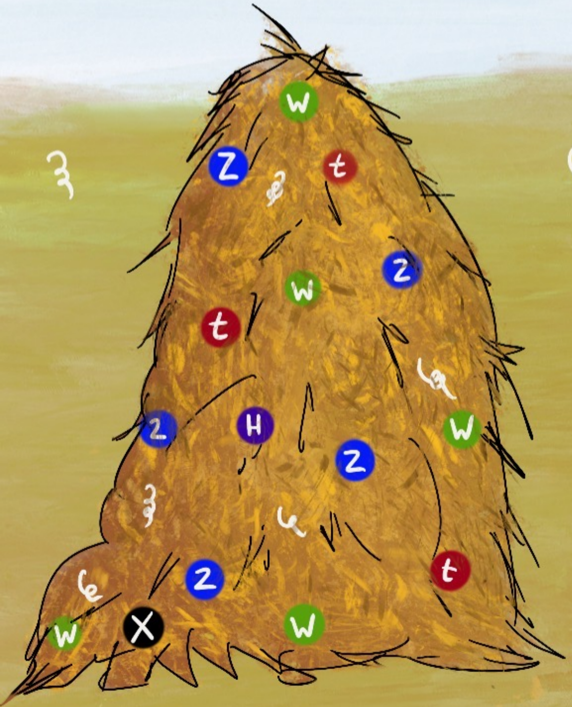
What has the LHC taught us about the Standard Model?



Heather Russell, University of Victoria
VISPA Research Centre

WNPPC – 17 February 2024

ATLAS EXPERIMENT

University of Victoria

(aside from discovering the Higgs boson)

Piste map

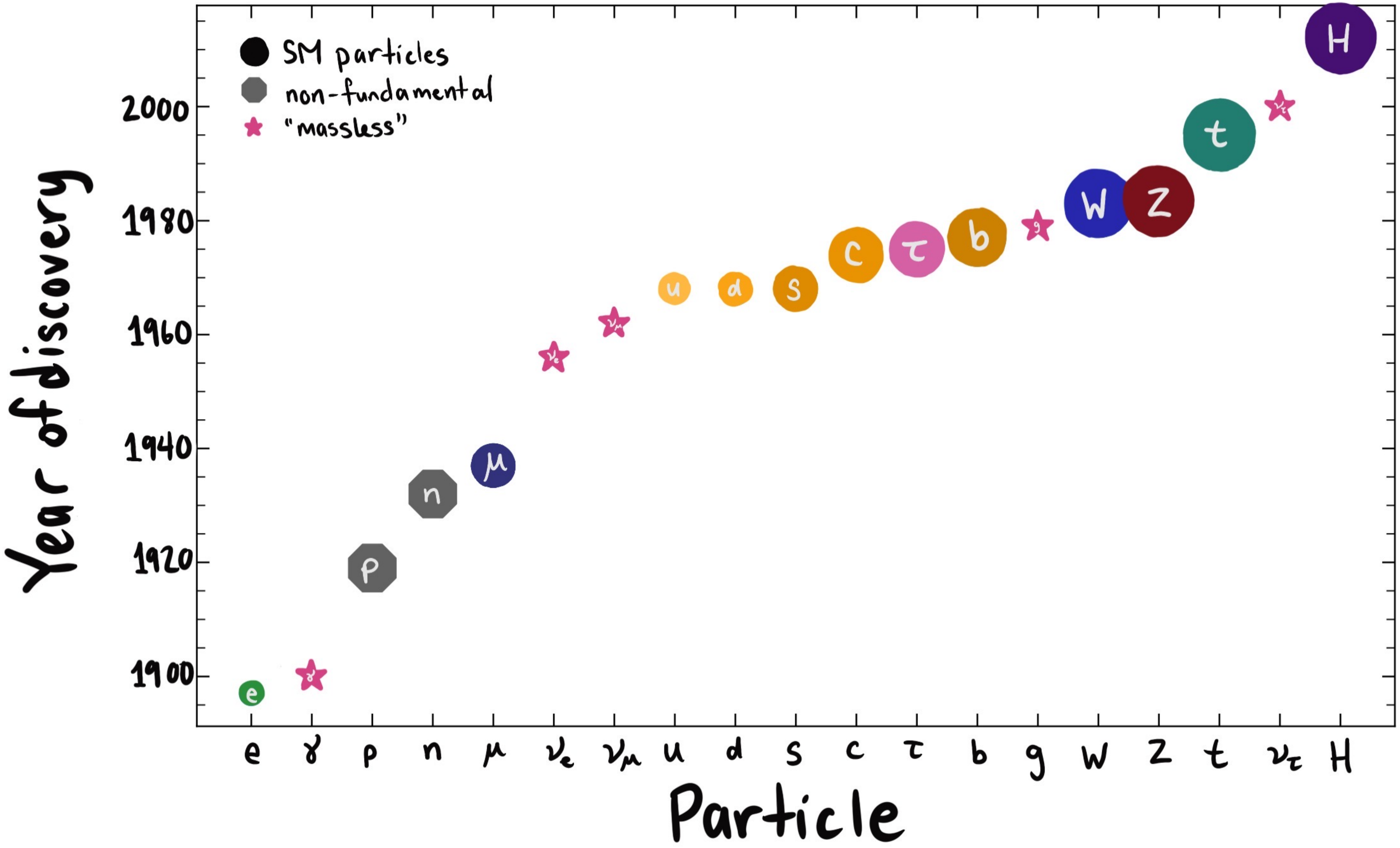
Introduction to the Standard Model and LHC physics

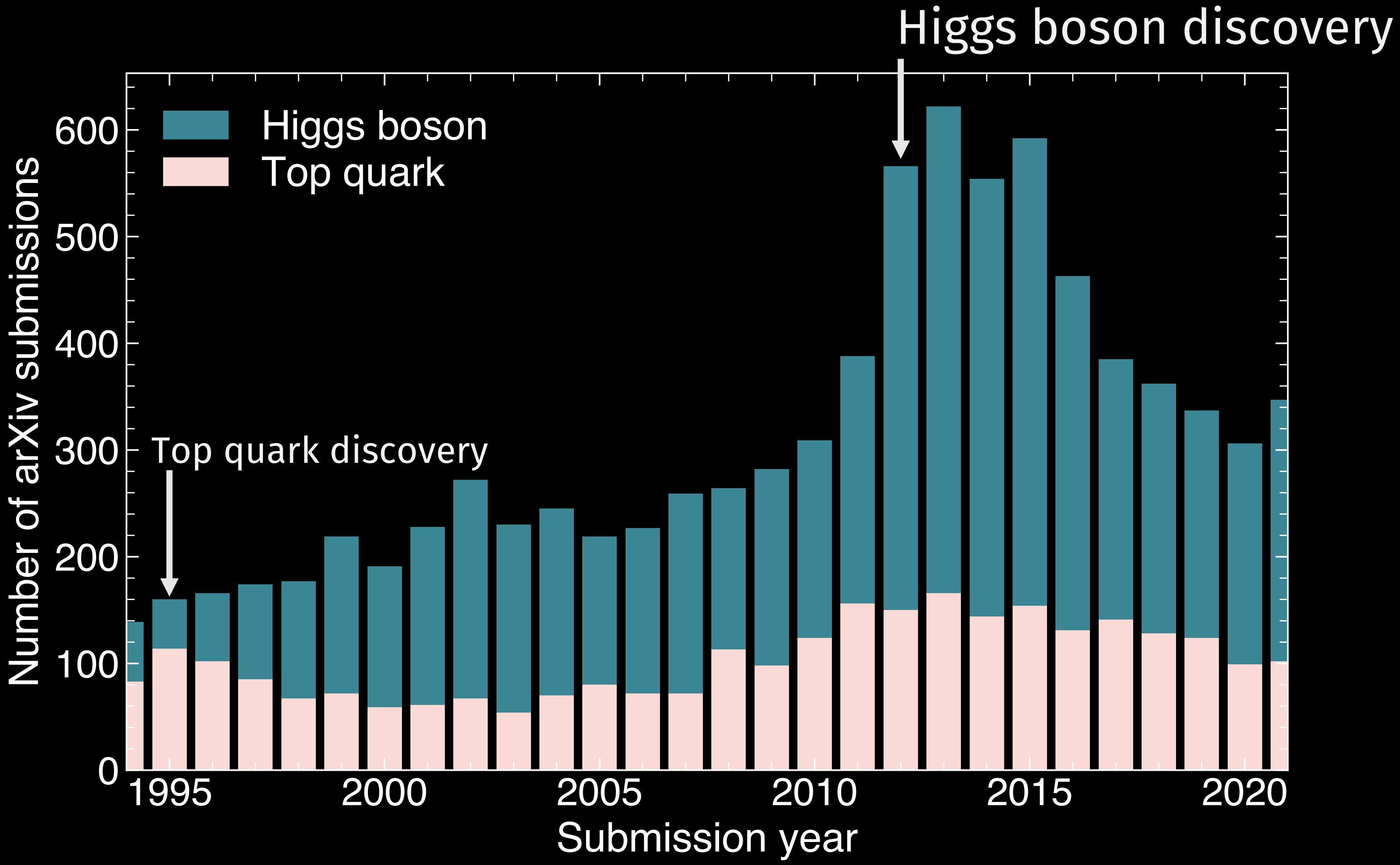
Why we want to do measurements of the Standard Model

Four topics for discussion:

1. Measuring the contents of the proton
2. Rare electroweak processes (quartic gauge couplings)
3. Top quark measurements
4. What the Standard Model is missing

Discovery timeline

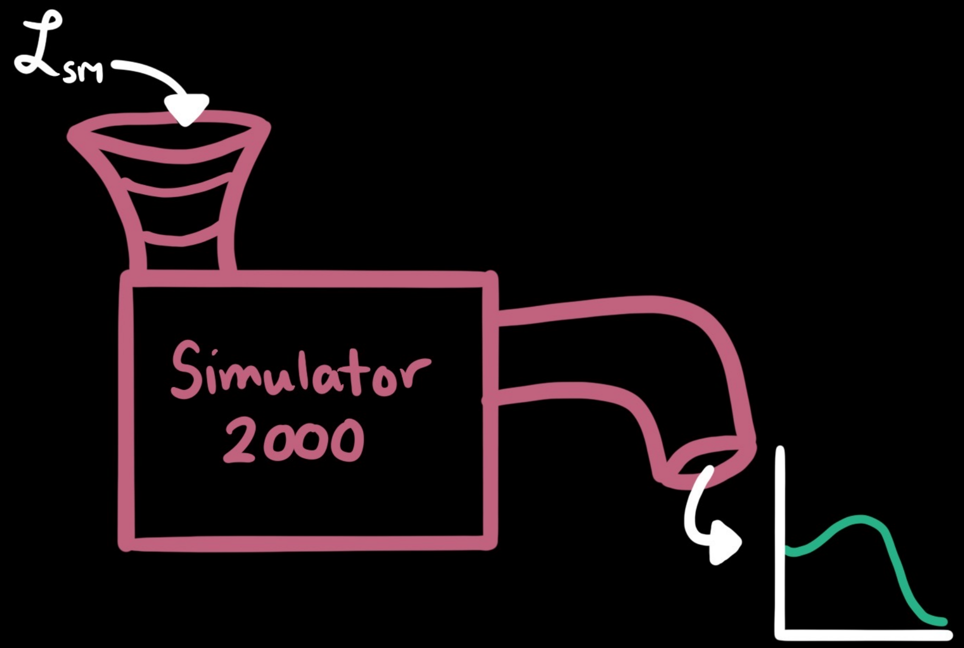


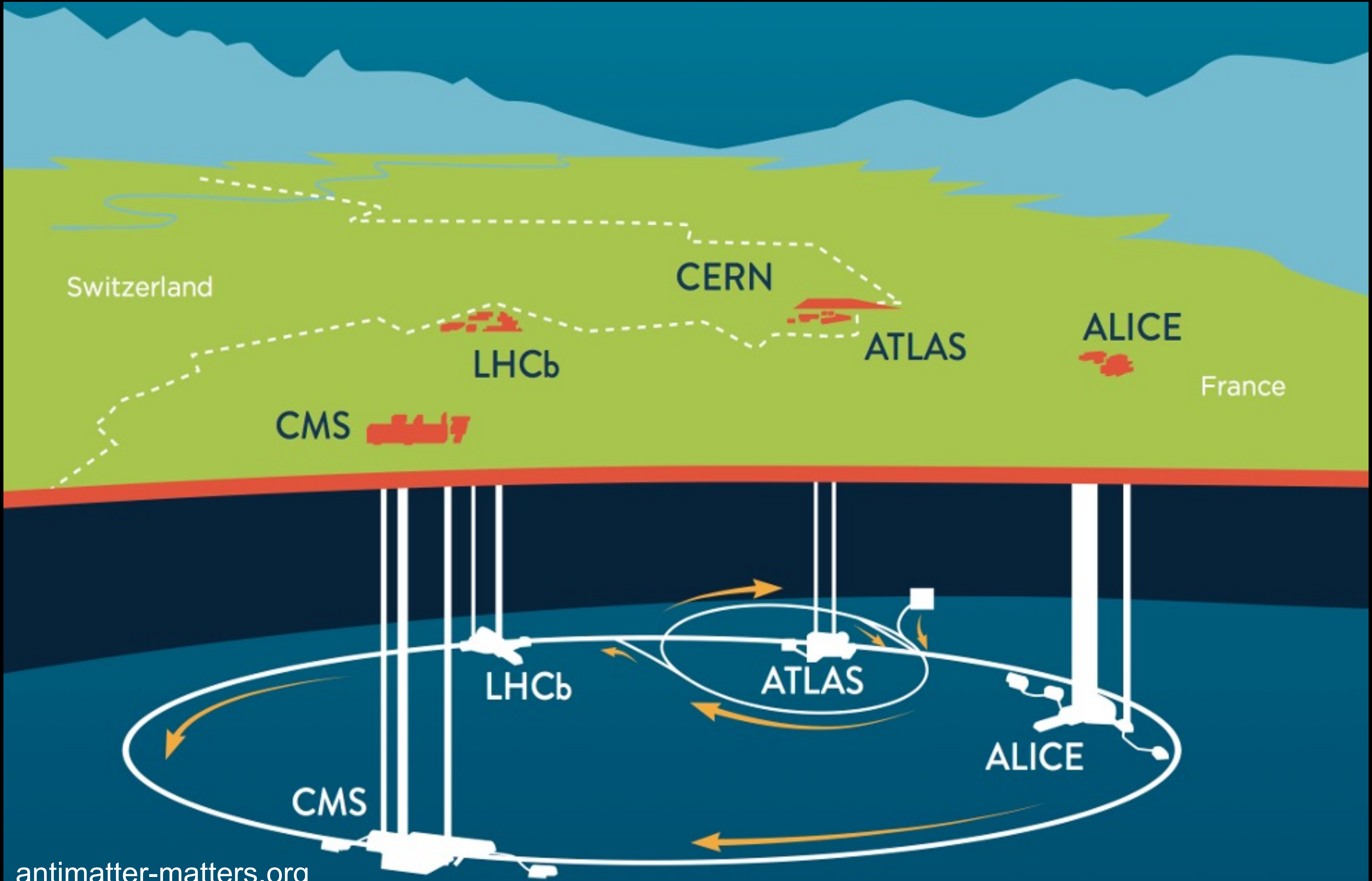


*histograms are not stacked

1. Does the Standard Model accurately describe all the particle interactions it predicts?

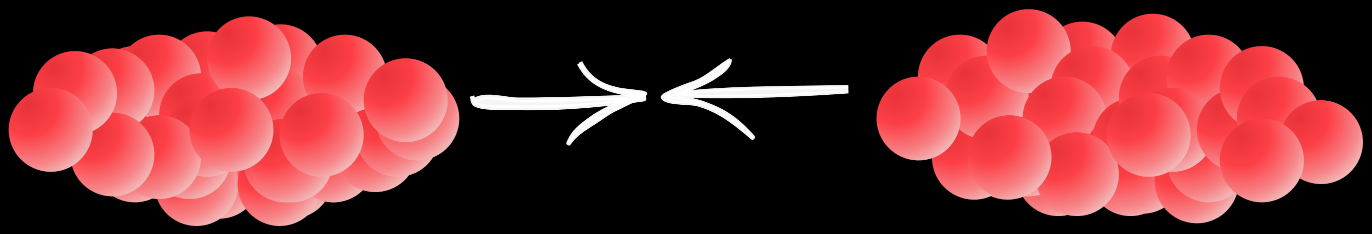
2. Are we accurately simulating what the Standard Model predicts happens @ the LHC?





antmatter-matters.org

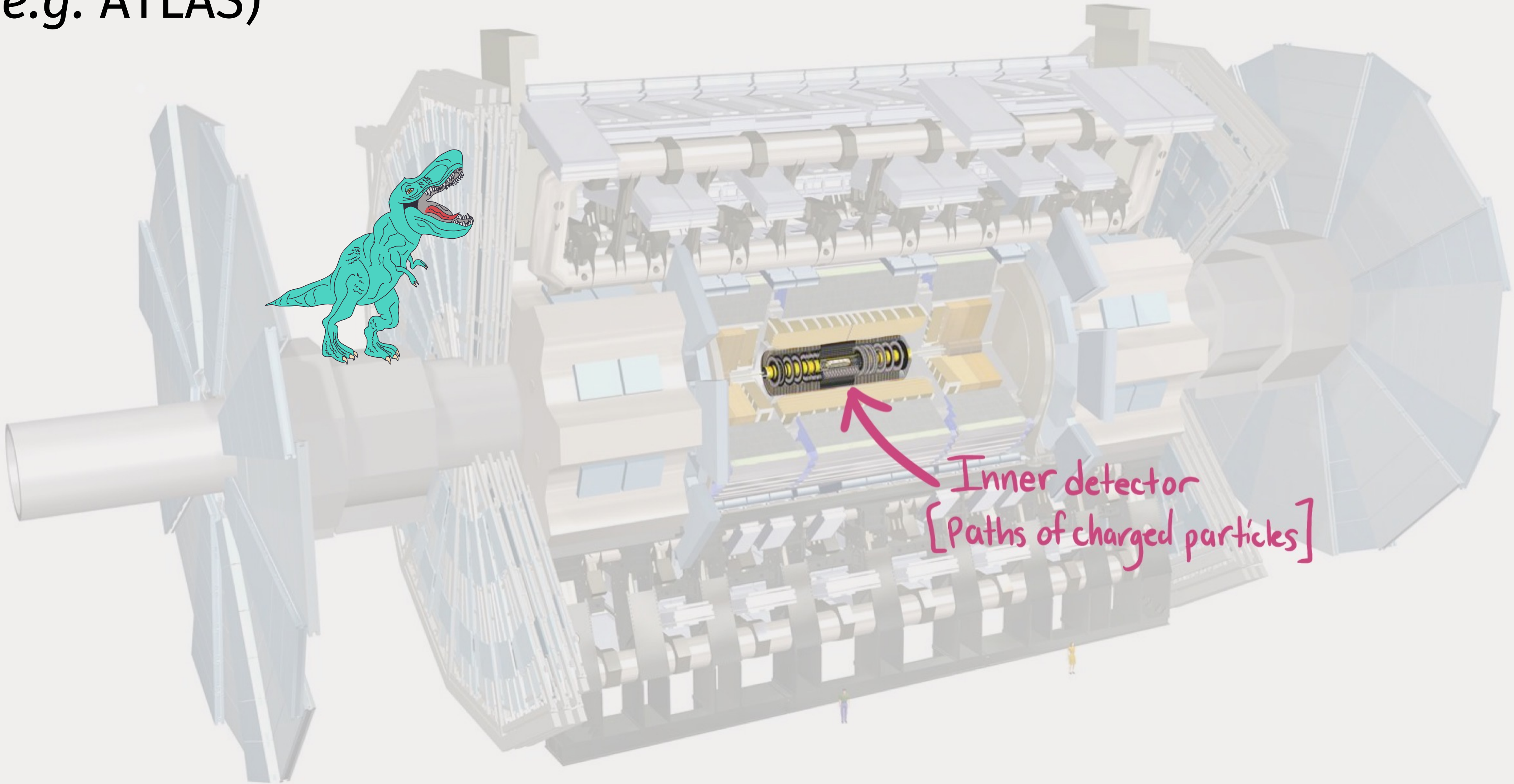
At the LHC, we collide (mainly) protons at very, very high energies



* not to scale
** not an accurate depiction of protons
*** not an accurate depiction of bunches

Particle detectors @ the LHC

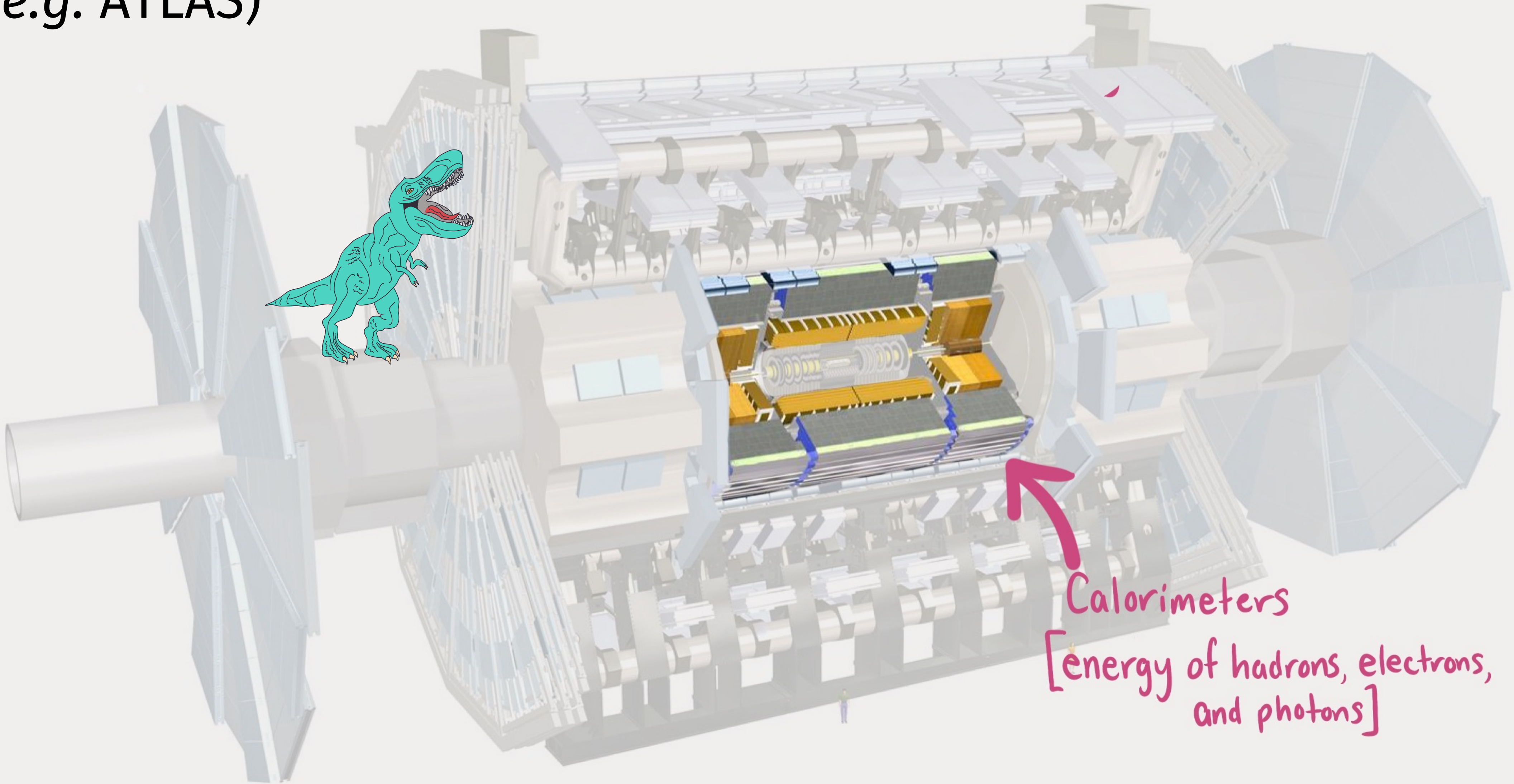
(*e.g.* ATLAS)



Learn more about the ATLAS detector: **atlas.cern/discover/detector/**
Or view it on [google streetview]

Particle detectors @ the LHC

(*e.g.* ATLAS)



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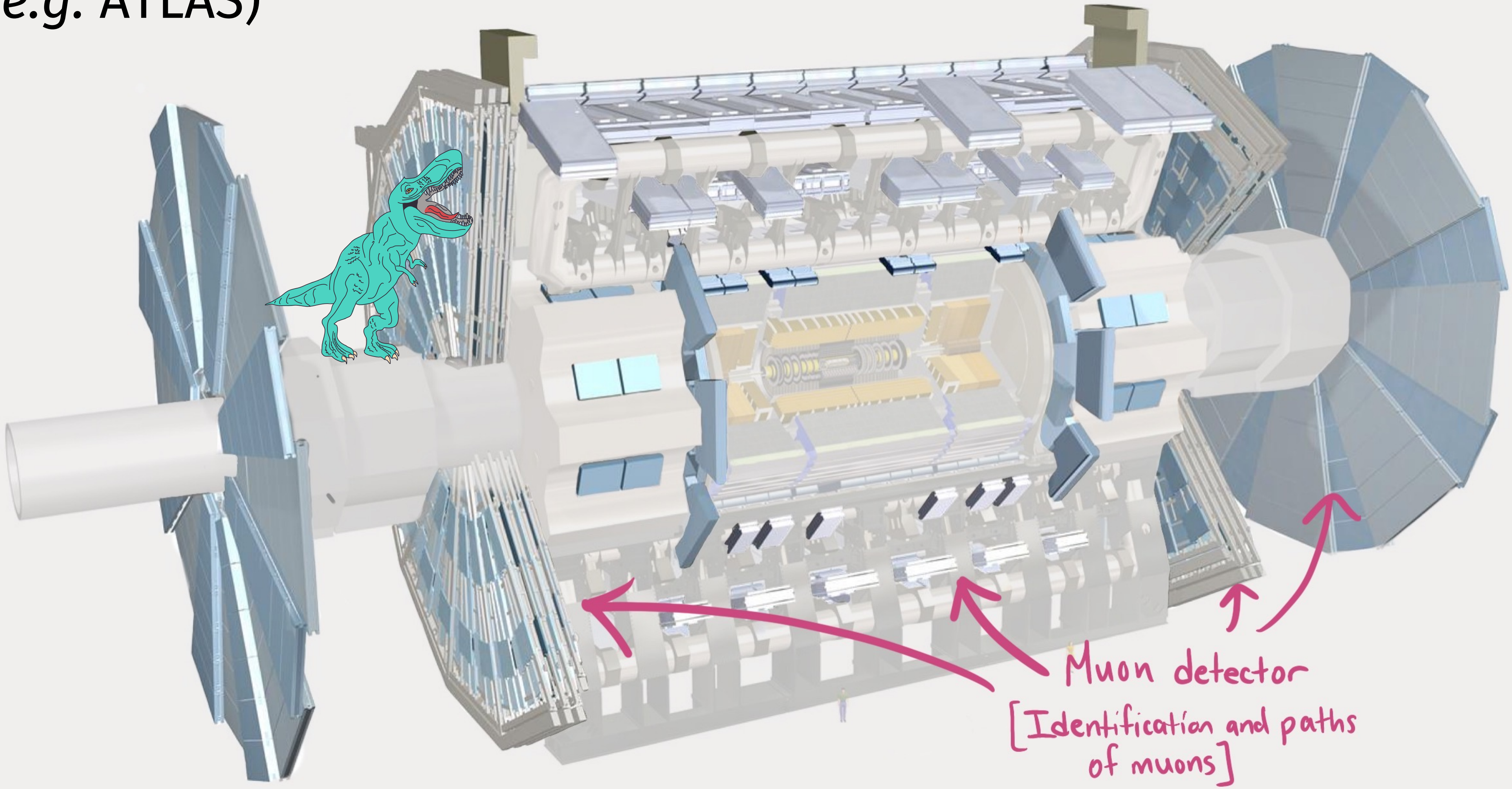
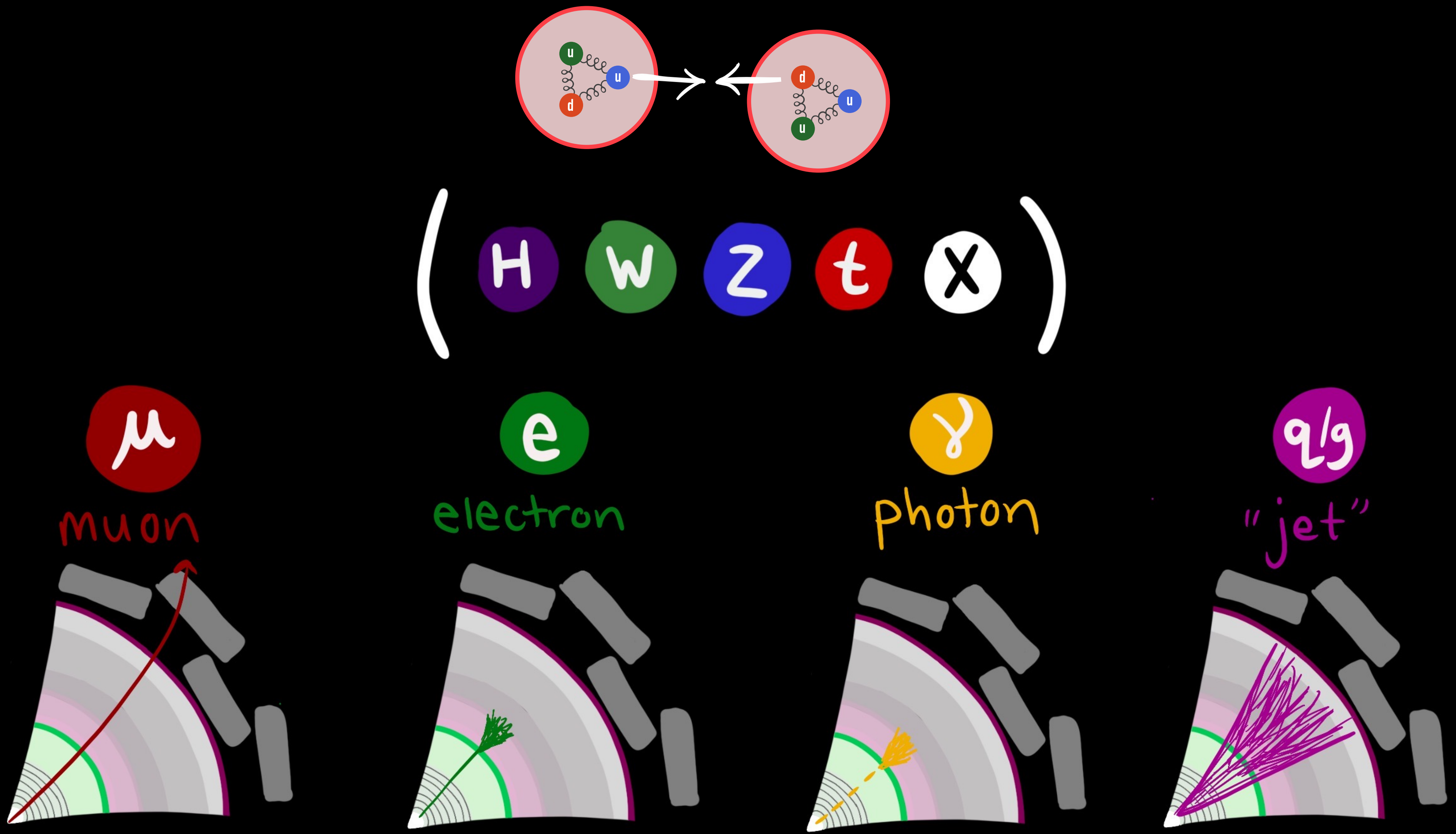
Particle detectors @ the LHC

