Towards a Measurement of Spin Correlations in ttbar Events at the LHC using Matrix Element Method

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The Top Quark

- The most massive particle known to date (m_t~173 GeV)
  - very short lifetime

$$\tau_t = \frac{1}{\Gamma_t} \sim 0.5\times 10^{-24}\, s < \frac{1}{\Lambda_{QCD}} < \frac{m_t}{\Lambda_{QCD}^2} \sim 3\times 10^{-21}\, s << \tau_b \sim 10^{-12}\, s$$

$$\tau_t < \tau(hadronization) < \tau(spin - decorrelation) << \tau_b$$

No hadronic bound states→ bare quark properties are accessible (mass, V_{tb}, charge, …).

spin effects propagate to decay products.

Measurements test
→ top quark being bare
→ pQCD in ttbar production
→ existence of
    → t→H^+b
    → production through heavy particles
    → heavy higgs → ttbar

ttbar Spin Correlations

- The spin correlation strength A is defined as

$$A = \frac{\left(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}\right) - \left(N_{\uparrow\downarrow} + N_{\downarrow\uparrow}\right)}{\left(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}\right) + \left(N_{\uparrow\downarrow} + N_{\downarrow\uparrow}\right)}$$

- *Not a free parameter of the SM Lagrangian*, but depends on:
  - SM couplings, production mode, collision energy, basis of the spin quantization axis, ...
- A is proportional to the fraction of events f with SM spin correlations

$$A_{basis}^{meas} = A_{basis}^{SM} f \qquad \text{where} \qquad f = \frac{N_{SM}}{N_{SM} + N_{non-SM}}$$

- At Tevatron: beam axis basis (A=0.37 in lepton+jets)
- At LHC: helicity basis (A=0.16 in lepton+jets)

ttbar Spin Correlations

$D0: f = 0.85 \pm 0.29 \left(stat \oplus sys\right)$ [MEM, PRL 108, 032004 (2012)]

$ATLAS:$ [Dilepton, ATLAS-CONF-2013-101]

$f = 1.19 \pm 0.09(stat) \pm 0.15(sys) \leftarrow \Delta\phi$

$f = 0.87 \pm 0.11(stat) \pm 0.12(sys) \leftarrow$ S-ratio of on-shell MEs from fusion of like-helicity gluons ← not MEM

$f = 0.75 \pm 0.19(stat) \pm 0.25(sys) \leftarrow \cos\left(\theta_+\right)\cos\left(\theta_-\right)$ helicity basis; direct extraction of A.

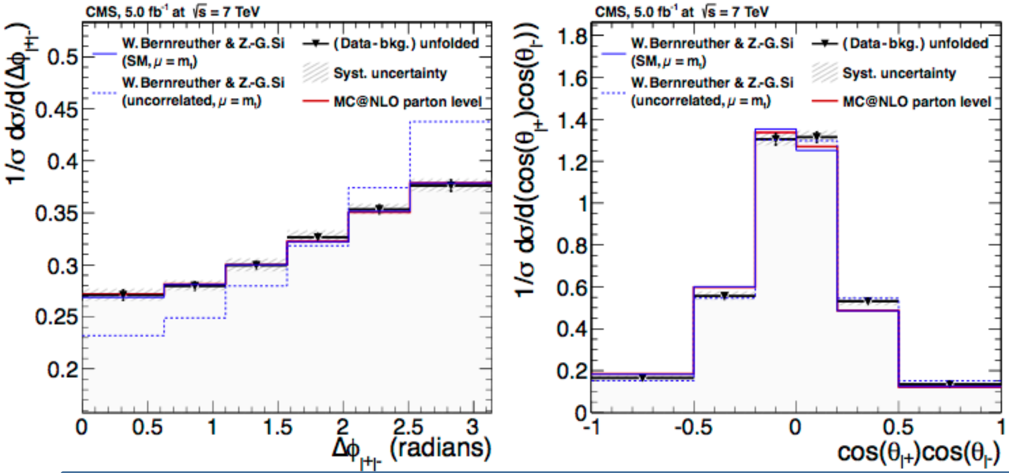
$f = 0.83 \pm 0.14(stat) \pm 0.17(sys) \leftarrow \cos\left(\theta_+\right)\cos\left(\theta_-\right)$ maximal basis; defined event by event.

$CMS: f = 0.74 \pm 0.08(stat) \pm 0.24(sys) \leftarrow \Delta\phi$

[Dilepton, CMS-PAS-TOP-12-004]

P. Uwer, PLB 609, 271 (2005)

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ \, d\cos\theta_-} = \frac{1}{4}\left(1 + A\,\alpha_+\alpha_- \cos\theta_+ \cos\theta_-\right)$$



All measurements are consistent with SM, i.e., f=1.

[Dilepton, CMS-PAS-TOP-13-003, arXiv:1311.3924v1]

ttbar Spin Correlations

- Angles between the decay products are the most sensitive variables to the spin correlation (depending on the final state particles).
- However, we have the potential to do better by exploiting the full event information.
  - Use matrix element method to construct templates based on event likelihoods

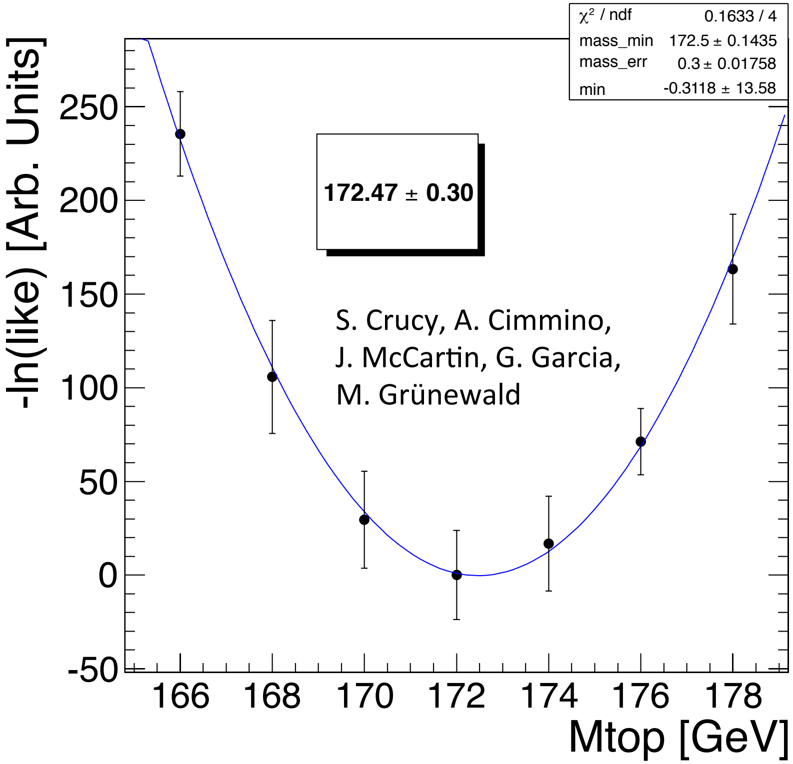
$$P\left(x_i \middle| H\right) = \frac{1}{\sigma_{obs}} \int f_{PDF}\left(q_1\right) f_{PDF}\left(q_2\right) dq_1 dq_2 \frac{(2\pi)^4 \left|M\left(y,H\right)\right|^2}{q_1 q_2 s} W\left(x,y\right) d\Phi_6$$

q_1 and q_2 : the initial parton kinematics
W(x,y) : Transfer Function that maps the reconstructed kinematics x to the parton level kinematics, y.
H: hypothesis under consideration

Calculate the likelihood/event for each hypothesis:
for the SM and the non-SM hypotheses.

First Steps in the Measurement: Strategy

- As opposed to top quark mass measurement: our hypotheses are discrete (i.e. SM & spin-uncorrelated SM)
  - We can not vary a parameter in the matrix element to obtain specific values of f (or A).
  - Instead we calculate the likelihoods for SM and non-SM cases separately.
  - SM and non-SM events can be mixed to obtain fractional f values for pseudo-experiments.



