Introduction to particle physics: experimental part

RAW data to Physics

• The road from collisions to physics publications

From RAW data to Standard Model particles

 About measuring properties of the final particles created from protonproton collisions

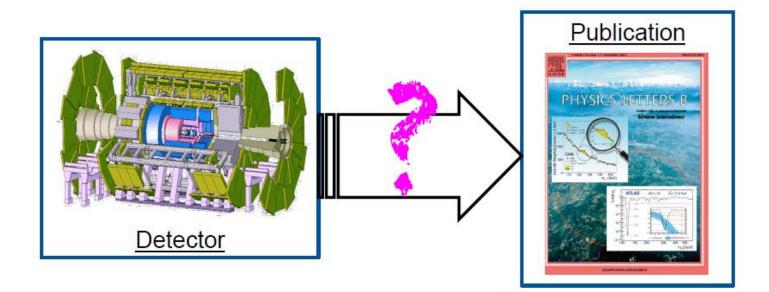
From Standard Model particles to measurements and searches

• About how we analys data using ingredients we have constructed

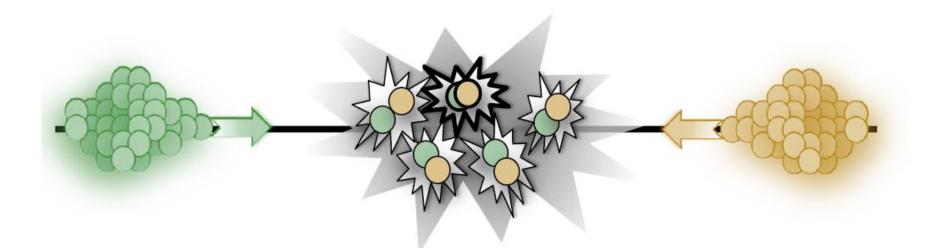
Large fraction of slides from A. Sfyrla lectures at CERN Summer School 2018

Prof. dr hab. Elżbieta Richter-Wąs

How do we deal with physics events from when they leave the detector till when they make it into our publications?



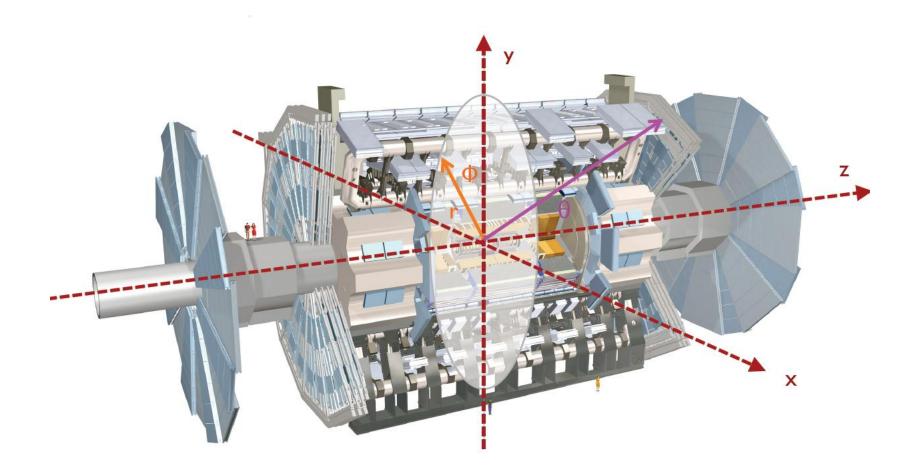
What is an event?



Proton bunches >10¹¹ protons/bunch colliding at 13 TeV and at ~30 MHz in Run-2 collided at 7/8TeV and at ~20 MHz in Run-1

In 2018: Up to 60 p-p collisions / bunch crossing

Collider experiment coordinates



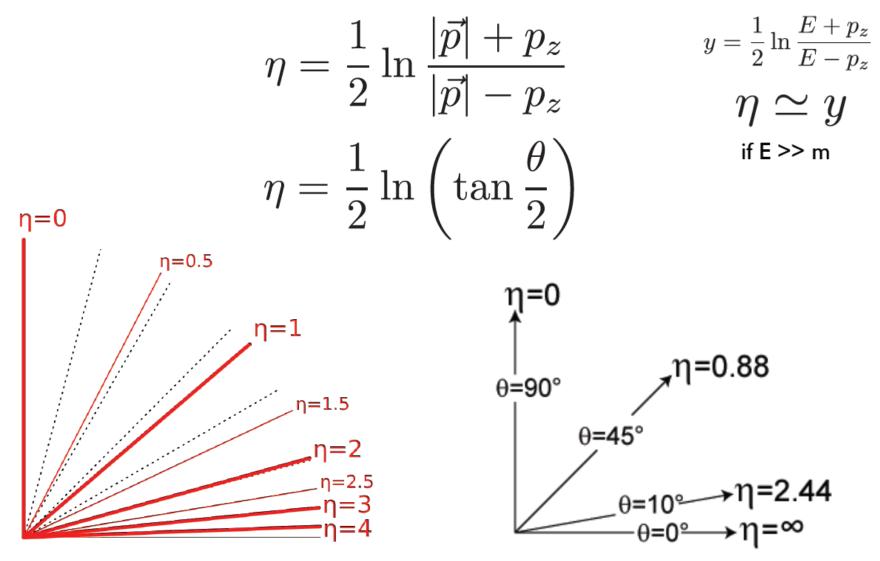
Rapidity

Lorentz factor
$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \cosh \varphi$$
 Hyperbolic cosine of "rapidity"
 $E = m \cosh \varphi$ $\varphi = \tanh^{-1} \frac{E}{|\vec{p}|} = \frac{1}{2} \ln \frac{E+|\vec{p}|}{E-|\vec{p}|}$

Particle physicists prefer to use modified rapidity along beam axis

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

Pseudorapidity



Transverse variables

- At hadron colliders, a significant and unknown fraction of the beam energy in each event escapes down the beam pipe.
- Net momentum can only be constrained in the plane transverse to the beam z-axis!

$$\sum p_{\mathbf{x}}(i) = 0 \qquad \sum p_{\mathbf{y}}(i) = 0$$

Missing transverse energy and transverse mass

 If invisible particle are created, only their transverse momentum can be constrained: missing transverse energy

$$E_T^{\text{miss}} = \sum p_T(i)$$

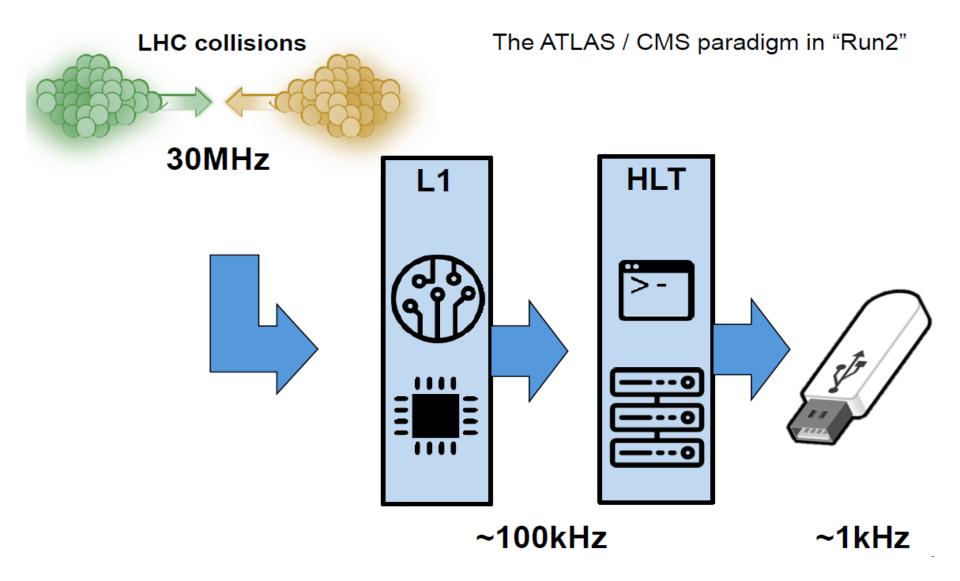
 If a heavy particle is produced and decays in two particles one of which is invisible, the mass of the parent particle can constrained with the transverse mass quantity

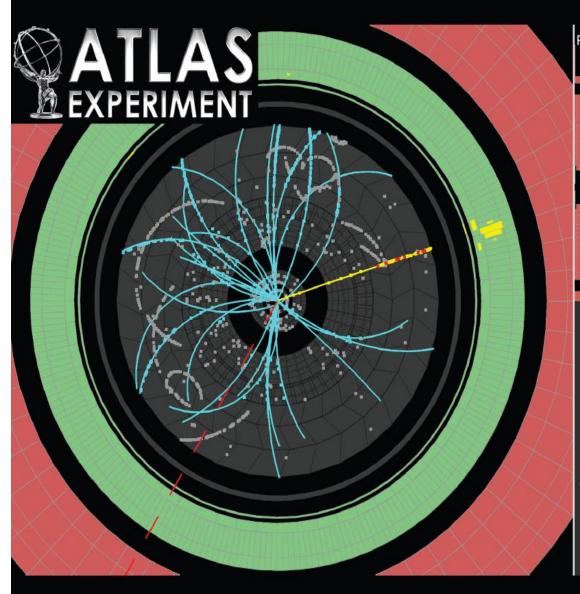
$$M_T^2 \equiv [E_T(1) + E_T(2)]^2 - [\mathbf{p}_T(1) + \mathbf{p}_T(2)]^2$$

= $m_1^2 + m_2^2 + 2[E_T(1)E_T(2) - \mathbf{p}_T(1) \cdot \mathbf{p}_T(2)]$

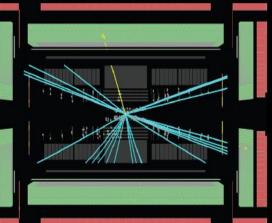
if $m_1 = m_2 = 0$ $M_T^2 = 2|\boldsymbol{p}_T(1)||\boldsymbol{p}_T(2)|(1 - \cos \phi_{12})|$

Triggering on physics





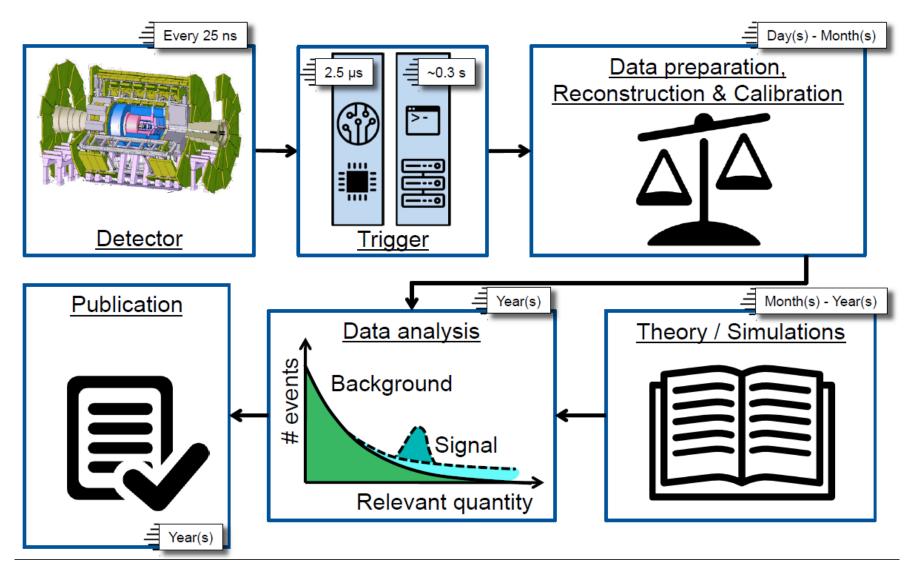
Run Number: 152409, Event Number: 5966801 Date: 2010-04-05 06:54:50 CEST



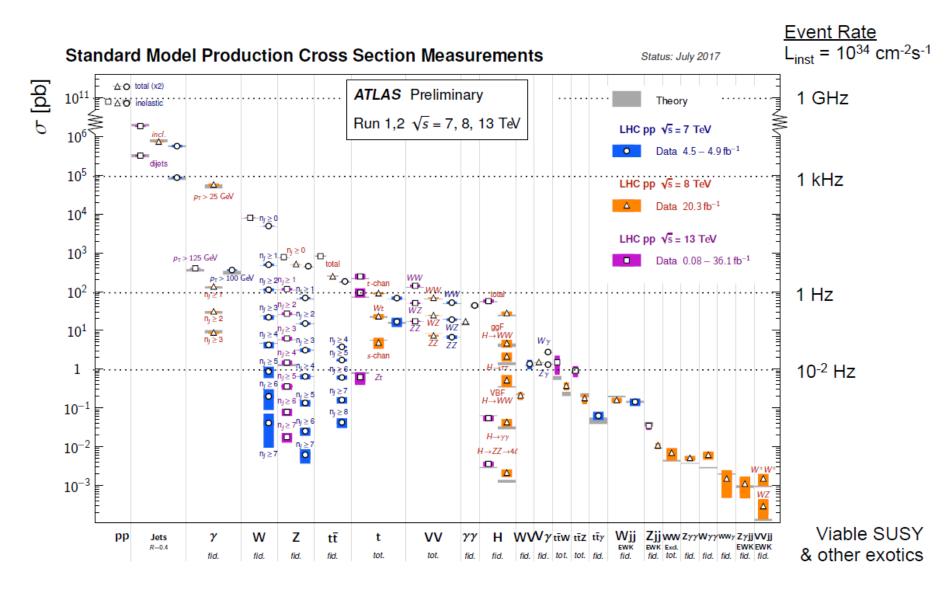
W→ev candidate in 7 TeV collisions

 $p_{T}(e+) = 34 \text{ GeV}$ $\eta(e+) = -0.42$ $E_{T}^{miss} = 26 \text{ GeV}$ $M_{T} = 57 \text{ GeV}$

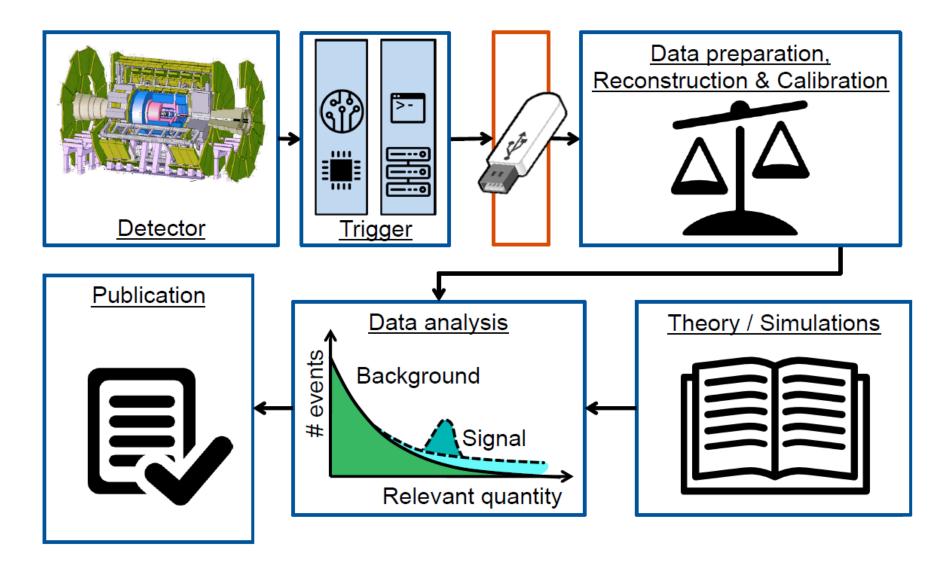
An event's lifetime



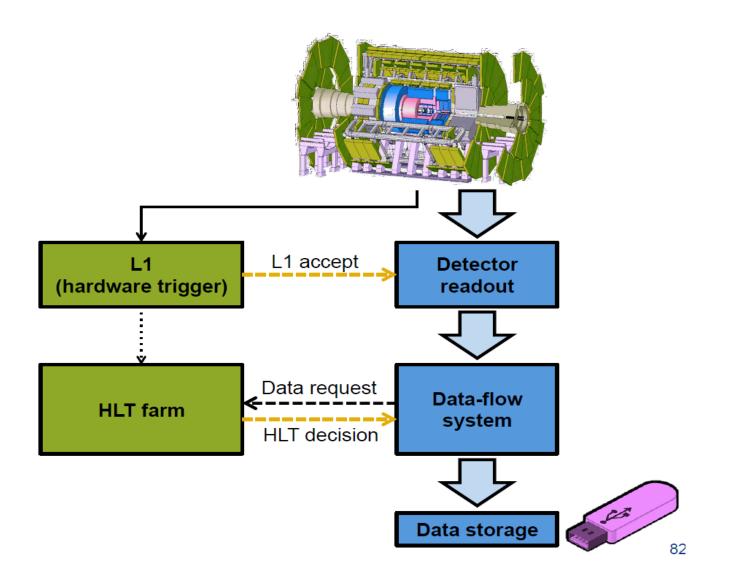
Reminder: $\sigma = \frac{\# \text{ events}}{L}$



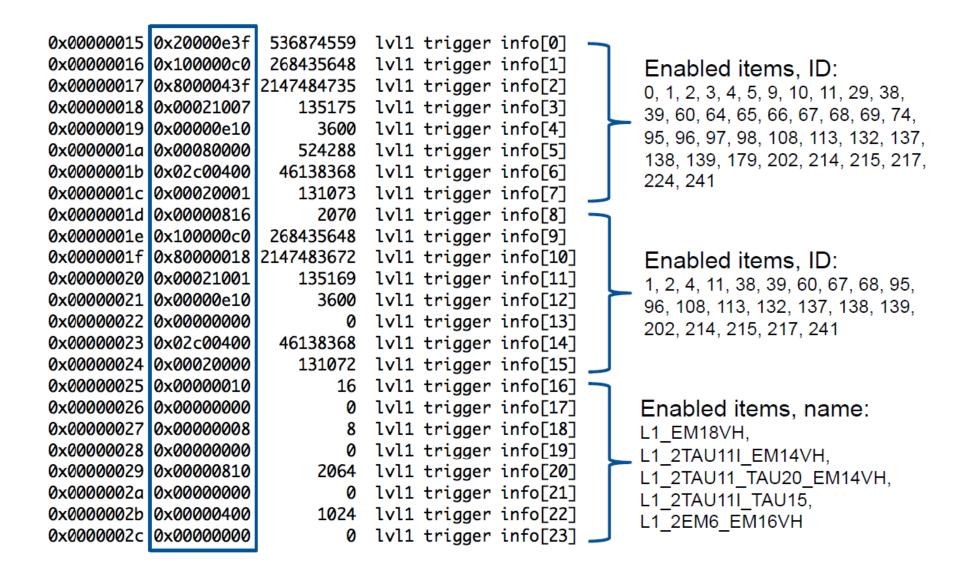
An events's lifetime



The Data Acquisition (DAQ)



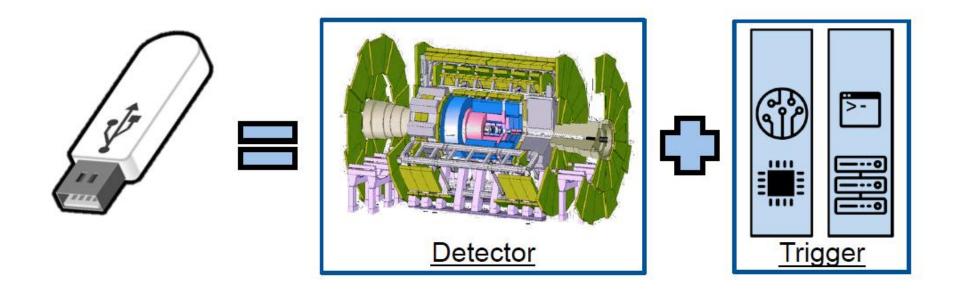
What does raw contain?



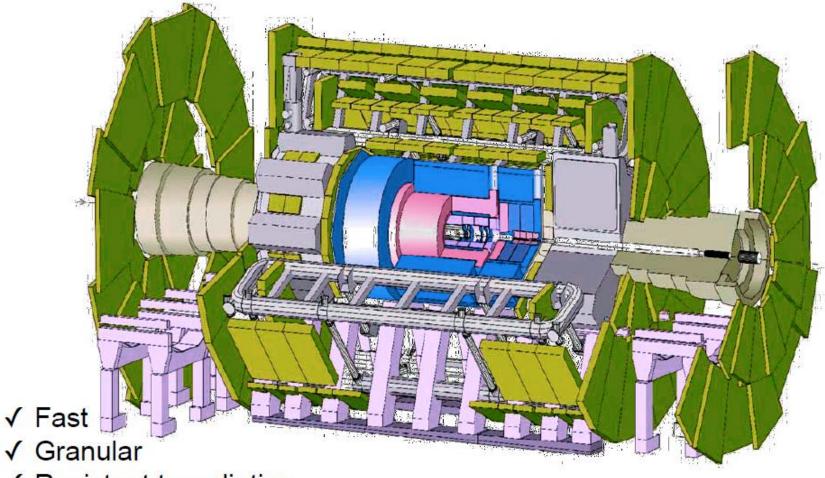
What does raw contain?

	ger info[0]	1,11.4	536874559	0x20000e3f	0~00000015
More than 300K such	ger info[1]		268435648	0x100000c0	
	ger info[2]		2147484735	0x8000043f	
words in each event,	ger info[3]		135175	0x00021007	
corresponding to the full	ger info[4]		3600	0x00000e10	
	ger info[5]		524288	0x00080000	
data from all the	ger info[6]		46138368	0x02c00400	
detector components.	ger info[7]		131073	0x00020001	0x0000001c
	ger info[8]	lvl1 t	2070	0x00000816	0x0000001d
	ger info[9]	lvl1 t	268435648	0x100000c0	0x0000001e
© Data size: 1-1.5MB /	ger info[10]	lvl1 t	2147483672	0x80000018	0x0000001f
event depending on the	ger info[11]	lvl1 t	135169	0x00021001	0x00000020
	ger info[12]	lvl1 t	3600	0x00000e10	0x00000021
compression. Pretty	ger info[13]	lvl1 t	0	0×000000000	0x00000022
consistent between	ger info[14]		46138368	0x02c00400	0x00000023
	ger info[15]		131072	0x00020000	
ATLAS and CMS.	ger info[16]		16	0x00000010	
	ger info[17]		0	0x000000000	
Challenge:	ger info[18]		8	0x0000008	
© Challenge:	ger info[19]		0	0x00000000	
make sense out of all	ger info[20]		2064	0x00000810	
these numbers!!	ger info[21]		0	0x00000000	
	ger info[22]		1024	0x00000400	
	ger info[23]	LVL1 t	0	0x00000000	0X0000002c

What does raw contain?

