

Top physics circa 2016

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Why the interest in top?

- Heaviest particle.
- Top quark Yukawa is the largest of SM couplings (for $\mu > 100$ GeV)

$$\alpha_t \equiv \frac{y_t^2}{4\pi}$$

- Decays before hadronization, preserving all spin information.

$$\Gamma(t \rightarrow W^+ b) \approx 1.5 \text{ GeV} \gg \Lambda_{\text{QCD}} \sim 200 \text{ MeV}$$

explore properties of a “bare quark”

- Important role in flavour physics
Flavour physics does NOT reciprocate (interfere)
- Role in EWSB?

- Why is electroweak symmetry spontaneously broken ?
Is the Higgs a fundamental scalar?
- What is the origin of dark matter ?
How does DM interact with us?
- What is the origin of baryogenesis ?
- What is the origin of flavor hierarchies and mixing ?

Top properties and interactions

- Basic top properties:
 - Gauge and Yukawa couplings: g_V, g_A , weak- and chromomagnetic moments, y_t
fixed SM params: measurements of deviations are indirect probes of underlying BSM dynamics
 - m_t, V_{tq} ($q = d, s, b$)
free params of SM. Precision \implies relations among other SM observables (EWPT, flavour physics, ...)

- Probe for BSM:
 - anomalous production properties:
 - m_{tt} and p_T distributions,
 - angular distributions
 - Asymmetries: A_{FB} , A_C
 - spin correlations
 - Non-SM decays: $t \rightarrow qZ$, $t \rightarrow q\gamma$, $t \rightarrow qll'$, $t \rightarrow qH$,
 - Production from BSM objects:
 - $Z' \rightarrow t\bar{t}$, $Z' \rightarrow t\bar{q}$
 - $Z', H' \rightarrow t + \bar{T}$
 - $T \rightarrow t + Z/H$
 - $\tilde{t} \rightarrow t + \chi^0$, $\tilde{b} \rightarrow t + W^-$
 - $\tilde{b}^* \rightarrow t + q$

$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2} (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2) \approx \frac{-\Lambda^2}{25}$$

Composite models (technicolor, effective lagrangians like little Higgs, topcolor...):

- effective 4 fermion operators involving top ?
- vector-like top partners
- new coloured scalars

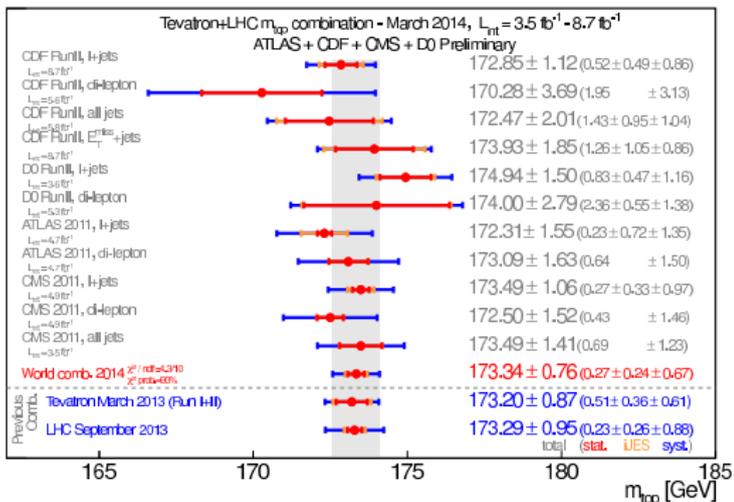
Extra-dimensional models:

- KK-modes of top and gluons
- Extra-dim realisations of composite models

SUSY:

- The top partner !
- stop coannihilation

Top mass



Definition of m_q ?

Heavy quarks:

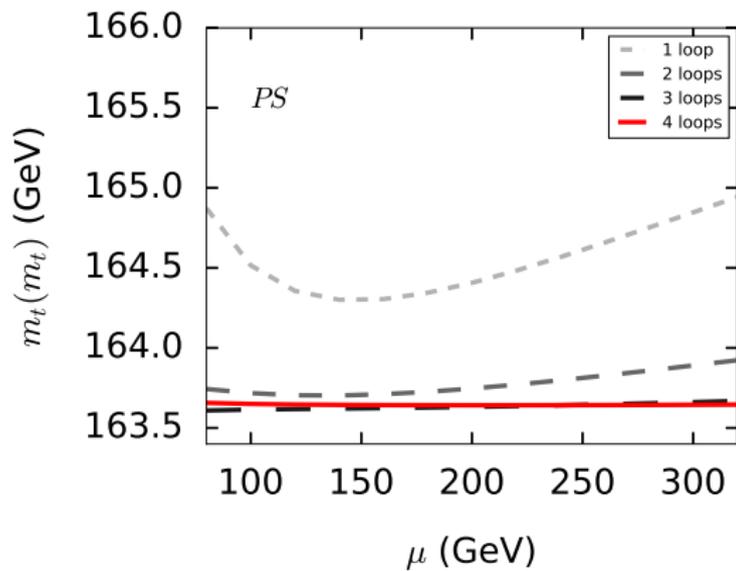
- On-shell definition : propagator $S_q(q)$ has a pole for $q^2 = (M_q^{\text{OS}})^2$.
- Very heavy resonance \mathcal{R} decaying to $t\bar{t}$:
 $\overline{\text{MS}}$ definition of $m_t(M_{\mathcal{R}})$: large logs automatically summed
- Threshold $t\bar{t}$ production : threshold mass
- ...

$$m_{\text{Bare}} = Z_m^{\overline{\text{MS}}} m_{\text{MS}} = Z_m^{\text{OS}} M_{\text{OS}}$$

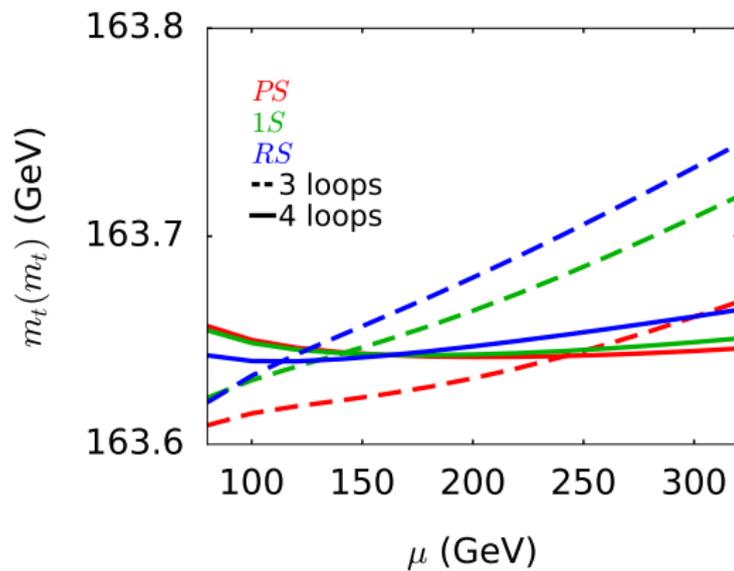
N³LO relation between $\overline{\text{MS}}$ mass and threshold mass:

Using $m_t \equiv m_t(m_t) = 163.643$ GeV and $\alpha_s^{(6)}(m_t) = 0.1088$,

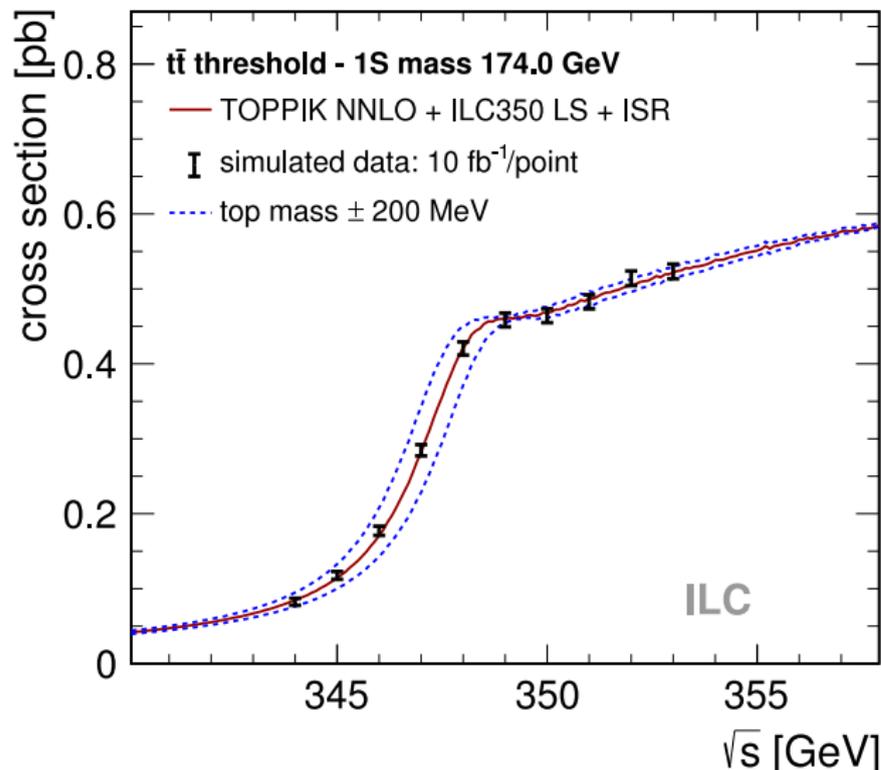
$$\begin{aligned} M_t &= m_t [1 + 0.4244 \alpha_s + 0.8345 \alpha_s^2 + 2.375 \alpha_s^3 + (8.49 \pm 0.25) \alpha_s^4] \\ &= 163.643 + 7.557 + 1.617 + 0.501 + 0.195 \pm 0.005 \text{ GeV} \end{aligned}$$



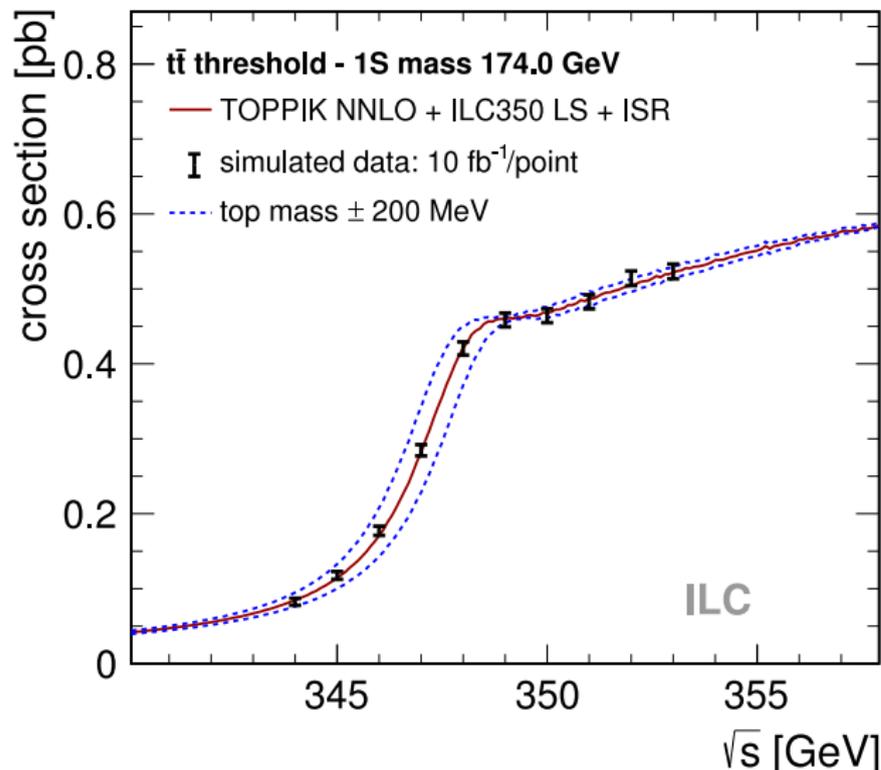
Different definitions of threshold masses:



Threshold scan at LC



Threshold scan at LC



Top Width

At LO,

$$\Gamma(t \rightarrow Wb) = \left(\frac{g_{tbW}}{g} \right)^2 \frac{G_\mu m_t^3}{8\sqrt{2}\pi} \left(1 - \frac{m_W^2}{m_t^2} \right)^2 \left(1 + \frac{2m_W^2}{m_t^2} \right)$$

Higher orders: $t \rightarrow W^+ + b + X$

Set $m_b = 0$ and bring it back later.

Cluster all final state partons into a single jet;

Define $\tau \equiv (p_b + p_X)^2 / m_t^2$

Limit of $\tau \rightarrow 0$: only soft and/or collinear radiations

In this region, factorization:

$$\frac{1}{\Gamma_t^{(0)}} \frac{d\Gamma_t}{d\tau} = \mathcal{H} \left(x \equiv \frac{m_W^2}{m_t^2}, \mu \right) \int dk dm^2 J(m^2, \mu) S(k, \mu) \delta \left(\tau - \frac{m^2 + 2E_J k}{m_t^2} \right) + \dots$$

where we have neglected nonsingular terms in τ and

$$E_J = (m_t^2 - m_W^2)/(2m_t)$$

$$\Gamma_t = \int_0^{\tau_0} d\tau \frac{d\Gamma_t}{d\tau} + \int_{\tau_0}^{\tau_{max}} d\tau \frac{d\Gamma_t}{d\tau} \equiv \Gamma_A + \Gamma_B,$$

τ_0 : dimensionless cutoff for τ ;

$$\tau_{max} = (1 - m_W/m_t)^2$$

Γ_A : infrared finite (IR div in the jet and soft function cancel against those from the hard function)

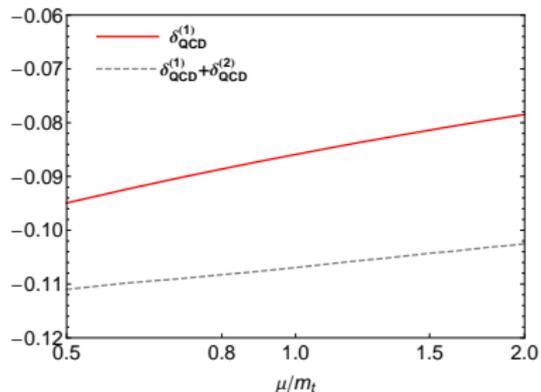
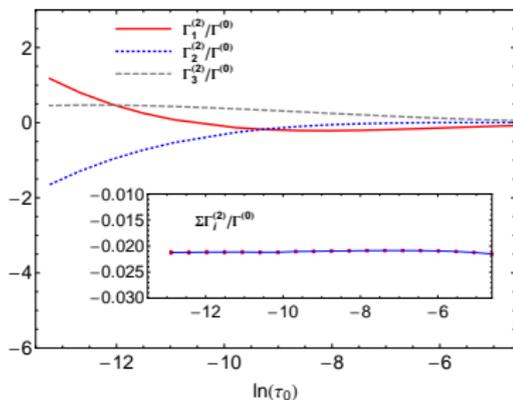
Γ_B : also IR finite

