Search for Anomalous Production of Prompt Like-sign Muon Pairs in ATLAS

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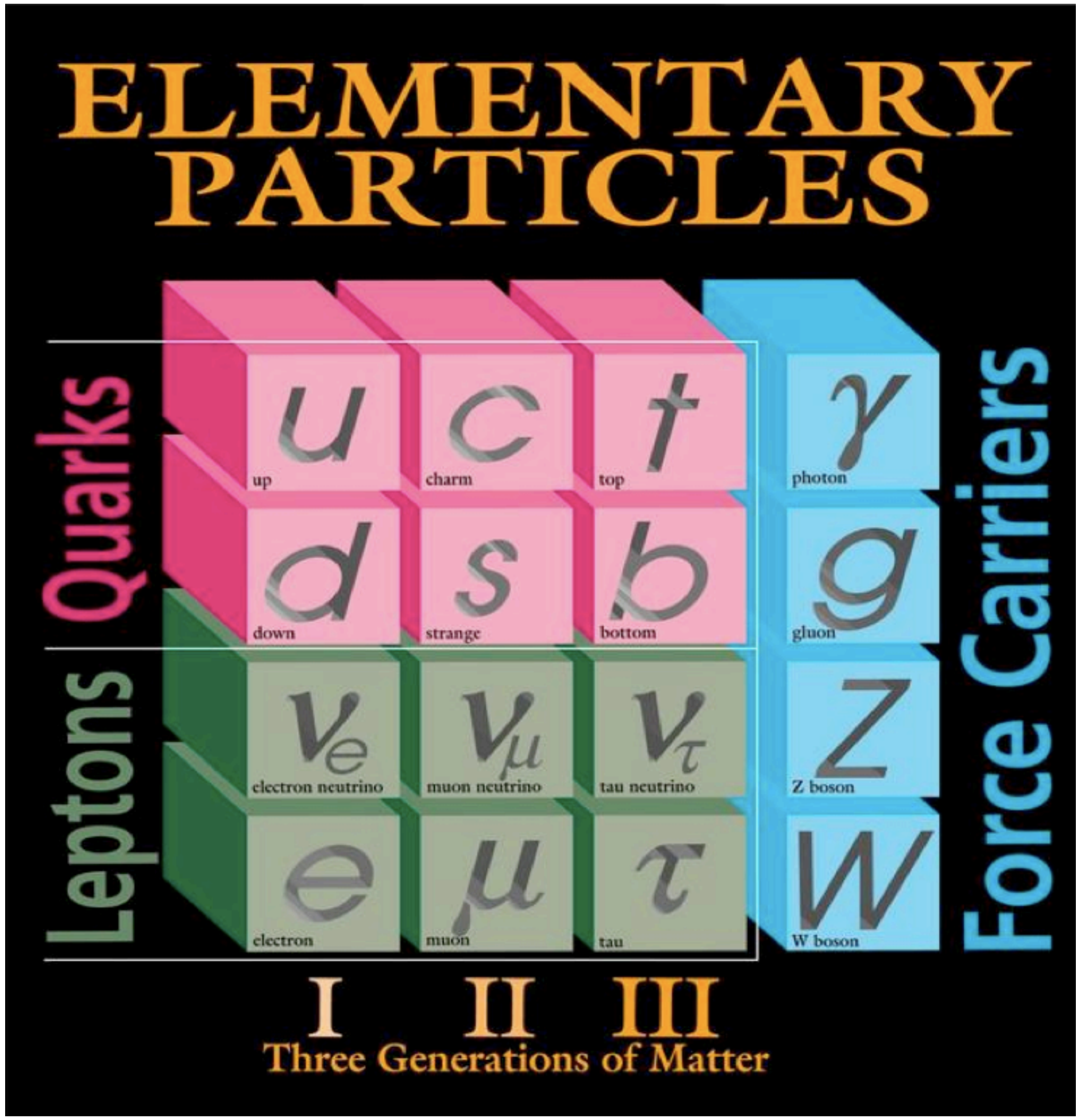
OUTLINE

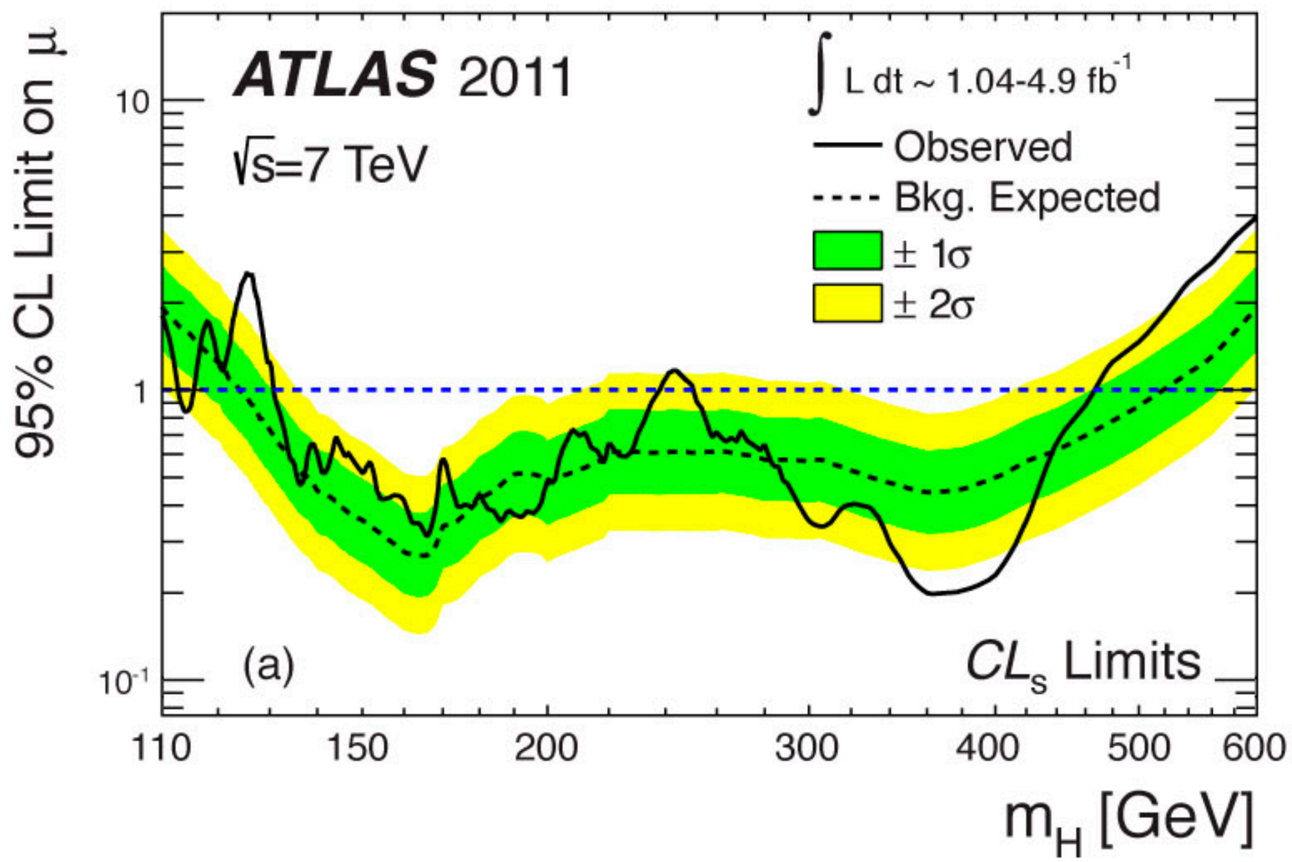
- Motivation
- Analysis strategy
- LHC & ATLAS
  - Inner detector
    - *tracking performance & alignment*
  - Muon system
    - *muon reconstruction & identification*
- Analysis details
  - Event selection
  - Background determination
  - Results & interpretation
- Outlook

Standard Model ... and beyond

- The Standard Model (SM)
  - Describing fundamental particles & their interactions
  - Remarkably successful in describing experimental data

- Predicts all force carriers to be massless
  - *Higgs mechanism*
  - Narrow mass range left for SM Higgs





ATLAS combined 95% upper CLs limits as function of m_H

arXiv:1202.1408

Standard Model ... *and beyond*

- What the Standard Model cannot explain
  - Neutrino masses
  - Dark matter
  - Matter/anti-matter asymmetry
    - *These questions probed by the LHC experiments*

- Exploring a new energy regime → start with inclusive analyses
  - Analysis presented today based on ***like-sign muon pairs*** ← ***arXiv:1201.1091***

Like-sign muons

- Pairs of prompt leptons with same charge rarely produced in the SM
  - WZ / ZZ
- Production rate can be enhanced in new physics models

- Experimental motivation
  - Trigger objects
  - High reconstruction efficiency

Prompt muon
Produced at primary event vertex or from decay of short-lived state (muons from b-hadrons considered non-prompt)

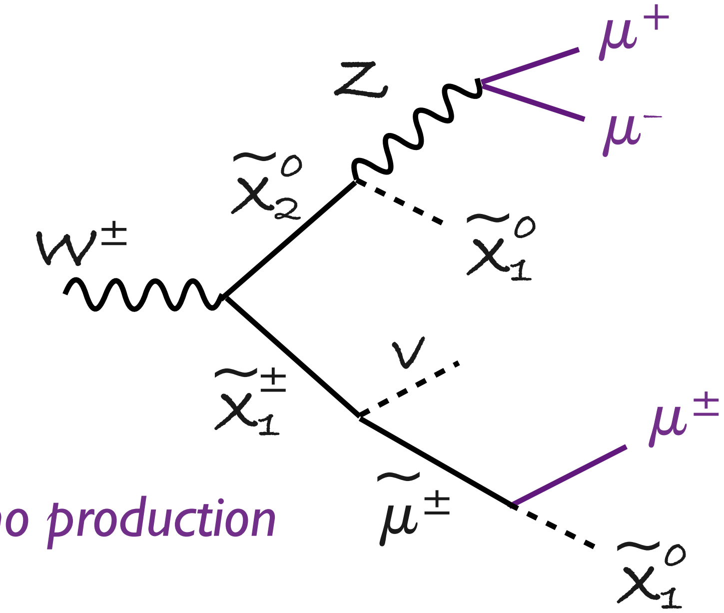
Like-sign muons & new physics

- Many potential new physics models give rise to like-sign leptons
  - Supersymmetry
  - 4th generation quarks
  - Heavy Majorana neutrinos
  - *FCNC giving like-sign top quarks*
  - *Models with doubly charged Higgs bosons*
  - ...

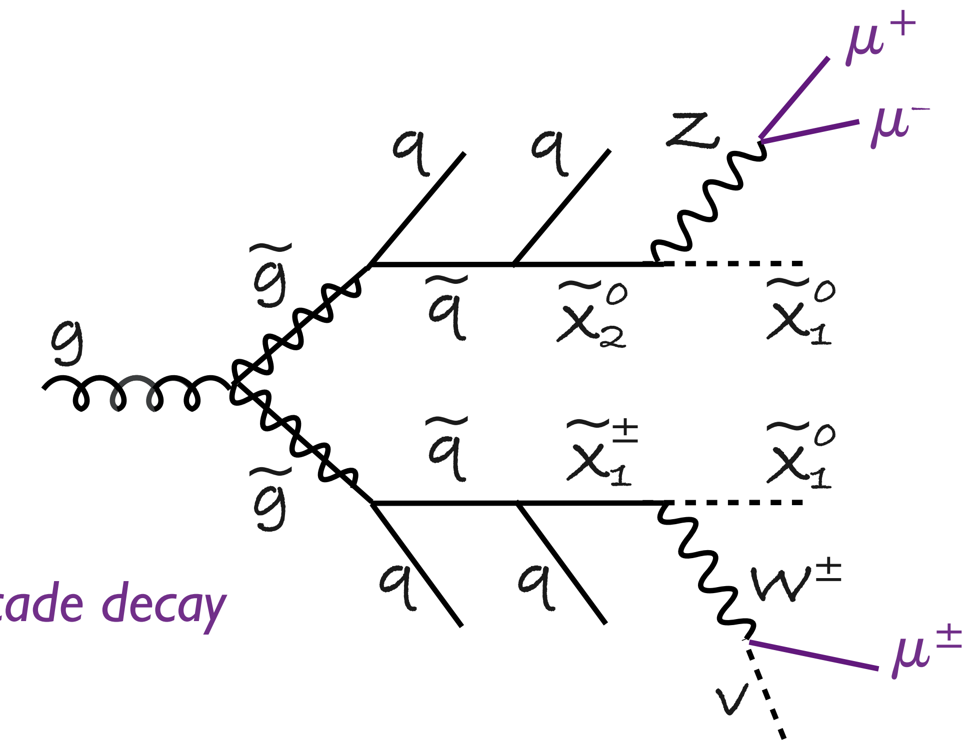
Like-sign muons & new physics

Supersymmetry

- Introduces supersymmetric partners to SM particles differing by 1/2 in spin
- Key motivations
  - The hierarchy problem
    - *Stabilize Higgs mass to radiative corrections*
  - Gauge coupling unification
  - Dark matter candidate
- Assuming conservation of matter parity
  - SUSY particles pair-produced
  - Lightest SUSY particles cannot decay



direct gaugino production

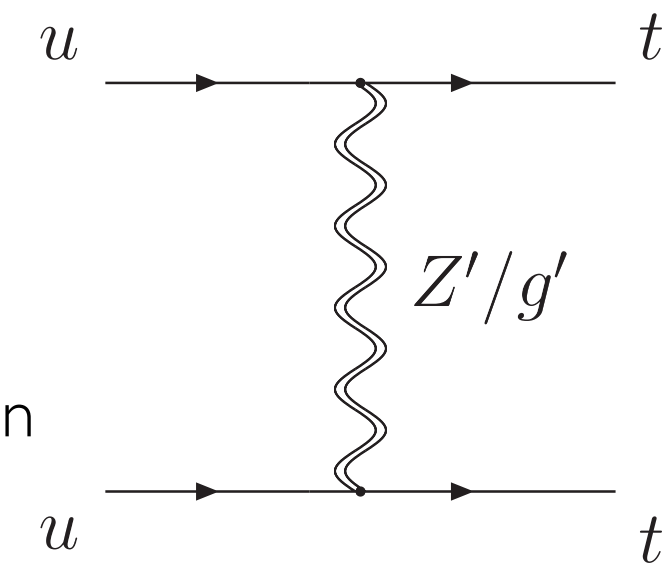


gluino cascade decay

Like-sign muons & new physics

Like-sign top quark production

- Produced through exchange of flavor-changing Z' boson
- Could explain forward-backward asymmetry observed at the Tevatron in ttbar production
  - Like-sign lepton final states if both tops decay leptonically

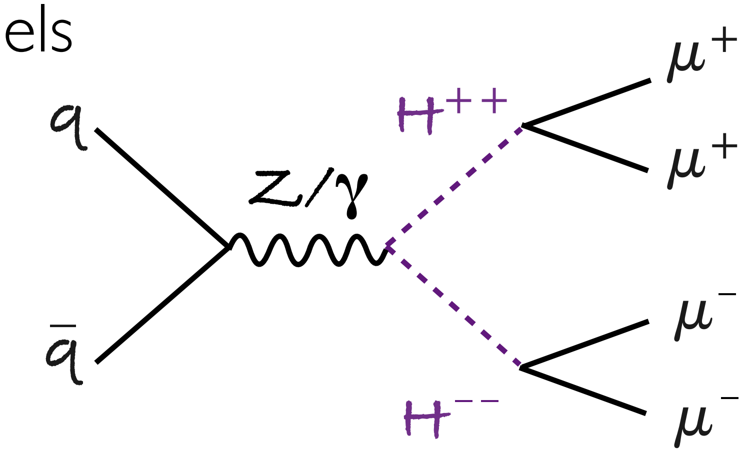


Berger et al.
PRL 106 201801 (2011)

- Previous best limit: $\sigma(Z' \rightarrow ttX) < 17$ pb (CMS)

Doubly charged Higgs

- Doubly charged Higgs bosons predicted in many new physics models
  - Higgs triplet models
  - Left-right symmetric model
- Dominant production is Drell-Yan pair-production



- Previous best limit: $m(H^{\pm\pm} \rightarrow \mu^\pm\mu^\pm) > 277$ GeV (CMS preliminary)

Pati & Salam,
PRD 10 (1974) 275

Analysis strategy

- Perform ***inclusive search*** in $\mu^{\pm}\mu^{\pm}$ final state
  - Base selection cuts only on muon properties
  - Cover largest possible phase space where backgrounds under control

- Understanding & constraining ***backgrounds***
  - Prompt muons from SM sources
  - Non-prompt muon background
  - Charge mis-identified muons

- Results & interpretations

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Main analysis challenge

- Understanding contribution of non-prompt muons
  - *Heavy flavor: b/c hadron decays*
  - *Pion/kaon decay-in-flight*
- Handles for reducing this background
  - *Muon isolation*
  - *Track impact parameter*

Analysis strategy

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- Understanding & constraining ***backgrounds***
  - Prompt muons from SM sources
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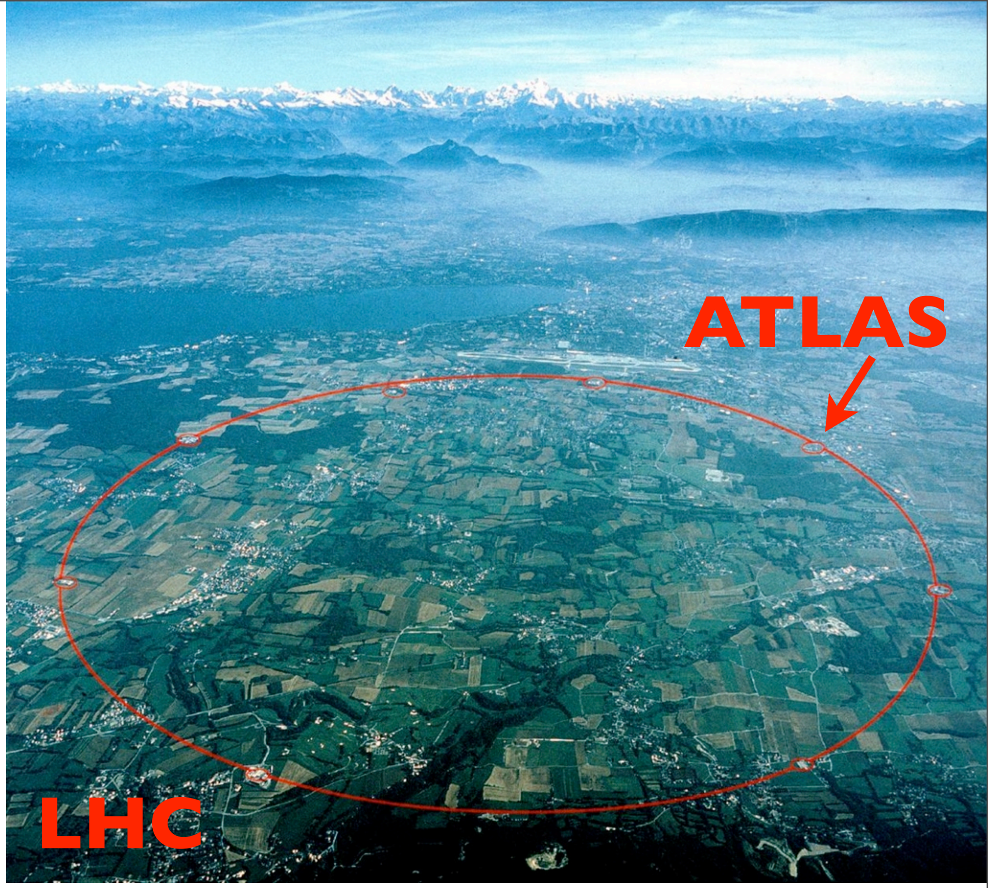
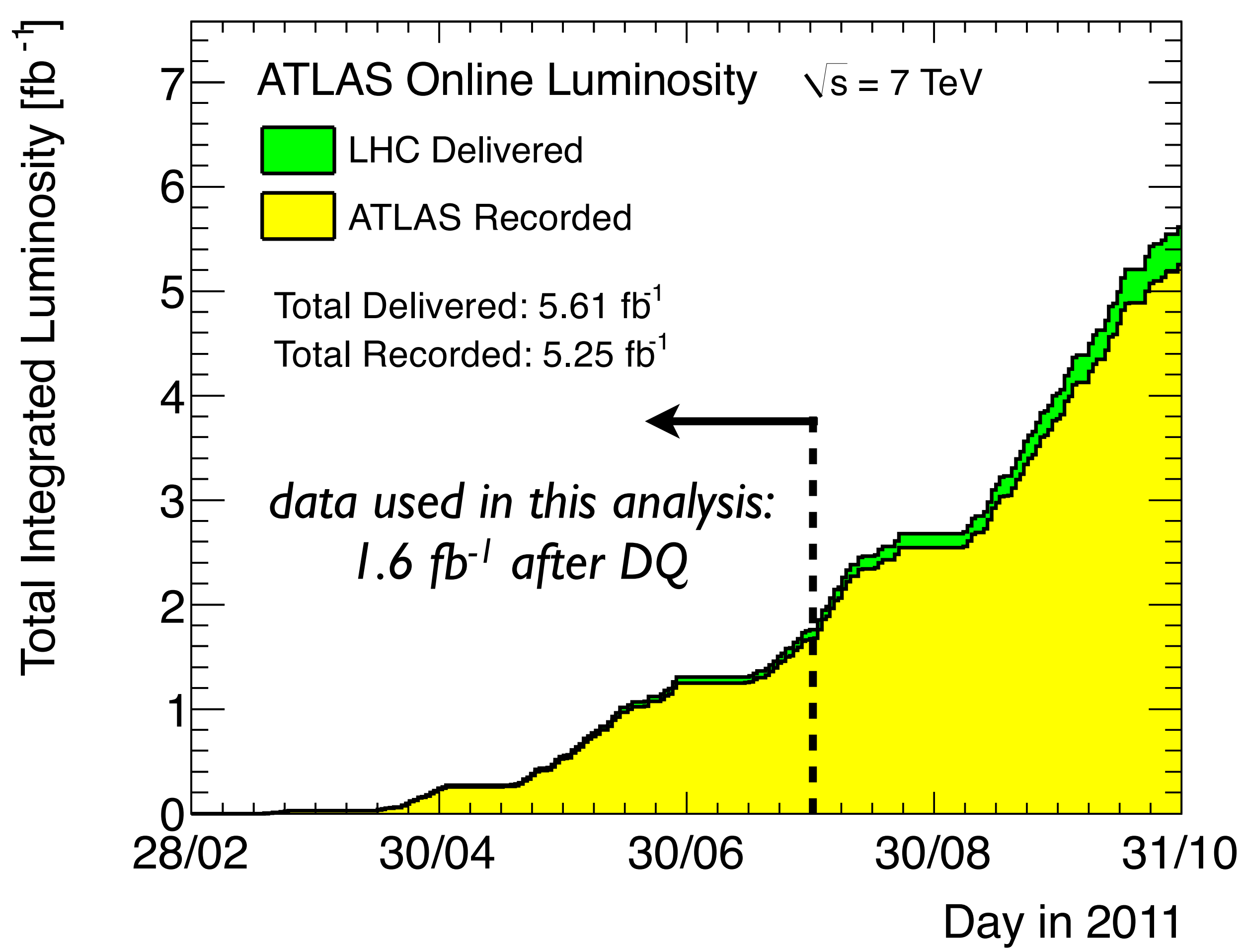
- Results & interpretations
  - Search data for overall excess
  - Narrow resonance search - mass peak in dimuon mass spectrum
  - If no significant deviations observed?
    - *Put constraints on cross-section of non-SM contributions within fiducial region*
    - *Constraints on mass of doubly charged Higgs bosons*

