Experimental prospects for strong dynamics at the LHC

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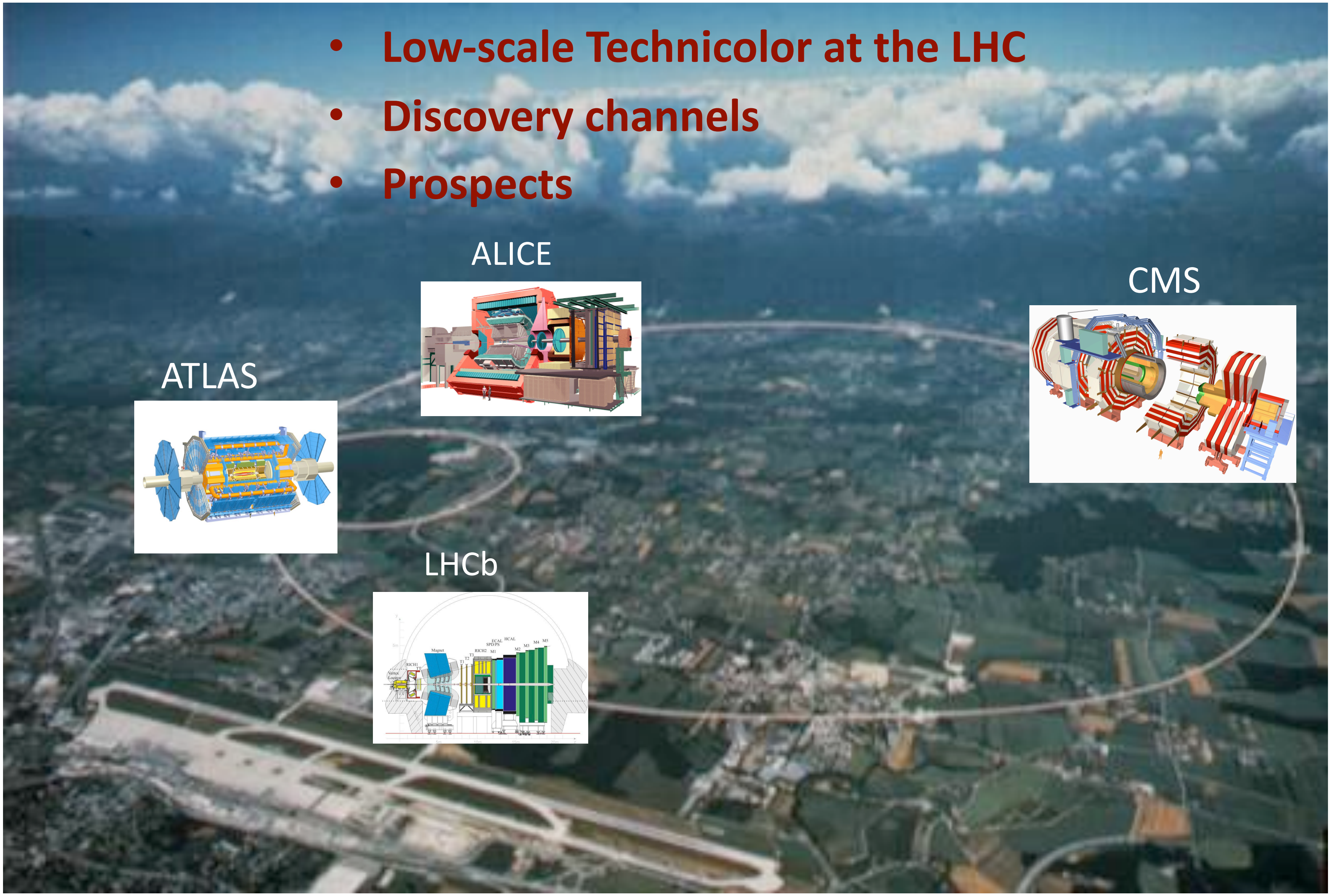
Lattice Gauge Theory for LHC Physics

- **Low-scale Technicolor at the LHC**
- **Discovery channels**
- **Prospects**



The importance of walking

- Experimentally accessible Low-scale technicolor (LSTC) spectrum
- Walking TC gauge coupling requires a large number of technifermion doublets

$$F_T = 246\,\mathrm{GeV}/\sqrt{N_D} \lesssim 100\,\mathrm{GeV}$$

- Walking enhances π_T masses

$$\rho_T \to \pi_T \pi_T\,; \quad \omega_T, a_T \to 3\pi_T \quad \text{are forbidden}$$

$$\rho_T,\ \omega_T,\ a_T \to (\gamma,\ W_L,\ Z_L) + (\pi_T,\ W_L,\ Z_L)$$

- Decay channels have distinctive signatures (narrow widths)

$$\Gamma(\rho_T) \simeq 1\text{–}5\,\mathrm{GeV} \text{ and } \Gamma(\omega_T) \simeq 0.1\text{–}0.5\,\mathrm{GeV}.$$

Discovery Channels

- Phenomenology set forth in the "Technicolor Straw-man Model" TCSM
  - Lightest ρ_T and ω_T lie below 0.5 TeV and they decay to γ, W, Z, π_T
- Primary LSTC discovery channels at the LHC

$$\begin{aligned} \rho_T^{\pm} &\rightarrow W_L^{\pm} Z_L^0 \rightarrow \ell^{\pm}\ell^{+}\ell^{-} \not{E}_T \\ a_T^{\pm} &\rightarrow \gamma W_L^{\pm} \rightarrow \gamma\, \ell^{\pm} \not{E}_T \\ \omega_T &\rightarrow \gamma Z_L^0 \rightarrow \gamma\, \ell^{+}\ell^{-} \end{aligned}$$

- These do not involve techni-pions…
  - essential feature of technicolor

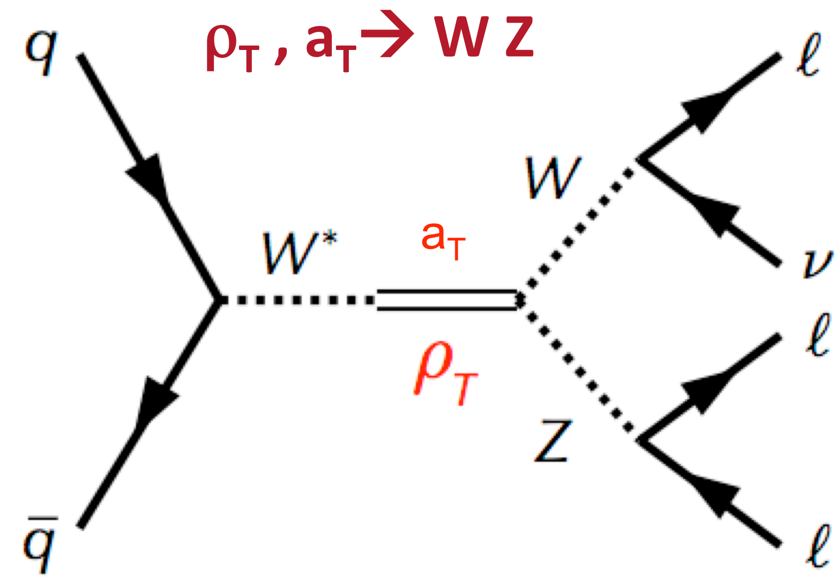
$$
\begin{aligned}
\rho_T^{\pm} &\rightarrow W_L^{\pm} Z_L^0 \rightarrow \ell^{\pm} \ell^{+} \ell^{-} \not{E}_T \\
a_T^{\pm} &\rightarrow \gamma W_L^{\pm} \rightarrow \gamma\, \ell^{\pm} \not{E}_T \\
\omega_T &\rightarrow \gamma Z_L^0 \rightarrow \gamma\, \ell^{+} \ell^{-}
\end{aligned}
$$

Signature

Dominant Feynman diagram
for production at the LHC

(clean with leptonic W & Z decays)

Generated with PYTHIA for mass points accessible with early data.



$\sqrt{s} = 10$ TeV

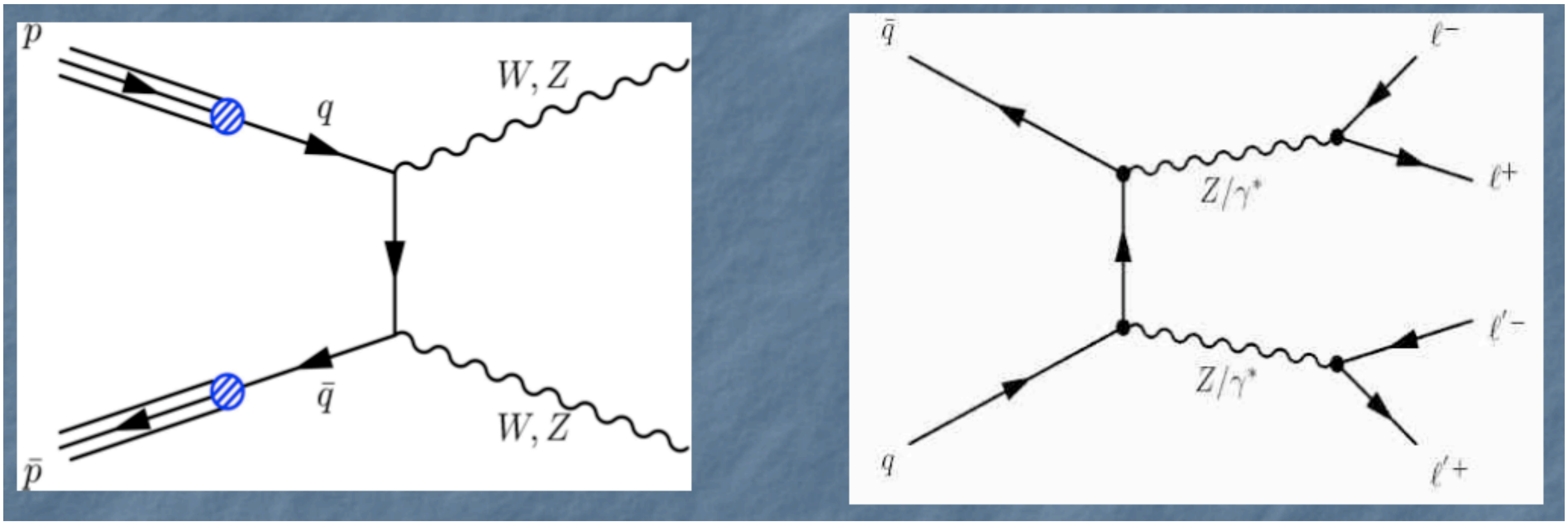
Parameter Set	$m_{\rho_T} = m_{\omega_T}$ (GeV)	m_{a_T} (GeV)	m_{π_T} (GeV)	$M_V = M_A$ (GeV)	$\sigma\times$ BR (fb)
A	225	250	150	225	232
B	300	330	200	300	74
C	400	440	275	400	24
D	500	550	350	500	9

Analysis Cuts Optimized separately

LO PYTHIA cross sections (include branching fractions into electrons/muons)

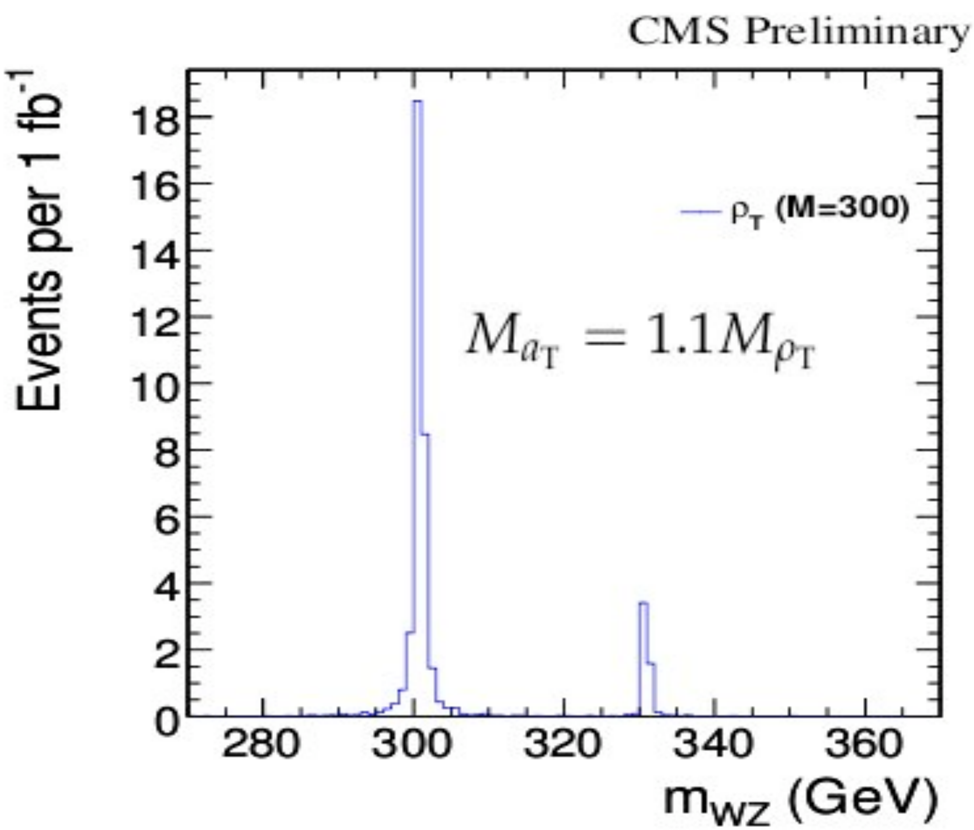
Backgrounds

SM diboson production (WZ, ZZ)



\+ components of top pair production, Z+ jets, VQQ

Generator-level



Then processed using CMS GEANT4 simulation

Pre-selection/Z reconstruction

Trigger ("online selection") using single muon and electron triggers
-- Efficiency of the trigger selection > 99%

Require at least 3 leptons with $p_T > 10$ GeV

The pair of like-flavored, opposite charge leptons with invariant mass closest to the Z boson are assigned Z-candidacy.

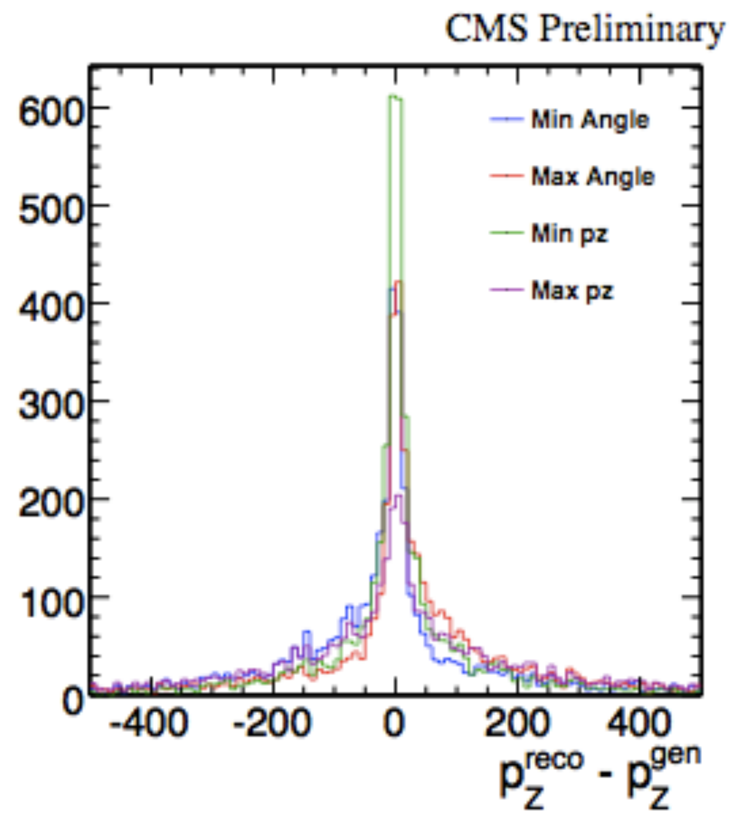
If two non-overlapping Z candidates are found (50 < invmass < 120) the event is rejected.
---Helps with ZZ background rejection.

If there is only one Z candidate, a tighter mass window cut is applied (5 times the width of the Z, ~12.5 GeV).

