Missing Transverse Momentum Reconstruction at ATLAS

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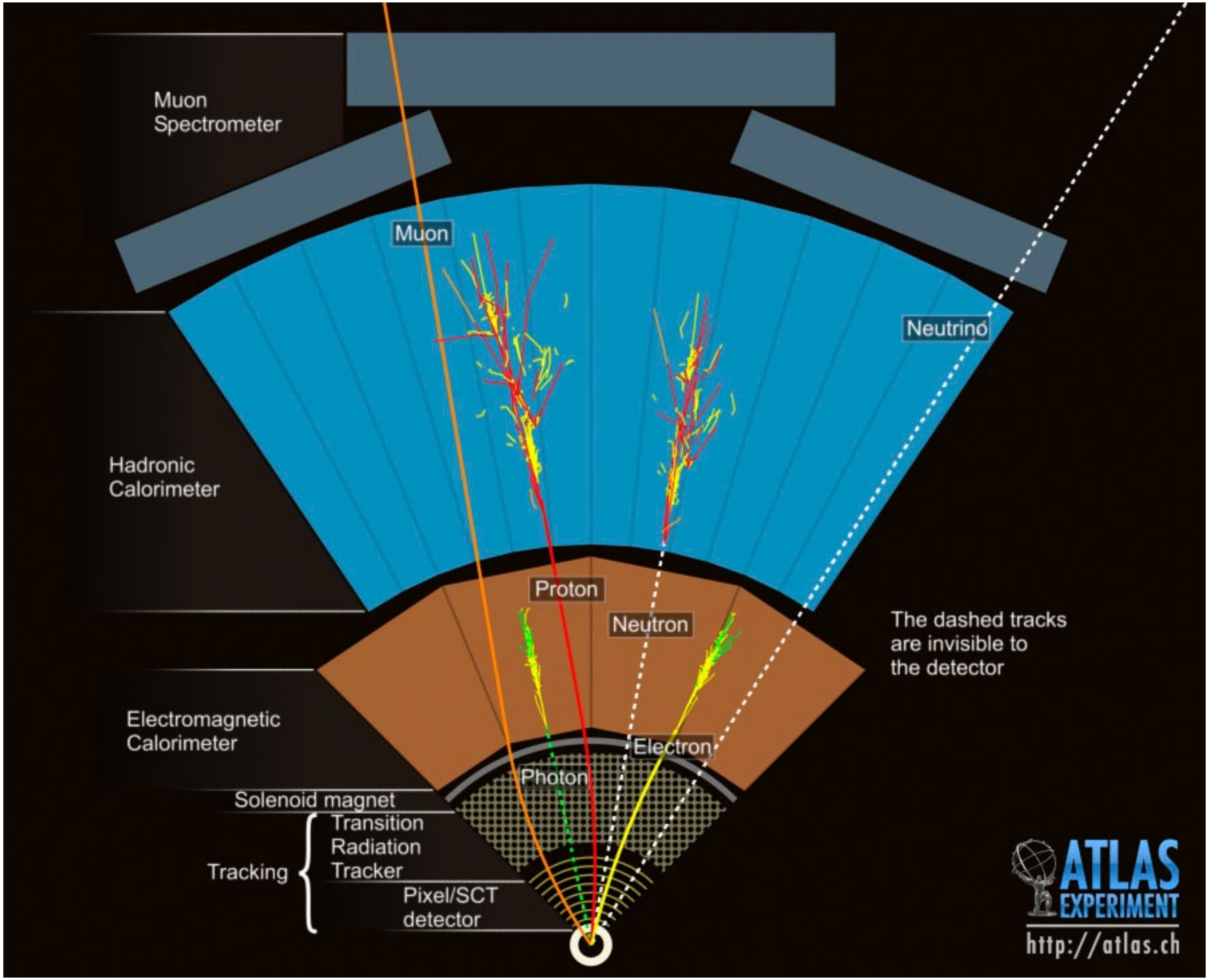
High Energy Particle Physics Workshop 2015

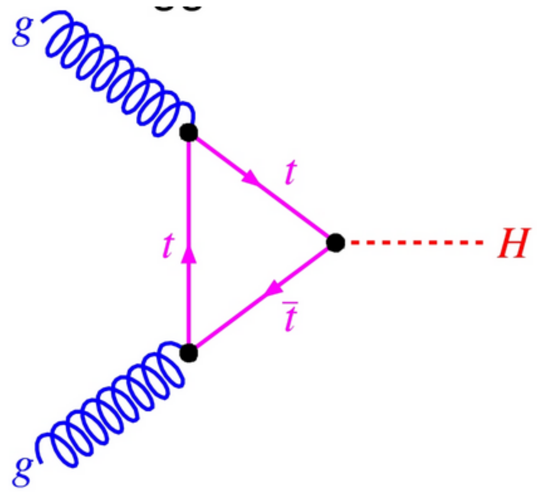
Why Missing Energy?

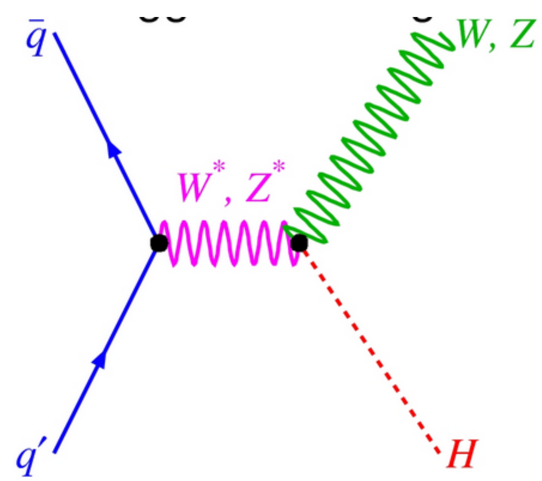


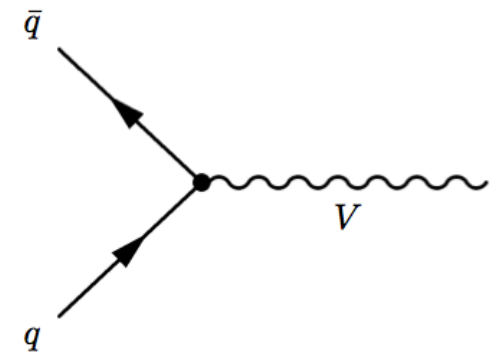
- Events with neutrinos:
  - W, Z (top, Higgs)
- New physics
  - SUSY
  - "dark" sector particles
- All show signal of "missing" momentum in the detector

Proton-Proton Physics at Hadron Colliders

- We're used to looking at diagrams of the form: (ggF & associated Higgs production, LO V boson production)

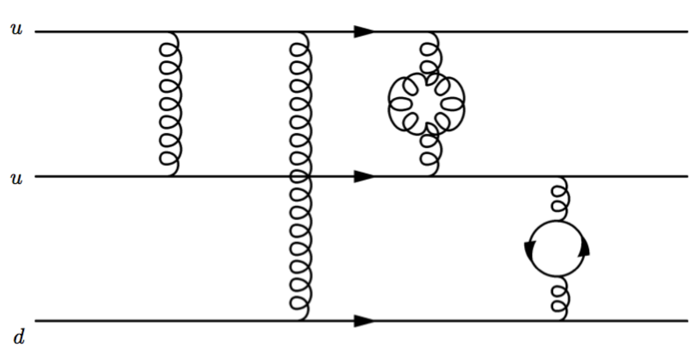


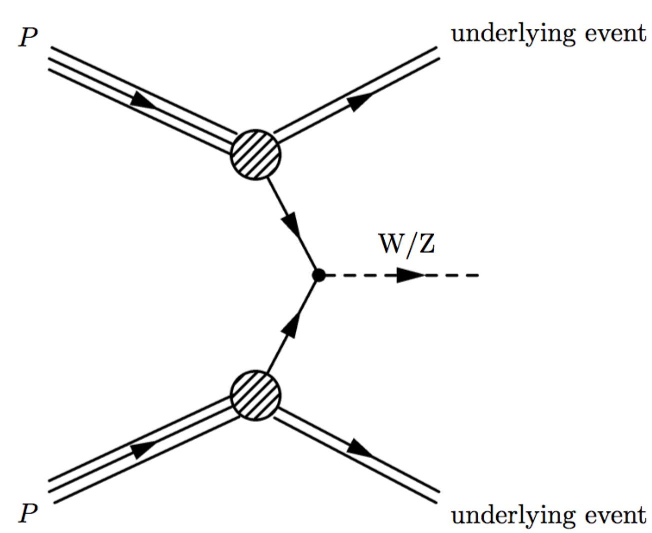


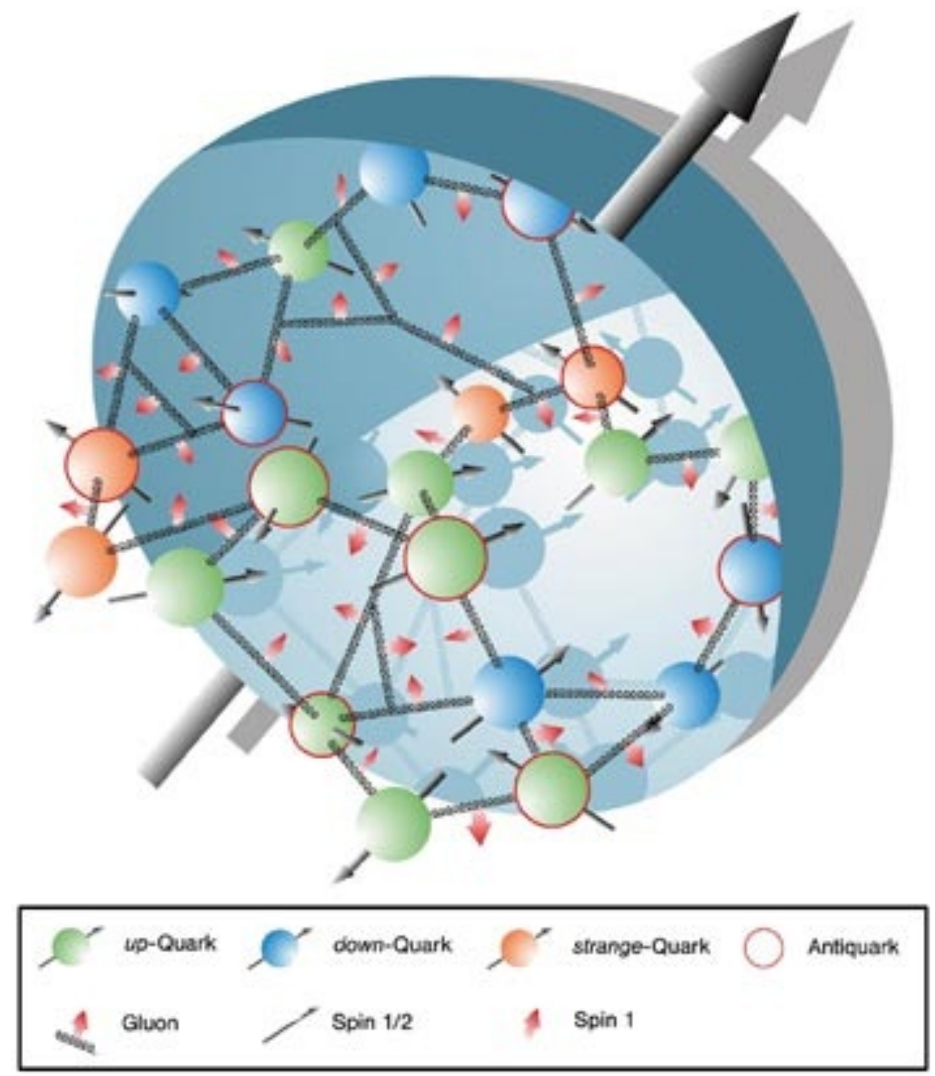


  - where we only consider the individual partons involved in the hard interaction.

- In reality, what happens in a pp collision is much messier:







We only know the total energy of the proton, not the energy of the individual partons

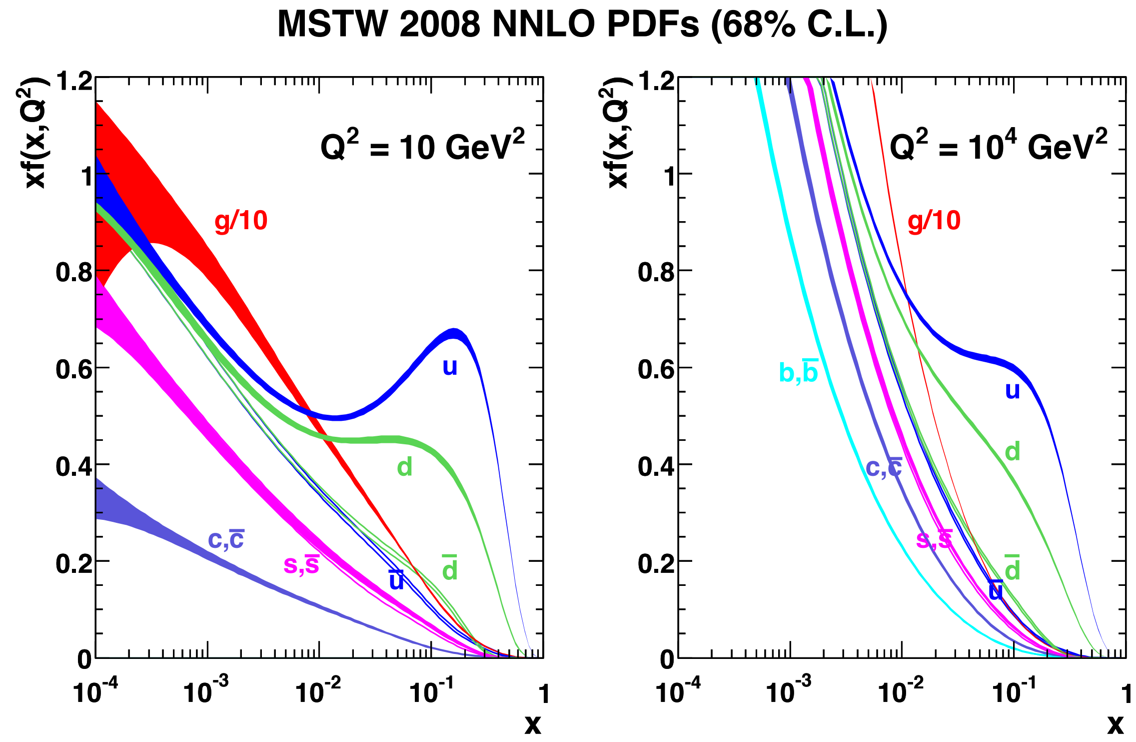
Proton structure functions & Transverse Momentum

- The proton structure functions are functions of the energy scale and the fraction of the momentum of the proton carried by the individual parton.
- These structure functions can be written as a sum over the PDFs.

$$F_2(x,Q^2) = \sum_i e_i^2 f_i(x,Q^2)x$$

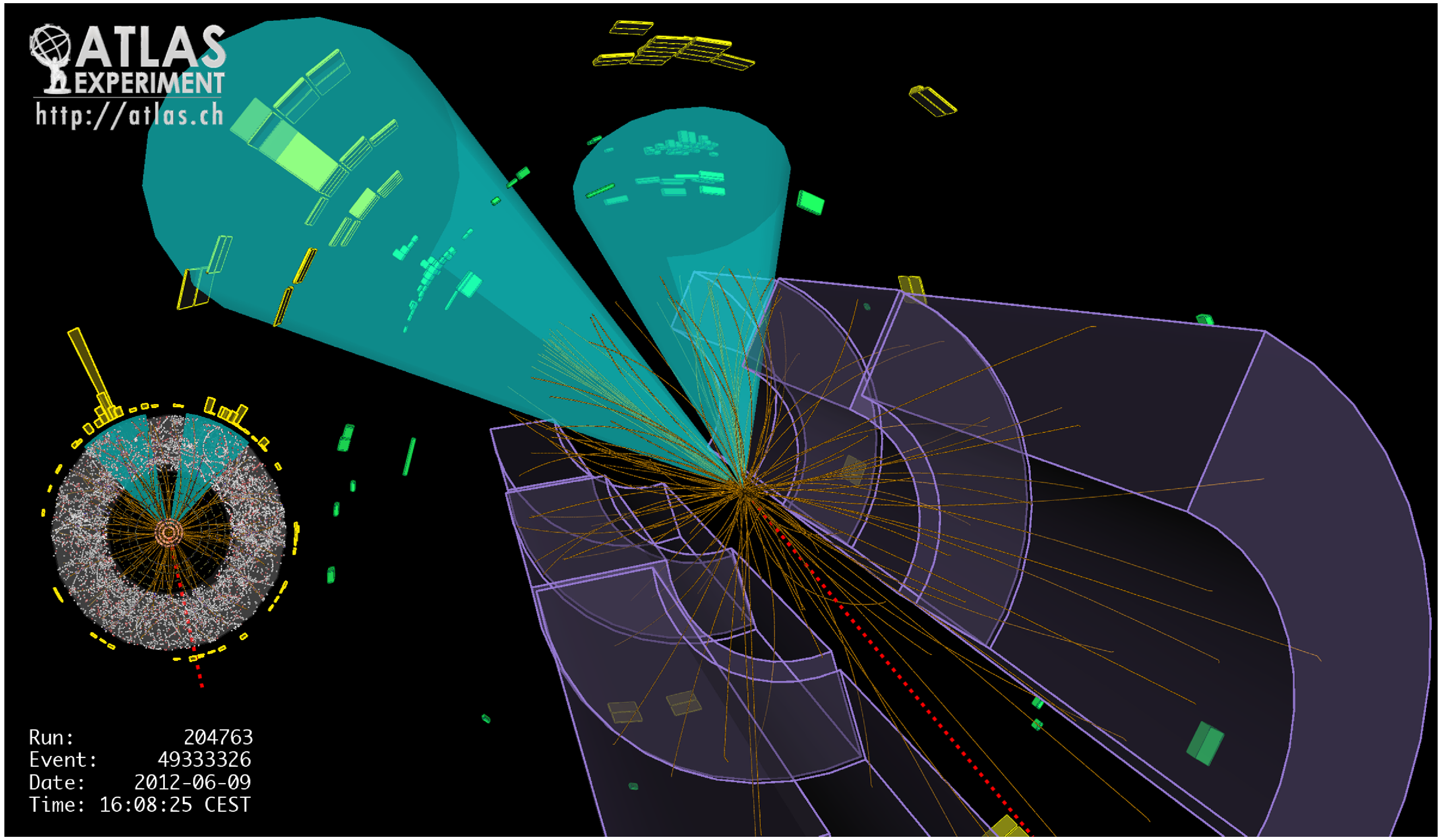
$$x = \frac{p_i}{\sqrt{s}/2}$$

Larger x: valence quarks dominate
Small x: contributions from qqbar sea become important



- Since the momenta of the interacting partons is not known, a complete measurement of the energy of the event is not possible
- However, the initial transverse momentum of the partons is approximately 0 wrt beam energy
- Therefore, the total resultant transverse momentum should also be zero - as long as you take the effects from both the hard interaction, and the underlying event into account.

Measuring energy in ATLAS (ETmiss)



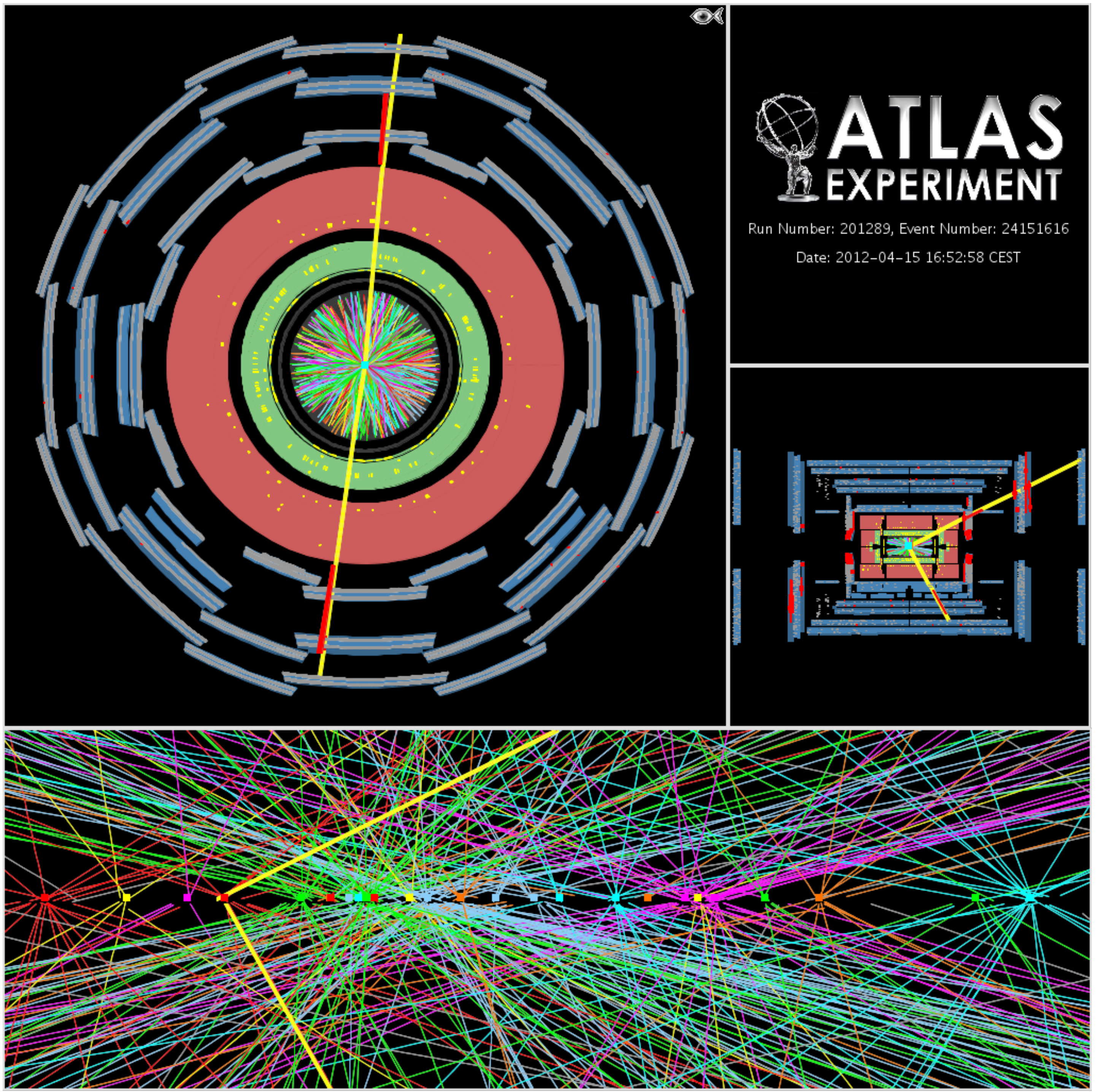
Advantage: provides a complete measurement of the magnitude of the missing energy from all events (vertices)

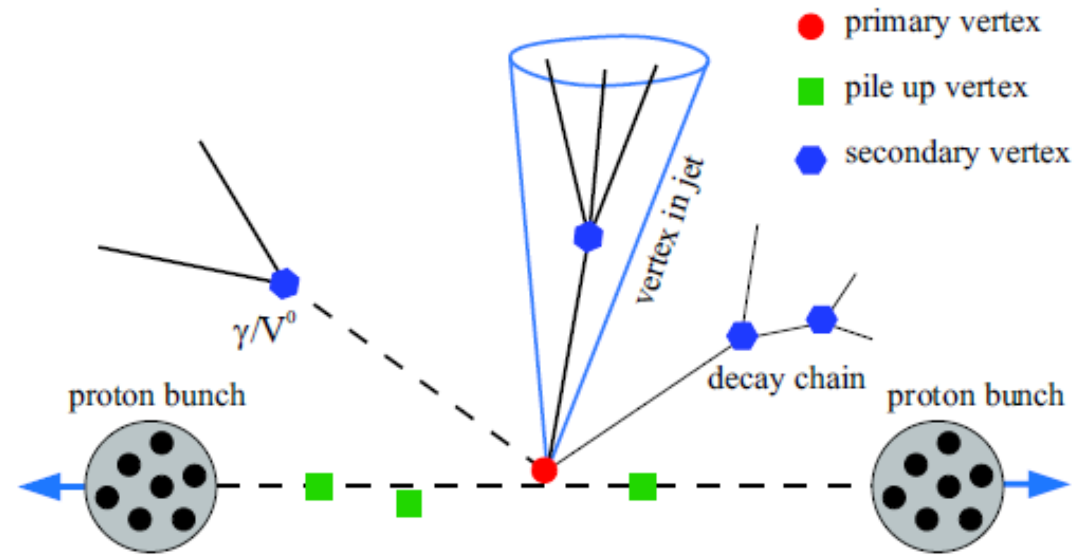
$$E_{x,y}^{\text{miss}} = E_{x,y}^{\text{miss},\ e} + E_{x,y}^{\text{miss},\ \gamma} + E_{x,y}^{\text{miss},\ \tau_{had}} + E_{x,y}^{\text{miss},\ jets} + E_{x,y}^{\text{miss},\ \mu} + E_{x,y}^{\text{miss},\ soft\ term}$$

