar{X}^{+}X^{+}H+\bar{X}^{-}X^{-}H+\frac{1}{c^{2}}\bar{X}^{0}X^{0}H]+$ $\begin{array}{l}\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+-\bar{X}^-X^0\phi^-]+\frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+-\bar{X}^0X^+\phi^-]+\\ igMs_w[\bar{X}^0X^-\phi^+-\bar{X}^0X^+\phi^-]+\frac{1}{2}igM[\bar{X}^+X^+\phi^0-\bar{X}^-X^-\phi^0] \end{array}$

 $-\tfrac{1}{2} \partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc} \partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4} g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\ \tfrac{1}{2} i g^2_s \big(\bar{q}^{\sigma}_i \gamma^\mu q^{\sigma}_j \big) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_ \partial_\nu W^-_\mu - \nonumber$ $\label{eq:21} \begin{array}{l} M^2 W^+_ \mu W^-_ \mu - \frac{1}{2} \partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2 c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \frac{1}{2} m^2_H H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2 c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2 M^2}{g^$ $\begin{array}{l} \frac{1}{2} m_h^2 H^2 - O_\mu \phi^2 O_\mu \phi^- - M^2 \phi^2 \phi^- - \frac{1}{2} O_\mu \phi^2 O_\mu \phi^- - \frac{1}{2 c_w^2} M \phi^2 \phi^- - \beta_h \left[\frac{1}{g^2} + \frac{2 M^2}{g^2} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2 \phi^+ \phi^-) \right] + \frac{2 M^4}{g^2} \alpha_h - ig_c v_w \left[\partial_\nu Z^0_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - Z^0_\nu (W_\mu^+ \partial$ $\frac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] \frac{1}{2}g_{\mu\nu}^{(1)} + \frac{1}{2}g_{\tau}^{(1)} + \frac{1}{2}g_{\tau}^{(2)}Z_{\mu}^{0}Z_{\mu}^{0}H - \frac{1}{2}ig[W_{\mu}^{+}(\phi^{0}\partial_{\mu}\phi^{-} - \phi^{-}\partial_{\mu}\phi^{0}) - W_{\mu}^{-}(\phi^{0}\partial_{\mu}\phi^{+} - \phi^{+}\partial_{\mu}\phi^{0})] + \frac{1}{2}g[W_{\mu}^{+}(H\partial_{\mu}\phi^{-} - \phi^{-}\partial_{\mu}H) - W_{\mu}^{-}(H\partial_{\mu}\phi^{+} - \phi^{+}\partial_{\mu}$ $\begin{array}{c} i g s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - i g \frac{1-2 c_w^2}{2 c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\ i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] - \end{array}$ $\frac{1}{4}g^2\frac{1}{c^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-]-\frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^-+$ $(\bar{u}_j^{\lambda}\gamma^{\mu}(1+\gamma^5)C_{\lambda\kappa}d_j^{\kappa})]+\frac{i g}{2\sqrt{2}}W_{\mu}^{-}[(\bar{e}^{\lambda}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})+(\bar{d}_j^{\kappa}C_{\lambda\kappa}^{\dagger}\gamma^{\mu}(1+\gamma^5)\nu^{\lambda})]$ $[\gamma^5(u_i^{\lambda})] + \frac{ig}{2\sqrt{2}}\frac{m_i^{\lambda}}{M}[-\phi^+(\bar{\nu}^{\lambda}(1-\gamma^5)e^{\lambda}) + \phi^-(\bar{e}^{\lambda}(1+\gamma^5)\nu^{\lambda})] \tfrac{q}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) +$ $m_u^{\lambda}(\bar{u}_j^{\lambda}C_{\lambda\kappa}(1+\gamma^5)d_j^{\kappa}]+\frac{ig}{2M\sqrt{2}}\phi^{-}[m_d^{\lambda}(\bar{d}_j^{\lambda}C_{\lambda\kappa}^{\dagger}(1+\gamma^5)u_j^{\kappa})-m_u^{\kappa}(\bar{d}_j^{\lambda}C_{\lambda\kappa}^{\dagger}(1-\gamma^5)u_j^{\kappa}].$ $\gamma^5) u_j^\kappa\big] -\tfrac{g\, m_u^\lambda}{M} H(\bar u_j^\lambda u_j^\lambda) -\tfrac{g\, m_d^\lambda}{M} H(\bar d_j^\lambda d_j^\lambda) +\tfrac{ig\, m_u^\lambda}{M} \phi^0(\bar u_j^\lambda \gamma^5 u_j^\lambda) \frac{i g}{2}\frac{m_d^{\lambda}}{M}\phi^0(\bar{d}_j^{\lambda}\gamma^5d_j^{\lambda})+X^+(\partial^2-M^2)X^++\bar{X}^-(\partial^2-M^2)X^-+\bar{X}^0(\partial^2-M^2)X^ \frac{M^2}{c^2}\Big)X^0+\bar{Y}\partial^2Y+igc_wW^+_\mu(\partial_\mu\bar{X}^0X^--\partial_\mu\bar{X}^+X^0)+ig s_wW^+_\mu(\partial_\mu\bar{Y}X^- \partial_\mu \bar{X}^+ Y) + ig c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{X}^X)^+) + ig c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^0 X^-)$ $\partial_{\mu}\bar{X}^{-}X^{-}$) – $\frac{1}{2}gM[\bar{X}^{+}X^{+}H+\bar{X}^{-}X^{-}H+\frac{1}{c^{2}}\bar{X}^{0}X^{0}H]+$ $\begin{array}{l}\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+-\bar{X}^-X^0\phi^-]+\frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+-\bar{X}^0X^+\phi^-]+\\ igMs_w[\bar{X}^0X^-\phi^+-\bar{X}^0X^+\phi^-]+\frac{1}{2}igM[\bar{X}^+X^+\phi^0-\bar{X}^-X^-\phi^0] \end{array}$

