SUSY at the LHC: part1

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LHC: pp Collider $\sqrt{s}$=14 TeV Startup: mid-2007

Main motivations:

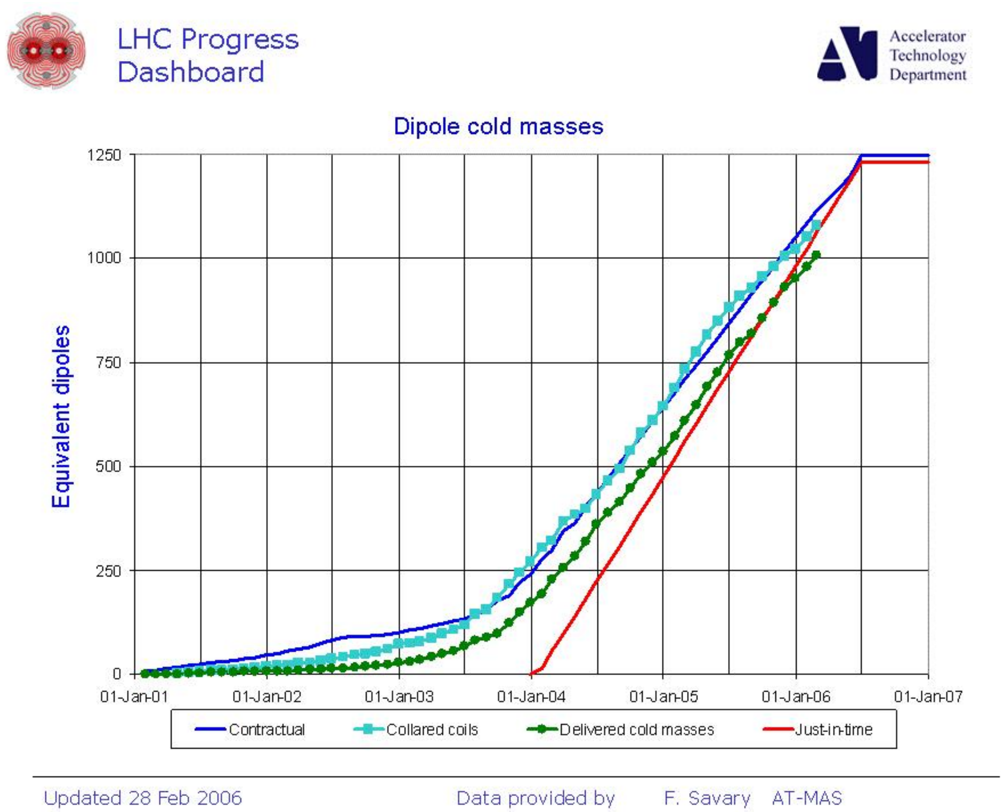
- Elucidate the mechanism of ElectroWeak Symmetry breaking:
  - Look for Higgs boson in allowed interval 100 GeV-1 TeV
  - In absence of low mass Higgs, study production of longitudinal gauge boson pairs.
- Find evidence for possible deviation from the Standard Model
  - Strong theoretical motivations to think that SM is only effective theory
  - In order to solve some of the theoretical difficulties with SM, deviations should be observable at $\sim$TeV scale

LHC Energy

$\sqrt{s} = 14$ TeV: explore the TeV scale, search for new massive particles up to 5 TeV

Maximum energy limited by the bending power needed to fit ring in 27 Km circumference LEP tunnel

$$p(\text{TeV}) = 0.3\text{B (T) R(km)}$$



LHC: $B = 8.4$ T:

~1300 superconducting dipoles working at 1.9 K

On track for closing the machine in 2007

Luminosity:

$$\mathcal{L} = \frac{N}{\sigma}$$

with $\mathcal{L}$: Luminosity N: event frequency, σ: cross-section

Two luminosity scenarios:

- peak$\sim 10^{33}$ cm^{-2}s^{-1} - initial "low luminosity": $\int \mathcal{L}\mathrm{dt} = 10\ \mathrm{f}b^{-1}$ per year
- peak$\sim 10^{34}$ cm^{-2}s^{-1} - design "high luminosity": $\int \mathcal{L}\mathrm{dt} = 100\ \mathrm{f}b^{-1}$ per year

Benchmark: ensure detection of Higgs boson in the range 100 GeV-1 TeV

$m(H) \sim 100 - 150$ GeV	$H \rightarrow \gamma\gamma$	$\sigma \times BR \times \epsilon \sim 10 - 20$ fb	$S/B \sim 1/50$
$m(H) = 1$ TeV	$H \rightarrow WW \rightarrow \ell\nu jj$	$\sigma \times BR \times \epsilon \sim 2 - 3$ fb	$S/B \sim 1/2$

Discovery when statistical significance for signal $S/\sqrt{B} > 5 \rightarrow$

Required integrated luminosity for discovery (no K-factors):

- $H \rightarrow \gamma\gamma$: $\sim$1000 events ~ 100 fb^{-1}
- $H \rightarrow WW$: $\sim$50 events ~ 20 fb^{-1}

How is luminosity $\mathcal{L}$ achieved?

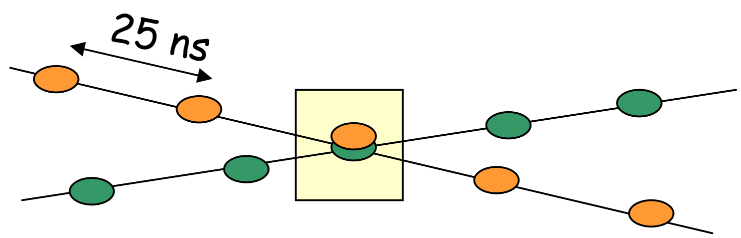
If two beams containing n_1 and n_2 particles collide with a frequency f:

$$\mathcal{L} = f \frac{n_1 n_2}{4\pi\sigma_{beam}^2}$$

with σ_{beam} gaussian transverse beam profile

LHC values: $n_1 = n_2 = 10^{11}$, and $\sigma_{beam} \sim 16 \times 10^{-6}$ m, determined by the physics of colliding beams.

To achieve $\mathcal{L} = 10^{34}$ cm^{-2}s^{-1}, LHC has to run with a bunch crossing every 25 ns



Inelastic proton-proton cross-section at $\sqrt{s} = 14$ TeV is ~ 70 mb $\Rightarrow$

LHC interaction rate at high luminosity: $\sim 7 \times 10^{-2} \times 10^{-24} \times 10^{34} = 7 \times 10^{8}$ Hz

40 MHz crossing frequency: $\Rightarrow \sim 25$ superimposed interactions per crossing (pile-up)

Characteristics of pile-up interactions

Soft partonic interactions: describe with non-perturbative phenomenological models

Collider jargon: "Minimum bias": experimental definition: depends on experiment's trigger. Usually associated to non-single diffractive events

