Electroweak production of top quarks

The XXII International Workshop
High Energy Physics and Quantum Field Theory
Samara, Russia, 2015

L. Dudko

SINP MSU, Moscow

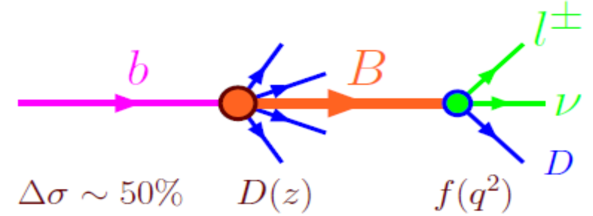
Why We Like Top Quark

- We do not expect the formation of top hadrons therefore, top quark decays before hadronization

$$\tau_t = \frac{1}{\Gamma_{\text{tot}}} \simeq \frac{1}{1.60\ \text{ГэВ}} = 4 \times 10^{-25}\ \ \text{сек}$$

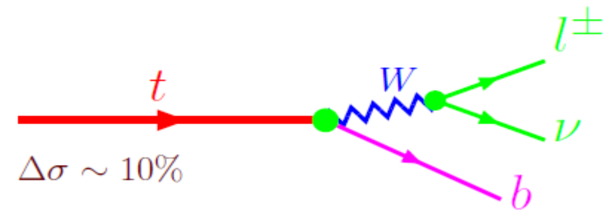
$$\tau_{\text{адр}} \sim \frac{1}{\Lambda_{\text{КХД}}} \simeq 5\ \ \text{ГэВ}^{-1} = 3.3 \times 10^{-24}\ \ \text{сек}$$

$hh \Rightarrow$



Uncertainty $\sim\ \Delta\sigma \otimes D(z) \otimes f(q^2)$

$hh \Rightarrow$



Uncertainty $\sim\ \Delta\sigma$

- Top quark decays through ONE decay channel

$$t \to bW^+,\ \text{BR}(t \to \text{other}) \leq \mathcal{O}(10^{-3})$$

- The total and differential rates are calculated with 𝕆(10%) accuracy

- Top quark is unique and powerful instrument to study SM physics and search for manifestation of New Physics beyond SM

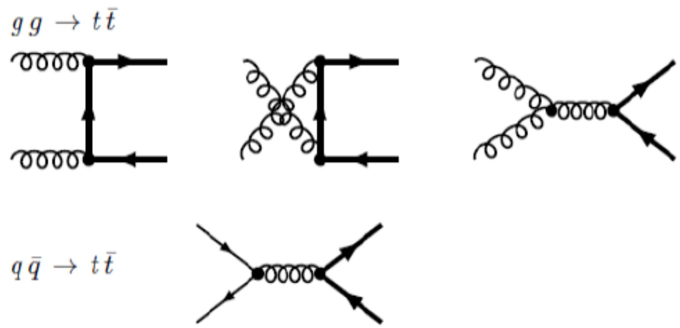
Study of top quark

- Total production cross sections, ratio of t to $\bar{t}$ CS
- Differential cross sections (p_T, η, M, spin correlations)
- Fiducial measurements
- Measurement of m_t, $\Gamma_{tot}(t \to X)$, V_{tb}
- Test $gt\bar{t}$, Wtb, ttH, tHq
- top production and decay due to "New Physics"
  - anomalous $gt\bar{t}$, Wtb couplings
  - Flavor Changing Neutral Current (FCNC)
  - New bosons ($H^{\pm}$, W ', Z')
  - Extra dimensions, ...

Top quark production processes

$t\bar{t}$ pair production (QCD)

	σ_{NLO} (пб)
Tevatron ($\sqrt{s} = 1.96$ ТэВ $p\bar{p}$)	$7.08 \pm 5\%$
LHC ($\sqrt{s} = 7$ ТэВ pp)	$165 \pm 6\%$
LHC ($\sqrt{s} = 8$ ТэВ pp)	$234 \pm 4\%$
LHC ($\sqrt{s} = 14$ ТэВ pp)	$920 \pm 5\%$

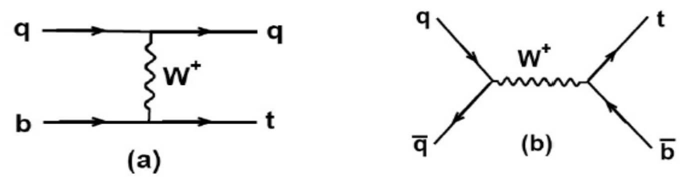


90%

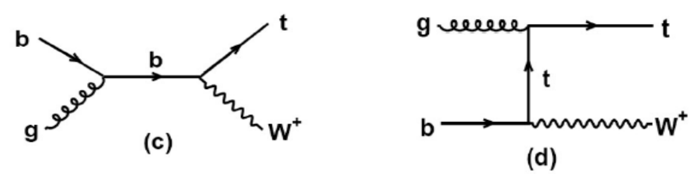
10%

$t(\bar{t})$ single production (electroweak)

	s-channel	t-channel	Wt
Tevatron[50] ($\sqrt{s} = 1.96$ TeV $p\bar{p}$)	$1.04 \pm 4\%$	$2.26 \pm 5\%$	$0.14 \pm 20\%$
LHC[63,72] ($\sqrt{s} = 7$ TeV pp)	$4.6 \pm 5\%$	$64 \pm 4\%$	$15.6 \pm 8\%$
LHC[73] ($\sqrt{s} = 8$ TeV pp)	$5.55 \pm 4\%$	$87.2^{+4}_{-3}\%$	$11.1 \pm 7\%$
LHC[52] ($\sqrt{s} = 14$ TeV pp)	$12 \pm 6\%$	$243 \pm 4\%$	$75 \pm 10\%$



