Spin correlation and top polarization at Tevatron and LHC

A historical perspective

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On behalf of the ATLAS, CDF, CMS and D0 collaborations

Top at Twenty, Fermilab, 9 April 2015

Top and angles

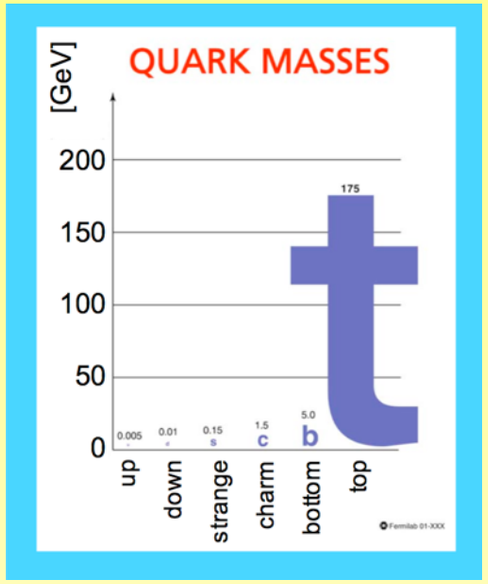
- The top quark is the heaviest elementary particle:

$$\mathcal{L}_{\text{Yukawa}} = -\lambda_t \overline{\psi_{Lt}} \Phi \psi_{Rt}$$

$$\lambda_t \approx 1 \text{ !!}$$

$$m_t >> m_b$$

$$\tau \approx 3.10^{-25} s << \tau_{\text{decorrel}} \approx 10^{-21} s$$

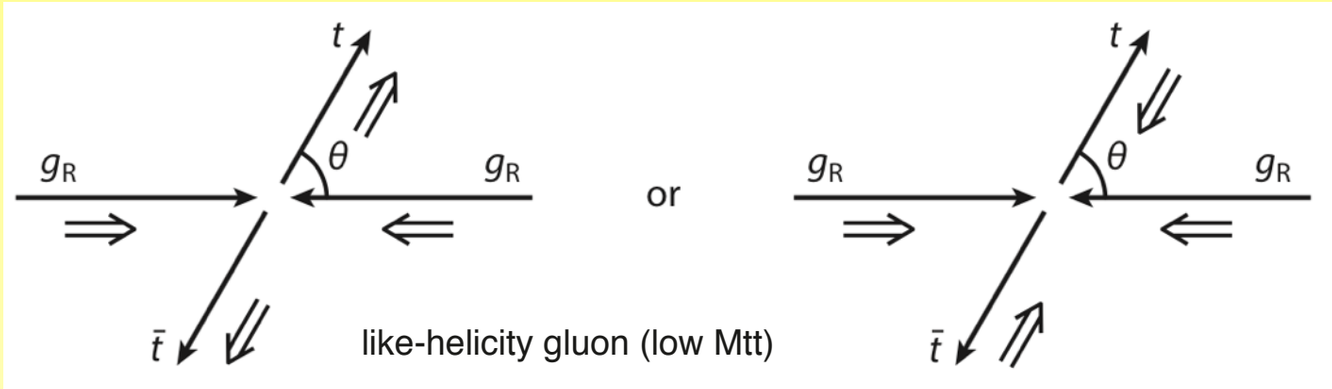


- Top quark spin and polarization
  - Spin: $t\bar{t}$ spins are correlated, information can be deduced from the angular distributions of decay products
    Can we then observe spin correlations in top quark pair production ?
  - Polarization:
    Negligible longitudinal polarization in $t\bar{t}$ (parity conservation in strong interaction)
    ≈100% polarization in single top (V-A structure)

- The top sector is unique to study quark spin and polarization
  - Can be altered by new physics (Z′, charged Higgs, SUSY, …)

Spin correlation predictions

- Spin configurations
  - Different and complementary at Tevatron and LHC



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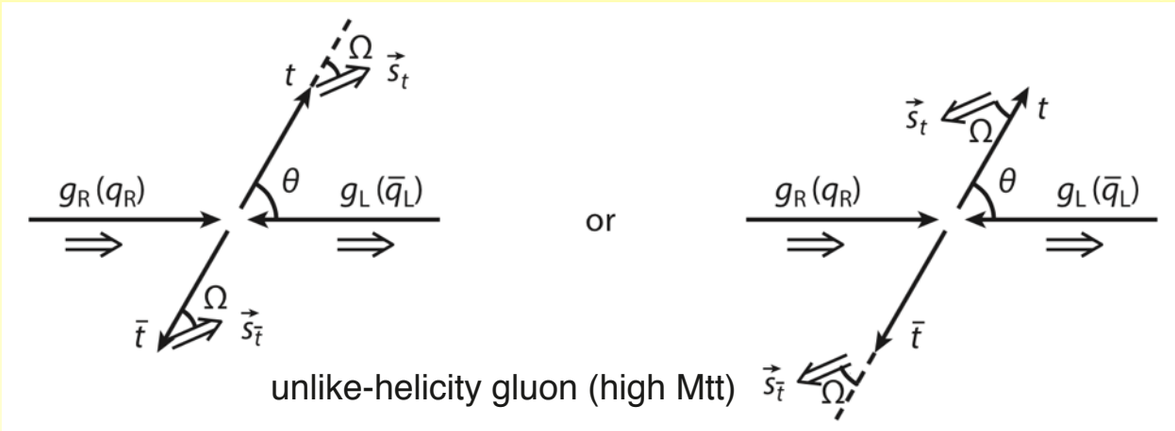


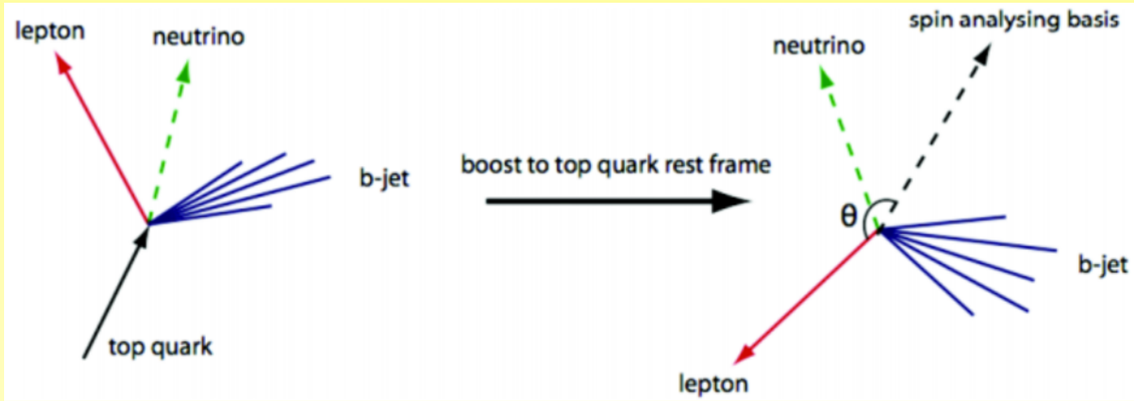
- Choice of quantization axis
  - Beam basis: direction of the colliding hadrons in the $t\bar{t}$ rest frame
  - Off-diagonal basis: vanishing $t\bar{t}$ like-spin contribution at LO
  - Helicity basis: t flight direction in the $t\bar{t}$ rest frame
  - Maximal basis: maximal correlation for production from gluon fusion

The $t\bar{t}$ decay product angular distribution

- Double differential distribution in polar angles
  - For two $t\bar{t}$ final-state decay product

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 + \alpha_1 P_1 \cos\theta_1 + \alpha_2 P_2 \cos\theta_2 + \alpha_1\alpha_2 A \cos\theta_1 \cos\theta_2)$$

θ: angle of the decay particule
P: degree of polarization (P≈0 in the SM)
α: spin-analyzing power of the decay particle
C = - $\alpha_1\alpha_2$A : $t\bar{t}$ spin correlation
(asymmetry in the $\cos\theta_1\cos\theta_2$ distribution)



$$C \equiv \frac{\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\downarrow} - \sigma_{\uparrow\downarrow} - \sigma_{\downarrow\uparrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\downarrow} + \sigma_{\uparrow\downarrow} + \sigma_{\downarrow\uparrow}} = \begin{cases} -0.456 & (-0.389) & \text{helicity at Tevatron,} \\ +0.910 & (+0.806) & \text{beamline at Tevatron,} \\ +0.918 & (+0.913) & \text{off-diagonal at Tevatron,} \\ +0.305 & (+0.311) & \text{helicity at LHC (14 TeV).} \end{cases}$$

LO (NLO: PRL87, 242002, 2001)

α=1 for the charged lepton and down-type quark at LO

α=-0.31 for u-type quark
α=-0.41 for b-quark

- Azimuthal correlations:
  - From interference between spin components
  - Easier to observe (lab frame)

$$\frac{1}{\sigma_t}\frac{d\sigma}{d\Delta\phi} = \frac{1}{2}(1 - D\cos\Delta\phi).$$

$$D = \begin{cases} +0.132 & \text{Tevatron,} \\ -0.353 & \text{LHC(14 TeV).} \end{cases}$$

for the dilepton channel
($t/\bar{t}$ rest frame)

Spin Correlation in $t\bar{t}$ Production from $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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Clark,[22] W.G. Cobau,[39] J. Cochran,[26] L. Coney,[34] B. Connolly,[27] W.E. Cooper,[29] D. Coppage,[36] D. Cullen-Vidal,[52] M.A.C. Cummings,[31] D. Cutts,[52] O.I. Dahl,[22] K. Davis,[21] K. De,[53] K. Del Signore,[42] M. Demarteau,[29] D. Denisov,[29] S.P. Denisov,[19] H.T. Diehl,[29] M. Diesburg,[29] G. Di Loreto,[29] P. Draper,[53] Y. Ducros,[10] L.V. Dudko,[18] S.R. Dugad,[13] A. Dyshkant,[19] D. Edmunds,[43] J. Ellison,[26] V.D. Elvira,[29] R. Engelmann,[48] S. Eno,[39] G. Eppley,[55] P. Ermolov,[18] O.V. Eroshin,[19] J. Estrada,[47] H. Evans,[45] V.N. Evdokimov,[19] T. Fahland,[25] S. Feher,[29] D. Fein,[21] T. Ferbel,[47] H.E. Fisk,[29] Y. Fisyak,[49] E. Flattum,[29] F. Fleuret,[22] M. Fortner,[31] K.C. Frame,[43] S. Fuess,[29] E. Gallas,[29] A.N. Galyaev,[19] P. Gartung,[26] V. Gavrilov,[17] R.J. Genik II,[20] K. Genser,[29] C.E. Gerber,[29] Y. Gershtein,[52] B. Gibbard,[49] R. Gilmartin,[27] G. Ginther,[47] B. Gobbi,[32] B. Gómez,[5] G. Gómez,[39] P.I. Goncharov,[19] J.L. 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(D0 Collaboration)

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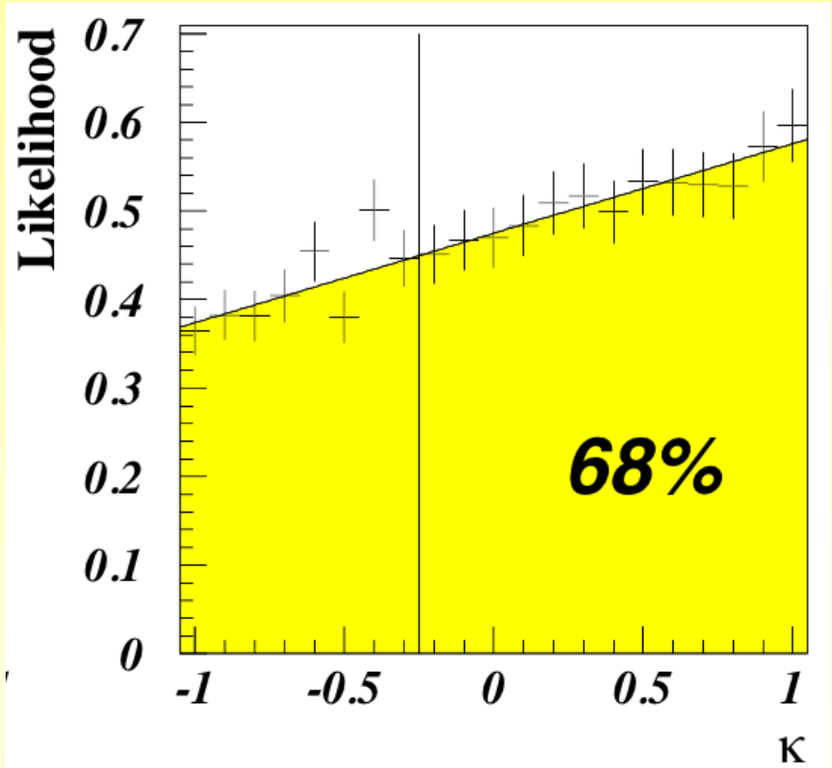
First search for spin correlation

PRL85, 256 (2000)

- Tevatron Run I, 125 pb^{-1}
  - Off-diagonal basis (optimal for $q\bar{q}$)
  - SM prediction: C=0.88 (@ 1.8 TeV)
  - 6 events in the dilepton channel, reconstructed with the neutrino weighting method
  - 2D binned likelihood ($\cos\theta^+$, $\cos\theta^-$)

Event Number	Event type	$\mathcal{A}$
10822	ee	0.34
12814	$e\mu$	-0.16
15530	$\mu\mu$	0.50
26920	$e\mu$	0.85
30317	ee	0.52
417	$e\mu$	-0.19
$< \mathcal{A} >$		0.31 ± 0.22



Result:
C > -0.15 at 95%CL

Measurement of $t\bar{t}$ spin correlation in $p\bar{p}$ collisions using the CDF II detector at the Tevatron

T. Aaltonen,[21] B. Álvarez González,[9,w] S. Amerio,[41a] D. Amidei,[32] A. Anastassov,[36] A. Annovi,[17] J. Antos,[12] G. Apollinari,[15] J. A. Appel,[15] A. Apresyan,[46] T. Arisawa,[56] A. Artikov,[13] J. Asaadi,[51] W. Ashmanskas,[15] B. Auerbach,[59] A. Aurisano,[51] F. Azfar,[40] W. Badgett,[15] A. Barbaro-Galtieri,[26] V. E. Barnes,[46] B. A. Barnett,[23] P. Barria,[44c,44a] P. Bartos,[12] M. Bauce,[41b,41a] G. Bauer,[30] F. Bedeschi,[44a] D. Beecher,[28] S. Behari,[23] G. Bellettini,[44b,44a] J. Bellinger,[58] D. Benjamin,[14] A. Beretvas,[15] A. Bhatti,[48] M. Binkley,[15,a] D. Bisello,[41b,41a] I. Bizjak,[28,aa] K. R. Bland,[5] B. Blumenfeld,[23] A. Bocci,[14] A. Bodek,[47] D. Bortoletto,[46] J. Boudreau,[45] A. Boveia,[11] B. Brau,[15,b] L. Brigliadori,[6b,6a] A. Brisuda,[12] C. Bromberg,[33] E. Brucken,[21] M. Bucciantonio,[44b,44a] J. Budagov,[13] H. S. Budd,[47] S. Budd,[22] K. Burkett,[15] G. Busetto,[41b,41a] P. Bussey,[19] A. Buzatu,[31] C. Calancha,[29] S. 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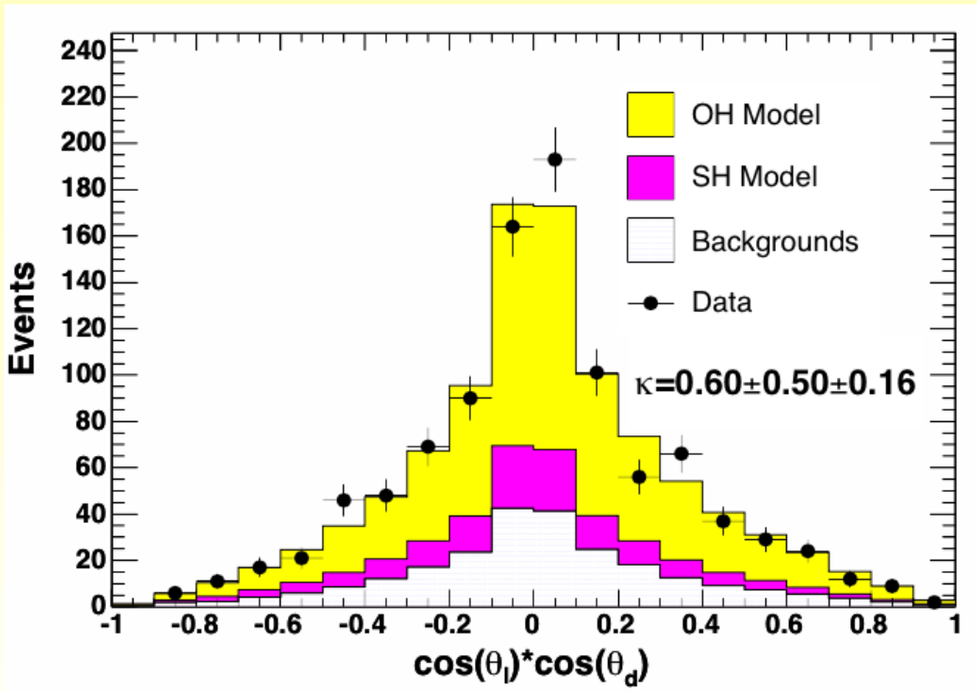
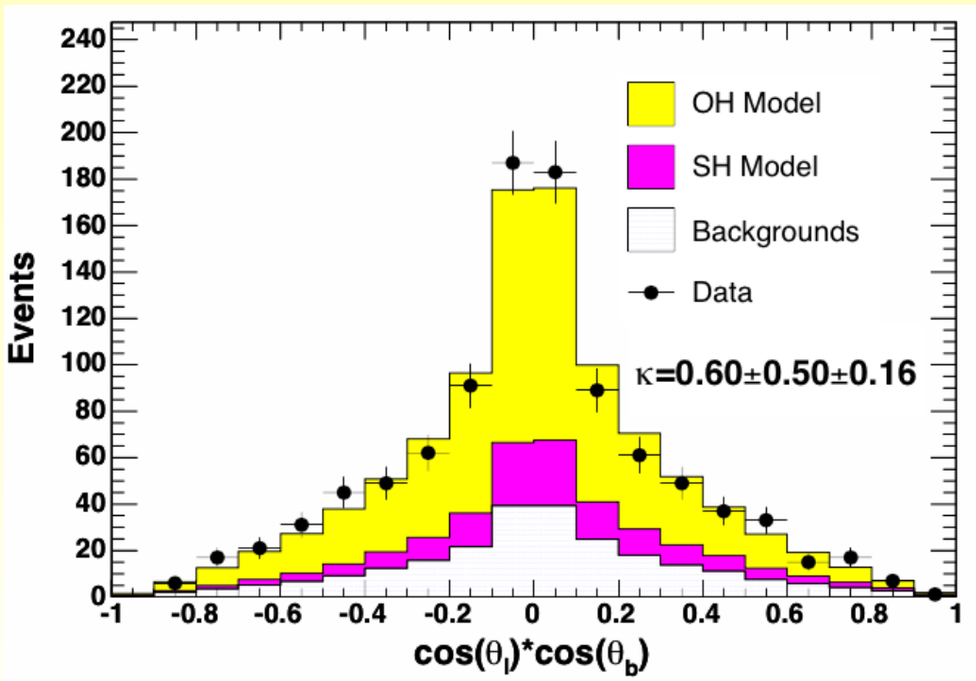
First spin correlation analysis in the lepton+jets channel

PRD83, 031104(R) (2011)