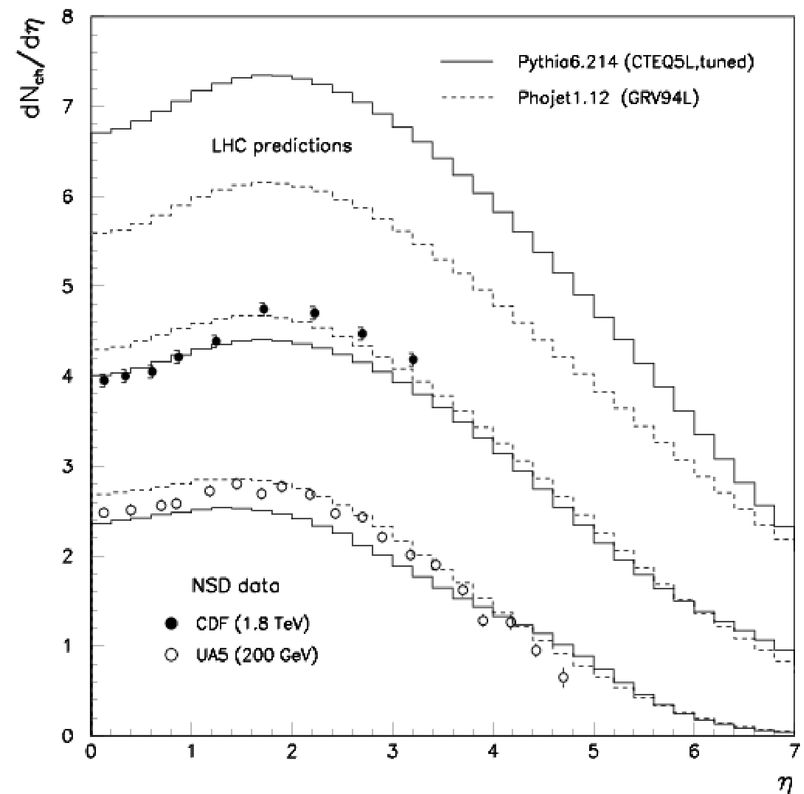
Measured at $Sp\bar{p}S$ and Tevatron, large uncertainties in extrapolation to LHC

Main features:

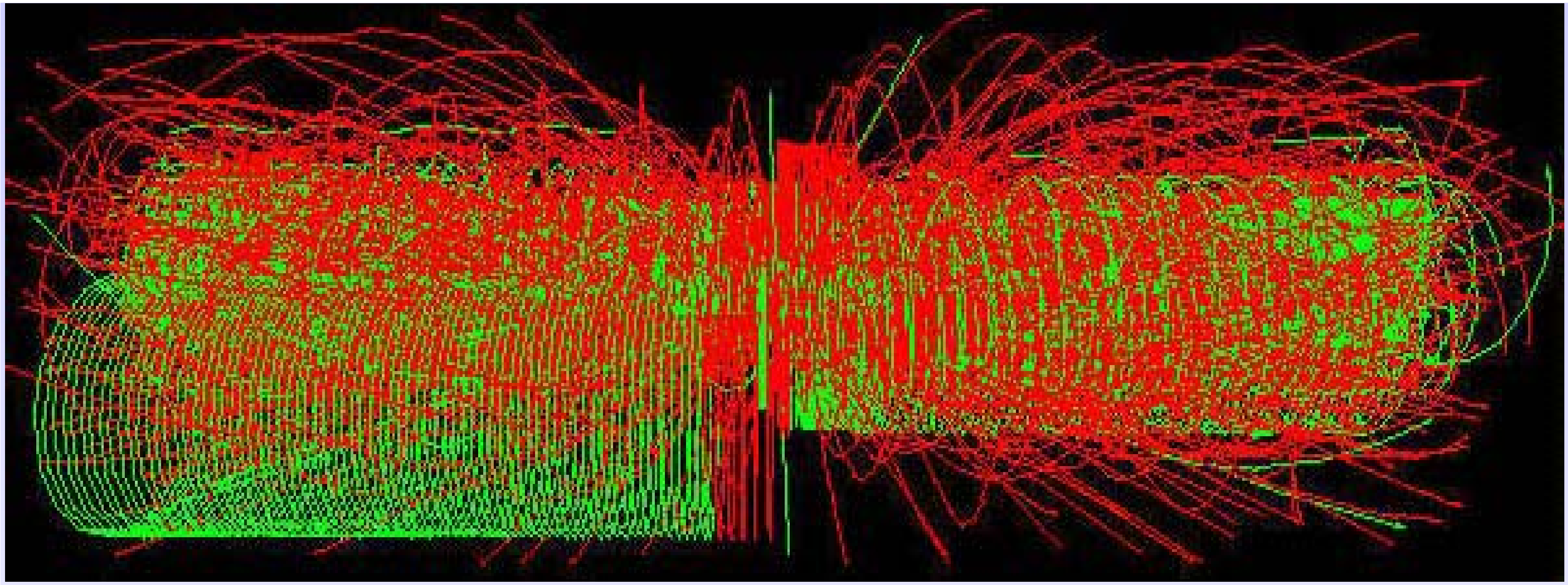
~7 charged particles per unit of rapidity⇒ ~ 100 charged particles over $|\eta| < 2.5$ per crossing

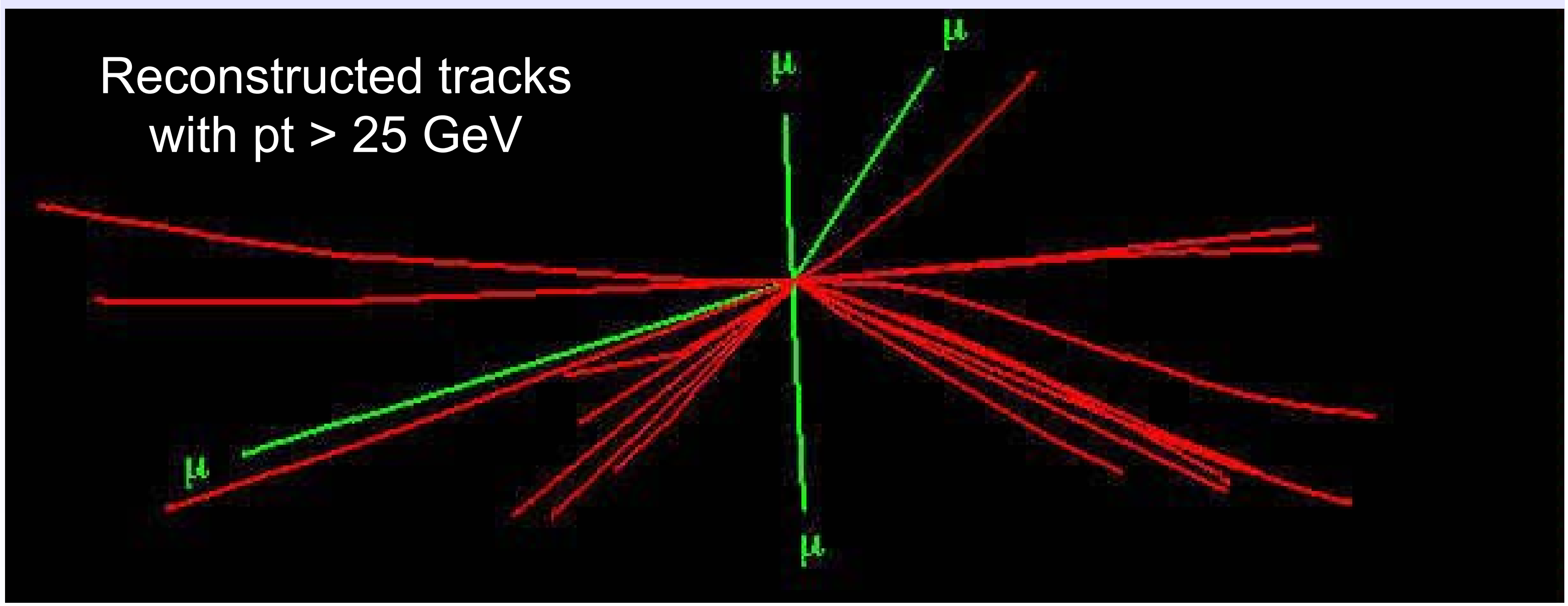
Significant radiation damage from interaction!