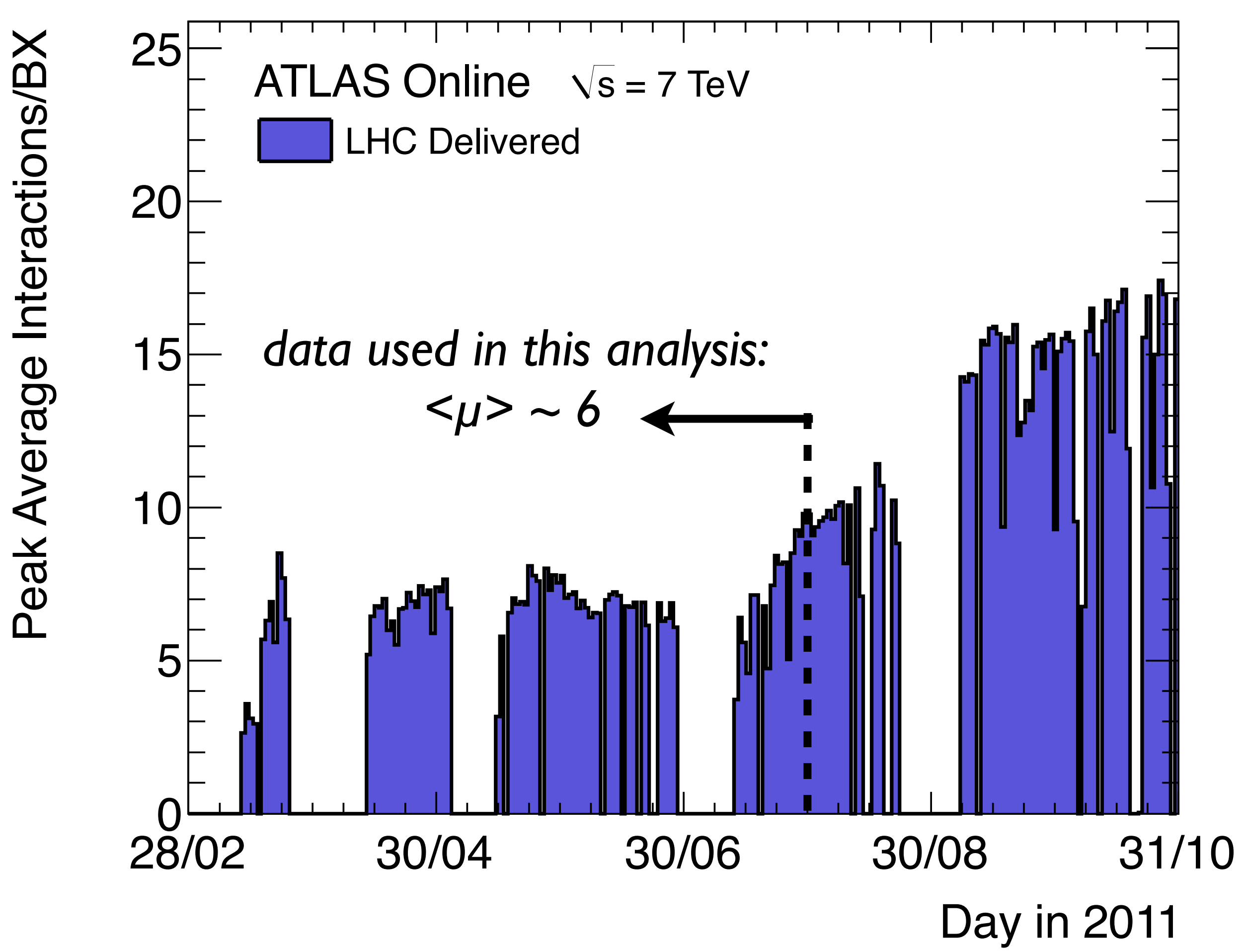
Fiducial region
Defined by the analysis event selection

The LHC

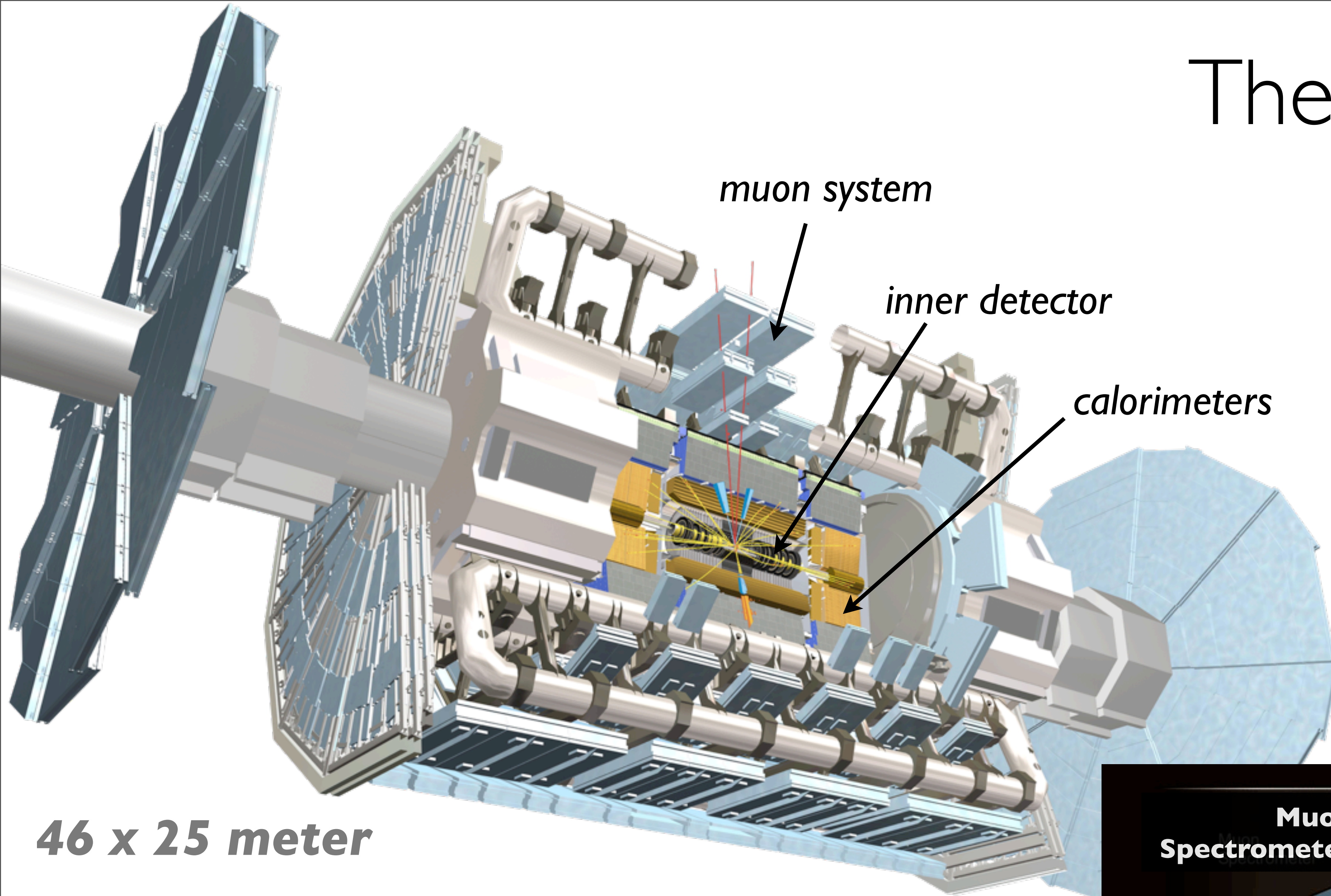
- Excellent performance in 2011
  - > 5 fb^{-1} of integrated luminosity
  - Max instantaneous luminosity ~ $3.6 \times 10^{33}\ cm^{-2}\ s^{-1}$
- ATLAS data-taking efficiency ~ 93.5%
  - DQ efficiency of 90-96%
- High luminosity → high pileup
  - Several interactions / bunch-crossing
    - *Challenge for trigger, lepton isolation, ...*







The ATLAS detector

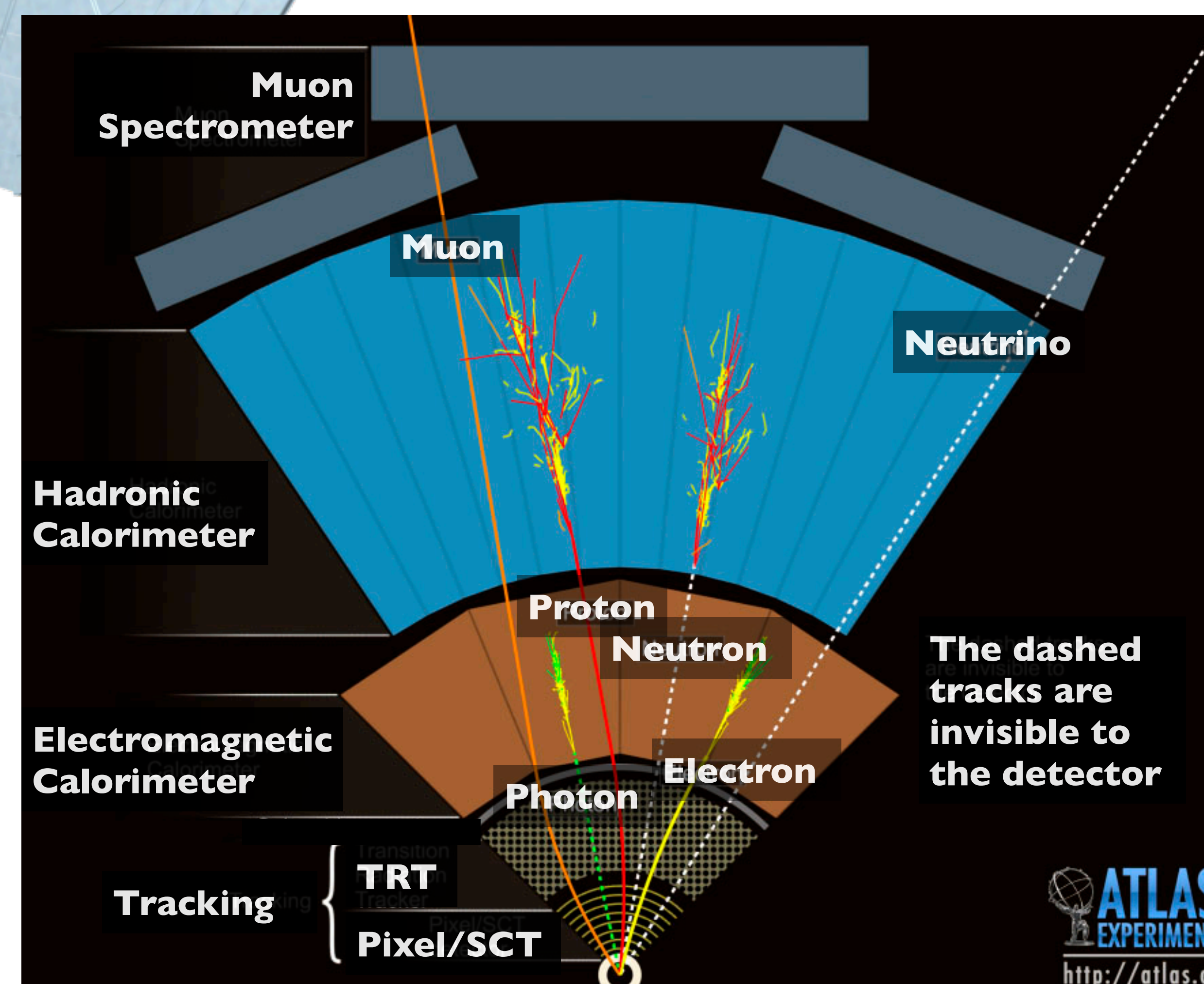


46 x 25 meter

Pseudo-rapidity
$\eta = -\ln(\tan\theta/2)$
Angular distance
$\Delta R = (\Delta\phi^2 + \Delta\eta^2)^{1/2}$

- General purpose detector
  - Barrel & 2 endcaps
- Inner tracking system
- Calorimeters to $|\eta| < 4.9$
  - EM & hadronic sections
- Toroidal muon system

Particle identification in ATLAS



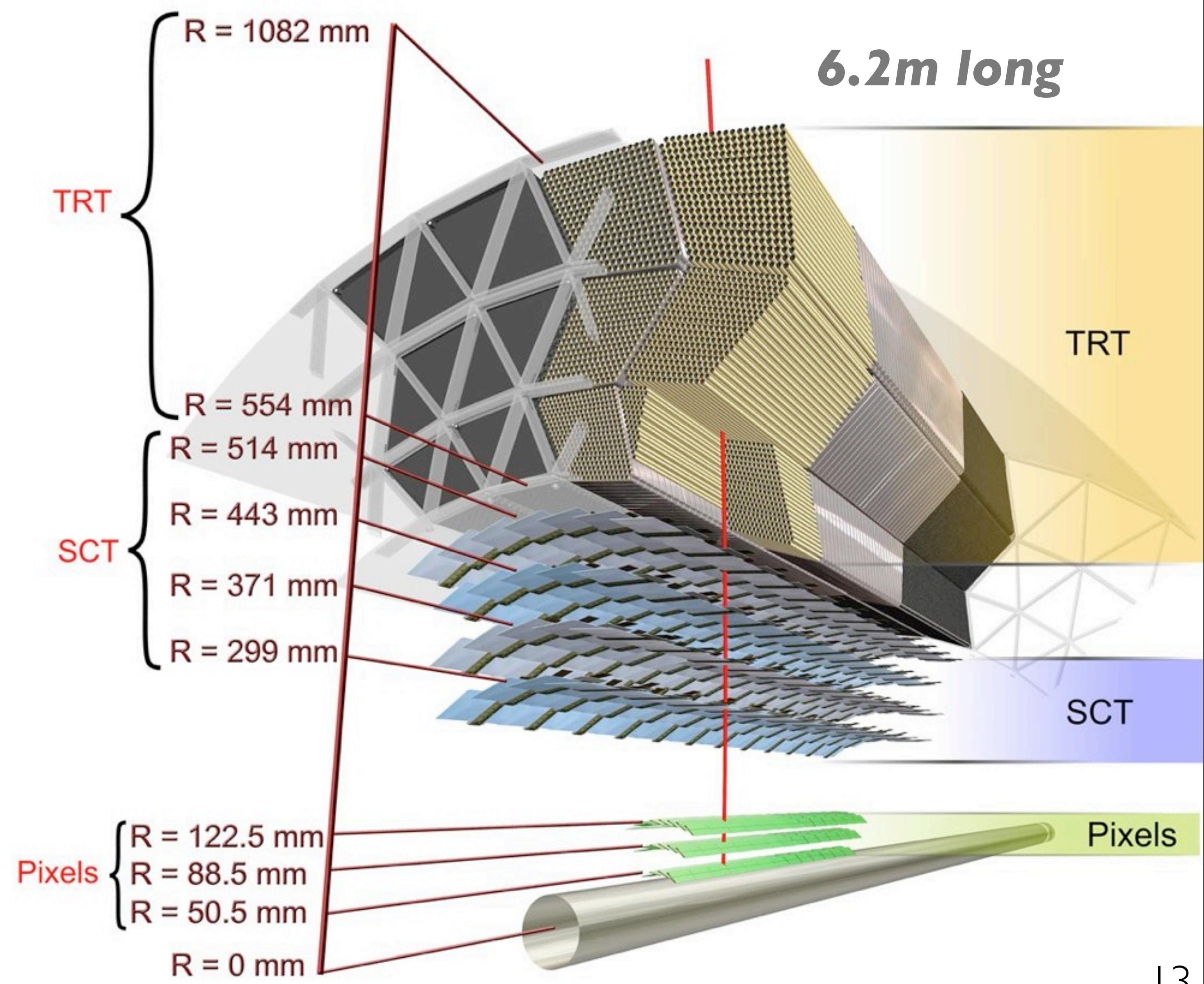
Inner detector tracking system

Resolutions, 100 GeV track
- *impact parameter ~12 μm*
- *transverse momentum ~5 GeV*

- Tracking central part of object reconstruction
- Inner detector
  - ***Pixel*** - silicon pixels, the innermost detector ~5 cm from beam line
  - ***SCT*** - silicon microstrips
  - ***TRT*** - straw tube transition radiation tracker
- Immersed in 2T solenoid field

Tracker requirements

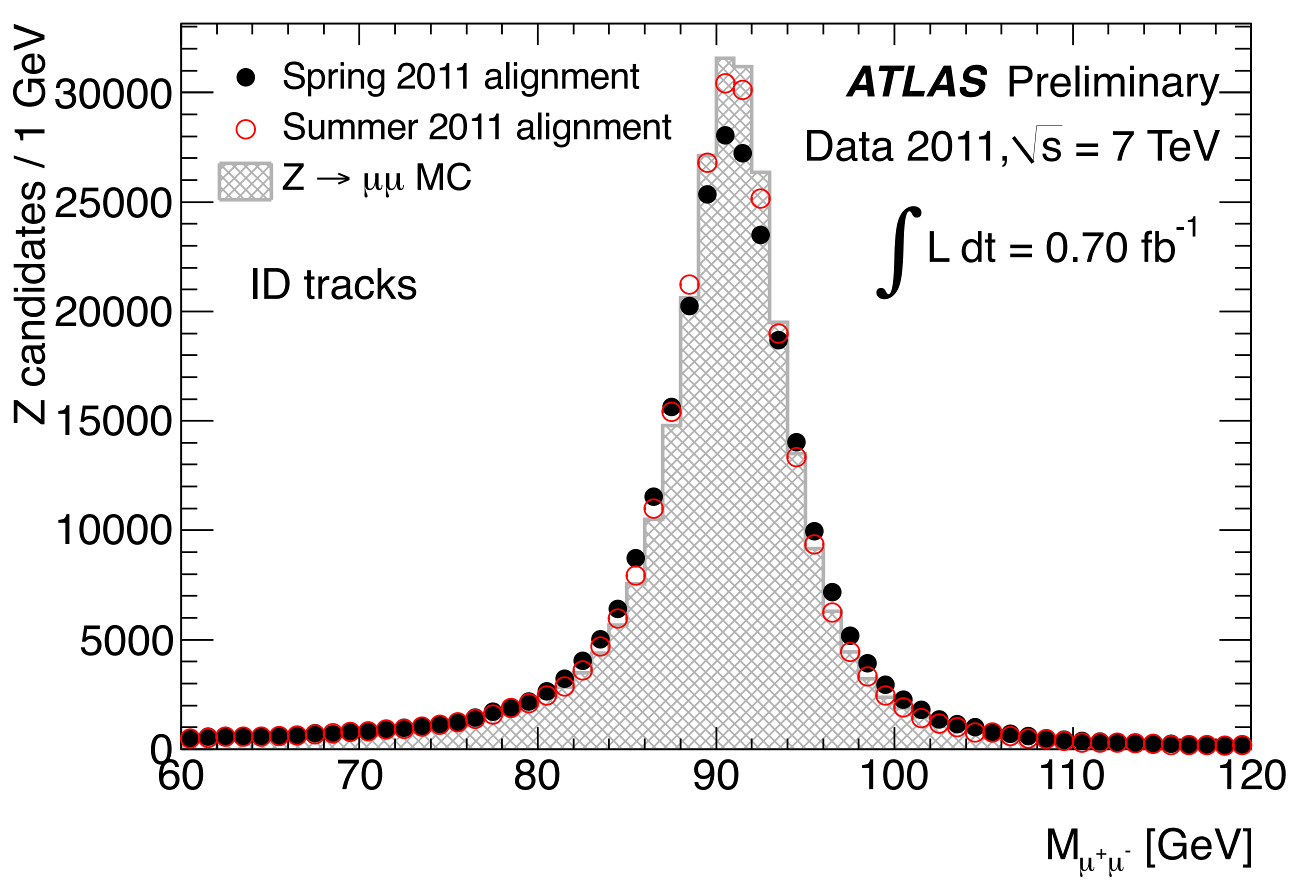
- Provide precision tracking for $|\eta| < 2.5$
- Precise primary & secondary vertex
  - b-tagging
- Transition radiation for electron identification

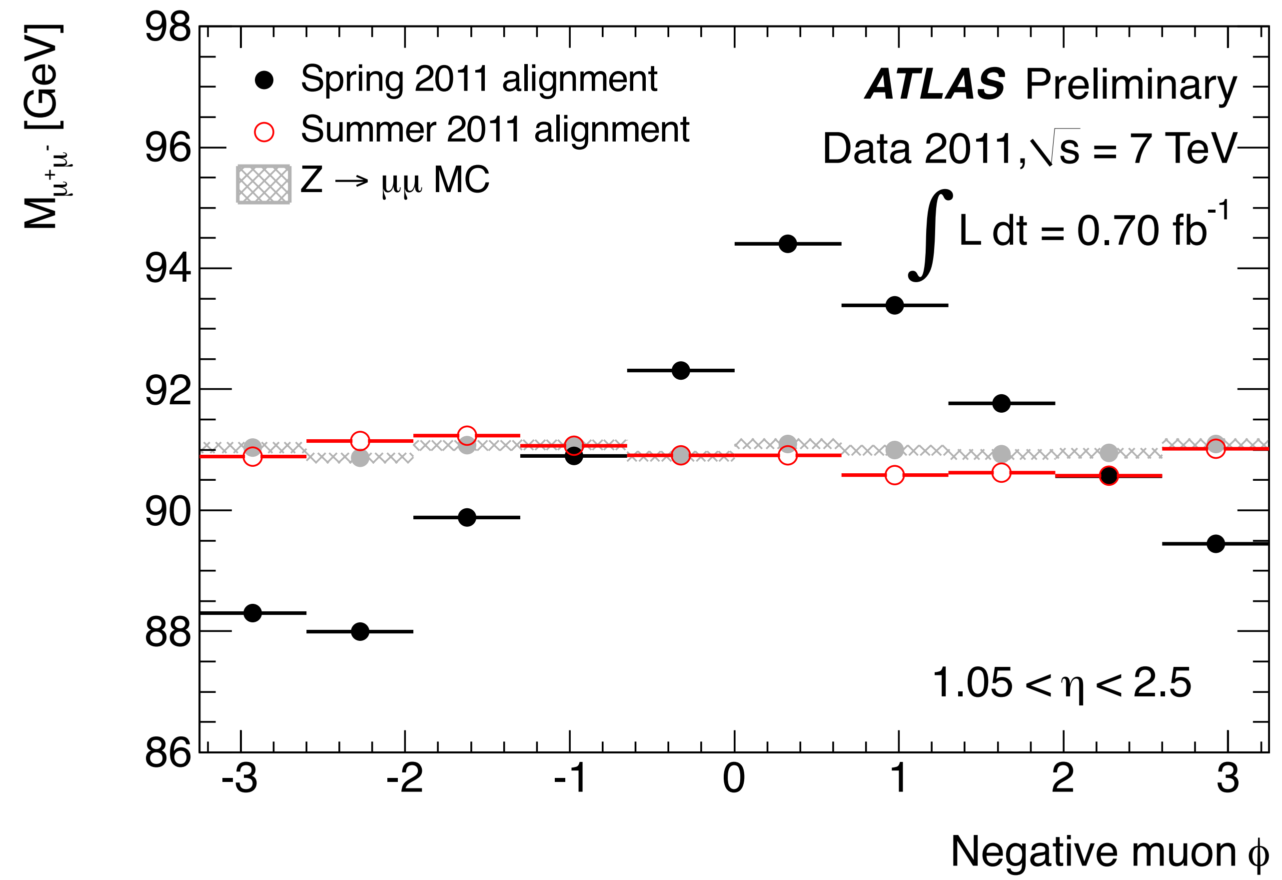


Inner detector alignment

- Precise knowledge of detector element positions crucial
  - Accurate momentum measurements & charge determination
  - Precise vertex reconstruction
- Alignment of > 35,000 d.o.f.
  - Use high-p_T tracks from collisions & cosmic rays
- Systematic biases
  - Observed large charged-dependent modulation in Z mass vs muon ϕ
  - Corrected by imposing external constraints during alignment procedure