- Tevatron Run II, 4.3 fb^{-1}
  - Helicity basis
  - SM prediction: κ=0.40 (@ 1.96 TeV)
  - Down-type quark: jet closest to the b-jet (in the W rest frame) Correct assignment 60% of the time
  - Template fit to the distributions of $\cos\theta_l * \cos\theta_d$ and $\cos\theta_l * \cos\theta_b$

$$\kappa = 0.60 \pm 0.50\ (\text{stat}) \pm 0.16\ (\text{syst})$$





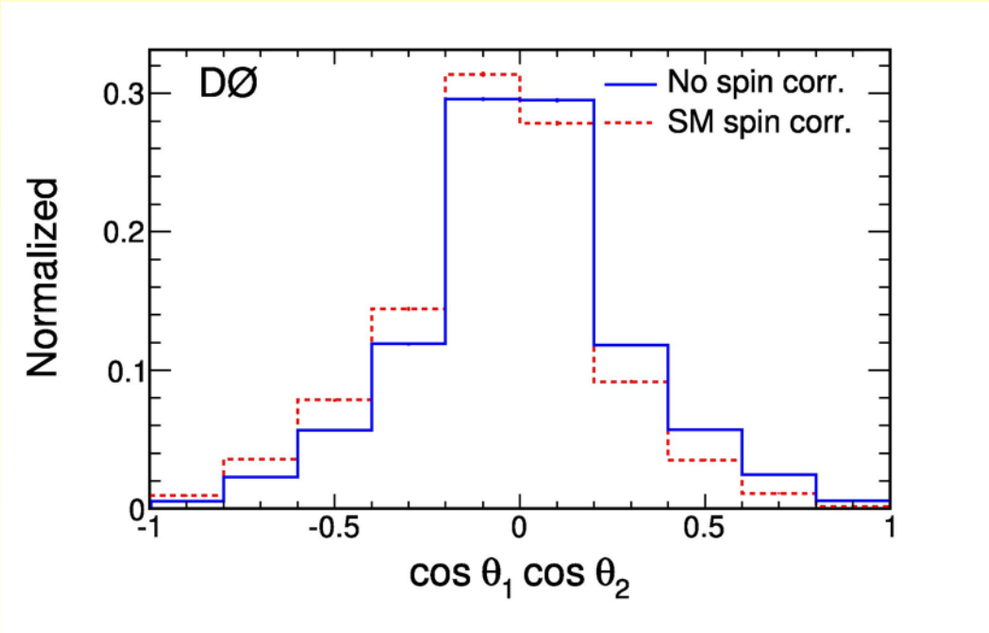
Spin correlation analysis in the dilepton channel

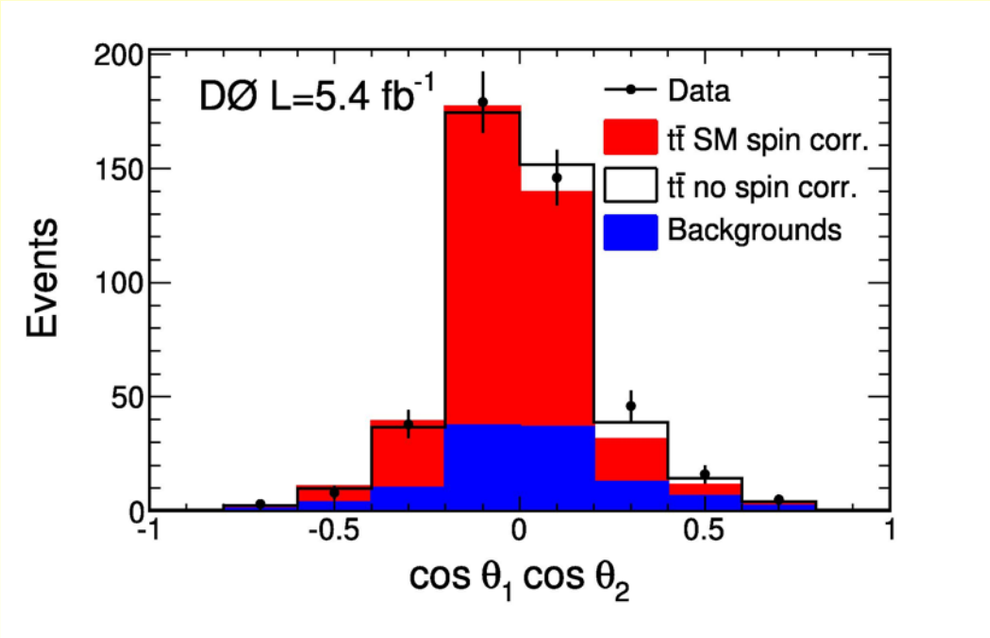
PLB702, 16 (2011)

- Tevatron Run II, 5.4 fb^{-1}
  - Beam basis
  - SM prediction: C=0.78 (@ 1.96 TeV, NLO)
  - Dilepton event reconstructed with the neutrino weighting method
  - Template fit to the distribution of $\cos\theta_{l1} * \cos\theta_{l2}$, simultaneous fit with the $t\bar{t}$ cross section

	$t\bar{t}$	Z	Diboson	Instrumental	Expected	Observed
Number of events	324^{+28}_{-28}	75^{+13}_{-13}	17^{+3}_{-3}	23^{+4}_{-4}	439^{+36}_{-36}	441

$$C = 0.10^{+0.45}_{-0.45}\ (\text{stat+syst})$$





First measurement of spin correlation using a matrix element approach

PRL107, 033001 (2011)

- Tevatron Run II, 5.4 fb^{-1}
  - Beam basis
  - Fraction f of $t\bar{t}$ event with correlated spin over total number of $t\bar{t}$ (f=1 in the SM)
  - Using a discriminant R based on per-event probability

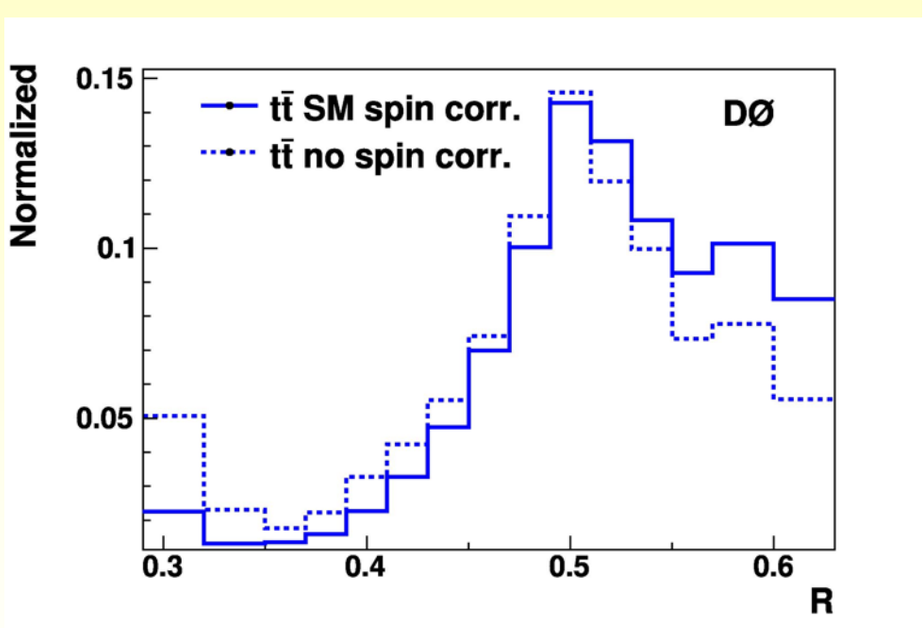
$$R = \frac{P_{\rm sgn}(x; H = c)}{P_{\rm sgn}(x; H = u) + P_{\rm sgn}(x; H = c)}$$

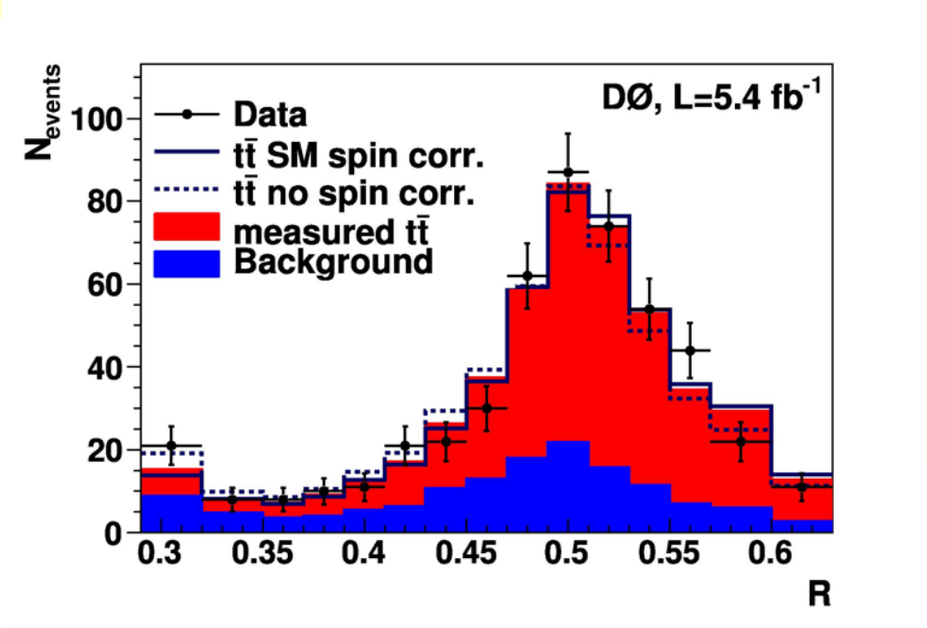
$$P_{\rm sgn}(x; H) = \frac{1}{\sigma_{\rm obs}} \int f_{\rm PDF}(q_1)\, f_{\rm PDF}(q_2) {\rm d}q_1 {\rm d}q_2 \cdot \frac{(2\pi)^4 \left|\mathcal{M}(y, H)\right|^2}{q_1 q_2 s} W(x, y)\, {\rm d}\Phi_6.$$

$$f_{\rm meas} = 0.74^{+0.40}_{-0.41}\,({\rm stat+syst})$$

$$C_{\rm meas} = 0.57 \pm 0.31({\rm stat + syst})$$

improve sensitivity by ~ 30% (compared to using a single distribution)





First evidence for spin correlation

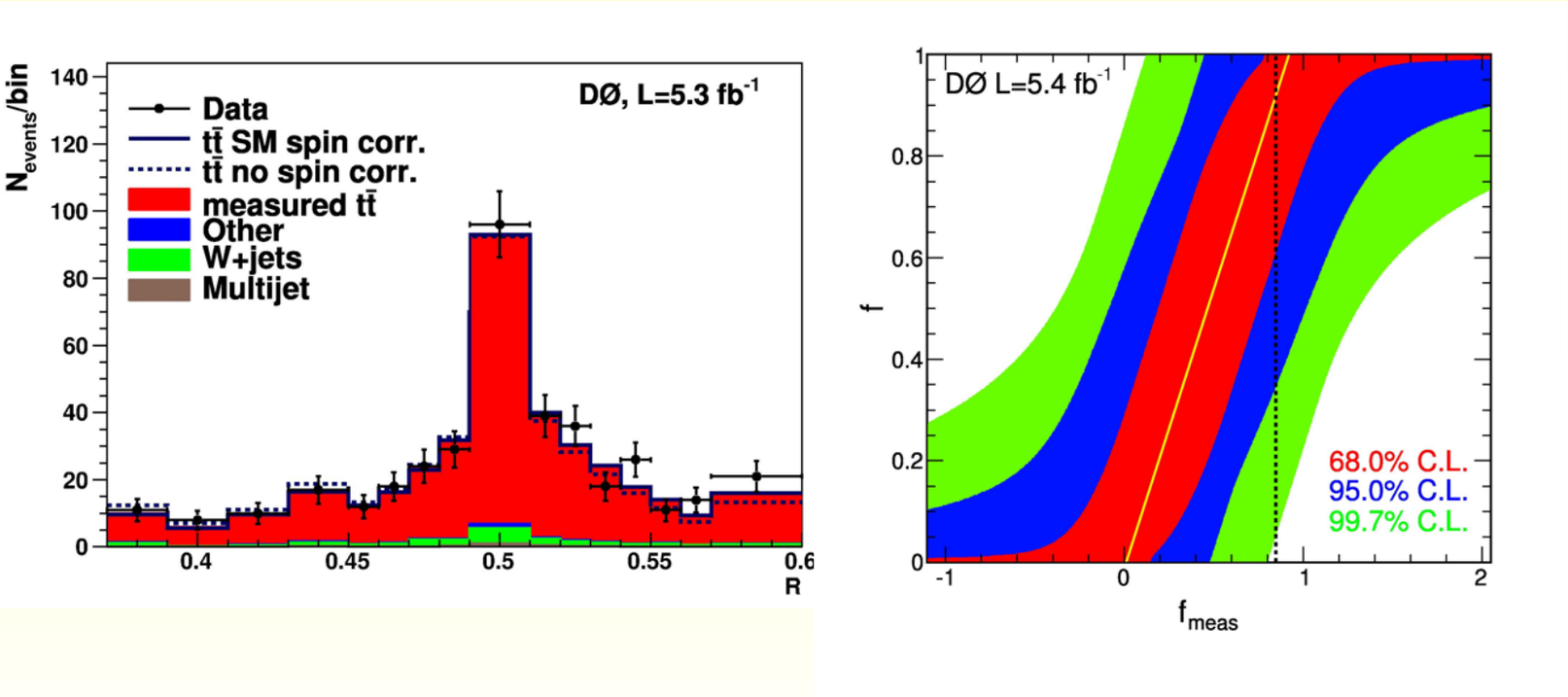
PRL108, 032004 (2012)

- Tevatron Run II, 5.3 fb^{-1}
  - Beam basis
  - Lepton+jets channel (combined with dilepton events)
    at least 2 b-jet candidates
  - Using a discriminant based on per-event probability computed with the $t\bar{t}$ matrix element
    all jet-parton assignment considered

$$f_{\mathrm{meas}} = 0.85 \pm 0.29(\mathrm{stat} + \mathrm{syst})$$

3.1 SD away from f=0

exclude: $f < 0.344\ (0.052)$ at the $95(99.7)\%$ C.L.



Source	+1SD	−1SD
Muon identification	0.003	−0.003
Electron identification and smearing	0.009	−0.008
PDF	0.058	−0.051
m_t	0.024	−0.040
Triggers	0.007	−0.008
Opposite charge selection	0.002	−0.002
Jet energy scale	0.005	−0.028
Jet reconstruction and identification	0.007	−0.035
b-tagging	0.012	−0.012
Normalization	0.039	−0.043
MC statistics	0.015	−0.015
Instrumental background	0.003	−0.003
Luminosity	0.023	−0.023
Multijet background	0.007	−0.007
Other	0.007	−0.007
MC statistics for template fits	0.156	−0.156
Total systematic uncertainty	0.176	−0.184
Statistical uncertainty	0.251	−0.258

PRL 108, 212001 (2012) PHYSICAL REVIEW LETTERS week ending 25 MAY 2012

Observation of Spin Correlation in $t\bar{t}$ Events from pp Collisions at $\sqrt{s} = 7$ TeV Using the ATLAS Detector

G. Aad *et al.**

(ATLAS Collaboration)

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Batley,[27] A. Battaglia,[16] M. Battistin,[29] F. Bauer,[135] H. S. Bawa,[142,f] S. Beale,[97] T. Beau,[77] P. H. Beauchemin,[160] R. Beccherle,[49a] P. Bechtle,[20] H. P. Beck,[16] S. Becker,[97] M. Beckingham,[137] K. H. Becks,[173] A. J. Beddall,[18c] A. Beddall,[18c] S. Bedikian,[174] V. A. Bednyakov,[64] C. P. Bee,[82] M. Begel,[24] S. Behar Harpaz,[151] P. K. Behera,[62] M. Beimforde,[98] C. Belanger-Champagne,[84] P. J. Bell,[48] W. H. Bell,[48] G. Bella,[152] L. Bellagamba,[19a] F. Bellina,[29] M. Bellomo,[29] A. Belloni,[56] O. Beloborodova,[106,g] K. Belotskiy,[95] O. Beltramello,[29] O. Benary,[152] D. Benchekroun,[134a] C. Benchouk,[82] M. Bendel,[80] N. Benekos,[164] Y. Benhammou,[152] E. Benhar Noccioli,[48] J. A. Benitez Garcia,[158b] D. P. Benjamin,[44] M. Benoit,[114] J. R. Bensinger,[22] K. Benslama,[129] S. Bentvelsen,[104] D. Berge,[29] E. Bergeaas Kuutmann,[41] N. Berger,[4] F. Berghaus,[168] E. Berglund,[104] J. Beringer,[14] P. Bernat,[76] R. Bernhard,[47] C. Bernius,[24] T. Berry,[75] C. Bertella,[82] A. Bertin,[19a,19b] F. Bertinelli,[29] F. Bertolucci,[121a,121b] M. I. Besana,[88a,88b] N. Besson,[135] S. Bethke,[98] W. Bhimji,[45] R. M. Bianchi,[29] M. Bianco,[71a,71b] O. Biebel,[97] S. P. Bieniek,[76] K. Bierwagen,[53] J. Biesiada,[14] M. Biglietti,[133a] H. Bilokon,[46] M. Bindi,[19a,19b] S. Binet,[114] A. Bingul,[18c] C. Bini,[131a,131b] C. Biscarat,[176] U. Bitenc,[47] K. M. Black,[21] R. E. Blair,[5] J.-B. Blanchard,[135] G. Blanchot,[29] T. Blazek,[143a] C. Blocker,[22] J. Blocki,[38] A. Blondel,[48] W. Blum,[80] U. Blumenschein,[53] G. J. Bobbink,[104] V. B. Bobrovnikov,[106] S. S. Bocchetta,[78] A. Bocci,[44] C. R. Boddy,[117] M. Boehler,[41] J. Boek,[173] N. Boelaert,[35] J. A. Bogaerts,[29] A. Bogdanchikov,[106] A. Bogouch,[89,a] C. Bohm,[145a] J. Bohm,[124] V. Boisvert,[75] T. Bold,[37] V. Boldea,[25a] N. M. Bolnet,[135] M. Bomben,[77] M. Bona,[74] V. G. Bondarenko,[95] M. Bondioli,[162] M. Boonekamp,[135] C. N. Booth,[138] S. Bordoni,[77] C. Borer,[16] A. Borisov,[127] G. Borissov,[70] I. Borjanovic,[12a] M. Borri,[81] S. Borroni,[86] V. Bortolotto,[133a,133b] K. Bos,[104] D. Boscherini,[19a] M. Bosman,[11] H. Boterenbrood,[104] D. Botterill,[128] J. Bouchami,[92] J. Boudreau,[122] E. V. Bouhova-Thacker,[70] D. Boumediene,[33] C. Bourdarios,[114] N. Bousson,[82] A. Boveia,[30] J. Boyd,[29] I. R. Boyko,[64] N. I. Bozhko,[127] I. Bozovic-Jelisavcic,[12b] J. Bracinik,[17] A. Braem,[29] P. Branchini,[133a] G. W. Brandenburg,[56] A. Brandt,[7] G. Brandt,[117] O. Brandt,[53] U. Bratzler,[155] B. Brau,[83] J. E. Brau,[113] H. M. Braun,[173] B. Brelier,[157] J. Bremer,[29] K. Brendlinger,[119] R. Brenner,[165] S. Bressler,[170] D. Britton,[52] F. M. Brochu,[27] I. Brock,[20] R. Brock,[87] T. J. Brodbeck,[70] E. Brodet,[152] F. Broggi,[88a] C. Bromberg,[87] J. Bronner,[98] G. Brooijmans,[34] W. K. Brooks,[31b] G. Brown,[81] H. Brown,[7] P. A. Bruckman de Renstrom,[38] D. Bruncko,[143b] R. Bruneliere,[47] S. Brunet,[60] A. Bruni,[19a] G. Bruni,[19a] M. Bruschi,[19a] T. Buanes,[13] Q. Buat,[54] F. Bucci,[48] J. Buchanan,[117] N. J. Buchanan,[2] P. Buchholz,[140] R. M. Buckingham,[117] A. G. Buckley,[45] S. I. Buda,[25a] I. A. Budagov,[64] B. Budick,[107] V. Büscher,[80] L. Bugge,[116] O. Bulekov,[95] M. Bunse,[42] T. Buran,[116] H. Burckhart,[29] S. Burdin,[72] T. Burgess,[13] S. Burke,[128] E. Busato,[33] P. Bussey,[52] C. P. Buszello,[165] F. Butin,[29] B. Butler,[142] J. M. Butler,[21] C. M. Buttar,[52] J. M. Butterworth,[76] W. Buttinger,[27] S. Cabrera Urbán,[166] D. Caforio,[19a,19b] O. Cakir,[3a] P. Calafiura,[14] G. Calderini,[77] P. Calfayan,[97] R. Calkins,[105] L. P. Caloba,[23a] R. Caloi,[131a,131b] D. Calvet,[33] S. Calvet,[33] R. Camacho Toro,[33] P. Camarri,[132a,132b] M. Cambiaghi,[118a,118b] D. Cameron,[116] L. M. Caminada,[14] S. Campana,[29] M. Campanelli,[76] V. Canale,[101a,101b] F. Canelli,[30,h] A. Canepa,[158a] J. Cantero,[79] L. Capasso,[101a,101b] M. D. M. Capeans Garrido,[29] I. Caprini,[25a] M. Caprini,[25a] D. Capriotti,[98] M. Capua,[36a,36b] R. Caputo,[80] R. Cardarelli,[132a] T. Carli,[29] G. Carlino,[101a] L. Carminati,[88a,88b] B. Caron,[84] S. Caron,[103] E. Carquin,[31b] G. D. Carrillo Montoya,[171] A. A. Carter,[74] J. R. Carter,[27] J. Carvalho,[123a,i] D. Casadei,[107] M. P. Casado,[11] M. Cascella,[121a,121b] C. Caso,[49a,49b,a] A. M. Castaneda Hernandez,[171] E. Castaneda-Miranda,[171] V. Castillo Gimenez,[166] N. F. Castro,[123a] G. Cataldi,[71a] F. Cataneo,[29] A. Catinaccio,[29] J. R. Catmore,[29] A. Cattai,[29] G. Cattani,[132a,132b] S. Caughron,[87] D. Cauz,[163a,163c] P. Cavalleri,[77] D. Cavalli,[88a] M. Cavalli-Sforza,[11] V. Cavasinni,[121a,121b] F. Ceradini,[133a,133b] A. S. Cerqueira,[23b] A. Cerri,[29] L. Cerrito,[74] F. Cerutti,[46] S. A. Cetin,[18b] F. Cevenini,[101a,101b] A. Chafaq,[134a] D. Chakraborty,[105] K. Chan,[2] B. Chapleau,[84] J. D. Chapman,[27] J. W. Chapman,[86] E. Chareyre,[77] D. G. Charlton,[17] V. Chavda,[81] C. A. Chavez Barajas,[29] S. Cheatham,[84] S. Chekanov,[5] S. V. Chekulaev,[158a] G. A. Chelkov,[64] M. A. Chelstowska,[103] C. Chen,[63] H. Chen,[24] S. Chen,[32c] T. Chen,[32c] X. Chen,[171] S. Cheng,[32a] A. Cheplakov,[64] V. F. Chepurnov,[64] R. Cherkaoui El Moursli,[134e] V. Chernyatin,[24] E. Cheu,[6]