W reconstruction

- Next reconstruct the W:
  - choose the remaining highest p_T lepton
  - assign neutrino a transverse momentum opposite to MET
  - force neutrino and third lepton to have invariant mass of W and calculate $p_Z(\nu)$

  - Quadratic ambiguity
    - Solve in favor of solution minimizing the p_Z
    - This solution is correct ~2/3 of the time



Lepton Selection

Loose Selection (Z)

- only requires that the electrons/muons have $p_T > 10$ GeV

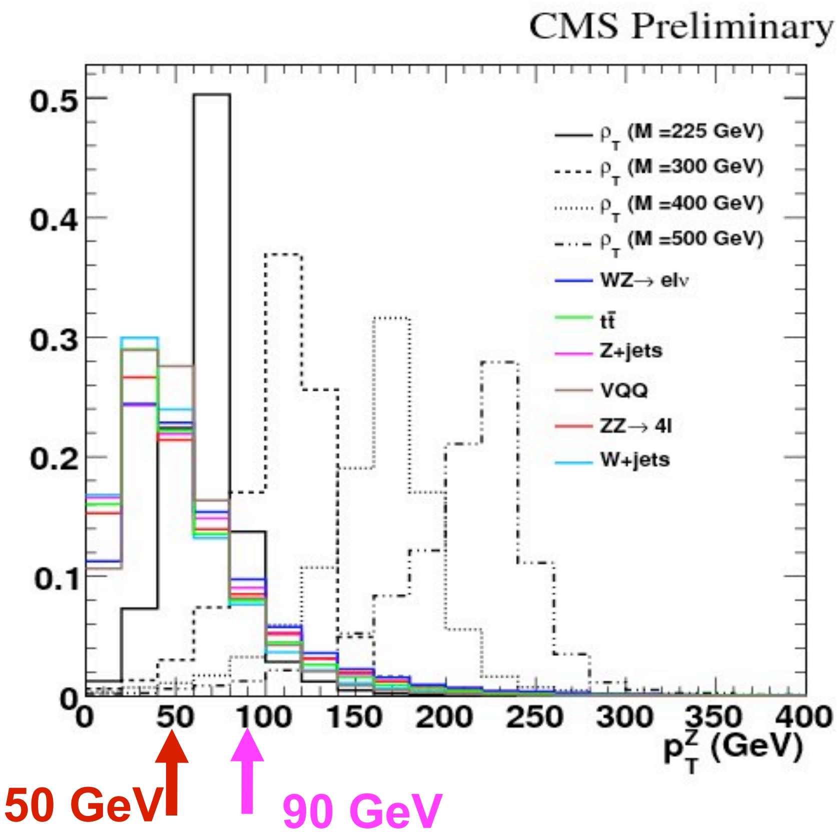
Tight Selection (W)

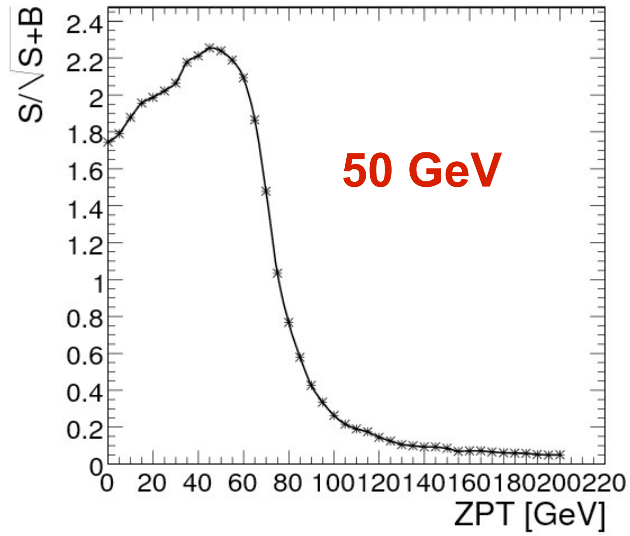
- Isolated leptons with $p_T > 20$ GeV

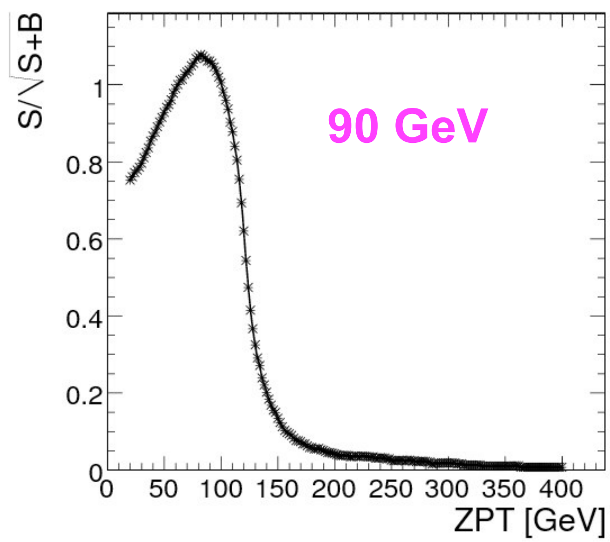
Optimization focused on maintaining high efficiency for signal events (all cuts near the 99% efficiency level), for an overall >90% efficiency on electron/muon selection for signal events.

Event Selection – Z p_T

Two sets of cuts: one for early data (optimized for **225 GeV** mass point), and one for higher luminosities (optimized for **300 GeV** mass point).

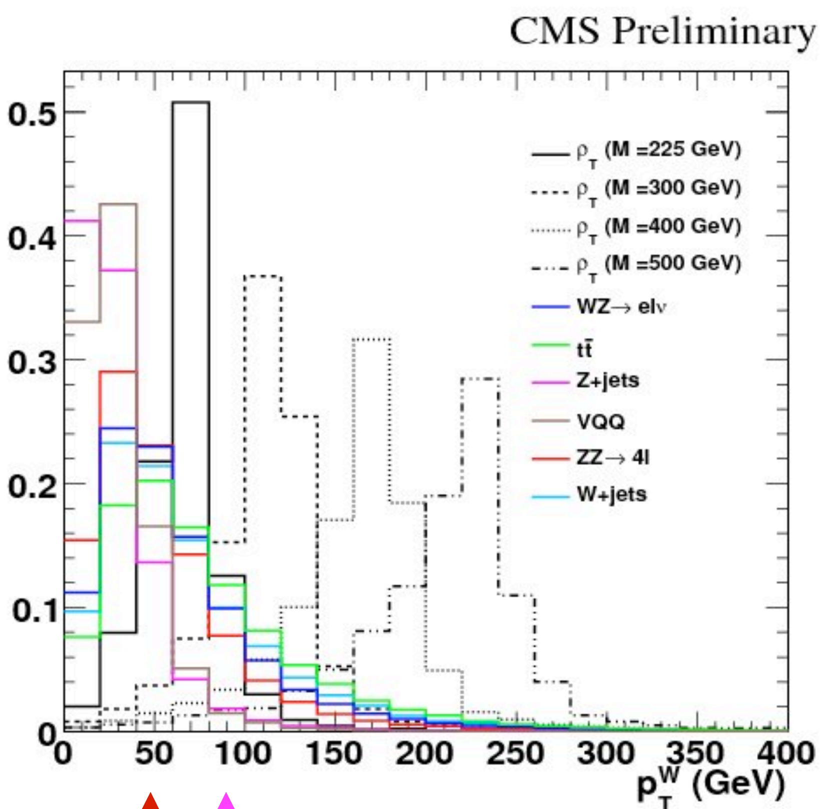




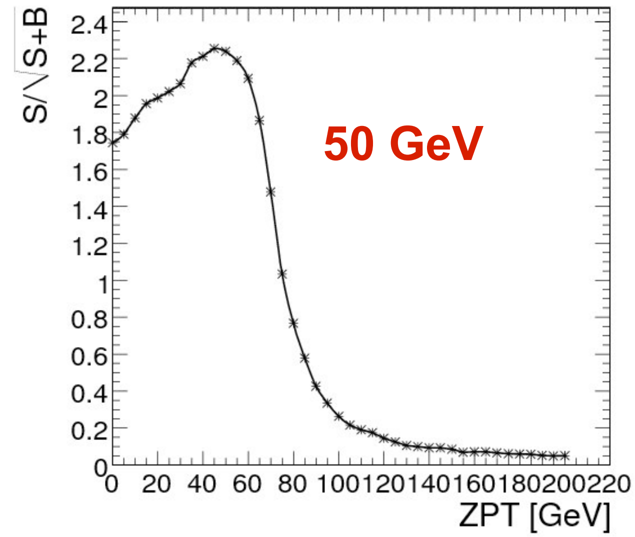


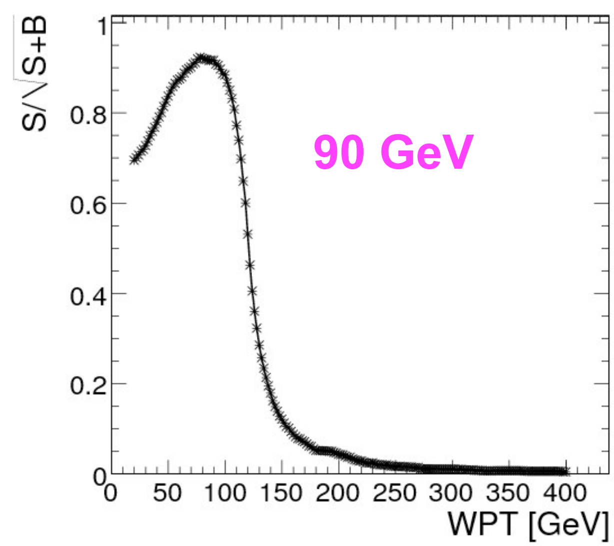
Event Selection – W p_T

Two sets of cuts: one for early data (optimized for **225 GeV** mass point), and one for higher luminosities (optimized for **300 GeV** mass point).



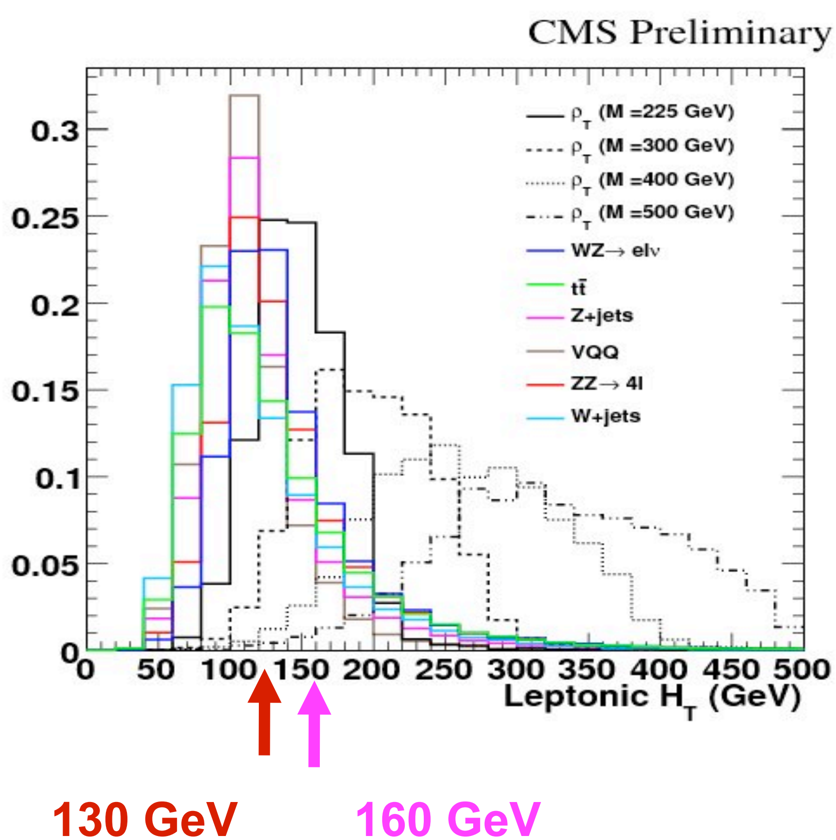
50 GeV **90 GeV**

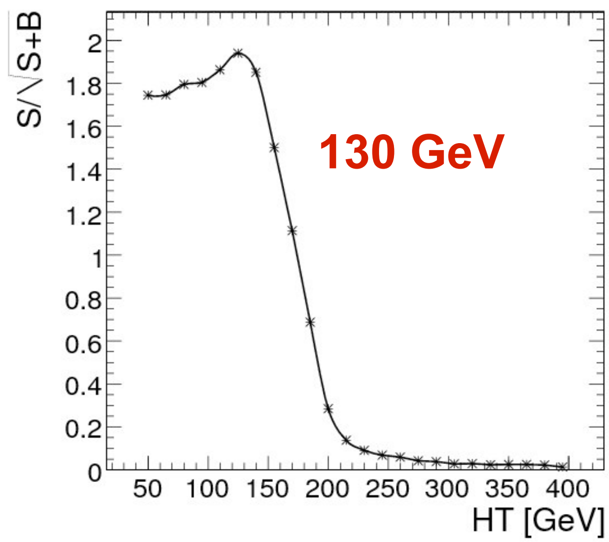


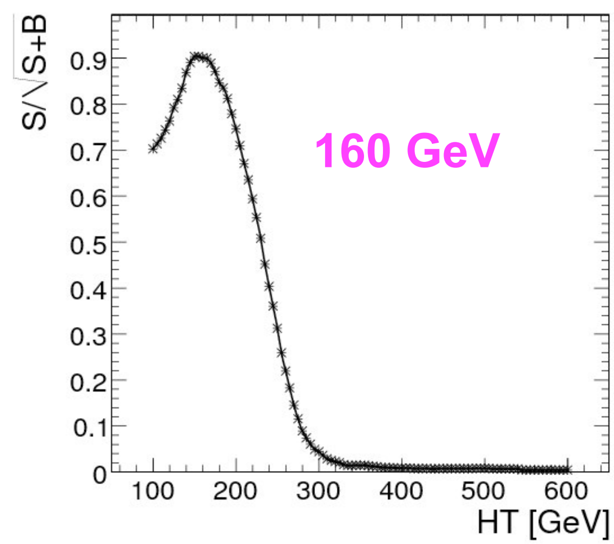


Event Selection – Leptonic H_T

Two sets of cuts: one for early data (optimized for **225 GeV** mass point), and one for higher luminosities (optimized for **300 GeV** mass point).