***Minimize* residuals:**
distance between extrapolated track position & recorded hit position in given module

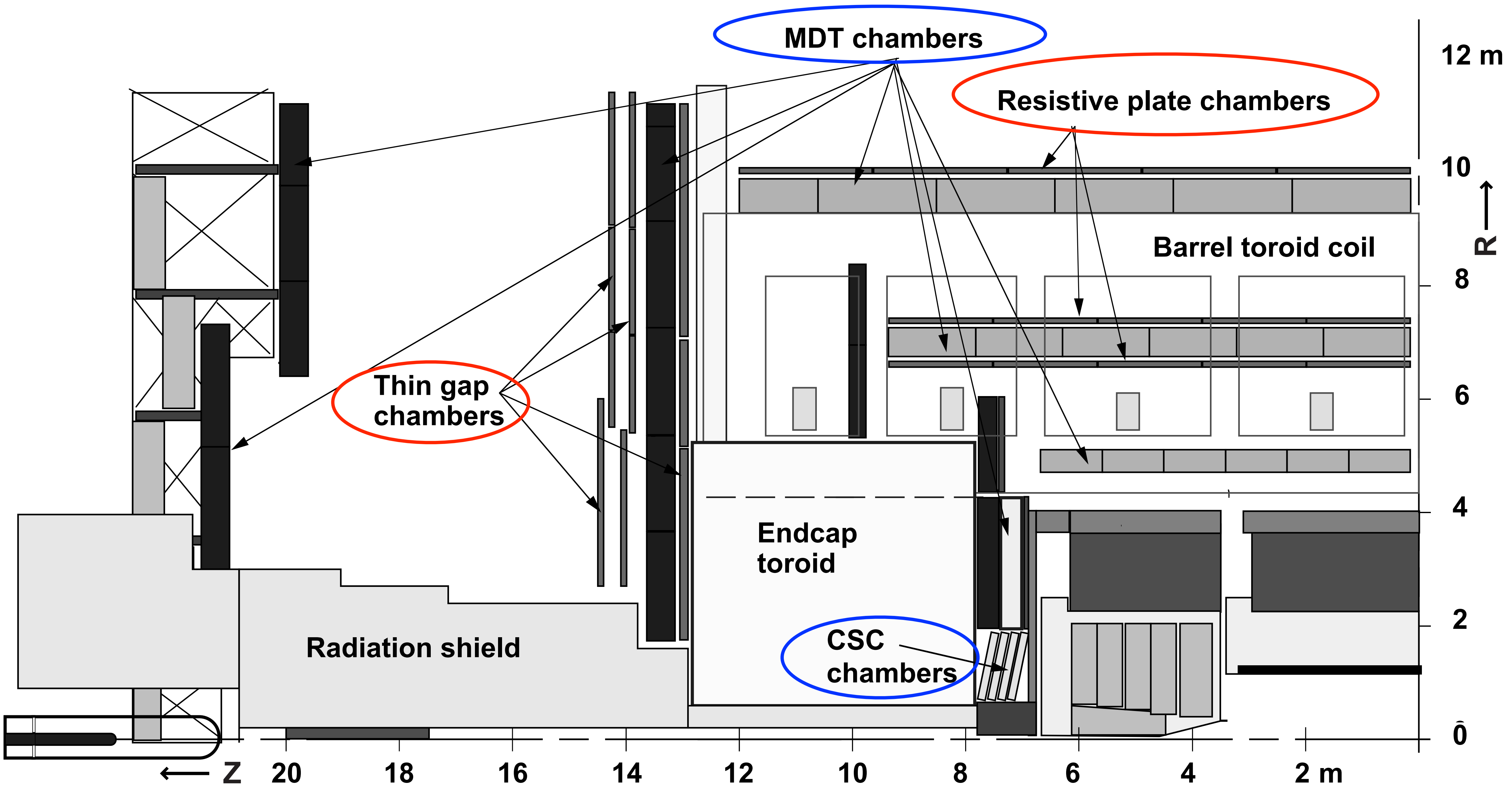




The muon system

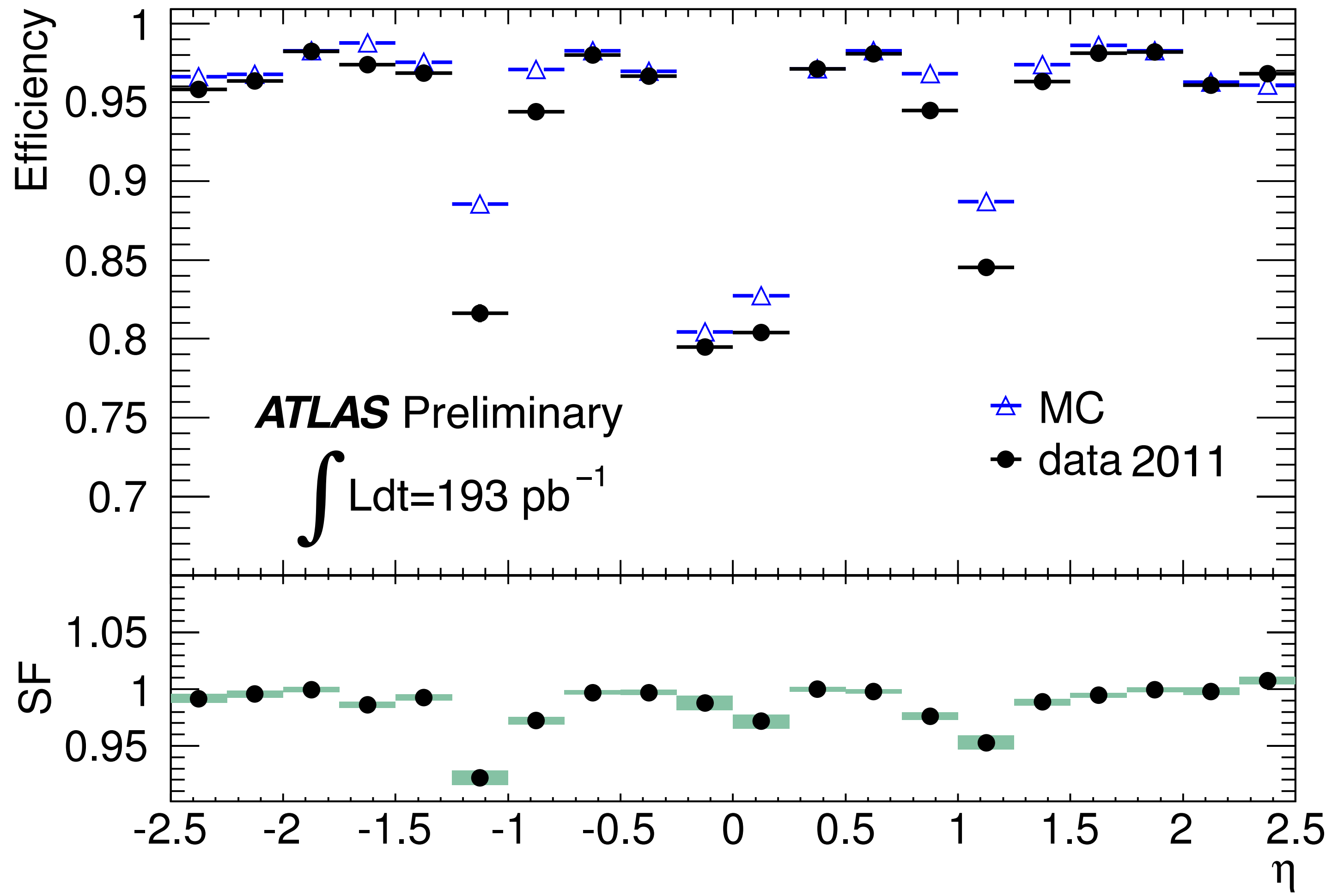
Muon p_T trigger thresholds:
@ Level 1 (online hardware-based): 10 GeV
@ High-level trigger: 18 GeV

- Cross-sectional view of the ATLAS muon system
  - **Tracking**
  - **Triggering**
- Three air-core superconducting toroids ~0.5 T field



Muon identification

- Several different muon identification algorithms
  - Muon spectrometer stand-alone muon
  - Inner detector track matched to track segments in muon system
  - ***Combined muon***
    - *Stand-alone muon combined with inner detector track for joint momentum measurement*
    - *Independent charge measurements from ID & MS →* ***used for this analysis***



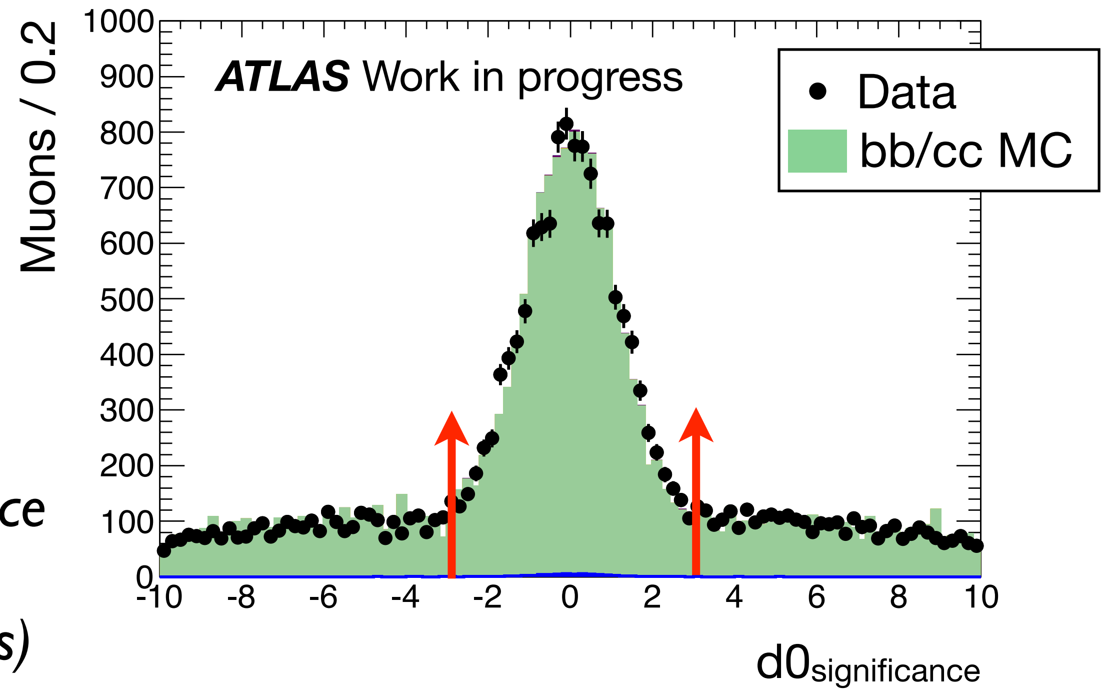
Combined muon reconstruction efficiency vs η

analysis: selection, backgrounds & systematics

Event selection: muons

- Basic selection requirements
  - $|\eta| < 2.5$
  - Transverse momentum: $p_T > 20$ GeV ⟵ Trigger + background rejection
  - Track impact parameter ⟵ Reject cosmic contamination
    - *Transverse $|d_0| < 0.2$ mm*
    - *Longitudinal $|z_0 \sin\theta| < 5$ mm*

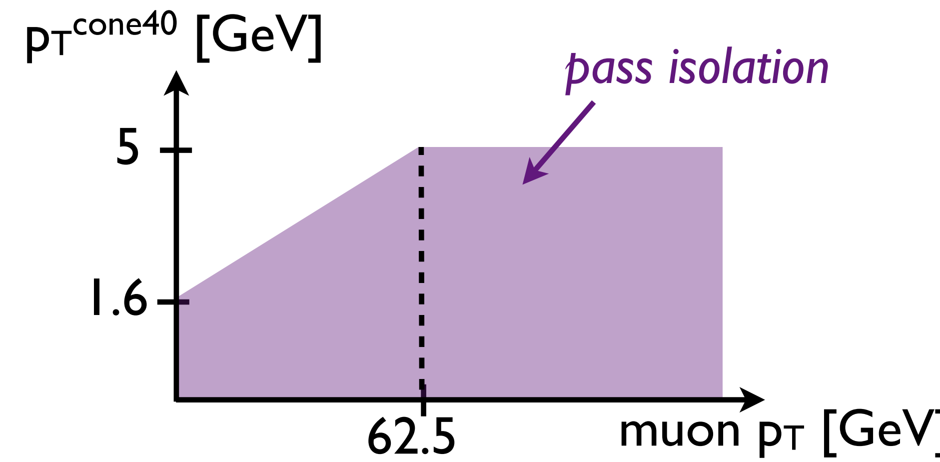
- Muon quality selection
  - ***Charge:*** $Q_{ID} == Q_{MS}$ ⟵ Reduce charge mis-identification rate
  - ***Impact parameter significance:*** $|d_0|/\sigma(d_0) < 3$ ⟵ Reduce non-prompt muon background
    - *long tails for non-prompt muons*
  - ***Track-based isolation***



Impact parameter significance for non-isolated muons (in same-sign dimuon events)

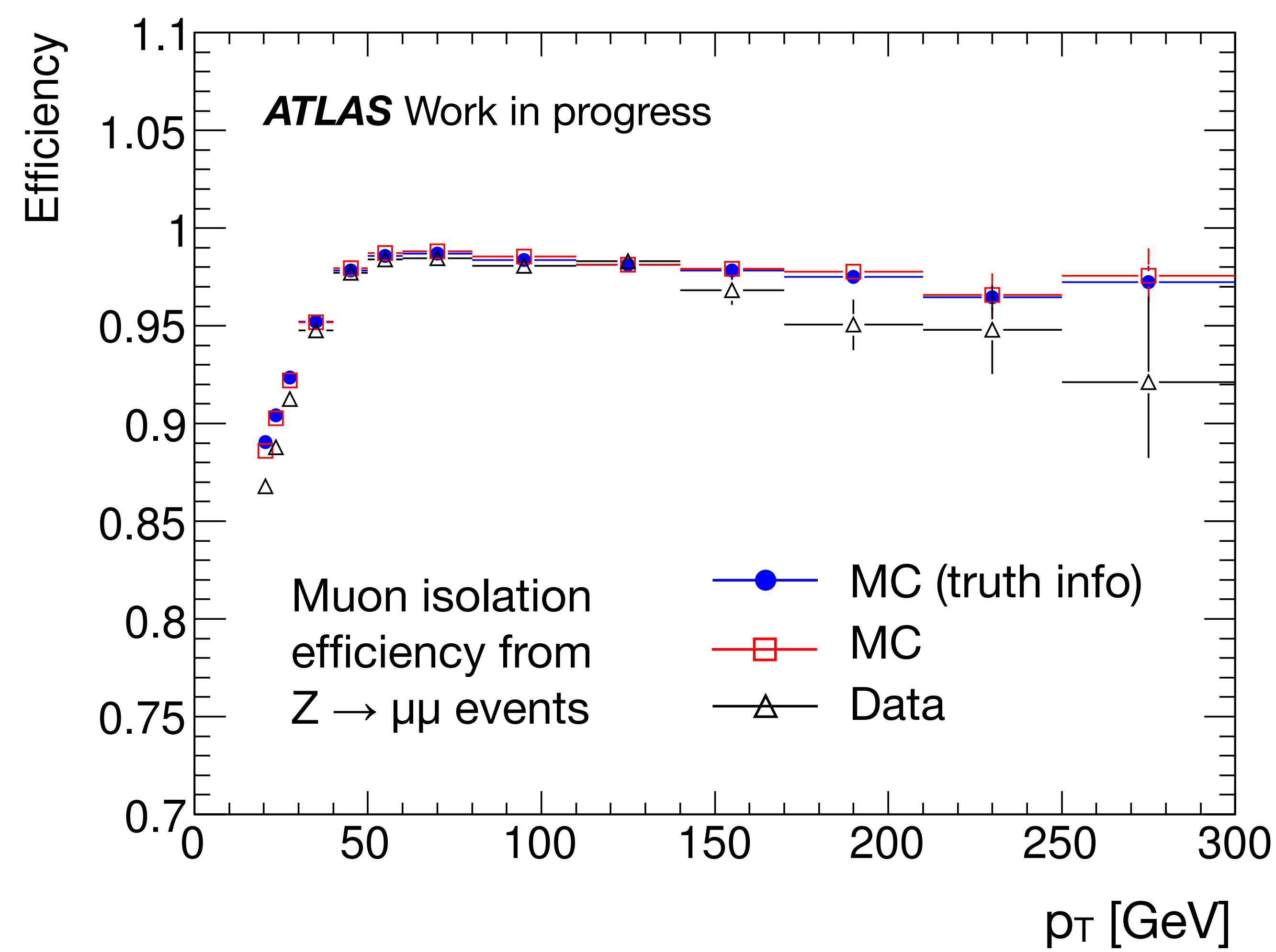
Muon isolation

- Track isolation
  - Scalar p_T sum of tracks with $p_T > 0.5$ GeV in cone of $\Delta R < 0.40$ (p_T^{cone40})
  - Track selection
    - *$|d_0| < 10$ mm, $|z_0| < 10$ mm & ≥ 4 silicon hits*
    - *Helps reduce dependence on pileup*



- Require: $p_T^{cone40}/p_T(\mu) < 0.08$ && $p_T^{cone40} < 5$ GeV
  - Tighter at low p_T where background most severe

- Reasonable modeling by simulation
  - Discrepancies addressed for systematic uncertainty



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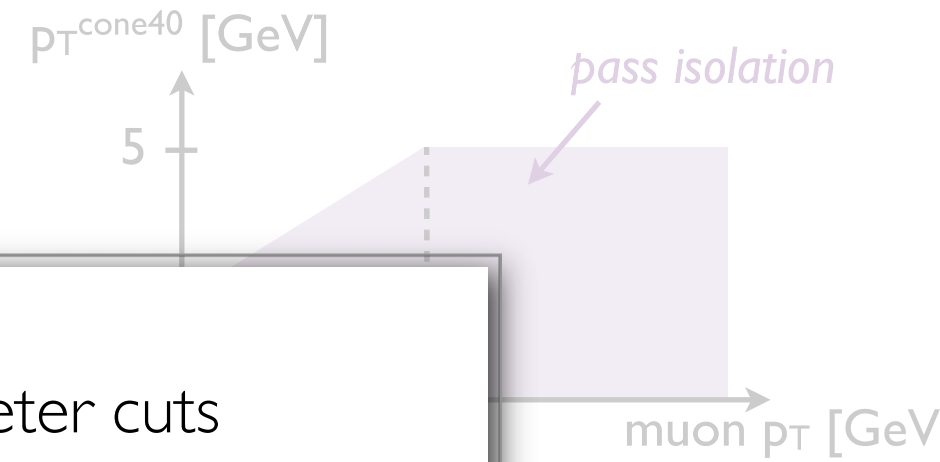
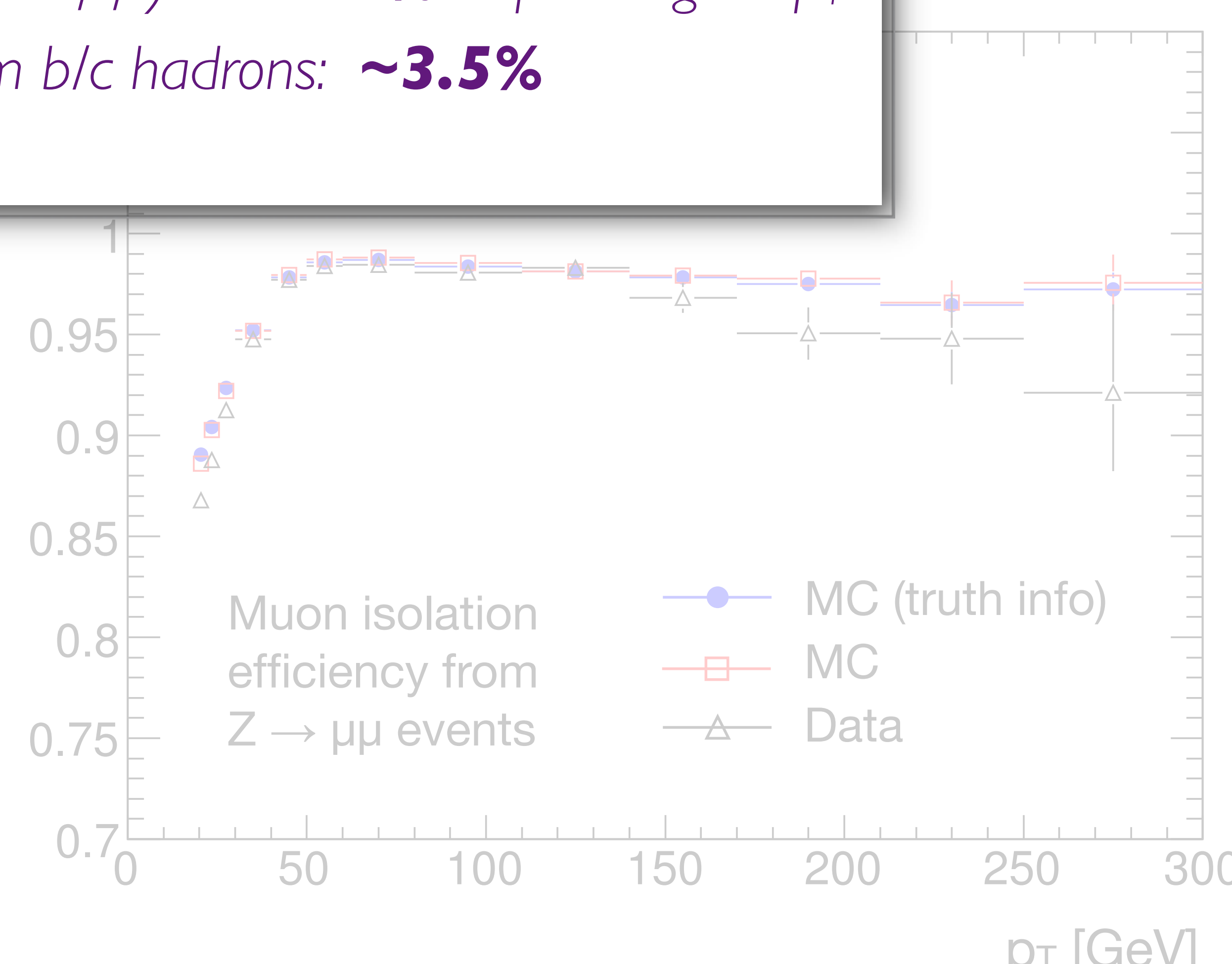


- Require: p_T^{cone40}
  - Tighter at low

- Efficiency of isolation + impact parameter cuts
  - *Prompt muons (from $Z \rightarrow \mu\mu$): **87-97%** depending on p_T*
  - *Non-prompt muons from b/c hadrons: **~3.5%***

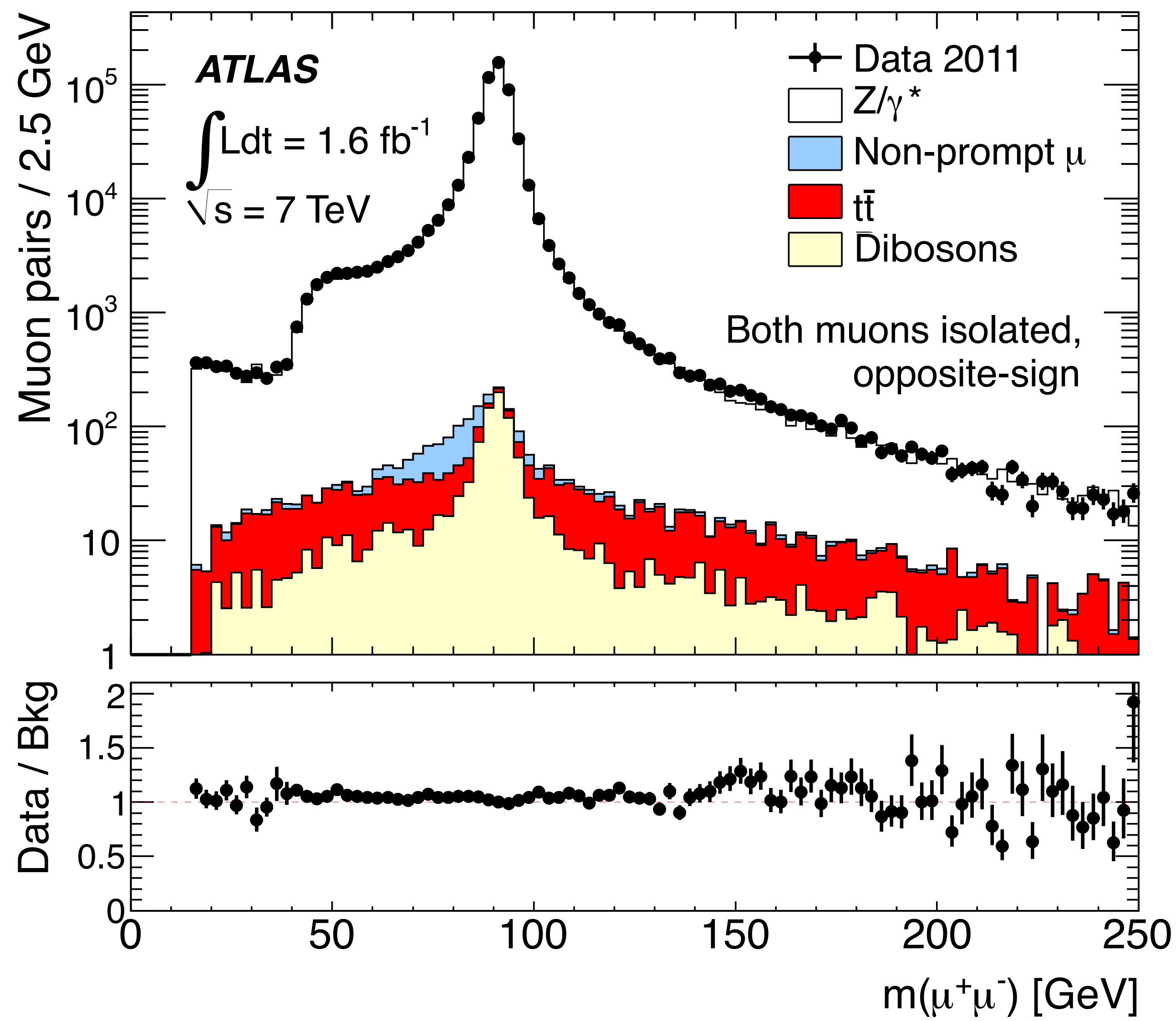
- Reasonable modeling by simulation
  - Discrepancies addressed for systematic uncertainty



Event selection: dimuon pairs

- Select pairs of good muons with equal charge
- Invariant mass:
  - m(μμ) > 15 GeV

- Opposite-sign control region
  - Verify understanding of prompt isolated muons from Drell-Yan
    - *estimate using using $Z \rightarrow \mu^+\mu^-$ MC*
  - Prediction in good agreement with observation



Backgrounds

- *Understanding & accurately estimating backgrounds most crucial part of the analysis*

- **(1)** SM production of prompt like-sign dimuons: ***dibosons***

- **(2)** Prompt opposite-sign dimuons where one muon is mis-measured: ***charge-flip***

