

Top Quark Pair Spin Correlation and Polarisation at CMS

Christian Schwanenberger

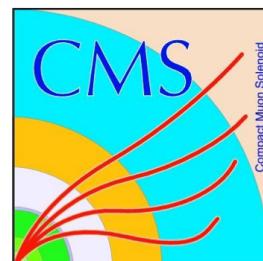


DESY

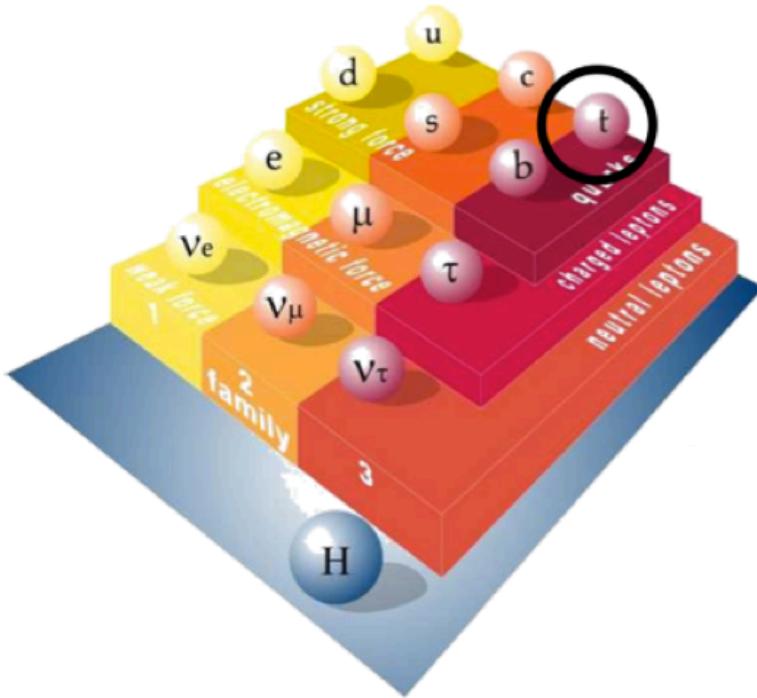


LHC TOP Working Group Meeting
28 May, 2019

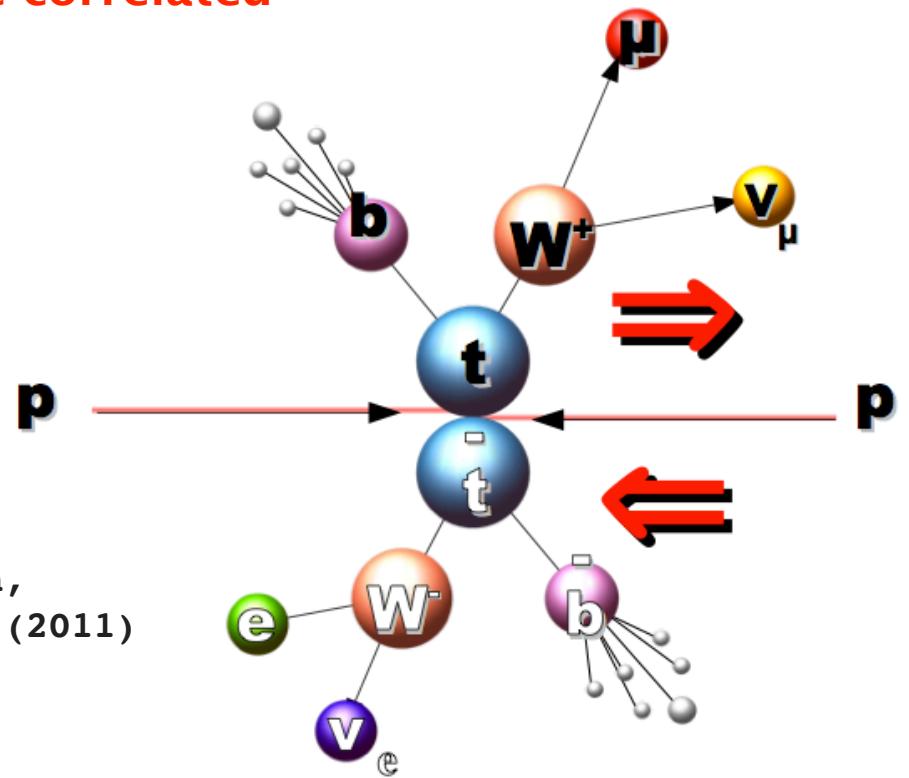
on behalf of



Top Pair Spin Correlation



- top quark: discovered in 1995 by CDF&DØ
- does the top quark have spin 1/2?
- top quark pair production: top quarks are not polarised, but spin of top and anti-top quarks are correlated



- top quarks have short lifetime:

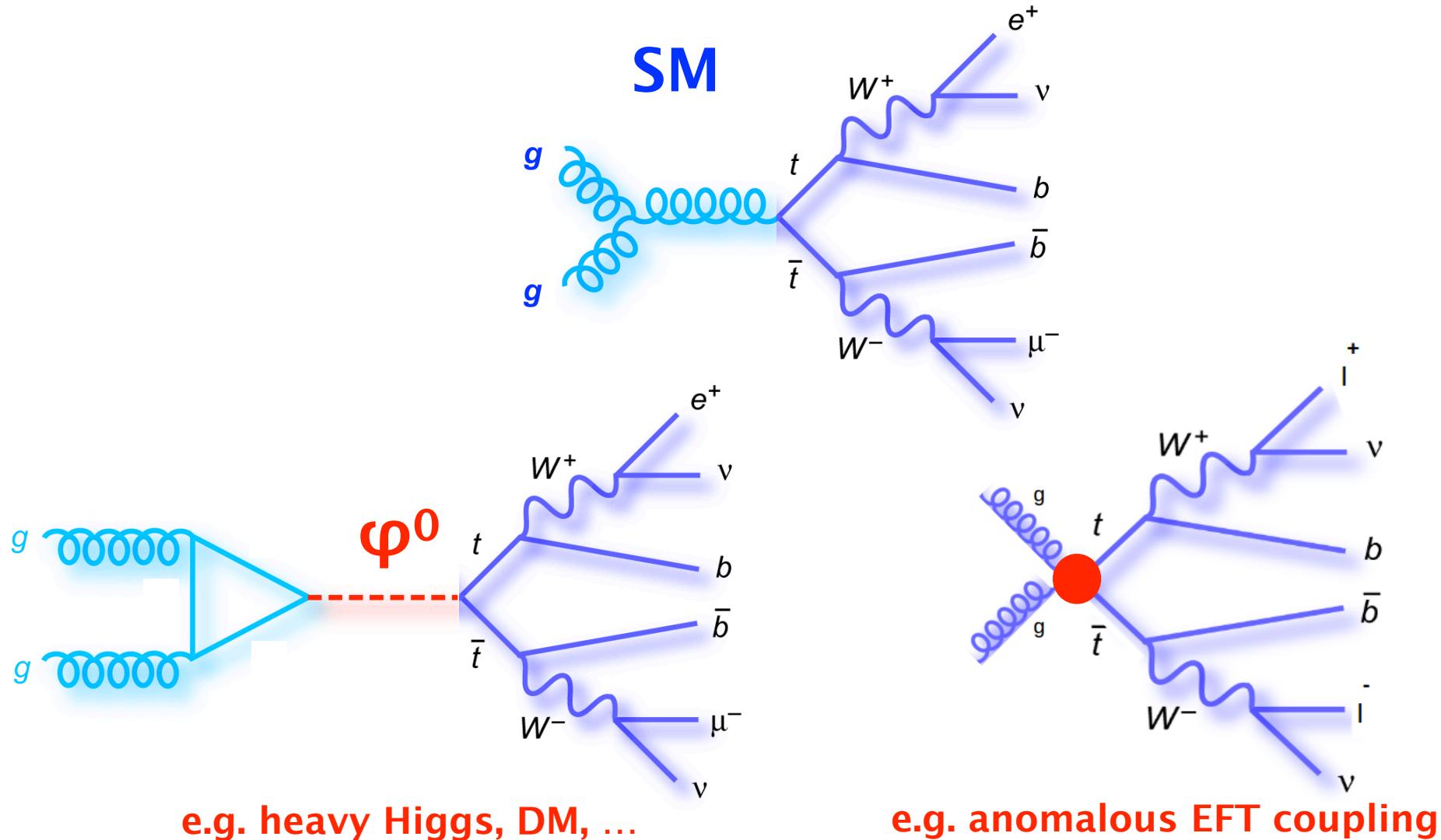
$$\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25} \text{ s}$$

DØ Collaboration,
PRL 106, 022001 (2011)

- decay before spins can flip
- spin information is contained in decay product
- measure $t\bar{t}$ spin correlation: consistent with SM prediction for a spin 1/2 particle?

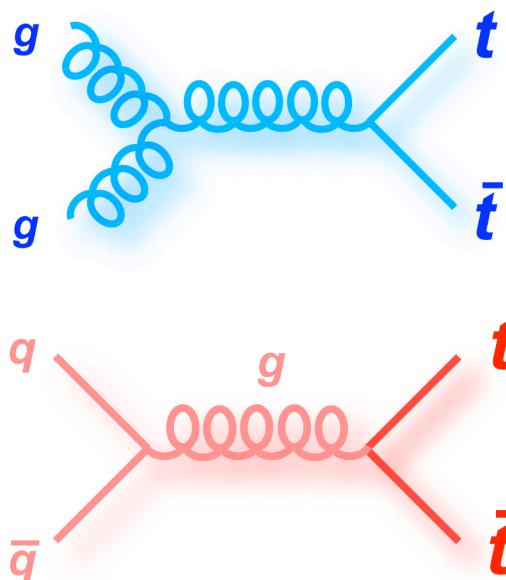
New physics impact on spin correlations

- important test of SM and sensitive search for physics beyond
- analyse the whole chain of top pair production and top decay



$t\bar{t}$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$



$$g(p_1) + g(p_2) \rightarrow t(k_1, s_1) + \bar{t}(k_2, s_2)$$

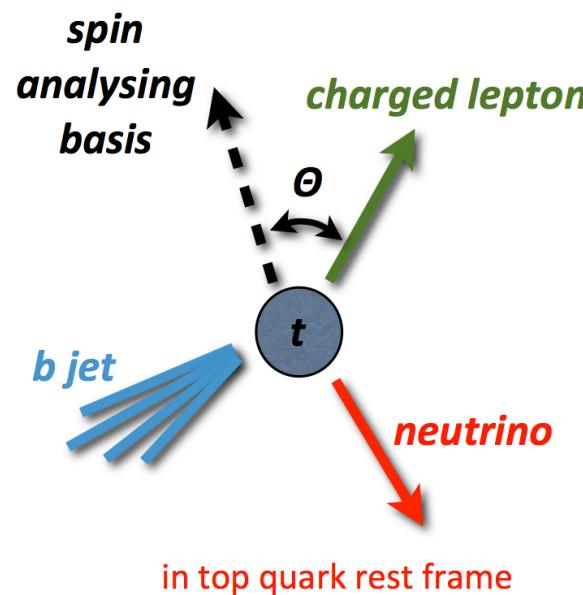
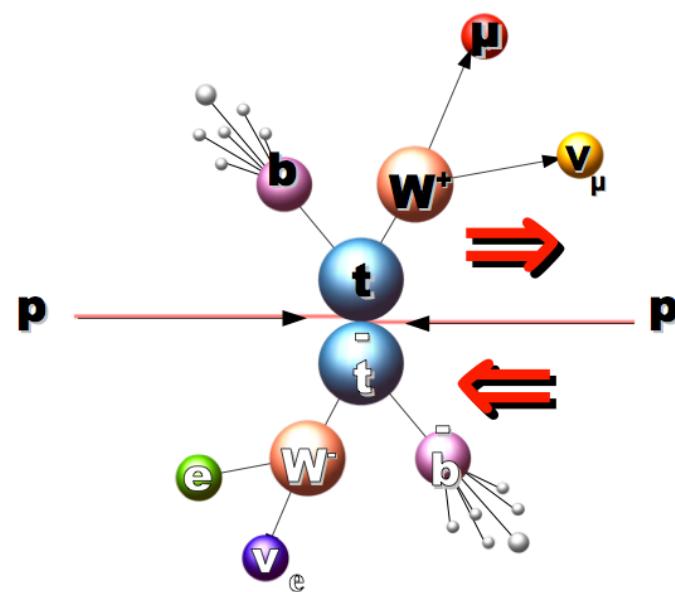
Bernreuther, Heisler, Si, JHEP 1512, 026 (2015)

$$q(p_1) + \bar{q}(p_2) \rightarrow t(k_1, s_1) + \bar{t}(k_2, s_2)$$

→ completely characterises spin dependence

$t\bar{t}$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$



- almost 100% analysis power

- spin information is contained in decay products

$t\bar{t}$ production density matrix

$$|M|^2 \propto A + B^+ \cdot s_1 + B^- \cdot s_2 + C_{ij} s_{1i} s_{2j}$$

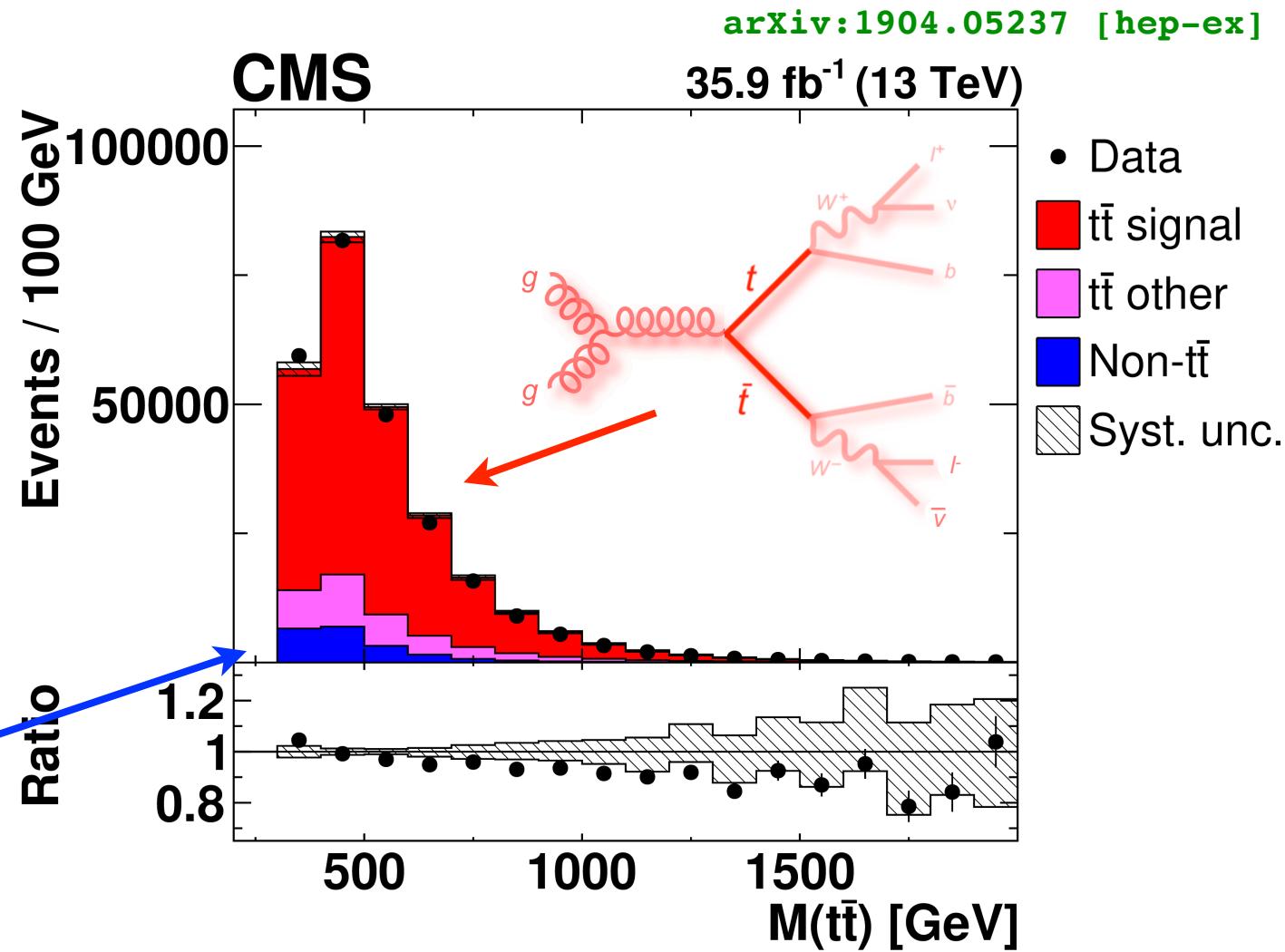
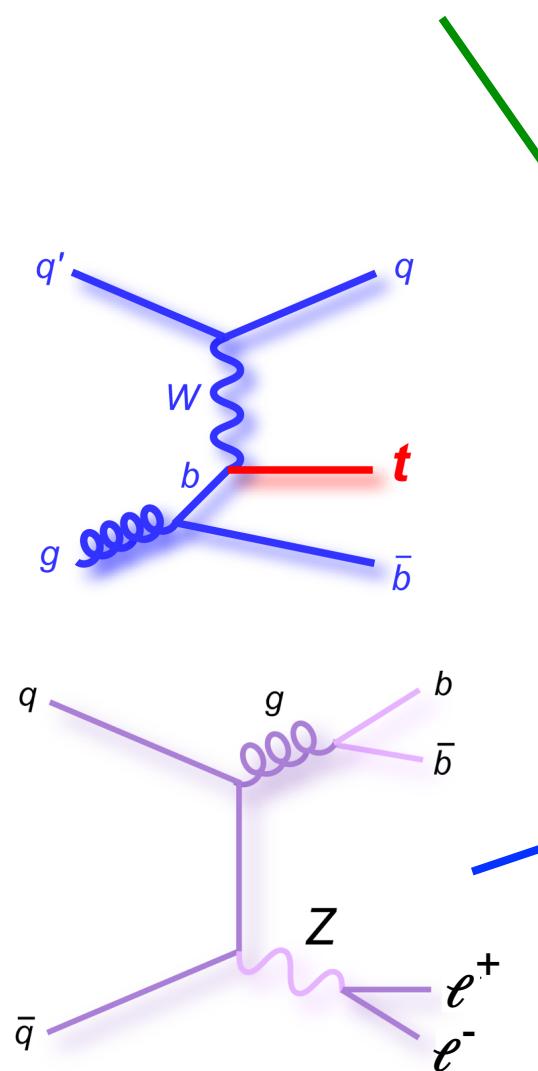


determines cross section and kinematical distributions independent of top spin (e.g. $m_{t\bar{t}}$ distribution etc.)

