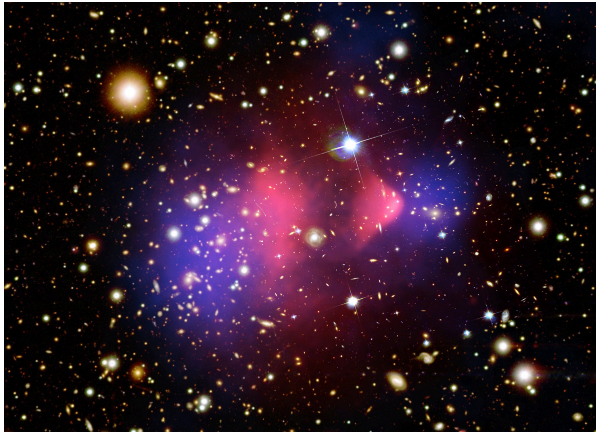
Searches for new phenomena in leptonic final states using the ATLAS detector

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

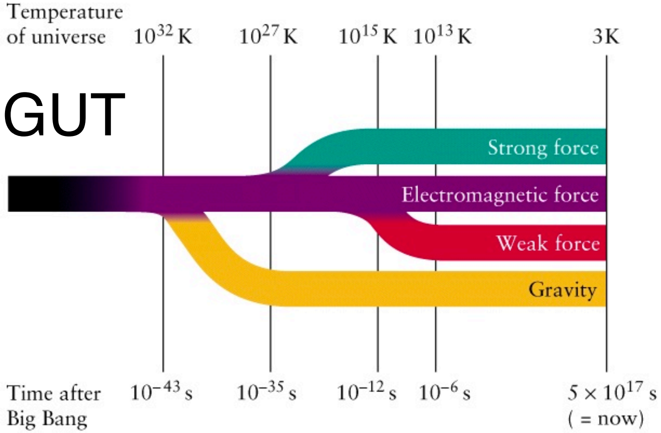
Sébastien Rettie, on behalf of the ATLAS Collaboration

13th Conference on the Intersections of Particle and Nuclear Physics
Palm Springs, CA, 31 May 2018

Physics Beyond The Standard Model

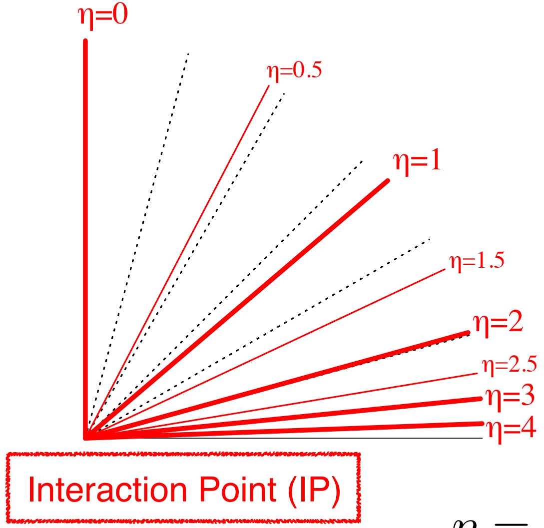


1. **What is Dark Matter?**
   LHC could be able to produce it.
2. **Grand Unified Theory (GUT)?**
   Unify all forces to a super force.
3. **Where did the anti-matter go?**
   We only know part of the story.
4. **Are there extra dimensions of space?**
   Could explain why gravity is so weak.
5. **Explore the unknown**
   Surprises can happen at any time.

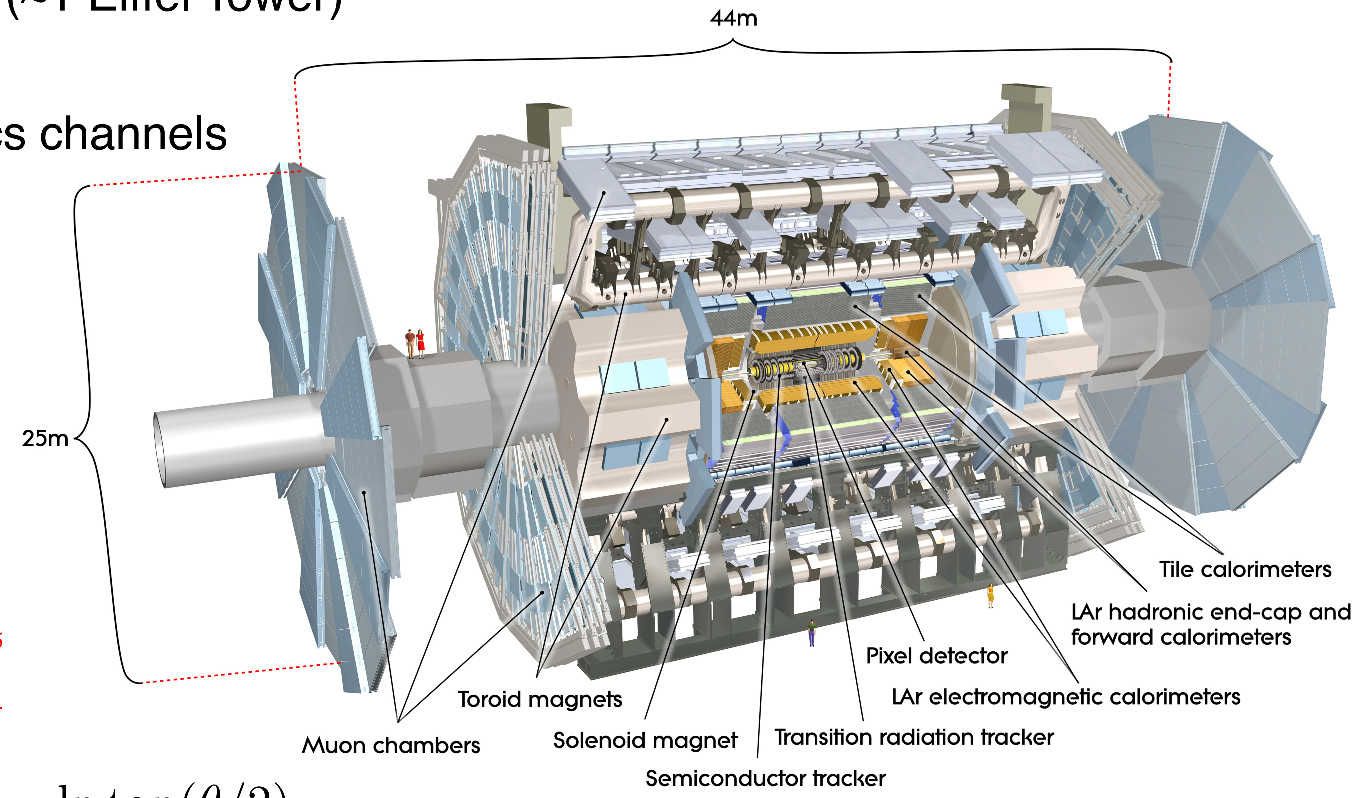


A Toroidal LHC ApparatuS

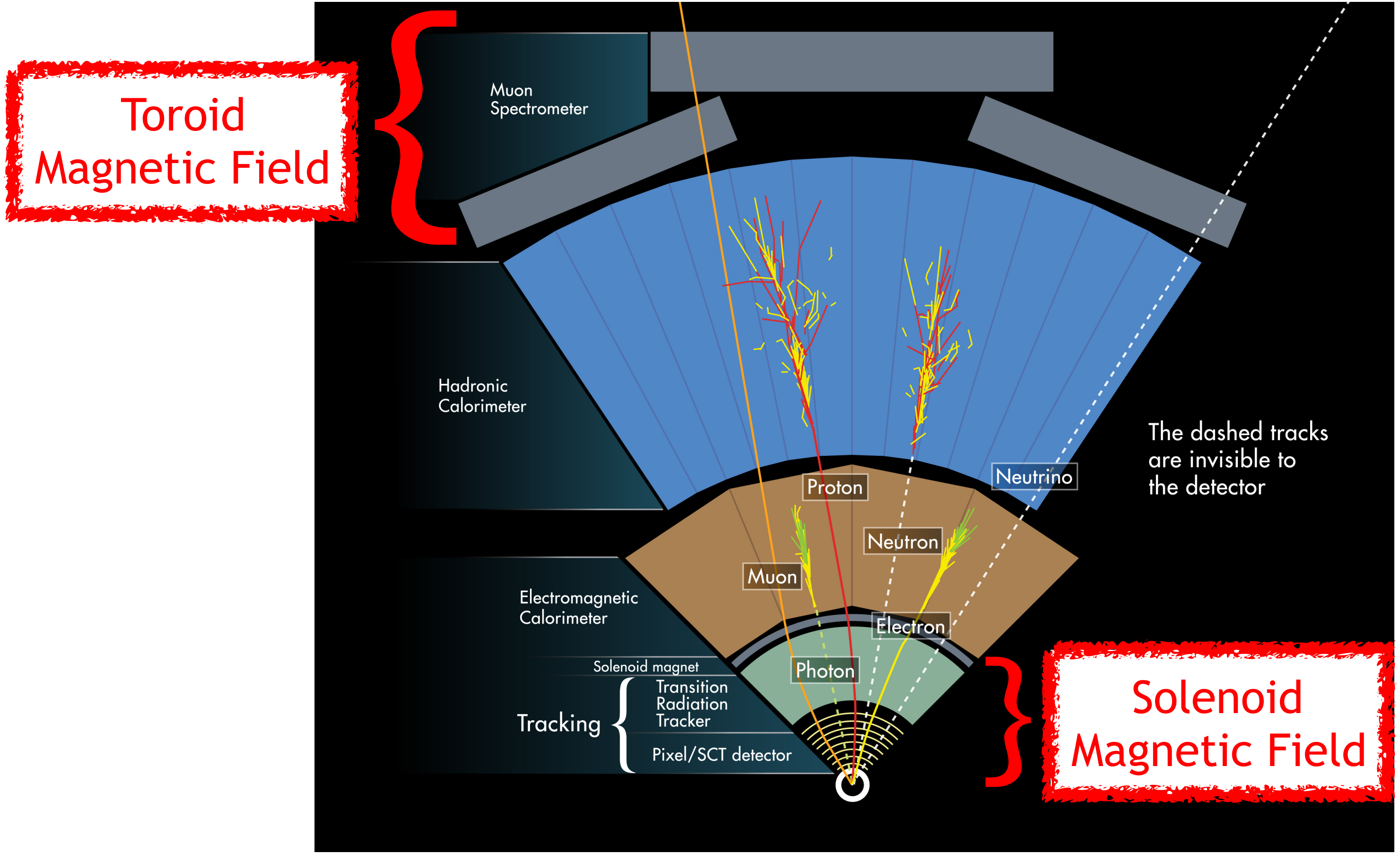
- Weighs 7000 tonnes (~1 Eiffel Tower)
- 3000 km of cables
- 100 Million electronics channels readout every 25ns.



$$\eta = -\ln\tan(\theta/2)$$

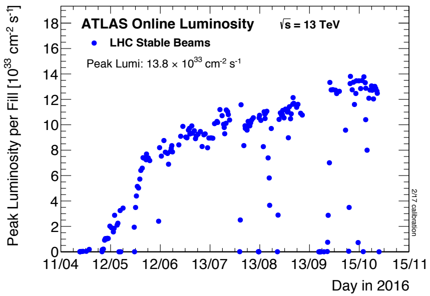


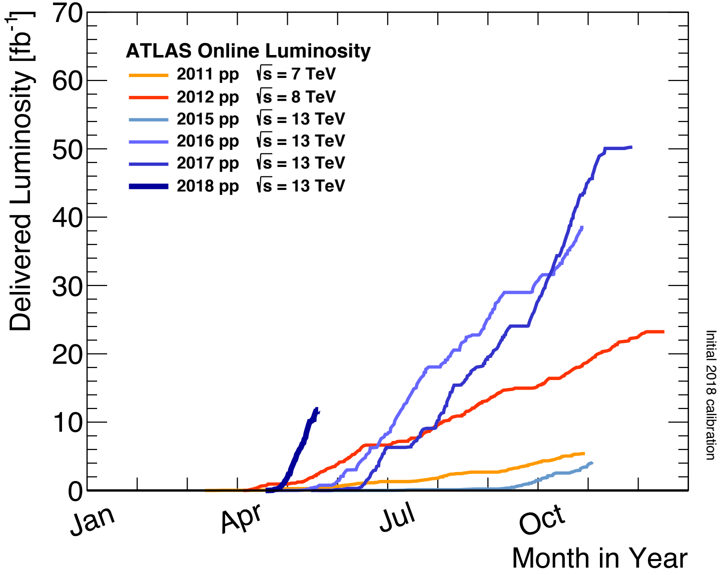
Particle Detection In ATLAS

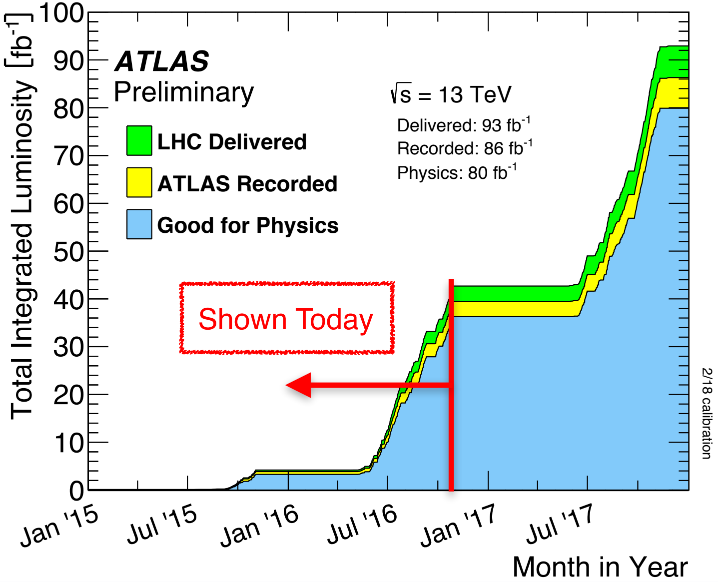


The LHC and ATLAS

- The LHC is **performing very well** overall
- Achieved design instantaneous luminosity in 2016
- Over **100 fb^{-1}** of pp data recorded at $\sqrt{s}$ = 13 TeV







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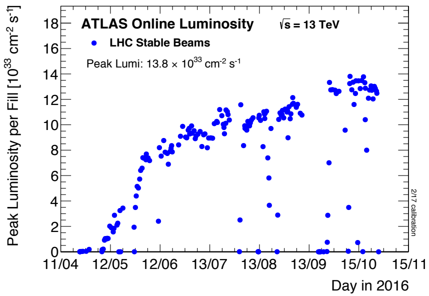
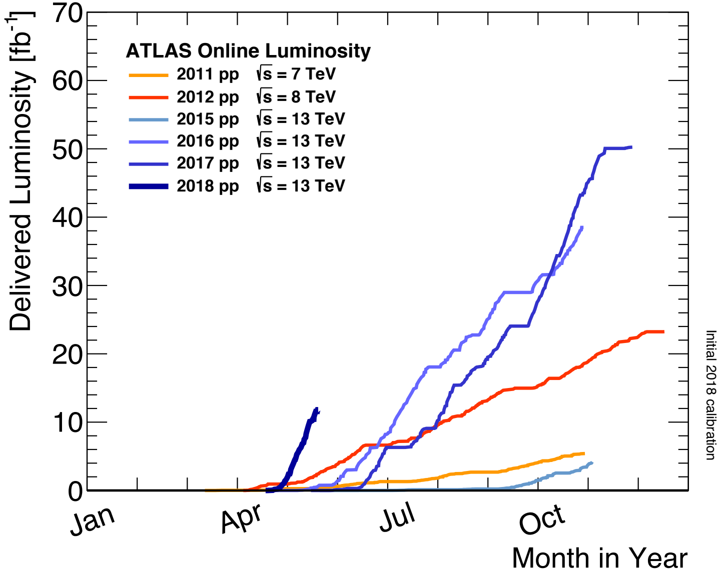
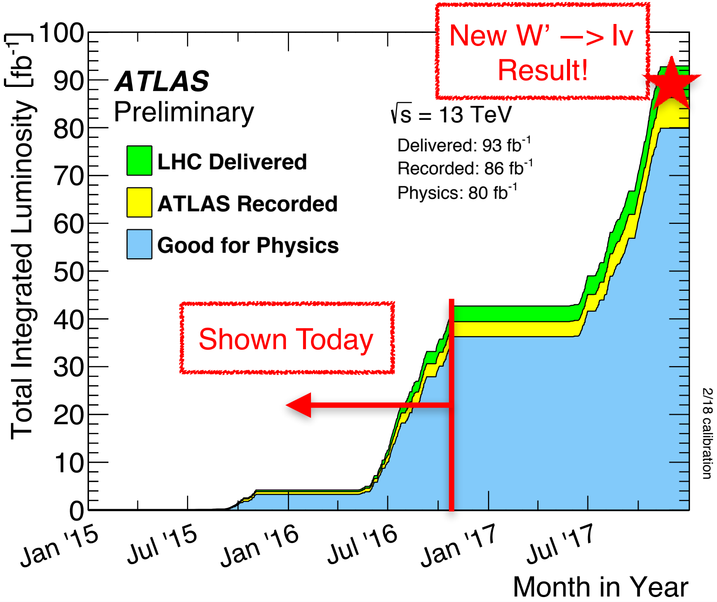
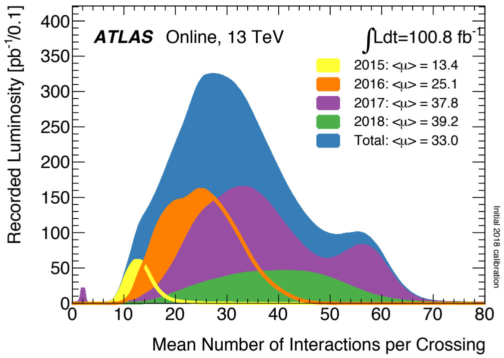