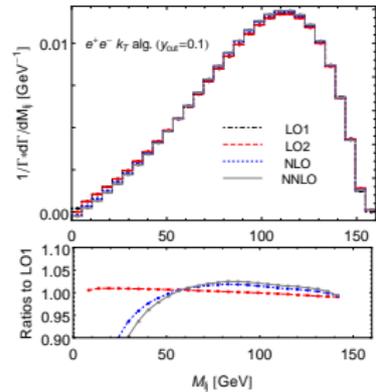
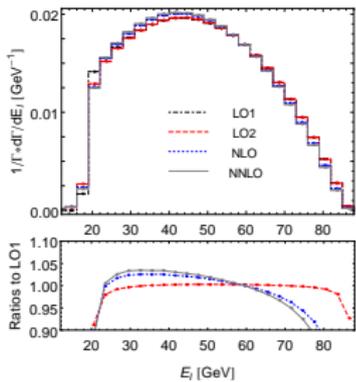
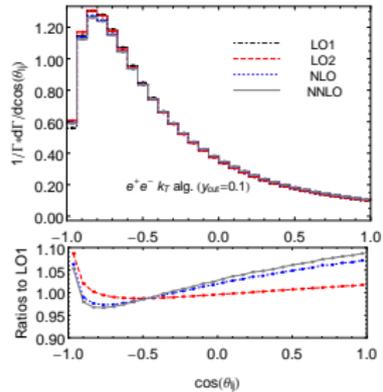
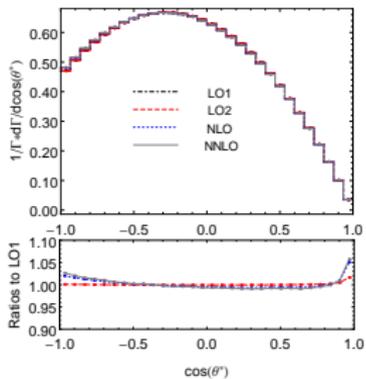
$\Gamma_t^{(0)} = \Gamma_{SM}(m_b = 0)$. Then,

$$\Gamma_t = \Gamma_t^{(0)} \left[1 + \delta_f^b + \delta_f^W + \delta_{EW} + \delta_{QCD}^{(1)} + \delta_{QCD}^{(2)} \right]$$

δ_f^W : finite width of W

m_t	$\Gamma_t^{(0)}$	δ_f^b	δ_f^W	δ_{EW}	$\delta_{QCD}^{(1)}$	$\delta_{QCD}^{(2)}$
172.5	1.4806	-0.26	-1.49	1.68	-8.58	-2.09
173.5	1.5109	-0.26	-1.49	1.69	-8.58	-2.09
174.5	1.5415	-0.25	-1.48	1.69	-8.58	-2.09





Top Width at the ILC

$$e^+e^- \rightarrow W^+W^-b\bar{b}$$

Contributions from

- Double resonant (di-top)
- Singly-resonant (single top)
- Non-resonant

Study $\frac{d^2\sigma}{dM(W^+, b) dM(W^-\bar{b})}$

b, \bar{b} : jets containing bottom

Inv. masses : $m_t \pm 50$ GeV

At NLO, $e^+e^- \rightarrow W^+W^-b\bar{b} + X$

Complex mass at the Lagrangian level.

Is a renormalization procedure.

Bare top-quark mass, m_0 replaced by a renormalized mass μ_t and a counter-term c_t , both of which are complex,

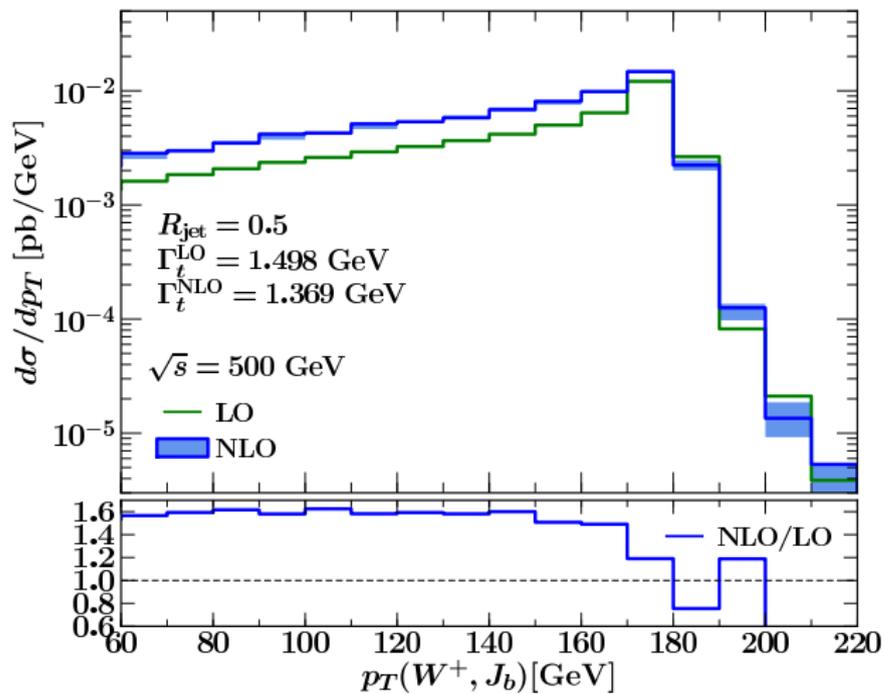
$$m_0 = \mu_t + c_t, \quad \mu_t^2 = m_t^2 - i m_t \Gamma_t$$

Γ_t considered as input

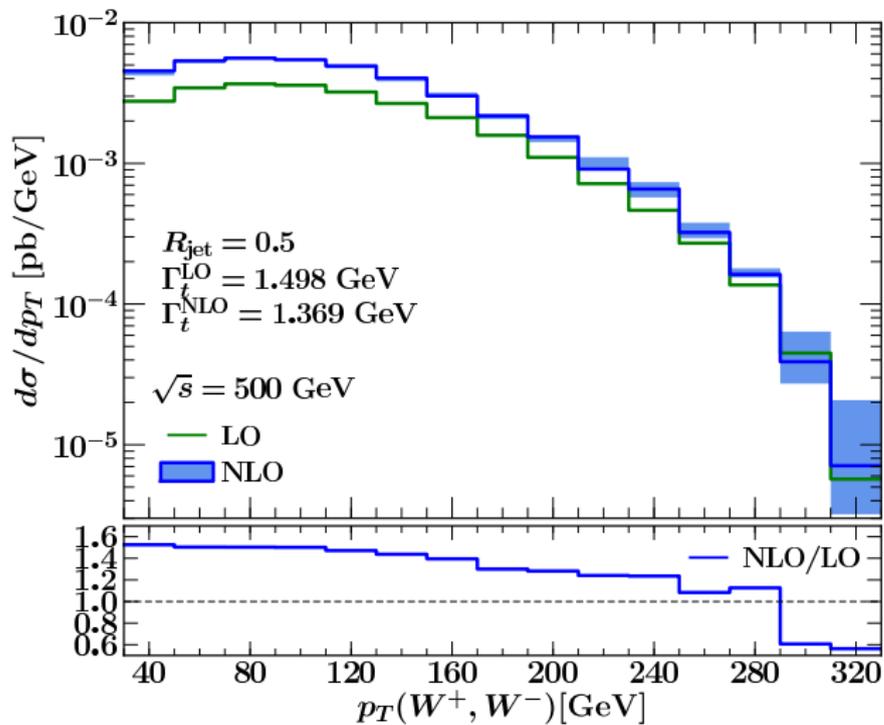
c_t chosen such that μ_t^2 corresponds to pole of the renormalized propagator.