- test of QCD predictions
- search for new physics

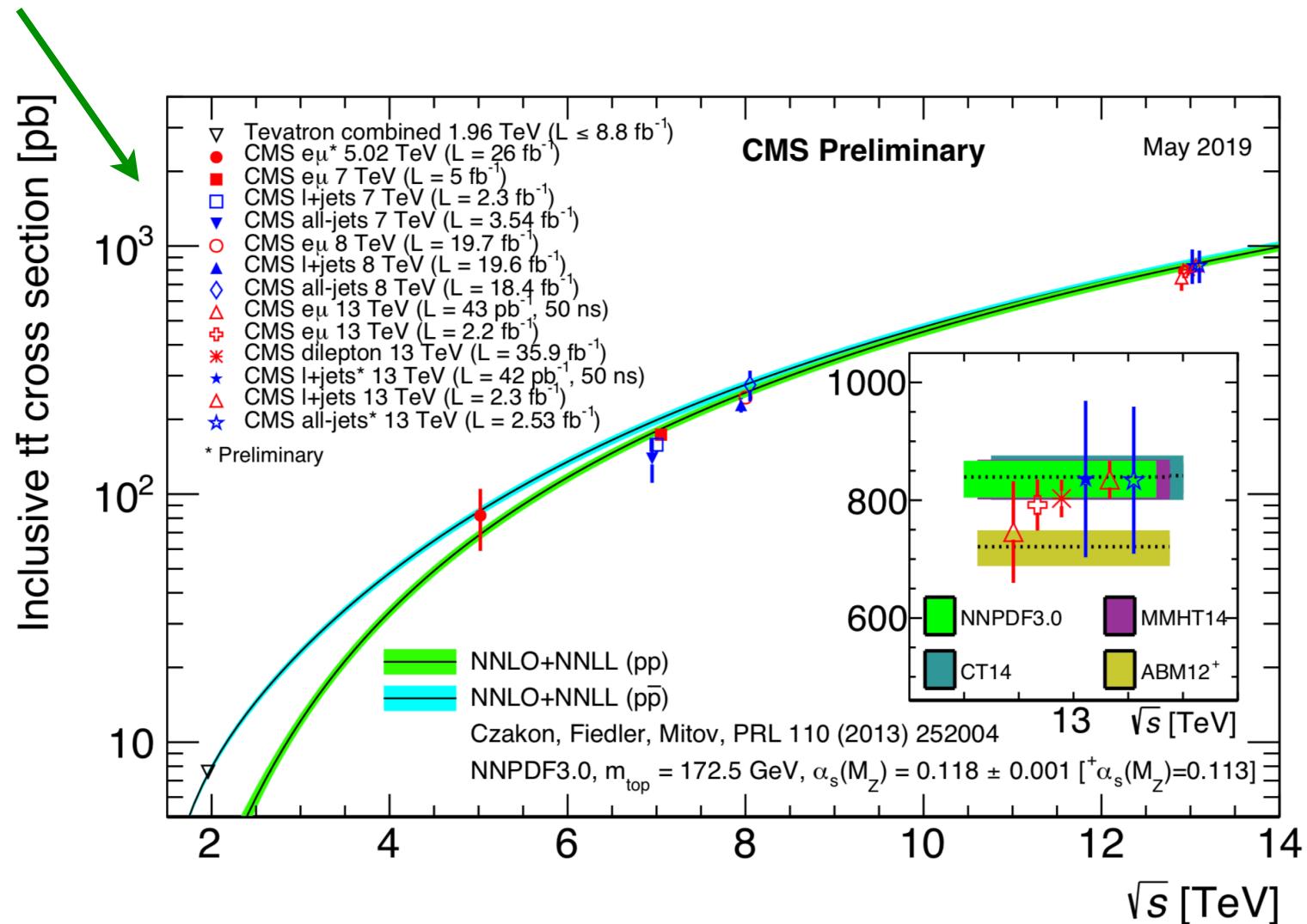
$t\bar{t}$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$



$t\bar{t}$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

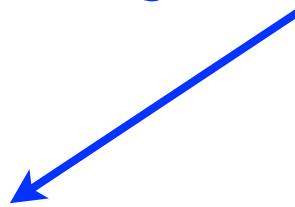


$t\bar{t}$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

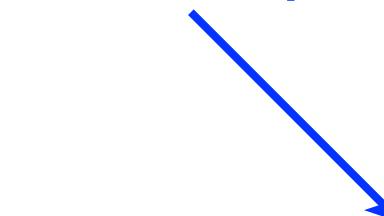
$$\tilde{B}_i^\pm = b_1^\pm \hat{p}_i + b_2^\pm \hat{k}_i + b_3^\pm n_i \quad \mathbf{n} = \hat{\mathbf{p}} \times \hat{\mathbf{k}}$$

longitudinal polarisation

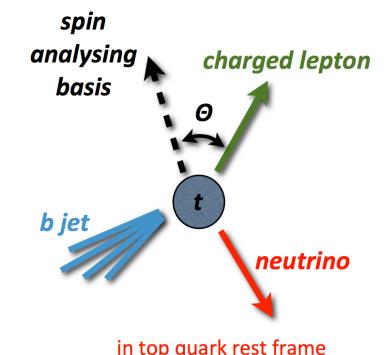


$\mathbf{b}_1^\pm, \mathbf{b}_2^\pm \neq 0$: P-violation
(=0 in LO QCD)

transverse polarisation



$\mathbf{b}_3^\pm \neq 0$: P-even, CP-violating
($\neq 0$ through absorptive parts)



$\bar{t}t$ production density matrix

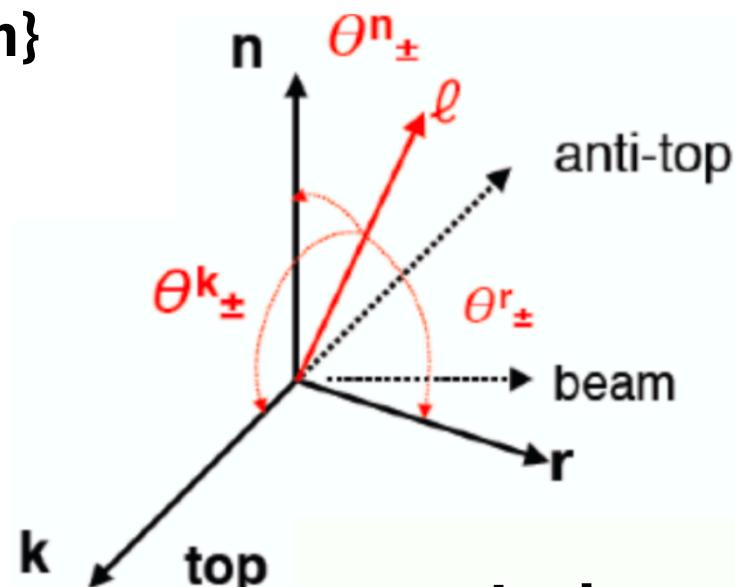
$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

$$\tilde{B}_i^\pm = b_k^\pm \hat{k}_i + b_r^\pm \hat{r}_i + b_n^\pm \hat{n}_i$$

longitudinal polarisation transverse polarisation

orthonormal basis:

{k,r,n}



$$\hat{\mathbf{r}} = \frac{1}{r}(\hat{\mathbf{p}} - y\hat{\mathbf{k}})$$

$$\hat{\mathbf{n}} = \frac{1}{r}(\hat{\mathbf{p}} \times \hat{\mathbf{k}})$$

$$y = \hat{\mathbf{k}} \cdot \hat{\mathbf{p}}, \quad r = \sqrt{1 - y^2}$$

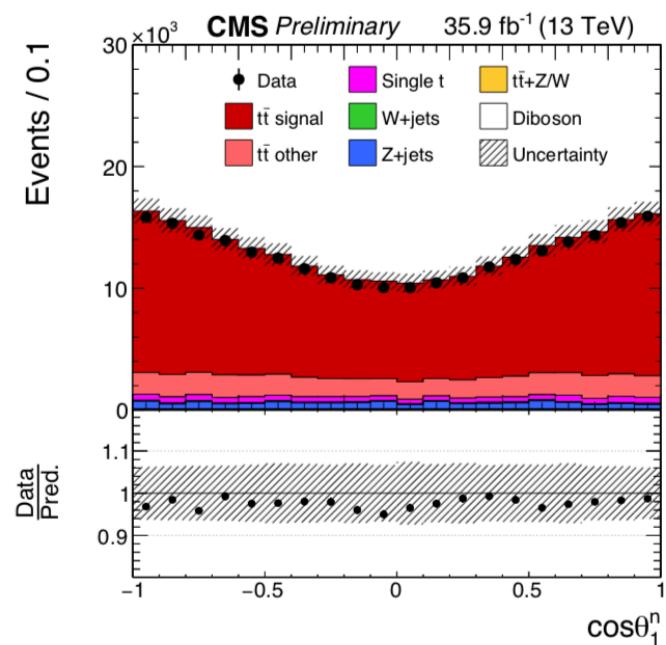
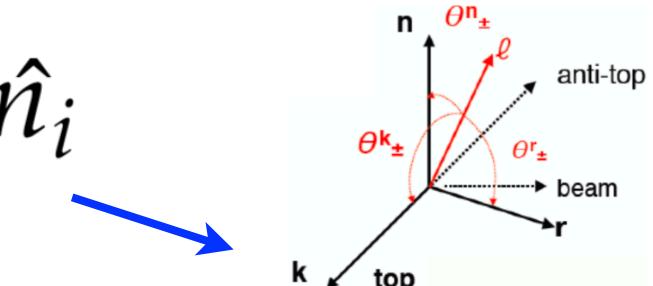
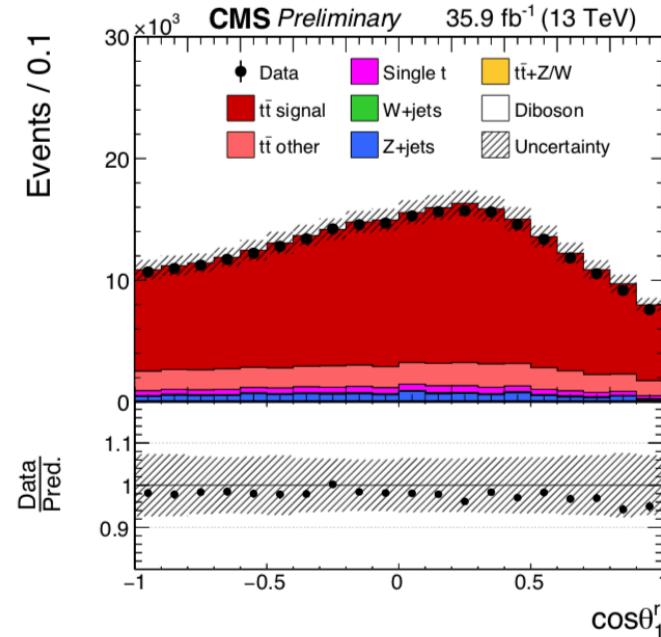
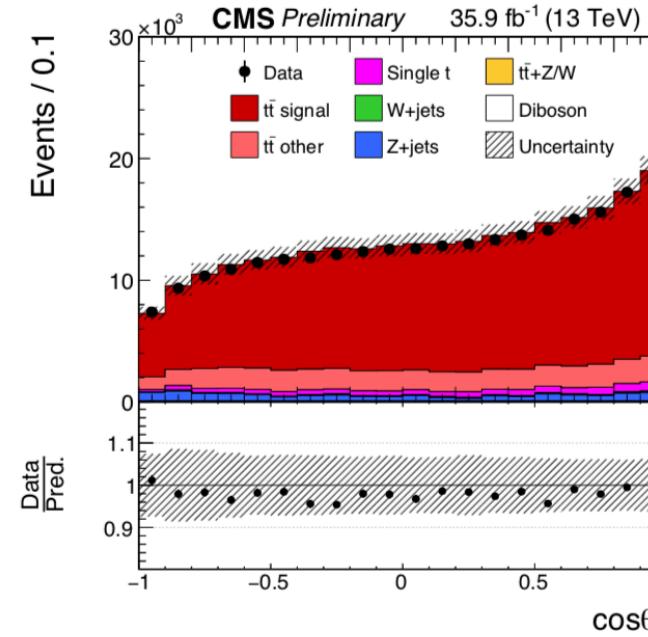
→ independent coefficient functions