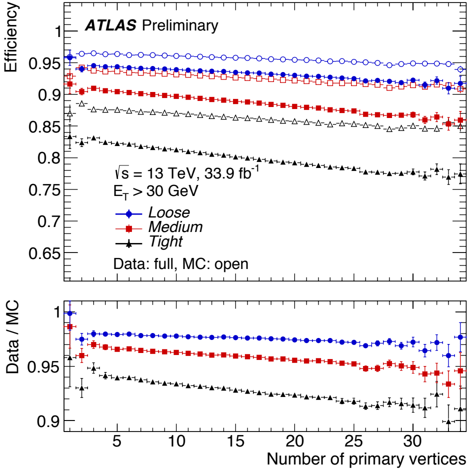


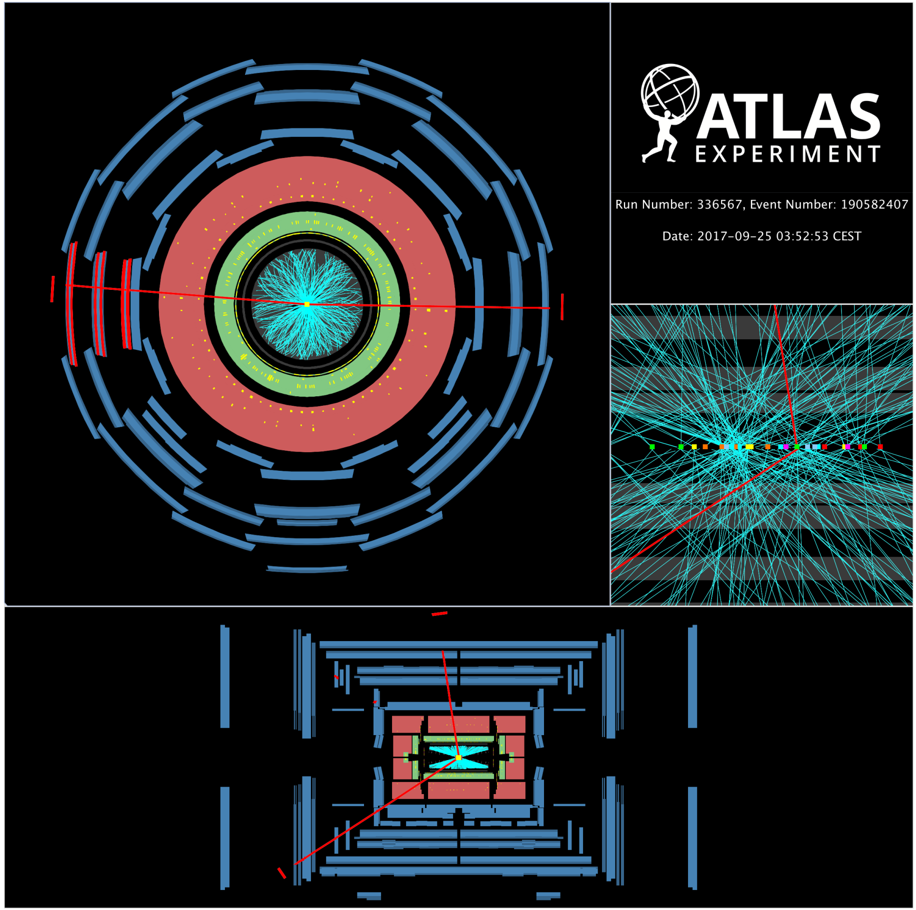


Detector Performance vs. Pileup

- **Harsh conditions**: interactions per bunch crossing (**pileup**) keeps increasing
- **Efficiency** of reconstructing leptons remains **high** even at large pileup
- Continuously working to **improve isolation definitions** to be pileup robust; paving the way for the HL-LHC where we expect <μ> ~ 200







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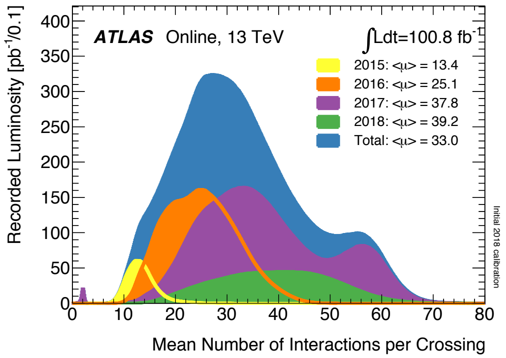

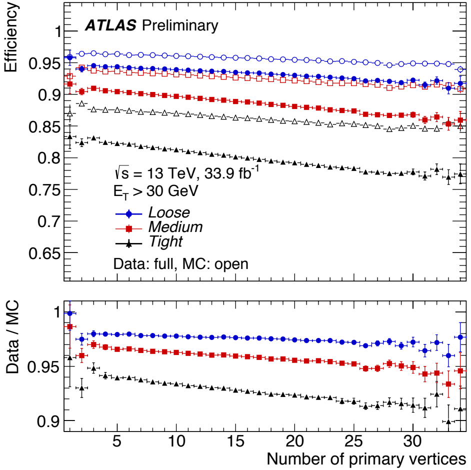

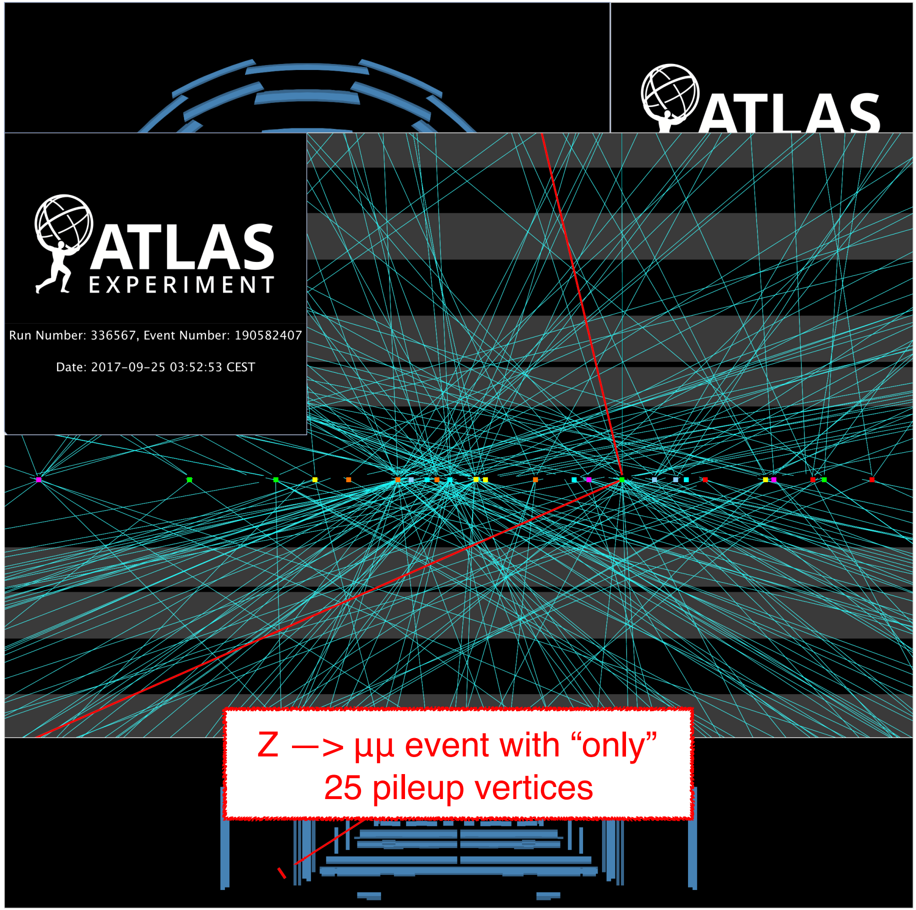

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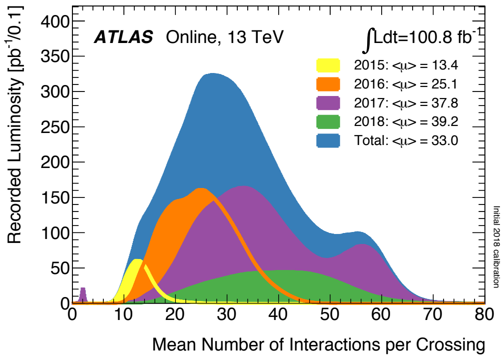
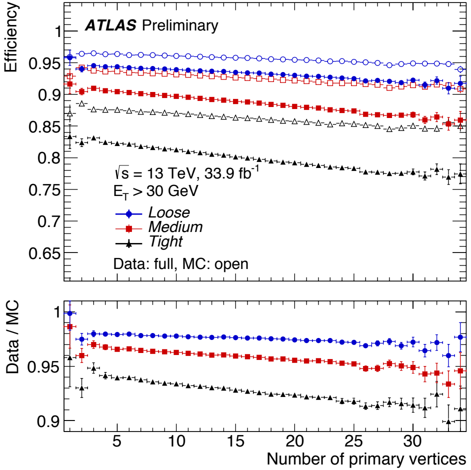
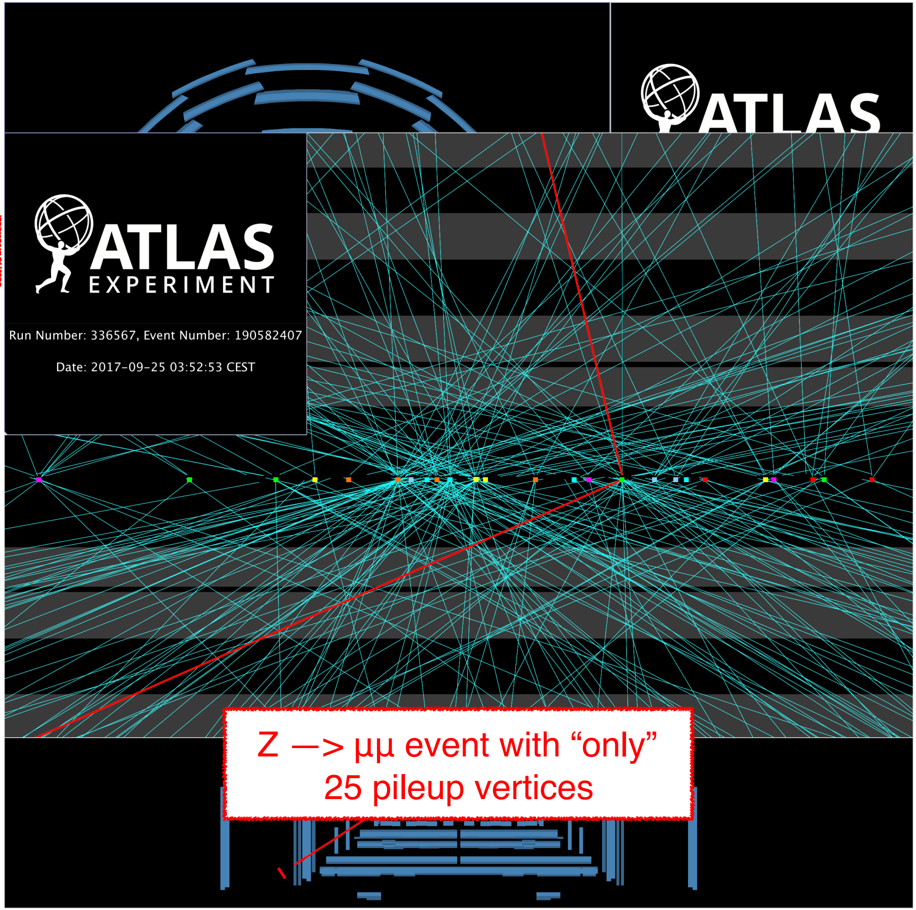
Electron ε_{ID}



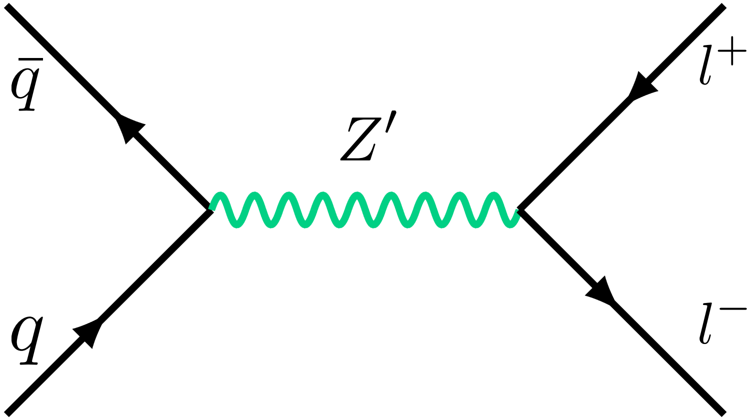


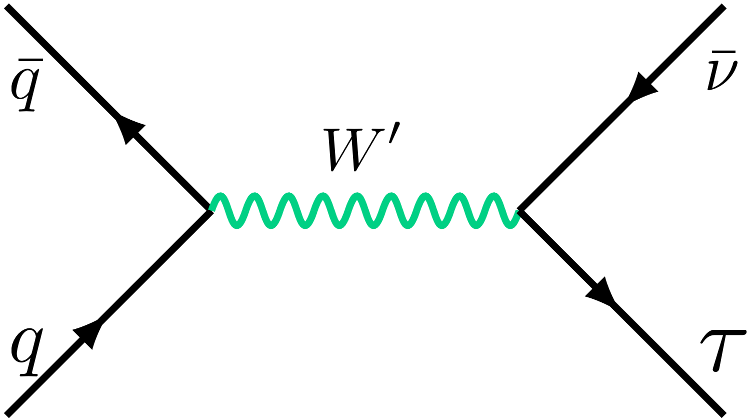


Z —> μμ event with "only" 25 pileup vertices

Leptonic Final State Searches

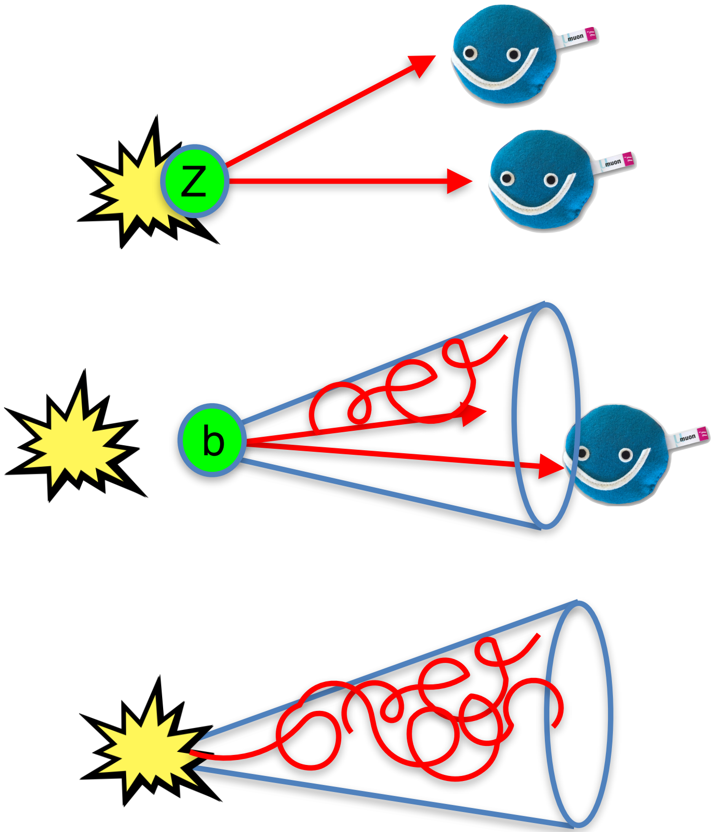
- Many BSM theories predict the existence of resonances with **leptonic final states**
  - Grand Unification Theory
  - Sequential Standard Model
  - Left-Right Symmetric Model
  - …
- Final states with leptons have **lower backgrounds** and can be **efficiently triggered**
- The ATLAS detector resolution allows a good mass measurement of BSM resonances decaying to leptons
- In the following, "l" refers to electrons or muons, not taus





Common Challenges - Fakes

- **Prompt:** Lepton directly produced in the hard interaction. Should be well isolated.
  - Z —> ll, W —> lv, t —> lvb
- **Non-Prompt:** Other leptons in the event. Not well isolated and/or displaced from the primary vertex.
  - Meson decay, photon conversion, etc.
- **Fake:** Non-lepton particle that gets misidentified as a lepton by the reconstruction software. Not well isolated.
  - Light jets (u, d, gluon initiated)



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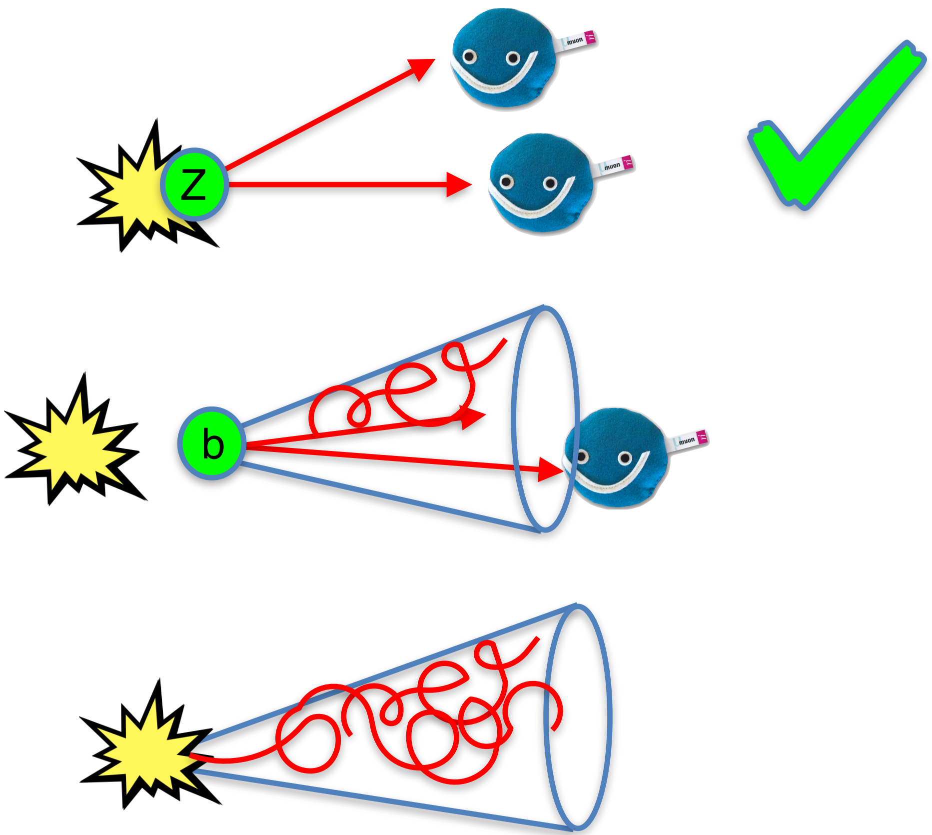

