p-p Physics at LHC

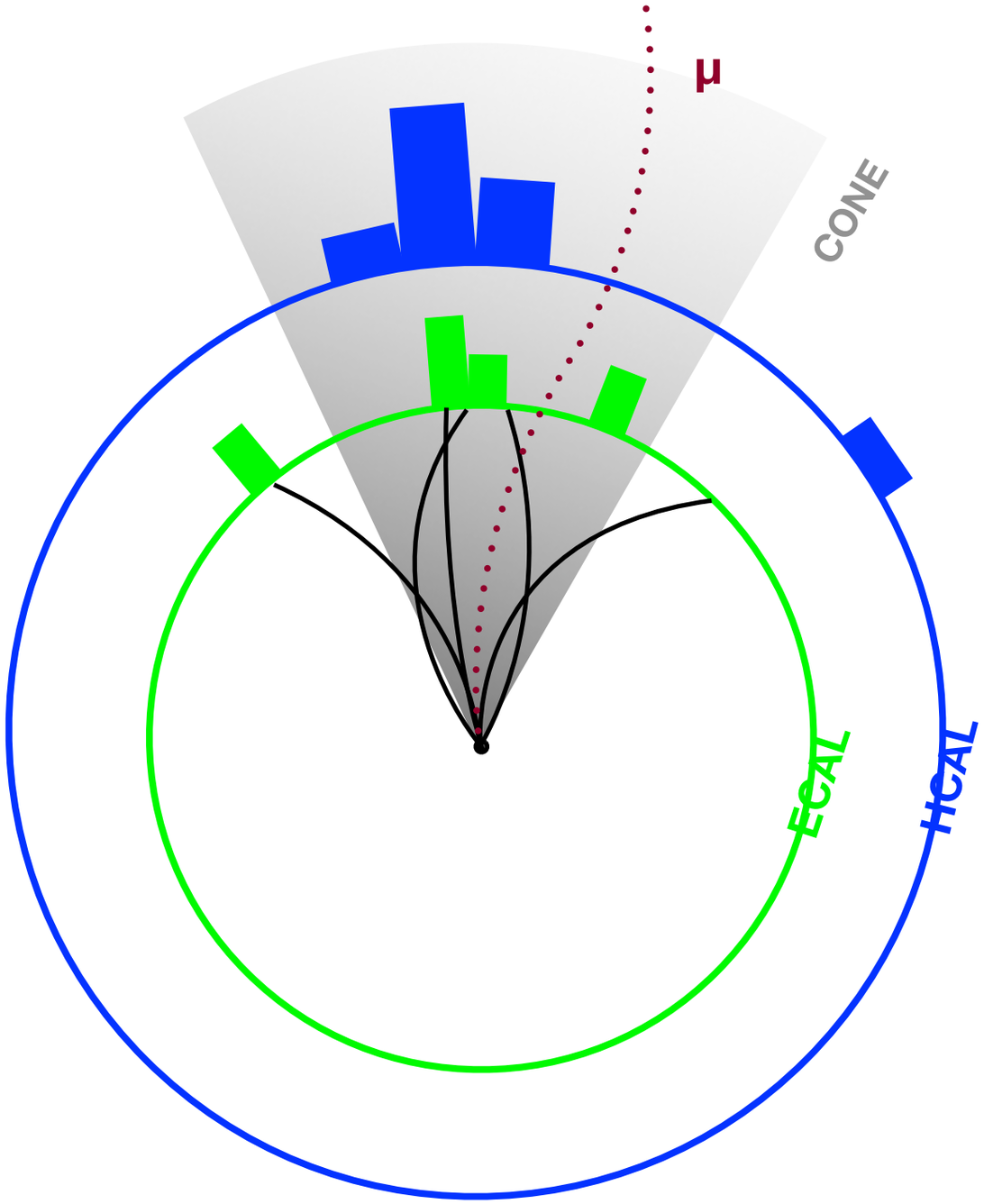
W, Z, and diboson production

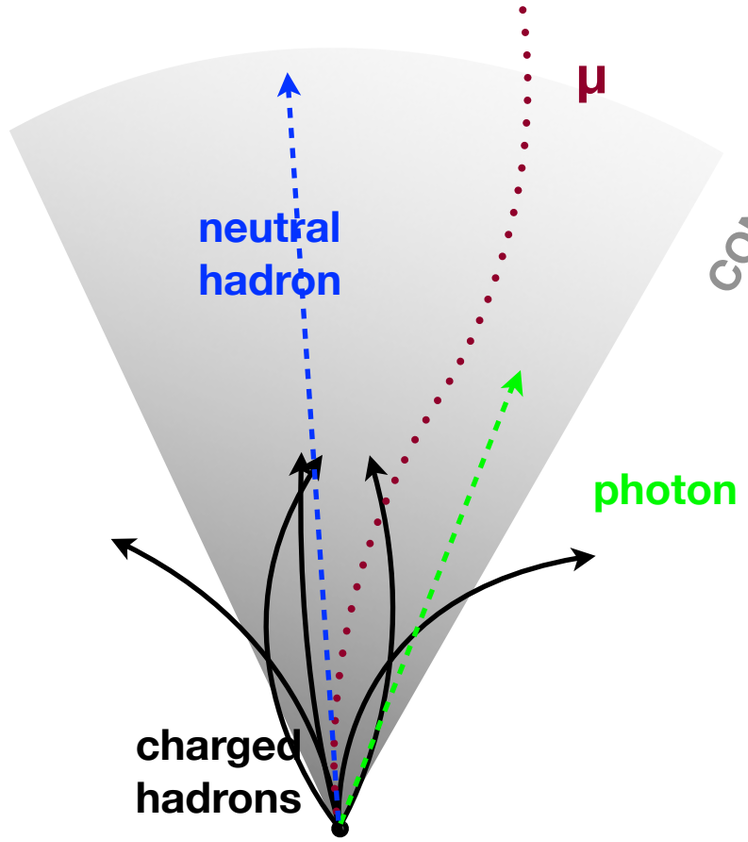
Lecture 5

Dipartimento di Fisica

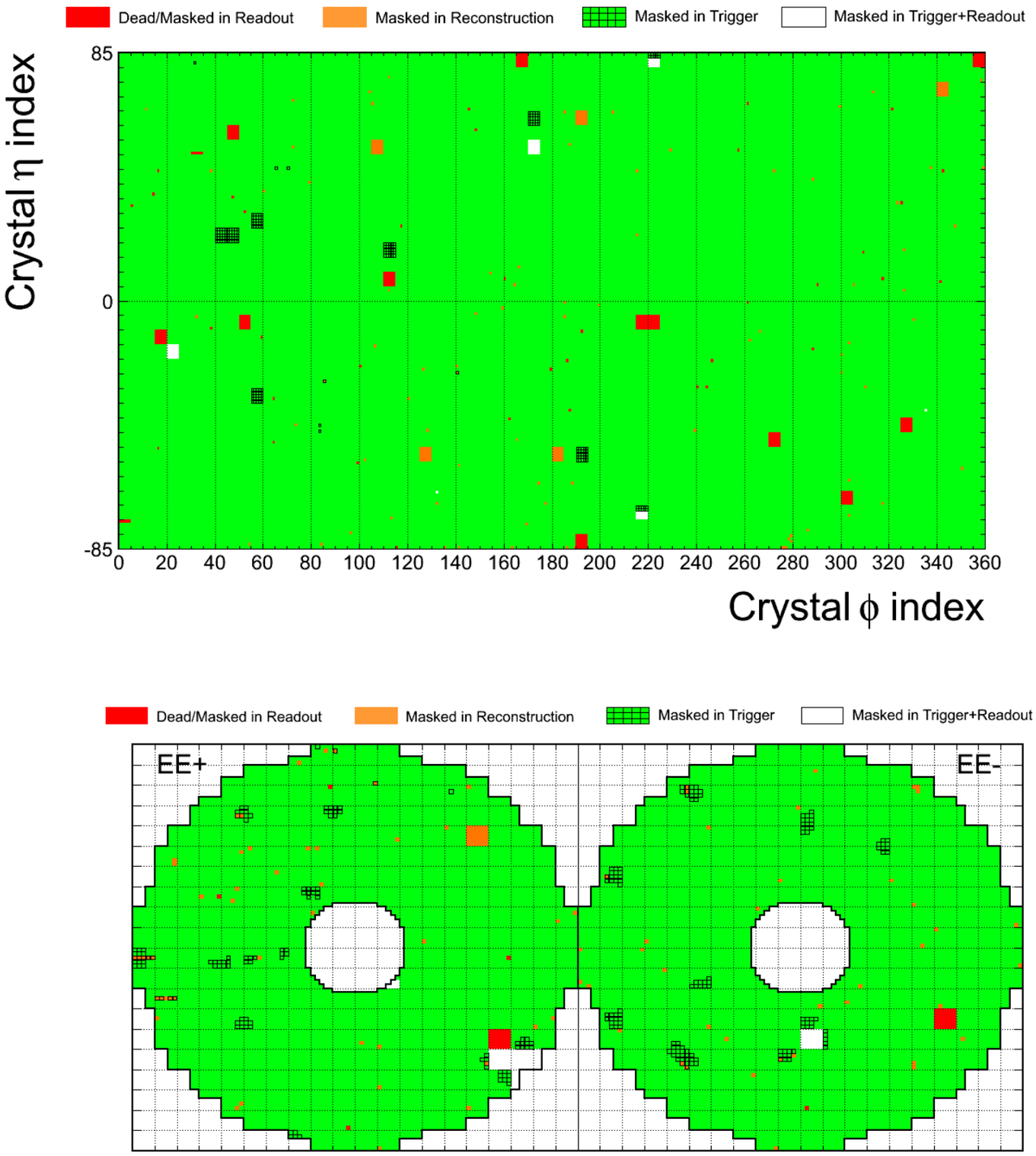
Sapienza
Università di Roma

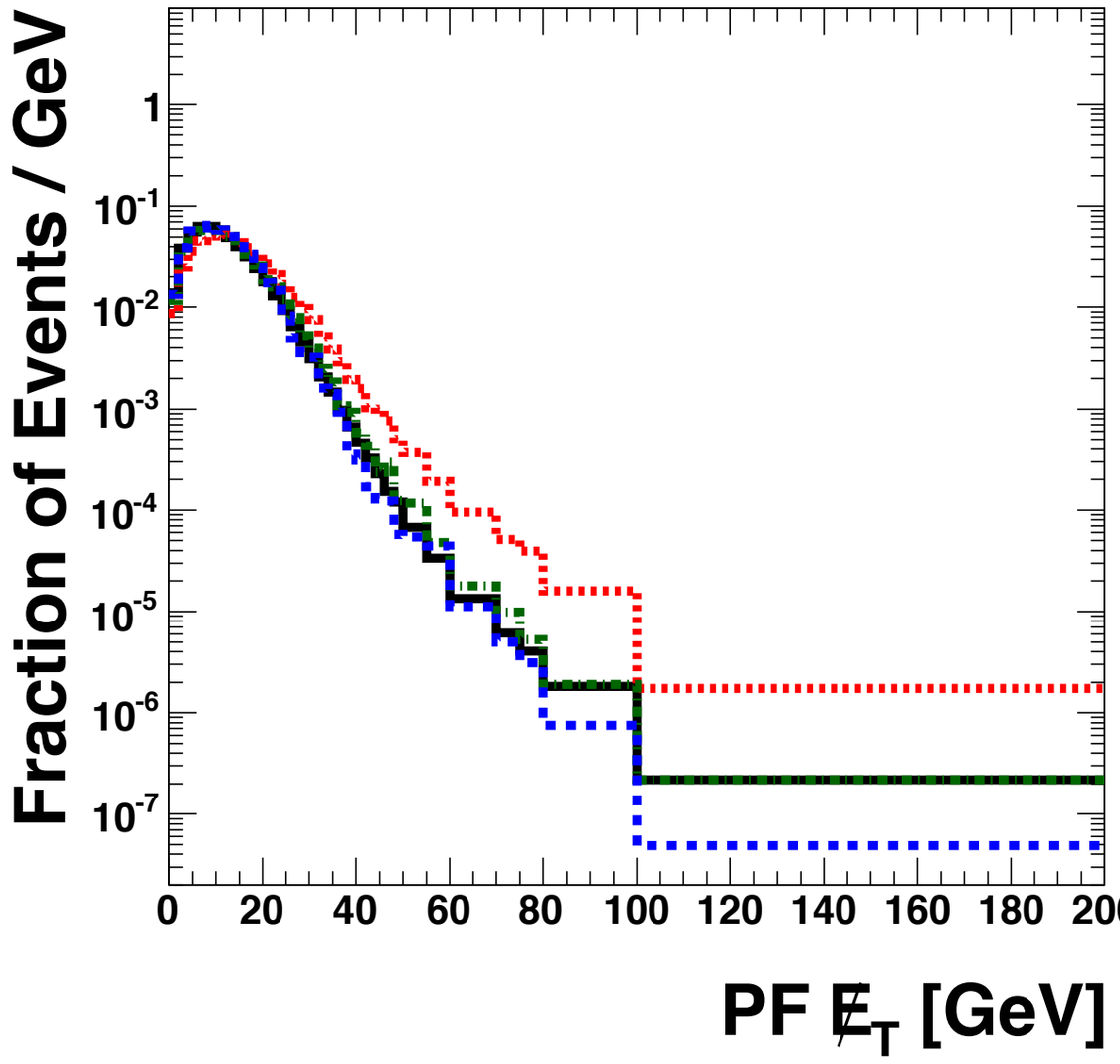
LEPTON ISOLATION



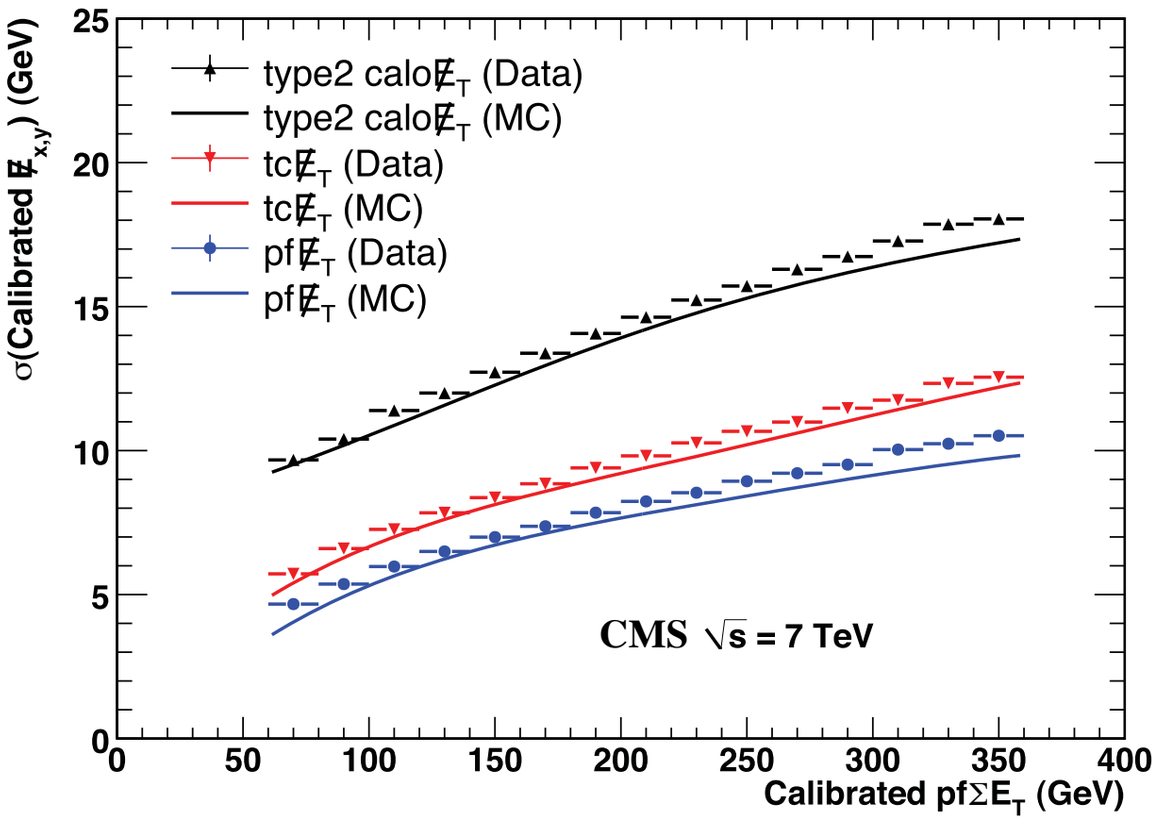


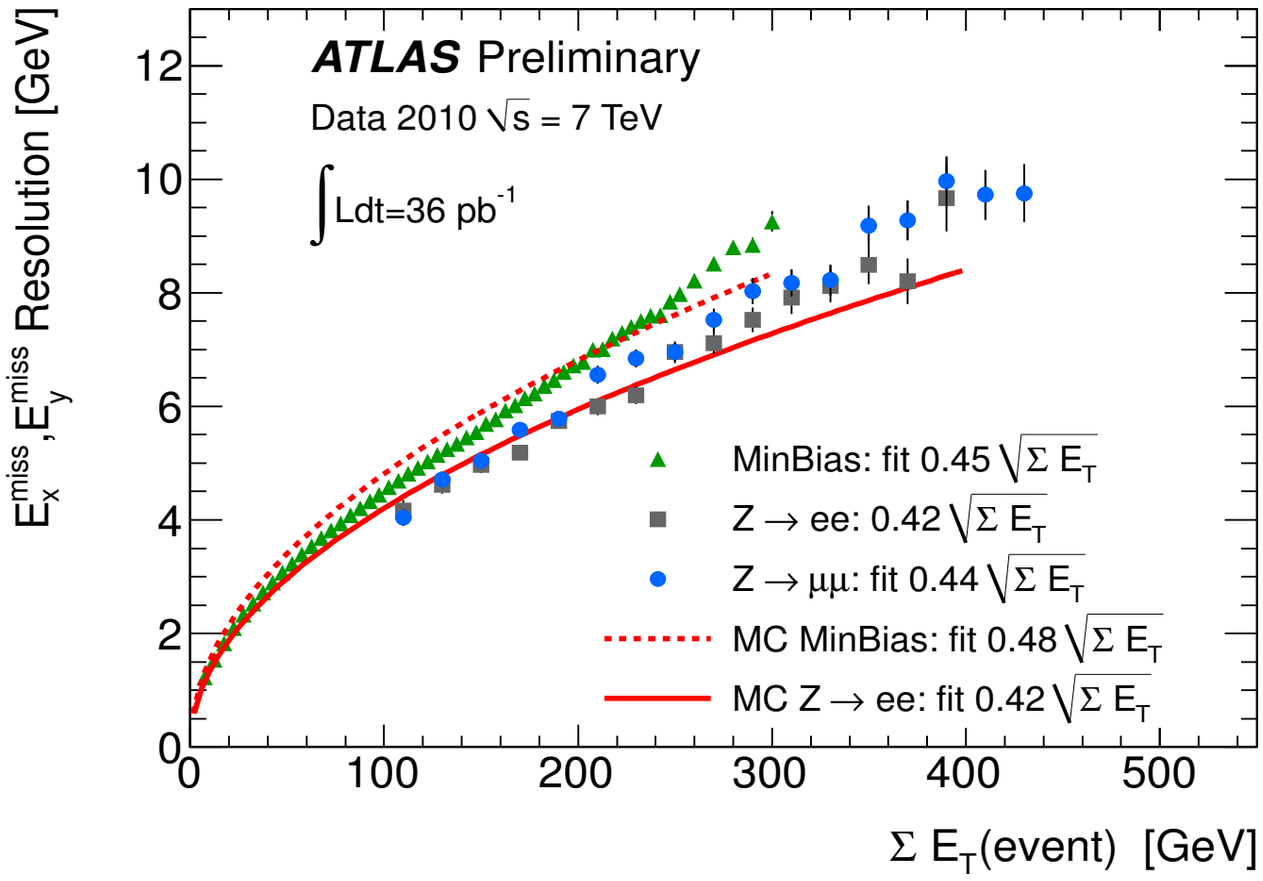
Detector Effects on MET





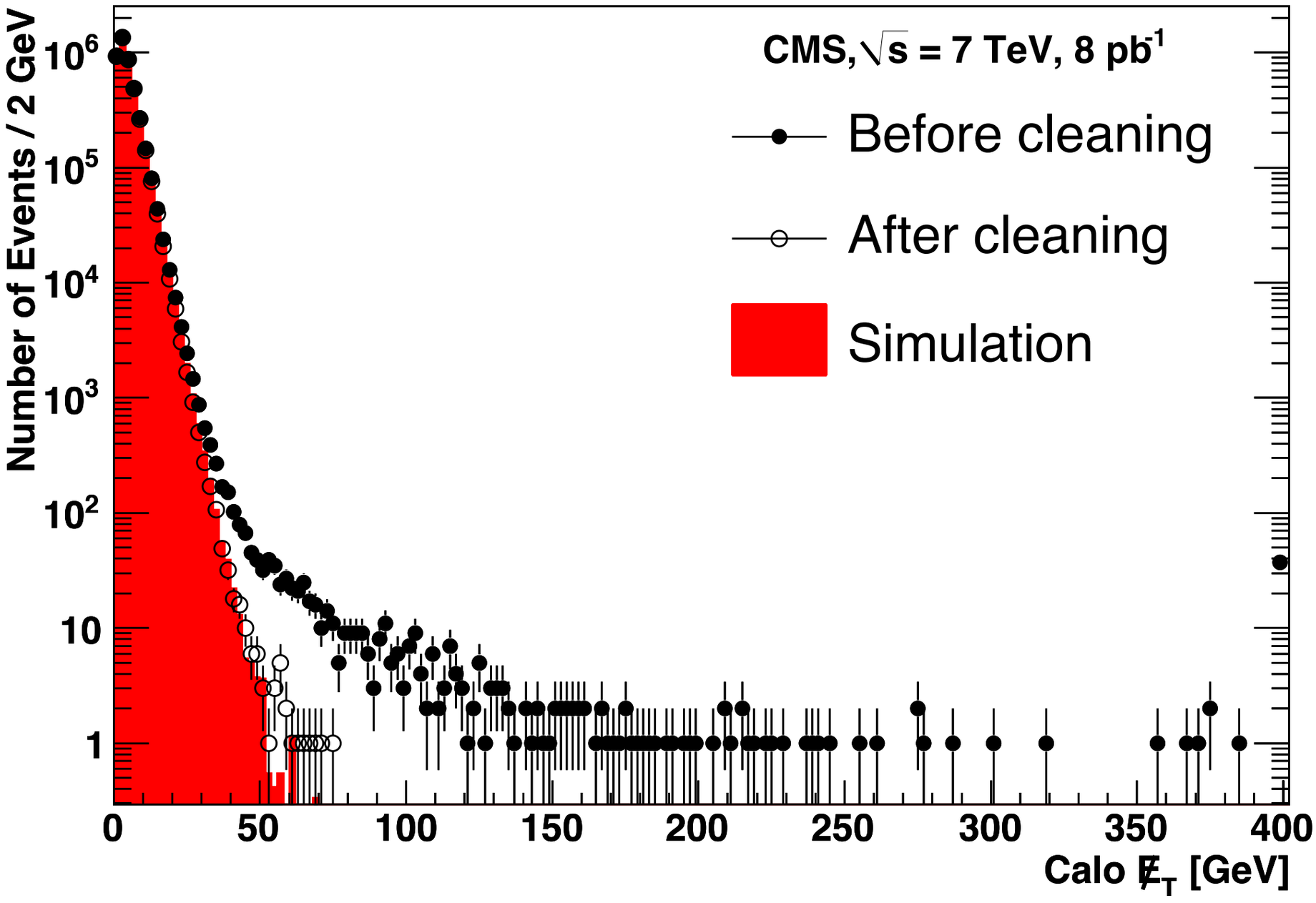
MET Resolution





- Reconstruction and Calibration of Missing Transverse Energy and Performance in Z and W events in ATLAS Proton-Proton Collisions at $\sqrt{s}$=7 TeV (ATLAS-CONF-2011-080)