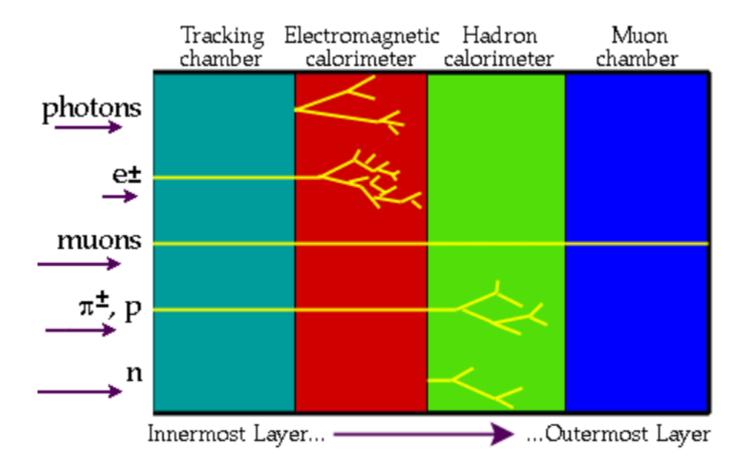


A detector (e.g. ATLAS)

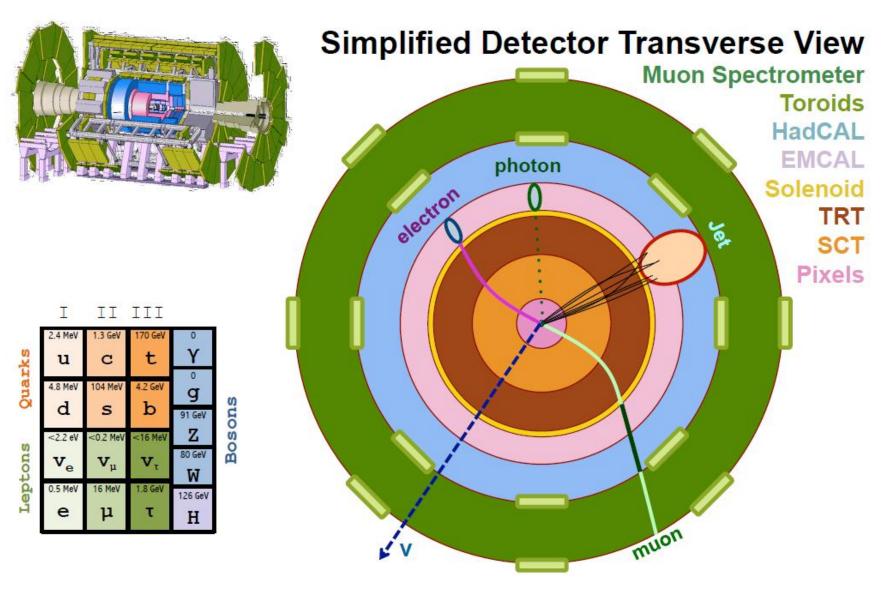


✓ Resistant to radiation

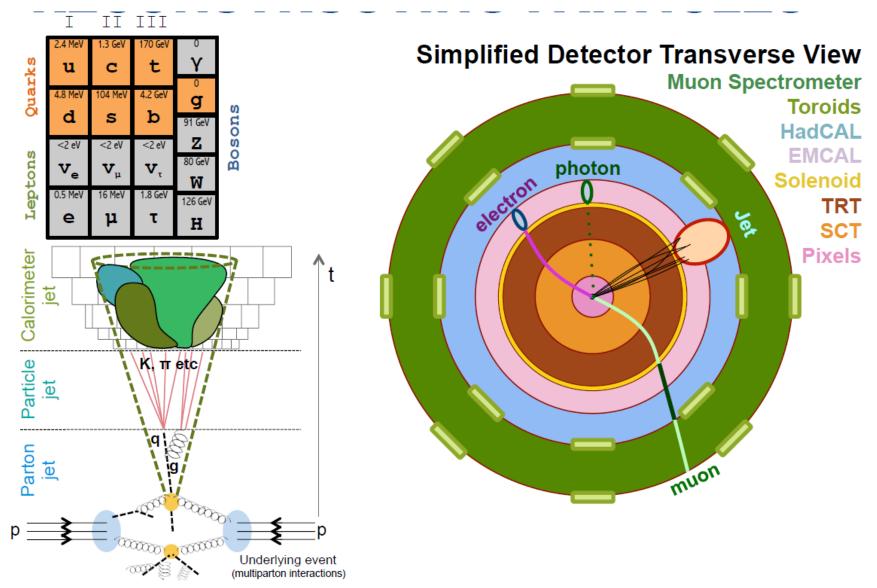
Particles through matter



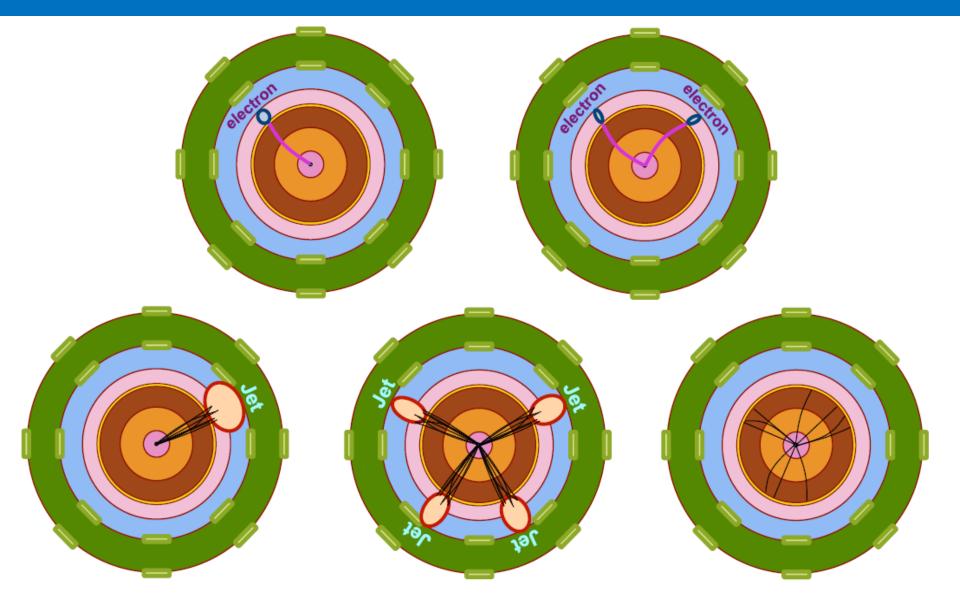
A detector (eg. ATLAS)



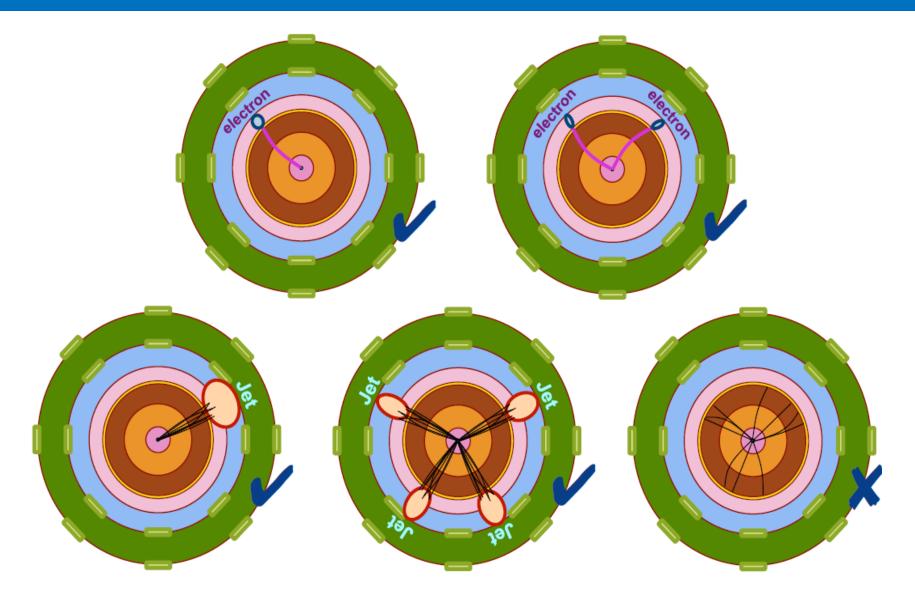
Reconstructing particles



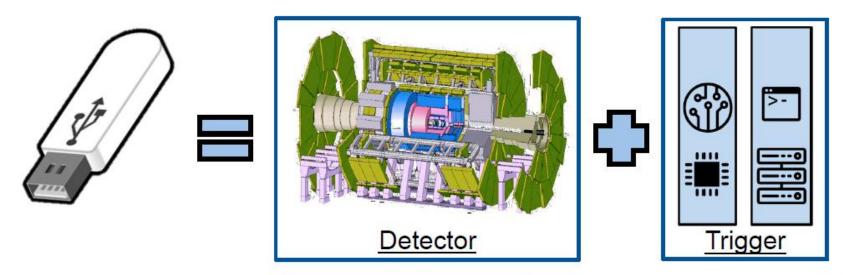
Online reconstruction



Triggering on physics



This is what raw data contain!

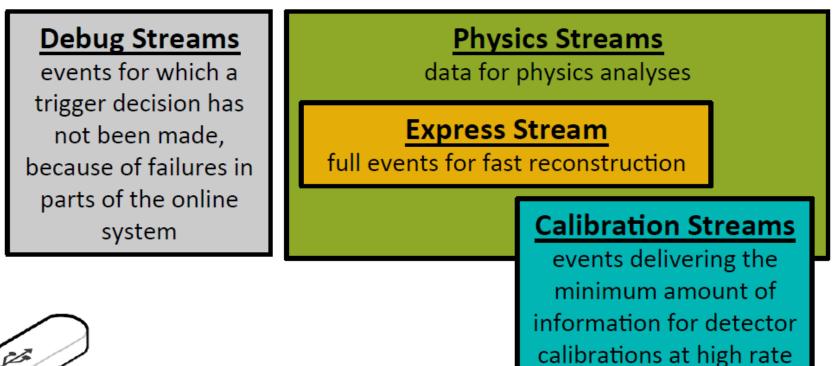


data to reconstruct offline!

decision plus online reconstructed objects

Streaming

- Streaming is based on trigger decisions at all stages
- The Raw Data physics streams are generated at the HLT output level



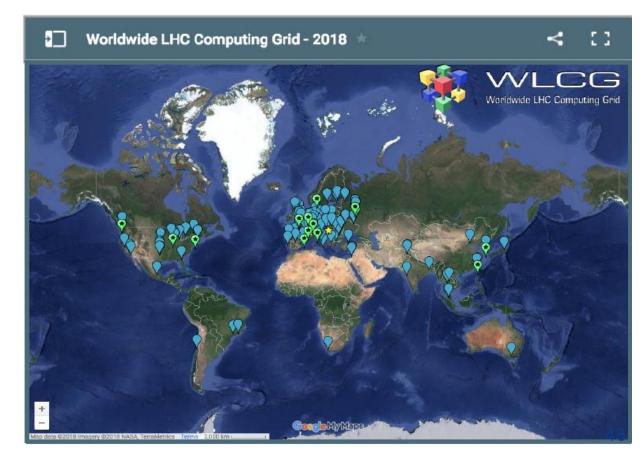


Huge amount of data ...

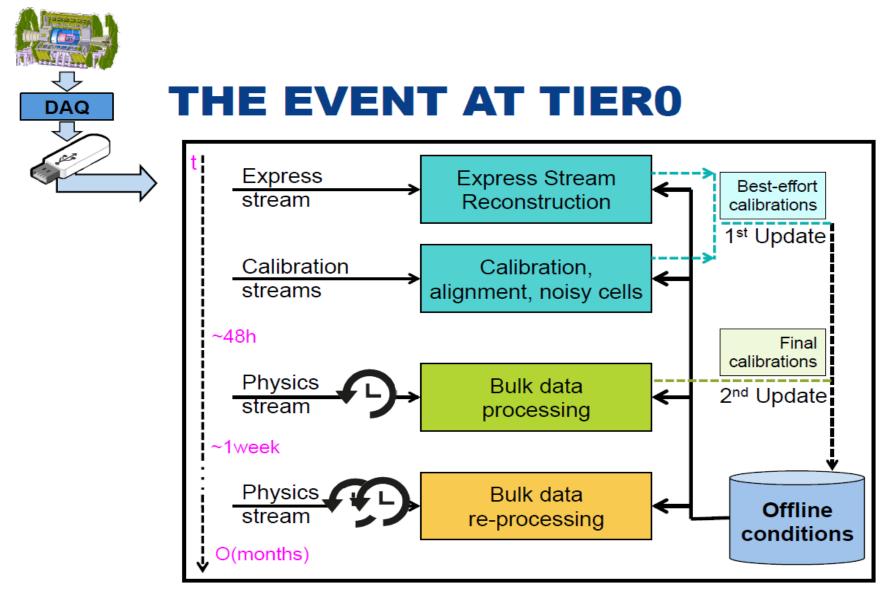
LHC delivered billions of recorded collision events to the LHC experiments from proton-proton and proton-lead collisions so far. This translates to many 100s PB of data recorded at CERN.



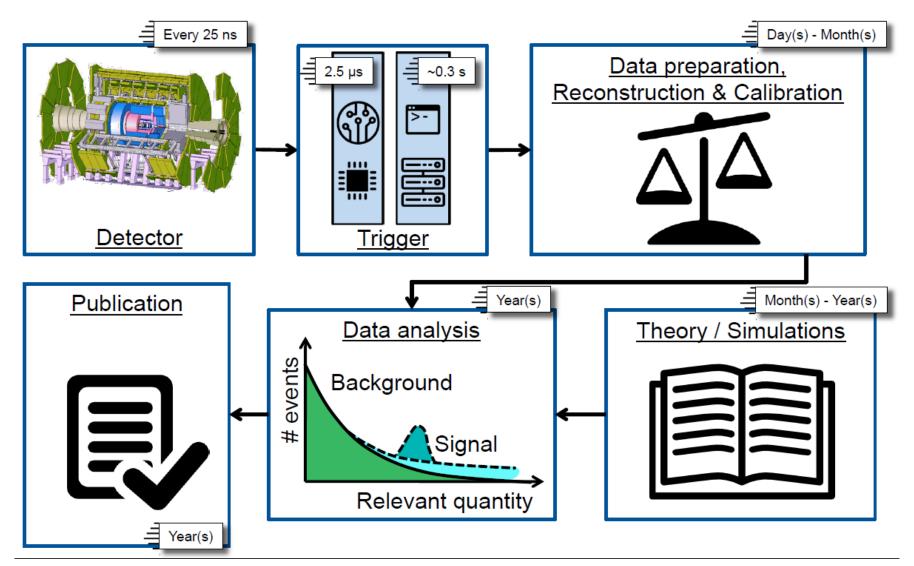
The challenge how to process and analyze the data and produce timely physics results was substantial but in the end resulted in a great success.



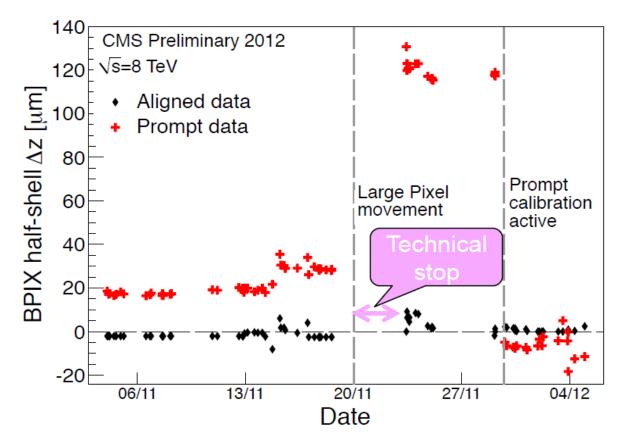
Huge amount of data ...



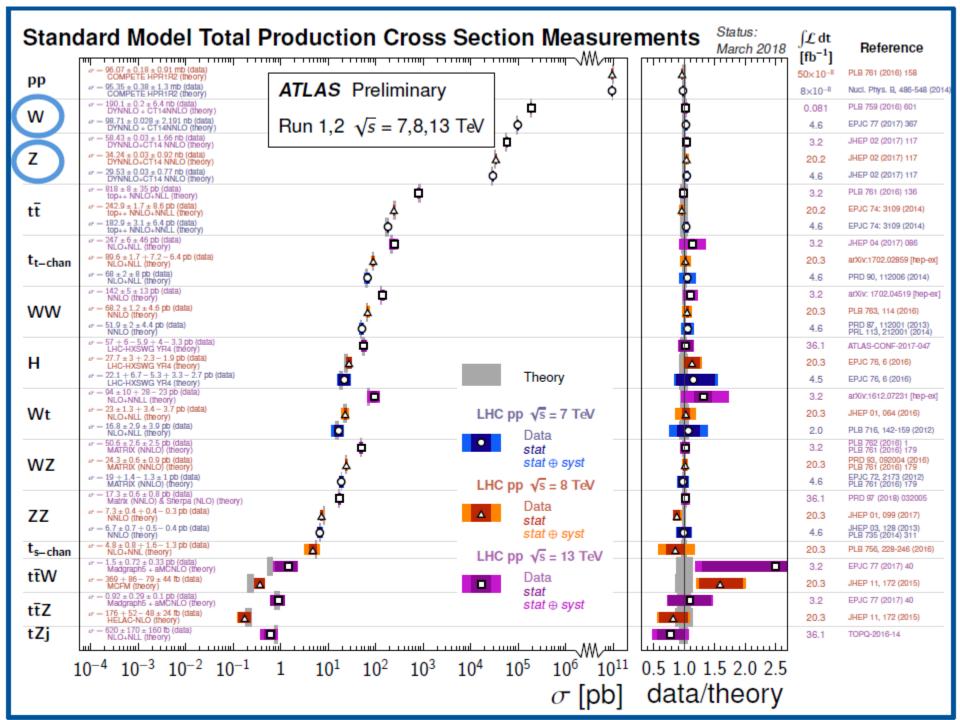
An event's lifetime



EG. alignment

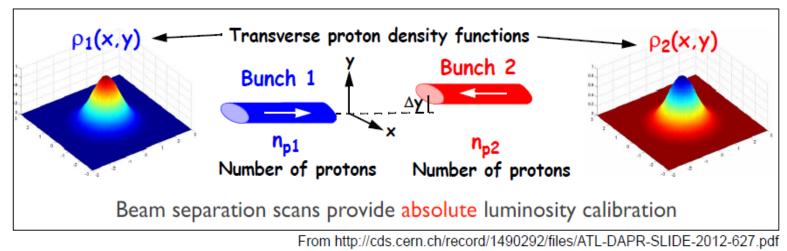


Day-by-day value of the relative longitudinal shift between the two half-shells of the BPIX as measured with the primary vertex residuals, for the last month of pp data taking in 2012.