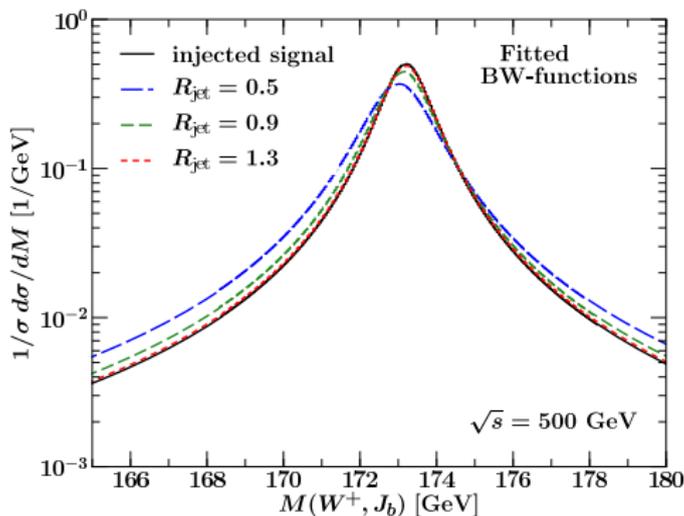
Fixed-order calc. \implies will extract pole mass, defined as $m_t^2 = \text{Re}[\mu_t^2]$.

Width is defined via $m_t \Gamma_t = \text{Im}[\mu_t^2]$.



error : $\mu_R \in [m_t/2, 2m_t]$





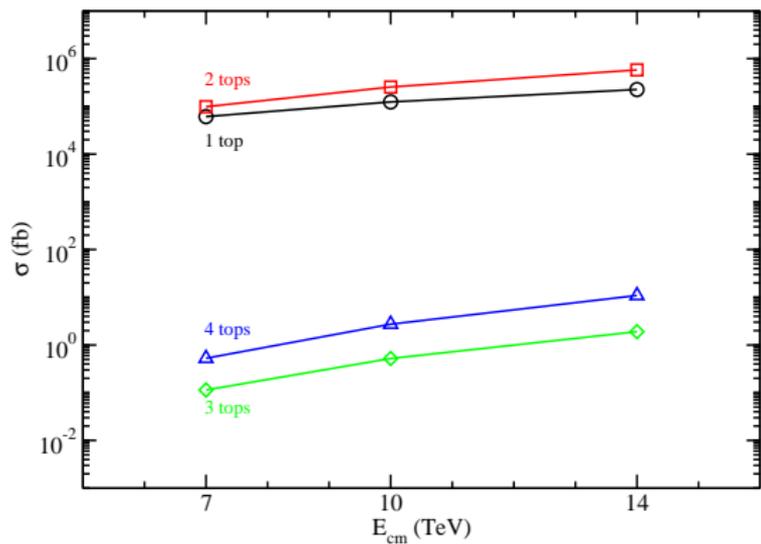
Input: $m_t = 173.2$ GeV &
 $\Gamma_t = 1.369$ GeV

Extracted:

- $R_{jet} = 0.5$: (173.00, 1.92)
- $R_{jet} = 0.9$: (173.14, 1.55)
- $R_{jet} = 1.3$: (173.20, 1.30)

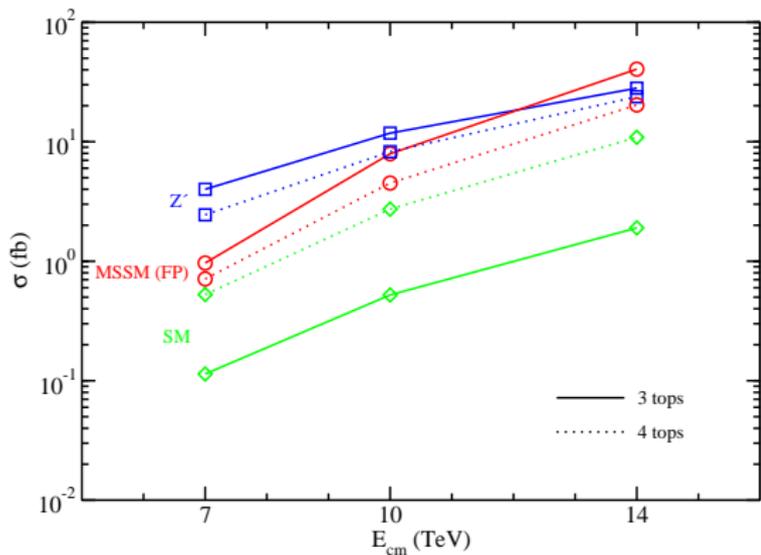
Larger R_{jet} : gluon radiation from intermediate top decays more likely to be clustered in a way that least distorts the LO BW shape near the resonance peak

Multi-top production



Inclusive Cross Sections at the LHC (fb)			
Process	$\sqrt{s} = 7 \text{ TeV}$	10 TeV	14 TeV
$pp \rightarrow 1t \text{ (Total)}$	66×10^3	138×10^3	258×10^3
$pp \rightarrow t + \dots$	42×10^3	85×10^3	154×10^3
$pp \rightarrow tW^-$	5.4×10^3	14×10^3	32×10^3
$pp \rightarrow tj$	35×10^3	68×10^3	117×10^3
$pp \rightarrow t\bar{b}$	1.8×10^3	3.1×10^3	4.8×10^3
$pp \rightarrow \bar{t} + \dots$	24×10^3	53×10^3	104×10^3
$pp \rightarrow \bar{t}W^+$	5.4×10^3	14×10^3	32×10^3
$pp \rightarrow \bar{t}j$	18×10^3	37×10^3	69×10^3
$pp \rightarrow \bar{t}b$	0.99×10^3	1.8×10^3	3.0×10^3
$pp \rightarrow t\bar{t}$	98×10^3	255×10^3	581×10^3

Inclusive Cross Sections at the LHC (fb)			
Process	$\sqrt{s} = 7$ TeV	10 TeV	14 TeV
$pp \rightarrow 3t$ (Total)	0.11	0.52	1.9
$pp \rightarrow t\bar{t} + \dots$	0.072	0.31	1.1
$pp \rightarrow t\bar{t}W^-$	0.027	0.16	0.69
$pp \rightarrow t\bar{t}j$	0.024	0.091	0.27
$pp \rightarrow t\bar{t}\bar{b}$	0.021	0.054	0.11
$pp \rightarrow t\bar{t}\bar{t} + \dots$	0.042	0.21	0.83
$pp \rightarrow t\bar{t}\bar{t}W^+$	0.028	0.16	0.68
$pp \rightarrow t\bar{t}\bar{t}j$	0.008	0.033	0.10
$pp \rightarrow t\bar{t}\bar{t}b$	0.0065	0.019	0.045
$pp \rightarrow t\bar{t}\bar{t}\bar{t}$	0.53	2.7	11



SM, Z' : $\sigma(tt\bar{t}) \gg \sigma(\bar{t}t\bar{t})$
 MSSM : almost equal.

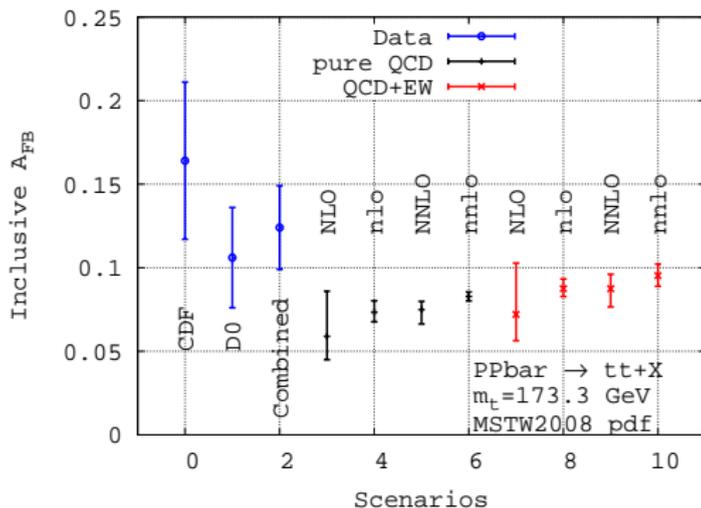
Forward-Backward Asymmetry

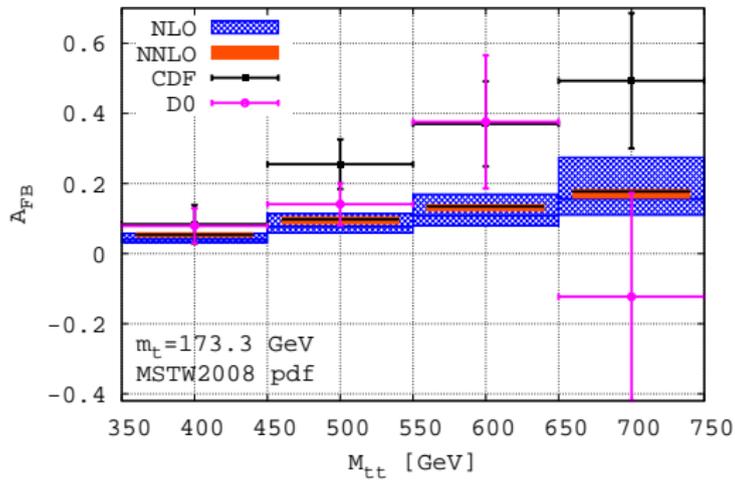
Differential cross section asymmetric in $\Delta y \equiv y_t - y_{\bar{t}}$.

