Top flavour physics

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Menu

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2. Top flavour beyond the SM
   - Benchmarks for non-SM top mixing
   - Top effective operators
   - Top mixing vs direct signals
3. Top flavour measurements
   - V_{tb}, V_{ts}, V_{td}
   - Top FCNC
   - CP violation in top decays

Top flavour in the SM

Top flavour in the SM

From the "top" point of view

The flavour structure is remarkably simple in the SM

- Charged current mixing: $|V_{tb}| \gg |V_{td}|\,,|V_{ts}|$

  ☞ $t \to Wb$ dominates with $\mathrm{Br} \simeq 1$

- FCNC very suppressed by GIM because $m_t \gg m_{d,s,b}$

  ☞ $\mathrm{Br}(t \to Zc\,/\,\gamma c\,/\,gc) \lesssim 10^{-12}$, can be safely ignored

- CP violation effects vanish in the chiral limit $m_{d,s} = 0$

  d and s are hardly distinguished at high energy, *e.g.* in top decays

Top flavour in the SM

From the "top" point of view

Then, for top production and decay at large colliders it is a good approximation to

- assume $V_{tb} = 1$, $V_{td} = V_{ts} = 0$
- ignore all FCNC
- ignore CP violation

Conversely: measuring V_{td}, V_{ts}, top FCNC or CP violation within the SM is extremely hard (if not impossible) at large colliders!

Top flavour in the SM

From the "bottom" point of view

For B physics V_{td}, V_{ts} are crucial parameters because top loops (enhanced by m_t) give dominant contribution

This allows to measure them:

$$\left.\begin{array}{l} M_{12}^{B_d} \propto (V_{td}^* V_{tb})^2 \\ M_{12}^{B_s} \propto (V_{ts}^* V_{tb})^2 \end{array}\right] \rightarrow \quad \frac{\delta m_{B_d}}{\delta m_{B_s}} \simeq \left| \frac{V_{td}}{V_{ts}} \right|^2 \text{ for example}$$

but this extraction is model-dependent, any new physics contributing to M_{12} will invalidate it

☞ For this reason, it is highly desireable to have direct measurements of V_{td}, V_{ts}, V_{tb} to cross-check

Top flavour beyond the SM

Top flavour beyond the SM

Considering flavour, we can classify BSM models in:

1. Models respecting 3×3 CKM unitarity

   SUSY | 2HDM | …

2. Models breaking 3×3 CKM unitarity (extra quarks)

   4^{th} gen. | T singlet $(2/3)$ | B singlet $(-1/3)$ | triplets | …

   Note that particular models may have more stuff (scalars, vector bosons …) but we may ignore them here

Both can give new effects on B physics but only 2 can have top flavour mixing different from SM

I look for benchmarks for top flavour so I will concentrate on 2

4^{th} (sequential) generation

The simplest of all these models: just add one complete generation [including leptons, for anomaly cancellation]

Also the least natural because 4^{th} generation neutrino must have $m_{\nu_4} > M_Z/2$, while $m_{\nu_{1-3}} \lesssim 0.3$ eV ☞ $10^{11} \times$ heavier!

Still, it is not experimentally excluded by EW data provided that

$$m_{t'} \gtrsim 400 \text{ GeV} \qquad m_{t'} - m_{b'} \simeq 50 \text{ GeV} \times \left(1 + \frac{1}{5} \frac{M_H}{115 \text{ GeV}}\right)$$

$$m_{\tau'} - m_{\nu_4} \sim 45 \text{ GeV}$$

$m_{t'} > 335$ GeV, $m_{b'} > 385$ GeV from direct search

[$m_{t'} \lesssim 500$ GeV from perturbativity, some other bounds too]

Top mixing similar to model with extra T [mainly with 3^{rd} gen.]

T singlet

Preferred “benchmark” for 3×3 CKM unitarity breaking

GIM breaking: FCNC at tree level in up sector

This is not a problem but a potentially new, striking effect

T mixing expected mainly with 3rd generation:

- more natural: mixing $\sim m_t/m_T$
- less constrained by low-energy data

T mixing with 3rd generation

T mixing $\Leftrightarrow$ departures from SM prediction for V_{tb} and Ztt

top quark

$$- \frac{g}{\sqrt{2}} V_{tb} \, \bar{t}_L \gamma^\mu b_L \, W_\mu^+$$

$$- \frac{g}{2c_W} \left(X_{tt}^L - \tfrac{4}{3} s_W^2 \right) \bar{t}_L \gamma^\mu t_L \, Z_\mu$$

SM $\rightarrow$ $V_{tb} \simeq 1$, $X_{tt}^L = 1$

new quark T

$$- \frac{g}{\sqrt{2}} V_{Tb} \, \bar{T}_L \gamma^\mu b_L \, W_\mu^+$$

$$- \frac{g}{2c_W} X_{Tt} \, \bar{T}_L \gamma^\mu t_L \, Z_\mu$$

mixing parameter: V_{Tb}

departures from SM:

$$|V_{tb}| \simeq 1 - \tfrac{1}{2} |V_{Tb}|^2$$

$$X_{tt}^L \simeq 1 - |V_{Tb}|^2$$

$$\boxed{\delta X_{tt}^L = 2 \delta |V_{tb}|}$$

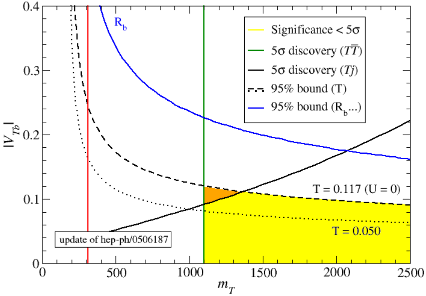
$$X_{Tt} \simeq |V_{Tb}| \left(1 - \tfrac{1}{2} |V_{Tb}|^2 \right)$$