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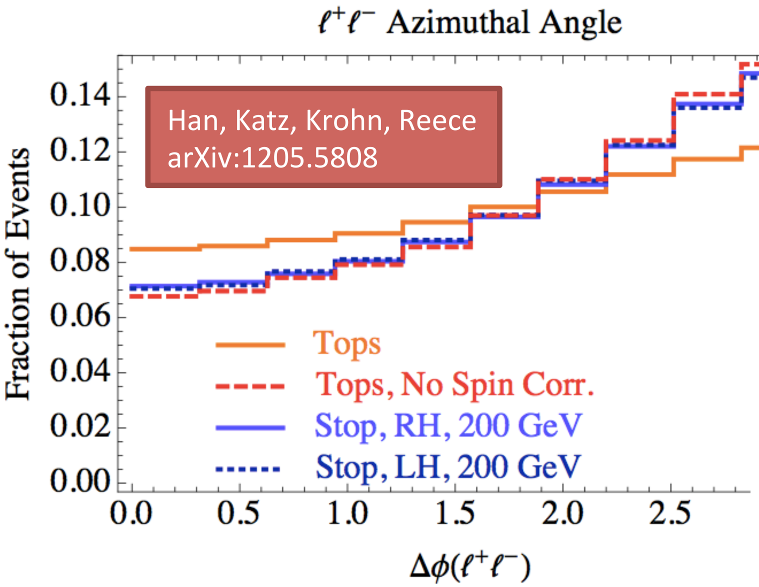
In the Mtop measurement with MEM, likelihood is a continuous function of Mtop.

ttbar Spin Correlations: non-SM Model

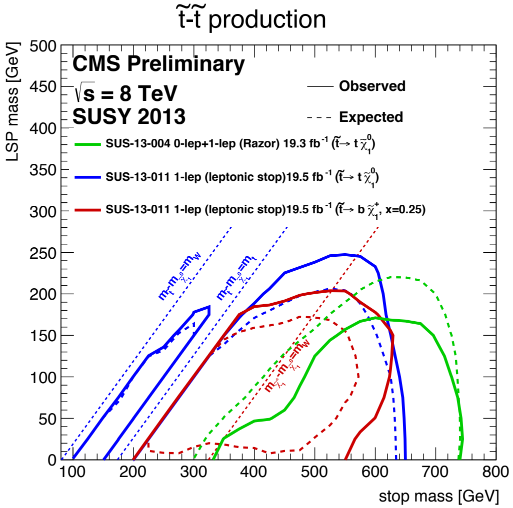
- f can be extracted by performing a template fit to the distribution of a variable that discriminates between SM and non-SM events.

Spin-uncorrelated SM: calculated by manually imposing spherical decay for the top quarks.
→ An "artificial model", but e.g. SUSY with m(stop)~m(top) predicts un-correlated spins as in "spin-uncorrelated SM".

$$f = \frac{N_{SM}}{N_{SM} + N_{non-SM}}$$



Han, Katz, Krohn, Reece
arXiv:1205.5808

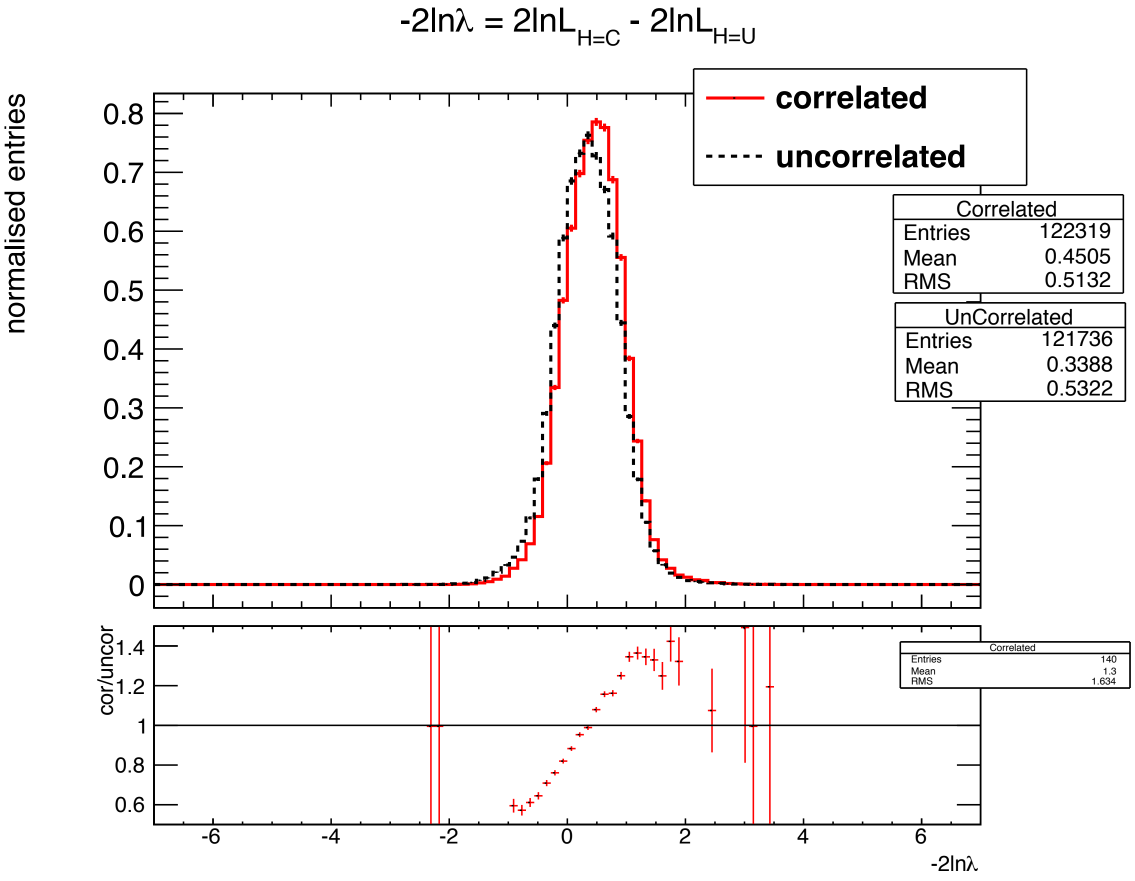


Effective theory: e.g. top chromo-moments (Bernreuther & Si, arXiv:1305.2066)

See also P. Artoisenet's talk

First Steps in the Measurement: Strategy

- With the event likelihoods (one for each hypothesis), we form a discriminating variable



$$-2\ln\lambda = -2\ln\frac{P\left(H_{non-SM}\right)}{P\left(H_{SM}\right)}$$

maximum discriminating variable (Neyman and Pearson Phil. Trans. R. Soc. Ser. A 231 (1933) 289)

- A template fit to this variable will be performed.
- Likelihoods calculated using MadWeight.

Templates at Gen Level with acceptance cuts.

First Steps in the Measurement: Matrix Elements

$$P\left(x_i \middle| H\right) = \frac{1}{\sigma_{obs}} \int f_{PDF}\left(q_1\right) f_{PDF}\left(q_2\right) dq_1 dq_2 \frac{(2\pi)^4 \left|M\left(y,H\right)\right|^2}{q_1 q_2 s} W\left(x,y\right) d\Phi_6$$

- For the likelihood calculation, we need the MEs describing the tt~ process for SM and non-SM cases valid for both on- and off-shell top quarks.
  - SM ME: is known from the SM Lagrangian and implemented as default in MadWeight and MadGraph.
  - non-SM:
    - *Spin-uncorrelated ME*: calculated by manually imposing spherical decay for the top quarks.
    - *Effective theory with top chromo-moments*
- The spin-uncorrelated ME had to be manually implemented in MadWeight and MadGraph5 (by replacing the SM ME by the spin-uncor. one in the fortran code).

The matrix elements were kindly provided to us by *Werner Bernreuther.*

First Steps in the Measurement: Matrix Elements

- The calculation are performed, taking into account only the following leading order Feynman diagrams for both SM and spin-uncorrelated cases.