$10⁰$ 10^{-1} 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 common 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

Mainly fast integrals

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

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!

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!

(Simulation != test data)

detector response simulation [Hard & Slow]

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

Detector reconstruction and tagging

Jet as a "particle cloud"

collision point

 \ddot{x}

 $\ddot{\ddot{\mathbf{y}}}$

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proton beams

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Data representation

proton beams

collision points of the second po

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Jet as a "particle cloud" Point Cloud: Set of N-dimensional vectors (e.g set of particles and their 4-momentum)

 \boldsymbol{n}

 $\frac{1}{2}$ outgoing particles $\frac{1}{2}$ **W boson?**

 \boldsymbol{n}

Jet tagging - our MNIST! B-quark?

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 →

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)

Generative of **a godels** for Simulation

 $O(10)$

 10^{-18} m

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Detector design, data acquisition and triggering

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

-60

 $O(10)$

 10^{-18} m

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

detector response simulation [Hard & Slow]

AI-assisted design of experiments [doi:10.1016/j.revip.2023.100085](https://doi.org/10.1016/j.revip.2023.100085)

- Make everything differentiable!
- Joint optimization of design parameters w.r.t. inference made with data

Example 1: **Muons** measured precisely but less efficiently

Example 2: Muons measured less precisely but more efficiently

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.**

The next-generation triggers CF for CERN detectors LHC **F**

The recently launched Next-Generation Triggers project is set to remarkably increase the efficiency, sensitivity and modelling of CERN experiments

The foundations of the NextGen project were laid in 2022 when a group of private donors, including former Google CEO Eric Schmidt, visited CERN. This first inspiring visit eventually evolved into an agreement with the Eric and Wendy Schmidt Fund for Strategic Innovation, approved by the CERN Council in October 2023, to fund a project that would pave the way for the future trigger systems at the HL-LHC and beyond: NextGen was born.