T mixing with 3rd generation

(m_T, V_{Tb}) constrained by

- T parameter
- radiative corrections to R_b

No constraints for $m_T = m_t$:
4×4 unitarity at work



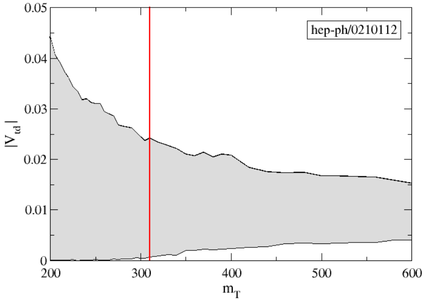
Tevatron: $m_T \gtrsim 310$ GeV → $V_{tb} \gtrsim 0.95$, $X_{tt}^L \gtrsim 0.9$

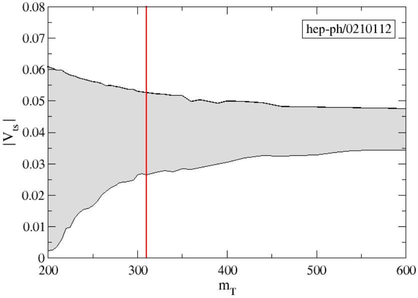
if T not seen at LHC → $V_{tb} \gtrsim 0.99$, $X_{tt}^L \gtrsim 0.985$

[no upper limits on T mass]

T mixing with 1st, 2nd generation

Some deviations in V_{td}, V_{ts} compatible with B physics constraints: new T quark in loop makes up for the difference

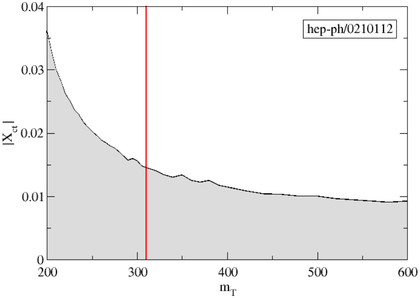




These plots tell us that we shouldn't be expecting large deviations but we have to measure V_{td}, V_{ts} anyway

Top FCNC

More interesting: top FCN couplings at tree level

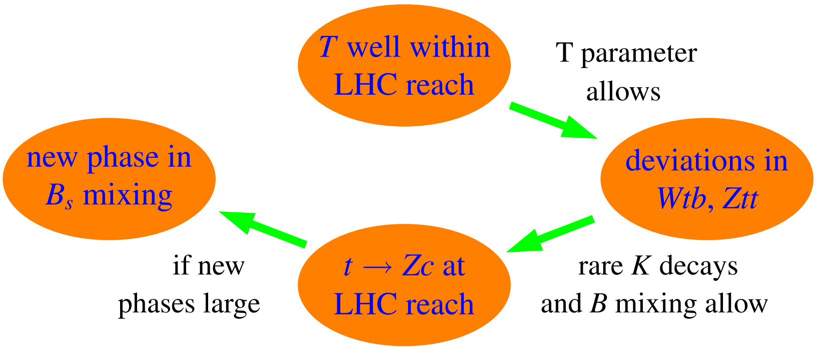


$$-\frac{g}{2c_W} X_{ct}\, \bar{c}_L \gamma^\mu t_L \, Z_\mu$$

$\mathrm{Br}(t \to Zc) \lesssim 1.1 \times 10^{-4}$ (visible at LHC)

T singlet: optimistic summary

hep-ph/0406151



phase in B_s mixing ($a_{J/\psi\phi}$) encourages search for other effects

… and if T not seen at LHC, forget everything else …

B singlet

A "substantial" breaking of 3×3 CKM unitarity requires $|V_{tb}| \not\simeq 1$

[Obvious for moduli, also true for phases]

With extra B singlets, agreement with measured R_b constains $|V_{tb}|$

relevant terms

$$- \frac{g}{\sqrt{2}} V_{tb} \, \bar t_L \gamma^\mu b_L \, W_\mu^+$$

$$- \frac{g}{2c_W} \left(-X_{bb}^L + \tfrac{2}{3} s_W^2\right) \bar b_L \gamma^\mu b_L \, Z_\mu$$

SM $\rightarrow$ $V_{tb} \simeq 1 \,, \quad X_{bb}^L = 1$

$$X_{bb}^L = |V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2$$

$$X_{bb}^L \simeq 1 \quad \rightarrow \quad |V_{tb}| \simeq 1$$

Is $V_{tb} \gtrsim 1$?

Some literature claims $|V_{tb}|^2 > 1$ is non-physical but …

Fermion couplings to W come through covariant derivative

$$\begin{aligned} D_\mu &= \partial_\mu + ig\,\vec{T}\cdot\vec{W}_\mu + \ldots \\ &= \partial_\mu + ig\left[\frac{1}{\sqrt{2}}\left(T_+ W_\mu^+ + T_- W_\mu^-\right) + T_3\, W_\mu^3\right] + \ldots \end{aligned}$$

T_i generators of $\mathrm{SU}(2)_L$

$T_\pm = T_1 \pm i\,T_2$ ladder operators

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp i W_\mu^2)$$

doublet $\begin{pmatrix} t_L \\ b_L \end{pmatrix}$ $\quad T_+|b_L\rangle = |t_L\rangle \quad \rightarrow \quad -\frac{g}{\sqrt{2}}\bar{t}_L\gamma^\mu b_L W_\mu^-$

mixing of weak eigenstates gives $|V_{tb}| \leq 1$ in the SM

Is $V_{tb} \gtrsim 1$?

Some literature claims $|V_{tb}|^2 > 1$ is non-physical but …

Fermion couplings to W come through covariant derivative

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triplet $\begin{pmatrix} T_L \\ B_L \\ Y_L \end{pmatrix}$ $\quad T_+ |B_L\rangle = \sqrt{2}\, |T_L\rangle \quad \rightarrow \quad -\frac{g}{\sqrt{2}} \sqrt{2}\, \bar{T}_L \gamma^\mu B_L W_\mu^-$

"V_{TB}" $= \sqrt{2} > 1$ for a triplet!

Is $V_{tb} \gtrsim 1$?

