Standard Model Physics at Colliders

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About me

Assistant Professor at UVic, Canada Research Chair Tier II in Experimental Particle Physics

Member of ATLAS and MATHUSLA collaborations

ATLAS Publications Committee member
ATLAS Canada EDI Coordinator
UVic EDI Committee Chair
CAP Particle Physics Division Chair

Previously:

- ATLAS Analysis Model Group Coordinator (2021–2023)
- ATLAS Standard Model Electroweak Subconvener (2019–2021)
- ATLAS BLS Trigger Signature Coordinator (2017–2019)
- *CERN Fellow (2020–2021)*
- *Postdoc @ McGill University (2017–2020)*
- *PhD @ University of Washington (2011–2016)*
- *MSc @ Perimeter Institute/Waterloo (2010–2011)*
- *BSc, Honours @ UVic (2005–2009)*

My never up-to-date CV

About me


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Outline

Colliders & Collisions

Why colliders?
Types of colliders and collisions
LHC & LHC parameters
Cross-sections & Luminosity
Pileup
Parton distribution functions
LHC pp collisions - kinematics

Detectors & Detection

Particle interactions with matter
Particle detectors
Particle “objects”
Jets & hadronisation
Reconstruction and identification
Missing transverse momentum

Intro SM measurements

What are measurements?
Anatomy of HEP plots & analysis
Introduction to WZ

Data acquisition

Triggering and readout
Limitations on triggering bandwidth, storage
Different strategies: partial event building, trigger-level analysis, parked data
MC Generators and Simulation

SM Measurements

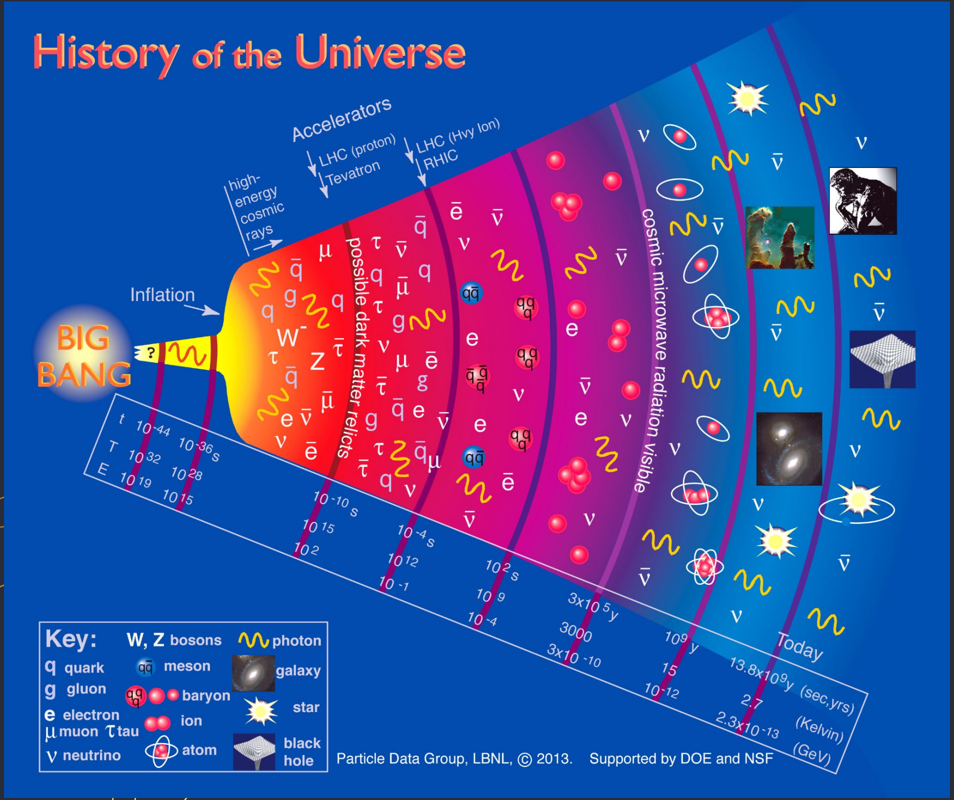
W mass measurements
Top quark measurements
QCD measurement
Electroweak physics
Higgs boson measurements
Flavour physics
Effective field theories

Uncertainties, unfolding

Different types of uncertainties
Modelling uncertainties: PDF, scale, alpha_s, shower, ugly ones
How to compare results to theory

Colliders and collisions

Why do we say the LHC takes us all the way back to the early universe?

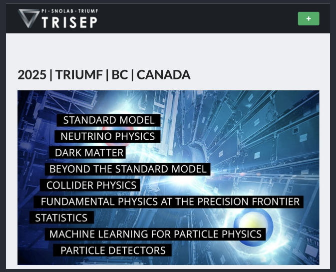


At the beginning, the universe was **hot** (high energy)

To study what interactions might have happened at this time to give us e.g. the matter–antimatter asymmetry, we need to **recreate these conditions**

Accelerators put a huge amount of energy into a **tiny volume**: LHC beams have a very high *energy density*, reaching back to t = 10^{-10}s!

Why do we need colliders?



today

Equal amounts of matter and antimatter

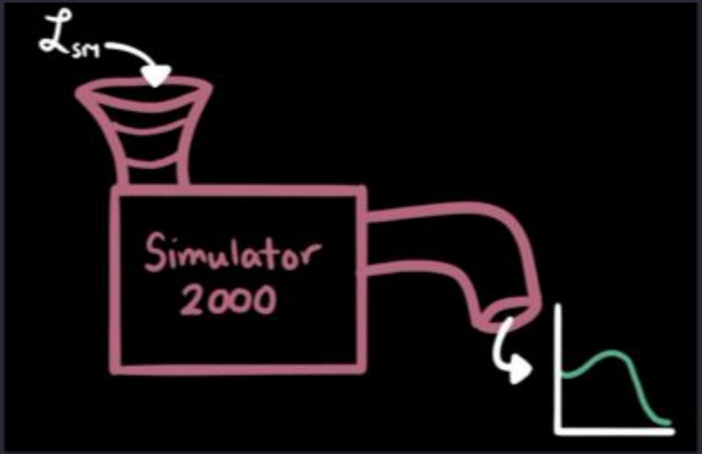
Universe is matter dominated

→ Need to access **energies > 1 MeV** to understand what happened in the early universe

why does it matter? (discuss)

Why do we need colliders?

1. What is dark matter? If it is a particle, can we create it at colliders?
2. What mechanism led to the current baryon asymmetry of the universe?
3. Does the Standard Model accurately describe all the particle interactions it predicts?



4. Are we accurately simulating what the SM predicts happens @ the LHC?

5 - up to you - why is the weak force so much stronger than gravity? Why is there such a discrepancy between particle masses?

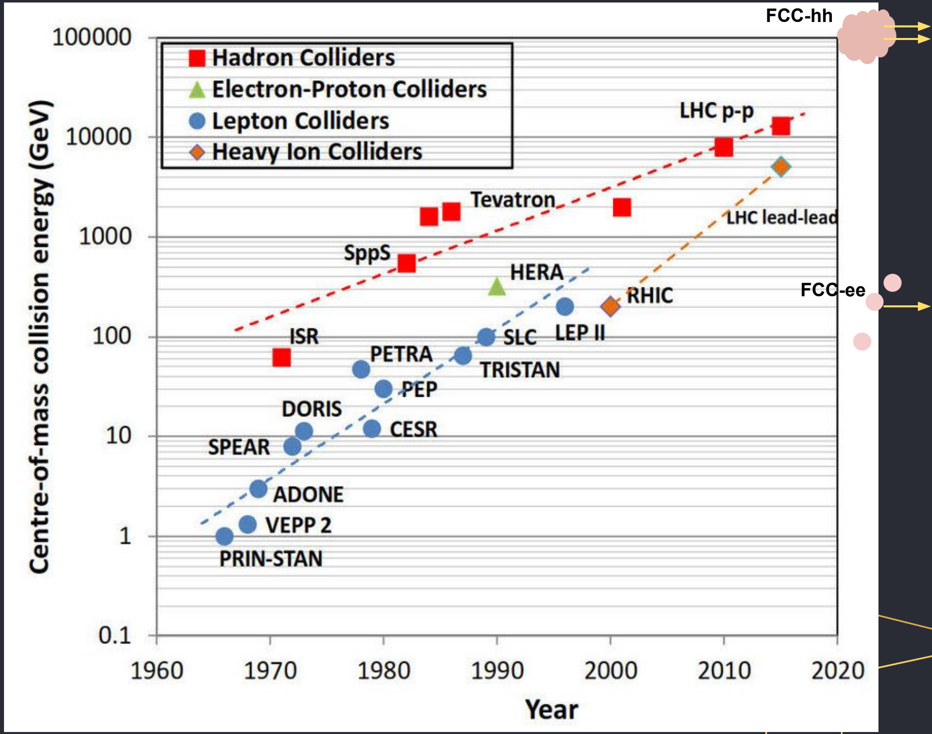
Reading: arXiv:2505.00694

Hadron vs lepton colliders

Linear colliders: one long acceleration, beam loss @ end

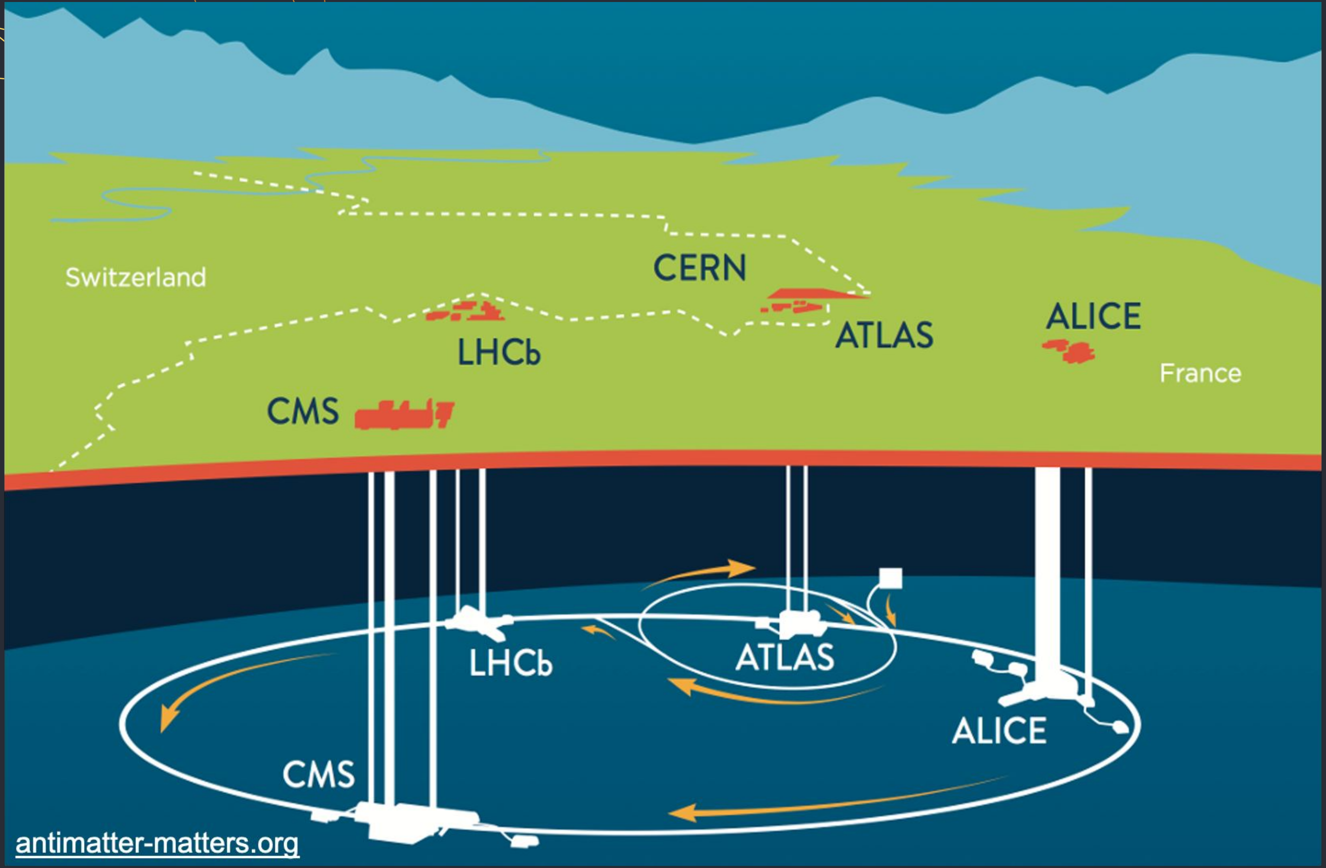
Circular colliders: maintain beams, but accelerate in circle: limited by synchrotron radiation

Lower for higher mass particles @ same magnetic field (force): **heavier particles** (e.g. protons) can be accelerated to **higher energies**



doi:10.1016/j.nima.2018.01.034

The Large Hadron Collider



27 km ring

Accelerates and collides protons and ions

I will focus on proton collisions

Currently operating at √s = 13.6 TeV (energy per beam is 6.8 TeV)

The Event

Basic: A single collision (e.g. the result of two protons colliding)

Advanced: Everything that happens in the detector in a given **bunch crossing**

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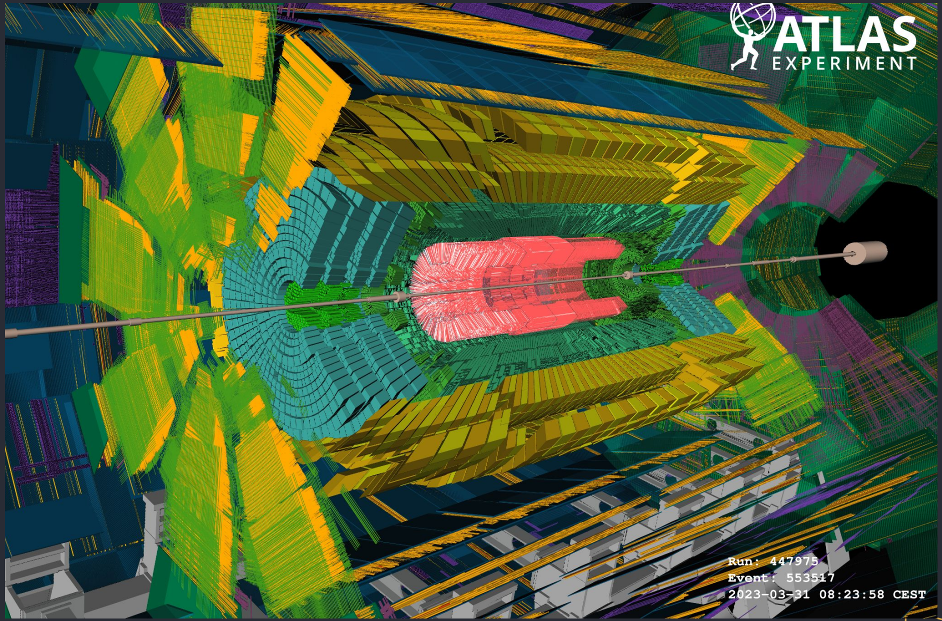


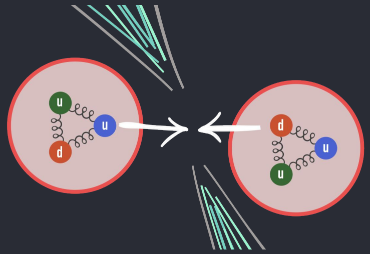
Beam splashes, 2023

Proton-proton collisions

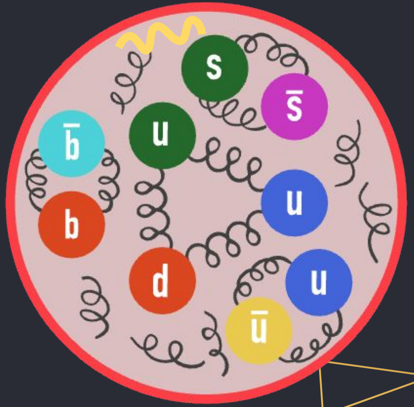
the quarks and gluons inside the proton undergo inelastic interactions and produce new particles

Partons can be valence quarks uud, sea quarks, gluons, or even photons!