1 PB/yr

1 EB/yr

1 TB/yr

★

66

• 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

72

ATLAS

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

72

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 ilcu il
Ilino 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** $\sigma^{pp}_{in} = 69.2 \ mb$ **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** $\left(\text{Lvl-2}\right)$ 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/

Prediction

Data flow architecture • Tailored hardware for a model • Each layer is separate compute unit

-
-
- Stay on-chip
- "Decisions are design time"

Ideally Reality

- •**Quantization**
- •**Pruning**
- **Ideally •Parallelisation** Reality
	- •**Knowledge distillation**

Quantization

Floating point 32: 4B numbers in [-3.4e38, +3.4e38]

Quantization

Quantising: int8 28=256 numbers in [-128,127]

xq = *Clip*(*Round*(*xf scale*))

Weights Layer 1 Weights Layer 2

Fixed point

Weights Layer 1¹ Weights Layer 2

Fixed point **0101.1011101010**

width

integer fractional

Weights Layer 1 Weights Layer 2 Scan integer bits Weights La

Efficient NN designed and the Communication of the Com

fractional values of the content of
The content of the c

er and the FAGA we use fixed the fixed point of the fixed point representation of the contract of the fixed point representation of the contract of the contra

- Operations are integrating the care in the care of the canonical contract of the canonical canonical contract of the canonical care and the canonical canonical canonical canonical canonical canonical canonical canonical

er and the correct data to make sure we have the correct data types! The correct data types!

Scan fraction and the second control of the second control of the second control of the second control of the s Weights Layer 2

Forward pass →

\blacksquare **+Quantization-aware training**

← Back propagation

[Nature Machine Intelligence 3 \(2021\)](https://www.nature.com/articles/s42256-021-00356-5)

→Knowledge Distillation

Can we have the best of both worlds?

Train Inference

Soft labels contain information!!

Train student to learn both true and predicted (teacher) labels!

 $L_{total} = \beta \times L_{Distillation} + \alpha \times L_{student}$

Student learns subtle learned features from teacher!

Using knowledge distillation for CNN in hardware Calorimeter Trigger!

Anomaly score = input - output

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.* sii.
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 $\frac{1}{\sqrt{1}}$ $\sum_{i=1}^n C_{ij}$ with $C^{\epsilon} = \begin{bmatrix} 1 & \cdots & 0 \\ \cdots & \cdots & \cdots & 0 \end{bmatrix}$ 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 $\sqrt{2}$ $\frac{1}{2}$
 $\frac{1}{2}$ \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
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BBB
BBBBBBBBB $k_{3,1}$ $k_{3,2}$ $\left(\frac{\tilde{k}_{0,j}}{\tilde{k}_{3,N}}\right)$ \tilde{k} *k*1*,j* ˜ *k*2*,j* 关
Ki *k*3*,j* $\sum_{i=1}^{n}$ en
Eb
ida $\mathbf{E} = \mathbf{E} = \mathbf{E} \mathbf{E}$ \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 $k_{0,1}$ $k_{0,2}$ \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)

Semantic segmentation for autonomous vehicles

…and outside

[N. Ghielmetti et al.](https://iopscience.iop.org/article/10.1088/2632-2153/ac9cb5)

Other examples

- *• [For fusion science phase/mode monitoring](https://indico.cern.ch/event/1156222/contributions/5058420/attachments/2535257/4363120/CJH_FML4Science-10_4_22.pdf)*
- *• [Crystal structure detection](https://docs.google.com/presentation/d/1gnAqn4gpZvx4JVVD8dqbXKMsZ_vpguO9hxC7zH0jv6w/edit#slide=id.g13512715b6e_0_5)*
- *• [Triggering in DUNE](https://indico.cern.ch/event/1156222/contributions/5062816/attachments/2522993/4338612/fast_ml_2022_gk.pdf)*
- *• [Accelerator control](https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.24.104601)*
- *• [Magnet Quench Detection](https://ieeexplore.ieee.org/document/9354037)*
- *• [MLPerf tinyML benchmarking](https://arxiv.org/abs/2206.11791)*
- *• [Food contamination detection](https://ieeexplore.ieee.org/document/9181293)*
- *•* etc….

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

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

Capture Physics

Physics feature (says meow)

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

Theorists N-D Space

NN

Capture Physics

(Graph) NN N-D Space

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

Detector design, data acquisition and triggering

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

Generative signal dels for detector response

GEN

 $O(10)$

 10^{-18} m

