Spin Physics at the LHC

Jonas Strandberg

1. Introduction to the LHC
2. Spin Measurements in Top Quark Physics
3. Measuring the Spin of the Higgs Boson
4. Spin Measurements of SUSY Particles
5. Conclusions

1. Introduction

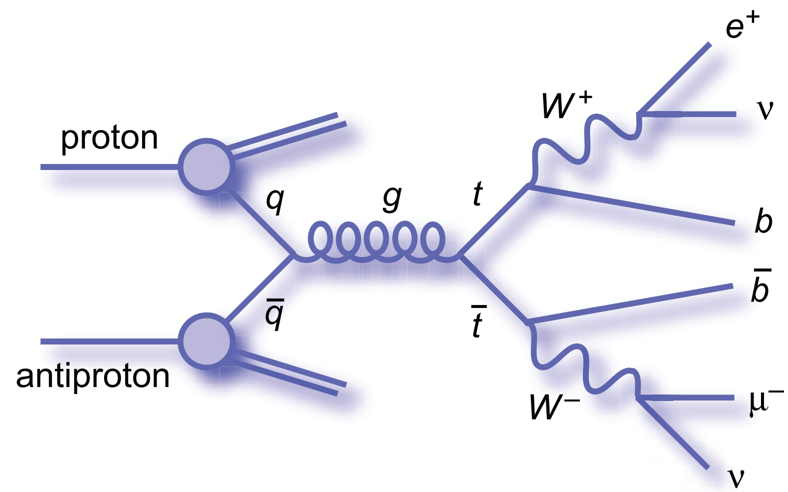
- Spin physics at the LHC is a vast topic, unfortunately I can only show you a fraction of all the available studies.
  - I will concentrate on physics which is only accessible at the highest energy accelerators like the LHC.
  - Will have to completely ignore all the exciting measurements to be made on b-quark hadrons.
- The results discussed in this talk are not my own. Will give an example of the physics done in three areas: Top, Higgs and SUSY.
  - Spin measurements play a very important role even for physics at the energy frontier.
  - Hopefully these will give you a flavor of the many exciting things that are awaiting us in the LHC era.

The Large Hadron Collider

- The world's largest and highest energy particle collider.
  - Will collide protons at a center-of-mass energy of 14 TeV.
- Located 100 m underground, outside Geneva, Switzerland.
- Four major experiments, ATLAS, CMS, ALICE and LHCb.
  - Records and analyzes the LHC proton collisions.
  - Will concentrate on results from ATLAS in this talk.

2. Spin Measurements in Top Quark Physics

- The t is the heaviest known particle with $M_t = 173$ GeV.
- Discovered in 1995 by CDF and DØ at the Tevatron.
- Top quarks produced:
  - Pairs: $gg \to t\bar{t},\ q\bar{q} \to t\bar{t}$.
  - Singles: $q\bar{q}' \to tb$, $gq \to tbq$.



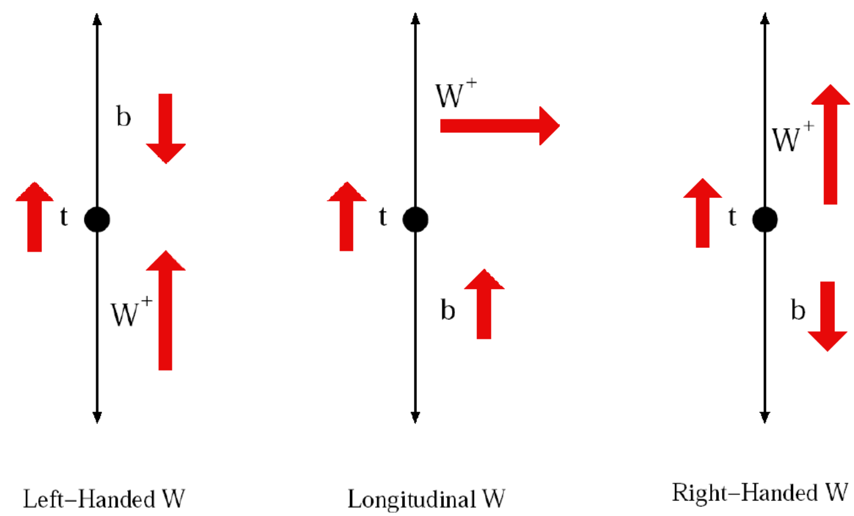
- Decays almost 100% through $t \to Wb$, the coupling $V_{tb} \simeq 1$.
  - Final state determined by the decay of the W bosons.
- Decays before hadronization, allows for probing the quark properties. Spin information transferred to the daughters.
- The LHC will be a top quark factory, producing millions of $t\bar{t}$ pairs.
  - Top quark physics will enter the realm of precision physics.

Measuring the W Helicity

- W polarization in the $t \rightarrow Wb$ decay unambiguously predicted by the SM, direct test of the V-A structure of the tWb vertex:

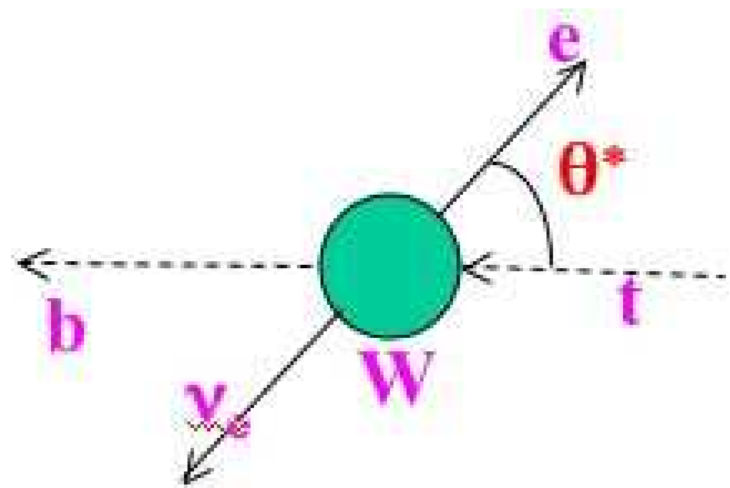
$$
\begin{aligned}
F_L &= \frac{2M_W^2}{M_t^2 + 2M_W^2} = 0.297 - 0.002 \times (M_t - 175) \\
F_0 &= \frac{M_t^2}{M_t^2 + 2M_W^2} = 0.703 + 0.002 \times (M_t - 175) \\
F_R &= 0
\end{aligned}
$$

