Top-quark charge asymmetry and polarization in $t\bar{t}W$ production at the LHC

Marco Zaro, LPTHE - UPMC Paris VI

in collabortion with
F. Maltoni, M. Mangano, I.Tsinikos, arXiv:1406.3262

X Rencontres du Vietnam

Physics at the LHC and beyond

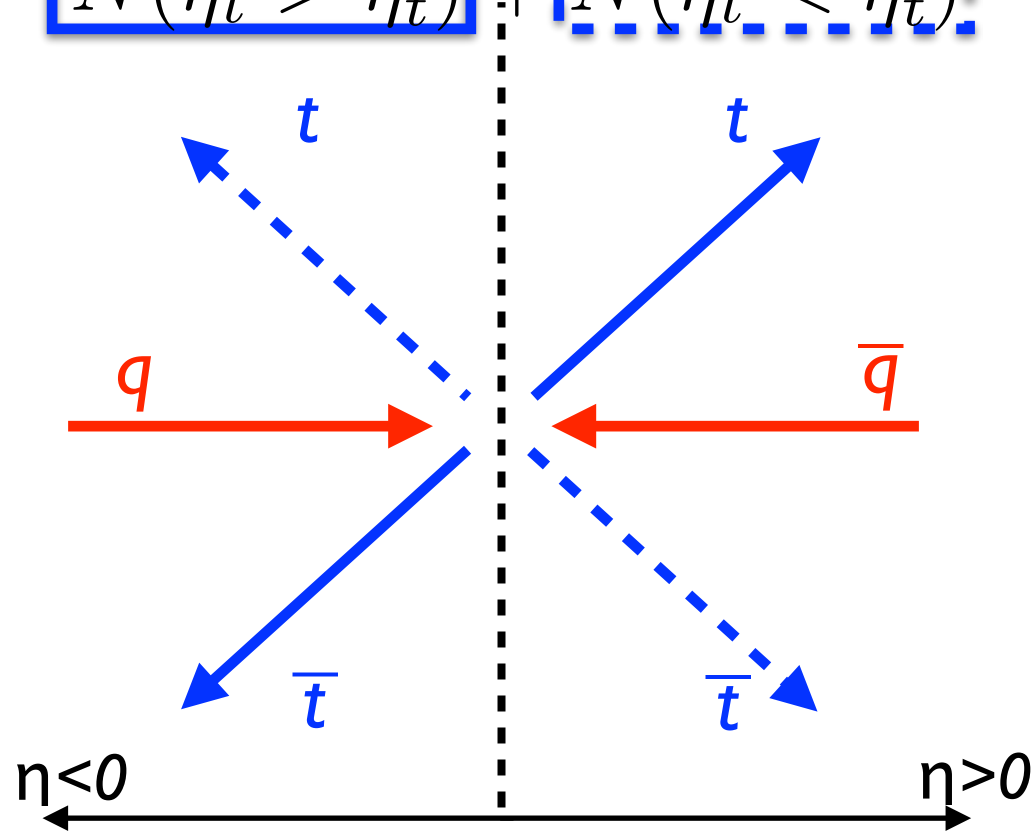
August 11, 2014

LHCPhenoNet

The top-quark asymmetry

The top-quark asymmetry at hadron colliders

- Definition: $A_t^{FB} = \frac{N(\eta_t > \eta_{\bar{t}}) - N(\eta_t < \eta_{\bar{t}})}{N(\eta_t > \eta_{\bar{t}}) + N(\eta_t < \eta_{\bar{t}})}$



- gg→$t\bar{t}$ does not give any asymmetry
- NLO QCD predicts $A_t^{FB}>0$

Top quark asymmetry at the Tevatron

- QCD asymmetry can be tested at hadron colliders
- Use $p\bar{p}$ colliders (Tevatron):
  - p mostly contains quarks, $\bar{p}$ mostly anti-quarks
  - gg (symmetric) contribution is small (10% of the x-sect)
  - SM prediction: A_t= 8.8±0.6 %
  - Measured values (beginning 2014):
    - CDF: A_t=16.4±4.7 %
    - D0: A_t=19.6±6.5 %
  - 2σ tension
    - A manna for model builders!

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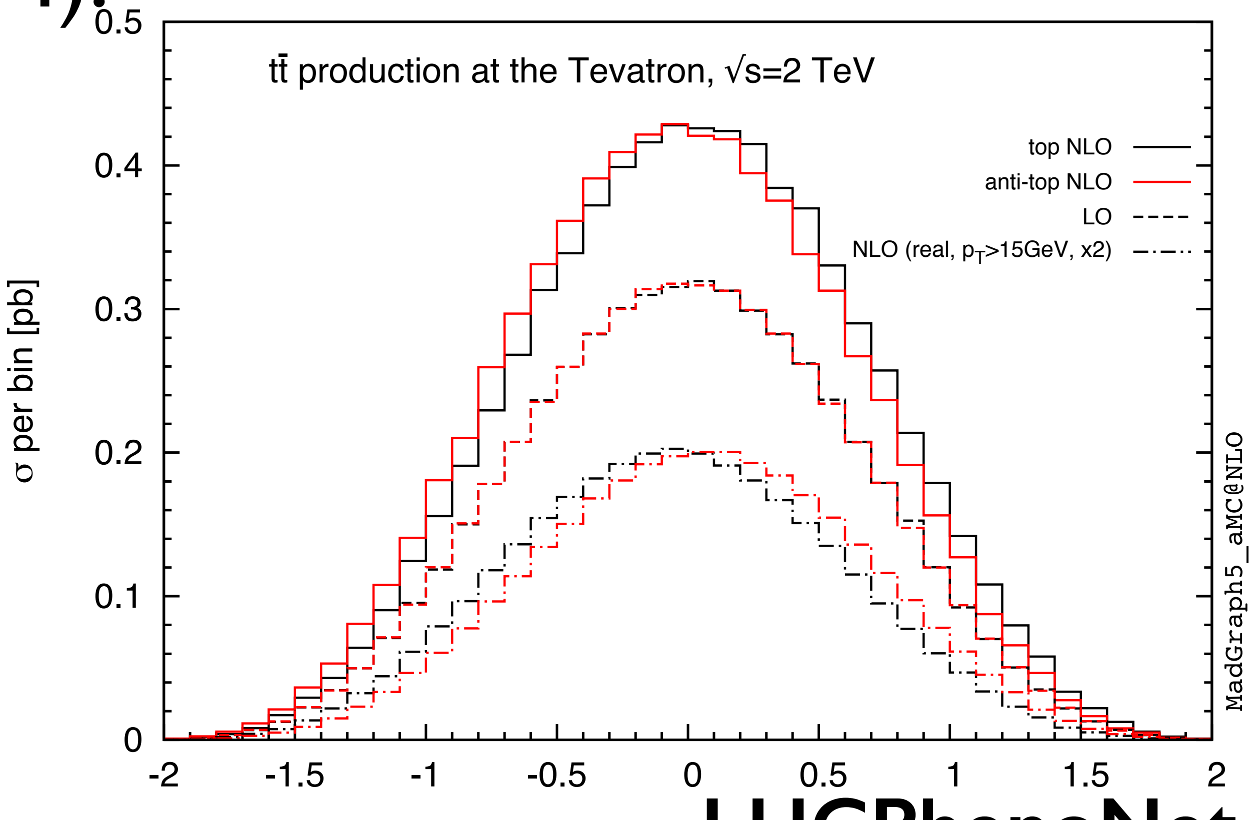

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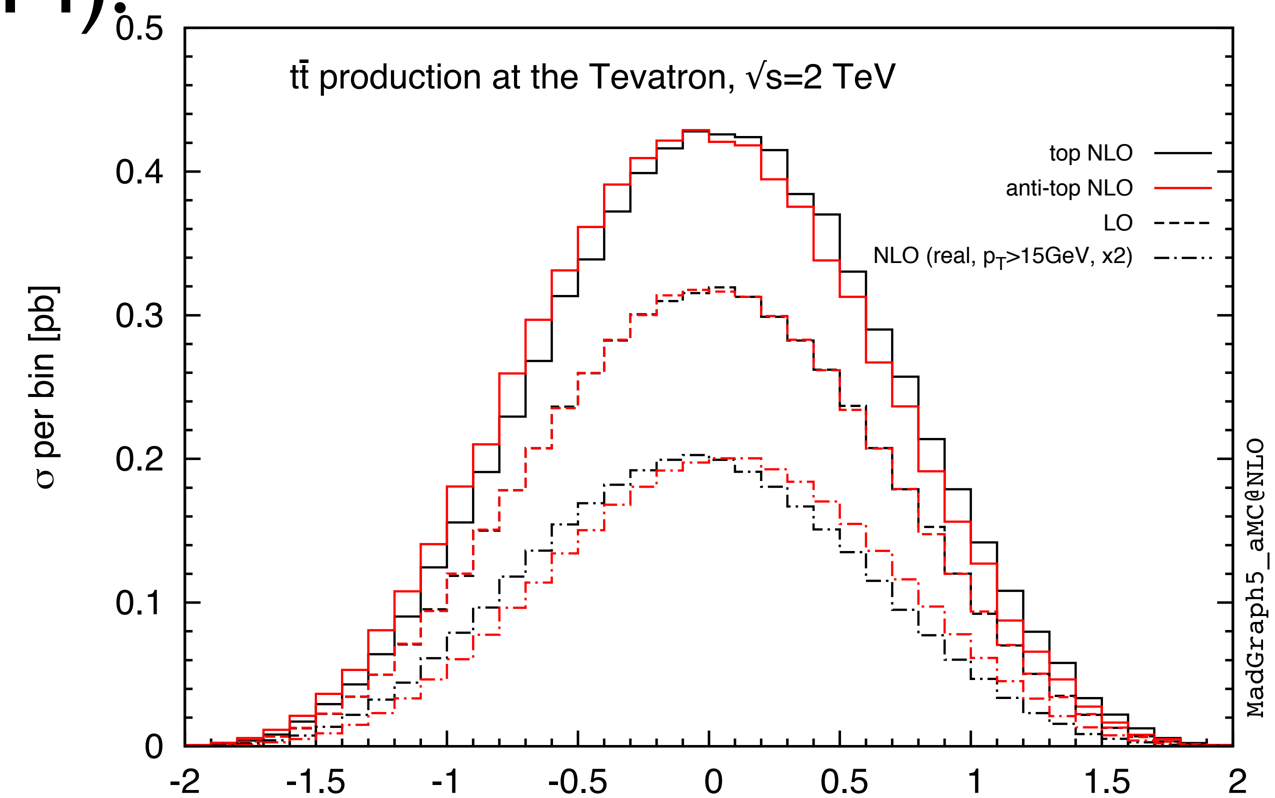