Some literature claims $|V_{tb}|^2 > 1$ is non-physical but …

Fermion couplings to W come through covariant derivative

$$\begin{aligned} D_\mu &= \partial_\mu + ig\,\vec{T}\cdot\vec{W}_\mu + \dots \\ &= \partial_\mu + ig\left[\frac{1}{\sqrt{2}}\left(T_+ W_\mu^+ + T_- W_\mu^-\right) + T_3\,W_\mu^3\right] + \dots \end{aligned}$$

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… mixing with a triplet can give $V_{tb} > 1$

Note that Tevatron lower limits on $|V_{tb}|$

$|V_{tb}| > 0.71$ at 95% CL (CDF)

$|V_{tb}| > 0.78$ at 95% CL (D0)

do not only assume $V_{td}, V_{ts} \ll V_{tb}$ but also $|V_{tb}| \leq 1$

☞ they are valid only for the SM and a subset of its extensions

Top effective operators

Top effective operators

Let us go more general

NPB 268:621 (1986)

When discussing indirect (mixing) signals of heavy resonances it is useful to use an effective operator formalism

$$\mathcal{L} = \mathcal{L}_4 + \mathcal{L}_6 + \dots$$

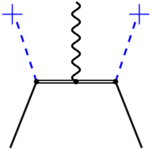
where

$\mathcal{L}_4 = \mathcal{L}_{\rm SM}$ ➙ SM Lagrangian

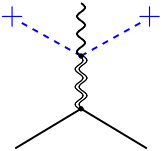
$\mathcal{L}_6 = \sum_x \frac{\alpha_x}{\Lambda^2} O_x$ ➙ O_x gauge-invariant building blocks

Parameterise indirect effects of new physics at scale $\Lambda > v$

New physics contributions to top trilinear couplings

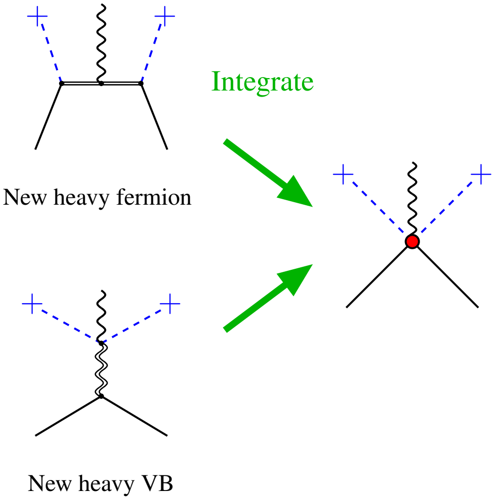


New heavy fermion

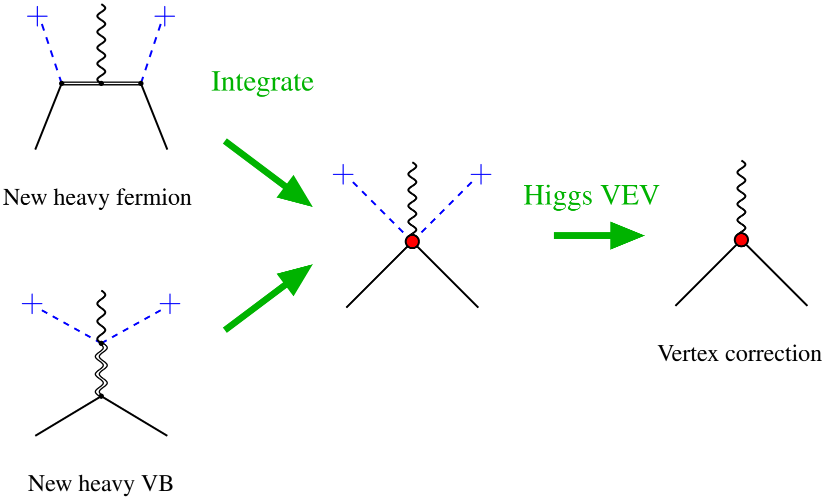


New heavy VB

New physics contributions to top trilinear couplings



New physics contributions to top trilinear couplings



Vertex corrections from dim 6 operators:

0811.3842

① Gauge interactions: only γ^μ and $\sigma^{\mu\nu} q_\nu$ terms

② Higgs: only scalar and pseudo-scalar terms

☞ This is general for any two-fermion vertices, not only the top quark!

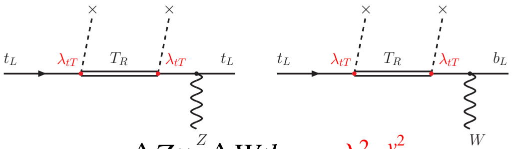
So simple after eliminating many redundant operators

Top mixing vs direct signals

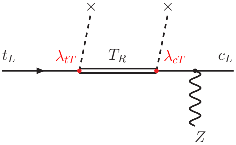



Top mixing corrections vs direct signals

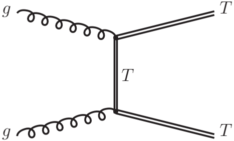
hep-ph/0007316



$$\Delta Ztt, \Delta Wtb \ \propto \ \lambda_{tT}^2 \frac{v^2}{M^2}$$



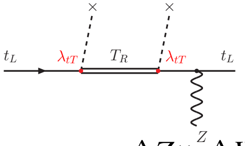
$$t \to Zc \ \propto \ \lambda_{tT}^2 \lambda_{cT}^2 \frac{v^4}{M^4}$$

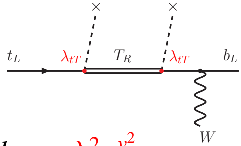


$$\sigma \propto \frac{1}{M} \frac{1}{\mathrm{PDF}(2M)}$$

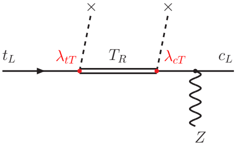
Top mixing corrections vs direct signals