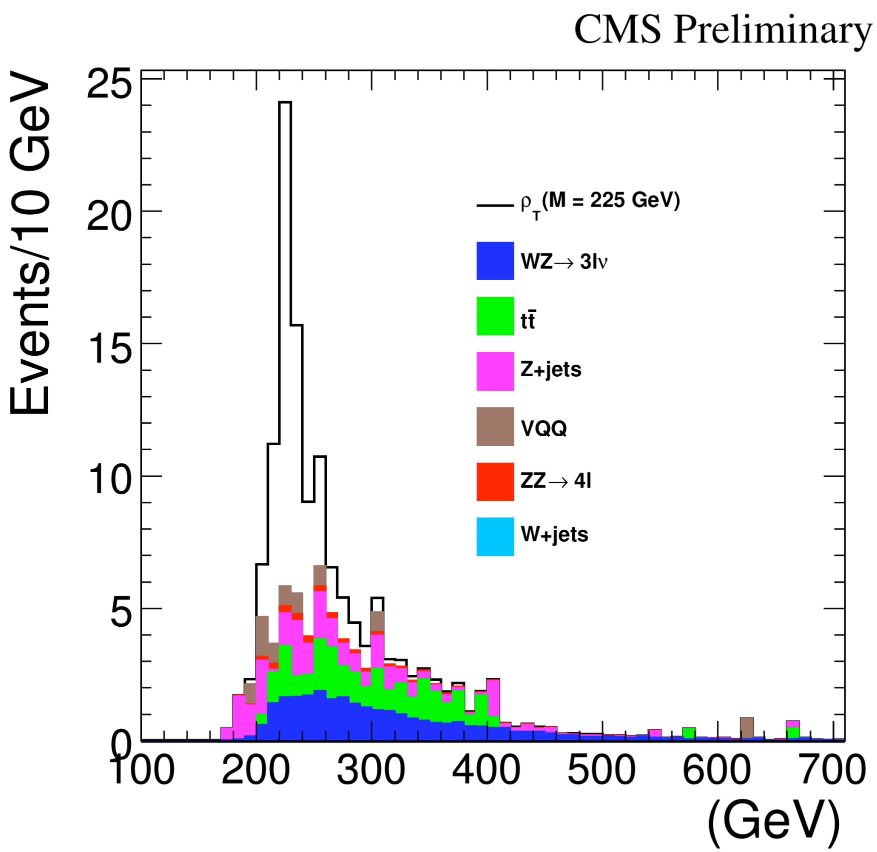


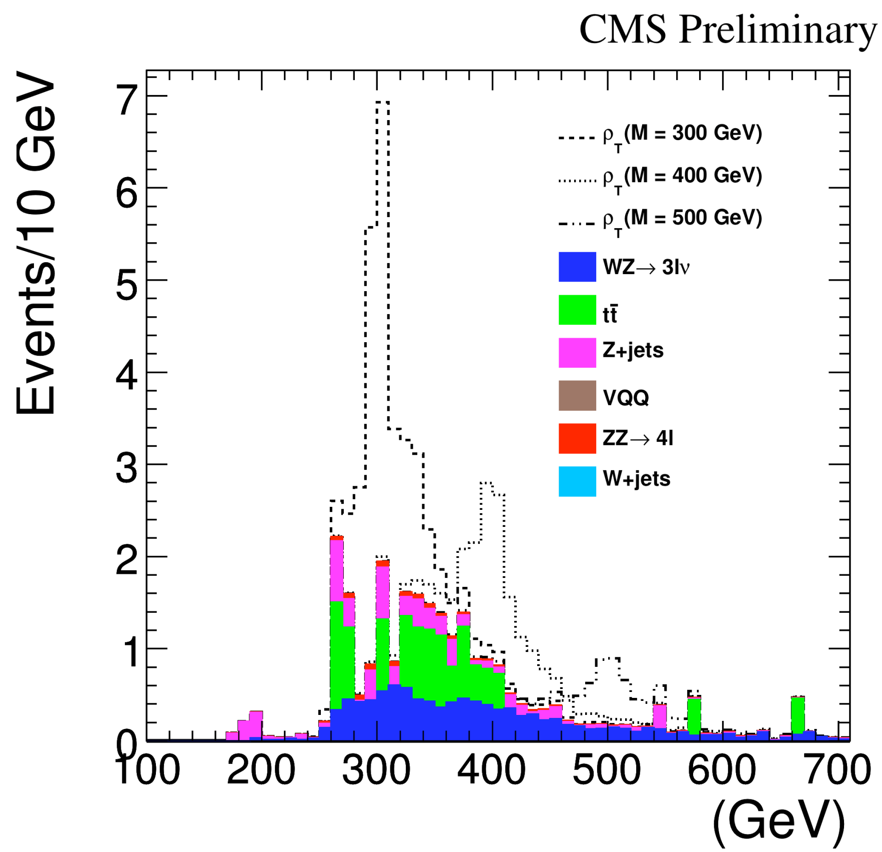




WZ Invariant Mass

@ $1fb^{-1}$

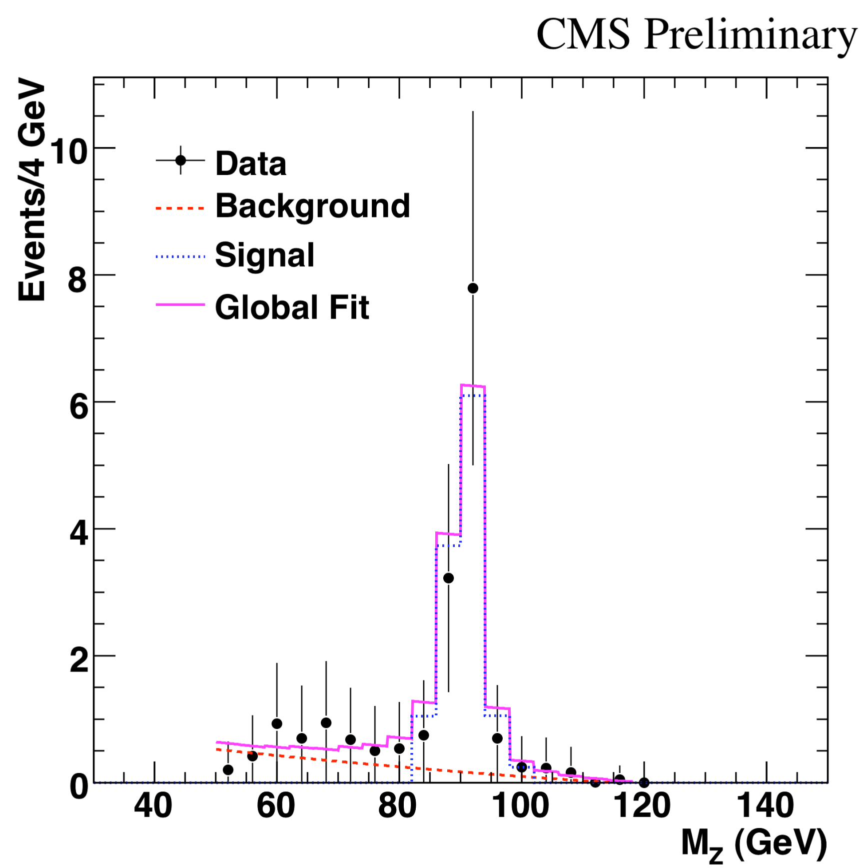




Mass window of 1.4 Gaussian sigmas. Phys. Rev. D62 (2000) 035004

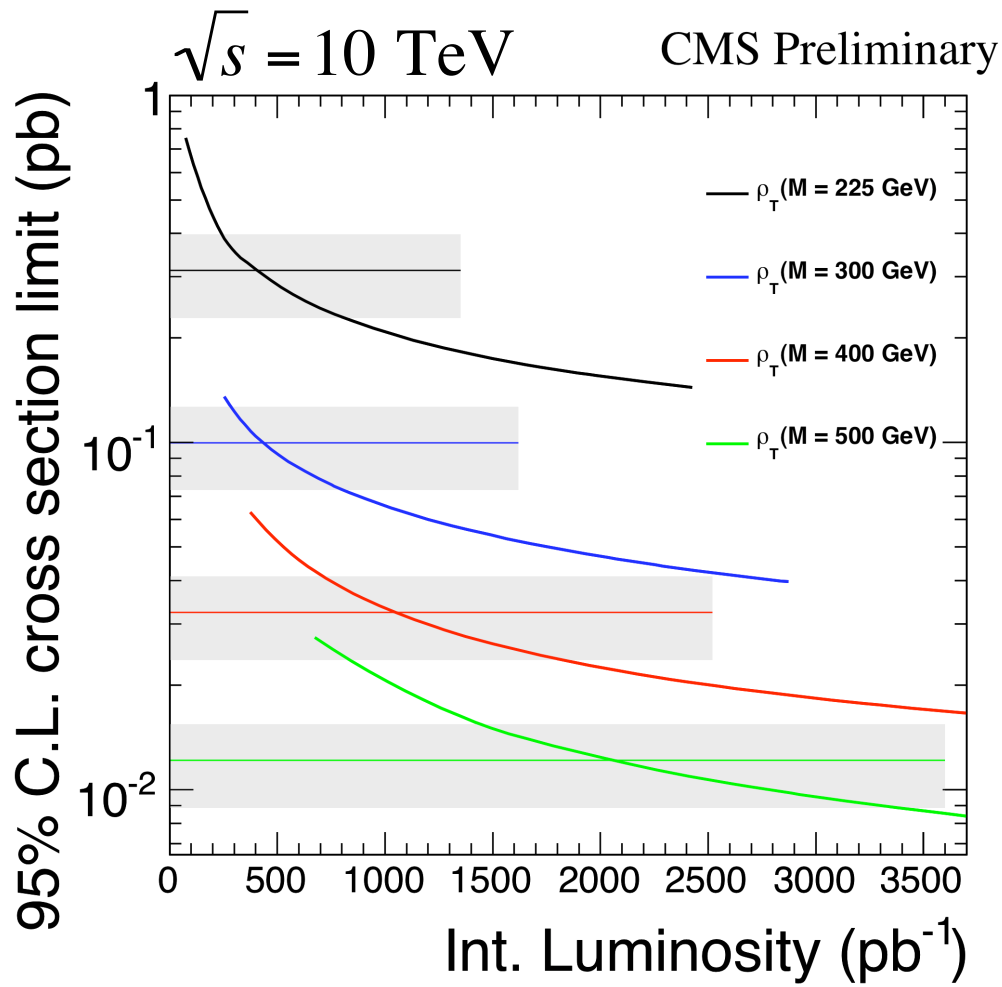
Background estimation

- Physics Background
  - SM di-boson
- Instrumental Background
  - With a genuine Z boson
    - Z+jets, Zbb
  - Without a genuine Z boson
    - ttbar, W+jets
      - (Sideband subtraction method)



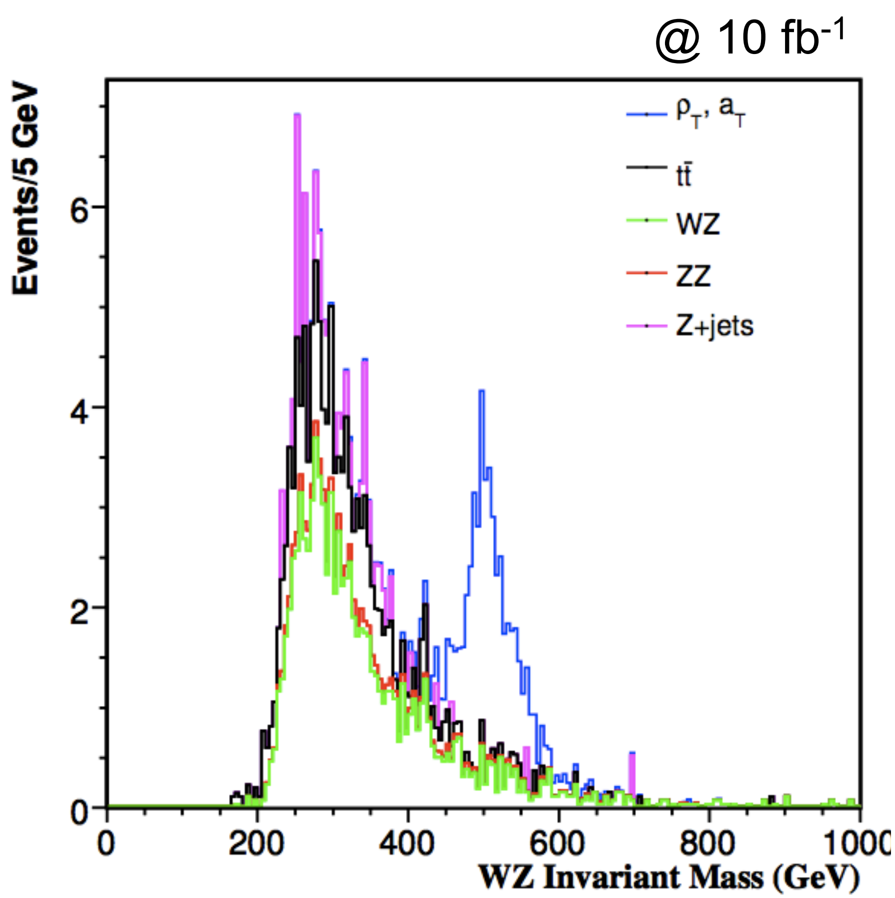
Exclusion Limits

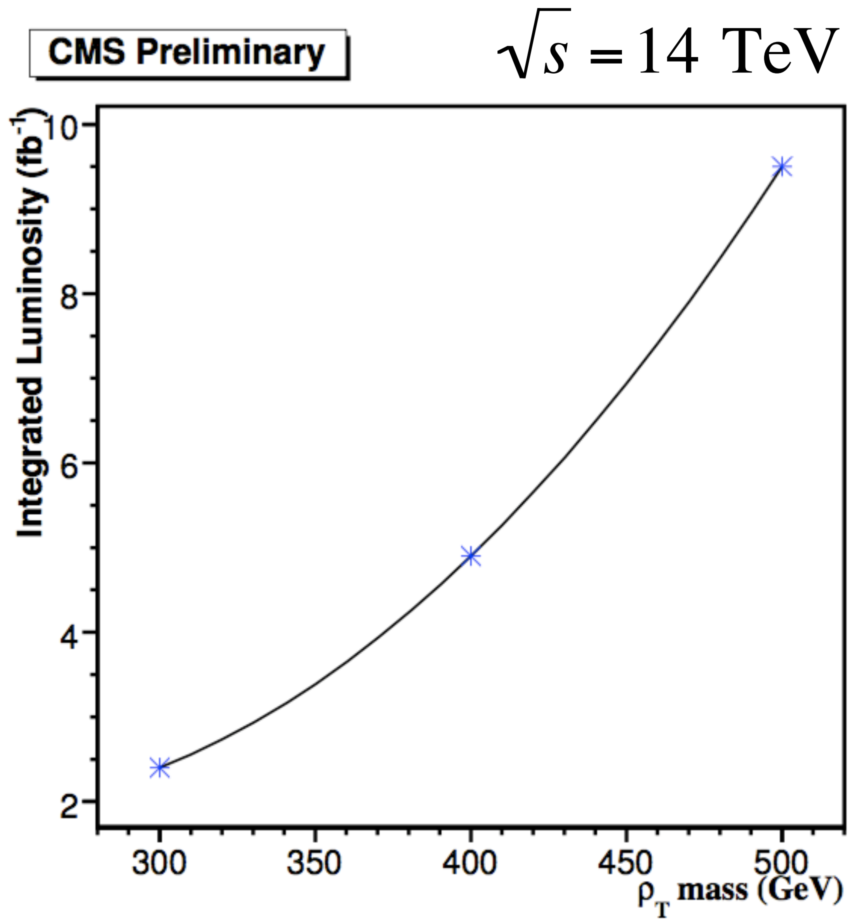
- Exclude masses of up to 300 GeV with 450 pb^{-1}
- > 1fb^{-1} needed for excluding higher masses at 10 TeV
- > 1fb^{-1} needed for 5σ discovery at 10 TeV



CMS @ Les Houches 2007

- Les Houches 2007: Low-Scale Technicolor at the LHC (Azuelos, Black, Bose, Ferland, Gershtein, Lane and Martin)



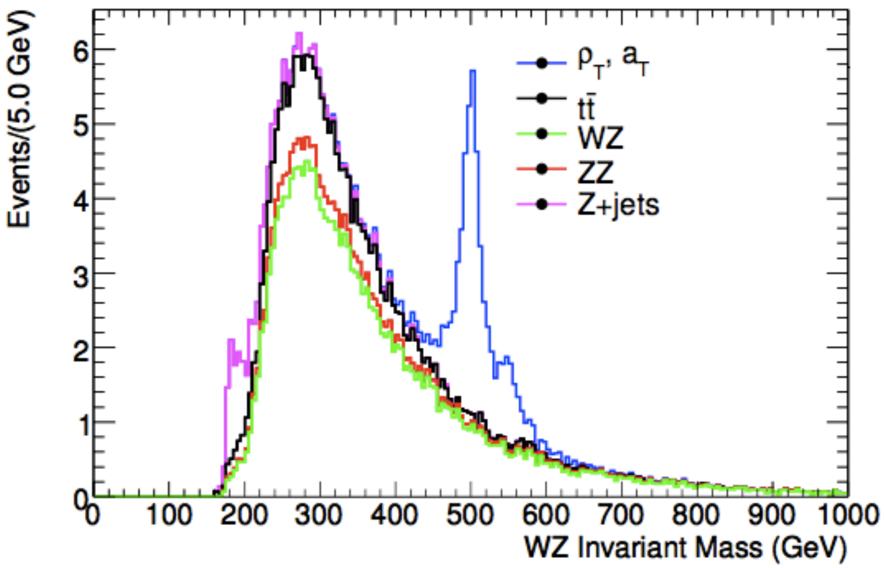


Fast Simulation

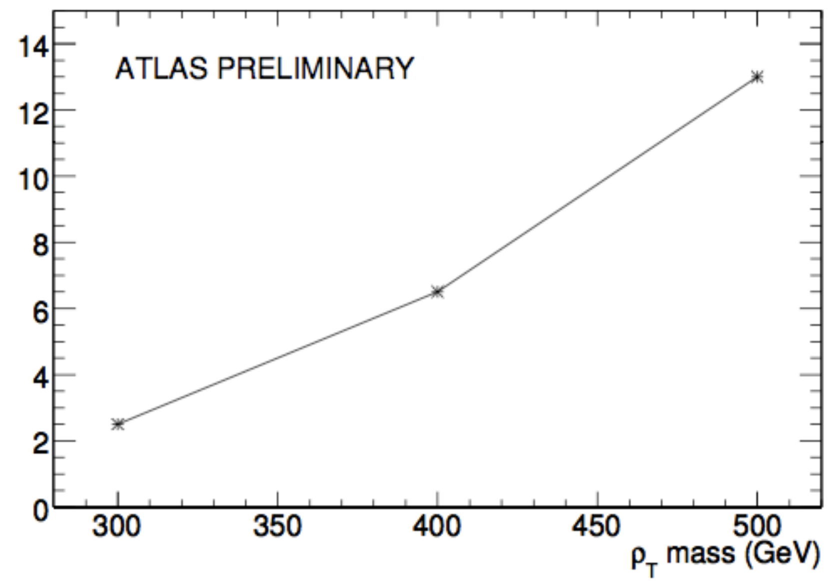
ATLAS @ Les Houches 2007

- Les Houches 2007: Low-Scale Technicolor at the LHC (Azuelos, Black, Bose, Ferland, Gershtein, Lane and Martin)

@ 10 fb^{-1}



$\sqrt{s} = 14$ TeV



Fast Simulation

Angular Distributions

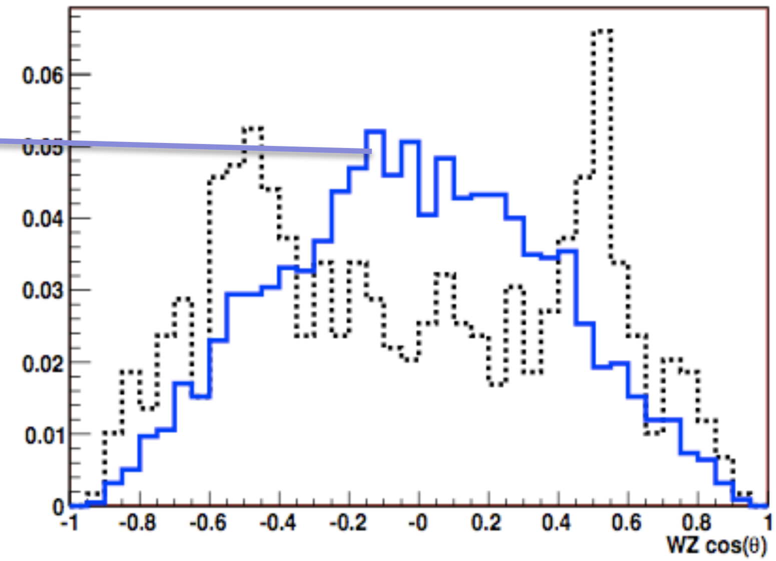
- Decay angular distributions could provide compelling evidence for technicolor

$$\sqrt{s} = 14\ \text{TeV}$$

$$\frac{d\sigma(\bar{q}q \to \rho_T^{\pm} \to W_L^{\pm} Z_L^{0})}{d(\cos\theta)} \propto \sin^2\theta$$

$$\frac{d\sigma(\bar{q}q \to a_T^{\pm} \to \gamma W_L^{\pm})}{d(\cos\theta)} \propto 1 + \cos^2\theta$$

