FROM RAW DATA TO PHYSICS

LECTURE 2

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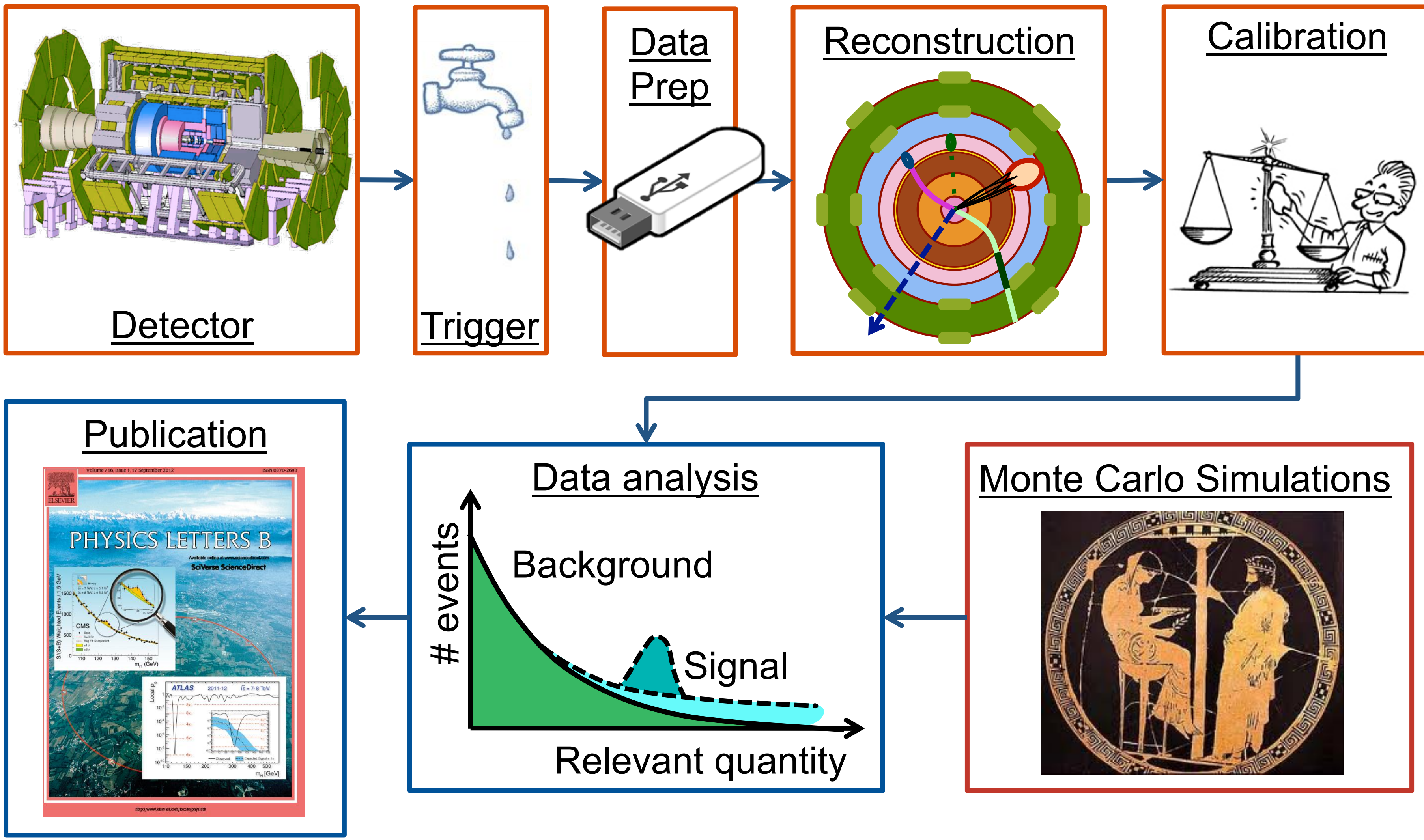
Detector
Trigger
Data Prep
Reconstruction
Calibration
Publication
PHYSICS LETTERS B
Data analysis
events
Background
Signal
Relevant quantity
Monte Carlo Simulations

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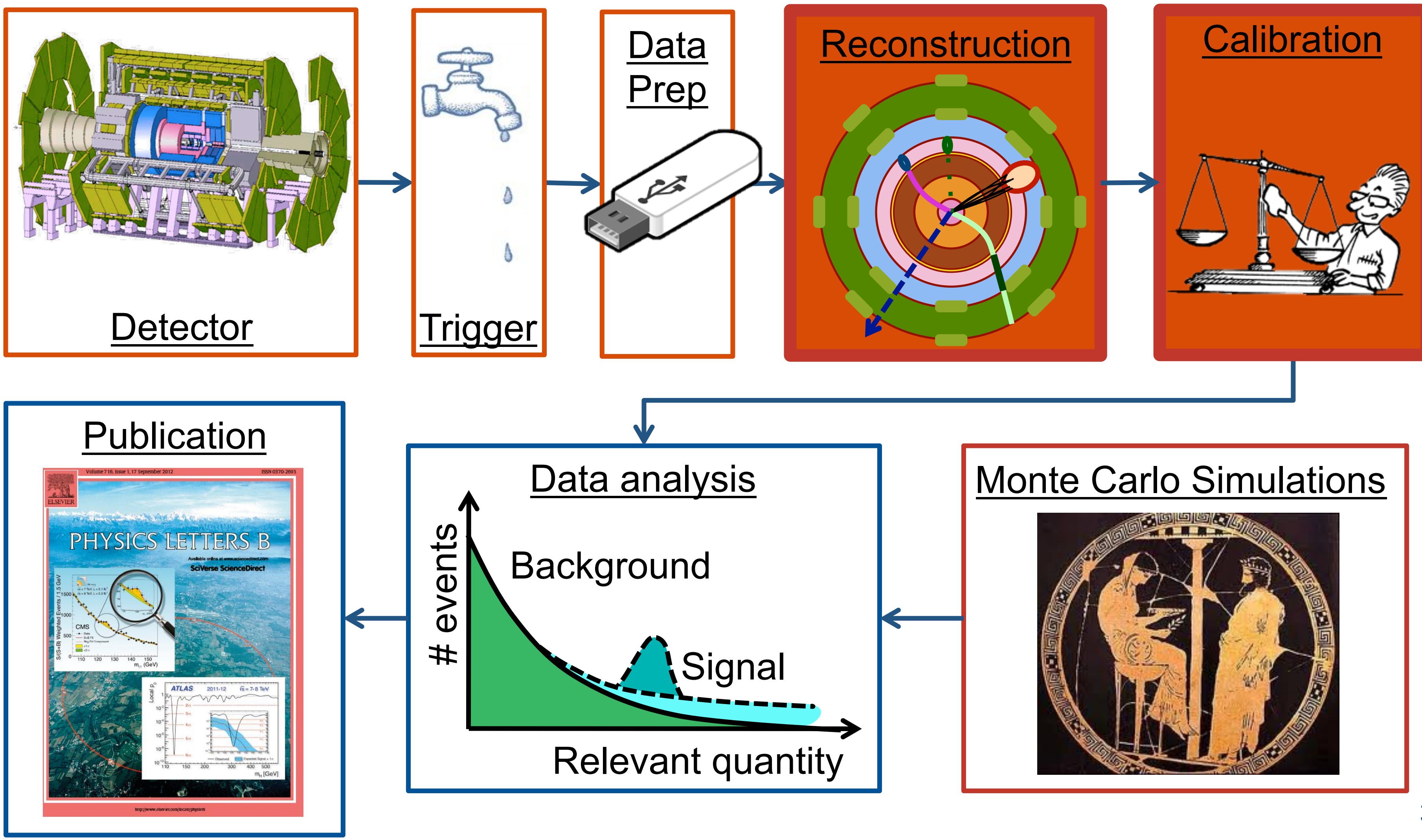
Detector
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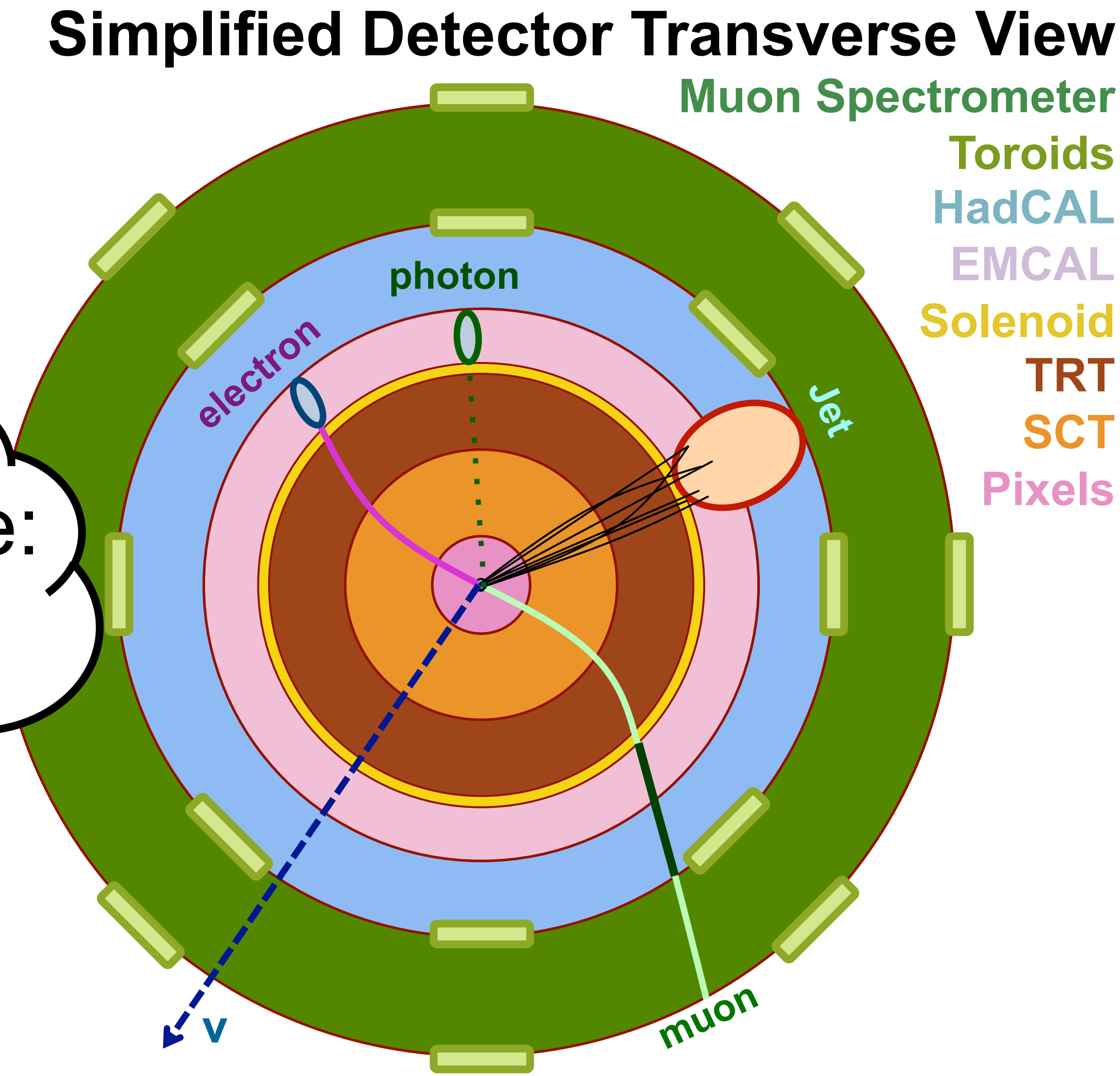
WHAT DO WE RECONSTRUCT

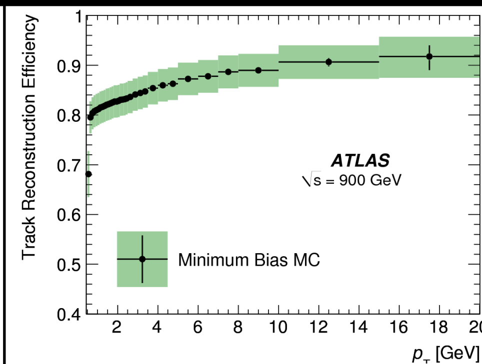
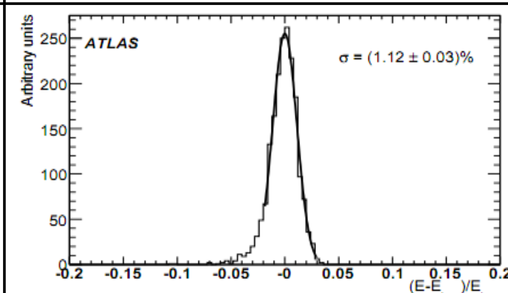
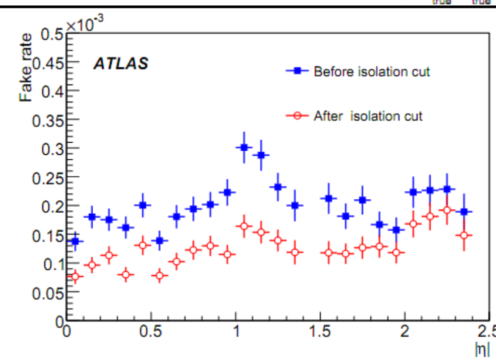
Tracks and Clusters

Combining those: "objects" ("particles")



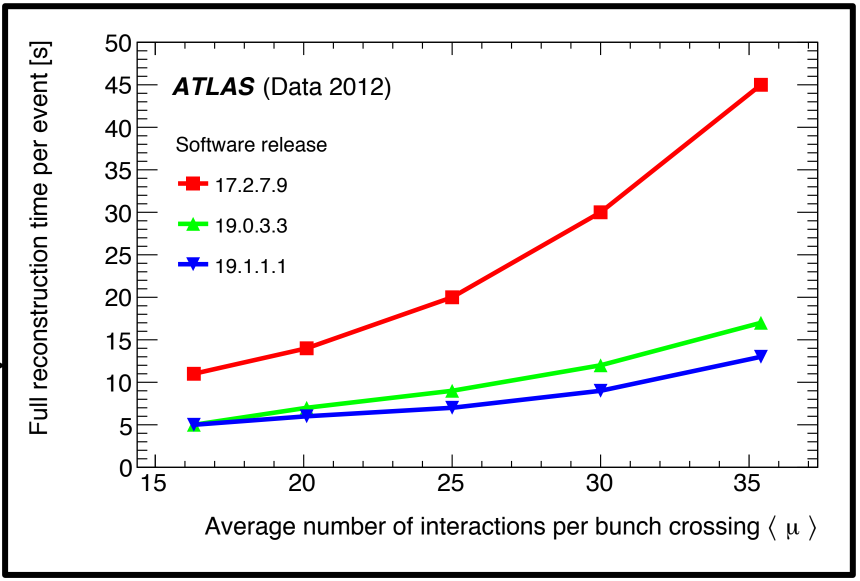
RECONSTRUCTION – FIGURES OF MERIT

“**true**” quantity: quantity at MC generator level.

	Definition	Example		Needs be:
Efficiency	how often do we reconstruct the object	tracking efficiency = (number of reconstructed tracks) / (number of true tracks)		High
Resolution	how accurately do we reconstruct the quantity	energy resolution = (measured energy – true energy) / (true energy)		Good
Fake rate	how often we reconstruct a different object as the object we are interested in	a jet faking an electron, fake rate = (Number of jets reconstructed as an electron) / (Number of jets)		Low

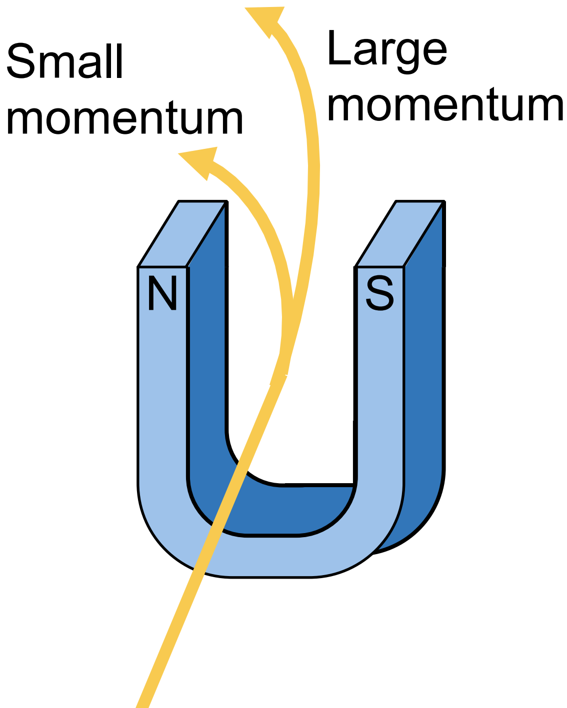
RECONSTRUCTION – GOALS

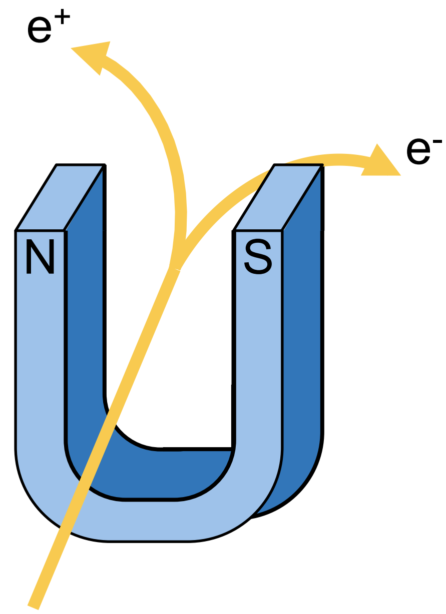
- **High efficiency.**
- **Good resolution.**
- **Low fake rate.**
- **Robust against detector problems and data-taking conditions.**
  - Noise.
  - Dead regions of the detector.
  - Increased pile-up.
- **Computing-friendly.**
  - CPU time per event.
  - Memory use.



WHY DO WE NEED THE MAGNETIC FIELD?

Reminder!

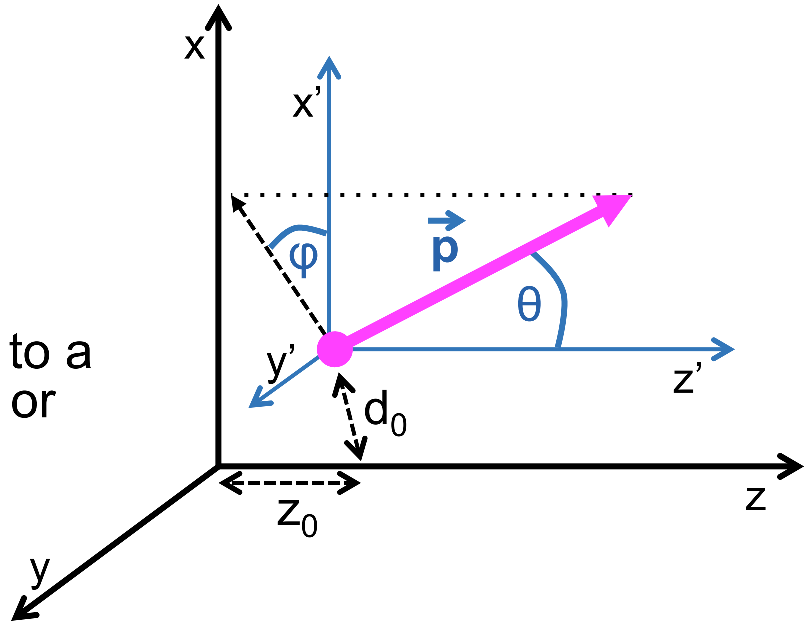




TRACKING IN A NUTSHELL

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

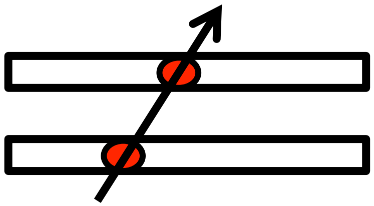
- **For a track we measure:**
  - Its momentum;
  - It's direction;
  - Its charge;
  - Its "perigee": the closest point to a reference line, transverse (d_0) or longitudinal (z_0).



- **Tracks are key ingredients of most of particle reconstruction.**

TRACKING IN A NUTSHELL – TRACK FITTING

- **Perfect measurement – ideal**



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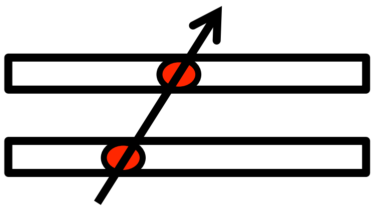
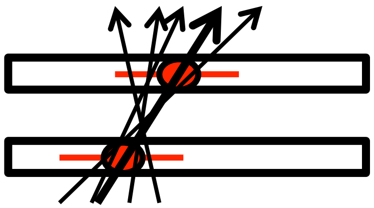


- **Imperfect measurement – reality**



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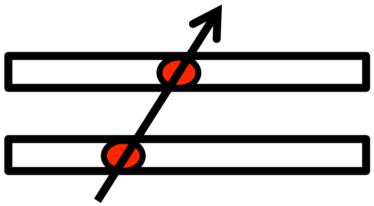

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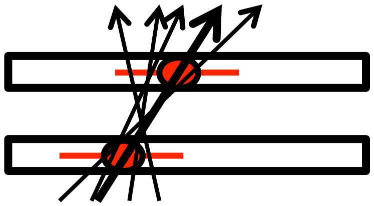
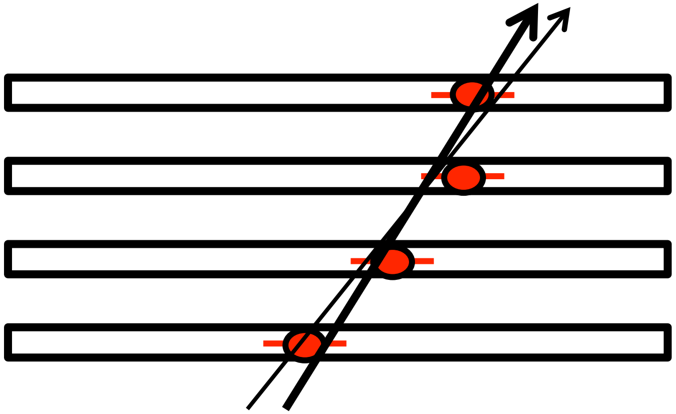


- Small errors and more points help to constrain the possibilities



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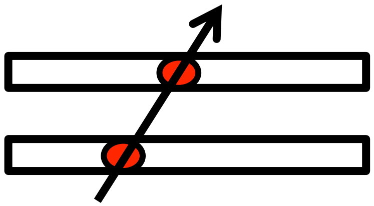

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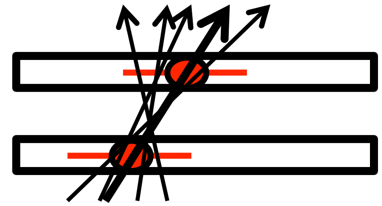

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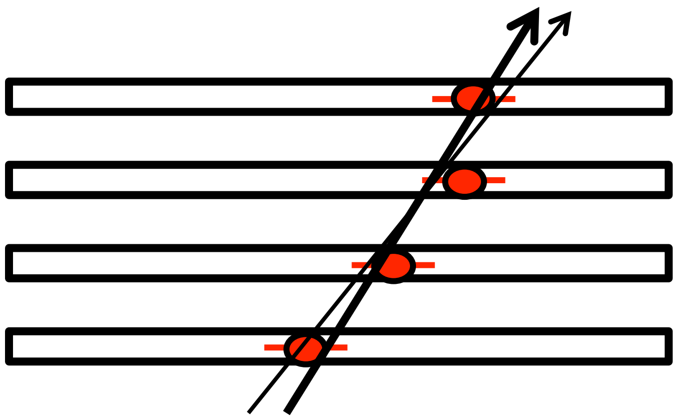

- **Quantitatively:**
  - Parameterize the track;
  - Find parameters by Least-Squares-Minimization;
  - Obtain also uncertainties on the track parameters.

TRACKING IN A NUTSHELL – TRACK FITTING

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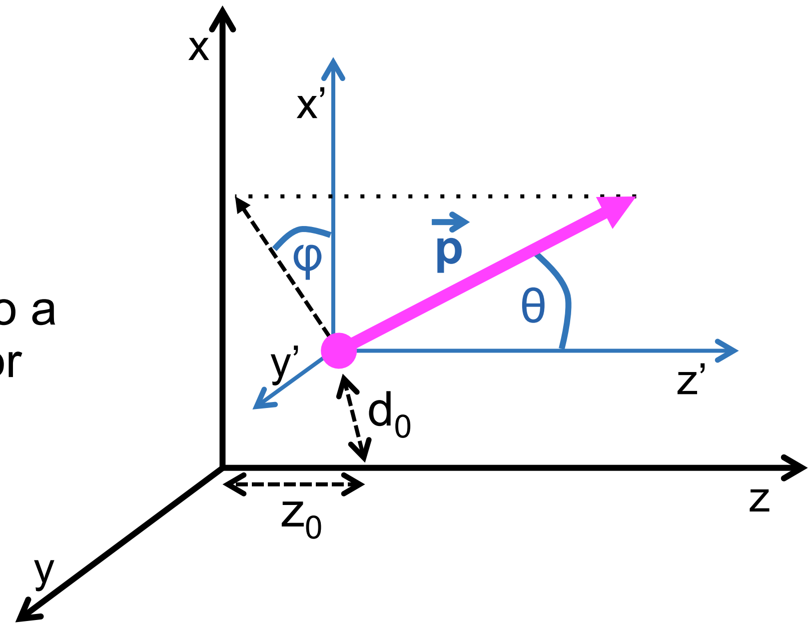

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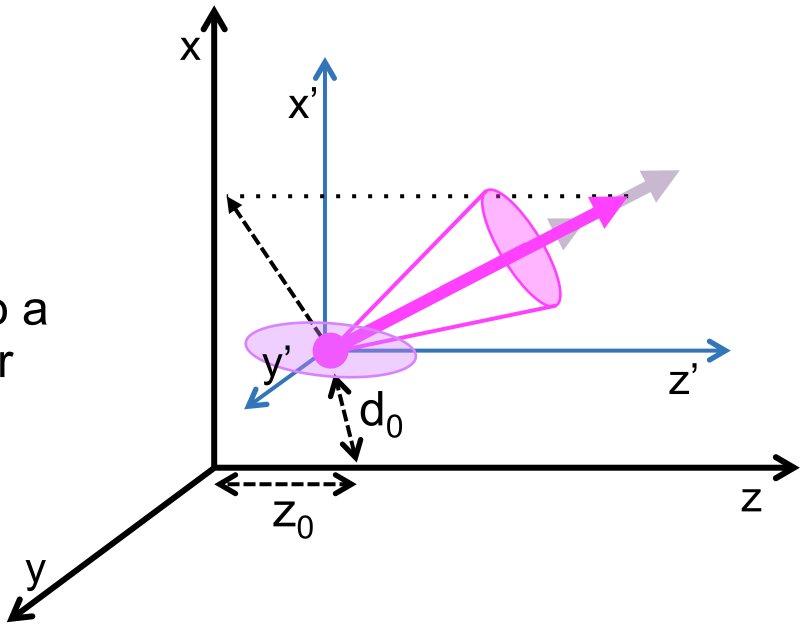
  - And their uncertainties!



- **Small uncertainties are required.**
  - δd0 is O(10μm) and δθ O(0.1mrad).
  - Allows separation of tracks that come form different particle decays (which can be separated at the order of mm).

TRACKING – THE UNCERTAINTIES

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

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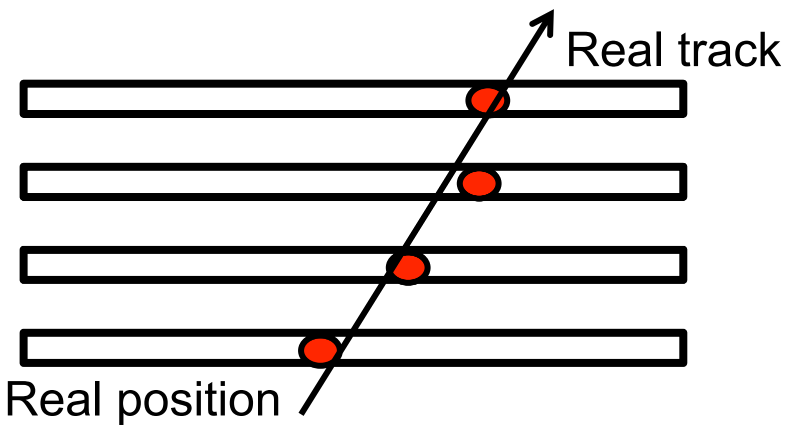

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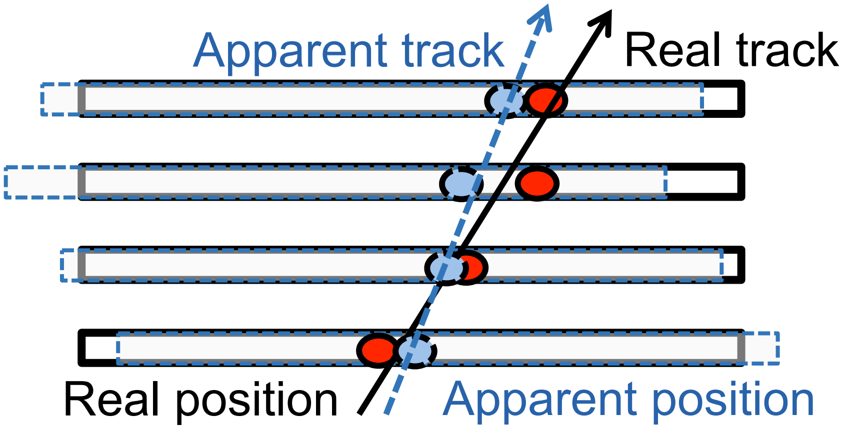
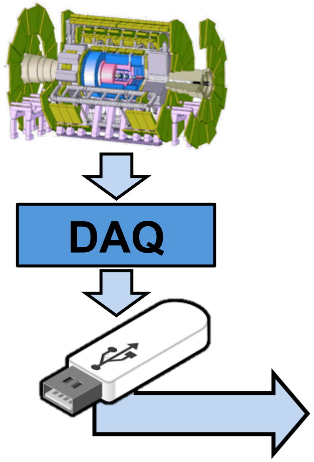
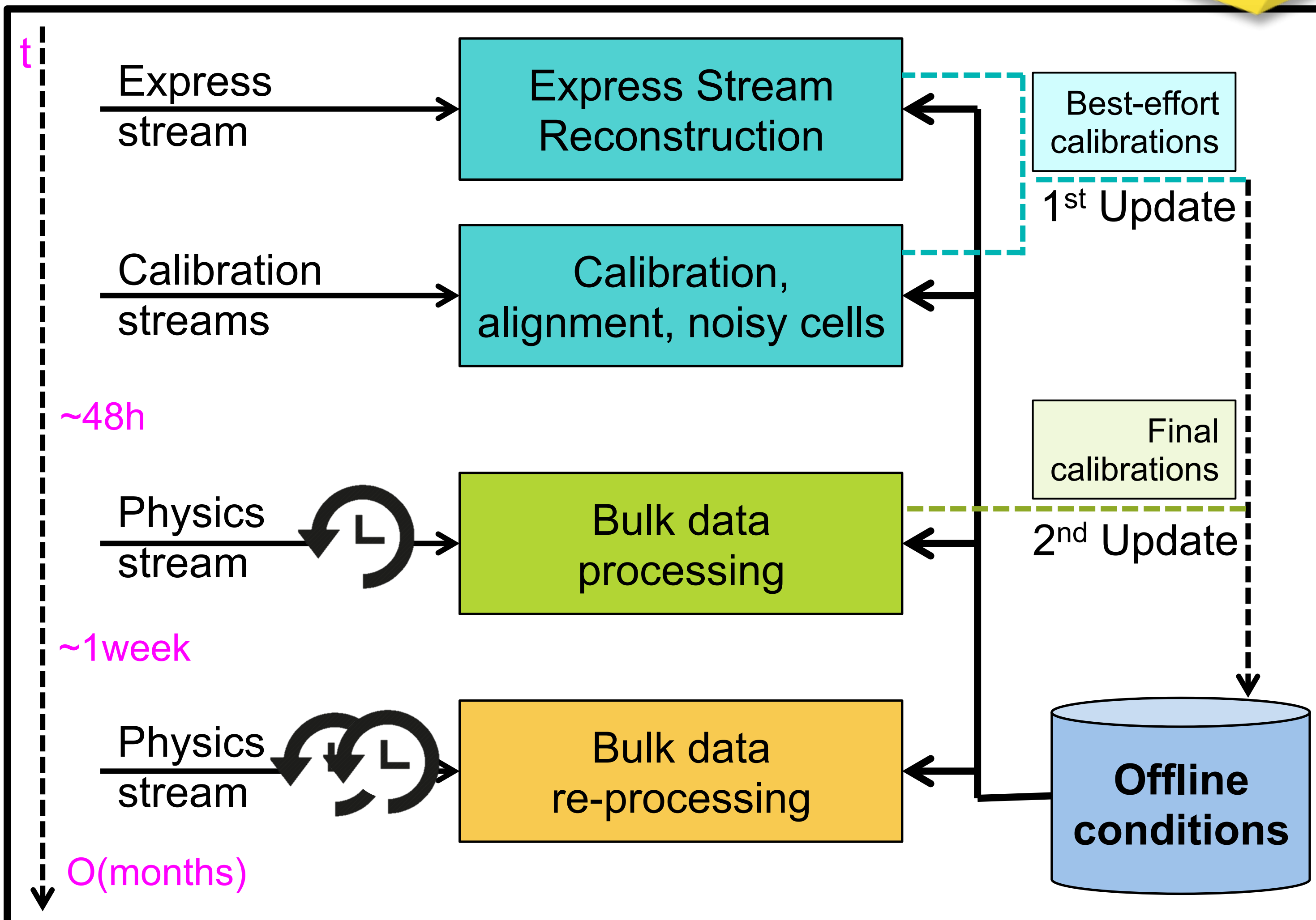




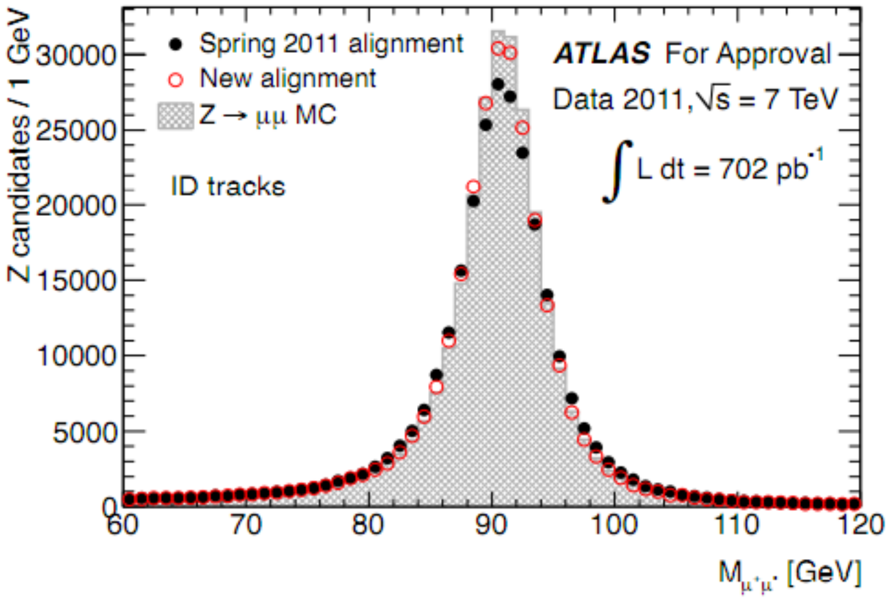
THE EVENT AT TIER0

Reminder!