S. L. Cheung,[157] L. Chevalier,[135] G. Chiefari,[101a,101b] L. Chikovani,[50a] J. T. Childers,[29] A. Chilingarov,[70] G. Chiodini,[71a] A. S. Chisholm,[17] R. T. Chislett,[76] M. V. Chizhov,[64] G. Choudalakis,[30] S. Chouridou,[136] I. A. Christidi,[76] A. Christov,[47] D. Chromek-Burckhart,[29] M. L. Chu,[150] J. Chudoba,[124] G. Ciapetti,[131a,131b] A. K. Ciftci,[3a] R. Ciftci,[3a] D. Cinca,[33] V. Cindro,[73] M. D. Ciobotaru,[162] C. Ciocca,[19a] A. Ciocio,[14] M. Cirilli,[86] M. Citterio,[88a] M. Ciubancan,[25a] A. Clark,[48] P. J. Clark,[45] W. Cleland,[122] J. C. Clemens,[82] B. Clement,[54] C. Clement,[145a,145b] R. W. Clifft,[128] Y. Coadou,[82] M. Cobal,[163a,163c] A. Coccaro,[171] J. Cochran,[63] P. Coe,[117] J. G. Cogan,[142] J. Coggeshall,[164] E. Cogneras,[176] J. Colas,[4] A. P. Colijn,[104] N. J. Collins,[17] C. Collins-Tooth,[52] J. Collot,[54] G. Colon,[83] P. Conde Muiño,[123a] E. Coniavitis,[117] M. C. Conidi,[11] M. Consonni,[103] S. M. Consonni,[88a,88b] V. Consorti,[47] S. Constantinescu,[25a] C. Conta,[118a,118b] G. Conti,[56] F. Conventi,[101a,j] J. Cook,[29] M. Cooke,[14] B. D. Cooper,[76] A. M. Cooper-Sarkar,[117] K. Copic,[14] T. Cornelissen,[173] M. Corradi,[19a] F. Corriveau,[84,k] A. Cortes-Gonzalez,[164] G. Cortiana,[98] G. Costa,[88a] M. J. Costa,[166] D. Costanzo,[138] T. Costin,[30] D. Côté,[29] R. Coura Torres,[23a] L. Courneyea,[168] G. Cowan,[75] C. Cowden,[27] B. E. Cox,[81] K. Cranmer,[107] F. Crescioli,[121a,121b] M. Cristinziani,[20] G. Crosetti,[36a,36b] R. Crupi,[71a,71b] S. Crépé-Renaudin,[54] C.-M. Cuciuc,[25a] C. Cuenca Almenar,[174] T. Cuhadar Donszelmann,[138] M. Curatolo,[46] C. J. Curtis,[17] C. Cuthbert,[149] P. Cwetanski,[60] H. Czirr,[140] P. Czodrowski,[43] Z. Czyczula,[174] S. D'Auria,[52] M. D'Onofrio,[72] A. D'Orazio,[131a,131b] P. V. M. Da Silva,[23a] C. Da Via,[81] W. Dabrowski,[37] A. Dafinca,[117] T. Dai,[86] C. Dallapiccola,[83] M. Dam,[35] M. Dameri,[49a,49b] D. S. Damiani,[136] H. O. Danielsson,[29] D. Dannheim,[98] V. Dao,[48] G. Darbo,[49a] G. L. Darlea,[25b] W. Davey,[20] T. Davidek,[125] N. Davidson,[85] R. Davidson,[70] E. Davies,[117,d] M. Davies,[92] A. R. Davison,[76] Y. Davygora,[57a] E. Dawe,[141] I. Dawson,[138] J. W. Dawson,[5,a] R. K. Daya-Ishmukhametova,[22] K. De,[7] R. de Asmundis,[101a] S. De Castro,[19a,19b] P. E. De Castro Faria Salgado,[24] S. De Cecco,[77] J. de Graat,[97] N. De Groot,[103] P. de Jong,[104] C. De La Taille,[114] H. De la Torre,[79] B. De Lotto,[163a,163c] L. de Mora,[70] L. De Nooij,[104] D. De Pedis,[131a] A. De Salvo,[131a] U. De Sanctis,[163a,163c] A. De Santo,[148] J. B. De Vivie De Regie,[114] G. De Zorzi,[131a,131b] S. Dean,[76] W. J. Dearnaley,[70] R. Debbe,[24] C. Debenedetti,[45] B. Dechenaux,[54] D. V. Dedovich,[64] J. Degenhardt,[119] M. Dehchar,[117] C. Del Papa,[163a,163c] J. Del Peso,[79] T. Del Prete,[121a,121b] T. Delemontex,[54] M. Deliyergiyev,[73] A. Dell'Acqua,[29] L. Dell'Asta,[21] M. Della Pietra,[101a,j] D. della Volpe,[101a,101b] M. Delmastro,[4] N. Delruelle,[29] P. A. Delsart,[54] C. Deluca,[147] S. Demers,[174] M. Demichev,[64] B. Demirkoz,[11,l] J. Deng,[162] S. P. Denisov,[127] D. Derendarz,[38] J. E. Derkaoui,[134d] F. Derue,[77] P. Dervan,[72] K. Desch,[20] E. Devetak,[147] P. O. Deviveiros,[104] A. Dewhurst,[128] B. DeWilde,[147] S. Dhaliwal,[157] R. Dhullipudi,[24,m] A. Di Ciaccio,[132a,132b] L. Di Ciaccio,[4] A. Di Girolamo,[29] B. Di Girolamo,[29] S. Di Luise,[133a,133b] A. Di Mattia,[171] B. Di Micco,[29] R. Di Nardo,[46] A. Di Simone,[132a,132b] R. Di Sipio,[19a,19b] M. A. Diaz,[31a] F. Diblen,[18c] E. B. Diehl,[86] J. Dietrich,[41] T. A. Dietzsch,[57a] S. Diglio,[85] K. Dindar Yagci,[39] J. Dingfelder,[20] C. Dionisi,[131a,131b] P. Dita,[25a] S. Dita,[25a] F. Dittus,[29] F. Djama,[82] T. Djobava,[50b] M. A. B. do Vale,[23c] A. Do Valle Wemans,[123a] T. K. O. Doan,[4] M. Dobbs,[84] R. Dobinson,[29,a] D. Dobos,[29] E. Dobson,[29,n] J. Dodd,[34] C. Doglioni,[48] T. Doherty,[52] Y. Doi,[65,a] J. Dolejsi,[125] I. Dolenc,[73] Z. Dolezal,[125] B. A. Dolgoshein,[95,a] T. Dohmae,[154] M. Donadelli,[23d] M. Donega,[119] J. Donini,[33] J. Dopke,[29] A. Doria,[101a] A. Dos Anjos,[171] M. Dosil,[11] A. Dotti,[121a,121b] M. T. Dova,[69] J. D. Dowell,[17] A. D. Doxiadis,[104] A. T. Doyle,[52] Z. Drasal,[125] J. Drees,[173] N. Dressnandt,[119] H. Drevermann,[29] C. Driouichi,[35] M. Dris,[9] J. Dubbert,[98] S. Dube,[14] E. Duchovni,[170] G. Duckeck,[97] A. Dudarev,[29] F. Dudziak,[63] M. Dührssen,[29] I. P. Duerdoth,[81] L. Duflot,[114] M-A. Dufour,[84] M. Dunford,[29] H. Duran Yildiz,[3a] R. Duxfield,[138] M. Dwuznik,[37] F. Dydak,[29] M. Düren,[51] W. L. Ebenstein,[44] J. Ebke,[97] S. Eckweiler,[80] K. Edmonds,[80] C. A. Edwards,[75] N. C. Edwards,[52] W. Ehrenfeld,[41] T. Ehrich,[98] T. Eifert,[142] G. Eigen,[13] K. Einsweiler,[14] E. Eisenhandler,[74] T. Ekelof,[165] M. El Kacimi,[134c] M. Ellert,[165] S. Elles,[4] F. Ellinghaus,[80] K. Ellis,[74] N. Ellis,[29] J. Elmsheuser,[97] M. Elsing,[29] D. Emeliyanov,[128] R. Engelmann,[147] A. Engl,[97] B. Epp,[61] A. Eppig,[86] J. Erdmann,[53] A. Ereditato,[16] D. Eriksson,[145a] J. Ernst,[1] M. Ernst,[24] J. Ernwein,[135] D. Errede,[164] S. Errede,[164] E. Ertel,[80] M. Escalier,[114] C. Escobar,[122] X. Espinal Curull,[11] B. Esposito,[46] F. Etienne,[82] A. I. Etienvre,[135] E. Etzion,[152] D. Evangelakou,[53] H. Evans,[60] L. Fabbri,[19a,19b] C. Fabre,[29] R. M. Fakhrutdinov,[127] S. Falciano,[131a] Y. Fang,[171] M. Fanti,[88a,88b] A. Farbin,[7] A. Farilla,[133a] J. Farley,[147] T. Farooque,[157] S. Farrell,[162] S. M. Farrington,[117] P. Farthouat,[29] P. Fassnacht,[29] D. Fassouliotis,[8] B. Fatholahzadeh,[157] A. Favareto,[88a,88b] L. Fayard,[114] S. Fazio,[36a,36b] R. Febbraro,[33] P. Federic,[143a] O. L. Fedin,[120] W. Fedorko,[87] M. Fehling-Kaschek,[47] L. Feligioni,[82] D. Fellmann,[5] C. Feng,[32d] E. J. Feng,[30] A. B. Fenyuk,[127] J. Ferencei,[143b] J. Ferland,[92] W. Fernando,[108] S. Ferrag,[52] J. Ferrando,[52] V. Ferrara,[41] A. Ferrari,[165] P. Ferrari,[104] R. Ferrari,[118a] D. E. Ferreira de Lima,[52] A. Ferrer,[166] M. L. Ferrer,[46] D. Ferrere,[48] C. Ferretti,[86] A. Ferretto Parodi,[49a,49b] M. Fiascaris,[30] F. Fiedler,[80] A. Filipčič,[73] A. Filippas,[9] F. Filthaut,[103] M. Fincke-Keeler,[168] M. C. N. Fiolhais,[123a,i] L. Fiorini,[166] A. Firan,[39]

G. Fischer,[41] P. Fischer,[20] M. J. Fisher,[108] M. Flechl,[47] I. Fleck,[140] J. Fleckner,[80] P. Fleischmann,[172] S. Fleischmann,[173] T. Flick,[173] A. Floderus,[78] L. R. Flores Castillo,[171] M. J. Flowerdew,[98] M. Fokitis,[9] T. Fonseca Martin,[16] D. A. Forbush,[137] A. Formica,[135] A. Forti,[81] D. Fortin,[158a] J. M. Foster,[81] D. Fournier,[114] A. Foussat,[29] A. J. Fowler,[44] K. Fowler,[136] H. Fox,[70] P. Francavilla,[11] S. Franchino,[118a,118b] D. Francis,[29] T. Frank,[170] M. Franklin,[56] S. Franz,[29] M. Fraternali,[118a,118b] S. Fratina,[119] S. T. French,[27] F. Friedrich,[43] R. Froeschl,[29] D. Froidevaux,[29] J. A. Frost,[27] C. Fukunaga,[155] E. Fullana Torregrosa,[29] J. Fuster,[166] C. Gabaldon,[29] O. Gabizon,[170] T. Gadfort,[24] S. Gadomski,[48] G. Gagliardi,[49a,49b] P. Gagnon,[60] C. Galea,[97] E. J. Gallas,[117] V. Gallo,[16] B. J. Gallop,[128] P. Gallus,[124] K. K. Gan,[108] Y. S. Gao,[142,f] V. A. Gapienko,[127] A. Gaponenko,[14] F. Garberson,[174] M. Garcia-Sciveres,[14] C. García,[166] J. E. García Navarro,[166] R. W. Gardner,[30] N. Garelli,[29] H. Garitaonandia,[104] V. Garonne,[29] J. Garvey,[17] C. Gatti,[46] G. Gaudio,[118a] B. Gaur,[140] L. Gauthier,[135] P. Gauzzi,[131a,131b] I. L. Gavrilenko,[93] C. Gay,[167] G. Gaycken,[20] J-C. Gayde,[29] E. N. Gazis,[9] P. Ge,[32d] C. N. P. Gee,[128] D. A. A. Geerts,[104] Ch. Geich-Gimbel,[20] K. Gellerstedt,[145a,145b] C. Gemme,[49a] A. Gemmell,[52] M. H. Genest,[54] S. Gentile,[131a,131b] M. George,[53] S. George,[75] P. Gerlach,[173] A. Gershon,[152] C. Geweniger,[57a] H. Ghazlane,[134b] N. Ghodbane,[33] B. Giacobbe,[19a] S. Giagu,[131a,131b] V. Giakoumopoulou,[8] V. Giangiobbe,[11] F. Gianotti,[29] B. Gibbard,[24] A. Gibson,[157] S. M. Gibson,[29] L. M. Gilbert,[117] V. Gilewsky,[90] D. Gillberg,[28] A. R. Gillman,[128] D. M. Gingrich,[2,e] J. Ginzburg,[152] N. Giokaris,[8] M. P. Giordani,[163c] R. Giordano,[101a,101b] F. M. Giorgi,[15] P. Giovannini,[98] P. F. Giraud,[135] D. Giugni,[88a] M. Giunta,[92] P. Giusti,[19a] B. K. Gjelsten,[116] L. K. Gladilin,[96] C. Glasman,[79] J. Glatzer,[47] A. Glazov,[41] K. W. Glitza,[173] G. L. Glonti,[64] J. R. Goddard,[74] J. Godfrey,[141] J. Godlewski,[29] M. Goebel,[41] T. Göpfert,[43] C. Goeringer,[80] C. Gössling,[42] T. Göttfert,[98] S. Goldfarb,[86] T. Golling,[174] A. Gomes,[123a,c] L. S. Gomez Fajardo,[41] R. Gonçalo,[75] J. Goncalves Pinto Firmino Da Costa,[41] L. Gonella,[20] A. Gonidec,[29] S. Gonzalez,[171] S. González de la Hoz,[166] G. Gonzalez Parra,[11] M. L. Gonzalez Silva,[26] S. Gonzalez-Sevilla,[48] J. J. Goodson,[147] L. Goossens,[29] P. A. Gorbounov,[94] H. A. Gordon,[24] I. Gorelov,[102] G. Gorfine,[173] B. Gorini,[29] E. Gorini,[71a,71b] A. Gorišek,[73] E. Gornicki,[38] S. A. Gorokhov,[127] V. N. Goryachev,[127] B. Gosdzik,[41] M. Gosselink,[104] M. I. Gostkin,[64] I. Gough Eschrich,[162] M. Gouighri,[134a] D. Goujdami,[134c] M. P. Goulette,[48] A. G. Goussiou,[137] C. Goy,[4] S. Gozpinar,[22] I. Grabowska-Bold,[37] P. Grafström,[29] K-J. Grahn,[41] F. Grancagnolo,[71a] S. Grancagnolo,[15] V. Grassi,[147] V. Gratchev,[120] N. Grau,[34] H. M. Gray,[29] J. A. Gray,[147] E. Graziani,[133a] O. G. Grebenyuk,[120] T. Greenshaw,[72] Z. D. Greenwood,[24,m] K. Gregersen,[35] I. M. Gregor,[41] P. Grenier,[142] J. Griffiths,[137] N. Grigalashvili,[64] A. A. Grillo,[136] S. Grinstein,[11] Y. V. Grishkevich,[96] J.-F. Grivaz,[114] M. Groh,[98] E. Gross,[170] J. Grosse-Knetter,[53] J. Groth-Jensen,[170] K. Grybel,[140] V. J. Guarino,[5] D. Guest,[174] C. Guicheney,[33] A. Guida,[71a,71b] S. Guindon,[53] H. Guler,[84,o] J. Gunther,[124] B. Guo,[157] J. Guo,[34] A. Gupta,[30] Y. Gusakov,[64] V. N. Gushchin,[127] P. Gutierrez,[110] N. Guttman,[152] O. Gutzwiller,[171] C. Guyot,[135] C. Gwenlan,[117] C. B. Gwilliam,[72] A. Haas,[142] S. Haas,[29] C. Haber,[14] H. K. Hadavand,[39] D. R. Hadley,[17] P. Haefner,[98] F. Hahn,[29] S. Haider,[29] Z. Hajduk,[38] H. Hakobyan,[175] D. Hall,[117] J. Haller,[53] K. Hamacher,[173] P. Hamal,[112] M. Hamer,[53] A. Hamilton,[144b,p] S. Hamilton,[160] H. Han,[32a] L. Han,[32b] K. Hanagaki,[115] K. Hanawa,[159] M. Hance,[14] C. Handel,[80] P. Hanke,[57a] J. R. Hansen,[35] J. B. Hansen,[35] J. D. Hansen,[35] P. H. Hansen,[35] P. Hansson,[142] K. Hara,[159] G. A. Hare,[136] T. Harenberg,[173] S. Harkusha,[89] D. Harper,[86] R. D. Harrington,[45] O. M. Harris,[137] K. Harrison,[17] J. Hartert,[47] F. Hartjes,[104] T. Haruyama,[65] A. Harvey,[55] S. Hasegawa,[100] Y. Hasegawa,[139] S. Hassani,[135] M. Hatch,[29] D. Hauff,[98] S. Haug,[16] M. Hauschild,[29] R. Hauser,[87] M. Havranek,[20] B. M. Hawes,[117] C. M. Hawkes,[17] R. J. Hawkings,[29] A. D. Hawkins,[78] D. Hawkins,[162] T. Hayakawa,[66] T. Hayashi,[159] D. Hayden,[75] H. S. Hayward,[72] S. J. Haywood,[128] E. Hazen,[21] M. He,[32d] S. J. Head,[17] V. Hedberg,[78] L. Heelan,[7] S. Heim,[87] B. Heinemann,[14] S. Heisterkamp,[35] L. Helary,[4] C. Heller,[97] M. Heller,[29] S. Hellman,[145a,145b] D. Hellmich,[20] C. Helsens,[11] R. C. W. Henderson,[70] M. Henke,[57a] A. Henrichs,[53] A. M. Henriques Correia,[29] S. Henrot-Versille,[114] F. Henry-Couannier,[82] C. Hensel,[53] T. Henß,[173] C. M. Hernandez,[7] Y. Hernández Jiménez,[166] R. Herrberg,[15] A. D. Hershenhorn,[151] G. Herten,[47] R. Hertenberger,[97] L. Hervas,[29] G. G. Hesketh,[76] N. P. Hessey,[104] E. Higón-Rodriguez,[166] D. Hill,[5,a] J. C. Hill,[27] N. Hill,[5] K. H. Hiller,[41] S. Hillert,[20] S. J. Hillier,[17] I. Hinchliffe,[14] E. Hines,[119] M. Hirose,[115] F. Hirsch,[42] D. Hirschbuehl,[173] J. Hobbs,[147] N. Hod,[152] M. C. Hodgkinson,[138] P. Hodgson,[138] A. Hoecker,[29] M. R. Hoeferkamp,[102] J. Hoffman,[39] D. Hoffmann,[82] M. Hohlfeld,[80] M. Holder,[140] S. O. Holmgren,[145a] T. Holy,[126] J. L. Holzbauer,[87] Y. Homma,[66] T. M. Hong,[119] L. Hooft van Huysduynen,[107] T. Horazdovsky,[126] C. Horn,[142] S. Horner,[47] J-Y. Hostachy,[54] S. Hou,[150] M. A. Houlden,[72] A. Hoummada,[134a] J. Howarth,[81] D. F. Howell,[117] I. Hristova,[15] J. Hrivnac,[114] I. Hruska,[124] T. Hryn'ova,[4] P. J. Hsu,[80] S.-C. Hsu,[14] G. S. Huang,[110] Z. Hubacek,[126] F. Hubaut,[82] F. Huegging,[20] A. Huettmann,[41] T. B. Huffman,[117] E. W. Hughes,[34] G. Hughes,[70] R. E. Hughes-Jones,[81]