(*e.g.* ATLAS)

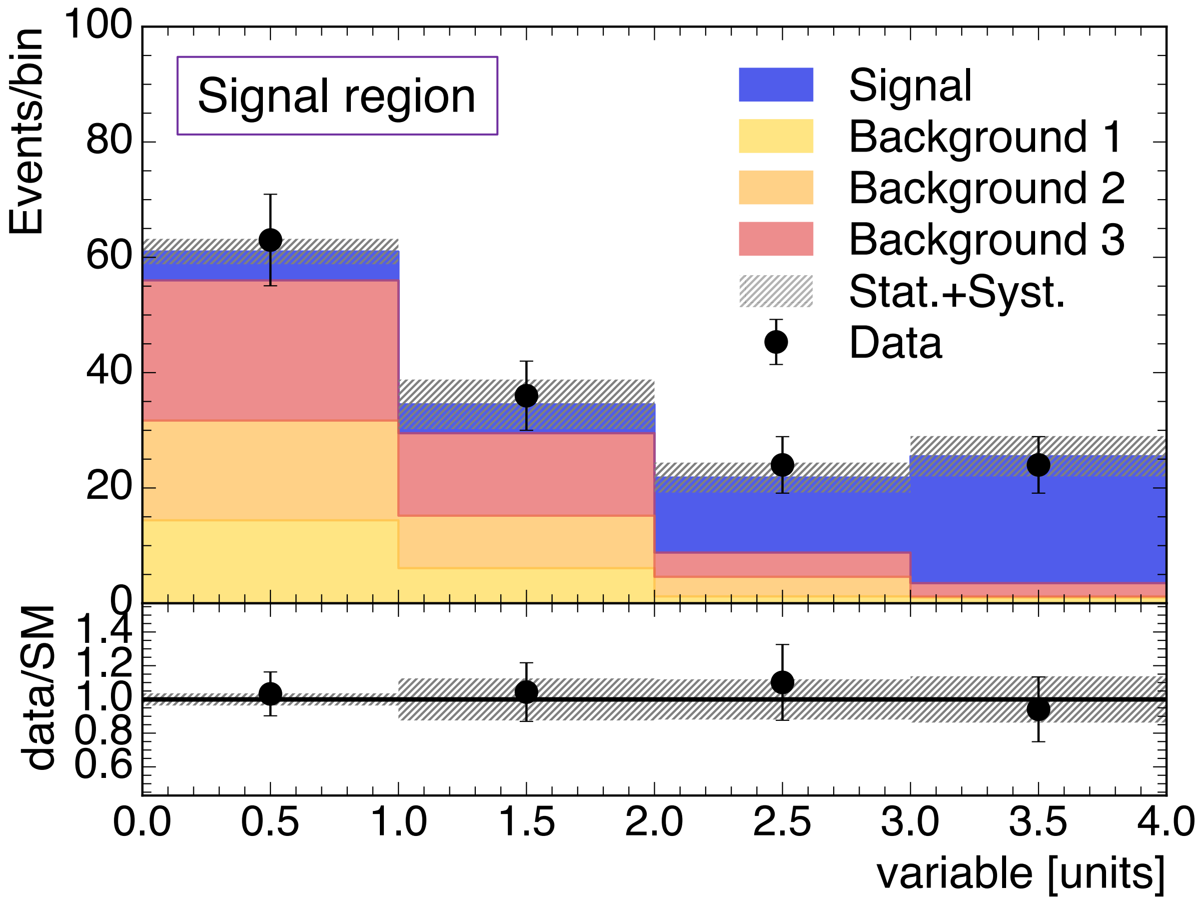


Learn more about the ATLAS detector: **atlas.cern/discover/detector/**
Or view it on [google streetview]

ATLAS produces a **different signal** for each particle



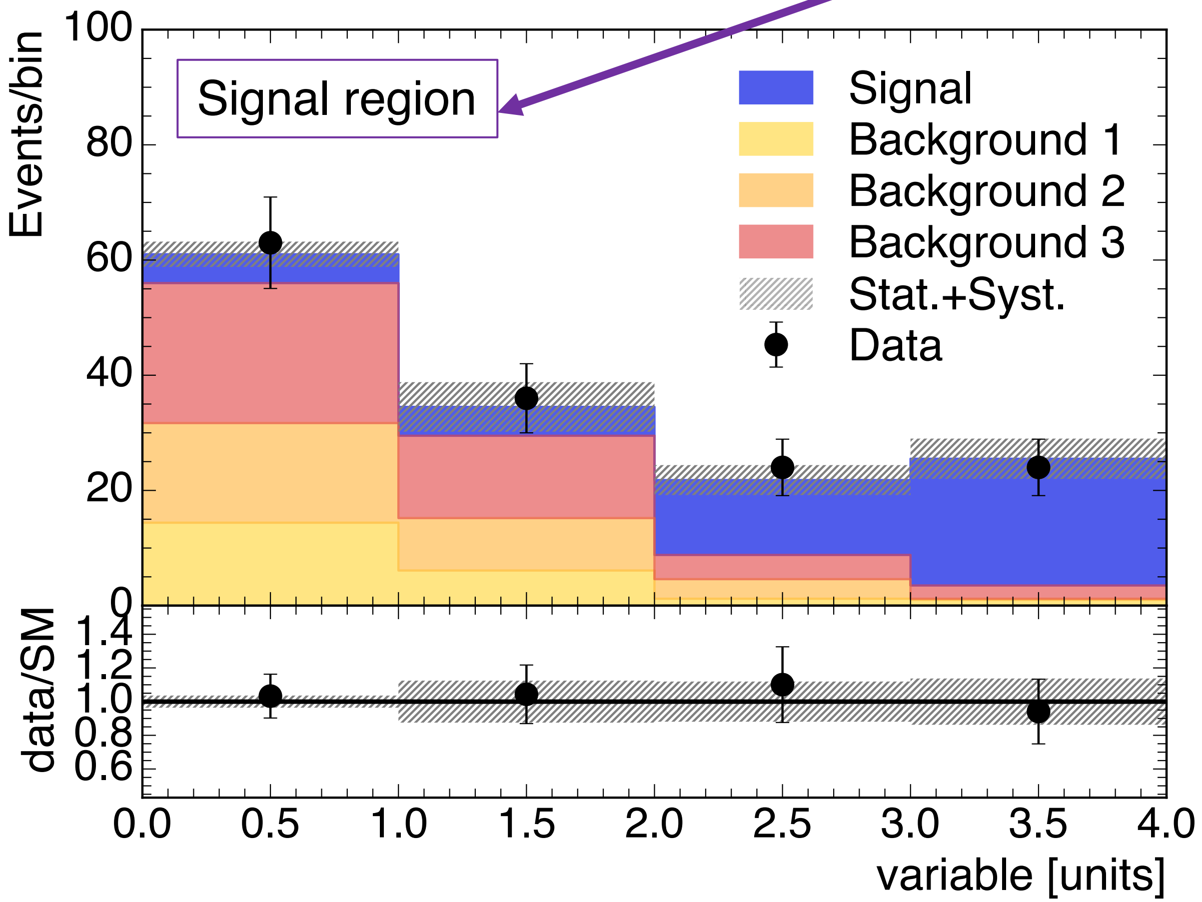
Plots in particle physics



Measurement of a **Standard Model processes**

Plots in particle physics

Requirement on events to be in the plot

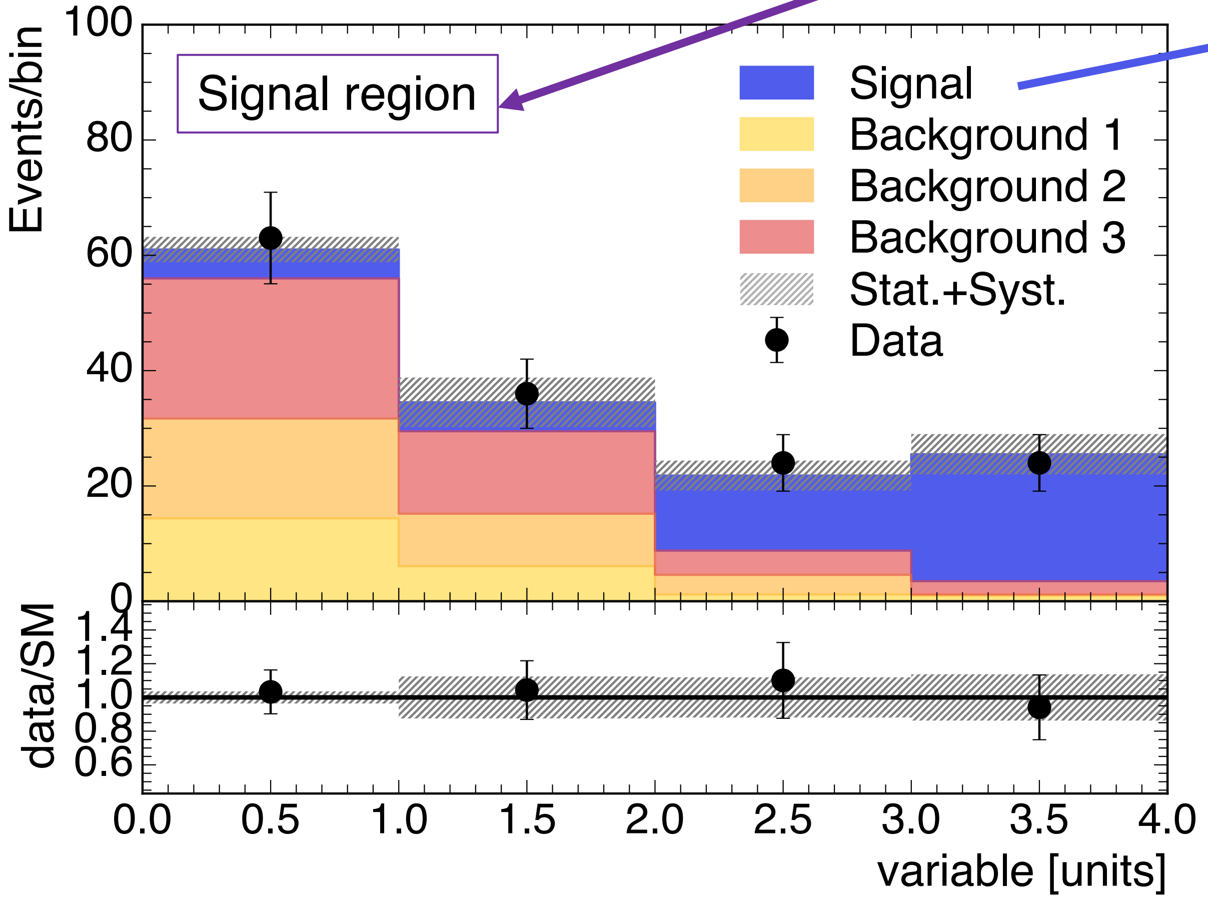


Measurement of a **Standard Model processes**

Plots in particle physics

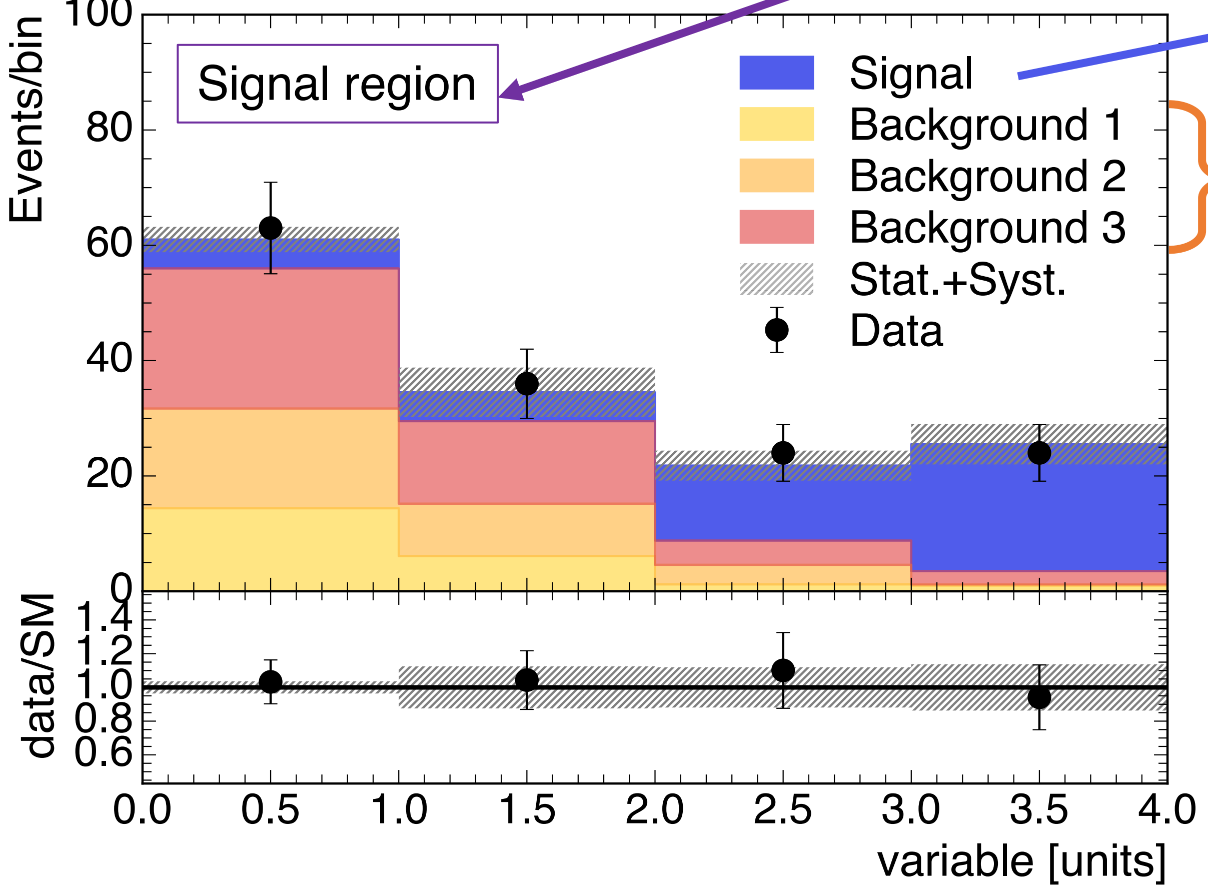
Requirement on events to be in the plot

Expected events from the signal process



Measurement of a **Standard Model processes**

Plots in particle physics



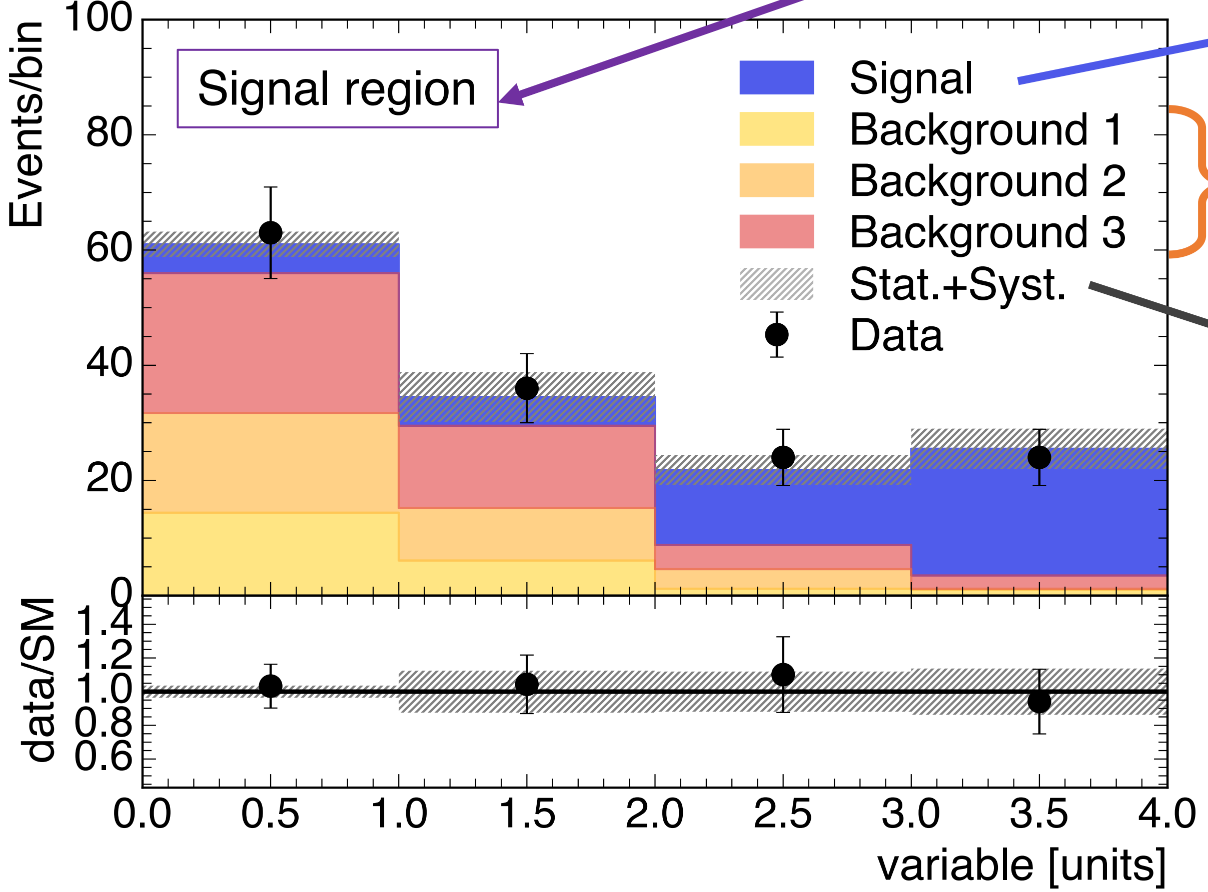
Requirement on events to be in the plot

Expected events from the signal process

Expected events from non-signal processes

Measurement of a **Standard Model processes**

Plots in particle physics



Requirement on events to be in the plot

Expected events from the signal process

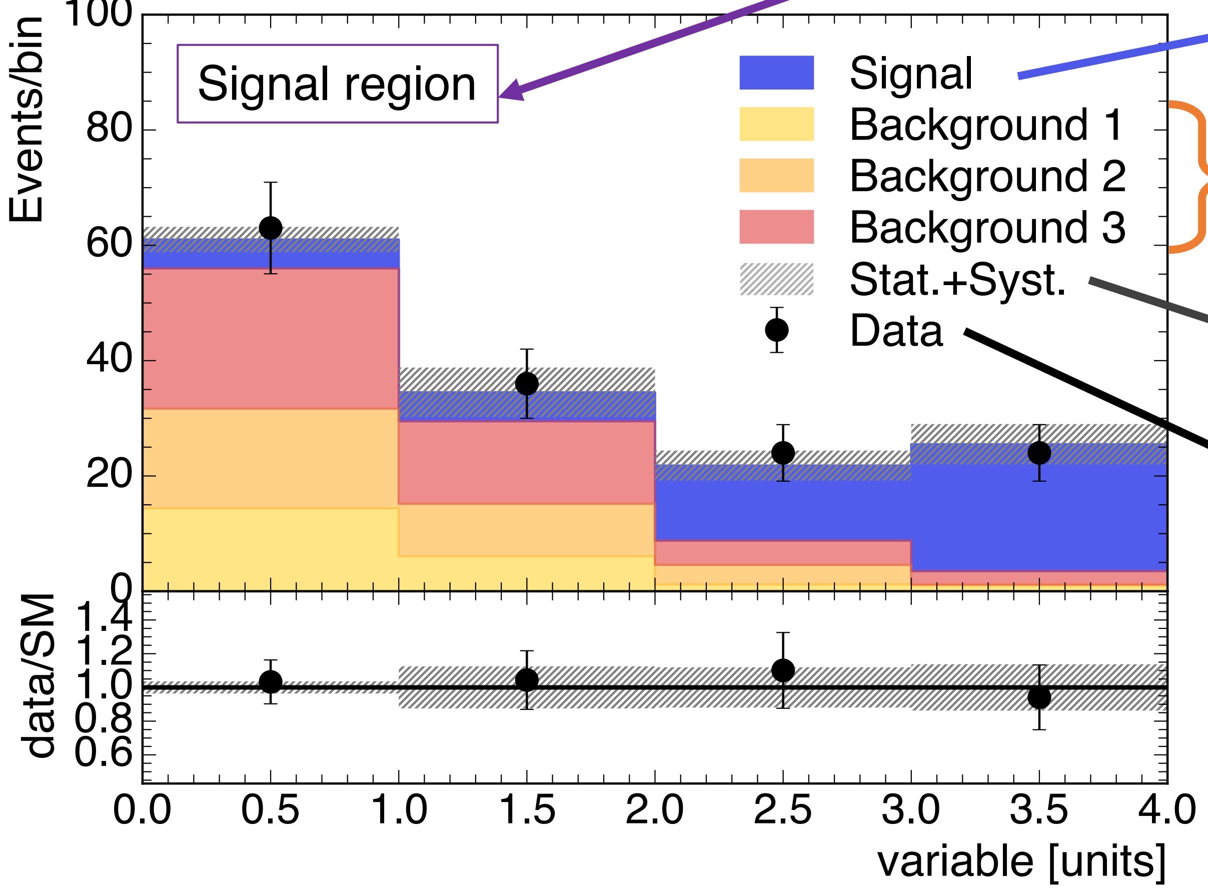
Expected events from non-signal processes

Carefully determined uncertainties on all predictions

Measurement of a **Standard Model processes**

Plots in particle physics

Requirement on events to be in the plot



Expected events from the signal process

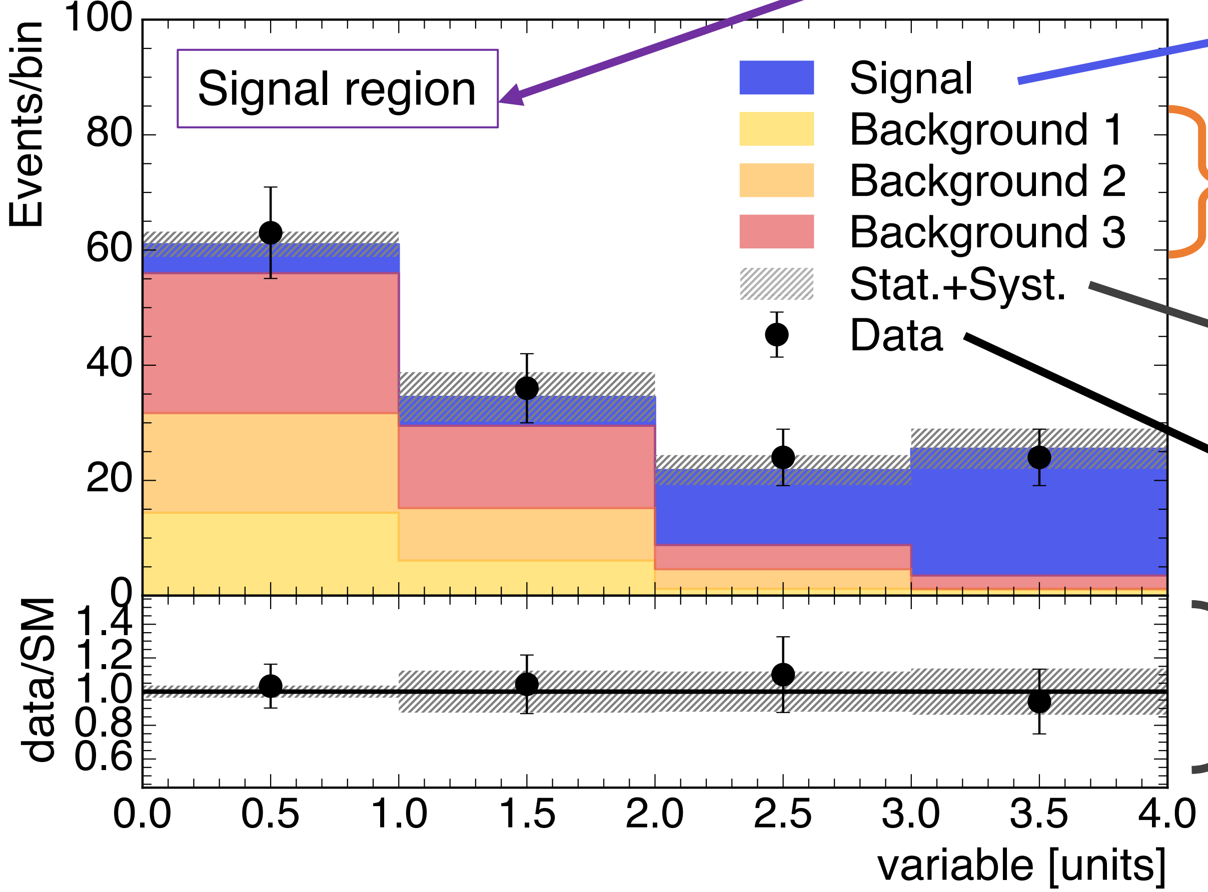
Expected events from non-signal processes

Carefully determined uncertainties on all predictions

Events we observed in data!