- **(3)** Muons from hadronic decays: ***non-prompt muons***

Backgrounds

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- **(1)** SM production of prompt like-sign dimuons: ***dibosons***
- **(2)** Prompt opposite-sign di
- **(3)** Muons from hadronic de

- Dominant & irreducible background
- Well-modeled in simulation → MC-based prediction
  - *WZ / ZZ: normalize to NLO cross section*
  - *Smaller contributions from: $W^{\pm}W^{\pm}$ / $t\bar{t}W$*
- Resulting background:

Process	***$m(\mu^{\pm}\mu^{\pm})$ > 15 GeV***
WZ	48.4 ± 6.3
ZZ	10.6 ± 1.4
$W^{\pm}W^{\pm}$	2.7 ± 1.3
$t\bar{t}W$	1.4 ± 0.7

Backgrounds

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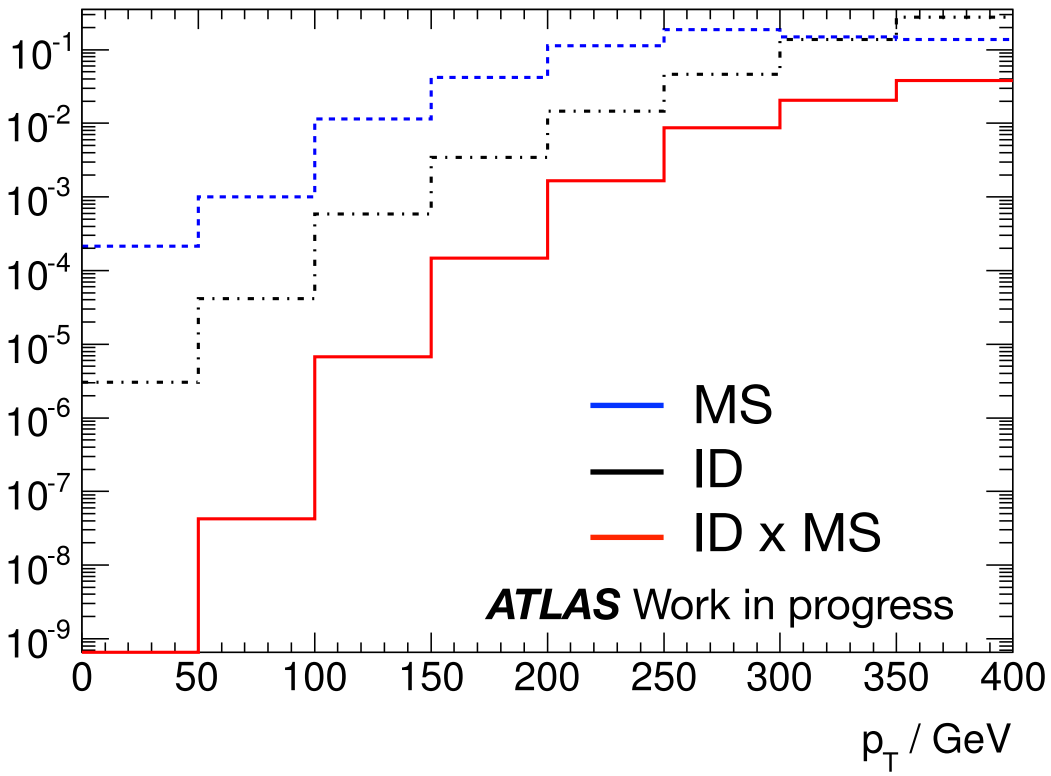
- **(3)** Muons from hadronic decays:

67% upper limit on charge flip rate



- Estimate from MC, cross-check using data
- Charge mis-identification rate
  - *Measure separately for ID/MS using Z events*
  - *$Q^{ID} == Q^{MS}$ → both must be mis-measured for charge flip*
  - *Apply combined rate to opposite-pairs in MC → upper systematic limit*
- Resulting background:

Process	***$m(\mu^{\pm}\mu^{\pm}) > 15$ GeV***
charge-flip	0 +2.7/-0.0

Backgrounds

- *Understanding & accurately estimating backgrounds most crucial part of the analysis*

- **(1)** SM production of prompt like-sign dimuons: ***dibosons***

- **(2)** Prompt opposite-sign dimuons where one muon is mis-measured: ***charge-flip***

- **(3)** Muons from hadronic decays: ***non-prompt muons***

- Predominantly from heavy-flavor decays
  - *Largely suppressed through selection cuts*
- Estimated using data-driven techniques
  - *Determine rate with which non-prompt muons pass isolation selection*

Non-prompt isolation probability

- Derive rate in regions enhanced in non-prompt muons

◉ *High $d0_{significance}$ (>5)* ⟵ probes ***heavy-flavor*** decays

- *Dimuon sample*
  - analysis is dimuon events - most similar to signal region
  - require $15 < m(\mu\mu) < 55$ GeV
- *Single muon sample*
  - higher statistics

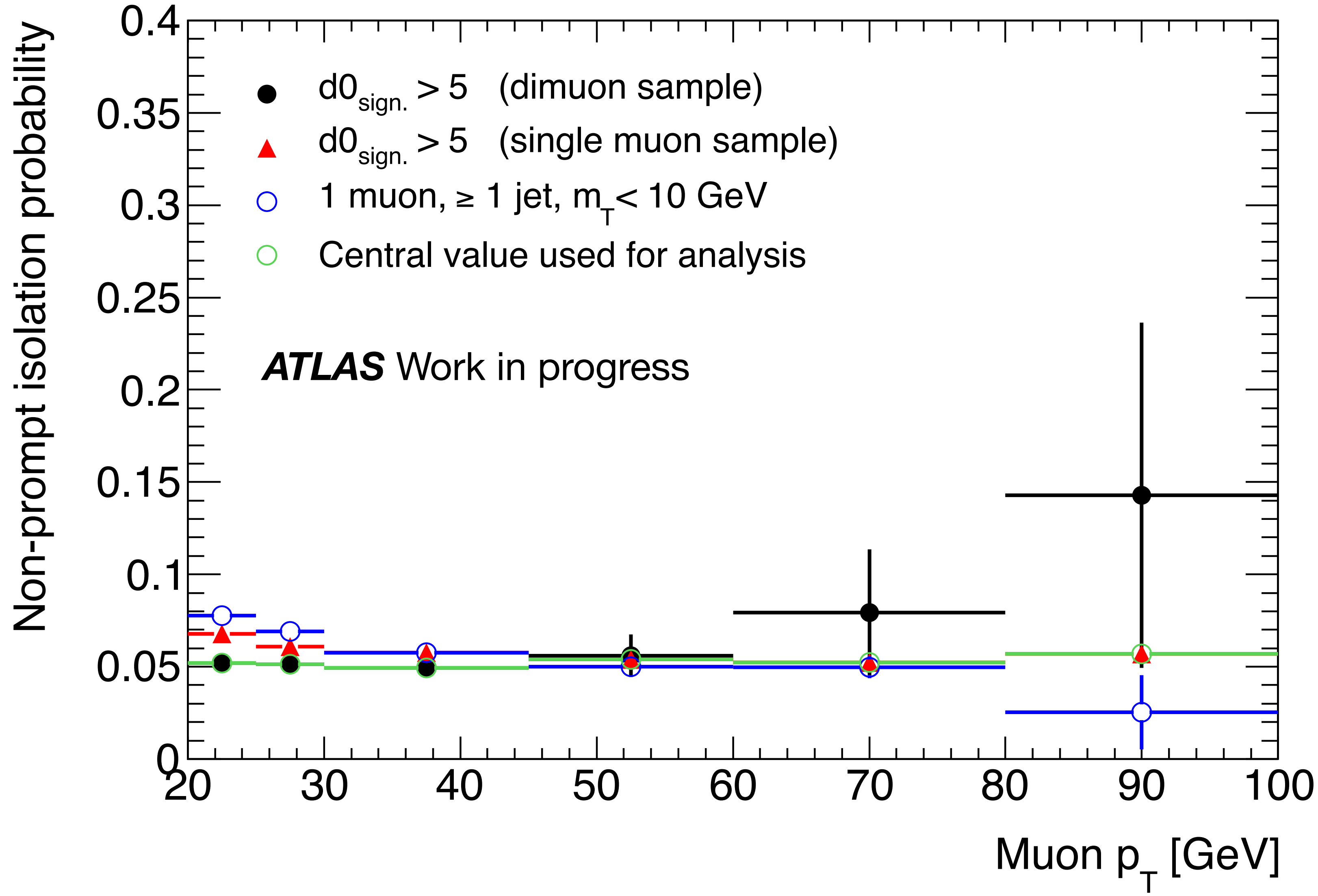
◉ *Low m_T region* ⟵ probes also ***decay-in-flight***

- *Exactly one muon & at least one jet*
- *$m_T < 10$ GeV*
  - reduce contribution of prompt muons from W
  - remaining prompt muon contribution subtracted based on MC

$$m_T(W) = \sqrt{2p_T^l p_T^\nu (1 - cos[\phi^l - \phi^\nu])}$$

Resulting isolation probability

- Isolation requirement: $p_T^{cone40}/p_T(\mu) < 0.08$ && $p_T^{cone40} < 5$ GeV
- Non-prompt isolation probability vs p_T for different control samples: 5-8%
  - Central value derived using muons with $d0_{significance} > 5$
  - Difference between samples used to asses systematic uncertainty
  - For high p_T, statistical uncertainty large → assign 100% systematic uncertainty



Signal region predictions

- Contribution to signal region estimated using ***matrix method***
- Define two set of muons, *exclusive* of each other
  - **T** tight = *PASS* isolation
  - **L** loose = *FAILS* isolation

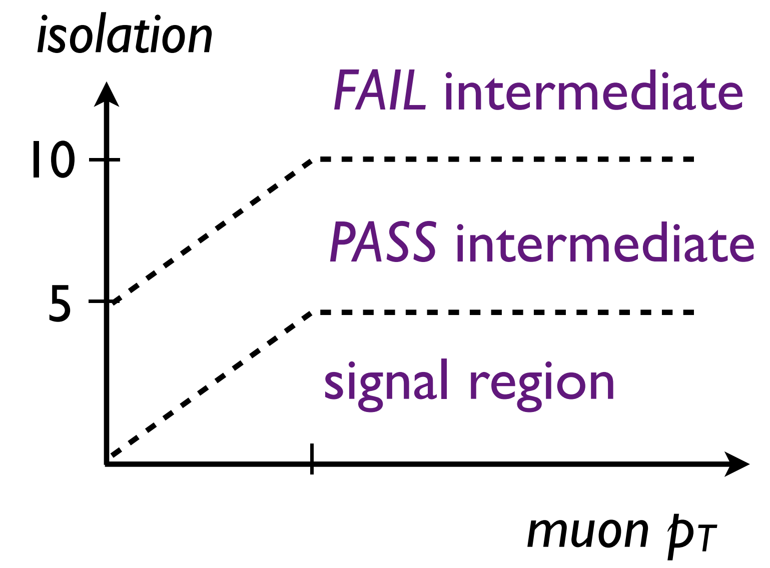
signal events! *use these to predict non-real background to signal!*

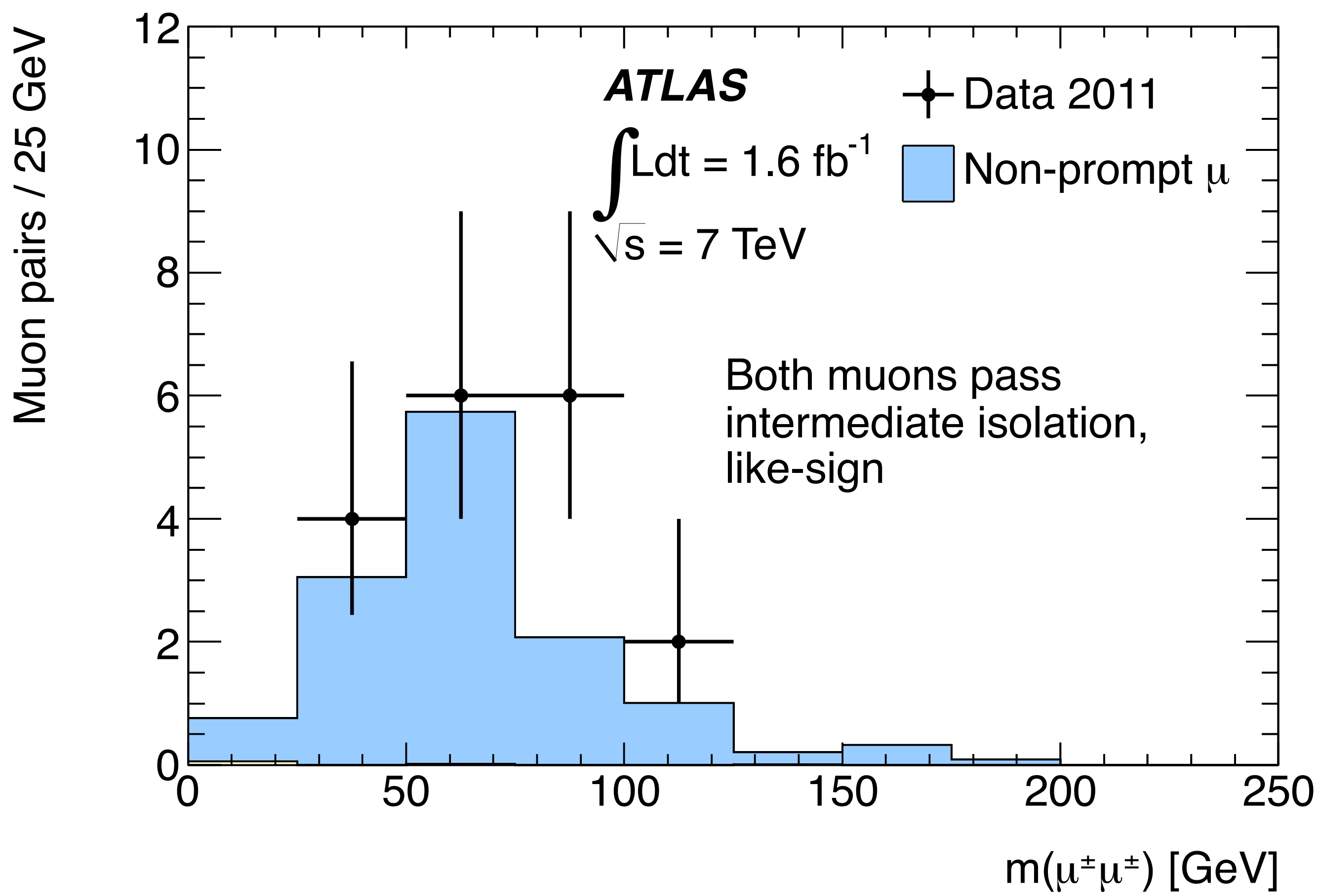
- Separate dimuon pairs into **TT** / **TL** / **LT** / **LL**
- Method relates ***observed dimuon composition*** to underlying ***real/fake composition***
  - Inputs are the rates with which prompt & non-prompt muons pass isolation

◉ *Cross check prediction using non-prompt muon enhanced **control regions**!*

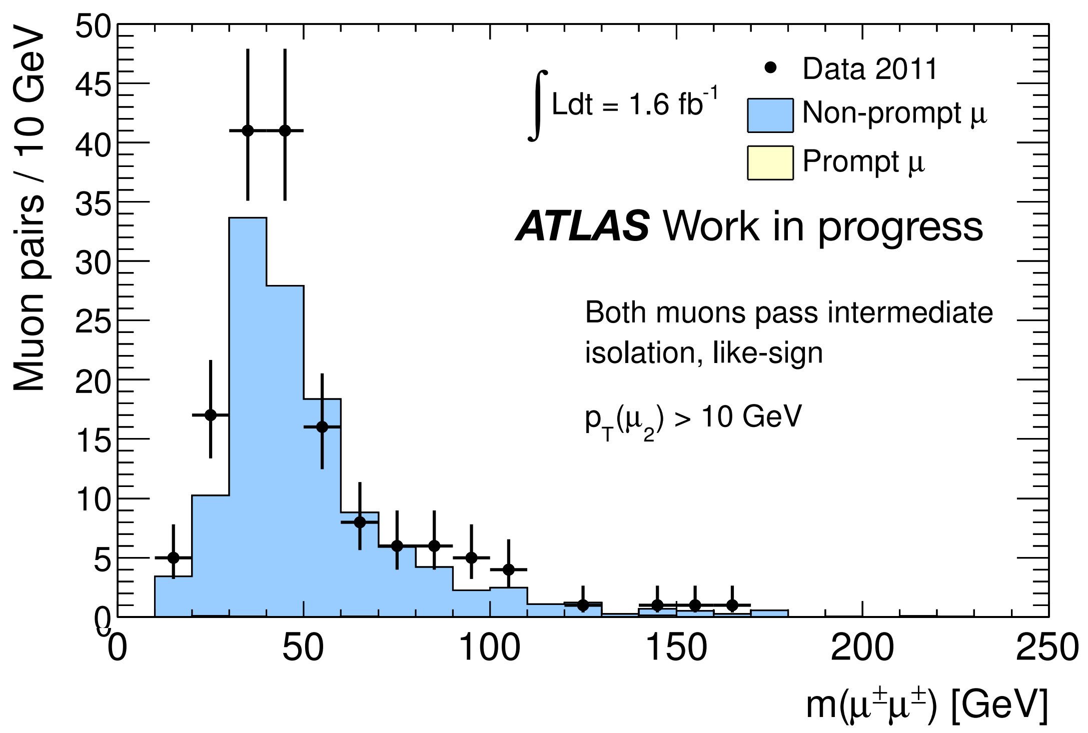
Control region: intermediate isolation

- Predict intermediately isolated region
  - Both muons fail signal region isolation but pass looser isolation cut
  - Muons pass other selection cuts
    - *$d0_{significance} < 3$*
    - *Like-sign muons*
  - Predict $14^{+4/-5}$ & observe 18 ***- good agreement!***



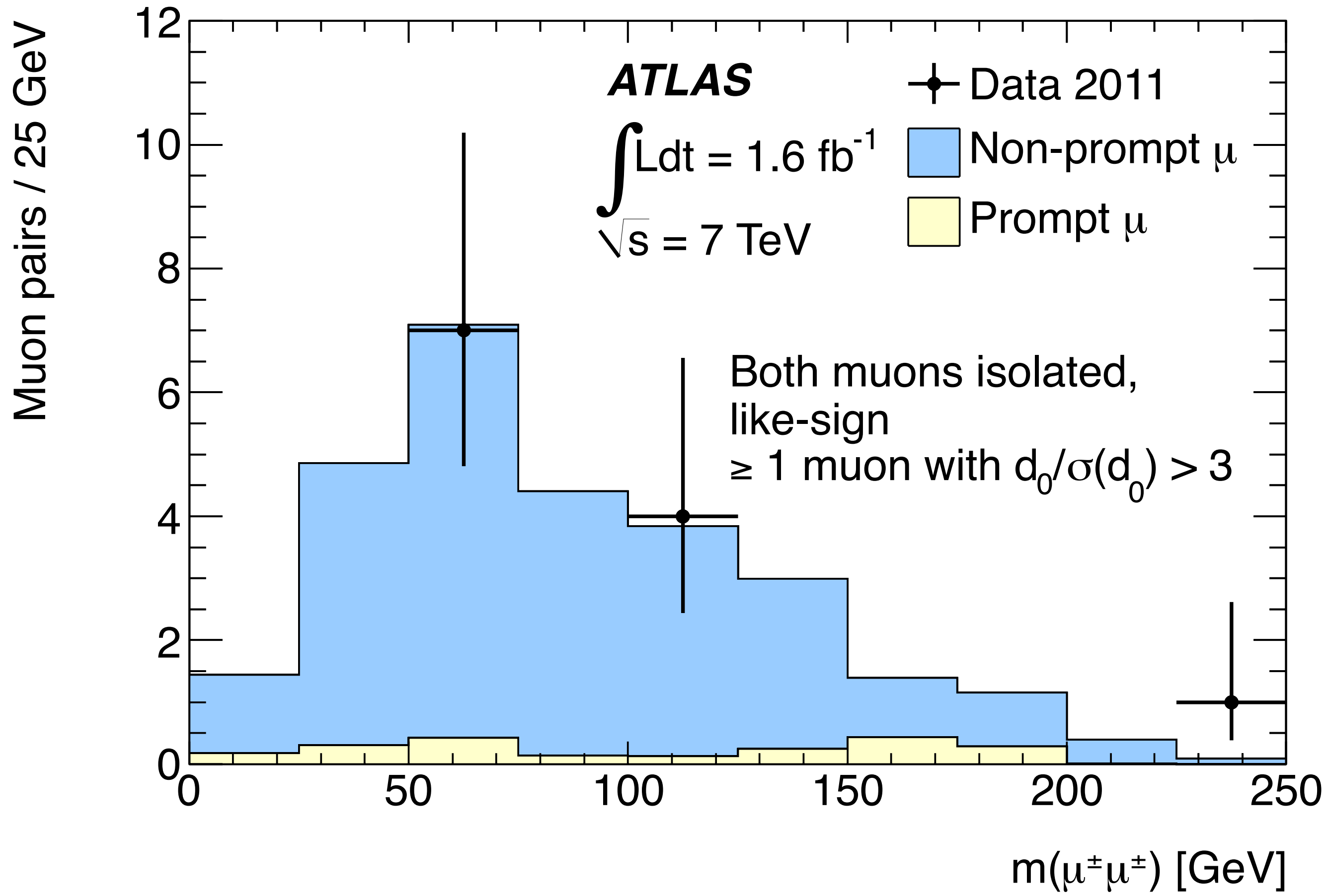


For higher statistics compare $p_T(\mu_2) > 10$ GeV - good modeling



Control region: high $d0_{significance}$

- Require at least one muon to *FAIL* the $d0_{significance}$ cut (> 3)
  - Require both muons to pass all other selection cuts
    - *Signal region isolation*
    - *Like-sign muons*
  - Predict $29^{+7/-9}$ & observe 12 ***- 1.8 sigma downward fluctuation***



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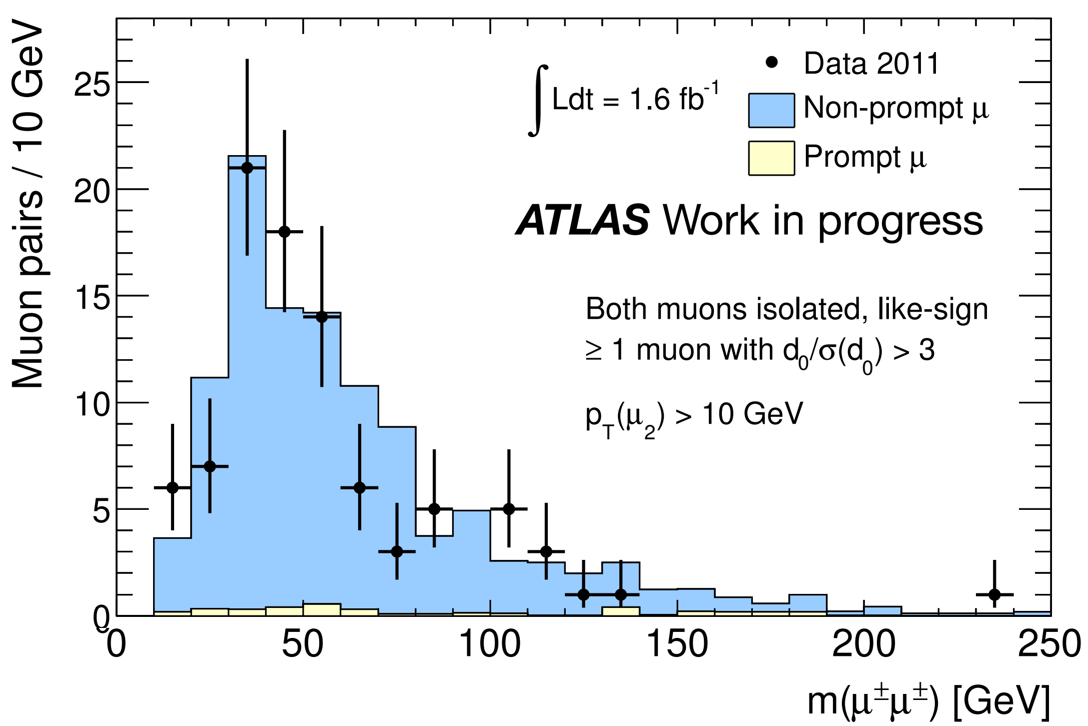

Systematic uncertainties

- Several systematic uncertainties may change signal acceptance & background estimate
- Small uncertainties on lepton identification