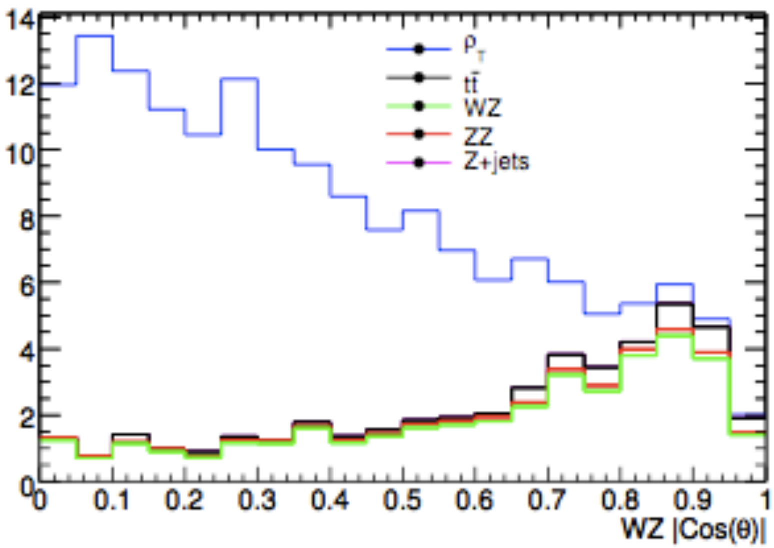
$$\frac{d\sigma(\bar{q}q \to \omega_T \to \gamma Z_L^{0})}{d(\cos\theta)} \propto 1 + \cos^2\theta$$

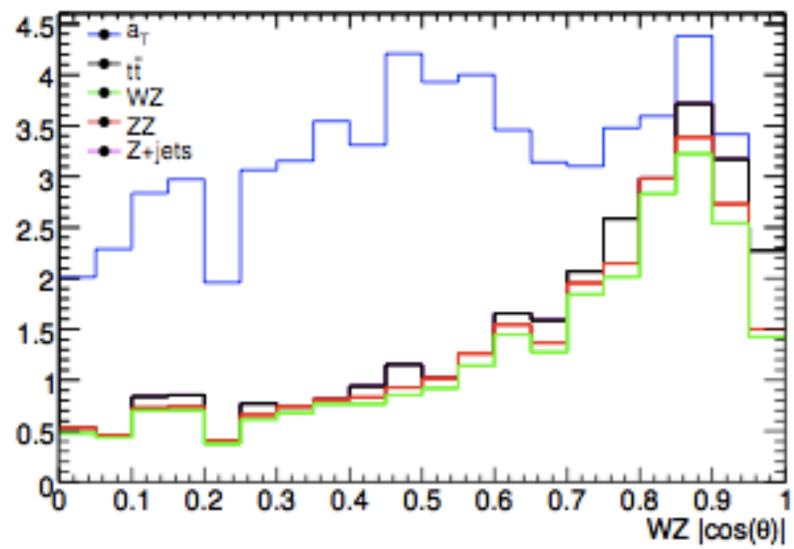


Angular Distributions

@ 50 fb^{-1}

$\sqrt{s} = 14$ TeV



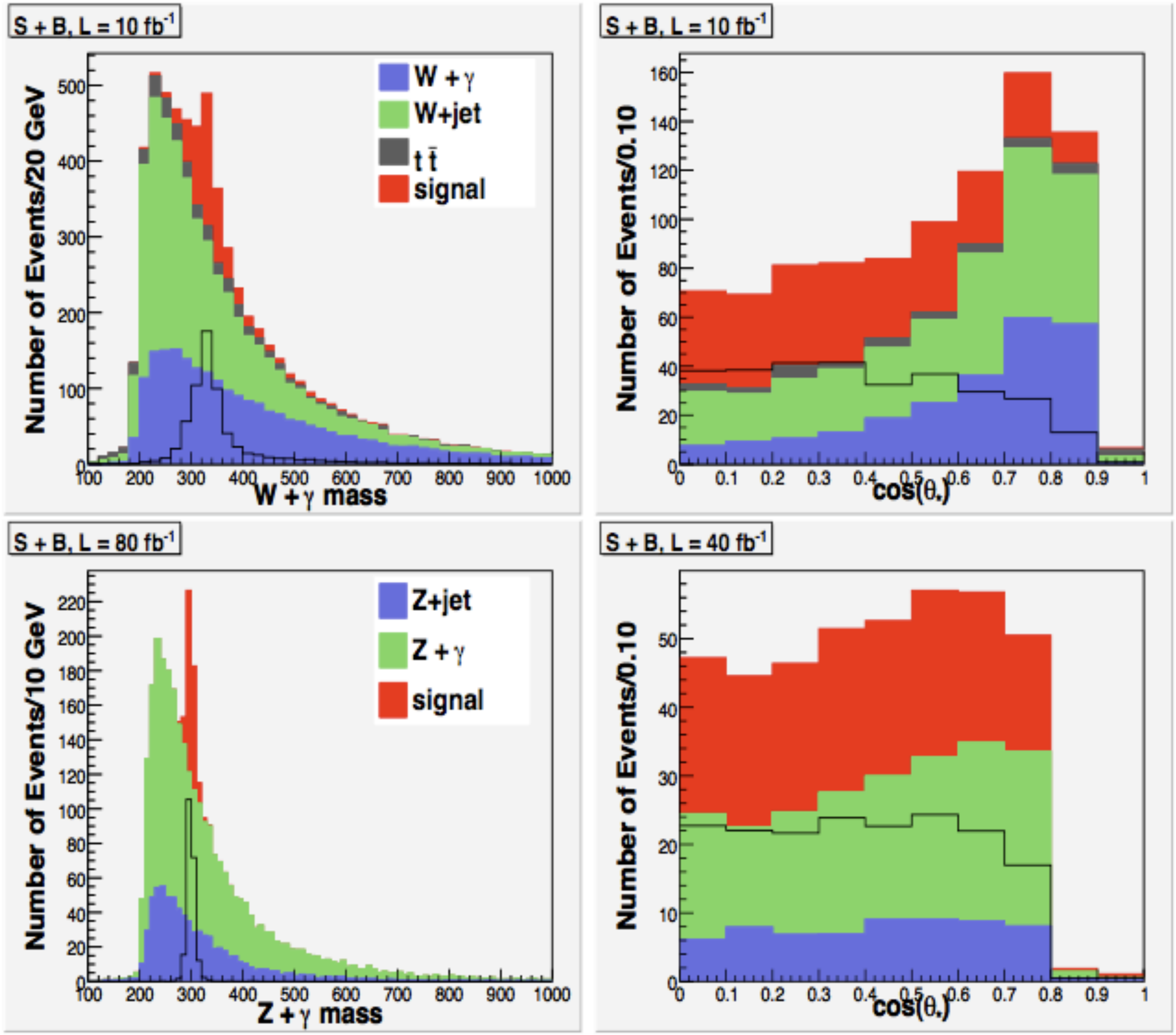


$$\rho_T^\pm \;\rightarrow\; W_L^\pm Z_L^0 \rightarrow \ell^\pm \ell^+ \ell^- \not{E}_T$$

$$a_T^\pm \;\rightarrow\; \gamma W_L^\pm \rightarrow \gamma\, \ell^\pm \not{E}_T$$

$$\omega_T \;\rightarrow\; \gamma Z_L^0 \rightarrow \gamma\, \ell^+ \ell^-$$

PGS


S + B, L = 10 fb-1
Number of Events/20 GeV
W + γ mass
W + γ
W+jet
t t̄
signal
S + B, L = 10 fb-1
Number of Events/0.10
cos(θ.)
S + B, L = 80 fb-1
Number of Events/10 GeV
Z + γ mass
Z+jet
Z + γ
signal
S + B, L = 40 fb-1
Number of Events/0.10
cos(θ.)

Other discovery channels

- Principal channel at the Tevatron is swamped by the ttbar background at the LHC

$$\rho_T \to W^{\pm}\pi_T^{\mp,0} \to \ell^{\pm}\nu_{\ell}bj,$$

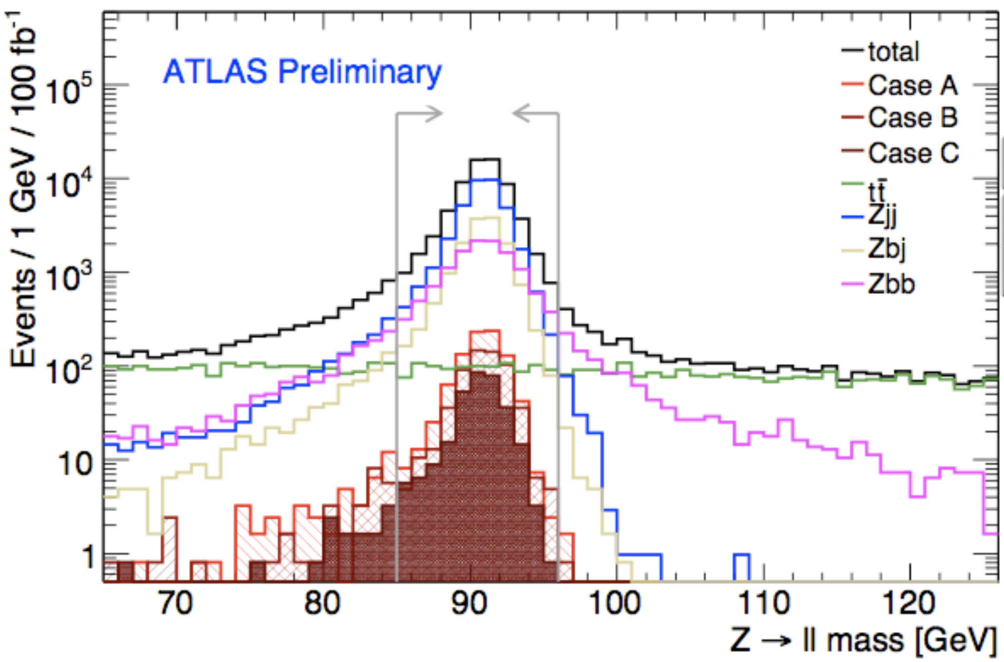
- Can consider

$$pp \to \rho_T^{\pm}/a_T^{\pm} \to Z^0\pi_T^{\pm} \to \ell^+\ell^-bj$$

  - dominated less by background (in comparison)
  - can discover $\rho_{T,}$ a_T peaks in the same final state
  - Need a techni-pion to connect resonance to technicolor

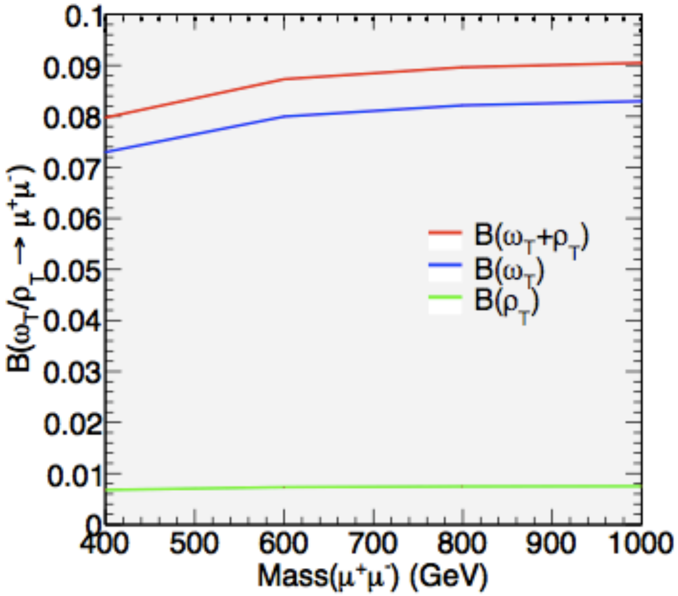
$$pp \rightarrow \rho_T^{\pm}/a_T^{\pm} \rightarrow Z^0\pi_T^{\pm} \rightarrow \ell^+\ell^- bj$$

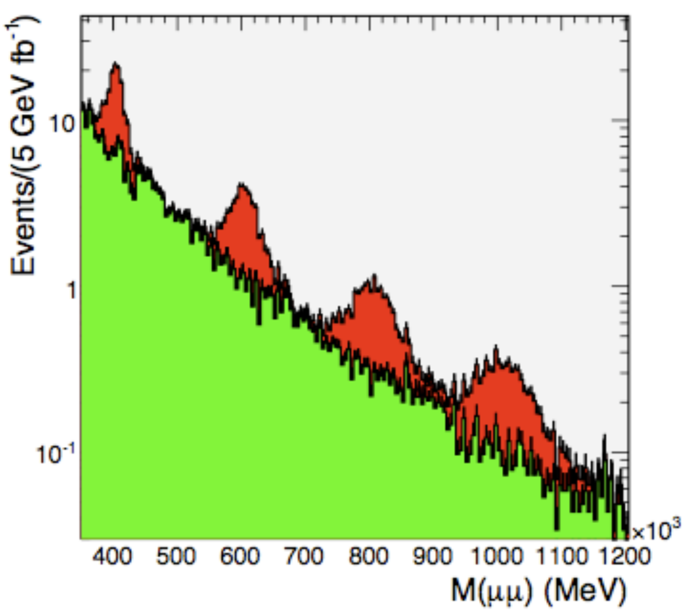
Sample	$M_{\rho_T}, M_{\omega_T}, \Lambda_{V_T}, \Lambda_{A_T}$ [GeV]	M_{a_T} [GeV]	M_{π_T} [GeV]	$M_{\pi'_T}$ [GeV]	σxBR [fb] ρ_T	σxBR [fb] a_T
A	300	330	200	400	98.7	58.9
B	400	440	275	500	71.2	17.4
C	500	550	350	600	36.5	8.9

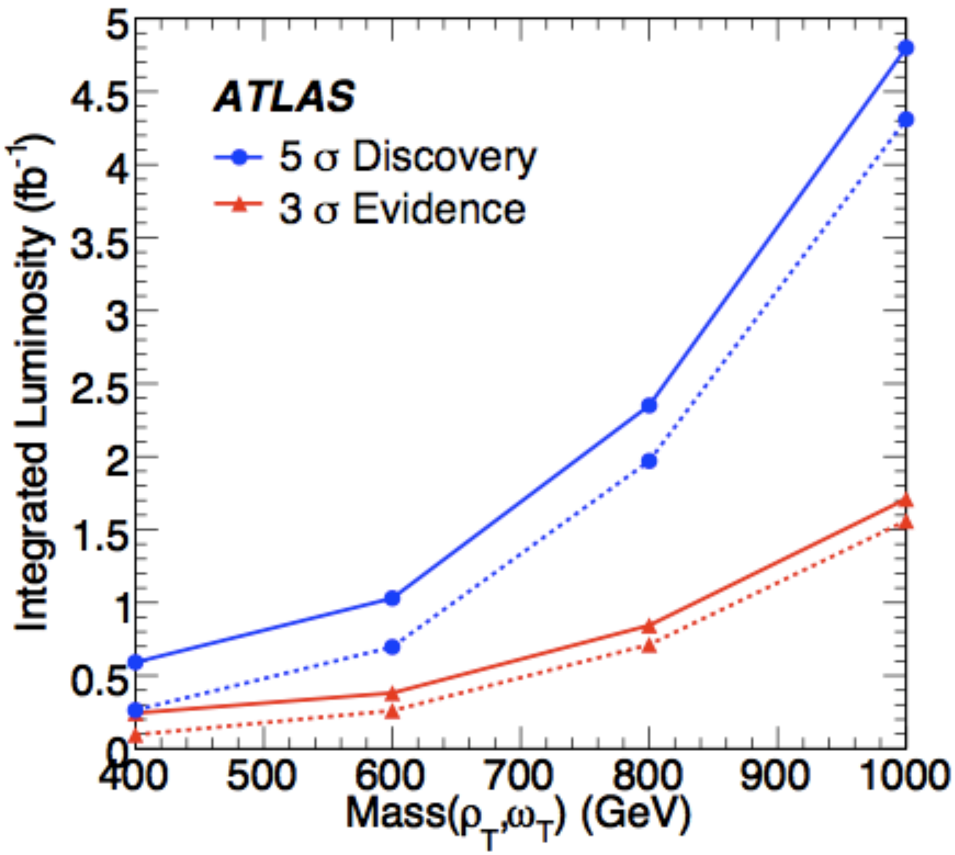


Sample	peak	A	B	C
Luminosity [fb^{-1}]	$\rho_T^{\pm}$	8.3	15.1	14.8
	$a_T^{\pm}$	47.5	106	390