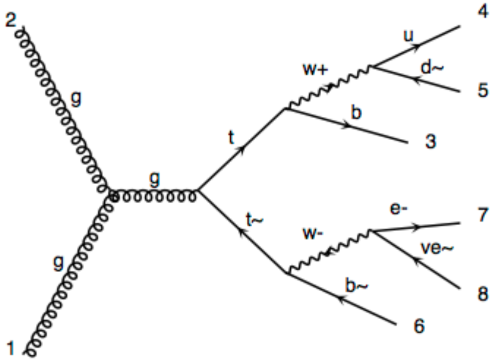


diagram 1 QCD=2, QED=4

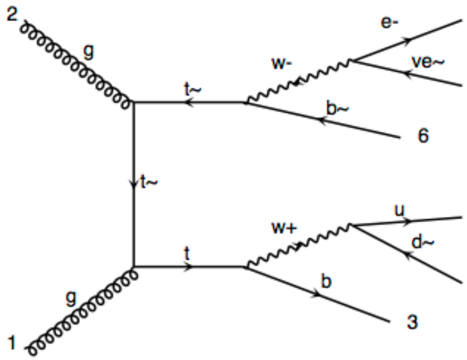


diagram 2 QCD=2, QED=4

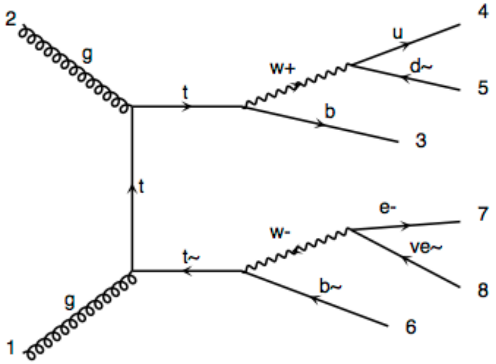


diagram 3 QCD=2, QED=4

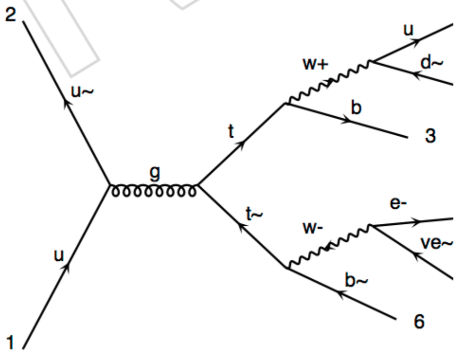
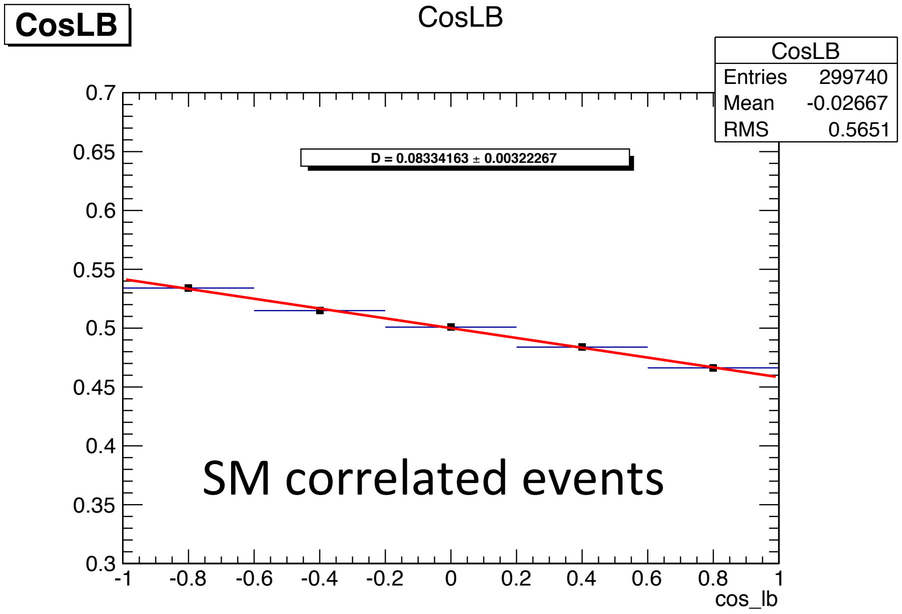


diagram 1 QCD=2, QED=4

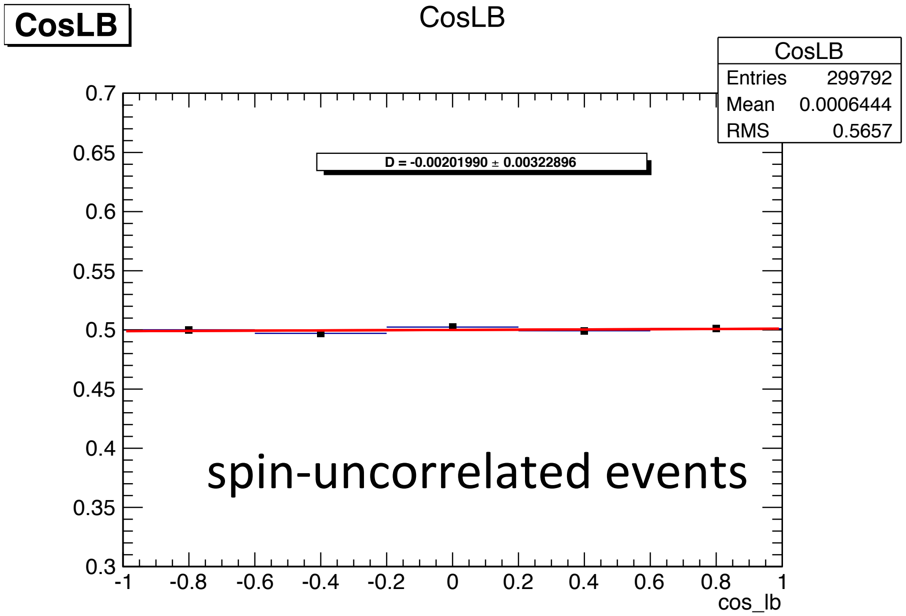
Method will be calibrated using MC@NLO (or PowHeg).

First Steps in the Measurement: Matrix Elements

- The implementation of matrix elements was tested by generating events using the default and spin-uncorrelated MEs implemented in MadGraph and checking the angular distributions and cross-sections.



SM correlated events



spin-uncorrelated events

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi_{lb}} = \frac{1}{2}\left(1 - D_{lb}\cos\varphi_{lb}\right)$$

W. Bernreuther et al. Nucl. Phys. B 690 (209) 81

The Measurement and Closure Tests

- With the ability to generate events in both hypotheses, we can validate the feasibility of this measurement.
- The measurement is two-fold:
  - First discriminate between SM and spin-uncorrelated hypotheses → hypothesis testing
  - Extract the spin correlation strength A by measuring the fraction of events f with SM spin correlations.

