Search for Flavor Changing Neutral Currents in Top Quark Decays

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August 16, 2012

Outline

- Top Quark Physics
  - Motivation
- ATLAS Detector
- Object and Event Selection
- Backgrounds
- Systematic Uncertainties
- Limit Calculation
- Conclusions

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Top Quark

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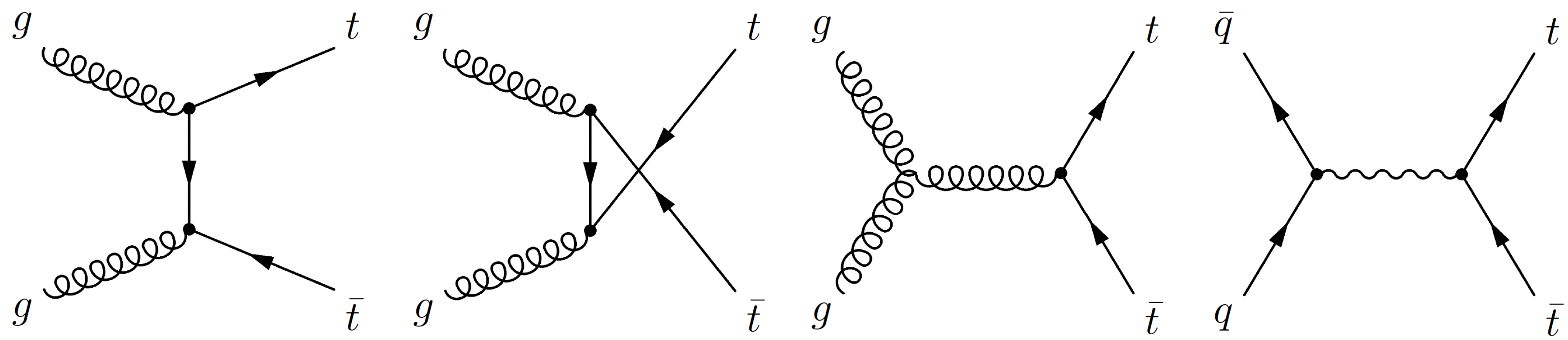
Deviations from the **decay** and **production** predictions from the SM give a model-independent test for physics beyond SM.

LHC is a Top Quark **Factory**

Top Quark Pair Production

Top quark pairs are produced via:



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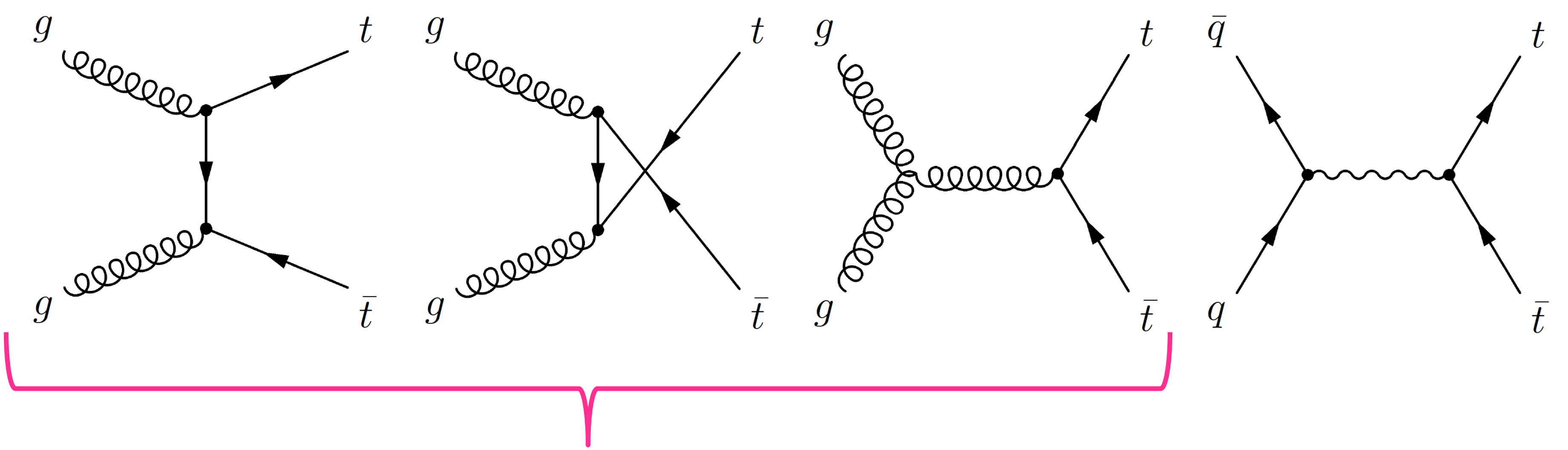

Gluon Fusion
~90% of the time
in the LHC

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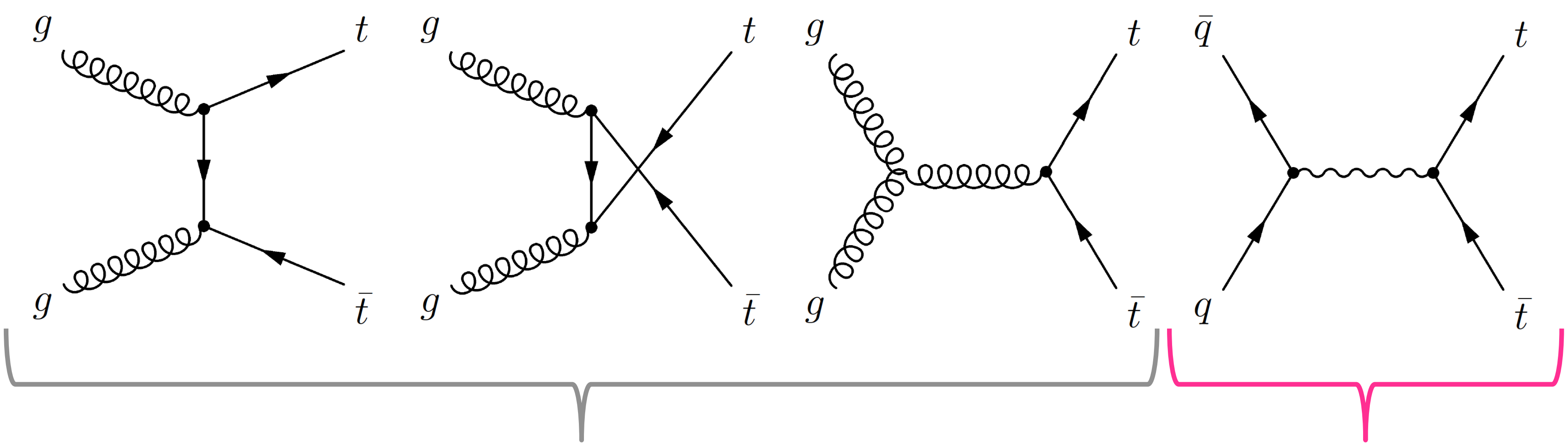

Gluon Fusion
~90% of the time
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Quark Annihilation
~85% of the time
in the Tevatron

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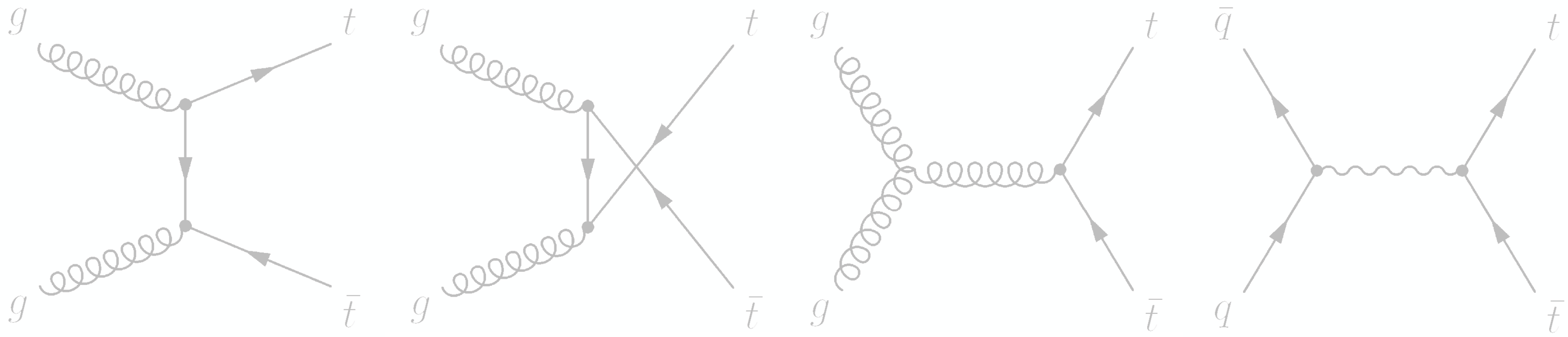
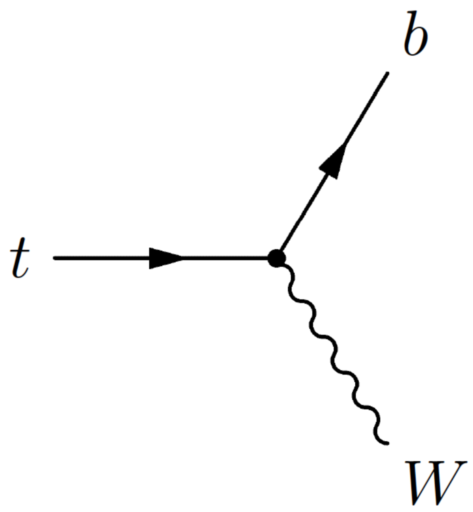


Top Quarks can also be produced via single-top quark production mechanisms.

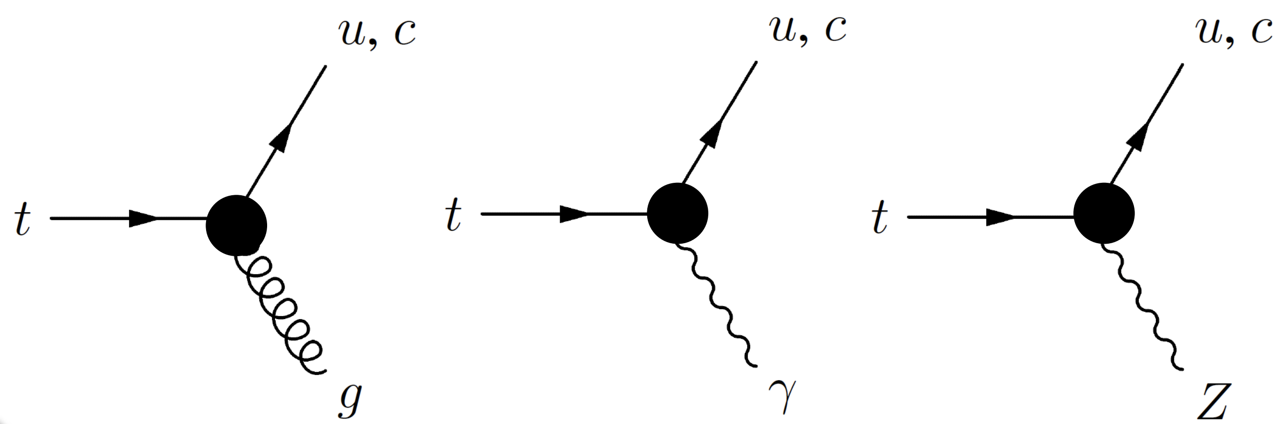
Top Quark Decay

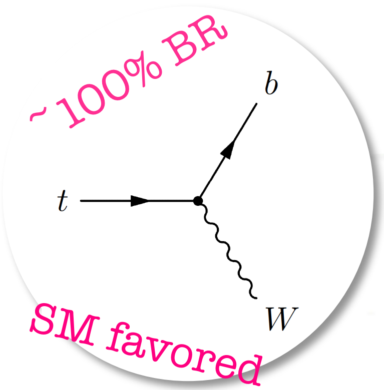
SM favored decay:



Top Quark Decay

Other decays are possible via **flavor changing neutral currents**





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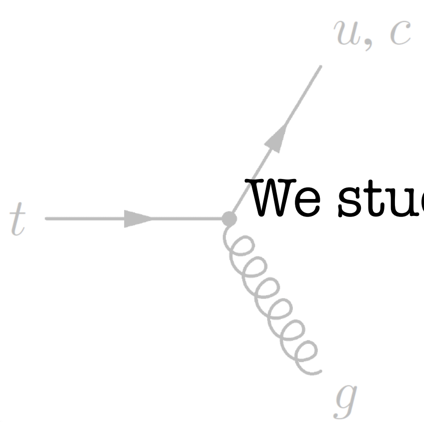
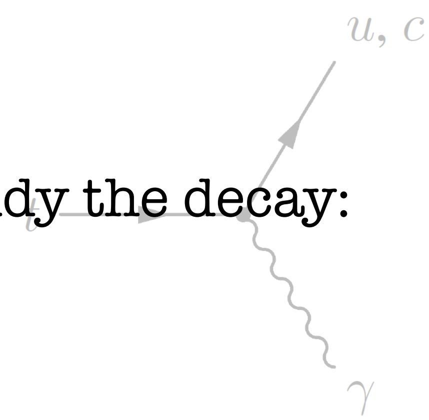
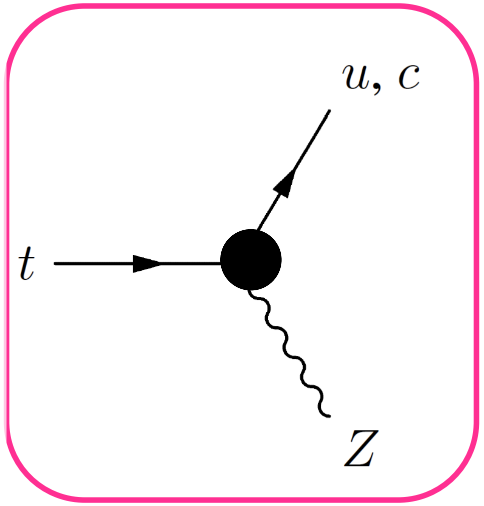
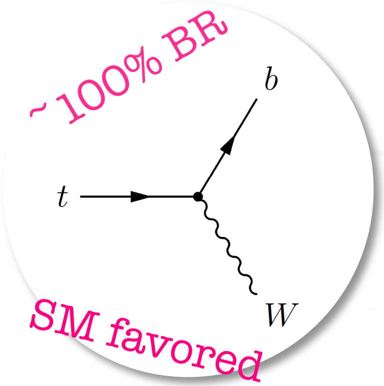


We study the decay:





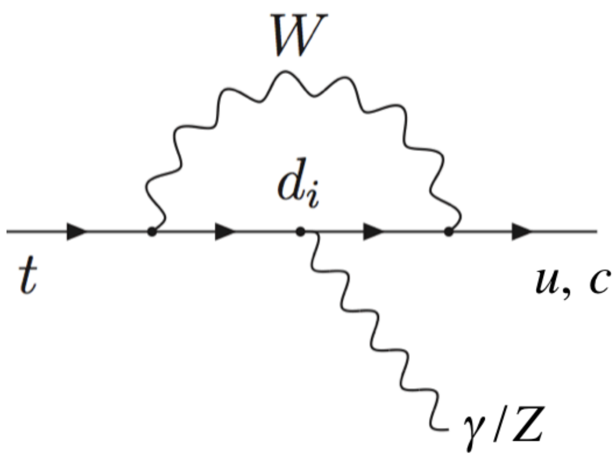
$$t \longrightarrow Zq$$



Flavor Changing Neutral Currents

FCNC do not exist at tree level in the SM.

Higher order electroweak interactions do allow FCNC:



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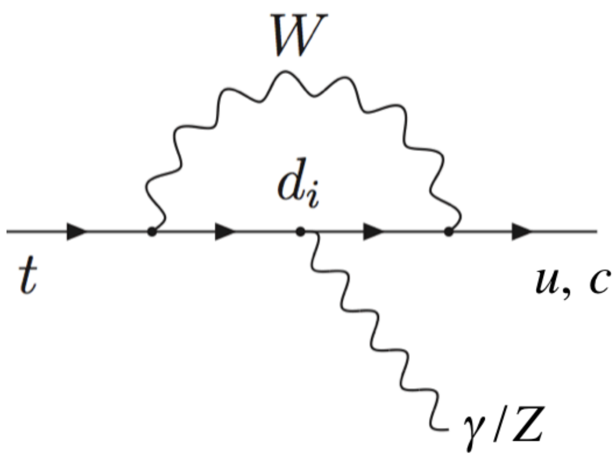

However, the GIM mechanism highly suppresses the contribution from these diagrams...

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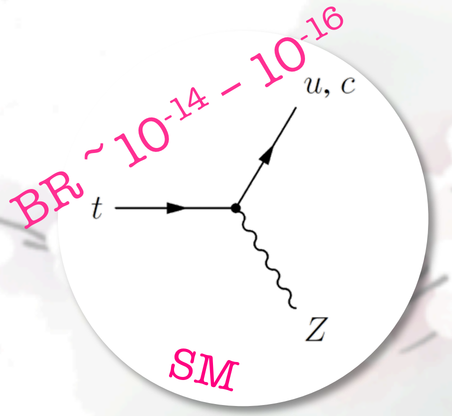

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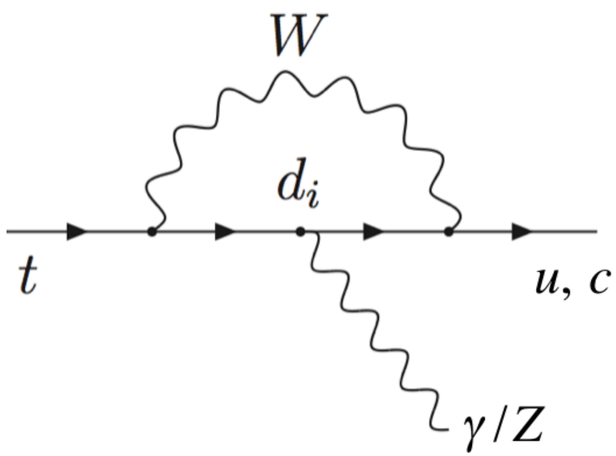

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Beyond SM FCNC

SM extensions predict higher branching ratios for top quark FCNC decays:

Process	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}

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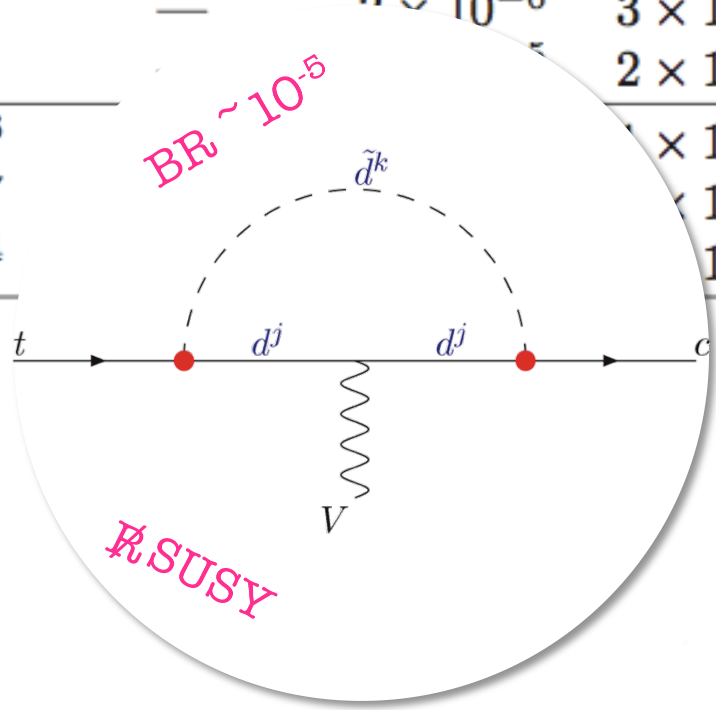

E. g. in some R-parity violating SUSY models, the BR can be enhanced up to ~10^{-5}

Flavor Changing Neutral Currents

Current Experimental Limits

	LEP	HERA	Tevatron	LHC
$BR(t \to q\gamma)$	2.4% [41–45]	0.64% $(tu\gamma)$ [47]	3.2% [51]	—
$BR(t \to qZ)$	7.8% [41–45]	49% (tuZ) [48]	3.2% [52]	0.73% [2]
$BR(t \to qg)$	17% [46]	13% [48–50]	2.0×10^{-4} (tug) 3.9×10^{-3} (tcg) [54]	5.7×10^{-5} (tug) 2.7×10^{-4} (tcg) [55]

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Before the LHC searches, best limit from D0 Collaboration:

$$BR(t \to Zq) < 3.2\%$$

using top quark pairs, with W- and Z-bosons decay leptonically.

Flavor Changing Neutral Currents

Search for FCNC in top quark decays:

In top quark pair production events:
with one top quark decaying through $t \to qZ$,
and the other through the SM dominant mode $t \to bW$.