$< p_T > \sim 500$ MeV ⇒ can select interesting particles by cut in p_T



Example: $h \to 4\mu$ event in CMS at high luminosity





Large impact on detector design:

- **Speed:**

  LHC detectors must have fast response otherwise integrate over too many bunch crossings

  Typical response time: 20-50 ns$\longrightarrow$ integrate over 1-2 bunch crossings

  $\Rightarrow$ very challenging readout electronics

- **Granularity:**

  LHC detectors must be highly granular to minimise probability that pile-up particles in same detector element as interesting object

  $\Rightarrow$ Large number of electronics channels

- **Radiation hardness:**

  High flux of particles from pp collisions $\Rightarrow$ high radiation environment

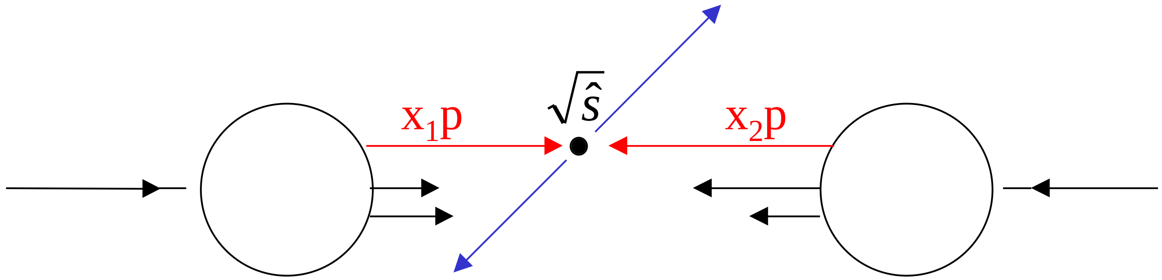
  In 10 years of LHC data: up to $10^{17} n$ cm^{-2}, up to 10^7Gy

  Radiation decrease like d^2 from beam: detectors near beam pipe mostly affected

  $\Rightarrow$ Need radiation resistant detector technologies especially at high $|\eta|$

  $\Rightarrow$ Need also radiation hard electronics

Basics of hadron collider physics



Quarks and gluons (partons) taking part in hard (high Q^2) interactions carry only a fraction of proton momentum

Spectator quarks not taking part in hard interaction fly along proton direction $\Rightarrow$ their fragmentation product go undetected in the beam pipe

Energy in center of mass system (CMS) available for interaction $\sqrt{\hat{s}}$:

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s}$$

With $\sqrt{s} = 14$ TeV , proton-proton CMS energy

x_1, x_2 fraction of proton momentum carried by respectively parton 1 and 2

Typically $x_1 \neq x_2 \Rightarrow$ Hard interaction system boosted in the lab reference frame

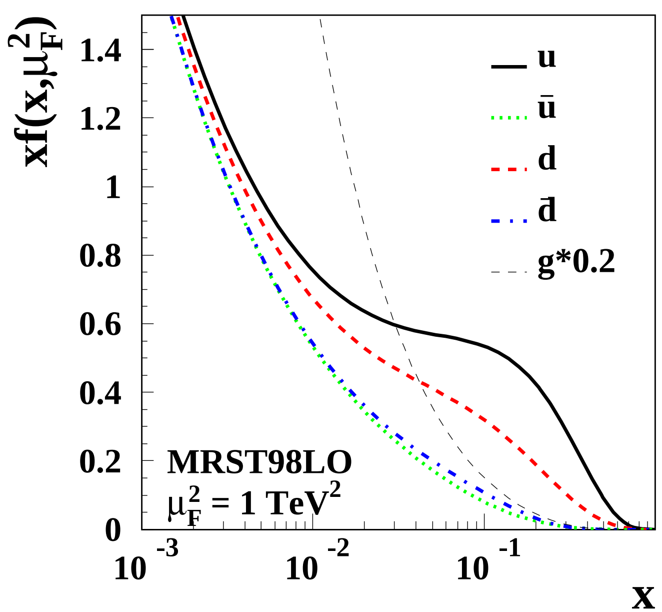
Parton distribution functions

Momentum distribution of partons in protons given by universal parton distribution functions (PDF)

$$xf(x, Q^2)$$

Universal: do not depend on the hard scattering process in which partons take part

Phenomenological function extracted mostly from Deep Inelastic Scattering of leptons on hadrons



For $x_1 \sim x_2$:

- W/Z production: $x \sim 0.1$
- $\bar{t}t$ production: $x \sim 0.15$
- 1 TeV SUSY: $x \sim 0.4$
- 5 TeV Z': $x \sim 0.6$

Proton-proton cross-section

Convolution of PDF's with partonic cross-section

$$\sigma = \sum_{a,b} \int dx_1 dx_2 f_a(x_1, Q^2) f_b(x_2, Q^2) \hat{\sigma}_{a,b}(x_a, x_b)$$

Dynamical information contained in partonic cross-section $\hat{\sigma}$

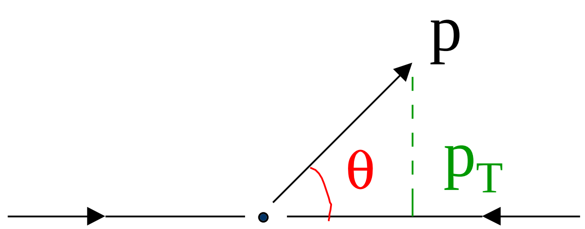
Need to deconvolve structure functions $\Rightarrow$ uncertainty in extracting physical parameters from cross-section measurement

Proton beam is wide-band parton beam:

- Ideal for exploration and discovery: span a large range of center of mass energies
- Variable $\hat{s}$ $\longrightarrow$ less kinematic constraints for final state reconstruction
- Explorable $\hat{s}$ is a function of both luminosity and and proton-proton energy: can extend reach by pushing luminosity

Variables in hadron collider physics

- Transverse momentum p_T:

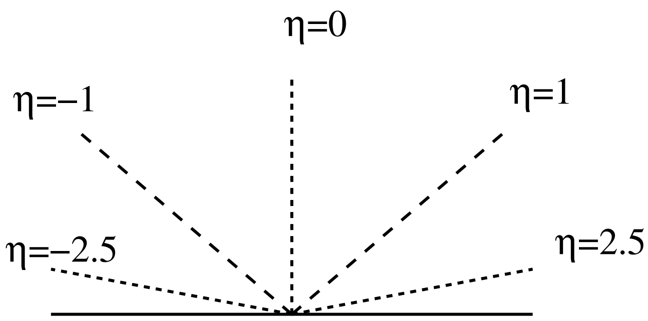


$$p_T \equiv p \sin\theta$$

Component of momentum of particles

in the plane perpendicular to the beam axis

- Pseudorapidity η



$$\eta \equiv -\log(\tan\frac{\theta}{2})$$

$\eta = 0$: $\theta = 90$ $\quad$ $\eta = 1$: $\theta \sim 40$

$\eta = 2.5$: $\theta \sim 10$ $\quad$ $\eta = 5$: $\theta \sim 0.8$

Equivalent to rapidity y for massless particles

Better variable than polar angle θ : η distribution is independent of the boost

Implications for particle detection: typically detectors segmented in θ: $\Delta\eta \sim \Delta\theta$ for $|\eta| \lesssim 1$, very poor η granularity for $3 < |\eta| < 5$

The $\not{E}_T$ variable

Total energy and momentum in final and initial state equal: $(E_f, \vec{p}_f)$=$(E_i, \vec{p}_i)$.