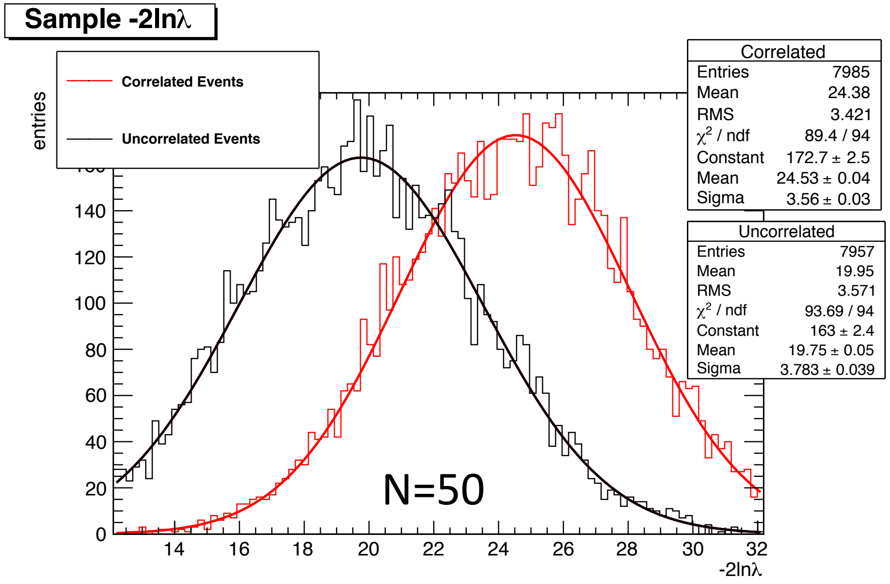
Closure Tests: Hypothesis Testing

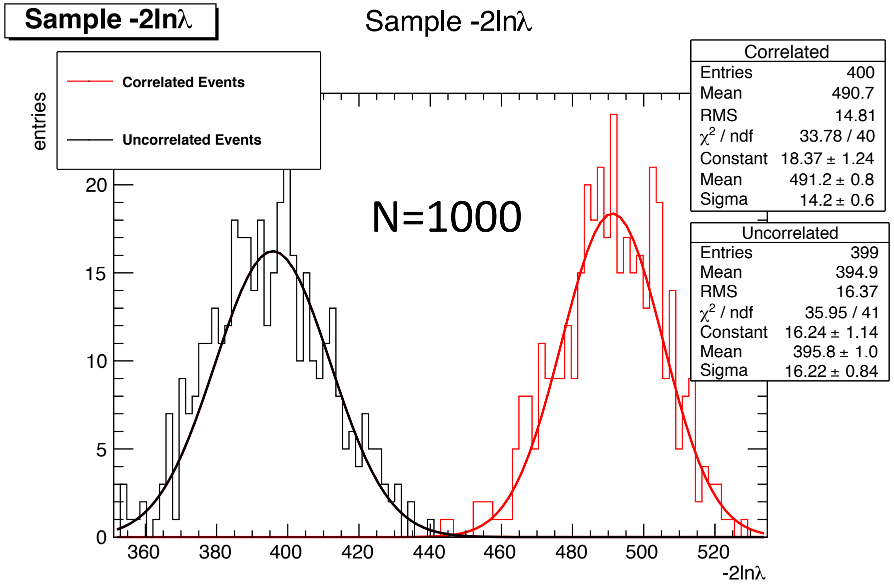
- The sample likelihood can be calculated from the event likelihoods: $-2\ln\lambda_{\text{event}}$

$$-2\ln\lambda_{sample} = -2\sum\ln\lambda_{event}$$

  - Generate two event pools (one SM and one spin-uncorrelated), with each event processed under both hypotheses.
  - Split event pools in pseudo-data of sample size N and calculate $-2\ln\lambda_{\text{sample}}$.

Closure Tests: Hypothesis Testing



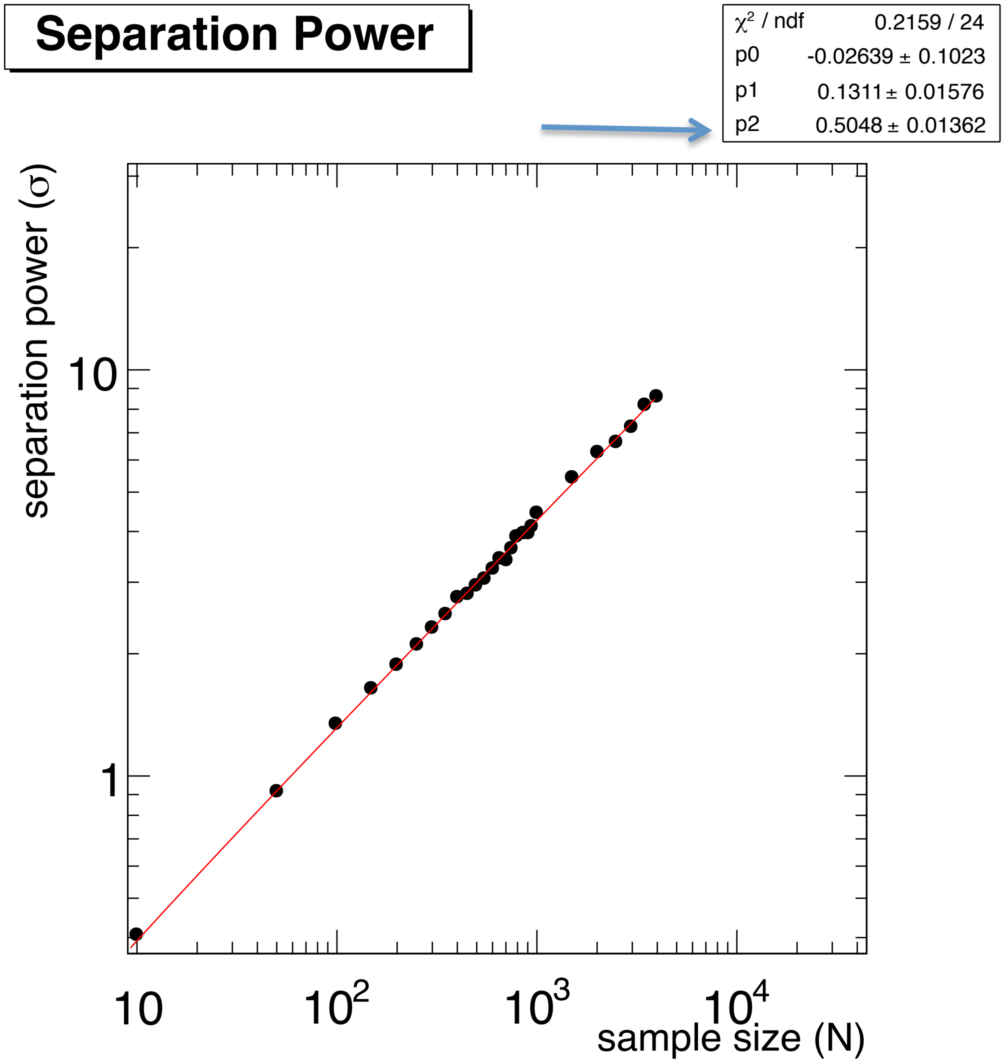


- Pseudo-experiments give a Gaussian distribution for $-2\ln\lambda_{\text{sample}}$.
- The separating power increases with sample size N and given by

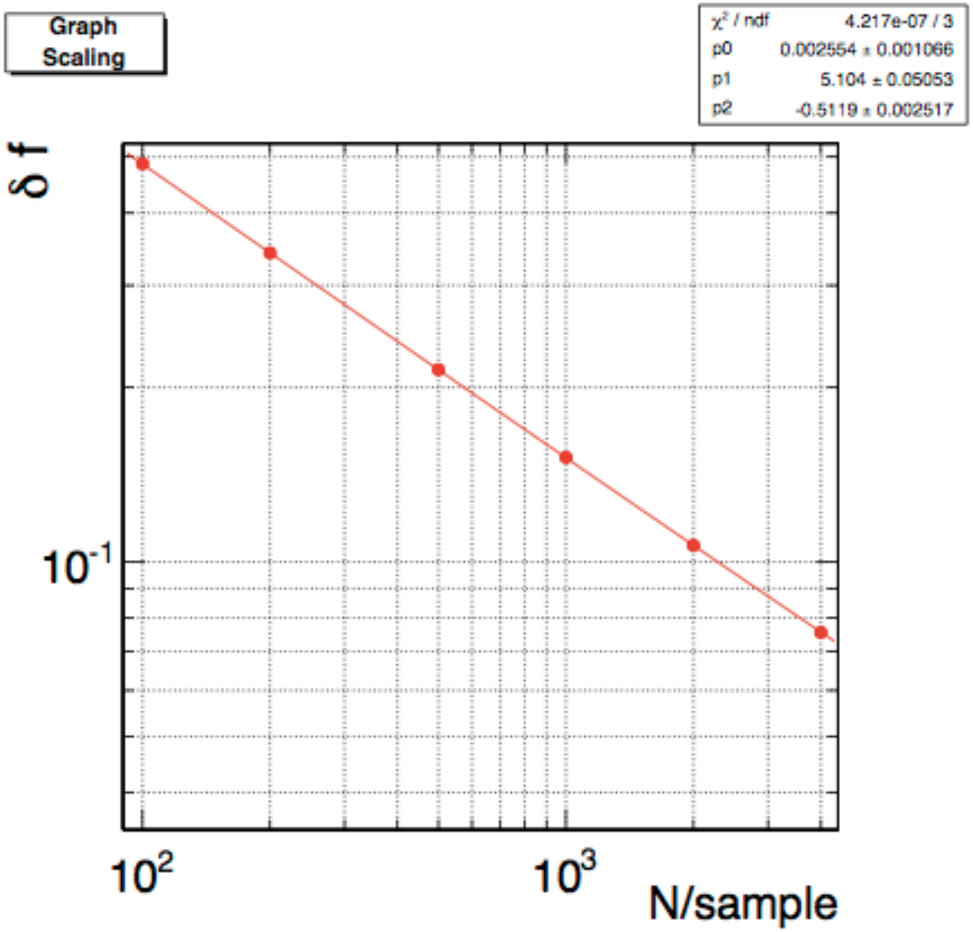
$$\sigma = \frac{\mu_1 - \mu_2}{\sqrt{\sigma_1^2 + \sigma_2^2}}$$

Closure Tests: Hypothesis Testing

- The separating power scales with the square root of the sample size, as expected.