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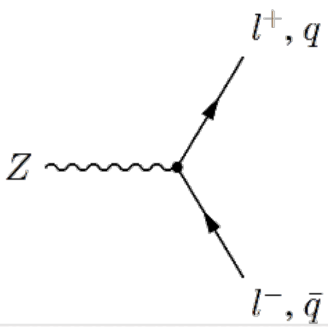
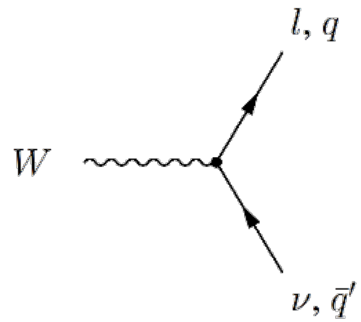
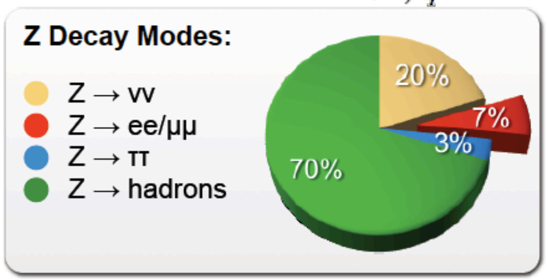
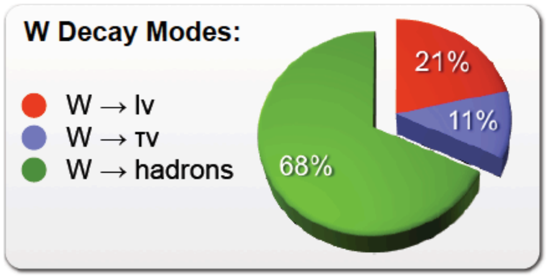
Only leptonic decays of the W- and Z-bosons are used as signal









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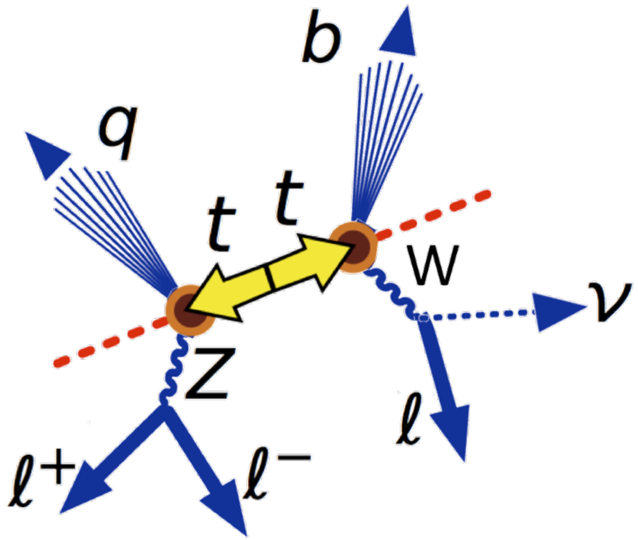

$$t\bar{t} \rightarrow bWqZ \rightarrow b\ell\nu q\ell\ell$$

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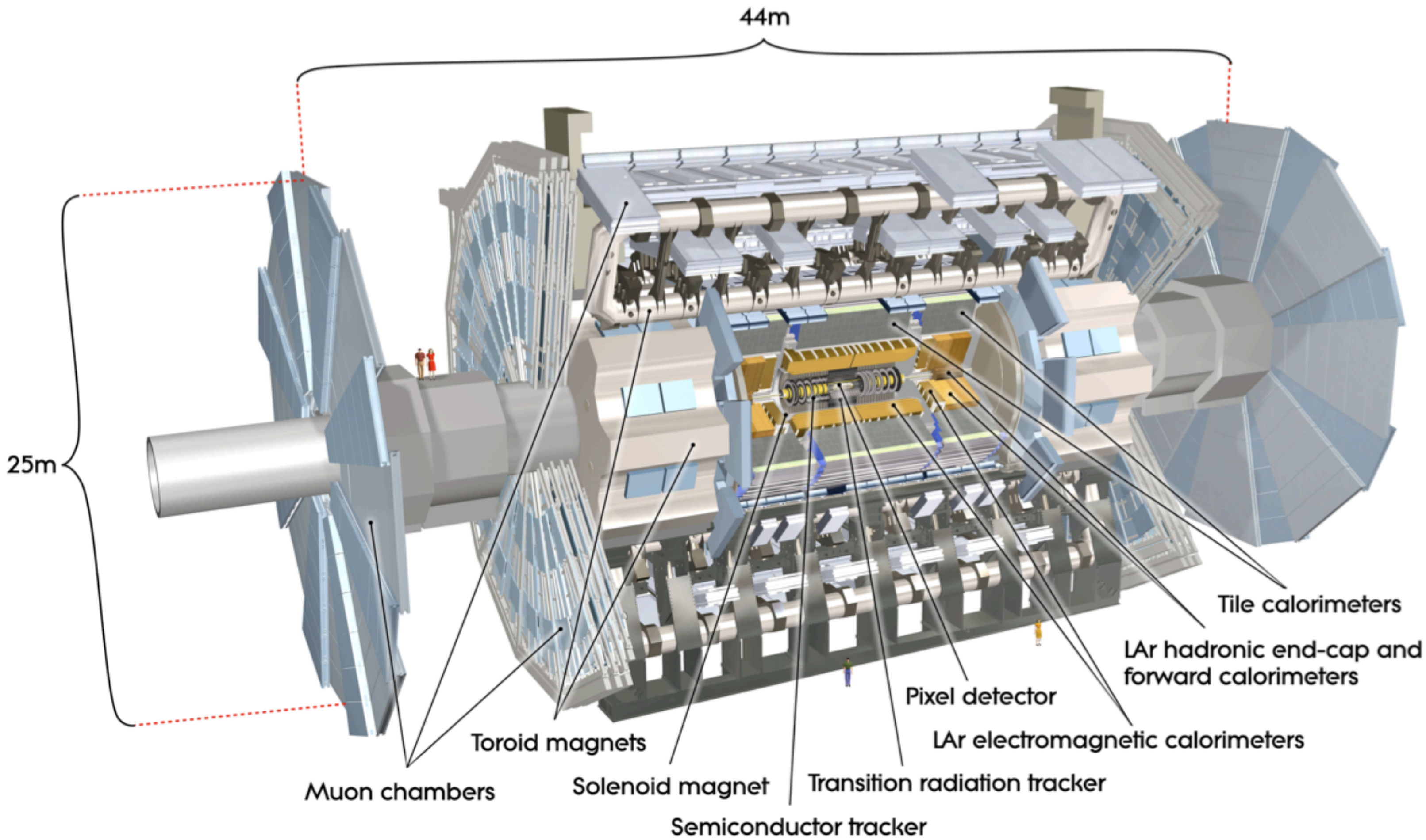
Large Hadron Collider @CERN

World's largest and most energetic particle collider!
pp collisions at $\sqrt{s}$ = **7 TeV** in 2010-2011,
and a peak luminosity:
$3.6 \times 10^{33}\ cm^{-2}s^{-1}$

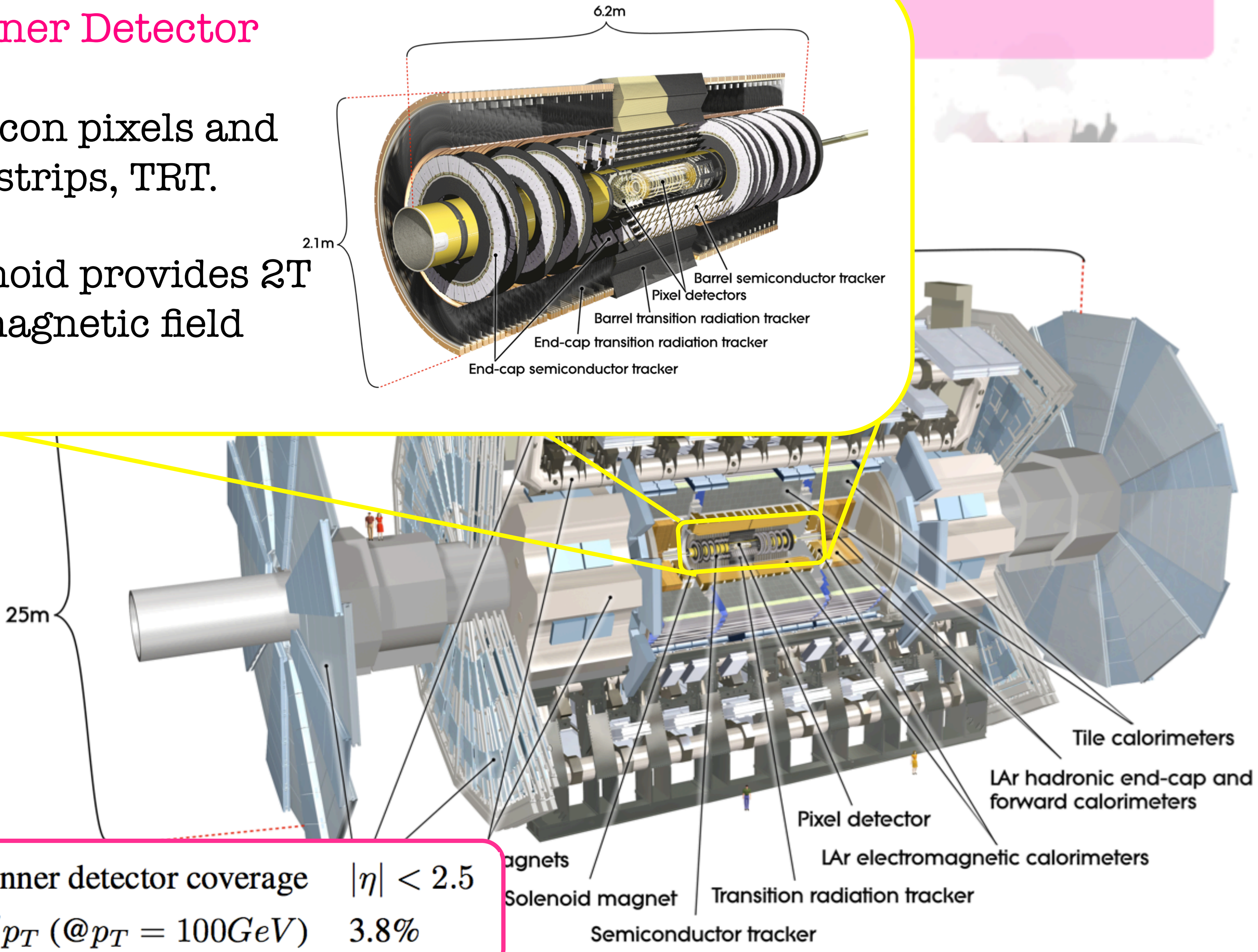
ATLAS Detector



Inner Detector

Silicon pixels and strips, TRT.

Solenoid provides 2T magnetic field



inner detector coverage	$\|\eta\| < 2.5$
$\sigma(p_T)/p_T$ (@$p_T = 100GeV$)	3.8%

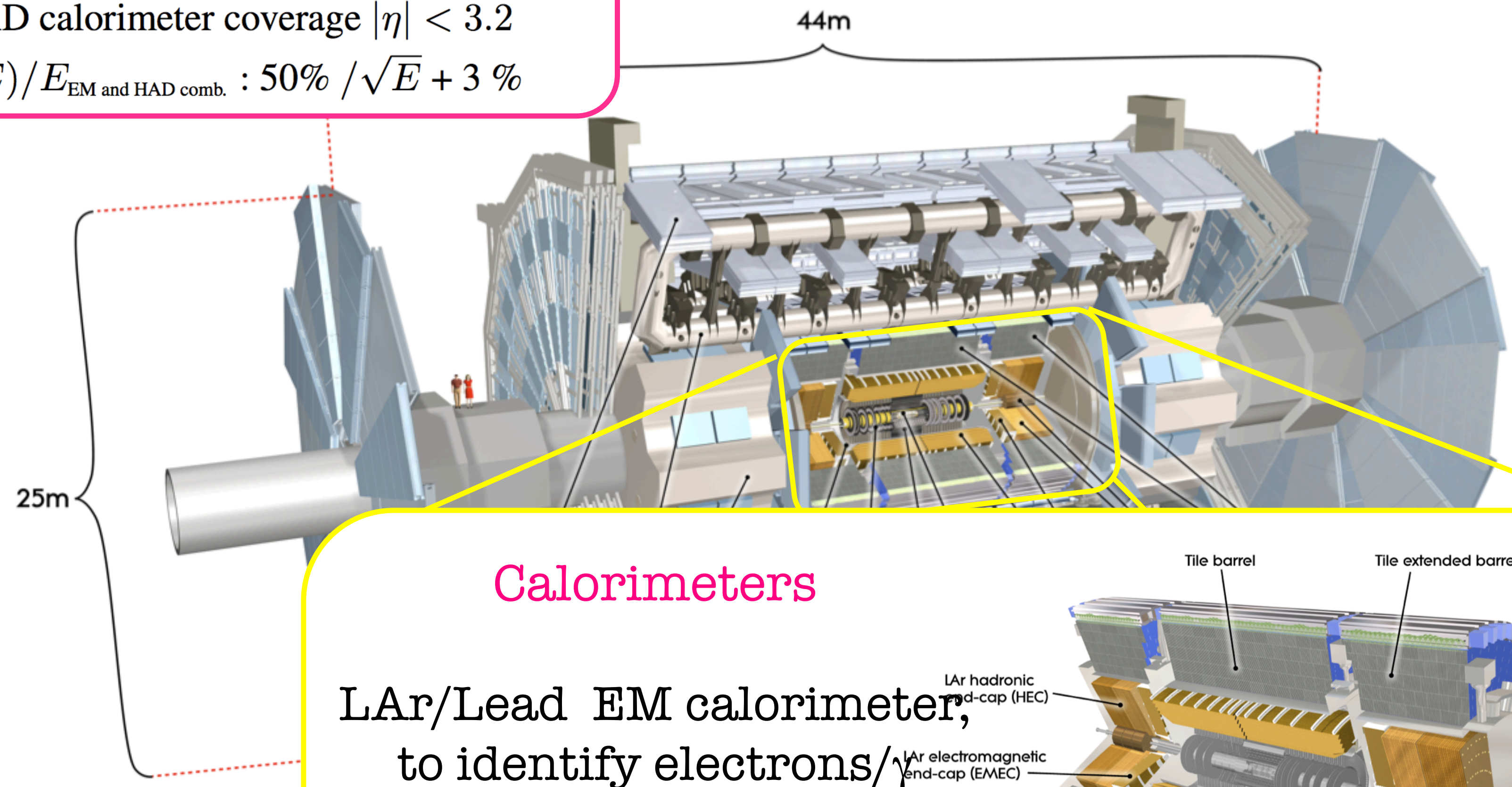
ATLAS Detector

EM calorimeter coverage $|\eta| < 3.2$

$\sigma(E)/E$: 10% $/\sqrt{E} + 0.7$ %

HAD calorimeter coverage $|\eta| < 3.2$

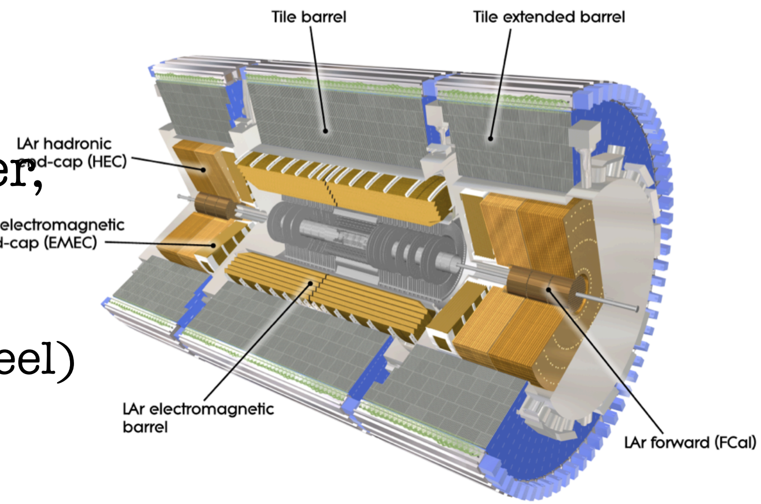
$\sigma(E)/E_{\text{EM and HAD comb.}}$: 50% $/\sqrt{E} + 3$ %



Calorimeters

LAr/Lead EM calorimeter,
to identify electrons/γ

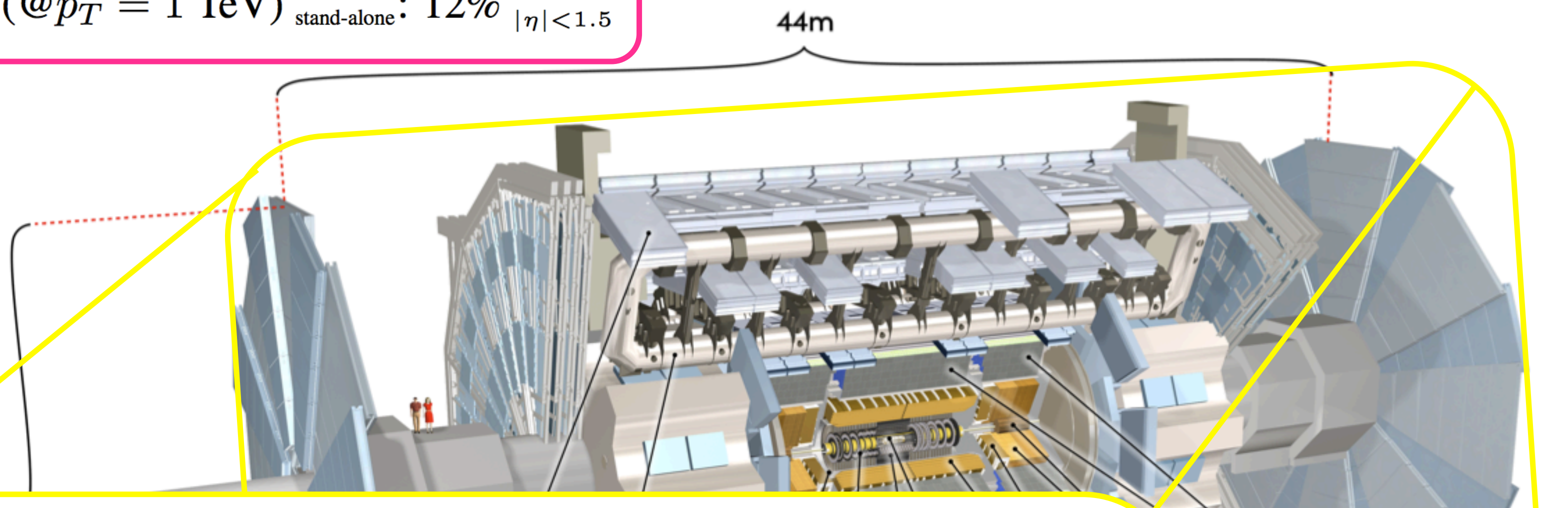
Scintillation-tile (plastic/steel)
hadronic calorimeter



ATLAS Detector

muon spectrometer coverage $|\eta| < 2.7$

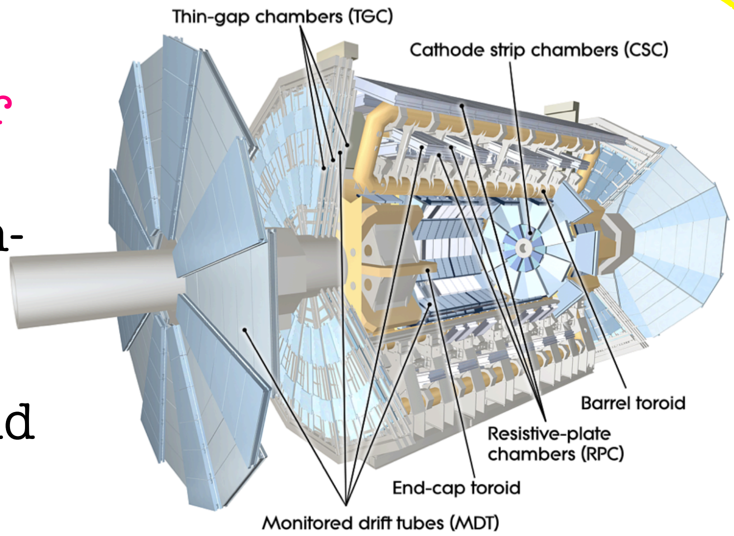
$\sigma(p_T)/p_T$ (@$p_T = 1$ TeV)$_{\text{stand-alone}}$: 12% $_{|\eta|<1.5}$



Muon Spectrometer

With trigger and high-precision chambers

Toroidal magnetic field



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Object Selection

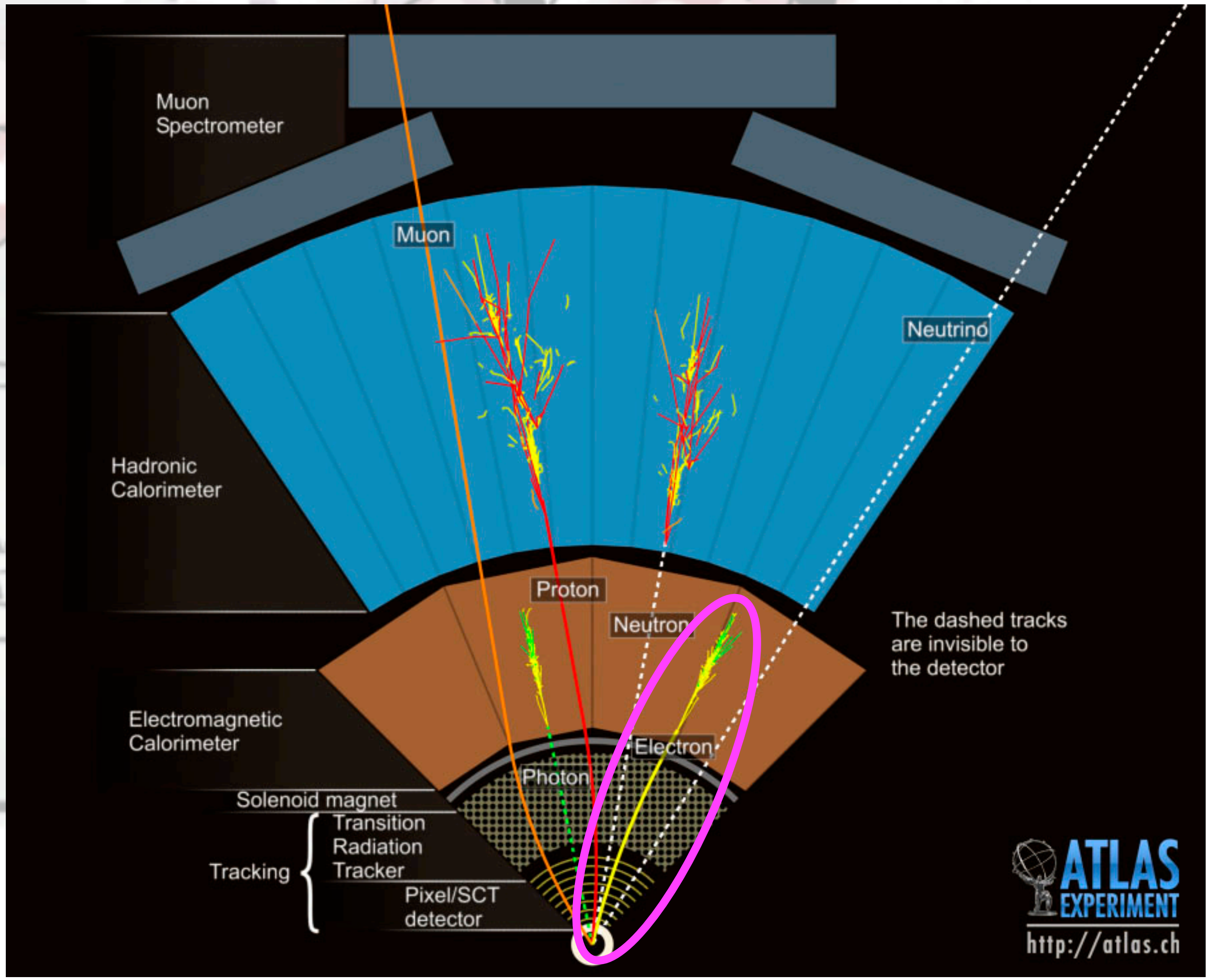
ID electrons

Isolated Electromagnetic clusters associated to Inner Detector track.