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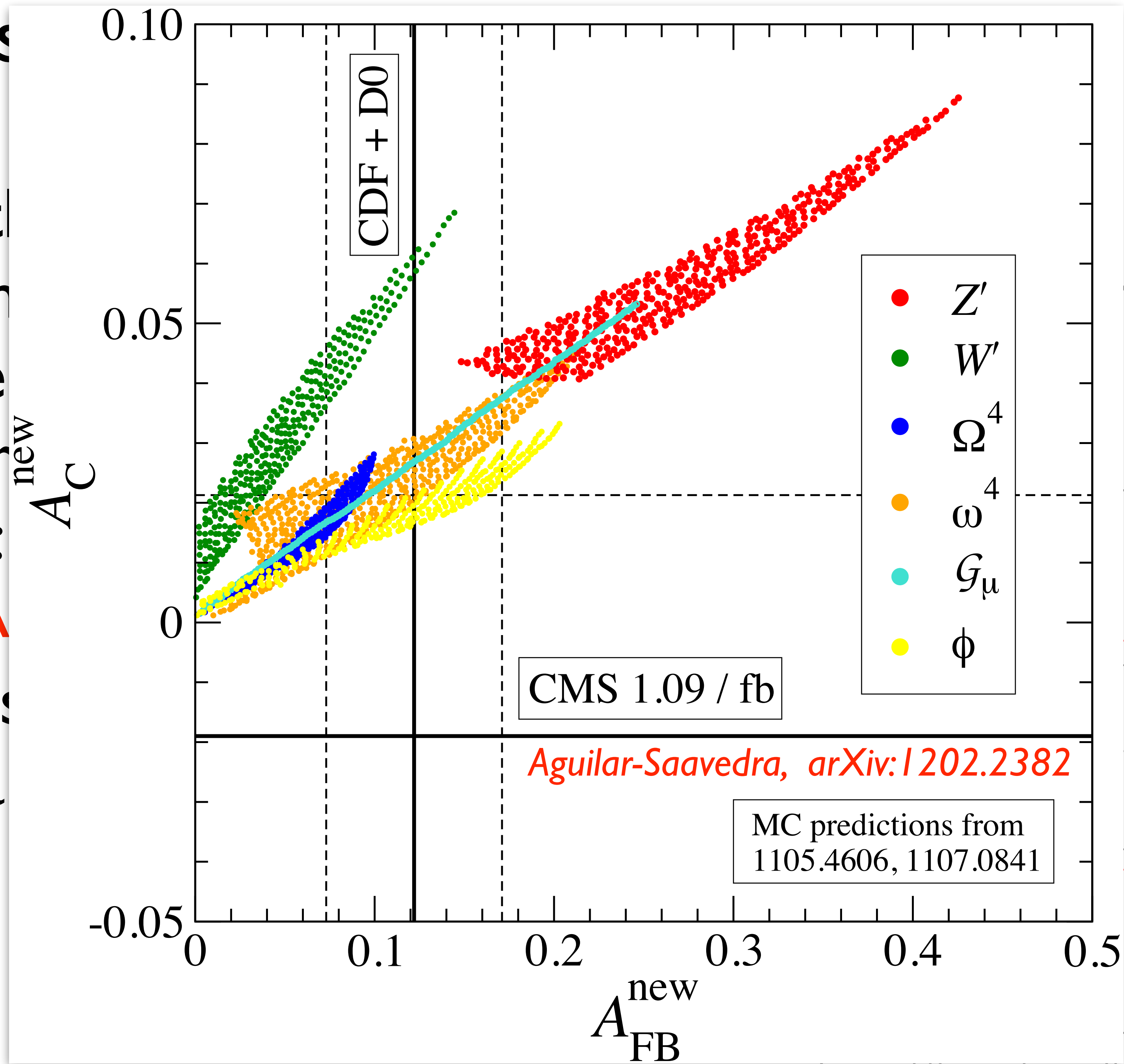

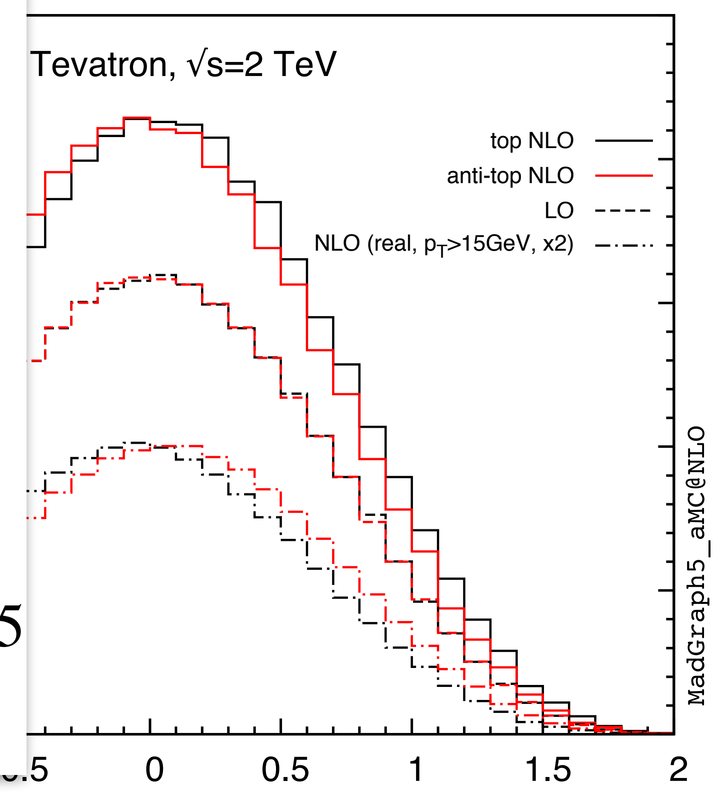

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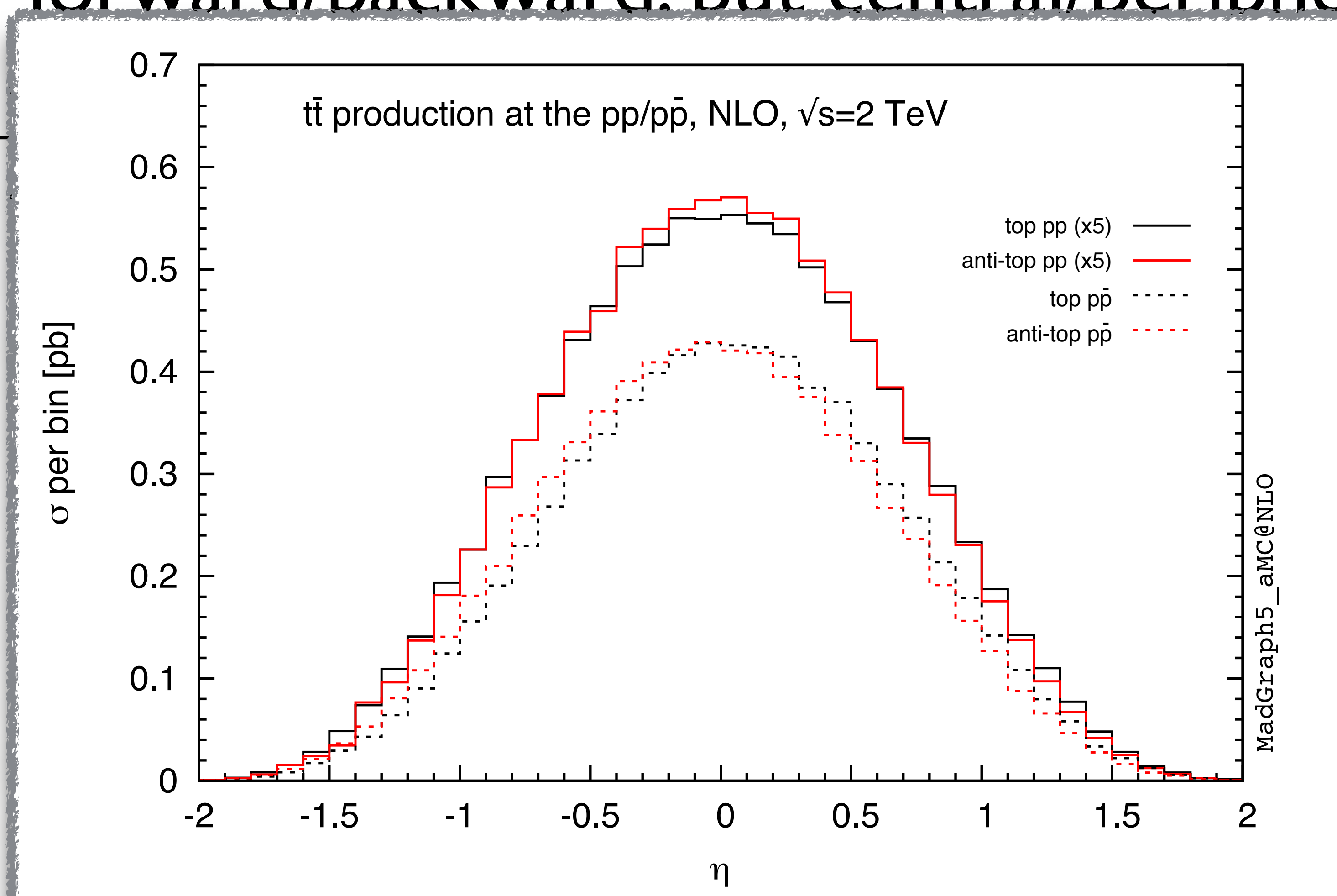

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  - Asymmetry is a very small effect (<1% at 8TeV)

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  - Asymmetry is a very small effect (<1% at 8TeV)
- Preliminary measurements by ATLAS and CMS (at 7 and 8 TeV) show no strong deviation from the SM prediction

CMS-PAS-TOP-12-010,
ATLAS-CONF-2012-057,
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  - Asymme…
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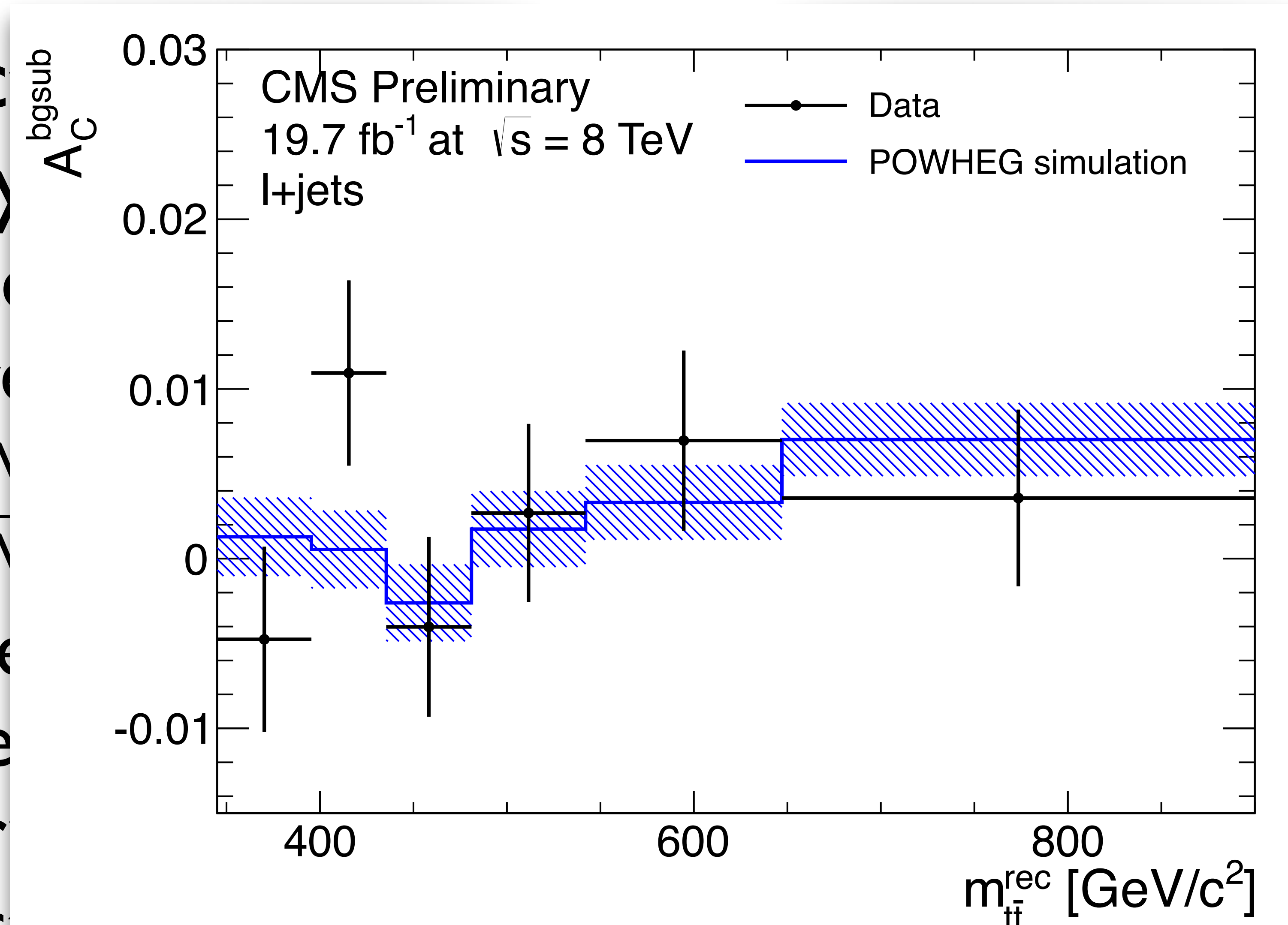