Measurement of a **Standard Model processes**

Plots in particle physics



Requirement on events to be in the plot

Expected events from the signal process

Expected events from non-signal processes

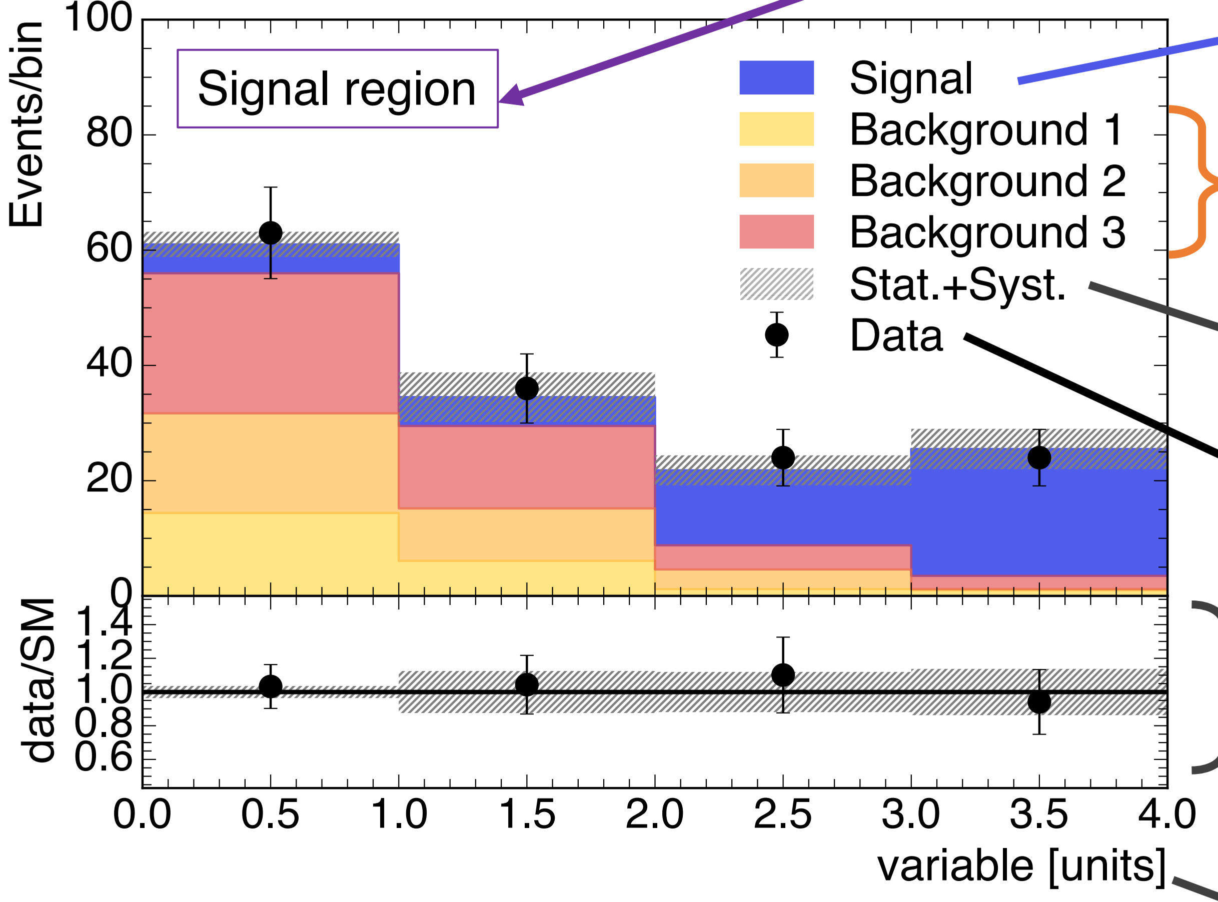
Carefully determined uncertainties on all predictions

Events we observed in data!

Convenient ratio to compare prediction to observation

Measurement of a **Standard Model processes**

Plots in particle physics



Requirement on events to be in the plot

Expected events from the signal process

Expected events from non-signal processes

Carefully determined uncertainties on all predictions

Events we observed in data!

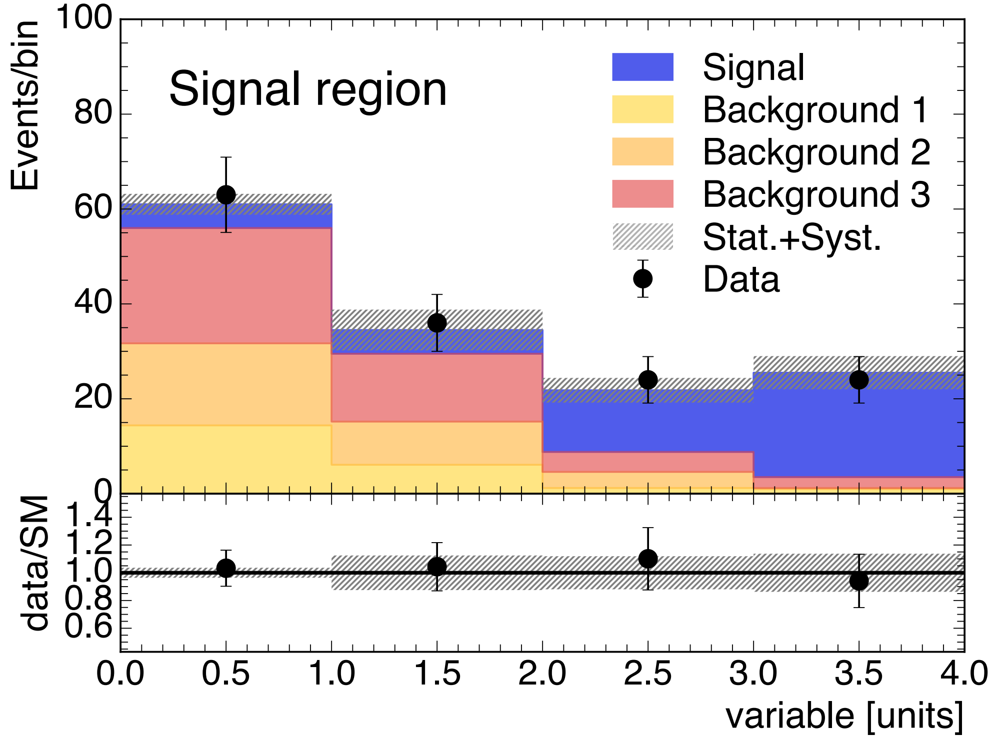
Convenient ratio to compare prediction to observation

An **observable** that helps separate signal and background

Measurement of a **Standard Model processes**

Observing particles or processes

Test the **null hypothesis**: measure the probability of observing what you see, or more extreme, if the particle/process did **not** exit.

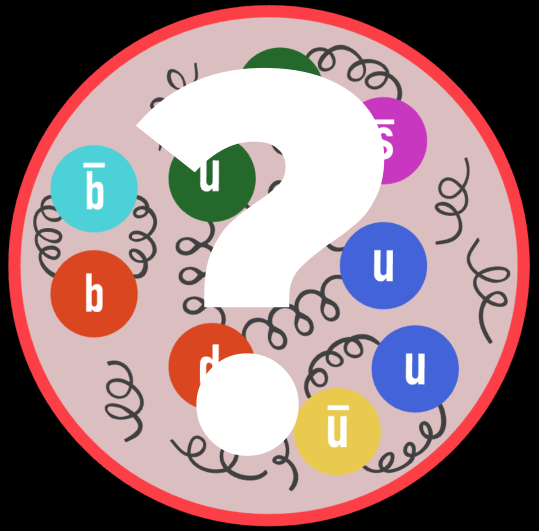


p-value	probability	N-σ
0.05	95%	1.64 σ significance
0.0013	99.87%	3 σ significance **"evidence"**
0.0000003	99.99997%	5 σ significance **"observation"**

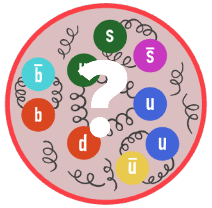
One-sided!

How likely would that data shape be if there were **no** signal?

1. What are we actually colliding?



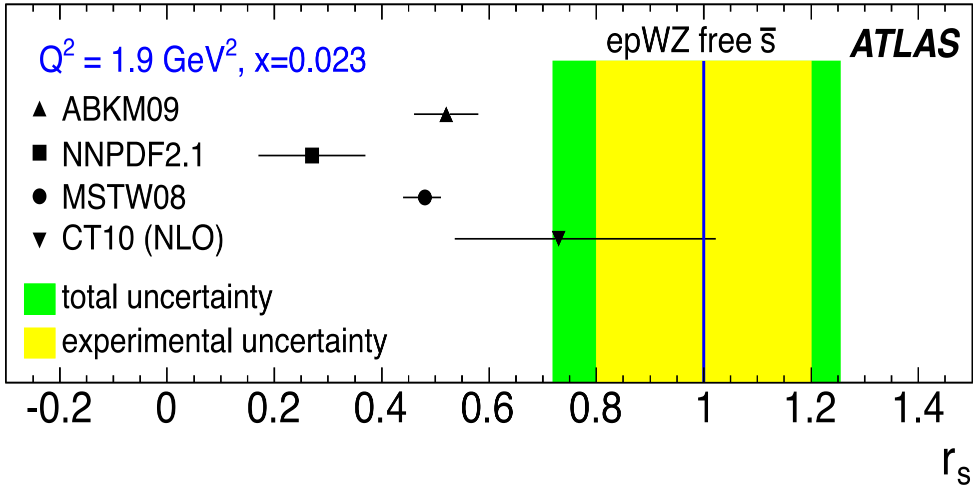
Parton distribution functions



measure the "strangeness" of the proton:

$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

2012:



HERA measurements
(*e*-*P* collider)

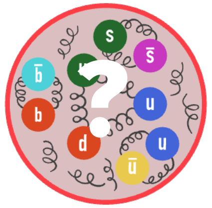
ATLAS measurements
(of all sorts)

xFitter

Eur. Phys. J. C 82 (2022) 438

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2020-32/

Parton distribution functions



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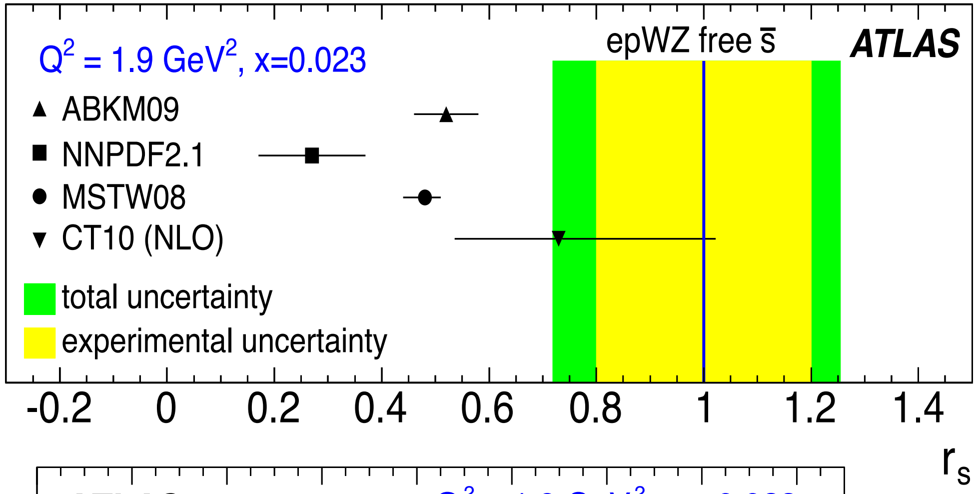
HERA measurements
(e-P collider)

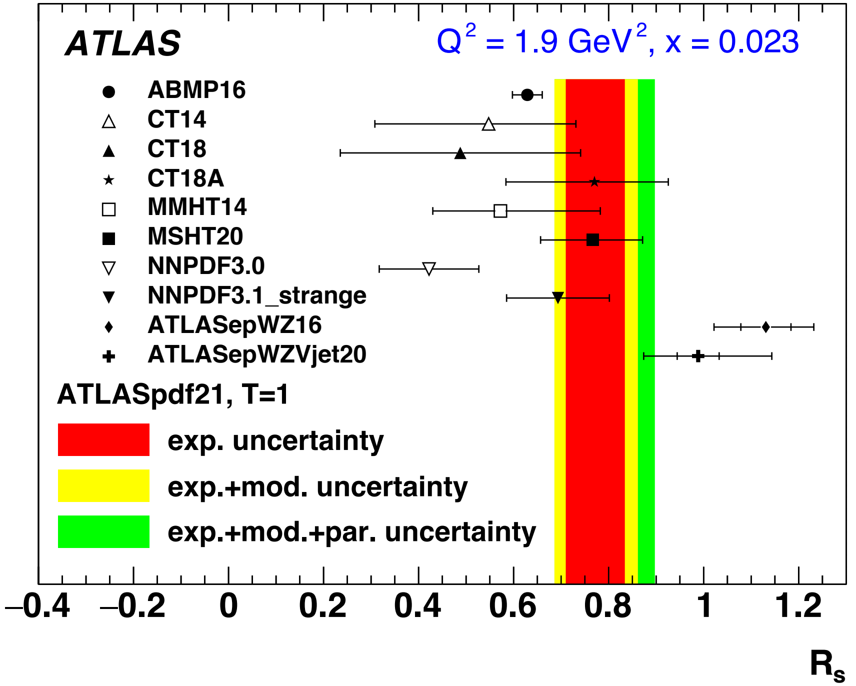
ATLAS measurements
(of all sorts)

xFitter

2012:



2021:



Eur. Phys. J. C 82 (2022) 438

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2020-32/

2. Observations of rare electroweak processes

The Standard Model

force carriers

fermion interactions

$$\mathcal{L}_{\rm SM} = \boxed{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}} + \boxed{i\bar{\psi}\not{D}\psi}$$

Higgs field

$$\boxed{+D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi)}$$

$$\boxed{+\bar{\psi}_L\hat{Y}\Phi\psi_R + h.c.}$$

fermion masses

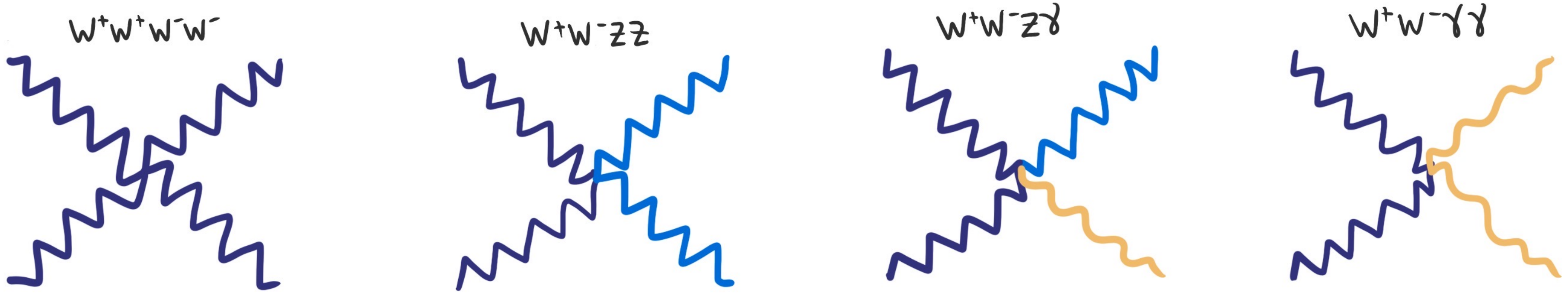
Interactions of weak bosons

Triple couplings

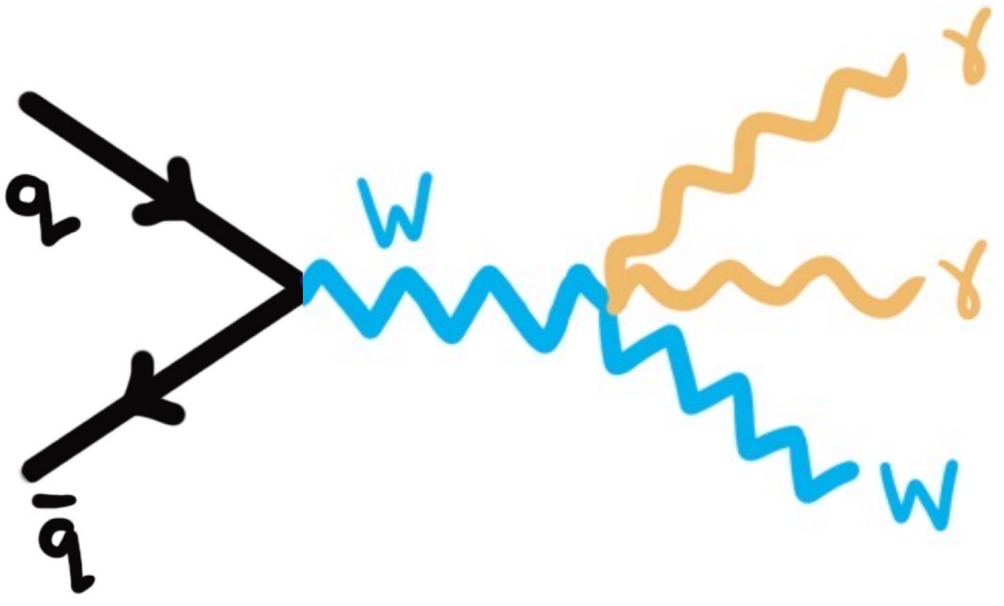
$$
\begin{aligned}
\mathcal{L}_{EW,WZA} = \; & ig\cos\theta_W[(W_\mu^- W_\nu^+ - W_\nu^- W_\mu^+)\partial^\mu Z^\nu + W_{\mu\nu}^+ W^{-\mu} Z^\nu - W_{\mu\nu}^- W^{+\mu} Z^\nu] \\
& + ig\sin\theta_W[(W_\mu^- W_\nu^+ - W_\nu^- W_\mu^+)\partial^\mu A^\nu + W_{\mu\nu}^+ W^{-\mu} A^\nu - W_{\mu\nu}^- W^{+\mu} A^\nu] \\
& + g^2\cos^2\theta_W(W_\mu^+ W_\nu^- Z^\mu Z^\nu - W_\mu^+ W^{-\mu} Z_\nu Z^\nu) \\
& + g^2\sin^2\theta_W(W_\mu^+ W_\nu^- A^\mu A^\nu - W_\mu^+ W^{-\mu} A_\nu A^\nu) \\
& + g^2\sin\theta_W\cos\theta_W[W_\mu^+ W_\nu^-(Z^\mu A^\nu + Z^\nu A^\mu) - 2W_\mu^+ W^{-\mu} Z_\nu A^\nu)] \\
& + \frac{1}{2}g^2(W_\mu^+ W_\nu^-)(W^{+\mu} W^{-\nu} - W^{+\nu} W^{-\mu})
\end{aligned}
$$

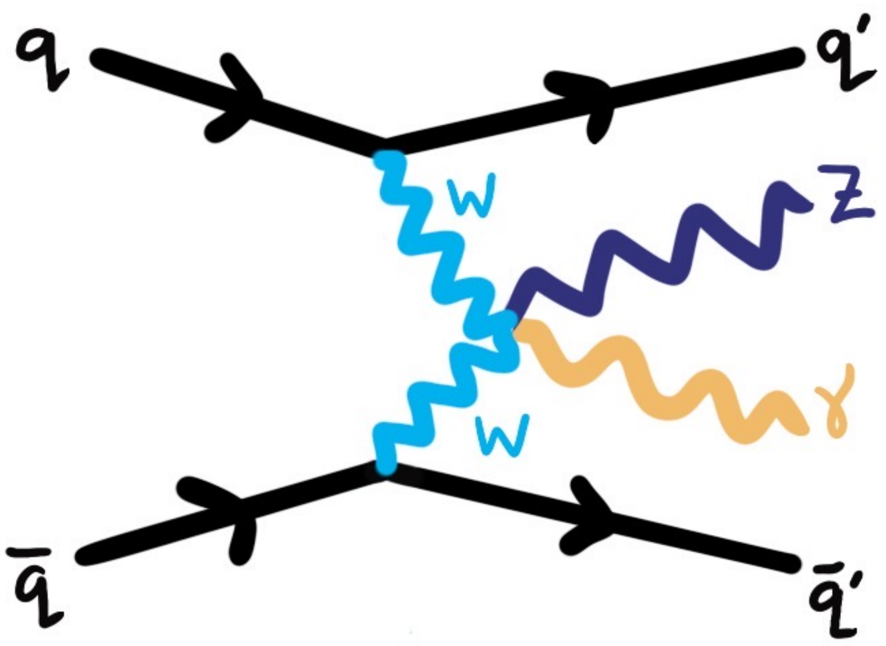
Quartic couplings!

all terms with **four** interacting bosons come with a factor of g^2 ($g < 1$)→ this means they are **extra suppressed**



Rare electroweak processes @ the LHC



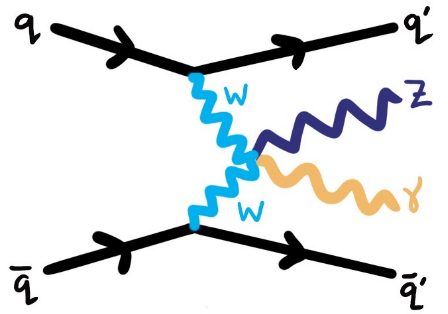


Triboson production

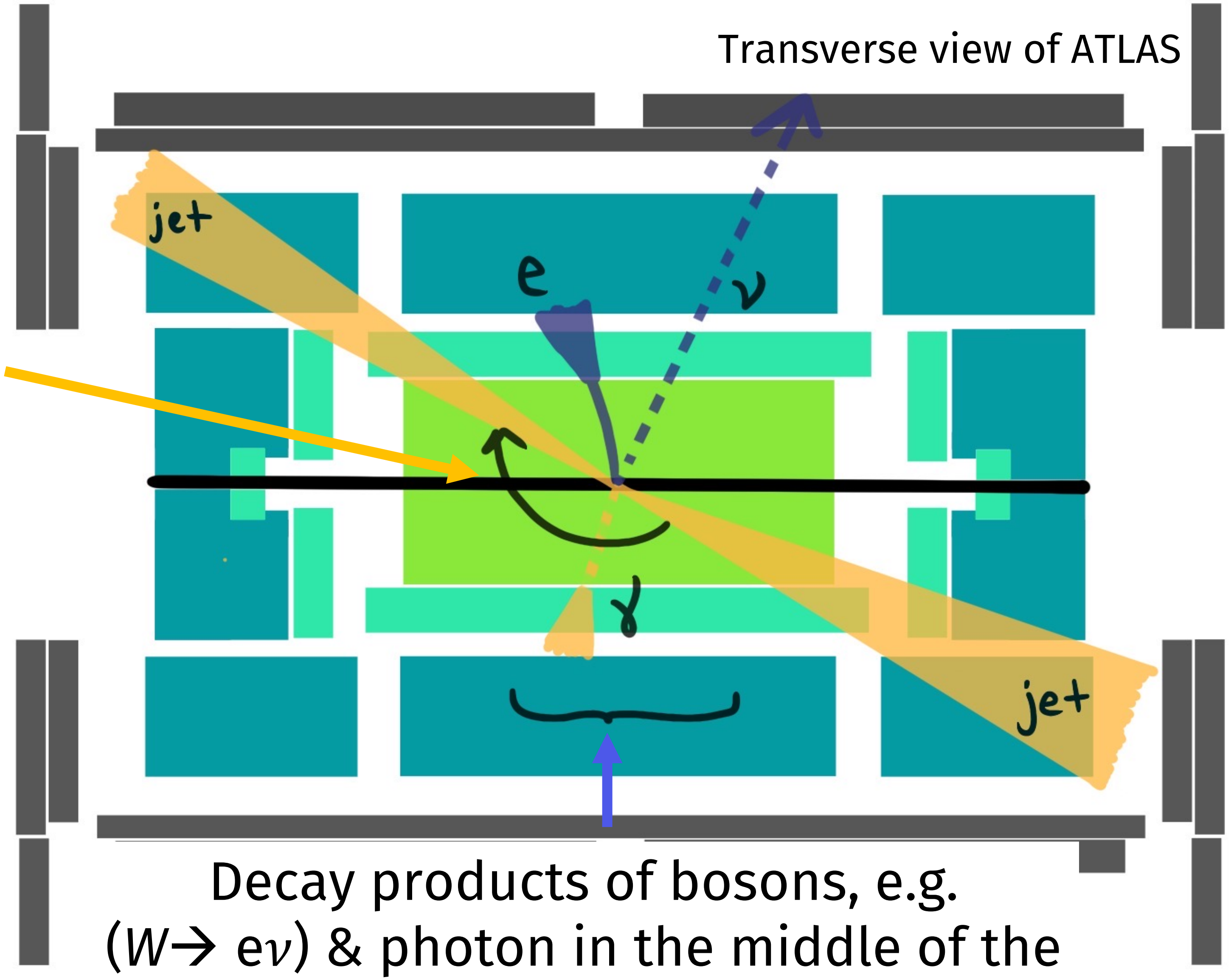
[featured in the next talk (A. Ambler)]

Vector boson scattering

Vector boson scattering



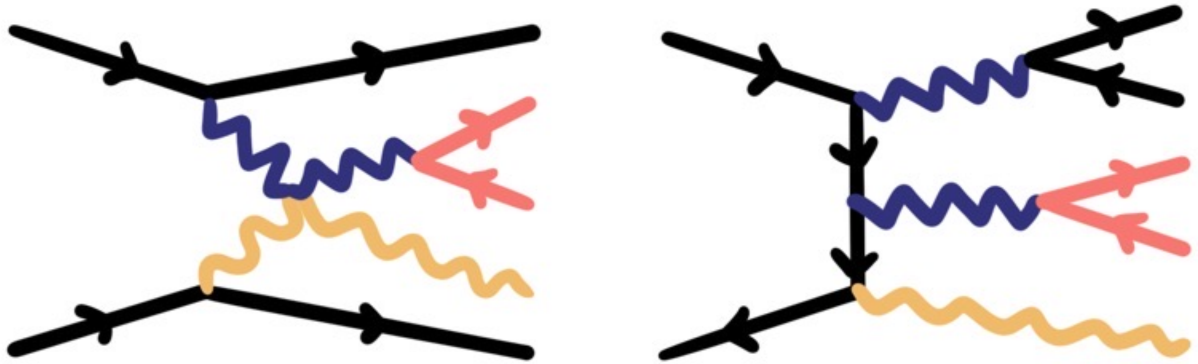
Two well separated jets, with no jets in between



Decay products of bosons, e.g. ($W \rightarrow e\nu$) & photon in the middle of the detector, between the jets