Initial state in collider: $E_i = \sqrt{s}$, $\vec{p}_i = 0$

For e^+e^- collider all final state particles in detector acceptance $\vec{p}_f = 0$, if non-interacting particle with momentun $\vec{p}^\nu$ produced $(\nu, \tilde{\chi}_1^0)$, then $\vec{p}_f \neq 0$, and

$$\vec{p}^\nu = \vec{p}^{miss} = -\sum_j \vec{p}_j = -\vec{p}_f$$

With j running on all the detected particles

For hadron collider: particles from spectator quarks undetected in the beam pipe, $\vec{p}_f \neq 0$

$\Sigma_k\, (\vec{p}_T)_k \sim 0$ for particles k outside acceptance $\Rightarrow \Sigma_j\, (\vec{p}_T)_j = 0$ for particles j in acceptance.

If non-interacting particle with momentun $\vec{p}_T^\nu$ produced:

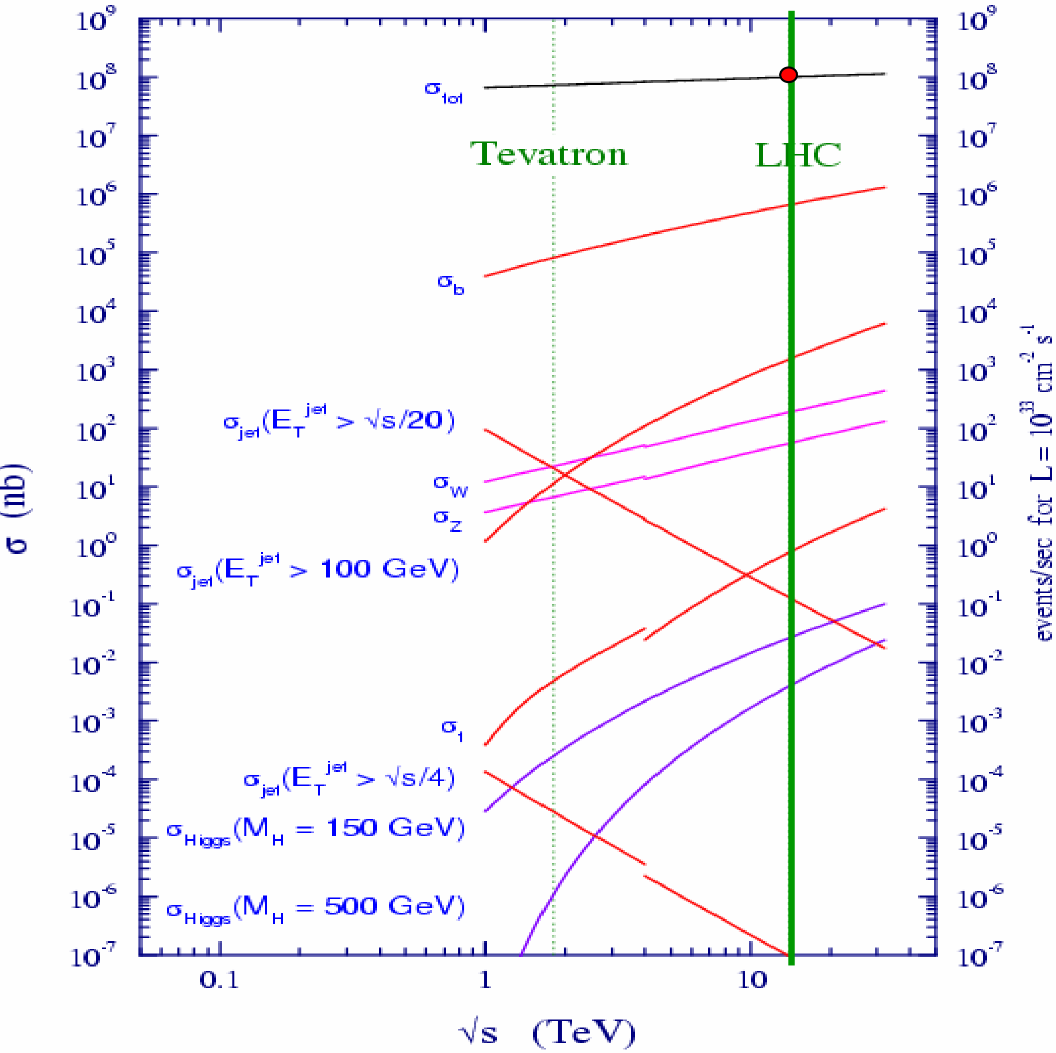
$$\vec{p}_T^\nu = \vec{p}_T^{miss} = -\sum_j (\vec{p}_T)_j$$

Approximate $\vec{p}_T^{miss}$ by $\not{E}_T$, vector sum of energy deposition in calorimeter cells:

$$E_x^{miss} = \sum_j E_j \sin\theta_j \cos\phi_j \quad E_y^{miss} = \sum_j E_j \sin\theta_j \sin\phi_j$$

j runs on cells with energy deposition and $\phi_j(\theta_j)$ respectively azimuthal and polar angle of cell j

Backgrounds to discovery physics



High p_T events dominated by QCD jet production:

- Strong production
- Many contributing diagrams

$\sigma_{jet}(E_T^{jet} > 100$ GeV$) \sim \mu$b

Signal processes rare:

- Involve heavy particles:

$\sigma_{\tilde{q}\tilde{q}}(m(\tilde{q}) \sim 1$ TeV$) \sim$ pb

- Have weak cross-section

$\sigma_{Higgs}(m(Higgs) = 100$ GeV$) \sim 30$ pb

QCD background from 5-6 orders of magnitude larger than signals

Overwhelming QCD backgrounds in exclusively hadronic channels

$\Rightarrow$ rely on final states involving γ, leptons, $\not\!\!E_T$, b-jets $\Rightarrow$ pay additional price in BR

Typical cross-section values:

Process	σ	Events/s	Events/year (low L)
$W \to e\nu$	15 nb	15	10^8
$Z \to ee$	1.5 nb	1.5	10^7
$\bar{t}t$	800 pb	0.8	10^7
$\bar{b}b$	500 μb	10^5	10^{12}
$\tilde{q}\tilde{q}$ (m$_{\tilde{q}}$ =1 TeV)	1 pb	0.001	10^4
Higgs (m$_H$ =0.8 TeV)	1 pb	0.001	10^4

Large statistics for discovery physics up to the TeV scale.