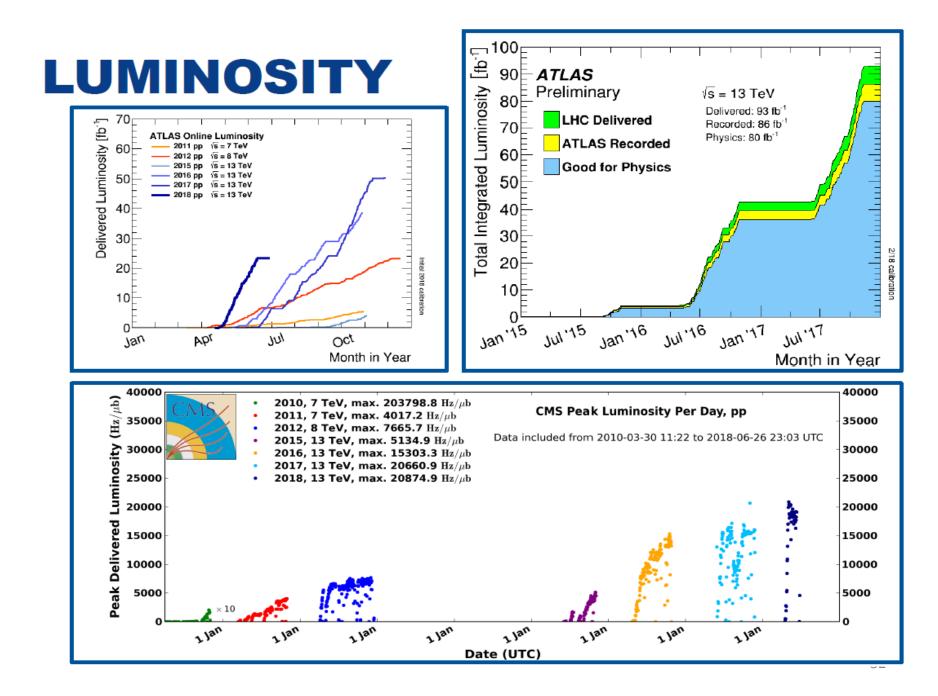


Luminosity determination

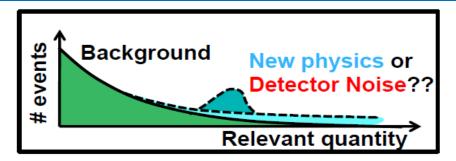
- A measurement of the number of collisions per cm² and second.
- Multiple methods used for determining luminosity: reducing uncertainties.
- Sormalization is done with beam-separation scan (Van-der-Meer scan). Requires careful control of beam parameters.



 Result: luminosity measurement with very small uncertainties (order of few %) with very fast turn-around time.



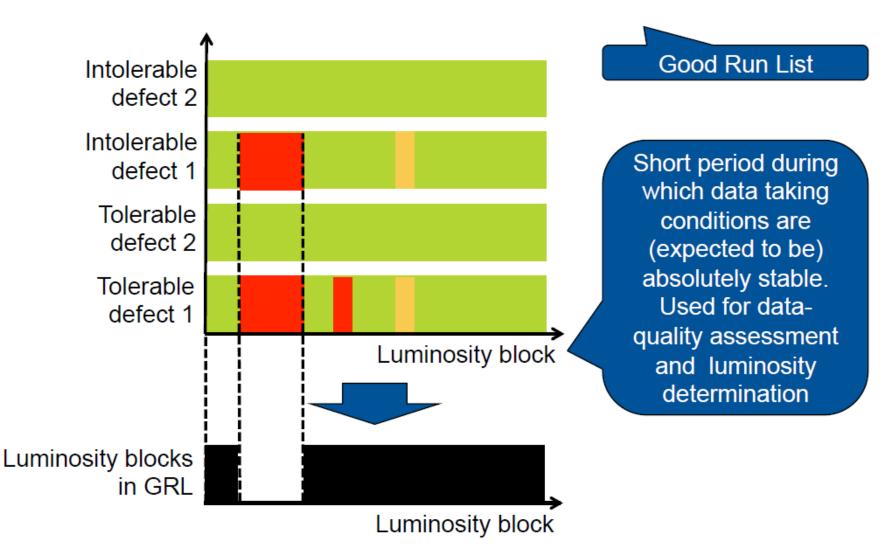
Data quality



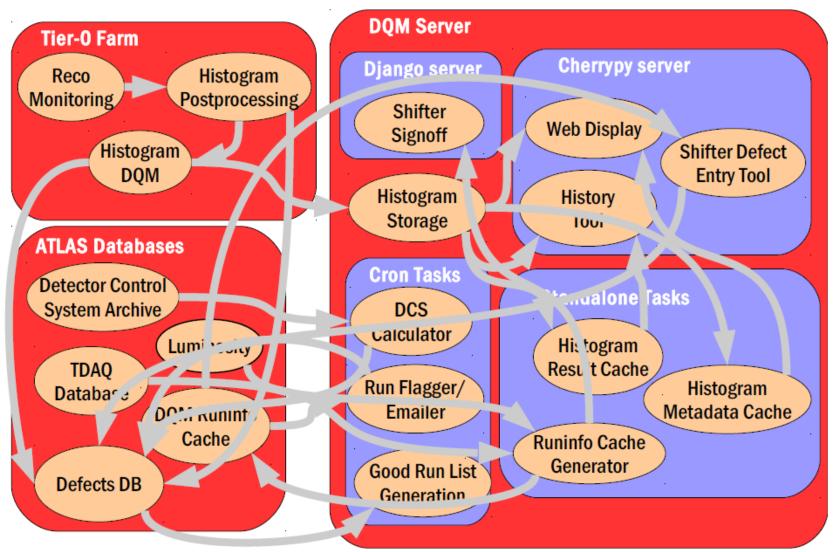
The data we analyze has to follow norms of quality such that our results are trustable.

- Online: Fast monitoring of detector performance during data taking, using dedicated stream, "express stream".
- Offline: More thorough monitoring at two instances:
 - Express reconstruction; fast turn-around.
 - Prompt reconstruction: larger statistics.
- What is monitored?
 - Noise in the detector.
 - Reconstruction (tracks, clusters, combined objects, resolution and efficiency).
 - Input rate of physics.
 - All compared to reference histograms of data that has been validated as "good".

Data quality and "GRL"

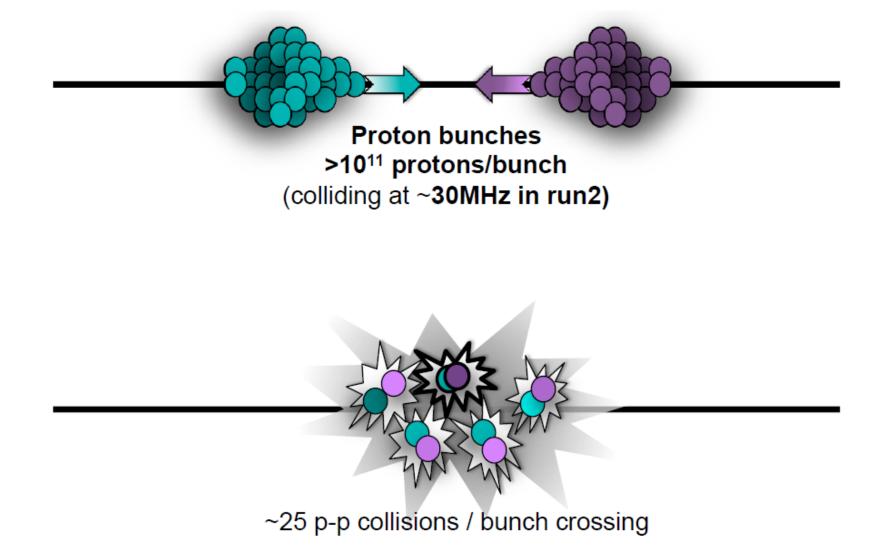


Data quality

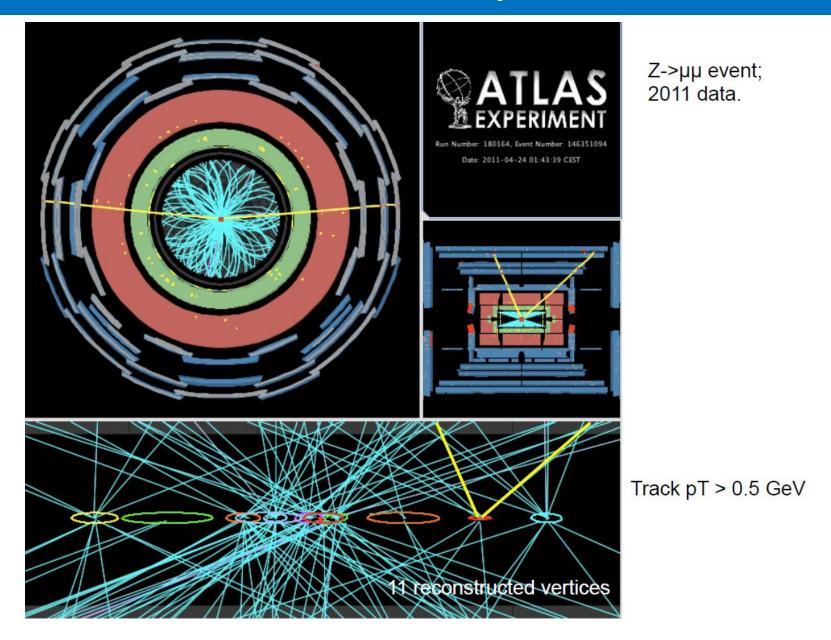


https://cds.cern.ch/record/2008725/files/ATL-SOFT-SLIDE-2015-179.pdf

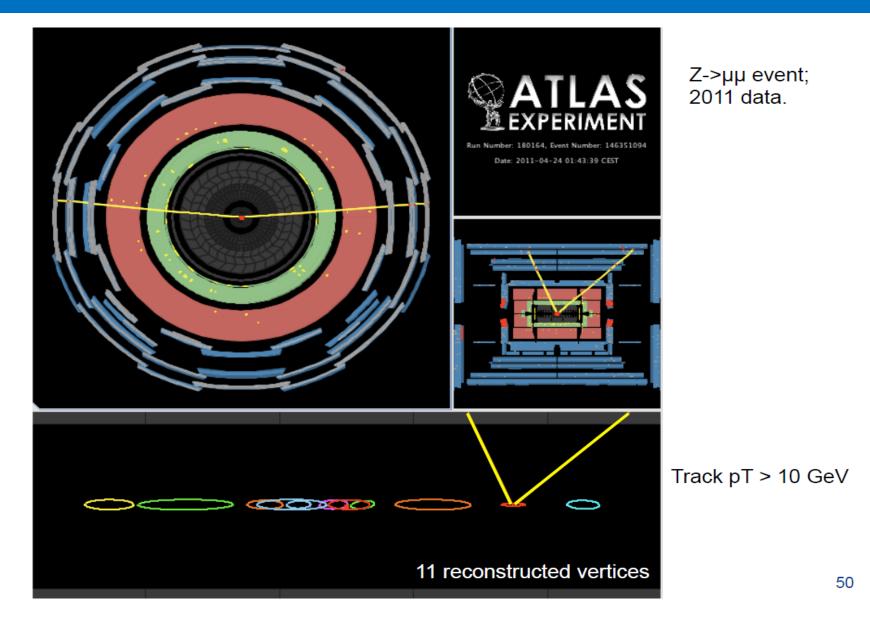
Pile-up

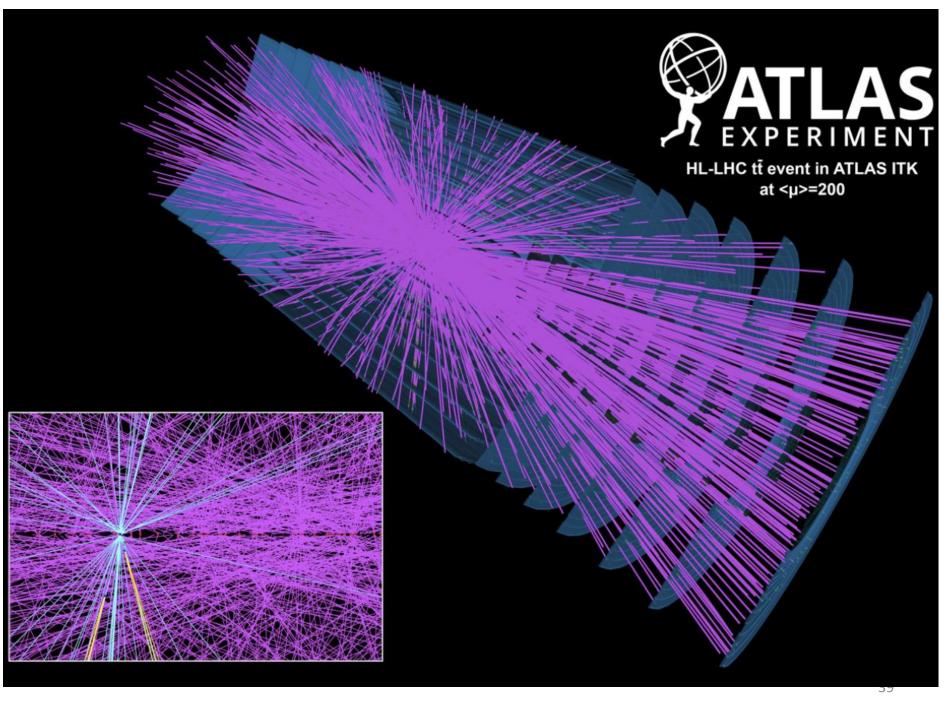


Pile-up



Pile-up





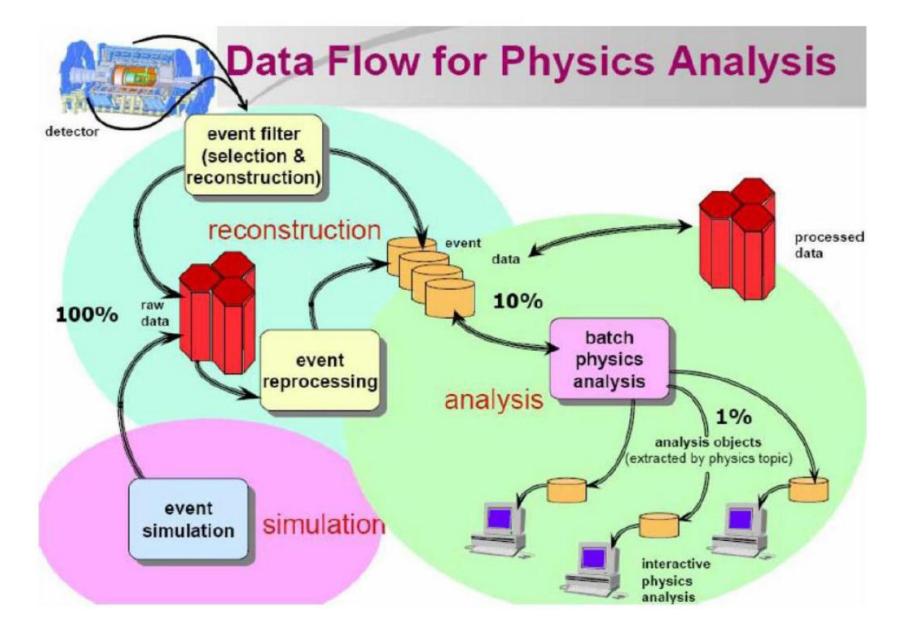
Monte Carlo simulation – why?

We only build one detector.

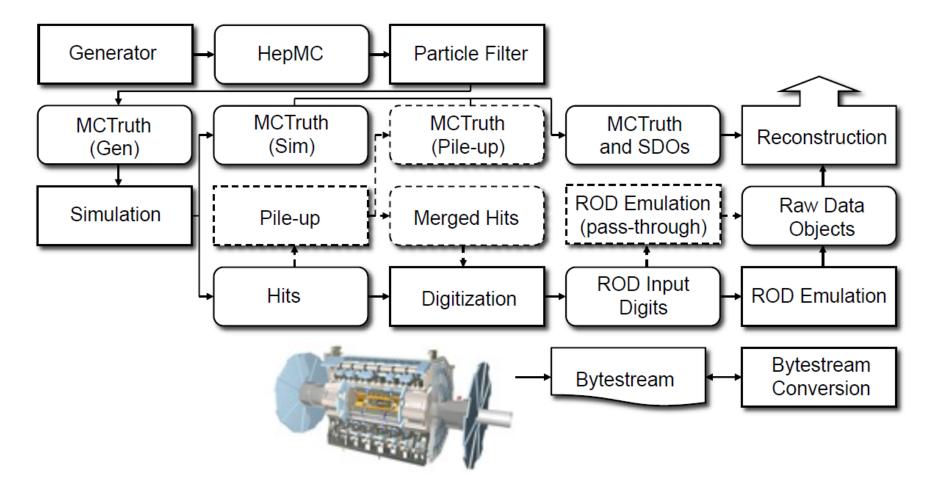
- It was a second to be a second to
- Item would a different detector design affect measurements?
- How does the detector behave to radiation?

In the detectors we only measure voltages, currents, times.

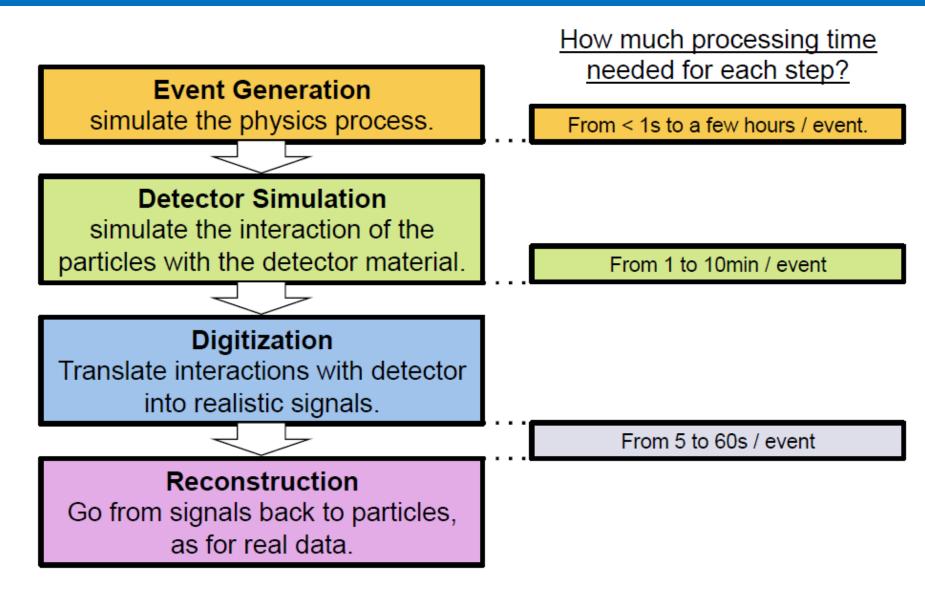
- It's an interpretation to say that such-and-such particle caused suchand-such signature in the detector.
- Simulating the detector behavior we correct for inefficiencies, inaccuracies, unknowns.
- We need a theory to tell us what we expect and to compare our data against.
- A good simulation is the way to demonstrate to the world that we understand the detectors and the physics we are studying.