Proton bunches of ~10^{11} protons collide every 25 ns



Partons inside each proton collide



Cross-sections (σ, xs, etc.)

a measurement of the **probability that an event occurs**

can be calculated from the SM

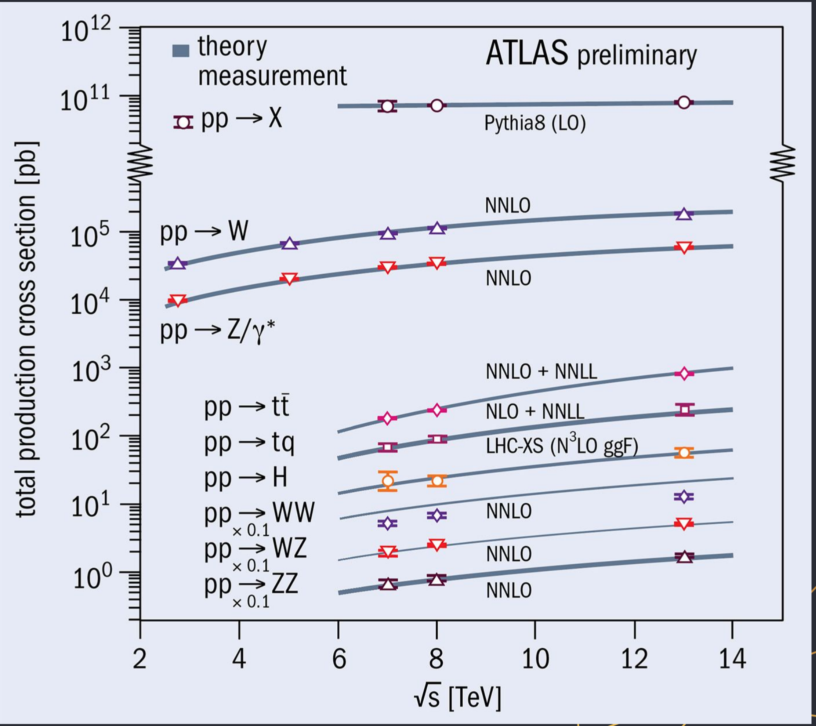
measured in units of "**barns**"

1 barn = 10^{-24} cm²

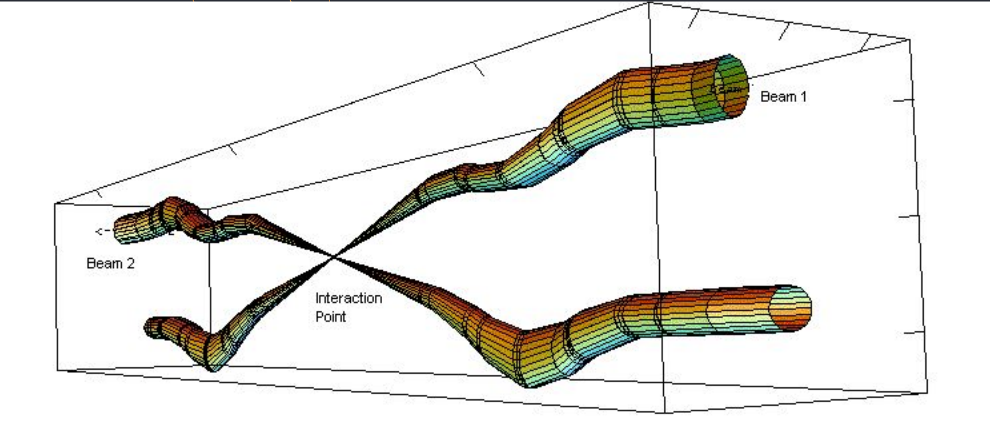
The number of events of a given process produced at the LHC is given by:

$$N_{evt}/\text{second} = \text{luminosity} \cdot \sigma$$

https://cerncourier.com/a/lhc-at-10-the-physics-legacy/



LHC Collisions & Luminosity



Relative beam sizes around IP1 (Atlas) in collision

Beams **cross** at each **interaction point**

Beams can be **focused** by the LHC to provide a specific target **luminosity**:

> either the maximum possible instantaneous luminosity or a **levelled** value

$$\mathcal{L} = \frac{f N_1 N_2 N_b}{4\pi\sigma_x\sigma_y}$$

N_1 & N_2 = number of protons per bunch in each beam
N_b = number of bunches in each beam
f = frequency of bunch crossings
$\boldsymbol{\sigma}_x$ & $\boldsymbol{\sigma}_y$ = gaussian density profiles of beams in x, y

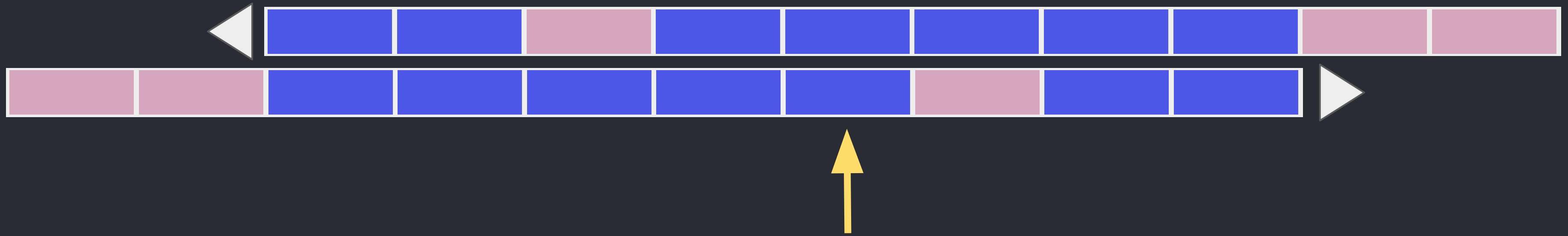
Derivation here: https://cds.cern.ch/record/941318/
More machine details: https://lhc-machine-outreach.web.cern.ch/
Play around with the LHC's luminosity calculator: https://lpc.web.cern.ch/lumiCalc.html

LHC Collisions

Protons are injected into the LHC in **bunches**, with a bunch spacing of **25 ns** (40 MHz); 3564 bunches in each beam

→Not **all** bunches are filled!

Both beams have the **same** fill pattern ("filling scheme")



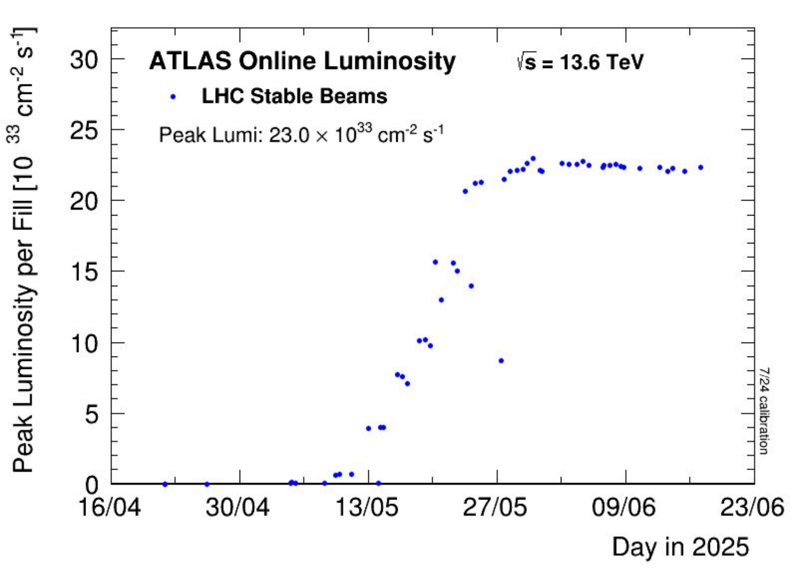
The pattern of **bunch crossings** tells you what to expect from each 25 ns interval:

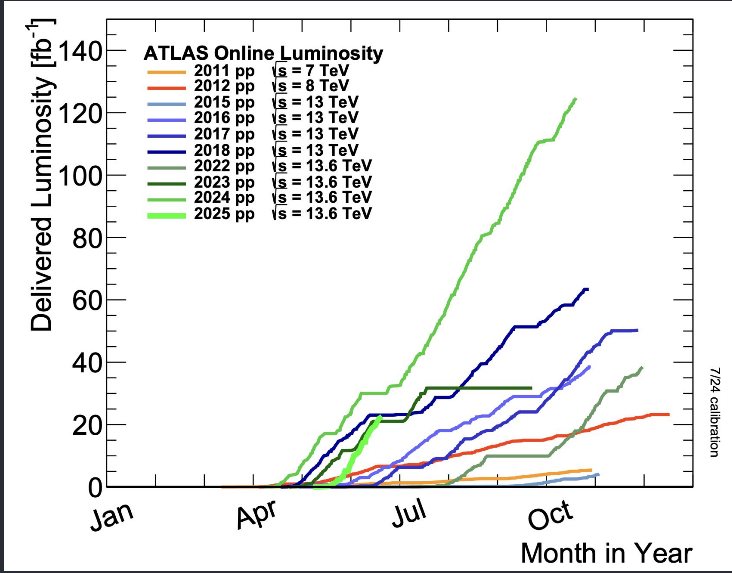
Starting @ arrow we would see **paired paired paired paired unpaired empty**

Generally around **2500 paired bunches** (/3564) in ATLAS and CMS (same!)

40 MHz bunch crossings → ~**30 MHz collisions**

Instantaneous vs integrated luminosity

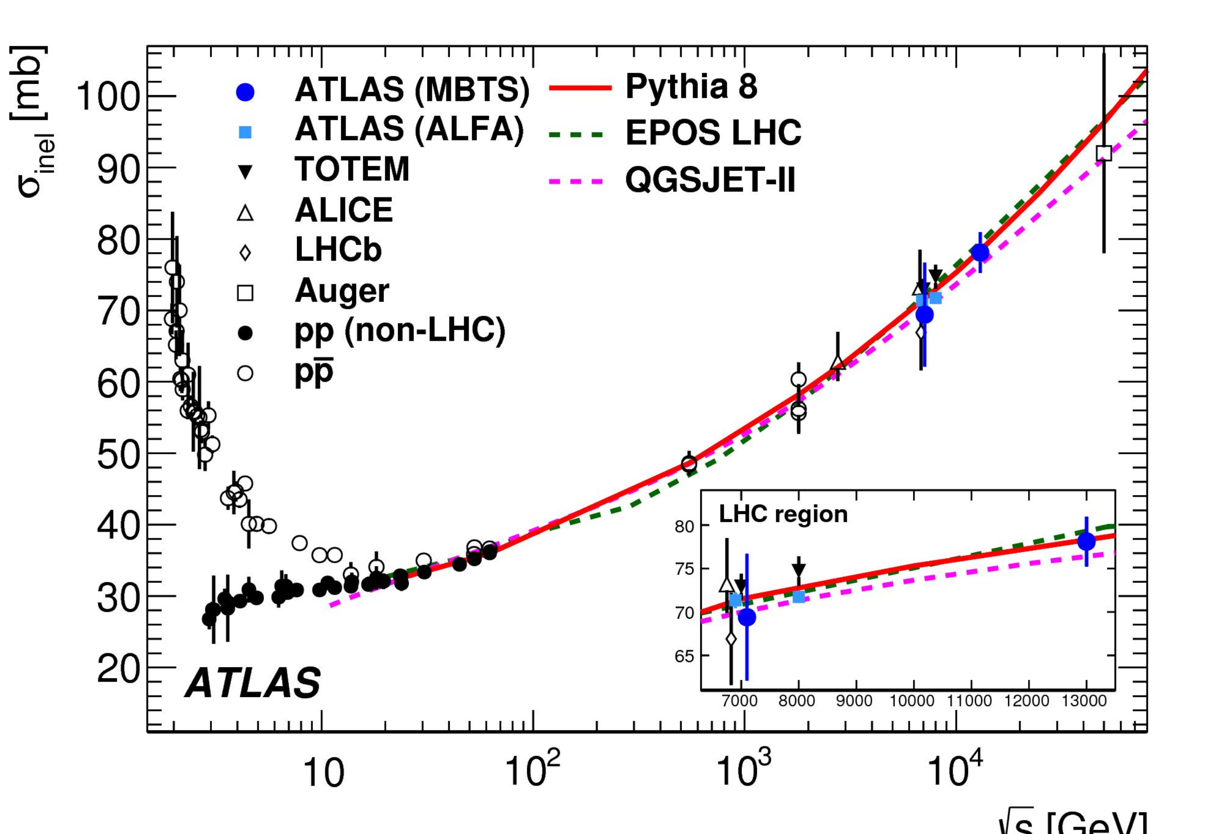




LuminosityPublicResultsRun3

Each time the LHC collides protons is a **fill**
Each **fill** has a peak instantaneous luminosity, a luminosity profile, and a fill length
Each fill has an **integrated luminosity** (inverse barns)

Inelastic vs elastic collisions



Phys. Rev. Lett. 117 (2016) 182002

Most protons don't make Higgs bosons!