Large cross-section for Standard Model processes:

- Large backgrounds to discovery
- Large control samples to calibrate backgrounds

Precision measurements dominated by systematic effects

ATLAS and CMS detectors

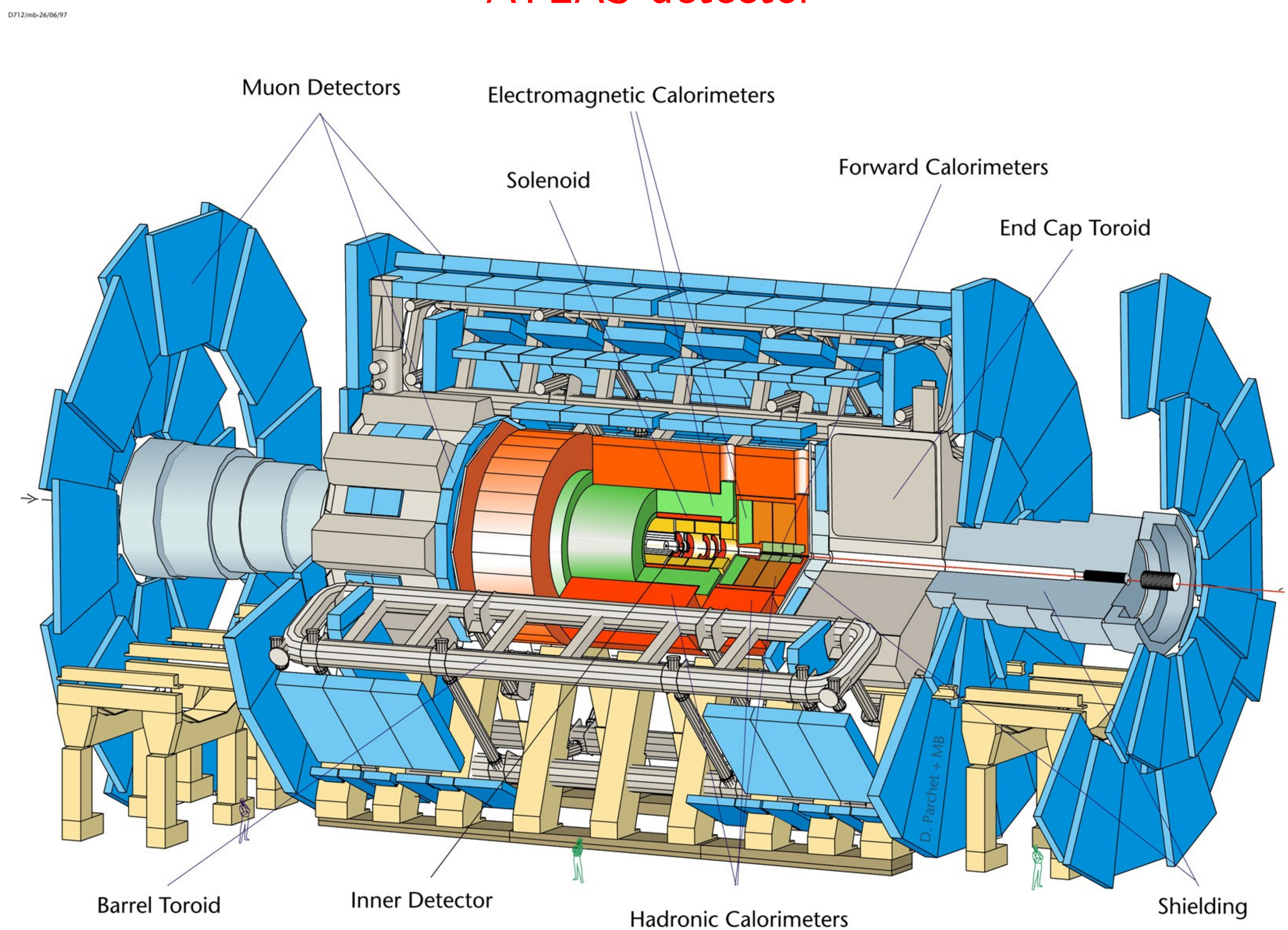
Do not know how new physics will manifest itself:

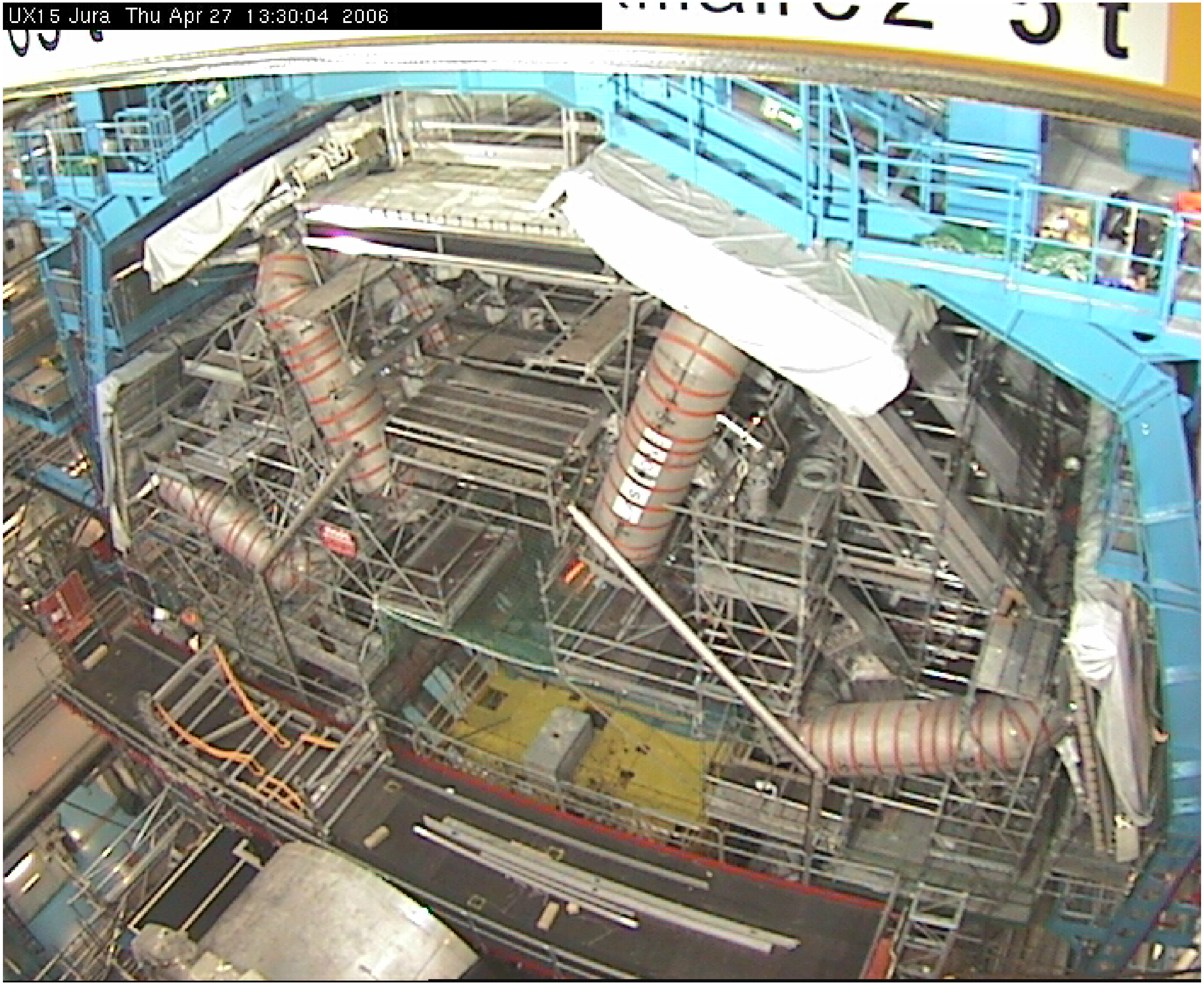
$\Rightarrow$ Detectors must be sensitive to as many particles and signatures as possible:

$$e,\ \mu,\ \tau,\ \nu,\ \gamma,\ \mathrm{jets},\ b-\mathrm{quarks}$$

- Momentum/charge of tracks and secondary vertices (e.g. from b-quark decays) measured in central tracker. Excellent momentum and position resolution required
- Energy and position of electrons and photons measured in electromagnetic calorimeters. Excellent position and energy resolution required
- Energy and position of hadrons and jets measured mainly in hadronic calorimeters. Good coverage and granularity required
- Muons identified and momentum measured in external muon spectrometer (+ central tracker). Excellent resolution required.
- Neutrinos "detected and measured" through measurement of missing transverse energy $\not\!\!E_T$. Calorimeter coverage over $|\eta| < 5$ needed