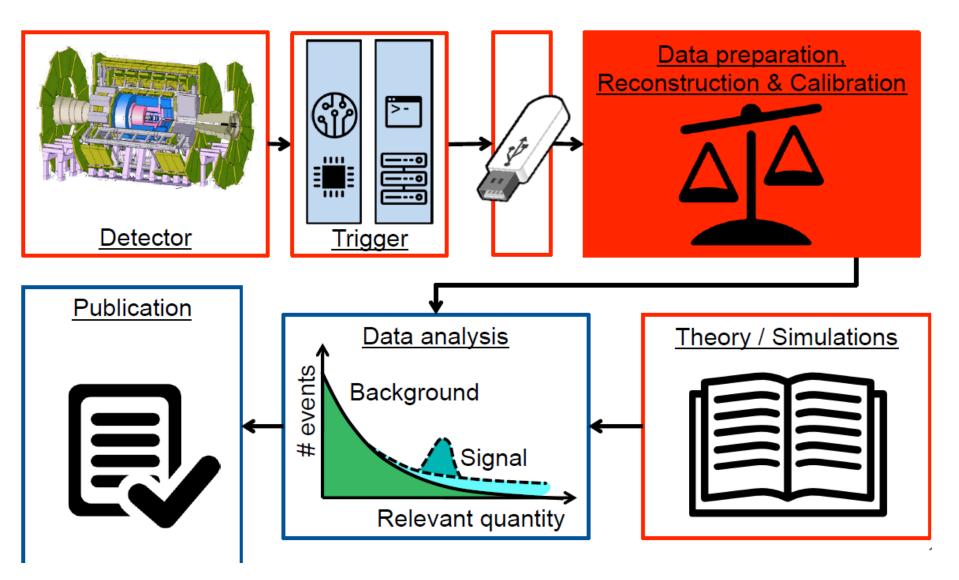
LHC simulation chain



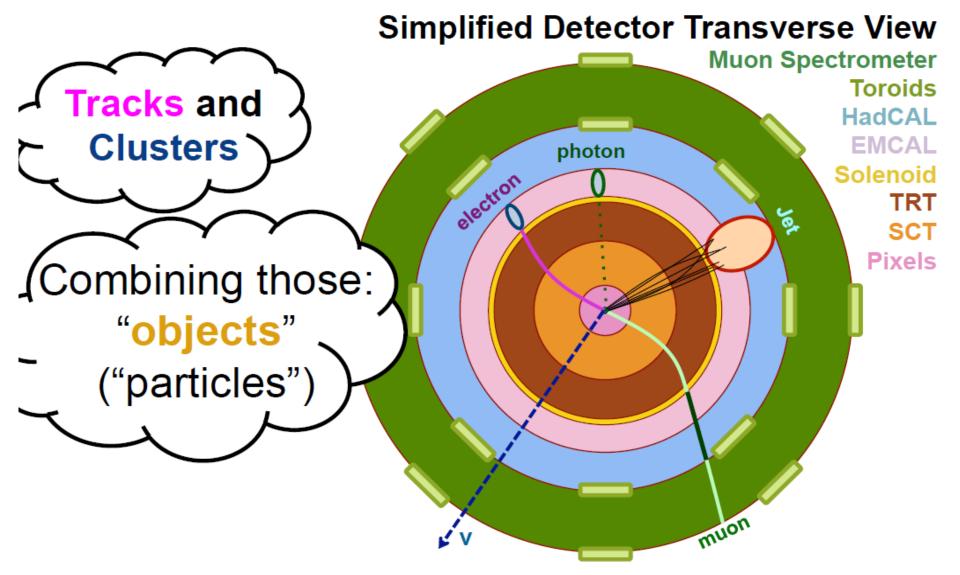
Monte Carlo production chain



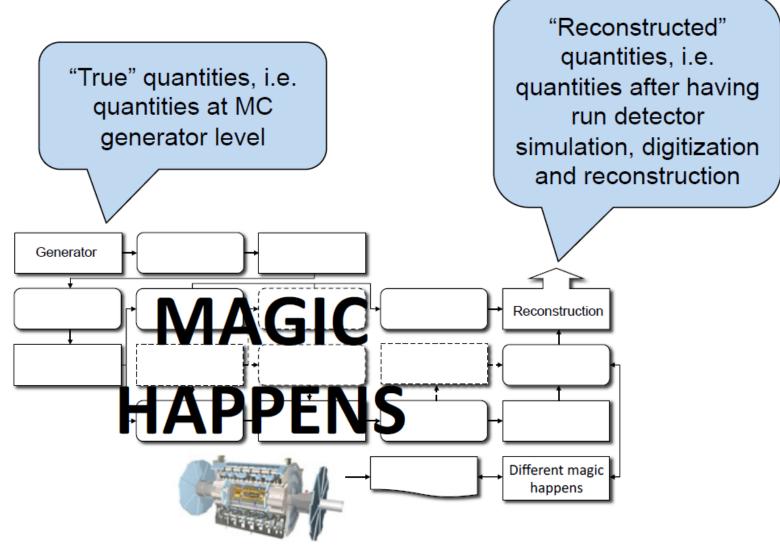
An event's lifetime



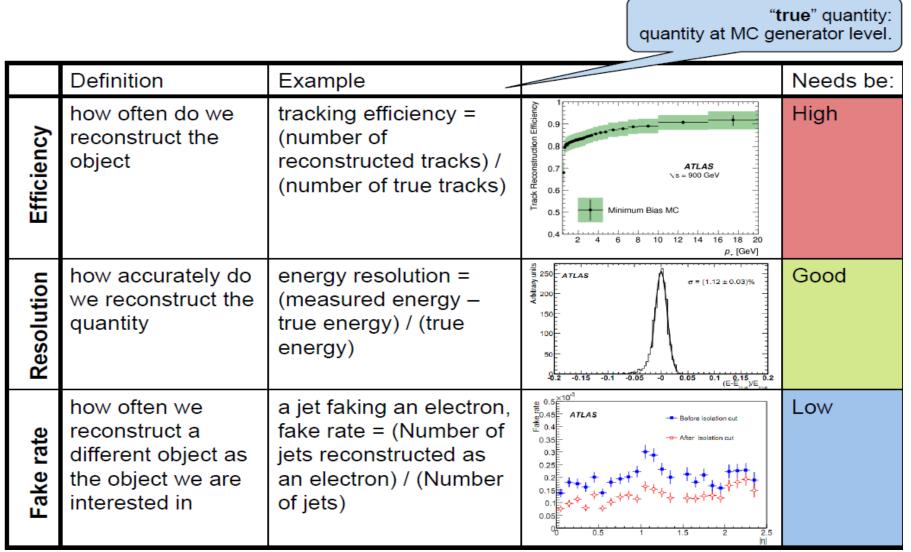
What do we reconstruct?



Reconstruction - figures of merit

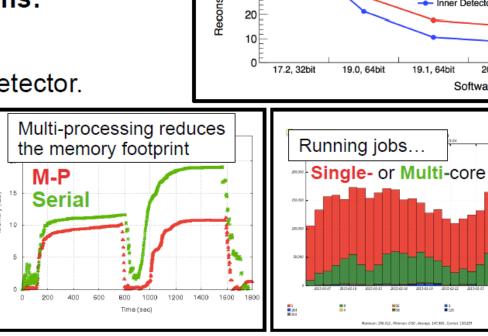


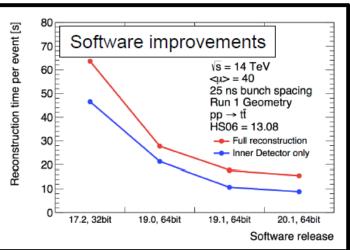
Reconstruction - figures of merit



Reconstruction - goals

- High efficiency. 0
- Good resolution. 0
- Low fake rate. 0
- Robust against detector problems 0 and data-taking conditions:
 - Noise. 0
 - Dead regions of the detector. 0
 - Increased pile-up.
- Computing-friendly. 0
 - CPU time per event. 0
 - Memory use. 0



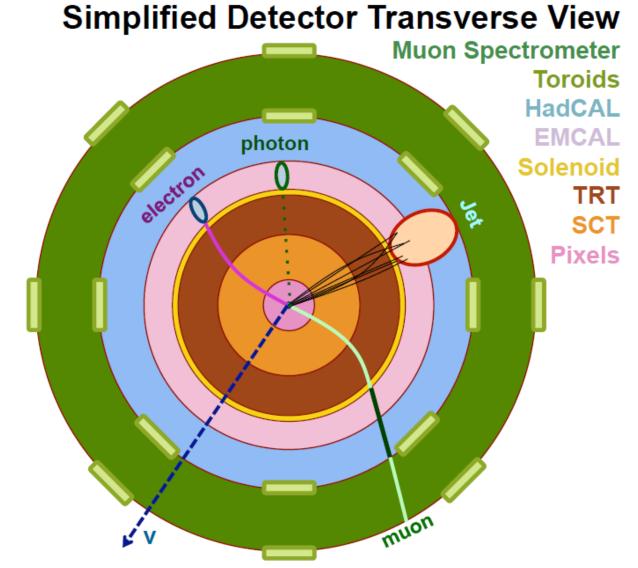


■56 ■56

■ 6 ■ 120

12

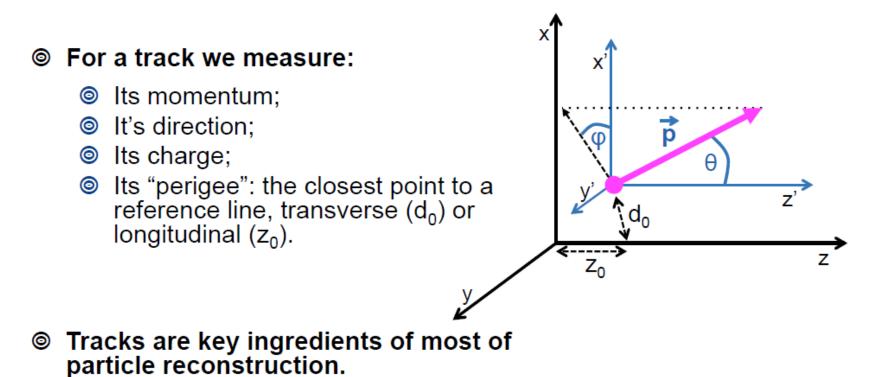
What do we reconstruct?





Tracking in a nutshell

 A track represents a measurement of a charged particle that leaves a trajectory as it passes through the detector.



Tracking in a nutshell: track fitting

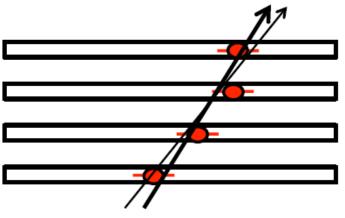
Perfect measurement – ideal



Imperfect measurement – reality



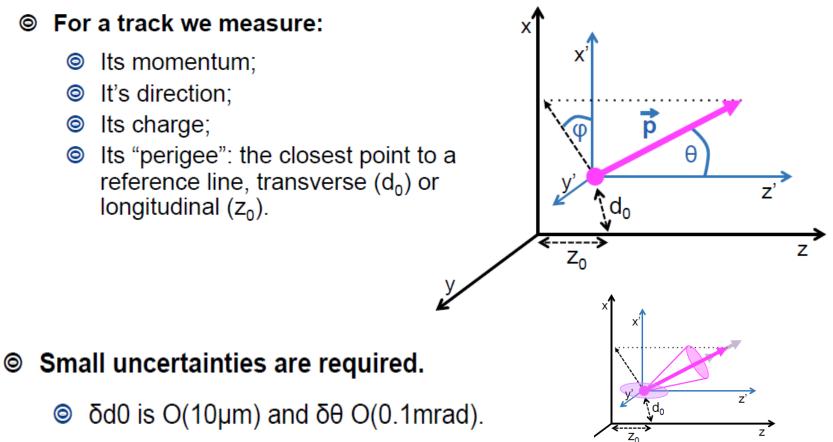
Small errors and more points help to constrain the possibilities



Quantitatively:

- Parameterize the track;
- Find parameters by Least-Squares-Minimization;
- Obtain also uncertainties on the track parameters.

Tracking in a nutshell: track fitting



Allows separation of tracks that come from different particle decays (which can be separated at the order of mm).

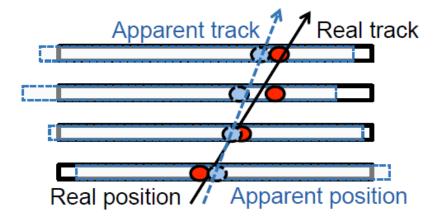
Tracking in a nutshell: the uncertainties

Presence of Material

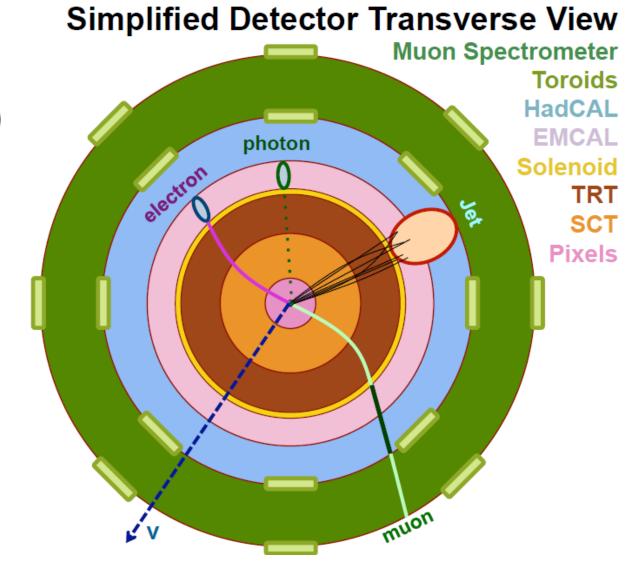
- Coulomb scattering off the core of atoms
- Energy loss due to ionization
- Bremsstrahlung
- Hadronic interaction

Misalignment

- Detector elements not positions in space with perfect accuracy.
- Alignment corrections derived from data and applied in track reconstruction.



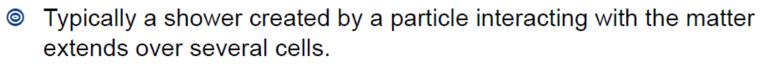
What do we reconstruct?





Clustering in a nutshell

- Reconstruct energy deposited in the calorimeter by charged or neutral particles; electrons, photons and jets. E/σ_{cel} Φ
- For a cluster we measure:
 - The energy;
 - The position of the deposit;
 - The direction of the incident particles;
- Calorimeters are segmented in cells.



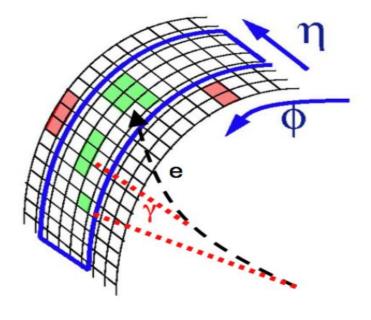
- Various clustering algorithms, e.g.:
 - **Sliding window**. Sum cells within a fixed-size rectangular window.
 - **Topo-clustering**. Start with a seed cell and iteratively add to the cluster the neighbor of a cell already in the cluster.

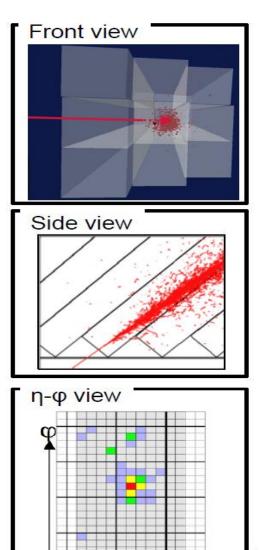
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Cluster finding – an example

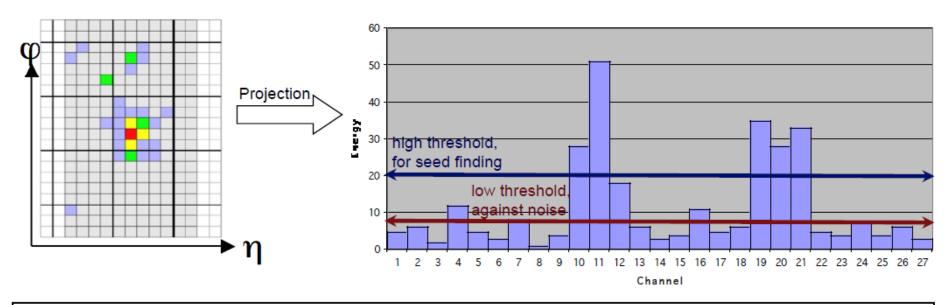
CMS crystal calorimeter – ECAL clusters

electron energy in central crystal ~80%, in 5x5 matrix around it ~96%.





Cluster finding – an example



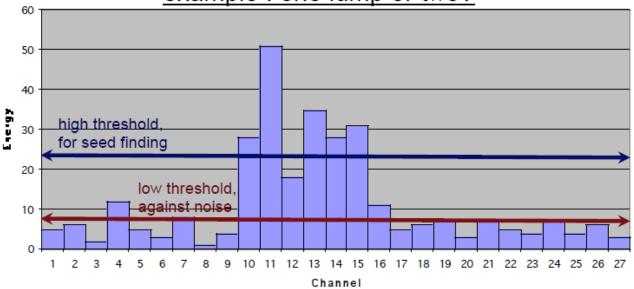
Simple example of an algorithm

- Scan for seed crystals = local energy maximum above a defined seed threshold
- Starting from the seed position, adjacent crystals are examined, scanning first in φ and then in η
- Along each scan line, crystals are added to the cluster if
 - 1. The crystal's energy is above the noise level (lower threshold)
 - 2. The crystal has not been assigned to another cluster already

Cluster finding – difficulties

Careful tuning of thresholds needed.

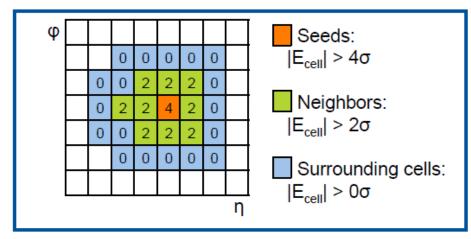
- needs usually learning phase;
- adapt to noise conditions;
- too low : pick up too much unwanted energy;
- too high : loose too much of "real" energy. Corrections/Calibrations will be larger.

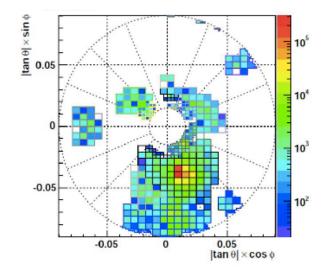


example : one lump or two?

Cluster finding – topological clustering

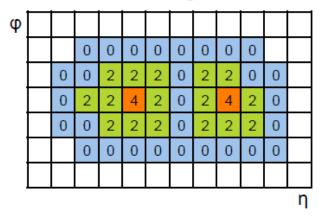
"Topological" clusters, i.e. "blobs" of energy inside the detector.

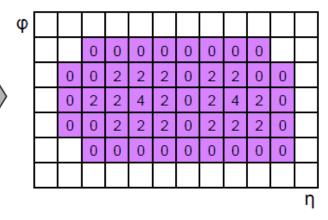




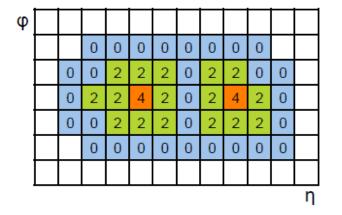
Cluster finding – merging and splitting

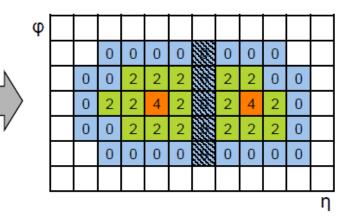
If clusters have common neighboring cells, they are merged according to the basic algorithm.





Clusters are split if more than one local maxima.



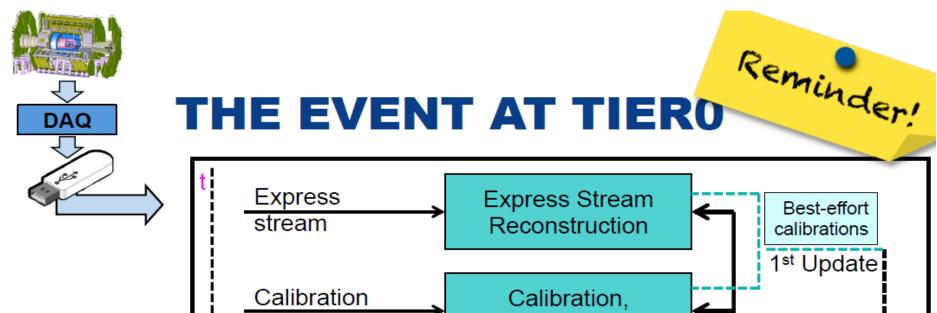


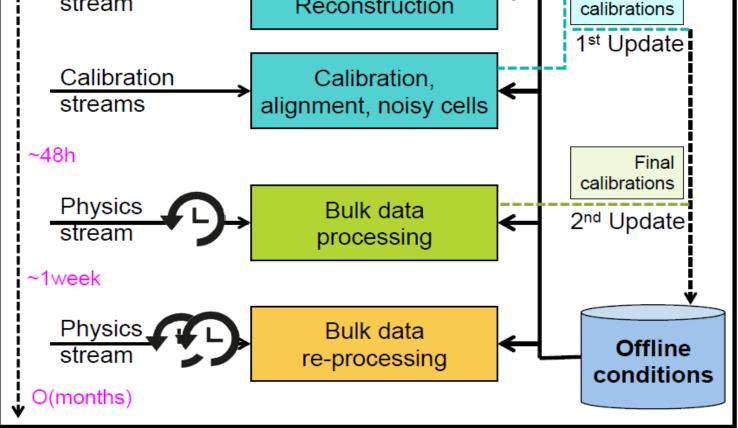
For common cells, a weight is applied to share them (shaded cells).

Cluster calibration

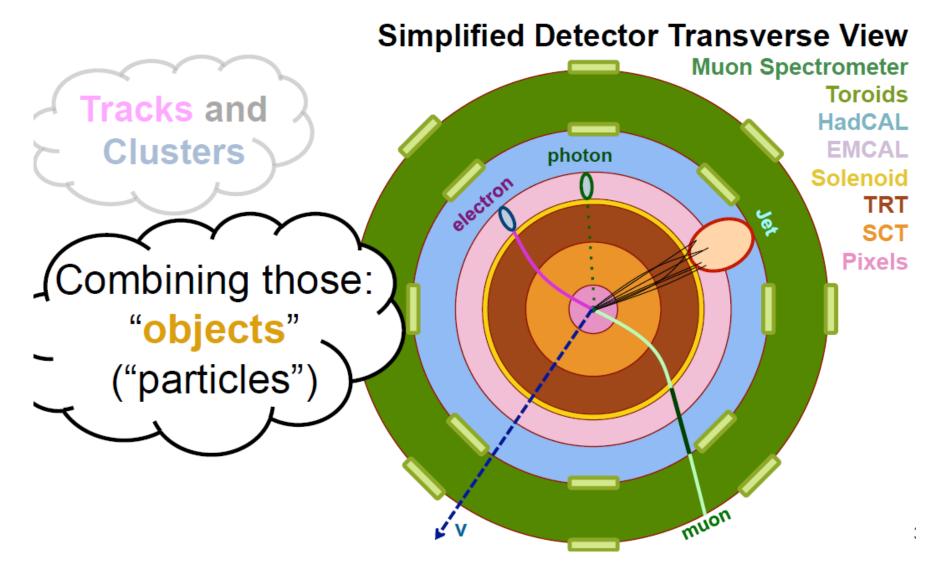
Possible energy measurements:

- Son-calibrated clusters: sum energy using baseline cell-level detector calibration.
 - That's NOT the true energy of the particle that originated the cluster.
- Social Content of C
 - the different calorimeter response on an EM (e.g. π⁰) or a hadronic (e.g. π[±]) deposition.
 - Ithe low energetic deposits, lost in the tails of the shower ("out-ofcluster" corrections, derived from simulation).
 - It the presence of dead material, i.e. material without a read-out device, where energy is lost.
- Corrections are complex functions of the energy and the position of the cluster and other parameters defining the cluster shapes.