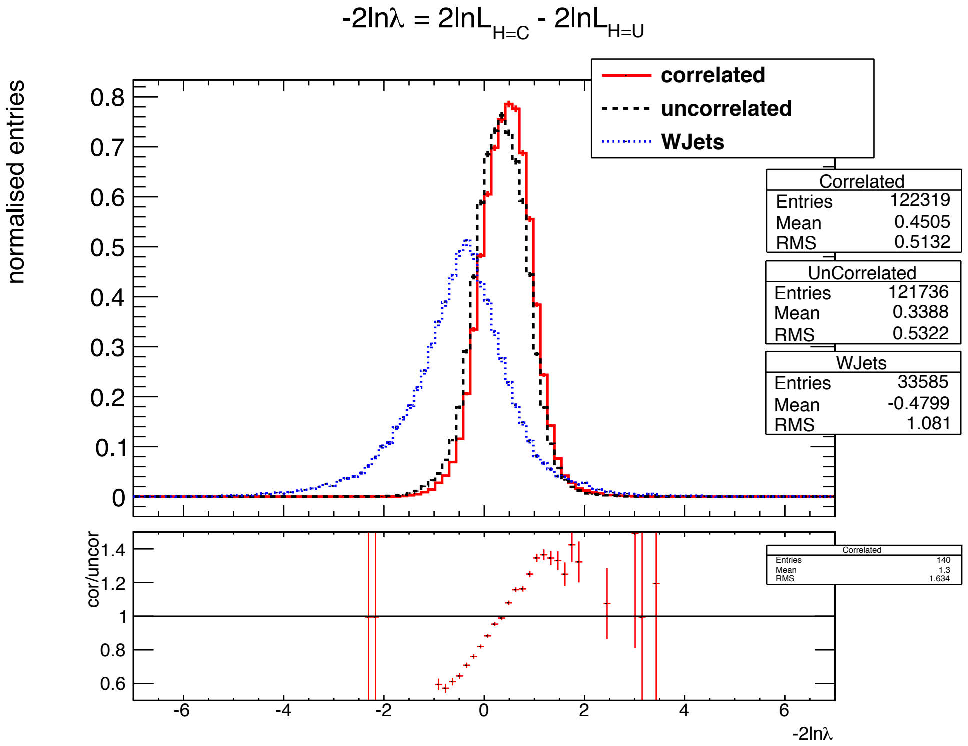
Error Scaling



- The mean fit error from pseudo-experiments vs. pseudo-experiment sample size.
- The error scales with 1/√N, as expected.
- ~100k high purity ttbar +jets events in 8 TeV CMS data (considering only up to 5 jets).
  - ~1% statistical precision at the generator level assuming an ideal detector.

Closure Tests: Spin Correlation Fraction

- $-2\ln\lambda_{evt}$: distribution with the most discriminating power.
- One template for SM events, one template for spin-uncorrelated events, (and template(s) for backgrounds).
  - Background likelihoods calculated using ttbar MEs on background events.



Template fit with maximum likelihood method using the fit model

$$\mathrm{m} = N_{t\bar{t}}\left[f^{SM}T_{SM} + \left(1 - f^{SM}\right)T_{spin-uncor}\right] + N_{bkg}T_{bkg}$$

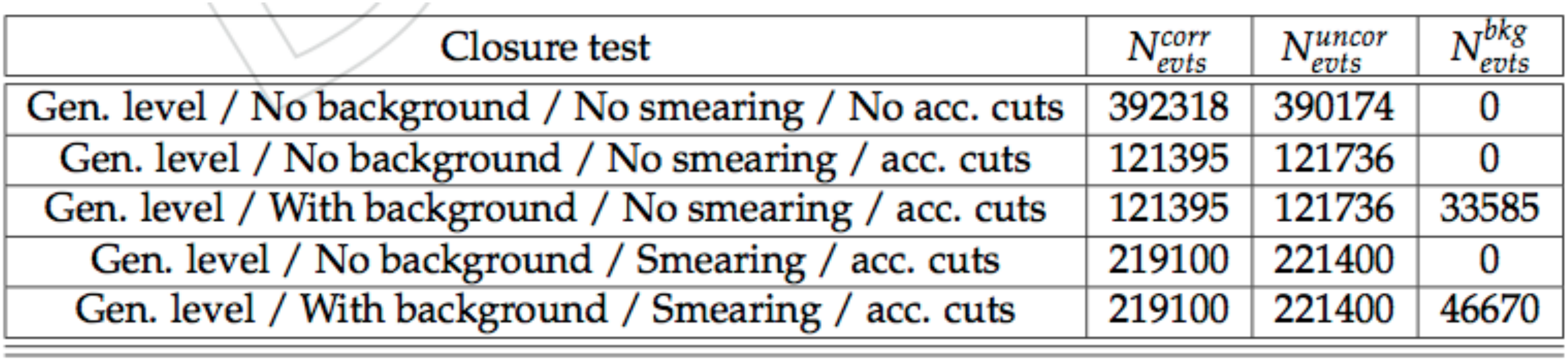
simultaneously extract f^{SM}, number of ttbar ($N_{tt\sim}$) and background (N_{bkg}) events

Closure Tests: Spin Correlation Fraction

- Closure tests
  - With varying spin correlation fractions.
  - Effects of backgrounds, acceptance cuts →
  - Transfer functions, ...

$$p_T(j) > 30\ \text{GeV}, |\eta(j)| < 2.4$$
$$p_T(e) > 30\ \text{GeV}, |\eta(e)| < 2.5$$

Double Gaussian for light jet and b jets.
Parametrization vs Energy and eta of the parton.



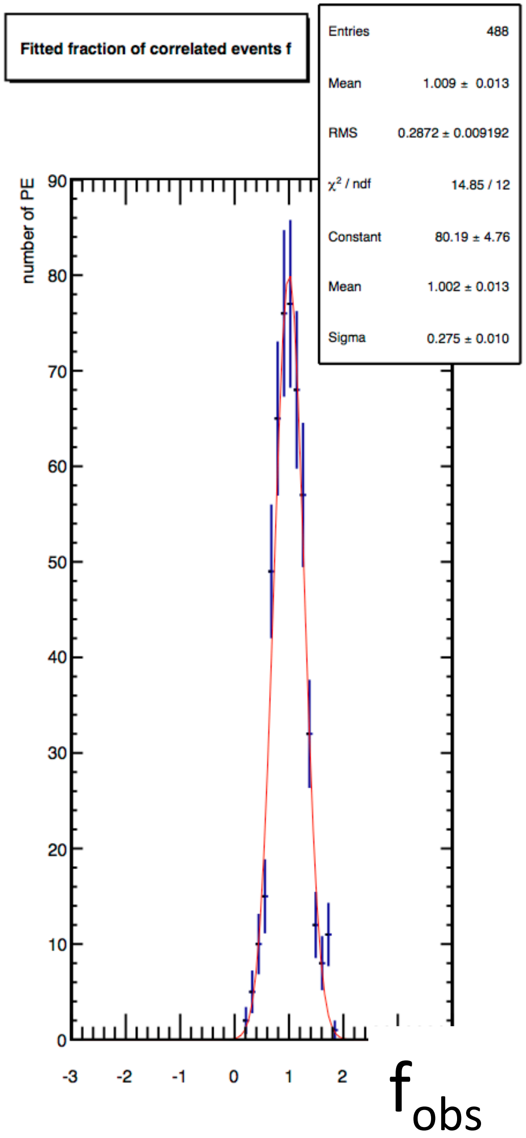
Closure test	N_{evts}^{corr}	N_{evts}^{uncor}	N_{evts}^{bkg}
Gen. level / No background / No smearing / No acc. cuts	392318	390174	0
Gen. level / No background / No smearing / acc. cuts	121395	121736	0
Gen. level / With background / No smearing / acc. cuts	121395	121736	33585
Gen. level / No background / Smearing / acc. cuts	219100	221400	0
Gen. level / With background / Smearing / acc. cuts	219100	221400	46670