TC decays to di-leptons



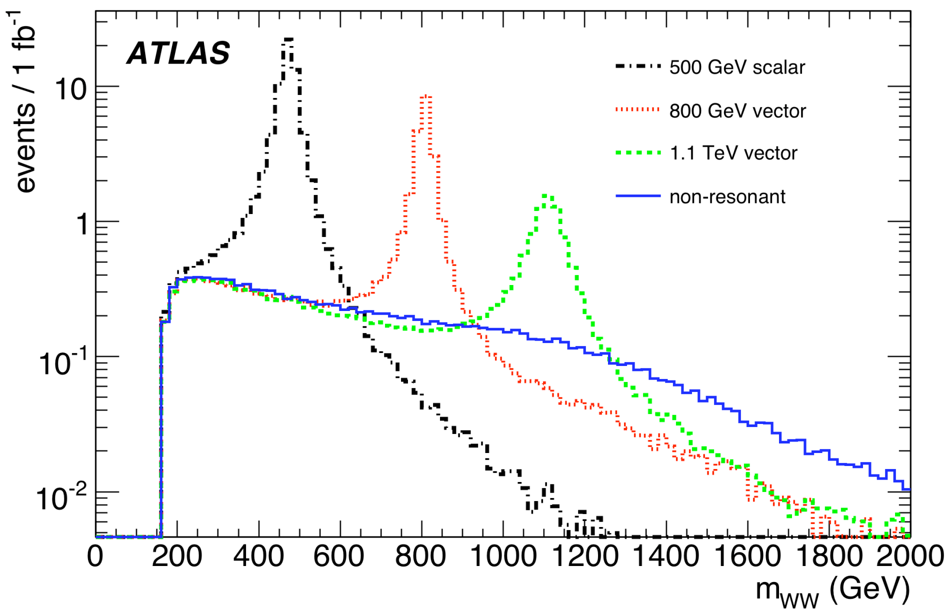




Vector Boson Scattering

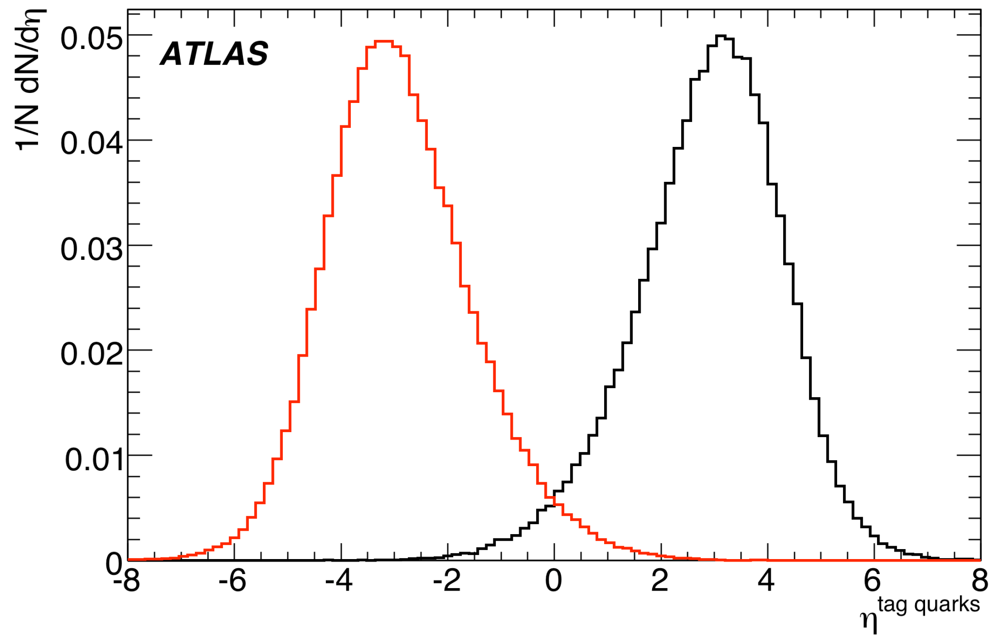
- Without a Higgs, WW cross-section violates unitarity
- Some new physics may exist in the form of vector boson pair resonances

$\sqrt{s} = 14\ \mathrm{TeV}$



Tag Jets

- Forward jets expected from VBF
- Tag forward jets
- Reject events with additional central jets (central jet veto)

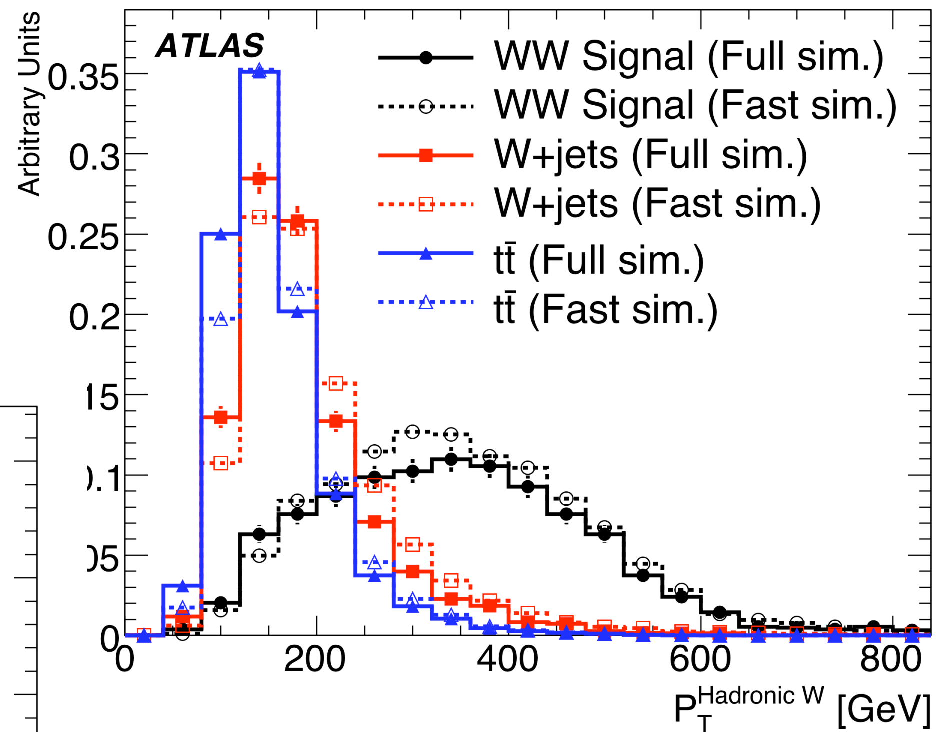


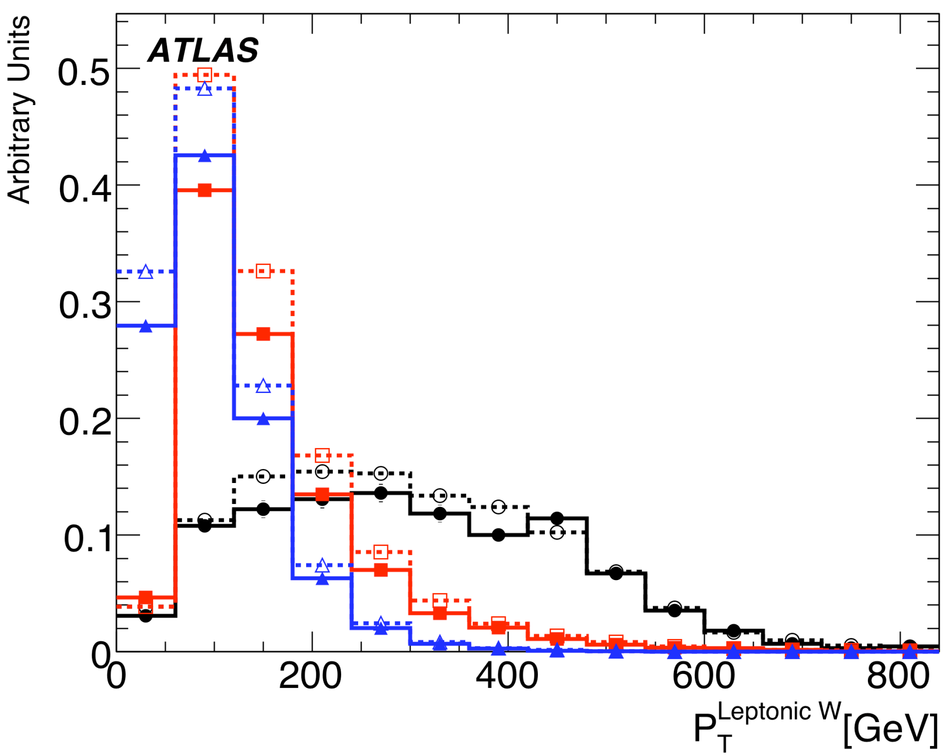
1. Require two jets with
   - $|\eta(jet)| > \eta_{\text{cut}}$ and $p_T(jet) > p_{T\text{cut}}$
   - opposite signed rapidity
   - at least one of them has an energy greater than a critical value E_{cut}
2. If more than one jet with the same sign rapidity satisfies the above cuts, choose the most energetic, labelled FJ1. The next one is labelled FJ2.
   - Require the tag-jet with the opposite sign of rapidity to satisfy $\Delta\eta(FJ1, FJ2) > \Delta\eta_{\text{cut}}$ and $E(FJ2) > E_{2\text{cut}}$

Backgrounds

Main backgrounds

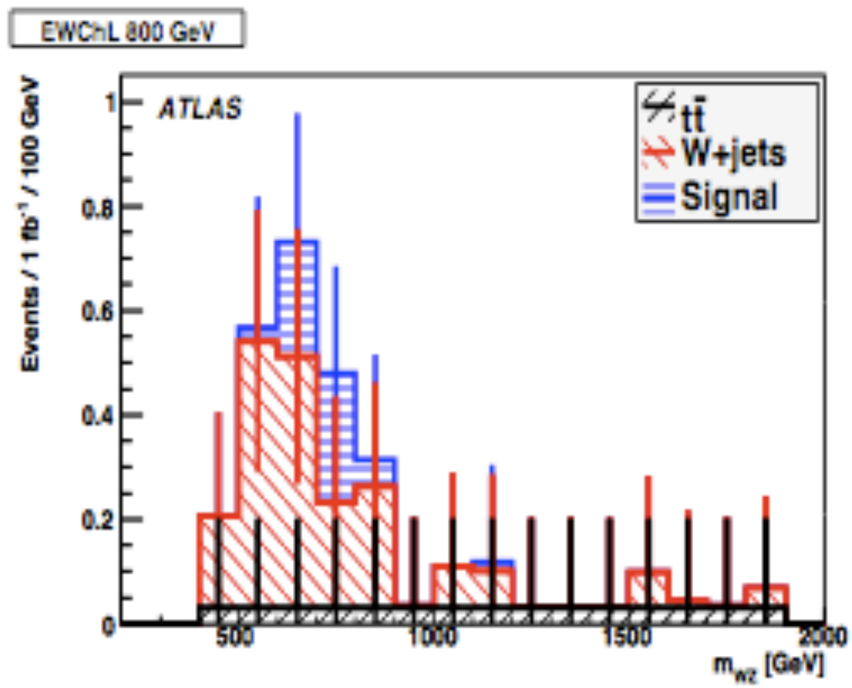
- Top, W/Z+jets
- Reduce with central jet veto

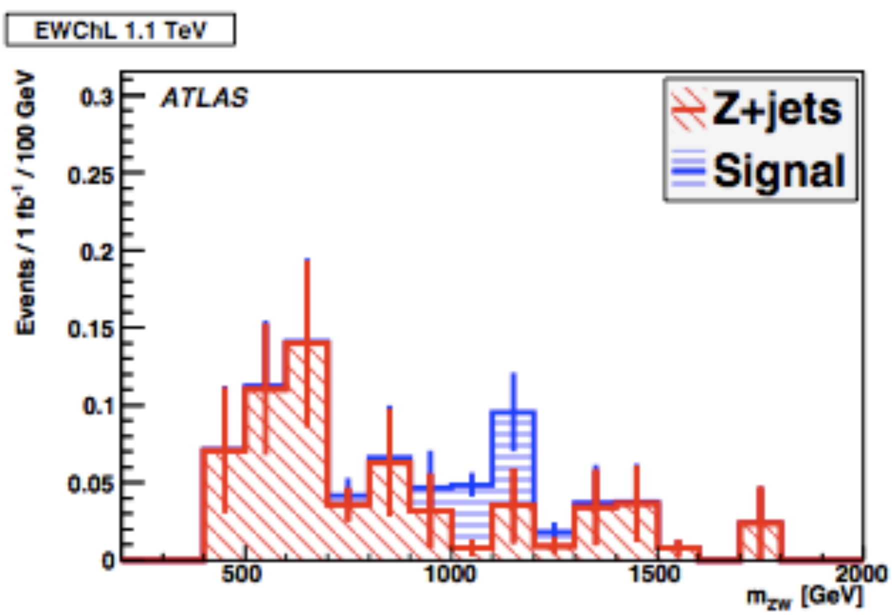




Signal over background

- Difficult Signal to reconstruct over background





Discovery Potential

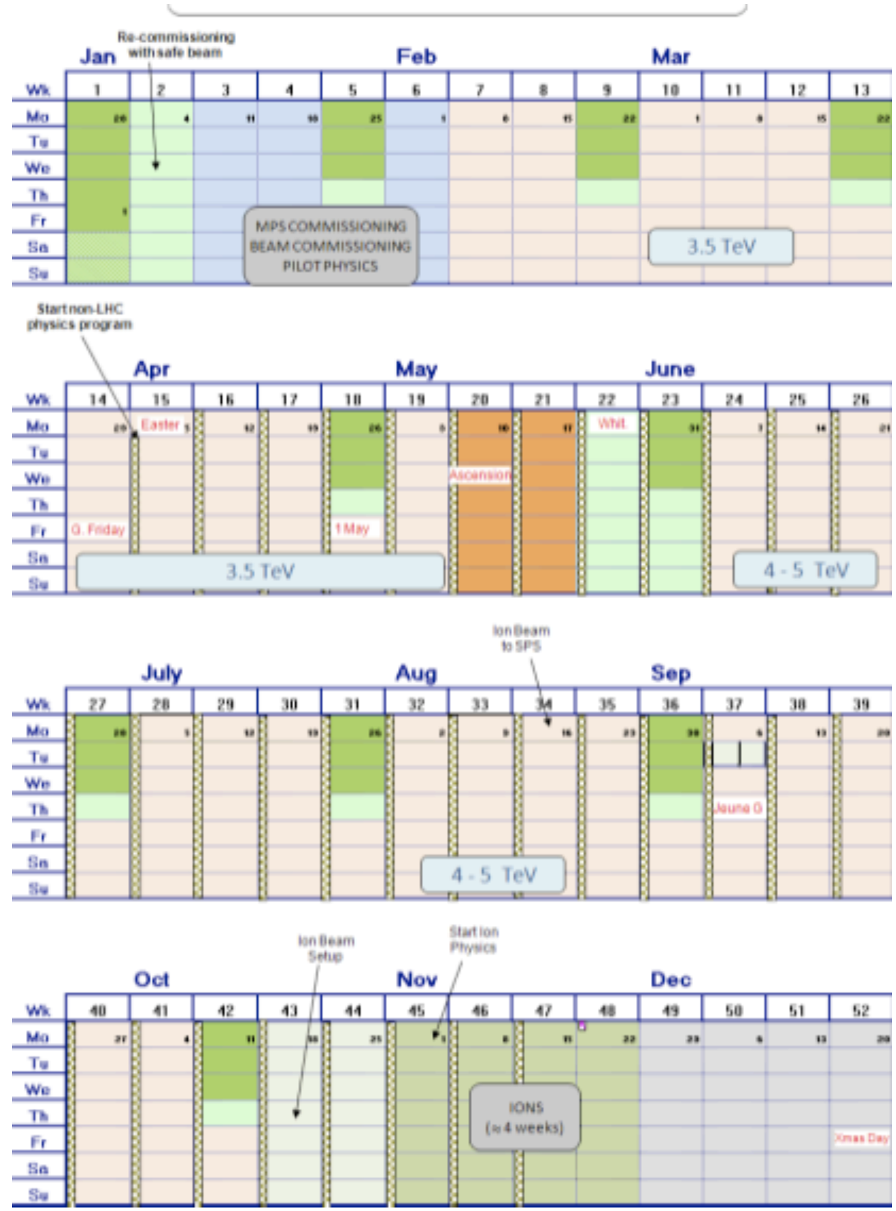
Process	Cross section (fb)		Luminosity (fb^{-1})		Significance
	signal	background	for 3σ	for 5σ	for 100 fb^{-1}
$WW/WZ \to \ell\nu\, jj$, $m = 500$ GeV	0.31 ± 0.05	0.79 ± 0.26	85	235	3.3 ± 0.7
$WW/WZ \to \ell\nu\, jj$, $m = 800$ GeV	0.65 ± 0.04	0.87 ± 0.28	20	60	6.3 ± 0.9
$WW/WZ \to \ell\nu\, jj$, $m = 1.1$ TeV	0.24 ± 0.03	0.46 ± 0.25	85	230	3.3 ± 0.8
$W_{jj}Z_{\ell\ell}$, $m = 500$ GeV	0.28 ± 0.04	0.20 ± 0.18	30	90	5.3 ± 1.9
$W_{\ell\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.40 ± 0.03	0.25 ± 0.03	20	55	6.6 ± 0.5
$W_{jj}Z_{\ell\ell}$, $m = 800$ GeV	0.24 ± 0.02	0.30 ± 0.22	60	160	3.9 ± 1.2
$W_{j}Z_{\ell\ell}$, $m = 800$ GeV	0.20 ± 0.02	0.09 ± 0.06	30	90	5.3 ± 1.3
$W_{j}Z_{\ell\ell}$, $m = 1.1$ TeV	0.11 ± 0.01	0.10 ± 0.06	90	250	3.1 ± 0.8
$W_{\ell\nu}Z_{\ell\ell}$, $m = 1.1$ TeV	0.070 ± 0.004	0.020 ± 0.009	70	200	3.6 ± 0.5
$Z_{\nu\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.32 ± 0.02	0.15 ± 0.03	20	60	6.6 ± 0.6