Some protons don't make new particles at all: elastic collisions

@ 13 TeV....

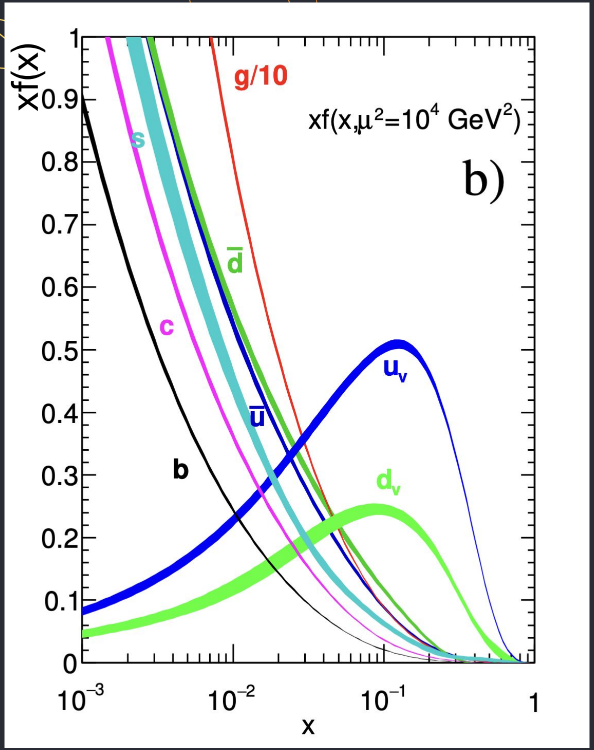
arXiv:1712.06153

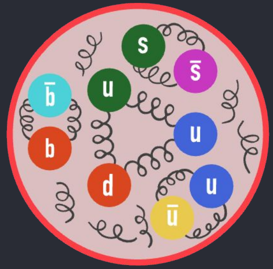
σ_{el} = (31.0±1.7) mb

σ_{inel}=(79.5±1.8) mb

Discuss: why is $\sigma_{inel}(pp)$ < $\sigma_{inel}(ppbar)$?

Parton distribution functions



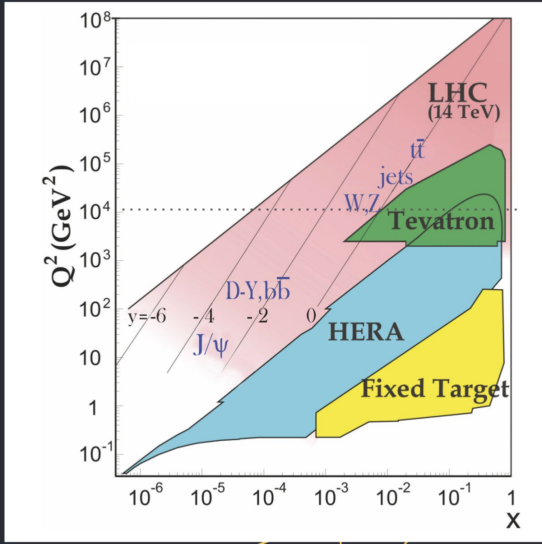


Partons each have a probability of colliding with a fraction *x* of the proton's momentum

PDF tells us the probability of two partons interacting at a given energy scale μ
(shown: μ = 100 GeV, roughly m_Z)

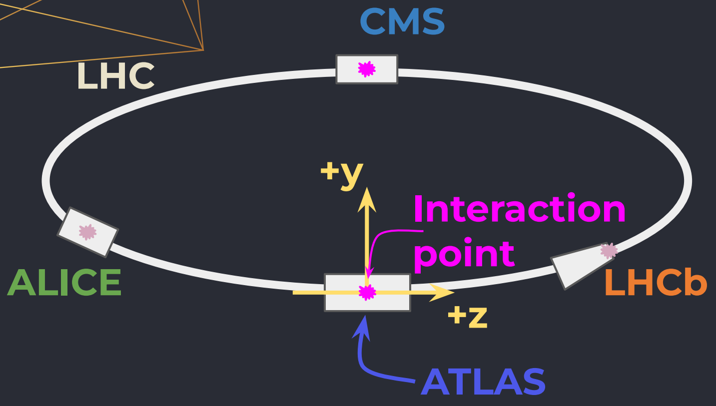
Determined via **fits** to experimental data:
- HERA (electron–proton)
- Tevatron (proton–antiproton)
- LHC (proton–proton)
- Fixed target experiments

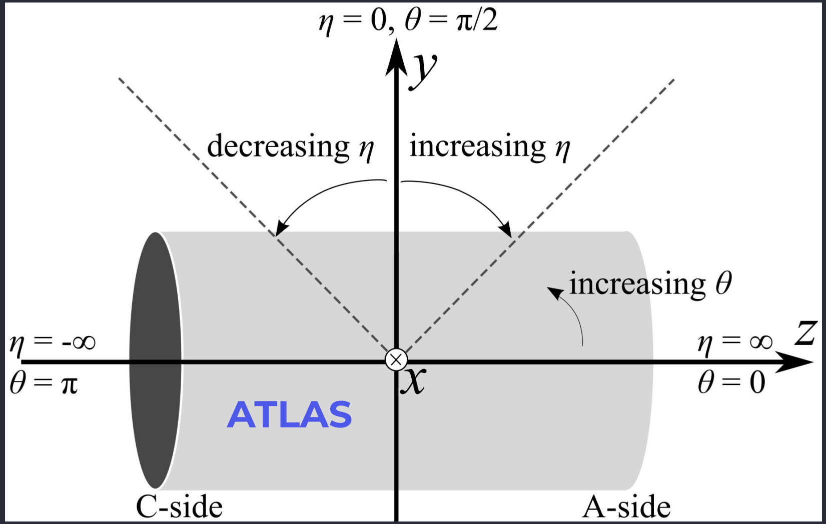
PDFs are the basis for every process we simulate at the LHC!



https://pdg.lbl.gov/2019/reviews/rpp2019-rev-structure-functions.pdf

Kinematics of LHC collisions





Detector coordinates: (x, y, z) or R, z, θ, φ. We generally use rapidity instead of θ:

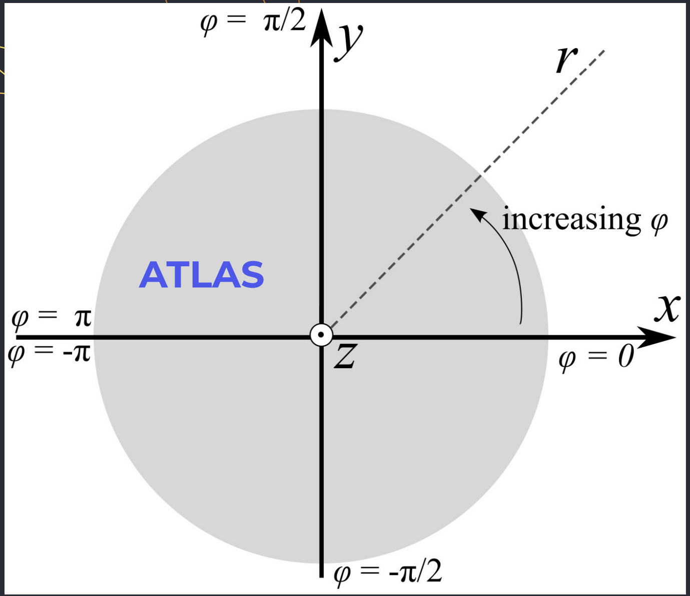
$$y = \frac{1}{2}\ln\left[\frac{E+p_z}{E-p_z}\right]$$

Differences in rapidity are **invariant under Lorentz transformations in z:** important because we don't know parton boost along z

$$\eta = -\ln\tan\frac{\theta}{2}$$

Equivalent to **pseudorapidity** (eta) for ~massless particles

Kinematics of LHC collisions



Beams collide along z, so there is **azimuthal symmetry** in particle production as well as **detector geometry** (mostly)

We often refer to **transverse** quantities, i.e.

$$r = \sqrt{x^2 + y^2}$$

Transverse momentum ("p T"): $p_{\mathrm{T}} = \sqrt{p_x^2 + p_y^2}$

Importance: incoming beams have $p_{\mathrm{T}} \sim 0$

… so after the collision we should have: $\sum_{\text{event}} \mathbf{p}_{\mathrm{T}} = 0$ — Unless there are **invisible particles** produced in the collision!

Pileup

...but wait, what happens to the other 10^{11} -1 protons in each bunch?

$$\mathcal{L} = \frac{f N_1 N_2 N_b}{4\pi\sigma_x\sigma_y}$$

Luminosity is **higher** when we have **more protons** in a **smaller area**

Higher luminosity means we produce **more events** from **rare processes**

But σ_{inel}(pp) is **large:** at nominal LHC luminosities, N “events” / bunch crossing is **greater than one**

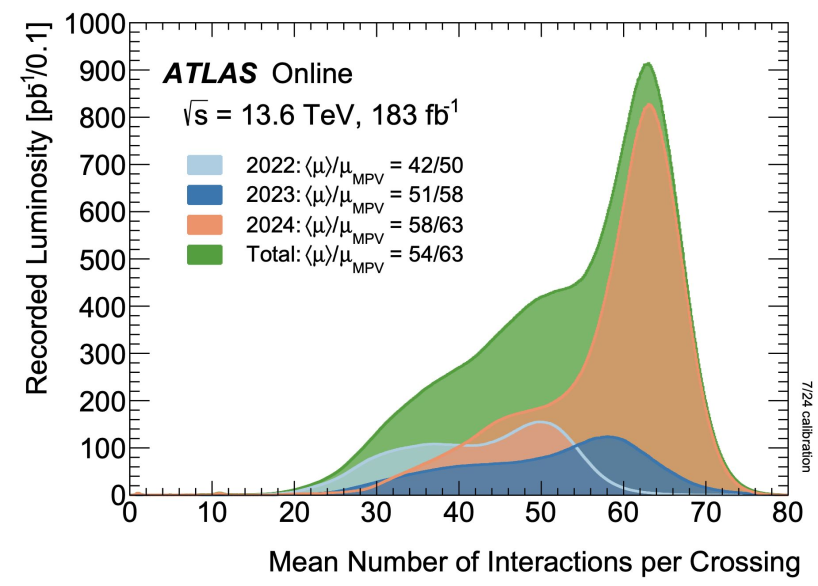
Most of these are **boring** (subjective) - lower-energy QCD interactions

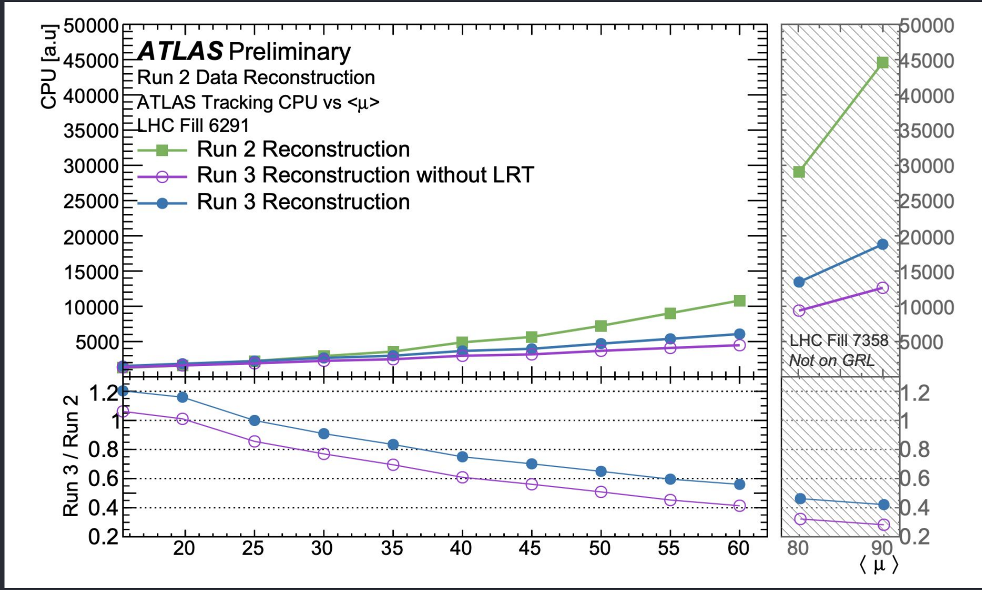
The highest energy **interaction** (largest $\sum_{track} p_T$) is referred to as the **hard scatter** or **primary interaction**

The other proton–proton interactions in the event are **pileup**

Pileup

ATLAS-PHYS-PUB-2021-012



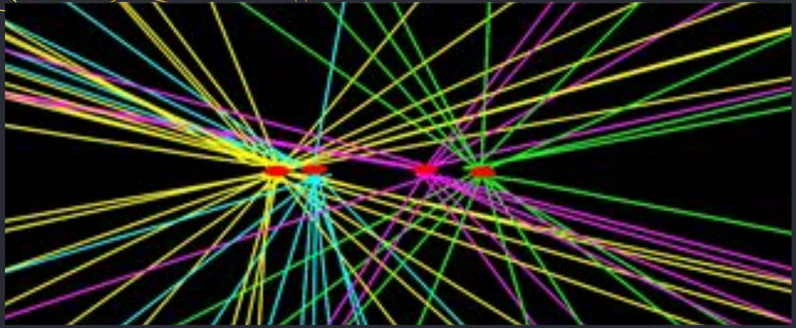


DataSummary

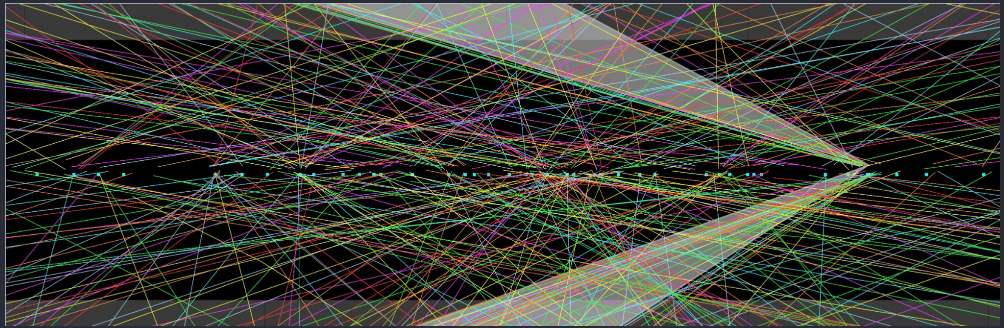
What happens if we extrapolate to HL-LHC values?

