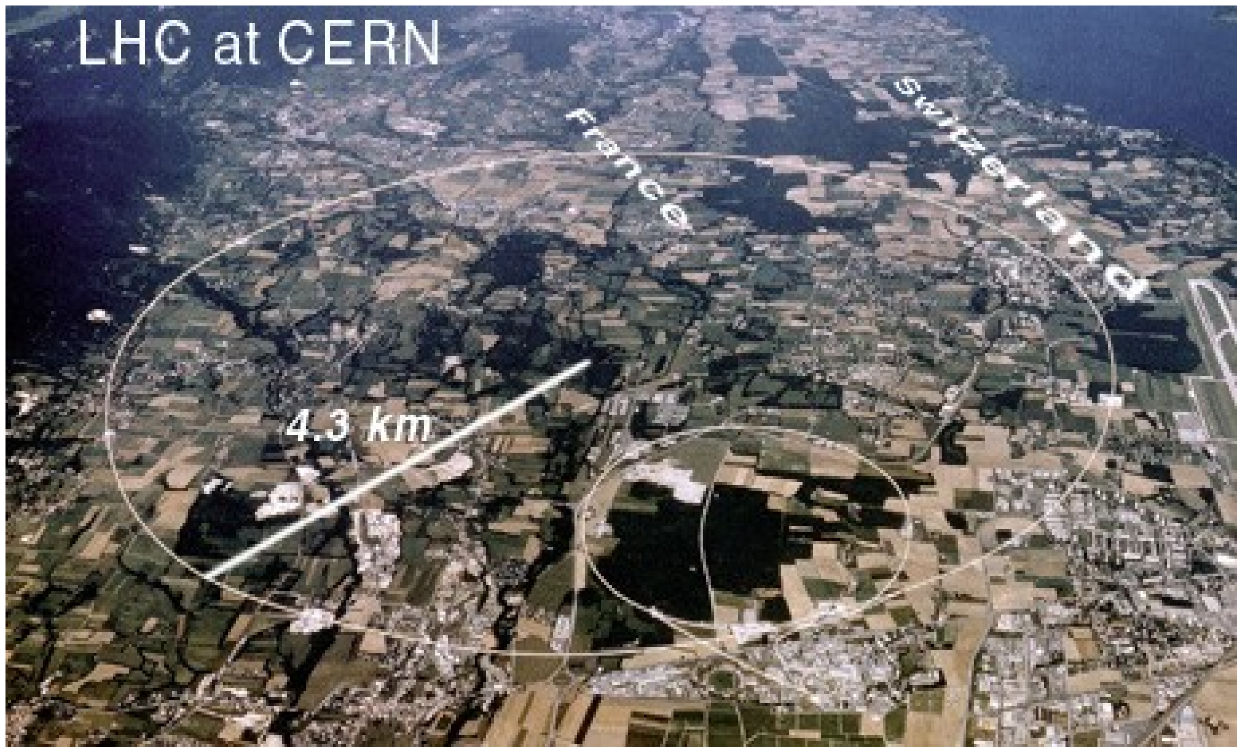
LHC experiment – part 2.



Summer student lectures, DESY Zeuthen 2011

Elin Bergeaas Kuutmann

Today

- Simulation
- Identifying particles

Particle identification;
“stable” and decaying

- Doing analysis

Higgs-hunting!

- Statistics

How do we know that
we saw something?

- Beyond the Standard Model

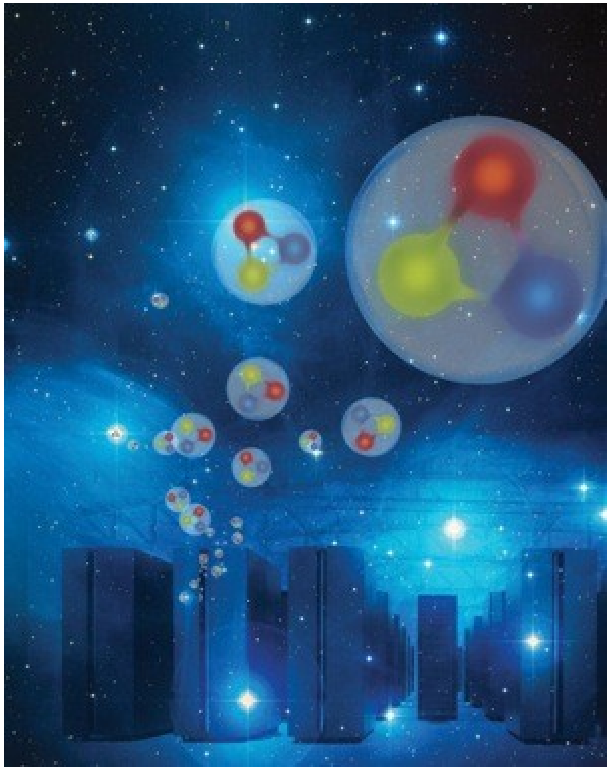
Some general comments

Figure from physicaplus.org.il

First: why? (ver 2.0)

Why do high-energy physics experiments, from the point-of-view of mankind?

- Expanding the frontiers of knowledge.
  Discover the electron of the 22nd century – whatever that might be
- International collaboration
  Peace!
- Spin-off effects
  This web thingy...



scientificamerican.com

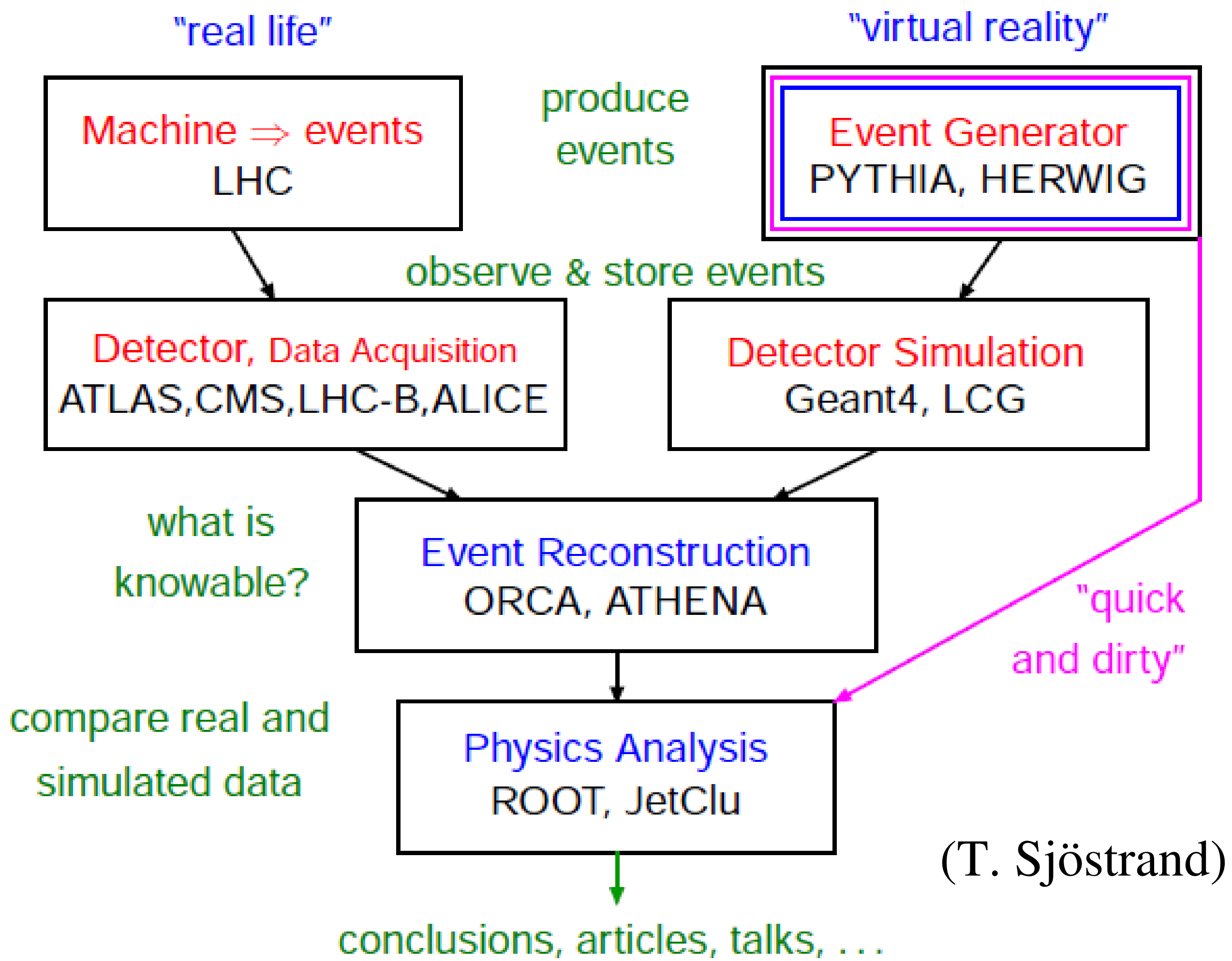
Simulations

Overview of simulation

Why do simulations?

