New Boson High Mass States at the LHC

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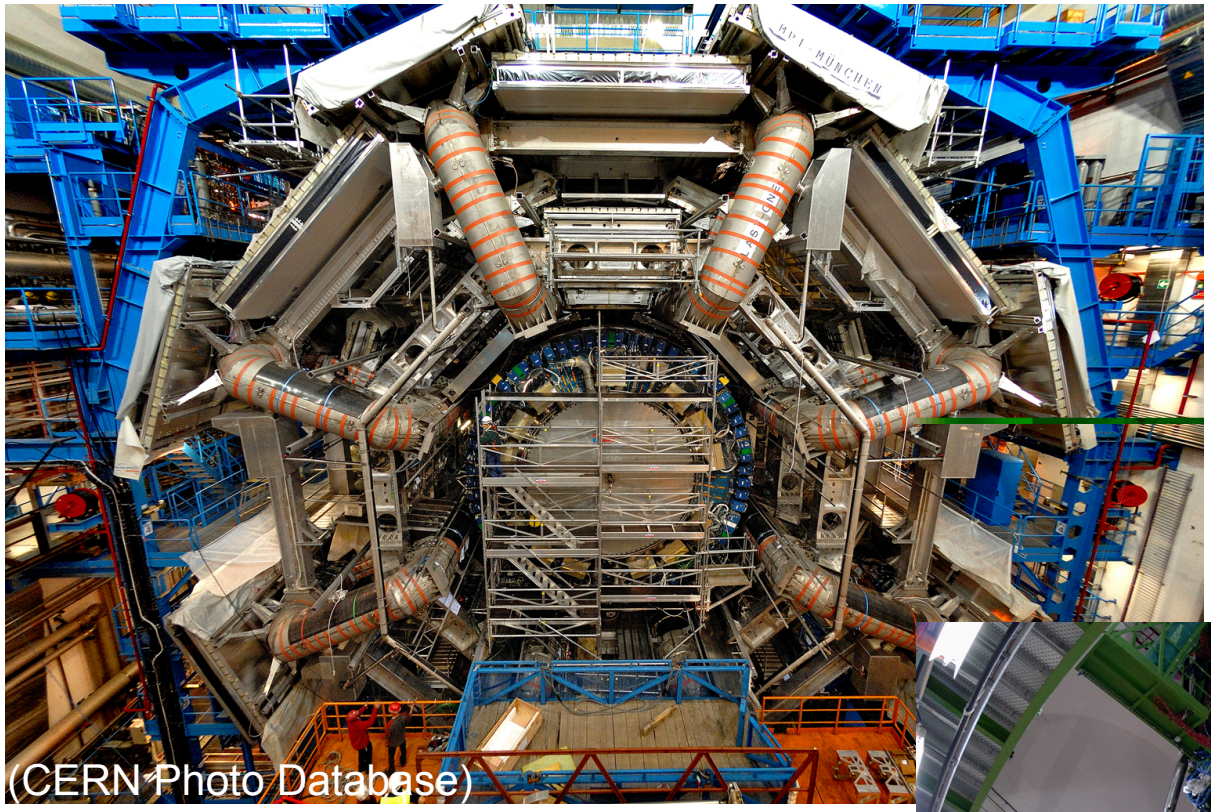
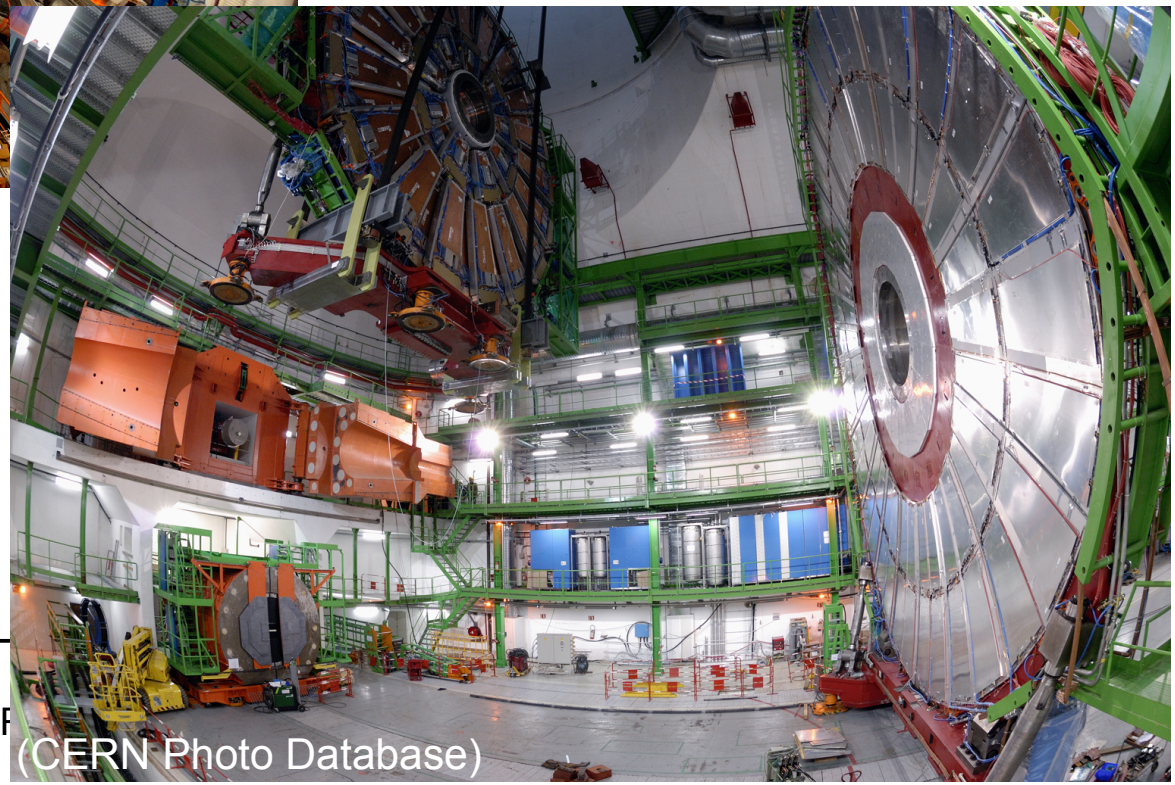
„Big Things“ appear at the LHC ...

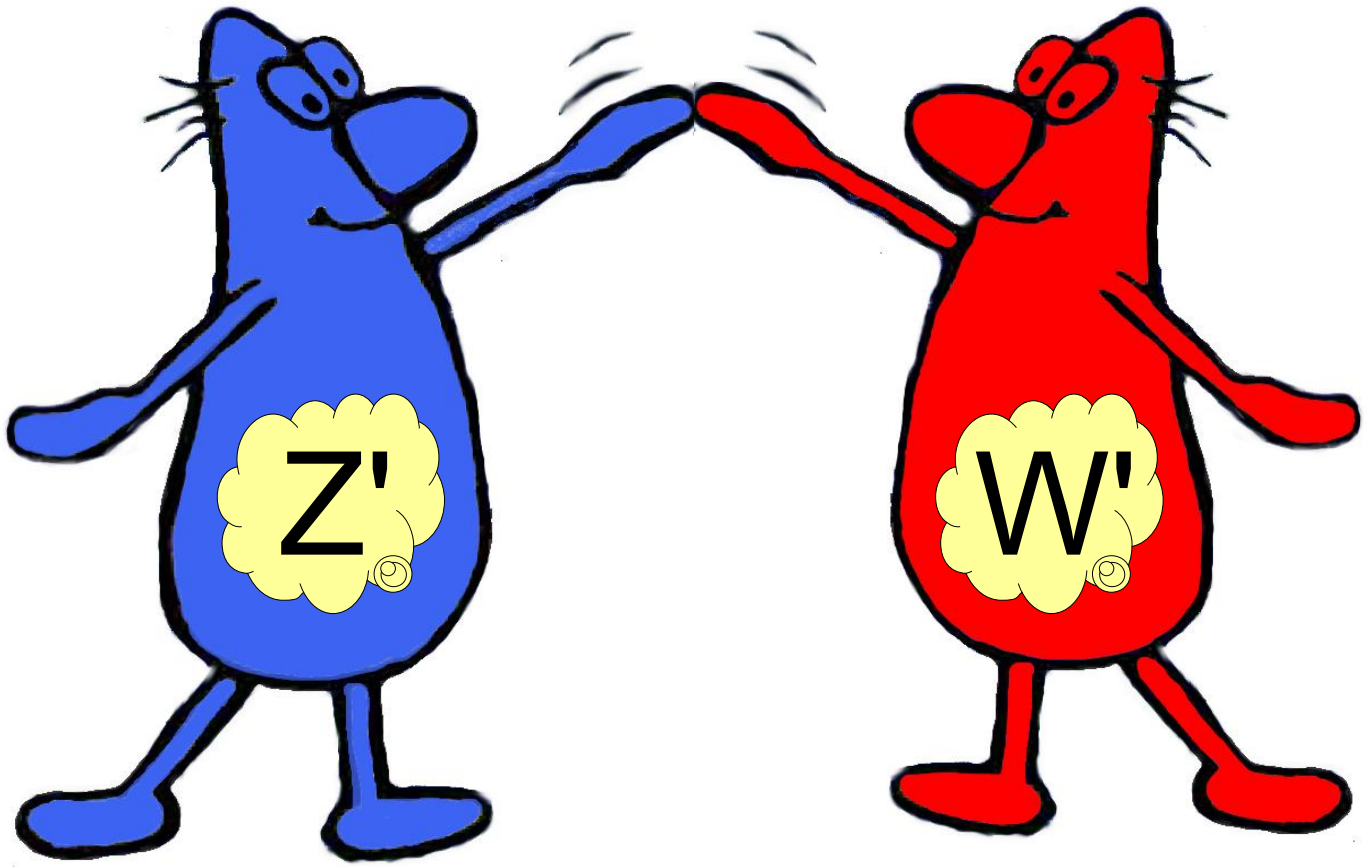


Installation of the ATLAS detector

Lowering one of the CMS Endcaps



Small „Big Things“ we hope to appear ...