MISSING TRANSVERSE ENERGY

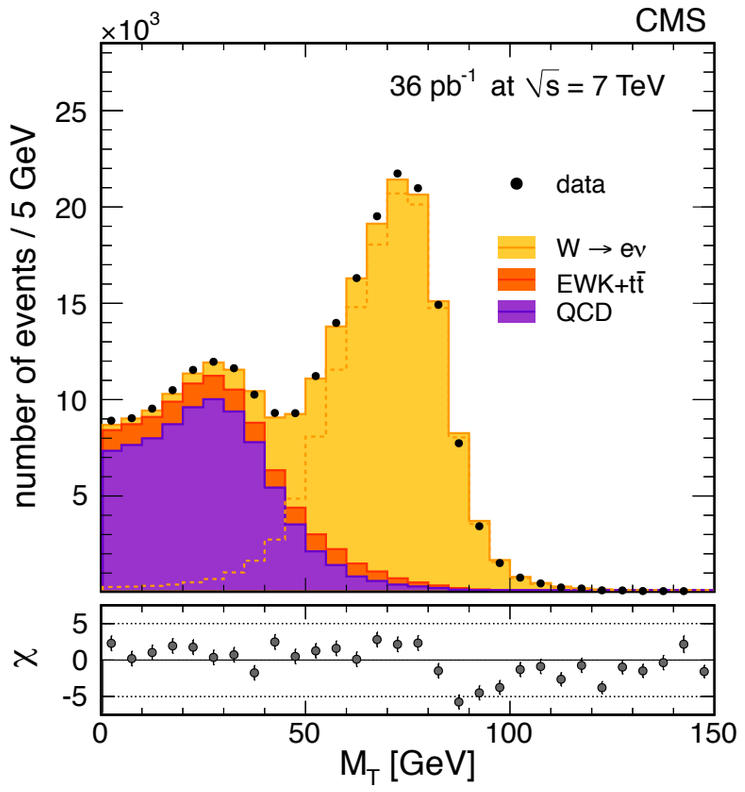


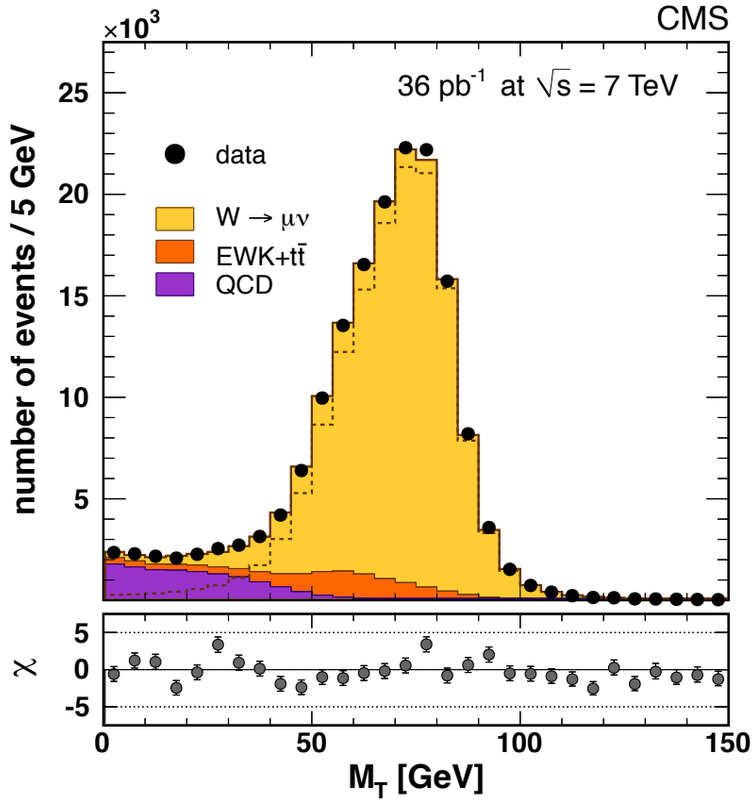
W AND Z MASS SPECTRA

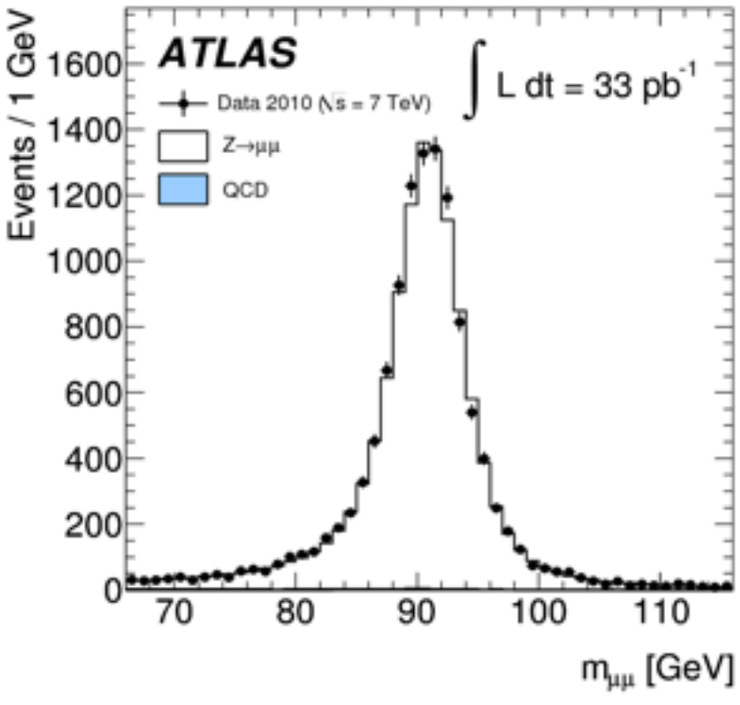
- Generally much higher background with electrons compared to muons

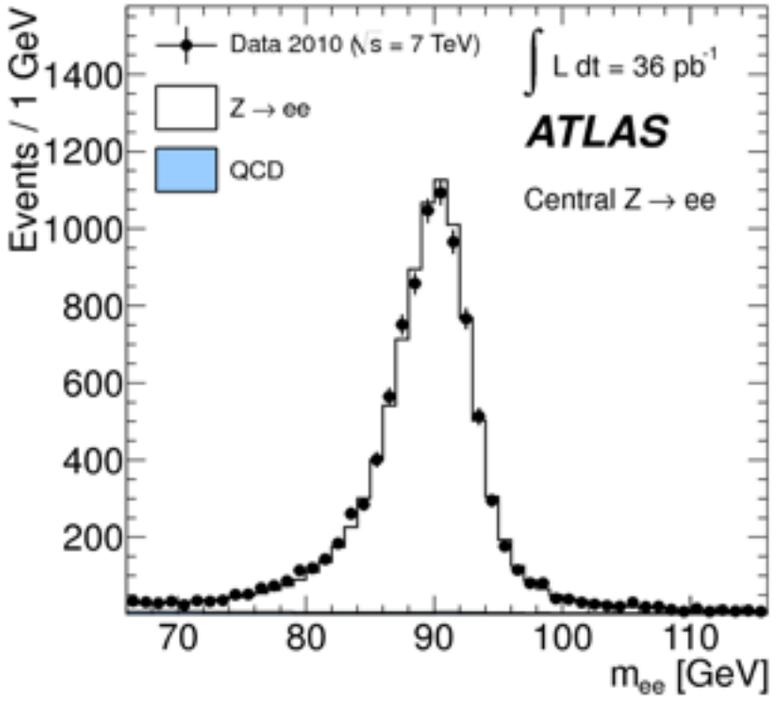
- Why?
  - Detector effects?
  - Physics?

- Note # of Z bosons typically x10 less than W



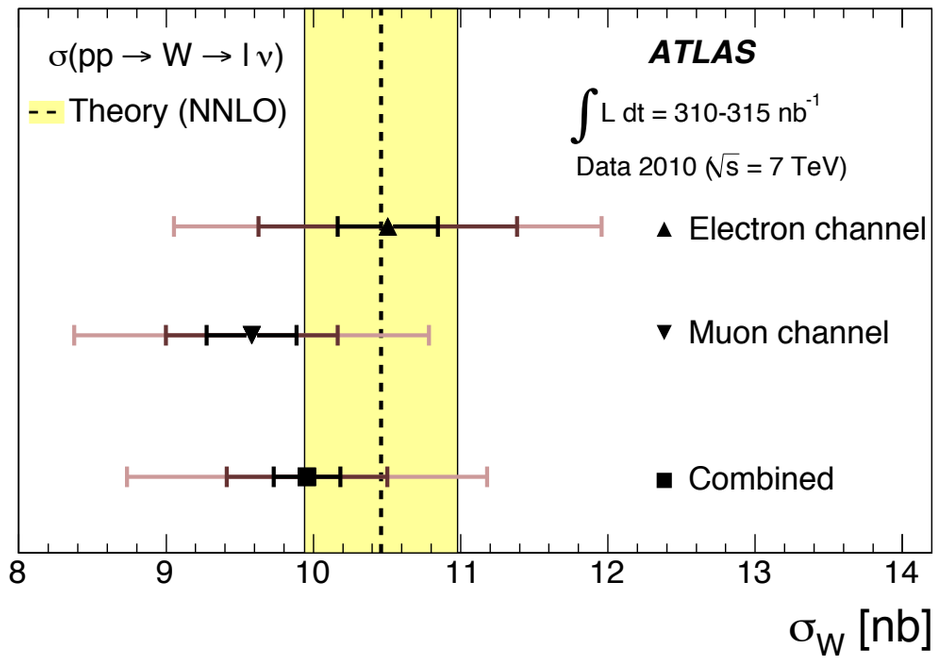


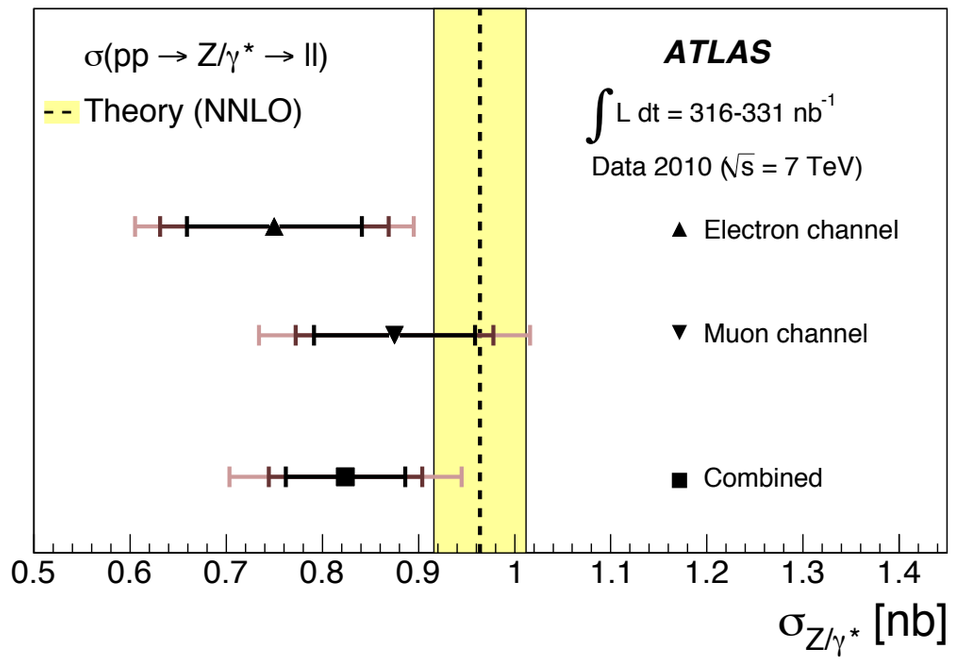


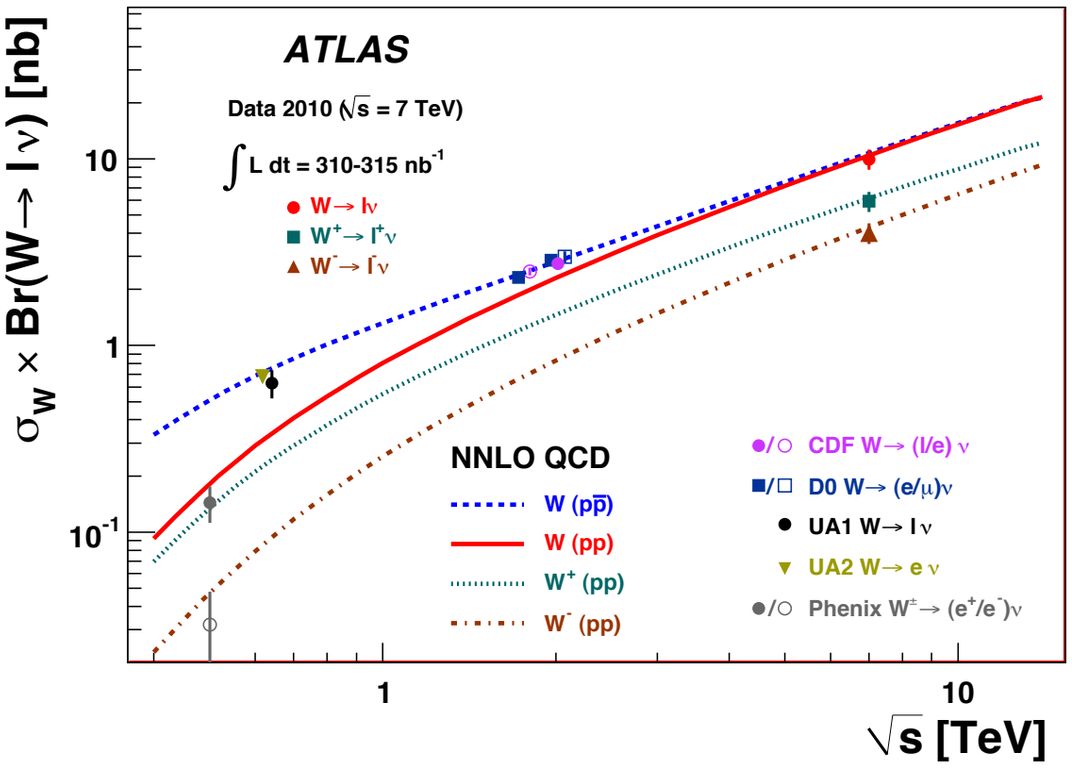


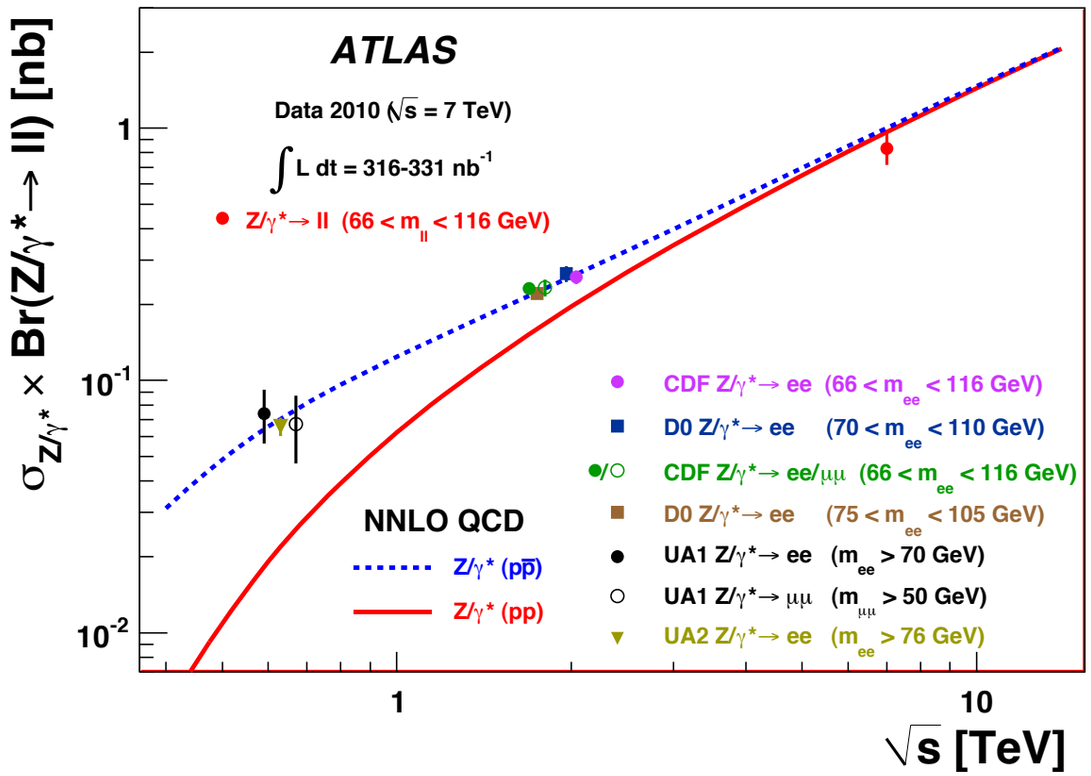
Measurement of inclusive cross section with ATLAS
Measurement of inclusive cross section with CMS