Simulation overview

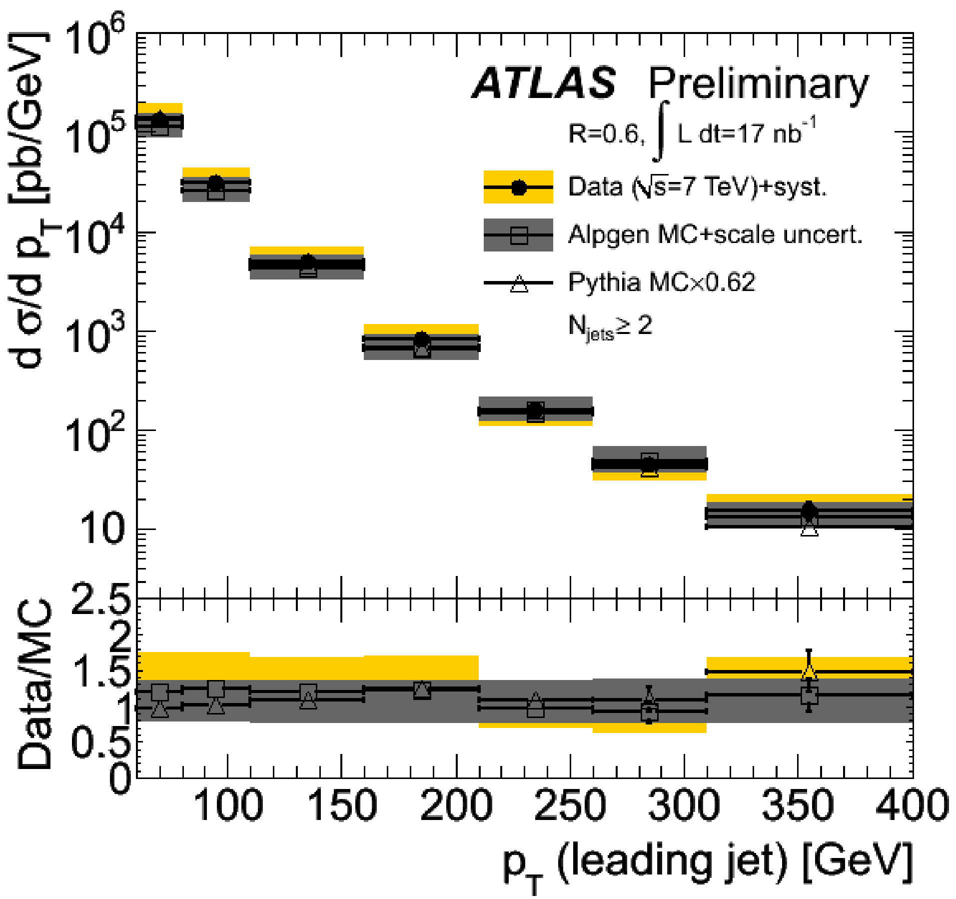
- Events (pp collisions) are generated
  - What is the distribution of partons (quarks and gluons) in the protons?
  - How do they interact?
- Hadronisation of quarks/gluons, decay of e.g. top, W.
- The particles' reactions in the detector is simulated.
- Reconstruct and analyse (almost) like data.



Why simulations?

- Need to compare experiment with theory.
- Theory: complex calculations, involving parton density functions (pp collision), how the hadrons form, how the particles react in the detector.
- If the observed cross section is lower or higher than the predicted, we might have discovered something!
- Constant feedback: the simulation should agree with known physics processes, experiments are compared with simulation.
- We can also prepare analyses and optimise algorithms.

Figure from ATLAS-CONF-2010-084



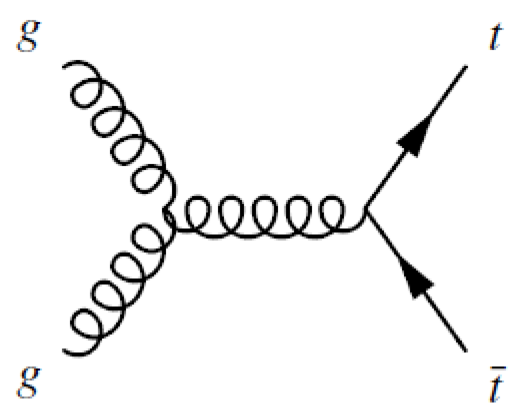
Creating particles

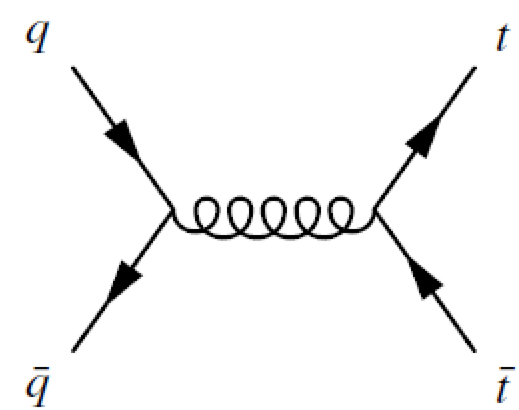
How do we get elementary particles from proton-proton collisions?

Proton-proton collisions

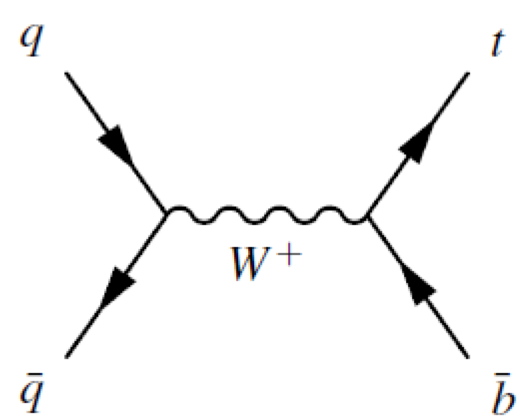
Actually we collide gluons or quarks.

Example how we can create $t\bar{t}$ pairs via the strong force.





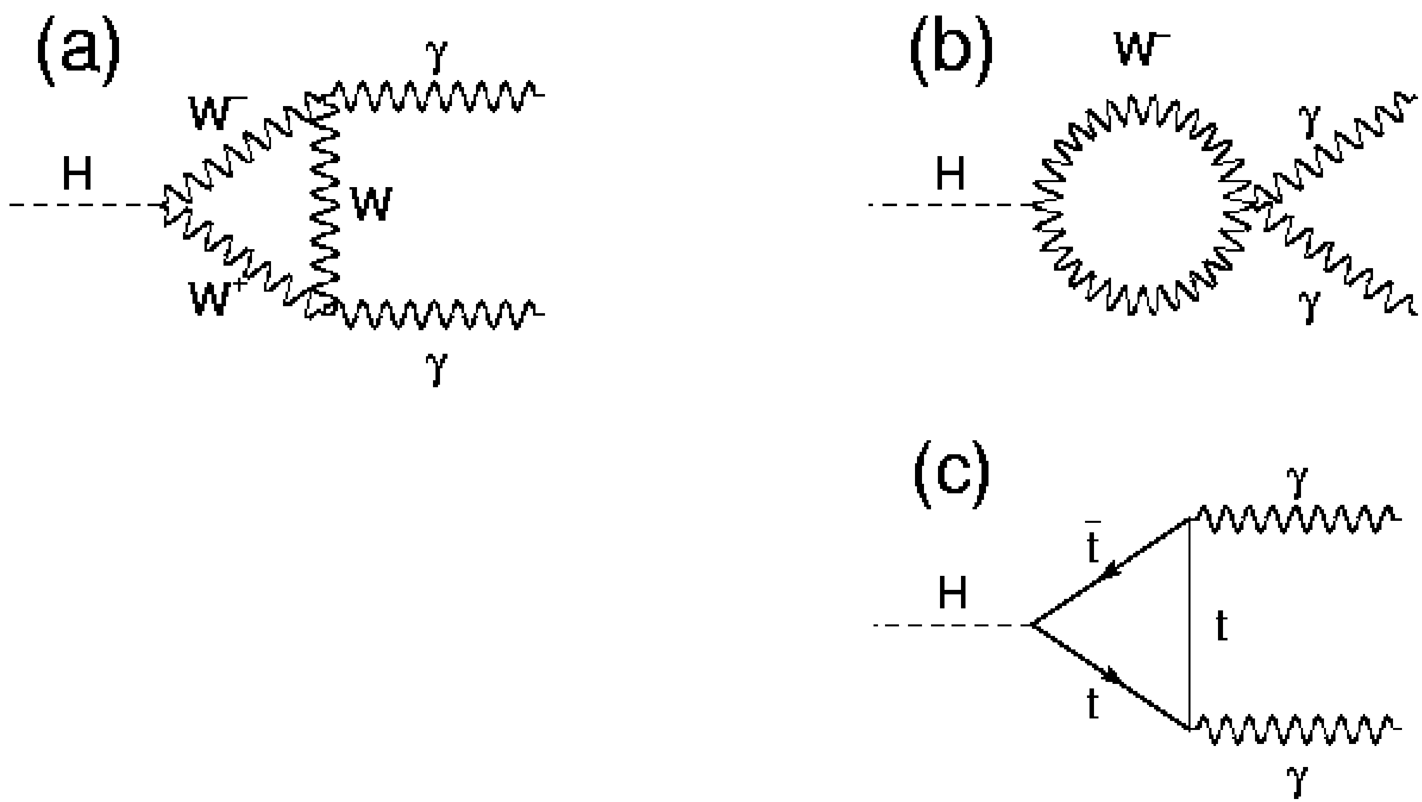
and via the weak force (single top production)



A sneaky thing: $H \rightarrow \gamma\gamma$

- Higgs couples heavily to massive particles.
- Photons are massless...
- $H \rightarrow \gamma\gamma$???

U. Egede, PhD thesis



Loops...

Before the next section:
Activation and recollection break

Identifying particles

Particle identification

electrons, muons, quark/gluons (jets)

Decaying particles

τ, W, Z, b quarks, top quarks, Higgs.