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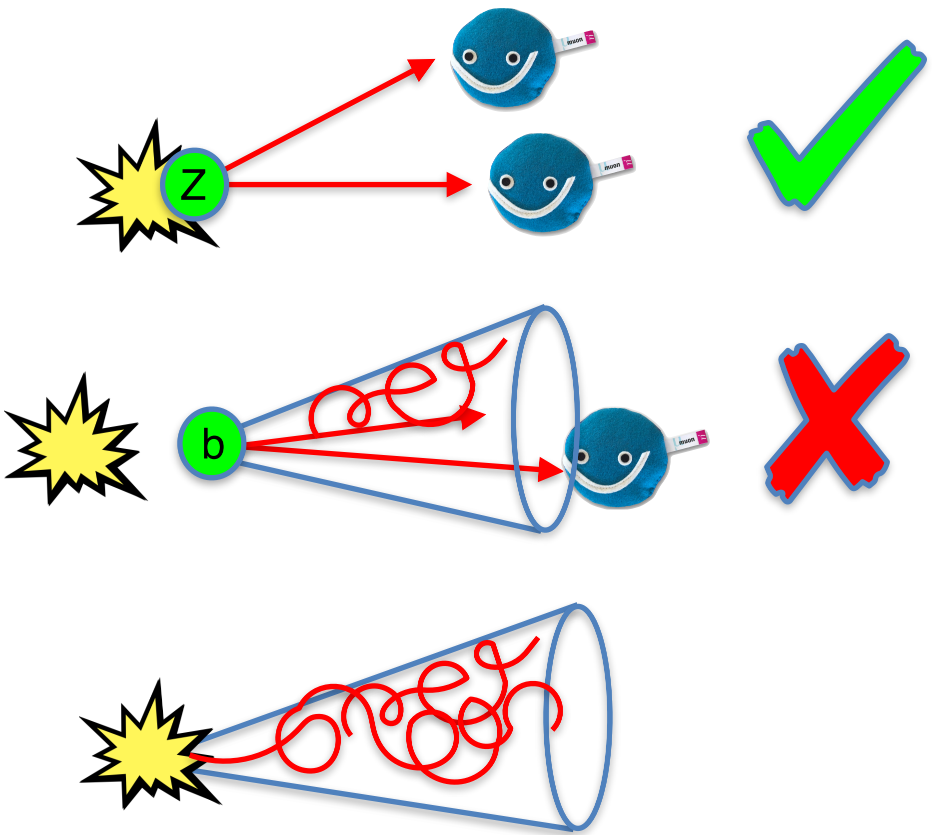

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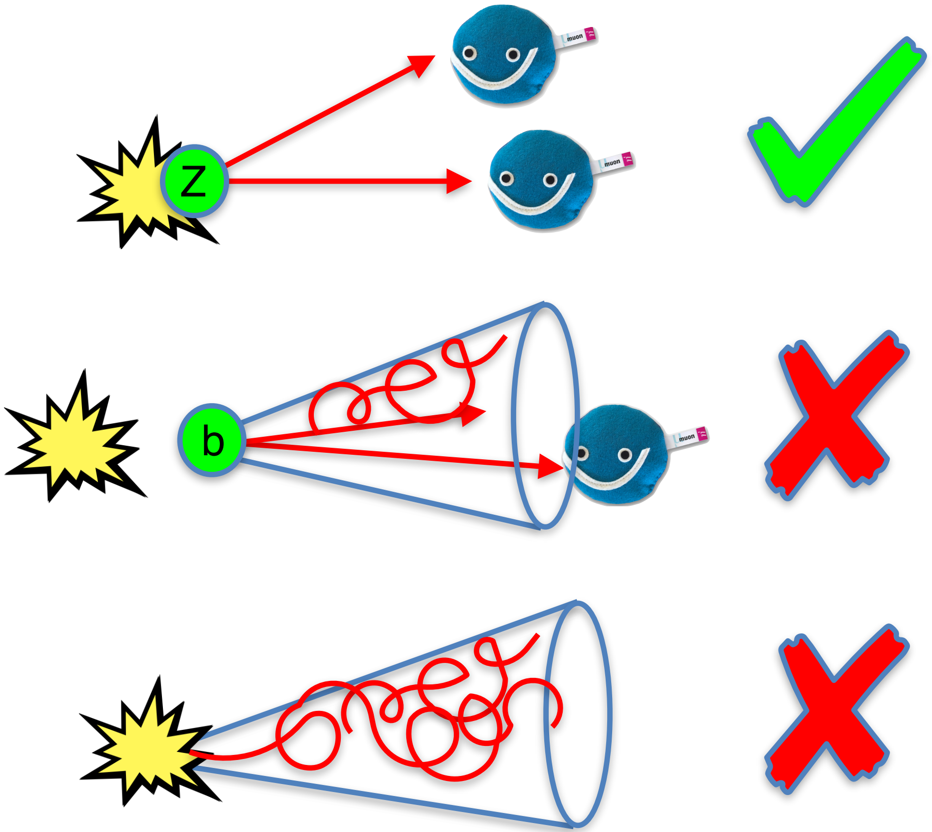
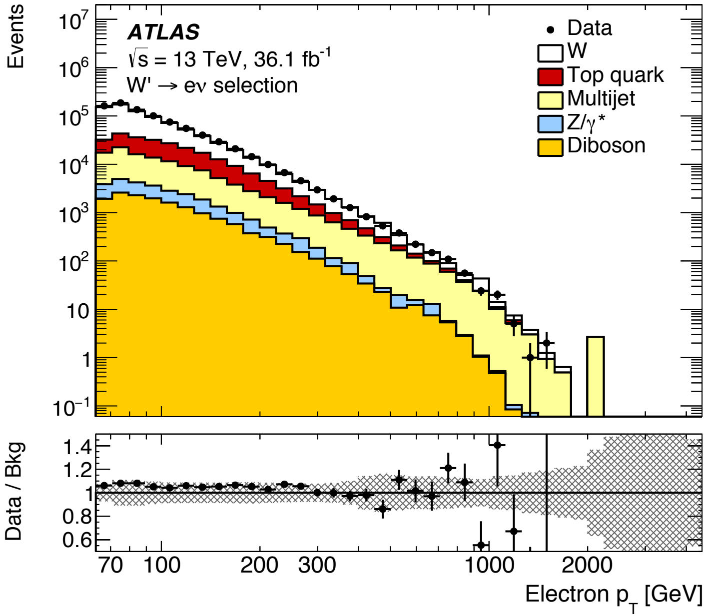


Fake Background Estimation

- Fake lepton backgrounds are very difficult to model accurately
  - Using a **data-driven** approach to model these backgrounds is very common
- Most widely used techniques include the **matrix method** and the **fake factor method**
  - Mathematically similar methods with small differences
- **Idea:** Use **side-band regions** in data (same selection as in signal region, but require at least one lepton to fail a requirement, e.g. identification or isolation)
- **Transfer factor** used to obtain the number of fakes in the signal region from measurements in the data side-band regions



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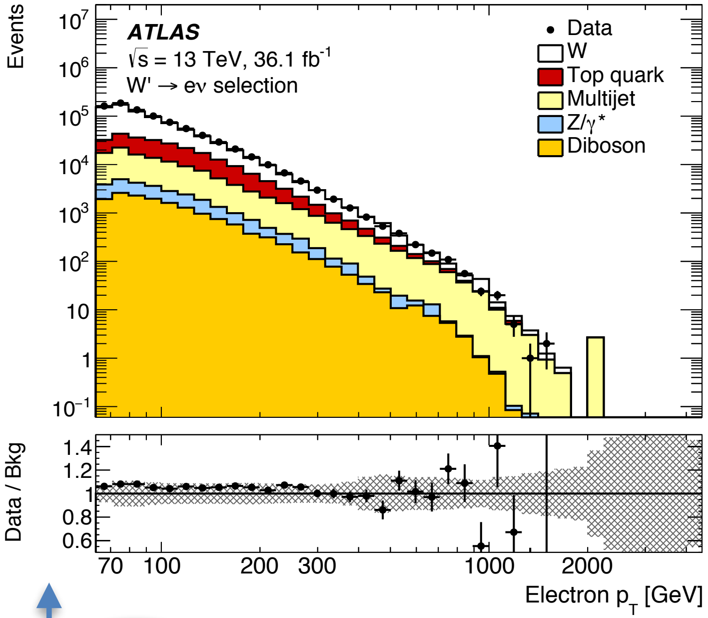

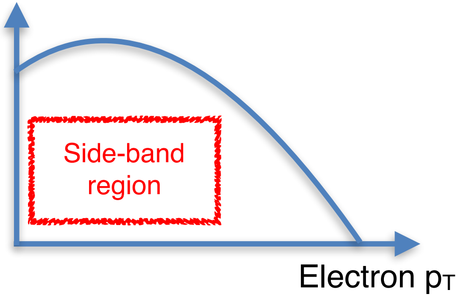

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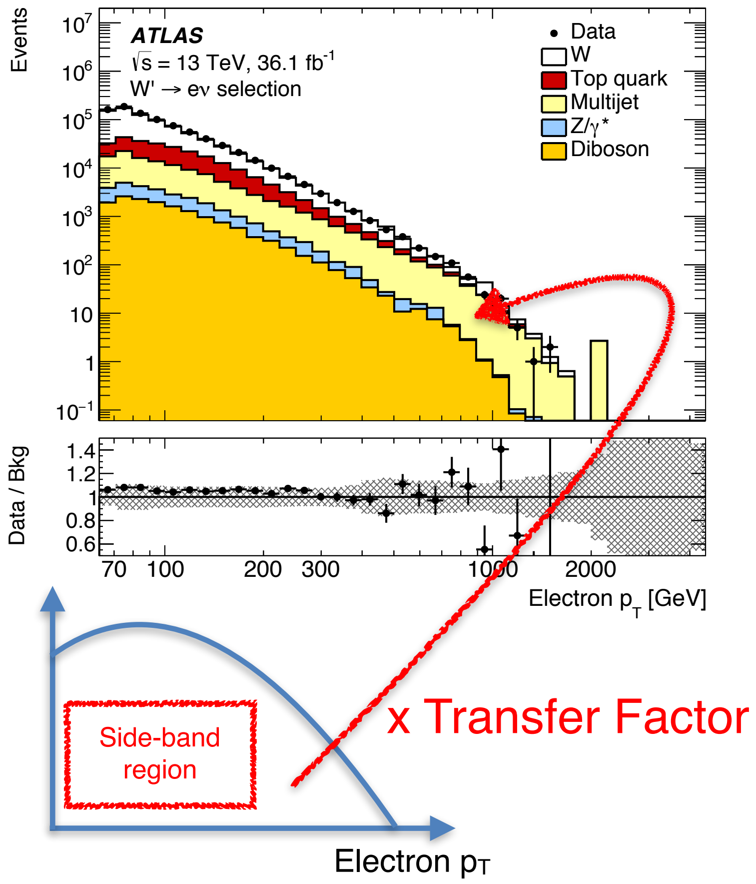
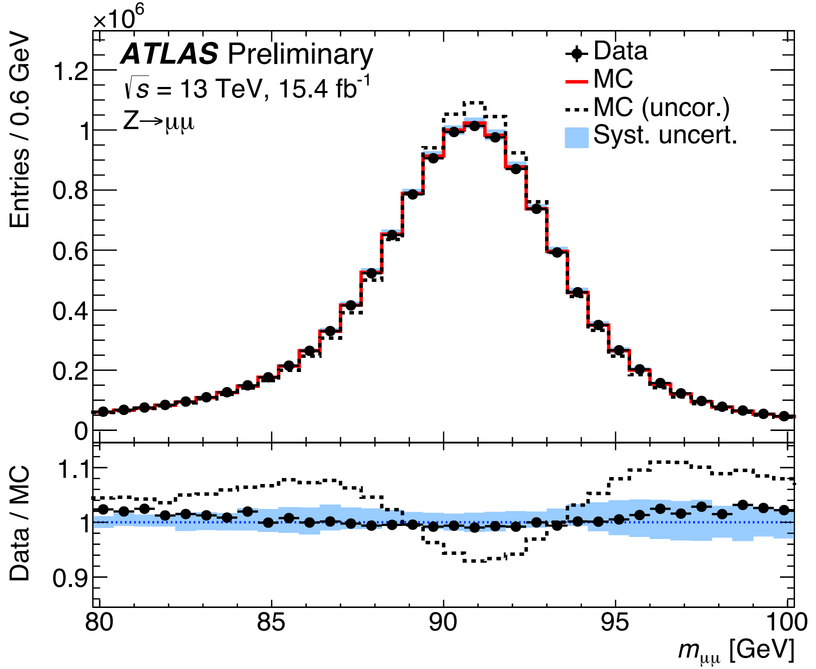


Momentum Scale & Resolution

- **Goal:** Precisely describe the p_T reconstructed in simulation; need to match the measurements in data
  - p_T often used in discriminating variables of BSM searches
- **Method:** Extract relevant parameters from data using a binned maximum-likelihood fit with templates derived from simulation which compares $m_{\mu\mu}$ and normalized ID-MS p_T difference distributions in Z and J/ψ data and simulation samples
- After applying momentum corrections, the line shapes of the Z and J/ψ peak between data and simulation match very well within systematic uncertainty!



- Impossible to cover all analyses with leptonic final states; will focus on 4 results today

[ATLAS-CONF-2018-017] Search for a new heavy gauge boson resonance decaying into a lepton and missing transverse momentum in 80 fb^{-1} of pp collisions at √s = 13 TeV with the ATLAS experiment	$W' \to \ell\nu$
[EXOT-2017-06] A search for high-mass resonances decaying to τν in pp collisions at √s = 13 TeV with the ATLAS detector	$W' \to \tau\nu$
[EXOT-2016-05] Search for new high-mass phenomena in the dilepton final state using 36 fb^{-1} of proton-proton collision data at √s = 13 TeV with the ATLAS detector	$Z' \to \ell\ell$
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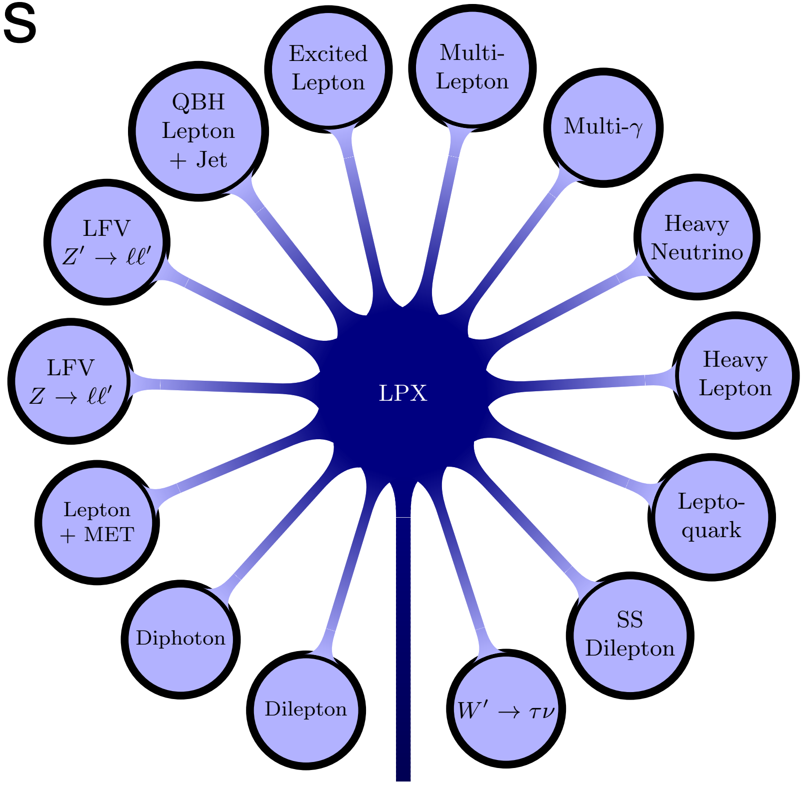

Courtesy of D. Hayden

Selected Results

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New for CIPANP 2018!