New Heavy Gauge Bosons

Outline

- W'/Z' theory in a nutshell
- How to find W'/Z'
- ATLAS & CMS
- Expected discovery reach
- Systematic studies
- Alignment
- The inverse LHC problem
- Summary

Z'/W' – What's that?!?

Definition:

- Generically: all massive bosons outside the Standard Model are
  - W' if they are electrically charged
  - Z' if they are electrically neutral

W'/Z' – Who ordered that?

- Models enlarging the SM gauge groups
  - Models embedding the SM gauge group
  - SO(10), SU(5), E_6
  - Left-Right-Symmetric models
- Theories with Extra Dimensions
- Little Higgs models
- Superstring inspired models

BUT most theoretical models have no prediction of the W'/Z' mass!

Why are we looking for them?

Motivation

- Prominent & clean signatures (in invariant mass spectra)
- Theory & detector benchmark channels
- „Second day physics“ („first day“: understand SM background)

I will focus on

- Leptonic decay channels (Pythia) = **discovery channels**
  - $W' \rightarrow e\nu / \mu\nu$ $\quad Z' \rightarrow ee / \mu\mu$
- Latest results from ATLAS and CMS (Physics TDR)
  - Events simulated in full/fast detector simulation
  - $\mathcal{L} = 2 \cdot 10^{33}\ cm^{-2}\ s^{-1}$ (low LHC luminosity)
  - 3.5 - 5 pile-up events per bunch crossing (every 25 ns)
  - 10 fb^{-1} per year expected (per experiment)

(See references for further investigated W' / Z' channels)

Investigated W' Models

Sequential Standard Model:

- W' as carbon copy of Standard Model W with different mass (= parameter)
- Coupling constants like SM ones
- No coupling to Standard Model W/Z
- BR(W' → μν) ≈ 10 %
- „Standard Candle“

(Pythia LO, 10 fb^{-1})

process	# events
W'(0.8 TeV) → μ ν	77000
W'(1 TeV) → μ ν	31100
W'(2 TeV) → μ ν	1600
W'(5 TeV) → μ ν	6
W → μ ν	171.000.000

Littlest Higgs Model:

[Arkani-Hamed et al, JHEP 207(2002)34]

- Minimal SM extension for solution of Hierarchy Problem
- Introduces 4 new bosons: W_H, Z_H, A_H (also new quark T and Higgses)
- Masses strongly constrained due to fine-tuning:

$$M_{W_H} < 6\ \mathrm{TeV}\left(\frac{m_h}{200\ \mathrm{GeV}}\right)^2$$

W_H, Z_h mass degenerated

- Couplings depend on single parameter θ
- Cross section similar to SSM W'

Investigated Z' Models

- Z'_{SSM} (Sequential Standard Model), Z' carbon copy of SM Z
- Z'_{LRM} Z'_{ALRM} (Left-Right-Symmetric models)
  - Z'/W' from additional $SU(2)_R$
- Z'_{χ} Z'_{ψ} Z'_{η} (E_6 and/or SO(10) models) from additional U(1)

Recipe:

- Use Pythia's Z'_{SSM} and modify couplings
- Full γ /Z/Z' interference included

Cross section rapidly decreasing with Z' mass

Model	Γ/M %	$Z' \to \mu^+\mu^-$ BR in %	$\sigma^{LO} \cdot$ Br, full interference, fb (PYTHIA)		
			1 TeV/c^2	3 TeV/c^2	5 TeV/c^2
Z_{SSM}	3.1	3.0	610	2.8	0.050
Z_{ψ}	0.6	4.0	340	1.7	0.032
Z_{η}	0.7	3.4	370	1.8	0.035
Z_{χ}	1.3	5.7	500	2.2	0.038
Z_{LRM}	2.2	2.3	500	2.3	0.040
Z_{ALRM}	1.6	8.6	740	3.7	0.077

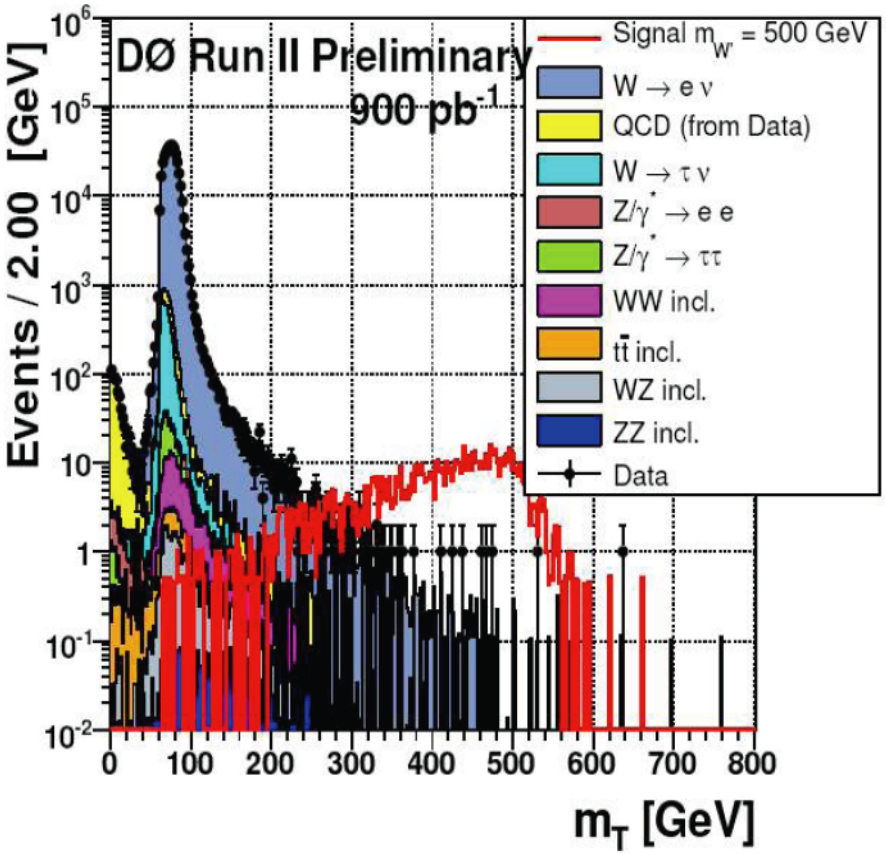
QCD corrections:
$K_{NNLO} = 1.35$

W'/Z' Hunters Guide

Principle of Z'/W'→ $\ell\ell$ / $\ell\nu$ search @ colliders:

- Reconstruct lepton(s)
  - High energy
  - Isolated
  - Opposite sign possible (Z')
- Get missing transverse energy MET (W')
- Calculate (transverse) invariant mass

➡ Clear signal
(Breit-Wigner (Z') or Jacobian (W'))