$p_T > 20$ GeV, $|\eta| < 2.47$

Exclude transition region between Barrel and End-Cap

Calo-iso($\Delta R < 0.2$) < 3.5GeV



Object Selection

ID electrons

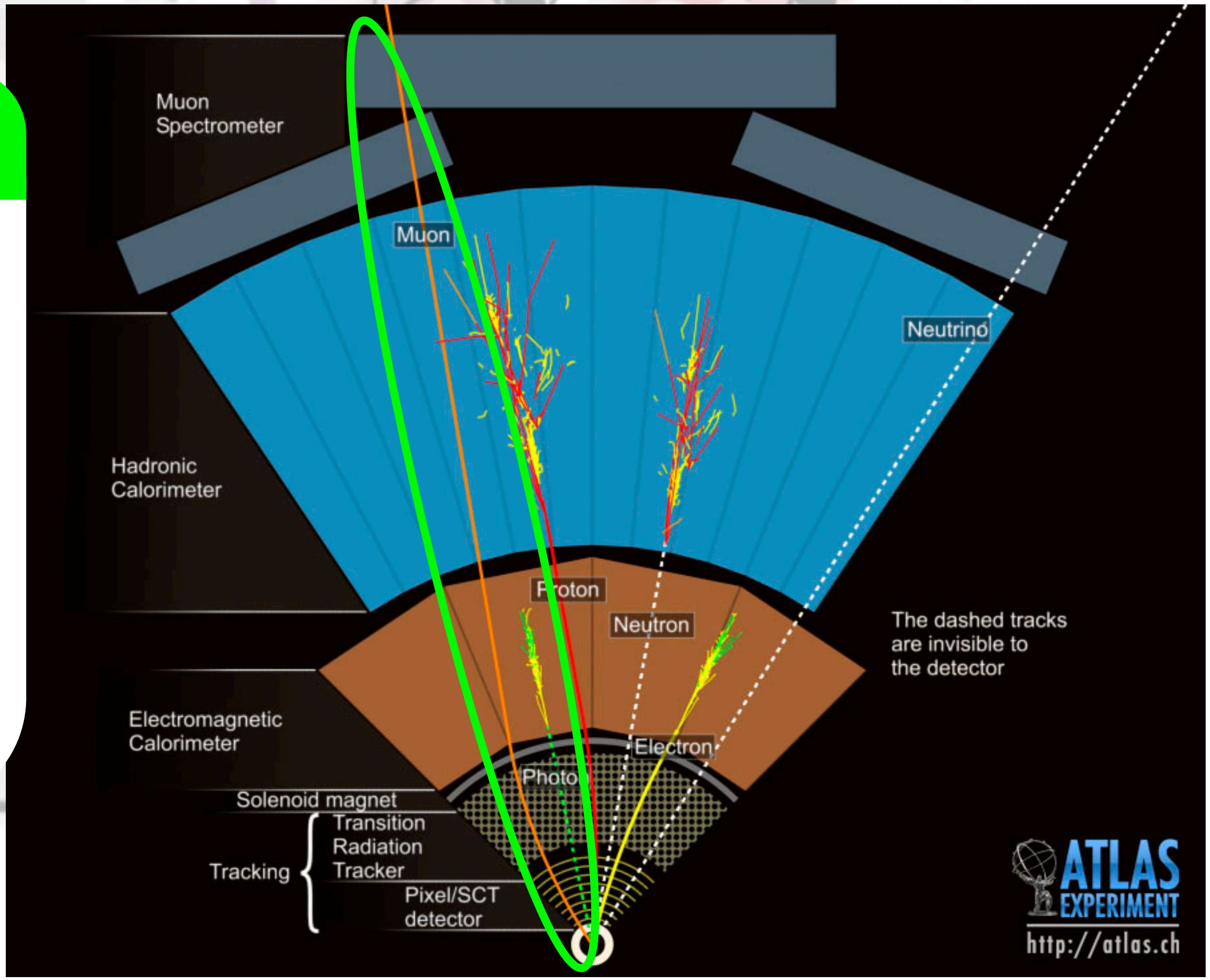
ID muons

Tracks segments from MS matched to tracks from Inner Detector, & refitted.

$p_T > 20$ GeV, $|\eta| < 2.5$

Calo-iso($\Delta R < 0.3$) < 4 GeV
Trk-iso($\Delta R < 0.3$) < 4 GeV

$|d_0| < 0.5$ mm



Object Selection

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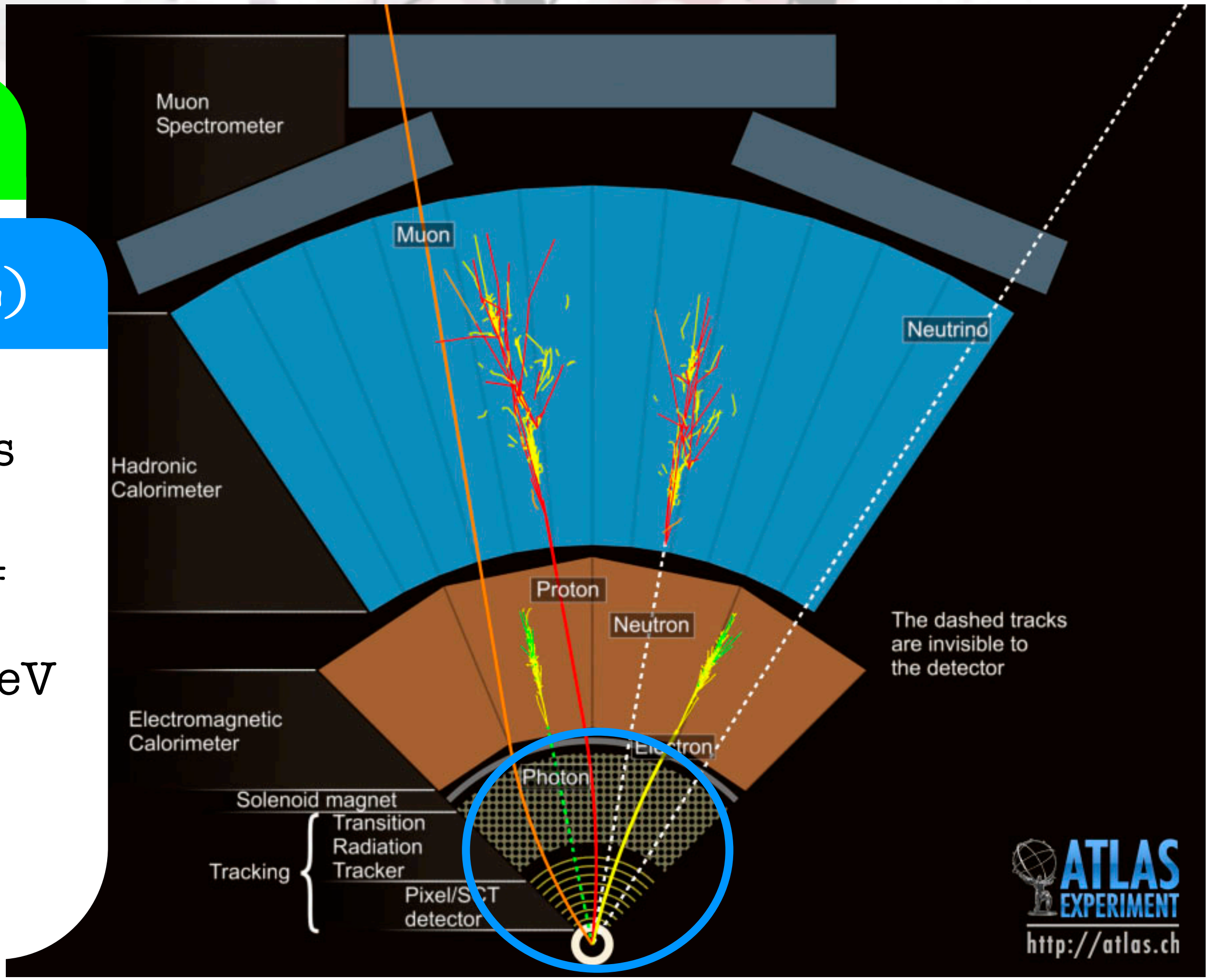
track-leptons (TL)

High quality
inner detector tracks

$p_T > 25$ GeV, $|\eta| < 2.4$

Trk-Iso($\Delta R < 0.3$) < 2GeV

Inner detector hit
requirements



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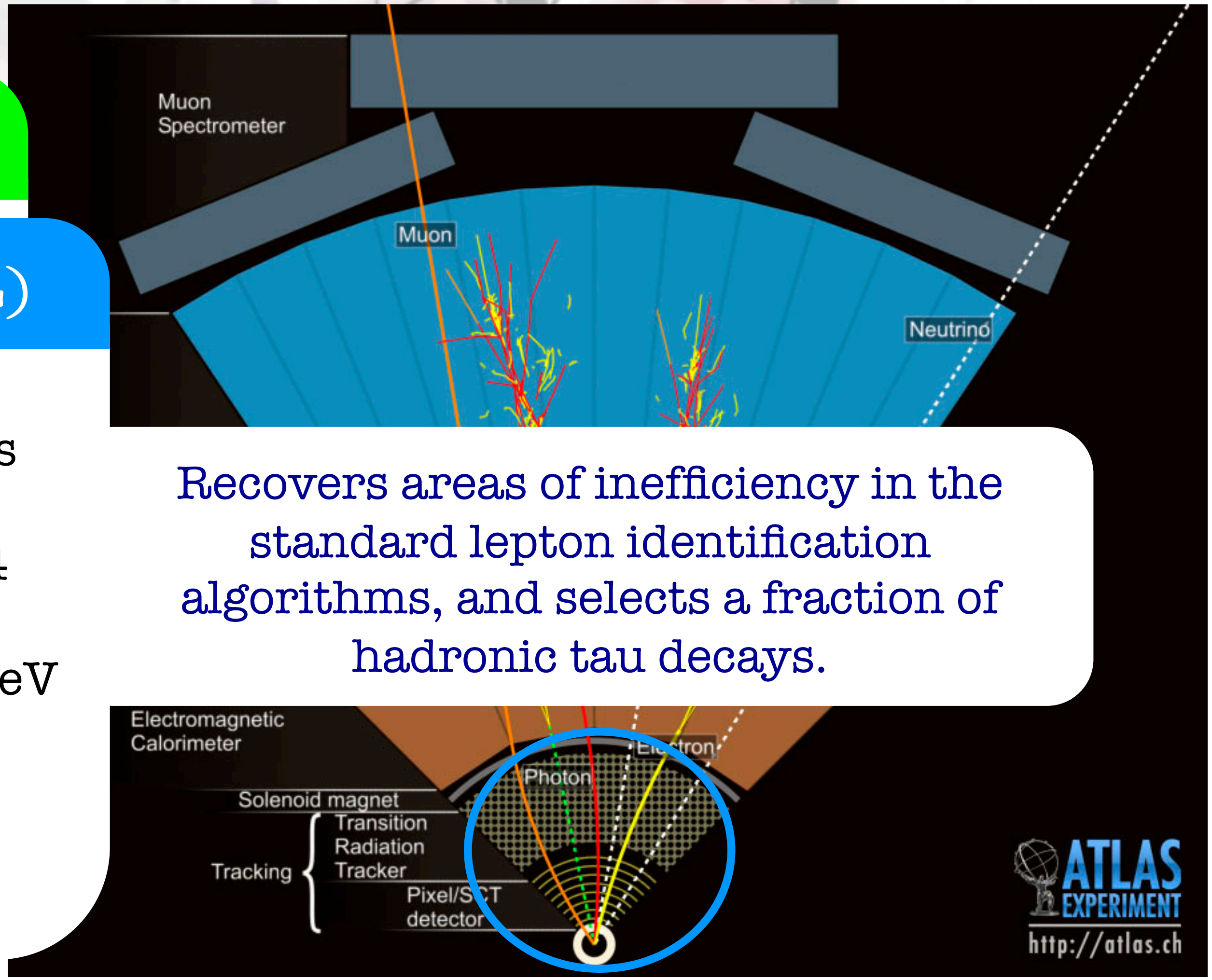


Recovers areas of inefficiency in the standard lepton identification algorithms, and selects a fraction of hadronic tau decays.

Object Selection

ID electrons

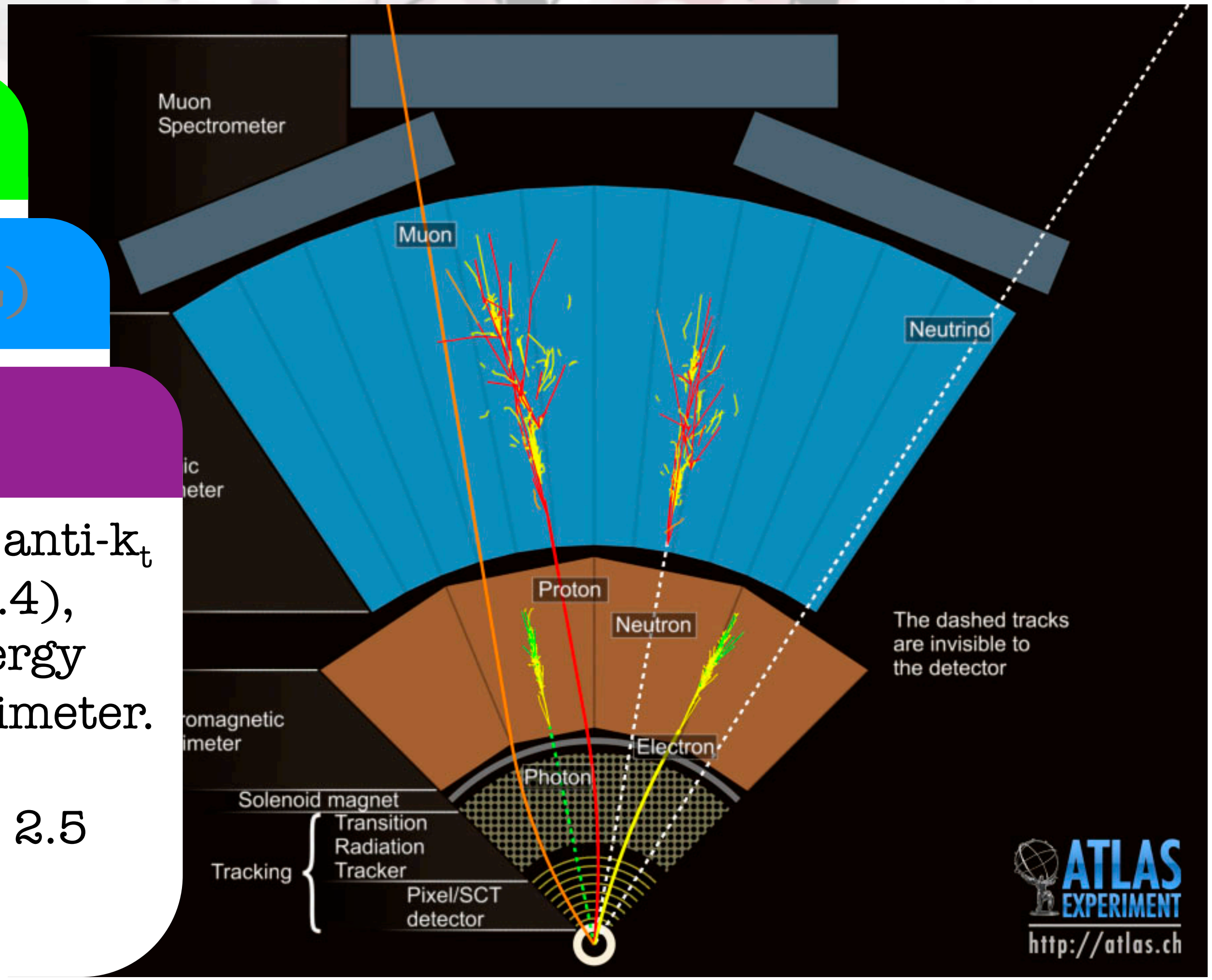
ID muons

track-leptons (TL)

ID jets

Reconstructed with anti-k_t algorithm (ΔR=0.4), starting from energy clusters in the calorimeter.