Pileup

...but wait, what happens to the other 10^{11} -1 protons in each bunch?



4 pileup vertices, 7 TeV data (2011)



65 pileup vertices, 13.6 TeV data (2024)

Often quantify pileup by $\langle \mu \rangle$: average number of interactions per bunch crossing

Average = average of **all bunches,** in a 60-second window (ATLAS definition)

HL-LHC projected pileup: $\langle \mu \rangle \sim 200$

Detecting particles at the LHC

Particle interactions with matter

Many types of matter interactions are exploited in LHC detectors....

For a different type of talk: transition radiation, Cherenkov radiation

Charged particles (e/mu/tau/p/pi/K/...) can... **(Also – they bend in magnetic fields!)**

Ionize matter (electromagnetic interactions) with **minimal impact** on their momentum

Tracking detectors: silicon detectors, gaseous drift tubes

Excite material (electromagnetically), generating scintillation light

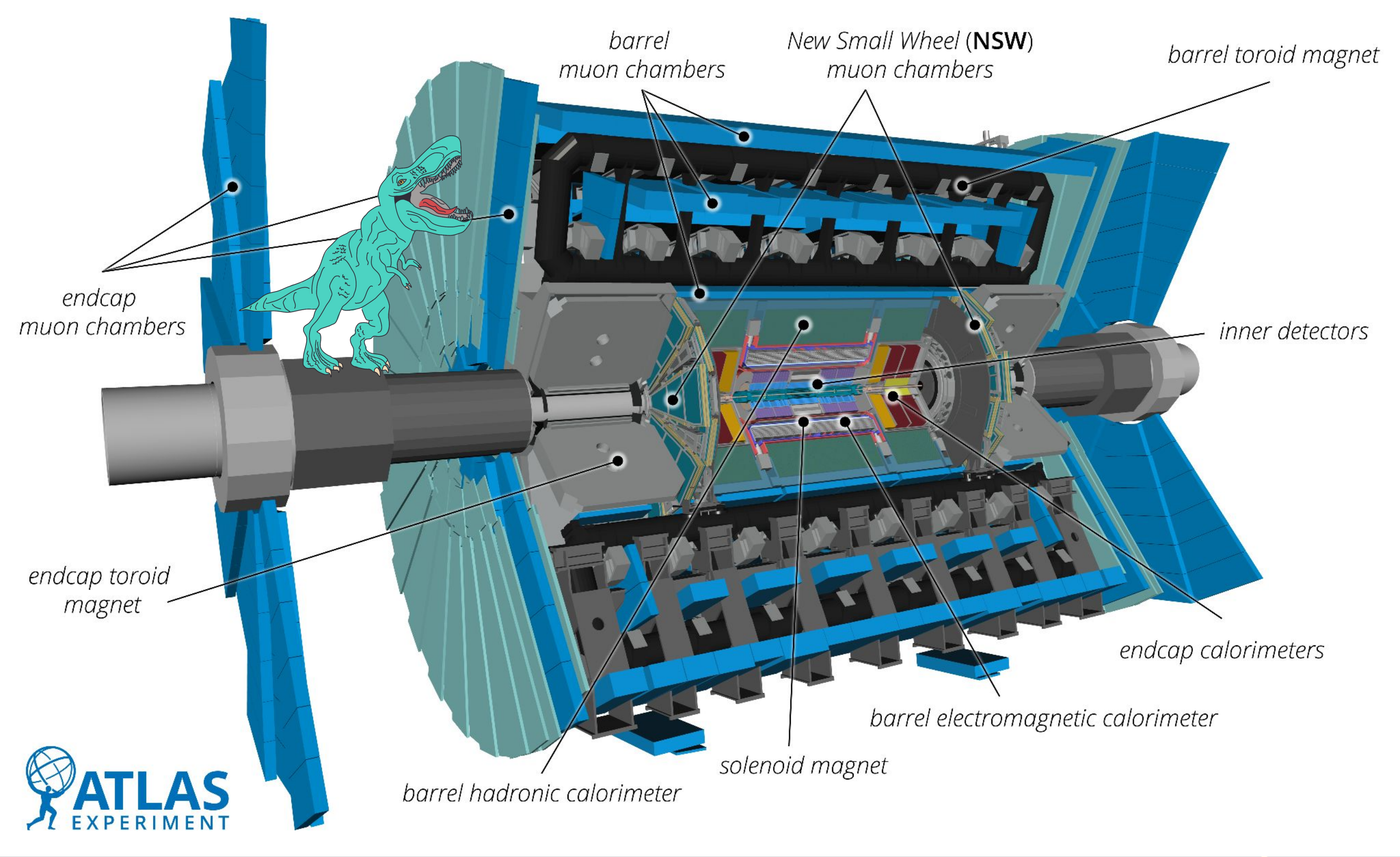
Tracking detectors and a component of sampling **calorimeters**

Photons can pair-produce via electromagnetic material interactions
Electrons can radiate photons, which pair produce

Hadrons (charged or neutral) interact via strong interactions in dense material

Sampling **calorimeters** can measure the light yield

ATLAS detector



From interactions to particle “objects”

DATA

detector calibration and alignment

particle reconstruction, vertexing

particle selection, disambiguation, secondary quantities

result!

Raw detector data (locations and e.g. charge)	Calorimeter cells, tracker hits, etc.	Reconstructed particle objects	Refined particle selection and analysis

Detector response

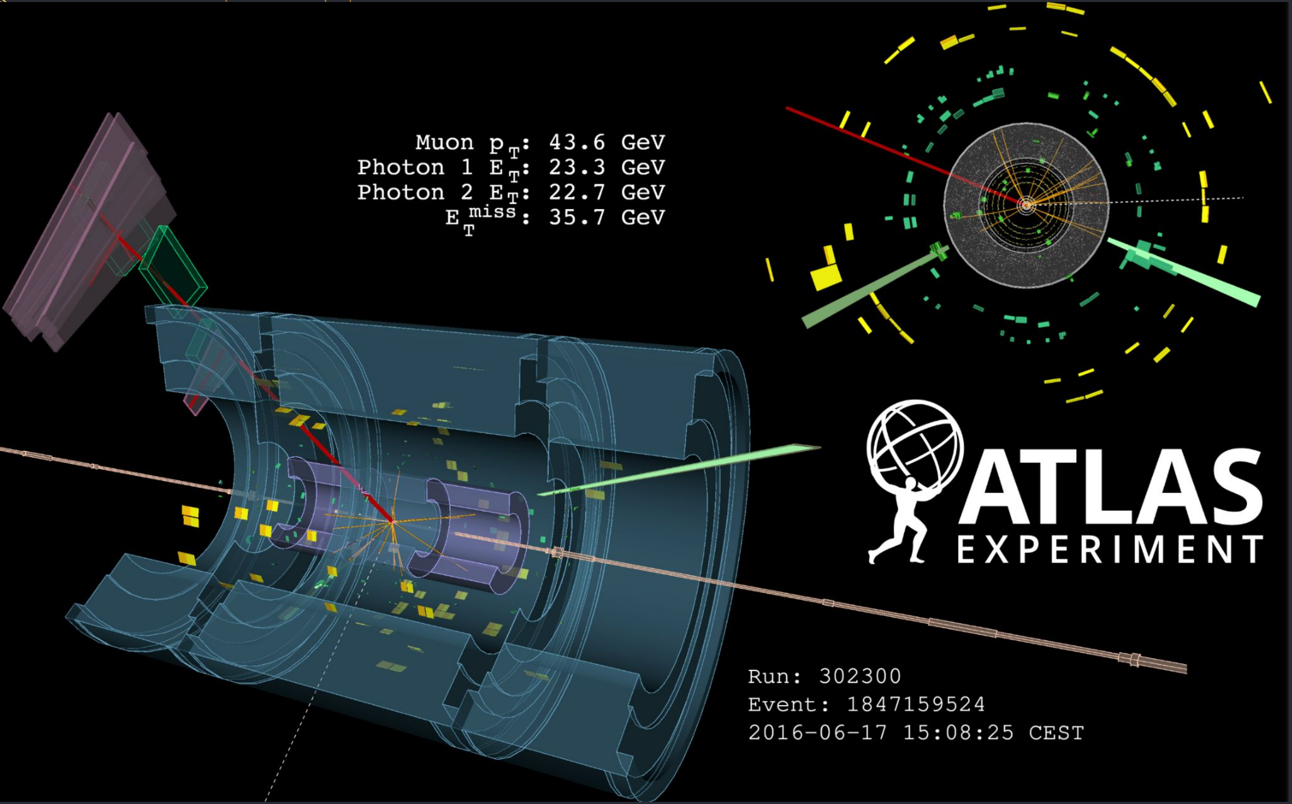
Simulation of material interactions (e.g. Geant4)

Particle decay, fragmentation, hadronization, showering (e.g. madgraph, pythia...)

Standard Model

SIMULATION

Detector objects



Tracks made from inner detector hits

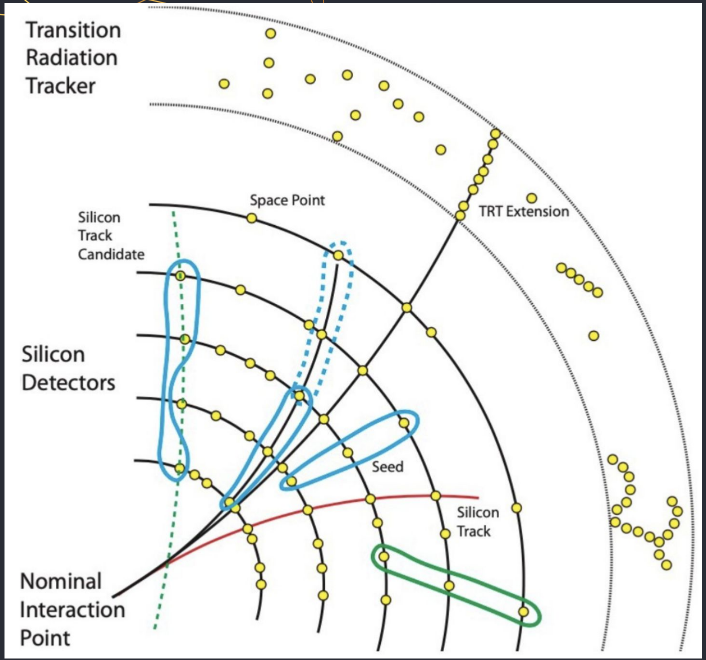
ECal cell energies

HCal cell energies

Tracks in the muon system

Track and vertex reconstruction

Separating the hard scatter from the pileup interactions



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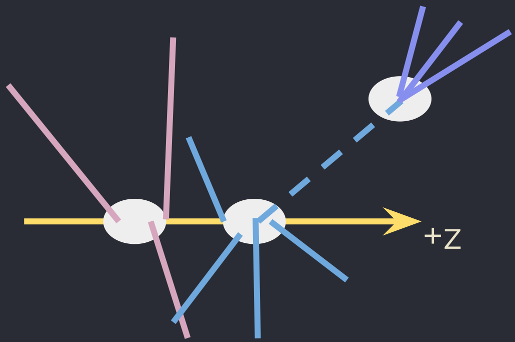


Multiple methods for vertex reconstruction

ACTS implementation of vertex reconstruction used on ATLAS

Tracks are assigned a probability of being associated each vertex

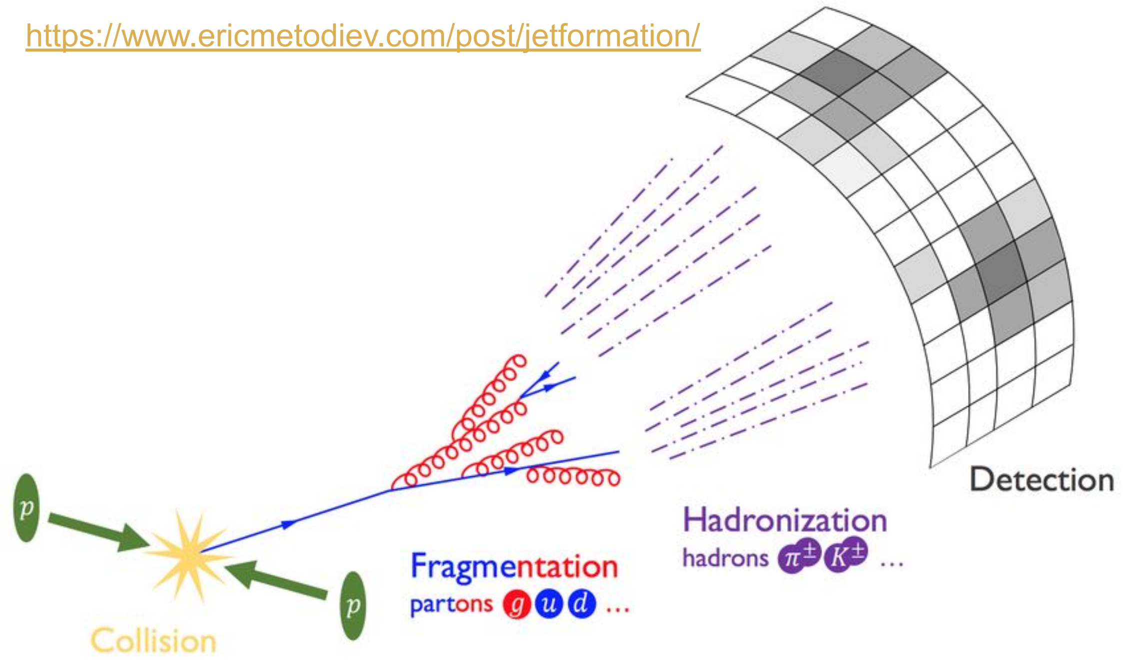
Separate algorithms used for **primary** and **secondary** vertices (e.g. *b*-hadron decays)

Primary vertex is used to identify which particles (likely) belong to the **hard scatter** and which are **pileup**

QCD, hadronization, confinement, and jets

…what actually happens when we produce a quark or gluon in a collision?