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Enhancing the top asymmetry at the LHC

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- What makes the top asymmetry small at the LHC is the large gluon luminosity
  - How to reduce/kill gg?

Look for $t\bar{t}$ production in association with "something" that prefers coupling to quarks

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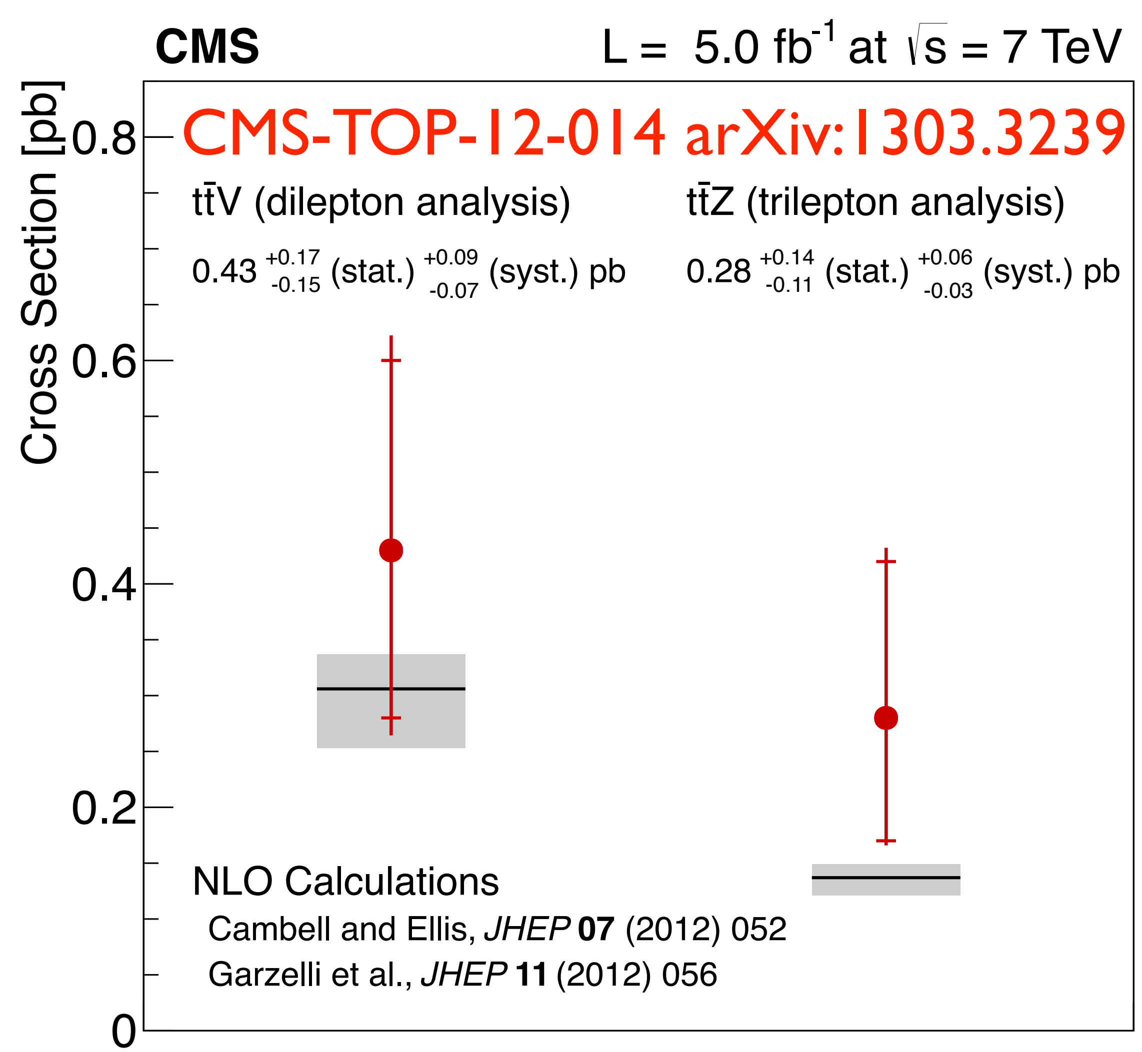
$t\bar{t}V$ at the LHC

- Cross-section measurements of $t\bar{t}V$ have been published by CMS for 7TeV
- More data expected to come from the 8TeV and the next 13TeV run



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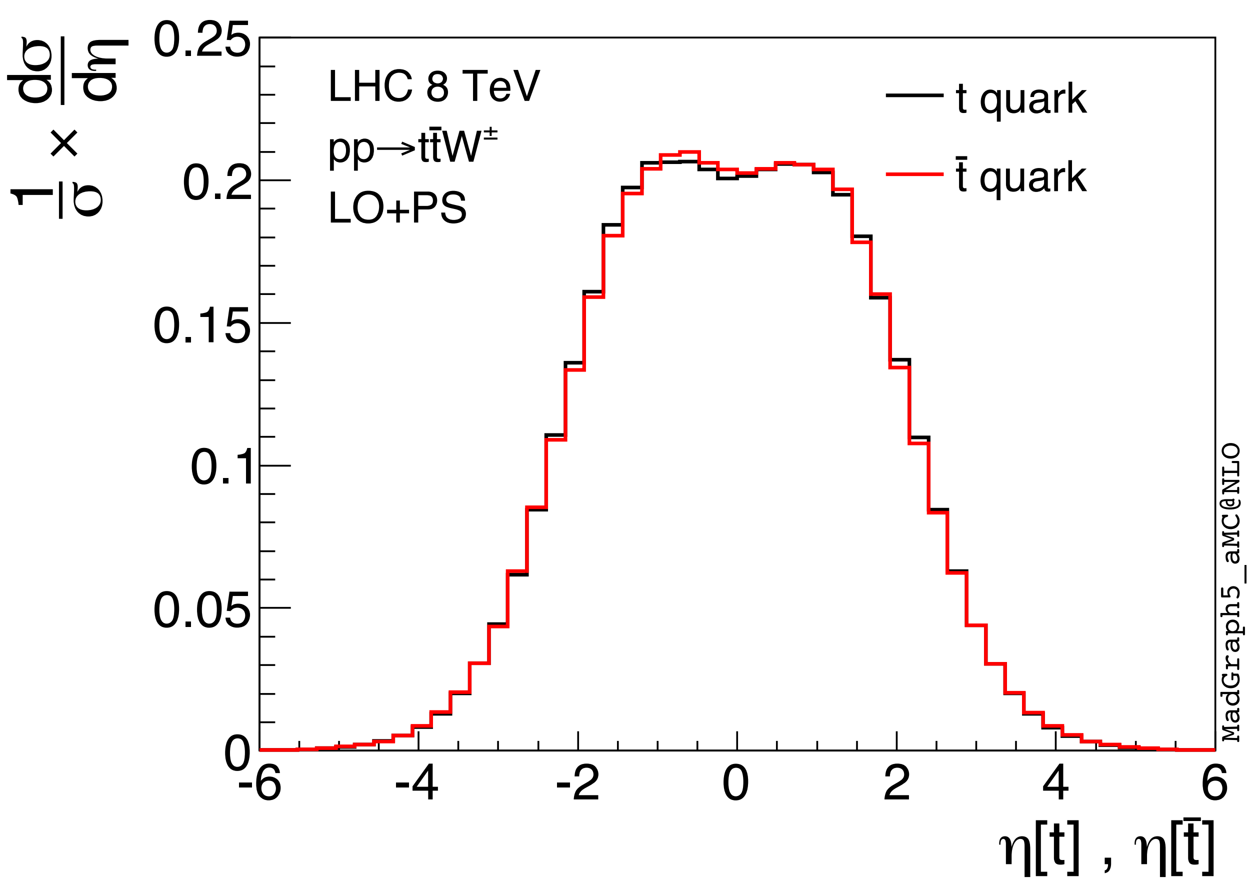
- The W boson kills the symmetric gg contribution, leaving only $q\bar{q}$
- The resulting asymmetry is much larger than in the $t\bar{t}$ inclusive case

8TeV

$t\bar{t}$	LO	LO+PS	NLO	NLO+PS
σ(pb)	$128.8^{+35\%+2\%}_{-24\%-3\%}$		$198^{+15\%+2\%}_{-14\%-3\%}$	
A_C^t (%)	0.01 ± 0.04	0.07 ± 0.03	$0.61^{+0.1}_{-0.08}$	$0.72^{+0.14}_{-0.09}$



	Order	$t\bar{t}W^{\pm}$	$t\bar{t}W^{+}$	$t\bar{t}W^{-}$
σ(fb)	NLO	$210^{+11\%}_{-11\%}$	$146^{+11\%}_{-11\%}$	$63.6^{+11\%}_{-11\%}$
A_C^t (%)	LO	0.01 ± 0.05	-0.02 ± 0.05	0.00 ± 0.05
	LO+PS	0.02 ± 0.03	0.05 ± 0.03	0.05 ± 0.03
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NLO(+PS) numbers computed with MadGraph5_aMC@NLO

J. Alwall, R. Frederix, S. Frixione, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, V. Hirschi, MZ arXiv:1405.0301