hep-ph/0007316

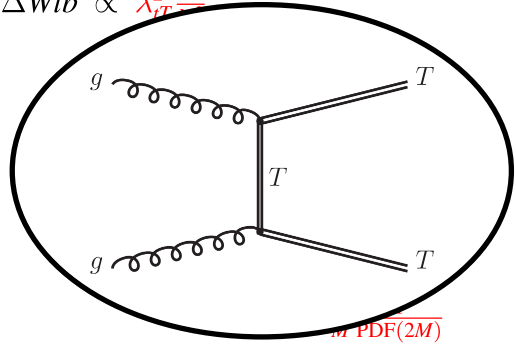




$$\Delta Ztt, \Delta Wtb \propto \lambda_{tT}^2 \frac{v^2}{\cdots}$$



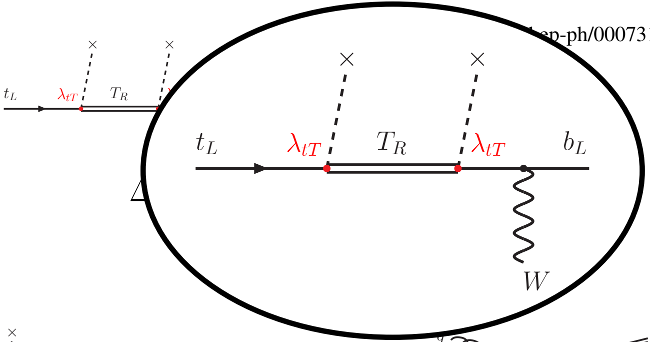
$$t \to Zc \propto \lambda_{tT}^2 \lambda_{cT}^2 \frac{v^4}{M^4}$$

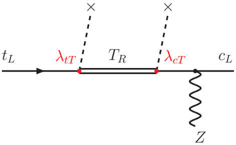


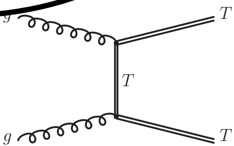
$$\frac{\cdots}{M\ \mathrm{PDF}(2M)}$$

Top mixing corrections vs direct signals

ep-ph/0007316







$$t \to Zc \;\propto\; \lambda_{tT}^2 \lambda_{cT}^2 \frac{v^4}{M^4}$$

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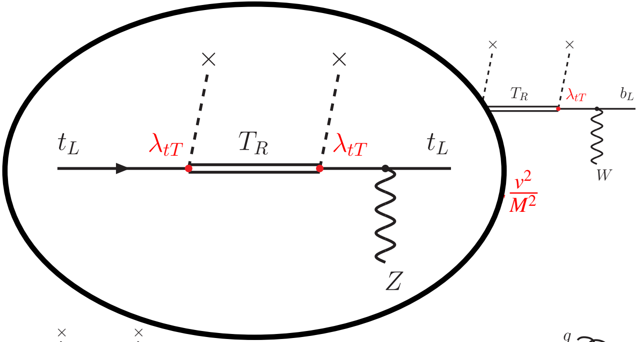
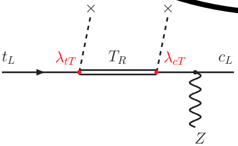
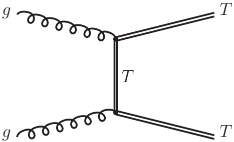
Top mixing corrections vs direct signals

hep-ph/0007316







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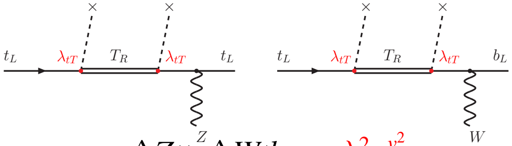

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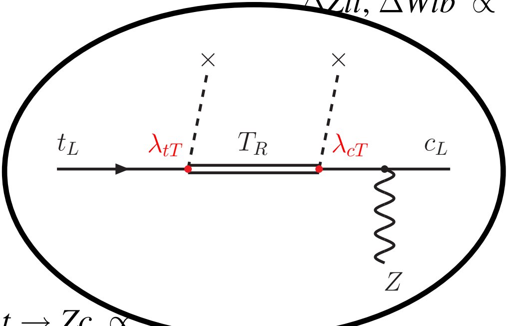

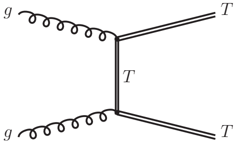

$$t \to Zc \;\propto$$

$$\sigma \propto \frac{1}{M} \frac{1}{\mathrm{PDF}(2M)}$$

Top mixing corrections vs direct signals

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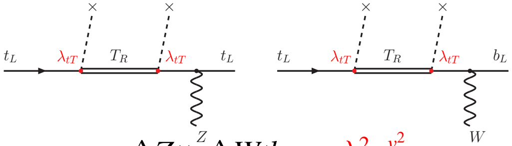
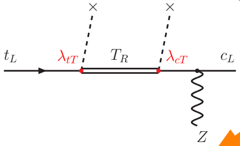
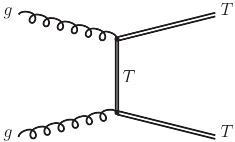


$$\Delta Ztt,\ \Delta Wtb \ \propto\ \lambda_{tT}^2 \frac{v^2}{M^2}$$

EW precision constraints



B, *K* physics



$$t \to Zc \ \propto\ \lambda_{tT}^2 \lambda_{cT}^2 \frac{v^4}{M^4}$$

$$\sigma \ \propto\ \frac{1}{M} \frac{1}{\mathrm{PDF}(2M)}$$

Top mixing corrections vs direct signals

PDF suppression is stronger in principle, but …

- λ_{tT} constrained by precision data
- λ_{cT} tightly constrained by low energy physics

… then, dominant effect depends on the type of new physics

Note also that

- effects on Ztt, Wtb are $\sim 1/\Lambda^2$ (interference with SM)
- FCNC effects are $\sim 1/\Lambda^4$ (tiny in SM) but much cleaner to see

Top flavour measurements

V_{td}, V_{ts}, V_{tb} at LHC

Single top processes are often quoted as measuring V_{tb} but …

- They are also sensitive to V_{td} and V_{ts}

  example: t-channel production

$$\sigma(qd \to q't) = A_d |V_{td}|^2$$
$$\sigma(qs \to q't) = A_s |V_{ts}|^2$$
$$\sigma(qb \to q't) = A_b |V_{tb}|^2$$

  with $A_d > A_s > A_b$!