Source of uncertainty	Processes affected	Effect on prediction
Muon identification	Signal WZ, ZZ, $W^{\pm}W^{\pm}$, $t\bar{t}W$	$\pm 1\%$
Muon isolation efficiency	Signal WZ, ZZ, $W^{\pm}W^{\pm}$, $t\bar{t}W$	-1.5%
Muon momentum measurement	Signal WZ, ZZ, $W^{\pm}W^{\pm}$, $t\bar{t}W$	$\pm 0.9\%$
Trigger efficiency	Signal WZ, ZZ, $W^{\pm}W^{\pm}$, $t\bar{t}W$	$\pm 0.3\%$
Luminosity	Signal WZ, ZZ, $W^{\pm}W^{\pm}$, $t\bar{t}W$	$\pm 3.7\%$
Non-prompt muon estimate	non-prompt muons	30-100%
WZ and ZZ cross section $W^{\pm}W^{\pm}$ and $t\bar{t}W$ cross section	WZ, ZZ $W^{\pm}W^{\pm}$, $t\bar{t}W$	12% 50%
Charge flip rate	Drell-Yan, $t\bar{t}$, WW	up to +2.7 pairs
MC statistics	WZ, ZZ, $W^{\pm}W^{\pm}$, $t\bar{t}W$	5-50%
Data control region statistics	non-prompt muons	3-45%

affects signal & prompt background

Systematic uncertainties

- Several systematic uncertainties may change signal acceptance & background estimate
- Small uncertainties from lepton identification
- Cross section uncertainties & limited MC statistics

Source of uncertainty	Processes affected	Effect on prediction
Muon identification	Signal WZ, ZZ, $W^{\pm}W^{\pm}$, $t\bar{t}W$	$\pm 1\%$
Muon isolation efficiency	Signal WZ, ZZ, $W^{\pm}W^{\pm}$, $t\bar{t}W$	-1.5%
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Luminosity	Signal WZ, ZZ, $W^{\pm}W^{\pm}$, $t\bar{t}W$	$\pm 3.7\%$
Non-prompt muon estimate	non-prompt muons	30-100%
WZ and ZZ cross section $W^{\pm}W^{\pm}$ and $t\bar{t}W$ cross section	WZ, ZZ $W^{\pm}W^{\pm}$, $t\bar{t}W$	12% 50%
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Data control region statistics	non-prompt muons	3-45%

prompt background

Systematic uncertainties

- Several systematic uncertainties may change signal acceptance & background estimate
- Small uncertainties from lepton identification
- Cross section uncertainties & limited MC statistics
- Uncertainties on non-prompt muon background

Source of uncertainty	Processes affected	Effect on prediction
Muon identification	Signal WZ, ZZ, $W^{\pm}W^{\pm}$, $t\bar{t}W$	$\pm 1\%$
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Muon momentum measurement	Signal WZ, ZZ, $W^{\pm}W^{\pm}$, $t\bar{t}W$	$\pm 0.9\%$
Trigger efficiency	Signal WZ, ZZ, $W^{\pm}W^{\pm}$, $t\bar{t}W$	$\pm 0.3\%$
Luminosity	Signal WZ, ZZ, $W^{\pm}W^{\pm}$, $t\bar{t}W$	$\pm 3.7\%$
Non-prompt muon estimate	non-prompt muons	30-100%
WZ and ZZ cross section $W^{\pm}W^{\pm}$ and $t\bar{t}W$ cross section	WZ, ZZ $W^{\pm}W^{\pm}$, $t\bar{t}W$	12% 50%
Charge flip rate	Drell-Yan, $t\bar{t}$, WW	up to +2.7 pairs
MC statistics	WZ, ZZ, $W^{\pm}W^{\pm}$, $t\bar{t}W$	5-50%
Data control region statistics	non-prompt muons	3-45%

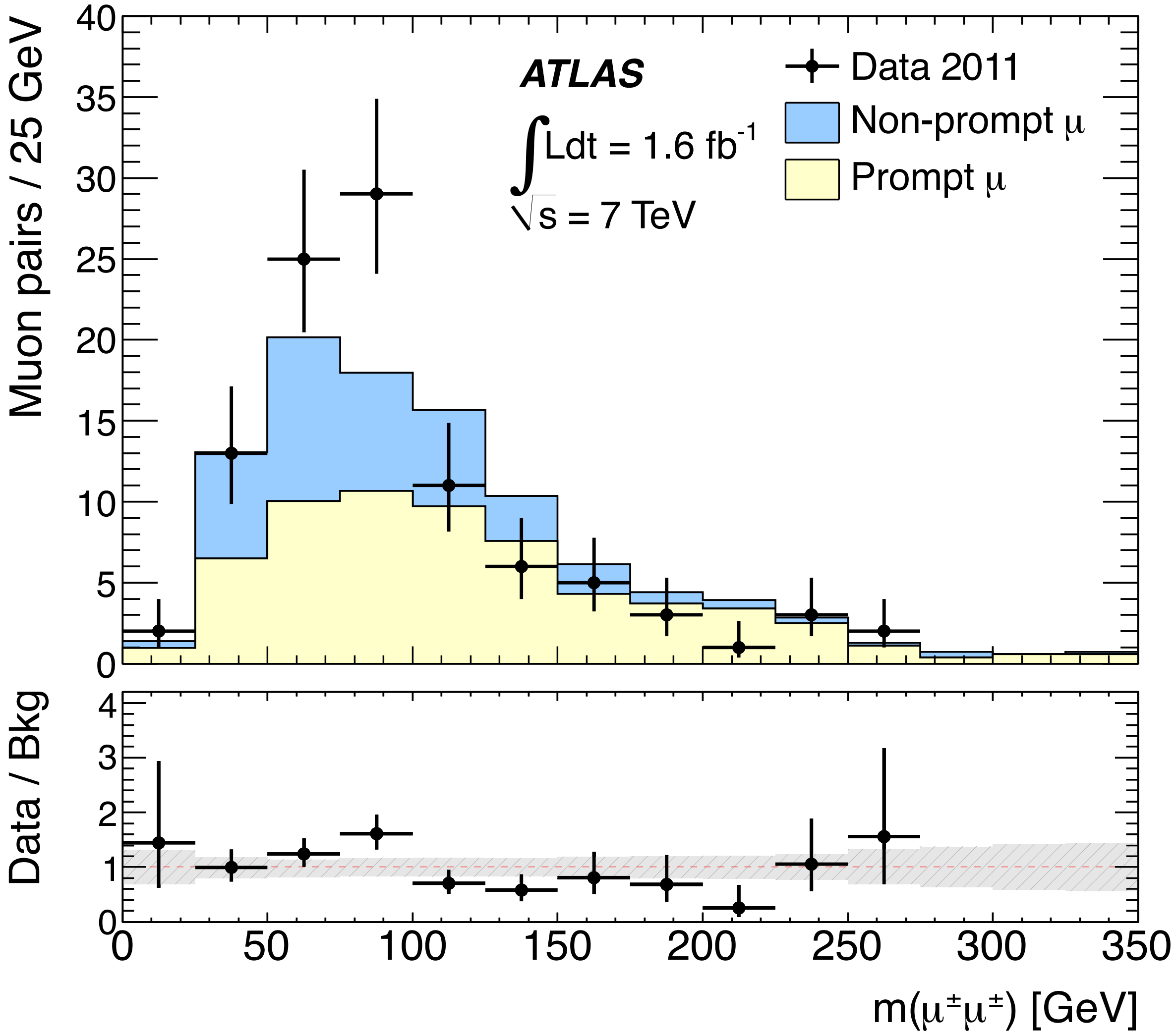
non-prompt muon background

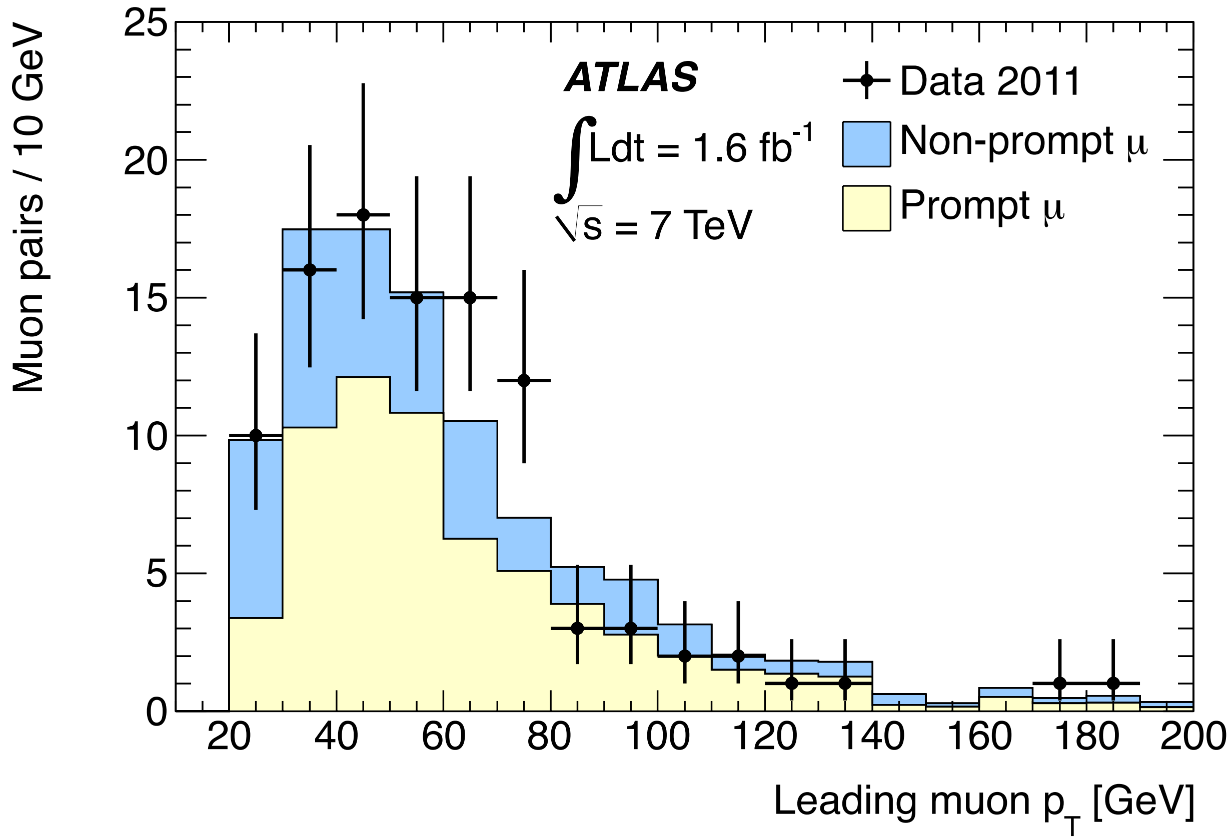
analysis: results & interpretations

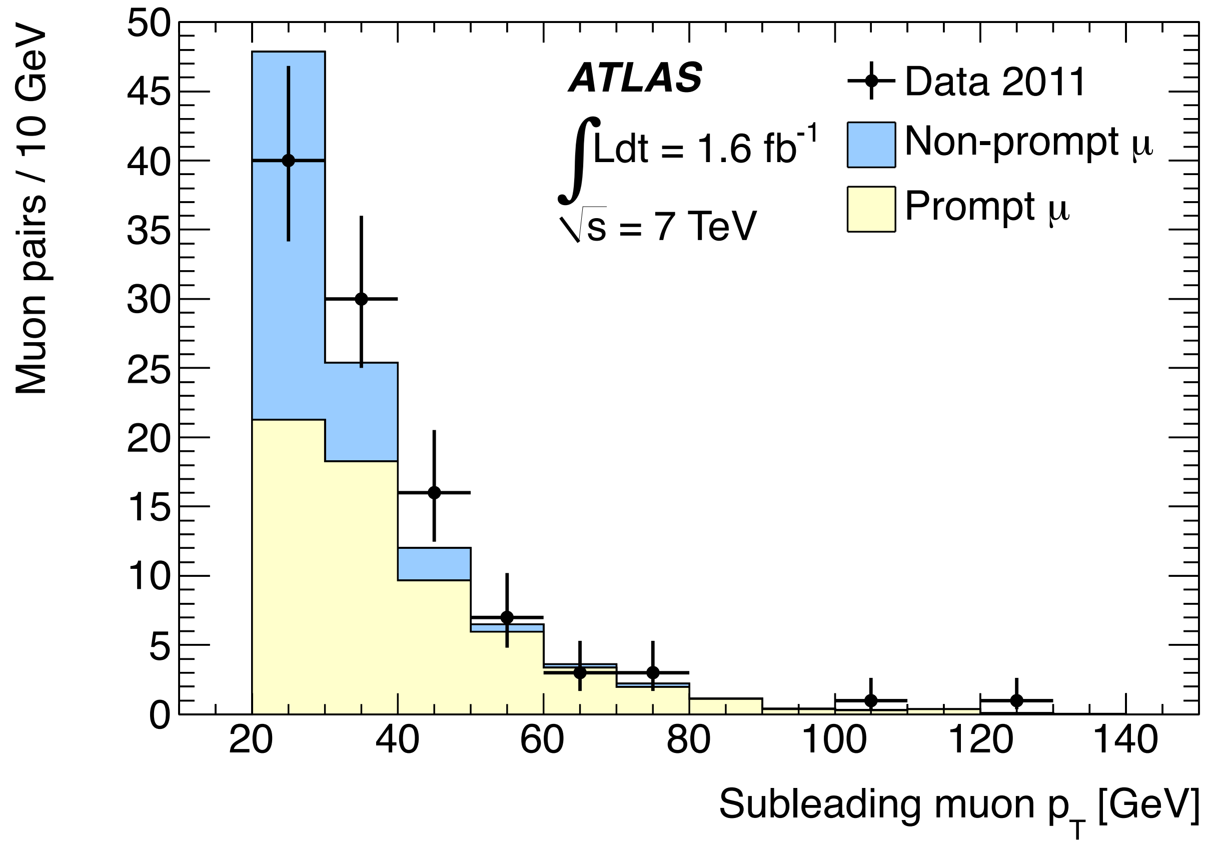
Results: kinematics

- Invariant mass of muon pair
- Leading & subleading muon p_T

- ***No significant excess observed in data!***

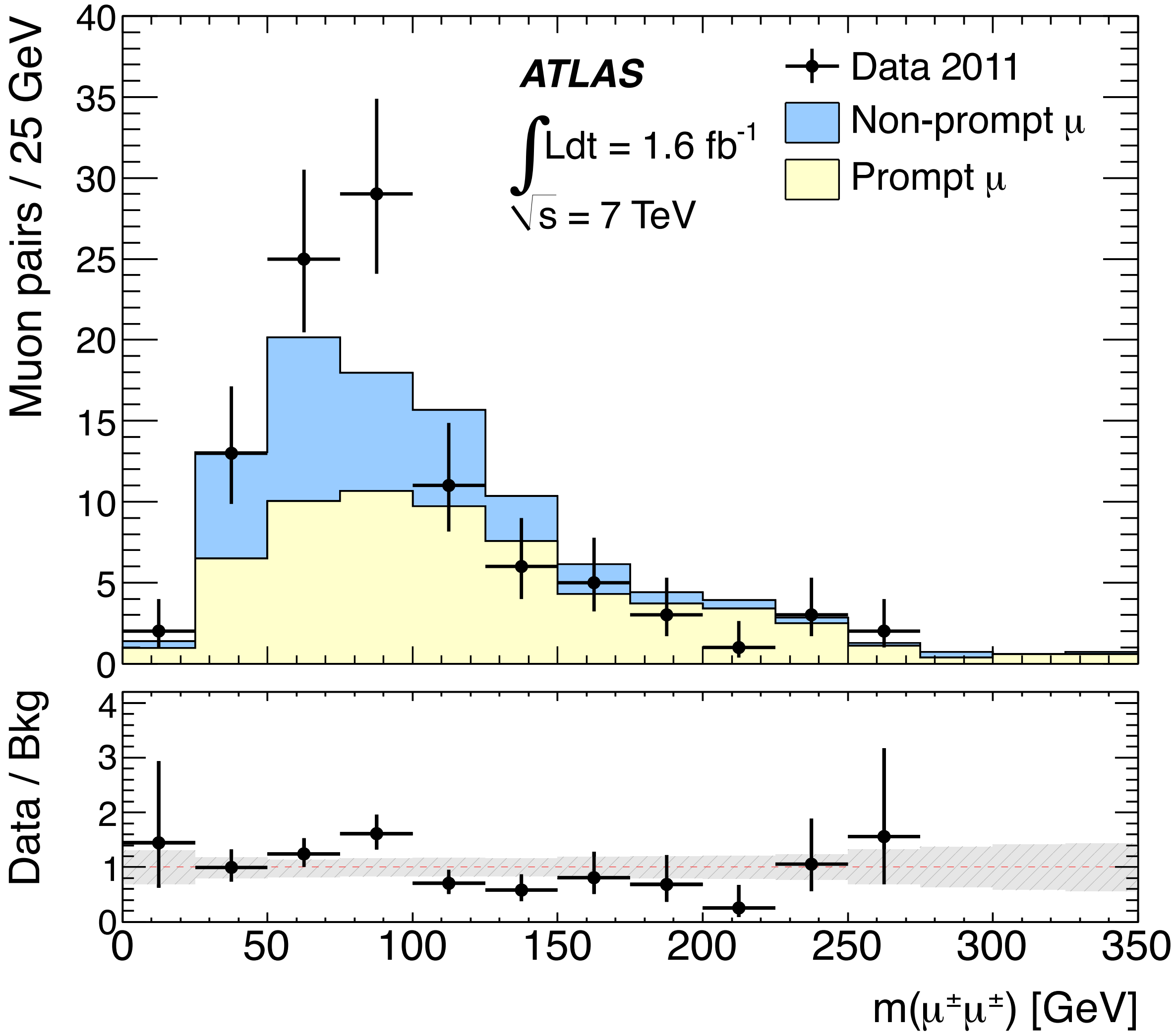






Results: kinematics

- Separate into 4 mass regions
  - > 15 GeV
  - > 100 GeV
  - > 200 GeV
  - > 300 GeV



- ***Observation in good agreement with SM predictions!***
  - Proceed to put limits...

Sample	Number of muon pairs with $m(\mu^\pm\mu^\pm)$			
	> 15 GeV	> 100 GeV	> 200 GeV	> 300 GeV
prompt muons	63.1 ± 7.8	34.9 ± 4.5	9.6 ± 1.6	2.24 ± 0.54
non-prompt muons	$37.5^{+10.3}_{-12.4}$	13.0 ± 4.5	1.8 ± 0.7	0.31 ± 0.18
charge flip	$0^{+2.7}_{-0}$	$0^{+0.9}_{-0.0}$	$0^{+0.7}_{-0.0}$	$0^{+0.61}_{-0.00}$
total	$100.6^{+13.2}_{-14.7}$	48.0 ± 6.4	$11.4^{+1.8}_{-1.7}$	$2.56^{+0.83}_{-0.57}$
data	101	32	7	1

>5% probability for background only hypothesis to fluctuate down

Limit setting

- No excess observed → set constraints on like-sign muon production from non-SM sources
  - Do counting experiment in bins of invariant mass
- Translate from number of pairs to a cross section → fiducial efficiency

$$\sigma_{95}^{fid}(\mu\mu) = \frac{N_{95}(\mu\mu)}{\epsilon_{fid} \int L dt}$$

upper limit on number of events from non-SM sources

efficiency of reconstructing events within the true fiducial region

- True fiducial region
  - $p_T(\mu) > 20$ GeV
  - $|\eta| < 2.5$
  - Separation from truth jet & truth prompt electron/muon with $p_T > 20$ GeV by dR > 0.40
    - *emulate isolation cut*
  - $m(\mu\mu) > 15$ GeV

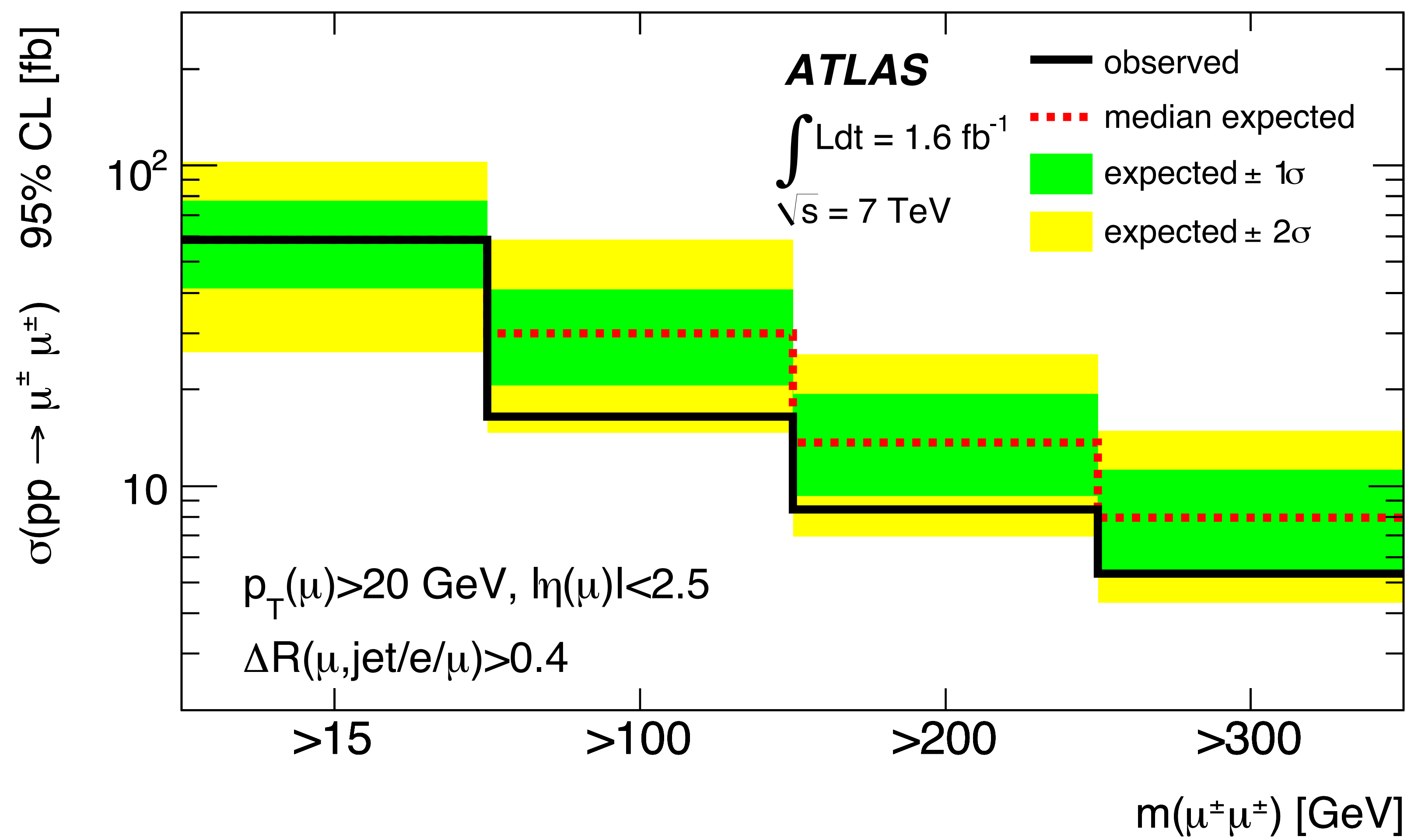
- Fiducial efficiency compared between different new physics models
  - Busy vs clean events
  - Lowest observed efficiency used (range between 44-73%)

Models considered: $H^{\pm\pm}$, $t_R t_R$, b' quark, W_R

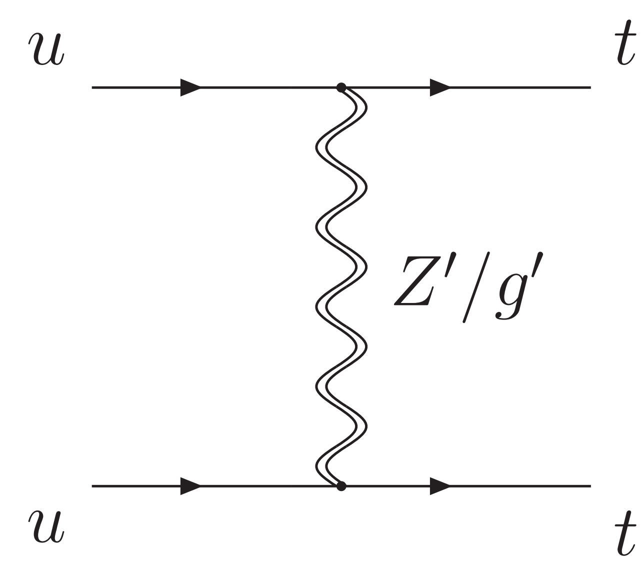
Fiducial cross-section limits

- Resulting cross-section limits determined for the four mass ranges considered
- Here combined positive & negative pairs

Mass range [GeV]	σ_{95}^{fid} [fb] expected	σ_{95}^{fid} [fb] observed
All muon pairs		
$m(\mu^\pm\mu^\pm) > 15$	58^{+19}_{-17}	58
$m(\mu^\pm\mu^\pm) > 100$	30^{+11}_{-9}	16
$m(\mu^\pm\mu^\pm) > 200$	$13.7^{+5.7}_{-4.4}$	8.4
$m(\mu^\pm\mu^\pm) > 300$	$8.0^{+3.3}_{-2.6}$	5.3