$p_T > 25$ GeV, $|\eta| < 2.5$



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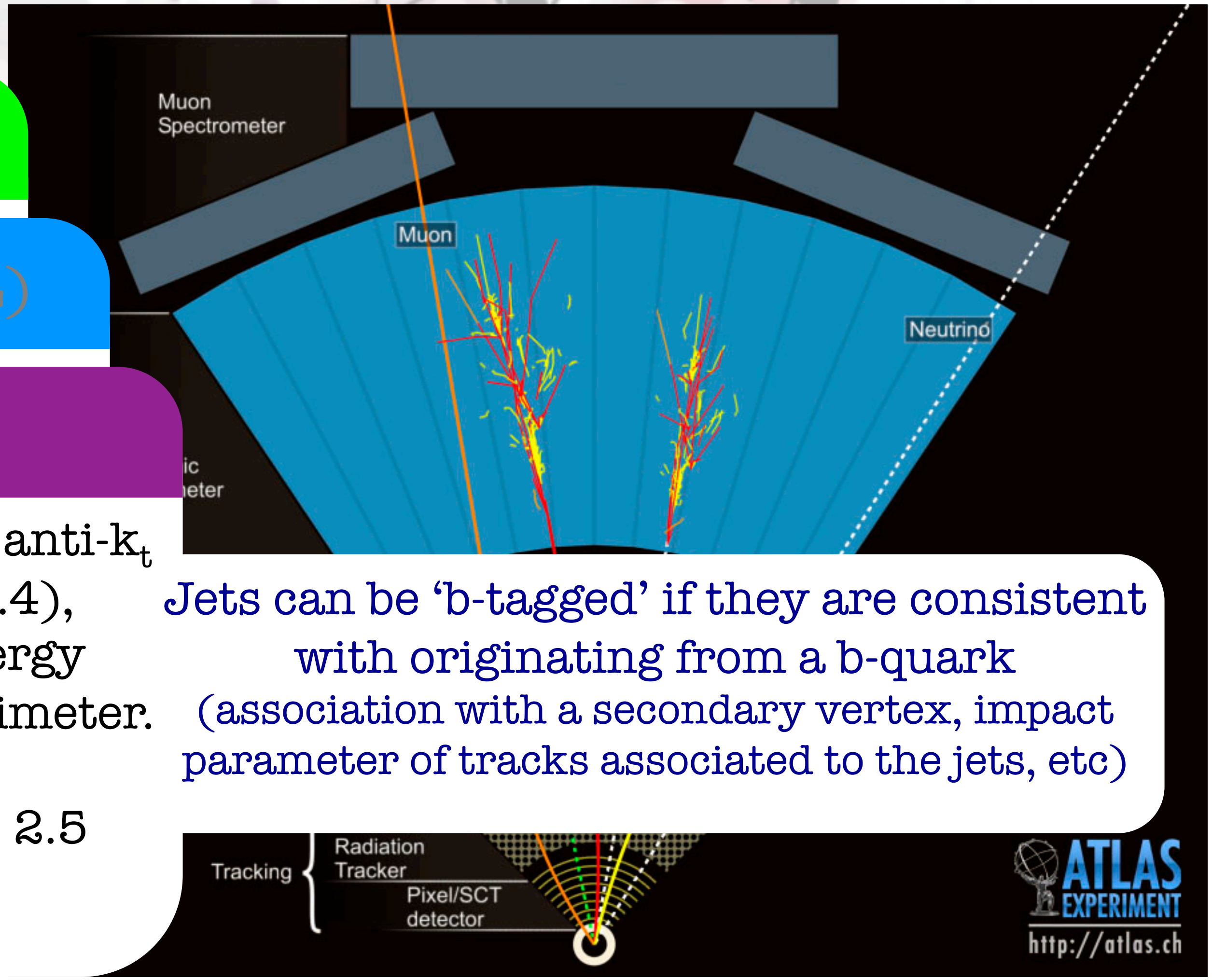


Jets can be 'b-tagged' if they are consistent with originating from a b-quark (association with a secondary vertex, impact parameter of tracks associated to the jets, etc)

Object Selection

ID electrons

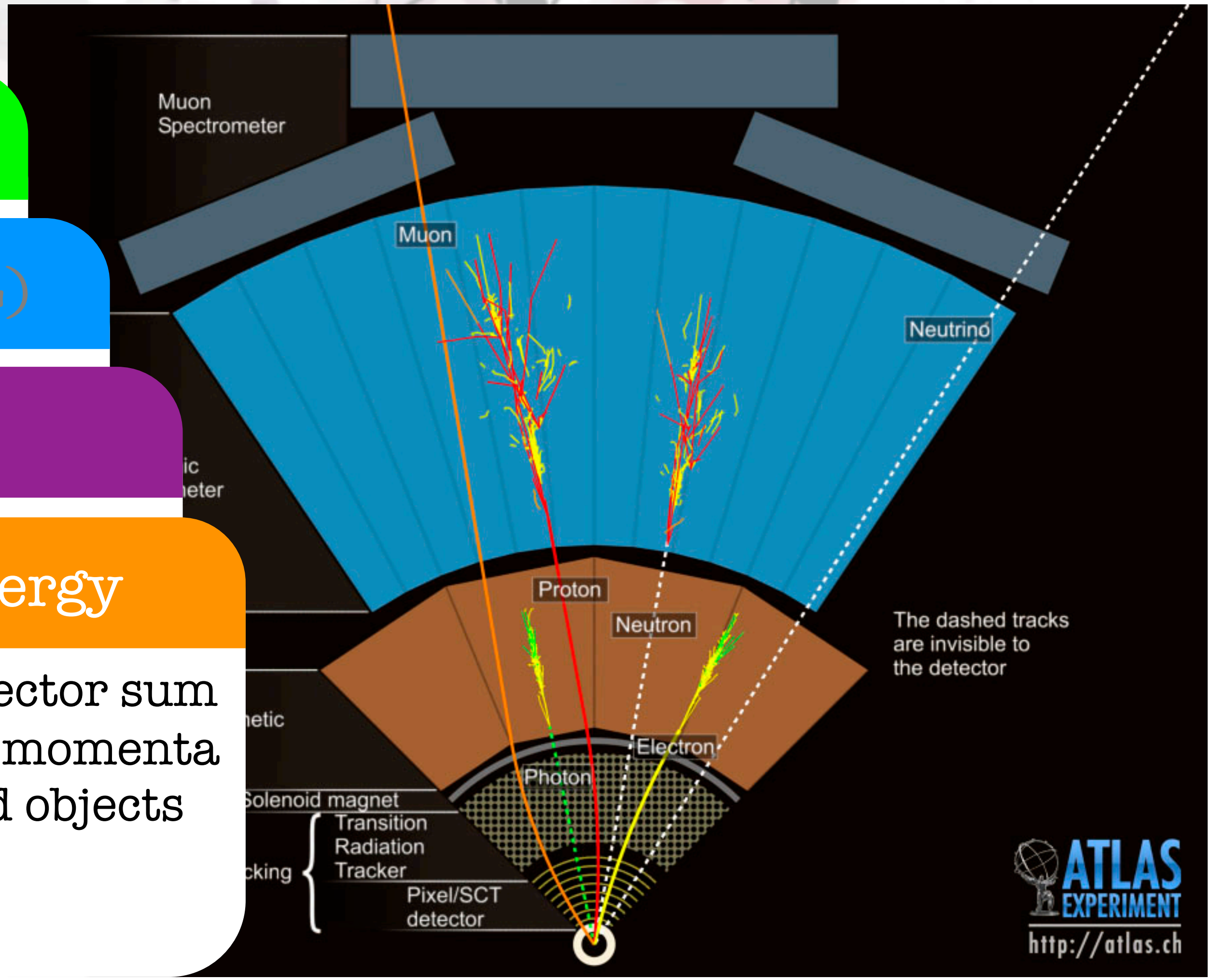
ID muons

track-leptons (TL)

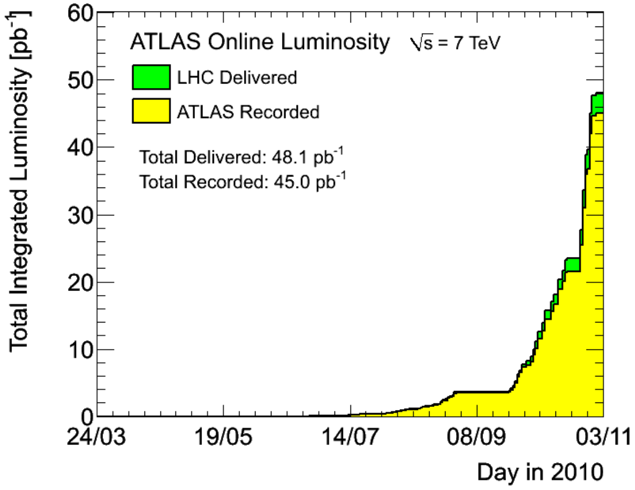
ID jets

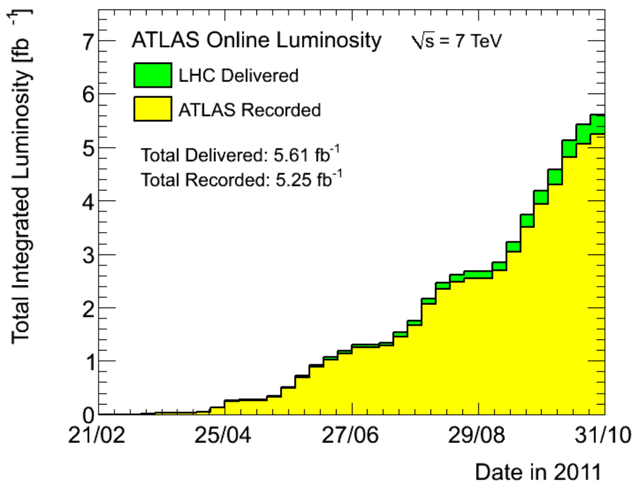
Missing energy

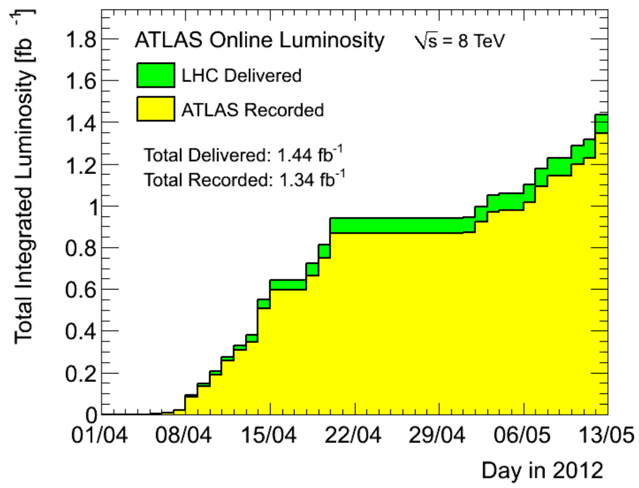
E_T^{miss}: Negative vector sum of the transverse momenta of reconstructed objects



Data Sample







	2010	2011	2012
# interactions per BC	2	6-12	$\sim$25
$\sqrt{s}$	7 TeV	7 TeV	8 TeV
peak luminosity	2.1×10^{32} cm^{-2}s^{-1}	3.6×10^{33} cm^{-2}s^{-1}	5.54×10^{33} cm^{-2}s^{-1}

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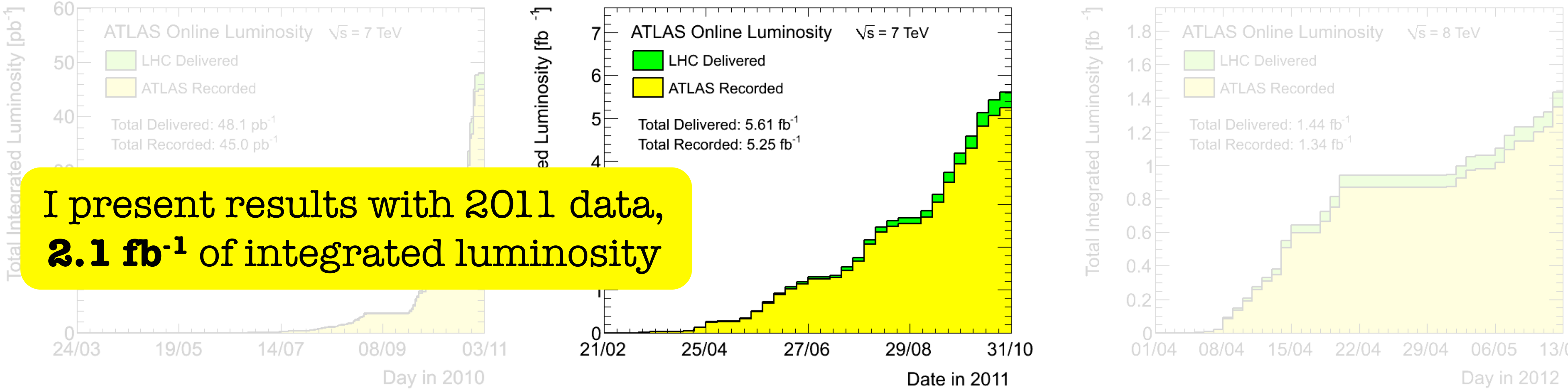

I present results with 2011 data, **2.1 fb^{-1}** of integrated luminosity

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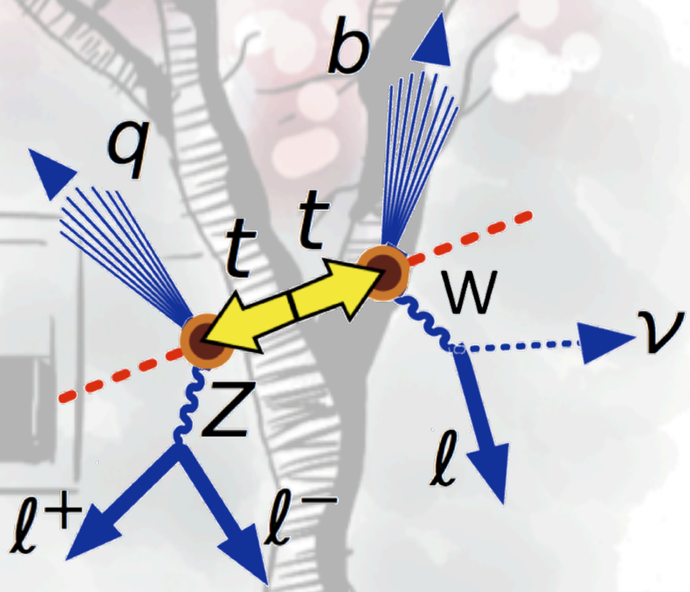
Event Selection

The final state is characterized by three isolated leptons, two of them reconstructing a Z-boson, missing energy, and at least two jets.



Event Selection

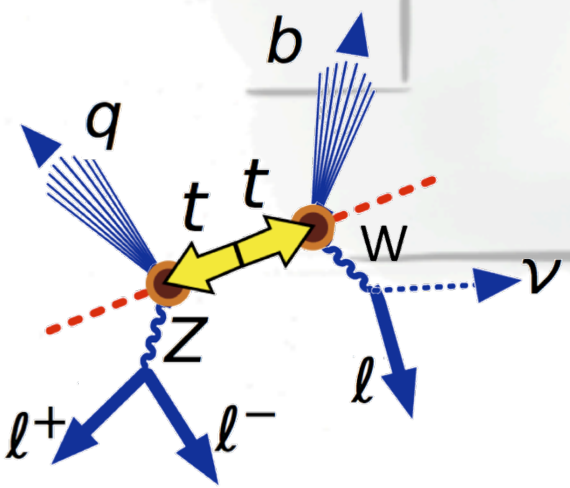
There are two orthogonal channels used for the final result:

2 ID + TL

2 leptons are fully identified, and the third one is allowed to be a high quality inner detector track.

3 ID

Selects 3 fully identified leptons (e, μ).



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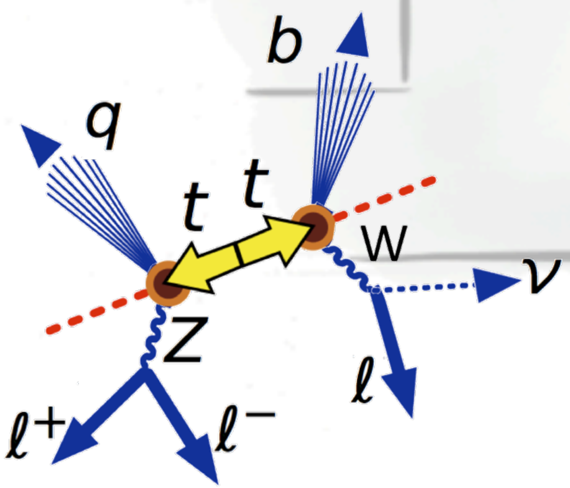


Track-leptons (**TL**) are exclusive of any electrons or muons (**ID** Leptons) selected by the 3ID analysis.

Event Selection

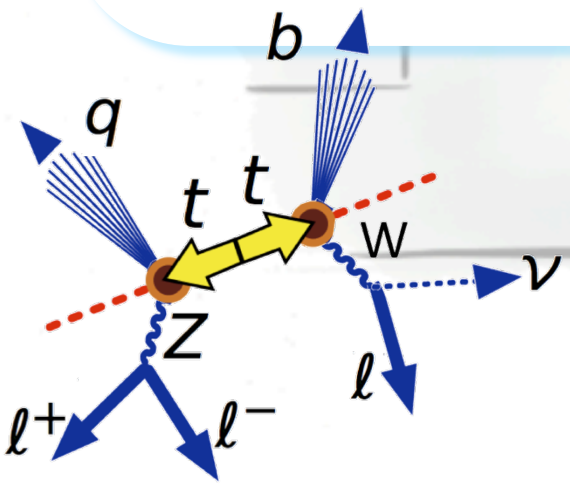
Preselection

- Basic Cuts, Trigger
- Exactly three leptons
  - all matched to the same Primary Vertex

2ID+TL Two ID leptons + one TL
$P_T^{TL} > 25$ GeV, $P_T^{e,\mu} > 20$ GeV

3ID Three ID leptons
$P_T^{lead} > 25$ GeV, $P_T^{sublead} > 20$ GeV

- Two leptons of the same flavor and opposite charge



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3ID Three ID leptons
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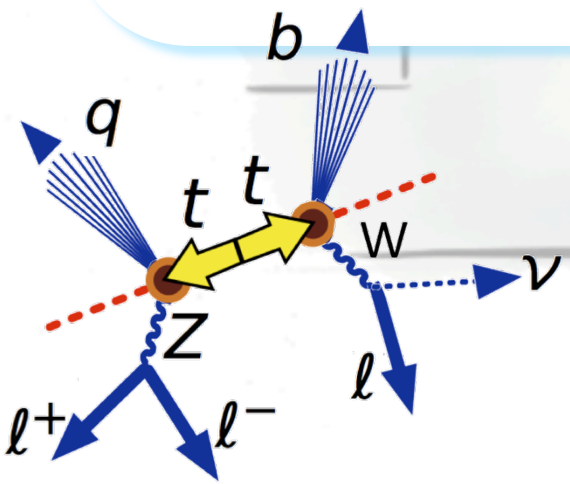
- Two leptons of the same flavor and opposite charge
- $E_T^{miss} > 20$ GeV
- Two or more ID jets

2ID+TL At least one jet b-tagged



Event Selection

Preselection

- Basic Cuts, Trigger
- Exactly three leptons
  - all matched to the same Primary Vertex

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$P_T^{TL} > 25$ GeV, $P_T^{e,\mu} > 20$ GeV

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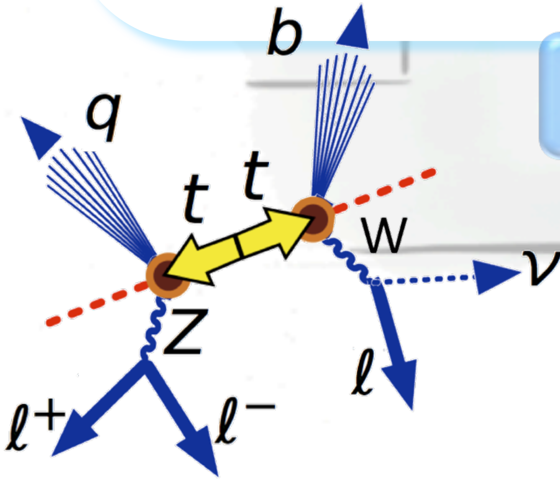

Final Selection

- Event Reconstruction

$$\chi^2 = \frac{\left(m^{reco}_{j_a\ell_a\ell_b} - m_t\right)^2}{\sigma_t^2} + \frac{\left(m^{reco}_{j_b\ell_c\nu} - m_t\right)^2}{\sigma_t^2} + \frac{\left(m^{reco}_{\ell_c\nu} - m_W\right)^2}{\sigma_W^2} + \frac{\left(m^{reco}_{\ell_a\ell_b} - m_Z\right)^2}{\sigma_Z^2}$$

2ID+TL Event Selection

Final Selection

- Event Reconstruction

To reconstruct the mass of the two top quarks and W- and Z-bosons , χ^2 is minimized:

$$\chi^2 = \frac{\left(m^{\text{reco}}_{j_a\ell_a\ell_b} - m_t\right)^2}{\sigma_t^2} + \frac{\left(m^{\text{reco}}_{j_b\ell_c\nu} - m_t\right)^2}{\sigma_t^2} + \frac{\left(m^{\text{reco}}_{\ell_c\nu} - m_W\right)^2}{\sigma_W^2} + \frac{\left(m^{\text{reco}}_{\ell_a\ell_b} - m_Z\right)^2}{\sigma_Z^2}$$

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- j_a, j_b loops over the two leading ID jets

$$\begin{aligned} m_t &= 172.5\ \text{GeV} & \sigma_t &= 14\ \text{GeV} \\ m_W &= 80.4\ \text{GeV} & \sigma_W &= 10\ \text{GeV} \\ m_Z &= 91.2\ \text{GeV} & \sigma_Z &= 3\ \text{GeV} \end{aligned}$$

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- j_a, j_b loops over the two leading ID jets

- ℓ_c, $Z \rightarrow \ell_a^+ \ell_b^-$: loop over the three leptons

- E_T^{miss} is taken to be the transverse component of the neutrino p_T^ν.
- p_Z^ν is the determined by the minimal χ^2

$$\begin{aligned} m_t &= 172.5 \text{ GeV} & \sigma_t &= 14 \text{ GeV} \\ m_W &= 80.4 \text{ GeV} & \sigma_W &= 10 \text{ GeV} \\ m_Z &= 91.2 \text{ GeV} & \sigma_Z &= 3 \text{ GeV} \end{aligned}$$

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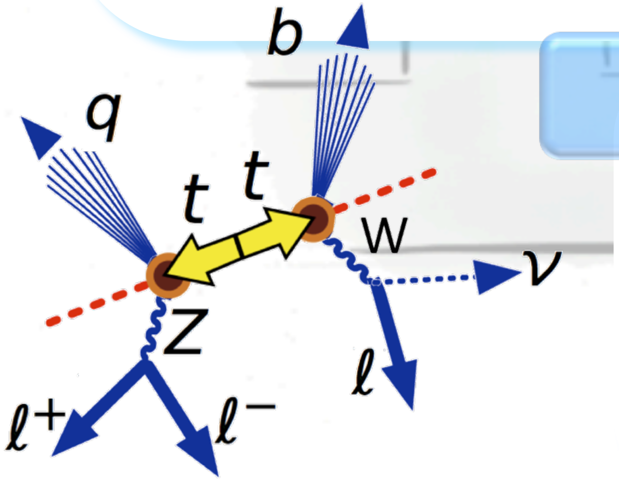

Final Selection

- Event Reconstruction
  - $|m_Z - m_Z^{reco}| < 15$ GeV
  - $|m_W - m_W^{reco}| < 30$ GeV
  - $|m_t - m_t^{reco}| < 40$ GeV

2ID + TL Gain

The 2ID+TL gives a 22% gain wrt the 3ID channel alone.

Gain

This gain comes mainly from e and μ in the transition regions and gaps in detector coverage.

There is also a partial recovery of efficiency losses in the e and μ selection and additional acceptance from hadronic taus.