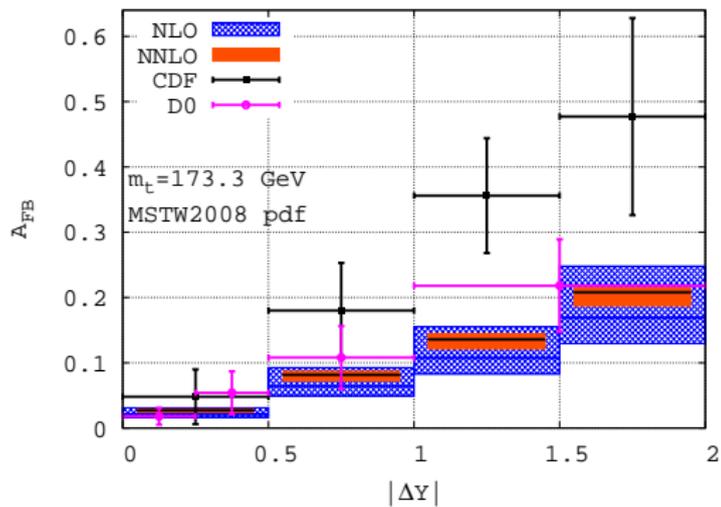
$$A_{FB}^{\text{bin}} = \frac{\sigma_{\text{bin}}^+ - \sigma_{\text{bin}}^-}{\sigma_{\text{bin}}^+ + \sigma_{\text{bin}}^-} \quad \sigma_{\text{bin}}^{\pm} = \int \theta(\pm \Delta y) \theta_{\text{bin}} d\sigma,$$

$$\begin{aligned} A_{FB}^{\text{bin}} &\equiv \frac{N_{\text{EW}} + \alpha_s^3 N_3 + \alpha_s^4 N_4 + \mathcal{O}(\alpha_s^5)}{\alpha_s^2 D_2 + \alpha_s^3 D_3 + \alpha_s^4 D_4 + \mathcal{O}(\alpha_s^5)} \\ &= \alpha_s \frac{N_3}{D_2} + \frac{N_{\text{EW}}}{\alpha_s^2 D_2} \\ &+ \alpha_s^2 \left(\frac{N_4}{D_2} - \frac{N_3 D_3}{D_2^2} \right) - \frac{N_{\text{EW}} D_3}{\alpha_s D_2^2} + \mathcal{O}(\alpha_s^3). \end{aligned}$$

	NLO	NNLO	NLO+NNLL
$\alpha_s^3 N_3 + \alpha_s^4 N_4$ [pb]	$0.394^{+0.211}_{-0.127}$	$0.525^{+0.055}_{-0.085}$	$0.448^{+0.080}_{-0.071}$
$\alpha_s^4 N_4$ [pb]	—	0.148	—
A_{FB} [%] (approx)	$7.34^{+0.68}_{-0.58}$	$8.28^{+0.27}_{-0.26}$	$7.24^{+1.04}_{-0.67}$
A_{FB} [%] (exact)	$5.89^{+2.70}_{-1.40}$	$7.49^{+0.49}_{-0.86}$	—







Asymmetry at the LHC

Need a reference axis.

Produce $t\bar{t}$ alongwith something else, say W

Better than $t\bar{t}g$ or $t\bar{t}\gamma$

$$A_c^t = \frac{N(\Delta_\eta^t > 0) - N(\Delta_\eta^t < 0)}{N(\Delta_\eta^t > 0) + N(\Delta_\eta^t < 0)}, \quad \Delta_\eta^t \equiv |\eta_t| - |\eta_{\bar{t}}|$$

QCD : radiative corrections $t\bar{t}$ production process induces non-vanishing

A_c^t

top quarks produced with a rapidity distribution wider than anti-top quarks.

A_C much smaller than Tevatron A_{FB}

$\sqrt{s} = 7 \text{ TeV}$:

$$\text{ATLAS : } A_{c,y}^t = 0.006 \pm 0.010_{\text{stat+syst}} ,$$

$$\text{CMS : } A_{c,y}^t = -0.010 \pm 0.017_{\text{stat}} \pm 0.008_{\text{syst}} ,$$

$$\text{CMS : } A_c^\ell = 0.009 \pm 0.010_{\text{stat}} \pm 0.006_{\text{syst}} .$$

SM:

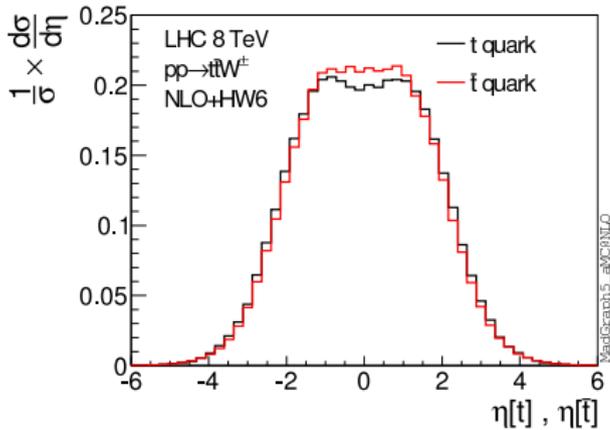
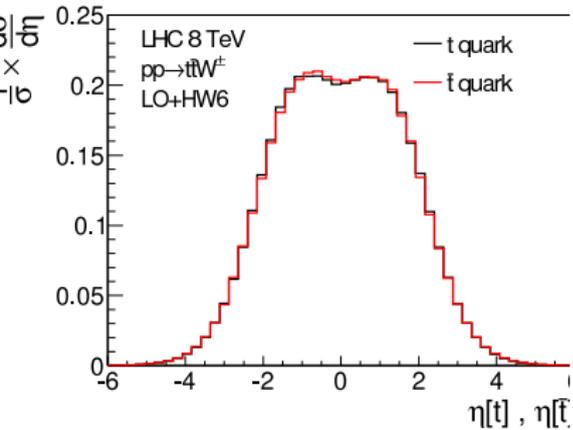
$$A_{c,y}^t(7 \text{ TeV}) = 0.0123 \pm 0.0005 ,$$

$$A_c^\ell(7 \text{ TeV}) = 0.0070 \pm 0.0003 .$$

Reduces for higher \sqrt{s}

$$A_{c,y}^t(8 \text{ TeV}) = 0.0111 \pm 0.0004$$

$$A_{c,y}^t(14 \text{ TeV}) = 0.0067 \pm 0.0004$$



Extent of A_C different for W^\pm

Total cross sections and the asymmetry for $pp \rightarrow t\bar{t}W^\pm$ at 8 TeV.
Uncertainties are estimated with scale variations.