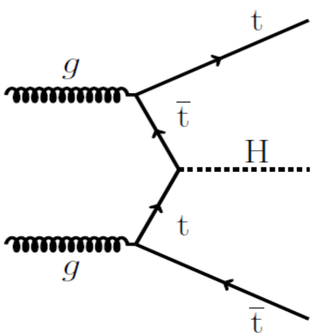
t-channel s-channel



associated tW production

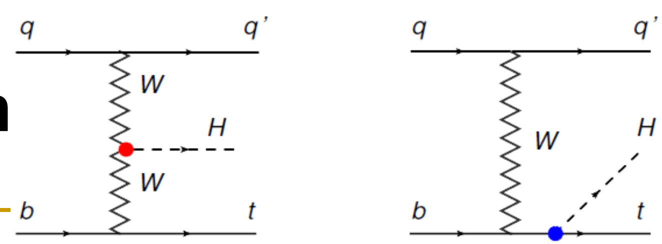
$t\bar{t}$H(W,Z) production

~ 0.1 pb

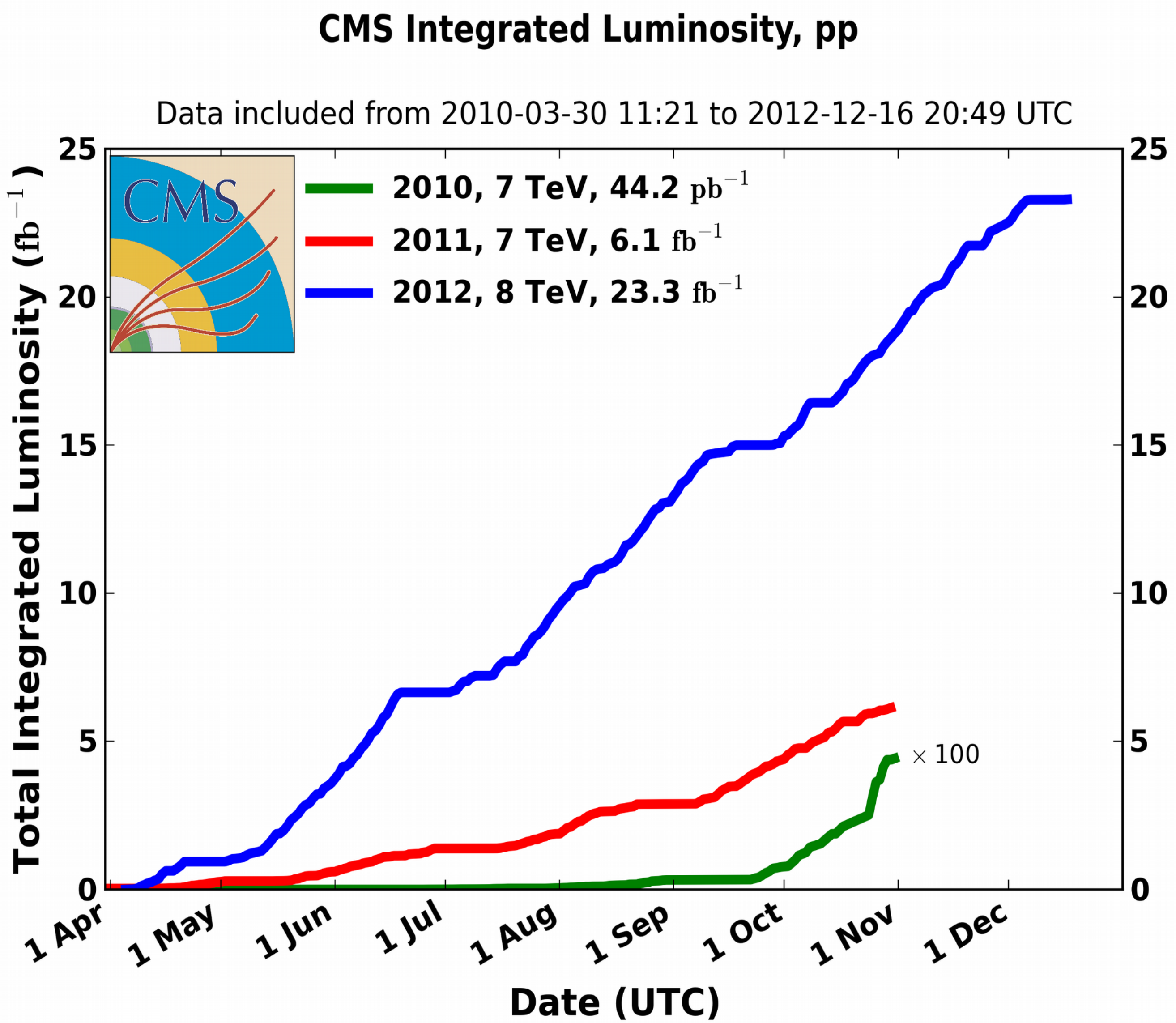


tHq production

~ 0.01 pb



LHC is a Top quark Factory



Top quark pairs

4.5×10^6

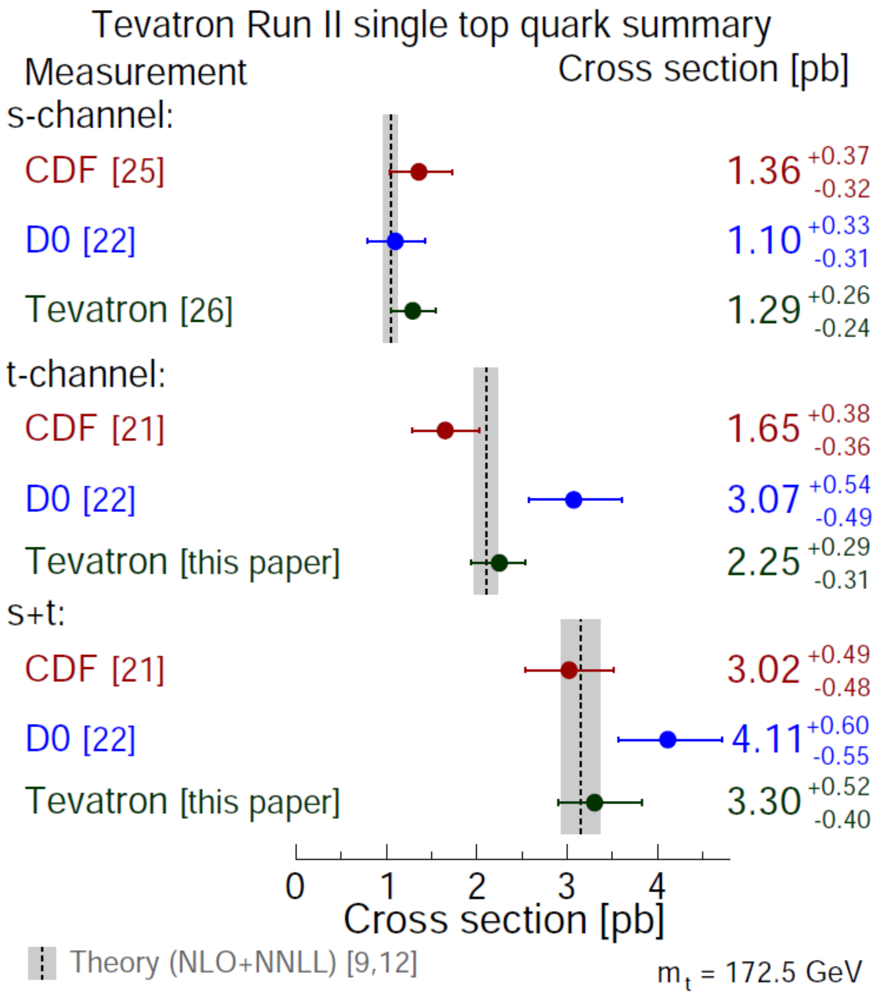
0.99×10^6

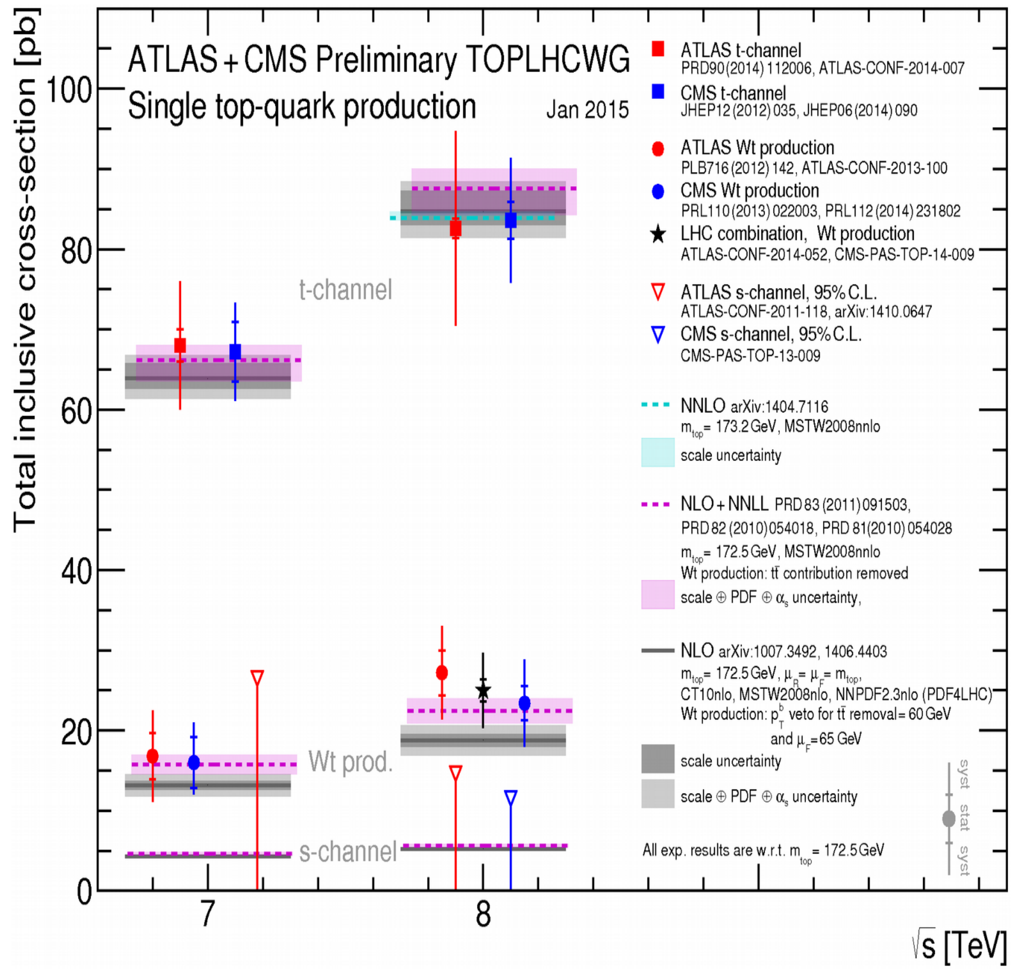
5.9×10^3

Analysis Methods

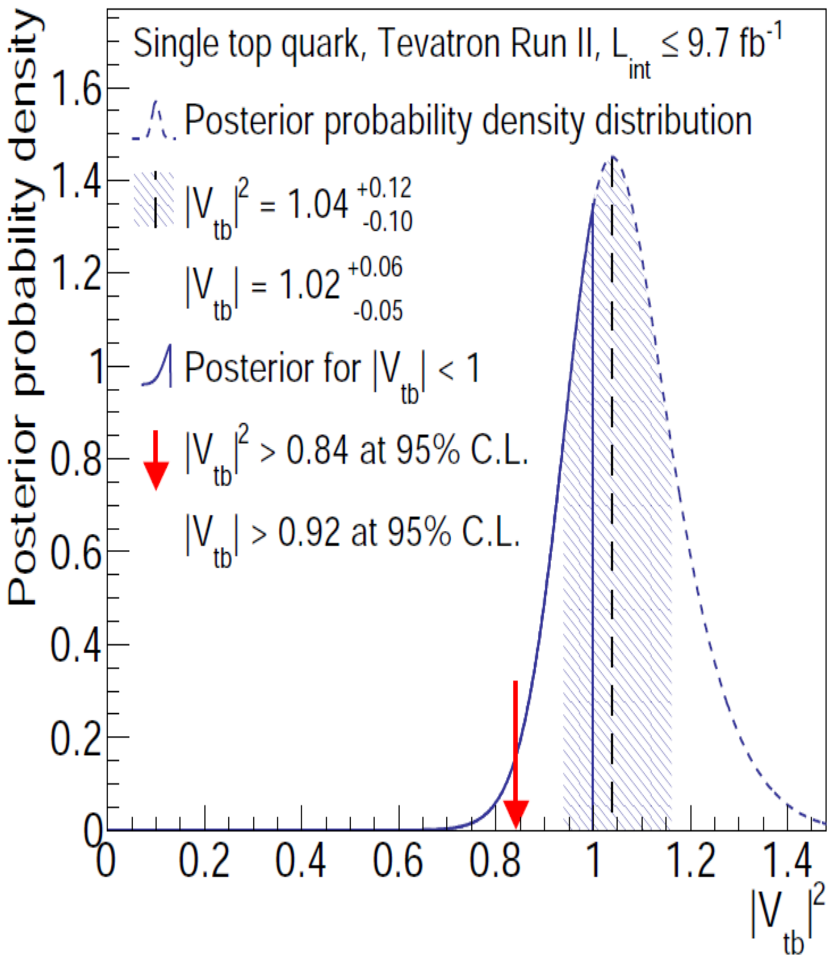
- Counting experiment
  - Number of events
  - Number of events after cut to multivariate discriminant
- Matrix element
  - Evaluate probability of the event for signal and background hypotheses based on analytic form of matrix element
- Template/likelihood
  - Form signal and background templates for an observable
  - Fit Data with templates
- Multivariate methods
  - Multivariate analysis (NN, BDT) of many discriminating variables
  - Output discriminant for the likelihood fit between Data and model

