Classic Particle Physics Experiment

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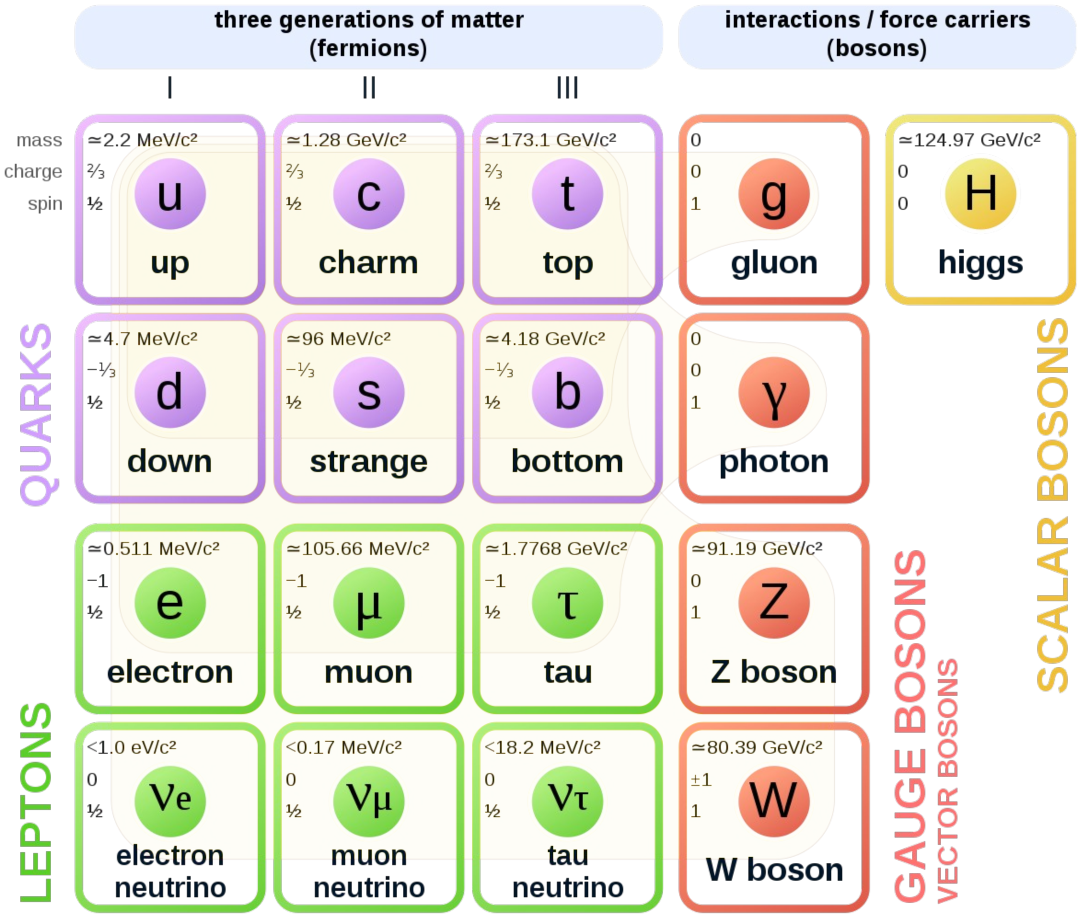
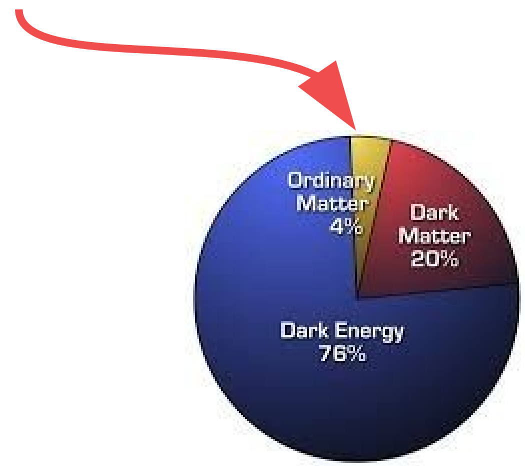
AVA school 2020

What do we want to study?

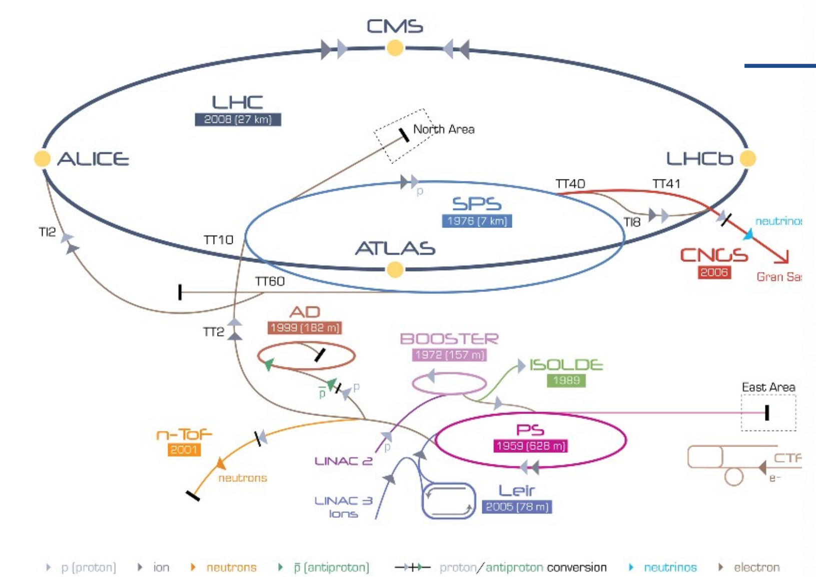
Standard Model of Elementary Particles

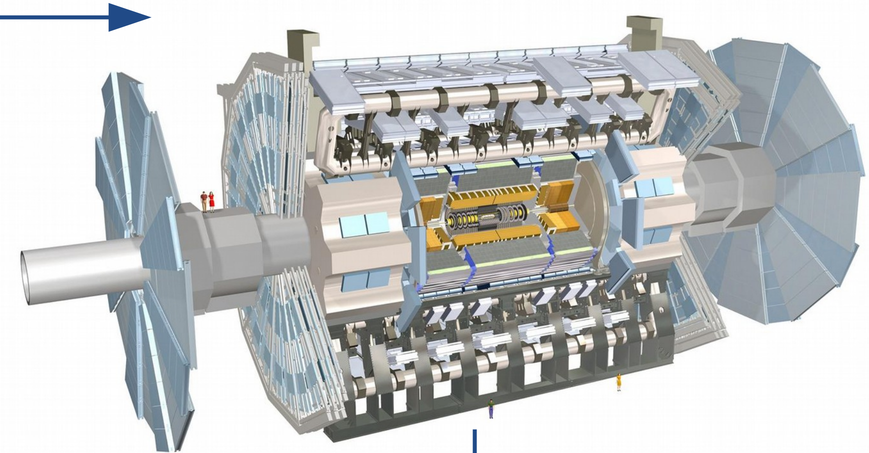


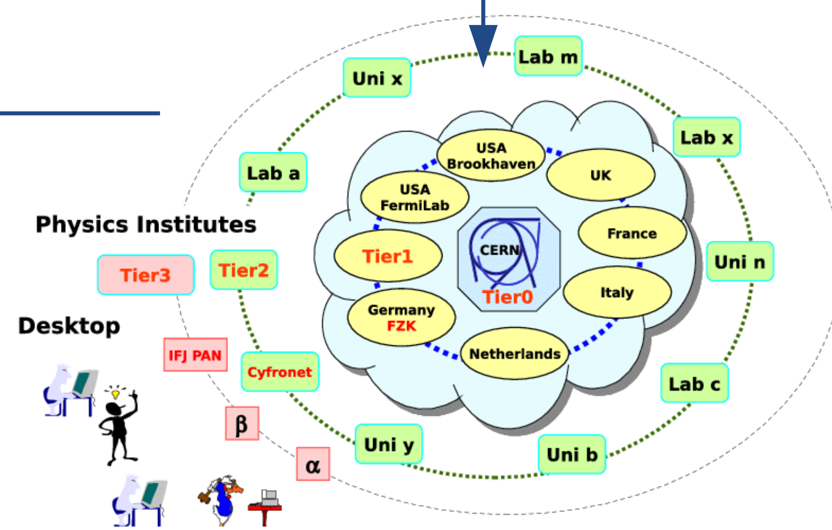


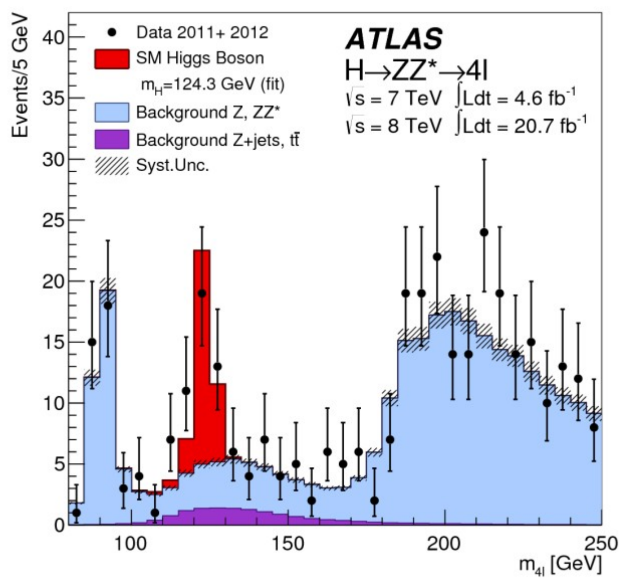
- Goal: study the matter and interactions at most fundamental level
  → test all parts of Standard Model (SM)
  → search for physics beyond SM (dark matter, supersymmetry, ...)

High energy particle experiment in nutshell









ACCELERATOR

What requirements to put on accelerator?

Goal: produce as many **interesting events** as possible

- the highest possible energy of interaction ($\sqrt{s}$)
  - higher energy → can observe particles with higher mass ($E=mc^2$)
  - Heissenberg's uncertainty principle:

$$\Delta x \cdot \Delta p \sim \hbar$$

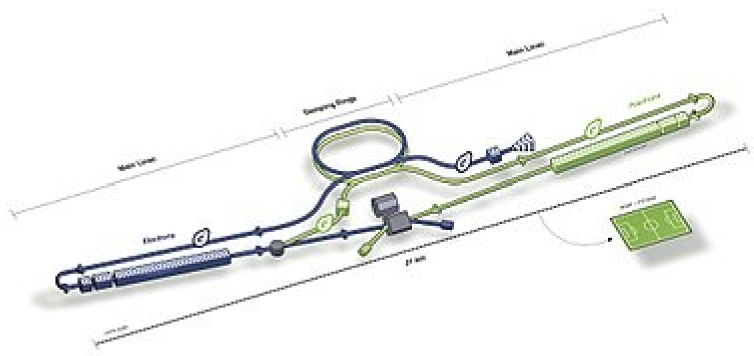
  → the higher momentum (energy), the smaller scales can be probed

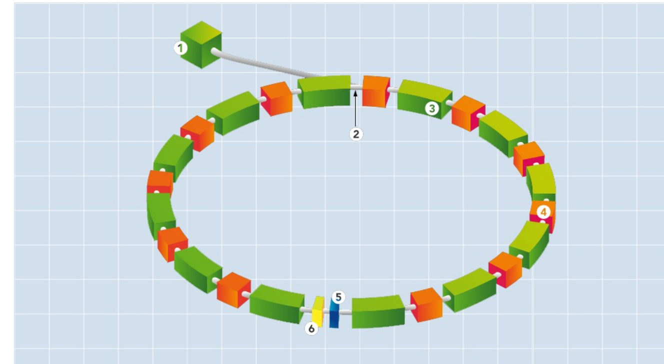
- the highest possible amount of collisions (luminosity)
  - the number of events for a given process:

$$N = \sigma \times Luminosity$$

  σ – the production rate of a given process (cross-section)
  - there is hidden the physics

How to get to high energy?

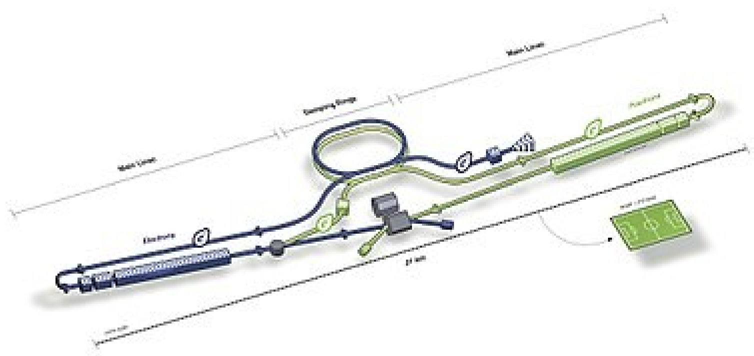


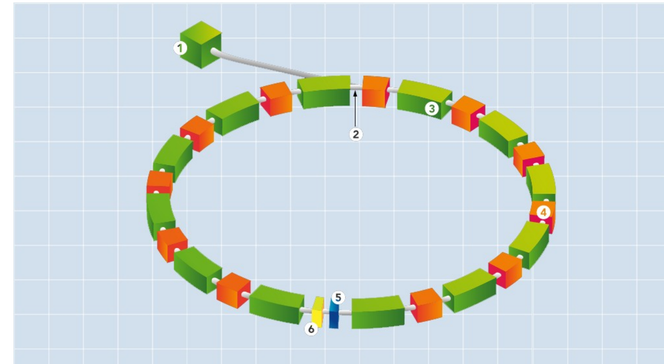


- linear vs. circular accelerators
  - circular colliders:
    - particles can be accelerated over many rotations → higher energy
    - the beams can be reused → larger integrated luminosity
    - there is fundamental limitation: accelerating charge particles radiate
      - Emitted power is inversely proportional to particle mass^4
        → severe limitation for electrons

→ typically using circular synchrotrons for protons, linear for electrons

How to get to high energy? (2)





- Why as big as possible circular?
  - Particle trajectories have to stay within beamline
  - Energy of protons on stable circular orbit in magnetic field:

$$E[GeV] \approx 0.3 \times B[T] \times R[m]$$

  - The higher radius 'R', the higher energy
- For a given radius R:
  - Need the highest possible dipole magnets to bend the trajectory
  - To bend protons at LHC (E=√s/2=6.5 TeV)→ magnets with B=8T needed
    - This is limiting factor! → the collision energy is set by the strength of dipole magnetic field
    - LHC: superconducting Niobium-Titanium coils cooled down to 1.9K

How to obtain high luminosity?

- The amount of data delivered is given by luminosity:

$$L = \int L_{inst}(t)\, dt$$

- Collision rate: instantaneous luminosity L(t)

$$L(t) = f \cdot n_B \frac{N_1 \cdot N_2}{Area} \cdot F = f \cdot n_B \frac{N_1 \cdot N_2}{4\pi \sigma_x \sigma_y} \cdot F$$

  f – revolution frequency (for a given radius it's ~constant) (LHC:11kHz)

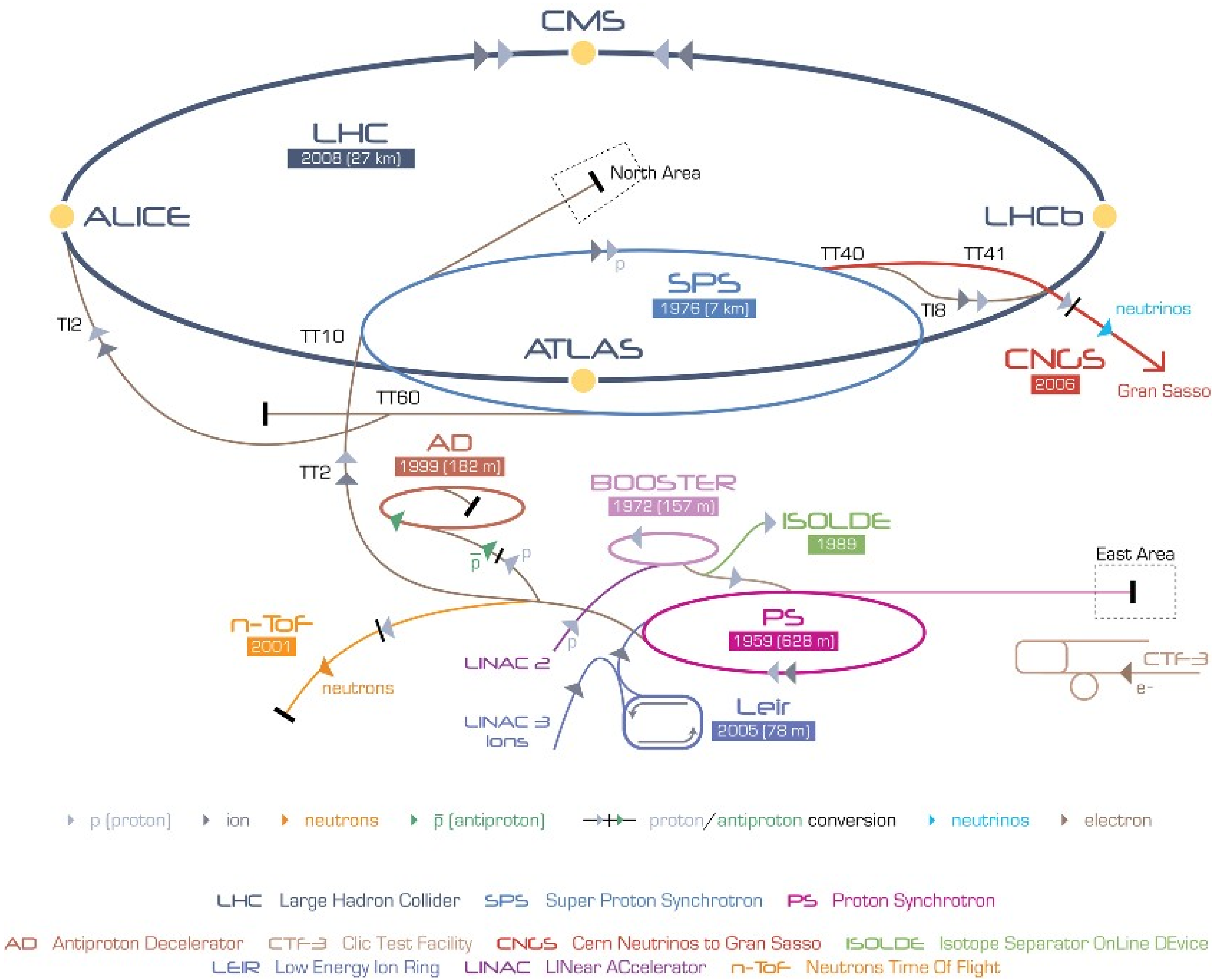
  n_B – number of bunches in a beam (~3000 → bunch crossing every 25ns)