Outline

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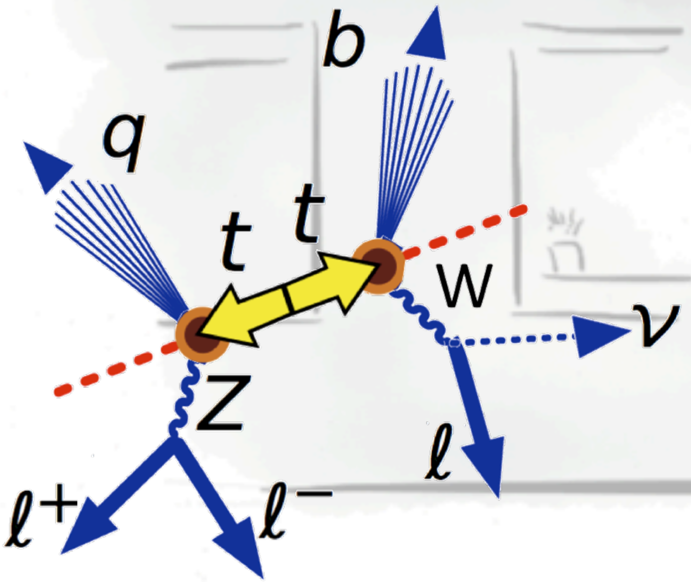
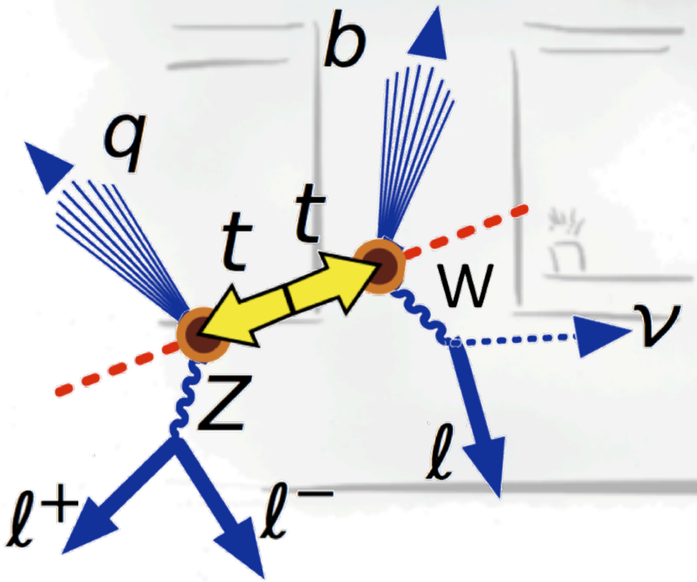
SM processes that have a similar final state topology



Backgrounds

SM processes that have a similar final state topology



Three Real Leptons

Dibosons WZ, ZZ
t-tbar+W, t-tbar+Z

at least one Fake Lepton

t-tbar, Z+jets, W+jets, WW, single top

Backgrounds

Three real leptons

Dibosons WZ, ZZ
t-tbar+W, t-tbar+Z

Determined using MC samples.

Contributes to ~15% of the 2ID + TL background.
Main background for the 3ID selection

Backgrounds

Fake Leptons

t-tbar, Z+jets, W+jets, WW, single top

Events with at least one fake → any object identified as a lepton that does not come from a W- or Z-boson.

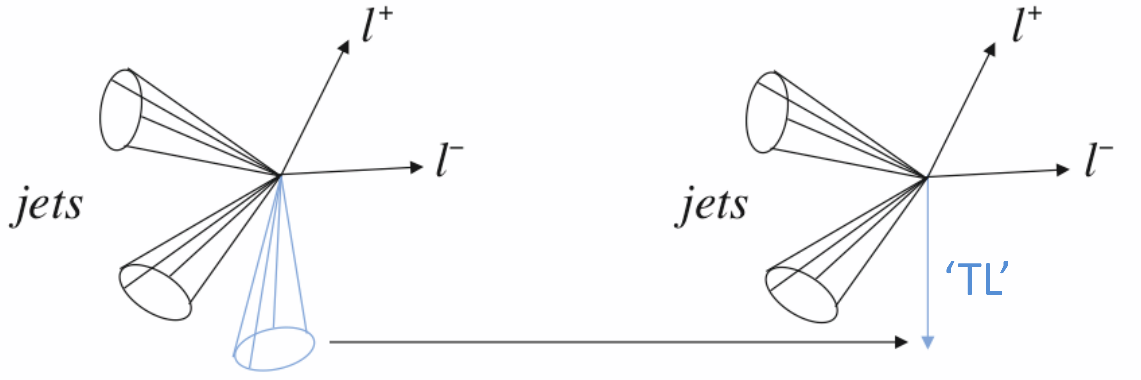
Evaluated with a data-driven (and MC) methods.

Dominant background source of the 2ID + TL.

2ID+TL Fake Leptons

2 ID + TL

Strategy



We measure the probability that a jet fakes a track, 'fake rate'

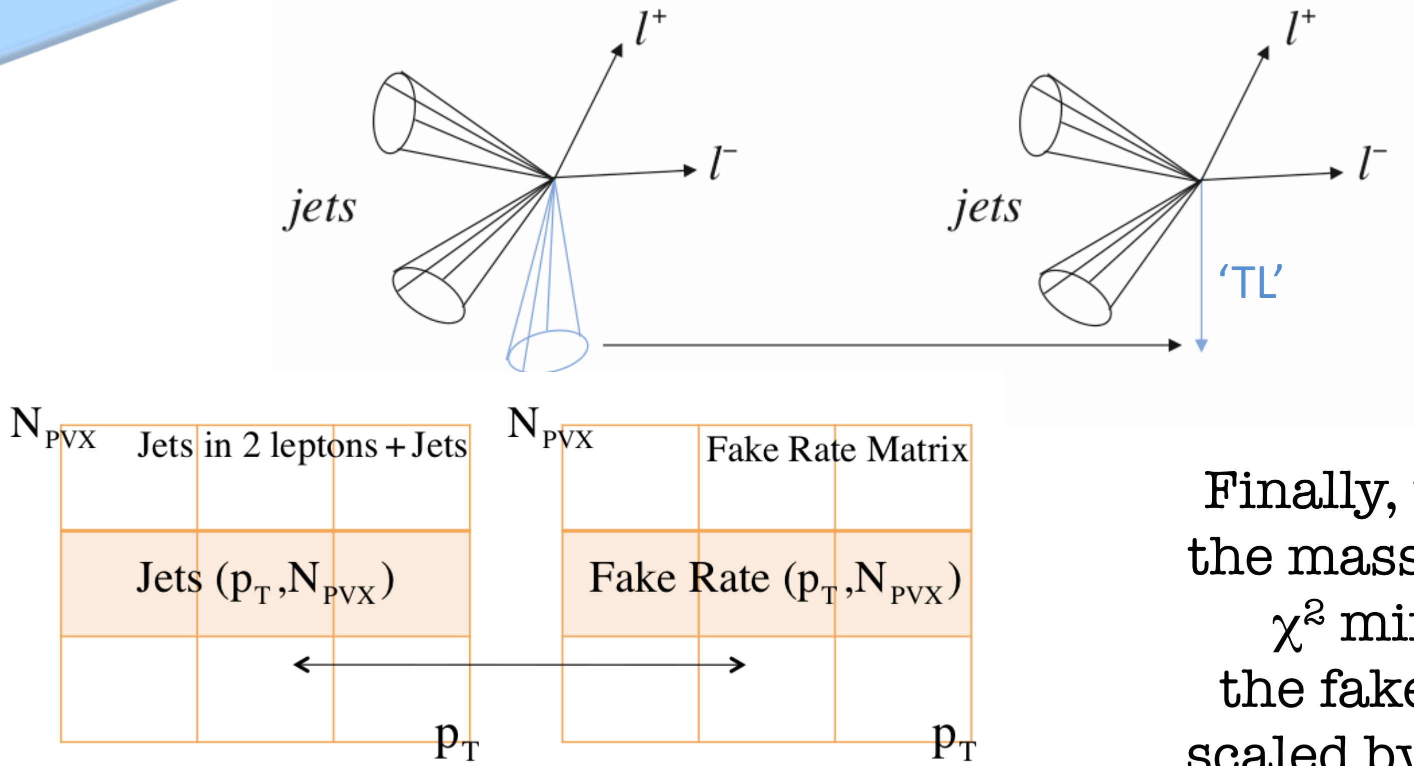
Measure the fake rates in γ+jets events

$$\text{Fake Rate}\,(p_T, N_{\text{PVX}}) = \frac{(p_T, N_{\text{PVX}})\ \text{of all selected track leptons}}{(p_T, N_{\text{PVX}})\ \text{of all ID jets \& jet} - \text{elements}}$$

2ID+TL Fake Leptons

Estimation

2 ID + TL



Finally, to account for the mass cuts after the χ^2 minimization, the fake prediction is scaled by (31.2±10.2)%

$$\text{Prediction} = \sum_{(p_T, N_{PVX})} \text{Jets}_{(p_T, N_{PVX})} \times \text{Fake Rate}_{(p_T, N_{PVX})}$$

3ID Fake Leptons

3 ID

Strategy

The background from fake leptons is estimated for events with one fake leptons, and events with 2 or 3 fake leptons.

3ID Fake Leptons

3 ID

Strategy

The background from fake leptons is estimated for events with one fake leptons, and events with 2 or 3 fake leptons.

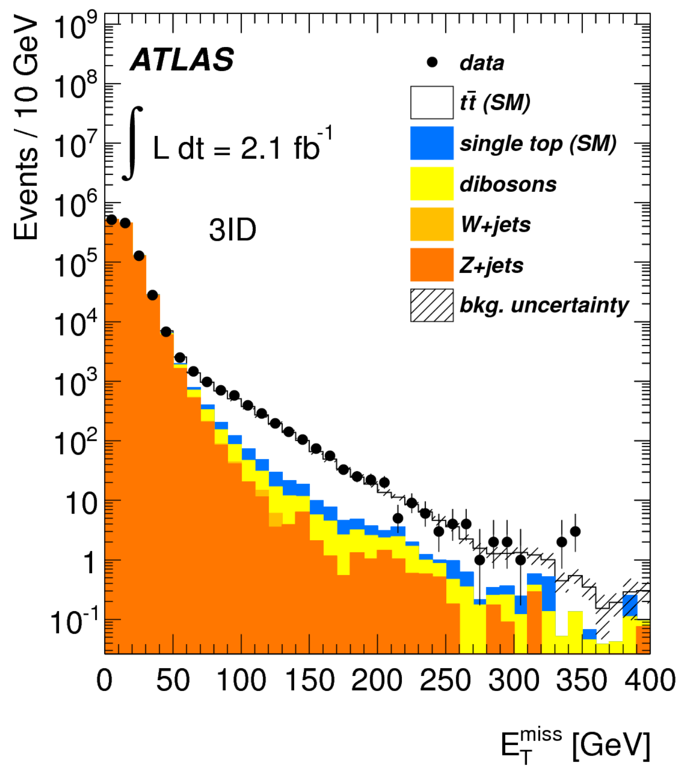
One fake events

- Z+jets

We use a control region to compute a **normalization** between data and MC.
Control region: Events with two leptons and $|m_{\ell\ell}^{reco} - 91.2\text{ GeV}| < 15\text{ GeV}$.

$$[N^{\rm Data}_{Z+\rm jets}]_{\rm SR} = \left[\frac{N^{\rm Data} - N^{\rm MC}_{\rm Other\ \ backgrounds}}{N^{\rm MC}_{Z+\rm jets}}\right]_{\rm CR} \cdot [N^{\rm MC}_{Z+\rm jets}]_{\rm SR}$$

A loose lepton selection is used, and a multiplicative factor is applied to the final result: (loose → tight) 0.063 ± 0.013



3ID Fake Leptons

3 ID

Strategy

The background from fake leptons is estimated for events with one fake leptons, and events with 2 or 3 fake leptons.

One fake events

- Z+jets

  We use a control region to compute a **normalization** between data and MC.
  A loose lepton selection is used, and a multiplicative factor is applied to the final result:
  (loose → tight) 0.063 ± 0.013

- Dileptonic t-tbar, single top (Wt), WW.

  Measured in MC with the loose lepton selection, and scaled down by the same factor.

3ID Fake Leptons

3 ID

Strategy

The background from fake leptons is estimated for events with one fake leptons, and events with 2 or 3 fake leptons.

2+3 fakes events

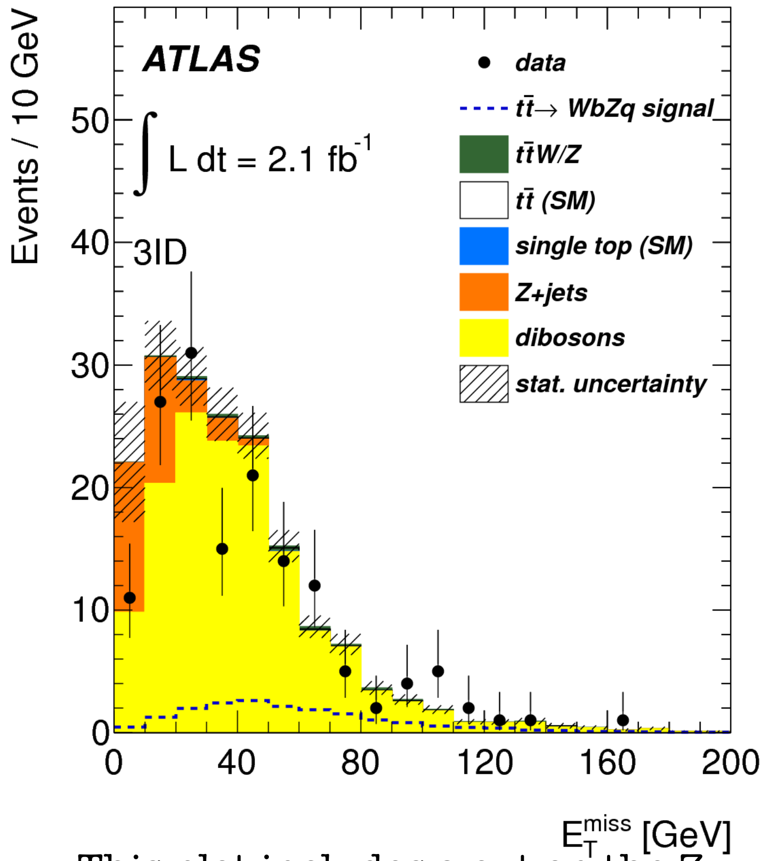
- QCD, W+jets ,s ingle top, single lepton t-tbar

Due to the requirements of two leptons with same charge and opposite sign (36 combinations), this background is extrapolated from the data events with 3 leptons of any flavor, but same charge (16 combination).

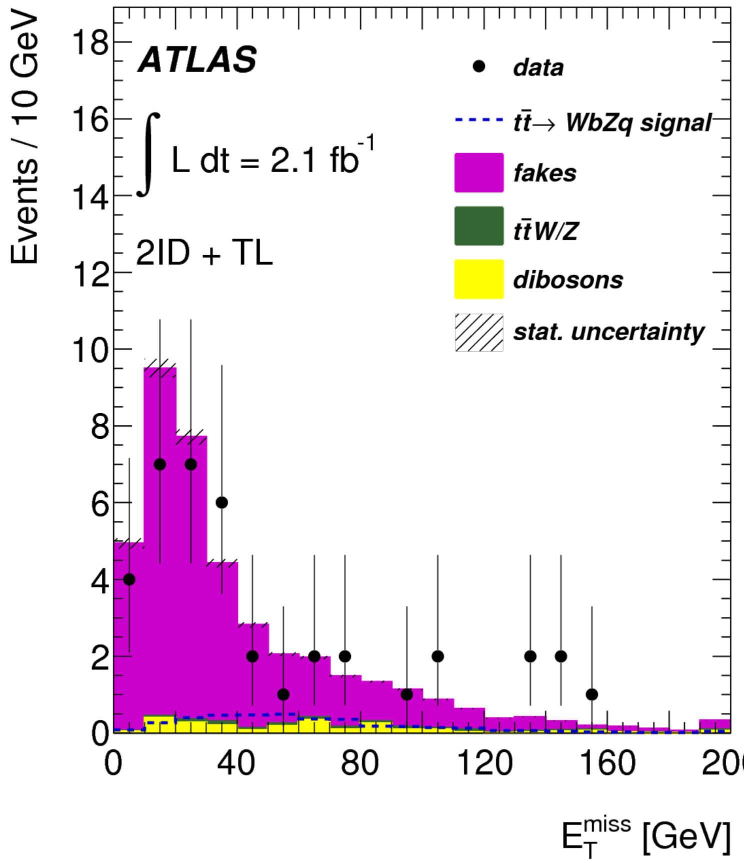
$$f = 36/16 = 2.25$$

E_T^{miss} Plots at pre-selection level

3 ID	2 ID + TL



This plot includes a cut on the Z-boson candidate invariant mass $|m_Z-91.2|<15$ GeV

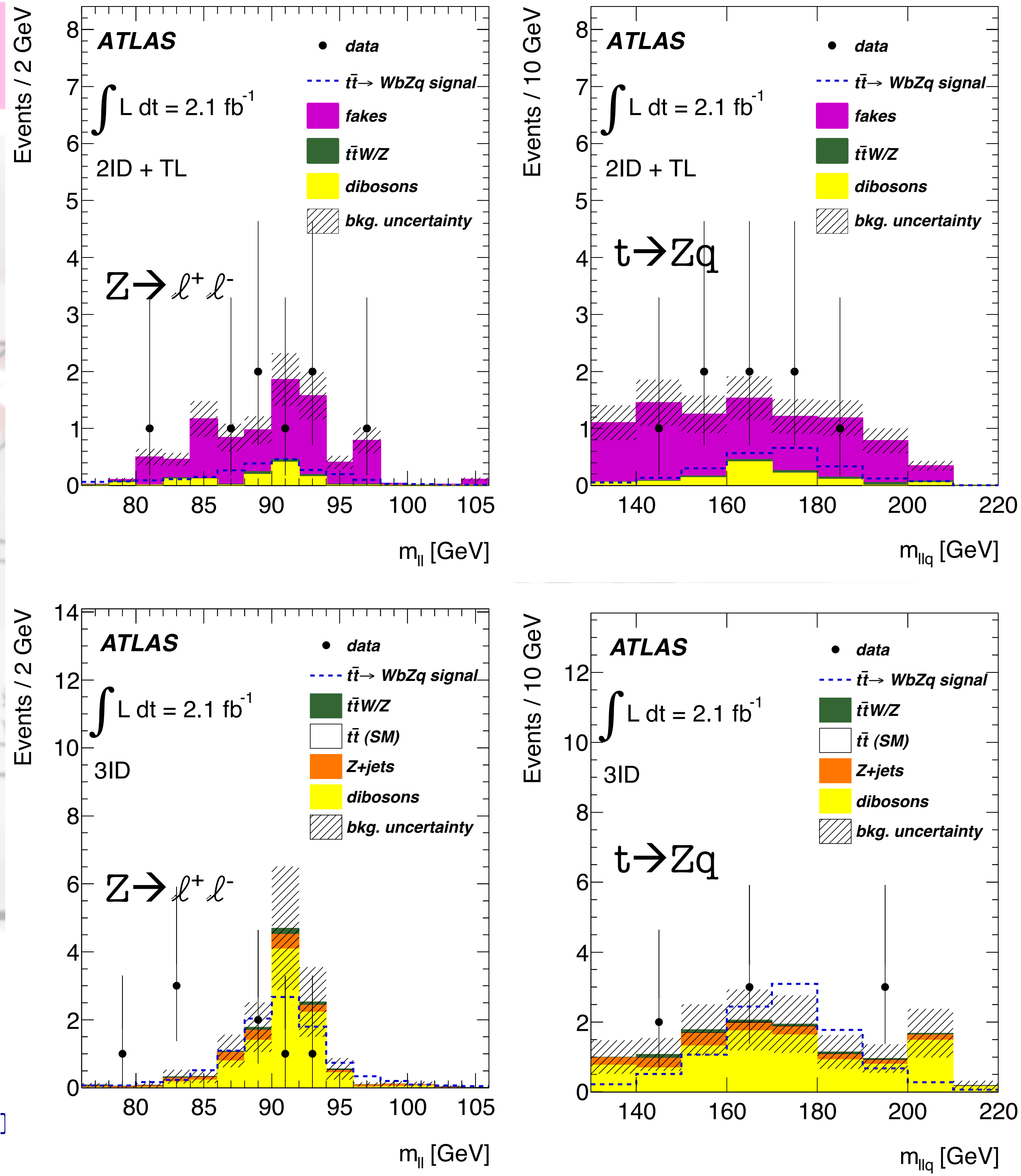


After b-tagging condition

2ID + TL Final Selection	
ZZ and WZ	$1.0\ ^{+0.5}_{-0.6}$
$t\bar{t}W$ and $t\bar{t}Z$	0.25 ± 0.05
fakes	7.6 ± 2.2
expected background	8.9 ± 2.3
data	8

Final Selection

3ID Final Selection	
ZZ and WZ	9.5 ± 4.4
$t\bar{t}W$ and $t\bar{t}Z$	0.51 ± 0.14
$t\bar{t}$, WW	0.07 ± 0.02
Z+jets	1.7 ± 0.7
Single top	0.01 ± 0.01
2+3 fake leptons	$0.0 \pm^{0,2}_{0,0}$
expected background	11.8 ± 4.4
data	8



Arely Cortes-Gonzalez

Outline

- Top Quark Physics
  - Motivation
- ATLAS Detector
- Object and Event Selection
- Backgrounds
- Systematic Uncertainties
- Limit Calculation
- Conclusions

Systematic Uncertainties

Systematic uncertainties can influence the expected number of signal and/or background events:

Systematic Uncertainties

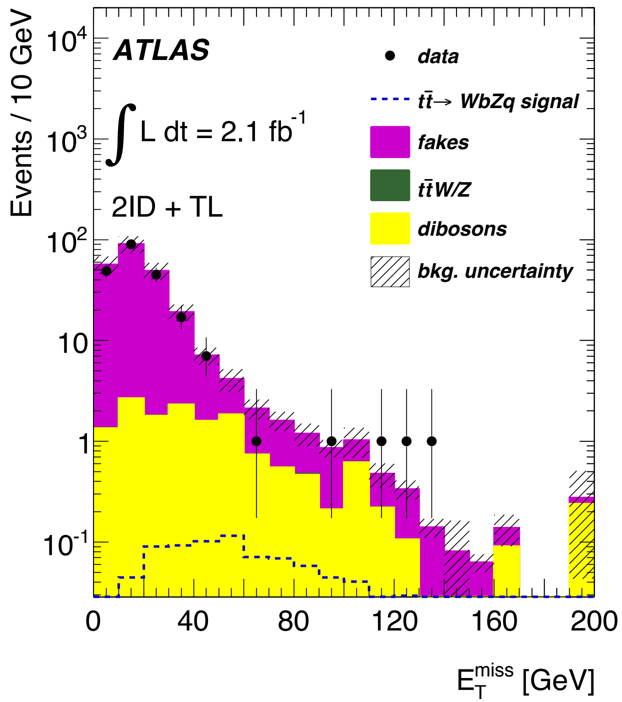
Systematic uncertainties can influence the expected number of signal and/or background events:

Fake TL Prediction

To estimate the systematic uncertainty on the prediction, the fake matrix is tested in control regions (orthogonal to signal regions) enriched with fake leptons.