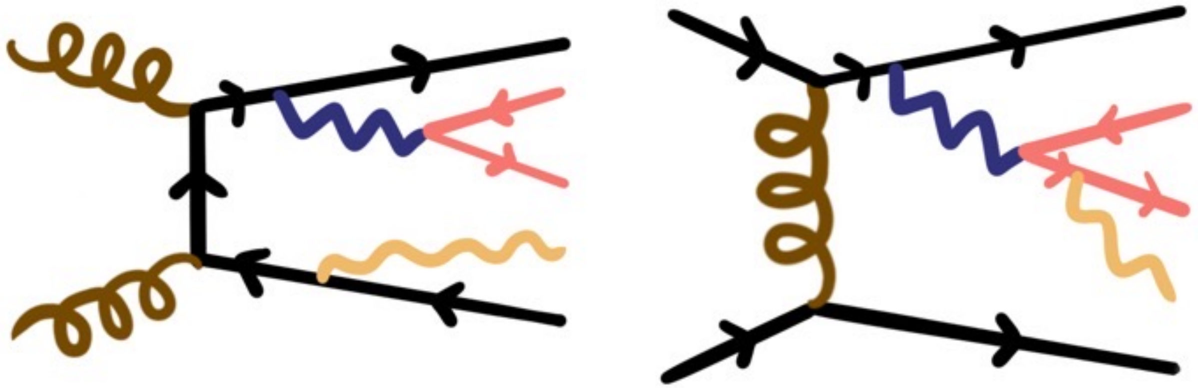
Electroweak production and backgrounds

Signal



Jets (quarks) are produced via electroweak interactions

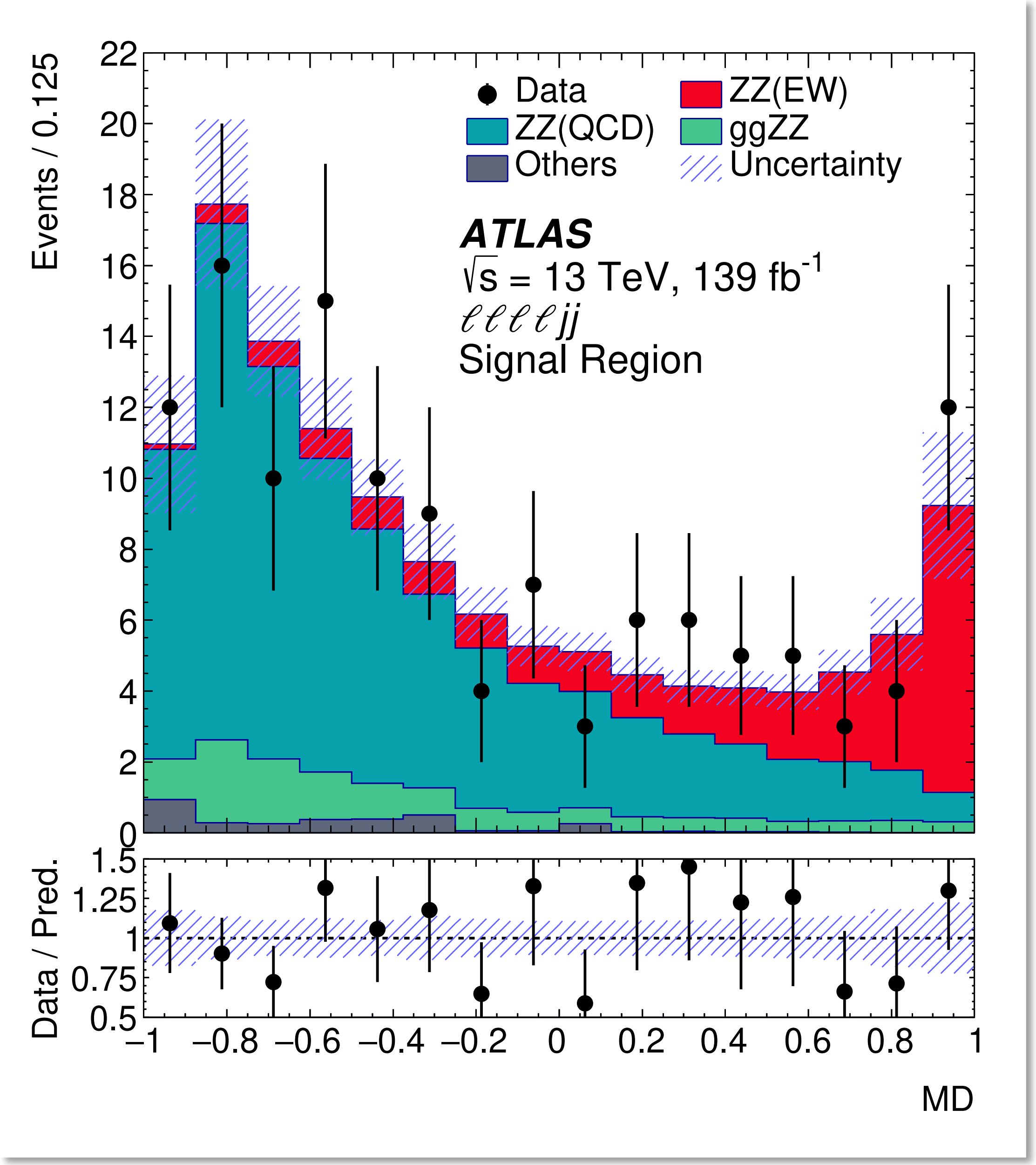
Background

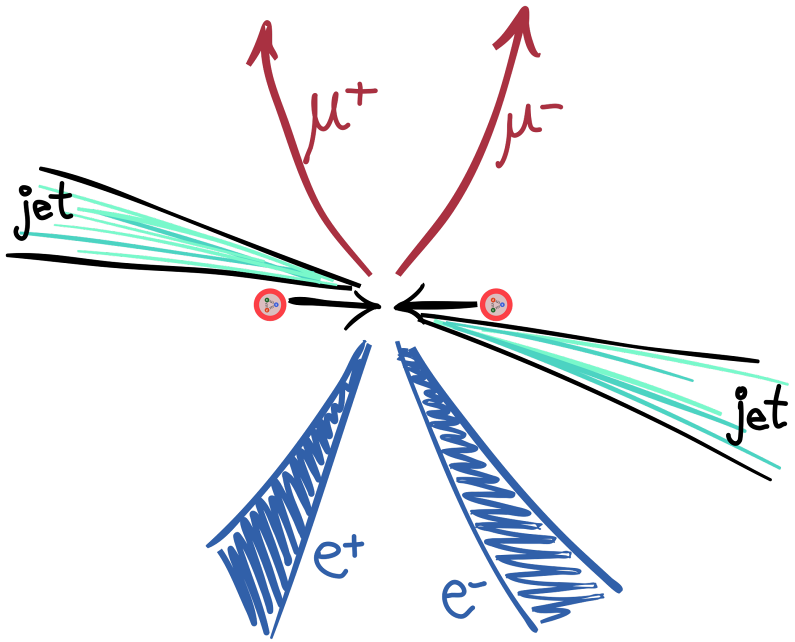


Jets (quarks) are produced via strong interactions

First observations @ the LHC - *ZZjj*

Nature Phys. 19 (2023) 237



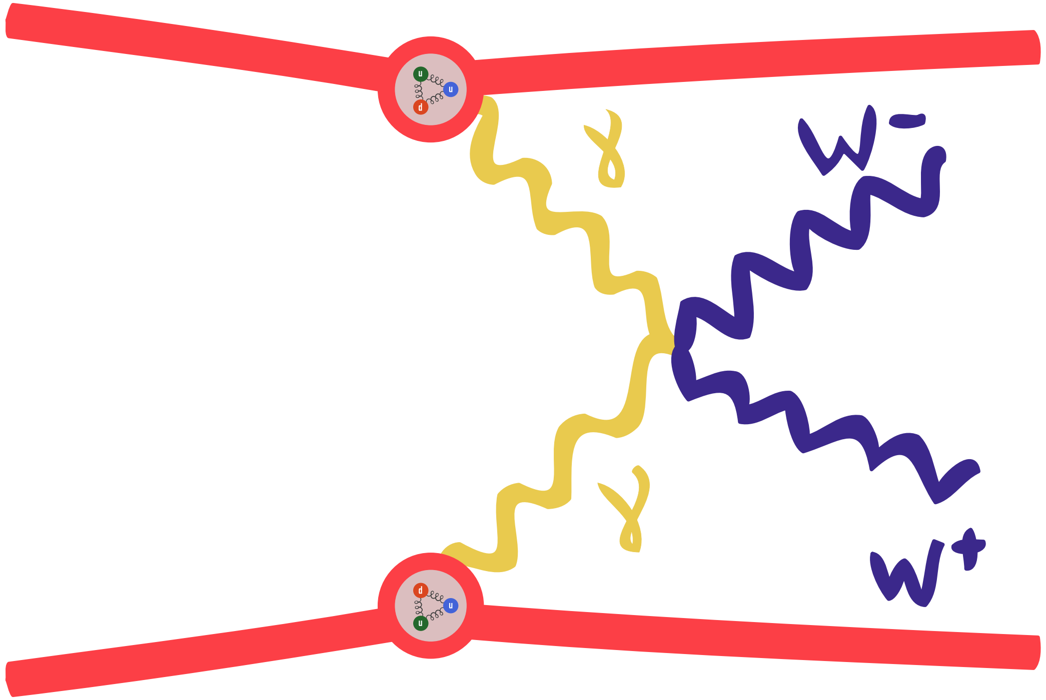


Observation of electroweak *ZZjj* production!

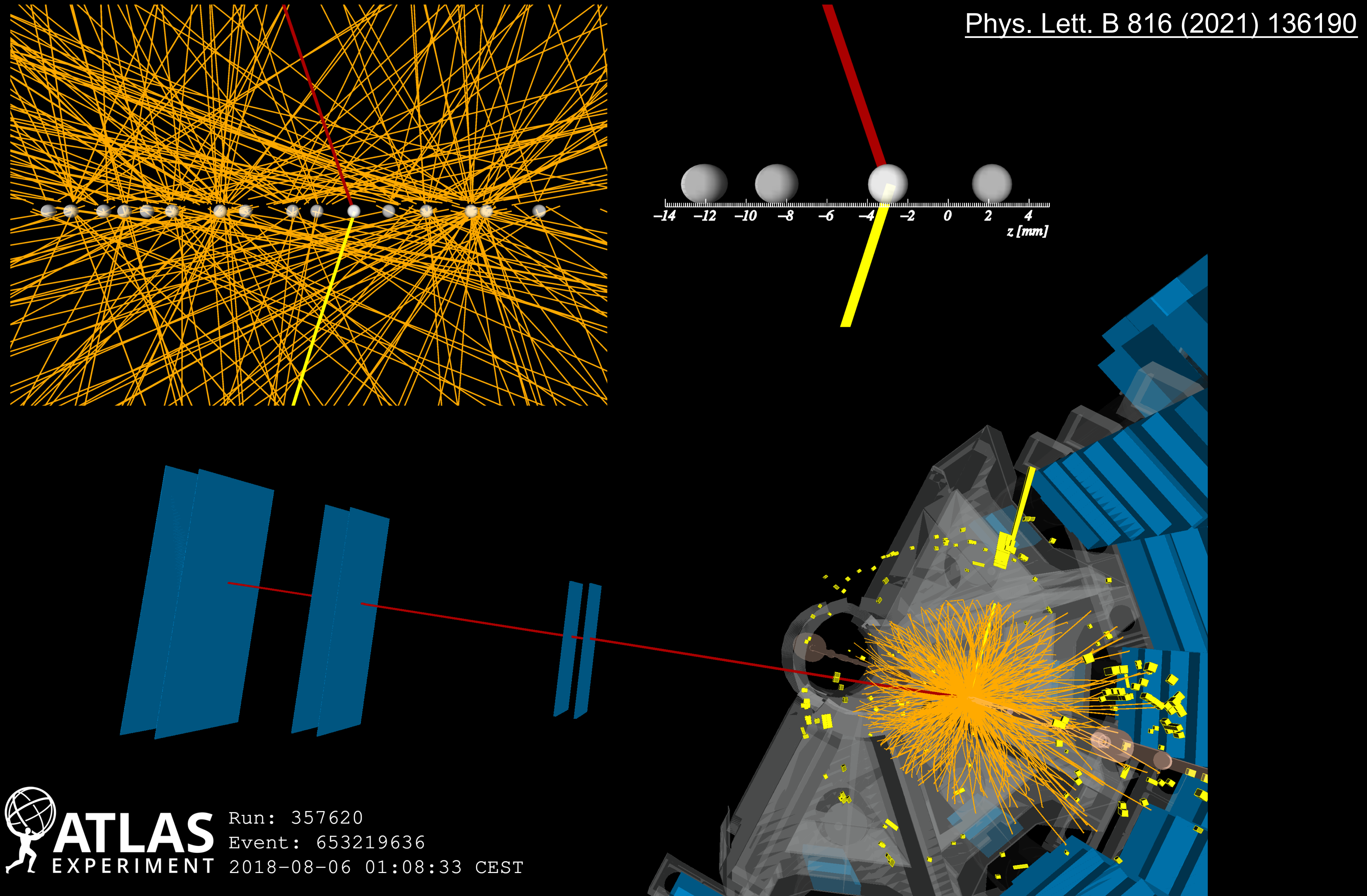
$$\sigma_{EW}^{ZZjj} = 0.82 \pm 0.21 \text{ fb}$$

➔ One of the smallest cross-sections observed/measured @ the LHC

LHC as a photon collider



- **Protons** (and ions!) can radiate photons
- If photons are radiated from both beams, the photons can interact inelastically, while the protons themselves stay intact



Phys. Lett. B 816 (2021) 136190
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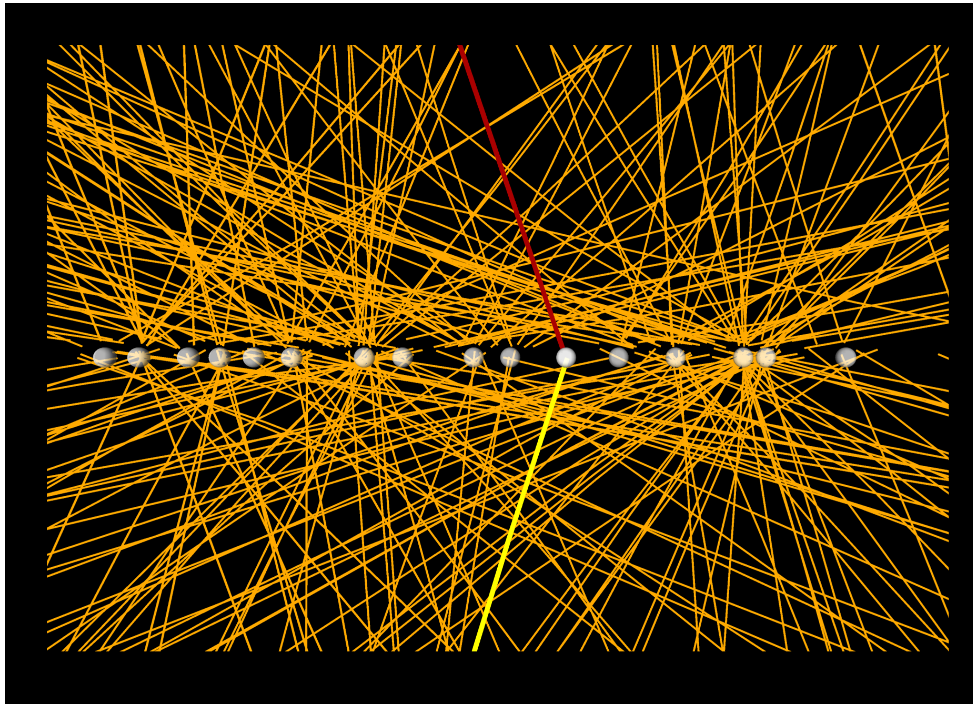
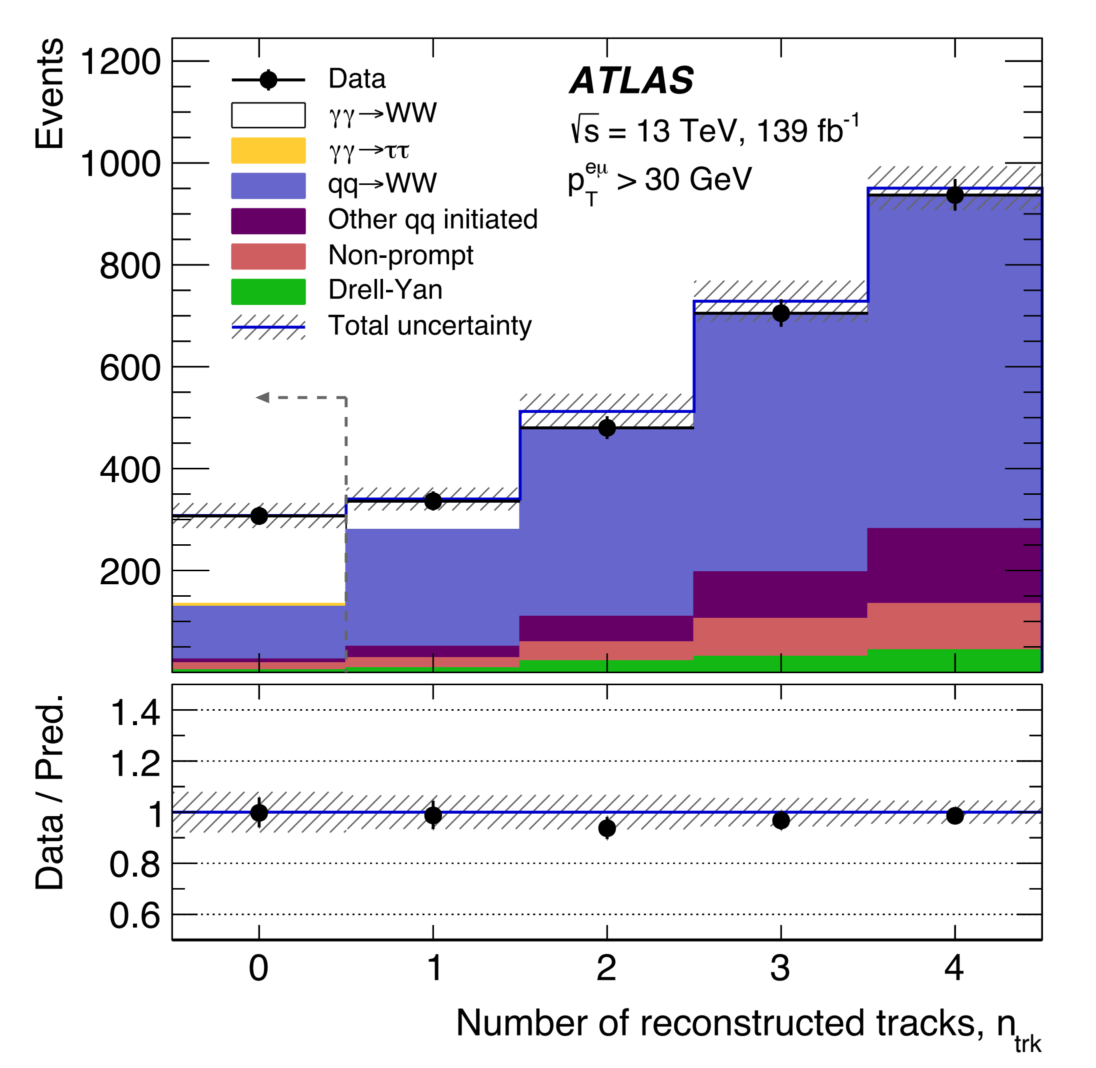
z [mm]
ATLAS
EXPERIMENT
Run: 357620
Event: 653219636
2018-08-06 01:08:33 CEST

LHC as a photon collider

Phys. Lett. B 816 (2021) 136190



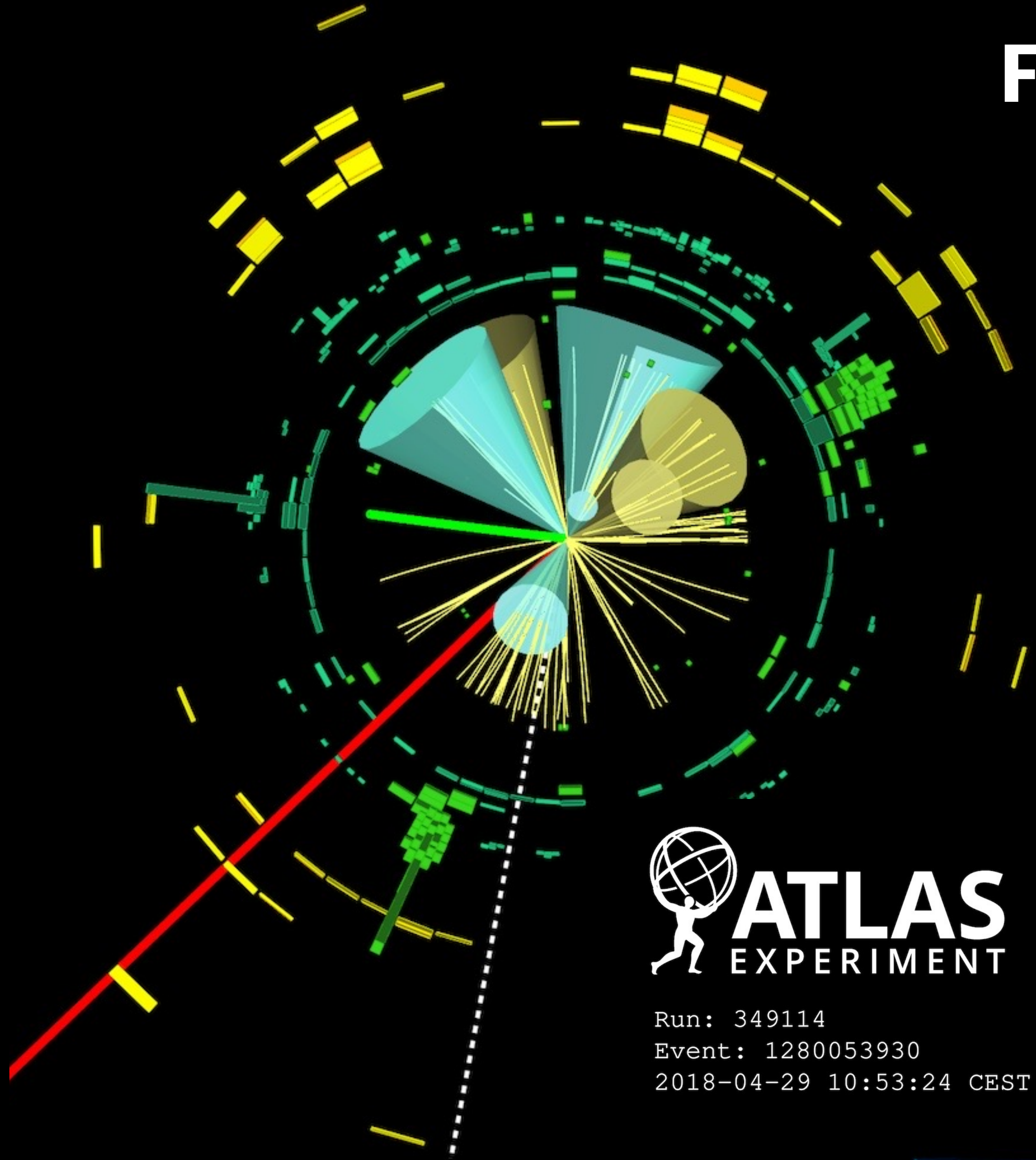


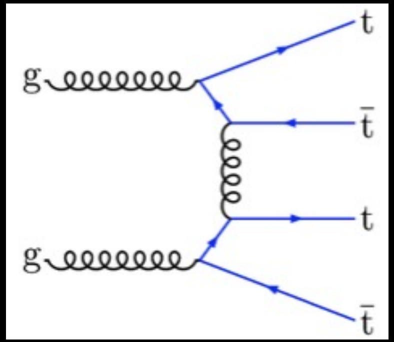
Observed significance: 8.4σ

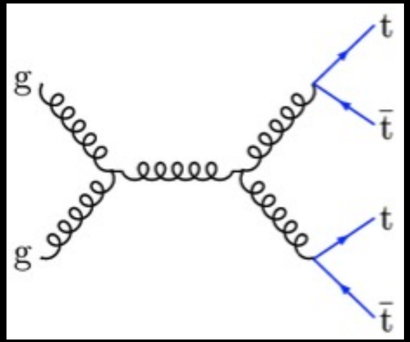
Fiducial cross-section of $\gamma\gamma \rightarrow WW$:
3.13 ± 0.31 (stat.) ± 0.28 (syst.) fb

3. What have we learned about the top quark at the LHC?

Four top quark production





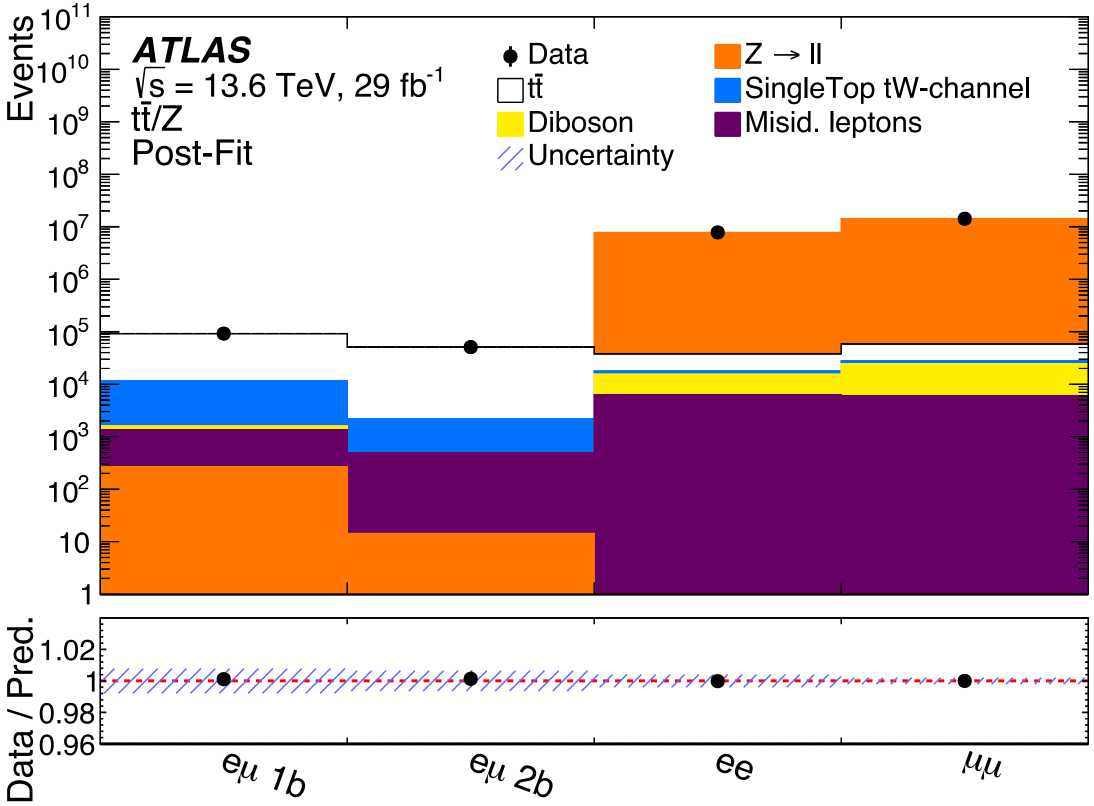


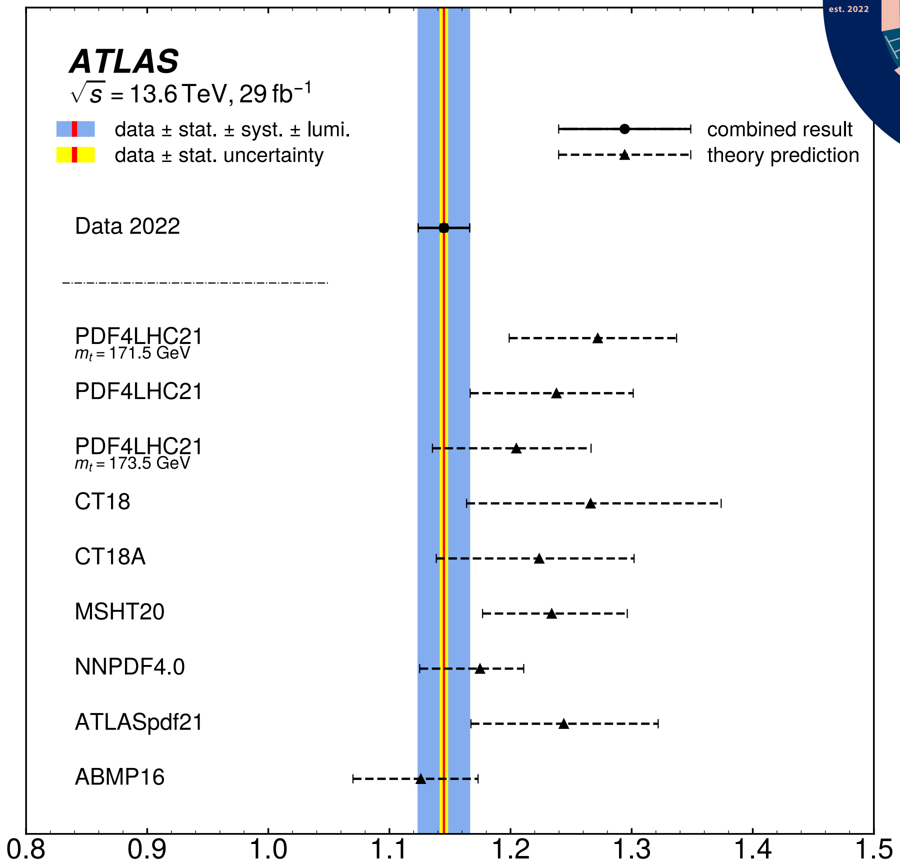
Each top quark decays to a *b* quark and a *W* boson