Limit on like-sign top quark production



- Direct translation of fiducial cross-section limit to specific model

- ***Like-sign top production*** through exchange of flavor-changing Z' boson
  - Like-sign tops at the LHC dominated by positive pairs
  - Consider only $\mu^+\mu^+$ since expect charge symmetric background

- Need acceptance of model & its uncertainty
  - Evaluate for different values of Z' mass in the four mass bins

$$\sigma_{95} = \frac{\sigma_{95}^{fid}(\mu\mu)}{A_{fid}}$$

- ***Resulting cross-section limit on $t_R t_R$ production***

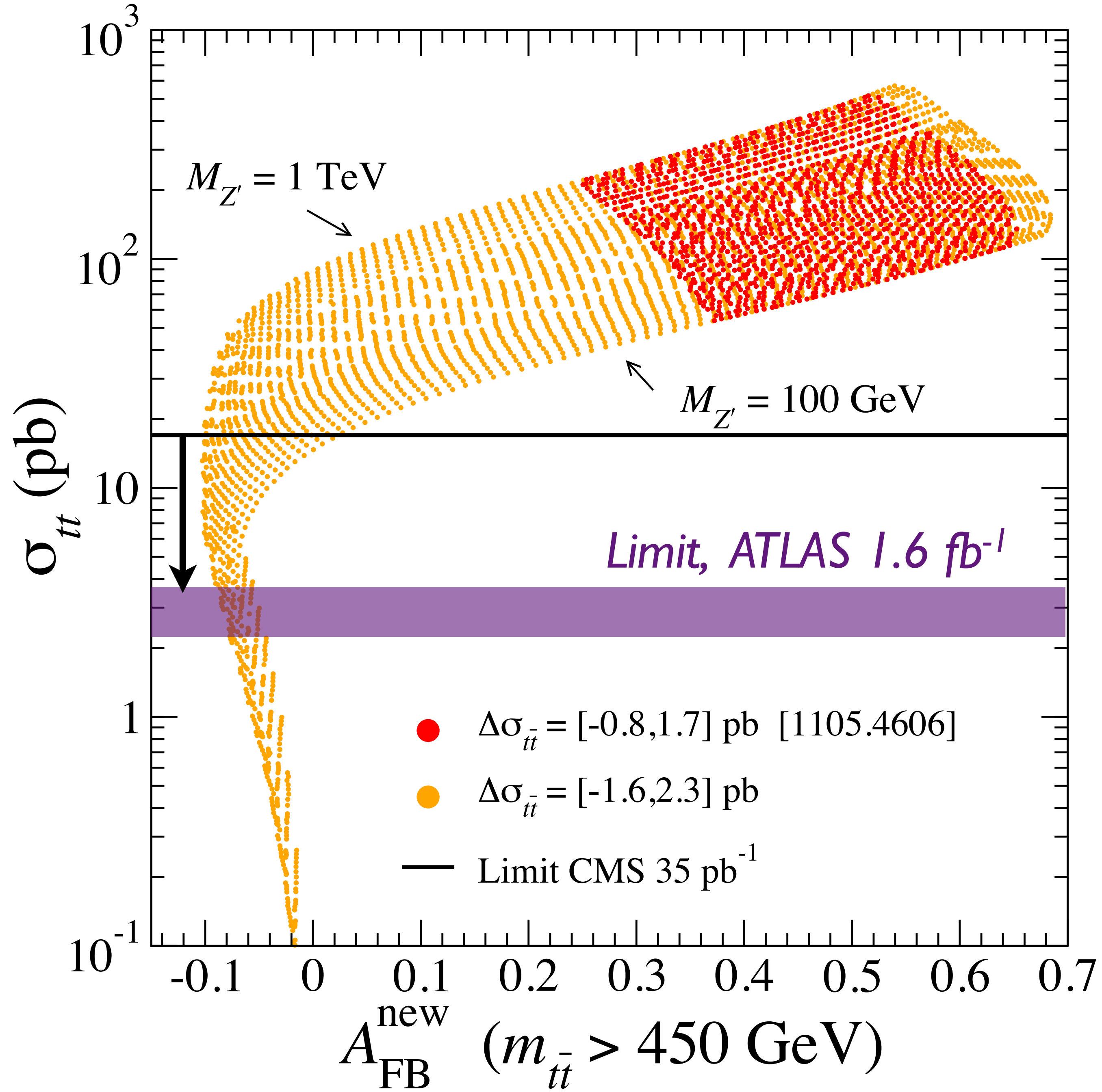
$m(Z')$	$\sigma_{95}(t_R t_R)$ [pb] expected	observed
100 GeV	$4.2^{+2.3}_{-0.9}$	3.7
150 GeV	$3.3^{+1.9}_{-0.7}$	3.0
200 GeV	$2.9^{+1.6}_{-0.6}$	2.6
$\gg$ 1 TeV	$2.5^{+1.4}_{-0.5}$	2.2

(t_L experimentally constrained from B_d - $\overline{B}_d$ mixing)

Interpretation of result

- Strongest limit to date on production cross section of like-sign top quark pairs
- Cross section required for $A_{FB}^{new} > 0$ excluded for Z' model

$A_{FB}^{new} > 0$ excluded by ATLAS



J.A. Aguilar Saavedra, shown at TOP2011

Dimuon resonance search

- Search dimuon mass for narrow resonance such as doubly charged Higgs bosons
  - Predicted by many new physics models
  - Observe good agreement between data & prediction → set limits

- Counting experiment in narrow ranges of dimuon mass
  - $0.9 \times m(\mu^\pm\mu^\pm) < M(H^{\pm\pm}) < 1.1 \times m(\mu^\pm\mu^\pm)$
- Estimate (acceptance x efficiency) from simulation (46 - 57%), translate to cross-section limit

$$\sigma_{HH} \times BR(H^{\pm\pm} \to \mu^\pm\mu^\pm) = \frac{N(\mu^\pm\mu^\pm)}{2 \times A \times \epsilon \times \mathcal{L}\mathrm{d}t}$$

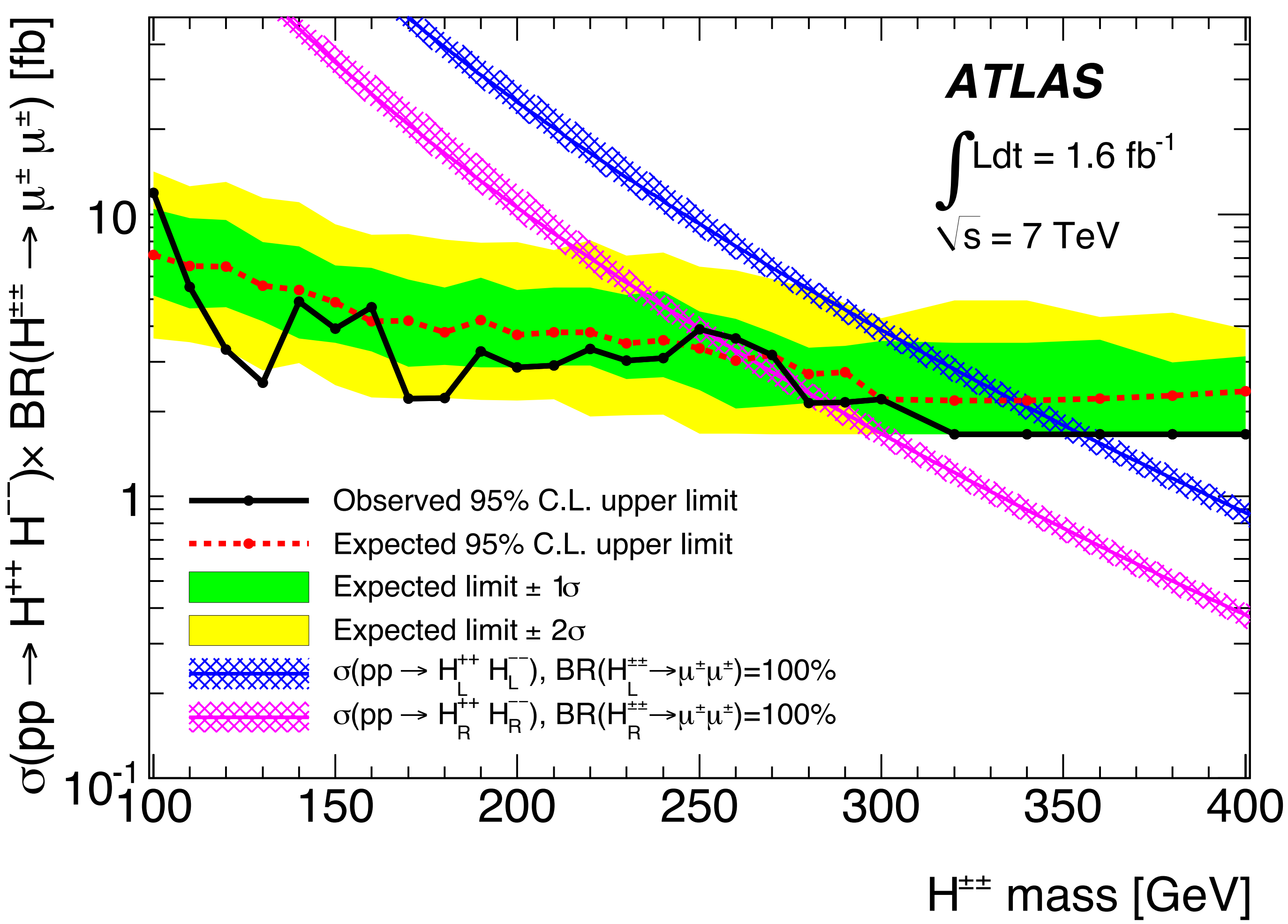
relative to number of $H^{\pm\pm}$ decaying to $\mu\mu$

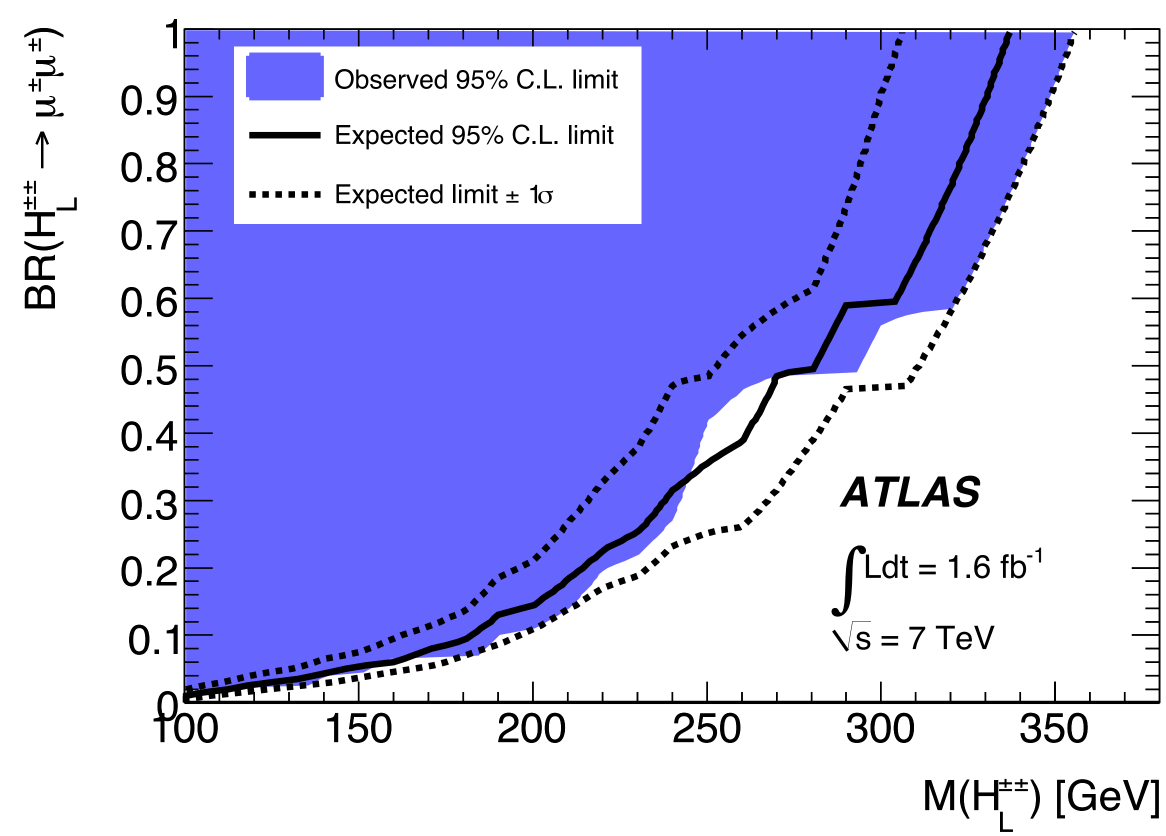
- Total acceptance uncertainty ~3.6%
  - PDF uncertainty
  - Interpolation between mass values
  - MC statistics

Results: doubly charged Higgs bosons

- Assuming BR ($H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$) = 100 %
  - $m(H^{\pm\pm}_{L}) > 355$ GeV
  - $m(H^{\pm\pm}_{R}) > 251$ GeV
- Assuming BR ($H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$) = 33 %
  - $m(H^{\pm\pm}_{L}) > 244$ GeV
  - $m(H^{\pm\pm}_{R}) > 209$ GeV

Different couplings of $H^{\pm\pm}_{R}$ / $H^{\pm\pm}_{L}$ to Z gives right-handed production cross section factor 2 lower



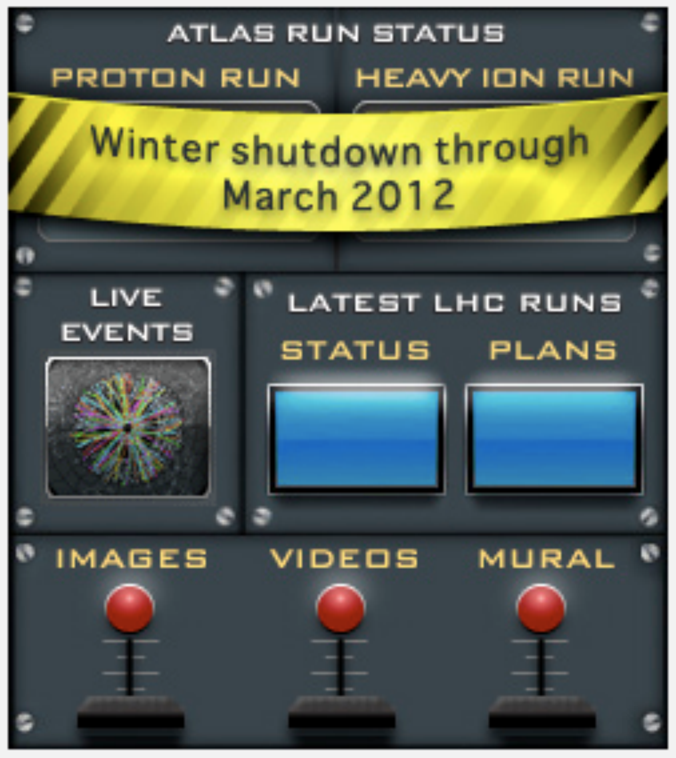


Outlook

- Like-sign muons important probe of beyond the SM physics
  - Inclusive analysis sensitive to a wide range of new physics models
  - Dedicated searches can provide further sensitivity

- Observe no significant excess in data over SM predictions
  - Set constraints on fiducial cross-section of $\mu^{\pm}\mu^{\pm}$ production & mass of $H^{\pm\pm}$ bosons
  - Analysis based on 1.6 fb^{-1} of data but ~5 fb^{-1} on disk & more to come!
    - *Ongoing work of updating to include full 2011 dataset & further fine-tune event selection cuts*

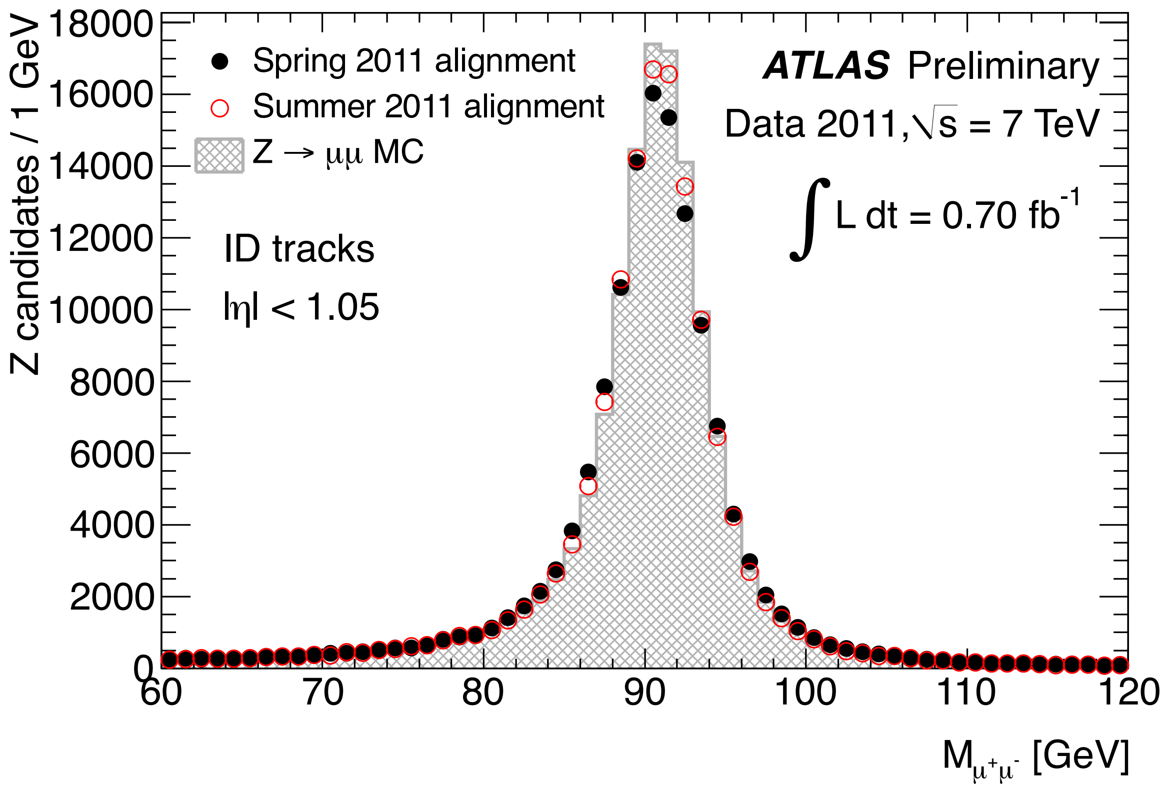
- It's an excellent time to do high-energy physics - next years have all the odds to provide great excitement!