IMPACT OF GOOD ALIGNMENT

- Improving the tracker alignment description in the reconstruction gives better track momentum resolution which leads to better mass resolution.



- Can see the reconstructed Z width gets narrower if we use better alignment constants. Very important for physics analysis to have good alignment.
- Alignment of detector elements can change with time, for example when the detector is opened for repair, or when the magnetic field is turned on and off.

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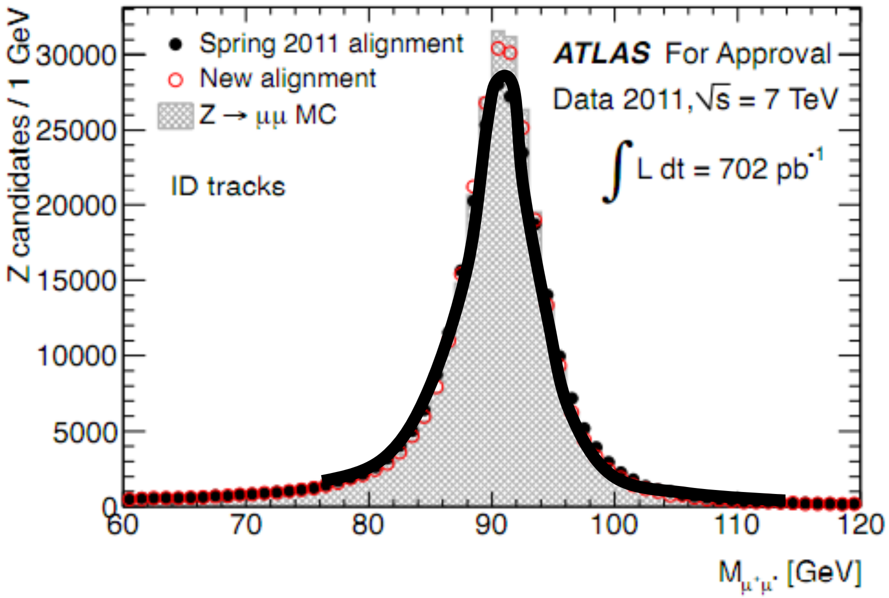

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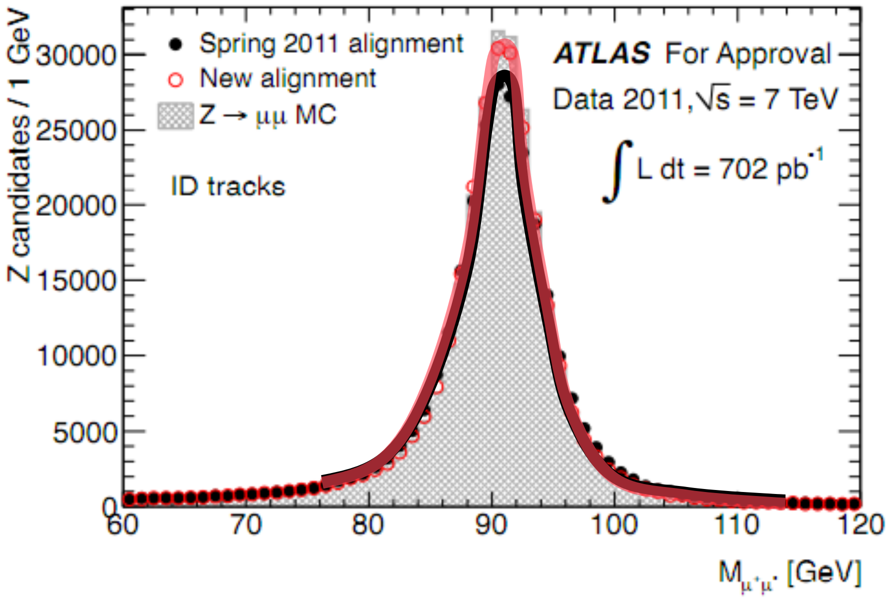

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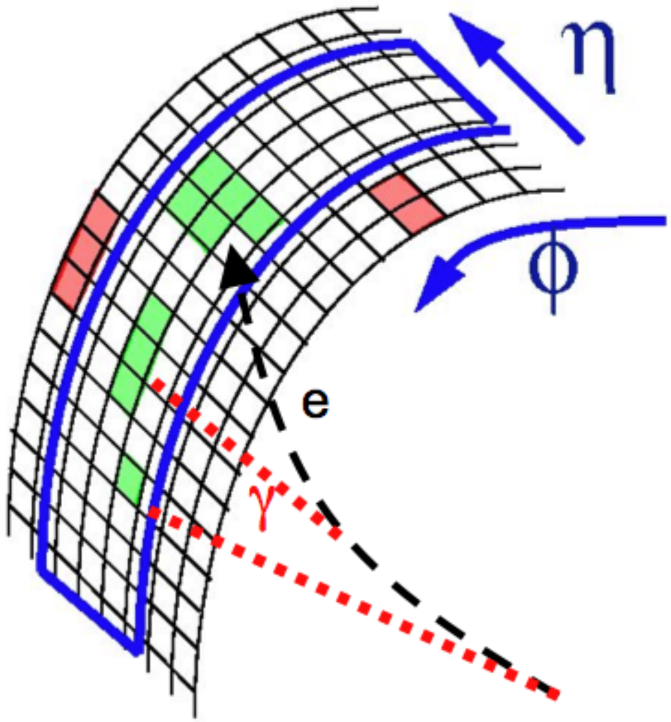
CLUSTERING IN A NUTSHELL

- **Reconstruct energy deposited in the calorimeter by charged or neutral particles; electrons, photons and jets.**
- **For a cluster we measure:**
  - The energy;
  - The position of the deposit;
  - The direction of the incident particles;
- **Calorimeters are segmented in cells.**
  - Typically a shower created by a particle interacting with the matter extends over several 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.

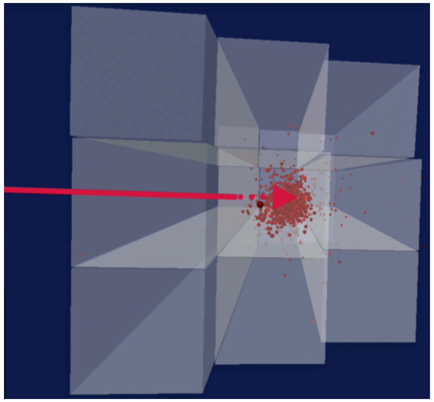
CLUSTER FINDING – AN EXAMPLE

CMS crystal calorimeter – ECAL clusters

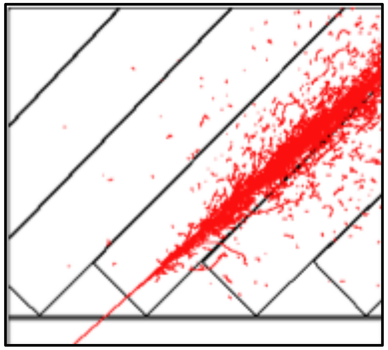
◎ electron energy in central crystal ~80%, in 5x5 matrix around it ~96%.



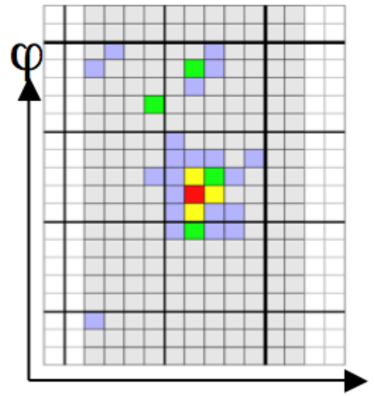
Front view



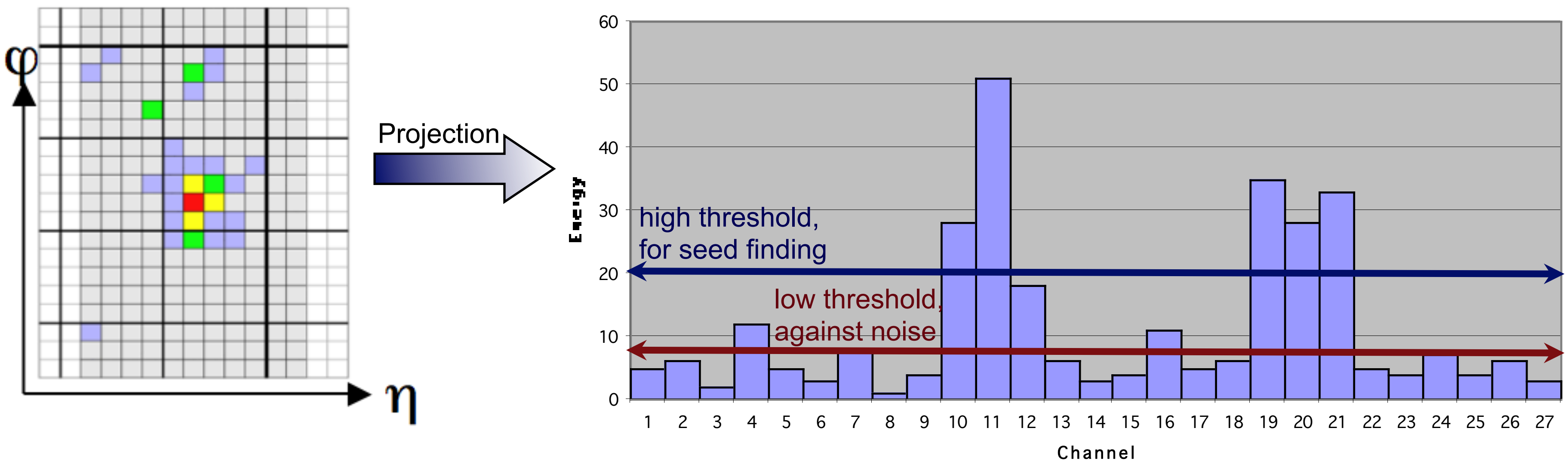
Side view



η-φ view



CLUSTER FINDING



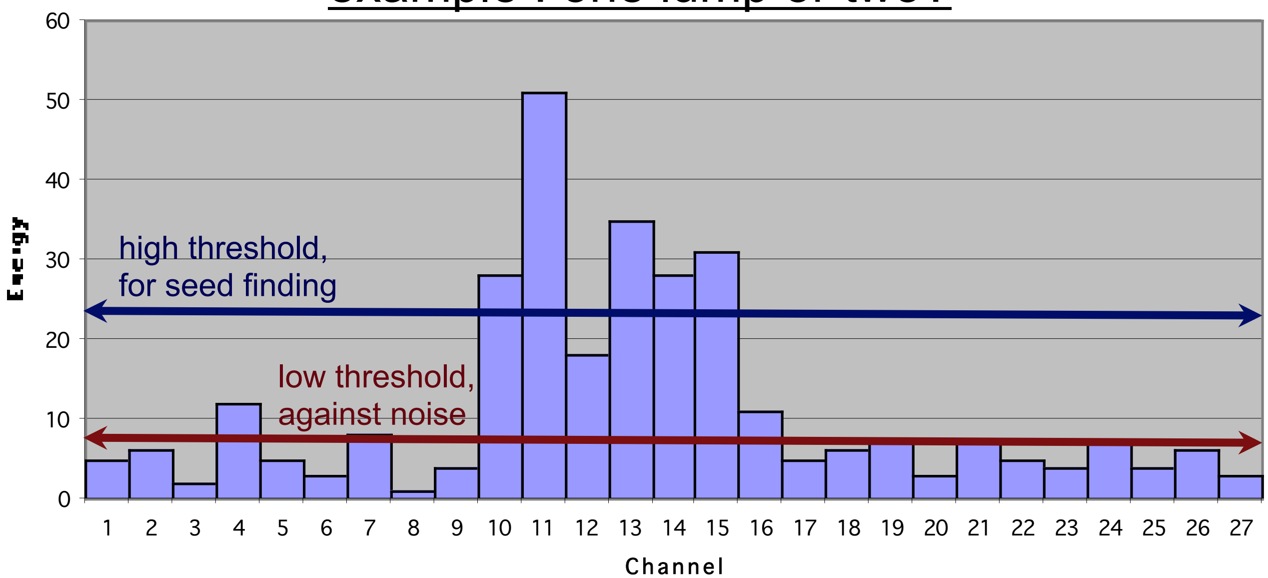
Simple example of an algorithm

- 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

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.

<u>example : one lump or two?</u>

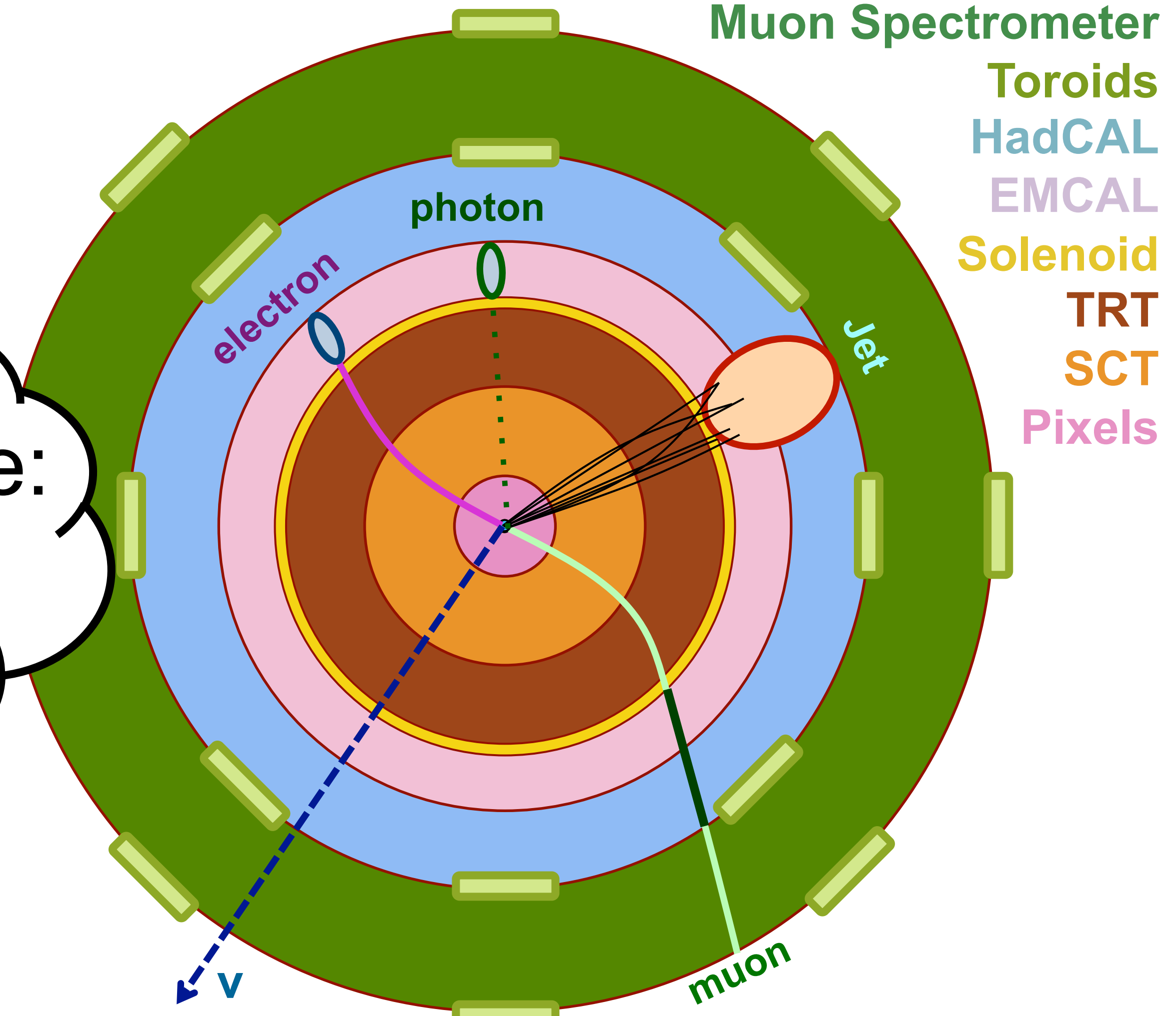


WHAT DO WE RECONSTRUCT

Tracks and Clusters

Combining those: "objects" ("particles")

Simplified Detector Transverse View



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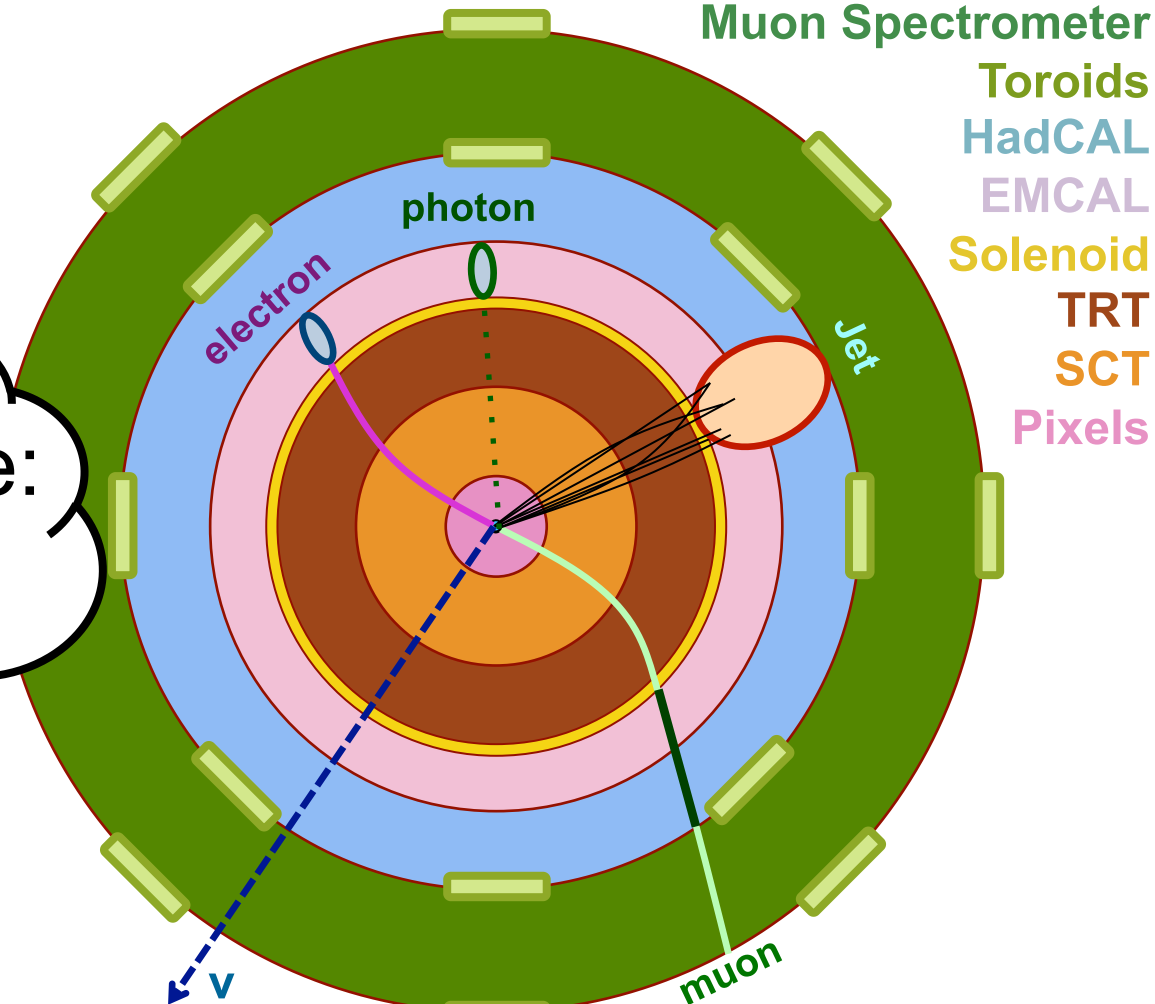

ELECTRONS / PHOTONS

- **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.

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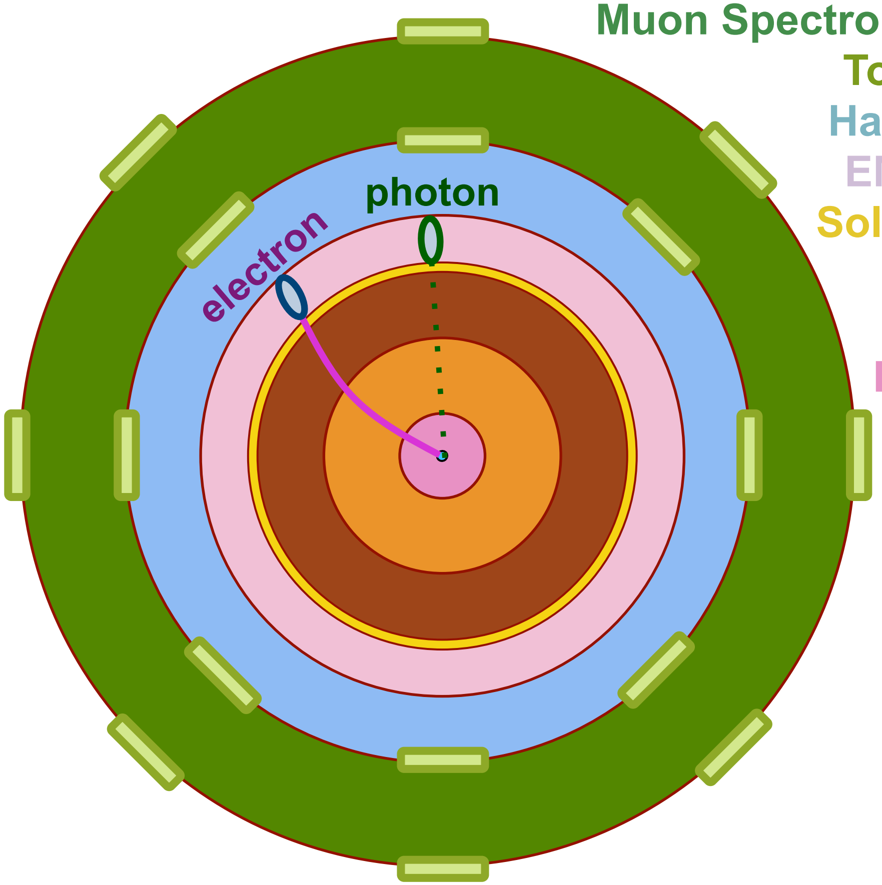

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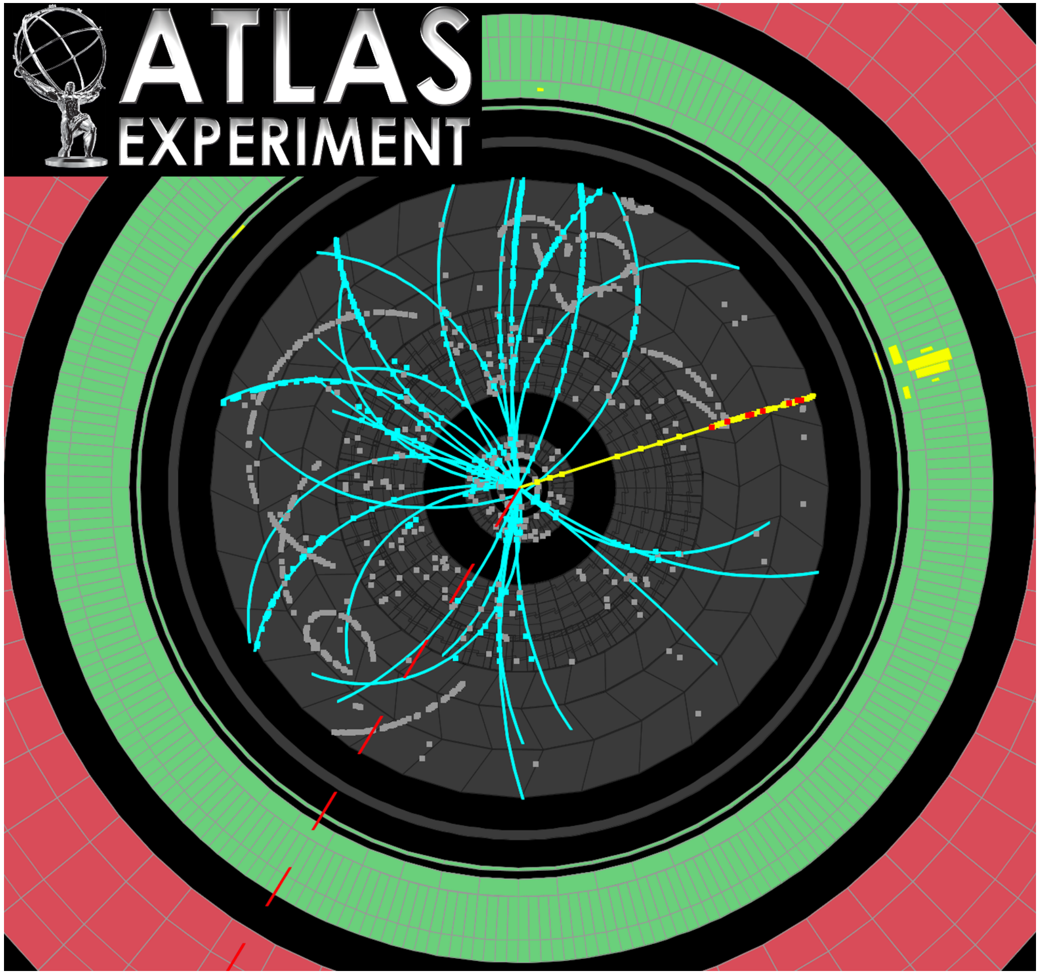
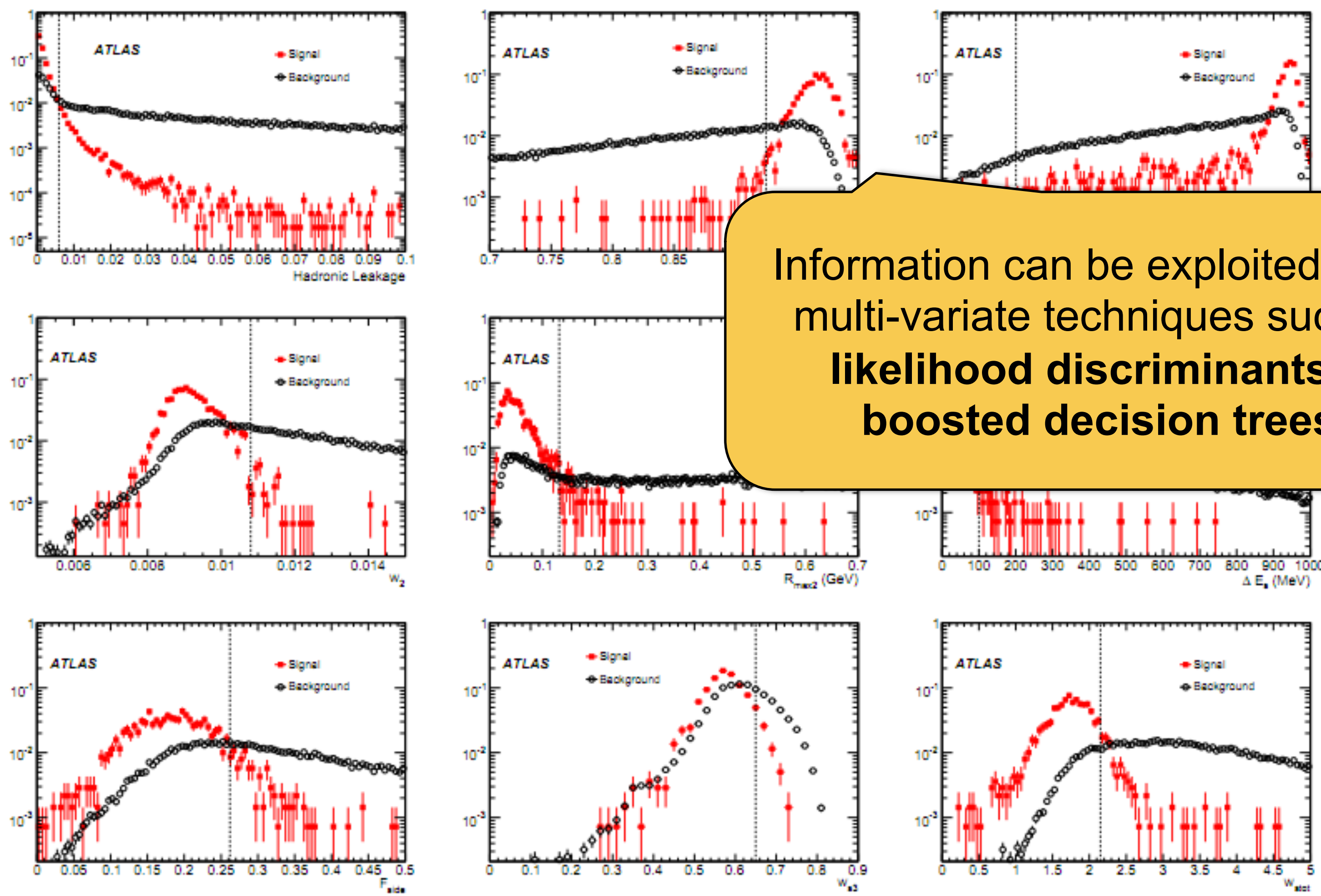


ELECTRONS / PHOTONS (BGRS)

- Hadronic jets leave energy in the calorimeter which can fake electrons or photons.
- Usually a Jet produces energy in the hadronic calorimeter as well as the electromagnetic calorimeter.
- Usually the calorimeter cluster is much wider for jets than for electrons/photons.
- So it should be “easy” to separate electrons from jets.
- However have many thousands more jets than electrons, so need the rate of jets faking an electron to be very small $\sim 10^{-4.}$
- Need complex identification algorithms to give the rejection whilst keeping a high efficiency.