- many **different** possible final states
- **huge amount of activity** in the detector
- Observed significance of 4.3σ
  "evidence"

Eur. Phys. J. C 80 (2020) 1085

First Run 3 measurement - $t\bar{t}/Z$ ratio





$R_{t\bar{t}/Z}$

Ratio measurements allow for the cancellation of many experimental and theoretical uncertainties

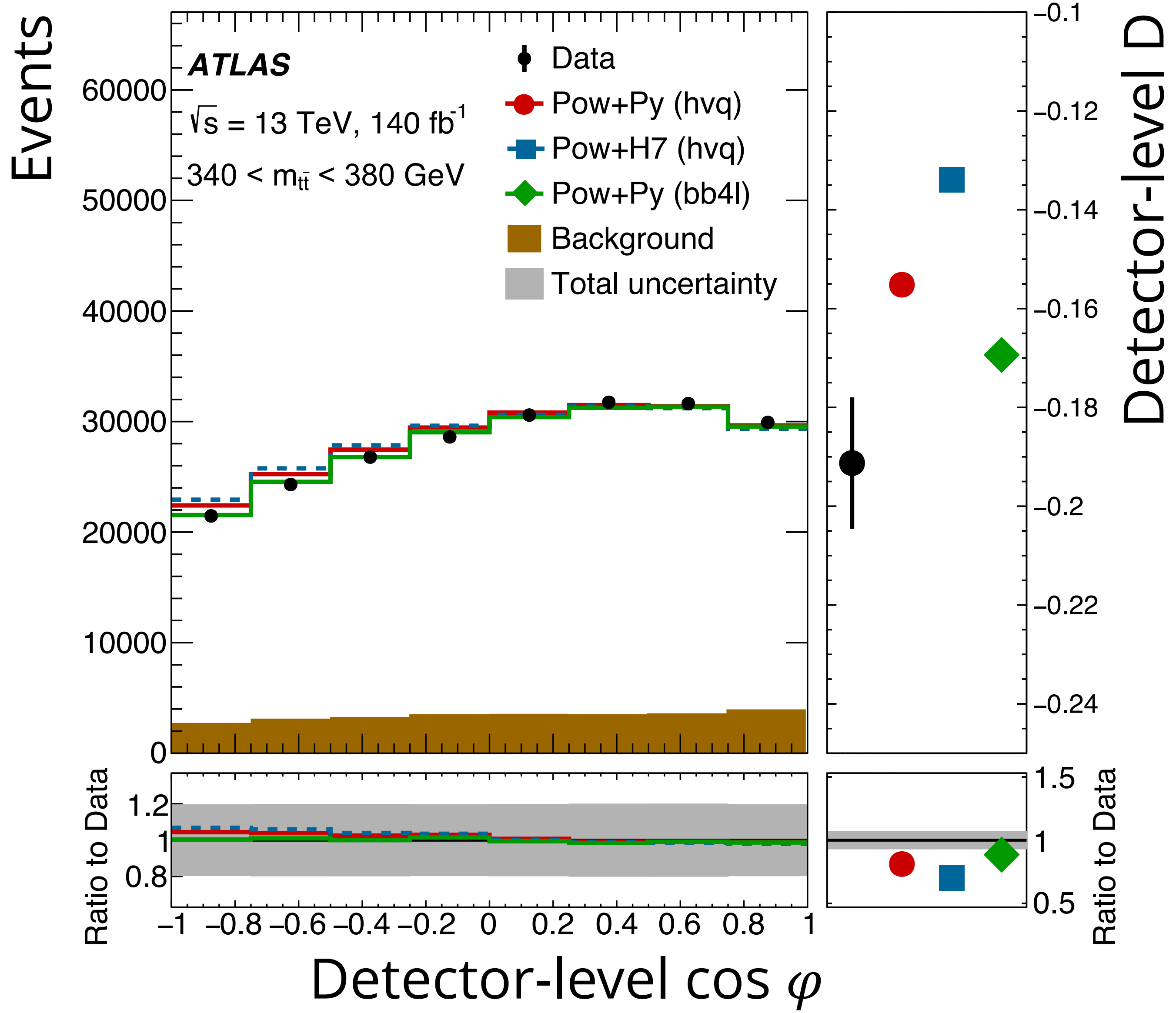
→ **Standard Model still operational at 13.6 TeV!**

Phys. Let. B 848 (2024) 138376

Observation of quantum entanglement

Calculate the **"entanglement marker" D** with cos φ, the scalar product of **lepton directions** in the *tt* rest frame:

$$D = -3 \cdot \langle \cos \varphi \rangle$$



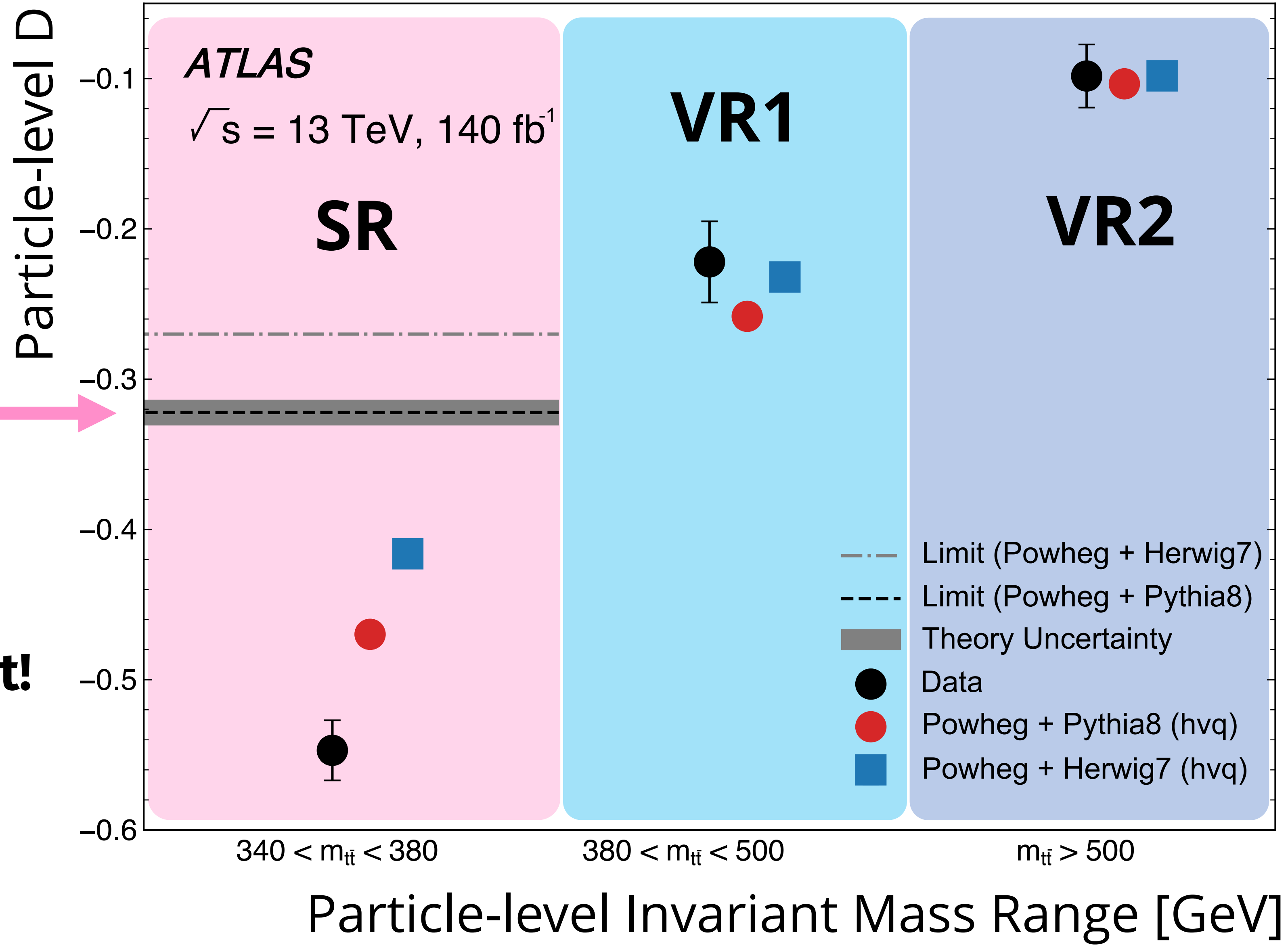
arXiv:2311.07288

Observation of quantum entanglement

Remove detector effects ("unfold") to **particle-level**

Observed value of D is below the -1/3 threshold for entanglement

➔ Highest-energy observation of entanglement!



arXiv:2311.07288

Where do we go next?

4. What is the Standard Model missing?

The Standard Model

force carriers

fermion interactions

$$\mathcal{L}_{\mathrm{SM}} = \boxed{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}} + \boxed{i\bar{\psi}\not{D}\psi}$$

Higgs field $\boxed{+D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi)}$

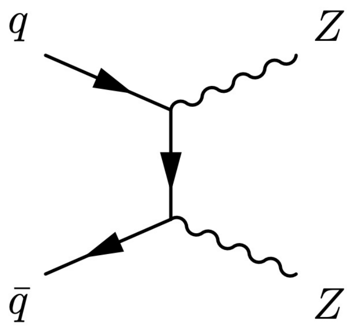
$\boxed{+\bar{\psi}_L\hat{Y}\Phi\psi_R + h.c.}$ fermion masses

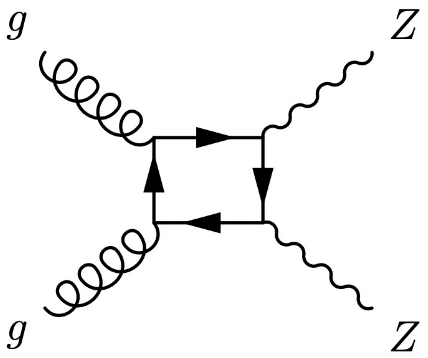
$+ \; \chi \; + \; \mathcal{L}_{CP} \; + \ldots$

Measurements as a tool for discovery

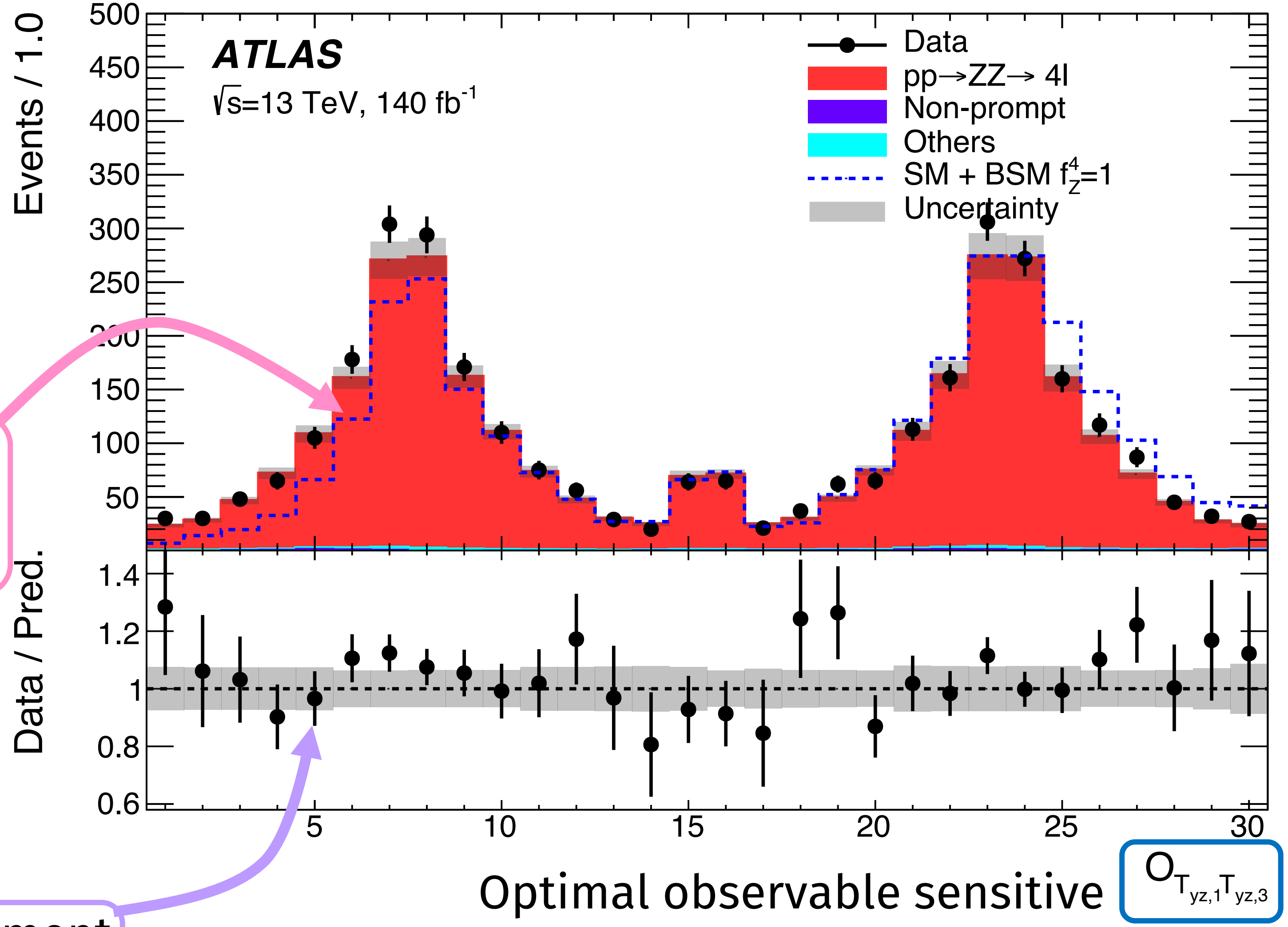
arXiv:2310.04350

Are electroweak interactions (e.g. the production of two *Z* bosons) as CP-conserving as the SM promises?





What we expect if there is an additional CP-odd interaction



Optimal observable sensitive to CP-odd effects

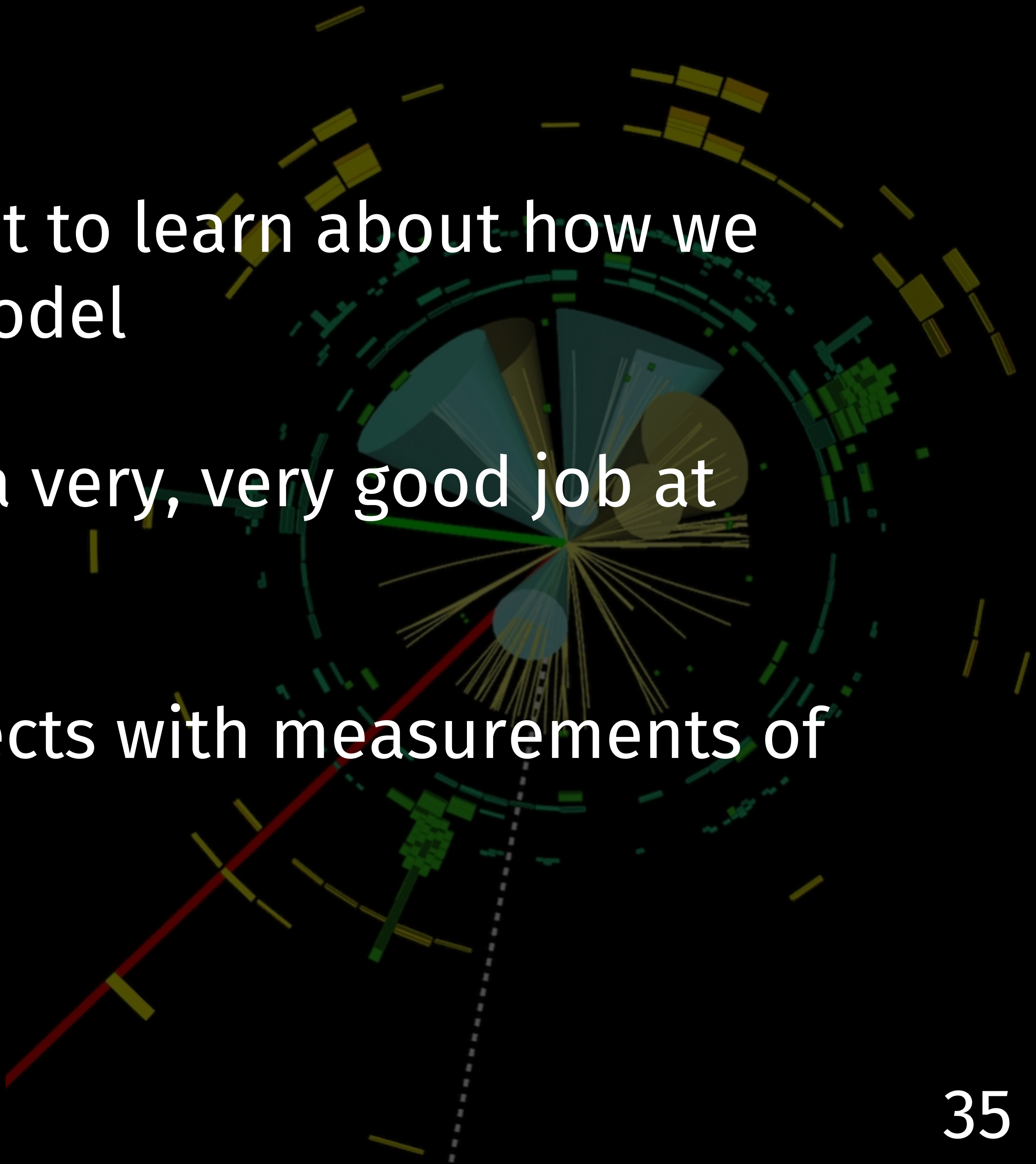
Our measurement matches the SM

what have we learned?

1. There is still a huge amount to learn about how we *implement* the Standard Model

2. The Standard Model does a very, very good job at describing LHC collisions

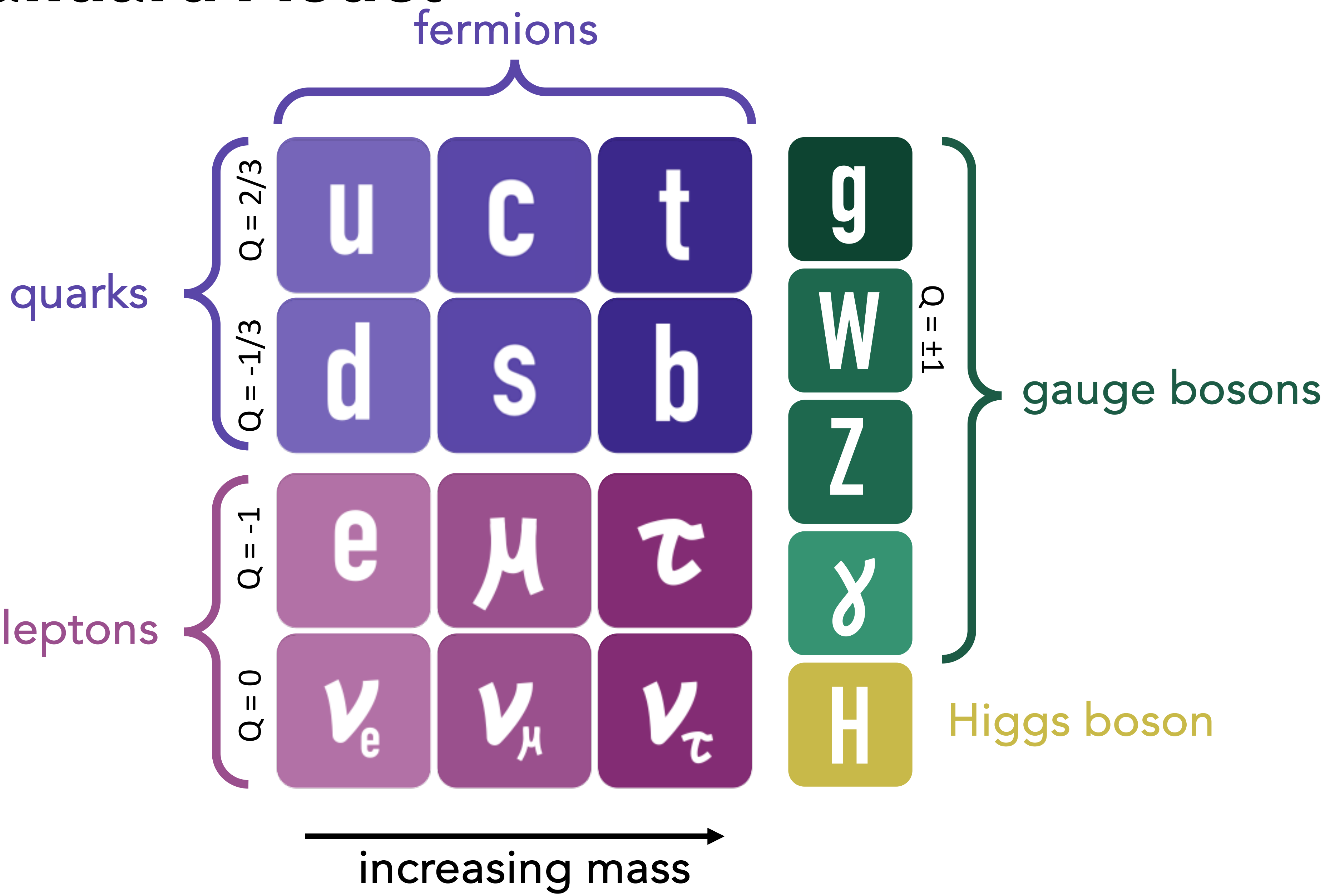
3. We can search for BSM effects with measurements of Standard Model processes



Some extra resources

- All public ATLAS results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome
- All ATLAS Physics Briefings:
  - https://atlas.cern/Updates/Briefing
- Excellent summary of top quark entanglement: https://indico.cern.ch/event/1328004/contributions/5664732/attachments/2763386/4812858/atlas_entanglement.pdf
- Visit ATLAS on google streetview: google streetview
- Watch me talk about how we select ATLAS events:
  - https://www.youtube.com/watch?v=06ICXSV72Y0

The Standard Model



The Standard Model

force carriers

fermion interactions

$$\mathcal{L}_{\mathrm{SM}} = \boxed{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}} + \boxed{i\bar{\psi}\not{D}\psi}$$

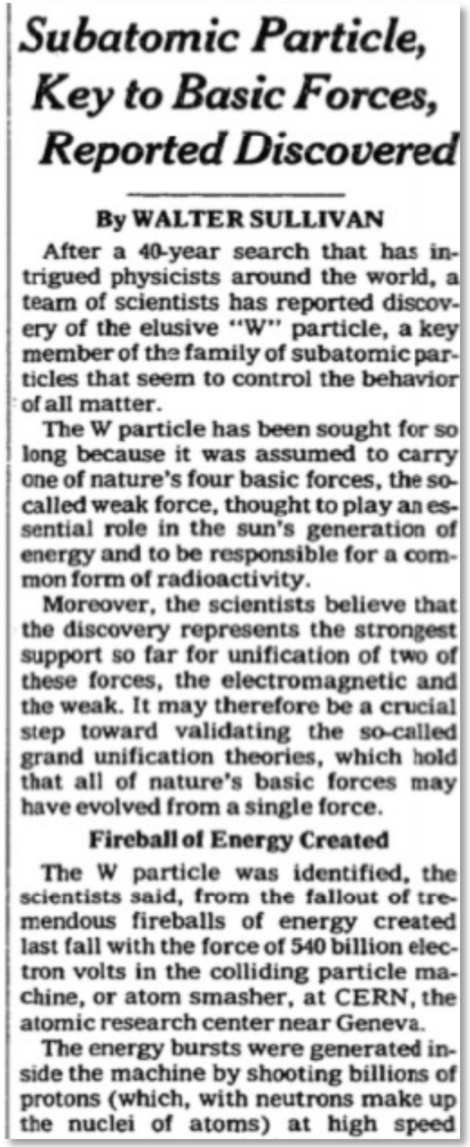
Higgs field

$$\boxed{+D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi)}$$

$$\boxed{+\bar{\psi}_L\hat{Y}\Phi\psi_R + h.c.}$$

fermion masses

Increasing importance?



Subatomic Particle, Key to Basic Forces, Reported Discovered

By WALTER SULLIVAN

After a 40-year search that has intrigued physicists around the world, a team of scientists has reported discovery of the elusive "W" particle, a key member of the family of subatomic particles that seem to control the behavior of all matter.

The W particle has been sought for so long because it was assumed to carry one of nature's four basic forces, the so-called weak force, thought to play an essential role in the sun's generation of energy and to be responsible for a common form of radioactivity.

Moreover, the scientists believe that the discovery represents the strongest support so far for unification of two of these forces, the electromagnetic and the weak. It may therefore be a crucial step toward validating the so-called grand unification theories, which hold that all of nature's basic forces may have evolved from a single force.

Fireball of Energy Created

The W particle was identified, the scientists said, from the fallout of tremendous fireballs of energy created last fall with the force of 540 billion electron volts in the colliding particle machine, or atom smasher, at CERN, the atomic research center near Geneva.

The energy bursts were generated inside the machine by shooting billions of protons (which, with neutrons make up the nuclei of atoms) at high speed

W boson, 1983

The New York Times

SENATE REJECTS AMENDMENT ON BALANCING THE BUDGET; CLOSE VOTE IS BLOW TO G.O.P.