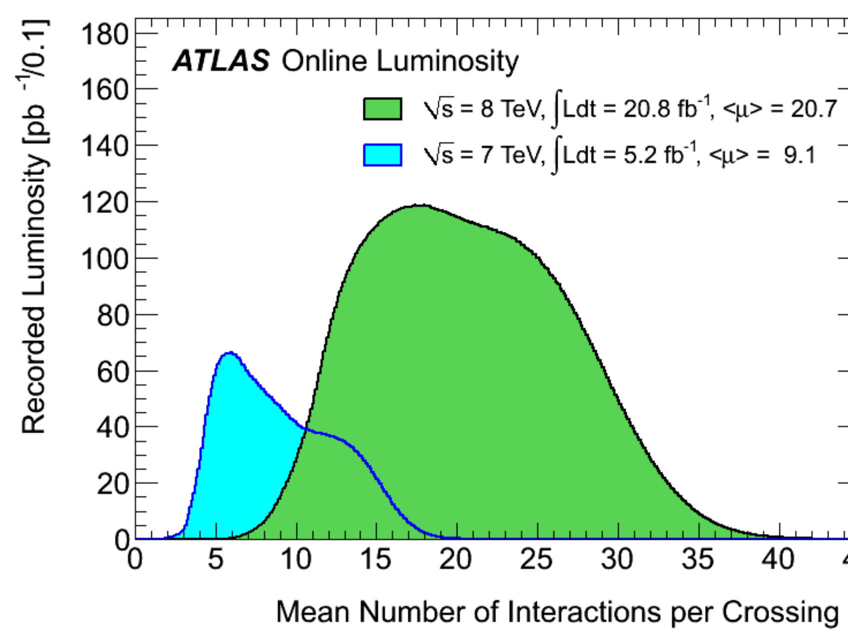
$$E_{\text{T}}^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}$$

$$\sum E_T = \sum E_{\text{T}}^{e} + \sum E_{\text{T}}^{\gamma} + \sum E_{\text{T}}^{\tau_{had}} + \sum E_{\text{T}}^{jets} + \sum p_{\text{T}}^{\mu} + \sum E_{\text{T}}^{soft\ term}$$

The problem of pileup







- A candidate Z boson decaying to a muon pair, with 25 reconstructed vertices in the event, recorded on April 15th 2012

Instead, use the tracks

- Select general objects such as electrons, muons and jets
  - 6 GeV "combined" muons
  - 10 GeV "medium" electrons
  - 25 (30) GeV jets from PV
  - Find their associated tracks, and group them in separate terms

- For all other tracks in the event, select the ones that pass the following cuts:

pT > 500 MeV	$|\eta| < 2.5$
at least 1 pixel hit	$|d0_wrtPV| < 1.5$mm
at least 6 SCT hits	$|z0\sin\theta_wrtPV| < 1.5$mm

These get grouped into a soft track term

- Apply extra cuts for "specialised cases"
  - cleaning up tracks around high pT electrons (UE and photon conversions)
  - fake very high pT tracks in dense jets
  - general tracks with very high misreconstructed pT (check q/p and calorimeter deposit

Track-based ETmiss (ie pTmiss) Reconstruction

- The pTmiss can then be calculated in a similar way to the ETmiss:

$$p_{x,y}^{\mathrm{miss,nominal}} = -\left(\sum_{electron\ tracks} p_{x,y} + \sum_{muon\ tracks} p_{x,y} + \sum_{jet\ tracks} p_{x,y} + \sum_{soft\ tracks} p_{x,y} \right)$$

$$\sum p_{T}^{\mathrm{nominal}} = \sum_{electron\ tracks} p_{\mathrm{T}} + \sum_{muon\ tracks} p_{\mathrm{T}} + \sum_{jet\ tracks} p_{\mathrm{T}} + \sum_{soft\ tracks} p_{\mathrm{T}}$$

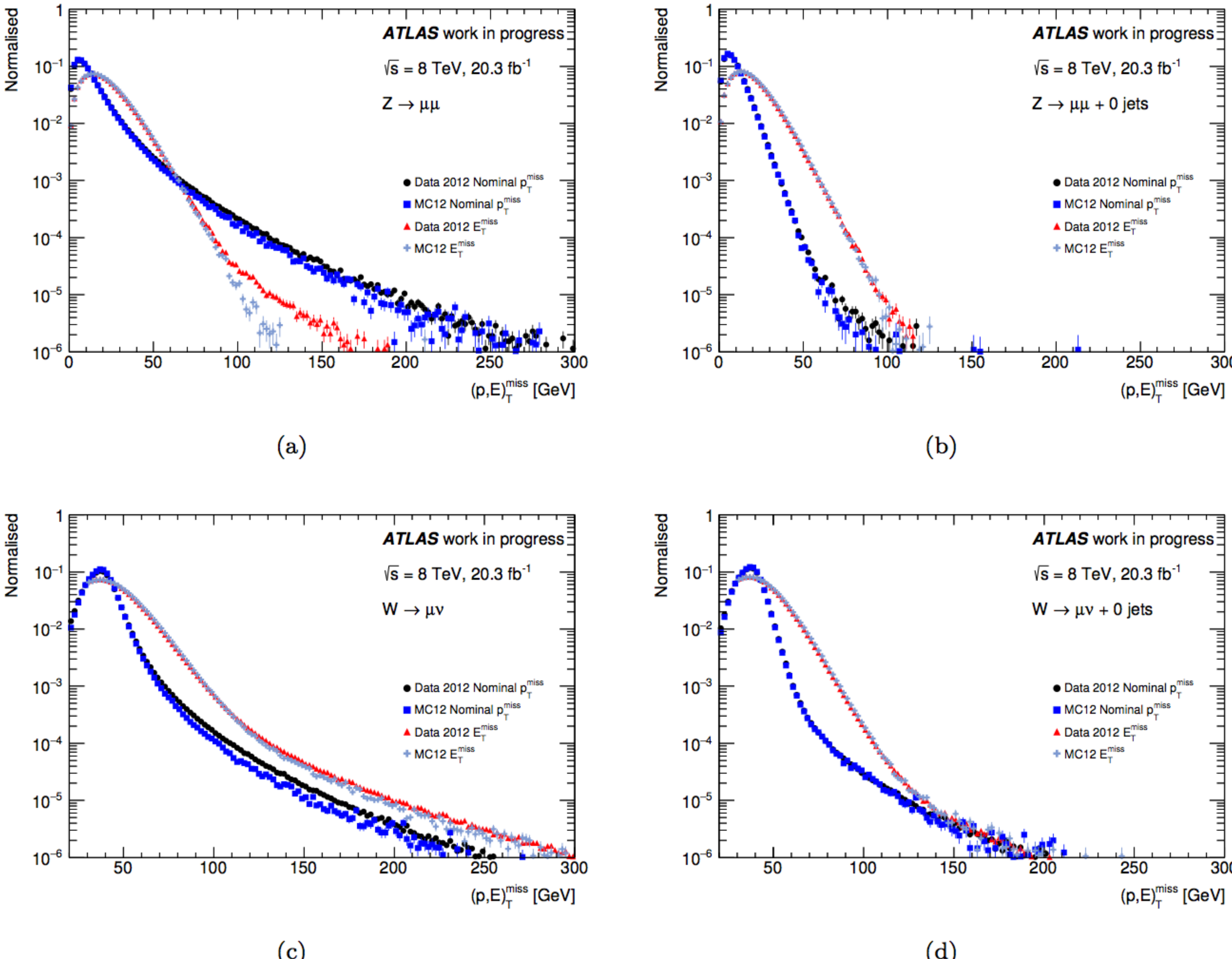
- with

$$p_{T}^{\mathrm{miss,nominal}} = \sqrt{\left(p_{x}^{\mathrm{miss,nominal}}\right)^{2} + \left(p_{y}^{\mathrm{miss,nominal}}\right)^{2}}$$

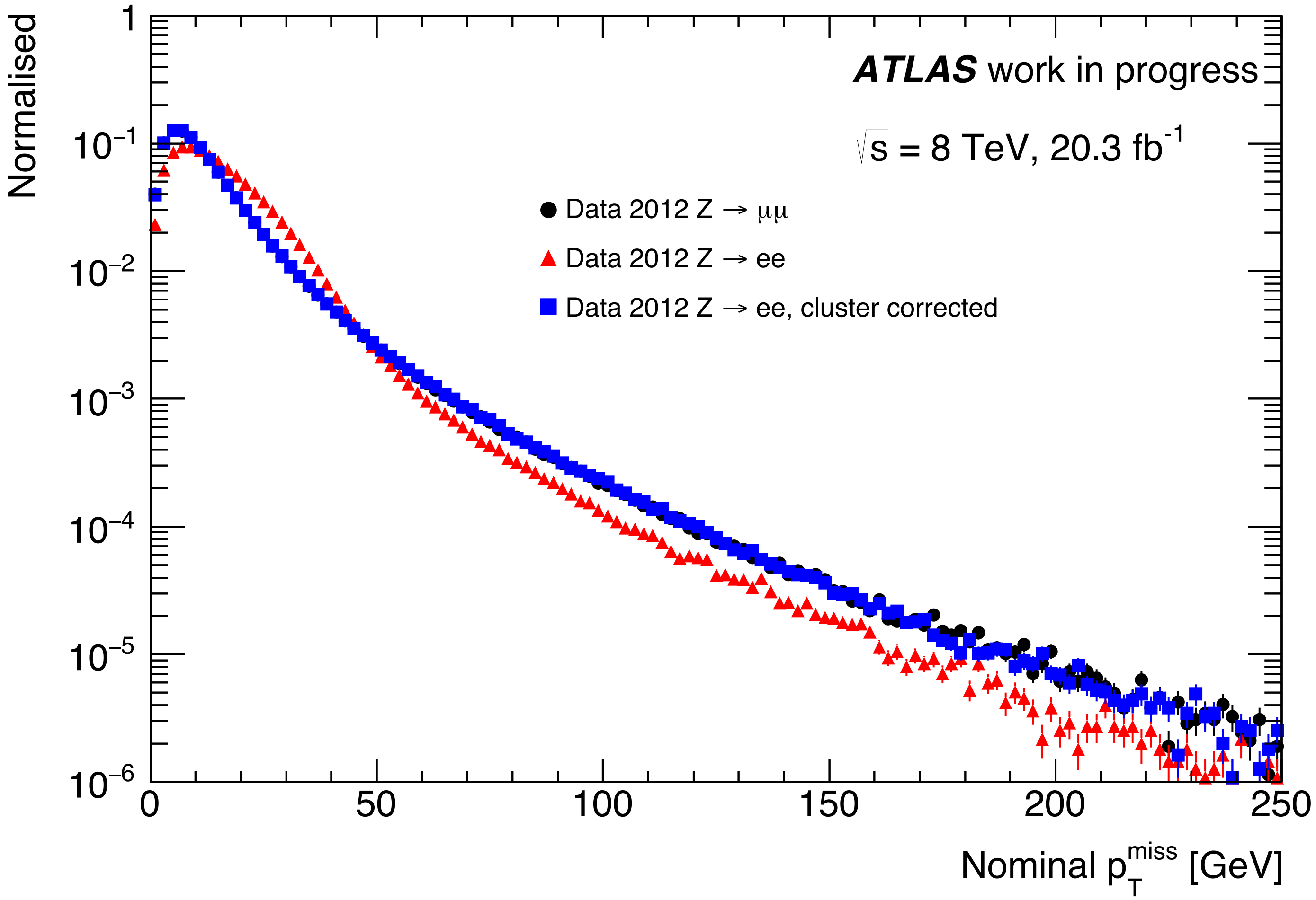
Advantage: Provides a measurement of the MET from the signal vertex only

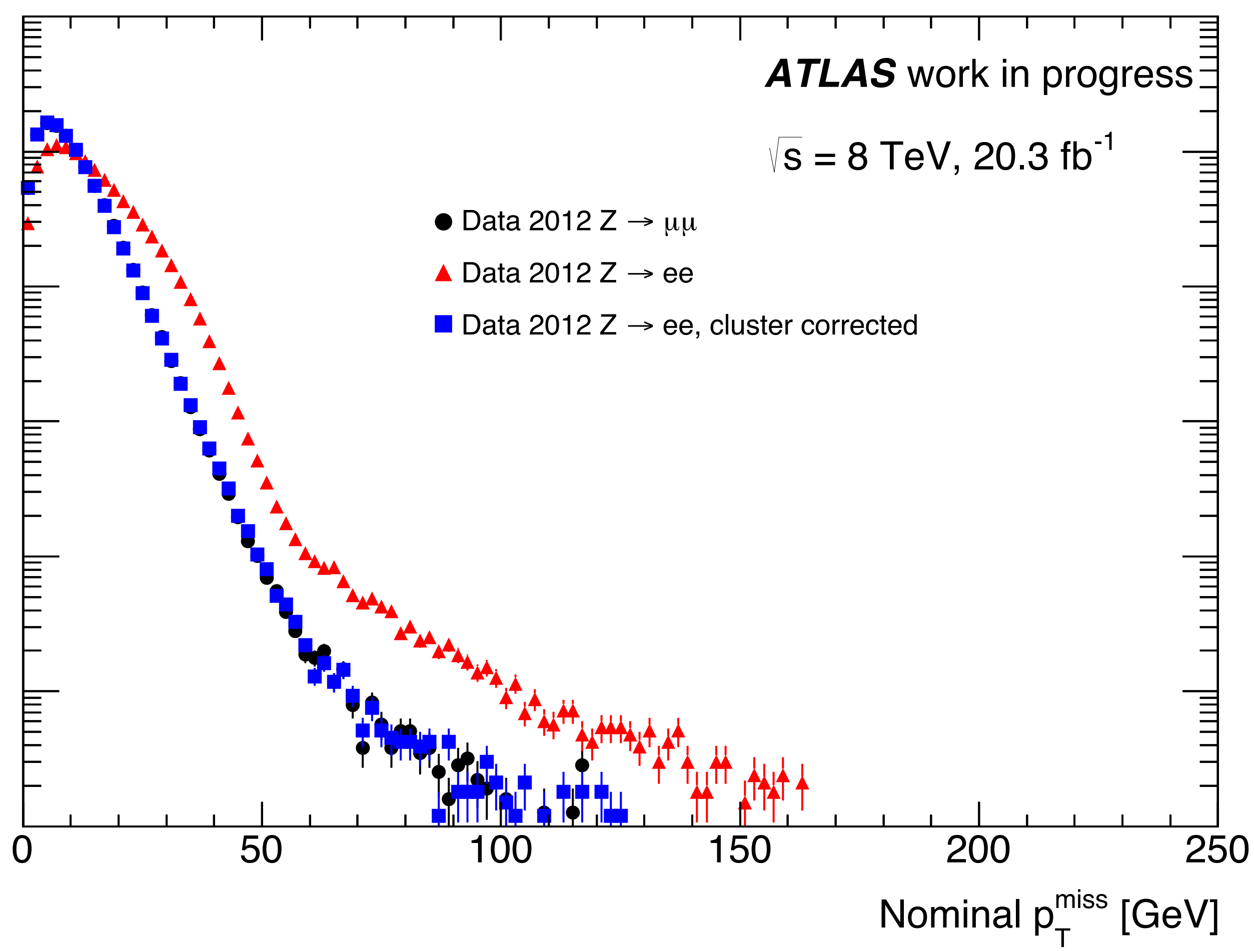
Disadvantage: Restricted to charged particles and ID acceptance

ETmiss and pTmiss for W and Z events

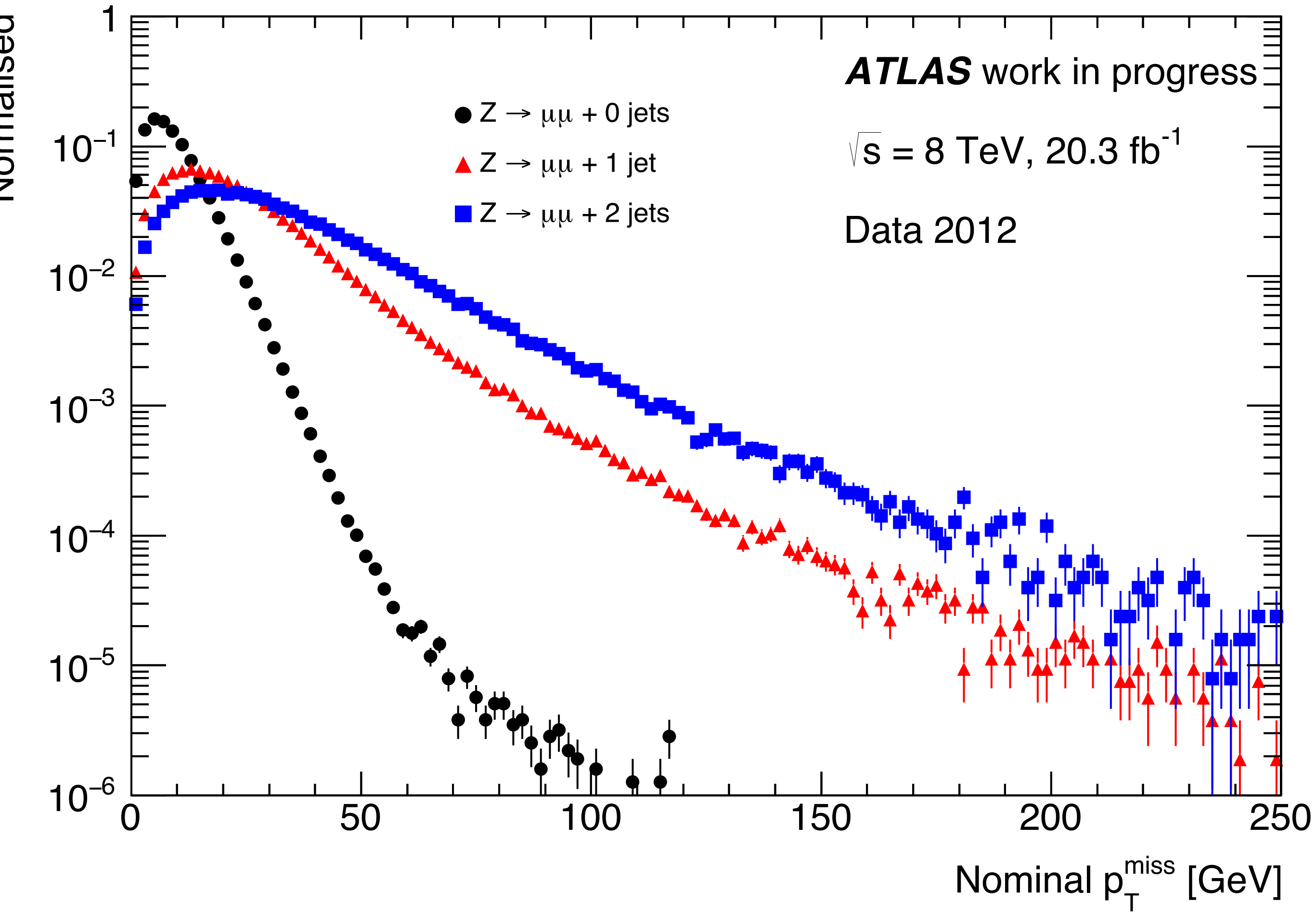


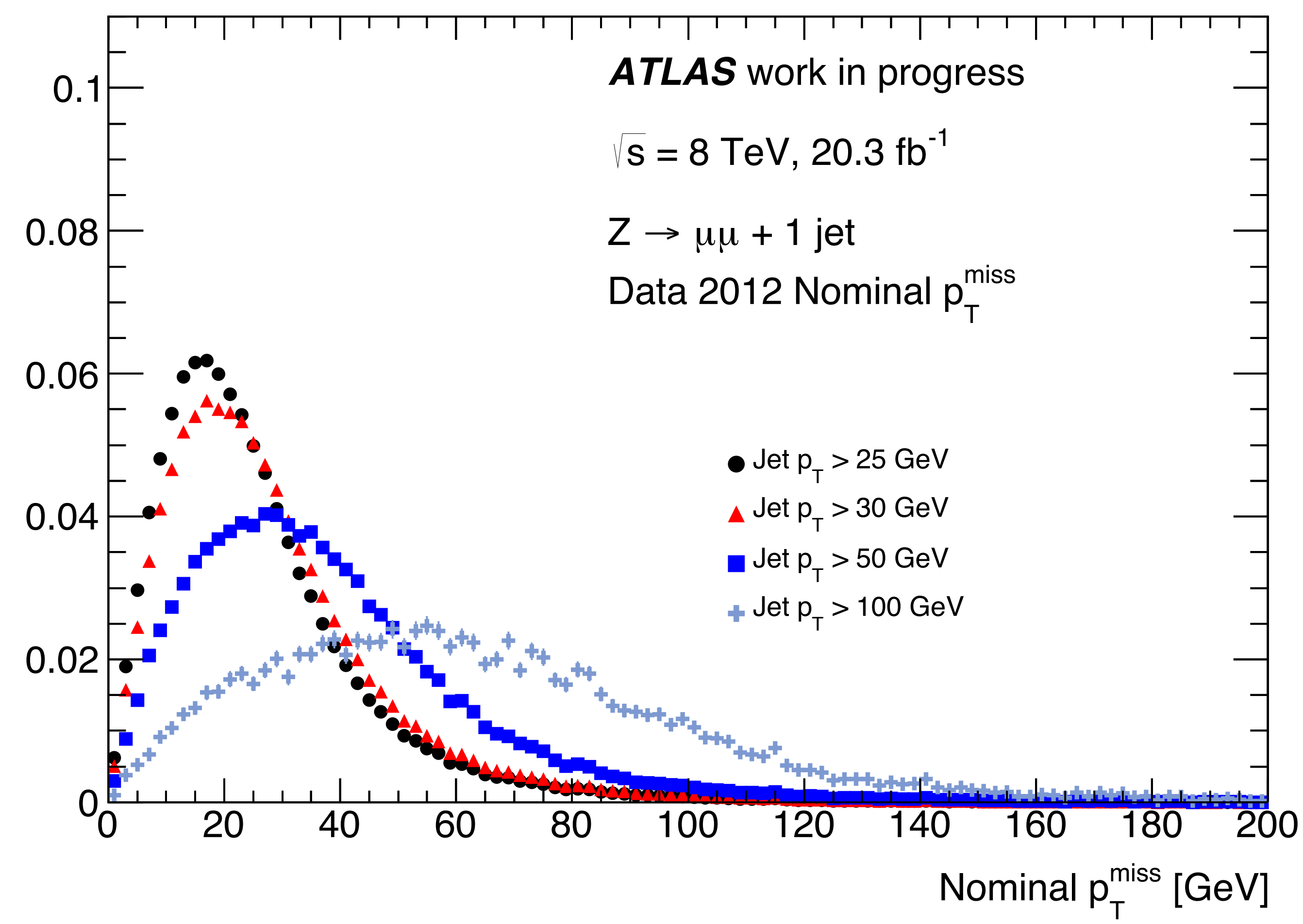
Electrons vs muons





and jets…


ATLAS work in progress
√s = 8 TeV, 20.3 fb-1
Data 2012
Z → μμ + 0 jets
Z → μμ + 1 jet
Z → μμ + 2 jets
Normalised
Nominal p_T^{miss} [GeV]