ELECTRONS / PHOTONS (BGRS)

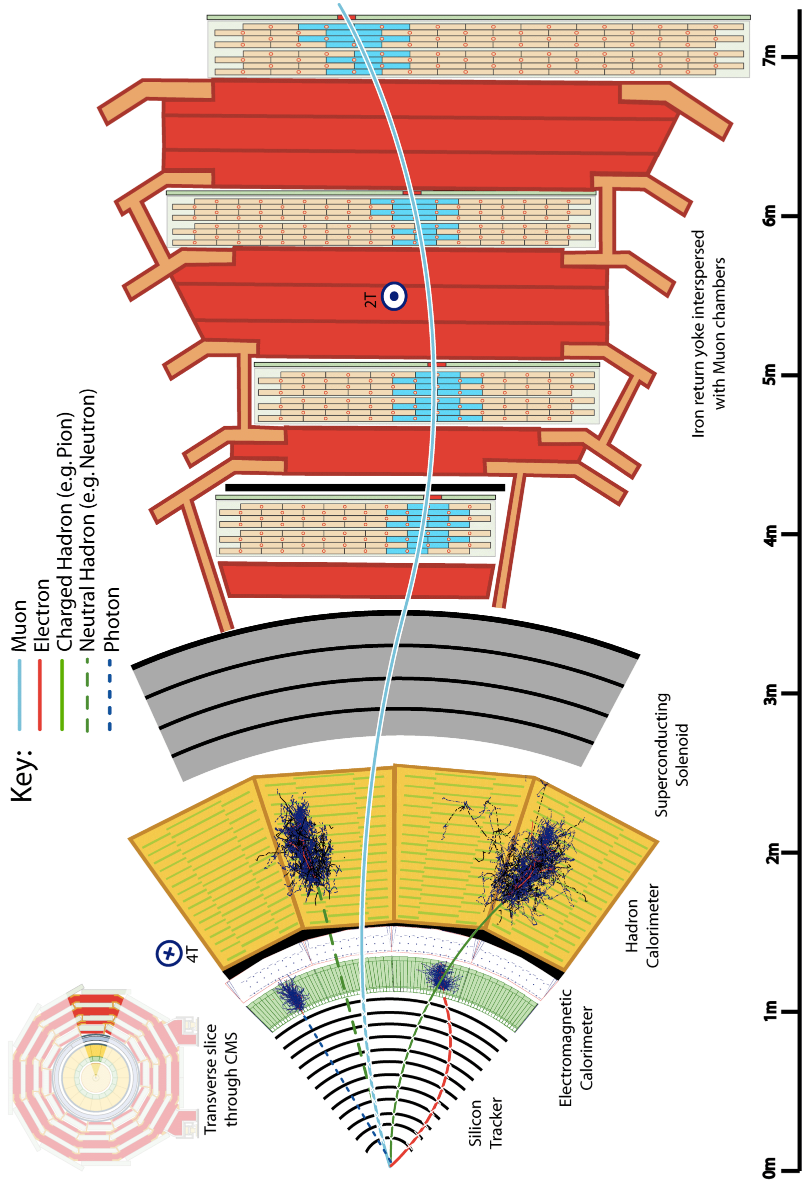


Information can be exploited using multi-variate techniques such as **likelihood discriminants** or **boosted decision trees**.

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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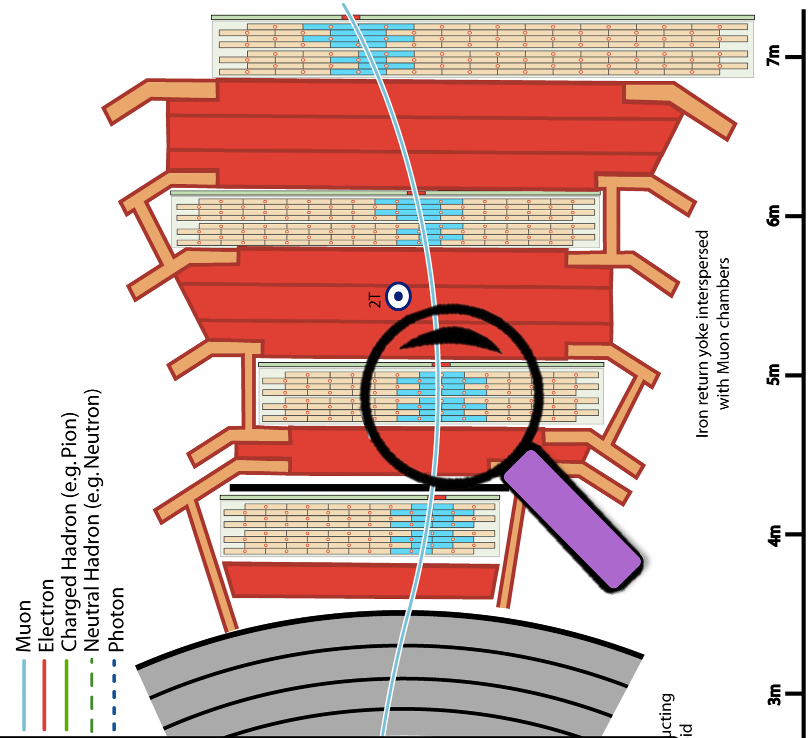
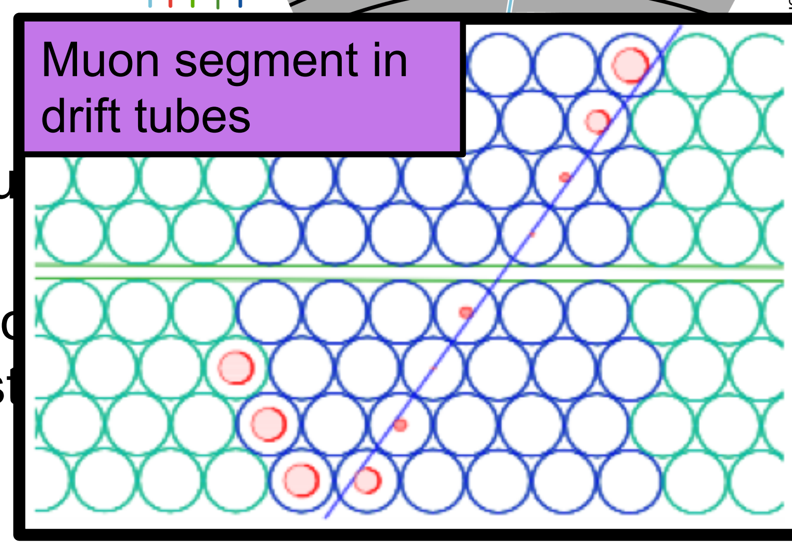
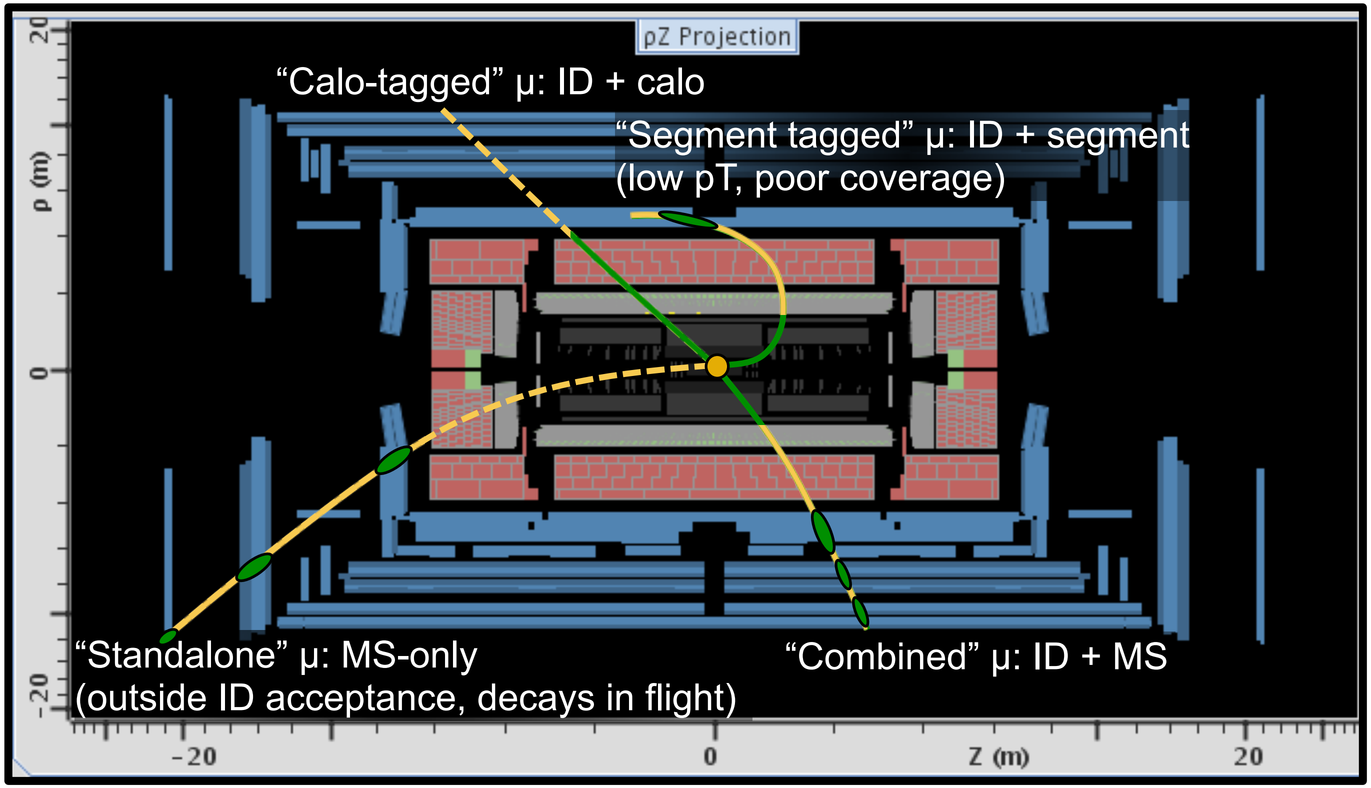




MUONS ON ATLAS



Simplified Detector Transverse View

"MS" { **Muon Spectrometer**

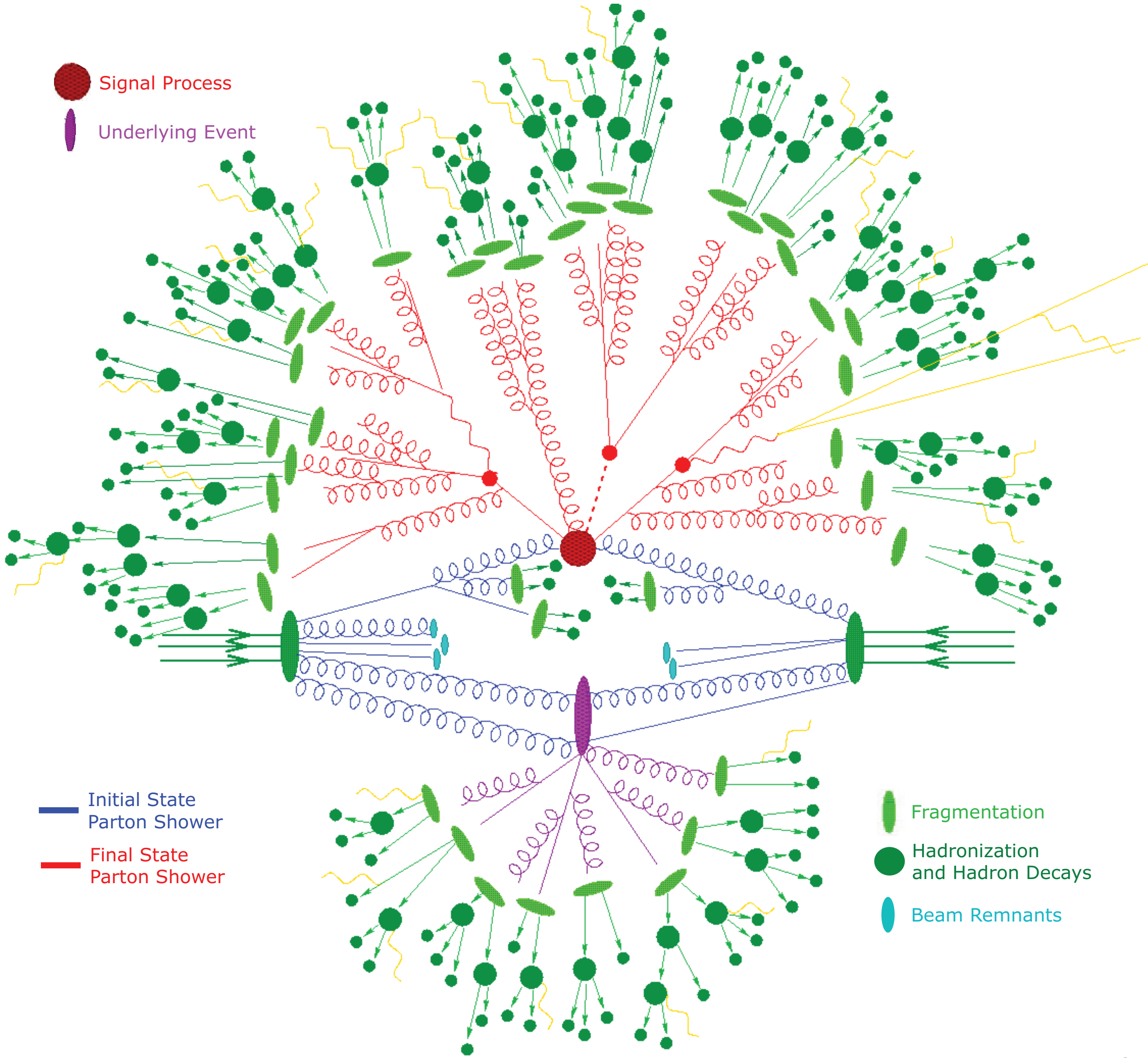
Toroids

"Calo" { **HadCAL**, **EMCAL**

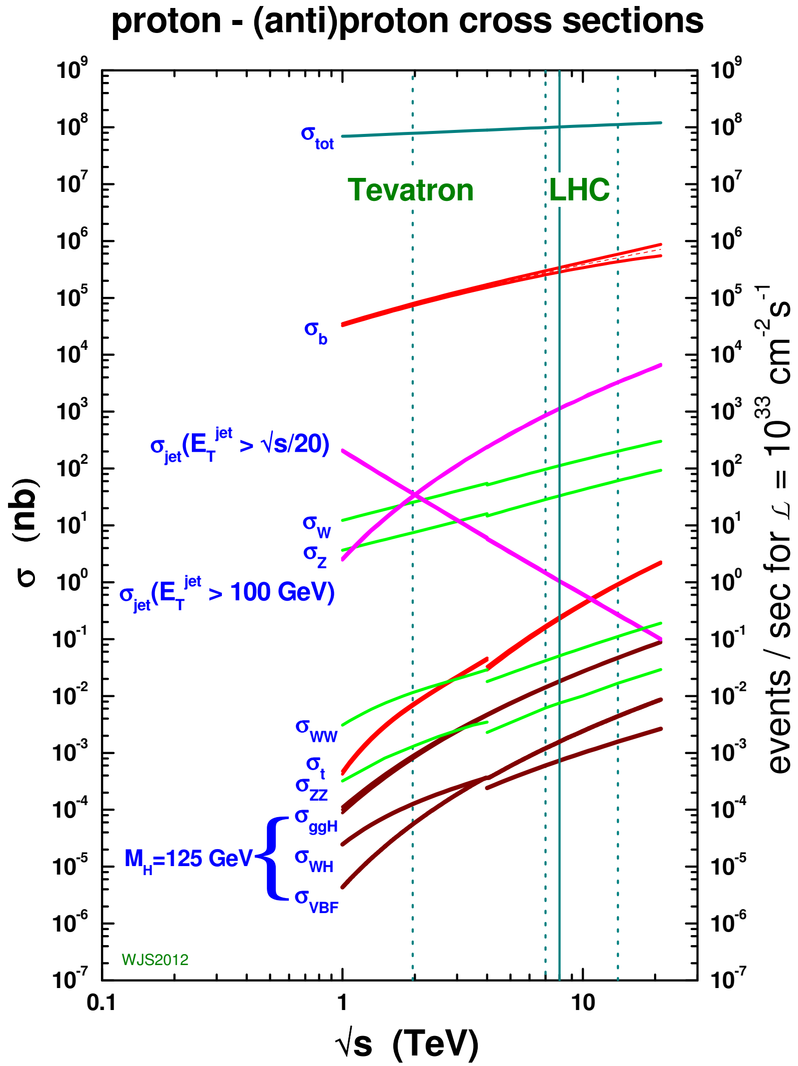
Solenoid

"ID" { **TRT**, **SCT**, **Pixels**

JETS


Signal Process
Underlying Event
Initial State
Parton Shower
Final State
Parton Shower
Fragmentation
Hadronization
and Hadron Decays
Beam Remnants

STANDARD MODEL PROCESSES

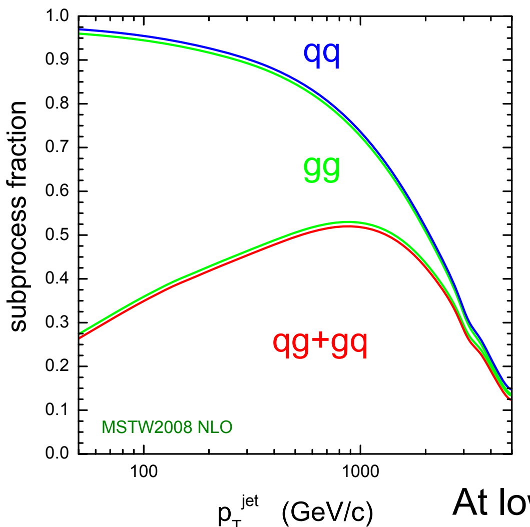


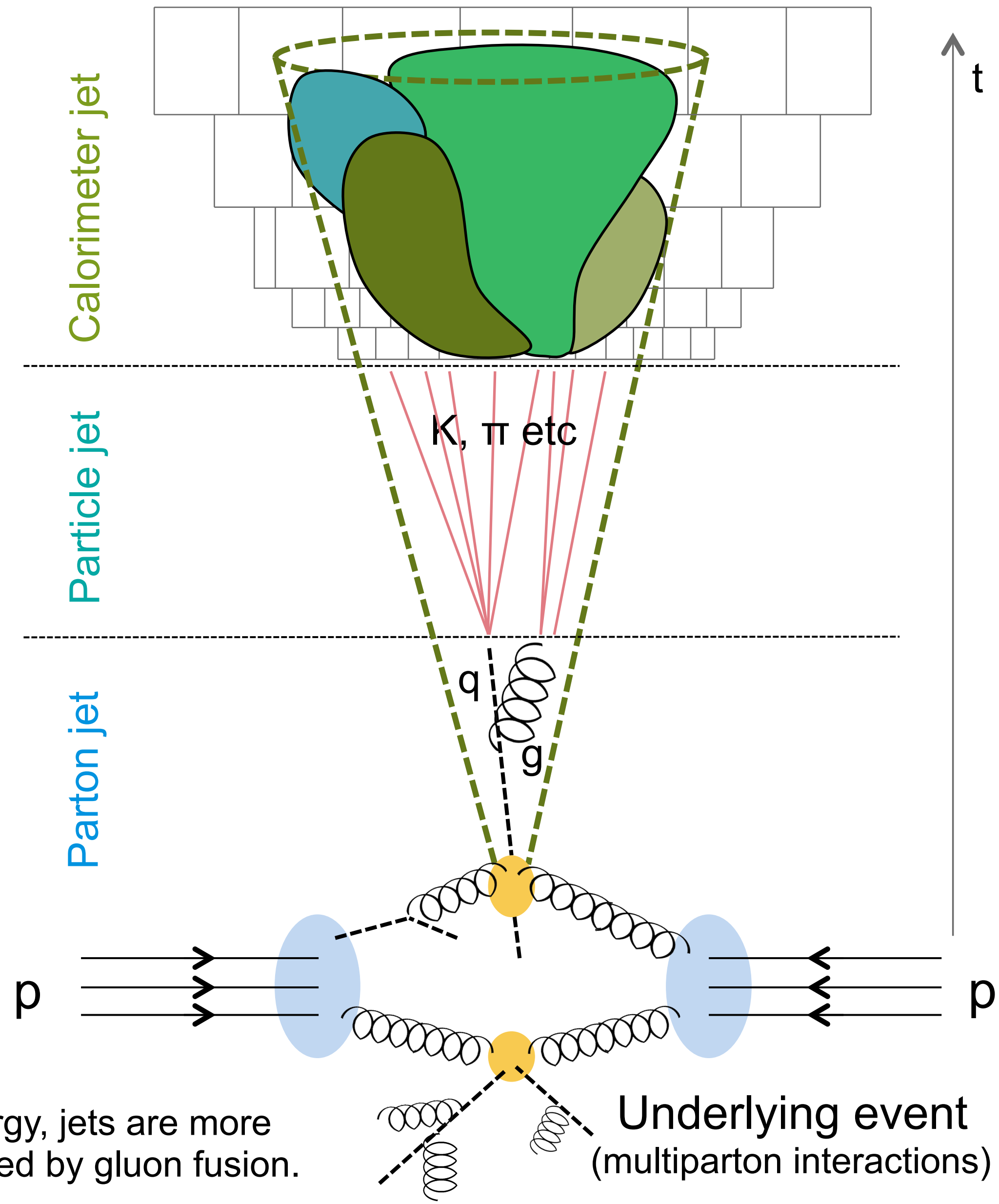
Jets are produced:

- by fragmentation of gluons and (light) quarks in QCD scattering.
- by decays of heavy 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

inclusive jet production at LHC ($\eta^{jet} = 0$)

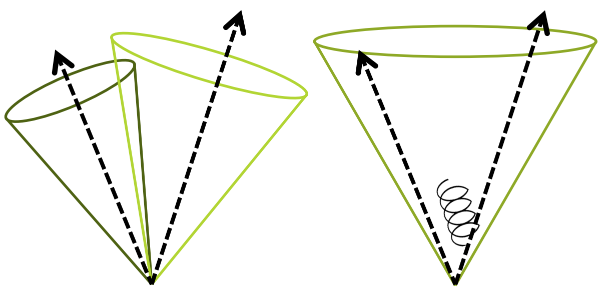




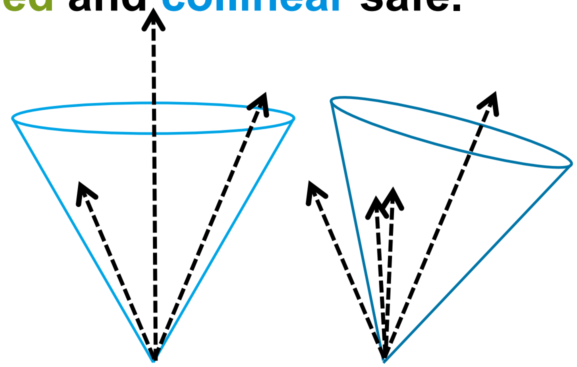
At low energy, jets are more likely produced by gluon fusion.

JET ALGORITHMS

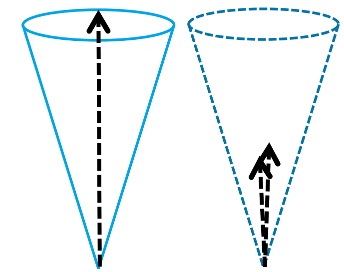
<u>Theoretical requirements</u>: infrared and collinear safe.



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

<u>Experimental requirements</u>: detector technology & environment independent, easily implementable.

Insignificant effects of detector
- Noise
- Dead material
- Cracks

Stability with
- Luminosity
- Pile-up
- Physics process

Fully specified
Fast

<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).

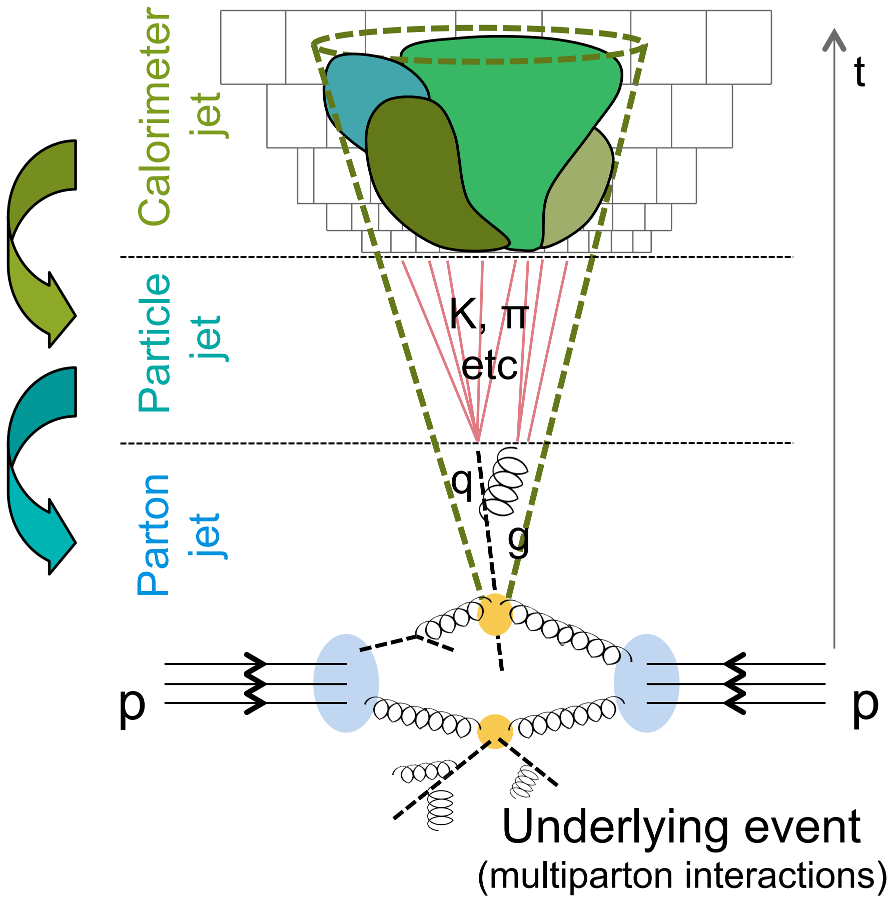
JET CALIBRATION

Correct the energy and position measurement and the resolution.

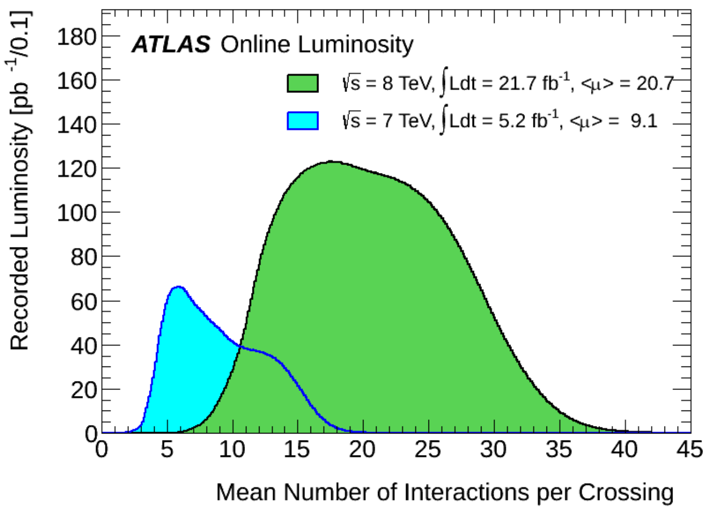
Account for:

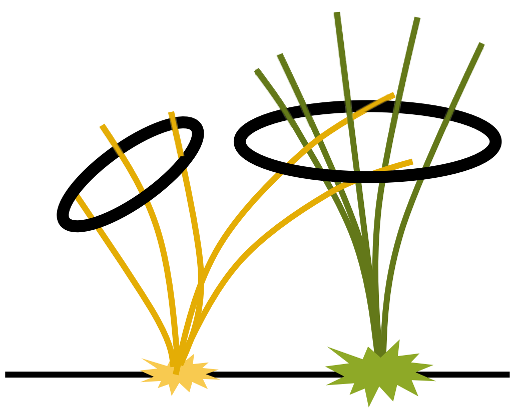
<u>Instrumental effects</u>
Detector inefficiencies
'Pile-up'
Electronic noise
Clustering, noise suppression
Dead material losses
Detector response
Algorithm efficiency

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

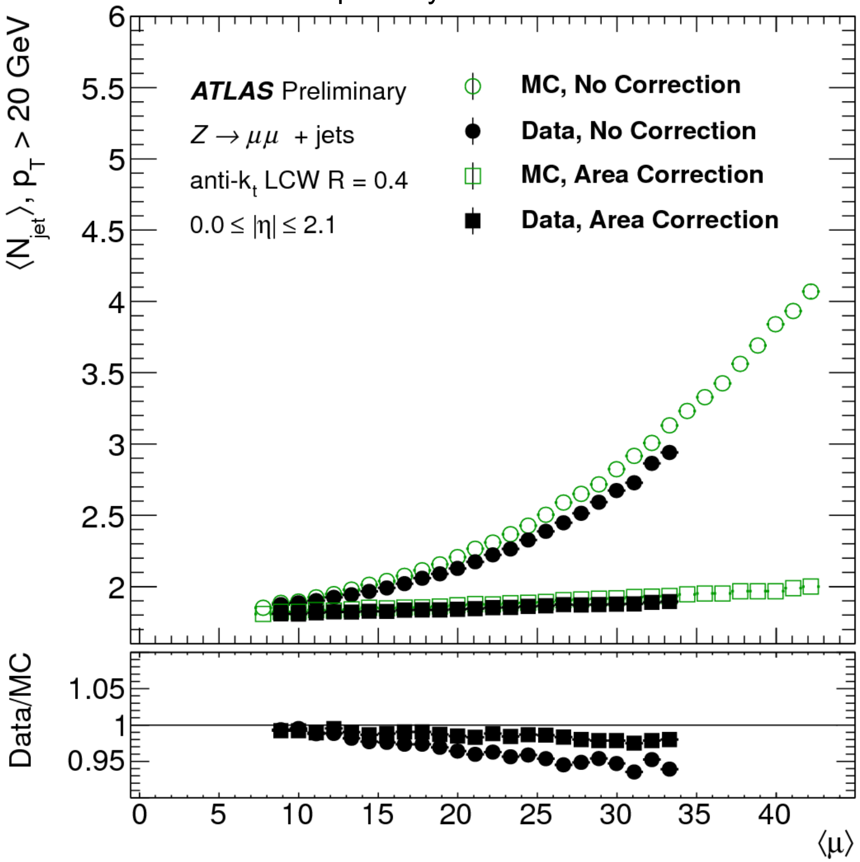


JETS & PILE-UP





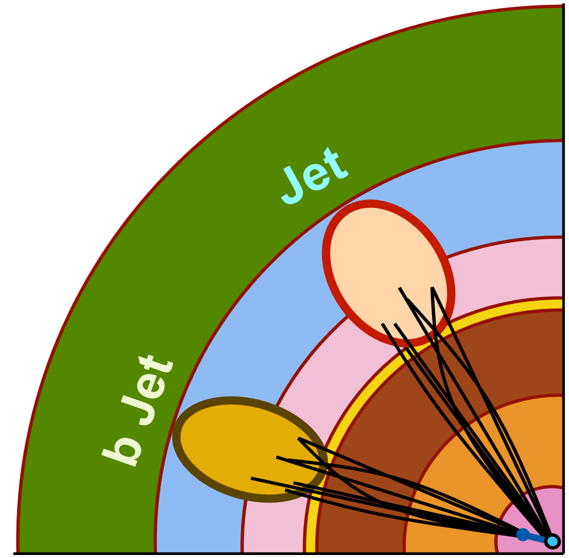
Multiple interactions from pile-up

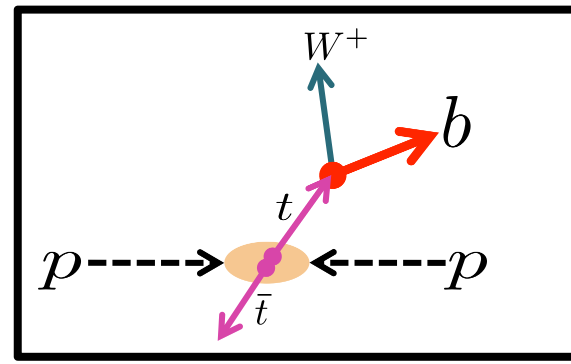


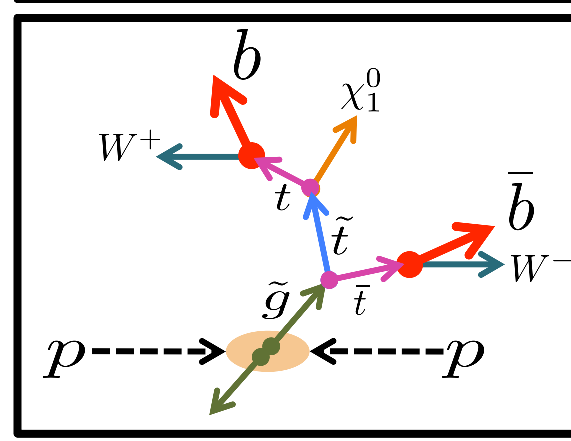
BJETS

- 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**.