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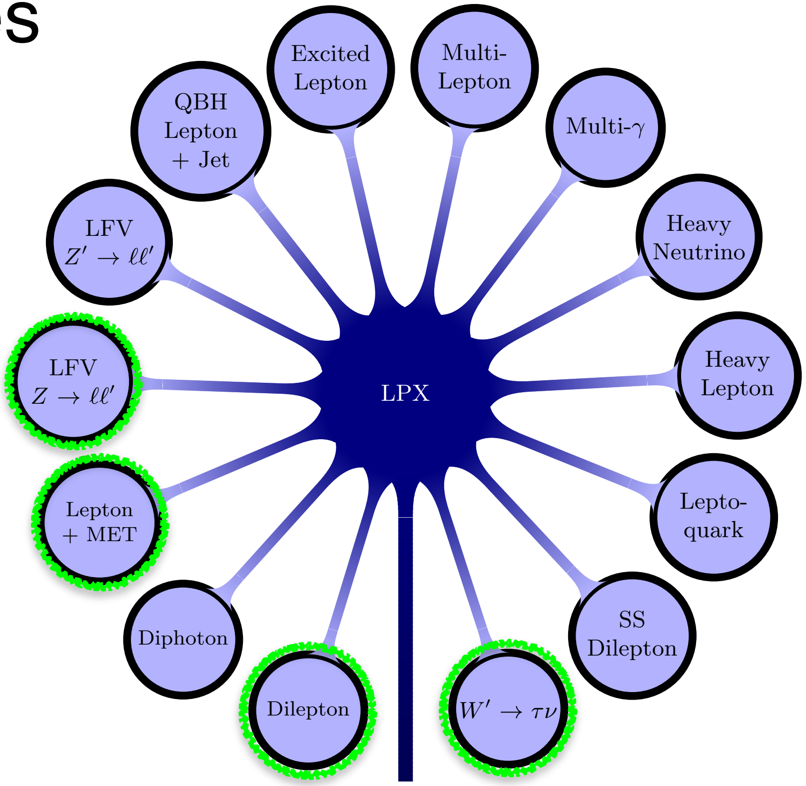

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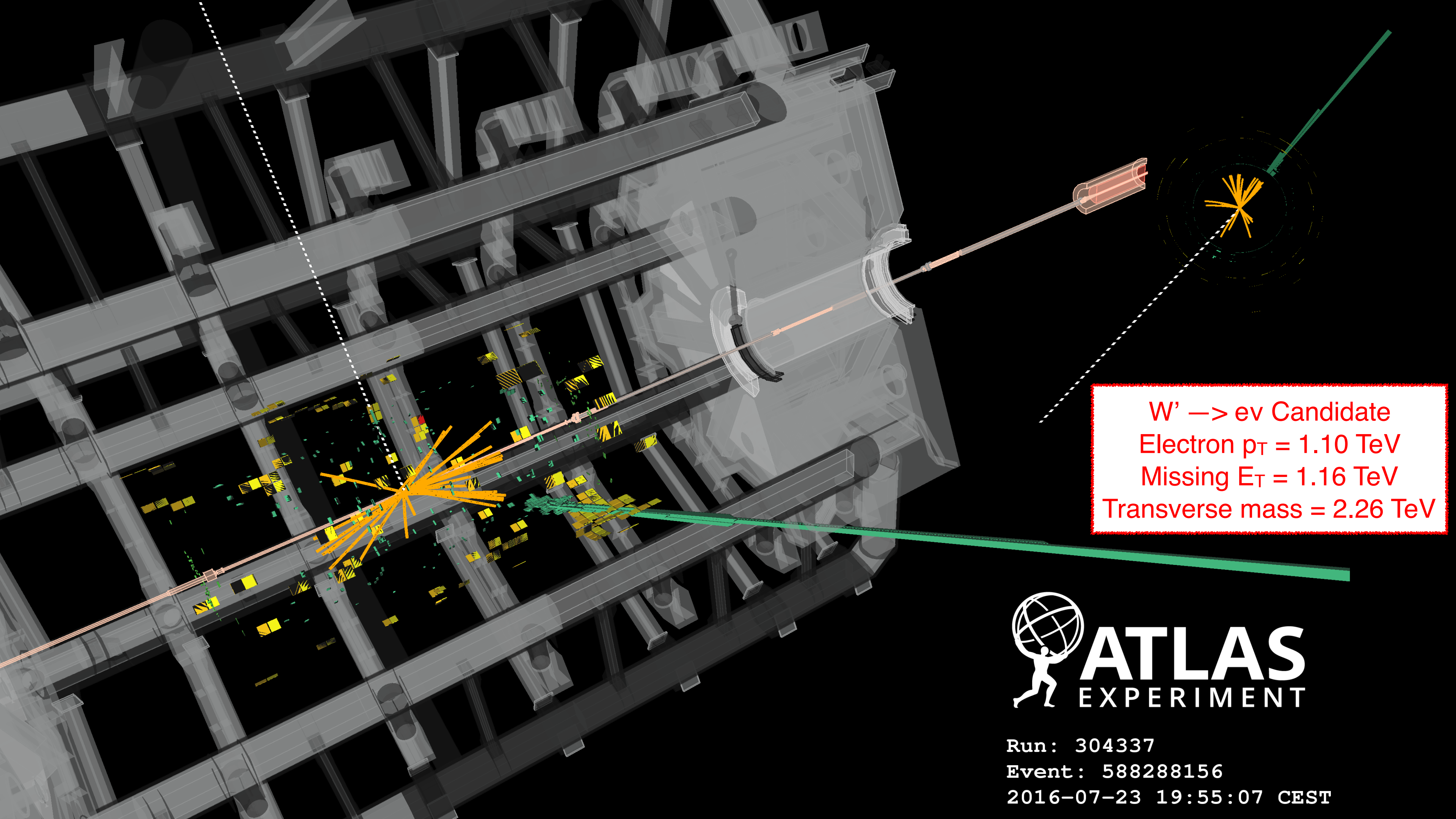

W' —> eν Candidate
Electron pT = 1.10 TeV
Missing ET = 1.16 TeV
Transverse mass = 2.26 TeV
ATLAS
EXPERIMENT
Run: 304337
Event: 588288156
2016-07-23 19:55:07 CEST

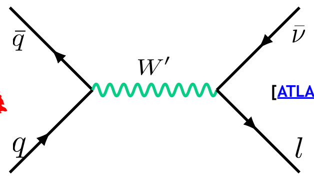
W’ Search

New for CIPANP 2018!

- Require **exactly one high-p_T isolated lepton** and **large missing transverse momentum**
- **Transverse mass** used as discriminating variable

$$m_T = \sqrt{2p_T E_T^{miss}(1-\cos\phi_{l\nu})}$$

- Multi-jet background estimated with the data-driven **matrix method**, all other backgrounds estimated with MC
  - Dominant background is W —> lν
- Dominating DY backgrounds are estimated with MC at NLO approximation with **k-factor** for NNLO QCD and NLO EW



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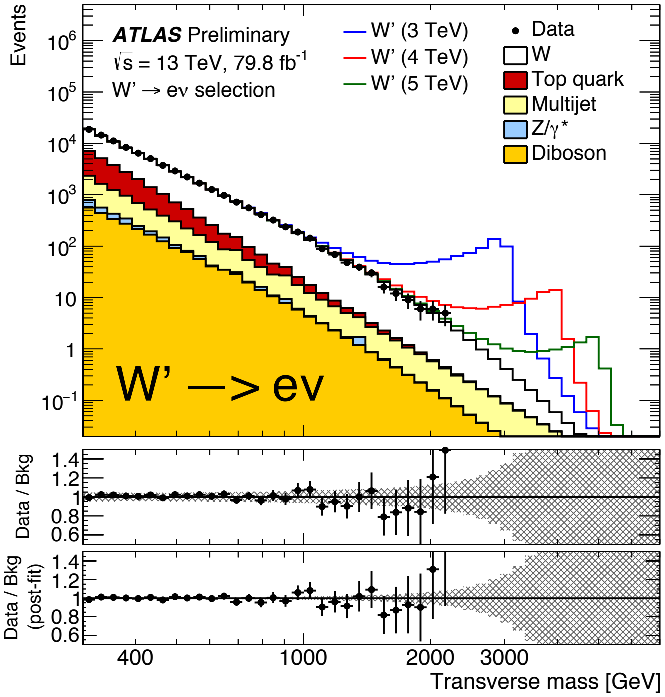

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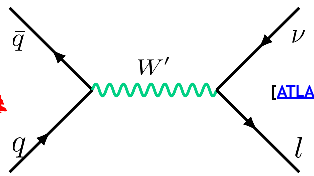

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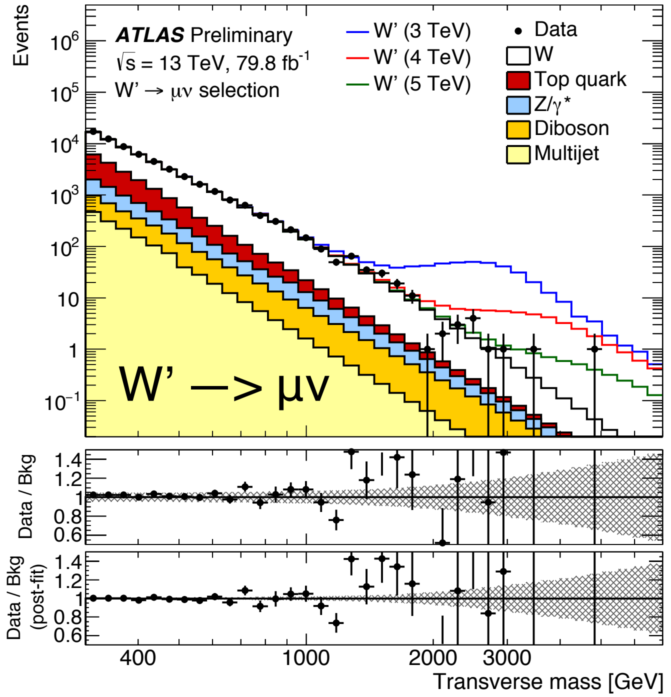
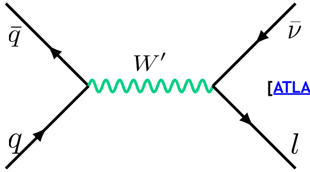


W’ Search Results

- Largest **systematic uncertainties** in SM background at 2 TeV:
  - Fake electron background (7%)
  - Muon reconstruction (7%)
  - Lepton momentum scale and resolution (3-4%)
  - PDF Variation (7-8%)
- No significant deviation from the SM expectation in the transverse mass spectrum
- Masses for W'_{SSM} excluded up to **5.6 TeV** at 95% CL
- Mass limit is **dominated by the electron channel** due to a better resolution of lepton energy at high transverse momenta

Decay	$m_{W'}$ lower limit [TeV] Expected	Observed
$W' \to e\nu$	5.4	5.7
$W' \to \mu\nu$	4.9	4.8
$W' \to \ell\nu$	5.5	5.6



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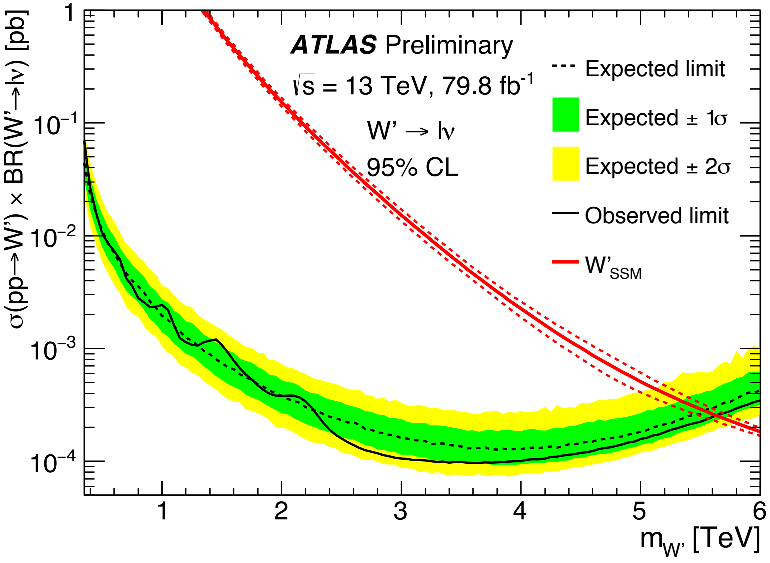

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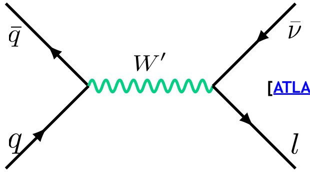
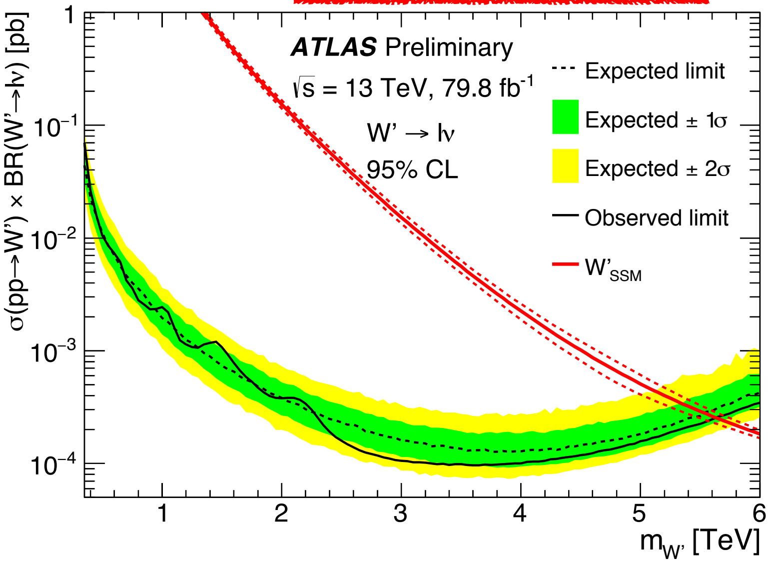
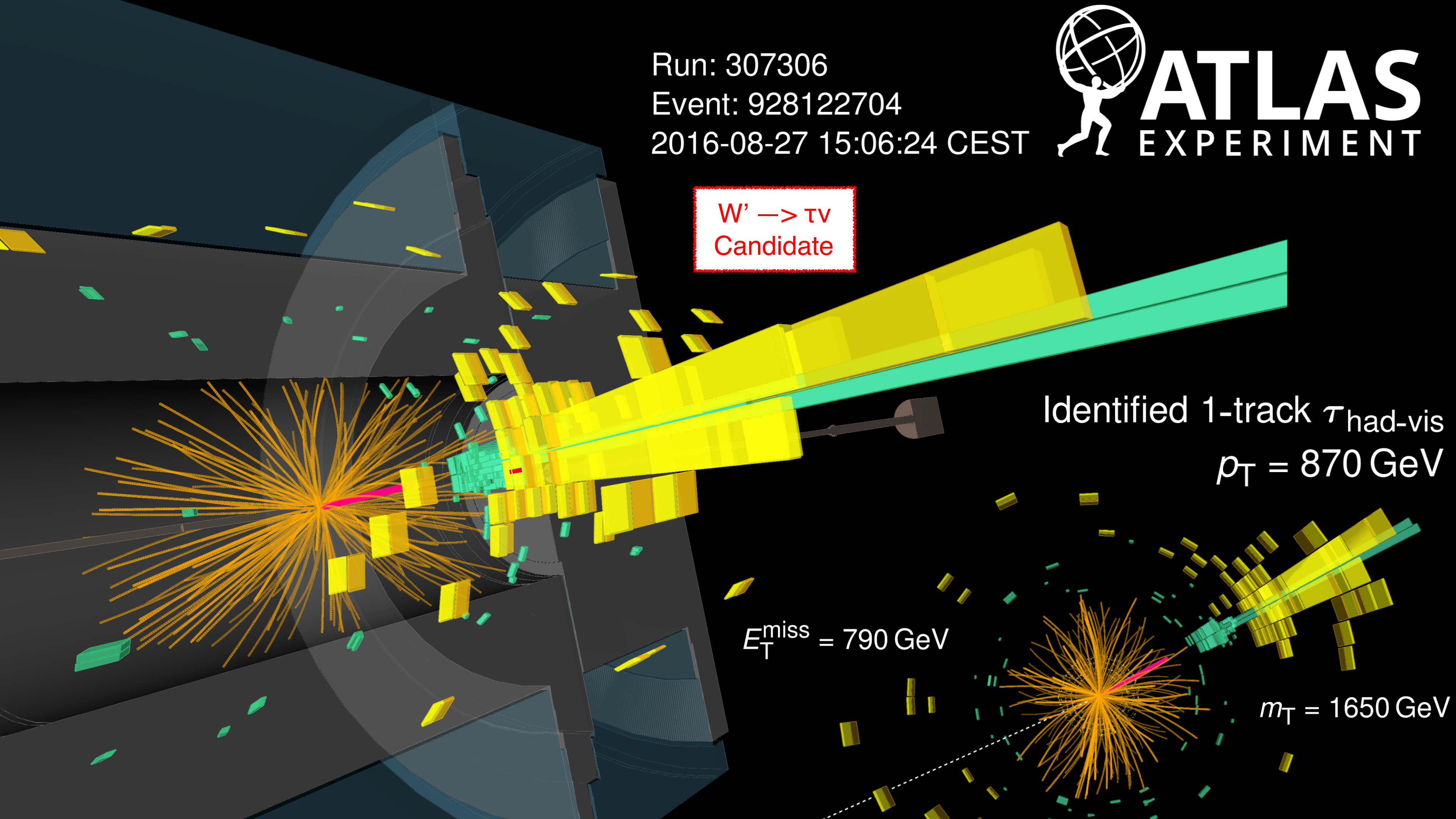


[ATLAS-CONF-2018-017]

500 GeV improvement w.r.t. 2015+2016 result!





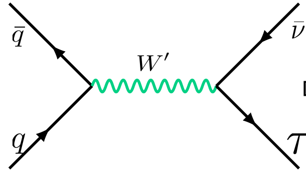
Run: 307306
Event: 928122704
2016-08-27 15:06:24 CEST
ATLAS
EXPERIMENT
W' —> τν
Candidate
Identified 1-track $\tau_{had\text{-}vis}$
p_T = 870 GeV
E_T^{miss} = 790 GeV
m_T = 1650 GeV

W' —> $\tau_{had}\nu$ Search

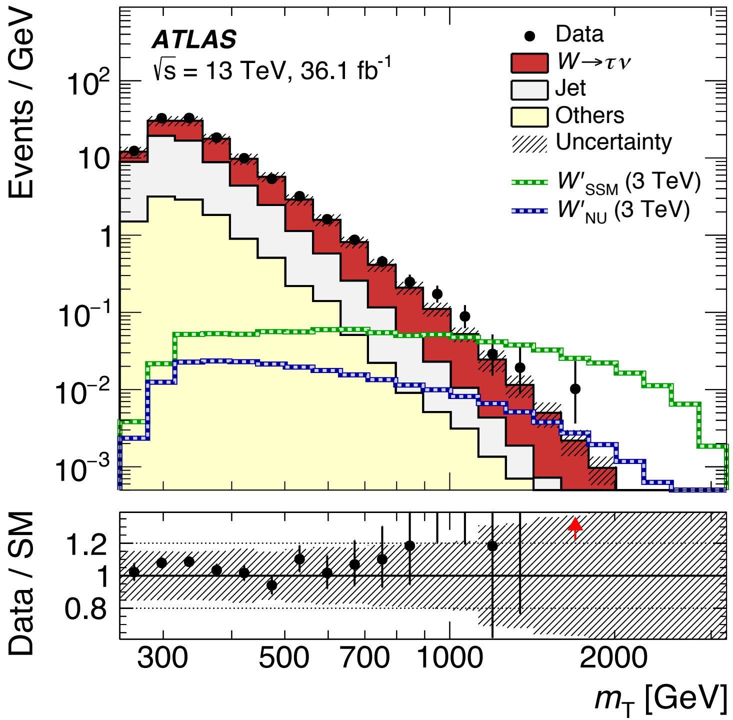
- W' can also decay into taus
- Use Sequential SM as benchmark
- Particularly important in models with **enhanced 3rd generation couplings**, e.g. Nonuniversal G(221)

$$SU(2)_l \times SU(2)_h \times U(1)$$

- Only consider **hadronically decaying taus** (~65% of total τ branching fraction); typically a neutrino, one or three charged pions, and up to two neutral pions
    - Jet background: data-driven **fake factor** method
    - Non-jet background: MC simulation
- **Counting experiment** performed in m_T tail