ATLAS work in progress
√s = 8 TeV, 20.3 fb-1
Z → μμ + 1 jet
Data 2012 Nominal p_T^{miss}
Jet p_T > 25 GeV
Jet p_T > 30 GeV
Jet p_T > 50 GeV
Jet p_T > 100 GeV
Nominal p_T^{miss} [GeV]

Object-corrected pTmiss

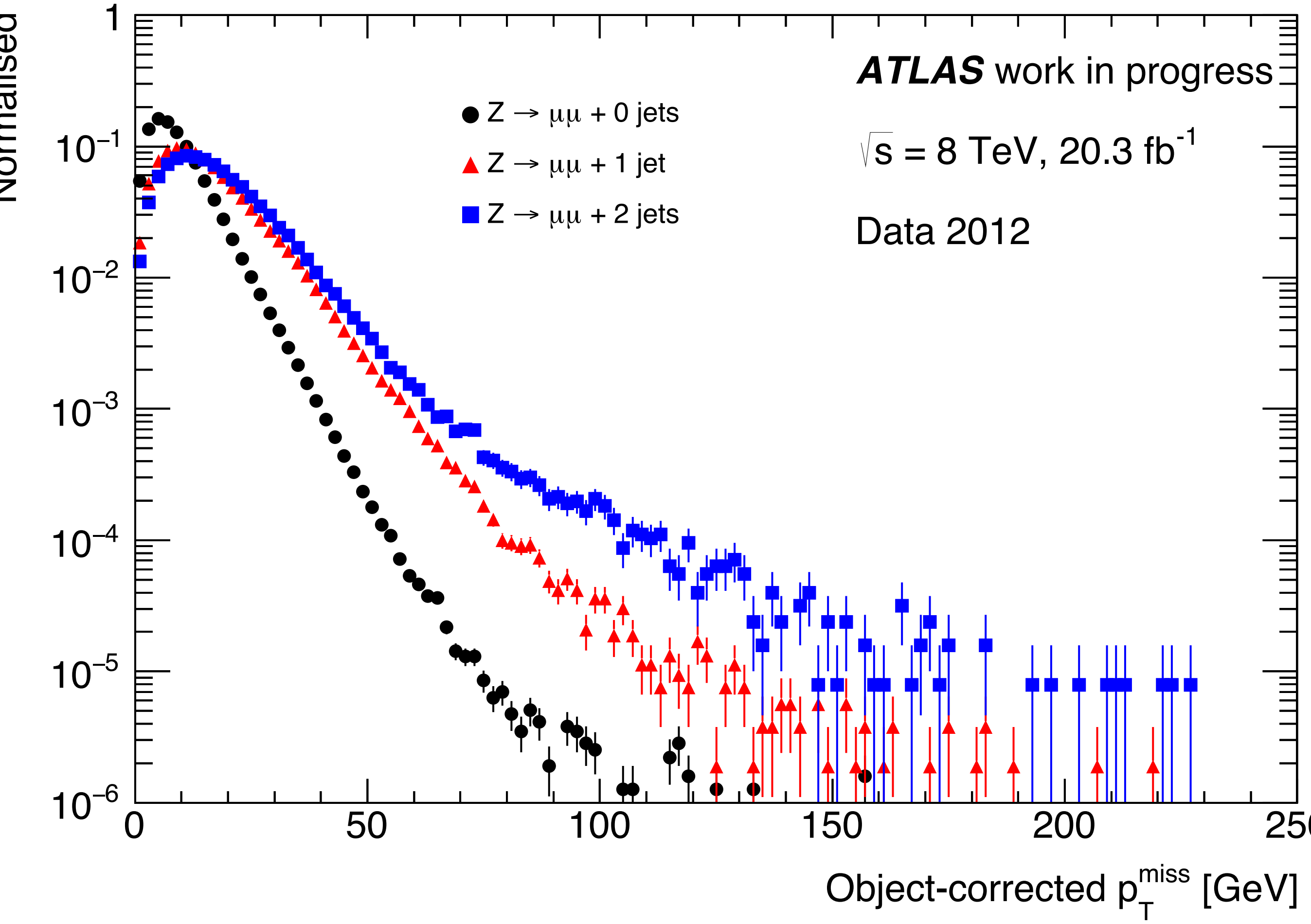
- Here, we replace the tracks of all hard objects with their fully reconstructed terms, taking advantage of the better, more complete pT measurement by the ATLAS detector

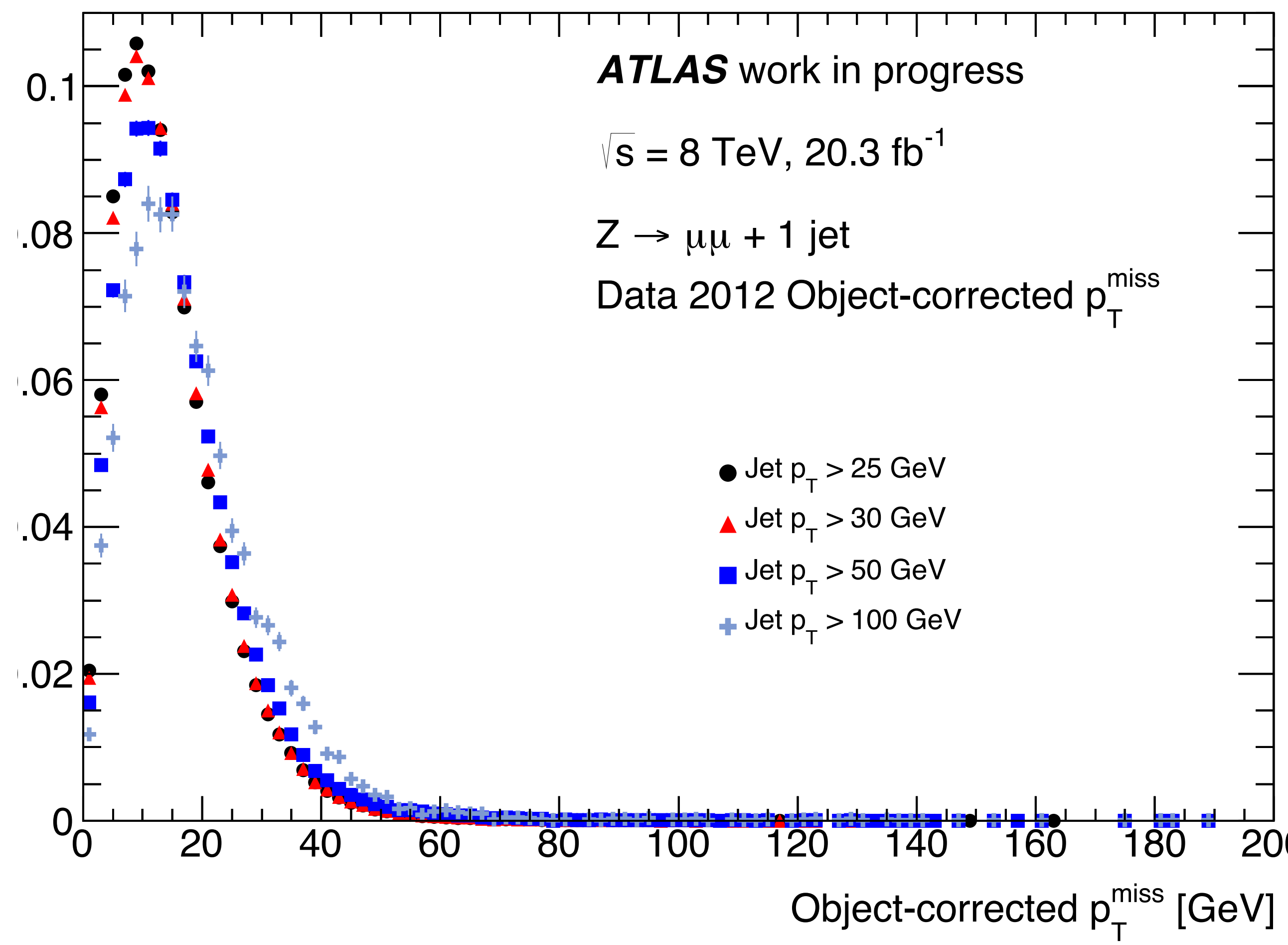
$$p_{x,y}^{\mathrm{miss,object}} = -\left(\sum_{electron\ object} p_{x,y} + \sum_{muon\ object} p_{x,y} + \sum_{jet\ object} p_{x,y} + \sum_{soft\ tracks} p_{x,y} \right)$$

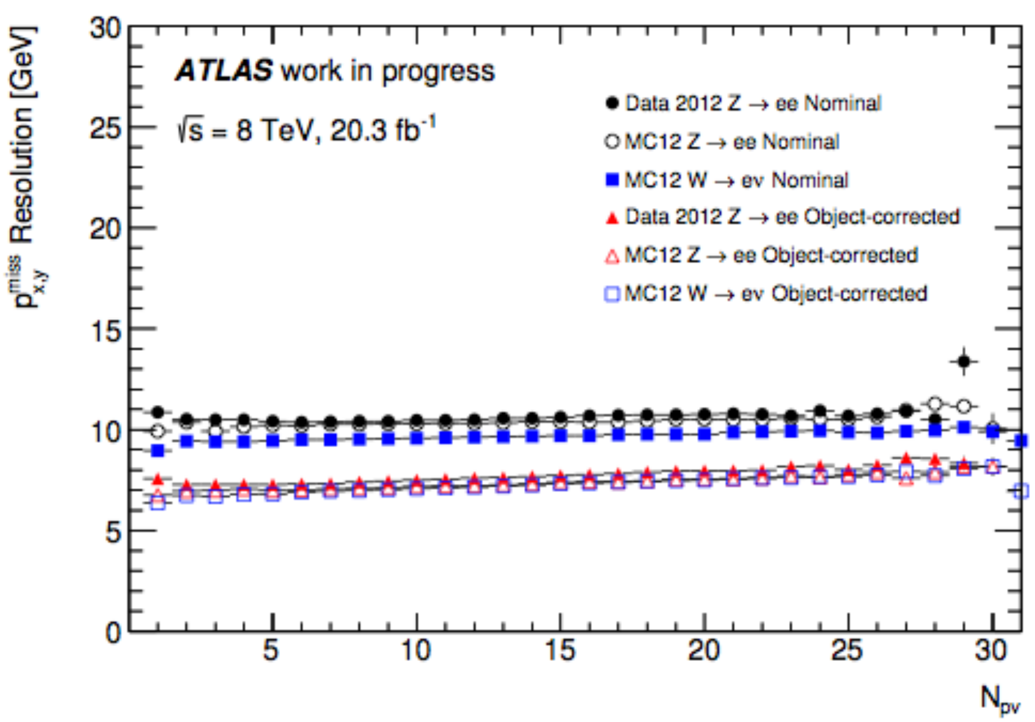
$$\sum p_T^{\mathrm{object}} = \sum_{electron\ object} p_{\mathrm{T}} + \sum_{muon\ object} p_{\mathrm{T}} + \sum_{jet\ object} p_{\mathrm{T}} + \sum_{soft\ tracks} p_{\mathrm{T}}$$

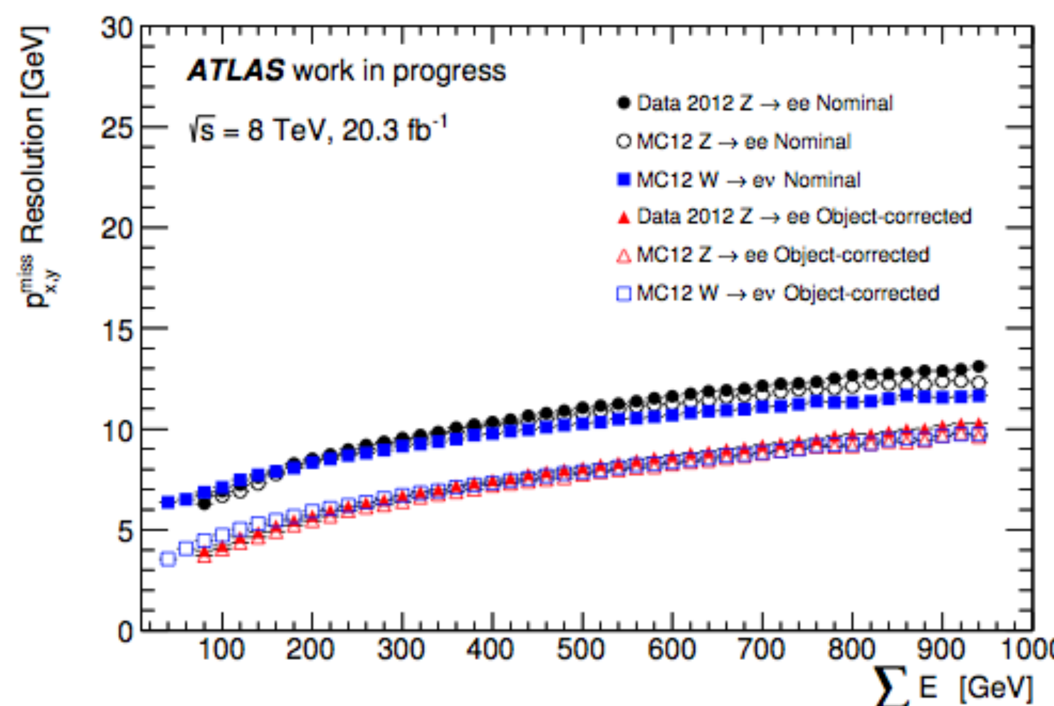
$$p_T^{\mathrm{miss,object}} = \sqrt{\left(p_x^{\mathrm{miss,object}}\right)^2 + \left(p_y^{\mathrm{miss,object}}\right)^2}$$

- Provides a (generally) better pTmiss measurement that is still pileup-robust
- Inspired the development of the "Track Soft Term" ETmiss which is now the default ETmiss measurement in ATLAS





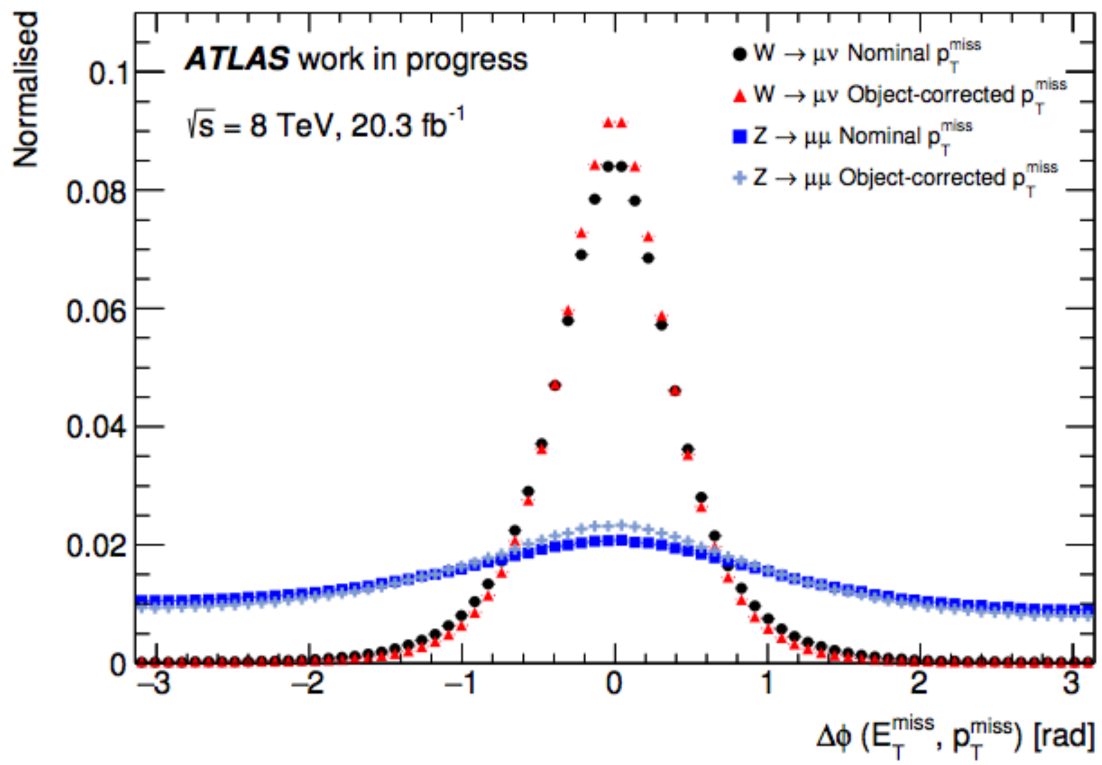




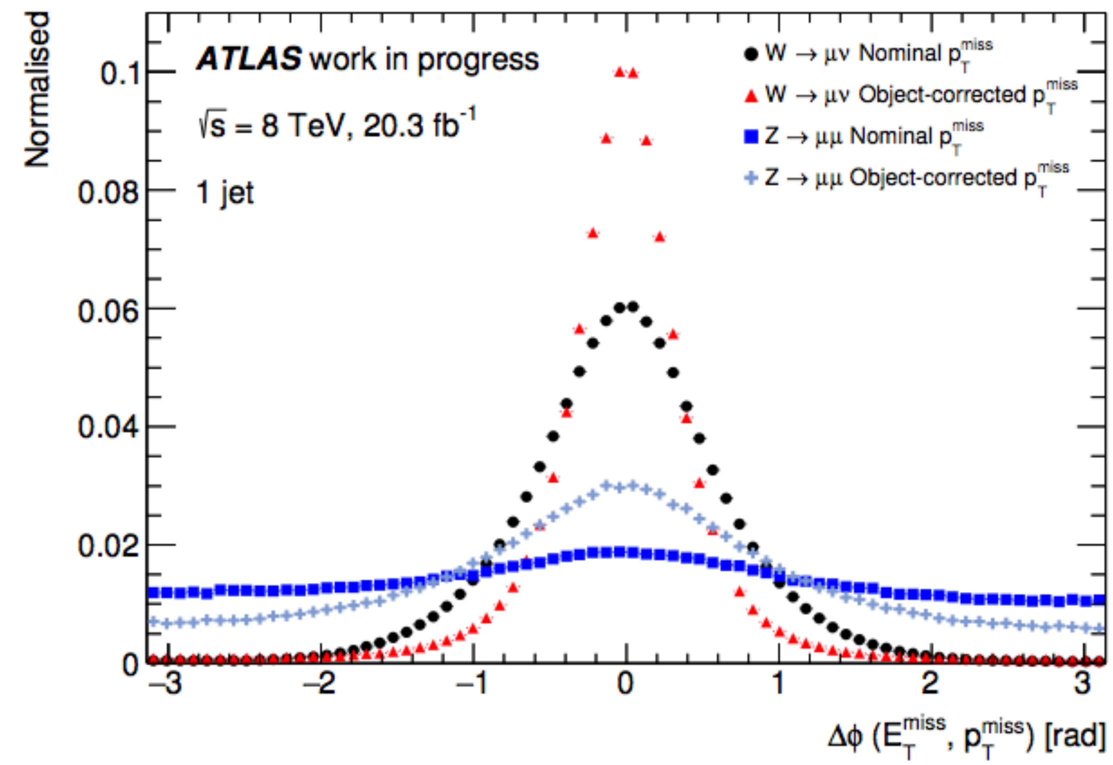
- Resolution shows stability with pileup

ATLAS EXPERIMENT

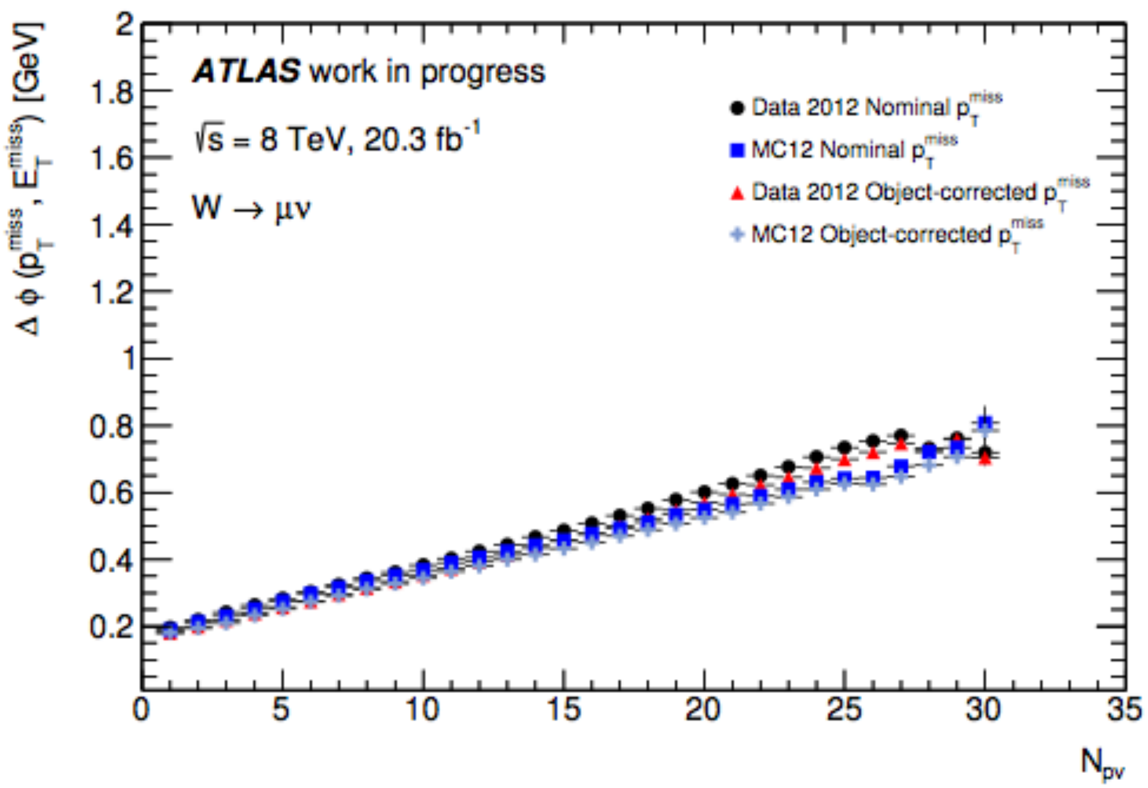
Direction



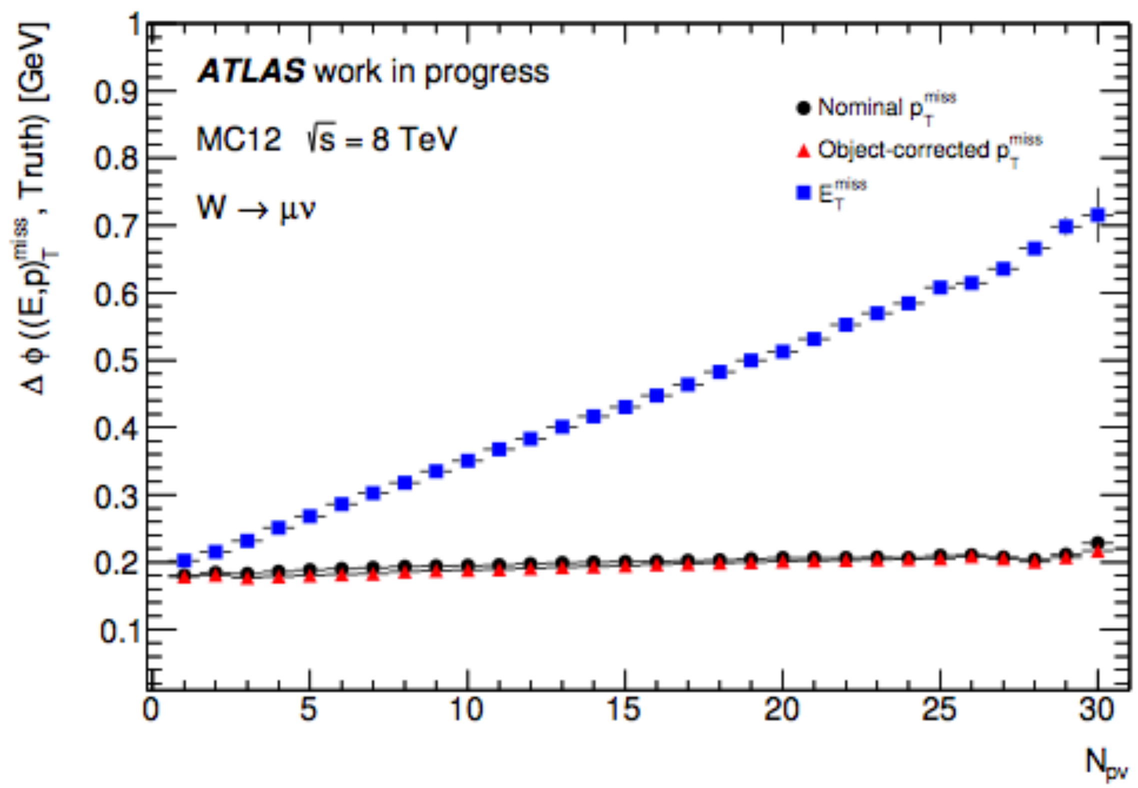
ATLAS work in progress
√s = 8 TeV, 20.3 fb⁻¹
W → μν Nominal p_T^{miss}
W → μν Object-corrected p_T^{miss}
Z → μμ Nominal p_T^{miss}
Z → μμ Object-corrected p_T^{miss}
Normalised
Δφ (E_T^{miss}, p_T^{miss}) [rad]