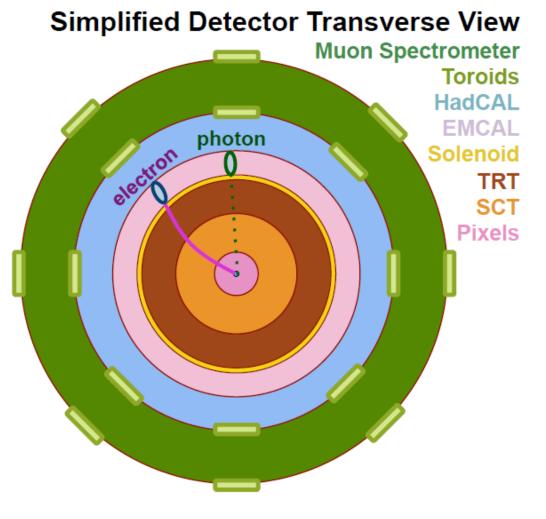


What do we reconstruct?



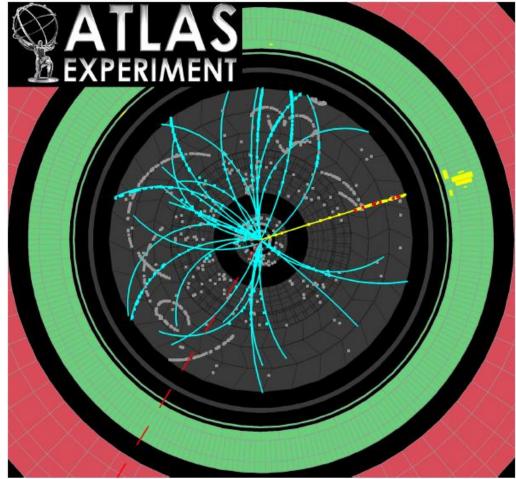
Electrons and photons

- Final Electron momentum measurement can come from tracking or calorimeter information (or a combination of both).
 - Often have a final calibration to give the best electron energy.
- Often want "isolated electrons".
 - Require little calorimeter energy or tracks in the region around the electron.



Electrons and photons

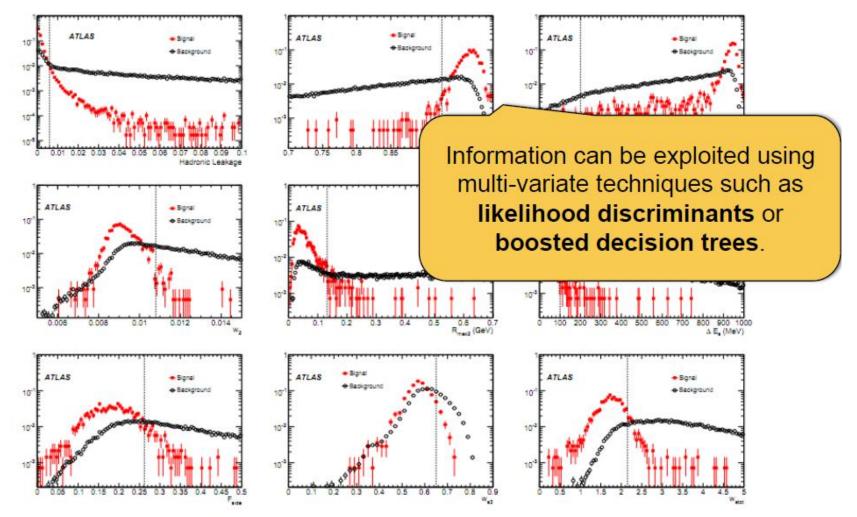
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- Often want "isolated electrons".
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Electrons and photons (backgrounds)

- Hadronic jets leave energy in the calorimeter which can fake electrons or photons.
- Substitution State of the st
- Substant Straight Straight
- So it should be "easy" to separate electrons from jets.
- Solution However have many thousands more jets than electrons, so need the rate of jets faking an electron to be very small ~10^{-4.}
- Need complex identification algorithms to give the rejection whilst keeping a high efficiency.

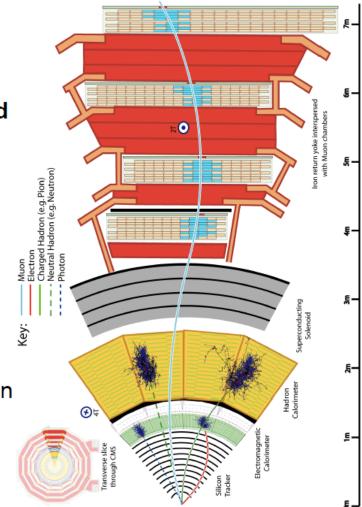
Electrons and photons (backgrounds)



Example of different calorimeter shower shape variables used to distinguish electron showers from jets in ATLAS

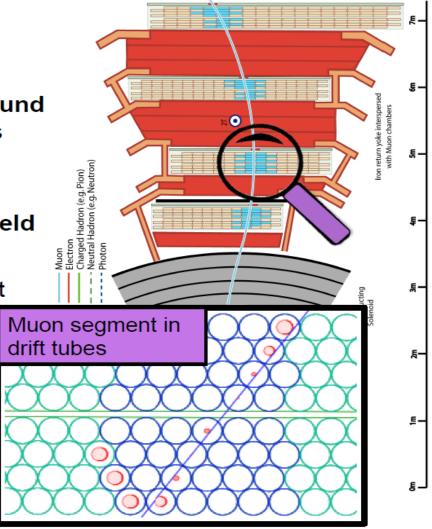
Muons

- Combine the muon segments found in the muon detector with tracks from the tracking detector
- Momentum of muon determined from bending due to magnetic field in tracker and in muon system
 - Combine measurements to get
 best resolution
 - Need an accurate map of the magnetic field in the reconstruction software
 - Alignment of the muon detectors also very important to get best momentum resolution



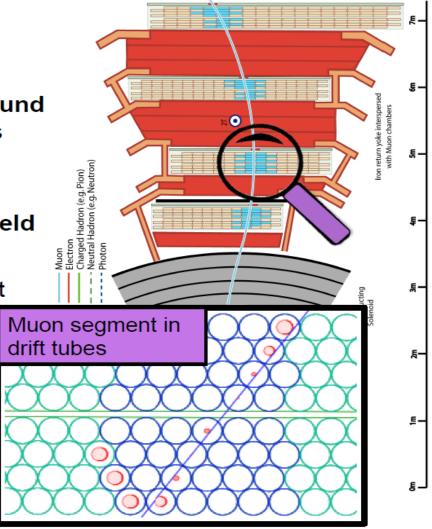
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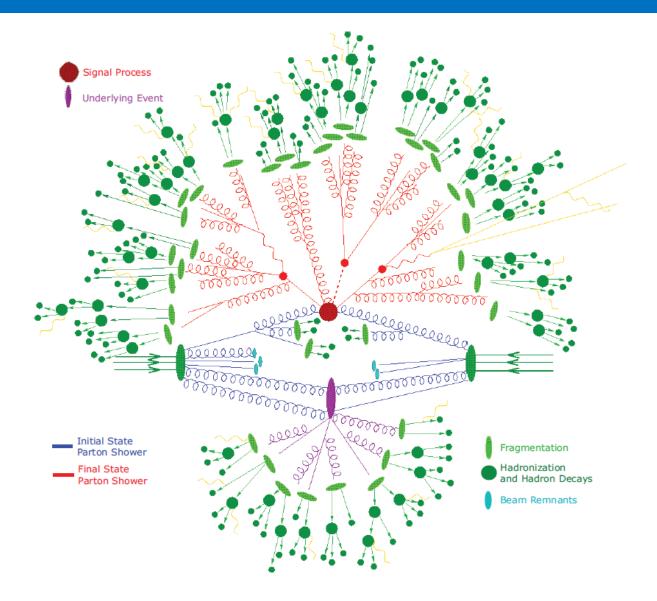


Muons

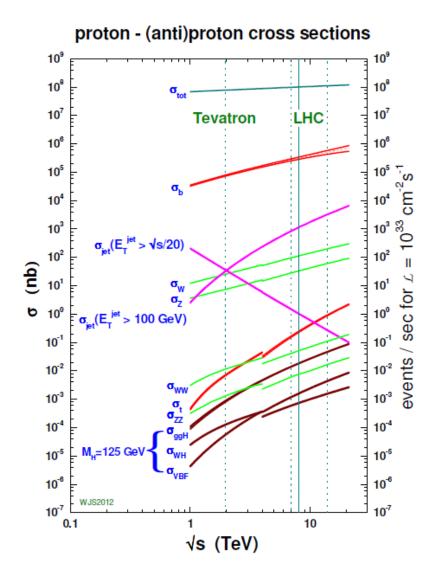
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Jets



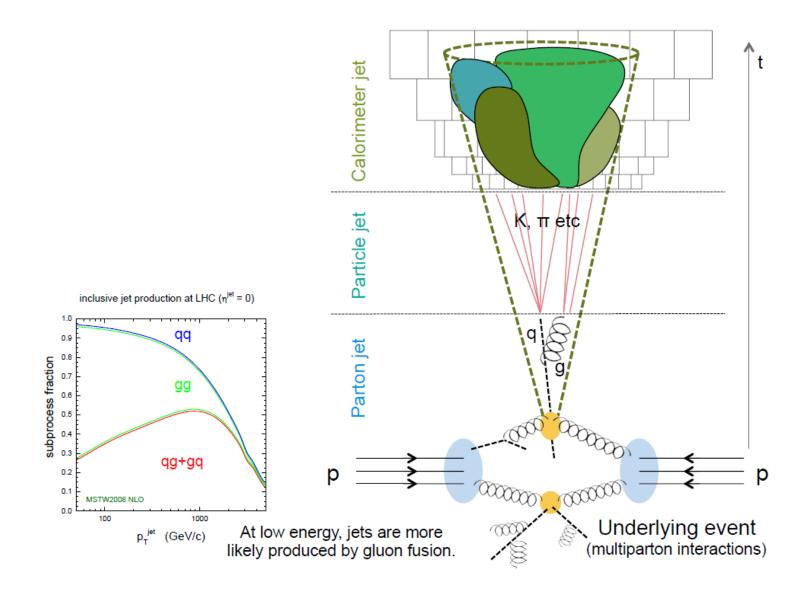
Standard Model processes



Jets are produced:

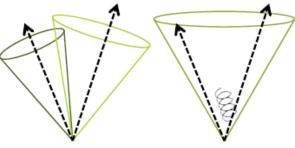
- by fragmentation of gluons and (light) quarks in QCD scattering.
- Solution Standard Standard Model particles, e.g. W & Z.
- In association with particle production in Vector Boson Fusion, e.g. Higgs.
- In decays of beyond the Standard Model particles, e.g. in SUSY.

Jets

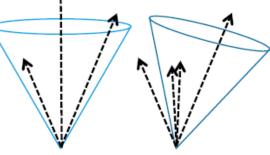


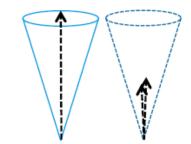
Jet algorithms

Theoretical requirements: infrared and collinear safe.



Soft gluon radiation should not merge jets





Final jet should not depend on the ordering of the seeds...

...and on signal split in two possibly below threshold

Experimental requirements: detector technology & environment independent, easily implementable.

Insignificant effects of detector	Stability with	Fully specified
Noise	Luminosity	Fast
Dead material	Pile-up	
Cracks	Physics process	

<u>Jet algorithm commonly used at the LHC</u>: 'anti- k_t '. A 'recursive recombination' algorithm. Starts from (topo-)clusters. Hard stuff clusters with nearest neighbor. Various cone sizes (standard R=0.4/0.5, "fat" R=1.0).

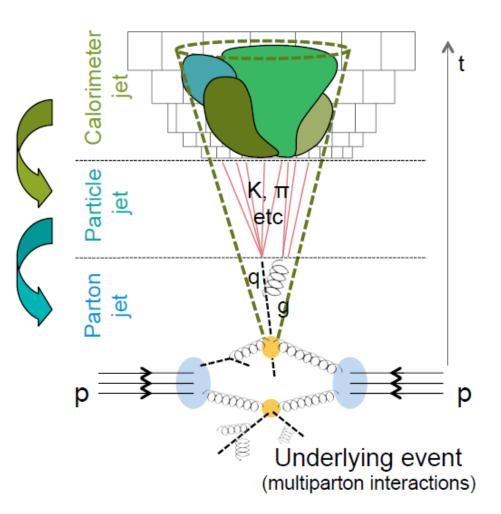
Jet calibration

Correct the energy and position measurement and the resolution.

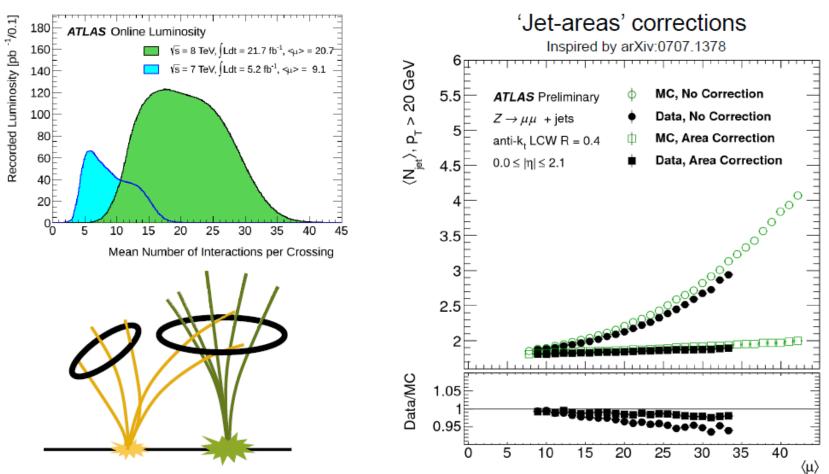
Account for:

Instrumental effects Detector inefficiencies 'Pile-up' Electronic noise Clustering, noise suppression Dead material losses Detector response Algorithm efficiency

<u>Physics effects</u> Algorithm efficiency 'Pile-up' 'Underlying event'



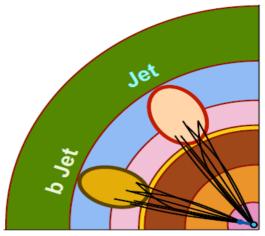
Jets & pile-up

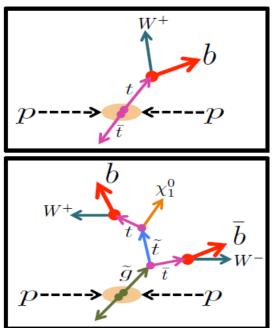


Multiple interactions from pile-up

b-jets

- In b-quarks have a lifetime of ~ 10⁻¹² s.
- They travel a small distance (fraction of mm) before decaying.
- A "displaced vertex" creates a distinct jet, so b-jets can be tagged (b-tagged).
- b-tagging uses sophisticated algorithms, mostly multi-variate.
- b-jets create distinct final states, important for both Standard Model measurements and searches for New Physics.





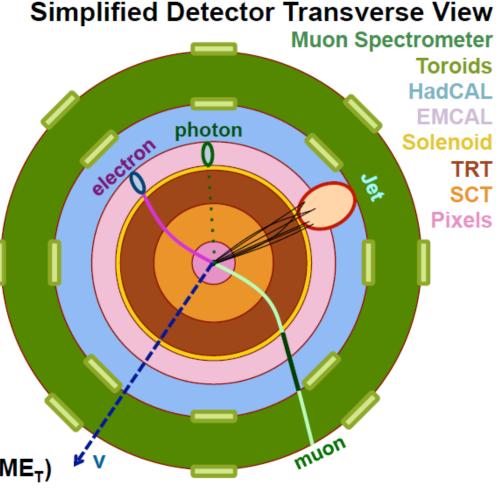
Missing transverse momentum

Dark Matter

In the transverse plane:

 $\sum \vec{\mathbf{p}}_{\mathrm{T}} = 0$

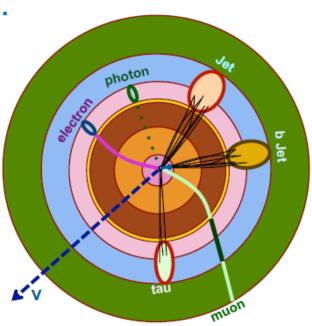
Missing Transverse Momentum (ME_T)



Missing transverse momentum

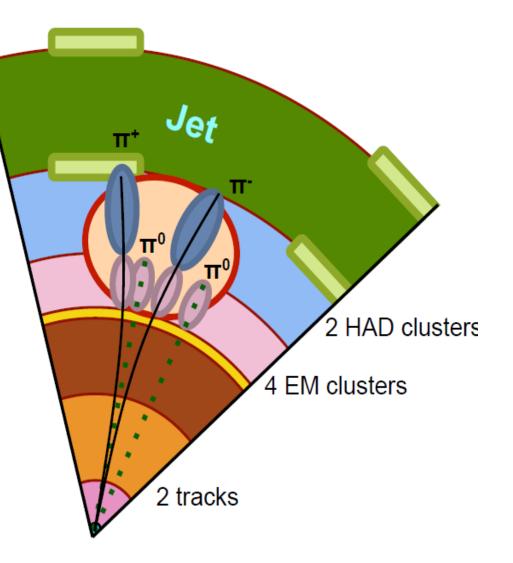
Impossible to measure particles that don't interact in the detector.

- Instead, measure everything else & require momentum conservation in the transverse plane.
- Sensitive to pile-up and detector problems.
- Only as good as its inputs.
- Subsection Stress St
- Add remaining soft energy.



Particle flow

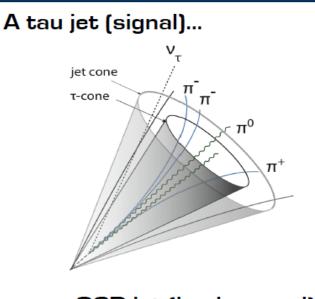
- "Flow of particles" through the detector.
- Reconstruct and identify all particles, photons, electrons, pions, …
- Use best combination of all subdetectors for measuring the properties of the particles.
- First used at LEP (ALEPH) and then at the LHC (CMS).



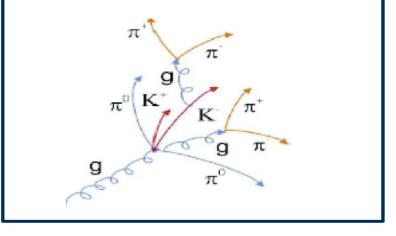
Reconstructing particles

Tau Decay Mode			B.R.
Leptonic		$\tau^{\pm} \rightarrow e^{\pm} + \nu + \nu$	17.8%
		$\tau^{\pm} \rightarrow \mu^{\pm} + \nu + \nu$	17.4%
Hadronic	1- prong	$\tau^{\pm} \rightarrow \pi^{\pm} + \nu$	11%
		$\tau^{\pm} \rightarrow \pi^{\pm} + \nu + n\pi^{0}$	35%
	3- prong	$\tau^{\pm} \rightarrow 3\pi^{\pm} + \nu$	9%
		$\tau^{\pm} \rightarrow 3\pi^{\pm} + \nu + n\pi^0$	5%
Other			~5%

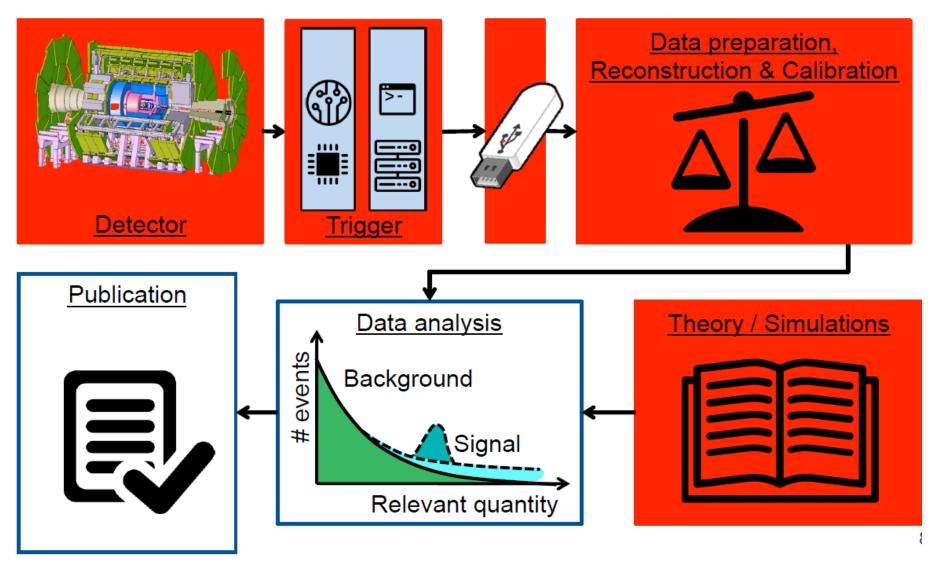
- Hadronic tau reconstruction extremely challenging.
- Solution Strack Multiplicity and shower shapes.