Longitudinal and transverse polarisation

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

$$\tilde{B}_i^\pm = b_k^\pm \hat{k}_i + b_r^\pm \hat{r}_i + b_n^\pm \hat{n}_i$$

CMS-PAS-TOP-18-006



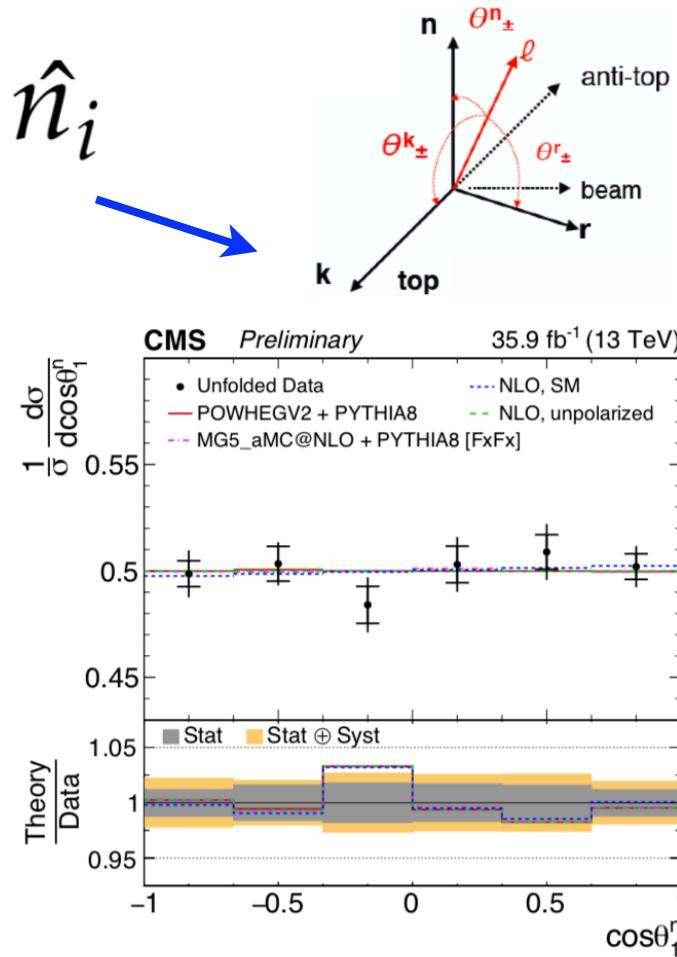
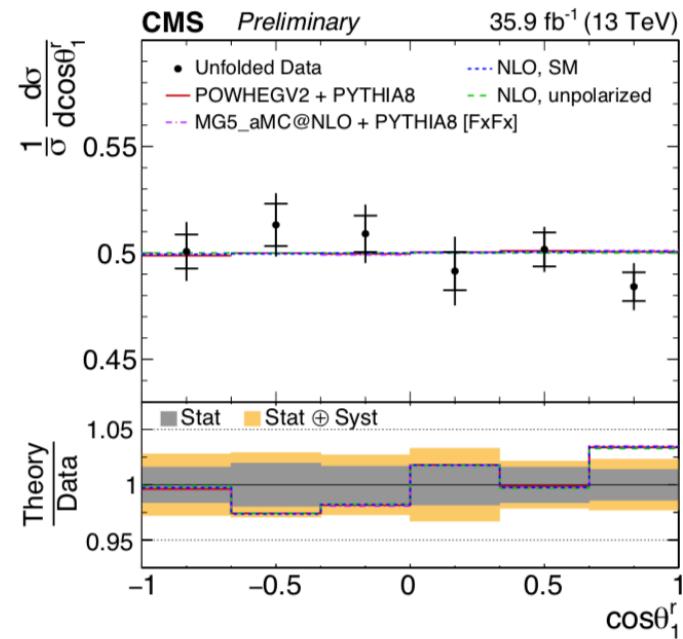
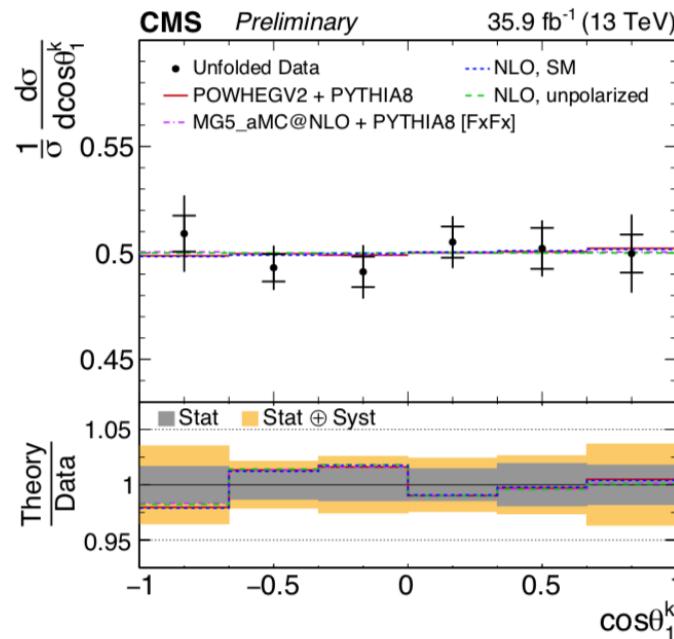
→ in agreement with SM

Longitudinal and transverse polarisation

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

$$\tilde{B}_i^\pm = b_k^\pm \hat{k}_i + b_r^\pm \hat{r}_i + b_n^\pm \hat{n}_i$$

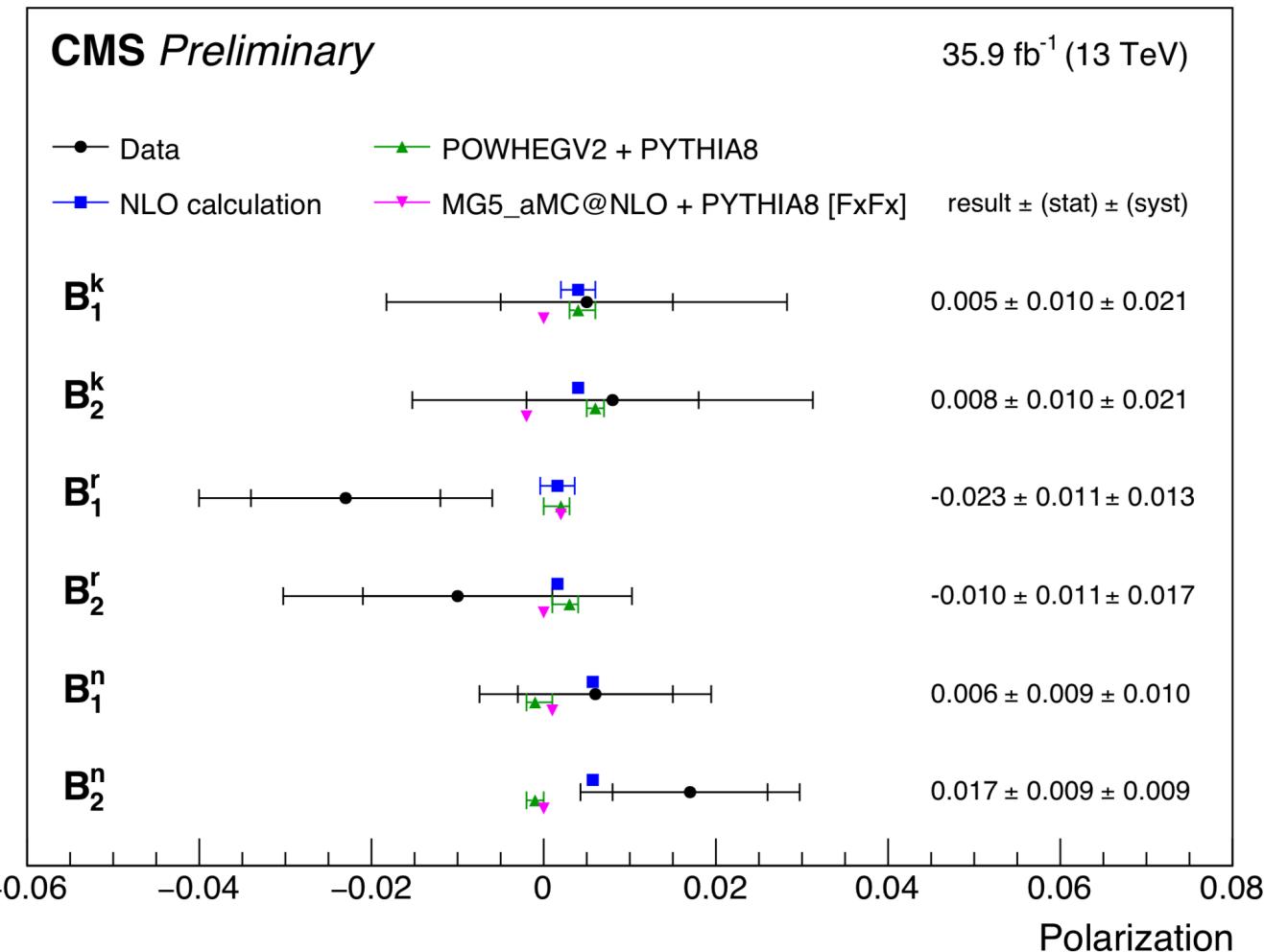
CMS-PAS-TOP-18-006



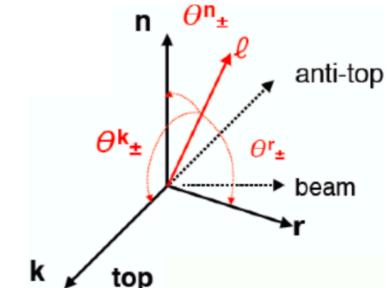
- unfold to top parton level with regularized unfolding method (TUnfold)
- extrapolate to full phase space

Longitudinal and transverse polarisation

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$



→ in agreement with SM



dominant uncertainties
from JES
(top rest frame
reconstruction)

$t\bar{t}$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

spin correlation

$$\begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$

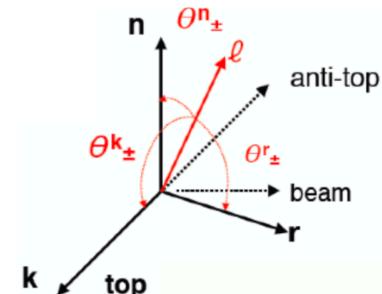
$\bar{t}t$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

spin correlation

$$\begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$

$$\begin{aligned} \tilde{C}_{ij} = & c_{kk} \hat{k}_i \hat{k}_j + c_{rr} \hat{r}_i \hat{r}_j + c_{nn} \hat{n}_i \hat{n}_j \\ & + c_{rk} (\hat{r}_i \hat{k}_j + \hat{k}_i \hat{r}_j) + c_{nr} (\hat{n}_i \hat{r}_j + \hat{r}_i \hat{n}_j) + c_{kn} (\hat{k}_i \hat{n}_j + \hat{n}_i \hat{k}_j) \\ & + c_n (\hat{r}_i \hat{k}_j - \hat{k}_i \hat{r}_j) + c_k (\hat{n}_i \hat{r}_j - \hat{r}_i \hat{n}_j) + c_r (\hat{k}_i \hat{n}_j - \hat{n}_i \hat{k}_j). \end{aligned}$$



$t\bar{t}$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

spin correlation

$$\begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$

$C_{kk}, C_{rr}, C_{nn}, C_{rk}$: C-even, P-even

#0 in LO QCD

$$\begin{aligned} \tilde{C}_{ij} = & c_{kk} \hat{k}_i \hat{k}_j + c_{rr} \hat{r}_i \hat{r}_j + c_{nn} \hat{n}_i \hat{n}_j \\ & + c_{rk} (\hat{r}_i \hat{k}_j + \hat{k}_i \hat{r}_j) + c_{nr} (\hat{n}_i \hat{r}_j + \hat{r}_i \hat{n}_j) + c_{kn} (\hat{k}_i \hat{n}_j + \hat{n}_i \hat{k}_j) \\ & + c_n (\hat{r}_i \hat{k}_j - \hat{k}_i \hat{r}_j) + c_k (\hat{n}_i \hat{r}_j - \hat{r}_i \hat{n}_j) + c_r (\hat{k}_i \hat{n}_j - \hat{n}_i \hat{k}_j). \end{aligned}$$

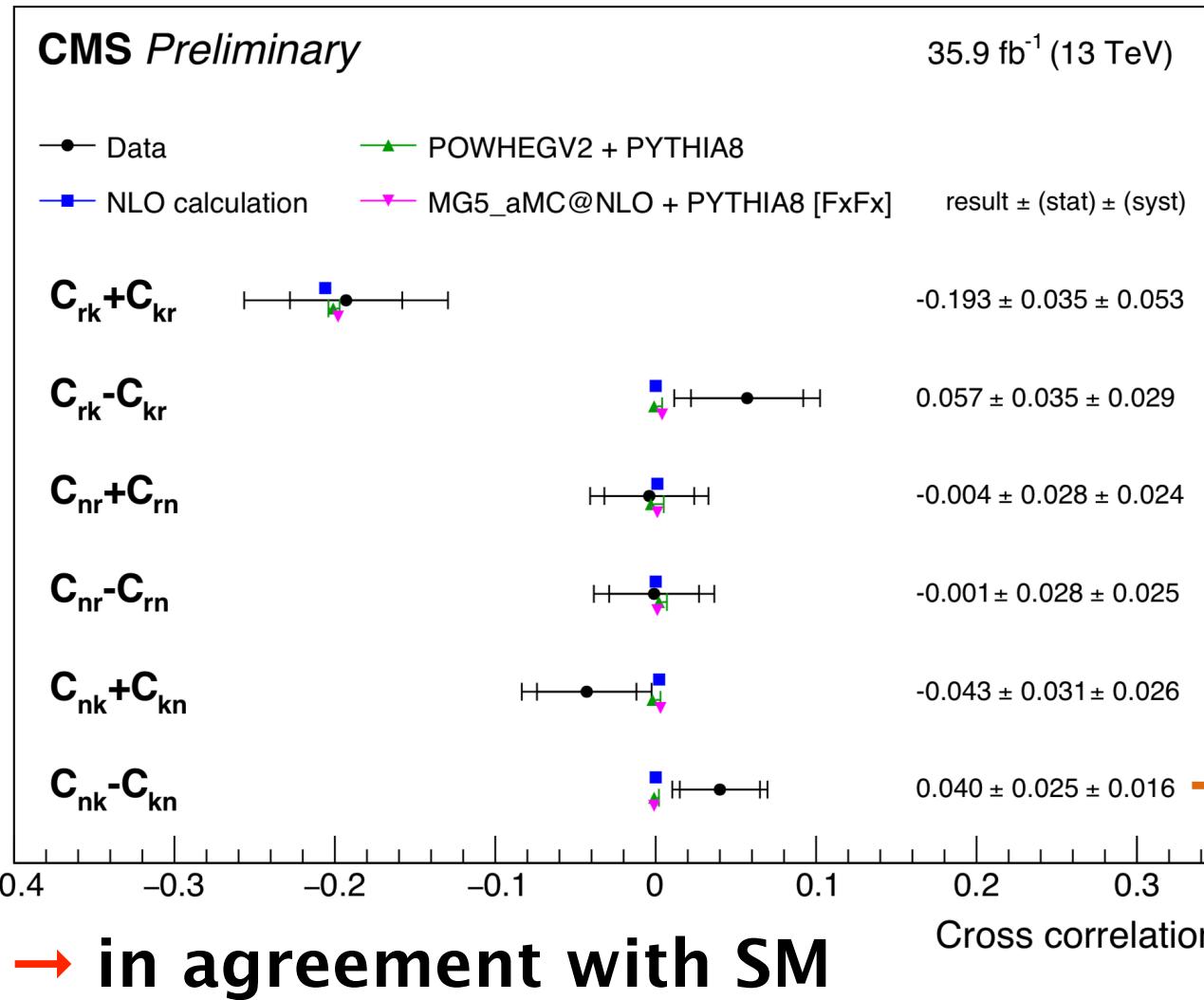
C_{nr}, C_{kn} : P-odd, CP-even

tiny in SM (absorpt. parts)

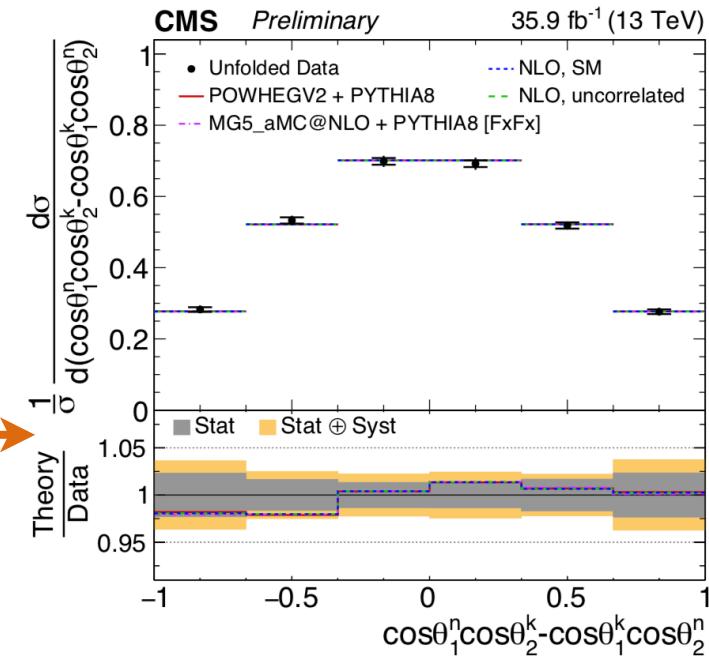
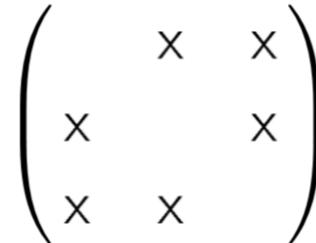
c_k, c_r : P-odd, CP-odd
#0 only in BSM