Big Gambles, Lost Bets Sank a Venerable Firm

Elusive Atomic Particle Found by Physicists

Prosecutor Is Sympathetic, but Officer Is Indicted

top quark, 1995

"All the News That's Fit to Print"

The New York Times

NEW YORK, THURSDAY, JULY 5, 2012

Oil Backed Up, Iranians Put It On Idled Ships

Subterfuge at Tankers as Embargo Tightens

ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX

SHIFT RENEWS CRITICISM

Move Aligns Him With Conservative Voices Within His Party

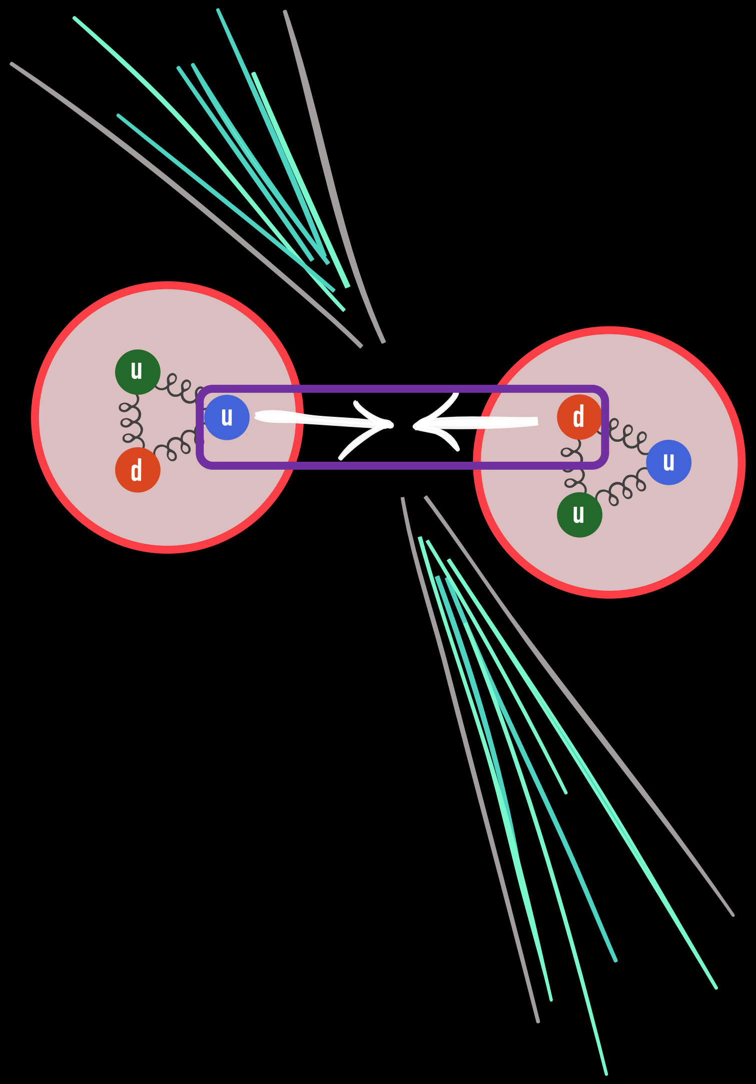
Physicists Find Elusive Particle Seen as Key to Universe

Date Night at the Zoo, if Rare Species Play Along

'I Think We Have It' Is Cheer of Day at

Higgs boson, 2012

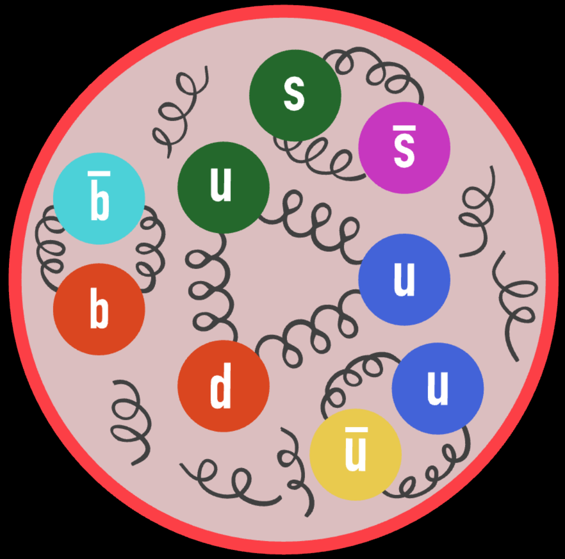
Proton-proton collisions



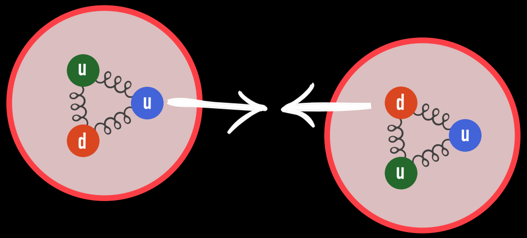
the quarks and gluons inside the proton undergo **inelastic** interactions and produce **new particles**

Proton-proton collisions

protons additionally contain a **sea** of quark-antiquark pairs and gluons, all of which can interact



When protons collide, **new particles** are produced

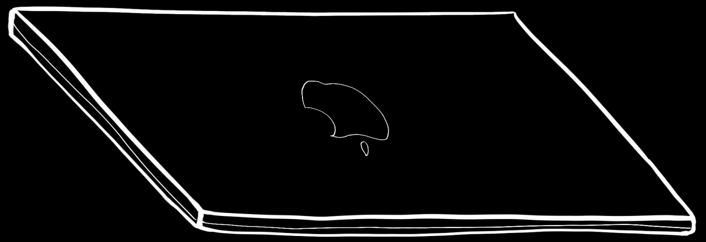


For example...

But why can’t we just save all collisions and check them out later, rather than filtering in real-time?

- Each collision is around 1 MB when we save it to disk

Laptop with
1 TB storage

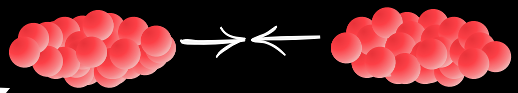


= ~ 1 million collisions
(1/30th of a second @ 30 MHz)

All data (2016):
300 petabytes

= ~ 300 billion collisions
(3 hours @ 30 MHz)

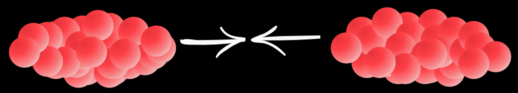
Proton-proton collisions

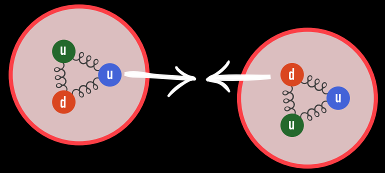


bunches collide every 25ns (with gaps → 30 MHz)

10^{11} protons!

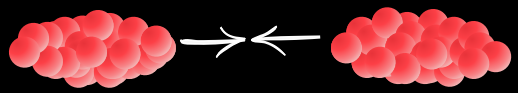
Proton-proton collisions

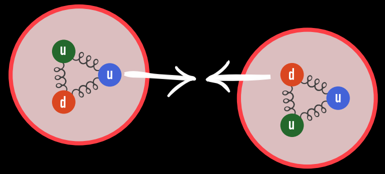




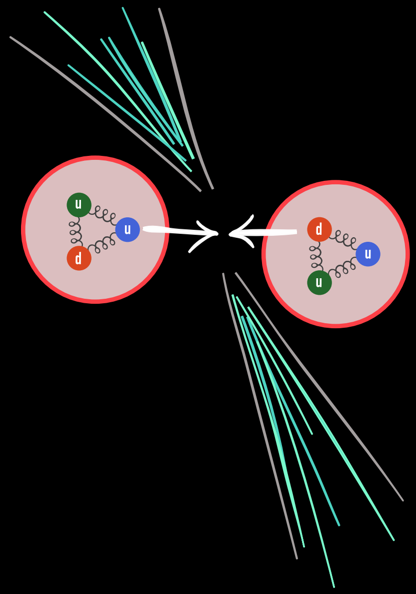
~36 p-p collisions **per bunch collision**

Proton-proton collisions



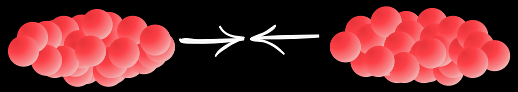


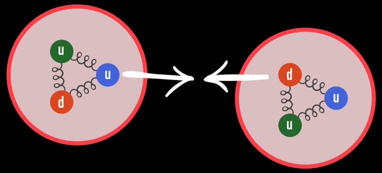
we choose interesting*
collisions to record
at ~1.5 kHz

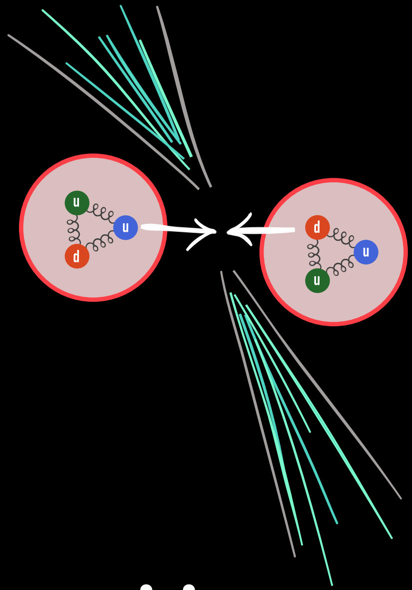


*subjective

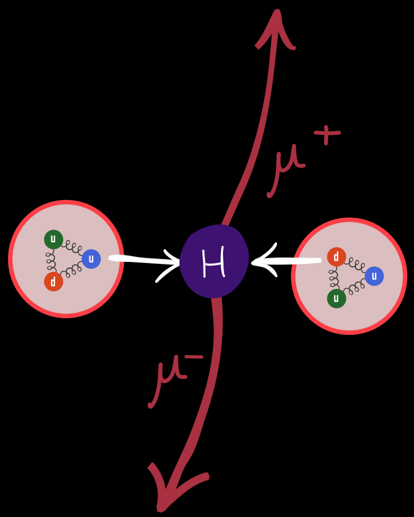
Proton-proton collisions



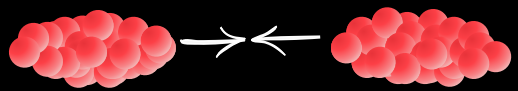


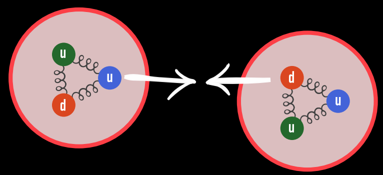


Some exciting, rare processes
occur as little as once per day!



Proton-proton collisions





we choose interesting*
collisions to record
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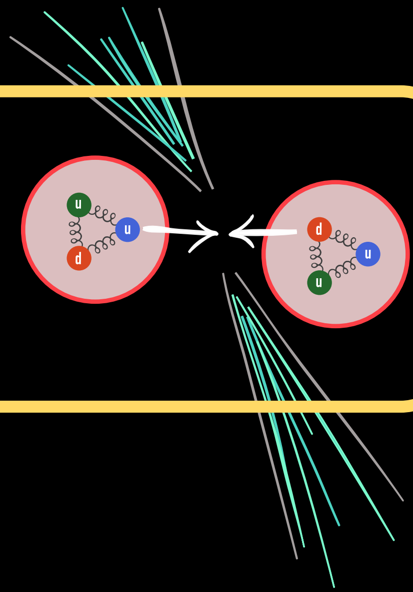
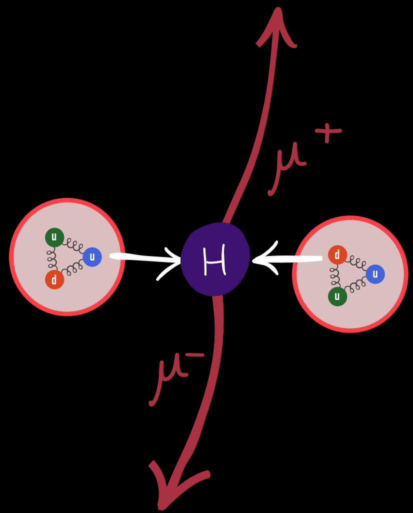




*subjective

How do we decide what types of events to save?

Things we know exist and want to study

Things that we've thought of that might exist that we want to search for

Things we haven't quite thought of yet but might want to look for in the future

How do we decide what types of events to save?

Things we know exist and want to study

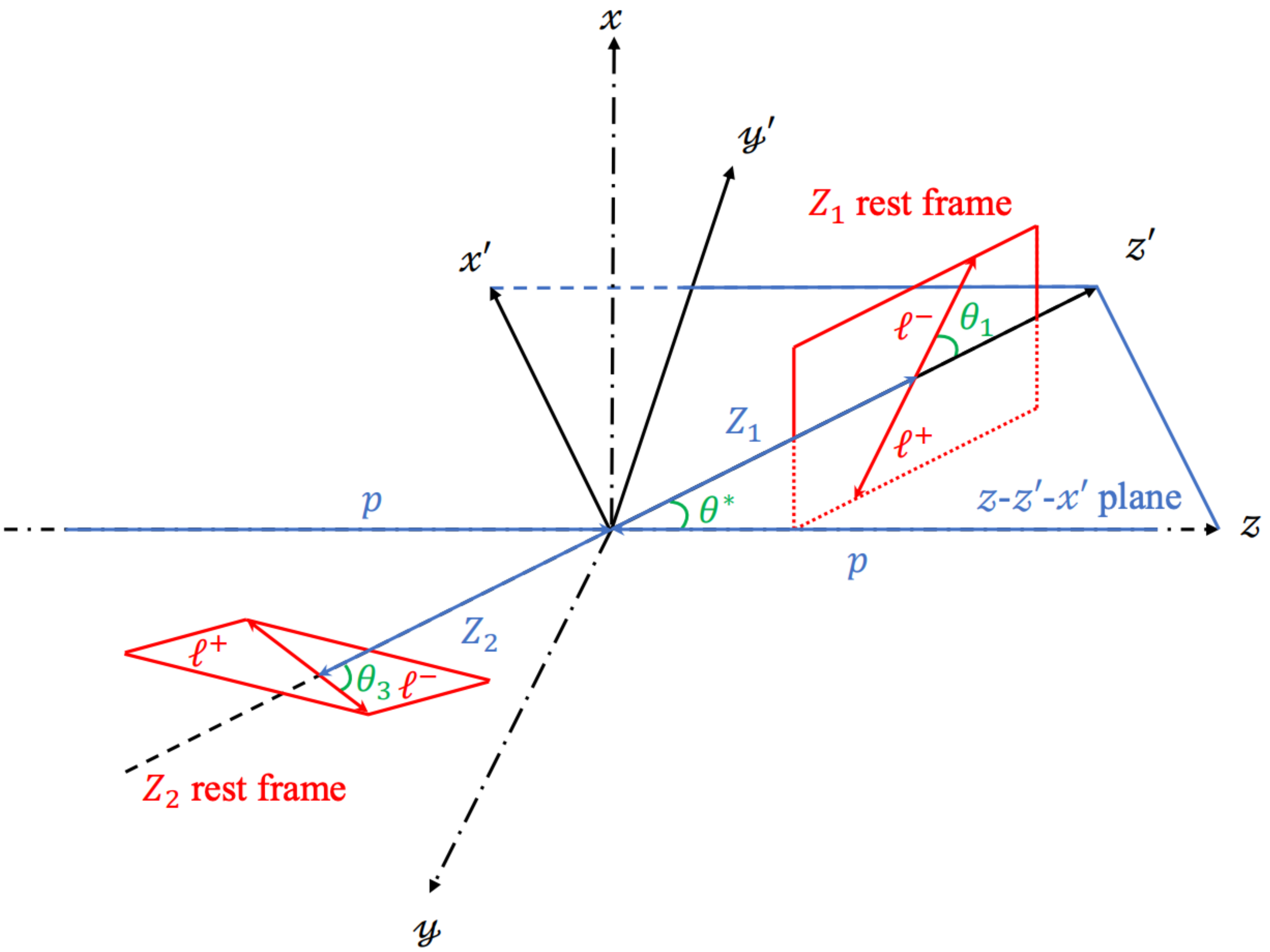
Things that we've thought of that might exist that we want to search for

Things we haven't quite thought of yet but might want to look for in the future

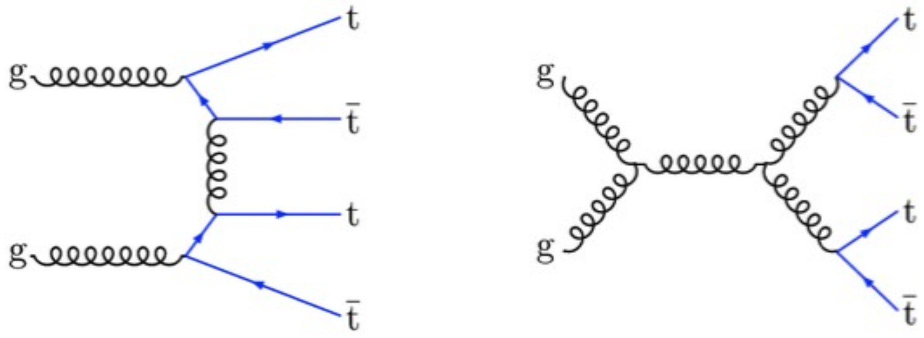
X

Angular variables for ZZ -> 4l CP properties

arXiv:2310.04350



Four top quark production

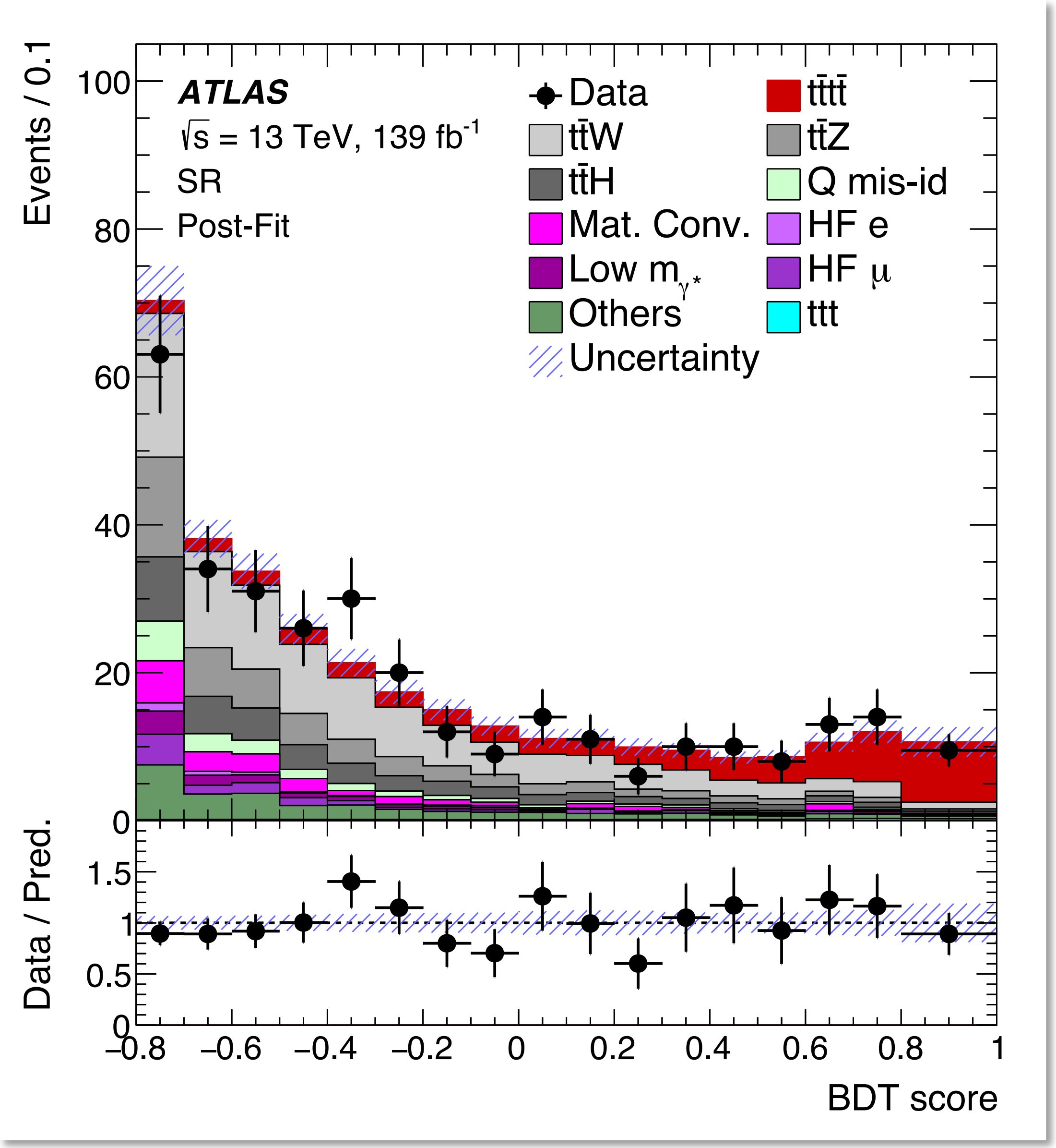


Each top quark decays to a *b* quark and a *W* boson

- many different possible final states

huge amount of activity in the detector

Observed significance of 4.3σ
(expected 2.4σ)

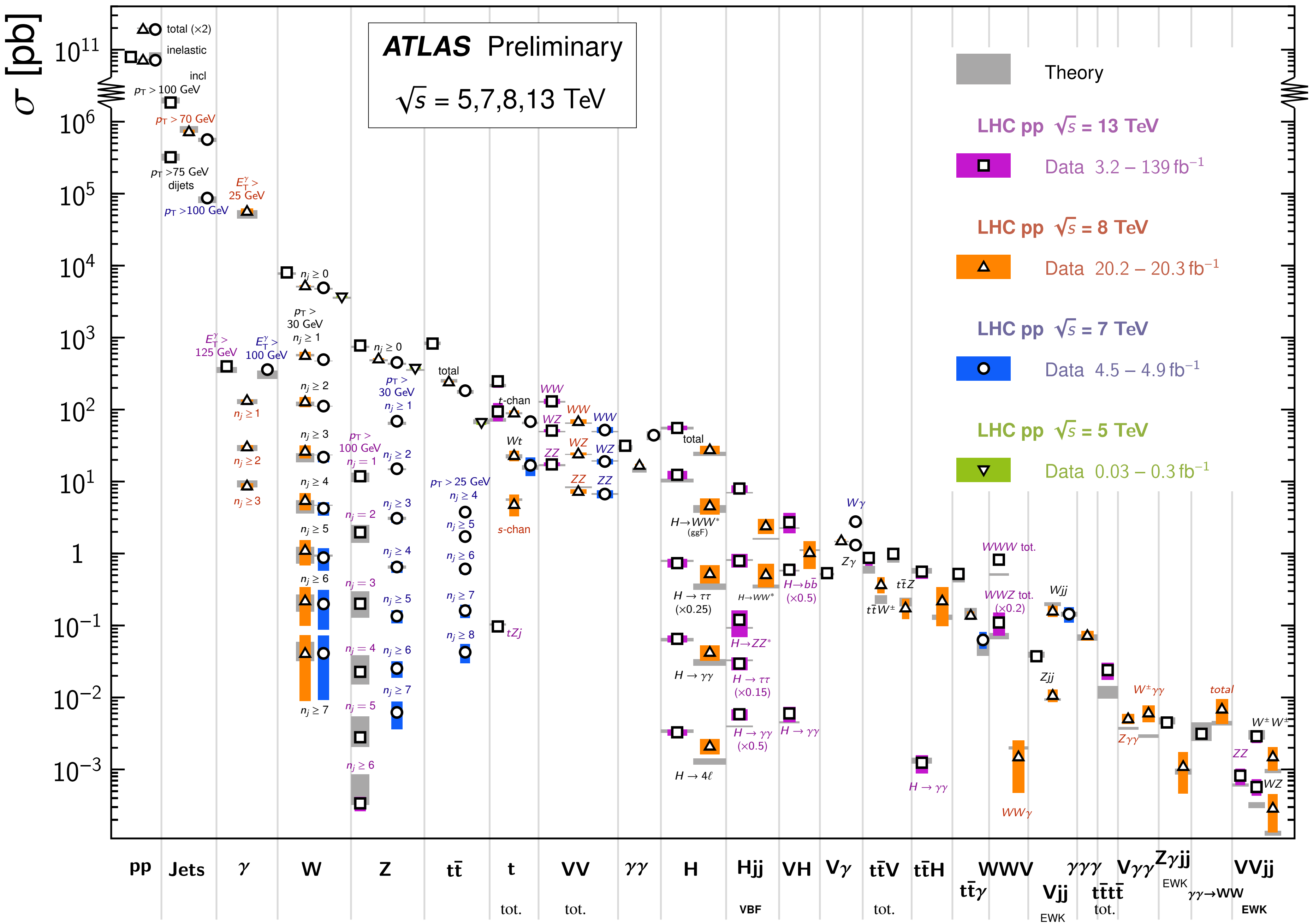


Eur. Phys. J. C 80 (2020) 1085

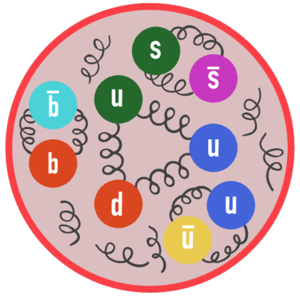
$$\mathcal{L}_{SM} = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2} \partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) -$$
$$igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)) - \frac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu -$$
$$Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \frac{1}{2} \partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \frac{1}{2} \partial_\mu\phi^0\partial_\mu\phi^0 -$$
$$\beta_h \Big(\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\Big) + \frac{2M^4}{g^2}\alpha_h -$$
$$g\alpha_h M (H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-) -$$
$$\frac{1}{8} g^2\alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2) -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2} g\frac{M}{c_w^2} Z^0_\mu Z^0_\mu H -$$
$$\frac{1}{2} ig \Big(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\Big) +$$
$$\frac{1}{2} g \Big(W^+_\mu (H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\Big) + \frac{1}{2} g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) +$$
$$M\,(\frac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+) - ig\frac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w M A_\mu (W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w} Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$
$$\frac{1}{4} g^2 W^+_\mu W^-_\mu (H^2 + (\phi^0)^2 + 2\phi^+\phi^-) - \frac{1}{8} g^2 \frac{1}{c_w^2} Z^0_\mu Z^0_\mu (H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-) -$$
$$\frac{1}{2} g^2\frac{s_w^2}{c_w} Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2} ig^2\frac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2} g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2} ig^2 s_w A_\mu H (W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^2 s_w^2 A_\mu A_\mu \phi^+\phi^- + \frac{1}{2} ig_s\, \lambda^a_{ij}(\bar q^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu - \bar e^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda(\gamma\partial + m_\nu^\lambda)\nu^\lambda - \bar u^\lambda_j(\gamma\partial +$$
$$m_u^\lambda)u^\lambda_j - \bar d^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu \Big(-(\bar e^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar d^\lambda_j\gamma^\mu d^\lambda_j)\Big) +$$
$$\frac{ig}{4c_w} Z^0_\mu \{(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar d^\lambda_j\gamma^\mu(\frac{4}{3} s_w^2 - 1 - \gamma^5)d^\lambda_j) +$$
$$(\bar u^\lambda_j\gamma^\mu(1 - \frac{8}{3} s_w^2 + \gamma^5)u^\lambda_j)\} + \frac{ig}{2\sqrt{2}} W^+_\mu \Big((\bar\nu^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\Big) +$$
$$\frac{ig}{2\sqrt{2}} W^-_\mu \Big((\bar e^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\Big) +$$
$$\frac{ig}{2M\sqrt{2}}\phi^+ \Big(-m_e^\kappa(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m_\nu^\lambda(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa) +$$
$$\frac{ig}{2M\sqrt{2}}\phi^- \Big(m_e^\lambda(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m_\nu^\kappa(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\Big) - \frac{g}{2}\frac{m_\nu^\lambda}{M}H(\bar\nu^\lambda\nu^\lambda) -$$
$$\frac{g}{2} \frac{m_e^\lambda}{M}H(\bar e^\lambda e^\lambda) + \frac{ig}{2}\frac{m_\nu^\lambda}{M}\phi^0(\bar\nu^\lambda\gamma^5\nu^\lambda) - \frac{ig}{2}\frac{m_e^\lambda}{M}\phi^0(\bar e^\lambda\gamma^5 e^\lambda) - \frac{1}{4}\,\bar\nu_\lambda\, M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa -$$
$$\frac{1}{4}\,\bar\nu_\lambda\, M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa + \frac{ig}{2M\sqrt{2}}\phi^+\Big(-m_d^\kappa(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\Big) +$$
$$\frac{ig}{2M\sqrt{2}}\phi^-\Big(m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\Big) - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) -$$
$$\frac{g}{2}\frac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar G^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar G^a G^b g^c_\mu +$$
$$\bar X^+(\partial^2 - M^2)X^+ + \bar X^-(\partial^2 - M^2)X^- + \bar X^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar X^0 X^- -$$
$$\partial_\mu\bar X^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar Y X^- - \partial_\mu\bar X^+ Y) + igc_w W^-_\mu(\partial_\mu\bar X^- X^0 -$$
$$\partial_\mu\bar X^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar X^- Y - \partial_\mu\bar Y X^+) + igc_w Z^0_\mu(\partial_\mu\bar X^+ X^+ -$$
$$\partial_\mu\bar X^- X^-) + igs_w A_\mu(\partial_\mu\bar X^+ X^+ -$$
$$\partial_\mu\bar X^- X^-) - \frac{1}{2} gM\Big(\bar X^+X^+H + \bar X^-X^-H + \frac{1}{c_w^2}\bar X^0X^0H\Big) + \frac{1-2c_w^2}{2c_w} igM\Big(\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-\Big) +$$
$$\frac{1}{2c_w} igM\Big(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\Big) + igMs_w\Big(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\Big) +$$
$$\frac{1}{2} igM\Big(\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0\Big)\,.$$

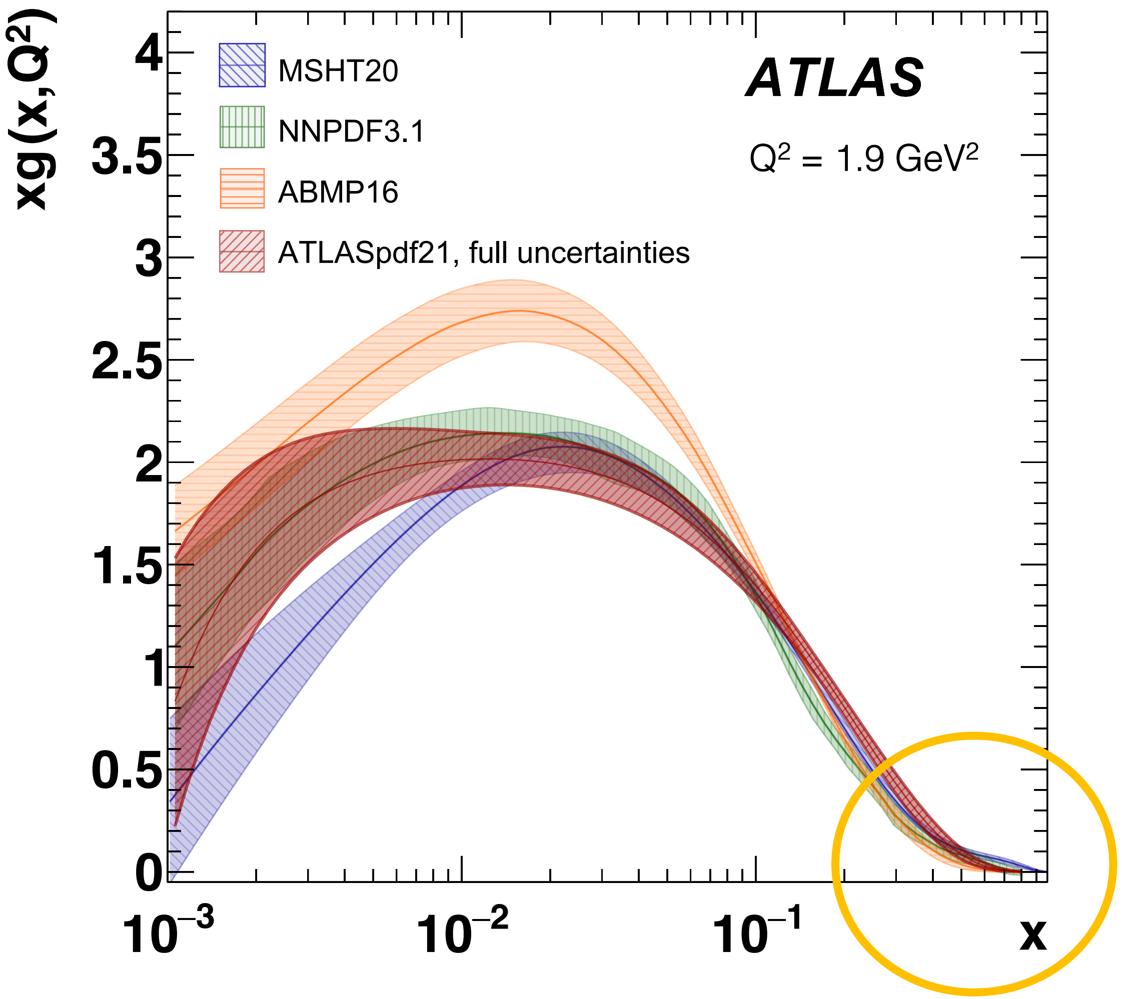
Standard Model Production Cross Section Measurements

Status: February 2022



Parton distribution functions





How much of a proton is gluons?