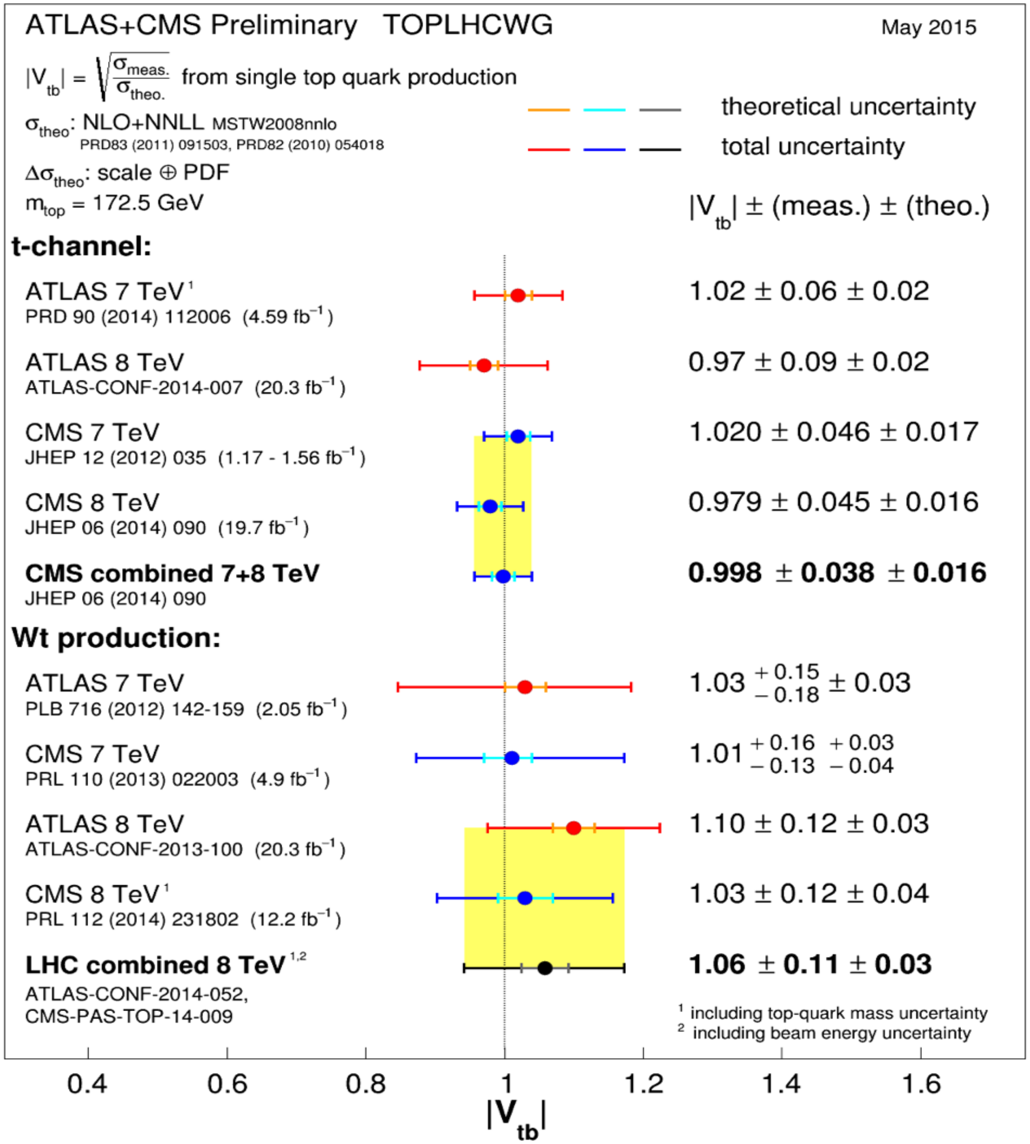
$t(\bar{t})$: Total Cross sections



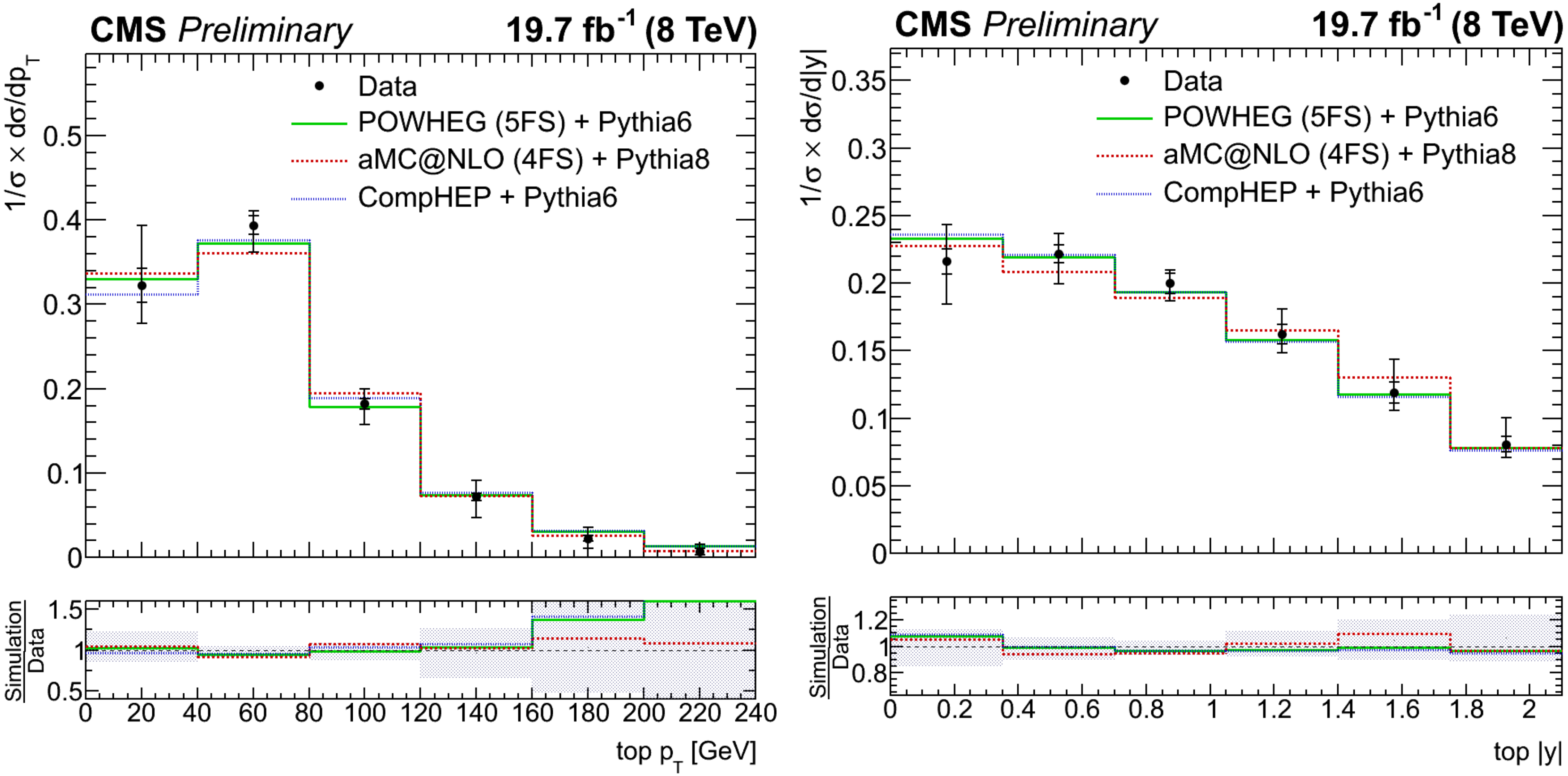


t($\bar{t}$): Vtb CKM matrix element measurement

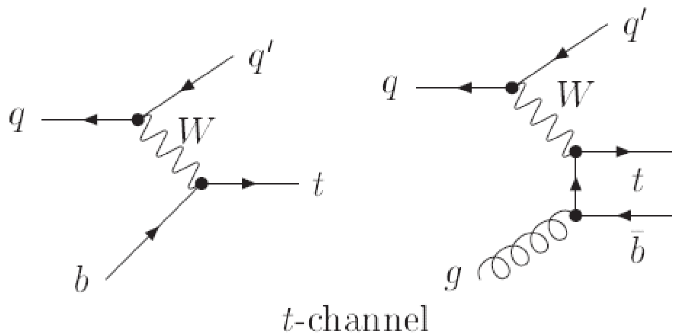




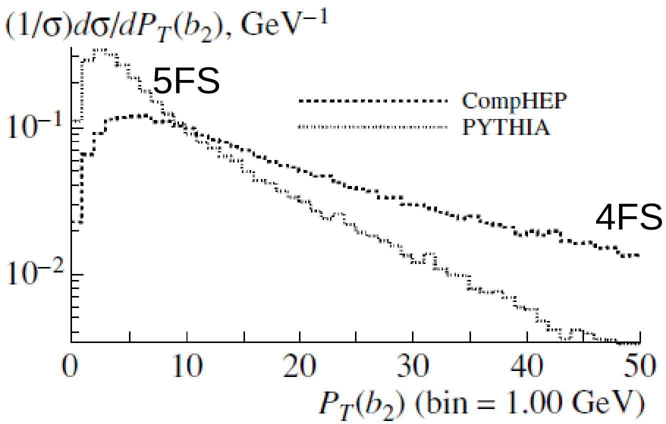
$t(\bar{t})$: Differential Cross Sections (t-channel)