$t\bar{t}$ cross correlation

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

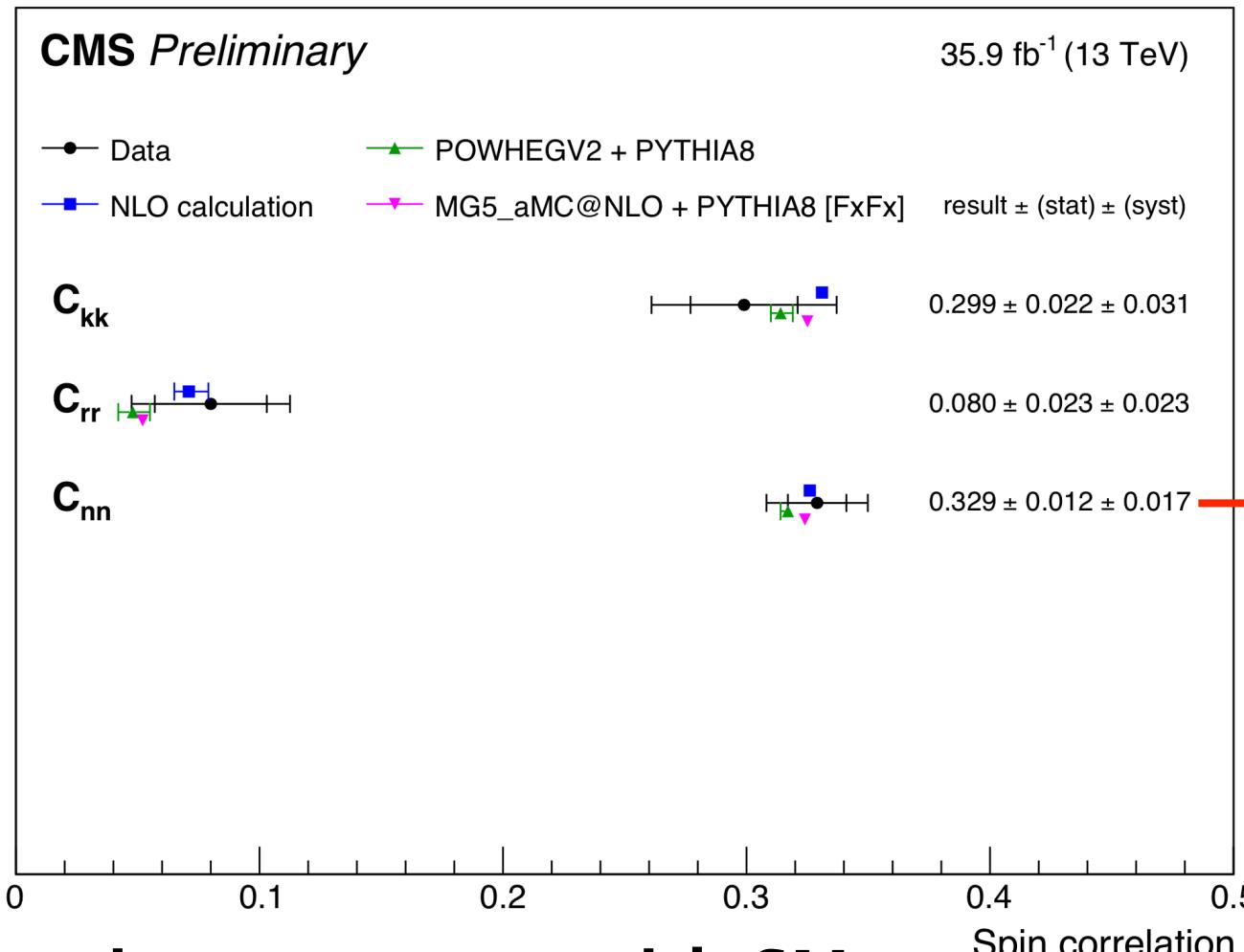


cross correlation



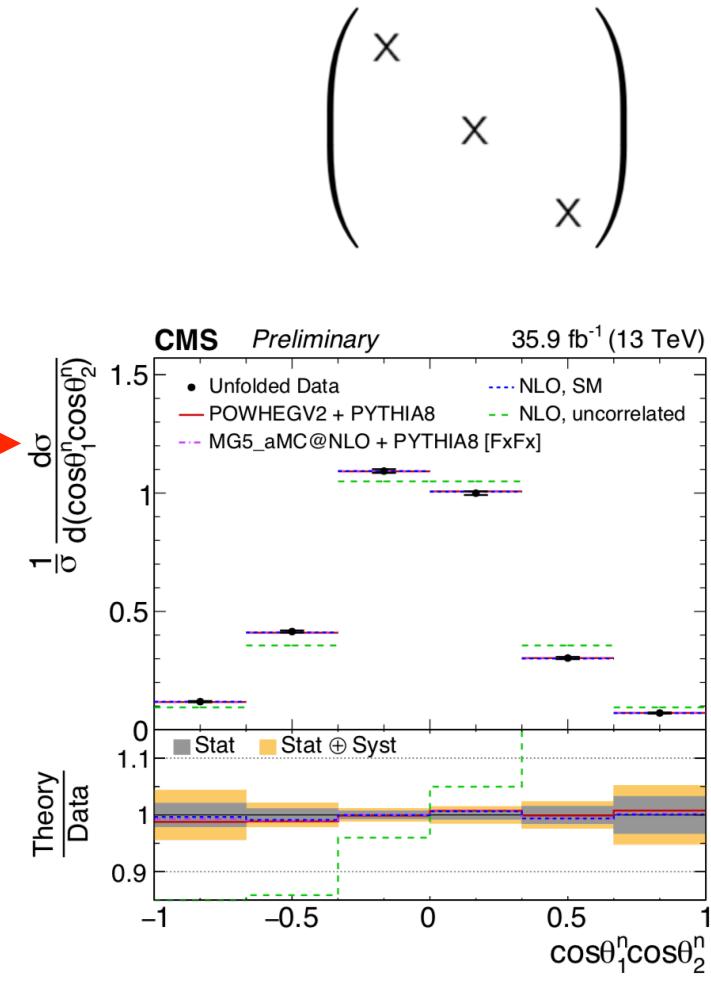
$t\bar{t}$ spin correlation

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$



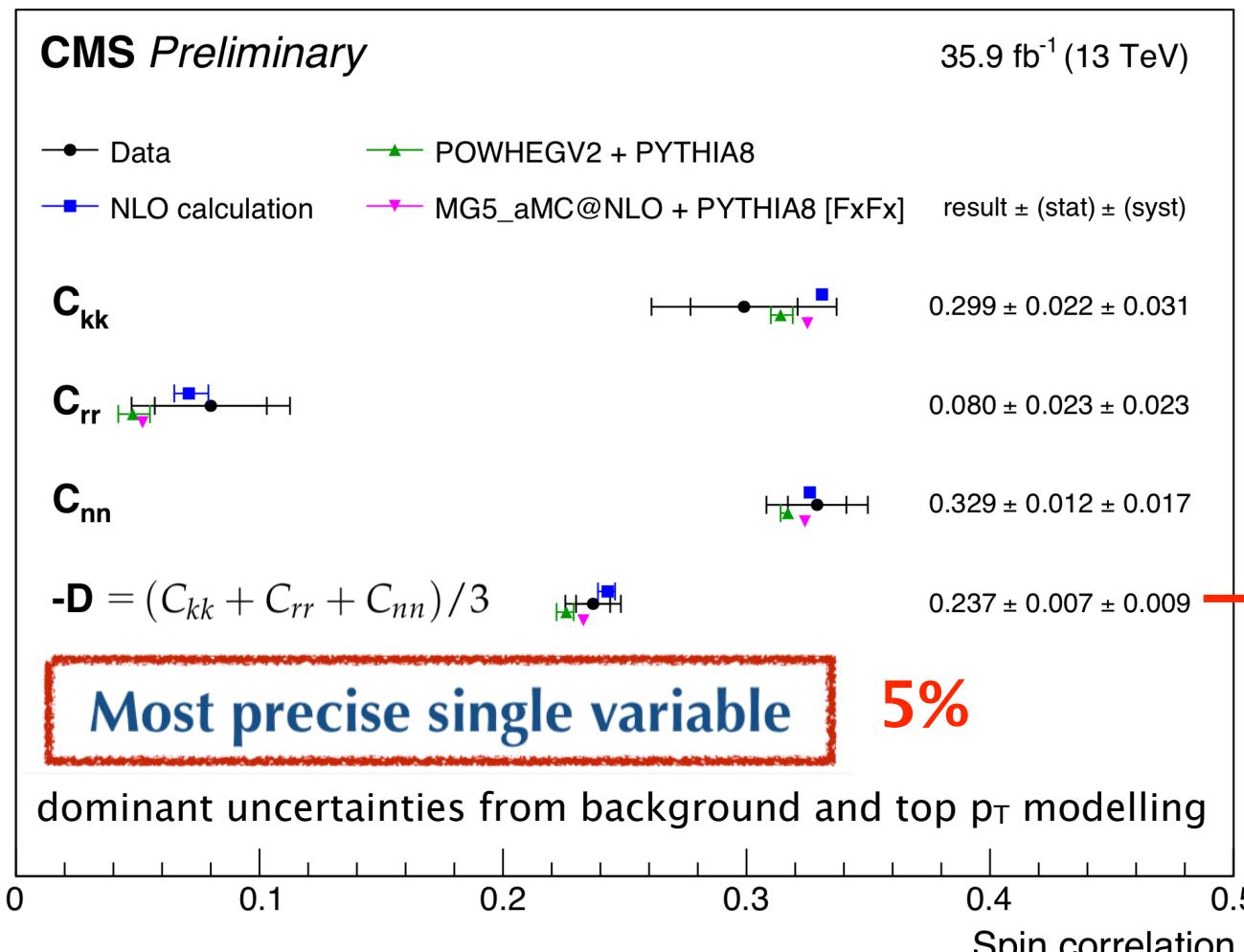
→ in agreement with SM

spin correlation

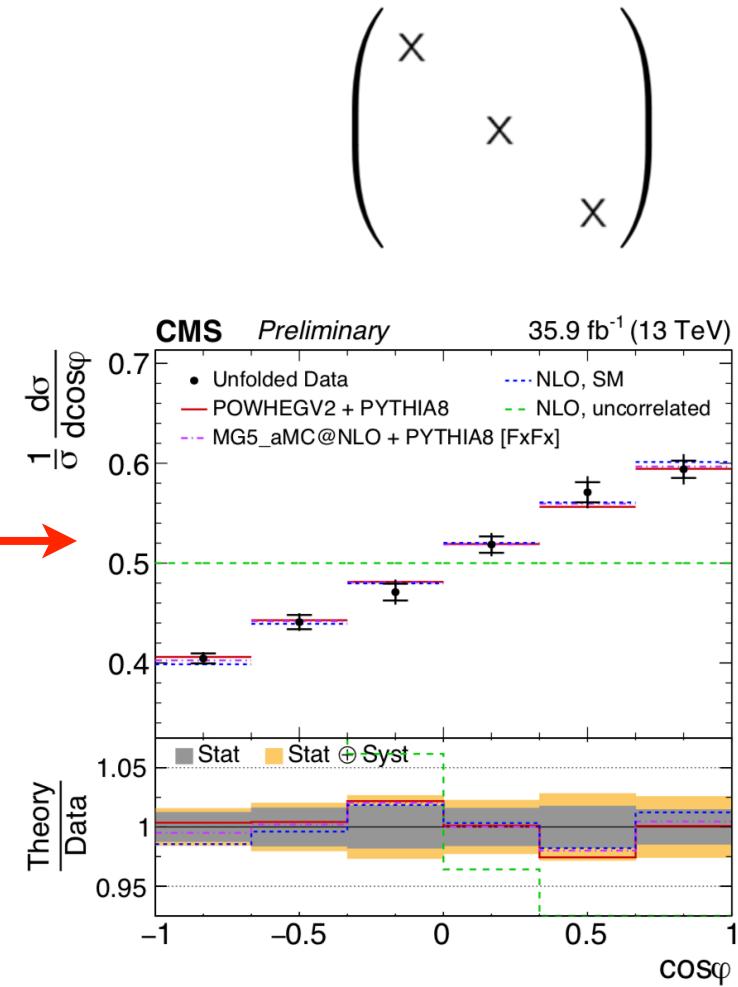


$t\bar{t}$ spin correlation

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

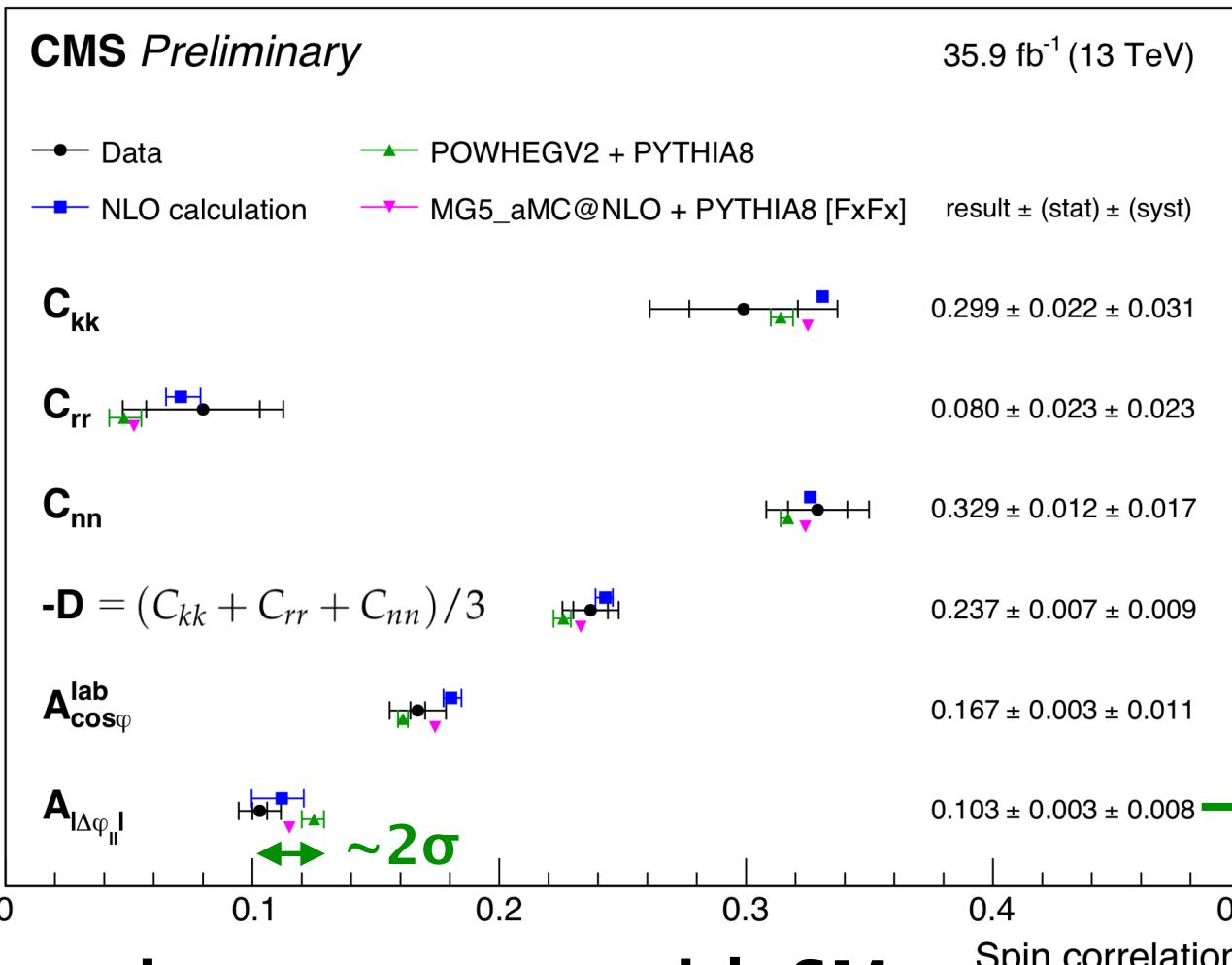


spin correlation

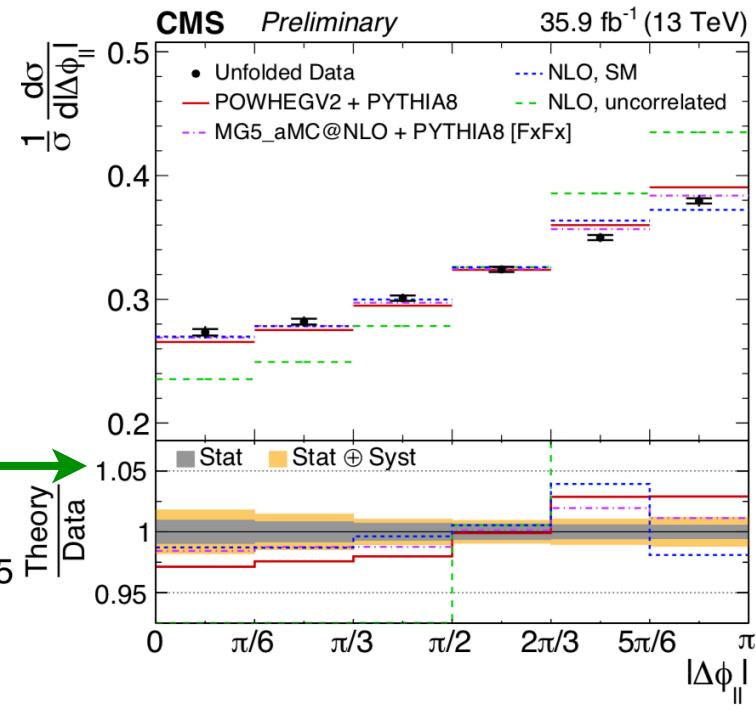
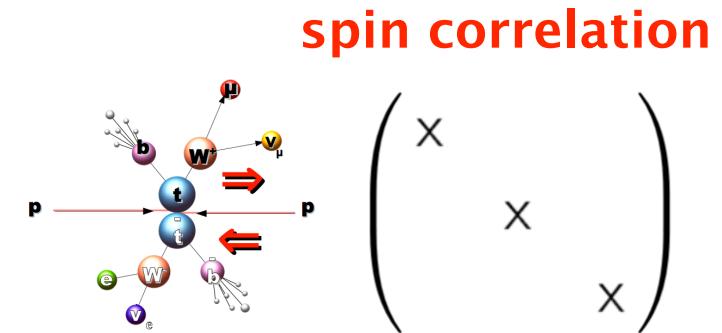