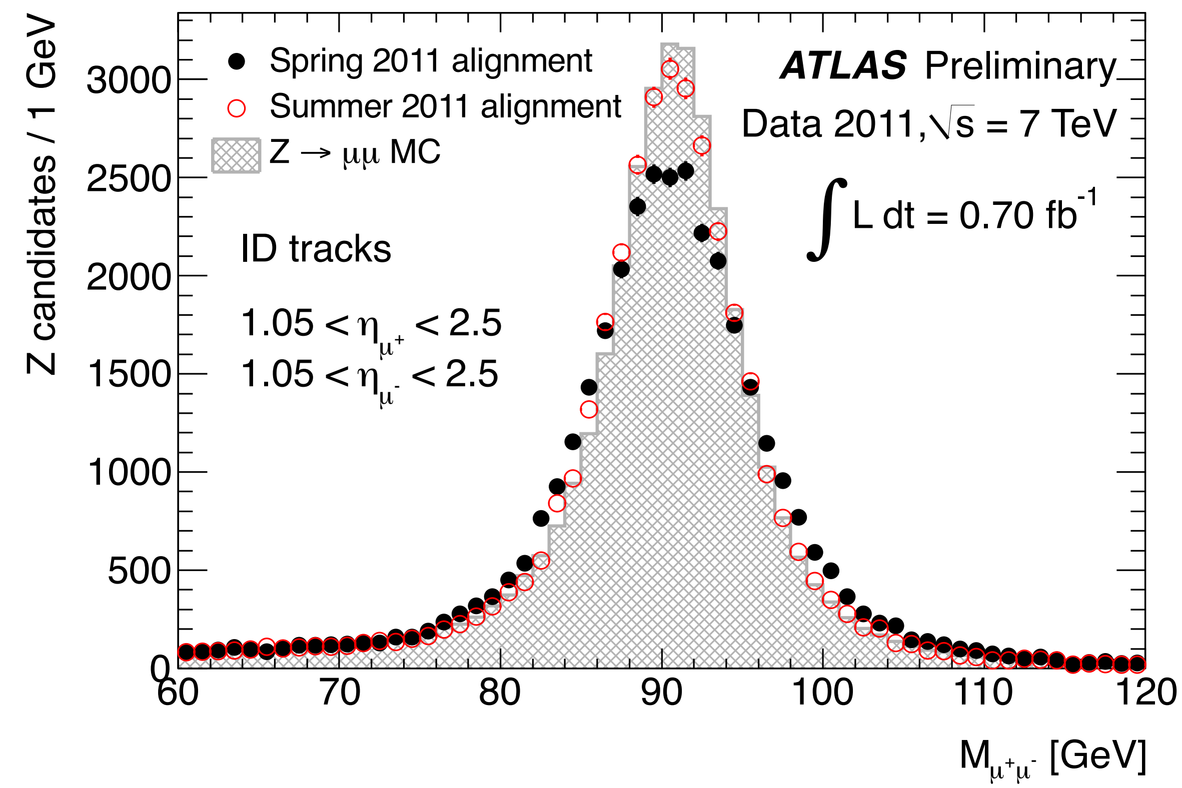
BACKUP

Inner detector alignment

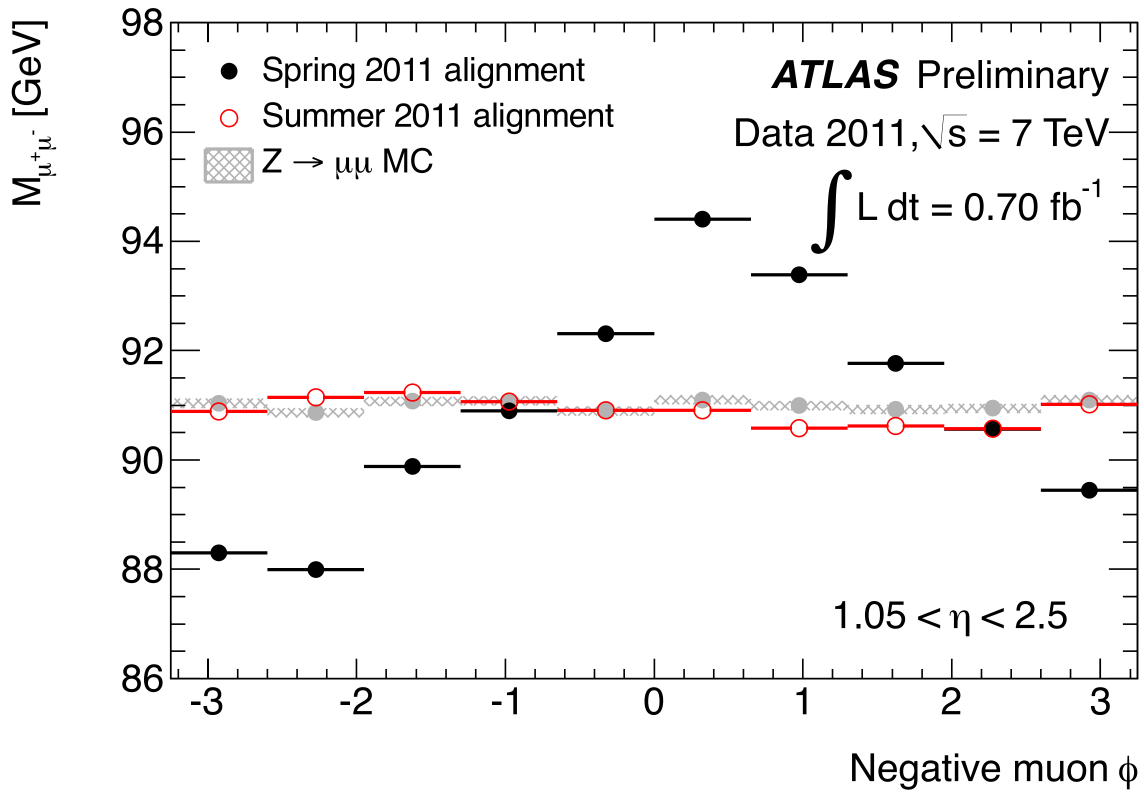
Barrel



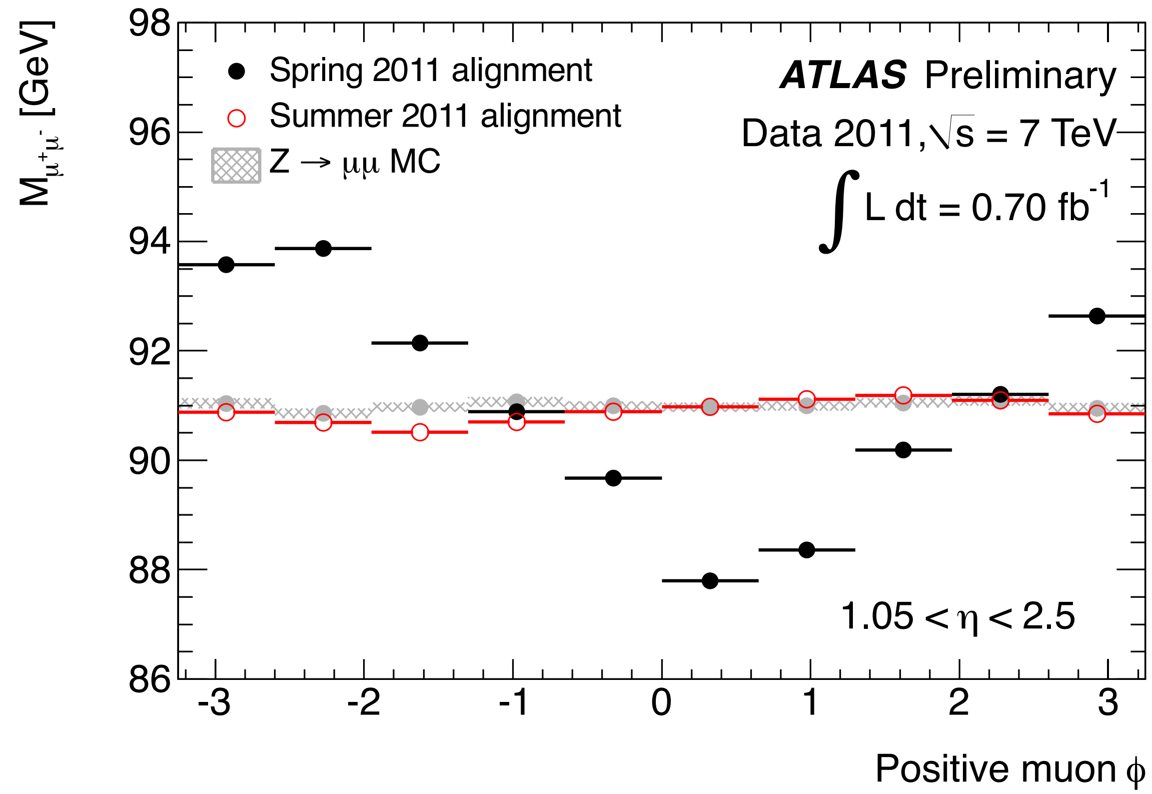
Endcap A



Negative muons in endcap A

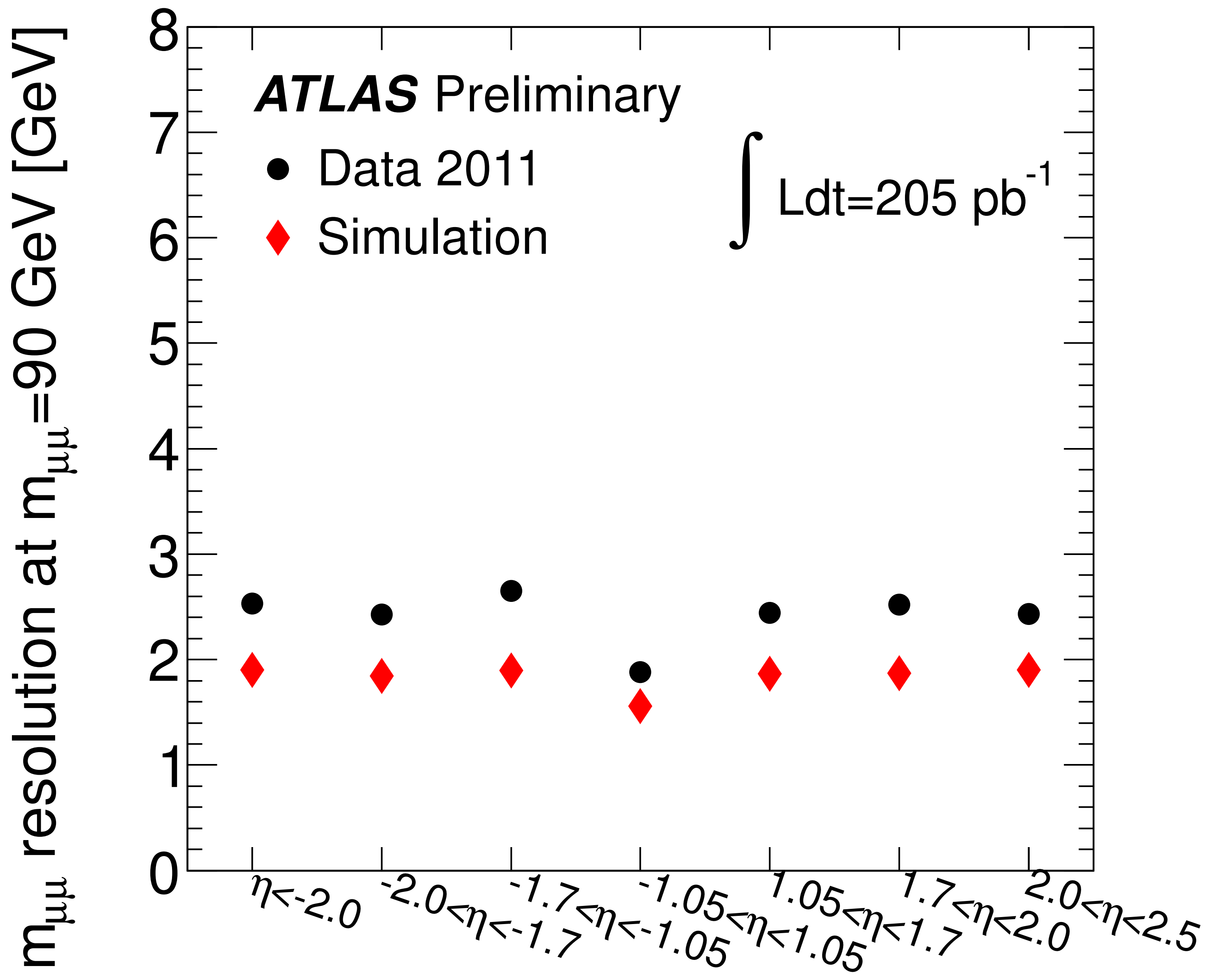


Positive muons in endcap A



Combined muon resolutions

- Dimuon mass resolution of combined muons in different pseudorapidity regions
  - Experimental resolution compared to MC predictions using Pythia → Z μμ events

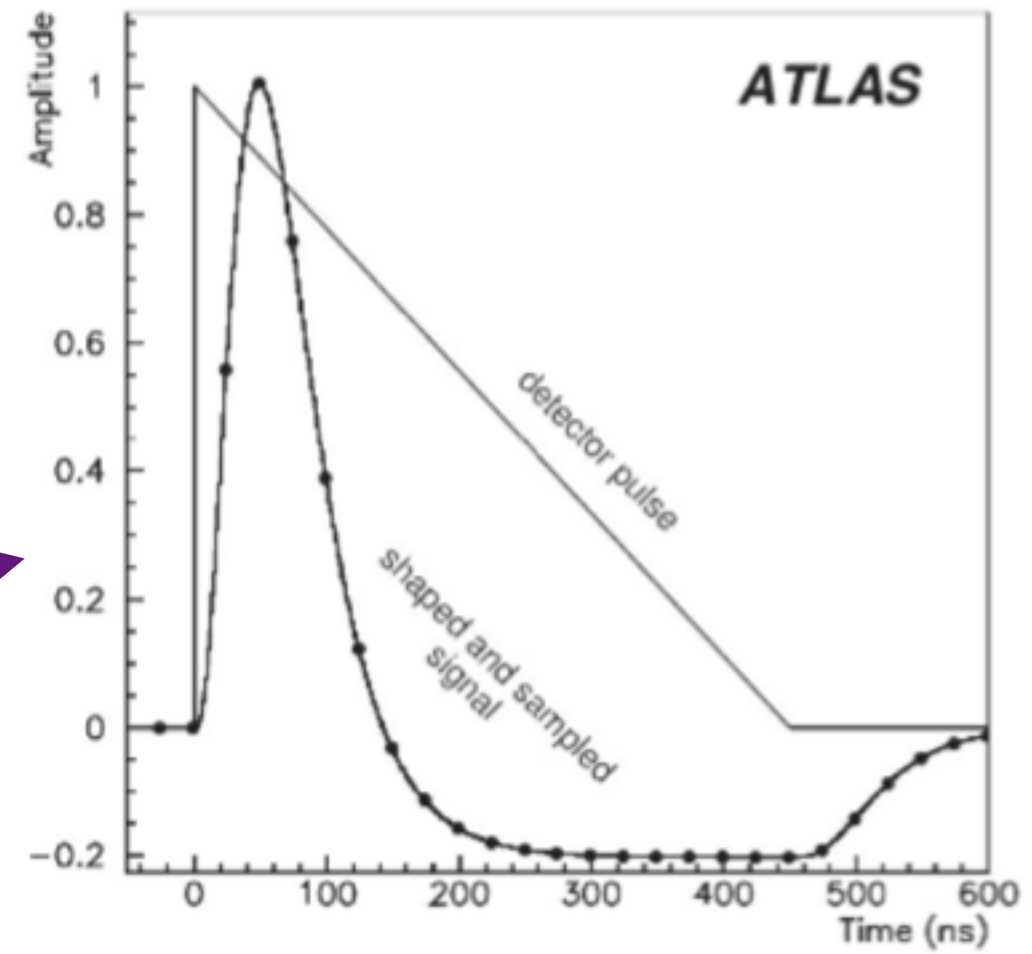


More on isolation & pileup

- Two types of pileup affecting isolation
  - ***In-time pileup*** → Overlapping interactions in the same bunch crossing
    - *Probe as isolation vs # primary vertices*
  - ***Out-of-time pileup*** → Contributions from activity in previous bunch crossings (related to limited detector readout)
    - *Effect dependent on bunch train position*
    - *Probe as isolation vs # preceding filled bunches (or BCID)*

LAr signal shape

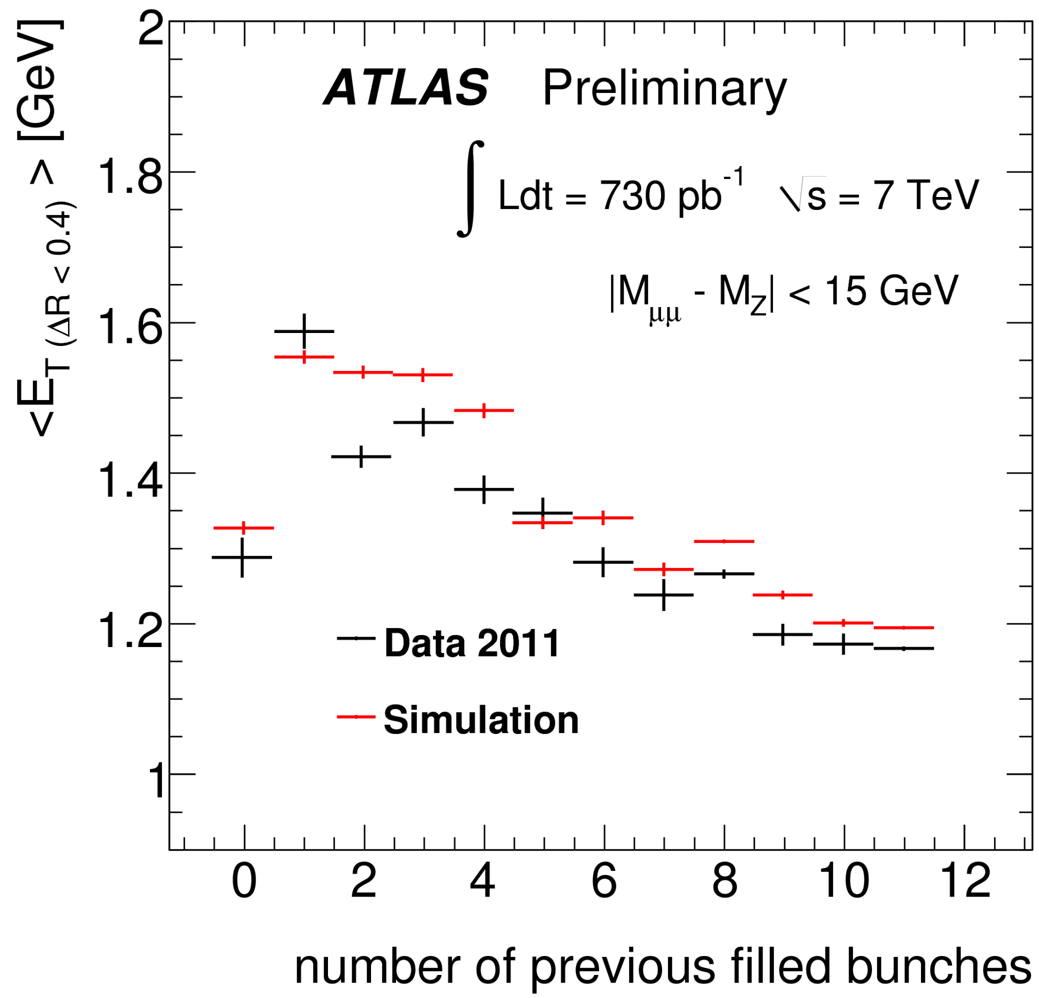
On average, the effects of pileup in LAr should approximately cancel (energy deposits from pileup contributions integrating out)



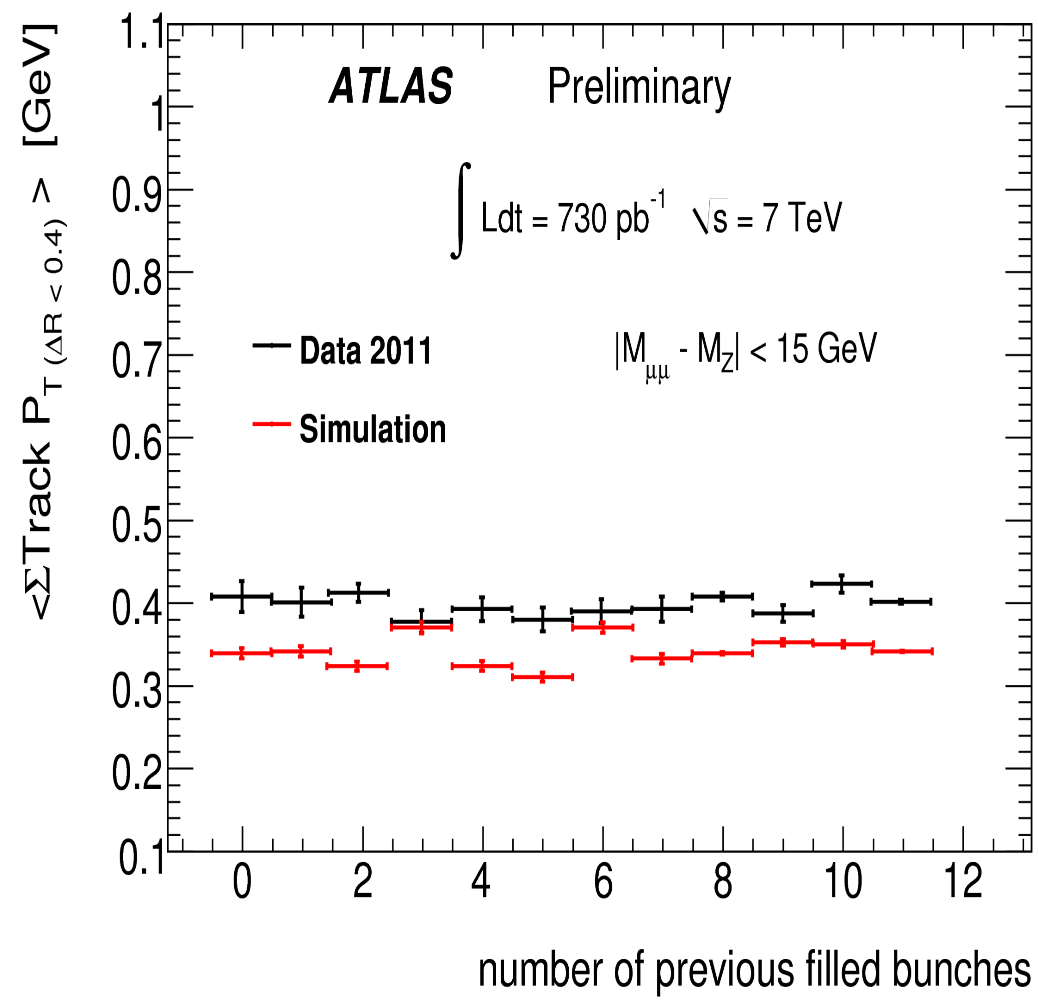
Out-of-time pileup

- Out of time pileup & muon isolation
  - **Right** Track isolation independent of BCID
  - **Left** Calorimetric isolation shows clear dependence on BCID
    - *Effect of calorimeter pulse shaping*

Calorimetric isolation



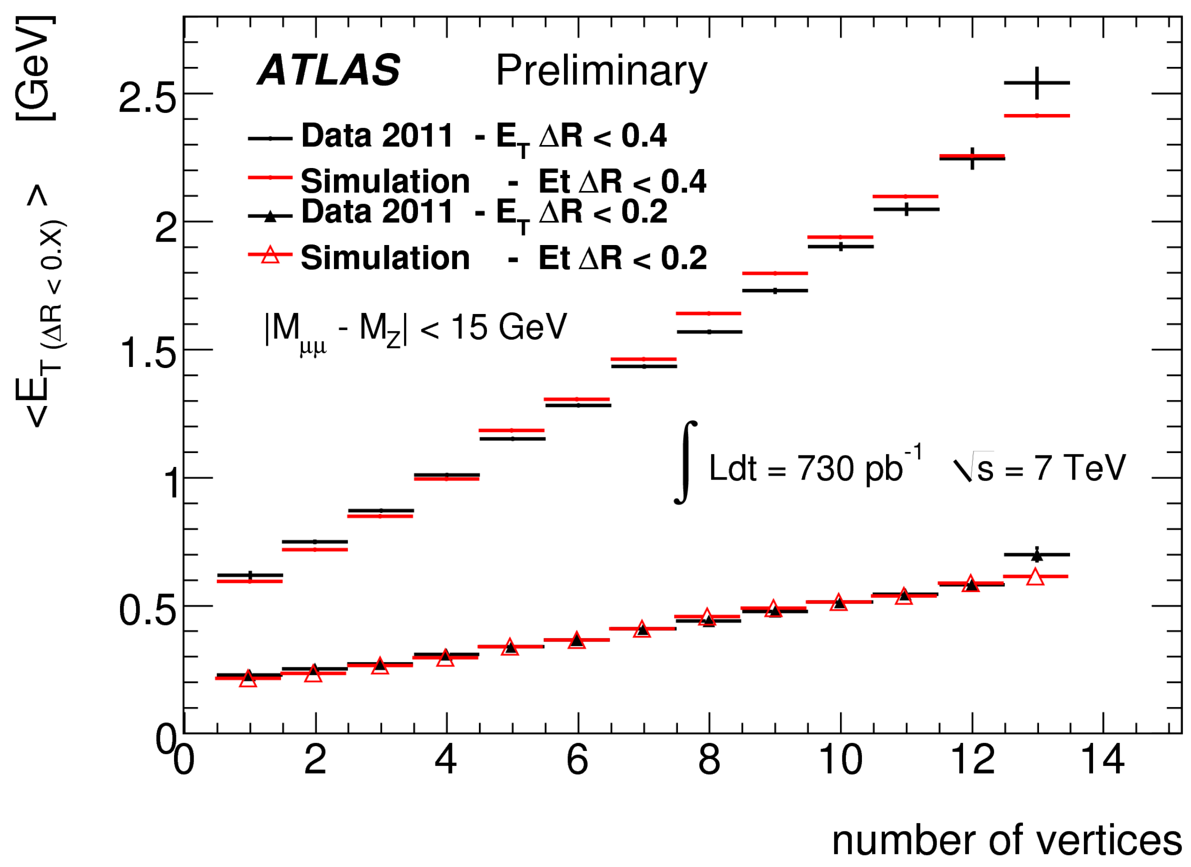
Track isolation



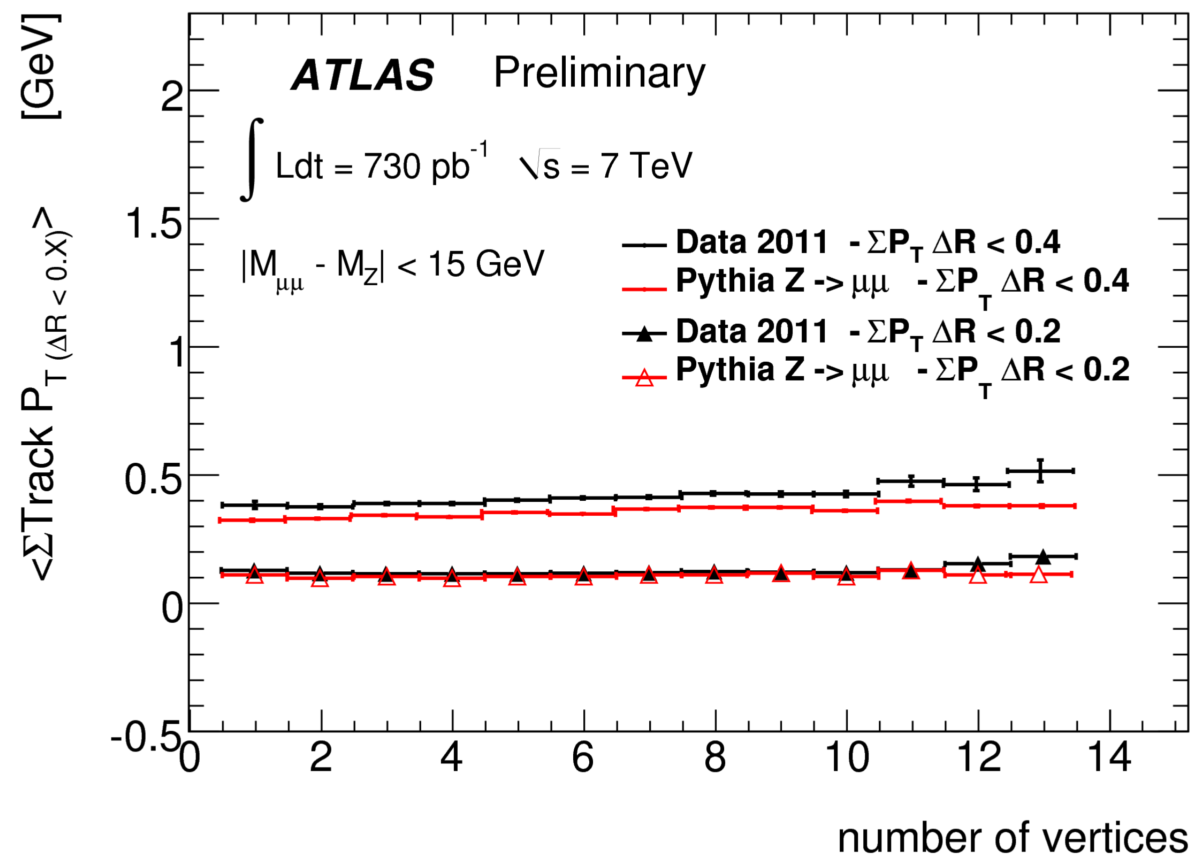
In-time pileup

- Study mean isolation vs # vertices
- Pileup dependence on isolation described in MC
  - Stronger pileup dependence with larger cone size
- Track isolation nearly independent on in-time pileup