First: a conceptual difference

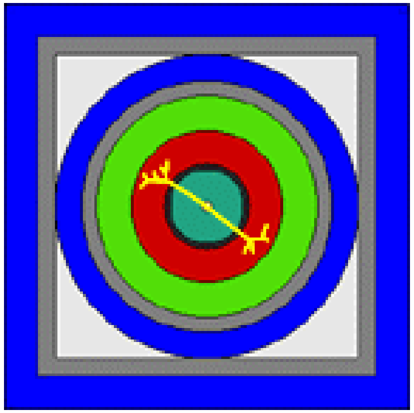
- When a theorist say “electron” he/she means a stable lepton with negative charge and a mass of approximately 0.5 MeV.
- When an experimentalist say “electron” he/she means an object that the electron-finding algorithm has identified as an electron.

Particle identification

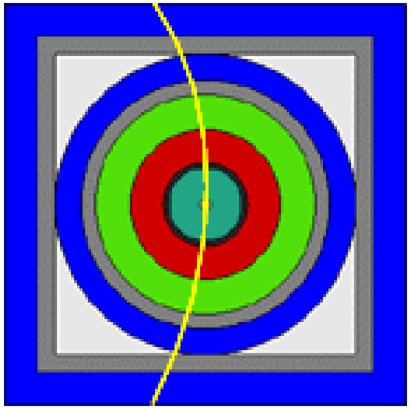
Figures from particleadventure.org

Electrons and photons

- EM showers, that are (reasonably) isolated in the calorimeter (no other energy deposits nearby).
- Tracks present: electron/positron
- No track: photon



e^+e^-



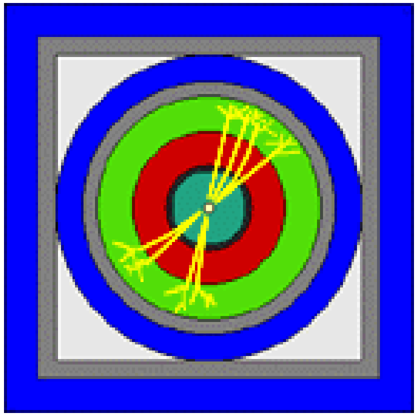
$\mu^+\mu^-$

Muons

- A detected particle in the muon system.
- Not much energy in the calorimeters (isolation).
- Possibly a matching to tracks in the inner detector (combined muon).

Quarks and gluons (jets)

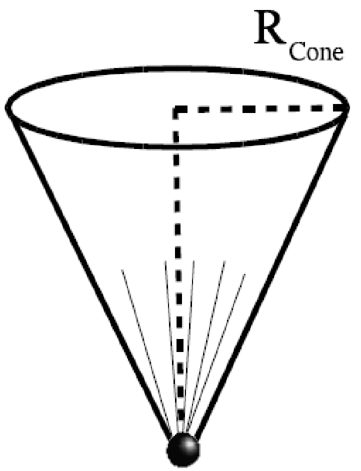
- Quarks and gluons are never free (colour confinement).
- They hadronise, and a spray of hadrons, a **jet**, hit the detector.



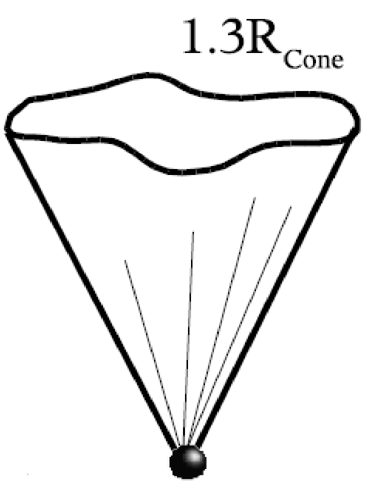
jets

Reconstruct the jet:
Jet algorithms – overview

- **Cone**: Put a cone of a certain opening angle, $\Delta R = \sqrt{(\Delta\eta^2 + \Delta\phi^2)}$, around a seed.



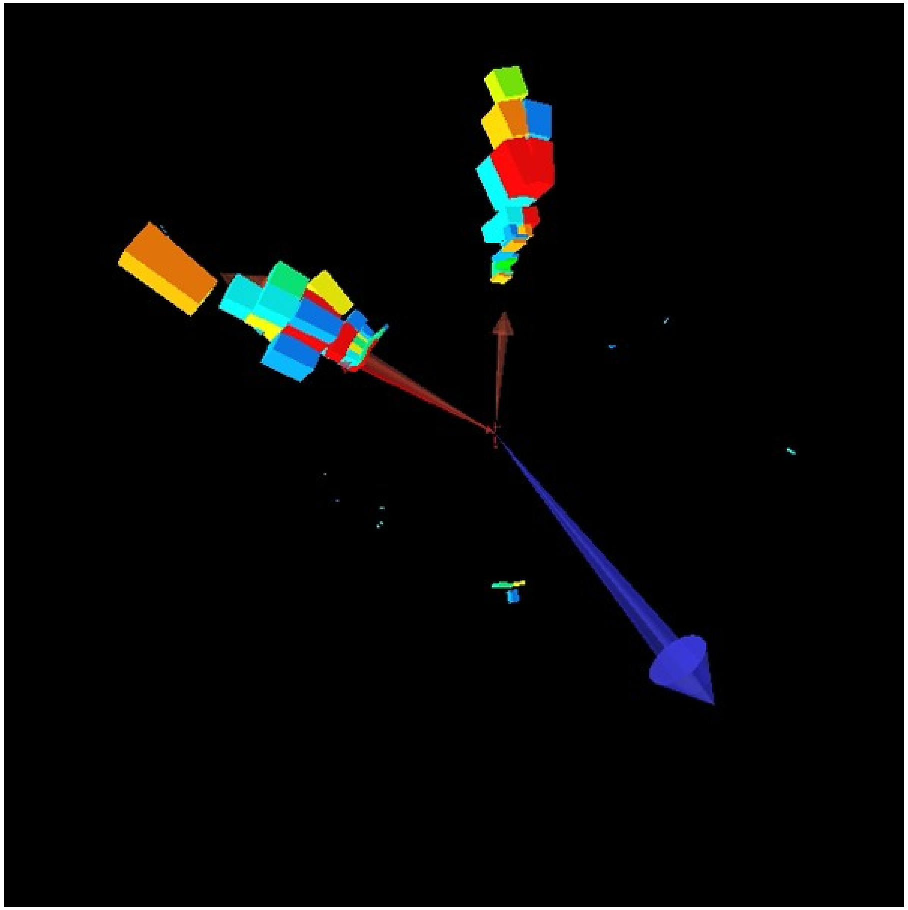
- **Sequential recombination jet algorithms:** Combine signals based on the transverse momentum and/or closeness.
  Can have asymmetric shapes.
  Examples:
  k_T, anti-k_T, Cambridge/Aachen...



Other jet algorithm types occur, but these are the most important in *pp* collisions.

To see the unseen: missing transverse energy

- Energy and momentum is conserved in the collisions.
- Sum all energy deposits (multiplied with direction) in the transverse plane, ΣE_T
- $\Sigma E_T = 0$ (energy conservation)
- If $\Sigma E_T \neq 0$, th remainder must belong to a particle that didn't interact. The missing energy is called E_T^{miss}.
- The particle could be a neutrino or maybe dark matter?



2 jets and E_T^{miss} in the D0 detector (Tevatron). www.fnal.gov/pub/today

Particle identification: decaying particles

- Particles are identified through their decay products. Compute invariant mass: $$M^2 = \left(\sum_{particles} E \right)^2 - \left\| \sum_{particles} p \right\|^2 \quad (c=1)$$

Particle decays:

- $Z \rightarrow l^+ l^- \ (l: e, \mu, \tau, \nu)$ or quarks
- $W^+ \rightarrow l^+ \nu$ or qq'
- $\tau^- \rightarrow e^- \overline{\nu}_e \nu_\tau, \ \mu^- \overline{\nu}_\mu \nu_\tau, \ \text{hadrons}$
- $t \rightarrow bW$
- *b* quark: decay of the *B* mesons (more follows soon)
- Higgs: the decay is mass dependent (as discussed yesterday)