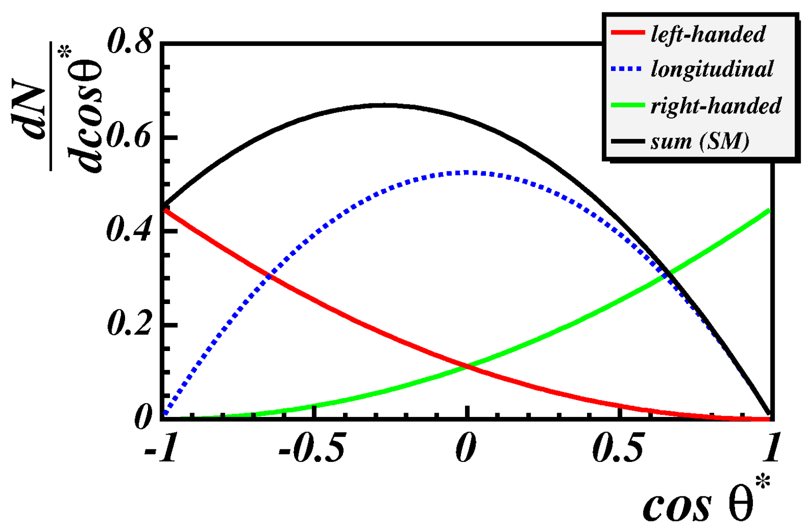
- Rightmost decay forbidden in SM for massless b.
- Sensitive to for example:
  - Anomalous V+A coupling.
  - Charged Higgs in the top decay, $t \rightarrow H^{\pm}b$.

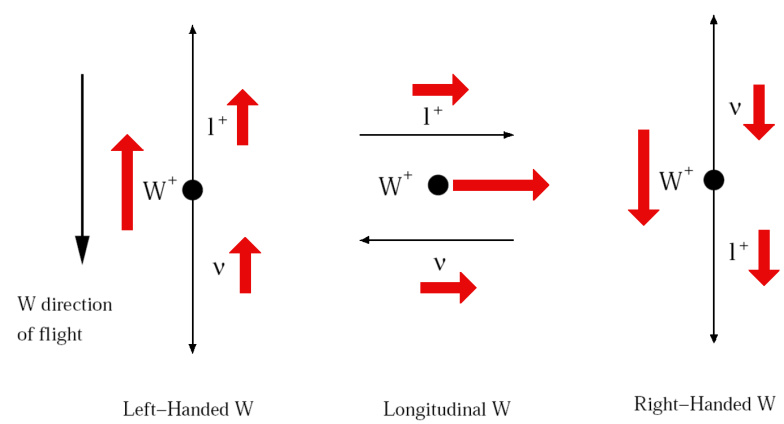


The Sensitive Variable

- Define the observable $\cos\theta^*$ (or sometimes called $\cos\Psi$).
  - θ^* angle between charged lepton in W rest frame and W direction in t rest frame.





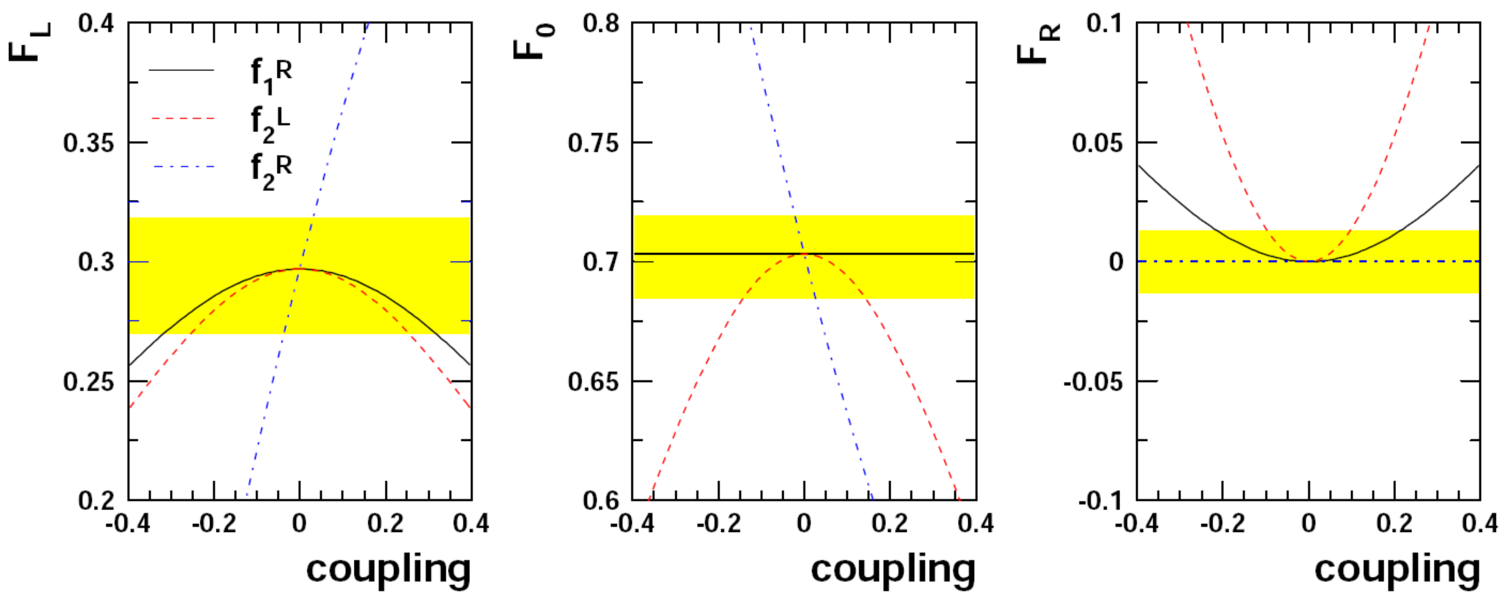


Sensitivity to Anomalous Couplings

- Do an expansion of the most general CP-conserving $\mathcal{L}$ for the tWb vertex and keep only the lowest two orders:

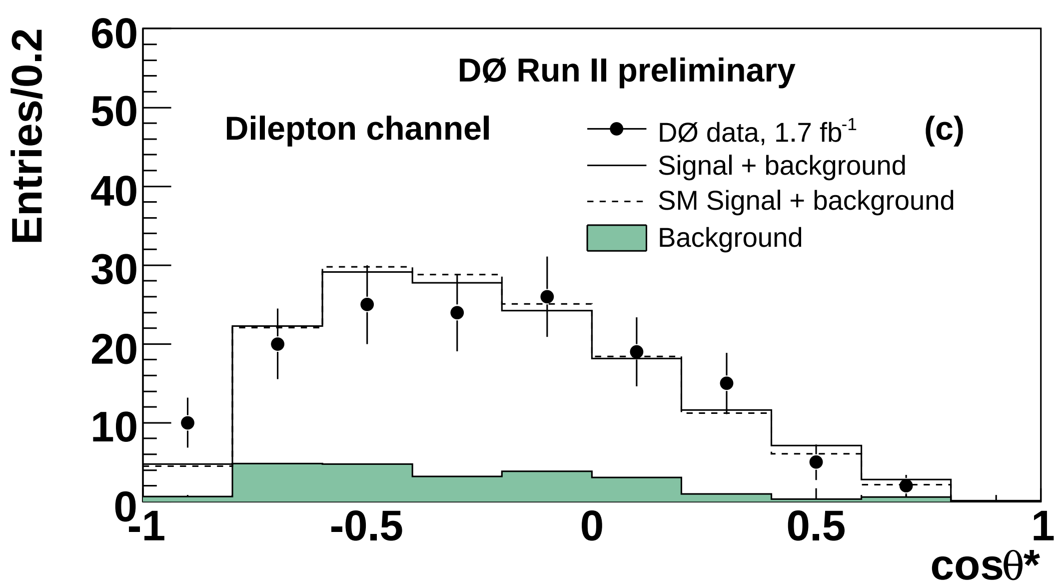
$$\mathcal{L} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu (f_1^L P_L + f_1^R P_R) t - \frac{g}{\sqrt{2}\Lambda} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t$$

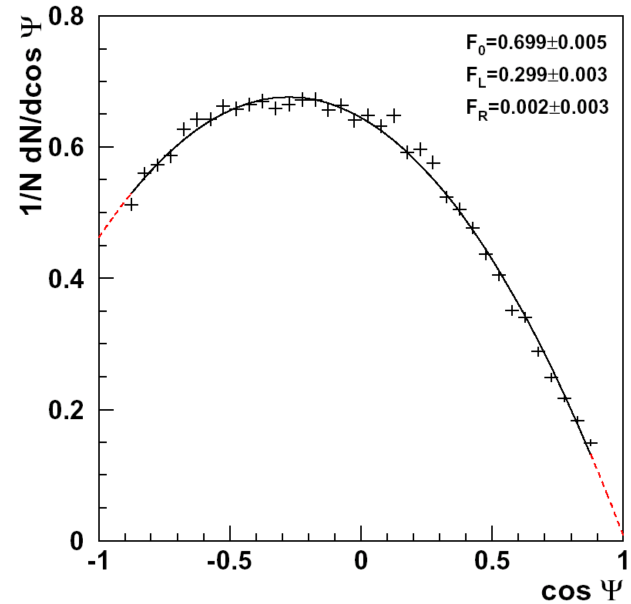
- f_1^L and f_1^R vector-like couplings, f_2^L and f_2^R tensor-like couplings.
- In the Standard Model, $f_1^L = V_{tb} = 1$ and $f_1^R = f_2^L = f_2^R = 0$.



W Helicity Results

- Current results from CDF with $1.9\ \mathrm{fb}^{-1}$ yields $F_0 = 0.66 \pm 0.16$ and $F_R = -0.03 \pm 0.07$. DØ also has similar results.
- With 10 fb^{-1} (one year at nominal luminosity) ATLAS will be able to measure F_0 to 2% accuracy and F_R to 1% accuracy.
  - Set limits on new anomalous couplings in the tWb vertex at $f_1^R < 0.3$, $f_2^L < 0.13$ and $f_2^R < 0.04$ at the 2σ confidence level.

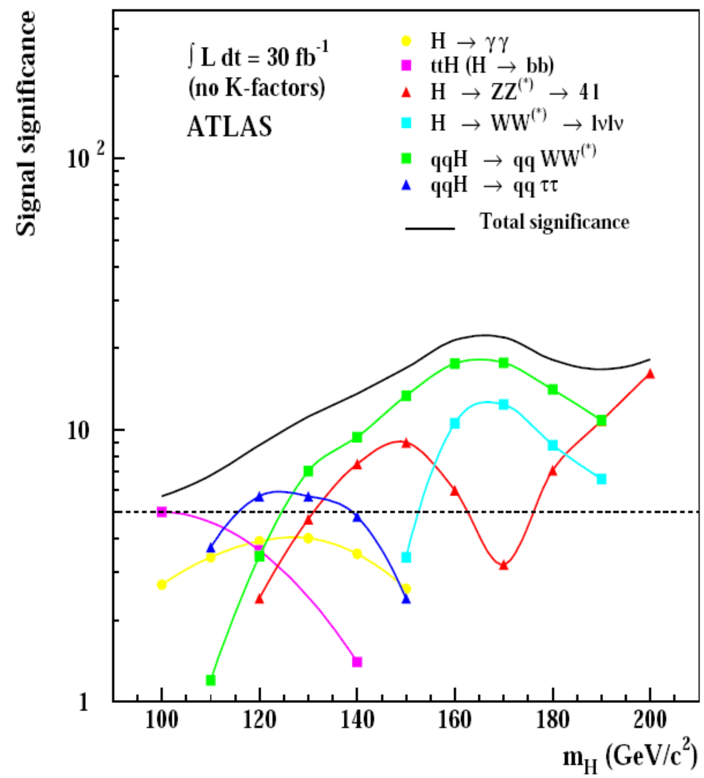




3. The Higgs Boson

- We know the electro-weak symmetry is broken at low energies.
  - Weak force is short ranged, W and Z bosons are massive.
- Higgs mechanism proposed in the 60′s as explanation for EWSB.
  - Introduces the Higgs field and predicts the Higgs boson.
  - So far there is no direct evidence for its existence.
- All properties of the Higgs boson are predicted from theory.
  - Except the mass, M_H.