ATLAS detector

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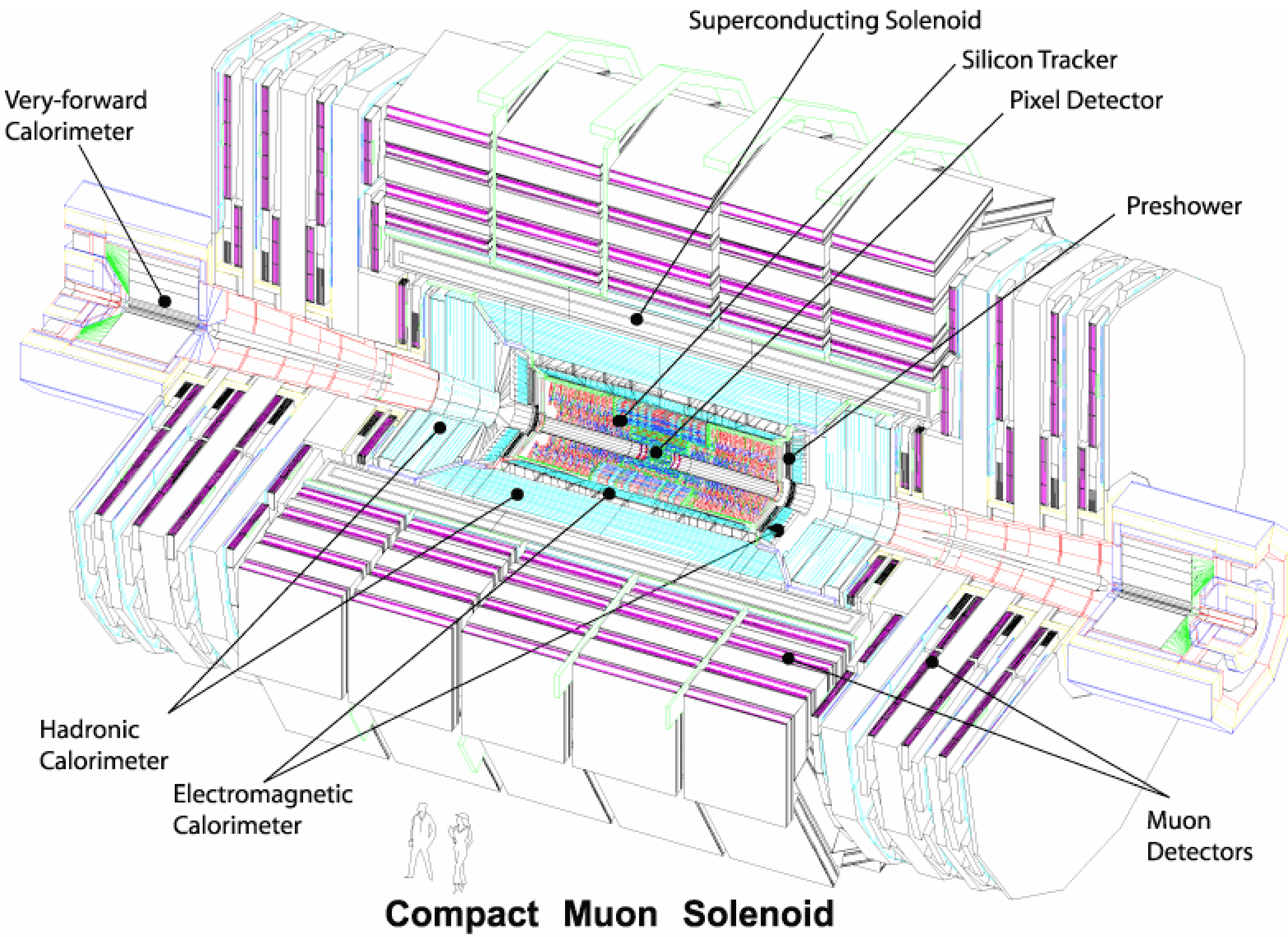
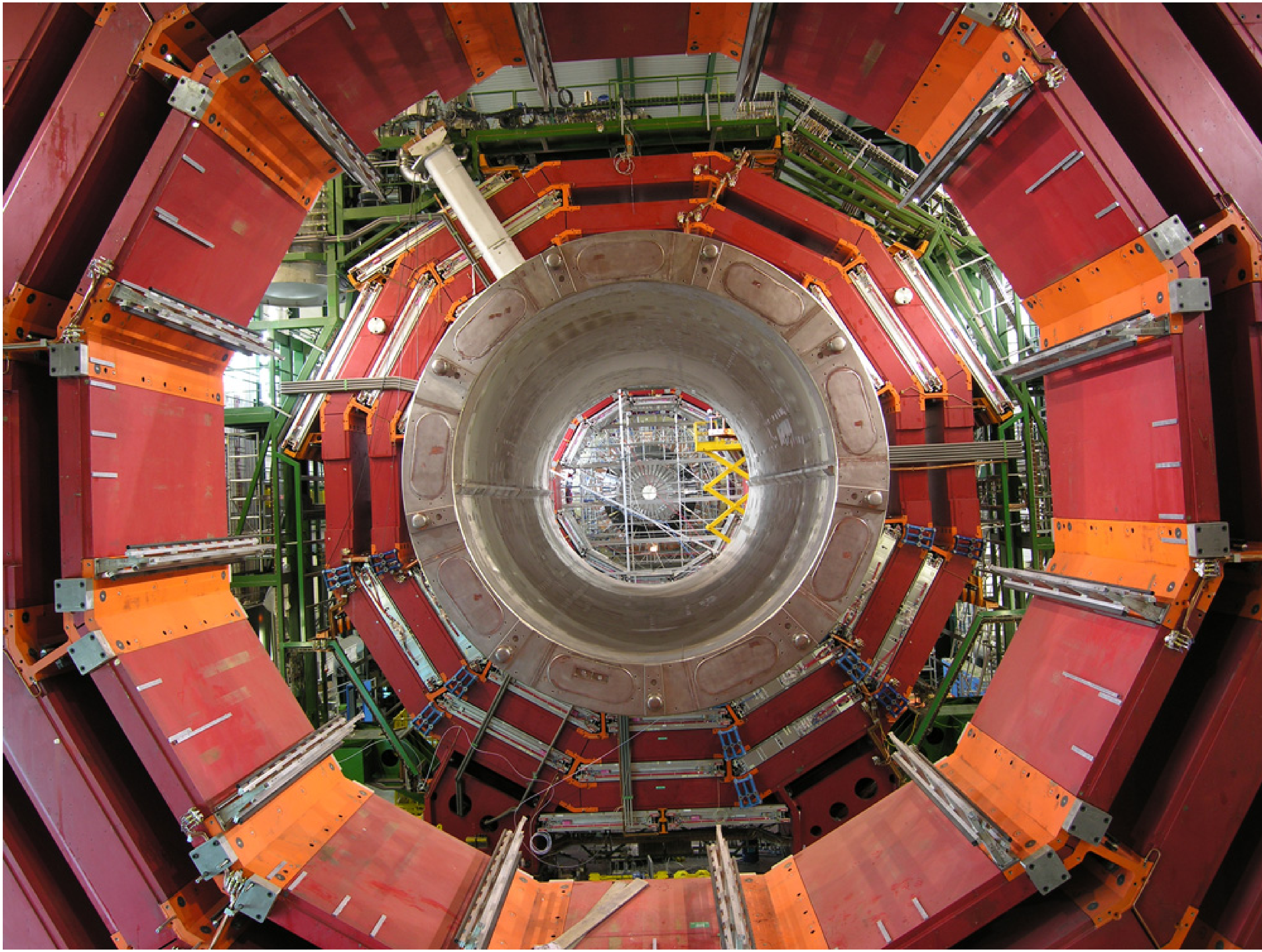
CMS detector