Example: a Z –> e^+e^- candidate event

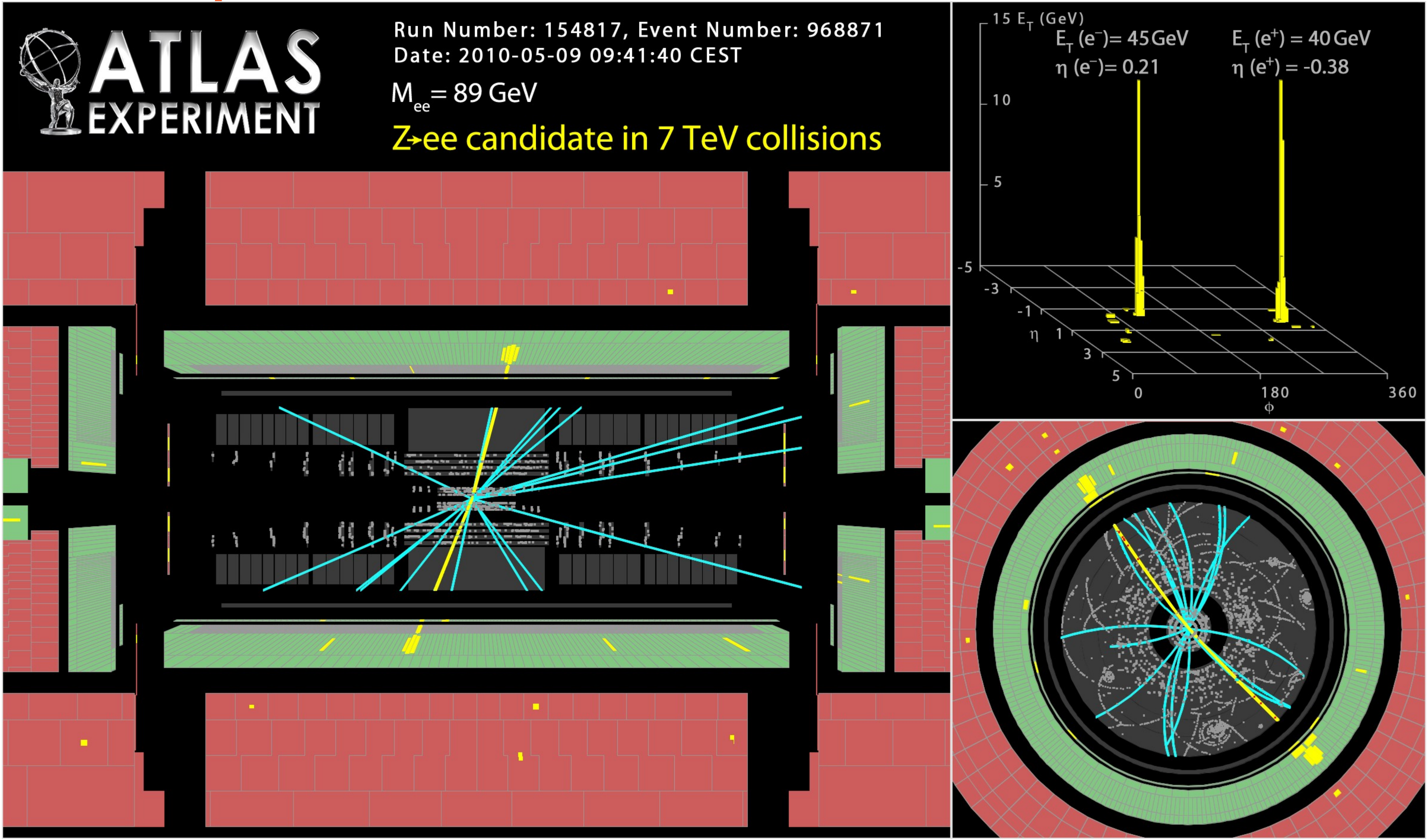


Image from https://twiki.cern.ch/twiki/bin/view/Atlas/EventDisplayPublicResults

B-tagging

- *b* quarks form B mesons, that decay in the beam pipe.
- The tracks from the resulting hadrons point to a secondary vertex.
- Presence of a secondary vertex in a jet: “b-tagged”
  Typically this is 50-70% efficient, but still a powerful way to reduce backgrounds from light jets.

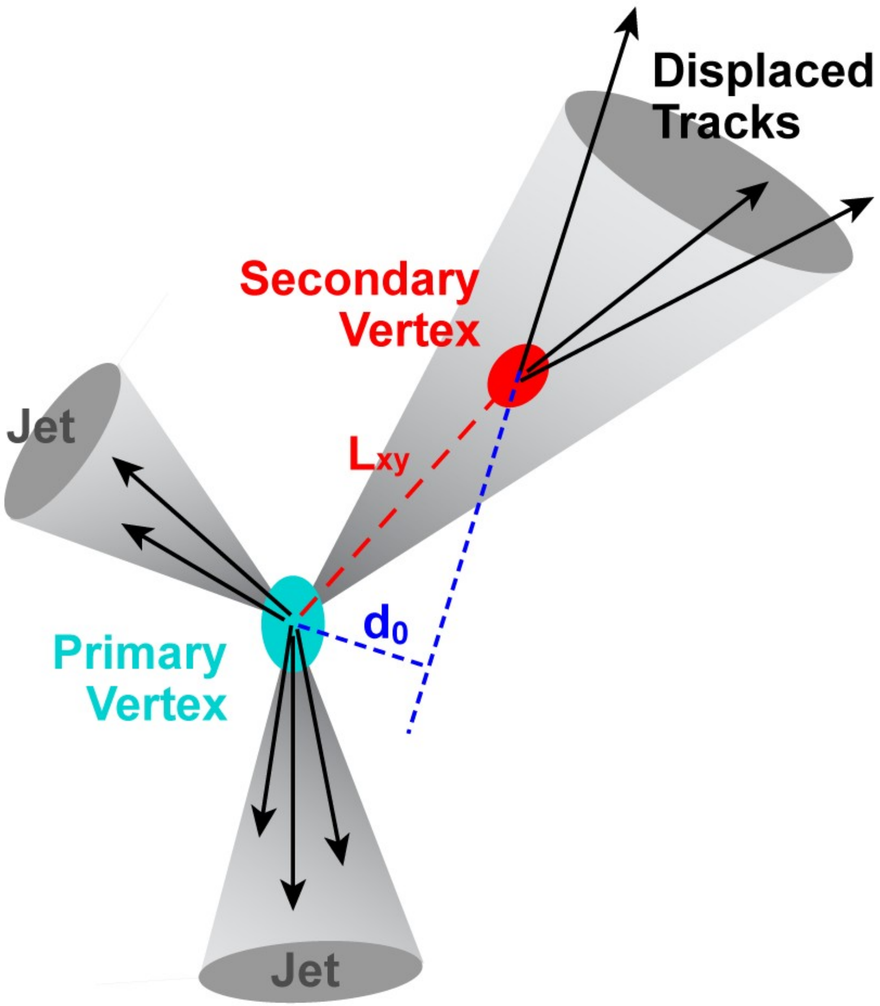


Figure from Phys. Rev. Lett. 103, 092001 (2009)

Analysis

Higgs hunting:

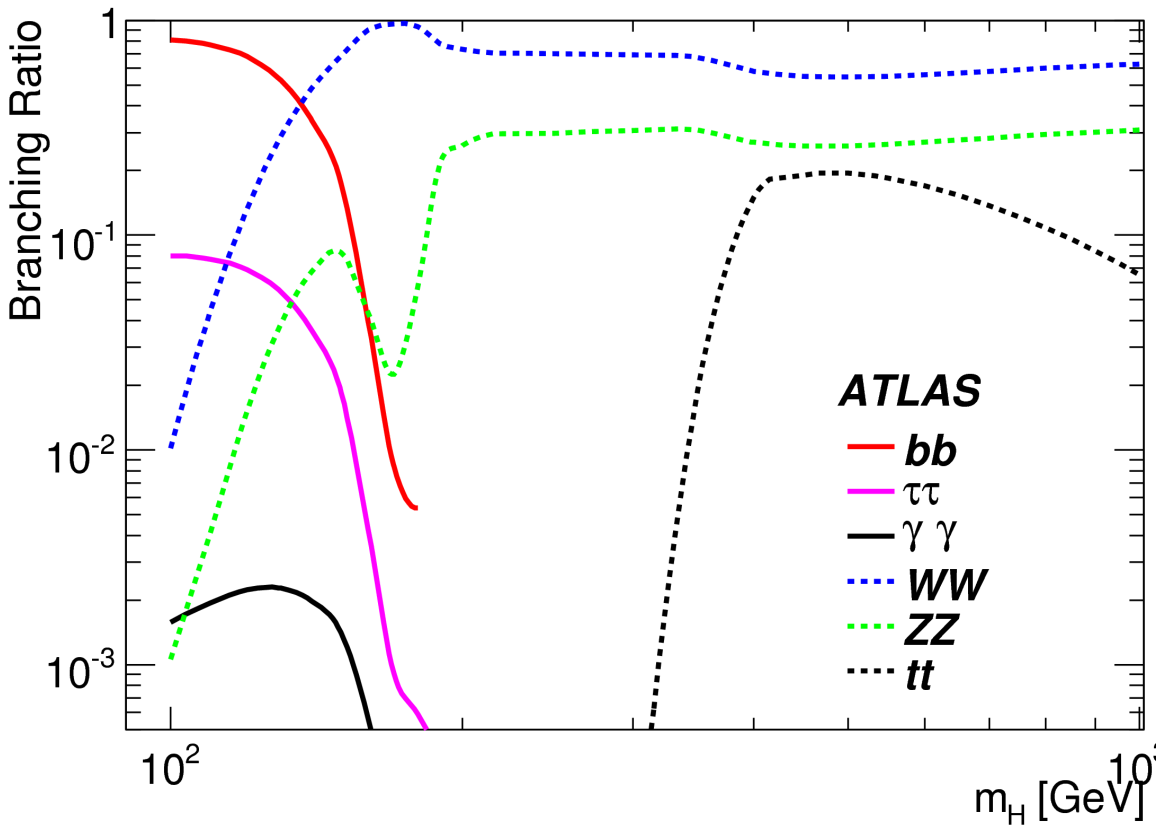
How to interpret the plots from the EPS conference

Decay modes and reconstruction of a light Higgs

Looking for the Higgs boson
Reminder from yesterday

- For a low-mass Higgs (favoured), $H \rightarrow b\bar{b}$ dominant.
Hard to detect (lots of b's and light jets in the background).
- $H \rightarrow \gamma\gamma$ is the "golden channel" (clean) but has low branching ratio.
- $H \rightarrow WW$ also likely.
- One other possible analysis:
Consider
$pp \rightarrow HV$, $V \rightarrow leptons$,
$H \rightarrow b\bar{b}$