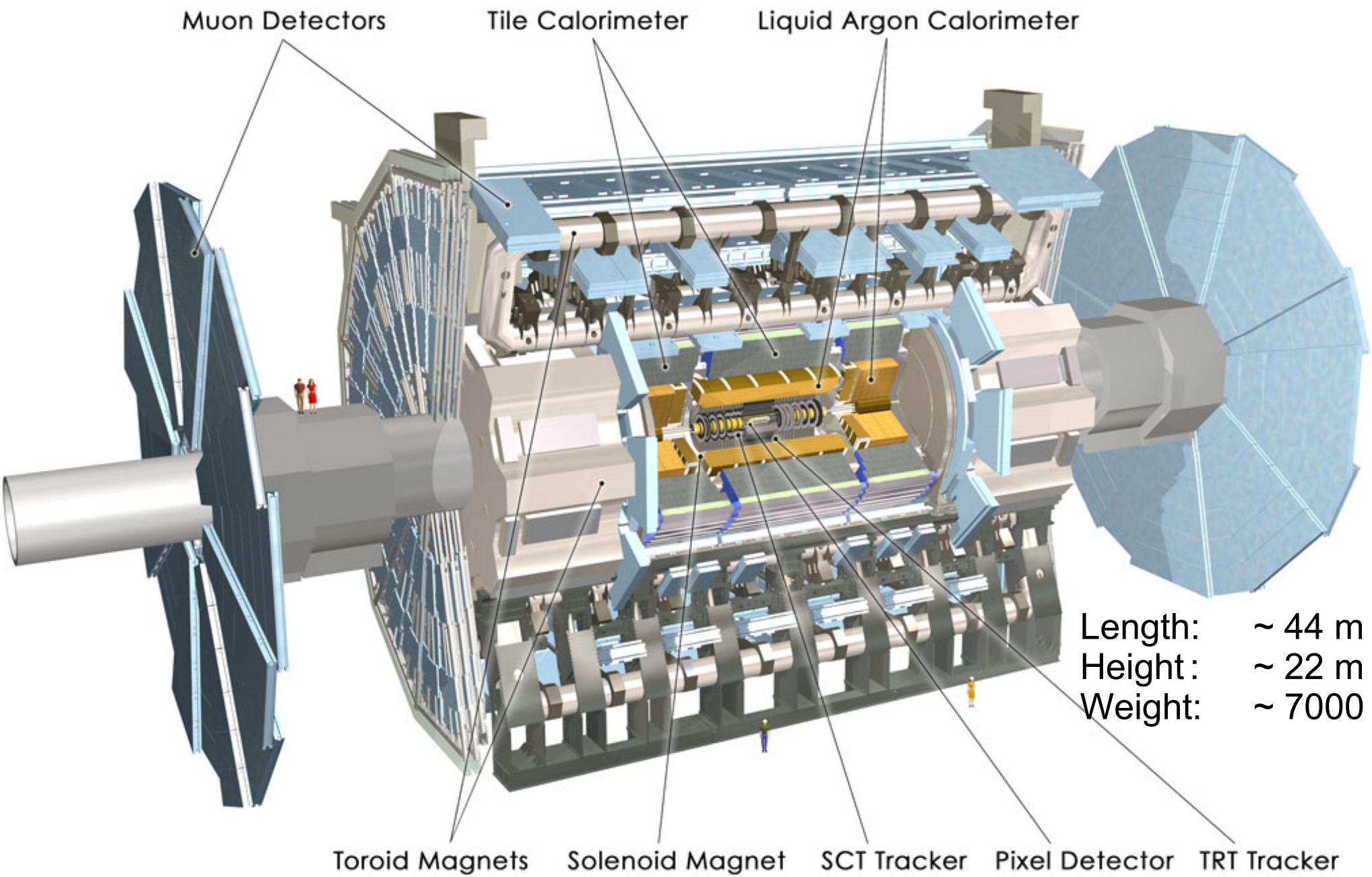


Recent Limits from Tevatron Run II:

- Approaching $M_{W'/Z'}$ = 1 TeV

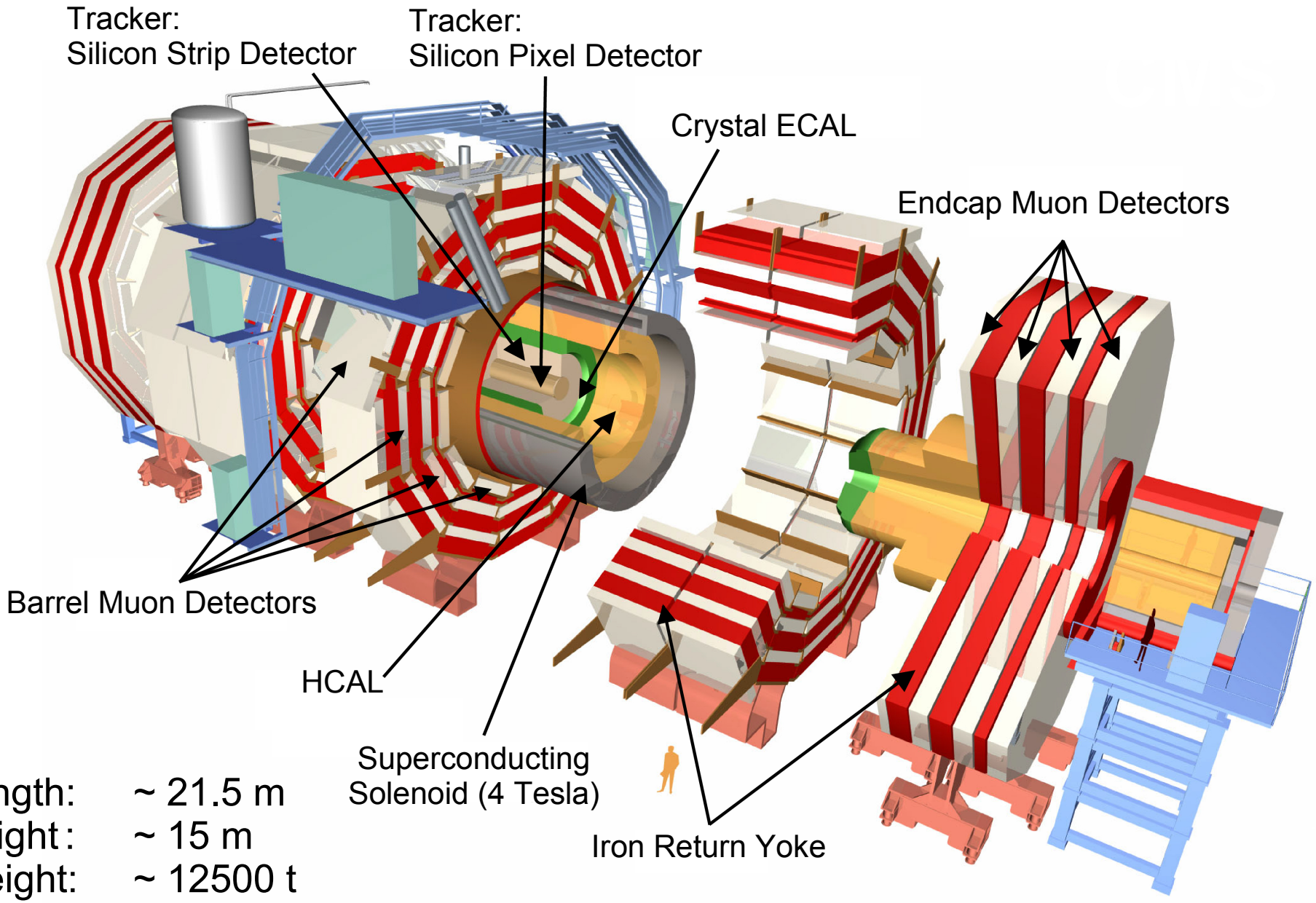
$M(W'_{SSM})$ > 965 GeV	(W' → eν, D0, preliminary)
$M(Z'_{SSM})$ > 850 GeV	(Z' → ee, CDF, preliminary)