[EXOT-2017-06]



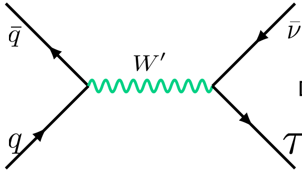
W' —> $\tau_{had}\nu$ Search

- W' can also decay into taus
- Use Sequential SM as benchmark
- Particularly important in models with **enhanced 3rd generation couplings**, e.g. non-universal G(221)

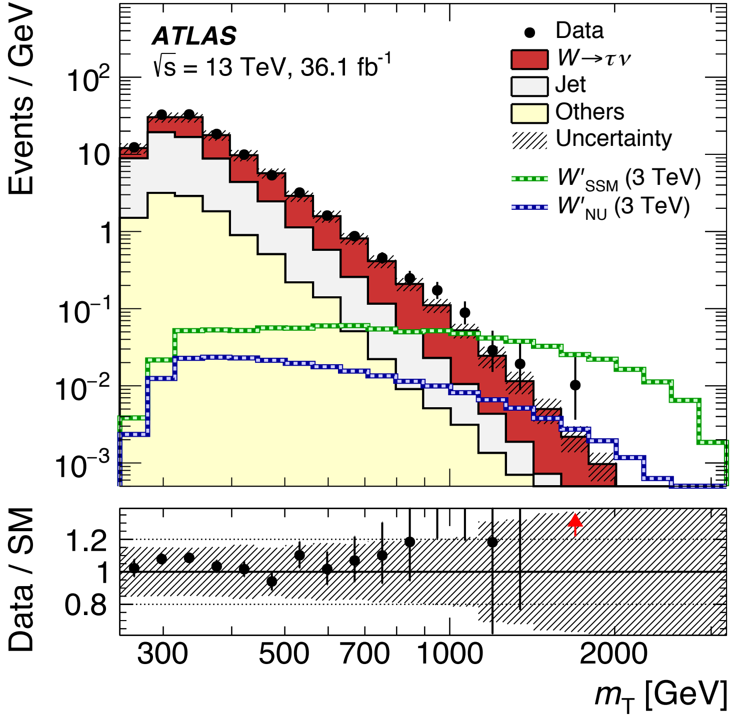
Couplings to light fermions | Couplings to heavy fermions

$$SU(2)_l \times SU(2)_h \times U(1)$$

- Only consider **hadronically decaying taus** (~65% of total τ branching fraction); typically a neutrino, one or three charged pions, and up to two neutral pions
  - Jet background: data-driven **fake factor** method
  - Non-jet background: MC simulation
- **Counting experiment** performed in m_T tail

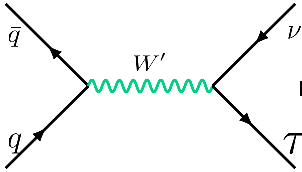


[EXOT-2017-06]

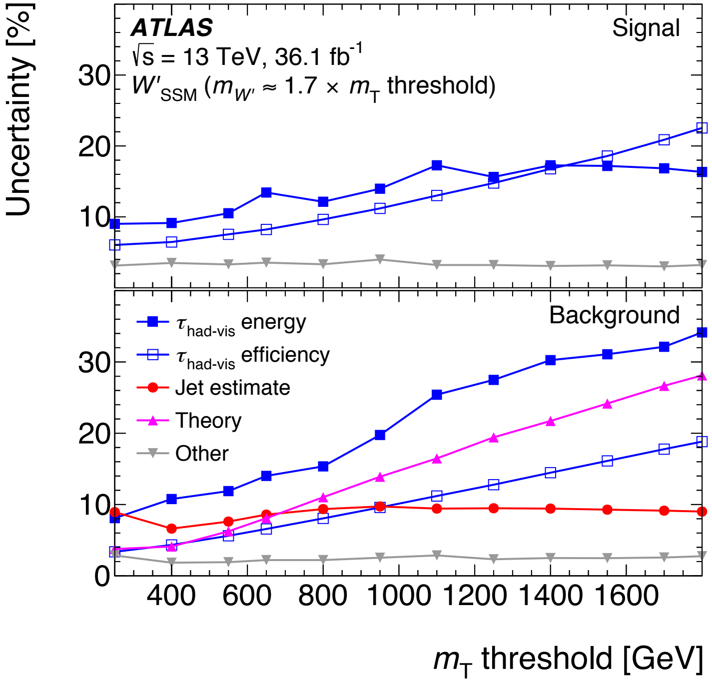


W' —> $\tau_{had}\nu$ Selection

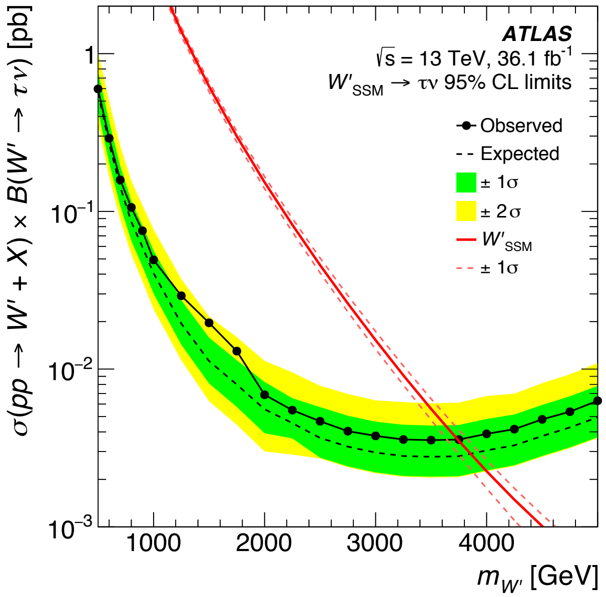
- **Missing E_T trigger** 70 - 110 GeV (depending on data-taking period)
- Missing E_T > 150 GeV —> minimize trigger efficiency uncertainty
- Visible tau decay products candidate ($\tau_{had\text{-}vis}$):
  - p_T > 50 GeV, $|\eta|$ < 2.4, one or three associated tracks, and electric charge of ± 1
  - Identification efficiency is ~60% at p_T = 100 GeV (~30% at p_T = 2 TeV)
- **Muon + electron veto** to reduce electrons misidentified as $\tau_{had\text{-}vis}$
- Multi-jet background suppressed by $0.7 < p_T^{\tau}/E_T^{Miss} < 1.3$

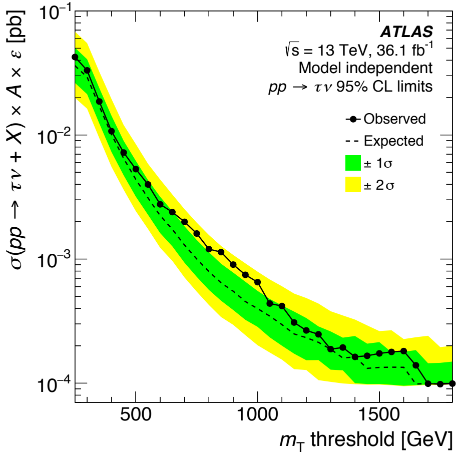


[EXOT-2017-06]

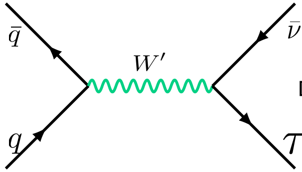


W' —> $\tau_{had}\nu$ Results

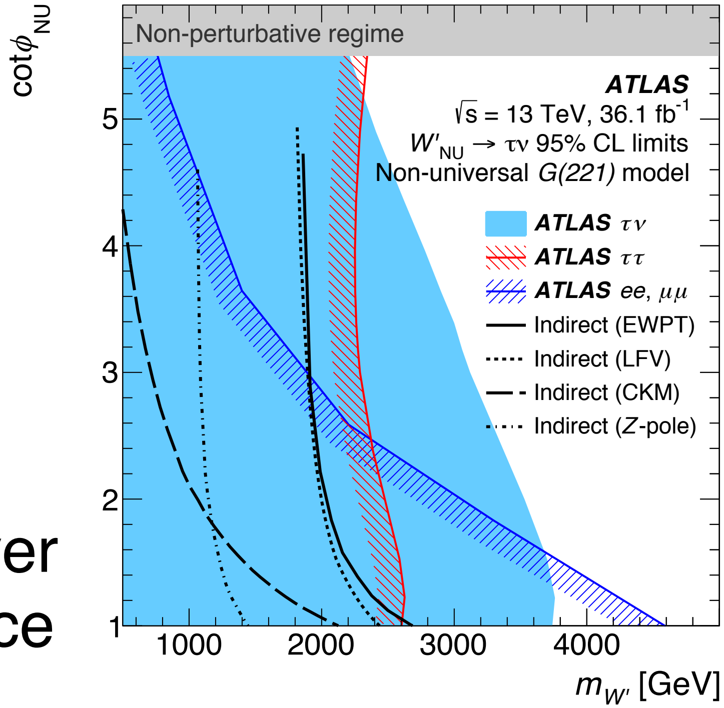




$$\tan\phi_{\mathrm{NU}} = \tilde{g}_h/\tilde{g}_l$$



[EXOT-2017-06]



- τν search is **complementary** to lν search and extends the sensitivity over a large fraction of the parameter space

Z' Search

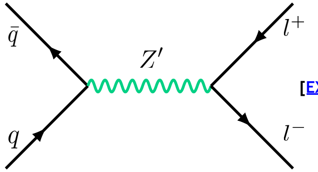
- GUT models based on the E_6 gauge group

$$E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi$$

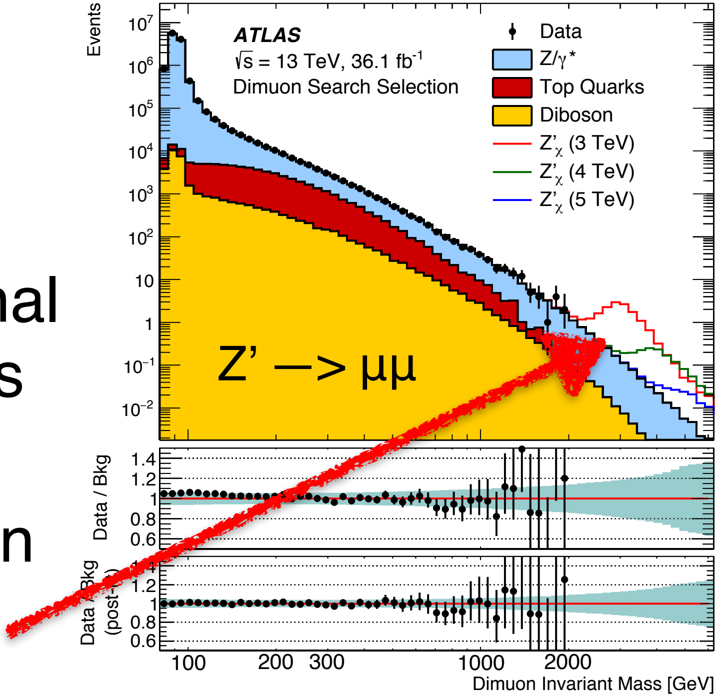
- Two additional U(1) gauge fields

$$Z'(\theta_{E_6}) = Z'_\psi \cos\theta_{E_6} + Z'_\chi \sin\theta_{E_6}$$

- Sequential SM (Benchmark): additional heavy bosons with same couplings as SM Z/W
- Observable as **narrow resonances** in dilepton invariant mass spectrum

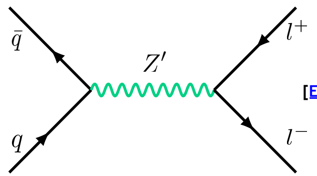


[EXOT-2016-05]

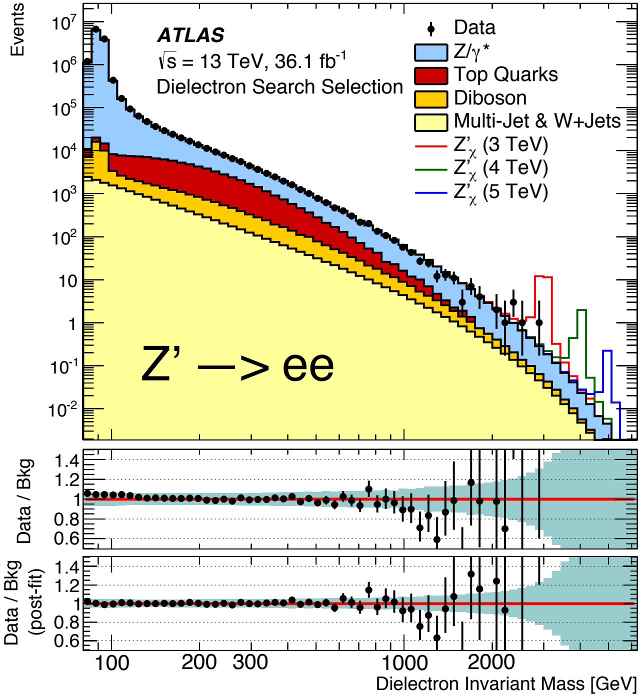


Z' Search

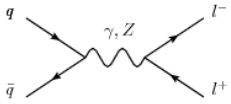
- Select events with one pair of same-flavour, isolated leptons with $p_T > 30$ GeV
- Multi-Jet & W+Jets backgrounds estimated with the **matrix method** (negligible in the muon channel)
- Dominating DY backgrounds are estimated with MC at NLO approximation with **k-factor** for NNLO QCD and NLO EW



[EXOT-2016-05]

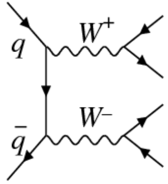


Drell-Yan Production



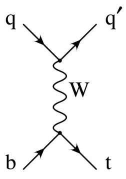
Generator	Powheg v2
Order	NLO
Shower	Pythia 8.186
PDF	CT10
Samples	Mass-Binned

Diboson Production

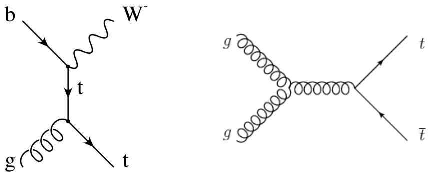


Generator	Sherpa 2.1.1
Order	NLO
Shower	Sherpa 2.1.1
PDF	CT10
Samples	Mass-Binned

Top Production



Generator	Powheg v2
Order	NLO
Shower	Pythia 6.428
PDF	CT10
Samples	Unbinned



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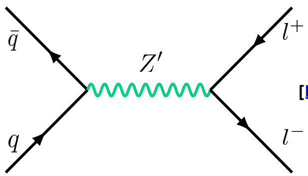
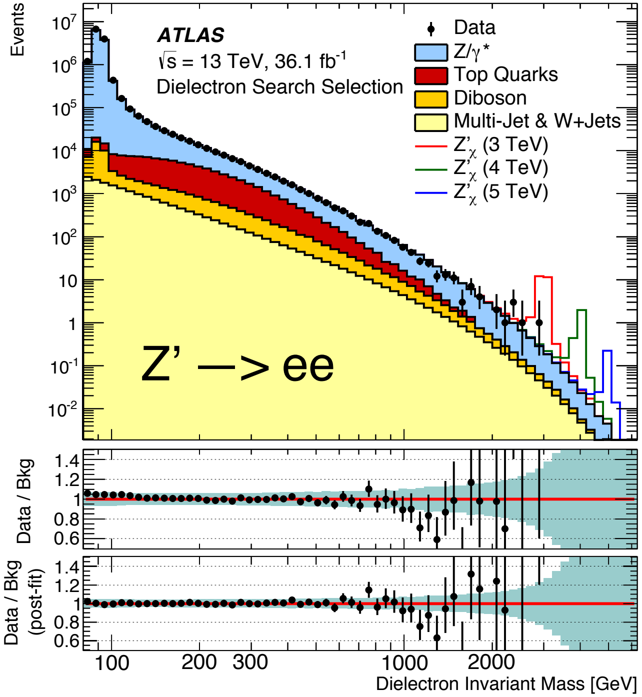
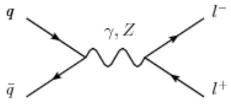
Dominant Background



[EXOT-2016-05]



Drell-Yan Production



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PDF	CT10
Samples	Mass-Binned

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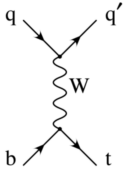

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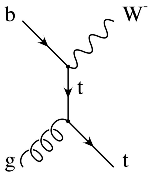
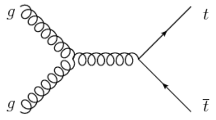
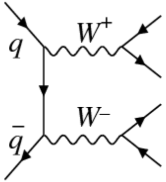




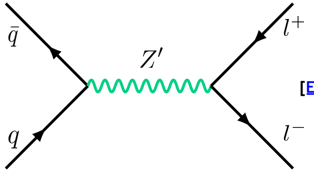
Diboson Production



Generator	Sherpa 2.1.1
Order	NLO
Shower	Sherpa 2.1.1
PDF	CT10
Samples	Mass-Binned