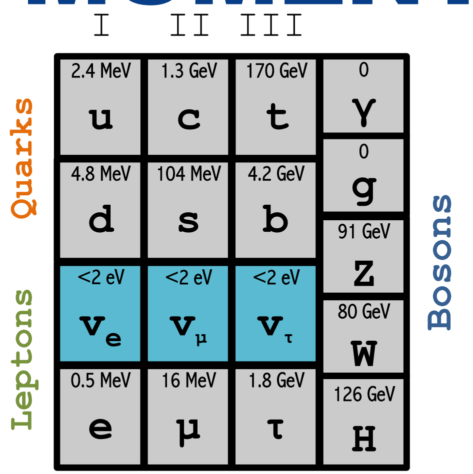
- b-jets create distinct final states, important for both **Standard Model measurements** and **searches for New Physics**.



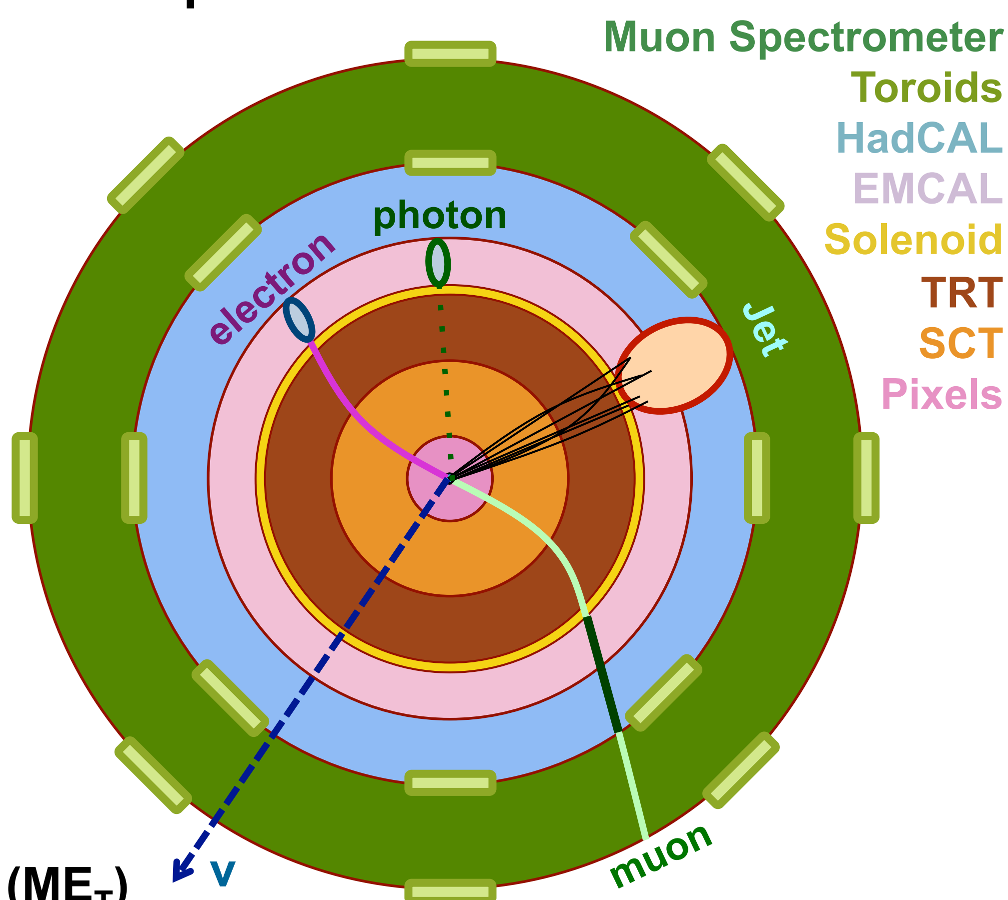




MISSING TRANSVERSE MOMENTUM – "ME$_T$"



Simplified Detector Transverse View

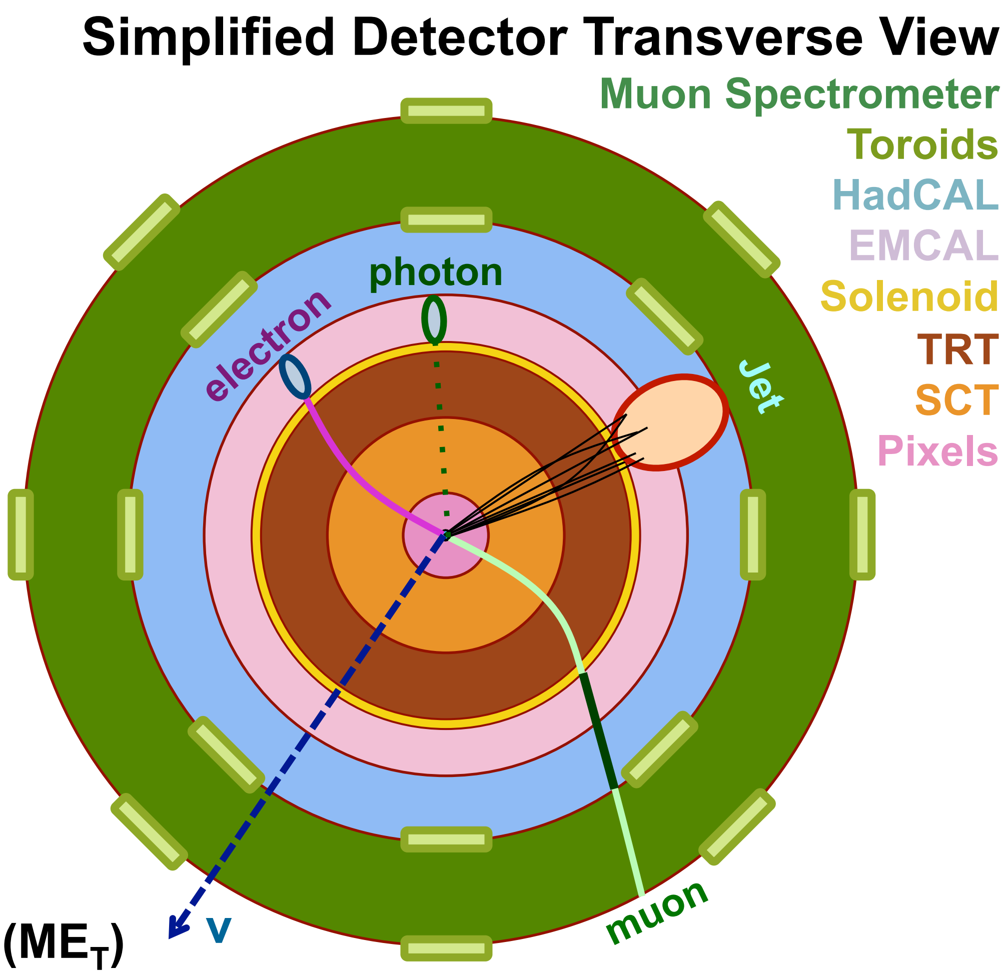


In the transverse plane:

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

Missing Transverse Momentum (ME$_T$)

MISSING TRANSVERSE MOMENTUM – "ME$_T$"



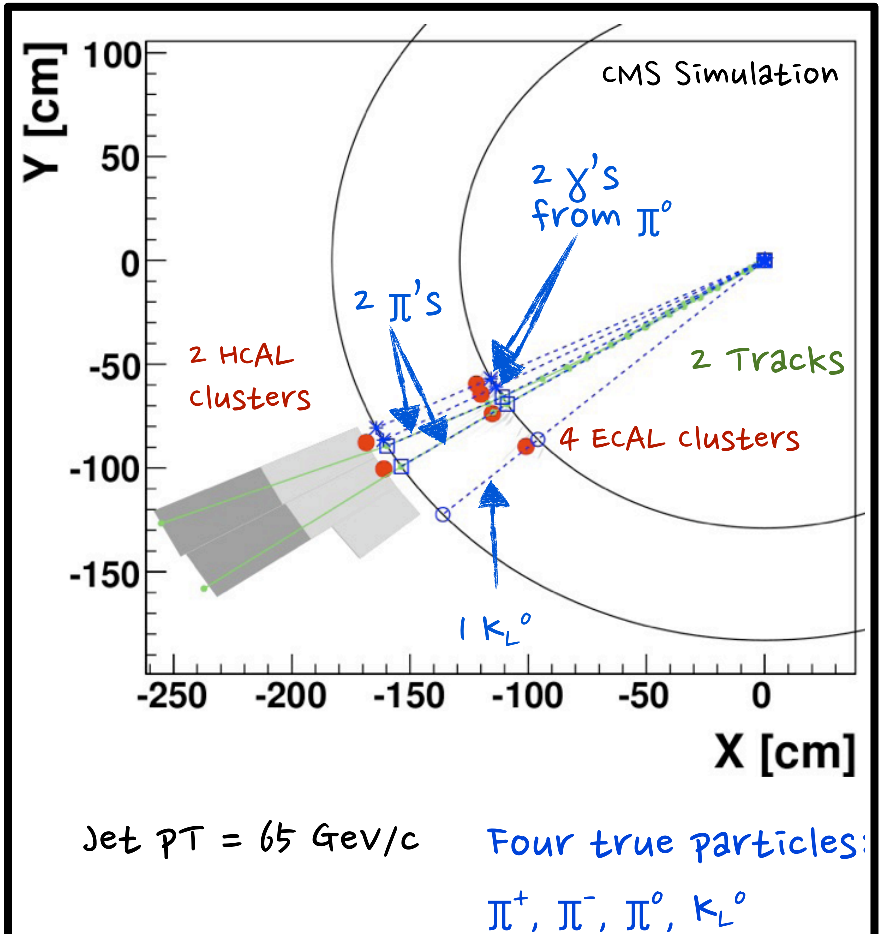
In the transverse plane:

$$\sum \vec{p}_T = 0$$

Missing Transverse Momentum (ME$_T$)

PARTICLE FLOW

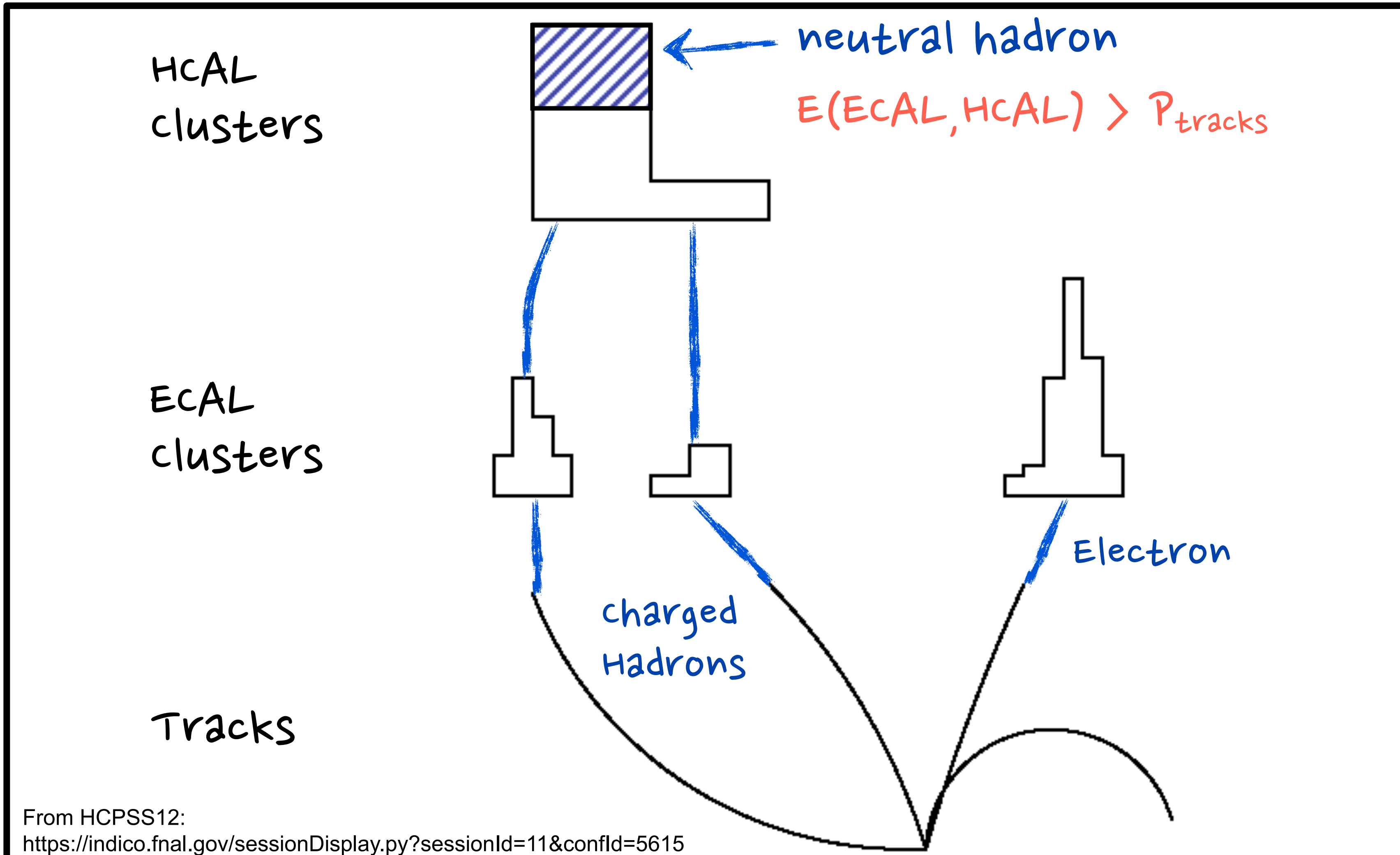
- "Flow of particles" through the detector.
- Reconstruct and identify all particles, photons, electrons, pions, …
- Use best combination of all sub-detectors for measuring E, η, φ, ID.
- Relies on
  - high precision, high efficiency tracking;
  - large magnetic field for good pT resolution and charged-to-neutral particle separation; and
  - highly granular calorimeter.
- First used at LEP (ALEPH) and then at the LHC (CMS).



From HCPSS12:
https://indico.fnal.gov/sessionDisplay.py?sessionId=11&confId=5615

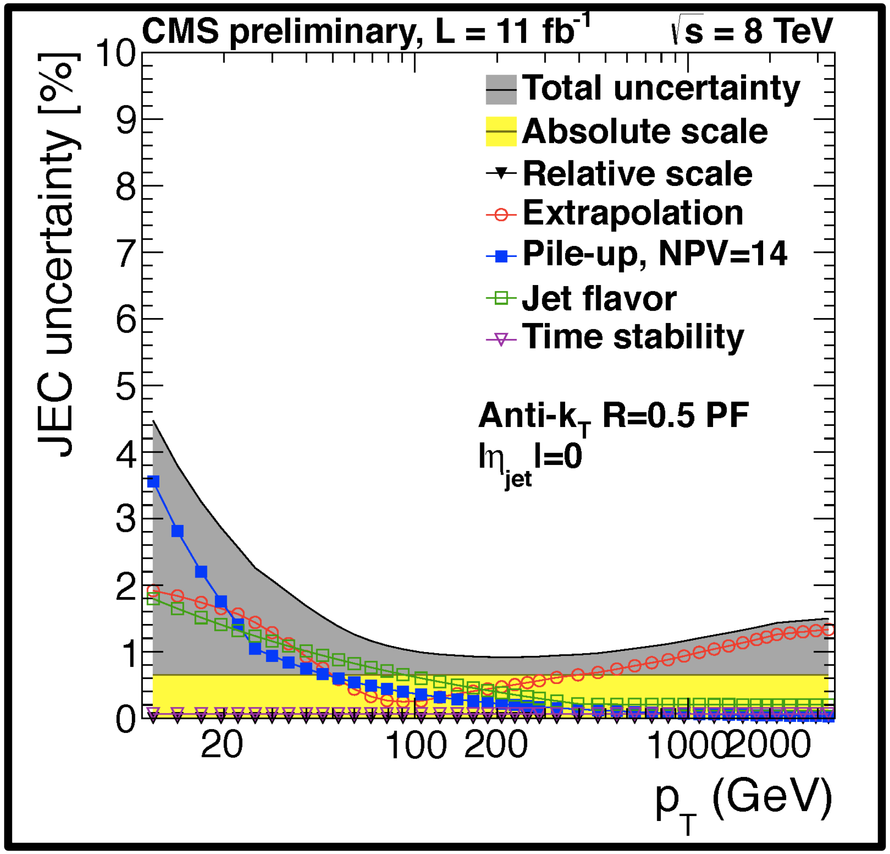
PARTICLE FLOW

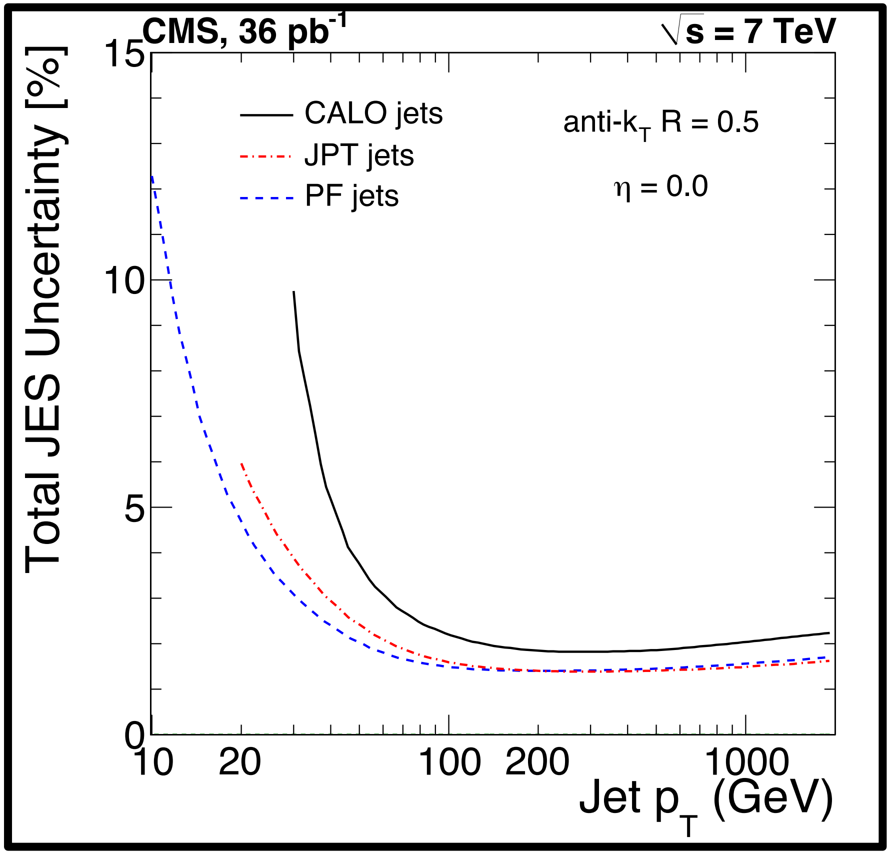
1. Associate hits within each detector.
2. Link across detectors.
3. Apply particle-ID and separation.



From HCPSS12:
https://indico.fnal.gov/sessionDisplay.py?sessionId=11&confId=5615

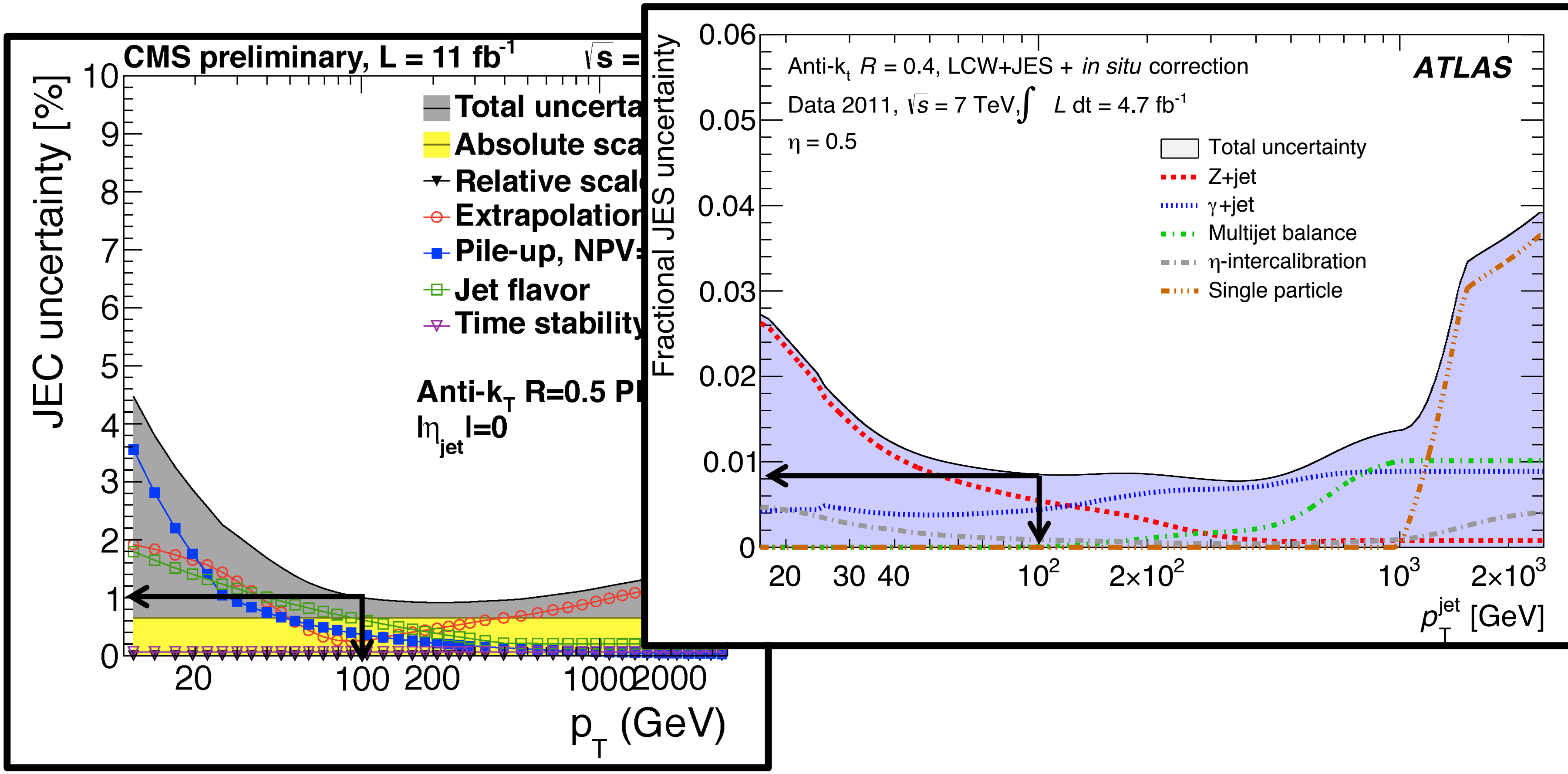
PARTICLE FLOW - PERFORMANCE





In Jet Energy Scale uncertainty, large improvements with respect to calo jets!

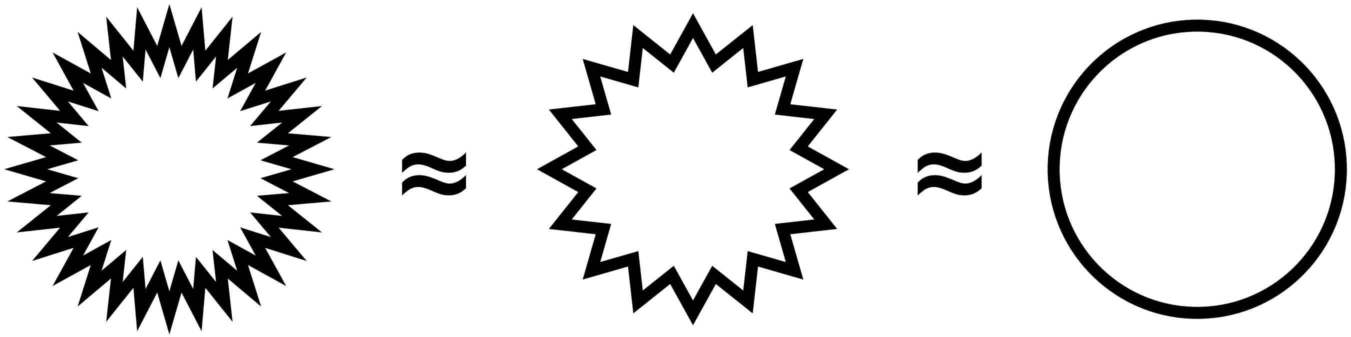
A COMPARISON



- At ~ 100GeV jets, PF jets (CMS) and calo jets (ATLAS) have similar performance.
- **Particle reconstruction always needs to be optimized depending on the detector technologies and experimental requirements.**

ONLINE RECONSTRUCTION

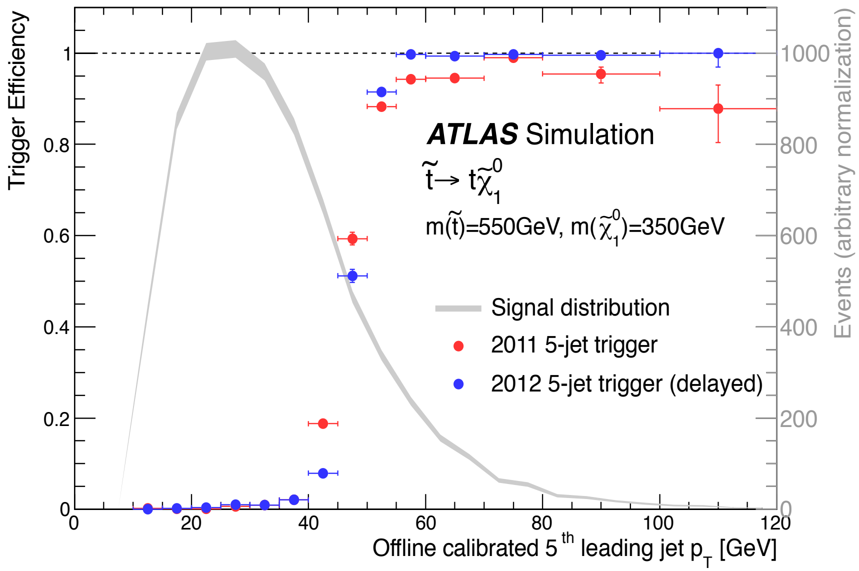
Objective: Trigger ("online") reconstruction same as "offline".
Problem: Time. Trigger decision needs to be taken fast.
Solution: Simplification.
Challenge: Clever simplification = good performance.

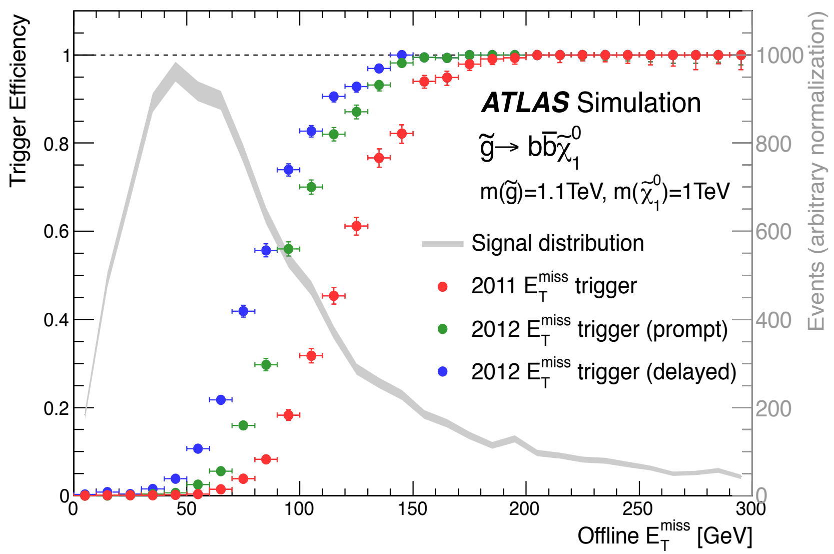


E.g. track reconstruction in regions of interest and simplified MET calculation.

ONLINE RECONSTRUCTION

$$\text{trigger efficiency} = \frac{\#\ \text{events passing offline selection \& trigger}}{\#\ \text{events passing offline selection}}$$





Clever ideas need to be deployed to bring online closer to offline, making efficiency curves **sharper** and **plateau closer to 1**.

EFFICIENCY MEASUREMENTS

Relevant beyond the trigger…

Tag and Probe

Select events based on requirements on one object (tag) and study the response of the second object (probe), not used in the event selection, using some constraint such as the Z mass.

- e.g. $Z \rightarrow \tau\tau$ events.
- Typically used for measurement of the identification efficiency.

Orthogonal sample

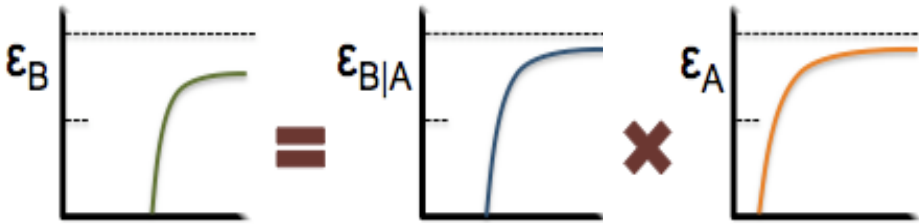
Measure directly the efficiency on an independent, orthogonal sample.