	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixel + strips TRD $\rightarrow$ particle identification B=2T $\sigma/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$	Si pixel + strips No particle identification B=4T $\sigma/p_T \sim 1.5\times10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb - liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 3\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scintillator + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ + catcher) $\sigma/E \sim 65\%/\sqrt{E} \oplus 0.05$
MUON	Air $\rightarrow$ $\sigma/p_T \sim 7$ % at 1 TeV standalone	Fe $\rightarrow$ $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

A few examples of required performance:

- Lepton measurement: $p_T \sim \mathrm{GeV} \rightarrow 5\mathrm{TeV}$ ($b \rightarrow lX$, W', Z')
- Mass Resolution (m~ 100 GeV):

  $\sim 1\%$ ($H \rightarrow \gamma\gamma, 4l$)

  $\sim 10\%$ ($W \rightarrow jj$, $H \rightarrow bb$)

- Calorimeter coverage: $|\eta| < 5$ (E_T^{miss}, forward jet tag)
- Particle identification :

  $\epsilon_b \sim 50\%$ $R_j \sim 100$ ($H \rightarrow bb$, SUSY)

  $\epsilon_\tau \sim 50\%$ $R_j \sim 100$ ($A/H \rightarrow \tau\tau$)

  $\epsilon_\gamma \sim 80\%$ $R_j \sim 10^3$ ($H \rightarrow \gamma\gamma$)

  $\epsilon_e > 50\%$ $R_j \sim 10^5$

- Trigger: 40 MHz$\rightarrow$ 100 Hz reduction

Electron-photon identification (ATLAS)

Separate electrons/photons from the overwhelming background of QCD jets

Reject charged hadrons in jets through longitudinal and lateral energy deposition pattern (lateral and longitudinal segmentation). Identify EM object

Main remaining background : fragmentation of quarks/gluons where a π^0 carries away most of the momentum, with the decay $\pi^0 \rightarrow \gamma\gamma$

Distinguish two photons from π^0 decay from single photon through detailed study of EM shower in Calorimeter

High EM calo granularity crucial to separate two photons

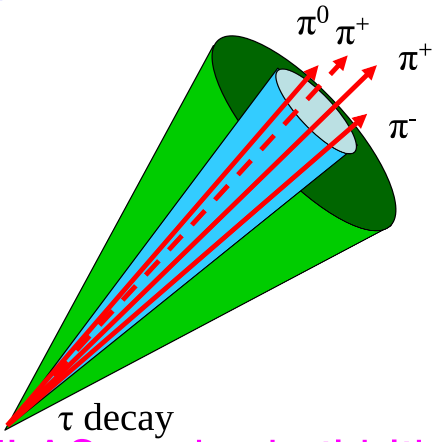
If track from $\pi^\pm$ superimposed to EM cluster can fake electron

Use matching between position/momentum of track and position/energy of EM cluster to reject fake electrons

Require excellent EM energy and position resolution

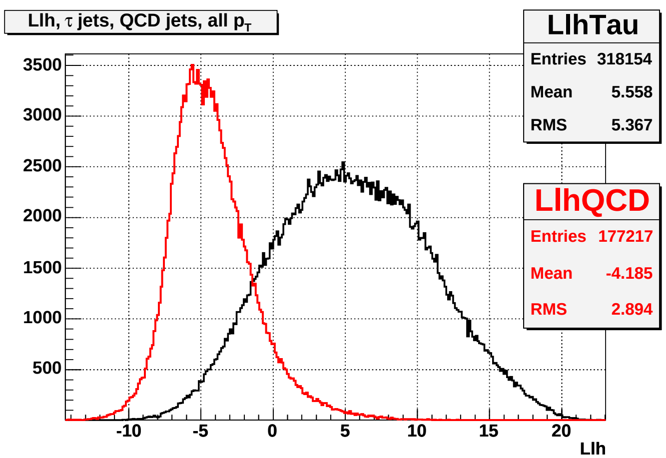
Identification of τ hadronic decays

Exploit difference between hadronic decays of τ's and QCD jets:

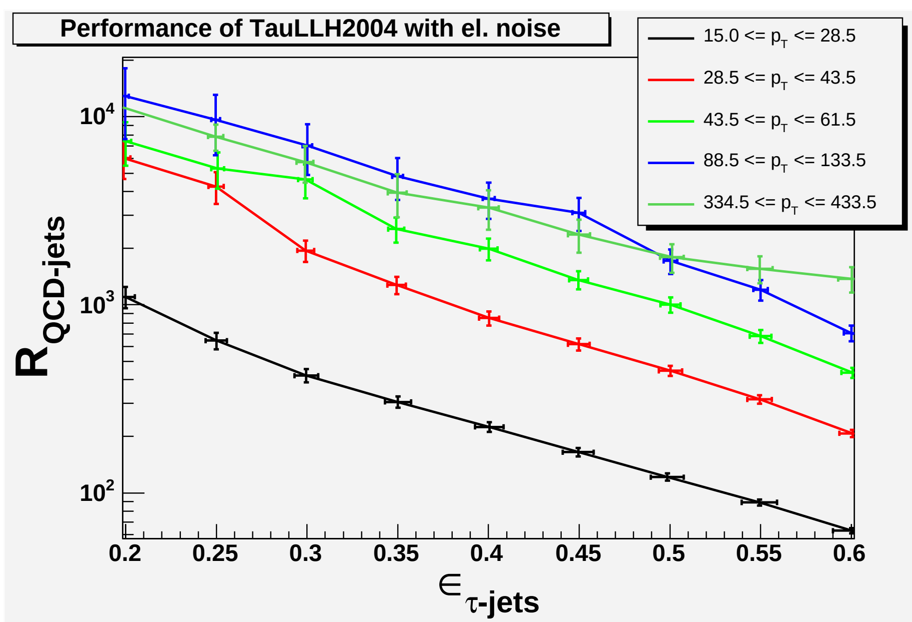


- Low track multiplicity ($1 < N_{tr} < 3$), charge
- Narrow jet in calo (Radius in EM calo, Number of strips in presampler)
- Impact parameter