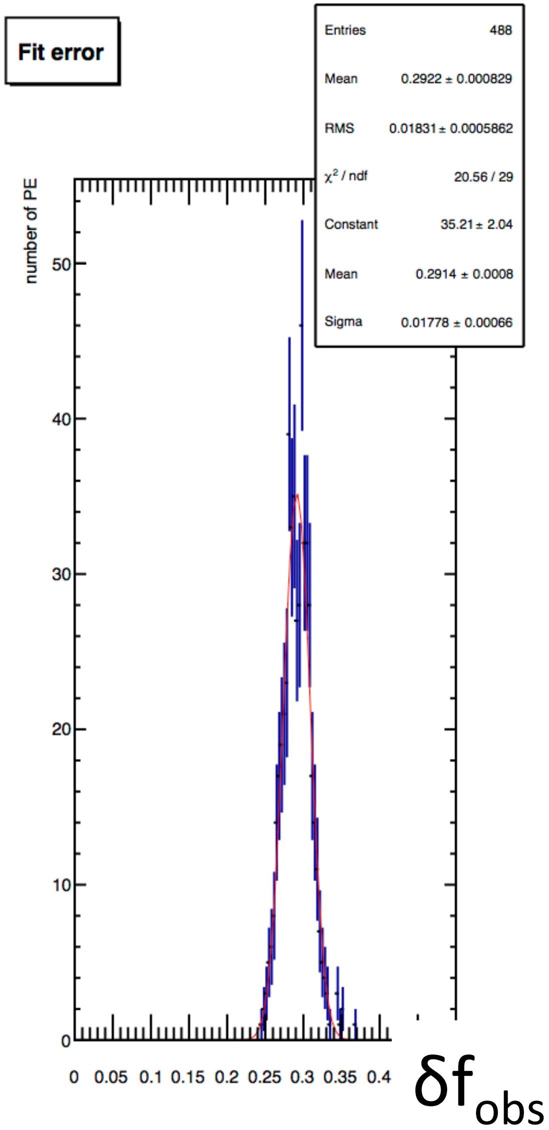
- Very CPU intensive, each event needs to be processed twice, 50 ev ~1h CPU time.
  - However, with the help of CERN computing resources, we have a reasonably fast turnaround time.

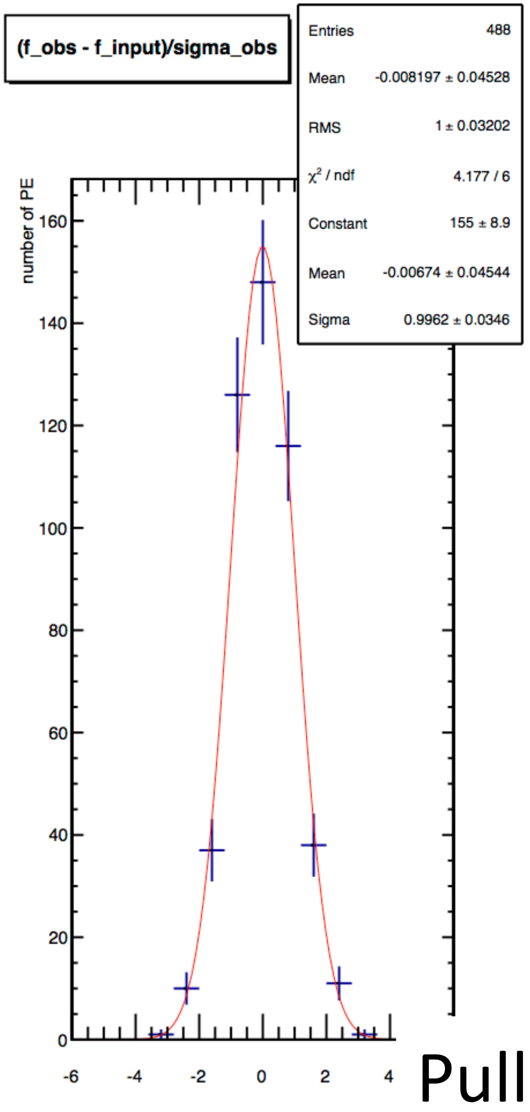
Closure Tests: Spin Correlation Fraction

- Generate pseudo-experiments of 500 events (Poisson fluctuated).
  - 10% Wjets, 90% SM events.
  - --> Expect the distributions to be a Gaussian centered around f=1, $N_{tt\sim}$=450 and N_{bkg}=50.
- Fits are performed with the RooFit package.
  - Template histograms are normalized and converted to PDFs.

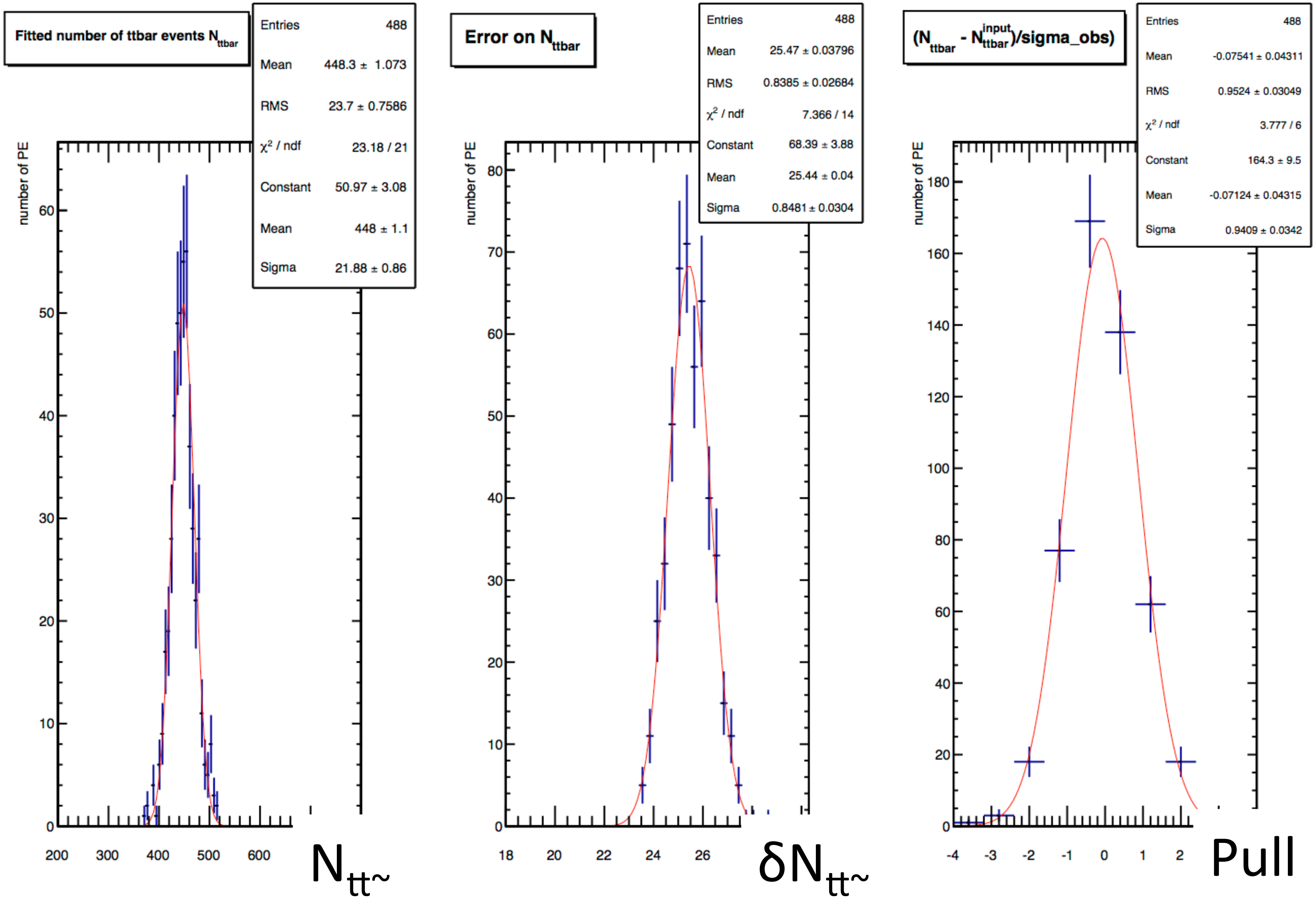
Closure Tests: Spin Correlation Fraction