- e.g. jet trigger efficiency on a sample triggered by muons,

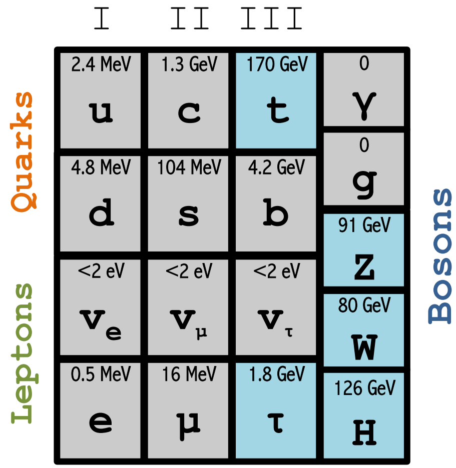
Bootstrap method

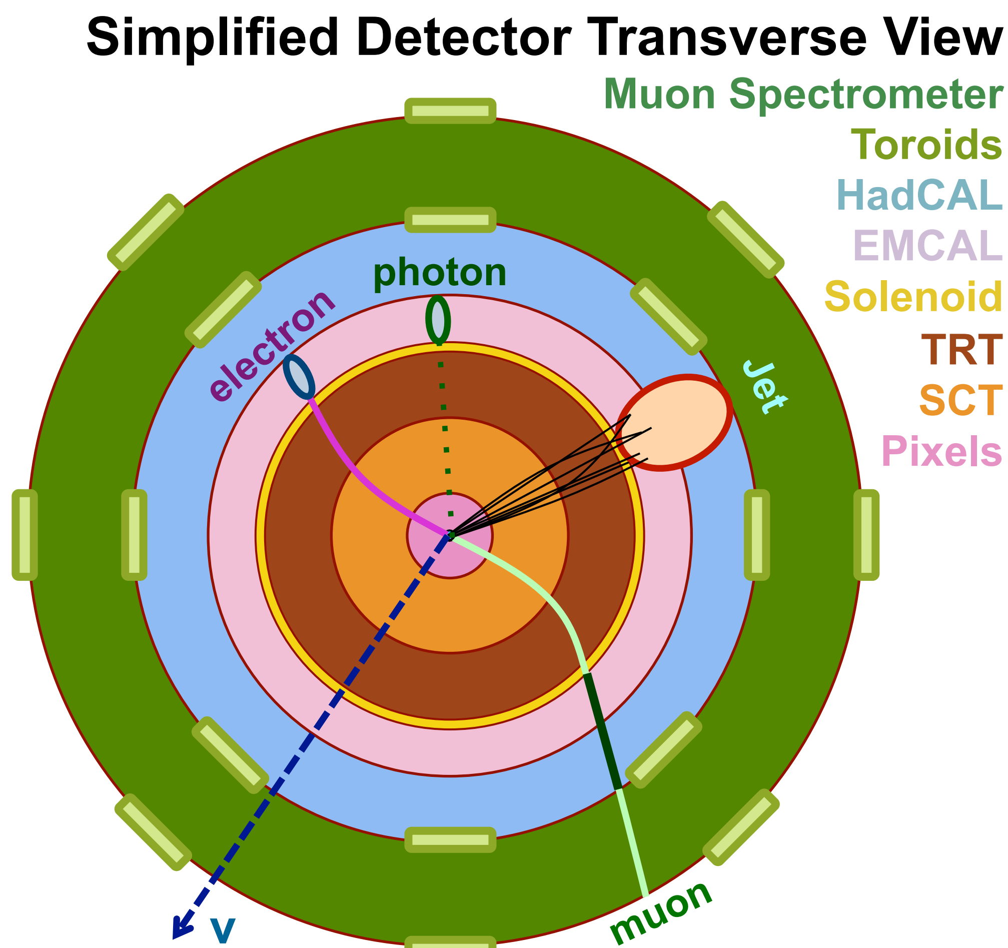
The efficiency, ε_B, of a selection B, inclusive compared to a selection A, can be determined in a sample of events passing selection A (provided that ε_A is measurable): $\varepsilon_B = \varepsilon_{B|A} \times \varepsilon_A$.

- e.g. trigger efficiencies,
  say B: tau50_loose & A: tau16_loose



RECONSTRUCTING PARTICLES



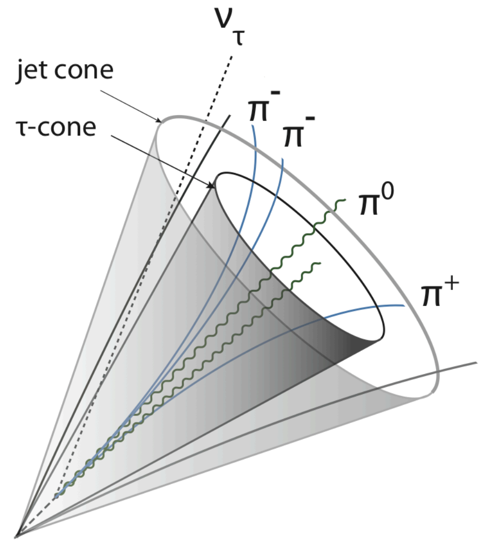


TAUS

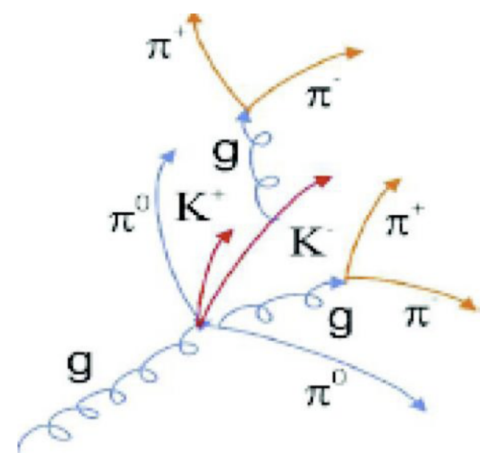
Tau Decay Mode			B.R.
Leptonic		$\tau^{\pm} \rightarrow e^{\pm} + \nu + \nu$	17.8%
		$\tau^{\pm} \rightarrow \mu^{\pm} + \nu + \nu$	17.4%
Hadronic	1-prong	$\tau^{\pm} \rightarrow \pi^{\pm} + \nu$	11%
		$\tau^{\pm} \rightarrow \pi^{\pm} + \nu + n\pi^{0}$	35%
	3-prong	$\tau^{\pm} \rightarrow 3\pi^{\pm}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

- Hadronic tau reconstruction extremely challenging.
- Using **multi-variate** techniques based on track multiplicity and shower shapes.

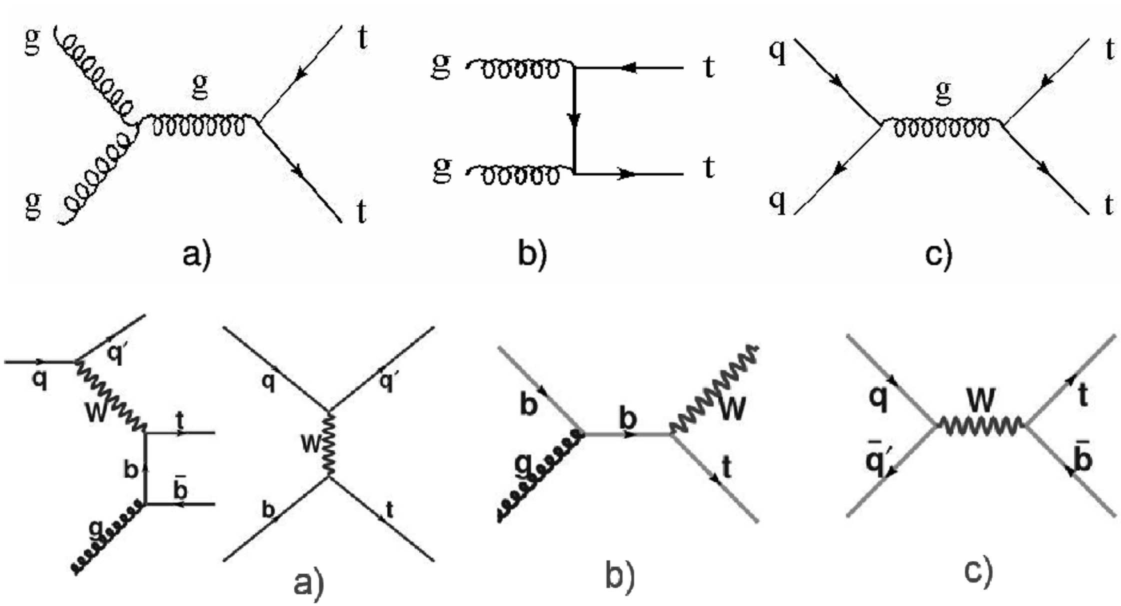
A tau jet (signal)…



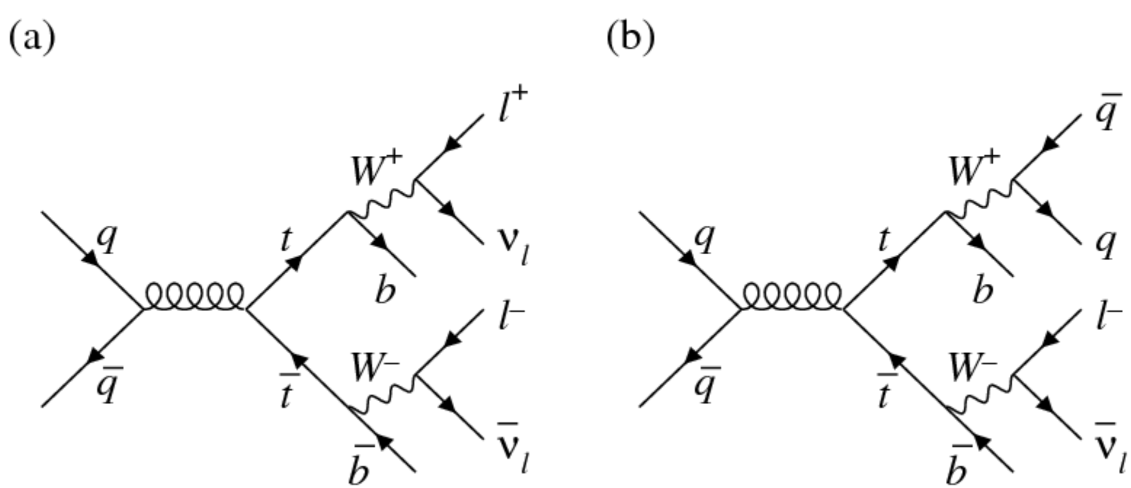
…vs. a QCD jet (background)



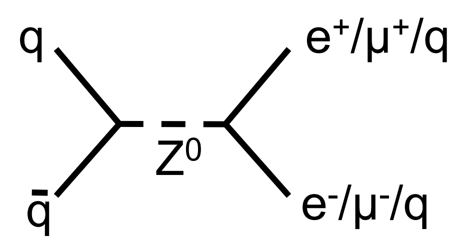
t,W,Z



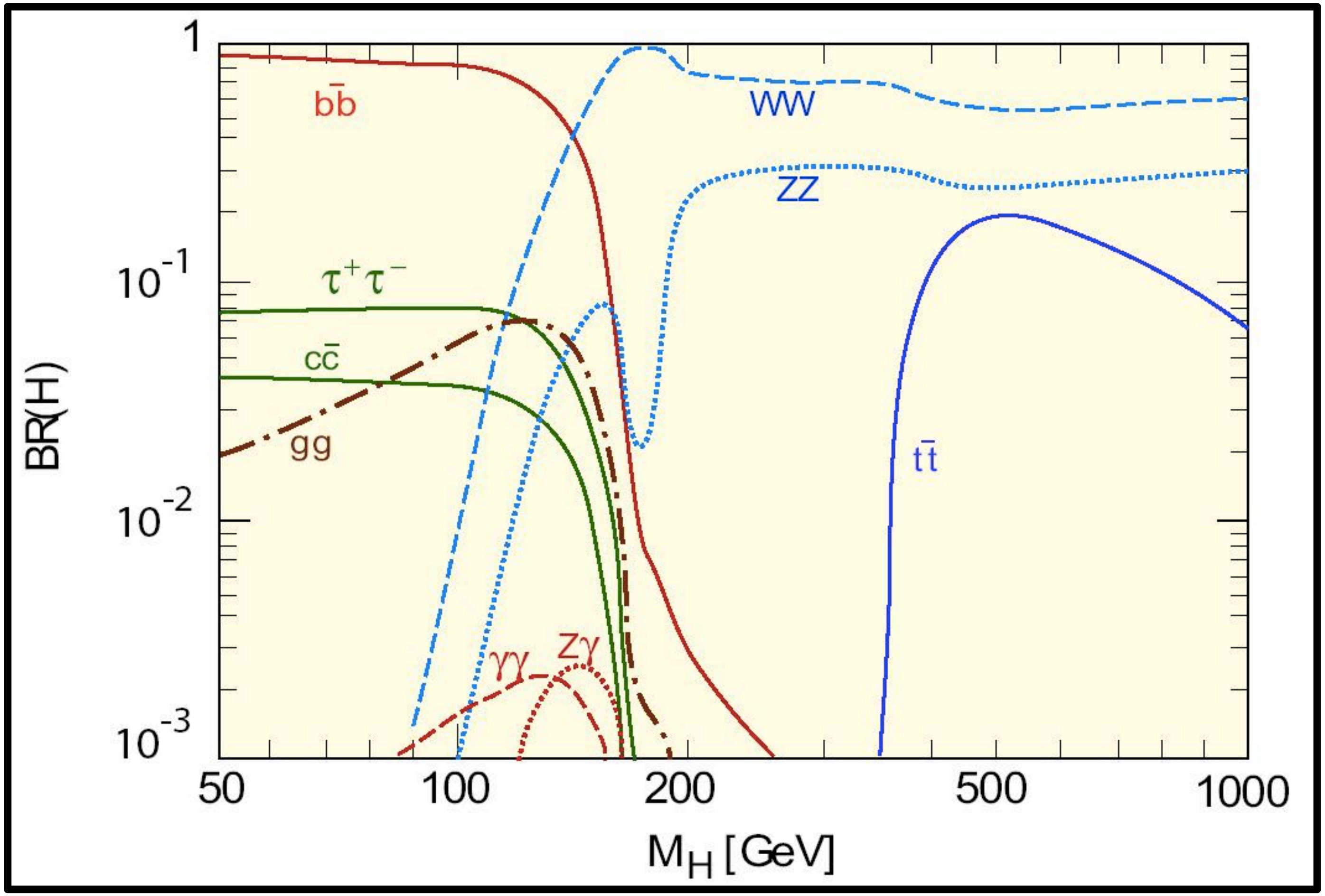
Diagrams from http://arxiv.org/pdf/1201.5844.pdf



Diagrams from http://arxiv.org/pdf/1004.1181.pdf



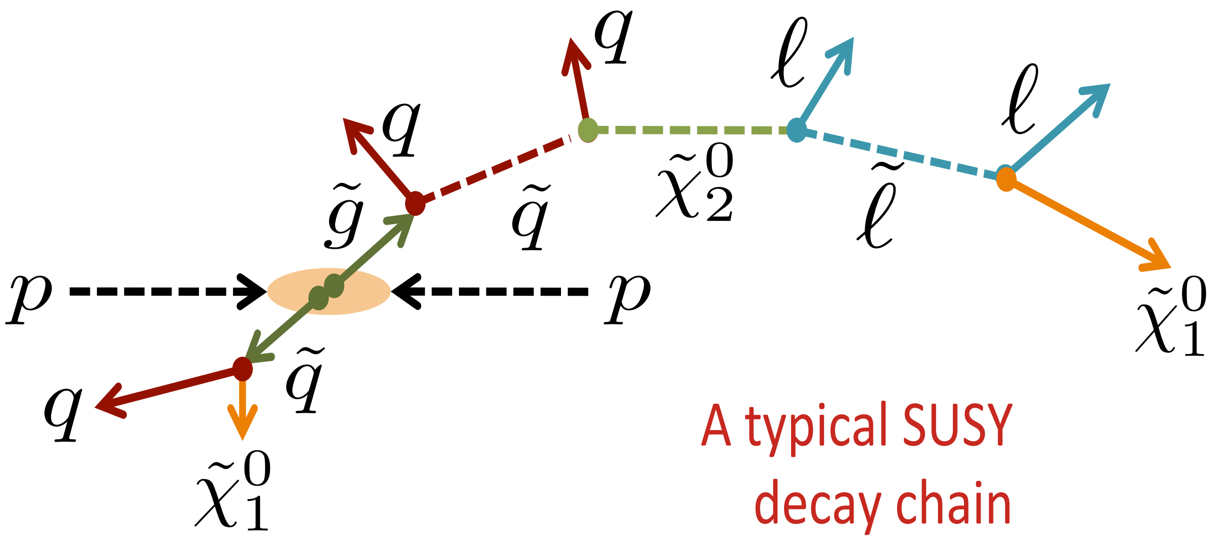
AND THE HIGGS!



HOW ABOUT NEW PARTICLES?

These decay to Standard Model particles or create Missing Energy…

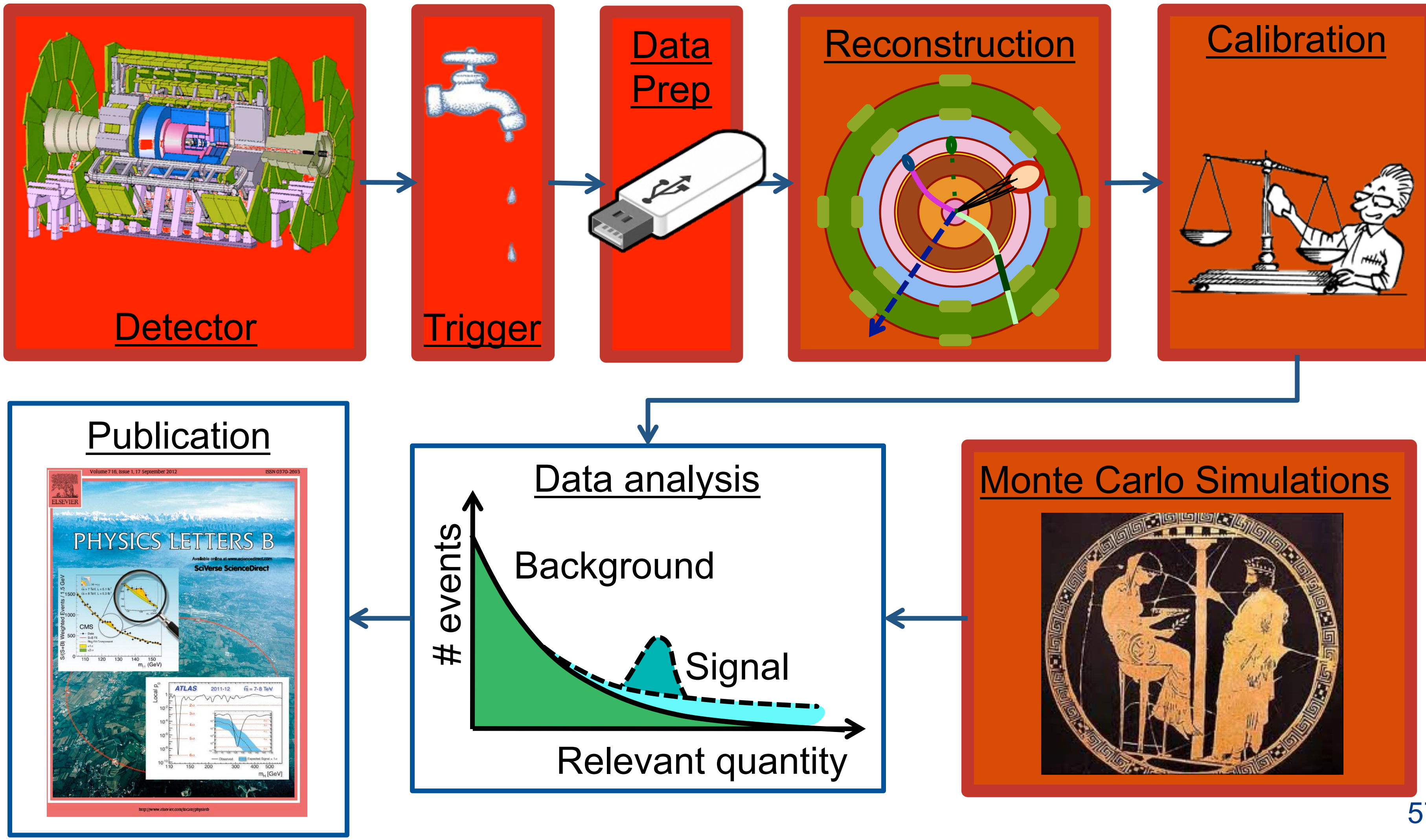
E.g.



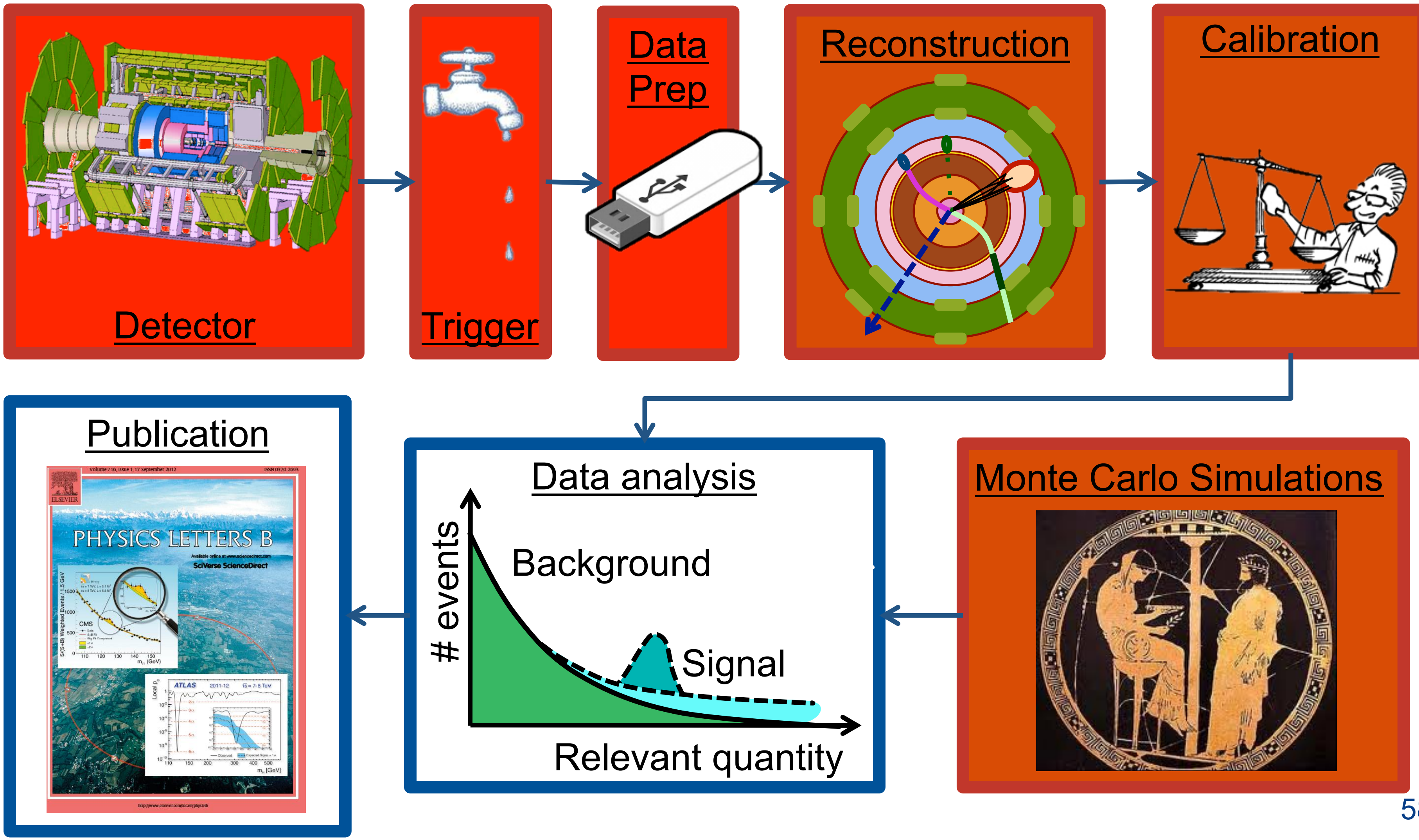
PHYSICS ANALYSES

- Measurements
  - Cross-section
  - Mass
  - Other properties
- Searches
  - Bump
  - Tail

END OF LECTURE 2



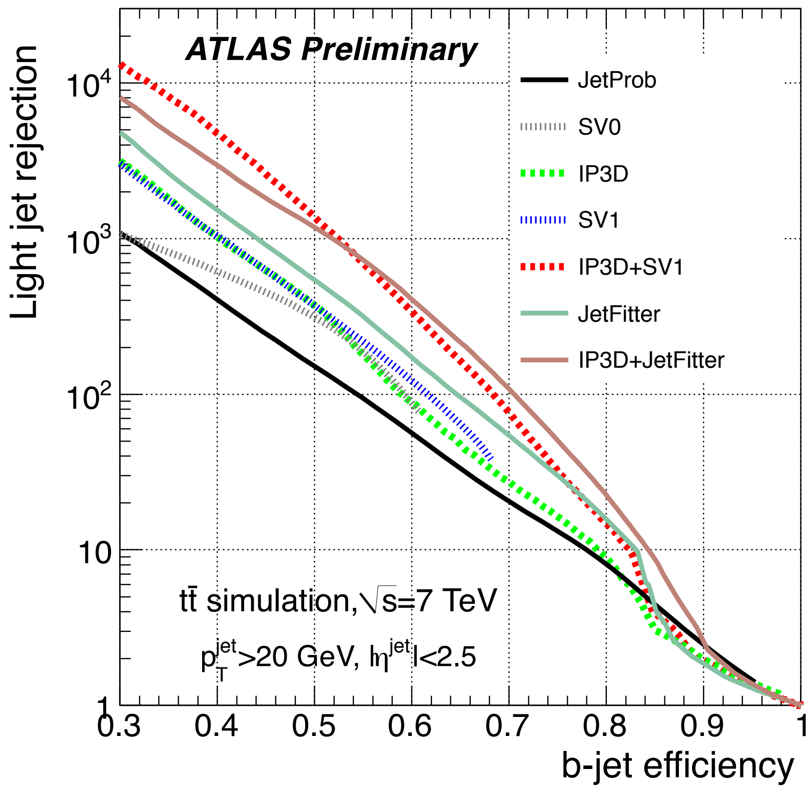
LECTURE 3



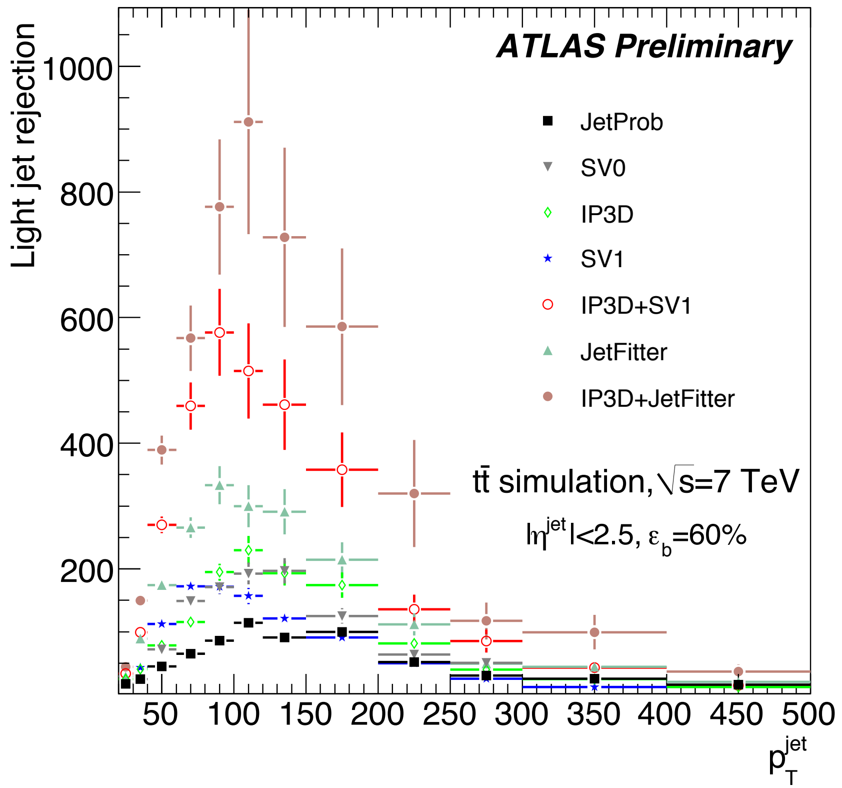
Detector
Trigger
Data Prep
Reconstruction
Calibration
Publication
PHYSICS LETTERS B
SciVerse ScienceDirect
CMS
ATLAS
Data analysis
events
Background
Signal
Relevant quantity
Monte Carlo Simulations

BACKUP

BJETS



ATLAS Preliminary
JetProb
SV0
IP3D
SV1
IP3D+SV1
JetFitter
IP3D+JetFitter
tt̄ simulation,√s=7 TeV
p_T^jet>20 GeV, |η^jet|<2.5
Light jet rejection
b-jet efficiency



ATLAS Preliminary
JetProb
SV0
IP3D
SV1
IP3D+SV1
JetFitter
IP3D+JetFitter
tt̄ simulation,√s=7 TeV
|η^jet|<2.5, ε_b=60%
Light jet rejection
p_T^jet

MISSING TRANSVERSE MOMENTUM

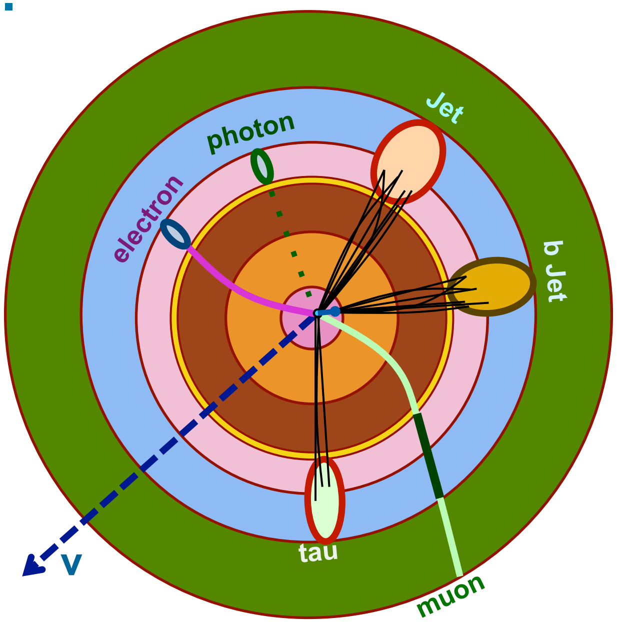
Impossible to measure particles that don't interact in the detector.

➲ Instead, measure everything else & require momentum conservation in the transverse plane.

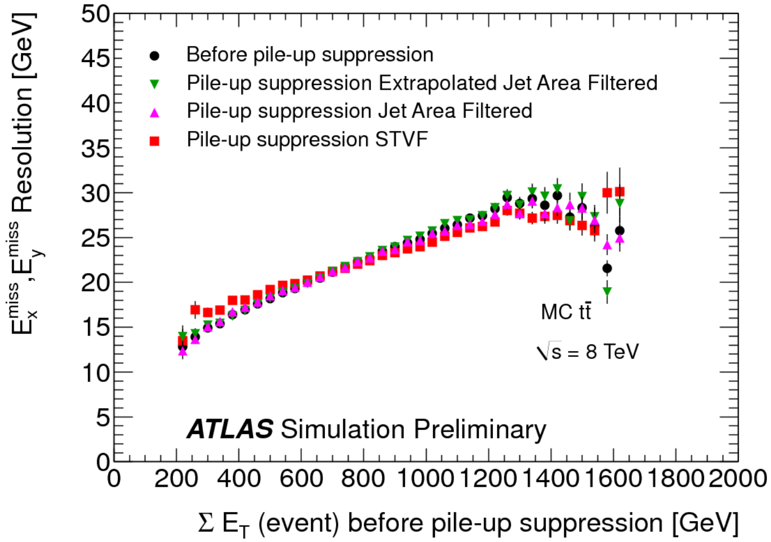
- Sensitive to pile-up and detector problems.