M. Huhtinen,[29] P. Hurst,[56] M. Hurwitz,[14] U. Husemann,[41] N. Huseynov,[64,q] J. Huston,[87] J. Huth,[56] G. Iacobucci,[48] G. Iakovidis,[9] M. Ibbotson,[81] I. Ibragimov,[140] R. Ichimiya,[66] L. Iconomidou-Fayard,[114] J. Idarraga,[114] P. Iengo,[101a] O. Igonkina,[104] Y. Ikegami,[65] M. Ikeno,[65] Y. Ilchenko,[39] D. Iliadis,[153] N. Ilic,[157] M. Imori,[154] T. Ince,[20] J. Inigo-Golfin,[29] P. Ioannou,[8] M. Iodice,[133a] V. Ippolito,[131a,131b] A. Irles Quiles,[166] C. Isaksson,[165] A. Ishikawa,[66] M. Ishino,[67] R. Ishmukhametov,[39] C. Issever,[117] S. Istin,[18a] A. V. Ivashin,[127] W. Iwanski,[38] H. Iwasaki,[65] J. M. Izen,[40] V. Izzo,[101a] B. Jackson,[119] J. N. Jackson,[72] P. Jackson,[142] M. R. Jaekel,[29] V. Jain,[60] K. Jakobs,[47] S. Jakobsen,[35] J. Jakubek,[126] D. K. Jana,[110] E. Jankowski,[157] E. Jansen,[76] H. Jansen,[29] A. Jantsch,[98] M. Janus,[47] G. Jarlskog,[78] L. Jeanty,[56] K. Jelen,[37] I. Jen-La Plante,[30] P. Jenni,[29] A. Jeremie,[4] P. Jež,[35] S. Jézéquel,[4] M. K. Jha,[19a] H. Ji,[171] W. Ji,[80] J. Jia,[147] Y. Jiang,[32b] M. Jimenez Belenguer,[41] G. Jin,[32b] S. Jin,[32a] O. Jinnouchi,[156] M. D. Joergensen,[35] D. Joffe,[39] L. G. Johansen,[13] M. Johansen,[145a,145b] K. E. Johansson,[145a] P. Johansson,[138] S. Johnert,[41] K. A. Johns,[6] K. Jon-And,[145a,145b] G. Jones,[117] R. W. L. Jones,[70] T. W. Jones,[76] T. J. Jones,[72] O. Jonsson,[29] C. Joram,[29] P. M. Jorge,[123a] J. Joseph,[14] J. Jovicevic,[146] T. Jovin,[12b] X. Ju,[171] C. A. Jung,[42] R. M. Jungst,[29] V. Juranek,[124] P. Jussel,[61] A. Juste Rozas,[11] V. V. Kabachenko,[127] S. Kabana,[16] M. Kaci,[166] A. Kaczmarska,[38] P. Kadlecik,[35] M. Kado,[114] H. Kagan,[108] M. Kagan,[56] S. Kaiser,[98] E. Kajomovitz,[151] S. Kalinin,[173] L. V. Kalinovskaya,[64] S. Kama,[39] N. Kanaya,[154] M. Kaneda,[29] S. Kaneti,[27] T. Kanno,[156] V. A. Kantserov,[95] J. Kanzaki,[65] B. Kaplan,[174] A. Kapliy,[30] J. Kaplon,[29] D. Kar,[43] M. Karagounis,[20] M. Karagoz,[117] M. Karnevskiy,[41] K. Karr,[5] V. Kartvelishvili,[70] A. N. Karyukhin,[127] L. Kashif,[171] G. Kasieczka,[57b] R. D. Kass,[108] A. Kastanas,[13] M. Kataoka,[4] Y. Kataoka,[154] E. Katsoufis,[9] J. Katzy,[41] V. Kaushik,[6] K. Kawagoe,[66] T. Kawamoto,[154] G. Kawamura,[80] M. S. Kayl,[104] V. A. Kazanin,[106] M. Y. Kazarinov,[64] R. Keeler,[168] R. Kehoe,[39] M. Keil,[53] G. D. Kekelidze,[64] J. S. Keller,[137] J. Kennedy,[97] M. Kenyon,[52] O. Kepka,[124] N. Kerschen,[29] B. P. Kerševan,[73] S. Kersten,[173] K. Kessoku,[154] J. Keung,[157] F. Khalil-zada,[10] H. Khandanyan,[164] A. Khanov,[111] D. Kharchenko,[64] A. Khodinov,[95] A. G. Kholodenko,[127] A. Khomich,[57a] T. J. Khoo,[27] G. Khoriauli,[20] A. Khoroshilov,[173] N. Khovanskiy,[64] V. Khovanskiy,[94] E. Khramov,[64] J. Khubua,[50b] H. Kim,[145a,145b] M. S. Kim,[2] S. H. Kim,[159] N. Kimura,[169] O. Kind,[15] B. T. King,[72] M. King,[66] R. S. B. King,[117] J. Kirk,[128] L. E. Kirsch,[22] A. E. Kiryunin,[98] T. Kishimoto,[66] D. Kisielewska,[37] T. Kittelmann,[122] A. M. Kiver,[127] E. Kladiva,[143b] J. Klaiber-Lodewigs,[42] M. Klein,[72] U. Klein,[72] K. Kleinknecht,[80] M. Klemetti,[84] A. Klier,[170] P. Klimek,[145a,145b] A. Klimentov,[24] R. Klingenberg,[42] J. A. Klinger,[81] E. B. Klinkby,[35] T. Klioutchnikova,[29] P. F. Klok,[103] S. Klous,[104] E.-E. Kluge,[57a] T. Kluge,[72] P. Kluit,[104] S. Kluth,[98] N. S. Knecht,[157] E. Kneringer,[61] J. Knobloch,[29] E. B. F. G. Knoops,[82] A. Knue,[53] B. R. Ko,[44] T. Kobayashi,[154] M. Kobel,[43] M. Kocian,[142] P. Kodys,[125] K. Köneke,[29] A. C. König,[103] S. Koenig,[80] L. Köpke,[80] F. Koetsveld,[103] P. Koevesarki,[20] T. Koffas,[28] E. Koffeman,[104] L. A. Kogan,[117] F. Kohn,[53] Z. Kohout,[126] T. Kohriki,[65] T. Koi,[142] T. Kokott,[20] G. M. Kolachev,[106] H. Kolanoski,[15] V. Kolesnikov,[64] I. Koletsou,[88a] J. Koll,[87] M. Kollefrath,[47] S. D. Kolya,[81] A. A. Komar,[93] Y. Komori,[154] T. Kondo,[65] T. Kono,[41,r] A. I. Kononov,[47] R. Konoplich,[107,s] N. Konstantinidis,[76] A. Kootz,[173] S. Koperny,[37] K. Korcyl,[38] K. Kordas,[153] V. Koreshev,[127] A. Korn,[117] A. Korol,[106] I. Korolkov,[11] E. V. Korolkova,[138] V. A. Korotkov,[127] O. Kortner,[98] S. Kortner,[98] V. V. Kostyukhin,[20] M. J. Kotamäki,[29] S. Kotov,[98] V. M. Kotov,[64] A. Kotwal,[44] C. Kourkoumelis,[8] V. Kouskoura,[153] A. Koutsman,[158a] R. Kowalewski,[168] T. Z. Kowalski,[37] W. Kozanecki,[135] A. S. Kozhin,[127] V. Kral,[126] V. A. Kramarenko,[96] G. Kramberger,[73] M. W. Krasny,[77] A. Krasznahorkay,[107] J. Kraus,[87] J. K. Kraus,[20] A. Kreisel,[152] F. Krejci,[126] J. Kretzschmar,[72] N. Krieger,[53] P. Krieger,[157] K. Kroeninger,[53] H. Kroha,[98] J. Kroll,[119] J. Kroseberg,[20] J. Krstic,[12a] U. Kruchonak,[64] H. Krüger,[20] T. Kruker,[16] N. Krumnack,[63] Z. V. Krumshteyn,[64] A. Kruth,[20] T. Kubota,[85] S. Kuday,[3a] S. Kuehn,[47] A. Kugel,[57c] T. Kuhl,[41] D. Kuhn,[61] V. Kukhtin,[64] Y. Kulchitsky,[89] S. Kuleshov,[31b] C. Kummer,[97] M. Kuna,[77] N. Kundu,[117] J. Kunkle,[119] A. Kupco,[124] H. Kurashige,[66] M. Kurata,[159] Y. A. Kurochkin,[89] V. Kus,[124] E. S. Kuwertz,[146] M. Kuze,[156] J. Kvita,[141] R. Kwee,[15] A. La Rosa,[48] L. La Rotonda,[36a,36b] L. Labarga,[79] J. Labbe,[4] S. Lablak,[134a] C. Lacasta,[166] F. Lacava,[131a,131b] H. Lacker,[15] D. Lacour,[77] V. R. Lacuesta,[166] E. Ladygin,[64] R. Lafaye,[4] B. Laforge,[77] T. Lagouri,[79] S. Lai,[47] E. Laisne,[54] M. Lamanna,[29] L. Lambourne,[76] C. L. Lampen,[6] W. Lampl,[6] E. Lancon,[135] U. Landgraf,[47] M. P. J. Landon,[74] J. L. Lane,[81] C. Lange,[41] A. J. Lankford,[162] F. Lanni,[24] K. Lantzsch,[173] S. Laplace,[77] C. Lapoire,[20] J. F. Laporte,[135] T. Lari,[88a] A. V. Larionov,[127] A. Larner,[117] C. Lasseur,[29] M. Lassnig,[29] P. Laurelli,[46] V. Lavorini,[36a,36b] W. Lavrijsen,[14] P. Laycock,[72] A. B. Lazarev,[64] O. Le Dortz,[77] E. Le Guirriec,[82] C. Le Maner,[157] E. Le Menedeu,[9] C. Lebel,[92] T. LeCompte,[5] F. Ledroit-Guillon,[54] H. Lee,[104] J. S. H. Lee,[115] S. C. Lee,[150] L. Lee,[174] M. Lefebvre,[168] M. Legendre,[135] A. Leger,[48] B. C. LeGeyt,[119] F. Legger,[97] C. Leggett,[14] M. Lehmacher,[20] G. Lehmann Miotto,[29] X. Lei,[6] M. A. L. Leite,[23d] R. Leitner,[125] D. Lellouch,[170] M. Leltchouk,[34] B. Lemmer,[53] V. Lendermann,[57a] K. J. C. Leney,[144b] T. Lenz,[104] G. Lenzen,[173] B. Lenzi,[29]

K. Leonhardt,[43] S. Leontsinis,[9] C. Leroy,[92] J-R. Lessard,[168] J. Lesser,[145a] C. G. Lester,[27] A. Leung Fook Cheong,[171] J. Levêque,[4] D. Levin,[86] L. J. Levinson,[170] M. S. Levitski,[127] A. Lewis,[117] G. H. Lewis,[107] A. M. Leyko,[20] M. Leyton,[15] B. Li,[82] H. Li,[171,t] S. Li,[32b,u] X. Li,[86] Z. Liang,[117,v] H. Liao,[33] B. Liberti,[132a] P. Lichard,[29] M. Lichtnecker,[97] K. Lie,[164] W. Liebig,[13] R. Lifshitz,[151] C. Limbach,[20] A. Limosani,[85] M. Limper,[62] S. C. Lin,[150,w] F. Linde,[104] J. T. Linnemann,[87] E. Lipeles,[119] L. Lipinsky,[124] A. Lipniacka,[13] T. M. Liss,[164] D. Lissauer,[24] A. Lister,[48] A. M. Litke,[136] C. Liu,[28] D. Liu,[150] H. Liu,[86] J. B. Liu,[86] M. Liu,[32b] Y. Liu,[32b] M. Livan,[118a,118b] S. S. A. Livermore,[117] A. Lleres,[54] J. Llorente Merino,[79] S. L. Lloyd,[74] E. Lobodzinska,[41] P. Loch,[6] W. S. Lockman,[136] T. Loddenkoetter,[20] F. K. Loebinger,[81] A. Loginov,[174] C. W. Loh,[167] T. Lohse,[15] K. Lohwasser,[47] M. Lokajicek,[124] J. Loken,[117] V. P. Lombardo,[4] R. E. Long,[70] L. Lopes,[123a] D. Lopez Mateos,[56] J. Lorenz,[97] N. Lorenzo Martinez,[114] M. Losada,[161] P. Loscutoff,[14] F. Lo Sterzo,[131a,131b] M. J. Losty,[158a] X. Lou,[40] A. Lounis,[114] K. F. Loureiro,[161] J. Love,[21] P. A. Love,[70] A. J. Lowe,[142,f] F. Lu,[32a] H. J. Lubatti,[137] C. Luci,[131a,131b] A. Lucotte,[54] A. Ludwig,[43] D. Ludwig,[41] I. Ludwig,[47] J. Ludwig,[47] F. Luehring,[60] G. Luijckx,[104] W. Lukas,[61] D. Lumb,[47] L. Luminari,[131a] E. Lund,[116] B. Lund-Jensen,[146] B. Lundberg,[78] J. Lundberg,[145a,145b] J. Lundquist,[35] M. Lungwitz,[80] G. Lutz,[98] D. Lynn,[24] J. Lys,[14] E. Lytken,[78] H. Ma,[24] L. L. Ma,[171] J. A. Macana Goia,[92] G. Maccarrone,[46] A. Macchiolo,[98] B. Maček,[73] J. Machado Miguens,[123a] R. Mackeprang,[35] R. J. Madaras,[14] W. F. Mader,[43] R. Maenner,[57c] T. Maeno,[24] P. Mättig,[173] S. Mättig,[41] L. Magnoni,[29] E. Magradze,[53] Y. Mahalalel,[152] K. Mahboubi,[47] S. Mahmoud,[72] G. Mahout,[17] C. Maiani,[131a,131b] C. Maidantchik,[23a] A. Maio,[123a,c] S. Majewski,[24] Y. Makida,[65] N. Makovec,[114] P. Mal,[135] B. Malaescu,[29] Pa. Malecki,[38] P. Malecki,[38] V. P. Maleev,[120] F. Malek,[54] U. Mallik,[62] D. Malon,[5] C. Malone,[142] S. Maltezos,[9] V. Malyshev,[106] S. Malyukov,[29] R. Mameghani,[97] J. Mamuzic,[12b] A. Manabe,[65] L. Mandelli,[88a] I. Mandić,[73] R. Mandrysch,[15] J. Maneira,[123a] P. S. Mangeard,[87] L. Manhaes de Andrade Filho,[23a] I. D. Manjavidze,[64] A. Mann,[53] P. M. Manning,[136] A. Manousakis-Katsikakis,[8] B. Mansoulie,[135] A. Manz,[98] A. Mapelli,[29] L. Mapelli,[29] L. March,[79] J. F. Marchand,[28] F. Marchese,[132a,132b] G. Marchiori,[77] M. Marcisovsky,[124] C. P. Marino,[168] F. Marroquim,[23a] R. Marshall,[81] Z. Marshall,[29] F. K. Martens,[157] S. Marti-Garcia,[166] A. J. Martin,[174] B. Martin,[29] B. Martin,[87] F. F. Martin,[119] J. P. Martin,[92] Ph. Martin,[54] T. A. Martin,[17] V. J. Martin,[45] B. Martin dit Latour,[48] S. Martin-Haugh,[148] M. Martinez,[11] V. Martinez Outschoorn,[56] A. C. Martyniuk,[168] M. Marx,[81] F. Marzano,[131a] A. Marzin,[110] L. Masetti,[80] T. Mashimo,[154] R. Mashinistov,[93] J. Masik,[81] A. L. Maslennikov,[106] I. Massa,[19a,19b] G. Massaro,[104] N. Massol,[4] P. Mastrandrea,[131a,131b] A. Mastroberardino,[36a,36b] T. Masubuchi,[154] P. Matricon,[114] H. Matsumoto,[154] H. Matsunaga,[154] T. Matsushita,[66] C. Mattravers,[117,d] J. M. Maugain,[29] J. Maurer,[82] S. J. Maxfield,[72] D. A. Maximov,[106,g] E. N. May,[5] A. Mayne,[138] R. Mazini,[150] M. Mazur,[20] M. Mazzanti,[88a] S. P. Mc Kee,[86] A. McCarn,[164] R. L. McCarthy,[147] T. G. McCarthy,[28] N. A. McCubbin,[128] K. W. McFarlane,[55] J. A. Mcfayden,[138] H. McGlone,[52] G. Mchedlidze,[50b] R. A. McLaren,[29] T. Mclaughlan,[17] S. J. McMahon,[128] R. A. McPherson,[168,k] A. Meade,[83] J. Mechnich,[104] M. Mechtel,[173] M. Medinnis,[41] R. Meera-Lebbai,[110] T. Meguro,[115] R. Mehdiyev,[92] S. Mehlhase,[35] A. Mehta,[72] K. Meier,[57a] B. Meirose,[78] C. Melachrinos,[30] B. R. Mellado Garcia,[171] L. Mendoza Navas,[161] Z. Meng,[150,t] A. Mengarelli,[19a,19b] S. Menke,[98] C. Menot,[29] E. Meoni,[11] K. M. Mercurio,[56] P. Mermod,[48] L. Merola,[101a,101b] C. Meroni,[88a] F. S. Merritt,[30] H. Merritt,[108] A. Messina,[29] J. Metcalfe,[102] A. S. Mete,[63] C. Meyer,[80] C. Meyer,[30] J-P. Meyer,[135] J. Meyer,[172] J. Meyer,[53] T. C. Meyer,[29] W. T. Meyer,[63] J. Miao,[32d] S. Michal,[29] L. Micu,[25a] R. P. Middleton,[128] S. Migas,[72] L. Mijović,[41] G. Mikenberg,[170] M. Mikestikova,[124] M. Mikuž,[73] D. W. Miller,[30] R. J. Miller,[87] W. J. Mills,[167] C. Mills,[56] A. Milov,[170] D. A. Milstead,[145a,145b] D. Milstein,[170] A. A. Minaenko,[127] M. Miñano Moya,[166] I. A. Minashvili,[64] A. I. Mincer,[107] B. Mindur,[37] M. Mineev,[64] Y. Ming,[171] L. M. Mir,[11] G. Mirabelli,[131a] L. Miralles Verge,[11] A. Misiejuk,[75] J. Mitrevski,[136] G. Y. Mitrofanov,[127] V. A. Mitsou,[166] S. Mitsui,[65] P. S. Miyagawa,[138] K. Miyazaki,[66] J. U. Mjörnmark,[78] T. Moa,[145a,145b] P. Mockett,[137] S. Moed,[56] V. Moeller,[27] K. Mönig,[41] N. Möser,[20] S. Mohapatra,[147] W. Mohr,[47] S. Mohrdieck-Möck,[98] A. M. Moisseev,[127,a] R. Moles-Valls,[166] J. Molina-Perez,[29] J. Monk,[76] E. Monnier,[82] S. Montesano,[88a,88b] F. Monticelli,[69] S. Monzani,[19a,19b] R. W. Moore,[2] G. F. Moorhead,[85] C. Mora Herrera,[48] A. Moraes,[52] N. Morange,[135] J. Morel,[53] G. Morello,[36a,36b] D. Moreno,[80] M. Moreno Llácer,[166] P. Morettini,[49a] M. Morgenstern,[43] M. Morii,[56] J. Morin,[74] A. K. Morley,[29] G. Mornacchi,[29] S. V. Morozov,[95] J. D. Morris,[74] L. Morvaj,[100] H. G. Moser,[98] M. Mosidze,[50b] J. Moss,[108] R. Mount,[142] E. Mountricha,[9,x] S. V. Mouraviev,[93] E. J. W. Moyse,[83] M. Mudrinic,[12b] F. Mueller,[57a] J. Mueller,[122] K. Mueller,[20] T. A. Müller,[97] T. Mueller,[80] D. Muenstermann,[29] A. Muir,[167] Y. Munwes,[152] W. J. Murray,[128] I. Mussche,[104] E. Musto,[101a,101b] A. G. Myagkov,[127] M. Myska,[124] J. Nadal,[11] K. Nagai,[159] K. Nagano,[65] A. Nagarkar,[108] Y. Nagasaka,[59] M. Nagel,[98] A. M. Nairz,[29] Y. Nakahama,[29] K. Nakamura,[154]