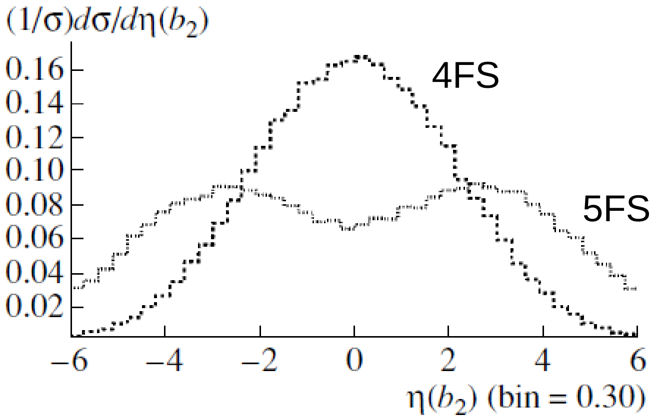


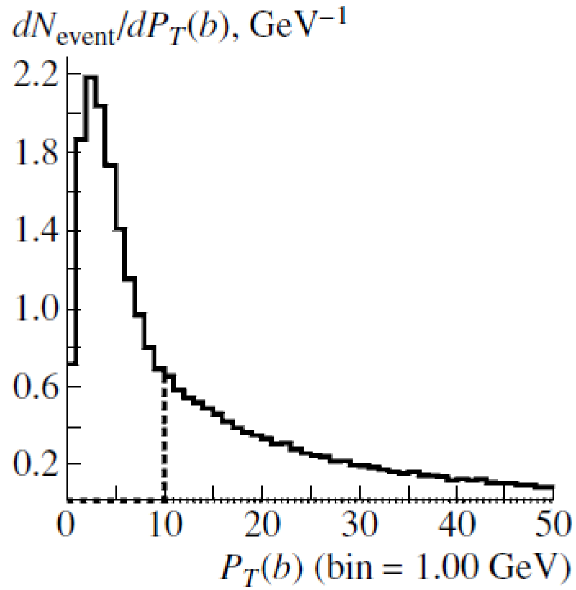
$t(\bar{t})$: Simulation issues in t-channel

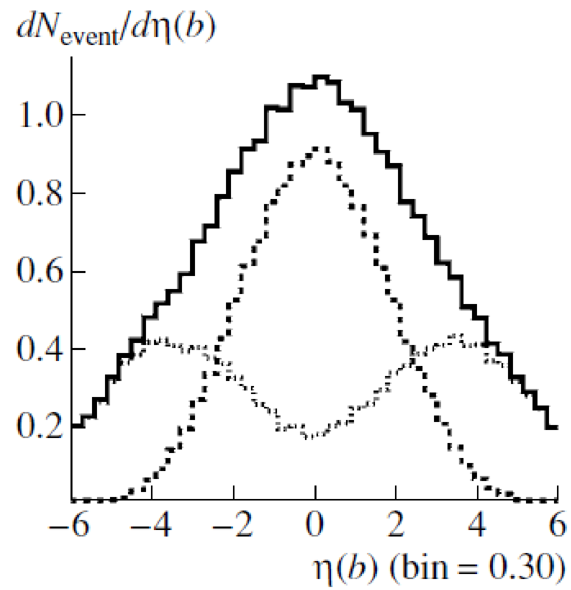


Matching of the LO diagram with initial b-quark (5FS)
And NLO diagram with initial gluon (4FS)

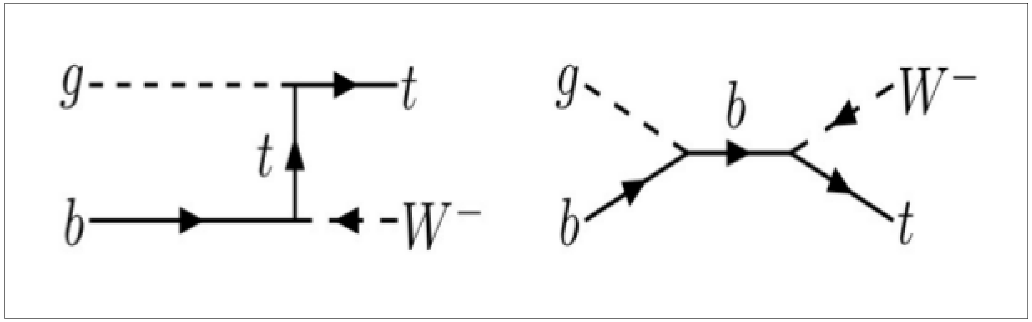






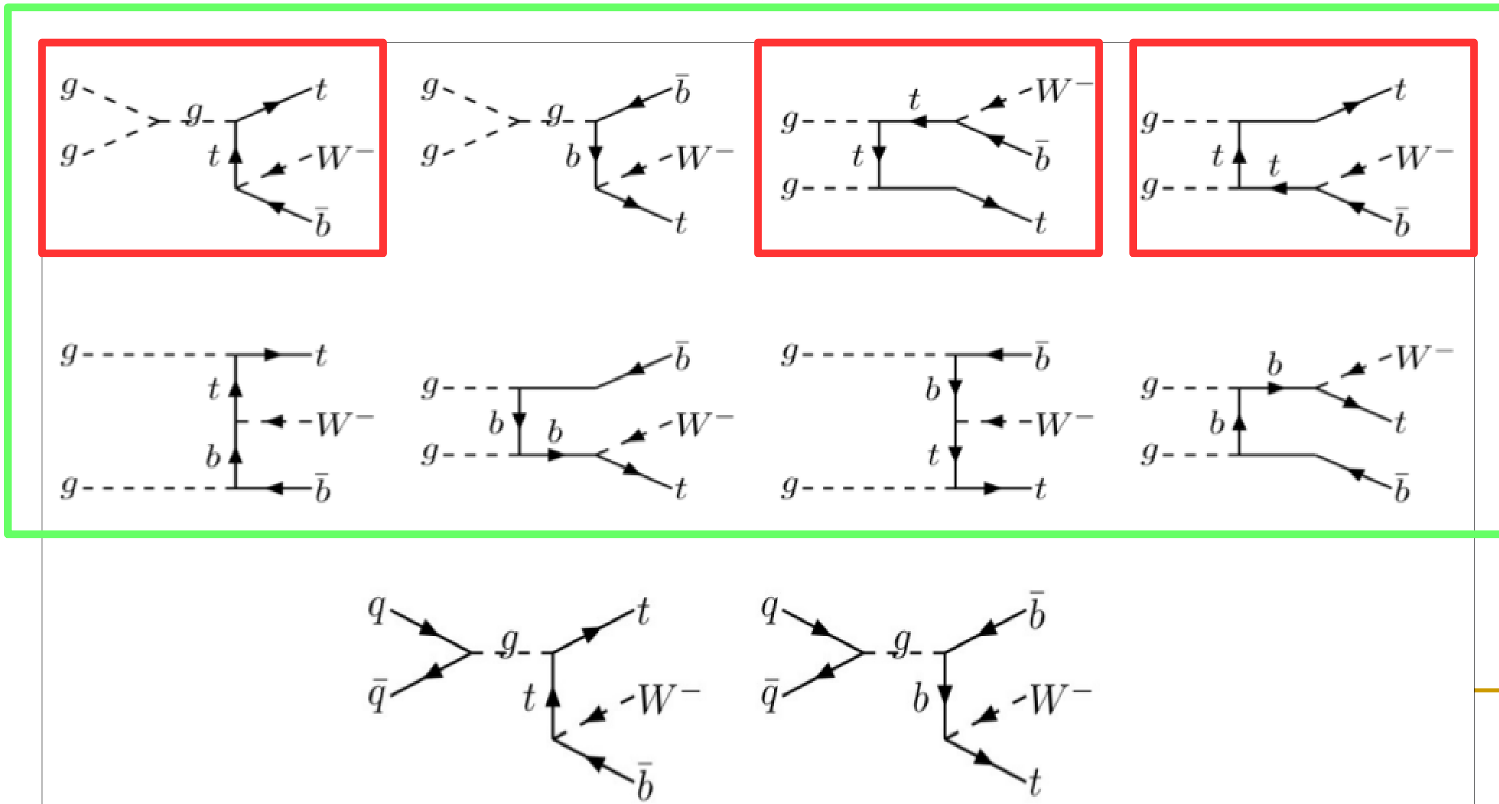


t($\bar{t}$): Simulation issues in tW channel (I)



Leading order (**LO**)
2->2 process
tW production

Next to leading order (**NLO**), O(1/log(mt/mb)), 2->3 processes, **tWb**

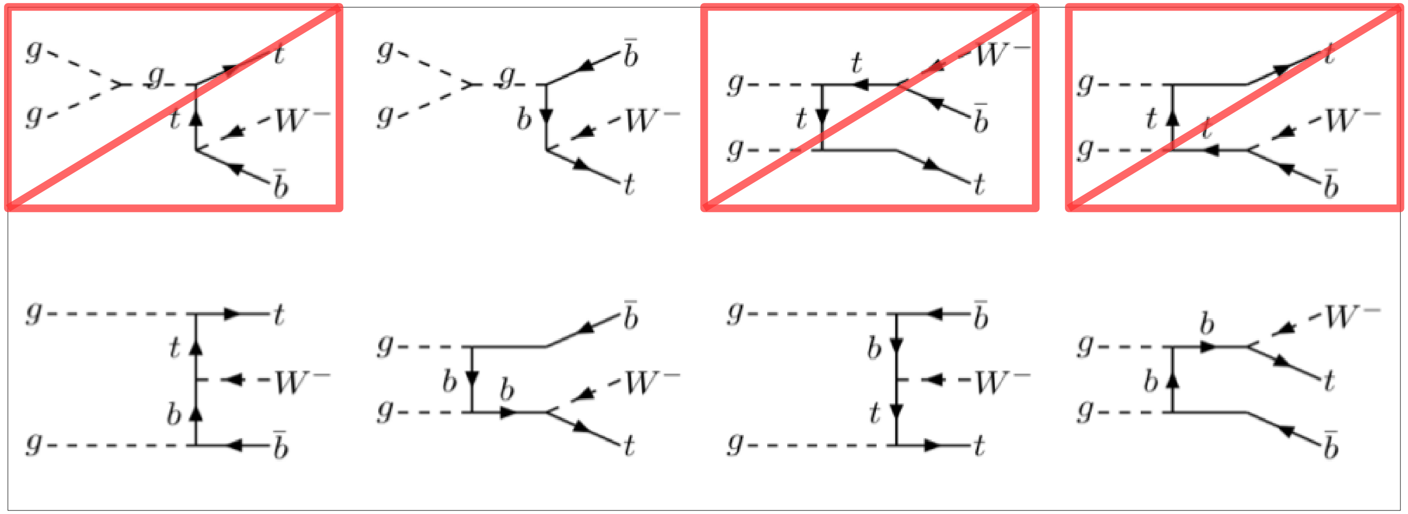


t tbar production

gluon gluon processes

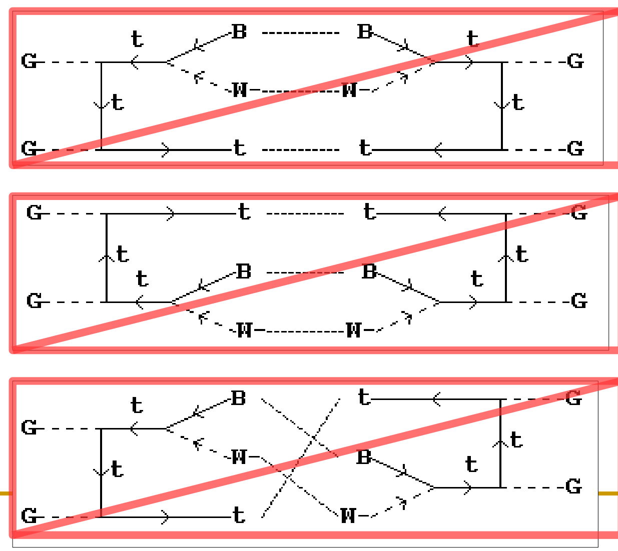
t($\bar{t}$): Simulation issues in tW channel (II)

Diagram removal scheme S. Frixione et al., arXiv:0805.3067.