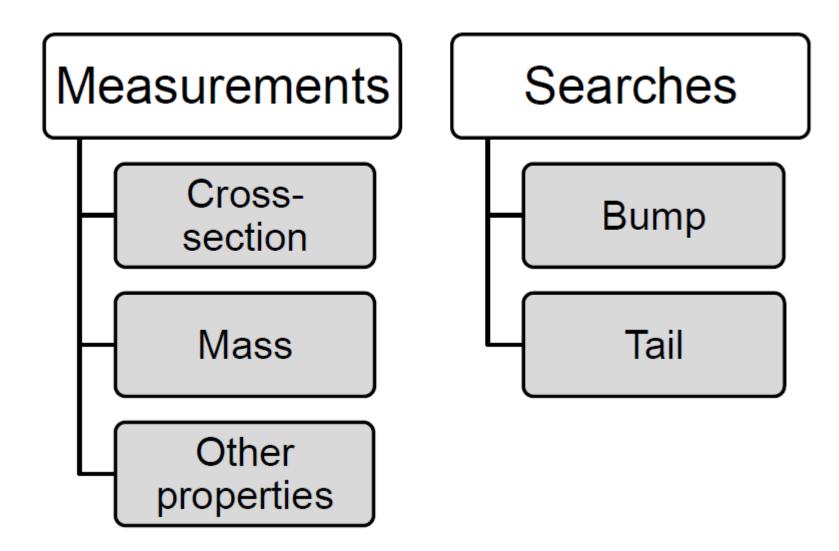
...vs. a QCD jet (background)



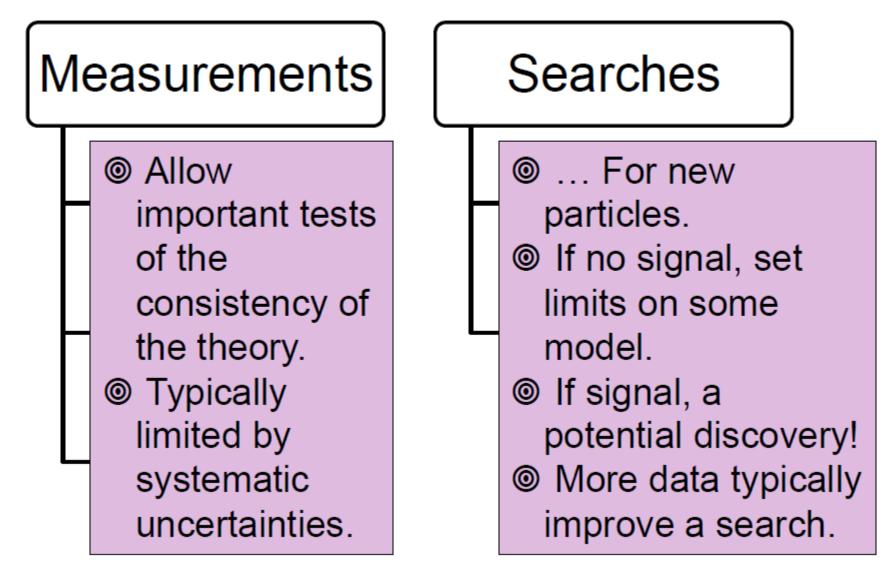
An event's lifetime



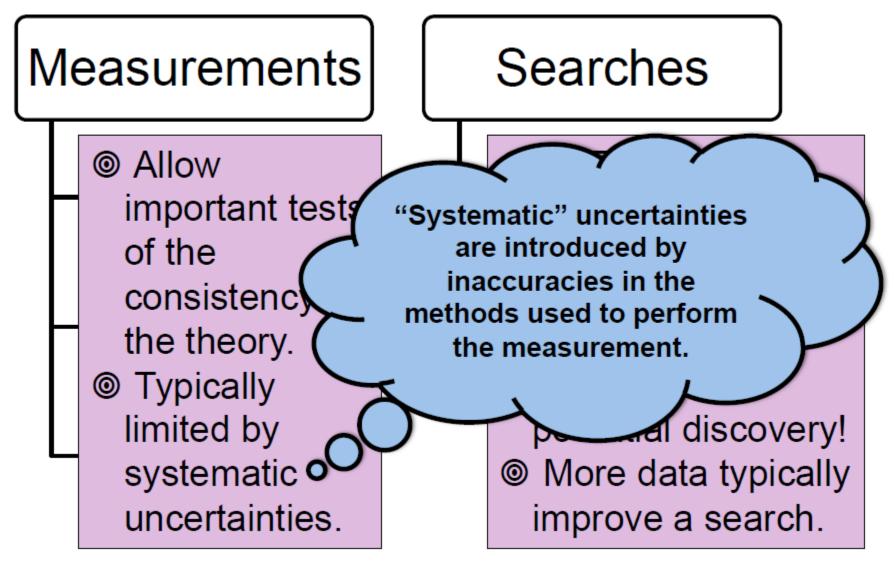
Physics analyses



Physcis analyses



Physics analyses



Physics analyses

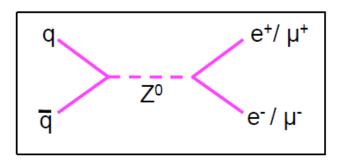
SIMPLE EXAMPLE:

MEASURING Z⁰ CROSS-SECTION AT LHC

Measuring Z⁰ cross-section at LHC

Solution State State

• We can reconstruct it in the e^+e^- or $\mu^+\mu^-$ decay modes



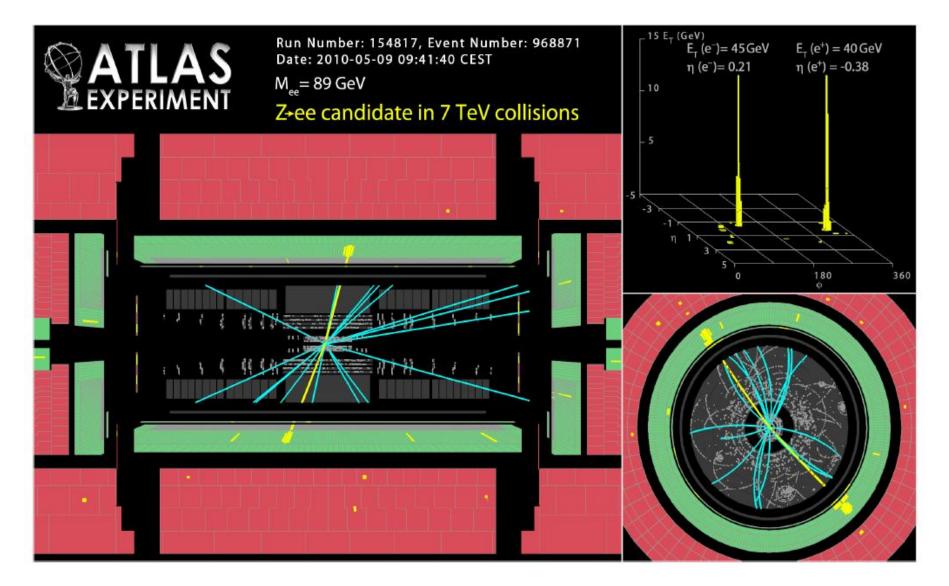
 Discovery and study of the Z^o boson was a critical part understanding the electroweak force.



◎ And now, at the LHC?

- Important test of theory: does the measurement agree with the theoretical prediction at LHC collision energy?
- A standard candle for studying reconstruction and deriving calibrations.
- Can be used for luminosity determination!

Physics analyses



Reconstructing Z⁰'s

How do we know it's a Z^o?

Identify Z decays using the invariant mass of the 2 leptons $M^2 = (L_1 + L_2)^2$ where $L_i = (E_i, \underline{p}_i) = 4$ -vector for lepton i

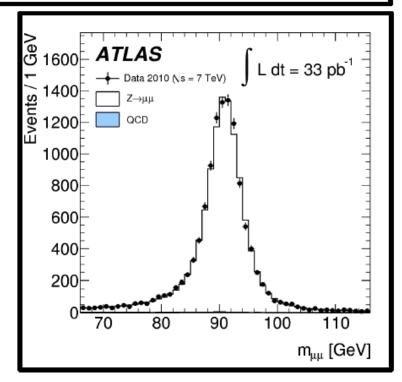
Under assumption that lepton is massless compared to mass of Z^0 => $M^2 = 2 E_1 E_2 (1 - \cos \theta_{12})$ where θ_{12} = angle between the leptons

So need to reconstruct the electron and muon energy and direction. Then can calculate the mass.

Select Z^O events with 'analysis cuts':

- Events with 2 high momentum electrons or muons
- Require the electrons or muons are of opposite charge
- With di-lepton mass close to the Z⁰ mass (e.g. 70<m_{I+I}<110 GeV)</p>

Very little background in Z^o mass region!



e*/ µ*

e⁻/μ⁻

70

Reconstructing Z⁰'s

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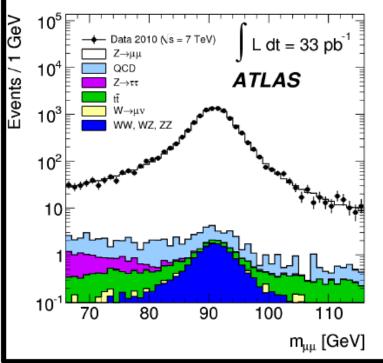
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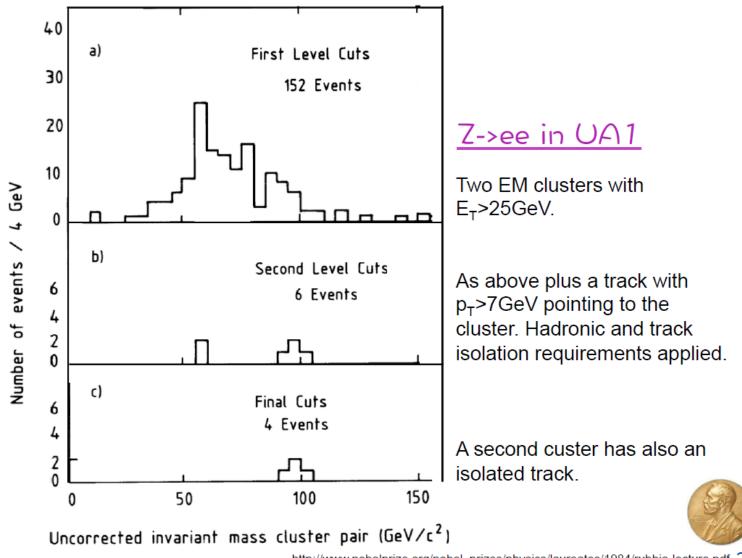


70

e*/ µ*

e-/μ-

A step back in time ...



http://www.nobelprize.org/nobel_prizes/physics/laureates/1984/rubbia-lecture.pdf 20

Measuring the Z⁰ cross-section

Theoretically

Cross-section calculated for:

- Specific production mechanism (pp, pp, e⁺e⁻)
- Centre-of-Mass of the collisions (7, 8, 13 TeV at LHC)

Experimentally

$$\sigma \cdot \mathrm{BR} = \frac{\mathrm{Number of events}}{\alpha \cdot \epsilon \cdot \mathrm{L}}$$

N of events:

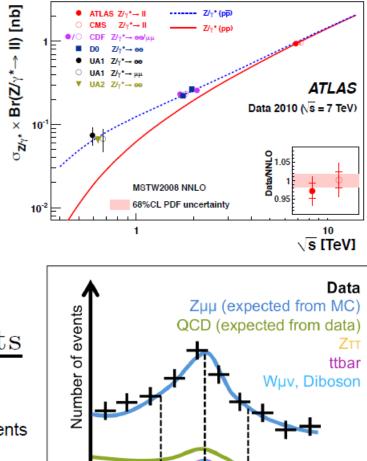
N of events on data – N of expected background events α – acceptance:

fraction of events passing selection requirements

ε – efficiency:

reconstruction efficiency of relevant objects

L – luminosity



m₁

 m_0

 m_2

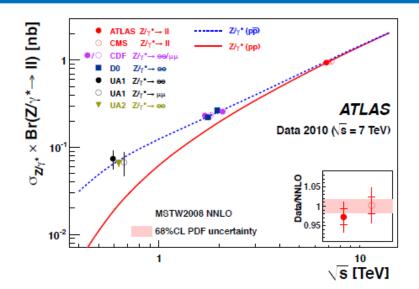
di-muon mass

Measuring the Z⁰ cross-section

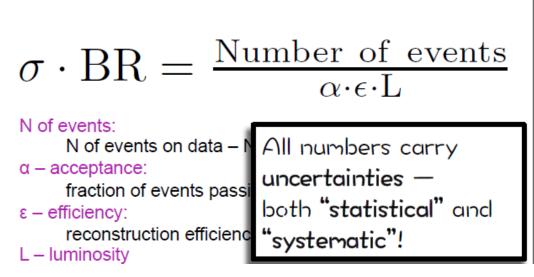
Theoretically

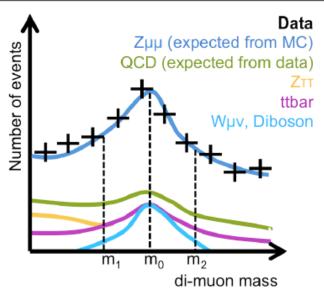
Cross-section calculated for:

- Specific production mechanism (pp, pp̄, e⁺e⁻)
- Centre-of-Mass of the collisions (7, 8, 13 TeV at LHC)