- Once that one allows for $V_{tb} \neq 1$, for consistency one must also allow for V_{td} and V_{ts} different from their SM value

  ☞ drop the assumption $V_{td}, V_{ts} \ll V_{tb}$

V_{td}, V_{ts}, V_{tb} at LHC: standard picture

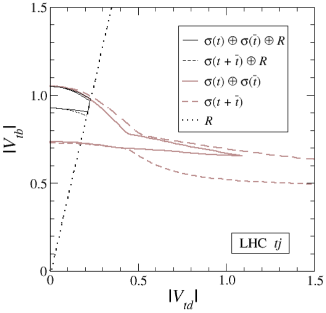
The three mixings can be extracted with combination of observables

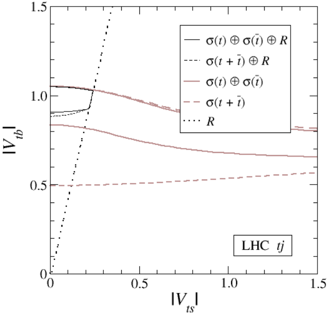
- ★ at Tevatron, s- and t-channel combination gives useful limits
- ★ at LHC, s-channel has very large uncertainty and is mostly useless for this See
- ★ moreover, t-channel and tW are “too similar” See
- ★ the key to obtain limits at LHC is the combination of t-channel and $R = \dfrac{\mathrm{Br}(t \to Wb)}{\mathrm{Br}(t \to Wq)}$

V_{td}, V_{ts}, V_{tb} at LHC

Complementarity of t-channel σ and R

0902.4718





- ★ for illustration, 1σ agreement with <u>each</u> observable required
- ★ notice that separate t and $\bar{t}$ measurements improve limits
- ★ the key to get good limits is the combination with R!

Improvement #1

Single top production: more than just cross sections

Single top cross sections $\propto |V_{td}|^2, |V_{ts}|^2, |V_{tb}|^2$ but there are more observables than just the total rate

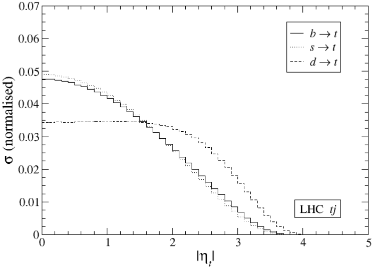
☞ the "blind" combination can be improved

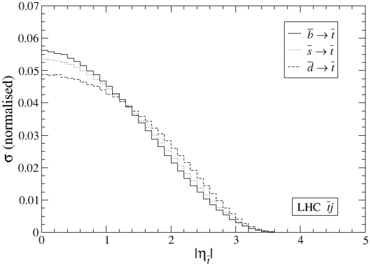
Key to distinguish d from s and b: top rapidity

initial d valence quarks ➙ larger average rapidities

☞ use rapidity to discriminate d against s and b

Top rapidity distributions for tj and $\bar{t}j$

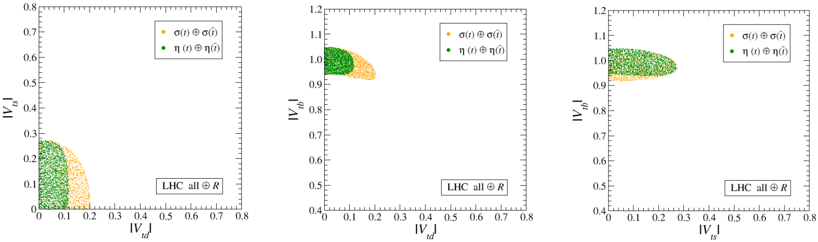




- ★ d very different from s and b for t production
- ★ separate t and $\bar{t}$ measurements important!

Including top rapidity

LHC limits including rapidity (optimistic)



in the best case:

- ★ $\times 2$ improvement in V_{td}
- ★ 15% improvement in V_{tb}
- ★ no difference for V_{ts}

Improvement #2

Top decay: more than just b tagging

1005.4647

Indeed, there is possibility to tag $t \to Ws$

- ★ use the cleaner dilepton channel (fewer jets)
  $t\bar{t} \to W^+ d_i \, W^- \bar{d}_j \to \ell^+ \nu d_i \, \ell^- \bar{\nu} \bar{d}_j \qquad d_i, d_j = d, s, b$
- ★ jets originating from s quarks have K's and Λ's ☞ tag
- ★ jets from b also have K's and Λ's from $b \to c \to s$ but
  - softer
  - displaced vertices from b decay
  - often accompanied by ℓ inside the jet
- ★ jets from d quarks have much fewer K's and Λ's

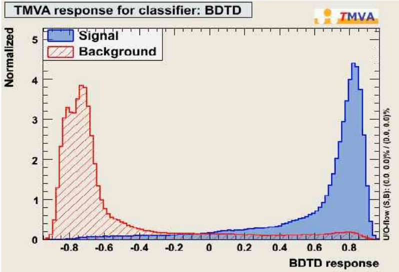
$t \to Ws$ tagging

Discriminant analysis for $t \to Ws$ tagging

Main features

requires b rejection better than $\frac{|V_{tb}|^2}{|V_{ts}|^2} \sim 600$

with the ratio $WbWs/WbWb$ we measure $\frac{|V_{ts}|^2}{|V_{tb}|^2}$



☞ The ratio $\frac{|V_{ts}|^2}{|V_{tb}|^2}$ is a new ingredient for the global fit 🙂

Top flavour-changing neutral currents

Top flavour-changing neutral currents

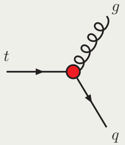
Many interesting papers on the subject

hep-ph/9506461 , 9603247 , 9606231 , 9702350 , 9703450 , 9704244 , 9705341 , 9805498 , 9806486 , 9808400 , 9811237 , 9811330 , 9905407 , 9906268 , 9909222 0011091 , 0004190 , 0012305 , 0102037 , 0208035 , 0210360 , 0406155 , 0409342 , 0506197 , 0508043 , 0704.1482 , 0712.1127 , 0802.2075 , 0805.0973 , 0810.3889 , 0811.1743 , 0811.3842 , 0904.2387 , 0910.4349 , 1003.3173 , 1004.0620 , 1004.0898 , . . .

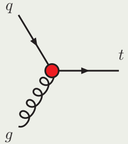
I will just give few general remarks

Many interesting processes for *gtq* ...