W/Z Cross Section at LHC

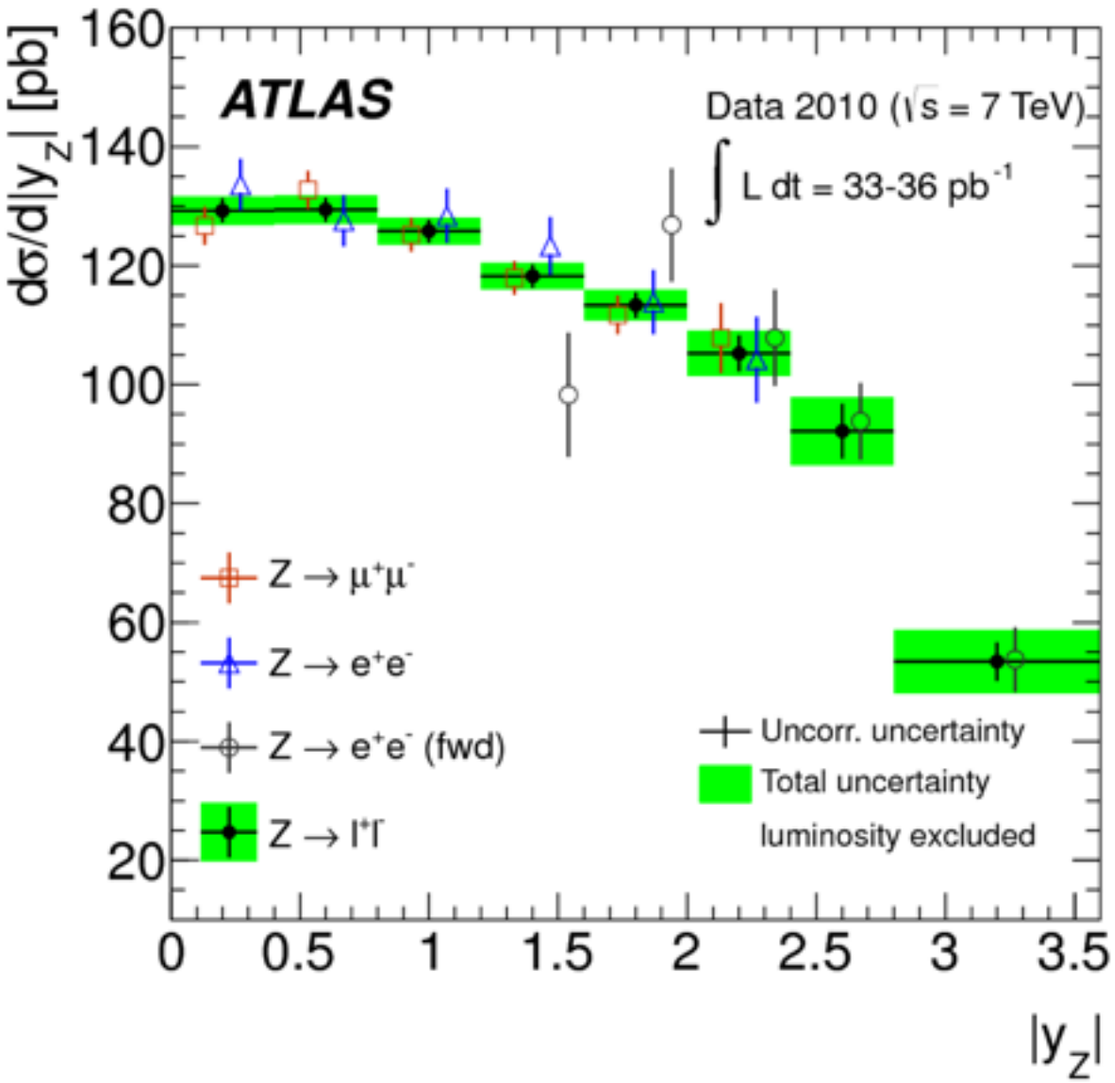


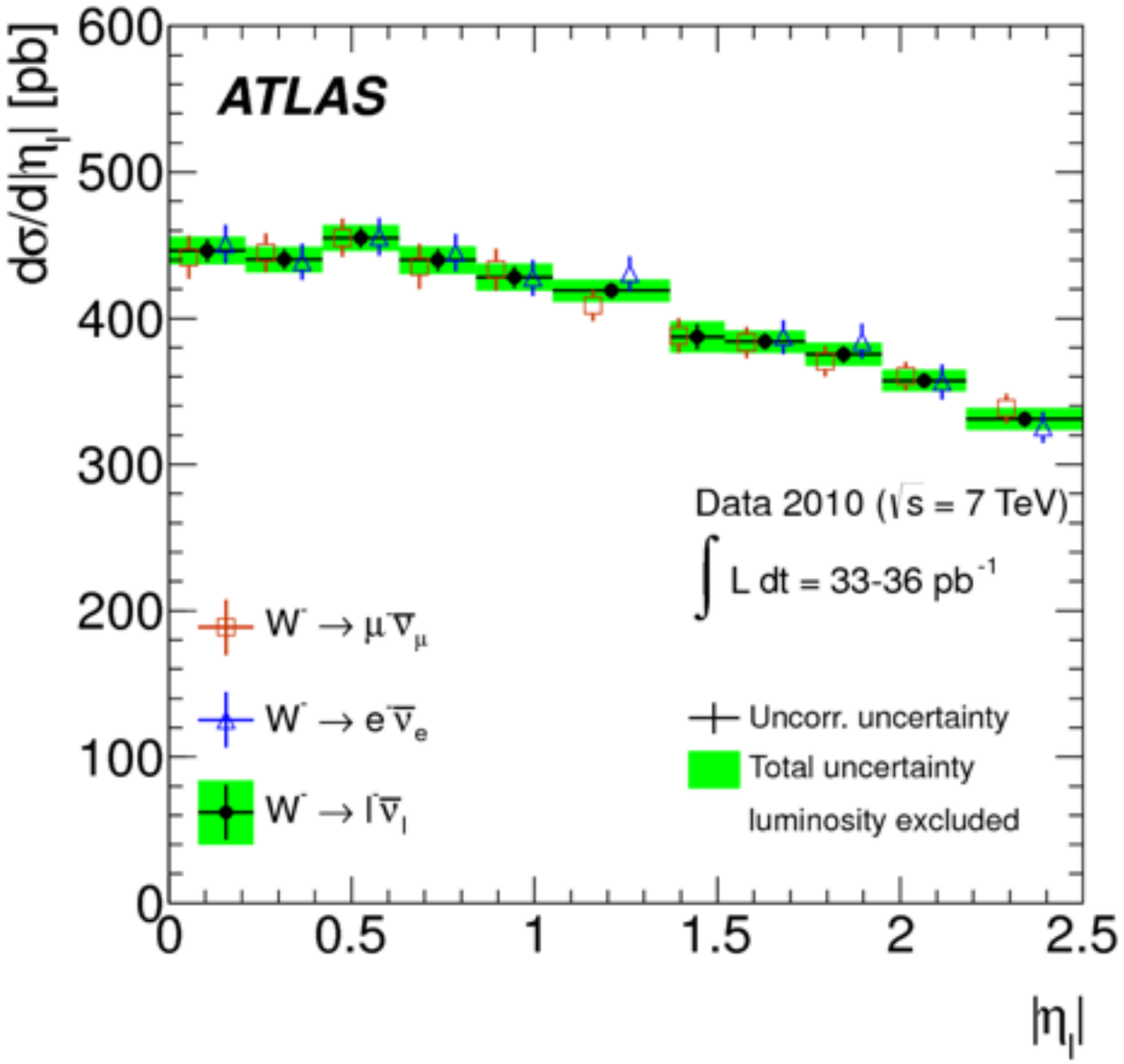






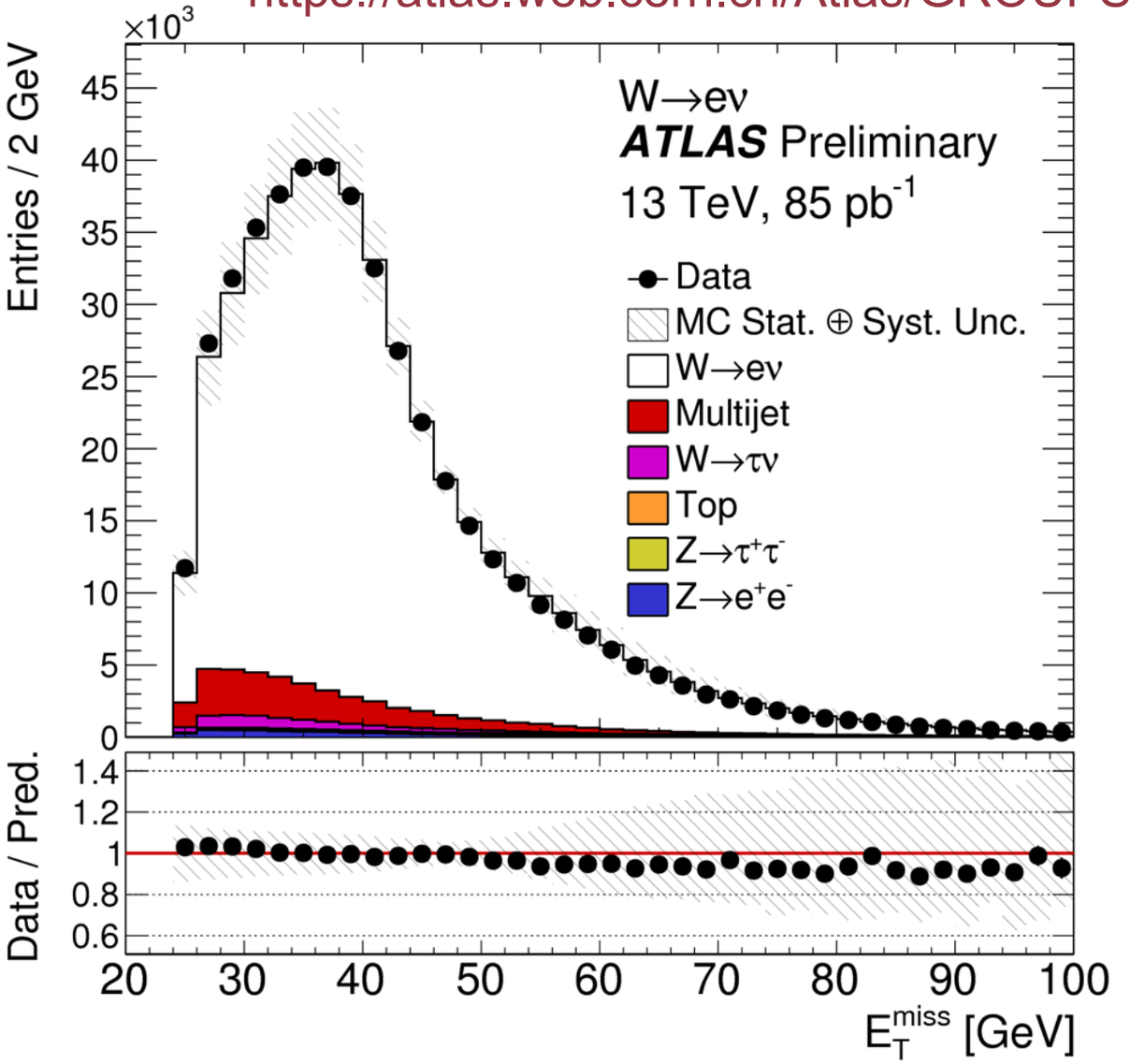
W/Z Differential Cross Section

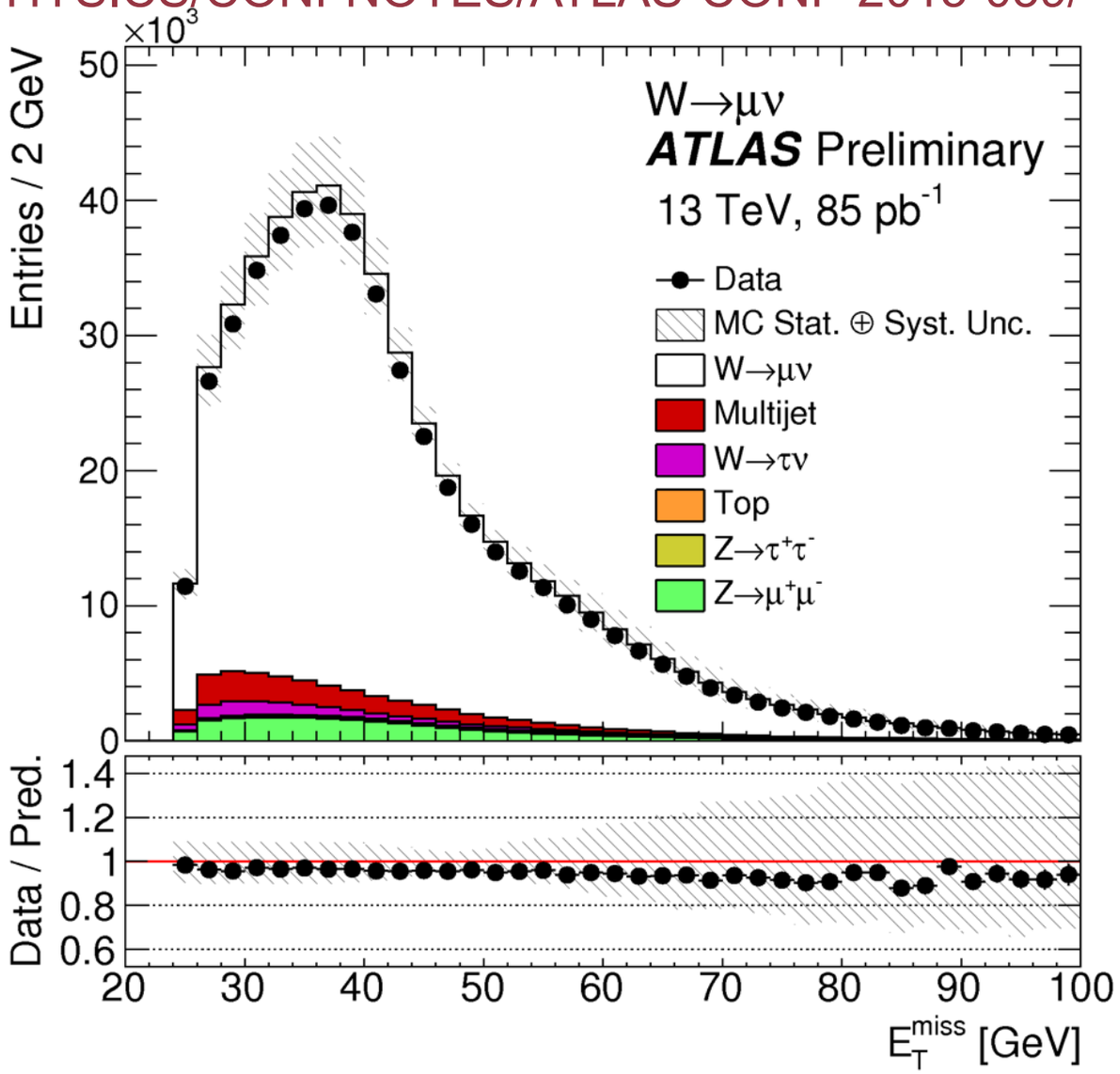




W AT 13 TEV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-039/

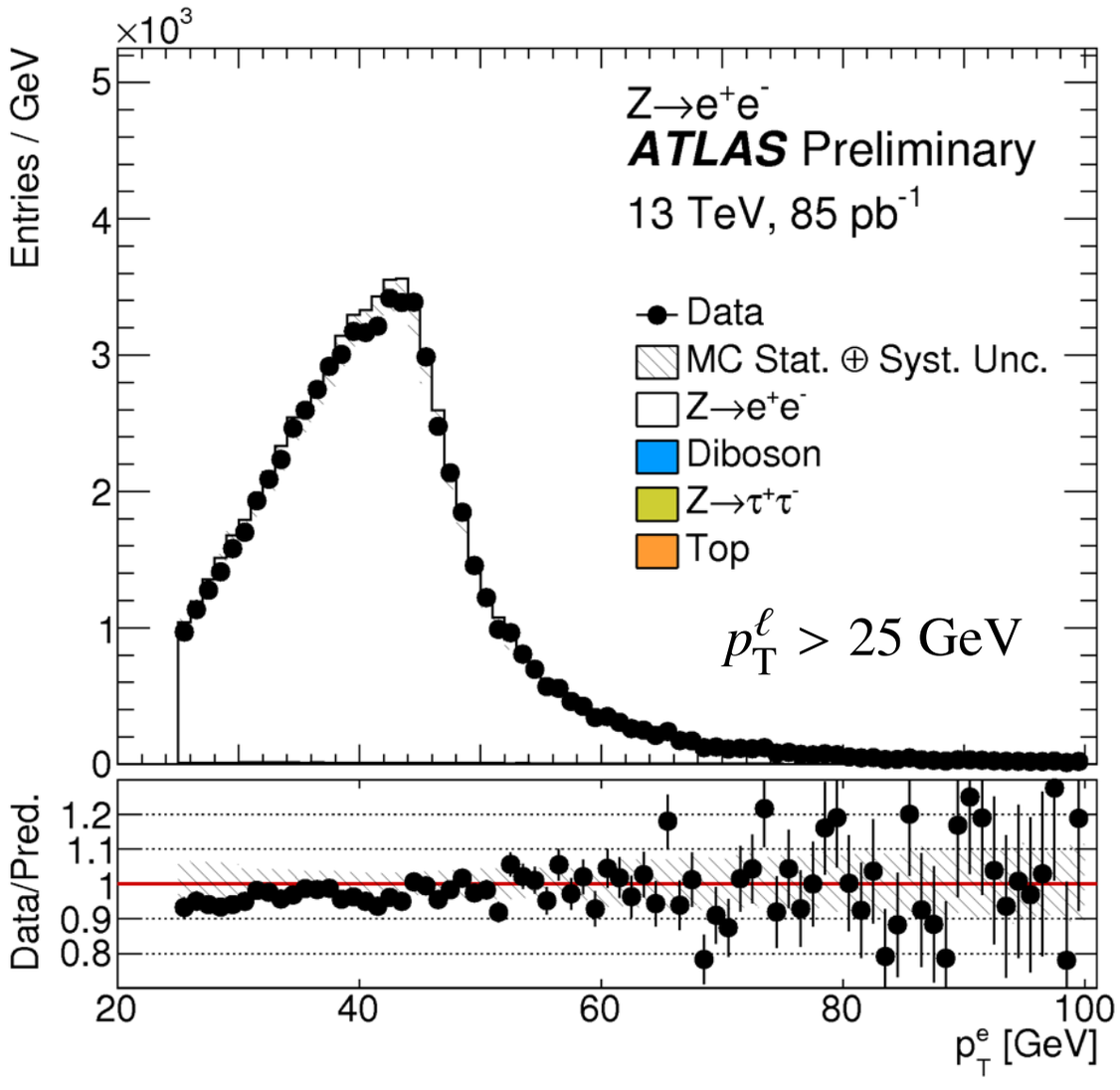


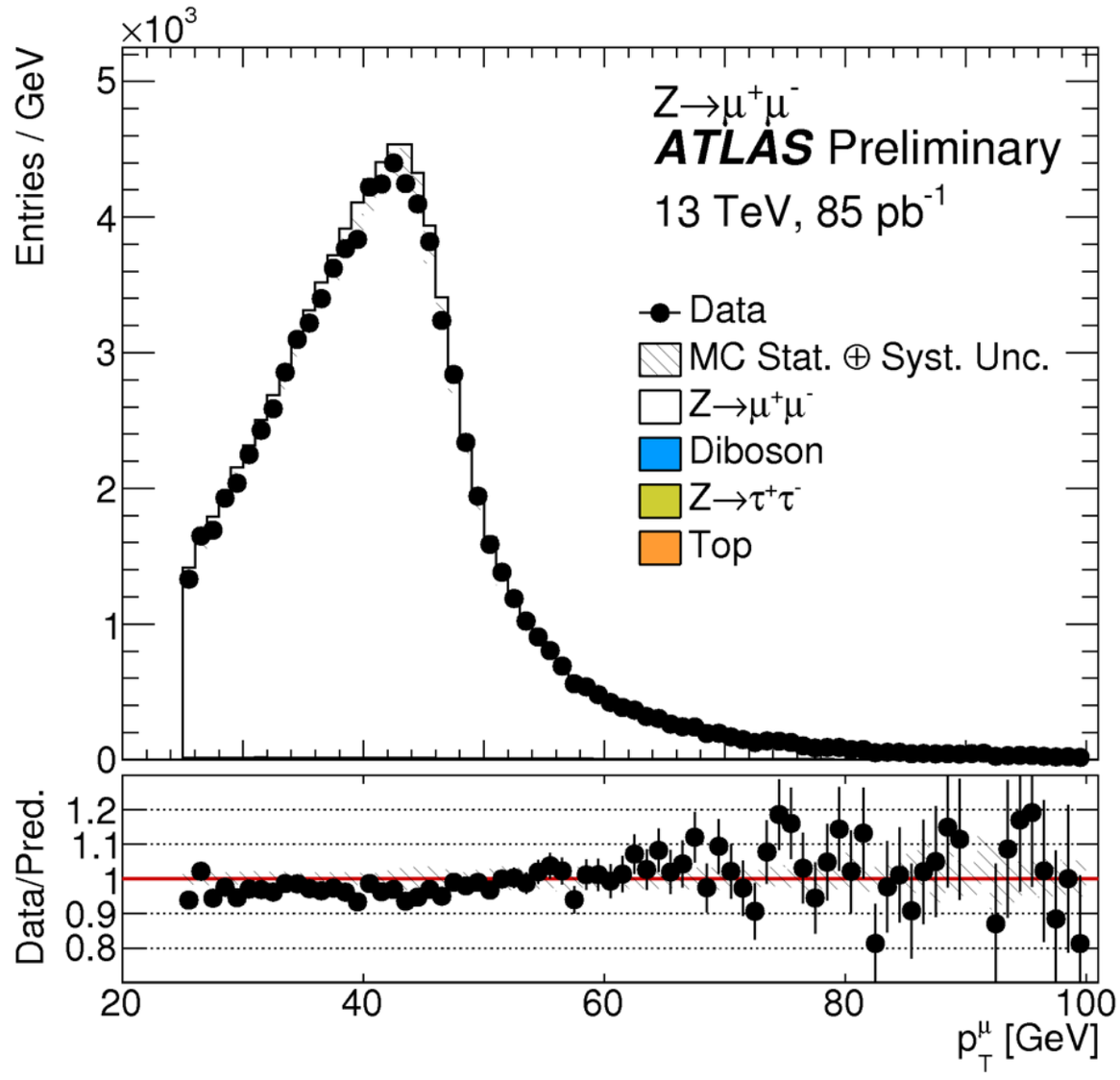


$p_{\mathrm{T}}^{\ell} > 25$ GeV

$\ell^{\pm}$	Observed candidates	Background (EW+top)	Background (Multijet)	Background-subtracted events N_W^{sig}
e^+	256923	10100 ± 600	$15200 \pm 300 \pm 6700$	$231600 \pm 500 \pm 6700$
e^-	206140	8900 ± 500	$15600 \pm 300 \pm 6900$	$181600 \pm 500 \pm 6900$
μ^+	272841	20420 ± 920	$12200 \pm 200 \pm 3500$	$240300 \pm 500 \pm 3600$
μ^-	214249	18210 ± 830	$11500 \pm 100 \pm 3100$	$184500 \pm 500 \pm 3200$

Z AT 13 TEV





$\ell^\pm$	Observed candidates	Background (EW+top)	Background (Multijet)	Background-subtracted events N_Z^{sig}
$e^\pm$	34955	$229 \pm 1 \pm 24$	$< 0.1\%$	$34730 \pm 190 \pm 20$
$\mu^\pm$	44899	$296 \pm 2 \pm 31$	$< 0.1\%$	$44600 \pm 210 \pm 30$