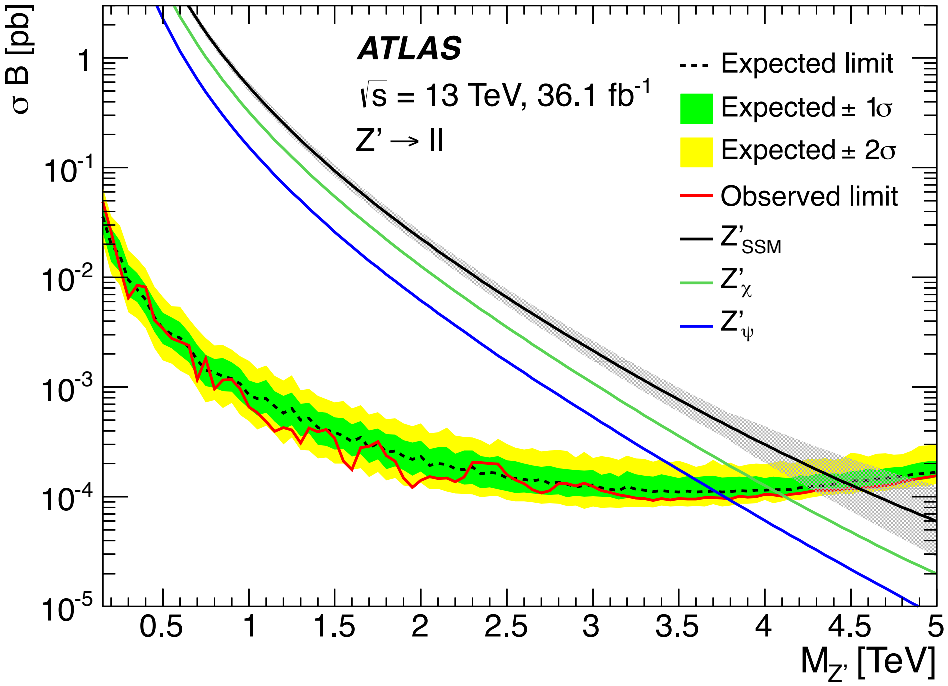
Z' Search Results

- Largest systematic uncertainties in SM background at 2 TeV:
  - Fake electron background (10%)
  - Muon reconstruction (10%)
  - Electron isolation (9.1%)
  - PDF Variation (7.7-8.7%)



[EXOT-2016-05]

Model	Width [%]	θ_{E_6} [Rad]	Lower limits on $m_{Z'}$ [TeV]					
			ee		$\mu\mu$		$\ell\ell$	
			Obs	Exp	Obs	Exp	Obs	Exp
Z'_{SSM}	3.0	-	4.3	4.3	4.0	3.9	4.5	4.5
Z'_{χ}	1.2	0.50	3.9	3.9	3.6	3.6	4.1	4.0
Z'_{S}	1.2	0.63 π	3.9	3.8	3.6	3.5	4.0	4.0
Z'_{I}	1.1	0.71 π	3.8	3.8	3.5	3.4	4.0	3.9
Z'_{η}	0.6	0.21 π	3.7	3.7	3.4	3.3	3.9	3.8
Z'_{N}	0.6	-0.08 π	3.6	3.6	3.4	3.3	3.8	3.8
Z'_{ψ}	0.5	0 π	3.6	3.6	3.3	3.2	3.8	3.7



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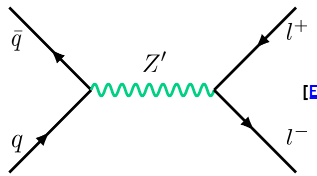

[EXOT-2016-05]

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			ee		$\mu\mu$		$\ell\ell$	
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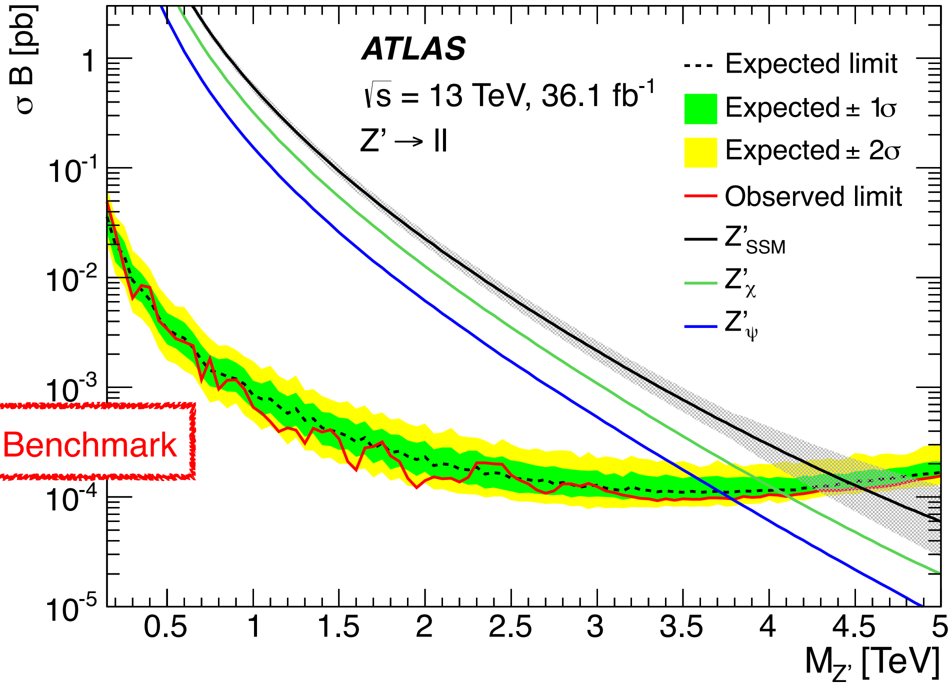
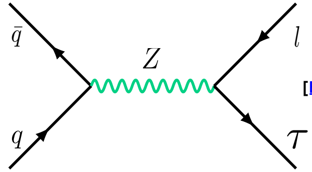
Z'_I	1.1	0.71 π	3.8	3.8	3.5	3.4	4.0	3.9
Z'_η	0.6	0.21 π	3.7	3.7	3.4	3.3	3.9	3.8
Z'_N	0.6	-0.08 π	3.6	3.6	3.4	3.3	3.8	3.8
Z'_ψ	0.5	0 π	3.6	3.6	3.3	3.2	3.8	3.7

Benchmark

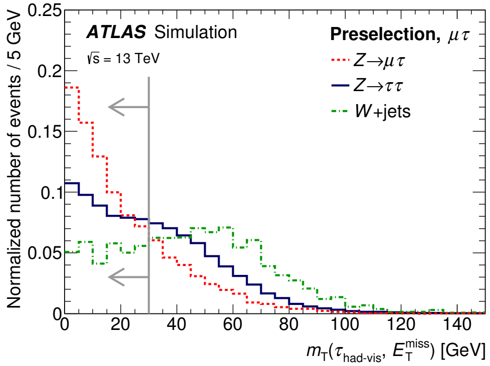


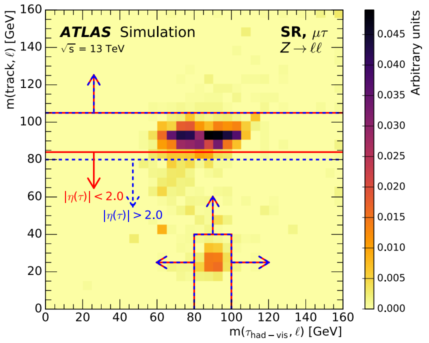
LFV Z Search

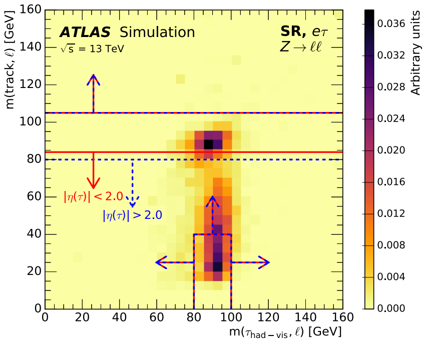
- Lepton-flavor-violating (LFV) Z boson decays are predicted by models with heavy neutrinos, extended gauge models, etc.
- Only consider **hadronically decaying** taus
- Signal events are expected to have the missing transverse momentum from the neutrino in a **direction close to the $\tau_{\text{had-vis}}$ candidate**
- **Reject** events where m(track or $\tau_{\text{had-vis}}$, l) is compatible with the **Z boson** mass
- Events where the $\tau_{\text{had-vis}}$ candidate originates from a quark- or gluon-initiated jet are estimated using the **fake factor** method, all other processes estimated from simulation



[EXOT-2016-36]

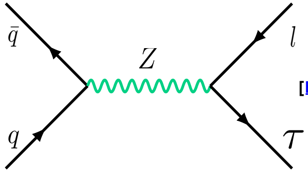




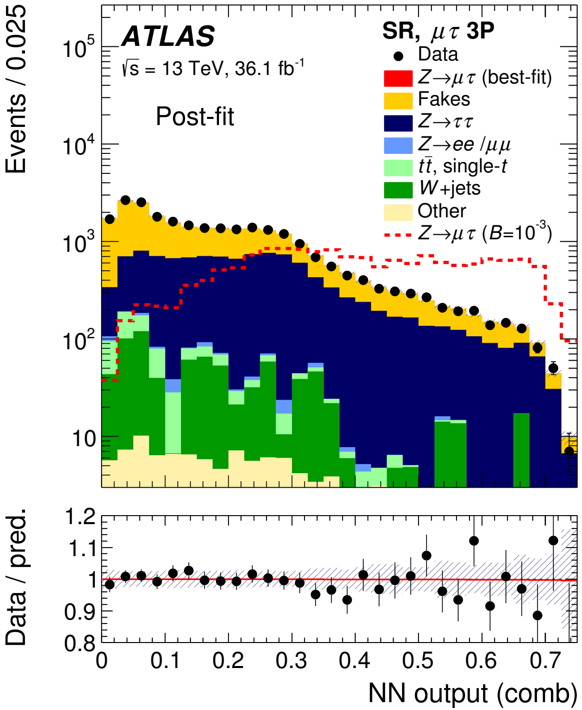


LFV Z Results

- SR events (ε ~3.2% for eτ and ~3.5% for μτ) are classified using **neural networks (NN)** trained to discriminate Z —> lτ signal from background events
- NN output distributions are analyzed in a **template fit** to data
- Quantify the size of the LFV decay **branching fraction** by setting upper limits using the CLs method



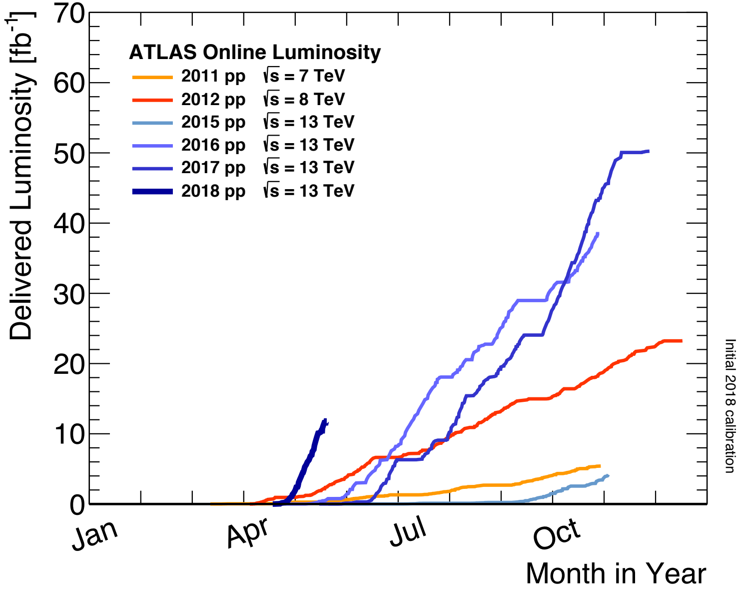
[EXOT-2016-36]



	$e\tau$	$\mu\tau$
$\mathcal{B}(Z \to \ell\tau)$	$(3.3^{+1.5}_{-1.4}) \times 10^{-5}$	$(-0.1^{+1.2}_{-1.2}) \times 10^{-5}$
$\mu(Z)$	$0.83^{+0.09}_{-0.07}$	$0.87^{+0.09}_{-0.08}$
$\mu(\text{fakes\_1P})$	$1.18^{+0.06}_{-0.06}$	$1.12^{+0.09}_{-0.08}$
$\mu(\text{fakes\_3P})$	$1.01^{+0.06}_{-0.05}$	$1.09^{+0.13}_{-0.14}$
Observed (expected) upper limit at 95% CL	$5.8(2.8) \times 10^{-5}$	$2.4(2.4) \times 10^{-5}$

Summary

- Rich program of new physics searches using leptonic final states
  - Many searches not covered here!
- Various BSM models are tested and stringent constraints are set
- No new physics for now, but more data coming —> stay tuned!
- Expect updates with full Run 2 data very soon!
- [ATLAS Exotics public results page]



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Thank you!
Merci!

Questions?

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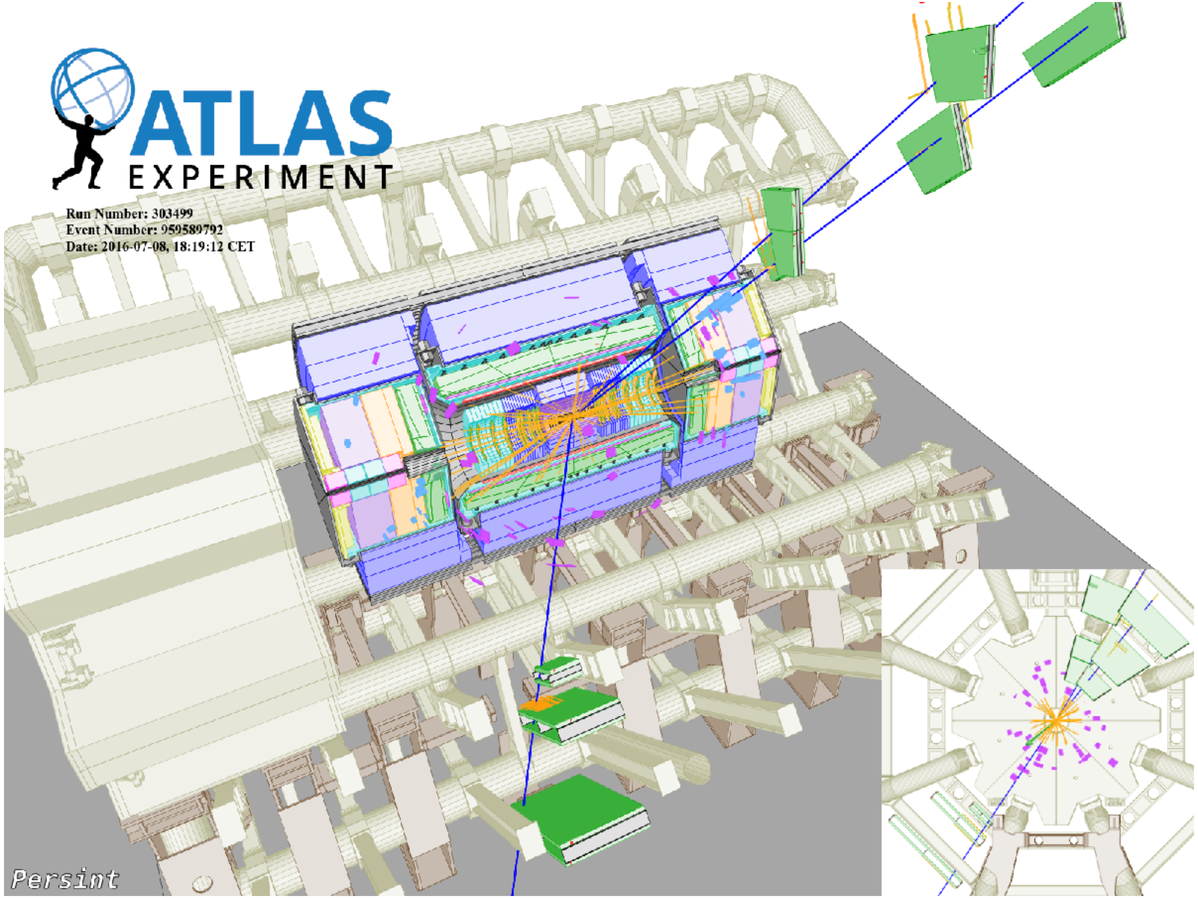
Backup

Z’ Event Display



Z' Selection

Electron Channel	Muon Channel
Event Level Criteria	
GRL	
Trigger: 2 electrons with p_T > 17 GeV (2e17_lhloose)	Trigger: 1 isolated μ with p_T > 26 GeV OR 1 μ with pT > 50 GeV (mu26_ivarmedium || mu50)
Event Cleaning	
At least two electrons	At least two combined muons
Lepton Level Criteria	
$\|\eta\|$ < 2.47 and exclude crack region	Muon p_T > 30 GeV
Good Object Quality	High p_T Muon Working Point
Electron E_T > 30 GeV	Bad Muon Veto
d_0 significance < 5	d_0 significance < 3
$\|z_0 * \sin\theta\|$ < 0.5 mm	$\|z_0 * \sin\theta\|$ < 0.5 mm
Electron ID: Likelihood Medium	Isolation WP: LooseTrackOnly
Isolation WP: Loose	Require Opposite Charge
Select Highest E_T/p_T Pair	
m_{ee} > 80 GeV	$m_{\mu\mu}$ > 80 GeV

Z' Systematic Uncertainties

- **Background:** relative systematic uncertainties in the total expected number of events at reconstructed m_{ll} of 2 TeV (4 TeV)
- **Signal:** Z'_{χ} signal with pole mass 2 TeV (4 TeV)
- **Largest theory uncertainty:** PDF Variation
- **Largest experimental uncertainty:** reconstruction efficiency (muon channel) and isolation efficiency (electron channel)

Source	Dielectron		Dimuon	
	Signal	Background	Signal	Background
Luminosity	3.2% (3.2%)	3.2% (3.2%)	3.2% (3.2%)	3.2% (3.2%)
MC Statistical	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)
Beam Energy	2.0% (4.1%)	2.0% (4.1%)	1.9% (3.1%)	1.9% (3.1%)
Pile-Up Effects	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)
DY PDF Choice	N/A	<1.0% (8.4%)	N/A	<1.0% (1.9%)
DY PDF Variation	N/A	8.7% (18.5%)	N/A	7.7% (12.8%)
DY PDF Scale	N/A	1.0% (2.0%)	N/A	<1.0% (1.5%)
DY α_S	N/A	1.6% (2.7%)	N/A	1.4% (2.2%)
DY EW Corrections	N/A	2.4% (5.5%)	N/A	2.1% (3.9%)
DY Photon-induced Corrections	N/A	3.4% (7.6%)	N/A	3.0% (5.4%)
Top Quarks Theoretical	N/A	<1.0% (<1.0%)	N/A	<1.0% (<1.0%)
Dibosons Theoretical	N/A	<1.0% (<1.0%)	N/A	<1.0% (<1.0%)
Reconstruction Efficiency	<1.0% (<1.0%)	<1.0% (<1.0%)	10.2% (16.8%)	10.2% (16.8%)
Isolation Efficiency	9.1% (9.7%)	9.1% (9.7%)	1.8% (2.0%)	1.8% (2.0%)
Trigger Efficiency	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)
Identification Efficiency	2.6% (2.4%)	2.6% (2.4%)	N/A	N/A
Lepton Energy Scale	<1.0% (<1.0%)	4.1% (6.1%)	<1.0% (<1.0%)	<1.0% (<1.0%)
Lepton Energy Resolution	<1.0% (<1.0%)	<1.0% (<1.0%)	2.7% (2.7%)	<1.0% (6.7%)
Multi-jet & W+jets	N/A	10.3% (129.2%)	N/A	N/A
Total	10.2% (11.3%)	18.0% (131.8%)	11.3% (17.7%)	14.1% (23.8%)