  N_1, N_2 – number of particles in a bunch (~10^{11} protons)

  Area – transverse area of the bunch

  – σ_x,σ_y– root-mean-square of beam width in horizontal/vertical direction ($\mathcal{O}$(10μm))
  – F – geometric factor of order $\mathcal{O}(1)$ to correct for crossing-angle of bunches
- Simultaneous optimization of all parameters to get the highest overall luminosity
  – e.g. stop running at certain small instantaneous luminosity and start new run

Accelerator chain



- Each accelerator typically increases energy of particles by order of $\mathcal{O}(10\text{-}100)$

My (only) direct accelerator experience

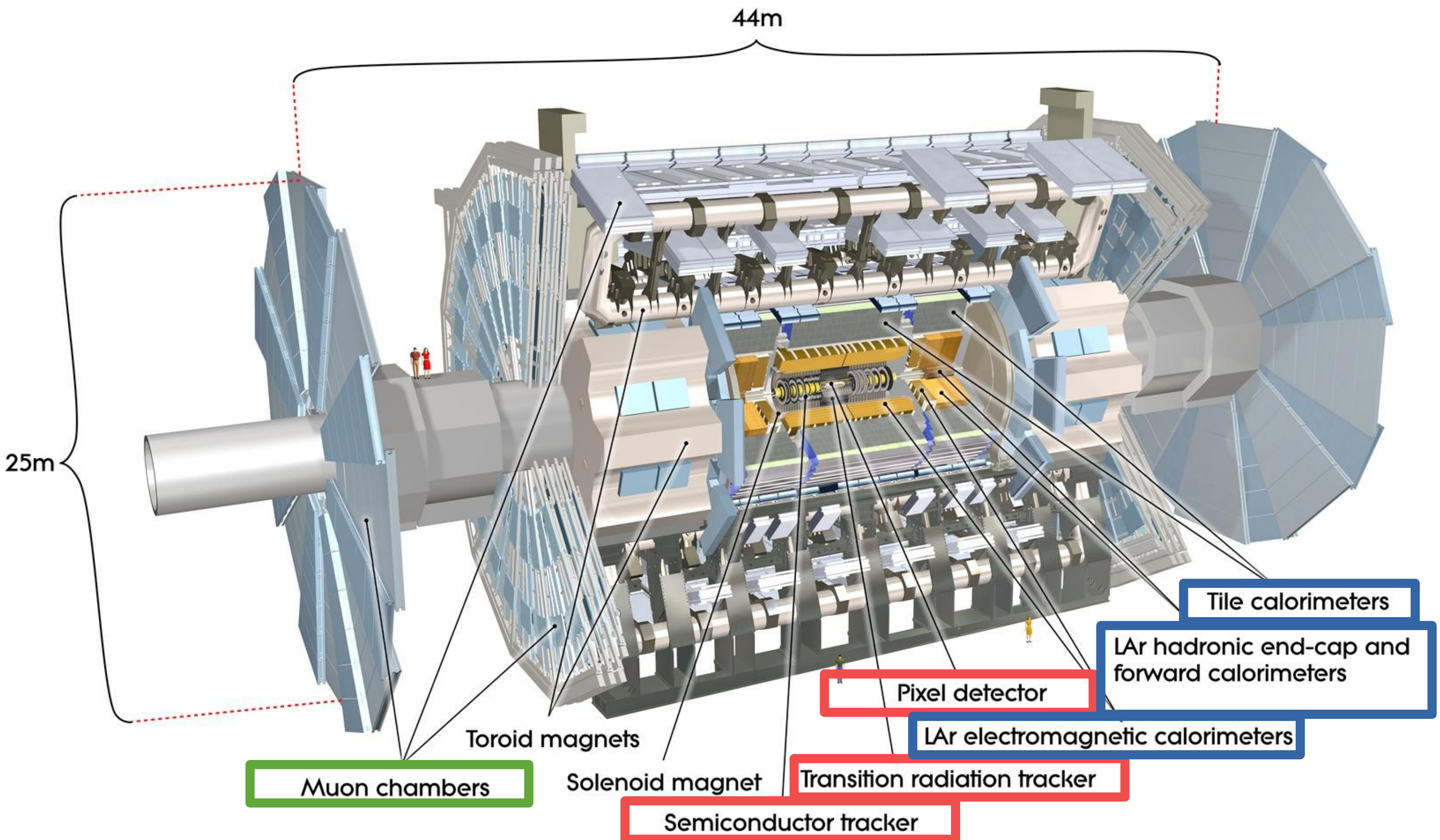
- Measuring magnet misalignments at Tevatron (Jun’09)

DETECTOR

What are we able to detect?

- Only ‘stable’ (within volume of detector) particles can be detected
  - Charged leptons: electrons, muons
  - Neutrinos not detected
  - Quarks can not be detected (colored particles)
    - But hadrons with long lifetime can (pions, kaons)
- Two ways to measure properties of particles interacting with matter:
  - Passively observing particles without disturbing the trajectory
    - charged particles interacting electromagnetically
  - Stop the particle and measure the energy deposited in the material
    - charged and neutral particles

Detector structure



TRACKING DETECTORS

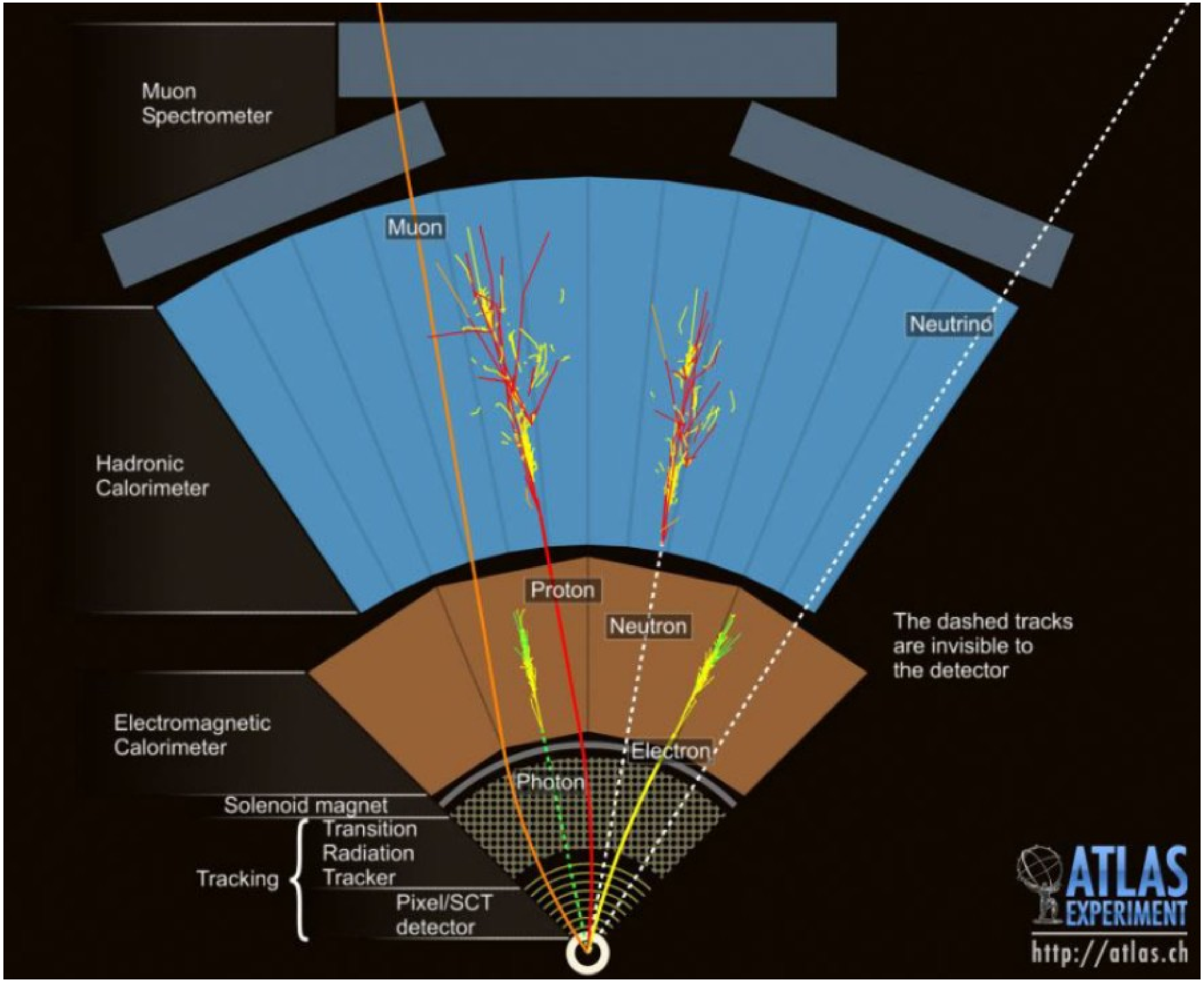
CALORIMETERS

MUON DETECTORS

General detector considerations

- design have to be optimized
  - e.g. more material in tracking detector have impact on reconstruction in outer parts of detector
- typical onion-like structure:
  - want to cover as much as possible (4π) in cover angle
  - want to distinguish between different particles
  - the part closest to interaction: tracking detectors
    - Must be before calorimeters which absorb particles
  - afterwards calorimeters (el, had)
    - electromagnetic:
      - must be first to absorb only elmag interacting particles (el., photons), to be able to distinguish from hadrons
    - hadronic: absorbing hadronically interacting particles
  - the last are muon detectors:
    - able to pass through all detectors

Particle detection



- Other hadrons (pions, haons) also absorbed in hadronic cal.

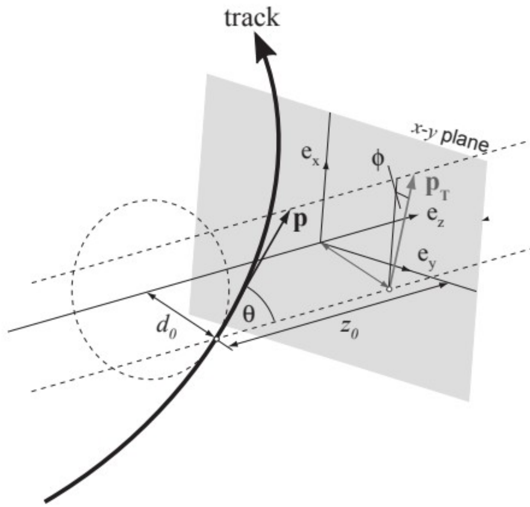
Tracking detectors

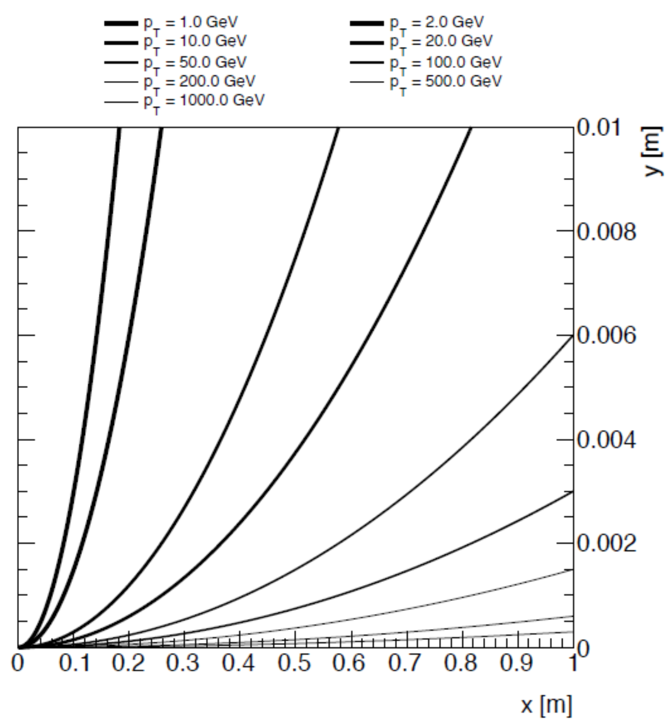
- measure hits along tracks of particles
  - elmag. interact. (ionization)
    → only charge particle tracks
    → Trajectory curved in magnetic field
- calculate momentum from the curvature of tracks
- typically, silicon semiconductor detectors used
  - excelent position resolution: $\mathcal{O}$(10 μm)
  - radiation hardness
- typical particle energies: $\mathcal{O}$(100 MeV-100 GeV)
- momentum resolution:

$$\phi \propto 1/R \propto 1/p \rightarrow \frac{dp}{p} \propto d\,\phi \cdot p \propto (const.) \cdot p \oplus d$$

bending angle

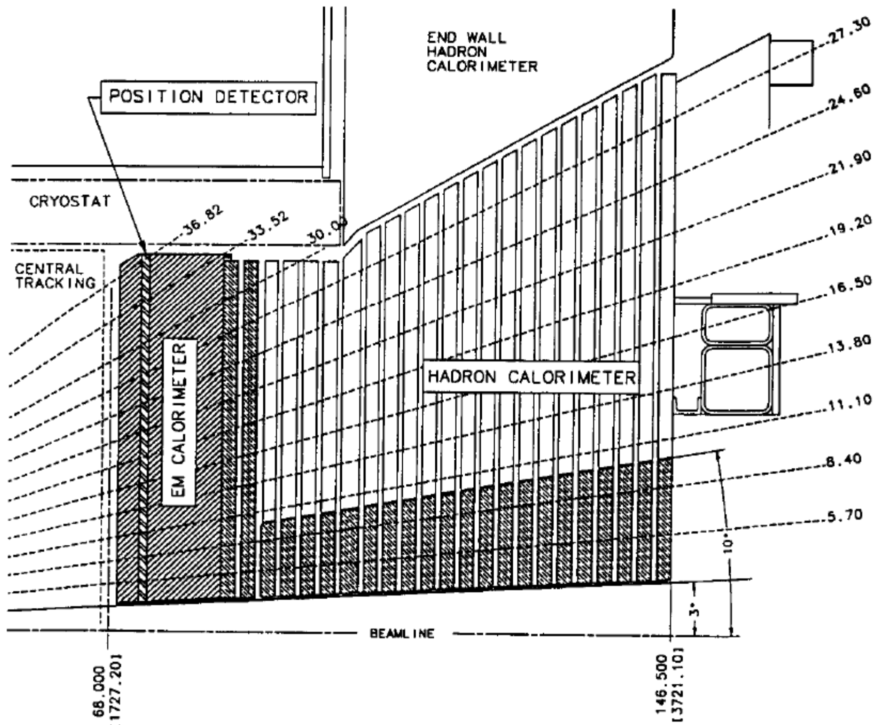
multiply scattering





Calorimeters (1)

- measure energy by absorbing particles
- sampling calorimeters:
  - active medium (generates signal)
    - Scintillator (CDF el.-mag.), liquid (ATLAS el.-mag.: liquid Ar)
  - passive medium (absorber)
    - the material with high density, e.g. steel (CDF/ATLAS had.), lead (CDF/ATLAS el.-mag.)