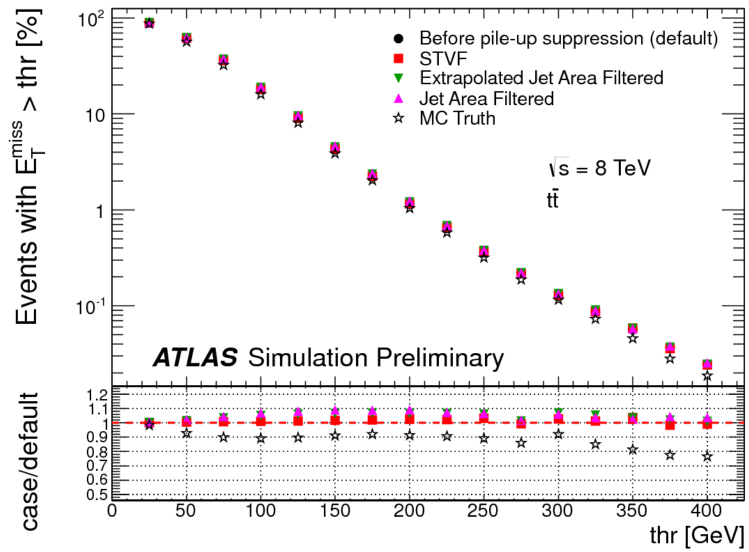
Only as good as its inputs.

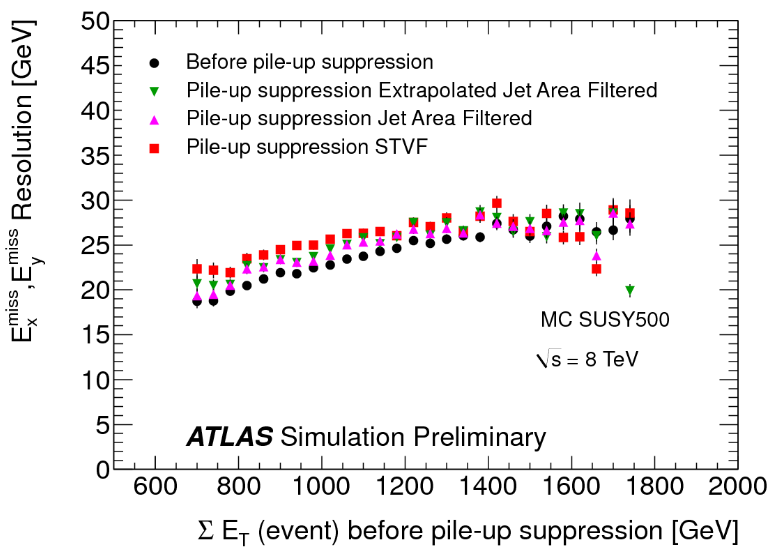
- Use calibrated physics objects: electrons, photons, muons, taus, jets.
- Add remaining soft energy.

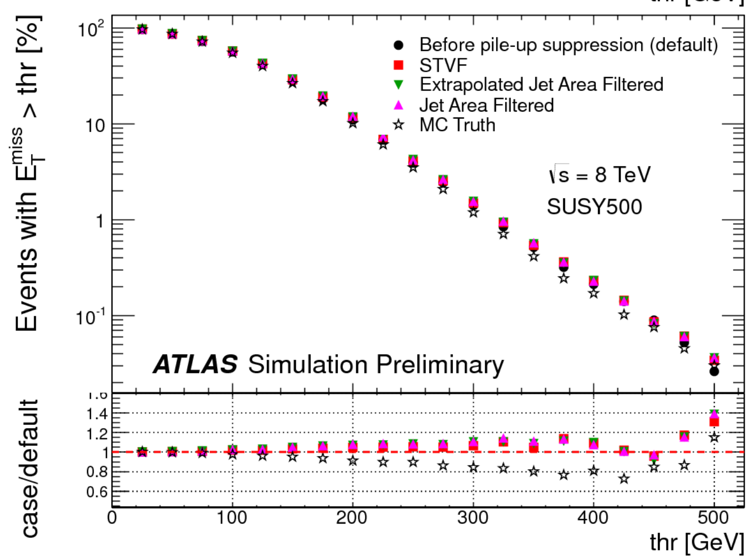


MISSING ET – PILEUP & TAILS

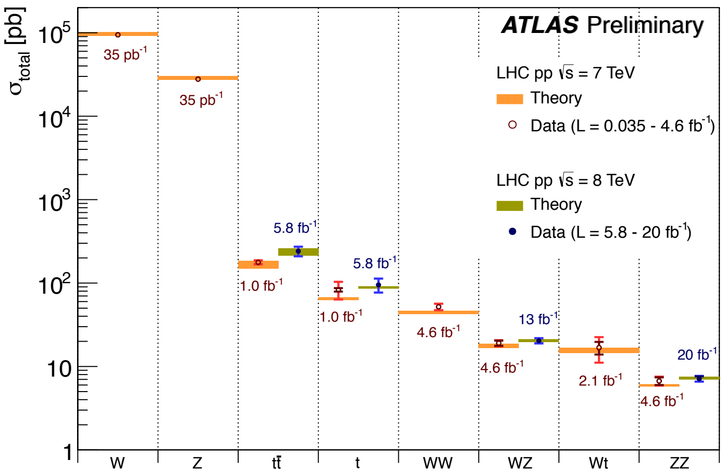


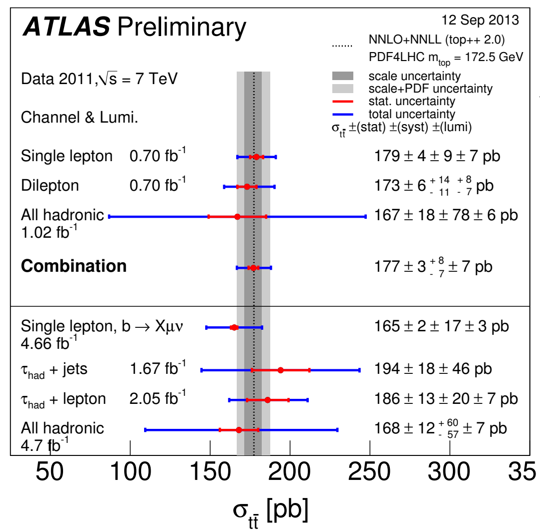


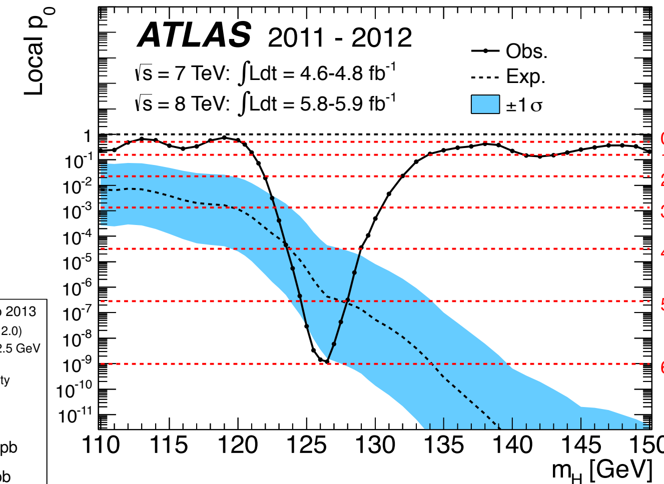


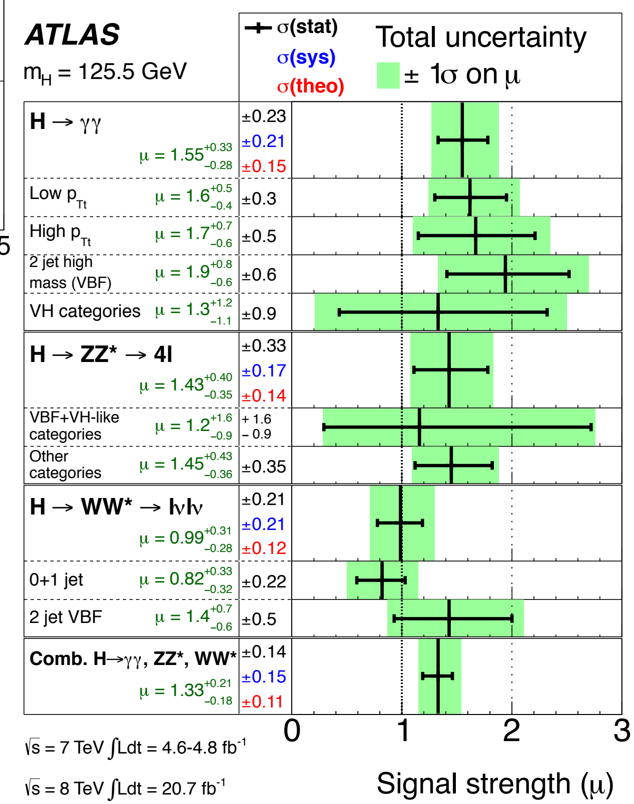


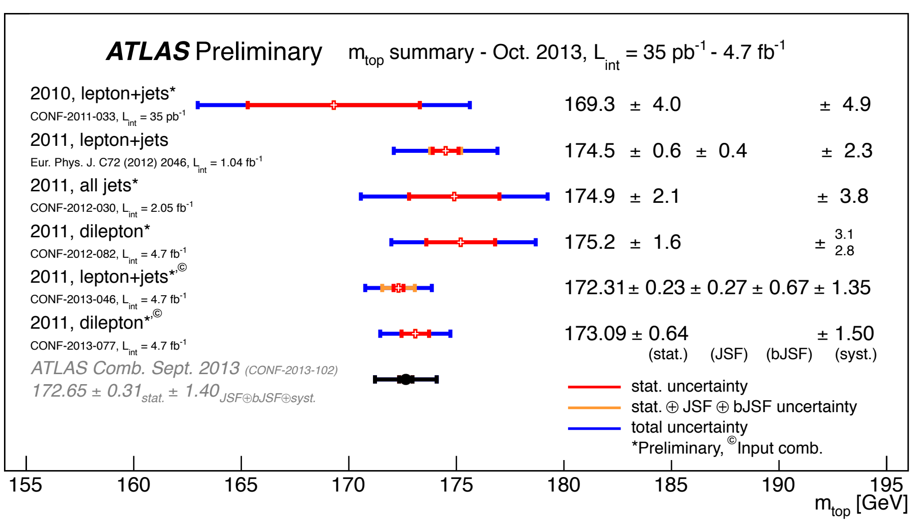
GRAND ATLAS (non-BSM) PHYSICS SUMMARY



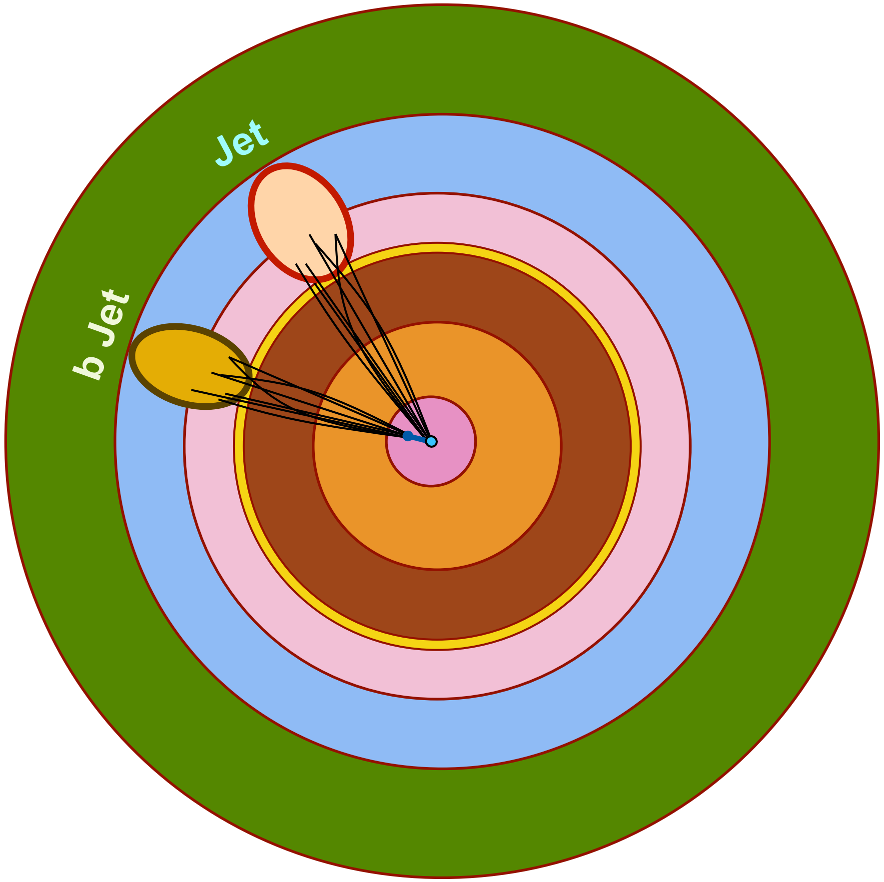




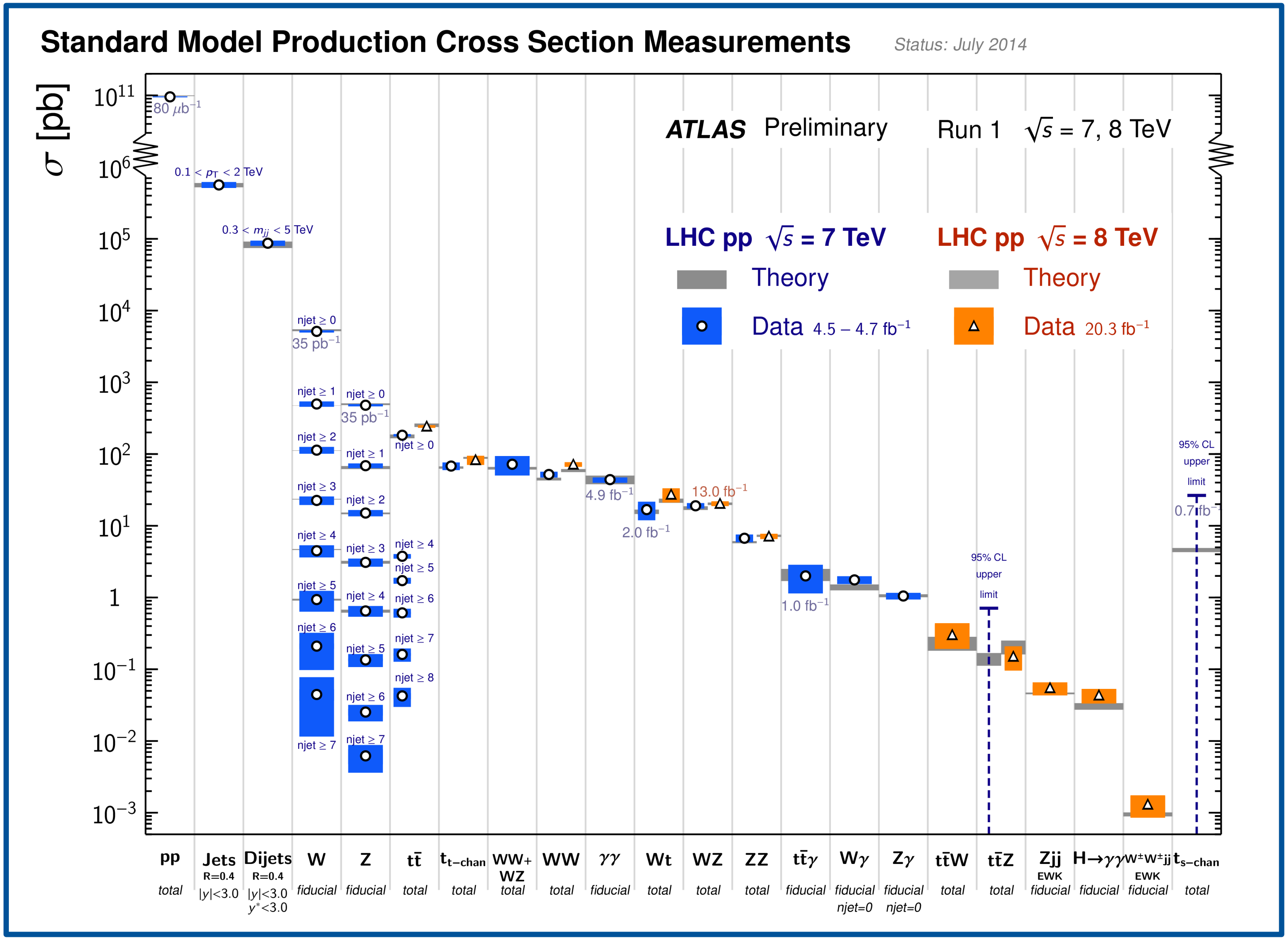




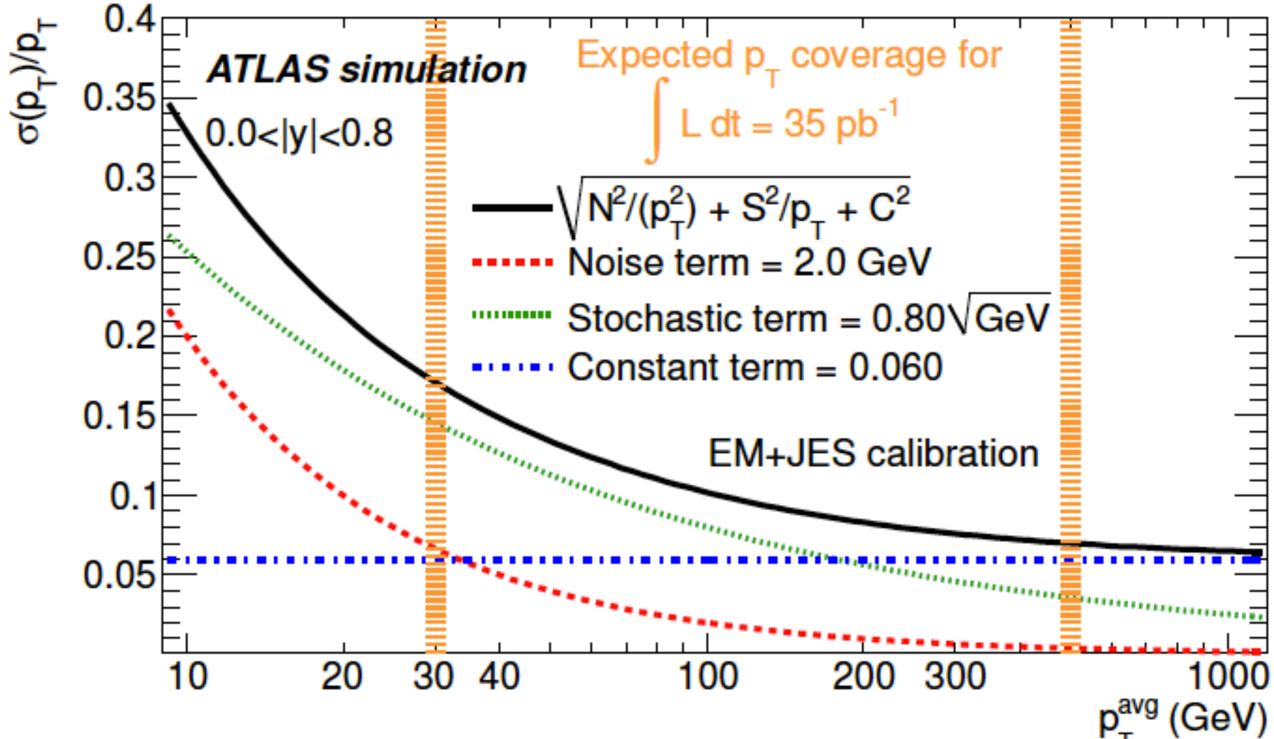
B-JET



STANDARD MODEL SUMMARY



THE SUSY MULTIJET SEARCH



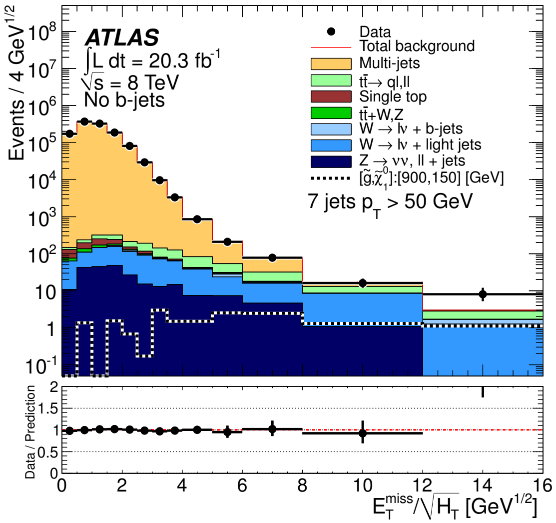
ATLAS-PERF-2011-04-001

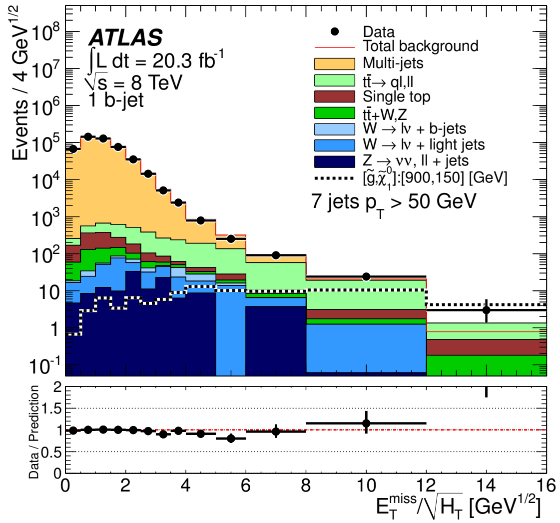
Why $ME_T/\sqrt{H_T}$?
⇒ a measure of ME_T in units of standard deviations of the fake ME_T

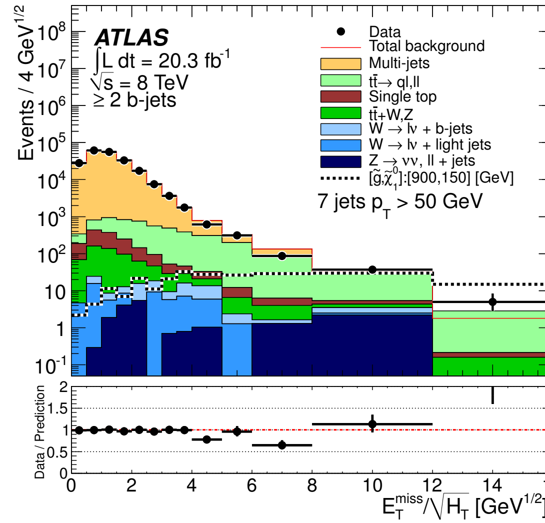
$$\frac{\sigma_{p_T}}{p_T} = \frac{N}{p_T} \oplus \frac{S}{\sqrt{p_T}} \oplus C$$

MULTI-JET BACKGROUND

Flavour stream

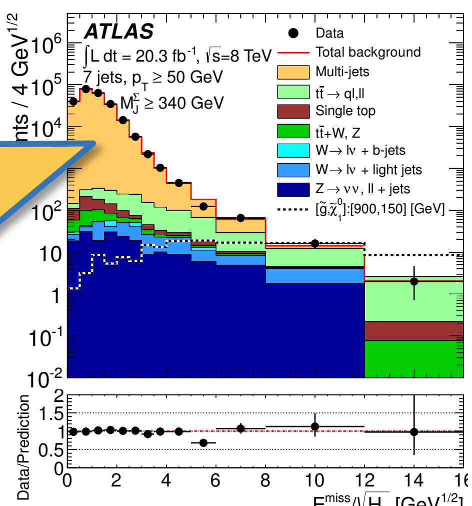


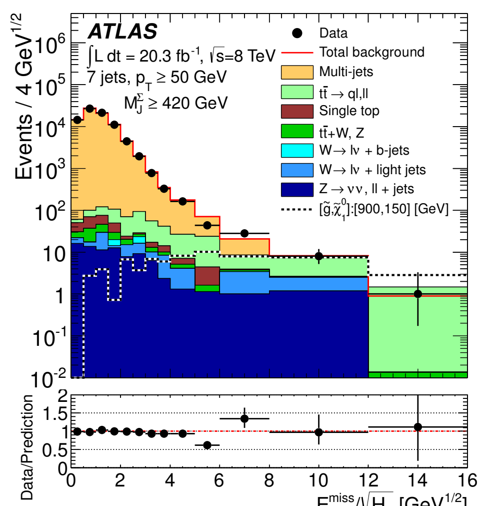




MJ stream

Template extracted from ‘6j50’ and validated in ‘7j50’





Discrepancies in control regions become uncertainties – dominant, on top of heavy flavour and ‘leptonic’ backgrounds.

LEPTONIC BACKGROUNDS

- ttbar (non-full-hadronic) + jets and W/Z + jets.
- Scale MC in control regions in data (through a multi-bin fit).

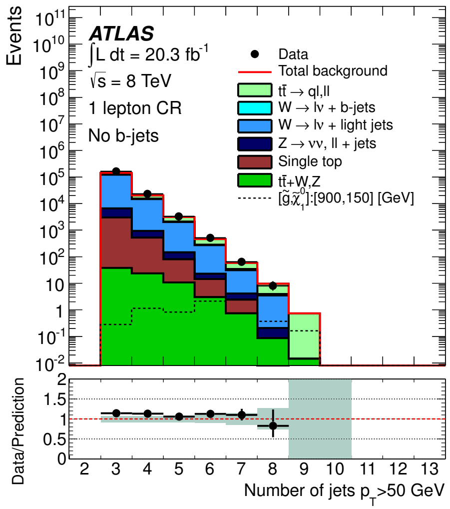
Single-lepton validation region	
Lepton p_{T}	$> 25\,\mathrm{GeV}$
Lepton multiplicity	Exactly one, $\ell \in \{e,\, \mu\}$
$E_{\mathrm{T}}^{\mathrm{miss}}$	$> 30\,\mathrm{GeV}$
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$	$> 2.0\ \mathrm{GeV}^{1/2}$
m_{T}	$< 120\,\mathrm{GeV}$
Jet p_{T}	As for signal regions (table 1)
Jet multiplicity	
b-jet multiplicity	
M_J^{Σ}	
Control region (additional criteria)	
Jet multiplicity	Unit increment if $p_{\mathrm{T}}^{\ell} > p_{\mathrm{T}}^{\mathrm{min}}$
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}\ (+p_{\mathrm{T}}^{\ell})}$	$> 4.0\ \mathrm{GeV}^{1/2}$

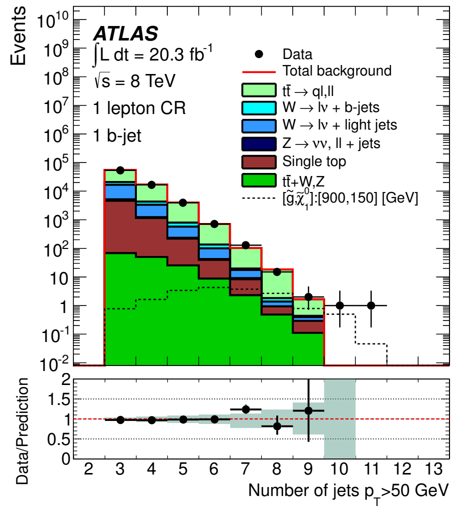
Two-lepton validation region	
Lepton p_{T}	$> 25\,\mathrm{GeV}$
Lepton multiplicity	Exactly two, $e\,e$ or $\mu\,\mu$
$m_{\ell\ell}$	$80\,\mathrm{GeV}$ to $100\,\mathrm{GeV}$
Jet p_{T}	As for signal regions (table 1)
Jet multiplicity	
b-jet multiplicity	
M_J^{Σ}	
Control region (additional criteria)	
$\lvert \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} + \mathbf{p}_{\mathrm{T}}^{\ell_1} + \mathbf{p}_{\mathrm{T}}^{\ell_2} \rvert / \sqrt{H_{\mathrm{T}}}$	$> 4.0\ \mathrm{GeV}^{1/2}$

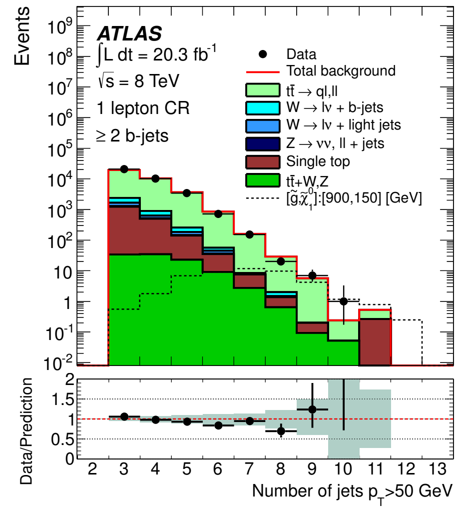
- Uncertainties dominating the leptonic background determination: JES/JER, b-tagging, pile-up and theory.

LEPTONIC BACKGROUND

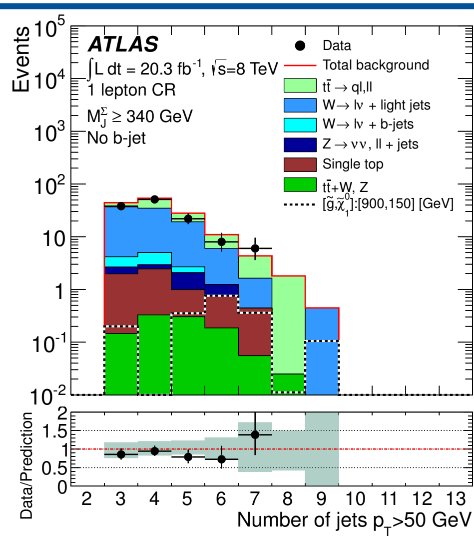
Flavour stream

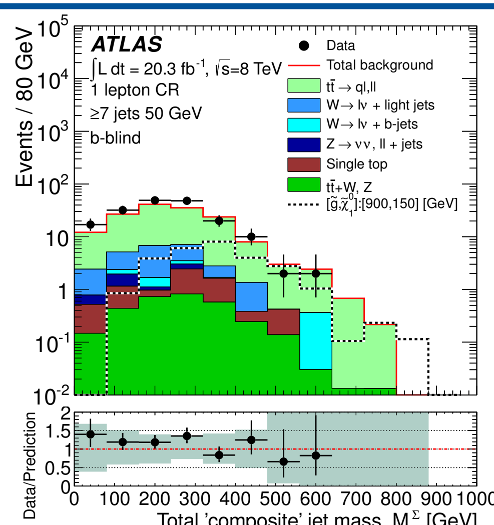






MJ stream





Uncertainties dominating the leptonic background determination: JES/JER, b-tagging, pile-up and theory.

THE STATISTICAL TREATMENT

Flavour stream

Simultaneous fit in the ‘j50’ and ‘j80’ signal regions separately.

- **ttbar & W+jets:** one control region per signal region.
  Normalization allowed to vary freely in the fit.
- **Other less significant backgrounds;** determined using MC.
  Constrained by their uncertainties.
- **Multijet background;** not constrained by control regions.
  Constrained by its uncertainties.

MJ stream

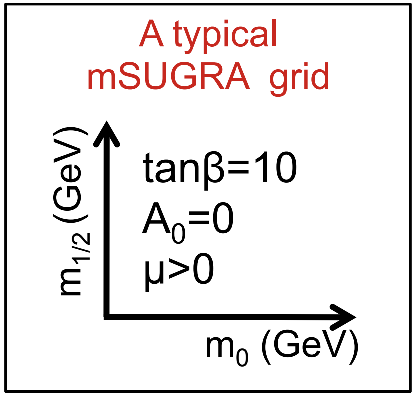
A fit performed in each signal region to adjust the normalization of ttbar and W backgrounds.