- LHC will settle the question of the Higgs boson.



Expected significance for low M_H with 30 fb^{-1}.

Spin and CP of the Higgs

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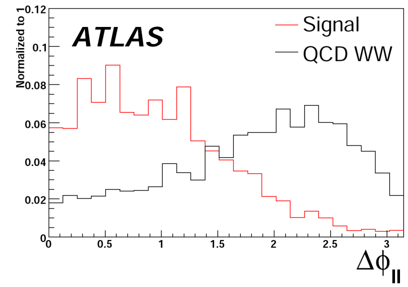
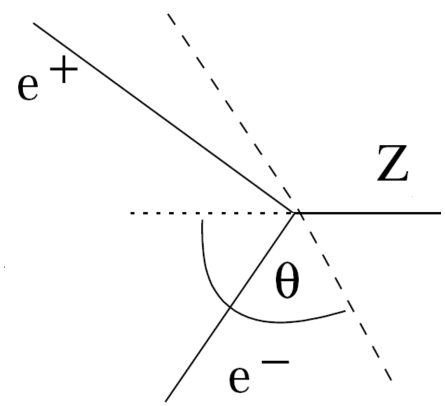


- The SM Higgs boson is a CP-even scalar (spin-0).
- $H \to WW$ analysis depends on a $\Delta\phi(\ell, \ell)$ correlation.
- $gg \to H$ production mode and $H \to \gamma\gamma$ decay only possible for spin-0.
- The $H \to ZZ \to 4\ell$ does not use spin or CP information in discovery.
  - Polarization of Z bosons depend on Higgs mass, for $M_H > 300$ GeV the Z's from the Higgs decay are mostly longitudinally polarized.
- In the center-of-mass of the Z boson, the angle θ follows:

$$\frac{d\Gamma}{d\cos\theta}(Z_L \to \ell\ell) \propto \sin^2\theta$$
$$\frac{d\Gamma}{d\cos\theta}(Z_T \to \ell\ell) \propto 1 + \cos^2\theta$$



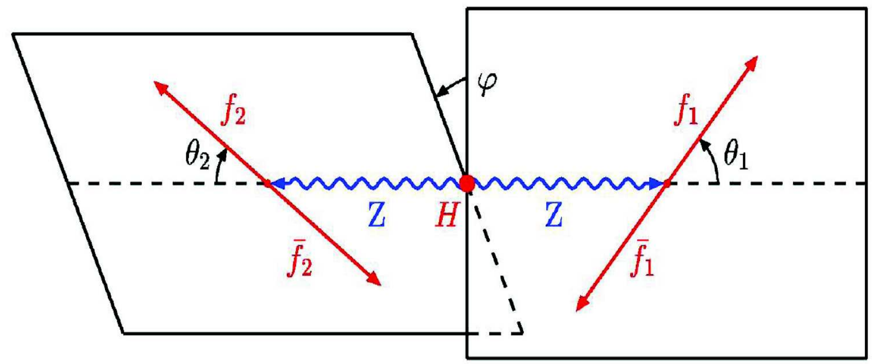
- Z from other processes are mostly transversely polarized.

Observables R, α and β

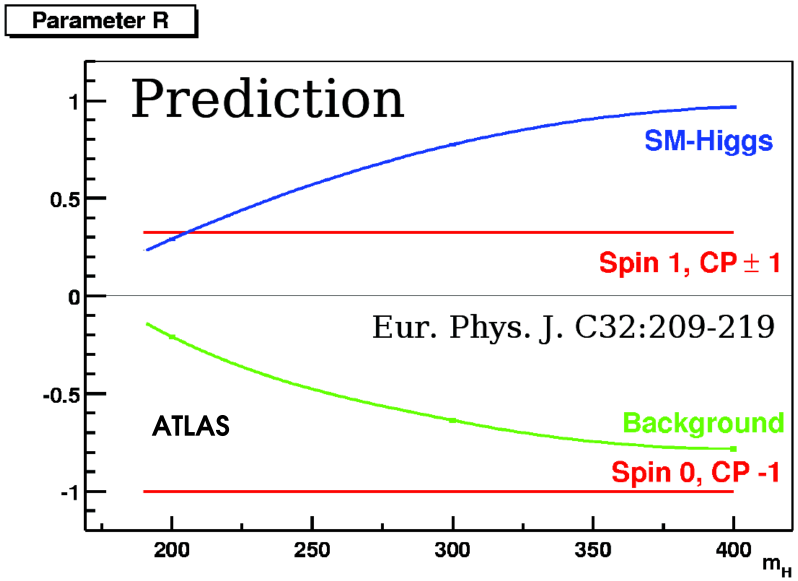
- The distribution of the angle between the 2 Z's decay planes, ϕ, expected to be non-uniform for transversely polarized Z bosons.
  - Correlation starts to disappear for $M_H > 300$, longitudinal Z's.
- Angular distributions for θ and ϕ described by:

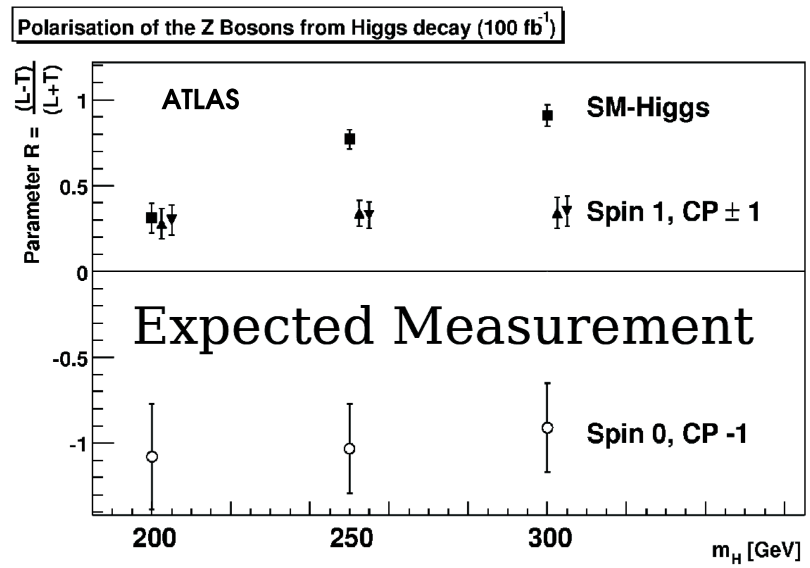
$$F(\phi) = 1 + \alpha\cos\phi + \beta\cos 2\phi$$
$$G(\theta) = T(1+\cos^2\theta) + L\sin^2\theta$$

- Define observables α, β and $R = (L-T)/(L+T)$.
- Test for:
  - Spin 1, CP +1
  - Spin 1, CP -1
  - Spin 0, CP -1



Measurement of R





- Predicted values of R as a function of the Higgs mass.
- Expected precision on the measurement of R (100 fb^{-1}).
- R provides good separation between the SM Higgs boson and the alternative Higgs bosons for $M_H > 230$ GeV.
  - For $M_H \approx 200$ GeV, a measurement of R is only able to exclude the pseudo-scalar alternative.

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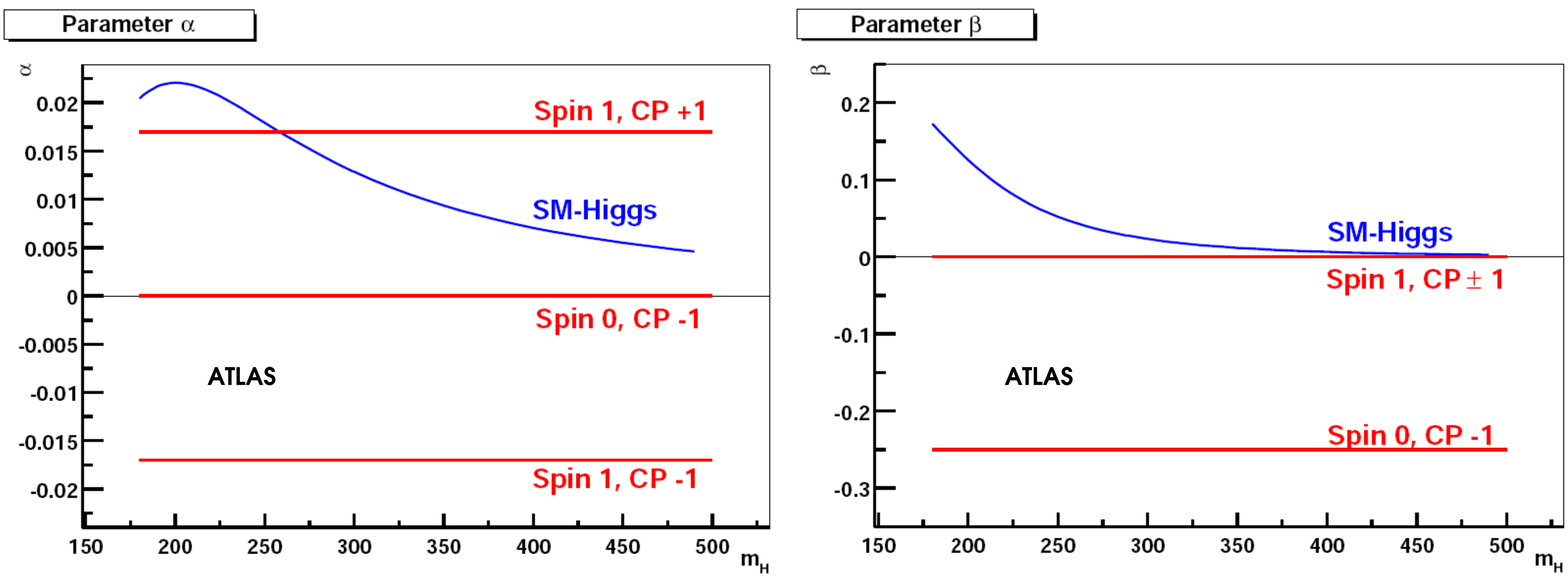
Predictions for α and β

- Measuring α and β helps pin down the CP and spin of the Higgs.
  - Can distinguish between spin-0 and spin-1 for $M_H = 200$ GeV.



- Sensitivity to α and β can be enhanced if information about the signs of the $\cos\theta$ terms for the Z bosons is used.