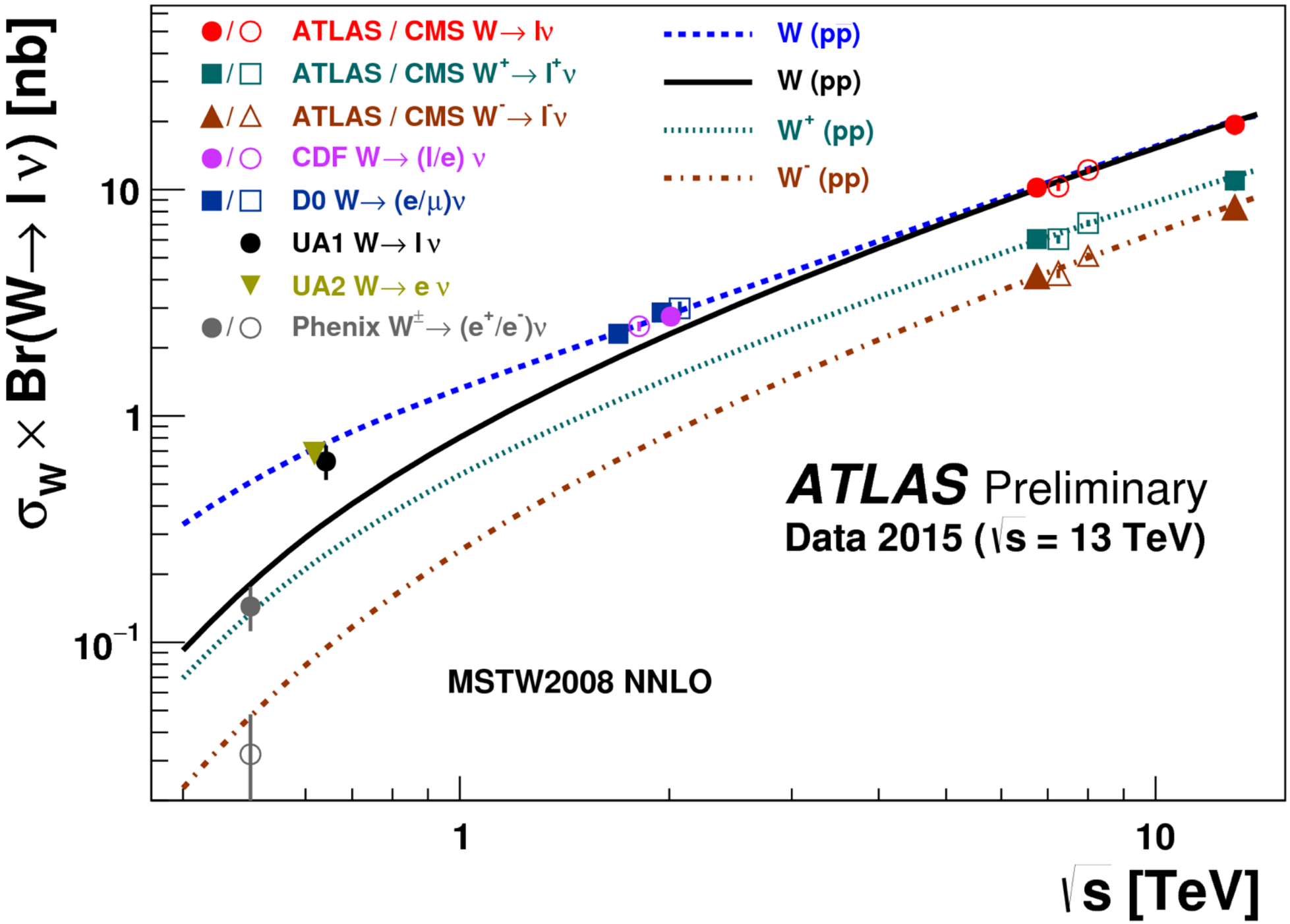
W AND Z BACKGROUNDS

Physics process	Generator	σ ($\cdot$ BR [pb])	Order	Reference
$W \to \ell\nu \quad (\ell = e, \mu, \tau)$	POWHEG +PYTHIA 8	$20400 \pm 5\%$	NNLO	[2,3,4,5]
$W^+ \to \ell^+\nu$		$11770 \pm 5\%$	NNLO	[2,3,4,5]
$W^- \to \ell^-\overline{\nu}$		$8640 \pm 5\%$	NNLO	[2,3,4,5]
$Z \to \ell^+\ell^- \quad (66 < m_{\ell\ell} < 116$ GeV)	POWHEG +PYTHIA 8	$1930 \pm 5\%$	NNLO	[2,3,4,5]
$t\bar{t} \quad (m_t = 172.5$ GeV)	POWHEG +PYTHIA 6	$830 \pm 6\%$	NNLO+NNLL	[27]
Dibosons	SHERPA	$99 \pm 6\%$	NLO	[31]
Dijet (e channel, $\hat{p}_{\mathrm{T}} > 21$ GeV)	PYTHIA 8	180×10^3	LO	[13]
$b\bar{b}$ (μ channel, $\hat{p}_{\mathrm{T}} > 15$ GeV)	PYTHIA 8	188	LO	[13]
$c\bar{c}$ (μ channel, $\hat{p}_{\mathrm{T}} > 15$ GeV)	PYTHIA 8	58	LO	[13]

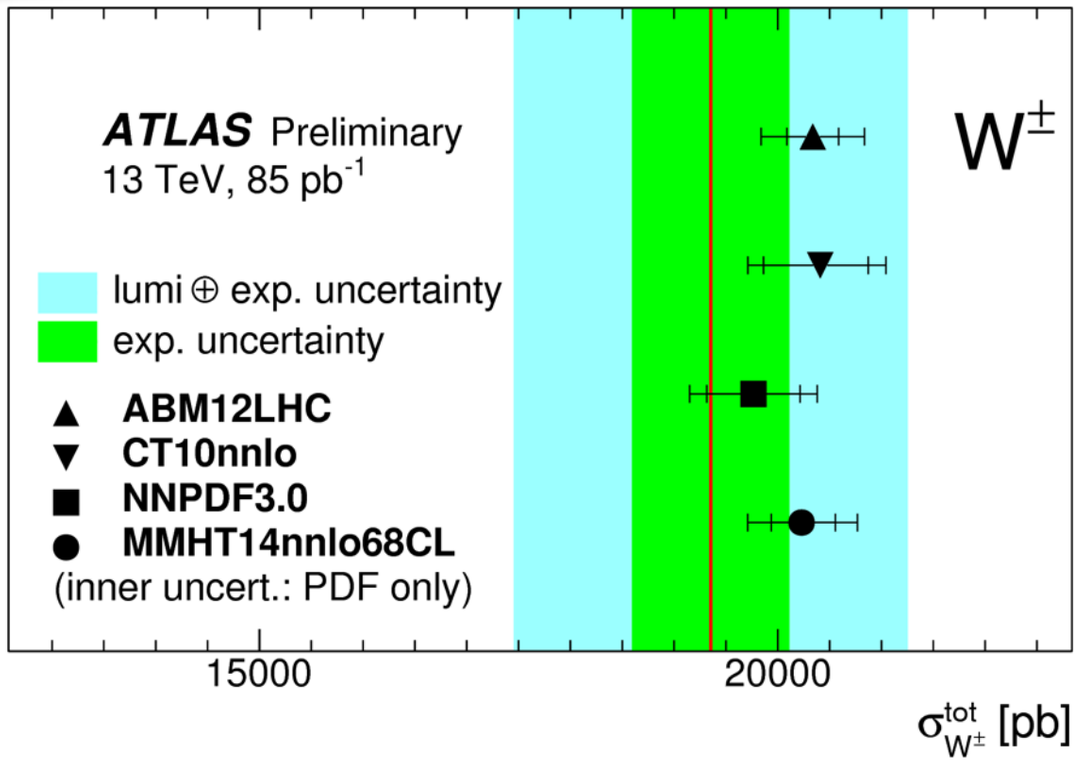
Cross sections @ 13 TeV

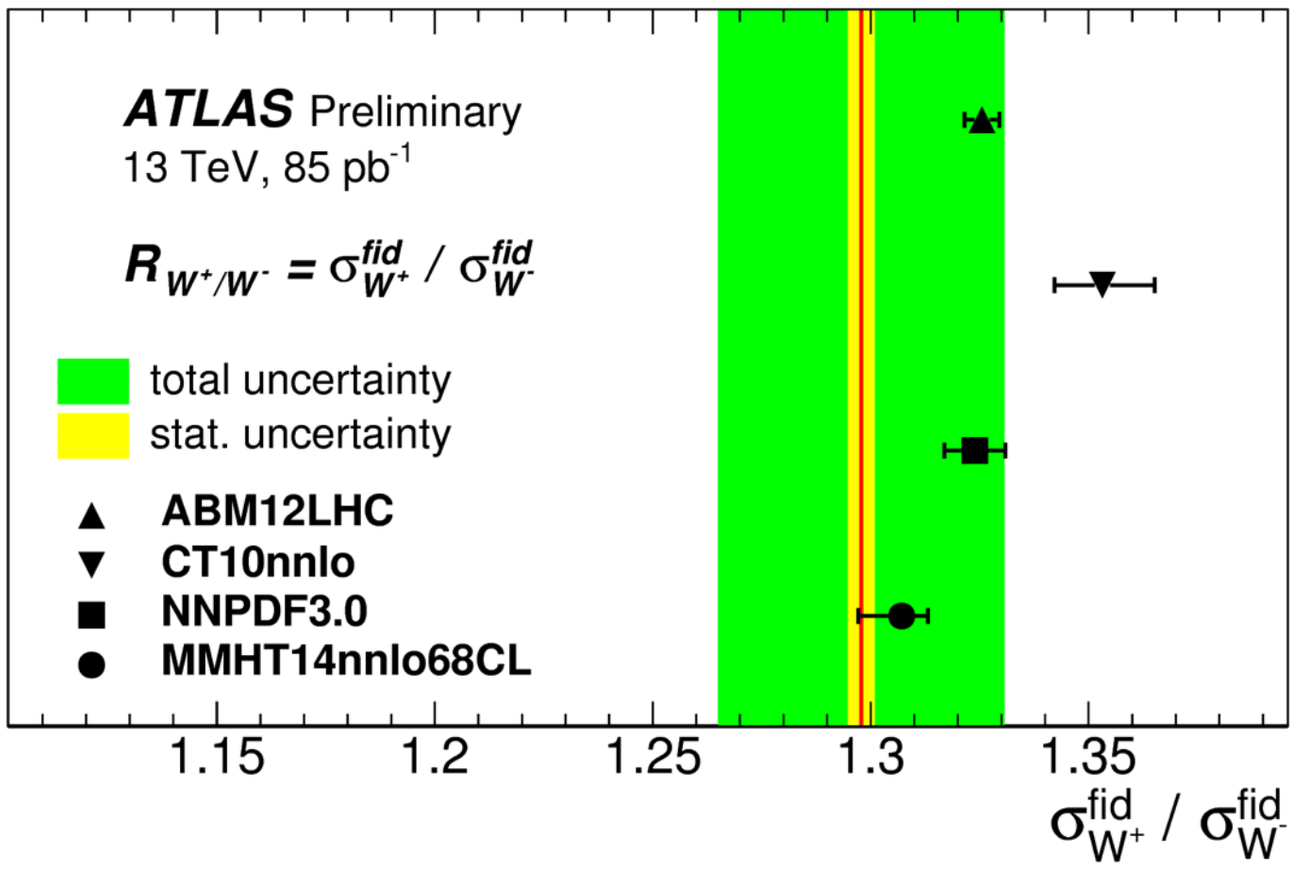
W Cross Section at 13 TeV

$$\sigma^{\text{tot}}_{W^{\pm}} = \sigma_W \cdot BR(W \to \ell\nu) = \frac{N^{\text{sig}}_W}{A_W \cdot C_W \cdot \mathcal{L}}$$

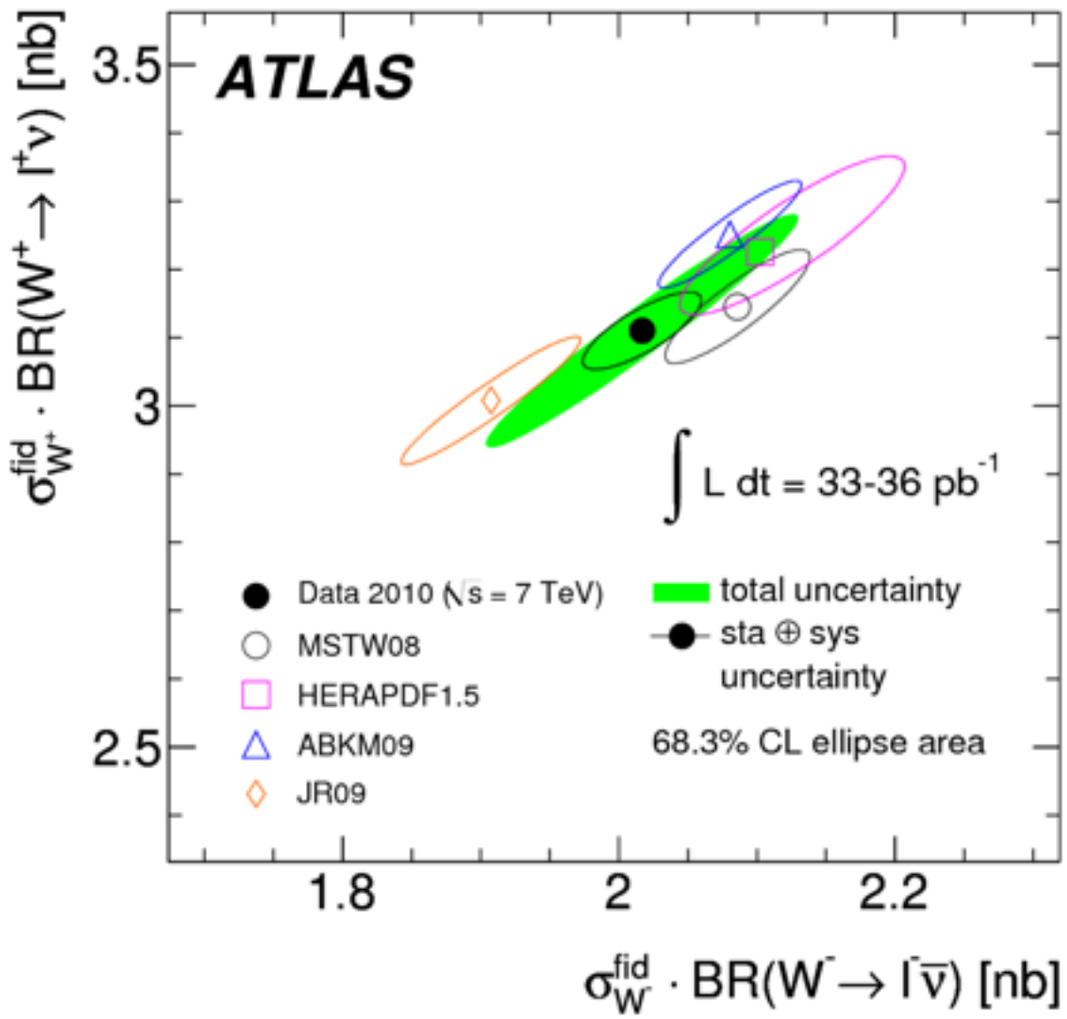


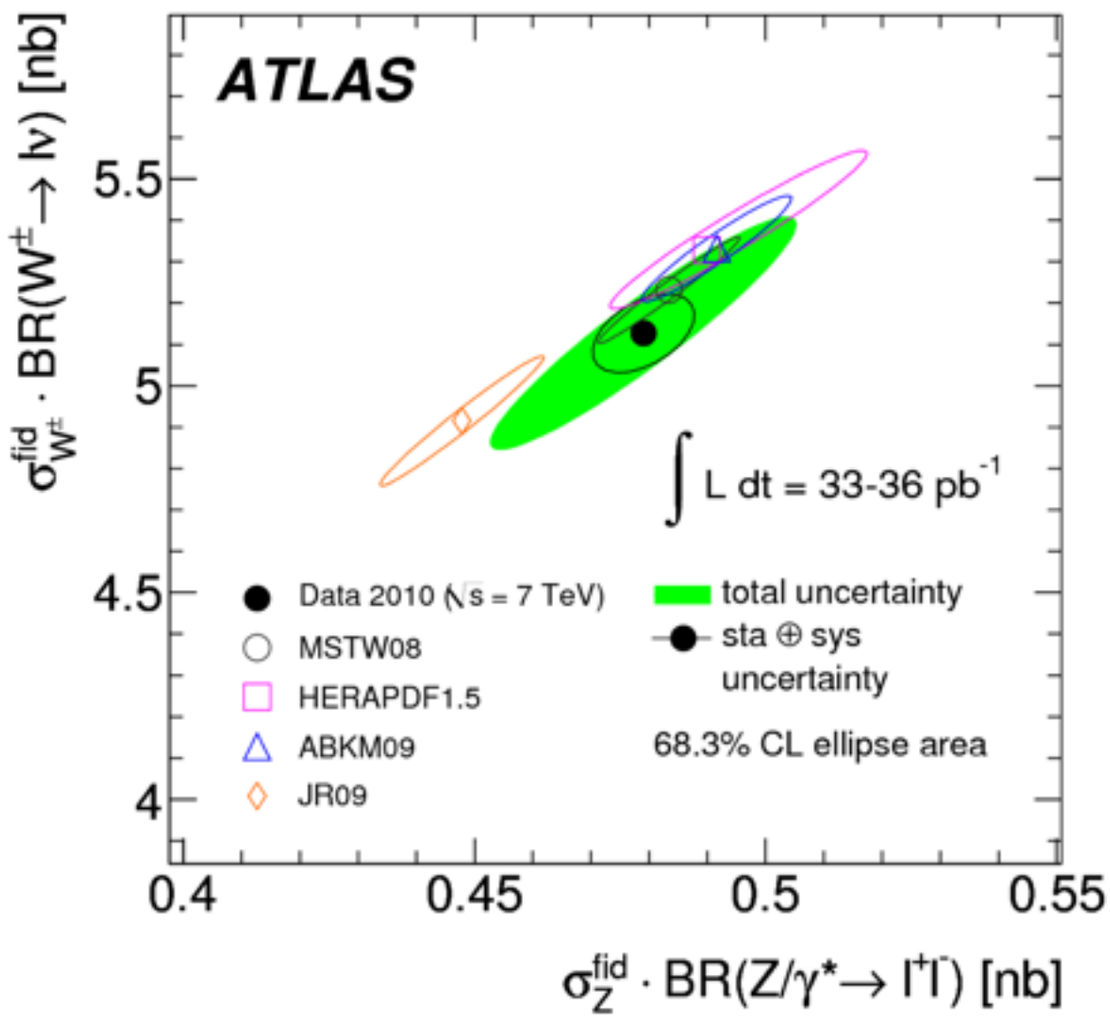
COMPARISON WITH THEORY





CONSTRAINT ON PDF FROM INCLUSIVE CROSS SECTION





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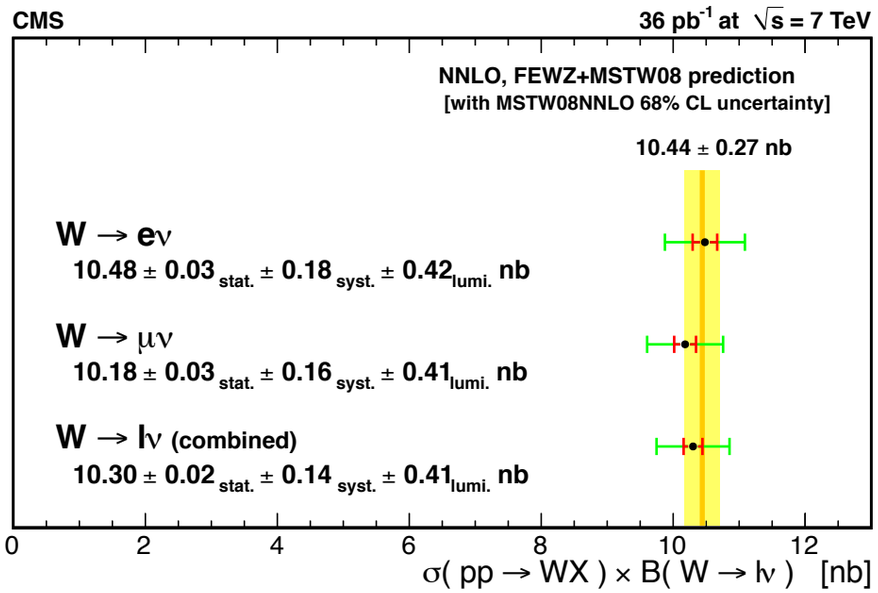
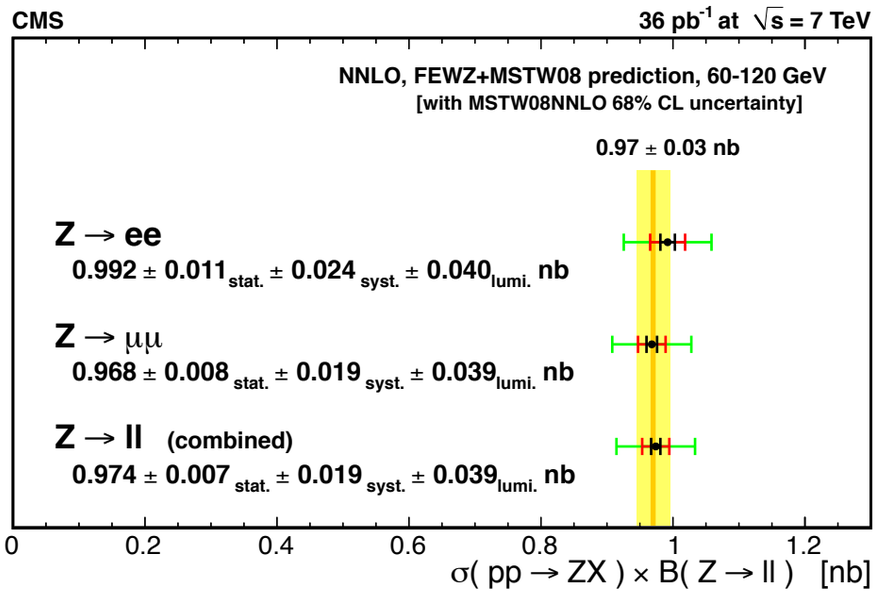
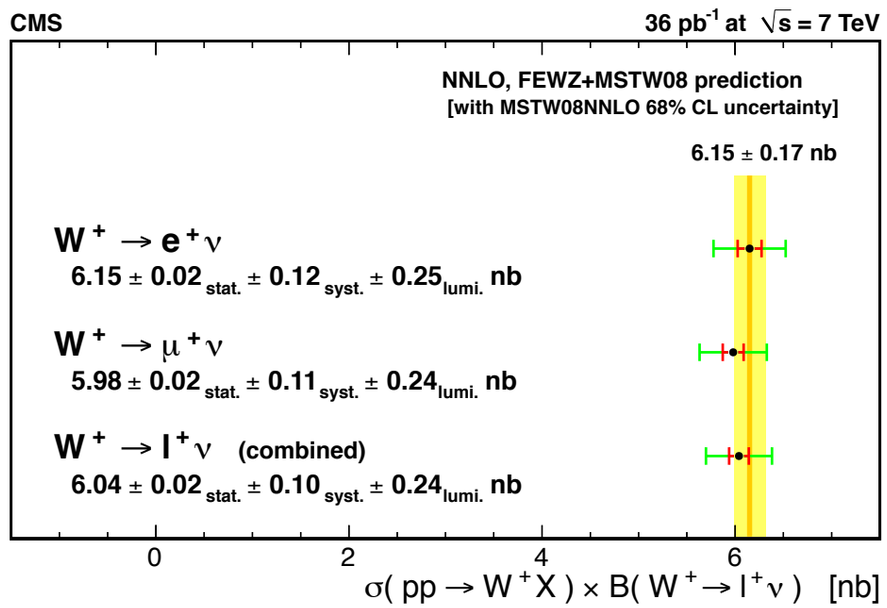
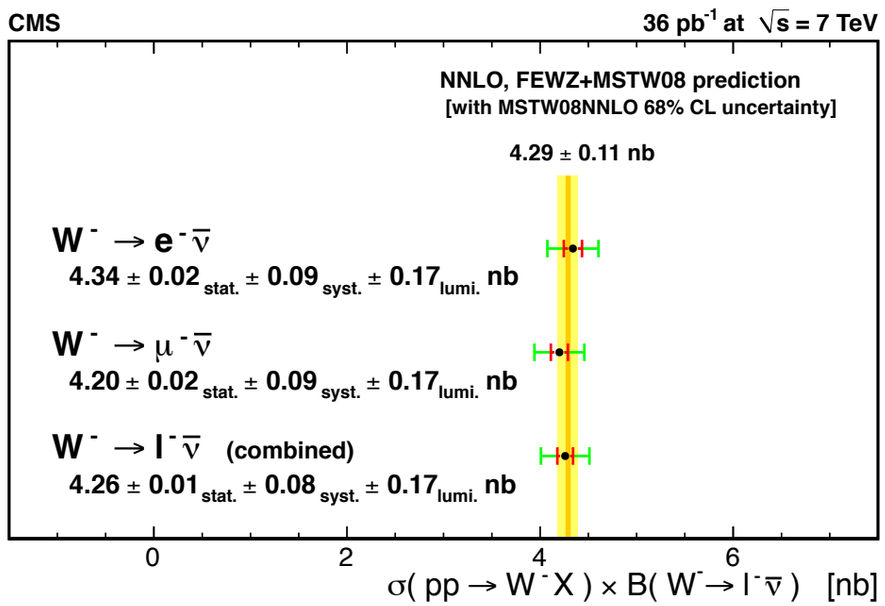
Data vs Theory Comparison