The ATLAS Detector



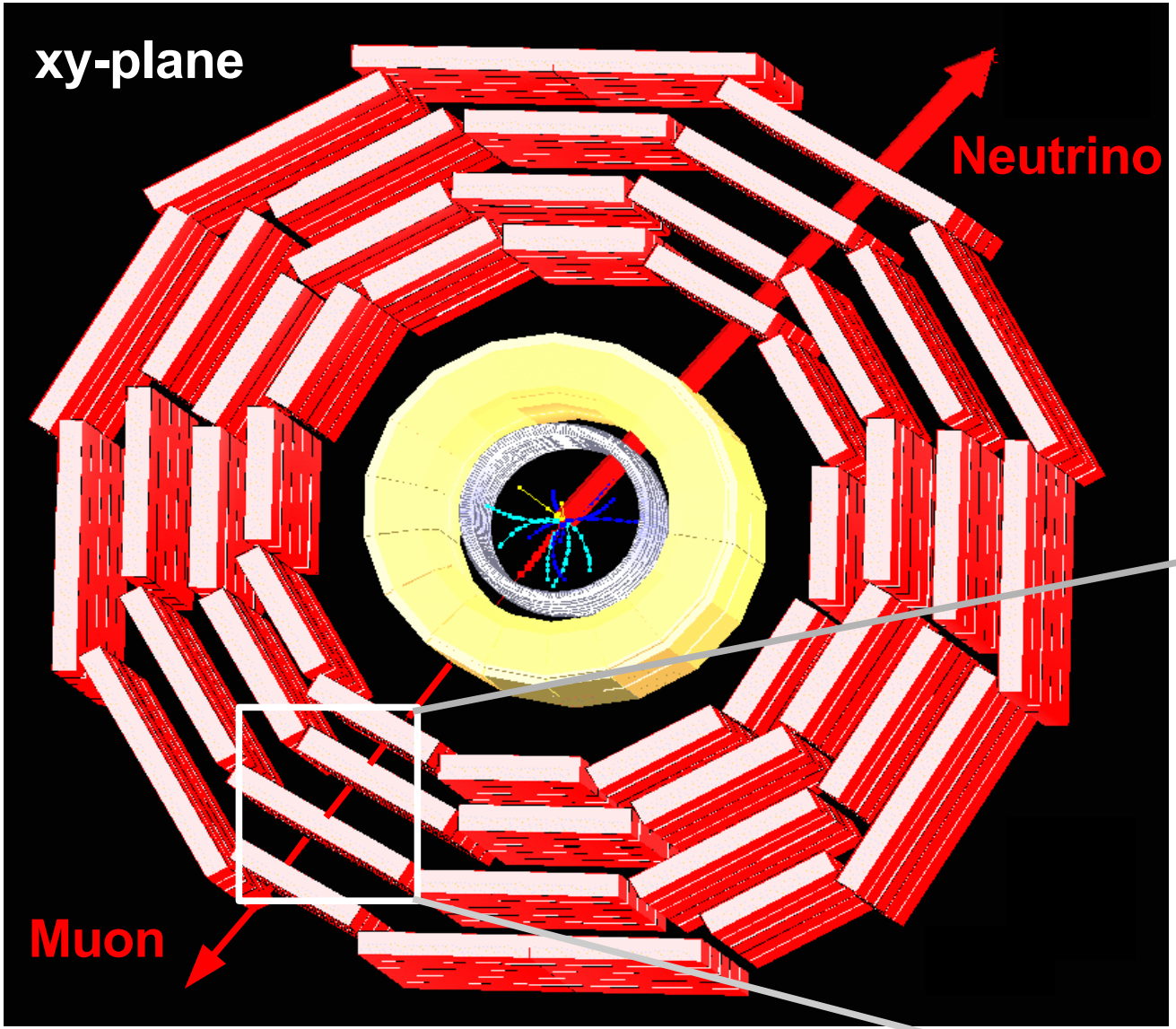
Length: ~ 44 m
Height: ~ 22 m
Weight: ~ 7000 t

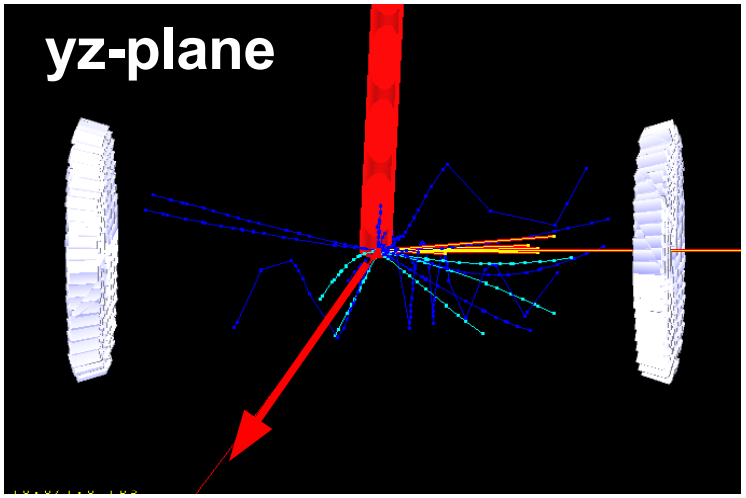
The CMS Detector

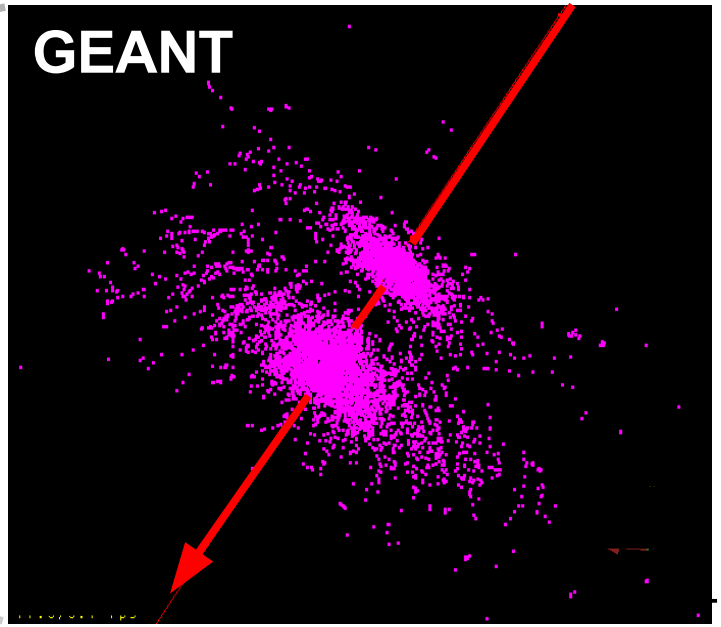


Length: ~ 21.5 m
Height: ~ 15 m
Weight: ~ 12500 t

What does a W' Event look like?







IGUANA

The CMS Event Display

Event Selection

$W' \rightarrow \ell\nu$

- Single offline lepton events
  - Isolated
- Require lepton fit quality
- Calculate MET
  - Using ECAL + HCAL deposits
  - Corrected by muon p_T
- Overall efficiency: ~90% (e,μ) (acceptance, single-ℓ trigger, selection)

$Z' \rightarrow \ell\ell$

- ≥ 2 offline leptons (good quality)
  - Opposite sign charge
  - Isolated
  - Back-to-back cut possible
- Special TeV muon reconstruction
  - Collect photons to recover μ−energy
- Overall eff. ~80% (μ), 50-80% (e) (accept., single/di-ℓ trigger, selection)

➡ Calculate (transverse) invariant mass

TeV-Electrons:

+ Energy/p_T resolution
- Identification
- Charge determination

TeV-Muons:

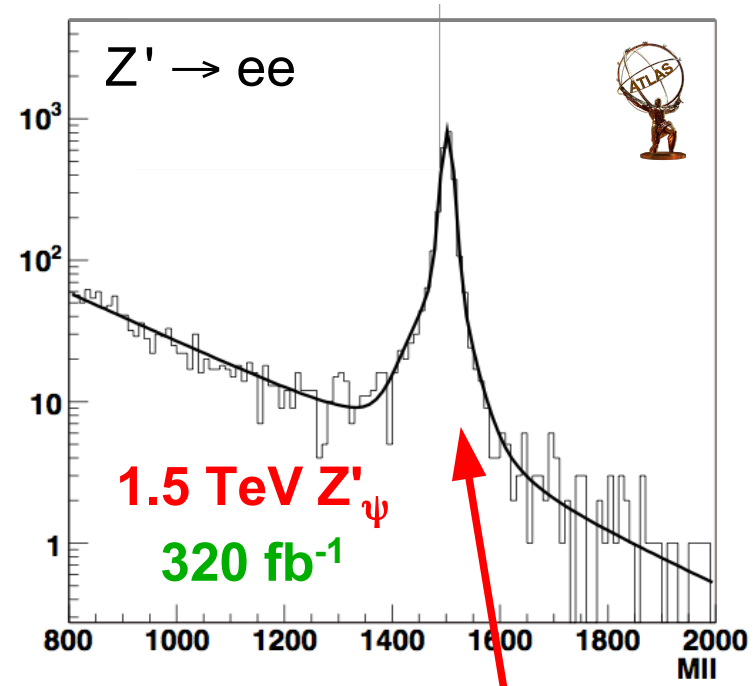
+ Identification
+ Charge determination
- p_T resolution (Bremsstrahlung)