Check two regions of E_T^{miss} for events with: two leptons + fake and one jet events.

Events with lepton+fake, done in the context of the cross section measurement.



A 20% systematic uncertainty is used for the fake leptons prediction.

Systematic Uncertainties

Systematic uncertainties can influence the expected number of signal and/or background events:

WZ, ZZ Background

- Cross Section
  Include the 5% theoretical uncertainty.

- HF content (when b-agging is used)
  Estimate by comparing different MC generators.

- **MC modelling**
  Using the Berend-Giele scaling with a 24% uncertainty per jet, added in quadrature (4% is used for the 0-jet bin).

	3ID		2ID+TL	
Source	Background	Signal	Background	Signal
Luminosity	4%	4%	<1%	4%
Electron trigger	4%	1%	<1%	<1%
Electron reconstruction modelling	10%	3%	<1%	2%
Muon trigger	3%	1%	<1%	<1%
Muon reconstruction modelling	7%	1%	<1%	1%
TL reconstruction modelling	—	—	2%	1%
Jet energy scale	11%	1%	1%	1%
Jet reconstruction efficiency	5%	2%	<1%	<1%
Jet energy resolution	1%	3%	1%	4%
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	4%	1%	<1%	<1%
LAr readout problem	3%	1%	<1%	1%
Pile-up	4%	<1%	<1%	<1%
b-tagging	—	—	1%	6%
Top quark mass	<1%	2%	—	3%
$\sigma_{t\bar{t}}$	<1%	8%	—	8%
ISR/FSR	<1%	3%	—	6%
PDFs	—	3%	—	3%
ZZ and WZ shape	33%	—	5%	—
ZZ and WZ cross section	4%	—	<1%	—
ZZ and WZ heavy-flavour content	—	—	<1%	—
Fake leptons	1%	—	17%	—
Total	38%	12%	18%	15%

Relative changes on the expected number of total background events and signal yield from different sources of systematic uncertainty.

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Why compute a Limit?

Final Selection

	3ID	2ID+TL
ZZ and WZ	$9.5 \pm ^{4.4}$	$1.0 \pm ^{0.5}_{0.6}$
$t\bar{t}W$ and $t\bar{t}Z$	0.51 ± 0.14	0.25 ± 0.05
$t\bar{t}$, WW	0.07 ± 0.02	7.6 ± 2.2
Z+jets	1.7 ± 0.7	
Single top	0.01 ± 0.01	
2+3 fake leptons	$0.0 \pm ^{0.2}_{0.0}$	
Expected background	11.8 ± 4.4	8.9 ± 2.3
Data	8	8
Signal efficiency	$(0.205 \pm 0.024)\%$	$(0.045 \pm 0.007)\%$

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Data	8	8
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Good agreement between data observation and expected Standard Model background.
No evidence for flavor changing neutral currents is found.

Limit Calculation

- We derive 95% CL limits on the BR for this FCNC decay using the modified frequentist (CL_s) likelihood method.
  - CL_s is used for small signals.

- Statistical and Systematic uncertainties are taken into account (Gaussian distributions).

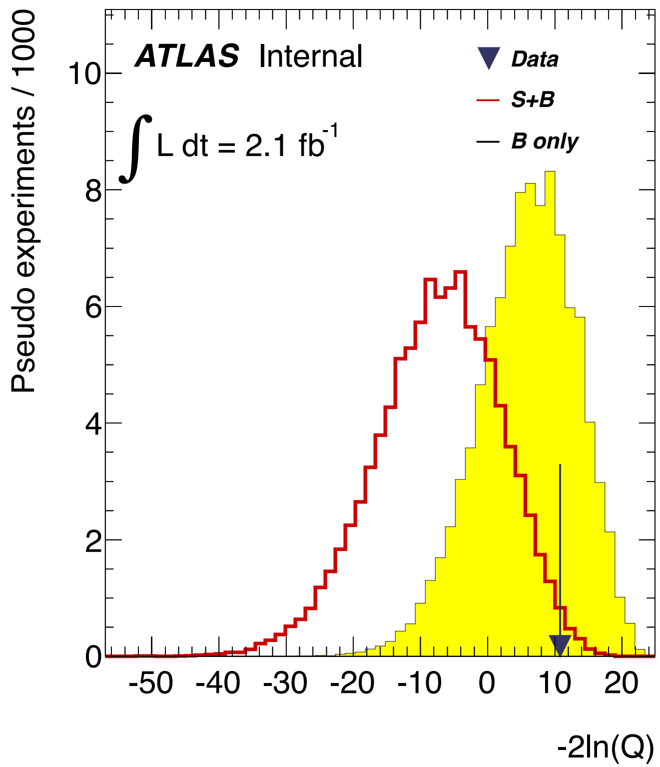
- For the combination: systematic uncertainties of the MC-backgrounds and signal samples are taken to be fully correlated between 3ID and 2ID+TL. Other sources (statistical and systematic) are considered uncorrelated.

Limit Calculation

Limit

- 10^5 pseudo experiments are performed to compare the *background-only* and the *signal+background* hypotheses to the data.
  - The statistical fluctuations of the pseudo –experiments are implemented using Poisson distributions.

- This gives a limit on the number of signal events.
  - Converted into upper limits on the corresponding BRs using the approximate NNLO calculation of the cross section: $\sigma_{t\bar{t}} = 165^{+11}_{-16}$ pb



Limit Calculation

Limit

channel	observed	(-1σ)	expected	$(+1\sigma)$
3ID	0.81%	0.63%	0.95%	1.42%
2ID+TL	3.18%	2.15%	3.31%	4.86%
Combination	0.73%	0.61%	0.93%	1.36%

Observed in data

Expected sensitivity, assuming that the data are described correctly by the SM

Conclusions

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Conclusions

FCNC in Top Quark Decays

- A search for flavor changing neutral currents in top quark decays has been presented.

- The search was performed in 2.1 fb^{-1} of 2011 *pp* collision data.

Conclusions

FCNC in Top Quark Decays

- A search for flavor changing neutral currents in top quark decays has been presented.

- The search was performed in 2.1 fb^{-1} of 2011 *pp* collision data.

- Two orthogonal channels were introduced: 2ID+TL and 3ID, and their results combined.
    - A publication has been submitted to JHEP.

2.1 fb^{-1}
arxiv: 1206.0257

Conclusions

FCNC in Top Quark Decays

- A search for flavor changing neutral currents in top quark decays has been presented.
- The search was performed in 2.1 fb^{-1} of 2011 *pp* collision data.
- Two orthogonal channels were introduced: 2ID+TL and 3ID, and their results combined.
- No evidence for FCNC signal has been found, and an upper limit on the $t \rightarrow Zq$ branching ration of

  BR < 0.73%

  is set at 95% CL. This observed limit is in agreement with the expected limit of BR < 0.93%

Thank you!

FCNC in R-parity violating SUSY

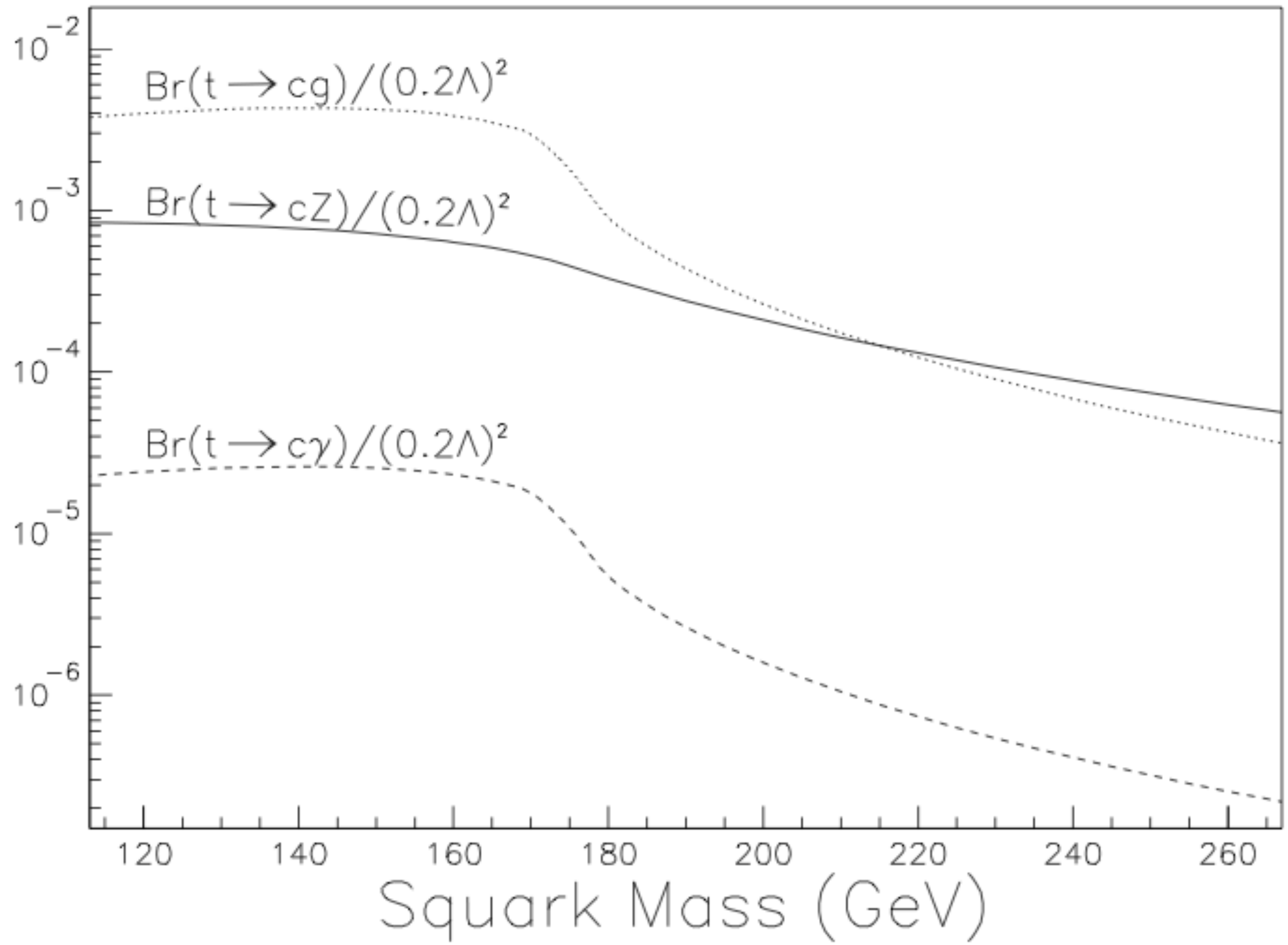


FIG. 3. The plot of $Br(t \to cV)/(0.2\Lambda)^2$ as a function of squark mass.

Λ being the product of the baryon number violating couplings.

Λ = 1, and masses as high as 170 GeV, for the values quoted before

Track inefficiencies

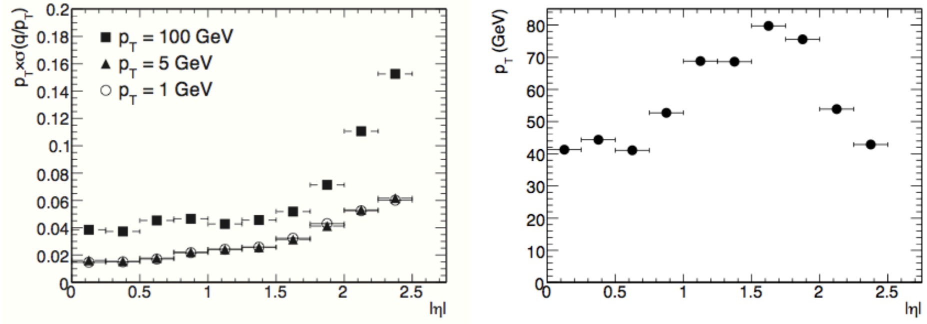


Figure 198. Relative transverse momentum resolution (left) as a function of $|\eta|$ for muons with $p_T = 1$ GeV (open circles), 5 GeV (full triangles) and 100 GeV (full squares). Transverse momentum, at which the multiple-scattering contribution equals the intrinsic resolution, as a function of $|\eta|$ (right).

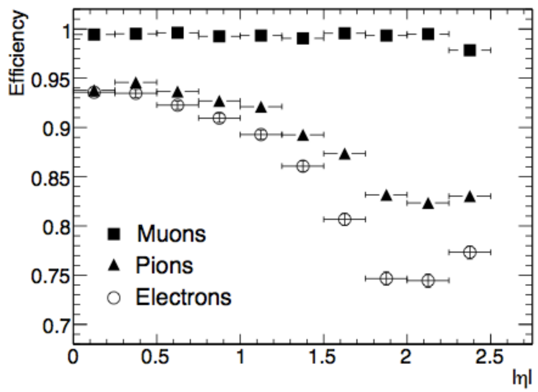


Figure 202. Track reconstruction efficiencies as a function of $|\eta|$ for muons, pions and electrons with $p_T = 5$ GeV. The inefficiencies for pions and electrons reflect the shape of the amount of material in the inner detector as a function of $|\eta|$.

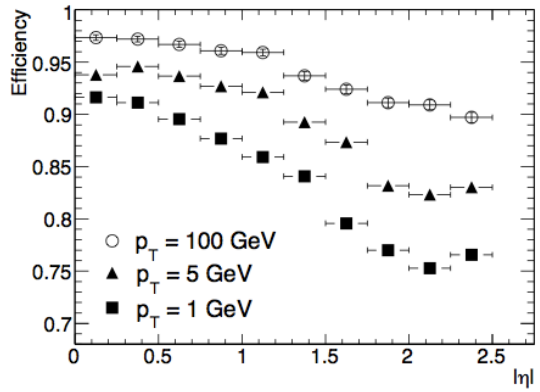


Figure 203. Track reconstruction efficiencies as a function of $|\eta|$ for pions with $p_T = 1$, 5 and 100 GeV.

Fake Lepton Systematic Uncertainty

Systematic uncertainties can influence the expected number of signal and/or background events:

	eTL				μTL			
#jets	O	B	P	(B-O)/P [%]	O	B	P	(B-O)/P [%]
0 (OS)	411	$436.3^{+38.4}_{-36.8}$	199.1 ± 9.3		460	$441.1^{+52.9}_{-52.0}$	321.9 ± 48.4	
1 (OS)	201	$207.1^{+16.9}_{-27.3}$	99.0 ± 4.2		247	$270.5^{+17.2}_{-16.5}$	142.5 ± 6.0	
2 (SS)	10	10.7 ± 0.8	7.6 ± 0.7		14	13.9 ± 1.0	11.1 ± 0.9	
3 (SS)	7	6.2 ± 0.5	5.4 ± 0.5		9	8.3 ± 0.7	7.0 ± 0.6	
4 (SS)	4	4.1 ± 0.4	3.8 ± 0.4		1	3.2 ± 0.4	3.1 ± 0.4	
≥ 5 (SS)	2	1.9 ± 0.1	1.8 ± 0.1		0	1.5 ± 0.2	1.4 ± 0.2	
Total	635	$666.4^{+41.9}_{-45.8}$	316.6 ± 10.3	$9.9^{+15.6}_{-16.5}$	731	$738.5^{+55.6}_{-54.6}$	487.0 ± 48.8	$1.5^{+12.7}_{-12.5}$

Background: includes the contribution from other sources (Z/g*, diboson, single top)
Prediction: contribution from fakes prediction only.

By comparing the agreement between background prediction and observation, we estimate a **20% systematic uncertainty** on the fake prediction

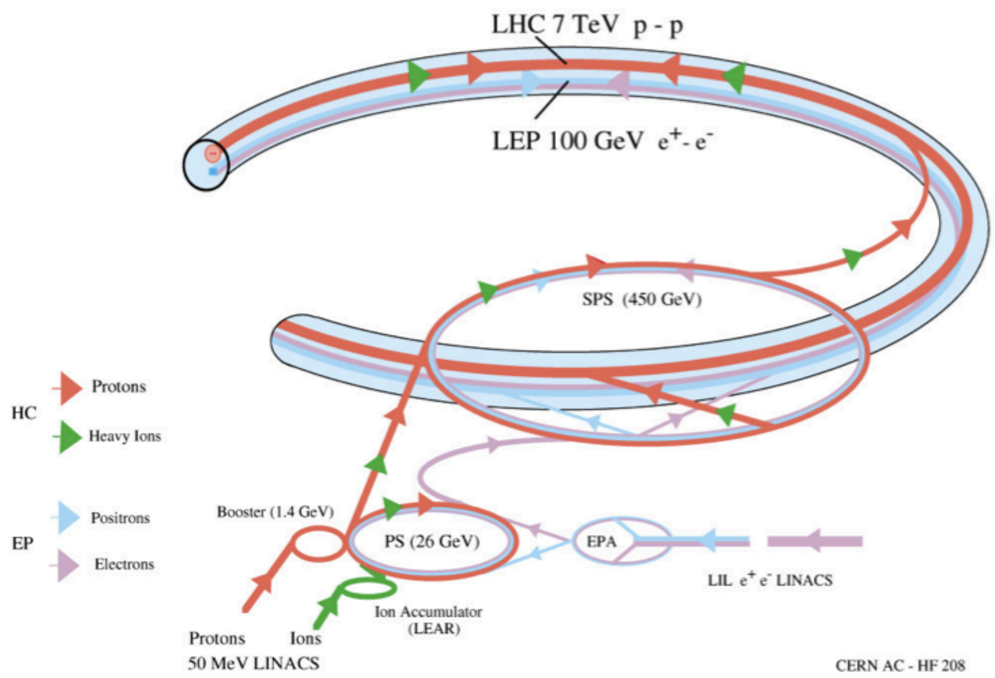
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2011-03

LHC

$$\mathcal{L} = \frac{N_b^2 n_b f_{\rm rev} \gamma_r}{4\pi \varepsilon_n \beta^*} F$$

	injection	collision
Proton energy [GeV]	450	7000
Relativistic gamma	479.6	7461
Number of particles per bunch	1.15×10^{11}	
Number of bunches	2808	
Bunch spacing [ns]	24.95	
Longitudinal emittance (4σ) [eVs]	1.0	2.5
Transverse normalized emittance [μm rad]	3.5	3.75
Circulating beam current [A]	0.584	
Stored energy per beam [MJ]	23.3	362
Geometric luminosity reduction factor	-	0.836

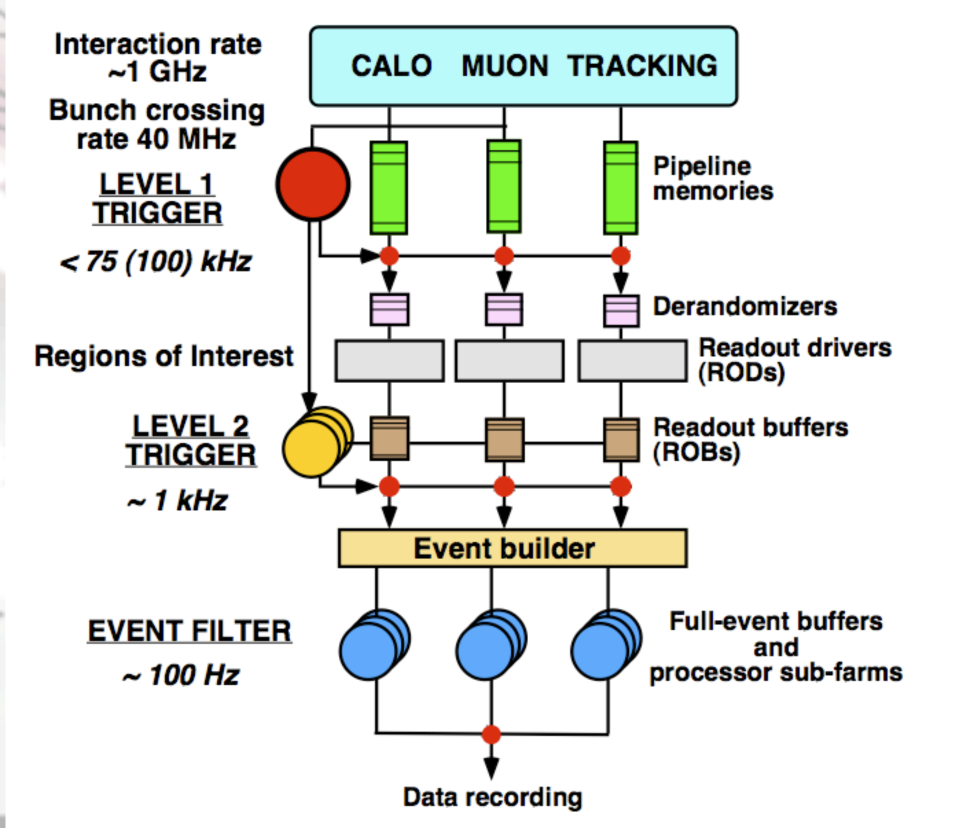
Assuming a peak luminosity of 10^{34} cm^{-2}s^{-1}



Trigger

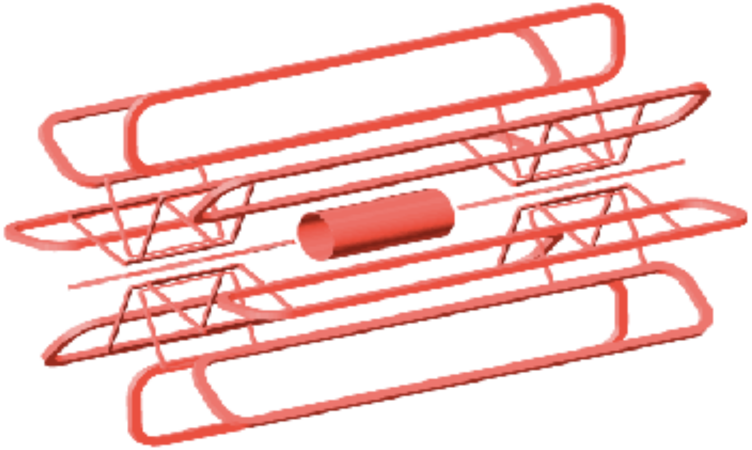
The level-1 (LVL1) trigger makes an initial selection using reduced granularity information from a subset of detectors, and based on combinations of objects required in coincidence or veto.
The level-2 trigger makes use of “region of interest” information provided by the LVL1 trigger.