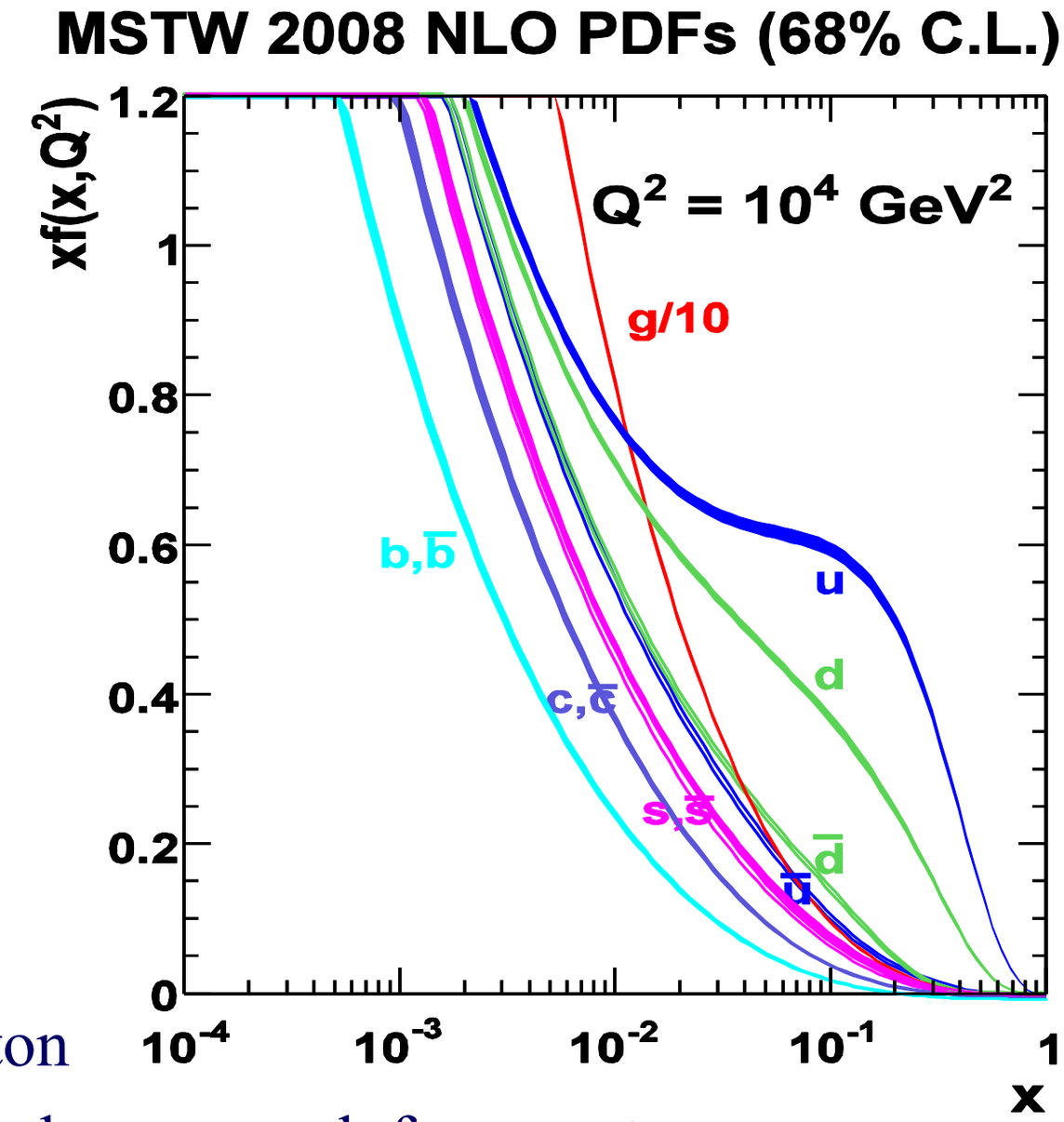


W Production Asymmetry

- Both at the Tevatron and the LHC W bosons are produced via

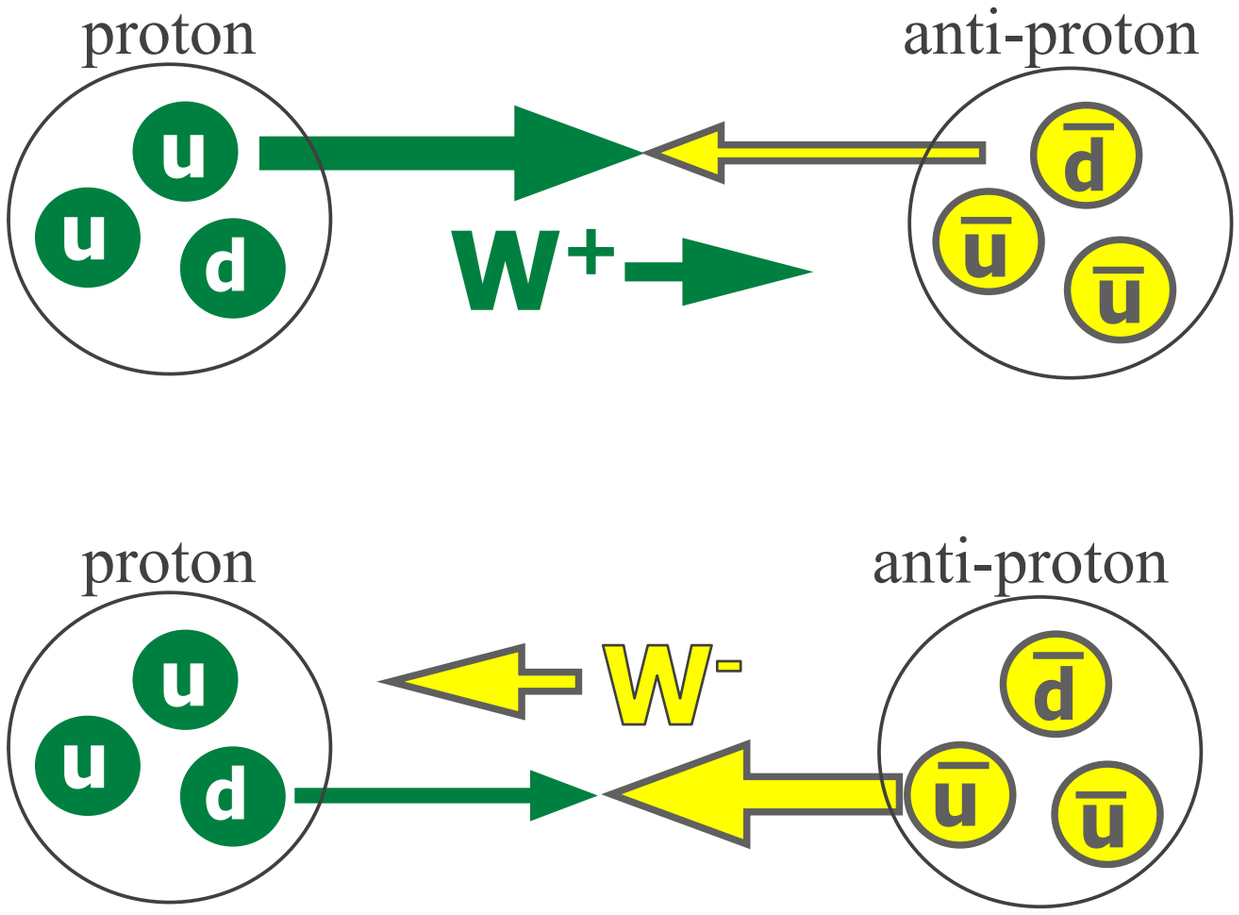
$$u\bar{d} \rightarrow W^{+}$$

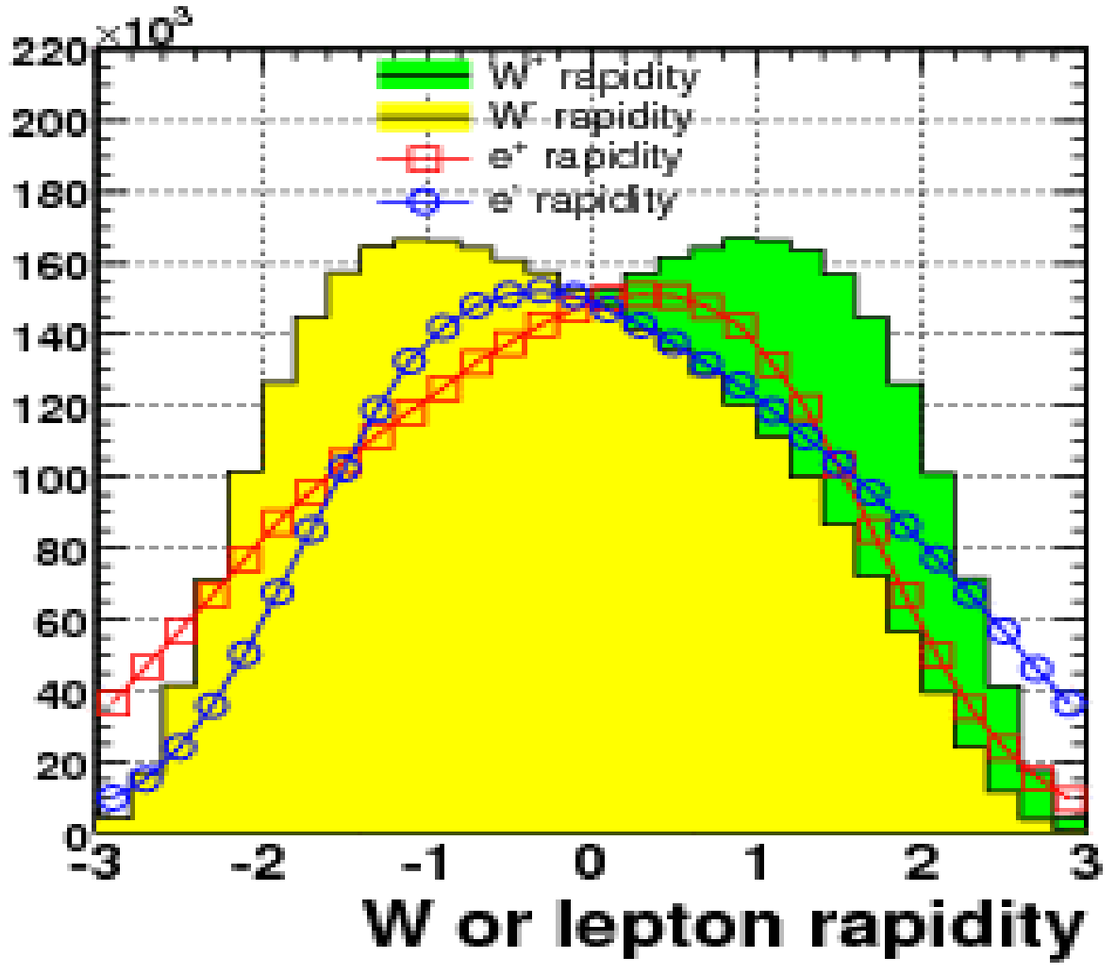
$$d\bar{u} \rightarrow W^{-}$$



- Tevatron:
  valence quark from proton
  and valence anti-quark from anti-proton
- LHC: a valence quark from proton and a sea quark from proton
- W production asymmetry is governed by the PDFs
  $\Rightarrow$ constrain the PDFs with asymmetry measurements

W Production Asymmetry @

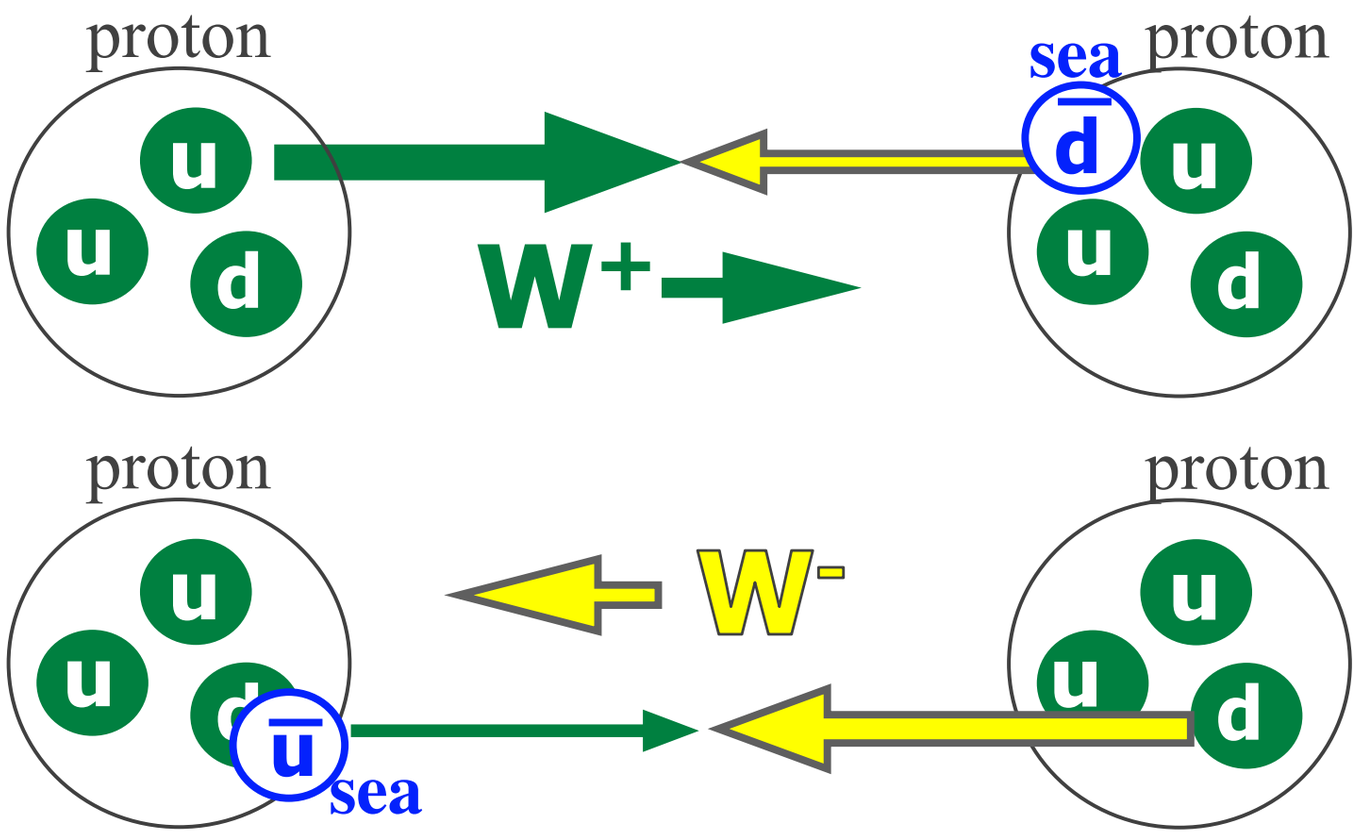




- Produced with valence quarks
- Total N(W+) = N(W-)
- Asymmetry
  as a function of W boson rapidity

$$A(y_W) = \frac{\frac{d\sigma(W^+)}{dy_W} - \frac{d\sigma(W^-)}{dy_W}}{\frac{d\sigma(W^+)}{dy_W} + \frac{d\sigma(W^-)}{dy_W}} \simeq \frac{u(x_1)/d(x_1) - u(x_2)/d(x_2)}{u(x_1)/d(x_1) + u(x_2)/d(x_2)}$$

W Production Asymmetry @ LHC



- W bosons are produced with valence quarks and see quarks
- $N(u_V) > N(d_V)$
  $\Rightarrow$ Total $N(W+) > N(W-)$

The inclusive ratio of cross sections for W+ and W- bosons production was measured by CMS to be 1.43 ± 0.05 CMS-EWK-10-006

LEPTON CHARGE ASYMMETRY

W rapidity cannot be reconstructed on event-by-event basis
due to non-measurable longitudinal neutrino momentum

W charge asymmetry

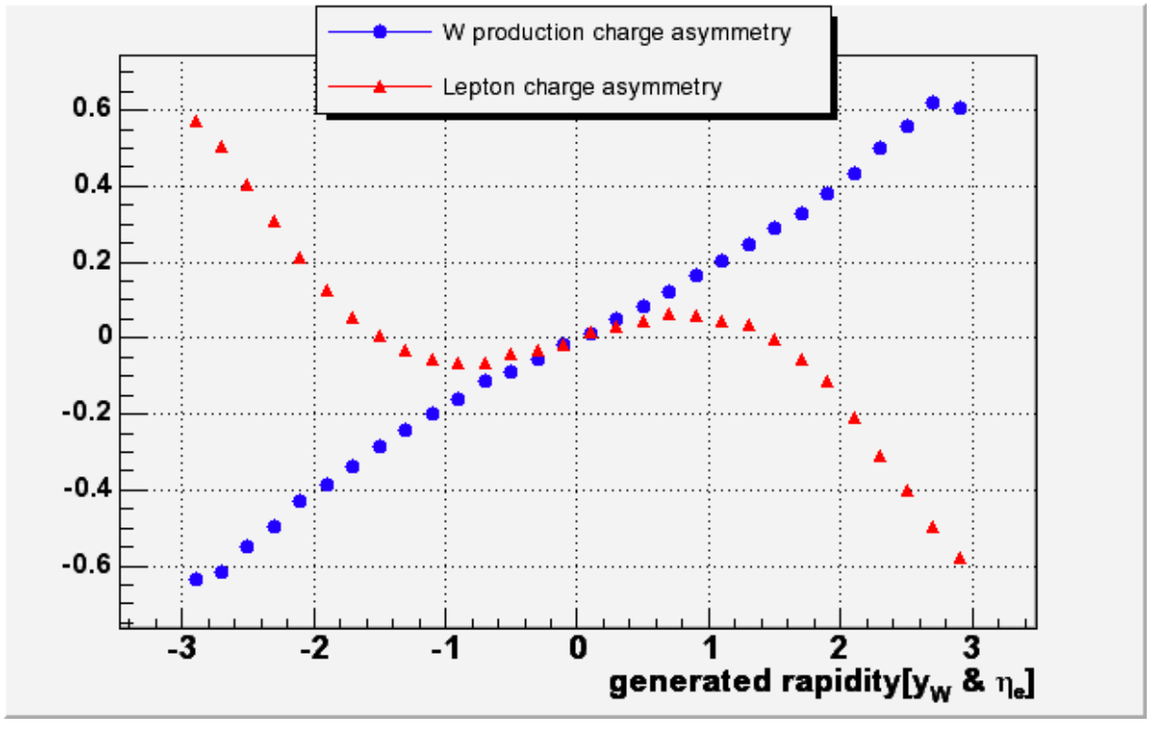
$$A(y_W) = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W}$$