Matrix Method (Z' —> ee)

- Jets can fake (i.e. be mis-identified as) leptons (**mainly electrons**). Multi-Jet and W+Jets production are dominant.
- Use data-driven approach —> Matrix Method
  - Measure fake rate ***f*** and real rate ***r***

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{pmatrix} r^2 & rf & fr & f^2 \\ r(1-r) & r(1-f) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)^2 & (1-r)(1-f) & (1-f)(1-r) & (1-f)^2 \end{pmatrix} \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}$$

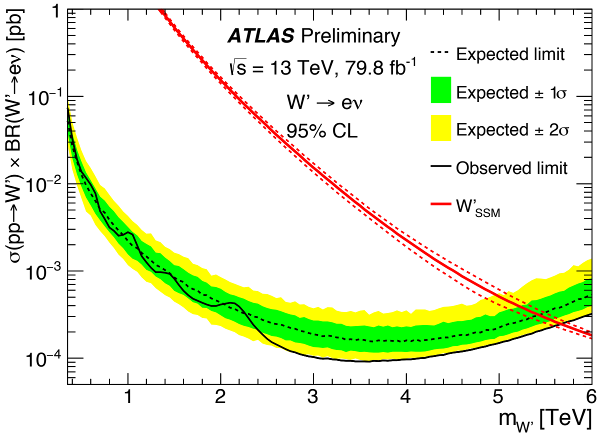
$$N_{TT} = r^2 N_{RR} + rf(N_{RF} + N_{RF}) + f^2 N_{FF}$$

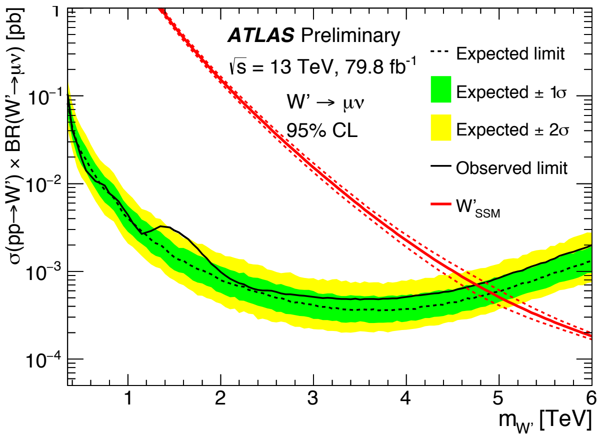
Multi-Jet & W+Jets Background

- N_{RF}, N_{FR}, and N_{FF} obtained through matrix inversion

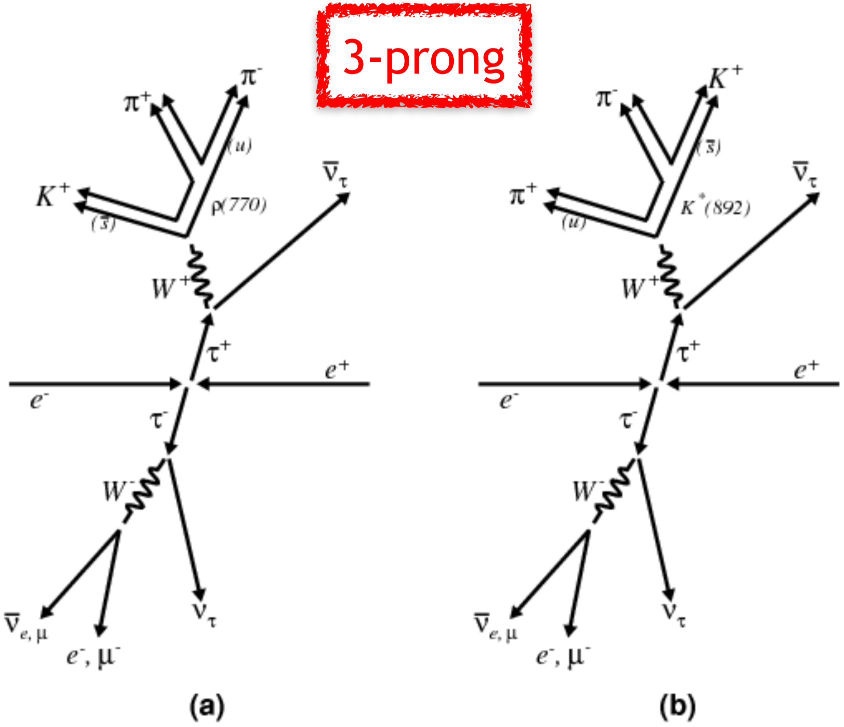
W' —> lv Systematics

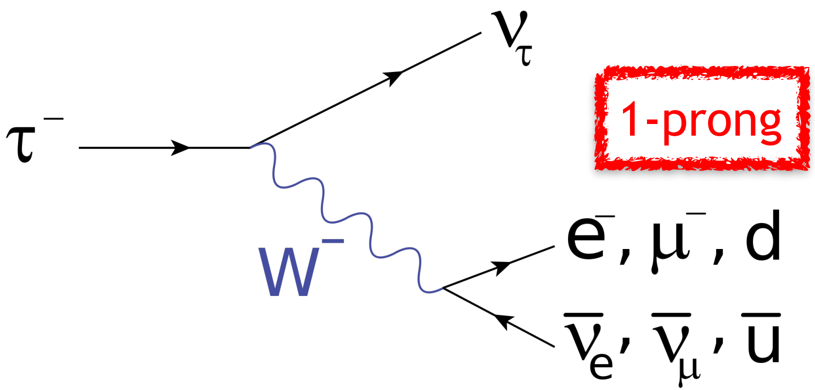
Source	Electron channel		Muon channel	
	Background	Signal	Background	Signal
Trigger	negl. (negl.)	negl. (negl.)	1% (1%)	2% (2%)
Lepton reconstruction and identification	negl. (negl.)	negl. (negl.)	7% (21%)	5% (29%)
Lepton momentum scale and resolution	4% (3%)	4% (3%)	3% (12%)	7% (10%)
Multijet background	7% (113%)	N/A (N/A)	1% (1%)	N/A (N/A)
Top extrapolation	2% (5%)	N/A (N/A)	3% (3%)	N/A (N/A)
Top normalization	$< 0.5\%$ ($< 0.5\%$)	N/A (N/A)	$< 0.5\%$ ($< 0.5\%$)	N/A (N/A)
Diboson extrapolation	2% (9%)	N/A (N/A)	3% (10%)	N/A (N/A)
PDF choice for DY	1% (14%)	N/A (N/A)	$< 0.5\%$ ($< 0.5\%$)	N/A (N/A)
PDF variation for DY	8% (12%)	N/A (N/A)	7% (11%)	N/A (N/A)
EW corrections for DY	4% (5%)	N/A (N/A)	4% (6%)	N/A (N/A)
Luminosity	2% (1%)	2% (2%)	2% (2%)	2% (2%)
Total	13% (115%)	4% (4%)	12% (29%)	9% (31%)





τ Decays

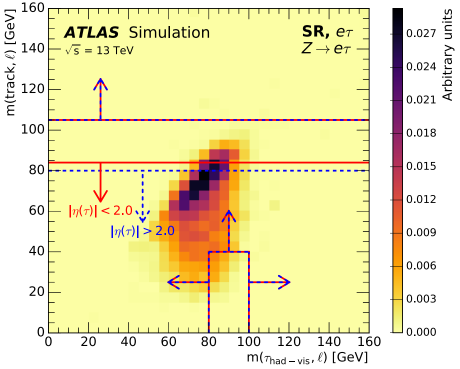

3-prong
π+
π-
K+
(u)
(s̄)
ρ(770)
ν̄τ
W+
τ+
e+
e-
τ-
W-
ν̄e, μ
e-, μ-
ντ
(a)
π-
K+
π+
(s̄)
(u)
K*(892)
ν̄τ
W+
τ+
e+
e-
τ-
W-
ν̄e, μ
e-, μ-
ντ
(b)

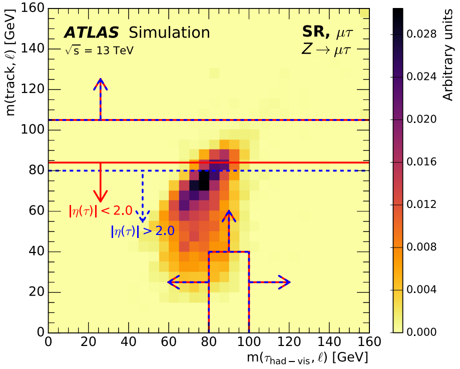

ντ
τ−
1-prong
W−
e−, μ−, d
ν̄e, ν̄μ, ū

W' —> ThadV

Process	Matrix Element	Non-perturbative
$W/Z/\gamma^*$	POWHEG-BOX 2, CT10, PHOTOS++ 3.52	PYTHIA 8.186, AZNLO, CTEQ6L1, EVTGEN 1.2.0
$t\bar{t}$	POWHEG-BOX 2, CT10	PYTHIA 6.428, P2012, CTEQ6L1, EVTGEN 1.2.0
Single top	POWHEG-BOX 1, CT10f4, MADSPIN	PYTHIA 6.428, P2012, CTEQ6L1, EVTGEN 1.2.0
Diboson	SHERPA 2.1.1, CT10	SHERPA 2.1.1

LFV Z Selection





Preselection	one isolated tight light lepton with $p_{\mathrm{T}} > 30$ GeV matched to a lepton selected at trigger level leading $\tau_{\text{had-vis}}$ with $p_{\mathrm{T}} > 20$ GeV, $N_{\tau}^{\text{tracks}} = 1$ or 3 and passing tight identification if $N_{\tau}^{\text{tracks}} = 1$: $0.0(0.1) < \lvert\eta_\tau\rvert < 1.37$ or $1.52 < \lvert\eta_\tau\rvert < 2.2(2.5)$ in $e\tau(\mu\tau)$ events if $N_{\tau}^{\text{tracks}} = 3$: $0.0 < \lvert\eta_\tau\rvert < 1.37$ or $1.52 < \lvert\eta_\tau\rvert < 2.5$ $q_\ell \times q_\tau = -1$ no b-jet, no additional light lepton
Signal Region	$m_{\mathrm{T}}(\tau_{\text{had-vis}}, E_{\mathrm{T}}^{\text{miss}}) < 35(30)$ GeV in $e\tau$ $(\mu\tau)$ events if $N_{\tau}^{\text{tracks}} = 1$ and $\lvert\eta_\tau\rvert < 2.0$: $m(\text{track}, \ell) < 84$ GeV or $m(\text{track}, \ell) > 105$ GeV if $N_{\tau}^{\text{tracks}} = 1$ and $\lvert\eta_\tau\rvert > 2.0$: $m(\text{track}, \ell) < 80$ GeV or $m(\text{track}, \ell) > 105$ GeV if $N_{\tau}^{\text{tracks}} = 1$ and $80 < m(\tau_{\text{had-vis}}, \ell) < 100$ GeV: $m(\text{track}, \ell) > 40$ GeV

LFV Z NN Input

Variable	Description	Z NN	Zll NN	W NN
$\hat{E}^{\text{lep}}$	light-lepton energy	✓	✓	✓
$\hat{p}_x^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ p_x	✓	✓	✓
$\hat{p}_z^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ p_z	✓	✓	✓
$\hat{E}^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ energy	✓	✓	✓
$\hat{p}_z^{\text{miss}}$	$E_{\text{T}}^{\text{miss}}$ component along z-axis	✓	✓	✓
$\hat{E}^{\text{miss}}$	magnitude of $E_{\text{T}}^{\text{miss}}$	✓	✓	✓
$p_{\text{T}}^{\text{tot}}$	transverse component of total momentum	✓	✓	✓
m_{coll}	collinear mass	✓	✓	✓
$\Delta\alpha$	see Eq. (1) [47]	✓	✓	✓
$m(\ell, \tau_{\text{had-vis}})$	invariant mass of light lepton and $\tau_{\text{had-vis}}$		✓	

Fake Factor Method (LFV Z —> τl)

The number of events from fakes in the SR is:

$$N_{\mathrm{SR}}^{\mathrm{fake}} = \sum_k \left(N_{\mathrm{SR,data}}^{\mathrm{fail}} - N_{\mathrm{SR,MC,not\ jet}\to\tau}^{\mathrm{fail}} \right)_k \times F_k,$$

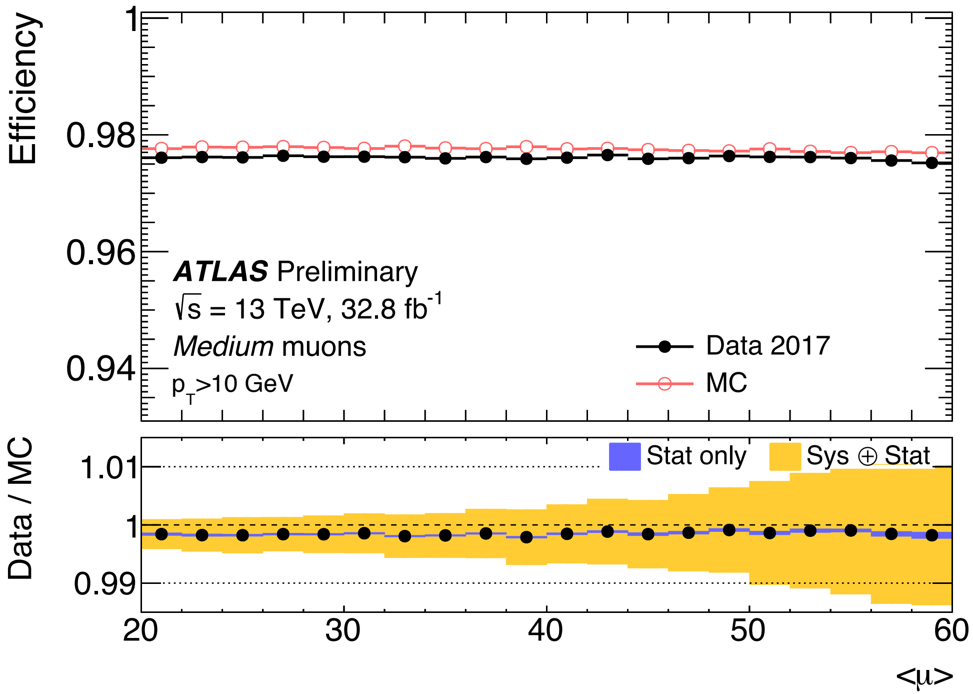
where F_k is the fake factor corresponding to the p_{T} (and track p_{T} for 1-prong $\tau_{\text{had-vis}}$) bin k, $N_{\mathrm{SR,data}}^{\mathrm{fail}}$ is the number of data events in the fail sideband in bin k, and $N_{\mathrm{SR,MC,not\ jet}\to\tau}^{\mathrm{fail}}$ is the number of events in the fail sideband in bin k for which the $\tau_{\text{had-vis}}$ candidate did not originate from a jet as predicted by simulation.

The sources of uncertainty in the estimate of the fake background are the statistical uncertainties in the F measurements in each bin, the statistical uncertainties of the data in the fail sideband and the uncertainty in R_i. All statistical uncertainties are treated as independent. The uncertainty in R_i is estimated by varying the estimated R_{W} by 50%, although this has a negligible impact on the sensitivity.