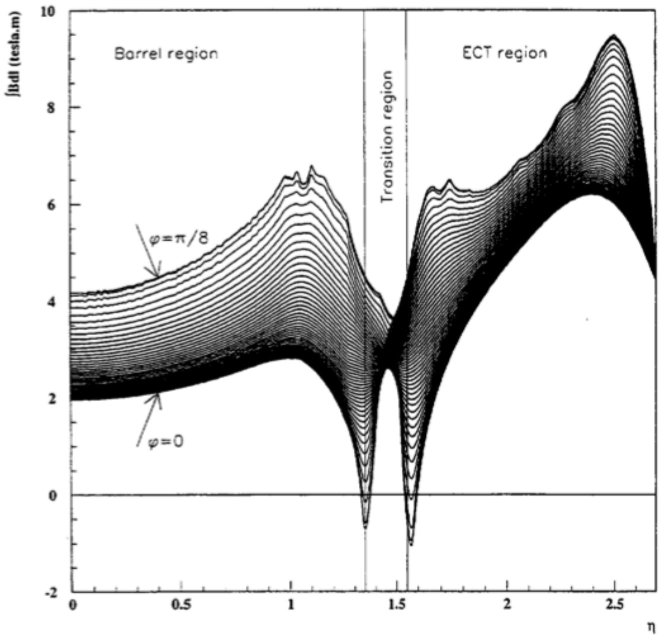
The event filter (EF) uses the full event data, together with the latest available calibration and alignment information to make the final selection of events to be recorded.

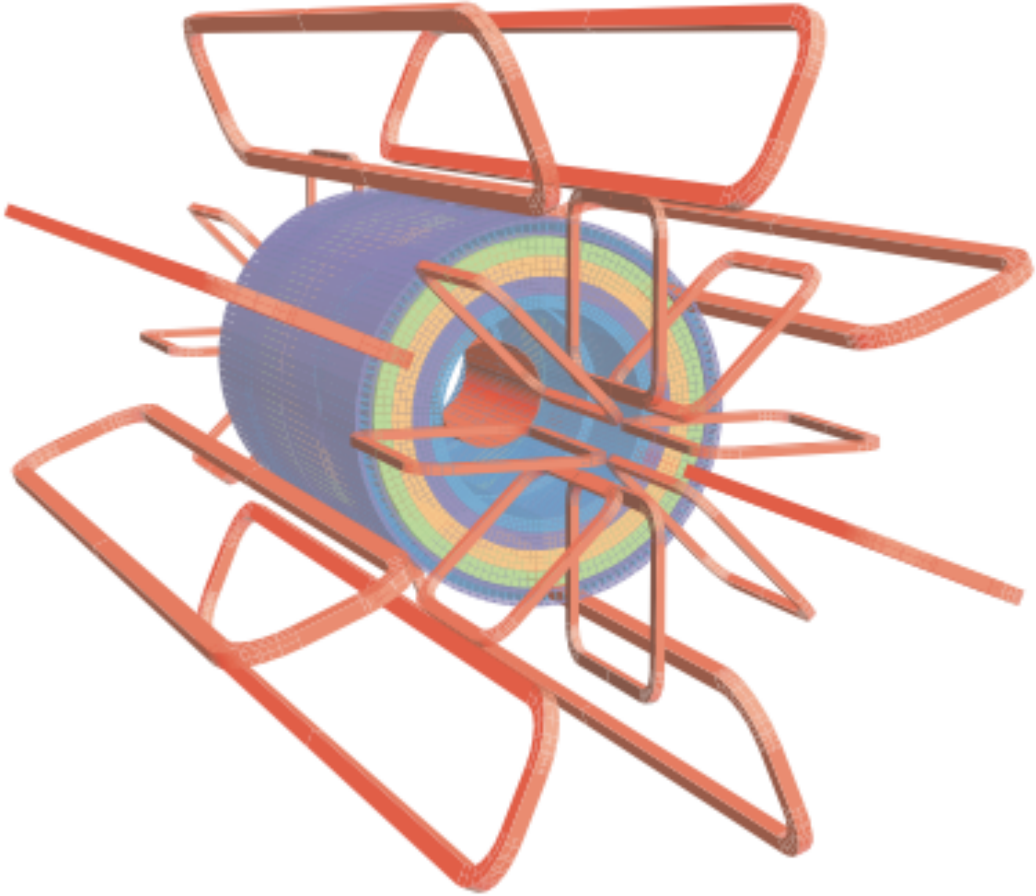


At the EF level, the lepton triggers require $p_T > 20$ GeV/c and $E_T < 6$ GeV in a cone of $\Delta R=0.2$ around the lepton.

Magnets

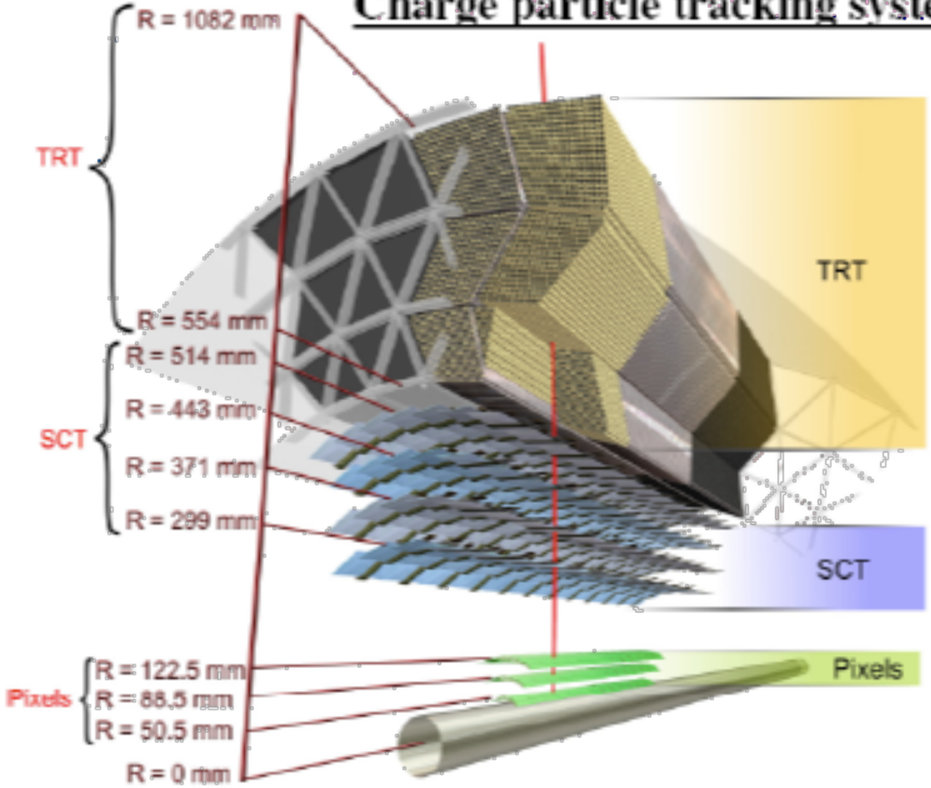






8 barrel toroid coils, with the end-cap coils interleaved. The solenoid winding lies inside the calorimeter volume.

Charge particle tracking system built on two technologies



Drift tubes:

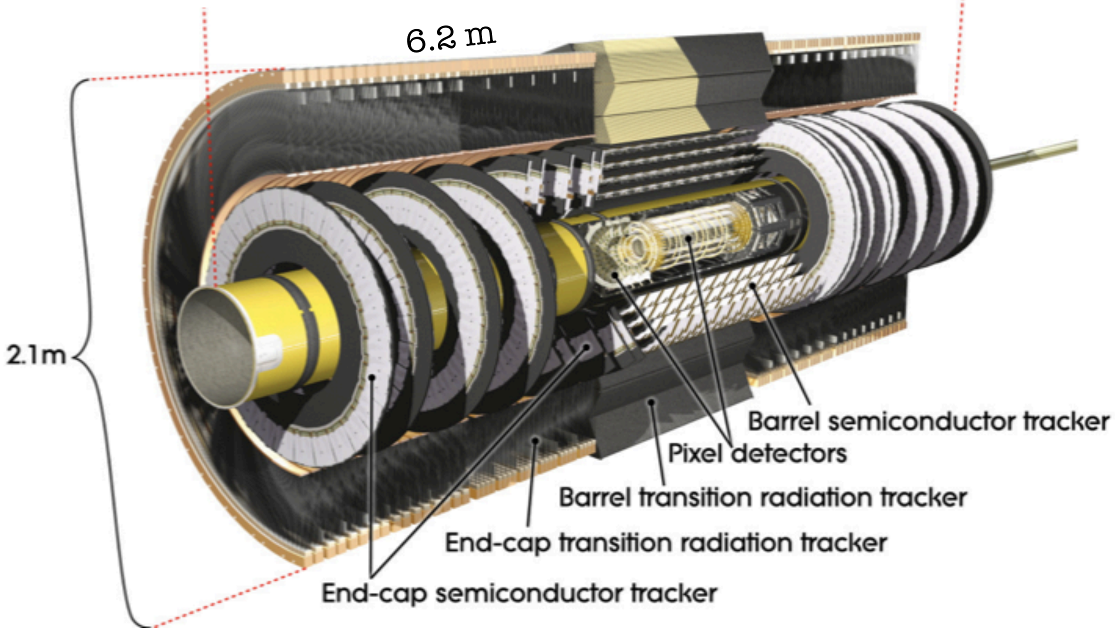
- ~300,000 straw tubes
- resolution 130 μm ($R\phi$)
- $XeCO_2O_2$
- 36 hits per track

Silicon:

- ~ 3M Si strips
- resolution: 23 μm ($R\phi$)
- 580 μm (Z)
- 4 -9 hits per track

- ~ 80M Si pixels
- resolution: 14 μm ($R\phi$)
- 115 μm (Z)
- 3 hits per track

System	position	area [m^2]	resolution σ [μm]	channels (10^6)	η coverage
Pixels	1 removable barrel layer	0.2	$R\phi = 10$, $z = 115$	16	± 2.5
	2 barrel layers	1.4	$R\phi = 10$, $z = 115$	81	± 1.7
	4 end-cap disks on each side	0.7	$R\phi = 10$, $R = 115$	43	$1.7 - 2.5$
SCT	4 barrel layers	34.4	$R\phi = 17$, $z = 580$	3.2	± 1.4
	9 end-cap wheels on each side	26.7	$R\phi = 17$, $R = 580$	3.0	$1.4 - 2.5$
TRT	axial barrel straws		130 (per straw)	0.10	± 0.7
	radial end-cap straws 36 straws per track		130 (per straw)	0.32	$0.7 - 2.5$



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EM calorimeter	barrel	end-cap	
coverage	$\|\eta\| < 1.465$	$1.375 < \|\eta\| < 3.2$	
longitudinal segmentation	3 samplings	3 sampling	$1.5 < \|\eta\| < 2.5$
		2 sampling	$1.375 < \|\eta\| < 1.5$
			$2.5 < \|\eta\| < 3.2$
granularity ($\Delta\eta \times \Delta\phi$)			
sampling 1	0.003×0.1	0.025×0.1	$1.375 < \|\eta\| < 1.5$
		0.003×0.1	$1.5 < \|\eta\| < 1.8$
		0.003×0.1	$1.8 < \|\eta\| < 2.0$
		0.003×0.1	$2.0 < \|\eta\| < 2.5$
		0.1×0.1	$2.5 < \|\eta\| < 3.2$
sampling 2	0.025×0.025	0.025×0.025	$1.375 < \|\eta\| < 2.5$
		0.1×0.1	$2.5 < \|\eta\| < 3.2$
sampling 3	0.050×0.025	0.05×0.025	$1.5 < \|\eta\| < 2.5$
Presampler	**barrel**	**end-cap**	
coverage	$\|\eta\| < 1.52$	$1.5 < \|\eta\| < 1.8$	
longitudinal segmentation	1 sampling	1 sampling	
granularity ($\Delta\eta \times \Delta\phi$)	0.025×0.1	0.025×0.1	
Hadronic tile	**barrel**	**end-cap**	
coverage	$\|\eta\| < 1.0$	$0.8 < \|\eta\| < 1.7$	
longitudinal segmentation	3 sampling	3 sampling	
granularity ($\Delta\eta \times \Delta\phi$)			
samplings 1 and 2	0.1×0.1	0.1×0.1	
samplings 3	0.2×0.1	0.2×0.1	
Hadronic LAr		**end-cap**	
coverage		$1.5 < \|\eta\| < 3.2$	
longitudinal segmentation		3 samplings	
granularity ($\Delta\eta \times \Delta\phi$)		0.1×0.1	$1.5 < \|\eta\| < 2.5$
		0.2×0.2	$2.5 < \|\eta\| < 3.2$
Forward calorimeter		**end-cap**	
coverage		$3.1 < \|\eta\| < 4.9$	
longitudinal segmentation		3 samplings	
granularity ($\Delta\eta \times \Delta\phi$)		$\sim 0.2 \times 0.2$	

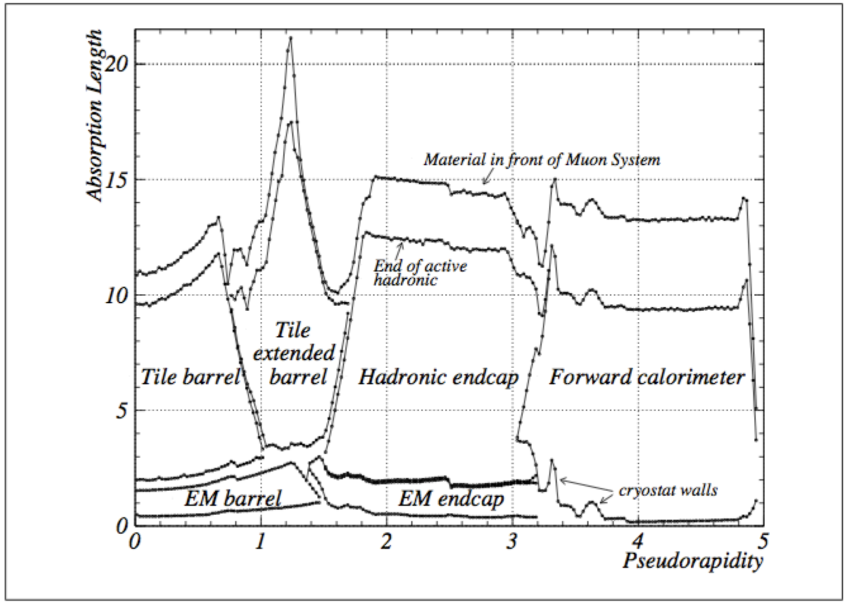
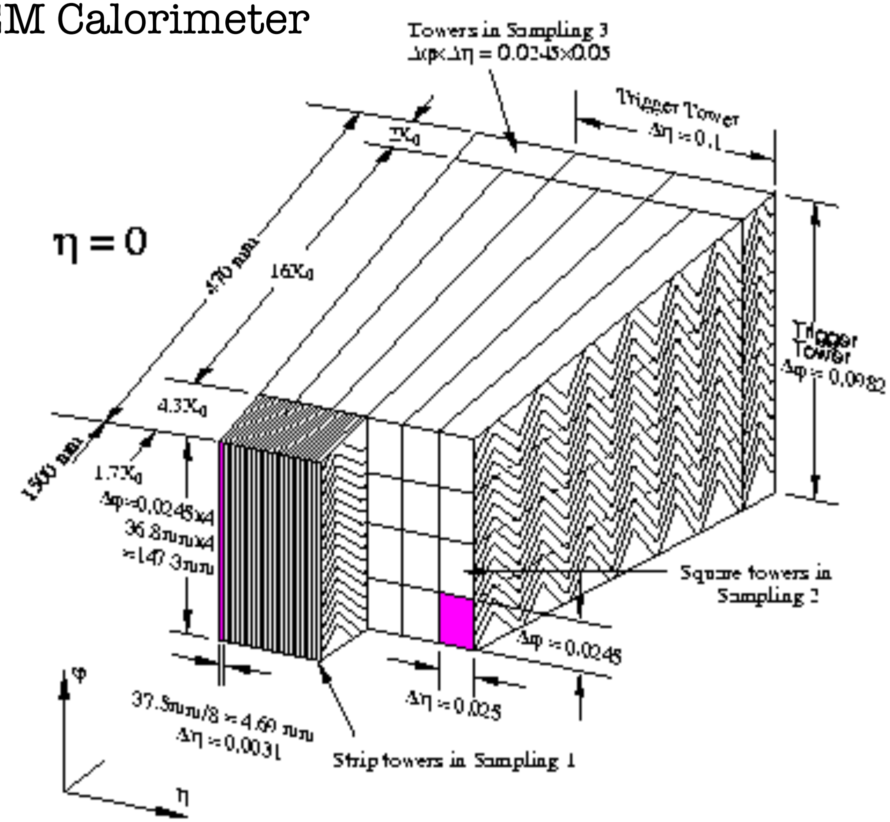


Figure 1-4 Amount of material (absorption lengths) in the ATLAS calorimetry as a function of η.