T. Nakamura,[154] I. Nakano,[109] G. Nanava,[20] A. Napier,[160] R. Narayan,[57b] M. Nash,[76,d] N. R. Nation,[21] T. Nattermann,[20] T. Naumann,[41] G. Navarro,[161] H. A. Neal,[86] E. Nebot,[79] P. Yu. Nechaeva,[93] T. J. Neep,[81] A. Negri,[118a,118b] G. Negri,[29] S. Nektarijevic,[48] A. Nelson,[162] T. K. Nelson,[142] S. Nemecek,[124] P. Nemethy,[107] A. A. Nepomuceno,[23a] M. Nessi,[29,y] M. S. Neubauer,[164] A. Neusiedl,[80] R. M. Neves,[107] P. Nevski,[24] P. R. Newman,[17] V. Nguyen Thi Hong,[135] R. B. Nickerson,[117] R. Nicolaidou,[135] L. Nicolas,[138] B. Nicquevert,[29] F. Niedercorn,[114] J. Nielsen,[136] T. Niinikoski,[29] N. Nikiforou,[34] A. Nikiforov,[15] V. Nikolaenko,[127] K. Nikolaev,[64] I. Nikolic-Audit,[77] K. Nikolics,[48] K. Nikolopoulos,[24] H. Nilsen,[47] P. Nilsson,[7] Y. Ninomiya,[154] A. Nisati,[131a] T. Nishiyama,[66] R. Nisius,[98] L. Nodulman,[5] M. Nomachi,[115] I. Nomidis,[153] M. Nordberg,[29] B. Nordkvist,[145a,145b] P. R. Norton,[128] J. Novakova,[125] M. Nozaki,[65] L. Nozka,[112] I. M. Nugent,[158a] A.-E. Nuncio-Quiroz,[20] G. Nunes Hanninger,[85] T. Nunnemann,[97] E. Nurse,[76] B. J. O'Brien,[45] S. W. O'Neale,[17,a] D. C. O'Neil,[141] V. O'Shea,[52] L. B. Oakes,[97] F. G. Oakham,[28,e] H. Oberlack,[98] J. Ocariz,[77] A. Ochi,[66] S. Oda,[154] S. Odaka,[65] J. Odier,[82] H. Ogren,[60] A. Oh,[81] S. H. Oh,[44] C. C. Ohm,[145a,145b] T. Ohshima,[100] H. Ohshita,[139] T. Ohsugi,[58] S. Okada,[66] H. Okawa,[162] Y. Okumura,[100] T. Okuyama,[154] A. Olariu,[25a] M. Olcese,[49a] A. G. Olchevski,[64] S. A. Olivares Pino,[31a] M. Oliveira,[123a,i] D. Oliveira Damazio,[24] E. Oliver Garcia,[166] D. Olivito,[119] A. Olszewski,[38] J. Olszowska,[38] C. Omachi,[66] A. Onofre,[123a,z] P. U. E. Onyisi,[30] C. J. Oram,[158a] M. J. Oreglia,[30] Y. Oren,[152] D. Orestano,[133a,133b] N. Orlando,[71a,71b] I. Orlov,[106] C. Oropeza Barrera,[52] R. S. Orr,[157] B. Osculati,[49a,49b] R. Ospanov,[119] C. Osuna,[11] G. Otero y Garzon,[26] J. P. Ottersbach,[104] M. Ouchrif,[134d] E. A. Ouellette,[168] F. Ould-Saada,[116] A. Ouraou,[135] Q. Ouyang,[32a] A. Ovcharova,[14] M. Owen,[81] S. Owen,[138] V. E. Ozcan,[18a] N. Ozturk,[7] A. Pacheco Pages,[11] C. Padilla Aranda,[11] S. Pagan Griso,[14] E. Paganis,[138] F. Paige,[24] P. Pais,[83] K. Pajchel,[116] G. Palacino,[158b] C. P. Paleari,[6] S. Palestini,[29] D. Pallin,[33] A. Palma,[123a] J. D. Palmer,[17] Y. B. Pan,[171] E. Panagiotopoulou,[9] B. Panes,[31a] N. Panikashvili,[86] S. Panitkin,[24] D. Pantea,[25a] M. Panuskova,[124] V. Paolone,[122] A. Papadelis,[145a] Th. D. Papadopoulou,[9] A. Paramonov,[5] D. Paredes Hernandez,[33] W. Park,[24,aa] M. A. Parker,[27] F. Parodi,[49a,49b] J. A. Parsons,[34] U. Parzefall,[47] S. Pashapour,[53] E. Pasqualucci,[131a] S. Passaggio,[49a] A. Passeri,[133a] F. Pastore,[133a,133b] Fr. Pastore,[75] G. Pásztor,[48,bb] S. Pataraia,[173] N. Patel,[149] J. R. Pater,[81] S. Patricelli,[101a,101b] T. Pauly,[29] M. Pecsy,[143a] M. I. Pedraza Morales,[171] S. V. Peleganchuk,[106] H. Peng,[32b] R. Pengo,[29] B. Penning,[30] A. Penson,[34] J. Penwell,[60] M. Perantoni,[23a] K. Perez,[34,cc] T. Perez Cavalcanti,[41] E. Perez Codina,[11] M. T. Pérez García-Estañ,[166] V. Perez Reale,[34] L. Perini,[88a,88b] H. Pernegger,[29] R. Perrino,[71a] P. Perrodo,[4] S. Persembe,[3a] V. D. Peshekhonov,[64] K. Peters,[29] B. A. Petersen,[29] J. Petersen,[29] T. C. Petersen,[35] E. Petit,[4] A. Petridis,[153] C. Petridou,[153] E. Petrolo,[131a] F. Petrucci,[133a,133b] D. Petschull,[41] M. Petteni,[141] R. Pezoa,[31b] A. Phan,[85] P. W. Phillips,[128] G. Piacquadio,[29] A. Picazio,[48] E. Piccaro,[74] M. Piccinini,[19a,19b] S. M. Piec,[41] R. Piegaia,[26] D. T. Pignotti,[108] J. E. Pilcher,[30] A. D. Pilkington,[81] J. Pina,[123a,c] M. Pinamonti,[163a,163c] A. Pinder,[117] J. L. Pinfold,[2] J. Ping,[32c] B. Pinto,[123a] O. Pirotte,[29] C. Pizio,[88a,88b] M. Plamondon,[168] M.-A. Pleier,[24] A. V. Pleskach,[127] E. Plotnikova,[64] A. Poblaguev,[24] S. Poddar,[57a] F. Podlyski,[33] L. Poggioli,[114] T. Poghosyan,[20] M. Pohl,[48] F. Polci,[54] G. Polesello,[118a] A. Policicchio,[36a,36b] A. Polini,[19a] J. Poll,[74] V. Polychronakos,[24] D. M. Pomarede,[135] D. Pomeroy,[22] K. Pommès,[29] L. Pontecorvo,[131a] B. G. Pope,[87] G. A. Popeneciu,[25a] D. S. Popovic,[12a] A. Poppleton,[29] X. Portell Bueso,[29] C. Posch,[21] G. E. Pospelov,[98] S. Pospisil,[126] I. N. Potrap,[98] C. J. Potter,[148] C. T. Potter,[113] G. Poulard,[29] J. Poveda,[171] V. Pozdnyakov,[64] R. Prabhu,[76] P. Pralavorio,[82] A. Pranko,[14] S. Prasad,[29] R. Pravahan,[7] S. Prell,[63] K. Pretzl,[16] L. Pribyl,[29] D. Price,[60] J. Price,[72] L. E. Price,[5] M. J. Price,[29] D. Prieur,[122] M. Primavera,[71a] K. Prokofiev,[107] F. Prokoshin,[31b] S. Protopopescu,[24] J. Proudfoot,[5] X. Prudent,[43] M. Przybycien,[37] H. Przysiezniak,[4] S. Psoroulas,[20] E. Ptacek,[113] E. Pueschel,[83] J. Purdham,[86] M. Purohit,[24,aa] P. Puzo,[114] Y. Pylypchenko,[62] J. Qian,[86] Z. Qian,[82] Z. Qin,[41] A. Quadt,[53] D. R. Quarrie,[14] W. B. Quayle,[171] F. Quinonez,[31a] M. Raas,[103] V. Radescu,[41] B. Radics,[20] P. Radloff,[113] T. Rador,[18a] F. Ragusa,[88a,88b] G. Rahal,[176] A. M. Rahimi,[108] D. Rahm,[24] S. Rajagopalan,[24] M. Rammensee,[47] M. Rammes,[140] A. S. Randle-Conde,[39] K. Randrianarivony,[28] P. N. Ratoff,[70] F. Rauscher,[97] T. C. Rave,[47] M. Raymond,[29] A. L. Read,[116] D. M. Rebuzzi,[118a,118b] A. Redelbach,[172] G. Redlinger,[24] R. Reece,[119] K. Reeves,[40] A. Reichold,[104] E. Reinherz-Aronis,[152] A. Reinsch,[113] I. Reisinger,[42] C. Rembser,[29] Z. L. Ren,[150] A. Renaud,[114] M. Rescigno,[131a] S. Resconi,[88a] B. Resende,[135] P. Reznicek,[97] R. Rezvani,[157] A. Richards,[76] R. Richter,[98] E. Richter-Was,[4,dd] M. Ridel,[77] M. Rijpstra,[104] M. Rijssenbeek,[147] A. Rimoldi,[118a,118b] L. Rinaldi,[19a] R. R. Rios,[39] I. Riu,[11] G. Rivoltella,[88a,88b] F. Rizatdinova,[111] E. Rizvi,[74] S. H. Robertson,[84,k] A. Robichaud-Veronneau,[117] D. Robinson,[27] J. E. M. Robinson,[76] A. Robson,[52] J. G. Rocha de Lima,[105] C. Roda,[121a,121b] D. Roda Dos Santos,[29] D. Rodriguez,[161] A. Roe,[53] S. Roe,[29] O. Røhne,[116] V. Rojo,[1] S. Rolli,[160] A. Romaniouk,[95] M. Romano,[19a,19b] V. M. Romanov,[64] G. Romeo,[26] E. Romero Adam,[166] L. Roos,[77] E. Ros,[166] S. Rosati,[131a] K. Rosbach,[48] A. Rose,[148] M. Rose,[75]

G. A. Rosenbaum,[157] E. I. Rosenberg,[63] P. L. Rosendahl,[13] O. Rosenthal,[140] L. Rosselet,[48] V. Rossetti,[11] E. Rossi,[131a,131b] L. P. Rossi,[49a] M. Rotaru,[25a] I. Roth,[170] J. Rothberg,[137] D. Rousseau,[114] C. R. Royon,[135] A. Rozanov,[82] Y. Rozen,[151] X. Ruan,[32a,ee] I. Rubinskiy,[41] B. Ruckert,[97] N. Ruckstuhl,[104] V. I. Rud,[96] C. Rudolph,[43] G. Rudolph,[61] F. Rühr,[6] F. Ruggieri,[133a,133b] A. Ruiz-Martinez,[63] V. Rumiantsev,[90,a] L. Rumyantsev,[64] K. Runge,[47] Z. Rurikova,[47] N. A. Rusakovich,[64] J. P. Rutherfoord,[6] C. Ruwiedel,[14] P. Ruzicka,[124] Y. F. Ryabov,[120] V. Ryadovikov,[127] P. Ryan,[87] M. Rybar,[125] G. Rybkin,[114] N. C. Ryder,[117] S. Rzaeva,[10] A. F. Saavedra,[149] I. Sadeh,[152] H.F-W. Sadrozinski,[136] R. Sadykov,[64] F. Safai Tehrani,[131a] H. Sakamoto,[154] G. Salamanna,[74] A. Salamon,[132a] M. Saleem,[110] D. Salihagic,[98] A. Salnikov,[142] J. Salt,[166] B. M. Salvachua Ferrando,[5] D. Salvatore,[36a,36b] F. Salvatore,[148] A. Salvucci,[103] A. Salzburger,[29] D. Sampsonidis,[153] B. H. Samset,[116] A. Sanchez,[101a,101b] V. Sanchez Martinez,[166] H. Sandaker,[13] H. G. Sander,[80] M. P. Sanders,[97] M. Sandhoff,[173] T. Sandoval,[27] C. Sandoval,[161] R. Sandstroem,[98] S. Sandvoss,[173] D. P. C. Sankey,[128] A. Sansoni,[46] C. Santamarina Rios,[84] C. Santoni,[33] R. Santonico,[132a,132b] H. Santos,[123a] J. G. Saraiva,[123a] T. Sarangi,[171] E. Sarkisyan-Grinbaum,[7] F. Sarri,[121a,121b] G. Sartisohn,[173] O. Sasaki,[65] N. Sasao,[67] I. Satsounkevitch,[89] G. Sauvage,[4] E. Sauvan,[4] J. B. Sauvan,[114] P. Savard,[157,e] V. Savinov,[122] D. O. Savu,[29] L. Sawyer,[24,m] D. H. Saxon,[52] J. Saxon,[119] L. P. Says,[33] C. Sbarra,[19a] A. Sbrizzi,[19a,19b] O. Scallon,[92] D. A. Scannicchio,[162] M. Scarcella,[149] J. Schaarschmidt,[114] P. Schacht,[98] D. Schaefer,[119] U. Schäfer,[80] S. Schaepe,[20] S. Schaetzel,[57b] A. C. Schaffer,[114] D. Schaile,[97] R. D. Schamberger,[147] A. G. Schamov,[106] V. Scharf,[57a] V. A. Schegelsky,[120] D. Scheirich,[86] M. Schernau,[162] M. I. Scherzer,[34] C. Schiavi,[49a,49b] J. Schieck,[97] M. Schioppa,[36a,36b] S. Schlenker,[29] J. L. Schlereth,[5] E. Schmidt,[47] K. Schmieden,[20] C. Schmitt,[80] S. Schmitt,[57b] M. Schmitz,[20] A. Schöning,[57b] M. Schott,[29] D. Schouten,[158a] J. Schovancova,[124] M. Schram,[84] C. Schroeder,[80] N. Schroer,[57c] G. Schuler,[29] M. J. Schultens,[20] J. Schultes,[173] H.-C. Schultz-Coulon,[57a] H. Schulz,[15] J. W. Schumacher,[20] M. Schumacher,[47] B. A. Schumm,[136] Ph. Schune,[135] C. Schwanenberger,[81] A. Schwartzman,[142] Ph. Schwemling,[77] R. Schwienhorst,[87] R. Schwierz,[43] J. Schwindling,[135] T. Schwindt,[20] M. Schwoerer,[4] G. Sciolla,[22] W. G. Scott,[128] J. Searcy,[113] G. Sedov,[41] E. Sedykh,[120] E. Segura,[11] S. C. Seidel,[102] A. Seiden,[136] F. Seifert,[43] J. M. Seixas,[23a] G. Sekhniaidze,[101a] S. J. Sekula,[39] K. E. Selbach,[45] D. M. Seliverstov,[120] B. Sellden,[145a] G. Sellers,[72] M. Seman,[143b] N. Semprini-Cesari,[19a,19b] C. Serfon,[97] L. Serin,[114] L. Serkin,[53] R. Seuster,[98] H. Severini,[110] M. E. Sevior,[85] A. Sfyrla,[29] E. Shabalina,[53] M. Shamim,[113] L. Y. Shan,[32a] J. T. Shank,[21] Q. T. Shao,[85] M. Shapiro,[14] P. B. Shatalov,[94] L. Shaver,[6] K. Shaw,[163a,163c] D. Sherman,[174] P. Sherwood,[76] A. Shibata,[107] H. Shichi,[100] S. Shimizu,[29] M. Shimojima,[99] T. Shin,[55] M. Shiyakova,[64] A. Shmeleva,[93] M. J. Shochet,[30] D. Short,[117] S. Shrestha,[63] E. Shulga,[95] M. A. Shupe,[6] P. Sicho,[124] A. Sidoti,[131a] F. Siegert,[47] Dj. Sijacki,[12a] O. Silbert,[170] J. Silva,[123a] Y. Silver,[152] D. Silverstein,[142] S. B. Silverstein,[145a] V. Simak,[126] O. Simard,[135] Lj. Simic,[12a] S. Simion,[114] B. Simmons,[76] R. Simoniello,[88a,88b] M. Simonyan,[35] P. Sinervo,[157] N. B. Sinev,[113] V. Sipica,[140] G. Siragusa,[172] A. Sircar,[24] A. N. Sisakyan,[64] S. Yu. Sivoklokov,[96] J. Sjölin,[145a,145b] T. B. Sjursen,[13] L. A. Skinnari,[14] H. P. Skottowe,[56] K. Skovpen,[106] P. Skubic,[110] N. Skvorodnev,[22] M. Slater,[17] T. Slavicek,[126] K. Sliwa,[160] J. Sloper,[29] V. Smakhtin,[170] B. H. Smart,[45] S. Yu. Smirnov,[95] Y. Smirnov,[95] L. N. Smirnova,[96] O. Smirnova,[78] B. C. Smith,[56] D. Smith,[142] K. M. Smith,[52] M. Smizanska,[70] K. Smolek,[126] A. A. Snesarev,[93] S. W. Snow,[81] J. Snow,[110] J. Snuverink,[104] S. Snyder,[24] M. Soares,[123a] R. Sobie,[168,k] J. Sodomka,[126] A. Soffer,[152] C. A. Solans,[166] M. Solar,[126] J. Solc,[126] E. Soldatov,[95] U. Soldevila,[166] E. Solfaroli Camillocci,[131a,131b] A. A. Solodkov,[127] O. V. Solovyanov,[127] N. Soni,[2] V. Sopko,[126] B. Sopko,[126] M. Sosebee,[7] R. Soualah,[163a,163c] A. Soukharev,[106] S. Spagnolo,[71a,71b] F. Spanò,[75] R. Spighi,[19a] G. Spigo,[29] F. Spila,[131a,131b] R. Spiwoks,[29] M. Spousta,[125] T. Spreitzer,[157] B. Spurlock,[7] R. D. St. Denis,[52] J. Stahlman,[119] R. Stamen,[57a] E. Stanecka,[38] R. W. Stanek,[5] C. Stanescu,[133a] M. Stanescu-Bellu,[41] S. Stapnes,[116] E. A. Starchenko,[127] J. Stark,[54] P. Staroba,[124] P. Starovoitov,[90] A. Staude,[97] P. Stavina,[143a] G. Steele,[52] P. Steinbach,[43] P. Steinberg,[24] I. Stekl,[126] B. Stelzer,[141] H. J. Stelzer,[87] O. Stelzer-Chilton,[158a] H. Stenzel,[51] S. Stern,[98] K. Stevenson,[74] G. A. Stewart,[29] J. A. Stillings,[20] M. C. Stockton,[84] K. Stoerig,[47] G. Stoicea,[25a] S. Stonjek,[98] P. Strachota,[125] A. R. Stradling,[7] A. Straessner,[43] J. Strandberg,[146] S. Strandberg,[145a,145b] A. Strandlie,[116] M. Strang,[108] E. Strauss,[142] M. Strauss,[110] P. Strizenec,[143b] R. Ströhmer,[172] D. M. Strom,[113] J. A. Strong,[75,a] R. Stroynowski,[39] J. Strube,[128] B. Stugu,[13] I. Stumer,[24,a] J. Stupak,[147] P. Sturm,[173] N. A. Styles,[41] D. A. Soh,[150,v] D. Su,[142] HS. Subramania,[2] A. Succurro,[11] Y. Sugaya,[115] T. Sugimoto,[100] C. Suhr,[105] K. Suita,[66] M. Suk,[125] V. V. Sulin,[93] S. Sultansoy,[3d] T. Sumida,[67] X. Sun,[54] J. E. Sundermann,[47] K. Suruliz,[138] S. Sushkov,[11] G. Susinno,[36a,36b] M. R. Sutton,[148] Y. Suzuki,[65] Y. Suzuki,[66] M. Svatos,[124] Yu. M. Sviridov,[127] S. Swedish,[167] I. Sykora,[143a] T. Sykora,[125] B. Szeless,[29] J. Sánchez,[166] D. Ta,[104] K. Tackmann,[41] A. Taffard,[162] R. Tafirout,[158a] N. Taiblum,[152] Y. Takahashi,[100] H. Takai,[24] R. Takashima,[68]