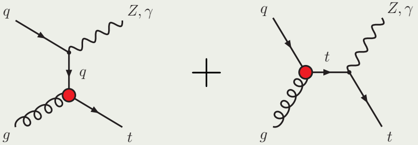
$t \to qg$



$gq \to t$

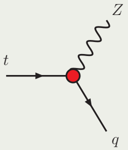


$gq \to Zt$

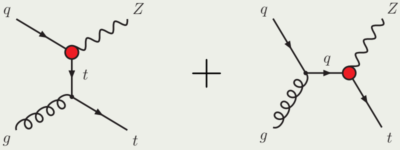


… and for Ztq …

$t \rightarrow qZ$

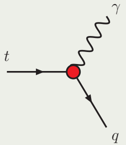


$gq \rightarrow Zt$

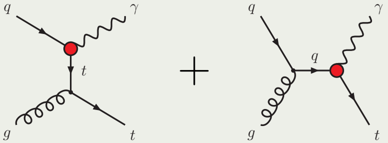


… and for γtq …

$t \to q\gamma$

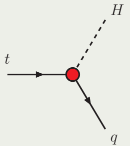


$gq \to \gamma t$

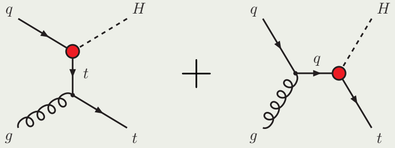


. . . and for Htq!

$t \to q\gamma$

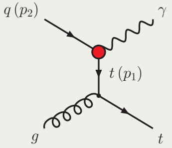


$gq \to Ht$

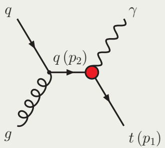


Theoretical framework?

Notice that some key processes involve off-shell vertices



t off-shell



q off-shell

In principle, these vertices have many different Lorentz structures and the study can become a nightmare

- usual vertex: γ^μ, $\sigma^{\mu\nu} q_\nu$ $\qquad q^\mu = (p_1 - p_2)^\mu = p_\gamma^\mu$
- off-shell: also k^μ, $\sigma^{\mu\nu} k_\nu$ $\qquad k^\mu = (p_1 + p_2)^\mu$

Here, effective operators come to our aid

Vertex corrections from dim 6 operators:

(again)

① Gauge interactions: only γ^μ and $\sigma^{\mu\nu} q_\nu$ terms

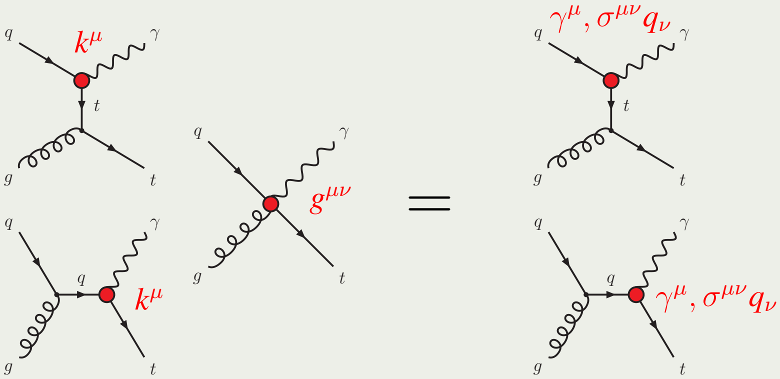
② Higgs: only scalar and pseudo-scalar terms

So simple after eliminating many redundant operators

Note: If you insist on introducing redundant operators you find relations due to gauge symmetry that allow you to write your amplitudes using only ① and ②

Gauge invariance at work: an example

Contributions to $gq \to \gamma t$



Top FCNC: one-slide summary

★ Effective operator framework greatly simplifies theoretical setup

few (≤ 4) anomalous couplings for each interaction

★ Many possible signals: relations allow for cross-checks

★ Expectations and LHC precision $(q = c)$

	SM	QS	2HDM	MSSM	$\not{R}$ SUSY	LHC 300 fb^{-1}
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	2×10^{-6}	3×10^{-5}	6.3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	2×10^{-6}	1×10^{-6}	1.7×10^{-5}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	8×10^{-5}	2×10^{-4}	(9.2×10^{-6})
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	10^{-5}	$\sim 10^{-6}$	(3.3×10^{-5})

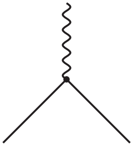
CP violation in top decays

CP violation in top decays

CP violation in top decays

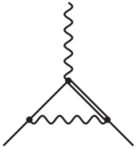
- ★ CP violation at high energy not yet probed (tiny in the SM)
- ★ Large sample of top quarks at LHC: good statistics
- ★ We will concentrate on $t \to Wb$ (leading channel)
- ★ Results also hold for $t \to Wd$, $t \to Ws$ but statistics and tagging are much worse

CP violation requires



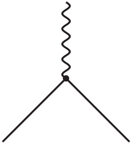
SM tree-level

$$+$$



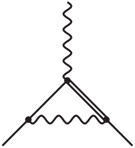
NP, maybe loop

CP violation requires



SM tree-level

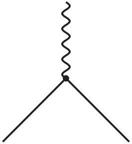
+



NP, maybe loop

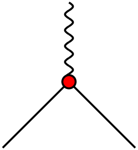
Heavy
new physics →

Equivalently



SM tree-level

+



effective vertex

Effective Wtb vertex from dim-6 operators

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

$$q = p_t - p_b = p_W$$

- ★ Using effective operators assumes that NP is heavy
  no absorptive phases in heavy particle loops
- ★ Lagrangian is Hermitian
- ★ Total rates equal for t and $\bar{t}$ ☞ look for other CP tests