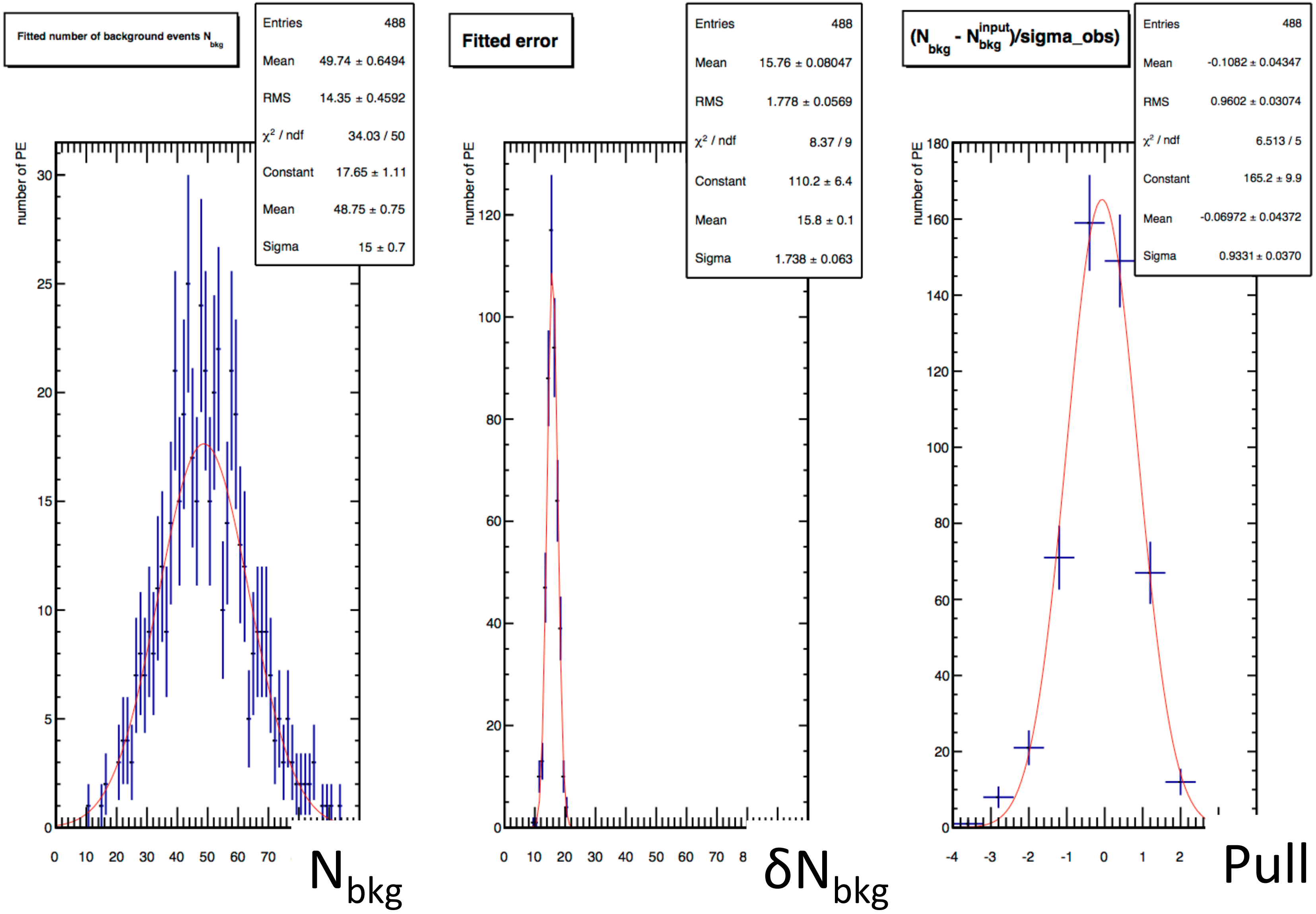




Closure Tests: Spin Correlation Fraction



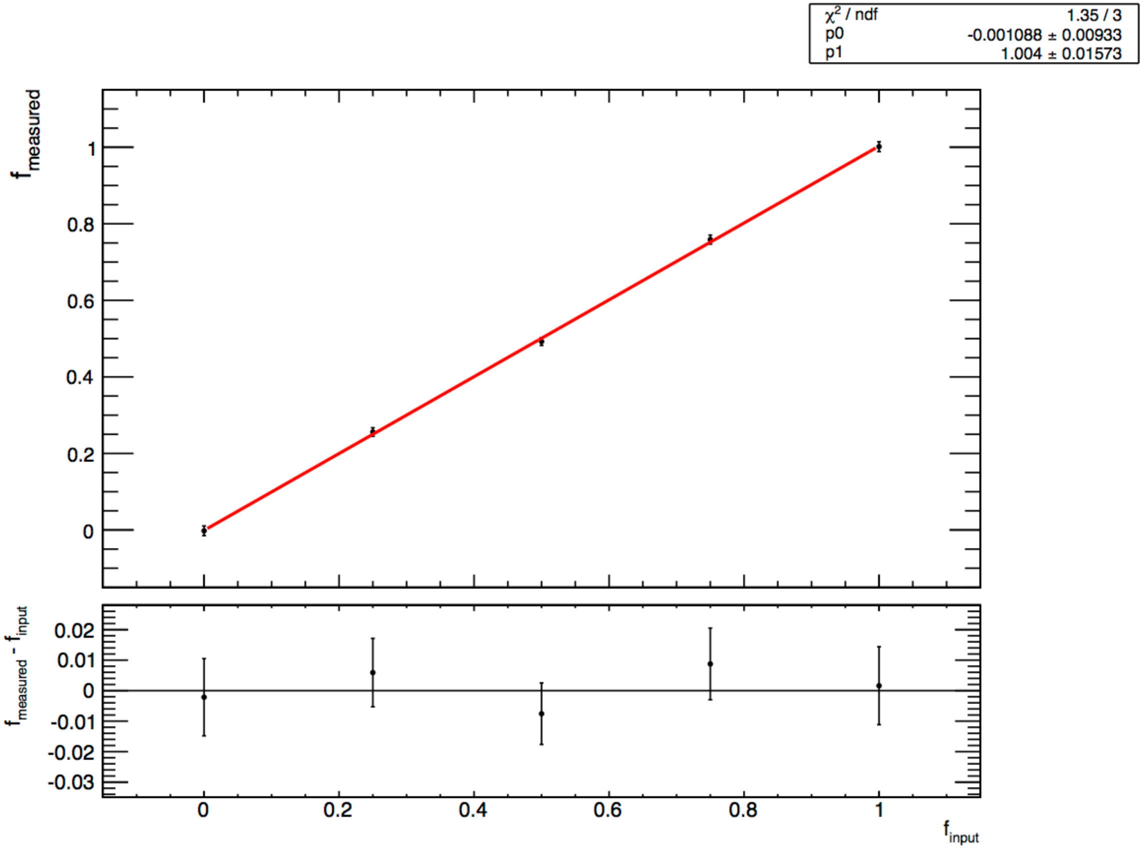
Closure Tests: Spin Correlation Fraction