$$y_W = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

lepton charge asymmetry

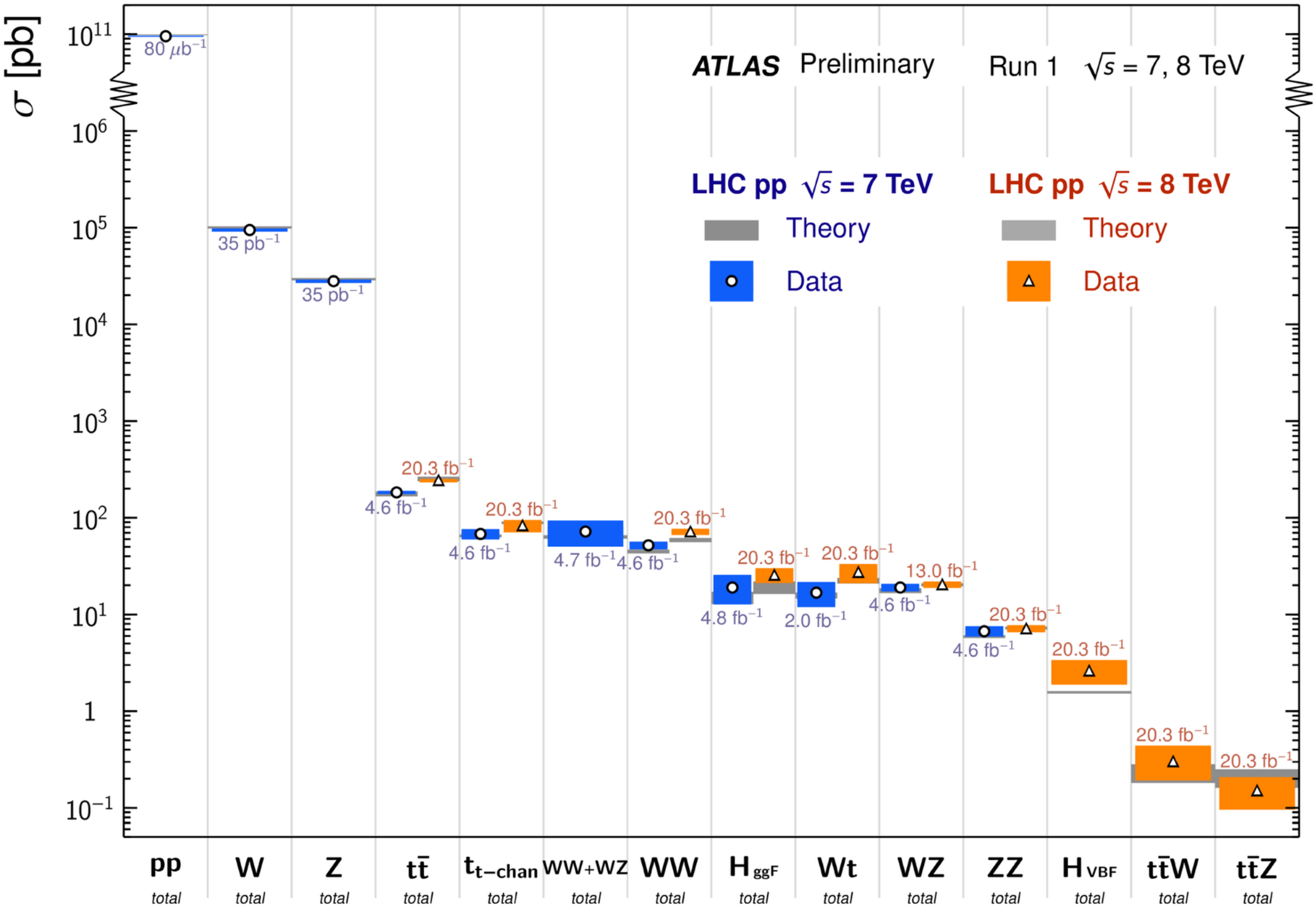
$$\boldsymbol{A(\eta_l) = \frac{d\sigma_+/d\eta_l - d\sigma_-/d\eta_l}{d\sigma_+/d\eta_l + d\sigma_-/d\eta_l} \sim \frac{d(x)}{u(x)}}$$ = $A(y_W) \otimes (V\text{-}A)$

$$x_{u,d} = \frac{M_W}{\sqrt{s}} e^{\pm y_W}$$



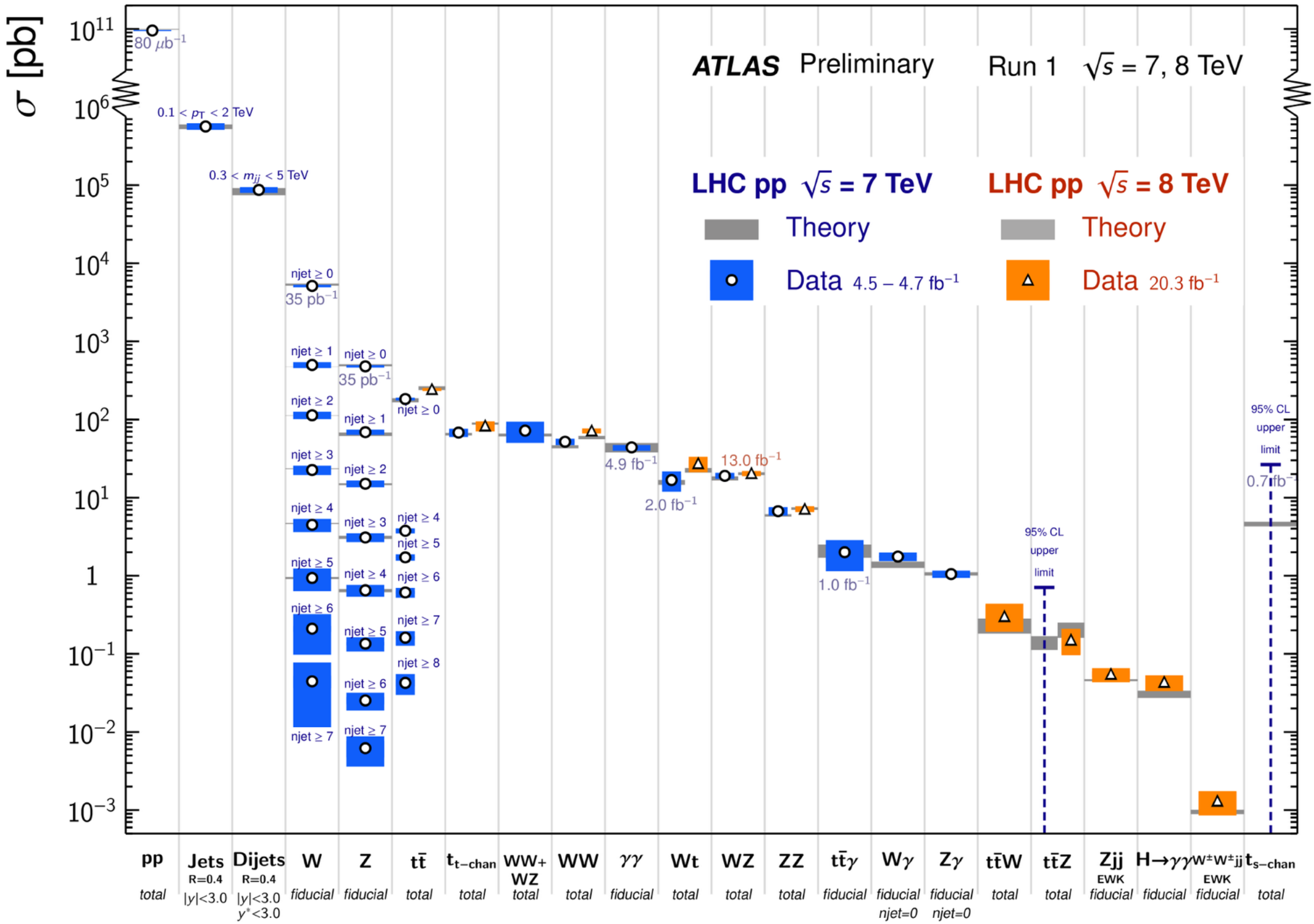
Standard Model Total Production Cross Section Measurements

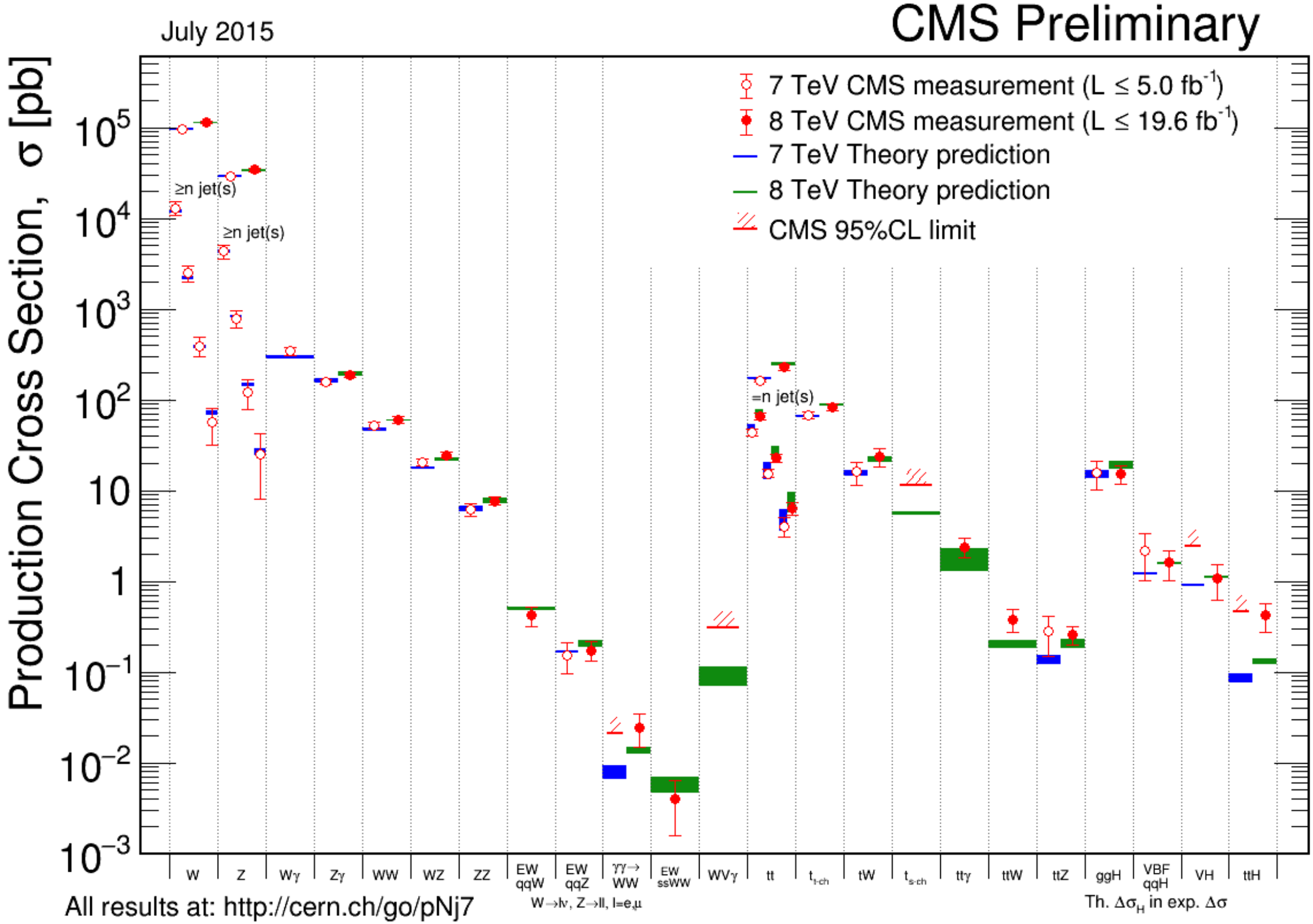
Status: July 2014



Standard Model Production Cross Section Measurements

Status: July 2014

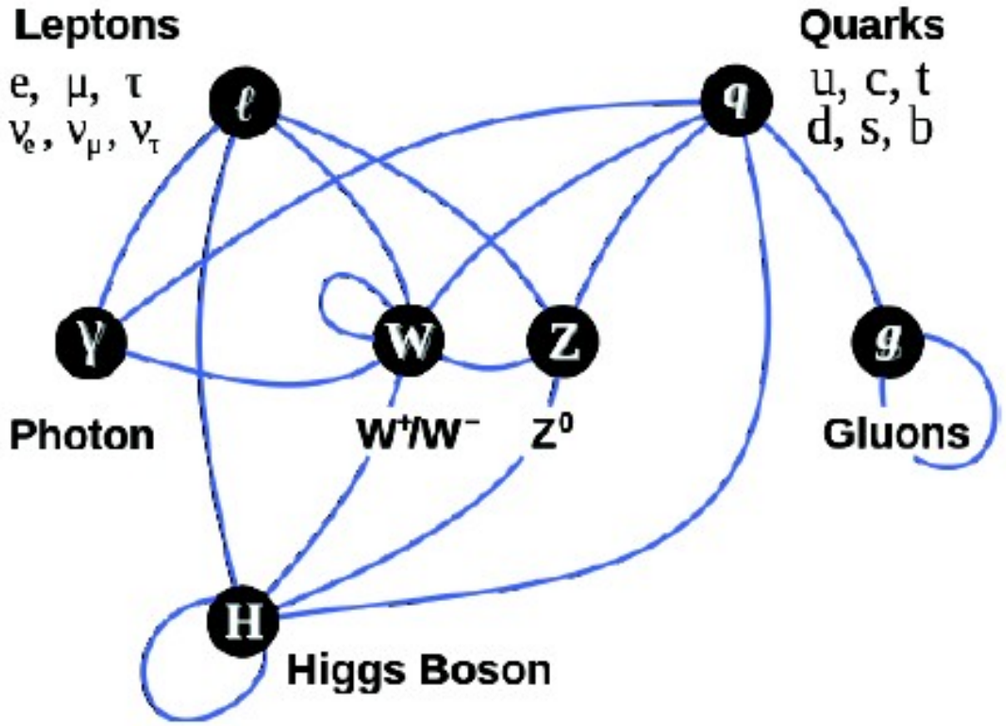



CMS Preliminary
July 2015
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
7 TeV Theory prediction
8 TeV Theory prediction
CMS 95%CL limit
≥n jet(s)
≥n jet(s)
=n jet(s)
W
Z
Wγ
Zγ
WW
WZ
ZZ
EW qqW
EW qqZ
γγ→ WW
EW ssWW
WVγ
tt
t t-ch
tW
t s-ch
ttγ
ttW
ttZ
ggH
VBF qqH
VH
ttH
W→lν, Z→ll, l=e,μ
Th. Δσ_H in exp. Δσ
All results at: http://cern.ch/go/pNj7

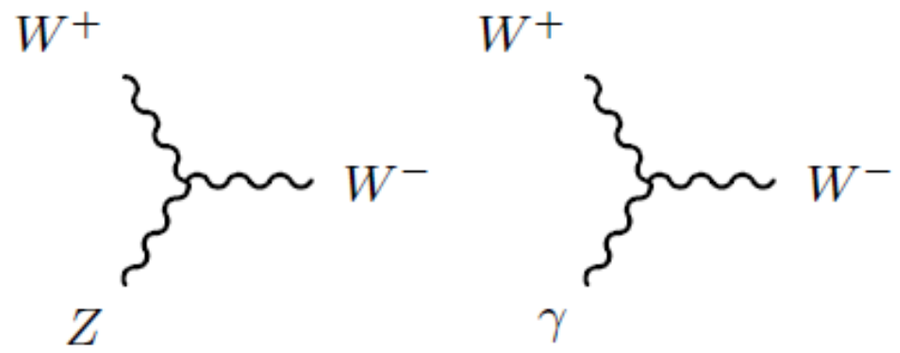
DI-BOSON PRODUCTION(WW, WZ, ZZ)

- Precision measurement of differential cross section
- Test of Quartic Gauge Coupling
- Search for new heavy resonances in VV final states

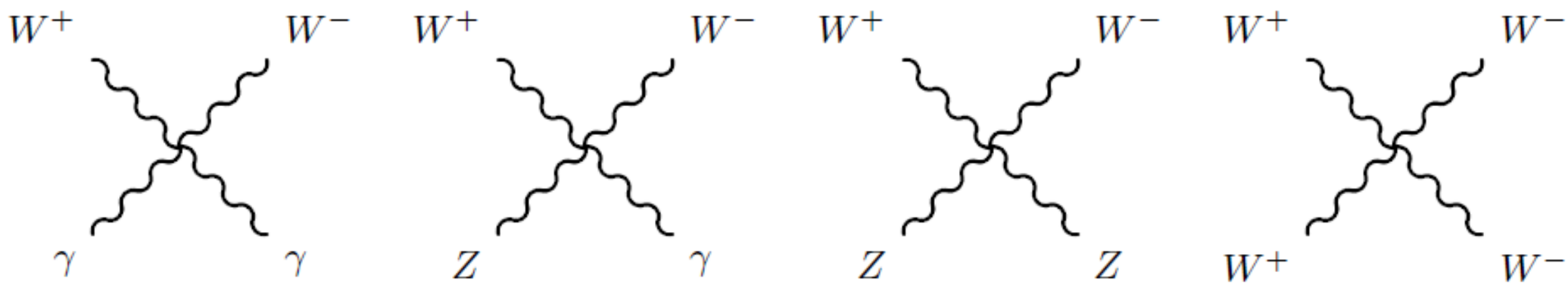
DI-BOSON PRODUCTION IN SM



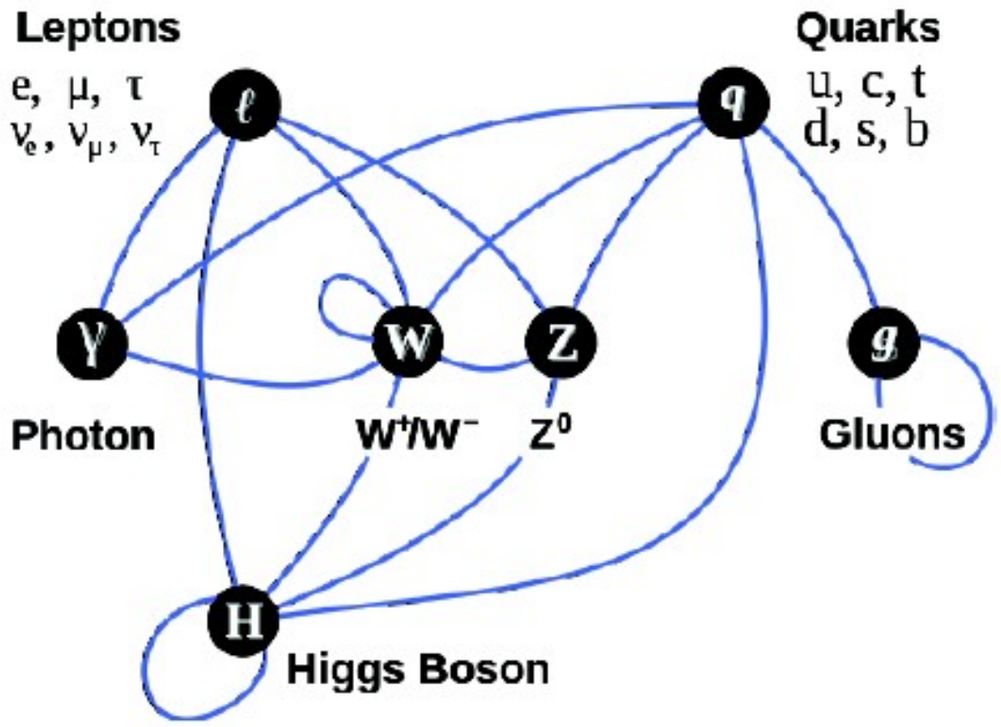
- **Triple gauge couplings (TGC)**



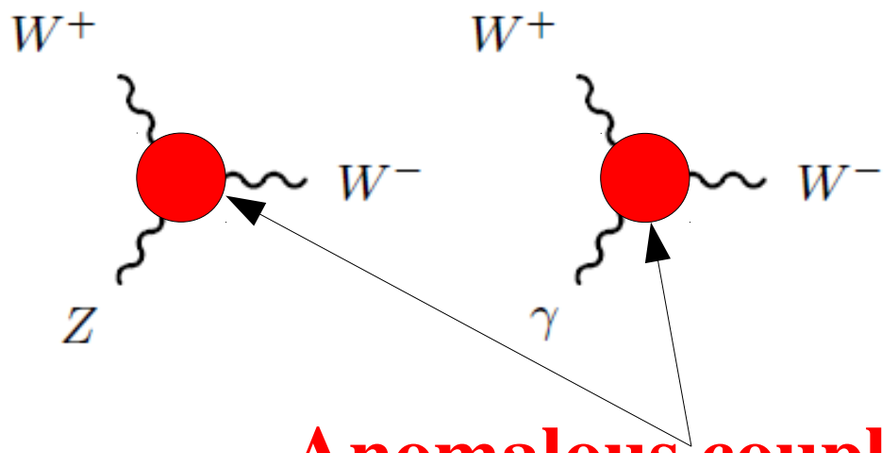
- **Quartic gauge couplings (QGC)**



ANOMALOUS PRODUCTION?