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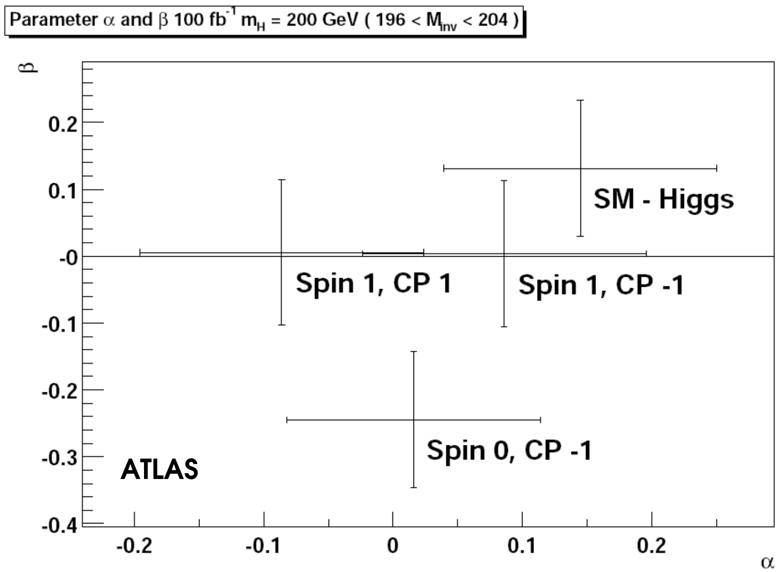
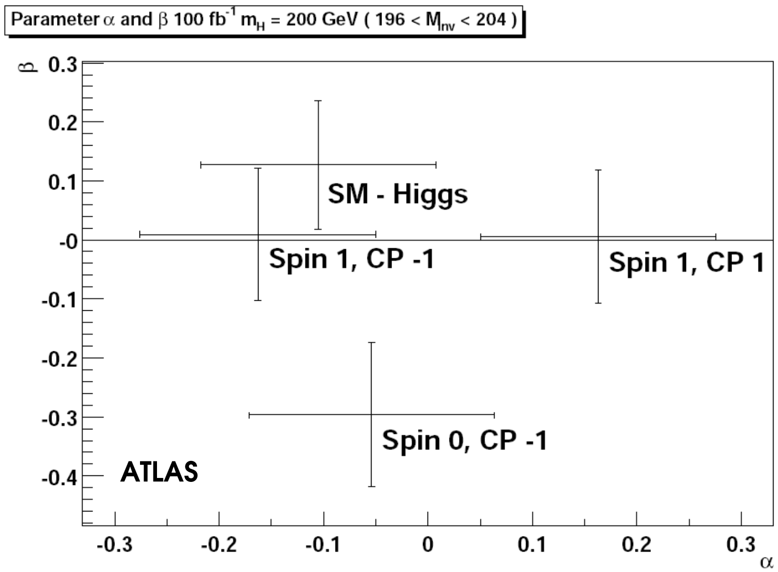
Expected Measurements of α and β





- Expected measurement of α and β when the sign of $\cos\theta_1$ is equal to the sign of $\cos\theta_2$.
- Expected measurement of α and β when the sign of $\cos\theta_1$ is opposite to the sign of $\cos\theta_2$.

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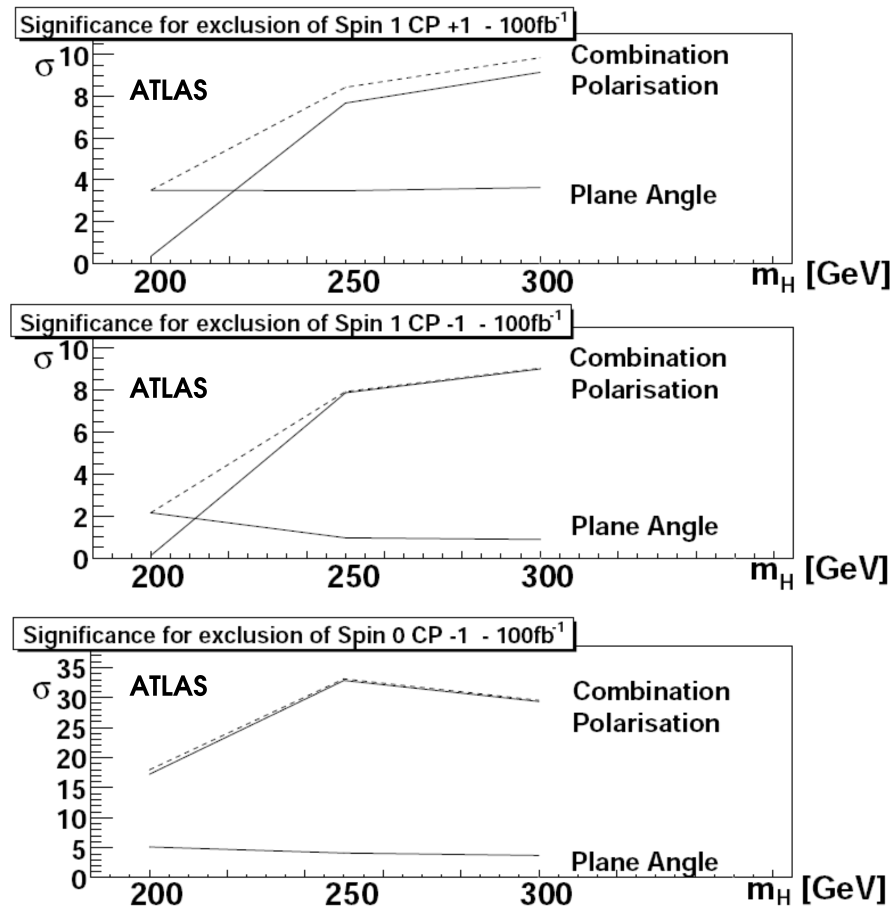
Excluding Anomalous Spin and CP

- Exclude anomalous values of spin and CP from:
  - Decay angle θ in the Z boson rest frame.
  - The angle ϕ between the decay planes of the Z's.
- Pseudo-scalar easy to exclude for all $M_H > 200$ GeV.
- 5σ exclusion of the spin-1 hypothesis for $M_H > 230$ GeV.