CDF calorimeter

Calorimeters (2)

- electromagnetic vs. hadronic calorimeters:
  - electromagnetic vs. nuclear interactions
  - electrons of energies >~10 MeV predominantly lose energy by bremsstrahlung (photon radiation)
  - high-energy photons by e+e- pair production
  - hadronic calorimeters typically larger
- resolution: E~N particles in shower, stochastic process: $\sigma(N)=\sqrt{N} \rightarrow \sigma(E)\sim\sqrt{E}$:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

Electronic noise

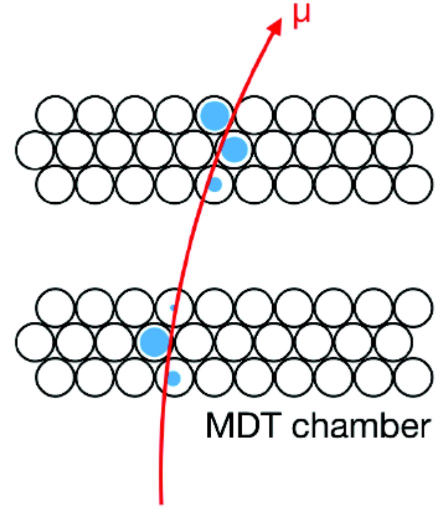
stochastic term

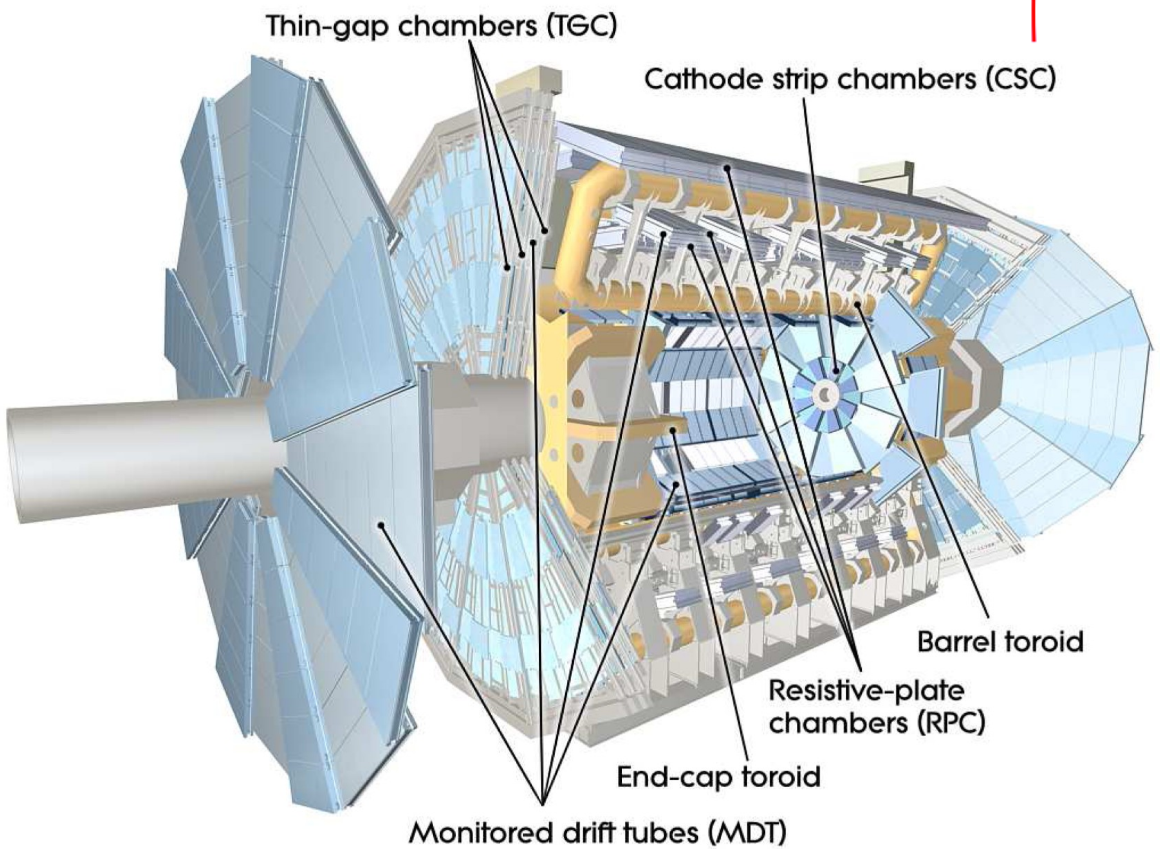
detector non-uniformity, etc.

- comparison to trackers:
  - calorimeters:
    - better resolution at high p_T
    - can reconstruct neutral particles
  - trackers:
    - better p_T resolution at low p_T,
    - better angular resolution, can distinguish pile-up

Muon detectors

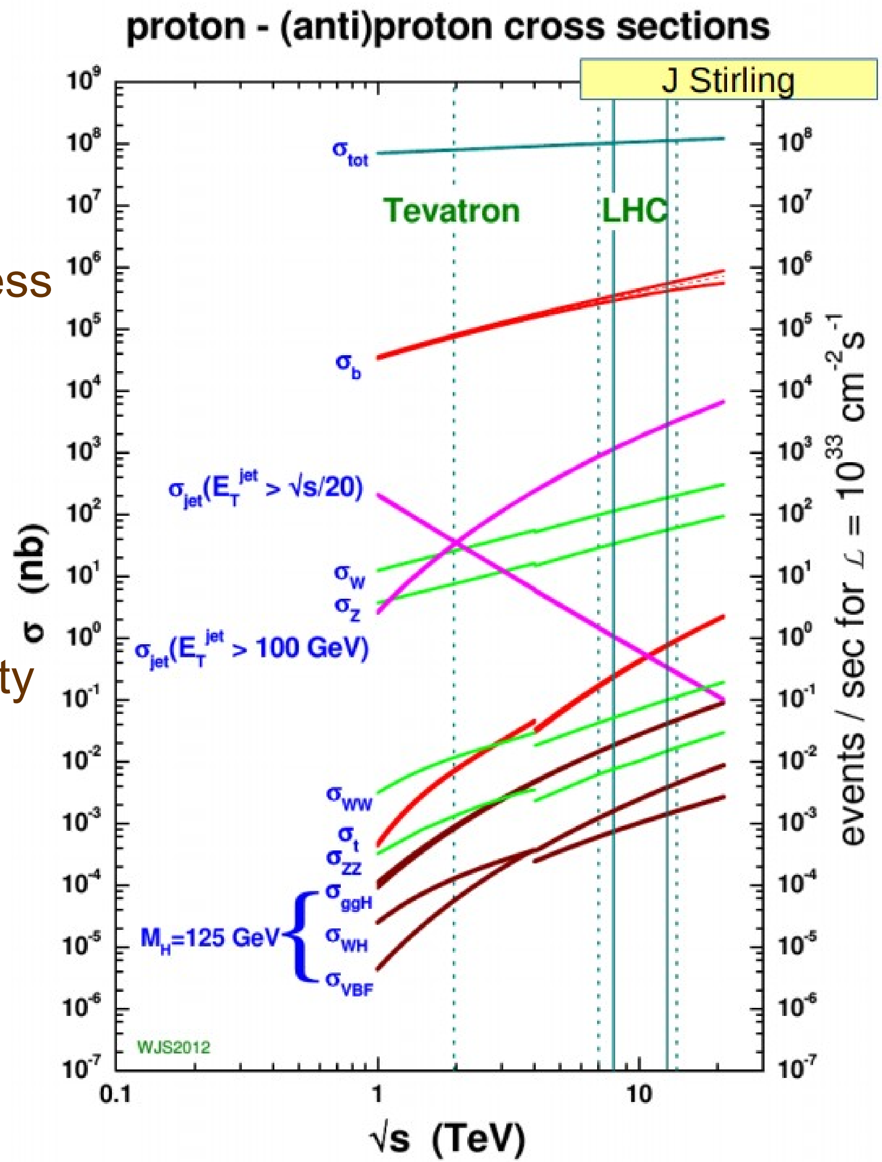
- help identify muons
- typically, drift tubes detectors
- combine hits from tracking and muon detectors to reconstruct muon tracks



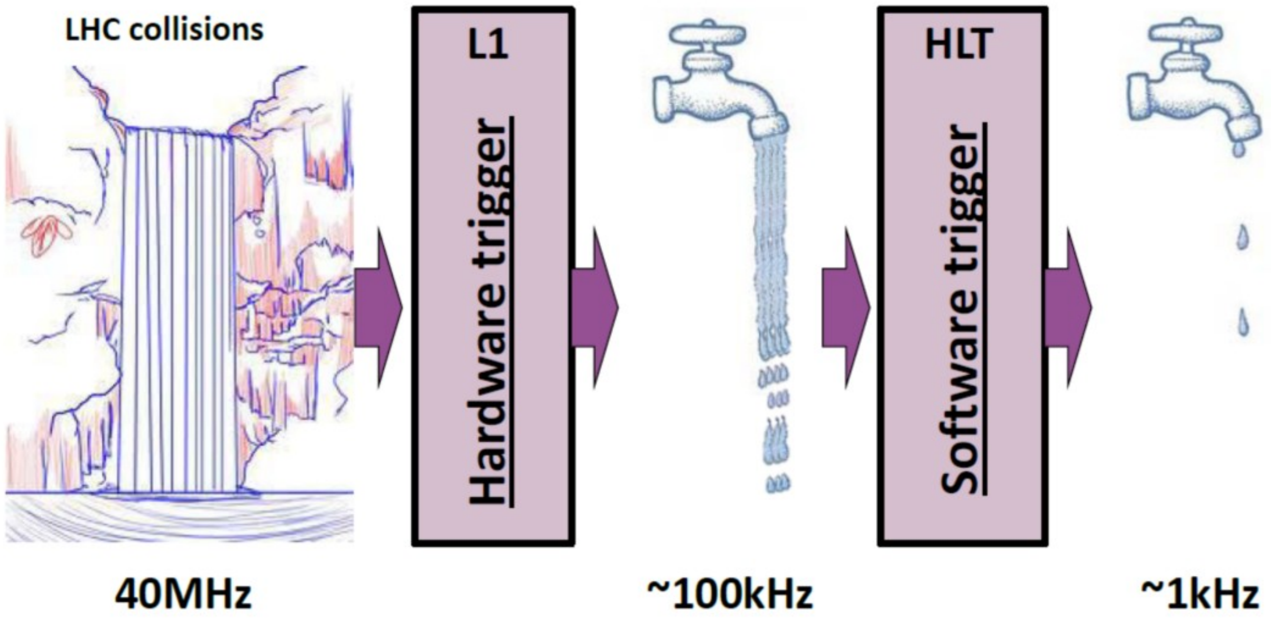


Trigger (1)

- LHC collisions: each 25ns
  → colliding rate 40MHz
- ATLAS: 100M channels → 1MB/event
  → 40TB/s of data→ too much to save/process
- even if we could save all events
  - not all events that interesting
    (W/Z and Top have 6-8 orders smaller cross-section than total cross-section)
  - we don't need arbitrary many events
    - At some point, systematic uncertainty dominate the statistical ones



Trigger (2)

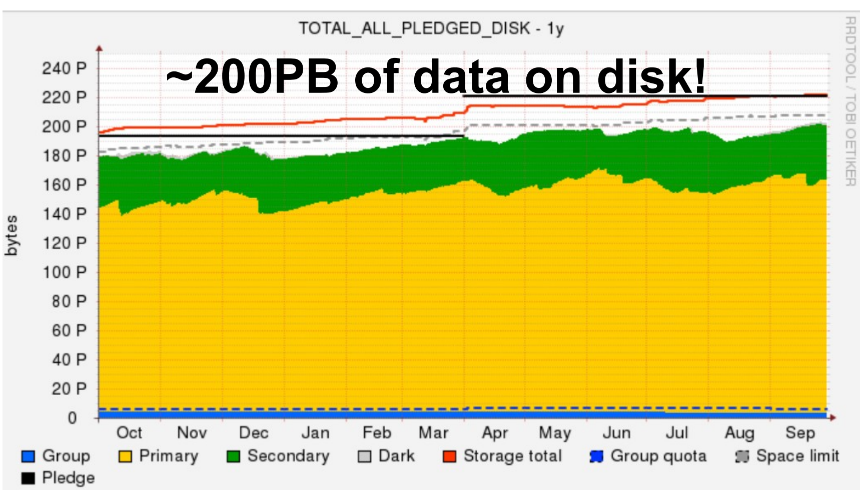


- trigger is responsible for real-time selection of the subset of events
- typically: trigger has 2-3 levels
  - 1st/2nd level: specific hardware using information only from part of the detector
  - 2nd/3rd level: software based
- we are able to save ~1kHz of events: $\mathcal{O}$(100-1000) MB/s
  - ~4-5 orders of magnitude reduction of rate

COMPUTING

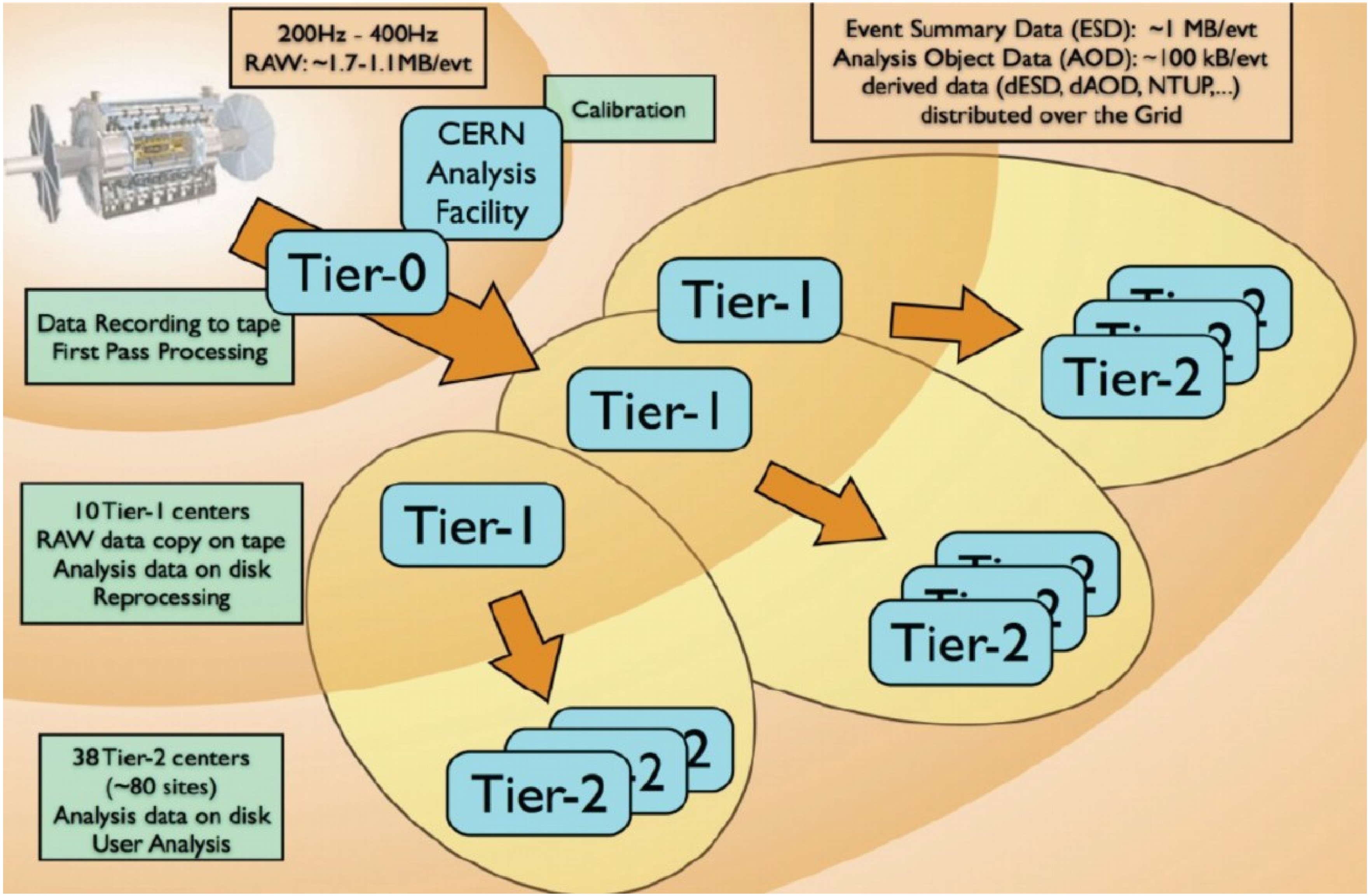
To set the stage

- we need to process and store
  - experimental data
    - Number of raw events: 1kHz * 200 days *50% efficiency ~ 10G ev./ year
    - Raw Size: 1MB/event * 10G events = 10 PB / year
  - simulated data
    - modeling processes, test of reconstruction, evaluation of systematics, ...
    - Typically, there are more than experimental data: more stats than in data, many processes, generators, settings, etc.
- typical processing time:
  - Data reconstruction: $\mathcal{O}(10)$ seconds / event $\rightarrow$ $\mathcal{O}$(1k-10k) CPUs / year
  - Simulation: $\mathcal{O}(1)$ minutes / event, but very broad range(~1min to ~few hours)