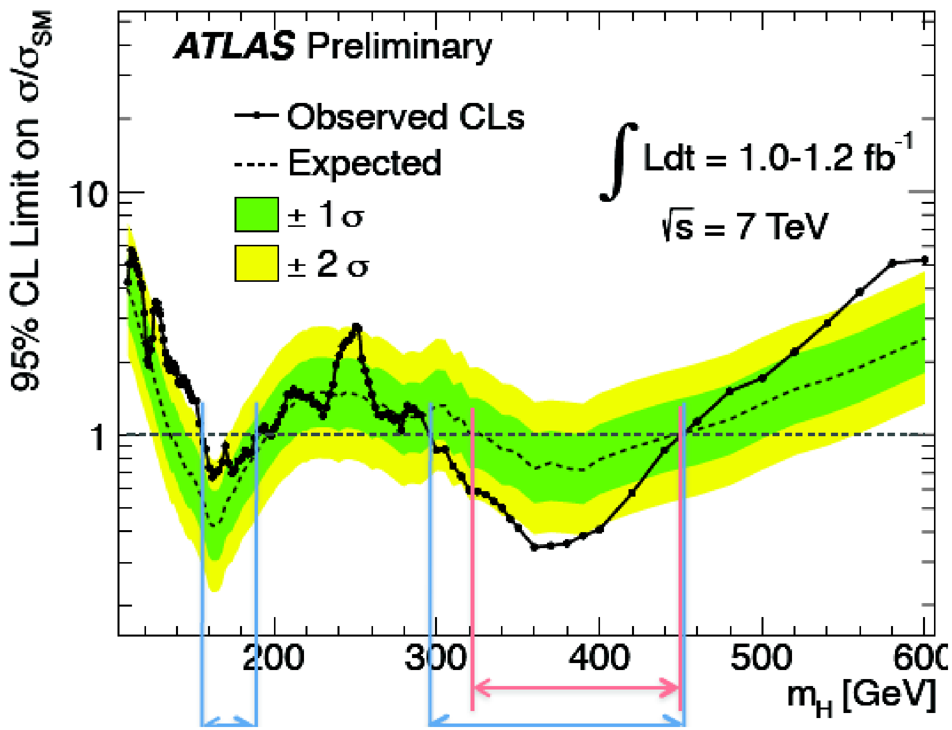
Figure from CERN-OPEN-2008-020



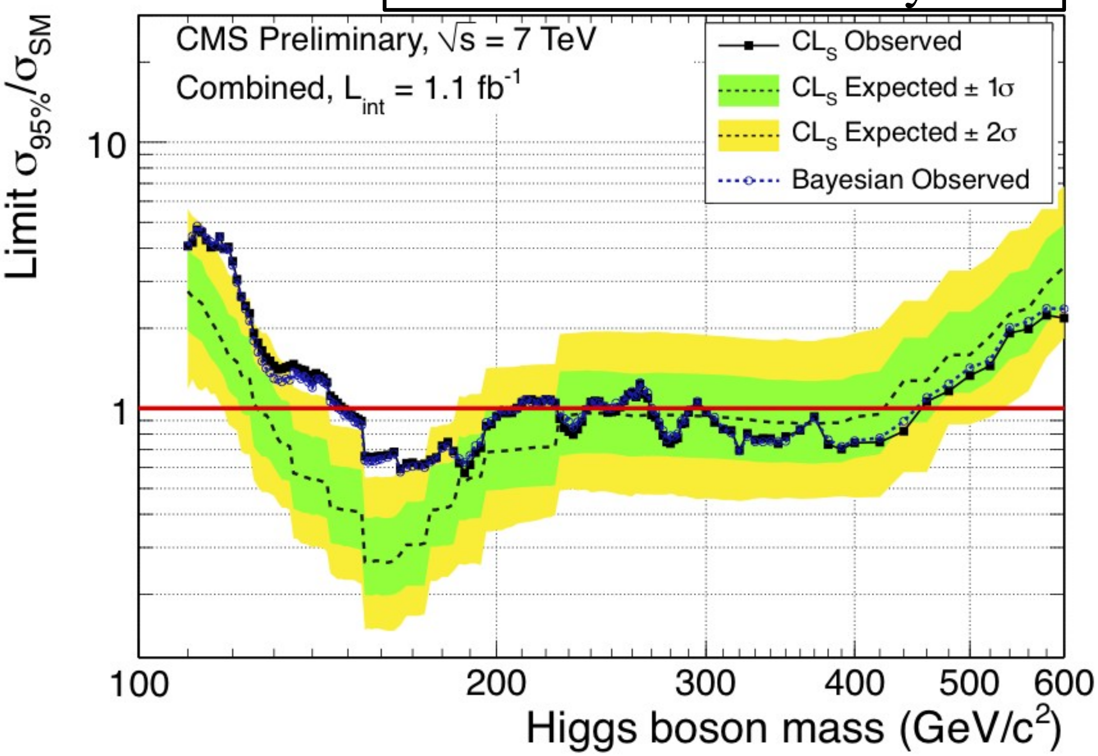
Before the Higgs hunting: Activation break

The recent Higgs hunting results...

- What do the plots tell?
- Which regions are excluded?
- Do we see something at 140 GeV?



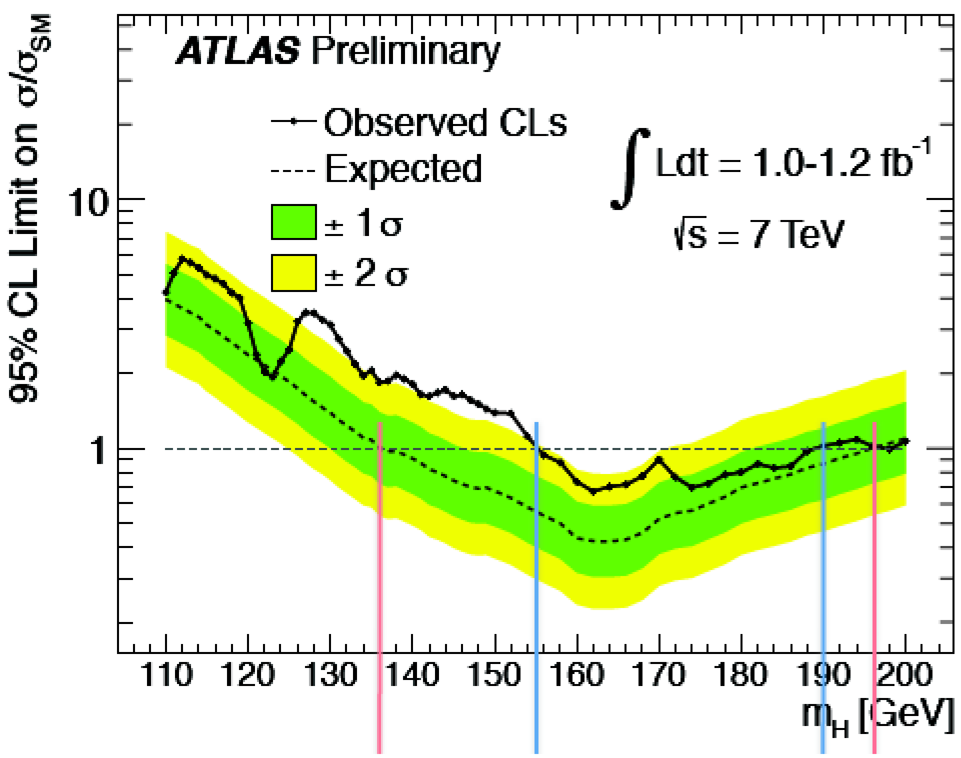
Presented at EPS 22 July 2011



What does the plot show?

- Combination of all channels; at low mass mainly $\gamma\gamma$, WW and bb.
- Cross section limit divided by SM cross section.
- Regions where the observed limit is below 1 are excluded.
- Regions where the observed limit is well above the expected is where we have an excess of events compared to SM predictions.