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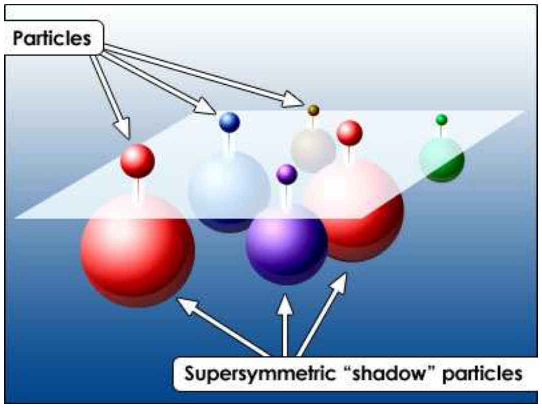
4. Spin Measurements in Supersymmetry

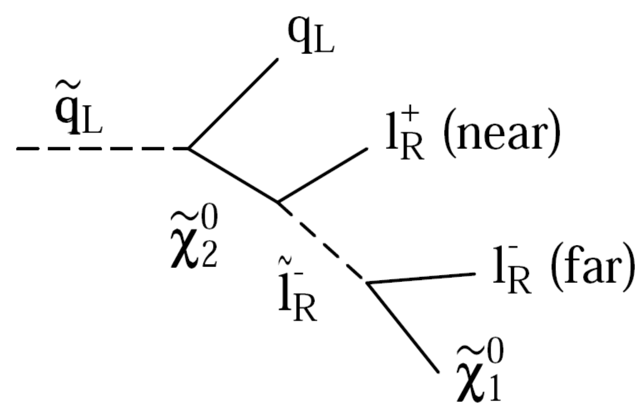
- Perhaps there is no other place where spin plays such a fundamental role as in the theory of Supersymmetry.
  - Postulates that for every known particle there is a super-partner with spin differing by $1/2$ unit.
- Phenomenology and (s)particle mass spectra depend on what assumptions are made in the model.
  - SUSY breaking mechanism, unification assumptions and so on.
  - I will be talking mainly about three sparticles: $\tilde{q}$, $\tilde{\chi}_2^0$ and $\tilde{\ell}$.
- LHC is a discovery machine:
  - SUSY could be found quickly.
- Determining the underlying theory:
  - Spin measurement can discriminate between SUSY or UED.



Measuring Spin Effects from $\tilde{\chi}_2^0$

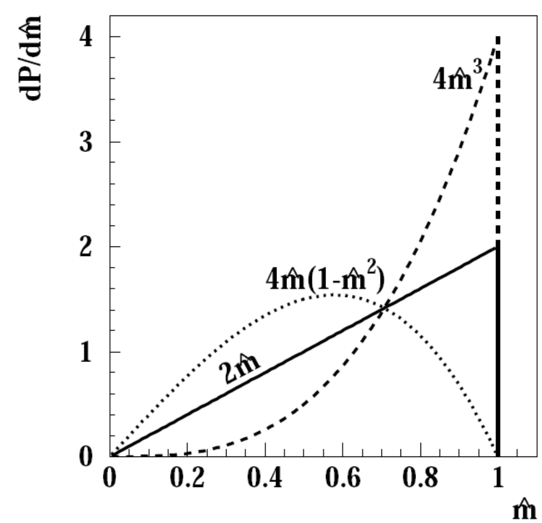
- Define θ^*, the angle between q and ℓ in the $\tilde{\chi}_2^0$ rest frame. Then:

$$\left(m_{\ell q}^{near}\right)^2 = 2|\mathbf{p}_\ell||\mathbf{p}_\mathbf{q}|(1-\cos\theta^*)$$
$$= \left(m_{\ell q}^{near}\right)^2_{max}\sin^2(\theta^*/2)$$



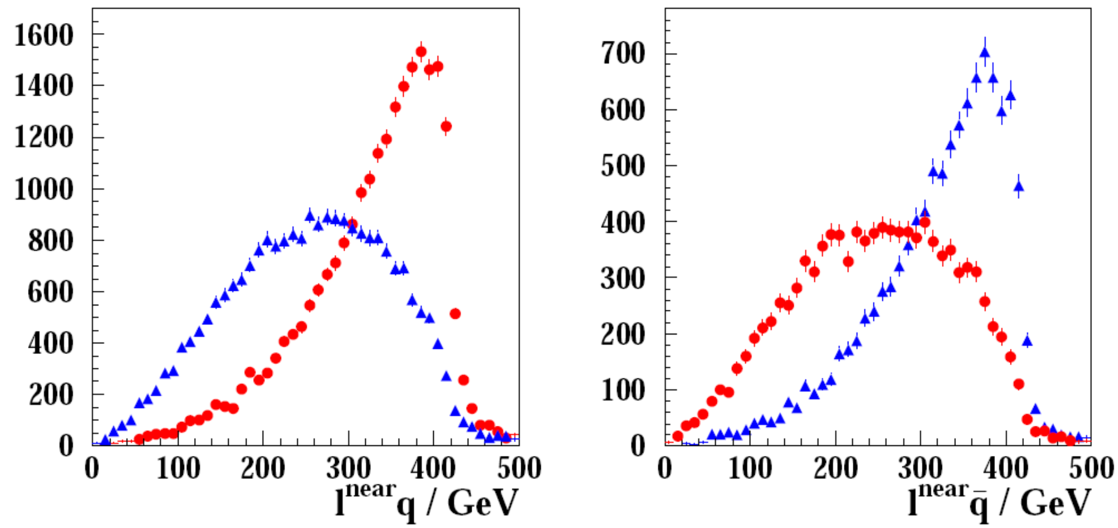
- Maximum for $\sin^2(\theta^*/2) = 1$, i.e. $\theta^* = \pi$.
- Defining $\hat{m} \equiv m_{\ell q}^{near}/(m_{\ell q}^{near})_{max} = \sin(\theta^*/2)$, the p.d.f. $dP/d\hat{m}$ is:

$$\frac{dP}{d\hat{m}} = 2\hat{m} \quad (phase-space)$$
$$\frac{dP}{d\hat{m}} = 4\hat{m}^3 \quad (for\ \ell^+ q\ or\ \ell^- \bar{q})$$
$$\frac{dP}{d\hat{m}} = 4\hat{m}(1-\hat{m}^2) \quad (for\ \ell^- q\ or\ \ell^+ \bar{q})$$



$\tilde{q} - \tilde{\bar{q}}$ Production Asymmetry

- Blue triangles:
  - Negative leptons.
- Red circles:
  - Positive leptons.
- Measure asymmetry for ℓ^-/ℓ^+ vs. $m_{\ell q}^{near}$.