$\sqrt{s} = 14$ TeV

Not an early data search but need to establish strategy for such searches

LHC plan for first run

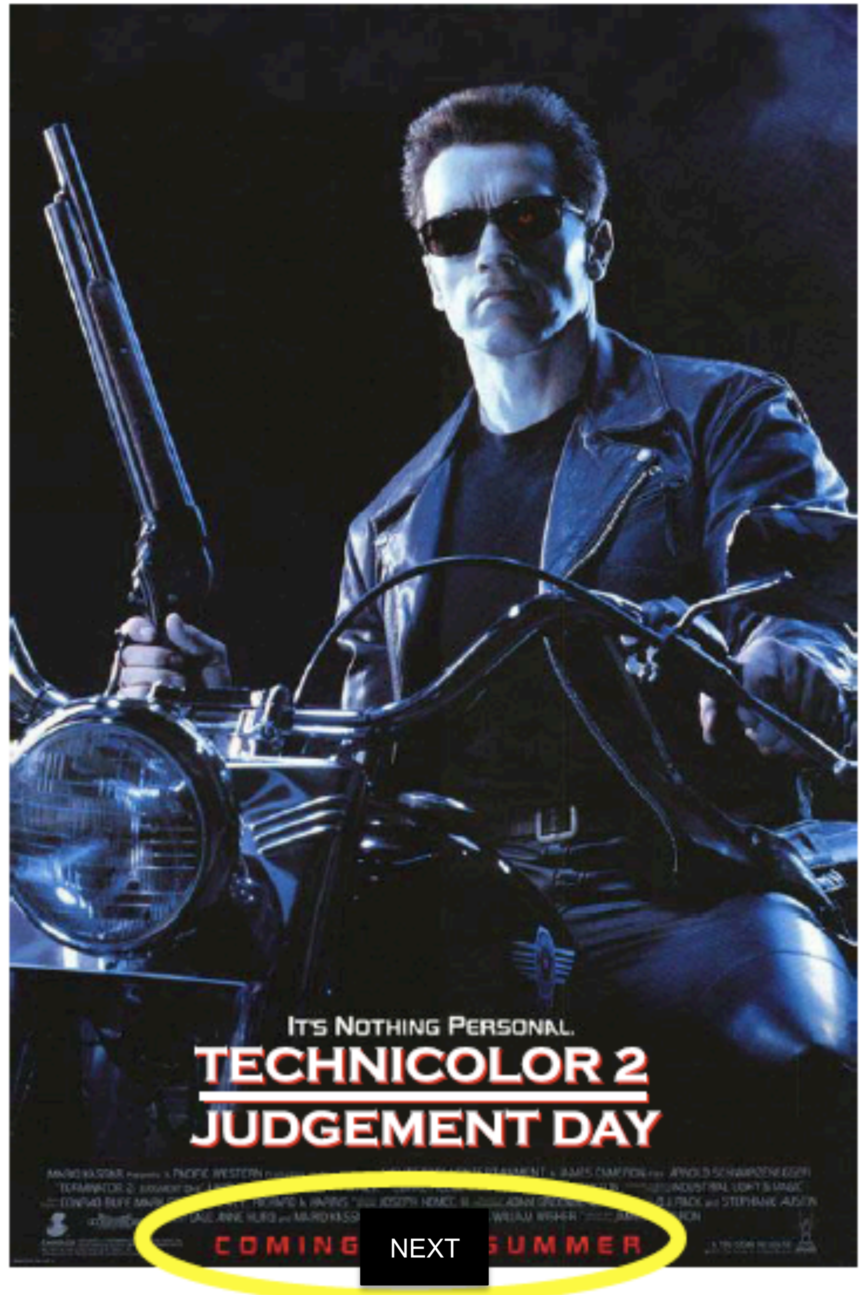
- Start with 7 TeV and then 8-10 TeV
  - will depend on operating experience
  - monitor all quenches for additional data etc.
- Schedule
  - 2009:
    - first beams in November
    - 1 month commissioning
  - 2010:
    - 1 month pilot run and commissioning
    - 3 months @ 7 TeV
    - 1 month step-up
    - 5 month 4-5 TeV
    - 1 month heavy ions



Conclusions

- The LHC will provide a very fertile ground for testing strong dynamics
- ATLAS and CMS are pursuing multiple analysis strategies and discovery channels
- We are ready and eager for beam!

The Return of Technicolor ?



Courtesy Markus Luty

BACKUP

Background estimation

- Physics Background
  - SM di-boson
- Instrumental Background
  - With a genuine Z boson
    - Z+jets, Zbb
  - Without a genuine Z boson
    - QCD, ttbar, W+jets
      - QCD background is estimated using QCD di-jet MC samples
      - Since the statistics are relatively small, we factorize the selection criteria into two independent requirements
        - » Probability of having one Z
        - » Probability of having one W
      - This will give an upper limit on the size of the background

Background estimation - QCD

For 225 GeV optimization

PAS

QCD Samples							
p_T (GeV)	Events Processed	σ_{LO} (pb)	$W \to e\nu$	$Z \to ee$	$W \to \mu\nu$	$Z \to \mu\mu$	WZ All 1 fb^{-1}(Upper Limit)
170–230	4.860E+04	4.833E+04	19	0	42	1	2.49E-00 ± 1.35E-00
230–300	5.940E+04	1.062E+04	33	0	48	20	5.12E-00 ± 9.70E-01
300–380	6.869E+04	2.635E+03	49	0	99	44	3.72E-00 ± 5.10E-01
380–470	4.666E+04	7.230E+02	49	0	86	65	2.96E-00 ± 3.66E-01
470–600	1.814E+04	2.410E+02	22	0	34	34	1.43E-00 ± 2.56E-01
600–800	2.020E+04	6.249E+01	28	0	53	66	8.32E-01 ± 1.18E-01
800–1000	1.692E+04	9.421E+00	22	0	51	91	2.21E-01 ± 3.10E-02
1000–1400	3.480E+04	2.344E+00	47	0	170	313	1.32E-01 ± 1.08E-02
1400–1800	2.938E+04	1.569E-01	39	0	189	485	2.01E-02 ± 1.53E-03
1800–2200	2.910E+04	1.381E-02	41	0	285	719	3.83E-03 ± 2.45E-04
2200–2600	2.232E+04	1.296E-03	16	0	283	720	5.61E-04 ± 3.76E-05
2600–3000	1.704E+04	1.140E-04	10	0	225	664	6.14E-05 ± 4.56E-06
3000–3500	2.136E+04	8.432E-06	7	0	320	939	5.68E-06 ± 3.58E-07
Total (170–3500)	–	–	–	–	–	–	16.94E-00 ± 1.80E-00

Additionally taking into account the efficiencies of the HT and invariant mass cut we estimate an approximate total QCD contribution of: $0.5^{+0.7}_{-0.4}$

Contribution from the low pT hat samples cross-checked with EM and muon enriched samples – found to be negligible
Also cross-checked by running analysis cuts on full QCD sample

Background estimation - QCD

For 300 GeV optimization

PAS

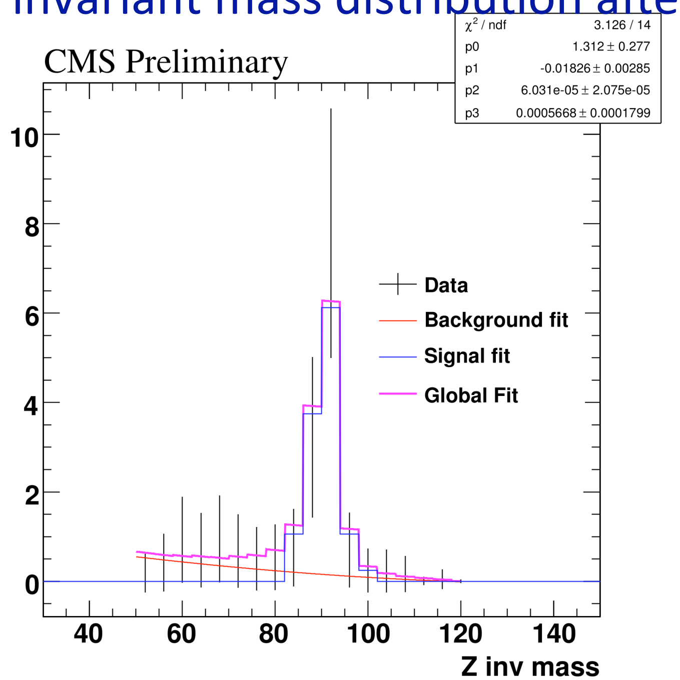
QCD Samples							
p_T (GeV)	Events Processed	σ_{LO} (pb)	$W \to e\nu$	$Z \to ee$	$W \to \mu\nu$	$Z \to \mu\mu$	WZ All 1 fb^{-1}(Upper Limit)
170–230	4.860E+04	4.833E+04	16	0	28	0	1.80E-00 $\pm$ 9.53E-01
230–300	5.940E+04	1.062E+04	33	0	37	7	1.69E-00 $\pm$ 4.58E-01
300–380	6.869E+04	2.635E+03	46	0	88	14	1.12E-00 $\pm$ 2.33E-01
380–470	4.666E+04	7.230E+02	45	0	76	32	1.33E-00 $\pm$ 2.05E-01
470–600	1.814E+04	2.410E+02	19	0	29	15	5.62E-01 $\pm$ 1.27E-01
600–800	2.020E+04	6.249E+01	25	0	46	34	3.81E-01 $\pm$ 6.46E-02
800–1000	1.692E+04	9.421E+00	20	0	46	34	7.60E-02 $\pm$ 1.33E-02
1000–1400	3.480E+04	2.344E+00	46	0	148	155	5.86E-02 $\pm$ 5.60E-03
1400–1800	2.938E+04	1.569E-01	36	0	169	253	9.47E-03 $\pm$ 8.25E-04
1800–2200	2.910E+04	1.381E-02	38	0	252	397	1.88E-03 $\pm$ 1.37E-04
2200–2600	2.232E+04	1.296E-03	16	0	268	401	2.97E-04 $\pm$ 2.23E-05
2600–3000	1.704E+04	1.140E-04	9	0	212	364	3.17E-05 $\pm$ 2.64E-06
3000–3500	2.136E+04	8.432E-06	6	0	308	581	3.38E-06 $\pm$ 2.33E-07
Total (170–3500)	–	–	–	–	–	–	7.02E-00 $\pm$ 1.11E-00

Additionally taking into account the efficiencies of the HT and invariant mass cut we estimate an approximate total QCD contribution of: $0.4^{+0.5}_{-0.3}$

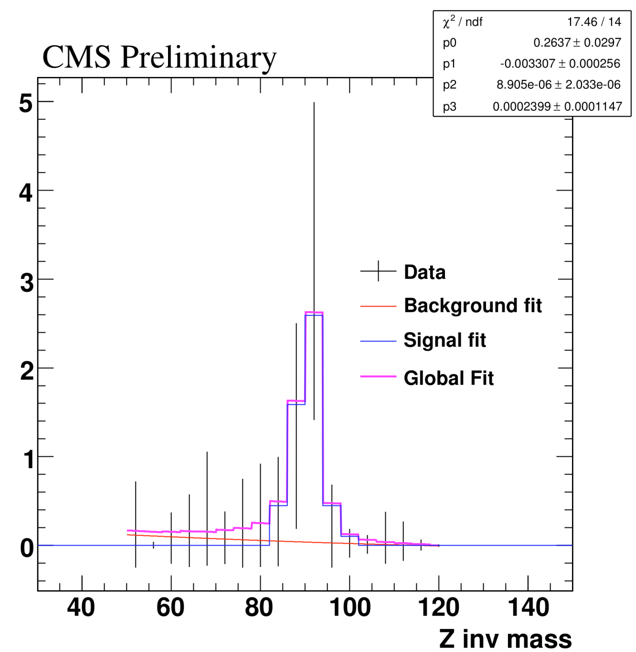
Contribution from the low pT hat samples cross-checked with EM and muon enriched samples – found to be negligible
Also cross-checked by running analysis cuts on full QCD sample

Data-driven ttbar background estimate

- Sideband subtraction method
- Assume processes with non-genuine Z bosons populate the tails of the Z invariant mass distribution
- Extract shape of Z boson peak from Z+jets and WZ samples
- Extract flat background from ttbar and W+jets sample and parameterize using a quadratic function
- Fit Z invariant mass distribution after all cuts to the sum of the above



225 GeV



300 GeV

PAS

@ $200 pb^{-1}$

Z+jets background estimation

- Extract background using the "matrix method"

- Define two samples
  - "Tight-cut" sample: events passing all cuts
  - "Loose-cut" sample: events passing all the selection cuts, except for the isolation cuts on the W daughter leptons

$$N_{loose} = N_{lep} + N_{jet}$$

$$N_{tight} = \varepsilon_{tight} N_{lep} + P_{fake} N_{jet}$$

Will be measured from data

Z+jets background estimate

- Tag and Probe method to be used for measuring the efficiency for the true leptons to pass the isolation cuts
- Use a Z-enriched sample containing the 300 GeV signal, Z+jets, W+jets and ttbar
  - Require two oppositely charged leptons with the same flavor and invariant mass within 50-120 GeV range
  - Only one Z candidate allowed
  - Leptons have pT > 15 GeV and pass lepton ID requirements

$$\varepsilon_{tight} = \frac{2(N_{TT} - B_{TT})}{(N_{TF} - B_{TF}) + 2(N_{TT} - B_{TT})}$$

TT=> both leptons pass isolation cuts
TF=> one lepton fails isolation cuts

$$\varepsilon_{tight} = (93.9 \pm 0.8)\%$$ Muons

$$= (96.5 \pm 1.3)\%$$ Electrons

Z+jets background estimate

- Isolated lepton fake rate is obtained from the W+jets, Z+jets, ttbar and VQQ samples
- Select very good quality W events
- Require a second lepton with opposite flavor and same charge (to reject Z, ttbar)
- Compare number of loose and tight leptons

p_fake: 0.30 ± 0.04 (electron)
p_fake: 0.33 ± 0.03 (muon)

Also, assume a 20% systematic uncertainty due to potential pT dependence of p_fake

- Solve matrix equation for N_{lep} and N_{jet}

PAS

M_{ρ_T} (GeV)	Type	$\epsilon_{tight} \cdot N_{lep}$	$P_{fake} \cdot N_{jet}$	True N_{lep}^{tight}
225	Electron	4.4±3.0	1.4±1.7	5.0±1.6
	Muon	1.8±2.9	2.4±2.0	5.3±1.7
300	Electron	2.1±1.9	0.3±1.0	2.1±0.6
	Muon	1.2±1.7	0.5±1.1	2.4±0.6

@ 200pb^{-1}

Systematic Uncertainties

- Theoretical uncertainties
  - 25% uncertainty for each SM background background (not estimated in a data-driven way)
    - Includes cross section uncertainty, K-factor uncertainty
  - 27% uncertainty for signal (as uncertainty band in exclusion plot)
    - Includes cross section uncertainty, K-factor uncertainty
- PDF uncertainty (6%)
- Lepton efficiency
  - 1% uncertainty per lepton
- MET uncertainty
  - Uncertainty of 10% due to JES
- W/Z pT requirement uncertainty
- Luminosity
  - 10%

Final counts and efficiencies

PAS

Sample	Efficiencies Signal (ϵ_{main})	Expected signal Events per 200 pb^{-1}	Expected background Events per 200 pb^{-1}
ρ_T (M=225 GeV)	0.137 ± 0.037	8.60 ± 3.17	4.75 ± 0.95
ρ_T (M=300 GeV)	0.186 ± 0.034	3.71 ± 1.15	1.79 ± 0.39
ρ_T (M=400 GeV)	0.251 ± 0.046	1.62 ± 0.50	1.05 ± 0.27
ρ_T (M=500 GeV)	0.254 ± 0.047	0.65 ± 0.20	0.24 ± 0.06