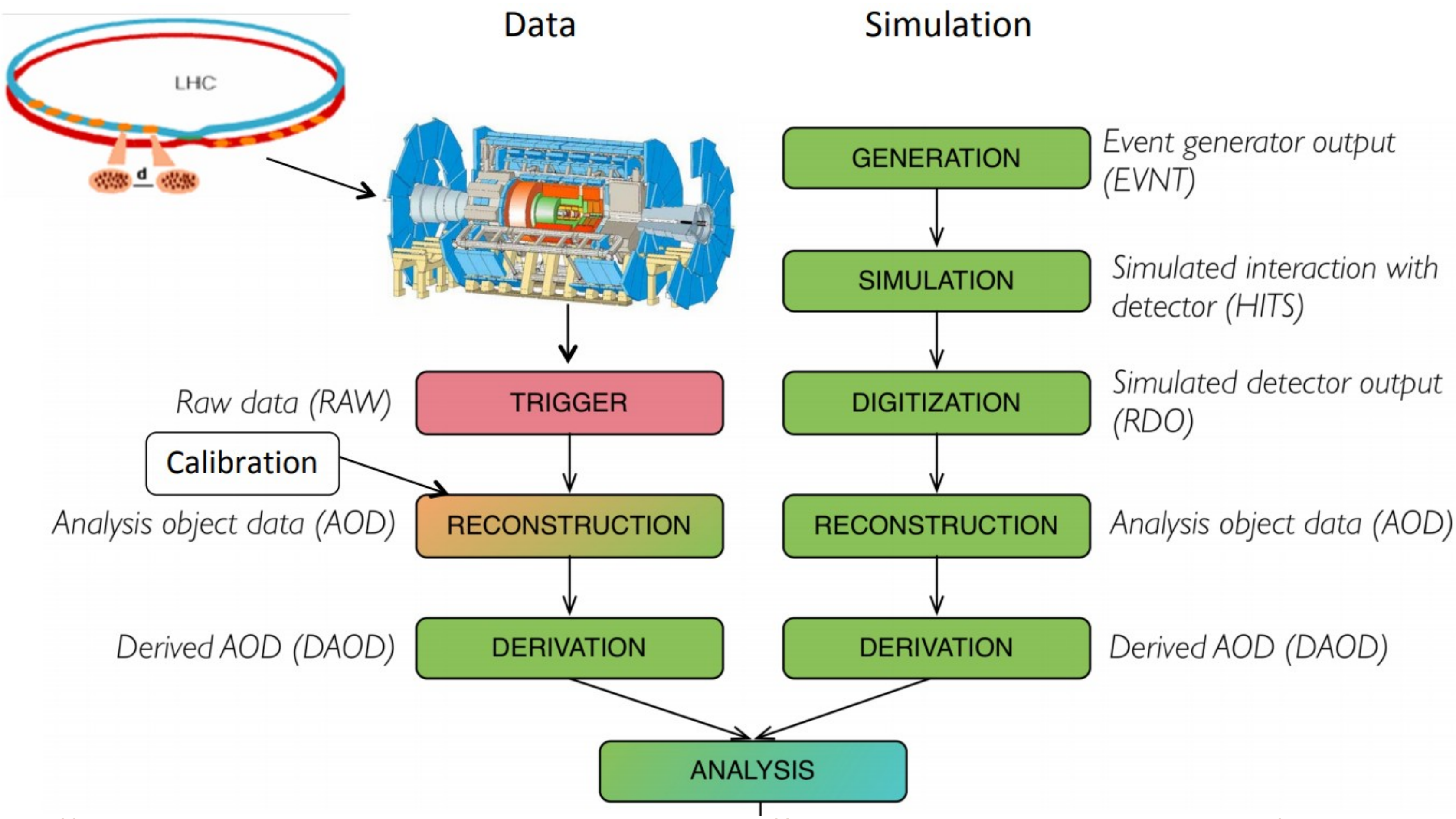


Computing model

- can not do all processing in one place → need distributed computing (grid)



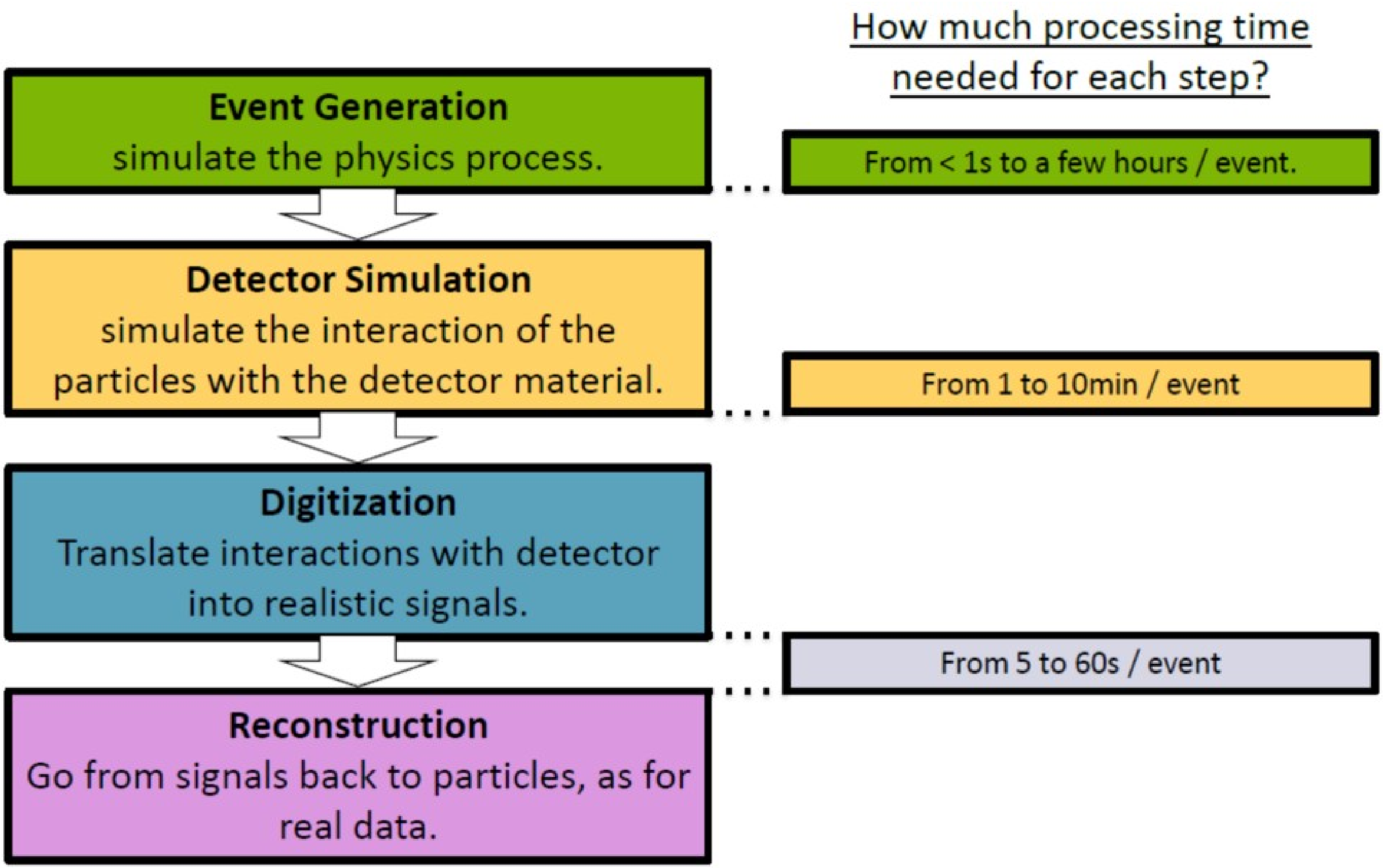
Typical steps in processing



- different physics groups typically need different objects, selections of events
  → using different set of files (in ATLAS: DAOD)
- final formats used in physics analysis typically ROOT ntuples
  - all-together $\mathcal{O}$(100 GB – 1 TB) in size
    → still need processing on grid / local computing cluster

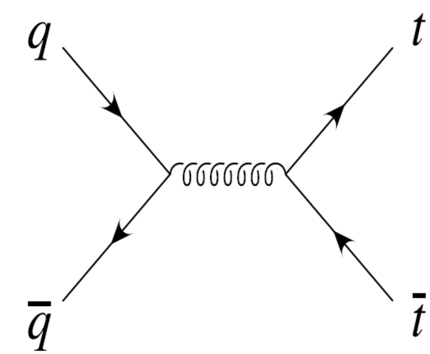
Simulation of events

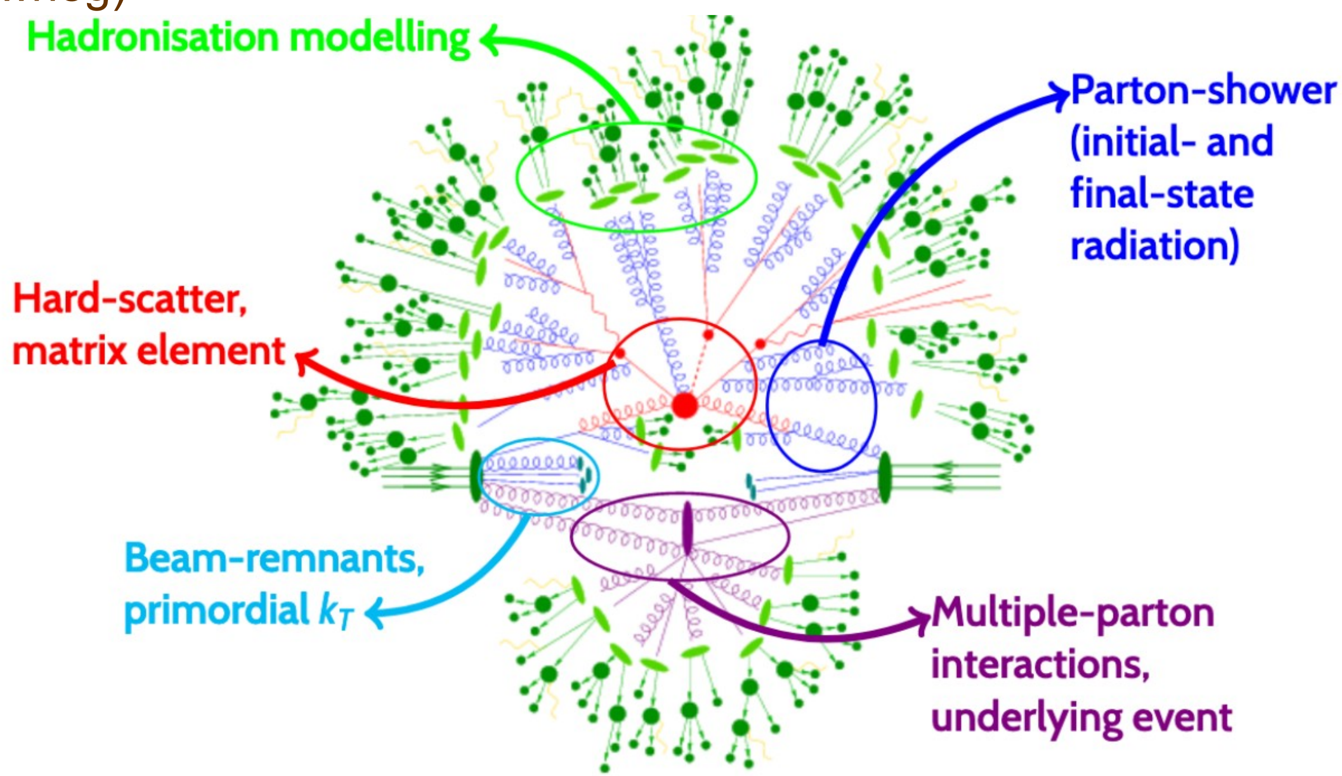
- Simulation of events based on Monte-Carlo (MC) methods



Event generation

- simulation of fundamental physics for a given process
- MC event generators perform the calculations of the underlying theory, e.g. quantum chromodynamics (QCD)
  - have different levels of precision
  - Typically, using next-to-leading order generators (e.g. Powheg)
- a few steps

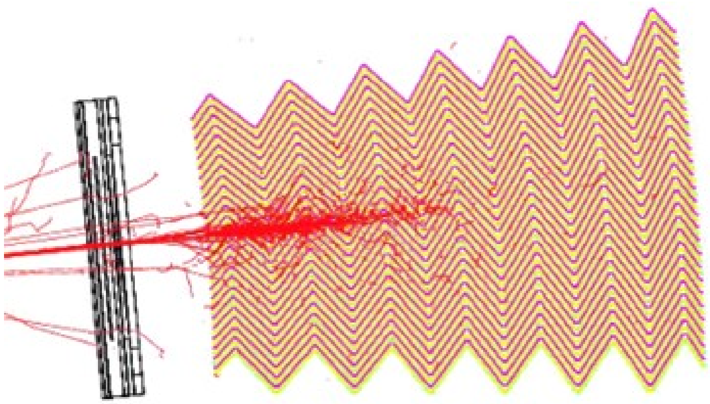




- typically the fastest step in simulation: $\mathcal{O}(<1\ \text{s})$/event
  - Huge variations in processing time (up to a few hours/event)

Detector Simulation

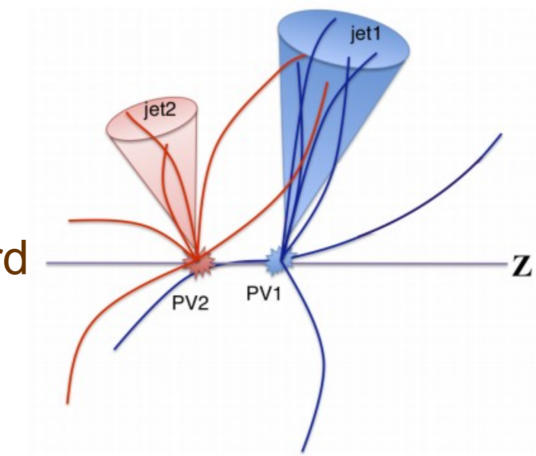
- simulate passage of generated particles through the detector
- using mostly Geant software
  - particle walks through the detector
  - most of the time spent in calorimeter
- where possible, using fast simulation
  - parameterize how a given particle will look like in detector (e.g. ‘a pion will look such-and-such’)
  - don’t walk particle through detector, rather smear things directly in detector
  - typical speed-up $\mathcal{O}$(10-100)
- typically, most CPU consuming part of simulation $\mathcal{O}$(1-10) minutes/event

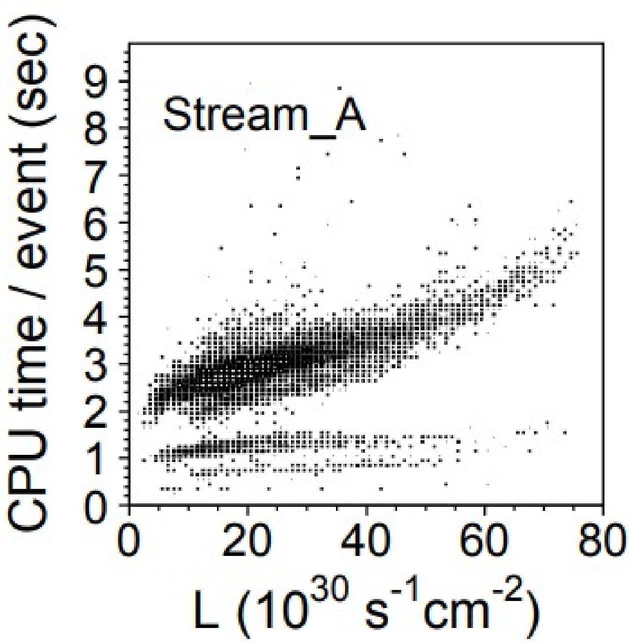


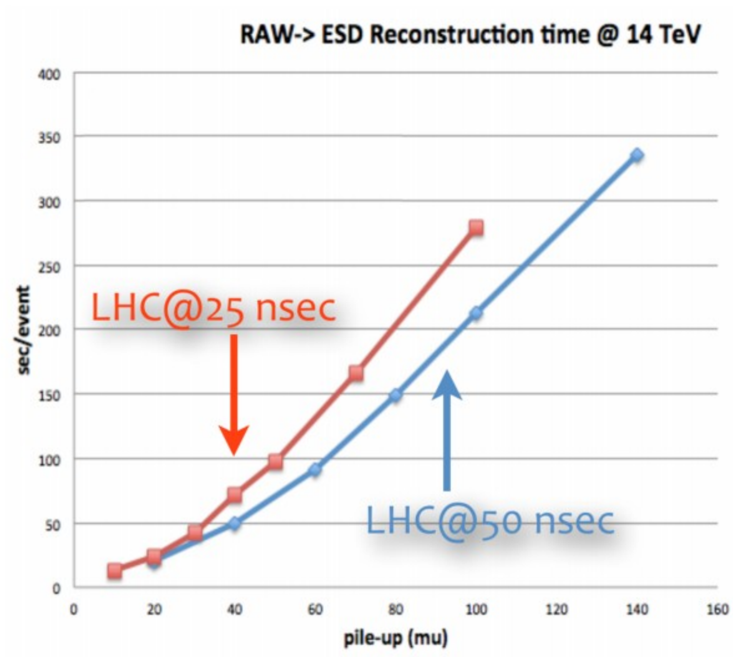
Sample	Full G4 Sim	Fast G4 Sim	Atlfast-II	Atlfast-IIF
Minimum Bias	551.	246.	31.2	2.13
$t\bar{t}$	1990	757.	101.	7.41
Jets	2640	832.	93.6	7.68
Photon and jets	2850	639.	71.4	5.67
$W^{\pm} \rightarrow e^{\pm}\nu_e$	1150	447.	57.0	4.09
$W^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$	1030	438.	55.1	4.13