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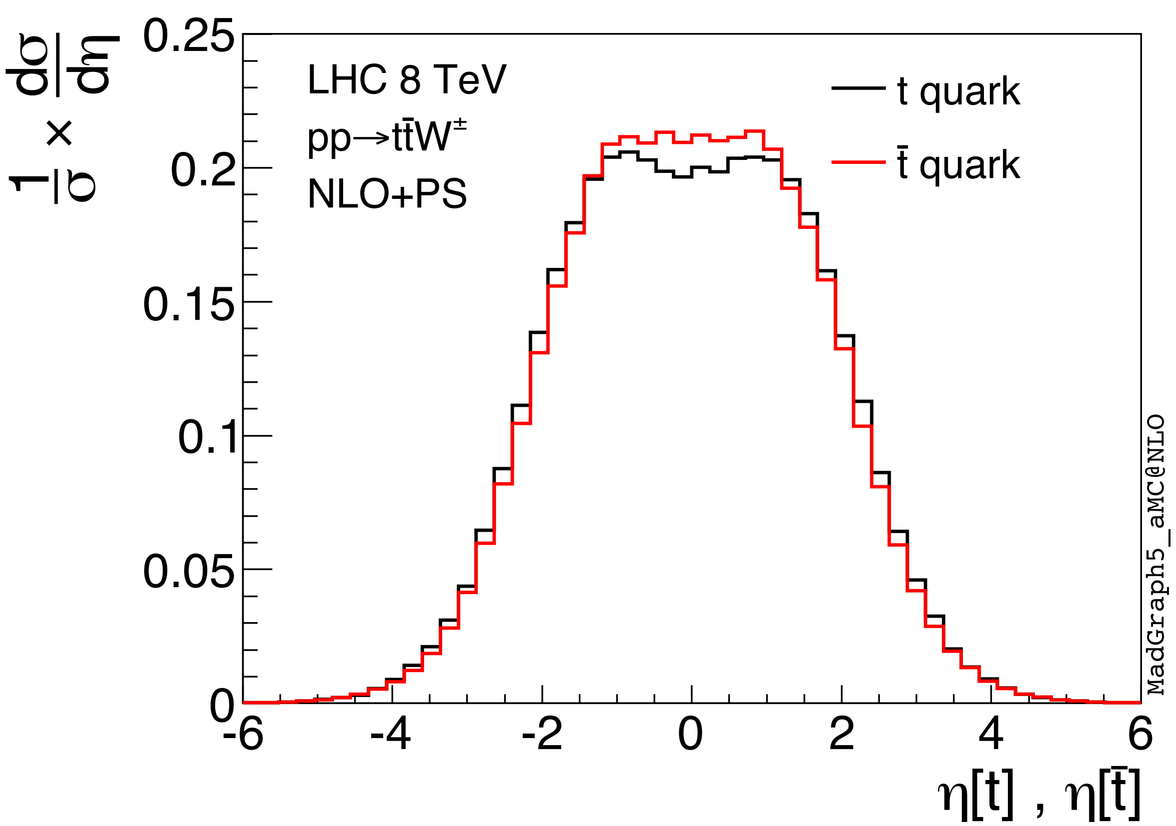

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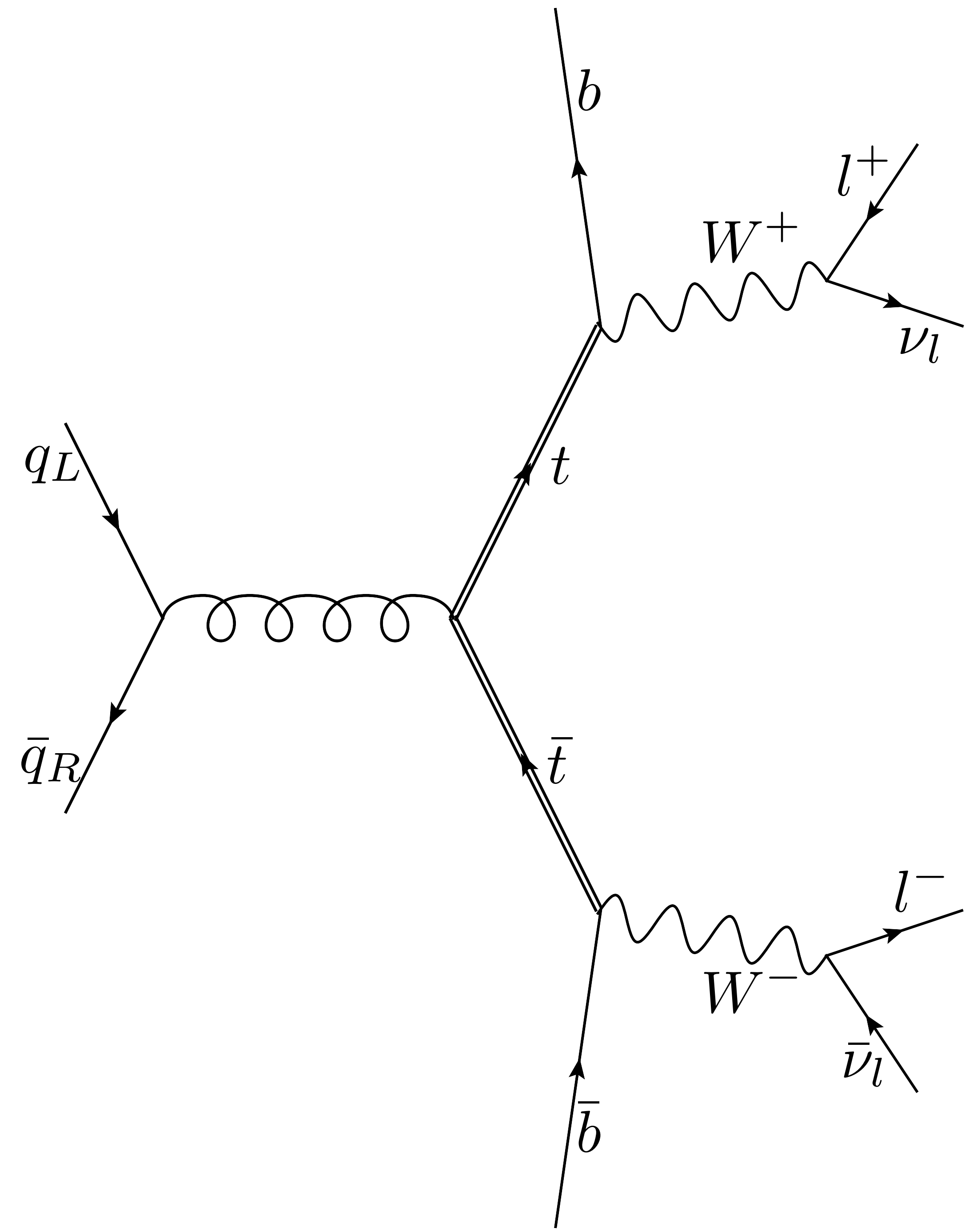
Polarisation effects

- Initial quarks are polarised by the W boson
  - $q\bar{q} \to t\bar{t}W$ is totally analogous to $q_L\bar{q}_R \to t\bar{t}$
- The produced tops are highly polarised, leading to asymmetric decay products already at LO
  - Leptons from tops are strongly correlated with top polarisation
  - Need to include spin-correlations to see this effect
  - Decay products asymmetries are much larger than the top one



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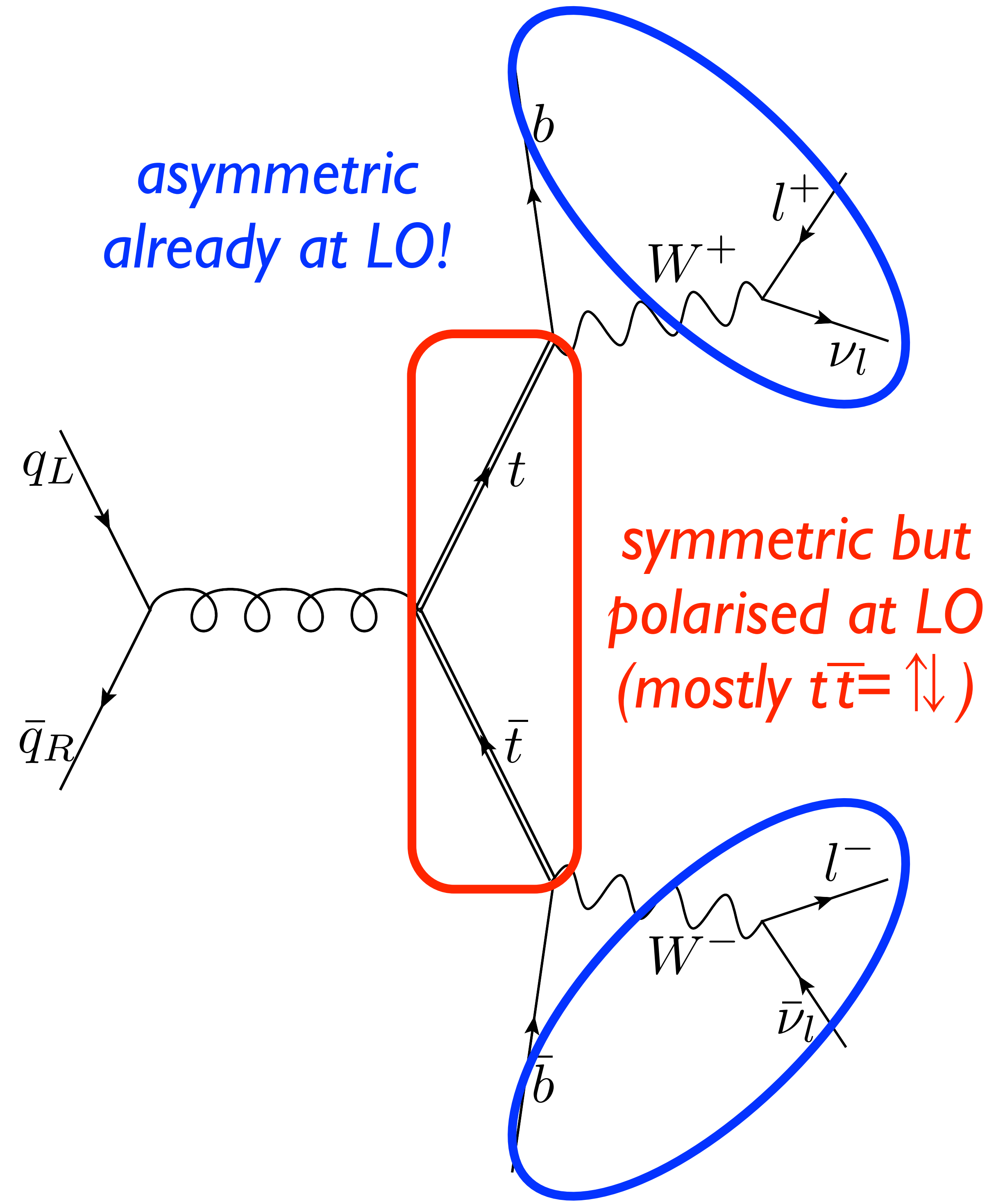
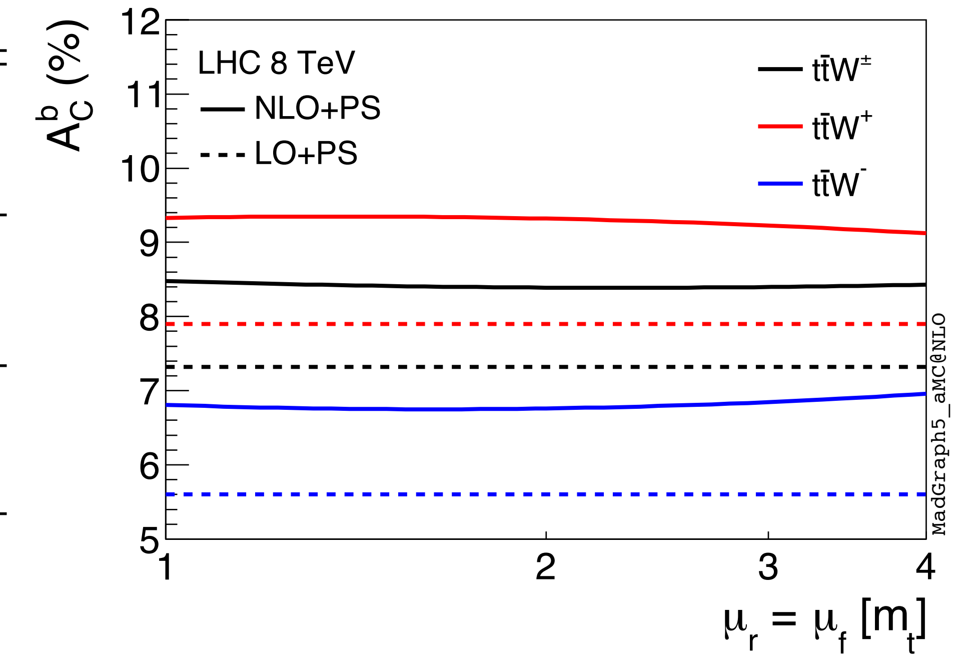
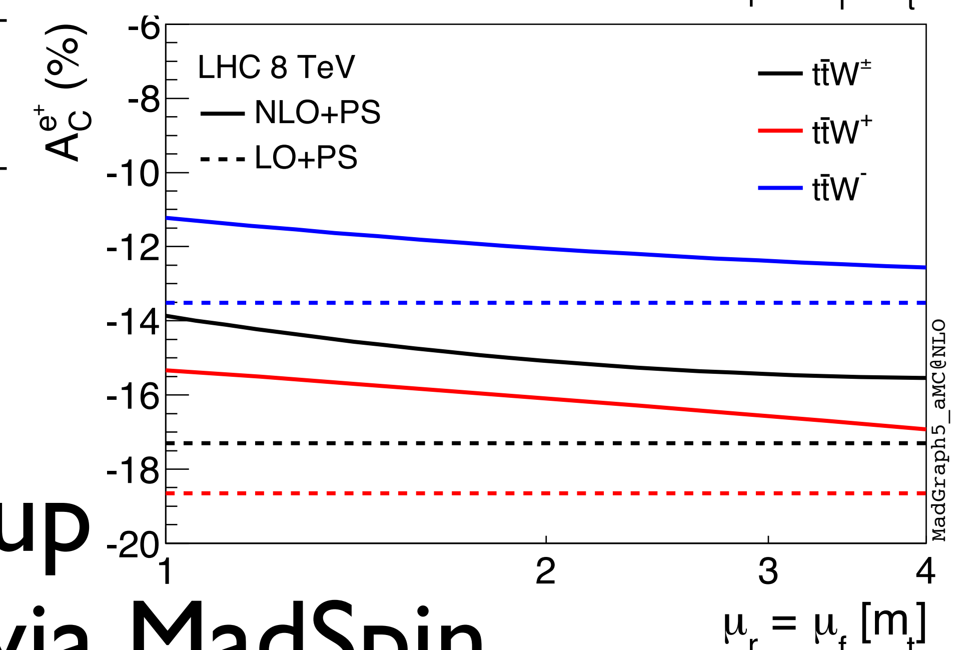