ATLAS work in progress
√s = 8 TeV, 20.3 fb⁻¹
1 jet
W → μν Nominal p_T^{miss}
W → μν Object-corrected p_T^{miss}
Z → μμ Nominal p_T^{miss}
Z → μμ Object-corrected p_T^{miss}
Normalised
Δφ (E_T^{miss}, p_T^{miss}) [rad]

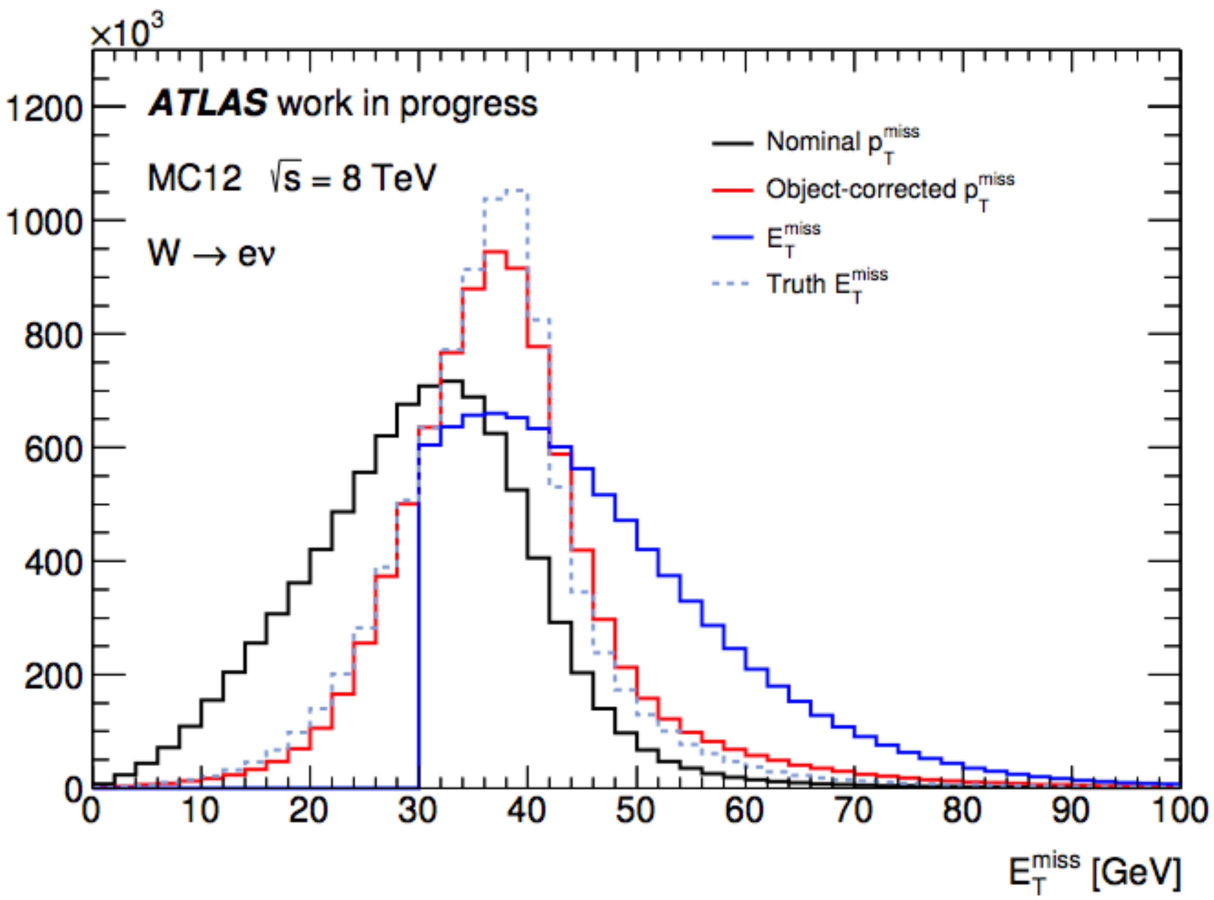


ATLAS work in progress
√s = 8 TeV, 20.3 fb⁻¹
W → μν
Data 2012 Nominal p_T^{miss}
MC12 Nominal p_T^{miss}
Data 2012 Object-corrected p_T^{miss}
MC12 Object-corrected p_T^{miss}
Δ φ (p_T^{miss}, E_T^{miss}) [GeV]
N_{pv}

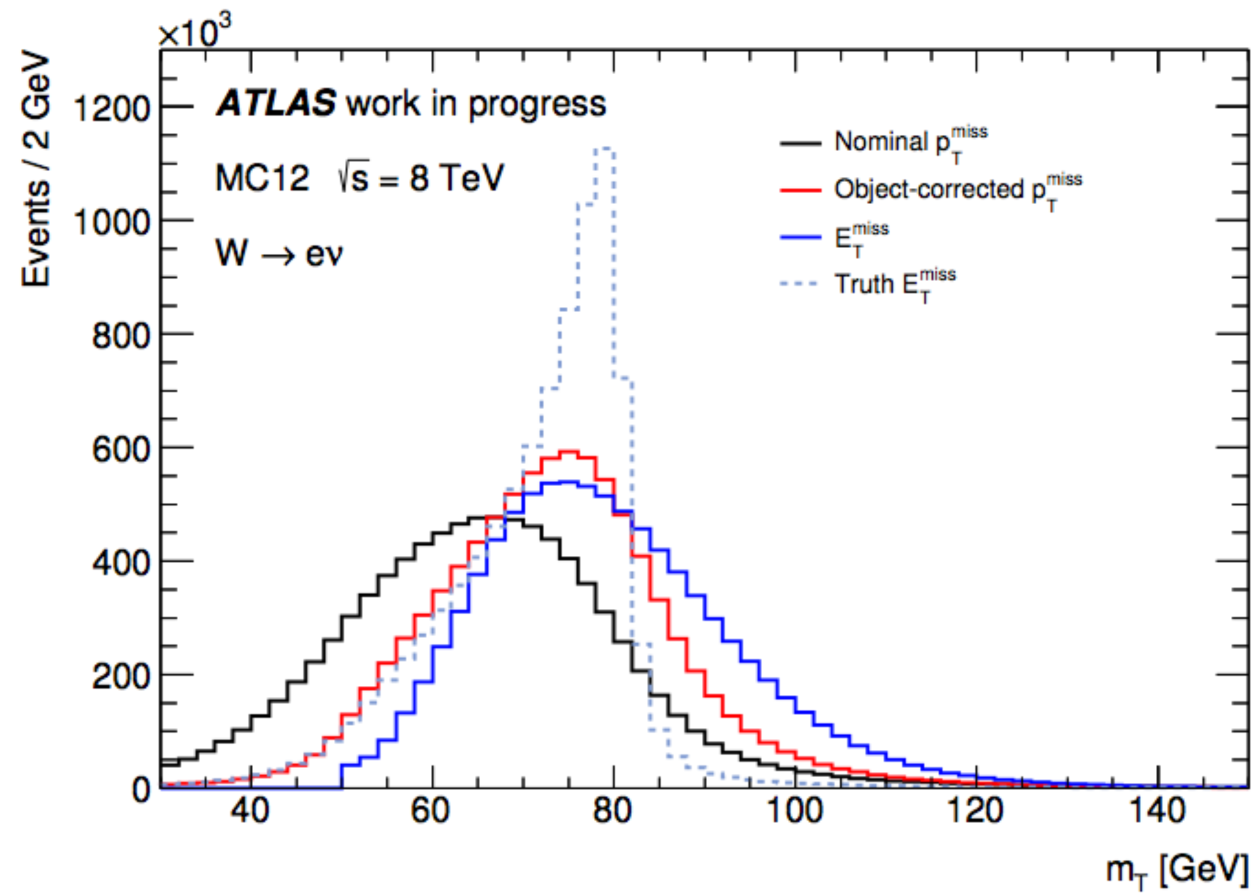


ATLAS work in progress
MC12 √s = 8 TeV
W → μν
Nominal p_T^{miss}
Object-corrected p_T^{miss}
E_T^{miss}
Δ φ ($(E,p)_T^{miss}$, Truth) [GeV]
N_{pv}

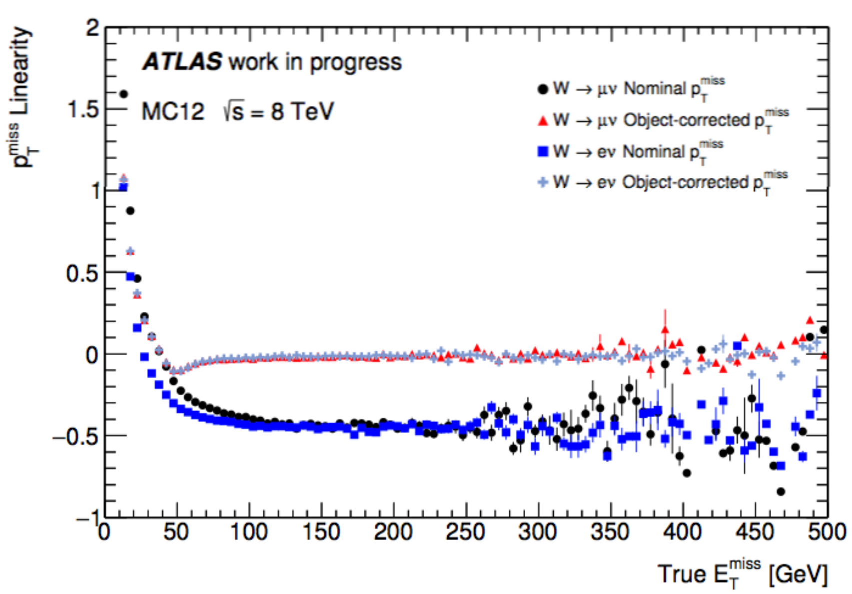
W scale


ATLAS work in progress
MC12 √s = 8 TeV
W → eν
Nominal p_T^miss
Object-corrected p_T^miss
E_T^miss
Truth E_T^miss
×10^3
0
200
400
600
800
1000
1200
0
10
20
30
40
50
60
70
80
90
100
E_T^miss [GeV]

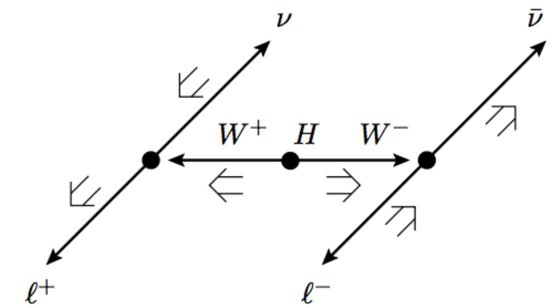
(a)


ATLAS work in progress
MC12 √s = 8 TeV
W → eν
Nominal p_T^miss
Object-corrected p_T^miss
E_T^miss
Truth E_T^miss
Events / 2 GeV
×10^3
0
200
400
600
800
1000
1200
40
60
80
100
120
140
m_T [GeV]

(b)


ATLAS work in progress
MC12 √s = 8 TeV
W → μν Nominal p_T^miss
W → μν Object-corrected p_T^miss
W → eν Nominal p_T^miss
W → eν Object-corrected p_T^miss
p_T^miss Linearity
−1
−0.5
0
0.5
1
1.5
2
0
50
100
150
200
250
300
350
400
450
500
True E_T^miss [GeV]

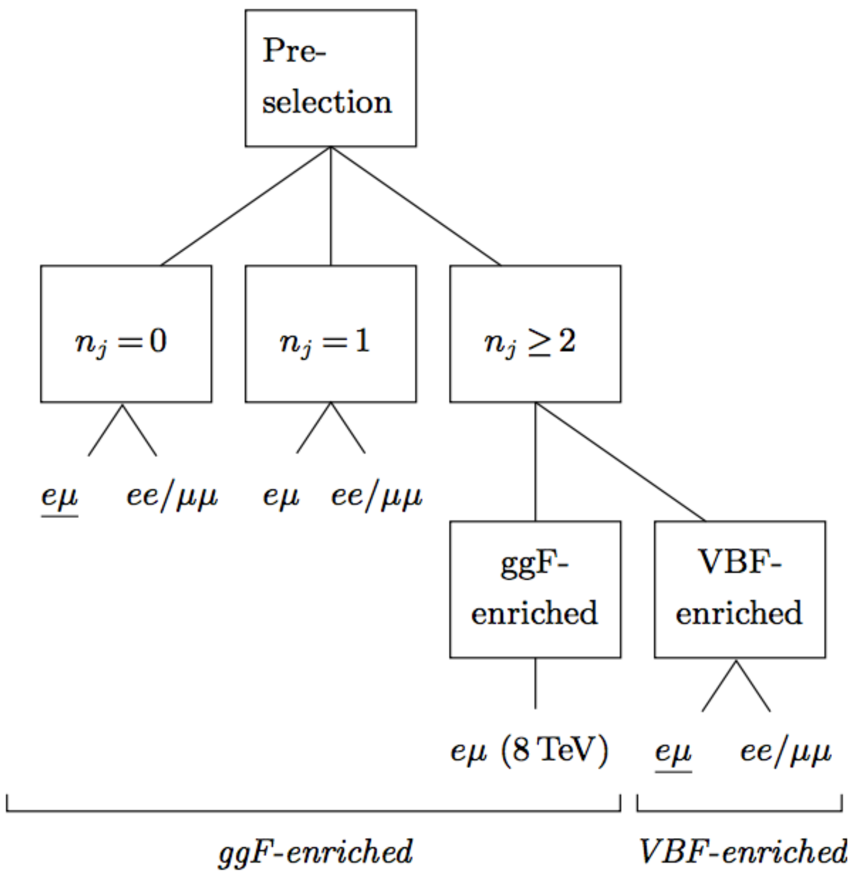
pTmiss in H→WW



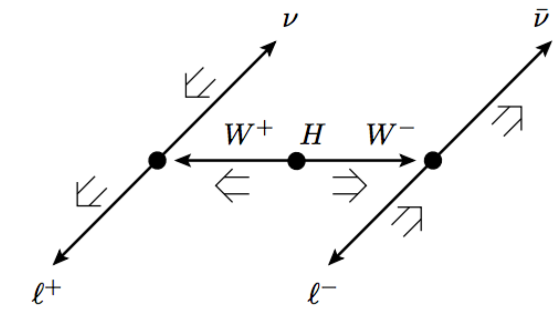
- The H → WW decays are identified by two oppositely-charged high pT leptons, with real ETmiss from the two neutrinos.
  - Largest source of bg: DY (especially in SF channel)

- A cut on ETmiss > 45 GeV was sufficient in 2011, but in 2012, with the increased Z background and decreased ETmiss resolution, raising the cut threshold decreased the signal efficiency significantly.

- Incorporating a cut on pTmiss > 40 (35) GeV in the event selections for the same-flavour 0 (1) jet ggF-enriched category therefore reduces the Drell-Yan background to a manageable level.

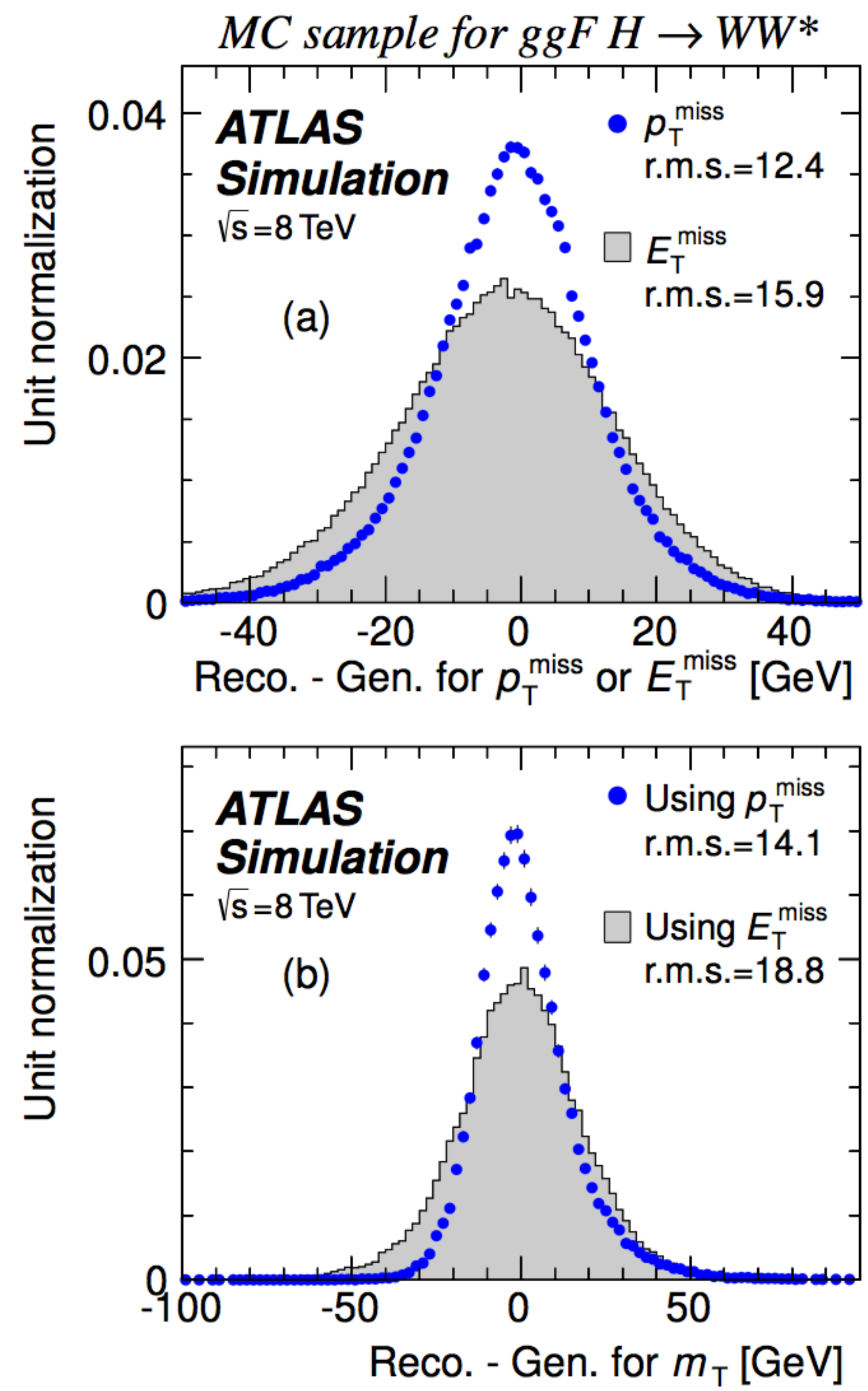


pTmiss in H→WW



$$\mathbf{m_T} = \sqrt{\left(\mathrm{E}_{\mathrm{T}}^{\ell\ell} + \mathrm{p}_{\mathrm{T}}^{\nu\nu}\right)^2 - \left|\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \mathbf{p}_{\mathrm{T}}^{\nu\nu}\right|^2}$$

- The H → WW signal yield in the ggF analysis is obtained from a direct fit to the transverse mass.
- A comparison was done for the mT reconstruction using both the ETmiss and object-corrected pTmiss, and it was found that the pmiss improved the signal resolution considerably, reducing the r.m.s. of the mT distribution from 19 to 14 GeV.
- The improved resolution significantly increases the discrimination between signal and certain background processes, and the object-corrected pTmis is therefore used for the mT calculation in all channels in the analysis.



Summary

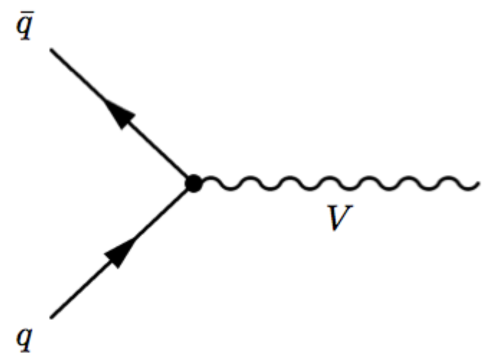
- The measurement of missing energy is an important contribution to a number of interesting physics analyses
  - The ATLAS calorimeter provides excellent energy resolution but is event-based and sensitive to pileup
  - A vertex-based missing energy calculation can be made using the momentum of tracks inside the ATLAS Inner Detector

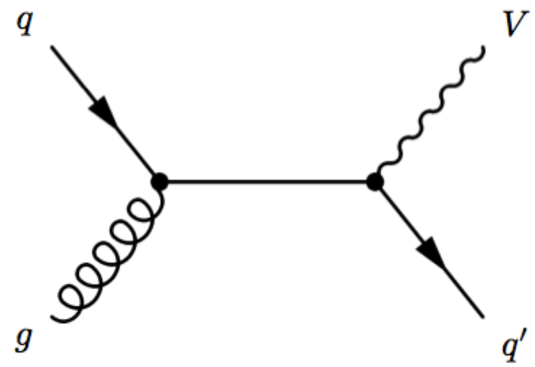
- The pTmiss shows good performance for a number of event topologies
  - Good correlation between the Track and Calo ETmiss for events with real ETmiss
  - The pTmiss resolution shows excellent stability with respect to pileup
  - The performance degrades in events with jets due to the larger fraction of neutrals and the fiducial coverage; but we can improve of the performance can by including the object terms
  - And, despite the more challenging beam conditions in 2012 (and simulations for Run 2) the pTmiss continues to perform well

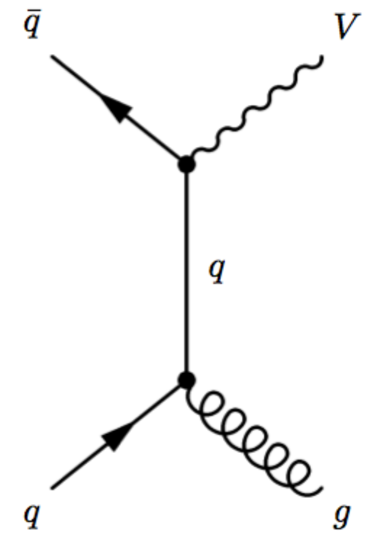
- The default ETmiss reconstruction for Run 2 will use a Track-based soft term to combat the more challenging pileup situation we anticipate in the coming run.