Reconstruction and pile-up

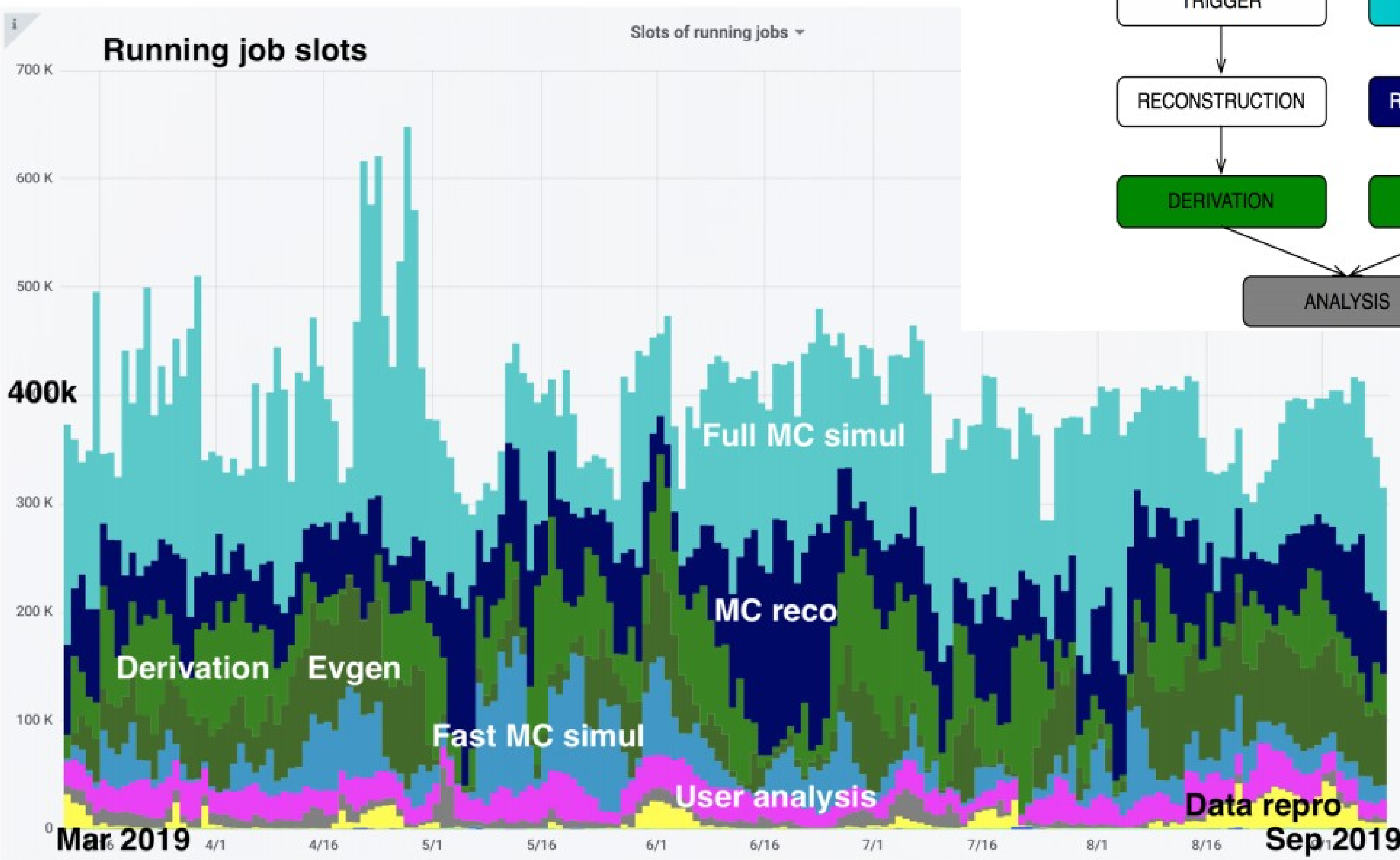
- taking RAW data from detector and turning them into analysis objects (electrons, muons, jets,…)
- multiply pp interactions (pile-up) possible when two proton bunches collide
  - Typically, one hard (high-p_T) collision and ord of $\mathcal{O}(10)$ of soft collisions
- processing time highly dependent on pile-up
  - Combinatorics in tracking

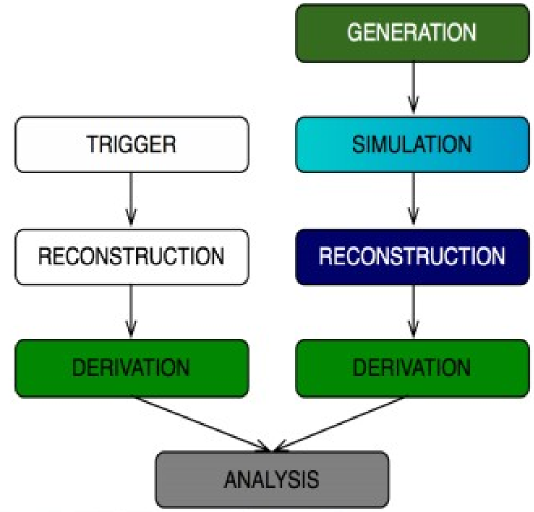






What kind of jobs are we running?





- typically, detector simulation (full+fast) uses most of processing time

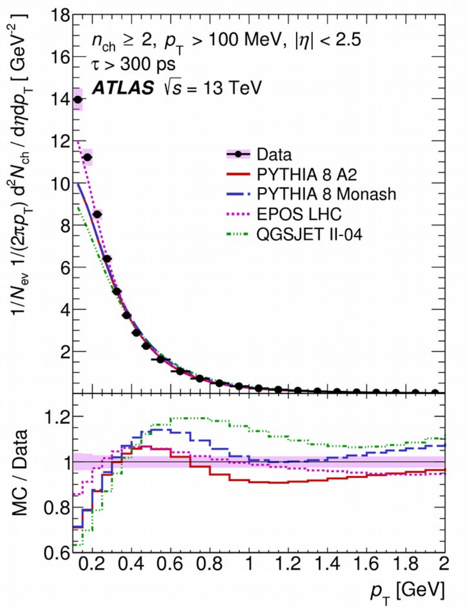
PHYSICS ANALYSIS

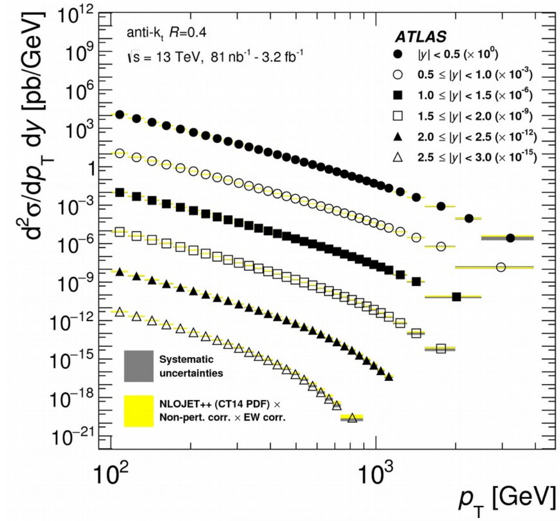
what kind of physics analysis possible?

- High-energy particle experiments are multipurpose experiments

  → test all parts of Standard Model (SM) and search for physics beyond SM

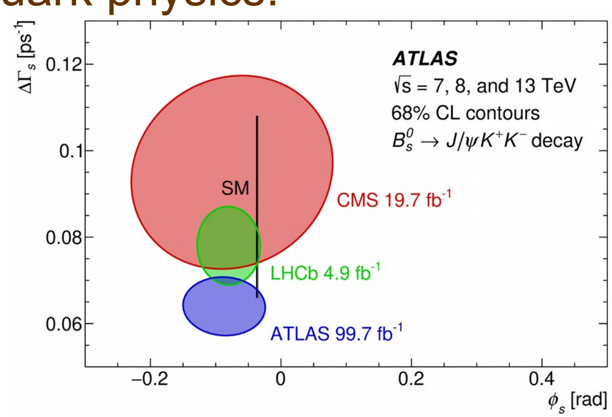
low p_T QCD

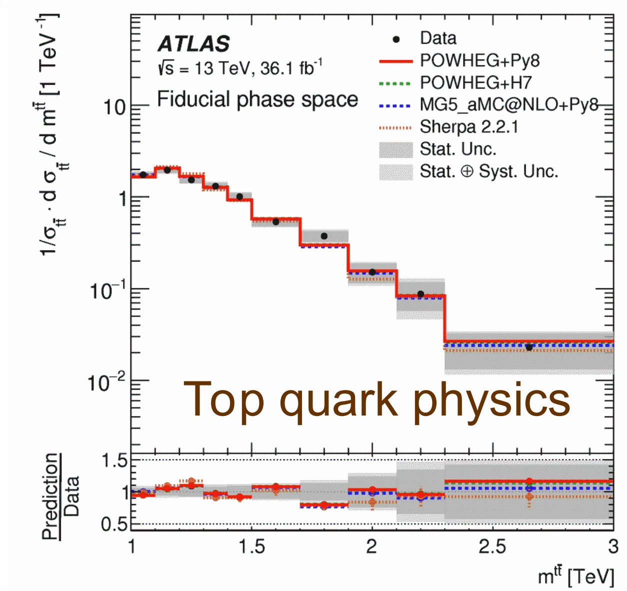




high-pT QCD tests
(jets cross-section)

b-quark physics:

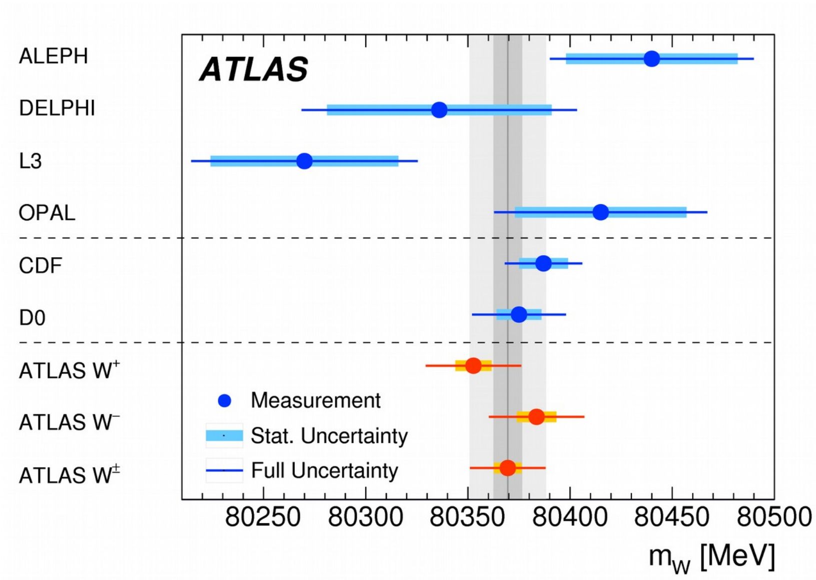




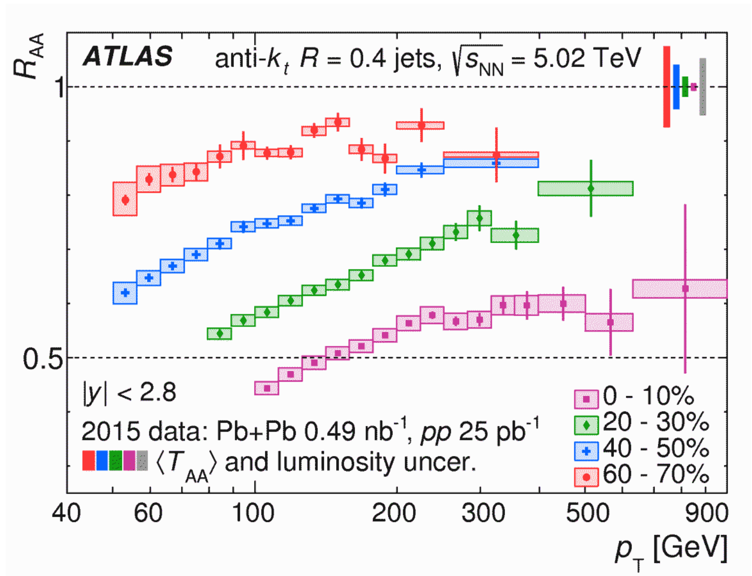
Top quark physics

what kind of physics analysis possible? (2)

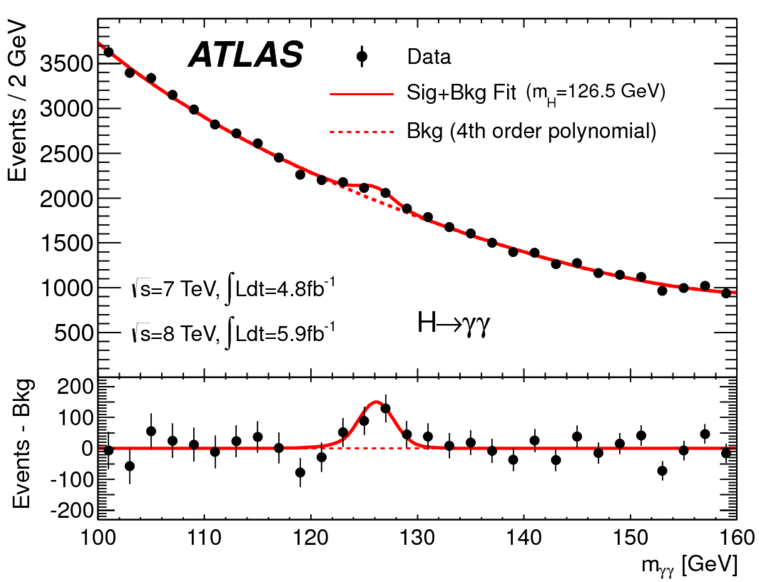
Electro-weak tests (W mass)



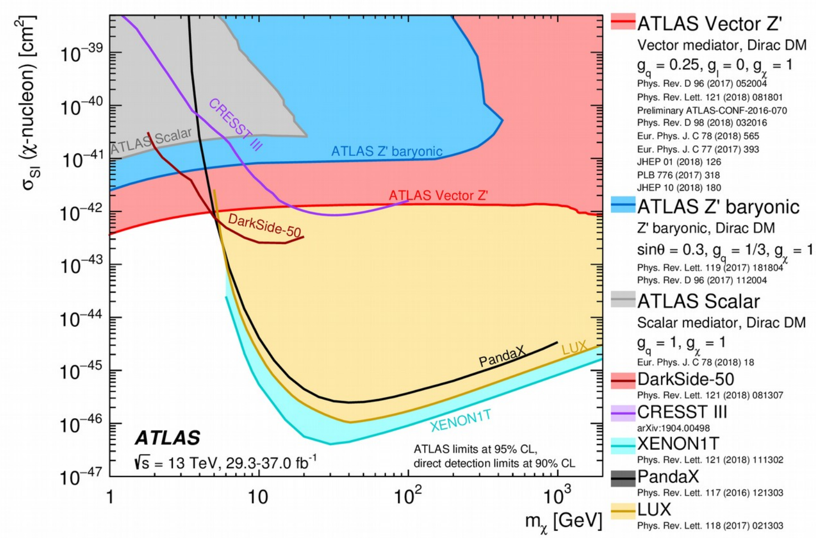
Heavy ion physics(e.g. jet suppression)



Higgs boson (observation)

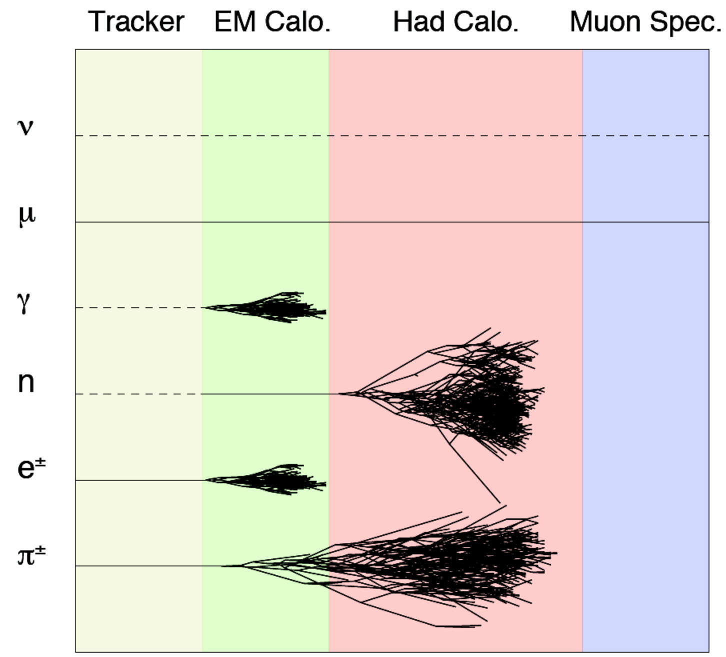


Search for new physics (e.g. dark matter):



Which basic objects do we reconstruct?