	Order	$t\bar{t}W^\pm$	$t\bar{t}W^+$	$t\bar{t}W^-$
$\sigma(\text{fb})$	LO	$140.5^{+27\%}_{-20\%}$	$98.3^{+27\%}_{-20\%}$	$42.2^{+27\%}_{-20\%}$
	NLO	$210^{+11\%}_{-11\%}$	$146^{+11\%}_{-11\%}$	$63.6^{+11\%}_{-11\%}$
A_c^t (%)	NLO	$2.49^{+0.75}_{-0.34}$	$2.73^{+0.74}_{-0.42}$	$2.03^{+0.81}_{-0.19}$
	NLO+PS	$2.37^{+0.56}_{-0.38}$	$2.51^{+0.62}_{-0.42}$	$1.90^{+0.51}_{-0.35}$

Ask for

- $t \rightarrow bW^+ \rightarrow be^+\nu_e$
 - $W^- \rightarrow \mu^-\bar{\nu}_\mu$
 - $\bar{t} \rightarrow \bar{b}W^- \rightarrow \bar{b}e^-\bar{\nu}_e$
 - $W^+ \rightarrow \mu^+\nu_\mu$.
- Can look for A_c^b and A_c^ℓ

	Order	$t\bar{t}W^\pm$	$t\bar{t}W^+$	$t\bar{t}W^-$
A_c^b (%)	LO+PS	$7.46^{+0.04}_{-0.05}$	$8.04^{+0.05}_{-0.06}$	$5.67^{+0.01}_{-0.01}$
	NLO+PS	$8.50^{+0.15}_{-0.10}$	$9.39^{+0.15}_{-0.10}$	$6.85^{+0.14}_{-0.11}$
A_c^ℓ (%)	LO+PS	$-17.10^{+0.09}_{-0.11}$	$-18.65^{+0.12}_{-0.14}$	$-13.53^{+0.01}_{-0.03}$
	NLO+PS	$-14.83^{+0.65}_{-0.95}$	$-16.23^{+0.72}_{-1.04}$	$-11.97^{+0.50}_{-0.75}$

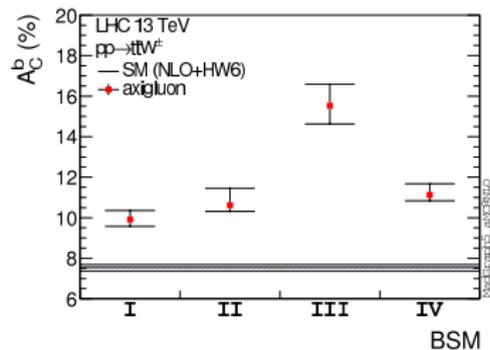
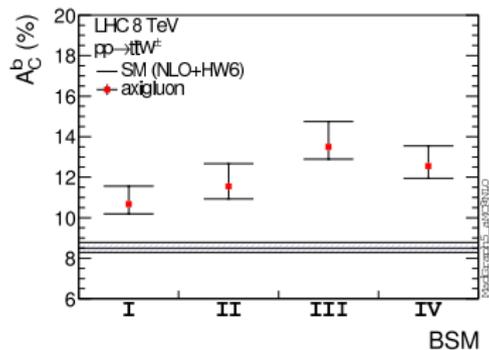
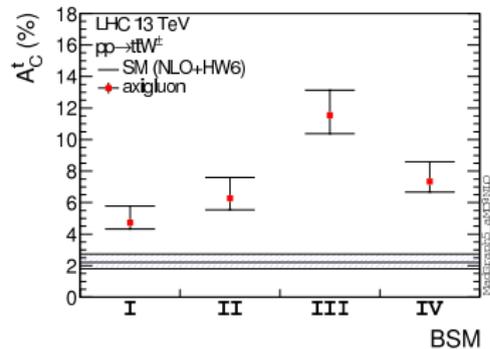
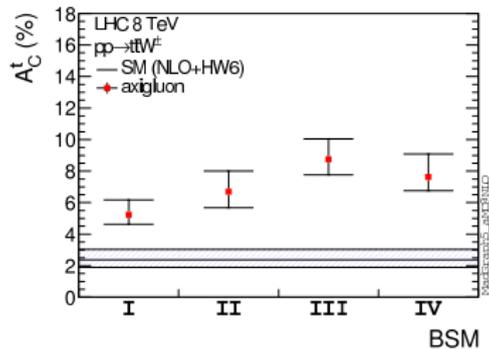
Look for BSM

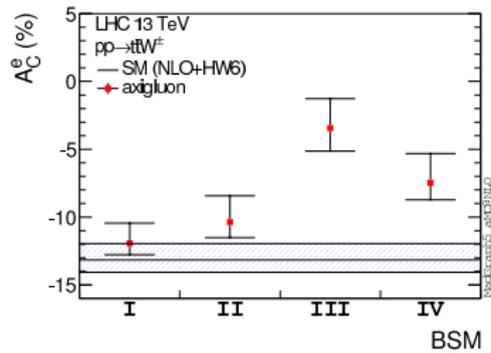
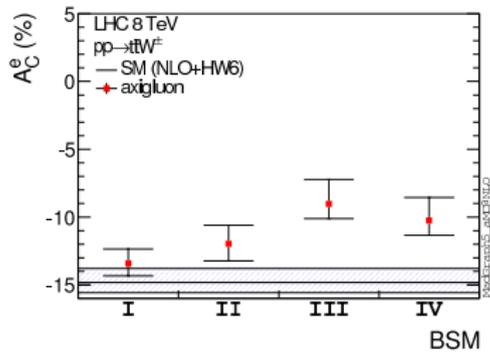
Axigluon-generated asymmetry

Heavy color-octet \tilde{G}

$$\mathcal{L} = \sum_i \tilde{G}^{\mu,a} [g_L^i \bar{q}_i T^a \gamma_\mu (1 - \gamma^5) q_i + g_R^i \bar{q}_i T^a \gamma_\mu (1 + \gamma^5) q_i] , \quad i = u, d, t$$

- Scenario I : $g_L^u = g_L^d = 0.5g_s$, $g_R^u = g_R^d = 0$,
 $m_{\tilde{G}} = 200 \text{ GeV}, \Gamma_{\tilde{G}} = 50 \text{ GeV}$
- Scenario II : $g_L^u = g_L^d = -0.4g_s$, $g_R^u = g_R^d = 0.4g_s$,
 $m_{\tilde{G}} = 200 \text{ GeV}, \Gamma_{\tilde{G}} = 50 \text{ GeV}$
- Scenario III : $g_L^u = g_L^d = -0.8g_s$, $g_R^u = g_R^d = g_R^t = 0$,
 $g_L^t = 6g_s$
 $m_{\tilde{G}} = 2 \text{ GeV}, \Gamma_{\tilde{G}} = 1123 \text{ GeV}$.
- Scenario IV : $g_L^u = g_L^d = 0.6g_s$, $g_R^u = -0.6g_s$, $g_R^d = 0$,
 $g_L^t = -4g_s$, $g_R^t = 4g_s$
 $m_{\tilde{G}} = 2 \text{ GeV}, \Gamma_{\tilde{G}} = 742 \text{ GeV}$.





Top-Z couplings

$$\mathcal{L}_{t\bar{t}Z} = e\bar{u}(p_t) \left[\gamma^\mu (C_{1,V}^Z + \gamma_5 C_{1,A}^Z) + \frac{i\sigma^{\mu\nu} q_\nu}{M_Z} (C_{2,V}^Z + i\gamma_5 C_{2,A}^Z) \right] v(p_{\bar{t}}) Z_\mu$$

SM :

$$C_{1,V}^Z = \frac{T_t^3 - 2Q_t \sin^2 \theta_w}{2 \sin \theta_w \cos \theta_w} \approx 0.24, \quad C_{1,A}^Z = \frac{-T_t^3}{2 \sin \theta_w \cos \theta_w} \approx -0.60,$$

Translatable to gauge-invariant operators in EFT.

UV renormalization and evolution of operators from EFT scale Λ down to the electroweak scale

\implies operators mix at NLO and additional $\log(M_Z/\Lambda)$ appear.