H. Takeda,[66] T. Takeshita,[139] Y. Takubo,[65] M. Talby,[82] A. Talyshev,[106,g] M. C. Tamsett,[24] J. Tanaka,[154] R. Tanaka,[114] S. Tanaka,[130] S. Tanaka,[65] Y. Tanaka,[99] A. J. Tanasijczuk,[141] K. Tani,[66] N. Tannoury,[82] G. P. Tappern,[29] S. Tapprogge,[80] D. Tardif,[157] S. Tarem,[151] F. Tarrade,[28] G. F. Tartarelli,[88a] P. Tas,[125] M. Tasevsky,[124] E. Tassi,[36a,36b] M. Tatarkhanov,[14] Y. Tayalati,[134d] C. Taylor,[76] F. E. Taylor,[91] G. N. Taylor,[85] W. Taylor,[158b] M. Teinturier,[114] M. Teixeira Dias Castanheira,[74] P. Teixeira-Dias,[75] K. K. Temming,[47] H. Ten Kate,[29] P. K. Teng,[150] S. Terada,[65] K. Terashi,[154] J. Terron,[79] M. Testa,[46] R. J. Teuscher,[157,k] J. Thadome,[173] J. Therhaag,[20] T. Theveneaux-Pelzer,[77] M. Thioye,[174] S. Thoma,[47] J. P. Thomas,[17] E. N. Thompson,[34] P. D. Thompson,[17] P. D. Thompson,[157] A. S. Thompson,[52] L. A. Thomsen,[35] E. Thomson,[119] M. Thomson,[27] R. P. Thun,[86] F. Tian,[34] M. J. Tibbetts,[14] T. Tic,[124] V. O. Tikhomirov,[93] Y. A. Tikhonov,[106,g] S. Timoshenko,[95] P. Tipton,[174] F. J. Tique Aires Viegas,[29] S. Tisserant,[82] B. Toczek,[37] T. Todorov,[4] S. Todorova-Nova,[160] B. Toggerson,[162] J. Tojo,[65] S. Tokár,[143a] K. Tokunaga,[66] K. Tokushuku,[65] K. Tollefson,[87] M. Tomoto,[100] L. Tompkins,[30] K. Toms,[102] G. Tong,[32a] A. Tonoyan,[13] C. Topfel,[16] N. D. Topilin,[64] I. Torchiani,[29] E. Torrence,[113] H. Torres,[77] E. Torró Pastor,[166] J. Toth,[82,bb] F. Touchard,[82] D. R. Tovey,[138] T. Trefzger,[172] L. Tremblet,[29] A. Tricoli,[29] I. M. Trigger,[158a] S. Trincaz-Duvoid,[77] T. N. Trinh,[77] M. F. Tripiana,[69] W. Trischuk,[157] A. Trivedi,[24,aa] B. Trocmé,[54] C. Troncon,[88a] M. Trottier-McDonald,[141] M. Trzebinski,[38] A. Trzupek,[38] C. Tsarouchas,[29] J. C-L. Tseng,[117] M. Tsiakiris,[104] P. V. Tsiareshka,[89] D. Tsionou,[4,ff] G. Tsipolitis,[9] V. Tsiskaridze,[47] E. G. Tskhadadze,[50a] I. I. Tsukerman,[94] V. Tsulaia,[14] J.-W. Tsung,[20] S. Tsuno,[65] D. Tsybychev,[147] A. Tua,[138] A. Tudorache,[25a] V. Tudorache,[25a] J. M. Tuggle,[30] M. Turala,[38] D. Turecek,[126] I. Turk Cakir,[3e] E. Turlay,[104] R. Turra,[88a,88b] P. M. Tuts,[34] A. Tykhonov,[73] M. Tylmad,[145a,145b] M. Tyndel,[128] G. Tzanakos,[8] K. Uchida,[20] I. Ueda,[154] R. Ueno,[28] M. Ugland,[13] M. Uhlenbrock,[20] M. Uhrmacher,[53] F. Ukegawa,[159] G. Unal,[29] D. G. Underwood,[5] A. Undrus,[24] G. Unel,[162] Y. Unno,[65] D. Urbaniec,[34] G. Usai,[7] M. Uslenghi,[118a,118b] L. Vacavant,[82] V. Vacek,[126] B. Vachon,[84] S. Vahsen,[14] J. Valenta,[124] P. Valente,[131a] S. Valentinetti,[19a,19b] S. Valkar,[125] E. Valladolid Gallego,[166] S. Vallecorsa,[151] J. A. Valls Ferrer,[166] H. van der Graaf,[104] E. van der Kraaij,[104] R. Van Der Leeuw,[104] E. van der Poel,[104] D. van der Ster,[29] N. van Eldik,[83] P. van Gemmeren,[5] Z. van Kesteren,[104] I. van Vulpen,[104] M. Vanadia,[98] W. Vandelli,[29] G. 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Y. Yamazaki,[66] Z. Yan,[21] H. Yang,[86] U. K. Yang,[81] Y. Yang,[60] Y. Yang,[32a] Z. Yang,[145a,145b] S. Yanush,[90] Y. Yao,[14] Y. Yasu,[65] G. V. Ybeles Smit,[129] J. Ye,[39] S. Ye,[24] M. Yilmaz,[3c] R. Yoosoofmiya,[122] K. Yorita,[169] R. Yoshida,[5] C. Young,[142] S. Youssef,[21] D. Yu,[24] J. Yu,[7] J. Yu,[111] L. Yuan,[32a,jj] A. Yurkewicz,[105] B. Zabinski,[38] V. G. Zaets,[127] R. Zaidan,[62] A. M. Zaitsev,[127] Z. Zajacova,[29] L. Zanello,[131a,131b] A. Zaytsev,[106] C. Zeitnitz,[173] M. Zeller,[174] M. Zeman,[124] A. Zemla,[38] C. Zendler,[20] O. Zenin,[127] T. Ženiš,[143a] Z. Zinonos,[121a,121b] S. Zenz,[14] D. Zerwas,[114] G. Zevi della Porta,[56] Z. Zhan,[32d] D. Zhang,[32b,hh] H. Zhang,[87] J. Zhang,[5] X. Zhang,[32d] Z. Zhang,[114] L. Zhao,[107] T. Zhao,[137] Z. Zhao,[32b] A. Zhemchugov,[64] S. Zheng,[32a] J. Zhong,[117] B. Zhou,[86] N. Zhou,[162] Y. Zhou,[150] C. G. Zhu,[32d] H. Zhu,[41] J. Zhu,[86] Y. Zhu,[32b] X. Zhuang,[97] V. Zhuravlov,[98] D. Zieminska,[60] R. Zimmermann,[20] S. Zimmermann,[20] S. Zimmermann,[47] M. Ziolkowski,[140] R. Zitoun,[4] L. Živković,[34] V. V. Zmouchko,[127,a] G. Zobernig,[171] A. Zoccoli,[19a,19b] Y. Zolnierowski,[4] A. Zsenei,[29] M. zur Nedden,[15] V. Zutshi,[105] and L. Zwalinski[29]

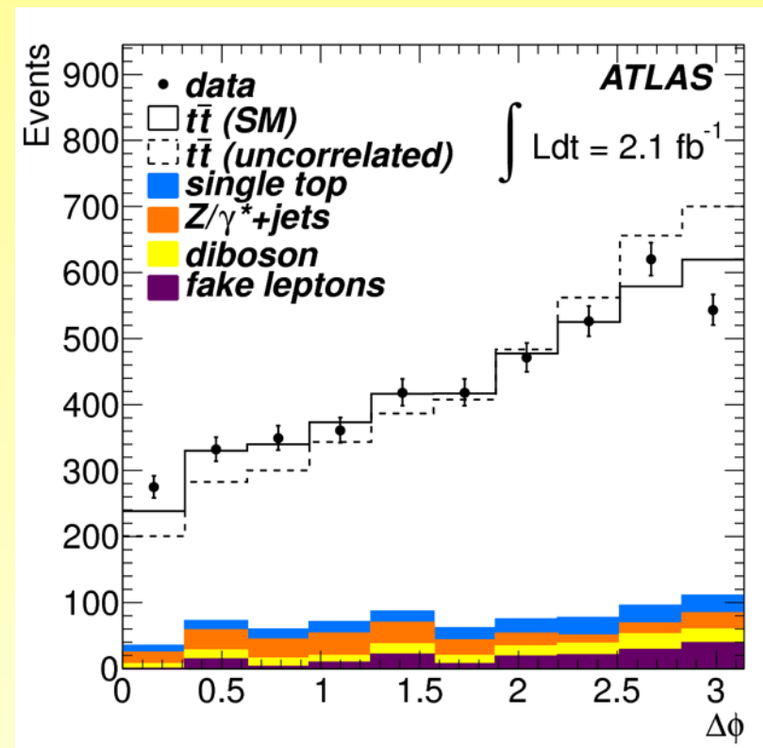
(ATLAS Collaboration)

First observation of spin correlation

PRL108, 212001 (2012)

- LHC 7 TeV, 2.1 fb^{-1}
  - Lab frame
  - Dilepton azimuthal angle, no need for top reconstruction
  - Template fit to the distribution of ΔΦ (SM, uncorrelated) to extract the amount of spin correlation

$Z/\gamma^*(\to e^+e^-/\mu^+\mu^-)$+jets (MC+DD)	64^{+11}_{-16}
$Z/\gamma^*(\to \tau\tau)$+jets (MC)	175 ± 29
Fake leptons (DD)	160^{+140}_{-70}
Single top (MC)	197 ± 21
Diboson (MC)	148 ± 20
Total (non-$t\bar{t}$)	740^{+150}_{-80}
$t\bar{t}$ (MC)	3530^{+280}_{-340}
Total expected	4270^{+320}_{-350}
Observed	4313



$$f^{SM} = 1.30 \pm 0.14\,(\text{stat})\ ^{+0.27}_{-0.22}\,(\text{syst})$$

5.1 SD away from f=0

Uncertainty source	Δf^{SM}
Data statistics	±0.14
MC simulation template statistics	±0.09
Luminosity	±0.01
Lepton	±0.01
Jet energy scale, resolution and efficiency	±0.12
NLO generator	±0.08
Parton shower and fragmentation	±0.08
ISR/FSR	±0.07
PDF uncertainty	±0.07
Top quark mass	±0.01
Fake leptons	+0.16/−0.07
Calorimeter readout	±0.01
All systematics	+0.27/−0.22
Statistical + Systematic	+0.30/−0.26

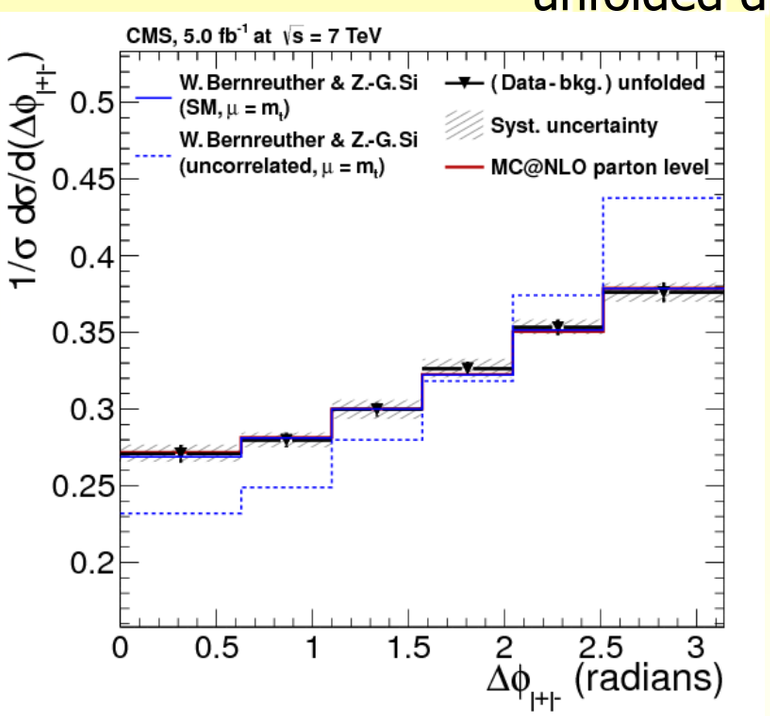
Spin correlation measurement in the dilepton channel

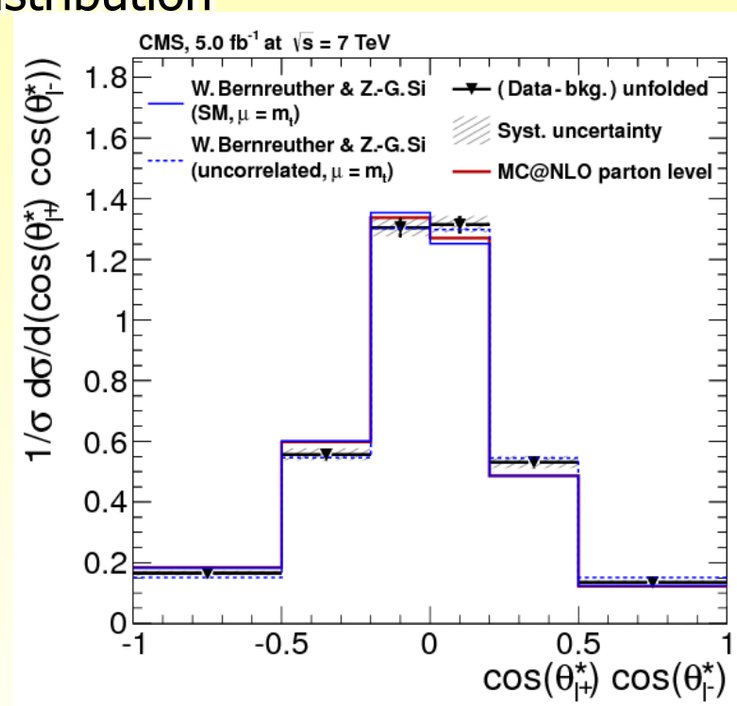
PRL112, 182001 (2014)

- LHC 7 TeV, 5 fb^{-1}
  - Helicity basis and lab frame
  - Dilepton events reconstructed using the matrix weighting technique (for the cosθ based measurement)
  - Angular asymmetry unfolded to parton level (singular value decomposition)

Asymmetry	Data (unfolded)	MC@NLO	NLO (SM, correlated)	NLO (uncorrelated)
$A_{\Delta\phi}$	$0.113 \pm 0.010 \pm 0.006 \pm 0.012$	0.110 ± 0.001	$0.115^{+0.014}_{-0.016}$	$0.210^{+0.013}_{-0.008}$
$A_{c_1c_2}$	$-0.021 \pm 0.023 \pm 0.025 \pm 0.010$	-0.078 ± 0.001	-0.078 ± 0.006	0

unfolded distribution



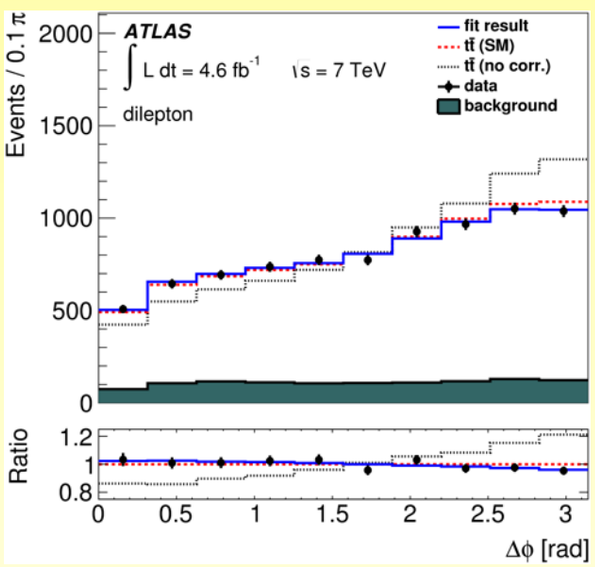


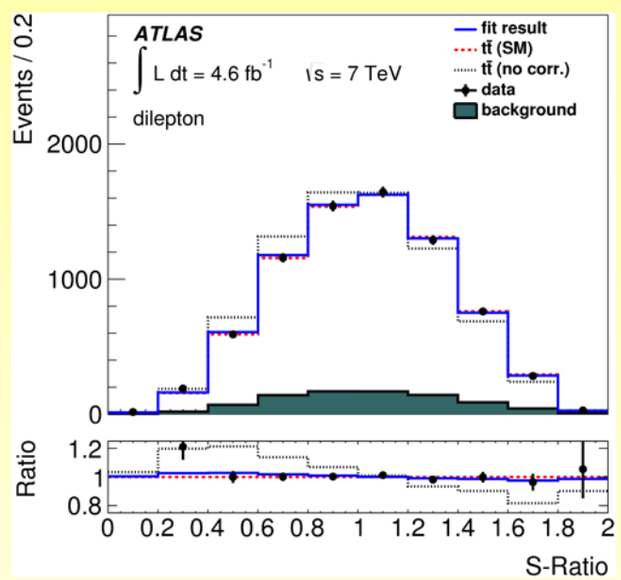
Asymmetry variable	$A_{\Delta\phi}$	$A_{c_1c_2}$
Jet energy scale	0.002	0.012
Lepton energy scale	0.001	0.001
Background	0.003	0.001
Fact. and renorm. scales	0.001	0.010
Top-quark mass	0.001	0.003
Parton distribution functions	0.002	0.002
Jet energy resolution	<0.001	<0.001
Pileup	0.002	0.002
b-tagging scale factor	<0.001	<0.001
Lepton selection	<0.001	<0.001
τ decay polarization	0.001	0.002
Unfolding	0.004	0.020
Total systematic uncertainty	0.006	0.025
Top p_T reweighting uncertainty	0.012	0.010

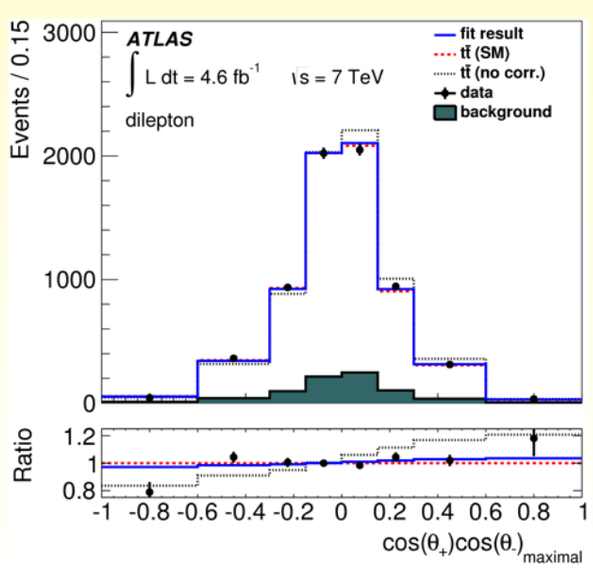
Spin correlation measurement in the dilepton and lepton+jets channels

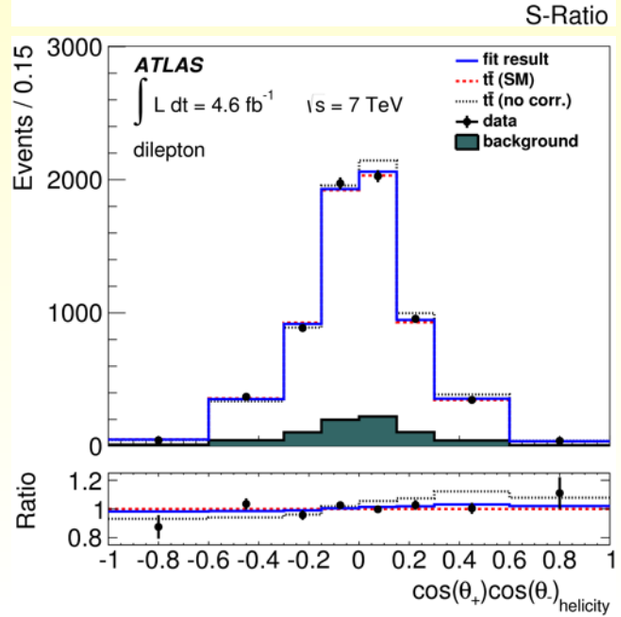
PRD90, 112016 (2014)