Polarisation effects: results

	Order	$t\bar{t}W^{\pm}$	$t\bar{t}W^{+}$	$t\bar{t}W^{-}$
$^{*}A_C^b$ (%)	LO+PS	$7.32^{+0.08}_{-0.28}$	$7.90^{+0.14}_{-0.16}$	$5.60^{+0.14}_{-0.08}$
	NLO+PS	$8.39^{+0.09}_{+0.04}$	$9.32^{+0.01}_{-0.20}$	$6.76^{+0.05}_{-0.11}$
A_C^e (%)	LO+PS	$-17.30^{-0.07}_{+0.27}$	$-18.65^{-0.18}_{+0.07}$	$-13.51^{-0.02}_{+0.05}$
	NLO+PS	$-15.1^{-1.2}_{+0.4}$	$-16.1^{-0.8}_{+0.8}$	$-12.1^{-0.9}_{+0.5}$

**b-jets, k_T-algo, R=0.5, p_T>20 GeV, |y|<4.5, MC-Truth*





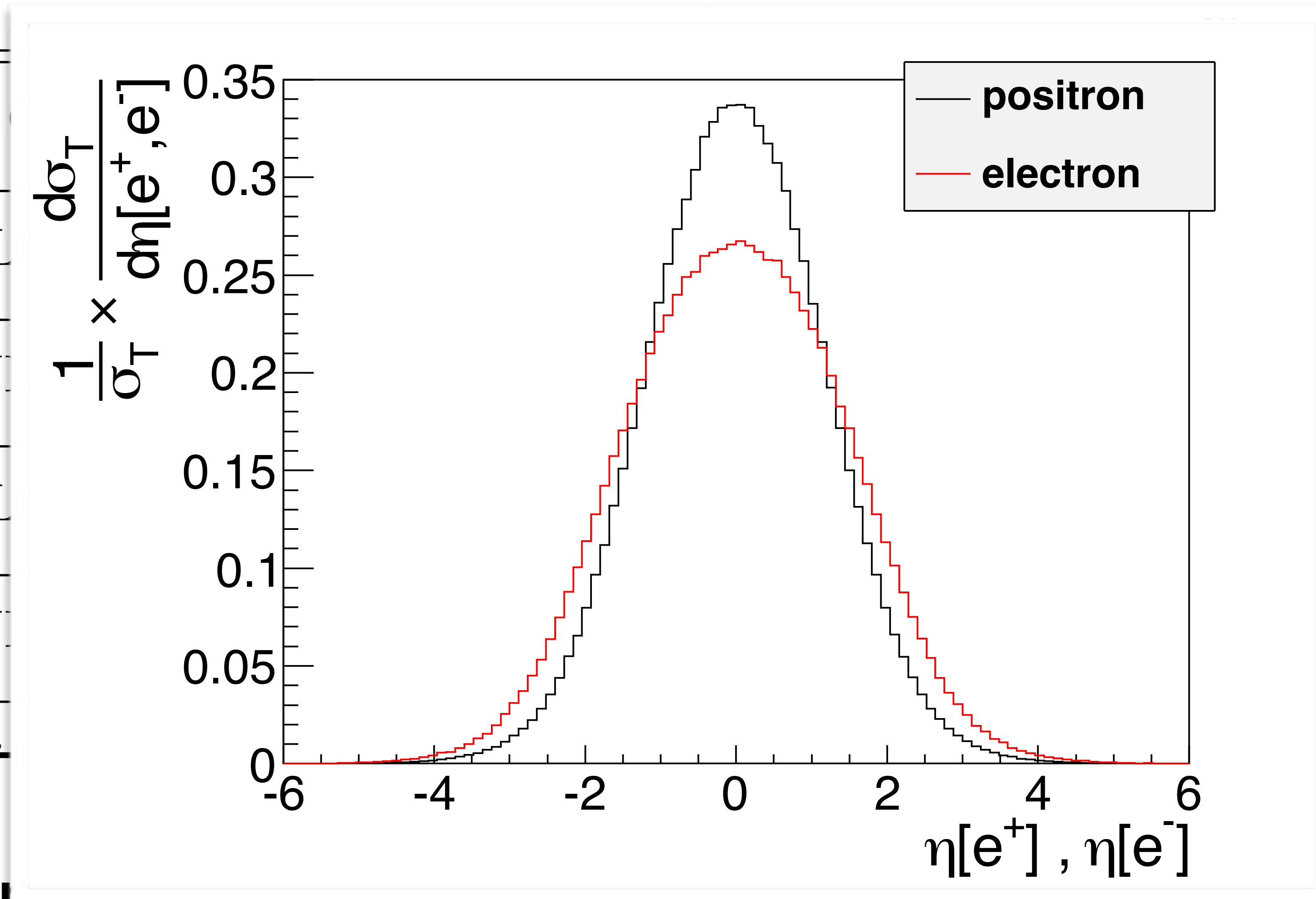
- Asymmetries are large!
- NLO corrections shift all numbers up
- Spin correlations included at NLO via MadSpin

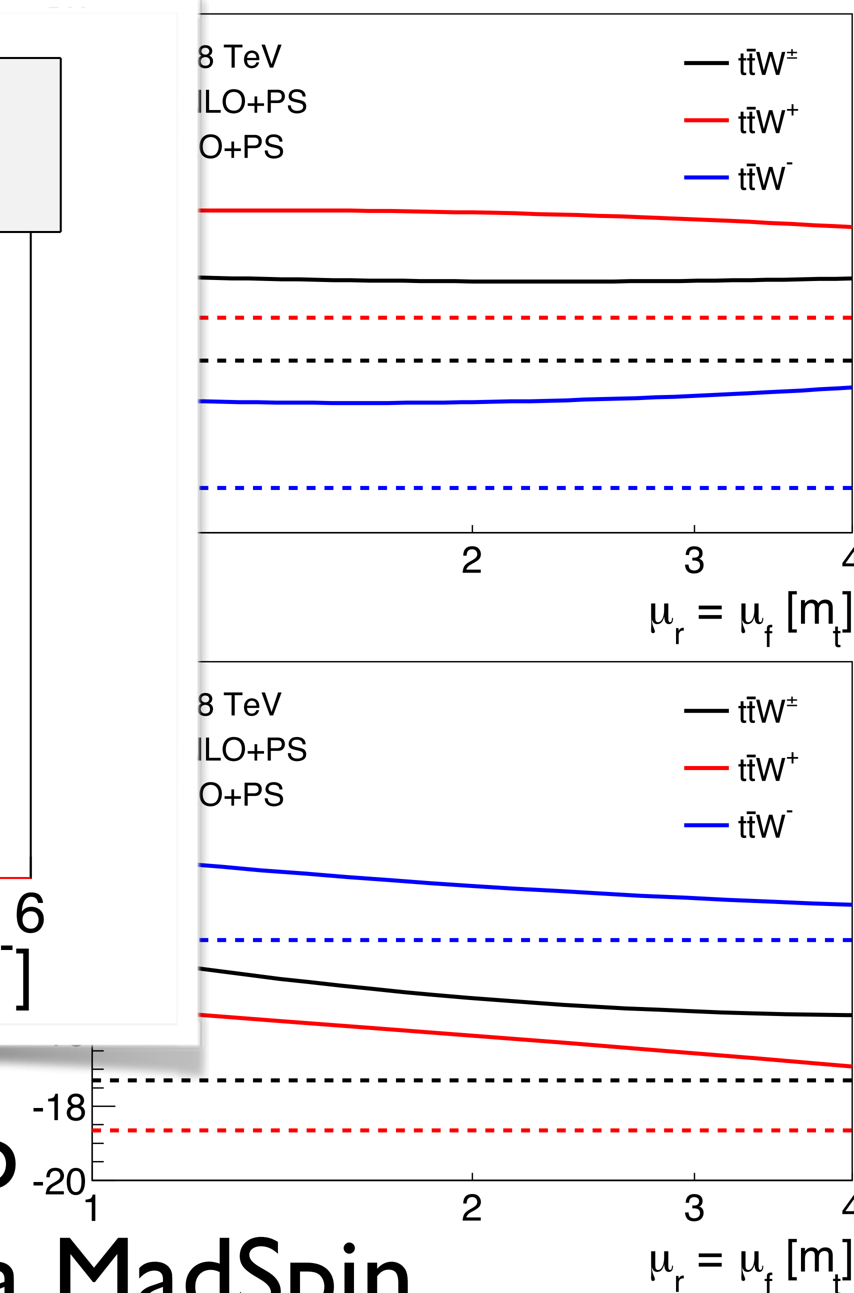
Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460