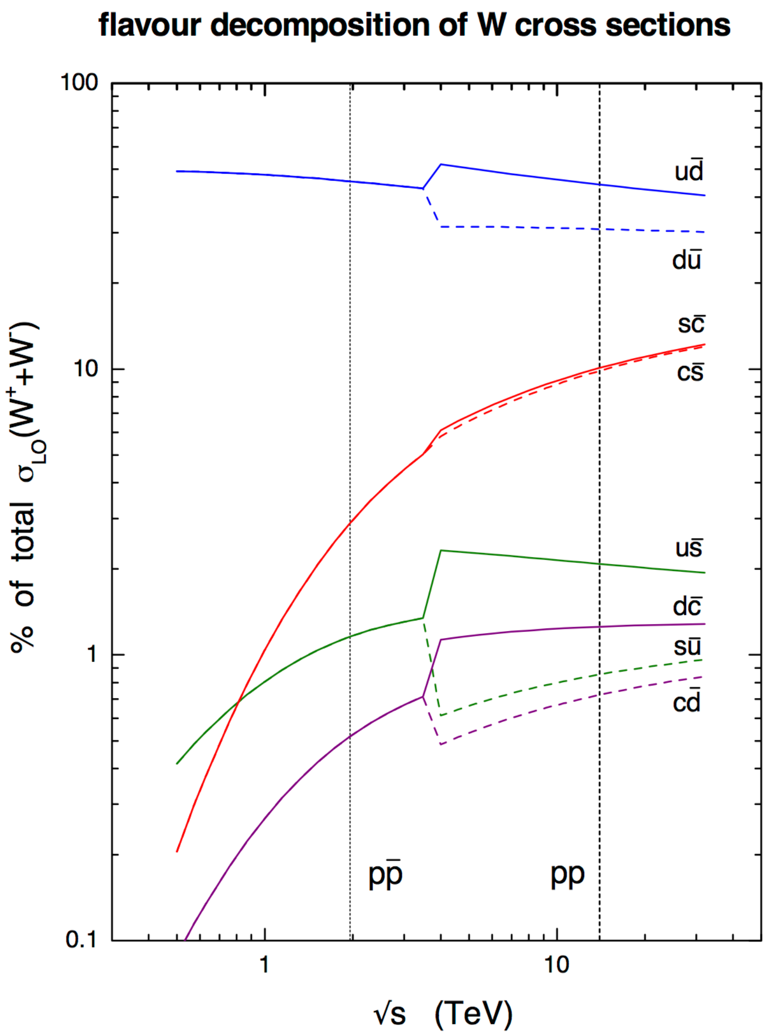
BACKUP

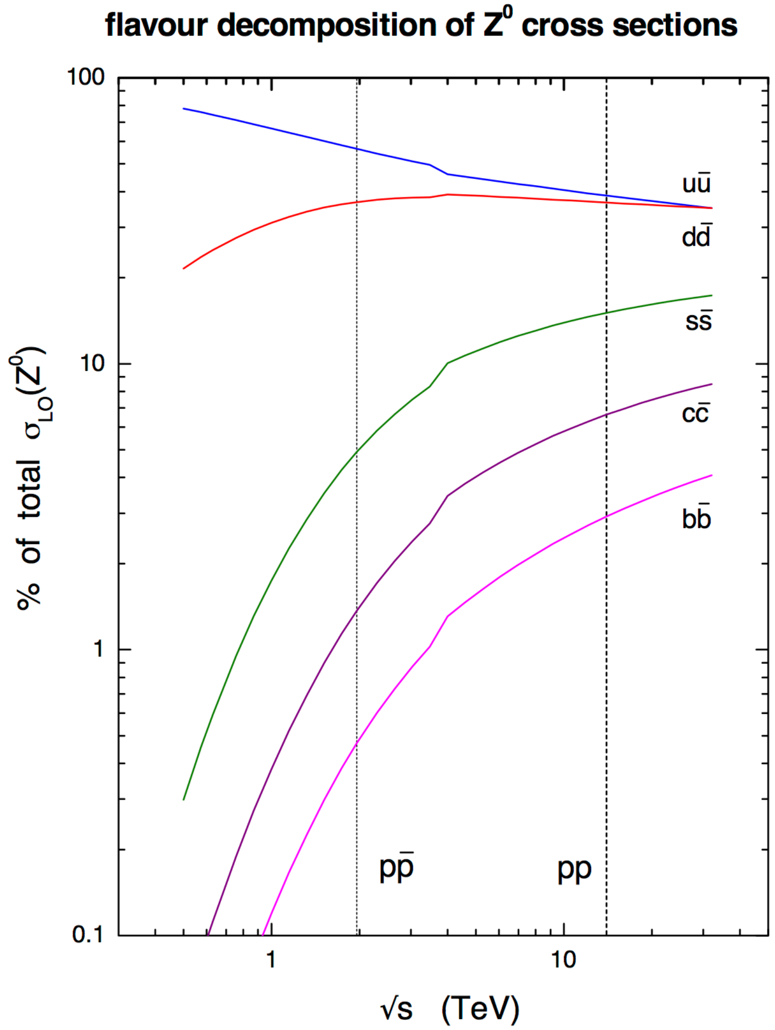
- LO and NLO contributions to vector boson production

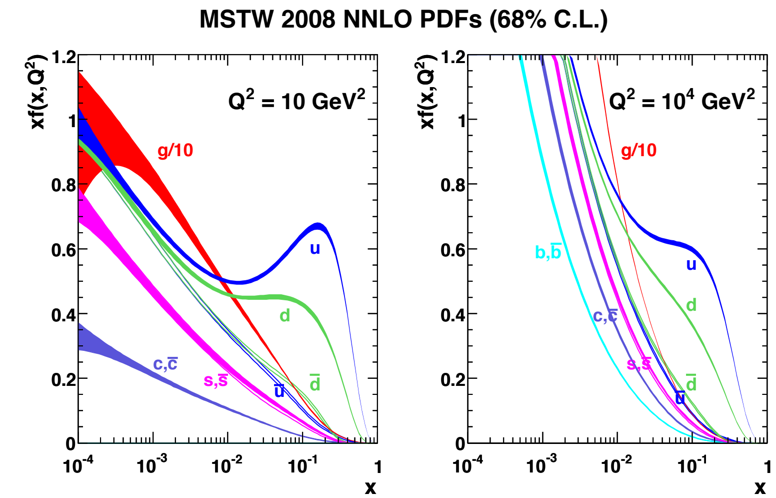






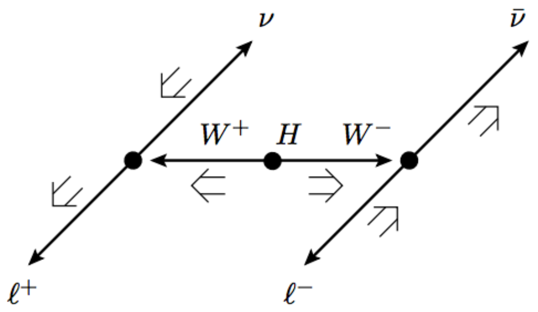




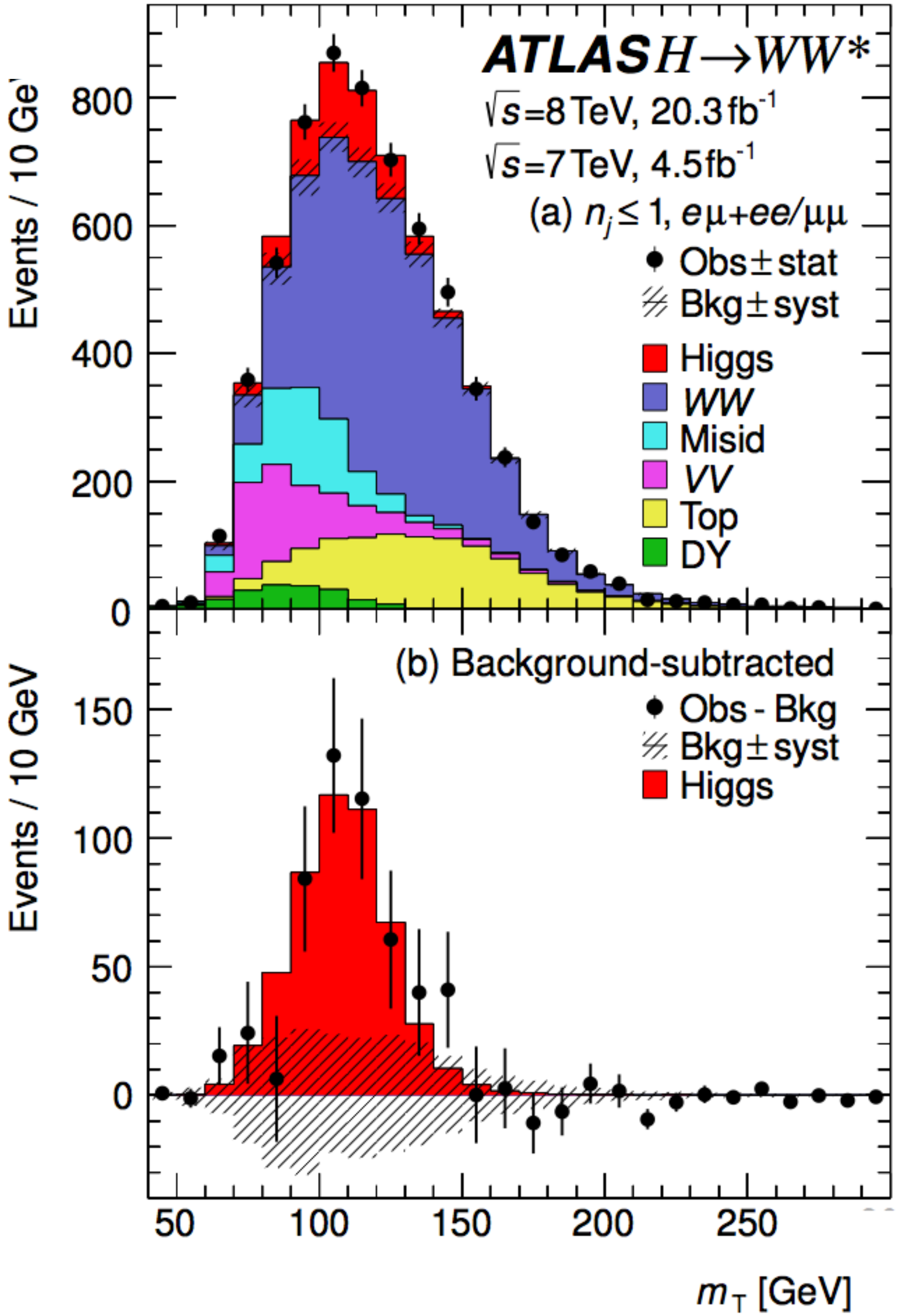


	Decay Mode	Measured Branching Ratio
W^+	hadrons	67.60 ± 0.27 %
	$e^+\nu_e$	10.75 ± 0.13 %
	$\mu^+\nu_\mu$	10.57 ± 0.15 %
	$\tau^+\nu_\tau$	11.25 ± 0.20 %
Z^0	hadrons	69.91 ± 0.06 %
	$\nu\bar{\nu}$	20.00 ± 0.06 %
	e^+e^-	3.363 ± 0.004 %
	$\mu^+\mu^-$	3.366 ± 0.007 %
	$\tau^+\tau^-$	3.370 ± 0.008 %

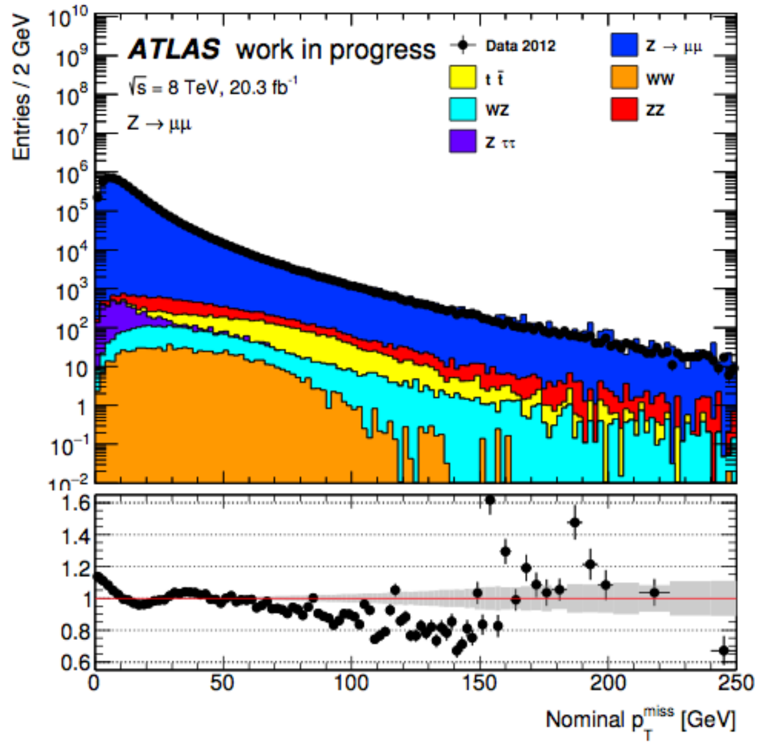
pTmiss in H→WW



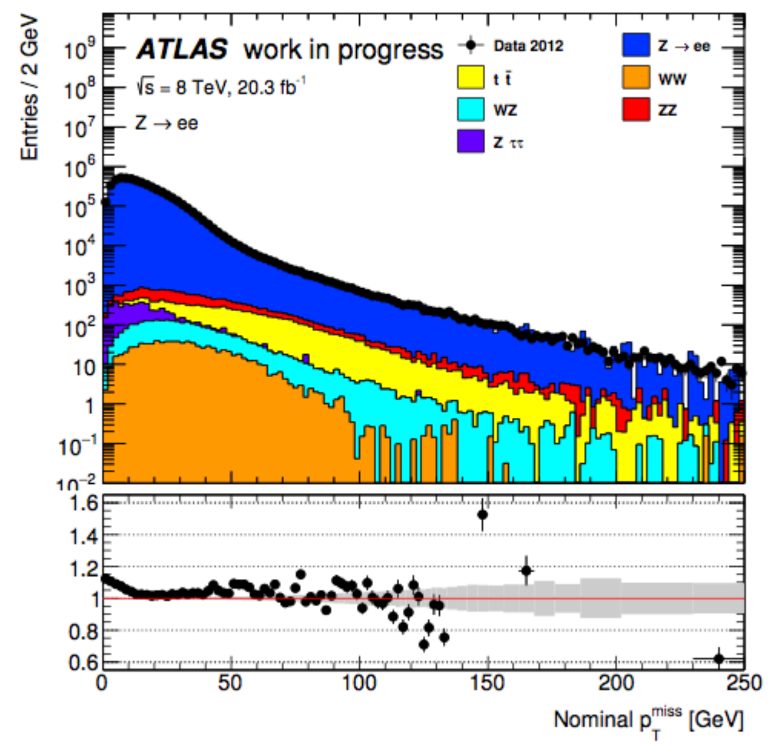
$$\mathbf{m_T} = \sqrt{\left(E_T^{\ell\ell} + p_T^{\nu\nu}\right)^2 - \left|\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{\nu\nu}\right|^2}$$



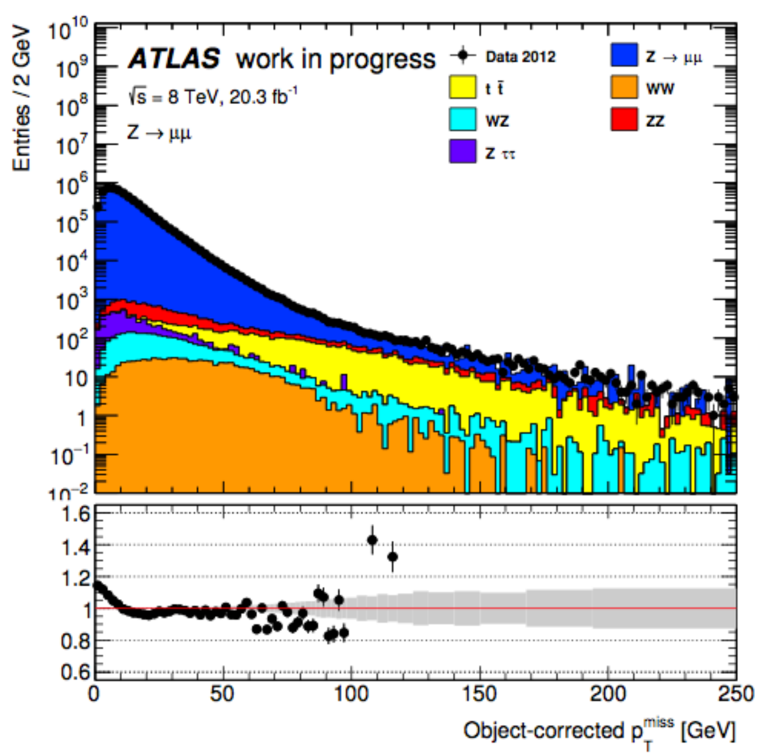
Monte Carlo agreement



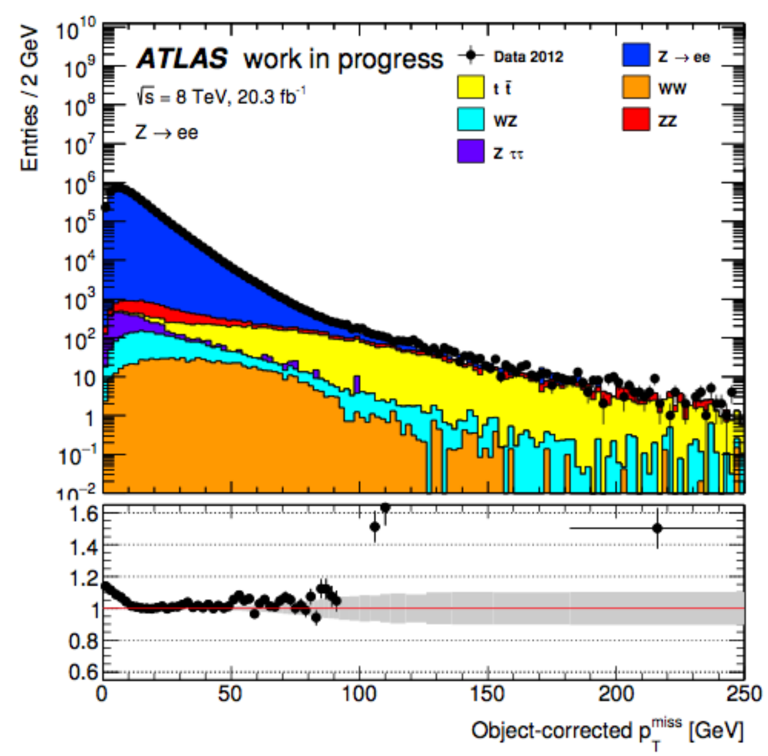
(a) Z → μμ nominal $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$



(b) Z → ee nominal $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$



(c) Z → μμ object-corrected $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$



(d) Z → ee object-corrected $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$

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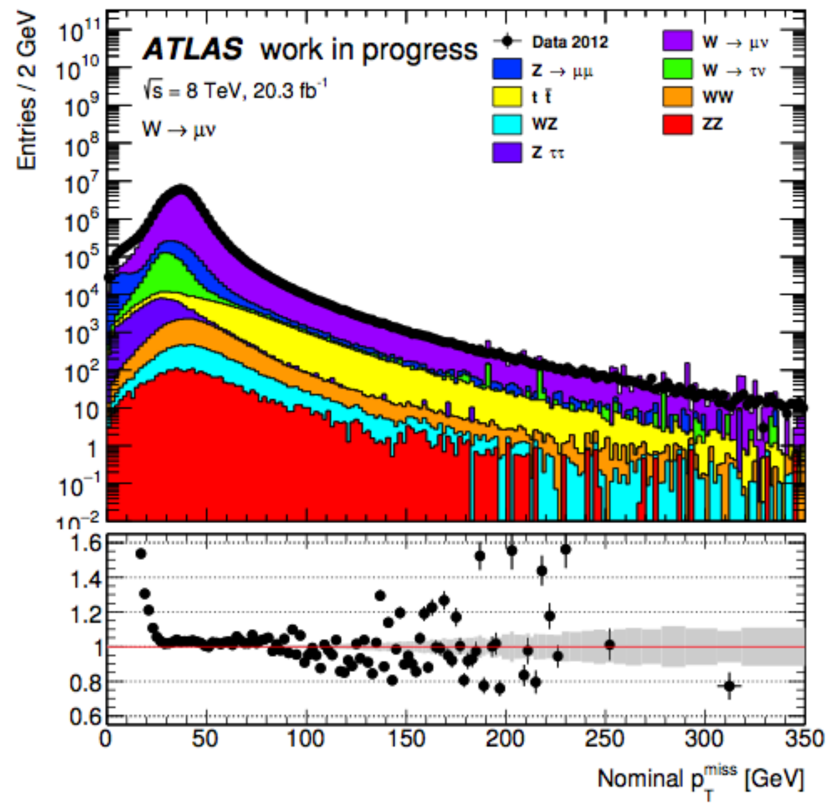
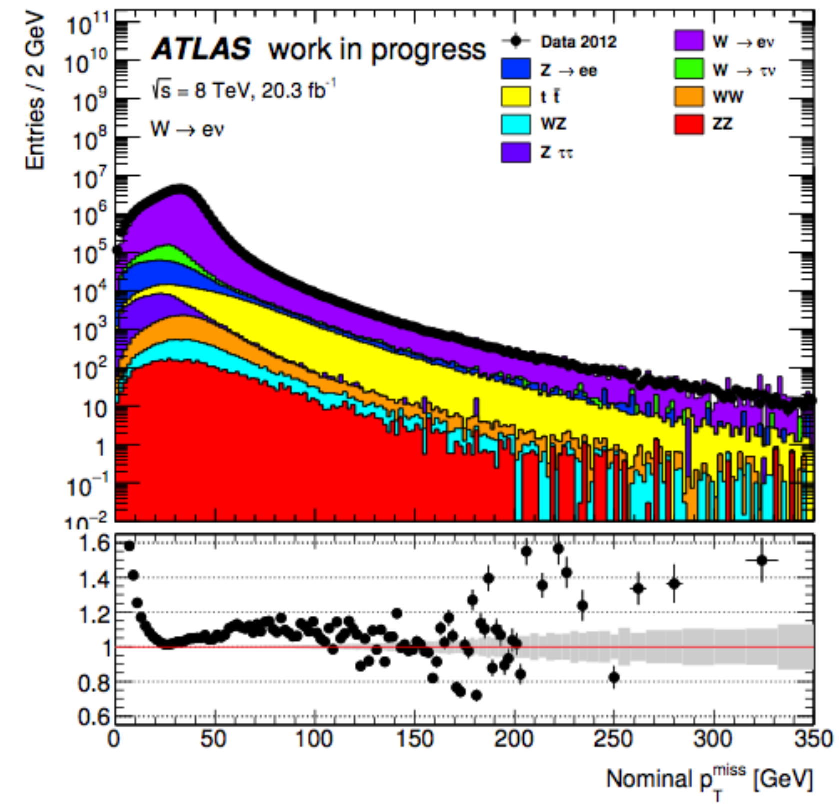
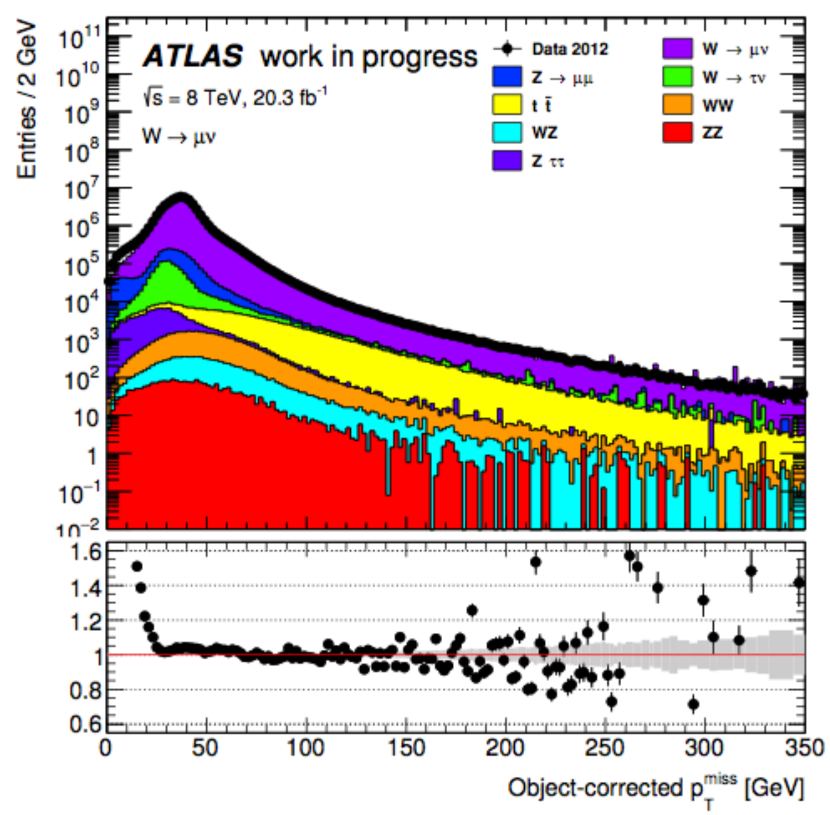
ATLAS EXPERIMENT