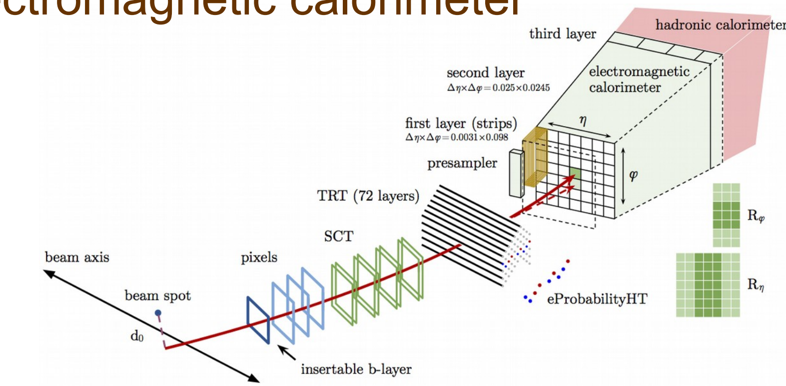
- We actually measure only track hits of charged particles and the deposited energy in the calorimeter
- Basic objects reconstructed from tracks and deposited energy:
  - Leptons
    - Electrons
    - Muons
    - Taus
  - Photons
  - Jets
    - Showers of particles originating from quarks/gluons
  - Missing transverse momentum
    - provides info about neutrinos



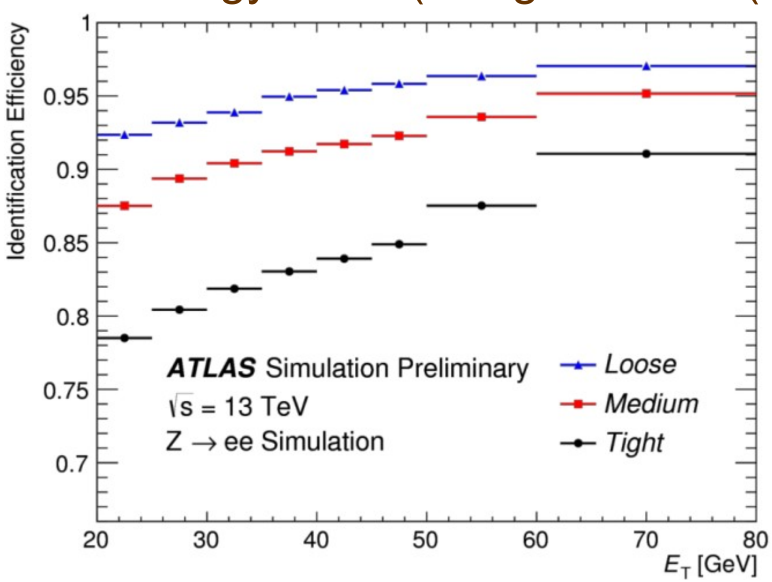
- Most of the analyses use some combination of these reconstructed objects

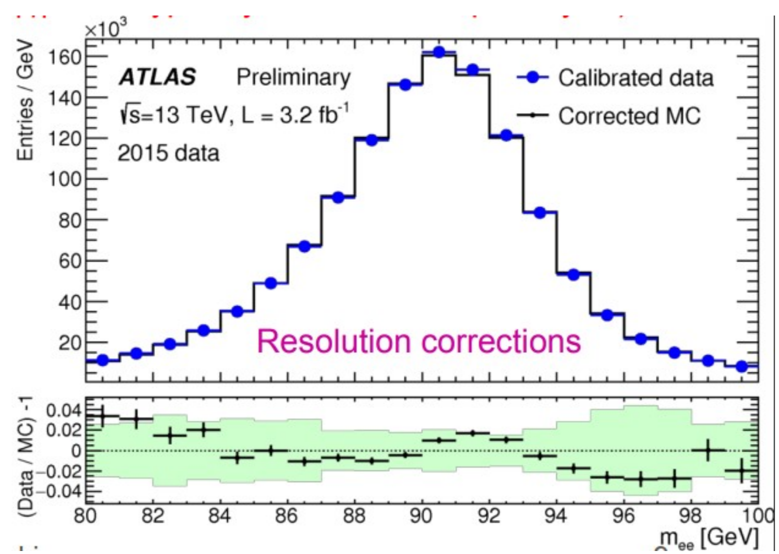
Electron & Photon reconstruction

- reconstructed from energy deposited in the electromagnetic calorimeter (clusters of calorimeter cells)
  - electron does have an associated track
  - photon does not



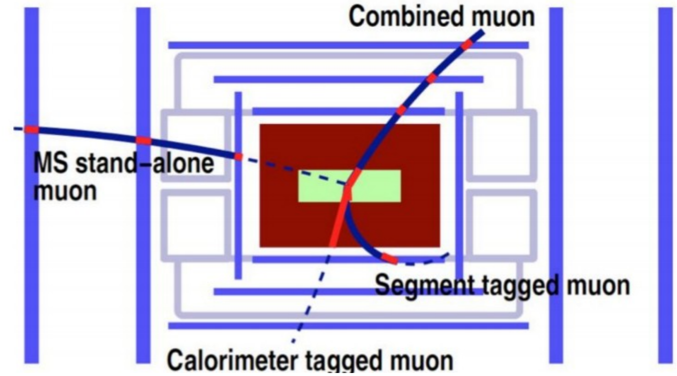
- the reconstructed electrons need to be corrected for data/MC difference in
  - probability of reconstruction (efficiency)
    - events in MC weighted with scale factor SF = eff_{data}/eff_{MC}
  - energy scale (using known m(Z) in Z→ ee data)



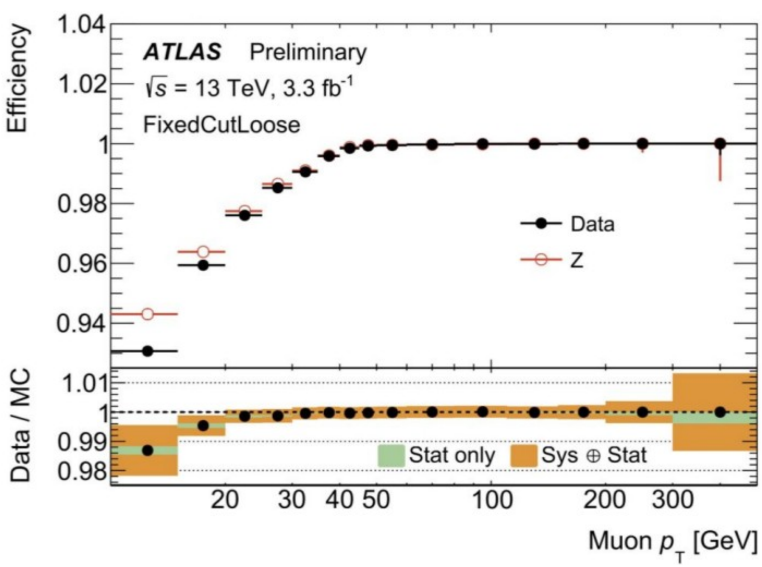


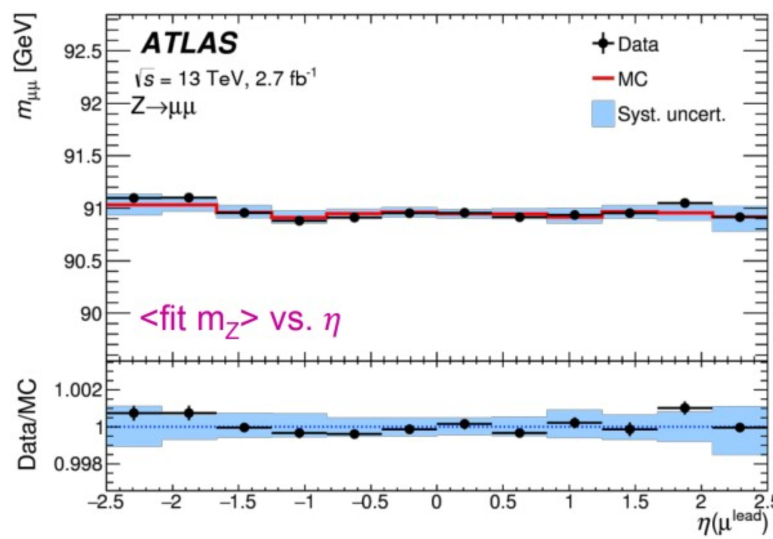
Muon reconstruction

- track reconstructed from hits in muon detectors and tracker
  - identified by hits in muon detectors
- muon trajectory bend by magnetic field
  → curvature determines momentum



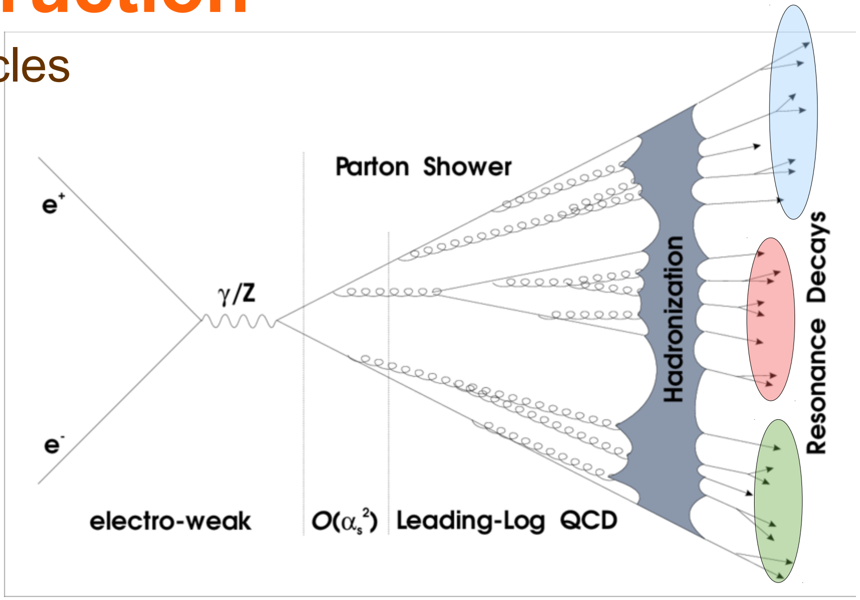
- muon efficiency and momentum calibrated using (Z or J/ψ)→μμ decays
- muon momentum scale known to <= 0.1%





Jet reconstruction

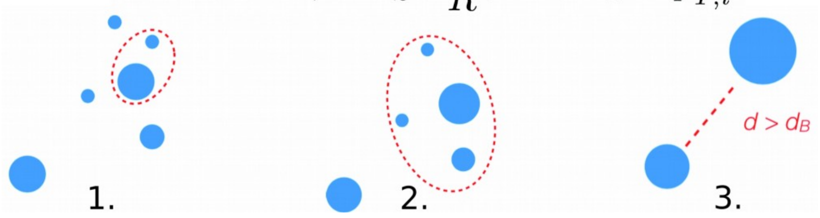
- partons (quarks/gluons) are colored particles
  – can not be observed directly
  – shower of particles in final state
  – set of particles close to each other form a jet

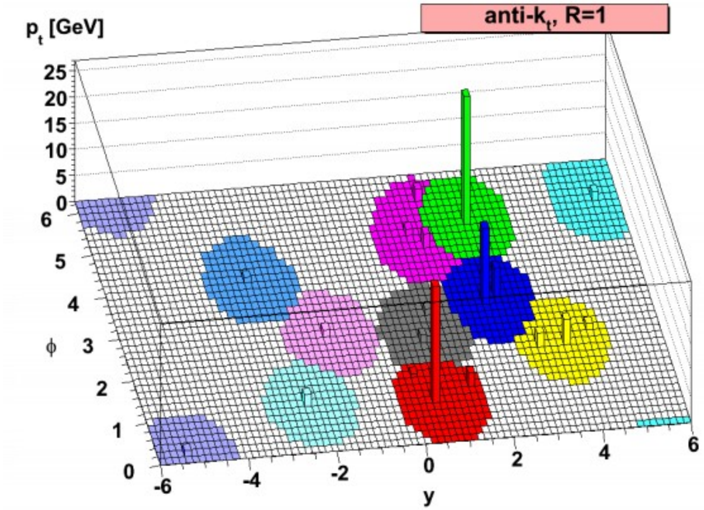


- a few different jet algorithms
- anti-k_T algorithm preferred lately
  – Repeat combining pairs of particles with smallest 'distance'(d_{ij}) until $d_{ij} > d_B$
  – One parameter: 'radius' R

$$\Delta^2_{i,j} = \phi^2 + y^2$$

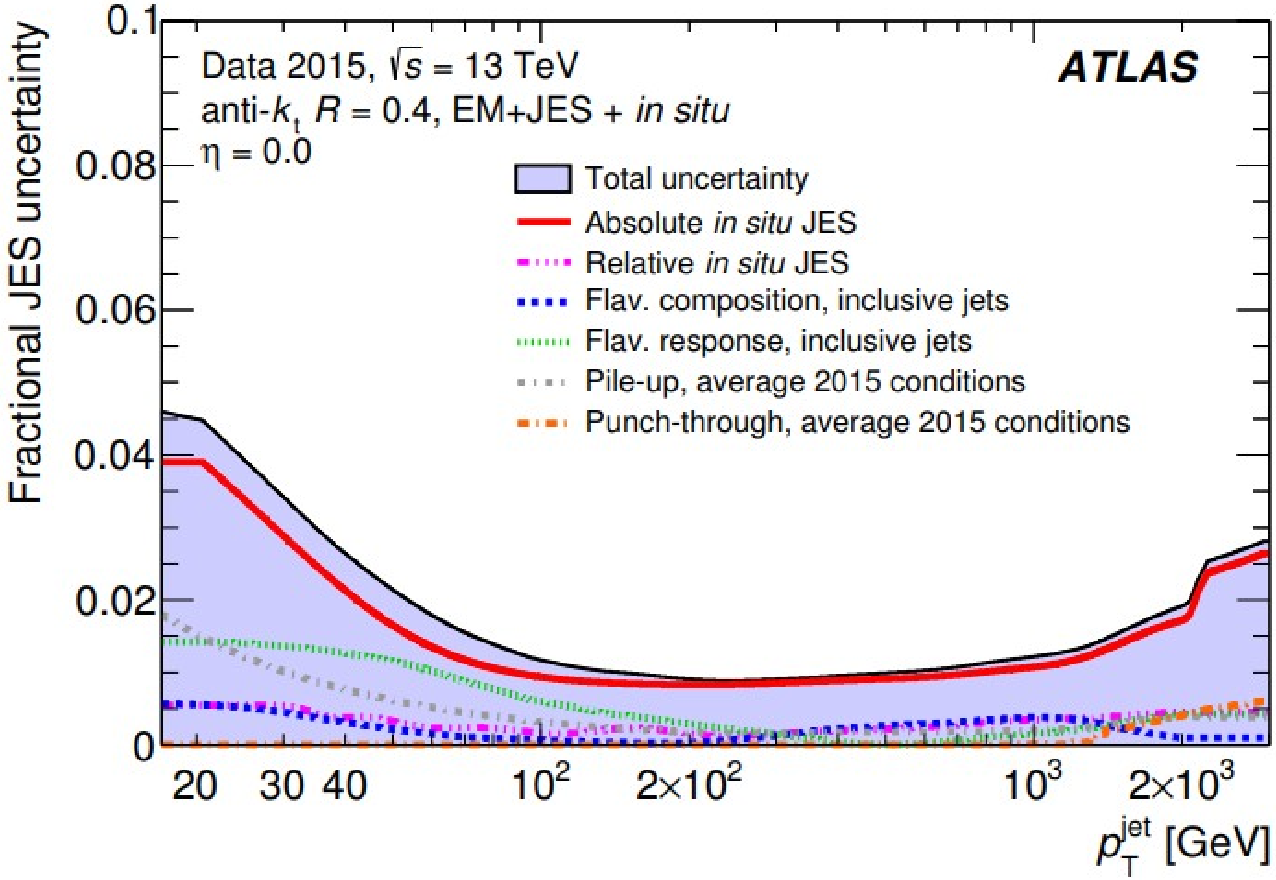
$$d = \min(p_{T,i}^{-1}, p_{T,j}^{-1}) \frac{\Delta^2_{i,j}}{R^2} \qquad d_B = p_{T,i}^{-2}$$