Polarisation effects: results

*A_C^b (%)	L	
	N	
A_C^e (%)	L	
	N	

*b-jets, k_T-





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Plans for the future…

		8 TeV	13 TeV	14 TeV	33 TeV	100 TeV
$t\bar{t}$	σ(pb)	$198^{+15\%}_{-14\%}$	$661^{+15\%}_{-13\%}$	$786^{+14\%}_{-13\%}$	$4630^{+12\%}_{-11\%}$	$30700^{+13\%}_{-13\%}$
	$A_C^t(\%)$	$0.72^{+0.14}_{-0.09}$	$0.45^{+0.09}_{-0.06}$	$0.43^{+0.08}_{-0.05}$	$0.26^{+0.04}_{-0.03}$	$0.12^{+0.03}_{-0.02}$
$t\bar{t}W^{\pm}$	σ(fb)	$210^{+11\%}_{-11\%}$	$587^{+13\%}_{-12\%}$	$678^{+14\%}_{-12\%}$	$3220^{+17\%}_{-13\%}$	$19000^{+20\%}_{-17\%}$
	$A_C^t(\%)$	$2.37^{+0.56}_{-0.38}$	$2.24^{+0.43}_{-0.32}$	$2.23^{+0.43}_{-0.33}$	$1.95^{+0.28}_{-0.23}$	$1.85^{+0.21}_{-0.17}$
	$A_C^b(\%)$	$8.50^{+0.15}_{-0.10}$	$7.54^{+0.19}_{-0.17}$	$7.50^{+0.24}_{-0.22}$	$5.37^{+0.22}_{-0.30}$	$3.36^{+0.15}_{-0.19}$
	$A_C^e(\%)$	$-14.83^{-0.65}_{+0.95}$	$-13.16^{-0.81}_{+1.12}$	$-12.84^{-0.81}_{+1.11}$	$-9.21^{-0.87}_{+1.05}$	$-4.94^{-0.63}_{+0.72}$

- Measuring asymmetry in $t\bar{t}$ production at a FC will be even more challenging
- $t\bar{t}W$ remains competitive

A look BSM

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- Several BSM solutions have been proposed to cure the discrepancies observed at the Tevatron
- What is their effect at the LHC, in particular for $t\bar{t}W$?

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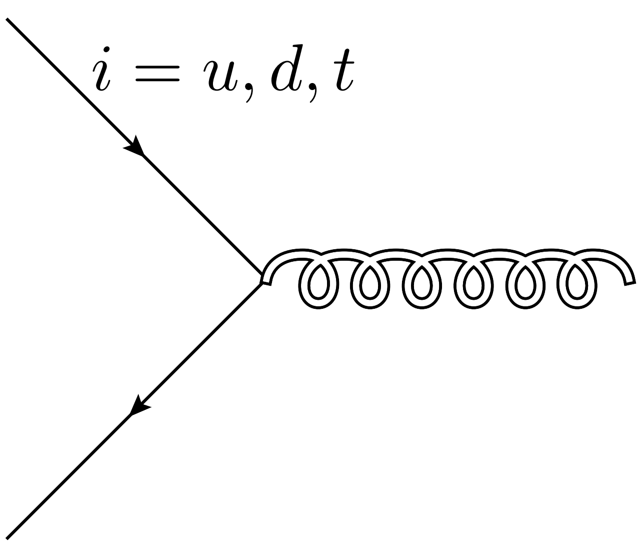
- Choose one simple case: the axigluon model *Frampton, Shu, Wang arXiv:0911.2955*
  - Extra color octet G which couples differently to quarks of different chiralities and to u/d and heavy quarks



$$= \quad \lambda^a \left(\frac{1-\gamma_5}{2} g_L^i + \frac{1+\gamma_5}{2} g_R^i \right) \gamma^\mu$$

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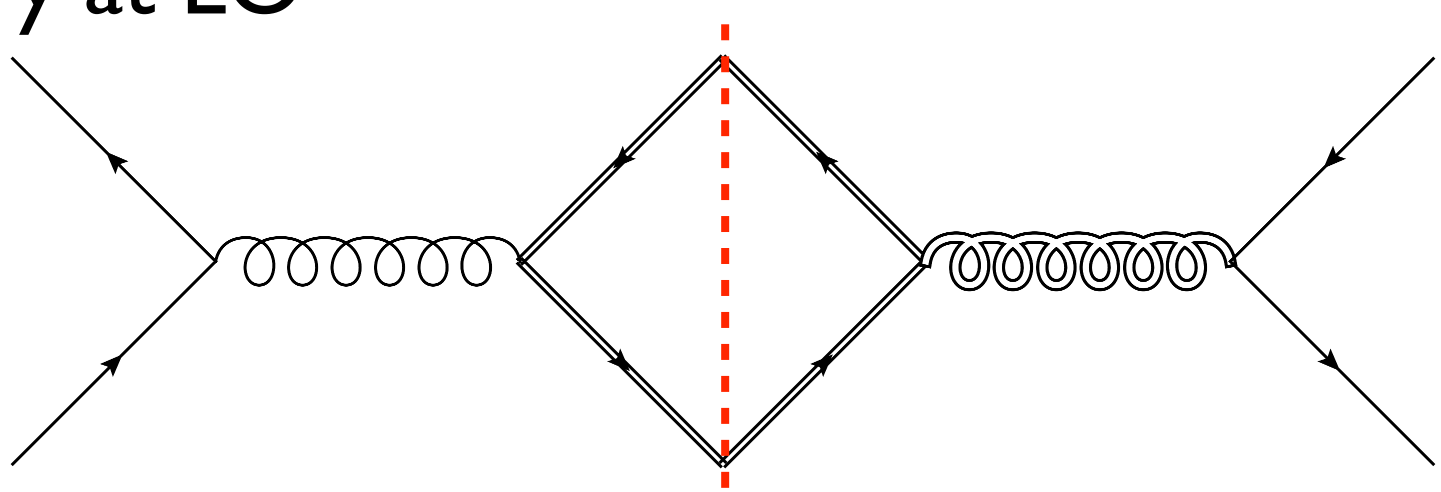
  - Extra color octet G which couples differently to quarks of different chiralities and to u/d and heavy quarks
  - The interference between the gluon and axigluon gives an asymmetry at LO

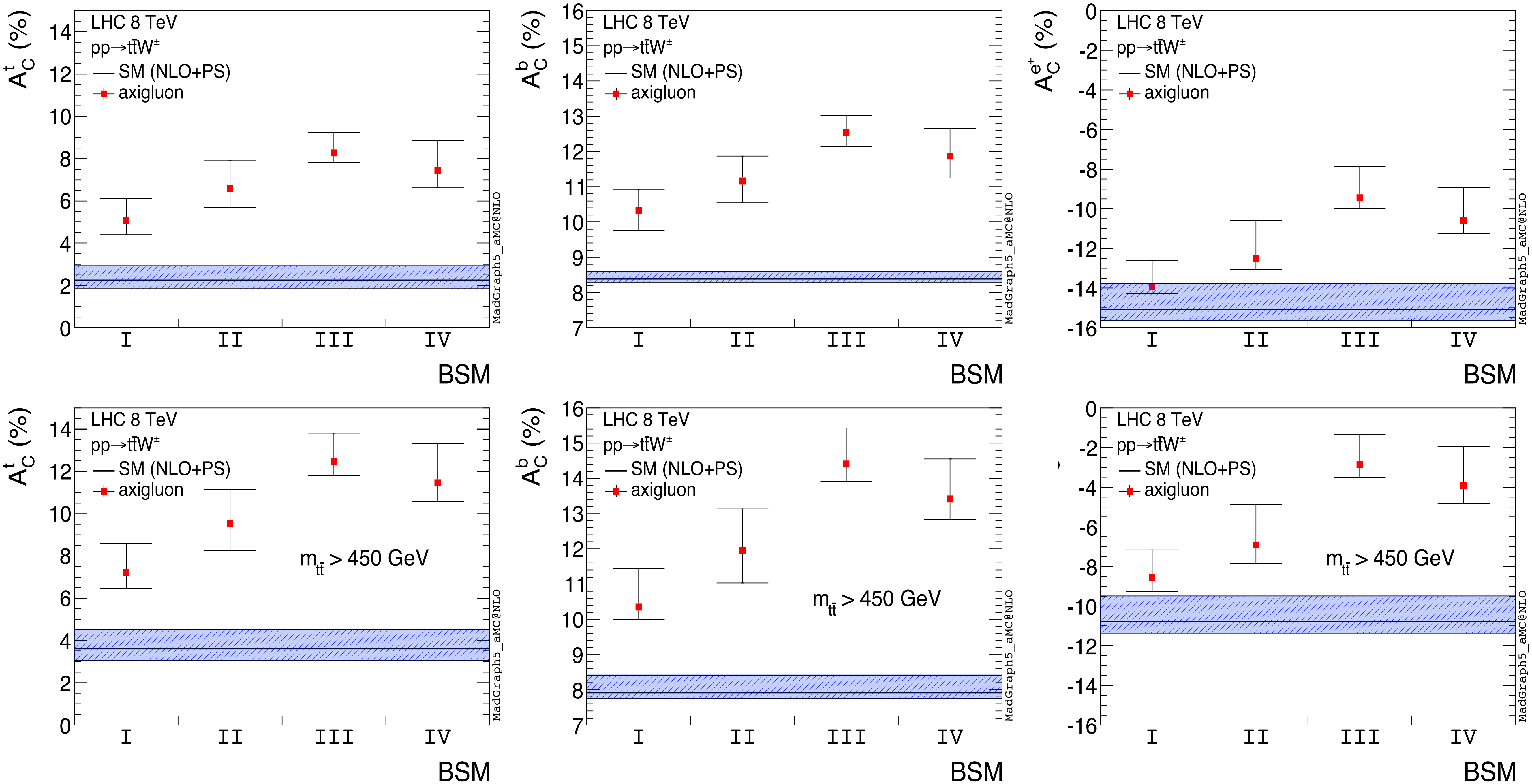


Benchmark scenarios:

Light, universal G		Heavy, non-universal G	
I (left)	II (axial)	III (left)	IV (axial)
m		m	
Γ_G		Γ	Γ
g	g	g	g
g	g	g	g^u
g_t		g	g

W boson polarises light quarks: σ=0 in right-handed scenarios

Results


LHC 8 TeV
pp→tt̄W±
SM (NLO+PS)
axigluon
A_C^t (%)
A_C^b (%)
$A_C^{e^+}$ (%)
I
II
III
IV
BSM
$m_{t\bar{t}} > 450$ GeV
MadGraph5_aMC@NLO

Conclusions

- The top quark asymmetry is a very intriguing observable which can provide us with some hints on new physics
- Its measurement at the LHC is very tricky
  - symmetric initial state
  - large gg fraction
- The associated production of a top pair and a W boson is a very interesting channel to look at
  - Larger asymmetry than $t\bar{t}$
  - Tops are highly polarised $\rightarrow$ asymmetric decay products at LO
  - Together with $t\bar{t}$, $t\bar{t}W$ can provide useful informations on NP
- What happens beyond MC-truth?