INTERPRETATIONS

‘Real models’

◎ **A minimal model, Constraint Minimal SUSY (CMSSM) (mSugra, i.e. gravity-mediated, based) only has 5 free parameters:**

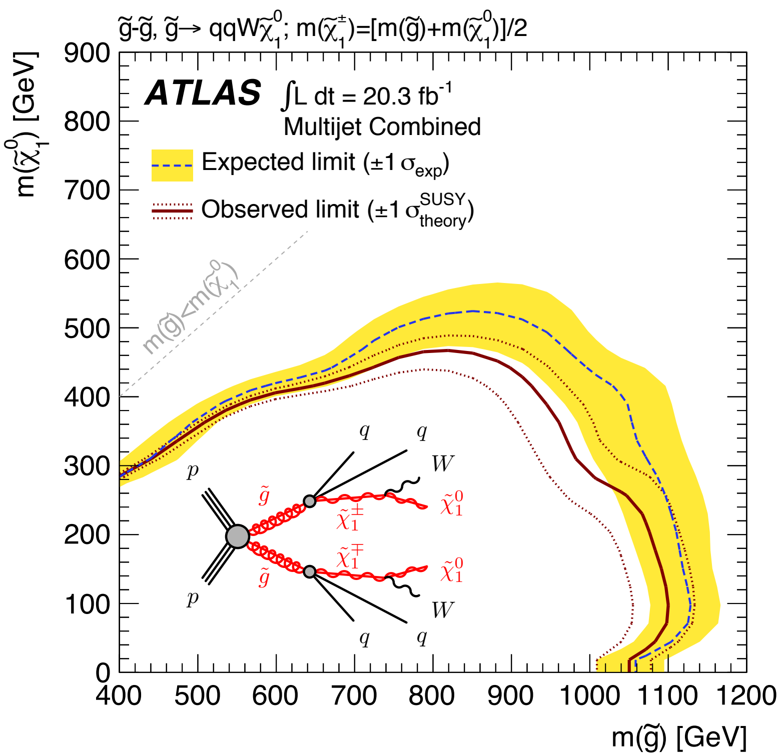
- Scalar mass parameter, $\mathbf{m_0}$
- Gaugino mass parameter, $\mathbf{m_{1/2}}$
- Trilinear Higgs-sfermion-sfermion coupling, $\mathbf{A_0}$
- Ratio of Higgs vaccum expectation values, **tanβ**
- Sign of SUSY Higgs parameter, **sign(μ)**

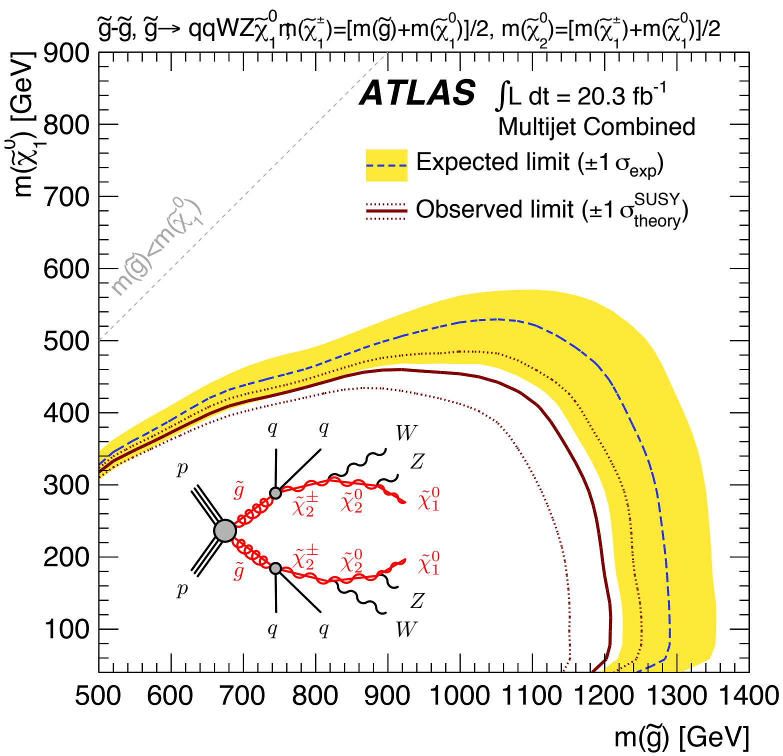


‘Simplified models’

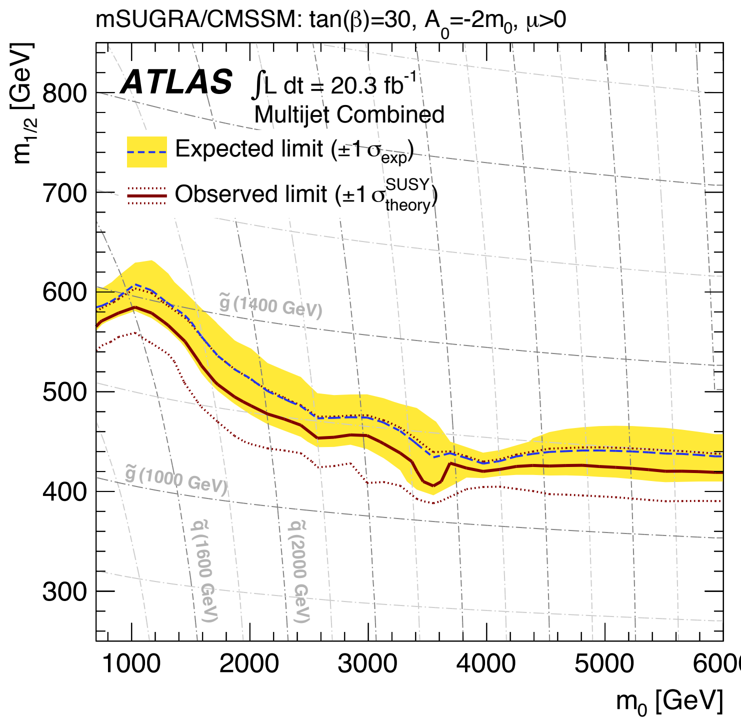
◎ **Simplified topologies with typically one production and one decay process. Provide useful information for theorists.**

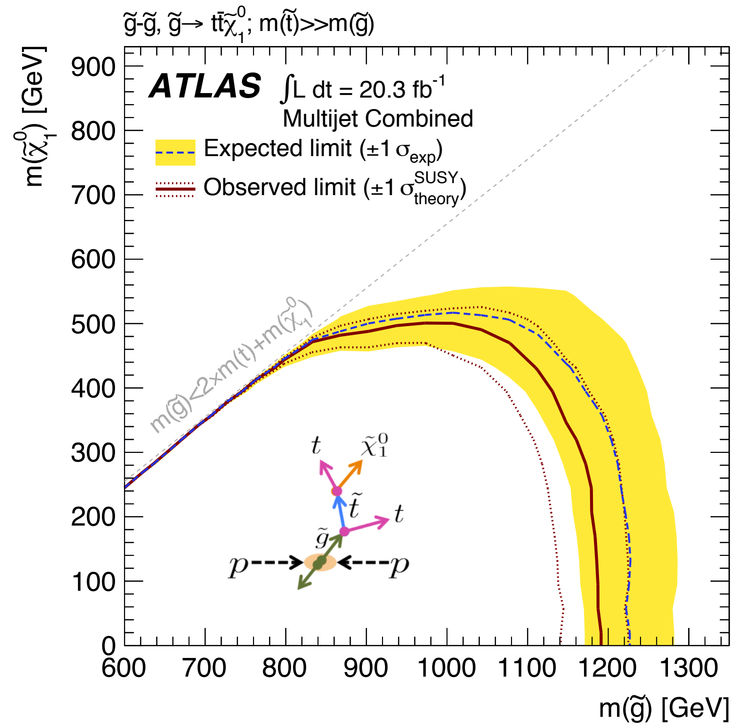
INTERPRETATIONS



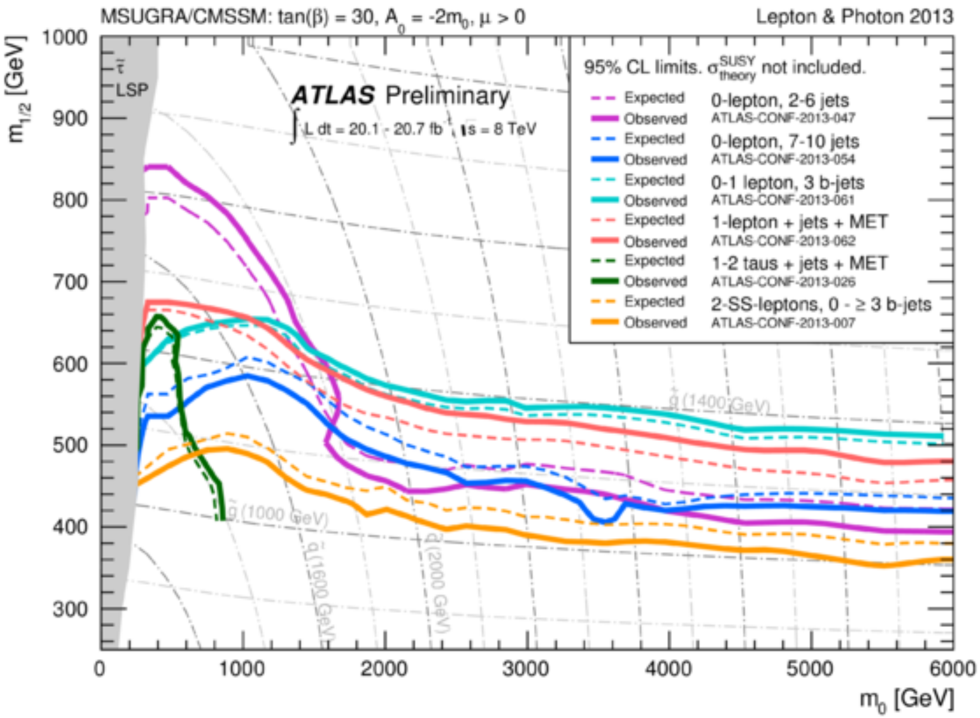


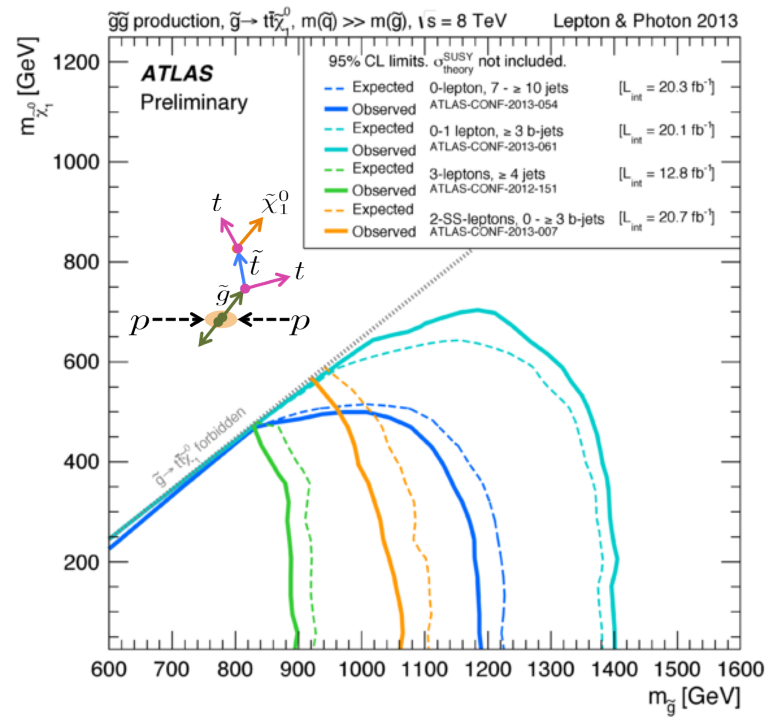
INTERPRETATIONS





INTERPRETATIONS





- **Note that the multijet analysis is not optimized for a specific model, it is built to be as model-independent as possible.**
- **Multijet analysis is strong in other simplified models, e.g. gluino pair production via 2-step decay to 12 jets.**

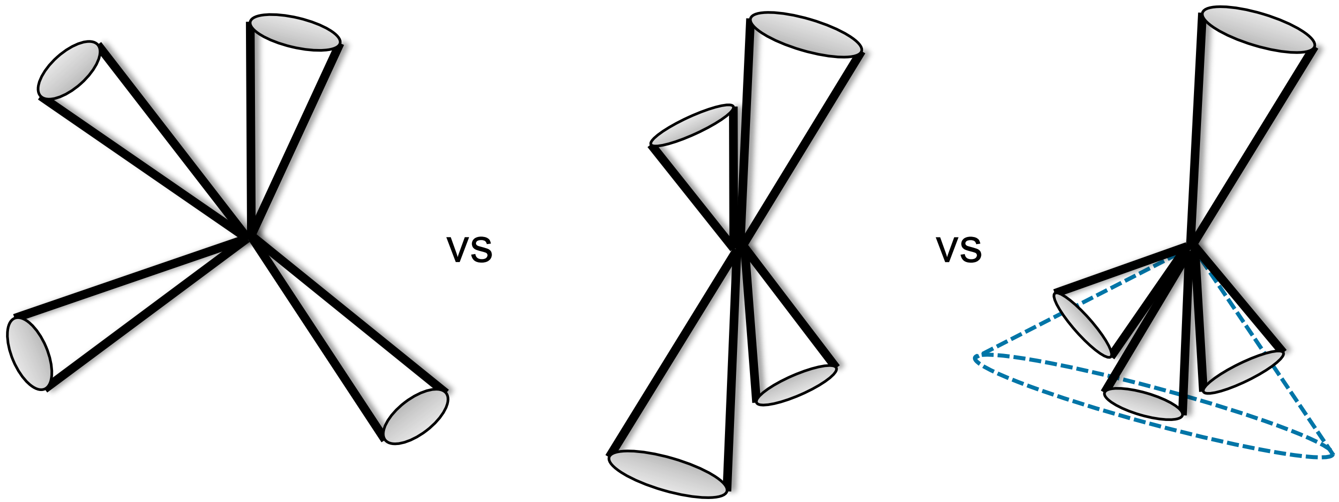
QCD BACKGROUNDS IN SUSY

All (SUSY) analyses use data-driven methods for assessing multi-jet SM production.

Monte Carlo can not be used when large multiplicities are involved:

- Inclusive multi-jet / multi-parton samples provided by Monte Carlo generators recently only.
  - E.g. only very latest Sherpa release provides NLO calculations up to four jets.
- Monte Carlo predictions have not yet been validated with multi-jet data.
- **Detailed comparisons between data and various Monte Carlo generators and theoretical predictions would provide extremely useful input to the theory community in understanding QCD.**
  - They would also provide a great understanding of a dominant SUSY background in view of run2.

E.G. FOUR-JET TOPOLOGIES & OBSERVABLES



Category	Variable
Simple kinematic & ratios	pT, η, φ, HT, p_{Ti}/p_{Tj}
Angles	$\Delta\eta_{ij}$, $\Delta\varphi_{ij}$, ΔR_{ij}
Masses & ratios	m_{ij}, m_{ijk}, m_4, m_i/m_{ij}, m_i/m_{ijk}, m_i/m_4
Event shapes	$\Sigma\, p_T^2 / \Sigma\, p^2$

E.G. FOUR-JET TOPOLOGIES & OBSERVABLES

Name	Definition	Comment
$p_{\mathrm{T}i}$	Transverse momentum of the ith jet	} Sorted descending in p_{T}
Y_i	Rapidity of the ith jet	
H_{T}	$\sum_{i=1}^{4} p_{\mathrm{T}i}$	Scalar sum of the p_{T} of the four jets
M_{jjjj}	$\left(\sum_{i=1}^{4} E_i\right)^2 - \left(\sum_{i=1}^{4} \mathbf{p}_i\right)^2$	Invariant mass of the four jets
$M_{\mathrm{jj}}^{\mathrm{min}}$	$\min_{\substack{i,j\in[1,4]\\ i\neq j}} \left(\left(E_i + E_j\right)^2 - \left(\mathbf{p}_i + \mathbf{p}_j\right)^2\right)$	Minimum invariant mass of any two jets
$\Delta\phi_{ij}^{\mathrm{min}}$	$\min_{\substack{i,j\in[1,4]\\ i\neq j}} \left(\lvert\phi_i - \phi_j\rvert\right)$	Min azimuthal separation of two jets
$\Delta Y_{ij}^{\mathrm{min}}$	$\min_{\substack{i,j\in[1,4]\\ i\neq j}} \left(\lvert Y_i - Y_j\rvert\right)$	Min rapidity separation of two jets
$\Delta\phi_{ijk}^{\mathrm{min}}$	$\min_{\substack{i,j,k\in[1,4]\\ i<j<k}} \left(\lvert\Delta\phi_{ij}\rvert + \lvert\Delta\phi_{jk}\rvert\right)$	Min azimuthal separation between three jets
$\Delta Y_{ijk}^{\mathrm{min}}$	$\min_{\substack{i,j,k\in[1,4]\\ i<j<k}} \left(\lvert\Delta Y_{ij}\rvert + \lvert\Delta Y_{jk}\rvert\right)$	Min rapidity separation between three jets
$\Delta Y_{ij}^{\mathrm{max}}$	$\Delta Y_{ij}^{\mathrm{max}} = \max_{i,j\in[1,4]} \left(\lvert Y_i - Y_j\rvert\right)$	Max rapidity difference between two jets
$\Sigma p_{\mathrm{T}}^{\mathrm{central}}$	Sum of p_{T} of the two central-rapidity jets	Excludes jets having $\Delta Y_{ij}^{\mathrm{max}}$

E.G. FOUR-JET MONTE CARLO SAMPLES

Name	Hard process	PDF	Parton shower	Underlying event	Tune
Pythia8-CT10	PYTHIA 8	CT10	PYTHIA 8	PYTHIA 8	AU2-CT10
Pythia8-CTEQ6L1	PYTHIA 8	CTEQ6L1(†)	PYTHIA 8	PYTHIA 8	AU2-CTEQ6L1
Herwig++	Herwig++	CTEQ6L1	Herwig++	Herwig++	UE-EE-3-CTEQ6L1
Alpgen+Herwig	Alpgen	CTEQ6L1	HERWIG 6	JIMMY	AUET2-CTEQ6L1
Alpgen+Pythia	Alpgen	CTEQ6L1	PYTHIA 6	PYTHIA 6	Perugia 2011C
Madgraph+Pythia	Madgraph	CTEQ6L1	PYTHIA 6	PYTHIA 6	AUET2B-CTEQ6L1
Sherpa	Sherpa		Sherpa	Sherpa	

Table 2: The different Monte Carlo generators used for comparison against the data are listed, together with the parton distribution functions, parton shower algorithms, underlying event and parameter tunes. (†) The Pythia8-CT6L1 sample uses CT10 when calculating the Matrix Element but CTEQ6L1 when simulating the parton shower and underlying event. The first listed sample (Pythia8-CT10) is used for the deconvolution of detector effects.

THE ATLAS TRIGGER SYSTEM

Rate (2012 conditions)

Hardware

20 MHz
Bunch crossing rate

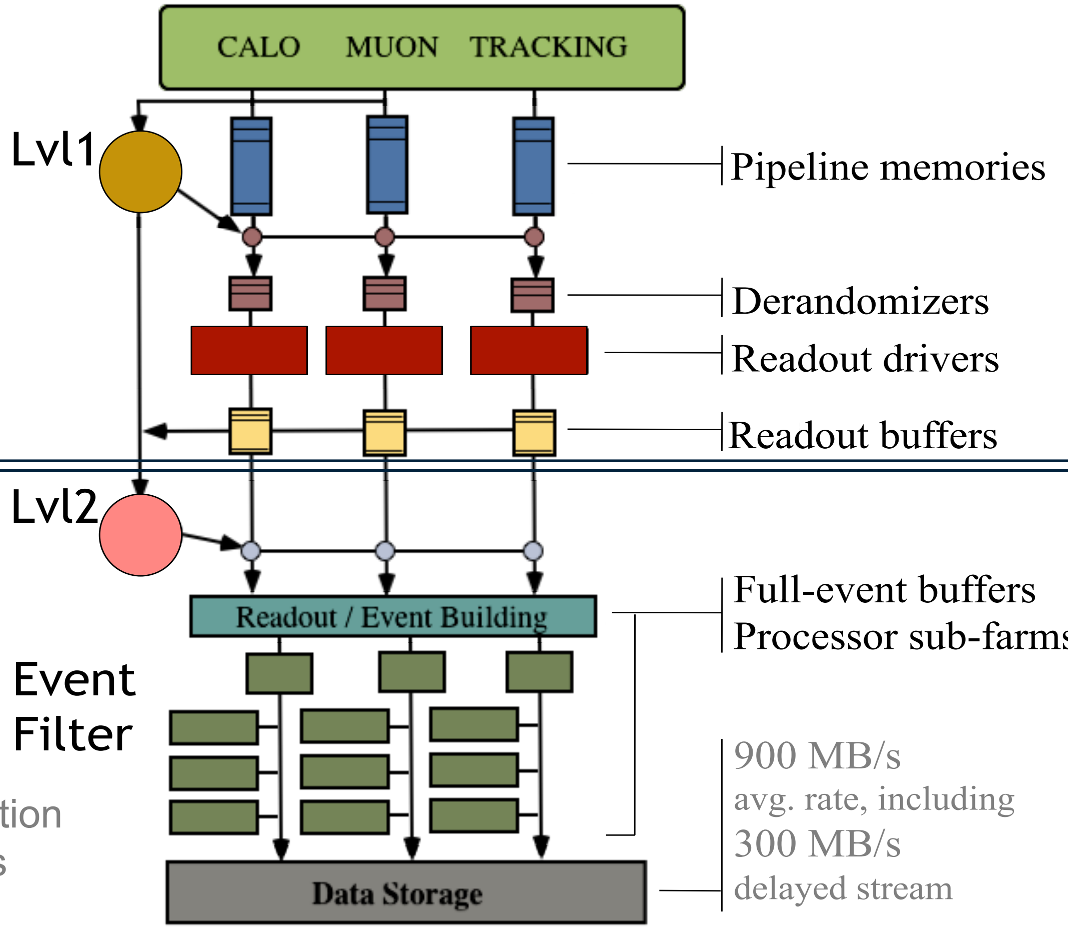
6.4×10^8
Interactions/s

75 kHz
Peak rate

Software

6 kHz
Peak rate

600 Hz
Avg. rate, including
200 Hz delayed stream
(stored for later reconstruction
when computing resources
available)

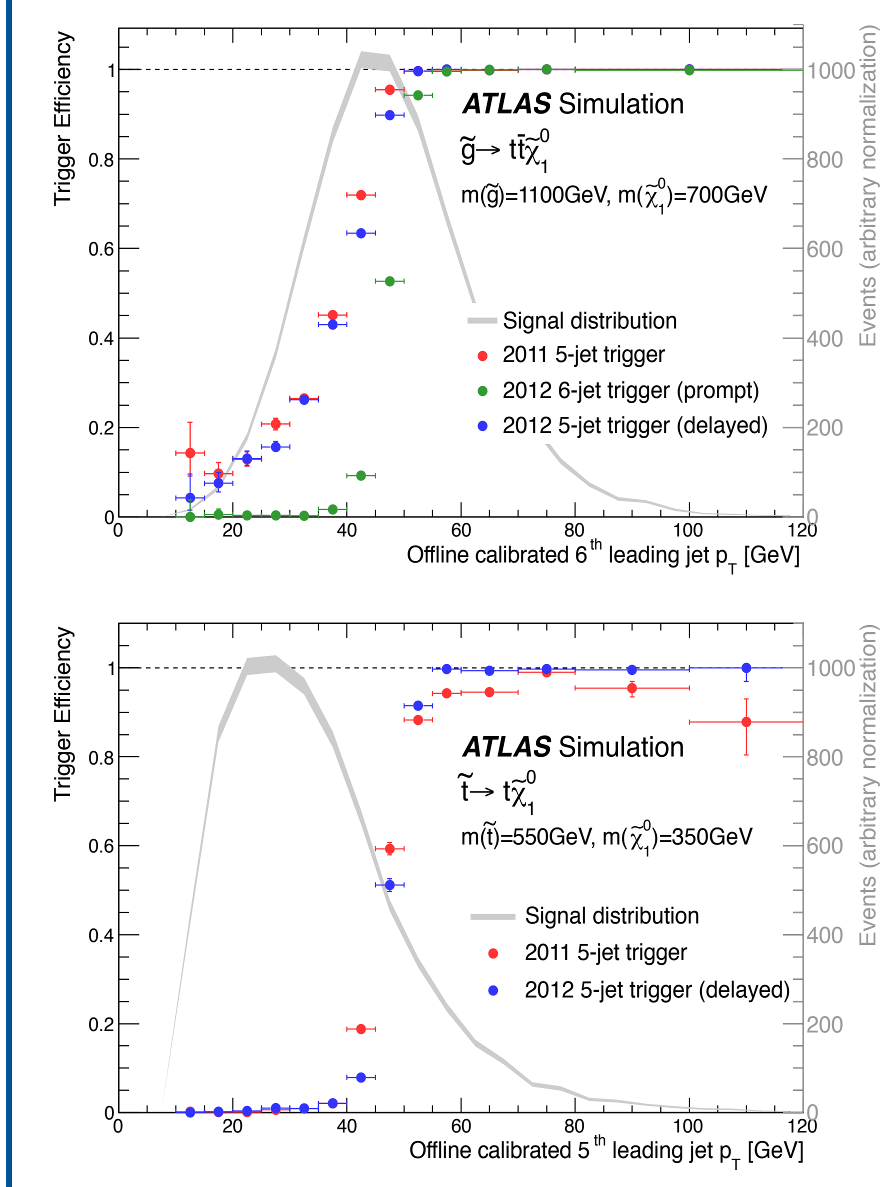


TRIGGER

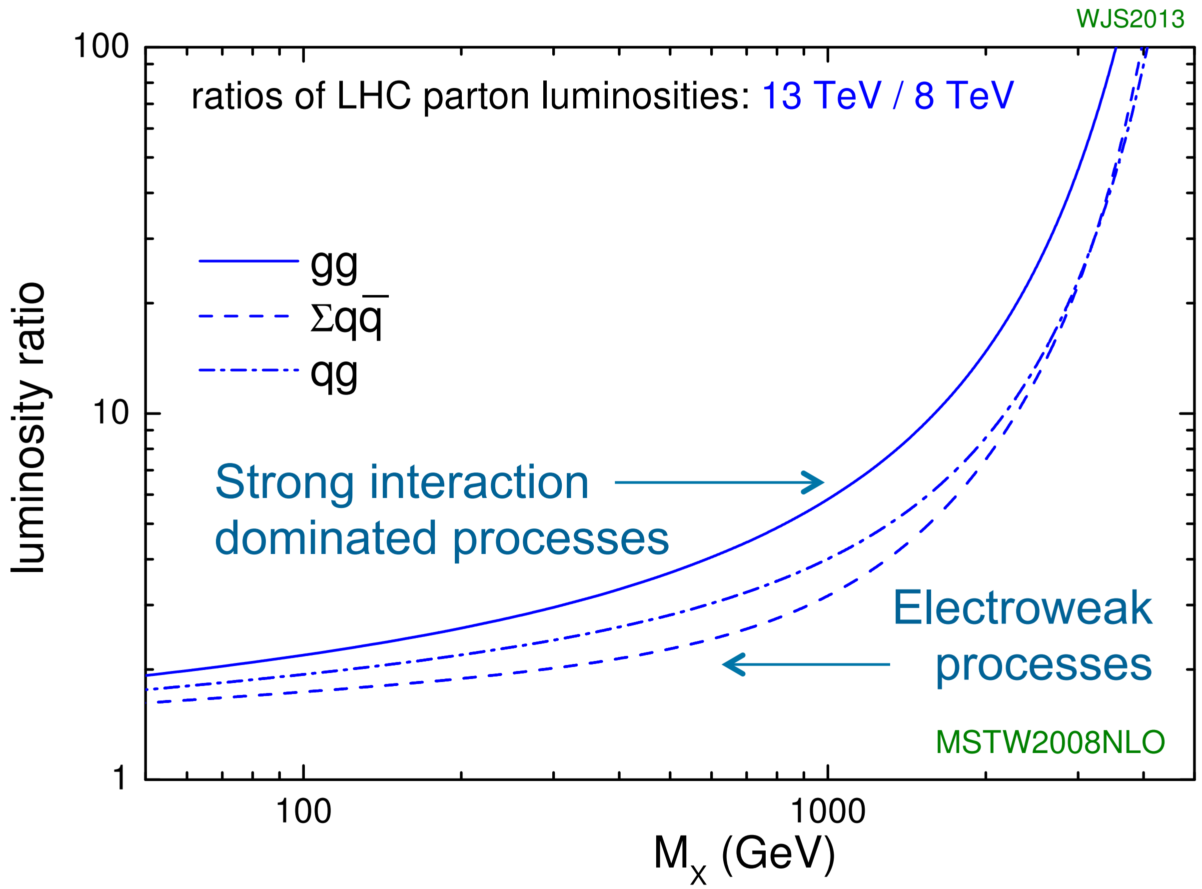
Signal triggers		
Jet Multiplicity	pT cut	|η|
6	45	3.2
5	55	

Background/support triggers	
Type	Purpose
Multijet (prescaled)	Efficiencies & Control regions
Single lepton	Control regions

Multijet trigger improvements in 2012



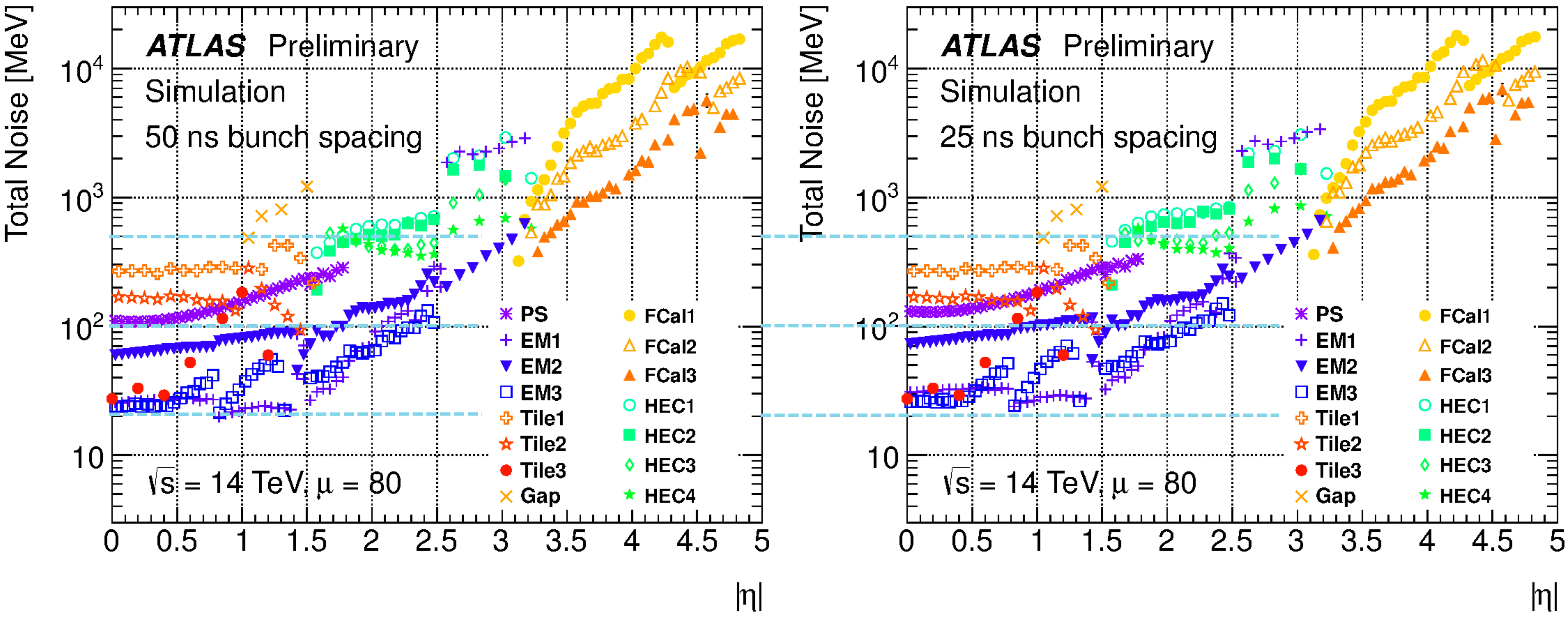
THE BENEFITS



THE CHALLENGES

The calorimeter

Simulated noise in the Liquid Argon and Tile calorimeters at the electron scale



THE 'SOLUTIONS'

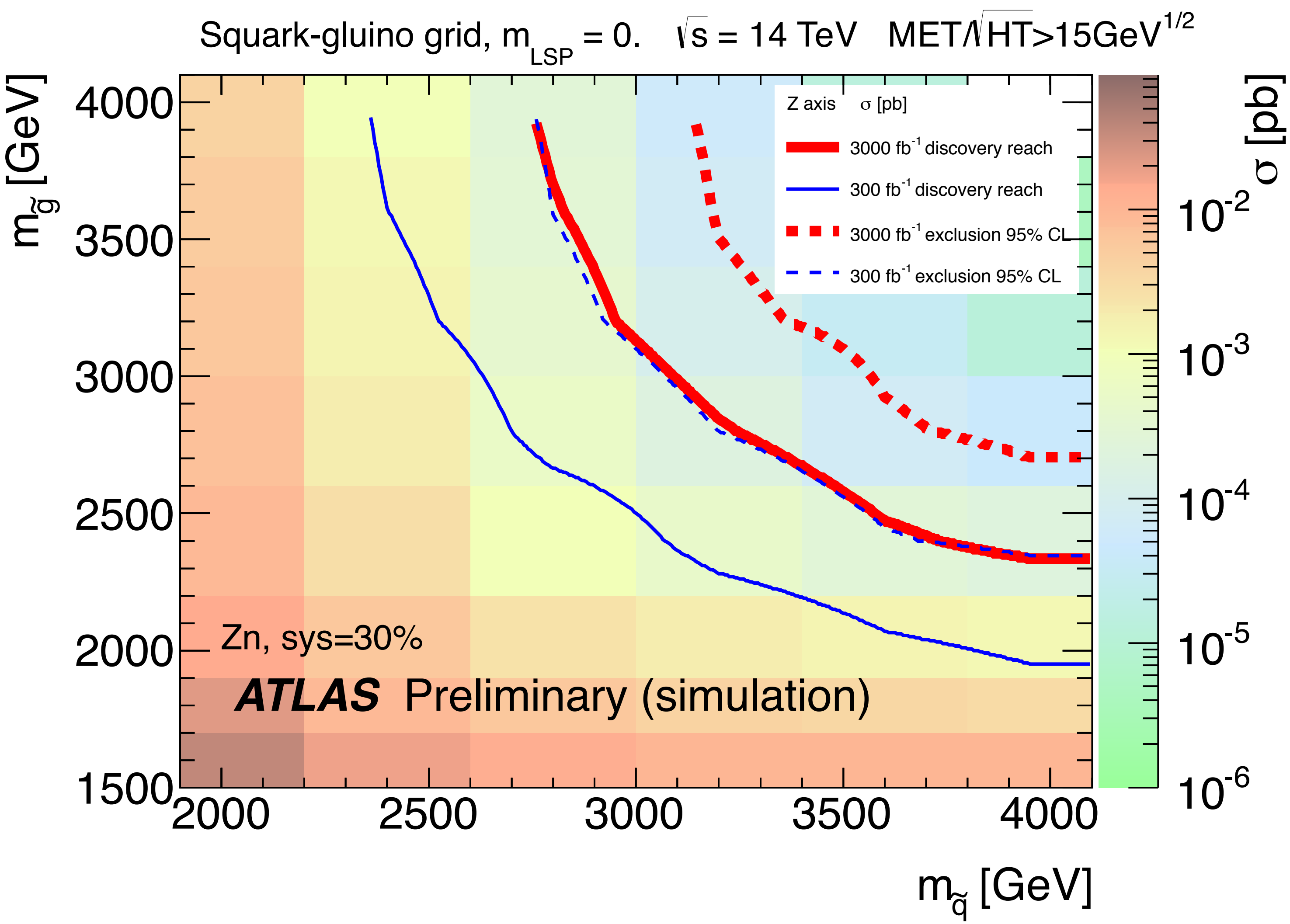
Detector extensions, e.g. extra muon chambers at $1.0<|\eta|<1.3$.