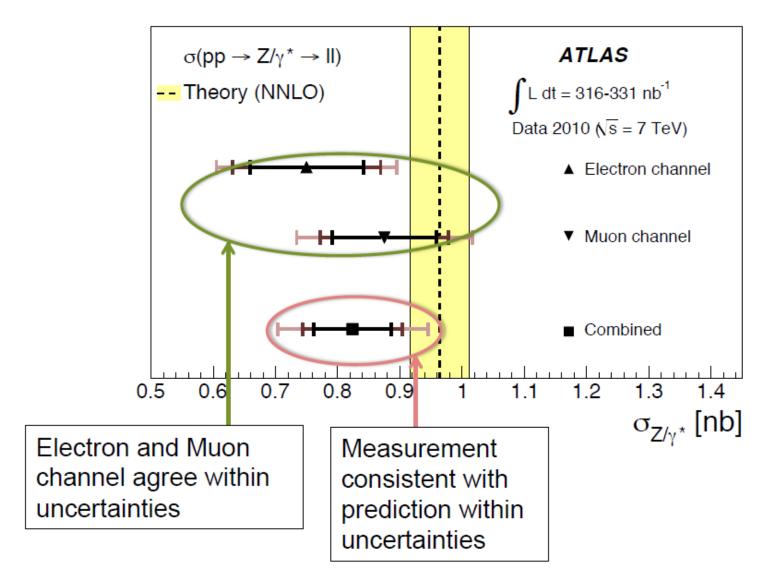


Experimentally

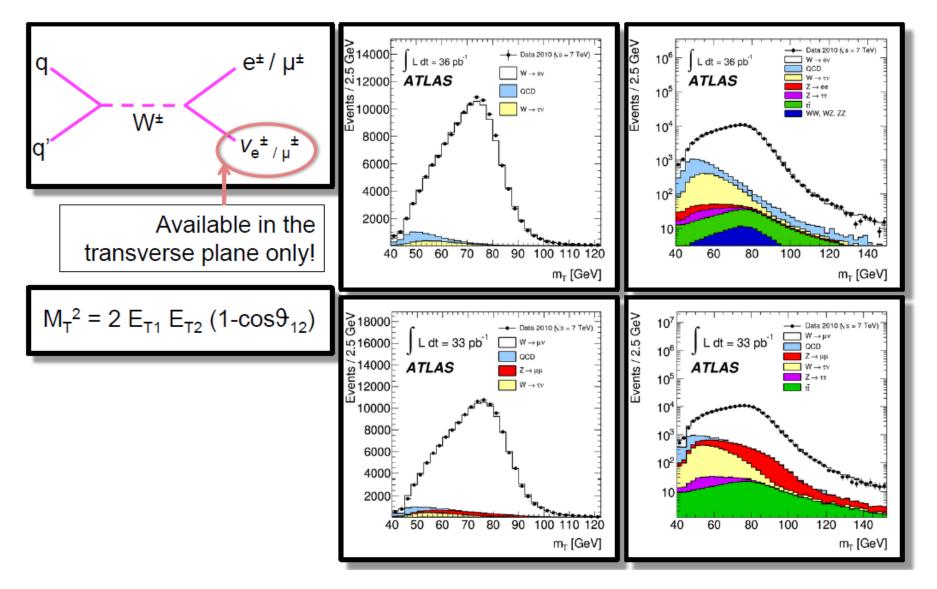




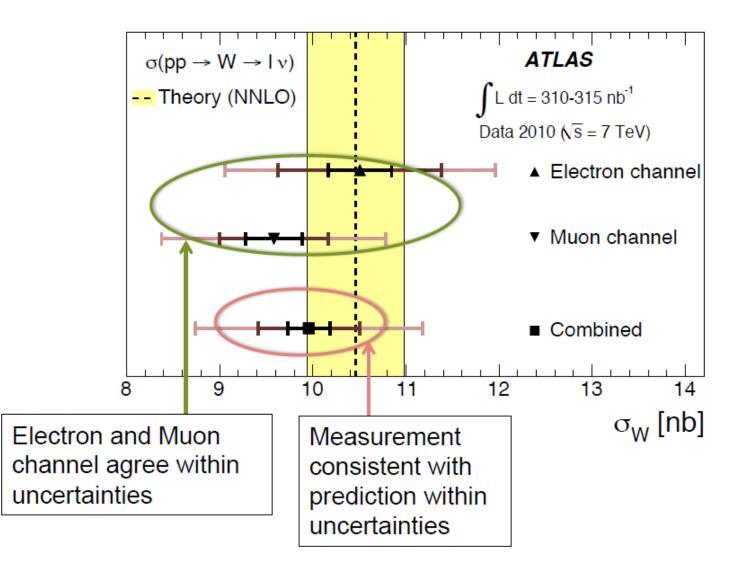
Measuring the Z⁰ cross-section



Measuring the W cross-section



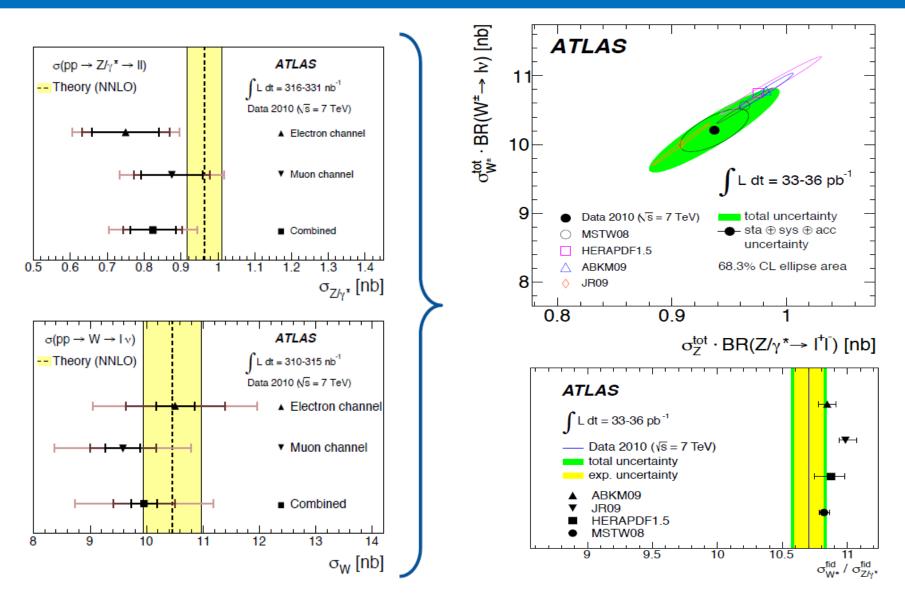
Measuring the W cross-section



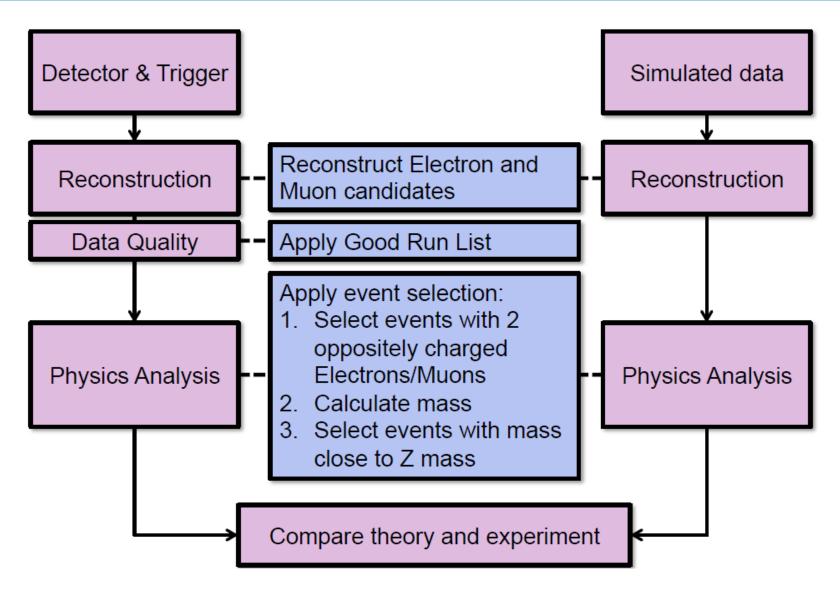
"Final" calibration

pp total	$\sigma = 95.35 \pm 0.38 \pm 1.3 \text{ mb (data)} \\ \text{COMPETE RRpi2u 2002 (theory)}$			4 8×10 ⁻	8 Nucl. Phys. B, 486-548 (2014)
Jets R=0.4	$\sigma = 563.9 \pm 1.5 + 55.4 - 51.4 \mathrm{nb} \mathrm{(data)} \\ \mathrm{NLCJet}_{**}, \mathrm{CT10} \mathrm{(theory)}$		0.1 < p _T < 2 TeV	4.5	arXiv:1410.8857 [hep-ex]
Dijets R=0.4 y <3.0, y*<3.0	$\sigma = 86.87 \pm 0.26 + 7.56 - 7.2 \text{ nb} (\text{data}) \\ \text{NLCUet++, CT10} (\text{theory})$	0.3 <	m ₂₀ < 5 TeV	4.5	JHEP 05, 059 (2014)
W total	$\sigma = 94.51 \pm 0.194 \pm 3.726 \text{ nb (deta)} \\ \text{FEWZ+HERAPDF1.5 NNLO (theory)}$		9	0.035	PRD 85, 072004 (2012)
Z	$\sigma=27.94\pm0.178\pm1.096~{\rm rb}~{\rm [data]} \\ {\rm FEWZ+HERAPDF1.5~NNLO~(theory)}$		¢	0.035	PRD 85, 072004 (2012)
tt	$\begin{array}{l} \sigma = 182.9 \pm 3.1 \pm 6.4 \ \mathrm{pb} \ \mathrm{(data)} \\ \mathrm{top++} \ \mathrm{NNLO+NNLL} \ \mathrm{(theory)} \\ \sigma = 242.4 \pm 1.7 \pm 10.2 \ \mathrm{pb} \ \mathrm{(data)} \\ \mathrm{top++} \ \mathrm{NNLO+NNLL} \ \mathrm{(theory)} \end{array}$	¢ 4		4.6 20.3	Eur. Phys. J. C 74: 3109 (2014) Eur. Phys. J. C 74: 3109 (2014)
t _{t-chan}	$ \begin{aligned} \sigma &= 68.0 \pm 2.0 \pm 8.0 \mathrm{pb} (\mathrm{data}) \\ \mathrm{NLO-NLL} (\mathrm{theory}) \\ \sigma &= 82.6 \pm 1.2 \pm 12.0 \mathrm{pb} (\mathrm{data}) \\ \mathrm{NLO-NLL} (\mathrm{theory}) \end{aligned} $	¢ 4		4.6 20.3	PRD 90, 112006 (2014) ATLAS-CONF-2014-007
WW+WZ	$\sigma = 68.0 \pm 7.0 \pm 19.0 \text{ pb (data)} \\ \text{MC@NLO (theory)}$	•	LHC pp $\sqrt{s} = 7 \text{ TeV}$ Theory	4.6	JHEP 01, 049 (2015)
WW total	$\sigma = 51.9 \pm 2.0 \pm 4.4 \text{ pb} (\text{data})$ MCFM (meory) $\sigma = 71.4 \pm 1.2 \pm 5.5 - 4.9 \text{ pb} (\text{data})$ MCFM (theory)	¢ ≰	Observed stat stat+syst	4.6 20.3	PRD 87, 112001 (2013) ATLAS-CONF-2014-003
Wt total	$\sigma = \frac{16.8 \pm 2.9 \pm 3.9 \text{ pb} \text{ (data)}}{\text{NLO+NLL (heory)}}$ $\sigma = 27.2 \pm 2.8 \pm 5.4 \text{ pb} \text{ (data)}$ NLO+NLL (heory)	р 		2.0 20.3	PLB 716, 142-159 (2012) ATLAS-CONF-2013-100
H _{ggF} total	$\sigma = 23.9 \pm 3.9 \pm 3.5 \ \mathrm{pb} \ \mathrm{(data)} \\ \mathrm{LHC}\mathrm{HOSWG} \ \mathrm{(theory)}$	4	LHC pp $\sqrt{s} = 8 \text{ TeV}$ Theory	△ 20.3	ATLAS-CONF-2015-007
wz ^{tota/}	$\sigma = 19.0 + 1.4 + 1.3 + 1.0 \text{ pb} (\text{data})$ MCFM (theory) $\sigma = 20.3 + 0.8 = 0.7 + 1.4 - 1.3 \text{ pb} (\text{data})$ MCFM (theory) $\sigma = 6.7 + 0.5 - 0.4 \text{ pb} (\text{data})$ MCFM (theory) $\sigma = 7.3 + 0.5 - 0.4 + 0.4 \text{ pb} (\text{tata})$	°. ?	Observed stat stat+syst	4.6 3 4.6 4.6 4.6	EPJC 72, 2173 (2012) ATLAS-CONF-2013-021 JHEP 03, 128 (2013)
total H vBF total	$\sigma = 7.1 + 0.5 - 0.4 \pm 0.4 \text{ pb (data)}$ $\sigma = 2.43 + 0.6 - 0.55 \text{ pb (data)}$ LHC-HOCSWG (theory)		Preliminary	20.3 ▲ 20.3	ATLAS-CONF-2013-020 ATLAS-CONF-2015-007
ttW	σ = 300.0 + 120.0 − 100.0 + 70.0 − 40.0 fb (data) MCFM (theory)	Run 1	$\sqrt{s} = 7, 8 \text{ TeV}$	20.3	ATLAS-CONF-2014-038
ttZ total	σ = 150.0 + 55.0 - 50.0 ± 21.0 fb (data) HELAC-NLO (theory)			20.3	ATLAS-CONF-2014-038

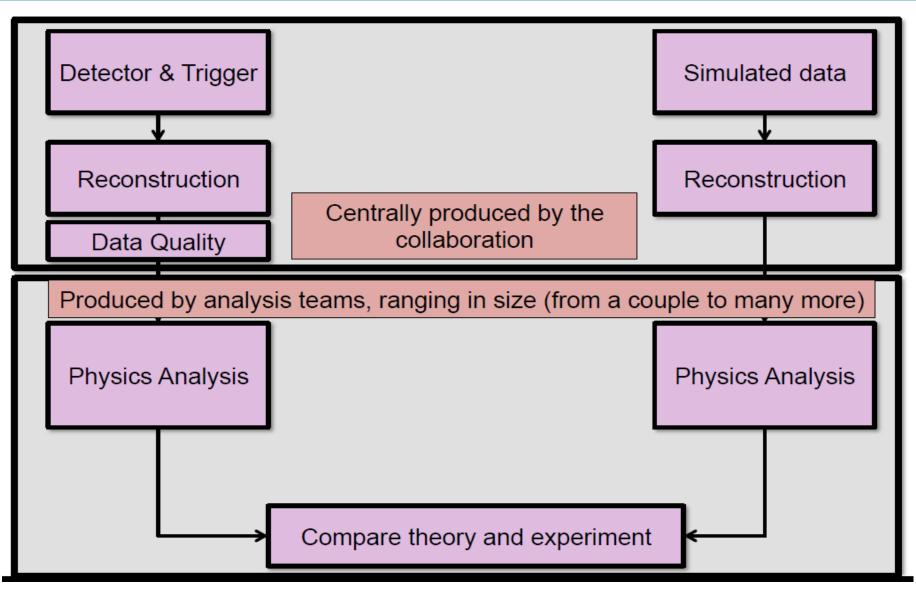
Measuring cross-sections ratio

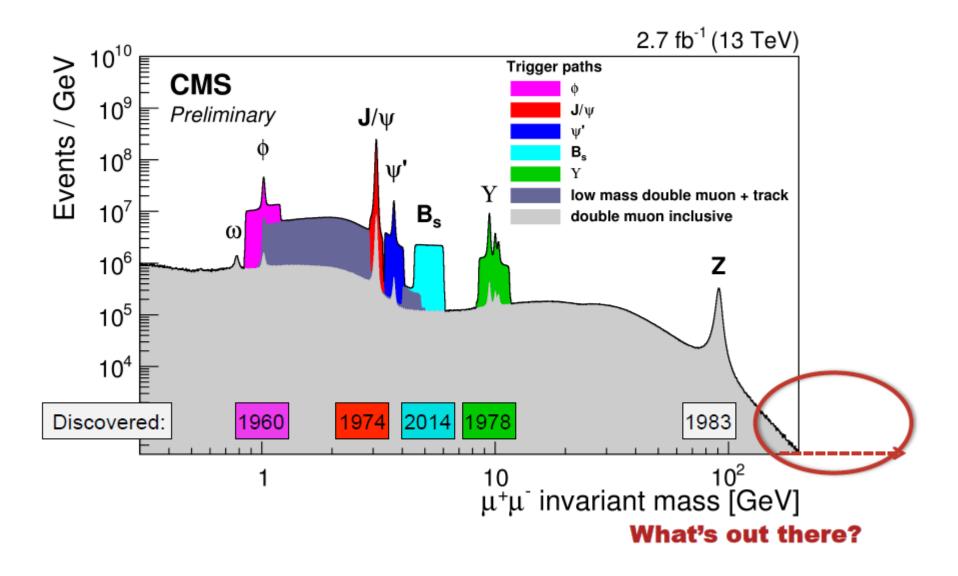


Analysis flow in Z⁰ cross-section measurement



Analysis flow in Z⁰ cross-section measurement



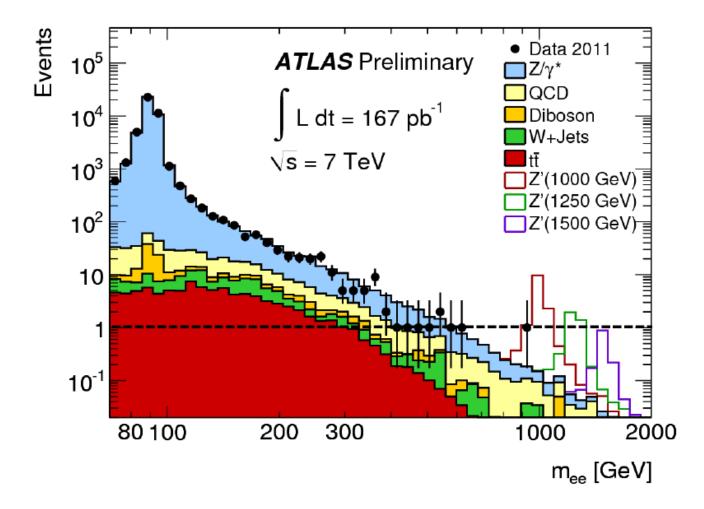


Simple search example

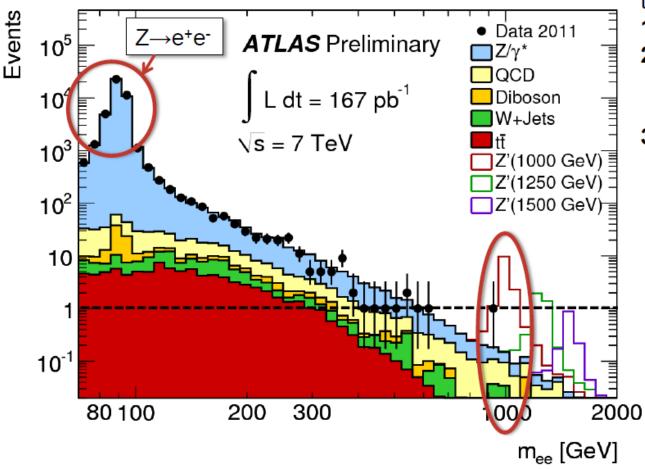
SIMPLE SEARCH EXAMPLE:

SEARCH FOR A HEAVY Z'

Iike Z->ee but at higher mass.



Iike Z->ee but at higher mass.

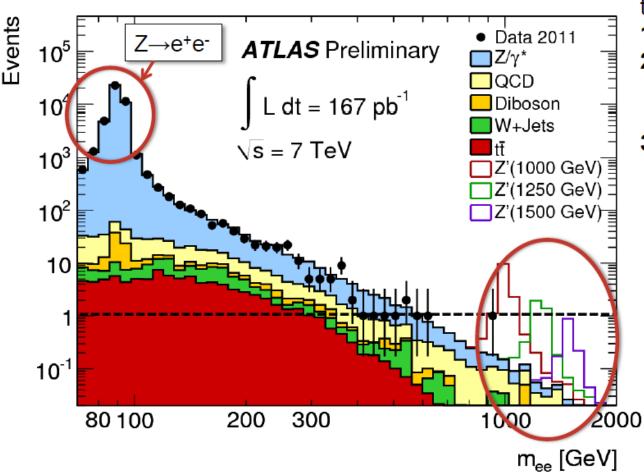


Select 2 electron candidates and plot their invariant mass for:

- 1. Data
- 2. Simulated background events
- 3. Simulated signal with different masses

Data inconsistent with a 1TeV Z'

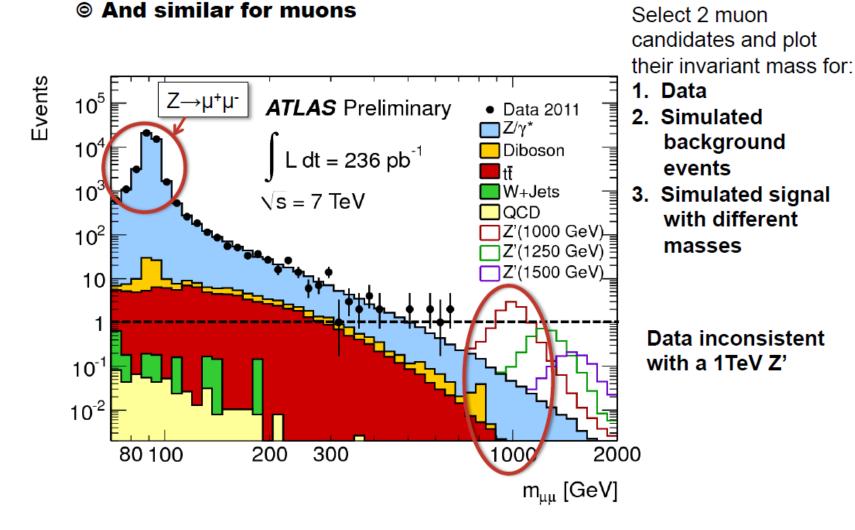
© Like Z->ee but at higher mass.



Select 2 electron candidates and plot their invariant mass for:

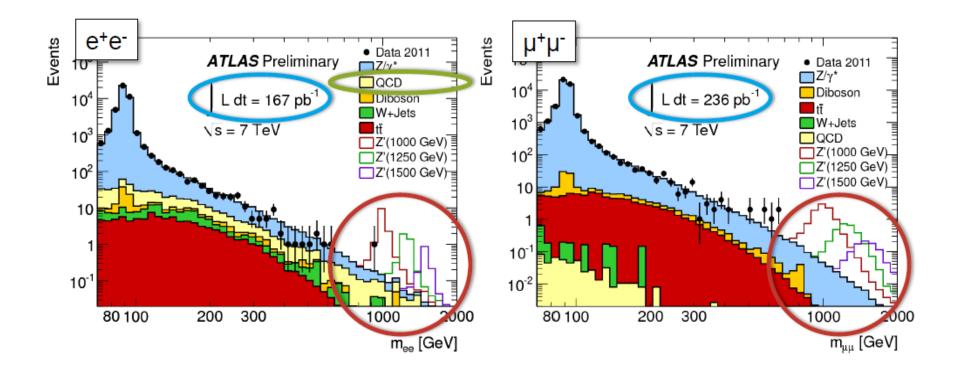
- 1. Data
- 2. Simulated background events
- 3. Simulated signal with different masses

Cross-section decreases with mass (higher the mass of the Z', the more data needed to discover it)



106

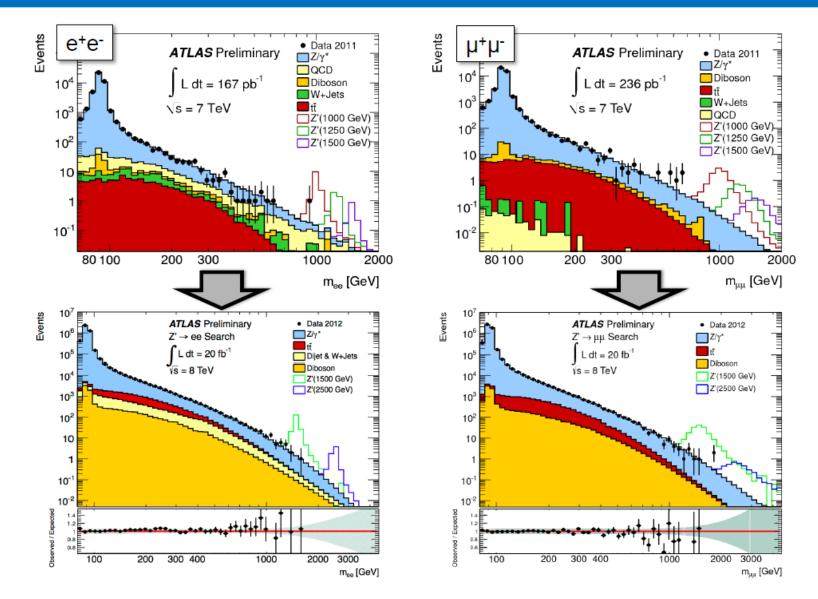
A small comparison



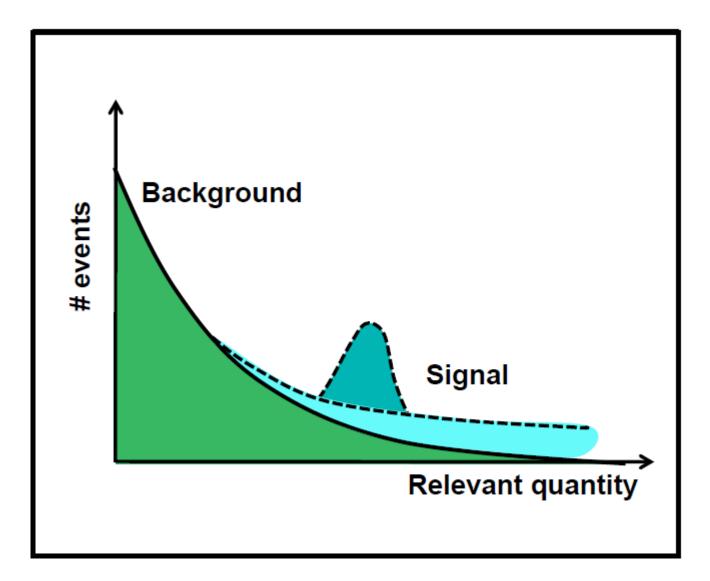
Differences in:

- Resolution
- Background composition
- Dataset

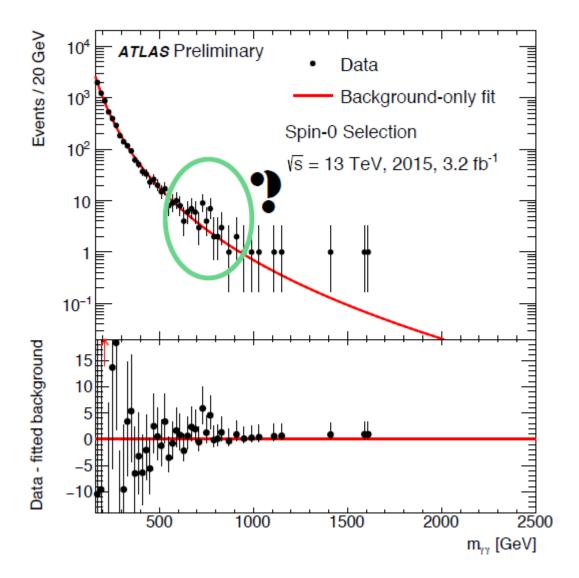
Evolution...



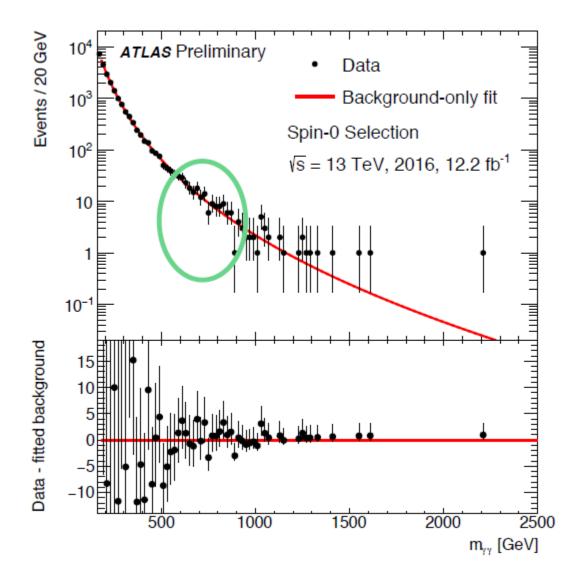
Searches



A well known bump search

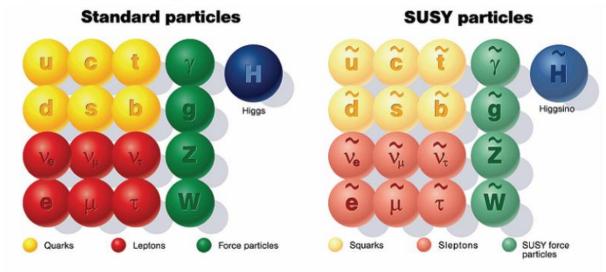


A well known bump search



Typical SUSY searches

Super-symmetry?