@ 200pb^{-1}

PAS

Process	ρ_T (M=225 GeV)	ρ_T (M=300 GeV)	ρ_T (M=400 GeV)	ρ_T (M=500 GeV)
WZ	1.42 ± 0.50	0.70 ± 0.22	0.51 ± 0.16	0.19 ± 0.06
ZZ	0.24 ± 0.08	0.08 ± 0.02	0.03 ± 0.01	0.02 ± 0.01
VQQ	0.76 ± 0.43	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
$t\bar{t}$	1.014 ± 0.46	0.62 ± 0.29	0.39 ± 0.21	0.00 ± 0.00
W + jets	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Z + jets	1.32 ± 0.50	0.38 ± 0.14	0.12 ± 0.04	0.03 ± 0.01

Using MC estimates

Background Estimates

PAS

@ 200pb^{-1}

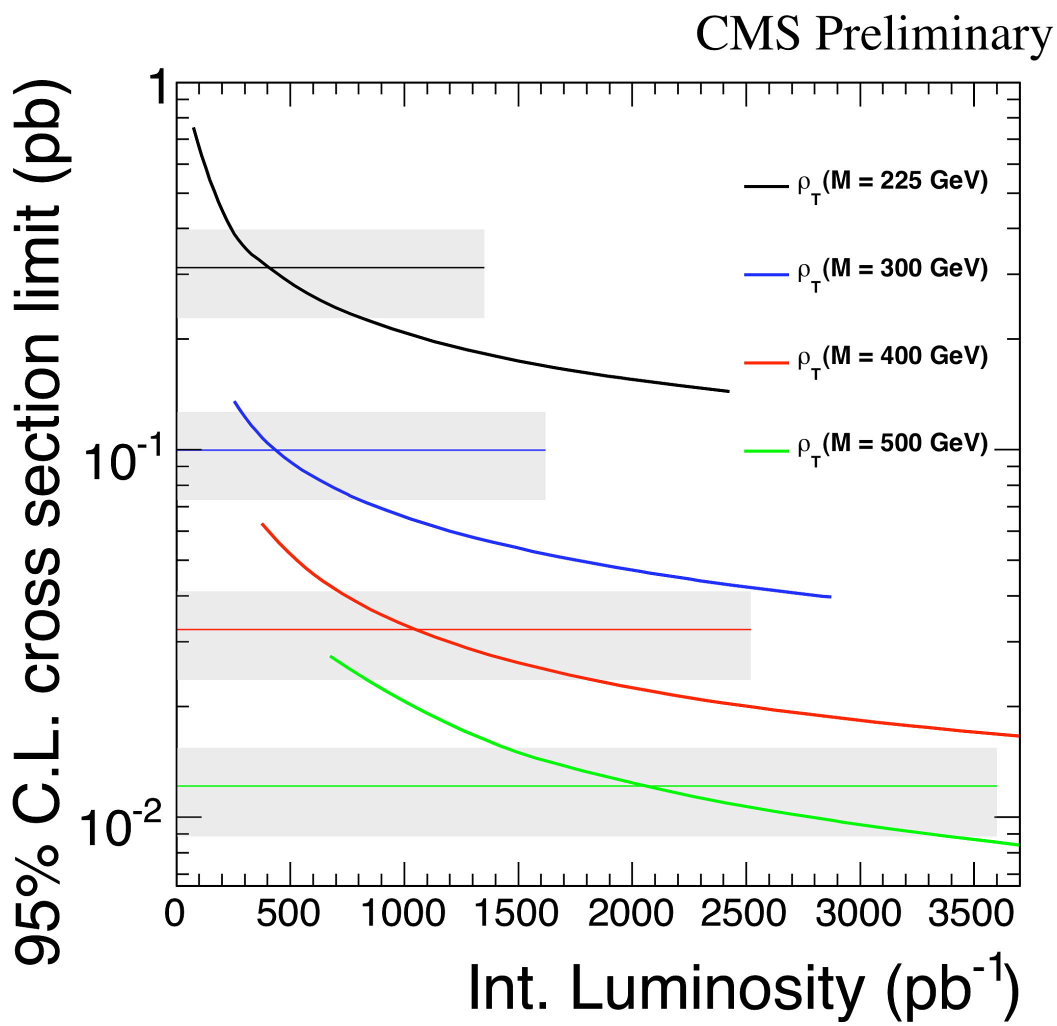
Process	ρ_T (M=225 GeV)	ρ_T (M=300 GeV)	ρ_T (M=400 GeV)	ρ_T (M=500 GeV)
WZ	$1.416 \pm 0.043 \pm 0.502$	$0.699 \pm 0.030 \pm 0.214$	$0.508 \pm 0.026 \pm 0.156$	$0.190 \pm 0.016 \pm 0.058$
ZZ	$0.236 \pm 0.004 \pm 0.084$	$0.079 \pm 0.003 \pm 0.024$	$0.032 \pm 0.002 \pm 0.010$	$0.015 \pm 0.001 \pm 0.005$
Z+jets and VQQ	$2.082 \pm 2.663 \pm 0.506$	$0.384 \pm 1.521 \pm 0.064$	$0.121 \pm 0.479 \pm 0.020$	$0.034 \pm 0.135 \pm 0.006$
$t\bar{t}$ and W+jets	$1.014 \pm 1.016 \pm 0.247$	$0.624 \pm 0.101 \pm 0.104$	$0.390 \pm 0.063 \pm 0.065$	$0.000 \pm 0.000 \pm 0.000$
Total	$4.76 \pm 2.85 \pm 0.76$	$1.79 \pm 1.52 \pm 0.25$	$1.05 \pm 0.48 \pm 0.17$	$0.24 \pm 0.14 \pm 0.06$

Use uncertainties from the data-driven results, central values from MC

Exclusion Limits

95% C.L. upper limit calculated using a Bayesian average and assuming Poisson statistics

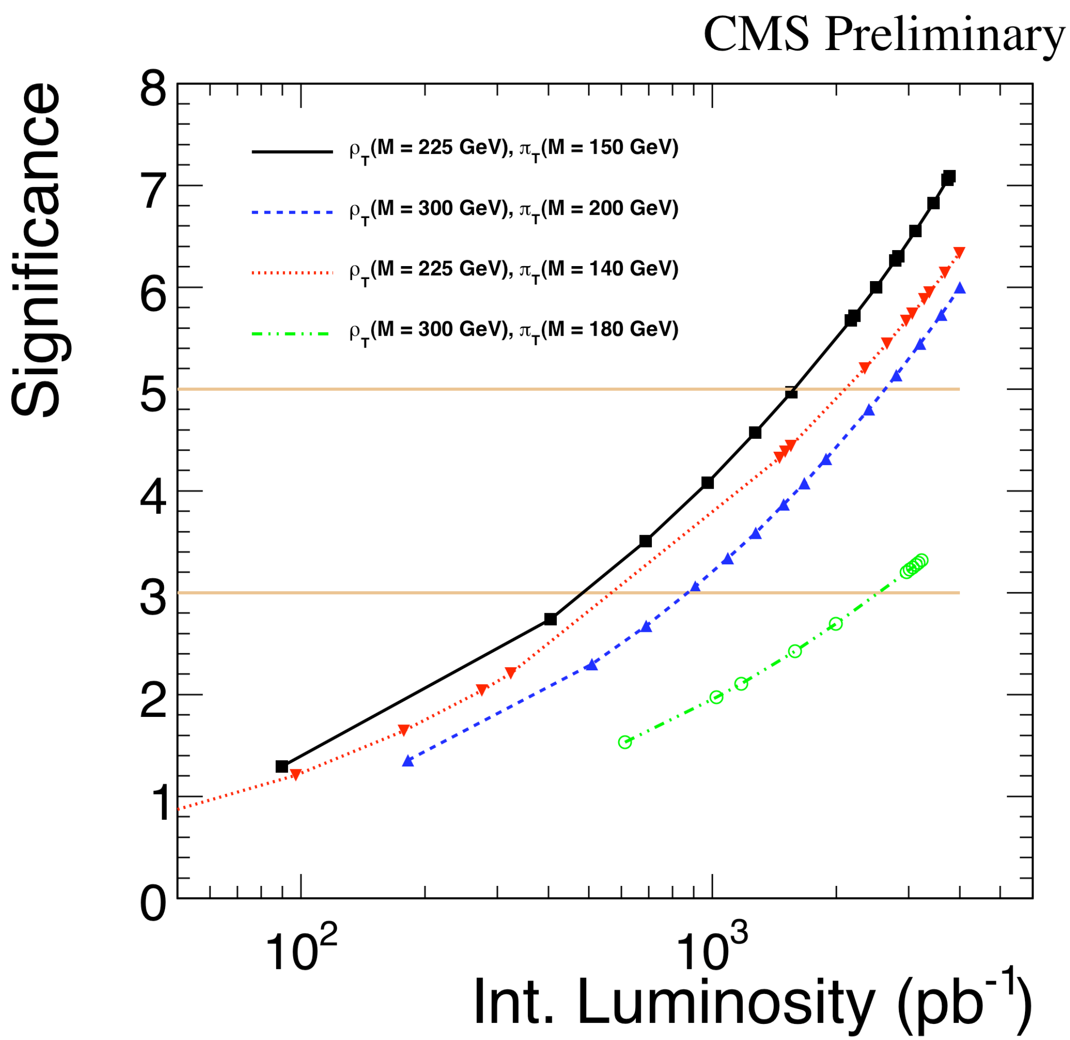
PAS



Discovery Potential

Compute probability of the expected background to fluctuate to or above the observed number of events

PAS



Results

Sample	Int. luminosity for 95% C.L limit [(+,-) theoretical uncertainty] (pb^{-1})	Int. Luminosity for 3σ evidence (pb^{-1})	Int. Luminosity for 5σ observation (pb^{-1})
ρ_T (M=225 GeV)	$400(240, 790)$	500	1600
ρ_T (M=300 GeV)	$440(290, 790)$	890	2660
ρ_T (M=400 GeV)	$1040(710, 1800)$	1600	> 4000
ρ_T (M=500 GeV)	$2050(1450, 3310)$	2500	> 4000
ρ_T (M=225 GeV),π_T (M=140 GeV)	$540(300, 1060)$	760	2150
ρ_T (M=300 GeV),π_T (M=180 GeV)	$1300(800, 2550)$	2640	> 4000

Samples

Process	Generator	Simulation	σ (pb)	Events
ρ_T ($M = 225$ GeV)	PYTHIA	Full	0.232	10 k
ρ_T ($M = 300$ GeV)	PYTHIA	Full	0.074	10 k
ρ_T ($M = 400$ GeV)	PYTHIA	Full	0.024	10 k
ρ_T ($M = 500$ GeV)	PYTHIA	Full	0.009	10 k
$WZ \to \ell\ell\ell\nu$	PYTHIA	Full	0.56	116 k
$ZZ \to \ell\ell\ell\ell$	PYTHIA	Full	0.07	263 k
$t\bar{t}$	PYTHIA	Fast	250.	1 M
VQQ	MADGRAPH	Full	289.	1 M
Z+jets	PYTHIA	Fast	—	—
QCD	PYTHIA	Full	—	—
W+jets	MADGRAPH	Fast	40000.	100 M
W+jets	MADGRAPH	Full	40000.	10 M

Most samples processed with full (GEANT4) detector simulation
FastSim used with some samples to increase statistics.

NLO cross sections/K-factors

PAS

Process	NLO cross section (pb)	K-factor value
ρ_T (M=225 GeV)	–	1.35 ± 0.27
ρ_T (M=300 GeV)	–	1.35 ± 0.27
ρ_T (M=400 GeV)	–	1.35 ± 0.27
ρ_T (M=500 GeV)	–	1.35 ± 0.27
WZ	0.750 ± 0.050	–
ZZ	0.110 ± 0.022	–
$t\bar{t}$	390 ± 20	–
VQQ	–	2.25 ± 0.5
Z + jets	5250 ± 150	–
W + jets	45000 ± 9000	–

Electron Identification

Electron Identification

Electron ID developed separately for:

1)“loose” sample (electrons from Z)

2) “tight” sample (electrons from W)

Optimization done to achieve highest possible efficiency for electrons with a small mis-identification rate

- Optimize loose criteria first
- Sequentially optimize criteria by choosing threshold values such that the signal efficiency exceeds 98%
  - aim for an overall efficiency > 90%
- Change order of the chosen criteria to assess correlation between criteria
- Retain variables that are as less correlated as possible
- Optimize separately for barrel and endcap

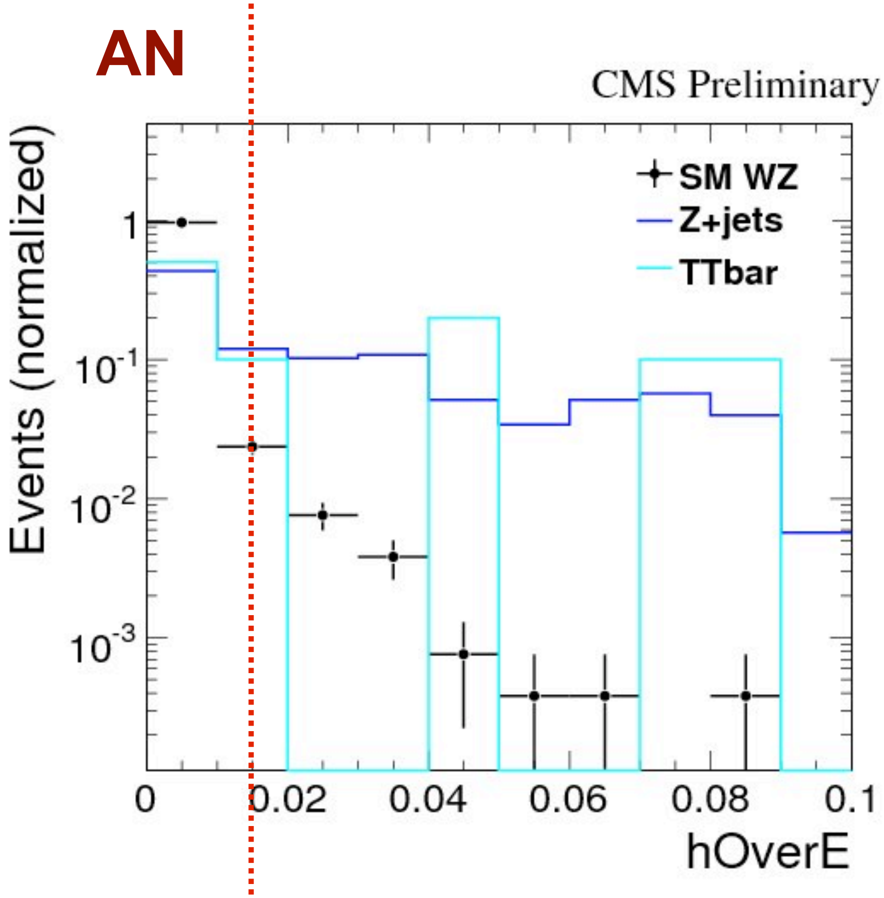
Electron Identification

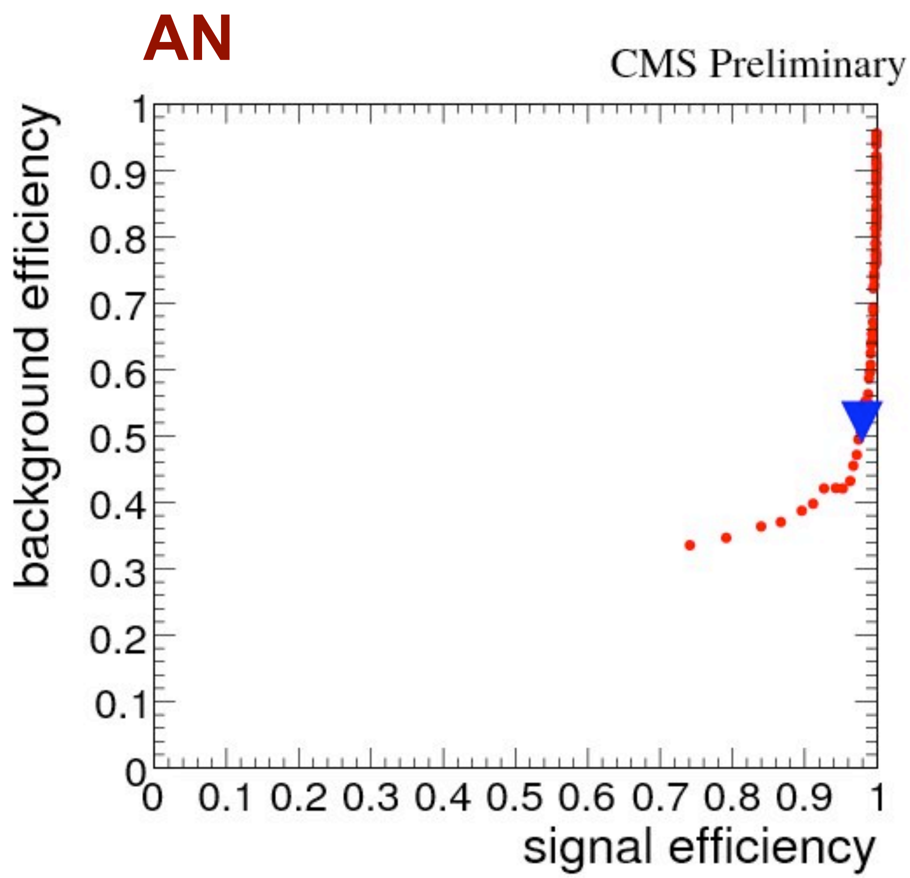
Electron ID developed separately for:
1)a "loose" sample (electrons from Z)
2)A "tight" sample (electrons from W)

Optimization done to achieve highest possible efficiency for electrons with a small mis-id rate

- Track-ECAL matching described in the azimuthal and pseudorapidity planes and denoted as $\Delta\phi$ and $\Delta\eta$, respectively.
- The η-width of the seed ECAL energy cluster denoted as $\sigma_{\eta\eta}$.
- The ratio of the ECAL shower energy to the momentum of the track at vertex, denoted as E/p.
- The ratio of the closest HCAL reconstructed hit to the ECAL energy, H/E.