Thanks for your attention!

Extra material

Polarised top pair production

more in Parke, Shadmi, hep-ph:9606419

- Initial quarks are polarised by the W boson
  - $q\bar{q} \to t\bar{t}W$ is totally analogous to $q_L\bar{q}_R \to t\bar{t}$

Possible top polarisation states in $q_L\bar{q}_R \to t\bar{t}$ (beam axis basis):

	$\beta \to 0$ (Thresh.)	$\beta \to 1$ (H.E.)
$\frac{d\sigma_{\uparrow\uparrow}}{d\cos\theta} = \frac{d\sigma_{\downarrow\downarrow}}{d\cos\theta} = \mathcal{N}(\beta)\frac{\beta^2(1-\beta^2)\sin^2\theta}{(1+\beta\cos\theta)^2}$	0	0
$\frac{d\sigma_{\downarrow\uparrow}}{d\cos\theta} = \mathcal{N}(\beta)\frac{\beta^4\sin^4\theta}{(1+\beta\cos\theta)^2}$	0	$\mathcal{N}(1)(1-\cos\theta)^2$
$\frac{d\sigma_{\uparrow\downarrow}}{d\cos\theta} = \mathcal{N}(\beta)\frac{[(1+\beta\cos\theta)^2+(1-\beta^2)]^2}{(1+\beta\cos\theta)^2}$	$4\mathcal{N}(0)$	$\mathcal{N}(1)(1+\cos\theta)^2$

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$\frac{d\sigma_{\downarrow\uparrow}}{d\cos\theta} = \mathcal{N}(\beta)\frac{\beta^4\sin^4\theta}{(1+\beta\cos\theta)^2}$	0	$\mathcal{N}(1)(1-\cos\theta)^2$
$\frac{d\sigma_{\uparrow\downarrow}}{d\cos\theta} = \mathcal{N}(\beta)\frac{[(1+\beta\cos\theta)^2+(1-\beta^2)]^2}{(1+\beta\cos\theta)^2}$	$4\mathcal{N}(0)$	$\mathcal{N}(1)(1+\cos\theta)^2$

- At threshold (leading contribution to the cross-section) only one polarisation survives: tops are fully polarised
- At high energies top polarisations are opposite, and #↑↓=#↓↑

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  - $q\bar{q} \rightarrow t\bar{t}$ …

Possible top … axis basis):

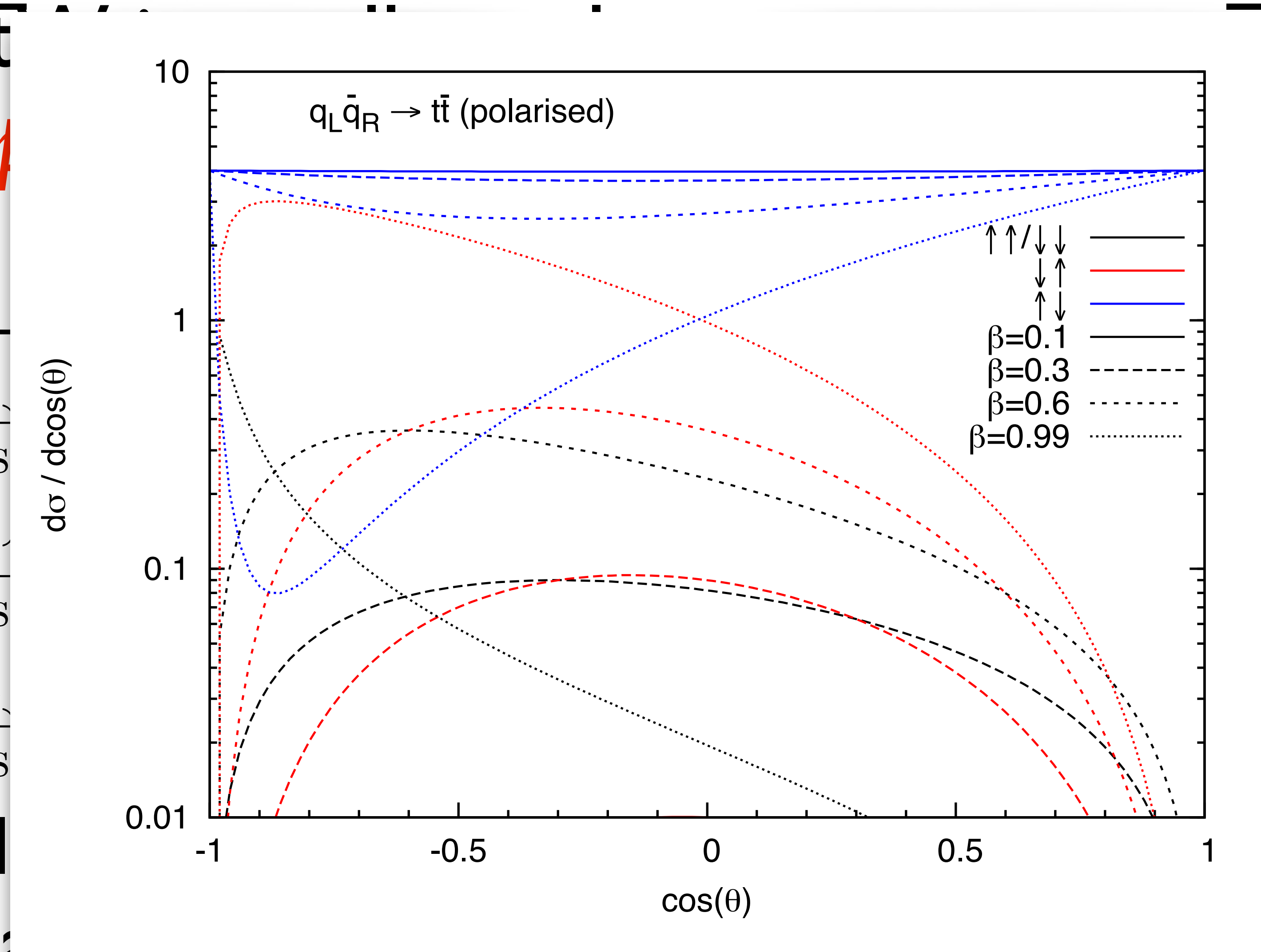
$\beta \rightarrow 1$

(H.E.)

$$\frac{d\sigma_{\uparrow\uparrow}}{d\cos\theta} = \frac{d\sigma_{\downarrow\downarrow}}{d\cos \ldots}$$

$$\frac{d\sigma_{\downarrow\uparrow}}{d\cos \ldots} \ldots (1-\cos\theta)^2$$

$$\frac{d\sigma_{\uparrow\downarrow}}{d\cos \ldots} \ldots (1+\cos\theta)^2$$



- At threshol… …ection) only one polaris…
- At high energies top polarisations are opposite, and #↑↓=#↓↑

Expected sensitivity

- Neglect acceptance and reconstruction efficiencies
- Tops decay into leptons
  - 8 TeV ($\mathcal{L} = 40 \text{ fb}^{-1}$):

    $\delta_{\text{rel}} A_C^t = 216\%, \delta_{\text{rel}} A_C^b = 59\%, \delta_{\text{rel}} A_C^e = 33\%$
  - 14 TeV ($\mathcal{L} = 300 \text{ fb}^{-1}$):

    $\delta_{\text{rel}} A_C^t = 45\%, \delta_{\text{rel}} A_C^b = 13\%, \delta_{\text{rel}} A_C^e = 8\%$
  - 100 TeV ($\mathcal{L} = 3000 \text{ fb}^{-1}$):

    $\delta_{\text{rel}} A_C^t = 3\%, \delta_{\text{rel}} A_C^b = 2\%, \delta_{\text{rel}} A_C^e = 1\%$

NLO: how to?

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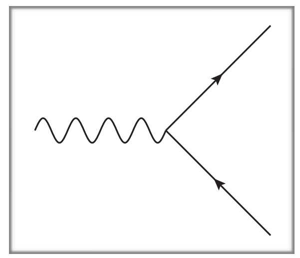

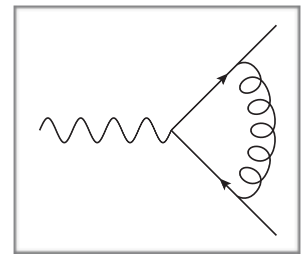

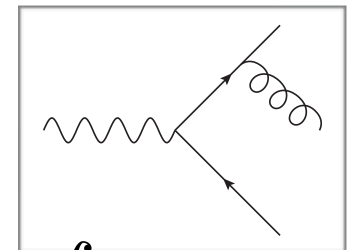

$$d\sigma^{n}_{NLO} \quad = \quad d\sigma^{n}_{LO} \quad + \quad d\sigma^{n}_{V} \quad + \int d\Phi_1 \, d\sigma^{n+1}_{R}$$

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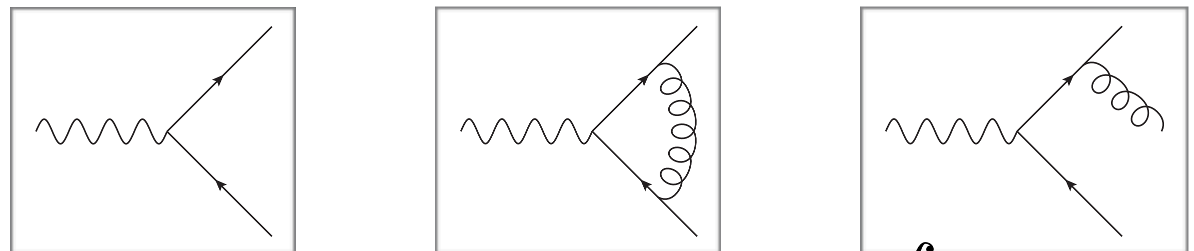

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  - Divergences cancel with those from virtuals (in D=4-2eps)
  - Need to cancel them before numerical integration (in D=4)

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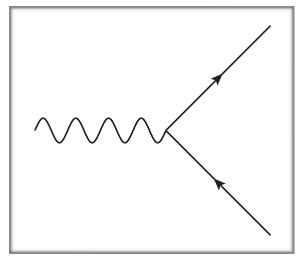
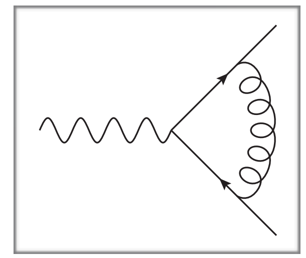
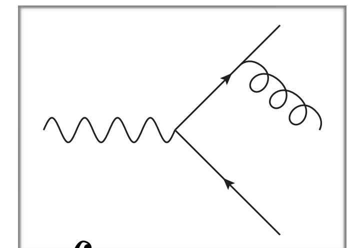