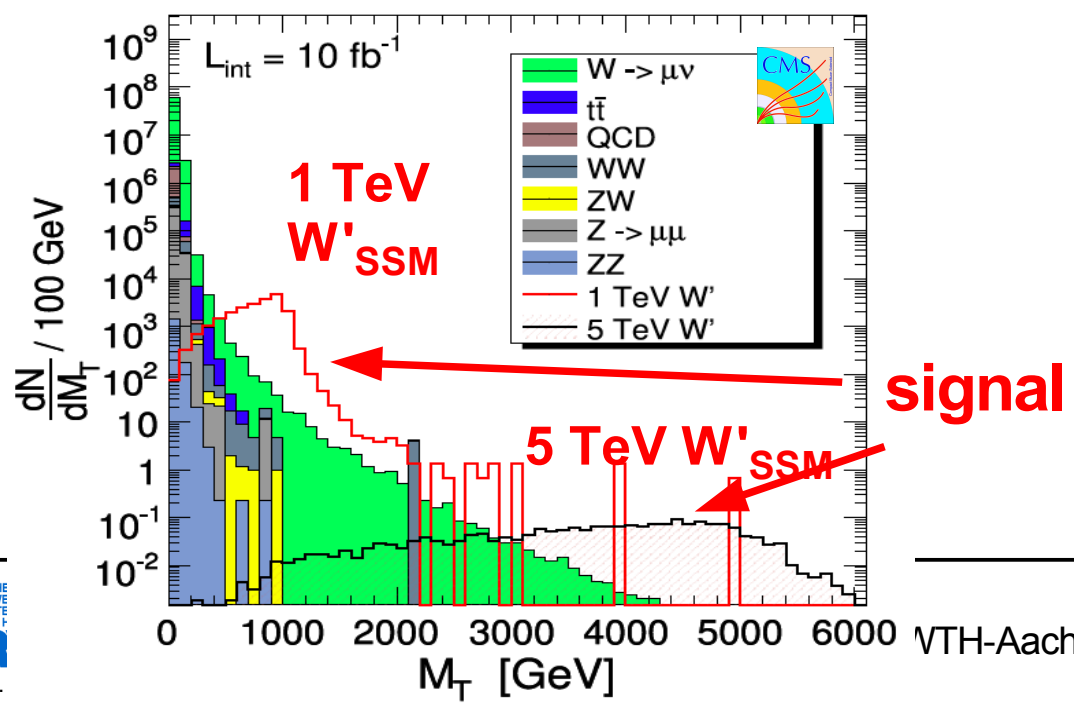
W'/Z' Backgrounds

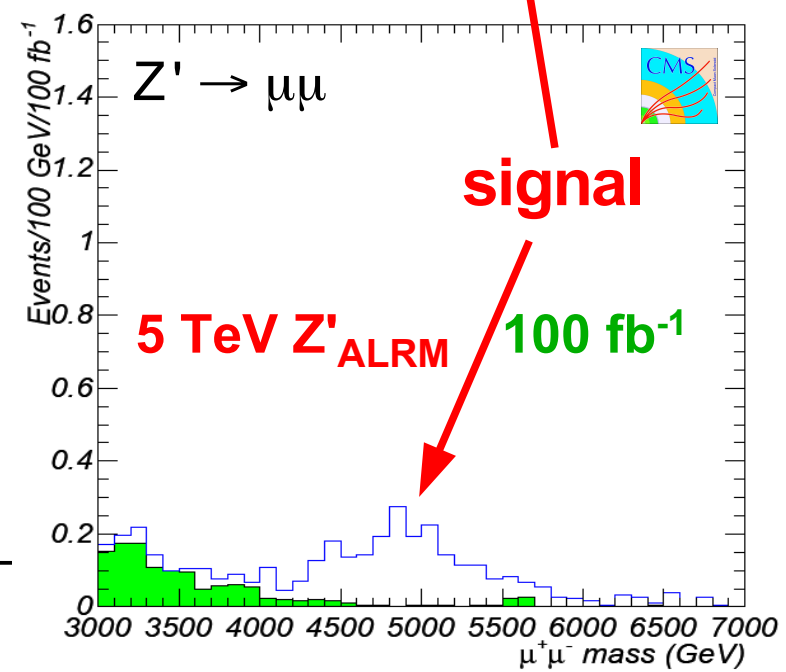
- Main & irreducible background
  - $W \rightarrow \ell\nu$, Drell-Yan respectively
- Further investigated backgrounds
  - QCD-jets, top pair production
  - Di-boson production (WW, WZ, ZZ)
  - Drell-Yan (for W')

Result:

- W/Z cross section large **BUT**
- Small contribution in W'/Z' signal region!







W' Discovery Potential

Method:

- CL_S method (used in LEP Higgs searches)
- Binned likelihood based on:

$$Q_i(m_{W'}) = \frac{P(\mu = s_i(m_{W'}) + b_i;\ n_i)}{P(\mu = b_i;\ n_i)}$$

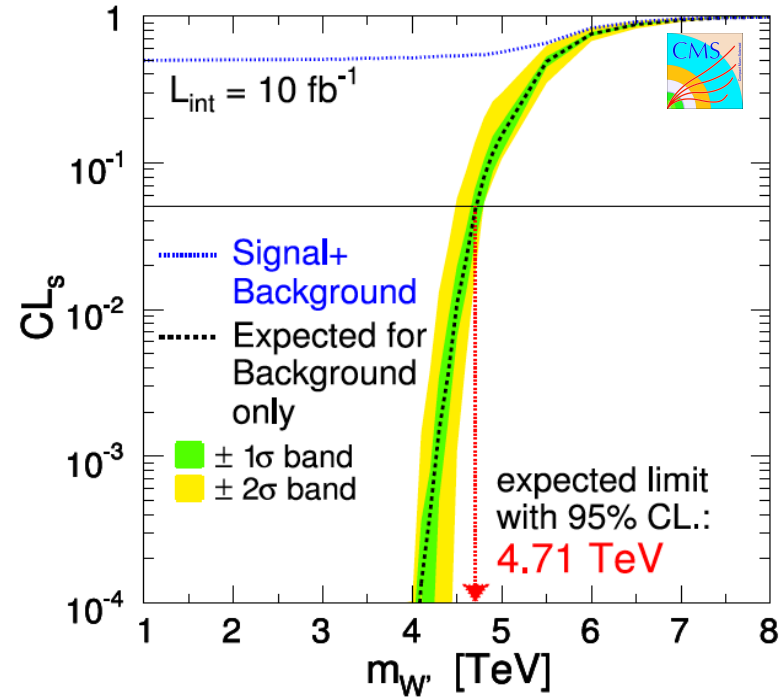
- Discovery (5σ) defined as:

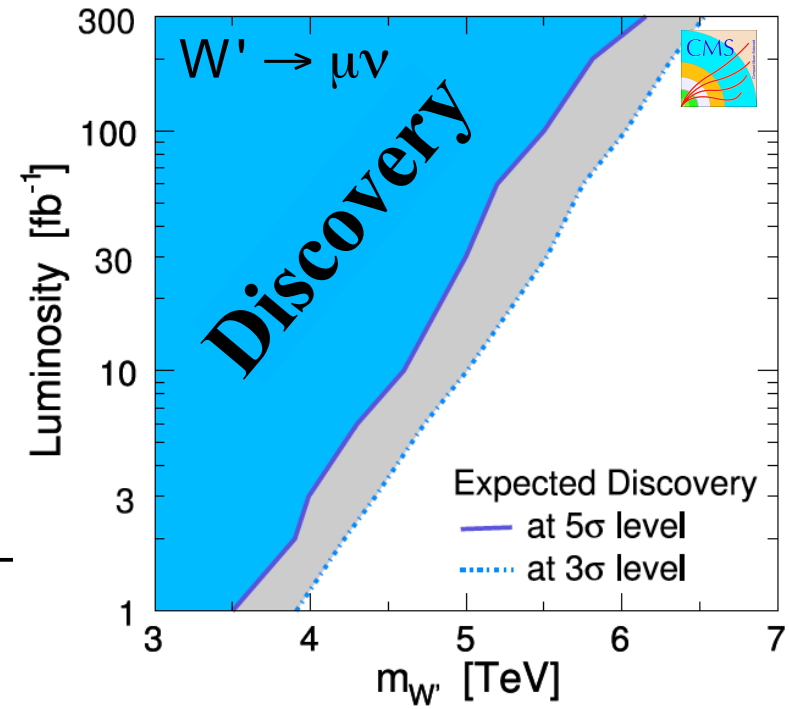
$$1 - \mathrm{CL_b} < 2.85 \cdot 10^7$$

- Exclusion limit (95% CL) defined as:

$$\mathrm{CL_s} < 0.05 \qquad \text{with} \qquad \mathrm{CL_s} = \frac{\mathrm{CL_{s+b}}}{\mathrm{CL_b}}$$

- Neglect bins with less than 5% signal





W' discovery reach:

$M(W'_{SSM}) > 4.6$ TeV (for 10 fb^{-1})

Littlest Higgs Discovery

Method:

- Fast detector simulation
- Significance estimator

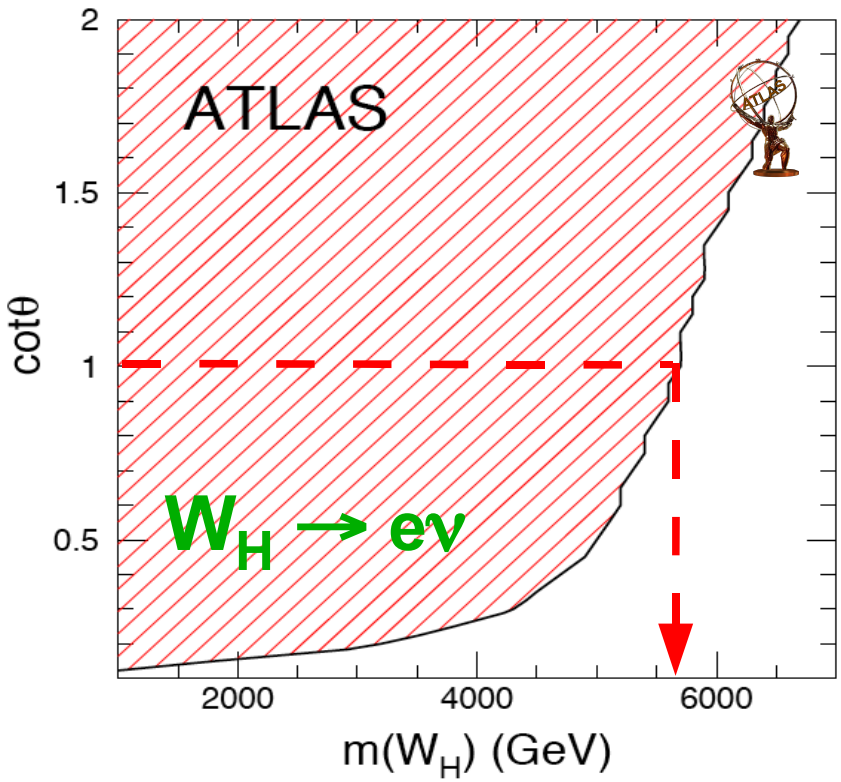
$$S_{c1} = \frac{N_s}{\sqrt{N_b}}$$

- Discovery: $S > 5$ and $N_S > 10$

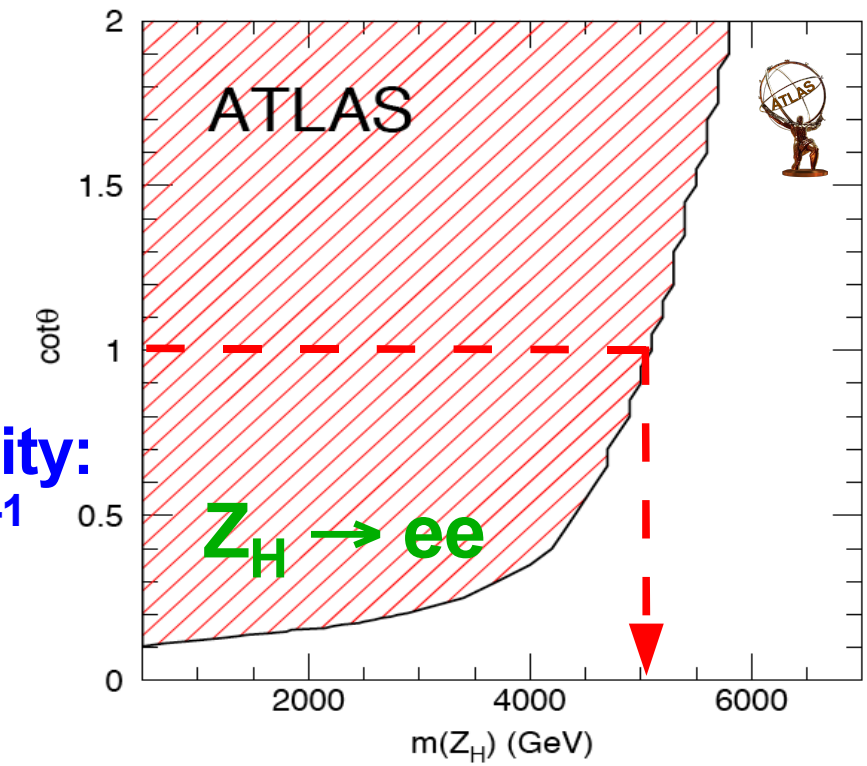
W' / Z' Discovery (cot θ = 1):

$M(W_H) > 5.7$ TeV
$M(Z_H) > 5.1$ TeV

(WH → tb also possible, Z → tt,bb tough)



Luminosity: 300 fb^{-1}



Z' Discovery

Method (unbinned likelihood):

- Fit function based on signal/bkg shape
  - Signal: Breit-Wigner × (Gaussian/exp.)
  - Bkg: exponential derived from MC

➡ Insensitive to normalization uncertainty!

- Input to significance estimator

$$S_{\mathcal{L}} = \sqrt{2\ln\left(\mathcal{L}_{s+b}/\mathcal{L}_b\right)} \qquad \text{(CMS)}$$

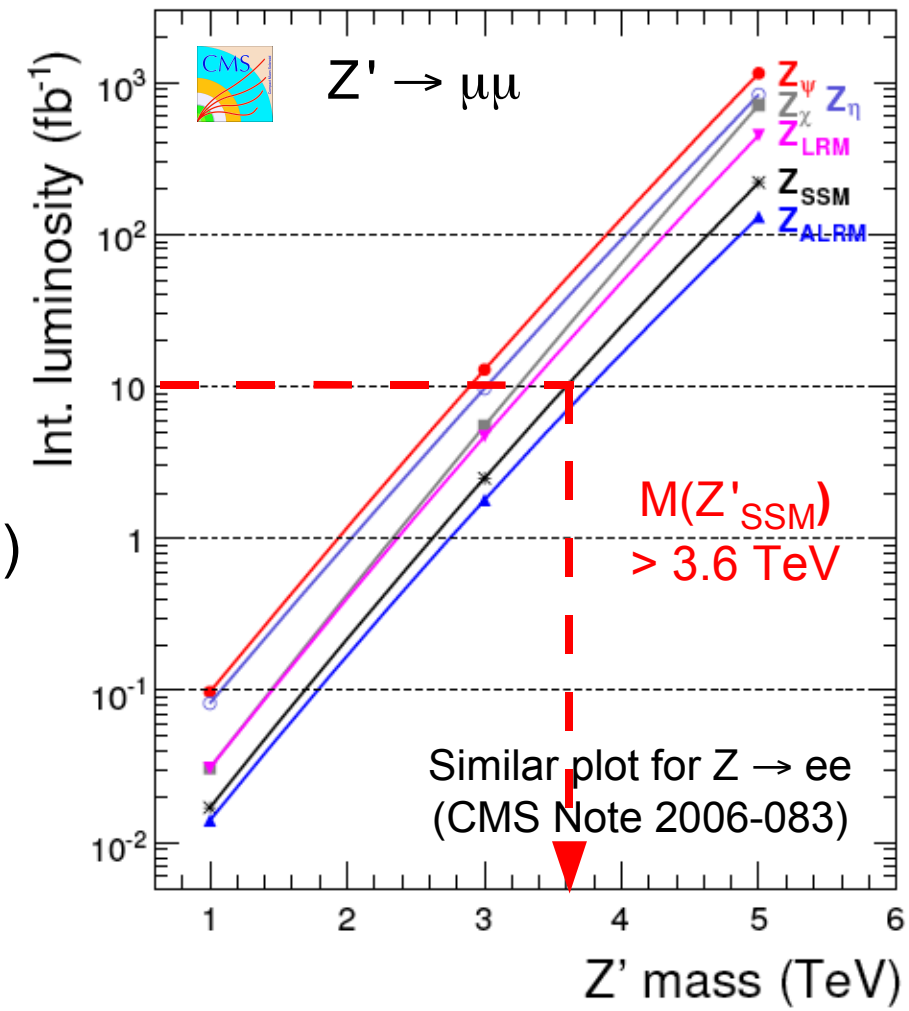
$$S_{c12} = 2 * \left(\sqrt{N_s + N_b} - \sqrt{N_b}\right) \qquad \text{(ATLAS)}$$