$t\bar{t}$ spin correlation

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

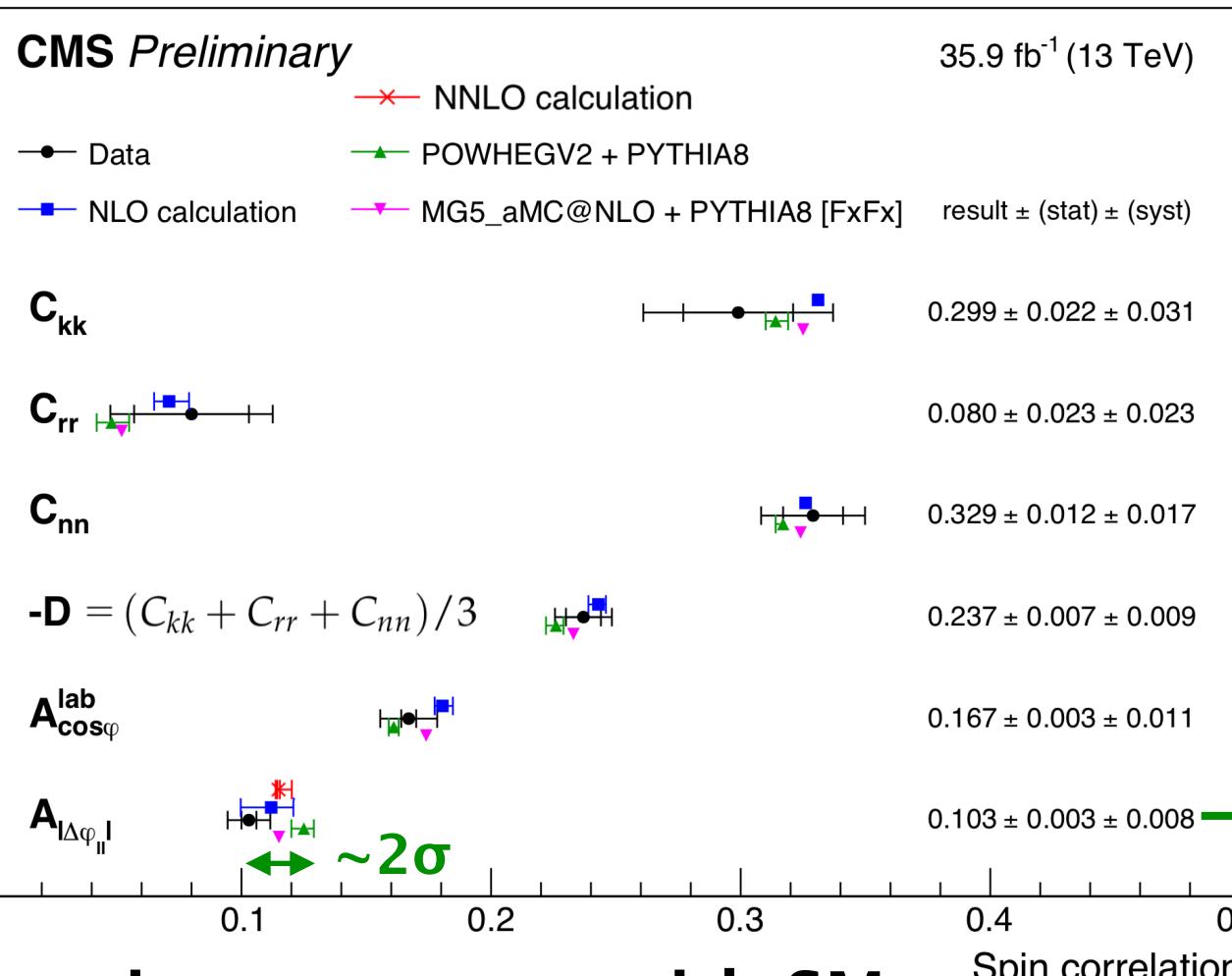


→ in agreement with SM



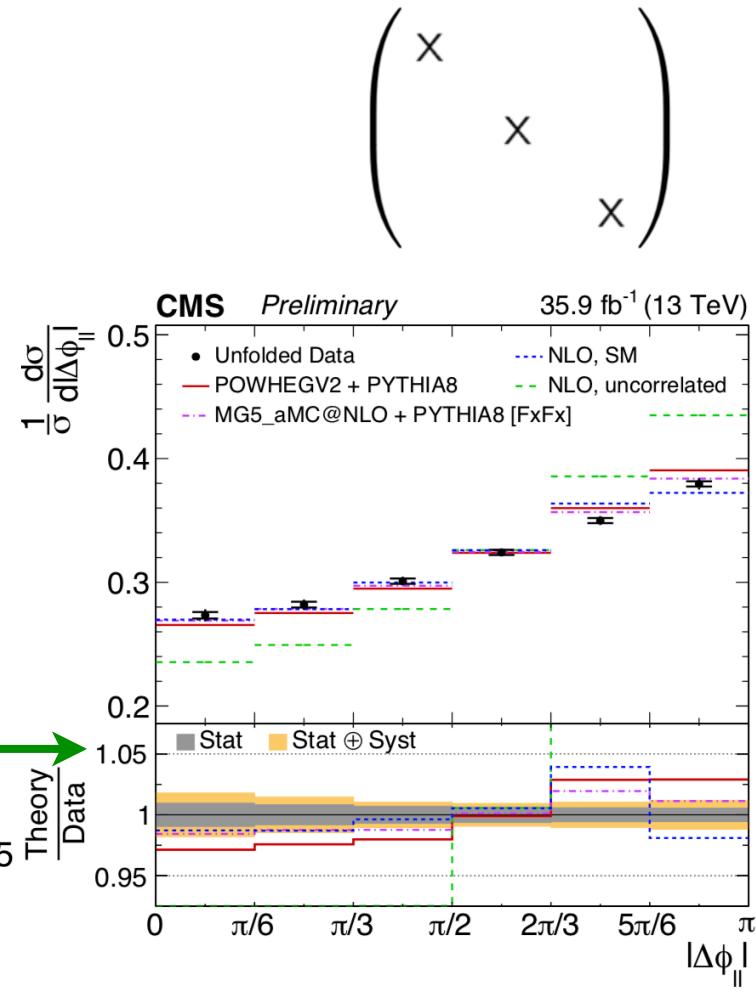
$t\bar{t}$ spin correlation

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$



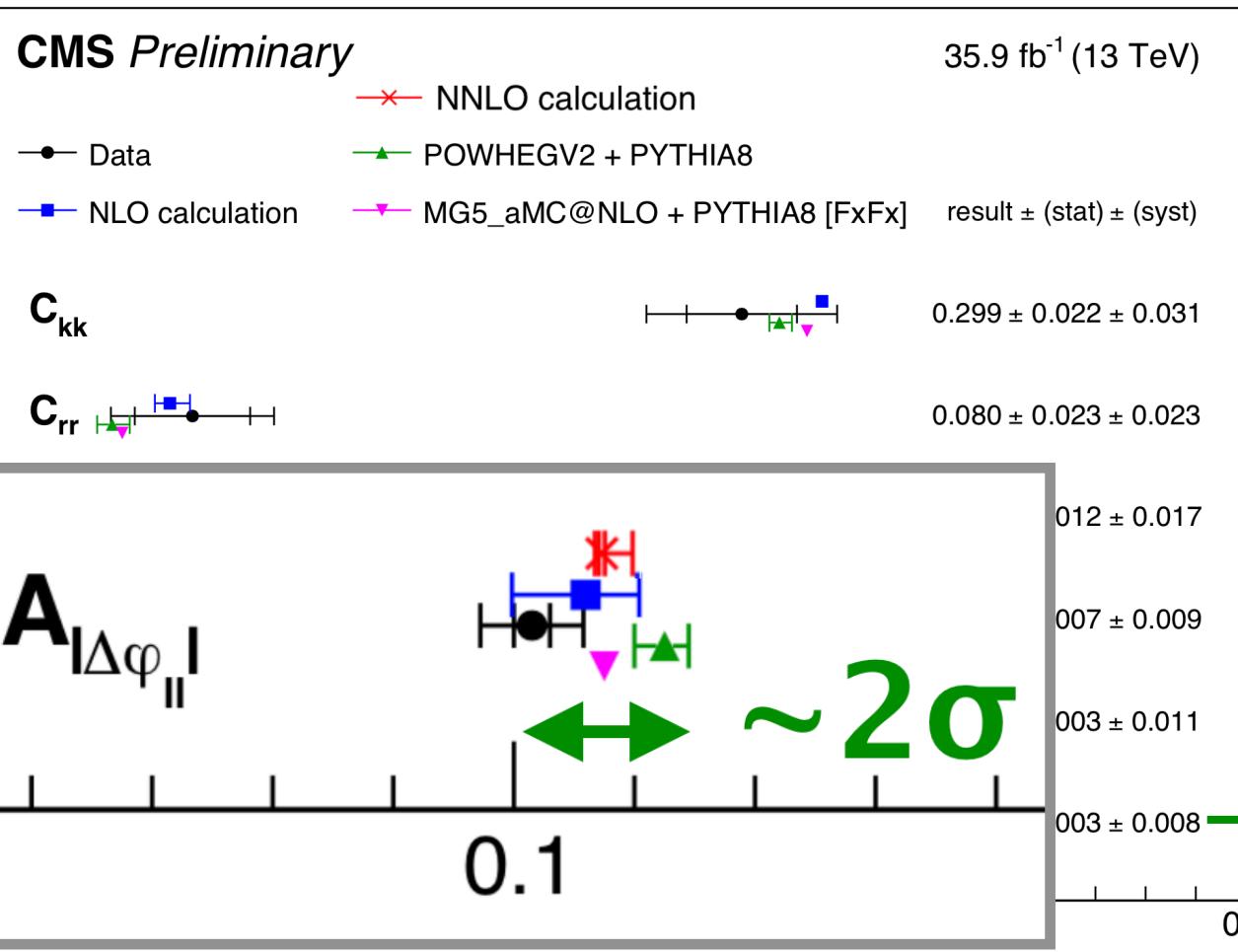
→ in agreement with SM

spin correlation

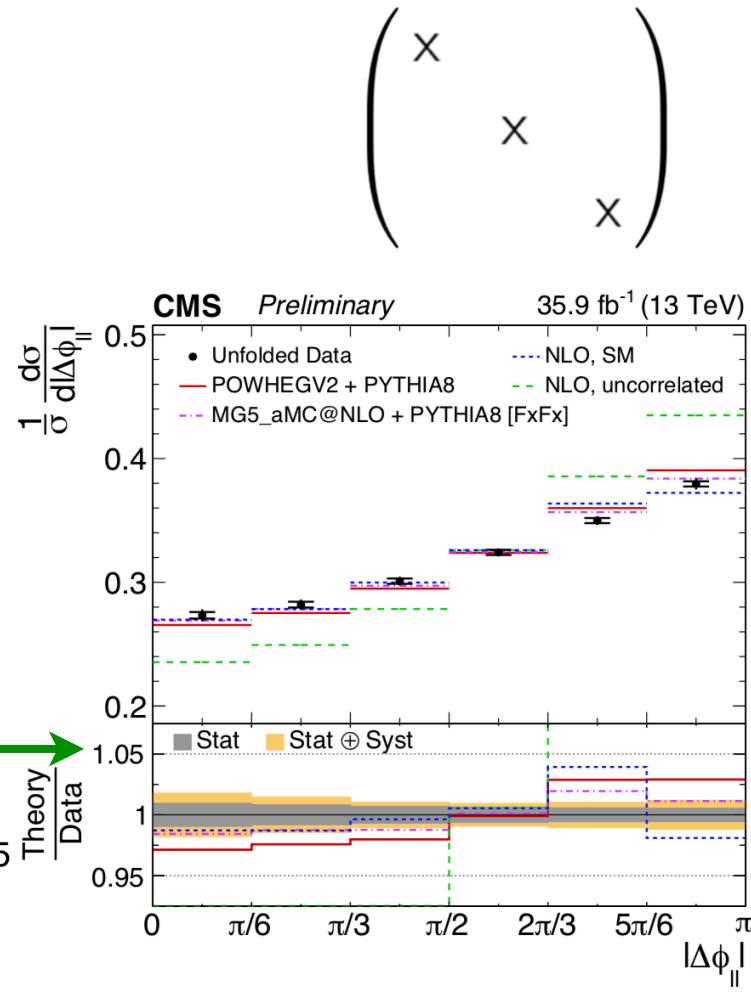


$t\bar{t}$ spin correlation

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$



spin correlation



$t\bar{t}$ spin correlation

$|M|^2$

CMS Preliminary

- Data
- NLO calculation

C_{kk}



$A_{|\Delta\phi_{II}|}$

0.1

Spin correlation

→ in agreement with SM

$$\frac{1}{\sigma} \frac{d\sigma}{d\Delta\phi_{\ell\ell}} = R_{LO} + R_{NLO}$$

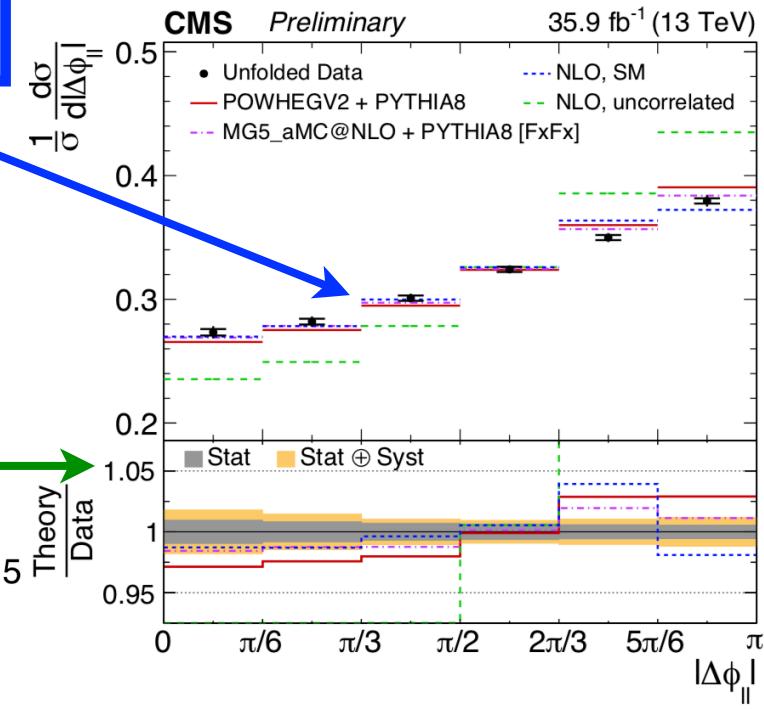
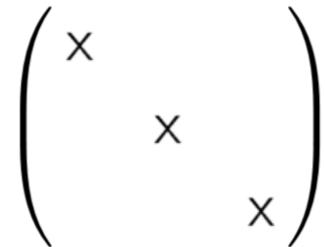
$$R_{LO} = \frac{1}{\sigma_{LO}} \frac{d\sigma_{LO}}{d\Delta\phi_{\ell\ell}}$$

$$R_{NLO} = \alpha_s(\mu) \left[\frac{1}{\sigma_{LO}} \frac{d\delta\sigma_{NLO}}{d\Delta\phi_{\ell\ell}} - \frac{\delta\sigma_{NLO}}{\sigma_{LO}^2} \frac{d\sigma_{LO}}{d\Delta\phi_{\ell\ell}} \right]$$