Confinement ensures there are no free quarks/gluons (or any states with colour charge)



Detector signature: inner detector tracks and calorimeter energy deposits in a cone

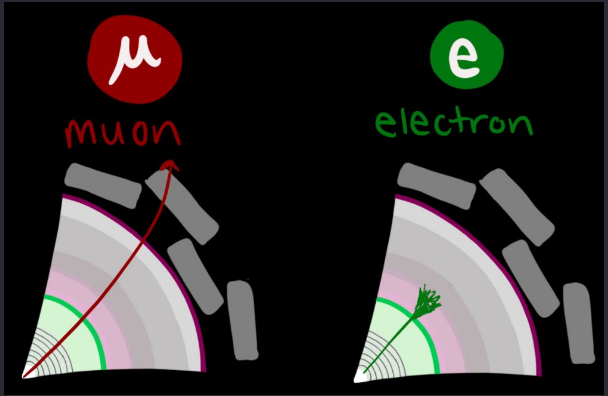
⇒ "jet"

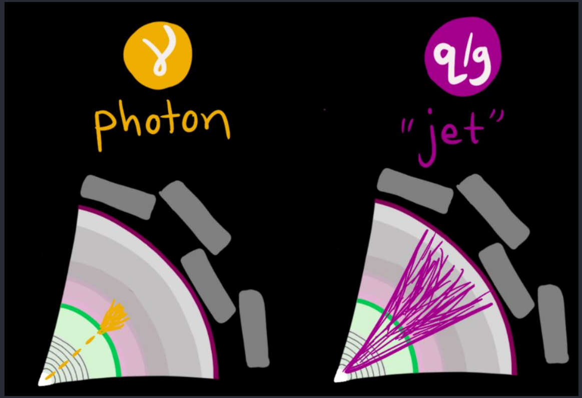
About 60% of jet energy is charged particles, 30% photons, 10% neutral hadrons (PDG review)

Reconstruction of jets from detector objects uses tracks and calorimeter clusters

Particle reconstruction

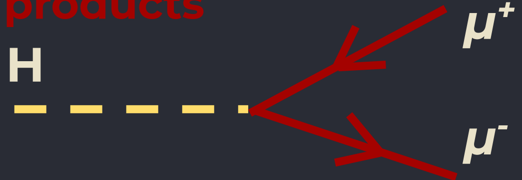
Each particle type leaves a unique signature in the detector and thus requires its own **reconstruction algorithms**





Particle	Track	EM Shower	Hadronic Shower	Muon Track
Jet (quark, gluon)	x	x	x	
b-Jet (b-quark)	x	x	x	maybe!
Electron	x	x		
Photon		x		
Muon	x			x
Neutrino				

We only* see **unstable** particles via their **decay products**



....even when they're a macroscopic line in a Feynman diagram

**sometimes we see both, if the lifetime is long enough!*

Exercise: particle lifetimes & signatures

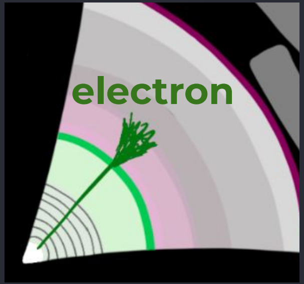
1. A fairly normal tau lepton from a SM decay has momentum p = 30 GeV. Do we see a **tau** track, and/or is the decay vertex resolvable?

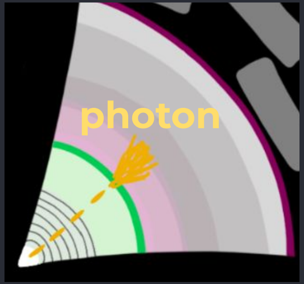
2. What about a 5 GeV $\boldsymbol{B^0}$ **meson?**

3. What happens to 10 GeV $\boldsymbol{K_s}$ **and** $\boldsymbol{K_L}$ **mesons** in the detector?

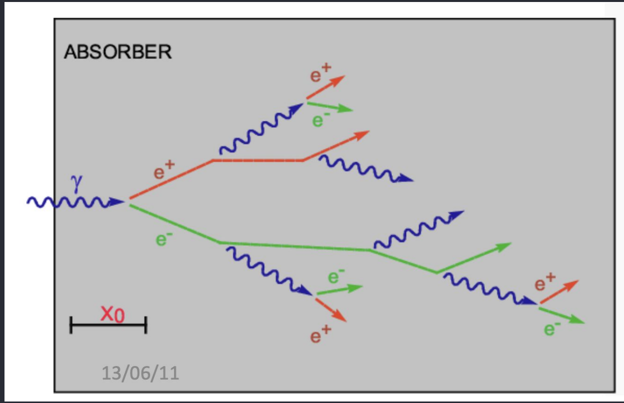
Electron and photon reconstruction

Electron and photons look, to first order, very similar in the ECal!





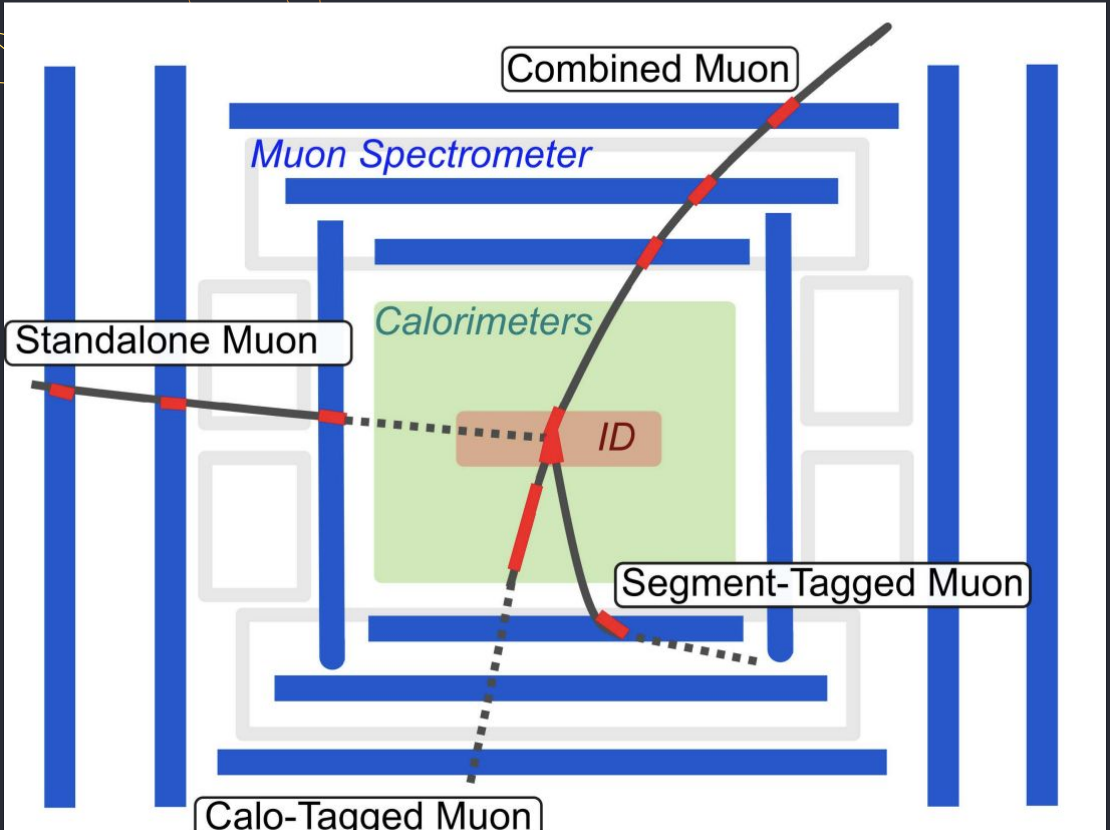
Incident photons **pair produce, but** incident electrons **radiate photons!**



Reconstruction follows:

1. Find clusters of energy in the ECal
2. Attempt to match cluster to a track
3. If there is a track that is matched to both a cluster and the primary vertex, the particle is reconstructed as an electron
4. If there are no tracks, it is a photon
5. But if there is one track or two, oppositely-charged tracks that point(s) to a *secondary vertex*, this is indicative of a *converted photon* (roughly 20% of photons!).

Muon reconstruction

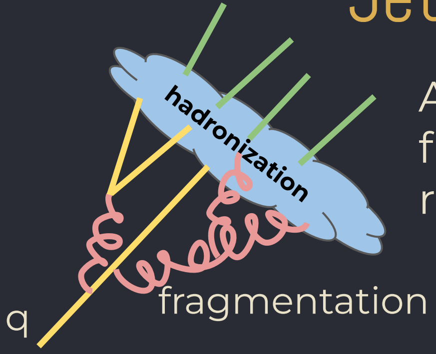


ATL-PHYS-PROC-2018-052

The “best” muons have **two tracks:** ID and muon spectrometer (MS), matched to each other with good chi-squared.

But to fill in gaps we also have muons missing one track, and muons that brem significantly in the calorimeter!

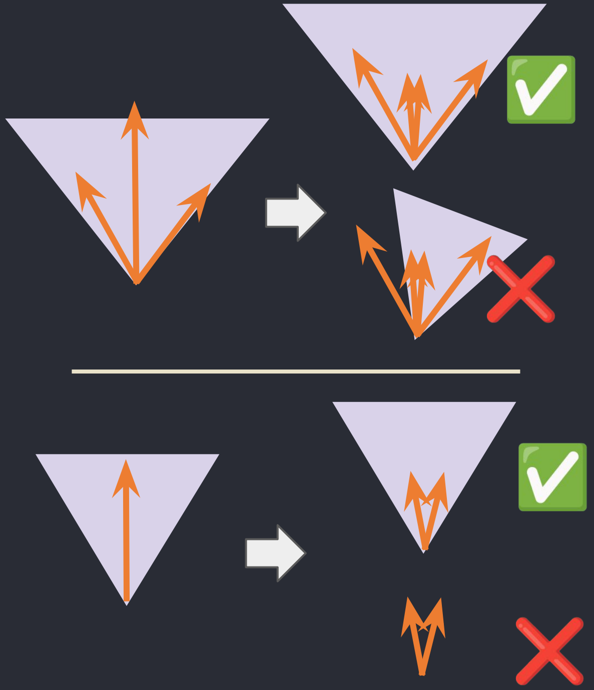
Jet reconstruction



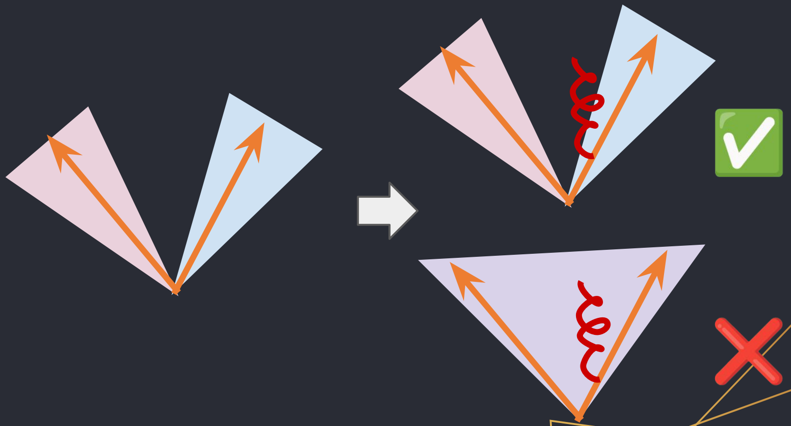
Hard parton

A high energy parton leads to a jet, with structure from fragmentation and hadronization. We need to ensure reconstruction algorithms are both **IR and collinear safe**

We do not want jets to change if a parton radiates a **collinear** gluon → **collinear safety**

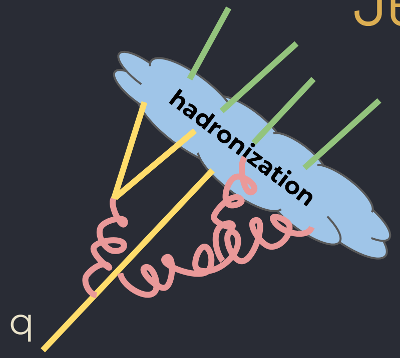


We do **not** want our jets to be sensitive to the addition of soft, collinear partons → **infrared safety**



More on jets: https://gsalam.web.cern.ch/repository/talks/2015-SaoPaulo-lecture4.pdf

Jet reconstruction



Two clustering algorithms (unsupervised learning) are commonly used: **Cambridge/Aachen** and **anti-k_T**