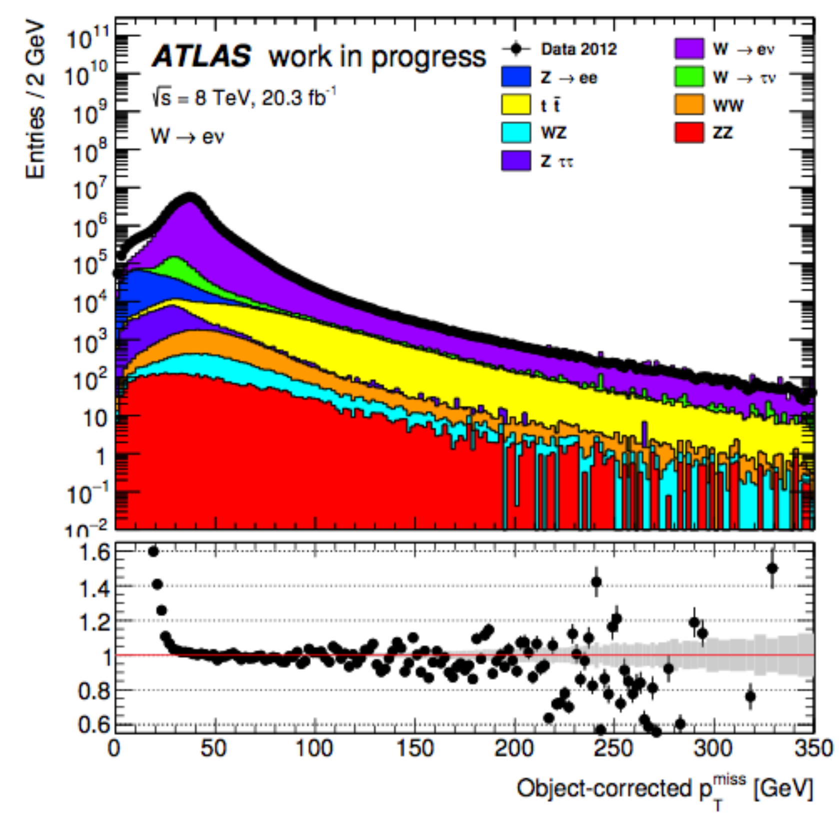


(a) W → $\mu\nu$ nominal $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$



(b) W → $e\nu$ nominal $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$





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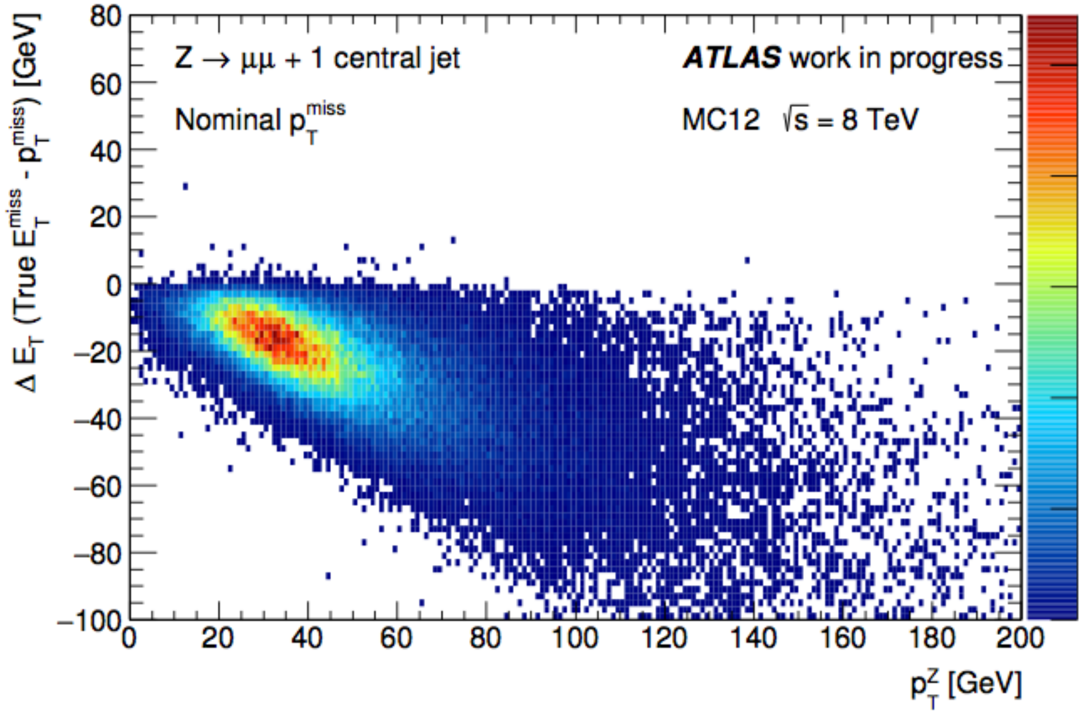
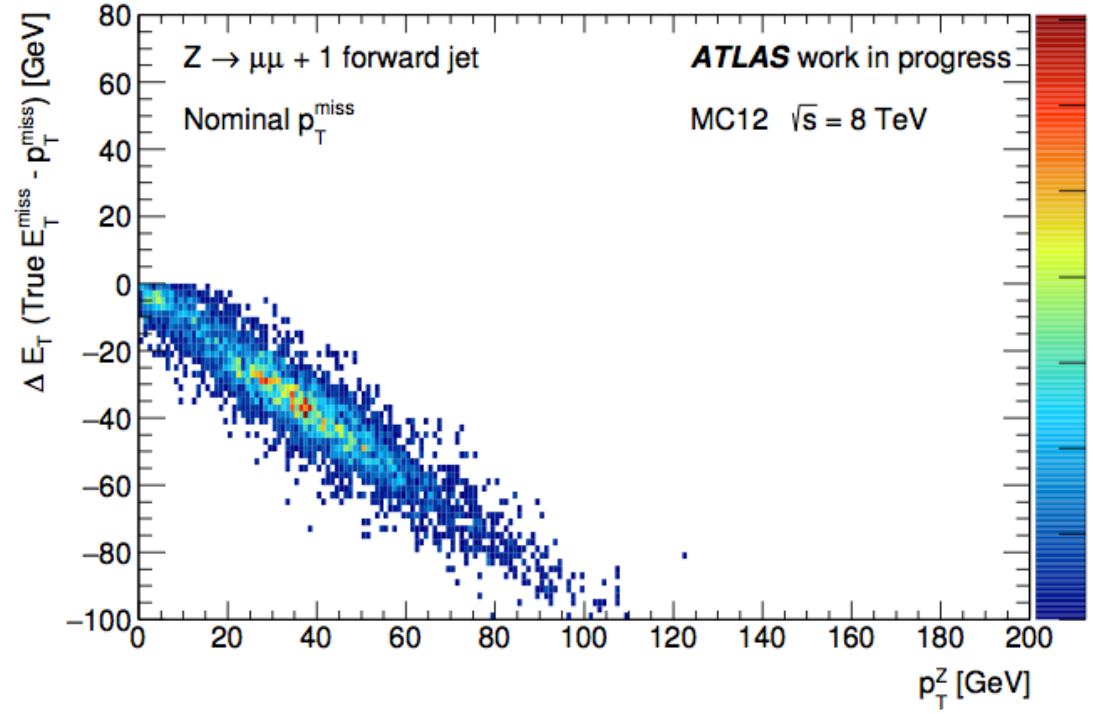
ATLAS EXPERIMENT

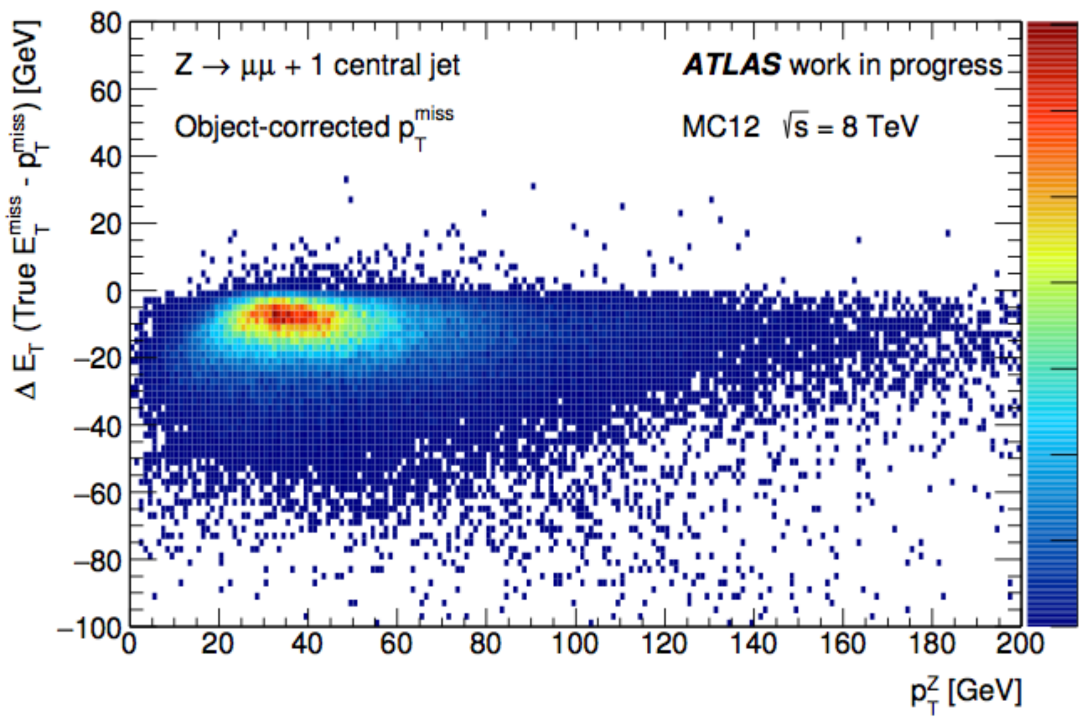
More on adding the jets:



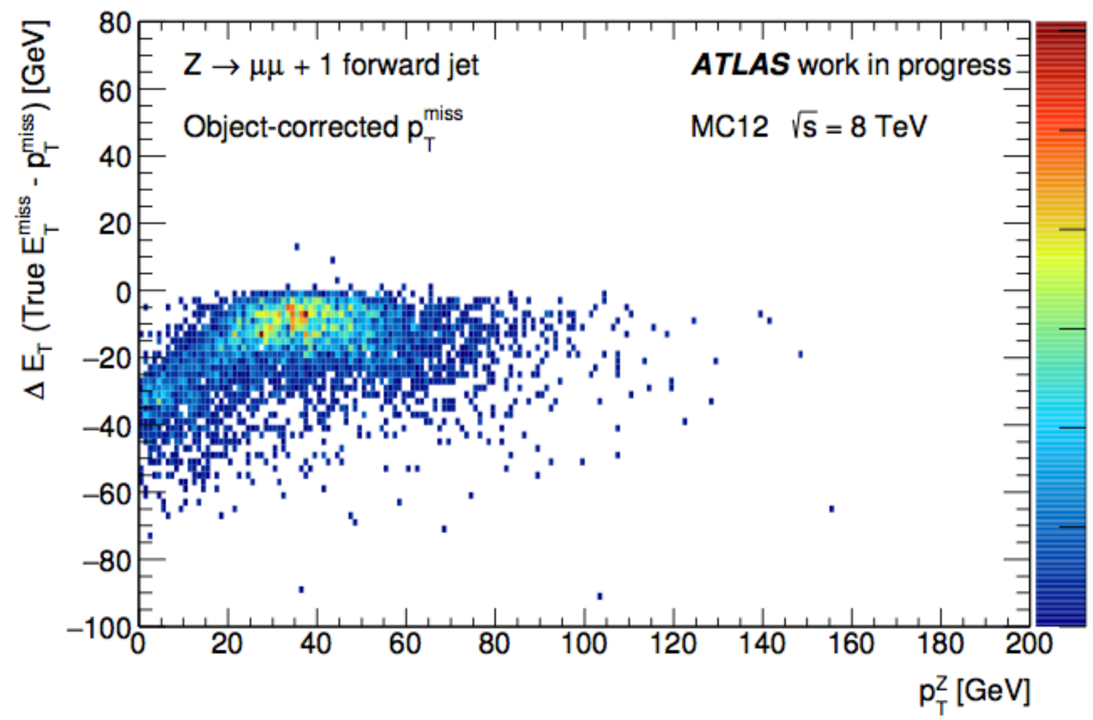
(a) Z + 1 central jet, nominal $\mathbf{p}_T^{miss}$



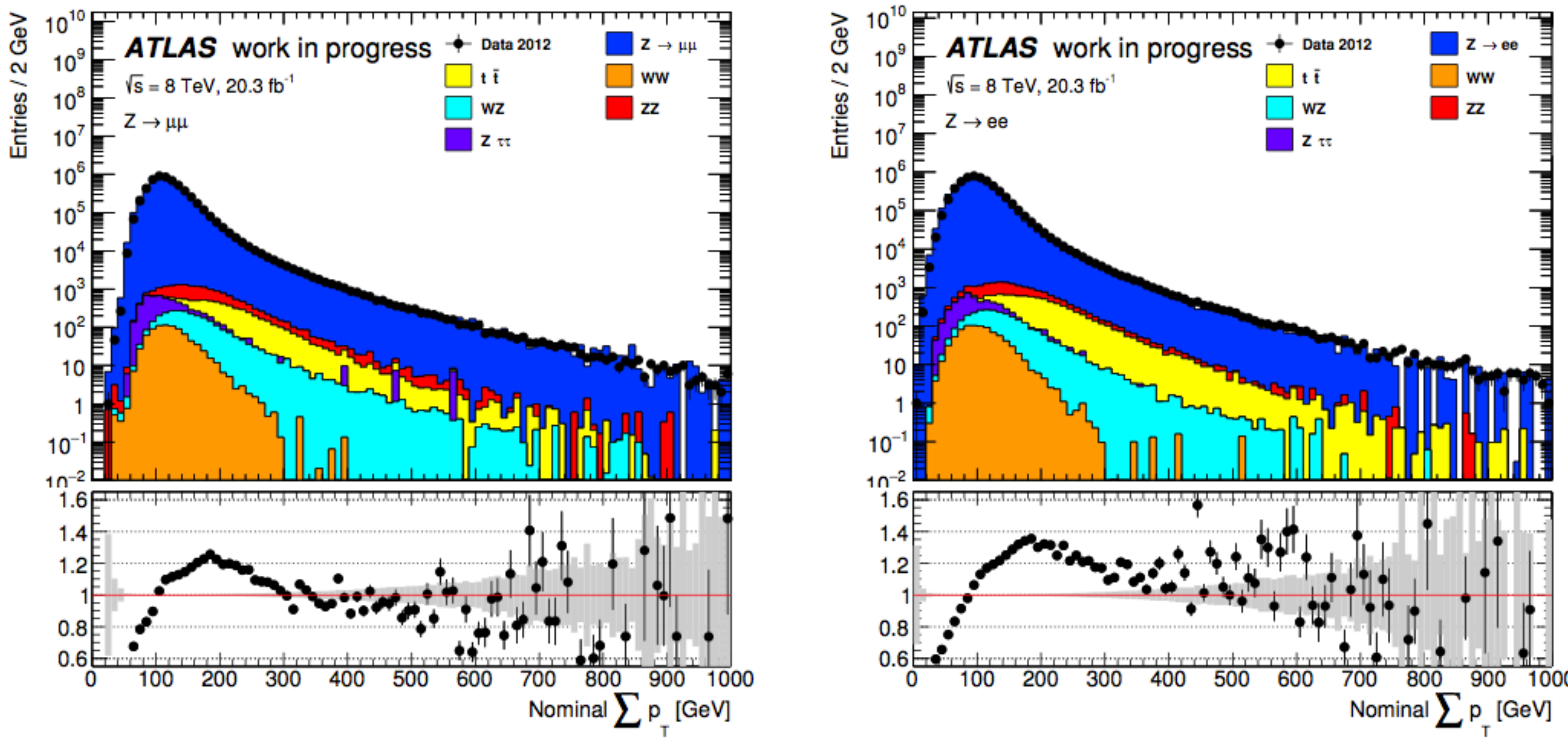
(b) Z + 1 forward jet, nominal $\mathbf{p}_T^{miss}$



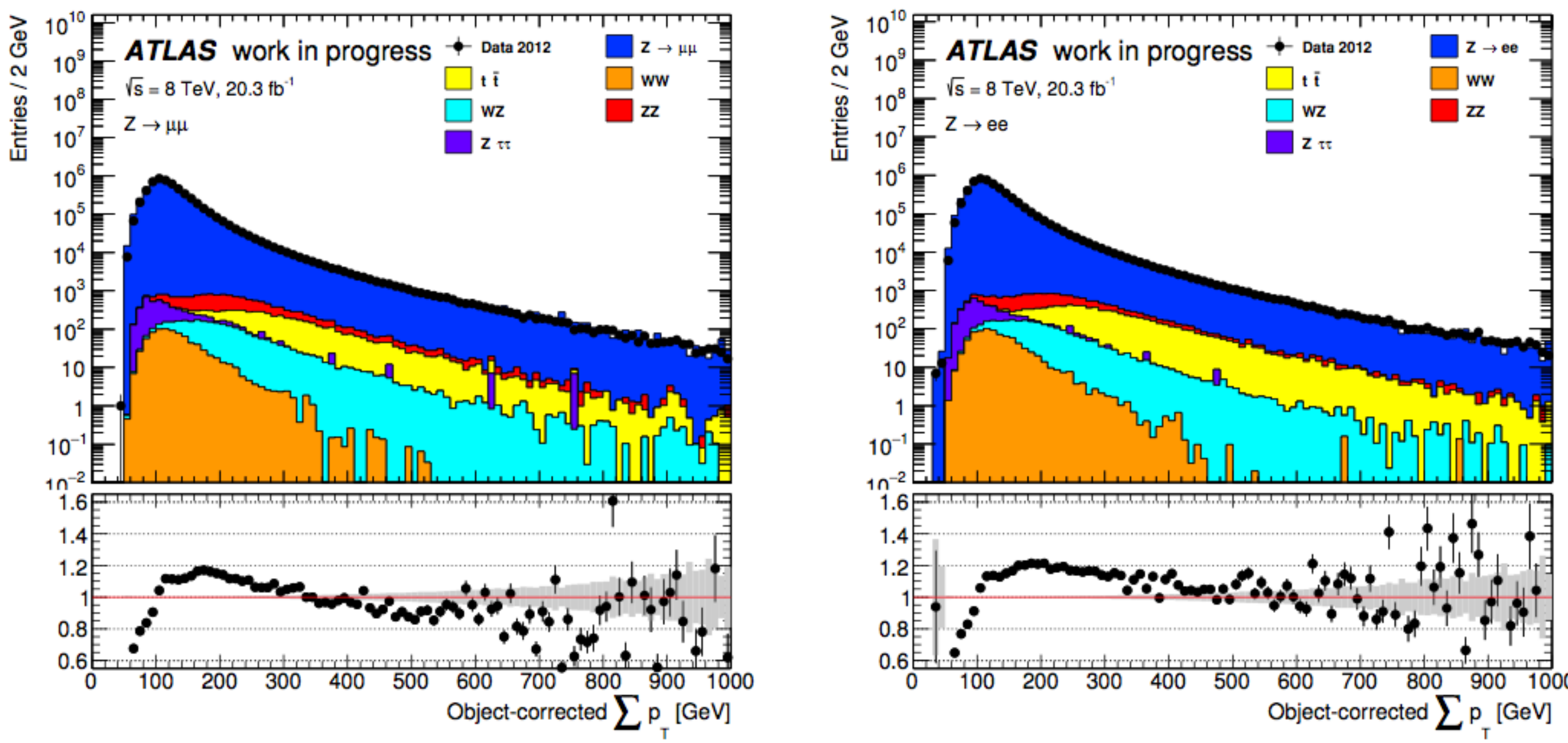
(c) Z + 1 central jet, object-corrected $\mathbf{p}_T^{miss}$