Ongoing trigger upgrade that will:

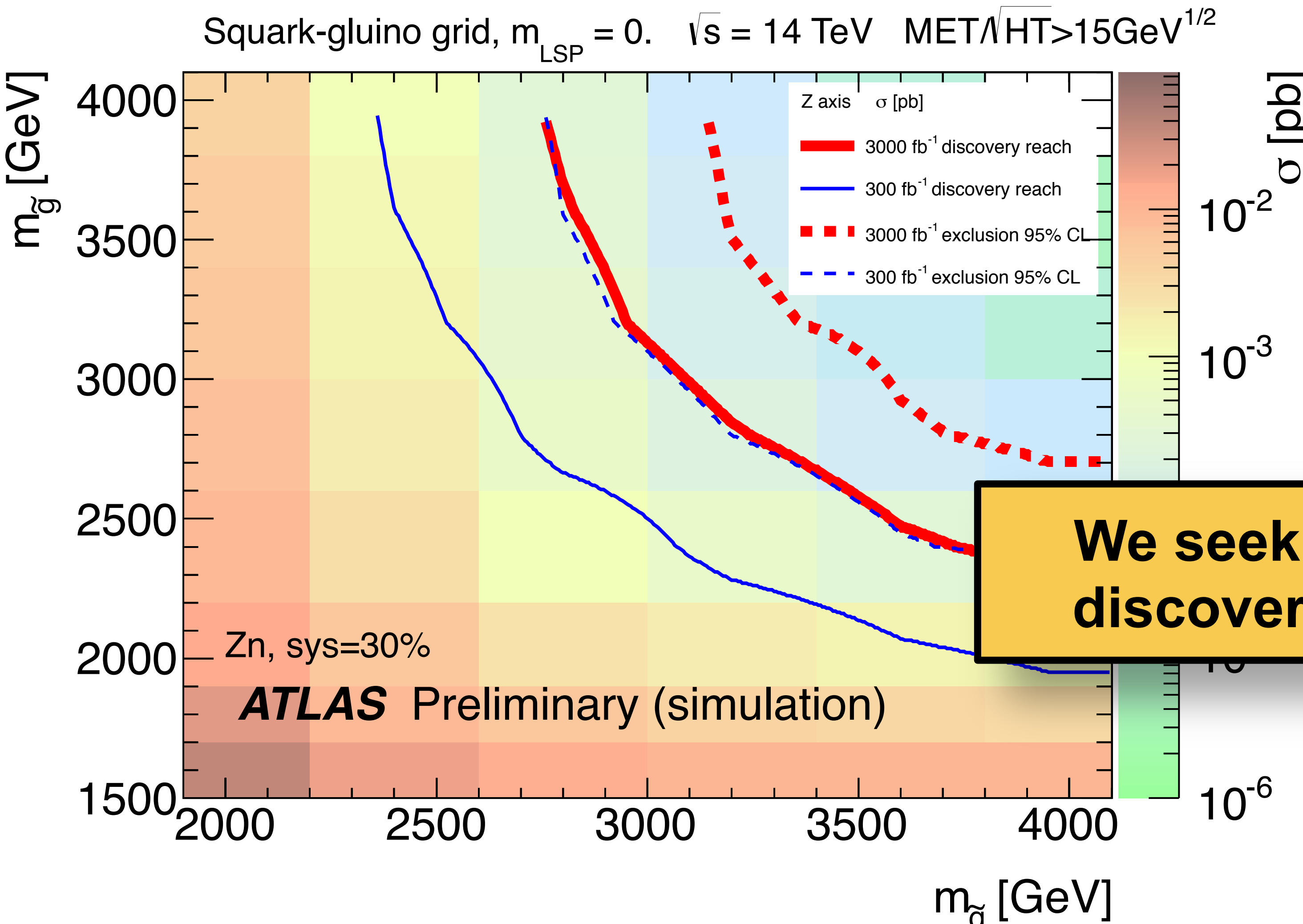
- Increase the peak L1 rate to 100kHz.
- Provide possibility to select on combined L1 quantities (angles, masses, etc).
- Provide tracks at the input of the HLT for better object ID.
- Ensure more efficient and flexible HLT reconstruction with a merged (L2 & EF) HLT.

Clever ideas for better & more robust object reconstruction.

THE PROSPECTS



THE PROSPECTS



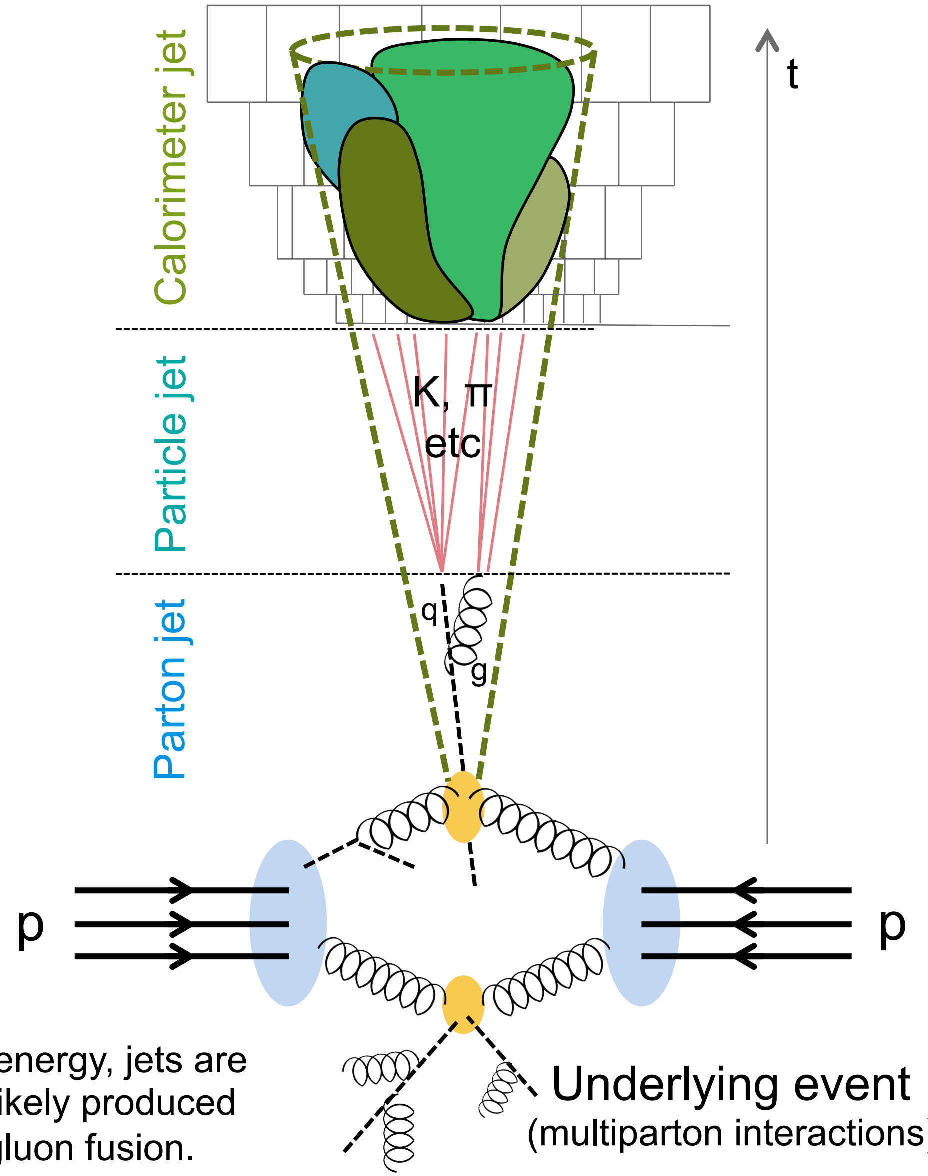
We seek a discovery.

JETS

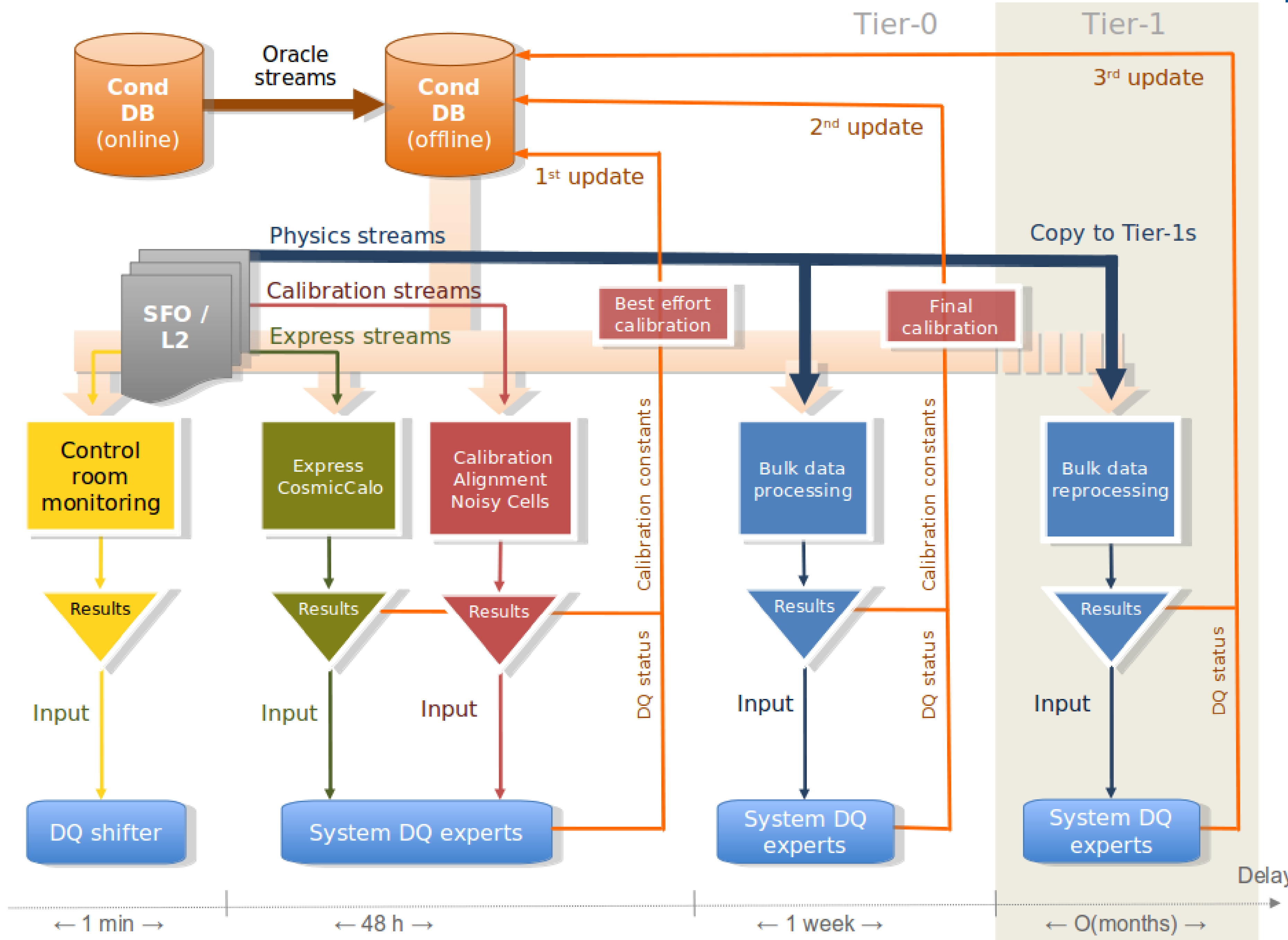
Detector inefficiencies
‘Pile-up’
Electronic noise
Clustering, noise suppression
Dead material losses
Detector response
Algorithm efficiency

Algorithm efficiency
‘Pile-up’
‘Underlying event’

Physics process of interest

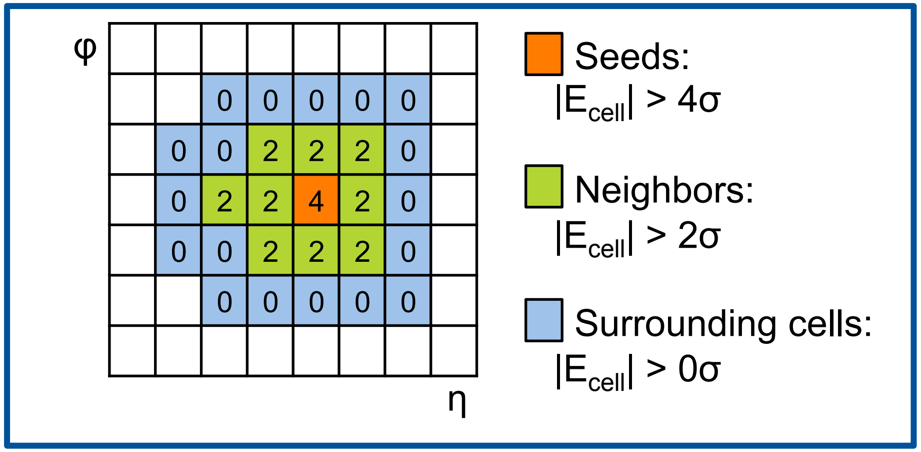


At low energy, jets are more likely produced by gluon fusion.


Tier-0
Tier-1
Cond DB (online)
Oracle streams
Cond DB (offline)
3rd update
2nd update
1st update
Physics streams
Copy to Tier-1s
SFO / L2
Calibration streams
Express streams
Best effort calibration
Final calibration
Control room monitoring
Express CosmicCalo
Calibration Alignment Noisy Cells
Calibration constants
Bulk data processing
Calibration constants
Bulk data reprocessing
Results
Results
Results
Results
Results
DQ status
DQ status
DQ status
Input
Input
Input
Input
Input
DQ shifter
System DQ experts
System DQ experts
System DQ experts
Delay
← 1 min →
← 48 h →
← 1 week →
← O(months) →

ANOTHER EXAMPLE – FROM ATLAS

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



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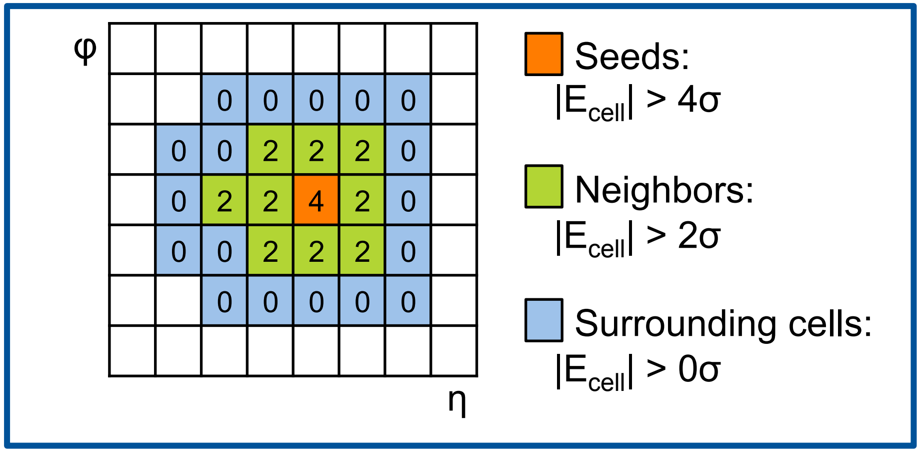

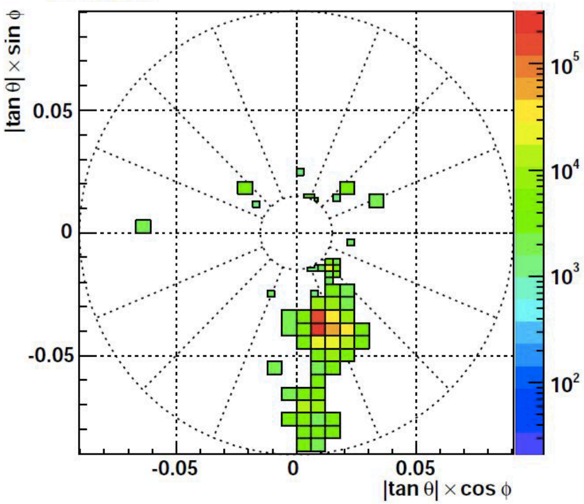

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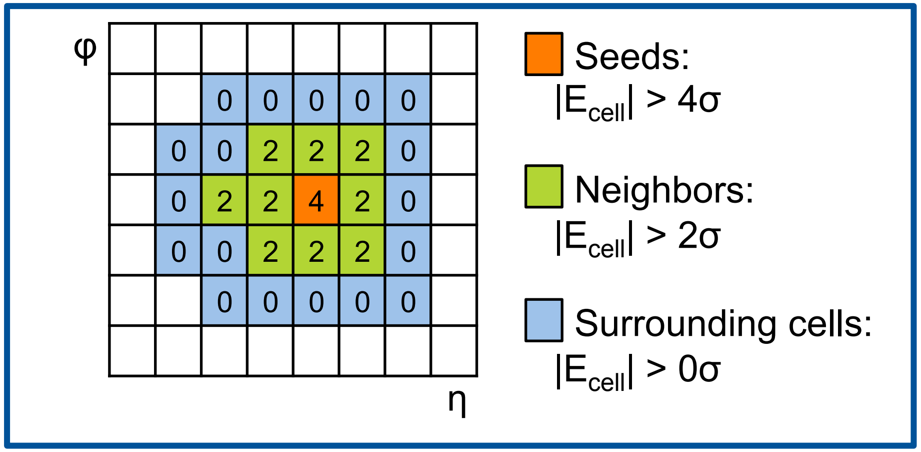

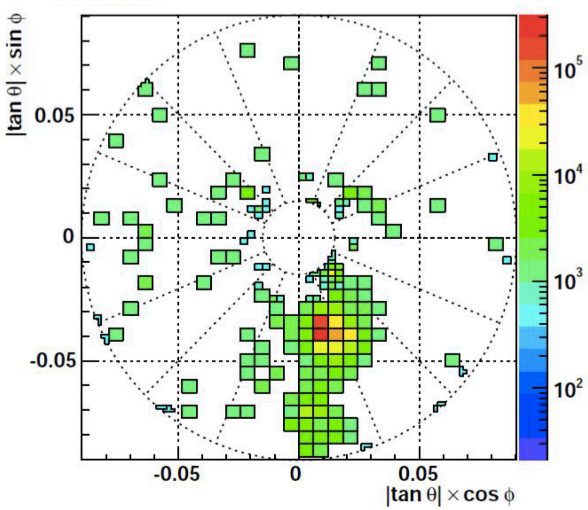

ANOTHER EXAMPLE – FROM ATLAS

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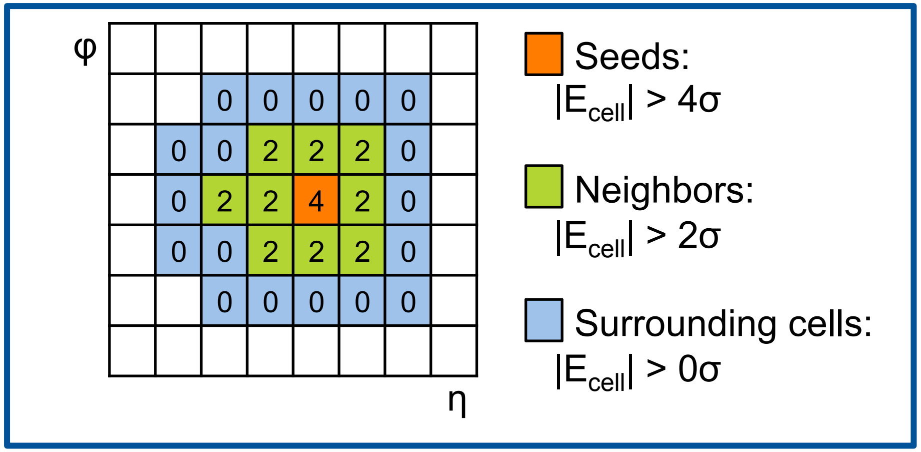
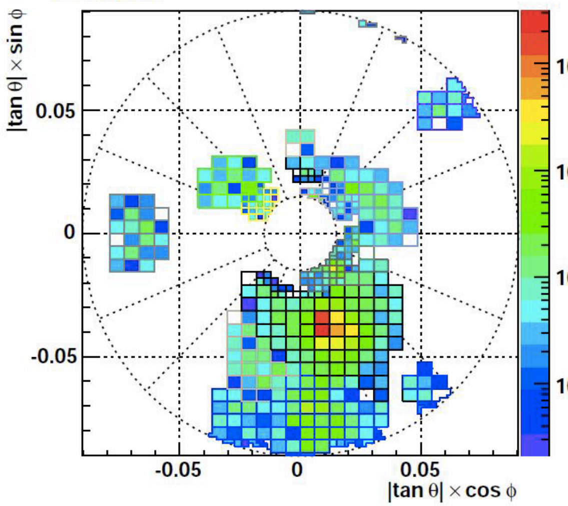
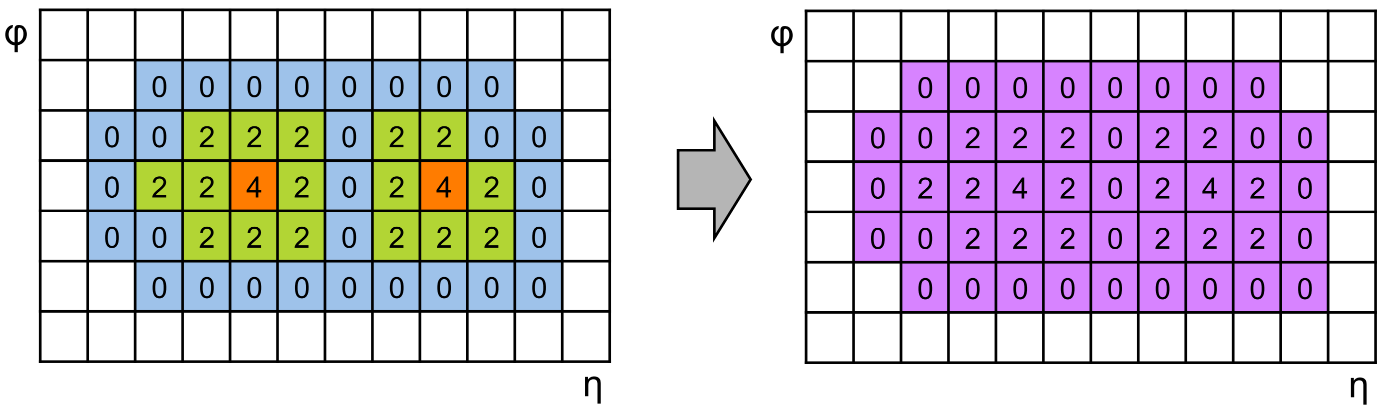


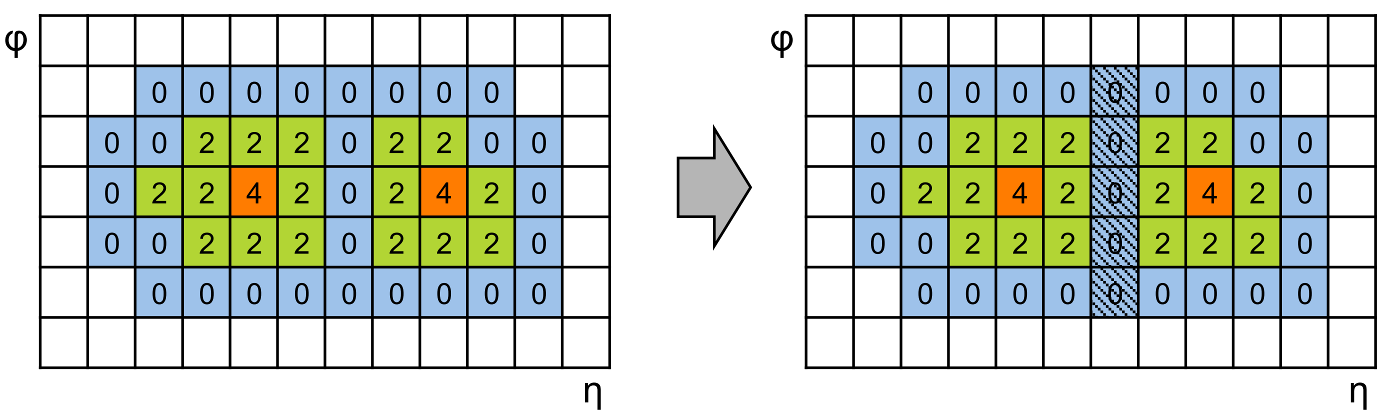


CLUSTER MERGING AND SPLITTING

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



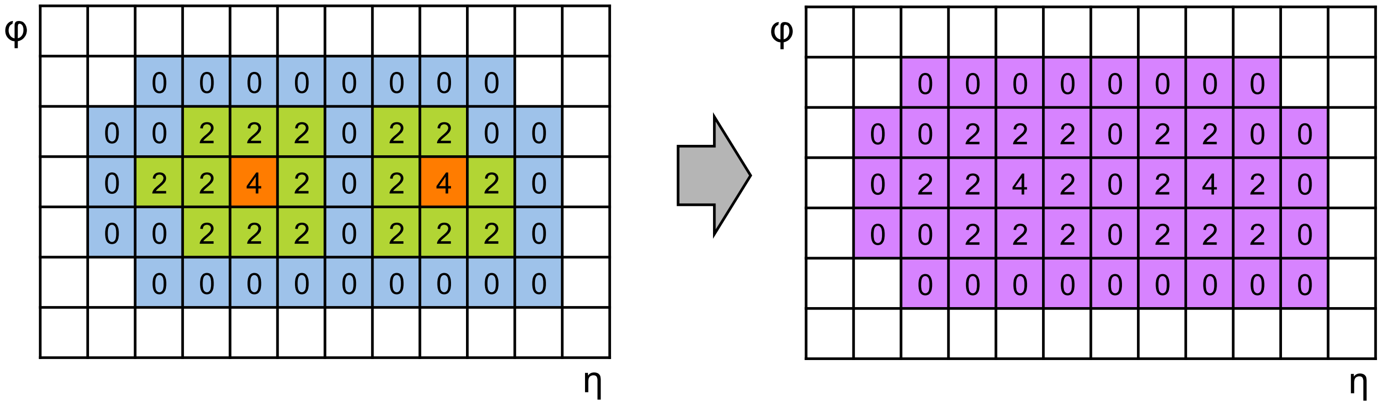
- Clusters are split if more than one local maxima.



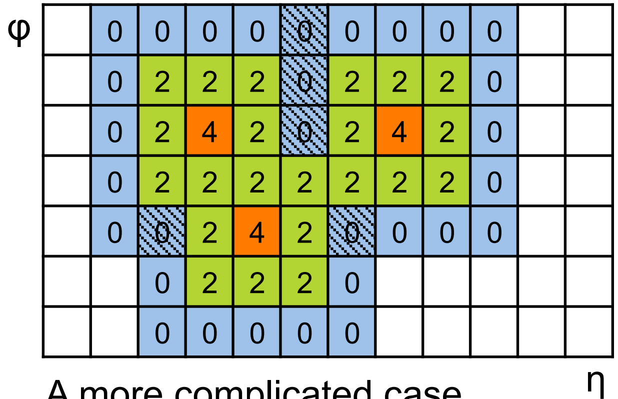
For common cells, a weight is applied to share them (shaded cells).

CLUSTER MERGING AND SPLITTING

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



- Split clusters with more than one local maxima.



A more complicated case…

CLUSTER CALIBRATION

Possible energy measurements:

- **Non-calibrated clusters: sum energy using baseline cell-level detector calibration.**
  - That's NOT the true energy of the particle that originated the cluster.
- **Local calibration: apply weights to correct for:**
  - the different **calorimeter response** on an EM (e.g. π^0) or a hadronic (e.g. $\pi^\pm$) deposition.
  - the low energetic deposits, lost in the tails of the shower (**"out-of-cluster"** corrections, derived from simulation).
  - 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.**

MUONS ON ATLAS

Simplified Detector Transverse View