Calorimeter

EM Calorimeter



Tile Calorimeter

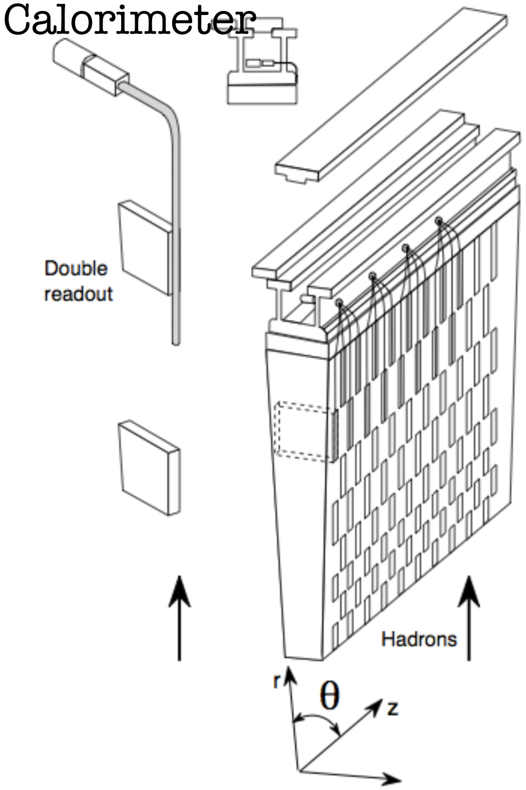
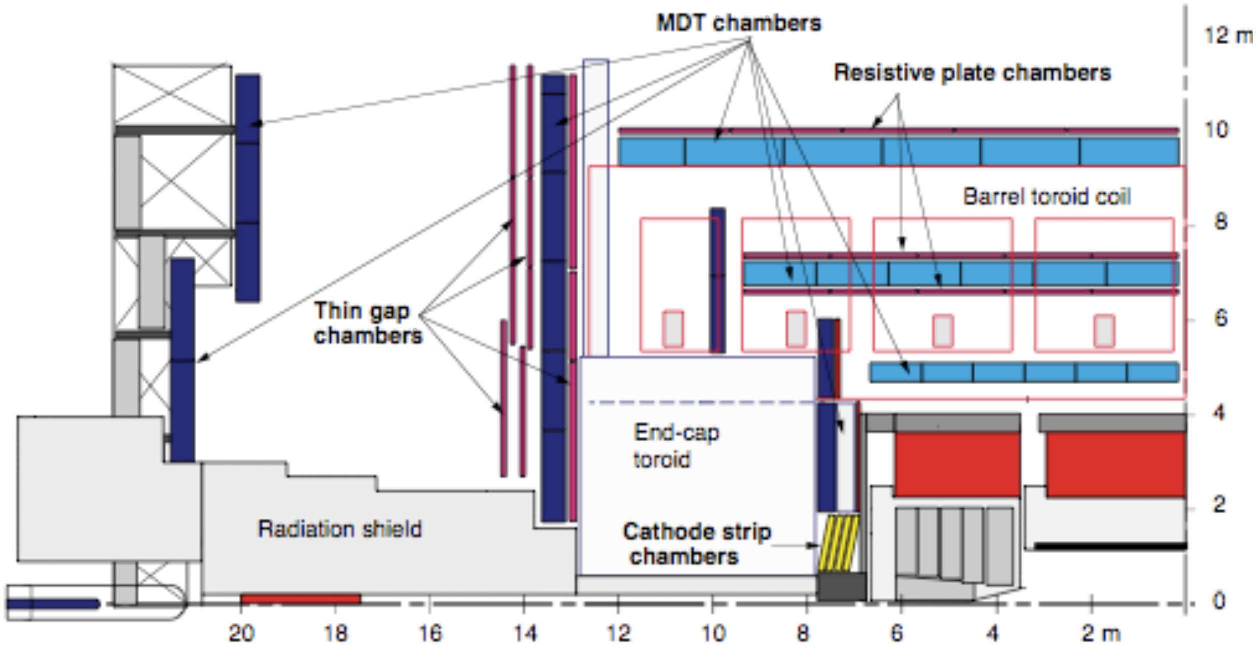
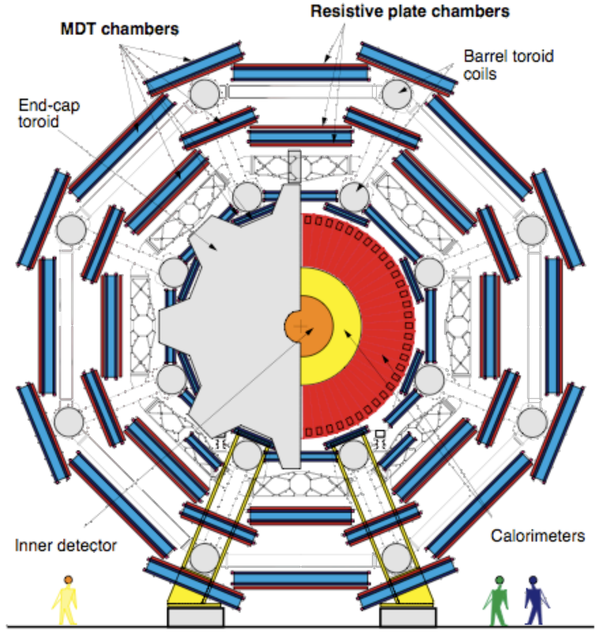


Figure 2-1 The principle of the Tile Calorimeter design.

Muon Spectrometer



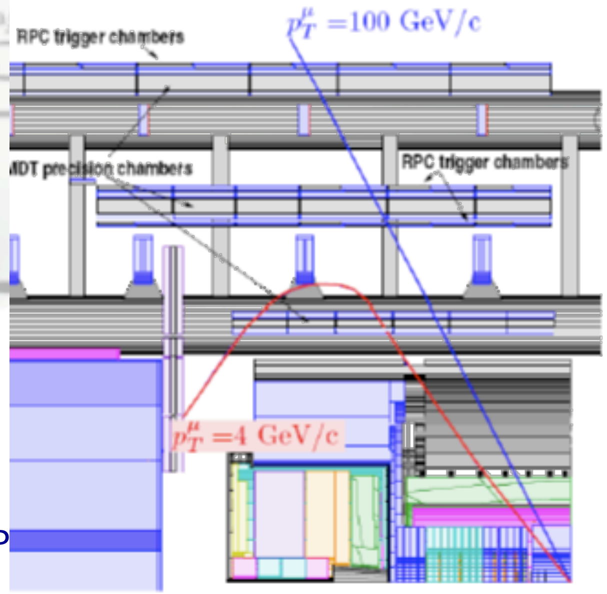


Precision chambers

- MDT (Monitored Drift Tube)
  - Barrel ($|\eta|<1.0$)
  - EndCap ($1.0<|\eta|<2.7$)
- CSC (Cathode Strip Chambers)
  - EndCap

Trigger Detectors

- RPC (Resistive Plate Chambers)
- TGC (Thin Gap Chambers)



Two regimes

p_T >6 GeV/c

Muons hit all spectrometer layers.

⇒ Can trigger on these muons.

⇒ p^μ measured in the muon spectrometer and inner detector.

$p_T \lesssim 6$ GeV/c

Muons hit only inner layers.

⇒ Cannot trigger on these muons.

⇒ p^μ measured only in the inner detector.

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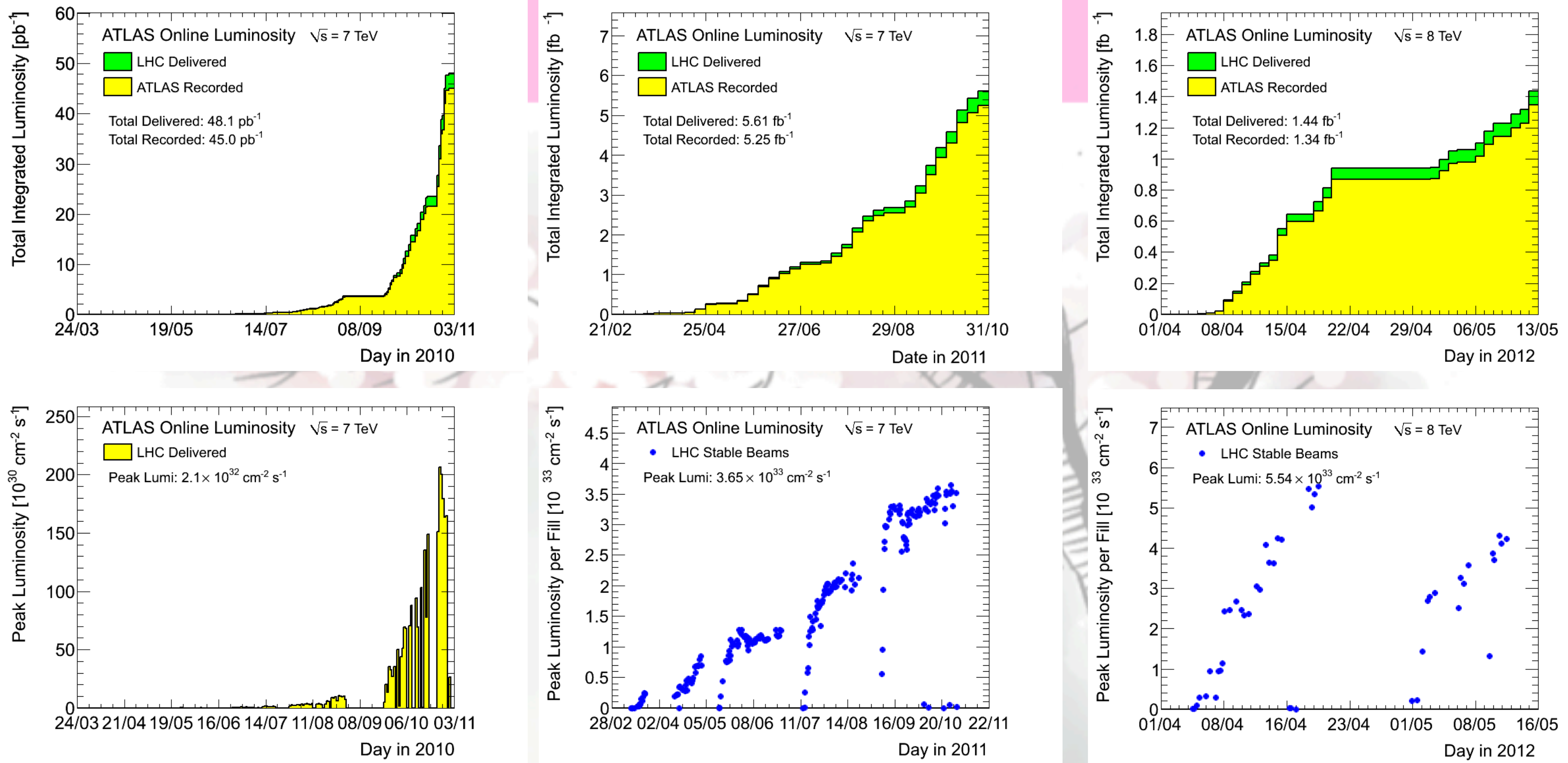


	2010	2011	2012
# interactions	2	6-12	∼25
peak luminosity	$2.1 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$3.6 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$5.54 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
# bunches	369	1331	1331
protons per bunch	1×10^{11}	1.45×10^{11}	$\sim 1.6 \times 10^{11}$
β^* (beam envelope @ IP)	3.5 m	1-1.15 m	0.6 m

Are

Systematic Uncertainties

Systematic uncertainties can influence the expected number of signal and/or background events:

Miscellaneous

- Luminosity
  Estimated to be 3.7%.

- b-tagging
  MC modelling of the b-tagging efficiency.

- ISR/FSR, Top quark mass, PDF used for signal generation, t-tbar cross section.

Systematic Uncertainties

Systematic uncertainties can influence the expected number of signal and/or background events:

Object Specific

- Muons, Electrons, TL

  MC modelling of Trigger (e, μ), reconstruction and identification efficiencies and of the energy/momentum scale and resolution.

- Jets

  Energy scale of light-quark jets and b-jets (including pile-up). MC modelling of jet energy resolution. Jet reconstruction efficiency.

- E_T^{miss}

  Corrections on the leptons and jets are propagated to the E_T^{miss}. Effect of energy in calorimeter not associated to reconstructed objects, low momentum jets, and MC modelling of pile-up.

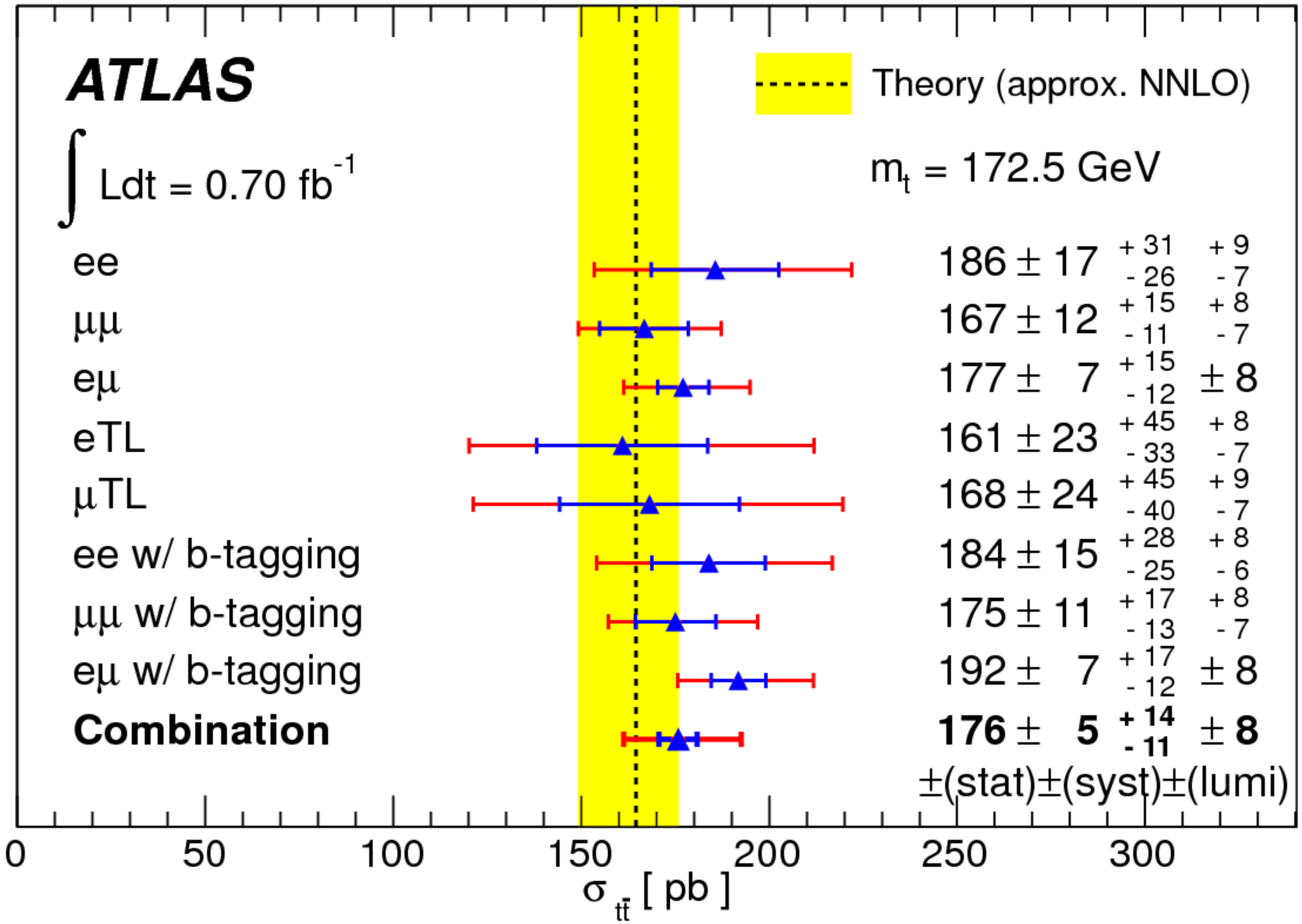
Simulated Samples

All MC samples are processed with the GEANT4 simulation of the ATLAS detector.

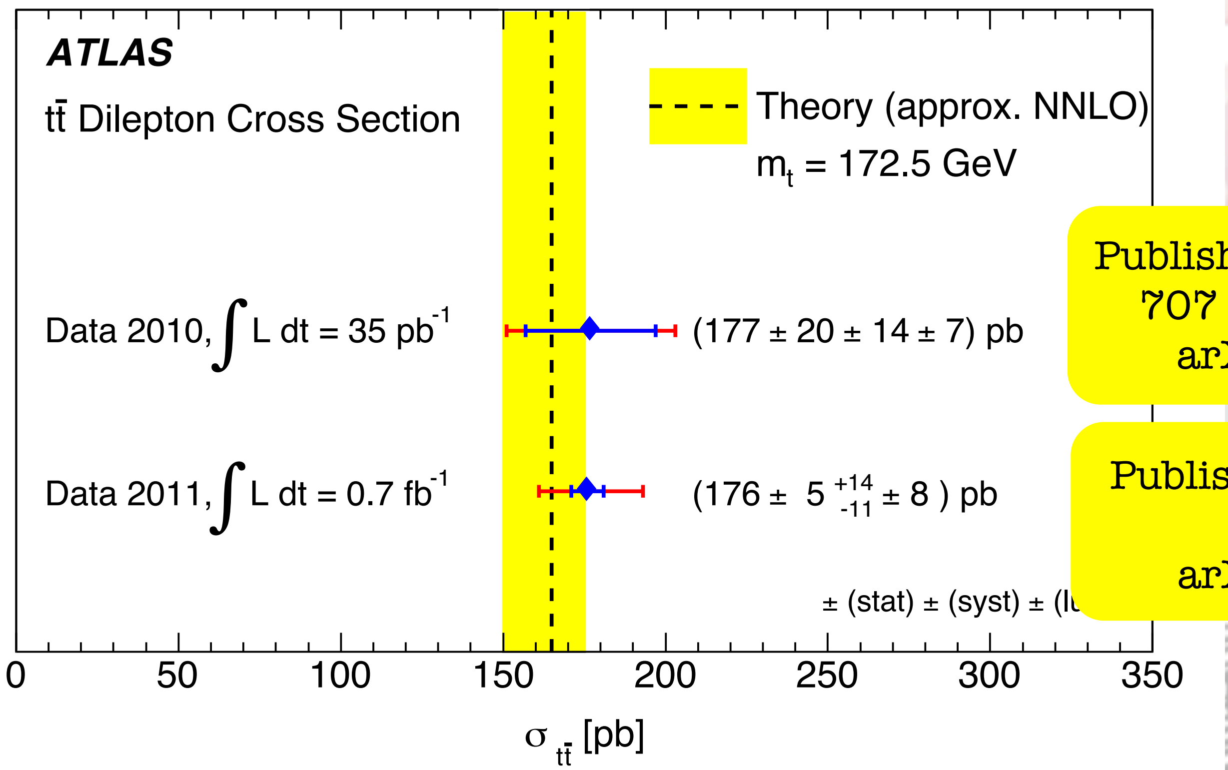
Process	Generator	PDF	other
$t\bar{t}$, single top-quark	MC@NLO	CTEQ6.6	$m_t = 172.5$ GeV
Z/γ^*+jets	ALPGEN	CTEQ6L1	Normalized to NNLO with kFactor = 1.25
WW, WZ, ZZ	ALPGEN	CTEQ6.1	Normalized to NLO with kFactor = 1.26 (WW), 1.28 (WZ), 1.30 (ZZ)
W+jets	background evaluated from data		

All MC simulated events are hadronized using the Herwig shower model supplemented by the Jimmy underlying event model

t-tbar Cross Section Dilepton Channel



t-tbar Cross Section Dilepton Channel

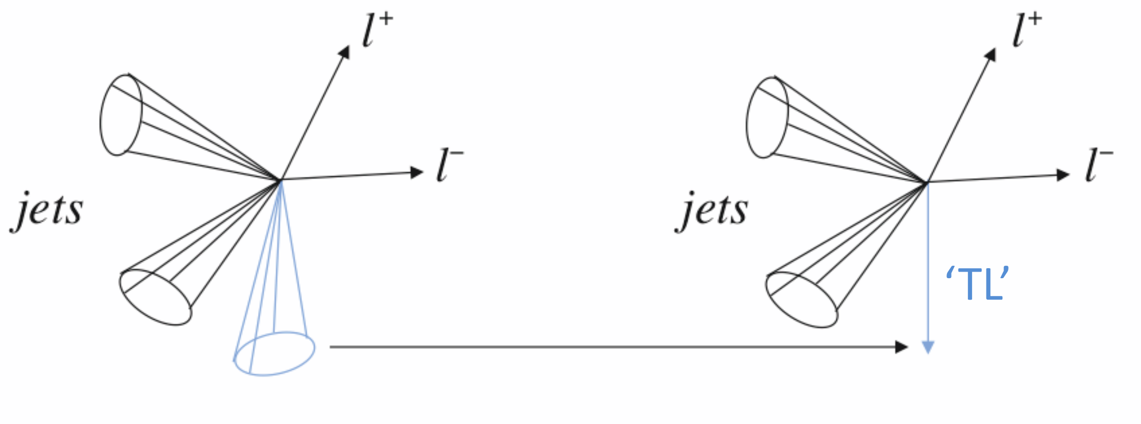


Published in Phys. Lett.B. 707 (2012) 459-477 arXiv:1108.3699

Published in JHEP 1205 (2012) 059 arXiv:1202.4892

Fake Leptons

Strategy



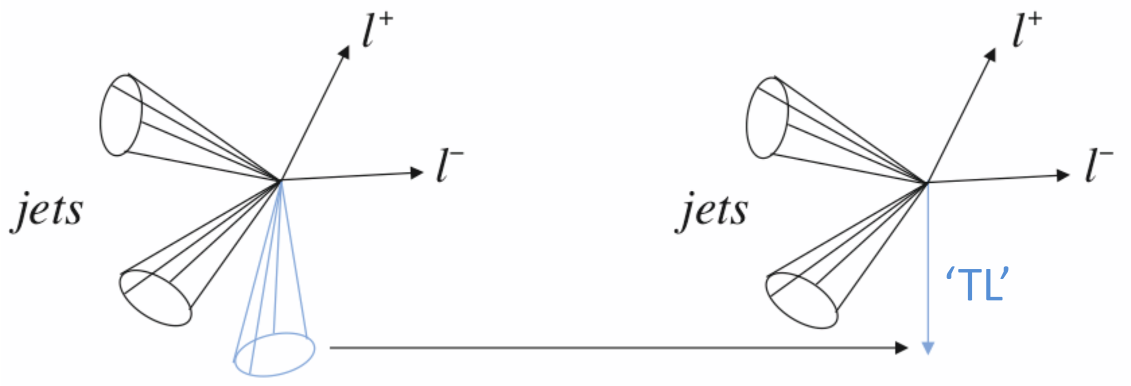
Parent sample
Events with two leptons (passing other event selection cuts)

→

Used to predict events with two leptons + one fake

Fake Leptons

Strategy



Parent sample
Events with two leptons (passing other event selection cuts) → Used to predict events with two leptons + one fake

Since we remove ID jets within ΔR<0.4 of a TL

two leptons events with N jets → Two lepton events + fakes with (N-1) jets