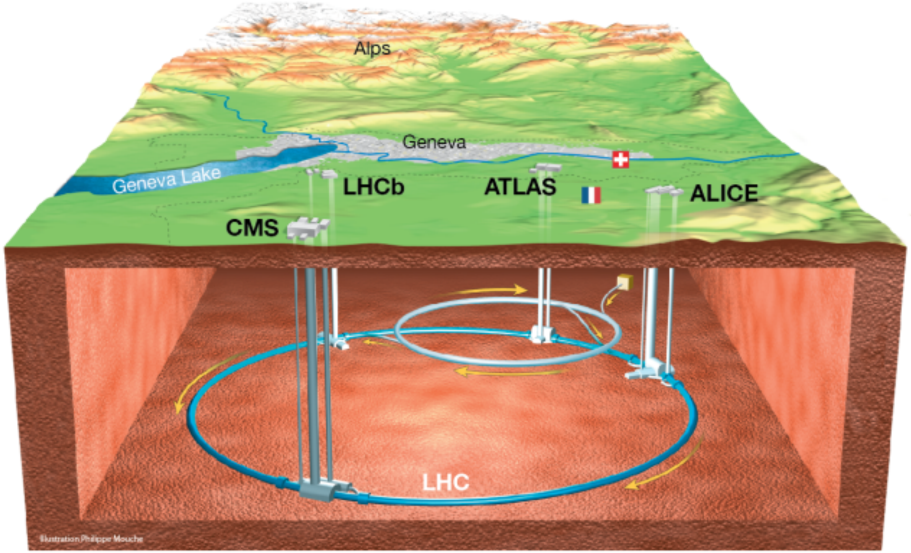
- F_k is measured in data as the ratio of the number of events where the $\tau_{\text{had-vis}}$ candidate passes the tight identification to the number of events where the $\tau_{\text{had-vis}}$ candidate fails in bins of the $\tau_{\text{had-vis}}$ p_{T}

Performance vs. Pileup

- For electron plot:
  - Errors are statistical and systematic
  - Lower efficiency in data than in MC arises from:
    - MC does not properly represent the 2016 TRT conditions
    - Known mismodelling of calorimeter shower shapes in the GEANT4 detector simulation
  - Both of these differences between data and MC were considered when optimising the likelihood-based selection criteria for 2016 data



The Large Hadron Collider (LHC)



- The LHC is a **proton-proton** collider
- **27 km** circumference
- 13 TeV center of mass **energy**
- 600 million collisions **per second**

- Accelerates protons **close to the speed of light**
- 4 **collision points**
- Kinetic energy stored in LHC ~

Muon Momentum Scale & Resolution

Energy loss in calorimeter and other materials (MS only)

Magnetic field integral and radial distortions of the detector

p_T scale bias ~ $\Delta s_0 + (1 + \Delta s_1) \cdot p_T$

p_T resolution ~ $\sqrt{(\Delta p_0 / p_T)^2 + \Delta p_1{}^2 + (\Delta p_2 \cdot p_T)^2)}$

Energy loss fluctuations in the material (MS only)

Multiple scattering, local radial distortions and local distortion of magnetic field

Intrinsic resolution and mis-alignments

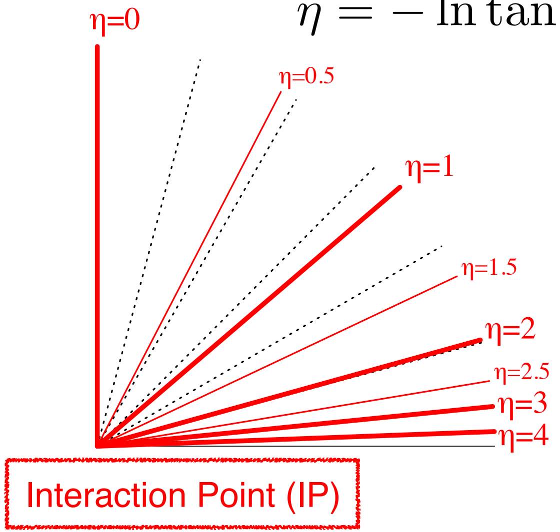
Muon Energy Loss

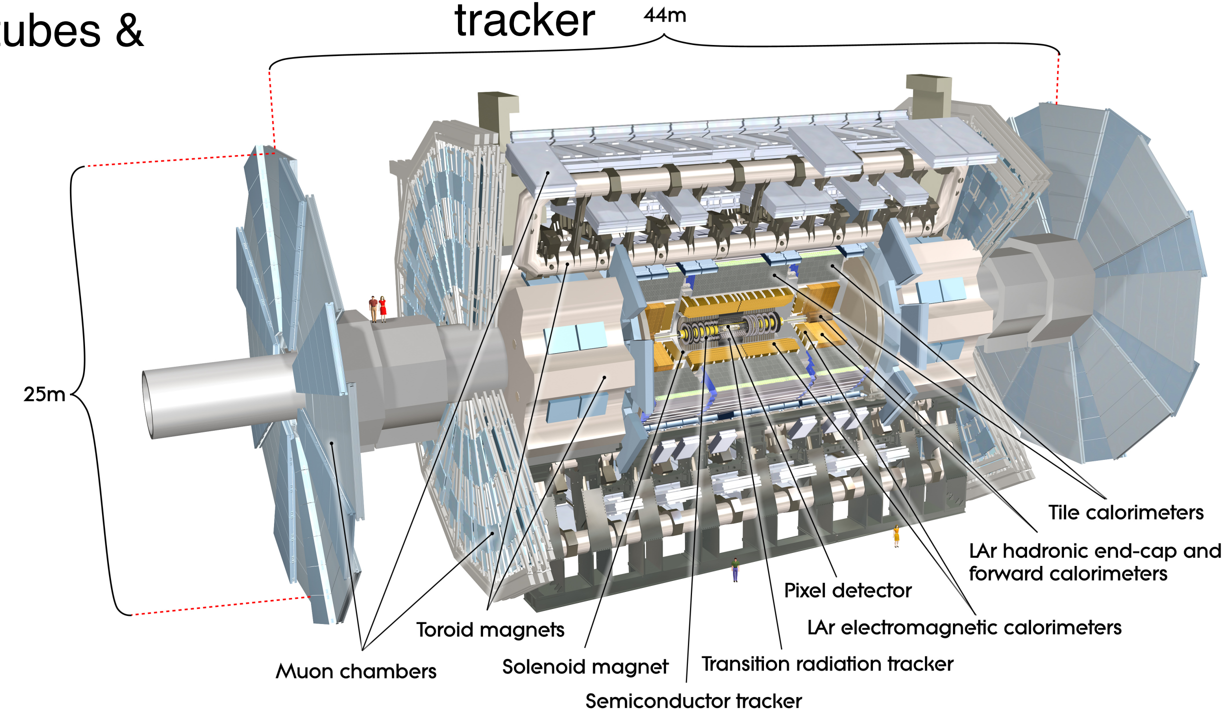
- Muon energy loss is estimated using a parametric function tuned based on the muon kinematics and the detector regions traversed; "ParamEnergyLoss".
- ParamEnergyLoss is used most of the time (>90%) when considering energy loss.
- Another way to estimate the muon energy loss is to measure the total energy deposition in calorimeter cells within a small cone around the muon; "MeasEnergyLoss".
- When MeasEnergyLoss >> ParamEnergyLoss, and the muon is isolated, MeasEnergyLoss is used in the muon reconstruction.

Muons In ATLAS

- Muon Spectrometer (MS): |η| < 2.7
  - Triggering: Resistive plate chambers & thin gap chambers
  - Tracking: Monitored drift tubes & cathode strip chambers
- Inner Detector (ID): |η| < 2.5
  - Silicon pixels, semiconductor tracker, and transition radiation tracker

$$\eta = -\ln\tan(\theta/2)$$

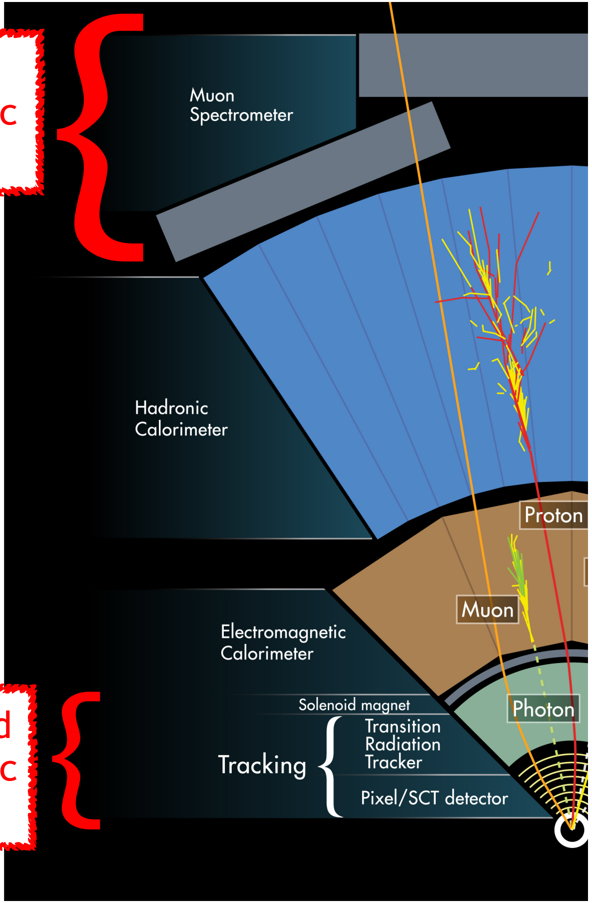




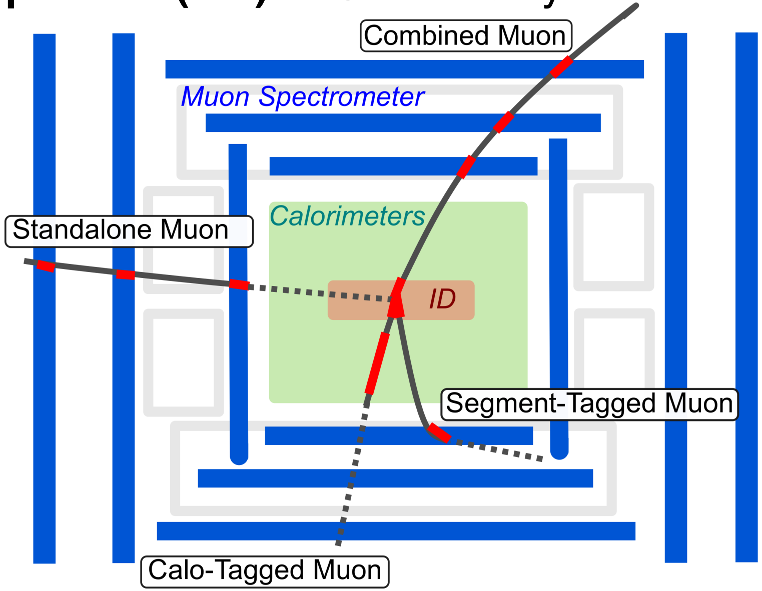
Muon Reconstruction Algorithms

Toroid Magnetic Field

Solenoid Magnetic Field



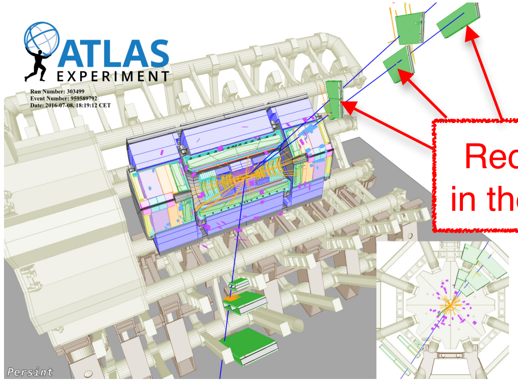
- **Combined (CB):** Global refit of ID + MS tracks
- **Segment-tagged (ST):** Track fit of ID + MS segment
- **Calorimeter-tagged (CT):** Track fit of ID + energy deposit in the calorimeter
- **Extrapolated (ME):** MS track only



Working Points

- **Loose:** Maximize reconstruction efficiency; uses all muon types
- **Medium:** Default selection for ATLAS; uses CB & ME muons
- **Tight:** Maximize purity; uses only CB & ME muons
- **Low-p_T:** Maximize efficiency and fake-rejection for $p_T < 5$ GeV
- **High-p_T:** Maximize momentum resolution for $p_T > 100$ GeV
- Optimization is on-going: Public results for high-p_T and low-p_T working points expected this summer

	$4 < p_T < 20$ GeV		$20 < p_T < 100$ GeV	
Selection	ϵ_μ^{MC} [%]	$\epsilon_{Hadrons}^{MC}$ [%]	ϵ_μ^{MC} [%]	$\epsilon_{Hadrons}^{MC}$ [%]
Loose	96.7	0.53	98.1	0.76
Medium	95.5	0.38	96.1	0.17
Tight	89.9	0.19	91.8	0.11
High-p_T	78.1	0.26	80.4	0.13



Require 3 stations in the MS at high-p_T

p_T Smearing & Scaling

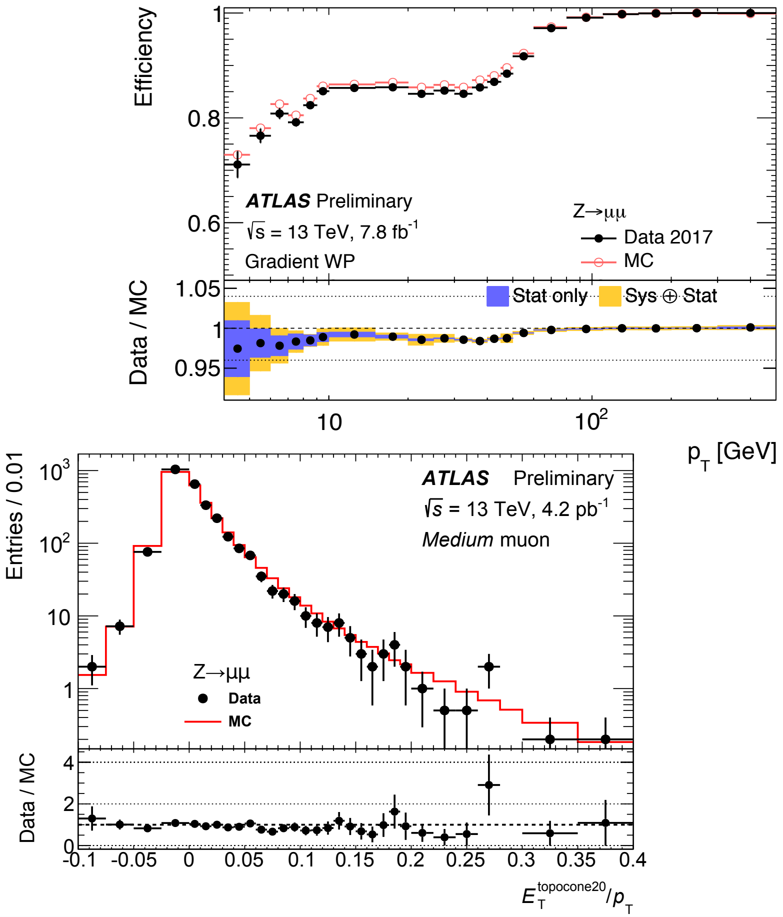
- Muon momentum is calculated using

$$\mathrm{p}_{\mathrm{T}}^{\mathrm{Cor,Det}} = \frac{\mathrm{p}_{\mathrm{T}}^{\mathrm{MC,Det}} + \sum_{n=0}^{1} s_n^{\mathrm{Det}}(\eta,\phi)\left(\mathrm{p}_{\mathrm{T}}^{\mathrm{MC,Det}}\right)^n}{1 + \sum_{m=0}^{2} \Delta r_m^{\mathrm{Det}}(\eta,\phi)\left(\mathrm{p}_{\mathrm{T}}^{\mathrm{MC,Det}}\right)^{m-1} g_m}$$

where Det ∈ [ID, MS], g_m is a normally distributed random variables with zero mean and unit width, $\Delta r_m^{Det}(\eta,\phi)$ describes the momentum resolution smearing, and $s_n^{Det}(\eta,\phi)$ describes the scale corrections

Isolation Variables

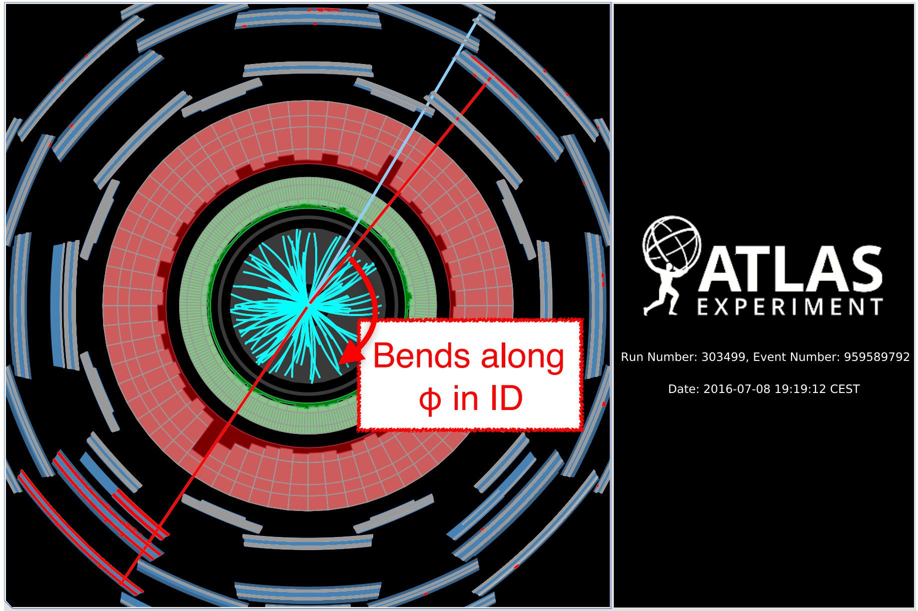
- $p_T^{varcone30}$: scalar sum of p_T of the tracks with $p_T > 1$ GeV in a cone of size $\Delta R = \min(10\ \text{GeV}/p_T, 0.3)$ around the muon
- $E_T^{topocone20}$: sum of the transverse energy of topological clusters in cone of size $\Delta R = 0.2$ around the muon

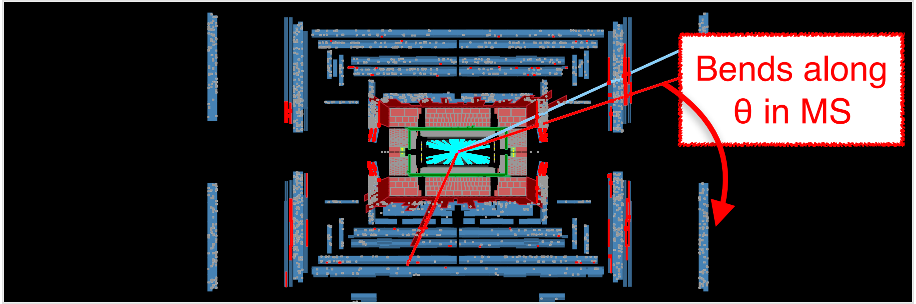


Muon Reconstruction Basics

- From the track fit, get M = (d_0, z_0, ϕ, θ, q/p)
- Inner Detector (ID) track has very precise hits close to the Interaction Point (IP), which helps to constrain d_0/z_0 and angles
- Muon Spectrometer (MS) track has better q/p resolution at high-p_T due to longer lever arm
- Combining ID and MS hits guarantees the best p_T determination

$$\mathrm{p_T} = p \sin\theta = \frac{\sin\theta}{|q/p|}$$





Continuously Improving ATLAS Software

- **Old Reconstruction**
  - Final track errors inflated to account for alignment uncertainties; chamber deweighted
  - Only in specific "critical" situations: Barrel/ Endcap and Small/Large sector overlap regions, misaligned chambers, etc.
- **New Reconstruction**
  - Fit the alignment discontinuities
    - ⟹ More realistic errors on q/p measurement
    - ⟹ Might allow recovery of vetoed MS regions for high-p_T muons
  - Possible using `AlignmentEffectOnTrack` (AEOT): specifies position and angle uncertainties on chamber hits
  - Track fit performed using **gaussian constraint** on chamber hits where alignment uncertainties are used as gaussian widths