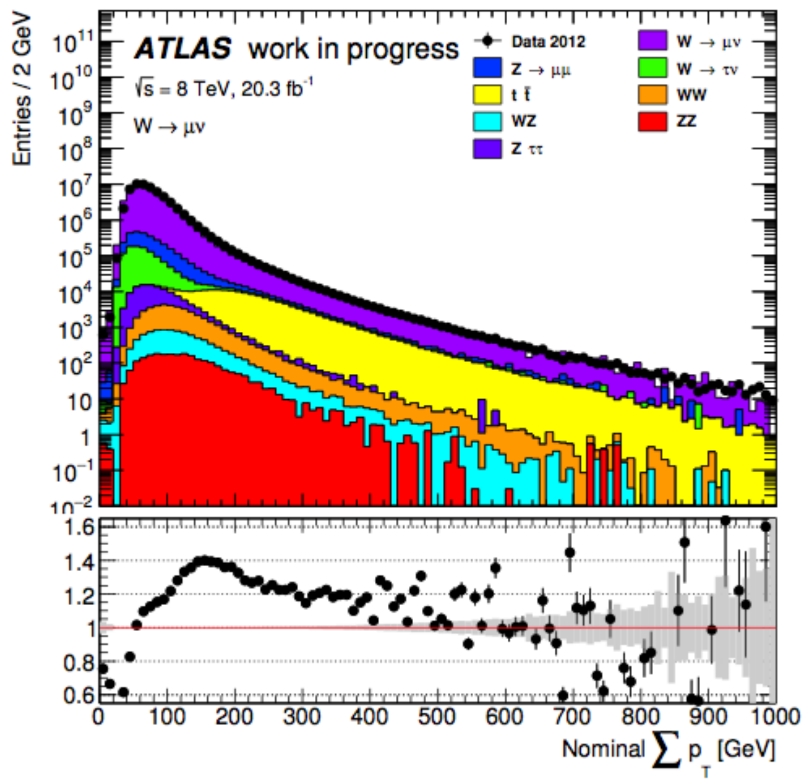


(d) Z + 1 forward jet, object-corrected $\mathbf{p}_T^{miss}$

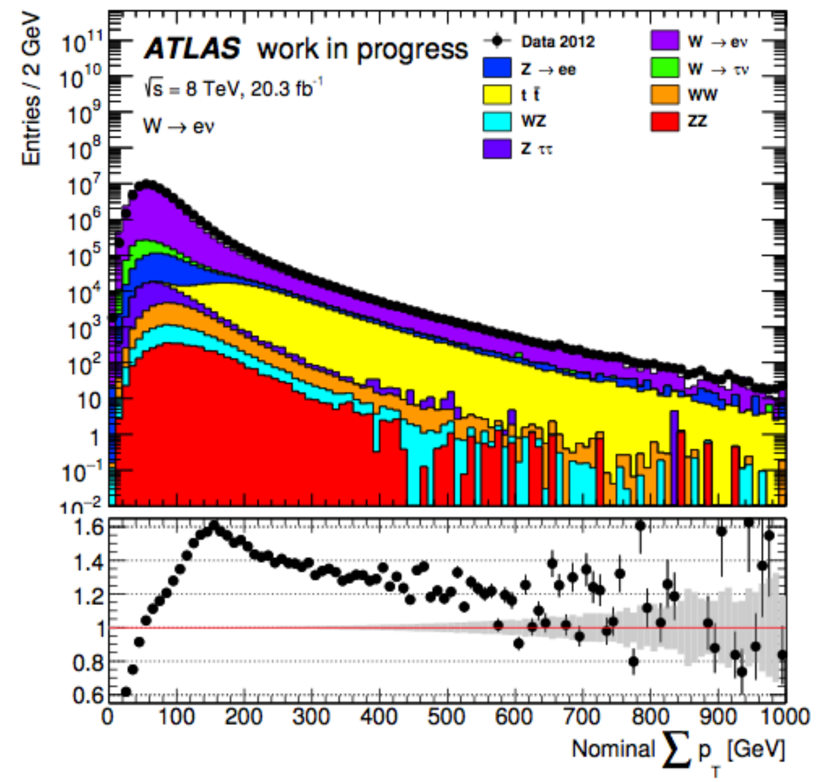


(a) $Z \rightarrow \mu\mu$ nominal Σp_{T} (b) $Z \rightarrow ee$ nominal Σp_{T}

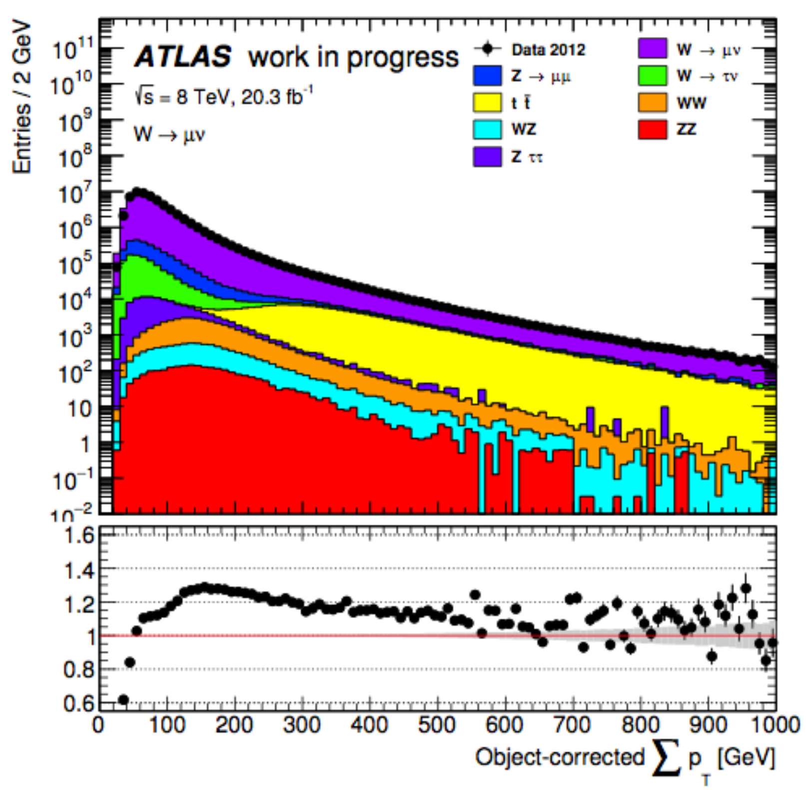




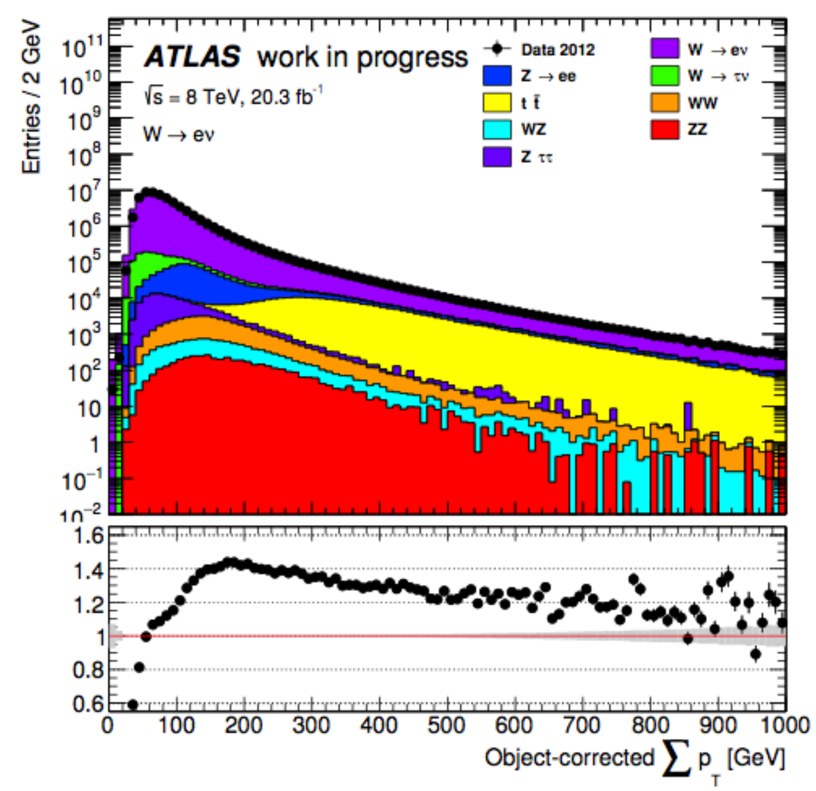
(a) W $\rightarrow \mu\nu$ nominal Σp_{T}



(b) W $\rightarrow e\nu$ nominal Σp_{T}

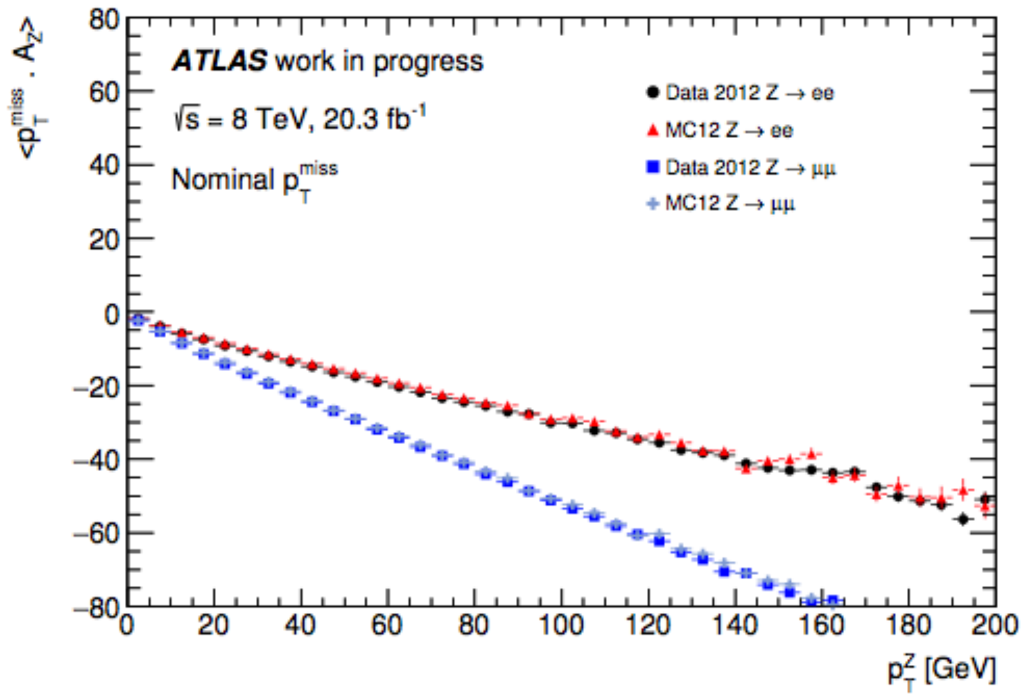


(c) W $\rightarrow \mu\nu$ nominal Σp_{T}



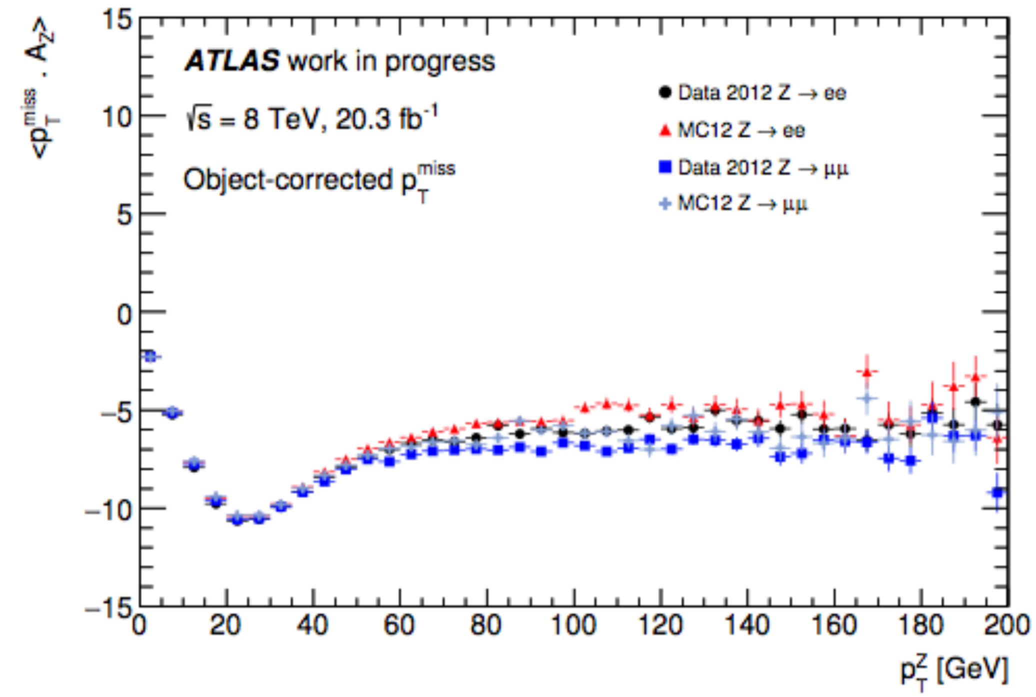
(d) W $\rightarrow e\nu$ nominal Σp_{T}

Z Scale



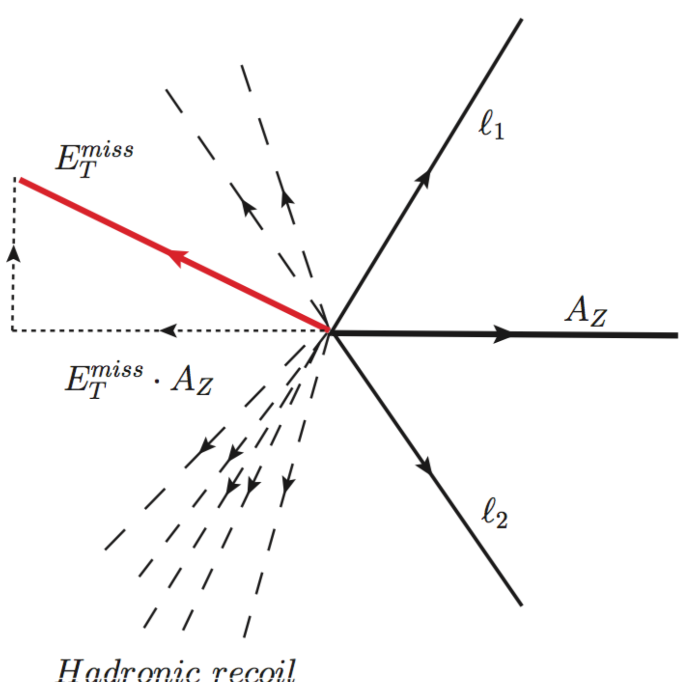
ATLAS work in progress
√s = 8 TeV, 20.3 fb⁻¹
Nominal p_T^{miss}
Data 2012 Z → ee
MC12 Z → ee
Data 2012 Z → μμ
MC12 Z → μμ
<p_T^{miss} · A_Z>
p_T^Z [GeV]

(a)

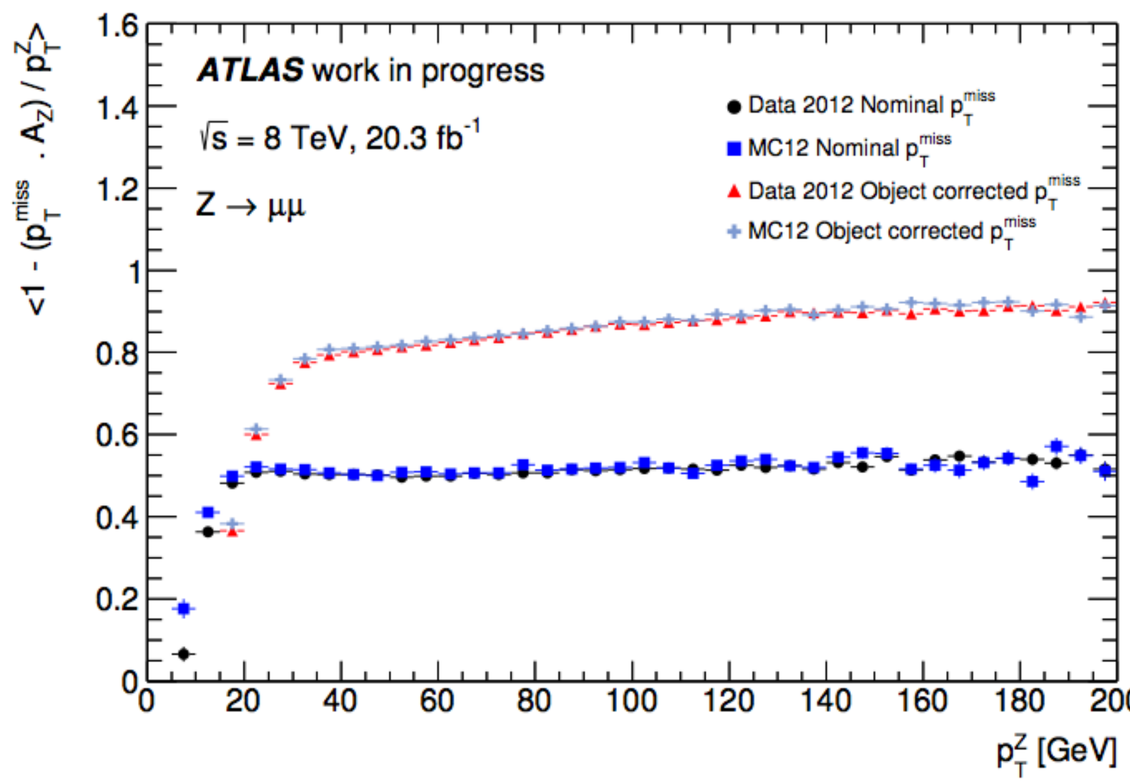


ATLAS work in progress
√s = 8 TeV, 20.3 fb⁻¹
Object-corrected p_T^{miss}
Data 2012 Z → ee
MC12 Z → ee
Data 2012 Z → μμ
MC12 Z → μμ
<p_T^{miss} · A_Z>
p_T^Z [GeV]

(b)

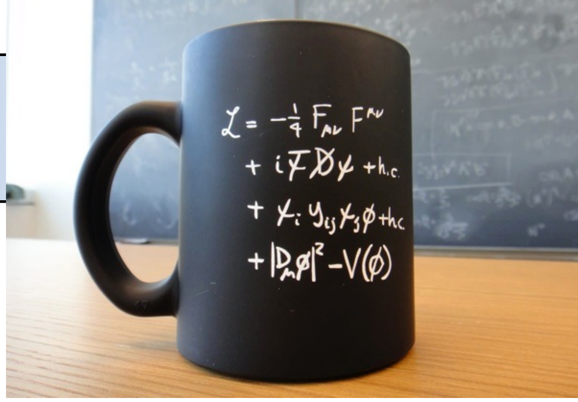


E_T^{miss}
ℓ_1
A_Z
$E_T^{miss} \cdot A_Z$
ℓ_2
Hadronic recoil



ATLAS work in progress
√s = 8 TeV, 20.3 fb⁻¹
Z → μμ
Data 2012 Nominal p_T^{miss}
MC12 Nominal p_T^{miss}
Data 2012 Object corrected p_T^{miss}
MC12 Object corrected p_T^{miss}
<1 - (p_T^{miss} · A_Z) / p_T^Z>
p_T^Z [GeV]

The Standard Model in a Nutshell



$$\mathcal{L} = -\tfrac{1}{4} W_{\mu\nu} W^{\mu\nu} - \tfrac{1}{4} B_{\mu\nu} B^{\mu\nu} - \tfrac{1}{4} G^{\alpha}_{\mu\nu} G^{\mu\nu}_{\alpha}$$

{ $W^{\pm}$, Z, γ and gluon kinetic energies and self-interactions

$$+ \bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \tfrac{1}{2} g \tau_i W^{i}_{\mu} - g' \tfrac{Y}{2} B_{\mu}\right) L + \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - g' \tfrac{Y}{2} B_{\mu}\right) R$$

{ Lepton and quark kinetic energies, and their interactions with $W^{\pm}$, Z and γ

$$+ g_s \left(\bar{q}\gamma^{\mu} T_{\alpha} q\right) G^{\alpha}_{\mu}$$

{ Interactions of quarks with gluons

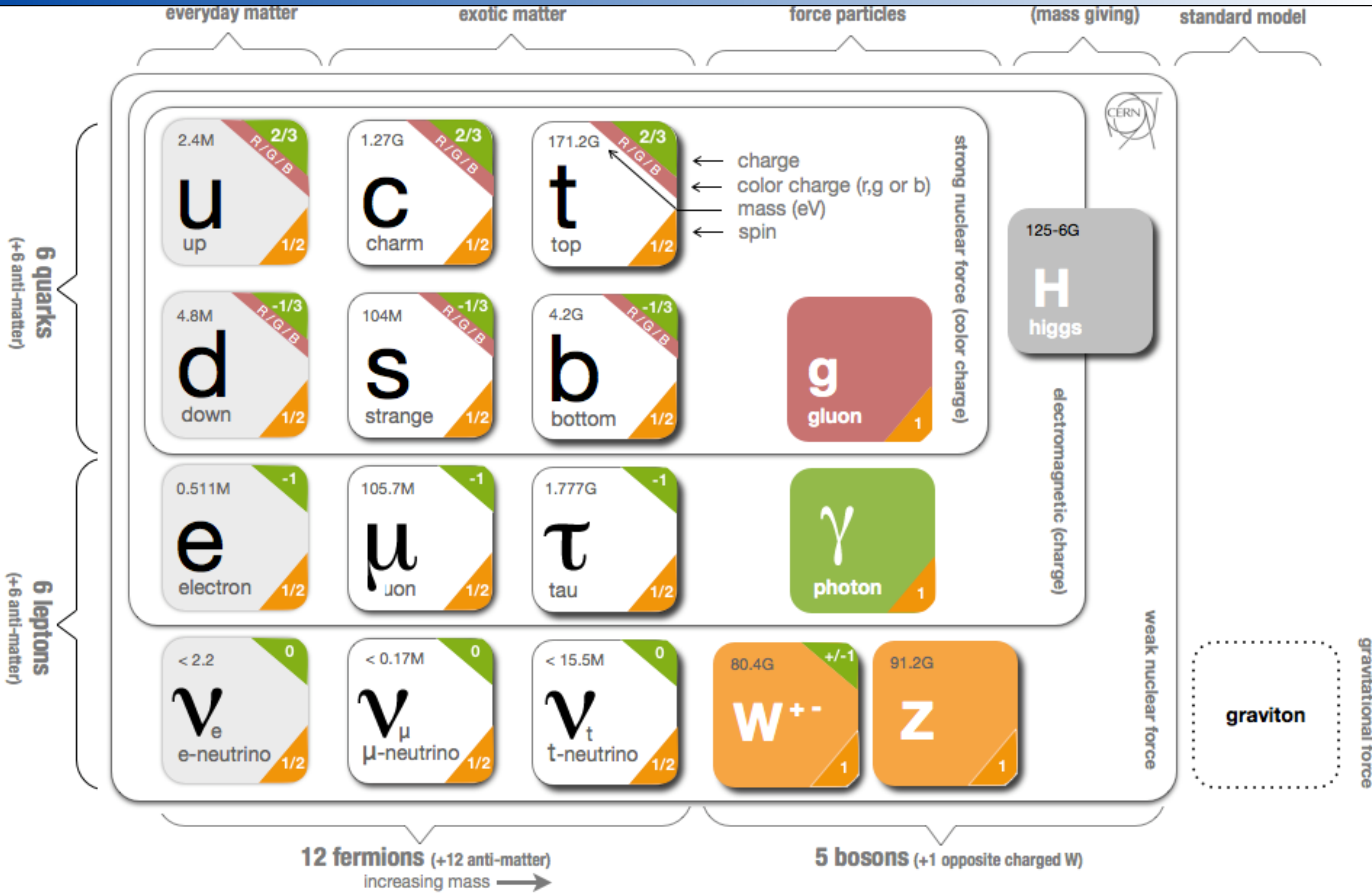
$$+ \left|\left(i\partial_{\mu} - \tfrac{1}{2} g \tau_i W^{i}_{\mu} - g' \tfrac{Y}{2} B_{\mu}\right) \Phi\right|^2 V(\Phi)$$

{ $W^{\pm}$, Z and γ masses and coupling to the Higgs boson

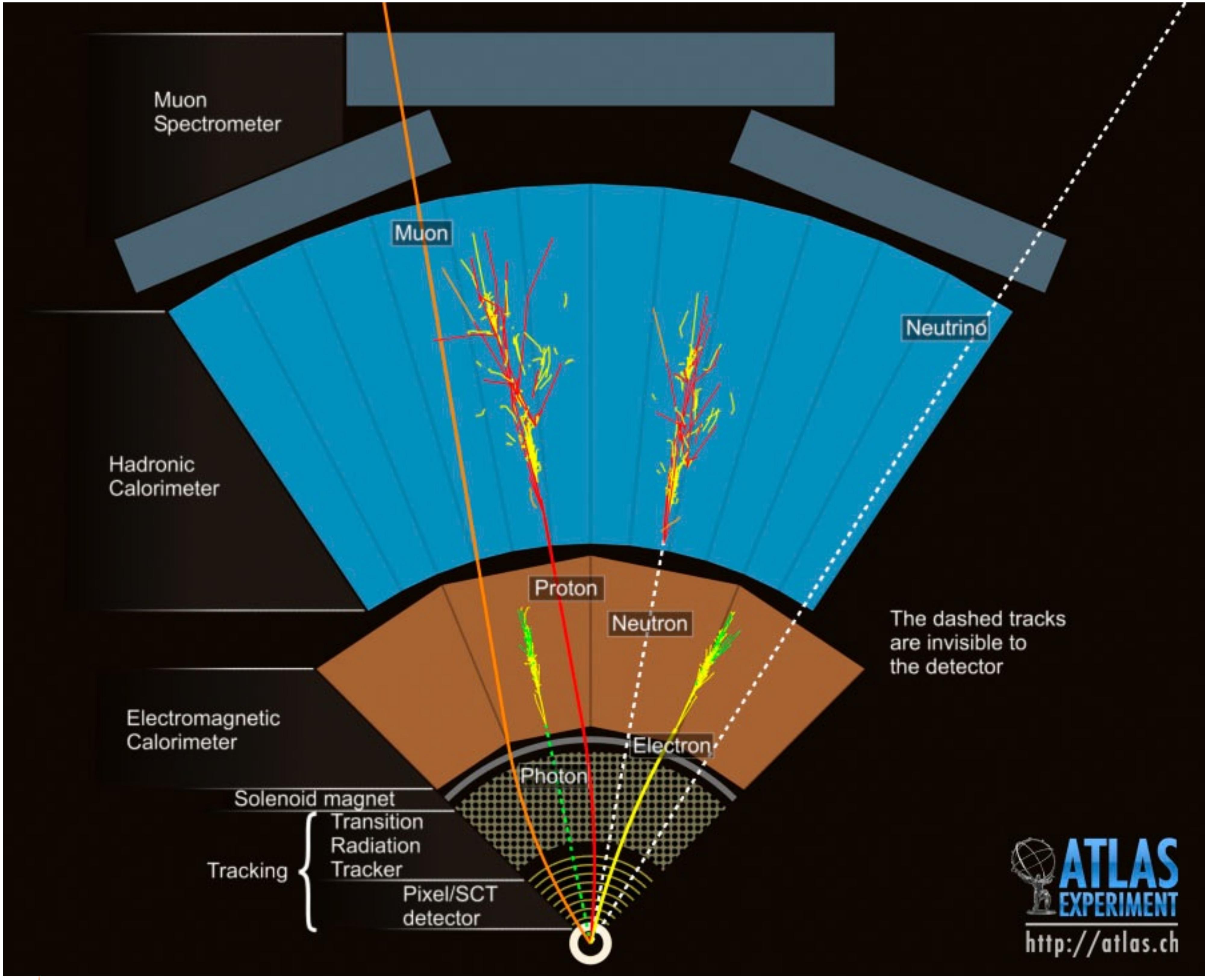
$$- \left(G_1 \bar{L} \Phi R + G_2 \bar{L} \Phi^c R\right) + \text{hermitian conjugates}$$