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$

Cambridge/Aachen

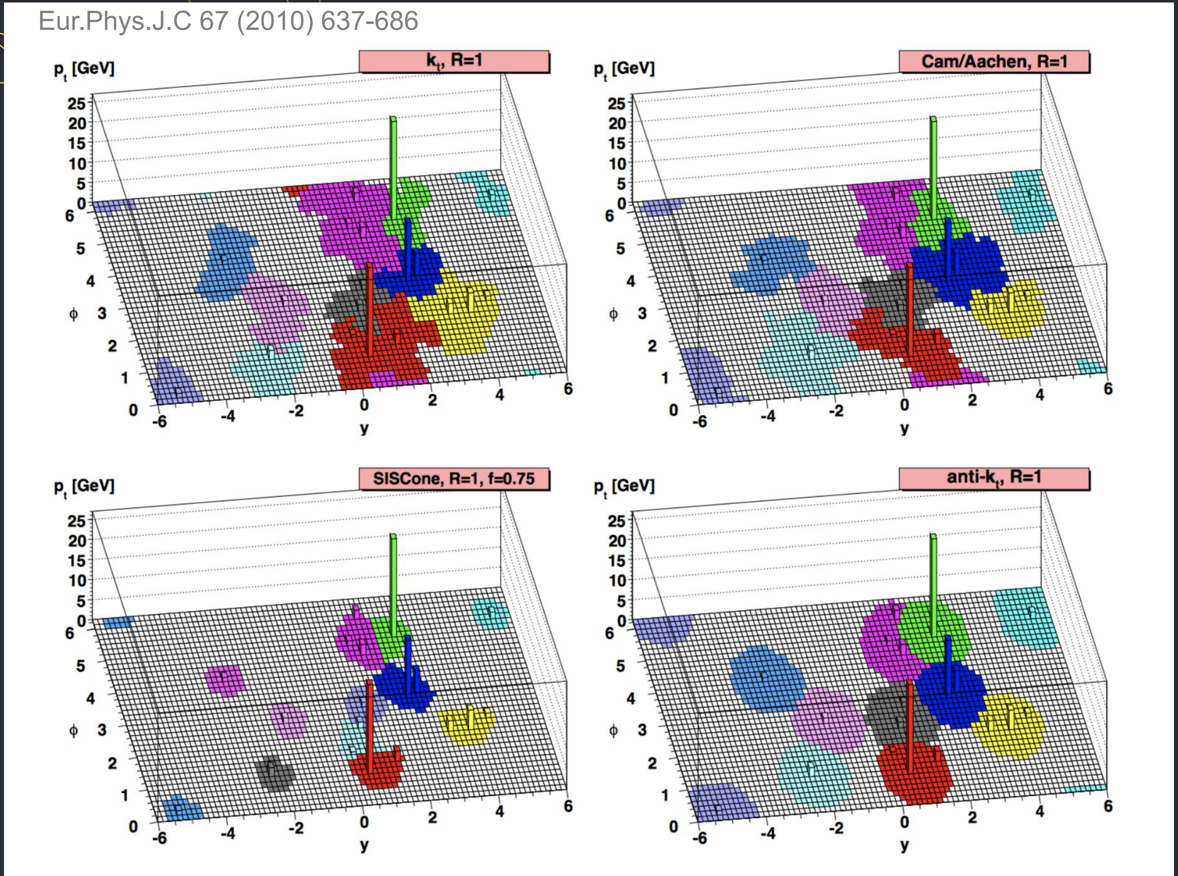
1. Choose a jet radius *R*
2. Collect all objects you want to cluster
3. Calculate all angular distances ΔR_{ij}
4. Combine pairs of objects with smallest ΔR_{ij}
5. Continue until all $\Delta R_{ij} > R$, at which point you have only jets!

anti-k_T

1. Choose a jet radius *R*
2. Collect all objects you want to cluster
3. Calculate all $d_{i,j} = \min\left(\frac{1}{p_{\mathrm{T},i}^2}, \frac{1}{p_{\mathrm{T},j}^2}\right)\frac{\Delta R_{i,j}^2}{R}$
4. Combine pairs of objects with smallest $d_{i,j}$ if $d_{i,j} < d_{i,B} = 1/p_{\mathrm{T},i}^2$
5. Continue until all objects have $d_{i,j} > d_{i,B}$, at which point you have only jets!

More on jets: https://gsalam.web.cern.ch/repository/talks/2015-SaoPaulo-lecture4.pdf

Comparison of jet reconstruction algorithms



Exact same inputs

Four different algorithms

k_T is like anti-k_T but p_T^2 instead of $1/p_T^2$

Lesson: it is always important to carefully define what you are doing!

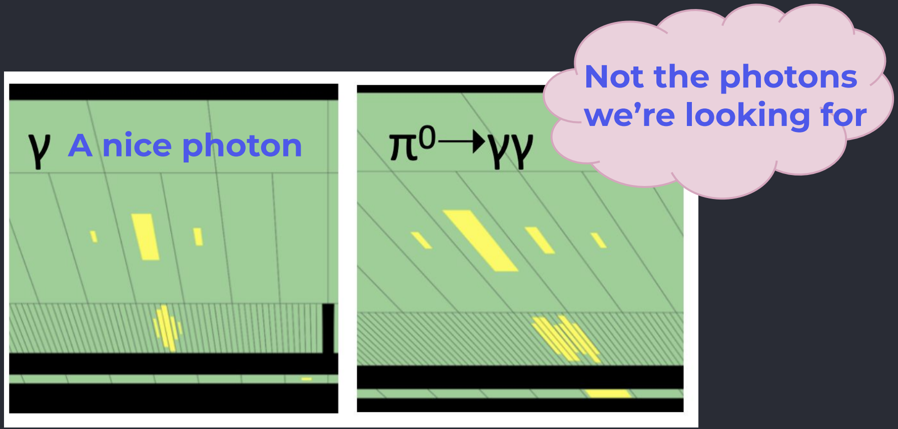
Identification

Signatures aren’t as unique as we’d like, so we apply further *identification criteria* to separate “good” objects from not-so-good ones

Different types of identification:

1. “Cut-based”
2. Likelihood optimized
3. Machine learning approaches:
   a. Boosted decision trees (BDTs)
   b. Neural networks
   c. Graph neural networks
   d. Recurrent neural networks
   e. Feedforward neural networks
   f. Convolutional neural networks

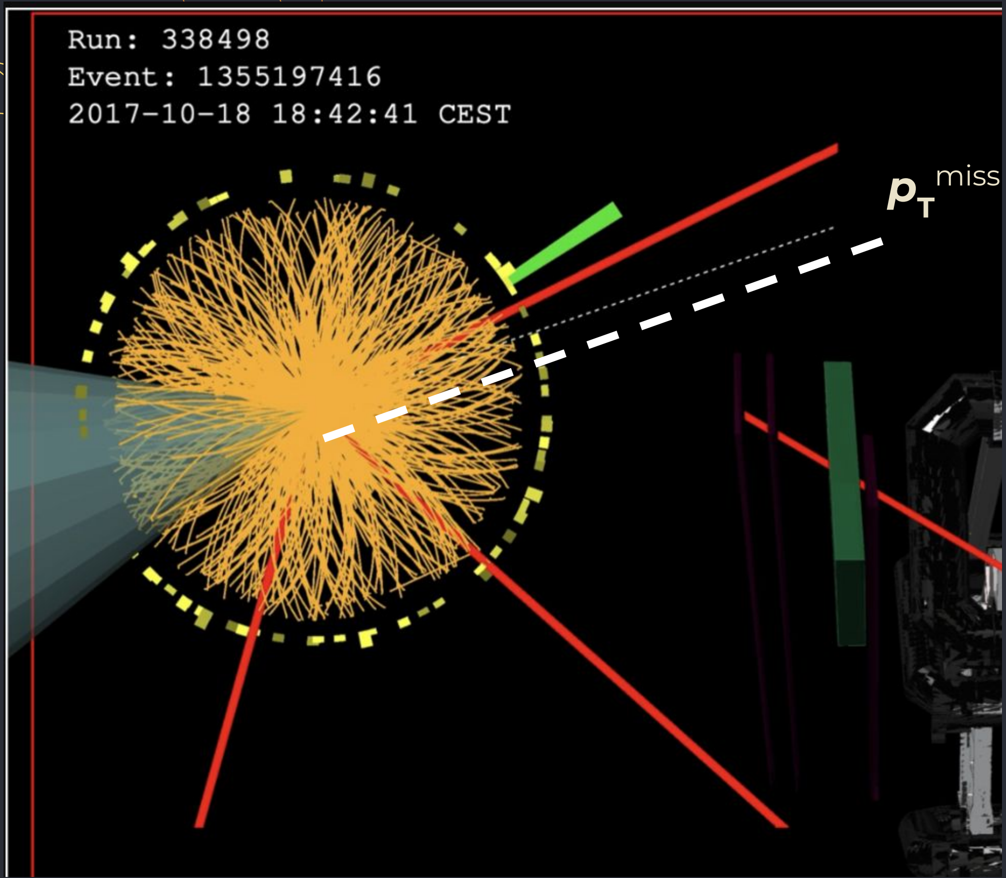
We use these to identify objects as e.g. loose (OK looking), medium, tight (great looking)



Inputs to ID algorithms include:

- Track parameters, like nHits, impact parameters
- Calorimeter shower shapes
- Calorimeter energy ratios
- Properties of secondary vertices

Missing transverse momentum (MET)



Candidate event, *ZH, Z→μμ, H→WW, WW →eνμν*

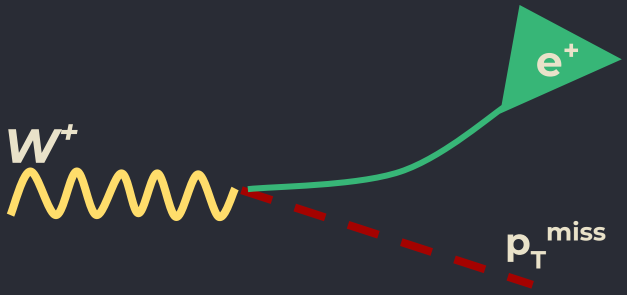
We can't see neutrinos, but we can **infer their presence!**

Careful when calculating MET:

1. Ensure all objects come from the same vertex
2. Ensure no object is double counted
3. Make sure soft energy deposits (calorimeter clusters, tracks) are accounted for even if they can't make nice jets
4. Correct for residual pileup energy contributing to the event

Common composite variables

Transverse mass: particles with invisible decay products can't be fully reconstructed!



$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T},\ell}\, p_{\mathrm{T}}^{\mathrm{miss}}(1-\cos(\Delta\varphi))}$$

*careful: multiple definitions exist!

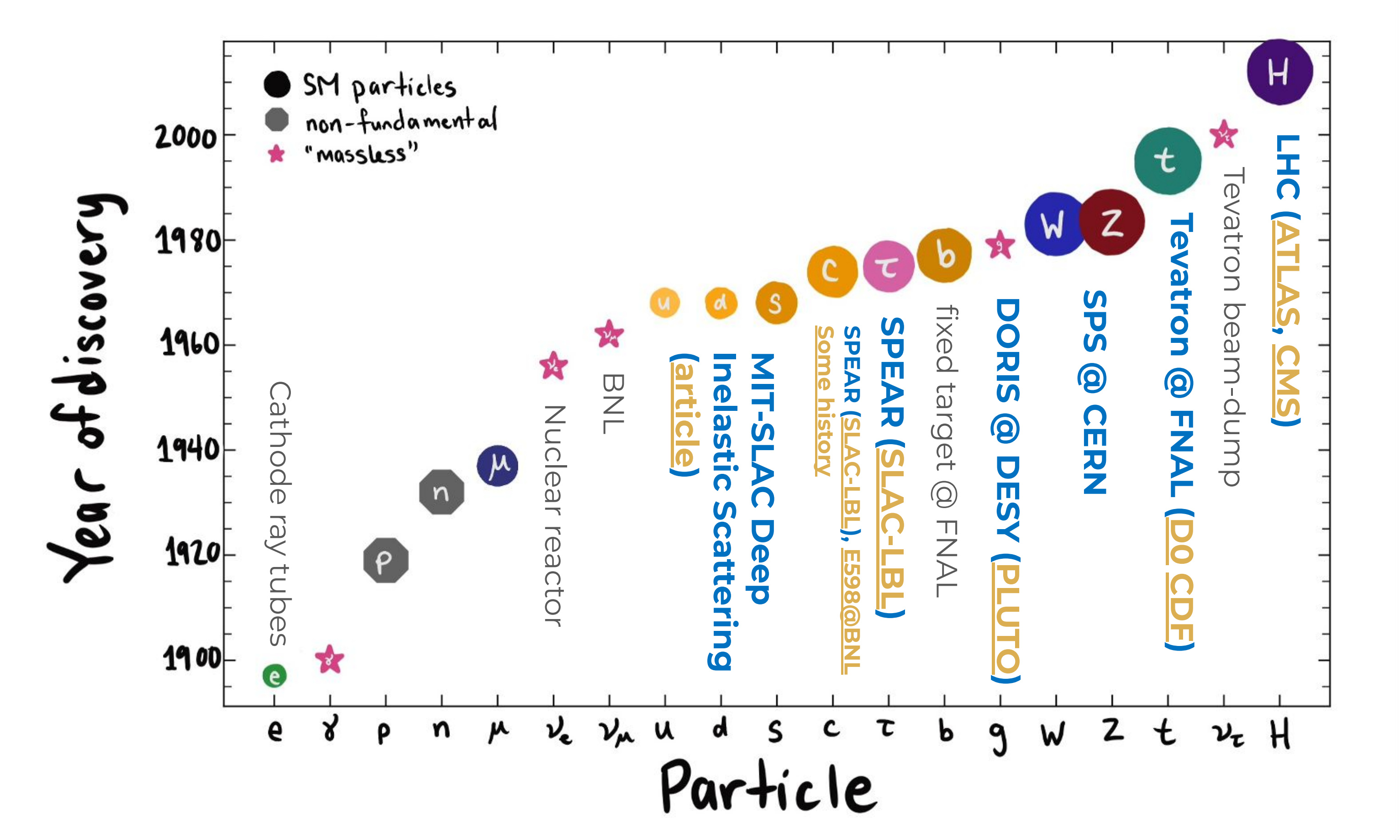
Transverse energy (H_T): analysis-dependent, either total sum of hadronic energy or total sum of *all visible particles*

Invariant mass: N particles can be combined to see what mass particle they could have decayed from - even if there is no single decay, this is useful for understanding the energy scale of the process

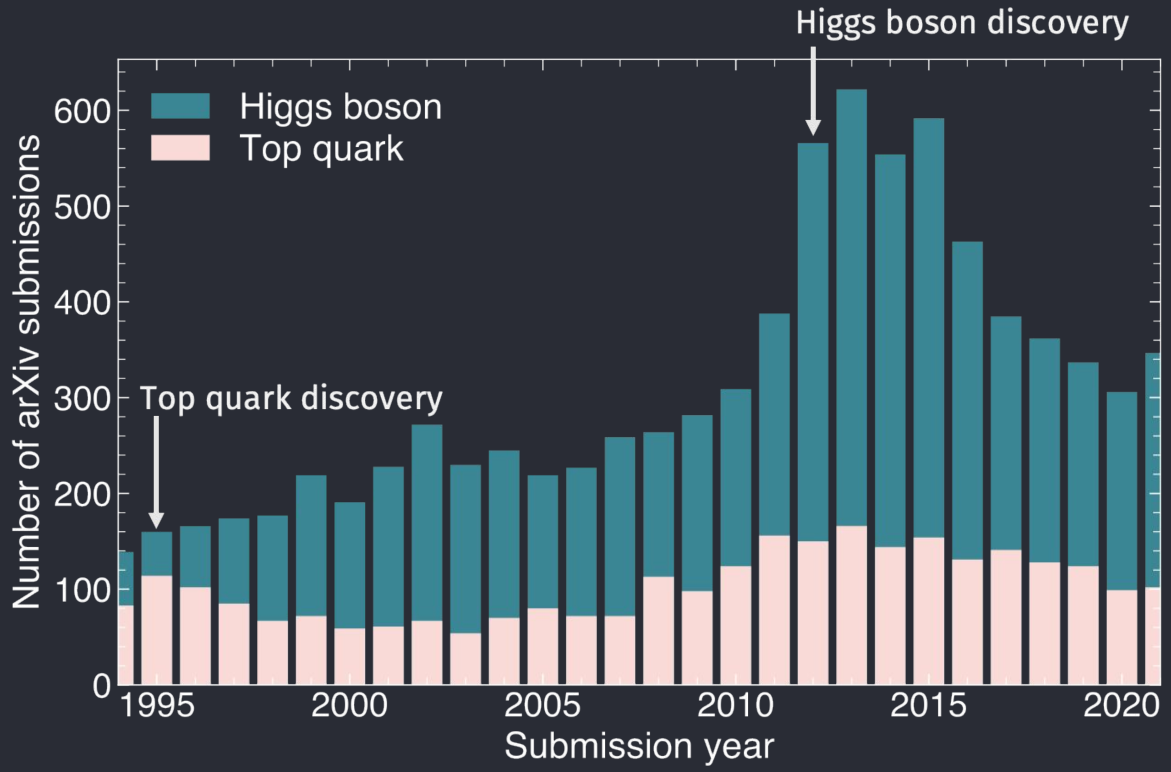
$$m_{inv,N}^2 = \left(\sum_i^N p_i^\mu\right)^2$$

Standard model measurements

Timeline of particle discoveries



Discovery is just the start



*histograms are not stacked

What counts as a measurement?