At the LHC

$pp \rightarrow t\bar{t}Z$ at NLO QCD corrections to with leptonic branchings of the Z
 t 's treated in the narrow-width approximation (parametric in Γ_t/m_t)

Additional UV-singularities at NLO.

Subtract divergences through a redefinition of the $C_{2,V/A}^Z$ couplings

$$C_{2,V/A}^Z \rightarrow C_{2,V/A}^Z \left(1 + \frac{\alpha_s}{4\pi} C_F \left(\frac{\mu_{\text{ren}}^2}{M_Z^2} \right)^\epsilon \frac{\Gamma(1+\epsilon)}{\epsilon} \right),$$

Universality in processes $pp \rightarrow t\bar{t}Z$ and $e^+e^- \rightarrow t\bar{t}$

$$pp \rightarrow t\bar{t} Z/\gamma^* \rightarrow bj\bar{j} \bar{b}\ell^-\bar{\nu} \ell^-\ell^+$$

One W boson decaying hadronically, the other leptonically.

3 charged leptons, 4 jets (two may be b -tagged), and missing energy.

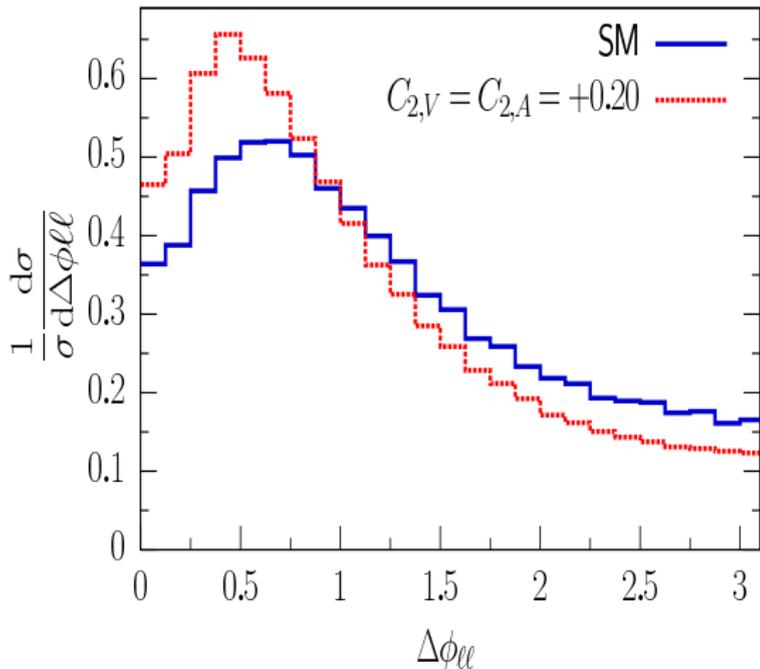
$$\begin{aligned} p_T^\ell &> 20 \text{ GeV}, & |y^\ell| &< 2.4, \\ p_T^j &> 30 \text{ GeV}, & |y^j| &< 2.4, \\ R_{\ell j} &> 0.3, & R_{\ell\ell} &> 0.3, \\ |m_{\ell\ell} - M_Z| &< 20 \text{ GeV}. \end{aligned}$$

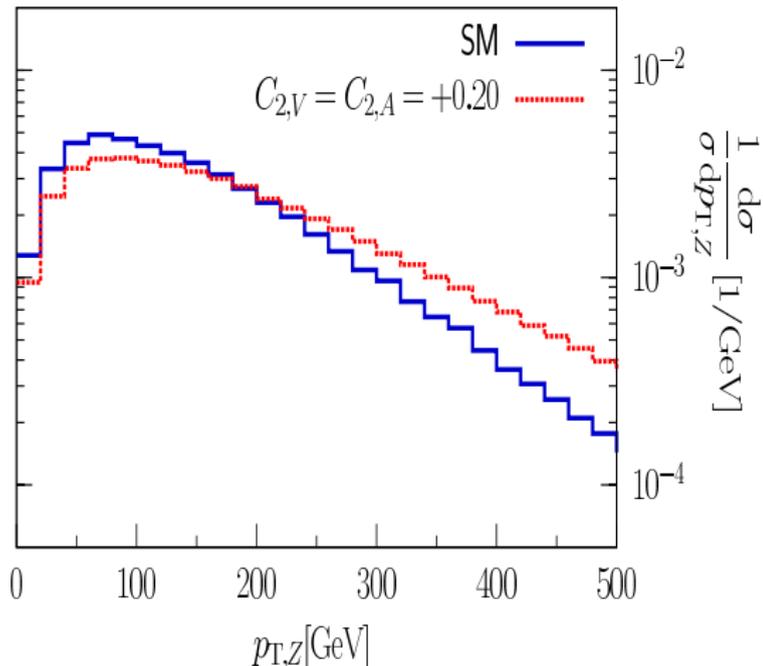
SM:

$$\sigma^{\text{LO}} = 2.04_{-24\%}^{+36\%} \text{ fb}, \quad \sigma^{\text{NLO}} = 3.38_{-18\%}^{+19\%} \text{ fb},$$

Fitting exercise : Assume $\sim 30\%$ error for LO and $\sim 15\%$ for NLO.

$$\sigma^{\text{LO}}(C_{2,V}^Z = C_{2,A}^Z = 0.2) = 3.51 \text{ fb}, \quad \sigma^{\text{NLO}}(C_{2,V}^Z = C_{2,A}^Z = 0.2) = 5.99 \text{ fb}.$$



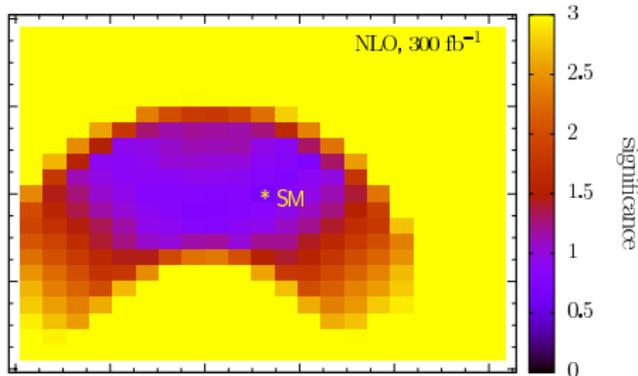
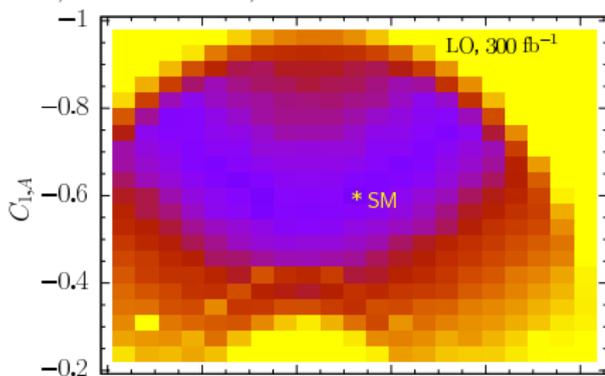


Difference more pronounced for $(C_{2,V}^Z, C_{2,A}^Z)$ than for $(C_{1,V}^Z, C_{1,A}^Z)$.