{ Lepton and quark masses and coupling to the Higgs boson

The Standard Model Particles

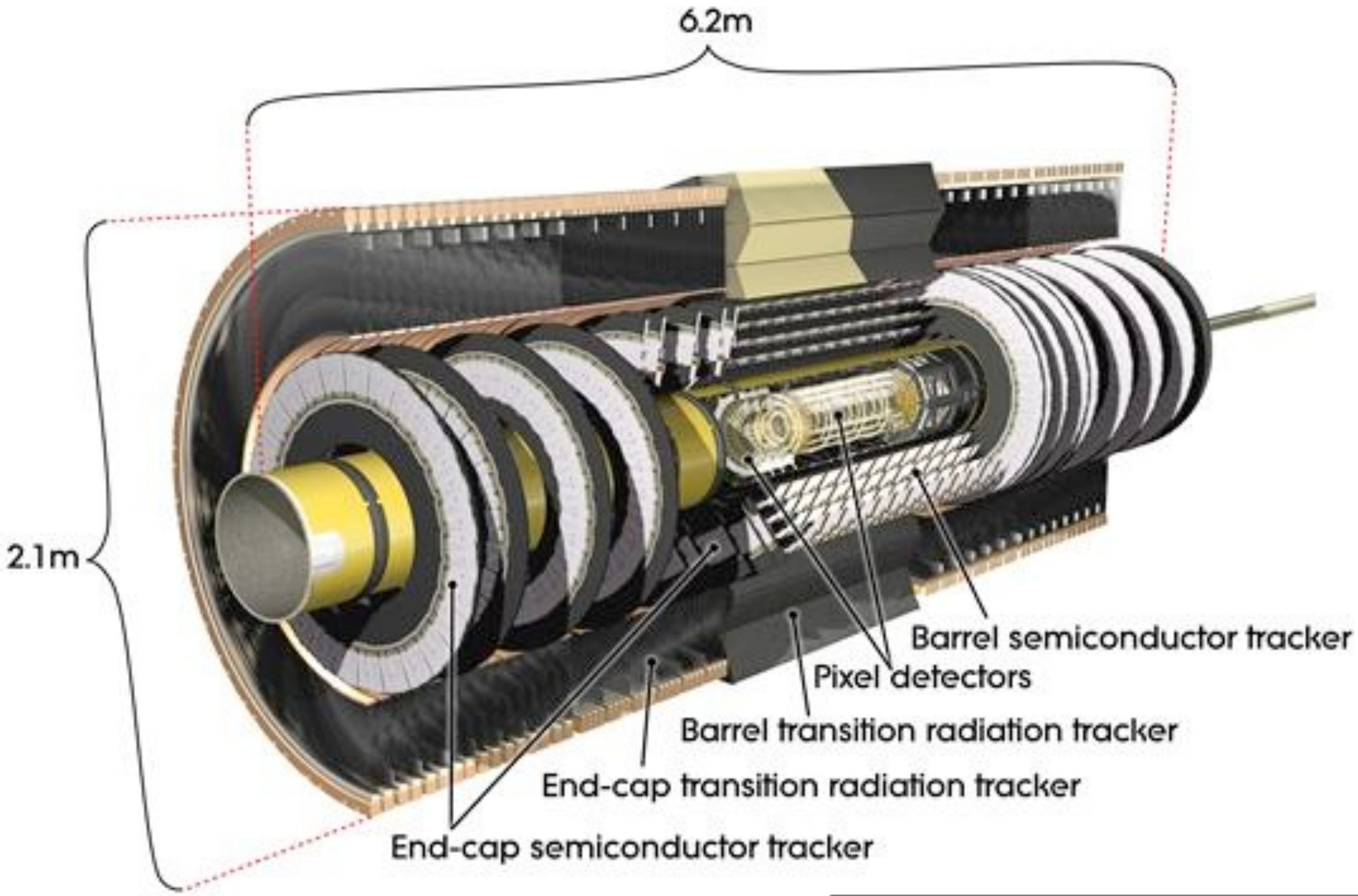


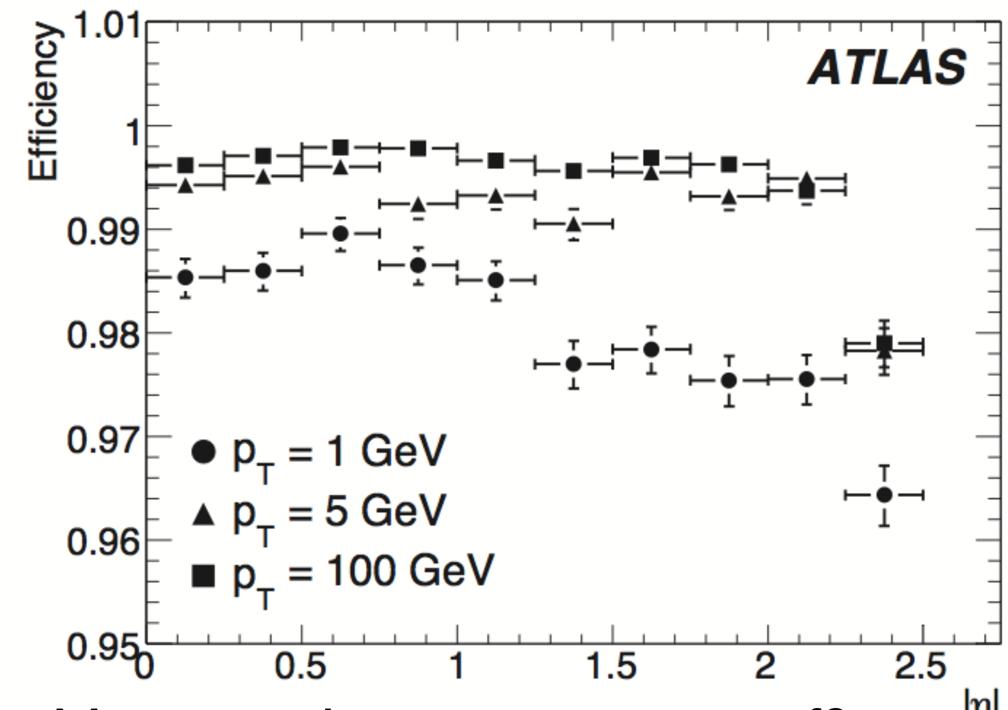
A (very quick) ATLAS overview



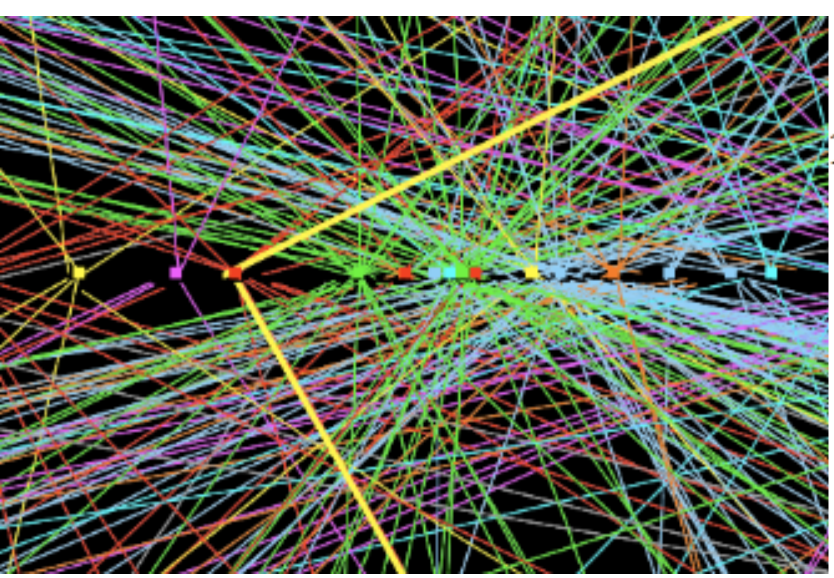
- Reconstructed objects:
  - e/γ
  - taus
  - jets
  - muons
  - other (soft) tracks
  - missing transverse energy

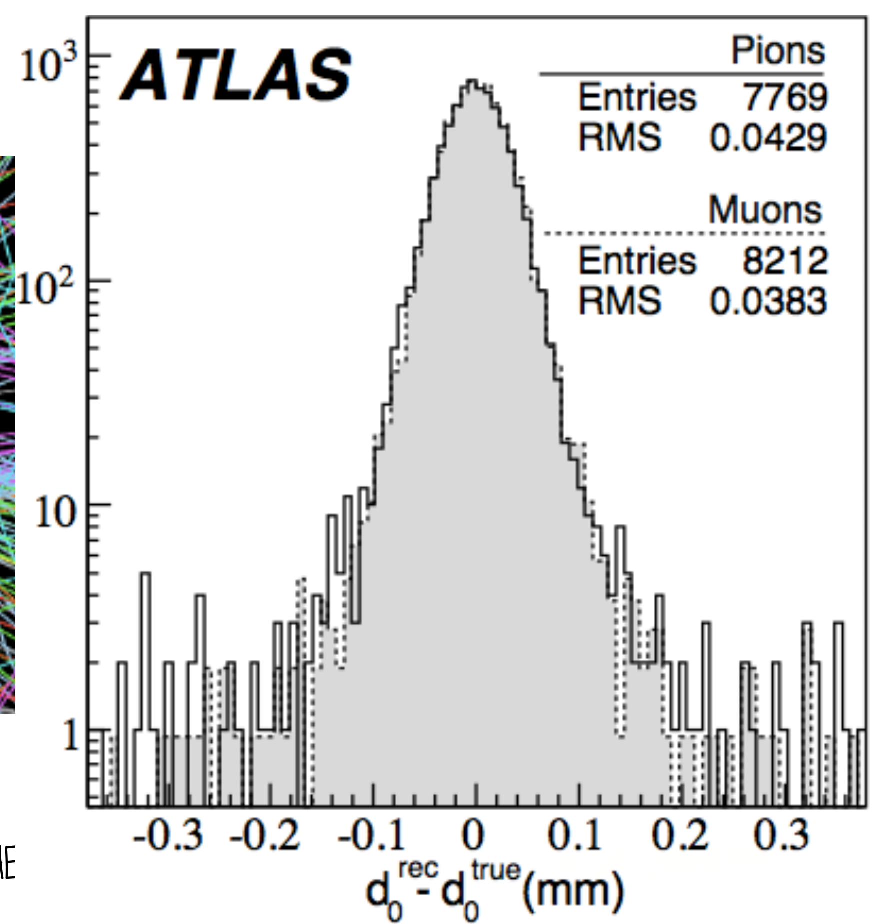
The ATLAS Inner Detector

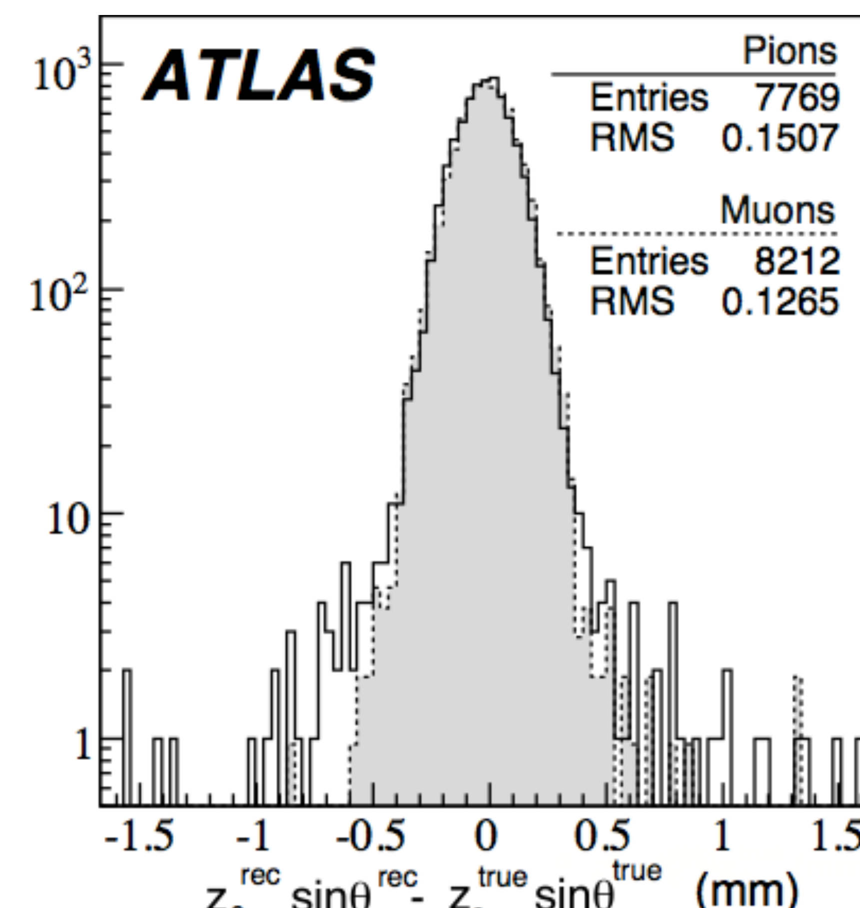




Muon track reconstruction efficiency



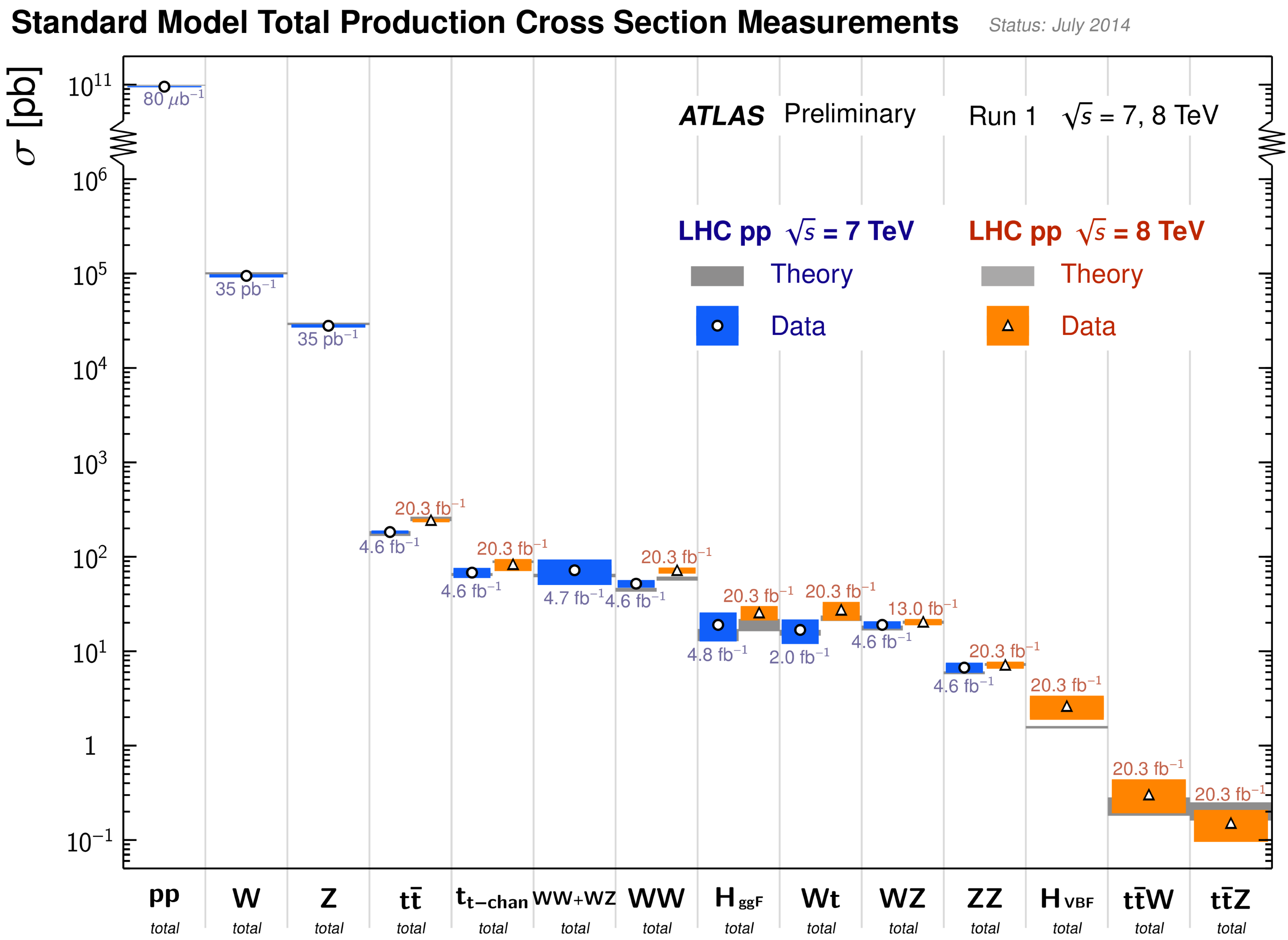




$$Q^2 = (x_1 p_1 + x_2 p_2)^2 = M_V^2 \approx 10^4 \text{ GeV}$$

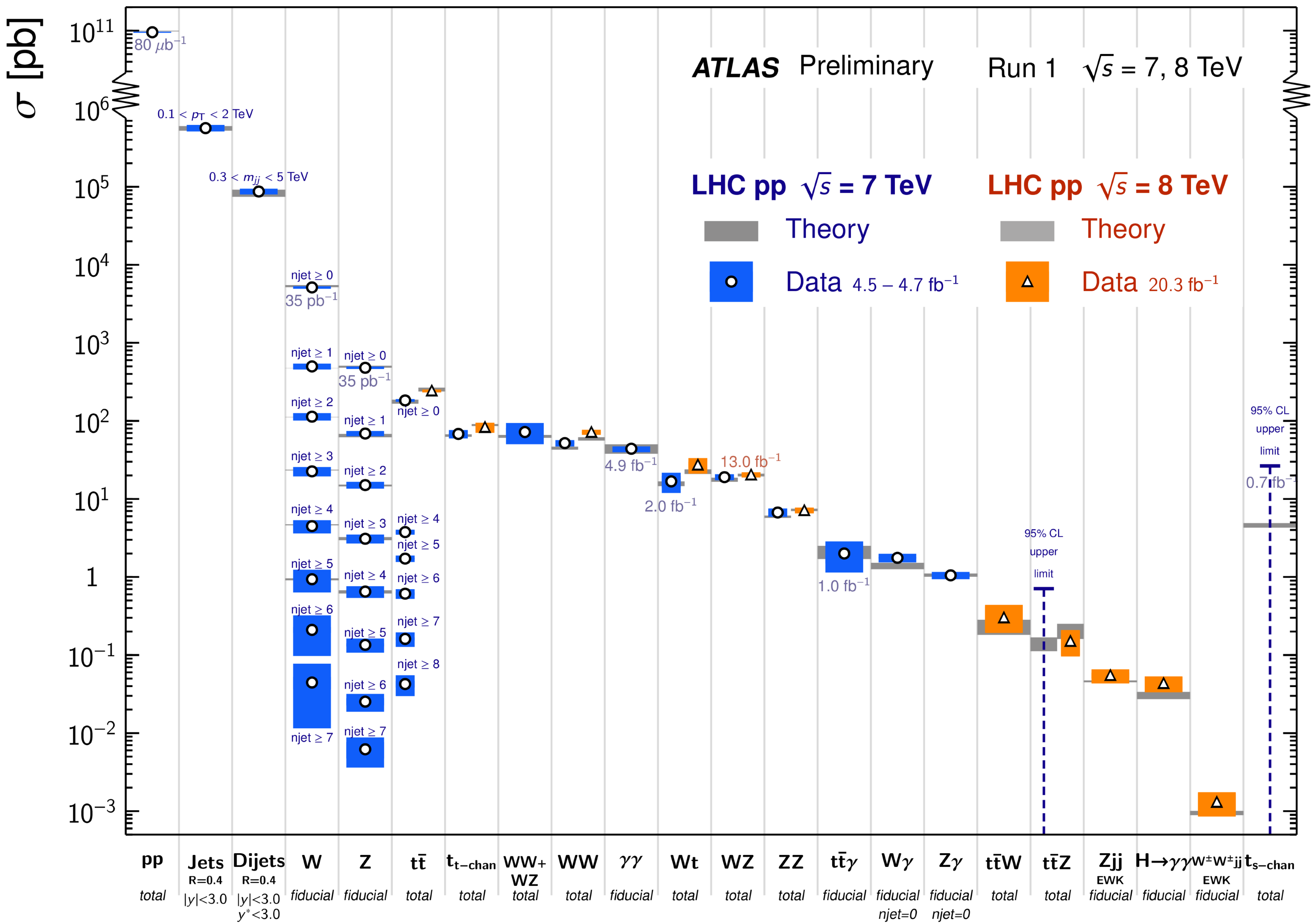
Order	W/Z production process	
LO	$q + \bar{q} \rightarrow V$	
NLO	$q + \bar{q} \rightarrow V$	(one-loop correction)
	$q + \bar{q} \rightarrow V + g$	
	$q(\bar{q}) + g \rightarrow V + q(\bar{q})$	
NNLO	$q + \bar{q} \rightarrow V$	(two-loop correction)
	$q + \bar{q} \rightarrow V + g$	(one-loop correction)
	$q + \bar{q} \rightarrow V + g + g$	
	$q(\bar{q}) + g \rightarrow V + q(\bar{q})$	(one-loop correction)
	$q(\bar{q}) + g \rightarrow V + q(\bar{q}) + g$	
	$q + \bar{q} \rightarrow V + q + \bar{q}$	
	$q(\bar{q}) + q(\bar{q}) \rightarrow V + q(\bar{q}) + q(\bar{q})$	
	$g + g \rightarrow V + q + \bar{q}$	

Table 2.2: Vector boson production processes at LO, NLO, and NNLO at the LHC.


Standard Model Total Production Cross Section Measurements
Status: July 2014
σ [pb]
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
LHC pp √s = 7 TeV
Theory
Data
LHC pp √s = 8 TeV
Theory
Data
80 μb⁻¹
35 pb⁻¹
35 pb⁻¹
4.6 fb⁻¹
20.3 fb⁻¹
4.6 fb⁻¹
20.3 fb⁻¹
4.7 fb⁻¹
4.6 fb⁻¹
20.3 fb⁻¹
4.8 fb⁻¹
20.3 fb⁻¹
2.0 fb⁻¹
20.3 fb⁻¹
4.6 fb⁻¹
13.0 fb⁻¹
4.6 fb⁻¹
20.3 fb⁻¹
20.3 fb⁻¹
20.3 fb⁻¹
20.3 fb⁻¹
pp total
W total
Z total
tt̄ total
t t−chan total
WW+WZ total
WW total
H ggF total
Wt total
WZ total
ZZ total
H VBF total
tt̄W total
tt̄Z total

Standard Model Production Cross Section Measurements

Status: July 2014



W/Z Event Selections

	Z→ll	W→lν
Preselections	GRL (Data)	GRL (Data)
	≥1 good vertex with ≥3 tracks	≥1 good vertex with ≥3 tracks
	Dilepton Trigger	Single lepton Trigger
	No bad jets and no ugly jets	No bad jets and no ugly jets
	Not in LAr Hole (E-H)	Not in LAr Hole (E-H)
Electron selections	Medium++ electron	Tight++
	cluster pT >25 GeV	cluster pT >25 GeV
	|η|<2.47 and not in crack	|η|<2.47 and not in crack
	author 1 or 3	author 1 or 3
Muon selections	Staco Combined Muon	Staco Combined Muon
	pT>25 GeV	pT>25 GeV
	|η| < 2.4	|η| < 2.4
	author 1 or 6	author 1 or 6
	isolation on cone20 < 0.1	isolation on cone20 < 0.1
Final event selection	Exactly two oppositely charged leptons	1 tight lepton, no second high pT lepton
	66 GeV < M	MET > 25 GeV and M