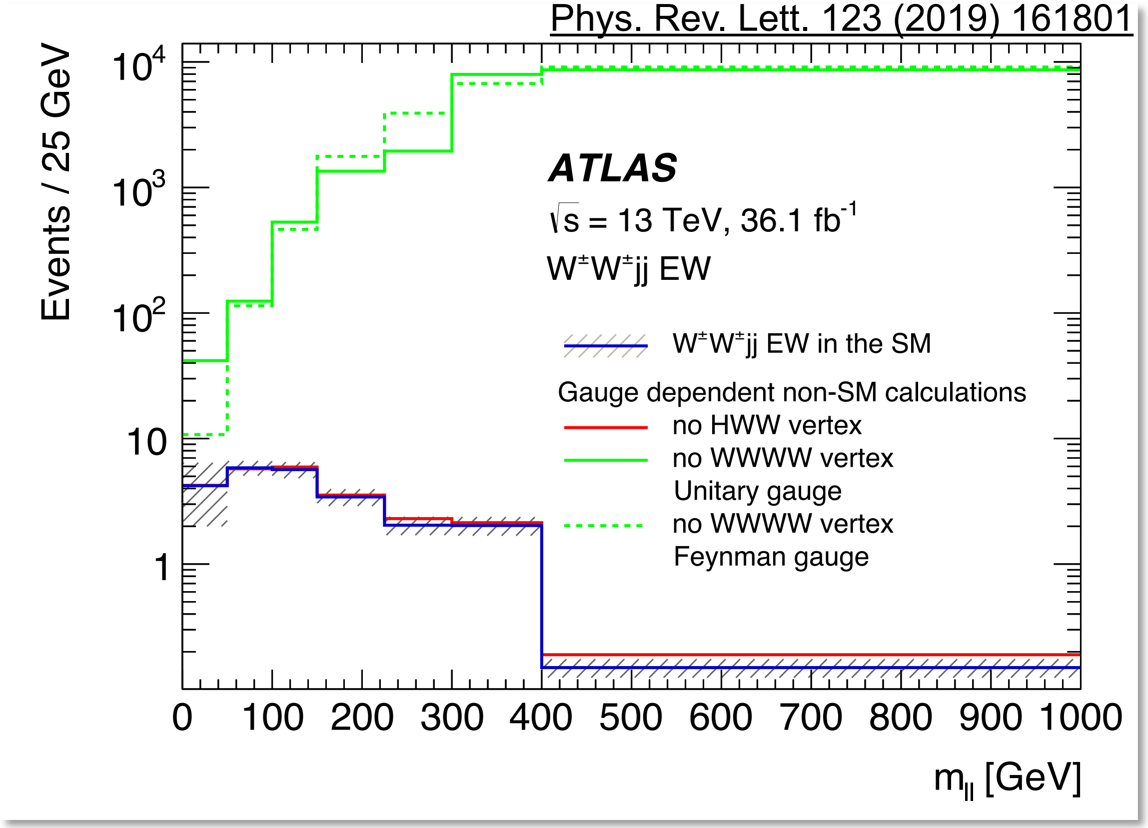
What fraction of the proton's energy do the gluons carry?

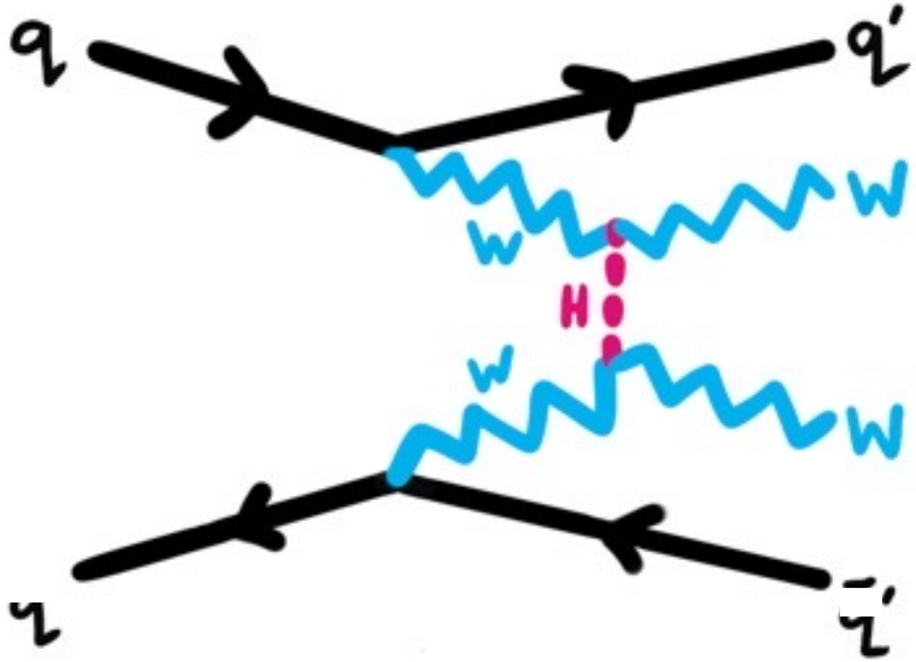
← The gluons that would make heavy new particles

[Eur. Phys. J. C 82 (2022) 438](https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2020-32/)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2020-32/

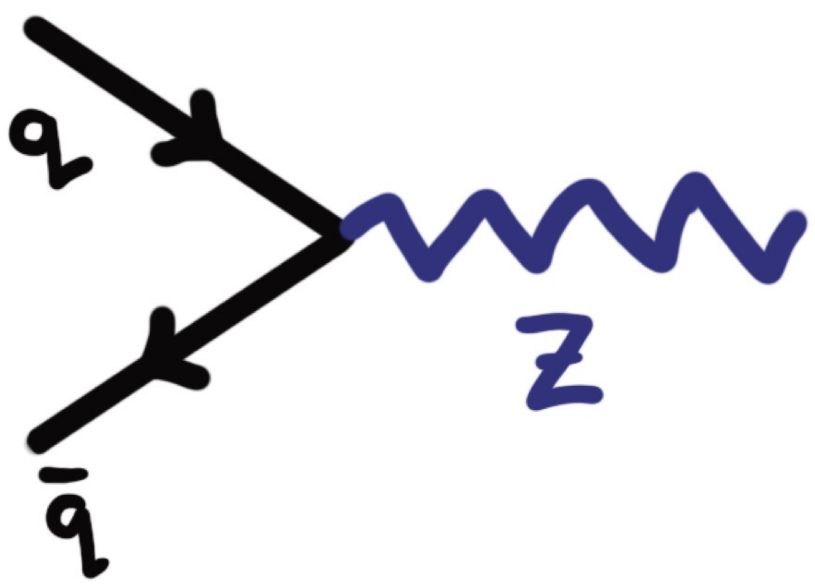
Vector boson scattering and unitarity



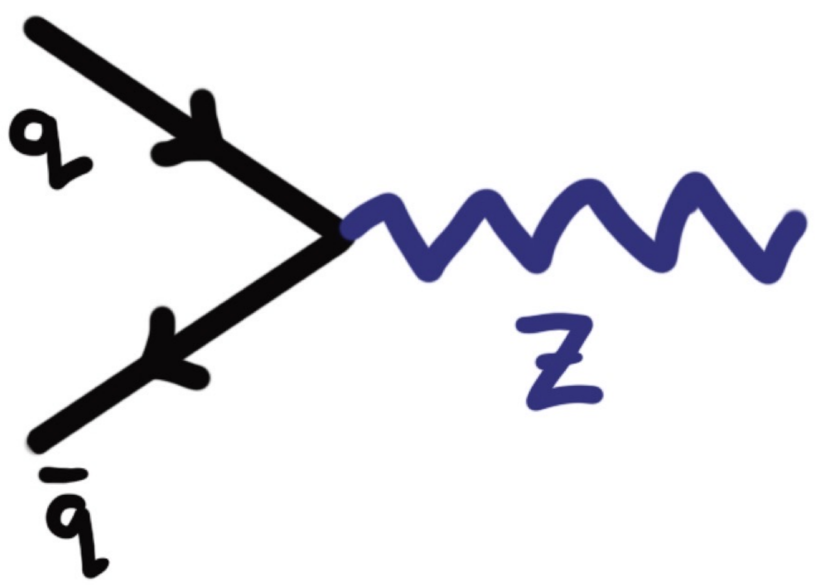


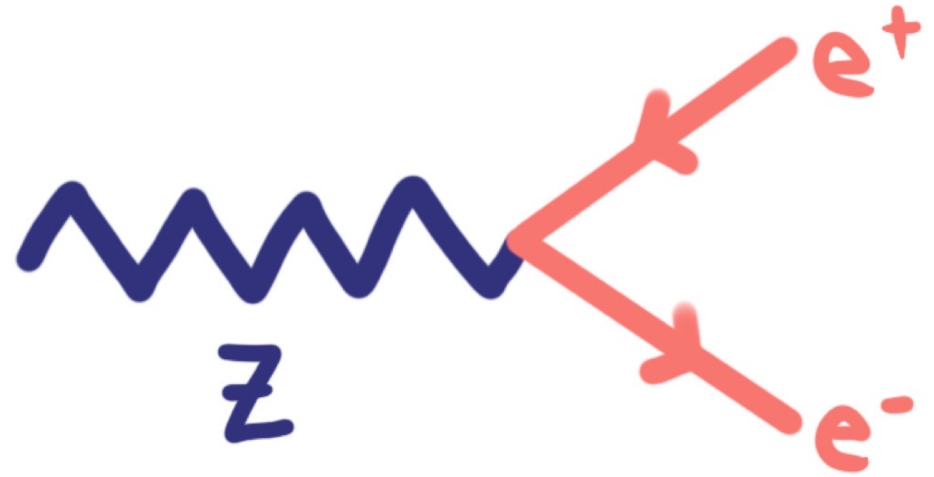
- Without the HWW vertex, do not have unitarity (rate explodes @ v. high energies)
  - VBS is an interesting probe of Higgs physics
- The calculation is gauge-dependent: different choices give different results
- We **measure** the coherent sum of all processes: electroweak production

Visualizing particle interactions

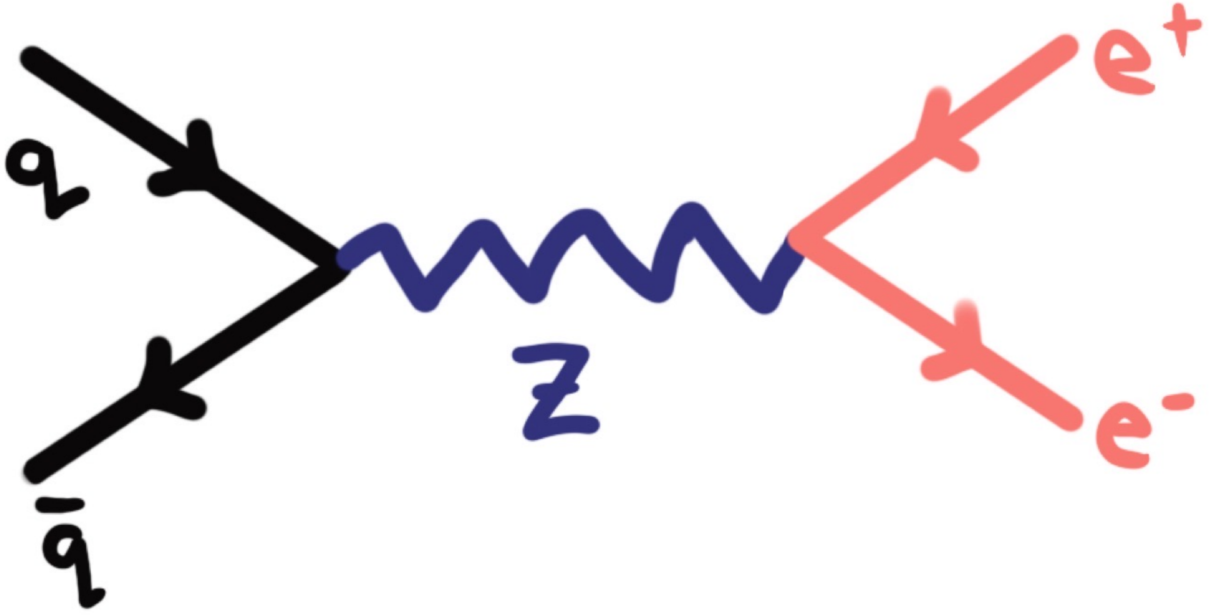


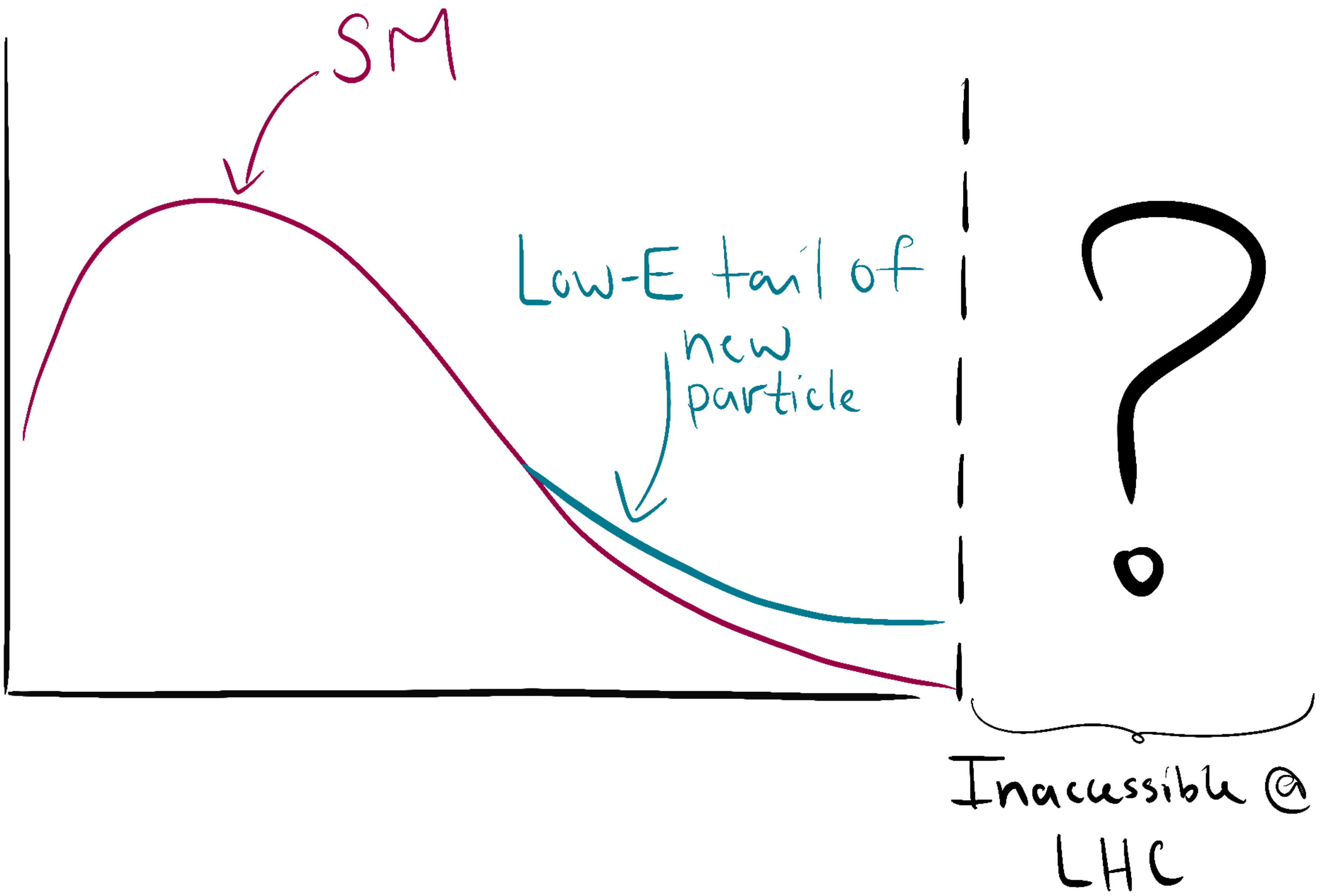
Visualizing particle interactions

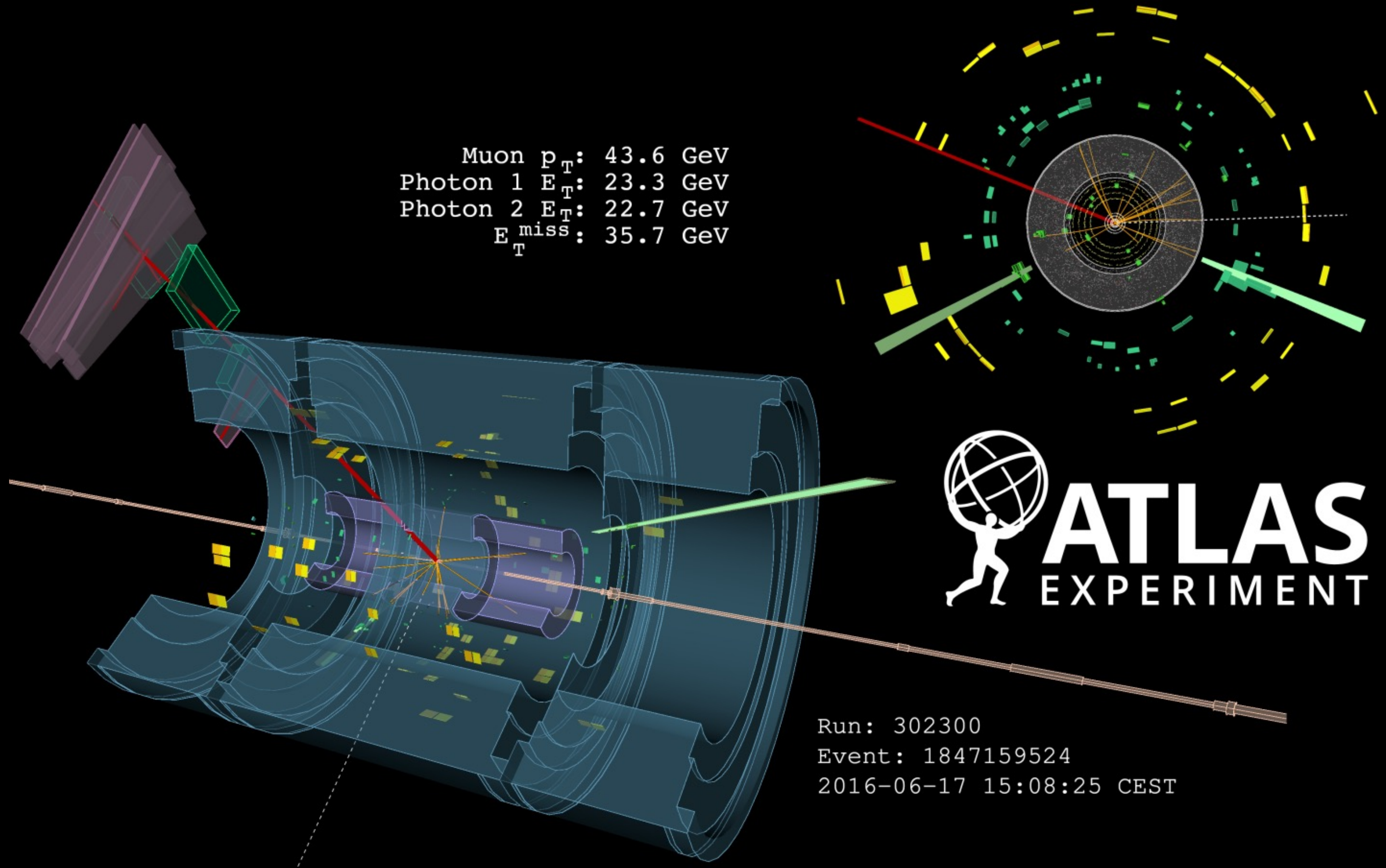




Visualizing particle interactions



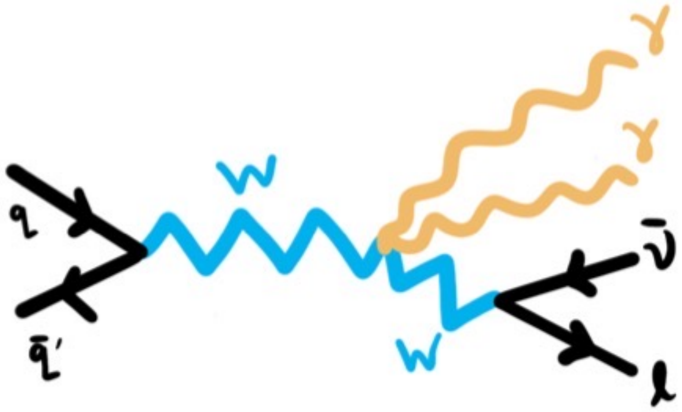

SM
Low-E tail of new particle
?
Inaccessible @ LHC



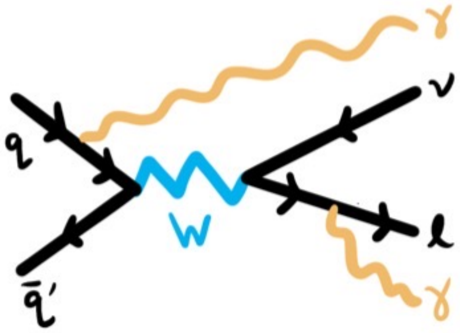
Muon p_T: 43.6 GeV
Photon 1 E_T: 23.3 GeV
Photon 2 E_T: 22.7 GeV
E_T^{miss}: 35.7 GeV
ATLAS
EXPERIMENT
Run: 302300
Event: 1847159524
2016-06-17 15:08:25 CEST

First observations @ the LHC – *Wγγ*

arXiv:2308.03041



The desired signal



Also signal

First observations @ the LHC – *Wγγ*

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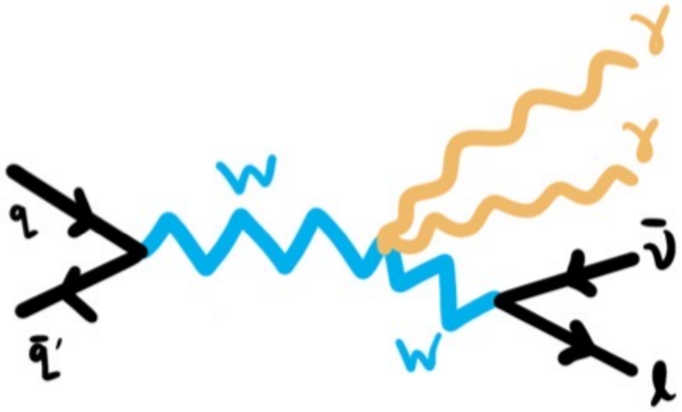
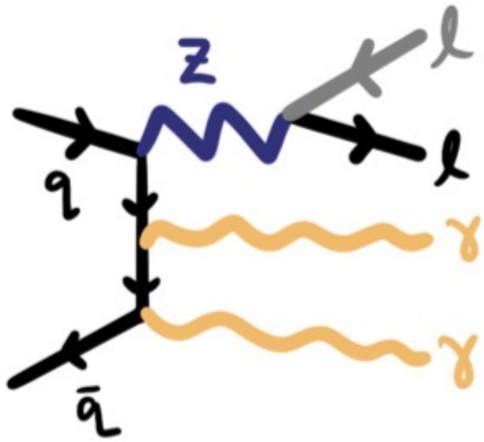
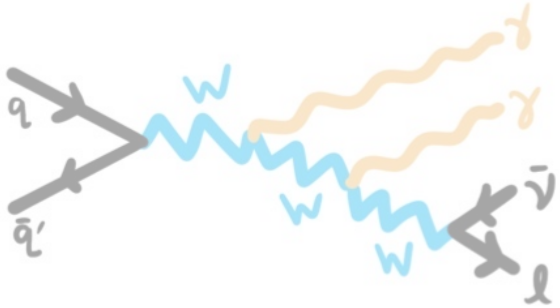