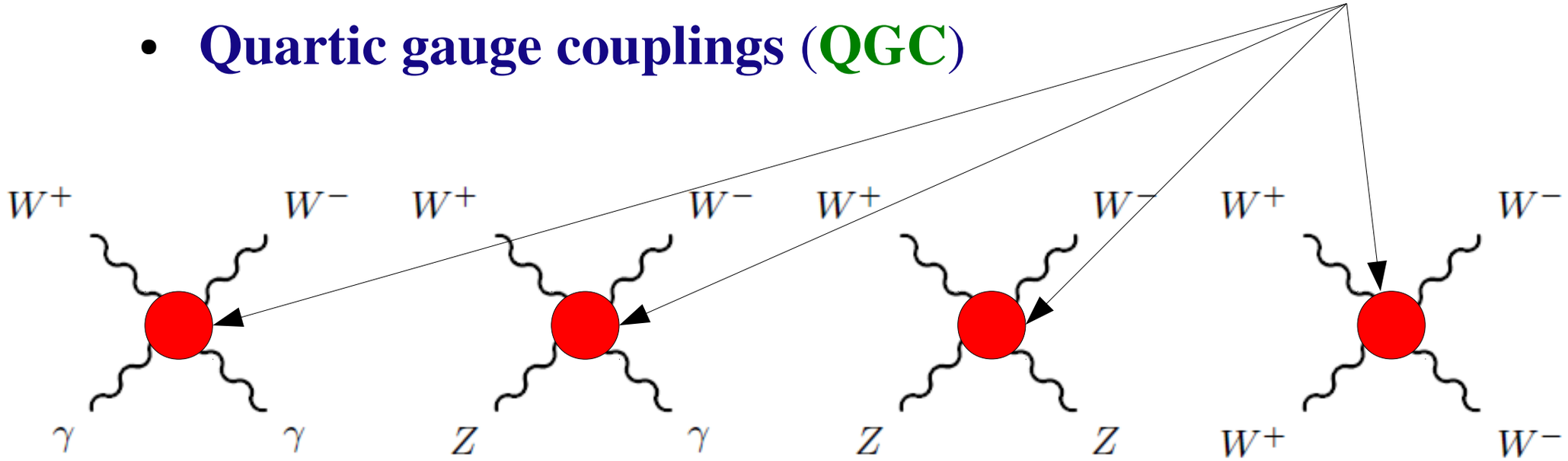


- **Triple gauge couplings (TGC)**



Anomalous couplings
+ what forbidden in SM

- **Quartic gauge couplings (QGC)**



Di-Boson Final states

Cross Section

4ℓ	$3\ell 1\nu$	$\ell^{\pm}\ell^{\pm}2\nu$	$2\ell 2\nu$	$2\ell b\bar{b}$	$\ell\nu b\bar{b}$	$\ell\nu 2j$
ZZ	WZ	$W^{\pm}W^{\pm}$	WW	ZZ	WZ	WW

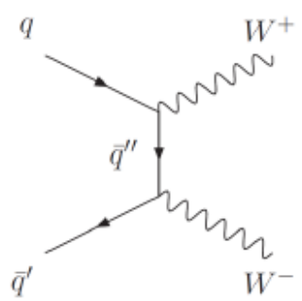
ZZ WZ

Background

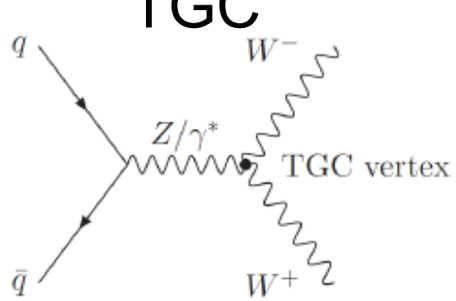
Purity

DI-BOSON PRODUCTION(WW, WZ, ZZ)

qqbar → VV

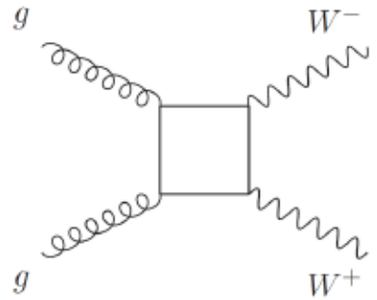


TGC



+ NLO qqbar +

gg→ VV



(LHC: few % of xsec with ~50% uncertainty)

WW,WZ,ZZ forbidden for ZZ

forbidden for ZW

- SM test: TGC fixed by ewk gauge structure

  → any deviation from SM in VV xsec is direct hint of NP in bosonic sector

- Backgrounds for high mass Higgs→VV

  → test to establish Higgs search techniques

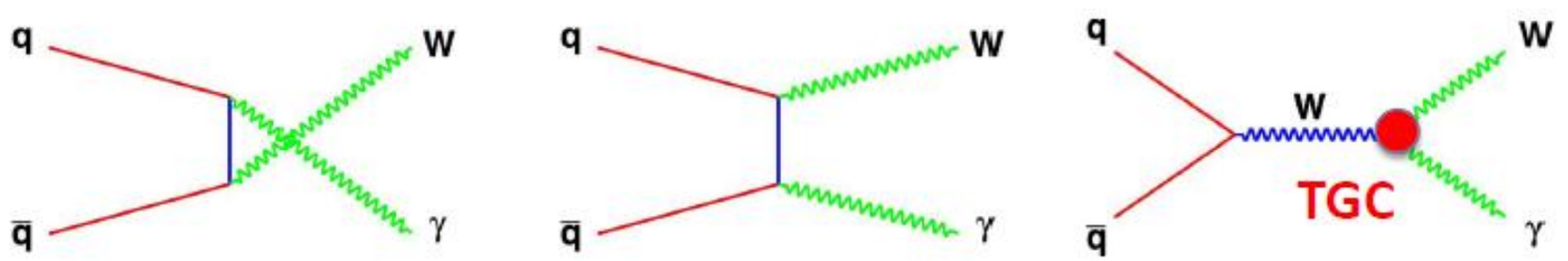
CHARGED TRIPLE GAUGE COUPLING

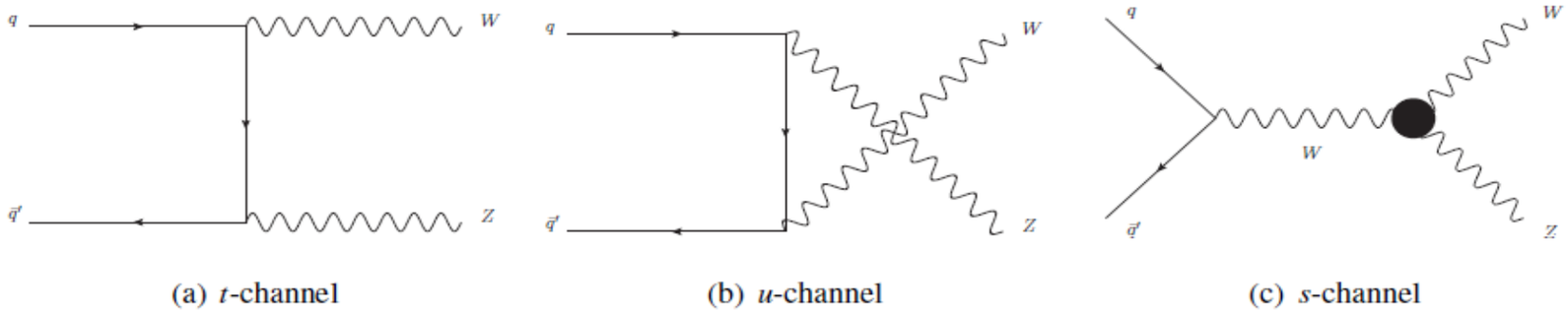
$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V (W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu V^{\nu\lambda}$$

V:Z/γ

general effective Lagrangian
+ C and P conservation
⇒ 5 parameters

g_1^Z, κ_γ, κ_Z, λ_γ, λ_Z





(a) t-channel (b) u-channel (c) s-channel

$$\mu_W = \frac{e}{2M_W}(2 + \Delta\kappa_\gamma + \lambda_\gamma),$$

$$Q_W = -\frac{e}{M_W^2}(1 + \Delta\kappa_\gamma - \lambda_\gamma)$$

to preserve unitarity:

$$\alpha(\hat{S}) = \frac{\alpha_0}{(1 + \hat{s}/\Lambda^2)^2}$$

SM constraints : $\kappa_\gamma = g_1^Z = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$

BSM searches use two reduced parameter sets :

$SU(2)\times U(1) : \Delta\kappa_z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$ **and** $\lambda_\gamma = \lambda_Z$

Related to tree-level unitarity constraints: 3 parameters

$HISZ : \Delta\kappa_z = \Delta g_1^Z (\cos^2\theta_W - \sin^2\theta_W)$

Equal coupling between SU(2)xU(1) and Higgs fields : 2 parameters

– production of new particles decaying to Zγ or Wγ
– new interactions that increase the strength of the TGCs

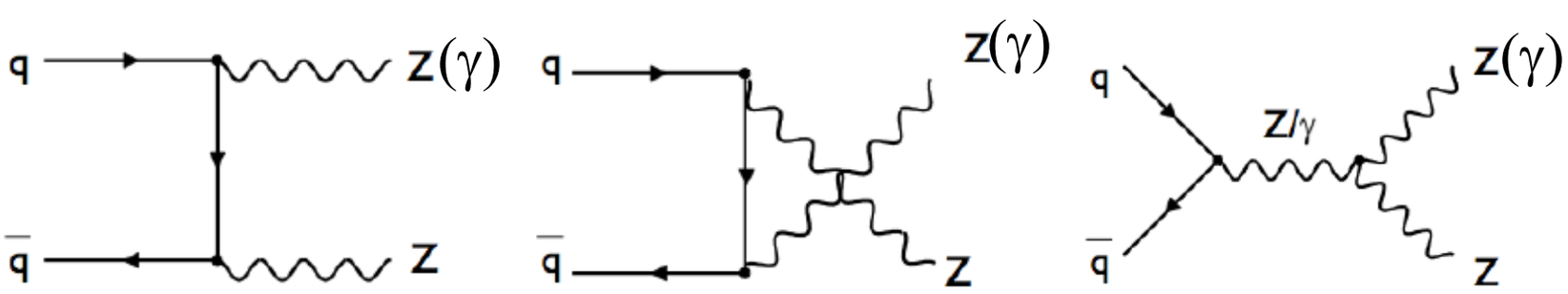
NEUTRAL TRIPLE GAUGE COUPLING

$$\mathcal{L}_{Z\gamma V} = -ie\left[\left(h_1^V F^{\mu\nu} + h_3^V \widetilde{F}^{\mu\nu}\right) Z_\mu \frac{\left(\Box + m_V^2\right)}{m_Z^2} V_\nu \right.$$

CP conserving $h_{3,4}{}^V$

$$\left. + \left(h_2^V F^{\mu\nu} + h_4^V \widetilde{F}^{\mu\nu}\right) Z^\alpha \frac{\left(\Box + m_V^2\right)}{m_Z^4} \partial_\alpha \partial_\mu V_\nu \right]$$

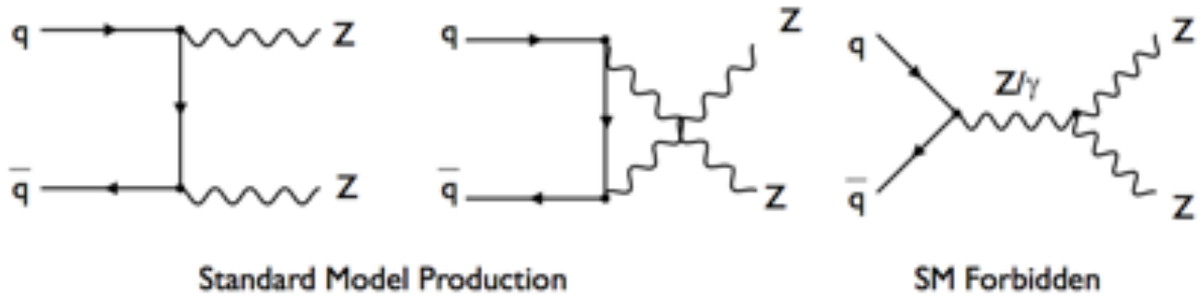
$V = Z$ *or* γ



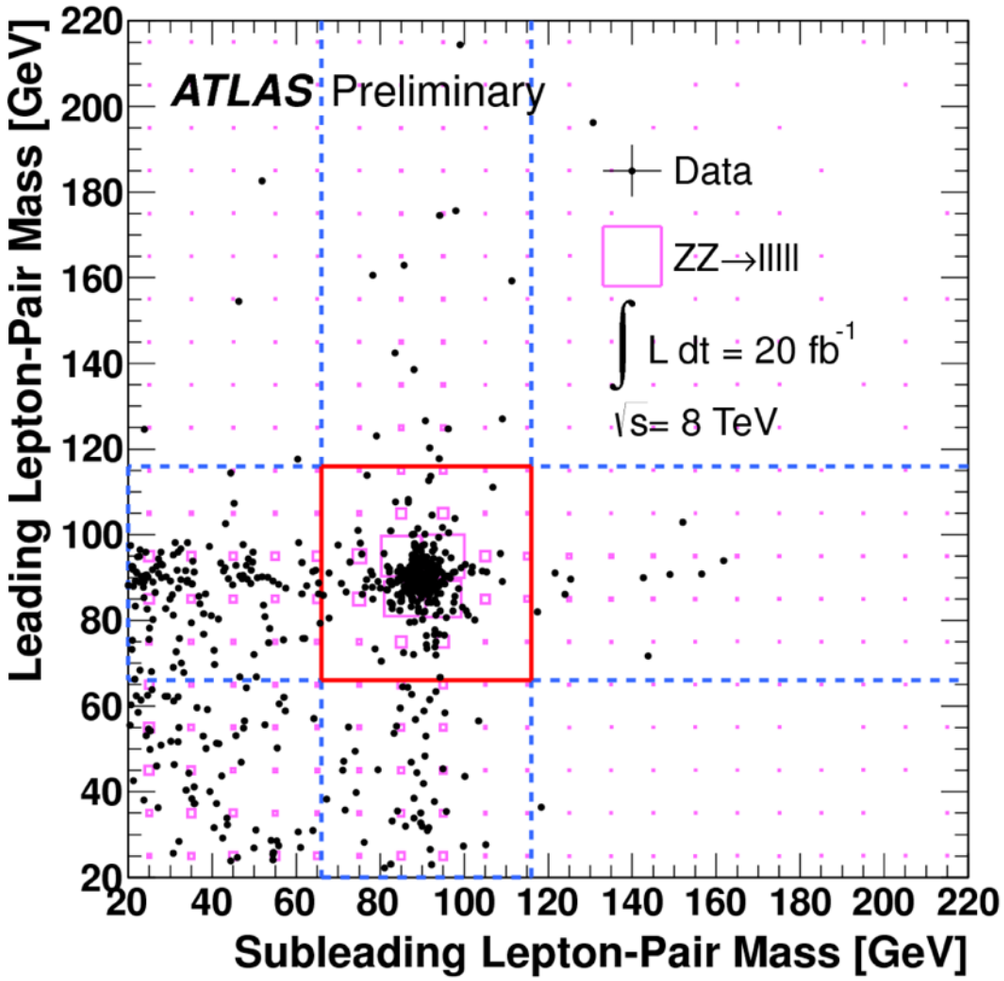
$$\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2}\left[f_4^V(\partial_\mu V^{\mu\beta}) Z_\alpha (\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta} Z_\beta\right]$$