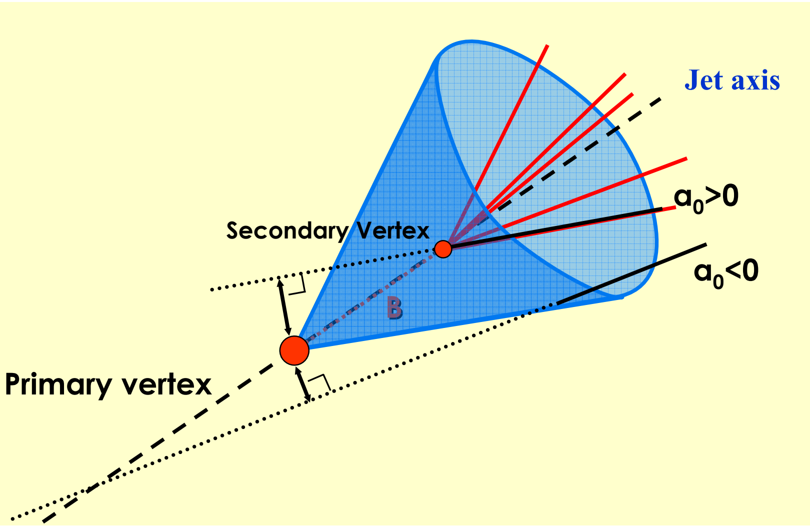
ATLAS study: build likelihood function in bins of jet P_T ($15 < P_T < 600$ GeV)



ATLAS preliminary



B-tagging

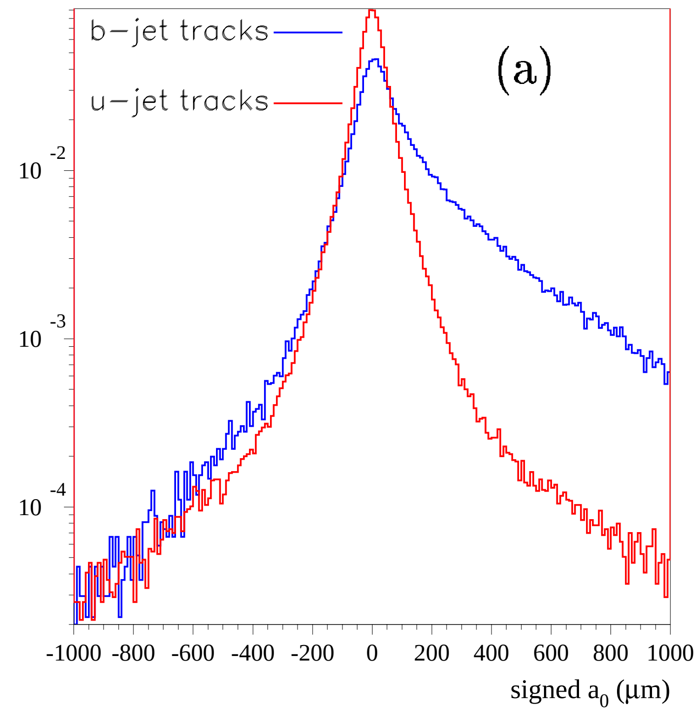


b-hadrons decay a a few mm away from interaction vertex

Measure decay path of b-hadrons through impact parameter: minimum distance from primary vertex

Distribution of impact parameter symmetric for tracks from fragmentation of light quarks

Significant enhancement of positive impact parameters for tracks from b-hadron decays

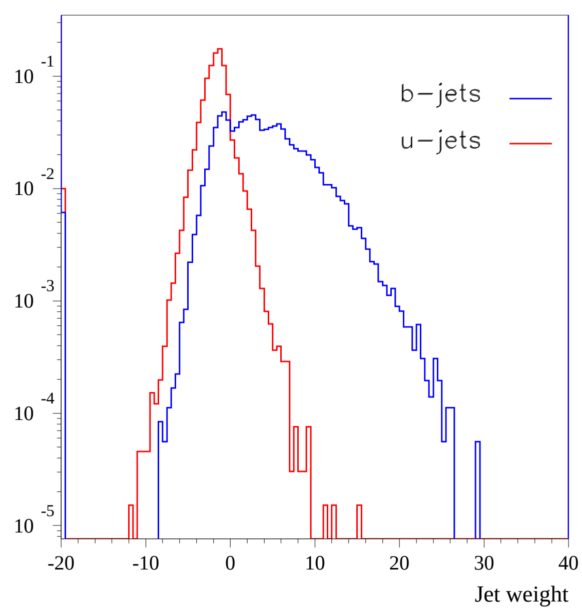


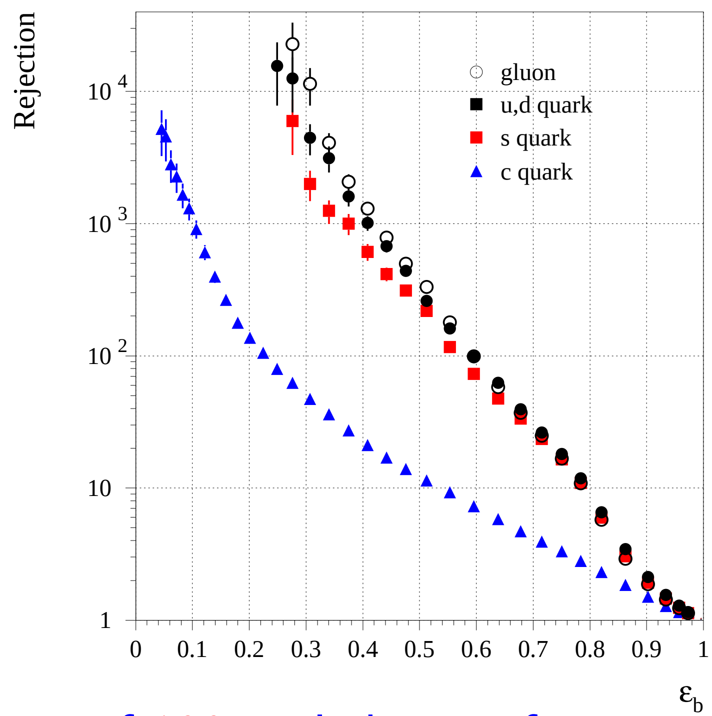
B-tagging (cont)

For a jet, build likelihood function from the impact parameter of the tracks associated to it

ATLAS: Study samples of fully simulated WH, ttH, $\bar{t}t$ events

Measure rejection on QCD jets as a function of tagging efficiency





ATLAS TDR: rejection factor of 100 on light jets for $\epsilon_b = 60\%$

Large Menu of physics topics:

- Standard Model:
  - W mass measurement (goal 15 MeV), triple Gauge Couplings (to 10^{-3})
  - Top physics: measure m$_t$, $\sigma_{\bar{t}t}$, polarisation, rare decays, single top....
  - Soft interactions, QCD, B-physics, ...
- Higgs searches, both SM and SUSY
- New physics:
  - SUSY
  - Extra Dimensions
  - Leptoquarks, extra gauge bosons, technicolor, compositeness, ...

Concentrate on SUSY and Extra Dimension theories, most mature candidates for new physics