~~t t-bar production~~

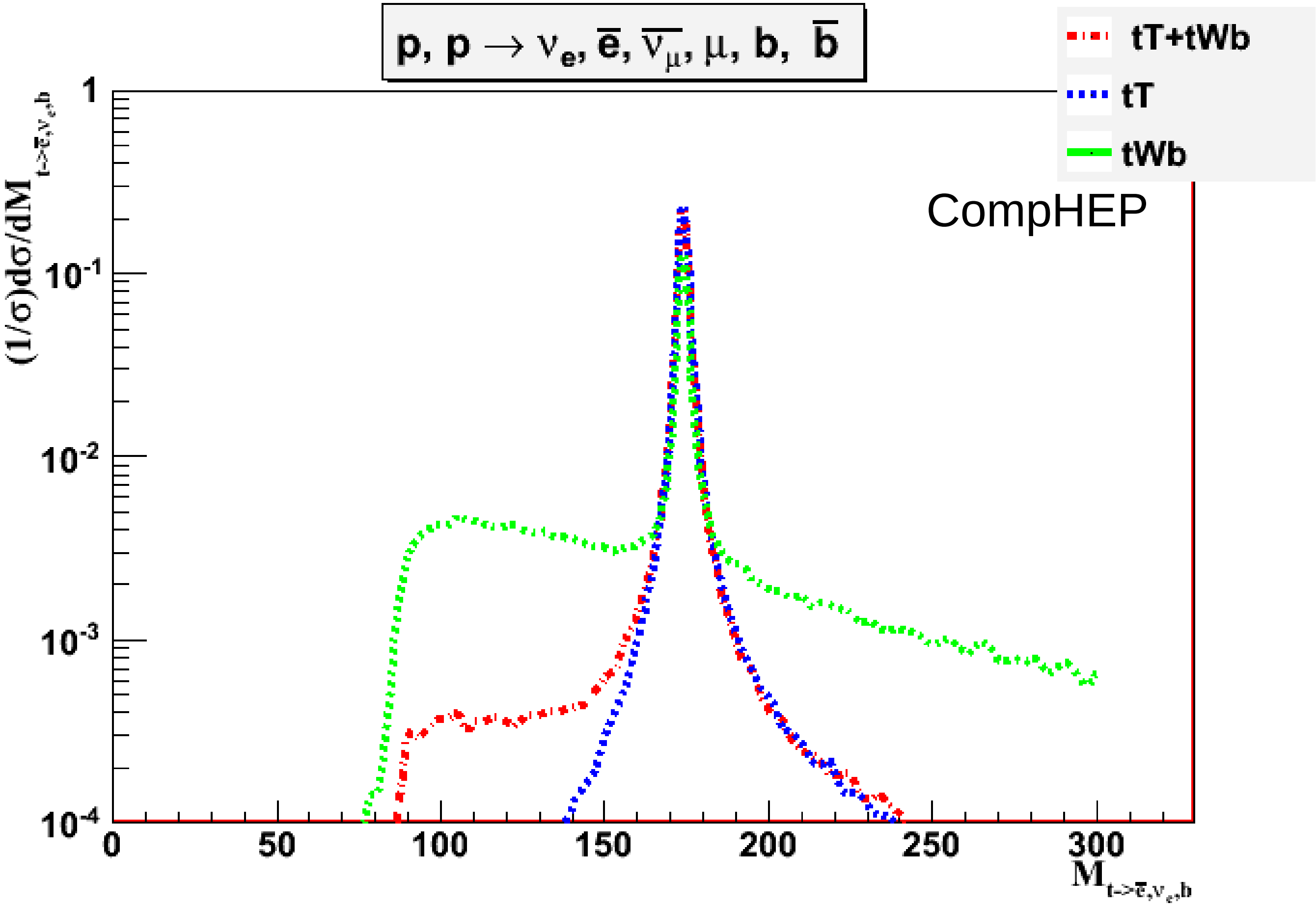
Diagram subtraction Scheme
T. M. P. Tait, arXiv:hep-ph/9909352



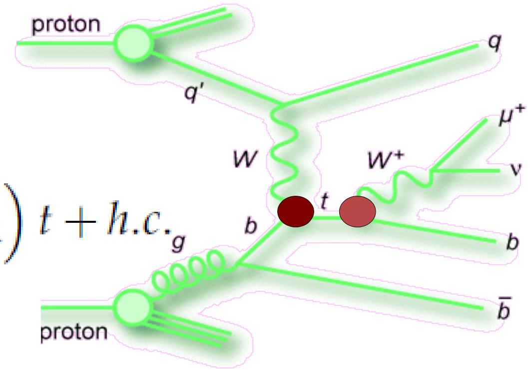
Kinematic separation
A.Belyaev, E. Boos, arXiv:hep-ph/0003260

$t(\bar{t})$: Simulation issues in tW channel (III)

The interference between tW (single resonance) and ttbar (double resonance) diagrams is negative and important. The most correct way is to simulate tW+ttbar all together.



Anomalous Wtb couplings in t-channel



General form of the effective Wtb vertex lagrangian.

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_V^L P_L + f_V^R P_R\right) t W_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}\partial_\nu W_\mu^-}{M_W}\left(f_T^L P_L + f_T^R P_R\right) t + h.c.$$

	Left and right vector operators		Left and right tensor operators		
SM:	Vtb	0	0	0	(1000)

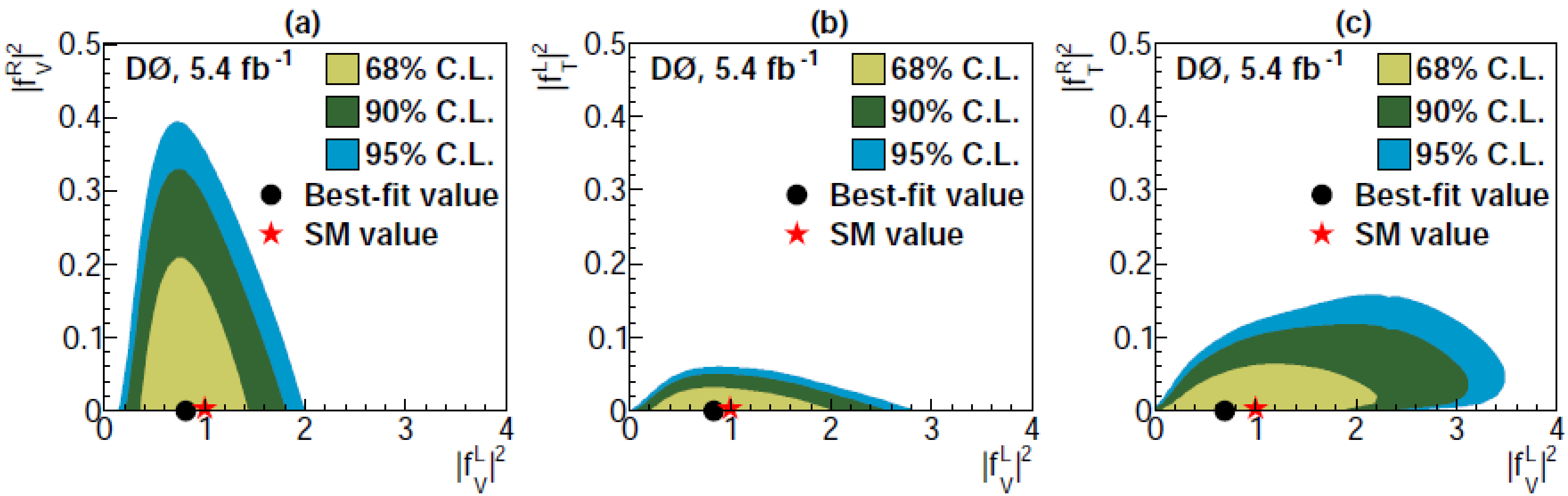
Factorize the couplings and kinematic terms in order to simulate kinematics with all values of the couplings