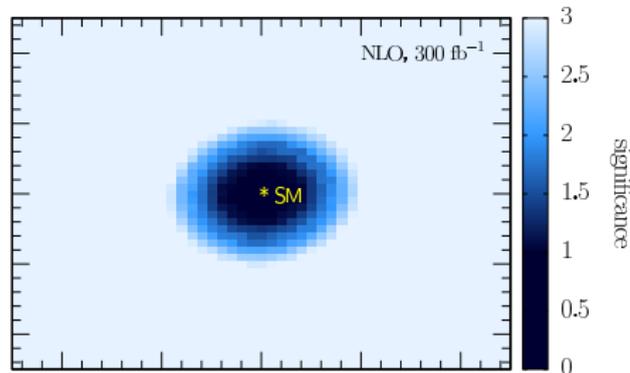
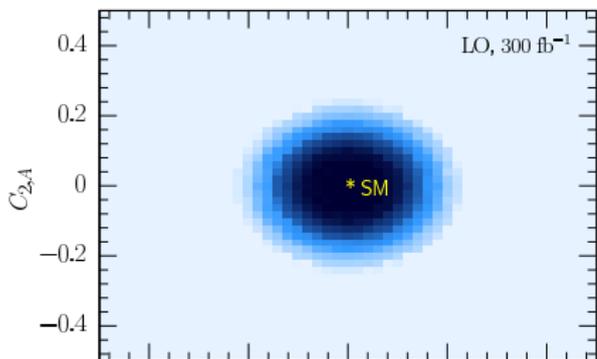
$C_{1,V/A}^Z$: change overall strength of the couplings

$C_{2,V/A}^Z$: change Lorentz structure.

$$C_{2,V}^Z = 0 = C_{2,A}^Z$$



$(C_{1,V}^Z, C_{1,A}^Z)$: SM values



At the ILC

$e^+e^- \rightarrow t\bar{t}$; One top decays hadronically, other leptonically

Assumption: $t\bar{t}\gamma$ unchanged

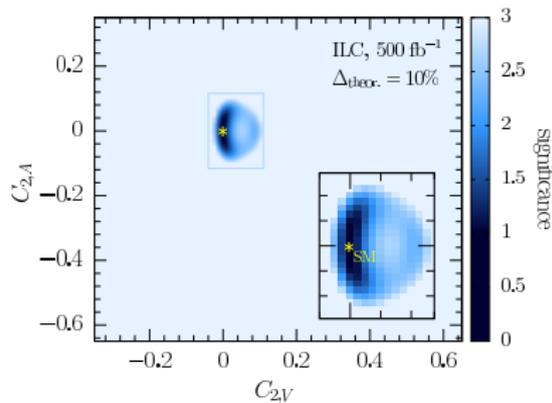
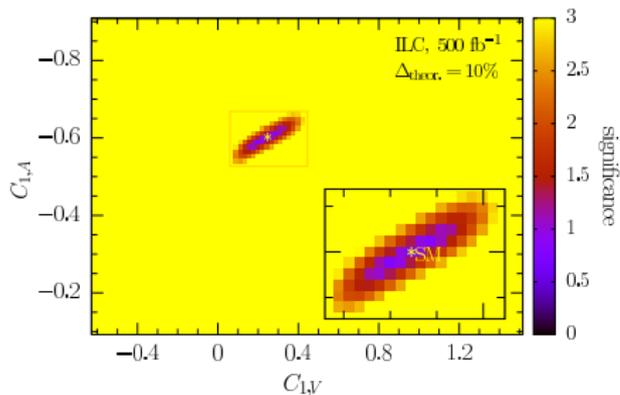
At $\sqrt{s} = 500\text{GeV}$,

$$\begin{aligned} p_T^\ell &> 20 \text{ GeV}, & |y^\ell| &< 2.5, \\ p_T^j &> 20 \text{ GeV}, & |y^j| &< 2.5, \\ p_T^{\text{miss}} &> 20 \text{ GeV}, & R_j(k_\perp^{-1}) &= 0.4 \end{aligned}$$

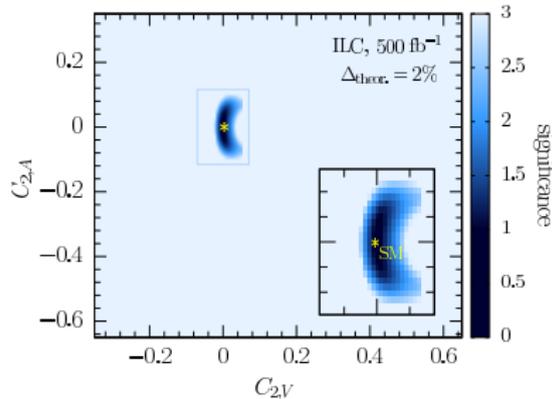
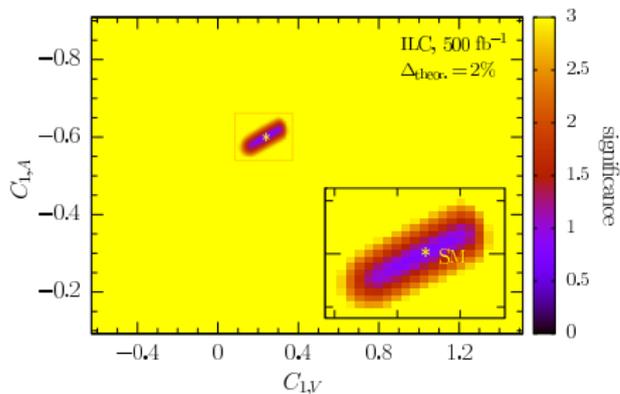
$$\sigma^{\text{NLO}} = 90.0 \pm 0.8 \text{ fb}$$

For 500 fb^{-1} , will have 45000 events.

10% theoretical error:



2% theoretical error:



For 2% error,

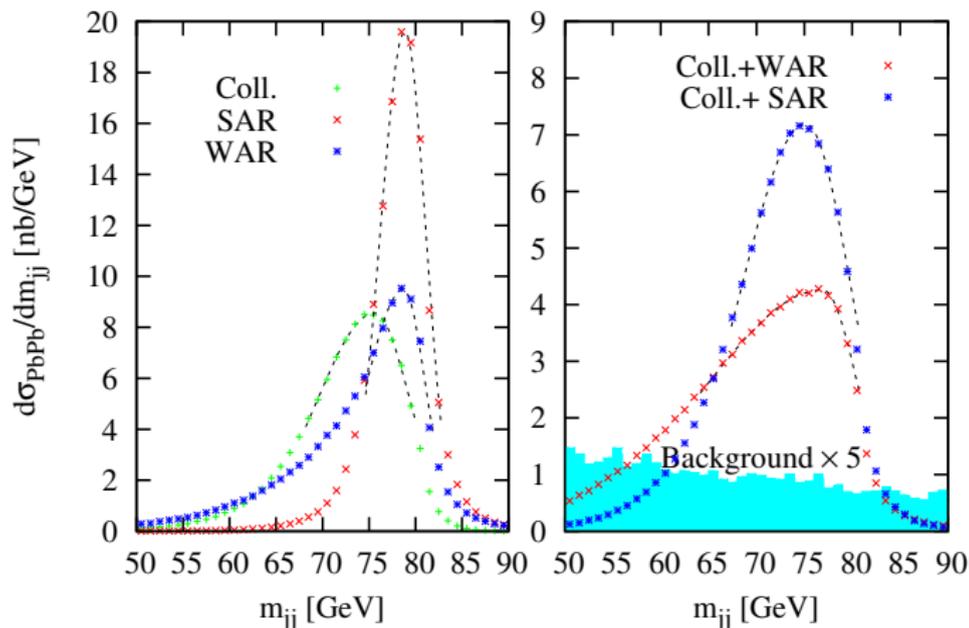
$$C_{1,V}^Z = 0.24_{-0.11}^{+0.08} \text{ and } C_{1,A}^Z = -0.60_{-0.04}^{+0.04}$$

and

$$|C_{2,A}^Z| \lesssim 0.08, \text{ and } -0.02 \lesssim C_{2,V}^Z \lesssim 0.04 \text{ at the 95\% C.L.}$$

Top as a probe for QGP

$t\bar{t}$ production in Pb-Pb collisions.
Jet energy quenching. Not for leptons.



Interesting issues that I left out

- Boosted top
- Top partners
- Top as a conduit for DM
- Top as a composite
- Is the Higgs a Top (partner) composite?