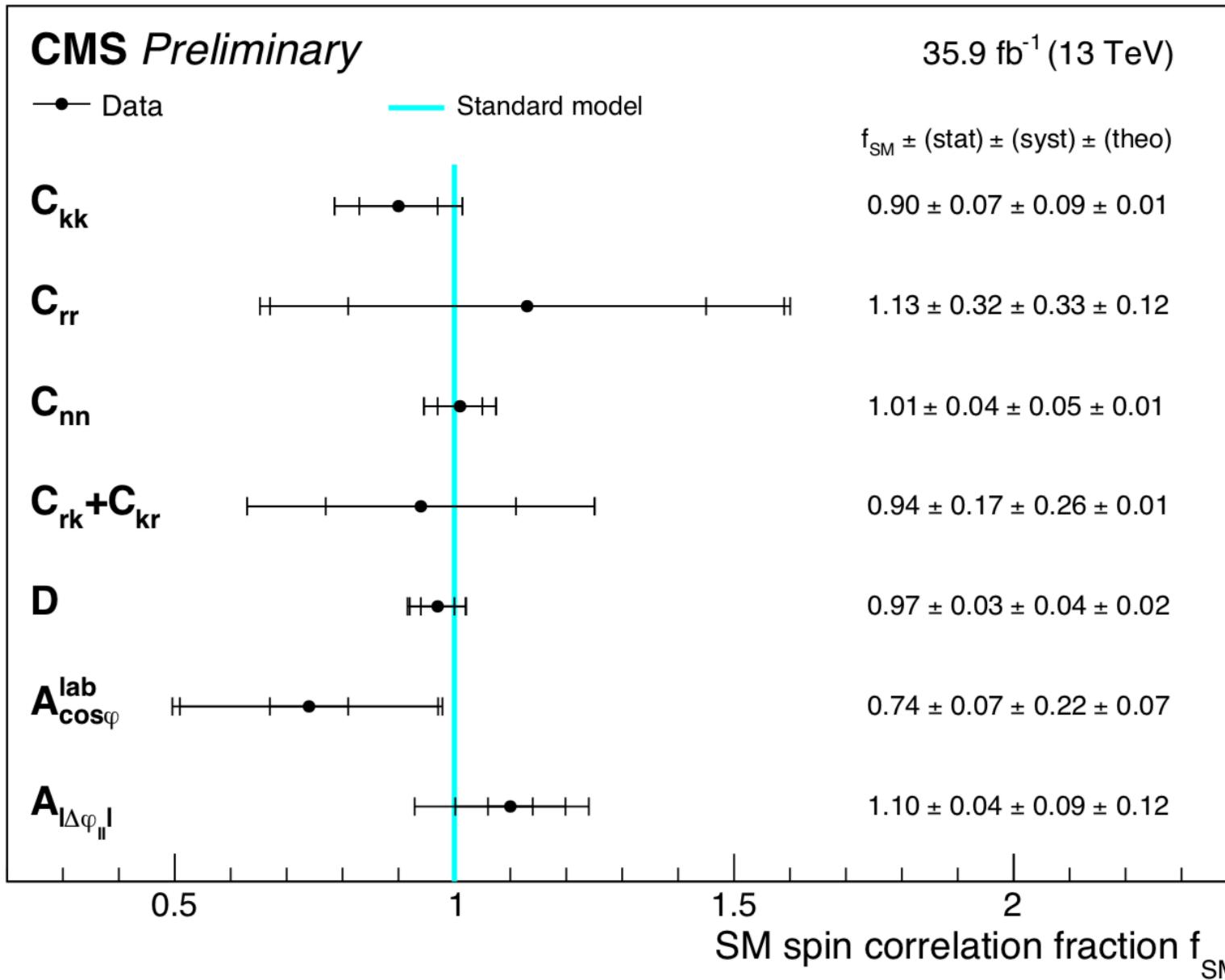
difference to MCs of $O(\alpha_s^2)$ rel. to LO

$$\cdot S_2 + C_{ij} S_{1i} S_{2j}$$

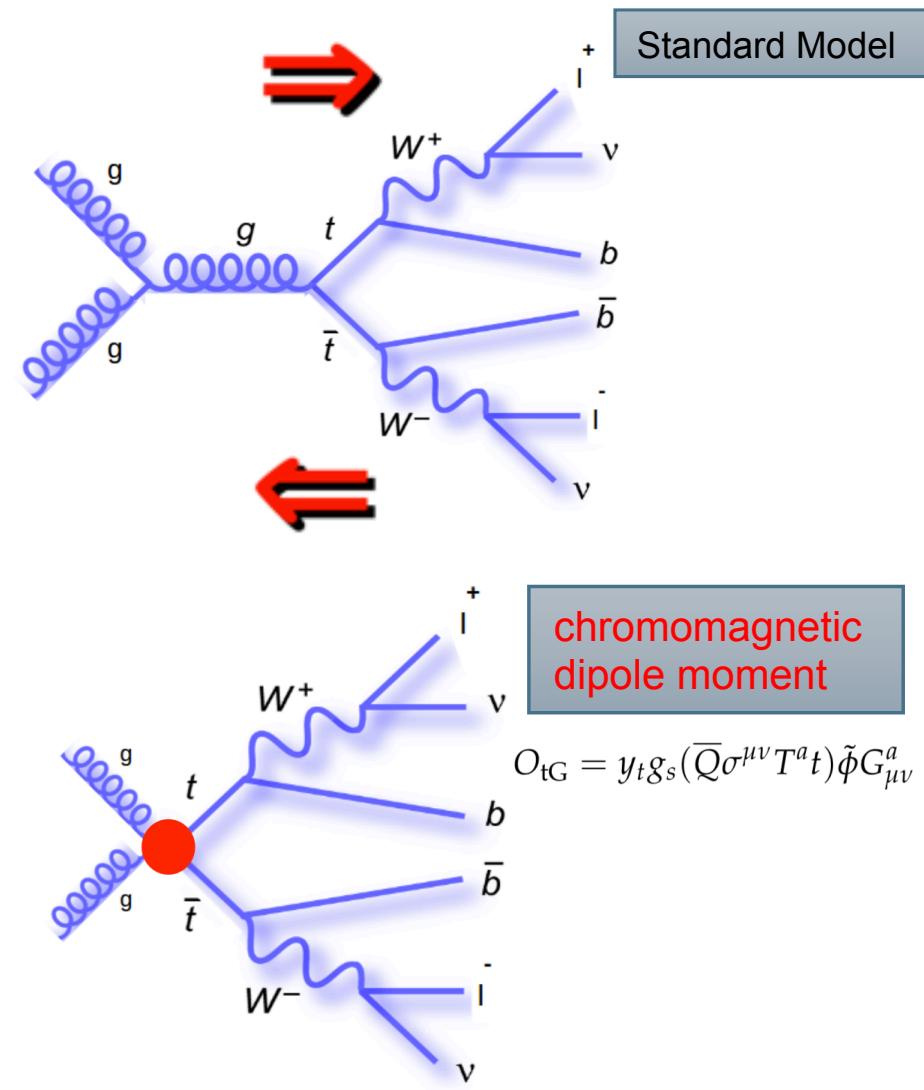
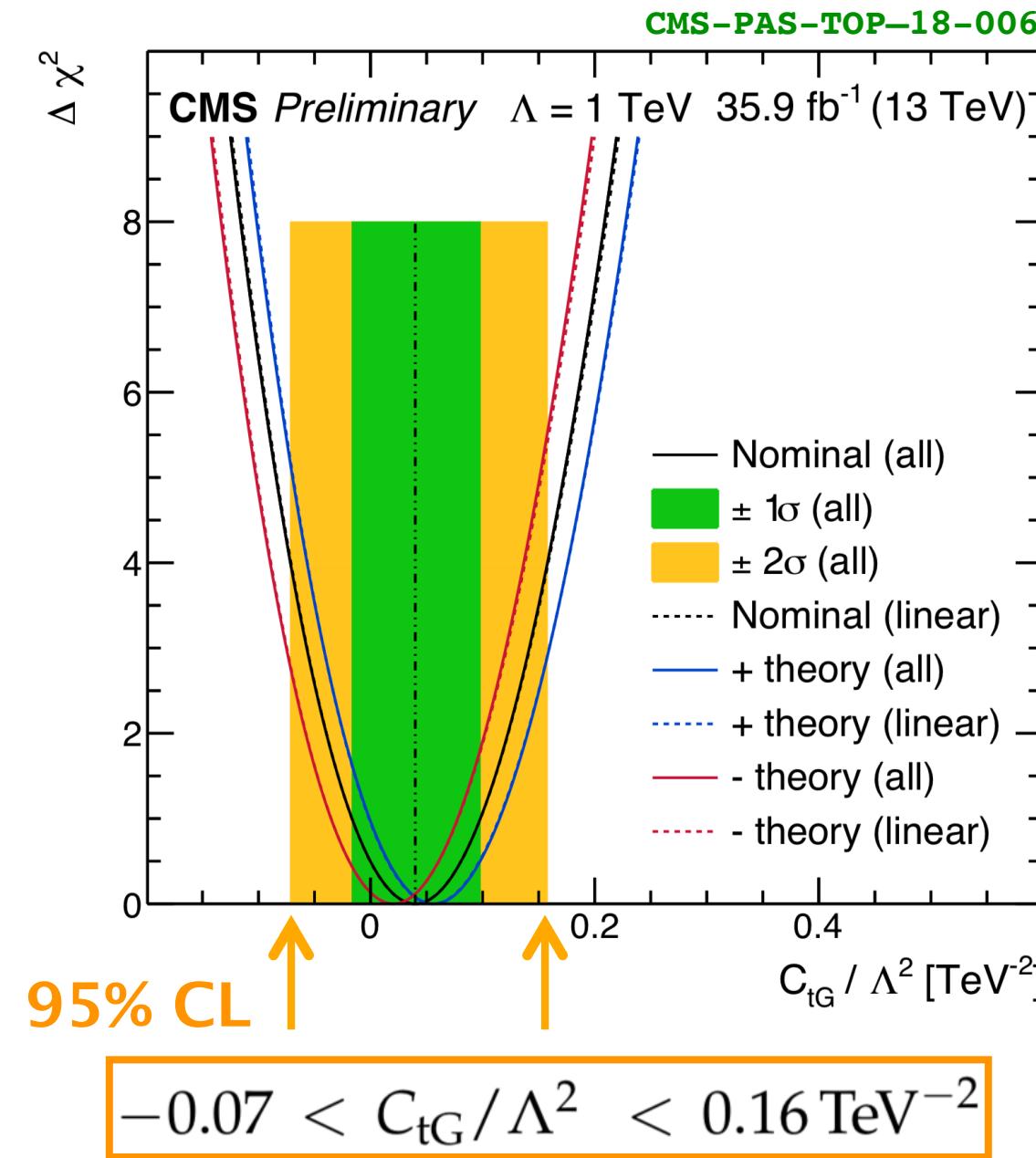
spin correlation



Spin correlation strength



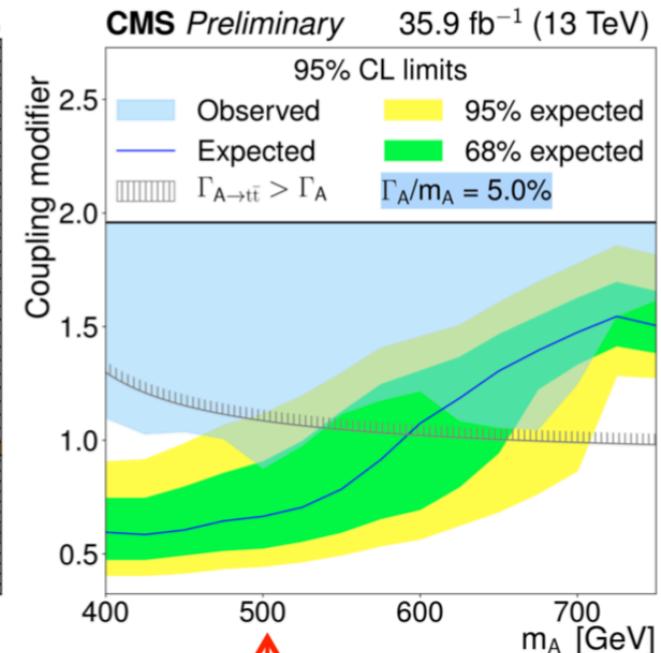
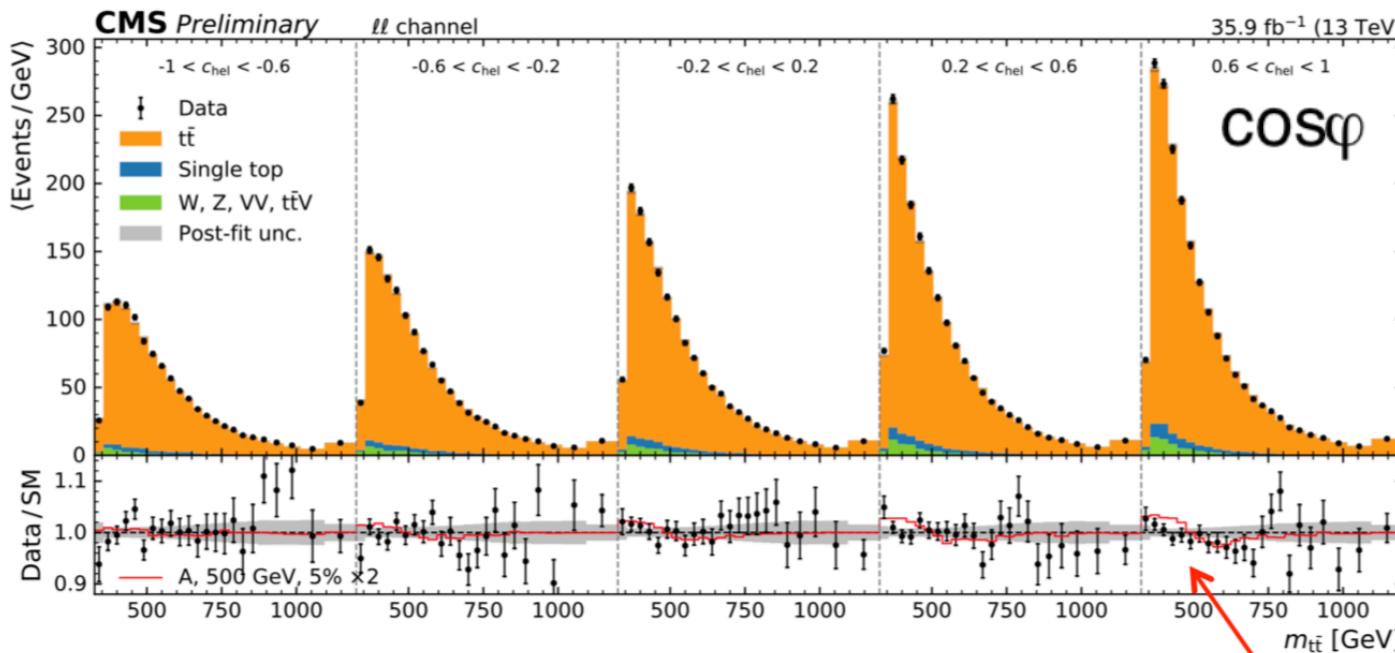
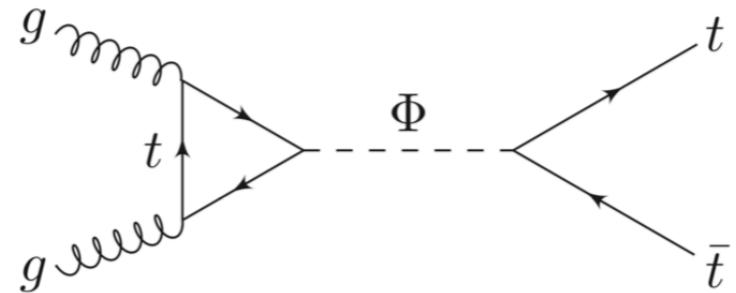
Search for EFT



→ strongest direct constraint to date!

Search for Heavy Higgs / DM production

- spin information allows to explore scalar/pseudoscalar nature of heavy Higgs/DM mediator
- combining dilepton and l+jets channels
- published as **CMS-PAS-HIG-17-027**



→ spin correlation variables help significantly!

pseudoscalar
 $m_A=500 \text{ GeV}, \Gamma_A/m_A = 5\%$

Conclusions

“They are spinning, the tops!”