Closure Tests: Spin Correlation Fraction

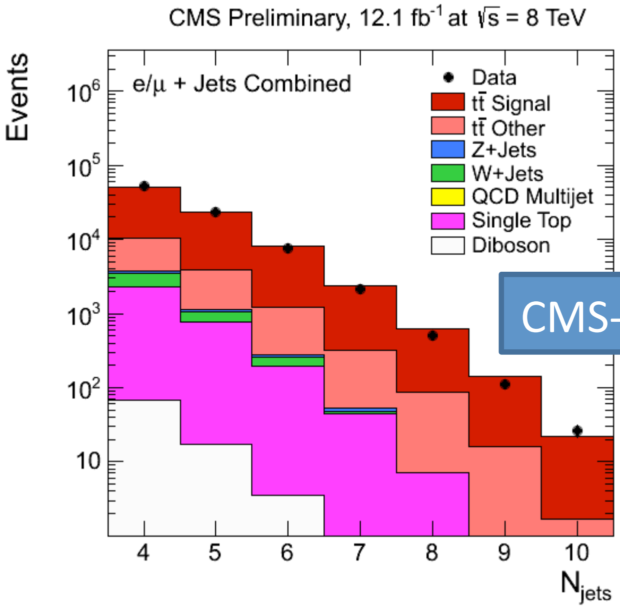
- We manually mix the two event pools (SM and spin-uncorrelated) to simulate samples with varying degrees of mixing.
- *We can extract any fraction f precisely without a bias.*

We correct the fit errors for correlations between the data points.



Closure Tests

- Closure tests are successful: we can extract the signal f, ttbar and background cross sections simultaneously.
- The closure tests assumed correct jet-parton assignments with no extra jets in the event.



CMS-TOP-12-027

+ MEs used in MEM are LO , i.e. can take only 4 jets as input.

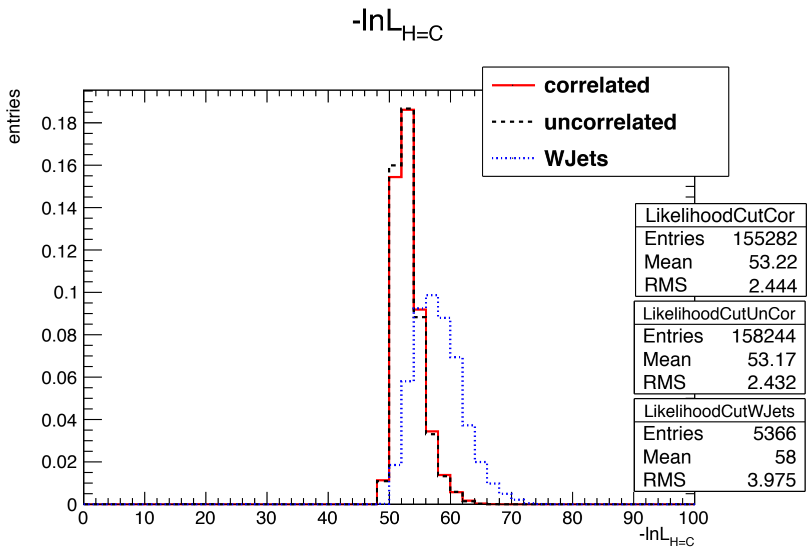
MEM+Kinematic Fitter

- Require ≥ 2 b-tags.
- Use a kinematic fitter
  - to choose the 4 jets coming from the ttbar decay
  - and calculate the likelihood only for the selected permutation
    - significant decrease in CPU requirements.

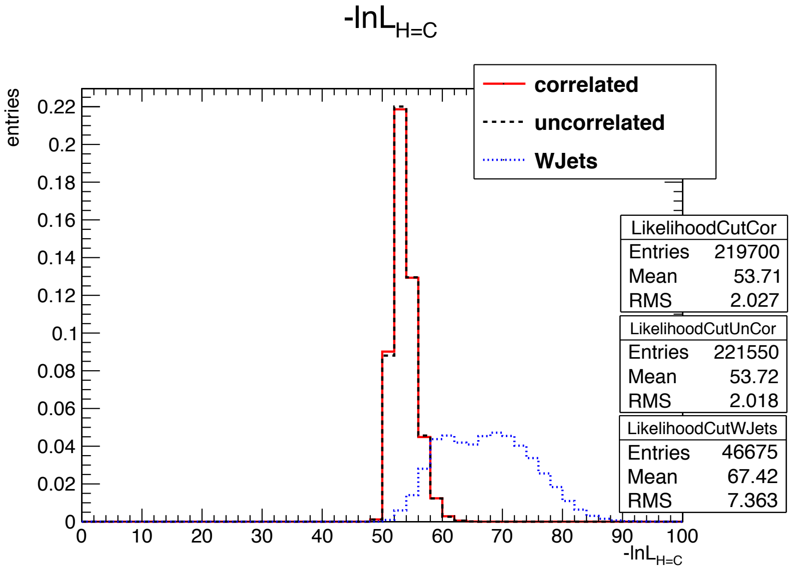
- **Kinematic fitter** modifies the kinematics within object resolutions to obtain kinematics most suitable with constraints (e.g. W_{had}=80.4 GeV, $m_{top}=m_{anti\text{-}top}$)
- The solution with the lowest χ^2 and consistent with b-tagging information is taken as the best estimate for the correct permutation.
  - *Can it simplify the transfer functions or make them obsolete?*

Likelihoods and Kinematic fitter

Kinematic fitter kinematics with quality cuts



No Kinematic fitter
All permutations in MadWeight



→ Likelihoods from SM & spin-uncor evts and bkg sample under the spin corr hypothesis (H=C)

Using the kinematics determined by kinematic fitter (or adding extra quality criteria) forces the background to be ttbar-like.

+ A certain contamination of wrong jet-parton permutations will always be present

→ Increases the uncertainty.

→ Running over all permutations in MadWeight ensures the correct one is always considered and yields smaller uncertainty.

I/FSR

- Our LO MEs do not treat radiated jets.
- Ignoring these means working with wrong kinematics.
    - Use only 4 and 5 jet events and treat them separately (or not).
    - Test the ISR treatment in MadWeight.
    - ..

Systematic Uncertainties

- Three types:
  - Type 0: Normalization uncertainties
    - absolute and background normalizations, integrated luminosity.
  - Type 1: Effects that change the template shapes but can be estimated w/o re-running MadWeight.
    - lepton, trigger, b-tag efficiencies vs pT and eta.
    - pile-up
    - Template stats., PDF uncertainties through weights
    - Kinematic Fit (effect of top mass window and chi2 cut if used).
  - Type 2: Effects that require re-running MadWeight →

Systematic Uncertainties

- Effects that require re-running MadWeight.
  - Jet energy scale and resolution
    - light jets and b jets
      - any uncertainty due to resolution or transfer functions are included in jet energy scale and resolution uncertainties.
    - Taylor expansion of the TFs suggested by Rieck et al. (yesterday) seems reasonable (to be tested. If works → type 1.).
  - Top quark mass
    - Samples with different assumed top mass values.
    - But re-weighting might work within δm_t (then → type 1)
  - ISR/FSR
  - Samples with different renorm. & fact. scales.
  - Method calibration
  - Signal and background modeling
  - Hadronization
  - Underlying event, Color reconnection
  - ...

→ Reweighting if only SM samples exist.

Summary

- Spin correlated and uncorrelated matrix elements implemented and tested.
- Validation and study of statistical properties at the generator level + generator level with smeared jets done.
- Studies with kinematic fit + MEM.
- *ttbar spin correlation can be measured with high statistical precision using template fits to likelihood ratios determined from matrix element calculations using MadWeight.*
- *A kinematic fitter helps the measurement in selecting the correct 4 jets to be used as input to MadWeight, however, using the updated kinematics from the kinematic fitter worsens the discriminating power and the precision of the measurement.*
- *Measurement to come in 2014 with 8 TeV LHC data!*

Thanks!

- W. Bernreuther for providing all necessary matrix elements.
- O. Mattelaer, P. Artoisenet for their great help in MadGraph and MadWeight.
- And S. Frixione for discussions and his help in theoretical issues.
- V. Adler for providing the transfer and resolution functions.
- Workshop organizers.