ID Optimization





Choose threshold such that signal efficiency > 98%

Barrel and endcap optimized separately

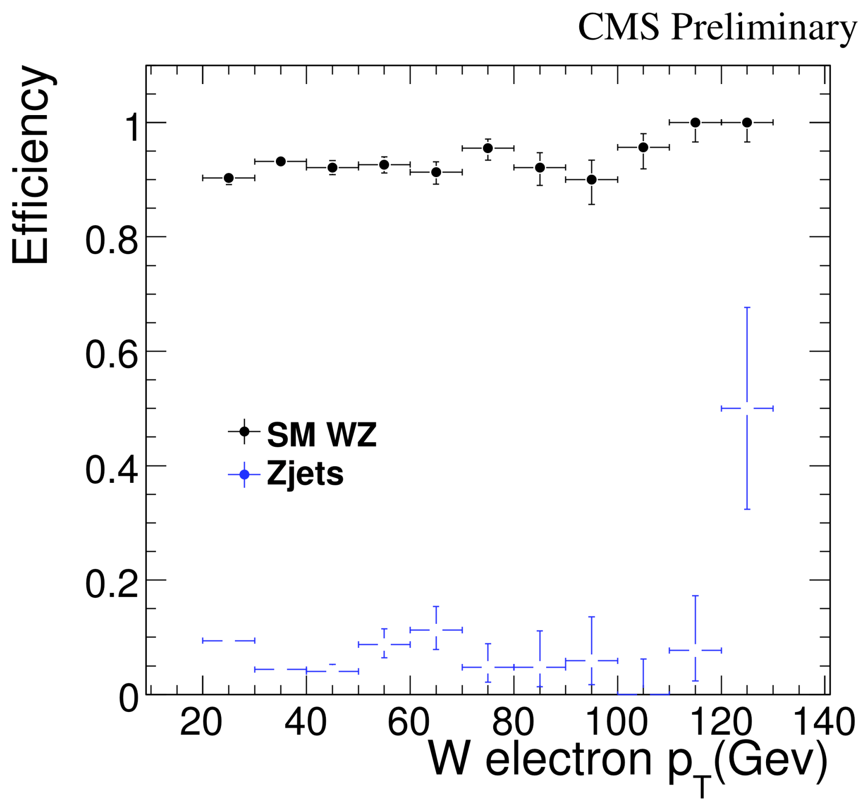
Electron Selection

PAS

Criteria	Barrel threshold	Endcap threshold
p_T (Z electron)	> 15 GeV	> 15 GeV
$\lvert\Delta\eta\rvert$	< 0.005	< 0.007
$\lvert\Delta\phi\rvert$	< 0.040	< 0.040
$\sigma_{\eta\eta}$	< 0.011	—
E/p	> 0.76	> 0.68
H/E	< 0.016	< 0.025
p_T (W electron)	> 20 GeV	> 20 GeV
Relative calorimeter isolation	< 0.1	< 0.16
Relative track isolation	< 0.1	< 0.1

ID Efficiency (loose)

PAS

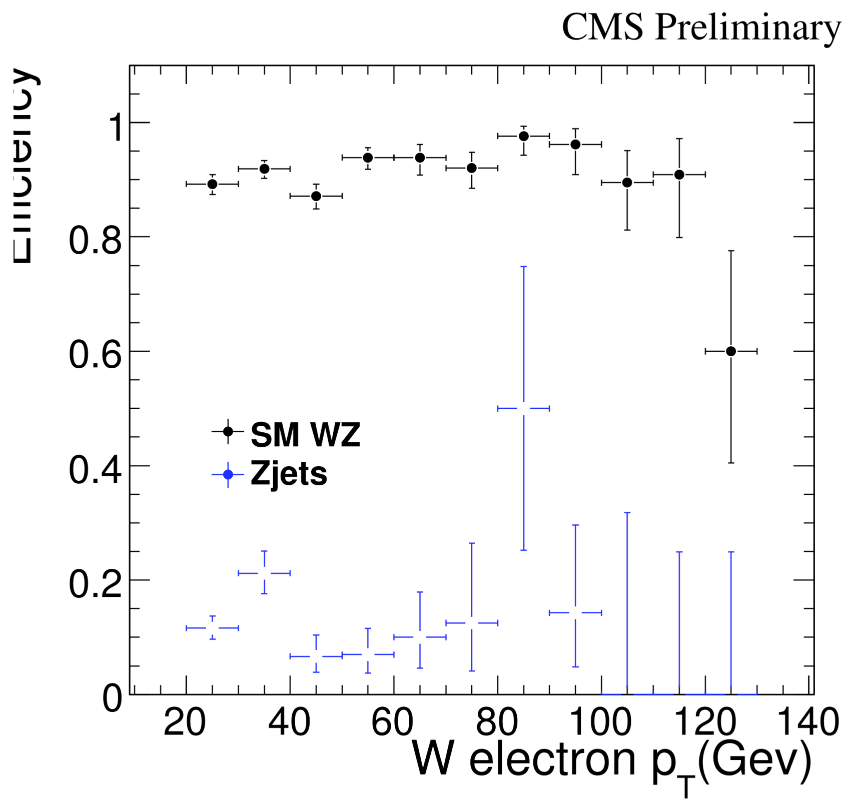


Barrel

Signal efficiency: 0.904 +- 0.006

Mis-id rate: 0.038+-0.004

PAS

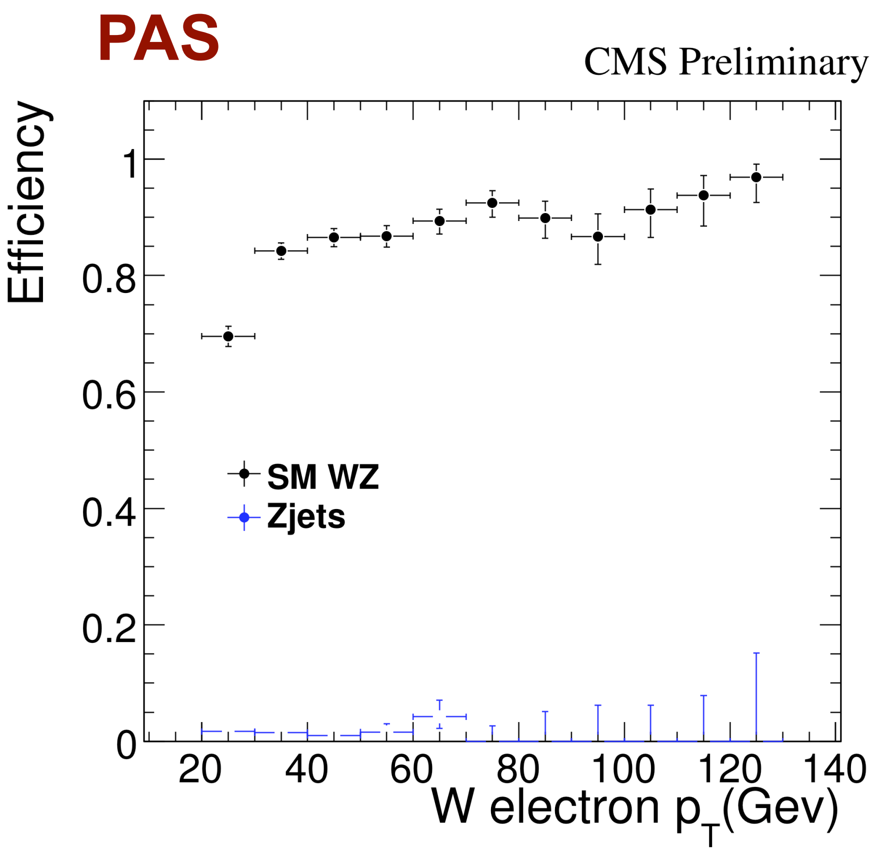


Endcap

Signal efficiency: 0.908 +- 0.008

Mis-id rate: 0.128+-0.015

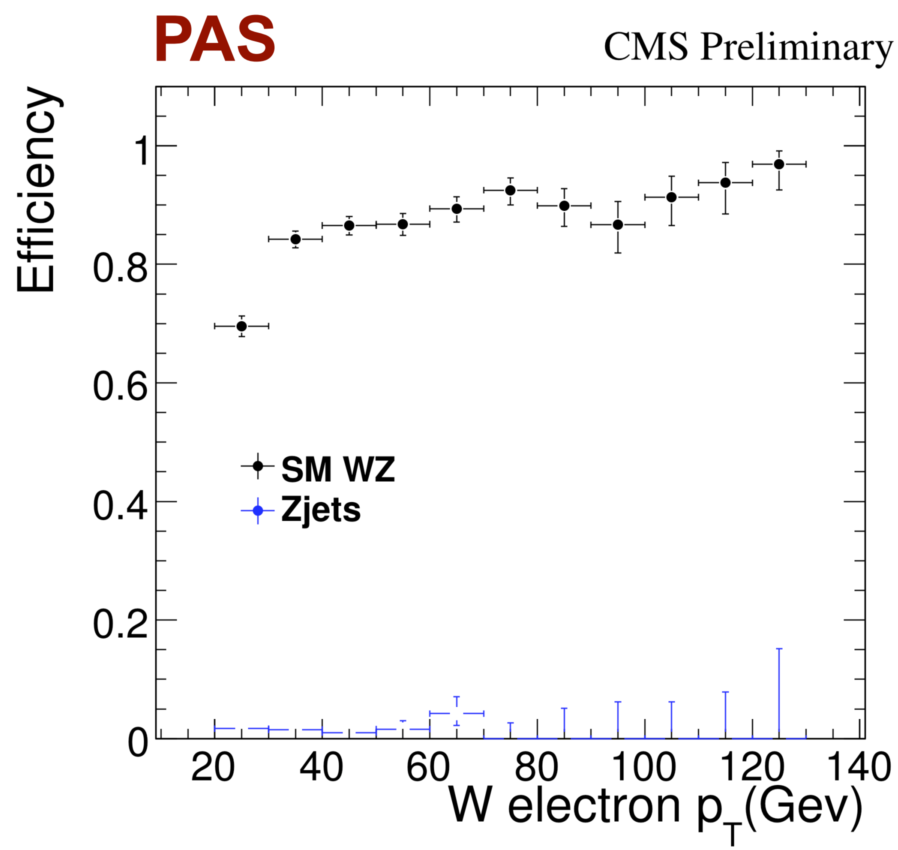
ID Efficiency (tight)



Barrel

Signal efficiency: 0.815 +- 0.073

Mis-id rate: 0.009+-0.001



Endcap

Signal efficiency: 0.85 +- 0.01

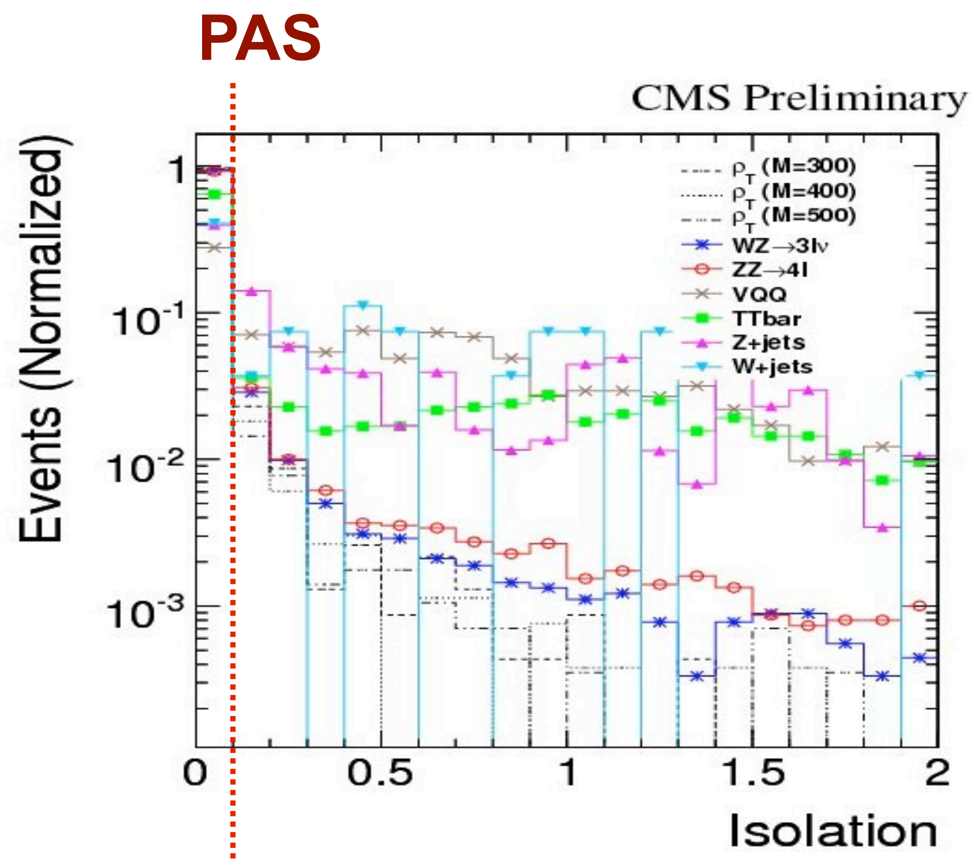
Mis-id rate: 0.068+-0.011

Combined Relative Isolation

Sum of ECAL + Tracker scaled by p_T of muon
No HCAL

Cut at 0.1

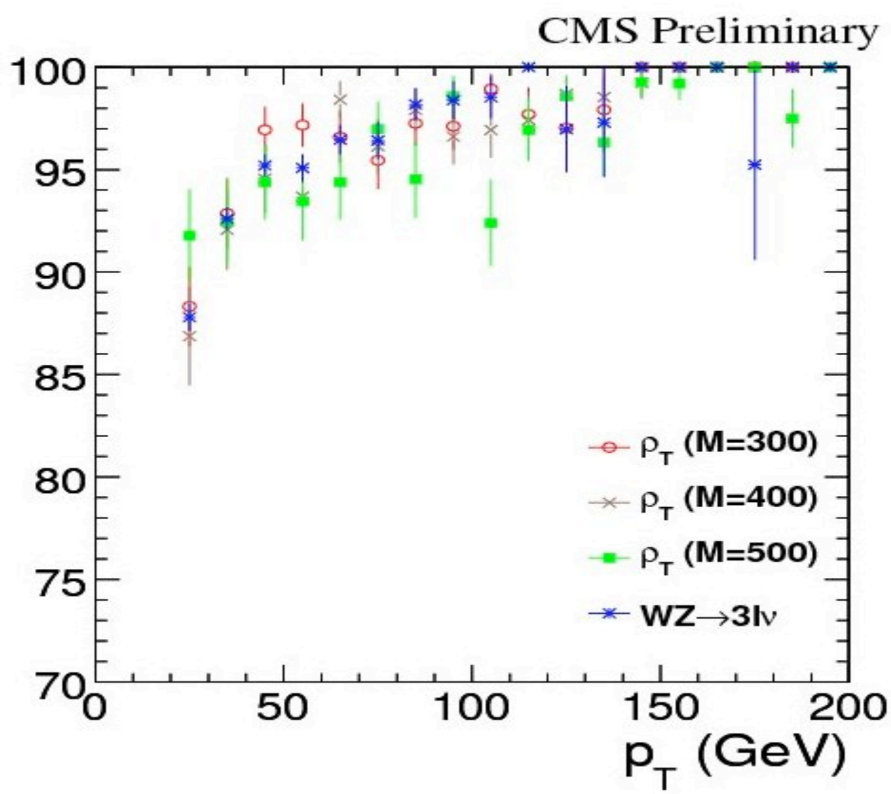
No improvement after this when using HCAL based isolation



Muon Selection Efficiency

PAS

Overall efficiency



Overall fake rate