Observing new **particles** or **interactions**

Measuring particle properties (mass, spin, width, couplings, branching ratios)

Measuring SM properties (e.g. strong coupling constant)

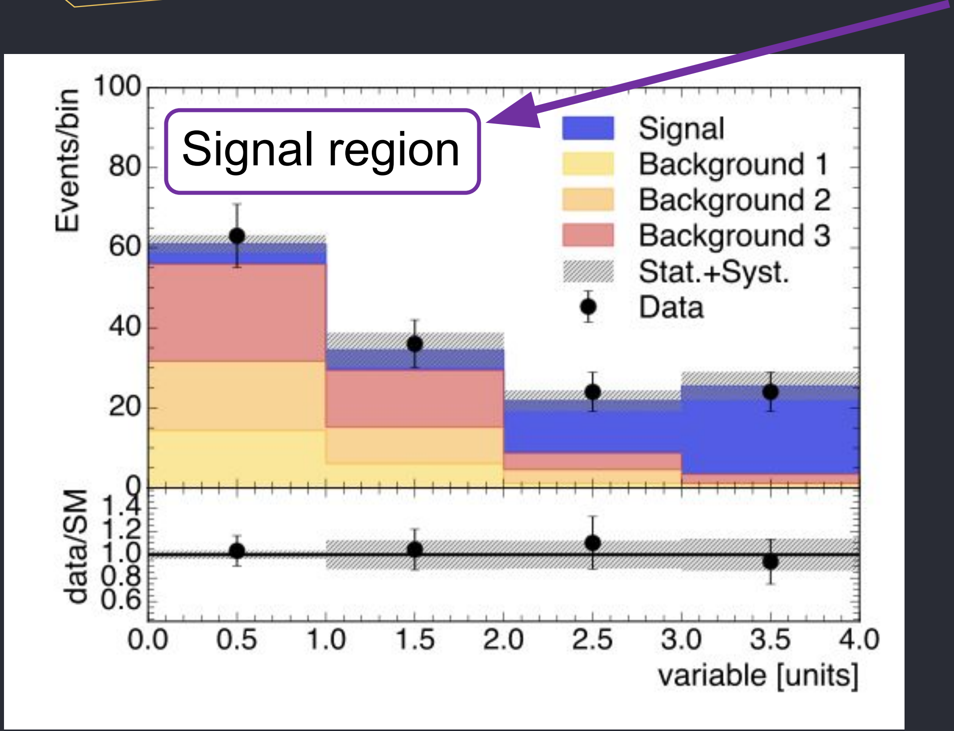
Measuring both **inclusive cross-sections** of SM processes

Measuring **differential cross-sections** of SM processes, including:

- Kinematic variables
- Angular distributions and correlations
- Properties of interactions, e.g. polarization

Testing hypotheses of the SM (e.g. lepton universality)

Measurement of a Standard Model processes



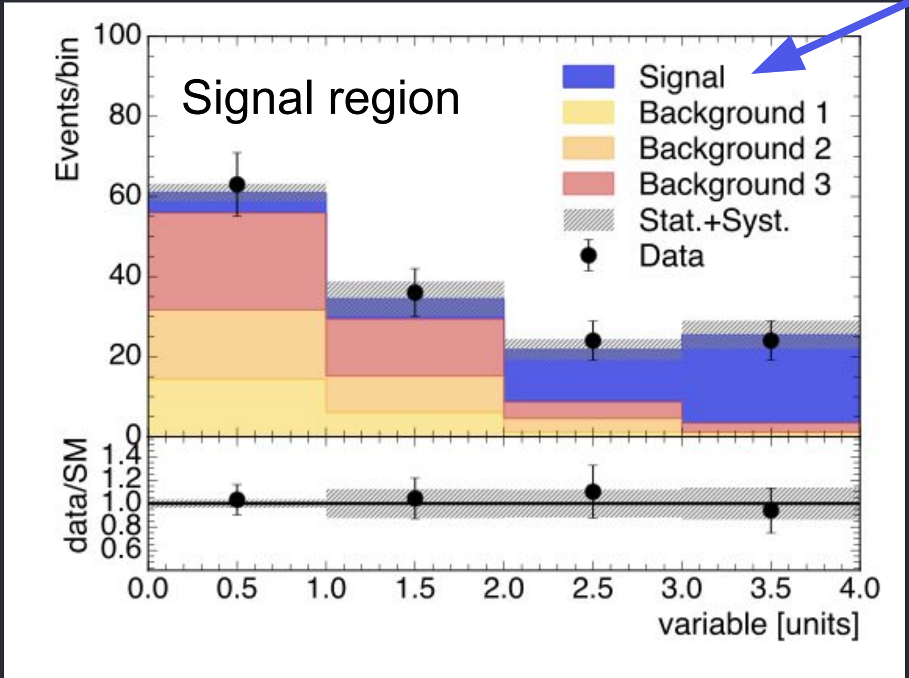
Identify some **event selection requirements** that preferentially select the process we want to study/measure

Signal region: generally a region where we have a lot of signal with low background (can be more than one!)

Control regions: regions enriched in specific backgrounds to help us *control* them

Validation regions: regions we can use to check the analysis in

Measurement of a Standard Model processes

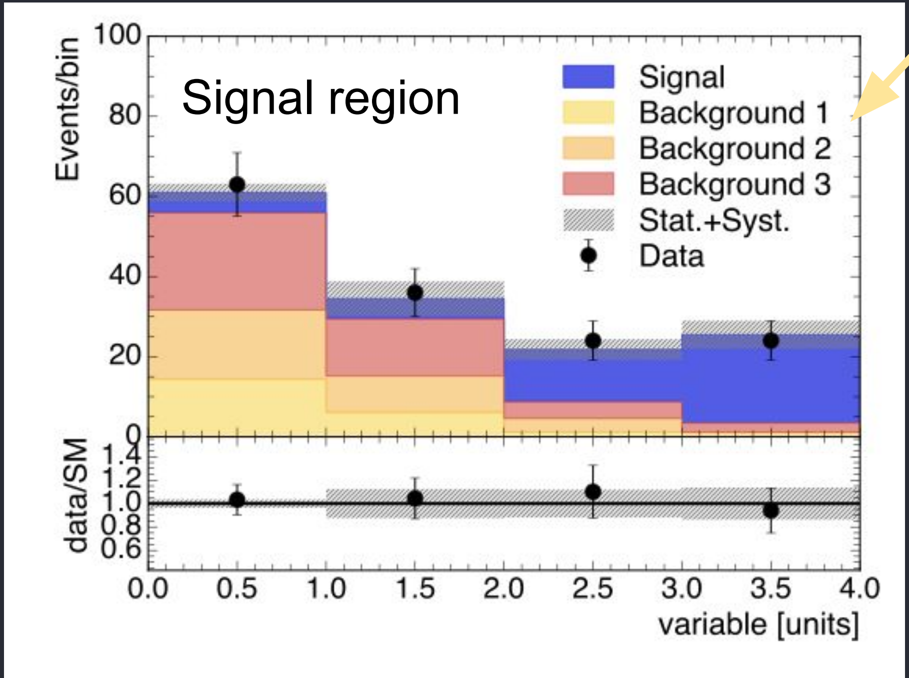


Simulate your signal process

(generally already done so you can develop the signal region!)

What does the standard model **predict** we should see?

Measurement of a Standard Model processes

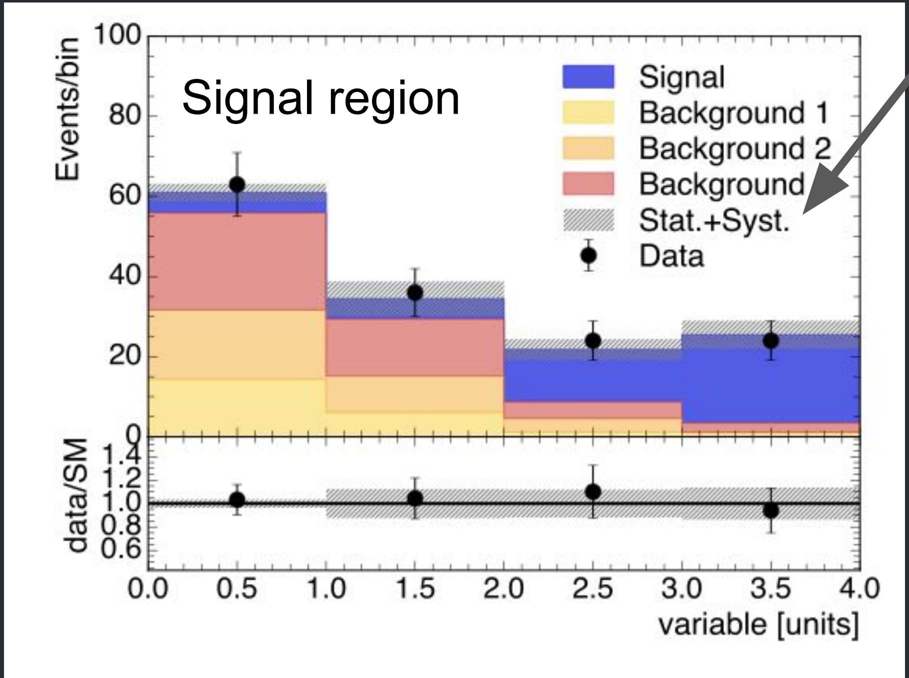


Simulate (or otherwise) determine all the different non-signal processes that contribute events to your signal region

Reducible backgrounds: processes that look similar but can be reduced with specific selection variables
e.g. W(ev) + jet events in a $H \to e^+e^-$ analysis

Irreducible backgrounds: SM events from other processes that will look identical no matter what you try
e.g. if you want to study $H \to e^+e^-$, you'll have an irreducible Drell-Yan background

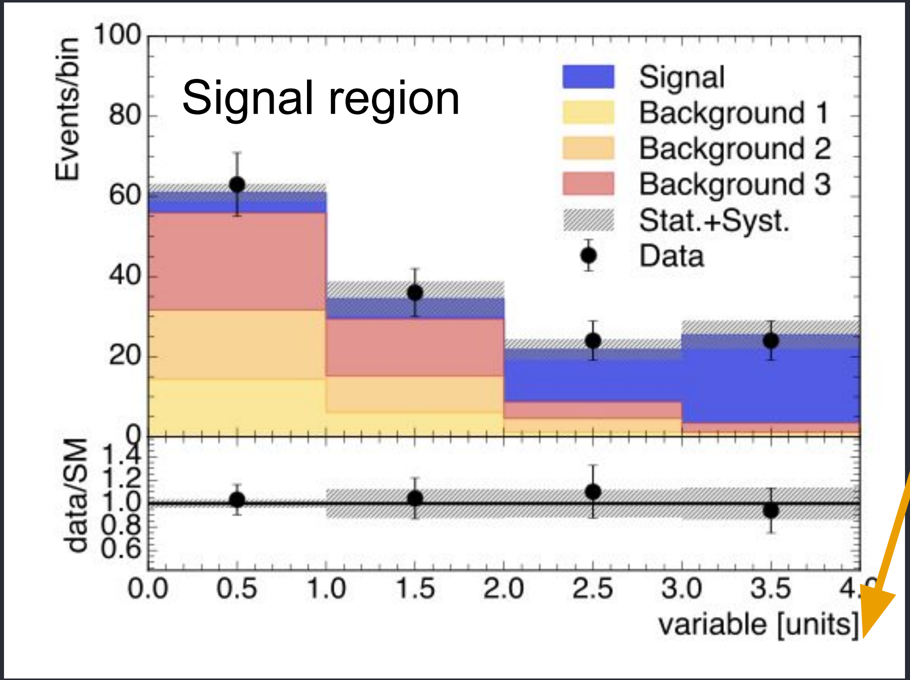
Measurement of a Standard Model processes



Carefully determine all the uncertainties on your predictions:

1. Statistical: sqrt(N) for **unweighted events** but simulation is almost always **weighted - so** $\delta^2 = \sum_{\text{events}} w_i^2$
2. Systematic: how well can we calibrate our electrons? How well does our simulation match data?
3. Modelling/theory: PDF uncertainties, strong coupling, NLO corrections, QCD corrections, parton showering, etc...