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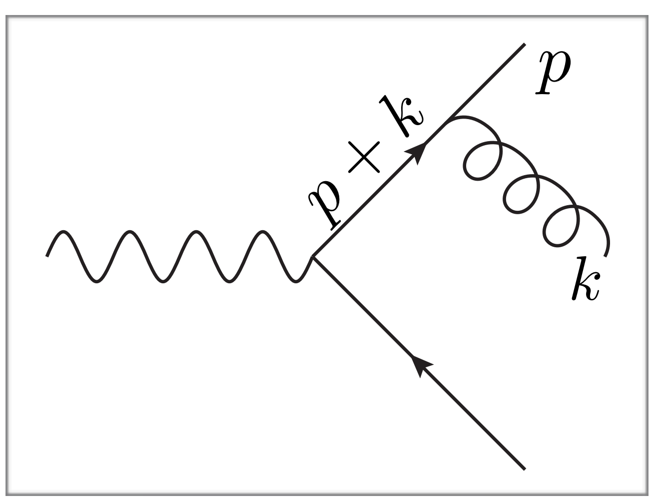
- Structure of divergences is universal:

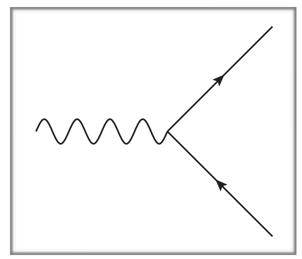


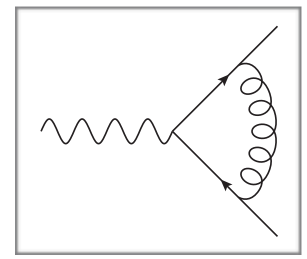
$$(p+k)^2 = 2E_p E_k (1 - \cos\theta_{pk})$$

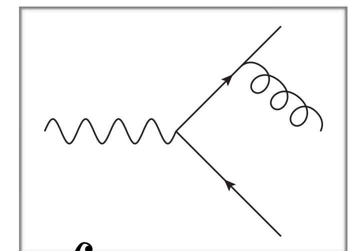
$$\lim_{p//k} |M_{n+1}|^2 \simeq |M_n|^2 \, P^{AP}(z)$$

$$\lim_{k\to 0} |M_{n+1}|^2 \simeq \sum_{ij} |M_n^{ij}|^2 \frac{p_i p_j}{p_i k \, p_j k}$$

NLO: how to?







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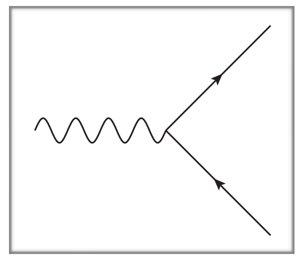 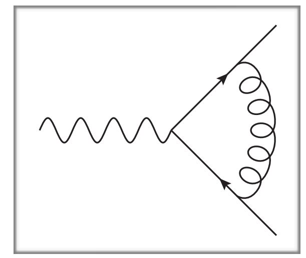 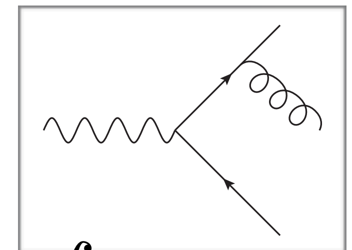

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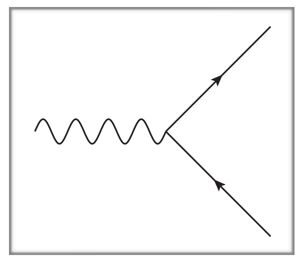
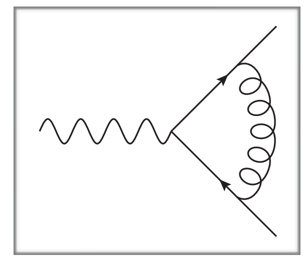
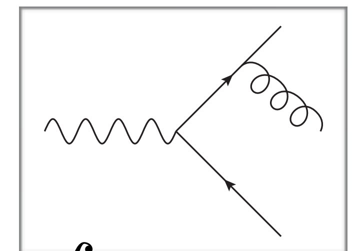

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How to do this in an efficient way?

The FKS subtraction

Frixione, Kunszt, Signer, arXiv:hep-ph/9512328

- Soft/collinear singularities arise in many PS regions
- Find parton pairs *i*, *j* that can give collinear singularities
- Split the phase space into regions with one collinear sing
  - Soft singularities are split into the collinear ones

$$|M|^2 = \sum_{ij} S_{ij} |M|^2 = \sum_{ij} |M|^2_{ij} \qquad \sum S_{ij} = 1$$

$$S_{ij} \to 1 \text{ if } k_i \cdot k_j \to 0 \qquad S_{ij} \to 0 \text{ if } k_{m\neq i} \cdot k_{n \neq j} \to 0$$

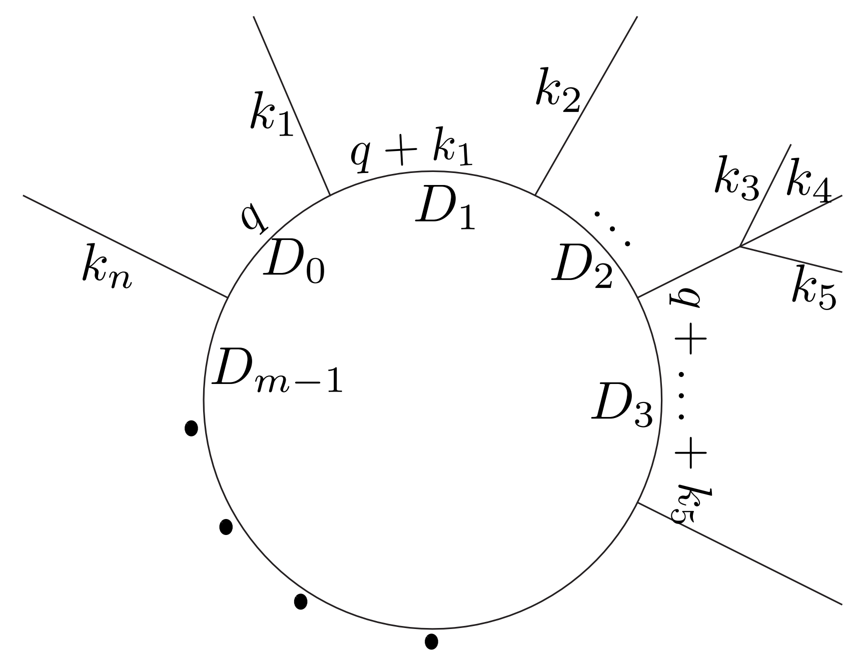
- Integrate them independently
  - Parallelise integration
  - Choose ad-hoc phase space parameterisation
- Advantages:
  - # of contributions ~ n^2
  - Exploit symmetries: 3 contributions for `X Y > ng`

Loops: the OPP Method

Ossola, Papadopoulos, Pittau, arXiv:hep-ph/0609007 & arXiv:0711.3596

- Passarino & Veltman reduction:
  - Write the amplitude at the integral level as linear combination of 1-...-4-point scalar integrals

$$
\begin{aligned}
A(q) &= \sum_{i_0<i_1<i_2<i_3}^{m-1} d(i_0 i_1 i_2 i_3) D_0(i_0 i_1 i_2 i_3) \\
&+ \sum_{i_0<i_1<i_2}^{m-1} c(i_0 i_1 i_2) C_0(i_0 i_1 i_2) \\
&+ \sum_{i_0<i_1}^{m-1} b(i_0 i_1) B_0(i_0 i_1) \\
&+ \sum_{i_0}^{m-1} a(i_0) A_0(i_0) \\
&+ R
\end{aligned}
$$



  - Do this at the integrand level

Loops: the OPP Method

Ossola, Papadopoulos, Pittau, arXiv:hep-ph/0609007 & arXiv:0711.3596

$$A(\bar{q}) = \frac{N(q)}{\bar{D}_0 \bar{D}_1 \cdots \bar{D}_{m-1}}$$

$$\begin{aligned} N(q) = & \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3)\right] \prod_{i \neq i_0, i_1, i_2, i_3}^{m-1} D_i \\ + & \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2)\right] \prod_{i \neq i_0, i_1, i_2}^{m-1} D_i \\ + & \sum_{i_0<i_1}^{m-1} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1)\right] \prod_{i \neq i_0, i_1}^{m-1} D_i \\ + & \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q; i_0)\right] \prod_{i \neq i_0}^{m-1} D_i \\ + & \tilde{P}(q) \prod_{i}^{m-1} D_i \,. \end{aligned}$$

- Sample the numerator at complex values of the loop momenta in order to reconstruct the *a,b,c,d* coefficients and part of the rational terms (R1)
- Use CutTools: fed with the loop numerator outputs the coefficients of the scalar integrals and CC rational terms (R1)
- Add R2-rational terms/UV counterterms
  - Model dependent but process-independent

Loop ME evaluation: MadLoop

Hirschi et al. arXiv:1103.0621

- Load the NLO UFO model
- Generate Feynman diagrams to evaluate the loop ME
- Add R2/UV renormalisation counter terms
- Interface to CutTools or to tensor reduction programs (in progress)
- Check PS point stability (and switch to QP if needed)
- Improved with the OpenLoops method *Cascioli, Maierhofer, Pozzorini arXiv:1111.5206*
- And much more (can be used as standalone or external OLP via the BLHA, handle loop-induced processes, …)

Matching in MC@NLO

- Use suitable counterterms to avoid double counting the emission from shower and ME, keeping the correct rate at order α_s:

$$\frac{d\sigma_{MC@NLO}}{dO} = \underbrace{\left(\mathcal{B} + \mathcal{V} + \int d\Phi_1 MC\right) d\Phi_n \; I^n_{MC}(O)}_{\text{S-events}} + \underbrace{(\mathcal{R} - MC)\, d\Phi_n \; d\Phi_1 \; I^{n+1}_{MC}(O)}_{\text{H-events}}$$

- MC depends on the PSMC's Sudakov:

$$MC = \left| \frac{\partial\left(t^{MC}, z^{MC}, \phi\right)}{\partial \Phi_1} \right| \frac{1}{t^{MC}} \frac{\alpha_s}{2\pi} \frac{1}{2\pi} P\left(z^{MC}\right) \mathcal{B}$$

- Available for Herwig6, Pythia6 (virtuality-ordered), Herwig++, Pythia8 (in the new release)
- MC acts as local counterterm
- Some weights can be negative (unweighting up to sign)
    - Only affects statistics

Including spin-correlations at NLO: MadSpin

Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460

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$$|M_{P+D}|^2 \,/\, |M_P|^2 > \mathrm{Rand}() \;\; \max\left(|\mathrm{M}_{\mathrm{P+D}}|^2 \,/\, |\mathrm{M}_{\mathrm{P}}|^2\right)$$

- Method originally used for $t\bar{t}$ and singletop

Frixione, Leanen, Motylinski, Webber, arXiv:hep-ph/0702198