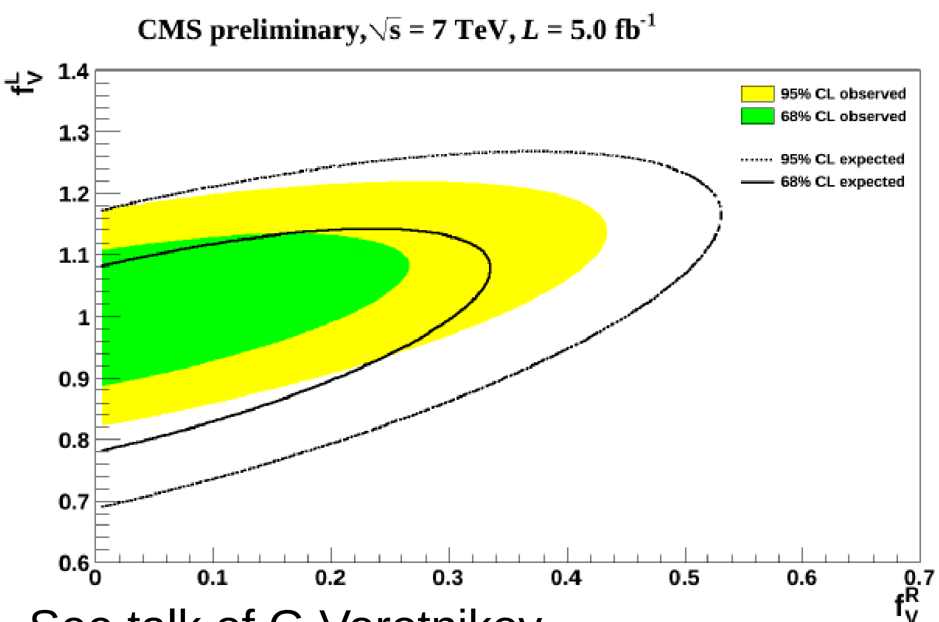
$$|M|^2_{\text{tot}} \sim \left((f_V^L)^2 A_p + (f_V^R)^2 B_p\right)\mathcal{B}(t \to l,\nu,b) \qquad \mathcal{B}(t \to l,\nu,b) = \left((f_V^L)^2 A_d + (f_V^R)^2 B_d\right)/w_{\text{tot}},$$

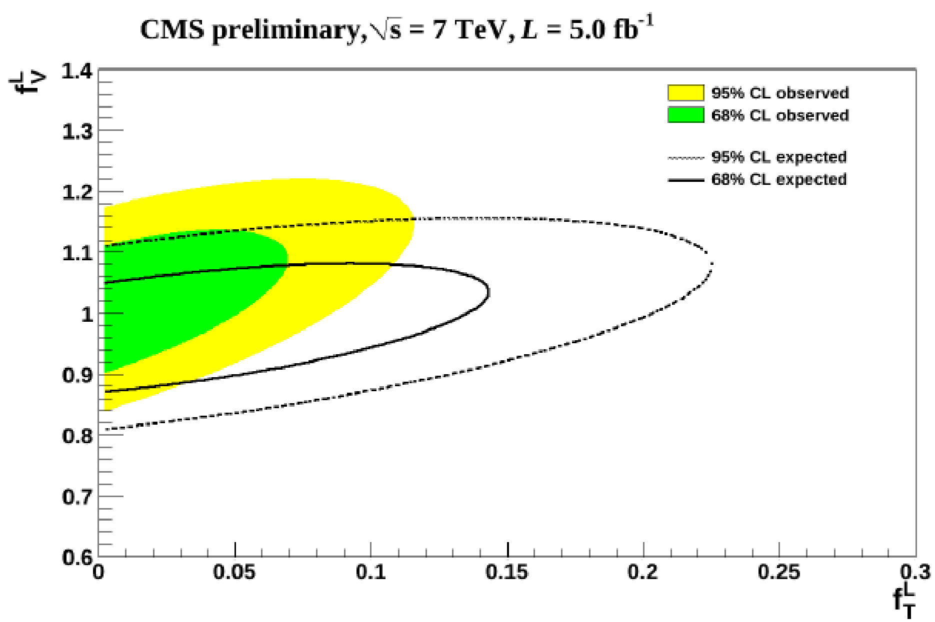
$$\sigma(f_V^L, f_V^R) = m(1000) + n(artificial) + k(0100) \quad m = \left(f_V^L\right)^4 \cdot w_{1000}/w_{\text{tot}},\ n = \left(f_V^L\right)^2\left(f_V^R\right)^2 \cdot w_{\text{art}-0100}/w_{\text{tot}},\ k = \left(f_V^R\right)^4 \cdot w_{0100}/w_{\text{tot}}.$$

$$|M|^2_{\text{tot}} \sim \left((f_V^L)^2 A_p + f_V^L f_T^R \cdot C_p + (f_V^R)^2 G_p\right)\mathcal{B}(t \to l\nu b) = \sum_{i=0}^{4} k_i \cdot P_{4-i} D_i \qquad k_i = (f_V^L)^{4-i}(f_T^R)^i \cdot \frac{w_i^{\text{top}}}{w_{\text{tot}}(f_V^L, f_T^R)}$$

Anomalous Wtb coupling limits

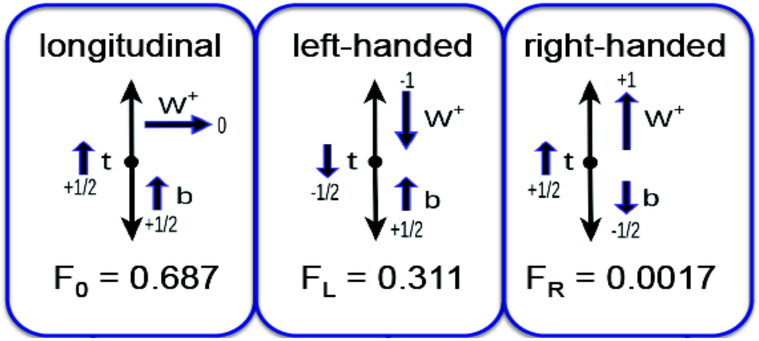


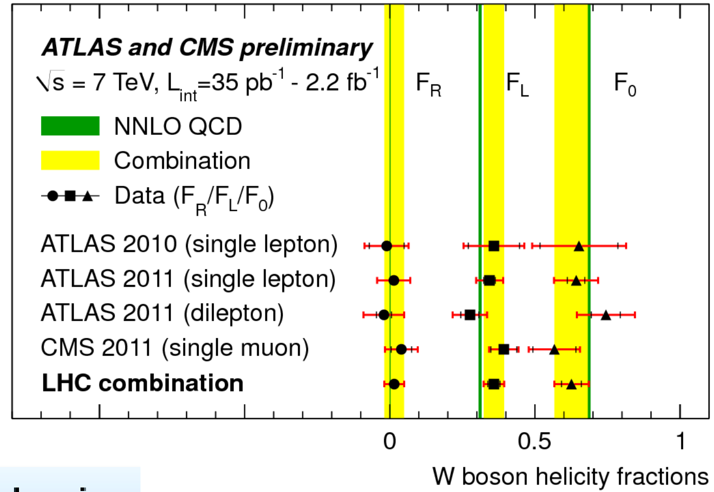




See talk of G.Vorotnikov

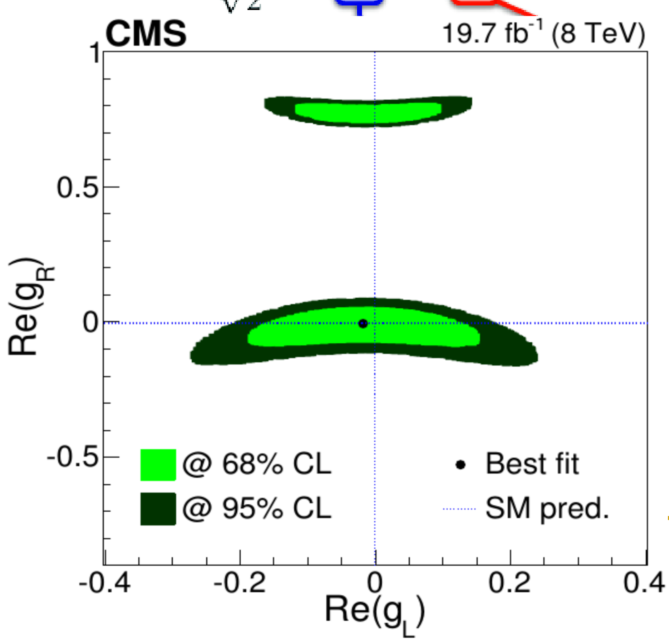
$t\bar{t}$: W helicity and Wtb

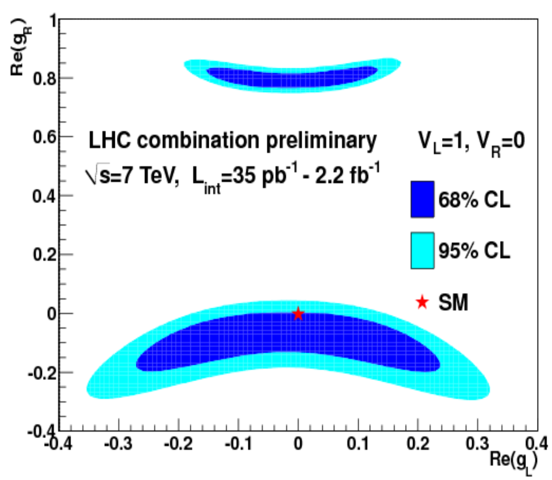


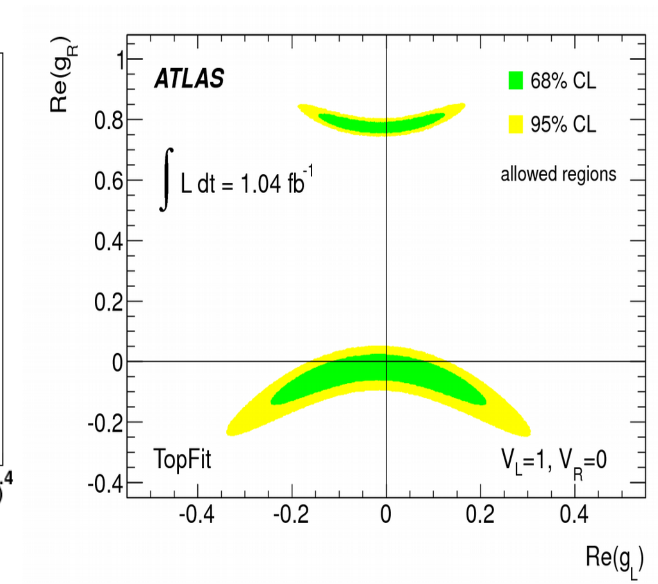


Agreement of helicity fractions with SM ⇨ Constraints on new physics contributions to Wtb vertex