The desired signal



Irreducible backgrounds



Also signal

First observations @ the LHC – *Wγγ*

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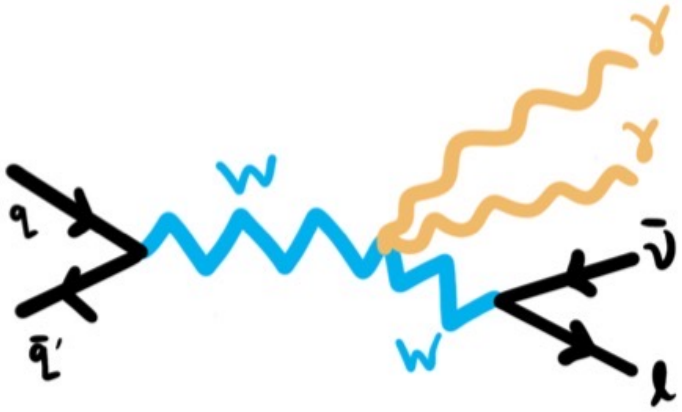
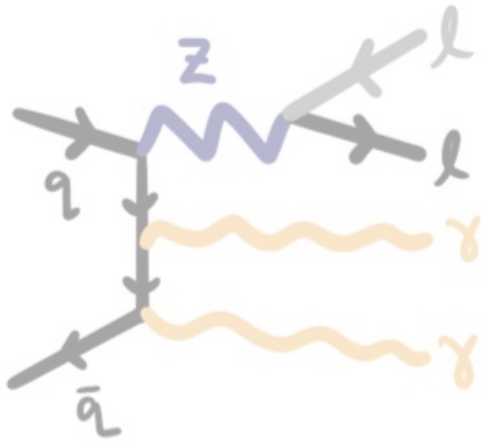
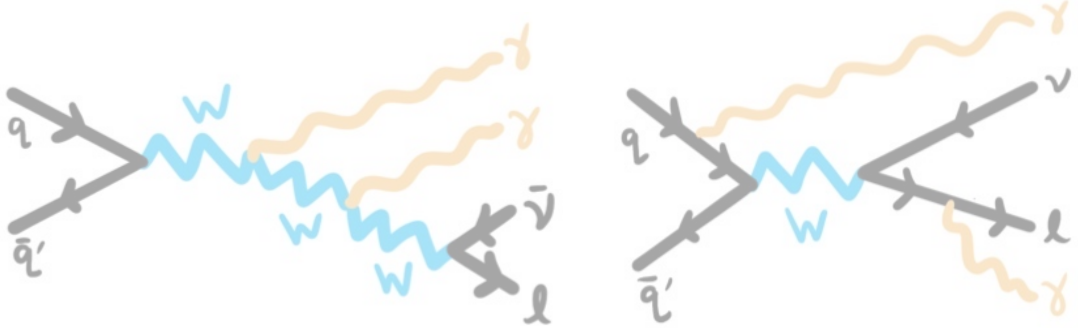


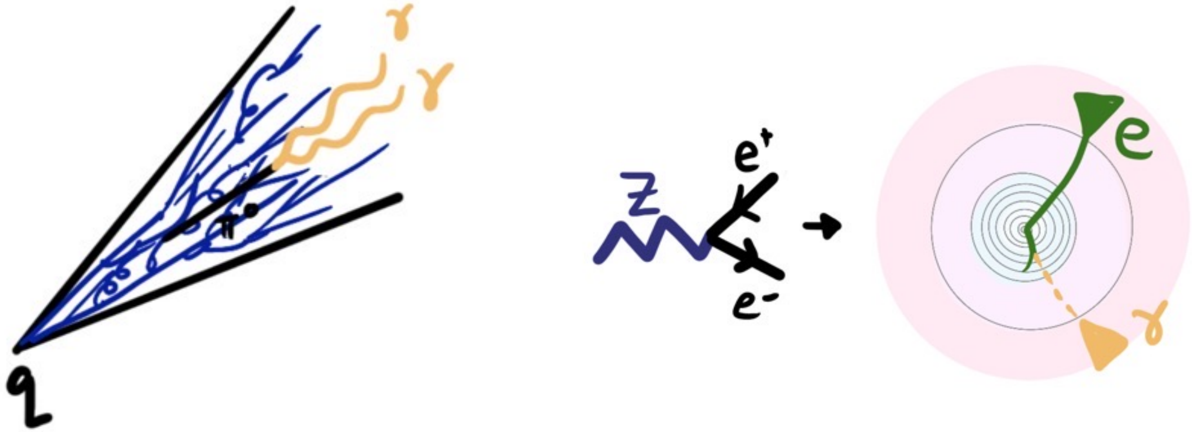
The desired signal



Irreducible backgrounds

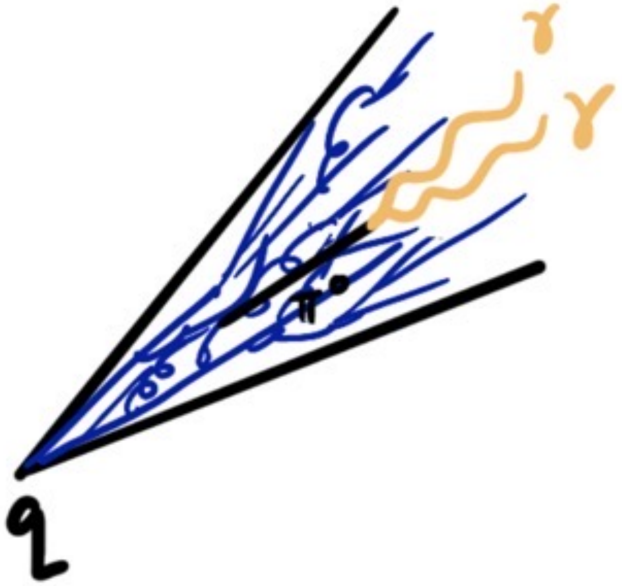


Also signal



Reducible “fake” backgrounds

First observations @ the LHC – *Wγγ*



- The LHC generates **a lot** of hadronic activity
- π^0 decays produced **two** (overlapping) photons

  shape of reconstructed photon is different

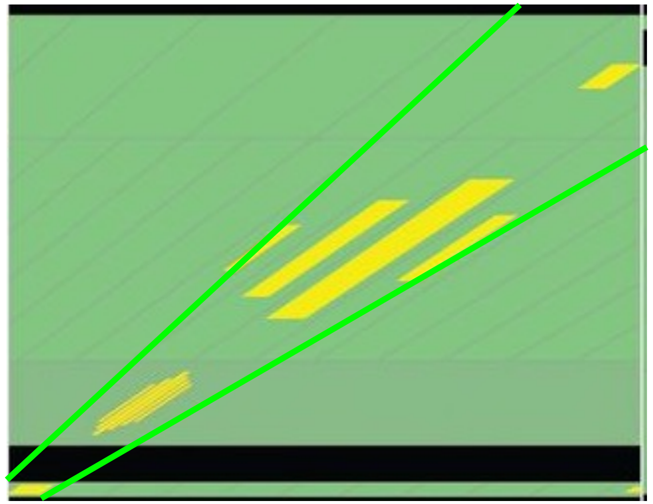
- photons are surrounded by hadronic activity

  photon is not *isolated*

…and either one or both photons could be “faked”:

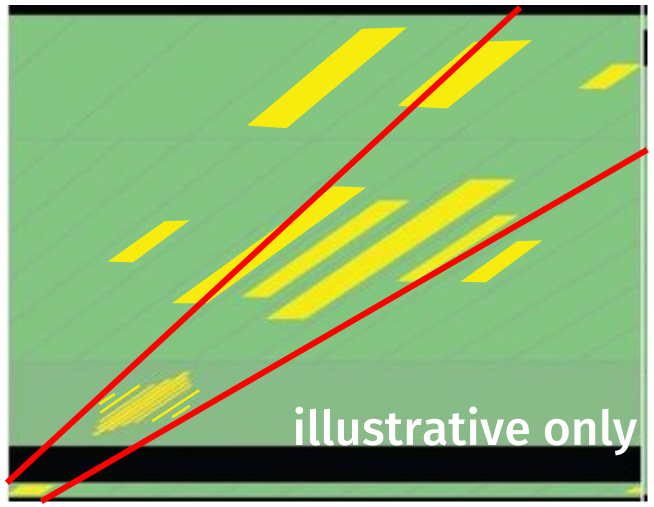
arXiv:2308.03041

First observations @ the LHC – *Wγγ*



Photon looks very photon-like

Photon is isolated in the calorimeters



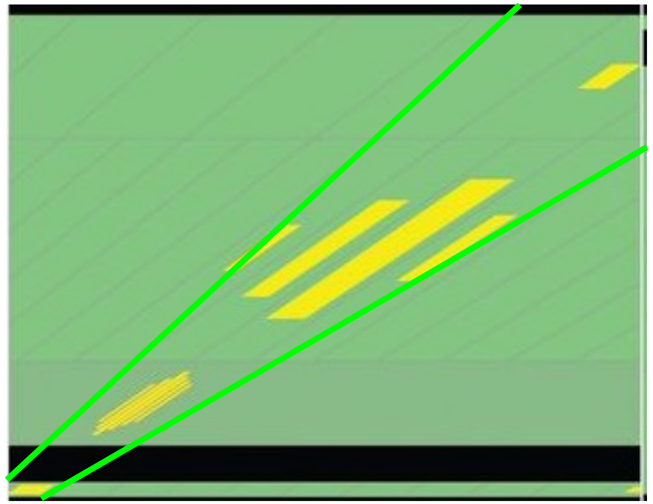
Photon looks very photon-like

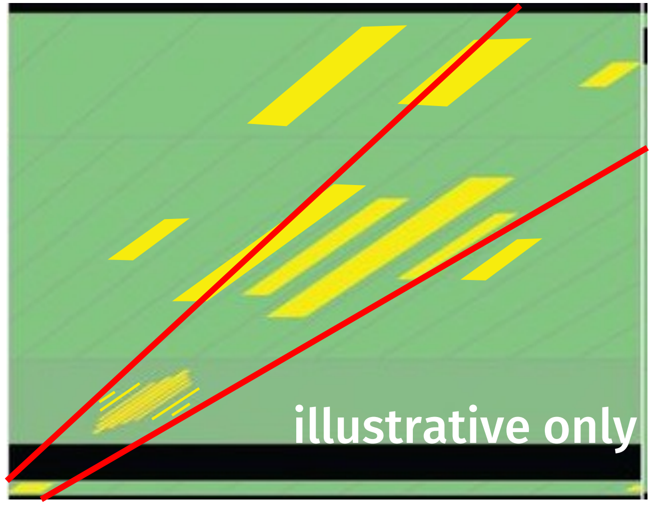
Photon has some energy surrounding it:

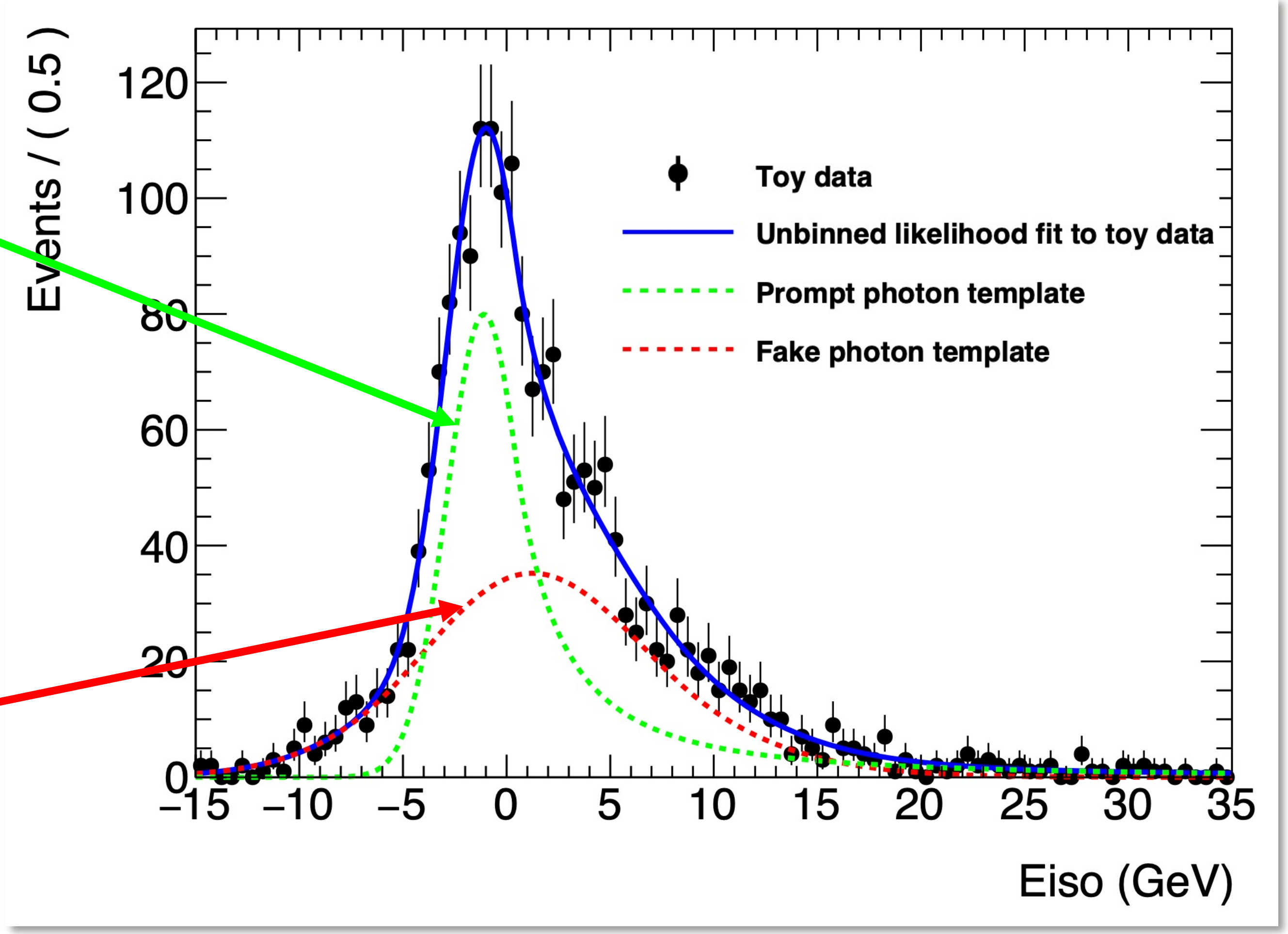
$$E_T^{iso} = \sum(\text{energy in surrounding cells})$$

Event displays from Science 338 (6114) 1576-1582

First observations @ the LHC – *Wγγ*







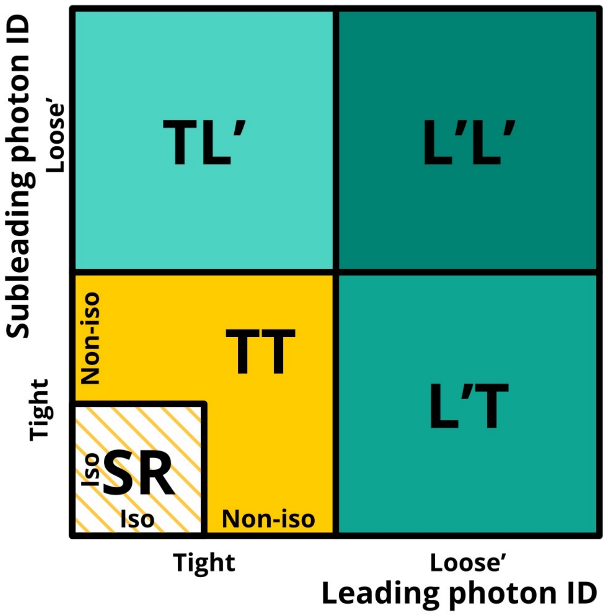
Data has **both** of these – **decompose** the distribution to measure how many photons are actually **background**

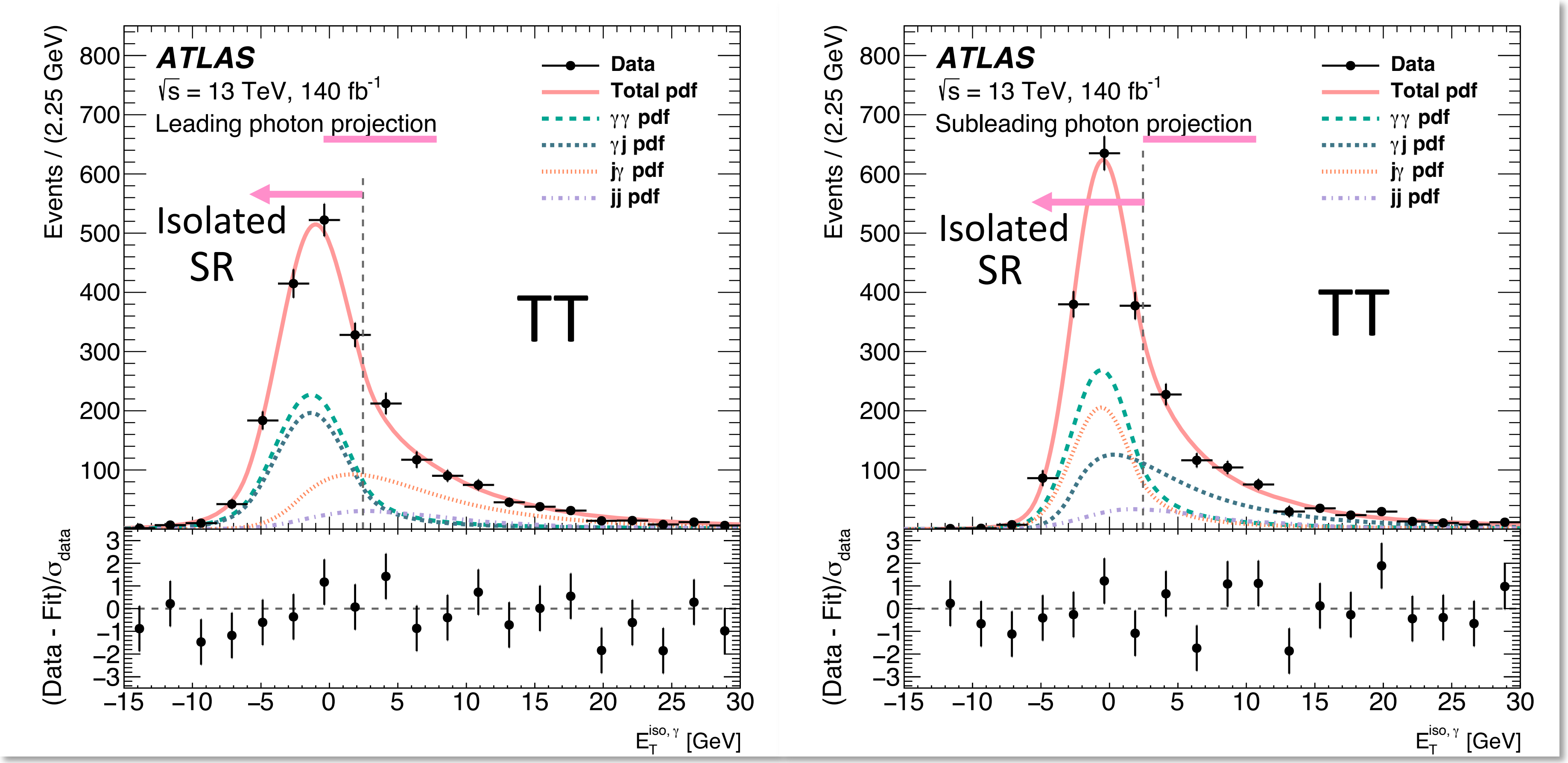
Event displays from Science 338 (6114) 1576-1582

First observations @ the LHC – *Wγγ*

Fit two-dimensional ***templates*** parametrizing the energy surrounding **each** photon

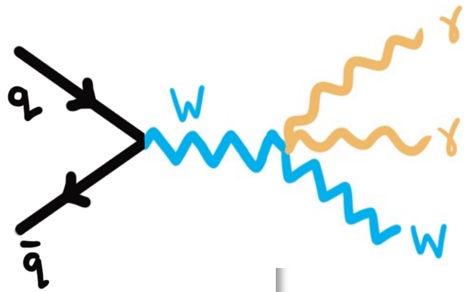
- one template for signal and one for each type of background
- integral of *γj+jγ+jj* templates in the isolated region = # background events

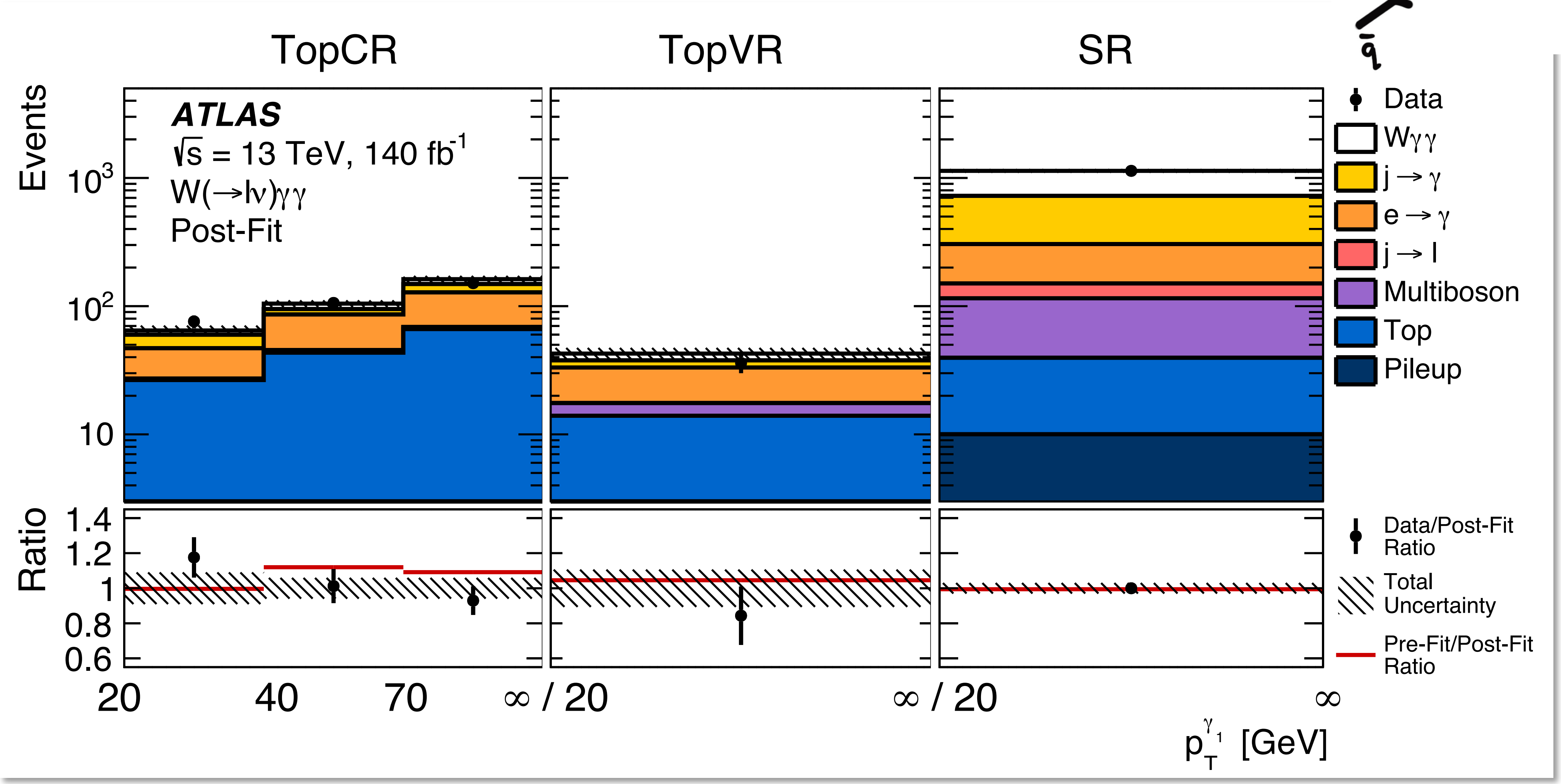




arXiv:2308.03041

First observations @ the LHC – *Wγγ*

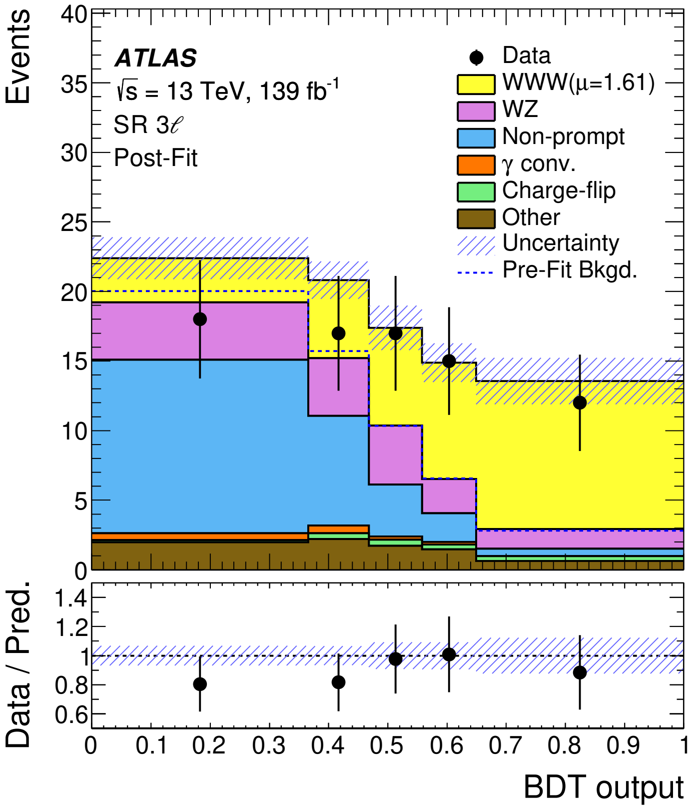


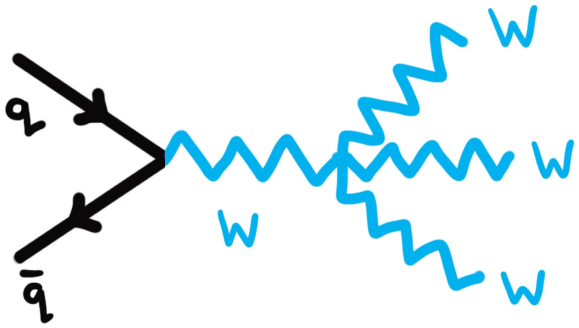


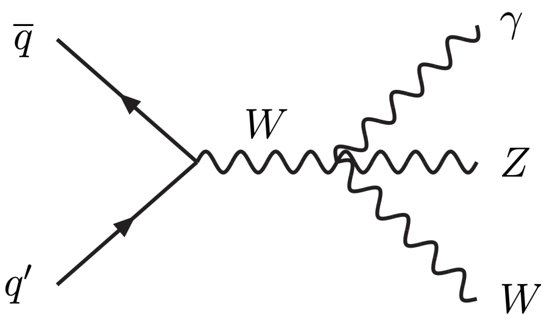
Observation of *Wγγ* production with a significance of 5.6σ

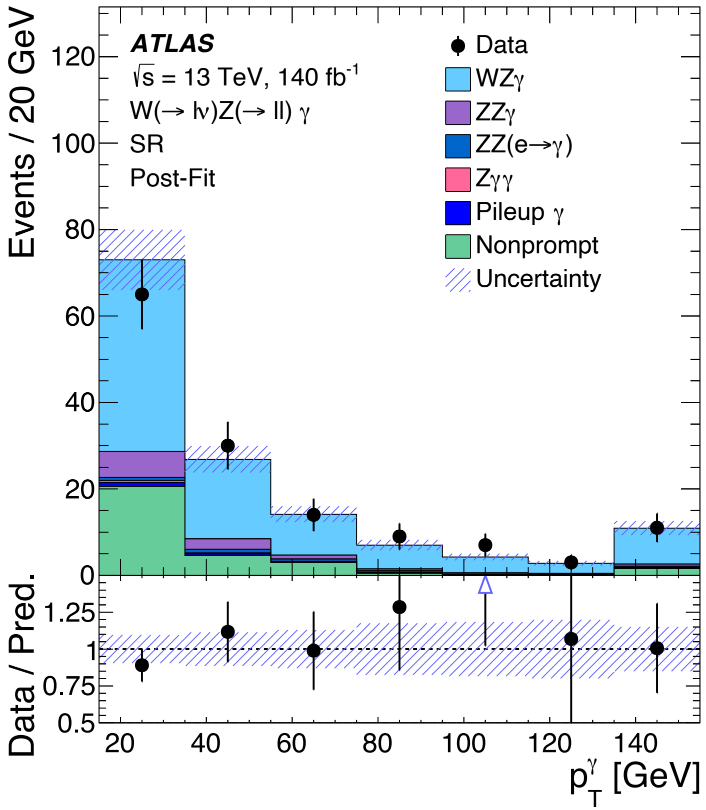
arXiv:2308.03041

First observations @ the LHC – *WWW*, *WZγ*









Observation of *WWW* production with a significance of 8.0σ

Observation of *WZγ* production with a significance of 6.3σ

Phys. Rev. Lett. 129 (2022) 061803

arXiv:2305.16994

First observations @ the LHC – *Wγγ*

[arXiv:2308.03041](https://arxiv.org/abs/2308.03041)