- **systematic** analysis of spin and polarisation properties by spin density matrix exploration
 - **high precision** measurements
 - **so far the tops are spinning as predicted by the SM**
 - **very sensitive** **searches** for new physics, such as for EFT couplings, heavy Higgs, etc.
- LHC offers new era of high precision that we have just entered and might lead to new discoveries



Backup

Observables and coefficient functions

Observable	Measured coefficient	Coefficient function
$\cos \theta_1^k$	B_1^k	b_k^+
$\cos \theta_2^k$	B_2^k	b_k^-
$\cos \theta_1^r$	B_1^r	b_r^+
$\cos \theta_2^r$	B_2^r	b_r^-
$\cos \theta_1^n$	B_1^n	b_n^+
$\cos \theta_2^n$	B_2^n	b_n^-
$\cos \theta_1^{k*}$	B_1^{k*}	b_k^+
$\cos \theta_2^{k*}$	B_2^{k*}	b_k^-
$\cos \theta_1^{r*}$	B_1^{r*}	b_r^+
$\cos \theta_2^{r*}$	B_2^{r*}	b_r^-
$\cos \theta_1^k \cos \theta_2^k$	C_{kk}	c_{kk}
$\cos \theta_1^r \cos \theta_2^r$	C_{rr}	c_{rr}
$\cos \theta_1^n \cos \theta_2^n$	C_{nn}	c_{nn}
$\cos \theta_1^r \cos \theta_2^k + \cos \theta_1^k \cos \theta_2^r$	$C_{rk} + C_{kr}$	c_{rk}
$\cos \theta_1^r \cos \theta_2^k - \cos \theta_1^k \cos \theta_2^r$	$C_{rk} - C_{kr}$	c_n
$\cos \theta_1^n \cos \theta_2^r + \cos \theta_1^r \cos \theta_2^n$	$C_{nr} + C_{rn}$	c_{nr}
$\cos \theta_1^n \cos \theta_2^r - \cos \theta_1^r \cos \theta_2^n$	$C_{nr} - C_{rn}$	c_k
$\cos \theta_1^n \cos \theta_2^k + \cos \theta_1^k \cos \theta_2^n$	$C_{nk} + C_{kn}$	c_{kn}
$\cos \theta_1^n \cos \theta_2^k - \cos \theta_1^k \cos \theta_2^n$	$C_{nk} - C_{kn}$	$-c_r$
$\cos \varphi$	D	$-(c_{kk} + c_{rr} + c_{nn})/3$
$\cos \varphi_{\text{lab}}$	$A_{\cos \varphi}^{\text{lab}}$	N/A
$ \Delta\phi_{\ell\ell} $	$A_{ \Delta\phi_{\ell\ell} }$	N/A

Systematic uncertainties: polarisation

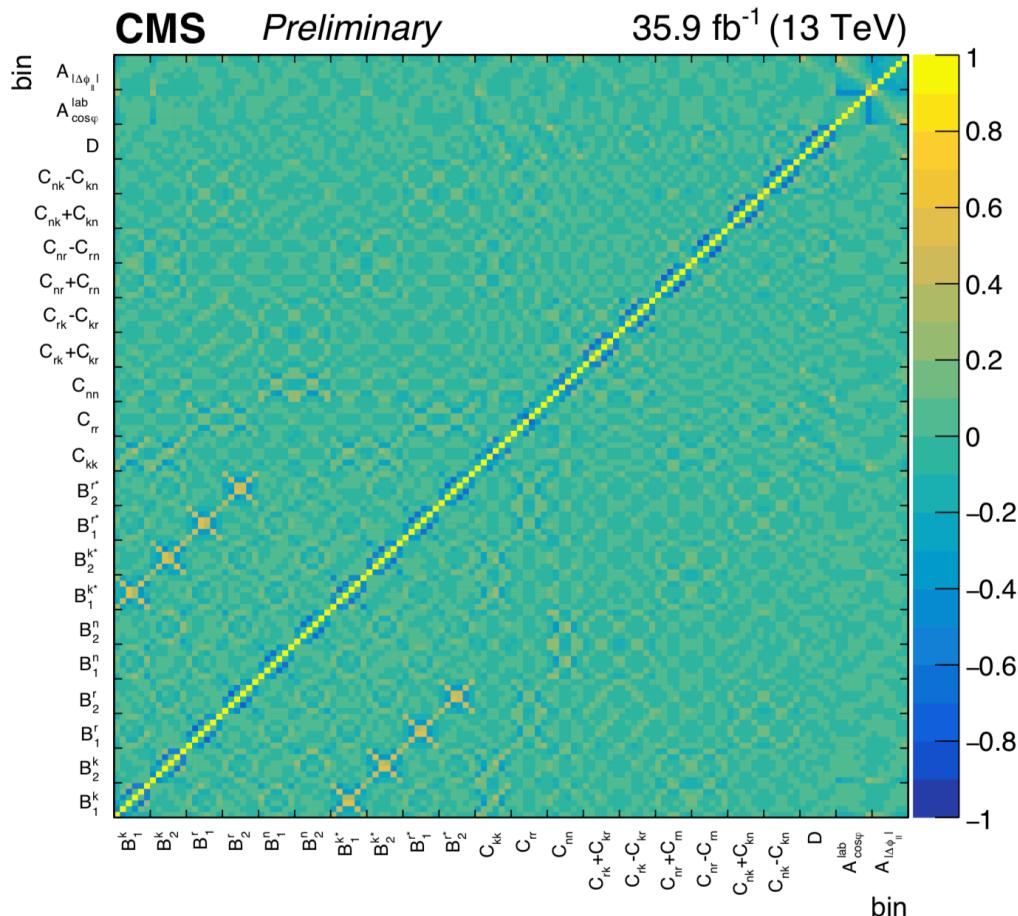
Source	Uncertainty									
	B_1^k	B_2^k	B_1^r	B_2^r	B_1^n	B_2^n	B_1^{k*}	B_2^{k*}	B_1^{r*}	B_2^{r*}
JER	0.001	0.002	0.001	0.001	0.001	0.001	0.000	0.001	0.001	0.001
JES	0.011	0.012	0.007	0.009	0.003	0.003	0.009	0.008	0.007	0.007
Unclustered energy	0.001	0.002	0.001	0.001	0.000	0.001	0.001	0.000	0.001	0.002
Pileup	0.000	0.000	0.002	0.002	0.000	0.001	0.001	0.001	0.000	0.000
Trigger	0.001	0.001	0.001	0.001	0.000	0.000	0.001	0.001	0.002	0.002
Lepton ID/isolation	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Kinematic reconstruction	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
b tagging	0.003	0.004	0.003	0.003	0.000	0.000	0.002	0.002	0.001	0.001
Background	0.008	0.008	0.005	0.008	0.001	0.001	0.004	0.005	0.002	0.002
Scale	0.005	0.004	0.004	0.009	0.003	0.004	0.003	0.004	0.006	0.005
B-fragmentation	0.009	0.009	0.004	0.005	0.000	0.001	0.001	0.001	0.001	0.001
B-hadron semi-lep. BF	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Color reconnection	0.005	0.003	0.003	0.004	0.008	0.005	0.006	0.008	0.006	0.008
Underlying event	0.001	0.003	0.001	0.003	0.002	0.003	0.003	0.002	0.004	0.004
ME/PS matching	0.006	0.006	0.004	0.001	0.003	0.004	0.003	0.003	0.004	0.004
Top quark mass	0.006	0.007	0.000	0.001	0.001	0.002	0.002	0.001	0.002	0.002
PDF	0.002	0.002	0.000	0.000	0.000	0.000	0.004	0.004	0.002	0.002
Top quark p_T	0.003	0.003	0.001	0.001	0.000	0.000	0.001	0.001	0.000	0.000
Total systematic	0.021	0.021	0.013	0.017	0.010	0.009	0.014	0.014	0.013	0.014
Data statistics	0.009	0.008	0.009	0.009	0.007	0.008	0.010	0.010	0.010	0.009
MC statistics	0.003	0.003	0.003	0.003	0.003	0.003	0.004	0.004	0.004	0.003
Background MC statistics	0.005	0.005	0.005	0.005	0.004	0.004	0.006	0.006	0.005	0.005
Total statistical	0.010	0.010	0.011	0.011	0.009	0.009	0.012	0.012	0.012	0.011
Total	0.023	0.024	0.017	0.020	0.013	0.013	0.018	0.019	0.018	0.017

Systematic uncertainties: spin correlation

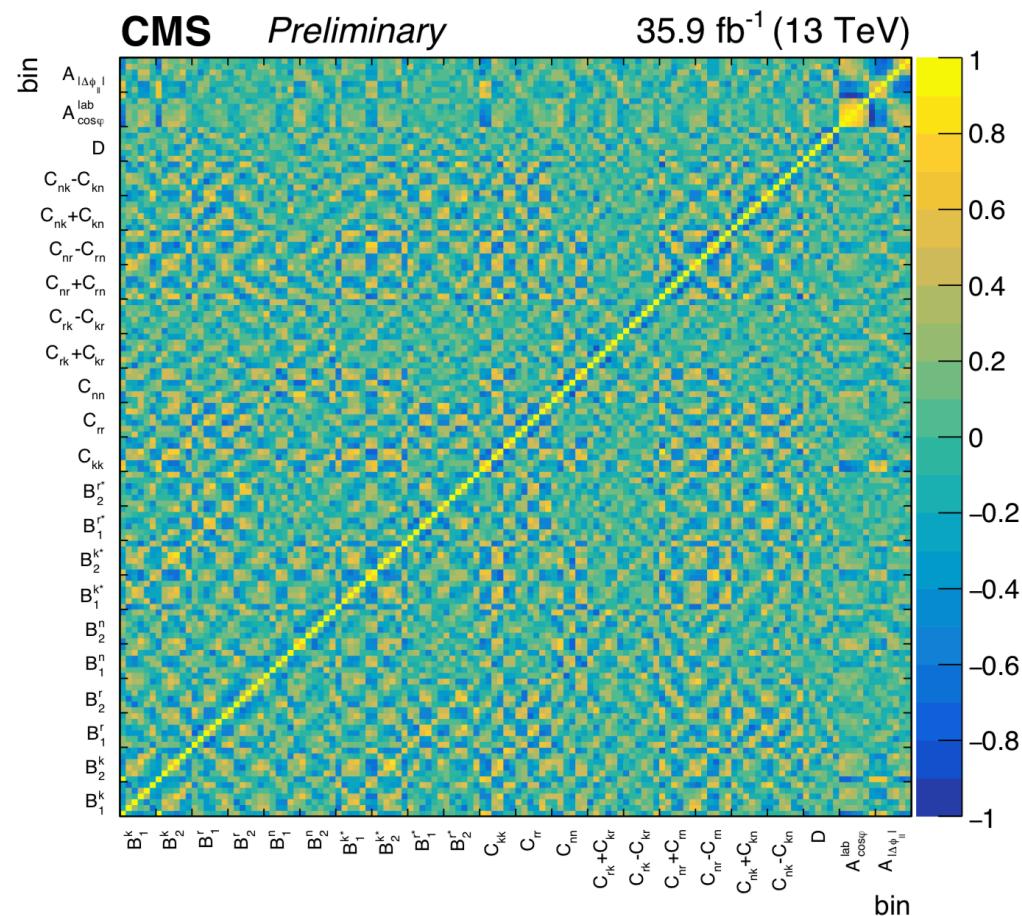
Source	Uncertainty											
	C_{kk}	C_{rr}	C_{nn}	$C_{rk} + C_{kr}$	$C_{rk} - C_{kr}$	$C_{nr} + C_{rn}$	$C_{nr} - C_{rn}$	$C_{nk} + C_{kn}$	$C_{nk} - C_{kn}$	D	$A_{\cos \varphi}^{\text{lab}}$	$A_{ \Delta\phi_{ee} }$
JER	0.001	0.001	0.001	0.004	0.002	0.001	0.001	0.003	0.001	0.000	0.000	0.000
JES	0.012	0.009	0.005	0.022	0.011	0.011	0.009	0.012	0.007	0.002	0.000	0.001
Unclustered energy	0.001	0.001	0.001	0.004	0.001	0.001	0.002	0.001	0.001	0.000	0.000	0.001
Pileup	0.002	0.000	0.001	0.004	0.001	0.001	0.002	0.001	0.001	0.001	0.000	0.001
Trigger	0.001	0.001	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Lepton ID/isolation	0.001	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Kinematic reconstruction	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
b tagging	0.004	0.001	0.002	0.005	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000
Background	0.017	0.009	0.008	0.025	0.006	0.004	0.004	0.007	0.003	0.004	0.008	0.002
Scale	0.012	0.006	0.007	0.026	0.011	0.007	0.014	0.011	0.007	0.003	0.002	0.003
B-fragmentation	0.014	0.002	0.005	0.017	0.001	0.001	0.001	0.002	0.001	0.003	0.000	0.001
B-hadron semi-lep. BF	0.000	0.001	0.001	0.002	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.000
Color reconnection	0.005	0.013	0.006	0.013	0.011	0.014	0.017	0.009	0.008	0.002	0.001	0.001
Underlying event	0.008	0.002	0.002	0.004	0.010	0.007	0.005	0.007	0.002	0.003	0.001	0.001
ME/PS matching	0.004	0.003	0.001	0.009	0.016	0.011	0.001	0.012	0.009	0.002	0.002	0.004
Top quark mass	0.001	0.002	0.006	0.006	0.009	0.002	0.002	0.009	0.001	0.002	0.001	0.000
PDF	0.005	0.005	0.001	0.004	0.001	0.001	0.001	0.001	0.001	0.002	0.007	0.002
Top quark p_T	0.008	0.010	0.005	0.019	0.000	0.001	0.000	0.001	0.000	0.004	0.003	0.005
Total systematic	0.031	0.023	0.017	0.053	0.029	0.024	0.025	0.026	0.016	0.009	0.011	0.008
Data statistics	0.018	0.019	0.010	0.029	0.029	0.024	0.025	0.025	0.020	0.006	0.003	0.003
MC statistics	0.007	0.007	0.004	0.011	0.011	0.009	0.009	0.010	0.008	0.002	0.001	0.001
Background MC statistics	0.011	0.010	0.005	0.018	0.017	0.012	0.010	0.015	0.012	0.003	0.002	0.002
Total statistical	0.022	0.023	0.012	0.035	0.035	0.028	0.028	0.031	0.025	0.007	0.003	0.003
Total	0.038	0.033	0.020	0.064	0.046	0.037	0.038	0.041	0.029	0.011	0.012	0.008