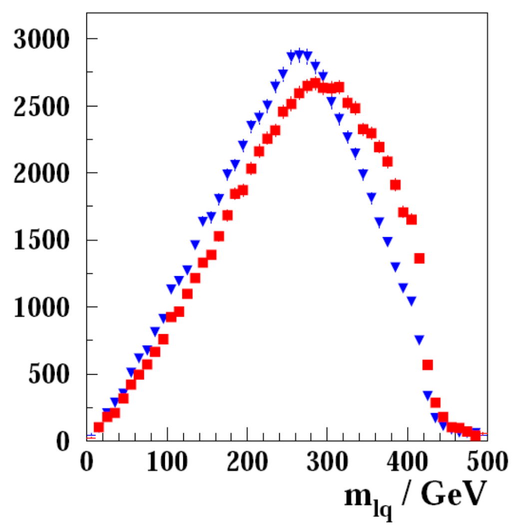
- If an equal amount of squarks and anti-squarks were produced, the $m_{\ell q}^{near}$ distribution would look identical for ℓ^- and ℓ^+.
- At the LHC, a pp collider, the processes $qg \to \tilde{q}\tilde{g}$ and $\bar{q}g \to \tilde{\bar{q}}\tilde{g}$ will produce more $\tilde{q}$ than $\tilde{\bar{q}}$ because of proton valence quarks.
  - Also the charge-symmetric $q\bar{q}, gg \to \tilde{q}\tilde{\bar{q}}$ does not dominate.

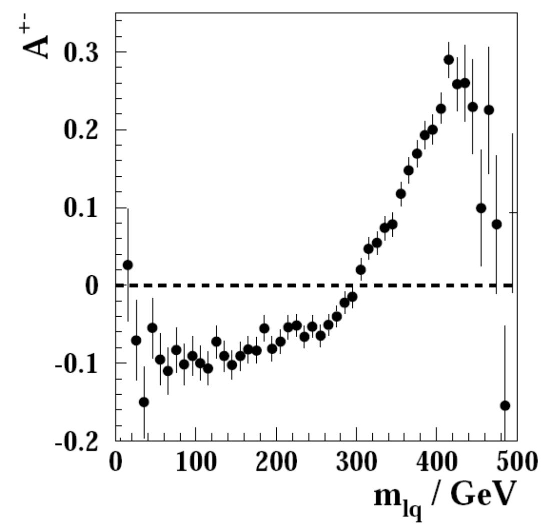
The Charge Asymmetry at the Parton Level

- Define the charge asymmetry in the differential cross-section:

$$A^{+-} \equiv \frac{s^+ - s^-}{s^+ + s^-}, \quad \text{where} \quad s^{\pm} = \frac{d\sigma}{d(m_{\ell^\pm q})}$$

- Experimentally difficult to identify ℓ^{near} and ℓ^{far}:
  - Asymmetry washed out from contamination of ℓ^{far}.

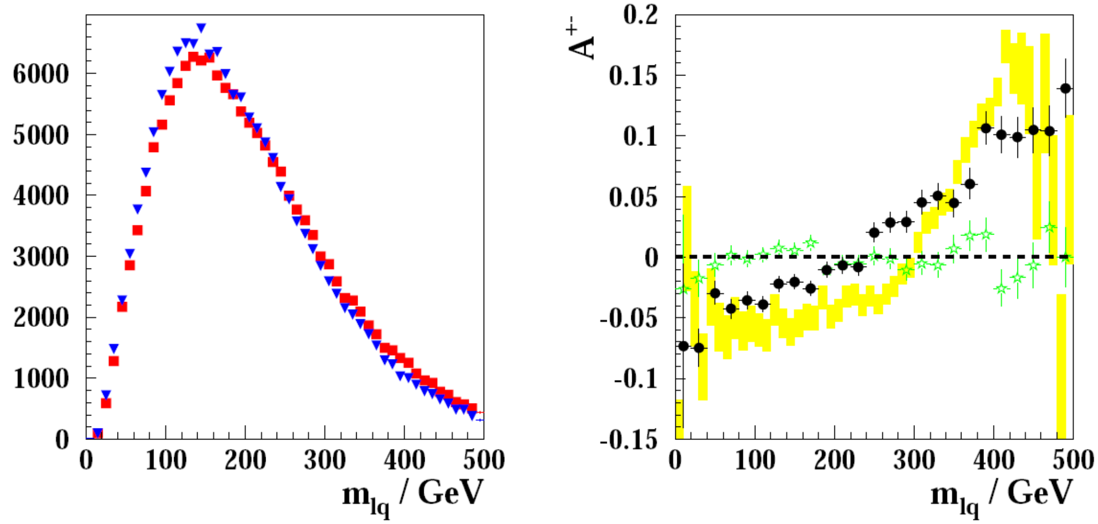




- Charge asymmetry distribution indicative of a $\tilde{\chi}_2^0$ with spin-$1/2$.

Experimental Asymmetry Results

- Detector smearing effects and background contamination further dilutes the observed charge asymmetry. With 500 fb^{-1}:



- Black points measured charge asymmetry as a function of $m_{\ell q}$.
  - Yellow band is parton level result scaled down by 0.6.
  - Green points result if spin correlations are neglected.
- Asymmetry in $\tilde{q}$ vs. $\tilde{\bar{q}}$ production detectable experimentally.

Summary and Conclusions

- Spin measurements are a large part of the LHC physics program.
  - True also in the new physics searches at very high p_T.
- Precision top quark measurements possible, with $10\ \mathrm{fb}^{-1}$ the W helicity in top decays will be known at the O(1%) level.
  - Anomalous couplings in the tWb vertex can be searched for.
- If the Higgs boson (the only spin-0 particle in the SM) exist, it should be discovered at last after over 40 years of searching for it.
  - Verify its scalar and CP-even nature from angle measurements in the $H \to ZZ$ decay for Higgs masses above 200 GeV.
- If SUSY is discovered, attempt to measure the charge asymmetry as a function of $m_{\ell q}^{near}$ to verify spin-$1/2$ nature of $\tilde{\chi}_2^0$.

With LHC collisions around the corner, exciting times are ahead!