Calorimetric isolation

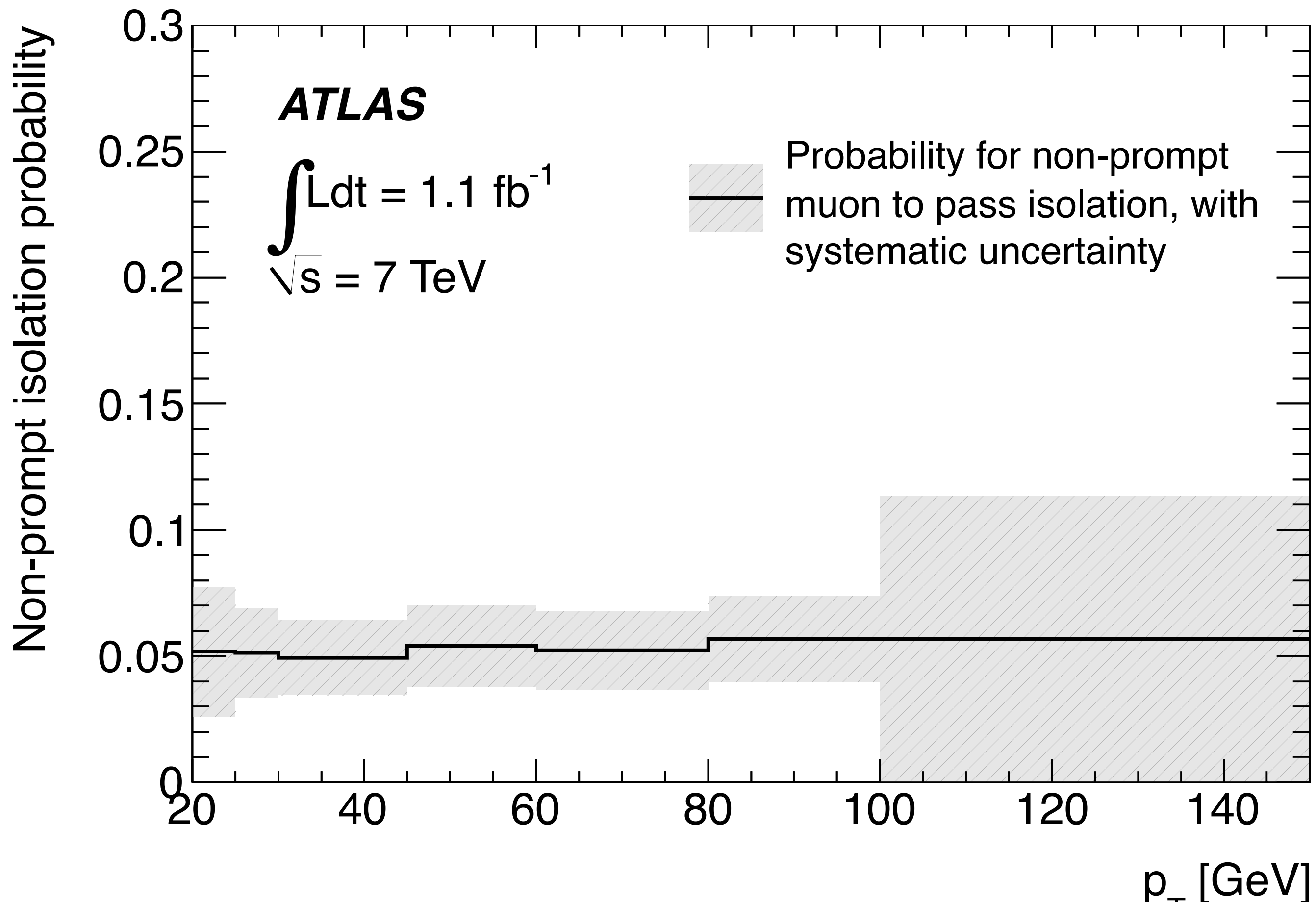


Track isolation



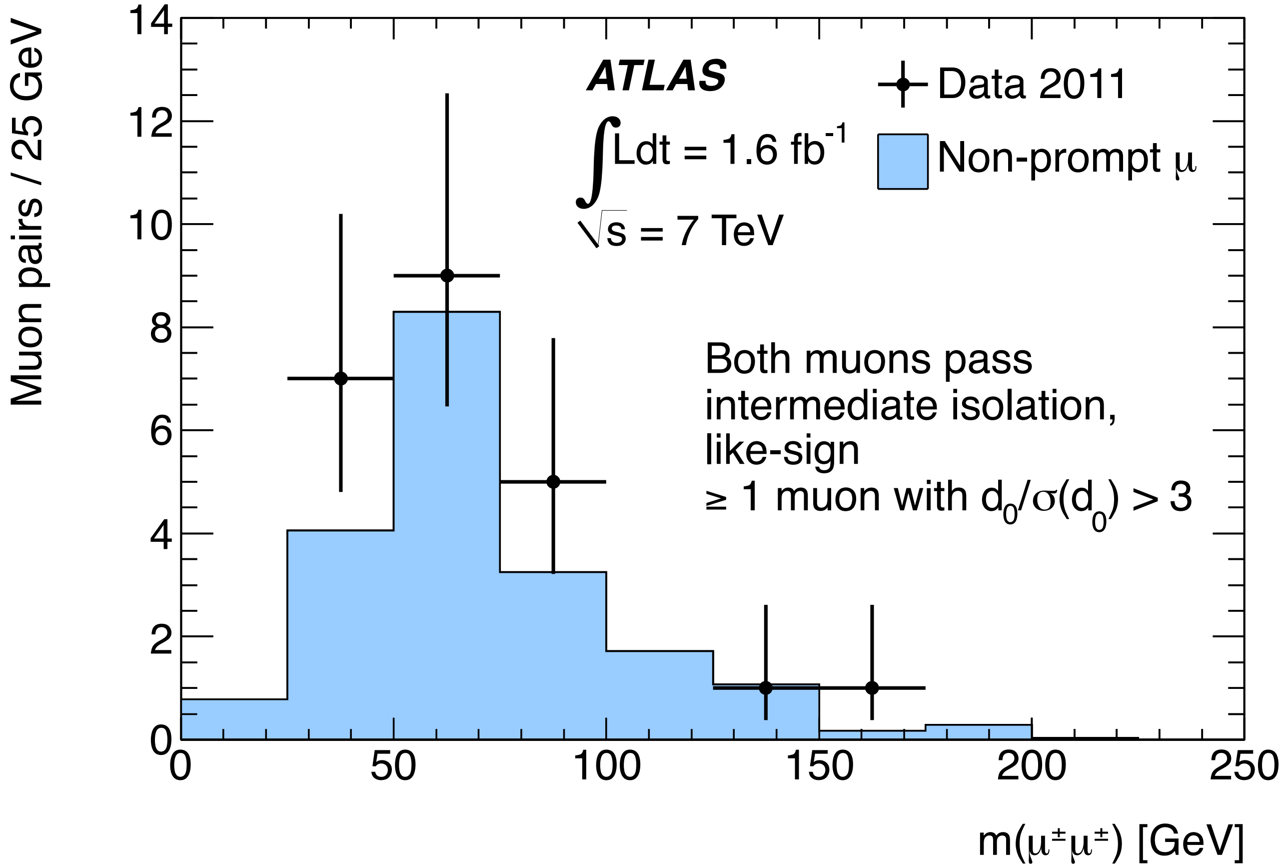
Systematics for non-prompt background

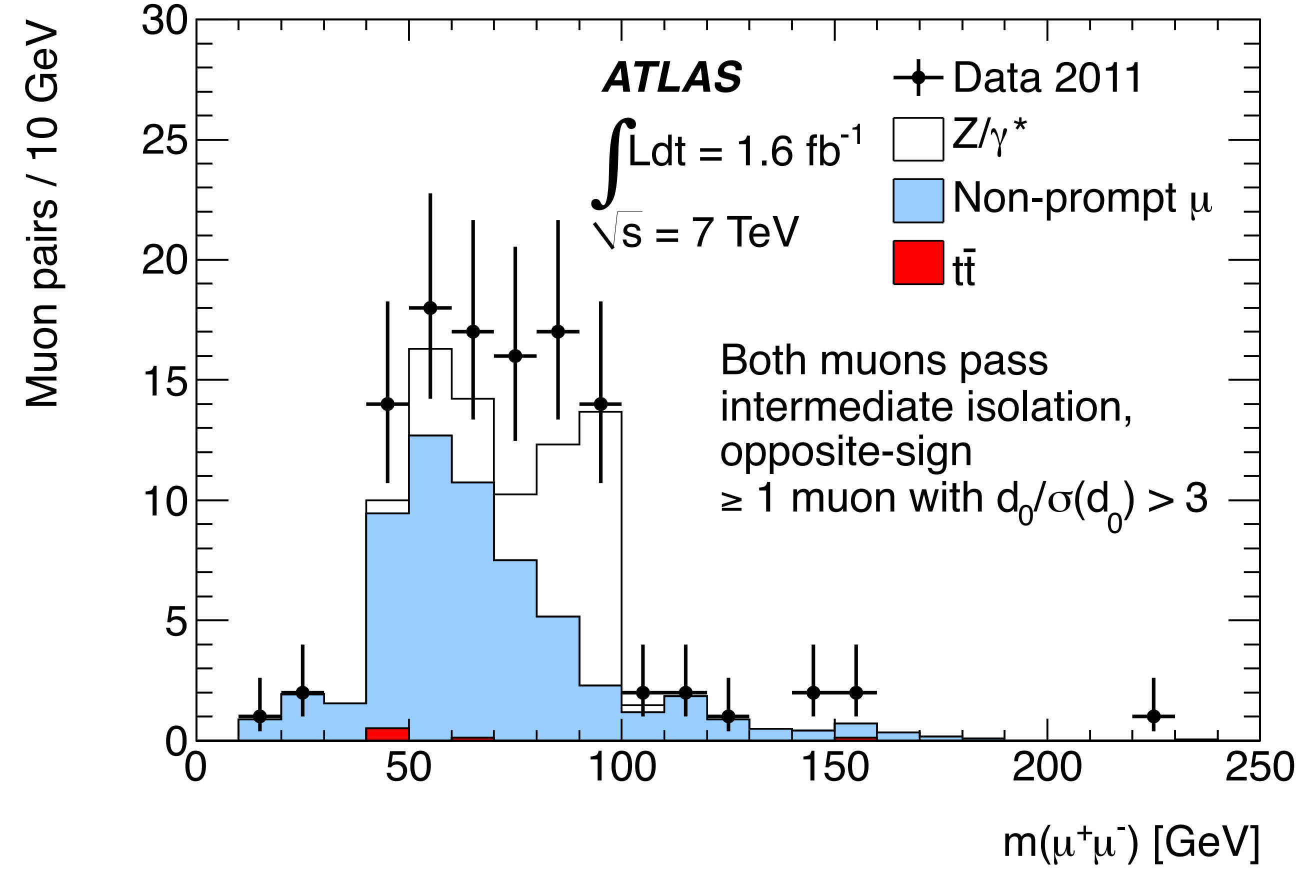
- *Central value*
  - Derived using muons with $d0_{significance} > 5$
  - Flat above 100 GeV at ~6%
- *Systematic uncertainty*
  - Estimate from observed differences in measured isolation probability
    - *High $d0_{significance}$ sample vs low m_T sample → **at least 30%** uncertainty at all p_T*
      - Larger uncertainty at low p_T (measurement differences) & high p_T (low statistics)
    - *At high p_T > 100 GeV, assign **100%** uncertainty*
  - Uncertainty on isolation rate propagated through to obtain estimated effect on non-prompt yield



Additional control regions

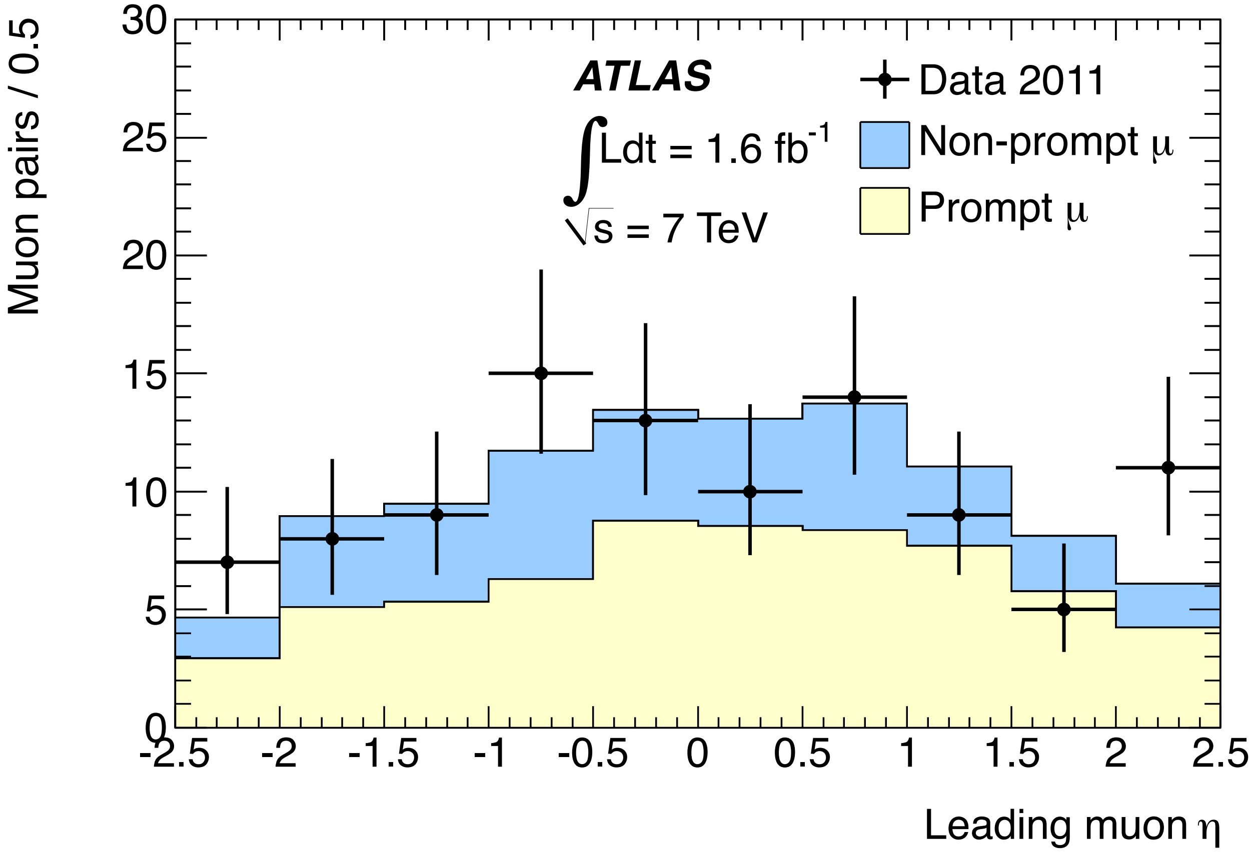
- Additional control regions defined by requiring both muons to pass an intermediate isolation requirement & at least one muon fail the $d0_{significance}$ cut
  - Opposite-sign pairs vs like-sign pairs
- Good agreement of data & prediction within the uncertainties

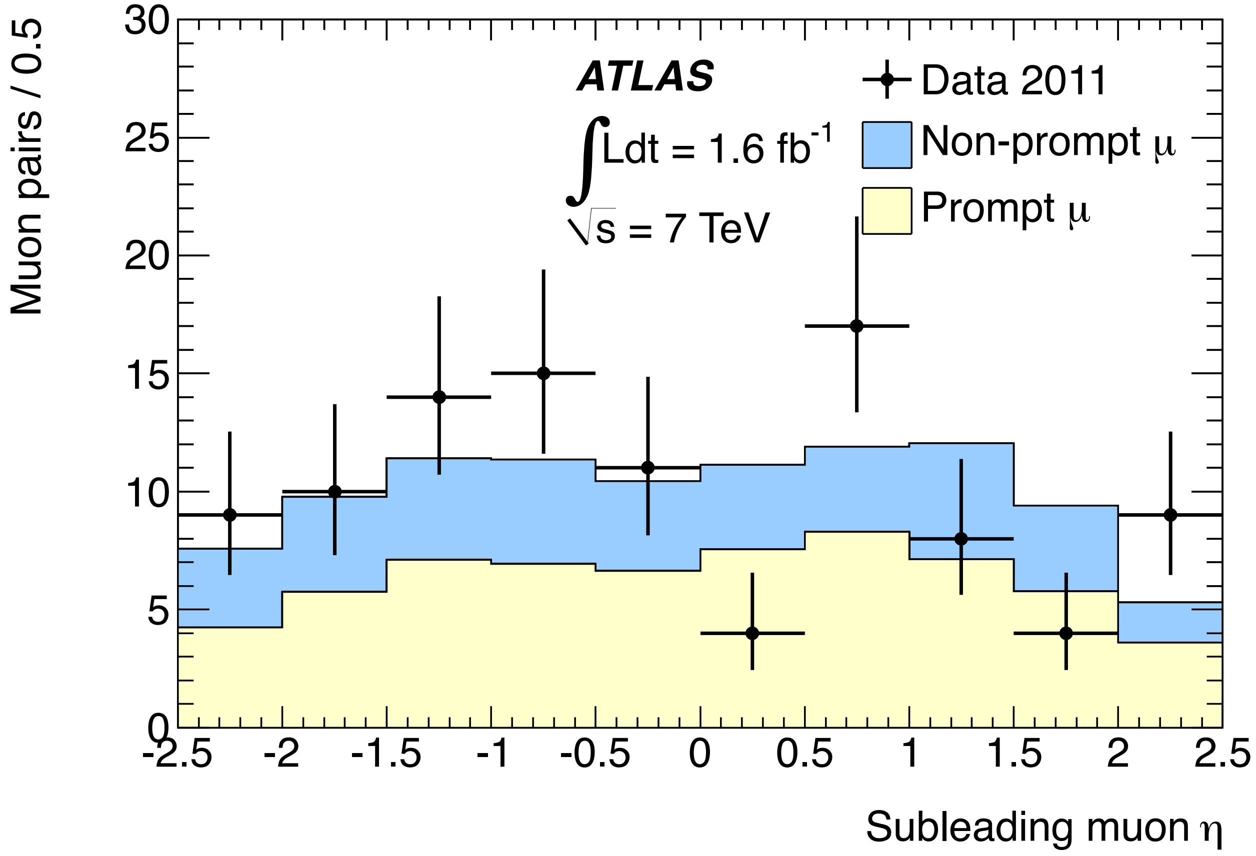




Results: muon kinematics

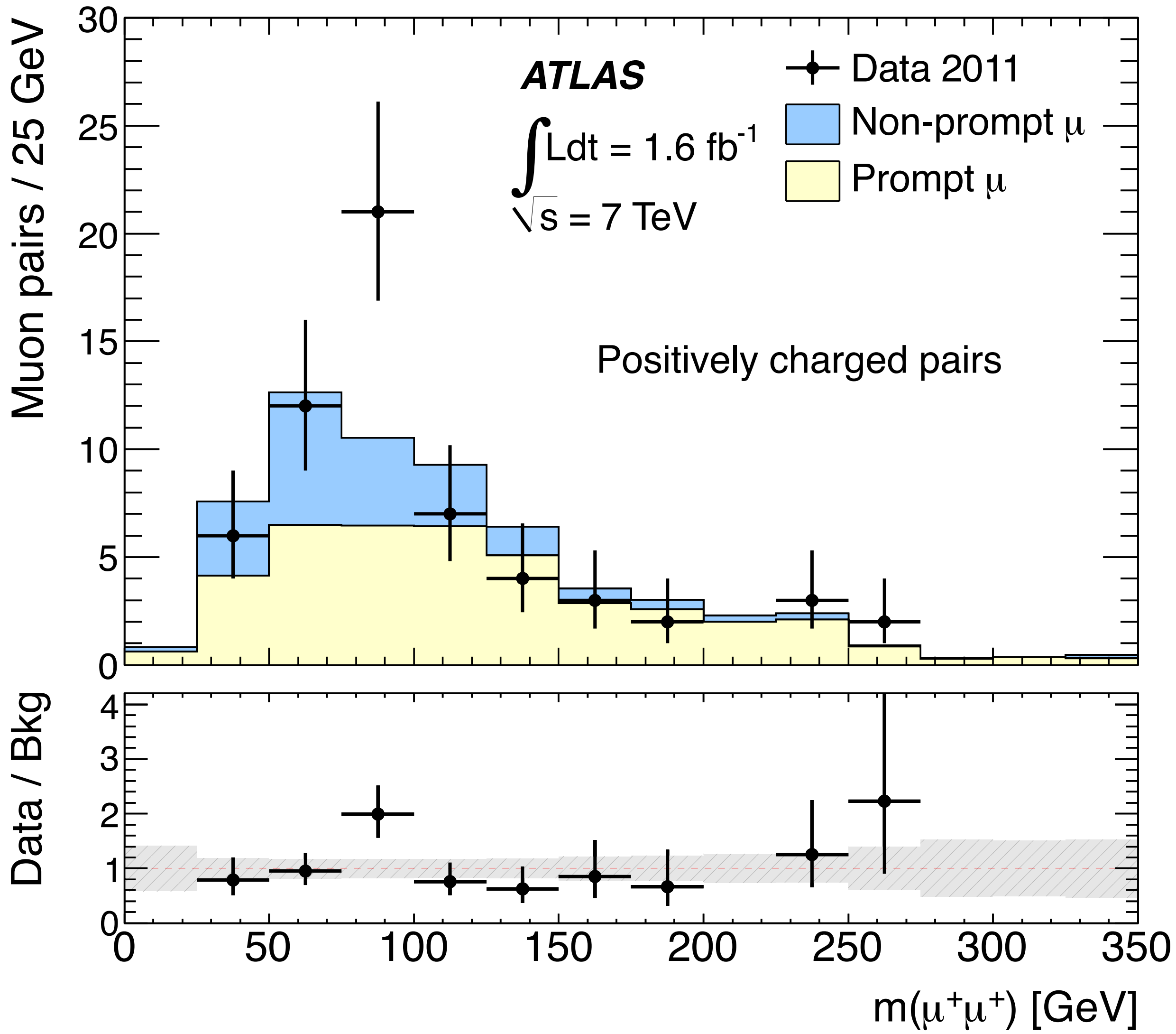
- Distribution of η for leading / subleading p_T muons

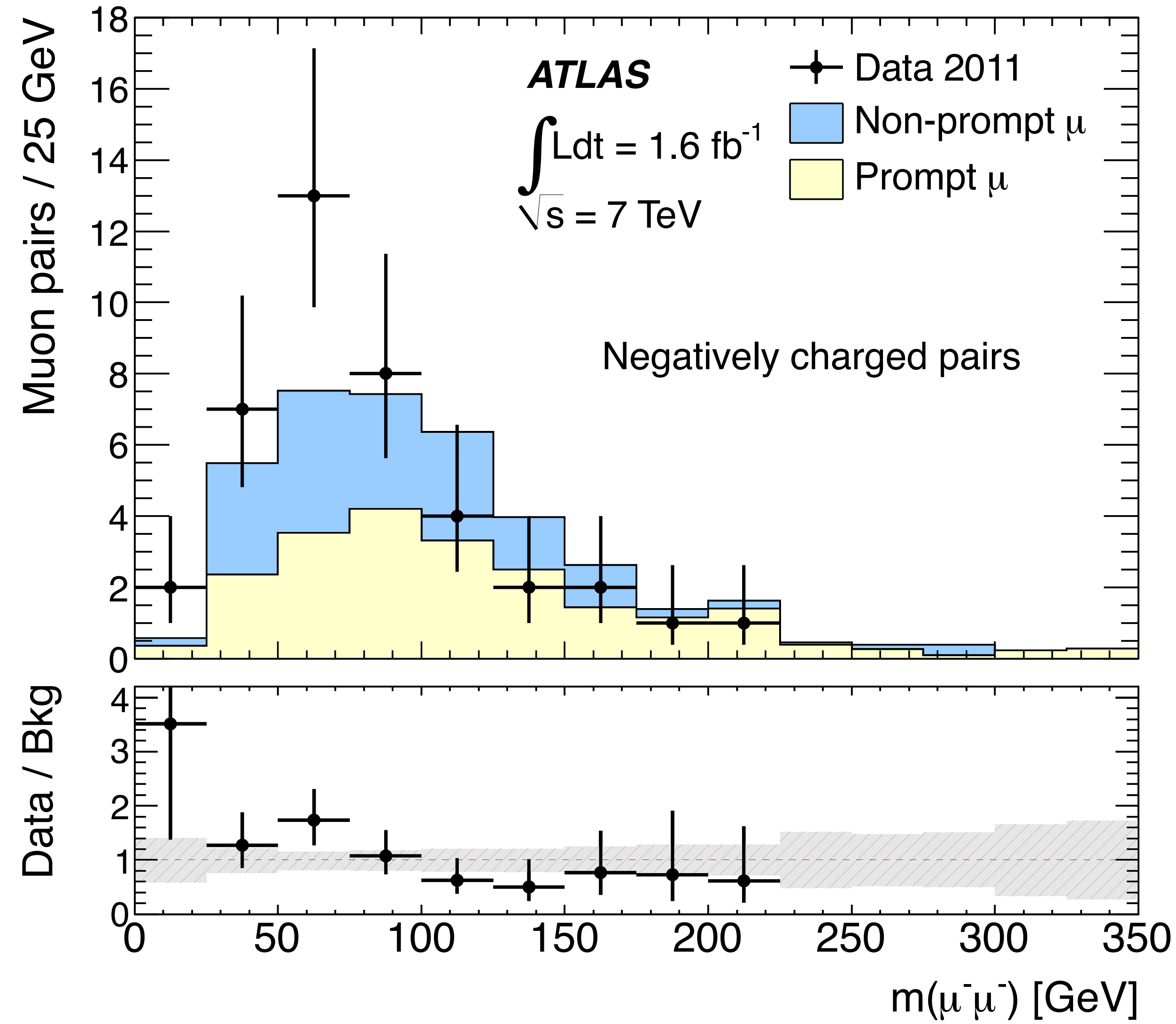




Results: invariant mass by charge

- Dimuon invariant mass spectrum, separated by positively/negatively charged pairs





Limits: doubly charged Higgs

- Limits on doubly charged Higgs production as function of branching ration to two muons