Decays described by density matrix $\left(\Gamma_{ij} = \frac{g^2 |\vec{q}\,|}{128\pi^2} \int M_{ij} \, d\cos\theta \, d\phi\right)$

$$M_{00} = A_0 + 2\frac{|\vec{q}\,|}{m_t} A_1 \cos\theta$$

$$M_{\pm\pm} = B_0 \, (1 \pm \cos\theta) \pm 2\frac{|\vec{q}\,|}{m_t} B_1 \, (1 \pm \cos\theta)$$

$$M_{0\pm} = M^*_{\pm 0} = \left[\frac{m_t}{\sqrt{2} M_W} (C_0 - i\, D_0) \pm \frac{|\vec{q}\,|}{\sqrt{2} M_W} (C_1 - i\, D_1)\right] \sin\theta e^{\pm i\phi}$$

$$M_{+-} = M_{-+} = 0$$

See

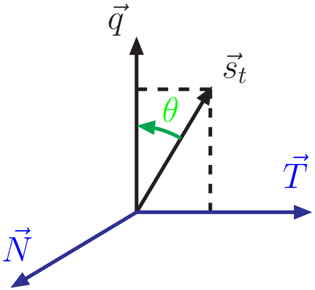
well-known helicity fractions $\left\{ \begin{array}{l} F_0 = \Gamma_{00}/\Gamma \\ F_+ = \Gamma_{++}/\Gamma \\ F_- = \Gamma_{--}/\Gamma \end{array} \right\}$ test A_0, B_0, B_1

the five remaining form factors A_1, C_0, C_1, D_0, D_1 are not probed!

New idea to study top decays

Use directions other than helicity to probe W spin

1005.5382



Transverse and normal directions

$\vec{q}$ → W mom in t rest frame
$\vec{s}_t$ → top spin

$$\vec{N} = \vec{s}_t \times \vec{q}$$
$$\vec{T} = \vec{q} \times \vec{N}$$

meaningful for polarised t decays

(e.g. in single top production)

Probing CP violation in top decays

W polarisation fractions F, F^T, F^N measured with suitable angular distributions See

Normal polarisation F^N probes complex phases of Wtb vertex

☞ $F_+^N = F_-^N$ in the SM and for real Wtb

Then, FB asymmetry $A_{\mathrm{FB}}^N = \frac{3}{4}\left[F_+^N - F_-^N\right]$ is CP-violating

zero if Wtb vertex real (V_L taken real by definition)

☞ $\boxed{A_{\mathrm{FB}}^N \simeq 0.64\, P\, \mathrm{Im}\, g_R}$ very sensitive to $\mathrm{Im}\, g_R$!

An all-time classic: $t \to Wb$ vs $b \to s\gamma$ (3σ limits)

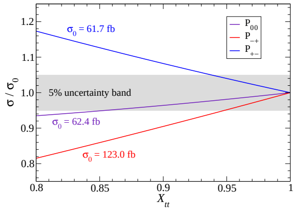
Top observables		$b \to s\gamma$
Re $V_L \leq 0.62$ Re $V_L \geq 1.21$	(σ_{tW})	Re $V_L \leq 0.83$ Re $V_L \geq 1.07$
Re $V_R \leq -0.111$ Re $V_R \geq 0.18$	(ρ_+)	Re $V_R \leq -0.0015$ Re $V_R \geq 0.0032$
$\lvert \mathrm{Im}\ V_R \rvert \geq 0.14$	(ρ_+)	$\lvert \mathrm{Im}\ V_R \rvert \gtrsim 0.01$
Re $g_L \leq -0.083$ Re $g_L \geq 0.051$	(ρ_+)	Re $g_L \leq -0.0019$ Re $g_L \geq 0.00090$
$\lvert \mathrm{Im}\ g_L \rvert \geq 0.065$	(ρ_+)	$\lvert \mathrm{Im}\ g_L \rvert \gtrsim 0.006$
$\lvert \mathrm{Re}\ g_R \rvert \geq 0.056$	(A_+)	Re $g_R \leq -0.33$ Re $g_R \geq 0.76$
$\lvert \mathrm{Im}\ g_R \rvert \geq 0.115$	(A_{FB}^N)	–

TIME FOR THE WINE!

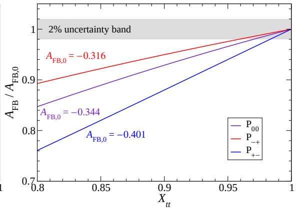
THANK YOU

ILC: X_{tt}^L dependence of observables

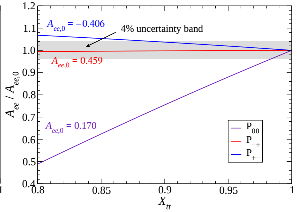
Total xsec



FB asymmetry



Sample spin asymmetry



- ★ Statistical errors $\lesssim 0.5\%$ for $L = 1000\ \mathrm{fb}^{-1}$ and any beam polarisation
- ★ Reasonable (?) systematic errors: $\Delta\sigma/\sigma = 5\%$
 $\Delta A_{\mathrm{FB}}/A_{\mathrm{FB}} = 2\%$ $\quad \Delta A_{ee}/A_{ee} = 4\%$
- ★ Precision $\Delta X_{tt}/X_{tt} \simeq 0.02$ for P_{00} or P_{+-}
- ★ A_{ee} very sensitive for P_{00} ☞ Use LHC input on anomalous Wtb couplings

Expected precisions for LHC measurements:

$$t\text{-channel}: \qquad \frac{\Delta\sigma}{\sigma} = 1.8\%\ (\text{stat}) \oplus 10\%\ (\text{sys})$$

$$s\text{-channel}: \qquad \frac{\Delta\sigma}{\sigma} = 20\%\ (\text{stat}) \oplus 48\%\ (\text{sys})$$

$$tW: \qquad \frac{\Delta\sigma}{\sigma} = 6.6\%\ (\text{stat}) \oplus 19.4\%\ (\text{sys})$$

$$R: \qquad \Delta R = 0.5\%\ (\text{stat}) \oplus 5\%\ (\text{sys}) \quad (?)$$

Back

Measuring V_{td}, V_{ts}, V_{tb} at LHC

Fit top mixings V_{td}, V_{ts}, V_{tb} combining constraints from

$$R = \frac{\mathrm{Br}(t \to Wb)}{\mathrm{Br}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

and single top xsec, in final states with a b-tagged jet

$$\begin{aligned}
\sigma(tj) &= \left[678.6\,|V_{td}|^2 + 270.2\,|V_{ts}|^2 + 149.1\,|V_{tb}|^2\right] R \text{ pb} \\
\sigma(\bar{t}j) &= \left[233.3\,|V_{td}|^2 + 163.0\,|V_{ts}|^2 + 84.17\,|V_{tb}|^2\right] R \text{ pb} \\
\sigma(t\bar{b}) &= 4.28\,|V_{tb}|^2 R \text{ pb} \\
\sigma(\bar{t}b) &= 2.61\,|V_{tb}|^2 R \text{ pb} \\
\sigma(tW) &= \left[259.4\,|V_{td}|^2 + 59.78\,|V_{ts}|^2 + 27.57\,|V_{tb}|^2\right] R \text{ pb} \\
\sigma(\bar{t}W) &= \left[94.81\,|V_{td}|^2 + 59.78\,|V_{ts}|^2 + 27.57\,|V_{tb}|^2\right] R \text{ pb}
\end{aligned}$$