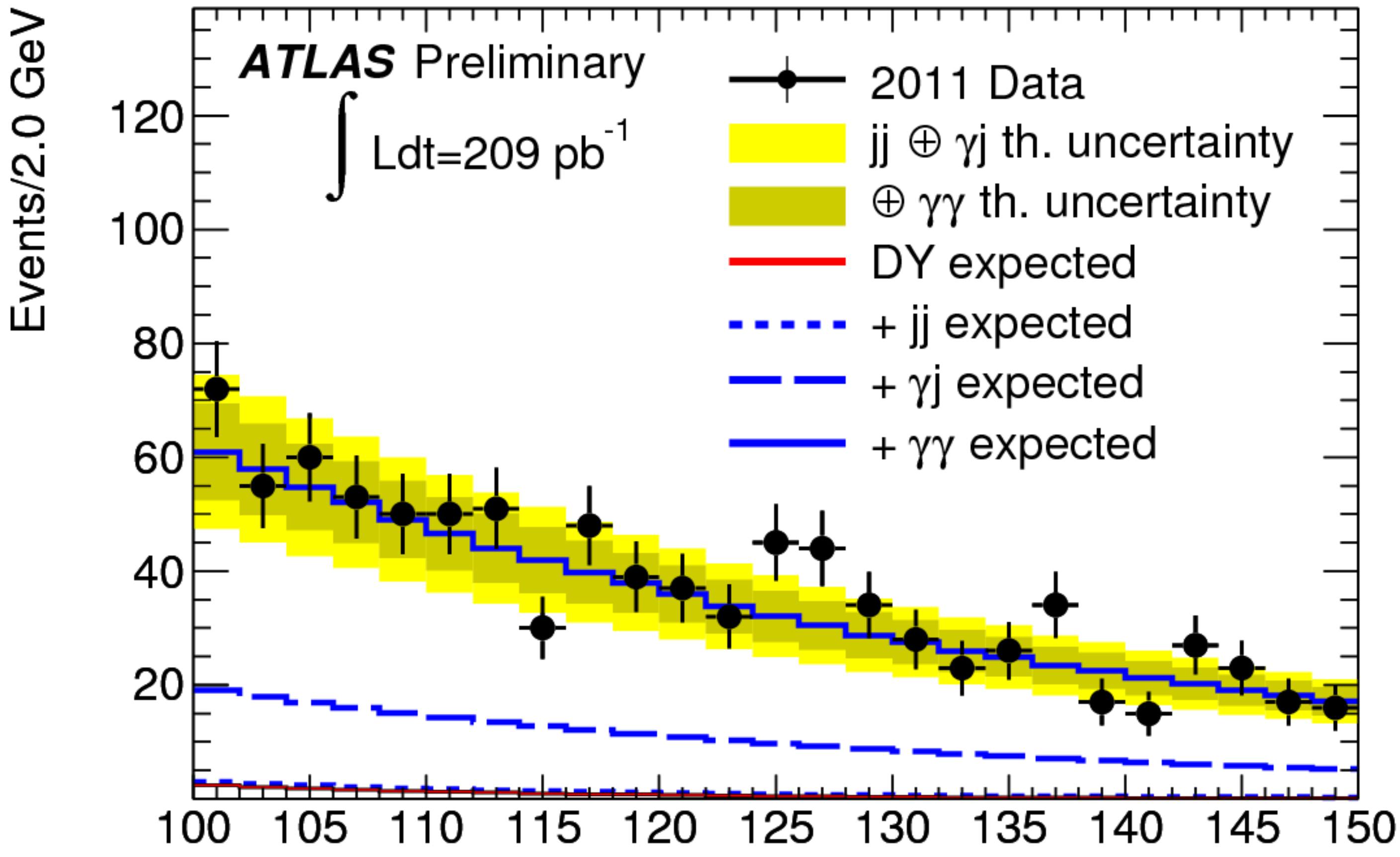
Presented at EPS 22 July 2011



$155 < M_H < 190$ and $295 < M_H < 450$ GeV excluded at @ 95% CL

How to reconstruct a Higgs event?

- We compare the expected background (often from simulation) with observed data.
- Here $H \rightarrow \gamma\gamma$
  We have a lot of background from other $\gamma\gamma$ processes and jets being mis-identified as γ.
- The production cross section of *H* is small and the branching ratio to $\gamma\gamma$ is tiny ($\sim 10^{-3}$)



ATLAS-CONF-2011-085

$H \rightarrow WW$

- Easiest to reconstruct if $WW \rightarrow l\nu l\nu$.
- But then we get 2 neutrinos!
- E_T^{miss} comes from both ν. No way to tell how the energy was shared. Mass resolution will be bad.

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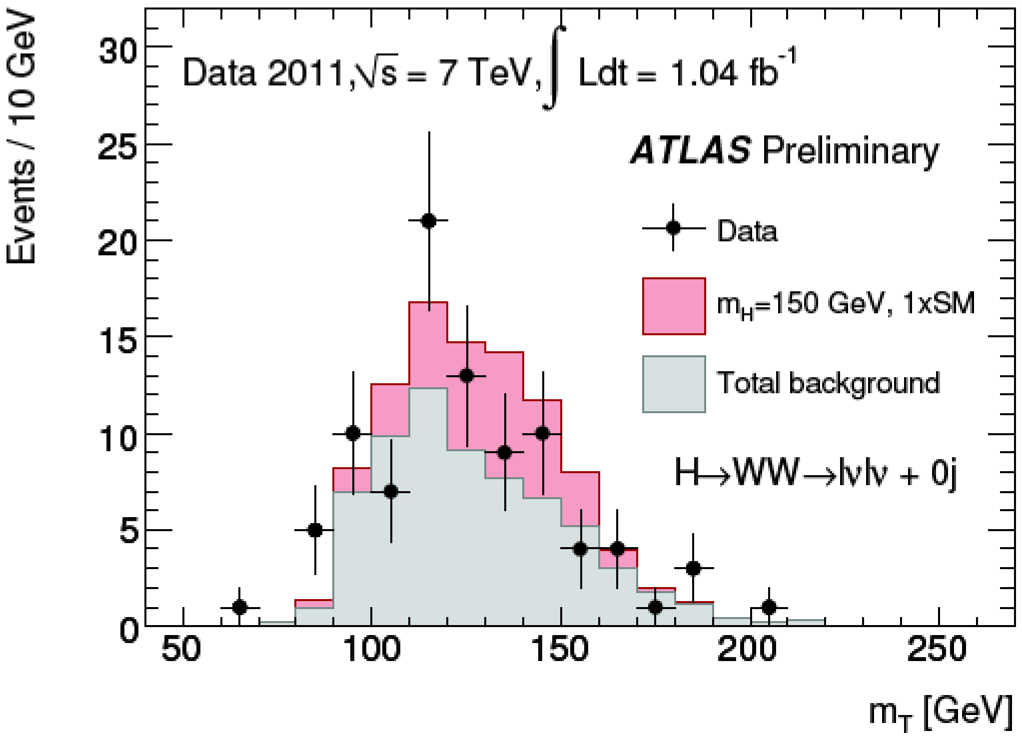
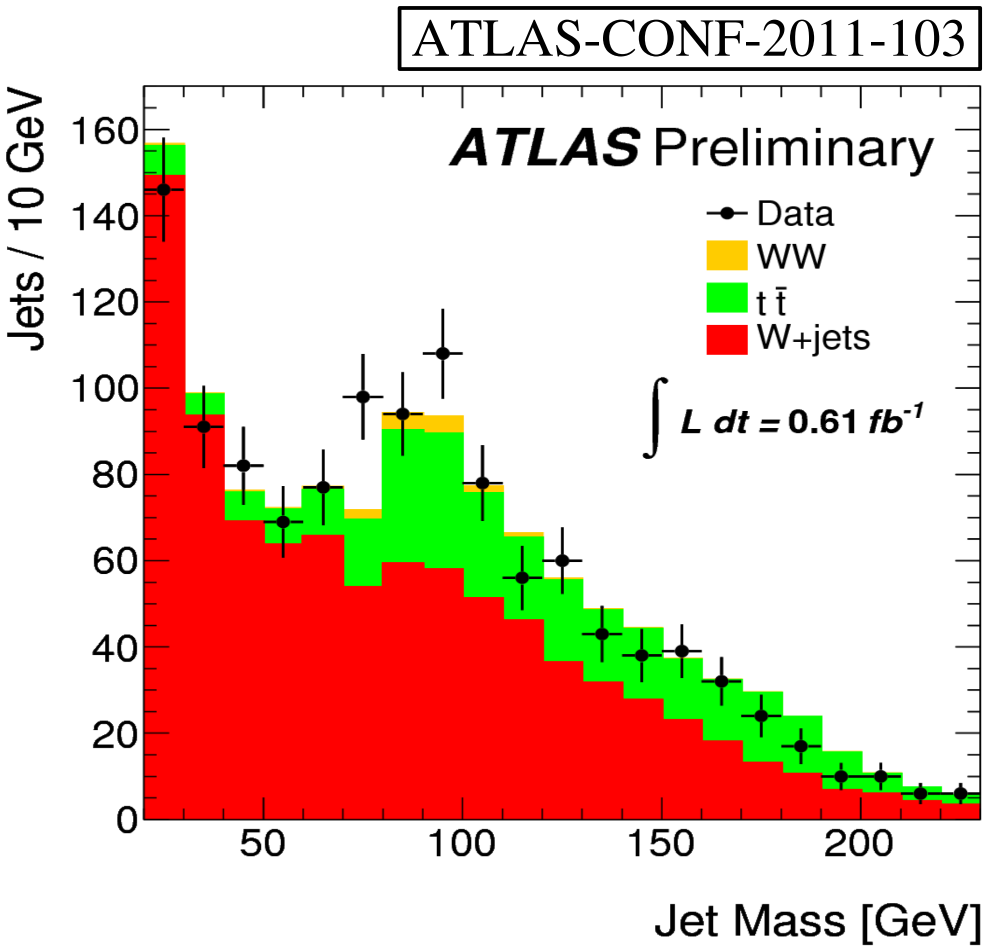


$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2},$$

$HW \to b\bar{b} + l\nu$ (boosted)

- The *b* quarks can merge into one jet => split the jet, study the sub-jets.
- Require 2 *b*-tagged sub-jets. (Not done here)
- Reconstruct the *W*.
- The jet mass distribution of subjets with p_T > 180 GeV in events consistent with a $WH \to l \nu b \bar{b}$ decay with p_T > 200 GeV.

  Uncorrected MC simulation prediction for $t\bar{t}$, W+jets and WW processes.