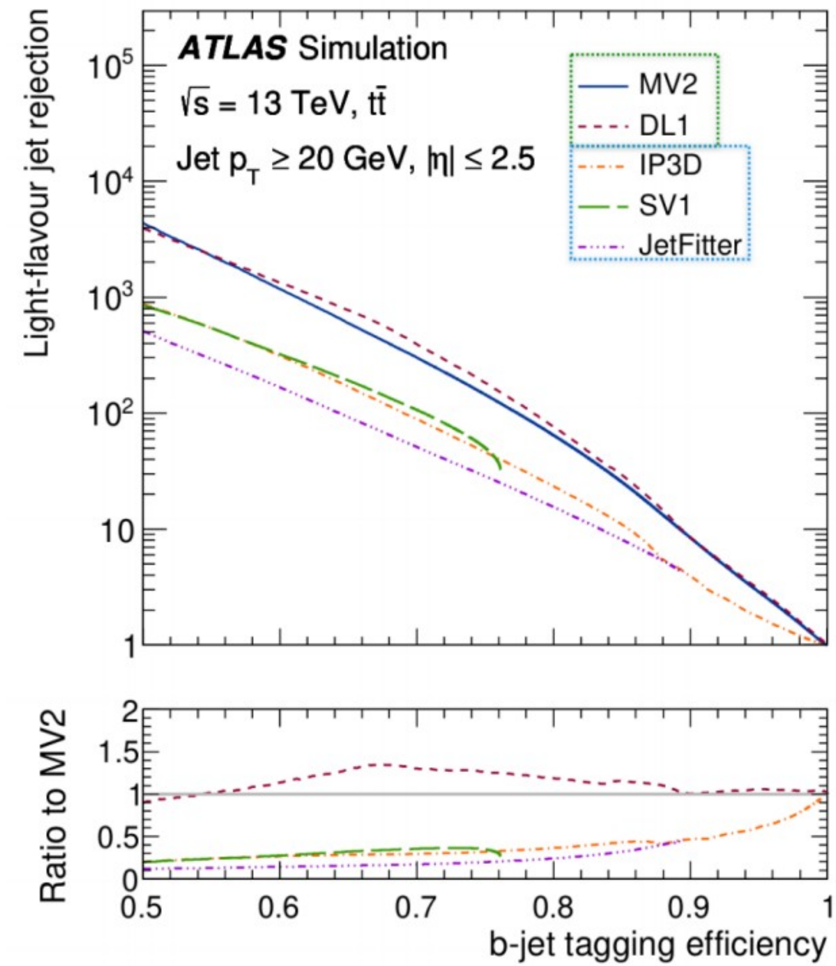
Jet reconstruction

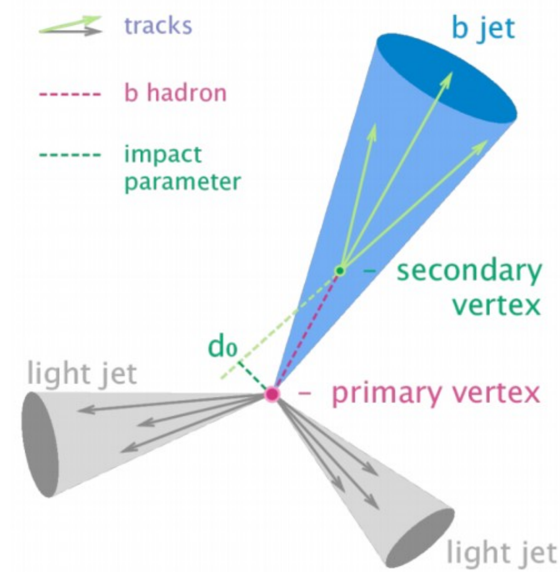
- jets are calibrated to the truth jet energy scale
  - correct for non-compensation of the calorimeter, inactive material, signal losses, out-of-cone particles, etc.
  - typical uncertainty $\mathcal{O}(1)\%$
  - up to ~100 various sources of uncertainties



b-jet identification

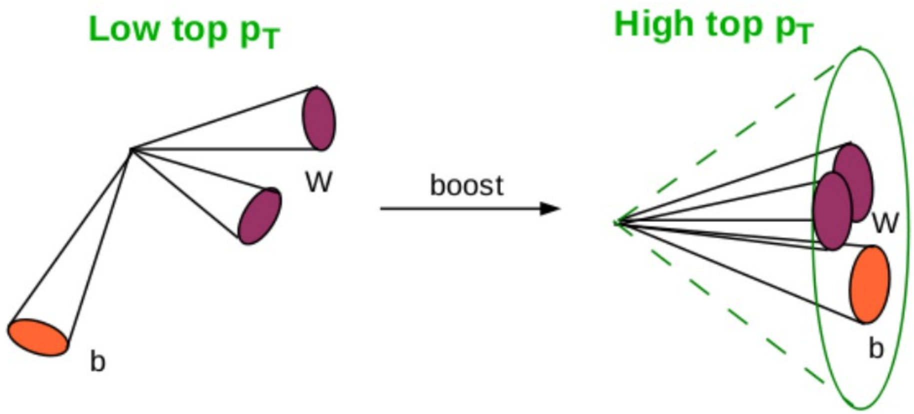
- many analyses rely on identifying jets originating from heavy-quarks
  - P(t→ Wb)~99%, P(H→ bb)~60%





- b(c)-hadrons:
  - High mass ~5(2) GeV
  - cτ ~ 450(120) μm
  - Decay length $\langle L_{xy} \rangle$ @70 GeV ~ 5(1.5)mm
- tagging algorithm relies on
  - high jet mass
  - secondary vertex
  - large impact parameter
  - large decay multiplicity

W boson/Higgs/Top-jets identification

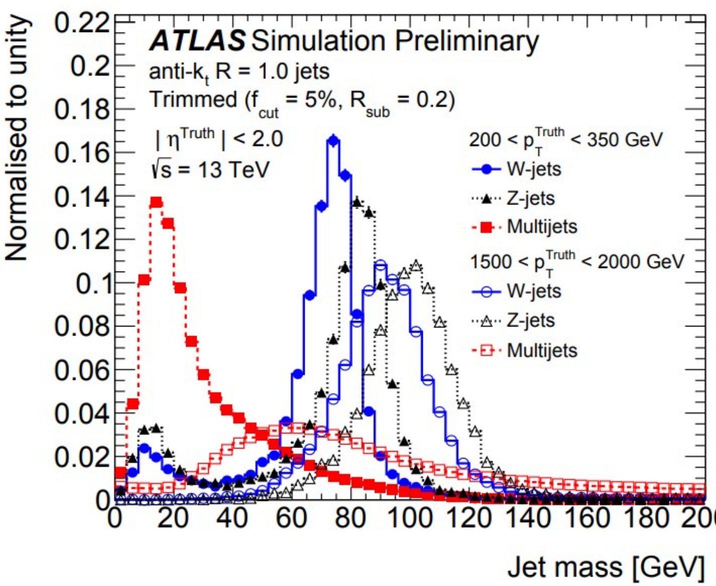


$R \simeq 2*m/p_T$

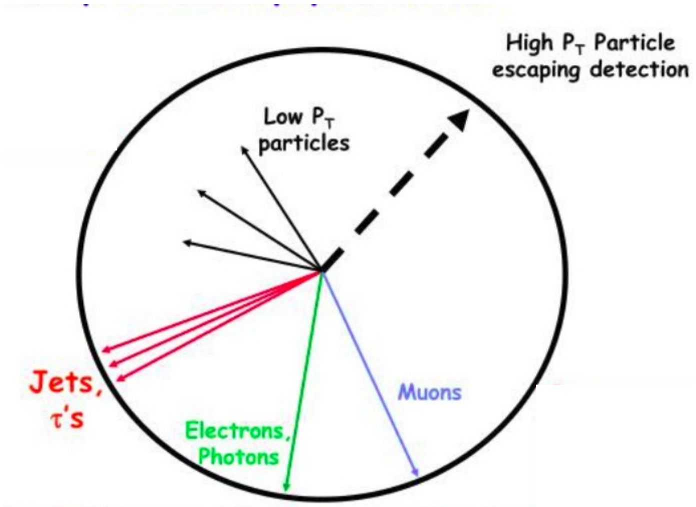
e.g. for R=1.0 and top-quark:

$p_T \geq 2*m_{TOP}$ ~ 350 GeV

- at high p_T, the decay products of W/Z/H bosons or top quarks are Lorentz-boosted and overlap
  - the reconstruction efficiency of decay products decreases
    → reconstruct instead as one large-radius jet ($R = \sqrt{(\varphi^2+y^2)}$ ~ 1.0)
- The inner structure of a quark/gluon initiated (light) jet very different from a jet of heavy object
  - e.g. jet mass

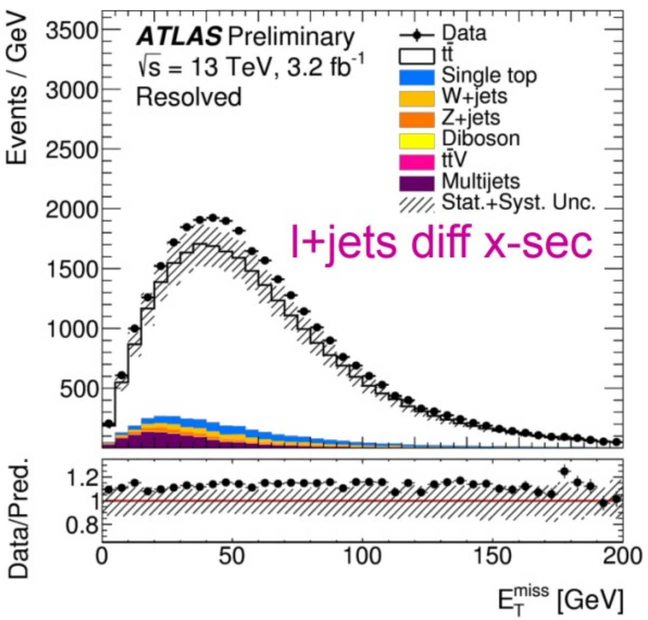


Missing-E_T reconstruction



- neutrinos escape the detection
- in transverse plane, p_T=0 in initial state
  - imbalance in final state → neutrino(s)
- to calculate missing E_T, need to measure ‘everything else’:

  missing E_T = - ∑ E_T of all objects
- useful to separate signal vs. background processes

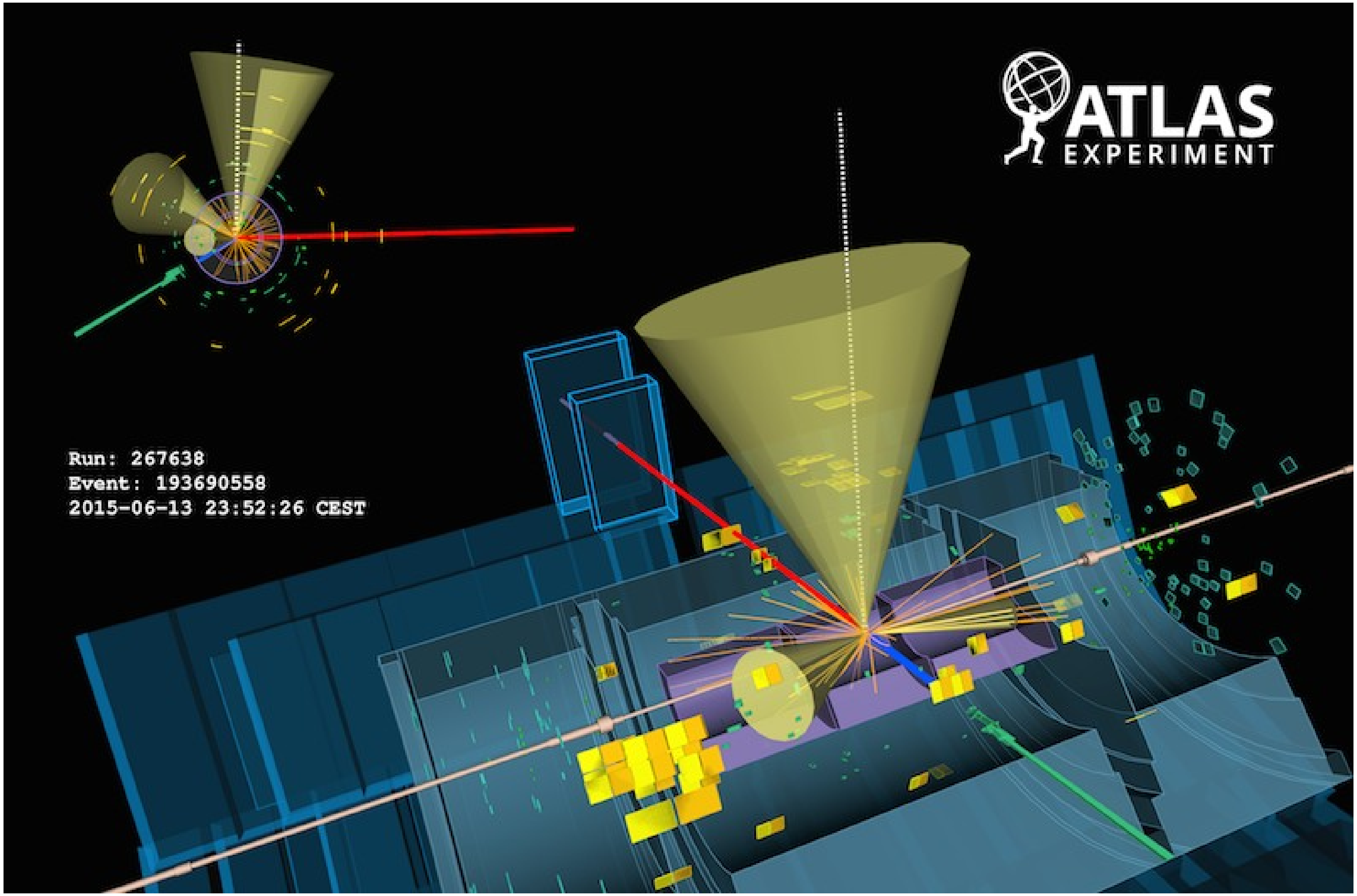


Physics Analysis ingredients

- in general, there are two different types of analyses:
  - measurements: this ‘known’ process/property looks like this
  - searches: this new process exists or not
- typical steps:
  - selection of candidate events
  - evaluation of background processes
  - statistical analysis to extract parameter of interest
  - evaluation of systematic uncertainties

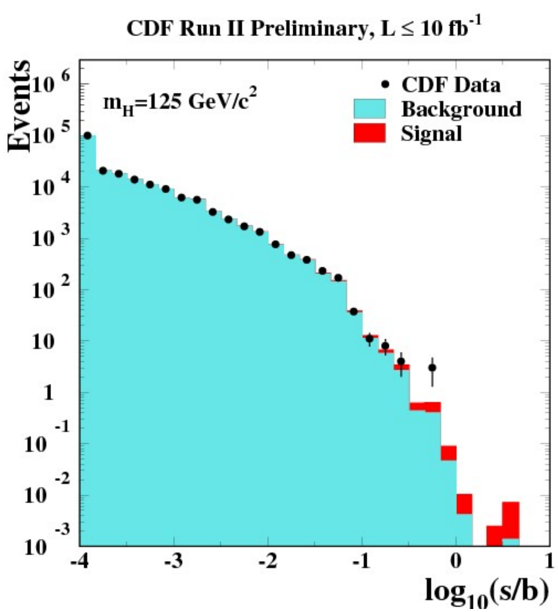
Physics Analysis: selection of events

- All physics analyses in particle physics are of statistical nature
  - We don't know to which process a given event in data corresponds

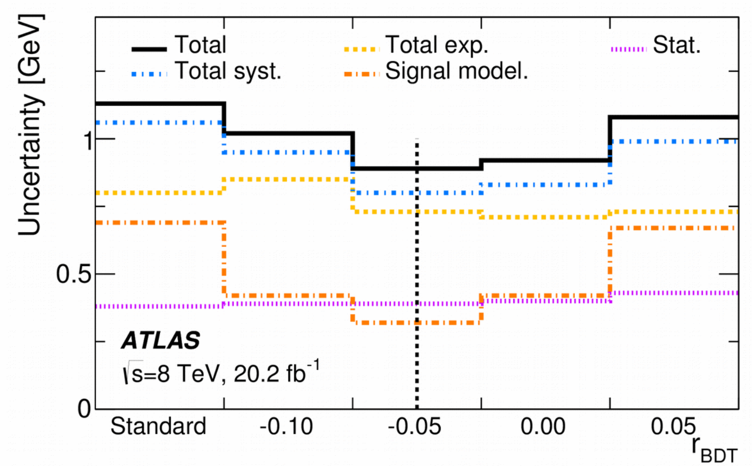


Physics Analysis: selection of events

- have to devise selection criteria
  - typically try to increase Signal/Background ratio
  - basic constrains come from detector coverage, available triggers
    - e.g. leptons p_T > 25 GeV (trigger), $|\eta|$ < 2.5 (tracker coverage)
  - optimized for a given type of analysis
    - searches: use loose cuts (try to maximize the selected signal events)
    - precise measurements: trade decreased statistics for improved systematics



CDF combined search for Higgs boson

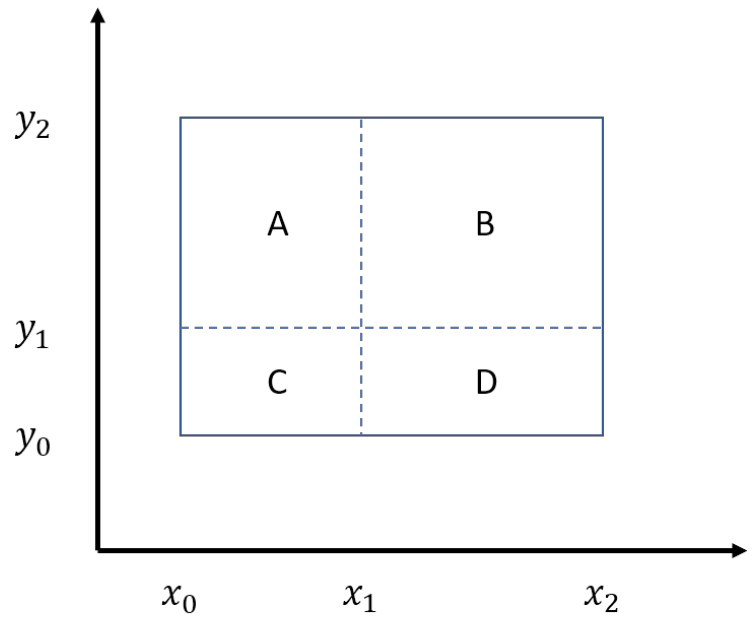


top mass analysis: optimizing overall uncertainty

Physics analysis: background evaluation

two main ways:

- estimated by MC simulation
  - Most of the processes
- estimated from data
  - Typically for mis-reconstructed events (fake leptons) or low probability events
  - Example:
    - ABCD method



D- signal concentrated region

A,B,C-bckg.(control) regions

2 independent(!) variables x,y

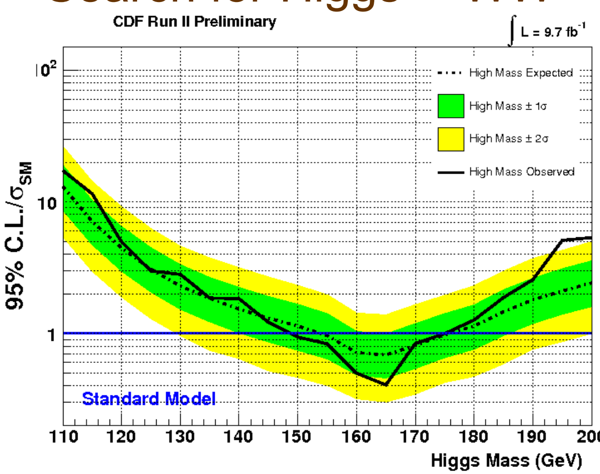
$$N_D/N_B = N_C/N_A \quad \Rightarrow \quad N_D = N_B * N_C/N_A$$

Physics analysis: statistical analysis

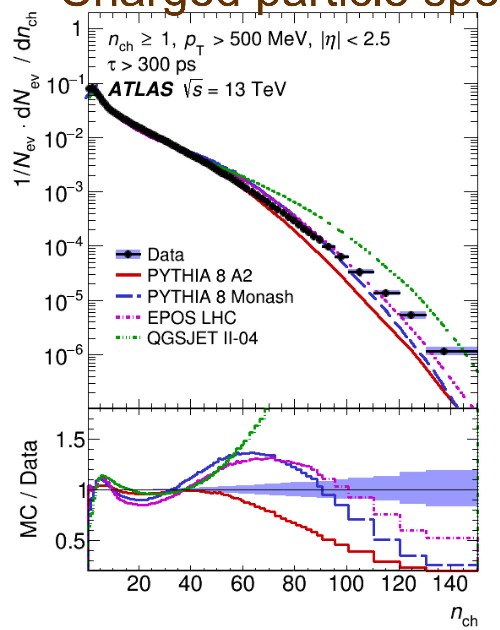
- probably the most diverse part of physics analysis
- typical analyses, procedures used and examples of physics analyses:

analysis	Procedure	example
cross-section	Event counting	Top pair cross-section
Differential cross-section	unfolding	Charged particle spectra
Property of particle	Template fit	W boson polarization
Low statistics analysis/search	Machine learning for signal/ background separation	Higgs search
Search for physics beyond SM	Setting limit on BSM model	Dark Matter search

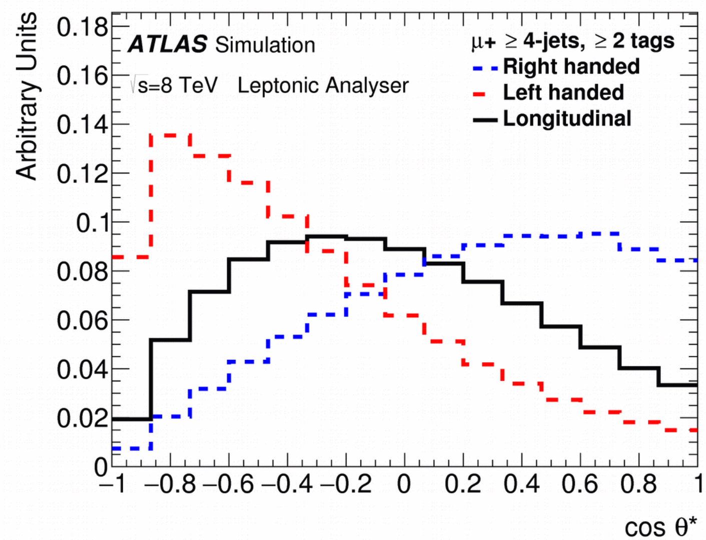
Search for Higgs→ WW



Charged particle spectra



W boson polarization



Physics analysis: systematic uncertainties

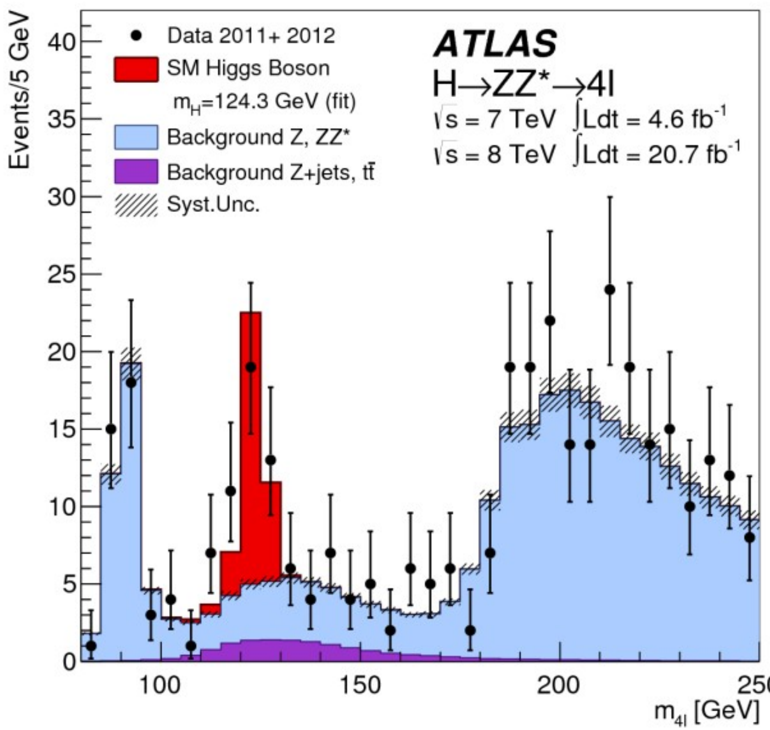
one of the most important parts of the analysis

- need to consider $\mathcal{O}(100)$ of various systematic sources
- the sources:
  - detector related
    - objects (leptons, jets, missing E_T) have uncertainties in reconstruction, identification, determining energy scale, ...
  - signal+background modeling
    - theoretical cross-sections uncertainties
    - hard process model, hadronization model, parton distribution functions,...

	$t\bar{t} \to$ lepton+jets			$t\bar{t} \to$ dilepton	Combination	
	$m_{top}^{\ell+jets}$ [GeV]	JSF	bJSF	m_{top}^{dil} [GeV]	m_{top}^{comb} [GeV]	ρ
Results	172.33	1.019	1.003	173.79	172.99	
Statistics	0.75	0.003	0.008	0.54	0.48	0
– Stat. comp. (m_{top})	*0.23*	*n/a*	*n/a*	*0.54*		
– Stat. comp. (JSF)	*0.25*	*0.003*	*n/a*	*n/a*		
– Stat. comp. (bJSF)	*0.67*	*0.000*	*0.008*	*n/a*		
Method	0.11 ± 0.10	0.001	0.001	0.09 ± 0.07	0.07	0
Signal MC	0.22 ± 0.21	0.004	0.002	0.26 ± 0.16	0.24	+1.00
Hadronisation	0.18 ± 0.12	0.007	0.013	0.53 ± 0.09	0.34	+1.00
ISR/FSR	0.32 ± 0.06	0.017	0.007	0.47 ± 0.05	0.04	−1.00
Underlying event	0.15 ± 0.07	0.001	0.003	0.05 ± 0.05	0.06	−1.00
Colour reconnection	0.11 ± 0.07	0.001	0.002	0.14 ± 0.05	0.01	−1.00
PDF	0.25 ± 0.00	0.001	0.002	0.11 ± 0.00	0.17	+0.57
W/Z+jets norm	0.02 ± 0.00	0.000	0.000	0.01 ± 0.00	0.02	+1.00
W/Z+jets shape	0.29 ± 0.00	0.000	0.004	0.00 ± 0.00	0.16	0
NP/fake-lepton norm.	0.10 ± 0.00	0.000	0.001	0.04 ± 0.00	0.07	+1.00
NP/fake-lepton shape	0.05 ± 0.00	0.000	0.001	0.01 ± 0.00	0.03	+0.23
Jet energy scale	0.58 ± 0.11	0.018	0.009	0.75 ± 0.08	0.41	−0.23
b-Jet energy scale	0.06 ± 0.03	0.000	0.010	0.68 ± 0.02	0.34	+1.00
Jet resolution	0.22 ± 0.11	0.007	0.001	0.19 ± 0.04	0.03	−1.00
Jet efficiency	0.12 ± 0.00	0.000	0.002	0.07 ± 0.00	0.10	+1.00
Jet vertex fraction	0.01 ± 0.00	0.000	0.000	0.00 ± 0.00	0.00	−1.00
b-Tagging	0.50 ± 0.00	0.001	0.007	0.07 ± 0.00	0.25	−0.77
E_T^{miss}	0.15 ± 0.04	0.000	0.001	0.04 ± 0.03	0.08	−0.15
Leptons	0.04 ± 0.00	0.001	0.001	0.13 ± 0.00	0.05	−0.34
Pile-up	0.02 ± 0.01	0.000	0.000	0.01 ± 0.00	0.01	0
Total	1.27 ± 0.33	0.027	0.024	1.41 ± 0.24	0.91	−0.07

Top mass measurement:
Summary of uncertainties

Physics Results



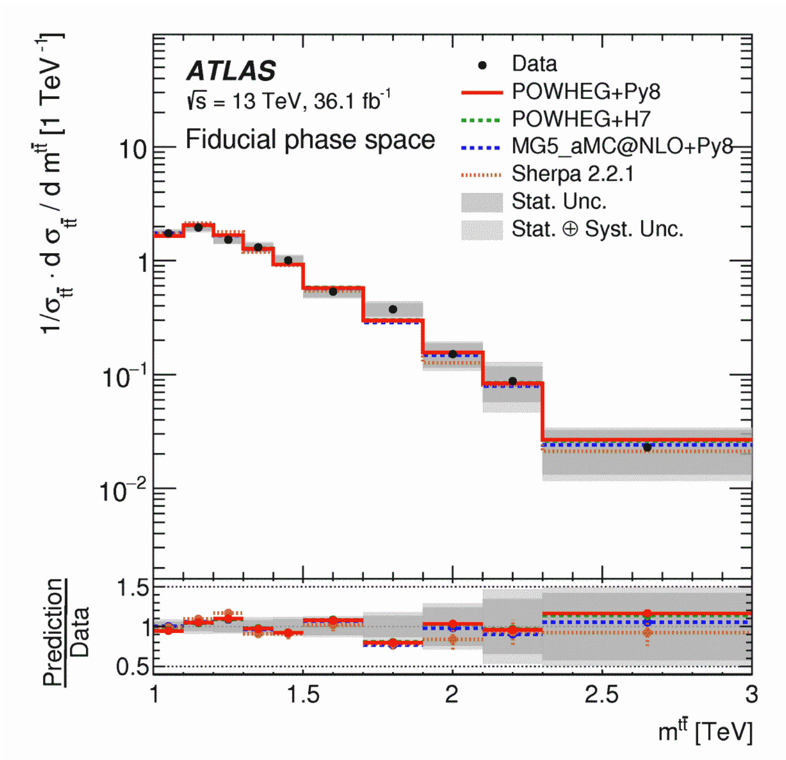
- such plots are then the result of many ($\mathcal{O}(10)$) years of many ($\mathcal{O}(1000)$) people's effort in design, build and operation of:
  - Accelerator: LHC approved in 1995
  - Detector: ATLAS collaboration formed in 1994
  - Computing: ~same time as detector
  - Particular physics analysis: a few years effort

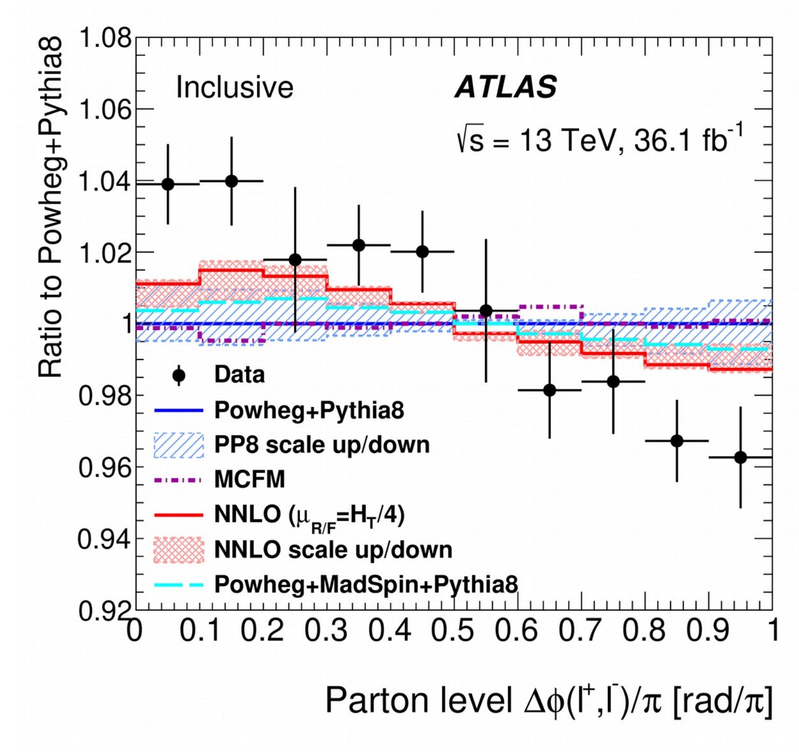
Conclusions

- Particle physics experiments are international endeavours
- They involve many ($\mathcal{O}(1000)$) people with expertise in different areas (particle acceleration, detectors, computing, physics analysis)
- The physics analysis is just the last (and typically quickest) step among all

BACKUP

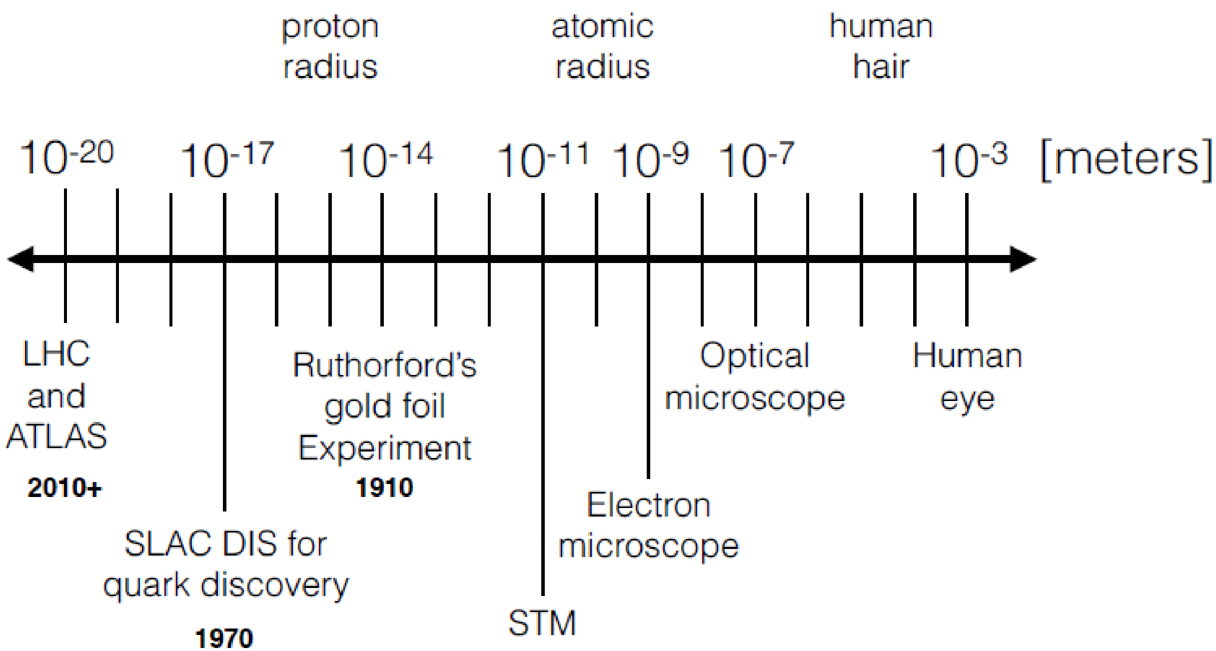
My current interests





- Top quark physics:
  - Top pair cross-section measurement in all hadronic channel in boosted regime
    - Can access high top quark p_T and top quark pair invariant mass
  - Top-antitop spin correlations
    - Specific prediction by SM which could be modified in beyond SM model
    - Evidence for 3σ deviation from SM in previous round of analysis

Various length scales



Particles interactions in detector

- Different ways particle leave energy in detector:
  - electrons: breamstrahlung
  - photons: electron pair production
  - muons: ionization
  - hadrons: ionization (charged particles), nuclear interactions