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-} + \mathrm{h.c.}$$

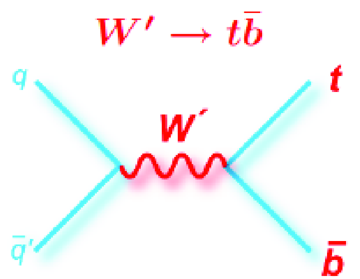


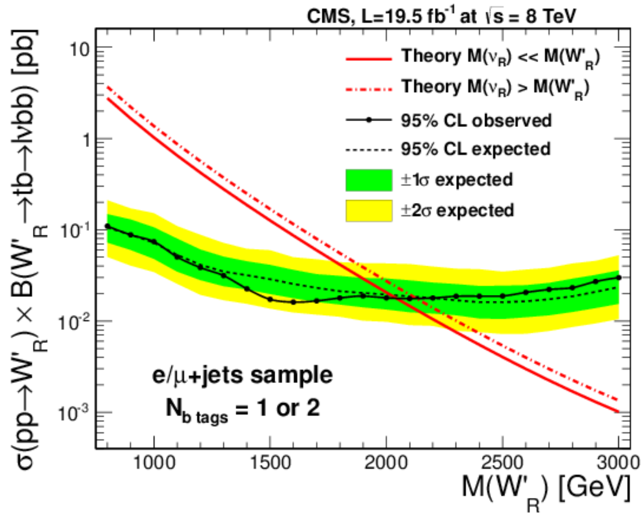


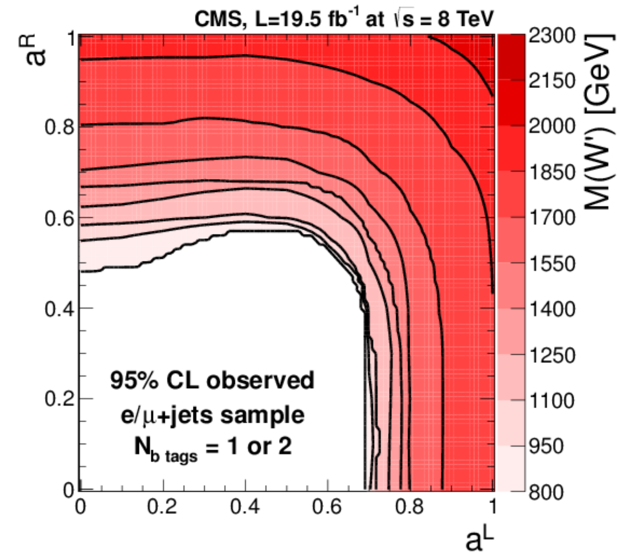


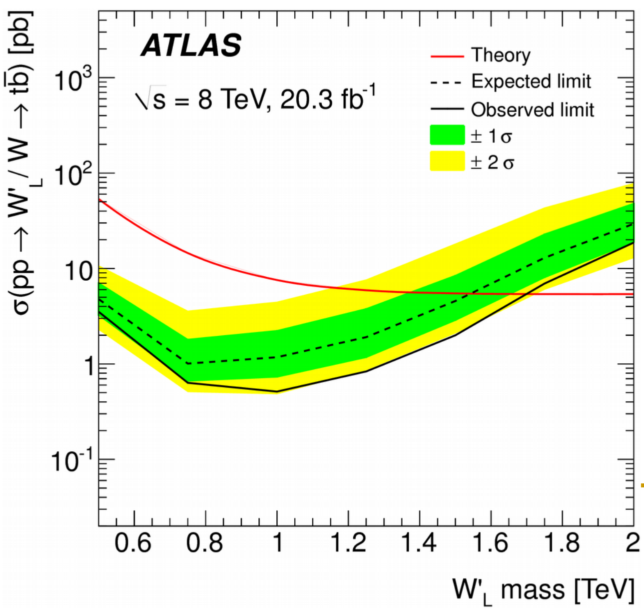
$t(\bar{t})$: Search for W' in single top

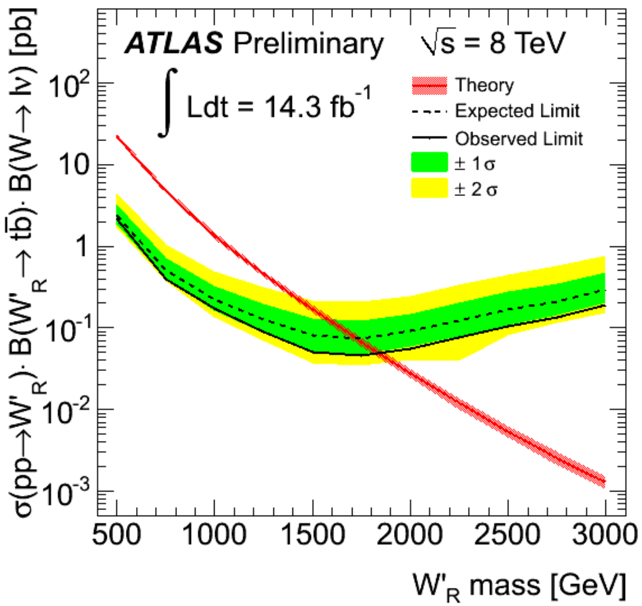
$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \bar{f}_i \gamma_\mu \left[a^R_{f_i f_j}(1+\gamma^5) + a^L_{f_i f_j}(1-\gamma^5) \right] W'^\mu f_j + \text{h.c.}$$

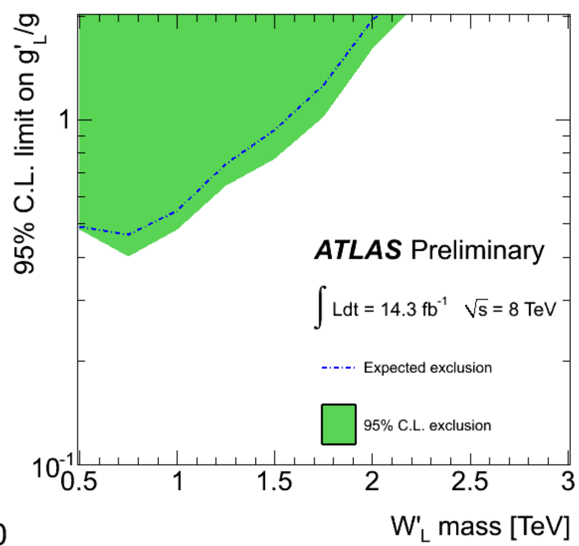






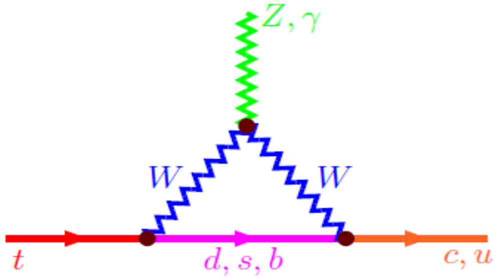






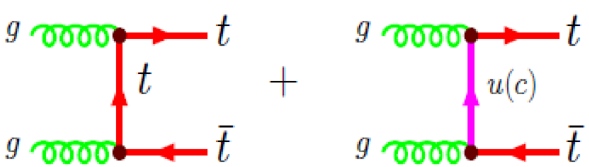
FCNC Search

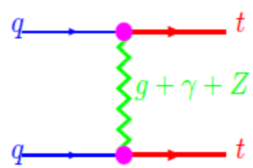
Flavor Changing Neutral Currents (FCNC) $t \to qg, \quad t \to q\gamma, \quad t \to qZ$

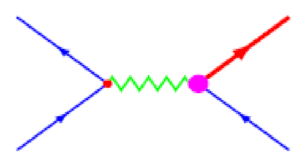


	SM	two-Higgs	SUSY
$B(t \to cg)$	$5 \cdot 10^{-11}$	10^{-6}	10^{-3}
$B(t \to c\gamma)$	$5 \cdot 10^{-13}$	10^{-6}	10^{-5}
$B(t \to cZ)$	$\sim 10^{-13}$	10^{-9}	10^{-4}

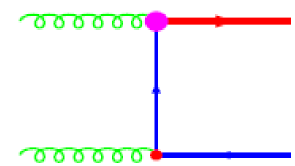
FCNC processes lead to additional contribution to $t\bar{t}$ and $t(\bar{t})$ or exotic final states