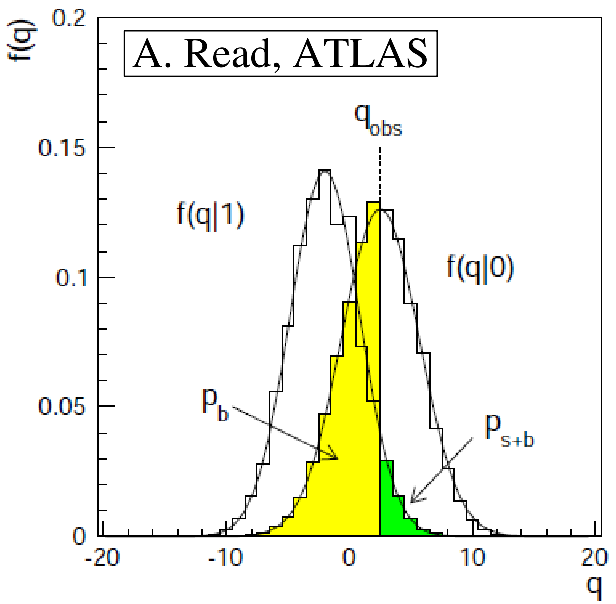
Statistics

We have reconstructed data and background.
How do we know if we saw a real effect?
What do we do if we didn't see anything?

Statistical method 1: CLs

- Frequentistic method
  Answers the question: Given a certain signal, what is the probability to observe the data we have?
- We define:

$$p_{s+b} = P(q \geqslant q_{obs} | s+b) = \int_{q_{obs}}^{\infty} f(q|s+b)\, dq \qquad p_b = P(q \leqslant q_{obs} | b) = \int_{-\infty}^{q_{obs}} f(q|b)\, dq$$



$$CL_s = \frac{p_{s+b}}{1-p_b} < \alpha$$

- $p_{(s+)b}$ is the probability for (signal +) background, given the test statistic q.
- $\alpha = 0.05$ by convention

Statistical method 2: Bayesian

- Bayes' theorem states that

Probability that we have signal *s* given data *d* (*posterior* probability)

Probability that we observe data *d* when we have signal *s*

$$P(s|d) = P(d|s) \cdot \frac{P(s)}{N}$$

Probability for *s*: Bayesian prior

Normalisation

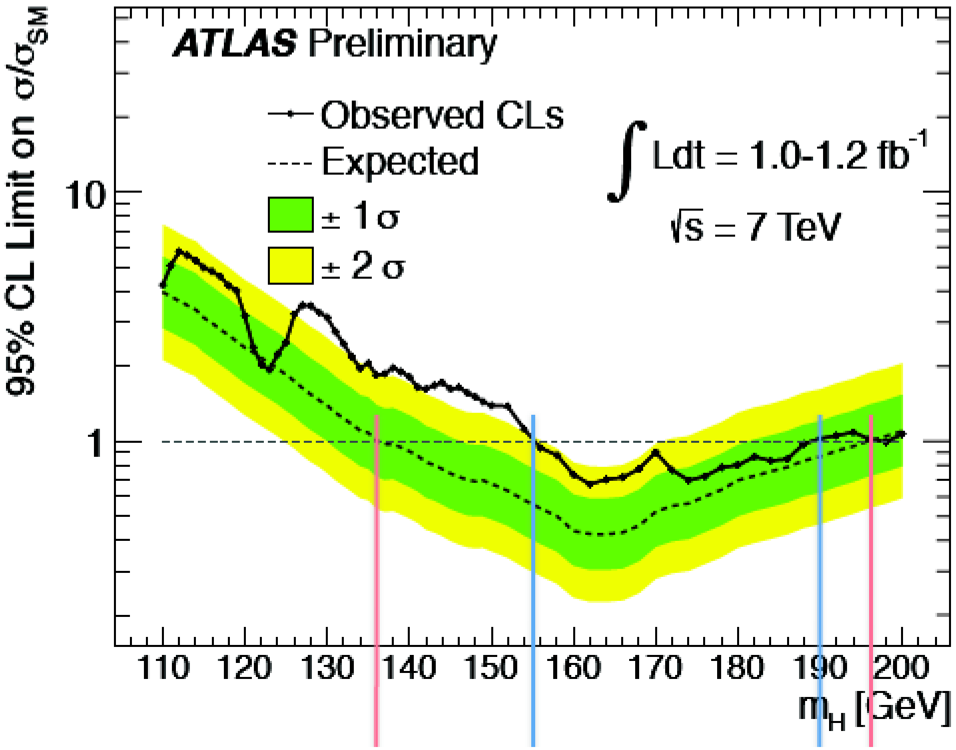
We don't know *P* (*s*), so it is normally taken to be uniform for *s*>0 (*flat prior*) and 0 if *s*<0

P (*s* |*d*) is what we want, but *P* (*d* |*s*) is what we easily can compute; Bayes theorem offers the “translation”. The only ambiguity is the prior.

Set and interpret a limit

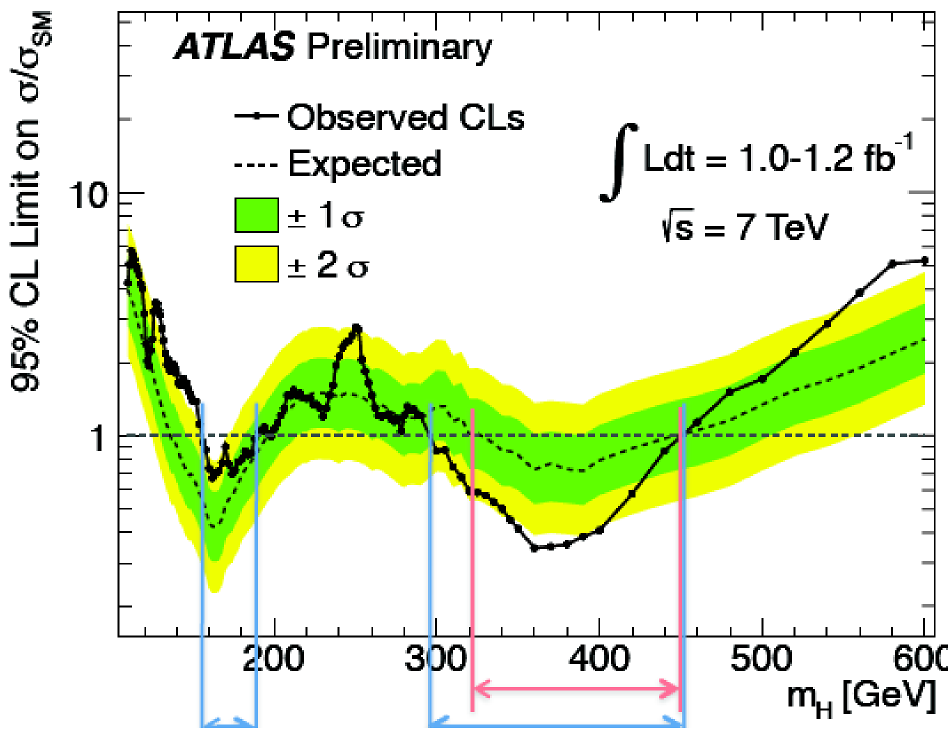
- Compare expected (background) and observed (data) limits.
- In the absence of a signal, we can set an upper limit on the phenomenon: given what we observe, what is the maximum amount of the signal that can hide in data?
- If the upper cross section limit is lower than the theoretical cross section, we can *exclude* that region.

- If the observed limit is higher than the expected, we have a data excess.
- BUT we must take into account that we look for an excess in many places: *trial factors* (the look-elsewhere effect)
- Limit setting is quite CPU-intense: can take a week on a good computing cluster.



Closing remarks on the Higgs results

- Both CMS and ATLAS see a 2-sigma excess around 140 GeV, mainly in the $H \to WW \to l\nu l\nu$ channel. Coincidence or a signal? Time will tell...
- ATLAS also sees excesses at 250 and 600 GeV. CMS does not. No signal likely!
- Trial factors (the look-elsewhere effect) have not been taken into account! The 2-sigma excess is not really 2 sigma...



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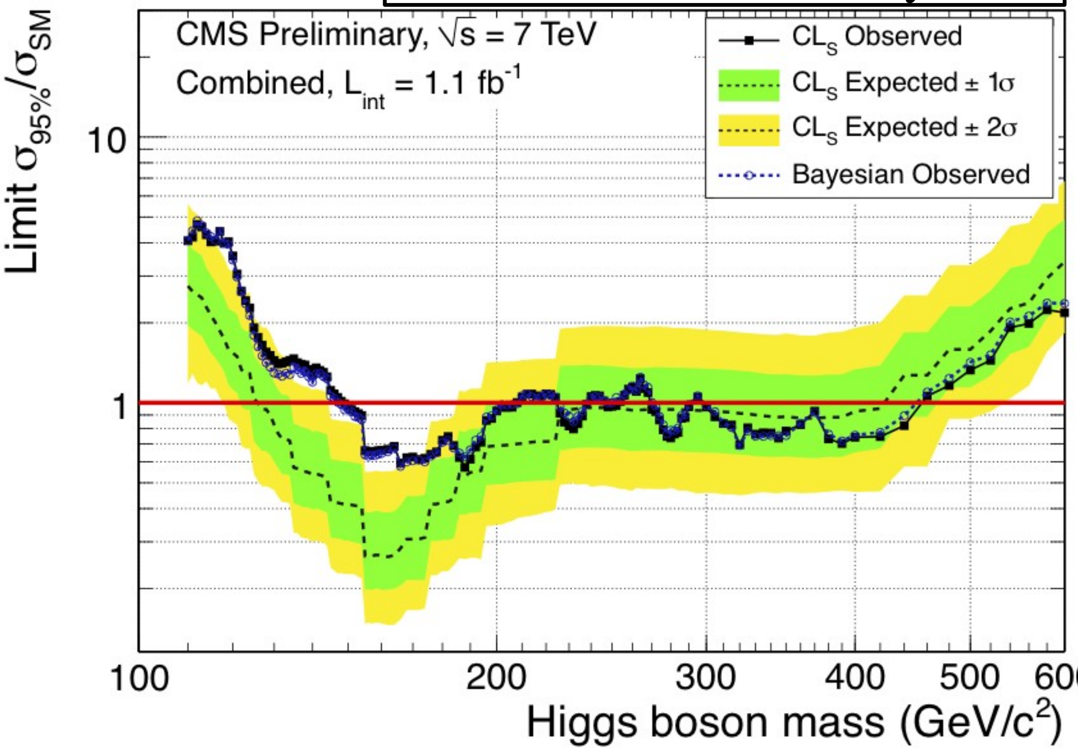


Beyond the Standard Model: a guidline

- What to look for?