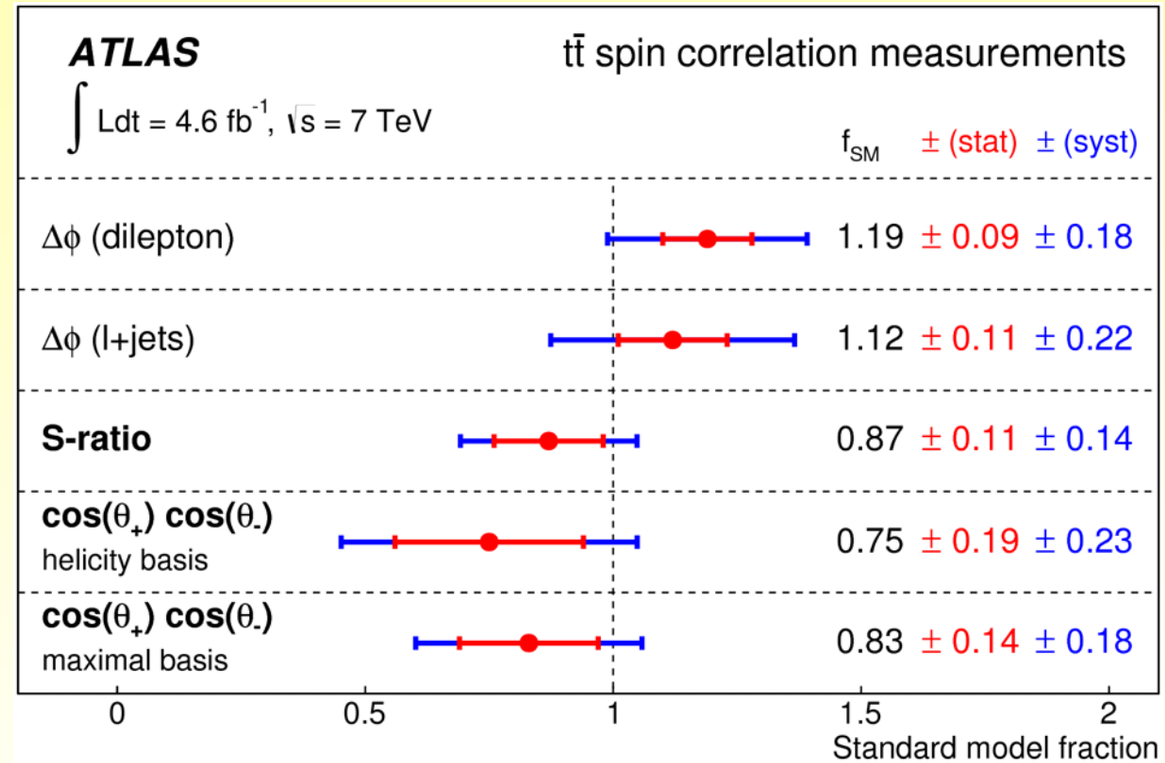
- LHC 7 TeV, 4.6 fb^{-1}
  - Dilepton reconstructed using the neutrino weighting method
    lepton+jets reconstructed with a likelihood
  - 4 observables: $\Delta\Phi$, S-ratio of matrix element (like-helicity gluon w/ or w/o spin correlation), $\cos\theta_+ * \cos\theta_-$ in the helicity and maximal basis
    different dependences to terms of the $t\bar{t}$ spin density matrices











Spin correlation and search for new physics

CMS PAS TOP-14-005

- LHC 7 TeV, 5 fb^{-1}
  - Search for anomalous $t\bar{t}g$ with ΔΦ distribution used for spin correlation measurement
  - Effective chromo-magnetic dipole moment

$$\mathcal{L}_{eff} = -\frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu} - \frac{\tilde{d}_t}{2} i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu}$$

$$\tilde{\mu}_t = \frac{g_s}{m_t}\hat{\mu}_t$$

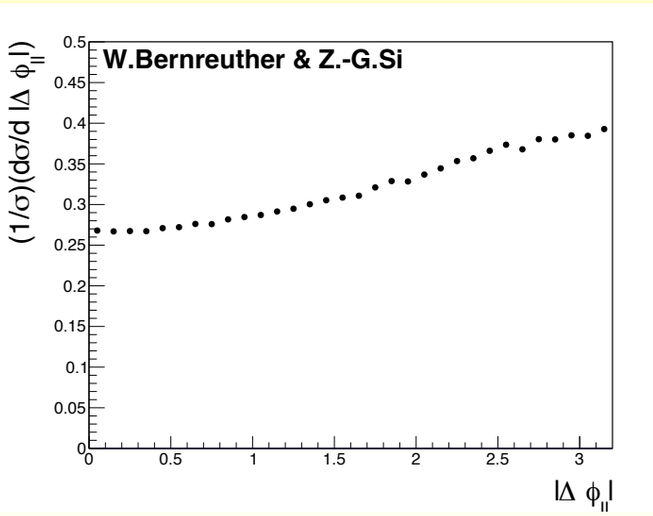
Small contribution from NP, restricted to Re(μ):

$$\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{ll}|} = \left(\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{ll}|}\right)_{SM} + \mathrm{Re}(\hat{\mu}_t)\left(\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{ll}|}\right)_{NP}$$

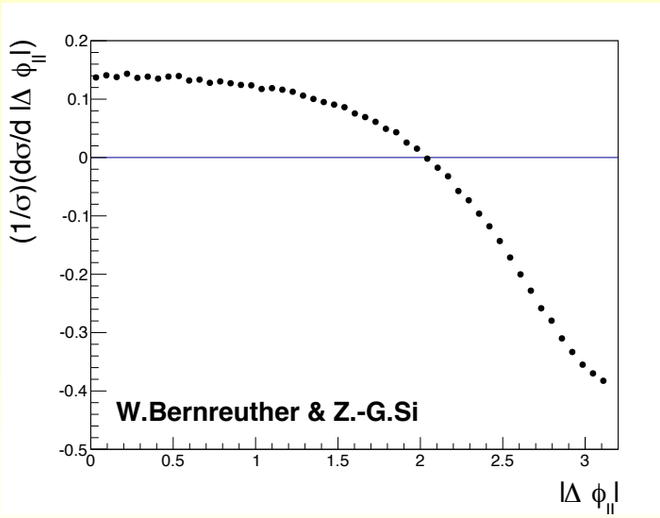
Result:

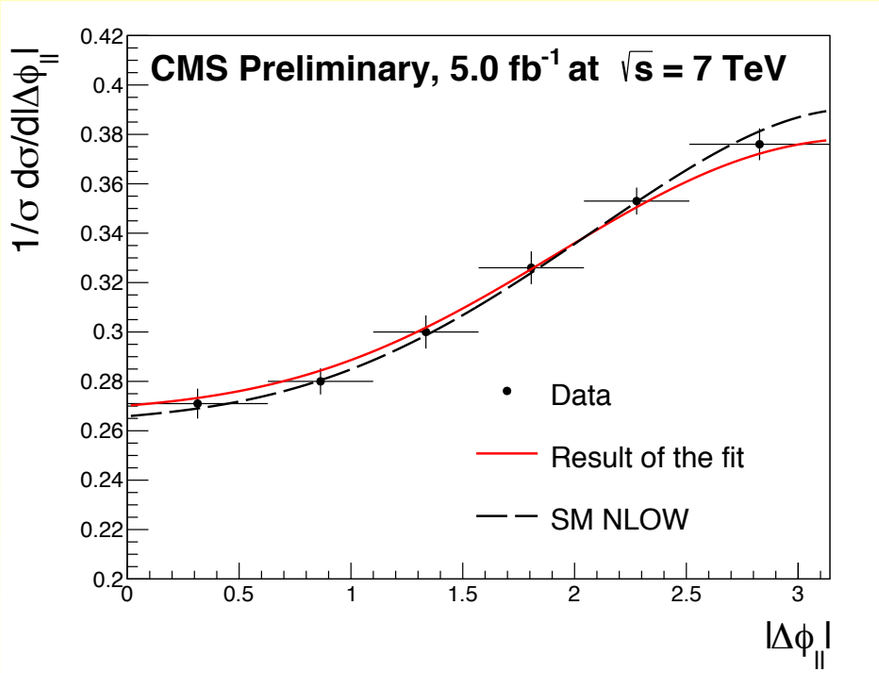
$-0.043 < \mathrm{Re}(\hat{\mu}_t) < 0.117$ at 95% CL

SM



NP





Spin correlation and search for new physics

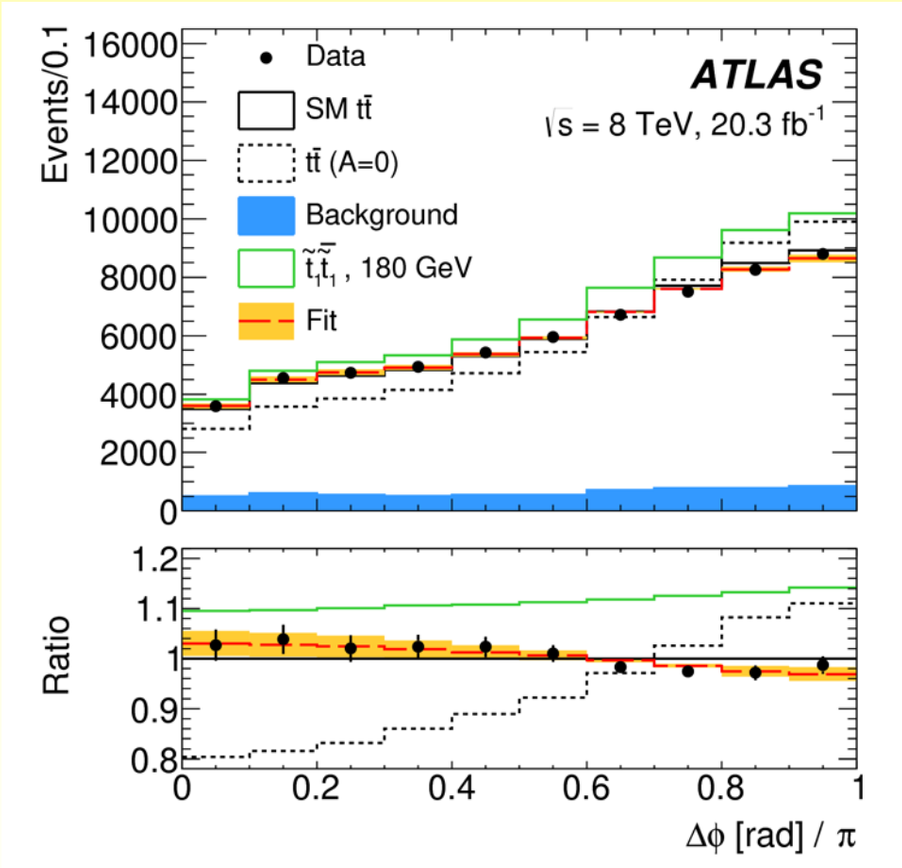
arXiv:1412.4742
accepted by PRL

- LHC 8 TeV, 20.3 fb^{-1}
  - Lab frame
  - In SUSY: if $\tilde{t}_1$ and $\tilde{\chi}_1$ are light: $\tilde{t}_1\bar{\tilde{t}}_1$ similar final state as $t\bar{t}$:
    $\tilde{t}_1 \longrightarrow t\,\tilde{\chi}_1$ ($m_{\tilde{t}1} > m_t + m_{\tilde{\chi}1}$)
    but zero spin correlation is predicted

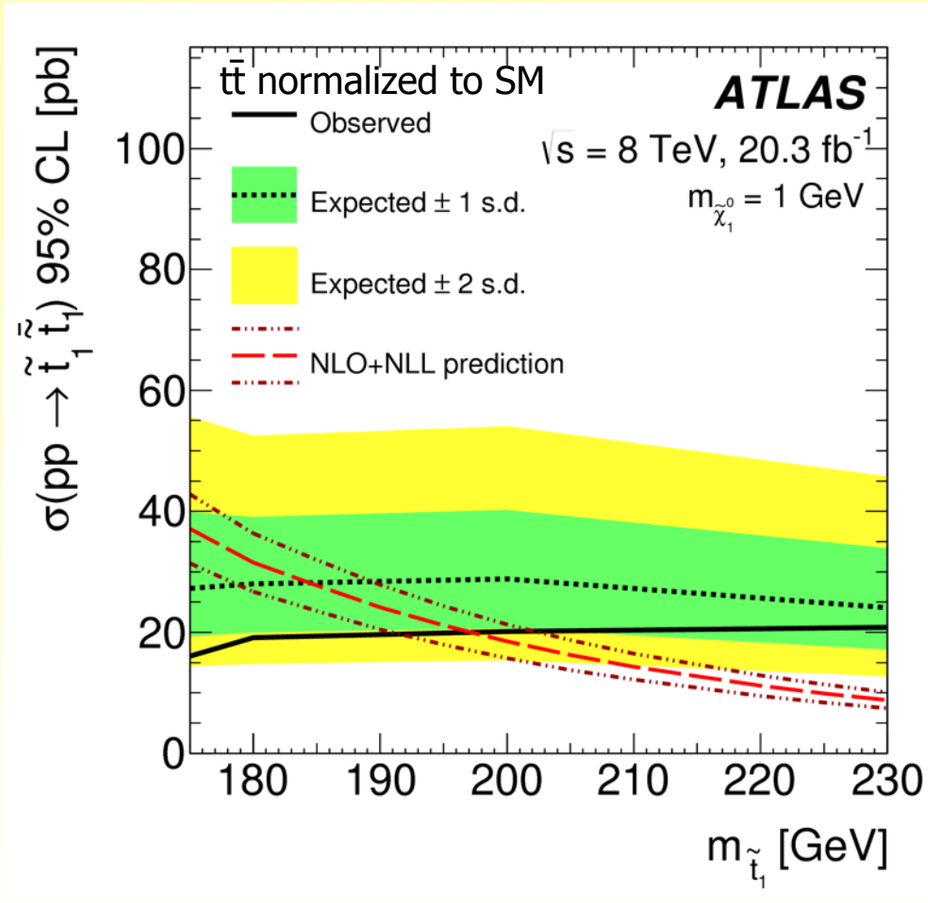
Process	Yield
$t\bar{t}$	$54000\,^{+3400}_{-3600}$
Z/γ^*+jets	2800 ± 300
tV (single top)	2600 ± 180
$t\bar{t}V$	80 ± 11
WW, WZ, ZZ	180 ± 65
Fake leptons	780 ± 780
Total non-$t\bar{t}$	6400 ± 860
Expected	$60000\,^{+3500}_{-3700}$
Observed	60424
$\tilde{t}_1\bar{\tilde{t}}_1$	7100 ± 1100
($m_{\tilde{t}_1} = 180$ GeV, $m_{\tilde{\chi}_1^0} = 1$ GeV)	

Floating $t\bar{t}$ normalization

f = 1.20 ± 0.05 (stat) ± 0.13 (syst).



Stops between the top quark mass and 191 GeV are excluded at 95% CL



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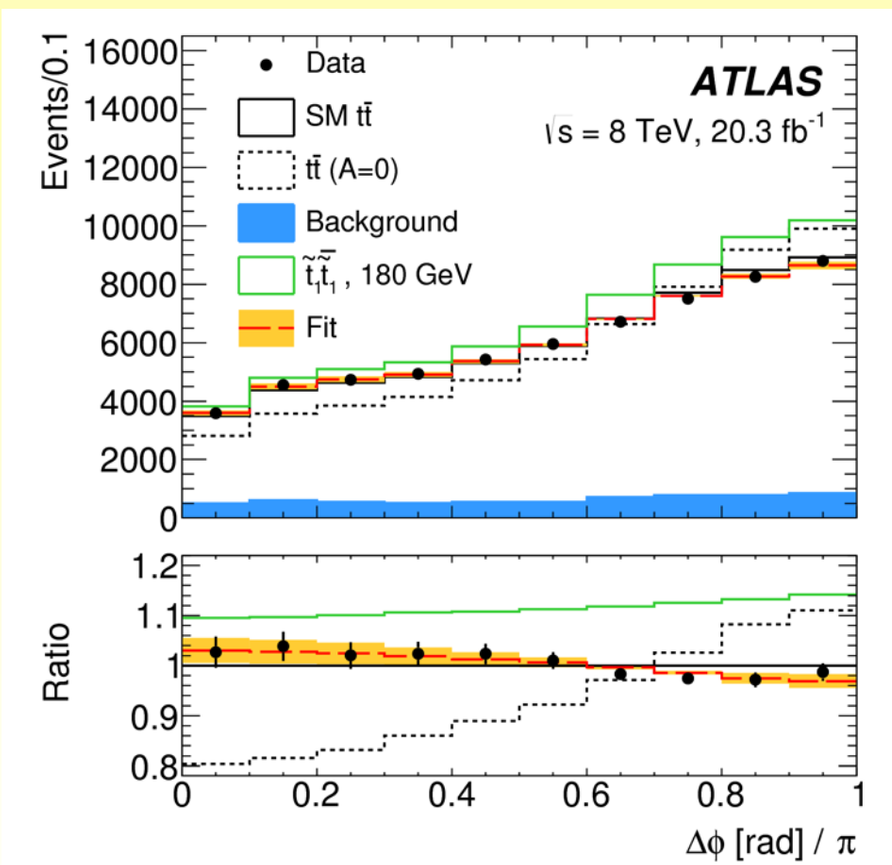

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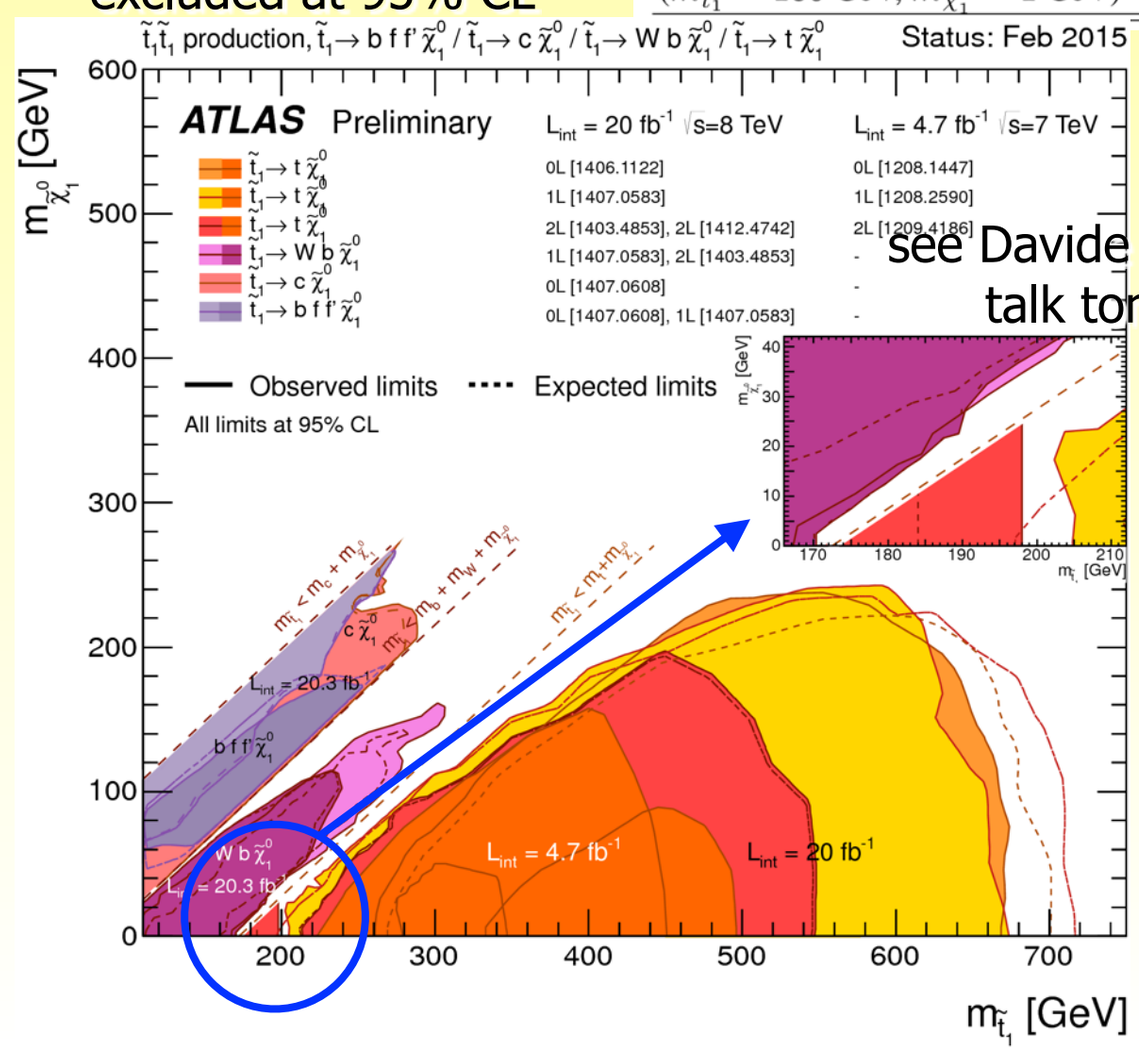