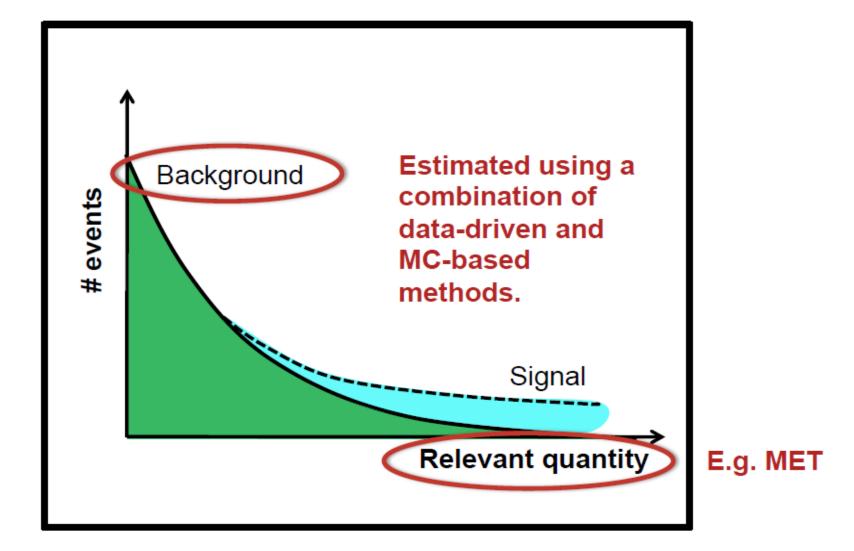
- Composite quark and/or leptons?
- New Heavy bosons?
- Gravitons?

...

Dark Matter particles?

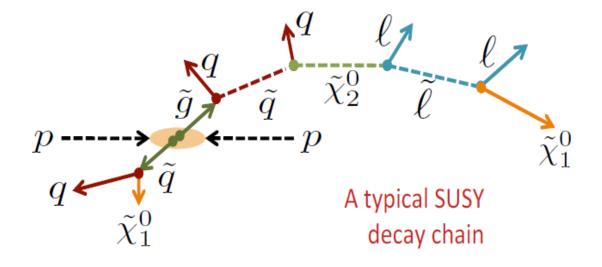


Typical SUSY searches

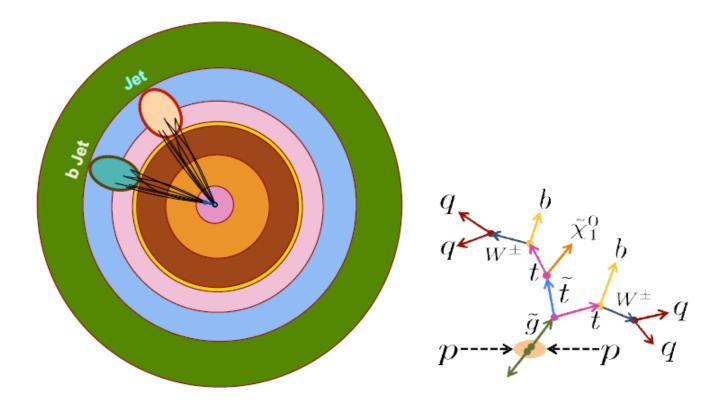


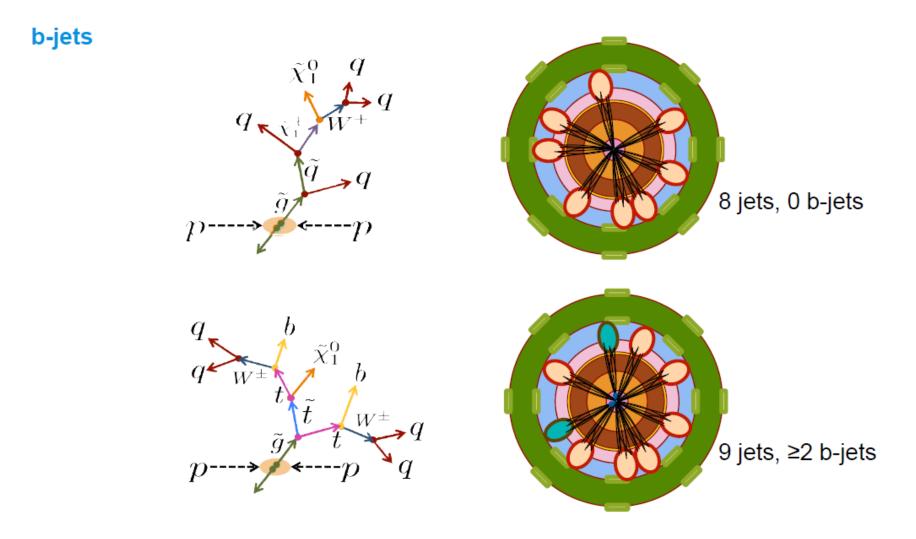
Another search example

SEARCH FOR SUSY IN EVENTS WITH LARGE JET MULTIPLICITIES



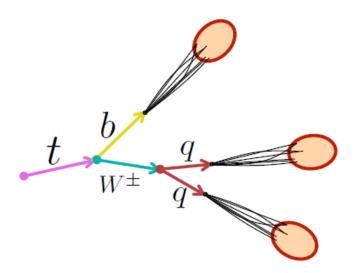
b-jets

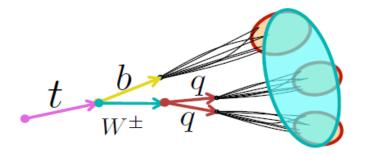




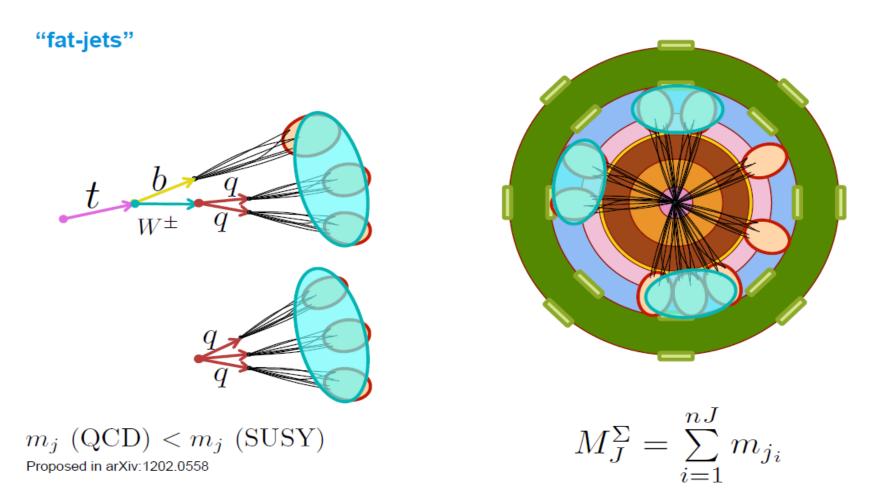
Signal regions can range in jet p_T and jet & b-jet multiplicity.







Fat-jets are a key signature in searches for boosted objects, e.g. boosted tops.



Signal regions can range in jet multiplicity and M_J^{Σ} cuts.

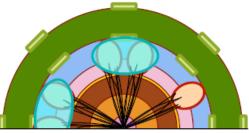
60

Example of search

"b-jet strea	ım"													
ID		8j5	0		9j5	0	≥10	j50		7j8	0		≥8j8	B O
Jet ŋ							< 2	2.0						
Jet p _T				50	Ge	٧					80 0	eV	,	
Jet count		=8	3		=9)	≥1	0		=7			≥8	3
b-jets	0	1	≥2	0	1	≥2	-		0	1	≥2	0	1	≥2
ME _T /√H _T			•	•	•	•	>40	GeV	1⁄2	•		•		•

"fat-jet stream" ------

ID	≥8	j50	≥9	j50	≥10	j50				
Jet ŋ	< 2.8									
Jet p _T	50 GeV									
Jet count	2	28	2	:9	≥10					
M_J^Σ (GeV)	>340	>420	>340	>420	>340	>420				
ME _T /√H _T	> 4 GeV ¹ / ₂									



Proposed in arXiv:1202.0558

$$M_J^{\Sigma} = \sum_{i=1}^{nJ} m_{j_i}$$

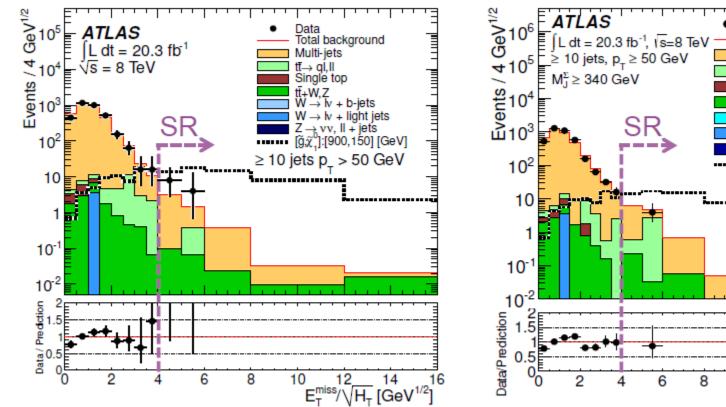
Results

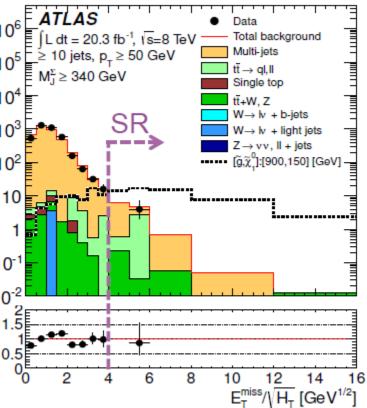
ID		8j50			210j50		
b-jets	0	1	≥2	0	1	≥2	0
Expected evts	35±4	40±10	50±10	3.3±0.7	6.1±1.7	8.0±2.7	7 1.37±0.3
Observed evts	40	44	44	5	8	7	3
Significance (σ)	0.7	-0.02	-0.6	0.8	0.6	-0.28	1.11
ID		7	j80			≥8j80	
b-jets	0		1	≥2	0	1	≥2
Expected evts	11.0±2	2.2 1	17±6	25±10	0.9±0.6	1.5±0.9	3.3±2.2
	12		17	13	2	1	3
Observed evts							

ID	≥8	3j50	≥9	50	≥10j50		
M_{J}^{Σ} (GeV)	340	420	340	420	340	420	
Expected evts	75±19	45±14	17±7	11±5	3.2±3.7	2.2±2.0	
Observed evts	<mark>6</mark> 9	37	13	9	1	1	
Significance (o)	-0.27	-0.6	-0.6	-0.34	-0.8	-0.6	

120

Results

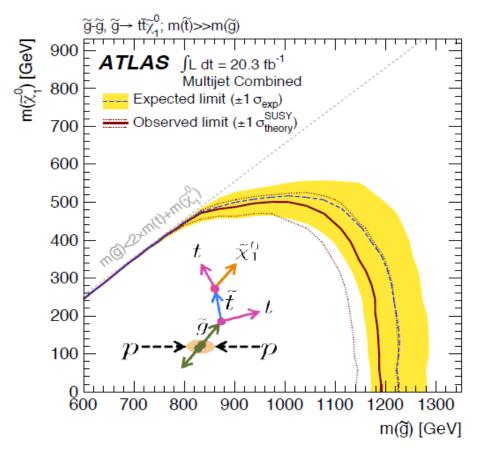




Interpretations

Real or Simplified models

Simplified topologies include typically one production and one decay process. Provide useful information for theorists.



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- Trigger
- Object definitions and event selections
- Background determination
- Systematic uncertainties
- Statistical methods
- Results
- Interpretations]

- Data-set and Monte Carlo samples
- Trigger
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- Statistical methol
- Results
- Interpretations]

The data and simulation samples used in the analysis. Data for the measurement / search, simulation to compare data to predictions.

Monte carlo sample specifics:

- Generator, tunes.
- Statistics.

- Data-set and Monte Carlo samples
- Trigger .
- Object defin
- Background det
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- Statistical methol
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- Interpretations]

The trigger used to collect the data with.

Trigger specifics:

- Prescales; typically unprescaled triggers are used, prescaled triggers for QCD / high stat measuments.
- Trigger (in)efficiencies.

- Data-set and Monte Carlo samples
- Trigger

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0

Stat

- Object definitions and event selections
 - The exact definition of objects (electrons, muon, jets, ...) and how these are combined in selecting events to be analyzed.

Object definition specifics:

"Flavor" of the identification (loose, medium, tight).
 Calibrations.

Event selection specifics:

- Inter Sevent cleaning (e.g. from noise and cosmics).
 - Momentum, geom. acceptance and multiplicity of objects.
 - Igher level cuts, such as invariant mass.
 - Signal regions".

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event
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- Systematic uncertainties
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Events that are imitating the signal we are searching for or measuring.

Background determination specifics:

- Can/must be data-driven or simulation-based.
- Walidation regions" and "control regions" required. These can use different triggers wrt signal regions.

- Data-set and Monte Carlo
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- Background determination
 A sector of the secto
- Systematic uncertainties
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- Any 'intermediate' measurement we have performed carries uncertainties (statistical and systematic).
- Systematic" uncertainties are introduced by inaccuracies in the methods used to perform the measurement.
- Efficiencies, acceptance, number of events, luminosity, cross sections used in Monte Carlo scaling...
- Some of them are "centrally" assessed by the performance groups of an experiment. Some of them are analysis-specific.

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Dealing with large data-sets, we use statistical methods to make sense of the numbers we measure.

Typical method:

Do a fit to extract signal from background.

Methodologies can vary a lot, but nowdays they are pretty unified within and across experiments.

Neural nets and other machine learning methods are broadly used, primarily to improve signal over background discrimination!

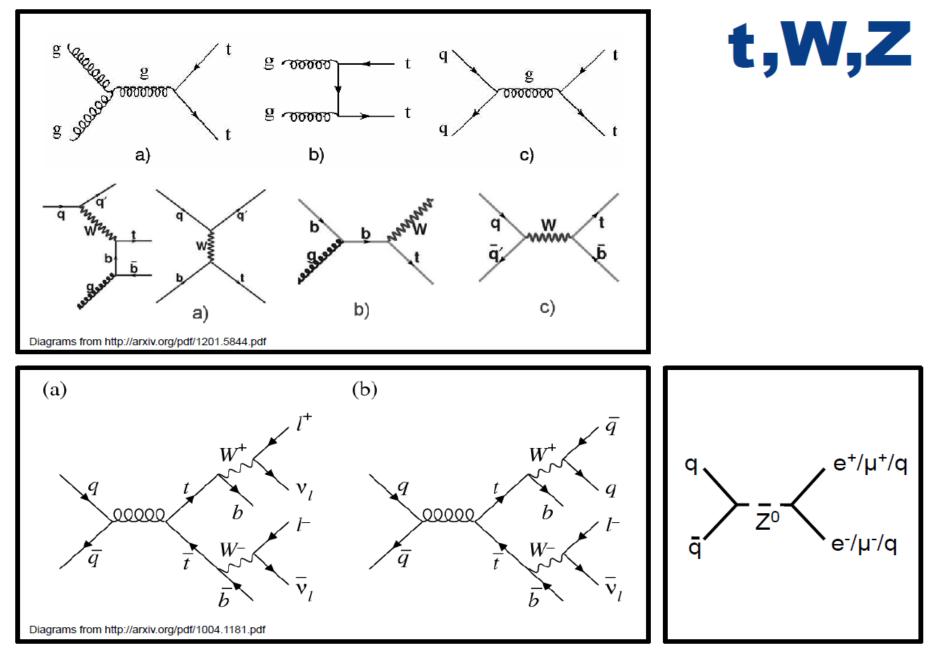
- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event selections
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- Systematic uncertainties
- Statistical methods
- Results •
- Interpretations]

Produce the results in tables and plots. These include details of what is found in the signal region.

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event selections
- Background determination
- Systematic uncertainties
- Statistical methods
- Results
- [Interpretations]

Put the results into context: interpret them in theoretical models.

SPARE SLIDES



Measuring particles

- Particles are characterized by
 - ✓ Mass [Unit: eV/c² or eV]
 - ✓ Charge [Unit: e]
 - ✓ Energy [Unit: eV]
 - ✓ Momentum [Unit: eV/c or eV]
 - ✓ (+ spin, lifetime, …)

Particle identification via measurement of:

e.g. (E, p, Q) or (p, β, Q) (p, m, Q) ...

• ... and move at relativistic speed

$$\begin{split} \beta &= \frac{v}{c} \quad \gamma = \frac{1}{\sqrt{1-\beta^2}} \\ \ell &= \frac{\ell_0}{\gamma} \quad \text{length contraption} \\ t &= t_0 \gamma \quad \text{time dilatation} \end{split}$$

$$E^{2} = \vec{p}^{2}c^{2} + m^{2}c^{4}$$
$$E = m\gamma c^{2} = mc^{2} + E_{\rm kin}$$
$$\vec{\beta} = \frac{\vec{p}c}{E} \qquad \vec{p} = m\gamma \vec{\beta}c$$

Relativistic kinematics in a nutschell

 $E^2 = \vec{p}^2 + m^2$ $\ell = \frac{\ell_0}{\ell}$ $E = m\gamma$ $\vec{p} = m\gamma\vec{\beta}$ $t = t_0 \gamma$ $\vec{\beta} = \frac{\vec{p}}{E}$

Relativistic kinematics in a nutschell

Center of mass energy

- In the center of mass frame the total momentum is 0
- In laboratory frame center of mass energy can be computed as:

$$E_{\rm cm} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p_i}\right)^2}$$

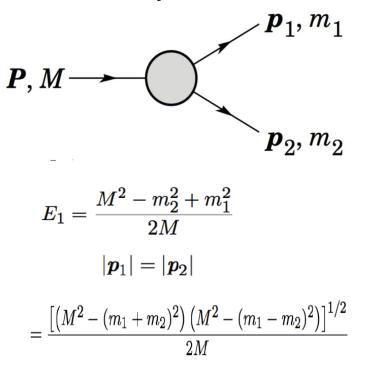
Hint: it can be computed as the "length" of the total four-momentum, that is invariant:

$$p = (E, \vec{p}) \qquad \sqrt{p \cdot p}$$

What is the "length" of a the four-momentum of a particle?

Kinematics

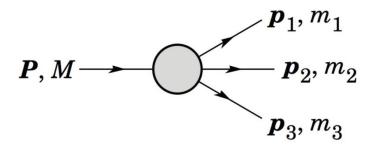
2-bodies decays



Invariant mass

$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p_i}\right)^2}$$

3-bodies decays

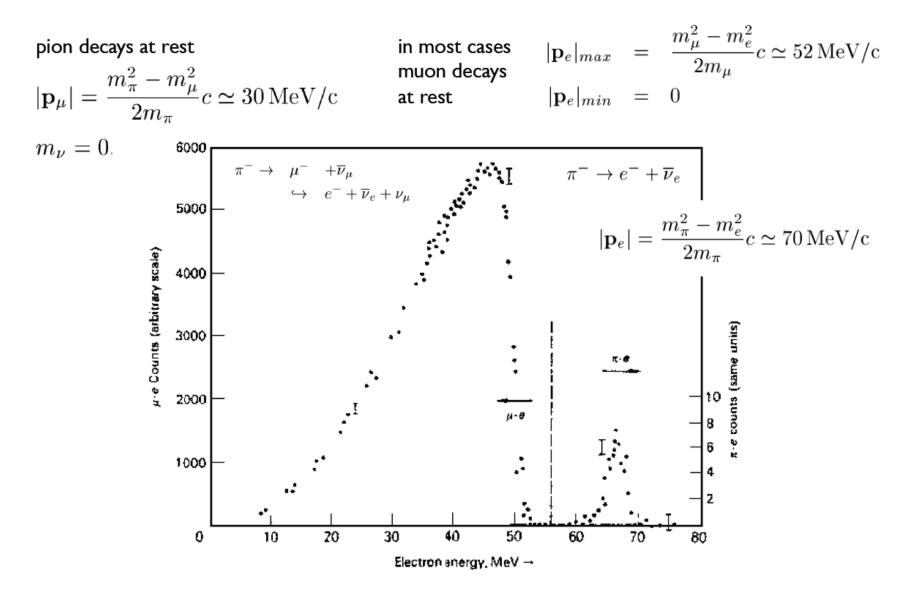


$$|\mathbf{p}_3| = \frac{\left[\left(M^2 - (m_{12} + m_3)^2 \right) \left(M^2 - (m_{12} - m_3)^2 \right) \right]^{1/2}}{2M}$$

 $\overrightarrow{p_3}$ $\overrightarrow{p_3}$ $\vec{p_3}$ $\overrightarrow{p_1}$ $\overrightarrow{p_2}$ $\overrightarrow{p_1}$ $\overrightarrow{p_2}$ $\overrightarrow{p_1}$ $\overrightarrow{p_2}$ (a)*(b)* (c) $\max(|\vec{p_3}|)$ $(m_{12})_{min} = m_1 + m_2$ $(m_{12})_{max} = M - m_3$ $\min(|\vec{p_3}|)$

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A real example: pion decays



HEP, SI and "natural" units

Quantity	HEP units	SI units
length	l fm	10 ⁻¹⁵ m
charge	e	1.602 · 10 ⁻¹⁹ C
energy	I GeV	I.602 x I0⁻¹º J
mass	I GeV/c ²	1.78 x 10 ⁻²⁷ kg
$\hbar = h/2$	6.588 x 10 ⁻²⁵ GeV s	1.055 x 10 ⁻³⁴ Js
с	2.988 x 10 ²³ fm/s	2.988 x 10 ⁸ m/s
ћс	197 MeV fm	•••
	"natural" units (ħ = c =	I)
mass	I GeV	
length	I GeV ⁻¹ = 0.1973 fm	
time	I GeV ⁻¹ = 6.59 x 10 ⁻²⁵ s	