Back

Form factors including b mass $\quad (x_b = m_b/mt, x_W = M_W/m_t)$

$$A_0 = \frac{m_t^2}{M_W^2}\left[|V_L|^2 + |V_R|^2\right]\left(1 - x_W^2\right) + \left[|g_L|^2 + |g_R|^2\right]\left(1 - x_W^2\right) - 4x_b \,\mathrm{Re}\,\left[V_L V_R^* + g_L g_R^*\right]$$
$$- 2\frac{m_t}{M_W}\mathrm{Re}\,\left[V_L g_R^* + V_R g_L^*\right]\left(1 - x_W^2\right) + 2\frac{m_t}{M_W}x_b\,\mathrm{Re}\,\left[V_L g_L^* + V_R g_R^*\right]\left(1 + x_W^2\right)$$

$$A_1 = \frac{m_t^2}{M_W^2}\left[|V_L|^2 - |V_R|^2\right] - \left[|g_L|^2 - |g_R|^2\right] - 2\frac{m_t}{M_W}\mathrm{Re}\,\left[V_L g_R^* - V_R g_L^*\right] + 2\frac{m_t}{M_W}x_b\mathrm{Re}\,\left[V_L g_L^* - V_R g_R^*\right]$$

$$B_0 = \left[|V_L|^2 + |V_R|^2\right]\left(1 - x_W^2\right) + \frac{m_t^2}{M_W^2}\left[|g_L|^2 + |g_R|^2\right]\left(1 - x_W^2\right) - 4x_b\,\mathrm{Re}\,\left[V_L V_R^* + g_L g_R^*\right]$$
$$- 2\frac{m_t}{M_W}\mathrm{Re}\,\left[V_L g_R^* + V_R g_L^*\right]\left(1 - x_W^2\right) + 2\frac{m_t}{M_W}x_b\,\mathrm{Re}\,\left[V_L g_L^* + V_R g_R^*\right]\left(1 + x_W^2\right)$$

$$B_1 = -\left[|V_L|^2 - |V_R|^2\right] + \frac{m_t^2}{M_W^2}\left[|g_L|^2 - |g_R|^2\right] + 2\frac{m_t}{M_W}\,\mathrm{Re}\,\left[V_L g_R^* - V_R g_L^*\right] + 2\frac{m_t}{M_W}x_b\,\mathrm{Re}\,\left[V_L g_L^* - V_R g_R^*\right]$$

$$C_0 = \left[|V_L|^2 + |V_R|^2 + |g_L|^2 + |g_R|^2\right]\left(1 - x_W^2\right) - 2x_b\,\mathrm{Re}\,\left[V_L V_R^* + g_L g_R^*\right]\left(1 + x_W^2\right)$$
$$- \frac{m_t}{M_W}\mathrm{Re}\,\left[V_L g_R^* + V_R g_L^*\right]\left(1 - x_W^4\right) + 4x_W x_b\,\mathrm{Re}\,\left[V_L g_L^* + V_R g_R^*\right]$$

$$C_1 = 2\left[-|V_L|^2 + |V_R|^2 + |g_L|^2 - |g_R|^2\right] + 2\frac{m_t}{M_W}\mathrm{Re}\,\left[V_L g_R^* - V_R g_L^*\right]\left(1 + x_W^2\right)$$

$$D_0 = \frac{m_t}{M_W}\mathrm{Im}\,\left[V_L g_R^* + V_R g_L^*\right]\left(1 - 2x_W^2 + x_W^4\right)$$

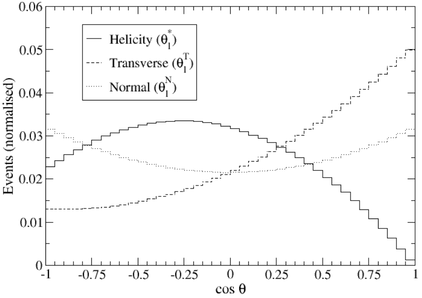
$$D_1 = -4x_b\,\mathrm{Im}\,\left[V_L V_R^* + g_L g_R^*\right] - 2\frac{m_t}{M_W}\mathrm{Im}\,\left[V_L g_R^* - V_R g_L^*\right](1 - x_W^2)$$

Back

How to measure polarisation fractions?

ℓ distributions in W rest frame $(P = 1)$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^X} = \frac{3}{8}(1+\cos\theta_\ell^X)^2\, F_+^X + \frac{3}{8}(1-\cos\theta_\ell^X)^2\, F_-^X + \frac{3}{4}\sin^2\theta_\ell^X\, F_0^X$$



θ_ℓ^* → angle between ℓ, $\vec{q}$
determine F_+, F_0, F_-

θ_ℓ^T → angle between ℓ, $\vec{T}$
determine F_+^T, F_0^T, F_-^T

θ_ℓ^N → angle between ℓ, $\vec{N}$
determine F_+^N, F_0^N, F_-^N

How to measure polarisation fractions?

…and when $P \neq 1$, distributions determined by "effective" Fs

$$\tilde{F}_{+}^{T,N} = \left[\frac{1+P}{2} F_{+}^{T,N} + \frac{1-P}{2} F_{-}^{T,N} \right]$$

$$\tilde{F}_{-}^{T,N} = \left[\frac{1+P}{2} F_{-}^{T,N} + \frac{1-P}{2} F_{+}^{T,N} \right]$$

$$\tilde{F}_{0}^{T,N} = F_{0}^{T,N}$$

of course, F_+, F_0, F_- determined independently of P

Back