- Discovery defined as: S > 5

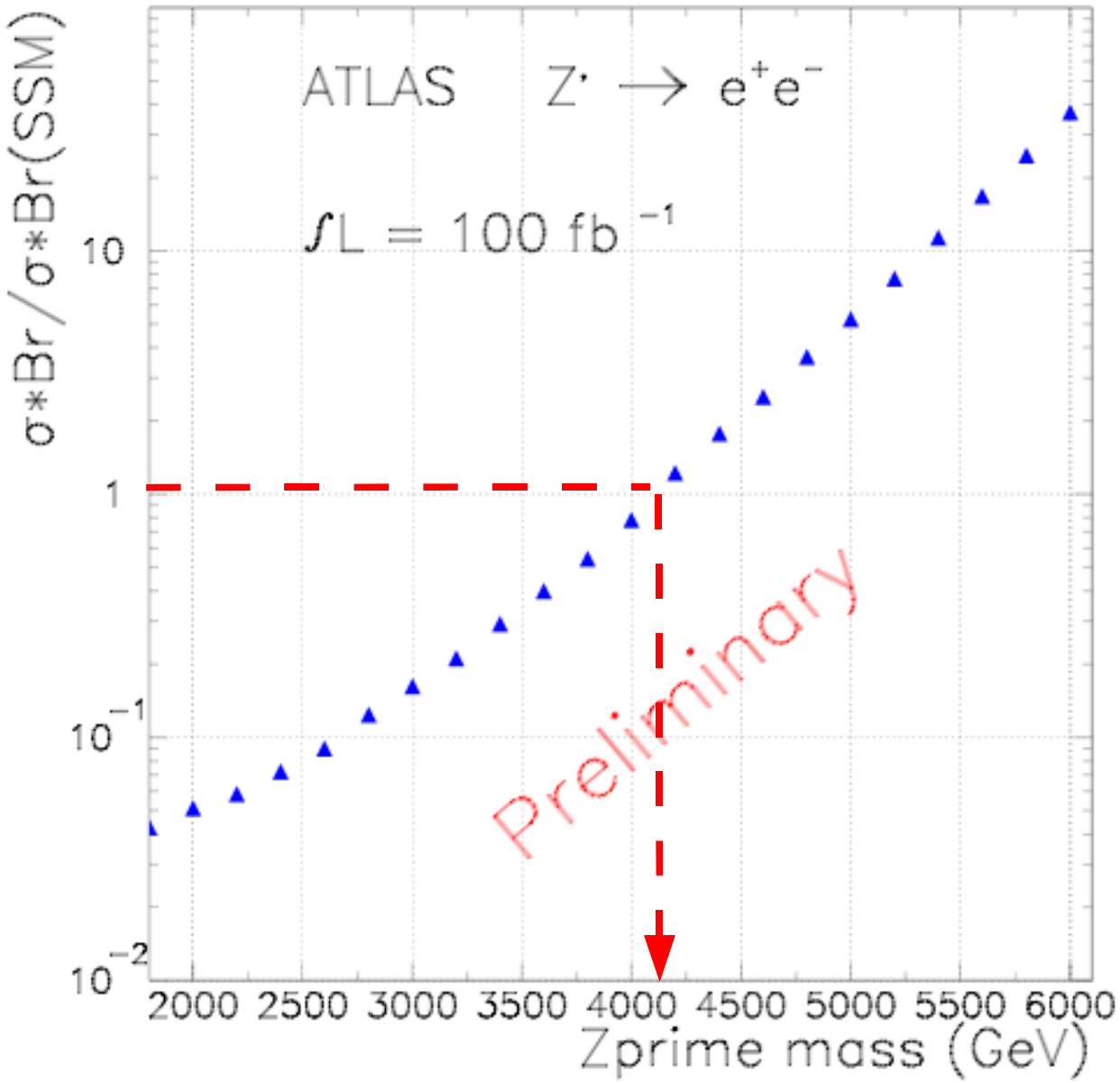
Z' discovery (depending on model):

$M_{Z'}$ = 2.9 - 3.8 TeV (for 10 fb^{-1})

5σ discovery as function of luminosity



Z' Discovery cont'd



Z' Discovery:

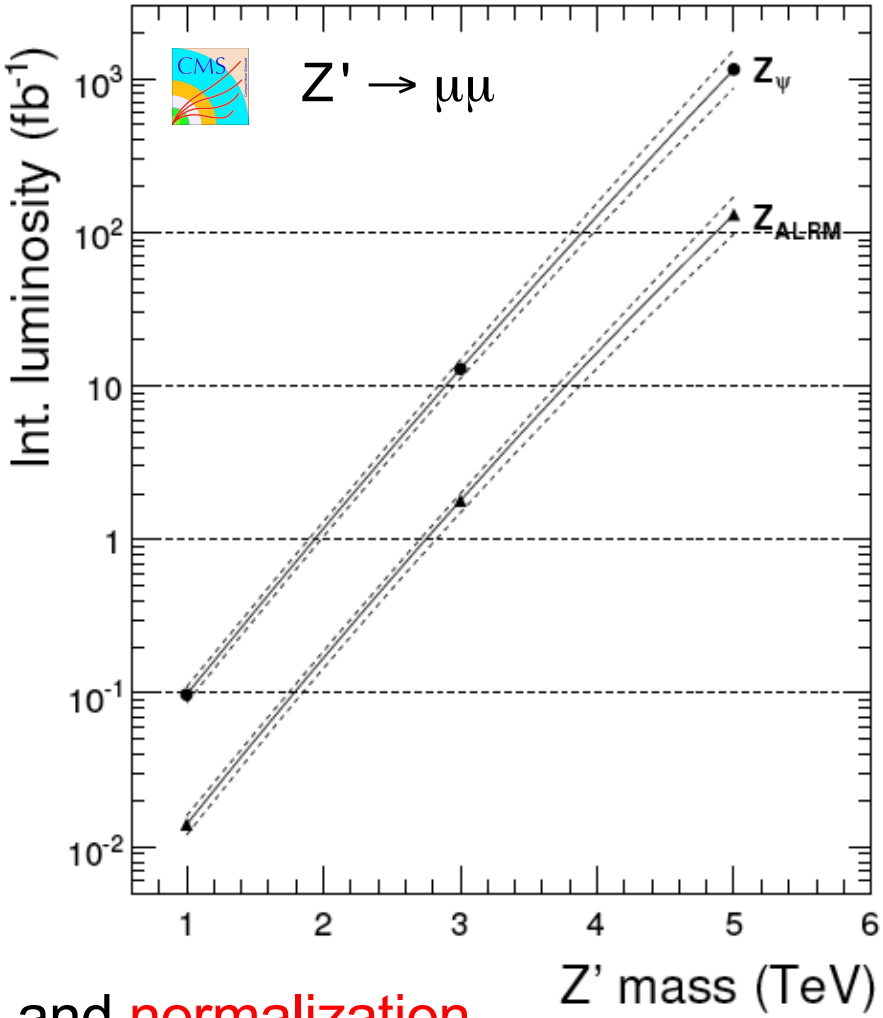
$M(Z'_{SSM}) > 4.2$ TeV

Luminosity:
100 fb^{-1}

Uncertainties

Theoretical (systematical):

- PDF uncertainties on cross section:
  - determined by using LHAPDF
  - $\Delta\sigma/\sigma \approx \pm 5\%, \pm 25\%$ (1, 5 TeV W' / Z')
- Hard process scale
  - Unphysical dependence of observables from renormalization/factorization scale
  - $\Delta\sigma/\sigma \approx \pm 1\%, +5\%/-25\%$ (1, 5 TeV Z' NNLO)
  - $\Delta\sigma/\sigma \approx \pm 4\%, \pm 14\%$ (1, 5 TeV W' LO)
- Higher-Order QCD/EWK corrections
- Uncertainty on background comparable



Experimental:

- Luminosity: $\Delta\mathcal{L}/\mathcal{L} = 5\%$ for 10 fb^{-1}
- Uncertainties on signal/background shape and normalization
- Alignment (see next slide)

Alignment Studies (Muonic Decays)

Methods:

- Two alignment scenarios in full CMS detector simulation:
  - „First data“, ~ 0.1 fb^{-1}, coarse alignment (Laser alignment, pixel detector track-aligned)
  - „Long term“, ~ 1 fb^{-1}, full alignment with tracks

Results:

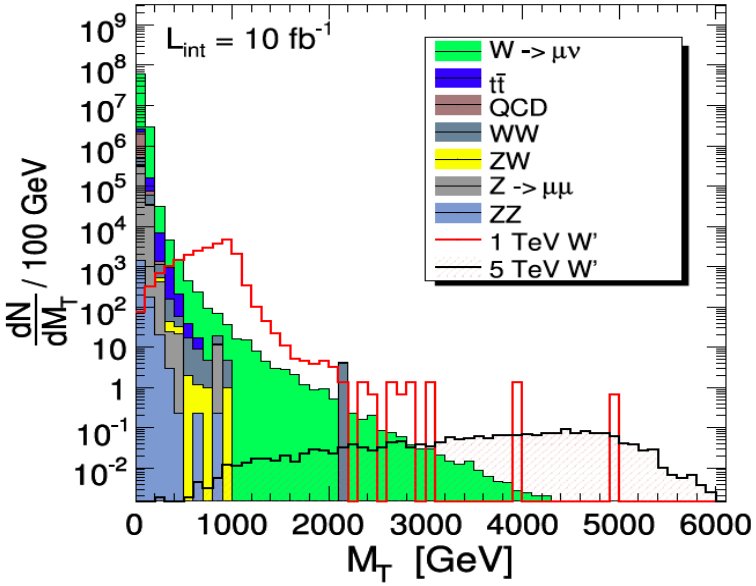
- No significant impact on discovery reach
- No „Non-Gaussian tails“ found
- BUT: di-muon mass resolution strongly dependent on alignment:
  - First data : 12% (1 TeV Z')
  - Long term: 4-9% (1-5 TeV Z')

➡ Determination of Z' width challenging!