Anomalies! For example

- A mass peak in an unexpected place.
  This could indicate a totally new particle.
- An excess of particles.
  A deficiency of particles.
  This indicates that our understanding of the couplings is inadequate – a new dynamics, mechanism or particle could be the cause.
- Nothing at all
  Large amounts of E_T^{miss} indicate a weakly interacting massive particle. Dark matter?

The things you wished for that I didn't have time to explain

- The CMS detector – read more at http://cms.web.cern.ch/cms/ and ask the CMS people here.
- Detailed calorimetry – one of my favourite subjects that require more time than given. I recommend the Particle Physics BriefBook, http://rkb.home.cern.ch/rkb/PH14pp/node1.html Calorimeter section as a starting point, and the references given there.
- sLHC (the LHC upgrade project). For some numbers about how powerful LHC will be, see http://project-slhc.web.cern.ch/project-slhc
- The Higgs mechanism. This is a theory question – ask Gabor on Thursday!
- Recent results (besides Higgs) – take a look at pdg.lbl.gov

Summary of lecture 2

- Today, we have produced particles, reconstructed particles and interpreted the Higgs results.
- This is useful, and super cool!
- Use your time here at DESY to talk to people, ask a million questions.
  (We do love to talk about our research)

References

- Overview information about CERN, LHC and ATLAS online: http://cern.ch, http://public.web.cern.ch/public/en/LHC/LHC-en.html, http://atlas.ch
- All experimentally verified particle properties: http://pdg.lbl.gov
- More about Monte Carlo generators: http://indico.cern.ch/conferenceDisplay.py?confId=a042790
- Browse CERN publications: http://cdsweb.cern.ch

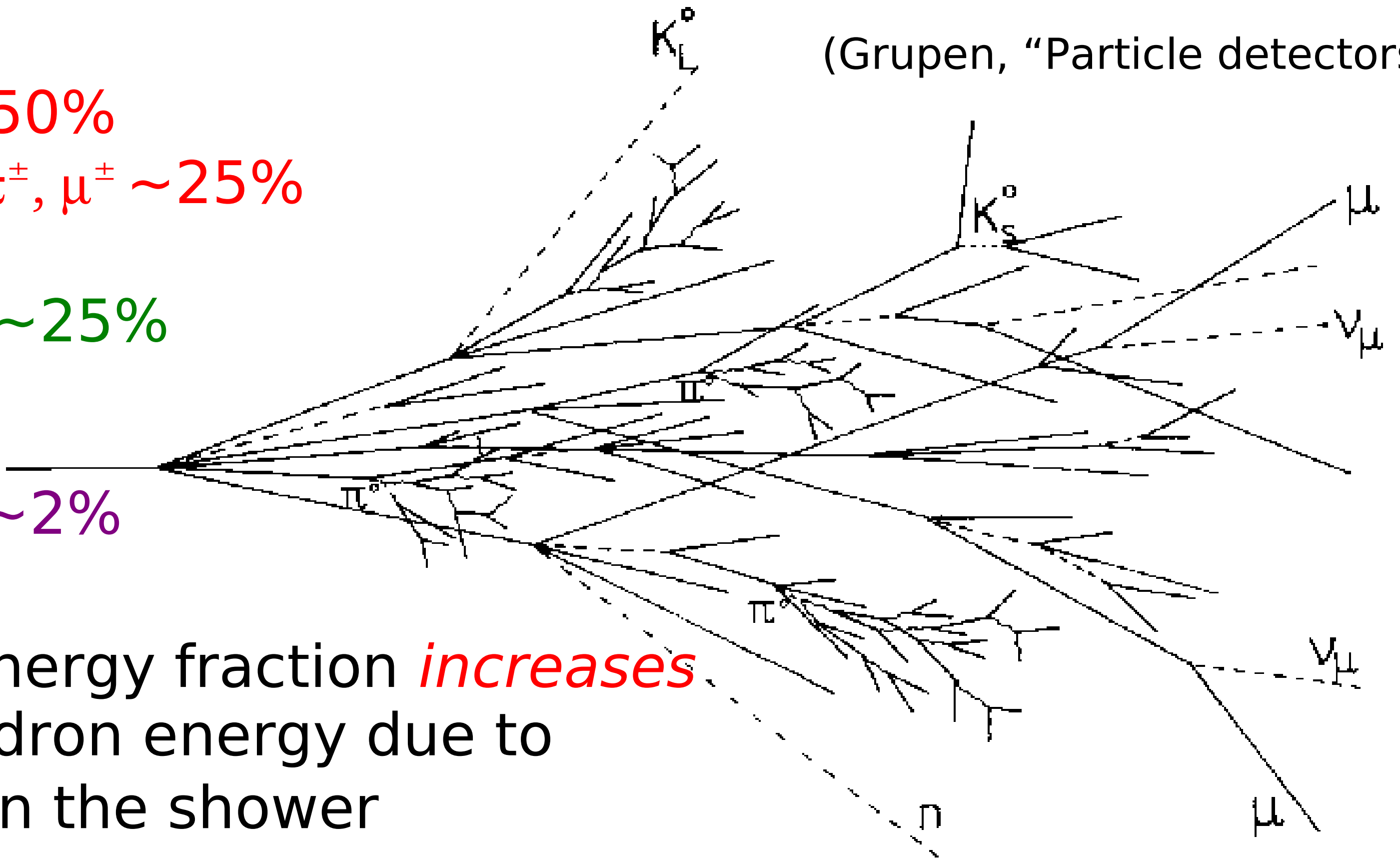
Extra material:

- more about jet algorithms
- more about Bayesian limit setting

Hadronic shower – from e.g. a pion

- Contents of a hadronic shower:
  - Visible energy
    from $e^{\pm}$; $\pi^0 \rightarrow \gamma\gamma$; ~50%
    ionisation from p, $\pi^{\pm}$, $\mu^{\pm}$ ~25%
  - Hadronic
    invisible energy ~25%
    (nuclear excitations, break-ups)
  - Escaped energy ~2%
    (mainly ν, some μ)

(Grupen, "Particle detectors")



- Electromagnetic energy fraction *increases* with increasing hadron energy due to production of π^0's in the shower
- Aim of hadronic calibration: Compensate for invisible and escaped energy.

Sequential recombination jet algorithms
The k_T algorithm

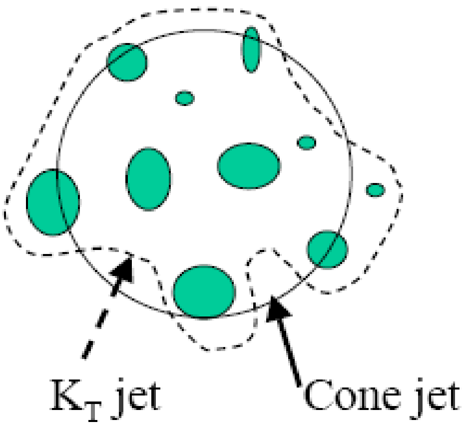
Main parameter: angular resolution D (=0.4 or 0.6)

Start with a list of input components i (e.g. clusters)

1) For each component, define $d_i = k_{T,i}^2$

For each pair (i, j) define

$$d_{ij} = \min(k_{T,i}^2,\ k_{T,j}^2)\ \Delta R_{ij}^2 / D^2$$



2) Find d_{min} = minimum of all d_i, d_{ij}

3) If d_{min} is a d_{ij}, merge clusters to a new cluste

If d_{min} is a d_i, the object is a jet. Remove cluster from list.

Repeat 1-3 until all clusters are in jets.

Sequential recombination jet algorithms summary overview

- k_T algorithm $\quad d_{ij} = \min(k_{Ti}^2, k_{Tj}^2)\Delta R_{ij}^2/R^2$
  hierarchical in relative p_T
- Cambridge/Aachen $\quad d_{ij} = \Delta R_{ij}^2/R^2$
  hierarchical in angle
- Anti-k_T $\quad d_{ij} = \min(k_{Ti}^{-2}, k_{Tj}^{-2})\Delta R_{ij}^2/R^2$
  gives perfectly conical jets

(M. Cacciari)

Bayesian limit setting overview

- Set a 95% credibility level upper limit.
- Likelihood function *L* for a particular mass ν

$$L_\nu(d|b_\nu, s) \equiv \prod_i \frac{(b_{\nu i} + s_i)^{d_i}}{d_i!} e^{-(b_{\nu i}+s_i)}$$

(**d**ata, **b**ackground, **s**ignal, *i* runs over the bins).

- Normalise the likelihood: P(d|s).
- Use Bayes' theorem to compute *P*(*s*|*d*) from *P*(*d*|*s*), using a flat prior.
- Integrate *P*(*s*|*d*) (the posterior probability) to 95%. That's the limit.
- Observed limit: use data.
- Expected limit: use background expectation to generate pseudo-data.