see Davide Gerbaudo's talk tomorrow

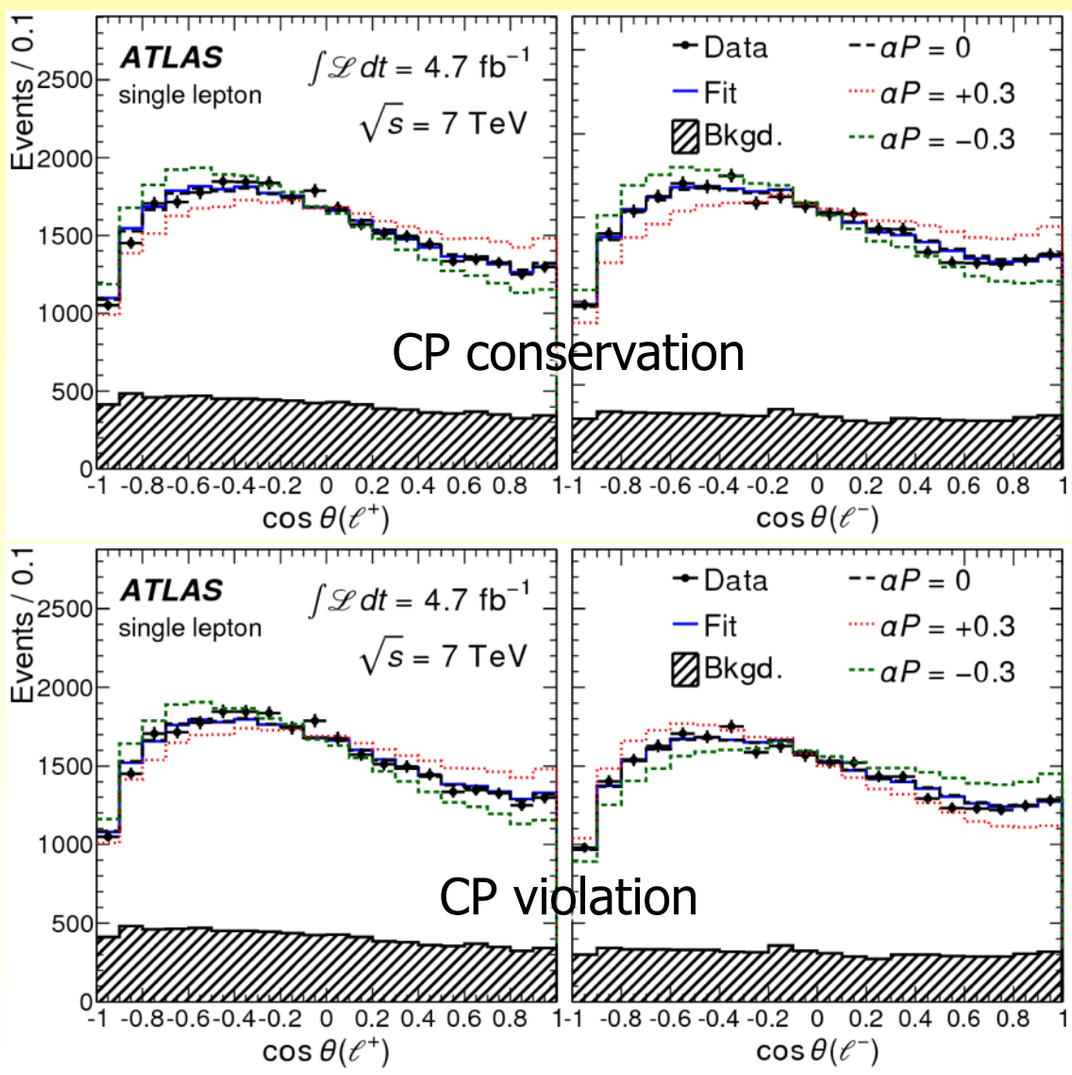
Measurement of the top quark polarization

PRL111, 232002 (2013)

PRL112, 182001 (2014)

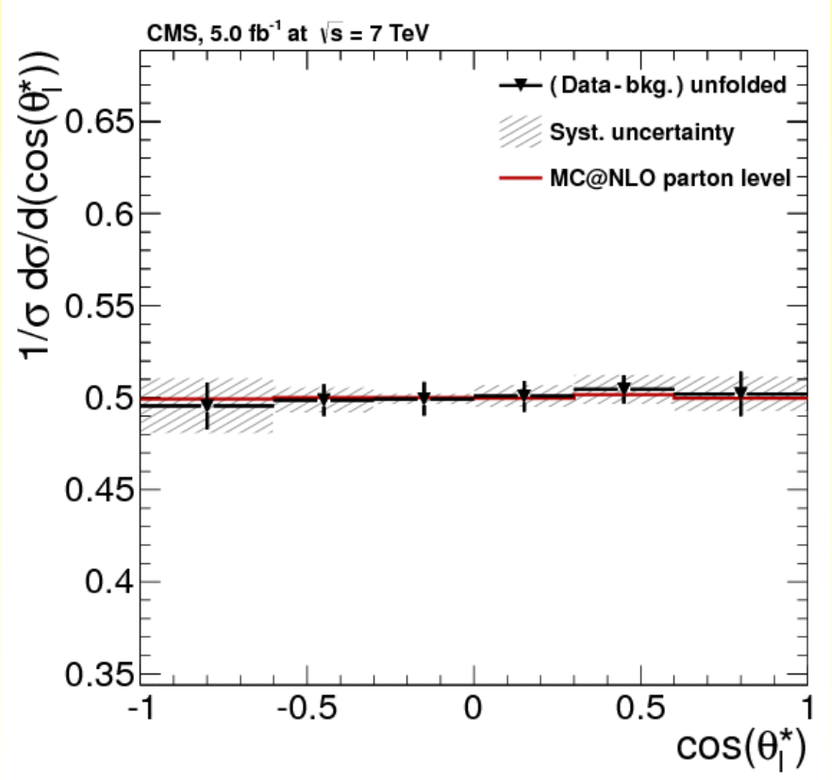
- First study at D0 (5.4 fb^{-1}) in the context of the FB asymmetry (PRD87, 011103(R), 2013)
- LHC 7 TeV, 4.7/5 fb^{-1}
  - Helicity basis
  - ATLAS: dilepton and lepton+jets, CMS: dilepton
  - Study the $\cos\theta_\ell$ distribution (w/ or w/o CP conservation, same or opposite $\alpha_\ell P$ for t and $\bar{t}$)

$$\alpha_\ell P_{\mathrm{CPC}} = -0.035 \pm 0.014(\mathrm{stat}) \pm 0.037(\mathrm{syst})$$
$$\alpha_\ell P_{\mathrm{CPV}} = 0.020 \pm 0.016(\mathrm{stat})^{+0.013}_{-0.017}(\mathrm{syst})$$



Asymmetry	Data (unfolded)	MC@NLO
A_P	$0.005 \pm 0.013 \pm 0.014 \pm 0.008$	0.000 ± 0.001

unfolded distribution



Top quark polarization in t-channel single top

CMS PAS TOP-13-001

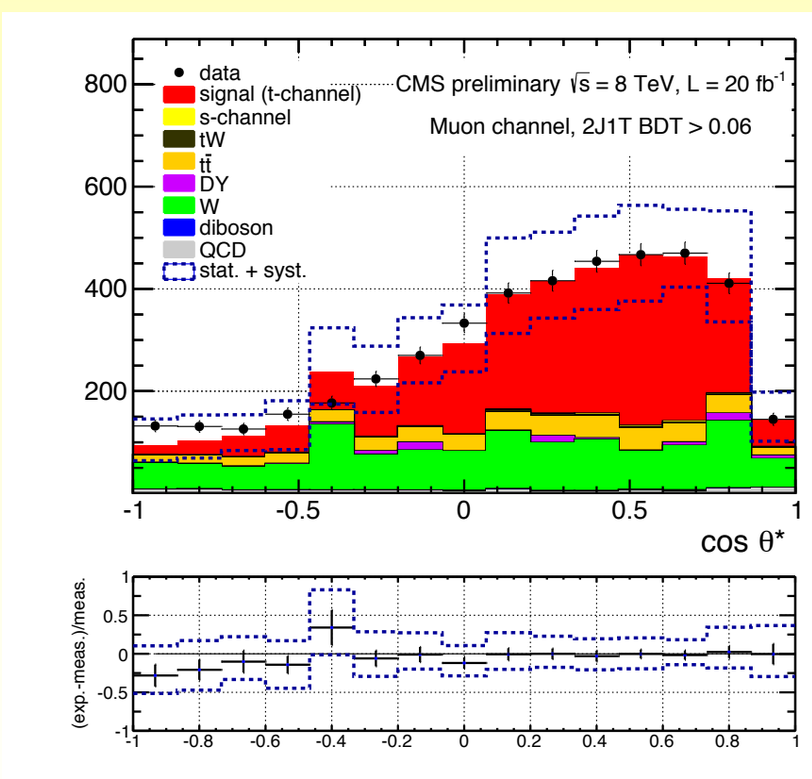
- LHC 8 TeV, 20 fb^{-1}
  - Top-quark spin axis: ~ direction of the spectator quark (untagged jet) in the top rest frame
  - BDT to separate t-channel from background
  - Unfold the $\cos\theta_\ell$ distribution (generalized matrix inversion)

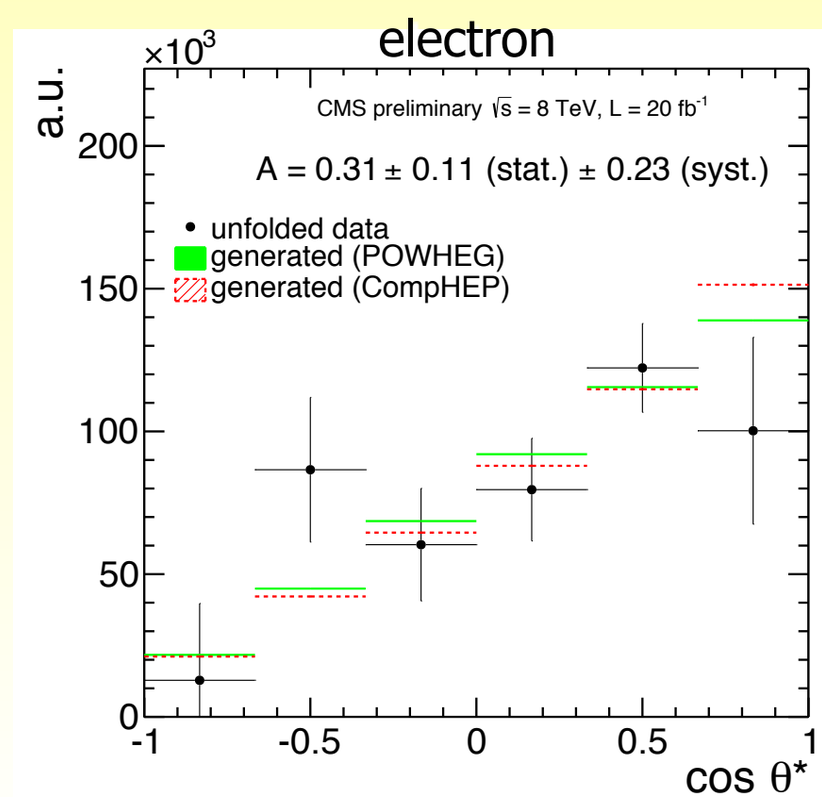
$$A_l \equiv \frac{1}{2} \cdot P_t \cdot \alpha_l \quad = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

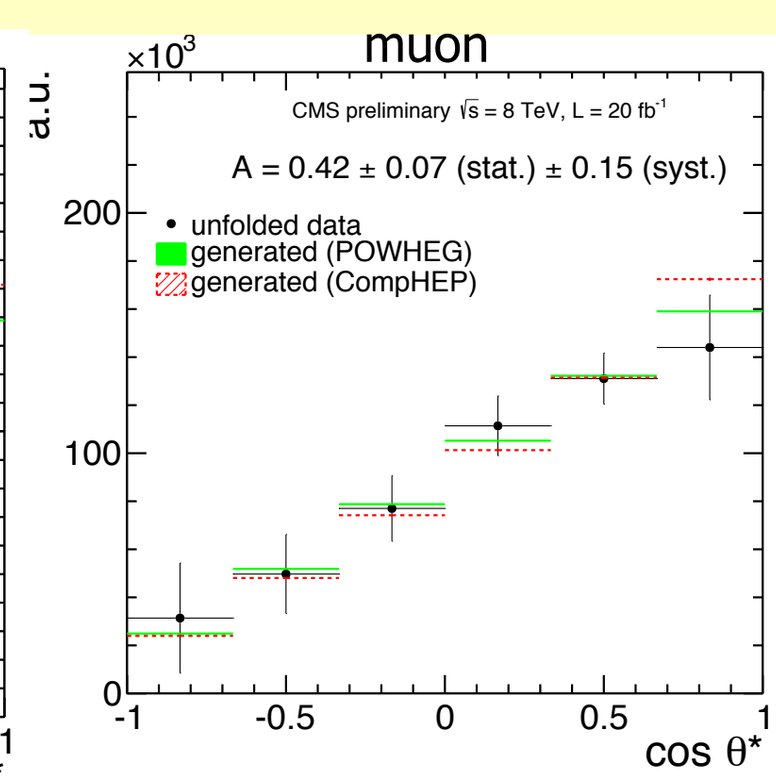
$$P_t = 0.82 \pm 0.12(stat.) \pm 0.32(syst.)$$ (α=1)

NLO SM prediction: P ≈ 0.88

Process	Muon channel	Electron channel
$t\bar{t}$	425.6 ± 47.7	254.0 ± 32.4
tW	29.0 ± 4.5	22.7 ± 4.0
s-channel	15.1 ± 2.5	6.1 ± 1.4
W+jets	1211.5 ± 139.5	533.2 ± 84.7
Z/γ^*+jets	71.7 ± 23.0	65.2 ± 25.9
Diboson	16.9 ± 2.5	10.8 ± 2.0
QCD	90.9 ± 14.1	85.5 ± 12.7
t-channel	2331.9 ± 99.8	1004.7 ± 67.4
Total Expected	4192.6 ± 118.8	1982.3 ± 77.8
Data	4303	1986



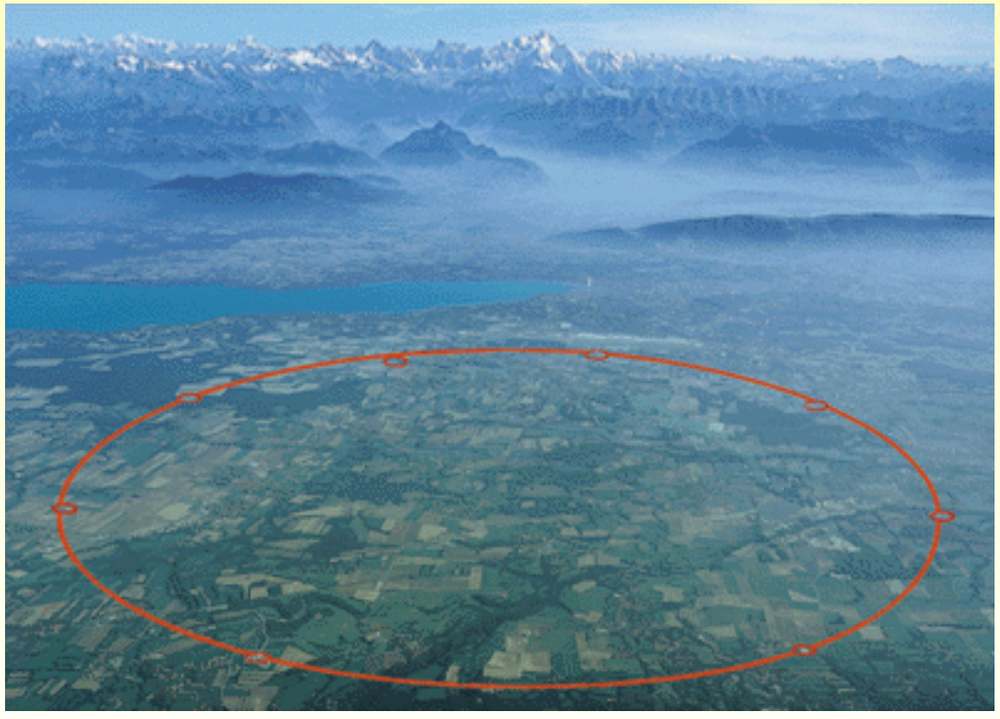




Conclusion

- The top sector is unique to study quark spin and polarization
  - Complementary measurements between Tevatron and LHC
  - We have observed $t\bar{t}$ spin correlation and performed the first measurement of top quark polarization
  - Allow to constrain new physics

- Still a lot to learn waiting for LHC Run 2 results
  - Differential measurements
  - Other spin density matrix measurements (transverse polarization, …)
  - Measurements in single top



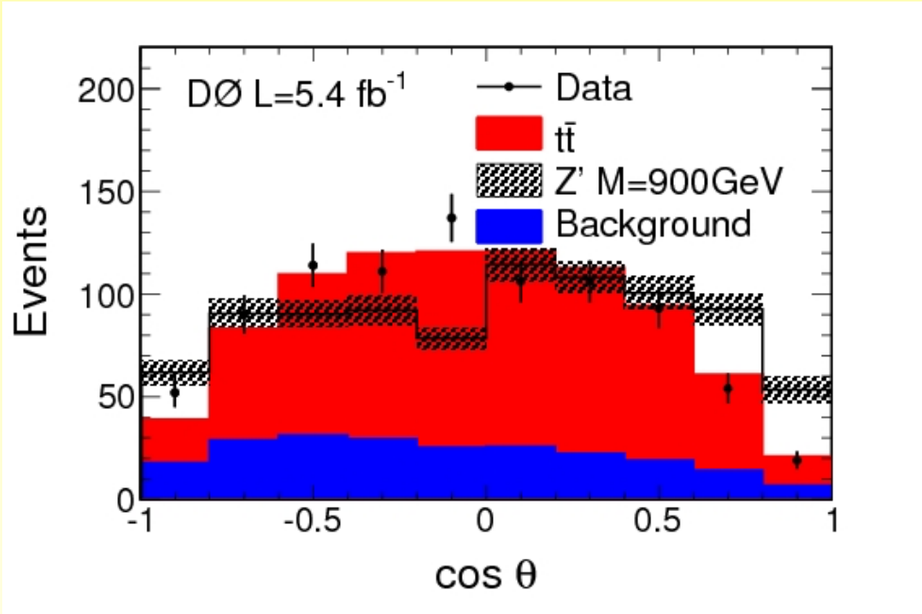
backup

Top quark polarization

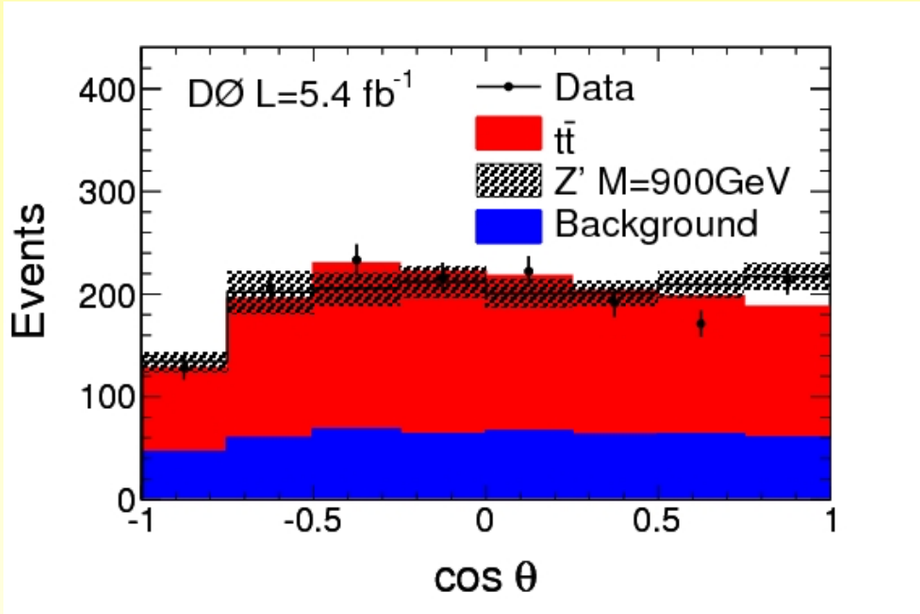
PRD87, 011103(R) (2013)

- Tevatron Run II, 5.4 fb^{-1}
  - First study of the longitudinal top quark polarization in the light of the FB asymmetry question
  - Top-quark polarization can change the correlation between $t\bar{t}$ FB asymmetry and leptonic FB asymmetry
  - Study the $\cos\theta^{\pm}$ distribution (assuming CP invariance)

dilepton



lepton+jets



Good agreement between data and SM predictions