- Use di-electron channel

  $\Delta p_T/p_T \sim 0.7$ % for $p_T = 1$ TeV electron

reminder:
W' invariant mass



(ATLAS: systematics and alignment studies during ongoing data challenge)

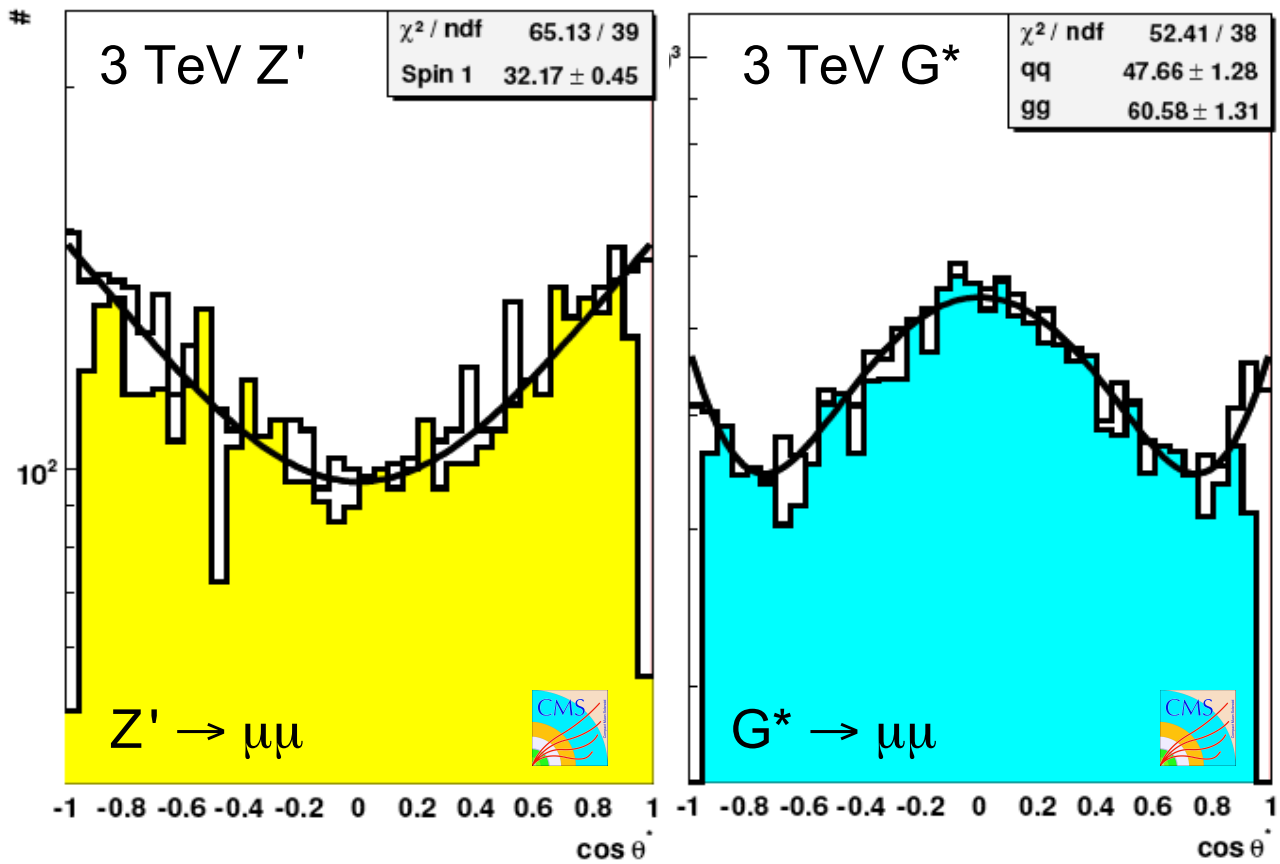
The Inverse LHC Problem

I found something, but what is it?

Model Discrimination

Z' against spin-2 particles:

- Graviton (e.g. Randall-Sundrum) $G^* \rightarrow \ell\ell$ also possible in TeV region
- Graviton G^* spin-2, Z' spin-1 particle
- Production: $qq \rightarrow Z'$ $qq \rightarrow G^*$ and $gg \rightarrow G^*$
- Investigate angular distribution $\cos\theta^*$ (even terms)
- Unbinned likelihood method applied
- Note: $G^* \rightarrow \gamma\gamma$ possible



Discrimination:

$$M_{Z'/G^*} = 1.2 - 3 \text{ TeV}$$

(c = 0.01-0.1, 300 fb^{-1}, 2σ)

Model Discrimination

What kind of Z':

- Is Z' accompanied by W'?

➡ distinction between U(1)- and SU(2)- Z' models

- Z' models predict different cross sections & width
- Investigate forward-backward asymmetry

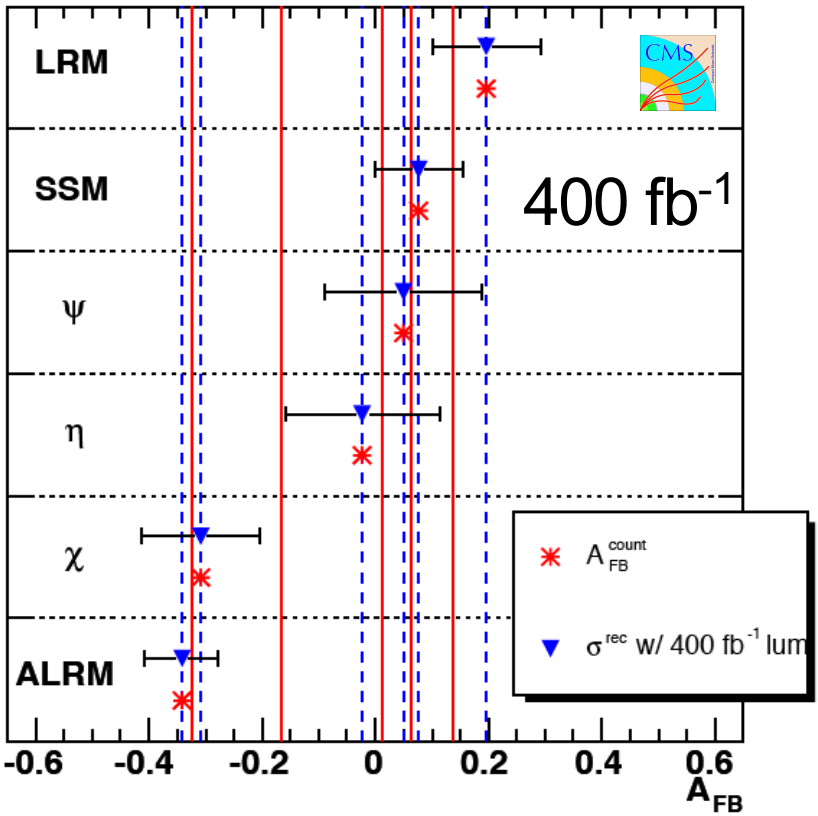
$$A_{\mathrm{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \qquad \sigma_F \equiv \int_0^1 \frac{d\sigma(q\bar{q} \to \mu^+\mu^-)}{d\cos\theta^*} d\cos\theta^*$$

θ^*: angle between quark and neg. muon in ll−centre-of-mass system

- Challenges:
  - Identification of quark for θ^*-determination (quark direction ≈ di-lepton long. direction)
  - Geometrical acceptance

(systematic uncertainties under investigation)

A_{FB} for different 3 TeV Z'



Summary

Theory:

- W'/Z' predicted by numerous theories
- Detector and theory benchmark channels

Experiment:

- The LHC will explore the W'/Z' TeV mass region
- Leptonic signatures with low background promising
- Expected discovery reach with leptonic decay channels (10 fb^{-1})
  - Z'_{SSM}: 3.6 TeV (μ), 3.5 TeV (e) [ATLAS: 4.2 TeV (e) 100 fb^{-1}]
  - W'_{SSM}: 4.6 TeV (μ)

(New ATLAS limits expected soon)

- Littlest Higgs Model W'/Z' well covered by LHC
- Z' models can be distinguished by W', cross section, branching ratio, angular distribution, width

LHC - Expect the unexpected!

We don't know what the LHC will bring up ...

... but it's very exciting to find that out!

Finally ...

Acknowledgement:

- Thanks to all ATLAS and CMS people contributing to the W'/Z' and related studies. Big thanks to the conference organizers!
- Special thanks to:
  J.Alcaraz, I.Beletelov, M.Bontenackels, T.Cox, B.Cousins, I.Hinchliffe, K.Hoepfner, T.Hebbeker, M.Kraemer, S.Lacaprara, F.Ledroit, N.Neumeister, L.Pape, E.Ros, T.Sjostrand, M.Spiropulu, S.Valuev, M.Zoeller
- All the people I have forgotten (10000 apologies)

References / Further reading:

- CMS Physics Technical Design Report 2 CERN/LHCC 2006-021
- Z': LHC Overview hep-ph/0610104
  ATLAS Notes 2006-003, 2006-024, 2005-010
  CMS Notes 2005-002, 2005-022, 2006-083, 2006-062, 2006-104
- W': hep-ph/0402037, ATLAS Note 2006-003, CMS Note 2006-117