Total correlation matrix: bins

- **statistical**

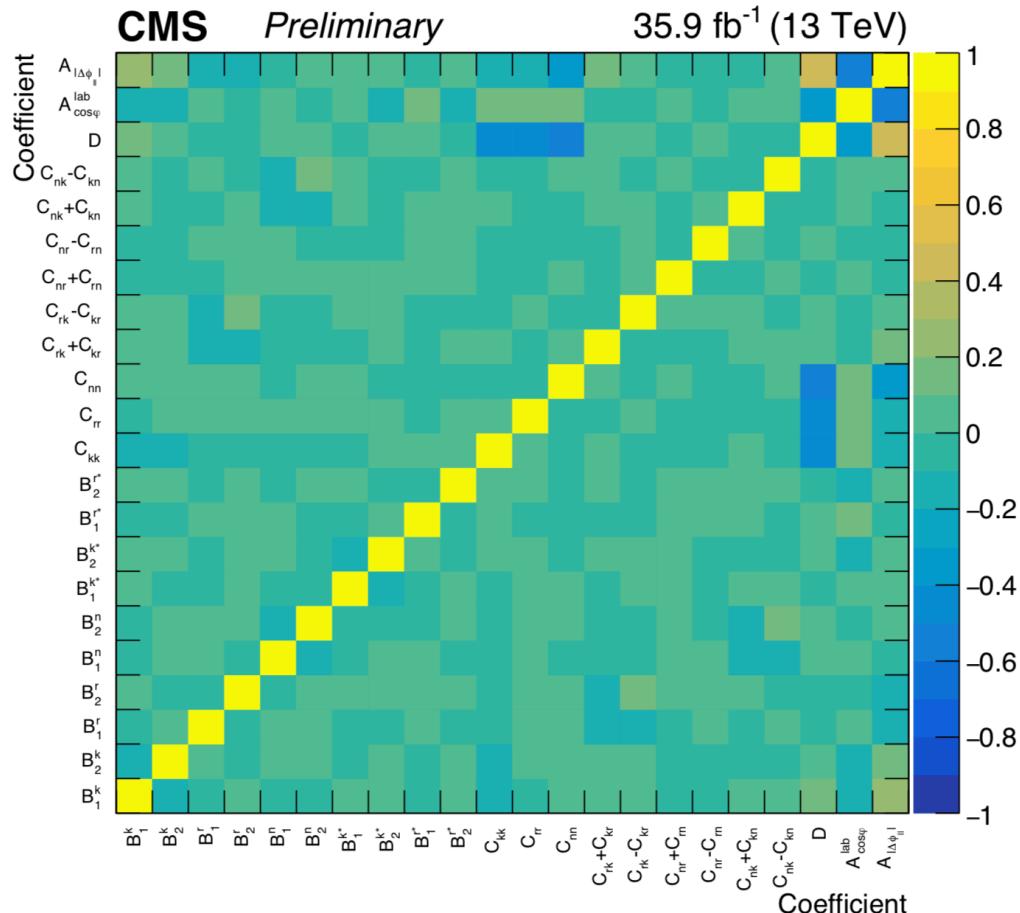


- systematic

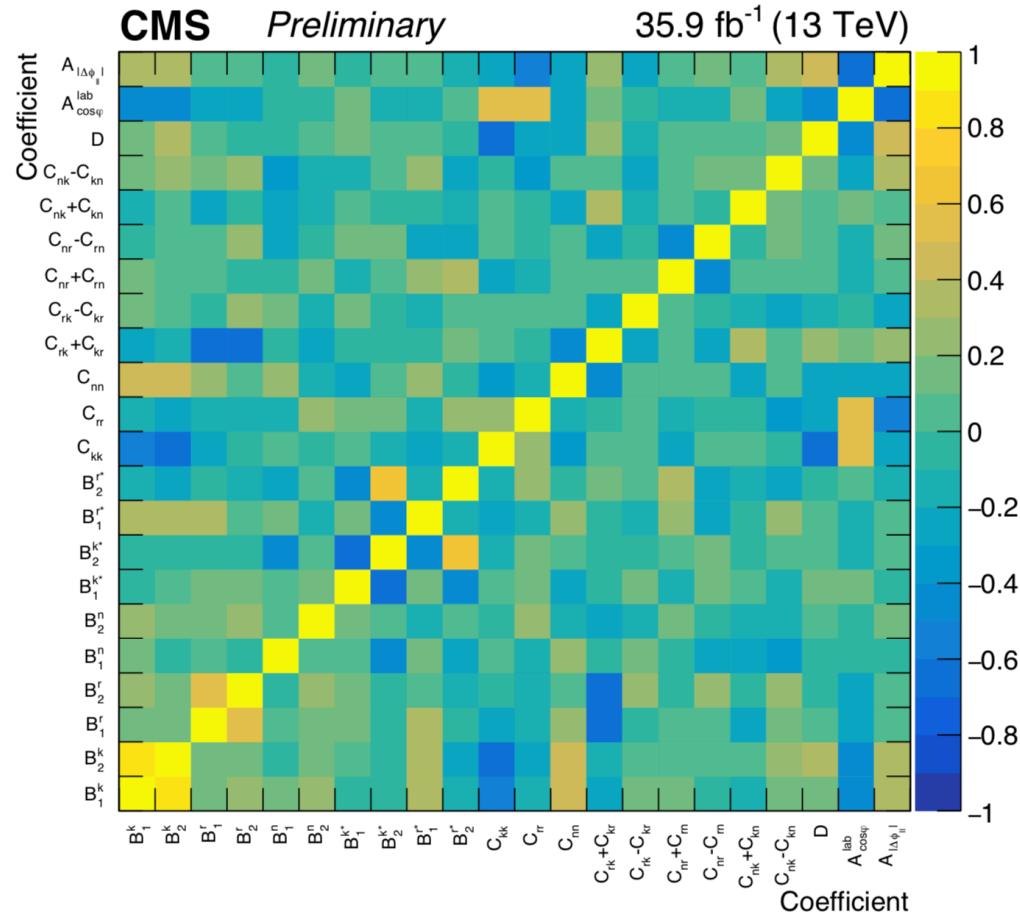


Total correlation matrix: coefficients

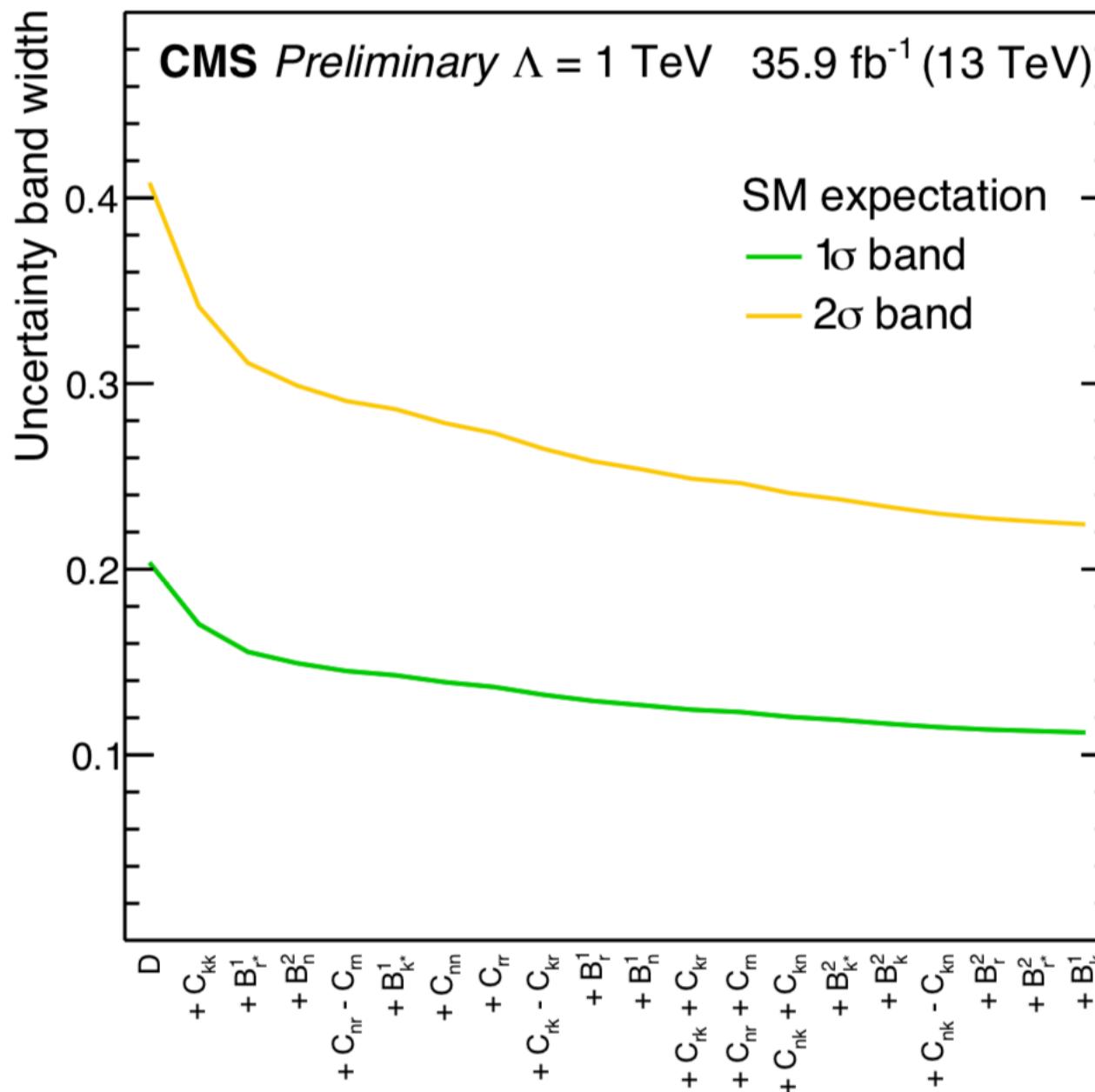
• statistical



• systematic



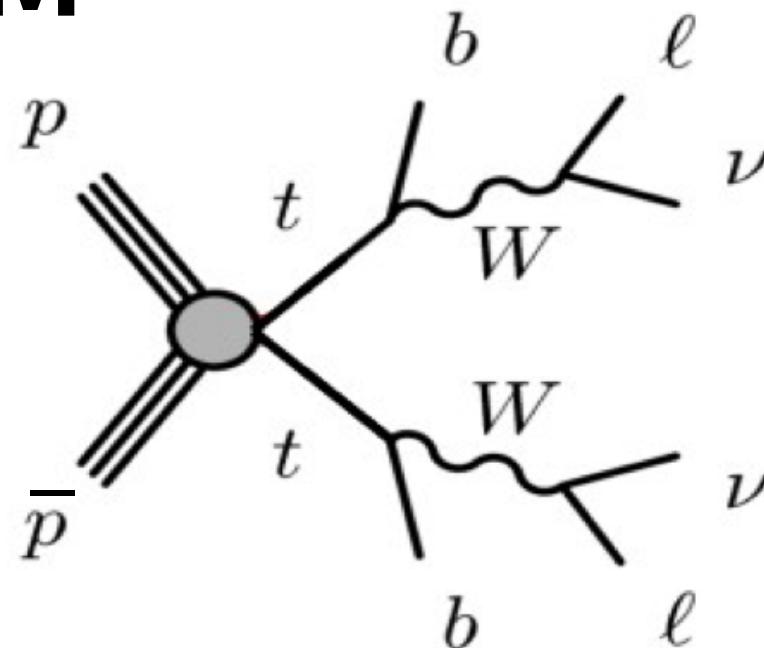
EFT coupling search



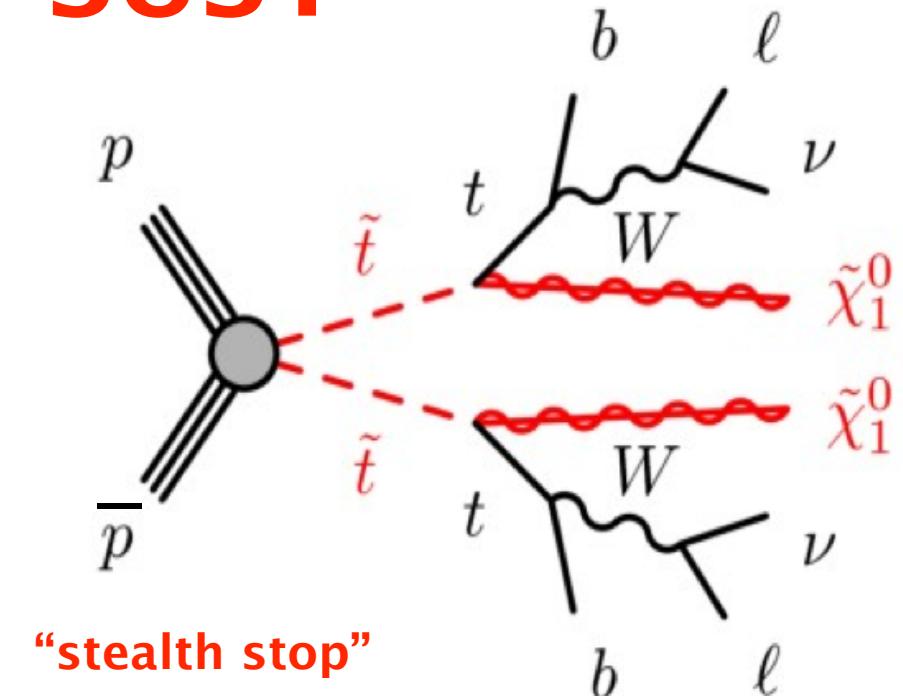
New physics impact on spin correlations

- important test of SM and sensitive search for physics beyond
- analyse the whole chain of top pair production and top decay

SM



SUSY

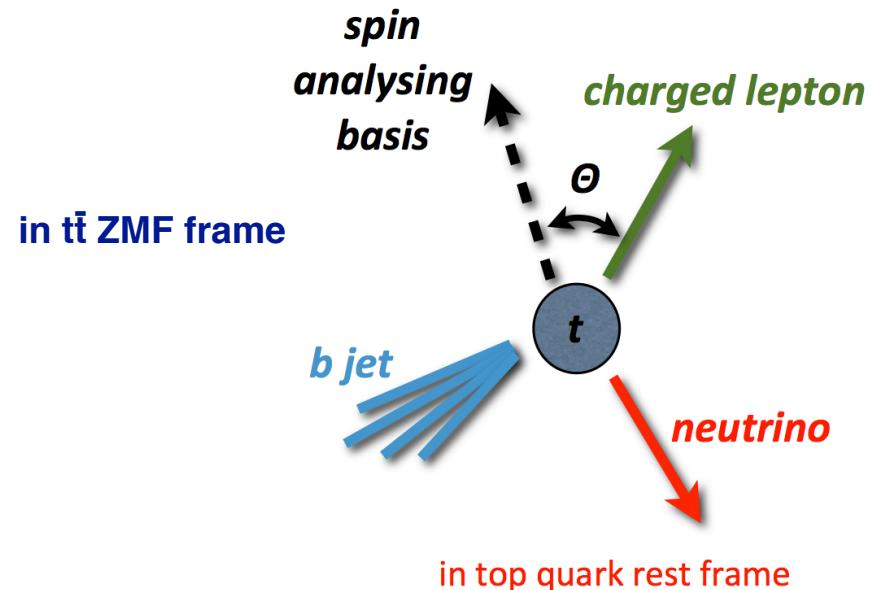


→ SM spin correlation

→ no spin correlation

Polarisation power

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta_i} = \frac{1}{2} (1 + \alpha_i \cos \theta_i)$$



dilepton channel promises largest sensitivity

Brandenburg, Si, Uwer,
Phys. Lett. B539, 235 (2002)

	b -quark	W^+	l^+	\bar{d} -quark or \bar{s} -quark	u -quark or c -quark
α_i (LO)	-0.41	0.41	1	1	-0.31
α_i (NLO)	-0.39	0.39	0.998	0.93	-0.31

$$\frac{1}{\sigma} \frac{d^2\sigma}{d \cos \theta_1 d \cos \theta_2} = \frac{1}{4} (1 - C \cos \theta_1 \cos \theta_2)$$

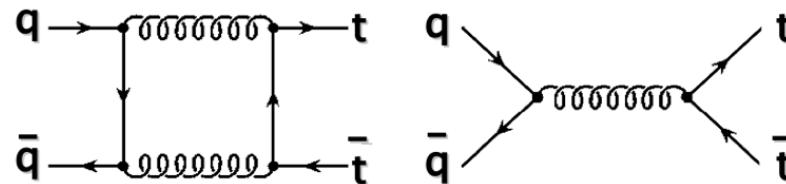
where $C = A \alpha_1 \alpha_2$

linear extraction:
 $A = C$

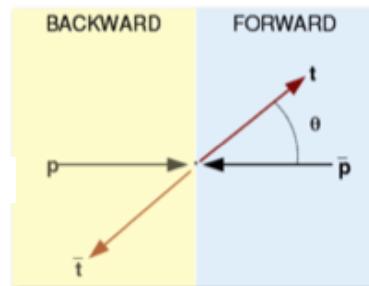
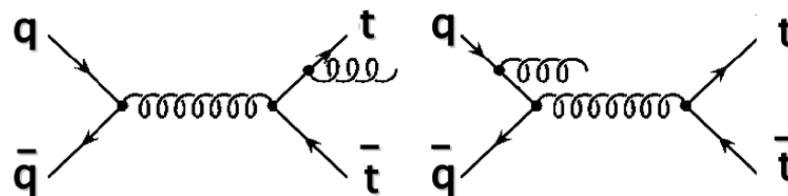
Charge Asymmetry

- asymmetry in $O(\alpha_s^3)$

interference between:



interference between:



$$A_{fb} = \frac{F - B}{F + B}$$

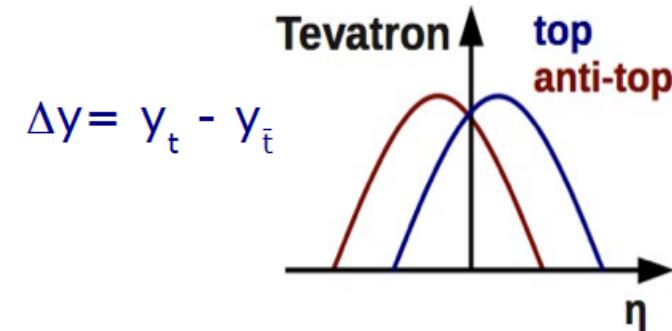
“NLO is LO for asymmetry”

NLO QCD

- complementary to the LHC

Tevatron

$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$



LHC

$$A_C = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)}$$