Measurement of a Standard Model processes



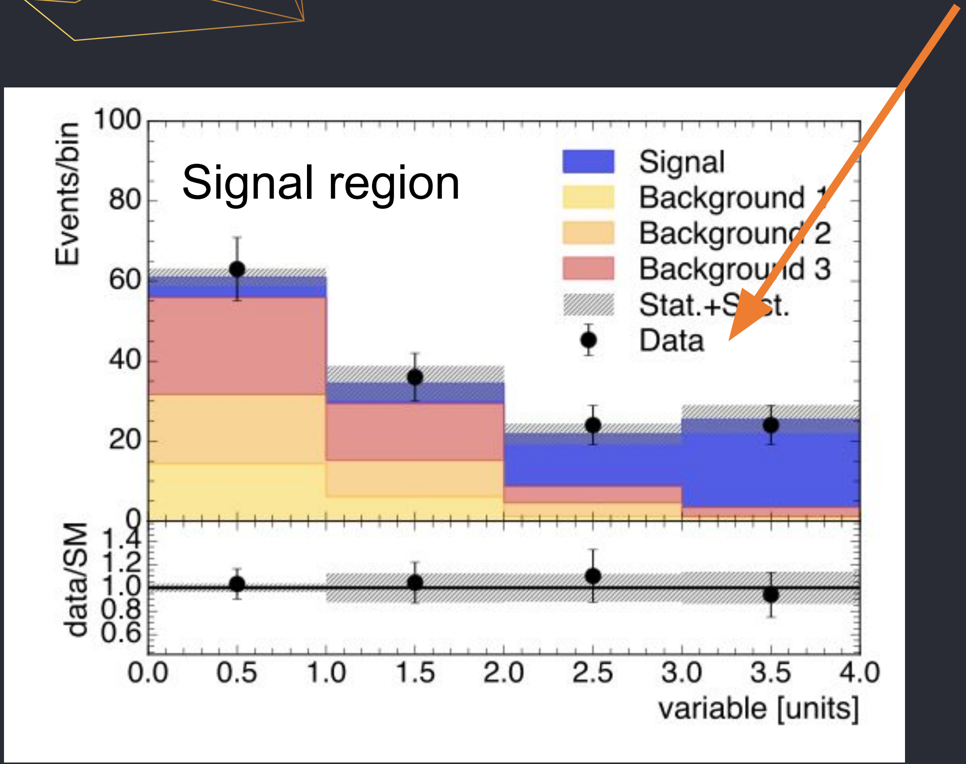
Choose some variable that distinguishes between signal and backgrounds, or is the quantity you want to measure

Choose a binning, uniform or not, generally informed by:

1. The **resolution** of the variable
2. The number of events/uncertainties
3. Background estimation methods
4. How the variable behaves in the model

(nb: some analyses run ***unbinned*** *but are still displayed with binned data!)*

Measurement of a Standard Model processes



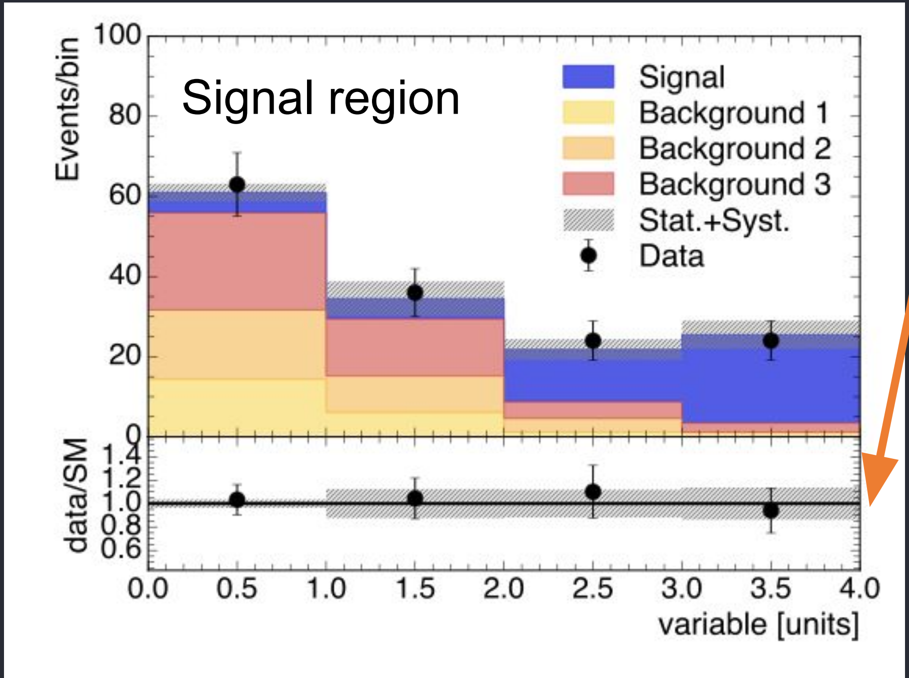
Look at the data!

For **searches**, we almost always do **blinded analyses**: no looking at the data until the analysis is **final.**

For **measurements**, this is analysis-dependent, but generally we still run blinded analyses - even when we know the process exists - though sometimes only the final observable(s), not the data itself!

Should the data have uncertainties? You decide!

Measurement of a Standard Model processes

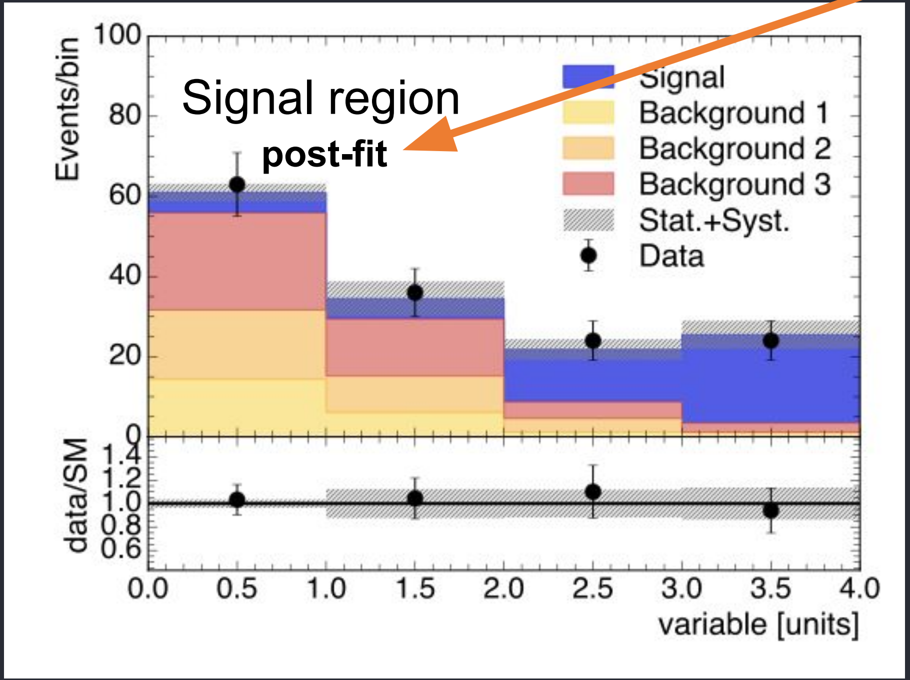


Usually we also show a **ratio plot** at the bottom:

Divide data by backgrounds+signal: provides a quick visualization of the agreement of the data with the prediction

Sometimes this is a **residual** or a **pull**

Measurement of a Standard Model processes



Generally we run **maximum likelihood fits** with **floating signal strengths** to extract the actual amount of signal observed in the data:

$$N_{pred} = \mu * s + b,$$

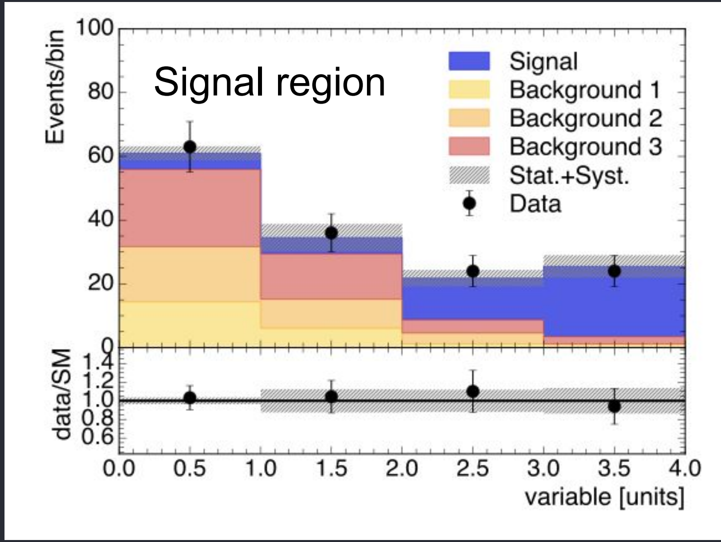
including nuisance parameters for both s and b.

Control regions are often included to constrain backgrounds, sometimes with multiple μ_{bkg} as well!

Plots in papers are usually **post-fit**, so the signal is **scaled** by the best-fit signal strength

Observation and measurement

Test the **null hypothesis**: measure the probability of observing what you see, or more extreme, if the particle/process did **not** exist (e.g. is μ_{sig} *consistent with zero?)*



p-value	probability	N-σ
0.05	95%	2 σ significance
0.003	99.7%	3 σ significance **"evidence"**
0.0000006	99.99994%	5 σ significance **"observation"**

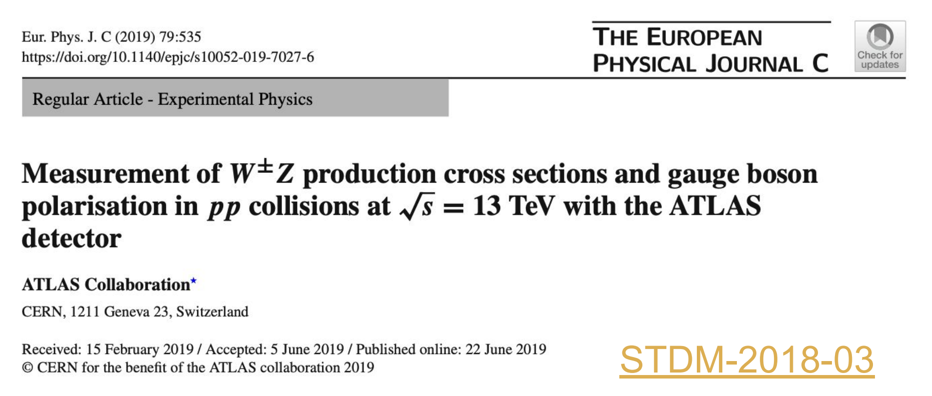
Example analysis: WZ

Example analysis: WZ

W and Z bosons are **unstable:** they do not travel through the detector, but instead decay **instantly**

hadronic → **quark pairs → jets**

leptonic → cleaner signature, but for *W* bosons contain a neutrino (missing transverse momentum: cannot fully reconstruct the *W!*)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https://doi.org/10.1140/epjc/s10052-019-7027-6
THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

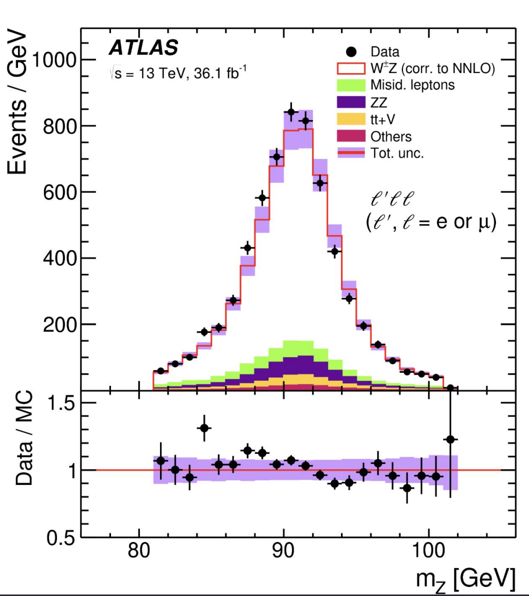
Measurement of $W^{\pm}Z$ production cross sections and gauge boson polarisation in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

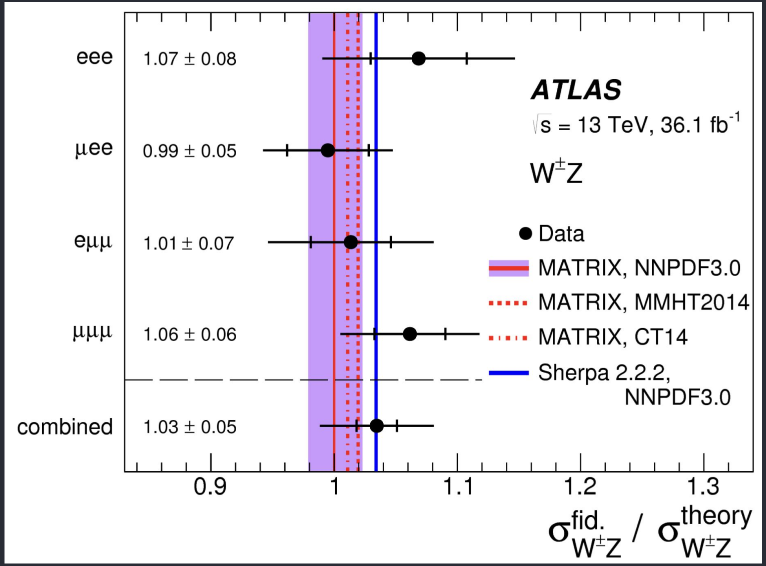
ATLAS Collaboration*
CERN, 1211 Geneva 23, Switzerland

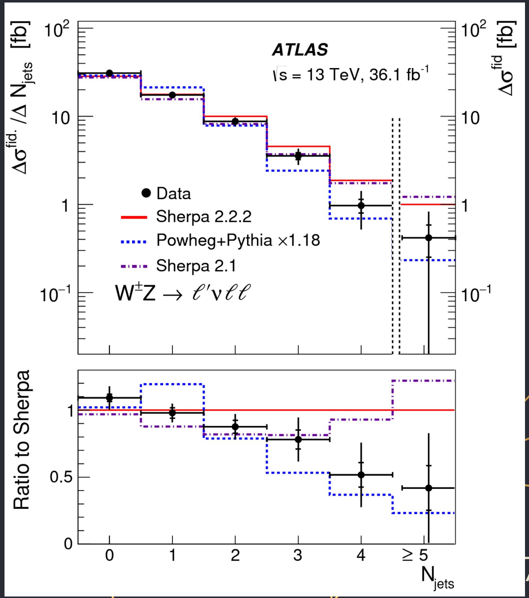
Received: 15 February 2019 / Accepted: 5 June 2019 / Published online: 22 June 2019

STDM-2018-03

ATLAS WZ publication using 36/fb of 13 TeV pp data







Questions?