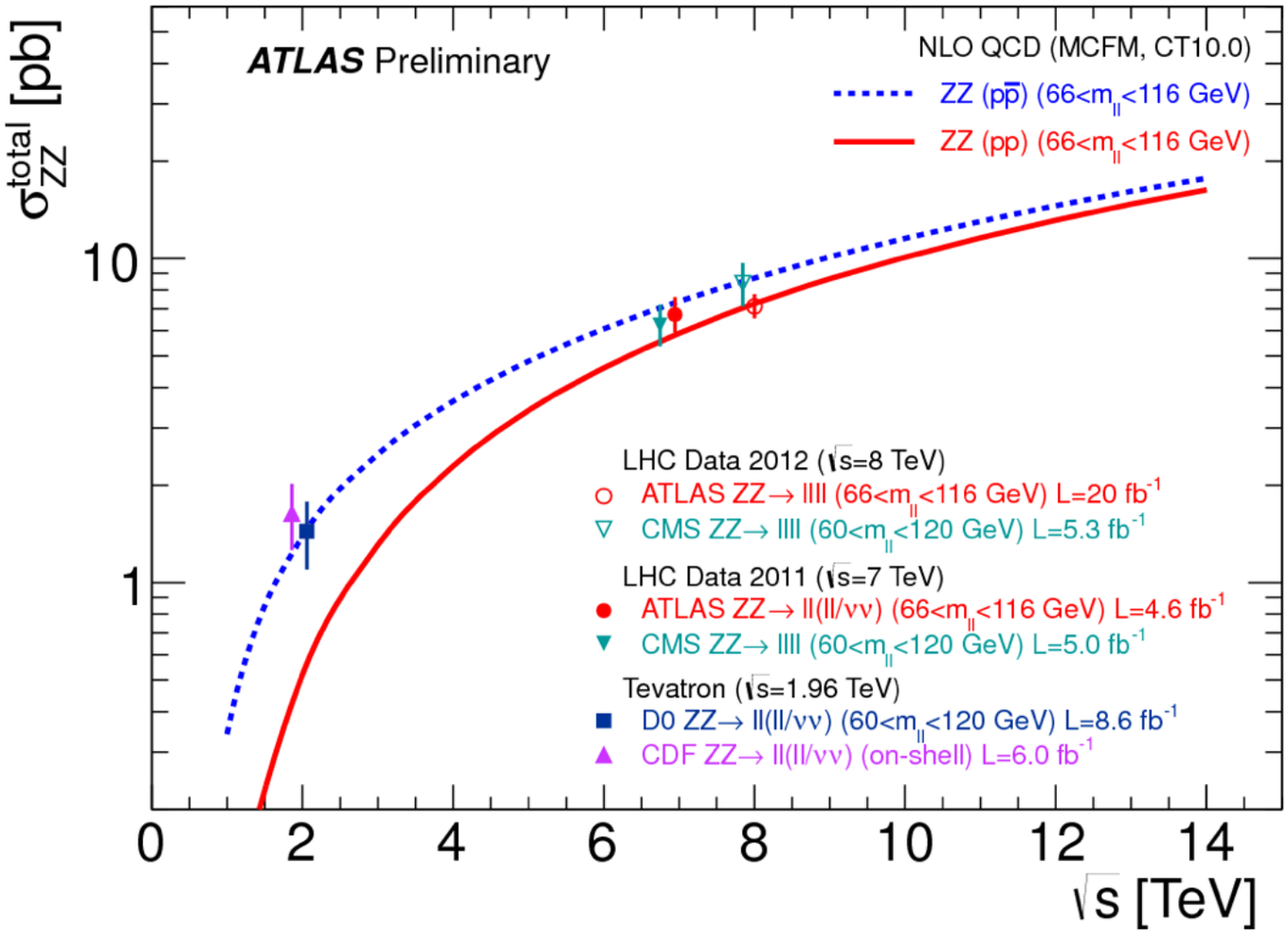
CP violating f_4^V
CP conserving f_5^V

ZZ PRODUCTION



Standard Model Production SM Forbidden

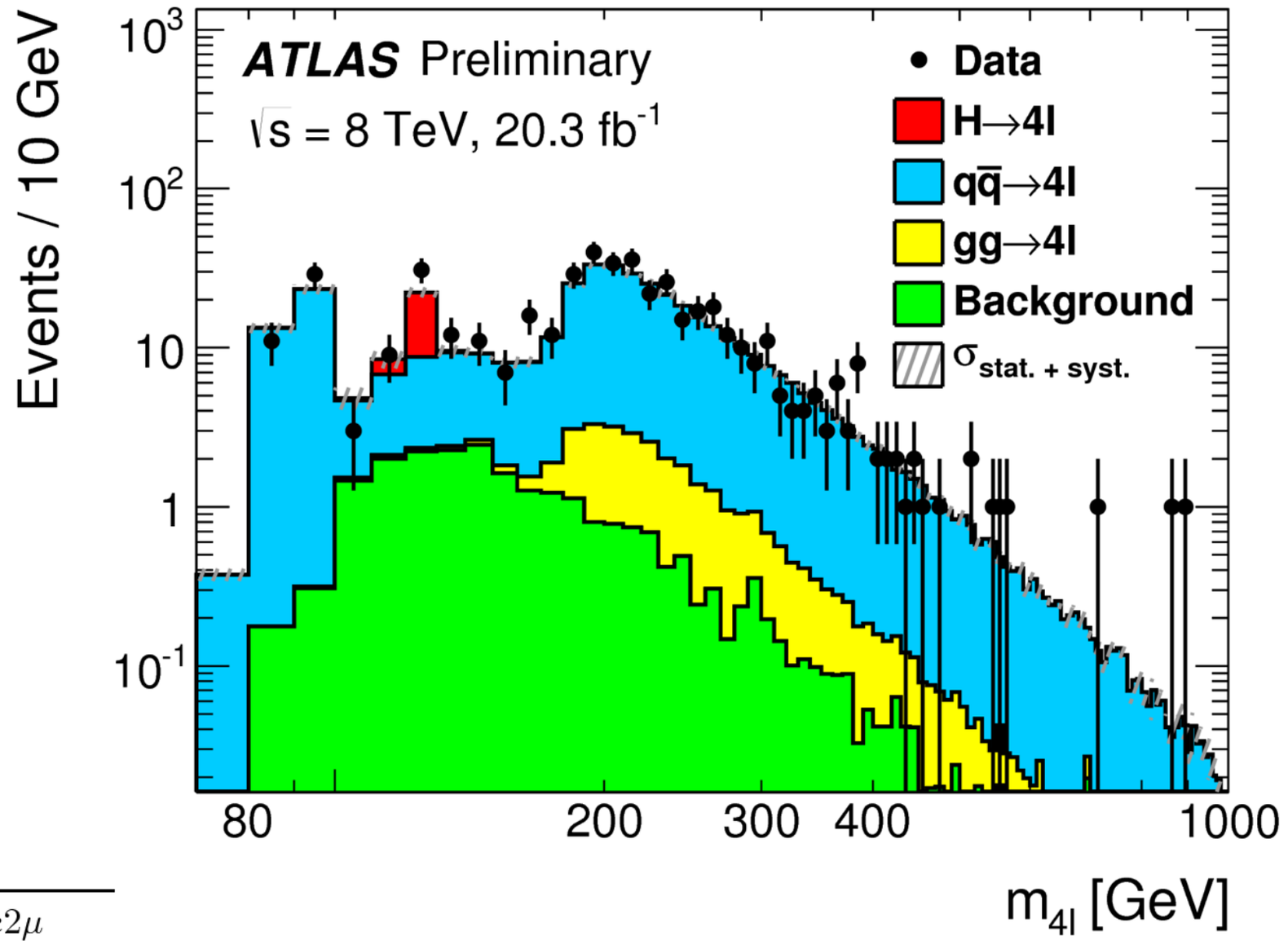




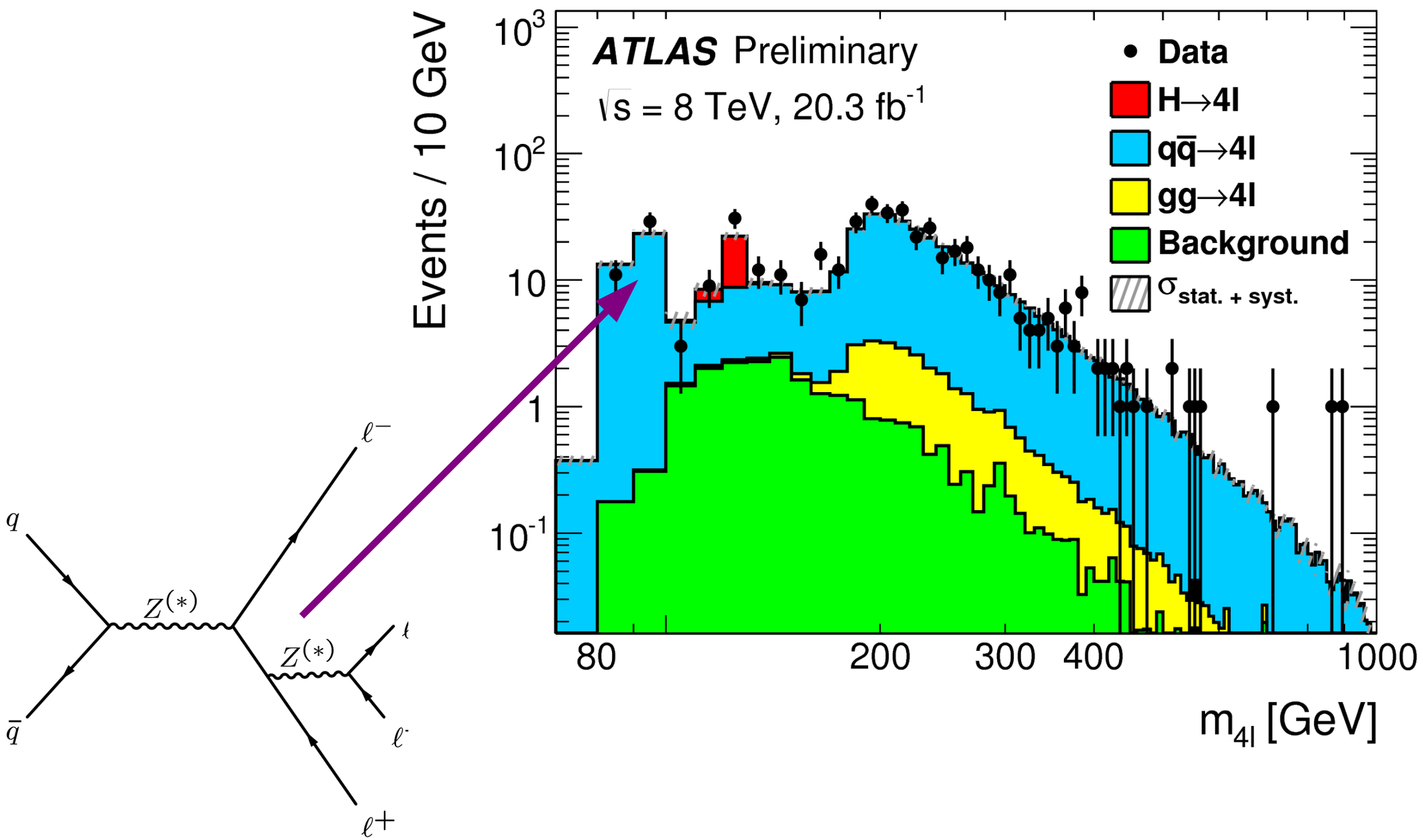
ZZ Final State

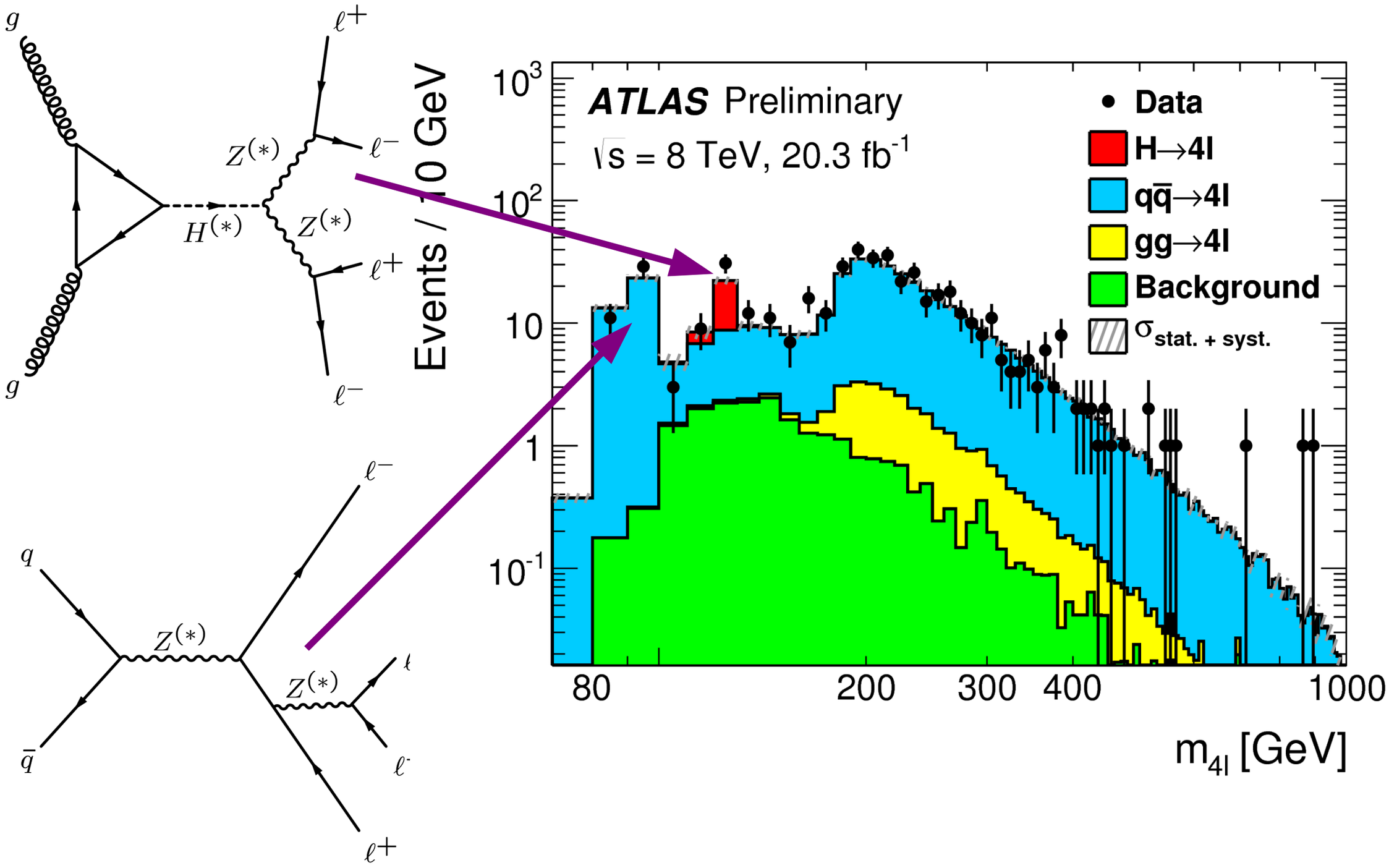
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-031/

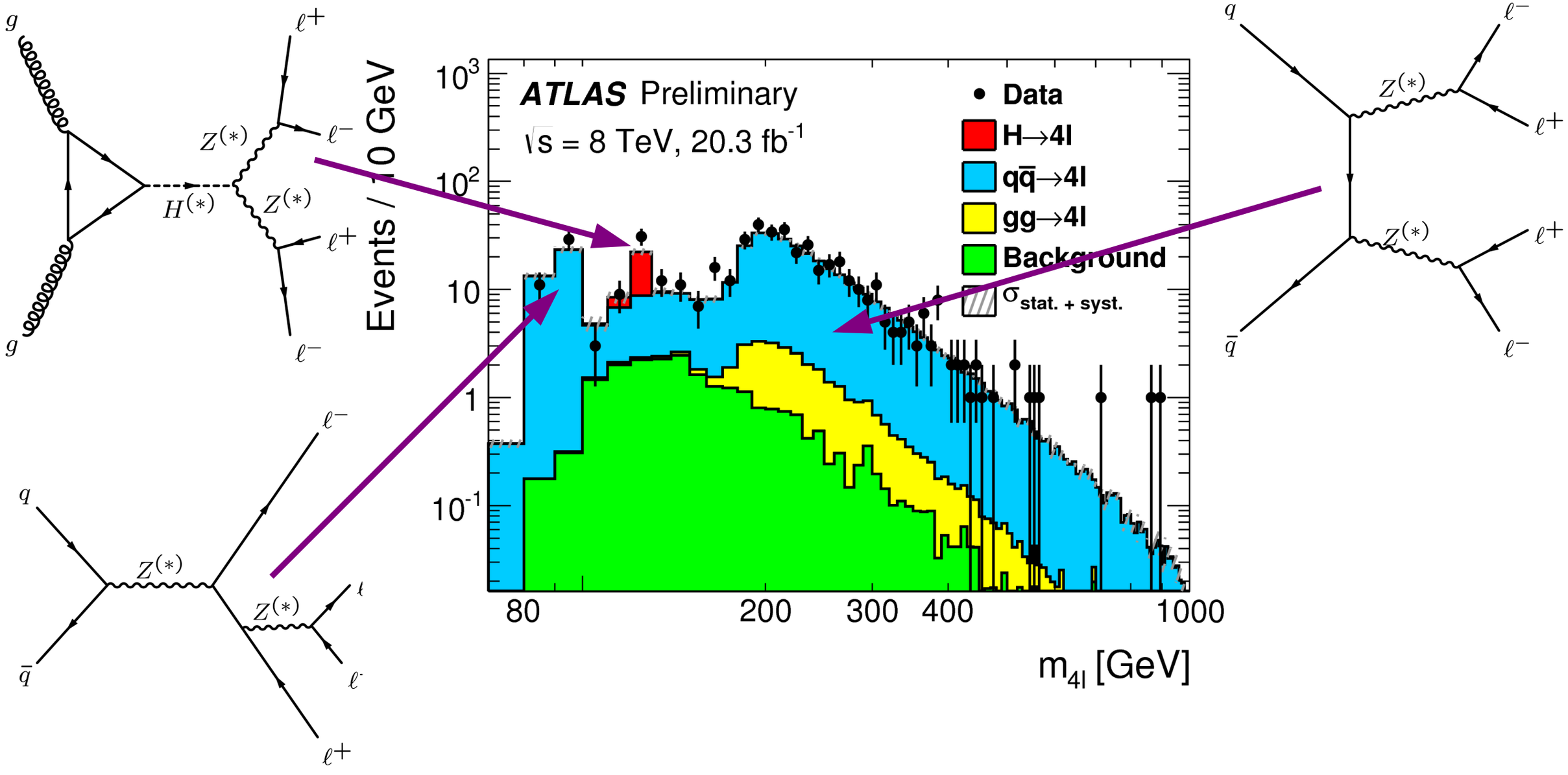
Lepton selection	
Muons:	$p_{\mathrm{T}} > 6$ GeV, $\lvert\eta\rvert < 2.7$
Electrons:	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.5$
Lepton pairing	
Leading pair:	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair:	The remaining SFOS with the largest $m_{\ell\ell}$
For both pairs:	$p_T^{\ell^+\ell^-} > 2$ GeV
Event selection	
Lepton $p_T^{\ell_1,\ell_2,\ell_3}$:	$> 20, 15, 10(8\ if\ \mu)$ GeV
Mass requirements:	$50 < m_{12} < 120$ GeV
	$12 < m_{34} < 120$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$ (0.2) for same- (different-) flavour leptons
J/ψ veto:	$m(\ell_i^+, \ell_j^-) > 5$ GeV
4ℓ mass range:	$80 < m_{4\ell} < 1000$ GeV

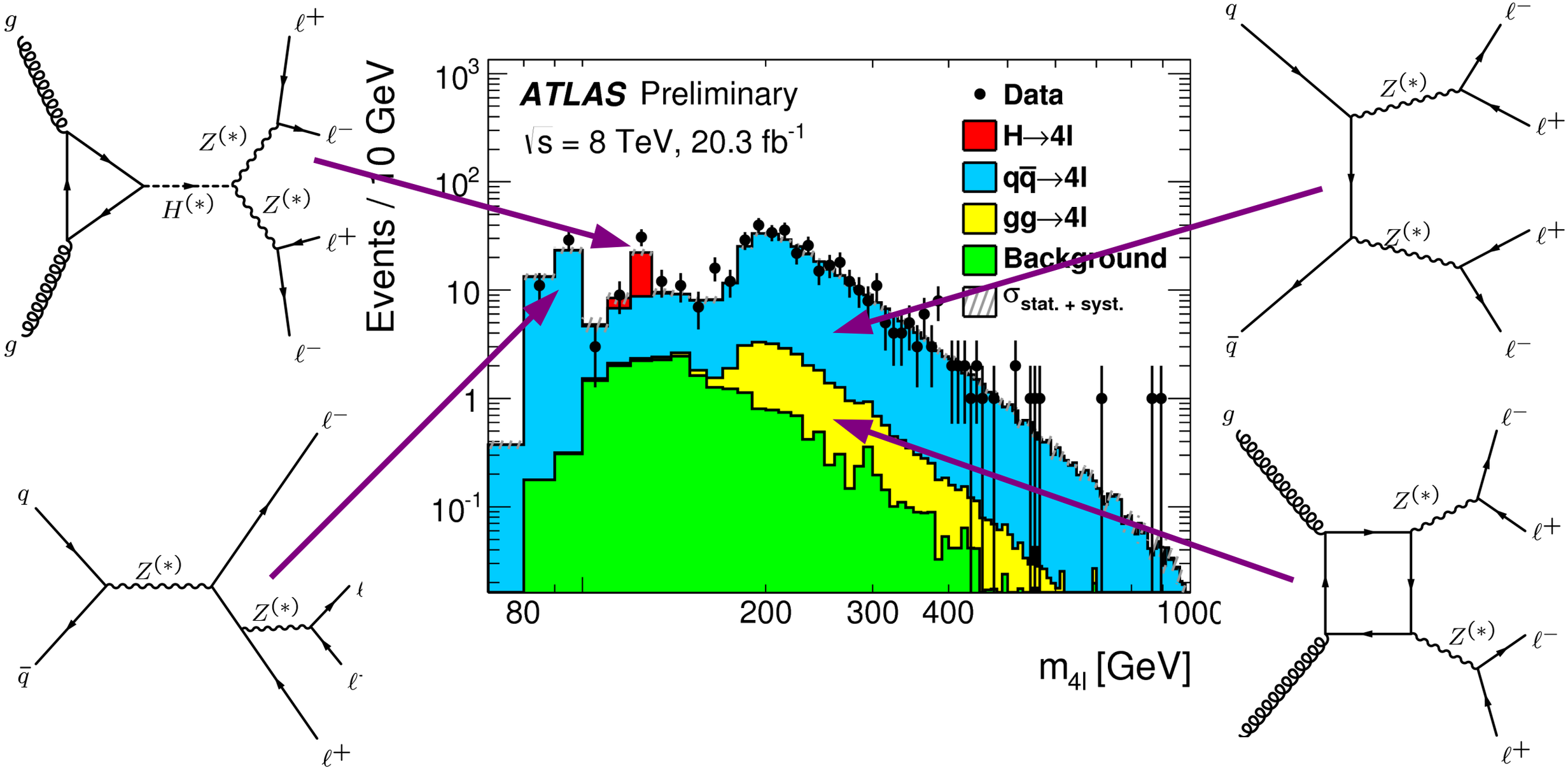


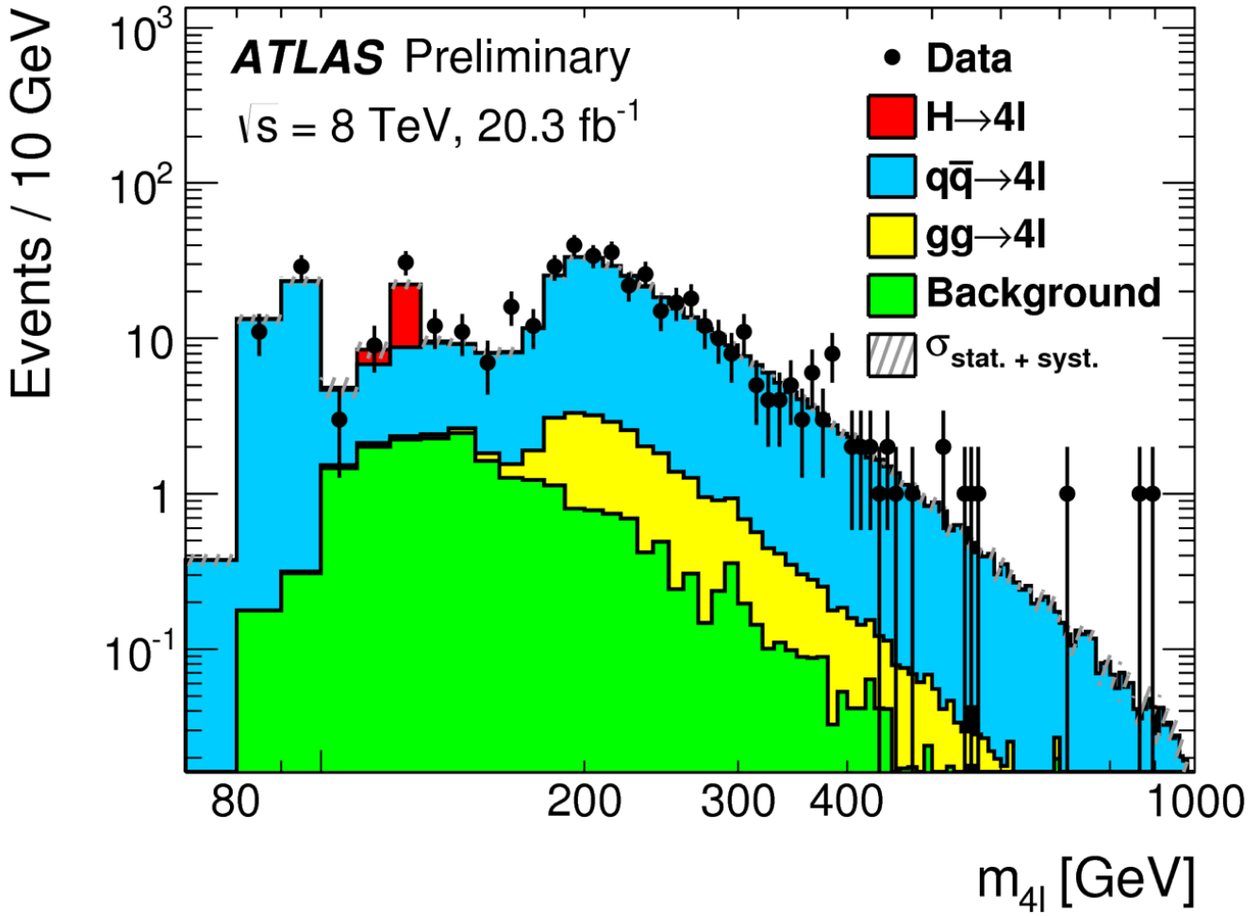
Process	$4e$	4μ	$2e2\mu$
$t\bar{t}$	0.45 ± 0.24	0.68 ± 0.19	1.3 ± 0.5
Z + jets	0.6 ± 0.29	5.3 ± 1.5	6.3 ± 1.4
Diboson	1.25 ± 0.18	0.83 ± 0.18	2.84 ± 0.34
Triboson	0.67 ± 0.12	0.97 ± 0.14	1.46 ± 0.19
Z+top	0.62 ± 0.15	1.19 ± 0.32	1.7 ± 0.5

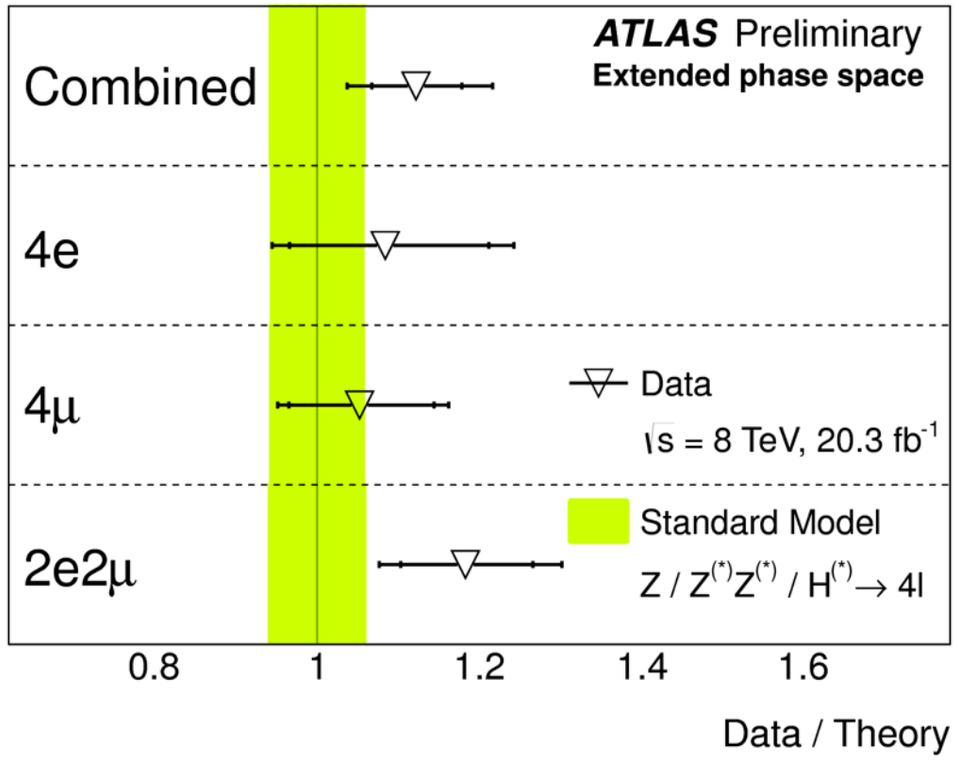

ATLAS Preliminary
√s = 8 TeV, 20.3 fb-1
Data
H→4l
qq̄→4l
gg→4l
Background
σstat. + syst.
Events / 10 GeV
m4l [GeV]
q
q̄
Z(*)
Z(*)
ℓ−
ℓ+


g
g
$H^{(*)}$
$Z^{(*)}$
$Z^{(*)}$
ℓ^+
ℓ^-
ℓ^+
ℓ^-
q
$\bar{q}$
$Z^{(*)}$
$Z^{(*)}$
ℓ^-
ℓ^+
ATLAS Preliminary
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Data
H→4l
qq̄→4l
gg→4l
Background
$\sigma_{stat. + syst.}$
Events / 10 GeV
10^3
10^2
10
1
10^{-1}
80
200
300
400
1000
m_{4l} [GeV]


ATLAS Preliminary
√s = 8 TeV, 20.3 fb-1
Data
H→4l
qq̄→4l
gg→4l
Background
σstat. + syst.
Events / 10 GeV
m4l [GeV]
g
ℓ+
ℓ−
Z(*)
H(*)
q
q̄


ATLAS Preliminary
√s = 8 TeV, 20.3 fb-1
Data
H→4l
qq̄→4l
gg→4l
Background
σstat. + syst.
Events / 10 GeV
m4l [GeV]
g
ℓ+
ℓ−
Z(*)
H(*)
q
q̄





Channel	N^{Data}	$N^{Total}_{expected}$	N^{signal}_{non-gg}	N^{signal}_{gg}	N^{MC}_{τ}	N_{bkg}
$4e$	85	80 ± 4	68.4 ± 3.4	6.24 ± 0.31	1.28 ± 0.06	3.6 ± 0.5
4μ	156	150.2 ± 2.9	128.2 ± 2.5	11.00 ± 0.21	2.18 ± 0.09	9.0 ± 1.5
$2e2\mu$	235	205 ± 5	172 ± 5	16.0 ± 0.4	3.08 ± 0.13	13.6 ± 2.1
Total	476	435 ± 9	369 ± 9	33.3 ± 0.8	6.54 ± 0.14	26.2 ± 3.6