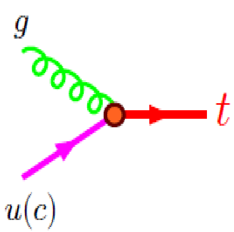


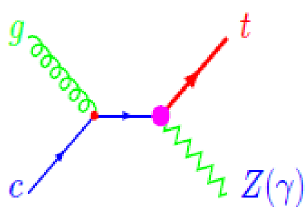


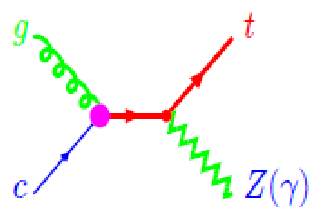
$q\bar{q} \to t\bar{c}$

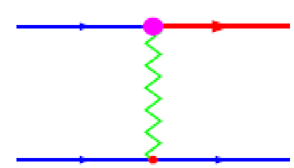


$gg \to t\bar{c}$

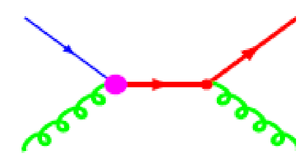








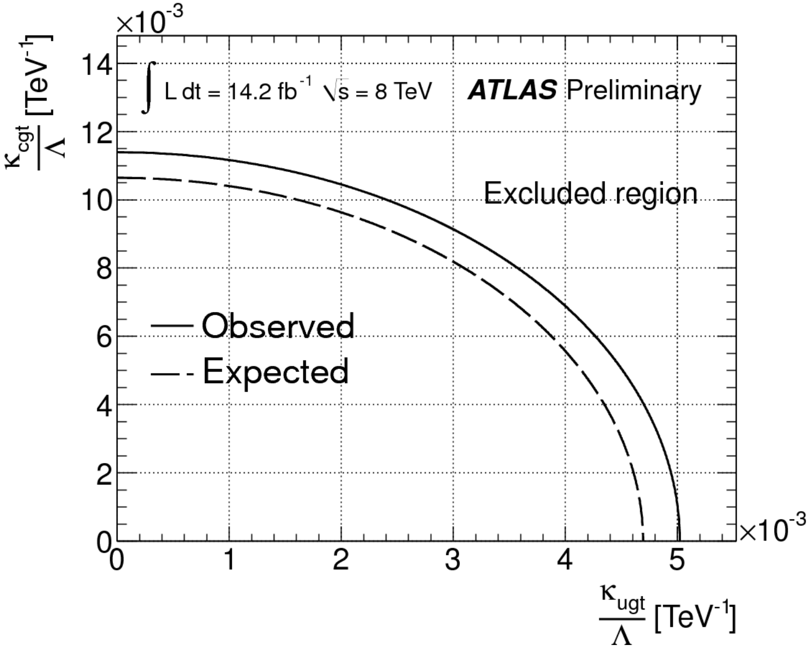
$c\bar{q} \to tq$

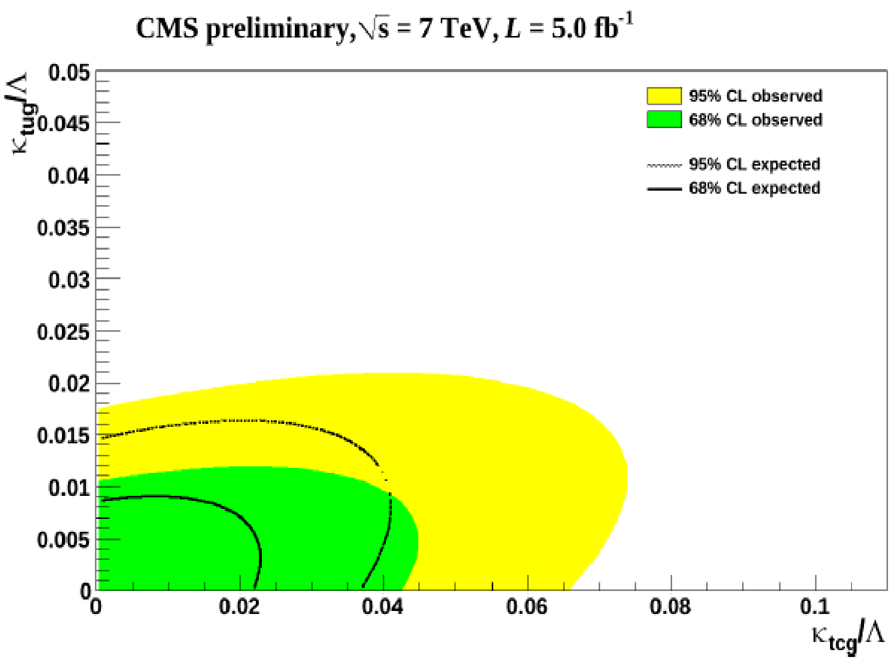


$cg \to tg$

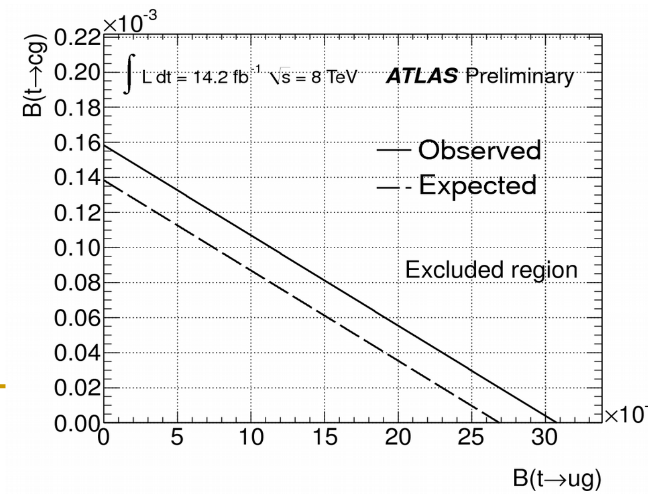
$t(\bar{t})$: FCNC Search in Single Top

$$g_s \frac{\kappa_{tug}}{\Lambda} \bar{u}\, \sigma^{\mu\nu} \frac{\lambda^a}{2} t\, G^a_{\mu\nu} + g_s \frac{\kappa_{tcg}}{\Lambda} \bar{c}\, \sigma^{\mu\nu} \frac{\lambda^a}{2} t\, G^a_{\mu\nu} + h.c$$





Or the same in branching limits:

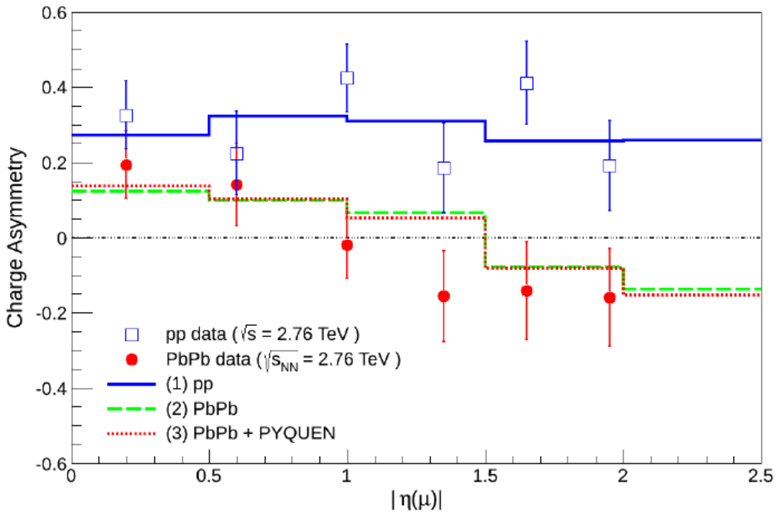


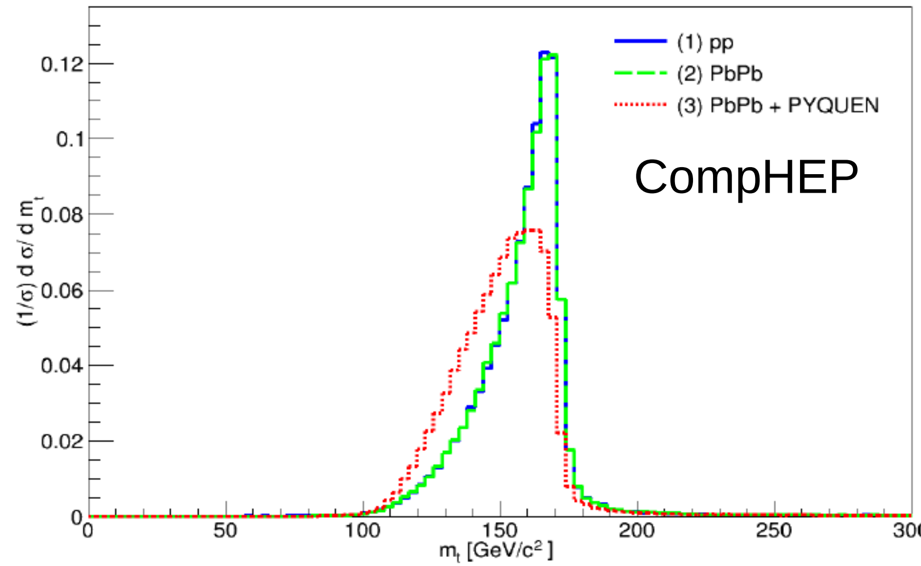
$$Br(t \to u+g) < 3.55 \times 10^{-4}\ (1.58 \times 10^{-4}),$$
$$Br(t \to c+g) < 3.44 \times 10^{-3}\ (1.05 \times 10^{-3})$$

See talk of I.Myagkov

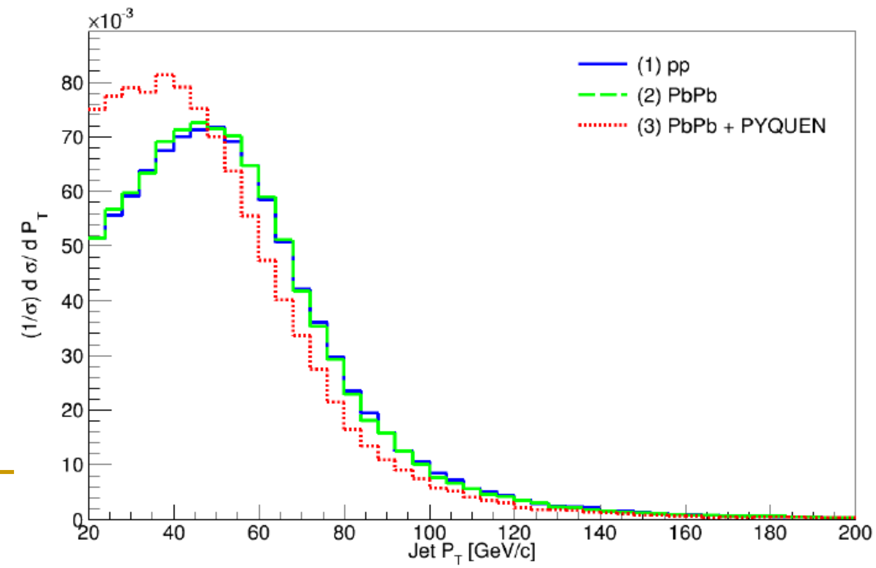
Single Top in Heavy Ion Collisions

Test of MC simulation





See talk of A.Baskakov
arXiv:1502.04875



Conclusion

- LHC becomes the main place for top physics, many analysis are published and most of the measurements supersede Tevatron measurements, but this is not the case for few of them (e.g. Single top s-channel process)
- Data demonstrates a good agreement with SM in top sector. There are no any significant evidence of deviation from SM in top physics.
- Details are available in the dedicated ATLAS, CMS, D0 and CDF publications.